Gaia & Stellar evolution

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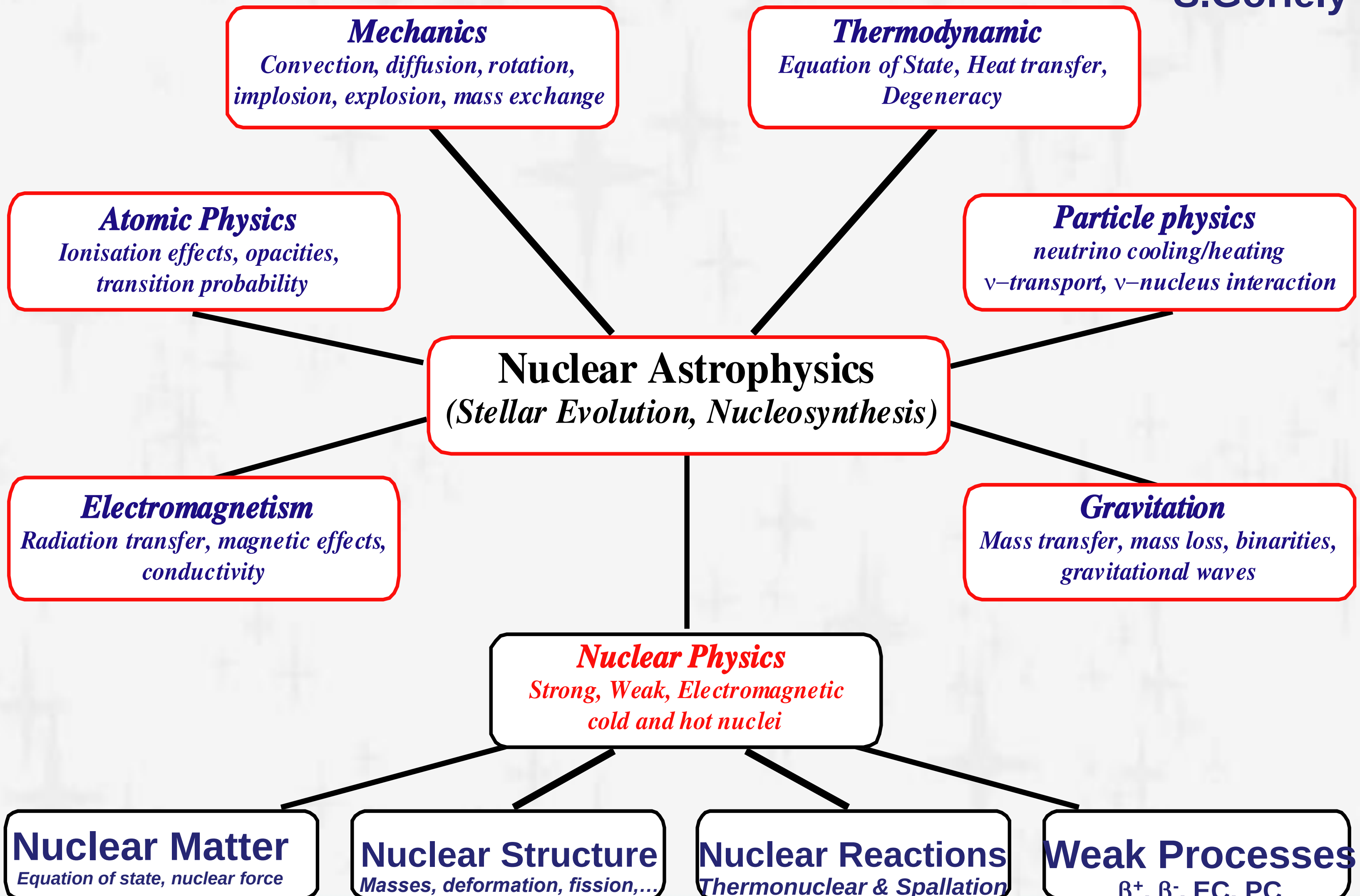
Stellar model ingredients

S.Goriely 2005



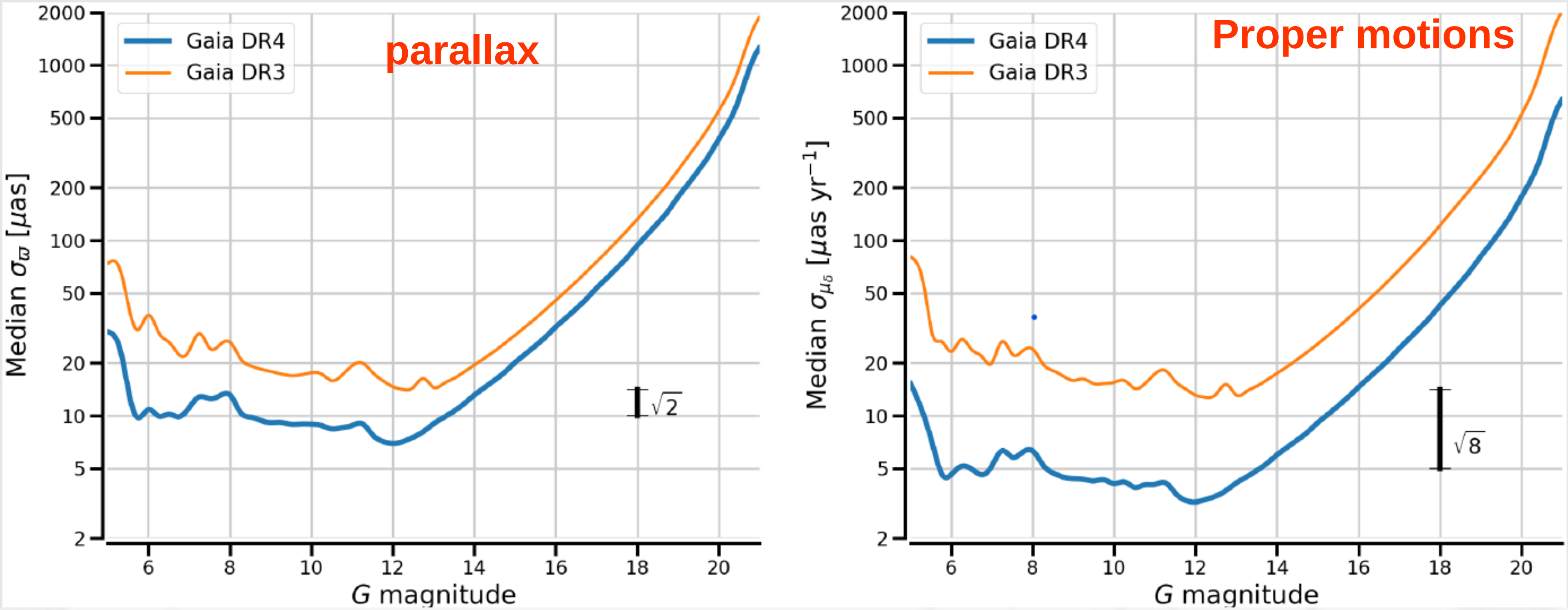
Current status of Stellar models

- 3D hydrodynamical models → still a challenge
- 1D models: simplified approched using free parameters: -
  - **mixing**(semiconvection,overshoot,diffusion,extra-mixing)
  - **rotation (**magnetic braking, rotational mixing)
  - **EOS** (critical for m<0.7 Mo)
  - **nuclear reaction rates**
  - **bolometric corrections** (ATLAS9, Phoenix...)

What Gaia will provide

- High quality parameters
  - Mag, colors, parallaxes, Teff, logg, chemical abundances,
  - Rotational velocity
- Good statistics
- + ground based spectroscopy (APOGEE, GALAH…WEAVE,4MOST) → Angela’s talk
- → fundamental for stellar evolution calibration

Astrometry

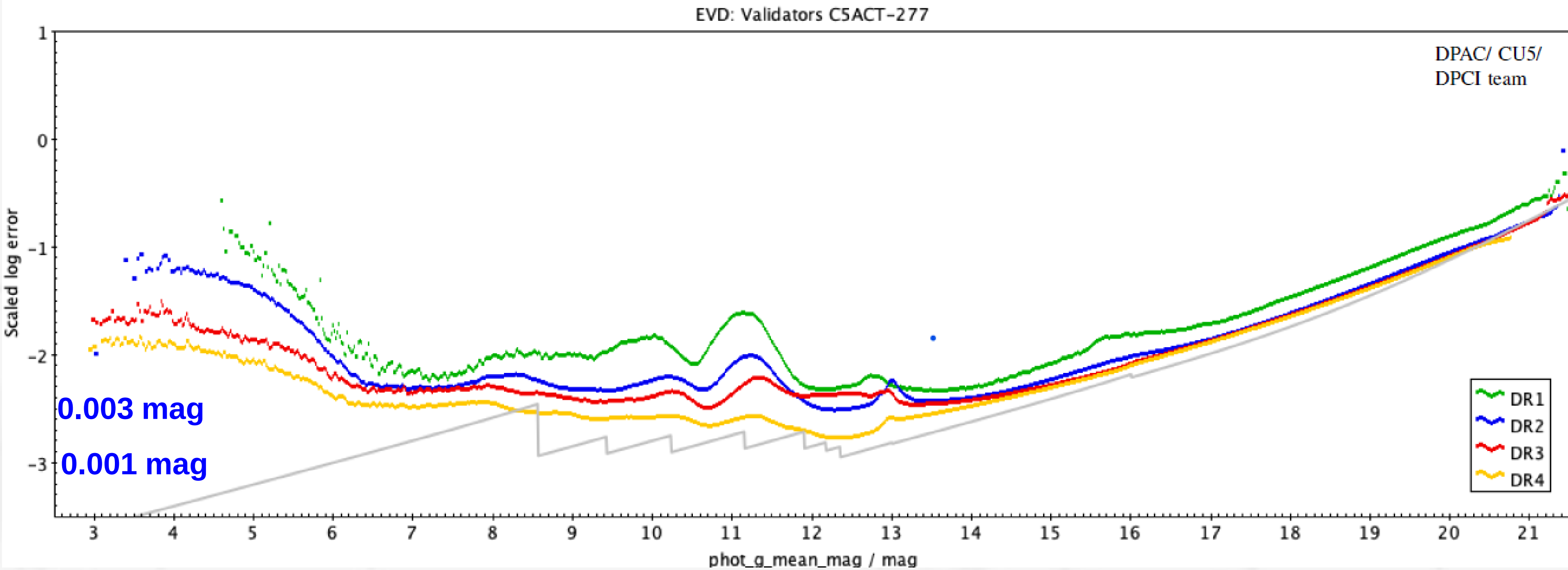


- Basic mission results improve with $t^{-0.5}$

  (Positions, parallaxes, photometry and radial velocities)→ factor 1.4 (DR4), 1.9(DR5)

- Proper motion improvement scales as $t^{-1.5}$
- Rapidly increasing gain in kinematics and dynamics→ factor 2.7 (DR4), 6.6 (DR5)

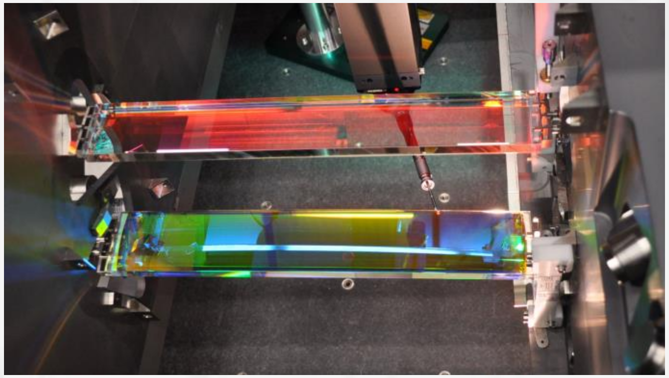
G, BP,RP Photometry



Uncertainties are scaled to single CCD transit

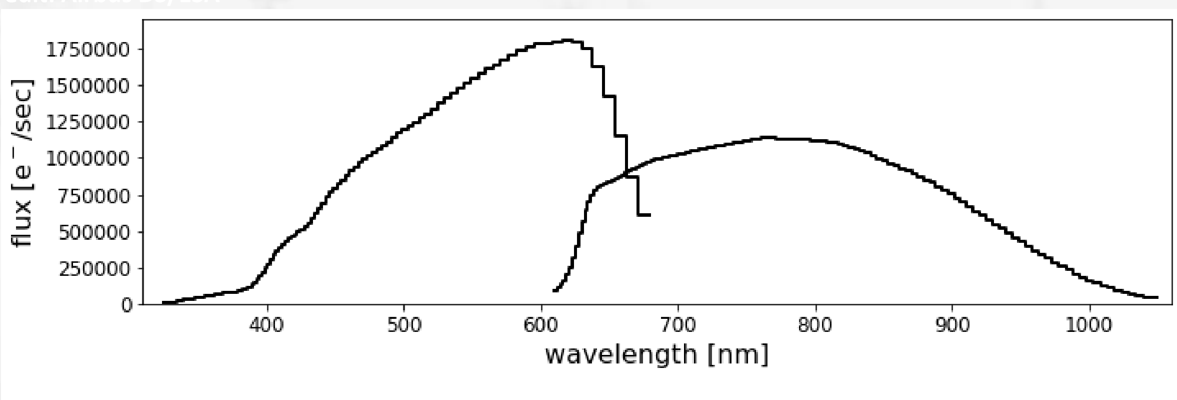
- shows the improvements in photometric processing from one release to the next
- The uncertainties on the means will include the effect increasing number of observations

