Observatoire des sciences de l'univers
Terre, homme, environnement, temps, astronomie
Franche-Comté • Bourgogne

Université Bourgogne Franche-Comté

Ultra cool dwarfs in Gaia

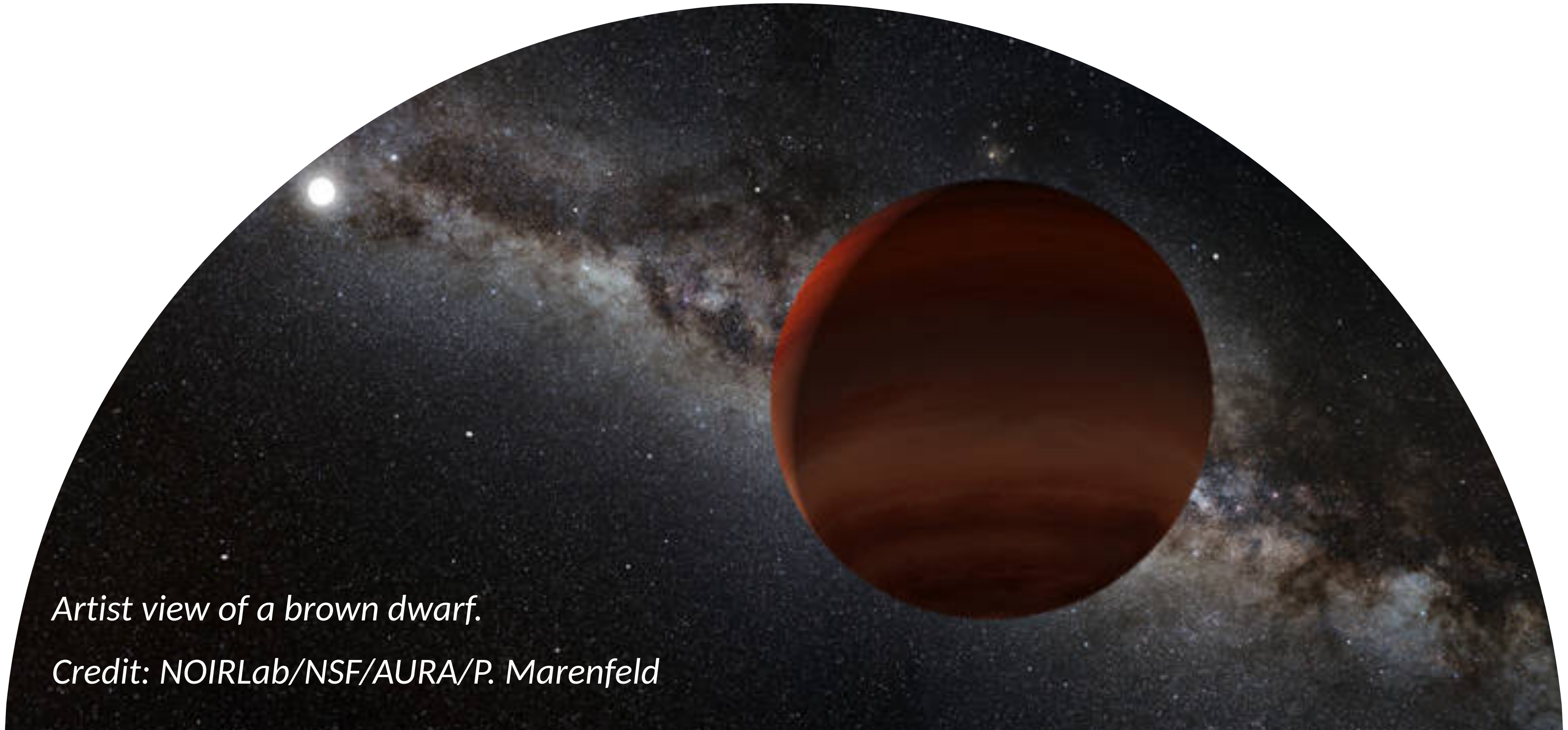
Céline Reylé

Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

Topics for this lecture

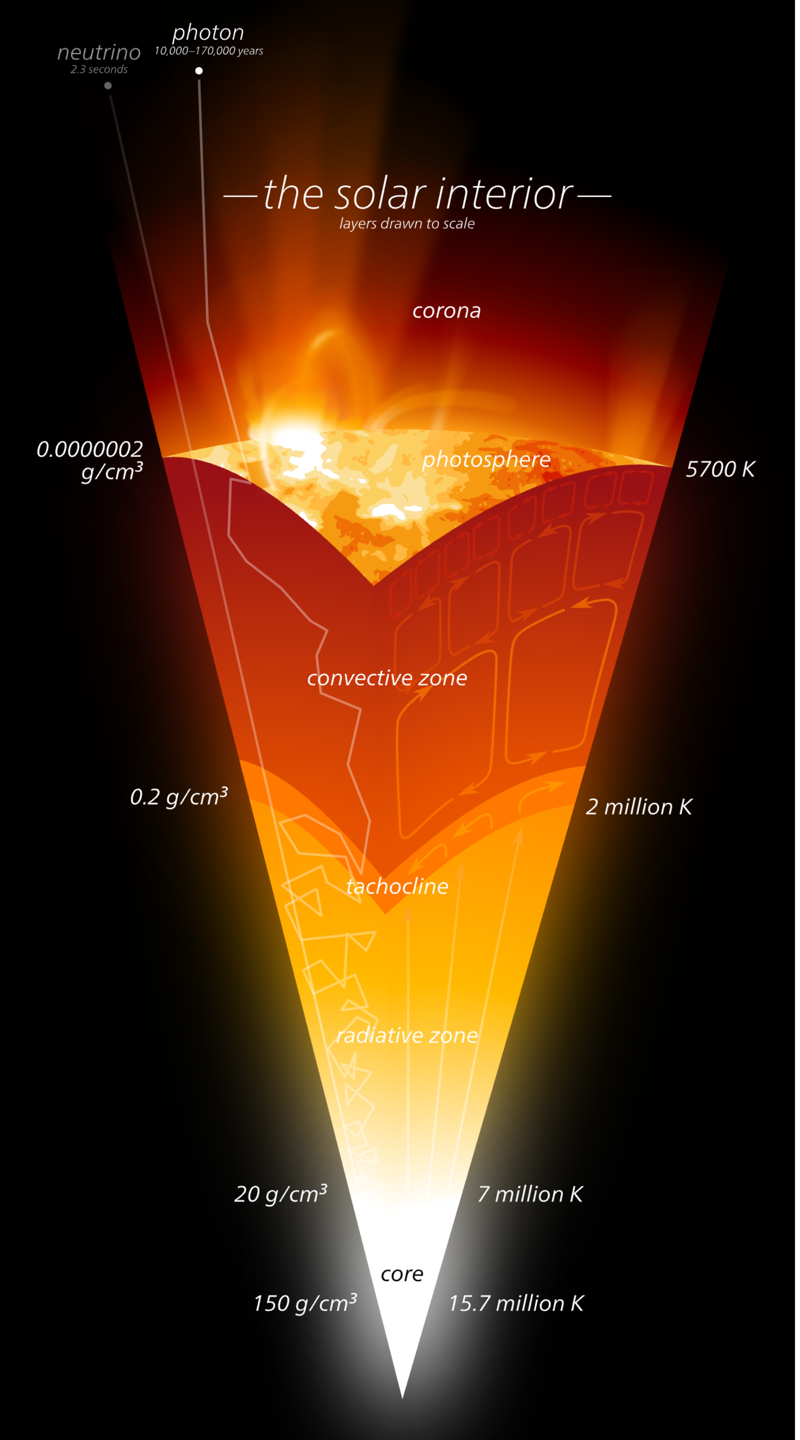
- Low-mass stars and brown dwarfs
- Why are they interesting to study?
- Ultra-cool dwarfs in *Gaia*: known objects and new discoveries
- Characterisation of ultra-cool dwarfs
- Towards a complete local census



Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

Low-mass stars and brown dwarfs



A vast amount of energy is released via nuclear fusion occuring in the core of a star.

$$\underbrace{4\,{}^{1}_{1}H}_{\substack{4\times 938\ MeV \\ = 3752\ MeV}} \rightarrow \underbrace{{}^{4}_{2}He + 2\,{}^{0}_{1}\bar{e} + 2\nu_e}_{3728\ MeV}$$

net mass loss
⇒ energy release

To fuse hydrogen, the core must have temperatures > 3x10^6 K.

On the Main Sequence, the thermal pressure from fusion keeps a star from gravitational collapse.
The star is in thermal and hydrostatic equilibrium.

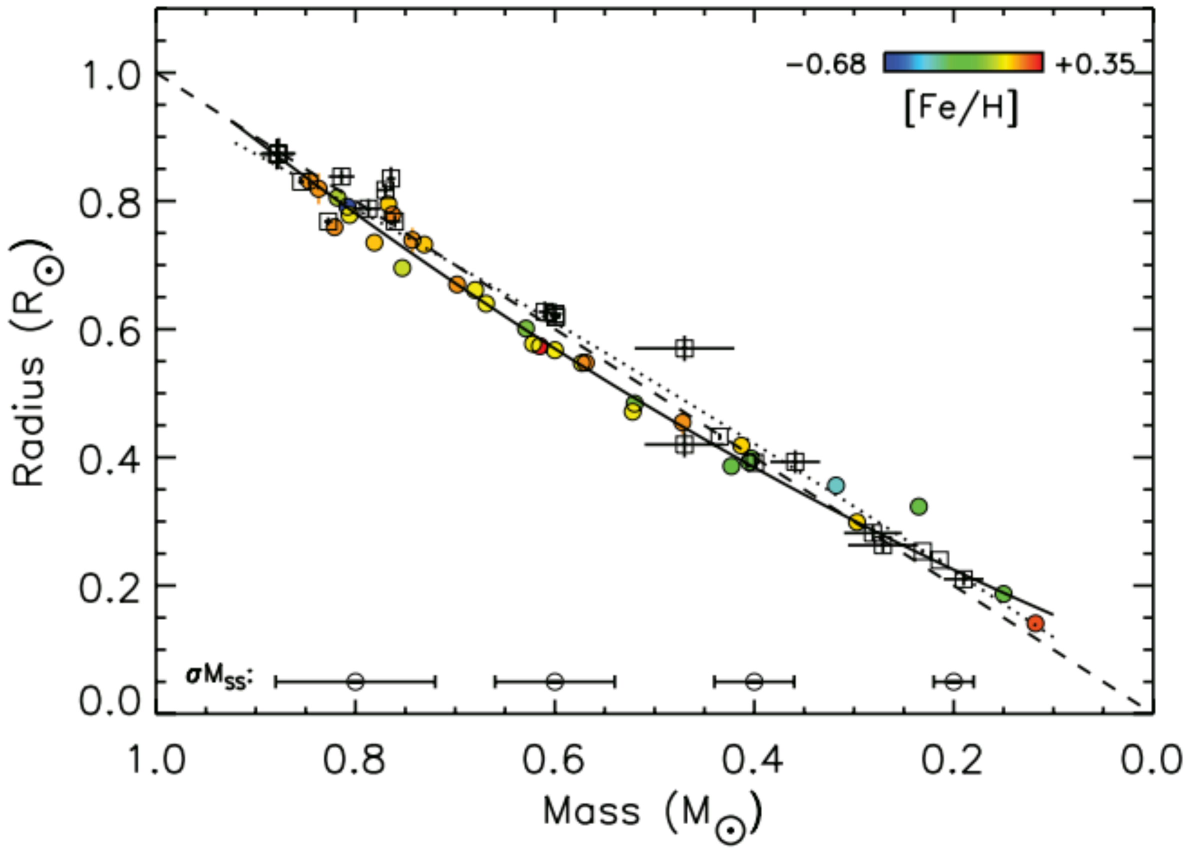
Credit: https://commons.wikimedia.org/wiki/File:The_solar_interior.svg

Low-mass stars and brown dwarfs

The stellar matter follows classical statistical physics: classical nearly perfect gas equation of state and quasistatic equilibrium condition

→ radius ∝ mass

The less mass a star has, the more it needs to contract to heat the core, and the smaller it will be on the Main Sequence.



Stellar empirical mass-radius relationship for main sequence K and M stars.

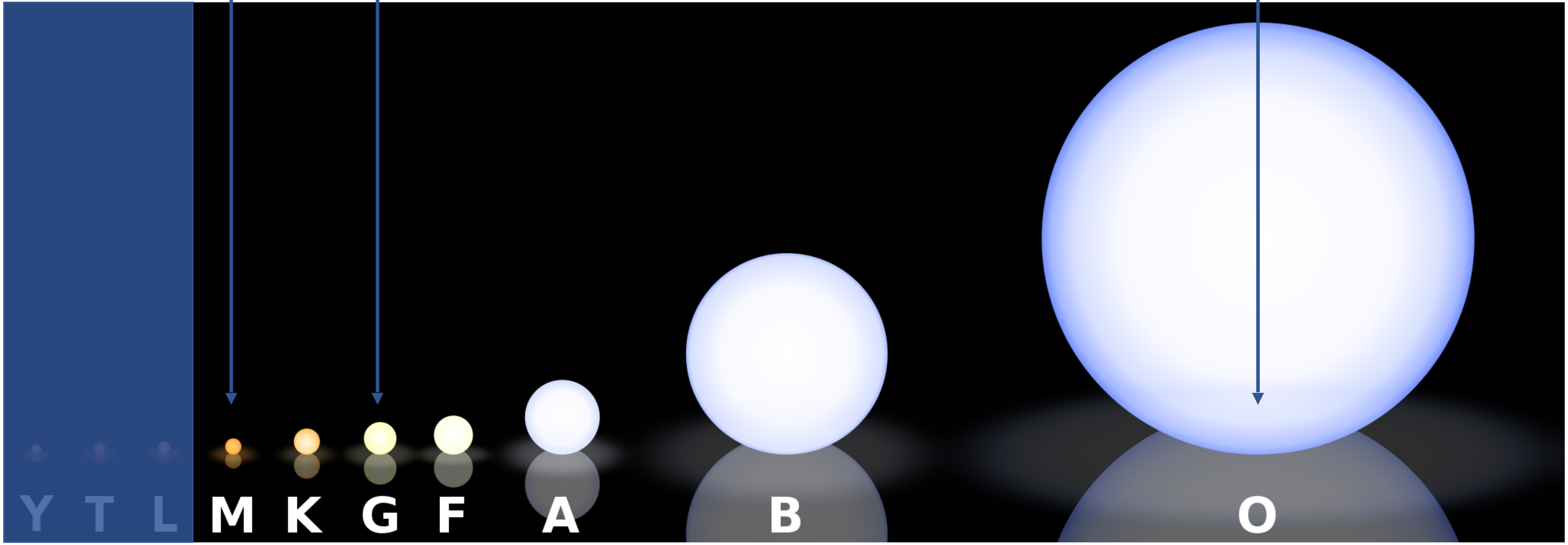
Boyajian et al, 2012

Low-mass stars and brown dwarfs

Lowest mass stars, tens smaller and less massive

Sun-like

Highest mass stars, several tens larger and more massive



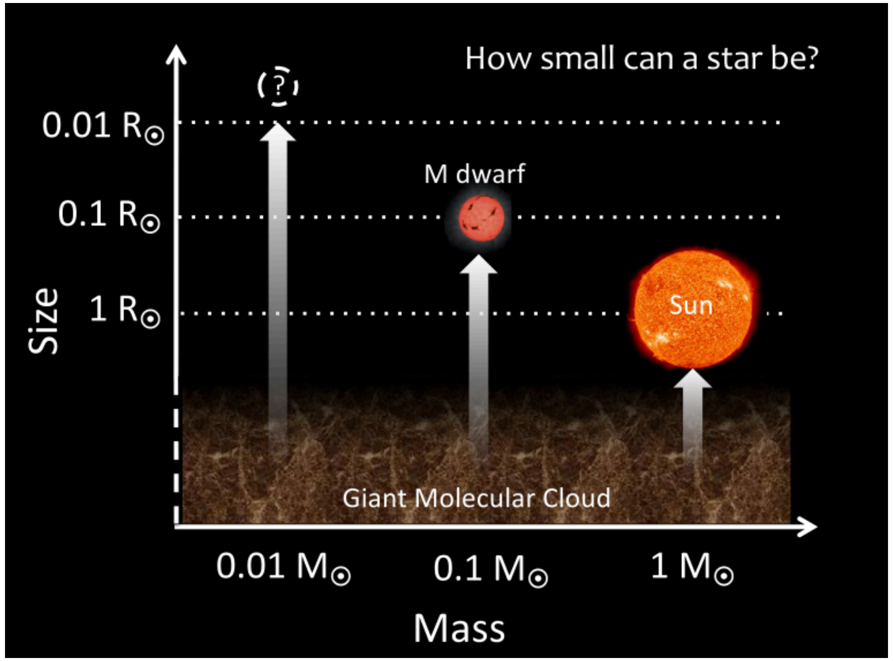
Credit: L. Reylé, adapted from http://en.wikipedia.org/wiki/File:Morgan-Keenan_spectral_classification.png

Low-mass stars and brown dwarfs

How small can a star be ?

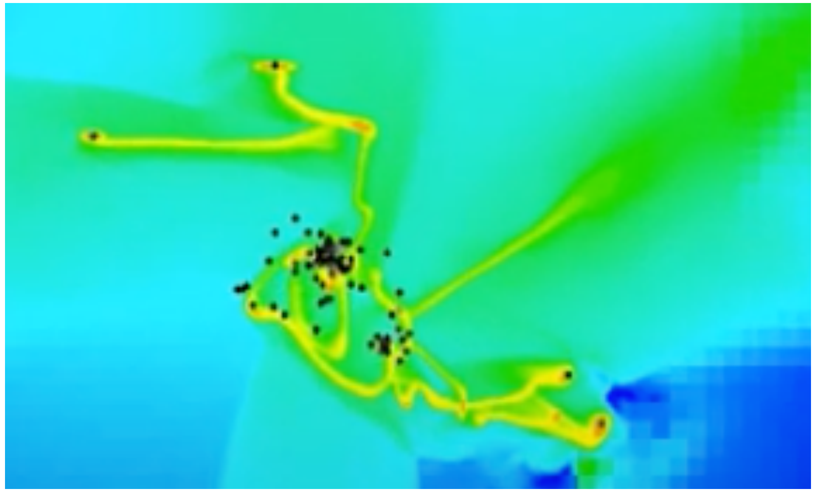
From filamentary clouds to prestellar cores to stars

André et al 2010
Credit: ESA/Herschel/ SPIRE/PACS « Gould Belt survey » Key Programme



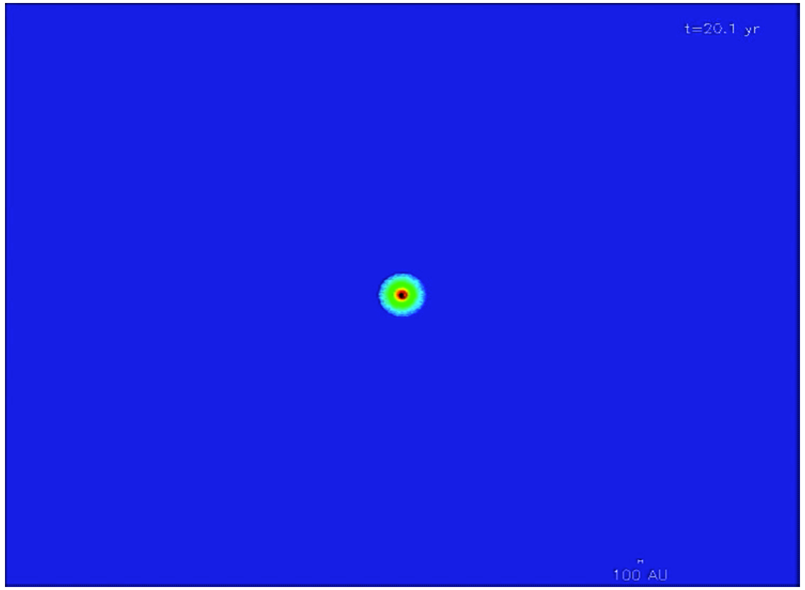
Courtesy of A. Burgasser

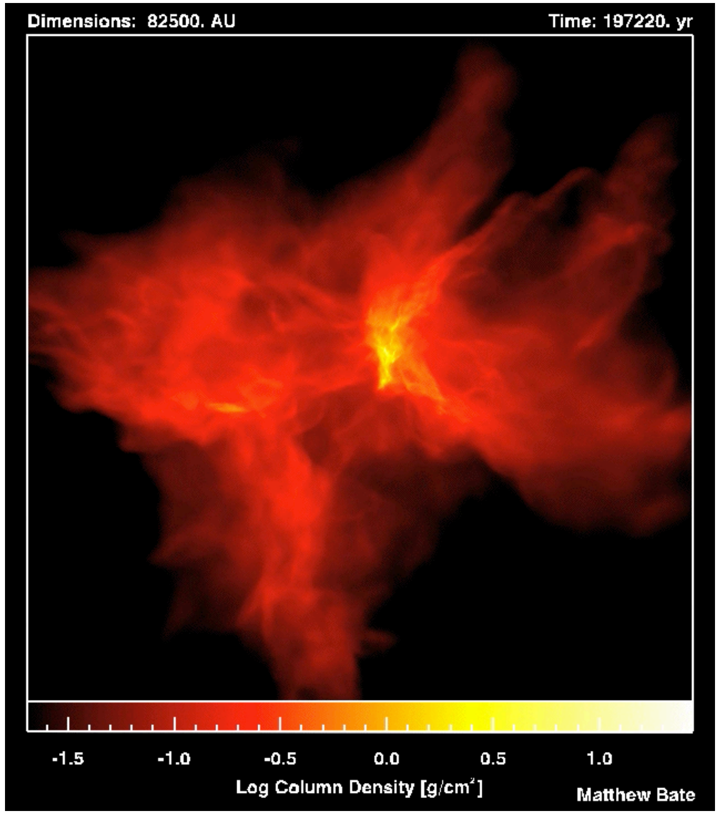
M_{Jeans}: need density of 10^7 cm^{-3} to form $M<0.07\ M_\odot$.
Barnard Bok globule has 1000 cm^{-3} *(Alves et al 2011)*



Gravoturbulent fragmentation

e.g. Padoan & Nordlund 2004; Hennebelle & Chabrier 2008, 2009; Bonnell et al 2008; Lomax et al 2016





Embryo ejection

e.g. Reipurth & Clarke 2001; Bate et al 2002; Goodwin et al 2004, Reipurth & Mikkola 2015

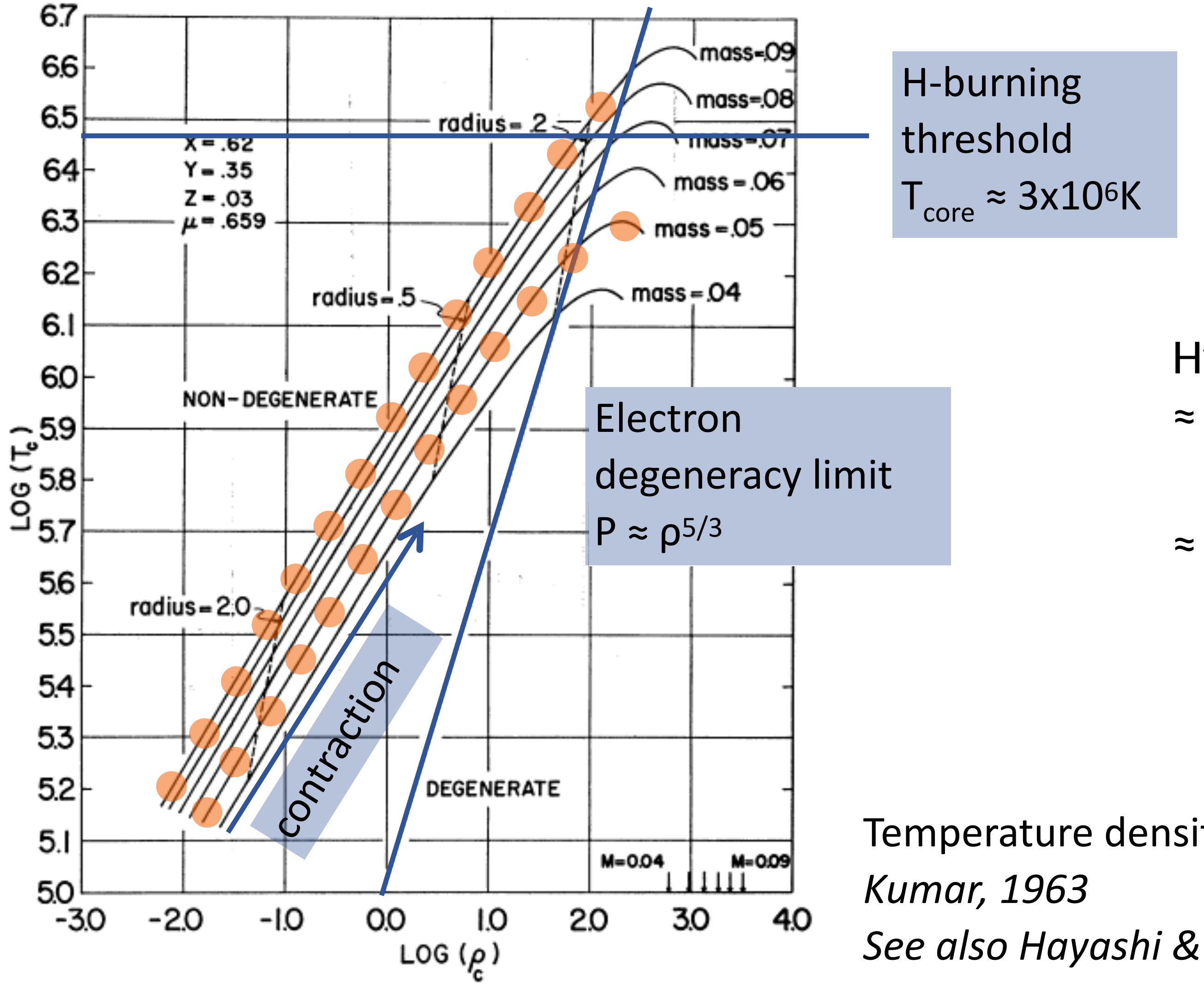
Disc fragmentation

e.g. Vorobyov & Basu 2006, 2010, 2012; Stamatellos et al 2007; Attwood et al 2009, Stamatellos et Herzceg 2015

Photoerosion

e.g. Whitworth & Zinnecker 2004; Green et al 2015

Low-mass stars and brown dwarfs



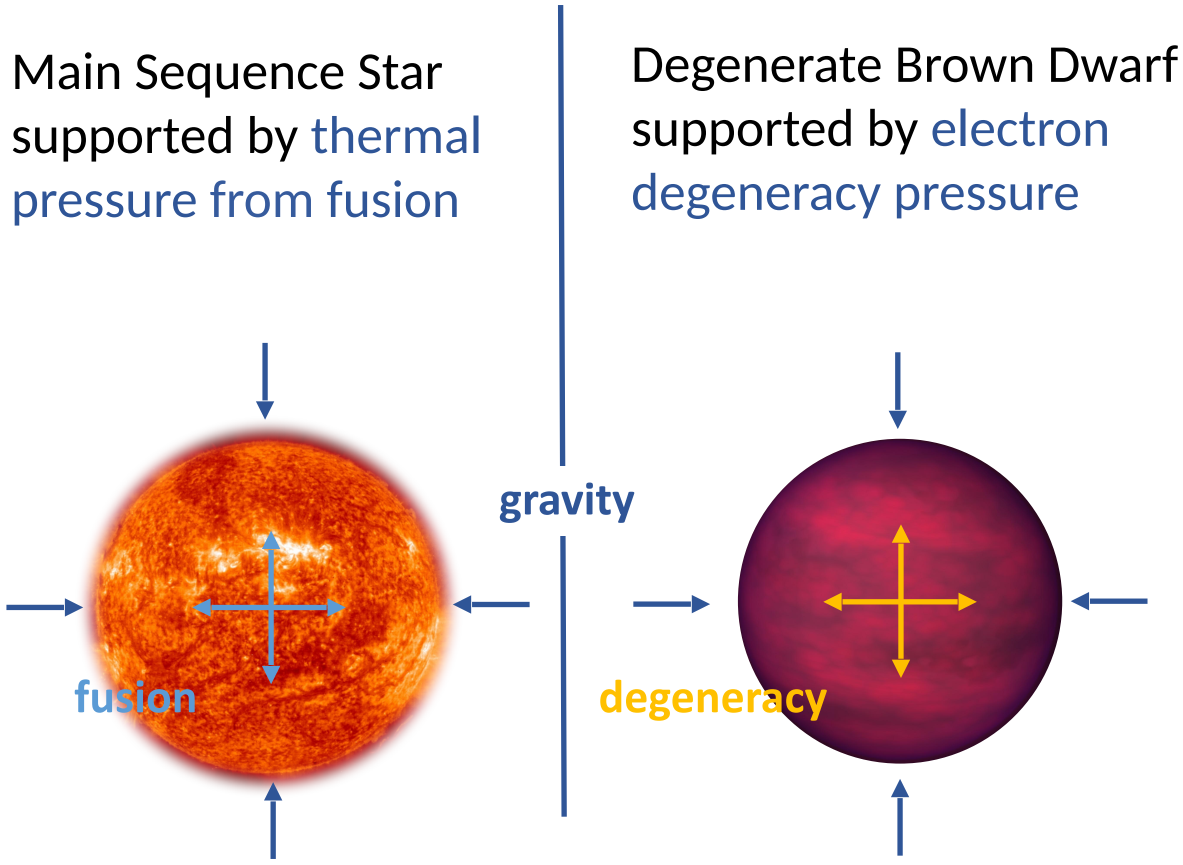
Hydrogen burning minimum mass
$\approx 0.07\ M_\odot$ (73 M_{jup}) at solar metallicity

$\approx 0.09\ M_\odot$ at low metallicity

Temperature density diagram for completely convective model
Kumar, 1963
See also Hayashi & Nakano (1963)

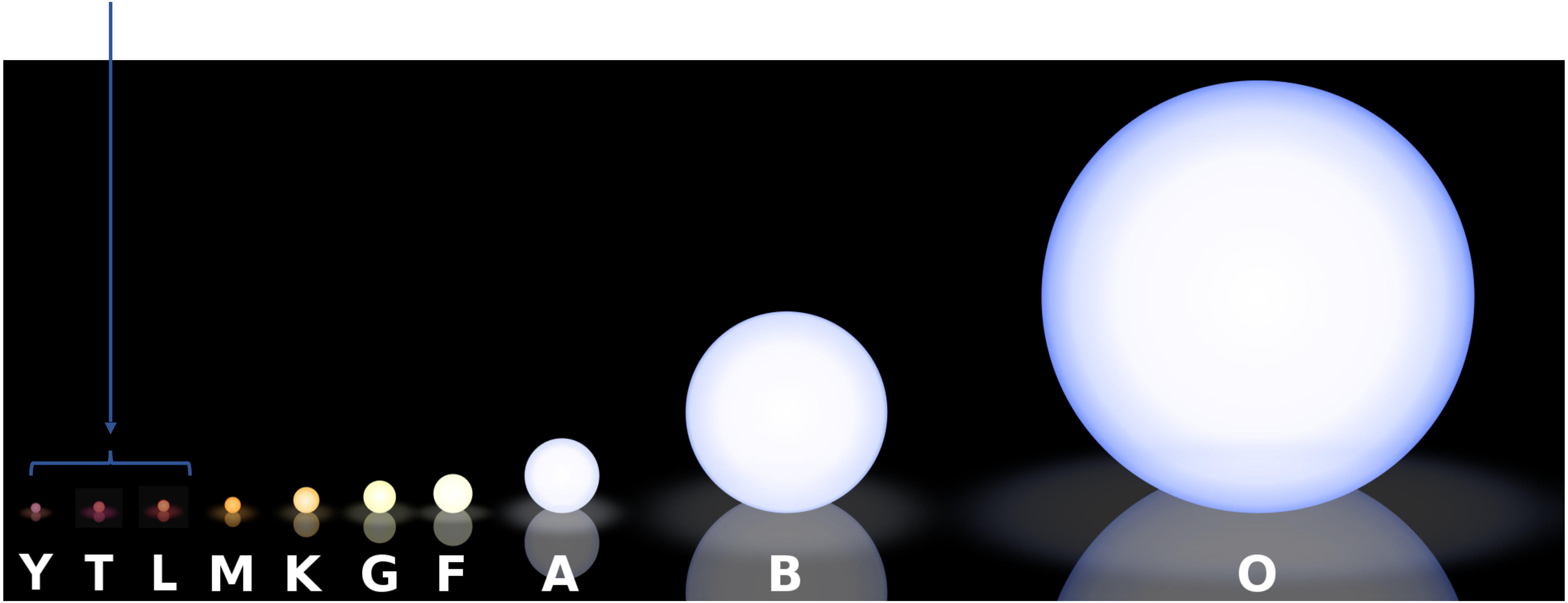
Low-mass stars and brown dwarfs

The object's collapse is stopped by electron degeneracy pressure. The macroscopic properties of the matter are then ruled by different physics and follow a different equation of state *(e.g. Saumon et al 1995, Chabrier et al 2023)*.



Low-mass stars and brown dwarfs

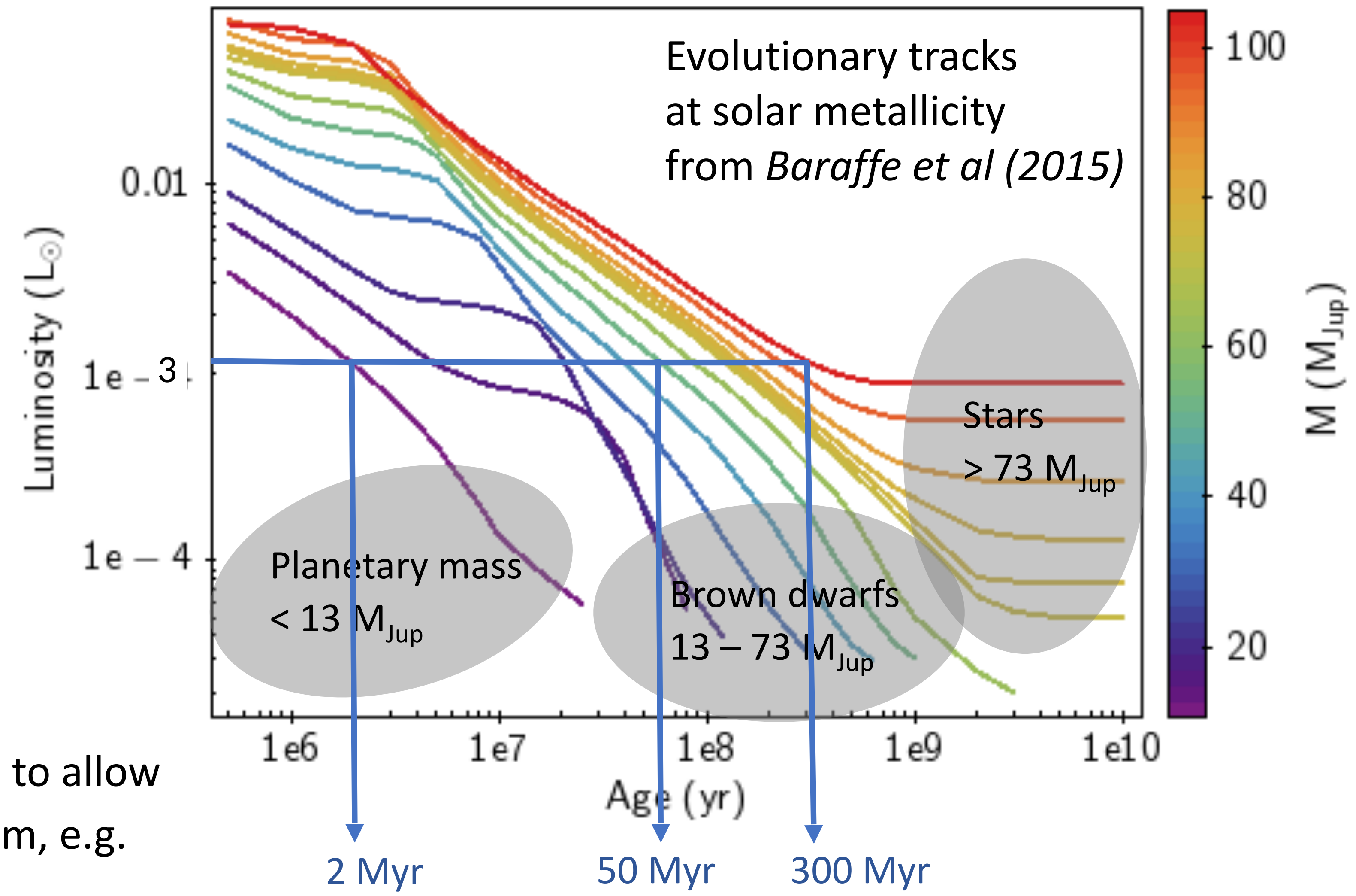
Brown dwarfs do not undergo stable hydrogen fusion → they cool down over time, progressively passing through later spectral types as they age.



