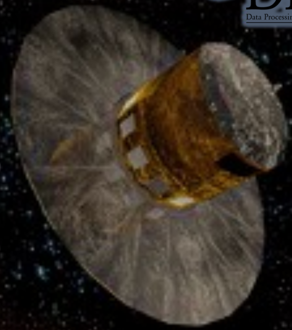
Stellar multiplicity seen from Gaia

... and here by van Gogh (La Nuit étoilée, 1889)

Frédéric Arenou (@obspm.fr)
IR CNRS, Observatoire de Paris / PSL
Gaia CU4/NSS lead



Why binaries ?

Motivations

Gaia DPAC

Scientific motivations

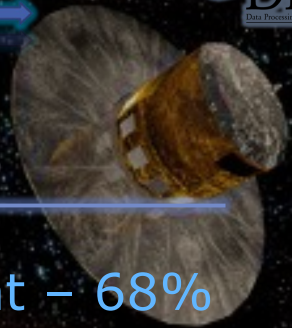
« Our uncertainties about binary star systems (and triples and so on) limit our capabilities in literally every single one of the Thematic Areas identified for Astro2020 »

- First sentence of the abstract of the Astro2020 Science White Papers by Price-Whelan et al., 2019, Stellar multiplicity: an interdisciplinary nexus, Bulletin of the AAS, 51(3)

More poetic motivations

« Binary stars are the cosmic choreographers of the universe, revealing their secrets through an eternal dance. They not only illuminate the depths of space but also provide invaluable insights into the fundamental forces and laws that govern our celestial tapestry.»

- OpenAI ChatGPT-3.5



Outline

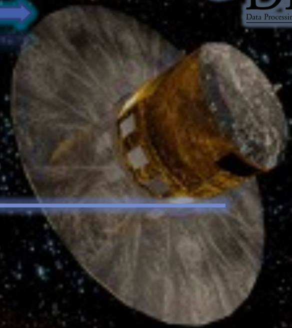
- Introduction – 10%
  - Multiple systems
  - Formation
  - Statistics
- Different kind of binaries – 28%
  - All the zoo
  - History
  - More than binaries
- Gaia processing of binaries – 41%
  - For all types
    - Formulae and methods
  - Combinations
- Gaia DR3 NSS content – 68%
  - Documentation summary
  - Mass estimation
  - Limitations
- e/DR3 scientific exploitation - 85%
  - DPACP-100
  - Long-term
  - Compact companions
  - Pulsating binaries
  - Methodology
- What is planned for DR4 – 100%
  - All the zoo
  - Conclusion

Why binary stars are important

- Stellar formation and evolution, galactic structure
  - Our Galaxy would look very different if all the stars were single.
  - Stellar evolution:
    - typical product of formation processes
    - possible abrupt end in supernovae.
  - Their role in the evolution of the Galaxy is therefore fundamental.

- Contribute to the measurement of stellar and galactic properties
  - Some types of binary stars allow direct measurements of certain physical quantities.
  - They represent an essential tool
    - In stellar physics, e.g. to weigh stars or measure their radius, estimate the age
    - In galactic physics by measuring the galactic potential via wide binaries, the highly energetic phenomena of interacting compact binaries, the study of galactic chemical evolution by type Ia supernovae, the distance scale by eclipsing binaries, etc.
  - Must realise that most are unresolved in many types of astronomical observations
    - So they disturb the inference on the various physical properties

- They are very common !



Motivations for this topic

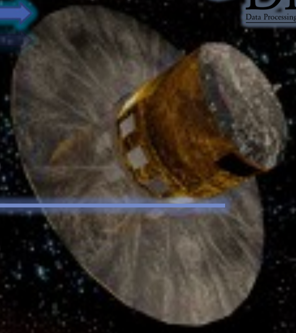
- Inferring the properties of NSS has always been difficult
  - Various detection methods each covering a small parameter range only
  - Complete samples are always much too small
  - Many selection functions, known or unknown → biases
- At the end of the Gaia mission, we will get for the first time :
  - A potentially huge survey of binaries/multiples
  - Capability of getting volume-limited samples for statistical studies
  - Through many detection methods, covering the full period range:
    - CU4 NSS Eclipsing binaries (+ much larger variability/CU7 sample)
    - CU4 NSS Spectroscopic binaries (SB): orbits, trends
    - CU4 NSS Astrometric binaries (AB): orbits, accelerations
    - CU8 DSC/MSC (multiple star)
    - CU3 common proper motions, separations large enough
- Exoplanets and brown dwarfs are also present
  - Although their nature + probably their formations, are different from stars
  - As they have just a smaller astro/photometric or spectroscopic signature.

Observation of binaries

Observing multiple stars

- Observational problems / capabilities
  - Binary systems cover all mass range,
    - From brown dwarf companions to massive twins,
  - and the range of orbital periods,
    - from hours to millions of years,
  - they are therefore only detectable by different techniques.

- In what follows, we will always distinguish as
  - « binary » the objects where the instrumentation makes it possible to ensure they are gravitationally bounded (e.g. orbital motion)
  - from « doubles » for which a doubt on the physical association can remain.
  - (same difference also between “ternary” and “triple” systems)



Binaries : Orbits

- Kepler's third law can be written as $a^3/P^2 = GM/(4\pi^2)$
  - where M is the total mass of the system, G the gravitational constant, P the period, and a the semi-major axis of the orbit.
  - In physical units adapted to the problem of double stars, we therefore have $(M_1 + M_2) = (å/\varpi)^3 / P^2$
  - giving the sum of the masses M_1 (for the primary star) and M_2 (the secondary object) in solar mass, $å = å_1 + å_2$ the measured semi-major axis of the relative orbit in angular units (e.g. mas), ϖ is the annual parallax in the same unit, and P the orbital period in years.

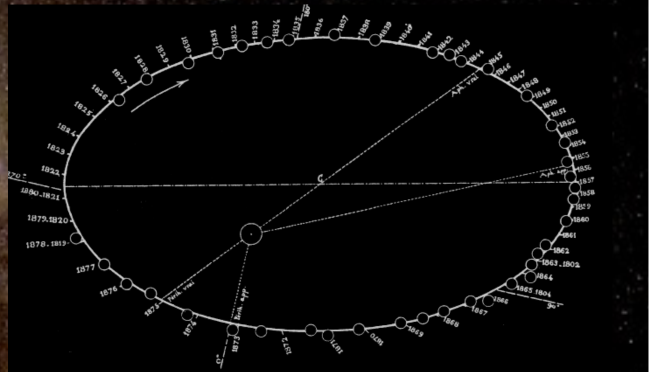
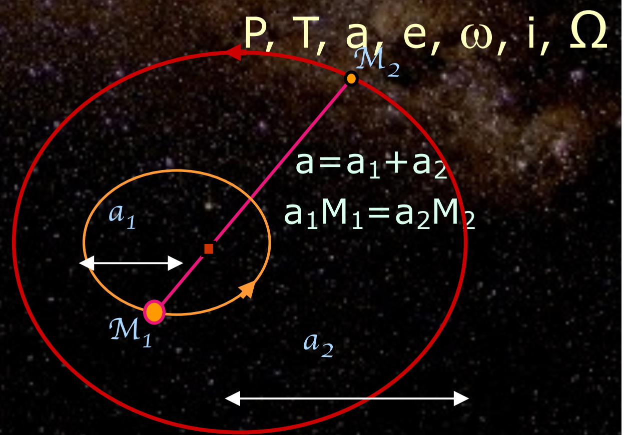


Fig. 73. — Orbite apparente de l'étoile double ξ Grande Ourse.

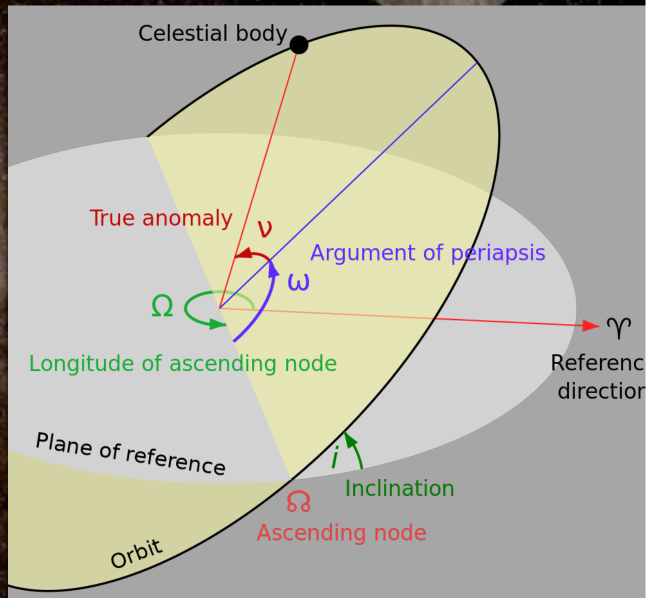
- Since the work of Herschel (William), the relative positions of the secondary are usually identified in polar coordinates with the separation ρ (usually in seconds of a degree) between the components, and the angle of position θ in degrees, counted positively from the North towards the East since Herschel (John).
- The trajectory of the secondary star relatively to the primary is a homothetic orbit of that of each component around the center of mass
- For astrometric binaries, what is obtained is the semi-major axis of the photocenter $å_0$, (= $å_1$ if the secondary is too faint). All that can be obtained is the astrometric mass function
  - $(M_1 + M_2)\,(B - ß)^3 = (å_0/\varpi)^3 / P^2$
  - With $B = M_2/(M_1+M_2)$ and $ß = L_2/(L_1+L_2)$ the mass and luminosity fractions

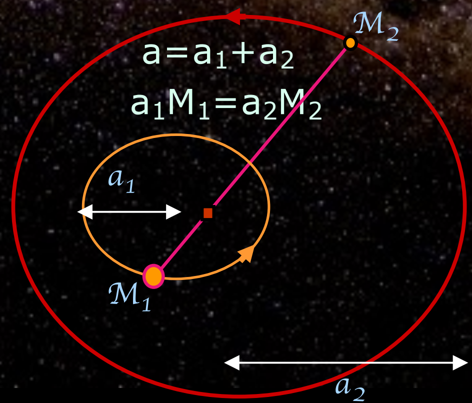


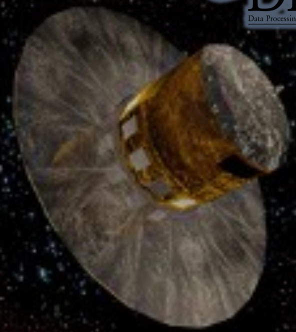
- *Suffix 1 for primary, 2 for secondary, 0 for photocenter*
- *Primary is the more massive (theorists)… or brightest (observers)*
- *We note $å_0$ the semi-major axis of the photocenter in angular units while $a_0 = å_0/\varpi$ is in au.*

Binaries : Orbits

- The elements P, T, a, e, i, ω, Ω, are called the Campbell elements .
- T is the epoch of passage through periastron,
- ω is the argument of periastron, the angle between node and periastron, in the plane of the true orbit and in the direction of the motion of the companion
- Ω is the position angle (measured from north through east) of the line of nodes joining the intersections of the true orbital and tangent planes. The ascending node is the node where the motion of the companion is directed away from the Sun. As it can be determined by radial-velocity measurements only, the value < 180° is used if the ascending node is unknown.
- *i* is the orbital inclination. This is the angle between the plane of projection and the true orbital plane. For 0° ≤ i < 90° the motion of the companion is direct (increasing position angles). For 90° < i ≤ 180° the motion is called retrograde.
- To simplify the orbit determination, one may use, instead of the 3 angles+a the so-called Thiele–Innes elements A,B,F,G:
  - $A = a (\cos\omega \cos\Omega - \sin\omega \sin\Omega \cos i)$
  - $B = a (\cos\omega \sin\Omega + \sin\omega \cos\Omega \cos i)$
  - $F = -a (\sin\omega \cos\Omega + \cos\omega \sin\Omega \cos i)$
  - $G = -a (\sin\omega \sin\Omega - \cos\omega \cos\Omega \cos i)$
- For astrometric binaries, what is obtained is the argument of periastron is ω_1 , while this is $\omega_2 = \omega_1 + \pi$ for resolved binaries





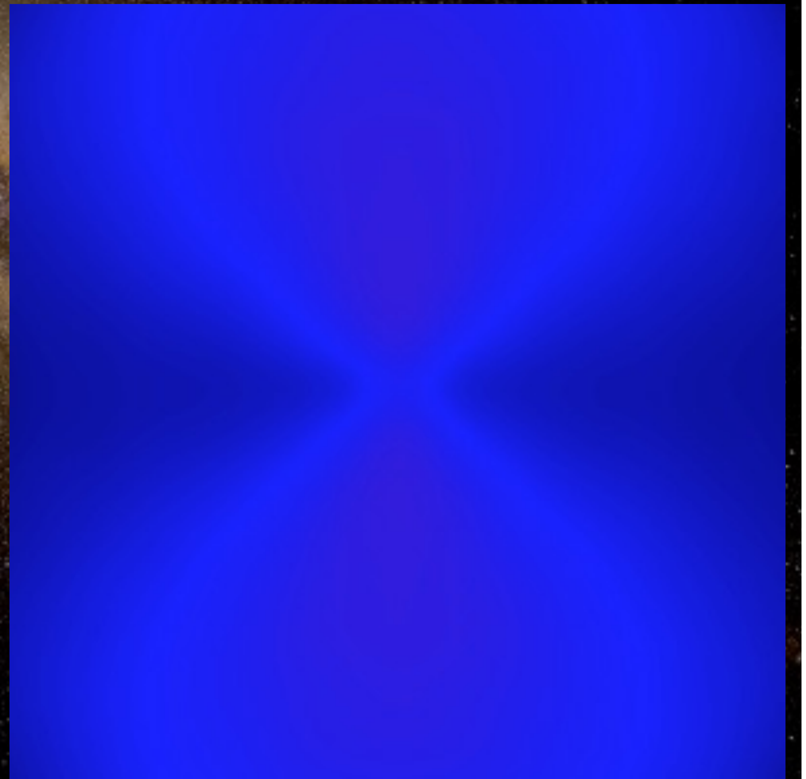


The beginnings

Formation and evolution

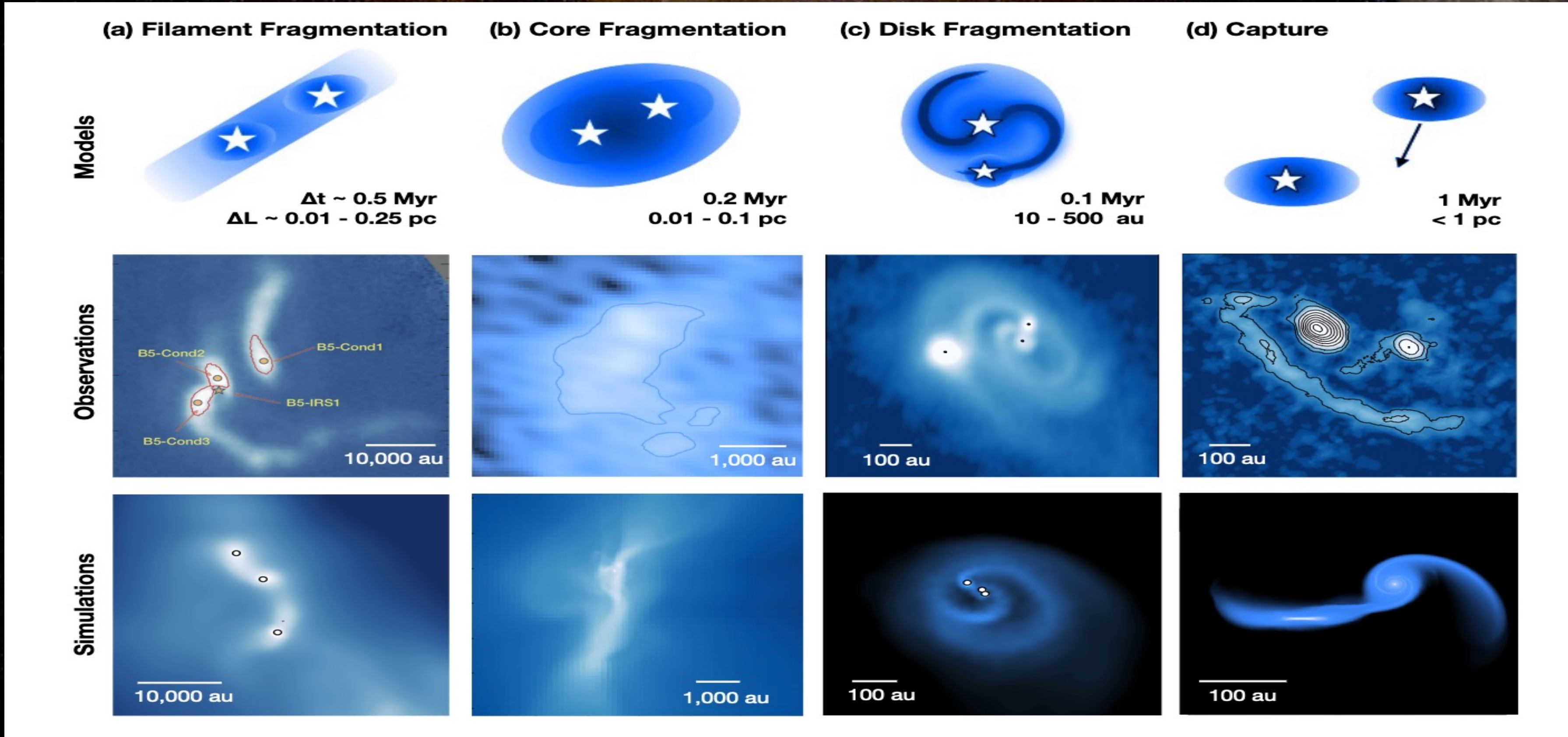
Formation of multiple stars

- Different mechanisms have been invoked in the past to explain the formation of multiple stars:
  - The broad scale of separation does not necessarily argue for a single formation mechanism.
  - fission, cluster disintegration, capture, fragmentation. This last mechanism seems to be the most frequent,
    - fragmentation of a dense molecular cloud (during its collapse, a cloud splits into several components)
    - disk fragmentation (a star and a disk are formed, the latter later splitting).
  - Capture requires, a process of subtracting kinetic energy, by tidal effect, via a disc, or 3th body.
  - Formation can continue by accretion, by dislocation (instability of multiples), or by interaction (in a cluster).



- Single stars are the exception, not the rule
  - The high multiplicity rate in the PMS phase unambiguously advocates that multiplicity is inherent to the star-formation process itself.

Formation of multiple stars



Top: Models and approximate range of time and length scales for various formation process.
Middle: Proposed observational examples: in Perseus (Pineda et al. 2015), in Ophiuchus (Kirk et al. 2017), in Perseus (Reynolds et al. 2021) and RW Aur (Rodriguez et al. 2018).
Bottom: numerical simulations. Guszejnov et al. (2021) Offner et al. (2016), Bate (2018), Muñoz et al. (2015).

Offner et al., 2023ASPC..534..275O

Detection and observing methods

- Despite the frequency of double or multiple objects, witnessing their formation is not easy. To enlighten one must therefore use:
  - at worst from observed parameters alone (separation and magnitudes),
  - at best from knowledge of the orbit (eccentricity and mass ratio).
  - characteristic signature in the component mass statistics
    - if there is a random capture and pairing mechanism, or if the matter condensed independently for the two protostars, or even if two very close embryos received the same amount of matter.
- Each method also provides access to different information and parameter domains:
  - from the short periods of eclipsing binaries to the longest periods of common proper motions,
  - spectral types and radial velocities of spectroscopic binaries or those with double spectra,
  - the luminosity of eclipsing binaries, the positions and motions of astrometric binaries.
  - No single method is optimal on its own:
    - E.g. access to the masses requires the combination of at least two techniques.


1,2,3 a lot
Statistics

Statistics of multiple stars

- Multiplicity fraction (aka sometimes as binary fraction)
  - the fraction of *primaries* with at least one companion
  - MF = (B + T + Q + …)/(S + B + T + Q + …)
    - where S, B, T, and Q are the # of single, binaries, triples, and quadruples
  - Triple/High-order fraction: THF = (T + Q + …)/(S + B + T + Q + …)

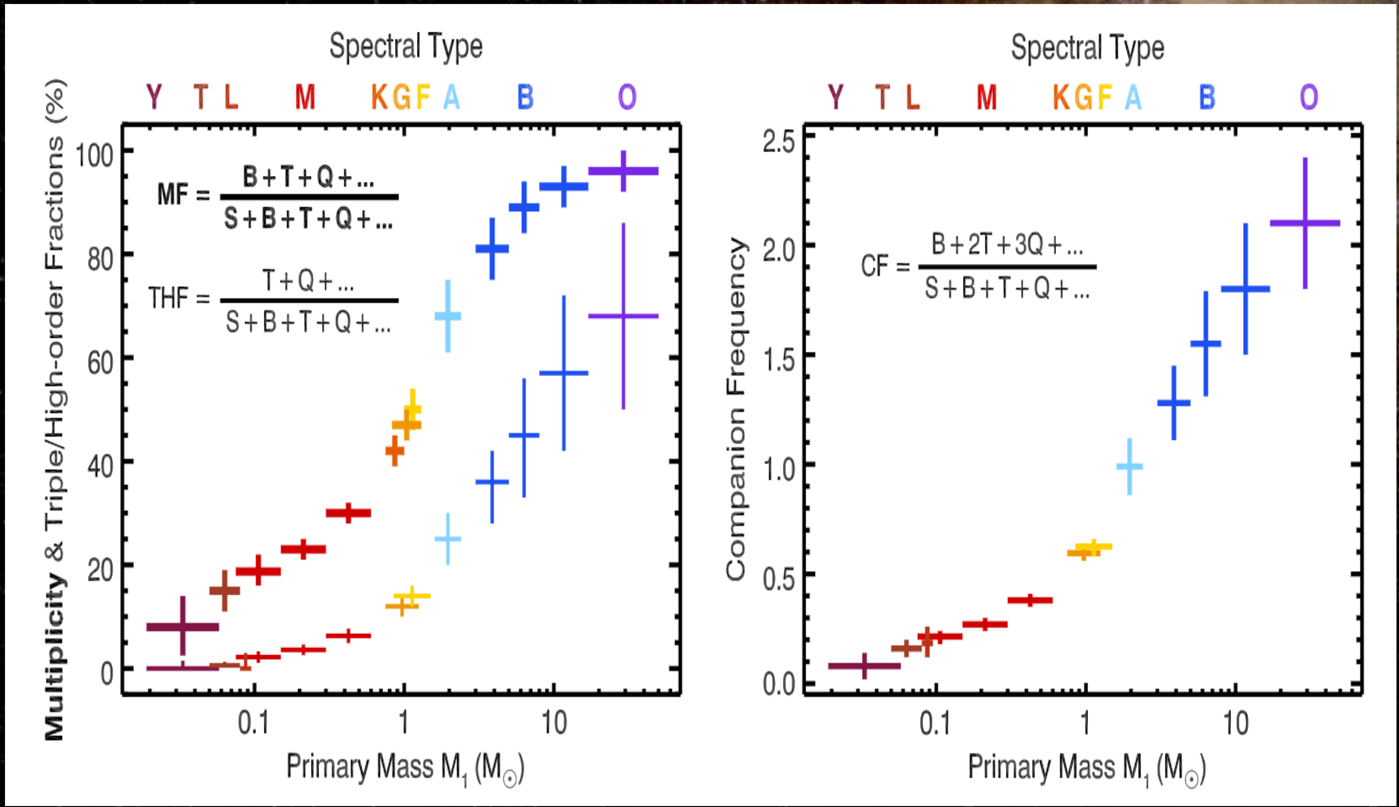
- The companion frequency
  - The average frequency of companions per *primary*
  - CF = (B + 2T + 3Q + …)/(S + B + T + Q + …)

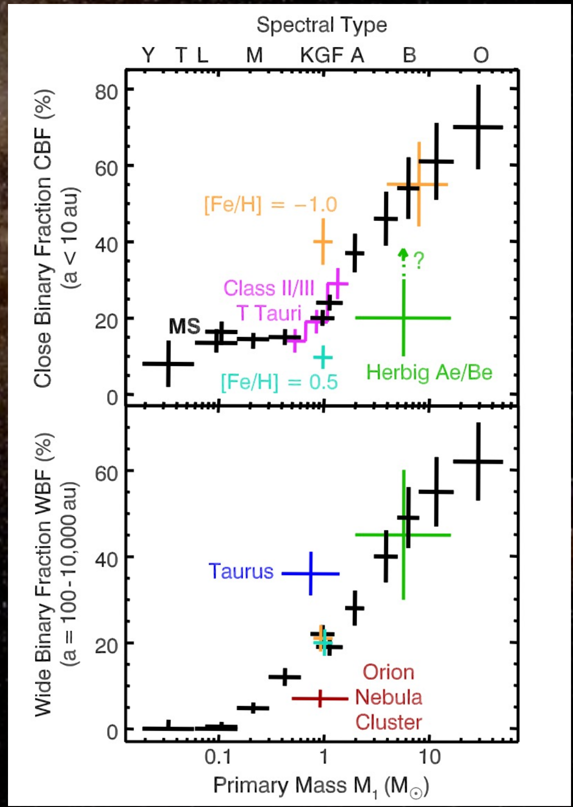
- Of interest (unbiased) are the statistics in volume-limited samples
- Although frequently we have magnitude-limited samples
  - Binaries almost twins are 0.75 mag brighter than analogous single stars
  - Corrections for Malmquist bias, sometimes called the Branch bias (Branch 1976) must be applied

Statistics of multiple stars

- Bias-corrected MS multiplicity fraction (left; thick)
- triple/high-order fraction (left; thin)
- companion frequency (right)

MS stars (thick black)
Close binary fraction (top)
Wide binary fraction (bot)

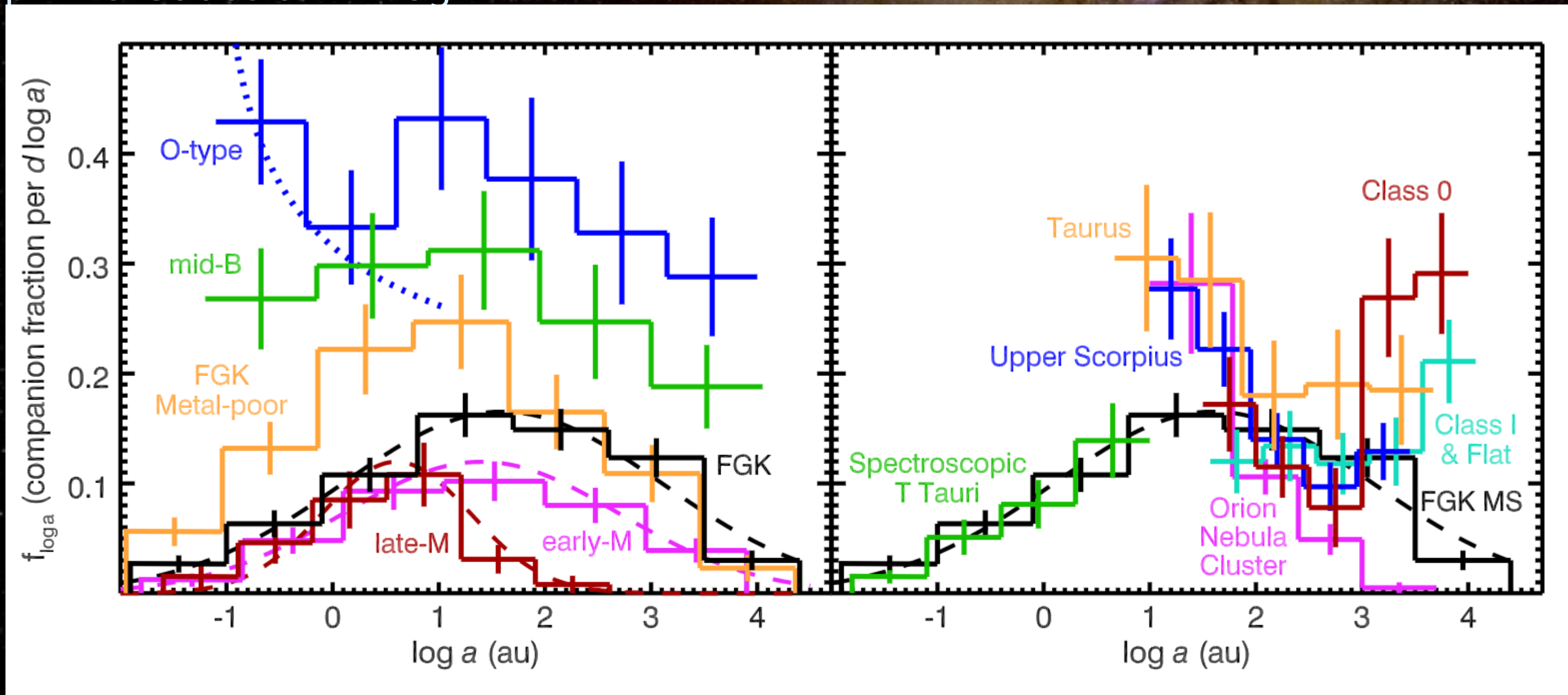




Offner et al., 2023ASPC..534..275O

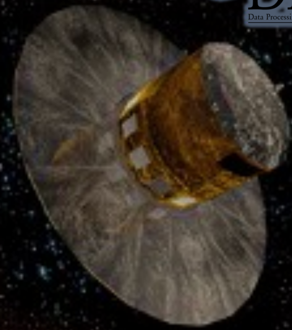
Statistics of multiple stars

- In the literature, pairs are often characterized as "close" or "wide,"
  - Close: < ~10 au, intermediate: 10 - 300 au, and wide separations > ~300 au
- Frequency of companions per decade of orbital separation
  - Left: separation distribution of MS binaries vs spectral type and metallicity.
  - Right: separation distribution of young solar-type binaries across different star-forming environments
  - Opik vs Gaussian in log



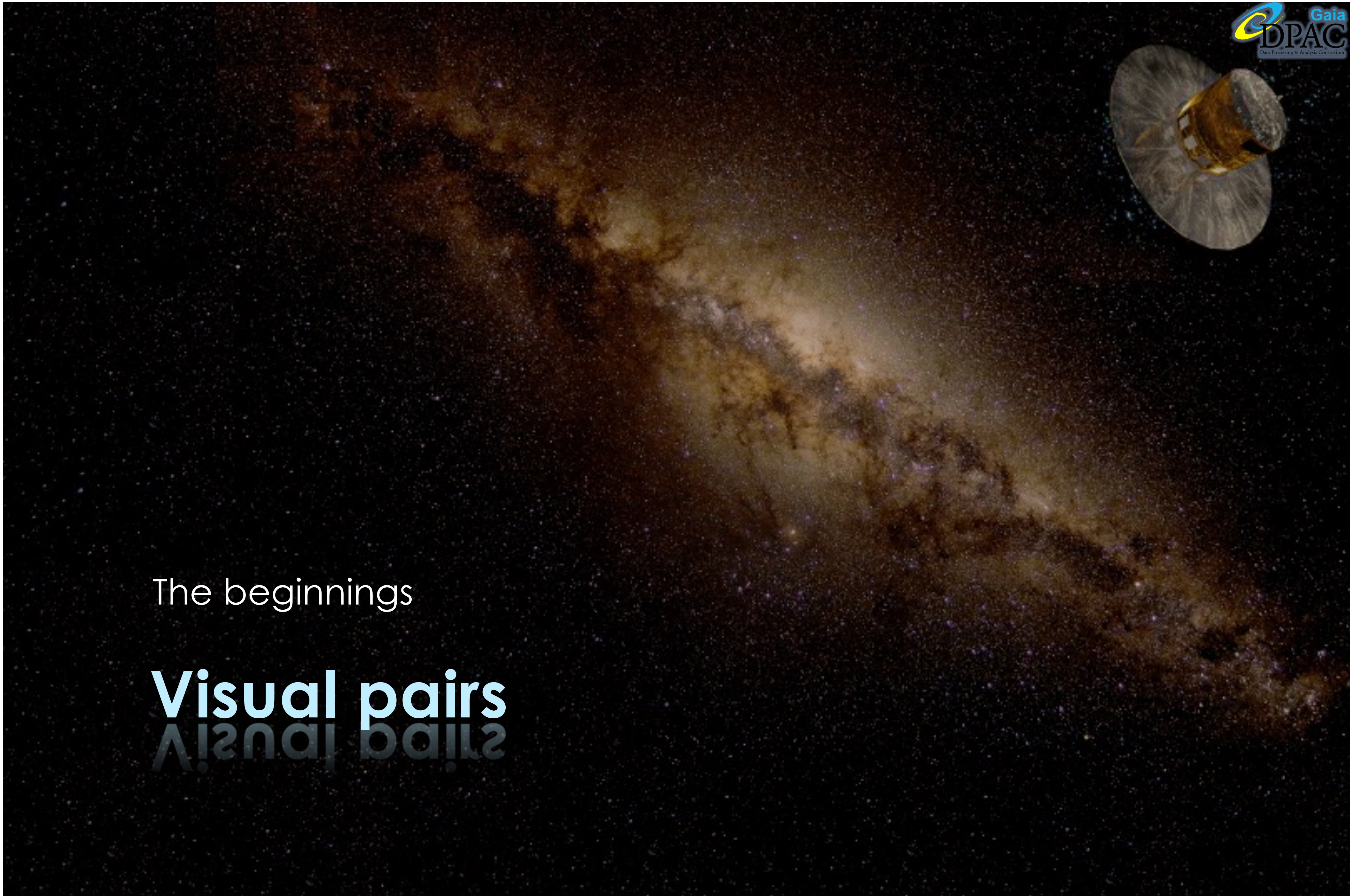
Offner et al., 2023ASPC..534..275O

Gaia DPAC



NB: Part of what follows is not *from* Wikipedia, it was written *for* wikipedia.fr 😃

Zoo of doubles and binaries



The beginnings

Visual pairs

Description

- A visual double star is
  - a pair of close stars on the sky
  - whose two components can be observed independently with an instrument such as a telescope,
    - this definition therefore depends in particular on the resolving power of the instrument.
  - Among these, visual *binaries* are those whose binary star property is revealed in general by the relative orbital motion of the secondary around the primary.

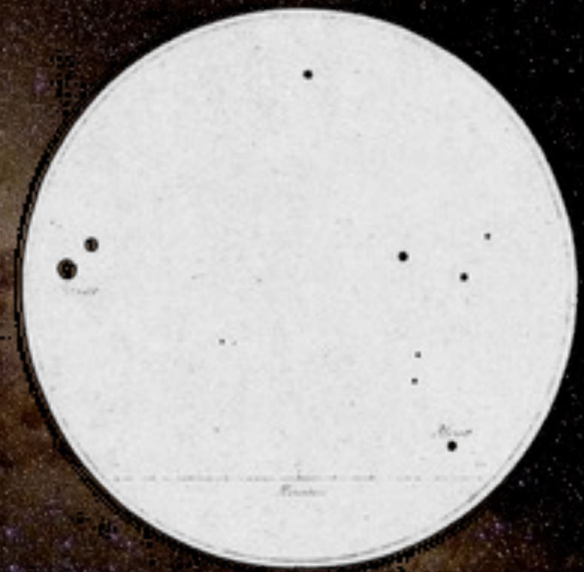


Fig. 70. — Mizar et Alcor dans le même champ.

Mizar A and B (left) are probably a couple physical, while Mizar with Alcor (right) possibly form an optical pair.
Figure: C. Flammarion (1882)

Optical doubles

- A couple of seemingly close stars
- But whose two components are actually separated by a great distance.
  - They appear as visual doubles because of their apparent proximity in projection on the sky and are therefore not true gravitationally bound binary stars.
- Historically, the debate to know if all the double stars observed were or not optical doubles essentially took place from the middle of the 18th century (Lambert, Michell) and was closed by William Herschel in 1803 with the discovery of the first binary stars
- Probability of dealing with a optical double
  - Under the simplifying assumption that the stars have in a small area of the sky a uniform surface density of stars per square arcsecond D with an apparent magnitude m,
  - The probability of having at least one star of magnitude m with a separation ρ from a given star is $P(\rho,m)=1-\exp(-\pi\, \rho^2\, D)$
  - At magnitude 20, observing one star within one arcsecond from another source: one chance out of 2 in the direction of the Baade window (galactic center), one out of 1000 in the direction of the galactic poles.

The beginnings

- Mizar and his jumper Alcor, with their 12' separation, have probably served as a visual acuity test since ancient times,
- the first use of the term « double star » originates from Ptolemy in the Almagest (~137):
  - these are ν1 and ν2 Sagittarii, with a separation of 14',
  - *"Quae in oculo [of Sagittarius] is nebulosa et bina"*
- The second act will be played out with the development of instrumentation: the invention of the astronomical telescope.
  - The history of double stars retains that the first "telescopic" double star is Mizar, but diverges as to the discoverer:
    - Was the Jesuit father Giovanni Baptista Riccioli in 1650 preceded by Benedetto Castelli, describing to his former master Galileo, on January 7, 1617 "una delle belle cose che siano in cielo"?

The beginnings

Date	Star	Author	Place
01-1617	Mizar	Benedetto Castelli	Pisa?
04-02-1617	θ1 Orionis (A,B,C)	Galileo	Bellosguardo
1650	Mizar	Father Giov.baptism.Riccioli	bologna
1656	θ1 Orionis (A,B,C)	Christiaan Huygens (D)	The Netherlands
20-03-1673	θ1 Orionis (D)	Jean Picard	
1664	γArietis	Robert Hooke	England
12-1685	α Crucis	Father Fontenay	Cape of good hope
1689	α Centauri	Father Richaud	Pondicherry
1719	Beaver	James Bradley	England
1753	61 Cygni	James Bradley	England

Catalogs

Date	Author (Catalog)	Number of pairs
1781	Christian Mayer	60
1782	William Herschel	269
1785	William Herschel	454
1827	Friedrich Georg Wilhelm Struve (STF)	3112
1906	SherburneWesley Burnham (BDS)	13665
1932	Robert Grant Aitken (ADS)	17180
1963	Jeffers, van de Bos, Greeby (IDS)	64247
1994	Dommanget & Nys (CCDM)	34031
1997	Hipparcos (DMSA)	23882
(May 2000)	Washington Double Star Catalog (WDS)	83286
2002	Tycho double star catalog (TDSC)	103259

- Initially these were chance discoveries, no systematic study was undertaken until the completion of the first Catalog of Double Stars by Christian Mayer at Mannheim in 1777-1778.

- The number of discoverers is much larger than the list above suggests.
  - E.g. the sons of Herschel (John) or of Struve (Otto).
  - On the other hand, the mentioned Catalogues contain on the one hand double (or multiple) stars which can be optical doubles as well as true binaries; on the other hand they are partly redundant:
  - in terms of pure discovery it seems that we should grant around 2640 to Wilhelm Struve, 1260 to Burnham, 4500 to Aitken and Hussey, at least 2996 for Hipparcos, 13250 for Tycho.

Visual binaries (I)

- The first confirmation of the existence of visual binaries was made by the astronomer-musician William Herschel on July 1st, 1802 before the Royal Society.
  - Difference between what Ptolemy called a "double star" and what he then called a binary star: "if a certain star should be situated at any, perhaps immense, distance behind another, and but little deviating from the line in which we see the first, we should have the appearance of a double star. But these stars being totally unconnected would not form a binary system. If, on the contrary, two stars should really be situated very near each other; and at the same time so far insulated as not to be materially affected by neighboring stars, remain united by the bond of their mutual gravitation toward each other".

- The idea itself was not new:
  - Christian Mayer in 1779: possibility of small suns orbiting larger ones,
  - Herschel (1782) had distanced himself at the time (premature assumption).
  - Lambert (1761) had argued that a binary should exhibit orbital motion, that this had not been observed ➔ optical doubles.
  - John Michell (1767), statistical argument: the probability was too low to find two such independent stars taken at random: "it is highly probable in particular, and next to a certainty in general, that such double stars... do really consist of stars placed together, and under the influence of some general law".

Visual binaries (II)

- Not Herschel's original idea
  - Bode's suggestion, in his comments on Mayer's catalog
    - Observation of pairs of unequal magnitude (the brightest being a priori the closest) could make it possible to measure proper motions
    - Study of the relative motion of double stars.
  - Using a similar argument, Herschel (1782) set about meticulously measuring a large number of pairs, beginning on November 11, 1776 with θ1 Orionis,
    - To measure a differential annual parallax
    - A suggestion made one century and a half earlier (1632) by Galileo: "...what great progress for astronomy? Because in this way, in addition to establishing the annual motion, we could come to know the size and the distance of the star. »
- Paradoxically, Herschel was not going to contribute on parallaxes
  - It will be necessary to wait for Bessel (1838) to acquire the first measure of parallax.
  - On the other hand, in a founding article of the study of binaries (1803), he was going to provide a list of orbital couples, with Castor first.
    - End of the controversy over the physical nature of a number of systems
    - Open way to prove both that Newton's law of gravitation was really universal (valid outside our solar system)
    - The stars could therefore have a different absolute magnitude (pairs of unequal magnitude)

Visual binaries (III): Orbits

- Mathematical proof: computing the orbit
  - Félix Savary (1827) calculated how to reconstruct the couple's orbit
    - non-trivial problem: the observed orbit is the projection on the tangent plane of the sky of the true orbit.
  - Savary's first « numerical application » was for ξ Ursae Majoris, with a 60 years period, this double having been discovered by Herschel on May 2, 1780,
  - His son John Herschel recalculated the orbit in 1831.
- The search and determination of orbits would then continue throughout the 19th and 20th centuries.
  - The Catalogue of Double and Multiple Stars in Certain Relative Motion by Camille Flammarion contained 819 pairs in 1878.
  - the Sixth Catalog of Visual Binary Star Orbits contained 3579 orbits of 3468 systems.