BPRP spectra



credit: Airbus DS/ESA

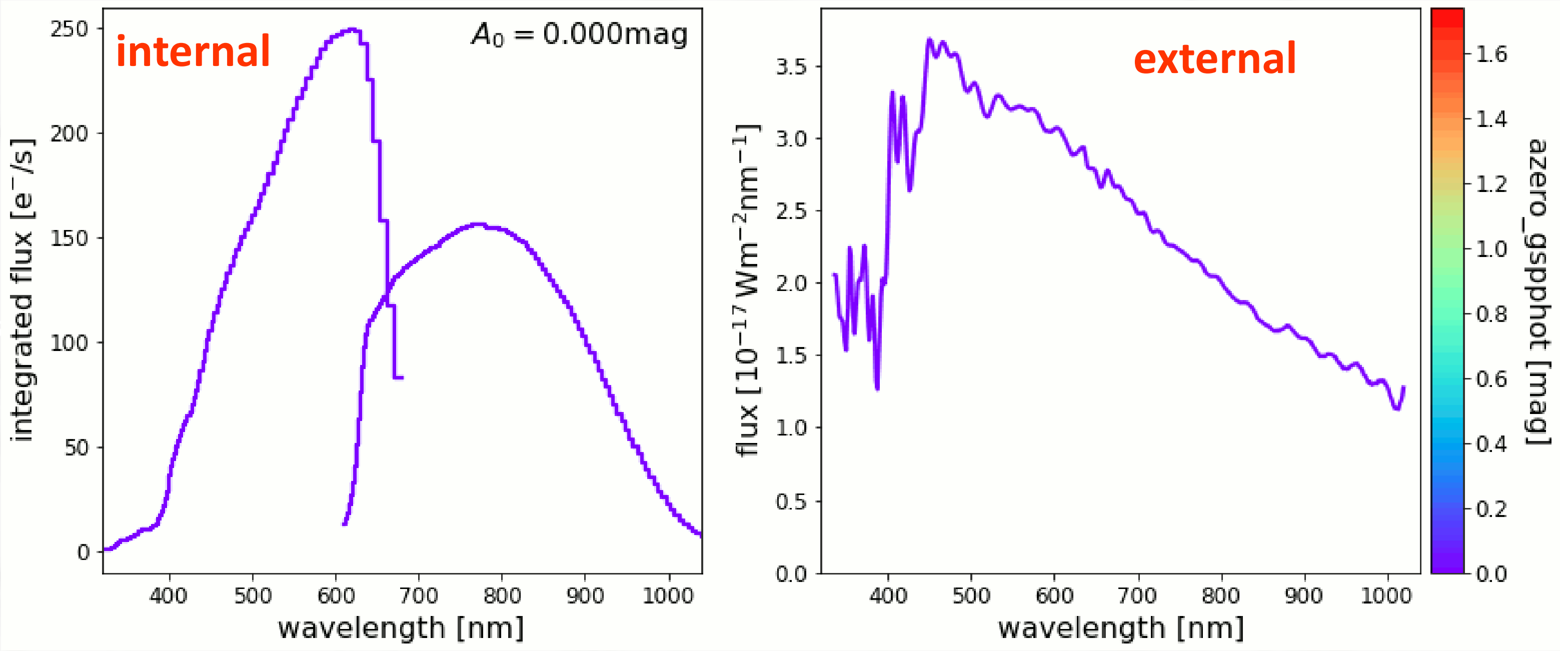
- 2 prisms: BP + RP = XP
- optical + NIR wavelength, resolution 20-60 (Montegriffo et al. 2023)



Solar type star

MS=Mean Spectra

BPRP spectra dependencies



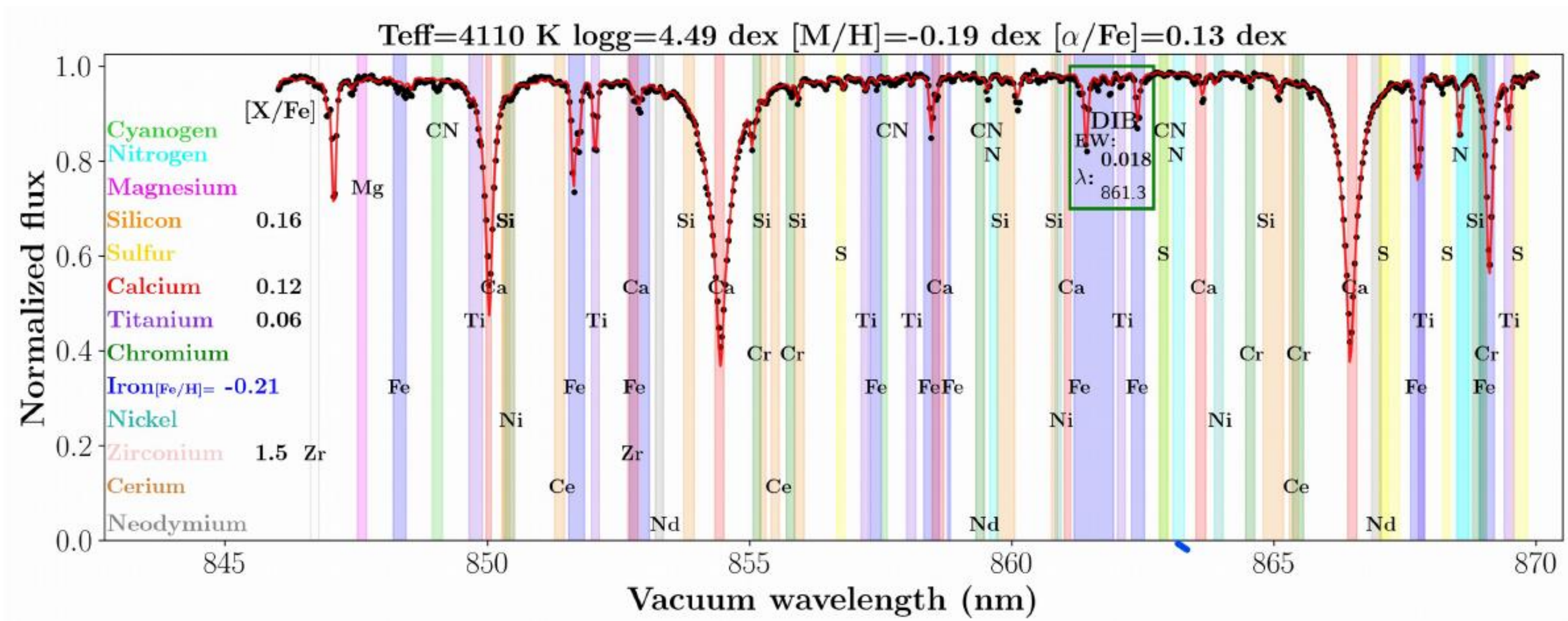
credit: Airbus DS

Solar type star

Effect of the extinction: Teff-AG degeneracy

RVS spectra

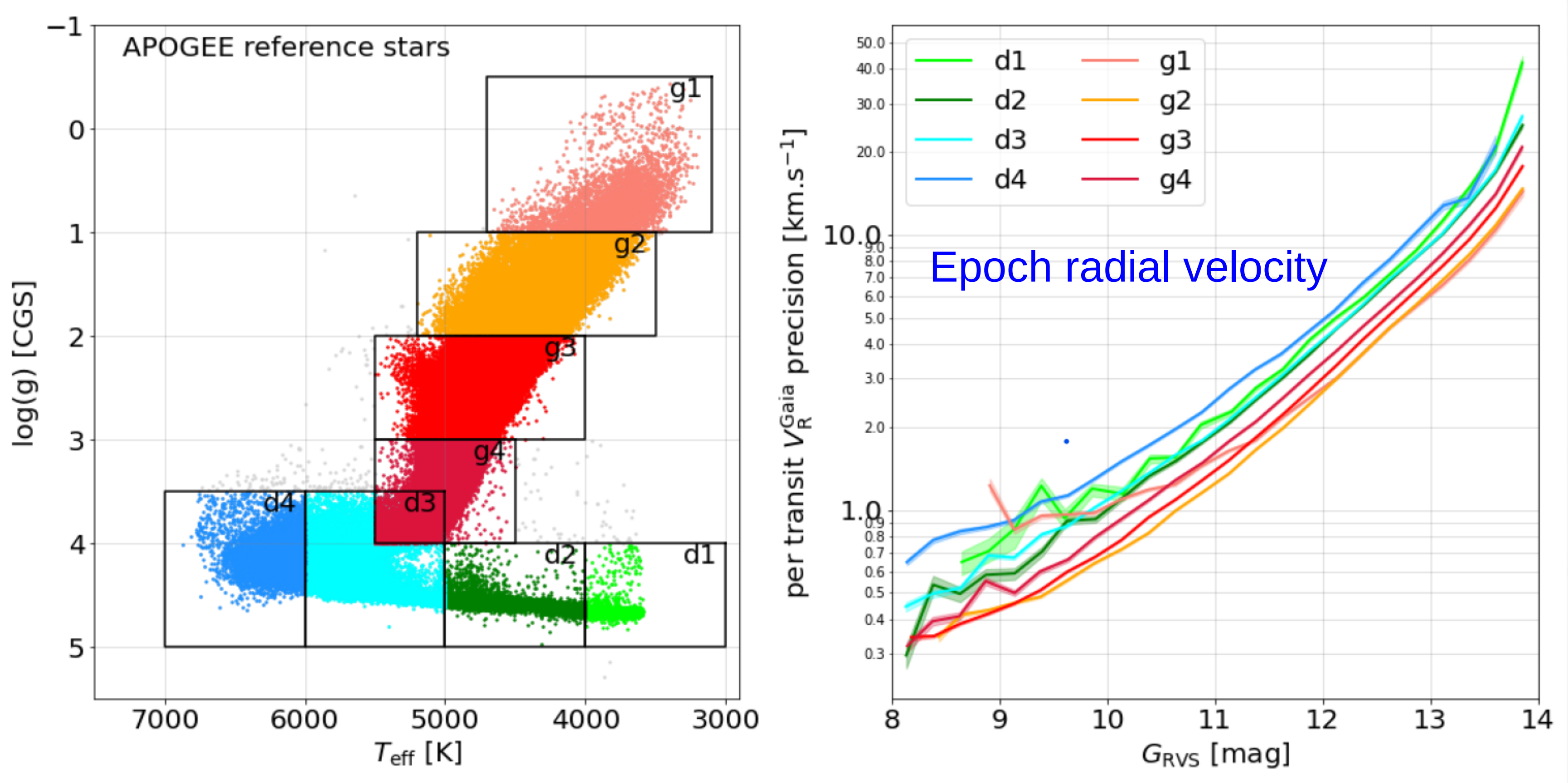
CU8/GSPspec: The chemical composition of **5.6 million** stars.



Gaia IoW. Credits:ESA/GAIA/DPAC-CU8-CU6 Recio-Blanco and the GSPspec team

- R=11,500
- Spectral range : CaII triplet: 846 - 870 nm

Radial velocities

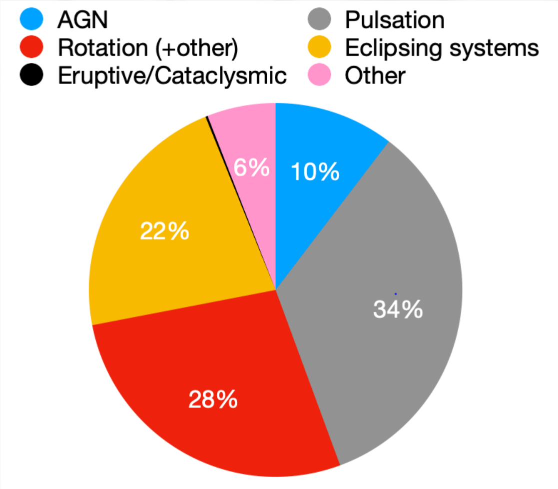


In DR3 33M of radial velocities

DR3 Variables

	Classified as variable
Total	10 509 536
Cepheids	15 021
Compact companions	6 306
Eclipsing binaries	2 184 477
Long-period variables	1 720 588
Microlensing events	363
Planetary transits	214
RR Lyrae stars	271 779
Short-timescale variables	471 679
Solar-like rotational modulation variables	474 026
Upper-main-sequence oscillators	54 476
Active galactic nuclei	872 228

Radial velocity time series	1898	Sample of Cepheids and RR Lyrae



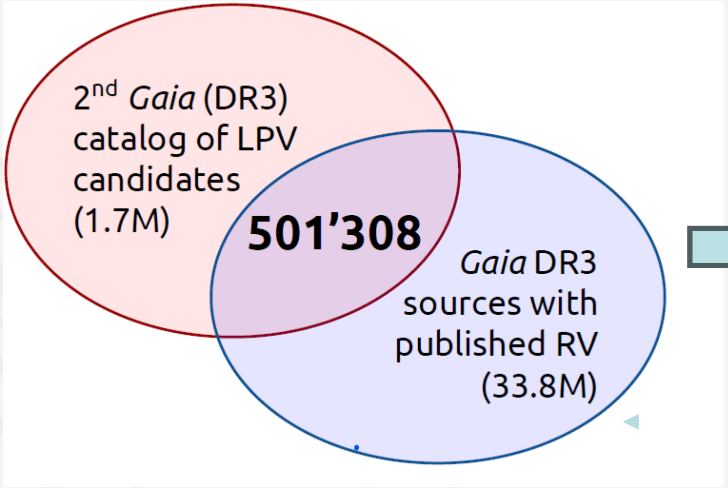
In DR2 500,000 stars in 6 variability type

Overview:

Eyer et al (2022) and references therein

Radial Velocities time series of LPVs

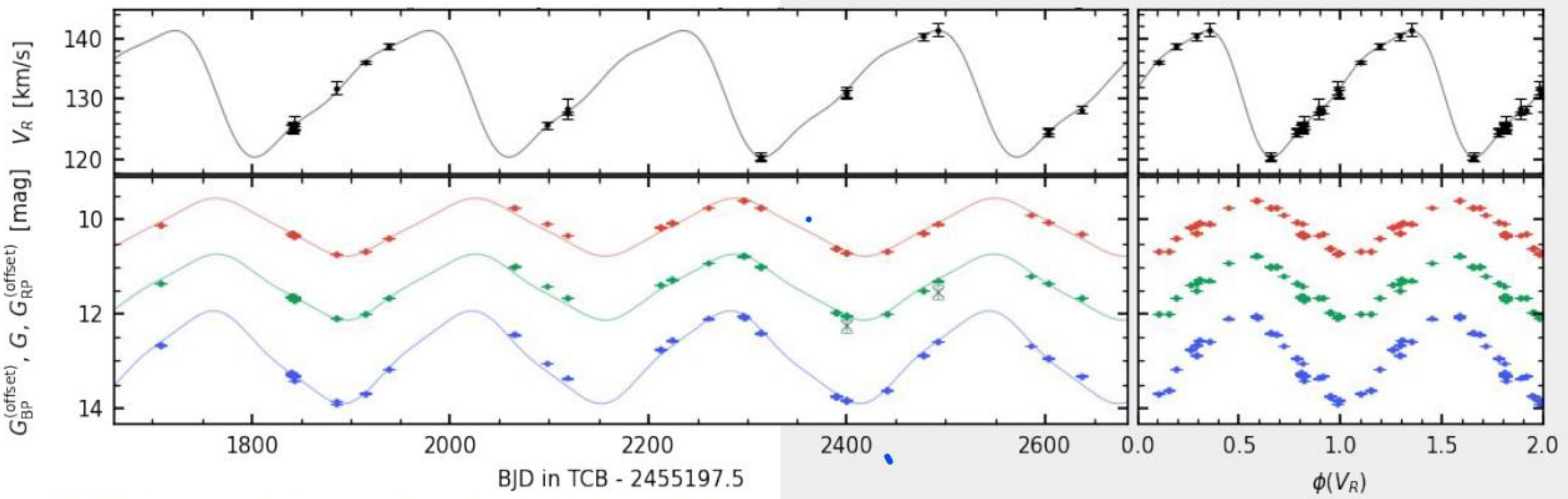
- In DR3 10 Million Variables
- Light curves for 1.7 M LPVs in DR3
- radial velocity time series of 2000 Cepheids and RR-Lyrae