Credit: L. Reylé, adapted from http://en.wikipedia.org/wiki/File:Morgan-Keenan_spectral_classification.png

Low-mass stars and brown dwarfs

The stellar-substellar limit



13 M_{Jup} is the mass limit to allow nuclear fusion (deuterium, e.g. *Burrows 1999*)

Low-mass stars and brown dwarfs

The stellar-substellar limit

Theoretical mass limit of hydrogen fusion

- *Chabrier & Baraffe (2000)* review

0.070–0.072 $M_\odot$ **73–75 M_{Jup}** depending on cloud opacities

- *Burrows et al. (2001)* review

0.070–0.075 $M_\odot$ **73–79 M_{Jup}** for solar metallicity

0.092 $M_\odot$ **96 M_{Jup}** for zero metallicity

- Cloudy models from *Saumon & Marley (2008)*

0.070 $M_\odot$ **73 M_{Jup}**

- Models from *Burrows et al. (2011)*

0.070–0.075 $M_\odot$ **73–79 M_{Jup}** assuming different helium fractions

- Models from *Baraffe et al. (2015)*

0.067–0.072 $M_\odot$ **70–75 M_{jup}**

- Models from *Marley et al. (2021)*

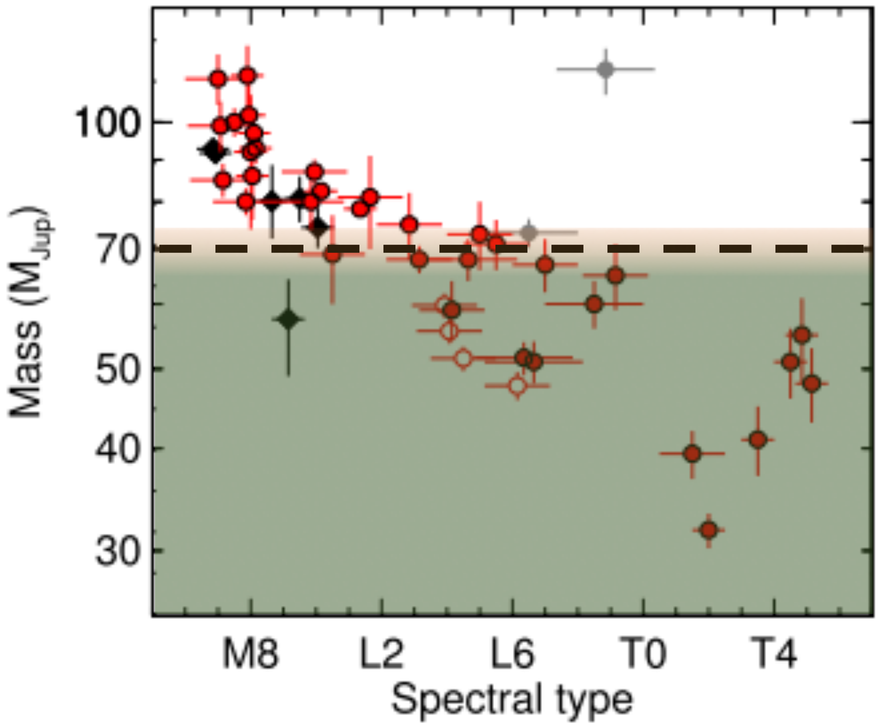
0.070 $M_\odot$ **73 M_{Jup}**

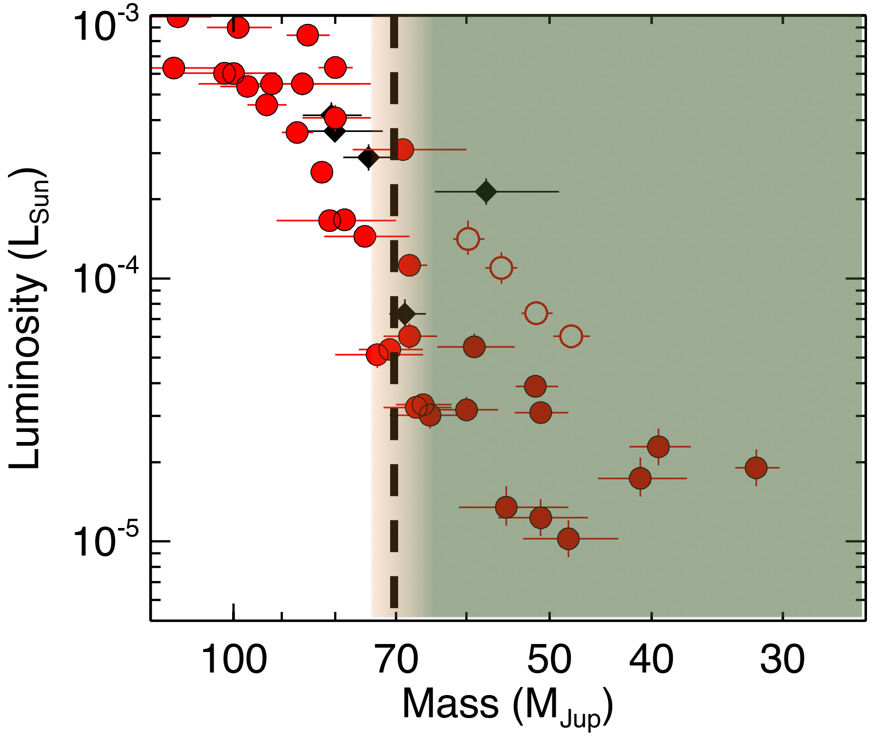
Low-mass stars and brown dwarfs

The stellar-substellar limit

Empirical mass limit of hydrogen fusion

Dupuy & Liu (2017) determined dynamical mass of 31 ultracool dwarfs binaries (M7-T5). Boundary defined by the maximum mass of the latest-type (late-L and T), or lowest luminosity objects: 70±4 M_{Jup}

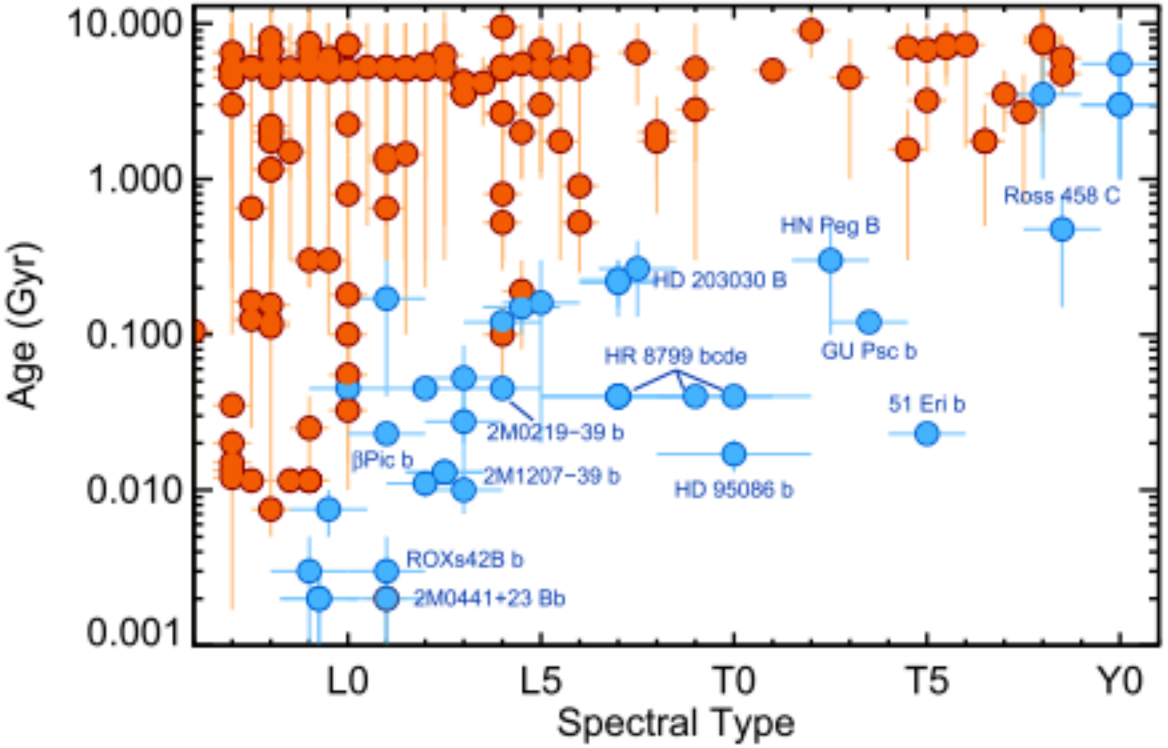




Low-mass stars and brown dwarfs

The stellar-substellar limit

Very low-mass stars, brown dwarfs, and planetary mass objects can have the same brightness.



Brown dwarfs and stars $>13M_{Jup}$

Planetary mass objects $<13M_{Jup}$

Ultracool substellar companions with well-constrained ages and spectroscopically derived classifications

Bowler 2016

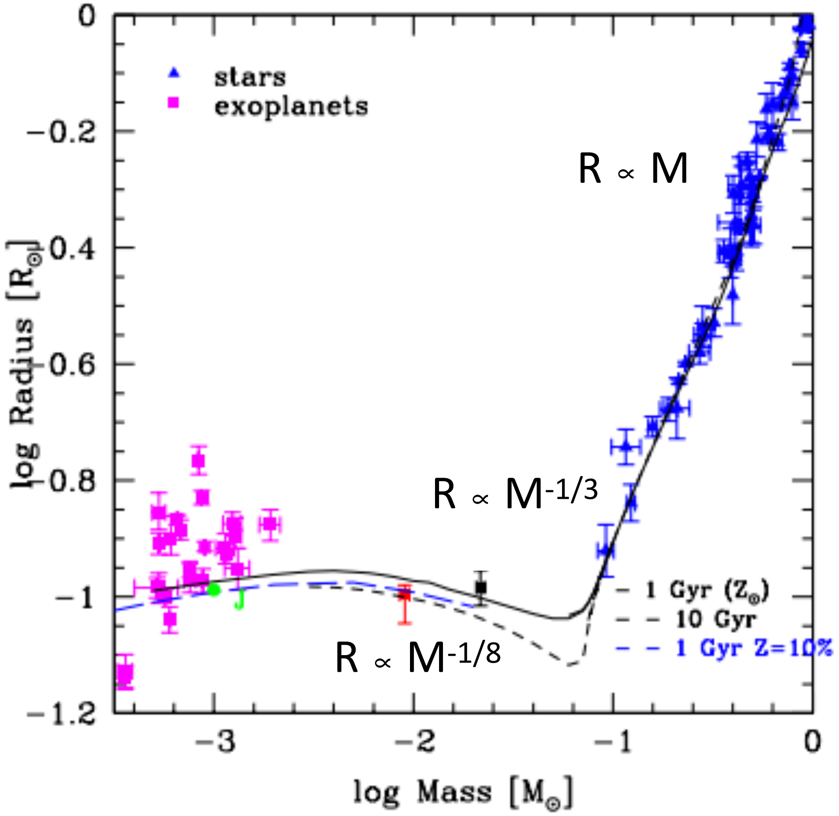
Low-mass stars and brown dwarfs

The stellar-substellar limit

Models predict a reversal of the mass–radius relation at the hydrogen burning limit

In a more massive brown dwarf, gravitational force is higher and causes a larger fraction of the brown dwarf to become degenerate, causing it to have a smaller radius

→ The mass–radius relation shows a local minimum at the most massive brown dwarfs



The minimum size is about the size of Jupiter

Mass-radius relation

Chabrier et al 2009

Low-mass stars and brown dwarfs

At given mass, theoretical isochrones predict that older objects have smaller radii

The stellar-substellar limit

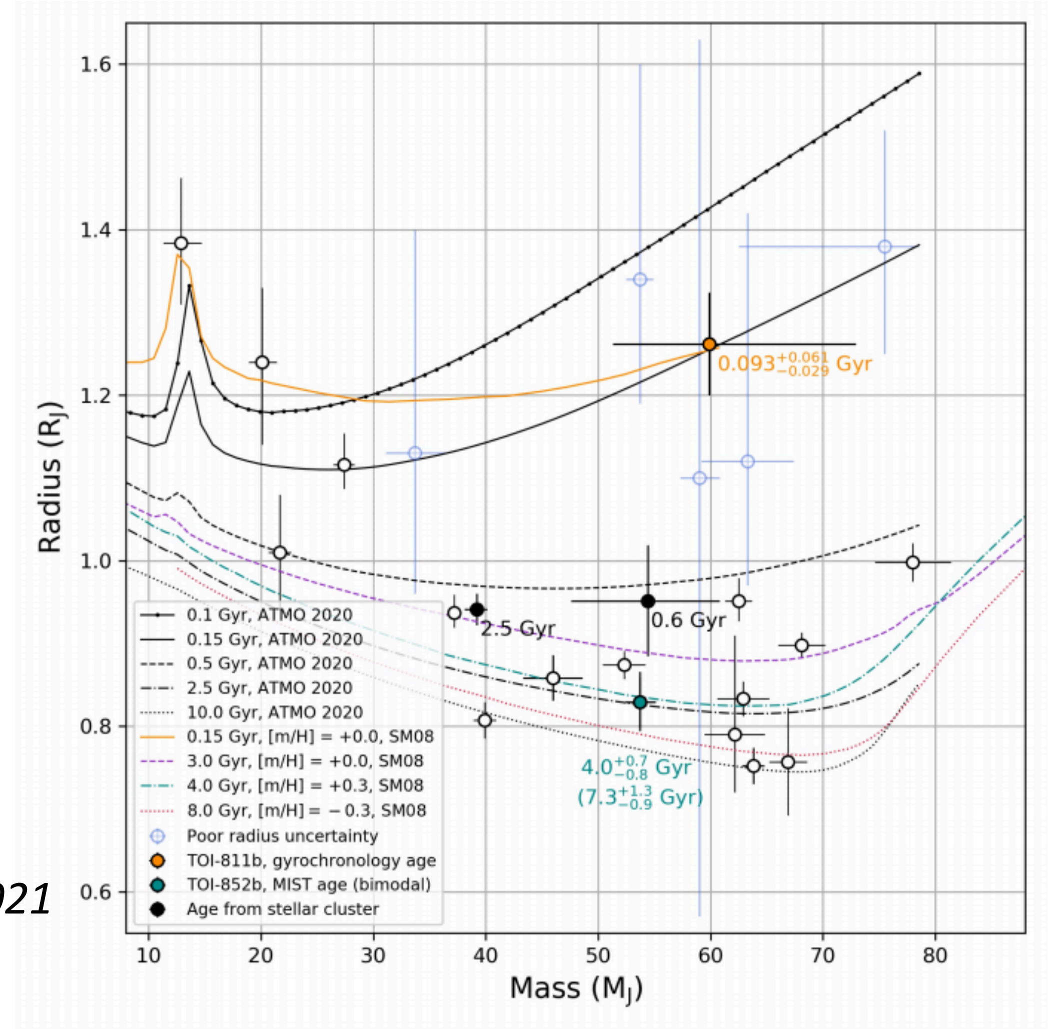
Transiting brown dwarfs and low mass stars with age estimate from the primary star

→ test of the age-radius effect

Transiting brown dwarfs generally validate model radii

Carmichael et al 2021

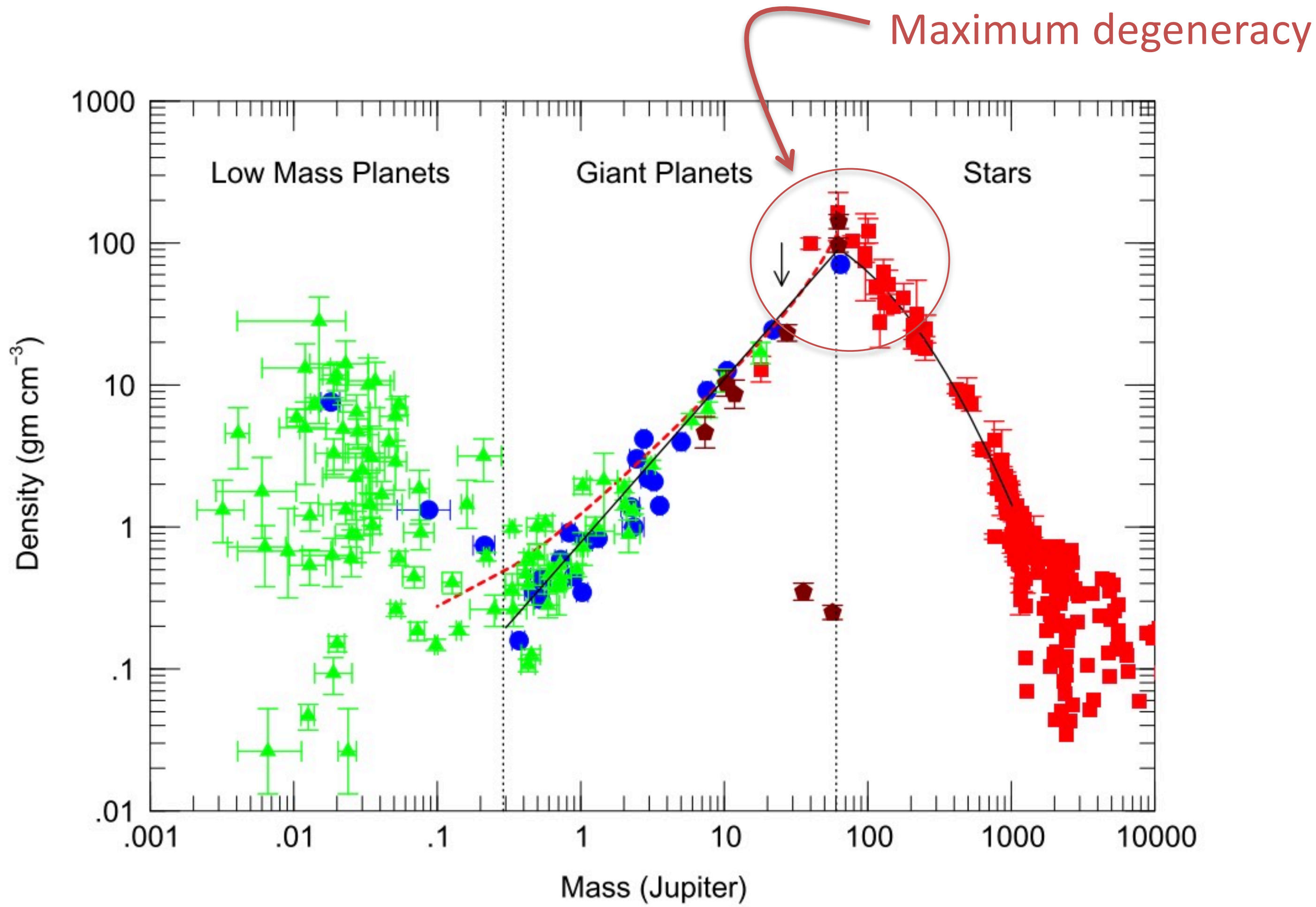
see also *Grieves et al. 2021*

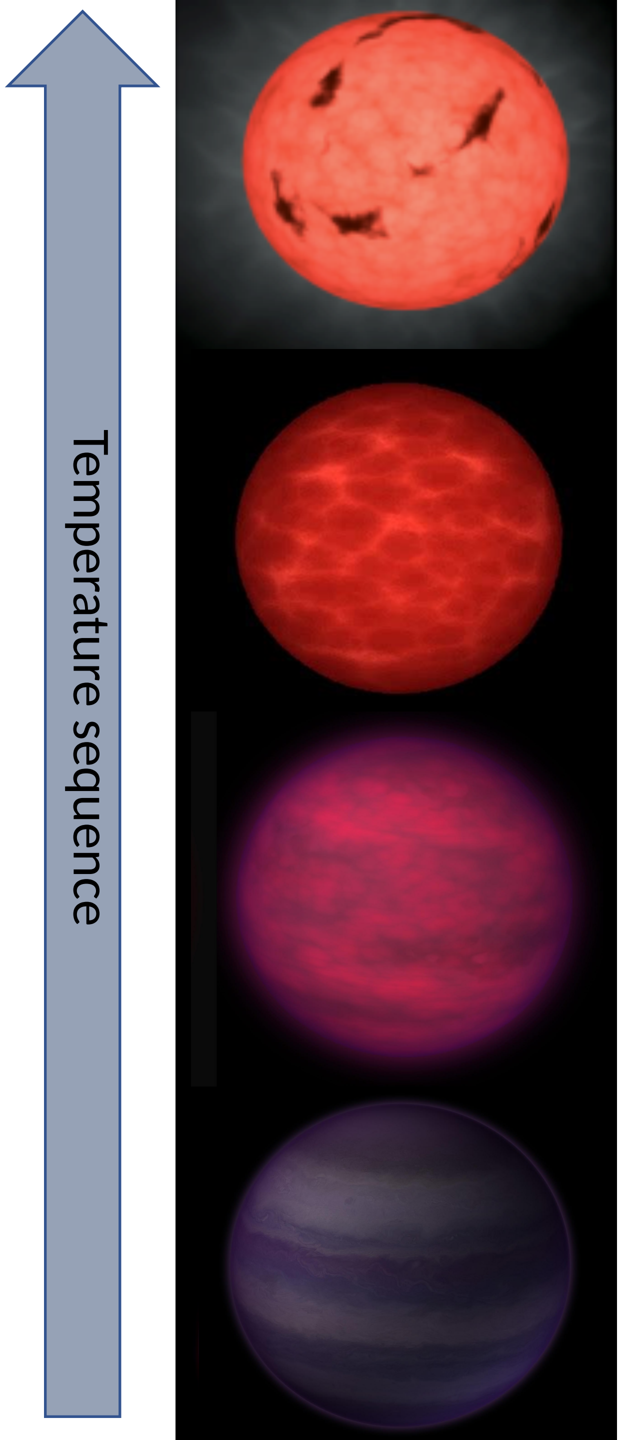


Low-mass stars and brown dwarfs

Brown dwarfs are the densest Hydrogen-rich objects known

The stellar-substellar limit





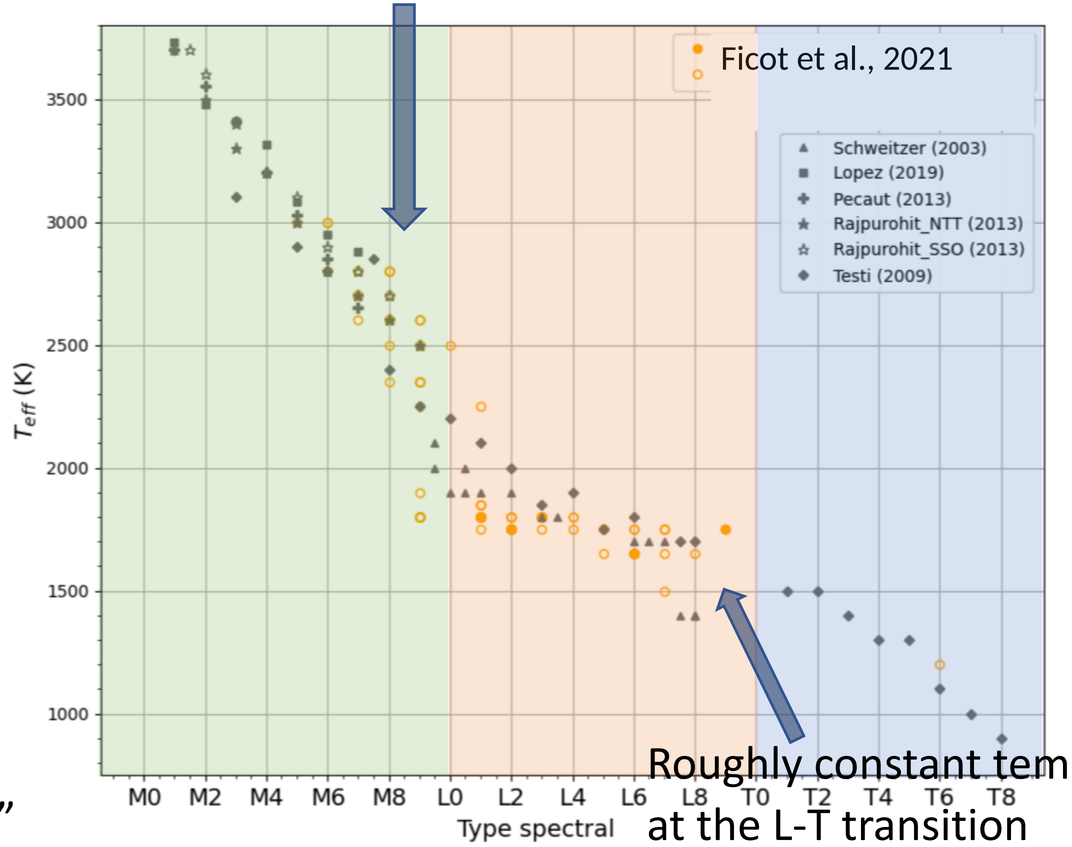
M-dwarfs
~3800-2100 K

L-dwarfs
~2100-1500 K

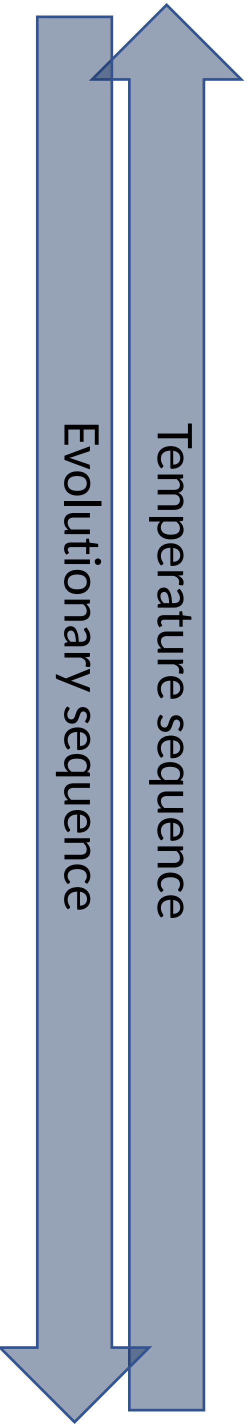
T-dwarfs
~1500-550 K

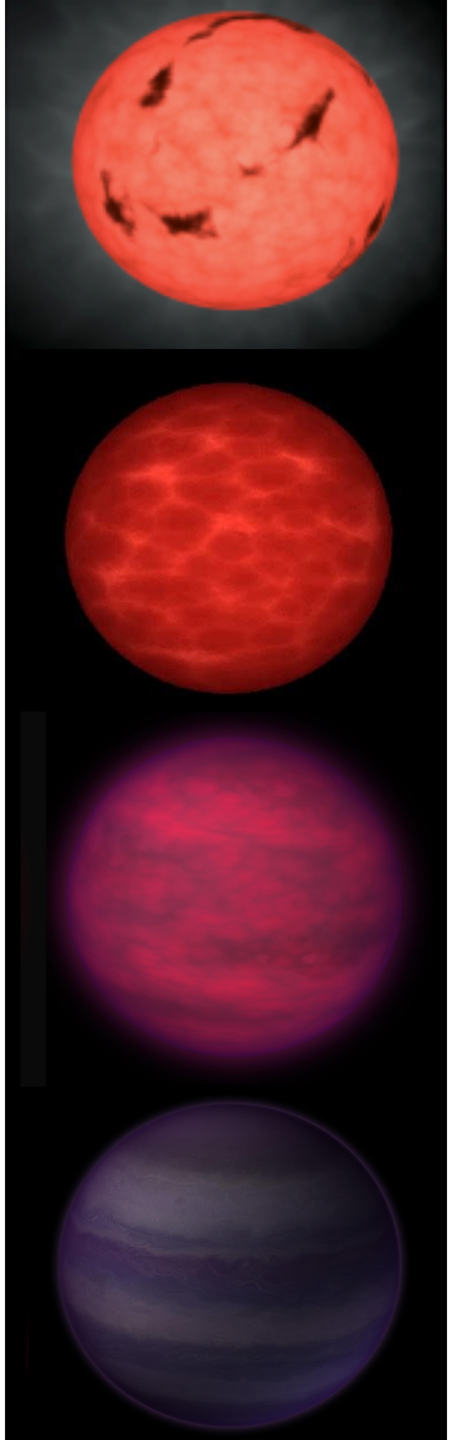
Y-dwarfs
~550-<250 K
“room-temperature”

Turning point explained as a consequence of solid grain formation starting at that temperature *(Allard et al 2012)*



Roughly constant temperature at the L-T transition *(Golimowski et al 2004)*





M-dwarfs

youngest brown dwarfs

L-dwarfs

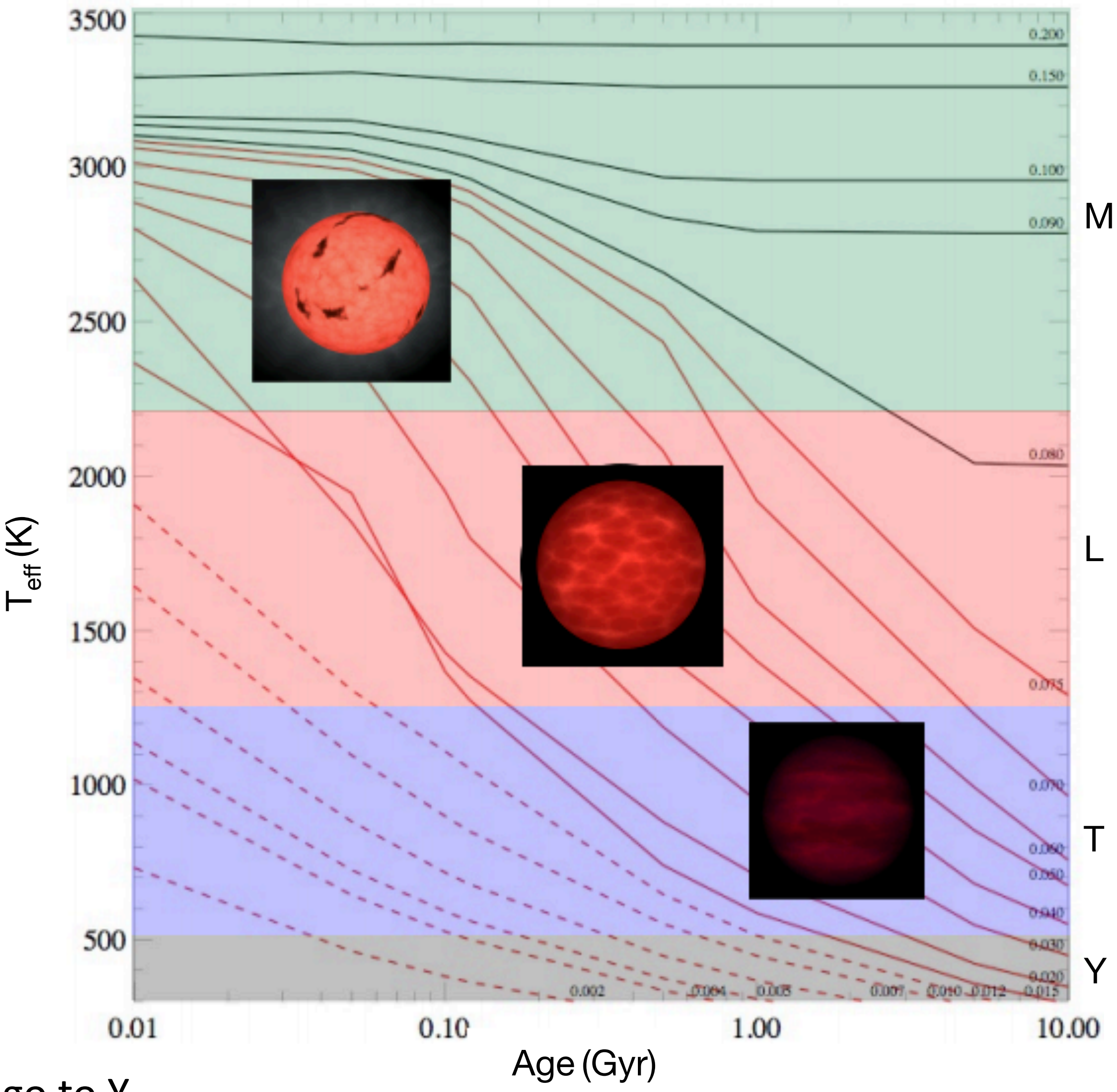
the edge of the H-burning main sequence is an L-dwarf

T-dwarfs

almost all brown dwarfs evolve from M to L to T spectral types

Y-dwarfs

the smallest brown dwarfs go to Y spectral type



Evolutionary Models from *Burrows et al 2001*

Topics for this lecture

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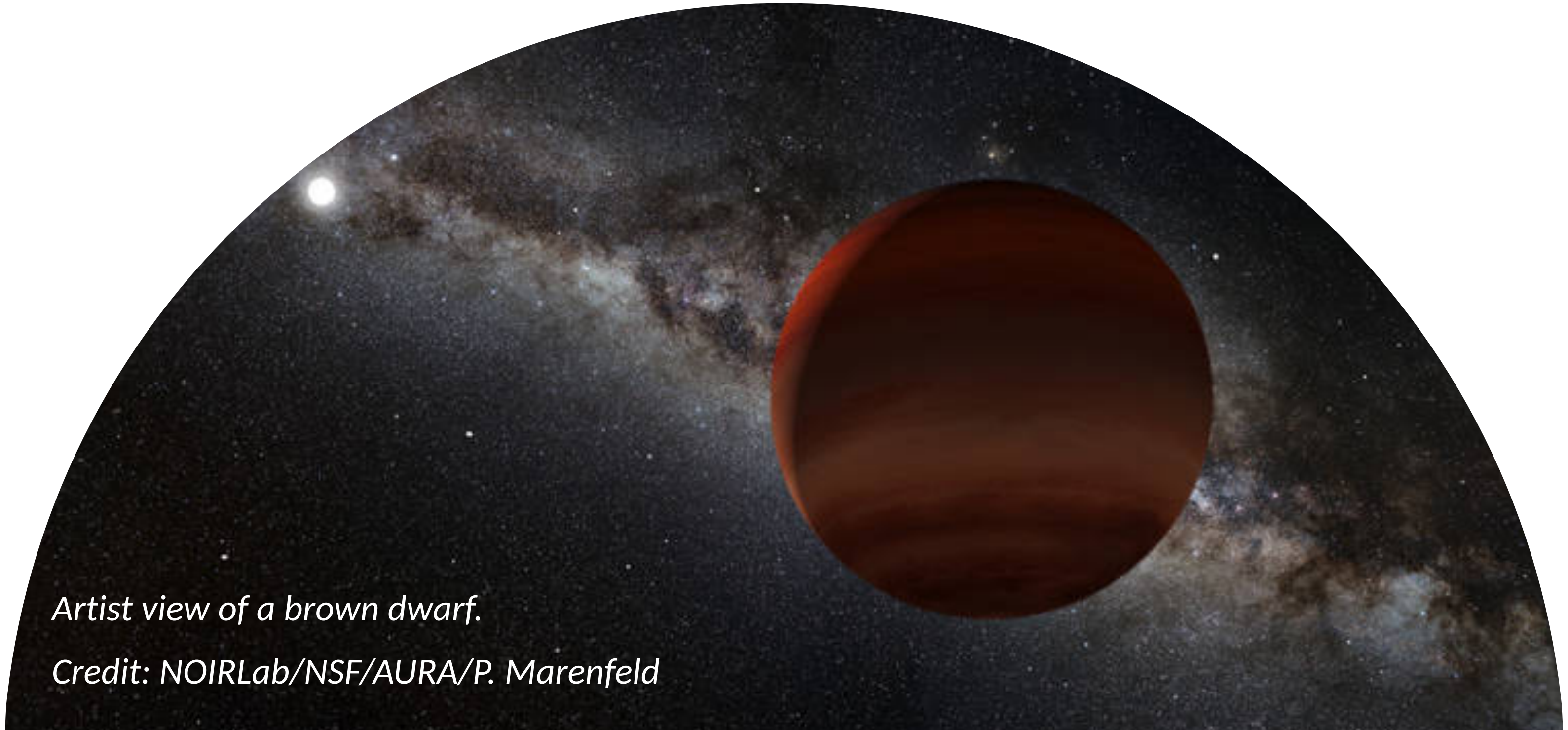
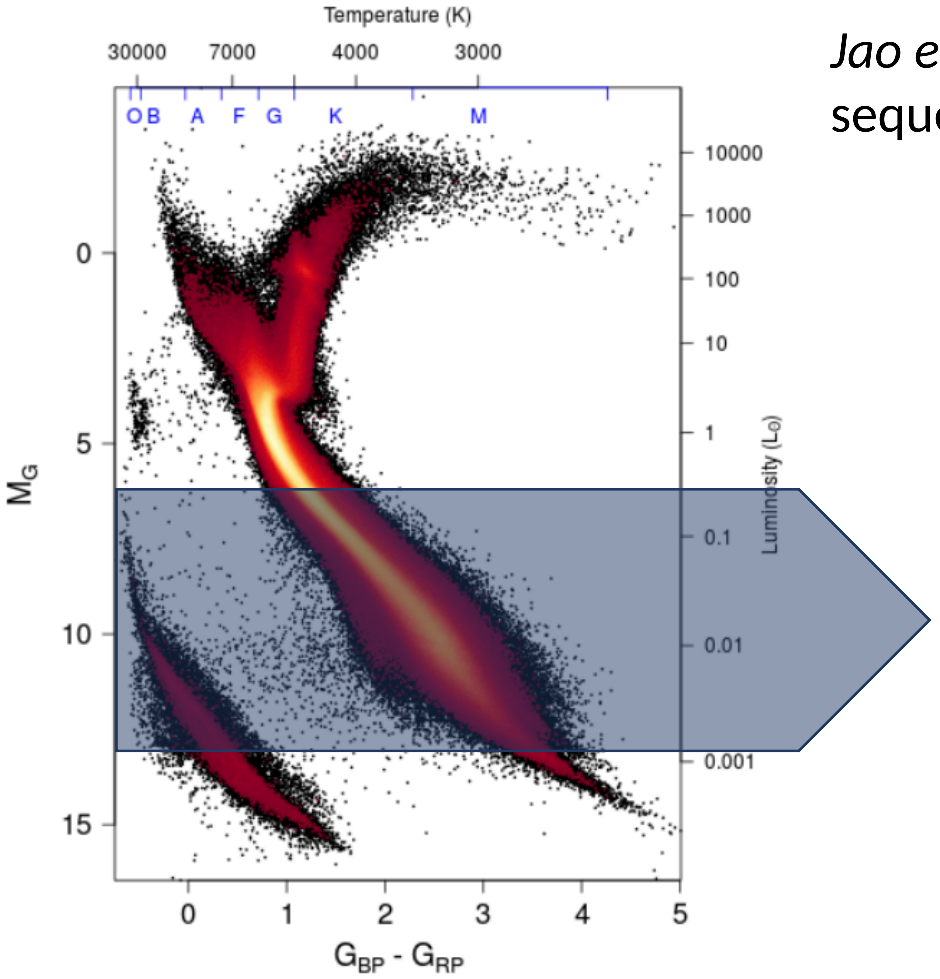
- Why are they interesting to study?
- Ultra-cool dwarfs in *Gaia*
- Characterisation of ultra-cool dwarfs
- Towards a complete census



Artist view of a brown dwarf.

