Details of the H-R diagram:

the 'hot' stars in Gaia DR3

Y. Frémat

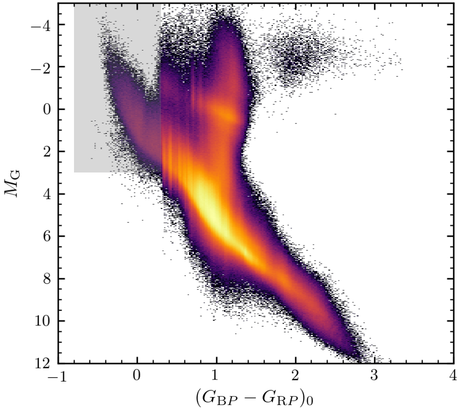
Royal observatory of Belgium (ROB)

Presentation Overview

- What are hot stars in Gaia ?
  - definition
  - how do they look like in Gaia's spectroscopy ?
- Overview of the methods used in Apsis to classify hot stars (GSP-Phot and ESP-HS)
- What information is available in Gaia DR3 ? Limits of application ?
- Summary and guidelines

What are 'Hot' Stars in Apsis ?

- $T_{\rm eff}$>7500 K
- intermediate to high mass stars
- A-, B-, O-type stars
- highly luminous, OCs, Galactic disk, higher reddening
- rapid rotators (median $V\sin i \sim 100\ \mathrm{km\,s^{-1}}$)
- 2 to 5 % of Gaia stars.
- all APs to be found in `gaiadr3.astrophysical_parameters`



Limited query on GSP-Phot and ESP-HS DR3 results.

What are 'Hot' Stars in Apsis ?

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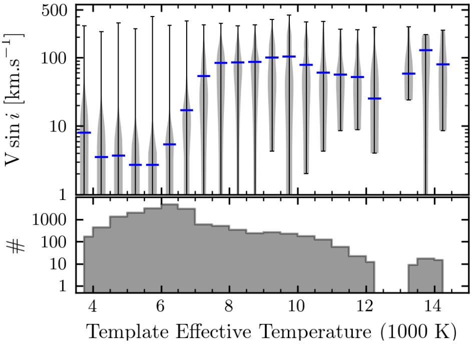

$V \sin i$ estimates taken from Glebocki & Gnaciski (2005)

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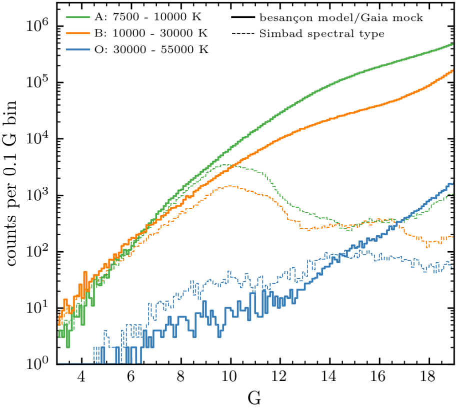
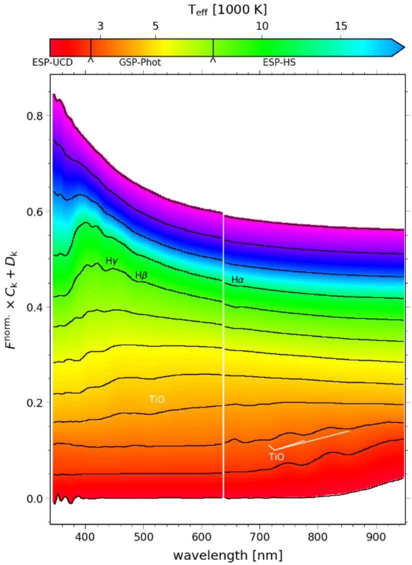
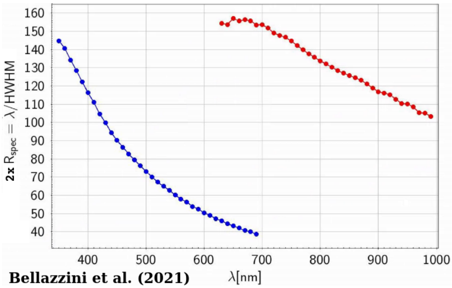


How are Hot Stars seen by Gaia's Spectrometers ?

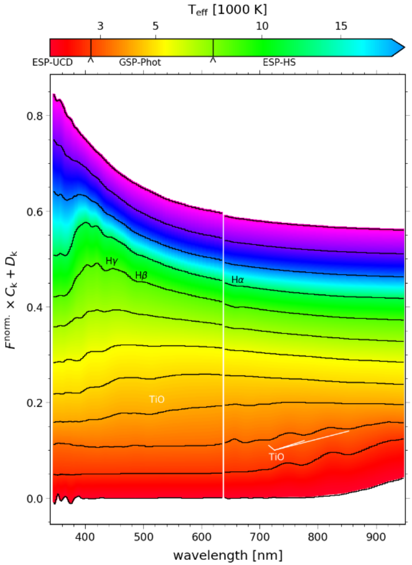


Fouesneau et al. 2023, Figure 4

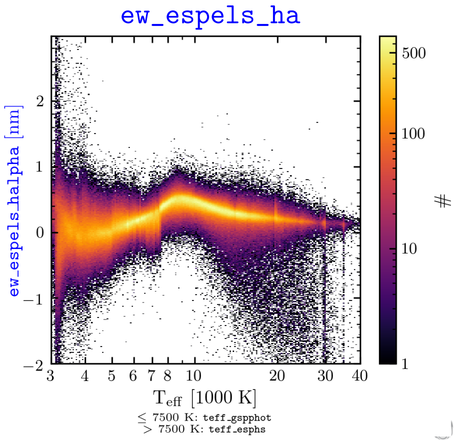


All Apsis input spectra have been time-averaged

How are Hot Stars seen by Gaia's Spectrometers ?