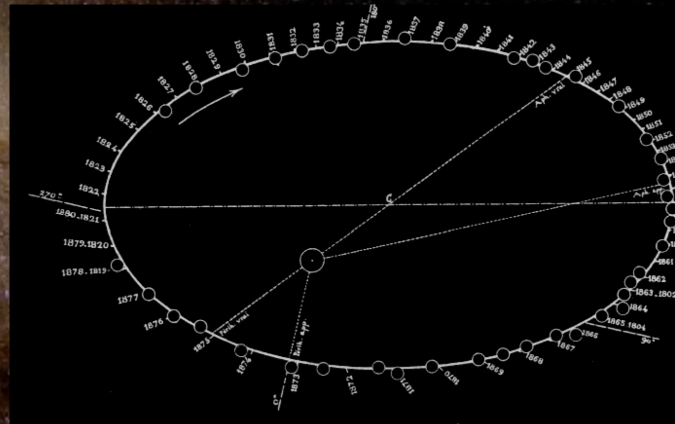
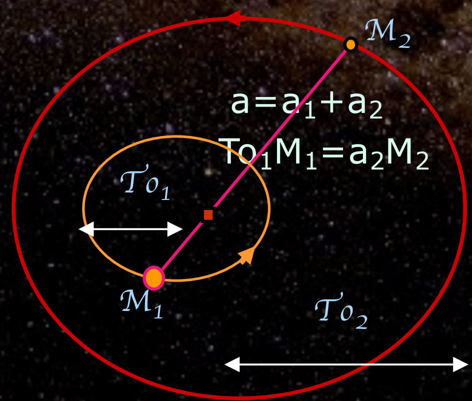
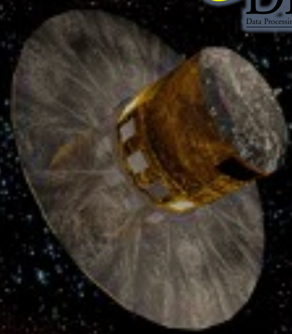


Fig. 73. — Orbite apparente de l'étoile double ξ Grande Ourse.

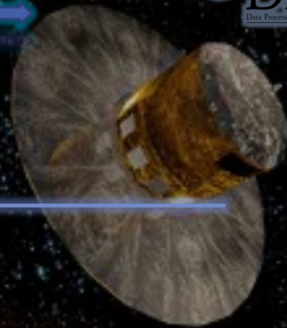
P, T, a, e, ω, i, Ω





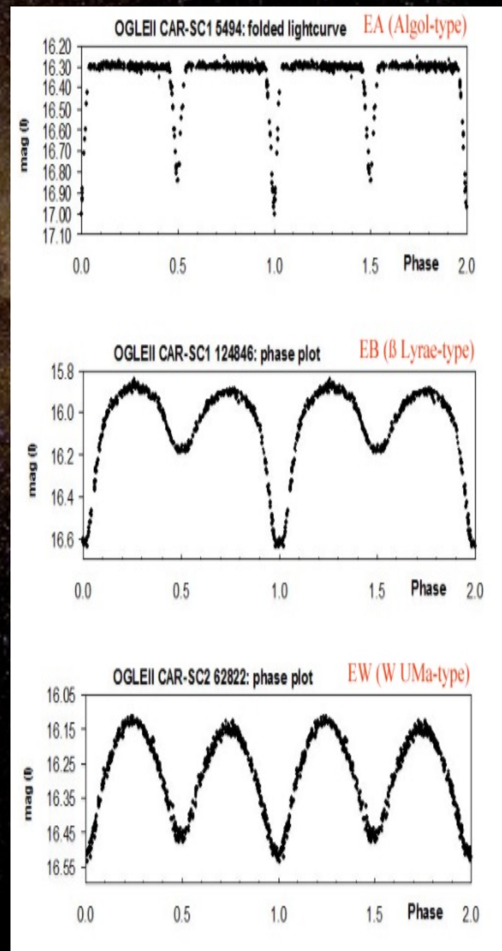
Hide and seek…

Eclipsing binaries



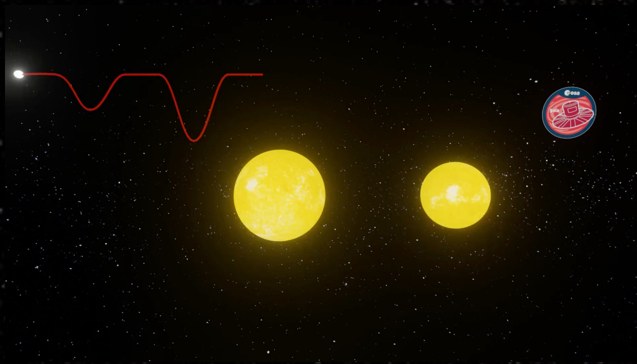
Description

- Has an orbital plane viewed almost edge-on
  - the normal to the orbit plane is ~ perpendicular to the line of sight
  - the components undergo mutual eclipses (occultations)
  - Observationally, the system appears as a variable star.
- Different types; when classified by the shape of the light curve:
  - the EA type, represented by Algol, having spherical or slightly elliptical components and a wide range of periods,
    - the light curve being characterized by constant periods alternated by periods of decrease in brightness;
  - the EB type, like β Lyrae, systems whose components are often semi-detached, one of the components filling its Roche lobe, with periods longer than one day,
    - often of early spectral type;
  - the EW type, like W Ursae Majoris, generally contact binaries, ellipsoidal components, with a period less than one day,
    - often of late spectral type.

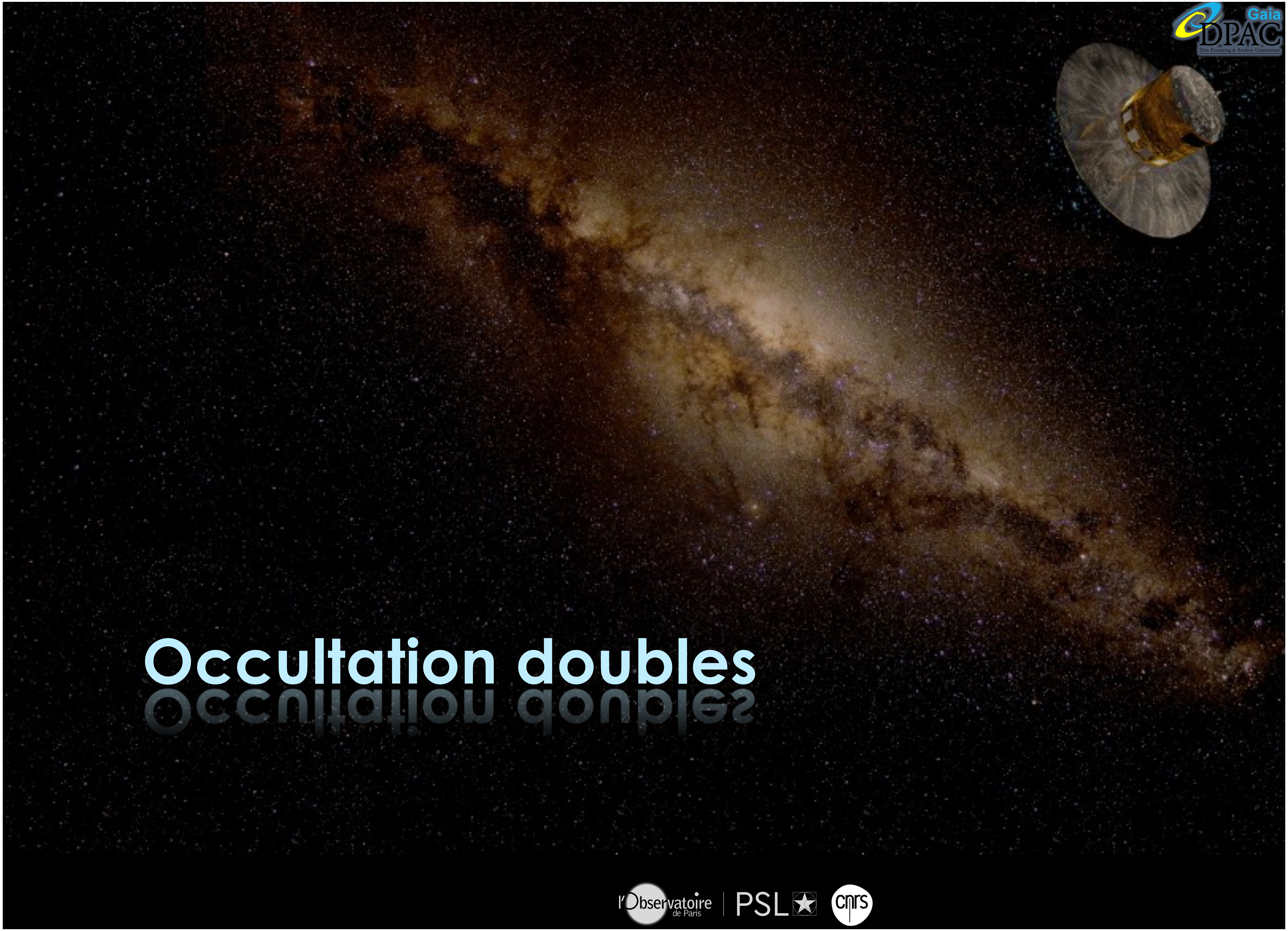


History

- Algol "the demon star"
  - A variability probably known since antiquity, forgotten until Montanari in 1667
- Then 1782 where John Goodricke Jr suspected this star to be periodically eclipsed
  - The young Goodricke (18 years old and deaf-mute!) determined a very precise period for this first known short-period variable,
  - He had the brilliant intuition that it "could hardly be explained otherwise than by... the interposition of a large body revolving around Algol..."
  - As we have seen, Herschel doubted it at that time and the confirmation of the Algol binarity had to wait more than a century for the discovery of spectroscopic binaries.

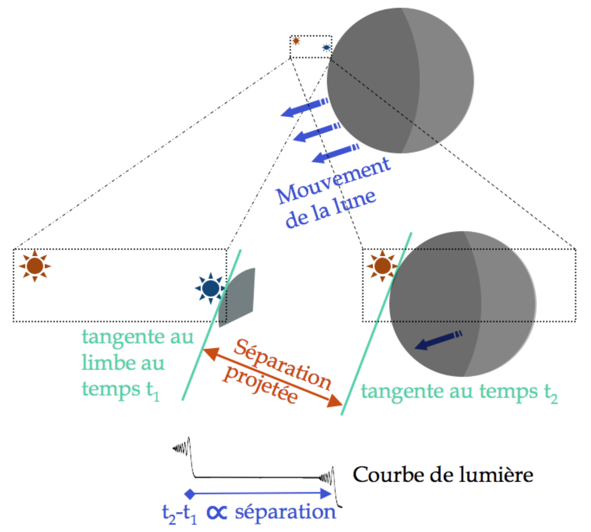


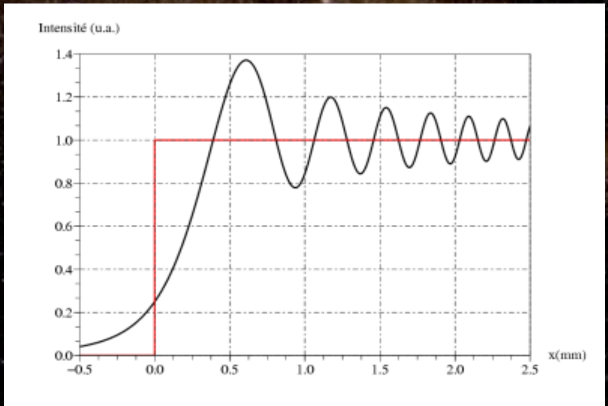
Occultation doubles



Definition

- The components are successively occulted by the Moon (or another body of the solar system) during the relative motion of this source with respect to the couple.
- Measurement of the time difference during the immersion (or emergence) of each component at the lunar edge,
  - this technique allows a high angular resolution, about a few thousandths of an arcsecond (mas)
- It is estimated that about 10% of occultation observations can lead to the discovery of the duplicity of the object.
- Mason's catalogue of occultation doubles (1995) contains 772 measurements for 357 systems.

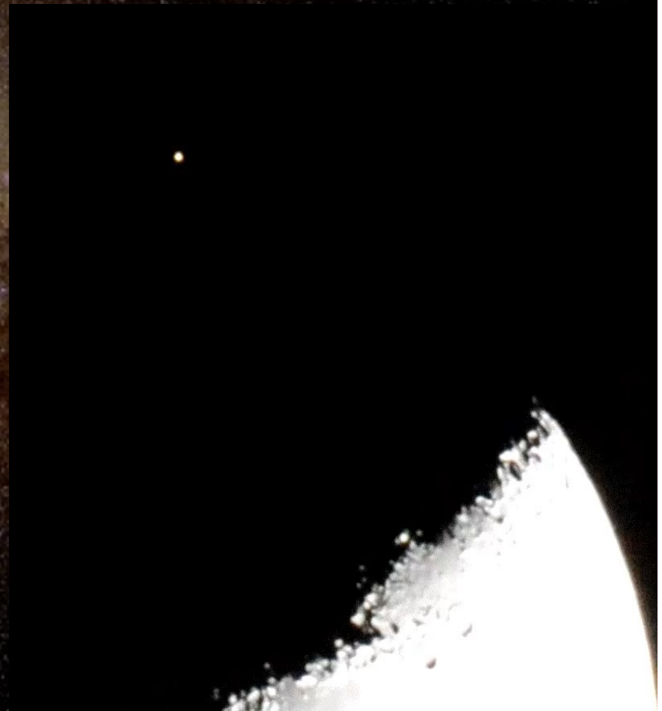




Diffraction by a screen edge

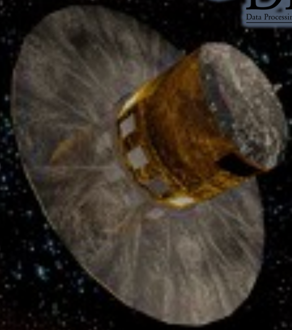
History

- The observation of stellar occultations is probably as old as humanity
  - one of the oldest mentions is in the Almagest
  - the first (+/-) usable indication of the moment of a stellar occultation waited until July 5, 1623: it is (Spica) observed in Paris by Ismaël Boulliau
- Antares (=Mars rival) is probably the first occultation double
  - A Professor Burg in Vienna, April 13, 1819: "*At 12:03:17.1 a.m. I observed the emergence of a star of magnitude 6.7, which after about 5 seconds suddenly appeared to me as a star of the first magnitude ... Perhaps Antares is a double star, and the small one seen first is so close to the main star that the two, even seen with a good telescope, does not appear separate*"
  - He was not believed at that time, the hypothesis of the refraction of a "lunar atmosphere" being favored
  - It was John Herschel who, in 1833, suggested that occultation measurements could bring high angular resolution to the detection of double stars.



… He saw it at the tip of his pen

Astrometric binaries



Description

- A star whose binarity is revealed by astrometry
  - Thanks to the orbital (non uniform) motion of the photocenter on the sky.
  - The two components generally not being (yet) resolved,
- In particular, when the companion is much fainter than the primary star, it is the reflex movement of the latter that is observed.
  - In general, this is the motion of the photocenter, not that of the primary

Motion of Sirius on the sky, after Camille Flammarion

History

- After being the first to accurately estimate a stellar parallax, that of 61 Cygni in 1838, Bessel would also accidentally discover the first two astrometric binaries
- In a letter of August 10, 1844, Bessel indicated that the proper motion of Sirius and Procyon was not uniform
  - After having eliminated various hypotheses, he correctly concluded in both cases the presence of a massive but dark body orbiting with a period of about half a century, a disturbing hypothesis which he justified by: "But light is no real property of mass. The existence of numerous visible stars can prove nothing against the existence of numberless invisible ones".
- Two years before Neptune's prediction
  - by Urbain Le Verrier two years later, of whom François Arago told that he "discovered the new planet at the tip of his pen".
- For the astrometric binaries, the confirmation required more time
  - It was first necessary to wait 7 years for the orbit of Sirius to be actually calculated (by Peters 1851),
  - the companion of Sirius was only seen in 1862 by Alvan Graham Clark and that of Procyon only in 1896 by John M. Schaeberle, thus transforming these astrometric binaries into visual binaries.
  - These new companions were the first known white dwarfs

Astrometric orbits

- Access to 5 parameters astrometric+ 7 orbital parameters

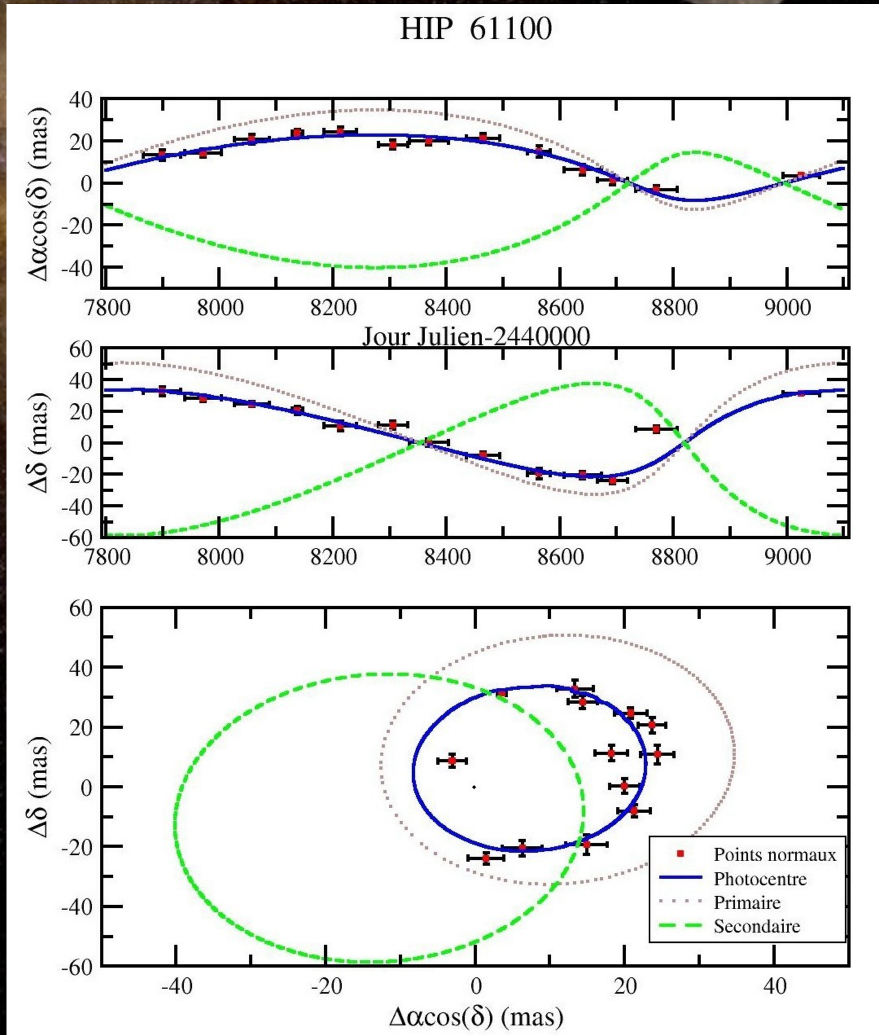
- Astrometric signature, if $M_2 << M_1$:

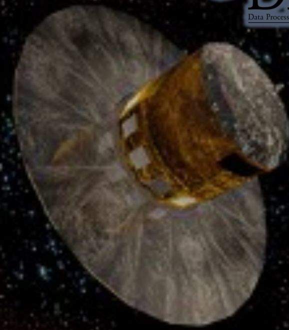
  - $\propto \cong \left(\frac{P}{M_1}\right)^{\frac{2}{3}} M_2 \varpi$

  - Sensitive to large periods, secondary masses, inversely proportional to distance

Photocentric orbit

- In the general case, the secondary may contribute to light
  - The photocenter is not on the primary
  - It may then have an orbit (with a semi-major axis which is not the one of the primary
- HIP 61100 (using Hipparcos data)
  - P ~ 1300 d,
  - semi-major axis $\mathring{a}_0$ ~ 31 mas
- The motion of the photocenter
  - depends on the mass ratio q
  - of the luminosity difference ΔH
  - $a_0 = a_1[1-(1+q^{-1})(1+10^{0.4}\ \Delta H)^{-1}]$



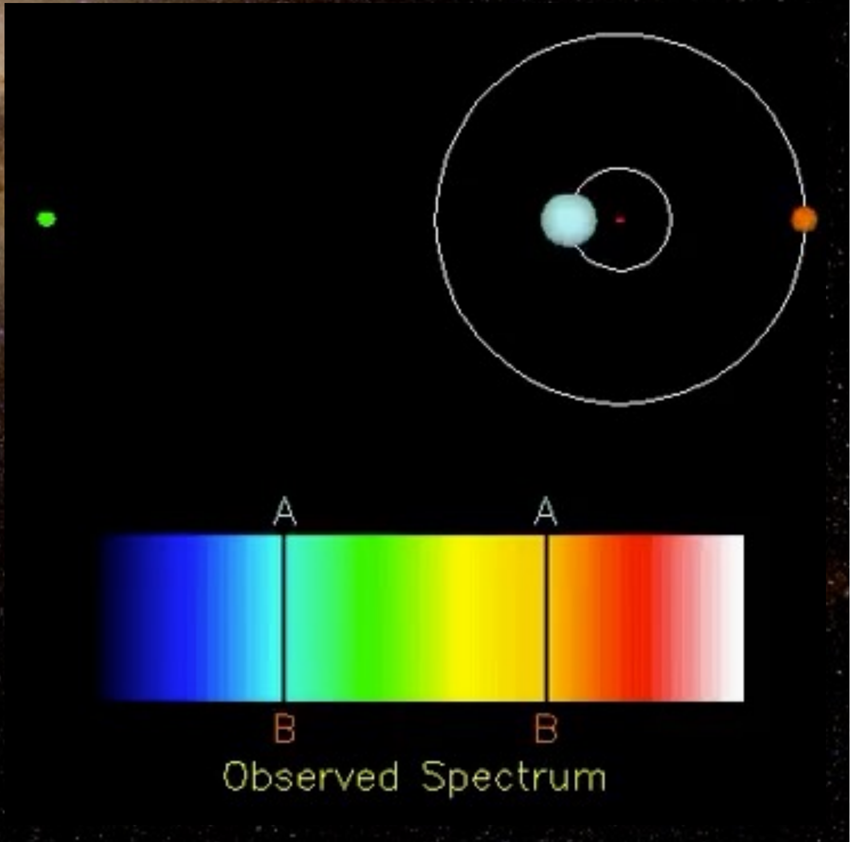


The start of stellar astrophysics

Spectroscopic binaries

Description

- Binary star whose orbital motion is evidenced by the variation of the radial velocity of one or both components of the system.
- This motion is measured using a spectrograph,
  - by observing the displacement by Doppler-Fizeau effect of the spectral lines of the star,
  - due to its orbital speed along the line of sight.
- This method has also led to the detection of a large number of the known extrasolar planets.
- Catalogue of spectroscopic binaries SB9:
  - 4021+ entries, 5040+ orbits as of today



Radial velocimetry

- Doppler effect

$$\mathbf{V_r} = \mathbf{c}\,\frac{\boldsymbol{\Delta\lambda}}{\lambda}$$

$$\mathbf{V_r} = \mathbf{V_\gamma} + \mathbf{K_1}\ [\mathbf{e}\cos\omega_1 + \cos(\omega_1 + \nu)]$$

- Obtained orbital parameters

$$\mathbf{P}, \mathbf{T}, \mathbf{e}, \omega_1 \text{ et}$$

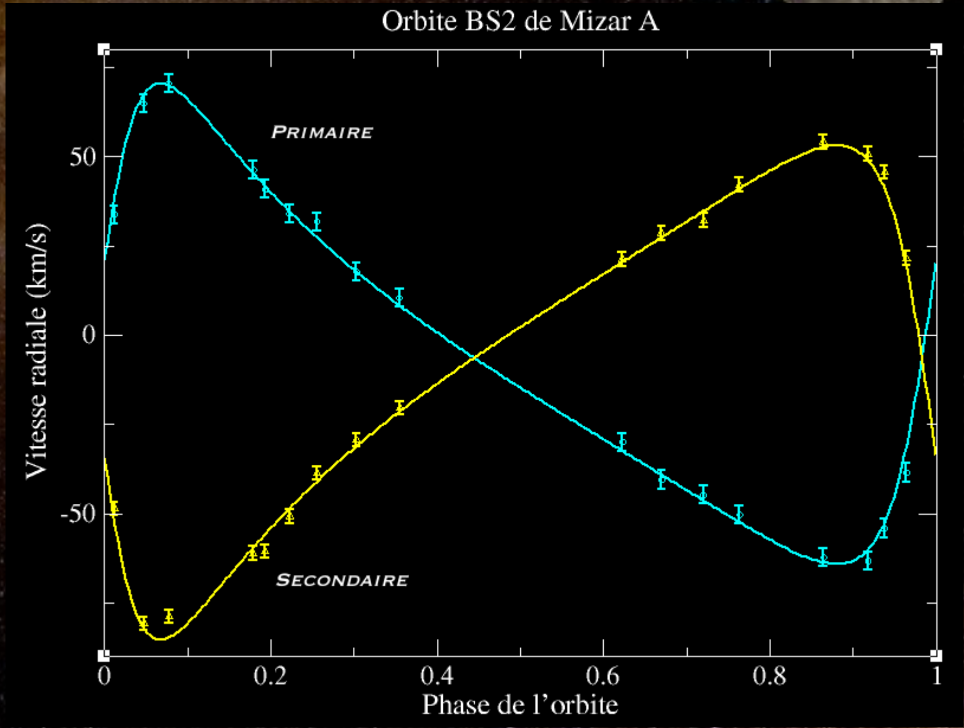
$$\mathbf{a_1}\sin\mathbf{i} = \frac{\mathbf{1}}{\mathbf{2\Pi}}\mathbf{K_1 P}\sqrt{\mathbf{1 - e^2}}$$

- Double-lined binary (SB2)

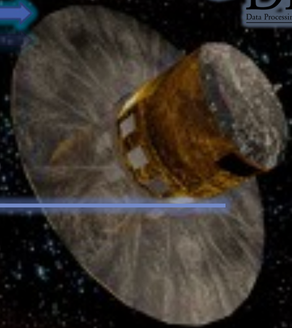
$$\mathbf{q} = \frac{\mathcal{M}_2}{\mathcal{M}_1} = \frac{\mathbf{K_1}}{\mathbf{K_2}} = \frac{\mathbf{a_1}}{\mathbf{a_2}}$$

- If $M_2 << M_1$:

$$\mathcal{M}_2 \sin\mathbf{i} \approx \left(\frac{\mathcal{M}_1}{\mathbf{P}}\right)^{\frac{2}{3}} \mathbf{a_1}\sin\mathbf{i}$$



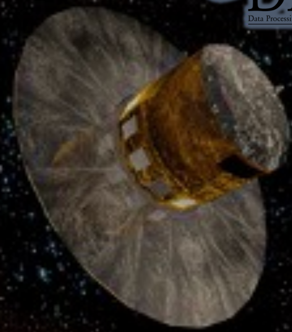
radial velocities of the two components of Mizar A, BS2



History

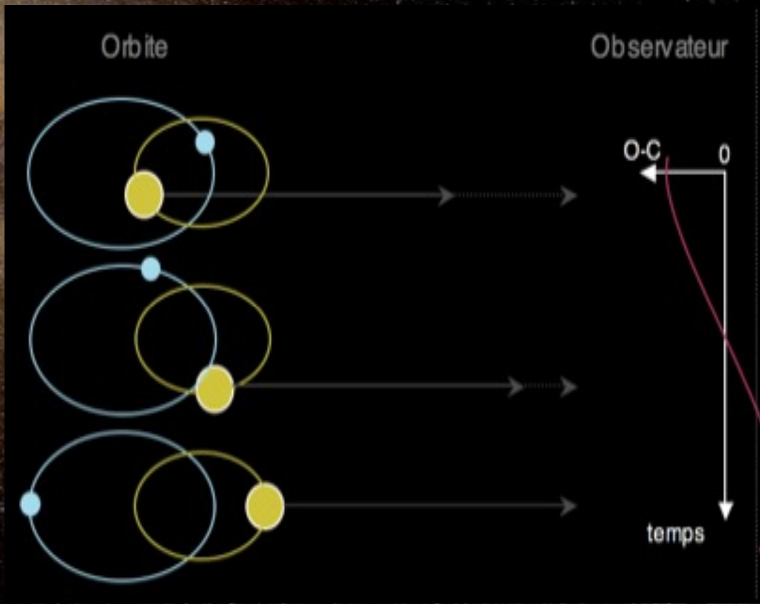
- Edward Charles Pickering saw lines doubled on Mizar in 1887
- Antonia C. Maury reobserved in 1889 and computed the orbit
  - Maury noticed that the spectral line K of calcium was sometimes fuzzy, sometimes double, with a periodicity of 52 days.
  - The hypothesis then formulated was that Mizar A was "*itself a double star with components of approximately the same luminosity, and too close together to have ever been visually resolved. Moreover, that the duration of revolution of the system is 104 days*. (Pickering, 1890).
  - Announced by Edward Charles Pickering on Nov. 13, 1889... and he authored the paper alone
  - Antonia C. Maury was thanked but not co-author of Pickering paper... Herschel asked Pickering *« to convey to Miss Maury my congratulations on having connected her name with one of the most notable advances in physical astronomy ever made »*.
  - She also found and computed the period of Beta Aurigae in 1889
  - Mizar:
    - Actually the period Mizar A is 20.5 days, the error coming from the highly eccentric orbit and the orientation of the major axis.
    - In 1908, Mizar B was also discovered as a spectroscopic binary, the secondary lines were too faint
    - Mizar is actually a visual binary, each of whose components, Mizar A and Mizar B are themselves spectroscopic binaries, making it a quadruple star.
- Hermann Carl Vogel observed the oscillatory phenomenon of Algol lines at the Potsdam Observatory, in November 1889:
  - Before a minimum in the light curve of this eclipsing binary, the star was moving away from the Sun, while it was approaching it after this minimum.
  - Not only was Algol's duplicity thus independently confirmed, but Vogel also gave an estimate of the diameters of Algol and its "companion", as well as the respective masses "4/9 and 2/9 solar mass".
  - In reality, Algol is now known to be at least a triple system, with the eclipsing couple having masses of 3.6 and 0.8 solar masses, respectively.

Light-travel time (LTT) binaries



Description

- A binary or multiple star
  - whose magnitude varies periodically
  - and whose orbital motion is evidenced by the change in this period (Light-Travel Time)
- The principle is that of a "clock in orbit",
  - whether it is a variable star, an eclipsing binary or a pulsar,
  - whose advance or delay shows that the object is approaching or moving away from the observer.
- Epoch of minima τ then $a_1 \sin i \sim \Delta \tau$
  - $K = (\tau_{max}-\tau_{min})/2$ = « semi-amplitude »



$$\tau = \frac{K}{\sqrt{1-e^2\cos^2\omega}}\left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega)+e\sin\omega\right]$$

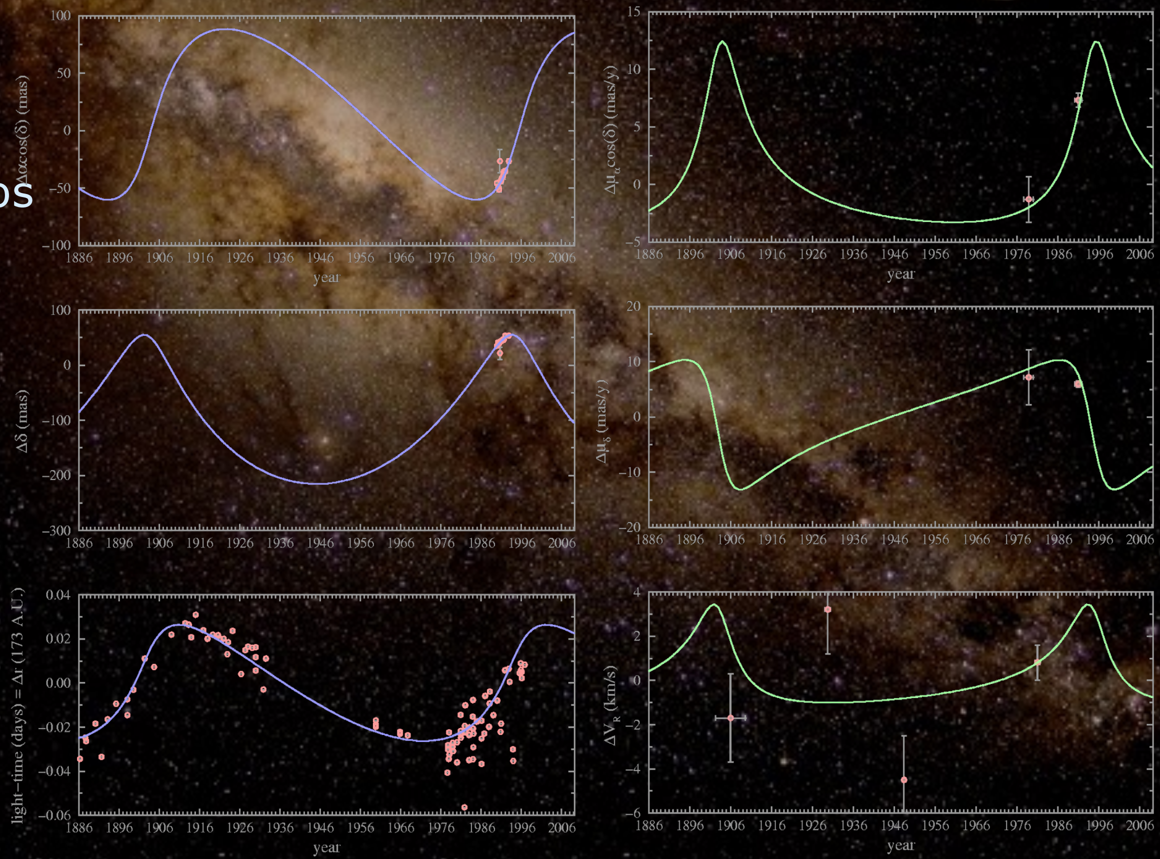
$$K = 499 a_1 \sin i \sqrt{1-e^2\cos^2\omega}$$

History

- The eclipsing binary Algol is a hierarchical triple system,
  - the eclipsing couple being of respective masses 3.6 and 0.8 solar masses, orbited with a period of 680 days by a companion of 1.6 solar masses.
- The first suggestion of the presence of a third body was made by Chandler (1892),
  - 2 years after the demonstration of Algol as a spectroscopic binary, with the light-travel time effect as proof.
  - In reality, the period indicated by Chandler (130 years) was incorrect, and it is the variation of the radial velocity which was used by Belopolsky in 1906 to highlight the reality of a third body with a period very close to this that we know now.
  - Nevertheless, the light-time effect was indeed present with the period of 680 days

The time of light

- Example of a ternary: R CMa
  - Known as eclipsing binary
  - And acceleration star in Hipparcos
  - Restatement result
    - P ≈ 91 years
    - Hipparcos + μ(1980)
    - M_3 ≈ 0.5 Msun
  - 2002AJ....123.2033R Ribas+

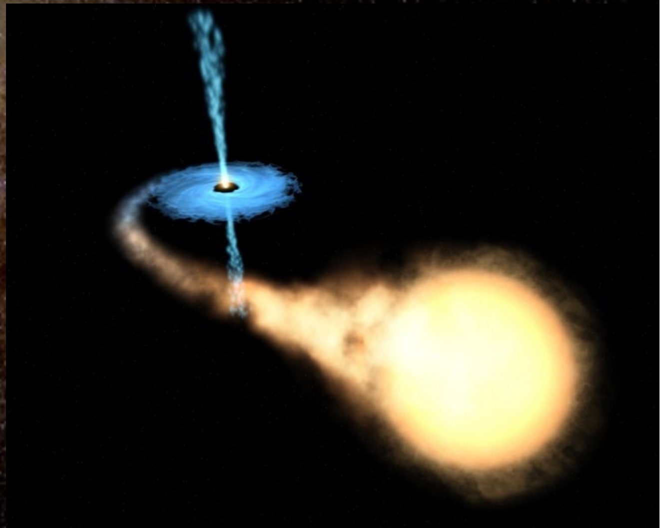


- Other examples
  - … the first confirmed exoplanet
  - Pulsar PSR 1257+12

X-ray binaries

Definition

- An X-ray binary is a "normal" star orbiting a neutron star or black hole with a short period.
  - The X-radiation comes from the enormous amount of energy given off by the accretion of star matter around the compact object.
- A simplified scenario for the formation of a massive X-ray binary
  - Two massive stars (> 12 solar masses) arrive on the main sequence;
  - About ten million years later, the more massive one has passed first to the stage of a red supergiant and its envelope fills the Roche lobe, beginning the transfer of mass towards the companion.
  - Later, having kept only its helium envelope, the star explodes into a supernova, the core collapses, transforming it into a neutron star.
  - The companion, which in turn has become a red supergiant, then transfers its mass to the neutron star, and a X-ray binary is observed.
  - The two objects may have a common envelope, the secondary explodes in turn, possibly leaving behind a couple of pulsars



microquasar GRO J1655-40 (artist view)

History

- An Aerobee 150 rocket launched from White Sands on June 19, 1962 at 6:59 GMT and whose flight lasted 6 minutes to an apogee of 224 km. Using Geiger counters installed in the nose of the rocket, Riccardo Giacconi's team would discover the brightest X-ray source in the sky after the Sun, Scorpius X-1.
- Under the X-ray binary hypothesis, that a couple could survive the supernova explosion of one of the components was nevertheless surprising, and was not explained by the effect of a prior mass transfer until the beginning of the 1970s.
  - Scorpius X-1 is now estimated to be a low mass (0.42 solar mass for the star) X-ray binary, orbiting a neutron star (1.4 solar mass) with a period of 18.9 hours.
- The following Aerobee rocket flights would gradually increase the number of known X-ray sources, in particular Cygnus X-1
  - a 2.5 kpc distant X-ray binary. It is now known as formed from the supergiant O9.7 Iab HDE 226868 of about 20 solar masses orbiting a compact object with a period of 5.6 days, probably a black hole since its mass seems to be around 10 solar masses
- The era of X satellites, longer observation time & spectral coverage & angular resolution.
  - Hercules X-1 is an X-ray binary, detected with the first satellite dedicated to X astronomy, UHURU, in 1971. It consists of a rotating neutron star with a period of 1.24s orbiting a stellar companion with a period of 1.7 days. The presence of eclipses then proved indubitably the binary nature of this object.
- Several other satellites were then launched (eg ROSAT, XMM-Newton, Chandra) and additional data is acquired on the ground.
- X-ray binaries are a very active subject of research: actual high-energy physics laboratories, they reveal the behaviour under extreme physical conditions (degenerate matter, very strong magnetic fields, relativistic behaviour) of close stellar couples.
  - About 200 LMXBs, IMXBs, 150 HMXBs…

Masses & luminosities of X-ray binaries

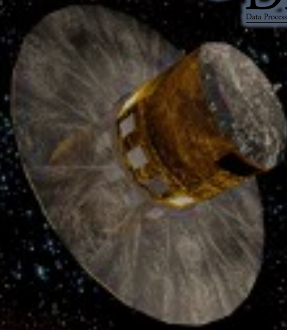
- For sources emitting a periodic signal,
  - see binary TTL as to how to get an indication of ground.
  - This is the case, for example, of neutron stars whose magnetic axis is not aligned with the axis of rotation, causing periodic modulation in the observation of the X flux.
- For the others, spectroscopy in optics or infrared can make it possible to obtain the radial velocity, and this is the case of Cygnus X-1
  - see spectroscopic binary for the method of obtaining an estimate of mass.
- When the orbital period is short, the probability that we can observe eclipses is increased,
  - see eclipsing binary.

- Mass estimates are nevertheless more complicated than for normal binaries (emission, period changes, etc).
  - These mass determinations are nevertheless important because they provide one of the rare methods to weigh a black hole in our Galaxy.

- As part of an LMXB, the accretion luminosity is $GM_1M' / R_1 \sim 0.1\ M'\ c^2$ where M_1 and R_1 are the masses and radii of the compact object and M' the rate of accretion;
  - the luminosity in the visible is 100 to 10000 times smaller than in X.