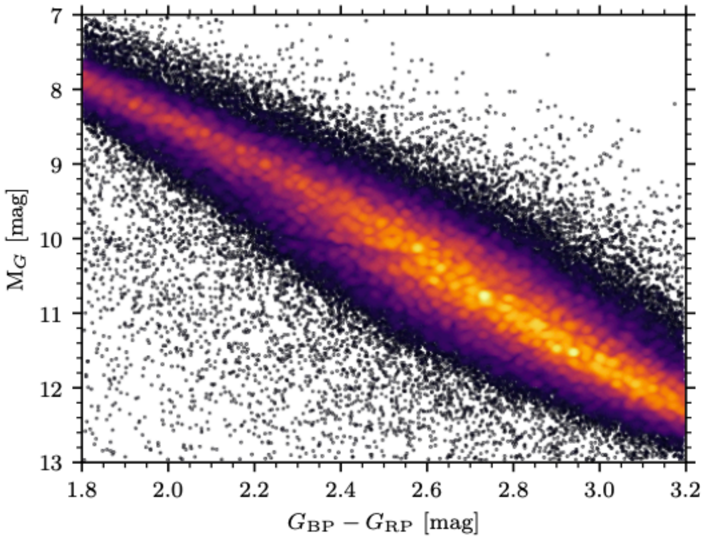
Credit: NOIRLab/NSF/AURA/P. Marenfeld

Why they are interesting to study



Colour absolute magnitude diagram from *Gaia* DR2, *Gaia Coll., Babusiaux et al 2018*

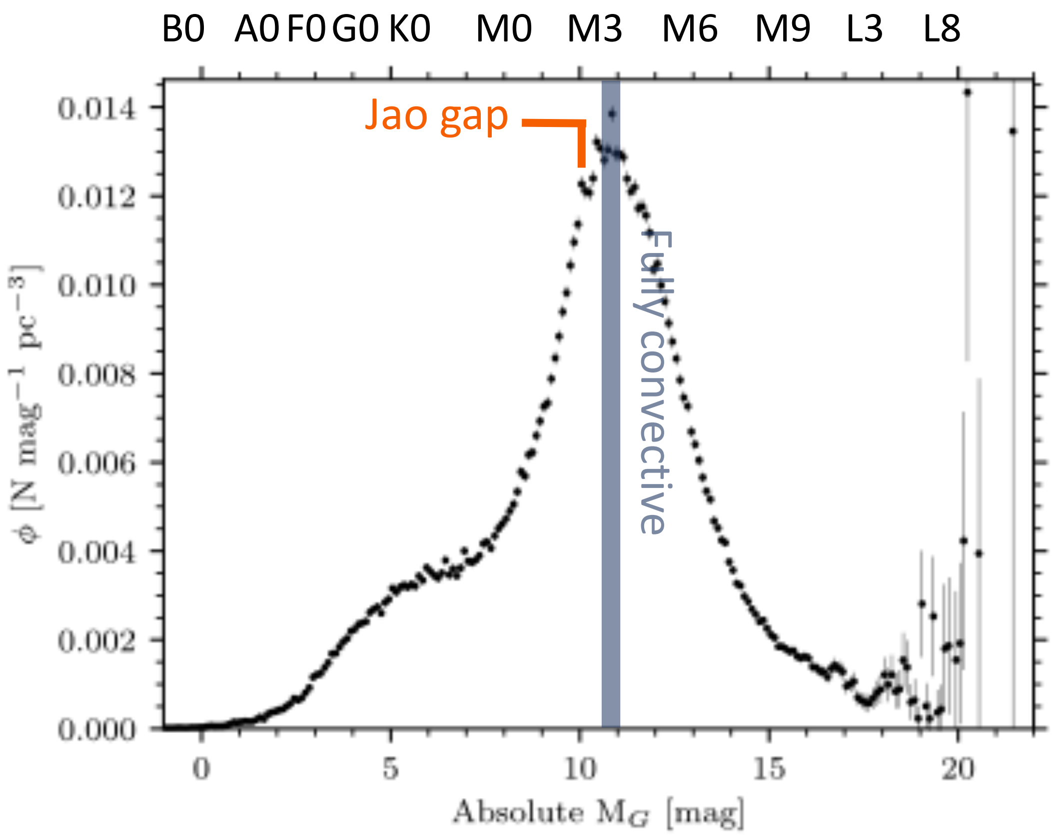
Jao et al. (2018) discovered a narrow gap (~0.05 mag) in the lower main sequence: M3, M~0.35 $M_\odot$, transition from partly to fully convective stars



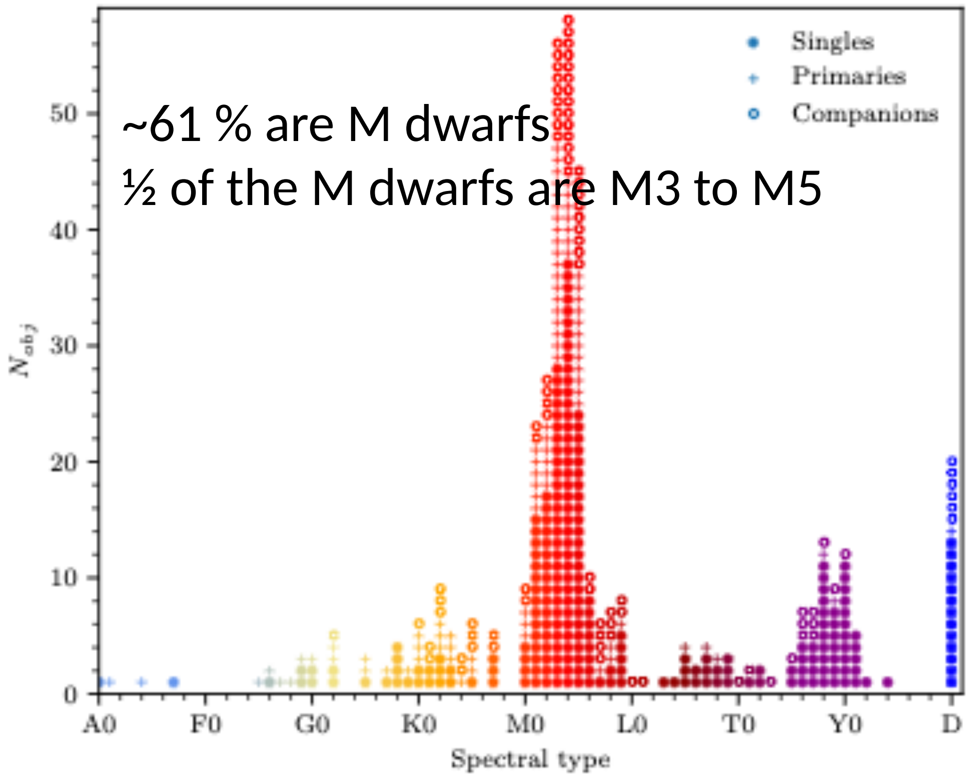
Related to structural instabilities caused by non-equilibrium ^{3}He fusion reactions *(MacDonald & Gizis 2018; Baraffe & Chabrier 2018; Feiden, Skidmore & Jao 2021)*

Why they are interesting to study

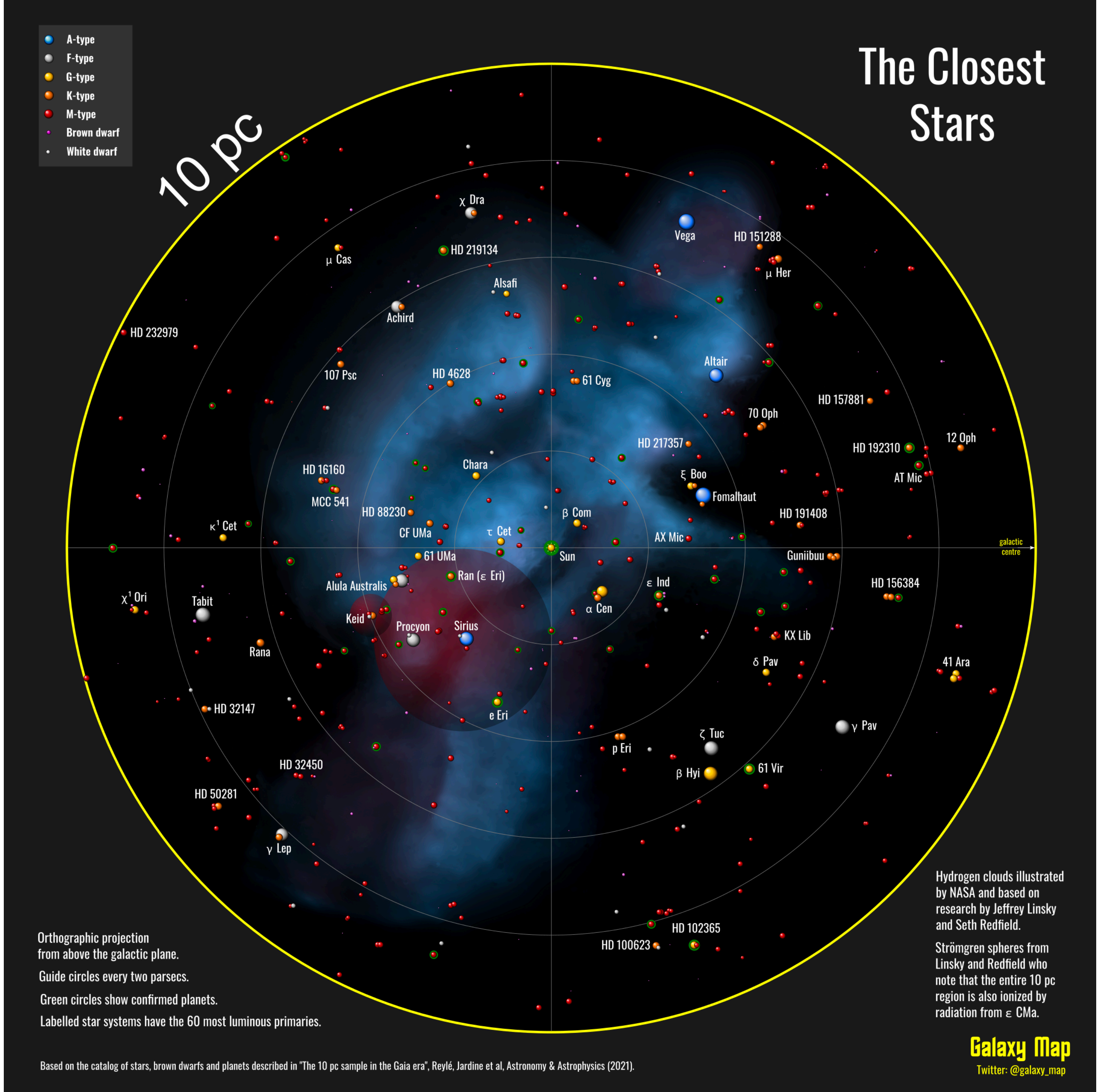
- They are the most numerous in the Galaxy
- They evolve so slowly that they span all ages and are in all populations



Luminosity function of the *Gaia* Catalogue of Nearby Stars (within 100 pc) *Gaia Coll., Smart et al 2021*



Spectral type distribution of the 10 pc sample *Reylé et al 2021* https://gruze.org/10pc/resources/

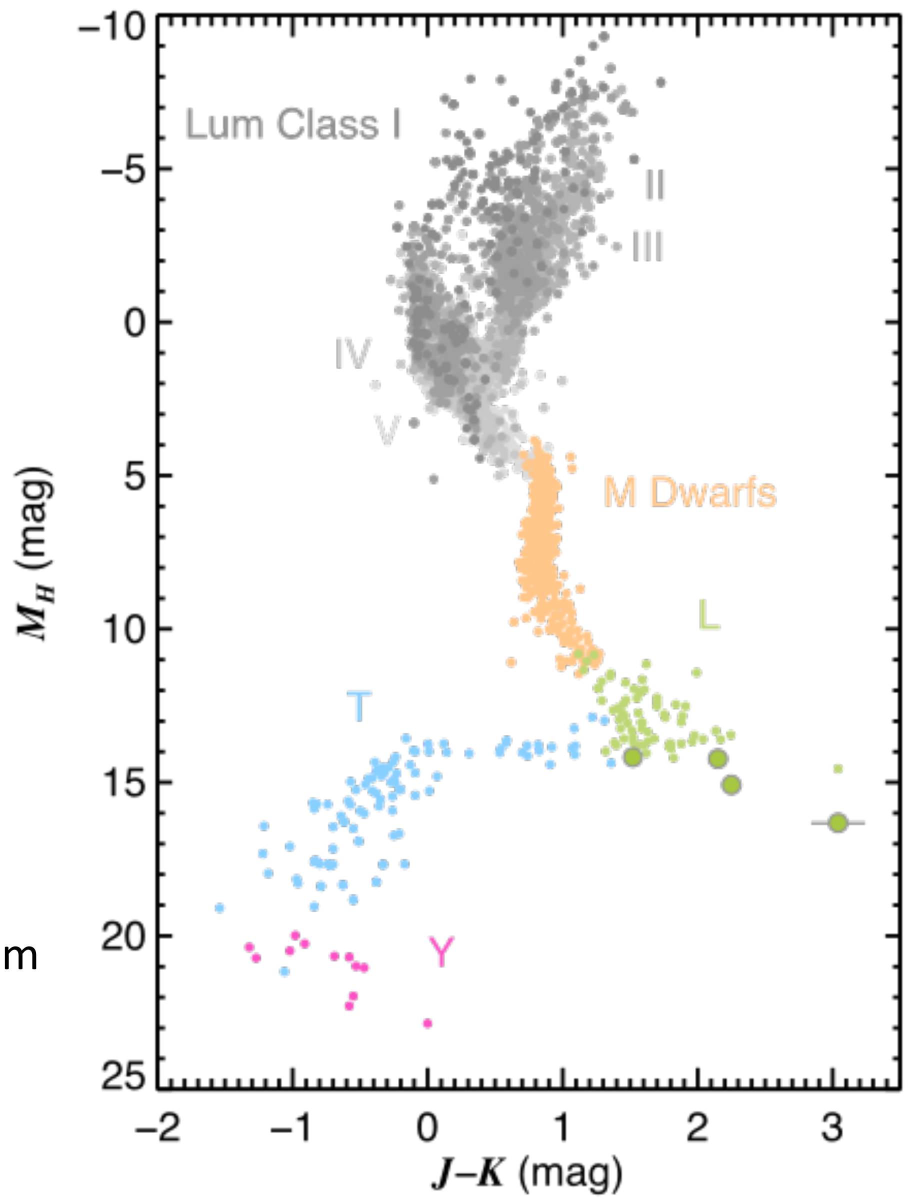


Why they are interesting to study

Ultracool dwarfs have a huge range of astrophysical properties!

Large variety of characteristics

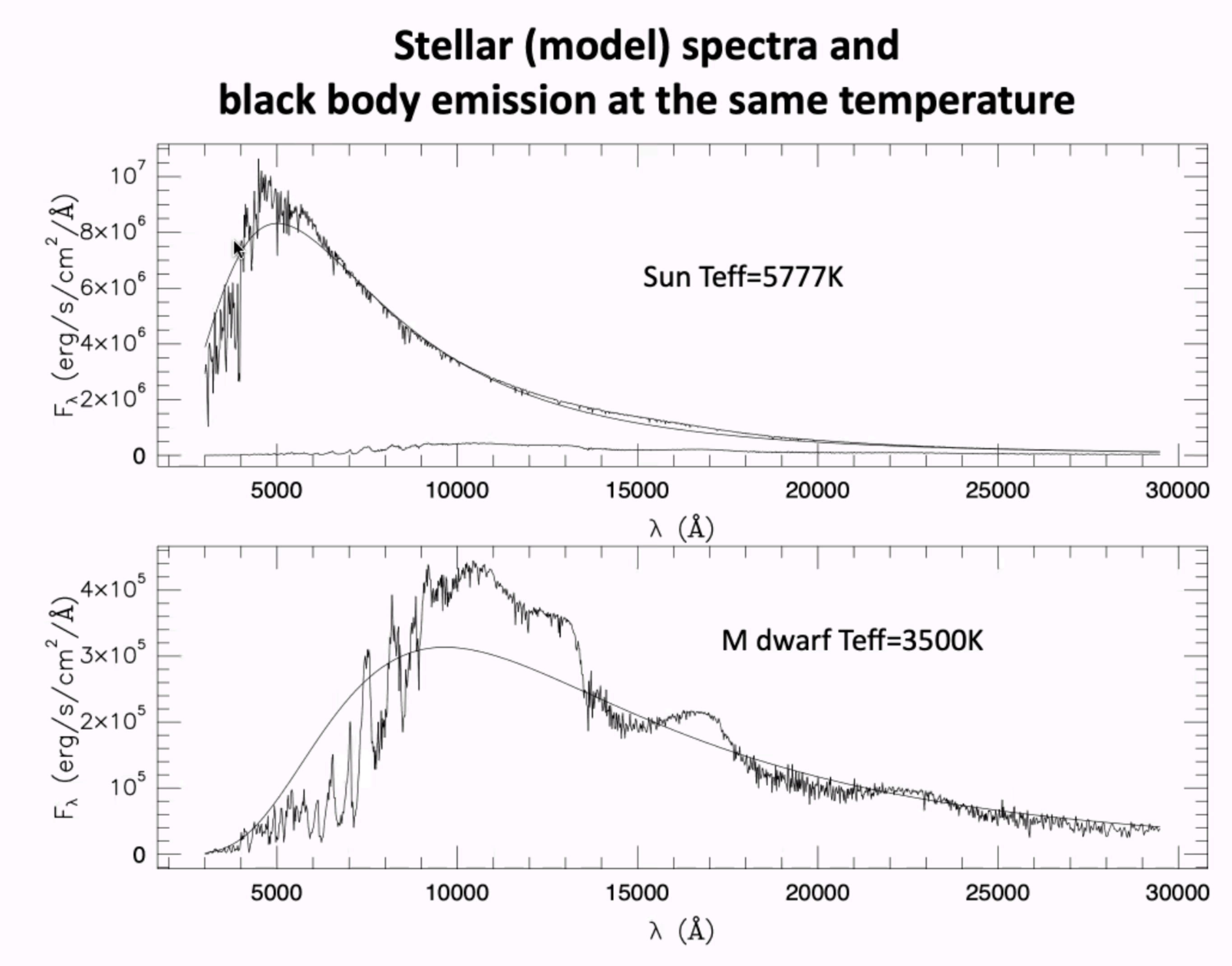
→ complex physical processes acting in their atmospheres.



Colour absolute magnitude diagram in 2MASS bands
Bowler 2016

Why they are interesting to study

- They still remain elusive due to their faint magnitude. Modeling their complex, cool, atmosphere is still a challenge



Courtesy of B. Plez

Why they are interesting to study

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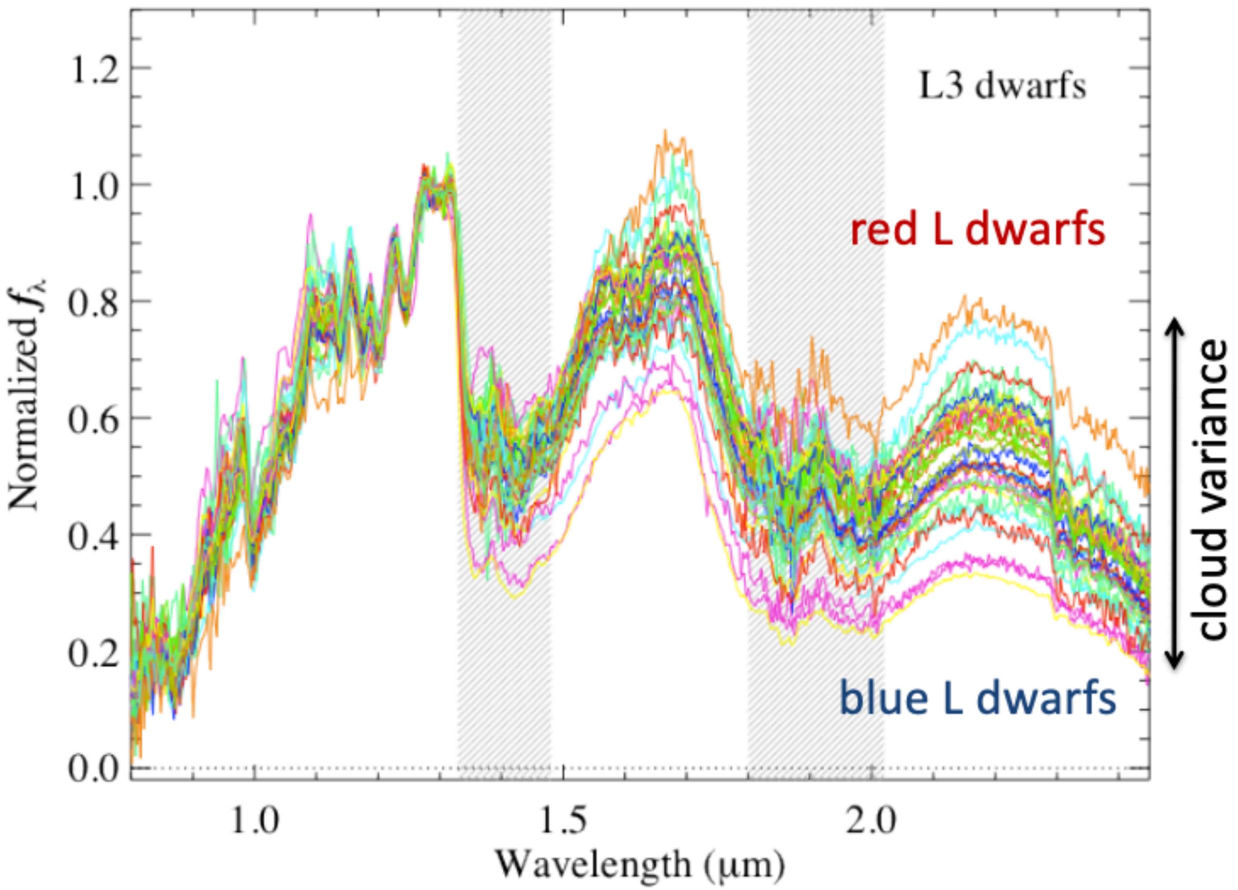
Illustration: the tricky case of L-dwarfs

Condensates modify the shape of the spectrum

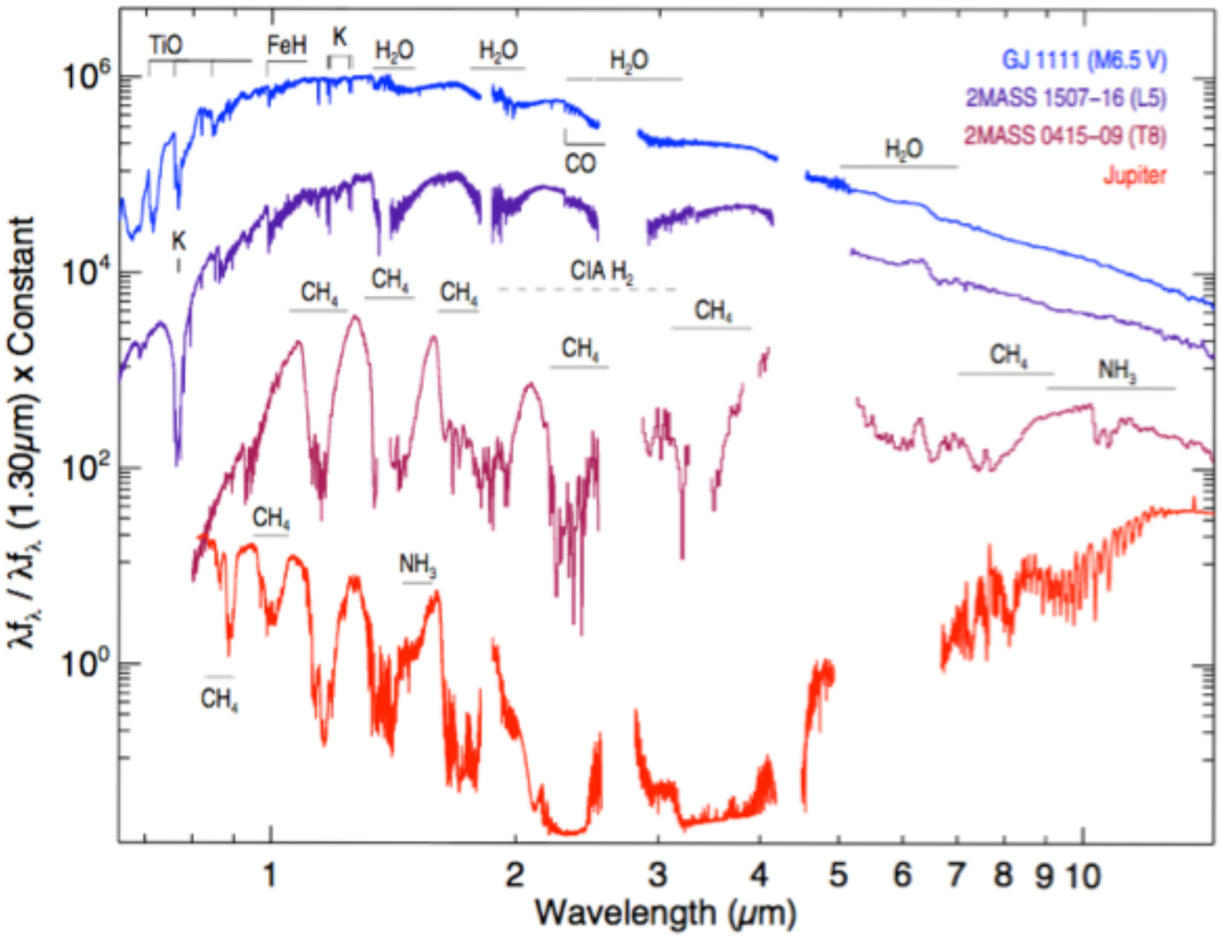
In the NIR, dust can lead to backwarming of the atmosphere, and alters the amount of H_2O and H_2.
Slight variations in the H_2O and H_2 opacities can lead to large differences.



Courtesy of A. Burgasser

Why they are interesting to study

- The lowest-mass brown dwarfs more closely resemble the gas giant planets than stars and therefore provide insight into the physical properties of extrasolar giant planets

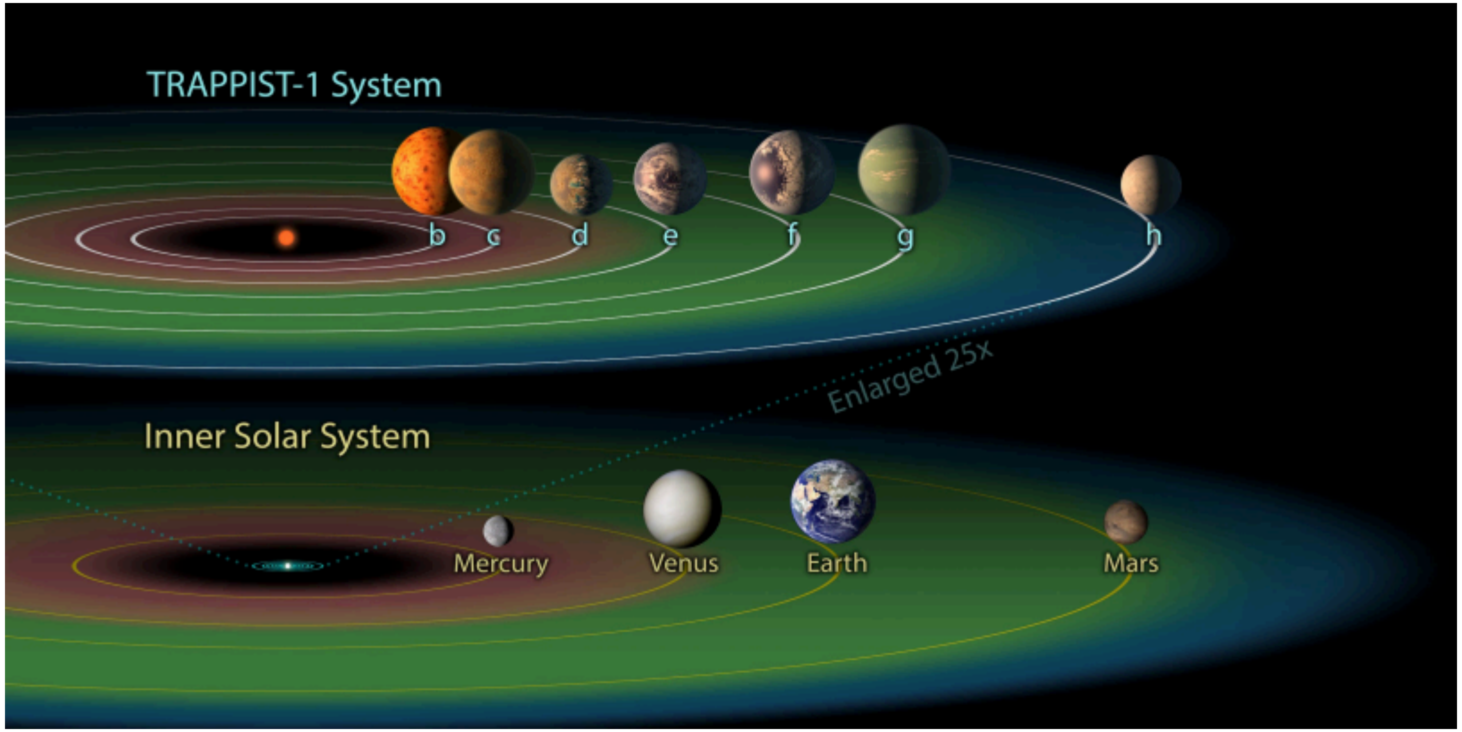


Marley & Leggett (2008)
data compiled by M. Cushing

Why they are interesting to study

- They host exoplanets, and are ideal targets for searches for potentially habitable terrestrial planets *(e.g. TRAPPIST-1, Gillon et al 2016, 2017; Proxima Cen, Anglada-Escude et al 2016; Ross 128, Bonfils et al 2018)*

→ galactic studies
→ stellar physics
→ exoplanetary studies



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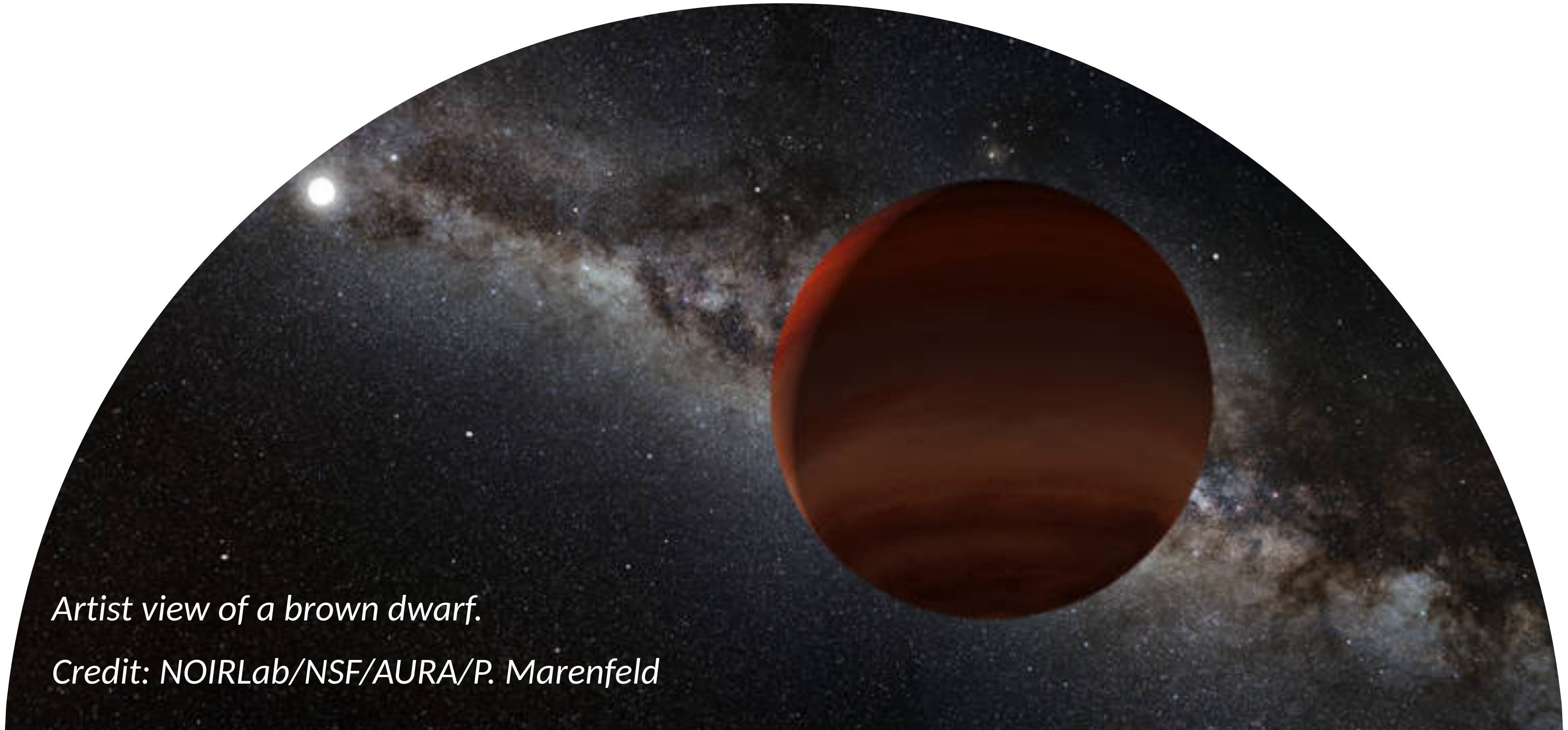


Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

Ultra-cool dwarfs in *Gaia*

Ultra-cool dwarfs (UCD) are ≥ M7 *(Kirkpatrick et al 1997)*
Their temperature is below ~2700 K *(e.g. Rajpurohit et al 2013)*
They are the link between stars and brown dwarfs as they span the transition from stellar to substellar masses.

The UCD census is incomplete even within 25 pc of the Sun, with 62% of M7-L5 catalogued *(Bardalez-Gagliuffi et al 2019)*

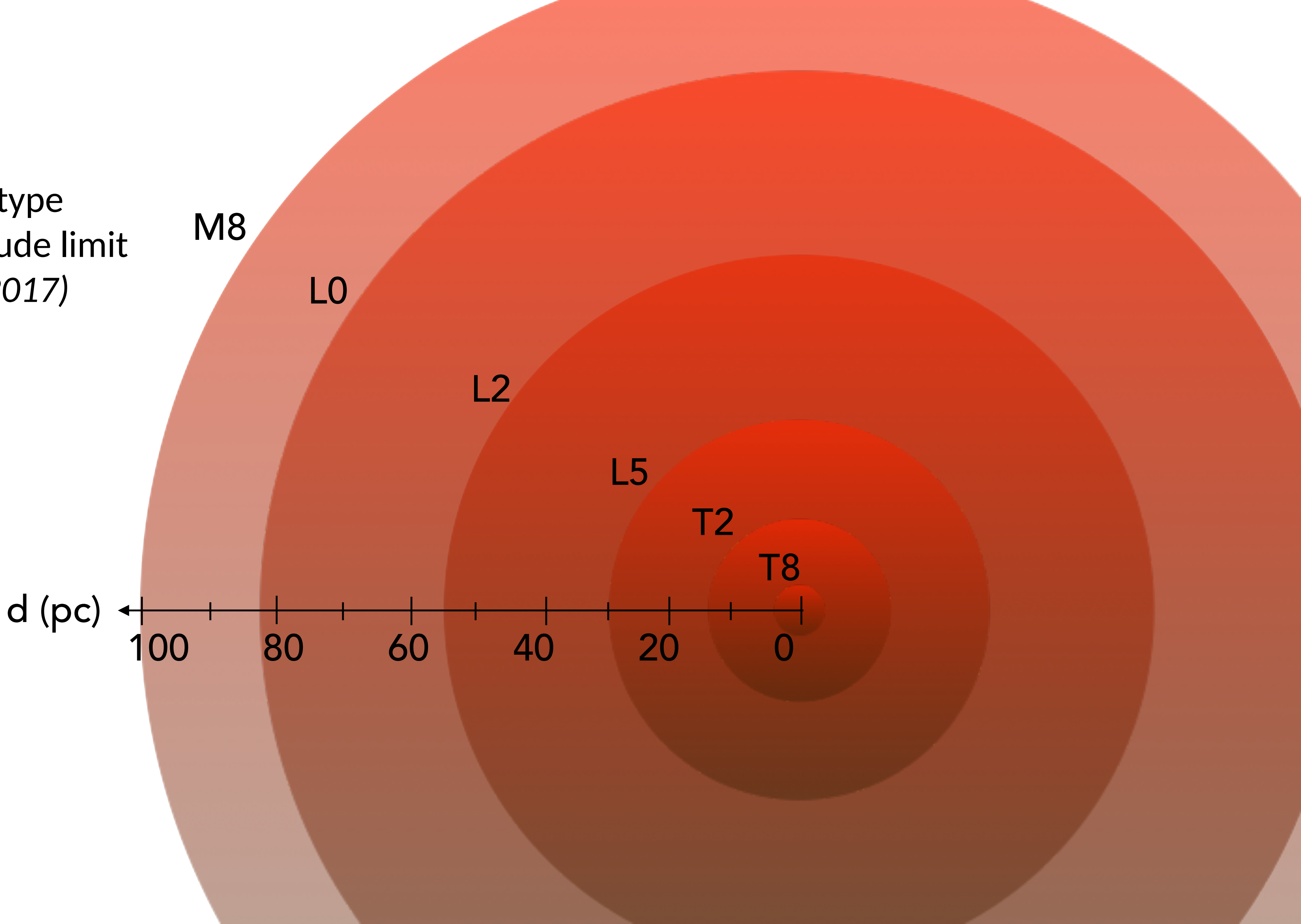
Gaia provides the means to uncover ultra-cool dwarfs through astrometric, rather than purely photometric, selection. They can be selected from their locus in the color absolute magnitude diagram.

Gaia holds the promise of a truly volume-complete sample.

Sarro et al 2013 estimated the expected end-of-mission number of UCDs in the *Gaia* archive: more than 40 000 objects, 600 objects between L0 and L5, 30 objects between L5 and T0, and 10 objects between T0 and T8.