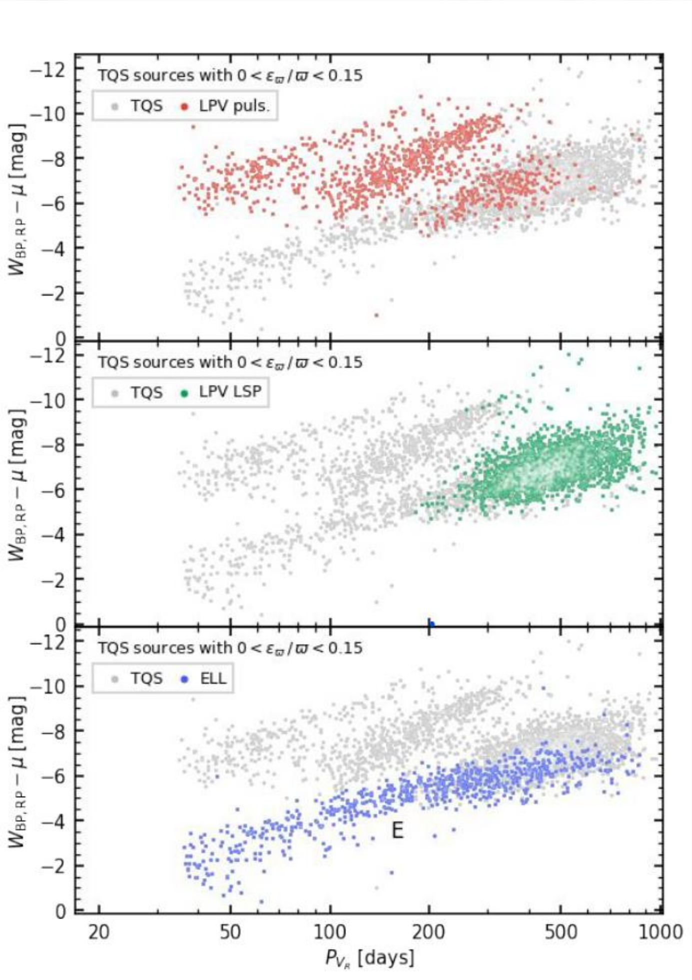
- 9614 LPV candidates with RV in DR3
- 34-months baseline RV + photometric time series
- pulsating stars
- ellipsoidal binaries
- red giants with long secondary periods

Gaia Collab, Trabucchi, Mowlavi, Lebzelter et al 2023

LPV final evolution of low & intermediate mass stars
Candidate ellipsoidal variables due to tidal interaction with a companion in a close binary system. → Michele's talk



RV / photometric time series of a pulsating LPV

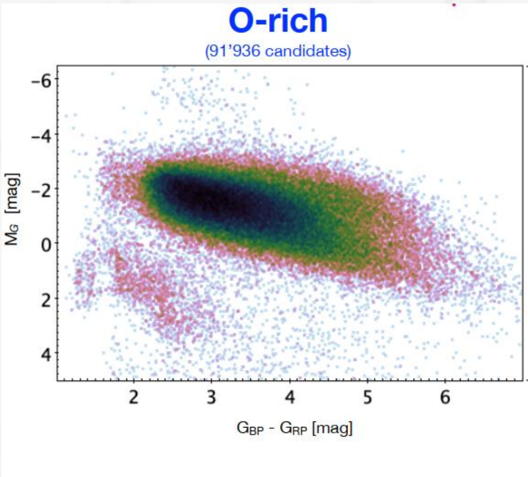


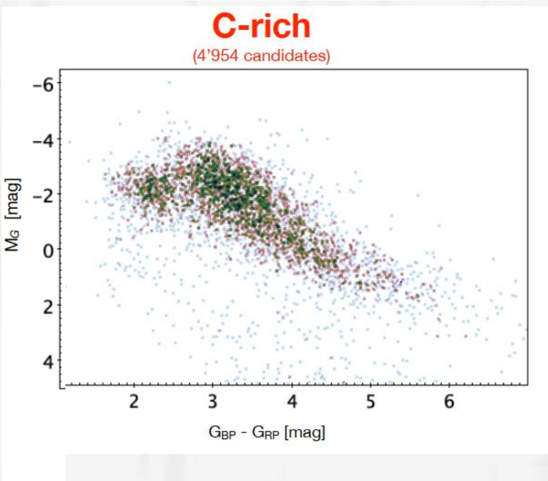
- **Pulsating long-period variables: Miras and semi-regular variables**

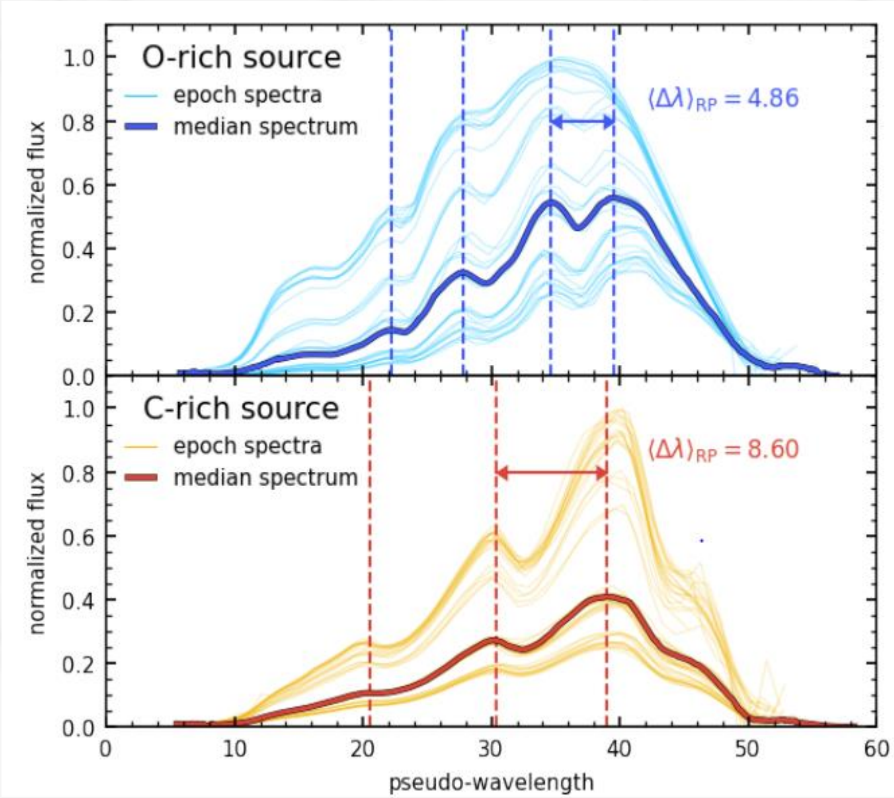
  $P_{VR} = P_{ph}$

- **Red giants with long secondary periods**

- **Ellipsoidal red giants**







TiO band near 900 nm

CN band near 800 nm

- LPV in DR3: 1.7 million, including 0.6 million carbon stars

Variable YSOs

Variability in YSOs occurs on timescales that span a wide range and depend on the physical processes

Gaia sensitive to variations of the order of 100-200 days (outbursts, circumbinary disk occultations)

79 375 candidates (40,000 unknown)

(Marton +2023)

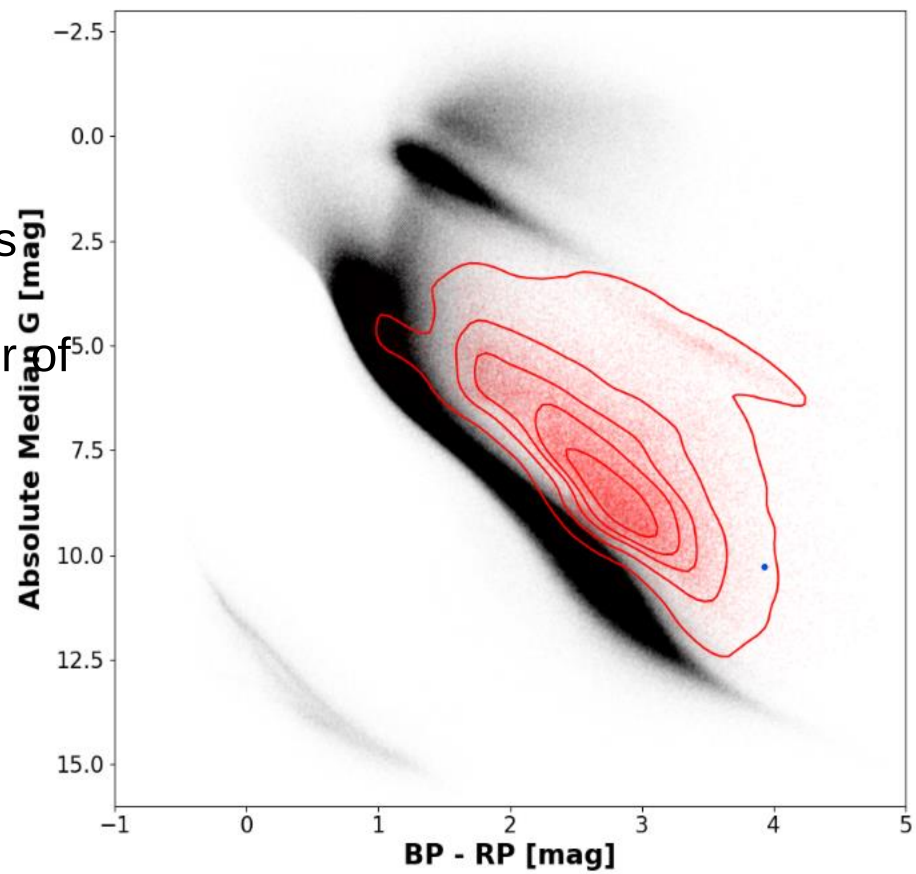


Fig. 1. Observational HRD of *Gaia* DR3 YSOs (red dots) and reference sources based on 4.2 million *Gaia* objects (black dots) selected based on their highly reliable parallax, sufficient S/N in both BP and RP bands, and the sufficiently high number of data points in their light curves. The *Gaia* DR3 YSOs occupy a specific region above the main sequence and below the giant branch. The contour levels are at 5%, 25%, 45%, 65%, and 85% of the maximum density value. In the comparison with other

Vbroad & Vsini

Vsini → the true projected rotational velocity

Vbroad:→ vsini +other broadening mechanisms (macroturbulence, pulsation, stellar winds, binarities, poor LSF correction) for Teff=3100 to 14 500 K (3M stars in DR3). From epoch spectra

vsini_esphs (astrophysical_parameters table) vsini for Teff> 7500 K,co-added spectra, rotation kernel