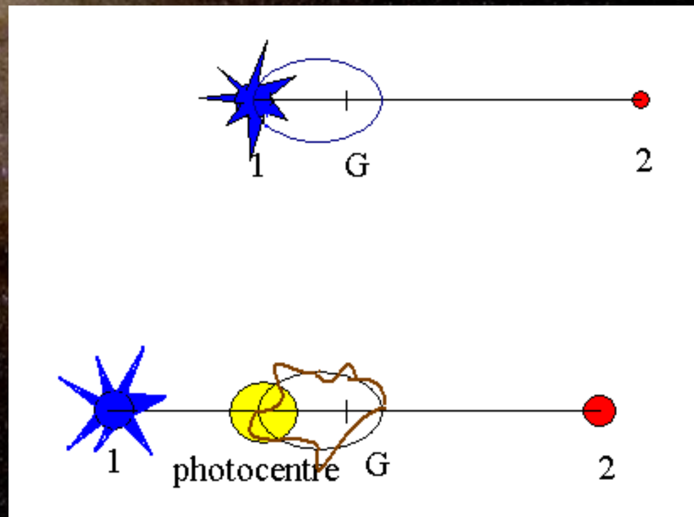
And others…

Unresolved movers

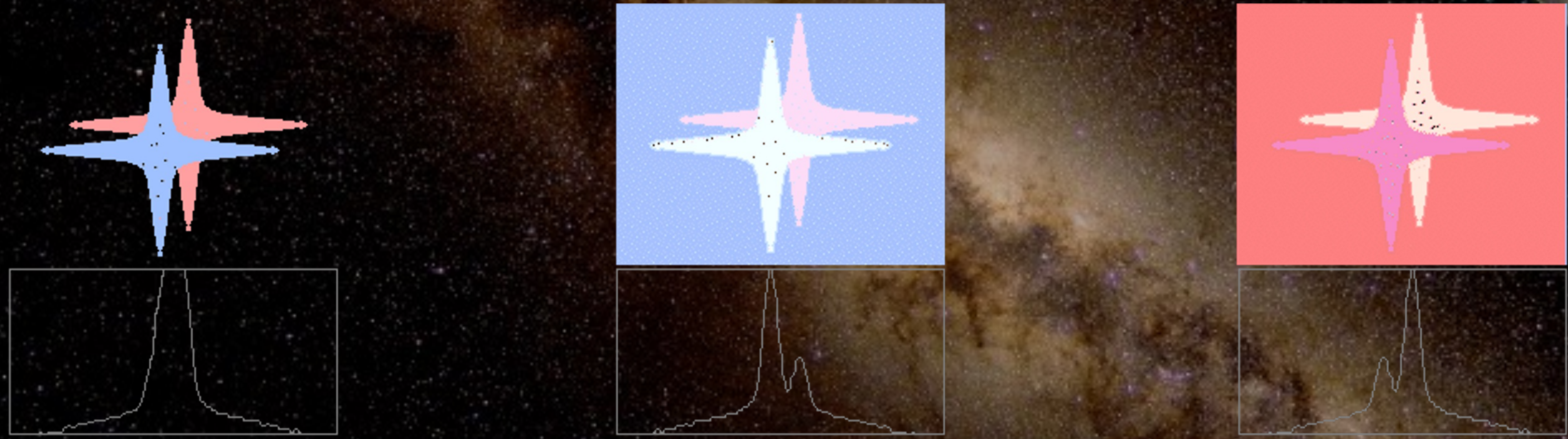


Variable-induced movers(VIM)

- A unresolved pair of which at least one of the components is variable
  - The position of the photocenter varies with the luminosity of the couple
  - It may or not be accompanied by an orbital motion
- Suggestion by Wielen (1996) for Hipparcos
  - Variability-Induced Mover (VIM)
  - En fact most of the Hipparcos VIMs came from bad chromaticity correction (V-I considered constant)

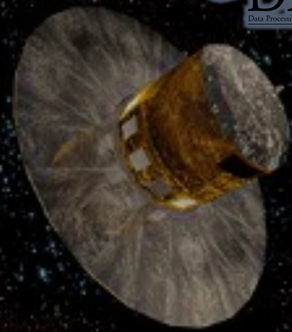


Color-induced binaries (CIM)



- Pair of unequal colors plus various filters → different photocenter…
- For ex: G0V+M0V gives ΔV=4.4 and ΔI=3 mag
- If the angular separation is ρ the difference in position of the photocenter is
  - $\rho[(1+10^{0.4 \times 4.4})^{-1} - (1+10^{0.4 \times 3})^{-1}] = 0.042\rho$ between V and I
- Suggestion:
  - Christy et al. (1983). Spectro-astrometry or chromatic position difference (CPD)
  - Currie, DG, Detection of double stars with the two-color refractometer 1983LowOB.167...28C
  - Sorokin & Tokovinin, Chromatic position difference - A technique for studying double stars, 1985PAZh...11..542S.
  - Then Wielen (1996) (colour-induced for Hipparcos)

l'Observatoire de Paris | PSL cnrs



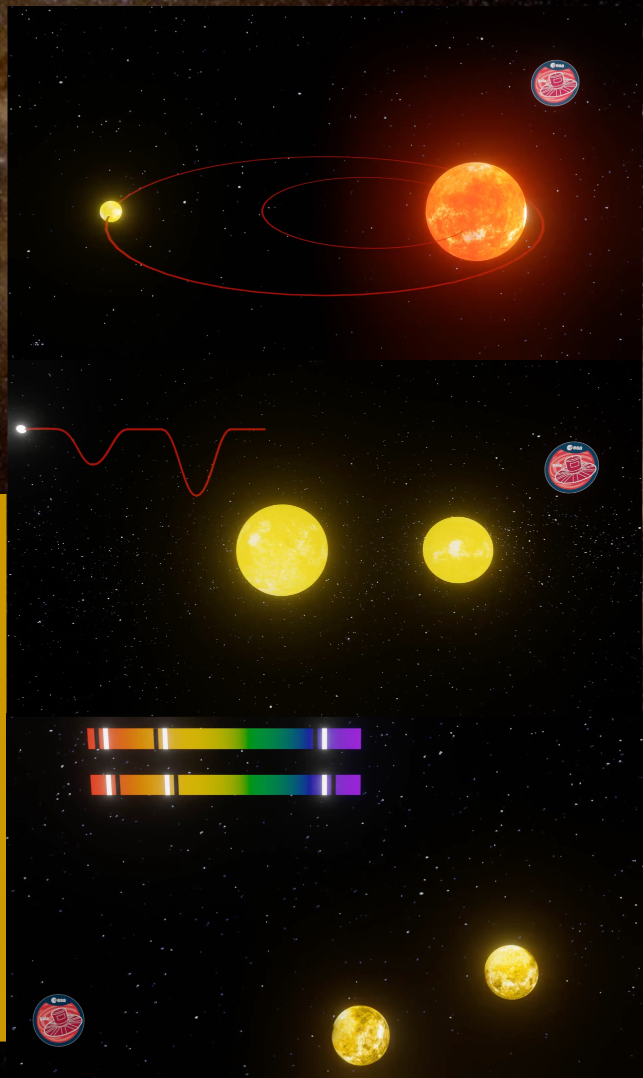
Gaia CU4/NSS processing

NSS = Non-Single Stars, from compact to substellar objects

Gaia Non-Single Stars

Gaia is able to detect:

- Astrometric binaries
- Eclipsing binaries
- Spectroscopic binaries



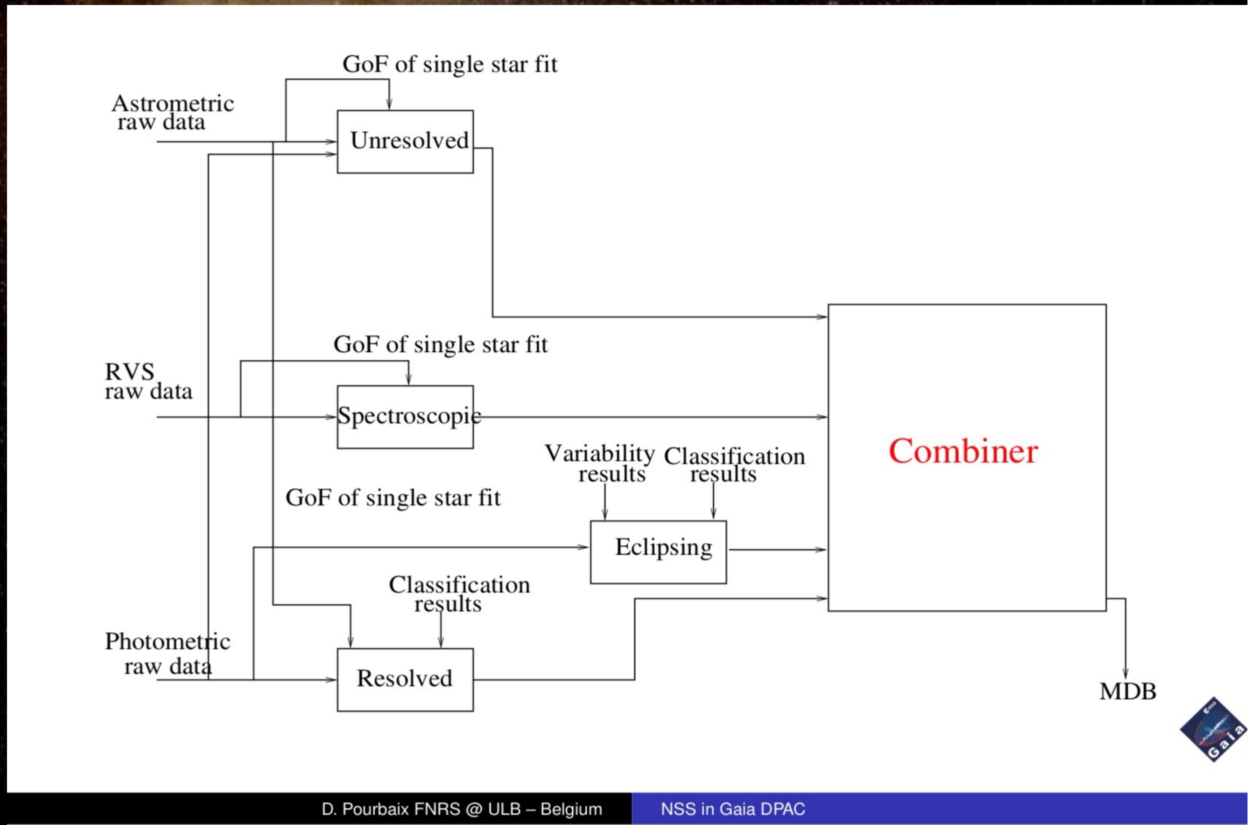
Photocentre motion only (system too far to be resolved)

Light curve variation when favourable orientation

Radial velocity variations (Doppler effect on spectral lines)

Binaries in CU4/NSS for DR3

- Astrometric binaries (AB)
- Spectroscopic binaries (SB1/2)
- Eclipsing binaries (EB)
- Combinations
- Resolved (not in DR3)
  - Well, present in the catalogue but not managed

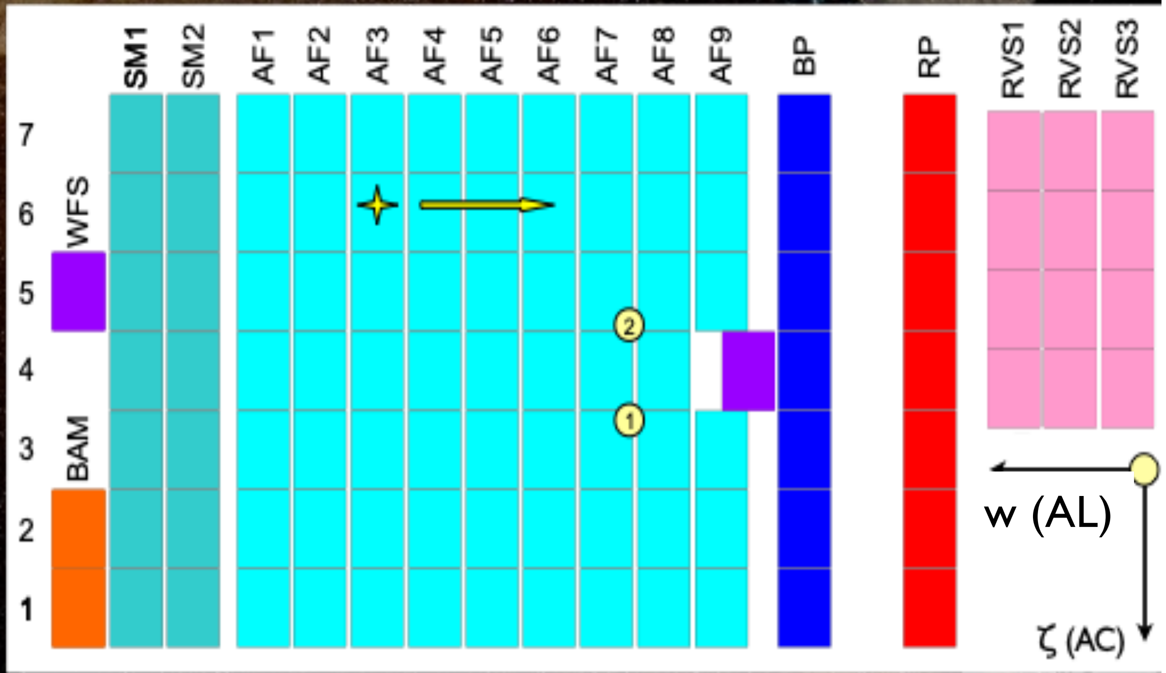


What is in gaia_source

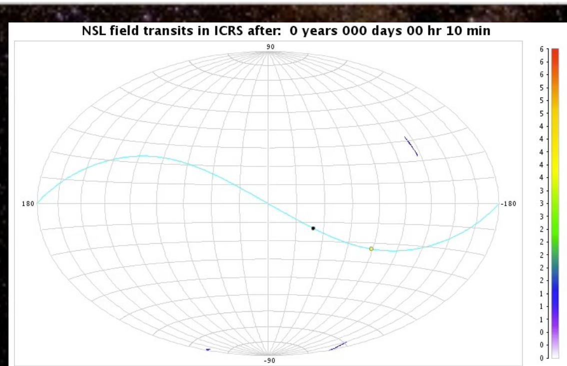
Before this : the standard model

The main astrometric solution (single stars)

- Notations
  - Reference point (α_0, δ_0)
  - time t wrt mid-mission
  - Proper motion $\mu_{\alpha\star}$, μ_δ
  - Parallax ϖ, parallax factor f_ϖ,
  - Scan angle ψ
    - defined as =0 when the field-of-view (FoV) is moving towards local North, and ψ=90° towards local East.



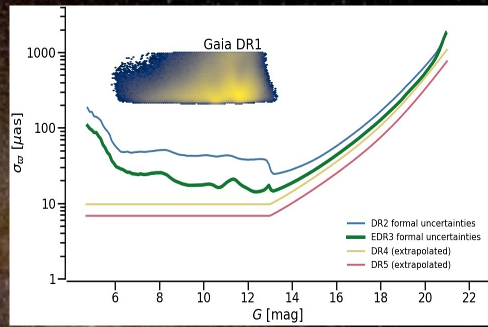
- Position (in mas) at time *t* for a single star
  - $\alpha(t) = \alpha_0 + \Delta\alpha + \mu_{\alpha\star}t + \varpi f_{\varpi\alpha}(t)$
  - $\delta(t) = \delta_0 + \Delta\delta + \mu_\delta t + \varpi f_{\varpi\delta}(t)$



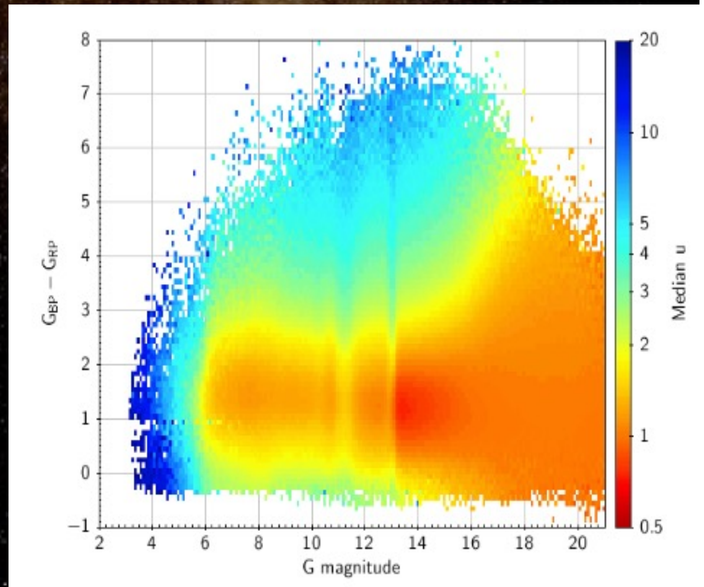
- Now, vs the reference position, along scan:
  - $w(t) = (\Delta\alpha + \mu_{\alpha\star}t) \sin\psi + (\Delta\delta + \mu_\delta t) \cos\psi + \varpi f_\varpi(t)$

Astrometric fit quality in the main catalogue

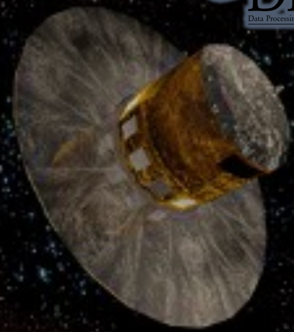
- The fit quality can be bad if
  - The standard astrometric model is for a single star: the model may be incorrect
    - In next slides we mention alternative models
  - There may have been outliers
    - However, in general, the AGIS fit is robust to this
  - Unfortunately there are also systematics
    - Mostly magnitude or colour calibration deficiencies



- The RUWE is the basic fit quality indicator
  - Renormalised Unit Weight Error (Lindegren LL-124)
  - The UWE is the ratio of "external" / "internal" errors
    - ~ $\sqrt{\Sigma r_i^2/\nu}$ with r_i the normalised residuals
    - Should be 1 for well behaved single sources
  - Why renormalised ? Because of systematics
  - The UWE_0 has been computed in a 2D G/BP-RP grid
    - RUWE of a source = $UWE/UWE_0(G,BP\text{-}RP)$
- The detection of Astro. binaries uses the RUWE



UWE(G,BP-RP for DR2, Lindegren et al

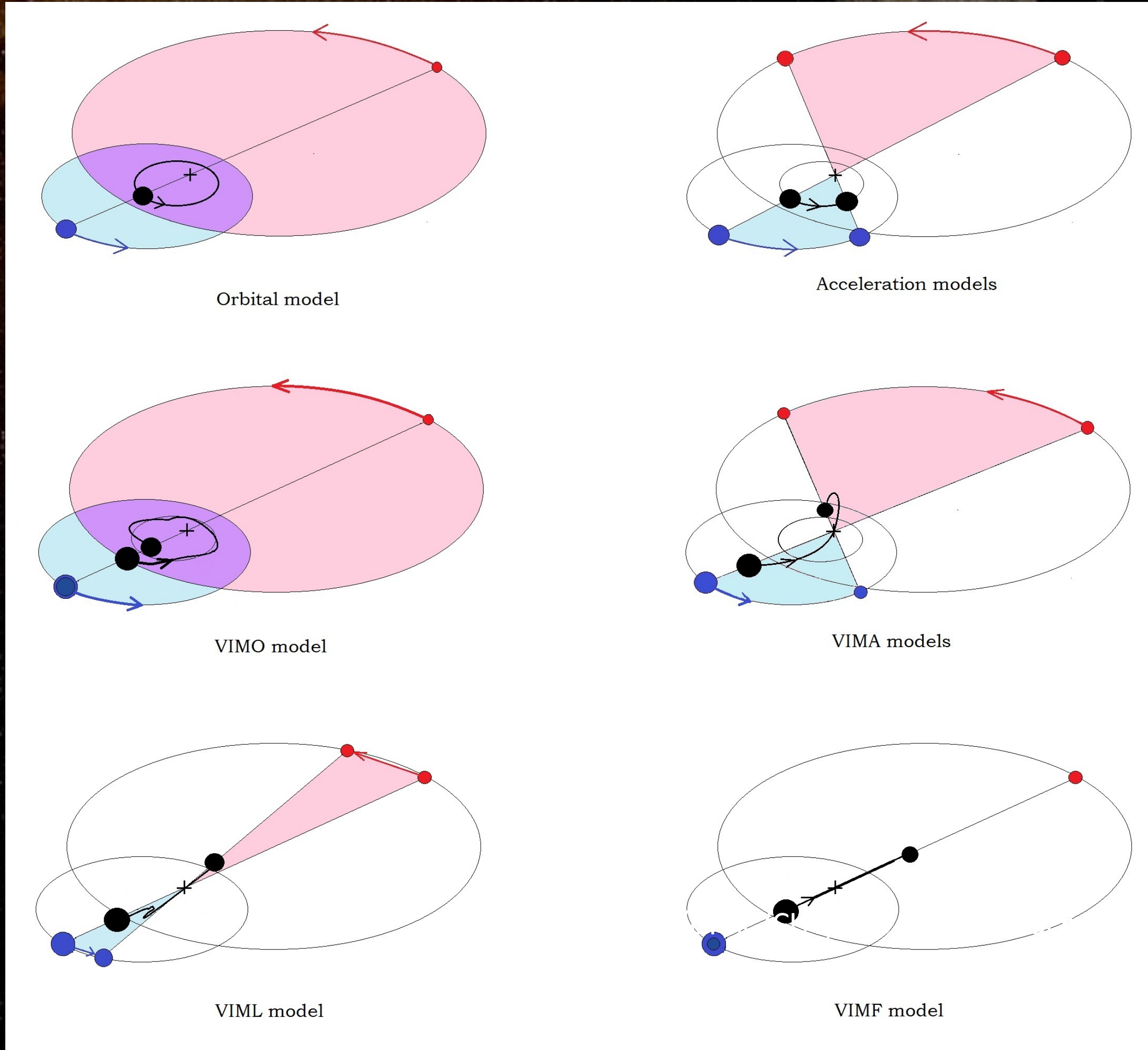


Handling astrometric binaries

The various models of astrometric binaries

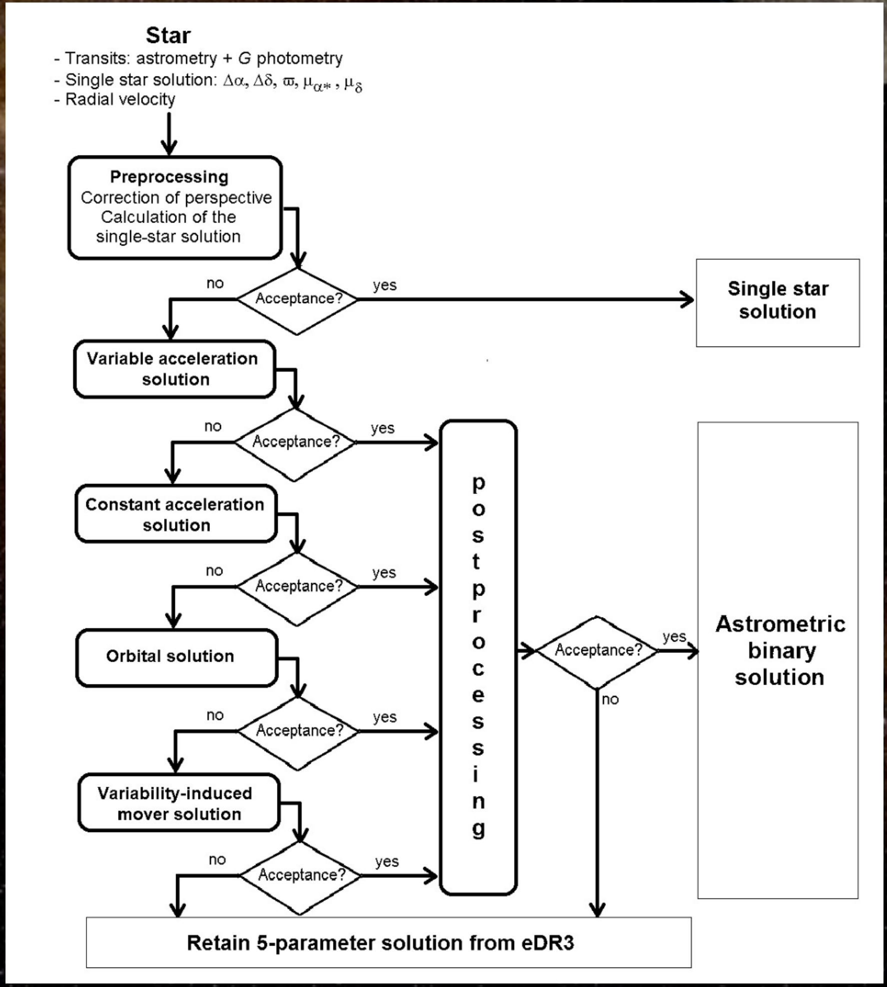
- By decreasing periods, acceleration 7p (5 astrometric parameters+ 2 acceleration), 9p, solutions orbitales.

- Variable Induced Movers (VIM):
  - for DR3, few survived, for reasons of contamination



AB Data treatment

- What was adopted for DR3
  - Ockham's razor: the simplest NSS model that matches the data with a correct fit is accepted first
  - A cascade of models, from the simplest to the most complex models



J-L Halbwachs et al., 2023A&A...674A...9H

Two astrometric pipelines

- The "binary" pipeline
  - Fast, from high-mass compact companions down to exoplanets
  - Applied blindly on millions of perturbed sources → large S/N needed
    - → on-ground follow-up verification is required on candidates
  - Model type = 'Orbital' or 'AstroSpectroSB1' in DR3
  - Other models are also produced (accelerations, variable binaries)

- The "exoplanet" pipeline
  - ≈ 20k sources with already known solutions, incl. all exoplanets
  - DE-MCMC and Genetic Algorithms for orbit determination
  - Can afford a lower S/N (as sources are already known to exist)
  - Model type = 'OrbitalTargetedSearch*' in DR3
  - This pipeline also runs on rejected solutions from the "binary" pipeline
    - With `OrbitalAlternative' model type

The astrometric solution (accelerations)

- For an acceleration solution, along scan:
  - $w(t) = [\ \Delta\alpha + \mu_{\alpha*}t + g_{\alpha*}\, k(t)\ ] \sin\psi + [\ \Delta\delta + \mu_\delta t + g_\delta\, k(t)\ ] \cos\psi + \varpi\, f_\varpi(t)$
  - With $g_{\alpha*}$, g_δ the acceleration components
  - And $k(t) = \frac{1}{2}\ [\ (t-T)^2 - \Delta T^2/3\ ]$
    - With T=2016.0 for DR3, ΔT half the time span of observations
    - Instead of the expected $\frac{1}{2}\, t^2$
    - To decrease correlations between pm and acceleration terms

- Beware of the perspective acceleration:
  - Based on the radial proper motion (RV divided by distance)
    - $\mu_r = V_r\, \varpi\, 24\pi\, y_d\, /\, (180\, au_m)$ with y_d =year in days and au_m = au in m
  - Requiring to correct the along-scan (AL) position by:

$$\Delta w = -\mu_r\,(t-T) \times \left(\frac{\partial w}{\partial \varpi}\,\varpi + \frac{\partial w}{\partial \mu_{\alpha*}}\,\mu_{\alpha*} + \frac{\partial w}{\partial \mu_\delta}\,\mu_\delta \right)$$

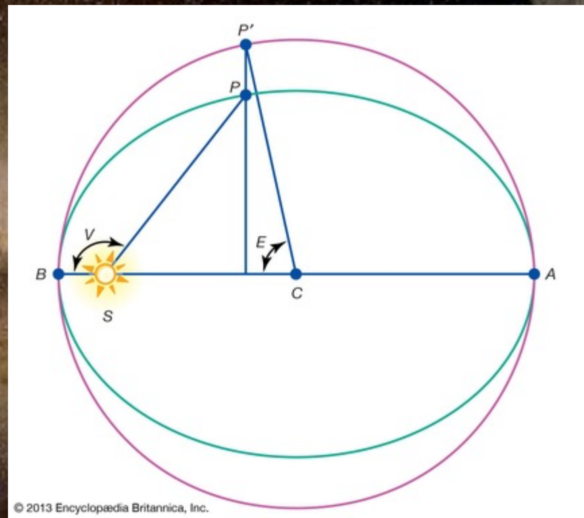
  - (could be used to measured the RV itself)

Gaia DPAC

The astrometric solution (orbits)

- Equations of motion are:
  - Define first the eccentric anomaly E(t) with
    - $E - e \sin E = 2\pi P (t - T_0)$
    - Kepler equation with no closed-form solution
  - Then the true anomaly v(t):

$$\tan\left(\frac{v}{2}\right) = \sqrt{\frac{1+e}{1-e}}\tan\left(\frac{E}{2}\right)$$



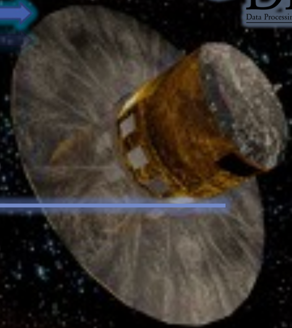
- Radius vector $\dot{r}$(t) is (in mas):
  - $\dot{r} = \mathring{a}_0 (1 - e \cos E)^2 = \mathring{a}_0 (1 - e^2) / (1 + e \cos v)$

- Observed astrometric motion is (in mas):

$$\begin{cases} \Delta\alpha\cos\delta = a_0 \frac{1-e^2}{1+e\cos\nu}\left[\cos(\nu+\omega)\sin\Omega + \sin(\nu+\omega)\cos\Omega\cos i\right] \\ \Delta\delta = a_0 \frac{1-e^2}{1+e\cos\nu}\left[\cos(\nu+\omega)\cos\Omega - \sin(\nu+\omega)\sin\Omega\cos i\right] \end{cases}$$

Gaia DPAC

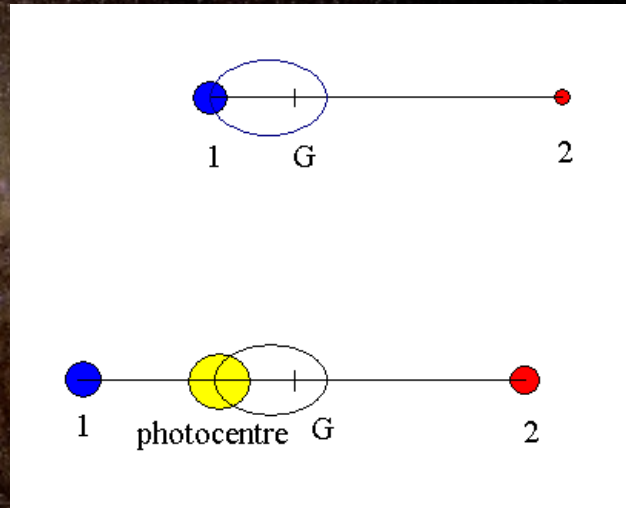
The astrometric solution (orbits)



- Solving for the angles (ω, Ω, i) is however complicated
- The A, B, F, G Thiele-Innes constants allow to linearize the problem
  - $\mathring{A} = + \mathring{a}_0 (\cos\omega \cos\Omega - \sin\omega \sin\Omega \cos i)$
  - $\dot{B} = + \mathring{a}_0 (\cos\omega \sin\Omega + \sin\omega \cos\Omega \cos i)$
  - $\dot{F} = - \mathring{a}_0 (\sin\omega \cos\Omega + \cos\omega \sin\Omega \cos i)$
  - $\dot{G} = - \mathring{a}_0 (\sin\omega \sin\Omega - \cos\omega \cos\Omega \cos i)$
- Define the elliptical rectangular coordinates X(t),Y(t) functions of E(t)
  - $X = \cos E - e$
  - $Y = \sqrt{(1-e^2)} \sin E$
- Then the orbital motion can be written
  - resp. $\dot{B} X + \dot{G} Y$ and $\mathring{A} X + \dot{F} Y$ in R.A. and dec.
- And the full astrometric model along scan is linear (Eq. Astro_sol)
  - $w(t) = (\Delta\alpha + \mu_{\alpha*} t + \dot{B} X + \dot{G} Y) \sin\psi + (\Delta\delta + \mu_\delta t + \mathring{A} X + \dot{F} Y) \cos\psi + \varpi f_\varpi$
- Explains why the Catalogue gives the Thiele-Innes (TI) elements
  - You can convert from TI to Campbell (semi-major axis+angles) with nsstools

Mass information for astrometric binaries

- When the solution is obtained alone (not combined with external data)
  - Gives the orbit or acceleration of the photocenter, not of the primary
  - An orbit only gives access to a "mass function"
    - $f(\mathfrak{M}) = (å_0/\varpi)^3/P^2 = (B-\beta)^3(\mathfrak{M}_A+\mathfrak{M}_B)$ in $\mathfrak{M}_\odot$
      - Where $å_0$ is the angular semi-major axis of the photocenter, P period in yr
      - $B=\mathfrak{M}_B/(\mathfrak{M}_A+\mathfrak{M}_B)$ the mass fraction
      - $\beta=L_B/(L_A+L_B)=1/(1+10^{0.4\Delta m})$ the luminosity fraction
    - Simplifies to $(å_1/\varpi)^3/P^2 = \mathfrak{M}_B^3/(\mathfrak{M}_A+\mathfrak{M}_B)^2$ for a dark companion
  - A weak astrometric signal thus originates from a low mass companion, or from nearly twin stars
    - With a luminosity law like $L \approx \mathfrak{M}^4$, then either $q\approx(f(\mathfrak{M})/\mathfrak{M}_A)^{1/3}$ or $q\approx1-(f(\mathfrak{M})/\mathfrak{M}_A)^{1/3}$
    - And the sign of B-β is unknown



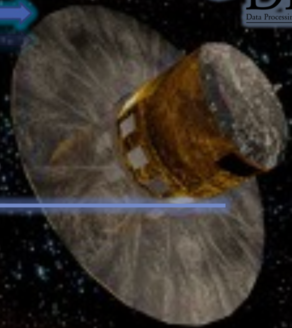
ESA/Gaia/DPAC/CU4/NSS, J-L Halbwachs

Finding a solution

- Cf. Halbwachs et al. , 2023A&A...674A...9H
- Linearising around a reference position
- Partial derivatives of AL vs coordinates are sin ψ, cos ψ resp.
  - Those of proper motion are these, divided by time
  - Cf. Eq. Astro_sol, 4 slides before
- For acceleration components, one seek to decrease the correlations
  - Hence the supplementary constant term (T=2016.0 for DR3)

$$\frac{\partial w}{\partial g_{\alpha*}} = \frac{1}{2}\frac{\partial w}{\partial \alpha*}\left[(t-T)^2 - \frac{\Delta T^2}{3}\right]$$

$$\frac{\partial w}{\partial g_{\delta}} = \frac{1}{2}\frac{\partial w}{\partial \delta}\left[(t-T)^2 - \frac{\Delta T^2}{3}\right]$$



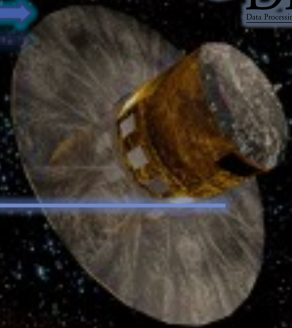
Quality of a solution

- Significance
  - Roughly speaking : S/N of the motion amplitude
    - For orbits: semi-major axis of photocenter divided by uncertainty = $\mathring{a}_0 / \sigma_{\mathring{a}0}$
    - For accelerations, module divided by uncertainty (p_1 and p_2 for ra and dec)

$$s = \frac{1}{\sigma_1 \sigma_2} \sqrt{\frac{p_1^2 \sigma_2^2 + p_2^2 \sigma_1^2 - 2 p_1 p_2 \rho_{12} \sigma_1 \sigma_2}{1 - \rho_{12}^2}}$$

- Goodness of fit
  - With ν the degree of freedom, and χ^2 the Σr_i^2 normalised residuals
  - If the residual uncertainties are unbiased, the cubic transformation F_2 should be normally distributed $\mathcal{N}(0,1)$, (cf. Wilson & Hilferty 1931)

$$F_2 = \sqrt{\frac{9\nu}{2}} \left[\left(\frac{\chi^2}{\nu} \right)^{1/3} + \frac{2}{9\nu} - 1 \right]$$

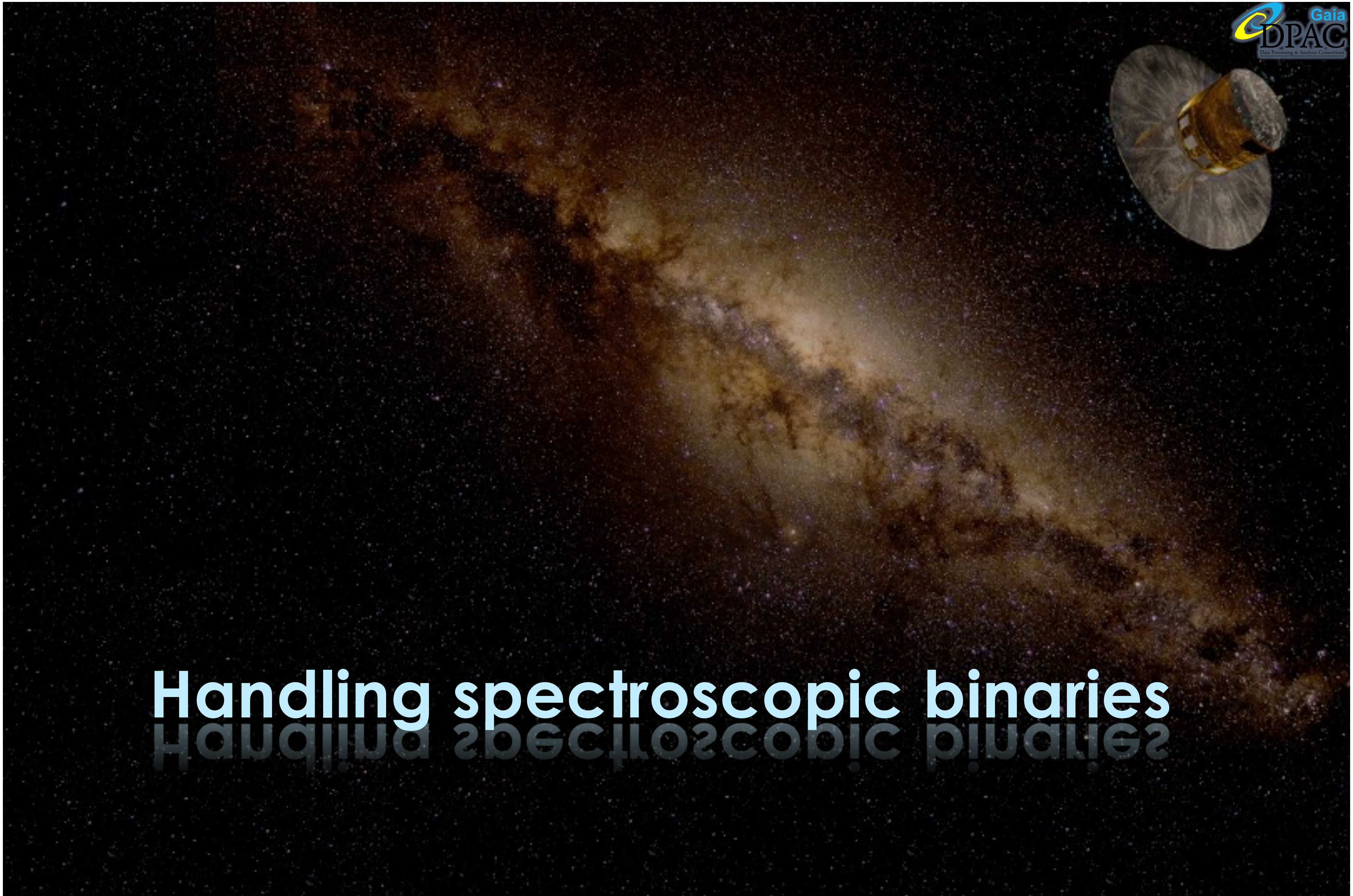


The alternative astrometric chains

- Cf. Holl et al., A&A 674, A10
  - 2 algorithms, both computationally expensive parameter search and Bayesian
  - Idea was to exploit low S/N while the main algo run on everything

1. Differential evolution Markov chain Monte Carlo (DE-MCMC)
   - Using TI linear parameters, only a reduced set of parameters are explored, PTe
   - # of chains = 2 x number of free parameters
2. Genetic Algorithm for Gaia (MIKS-GA)
   - a direct adaptation of yorbit used for searching for EP in RV data
   - particularly well suited for highly non-linear model with irregular sampling

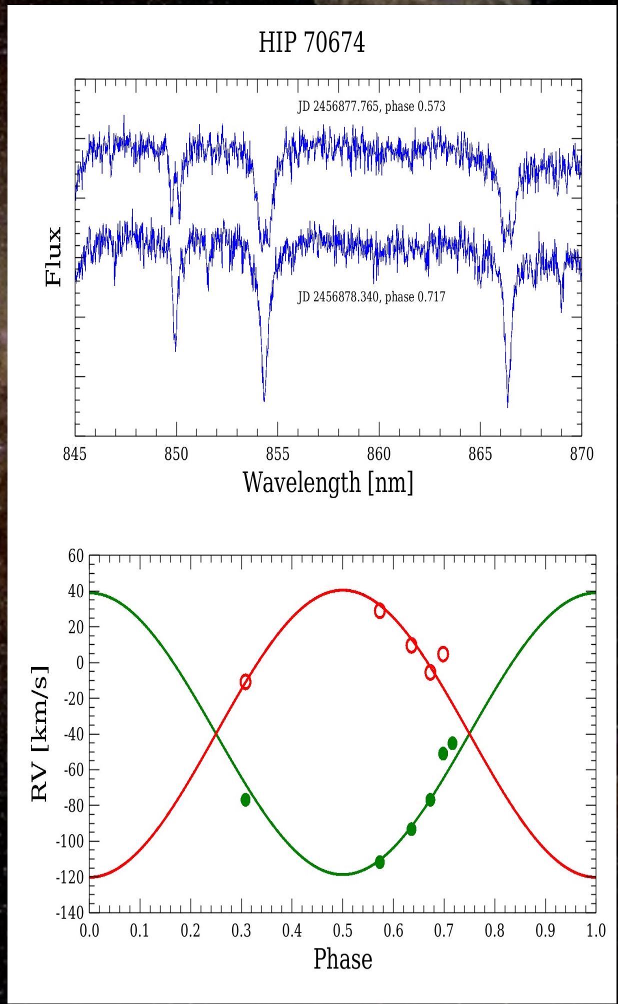
- Produces solutions nicknamed "OrbitalAlternative" in DR3
  - Run on 2.5 millions solutions that did not receive a good "standard" NSS solution
- Was also run on a sample of 19 845 sources already known EP/BD
  - From NASA EP archive, planet-search programmes, or known AB from Hipparcos
  - Nicknamed "OrbitalTargetedSearch" for DR3
  - Validated by comparison with known RV orbits ("OrbitalTargetedSearchValidated")