Ultra-cool dwarfs in *Gaia*

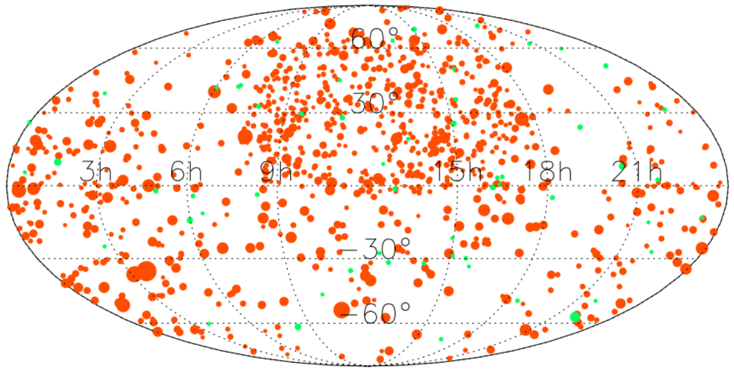
Distance limits vs spectral type assuming the *Gaia* magnitude limit G=20.7 *(from Smart et al 2017)*



Known objects

Ultra-cool dwarfs in *Gaia*

Gaia ultracool dwarf sample (GUCDS):
Catalogue of known L and T dwarfs spectroscopically confirmed.
1010 L + 58 T have a predicted magnitude $G_{est} \leq 21.5$
(Smart et al 2017)



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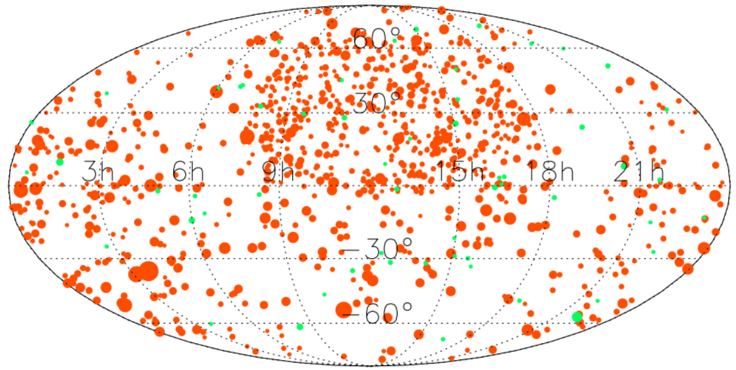
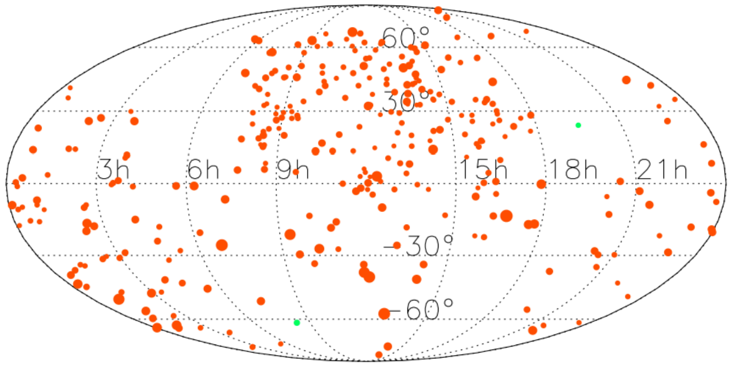
Xmatch of GUCDS with *Gaia* DR1:
319 L + 2 T (Smart et al 2017)
Used as a starting point py DPAC pipeline for parameter estimation purposes based on the Gaia RP spectra *(De Angeli et al 2023)*





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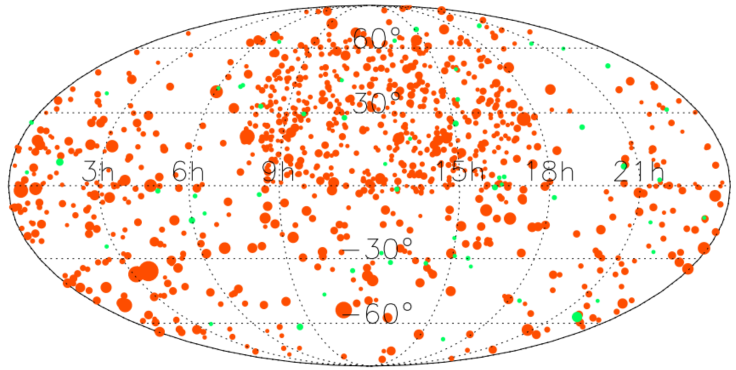

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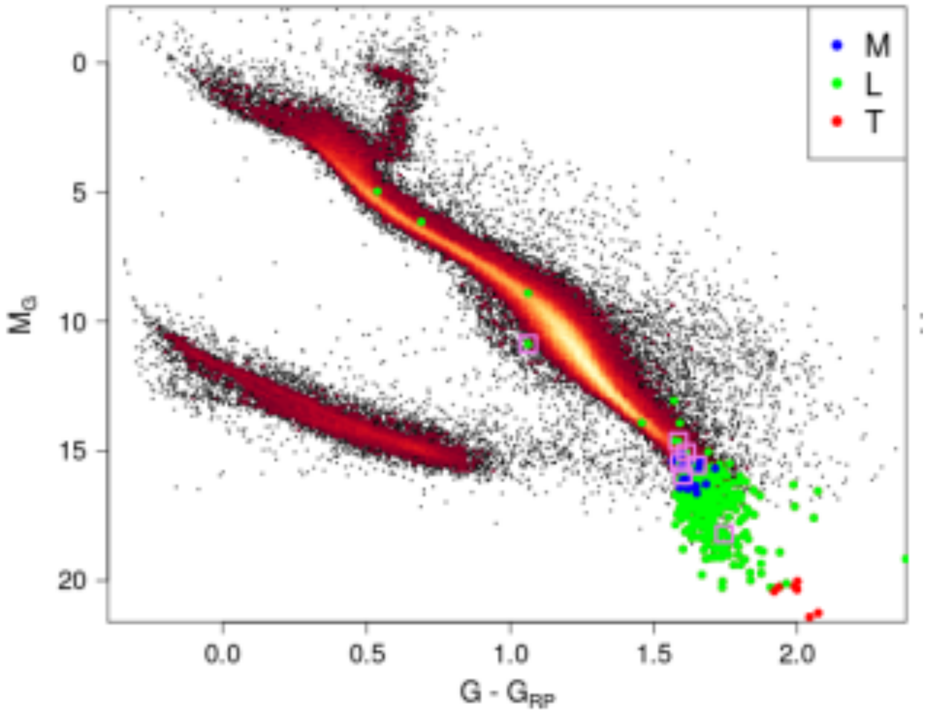

Xmatch of GUCDS with *Gaia* DR2:
21 M + 443 L + 7 T *(Gaia coll., Babusiaux et al 2018)*

Known objects

Ultra-cool dwarfs in *Gaia*

Gaia ultracool dwarf sample (GUCDS):
Catalogue of known L and T dwarfs spectroscopically confirmed.
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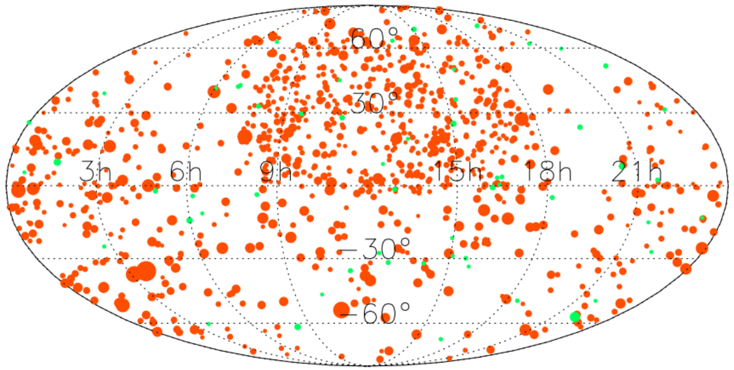
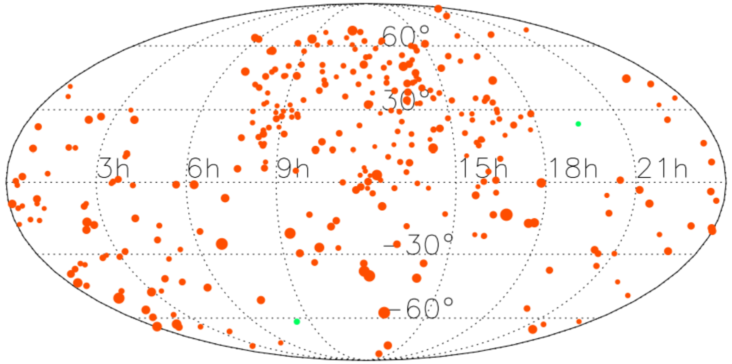
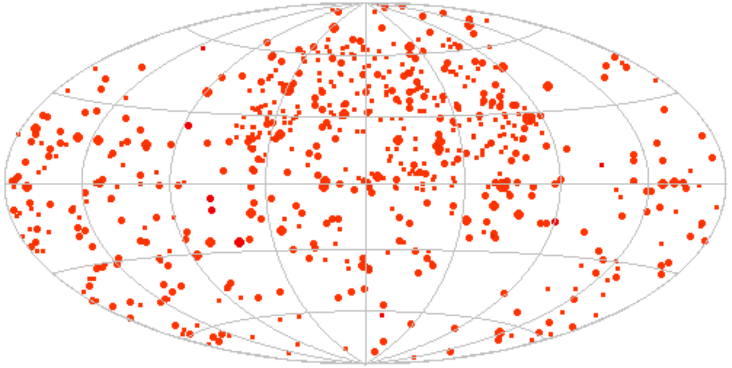
Xmatch of GUCDS with *Gaia* DR1:
319 L + 2 T (Smart et al 2017)
Used as a starting point py DPAC pipeline for parameter estimation purposes based on the Gaia RP spectra *(De Angeli et al 2023)*

Xmatch of GUCDS with *Gaia* DR2:
21 M + 443 L + 7 T *(Gaia coll., Babusiaux et al 2018)*
647 L + 16 T *(Reylé 2018)* -> 65%





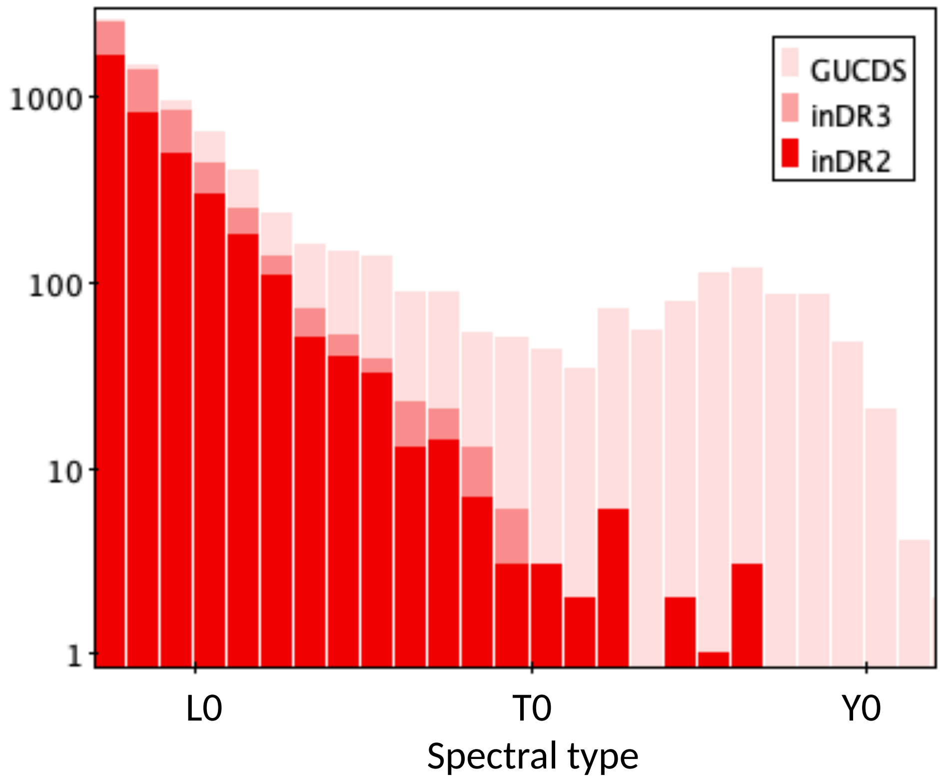


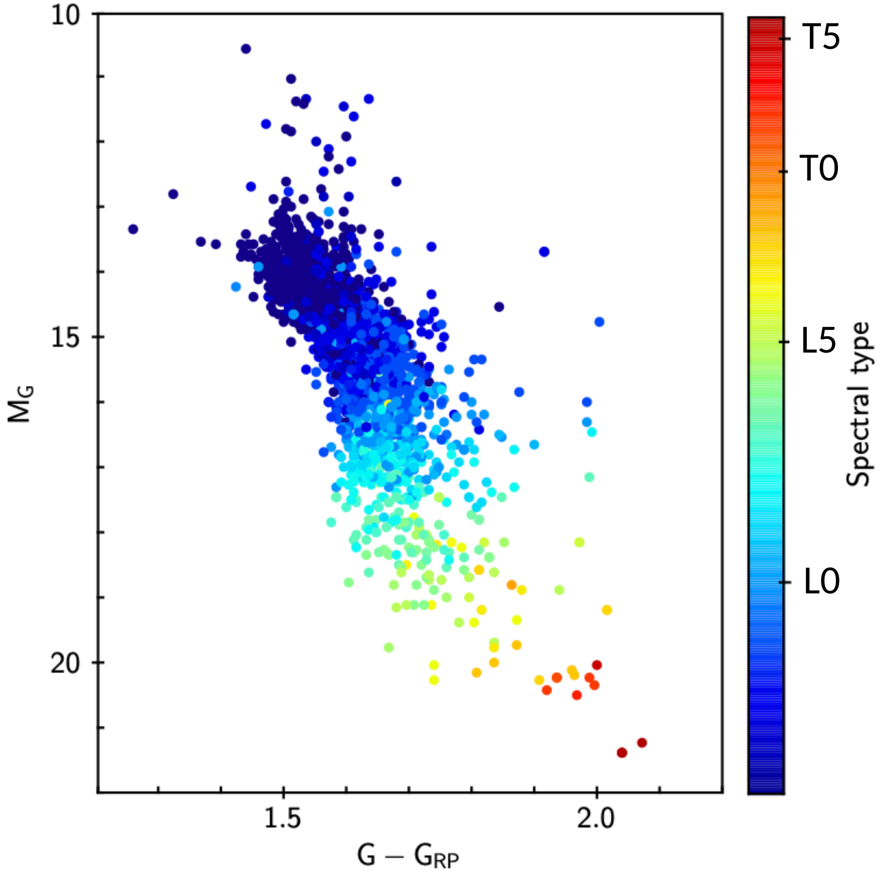
Known objects

Ultra-cool dwarfs in *Gaia*

Gaia DR2 :
3671 M7-M9 + 647 L + 16 T

Gaia DR3 :
4767 M7-M9 + 1061 L + 16 T





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Gaia DR2 :
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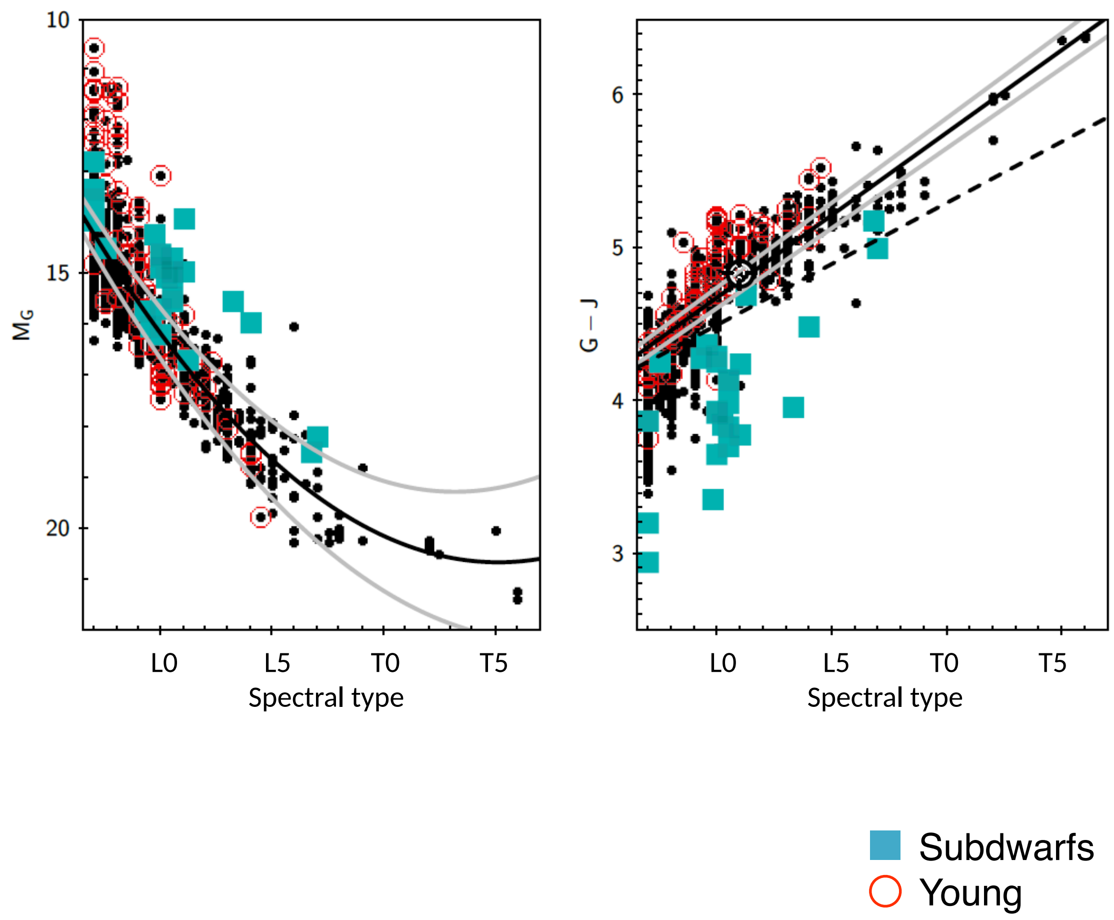
4767 M7-M9 + 1061 L + 16 T

Unprecedent sample, with distance estimate, to
- define absolute magnitude vs color, and vs spectral type relations



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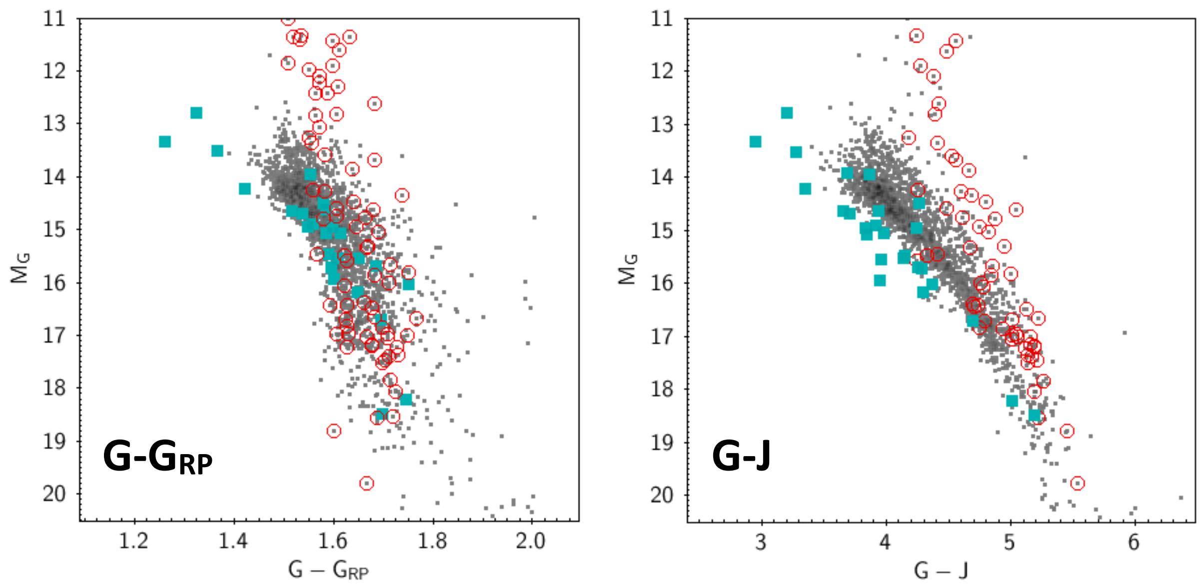
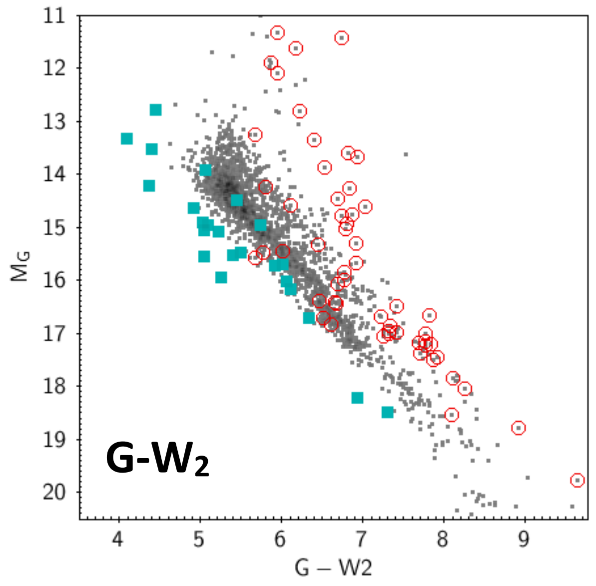
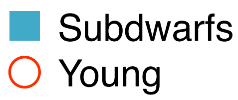
Unprecedent sample, with distance estimate, to

- compare with models





X-match with 2MASS and AllWISE from Marrese et al 2017



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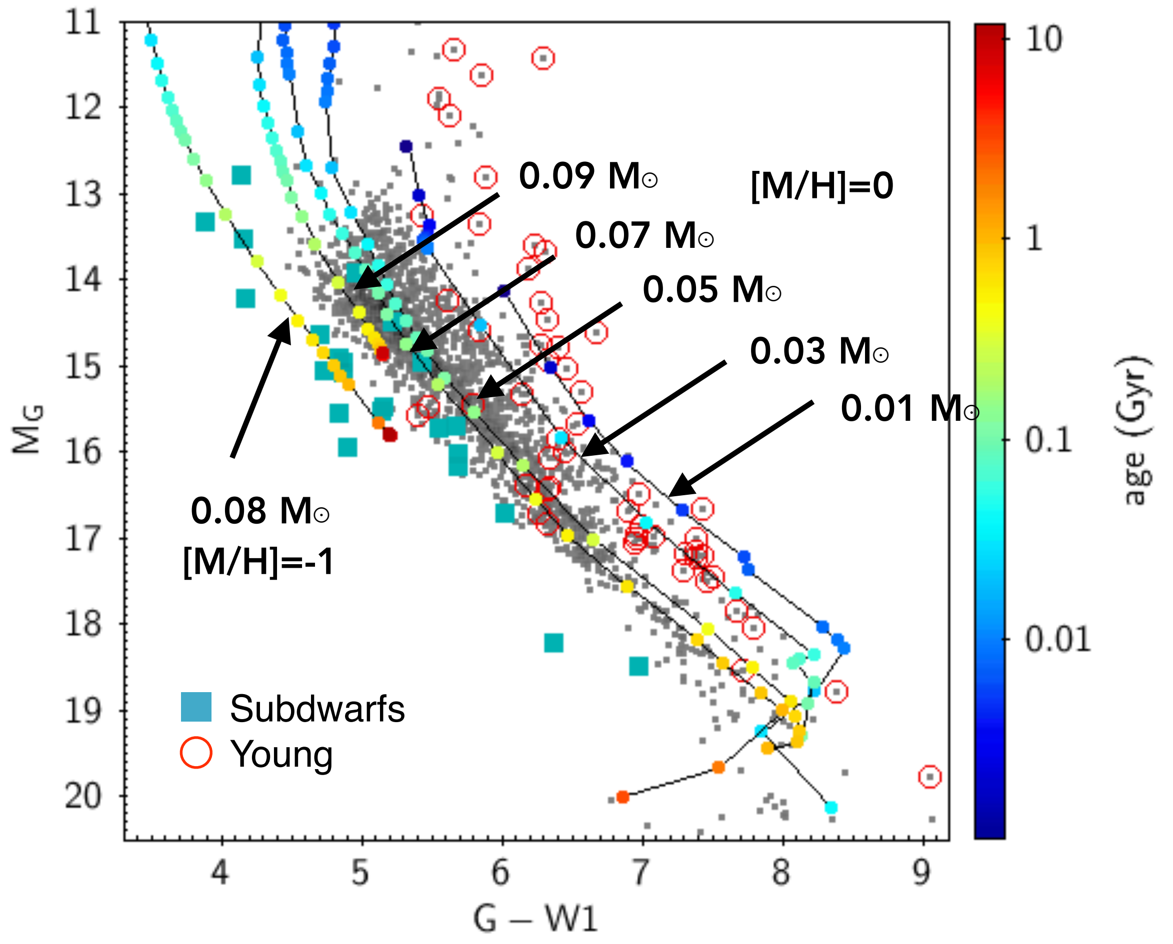
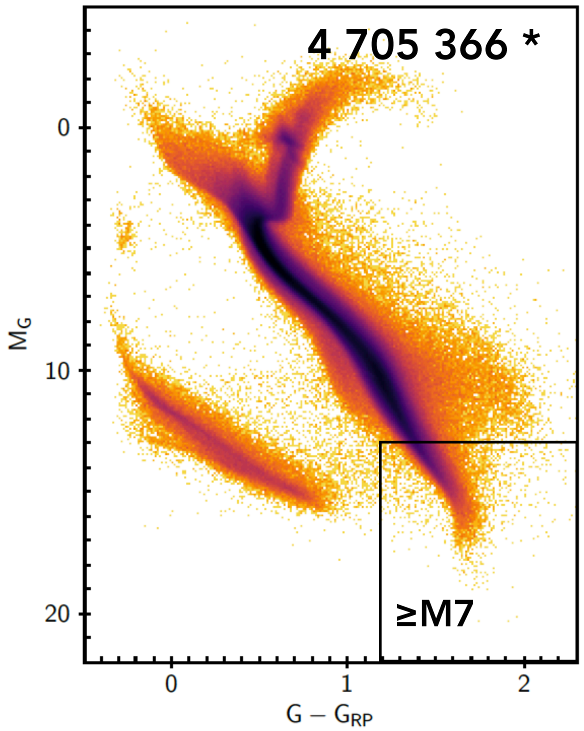


BT'Settl evolution models
(Allard et al 2013, Baraffe et al 2015)

New objects

Ultra-cool dwarfs in *Gaia*



- Selection of robust candidates from their excepted locus in the MG vs G-GRP diagram:

Gaia DR2 data filtered following *Gaia coll., Babusiaux et al 2018*

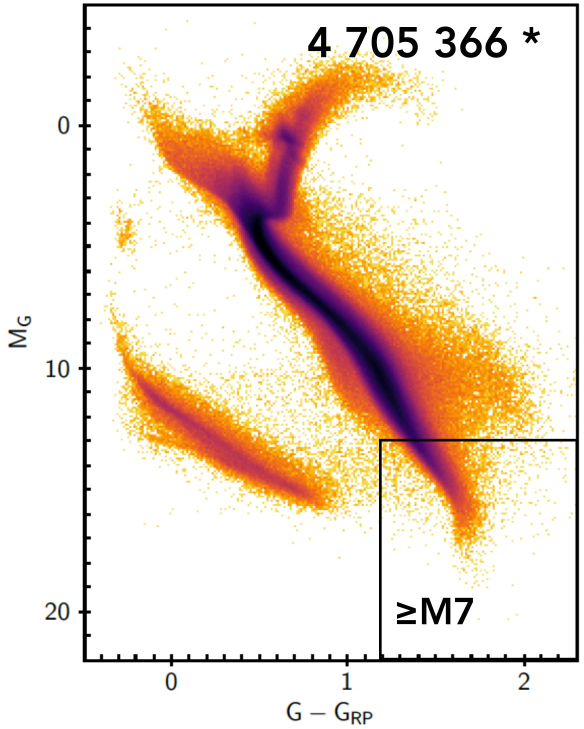
→ σ_{ϖ}<10%, σ_{MG}<0.22

→ σ_G<0.022, σ_{GRP}<0.054

→ E(B-V)<0.015 in *Capitanio et al 2017* 3D extinction map

New objects

Ultra-cool dwarfs in *Gaia*



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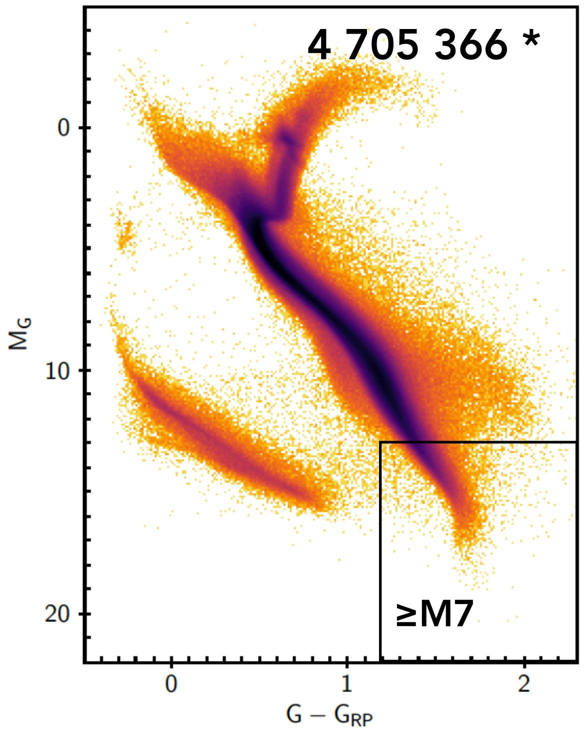
- Spurious candidates with strong RP/BP flux excess are removed *(Evans et al 2018, Arenou et al 2018)*

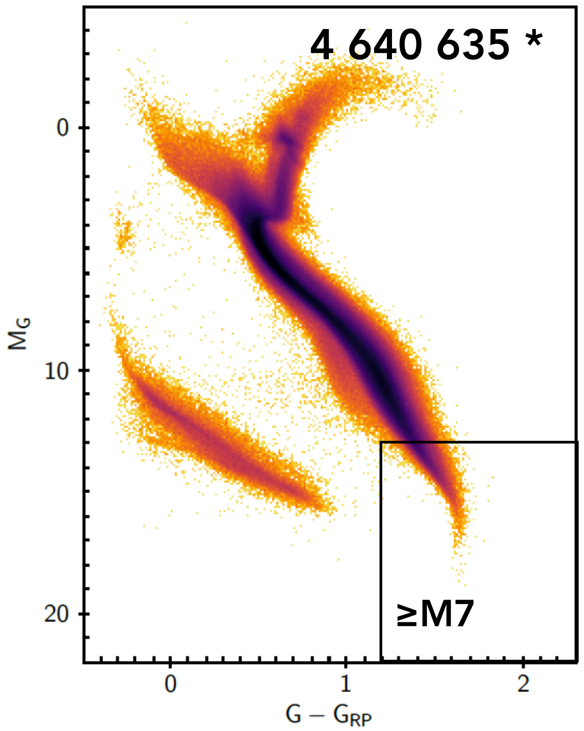
$$(I_{BP} + I_{RP})/I_G \geq 1.3 + 0.06 \times (G_{BP} - G_{RP})^2$$

New objects

Ultra-cool dwarfs in *Gaia*

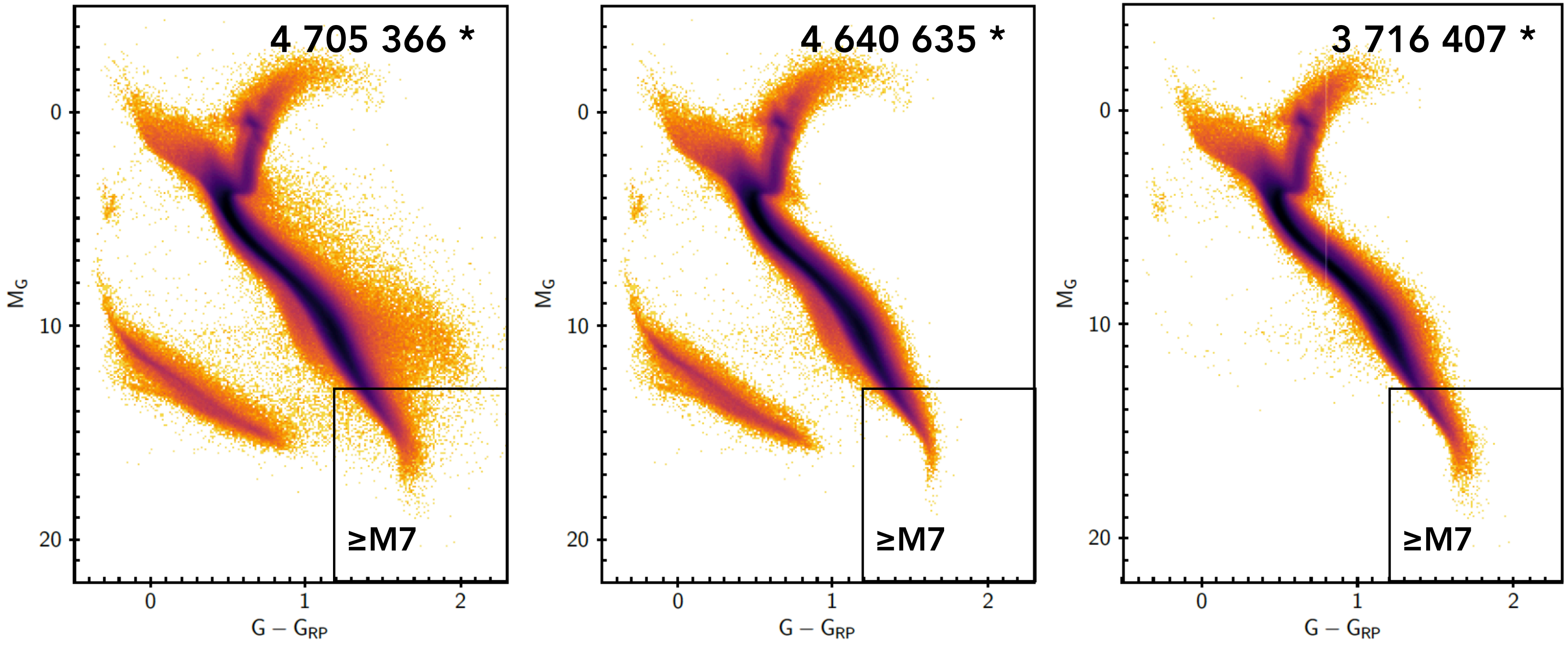
without … with the BP/RP color excess filter





New objects

Ultra-cool dwarfs in *Gaia*

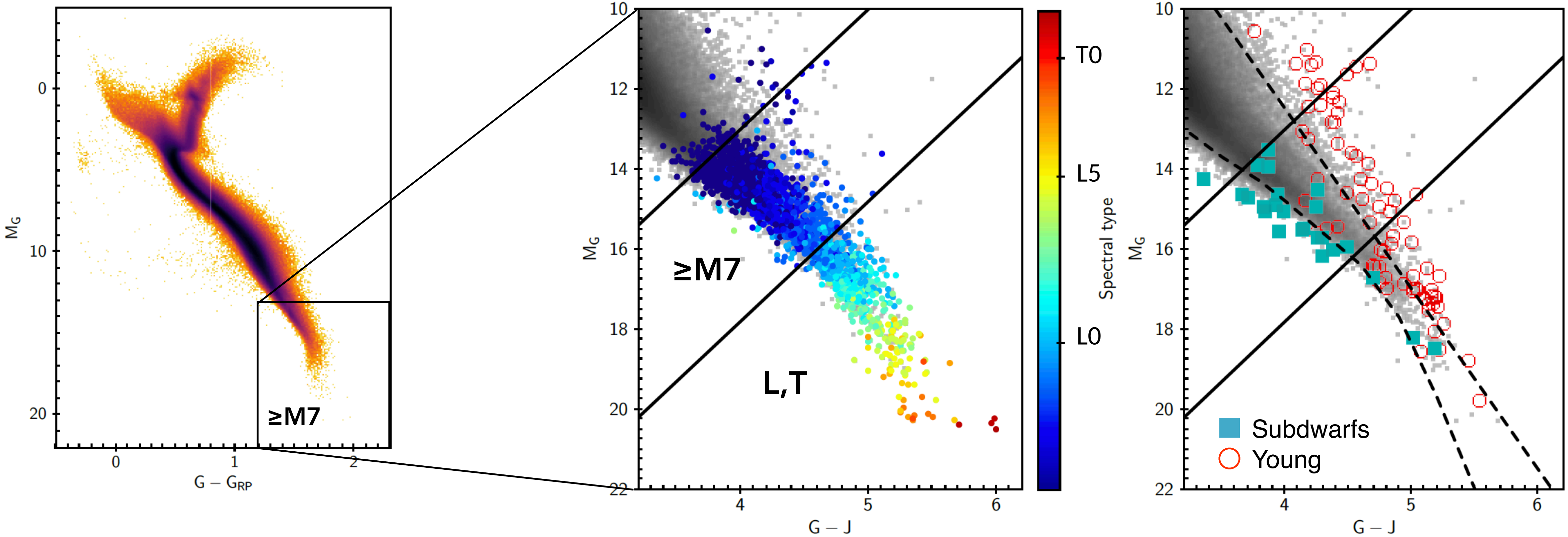


New empirical filter based on the 2MASS J mag *(Reylé, 2018)*

$$G - J \geq 1.42 \times (G - G_{RP})^2 - 0.94 \times (G - G_{RP}) + 1.55.$$

New objects

Ultra-cool dwarfs in *Gaia*

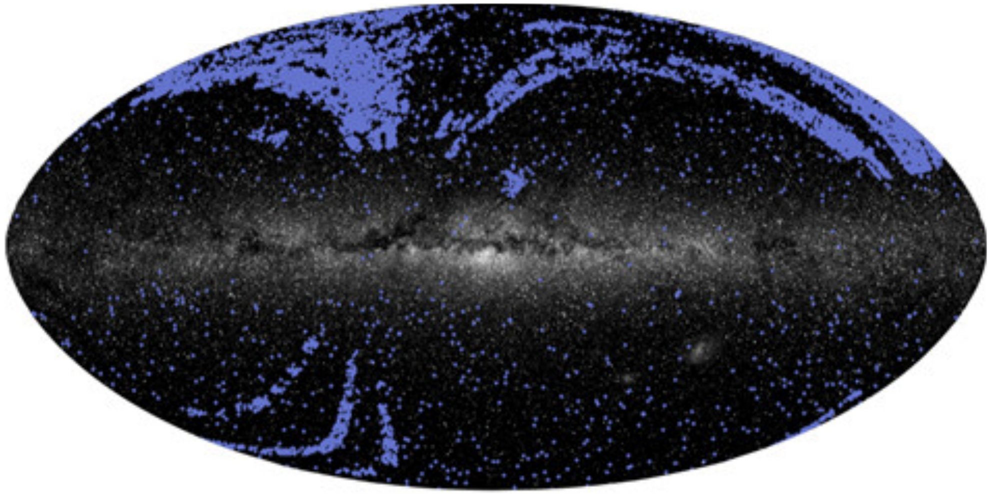


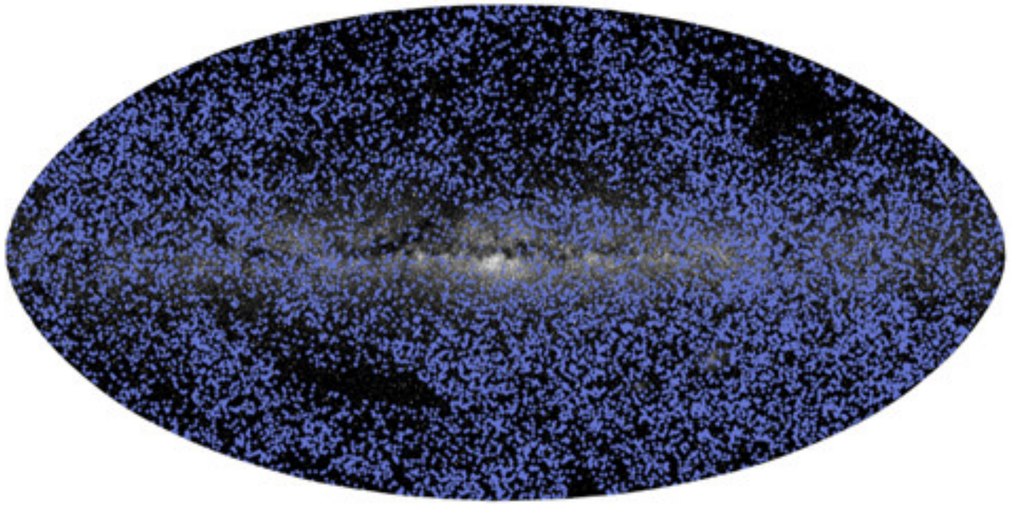
Selection in the HR diagram following the locus of the known UCD sample

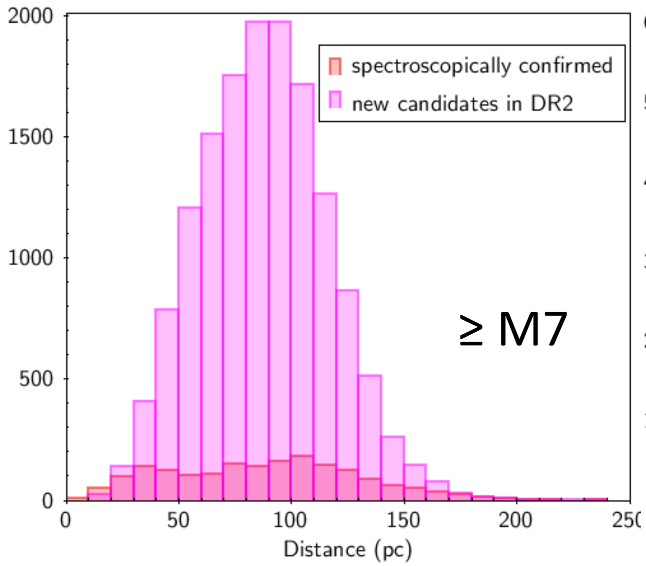
- New candidates: 14 176 ≥ M7 and 488 L (all earlier than L5)
- Young: 233 ≥ M7 and 70 L, subdwarf: 466 ≥ M7 and 17 L

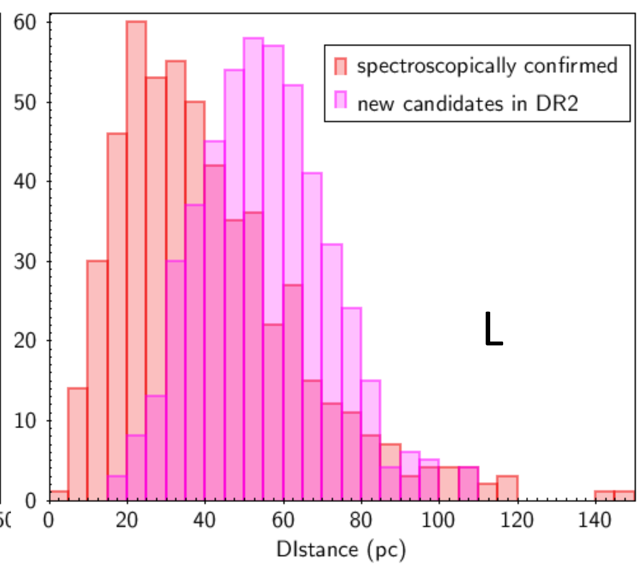
New objects

Ultra-cool dwarfs in *Gaia*







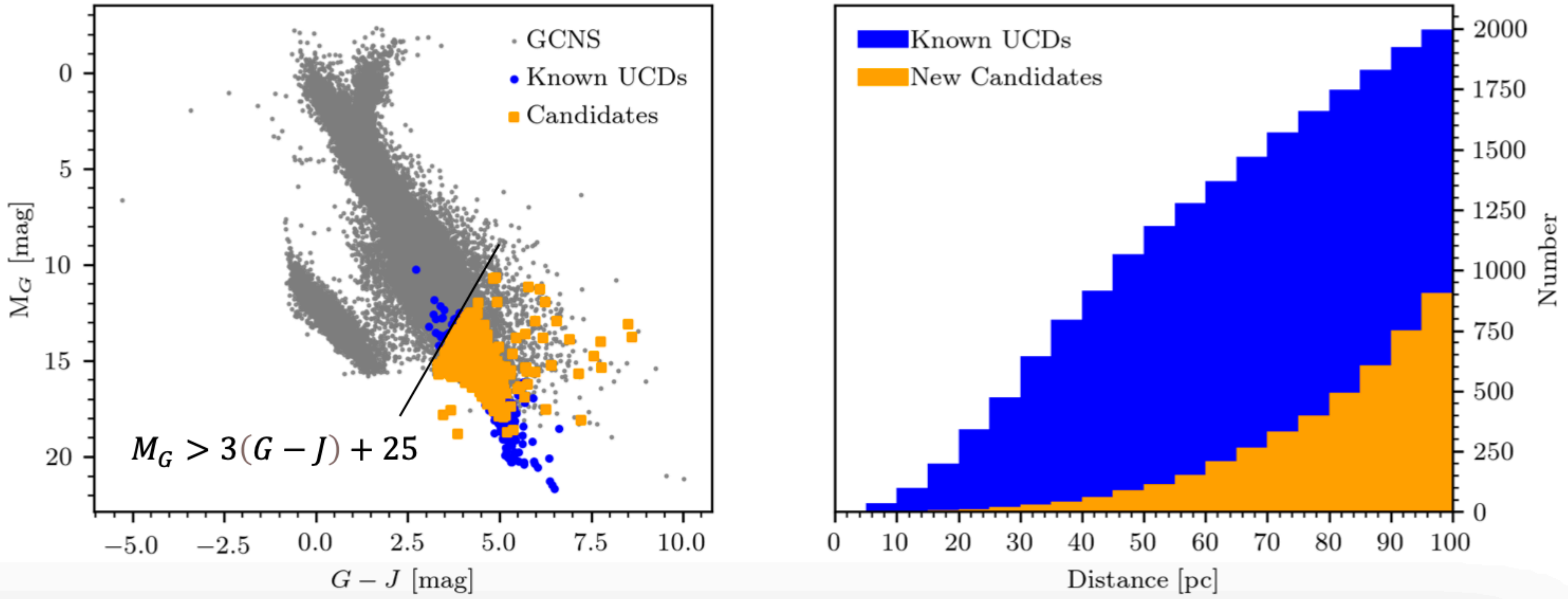


Up to d=30 pc:

160 ≥ M7, 218 L, 10 T	known in DR2
137 ≥ M7, 24 L	new candidates in DR2

New objects

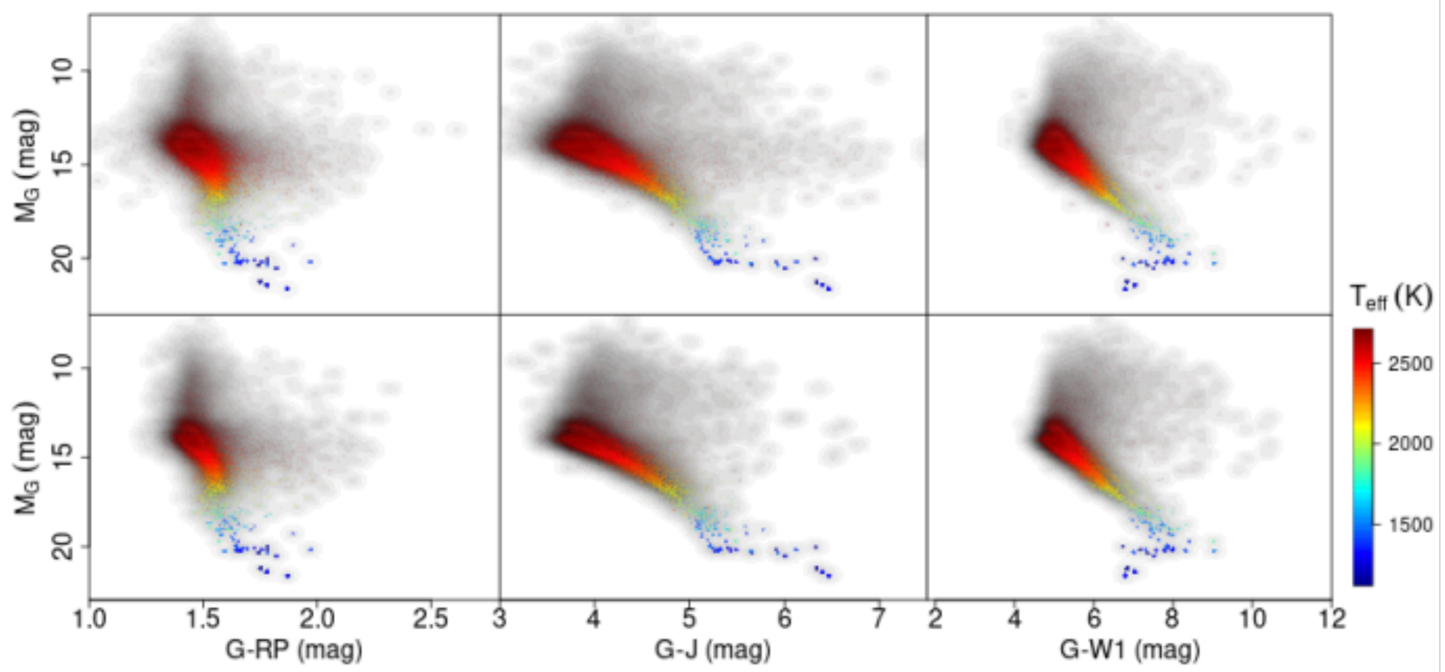
Ultra-cool dwarfs in *Gaia*

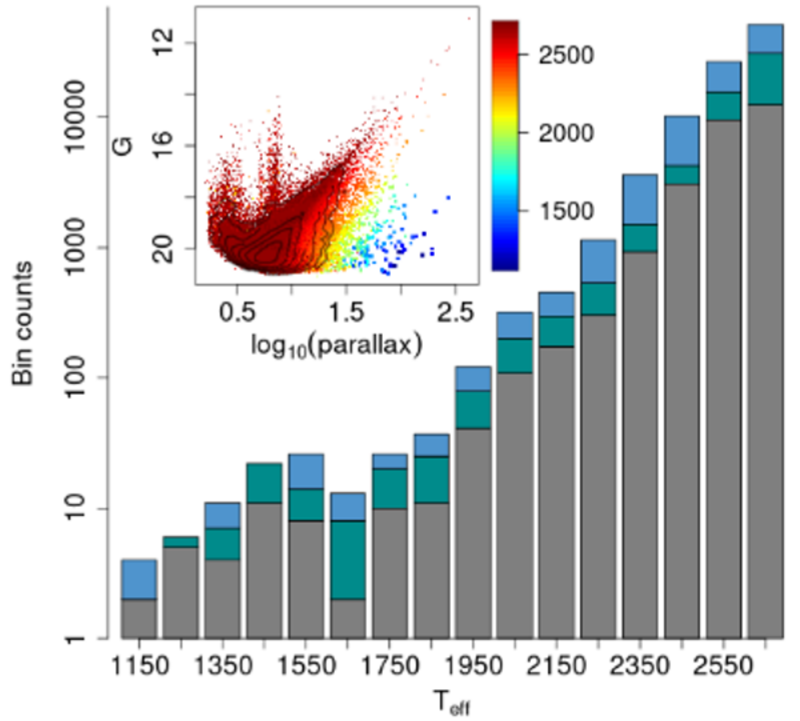


Gaia EDR3: the *Gaia* Catalogue of Nearby Stars (100 pc) contains 2879 additional candidates compared to Gaia DR2 *(Gaia coll., Smart et al 2021)*

New objects

Ultra-cool dwarfs in *Gaia*



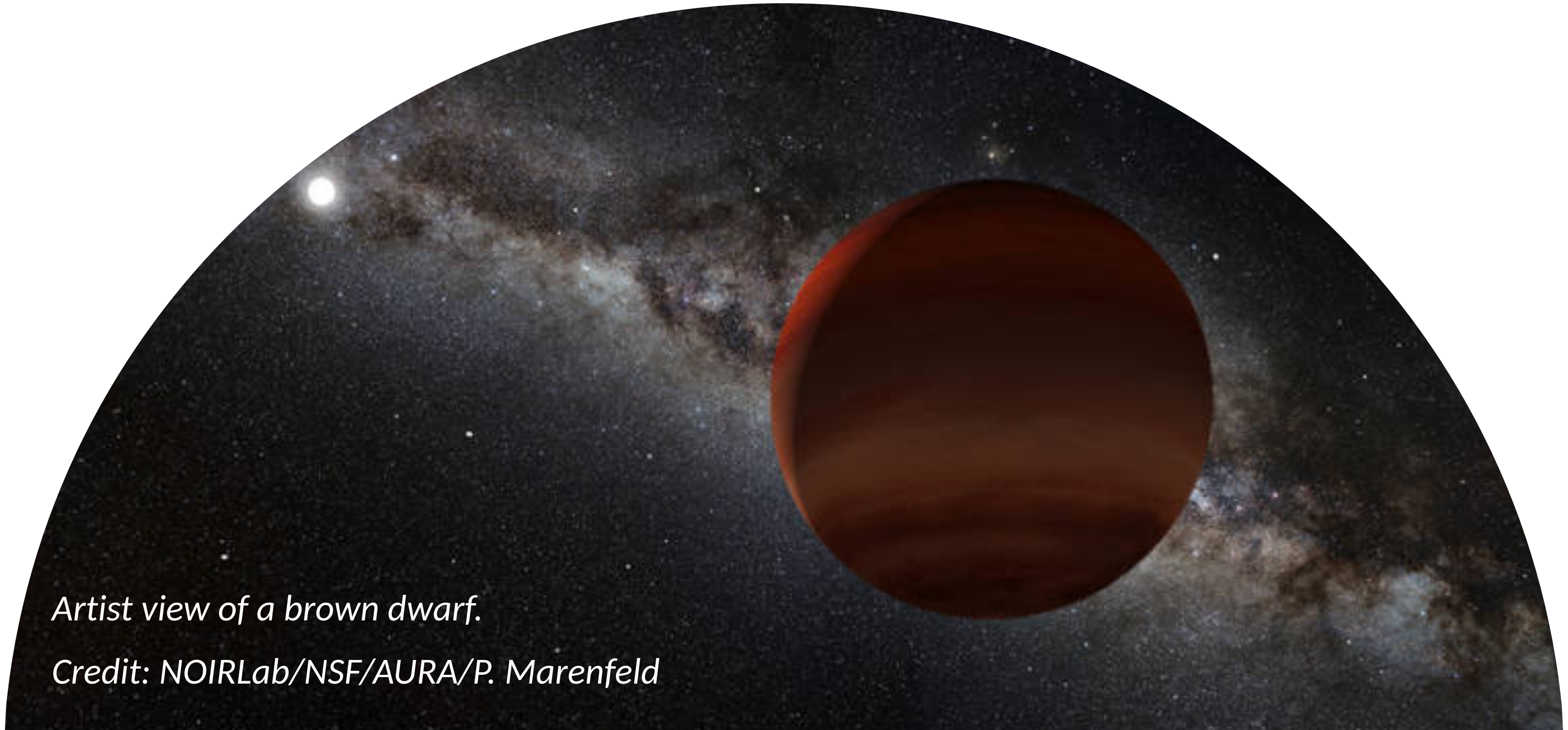


Gaia DR3 offers in addition the opportunity to use low-resolution spectra to refine and widen the selection. The ESP-UCD module infers T_{eff} from the shape of the RP spectrum.

94 158 UCD candidates with T_{eff} estimates below 2700 K *(Sarro et al, 2023)*

Topics for this lecture

- Low-mass stars and brown dwarfs
- Why are they interesting to study?
- Ultra-cool dwarfs in *Gaia*
- Characterisation of ultra-cool dwarfs
- Towards a complete local census



Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

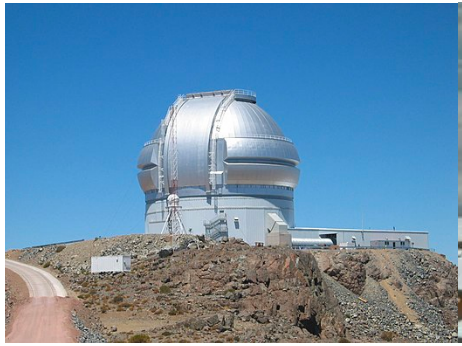
Characterisation of ultra-cool dwarfs

NIR spectroscopic follow-up

Several efforts have been made for spectroscopic follow-up in order to confirm their nature and further characterize them.

Use of multiple northern and southern 4m facilities Gemini, IRTF, Lick, Palomar, NTT, SOAR to observe:

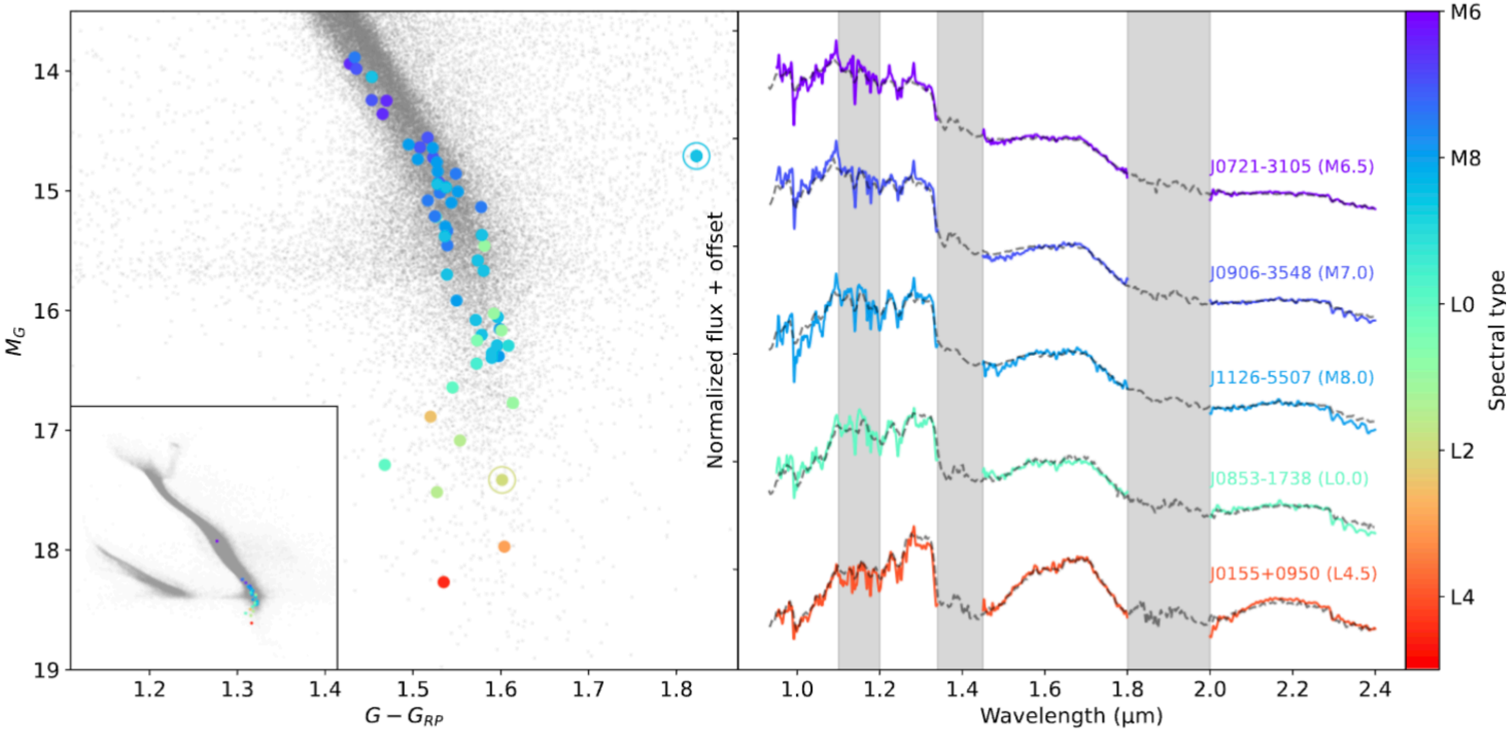
- The closest UCD (228 <30 pc, the completeness limit for *Gaia* at spectral type L5)
- Additionnal, more distant, L dwarfs (151 up to 60 pc)
- Few UCD in binary systems
- Few UCD with peculiar colours (possibly subdwarfs, or young, or unresolved binaries)



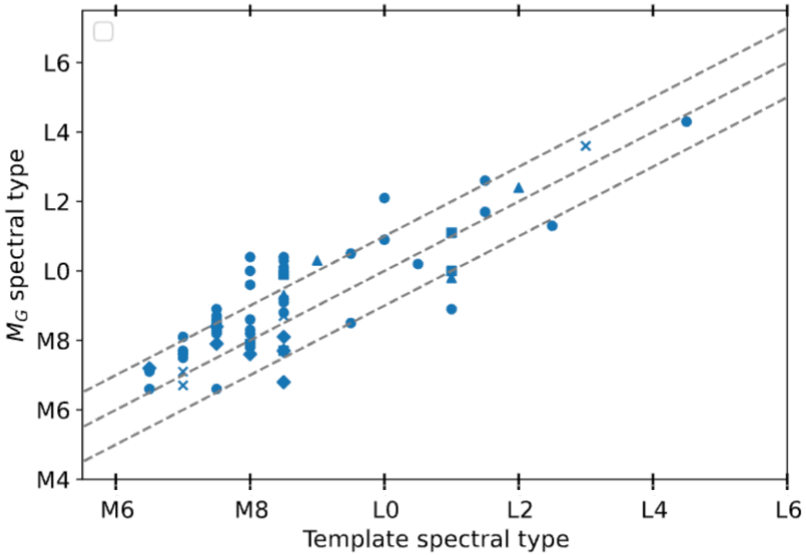

NIR spectroscopic follow-up

Characterisation of ultra-cool dwarfs

NIR spectroscopic follow-up of 60 UCD candidates with SOFI@NTT
Spectral type derived from template-matching using SPLAT *(SpeX Prism Library Analysis Toolkit, Burgasser & Splat Development Team 2017)*



Ravinet et al 2023



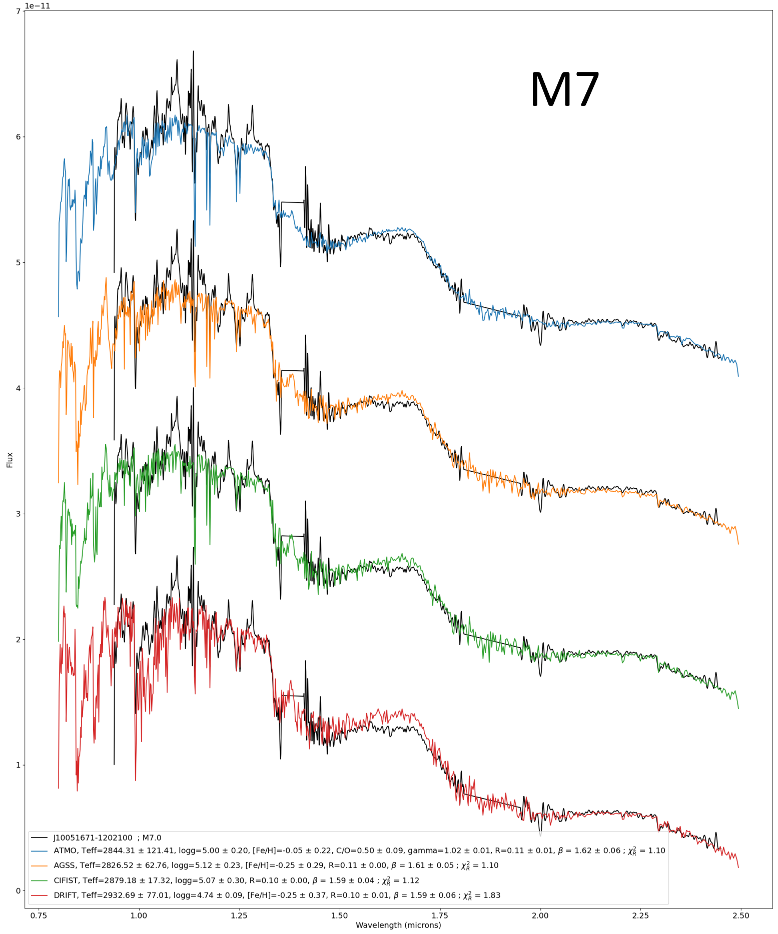
Standard deviation of 1 type.
The spectral typing from M_G (Reylé 2018) gives correct results.

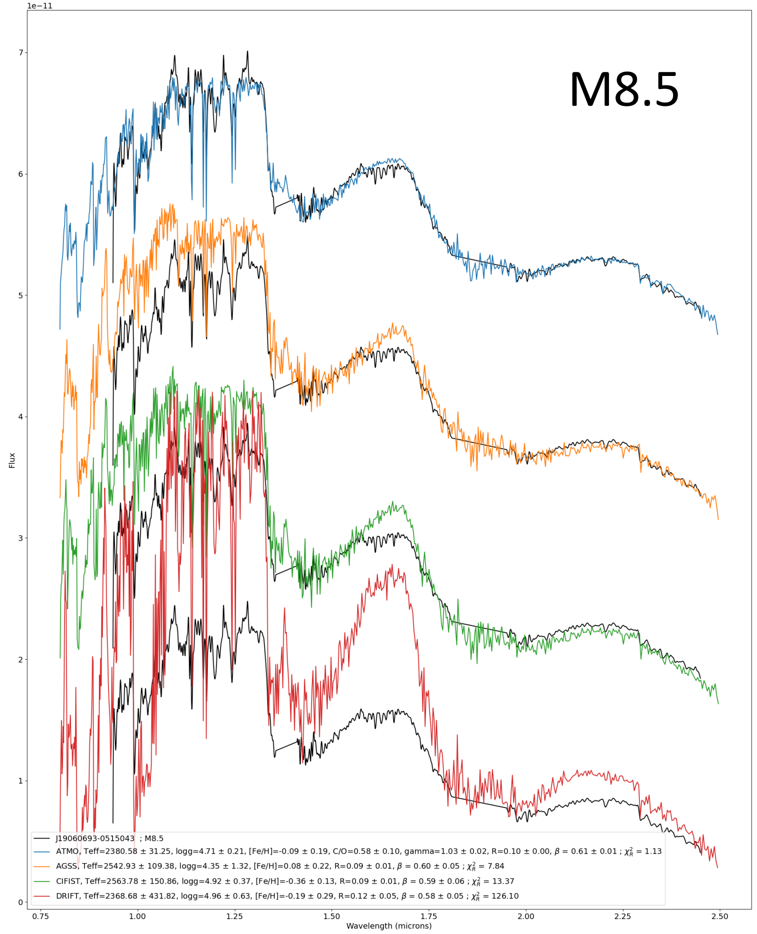
Characterisation of ultra-cool dwarfs

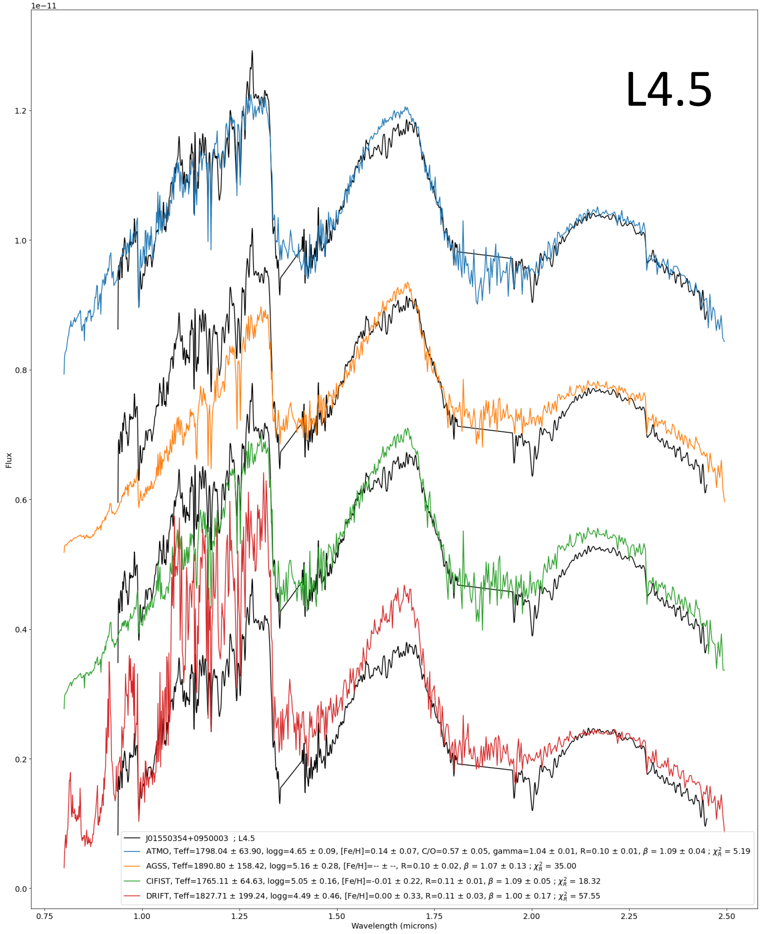
NIR spectroscopic follow-up

Ravinet et al in prep

NIR spectroscopic follow-up of 60 UCD candidates with SOFI@NTT
Comparison with synthetic spectra computed from atmospheric models DRIFT *(Witte et al 2011)* BT-Settl-CIFIST, BT-Settl-AGSS *(Allard 2014)*, ATMO *(Phillips et al 2020)*



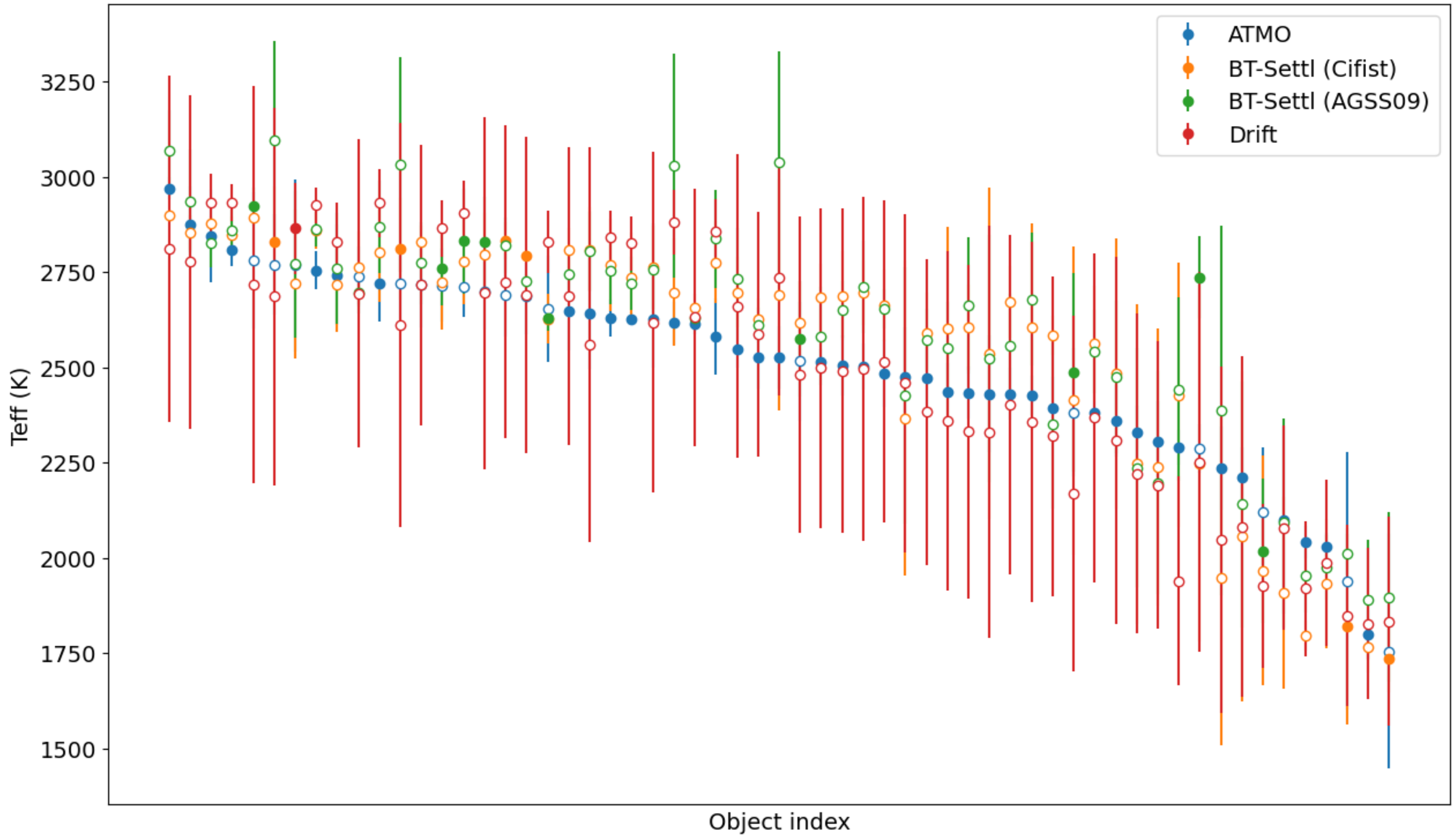




NIR spectroscopic follow-up

Characterisation of ultra-cool dwarfs

NIR spectroscopic follow-up of 60 UCD candidates with SOFI@NTT



Ravinet et al in prep

Characterisation of ultra-cool dwarfs

Astrophysical parameters

Gaia DR3 provides astrophysical parameters *(Creevey et al 2023)*

Gaia coll. Creevey et al 2023: The golden sample: an homogeneous sample of stars with high-quality astrophysical parameters by exploiting *Gaia* DR3

Contains ~20 000 UCDs

A&A 674, A39 (2023)
https://doi.org/10.1051/0004-6361/202243800

Gaia Data Release 3

Astronomy & Astrophysics
Special issue

Gaia Data Release 3

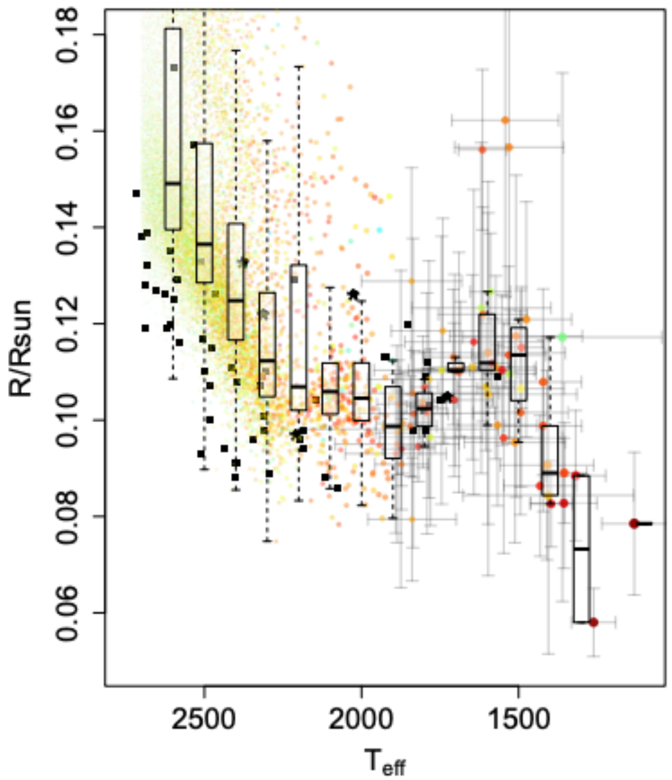
A golden sample of astrophysical parameters[⋆,⋆⋆]

Gaia Collaboration: O. L. Creevey[1,⋆⋆⋆], L. M. Sarro[2], A. Lobel[3], E. Pancino[4,5], R. Andrae[6], R. L. Smart[7], G. Clementini[8], U. Heiter[9], A. J. Korn[9], M. Fouesneau[6], Y. Frémat[3], F. De Angeli[10], A. Vallenari[11], D. L. Harrison[10,12], F. Thévenin[1], C. Reylé[13], R. Sordo[11], A. Garofalo[8], A. G. A. Brown[14], L. Eyer[15], T. Prusti[16], J. H. J. de Bruijne[16], F. Arenou[17], C. Babusiaux[18,17], M. Biermann[19], C. Ducourant[20],

Astrophysical parameters

Characterisation of ultra-cool dwarfs

T_{eff} from the ESP-UCD module
Radius from FLAME module



Black symbols from *Dieterich et al 2014*: sample of 63 M6 to L4 dwarfs with parallaxes, L_{bol} and T_{eff} determined from VRI JHK_s $W_1W_2W_3$ photometry and BT-Settl atmosphere models

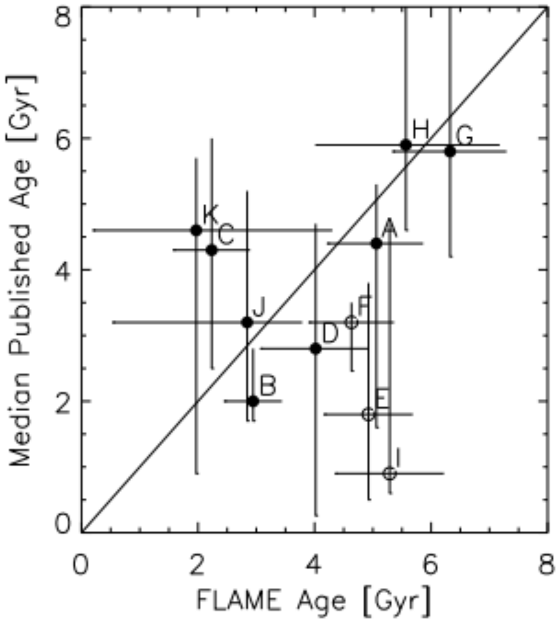
Astrophysical parameters

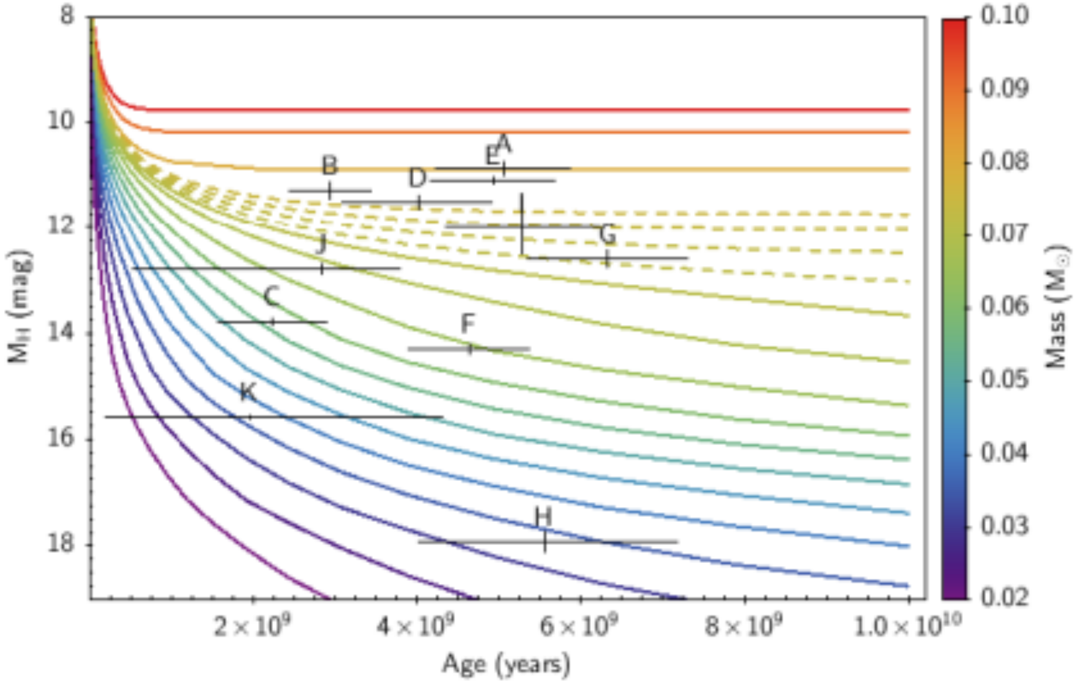
Characterisation of ultra-cool dwarfs

Unseen UCD-companions in the golden sample

Constrain the characteristics of faint UCDs that are beyond the mission magnitude limit but are in binary systems with brighter objects that are observed by *Gaia*.

→ the UCD has the same chemical composition, age, distance, and, after allowing for orbital motion, proper motions.





Wide binaries

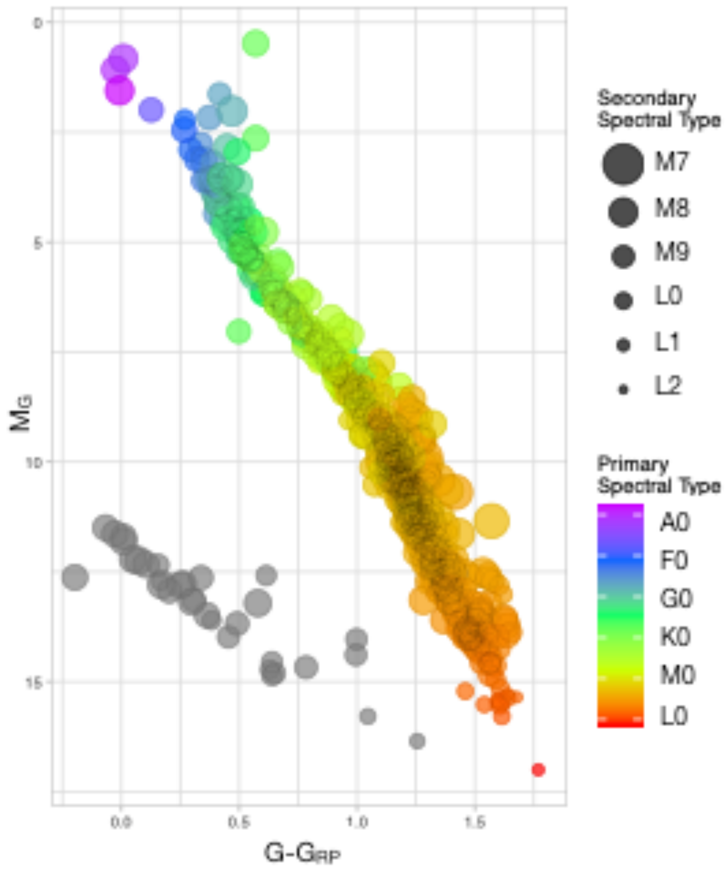
Characterisation of ultra-cool dwarfs

Multiplicity with *Gaia* can determined from distance, angular separation and proper motion measurements *(see eg Hwang et al. 2020; El-Badry & Rix 2018, Hartman & Lépine 2020, Gaia coll. Smart et al 2021, Sarro et al 2023)*.

$$\rho < 100\varpi$$
$$\Delta\varpi < \max[1.0, 3\sigma_{\varpi}]$$
$$\Delta\mu < 0.1\mu$$
$$\Delta\theta < 15^{\circ}$$

→ ρ query radius, equivalent to a maximum projected separation of 100 000 AU, conservative upper limit according to *Caballero (2009)*

Discovery of thousands of UCDs in binary systems
useful tools for testing stellar evolutionary models,
can be used as calibrators for age and metallicity relations.
See eg *Marocco et al 2020*: spectroscopic characterisation of L+L wide binaries



Reylé, Gimenez Sanchez, Lagarde 2021

Characterisation of ultra-cool dwarfs

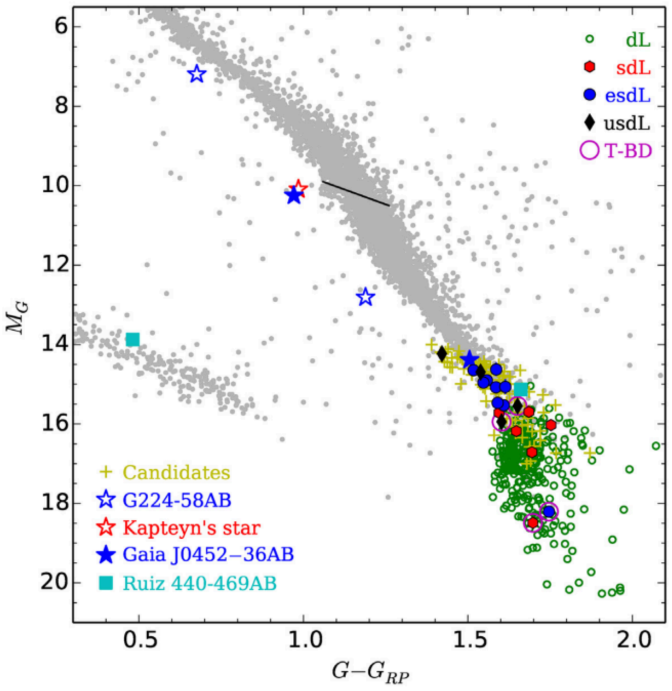
Wide binaries

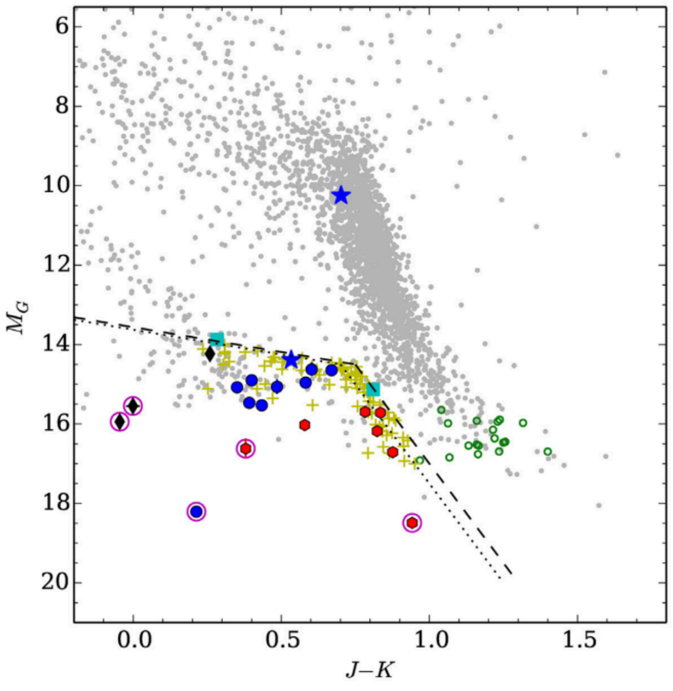
Zhang et al 2021, see also González-Payo 2022

- Selection of low-metallicity L dwarfs (subdwarfs) from their locus in optical and NIR colour-colour diagrams
- Confirmation with spectroscopic follow-up and use of Gaia to find companions from common position, parallax, proper motion

Gaia J0452-36AB
Kinematics compatible with halo
[Fe/H] ≈−1.4
T_{eff} ~ 3550 + 2600 K
esdM1+esdL0
projected separation of 15 828 AU

How such old wide systems survive?