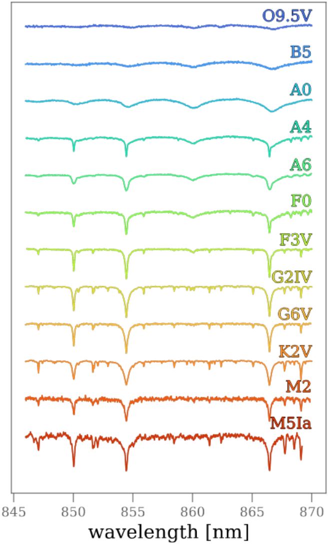


Fouesneau et al. 2023, Figure 4



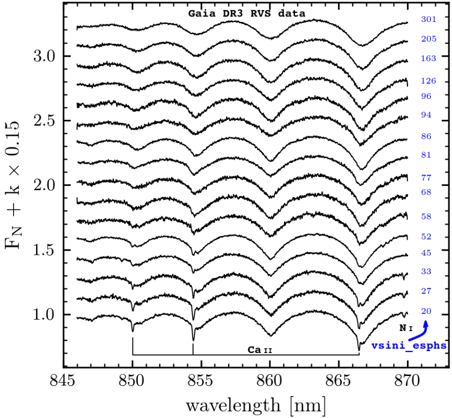
Creevey et al. 2023, adapted Figure 13

How are Hot Stars seen by Gaia's Spectrometers ?



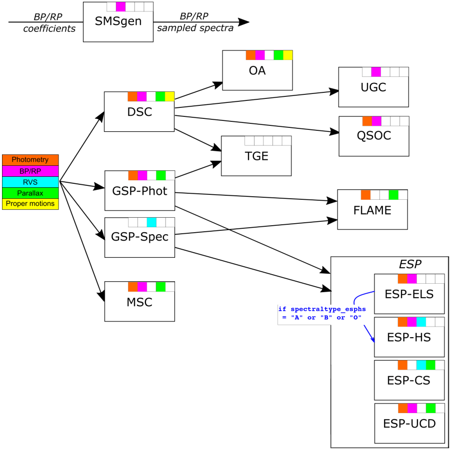
Fouesneau et al. 2023, Figure 6

All Apsis input RVS spectra have been time-averaged, R ∼ 11500

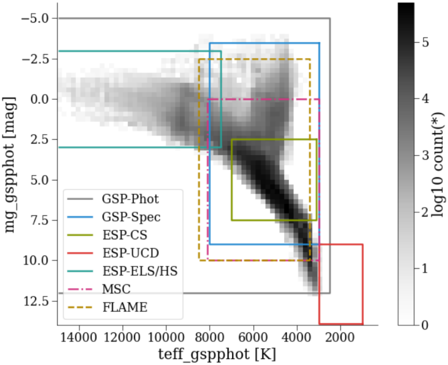


Zorec 2023, Figure 22

The Processing of Hot Stars by Apsis

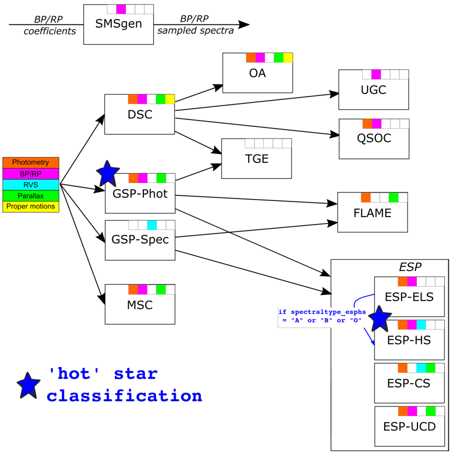


Creevey et al. 2023, adapted Figure 1

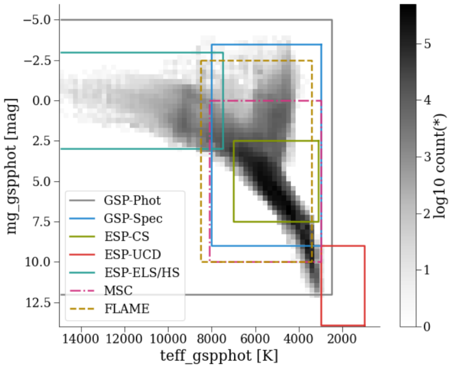


Creevey et al. 2023, Figure 7

The Processing of Hot Stars by Apsis



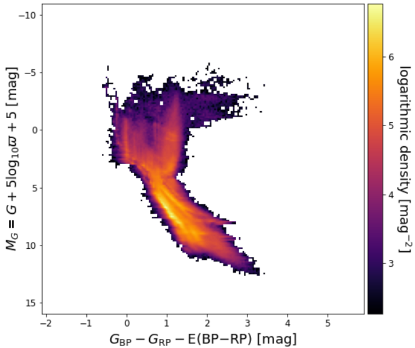
Creevey et al. 2023, adapted Figure 1



Creevey et al. 2023, Figure 7

GSP-Phot

- Andrae et al., 2023A&A...674A..27A
- fits the time averaged BP/RP, G, parallax
- derive fundamental parameters, [M/H], extinction/reddening
- $T_{\rm eff}$, $\log g$
- 4 synthetic spectra libraries (MARCS, PHOENIX, LL-models for A-type stars, OB Star TLUSTY libraries) + PASTEL isochrones



Andrae et al. 2023, Figures 4b & 5b

GSP-Phot

- Andrae et al., 2023A&A...674A..27A
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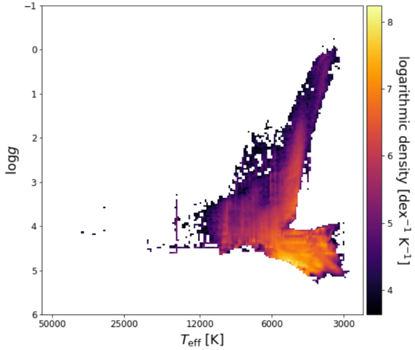
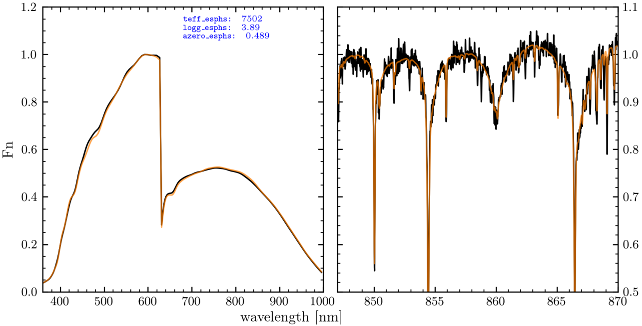