Handling spectroscopic binaries

Input for spectroscopic binaries

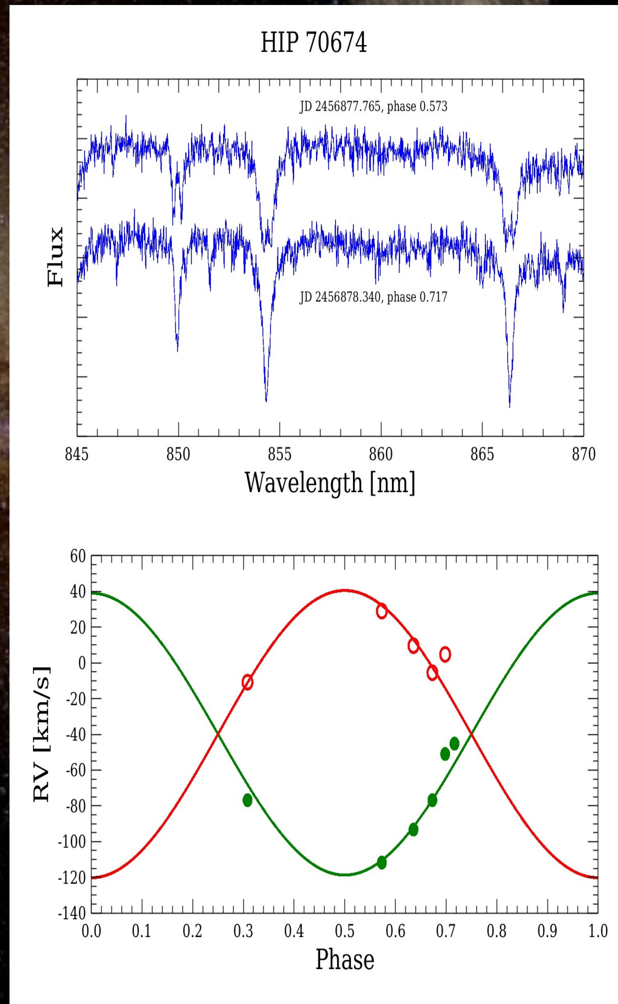
- RVS spectra are first managed in a pipeline
  - the RV being cross-correlated with a theoretical/ synthetic spectrum
- Transit measurements are performed with the Single Transit Analysis (STA) pipeline
  - Up to ~ $G_{RVS} < 12$
- The median of the epoch RVs of constant stars is given in the Catalogue
  - together with many other useful information
- Stars with variable RV are forwarded to the NSS SB processing
  - Using a threshold on the rv_renormalised_gof
  - Selecting A to M stars
  - Having more than 10 transits
- In DR3, SB are generally not distinguished from pulsating variables



ESA/Gaia/DPAC/CU4/NSS, Y. Damerdji, E. Gosset, T. Morel

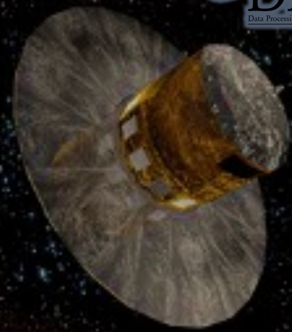
Processing of spectroscopic binaries

- Search periods for SB1
  - Heck-Manfroid-Mersch method (Fourier on irregular time series sampling)
- Candidate periods
  - Up to $4d^{-1}$ frequency, down to $1.4\Delta T$ (time-span)
  - Select 100 candidate frequencies
  - First look for an approximate solution
    - two-parameter space (e, T_0)
  - Then refinement of the elliptical solution
    - Assume a circular solution when the elliptical solution has a poorly conditioned covariance matrix.
  - Parameters: γ, P, K_1, e, ω_1, T_0 (+ K_2 for SB2)
- "Trend" solution also attempted
  - Using a polynomial (1st to 4th degree).
  - Choice of the adopted model using an F-test
- For SB2
  - Sorting of measurements
    - RV2 vs RV1 should give a straight line
    - which slope is the mass raito



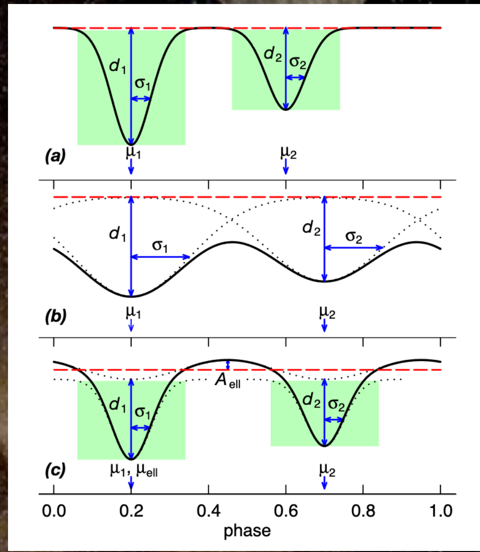
ESA/Gaia/DPAC/CU4/NSS, Y. Damerdji, E. Gosset, T. Morel

Handling eclipsing binaries

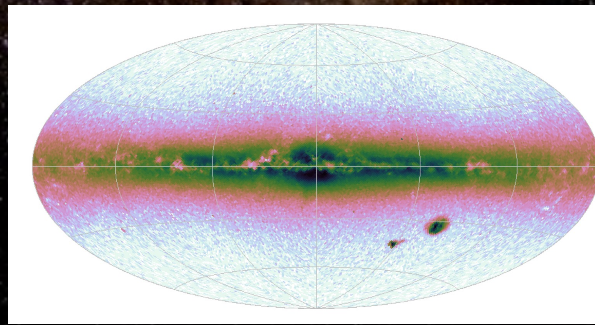


Input for eclipsing binaries parametrisation

- See Mowlavi et al. (2023A&A...674A..16M) and by Laurent tomorrow
- A catalogue of 2.1 million EB detected in DR3
  - much larger and less biased than existing catalogues
- Starts with the classification of variable objects performed within DPAC/CU7 (Rimoldini et al. 2023)
- Filters:
  - G<20
  - #FoV > 16 cleaned G measurements
  - skewness G time series > -0.2
- Then, estimation of photometric period, times of mid-eclipse, eclipse durations, depths, obtained by fitting luminosity curves (LCs) with two Gaussians
- Finally, statistical post-filtering
  - Consistent internal periods
  - P > 0.2d
  - Global ranking (fraction of variance unexplained) > 0.4
  - etc

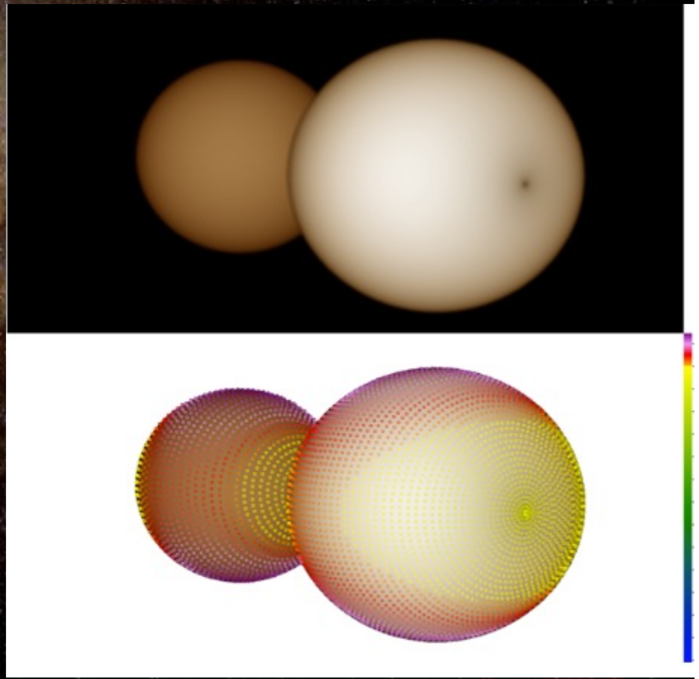


Mowlavi et al. (2023A&A...674A..16M)



Processing of eclipsing binaries

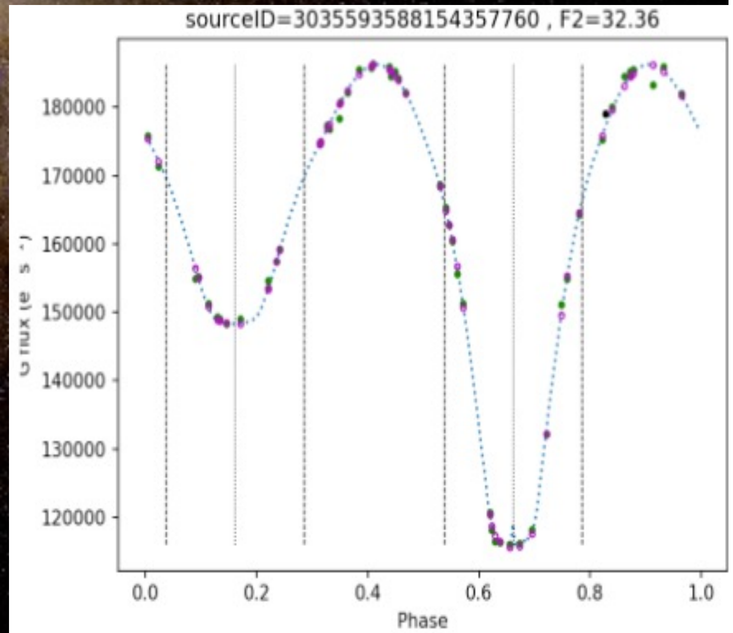
- A large effort to build a full-scale S/W
  - Siopis, Sadowski, Mowlavi et al., 2020CoSka..50..414S
  - Based on S/W code from Wilson-Devinney and Nightfall
- From a given set of physical parameters, a simulator generates synthetic light-curves (LCs) by calculating the flux emitted by the EB
- The solver fits the synthetic LCs to the observed data to determine the physical parameters. Highly non-linear, so this is done in two steps:
  - the observed LC is compared against a library of precomputed synthetic LCs to find one or more synthetic LCs that resemble the observed one.
  - Then, the physical parameters associated with the best-matched synthetic LCs are used as starting values in a local optimisation procedure
- Modelling stellar surfaces as equipotentials of the Roche potential, discretised using a mesh, and it can take into account the effects of :
  - limb darkening, gravity brightening, mutual irradiation, asynchronous rotation, the presence of a third light source, spots



C. Siopis, G. Sadowski

Processing of eclipsing binaries

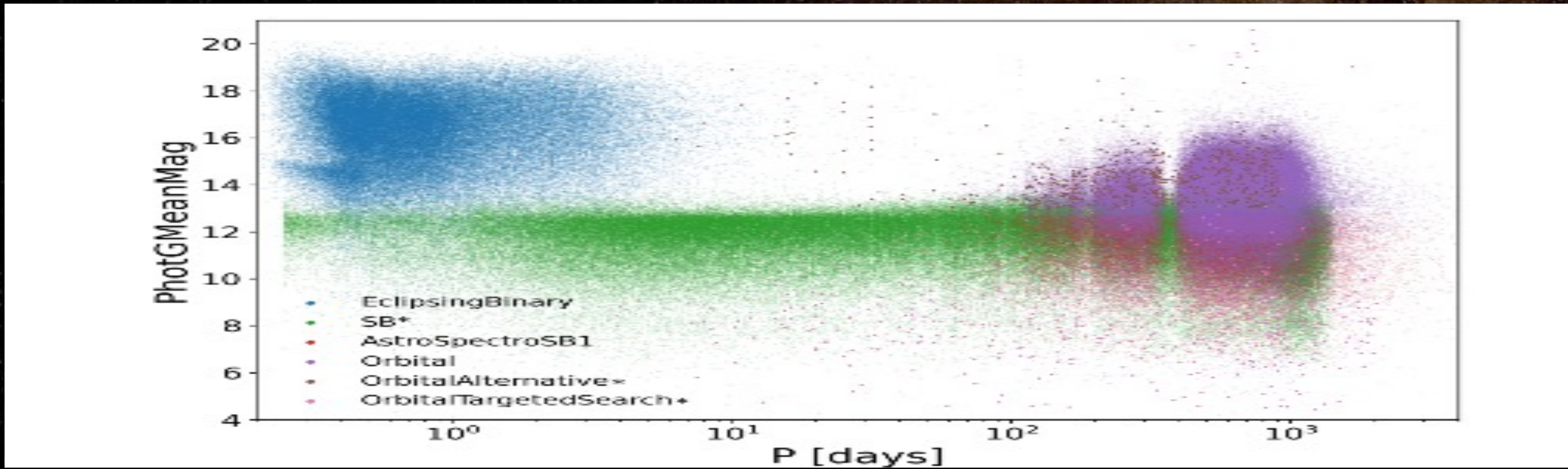
- Parameters:
  - time t_0 of eclipse of star 1 by 2, mass ratio q (M_2/M_1), fill factors s_1, s_2, asynchronous rotation ratios f1, f2, inclination i, eccentricity e, argument of periastron ω, and effective temperatures $Teff_1$ and $Teff_2$.
- Fill factors
  - detached when fill factors of stars, $s_1<1$ & $s_2 < 1$;
  - semi-detached (one component filling its critical lobe) when $s_1 = 1$ & $s_2 < 1$, or $s_1 < 1$ & $s_2 = 1$
  - overcontact (the stars share a common envelope) when $s_1 > 1$ or $s_2 > 1$
- For DR3, only G used, not BP and RP light curves (unsure about extinctions + some inconsistencies between G and XP), then
  - individual temperatures of components cannot then be determined,
  - the contribution of light from a possible third source cannot be accounted for correctly



Combining solutions

What can be combined

- To make a combinations between different solutions one needs:
  - An overlap between period ranges
    - Very short periods such as eclipsing binaries can rarely be also astrometric binaries or worst resolved binaries (except very nearby pairs)
  - A consistency between parameters of both solutions
    - Consistent periods and "amplitude"
- In practice, two types are feasible (due to their period range)
  - Eclipsing + Spectroscopic → EclipsingSpectroSB*
  - Spectroscopic + astrometric → AstroSpectroSB*

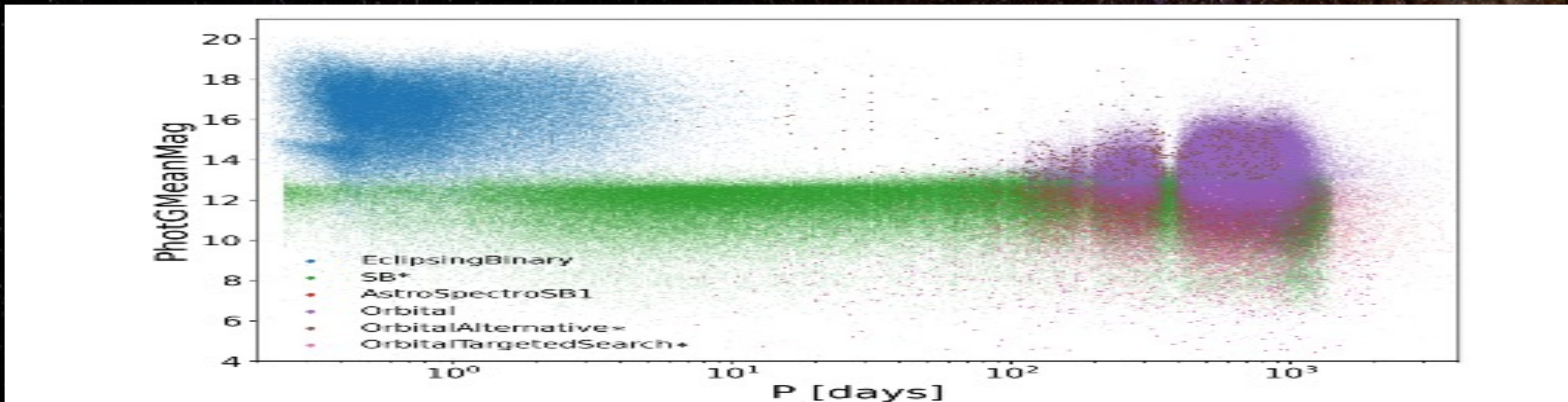


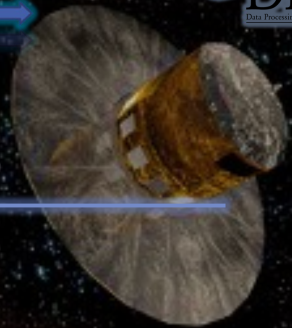
P. Gavras

Gaia collab., Arenou et al., 2023

Trying to combine solutions

- Why ?
  - To estimate more parameters in only one solution
    - Each kind of solution gives access to some parameters only
  - To constrain better some parameters (having a larger degree of freedom)
  - To check whether solutions are compatible
    - Inconsistency between solutions can be due to multiple systems
    - or to aliasing, outliers, etc.
- How ?
  - Low significance solutions were kept to attempt a combination
    - That were rejected from the catalogue if not combined





astroSpectroSB*

- Condition
  - [(P2 mod P1) < $5\sigma_{max}$ OR (P2 mod P1) < 0.1 P1 OR (P2 mod P1) > 0.9 P1]
    AND (P2/P1 < 1.1)
    AND [$K_{astro} \geq K_{spectro} - 2.8$ OR $0.7 * K_{astro} - 12 \leq K_{spectro}$]
  - Where K is the semi-amplitude

- Processing: completing Thiele-Innes A,B,F,G with C, H
  - $C = a_1 \sin\omega \sin i$
  - $H = a_1 \cos\omega \sin i$

$$\begin{aligned} \xi(t) &= \mathring{B}X + \mathring{G}Y \\ \eta(t) &= \mathring{A}X + \mathring{F}Y \\ \mathrm{RV}_1(t) &= CX' + HY' \end{aligned}$$

$$\begin{aligned} X &= \cos E - e \\ Y &= \sqrt{1-e^2}\sin E \\ X' &= \frac{-\kappa \sin E}{P(1 - e\cos E)} \\ Y' &= \frac{\kappa \cos E \sqrt{1-e^2}}{P(1 - e\cos E)} \end{aligned}$$

Model 1	Model 2
	47.3% SB1
92.2% Orbital	5.4% FirstDegreeTrendSB1
7.6% OrbitalPoorlyConstrained	12.4% SecondDegreeTrendSB1
0.1% OrbitalAlternative	0.2% ThirdDegreeTrendSB1
	34.6% StochasticSB1

eclipsingSpectroSB*

- Condition
  - $|K_{ES} - K_{spectro}| \leq 5 \sqrt{(e_{KES}^2 + e_{KSpectro}^2 + 1)}$ AND $significance_K \geq 5$ AND efficiency ≥ 0.5 AND g_rank ≥ 0.6 AND gmaxdist ≤ 0.5
    - gmaxdist = maximum distance in phase and flux in the band

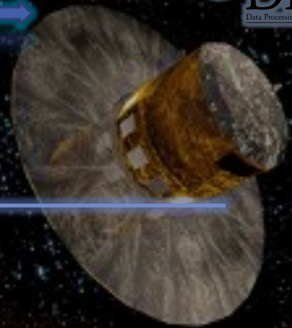
- Processing
  - Handling optionally radial velocities is included in eclipsing binary processing
  - i.e. RV are produced by the simulator together with photometry from a set of physical stellar parameters
    - Then fitted together

- *Note: there is a reservoir of solutions that can be combined offline*
  - Select sources in table vari_eclipsing_binary with |period – 1/frequency| < 5 period_error which are neither EclipsingBinary nor EclipsingSpectro → 1731 sources (compared to the 155 available EclipsingSpectro)

l'Observatoire de Paris | PSL cnrs

Gaia DR3 NSS content

Gaia DPAC



Gaia DR3: a new golden age for the study of stellar multiplicity

Gaia DR3 has measured orbits/trends for:

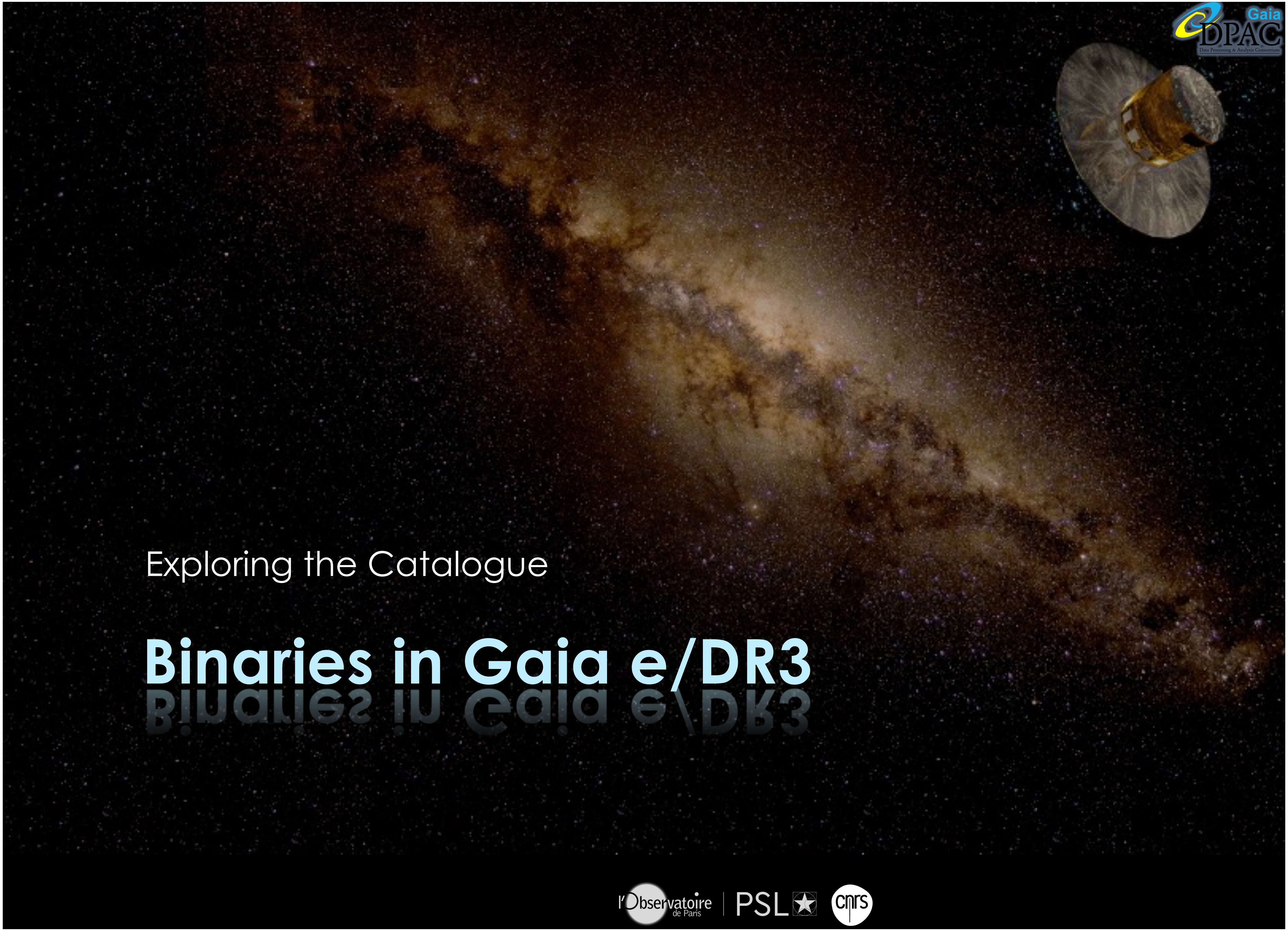
- Astrometric binaries ~ 135 000
  - ~ 40 × orbits in Orb6 catalogue
- Eclipsing binaries (2M) ~ 87 000
- Spectroscopic binaries ~ 185 000
  - ~ 45 × orbits in SB9 catalogue
- Astrometric + spectroscopic ~ 33 000

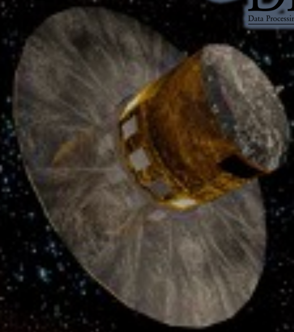
Crdits: ESA/Gaia/DPAC/CU4/NSS, Nathalie Bauchet

Photocentre motion only (system too far to be resolved)

Light curve variation when favourable orientation

Radial velocity variations (Doppler effect on spectral lines)


Gaia DPAC
Data Processing & Analysis Consortium
Exploring the Catalogue
Binaries in Gaia e/DR3
l'Observatoire de Paris
PSL
cnrs



Exploring the Catalogue

Resolved doubles/binaries

Resolved binaries

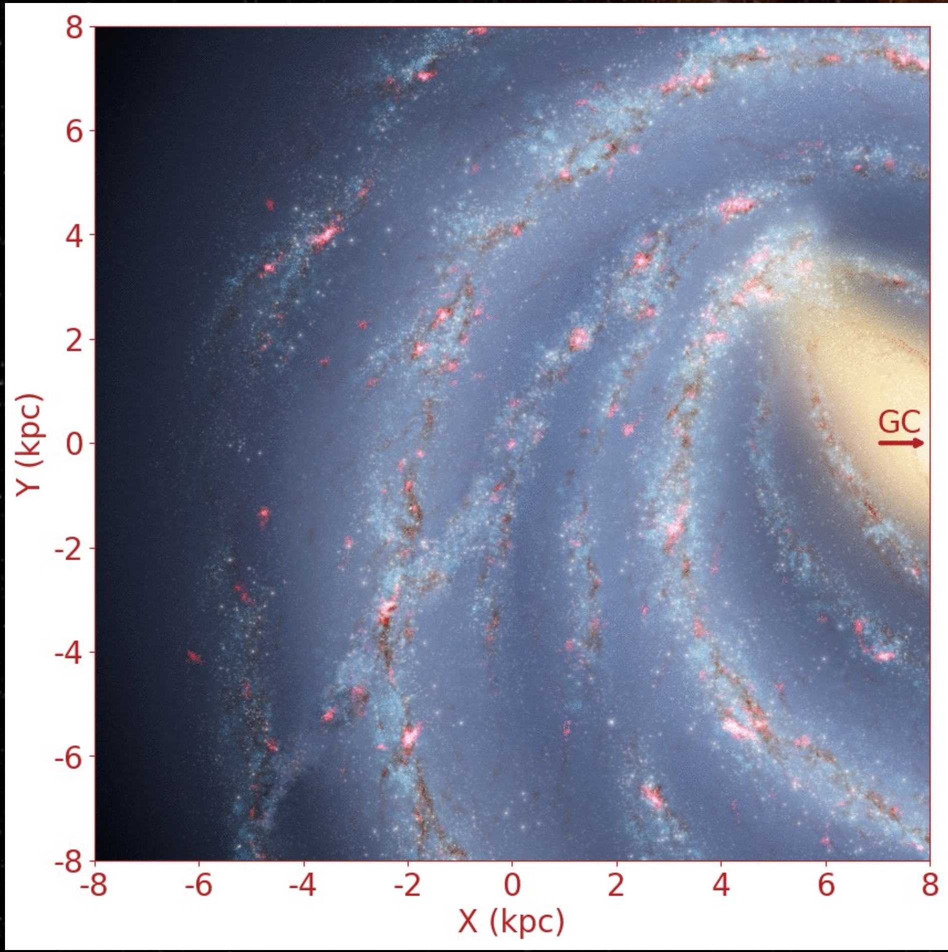
- These binaries were not handled as such in DR3
  - Will be handled for DR4+
- In many cases (separation large enough to avoid motion/ x-contamination)
  - Do not need to be handled together
  - Note however that data are correlated by small angle systematics
- A million binaries from Gaia eDR3: sample selection and validation of Gaia parallax uncertainties, El-Badry, et al. 2021MNRAS.506.2269E
  - resolved binary stars within ~1 kpc of the Sun
  - projected separations ranging from a few au to 1 pc

Unresolved binaries and multiple

The first Gaia NSS Catalogue

l'Observatoire de Paris | PSL | cnrs

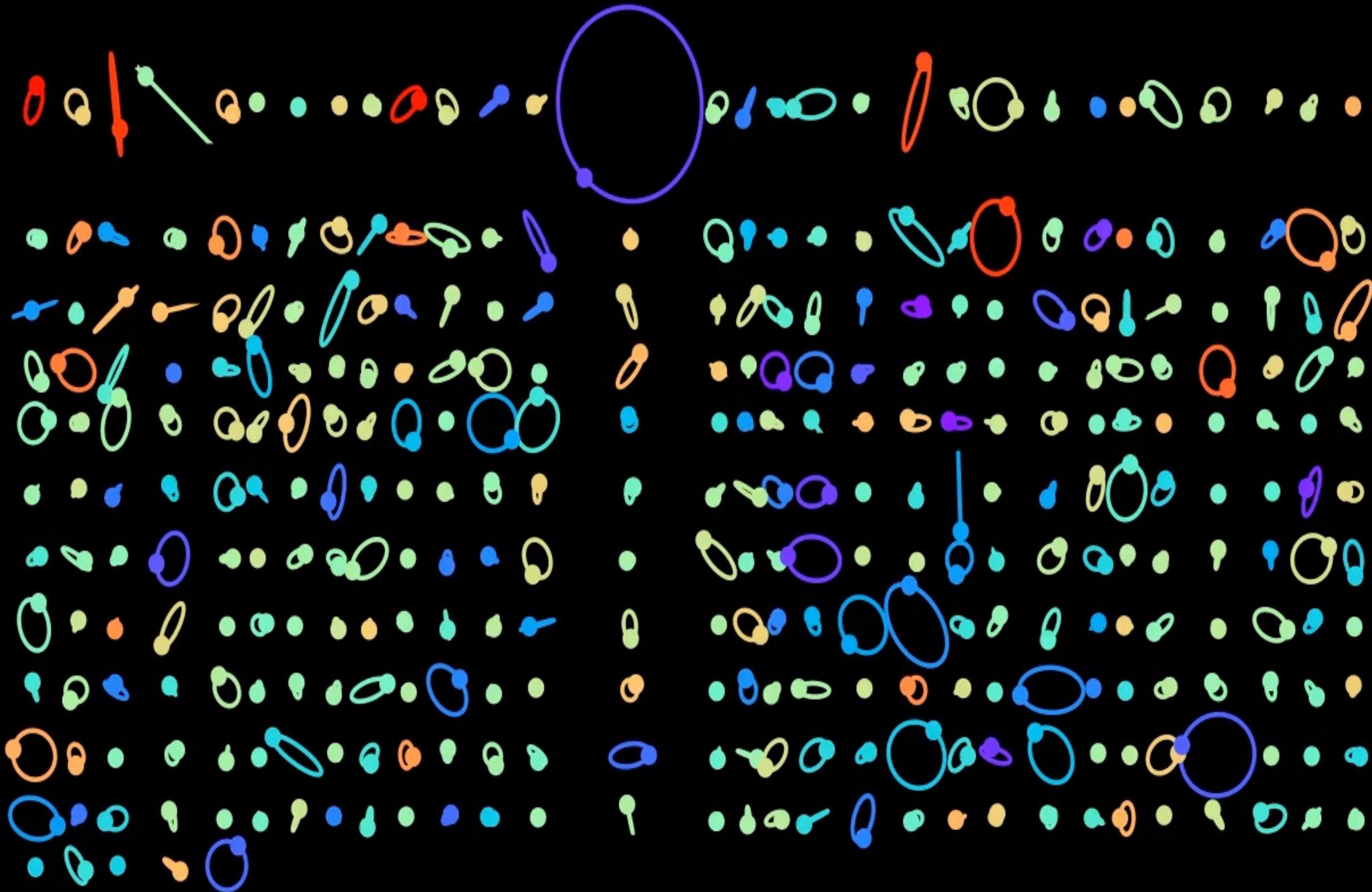
A full in-orbit observatory



Credits: ESA/Gaia/DPAC/CU4/NSS, Nathalie Bauchet

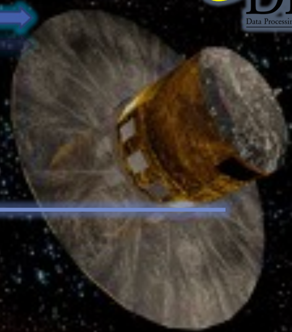
- ❑ Gaia can thus detect most frequent types of Non-Single Stars (NSS)
  - ❑ The largest NSS orbit catalogue
  - ❑ Down to the substellar regime

- Astrometric binaries ~ 135 000
- Spectroscopic binaries ~ 185 000
- AstroSpectroSB* ~ 33 000
- Eclipsing binaries ~ 87 000
- Resolved binaries → DR4



335 `Orbital` solutions within 50pc

ESA/Gaia/DPAC/CU4/NSS, Johannes Sahlmann



Raw content of NSS DR3 data

- 4 Tables in GACS
  - under "Gaia Data Release 3" folder, "Non-single stars" sub-folder
  - Different tables due to different sets of parameters
  - A query by source_id may return several solutions within or across tables
- By rough order of decreasing periods:

Table	nss_solution_type	Solutions	Description
nss_acceleration_astro	Acceleration7	246 947	Second derivatives of position (acceleration)
	Acceleration9	91 268	Third derivatives of position (jerk)
nss_two_body_orbit	Orbital	134 598	Orbital astrometric solutions
	OrbitalAlternative*	629	Orbital astrometric, alternative solutions
	OrbitalTargetedSearch*	533	Orbital astrometric, supplementary external input list
	AstroSpectroSB1	33 467	Combined orbital astrometric + spectroscopic solutions
	SB1 or SB2	186 905	Orbital spectroscopic solutions
	EclipsingSpectro	155	Combined orbital spectroscopic + eclipsing solutions
	EclipsingBinary	86 918	Orbits of eclipsing binaries
nss_non_linear_spectro	FirstDegreeTrendSB1	24 083	First order derivatives of the radial velocity
	SecondDegreeTrendSB1	32 725	Second order derivatives of the radial velocity
nss_vim_fl	VIMF	870	Variable-induced movers fixed

Table content for NSS orbital solutions

- In GACS: Gaia Data Release 3 → Non-single stars → gaiadr3.nss_two_body_orbit

Common to all

solution_id
source_id
nss_solution_type
bit_index
corr_vec
obj_func
goodness_of_fit
efficiency
significance
Flags
period
period_error
t_periastron
t_periastron_error
eccentricity
eccentricity_error

Astrometry

astrometric_n_obs_al
astrometric_n_good_obs_al
ra
ra_error
dec
dec_error
parallax
parallax_error
pmra
pmra_error
pmdec
pmdec_error
a_thiele_innes
a_thiele_innes_error
b_thiele_innes
b_thiele_innes_error
f_thiele_innes
f_thiele_innes_error
g_thiele_innes
g_thiele_innes_error
c_thiele_innes
c_thiele_innes_error
h_thiele_innes
h_thiele_innes_error
astrometric_jitter

Spectroscopy

rv_n_obs_primary
rv_n_good_obs_primary
rv_n_obs_secondary
rv_n_good_obs_secondary
center_of_mass_velocity
center_of_mass_velocity_error
semi_amplitude_primary
semi_amplitude_primary_error
semi_amplitude_secondary
semi_amplitude_secondary_error
conf_spectro_period
arg_periastron
arg_periastron_error

Eclipsing

phot_g_n_obs
phot_g_n_good_obs
mass_ratio
mass_ratio_error
fill_factor_primary
fill_factor_primary_error
fill_factor_secondary
fill_factor_secondary_error
inclination
inclination_error
temperature_ratio
temperature_ratio_error
temperature_ratio_definition
r_pole_sum
r_l1_point_sum
r_spher_sum
ecl_time_primary
ecl_time_secondary
ecl_dur_primary
ecl_dur_secondary
g_luminosity_ratio
input_period_error
g_rank

Distributions

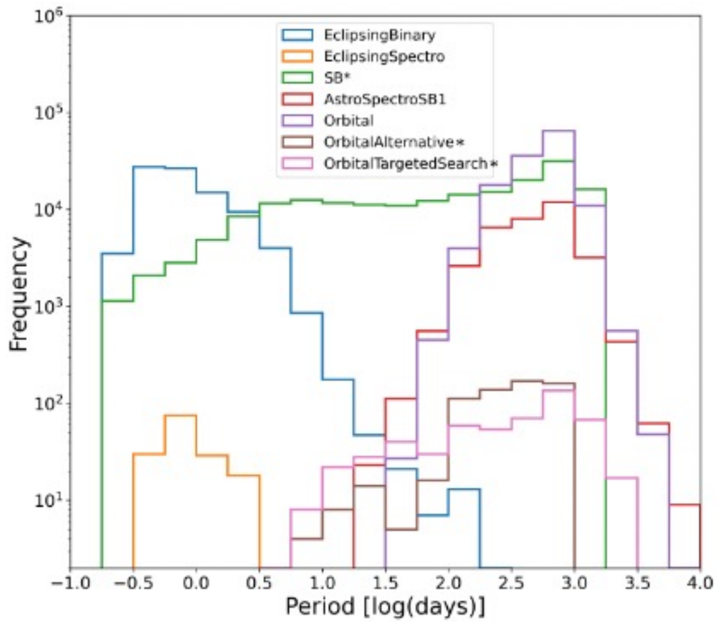


Fig. 2. Number of solutions for each solution type in the nss_two_body_orbit table as a function of period.

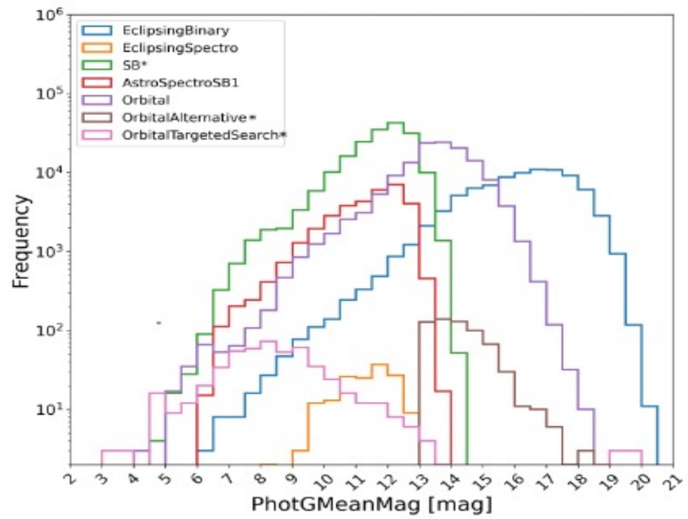
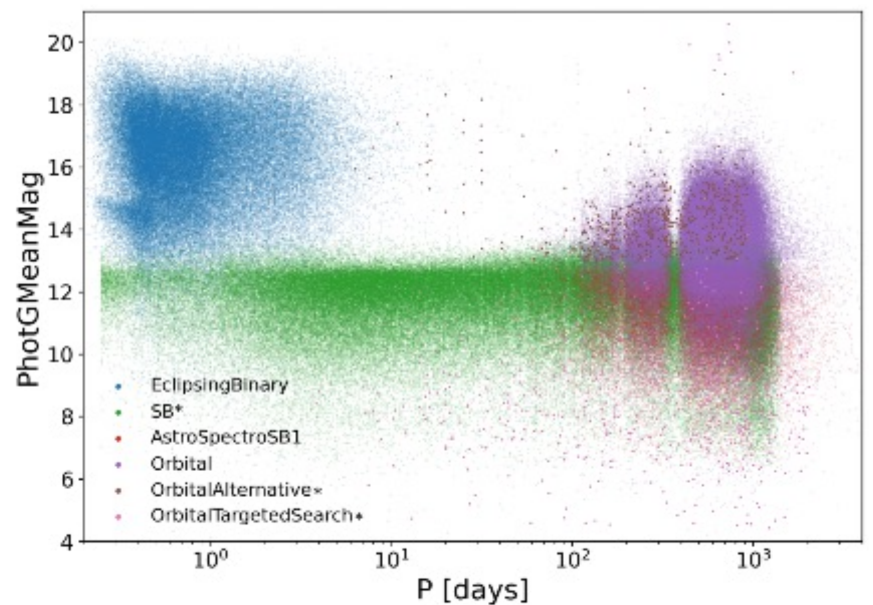
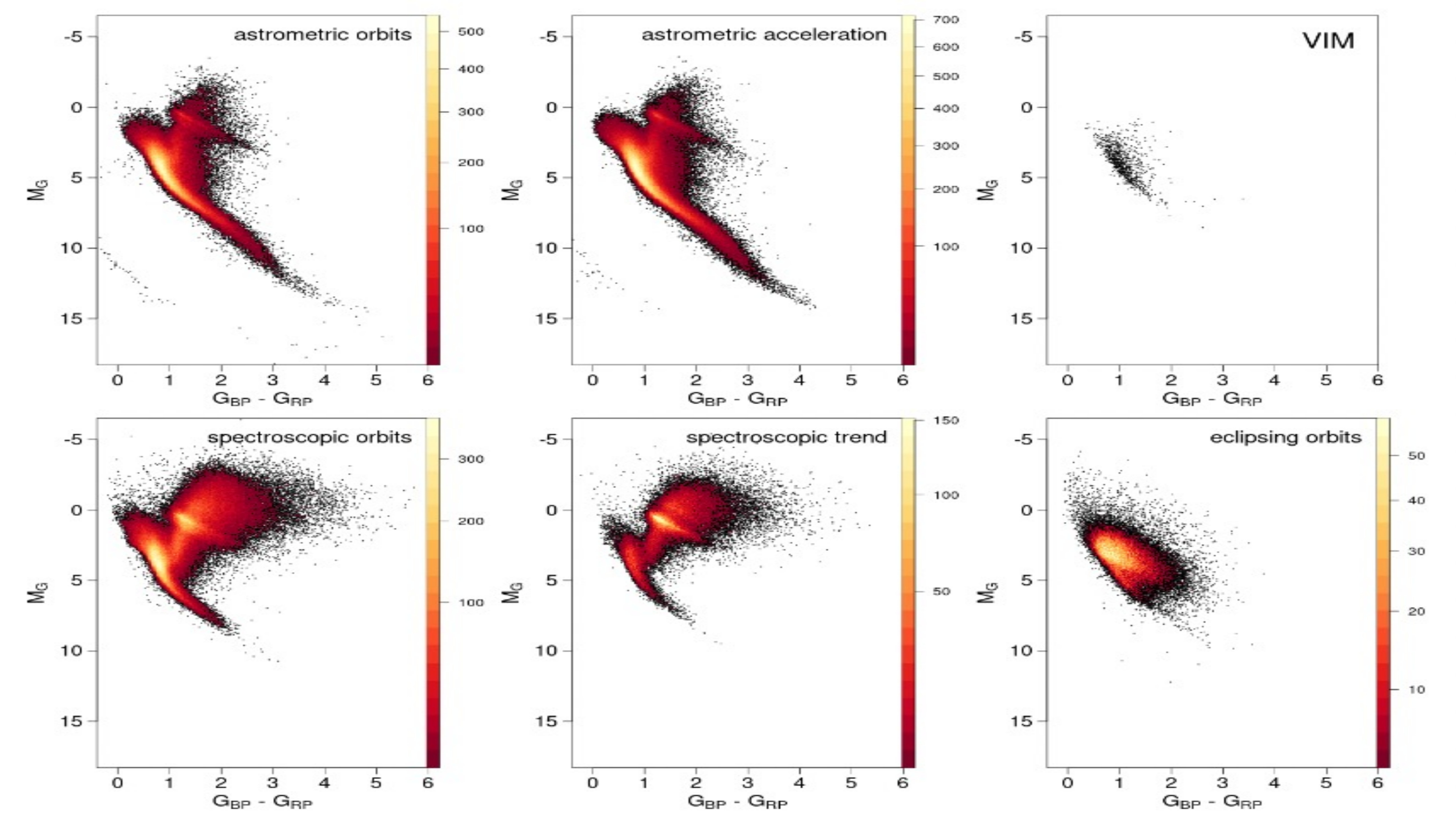


Fig. 1. Magnitude distribution for each solution type in the nss_two_body_orbit table.