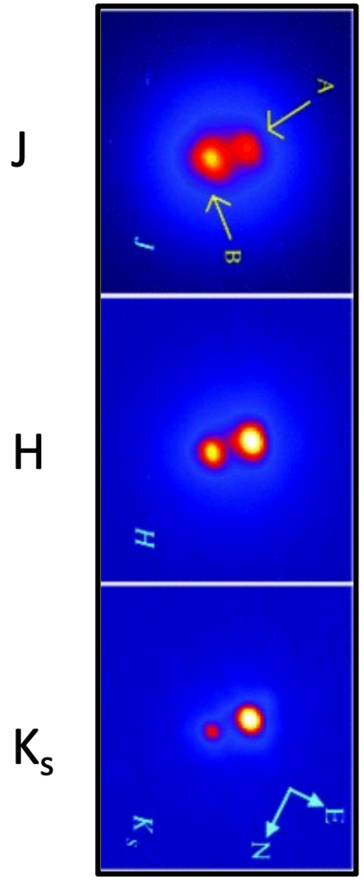


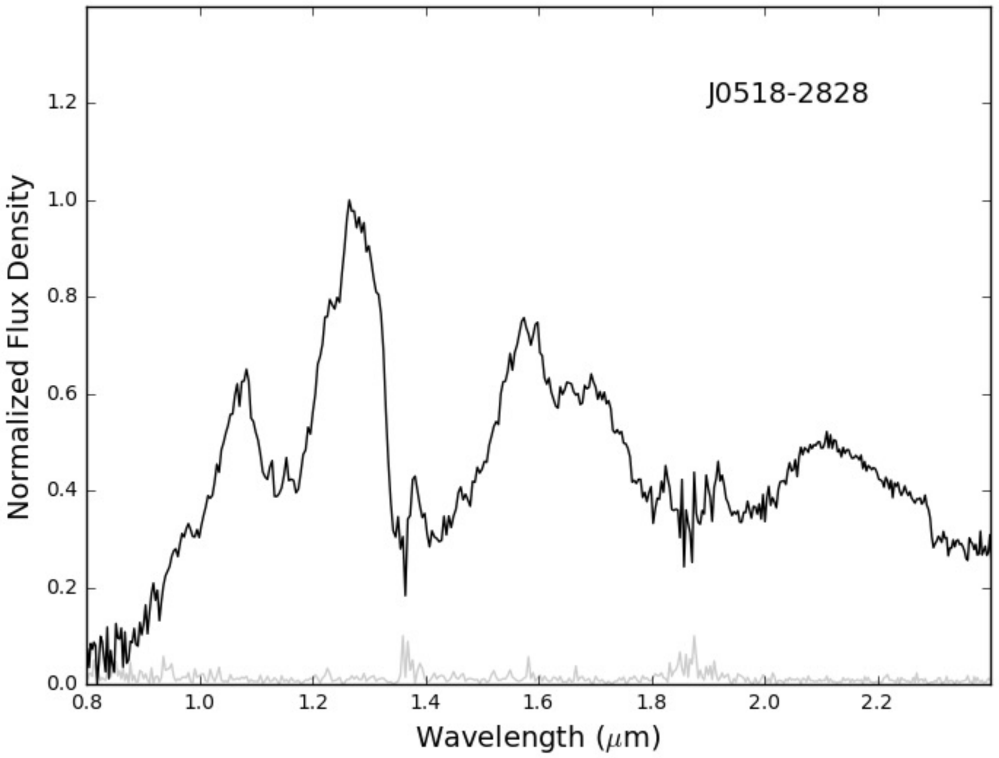
Characterisation of ultra-cool dwarfs

Spectral binaries

« Flux-reversal » binaries: binaries whose component straddle the L/T transition show a brighter secondary at 1 µm.

2M 1404-3159





Looper et al. (2008); Burgasser et al. (2010)

Characterisation of ultra-cool dwarfs

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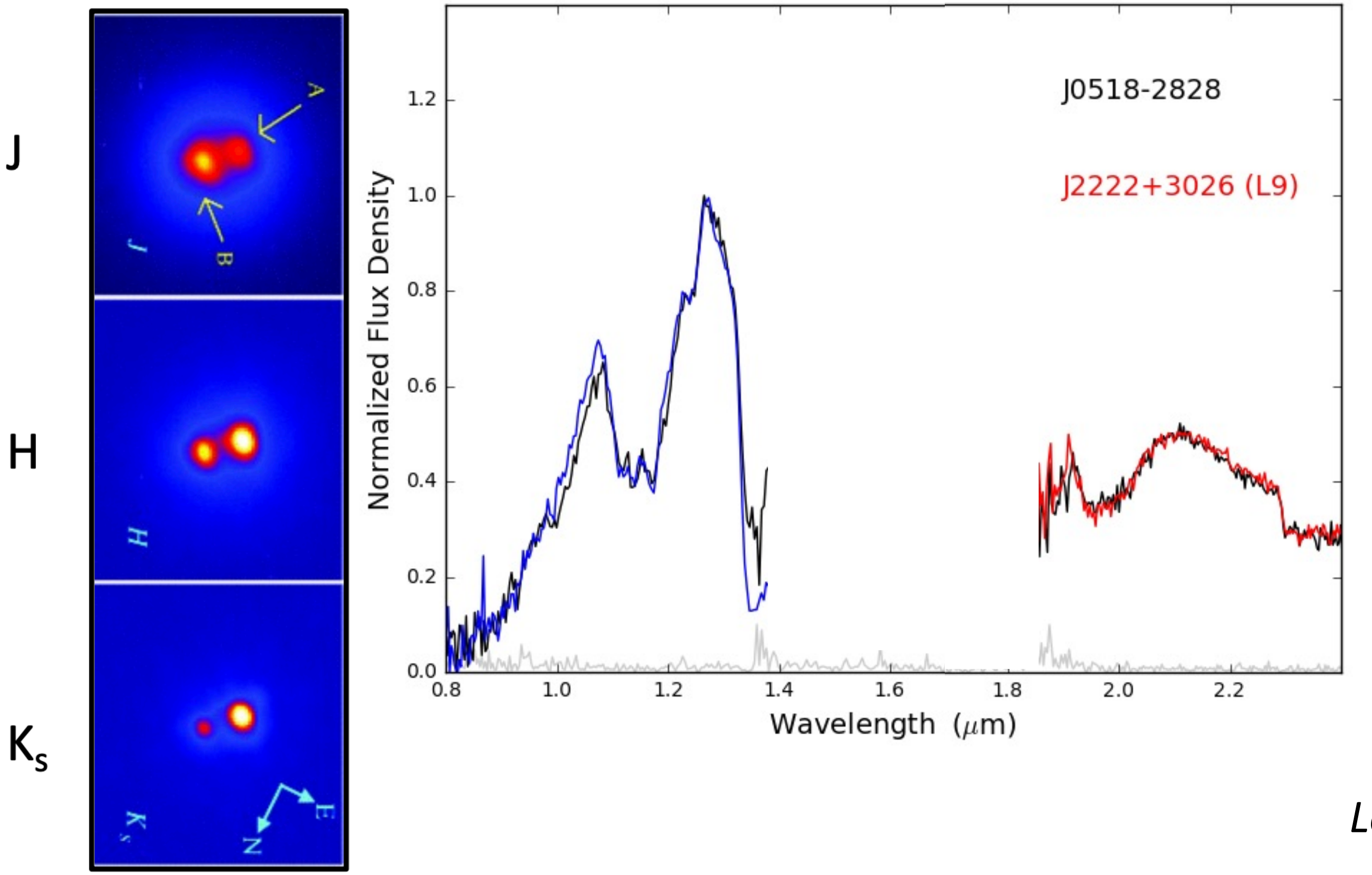

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Characterisation of ultra-cool dwarfs

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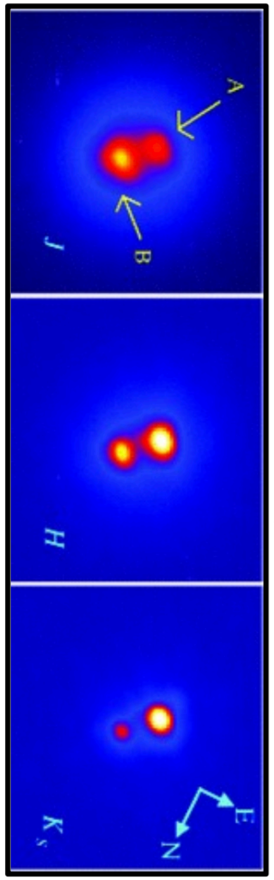
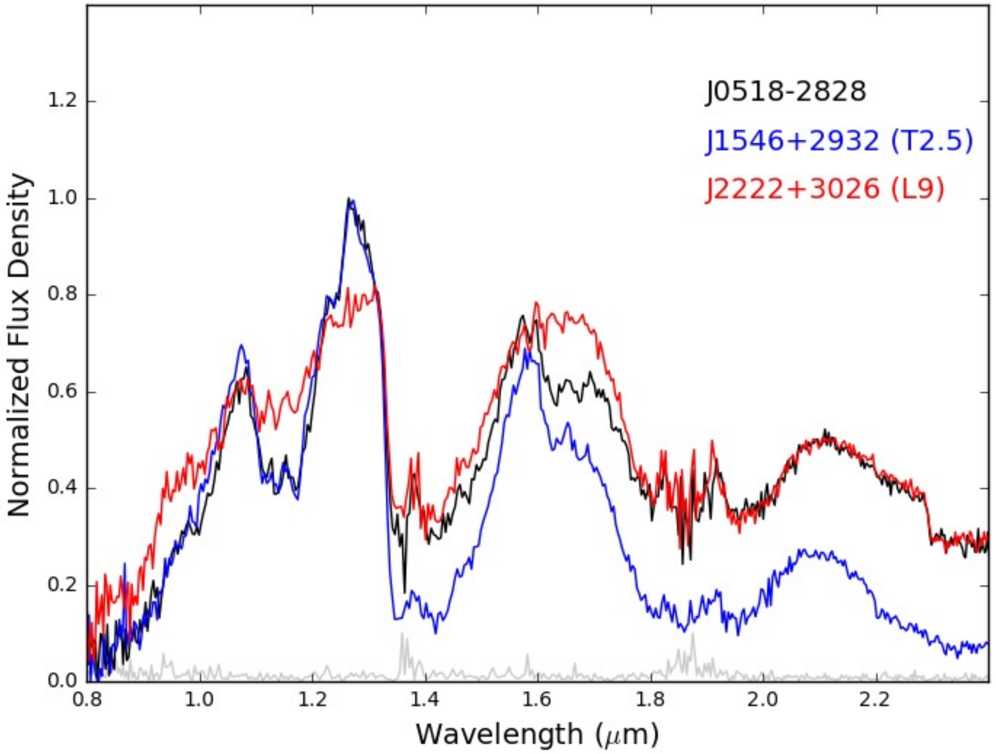
2M 1404-3159

J

H

K_s





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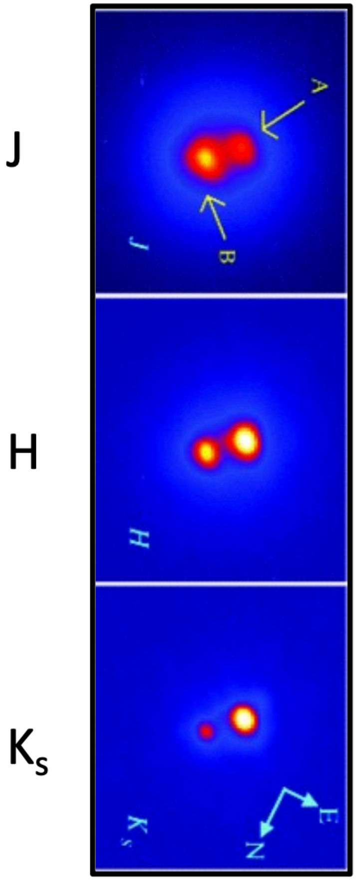

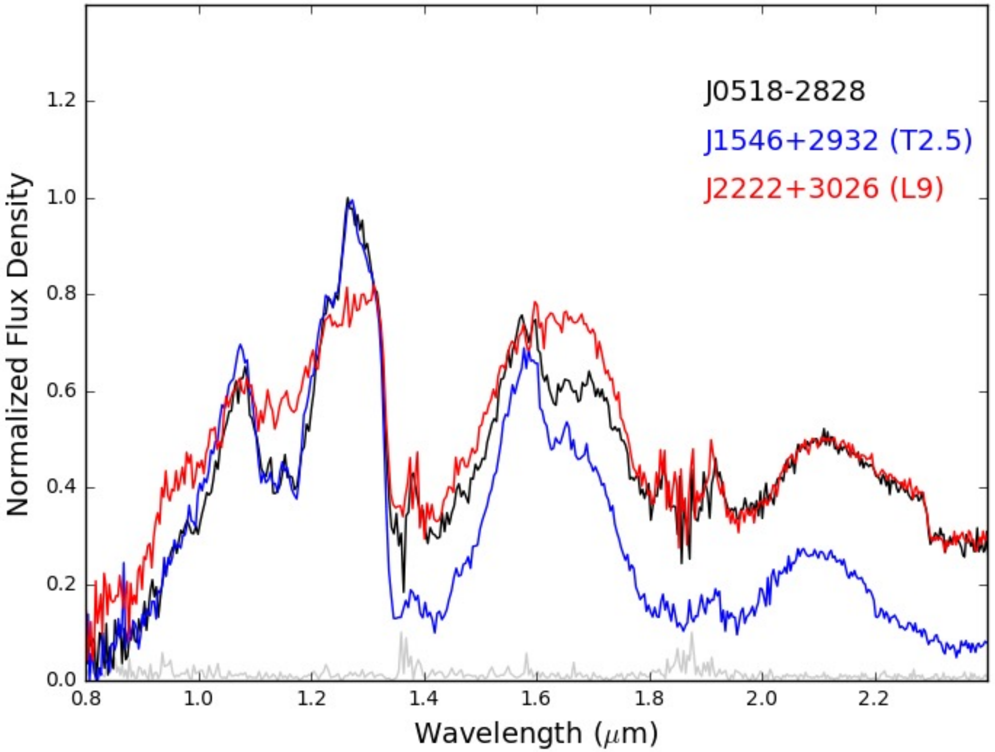

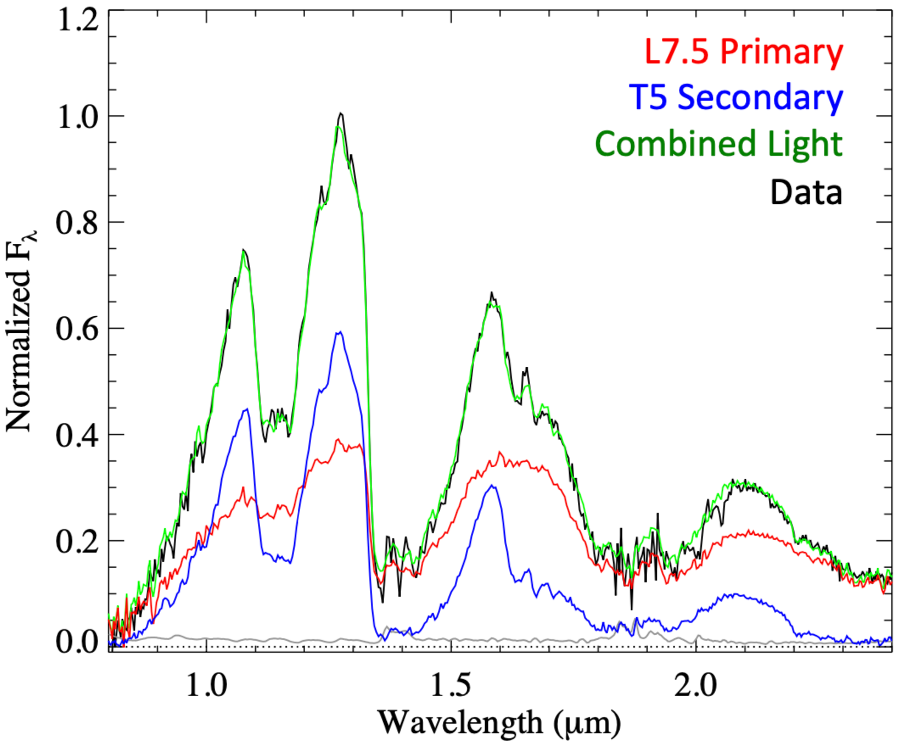

Looper et al. (2008); Burgasser et al. (2010)

Characterisation of ultra-cool dwarfs

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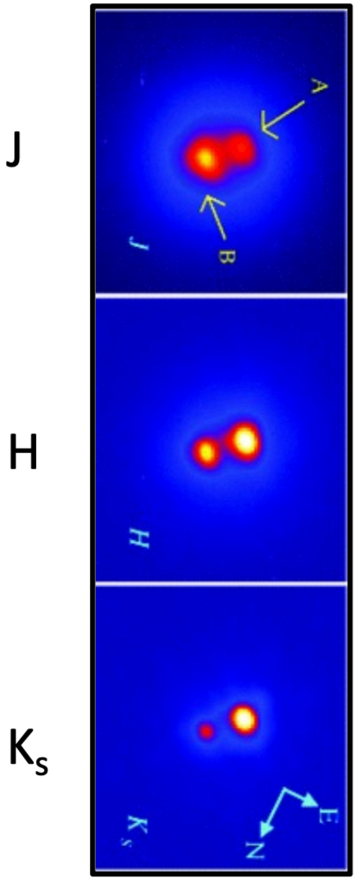
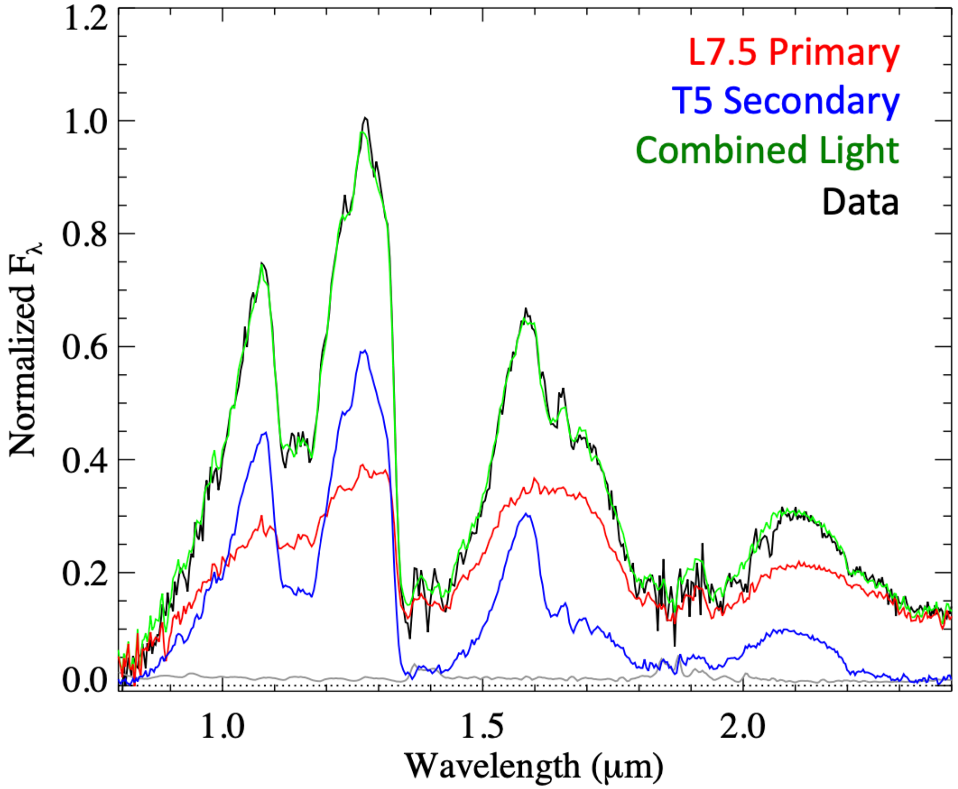


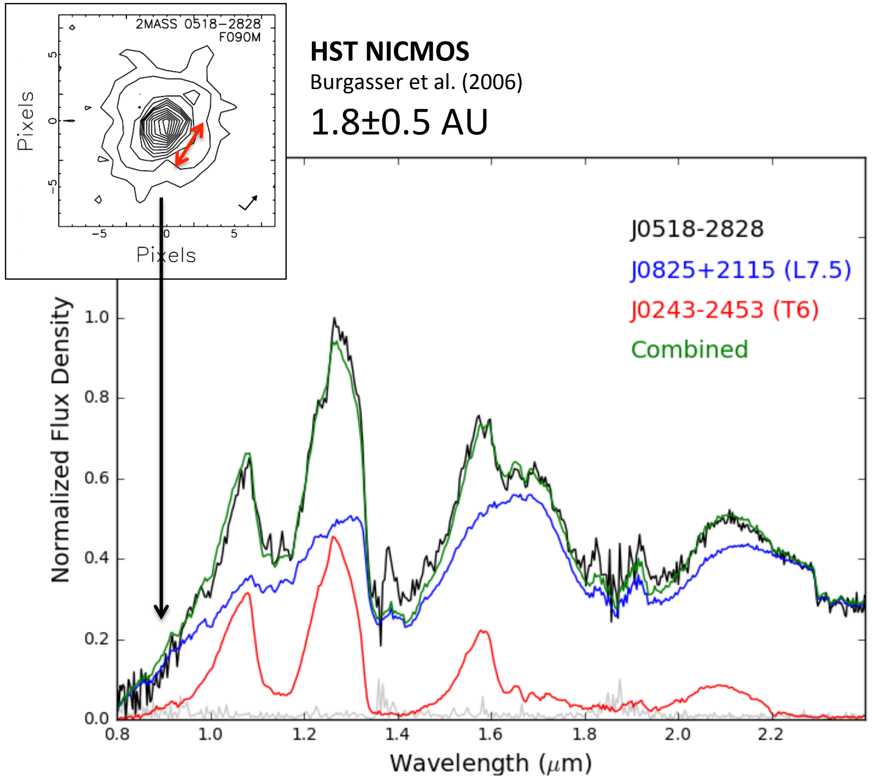


Looper et al. (2008); Burgasser et al. (2010)

Characterisation of ultra-cool dwarfs

Spectral binaries

Spectral binaries: unresolved binaries that can be identified by an index-identification technique.



Cruz et al 2004, Burgasser et al 2010

Characterisation of ultra-cool dwarfs

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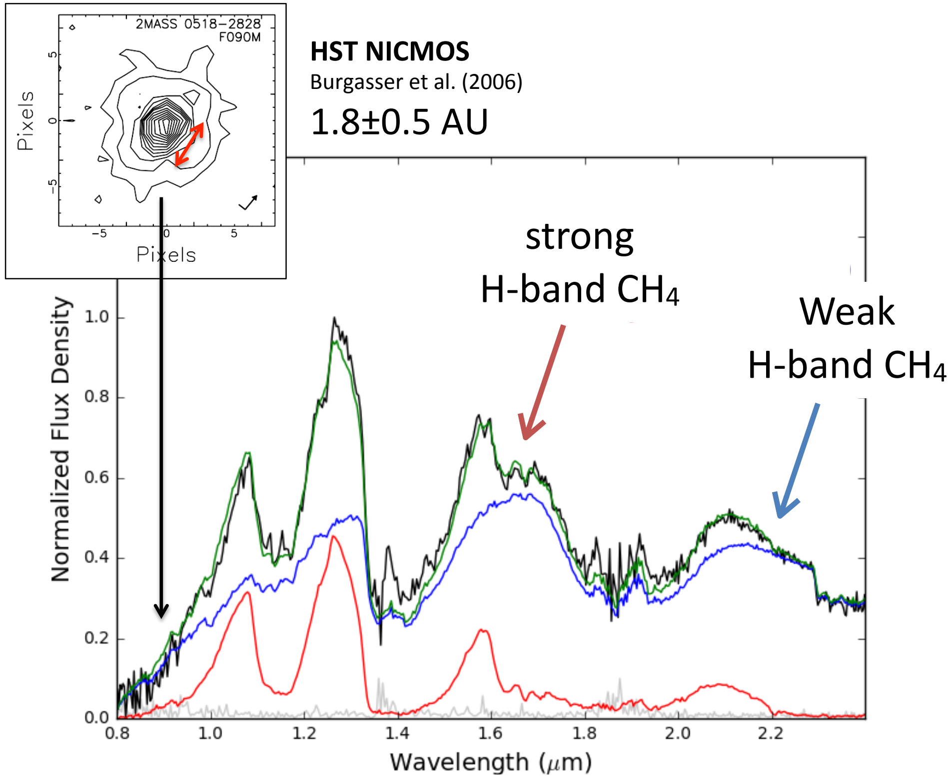

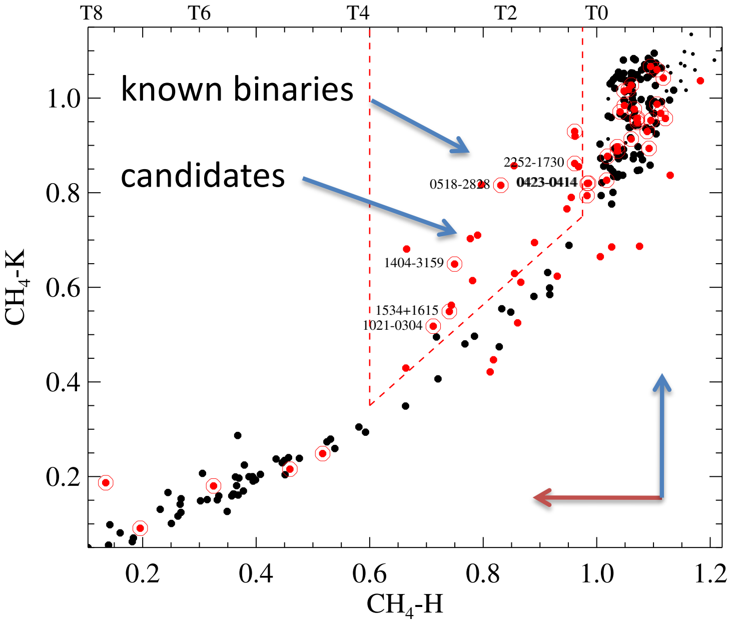

Burgasser et al 2010,
Bardalez Gagliuffi et al 2014

Cruz et al 2004, Burgasser et al 2010

Spectral binaries

Characterisation of ultra-cool dwarfs

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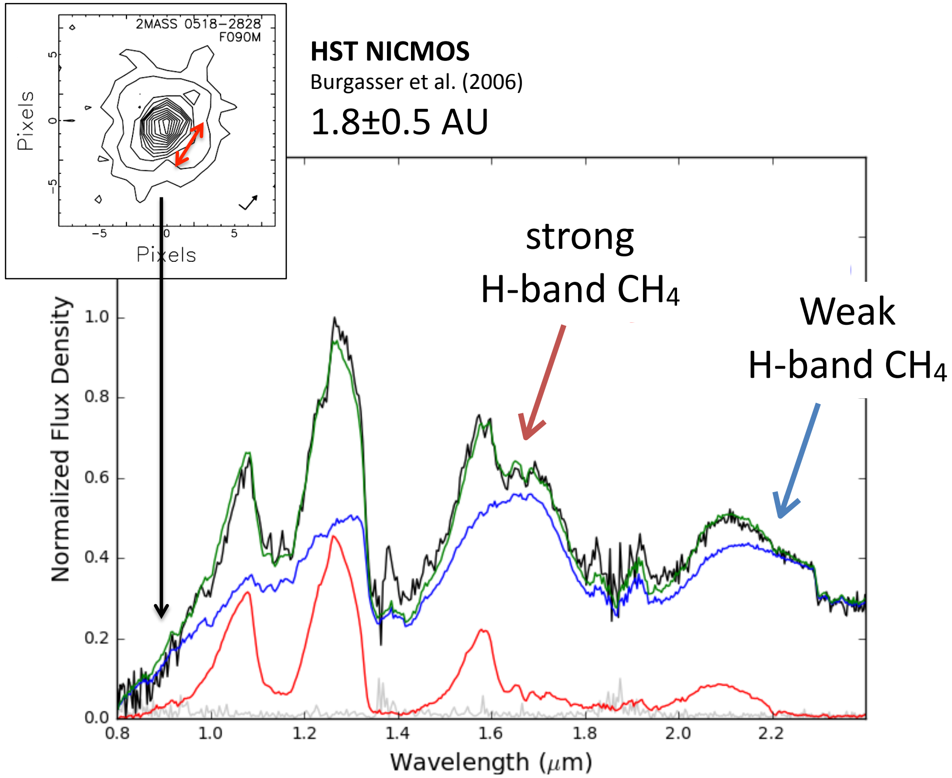
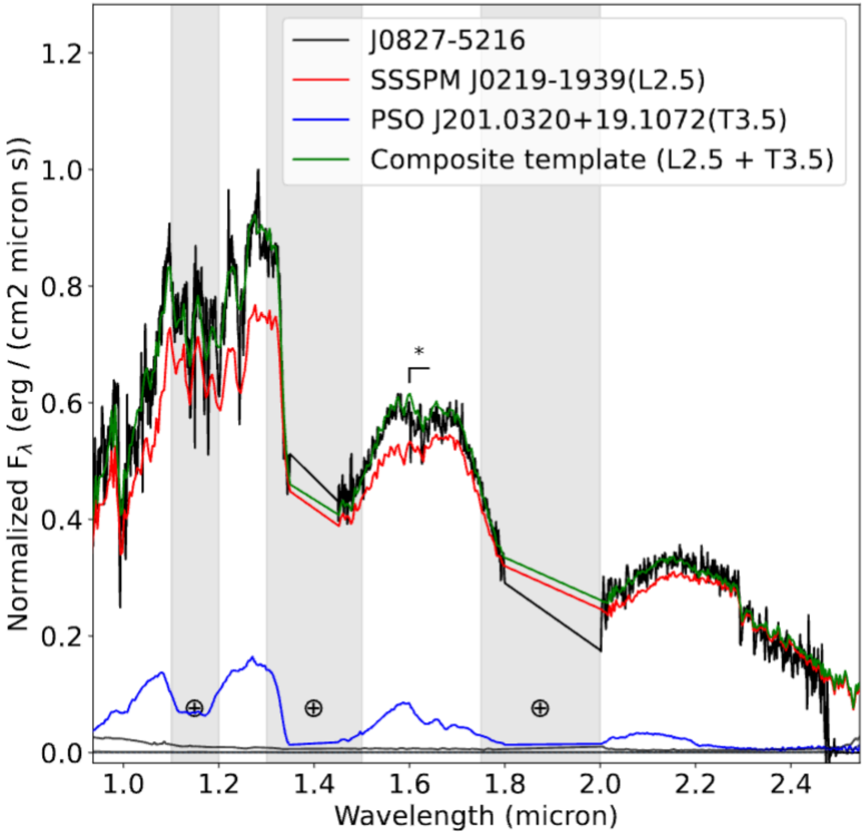


Cruz et al 2004, Burgasser et al 2010

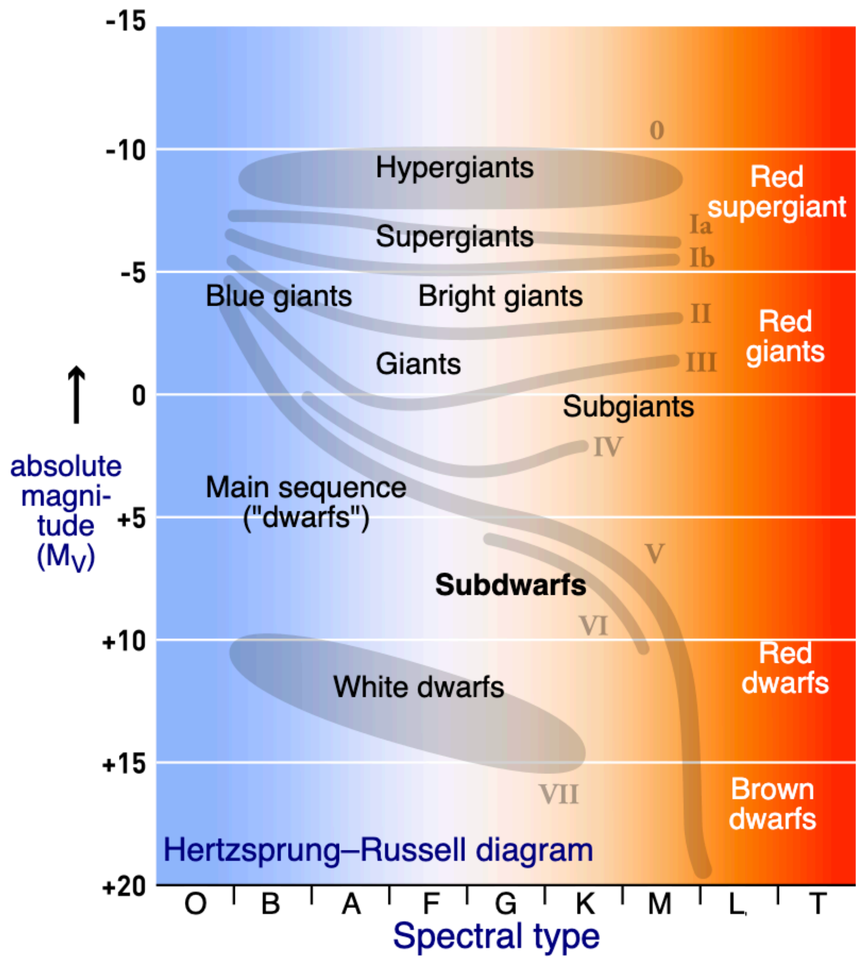


Ravinet et al, submitted

Characterisation of ultra-cool dwarfs

Subdwarfs

Name coined by Gerard Kuiper in 1939, to refer to a series of stars with anomalous spectra that were previously labeled as "intermediate white dwarfs". Noted sd.