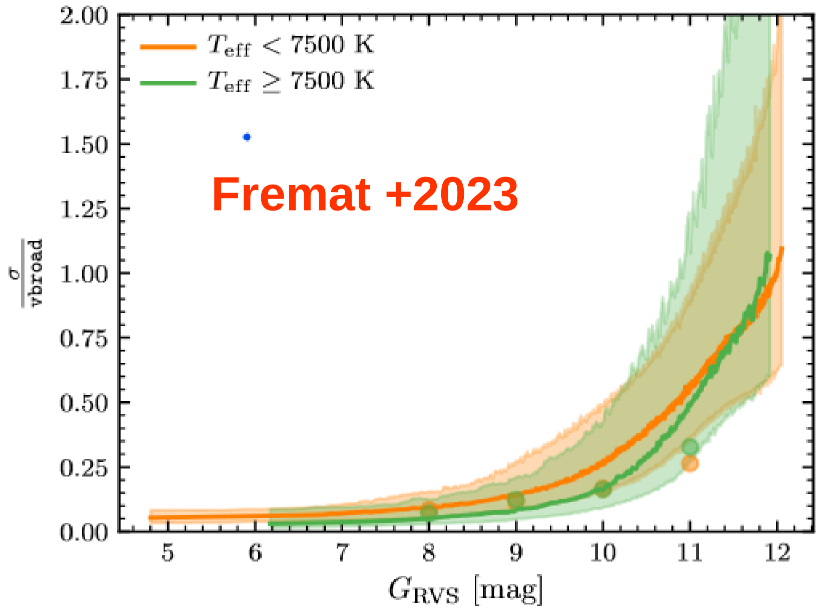
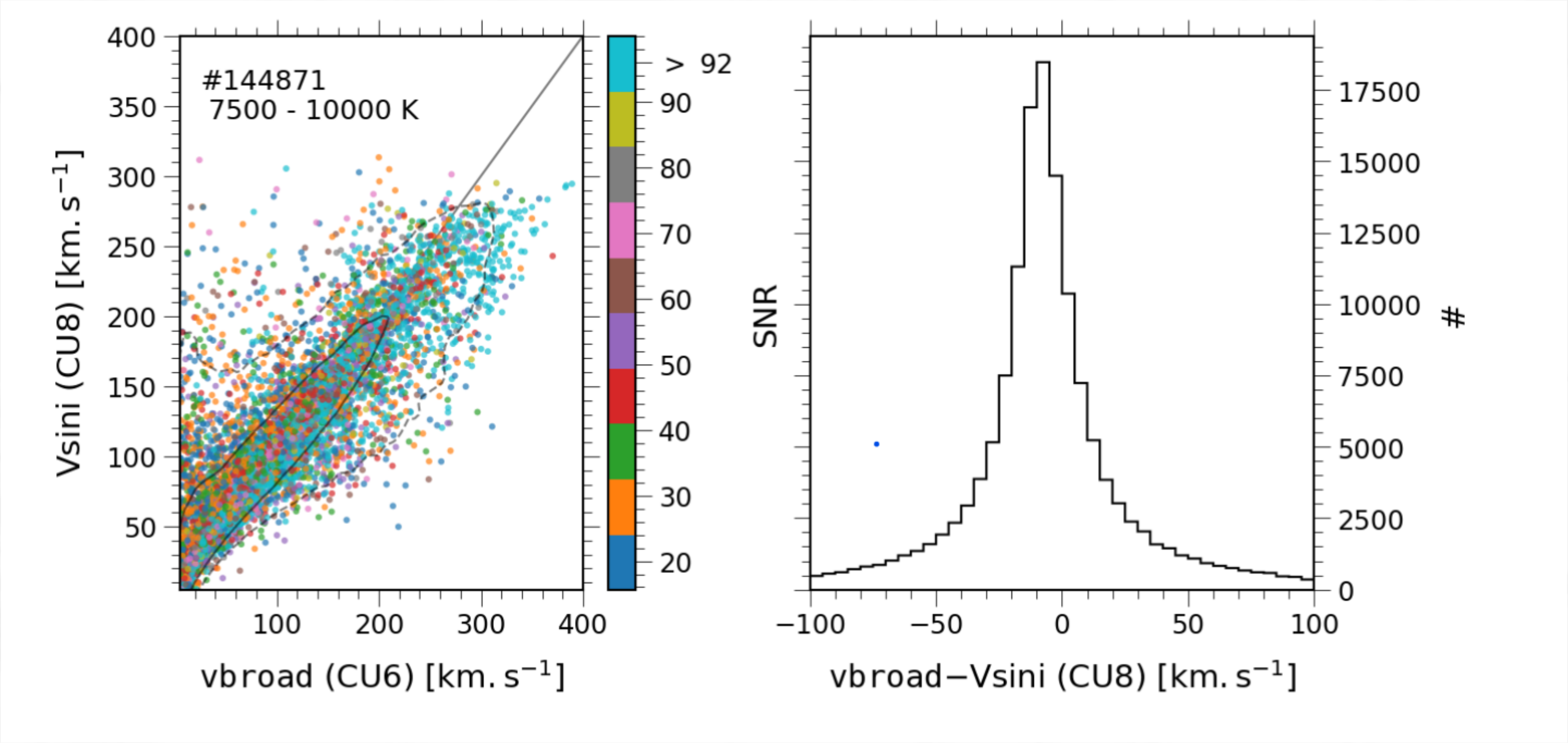


Fig. 9. Relative uncertainty on vbroad as a function of $G_{\rm RVS}$ magnitude for two $T_{\rm eff}$ ranges. Thick lines are the running median values (over 2000 targets), and the coloured regions correspond to the associated 15% and 85% quantiles. The filled circles are the relative uncertainties corrected for the z-score estimates performed in Sect. 5.

Vbroad & Vsini



Korn+2022, Gaia DR3 documentation,
https://gea.esac.esa.int/archive/documentation/GDR3/Data_analysis/chap_cu8par/sec_cu8par_validation/ssec_cu8par_qa_atmospheric-aps.html#SSS2

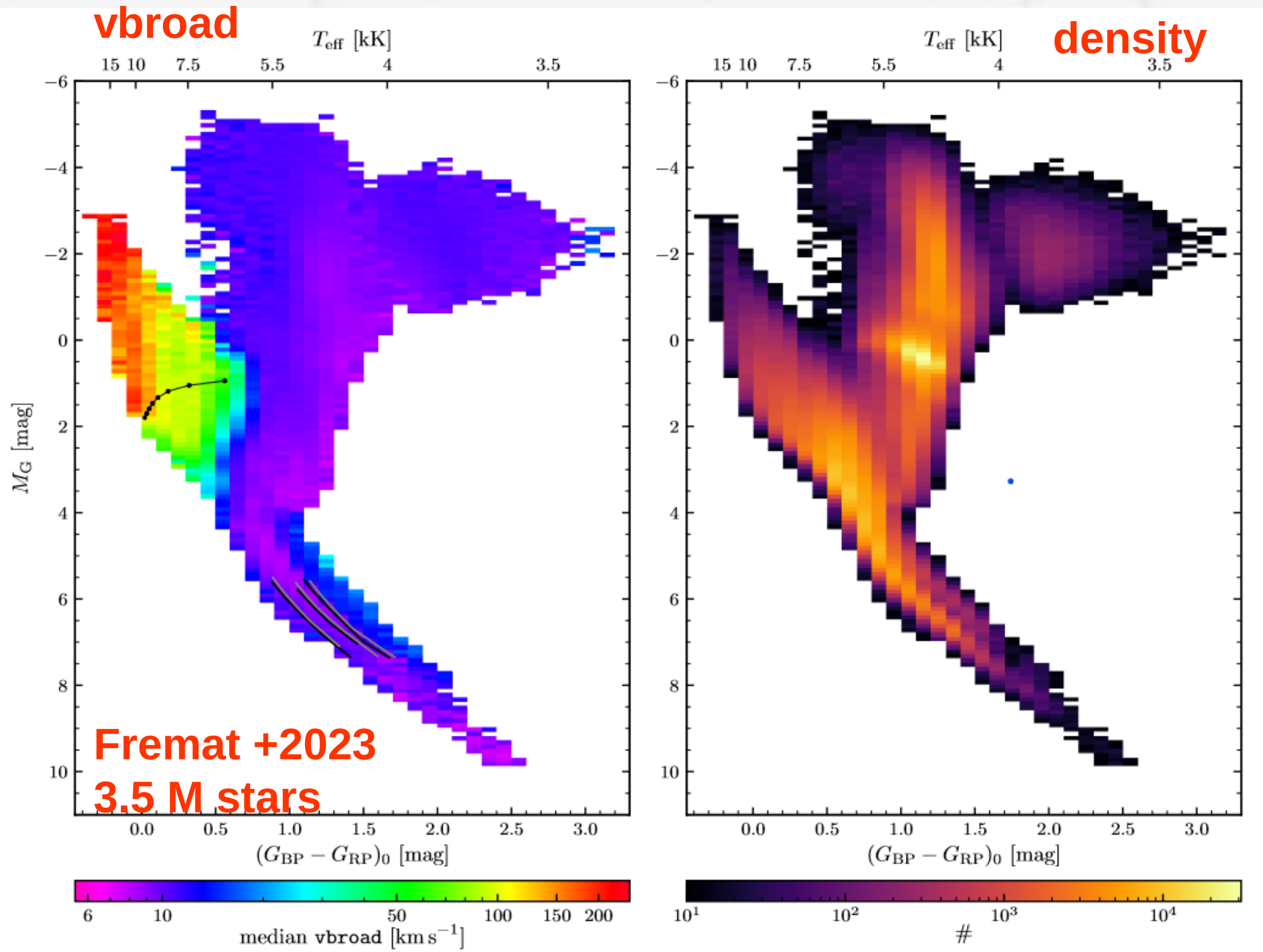
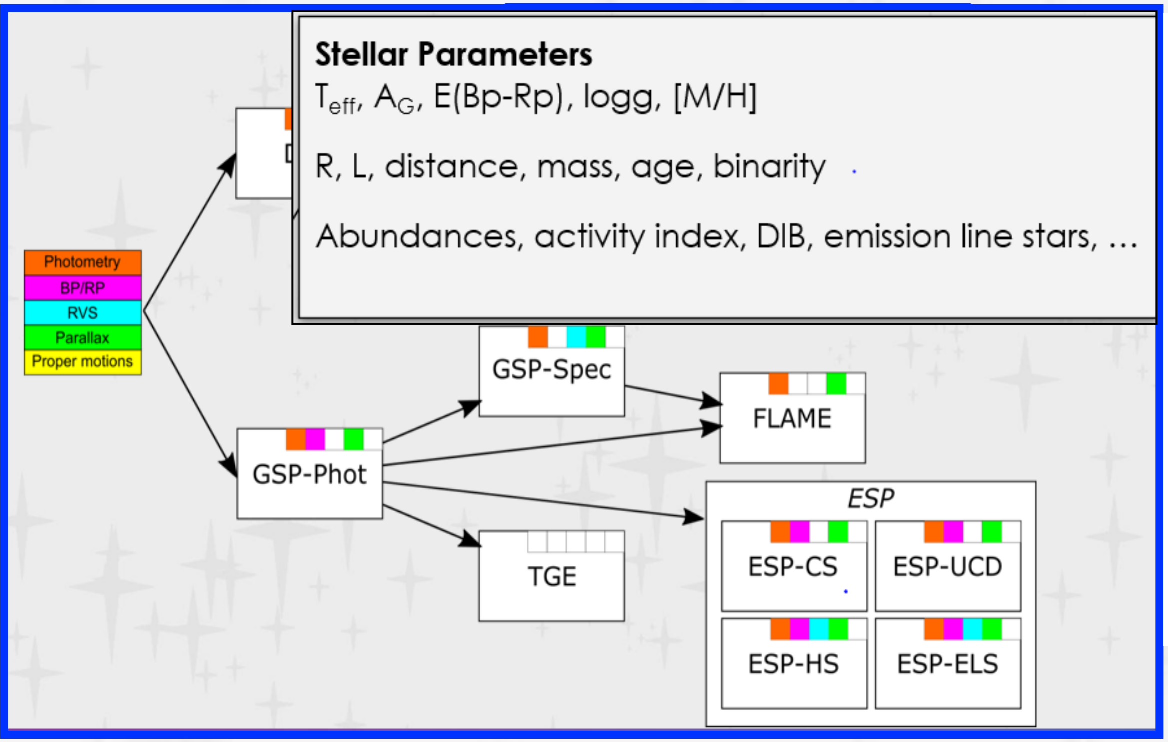
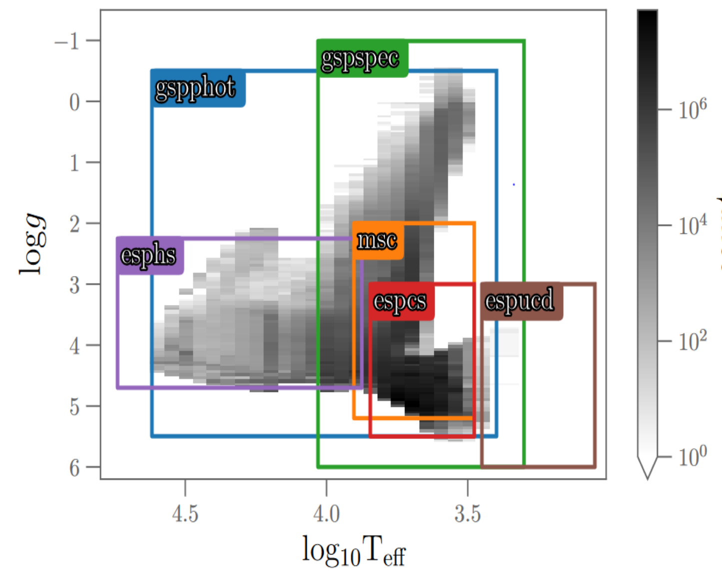


Fig. 16. Hertzsprung-Russell diagrams for a subsample of the *Gaia* DR3 vbroad catalogue (~1.8 million stars). The larger part of missing data is due to the lack of extinction parameters to correct for M_G and deredden $G_{BP} - G_{RP}$, which holds for about 43% of the sample. An additional cut is performed on the parallax quality ($\varpi/\sigma_\varpi > 10$) and removes 3.2% of the total sample. For hot stars, a selection is made on G_{RVS}, which removes an additional 2.5% of the sample (see text). The binning size is 0.1 by 0.1 mag. Bins containing fewer than ten stars are discarded. *Left panel*: maps the median vbroad values (in logarithmic colour scale), and the *right panel* shows the density, in order to better associate the rotational velocity map to the corresponding structures in the HRD. To guide the eye, the upper x-axes show the approximate T_{eff} scale, calibrated as a function of $G_{BP} - G_{RP}$ using the photometric temperatures. The evolutionary track of a 2 $M_\odot$ star in the *left panel*, sampled each 162.5 Myr, illustrates the