Andrae et al. 2023, Figures 4b & 5b

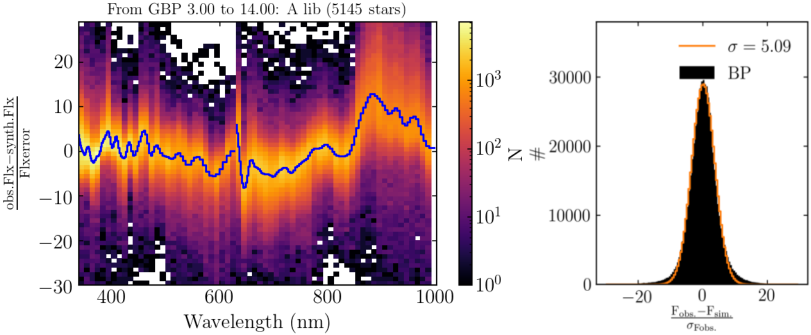
ESP-HS

- Input: time-averaged BP/RP and RVS spectra, G<17.65
- Synthetic spectrum fit to XP and RVS data (when available).
- rebinned to 3 samples
- Libs.: O. Kochukhov & D. Shulyak, OB star models (Lanz & Hubeny), Synspec
- Assumption: Solar chemical composition



ESP-HS

- Extinction: Fitzpatrick (1999), $R_V = 3.1$
- Synthetic/Simulations spectra of reference of A and B stars (w. strongren photometry) compared to Gaia XP data
- comparisons used to empirically improve the simulations, exclude domains
- no correlations taken into account



spectraltype_esphs, Pre-Selection of OBA Stars

- Random Forest algorithm
- Trained on all available synthetic spectra libraries (bands individually normalized) + (BP-RP)
- 340 - 600 nm & 640 - 800 nm
- Label/Spectral type tag follows mean T_{eff} ranges
- to be found in table `astrophysical_parameters`
- quality flag is qf=flags_esphs[1:2]

spectral type_esphs	effective temperature [K]		
M		$\leq$	3840
K	3840	-	5150
G	5150	-	5940
F	5940	-	7300
A	7300	-	9790
B	9790	-	30 000
O		$>$	30 000

spectraltype_esphs vs Simbad

Simbad (true, G < 18, qf ≤ 1) vs spectraltype_esphs (predicted)

	O	B	A	F	G	K	M	C
O	**316 R.: 47.6 P.: 52.6**	330 (49.7) (0.6)	5 (0.8) (0.0)	10 (1.5) (0.0)	1 (0.2) (0.0)	1 (0.2) (0.0)	1 (0.2) (0.0)	
B	267 (0.6) (44.4)	**41646 R.: 90.3 P.: 70.0**	3718 (8.1) (5.3)	428 (0.9) (0.4)	23 (0.0) (0.1)	5 (0.0) (0.1)	14 (0.0) (0.0)	
A	2 (0.0) (0.3)	16449 (19.9) (27.6)	**61978 R.: 74.9 P.: 89.1**	4272 (5.2) (4.2)	54 (0.1) (0.3)	11 (0.0) (0.1)	19 (0.0) (0.1)	
F	3 (0.0) (0.5)	857 (1.0) (1.4)	3580 (4.1) (5.1)	**82487 R.: 93.4 P.: 80.8**	1377 (1.6) (7.3)	24 (0.0) (0.3)	12 (0.0) (0.0)	1 (0.0) (0.0)
G	8 (0.0) (1.3)	149 (0.5) (0.3)	182 (0.6) (0.3)	13963 (45.7) (13.7)	**15973 R.: 52.3 P.: 84.3**	196 (0.6) (2.1)	50 (0.2) (0.1)	
K	1 (0.0) (0.2)	69 (0.6) (0.1)	103 (0.9) (0.1)	926 (8.3) (0.9)	1504 (13.5) (7.9)	**8007 R.: 71.9 P.: 85.3**	530 (4.8) (1.5)	4 (0.0) (0.0)
M	4 (0.0) (0.7)	11 (0.0) (0.0)	14 (0.0) (0.0)	51 (0.1) (0.0)	20 (0.1) (0.1)	750 (2.2) (8.0)	**33795 R.: 97.5 P.: 97.9**	27 (0.1) (0.3)
C			1 (0.0) (0.0)	1 (0.0) (0.0)		394 (4.0) (4.2)	95 (1.0) (0.3)	**9302 R.: 95.0 P.: 99.7**

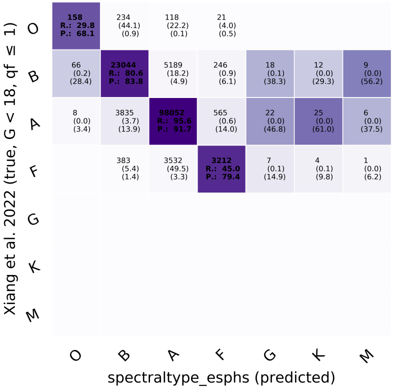
Simbad (true, G < 18, qf ≤ 5) vs spectraltype_esphs (predicted)

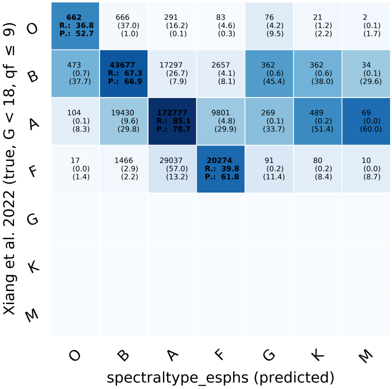
	O	B	A	F	G	K	M	C
O	**1070 R.: 49.5 P.: 35.1**	933 (43.1) (1.3)	11 (0.5) (0.0)	22 (1.0) (0.0)	3 (0.1) (0.0)	32 (1.5) (0.0)	85 (3.9) (0.1)	7 (0.3) (0.1)
B	1539 (2.8) (50.5)	**47013 R.: 84.3 P.: 64.4**	5381 (9.6) (5.9)	990 (1.8) (0.7)	429 (0.8) (0.7)	311 (0.6) (0.2)	98 (0.2) (0.2)	7 (0.0) (0.1)
A	38 (0.0) (1.2)	22736 (20.5) (31.1)	**77619 R.: 70.1 P.: 84.4**	9285 (8.4) (6.8)	283 (0.3) (0.5)	669 (0.6) (0.4)	75 (0.1) (0.1)	
F	49 (0.0) (1.6)	1750 (1.4) (2.4)	8358 (6.9) (9.1)	**101675 R.: 83.9 P.: 73.9**	7713 (6.4) (13.1)	1585 (1.3) (0.8)	75 (0.1) (0.1)	4 (0.0) (0.0)
G	52 (0.0) (1.7)	363 (0.3) (0.5)	392 (0.3) (0.4)	23637 (20.9) (17.2)	**44859 R.: 39.7 P.: 76.0**	43337 (38.4) (22.9)	208 (0.2) (0.3)	6 (0.0) (0.1)
K	87 (0.1) (2.9)	135 (0.1) (0.2)	187 (0.1) (0.2)	1775 (1.3) (1.3)	5481 (3.9) (9.3)	**127120 R.: 90.9 P.: 67.1**	5019 (3.6) (7.8)	38 (0.0) (0.4)
M	188 (0.3) (6.2)	73 (0.1) (0.1)	30 (0.0) (0.0)	107 (0.2) (0.1)	254 (0.4) (0.4)	10408 (15.0) (5.5)	**58008 R.: 83.8 P.: 89.9**	174 (0.3) (1.8)
C	22 (0.1) (0.7)	2 (0.0) (0.0)	2 (0.0) (0.0)	13 (0.1) (0.0)	21 (0.1) (0.0)	5986 (36.6) (3.2)	970 (5.9) (1.5)	**9335 R.: 57.1 P.: 97.5**