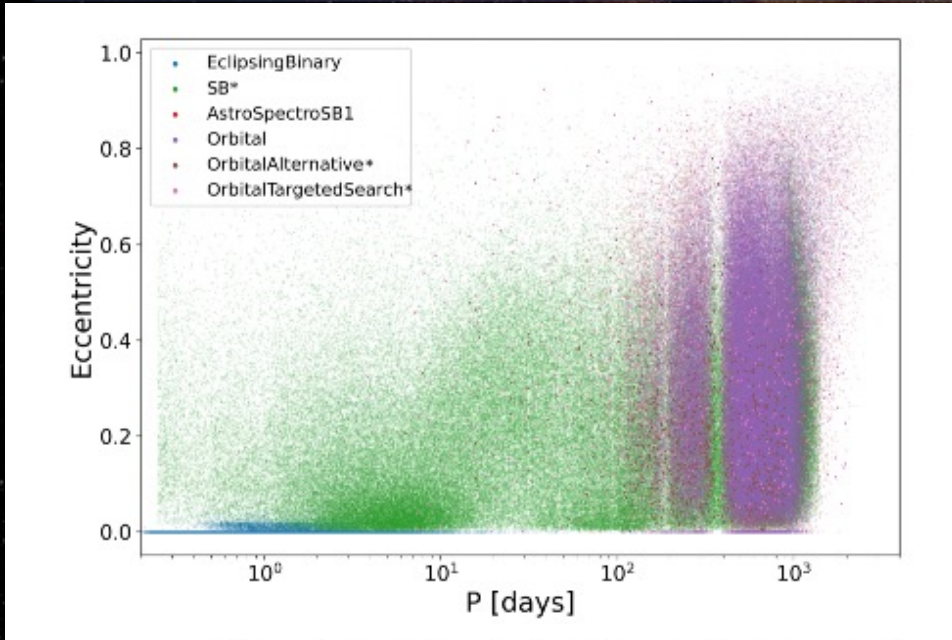
Gaia DPAC

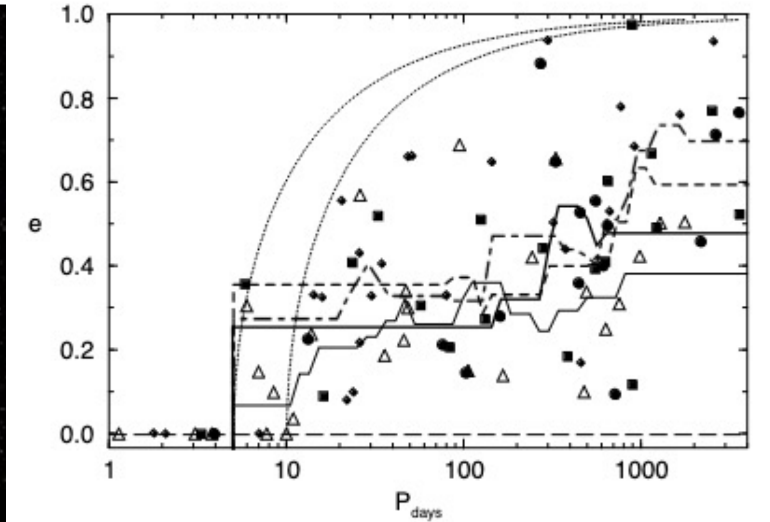
H-R diagrams for all kind of solutions



HR for various solutions with parallax S/N > 5 Gaia collab., Arenou et al., 2023

Period-eccentricity relation





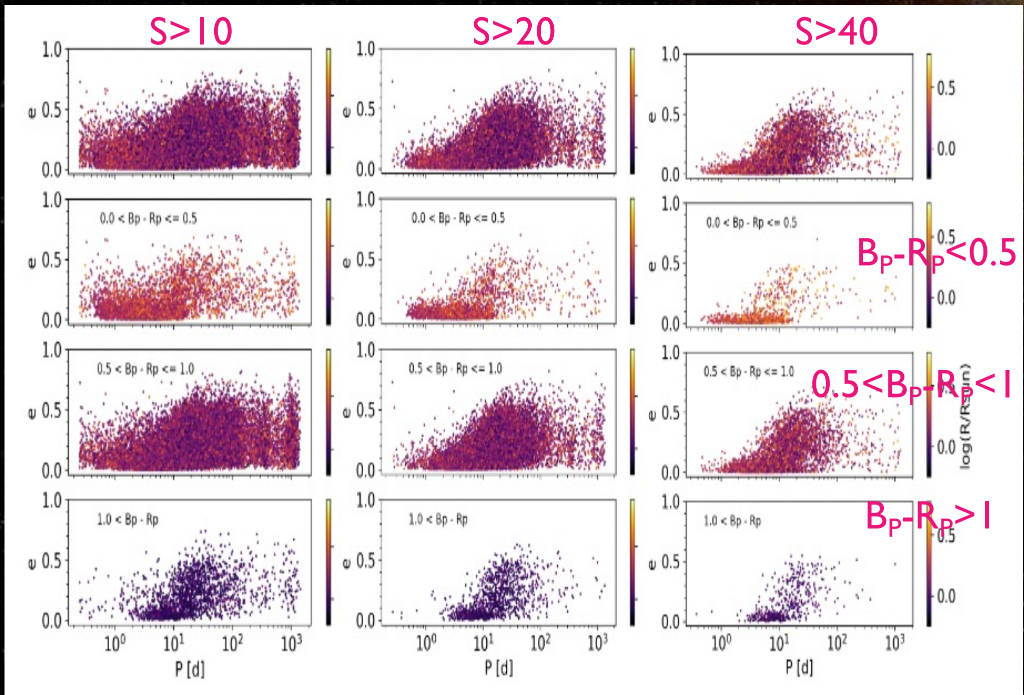
SB relation Halbwachs, Mayor, Udry, 2019

- What we expect:
  - Tidal circularisation at short periods
    - Depends on stellar type
  - An envelope $e < \sqrt{(1-(P_{cutoff}/P)^{2/3})}$
- Partly un/desired:
  - contamination by ternary systems
- Undesired but not unexpected:
  - contamination by spurious solutions

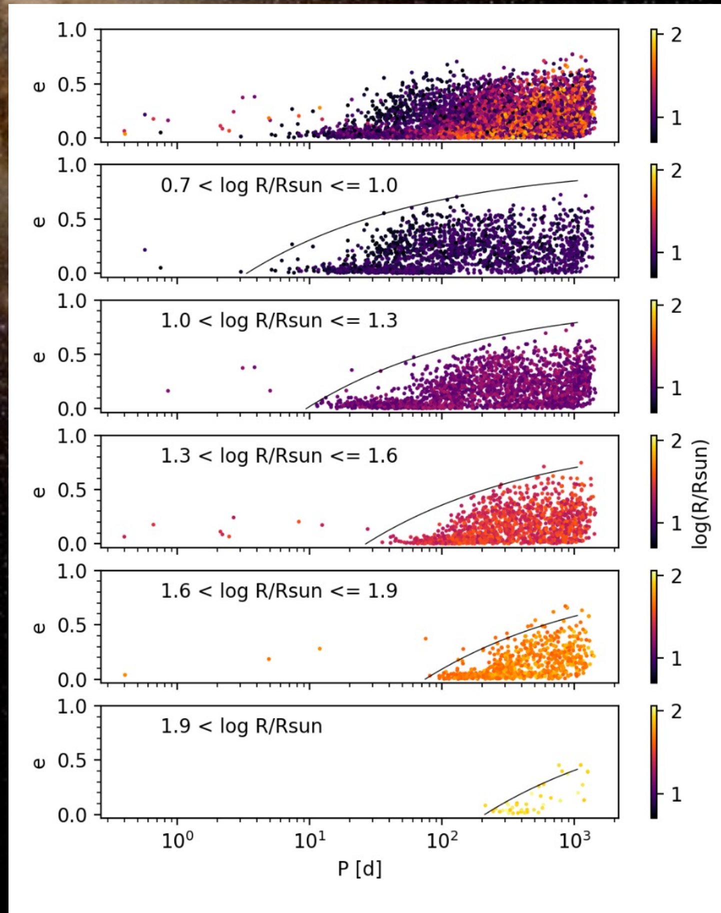
Period-eccentricity relation

- Period-eccentricity relation along the Main Sequence
  - Not so clear variation along the MS
  - Cleaning using significance also removes long periods

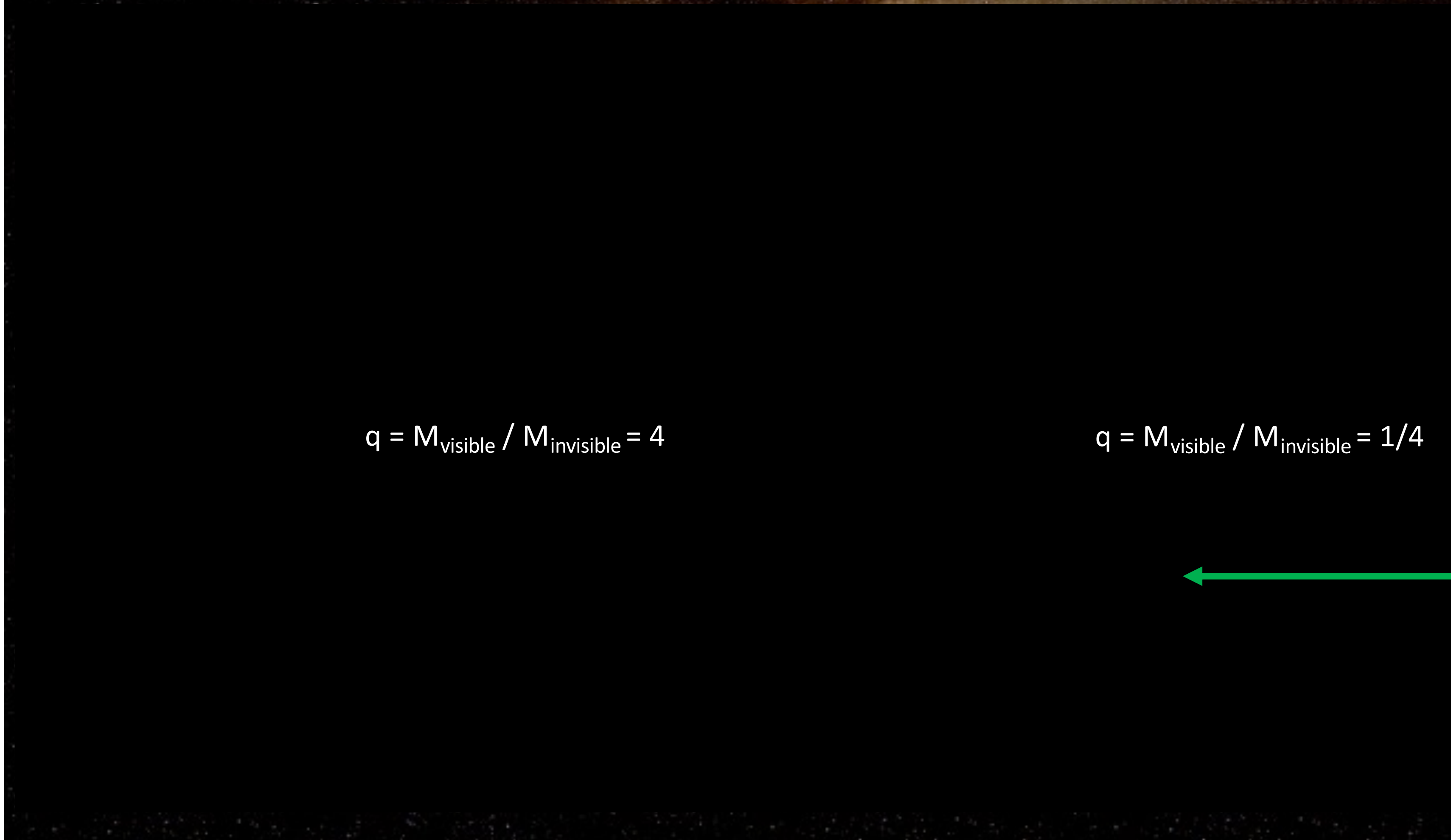
- Period-eccentricity for giants
  - Much more expected
  - (lines are where $P(1-e)^3$ constant)



Period eccentricity along Main Sequence [Gaia collab., Arenou et al., 2023]



SB with sub-luminous companions



Hence, large velocity variations, easily spotted

Discovery of several candidate binaries with dormant (i.e., non-accreting) non-luminous massive companions

(neutron stars or black holes)

Credit: Gilles Sadowski

Multiple stars (N>2)

- Useful for stellar formation
  - orbits coplanar? formation viscous accretion disc
  - mass ratios : disc fragmentation mechanism
- Multiple systems span a large period range
  - Here Gaia proves very handy
- Several ways to find them in Gaia DR3
  - Sources with both astrometric Orbital solution and SB1/SB2 solution, that were not combined
    - 152 triple systems having significance enough
    - SB* : internal system, Orbital: external
  - Also several hundreds being SB1 + acceleration
    - Period mode ~ 3d
  - Those in the El-Badry et al. (2021) catalogue of resolved binaries
    - 10 063 ternary systems, 52 quaternary
    - Note that this is multimodal : tidal interaction within the inner couple ?
- Already some insight from the NSS catalogue

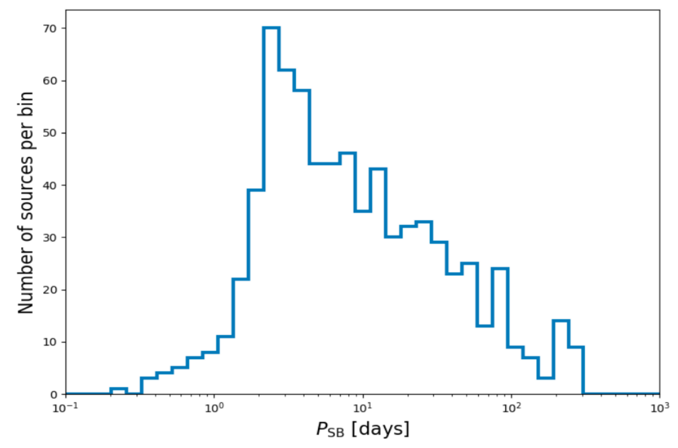


Fig. 52. Distribution of inner periods for triple systems found by comparing astrometric acceleration and SB solutions.

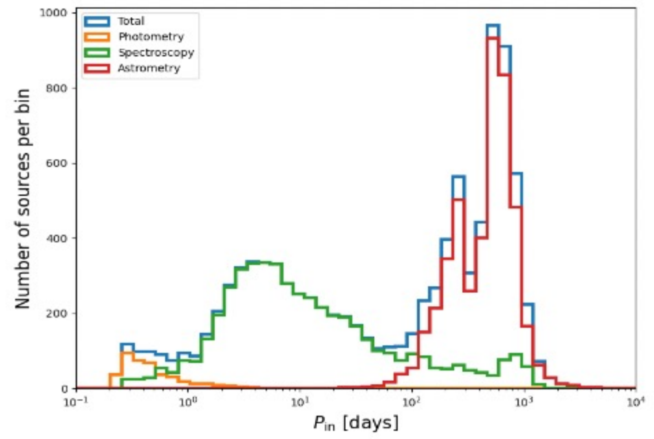


Fig. 54. Distribution of inner periods for triple systems found in El-Badry catalogue.

Gaia collab., Arenou et al., 2023

Exoplanets

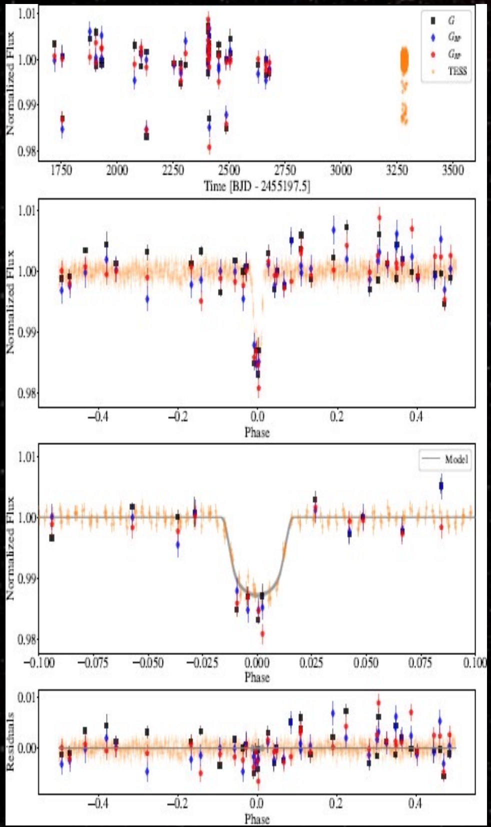
Gaia DR3 (few) candidate exoplanets

- There are candidates from all three canals in Gaia DR3
  - E.g. WASP-18b is re-discovered by radial velocity
  - A few dozens in total

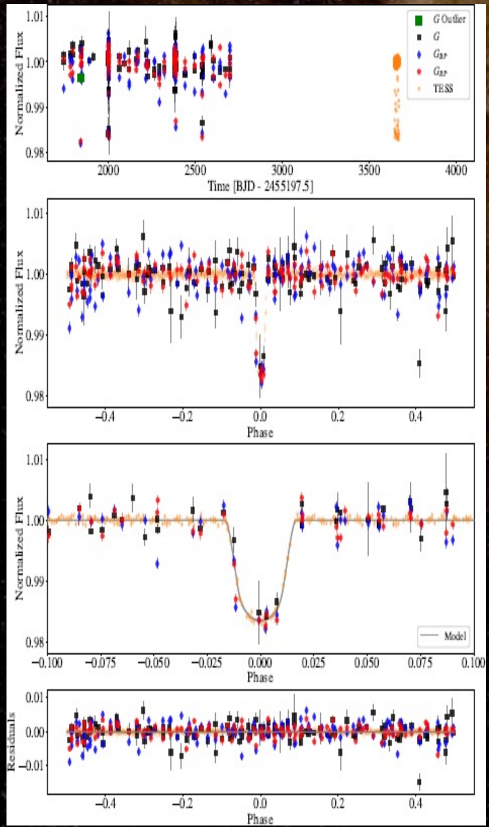
- Naming conventions
  - Candidate (Object of Interest)
    - Astrometric detection: Gaia-ASOI-#
    - Photometric transit: Gaia-TROI-#
    - Radial velocity: Gaia-RVOI-#
  - Confirmed
    - 'Gaia-#-a' and 'Gaia-#-b'

- Candidate list (to be updated)
  - https://www.cosmos.esa.int/web/gaia/exoplanets
    - Included in exoplanet.eu as soon as available

Gaia transiting planets



Gaia-1b: P=3.05d, M_p=1.78 M_J, R_p=1.23 R_J



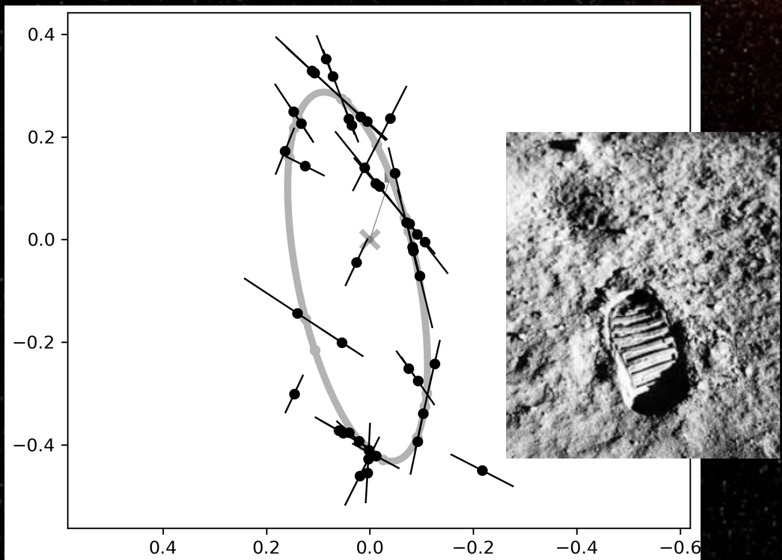
Gaia-2b: P=3.69d, M_p=0.77 M_J, R_p=1.33 R_J

- First detections by Gaia DR3
  - Around solar-type stars
  - 2 confirmed,
    - Panahi et al. 2022A&A...663A.101P
  - 214 known or candidates
    - Table vari_planetary_transit

Credit: : ESA/Gaia/DPAC, Panahi et al. 2022

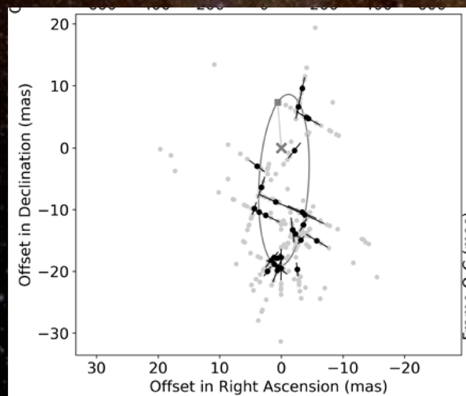
Astrometry: exoplanets, BD... or stars

HD 81040 b, P=850d,
1.2 $\mathfrak{M}_\odot$ + 7.53 $\mathfrak{M}_{Jup}$ (updated)



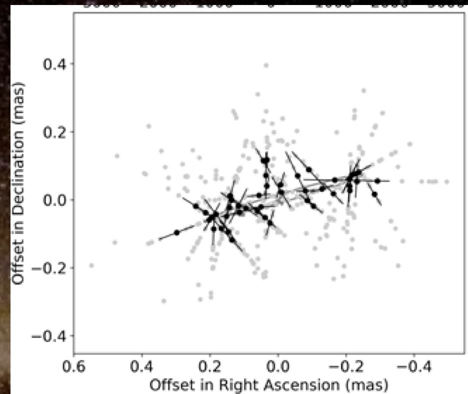
Credits: ESA/Gaia/DPAC, Johannes Sahlmann, Berry Holl

Brown dwarf binary 2M0805 (L4+T5)

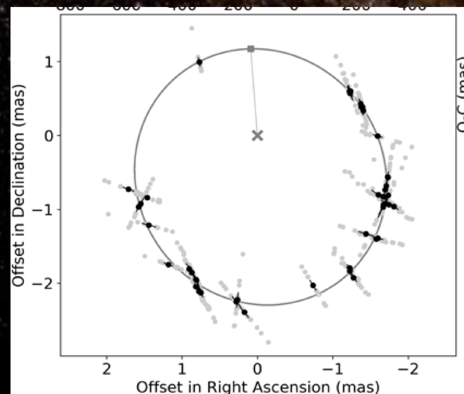


Credits: ESA/Gaia/DPAC
Johannes Sahlmann

A super-Jupiter orbiting the white dwarf WD 0141-675 ?



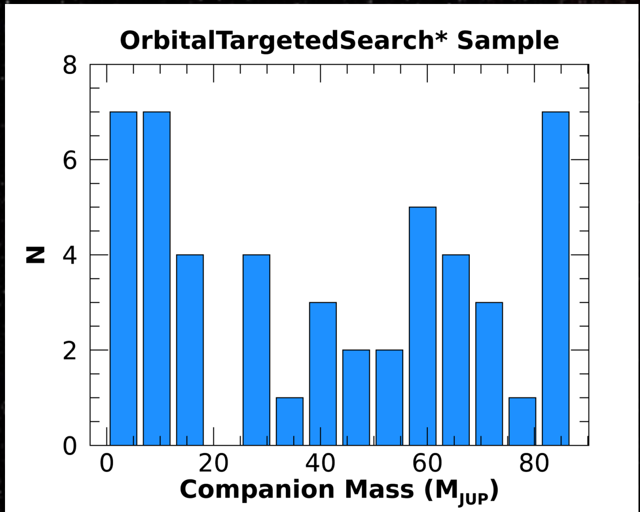
HD 114762 B: 1st substellar companion (Latham et al. 1989) is actually stellar

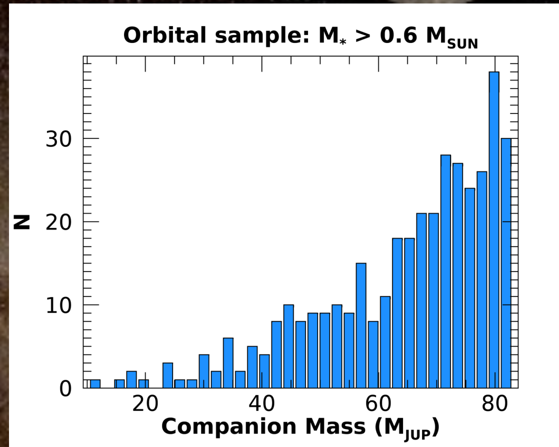


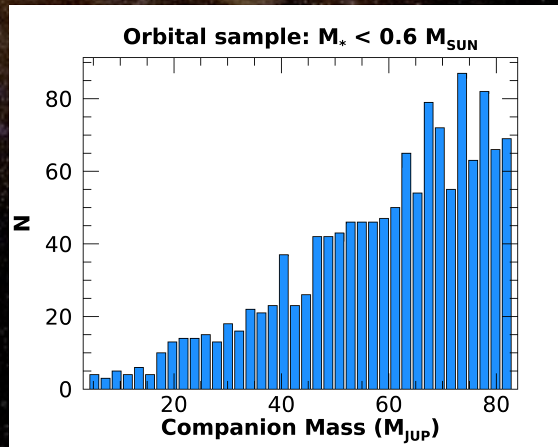
Getting true companion masses with DR3

- True mass = not the secondary mass x sin(i)

- BD desert with true masses
  - \`OrbitalTargetedSearch' sample
  - Shows the expected dip around 20-40 $\mathfrak{M}_{Jup}$







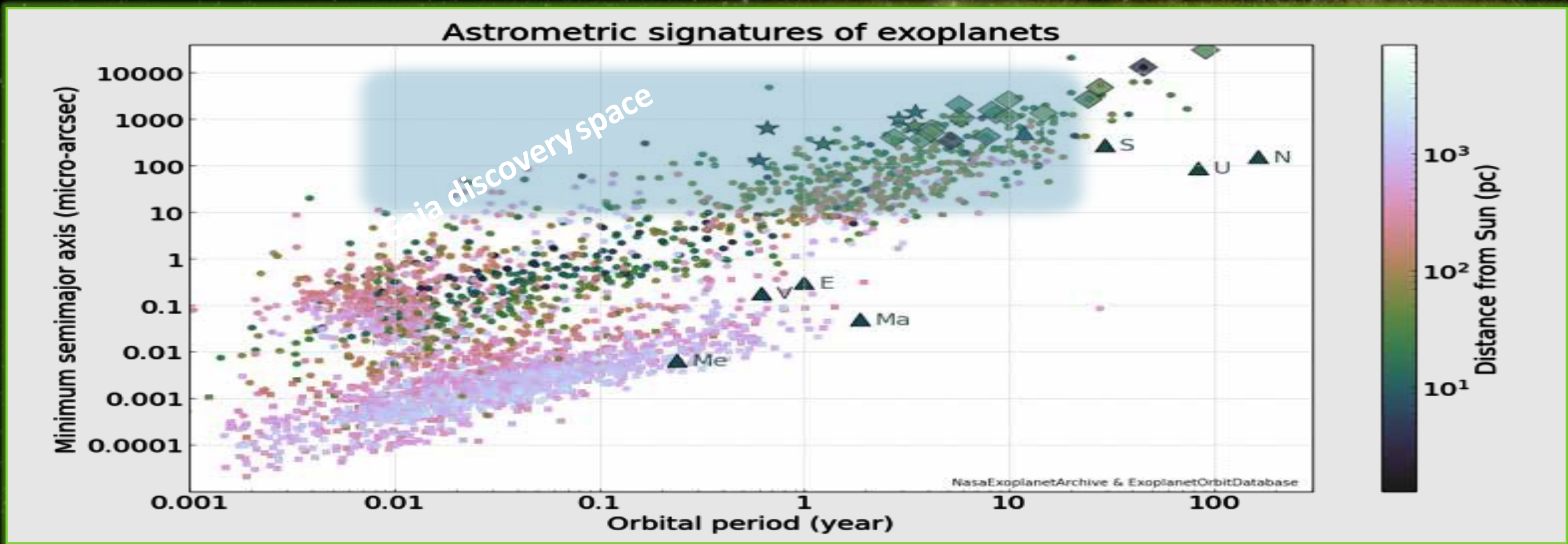
- A few dozens exoplanets and BD
  - With changes with primary mass

Not the same slope depending on the primary
Gaia Coll., Arenou et al. 2022

Gaia DPAC

The start of Gaia exoplanet work

- Exoplanets were initially planned for the end of the 5yr mission (DR4)
  - A few dozens published for DR3 (astrometric / spectroscopic / transits)
- For exoplanets, one (discrete though *important*) DR3 contribution is the host characterisation for hundreds of millions stars
- Much more EP are planned for DR4 (how many is unknown as yet)
  - with larger periods
  - There is an on-going better handling of spurious vs good solutions
  - Epoch astrometric data will also allow the combination with external data



Credits: Johannes Sahlmann

Ambiguity about the nature of the sources

- When selecting all low mass functions
  - $f(\mathfrak{M}) < 0.001$ (hoping to get $M_2 < 0.1\ \mathfrak{M}_\odot$ stars)
  - Two sequences appear →
- The astrometric mass function
  - Depends on the mass fraction
  - … minus the luminosity fraction

$$(\mathcal{M}_1 + \mathcal{M}_2)\left(\frac{\mathcal{M}_2}{\mathcal{M}_1 + \mathcal{M}_2} - \frac{F_2/F_1}{1 + F_2/F_1}\right)^3 = \frac{(a_0/\varpi)^3}{(P/365.25)^2}$$

- Low mass functions are either →
  - Substellar companions (EP/BD)
  - Or stellar twins
- Source characterisation is needed
  - Using Gaia astrophysical parameters

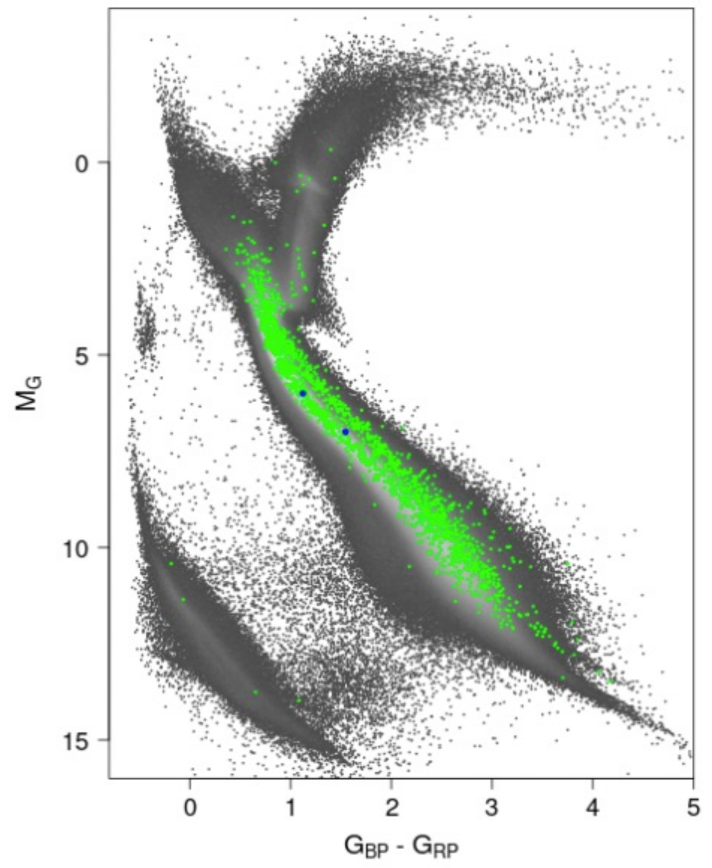
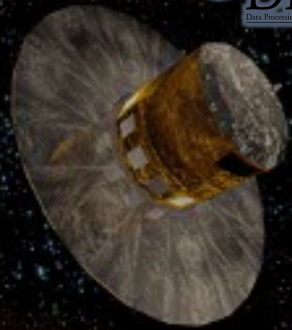


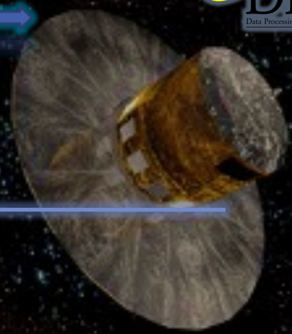
Fig. 47. H-R diagram of sources with low astrometric mass functions (< 0.001 $\mathcal{M}_\odot$; green dots); the grey background is the DR3 low extinc-

Gaia collab., Arenou et al., 2023



Will be the subject of the hands-on

Mass estimation



Masses from astrometric orbits

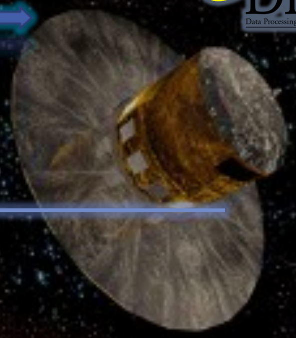
$$(\mathcal{M}_1 + \mathcal{M}_2) \cdot (B - \beta)^3 = \frac{(a_0/\varpi)^3}{(P/365.25)^2}$$

with $B = \mathcal{M}_2/(\mathcal{M}_1+\mathcal{M}_2)$
$\beta = F_2/(F_1+F_2)$

If one assume $\beta = 0$, then $\mathcal{M}_1$ can be estimated through isochrone fitting → $\mathcal{M}_2$
(e.g. exoplanets and compact object search)

- In the general case, the flux ratio is not known, so only upper and lower mass values can be derived.

Masses from spectroscopic orbits



- With P in days

SB1 → $$\frac{(\mathcal{M}_2 \sin i)^3}{(\mathcal{M}_1 + \mathcal{M}_2)^2} = 1.0385 \cdot 10^7 K_1^3 (1 - e^2)^{3/2} P$$ Needs $\mathcal{M}_1$ and the inclination

sin i = 1 gives a lower limit to $\mathcal{M}_2$

- Note that for astroSpectroSB1, we also have: $$\frac{\mathcal{M}_2^3 \sin^3 i}{(\mathcal{M}_1 + \mathcal{M}_2)^2} = \frac{(C^2 + H^2)^{3/2}}{(P/365.25)^2}.$$

SB2 → $$\frac{\mathcal{M}_2}{\mathcal{M}_1} = \frac{K_1}{K_2}$$ Needs $\mathcal{M}_1$ or the inclination

Inclination can be given by the **astrometric** or the **eclipsing** orbits
And we have $\mathbf{a_1 \sin i = \frac{1}{2\Pi} K_1 P \sqrt{1 - e^2}}$ and similar for a_2

Estimation of binary masses with Gaia DR3 orbits

Combination	$\mathcal{M}_1$	$\mathcal{M}_2$	F_2 / F_1
Astrometric + SB2	✓	✓	✓
Eclipsing + SB2	✓	✓	
Astrometric + SB1 + $\mathcal{M}_1$		✓	✓
Eclipsing + SB1 + $\mathcal{M}_1$		✓	
SB2 + $\mathcal{M}_1$		✓	
Orbital + $\mathcal{M}_1$		lower/upper	?
SB1 + $\mathcal{M}_1$		lower	

Estimating $\mathcal{M}_1$ from Gaia DR3

- FLAME masses (based on GSP-Phot or GSP-Spec)
  - ! assumed zero flux ratio !
    - While the secondary may contribute
  - ! used the parallax computed assuming a single star model !
    - While the parallax has been improved (changed?) with the NSS solution

- White Dwarf : assume $\mathcal{M}_1 = 0.65 \pm 0.16\ \mathcal{M}_\odot$

Estimating $\mathcal{M}_1$ from Gaia DR3

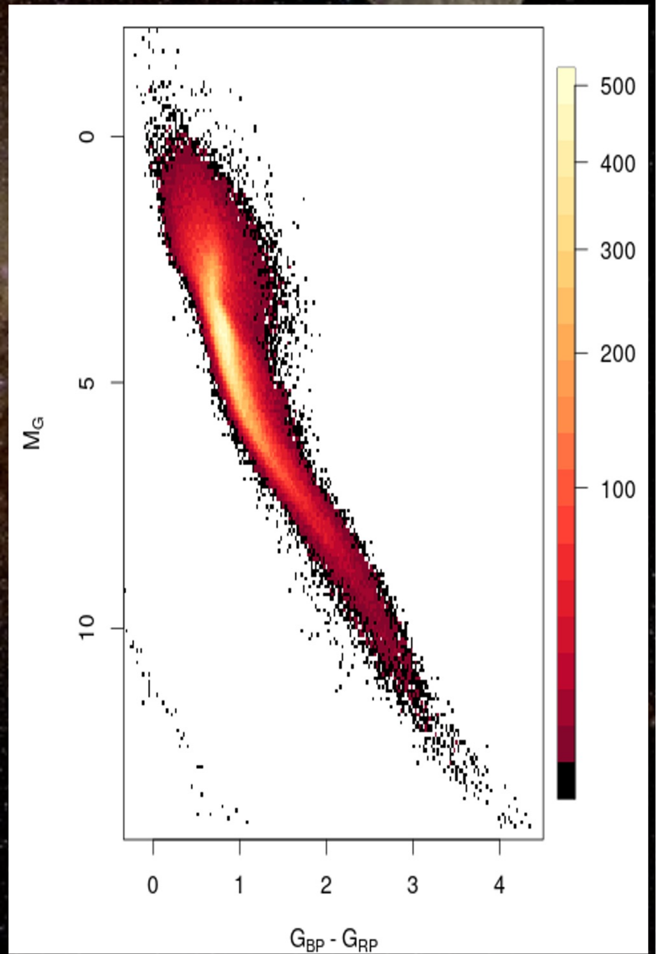
- Main-sequence mass-luminosity relation:
  - ← empirical or theoretical relations (e.g. isochrones)
  - ← extinction (e.g. 3D extinction map)
  - ← metallicity (or all assumed possible)
  - ← flux ratio (all possible are to be tested)
- ! triple cases
- ! pre-main sequence

Table gaiadr3.binary_masses

Main-sequence mass-luminosity relation + WD

(isochrones, 3D extinction map, all metallicities possible, all flux ratios tested)

Combination	#	$\mathcal{M}_1$	$\mathcal{M}_2$	F_2 / F_1
Astrometric + SB2	23	✓	✓	✓
Eclipsing + SB2	56	✓	✓	
Astrometric + SB1 + $\mathcal{M}_1$	19091		✓	✓
Eclipsing + SB1 + $\mathcal{M}_1$	226		✓	
SB2 + $\mathcal{M}_1$	3856		✓	
Orbital + $\mathcal{M}_1$	111792		lower/upper	?
SB1 + $\mathcal{M}_1$	60271		lower	



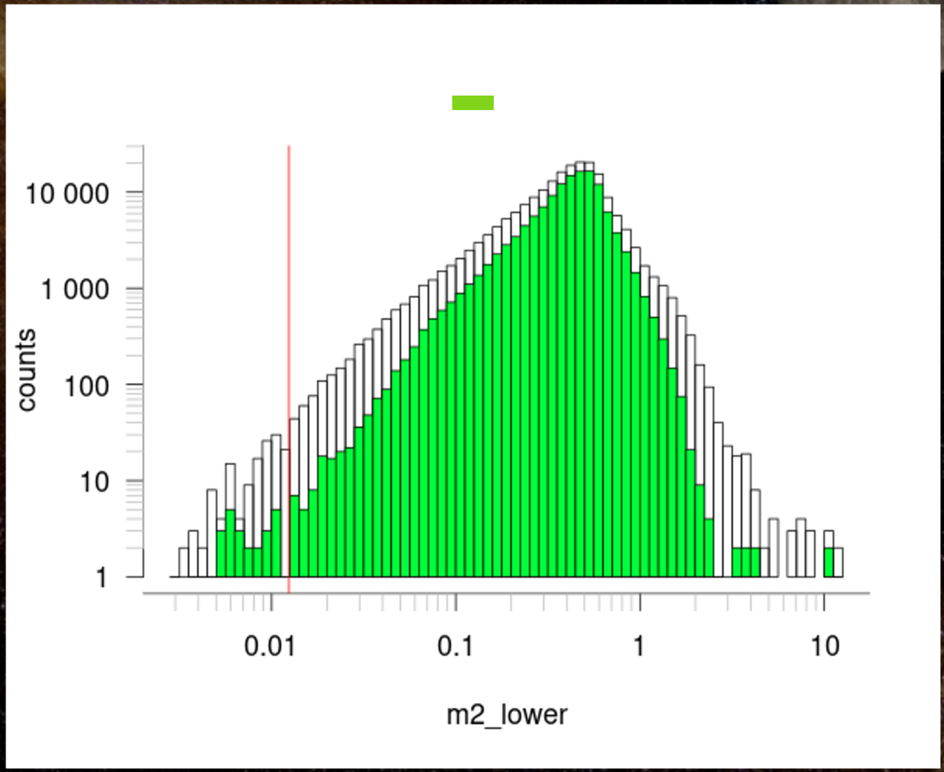
Gaia Collaboration, Arenou et al. 2022

gaiadr3.binary_masses

→ Exoplanet candidates

→ Black hole candidates

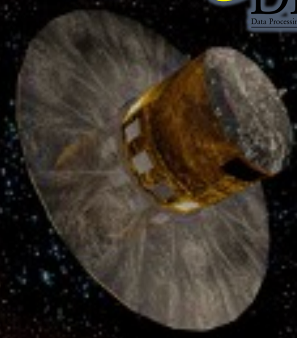
A very large catalogue of masses (and sometimes luminosities)



Gaia collab., Arenou et al., 2023

Note: you too can improve the knowledge on the masses on some stars by combining Gaia with external observations of SB2 (→ q) either from large catalogues (APOGEE) or from your own observations !