Astrophysical parameters



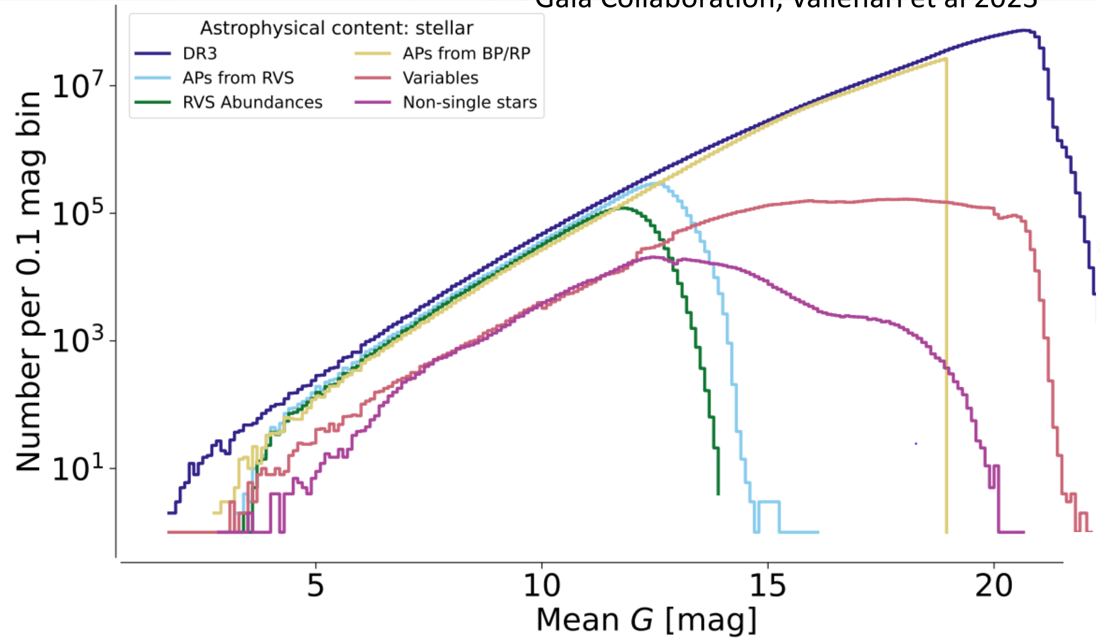


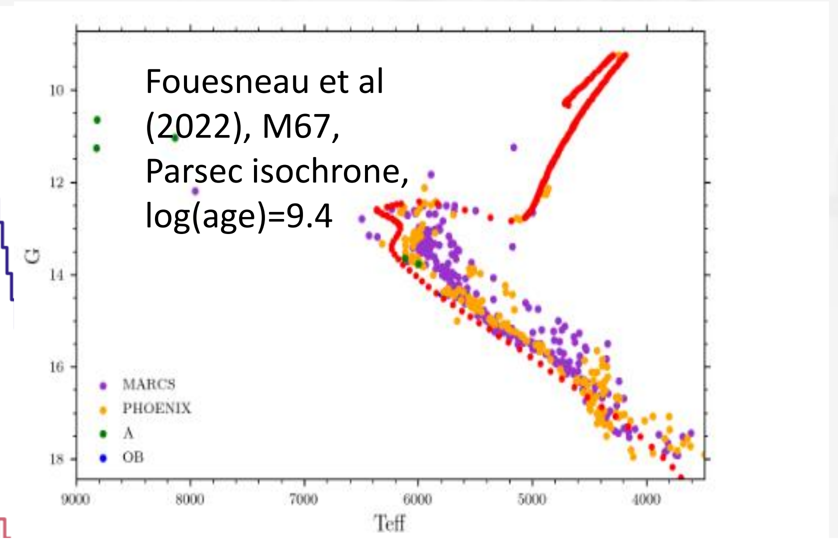
Online tool for interstellar extinction
https://www.cosmos.esa.int/web/gaia/dr3-extinction-as-function-of-l-b

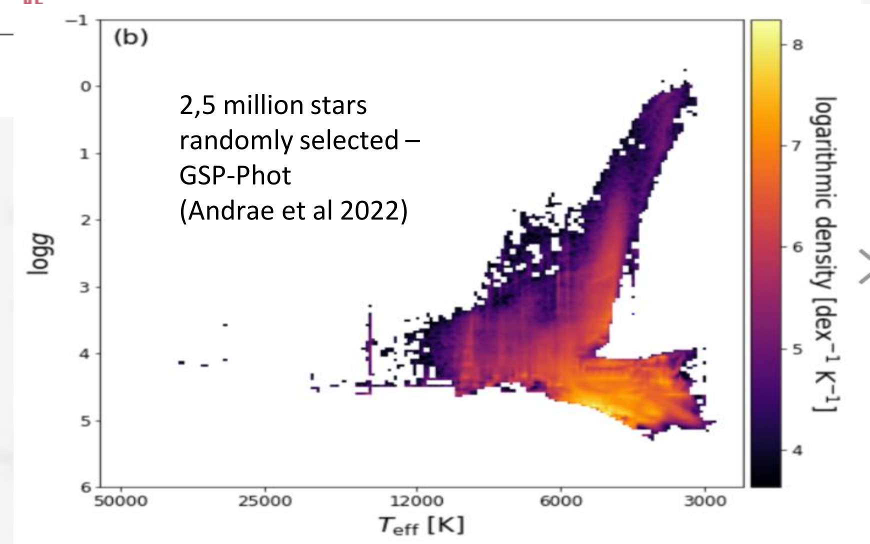
Andrae et al (2023)
Creveey et al (2023)
Fremat et al (2023)
Fouesneau et al (2023)
Recio-Blanco et al (2023)
Gaia Coll. Vallenari et al (2023)

Parameters from BPRP data

Gaia Collaboration, Vallenari et al 2023







- Typical uncertainties vs APOGEE:
- Δlog(g)= 0.2 MAD=0.4
- Δ logTeff=169 K MAD=418 K
- Δ[M/H]-APOGEE17=-0.2

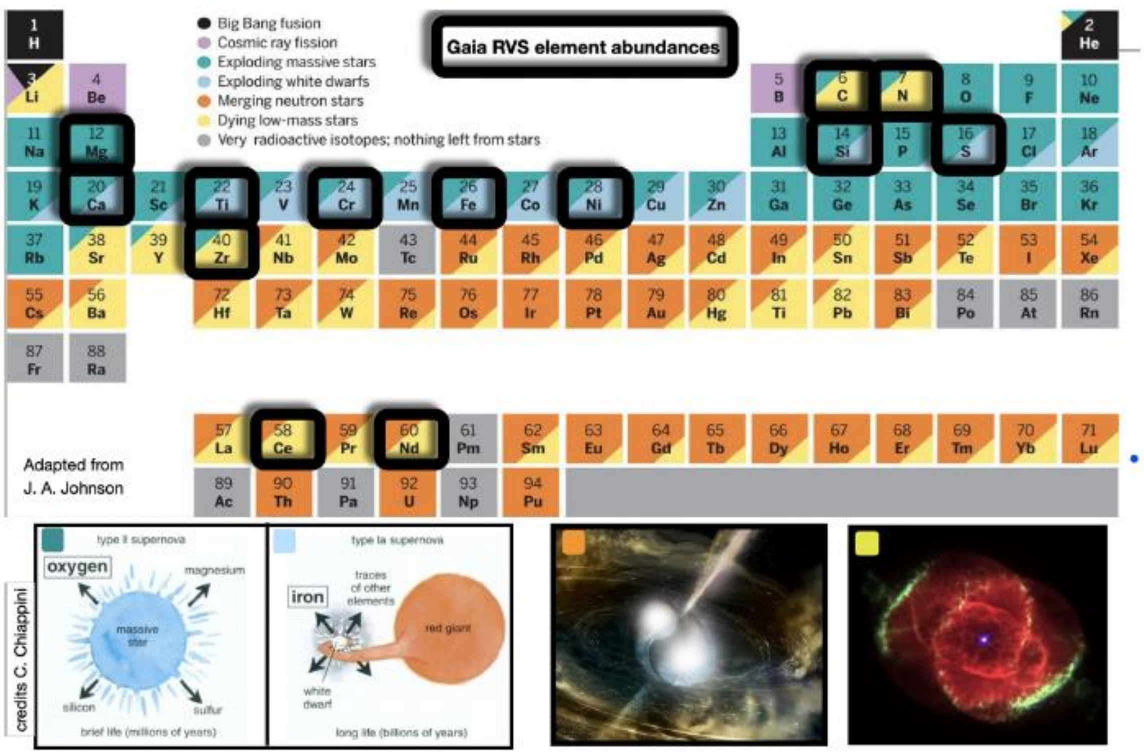
Systematics

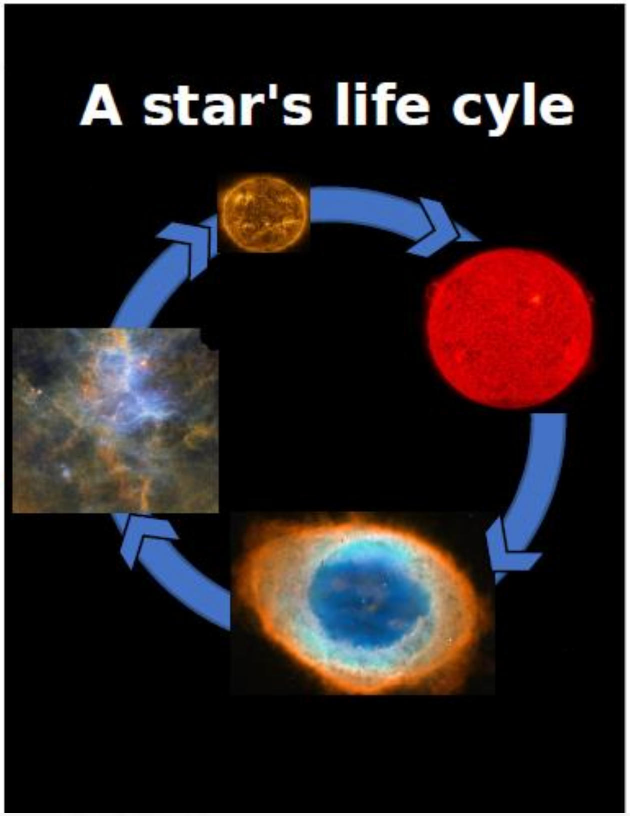
- Variability not taken into account
- Teff-AG degeneracy
- Parallax SN dependence
- Affected by crowding

(Gaia Collaboration, Vallenari et al 2022, Fouesneau et al 2022, Babusiaux et al 2022)

RVS chemical abundances

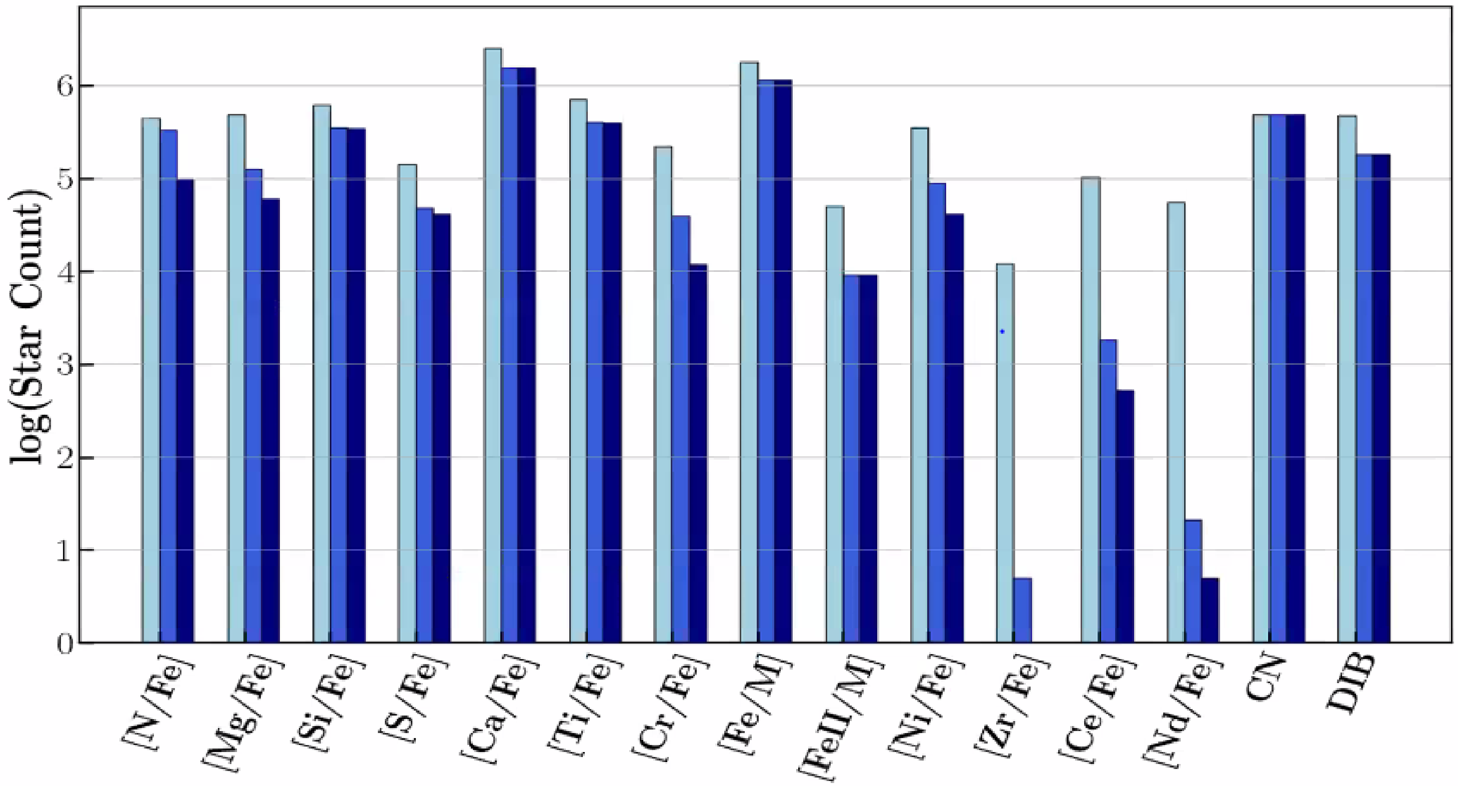
Different nucleosynthesis channels



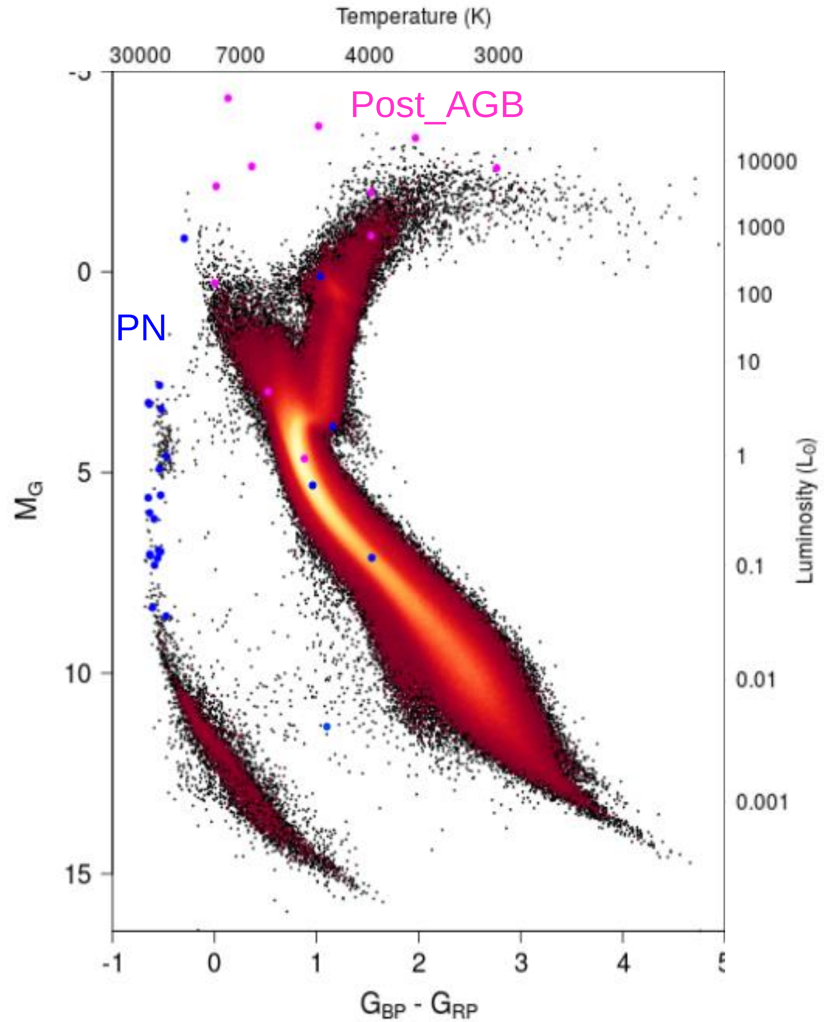


> 5 million stars

CU8/GSPspec: The chemical composition of 5.6 million stars



- Typical uncertainties vs APOGEE:
- Δlog(g)= 0.28 MAD=0.21
- Δ logTeff=10 K MAD=112 K
- Δ[M/H]-APOGEE17=-0.01 MAD=0.13 → check Recio-Blanco +2023 for selection flags



Gaia Coll, Babusiaux+2018

Fig. 5. *Gaia* HRD of sources with low extinction ($E(B-V) < 0.015$ mag) satisfying the filters described in Sect. 2.1 (4,276,690 stars). The colour scale represents the square root of the density of stars. Approximate temperature and luminosity equivalents for main-sequence stars are provided at the top and right axis, respectively, to guide the eye.