- qf=flags_esphs[1:2]
- color shades vary vertically, with lower (P) percentage in the cell
- contamination from neighbour types expected, but much stronger between O and B types

spectraltype_esphs vs LAMOST DR6

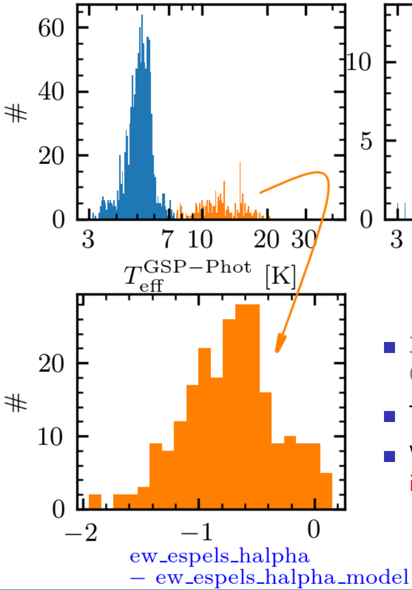
Xiang et al. 2022





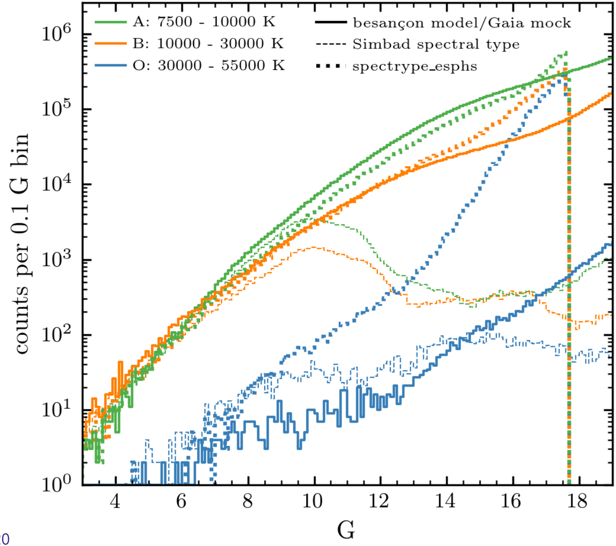
- Xiang et al's T_{eff} converted into spectral type tag. See Table A.1 in Creevey et al. 2022.
- 320 578 with ESP tag. 1865 received a G,K or M tag ...

spectraltype_esphs vs LAMOST DR6



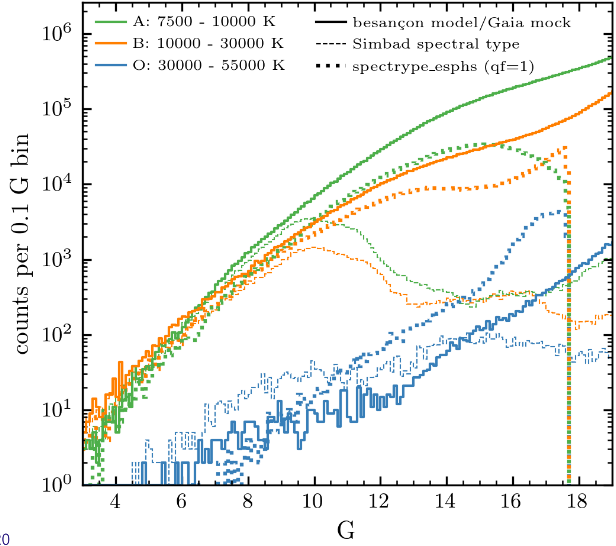
- 320 578 with ESP tag. 1865 received a G,K or M tag ...
- Tag more consistent with GDR3 results
- Wrong tag: probably due to x-match issues or due to emission.

ESP-HS: spectraltype_esphs



Robin et al. 2012
Rybizki et al. 2020

ESP-HS: spectraltype_esphs



Robin et al. 2012
Rybizki et al. 2020

APs @astrophysical_parameters Table

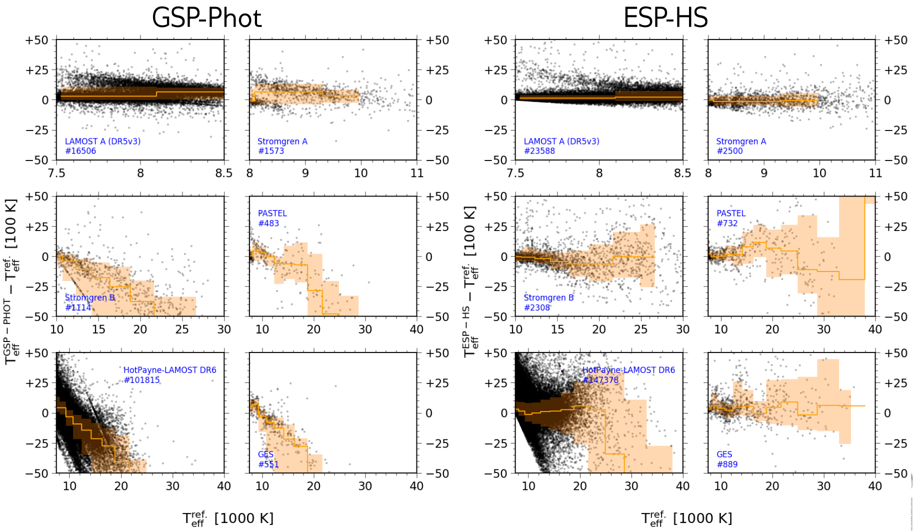
teff_gspphot
logg_gspphot
mh_gspphot
distance_gspphot
azero_gspphot
ag_gspphot
abp_gspphot
arp_gspphot
ebpminrp_gspphot
mg_gspphot
radius_gspphot
libname_gspphot

azero_esphs
ag_esphs
ebpminrp_esphs
teff_esphs
logg_esphs
vsini_esphs
flags_esphs
spectraltype_esphs