Characterisation of ultra-cool dwarfs

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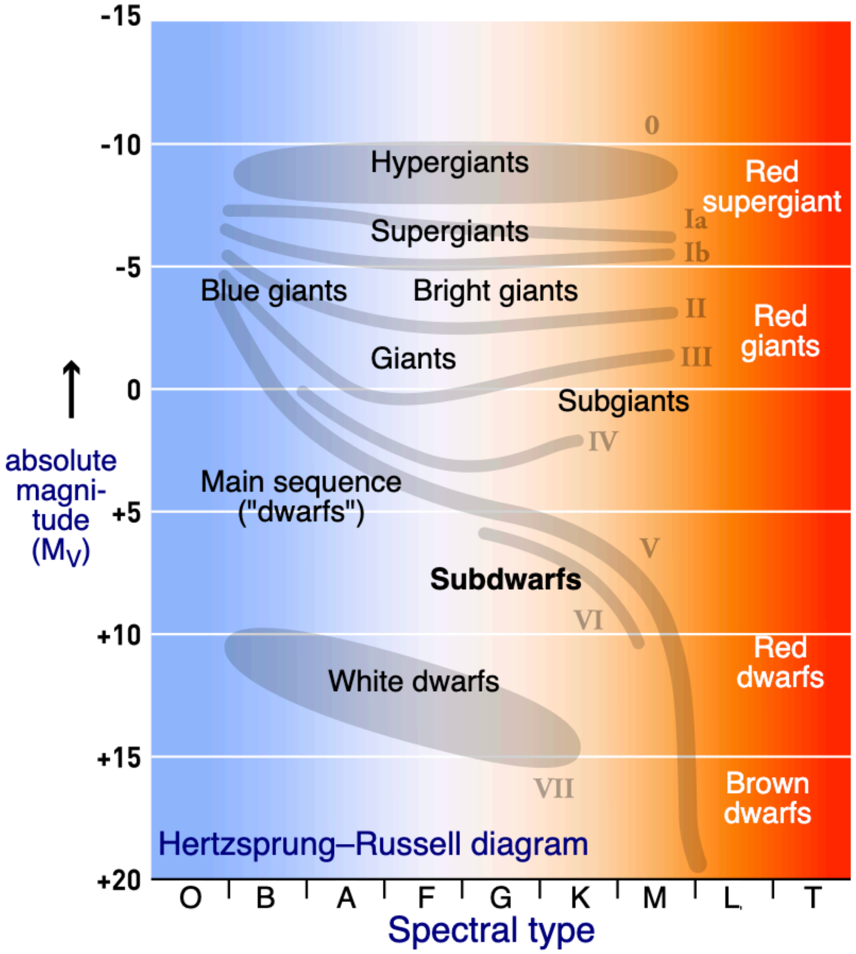
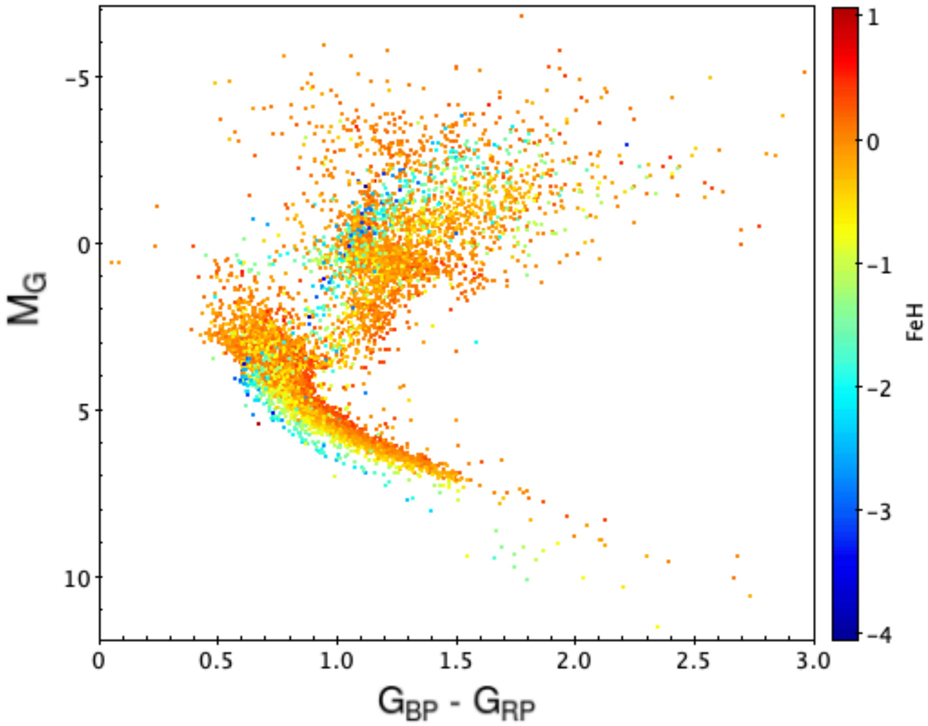


Subdwarfs are low-metallicity objects



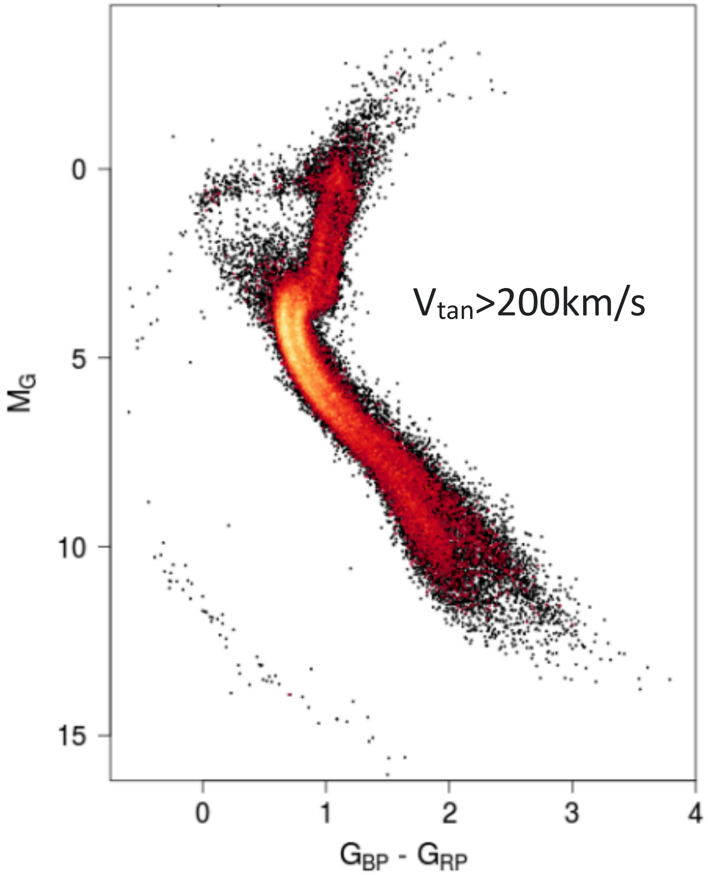
Metallicity [Fe/H] from the PASTEL catalogue

(Soubiran, Brouillet, Casamiquela 2022)

Subdwarfs

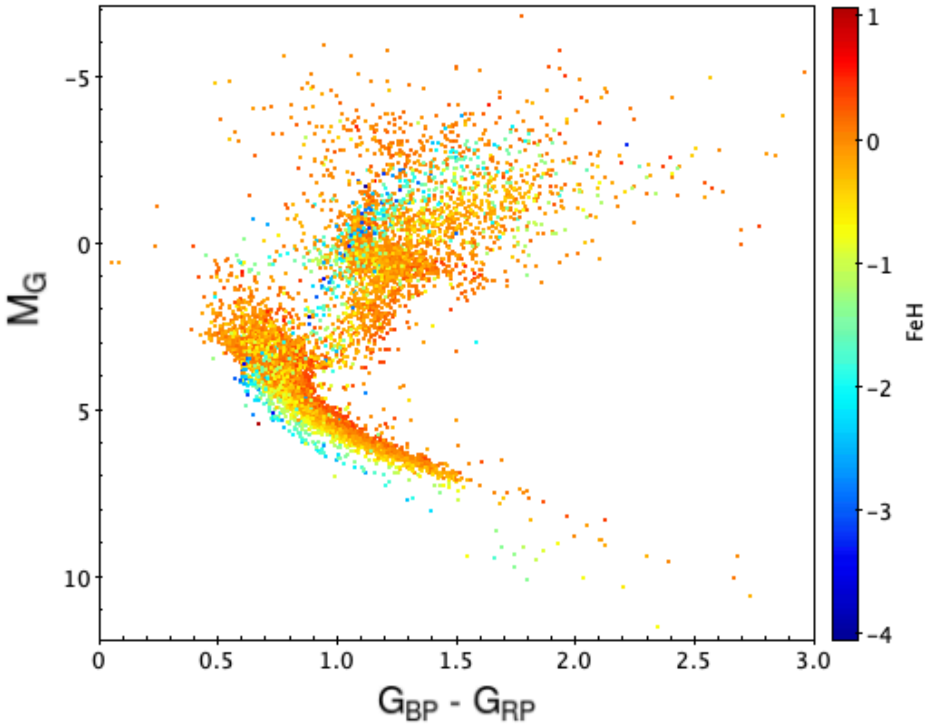
Characterisation of ultra-cool dwarfs

Cool subdwarfs are typically found to have thick disc or halo kinematics.



Gaia coll. Babusiaux et al 2018

Subdwarfs are low-metallicity objects



Metallicity [Fe/H] from the PASTEL catalogue

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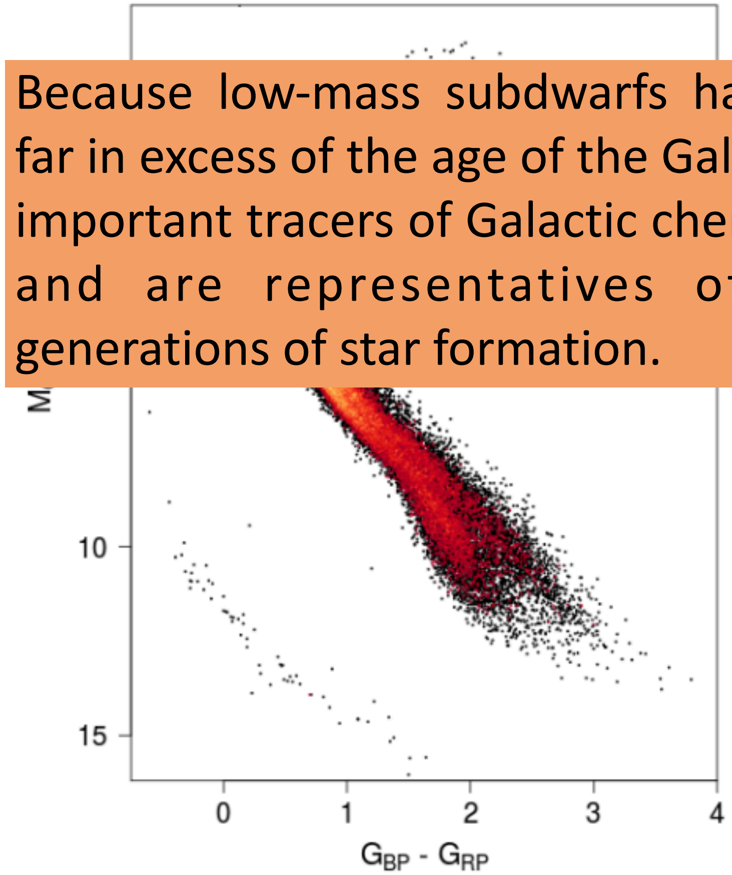
Characterisation of ultra-cool dwarfs

Subdwarfs

Cool subdwarfs are typically found to have thick disc or halo kinematics.

Because low-mass subdwarfs have lifetimes far in excess of the age of the Galaxy, they are important tracers of Galactic chemical history and are representatives of the first generations of star formation.



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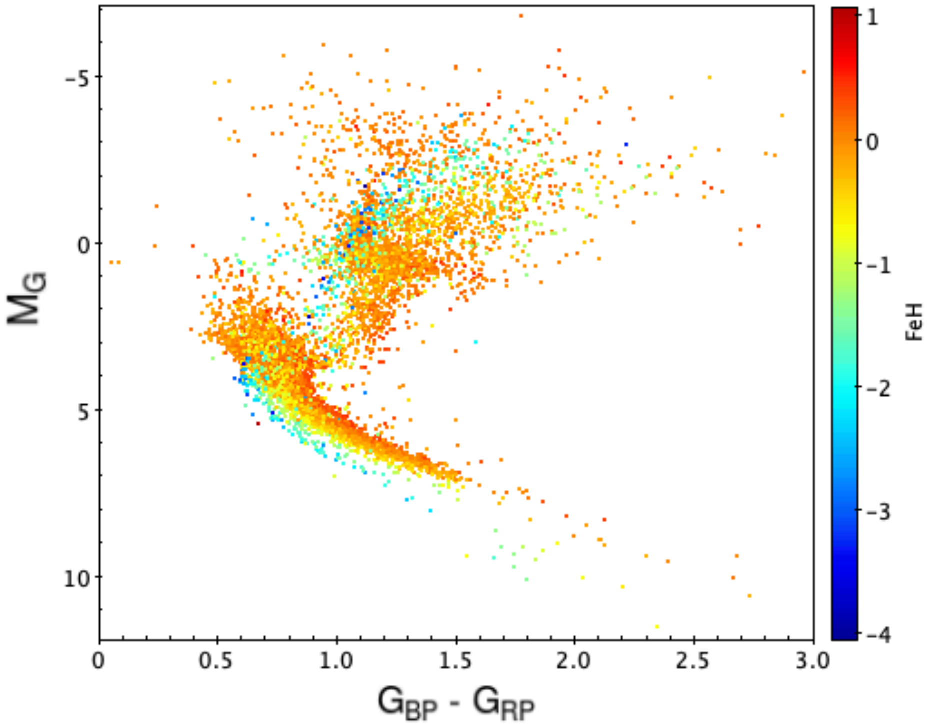


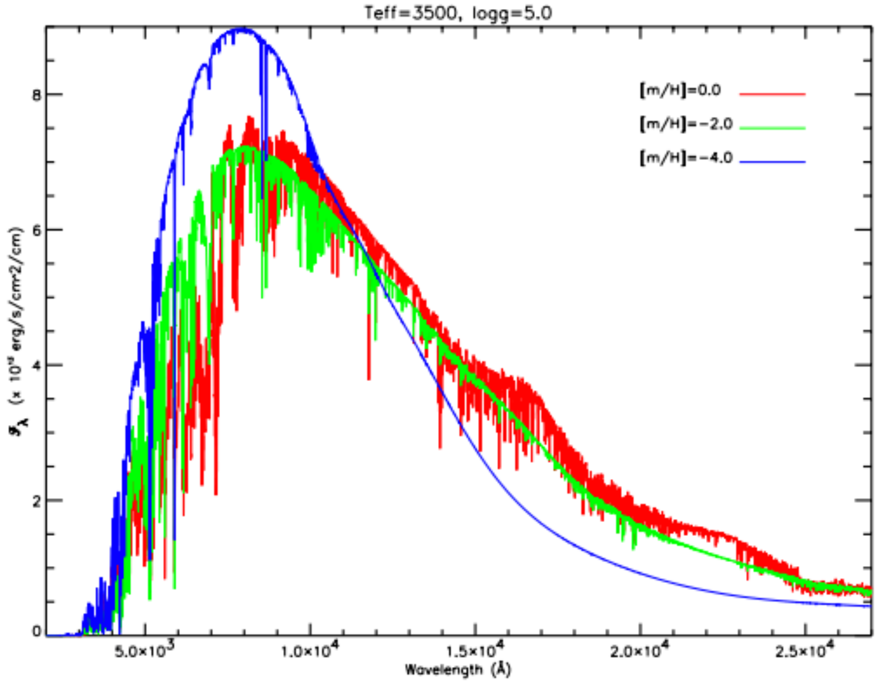
Metallicity [Fe/H] from the PASTEL catalogue *(Soubiran et al 2022)*

Characterisation of ultra-cool dwarfs

Subdwarfs

M-subdwarfs

To date hundreds of late-type M subdwarfs (Lépine et al 2003; Burgasser et al 2007; Lépine & Scholz 2008; Lodieu et al. 2012, 2017; Kirkpatrick et al. 2016) have been discovered with modern sky surveys



Jao et al. 2008

Because of a decreasing metallicity for subdwarfs, TiO opacity decreases. Less blanketing from TiO bands means more continuum flux radiated from hotter and deeper layers of the atmosphere.
The subdwarf spectrum is closer to that of a blackbody, and subdwarfs appear bluer.

Synthetic spectra at T_{eff}=3500 K and log(g)=5 from *Gaia* model grid *(Brott & Hauschildt 2005)*

Characterisation of ultra-cool dwarfs

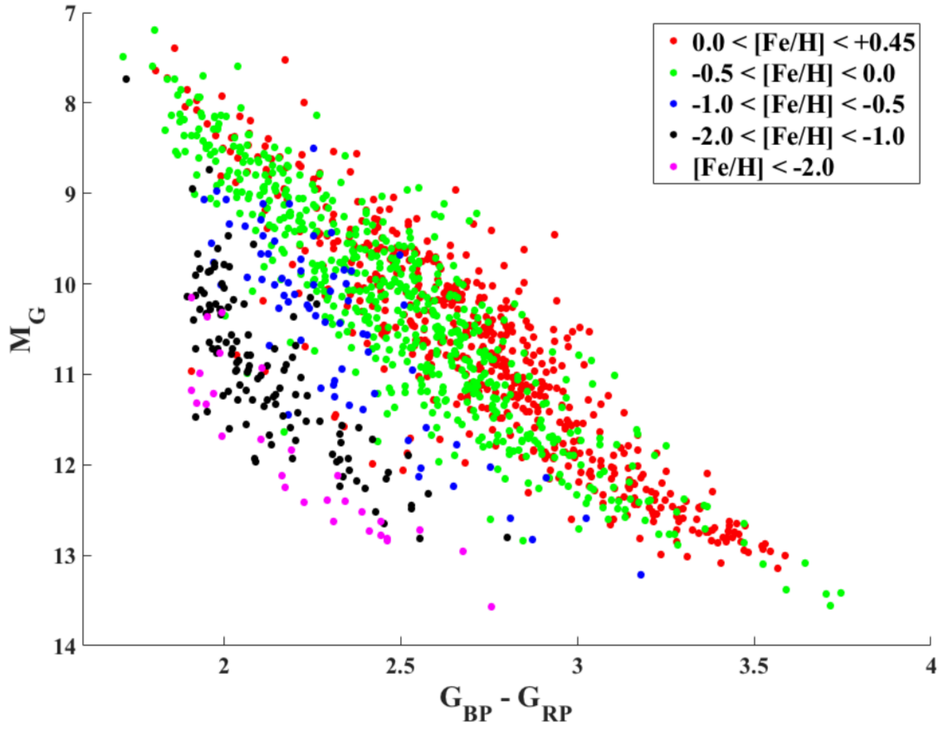
Subdwarfs

M-subdwarfs

Hejazi et al 2018

- Spectroscopic catalogue of ~1600 high proper motion (>0.4''/yr) M dwarfs and M subdwarfs
- Synthetic model fitting using BT-Settl atmospheric models. Fitting parameters T_{eff} , [Fe/H], [α/Fe], and log(g)
- Use of accurate parallaxes from Gaia DR2

→ Stars with different metallicity ranges fall into clearly distinct loci which can be used to develop photometric metallicity calibrations, in particular, for metal-poor M subdwarfs



Characterisation of ultra-cool dwarfs

Subdwarfs

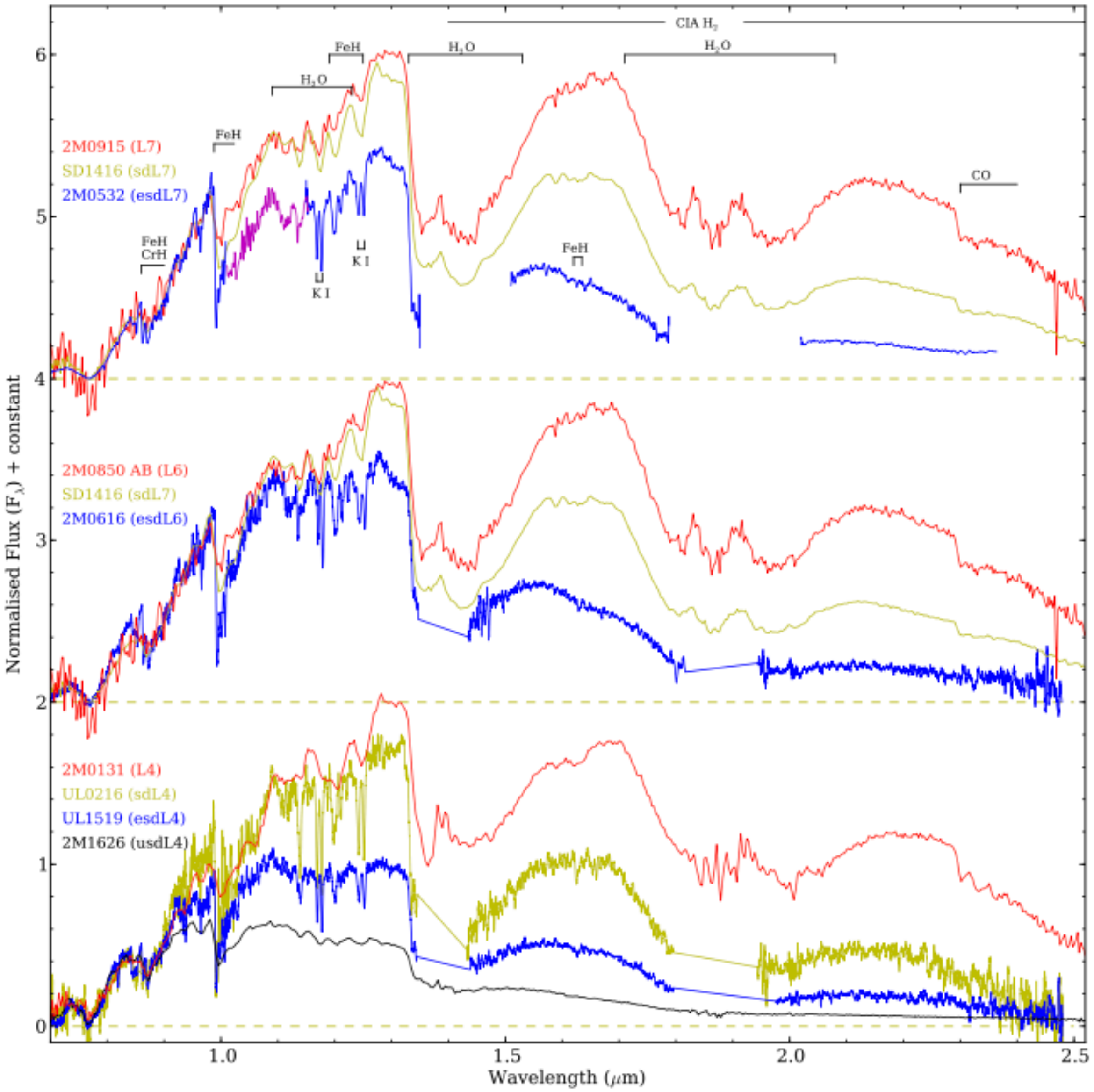
L-subdwarfs

To date, about 66 L subdwarfs (Burgasser et al. 2003; Kirkpatrick et al 2014; Zhang et al. 2017, 2018) have been discovered with modern sky surveys

Strong metal hydrides (e.g. FeH), weak or absent metal oxides (e.g. VO and CO), and enhanced collision-induced H_2 absorption (suppressed K and K-bands)

sd/esd: classification scheme of *Gizis 1997* extended to usd by *Lépine et al. 2007*

Zhang et al 2017



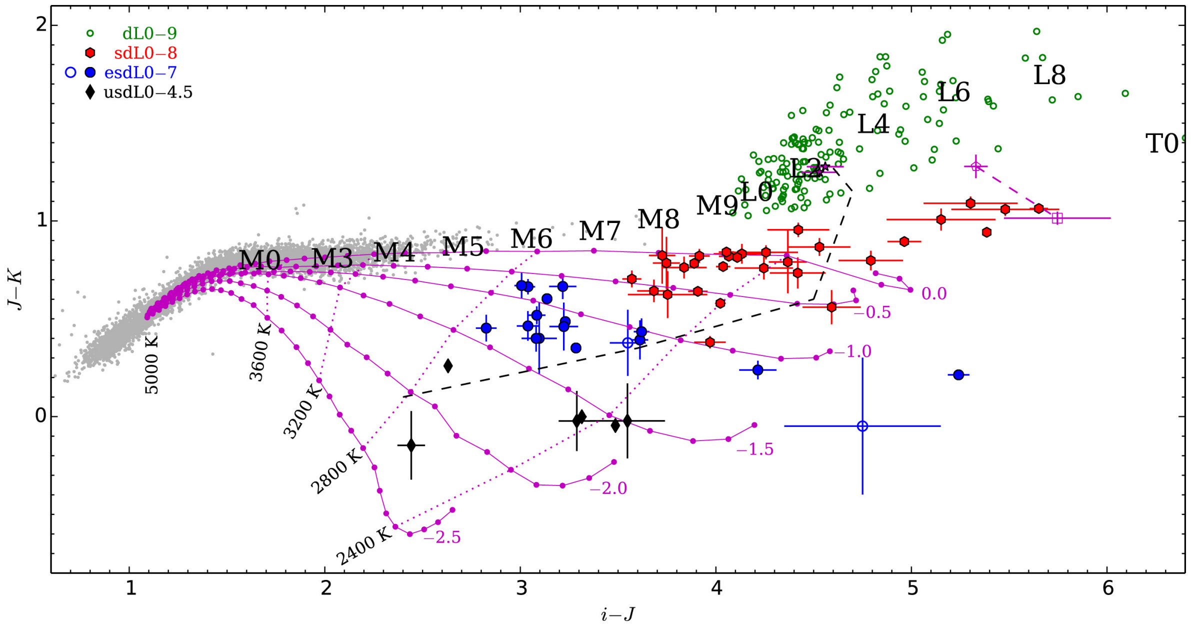
Characterisation of ultra-cool dwarfs

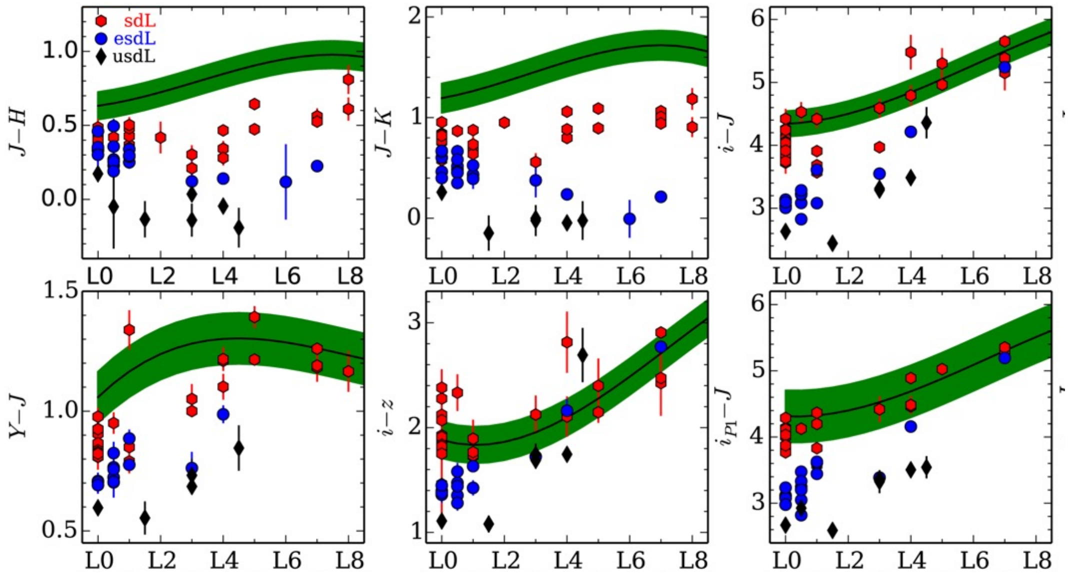
Subdwarfs

L-subdwarfs

Zhang et al 2018

- Selection of L subdwarfs from their locus in optical and NIR colour-colour diagrams
- Confirmation with spectroscopic follow-up





Characterisation of ultra-cool dwarfs

Subdwarfs

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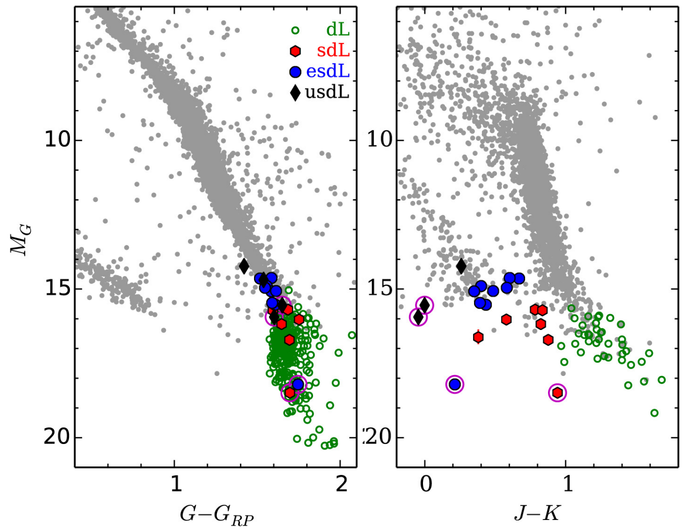
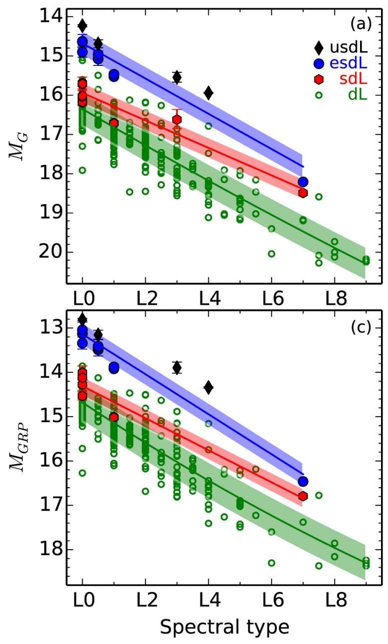
- 20 are in the *Gaia* catalogue





Characterisation of ultra-cool dwarfs

Subdwarfs

L-subdwarfs

Zhang et al 2018

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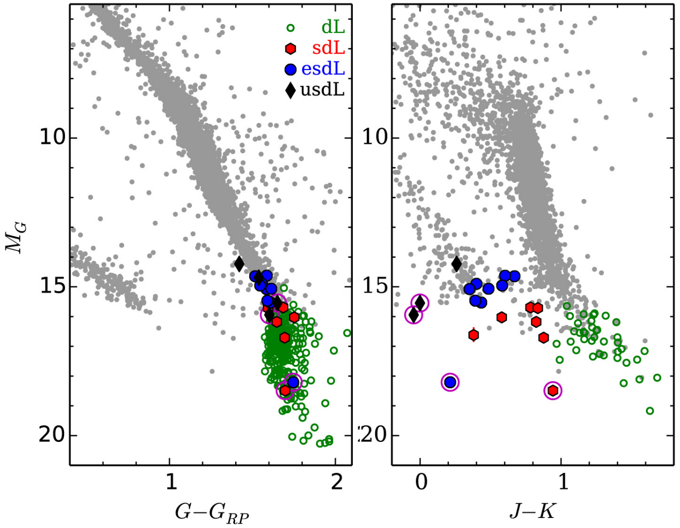
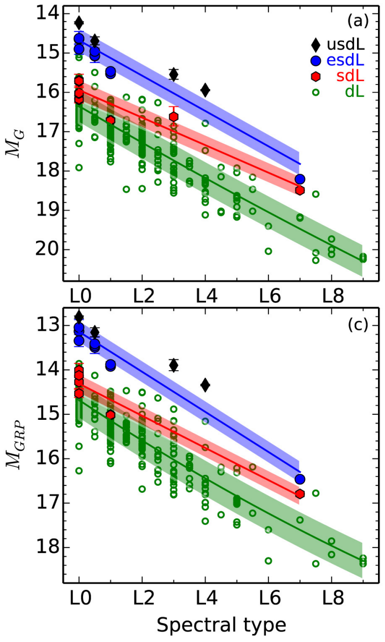
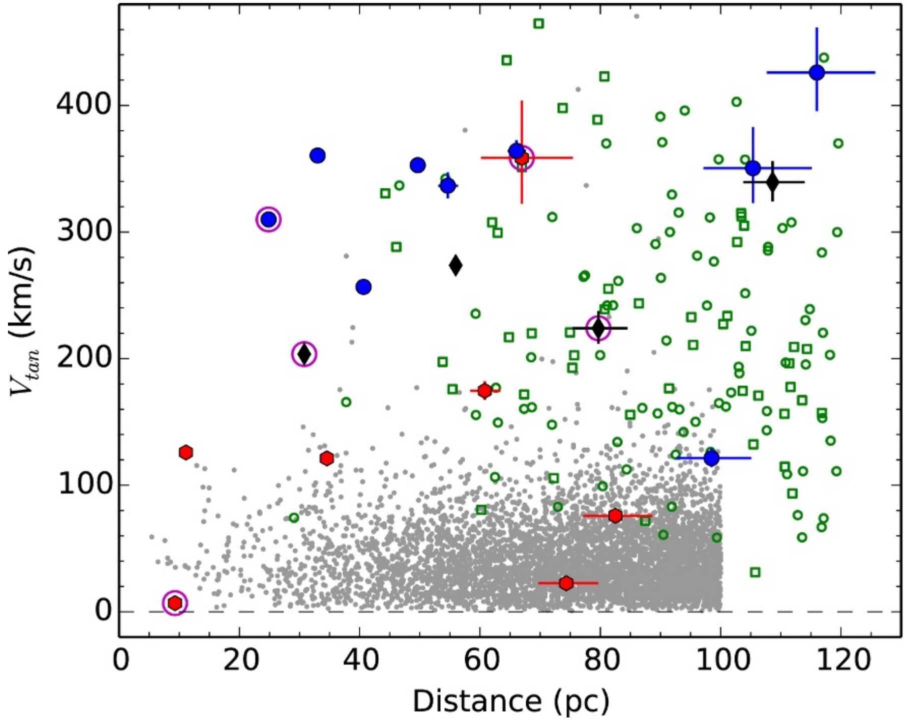
The sdL subclass mostly have thick disc kinematics. The esdL and usdL subclasses generally have halo kinematics, which is consisted to the esdM/usdM subclasses.



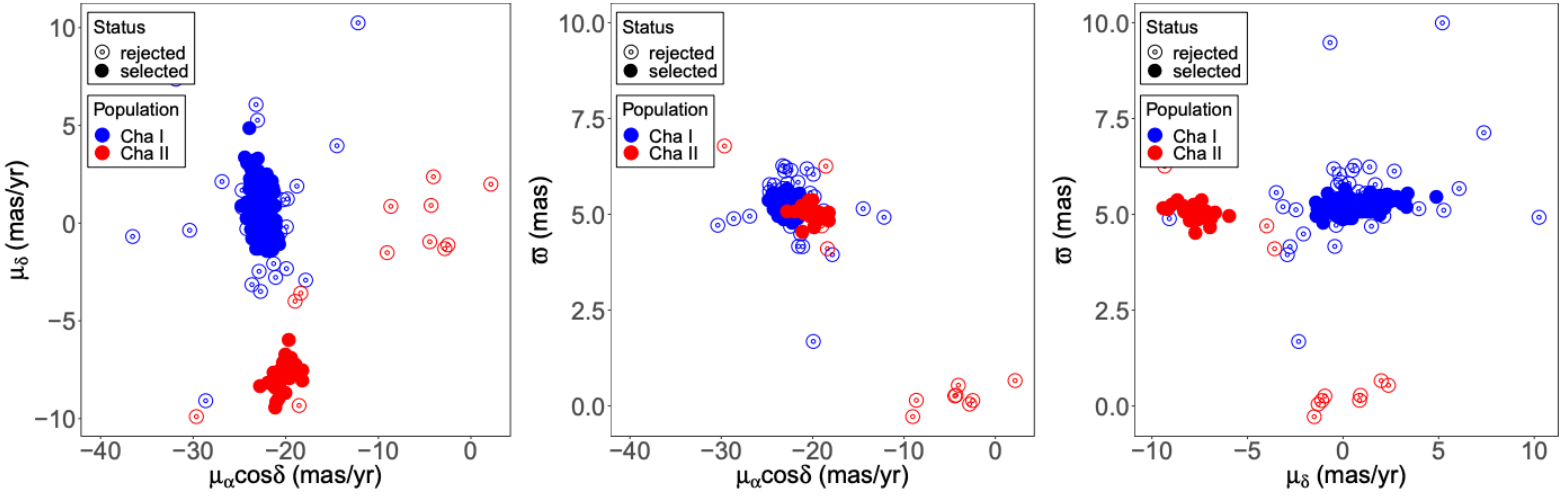




Characterisation of ultra-cool dwarfs

Young associations

The selection of members of young clusters or associations has become trivial with Gaia, but also the discovery new groups, using the parallax, position and motion of stars *(see eg Cantat-Gaudin et al 2019; Muzic et al 2022; Galli et al 2019, 2020, 2021; Tarricq et al 2021, 2022; Sarro et al 2023)*



Galli et al 2021 Revisiting the stellar populations of Chamaeleon I and Chamaeleon II with Gaia-DR2 data

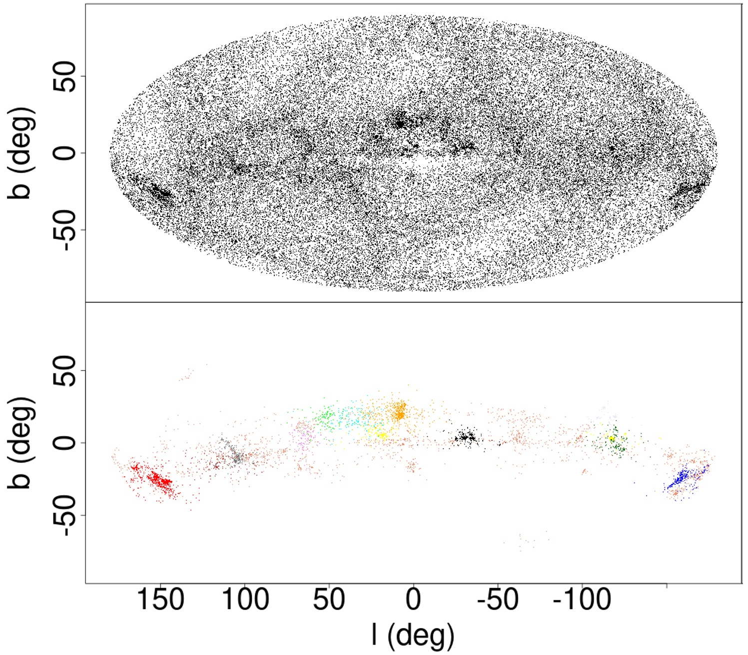
For young regions/groups in the solar neighborhood (up to ~500 pc) Gaia can be sensitive up to ~30M_{jup}. To summarize the conclusion, the mass function in the substellar regime doesn't vary much, at least within the error bars in the young clusters in the solar neighborhood *(Hervé Bouy, priv. comm.)*

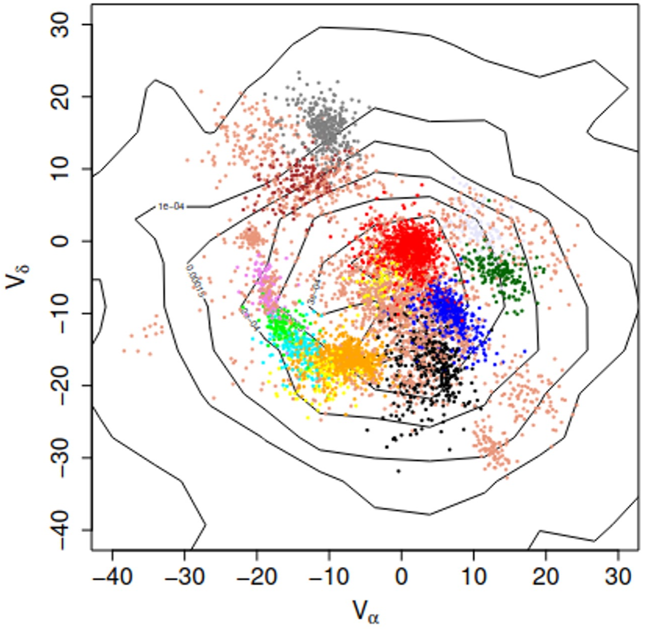
Characterisation of ultra-cool dwarfs

Young associations

Sarro et al 2023

- Sample of ~94 000 UCD candidates (Teff<2700K)
- Group identification using a hierarchical mode association clustering (HMAC) classification algorithm for the detection and characterisation of overdensities in the space of celestial coordinates, projected velocities, and parallaxes