- Also, resolving sources would constrain the sum of masses



Looking at what happened in the DR3 kitchen

DR3 processing details

How close is close

- ❑ Gaia can detect (resolve) double stars… down to some separation
  - ❑ Even when handled as a single source, the handling is not perfect
    - ❑ *between ≈ 9 mas and ≈ 0.27′′ separation, pointing is not exactly on photocenter*
  - ❑ Note that this depends on the X-match, calibration capabilities, # of transits
    - ❑ Improves from DRn to DRn+1 → explains why source_ids change with DR

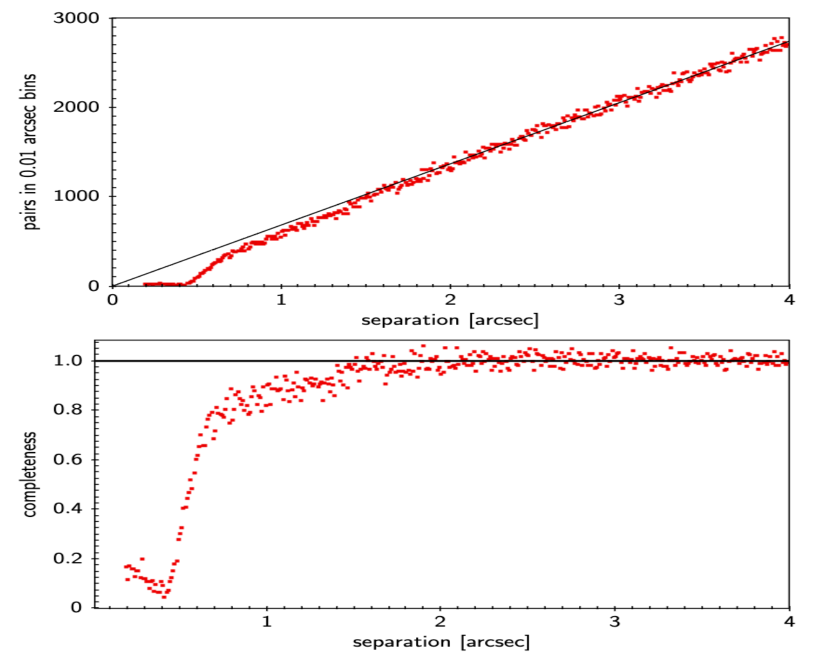


Fig. 7. *Top:* Histogram of source pair distances in a circular field of radius 0.5° centred at $(l, b) = (330°, -4°)$ with a line showing the expected relation for a random distribution of the sources. *Bottom:* Normalised histogram using the expected relation.

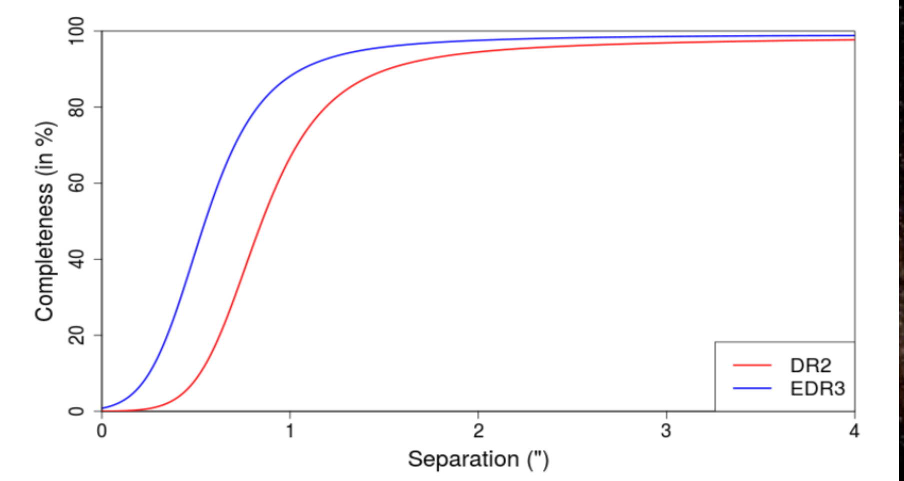
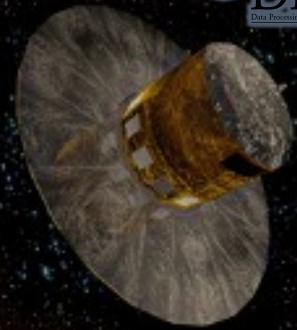


Fig. 8. Improvement of the completeness (in percent) of visual double stars from the WDS catalogue as a function of the WDS separation between components from *Gaia* DR2 (red) to *Gaia* EDR3 (blue).

Gaia eDR3. Catalogue validation, Fabricius et al., 2021A&A...649A...5F

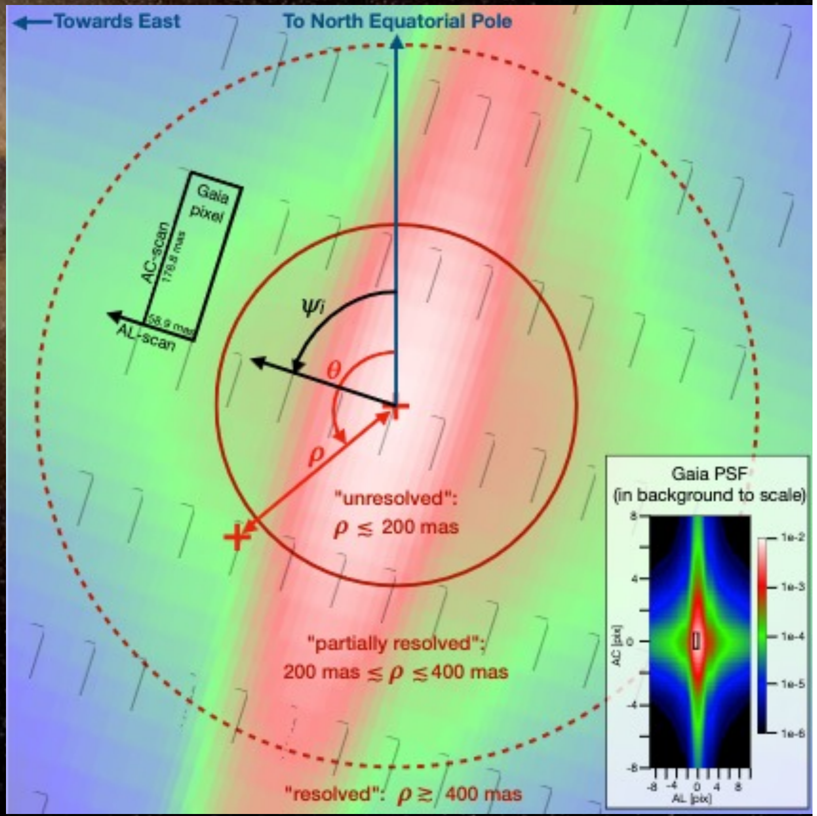
What happens for closer pairs ?

Spurious solutions



IPD modelling error of non-point-like sources

- Image Parameter Determination, (IPD, Castañeda et al. 2022
- A 2D PSF (G ≲ 13) or 1D Line Spread Function (LSF, G ≳ 13) is fitted
- For a double, depending on scan angle:
  - If separation ρ ≲ 200 mas: “unresolved”
  - If 200 ≲ ρ ≲ 400 mas: “partially resolved”
  - If ρ ≳ 400 mas: “resolved”
- For IPD on a double star:
  - When resolved, pixels of the secondary are excluded → position fitted is OK
    - like for unresolved case
  - Bias may occur for “partially resolved”
- For galaxies, same problem, plus the disk giving a high background



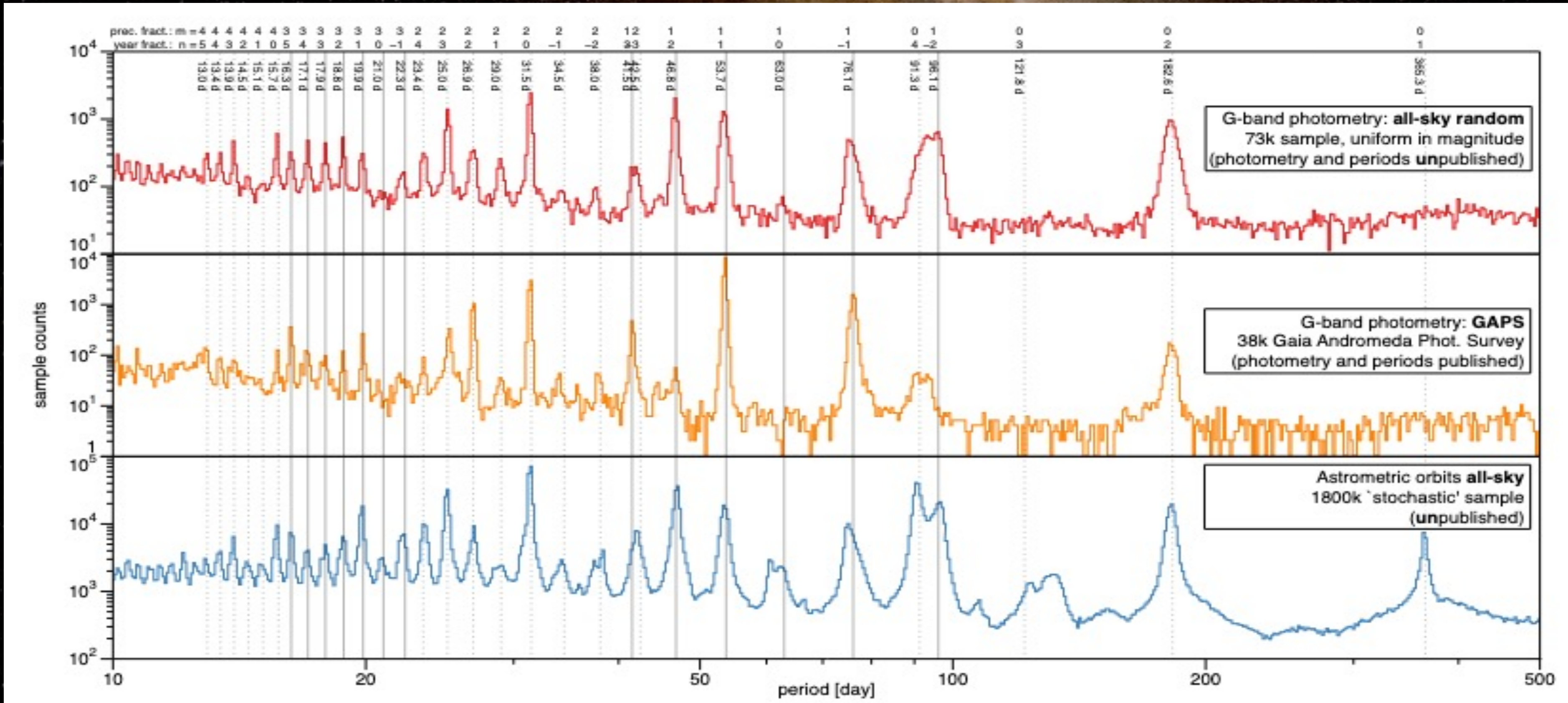
Red crosses: pair of ~twin sources
Holl et al., 2023A&A...674A..25H

IPD modelling error of non-point-like sources

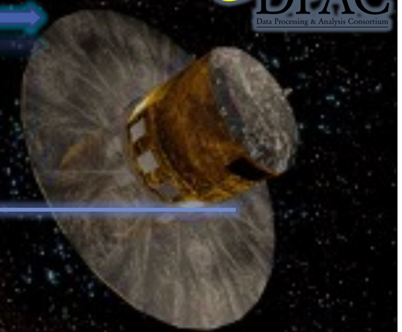
- Although multiple peaks are not (yet) fitted with 2 LSFs, flags exist
  - ipd_frac_multi_peak: % of windows where IPD identified > 1 peak
    - and masked the other peak
  - ipd_frac_odd_win: % transits with truncated windows or multiple gate
    - target is likely disturbed by a close brighter source
  - ipd_gof_harmonic_amplitude and ipd_gof_harmonic_phase, measuring the amplitude and phase of a model of the IPD goodness of fit (GoF)
    - $\ln(\chi2(\psi)) = c_0 + c_2 \cos2\psi + s_2 \sin2\psi$
    - as a function of the position angle of the scan angle ψ
    - ipd_gof_harmonic_phase is ~ the scan angle (±180°) corresponding to the worst fit → will give insight on double star orientation
- Caveat about this phase
  - For a close (unresolved) binary, say $\rho < 100$ mas
    - The worst fit is along the orientation of the pair
    - Being unresolved, ipd_frac_multi_peak is small
  - For a partially resolved
    - ipd_frac_multi_peak is large along the orientation of the pair, but the fit is the best here as the secondary has been suppressed
    - So the ipd_gof_harmonic_phase will differ from the position angle by 90°

Avoiding spurious solutions in NSS

- What happens when searching for periodic binary motion ?
  - Partially resolved double will appear with a spurious frequency in astrometric or photometric period search
    - Combination of precession period and yearly motion

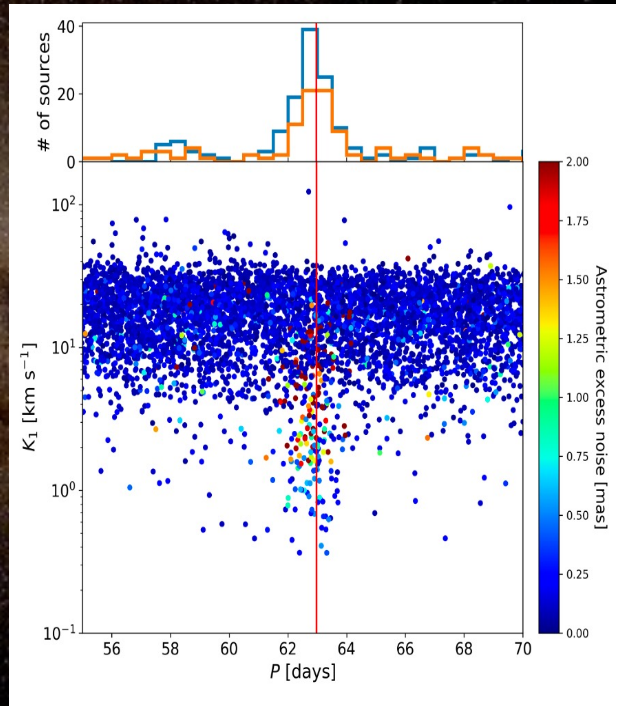


Holl et al., 2023A&A...674A..25H



Problems also on SBs

- A few % of the SB1 solutions may be spurious
  - Due to sparse time sampling
  - Mostly at short periods
  - E.g. Excess of solutions near the precession period →
- Note that there is a processing issue on RVS for non single stars
  - The calibration of spectroscopic data needs to know the precise position of the source on the CCDs on-board Gaia at the given epoch
    - Predicted position is incorrect if the source is handled as a bona fide single star
  - Circular problem because
    - NSS needs spectroscopic data (to detect and analyse the SBs)
    - But the the spectroscopic data needs NSS (to correct the position)
  - This is being solved for DR4 (at least for ABs)

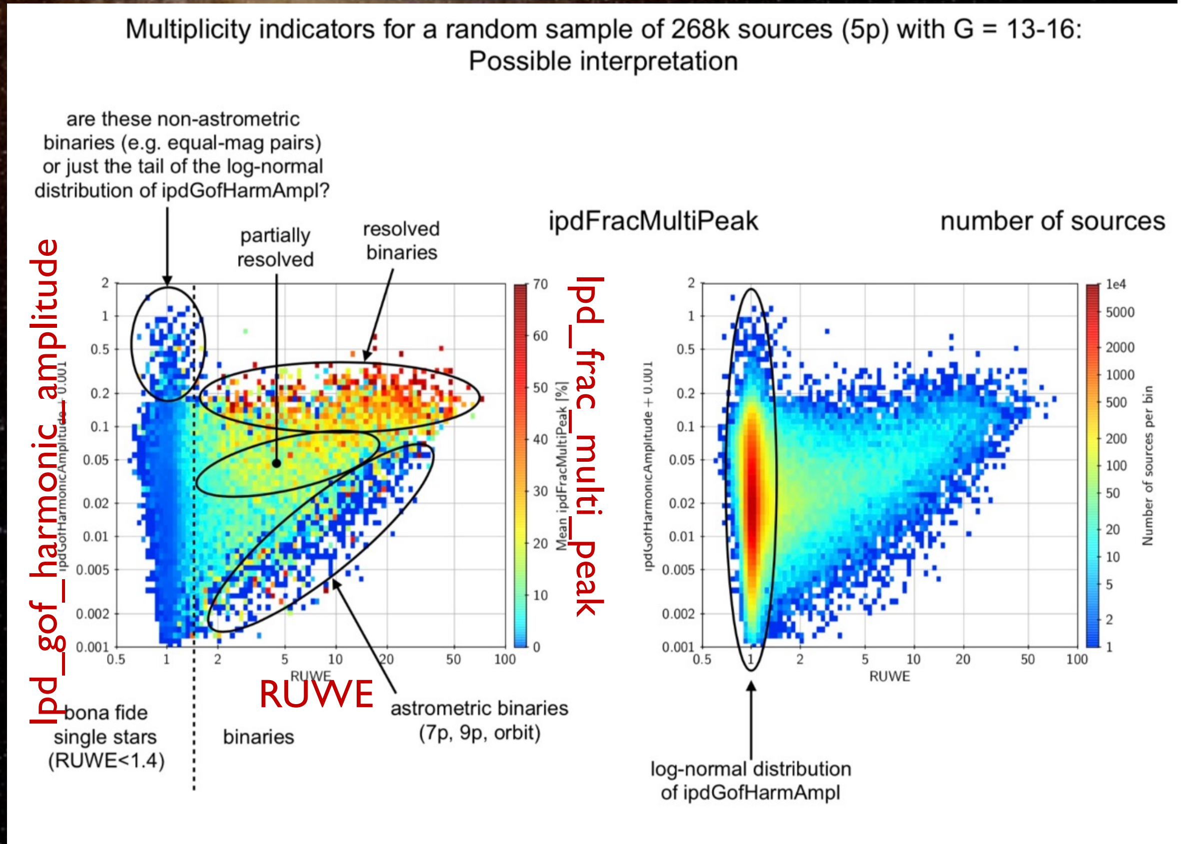


Spurious solutions near the psatellite recession period (62.97 days)5 Gaia collab., Arenou et al., 2023

Criteria for the detection of potential issues (I)

- That is, to detect (partially) resolved sources

- Useful gaia table parameters
  - ruwe
  - ipd_gof_harmonic_amplitude
  - ipd_frac_multi_peak
  - ipd_frac_odd_win
  - phot_bp_rp_excess_factor



: *Extract from: L. Lindegren, Multiplicity indicators in eDR3 from AGIS*

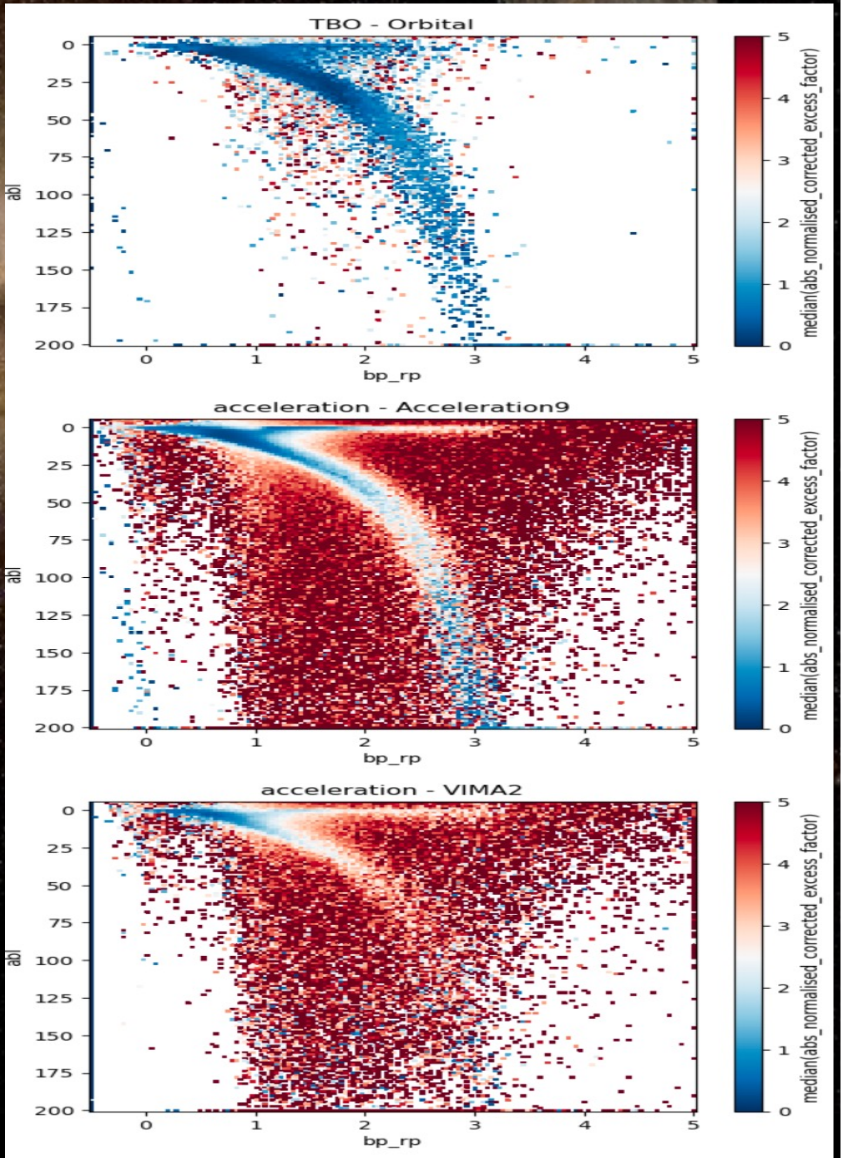
  - Interpretation of harmonic amplitude vs RUWE, coloured by multipeak

Gaia DPAC

Criteria for the detection of potential issues II

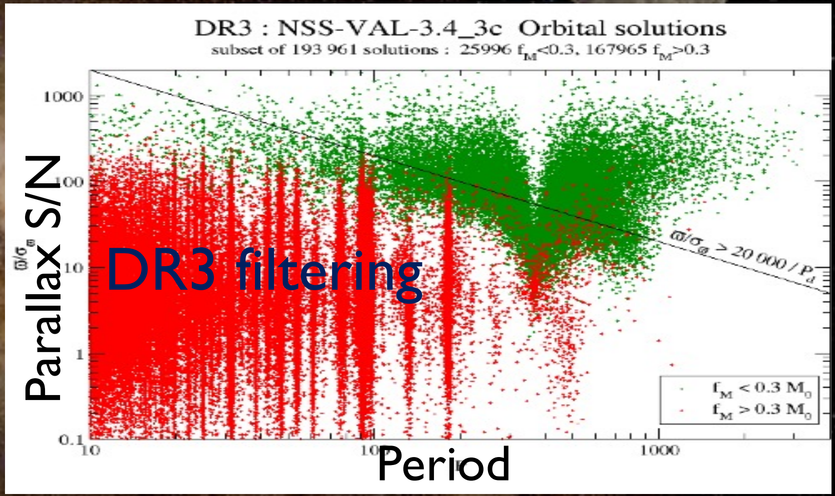
- ruwe
- ipd_gof_harmonic_amplitude
- ipd_frac_multi_peak
- ipd_frac_odd_win
- phot_bp_rp_excess_factor = (BP+RP)/G
  - Should be ~ 1 for single stars
  - A corrected BP/RP flux excess (C*) is defined in Riello et al., 2021
- This excess is indicative of contamination by a neighbour → bad astrometry
  - We use here an Astrometry-based luminosity (ABL, cf. Arenou & Luri, 1999) similar to an H-R diagram (to accept ϖ < 0)
  - Coloured by the normalised C*/σ
  - On a partial run (GAIA-C4-TN-OPM-FA-085)
  - Shown here on orbital, acceleration9 and VIMA solutions

$$a_V \equiv 10^{0.2M_V} = \varpi 10^{\frac{m_V+5}{5}}$$



Source contamination

- Several problems conspire
  - Astrometric signals are often due to resolved
  - Aliases with scanning law frequencies
  - Noise contamination
- DR3 filtering has been very harsh
  - Loosing many sources
  - In particular at low S/N (EP)
- Improvements can be expected
  - Model: resolved/acceleration/orbital
  - Cutoffs frequencies are needed
    - Cf. Holl. et al. 2022b



Credits: ESA/Gaia/DPAC Halbwachs et al. 2022

Initial DR3 selection for NSS processing

- In order to filter as much as possible the resolved sources, and to get the most significant solution, an initial DR3 filtering was applied
- Astrometry
  - RUWE > 1.4
  - AND ipd_frac_multi_peak <= 2
  - AND ipd_gof_harmonic_amplitude < 0.1
  - AND visibility_periods_used > 11
  - AND phot_g_mean_mag < 19
  - AND photometric excess C* < 1.645 σ
- Spectroscopy
  - rv_renormalised_gof > 4
  - #transits >= 10
  - 3875 < Template_teff < 8125
  - OR isSB2
- Eclipsing
  - From the CU7 selection (cf. Laurent)

A 'visibility period' groups observations separated from other groups by at least 4 days

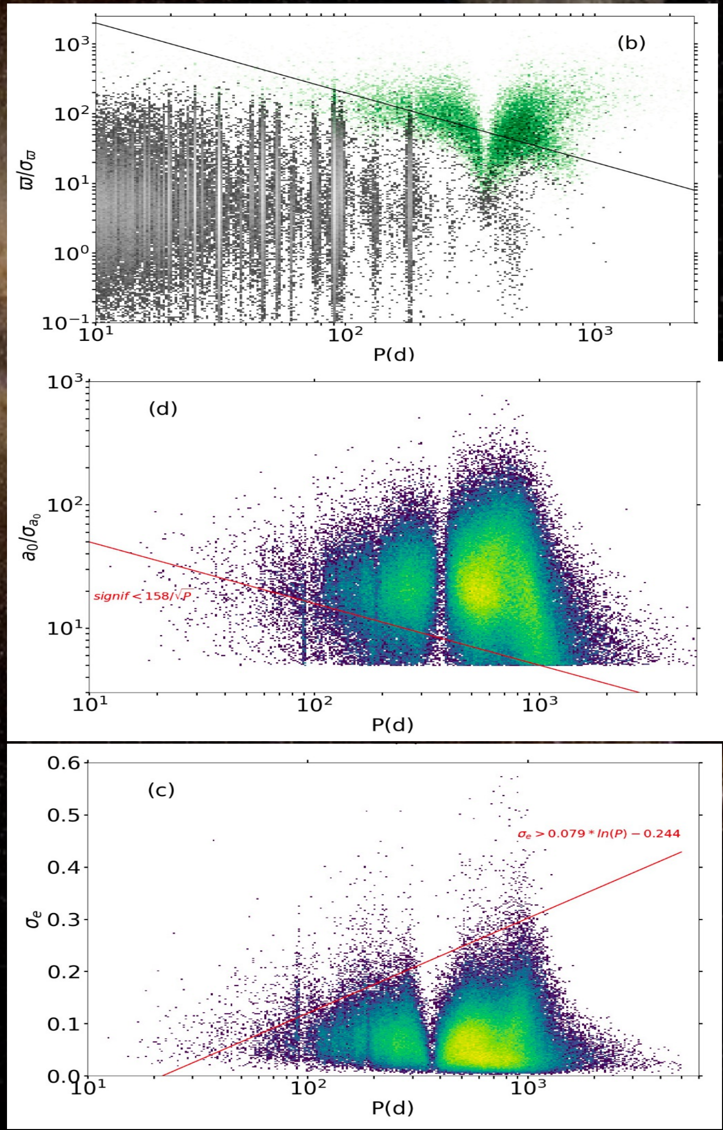
rv_renormalised_gof is analogous to the astrometric F2 of a constant RV

Gaia DPAC

Final AB selection for DR3

- A final filtering has been applied on
  - parallax S/N
  - Significance
  - Eccentricity_error

Model	Dimension	Significance	Selection conditions: significance	F_2	ϖ/σ_ϖ	Other
Acceleration :						
Constant	7	$s_7 = \frac{g}{\sigma_g}$	> 20	< 22	$> 1.2 s_7^{1.05}$	-
Variable	9	$s_9 = \frac{g}{\sigma_g}$	> 20	< 25	$> 2.1 s_9^{1.05}$	-
Orbital* :						
eccentric	12	$\frac{a_0}{\sigma_{a_0}}$	$> \max\left(5, \frac{158}{\sqrt{P_{\text{days}}}}\right)$	< 25	$> \frac{20\,000}{P_{\text{days}}}$	$\sigma_e < 0.079 \ln P_{\text{days}} - 0.244$
circular or pseudo-circular	10	$\frac{a_0}{\sigma_{a_0}}$	$> \max\left(5, \frac{158}{\sqrt{P_{\text{days}}}}\right)$	< 25	$> \frac{20\,000}{P_{\text{days}}}$	-
VIMF	7	$\frac{D}{\sigma_D}$	> 20	< 25	> 30	-

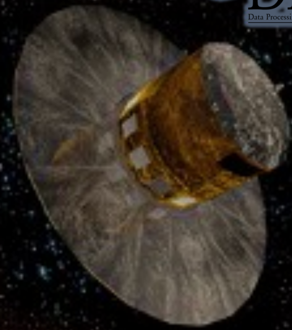


Limitations of Gaia DR3 analysis

- Astrometric binaries
  - Harsh filtering to avoid spurious solutions
    - Short periods missing
  - Underestimations
    - Significance should be multiplied by the unit-weight

- Spectroscopic binaries
  - A few percent of the SB1 solutions (short periods) due to sparse time sampling
    - Check using GoF, IPD flags, filter with *significance*
  - + some bad solutions due to SB2s handled (partially) as SB1
  - + there may be pulsating variables (present/ SB handling missing)
  - + contamination by nearby, brighter star

- Eclipsing binaries
  - Here GoF is frequently in excess, and uncertainties not reweighted
    - Better multiply them by unit-weight error

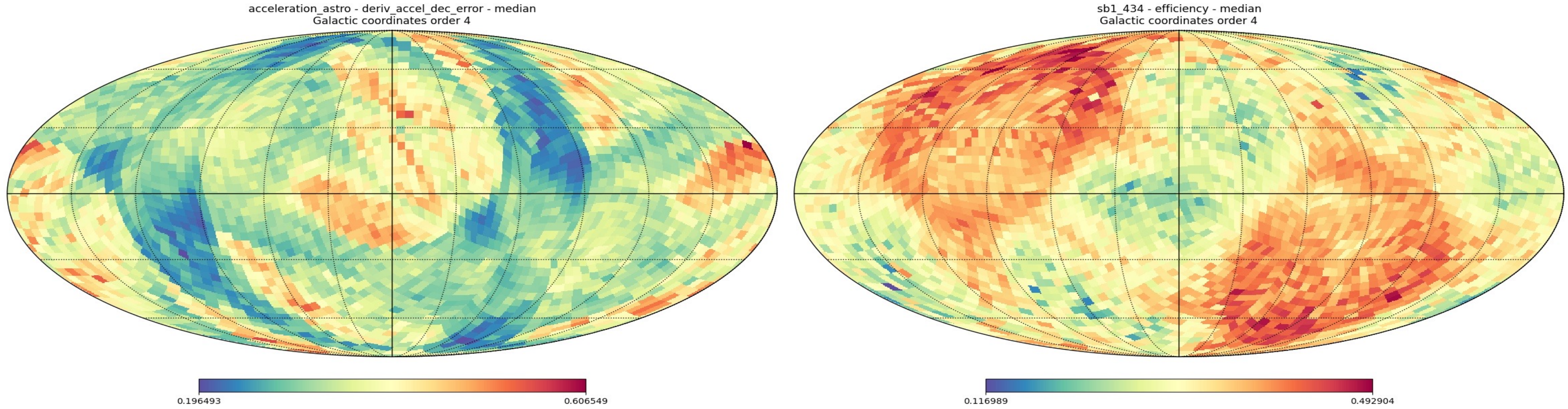


Which statistical properties to infer from the catalogue?

Selection function

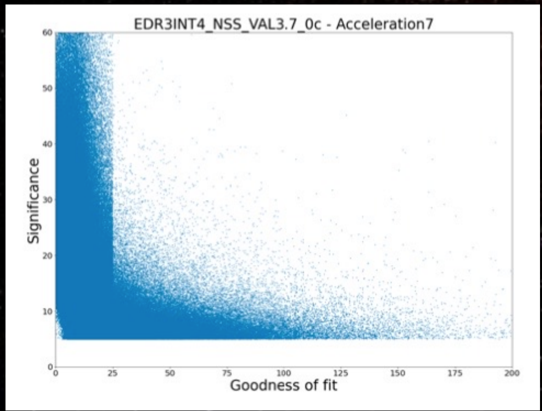
The selection function

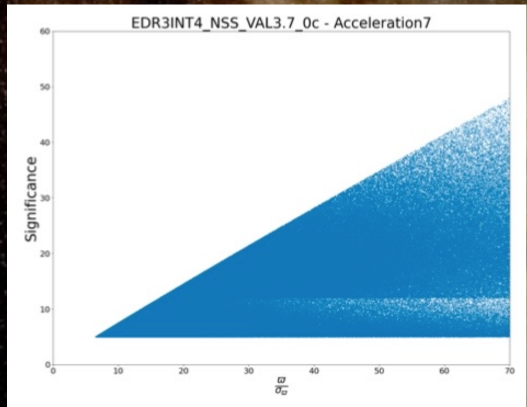
- Knowing the selection function is *mandatory* for any unbiased analysis of the statistical properties of a population
- It is the convolution of the true population distribution with (e.g.)
  - Instrument capability (limiting magnitude, resolution)
  - Probability of observation (magnitude- and scanning law- dependant)
  - Data reduction efficiency and type I/II compromises (see e.g. orbit filtering)
  - Type of motion (e.g. detectability of face-on orbit √2 larger than for edge-on)
  - Measurements errors

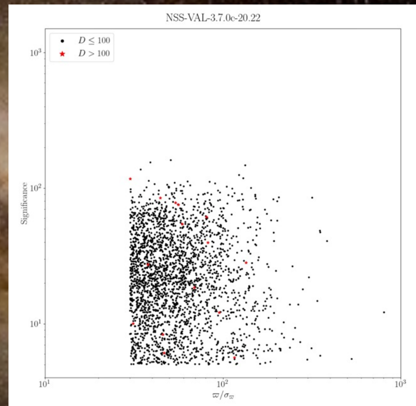


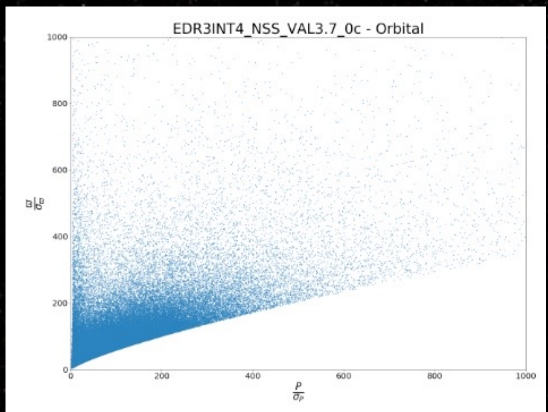
Gaia DPAC

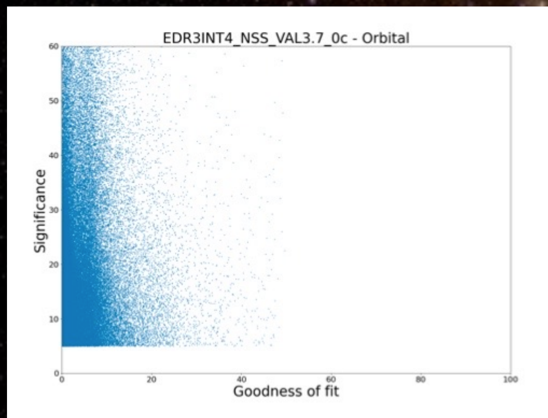
The selection function for Astrom. Binaries

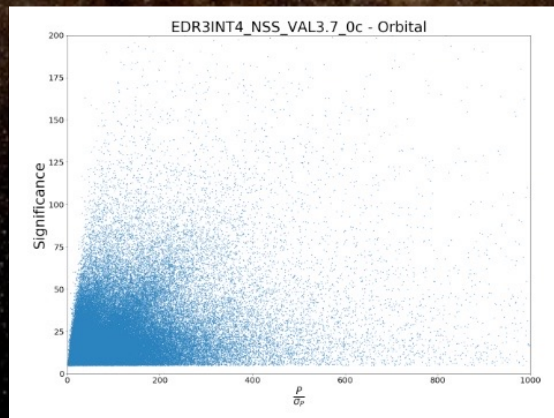












Incompleteness from NSS only

- Here we show only the selection on NSS solutions compared to some equivalent magnitude-limited numbers of stars in the main Catalogue
  - Using a "sky density factor" showing the ratio vs the median value
  - Large number of transits → better detectability → more solutions

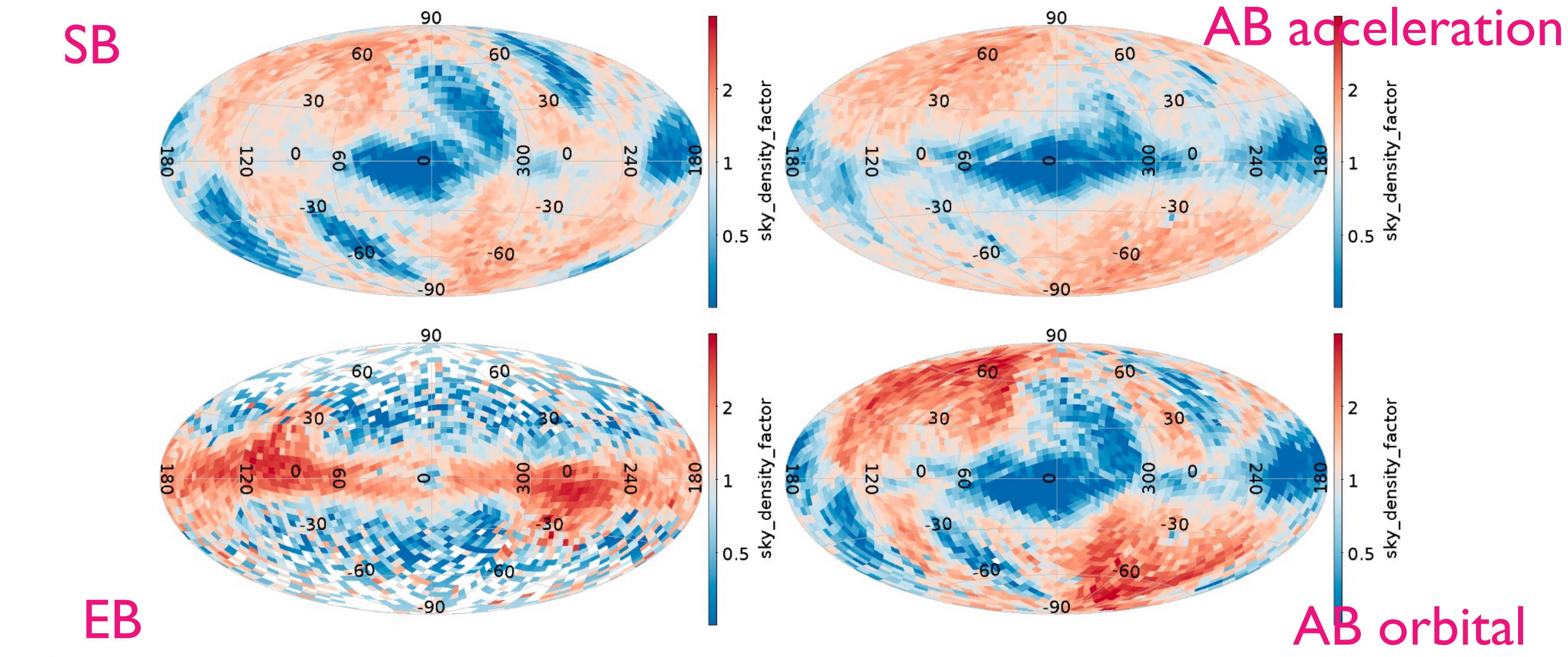
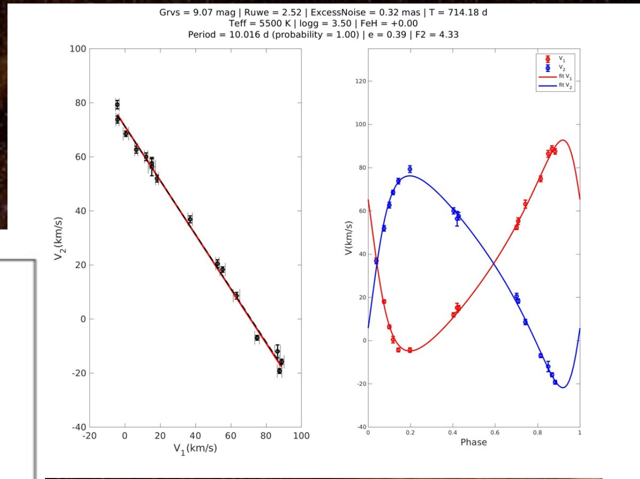


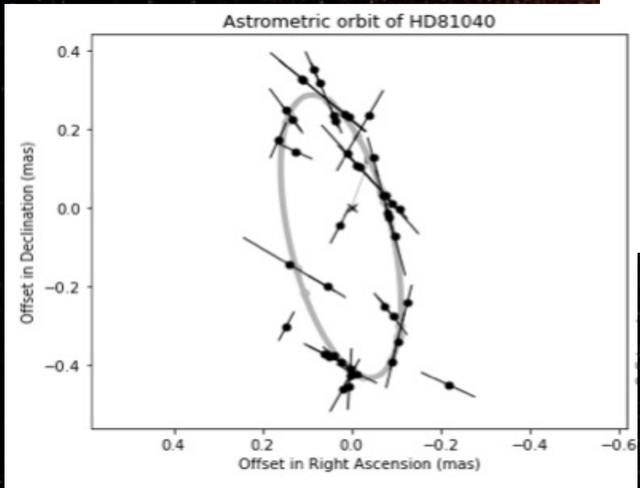
Fig. 6. Sky density factor (Galactic coordinates, healpix level 4, log scale, see text) illustrating the excess or deficit factors of NSS sources compared to their sky average value. *Panel a*: SB*, *Panel b*: Acceleration, *Panel c*: EclipsingBinary, *Panel d*: Orbital*.