⋆_gspphot_upper
⋆_gspphot_lower

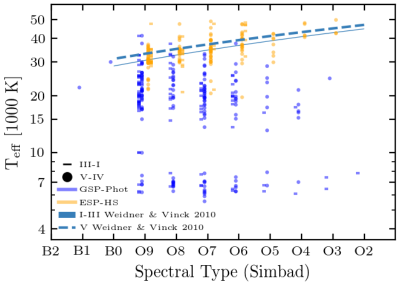
⋆_esphs_uncertainty

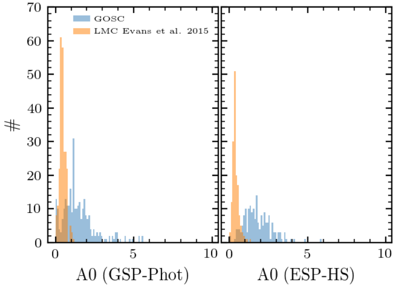
Effective Temperature



A: ∼ 300 K, B: 500 - 2000 K, O: 1000 - 5000 K

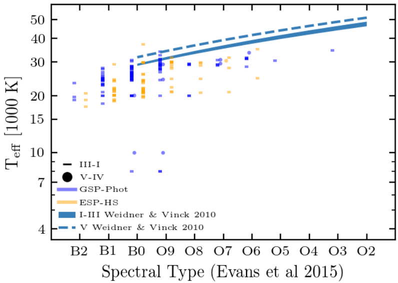
MW Temperature Scale

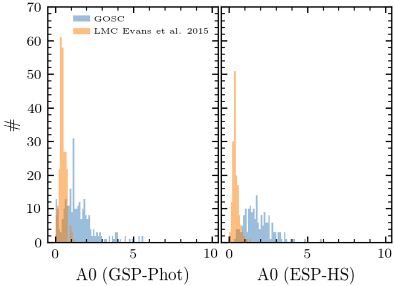




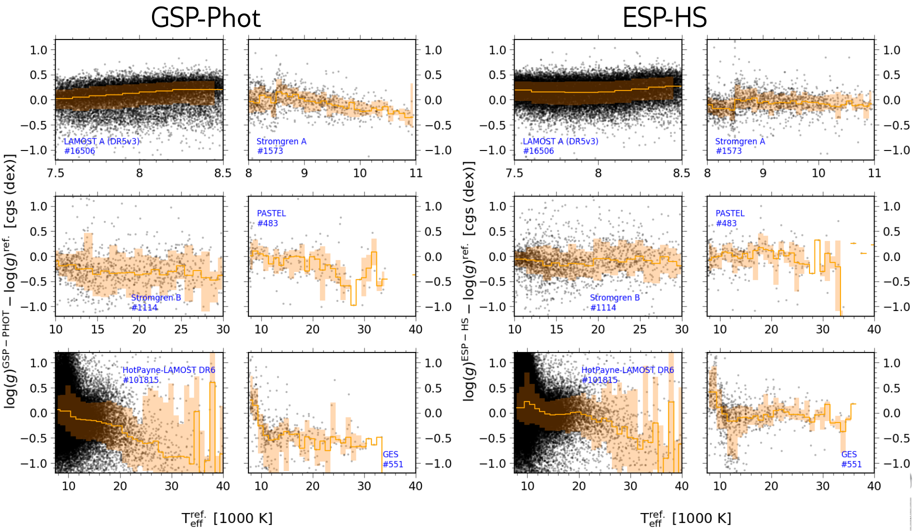
- priors adopted in GSP-Phot
- different kinds of template mismatches from library to library
- parallax uncertainties
- in a given library: specific systematics