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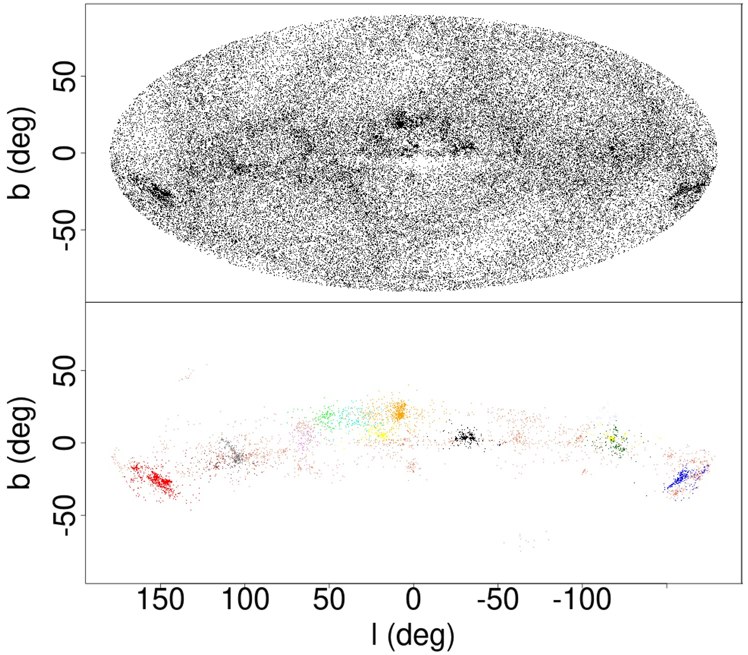
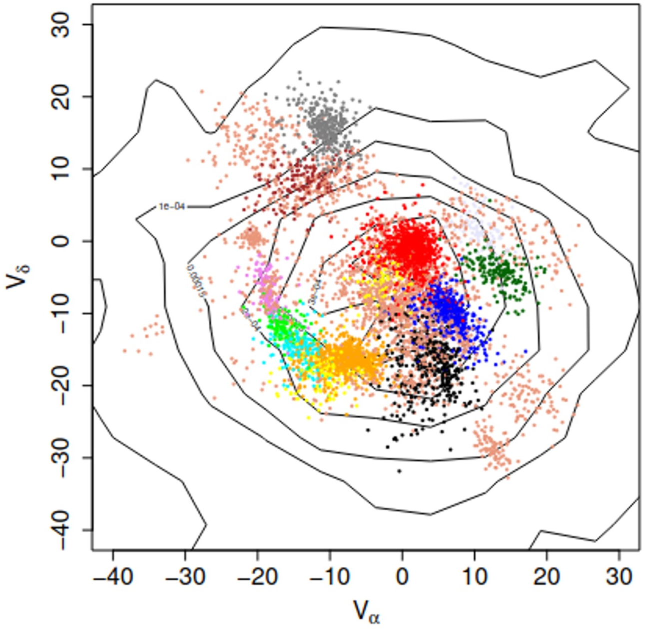
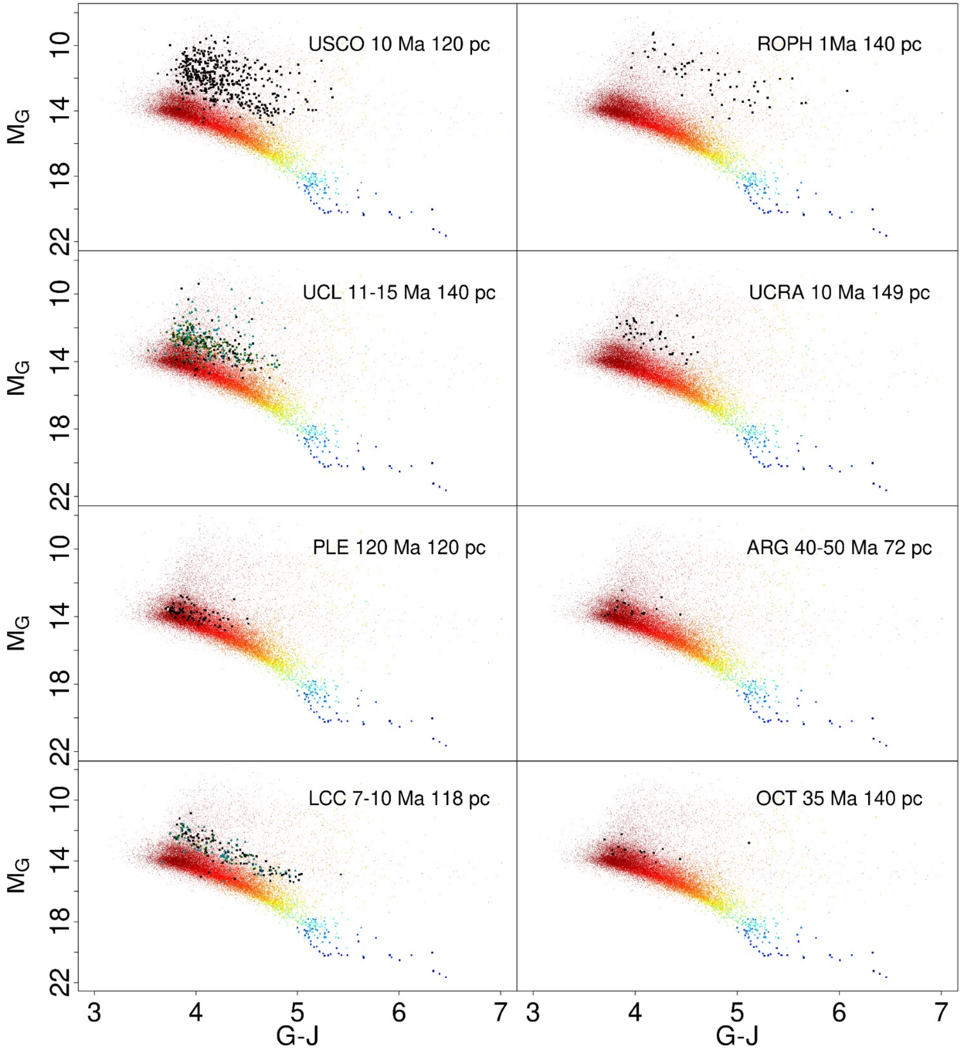




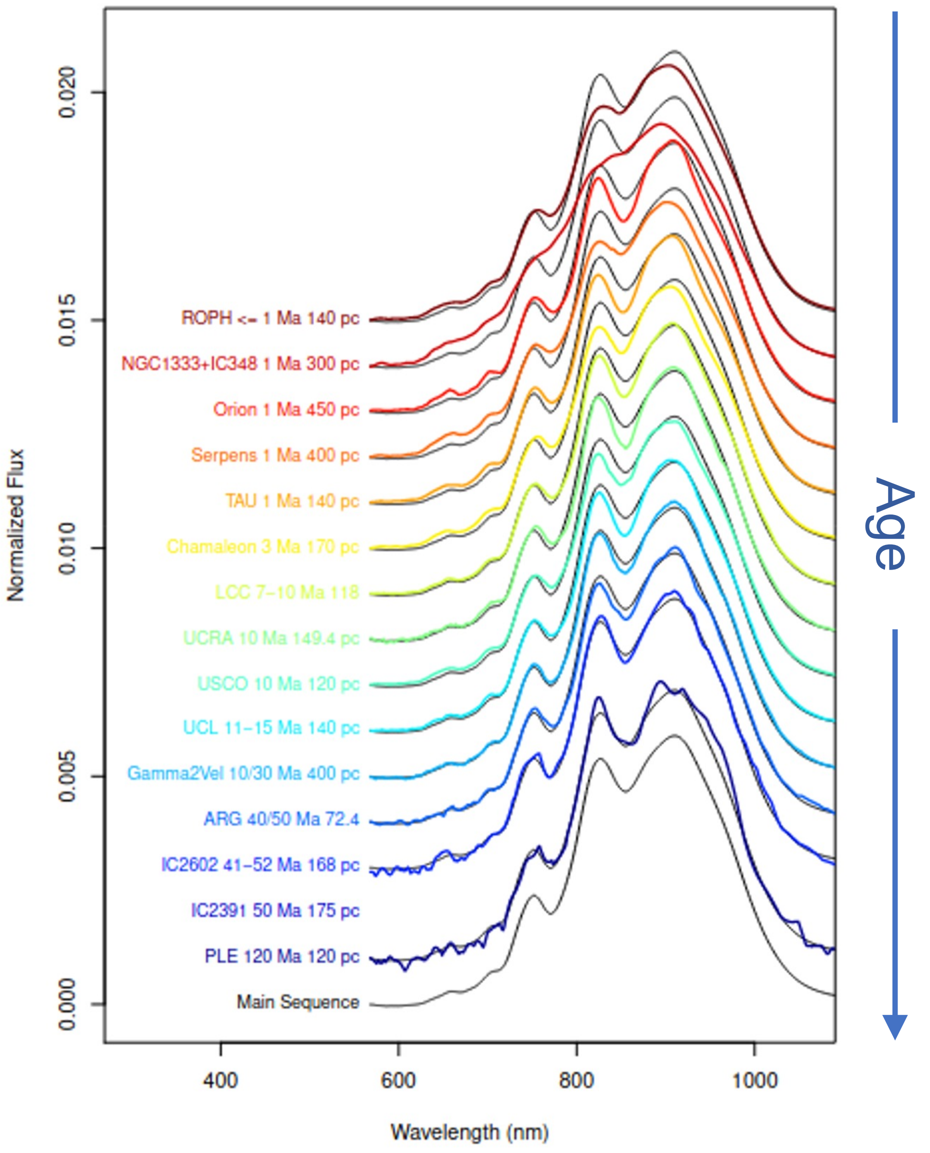


Characterisation of ultra-cool dwarfs

Young associations

Sarro et al 2023

- median RP spectrum in T_{eff} bins for sources outside these associations (Main Sequence) and in several clusters.
- There is a systematic trend of increasing band depths as the association becomes older
- By 10 Ma, the RP spectra of young and Main Sequence sources becomes undistinguishable
- To be used as the basis for the indication of youth in DR4.



Characterisation of ultra-cool dwarfs

Young associations

Gaia has enabled us to measure dynamic ages for some of these regions, which is very interesting because age is often poorly constrained in these young regions, since evolutionary models are not very reliable for such early ages.

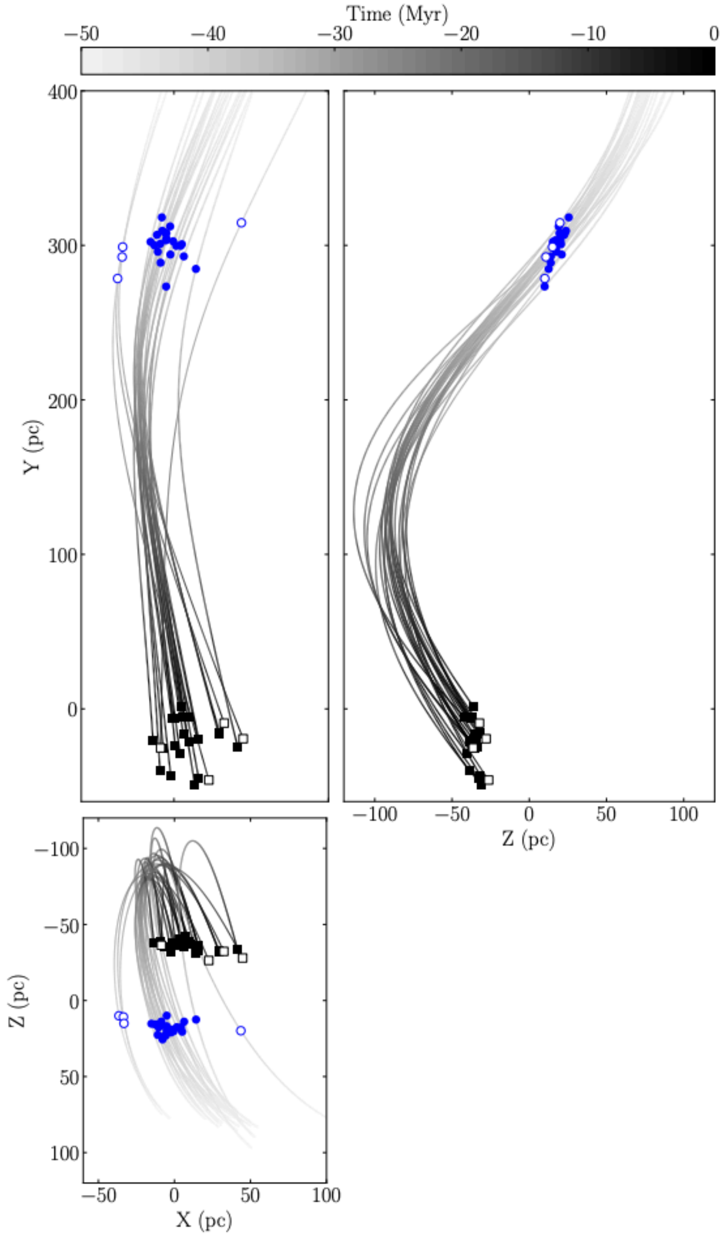
This methodology uses the present 3D positions and 3D velocities of individual stars and computes the stellar orbits back in time with a Galactic potential. The dynamical traceback age is the time when a group of stars was most concentrated in the past, that is, when the size of the group was at its minimum.

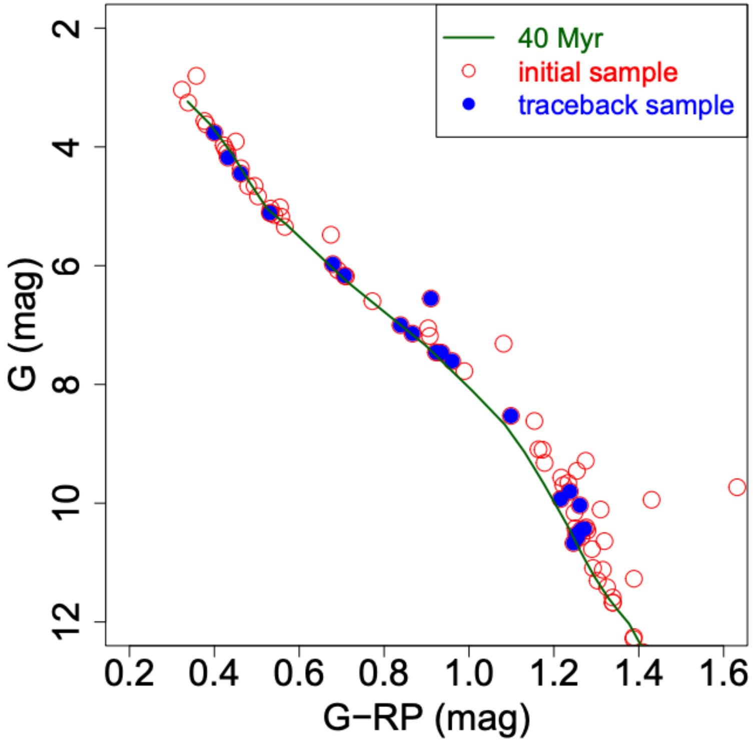
Characterisation of ultra-cool dwarfs

Young associations

Galli et al 2023

Dynamical age of Tucana-Horologium young stellar association: 38.5 Myr





Characterisation of ultra-cool dwarfs

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Galli et al 2023

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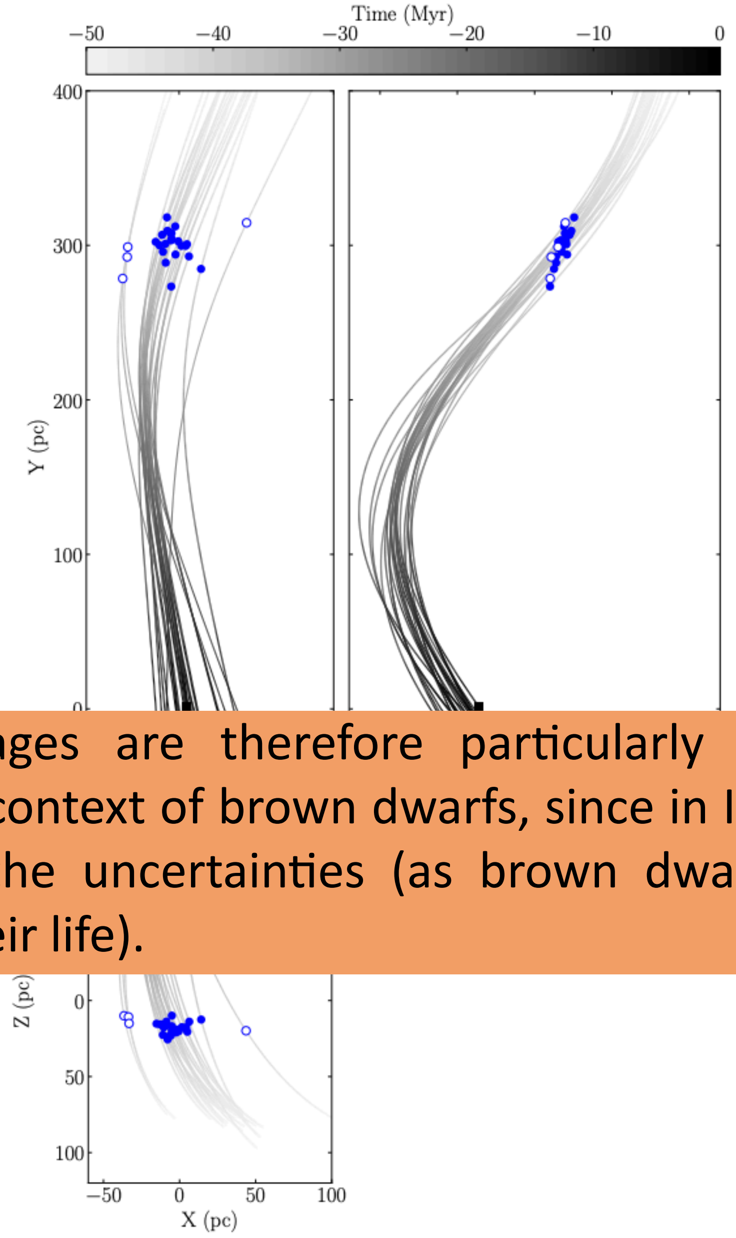
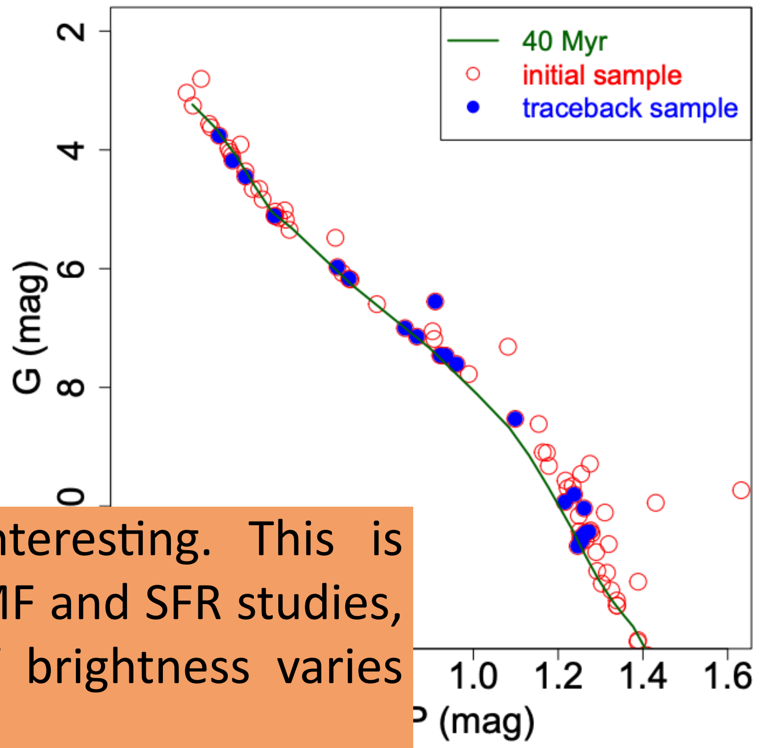




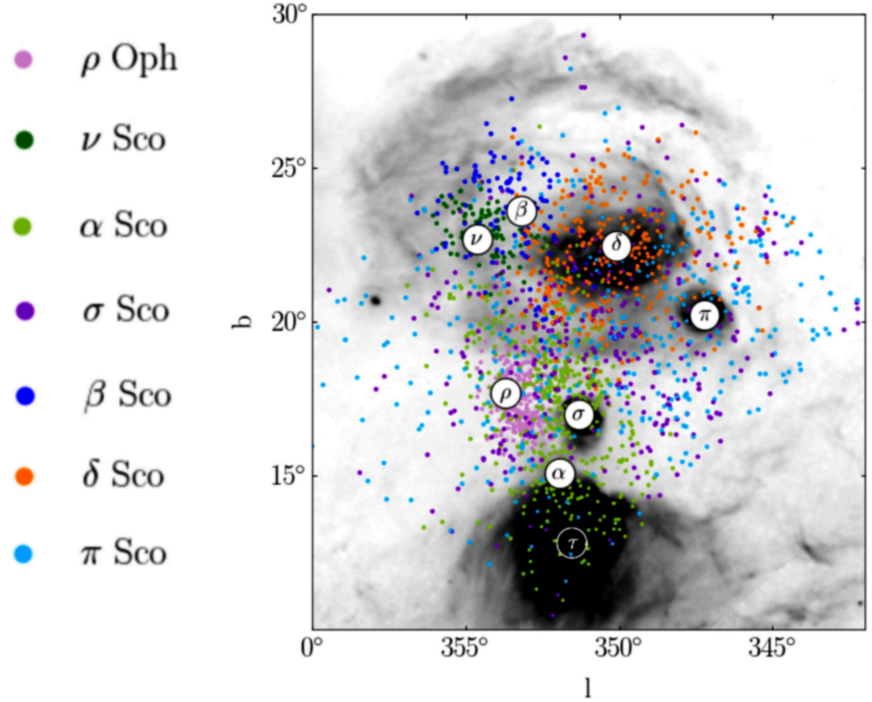
These model-independent ages are therefore particularly interesting. This is particularly important in the context of brown dwarfs, since in IMF and SFR studies, age uncertainty dominates the uncertainties (as brown dwarf brightness varies rapidly at the beginning of their life).

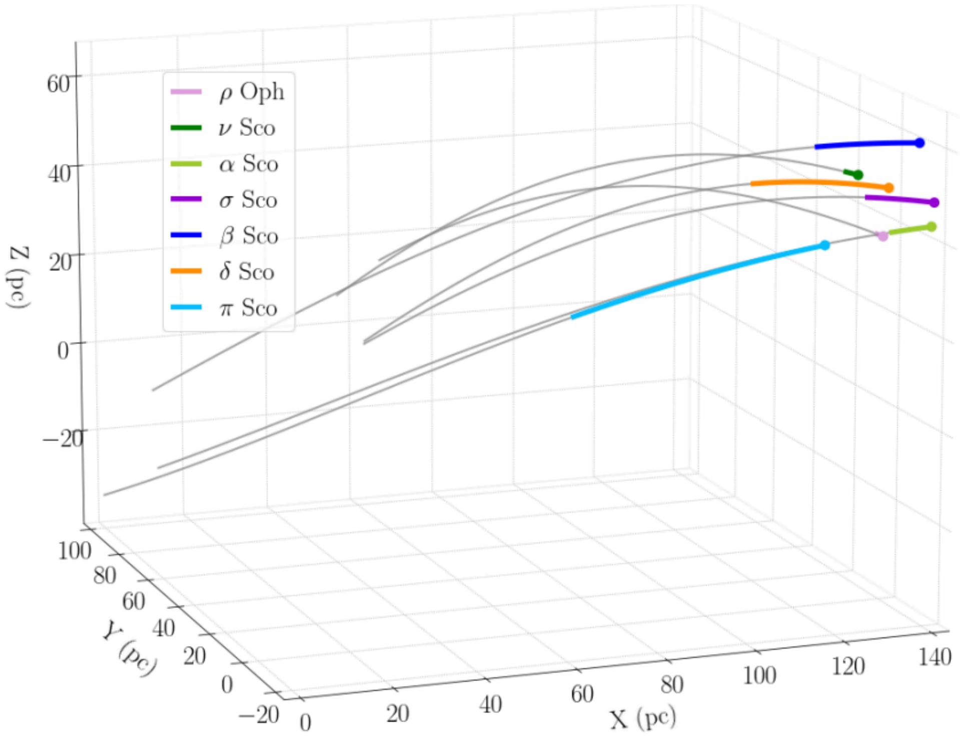
Characterisation of ultra-cool dwarfs

Young associations

Miret-Roig et al 2022 The star formation history of Upper Scorpius and Ophiuchus.

- *Gaia* astrometry + radial velocities to identify different kinematic structures in the 6D space of positions and velocities. Identification of 7 different groups
- The traceback analysis shows that Upper Scorpius and ρ Oph groups share a common origin.



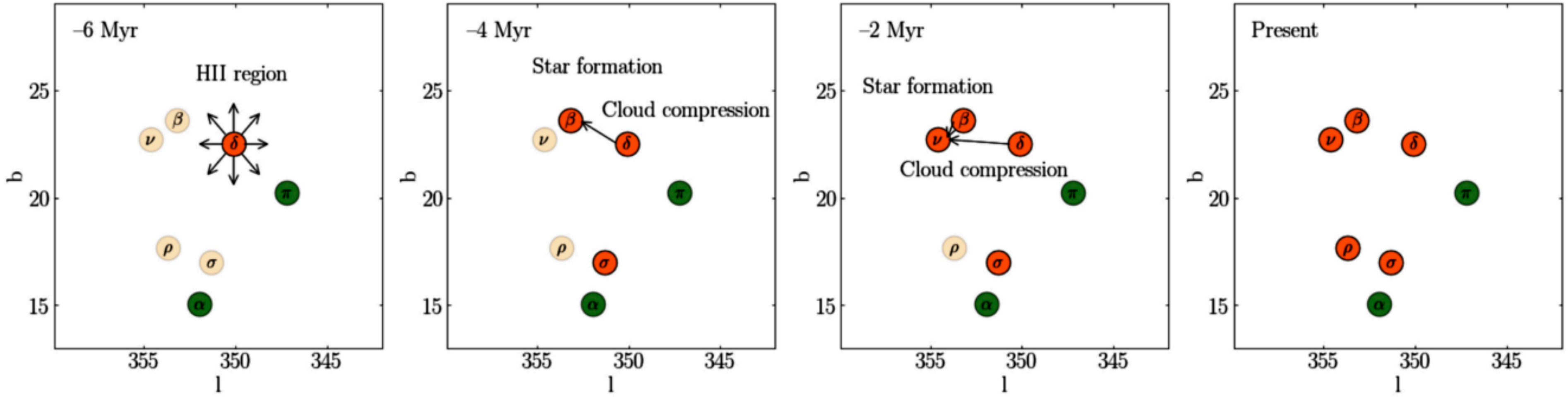


Characterisation of ultra-cool dwarfs

Young associations

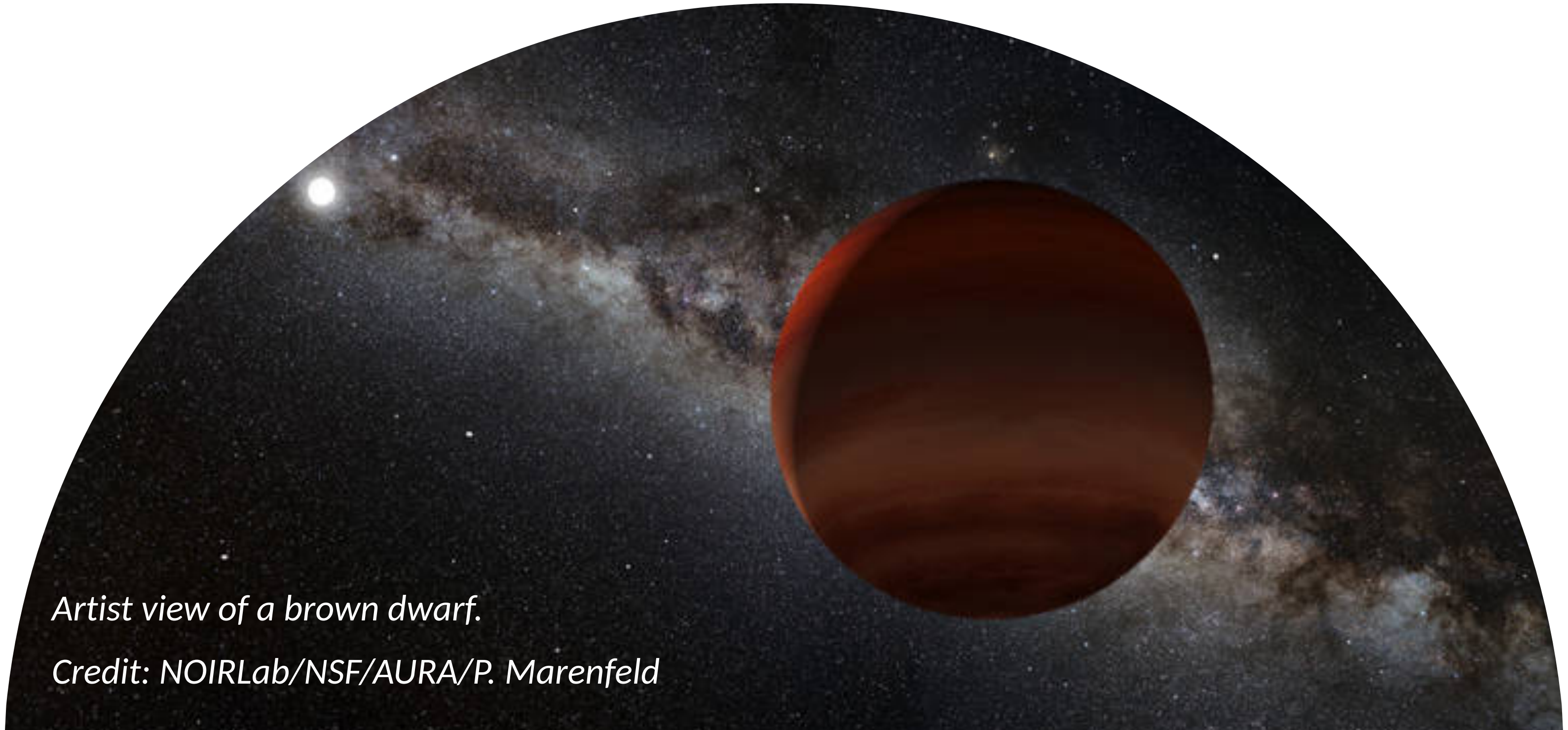
Miret-Roig et al 2022 The star formation history of Upper Scorpius and Ophiuchus.

- The proposed star formation scenario is likely a result of stellar feedback from massive stars, supernova explosions, and dynamic interactions between stellar groups and the molecular gas.



Topics for this lecture

- Low-mass stars and brown dwarfs
- Why are they interesting to study?
- Ultra-cool dwarfs in *Gaia*
- Characterisation of ultra-cool dwarfs
- Towards a complete local census



Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

Towards a complete local census

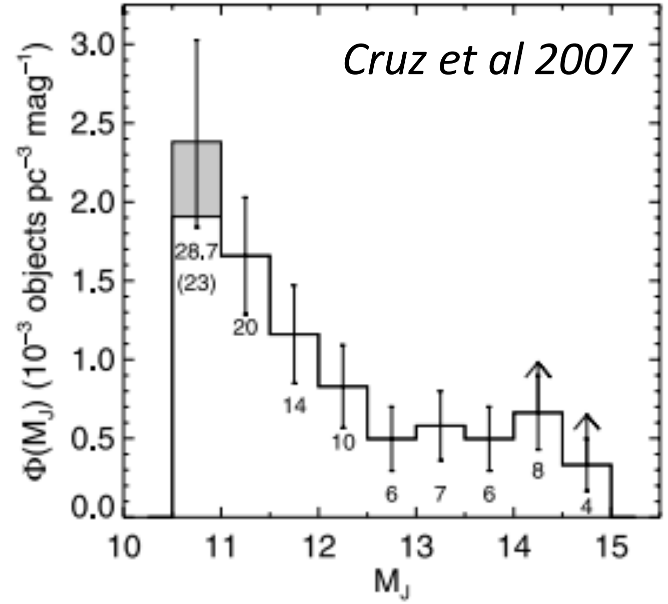
Gaia revealed a huge number of UCDs: a step towards a complete local census

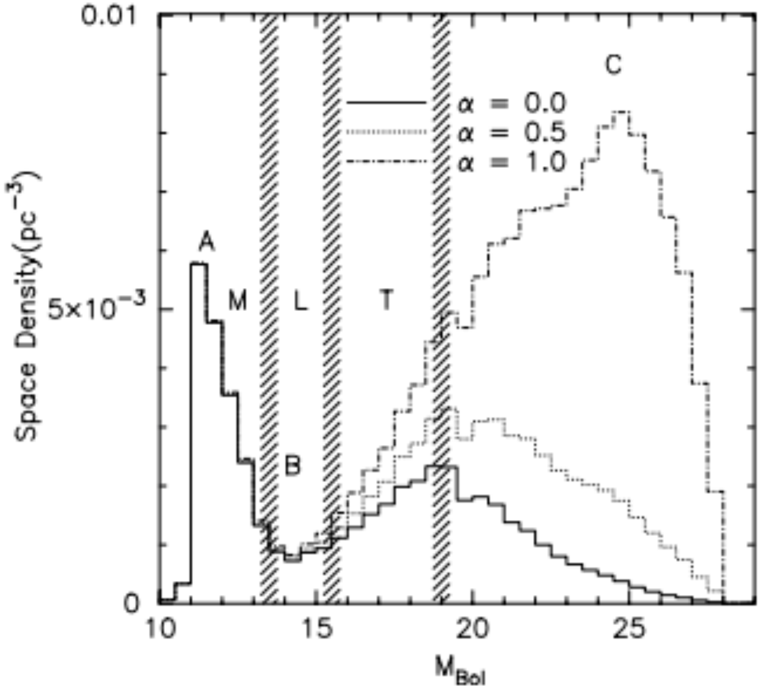
- The nearby sample is particularly important for the ultracool dwarfs (UCDs) which are the lowest-mass, coldest, and faintest products of star formation, making them difficult to study at large distances.
- Having a volume-complete sample, with good statistics, is crucial to compute precise bias-free densities, and to therefore determine luminosity, and mass functions that will be strong constraints on stellar and substellar formation theories.
- For substellar objects with no obvious mass-to-luminosity relation, the luminosity function is simulated assuming different initial mass fonctions and birth rates. Thus the comparison with the observed luminosity function allows to disentangle between the different formation scenarios, only if error bars are small enough.

Towards a complete local census

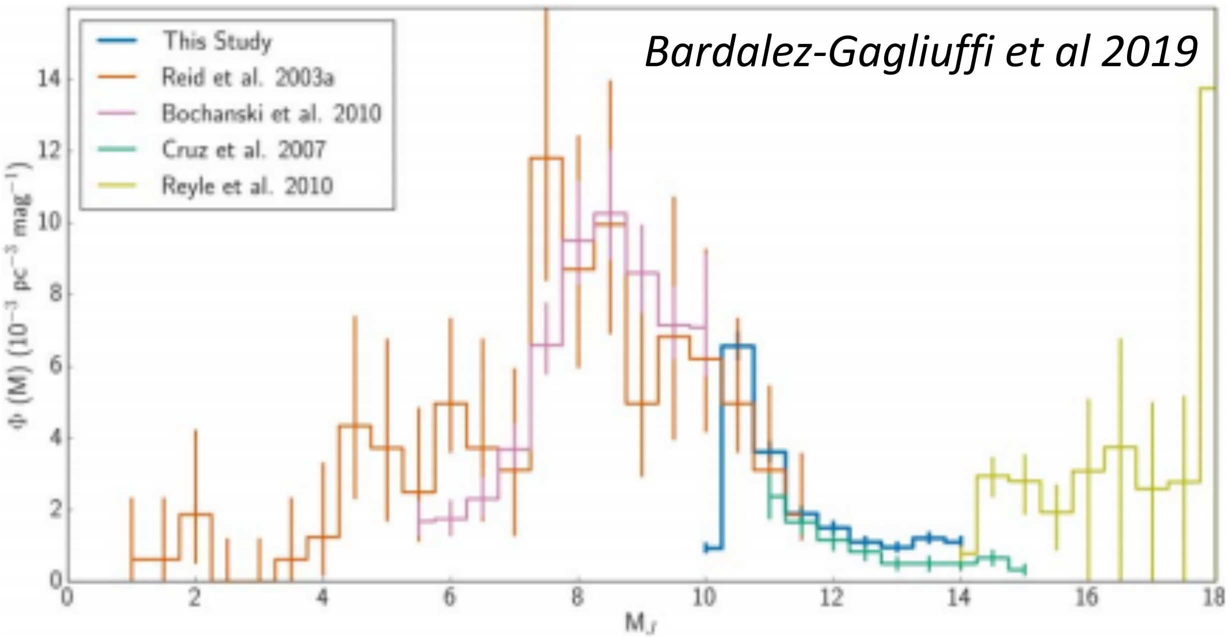
Field stars and brown dwarfs are several Gyr in average. Brown dwarfs depopulate rapidly earlier spectral types to go to later ones

→ Expected minimum in the density at the stellar/substellar boundary (as shown in simulations, eg *Burgasser et al 2004, Allen et al 2005*)





Simulated luminosity function assuming different initial mass functions *Allen et al (2005)*



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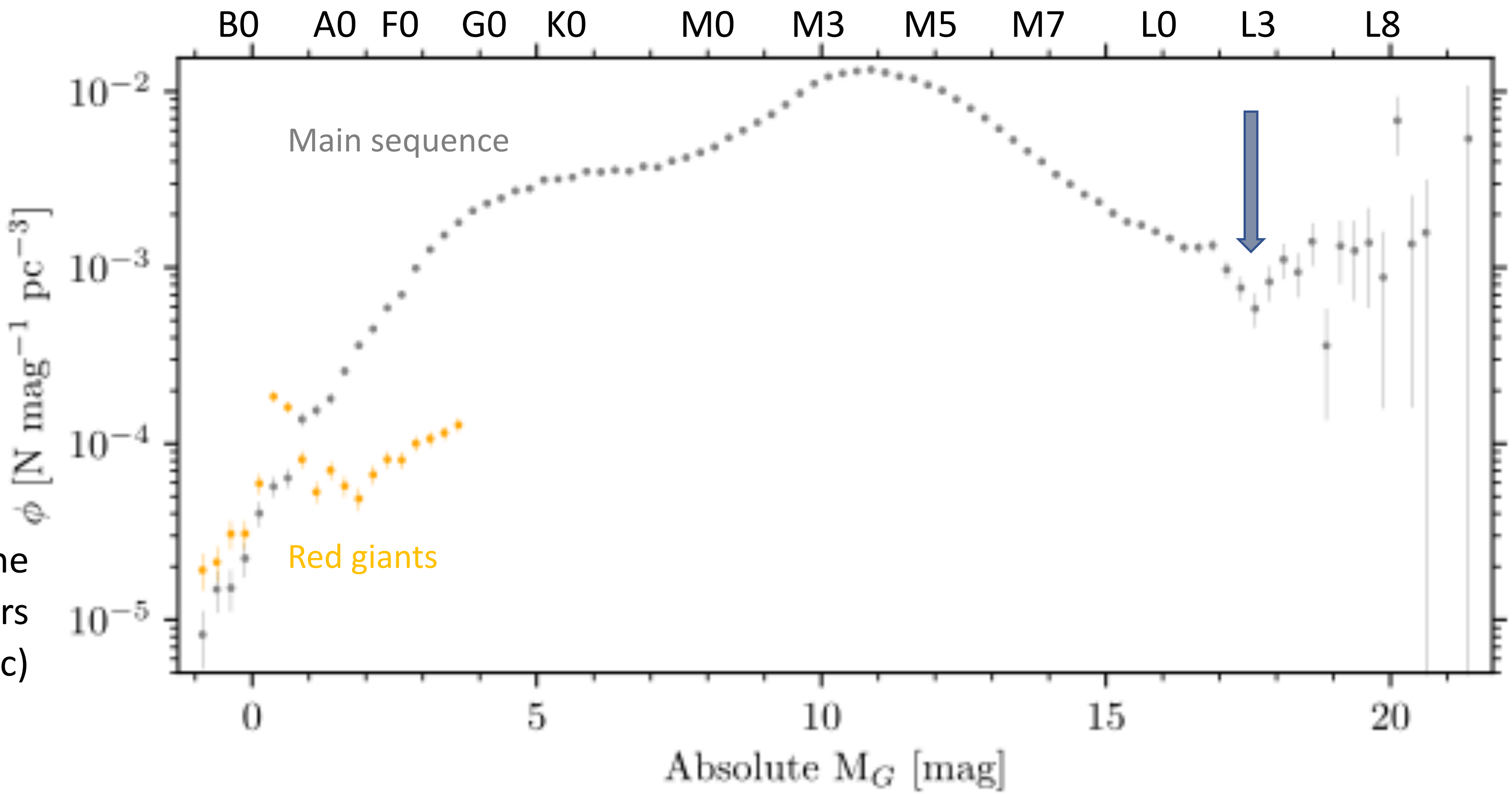

The luminosity function of the *Gaia* Catalogue of Nearby Stars (~330 000 stars within 100 pc)
Gaia Coll., Smart et al 2021

Conclusions

There are numerous ultracool dwarf candidates in *Gaia*, and more to come
High number, high precision, 5D information!

The precise locus in the HR diagram can give indication on the nature of the object: youth, binary, low metallicity.

A well-characterized sample with spectroscopic follow-up will be powerful **to test (sub)stellar models** (evolution, interior)

A well-characterized and complete volume-limited sample:

- provide luminosity and mass functions free of biases that plagued previous determinations
- Provide new insights on the stellar-substellar limit
- provide strong constraints on stellar and substellar formation theories.