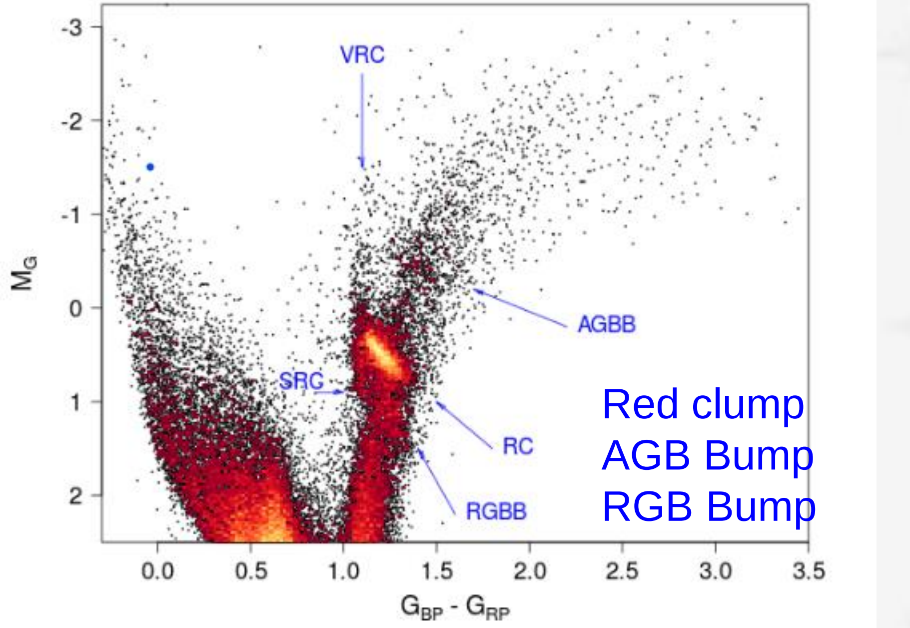
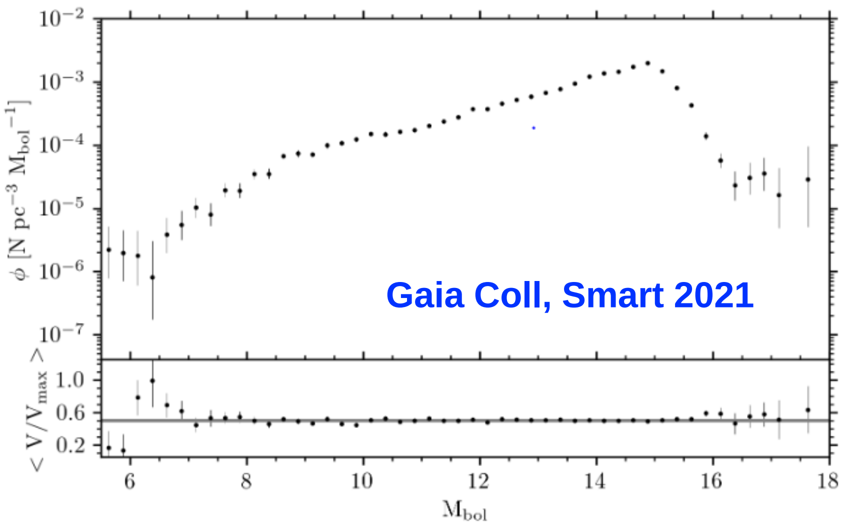


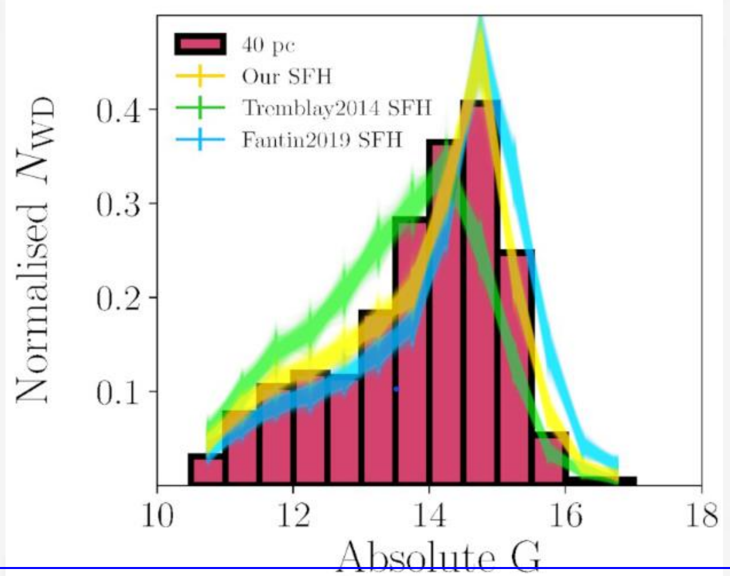
Fig. 10. *Gaia* HRD of low-extinction nearby giants: $\varpi > 2$ mas (500 pc), $E(B-V) < 0.015$ and $M_G < 2.5$ (29288 stars), with labels to the features discussed in the text.

AGB bump: the ignition of the He-burning shell
RGB bump:discontinuity in H abundances

Fundamental to understand mixing→ Giada's talk

A new view of local WDs

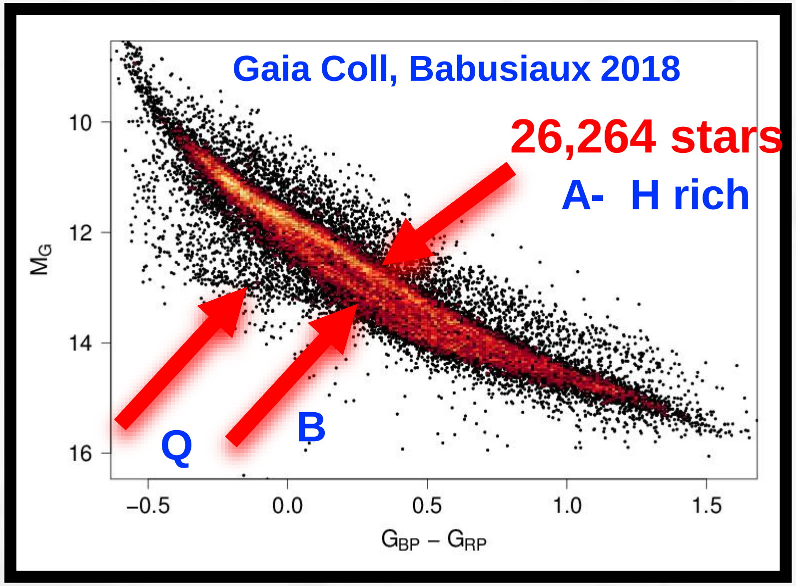


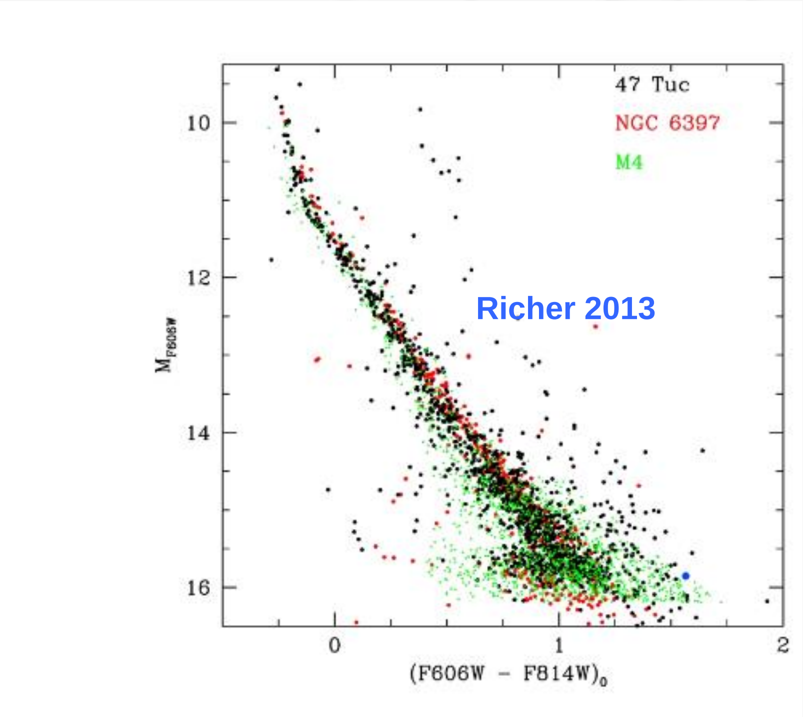


A uniform rate for the last 10.6 Gyr in yellow. green and blue SFH of Tremblay (2014), Fantin et al. (2019), Cukanovaite et al. 2023).

- WDs are the final evolution of stars of M<8-10 Mo
- 5-7% of the local stellar population in volume
- WDs can provide information on the MW history(disk, Ocs, bulge, halo) due to the long cooling time
- Before Gaia only 500 WDs in 50 pc (200 WDs with parallaxes)
- A new WD distribution (Gaia Collaboration, Babusiaux et al 2018, Gaia Collab)
- 33,000 WDs within 100 pc in the nearby star Catalog (Gaia Collab, Smart et al 2021) and 330,000 WDs in DR3
- Completeness ging from 97% (within 40 pc) to 67% for G<20
- Constant SFH from 10.6 Gyr to now

A new view of WDs





- Q &B sequences not visible in GCs
- Q: interior crystallisation : C, O, Ne cooling core get to a critical Teff leading to a phase transition from liquid to solid
  - → longer cooling delay than expected due to latent heating sources (mergers?)
- A : H rich atmospheres
- B : He rich atmospheres
- B not explained by pure He cooling: possibly traces of other elements (H, C)
- Review in Tremblay 2024