LMC Temperature Scale





Surface Gravity

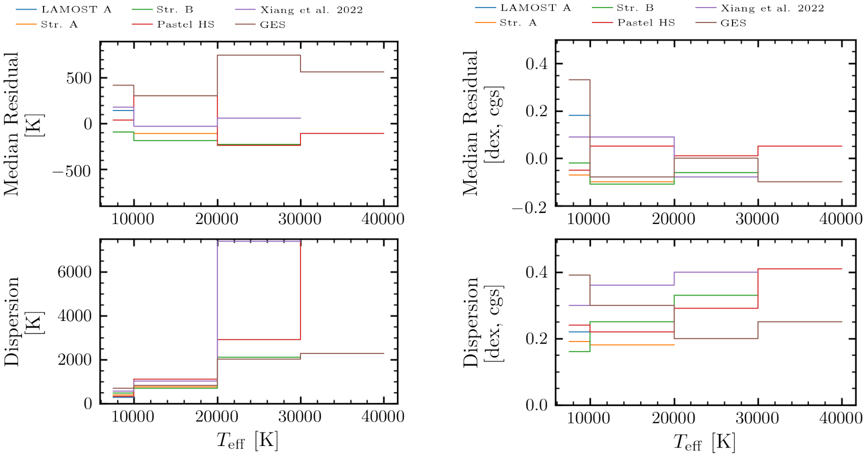


A: ∼0.2 dex, O: ∼0.4 dex

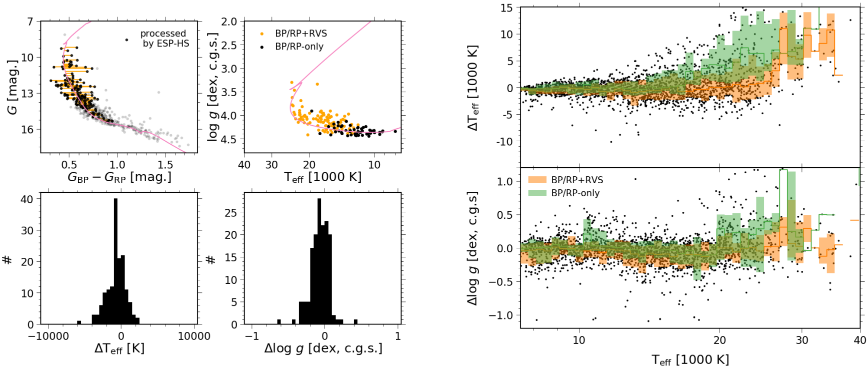
ESP-HS: Bias and Dispersion

Effective Temperature

Surface Gravity

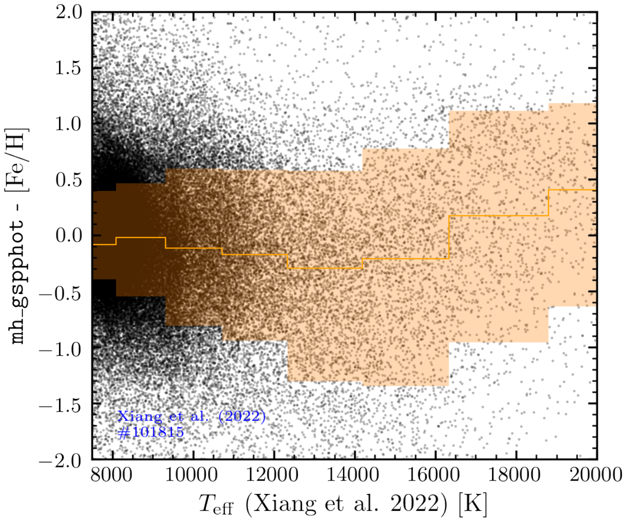


ESP-HS: AP Determination in Clusters

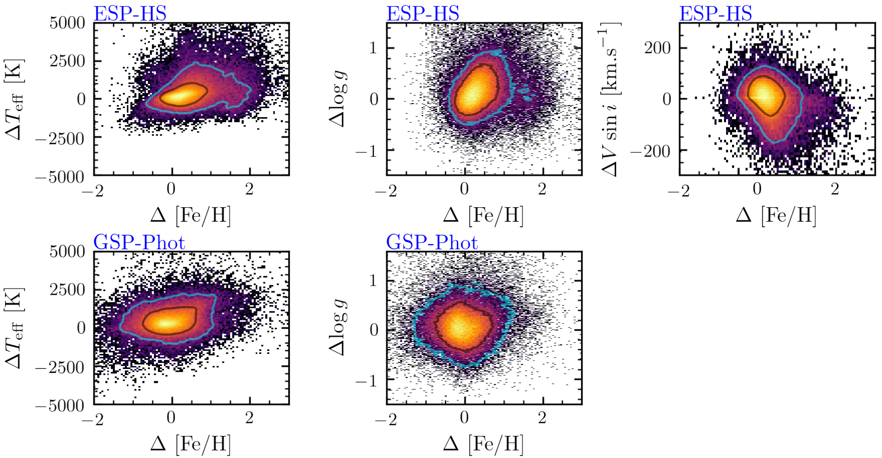


- Cluster members and parameters: Cantat-Gaudin et al. 2022
- Left: Case of NGC869, Right: 1524 members of 42 open clusters
- CD used to identify the closest isochrone point
- $T_{\rm eff}$: disp 800-6000 K; $\log g$: disp 0.15-0.30 dex

GSP-Phot: Metallicity

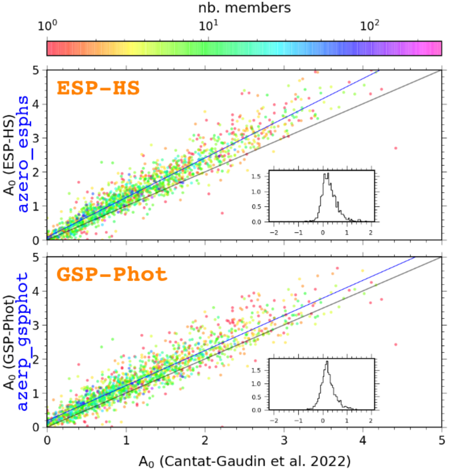


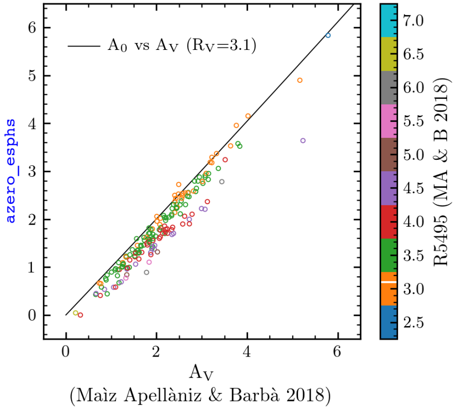
ESP-HS: Impact of the Solar Metallicity Assumption



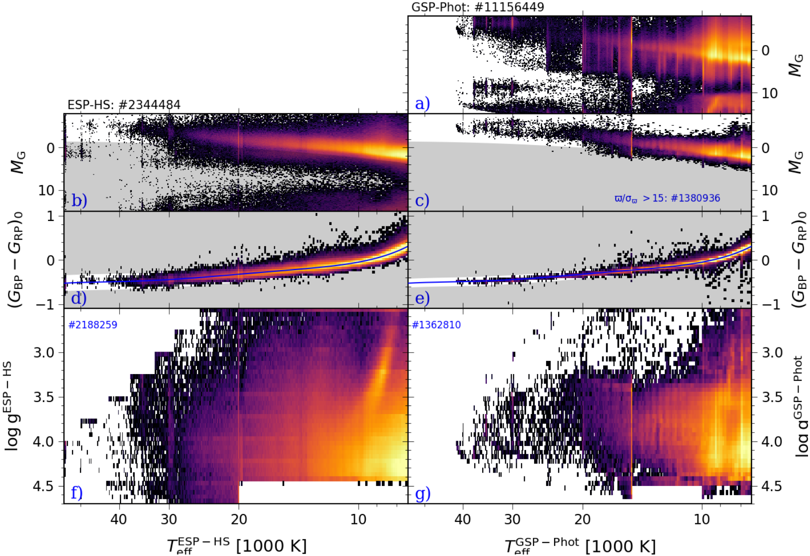
$T_{\rm eff} < 10\,000$ K, flags_esphs[0:1]=0 (BP/RP + RVS mode), same sample