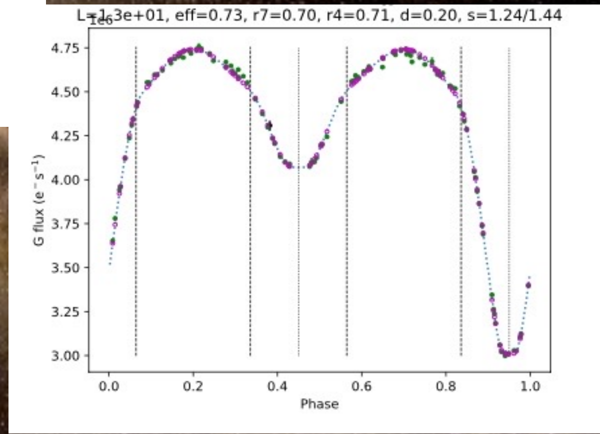
Gaia collab., Arenou et al., 2023

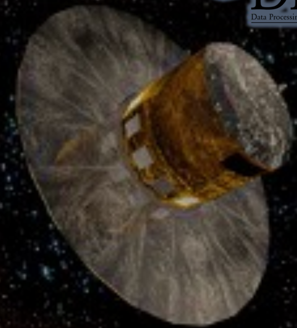
l'Observatoire de Paris | PSL cnrs

Scientific exploitation









DR3 NSS science exploitation

A teaser for the hidden treasure

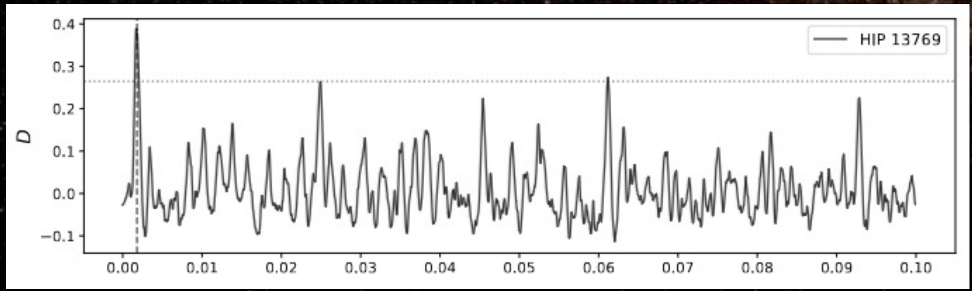
- Gaia Data Release 3. Stellar multiplicity, a teaser for the hidden treasure, Gaia Coll et al., 2023A&A...674A..34G
- Gaia Performance verification paper: illustrative applications
  - The binarity is studied in the RGB/AGB and a search for genuine SB1 among long-period variables is performed.
  - The discovery of new EL CVn systems illustrates the potential of combining the variability and binarity catalogues.
  - Potential compact object companions, mainly white dwarfs companions or double degenerates, but one candidate neutron star is also presented.
  - Towards the bottom of the main sequence, new binary ultracool dwarfs candidates are discovered with their masses estimated.
  - For the substellar regime shows the brown dwarf desert around solar-type stars using true, rather than lower limit masses, and suggests a lower frequency of giant planets around M dwarfs.
  - A super-Jupiter candidate planet orbiting a white dwarf, and two around solar-type stars, are proposed.
  - Beside binarity, the combination of these results or the use of wide binaries allows to detect higher order multiple systems.
- At that time, a caveat was mentioned: "results are tentative, candidates need confirmation"

Methodology

Searching for periodic signals in astrometry

- *Analytical determination of orbital elements using Fourier analysis. II. Gaia astrometry and its combination with radial velocities*, Delisle & Ségransan., 2022A&A...667A.172D

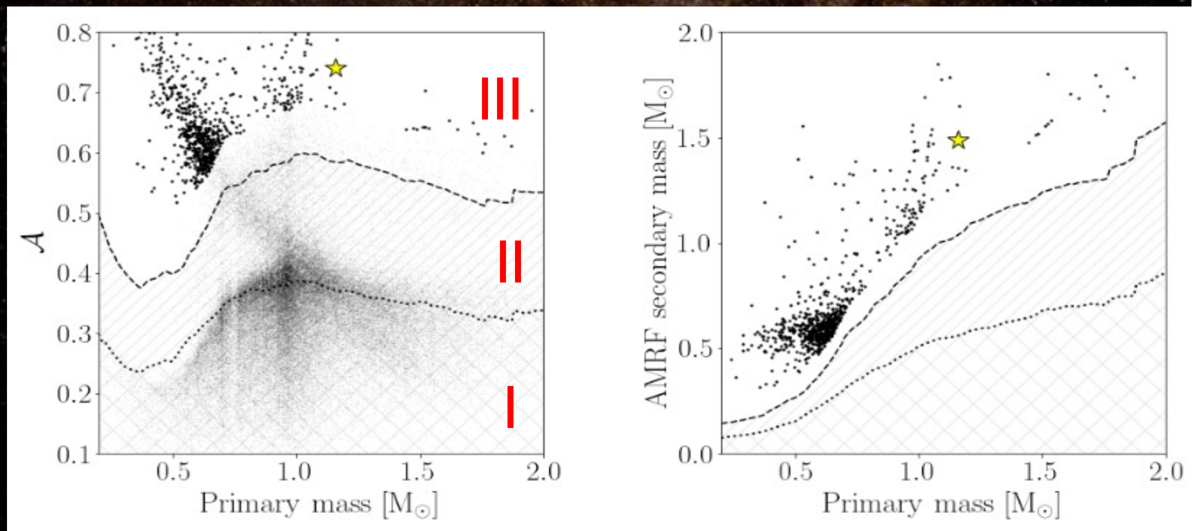
- *Model Independent Periodogram for Scanning Astrometry*, A. Binnenfeld et al., 2023A%26A...675A.124B
  - extension of phase-distance correlation periodogram (PDC), accounting for "nuisance" parameters to remove spurious peaks (here, e.g. the scan angle, but perhaps the photometry, thus a potential VIM effect too ?)
  - Tested on Hipparcos intermediate data



44M$_J$ BD companion, Dashed line: FAP = 0.001

Triage by AMRF

- Definition of an "astrometric mass ratio function" (AMRF)
  - $\mathcal{A} = (å_0/\varpi)\ \mathfrak{M}_1^{-1/3}\ P^{-2/3} = q/(1+q)^{2/3}\ (1 - \mathcal{S}\,(1+q)/[q\,(1+\mathcal{S})])$ with $\mathcal{S}$ luminosity ratio
  - Used to make a triage of companions (Shahaf et al., 2019) with a mass-luminosity relation
- Property of mass and luminosity ratio → 3 classes for the companion
  - I : single MS companion (but can also be a close binary or compact)
  - II : close binary of 2 MS (can't be a single companion or compact)
  - III : compact (can't be a single MS or binary MS)
- → help to build target list of compact objects

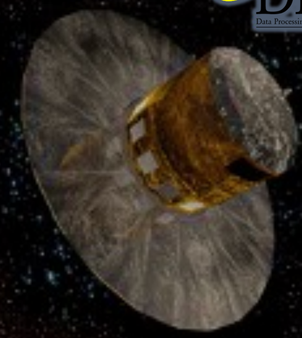


, Gaia collaboration, Arenou et al., 2023

Using the bad fits

- Even without NSS catalogues, the main catalogue gives insight on unresolved multiplicity
  - Astrometry : RUWE (IPD flags etc)
  - Spectroscopy : rv_renormalised_gof

- *Binary parameters from astrometric and spectroscopic errors - candidate hierarchical triples and massive dark companions in Gaia DR3*, Andrew et al. 2022MNRAS.516.3661A
  - 50 to 4641 sources with inferred $q>1$ and $M_2 > 3\ M_\odot$

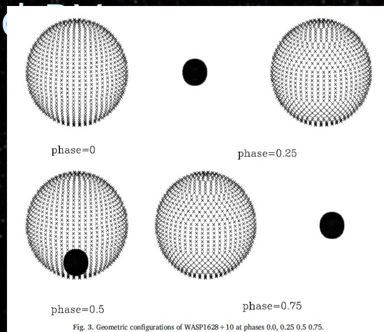


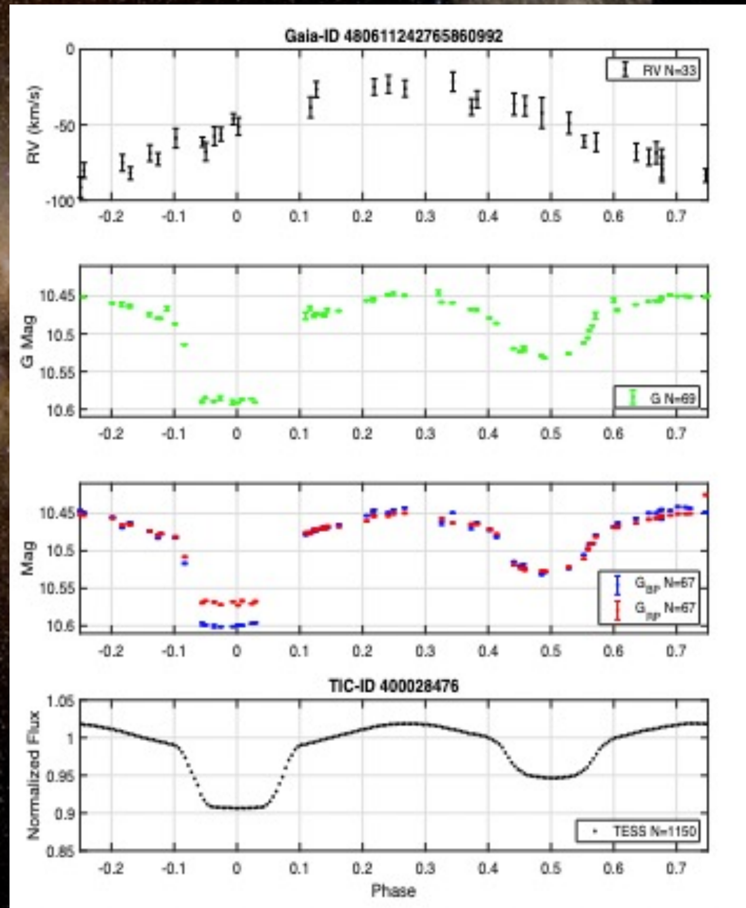
Variability

Binaries from photometry

Rare systems such as EL CVn

- Type
  - A pre-He-WD, low-mass (0.15-$0.33 M_{\odot}$), bloated, with a radius < ~ 0.5 $R_{\odot}$, and hotter than the more luminous A/F-type MS primary.
  - Results from the mass transfer from the evolved pre-HeWD progenitor to the currently observed primary star
- Observation
  - The primary eclipse is at phase 0.5, while the (deeper) secondary eclipse is at phase zero.
  - as preHe-WD secondary is hotter than primary
- Direct detection in Gaia
  - Combination of photometry an
    - Computing phase difference
  - → multi-instrumental Gaia !
  - 5 candidates found

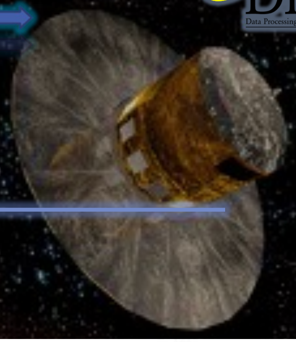




HD 23692 RV, G, XP, Tess photometry Gaia collab., Arenou et al., 2023

Accelerations, etc

Long term motion

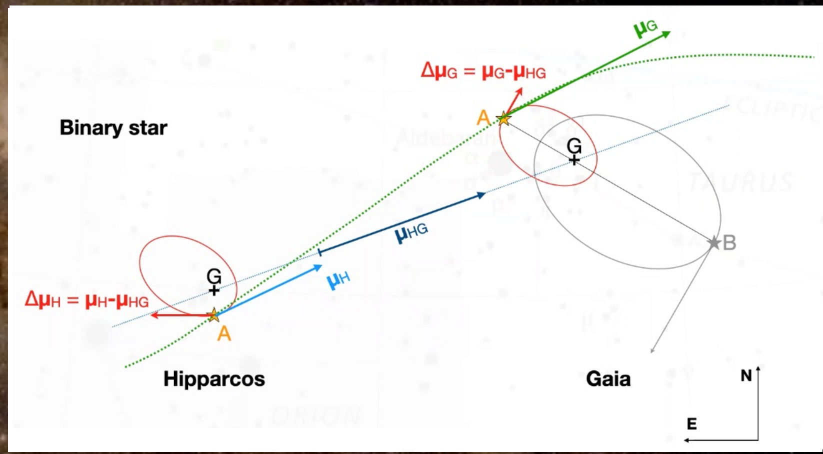


Proper motion anomaly (PMa)

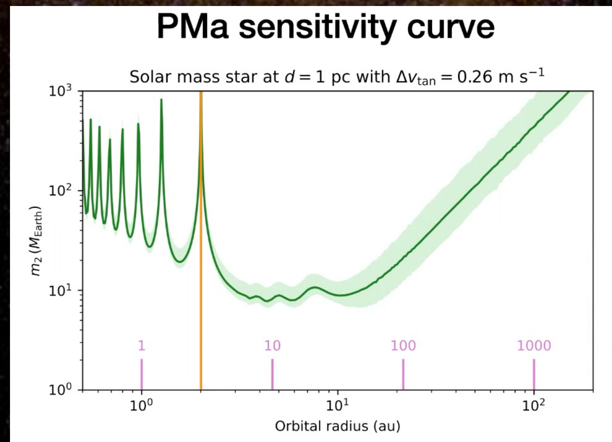
- For a binary, the long term proper motion is ≠ short term proper motion
- PMa=(Hipparcos minus long term proper motion) vs (Gaia minus long term pm)
  - Where long term = difference of positions
  - Gives access to

$$\frac{m_2}{\sqrt{r}} = \sqrt{\frac{m_1}{G}}\, v_1 = \sqrt{\frac{m_1}{G}} \left(\frac{\Delta\mu[\text{mas a}^{-1}]}{\varpi[\text{mas au}^{-1}]} \times 4740.470 \right)$$

- Observing window smearing + H-G time span → decrease of sensitivity
- Catalogues for Hipparcos stars of Hipparcos-Gaia DR3 PMa are available (Kervella et al. 2022, A8A, 657 A7; Brandt 2021, ApJS, 254, 42)
- PMa takes the relay of NSS orbits over a few years periods.
  - For DR3, detect between 4yr (smearing) and 75 yr (3x timespan H-G)



Pierre Kervella

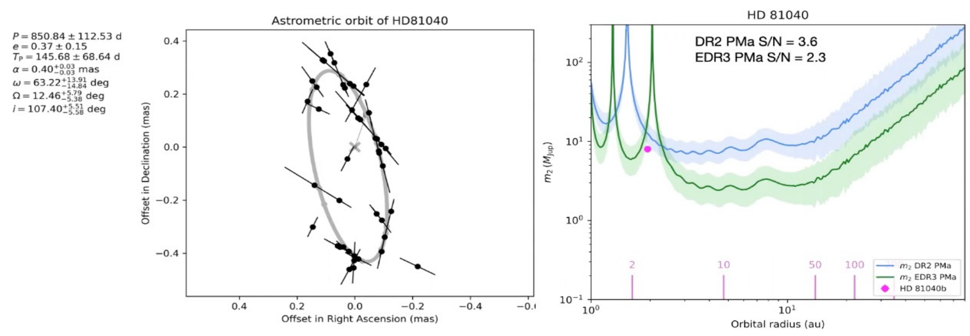


Gaia DPAC

DR3 NSS analysed using PMa

- Example of an EP detection
  - Shows the DR3 smearing window
- Vs DR3 NSS output:
  - 2/3 of TBO have a PMa signal
  - Detects almost all accelerations
  - Sensitive even to periods below the DR3 time window

Gaia DR3 NSS exoplanet detection



- Astrometric wobble of the star due to its ~ 8 M_J companion (Sozzetti et al. 2006; Stassun et al. 2017; Li et al. 2021) on a ~ 1000 days orbit.

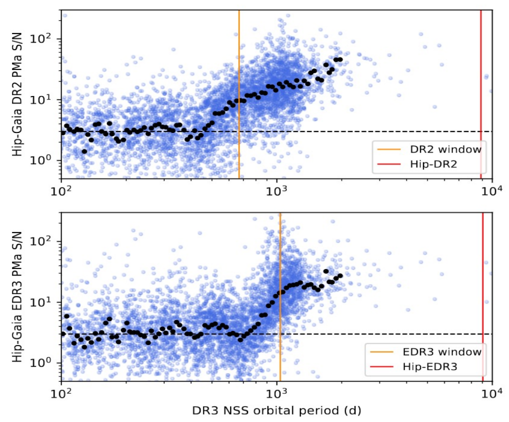


Fig. 15. Proper motion anomaly S/N as a function of the NSS catalogue orbital period for the DR2 PMa (*top panel*) from Kervella et al (2019a)); and the EDR3 PMa (*bottom panel*) from Kervella et al (2022)). The horizontal dashed line indicates the PMa S/N=3 significance limit.

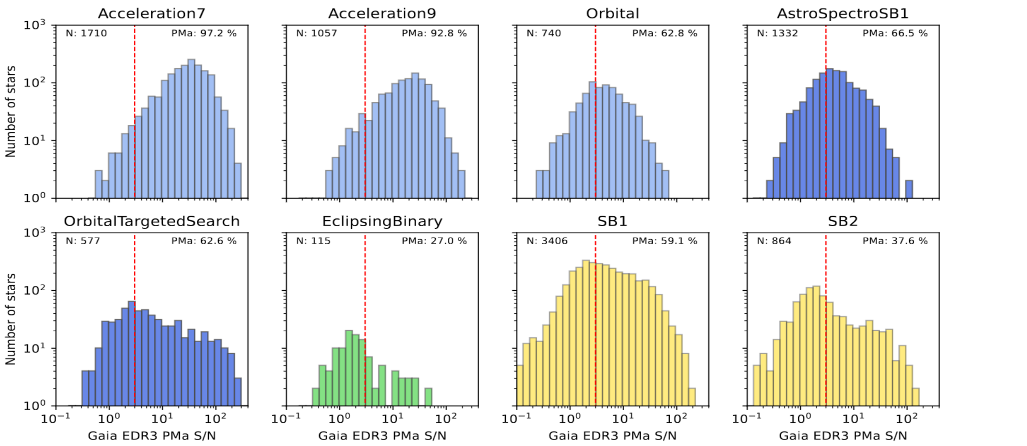


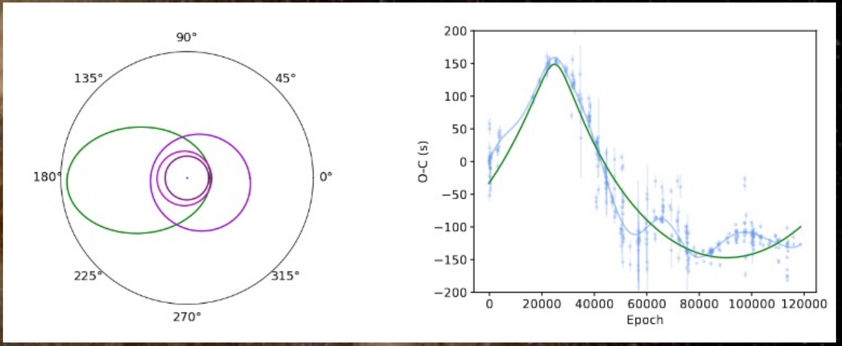
Fig. 14. Histogram of the number of NSS stars with different solution types that are present in the Hipparcos catalogue, as a function of the S/N of their *Gaia* DR3 proper motion anomaly from Kervella et al. (2022). The total number of targets *N* and the fraction of stars with a PMa S/N larger than 3 is displayed in each panel.

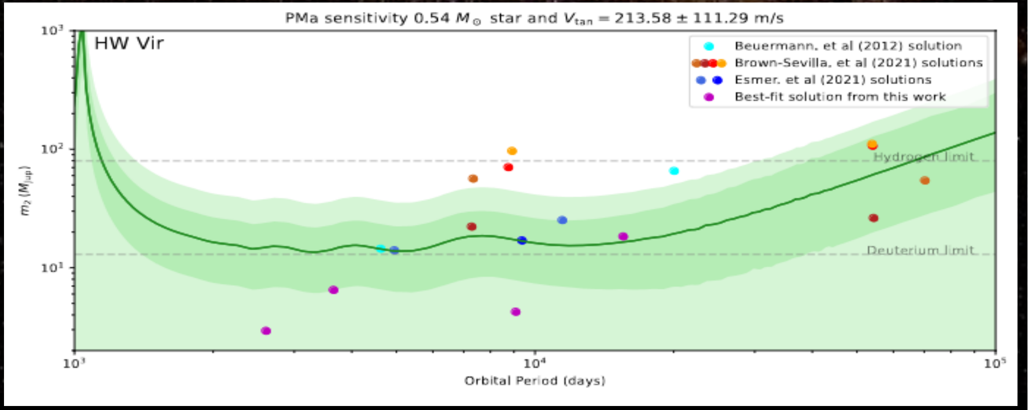
Gaia collab., Arenou et al., 2023

Gaia DPAC

PMa vs LTT

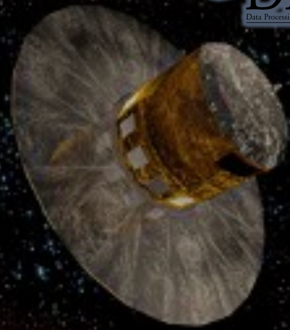
- *New evidence about HW Vir's circumbinary planets*
  - Baycroft et al., 2023arXiv230905716B
  - Post common-envelope eclipsing binary
  - Many circumbinary companions had been proposed using LTT
  - Here, proper motion anomaly is used
  - a tentative 2-σ signal of an acceleration due to 17 M_{jup}, 16 000 day eccentric.
  - discards some previously proposed companions, too massive to be consistent with the PMa





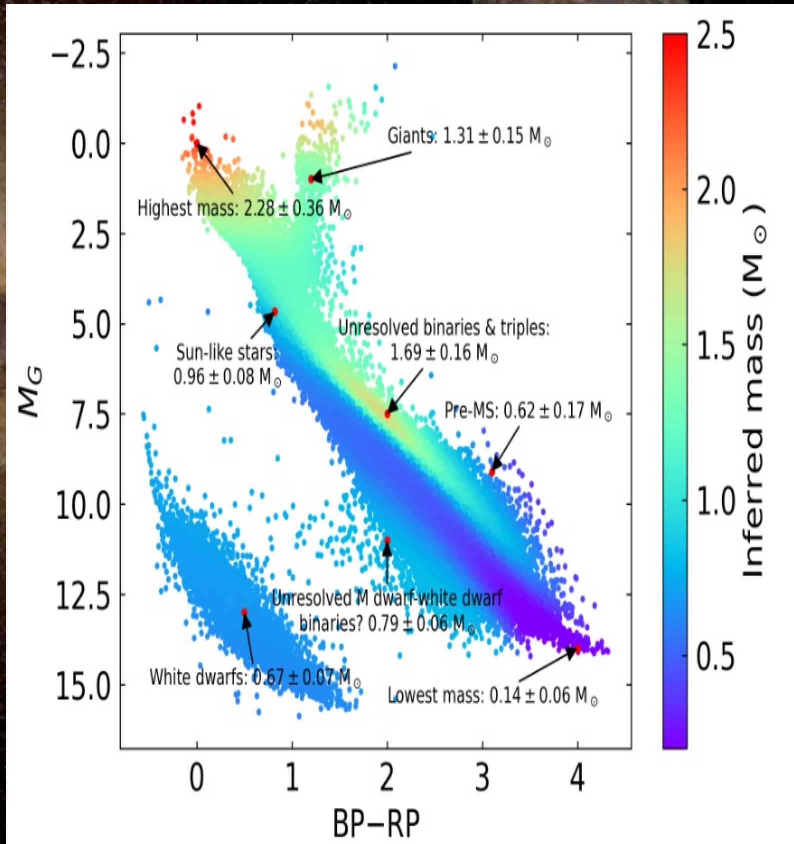
Mass, luminosity, etc

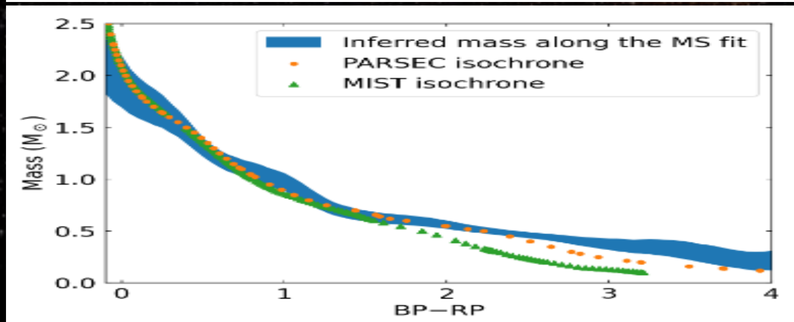
Properties of binaries



Dynamical masses from wide binaries

- *Dynamical masses across the Hertzsprung-Russell diagram*, Hwang et al.
  - Provides masses for 0.1-2 $M_\odot$
  - Uses 100k resolved binaries
    - El Badry et al.
  - And neural network
  - Based on Keplerian motion
    - Inferring total mass from orbital velocities and separations
    - Component masses using masses from HR
    - Marginalise over nuisance parameters (orientation of orbit, eccentricity)
  - Does not use astrophysical assumptions
    - ~ agrees with isochrones
      - Better with Parsec than Mist below 0.6$M_\odot$
    - Providing independent constraints
    - Suggest population of triple at M~6.5 ?

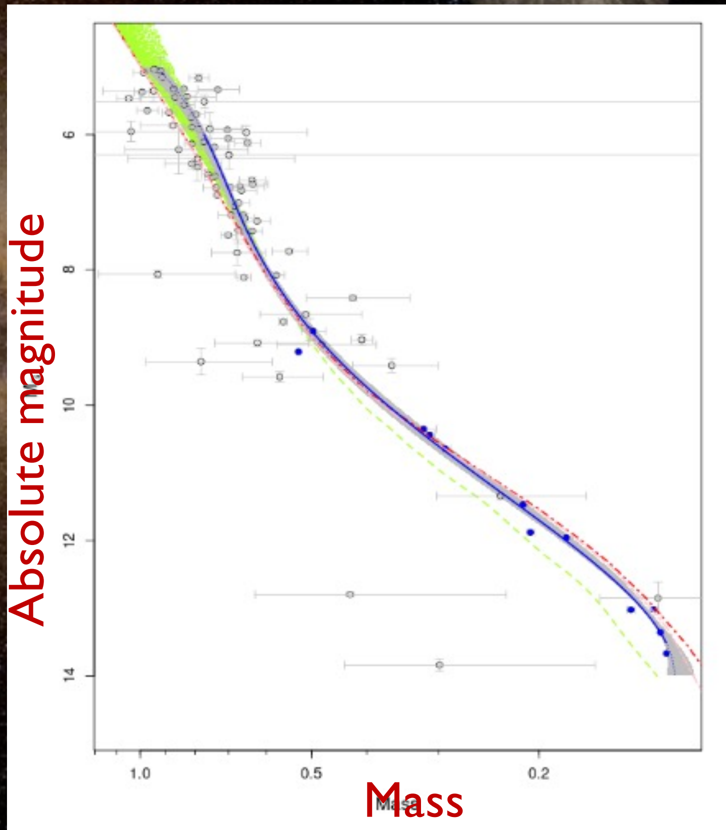




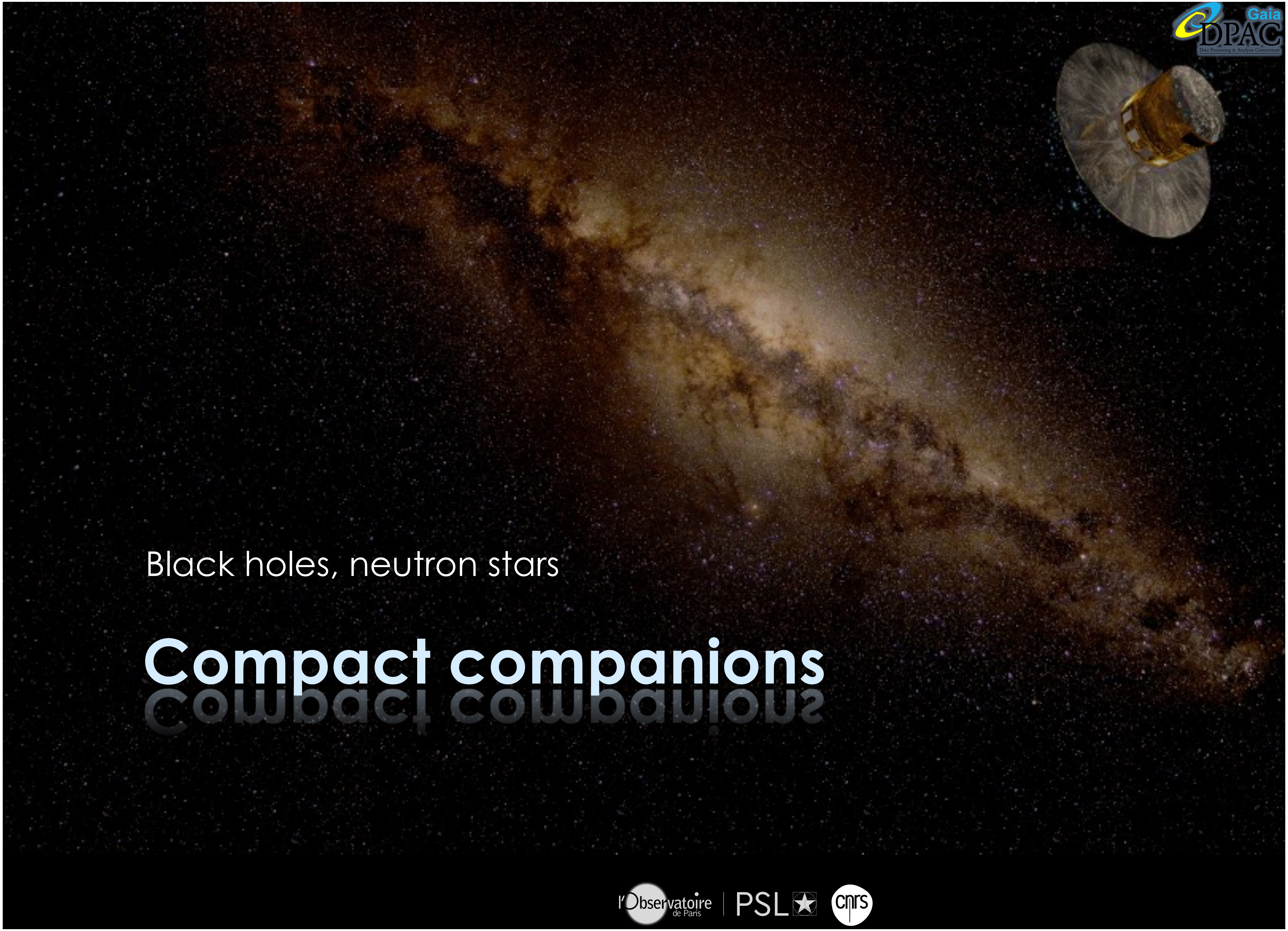
Mass-luminosity relation

- *Binaries masses and luminosities with Gaia DR3, Chevalier et al., 2023arXiv230716719C*
  - Combining NSS DR3 orbital solutions with SB2 from SB[9] or APOGEE and resolved binaries
  - $0.12\ M_\odot < \text{Mass} < 0.77\ M_\odot$ fit
  - $\log_{10}(M)=C_0+C_1M_G+C_2M_G^2+C_3M_G^3+C_4M_G^4$
    - For $6 < M_G < 13.5$

	best fit	upper	lower
C0	3.129	3.798	2.534
C1	-1.5406	-1.8377	-1.2672
C2	0.27513	0.32373	0.22954
C3	-0.021661	-0.025067	-0.018413
C4	0.0005991	0.0006855	0.0005148



Fit compared to PARSEC and BASTI solar metallicity


Black holes, neutron stars
Compact companions

White dwarf companions from Gaia PVP

- From astrometry
  - From the table gaiadr3.binary_masses, selecting fluxratio_upper=0 shows a peak at 0.61 $M_\odot$
  - The same using the AMRF estimation

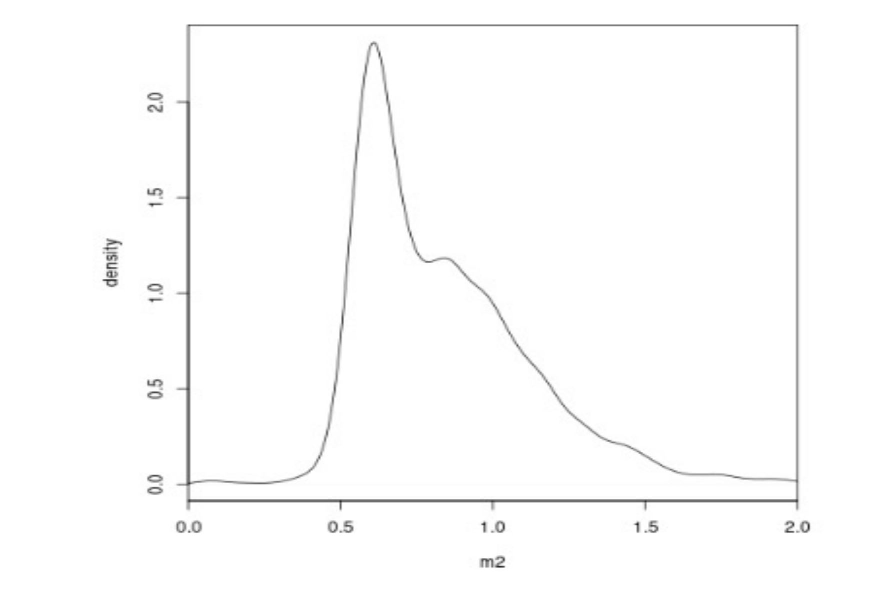


Fig. 16. Distribution of the secondary mass of astrometric solutions with fluxratio_upper = 0 in Table 2.

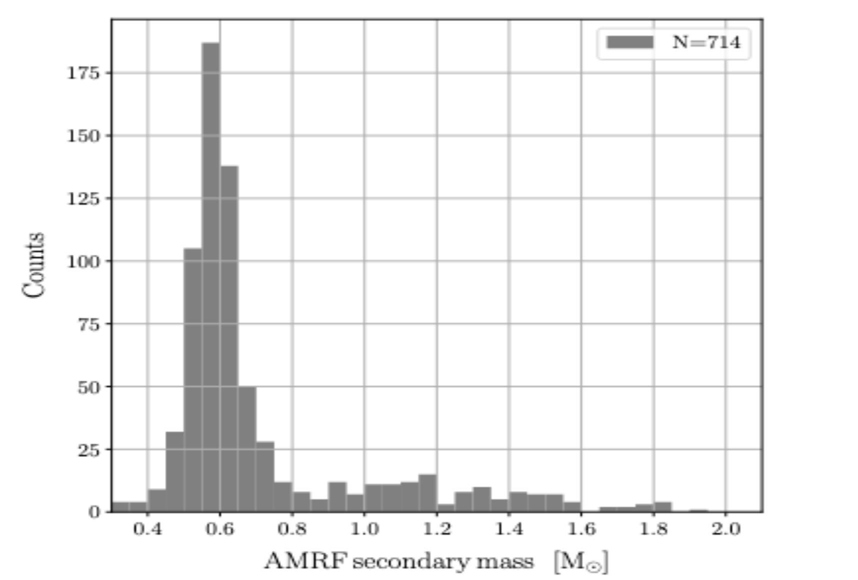
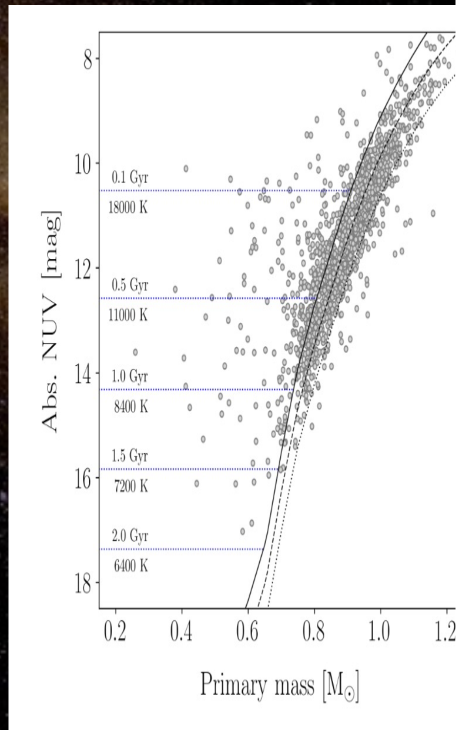


Fig. 36. A histogram of the companion masses for compact object candidates, up to a mass of 2.1 $\mathcal{M}_\odot$.