Probing the interior physics of M dwarfs

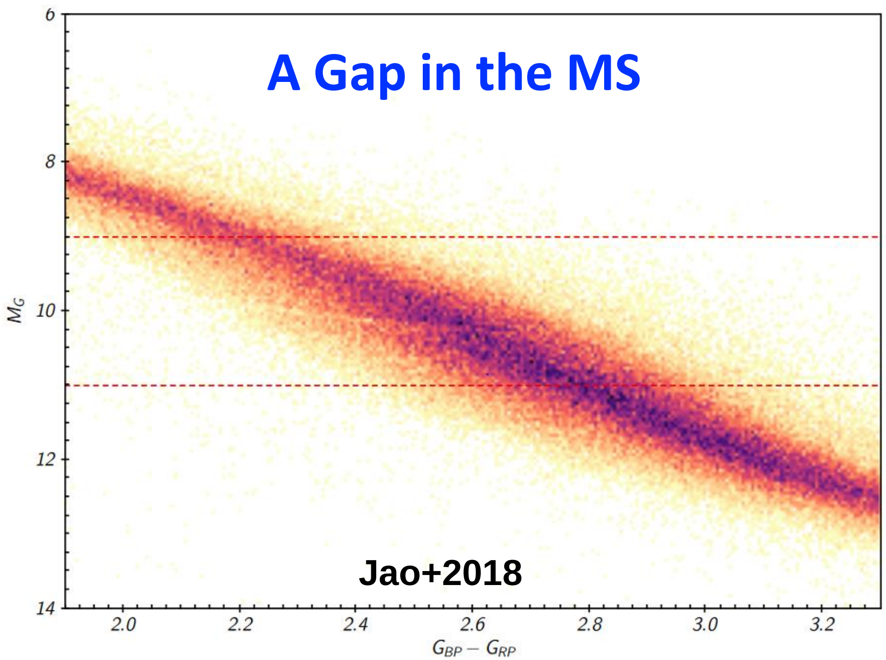
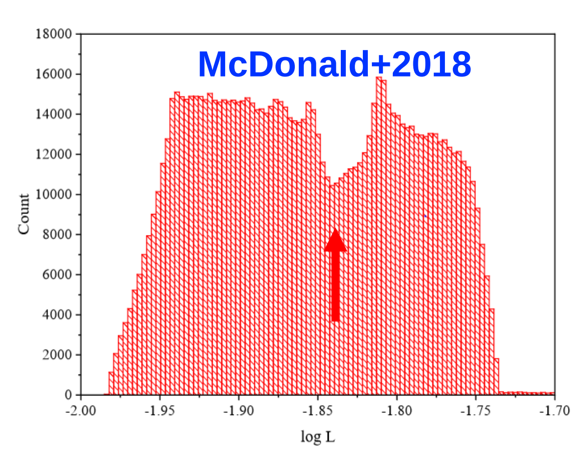
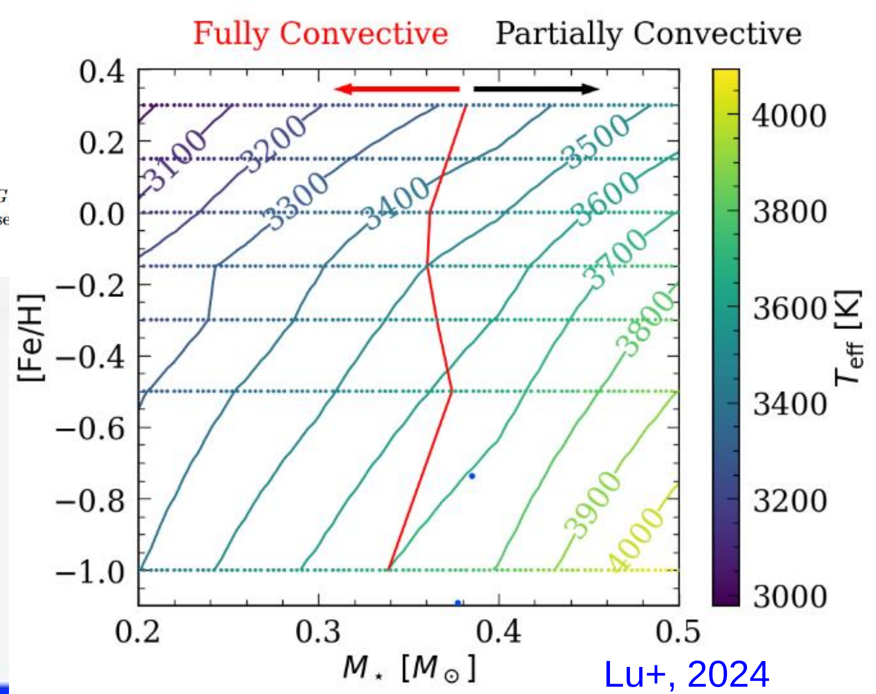
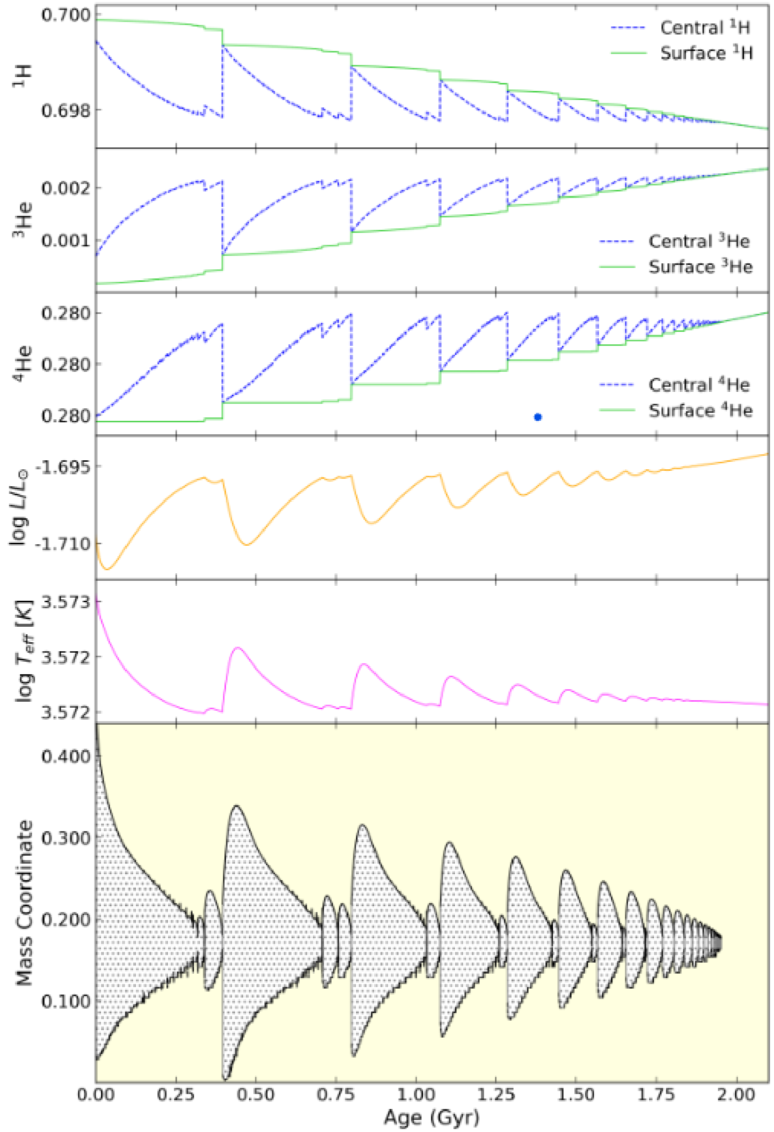


Figure 1. A portion of the observational HRD for stars within 100 pc in the *Gaia* DR2 dataset, using M_G and $G_{BP} - G$ thin, low density, gap is seen cutting through the main sequence. Two dashed lines ($M_G = 9$ and 11) represent a region se for further discussion, and plotted in Figure 2.



- A gap in the MS at MG= 10 (Jao+2018) of 0.05 mag
- M dwarf transition from partially to totally convective
- Probing the interior physics of M dwarfs
- Stars probed for magnetic activity, rotation (Boudreaux+2024, Lu+2024, Jao+2024)





Mansfield & Kroupa 2024

Figure 1. The top five plots give the surface and central abundances by mass fraction of hydrogen and helium, luminosity and effective temperature over time for a 0.37 $M_{\odot}$, $Z = 0.02$ model without overshooting or semi-convection

- Stars in the range 0.31-0.34 Mo are unstable and experience a sudden change in 3He central content and in luminosity(McDonald&Gizis 2018)
- Stars at 0.31-0.35 Mo have a radiative core on MS.
- At the 3He production a convective core is formed inside the radiative area
- Stars experience a merge of core and envelope

Radius inflation in M dwarfs

Somers+2021

PARSEC

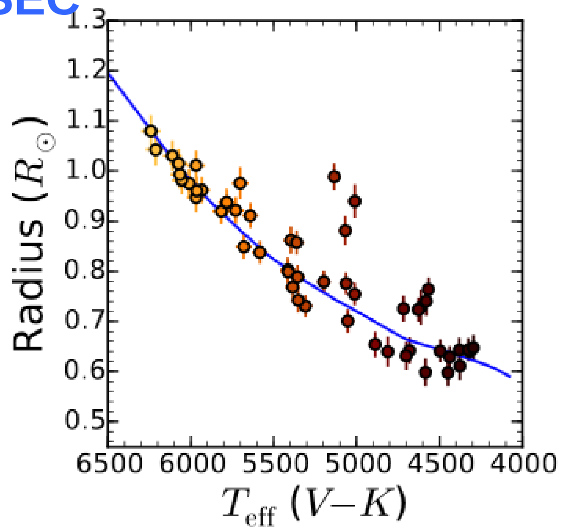
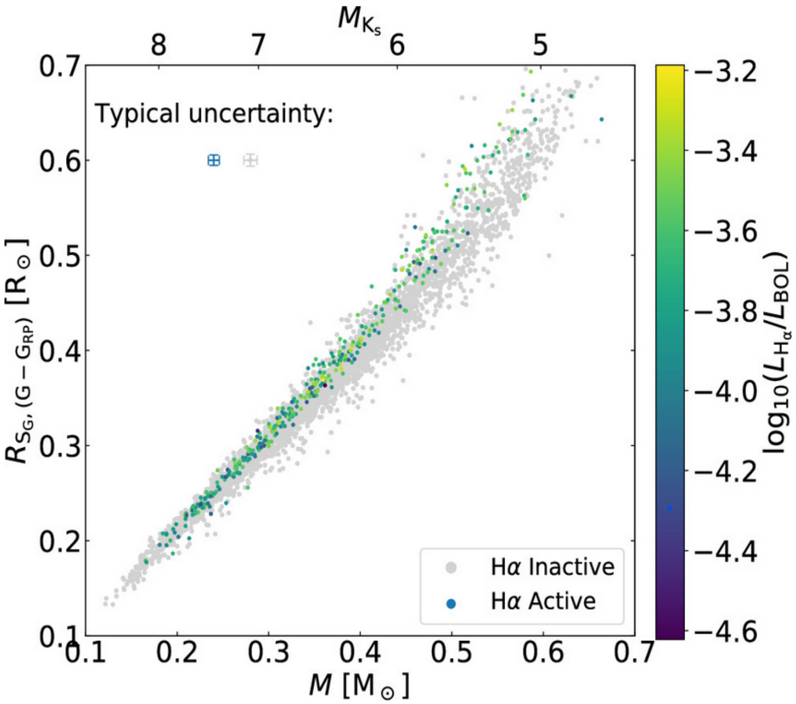


Figure 4. A comparison between the radii of our stars, derive procedure outlined in §2, and the stellar isochrones (blue line) of ~ 5700 K, but significant scatter below this value for both $T_{\rm eff}$ p



Kiman 2024

Zoom In Zoom Out Reset image size

Figure 8. Mass–radius relation for the sample from Kiman et al. (2019). Inactive stars according to Hα are shown in gray and active stars are color-coded by fractional Hα luminosity. We only include the typical uncertainly (median) of the sample. Active stars show larger radii than inactive

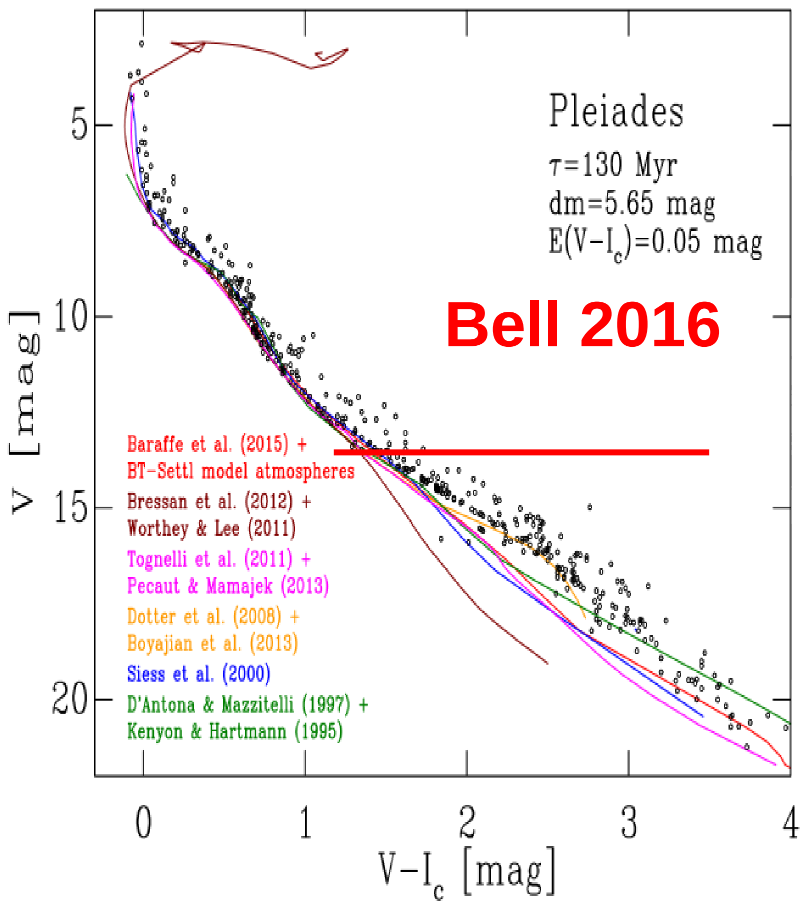
- **using angular diameters (interferometry)→each star's surface brightness and calibrate the surface brightness-colour relation using Gaia photometry**
- **Radii are inflated in rapidly rotating stars as effect of magnetic activity**

Gaia Ocs & stellar structure

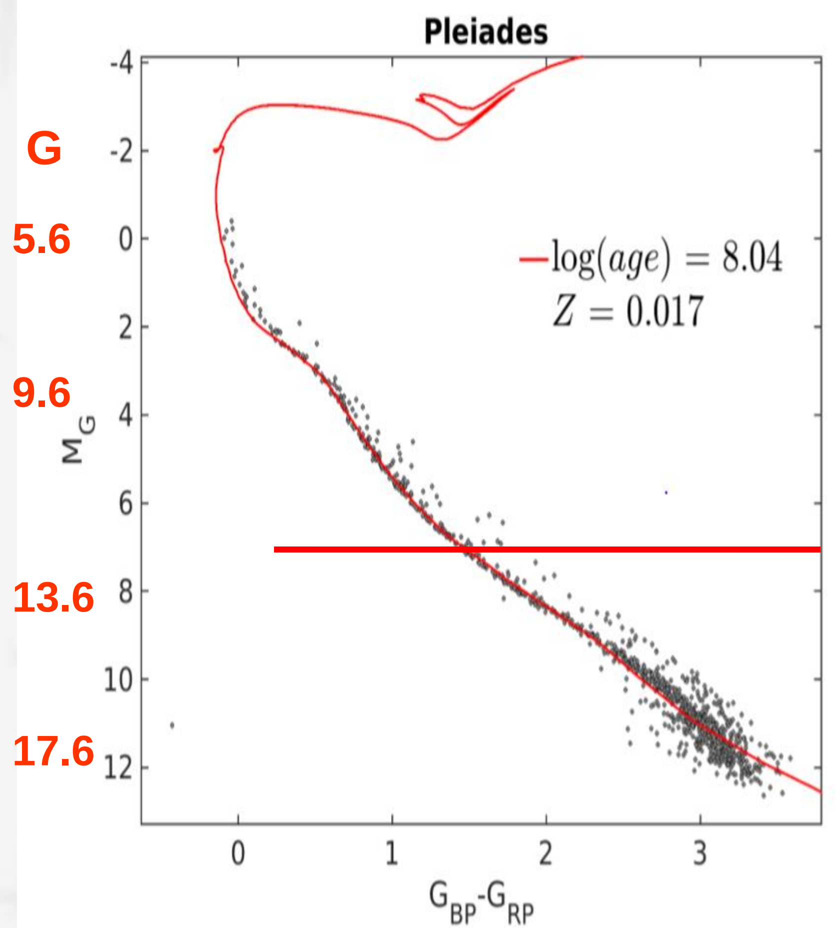
- Gaia Photometry+ Astrometry
- Revision of OC Catalogues (Cantat-Gaudin 2020, Anders+2020, Hunt&Reffert 2023,2024, Perren 2023…)
- OCs have 100-1000 stars → not well populated in the advanced stages (AGB)
- But : good membership, white dwarfs, structural parameters, parallaxes, well defined MS, rotation at turnoff, chemical abundances
- → good to calibrate stellar models
  - mixing(semiconvection,overshoot,diffusion,extra-mixing
  - rotation (magnetic braking, rotational mixing
  - nuclear reaction rates revision
  - bolometric corrections (ATLAS9, Phoenix...)
- → good to define fiducial sequences vs age, Z