Interstellar Extinction





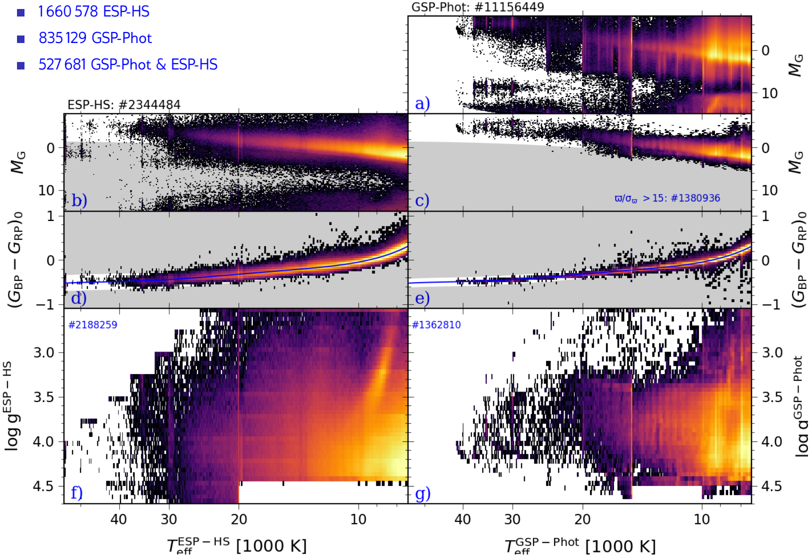
OBA Golden Sample



Creevey et al. 2023, Figure 1

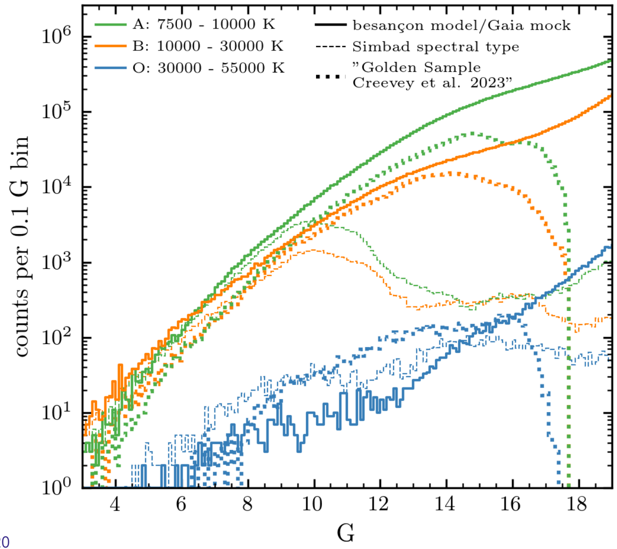
OBA Golden Sample

- Total of 3 023 388 "golden" OBA
- 1 660 578 ESP-HS
- 835 129 GSP-Phot
- 527 681 GSP-Phot & ESP-HS



Creevey et al. 2023, Figure 1

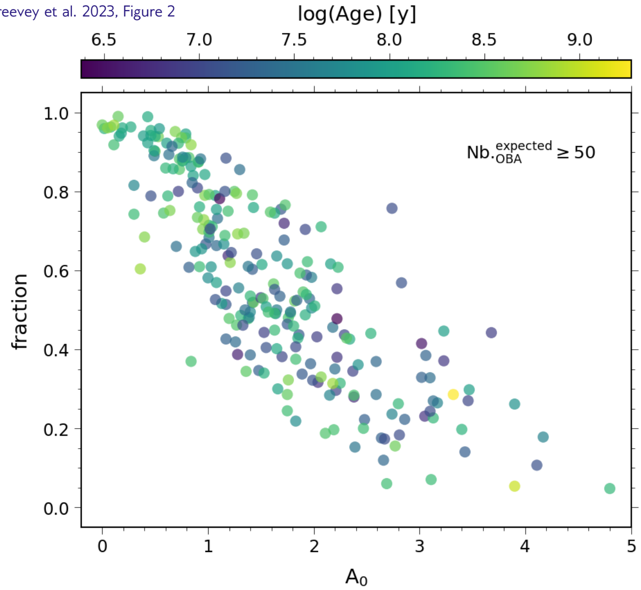
Golden Sample Magnitude Distribution



Robin et al. 2012
Rybizki et al. 2020

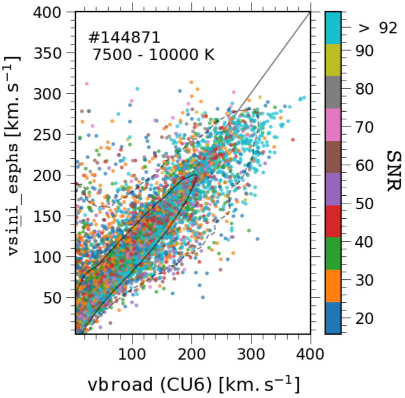
Completeness of the OBA Sample from OCs

Creevey et al. 2023, Figure 2

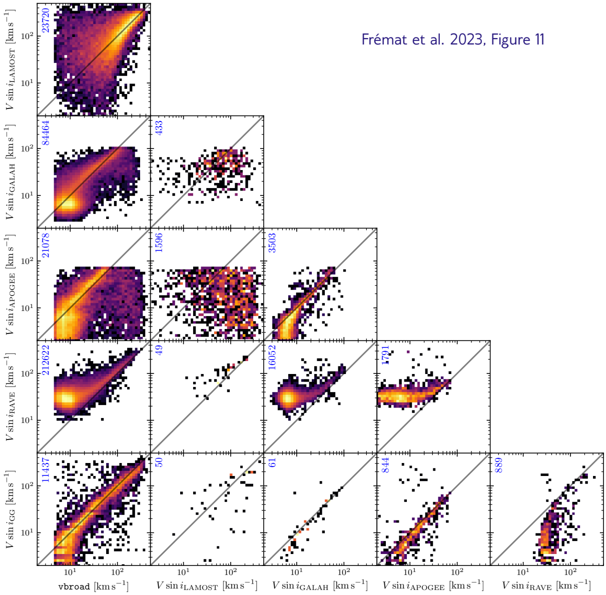


RVS Line Broadening Determination

- In GDR3, there exist 2 estimates of the RVS line broadening.
  - measured on single transit (epoch) data: `vbroad` in `gaia_source`
  - estimated on co-added spectra: `vsini_esphs`
- both assume no broadening other than rotation
- `vbroad` assumed for $T_{\rm eff} < 15\,000$ K
- `vsini_esphs` assumes Gaussian instruments LSF (R = 11 500), $T_{\rm eff} > 7500$ K



gaiasource.vbroad vs GB Surveys



Frémat et al. 2023, Figure 11

vsini_esphs vs LAMOST (Xiang et al. 2022)