Gaia collaboration, Arenou et al., 2023

Follow-ups of AMRF, etc analysis

- *White Dwarfs Revealed in Gaia's Candidate Compact Object Binaries*, Ganguly et al. , ApJ
  - Dark remnants (DRs) with luminous companions (LCs) in wide detached orbits
    - Using LC masses, and the Gaia astrometric mass function the DR masses are constrained for these sources
  - UV counterparts are found in the archival GALEX data for 49 of the 187 candidate sources
    - 15 have an UV excess → WD
    - 4 interesting extremely low-mass WDs (ELMWD), < $0.4M_\odot$, that were not known yet outside close pairs nor with LC companions
- *Triage of the Gaia DR3 astrometric orbits. II. A census of white dwarfs*, Shahaf et al., 2023arXiv230915143S
  - AMRF Class II or III, excluding those with secondary > $1.2M_\odot$
  - 3200 probable MS+WD binaries, separations of ~1 au, parameter space largely unexplored by other observational techniques
  - GALEX NUV vs M_1 suggests the cooling ages of many WDs based on UV excess can be derived
    - WD masses known → empirical initial-to-final mass relation ?

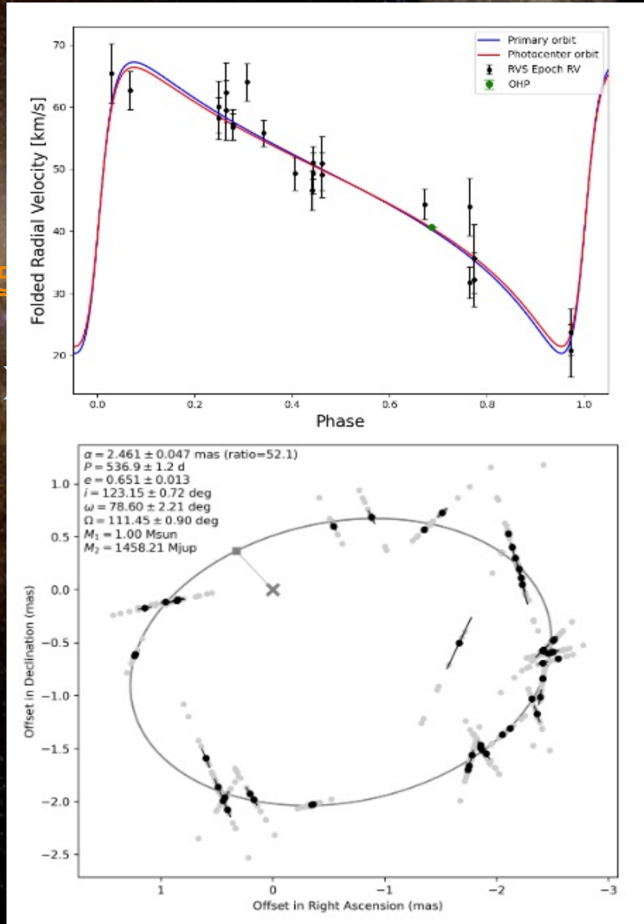


Solid: a 0.6M at virous cooling age
Shahaf et al., 2023arXiv230915143S

Gaia DPAC

More massive compact objects from Gaia PVP ?

- Potential dormant neutron star found ?
  - From astrometry, P=536 d
  - Pair initially estimated to be 1.2 $M_\odot$ + 1.5 $M_\odot$
    - Was reweighted by El Badry et al. 2023MNRAS.518.105
    - Actually LC is low metallicity → 0.77 + 1.23±0.06
    - So may be as well a massive WD (NS > 1.1, WD < 1.4)
- 12 SB1 with M_{2-} > 3 $M_\odot$ with and M_{2-} > M_{1+}
  - Dormant black hole companions ?
  - Touchy, need to be careful given the SB1 problems



Gaia DR3 513602552152793907
Astrom. + spectro., period 546 d
1.2 $\mathfrak{M}_\odot$ +1.5 $\mathfrak{M}_\odot$?

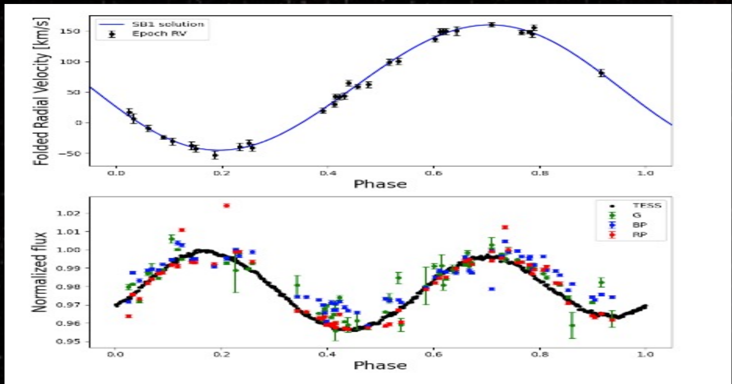
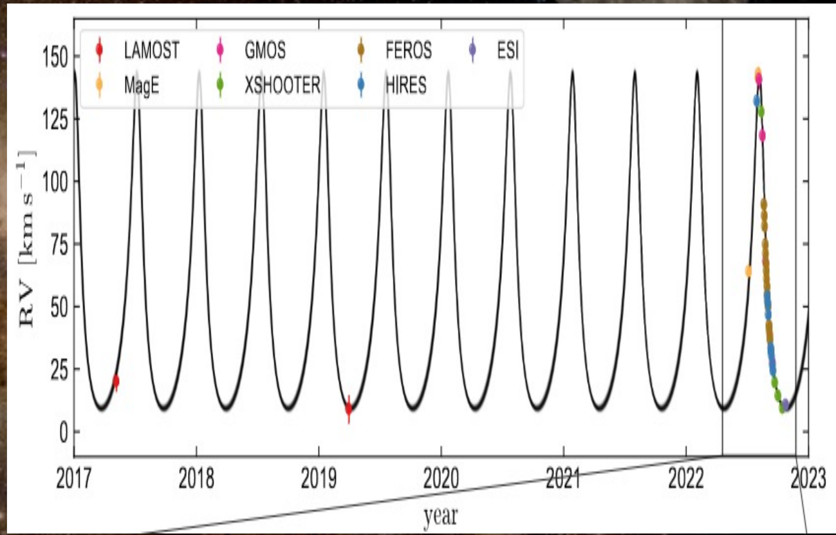


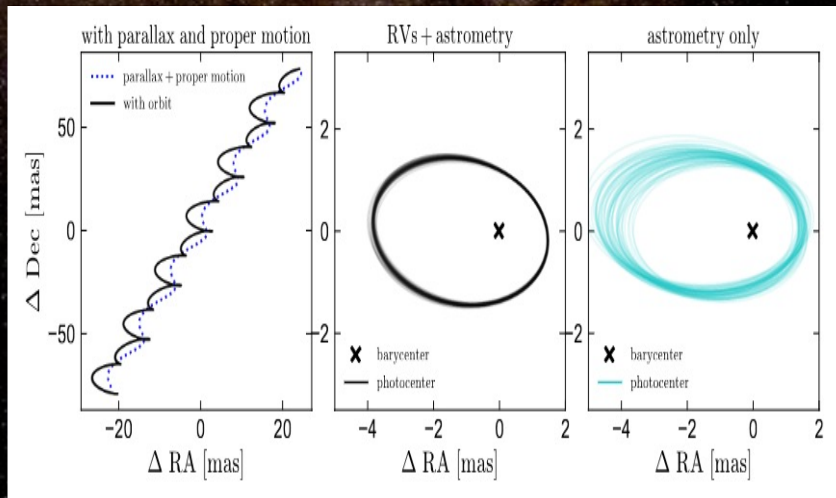
Fig. 45. Top panel: Phase-folded radial velocity of Gaia 2966694650501747328. Bottom panel: phase-folded TESS and Gaia normalized flux.

Crdits: ESA/Gaia/DPAC/CU4/NSS, Pasquale Panuzzo, Johannes Sahlmann

Dormant BH1

- *A Sun-like star orbiting a black hole, El-Badry et al., 2023MNRAS.518.1057E*
  - A G=13.8 solar-type star in Ophiuchus
  - A direct by-product of DR3 NSS solution
  - The NSS astrometric mass function already indicated that the companion would be massive
    - Will be re-discovered and re-weighted ($M_\odot$) during the hands-on tomorrow
  - What remained was to confirm using external data (RV)
    - Can be shown only through the reflex motion of the primary as it is dormant
      - Of course this could be 2 BH, 5 neutron stars, 10 massive WDs or 200 BDs ! But not stable…
    - The combination improves the solution
  - This is the nearest BH known
    - Suggests a significant number of dormant BH still to be found (Gaia DR4?)





El Badry et al. 2023MNRAS.518.1057E

Follow-up(s) → lists of potential targets

- *A Sample of Neutron Star and Black Hole Binaries Detected through Gaia DR3 Astrometry*, Andrews et al., 2023ApJ...954....4G

- *Triage of the Gaia DR3 astrometric orbits - I. A sample of binaries with probable compact companions*, Shahaf et al., 2023MNRAS.518.2991S
  - A sample of 177 systems with highly probable non-luminous massive companions, which is smaller but cleaner than the sample reported in Gaia DR3. The new sample includes eight candidates to be black-hole systems with compact-object masses larger than 2.4 $M_{\odot}$.

- Caveat
  - Many recent dormant BH candidates in binaries have turned out not to be BHs, but rather mass-transfer binaries containing undermassive, overluminous stars in short-lived evolutionary phases

Gaia DPAC

Secondary NS or BH from photometry?

- *Gomel et al. Ellipsoidal variables with possible black hole or neutron star secondaries,* 2023A%26A...674A..19G
  - Gomel et al. (2021a) introduced a new method to identify ellipsoidal variables hosting massive, unseen companions based on their light curves alone. Subsequently, they applied the method to the sample of candidate ellipsoidal variables published in DR3.
  - 6306 short-period probable ellipsoidal variables with relatively large-amplitude Gaia G-band photometric modulations that indicate a possible massive, undetected secondary.
  - Among these 262 sources whose light curves suggested the presence of an unseen companion more massive than the luminous primary, potentially indicative of a compact object.
- *Spectroscopic follow-up of black hole and neutron star candidates in ellipsoidal variables from Gaia DR3,* Nagarajan et al., 2023MNRAS.524.4367
  - obtained spectra for 14 of the most promising targets, derived minimum companion masses. Assuming random inclinations, the typical inferred companion mass makes it unlikely that any of these systems contain a BH or NS, and we consider alternative explanations for the observed variability. We can best reproduce the observed light curves and radial velocities with models for unequal-mass contact binaries with star spots


High order hierarchies
Multiple stars

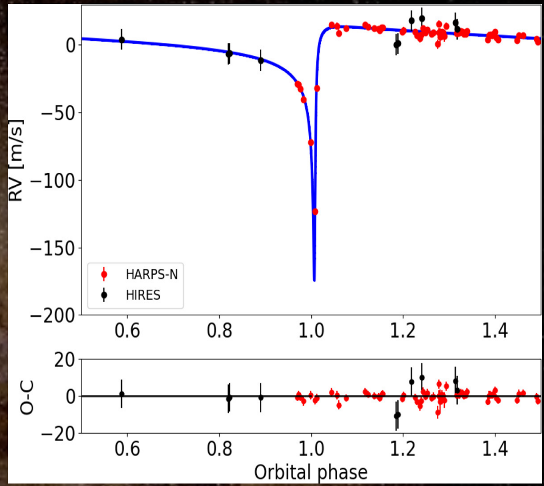
Gaia DPAC

High-order multiples

- *A Hunting Expedition For High-Order Hierarchies*, Powell et al., 2023MNRAS.524.4296P
  - matched eclipsing binaries fromTransiting Exoplanet Survey Satellite with Gaia catalogue of wide binaries
  - selected candidate quadruple (or higher order) systems based on RUWE.
    - A subset of 192 southern candidates located within 500 pc was observed by speckle interferometry, and 50 close pairs resolved for the first time
- *Binary parameters from astrometric and spectroscopic errors - candidate hierarchical triples and massive dark companions in Gaia DR3*, Andrew et al. 2022MNRAS.516.3661A

EP: new ones

- *A conundrum resolved: HIP 66074b/Gaia-3b characterised as a massive giant planet on a quasi-face-on and extremely elongated orbit?,* Sozzetti et al., 2023A&A...677L..15S
  - The nearby mid-K dwarf HIP 66074 was recently identified as host to a candidate super-Jupiter companion on a ~300 day, almost edge-on, orbit, based on Gaia Data Release 3 (DR3) astrometry.
  - With an estimated mass in the approximate range of 3−7 MJup, HIP 66074b (≡Gaia-3b) is the first exoplanet candidate astrometrically detected by Gaia to be successfully confirmed based on RV follow-up observations



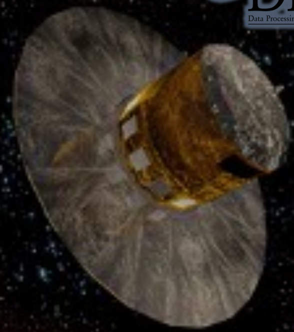
Other

Is NewtonEinstein standard gravity has-been?

- *Breakdown of the Newton–Einstein Standard Gravity at Low Acceleration in Internal Dynamics of Wide Binary Stars*, Chae, Kyu-Hyun 2023ApJ...952..128C
  - Using an analysis of nearby wide binaries (El-Badry et al. 2021)
  - A statistical relation between the Newtonian acceleration $g_N \equiv GM/r^2$ (M = total mass) and kinematic acceleration $g \equiv v^2/r$ is is compared with the prediction by Newtonian dynamics.
  - A gravitational anomaly found at weak gravitational acceleration $g_N < 10^{-9}$ m.s^{-2}
  - The systematic deviation agrees with the boost factor that the AQUAL theory predicts (modified gravity represented by the A-QUAdratic Lagrangian theory)
  - « The gravitational anomaly in the dynamics of binary stars cannot be attributed to dark matter because the required amount is absurd »

- *Statistical analysis of the gravitational anomaly in Gaia wide binaries*, Hernandez, X. 2023, https://arxiv.org/abs/2309.10995
- *Robust Evidence for the Breakdown of Standard Gravity*, Chae, arXiv:2309.10404
  - « Dark matter paradigm is now doomed to be abandoned and we are entering an era of a paradigm shift. »

l'Observatoire de Paris | PSL cnrs

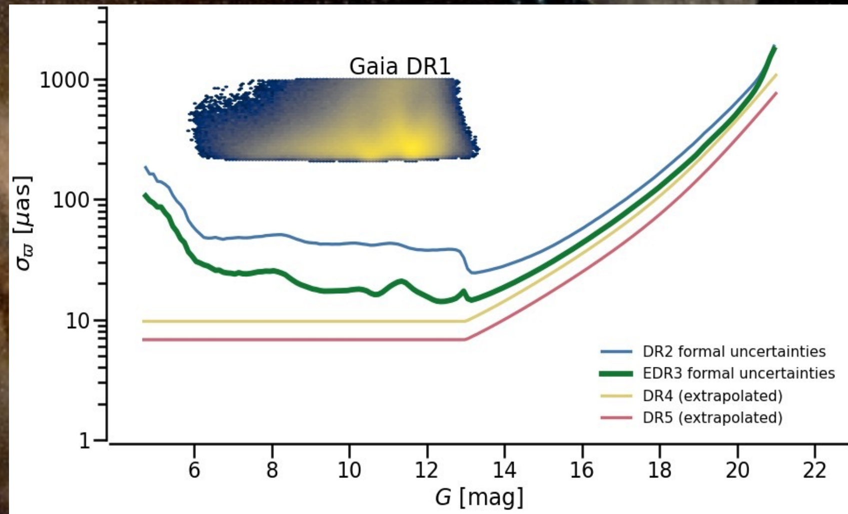


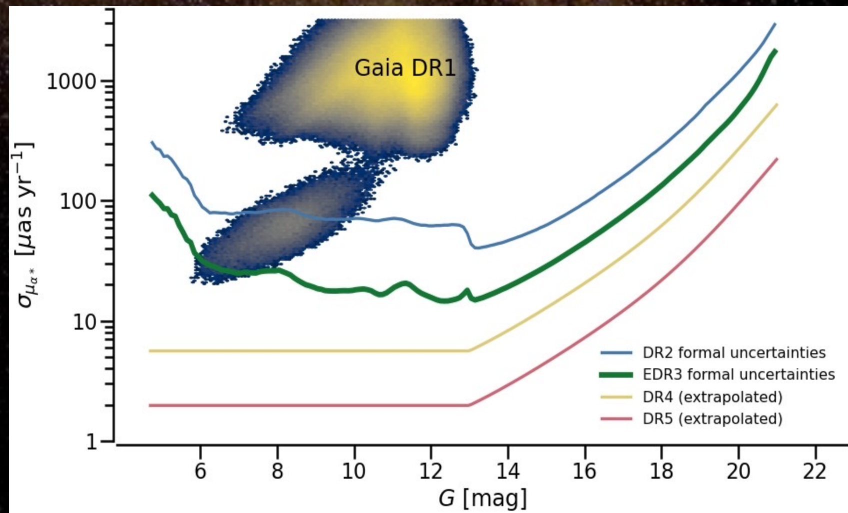
Towards Gaia DR4/5

Work in progress

Next Gaia data release: DR4

- Final release for the nominal mission
  - 66 months data vs 34
- Overall gain in astrometric precision in DR4 wrt DR3:
  - factor 1.4 for parallaxes, factor 2.8 for proper motions
- Foreseen data products
  - Full astrometric, photometric, and radial-velocity catalogues
  - All variable-star and non-single-star solutions
  - (un/resolved binaries and exoplanets)
  - Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars
  - All epoch and transit data for all sources, including all BP/RP/RVS spectra





Credits: ESA/Gaia/DPAC Anthony Brown

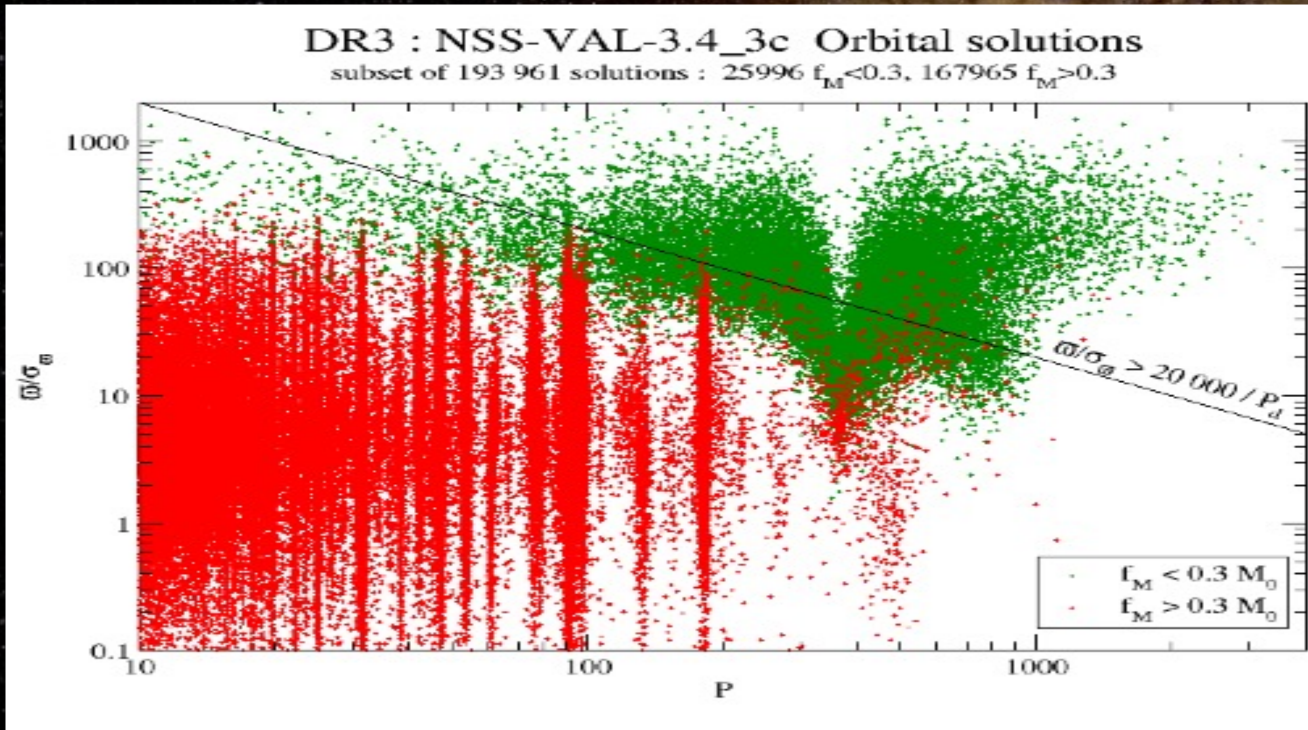
General NSS goals for DR4

- Manage (a large sample of) *resolved* binaries for the first time
- Improve the filtering of spurious solutions
  - Scan-angle related
- Increase significantly the number of sources
  - Better handling of spurious solutions + decrease of the S/N or RUWE threshold
  - In particular to better characterise sources underrepresented in DR3
    - E.g. Black Hole companions or Extrasolar planets/ at short periods
- Adding new type of composite solutions
  - E.g. SB1+Pulsation or SB1+SB1
- Include the derivation of masses as a catalogue product
  - This was given in a Performance Verification Paper only for DR3
- Improve the validation activities
  - E.g. using complementary RV data


Gaia DPAC
Data Processing & Analysis Consortium
Astrometric binaries
Filtering spurious solutions
l'Observatoire de Paris
PSL
cnrs

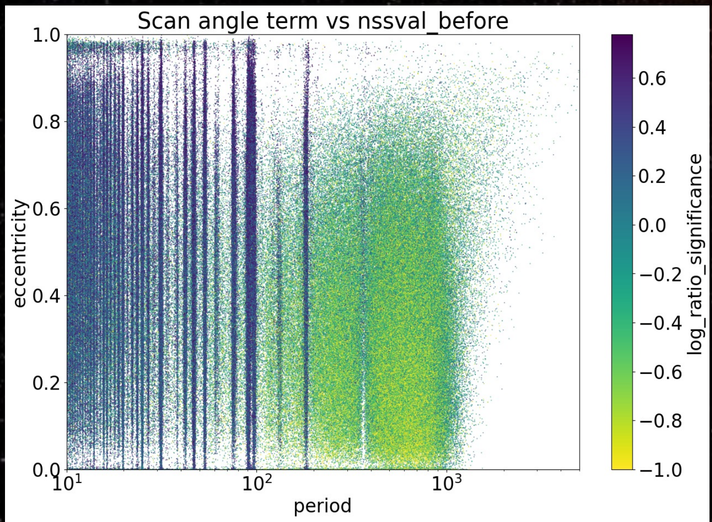
AB: DR3 filtering

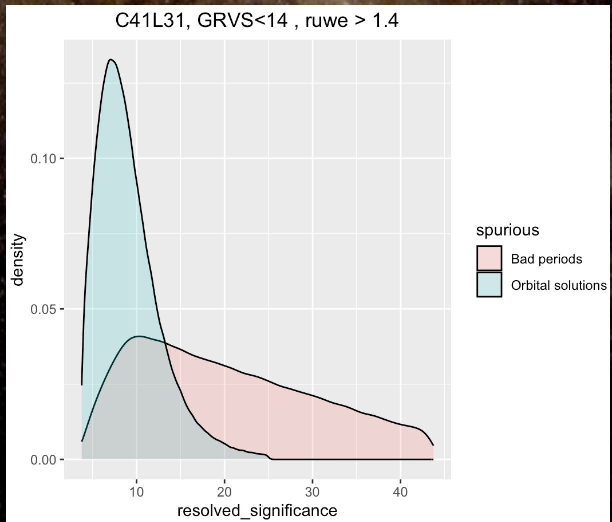
- The spurious (scan-angle related) periods were found early cycle 3
  - Not removing them would have created thousands spurious supermassive BH…
- A strong filtering was applied (here parallax S/N vs period)
  - That unfortunately also removed a lot of good solutions



AB: using a “scan-angle” model

- Reminder: G variation with scan angle for partially resolved sources
  - See Holl et al. article
  - Using epoch photometry with the 2ψ harmonic (c2,s2)
    - $G(\psi) = c_0 + c_2 \cos 2\psi + s_2 \sin 2\psi$
  - Using the epoch astrometry with a 3ψ harmonic (c3,s3)
    - Not that efficient, due to the input list filters on ipd_gof_harmonic_amplitude
  - Computing the significance (S/N) of these (c2,s2) terms

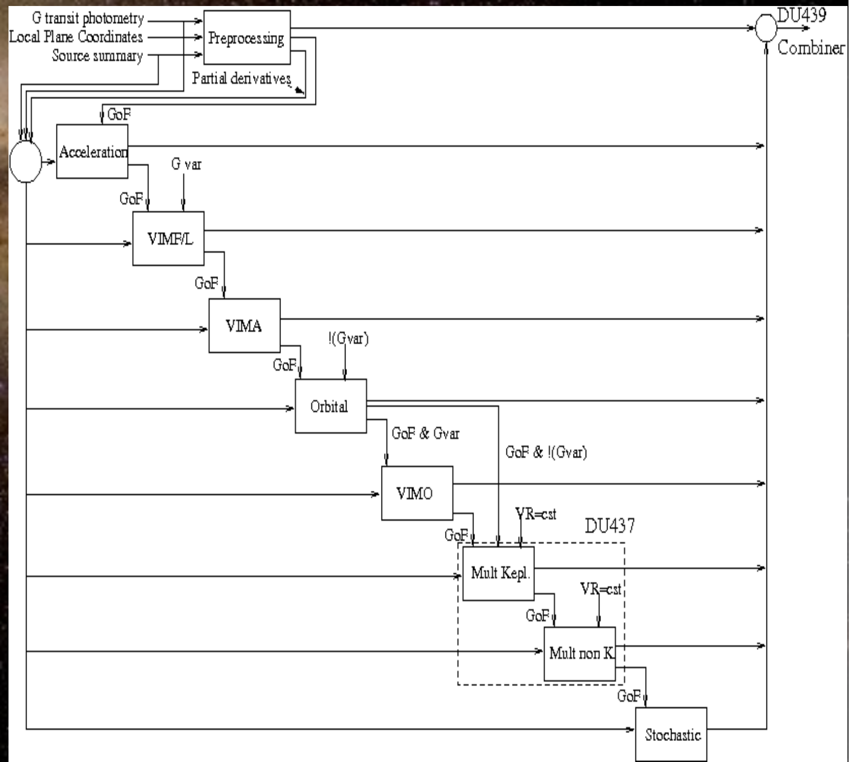




Colouring with the significance of the “scan-angle” model term suggests that most spurious periods would be removed over some threshold

AB: blunting the Ockham razor

- AB has used up to now a cascade process
  - The models are attempted successively by increasing complexity
    - A model is adopted if the fit is good enough
  - Even if conceptually the "cascade" is appealing as an Ockham's razor, it is not scientifically optimal
    - An orbital solution, even imprecise, may be preferable to an unusable acceleration solution

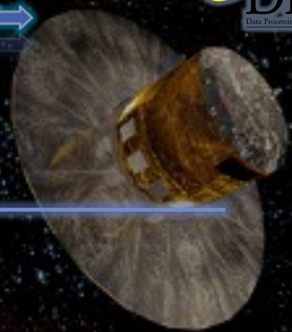


- A modification of the sequence is foreseen:
  - → test whether (at least partially) resolved → stop if too significant (a)
  - Test/Use an acceleration model → save solution if significant then continue
  - Test of an orbital model → adopt if preferable to acceleration model and break (b)
  - …

Still to come

- Most important change: acceleration solutions will be produced by the main astrometric processing (AGIS)
  - Rationale
    - The accelerations @ AGIS can use an input list larger than the NSS one
      - As NSS adds a RUWE > $RUWE_{min}$ constraint to reduce CPU
    - The robustness and consistency with AGIS 5p (6p) is better
  - Will actually be 10p (9p acceleration+jerk + colour term)

- Other work foreseen in the development plan
  - Management of uncertainties and robustness
  - A more user-oriented data model : publish Campbell rather than Thiele-Innes



AB: input list

- Starting to define the future list of targets
  - The (experimental) definition of the input list is two-fold:
    - A magnitude-limited selection
      - Typically phot_g_mean_mag < 18 AND RUWE > 1.05
    - A distance-limited selection
      - parallax > 5 AND RUWE > 0.9
  - to which is added in both cases :
    - A filtering on *multi_peak + ipd_gof_harmonic_amplitude to reject resolved doubles
  - This would represent about several dozen of million input sources
    - A very large fraction will not have a good solution however

Resolved sources

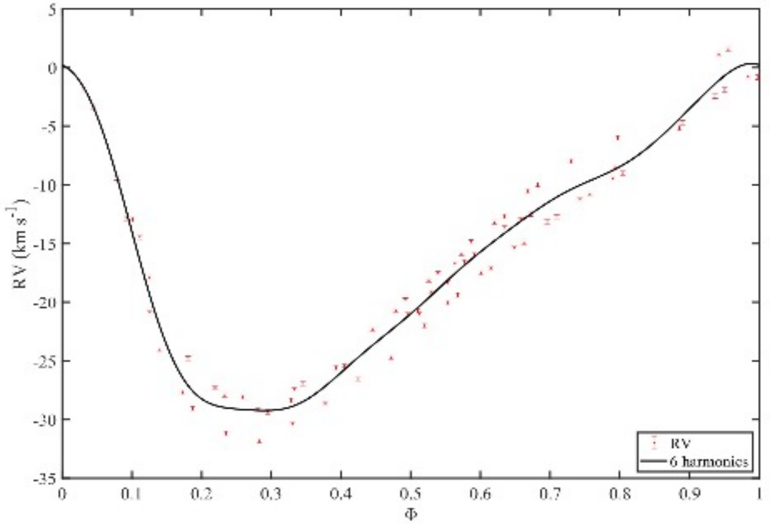
- A large fraction of Gaia sources are resolved
- If they are binaries, the astrometry can be improved,
  - by using simultaneously the transit information for each component
- The input list planned is the following (TBC)
  - ϖ > 0.1 mas, parallax S/N $\varpi/\sigma_\varpi > 3$
  - separation < 4 arcsec
  - About 34 million pairs to handle
    - selected from the preliminary DR4 astrometric solution
    - (this is NOT the output)
- The linear models planned:
  - ResolvedPairFixed (7p), same parallax and p.m.
  - ResolvedPairLinear (9p), same parallax
  - ResolvedPairAcceleration (13p)
  - ResolvedPairJerk (17p)

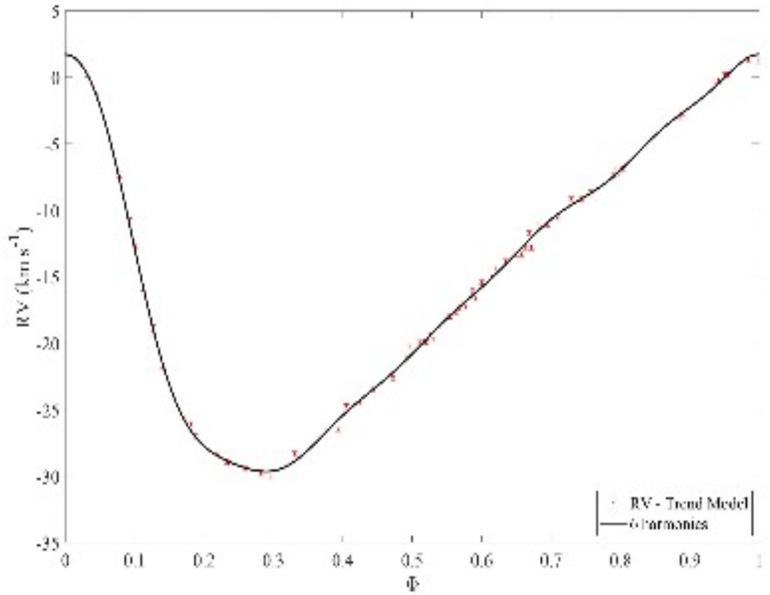
- Note: partially resolved sources will not be managed for DR4

Spectroscopic binaries

- Improve the identifications of trends
- Manage the complex solutions (DR3 was one solution type)
  - SB1+SB1,
  - trend+SB1,
  - pulsation+SB1

Cepheid source from Ripepi et al. (2022) with CU6 time series published in DR3





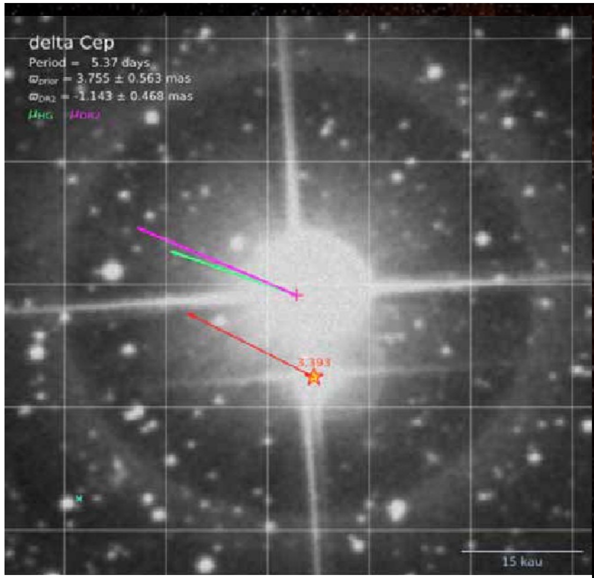
Eclipsing binaries

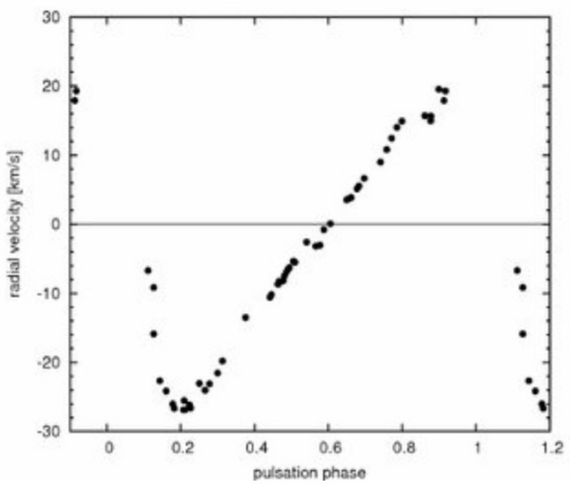
- Main change : fit B_P and R_P along with G
  - Requires extinction information from CU8 (astrophysical parameters)
  - Requires flux & limb darkening calculations from stellar atmosphere tables
  - Not a trivial problem
- Improve uncertainties & covariance matrix for the parameters
- Improve multiple reflections
- Fit the mass ratio
- Explore fitting ($e \sin \omega$, $e \cos \omega$) instead of (e , ω)
- Improve combination with SB solutions

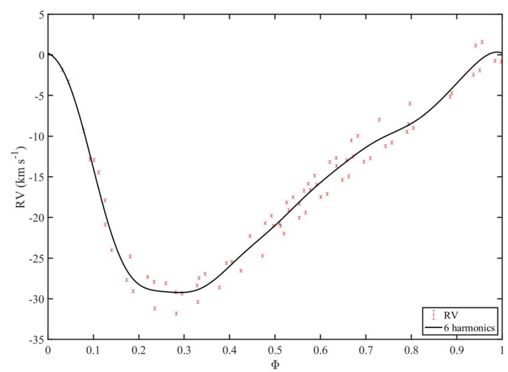
Extrasolar planets

- Significantly upgrade the existing software
  - Expanded models (e.g., allow for acceleration terms + full orbit)
  - Improved outlier treatment (on single-star fit residuals)
  - Improved period-finding capabilities
  - Improved error model
  - >1 solution in output, appropriate model parameter uncertainties
  - More robust solution comparison metrics (including multiples)

- Define new lists of reference sources as well as well-defined lists for blind search
  - (e.g., GCNS, but check complementarity/superpositions with DU432 input/output)

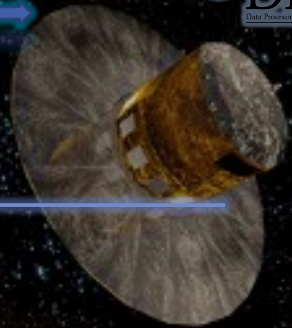






Special objects

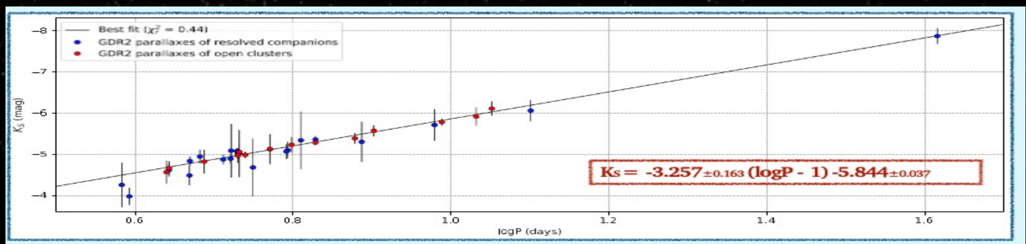
Cepheids / RR Lyrae

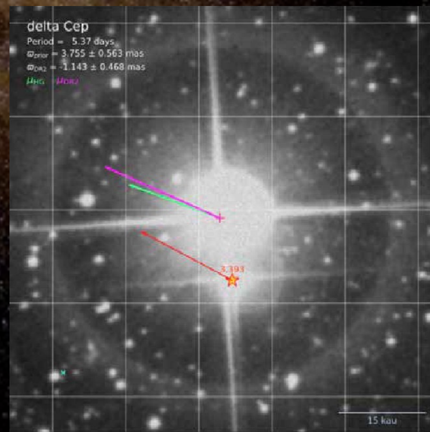


Pulsating stars in binary systems

- A significant fraction of pulsating stars are binaries
  - *Multiplicity of Galactic Cepheids and RR Lyrae stars from Gaia DR2. I. Binarity from proper motion anomaly*, 2019A&A...623A.116K
    - binary fraction of CCs is likely above 80%, while that of RRLs is at least 7%
  - *Multiplicity of Galactic Cepheids and RR Lyrae stars from Gaia DR2. II. Resolved common proper motion pairs*, 2019A&A...623A.117K
  - *The Milky Way Cepheid Leavitt law based on Gaia DR2 parallaxes of companion stars and host open cluster populations*, 2020A&A...643A.115B

- Handling these binaries is important for 2 reasons:
  1. A wrong model of motion may return wrong parameters
     - Incorrect parallax + p.m. for astrometric binaries
     - Incorrect systemic velocity or pulsating parameters for SB
  2. Getting an orbital model may give the dynamical mass





Proper motion of Delta Cep and companion (Kervella et al. 2019)

Pulsating stars in various NSS chains

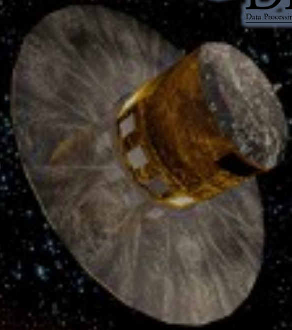
- Astrometry
  - Unresolved astrometric binaries
    - One advantage of Cepheids is that the flux ratio is ~ negligible
    - So the orbit depends only on the mass fraction, not on its difference with flux fraction
    - still the dynamical Cepheid mass requires the knowledge of primary companion mass
  - Resolved binaries (new in DR4)
  - In both cases, the fact that a source is pulsating does not impact the astrometric processing

- Photometry (eclipsing)
  - What about pulsating + eclipsing ?

    Non empty intersection between eclipsing and pulsating in DR3

- Spectroscopy
  - Here a special processing is needed as the RV curve is mixed orbit + pulsation
    - SB solutions were discarded for DR3
    - Will be handled for DR4

l'Observatoire de Paris | PSL cnrs



Conclusion

Insight on multiplicity

- Each method brings its category of binary, but also giving access to different information and domains of parameters:
  - From short periods eclipsing binaries to the longest periods of common proper motions
  - spectral types and radial velocities of SB or those with double spectra
  - Stellar structure for the eclipsing binaries,
  - the positions and velocities of astrometric binaries.

- Pairs are coeval → one component may give information on the other !

- Another striking aspect is that no single method is optimal on its own for determine the necessary stellar parameters;
  - Access to the masses of components e.g. requires combining at least two techniques.

- *As a full Observatory in orbit, Gaia provides insight on most kind of binaries and on the whole range of periods*
  - With a so large number of binaries that it kills the game
  - And Gaia DR4 and DR5 will much increase the DR3 numbers

The future

- Past and current situation: selection effects.
  - How to correctly know the distributions of the mass ratios if one selects the objects not resolved in apparent magnitude, favoring the detection of couples with the smallest differences in magnitude for the visual binaries, but disfavoring the twins for the astrometric binaries,
  - or if the instrumentation selects the largest semi-amplitudes of the spectroscopic binaries?
  - Period distributions: favouring short periods for spectroscopic binaries, and rather long ones for astrometric binaries.
- Exoplanets and brown dwarfs
  - Their natures, and probably their formations, are different from that of stars,
  - In observational terms, essentially analogous to stars, but with a smaller astrometric, photometric, or spectroscopic signature.
    - For radial velocimetry, the historical period of rare detections of low-mass companions, the brown dwarf desert has now given way to the impressive number of planetary companions that we know.
- Studies about exoplanetary systems has not weakened interest in binary systems.
  - The latter remain a privileged means to estimate the fundamental stellar parameters.
  - Then, the detection of binaries is sometimes a by-product of the search for exoplanets.
  - Finally, the unexpected discovery of exoplanets in binary systems amplifies, if need be, the need to understand all the formation mechanisms that are at work.

Some links

- MW-GAIA-COST Summer School "Exoplanets and astrostatistical analysis techniques"
  - https://zenodo.org/record/7081002
  - Slides and recordings are also available at https://zenodo.org/communities/mw-gaia-cost-exoplanets_astrostatistics_geneva_2022/search?page=1&size=20