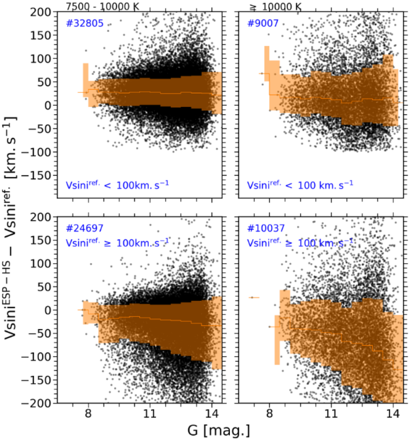
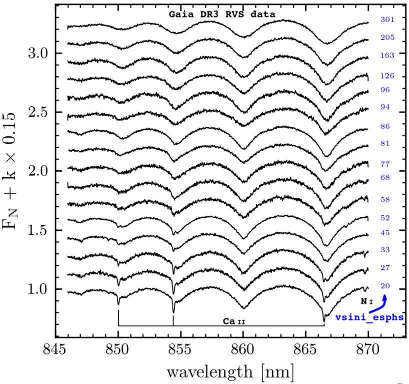


Figure 20 in Fouesneau et al. 2023

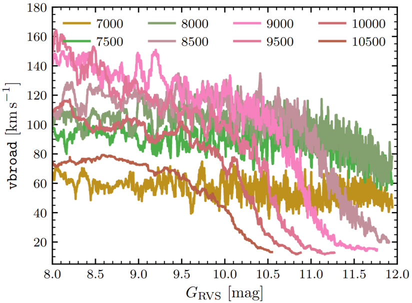


Zorec 2023, Figure 22

'Epoch' vbroad vs. 'Co-Added' vsini_esphs

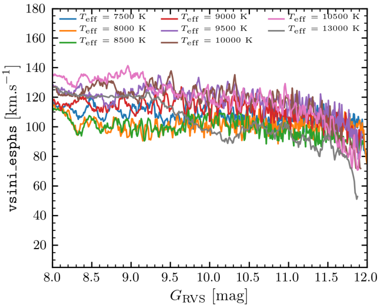
on epoch RVS spectra

Single Transit Analysis (CU6)



on co-added RVS spectra

ESP-HS (CU8)



Frémat et al. 2023, Figure 14

Summary on Gaia Hot Stars APs usage

- gaiadr3.gold_sample_oba_stars is a good start
- at $T_{\rm eff} > 10\,000$ K, ESP-HS APs should be preferred, especially when reddening becomes significant
- in the A-type domain GSP-Phot and ESP-HS are complementary (many non-overlapping targets), but when overlapping GSP-Phot APs should be preferred (metallicity)
- spectraltype_esphs is also a good way to start pre-selecting OBA stars, especially when no APs are available
- gaiasource.vbroad and vsini_esphs are statistically meaningful, but cautious is required on a case by case basis.

```
SELECT ap.source_id,ap.spectraltype_esphs,
 ap.teff_gspphot as T, (ap.teff_gspphot_upper-ap.teff_gspphot_lower)/2. as eT,
 ap.logg_gspphot as LOGG, (ap.logg_gspphot_upper-ap.logg_gspphot_lower)/2. as eLOGG,
 ap.mh_gspphot as MH, (ap.mh_gspphot_upper-ap.mh_gspphot_lower)/2. as eMH,
 'GSP-PHOT' as origin
FROM gaiadr3.astrophysical_parameters AS ap
INNER JOIN gaiadr3.gold_sample_oba_stars AS gs on gs.source_id=ap.source_id
WHERE ap.teff_gspphot IS NOT NULL AND ap.teff_esphs IS NULL
UNION
SELECT ap.source_id,ap.spectraltype_esphs,
 ap.teff_esphs as T, ap.teff_esphs_uncertainty as eT,
 ap.logg_esphs as LOGG, ap.logg_esphs_uncertainty as eLOGG,
 0 as MH, 0 as eMH,
 'ESP-HS' as origin
FROM gaiadr3.astrophysical_parameters AS ap
INNER JOIN gaiadr3.gold_sample_oba_stars AS gs on gs.source_id=ap.source_id
WHERE ap.teff_gspphot IS NULL AND ap.teff_esphs IS NOT NULL
UNION
SELECT ap.source_id,ap.spectraltype_esphs,
 ap.teff_gspphot as T, (ap.teff_gspphot_upper-ap.teff_gspphot_lower)/2. as eT,
 ap.logg_gspphot as LOGG, (ap.logg_gspphot_upper-ap.logg_gspphot_lower)/2. as eLOGG,
 ap.mh_gspphot as MH, (ap.mh_gspphot_upper-ap.mh_gspphot_lower)/2. as eMH,
 'GSP-PHOT' as origin
FROM gaiadr3.astrophysical_parameters AS ap
INNER JOIN gaiadr3.gold_sample_oba_stars AS gs on gs.source_id=ap.source_id
WHERE ap.teff_gspphot IS NOT NULL AND ap.teff_esphs IS NOT NULL AND ap.teff_esphs < 10000
UNION
SELECT ap.source_id,ap.spectraltype_esphs,
 ap.teff_esphs as T, ap.teff_esphs_uncertainty as eT,
 ap.logg_esphs as LOGG, ap.logg_esphs_uncertainty as eLOGG,
 0 as MH, 0 as eMH,
 'ESP-HS' as origin
FROM gaiadr3.astrophysical_parameters AS ap
INNER JOIN gaiadr3.gold_sample_oba_stars AS gs on gs.source_id=ap.source_id
WHERE ap.teff_gspphot IS NOT NULL AND ap.teff_esphs IS NOT NULL AND ap.teff_esphs >= 10000
```

Thank you for your attention

Oyster galaxy (https://www.etsy.com/shop/ScenesbyColleen)