Calibrating stellar isochrones

Pre-Gaia

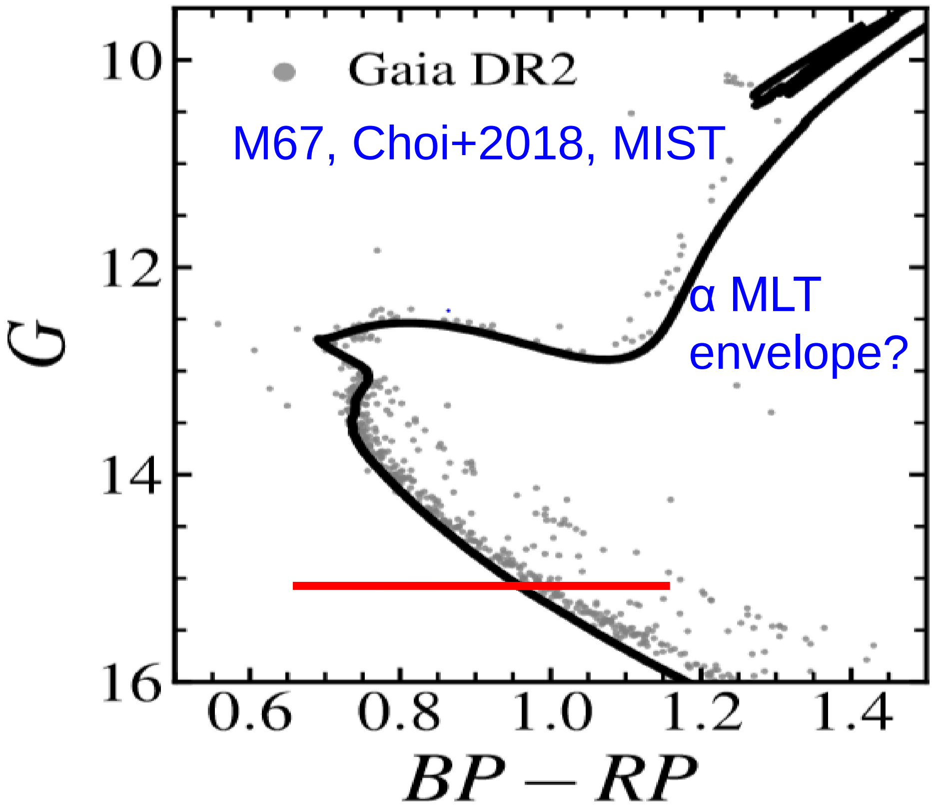


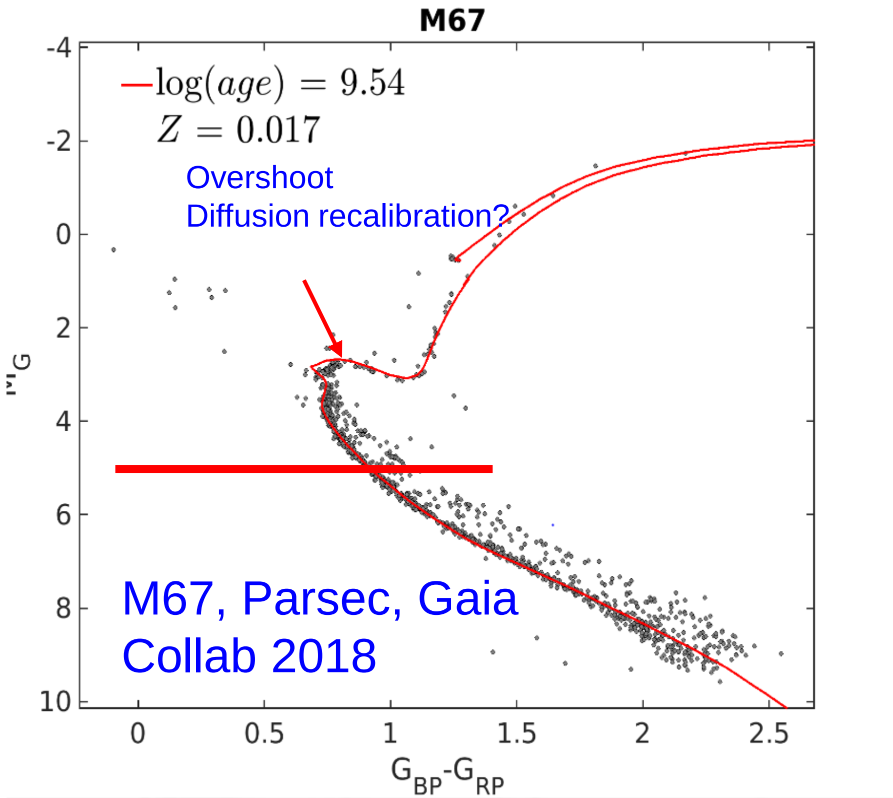
Gaia Coll., Babusiaux et al 2018
Parsec isochrones (2018)



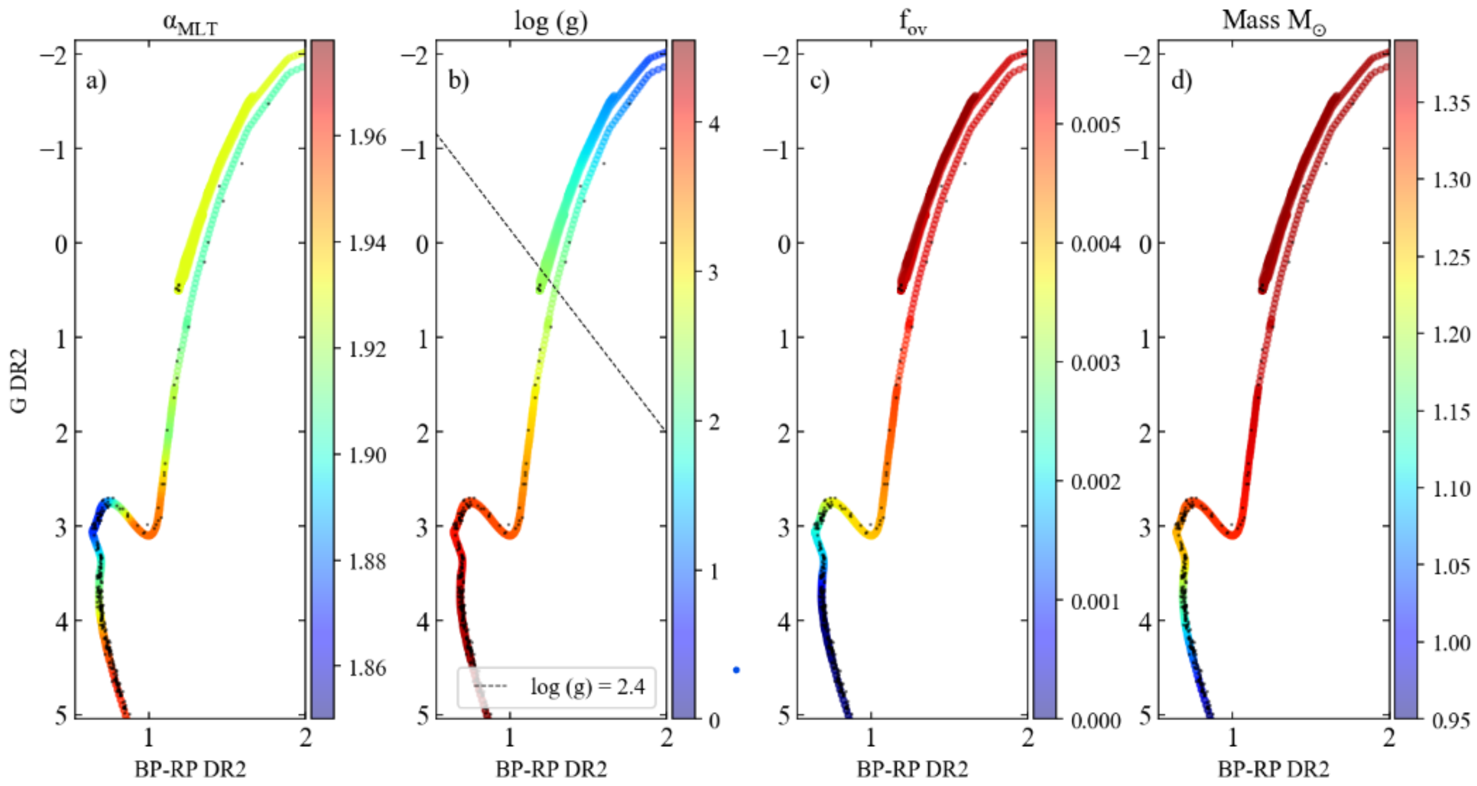
- the relation between the temperature and Rosseland mean optical depth T-τ from BT-Settl(Asplund 2000)
- Calibrated to the empirical M-radius relation (Chen 2014)

Calibrating stellar isochrones





$m - M = 9.73$, $[\mathrm{Fe/H}] = -0.01$, $\log(\mathrm{Age})\ [\mathrm{yr}] = 9.58$, and $A_V = 0.18$

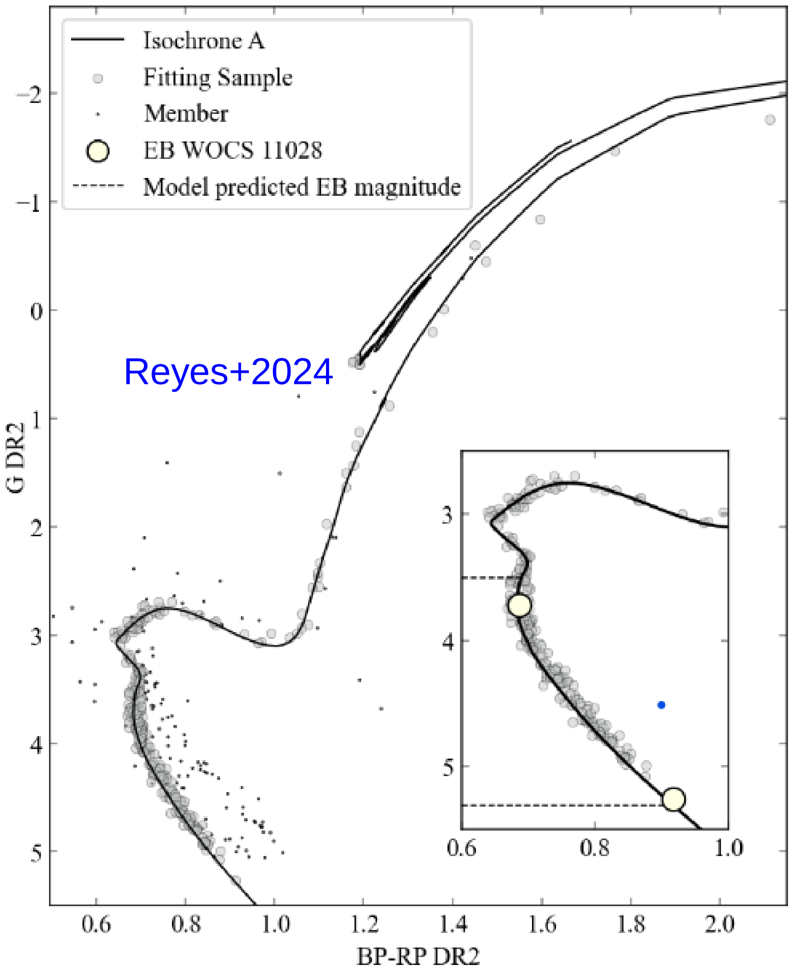


Reyes+2024

Figure 5. Isochrone A and M67 presumed single stars in absolute magnitude and colour-coded by (a) α_{MLT}, (b) $\log(g)$, (c) overshooting parameter f_{ov}, and (d) stellar mass. The dashed line in b) crosses the isochrone where the α_{MLT} 3D grid stops at $\log(g)$ 2.4. After that point in the evolution up the RGB, we set our models to maintain the last measured α_{MLT} value and after helium ignition α_{MLT} is set to 1.93.

fov the diffusive overshoot parameter in the core (→core size→turnoff) declines exponentially into the radiative zone

the convective mixing length parameter αMLT (l= αMLT Hp) changes with Teff-log(g) following 3D simulations (but not in RGB)– scaling factor calibrated on M67



Parameter	Isochrone A
Age	3.95 Gyrs
Distance modulus	9.614
Nuclear reaction network	h1, he3, he4, c12, n14, o16, ne20, mg24 (MESA's basic.net)
Solar mixture	AGSS09 (Asplund et al. 2009)
Z	0.016
Y	0.267
$\Delta Z/\Delta Y$	1.2
EoS	HELM (Timmes & Swesty 2000) + Skye (Jermyn et al. 2021) + FreeEOS (Irwin 2004) + OPAL (Rogers & Nayfonov 2002) + SCVH (Saumon et al. 1995)
Interior opacities	OPAL (Iglesias & Rogers 1993, 1996)
Opacities	AESOPUS (Marigo & Aringer 2009)
Atmospheres	T(τ), varying, Trampedach solar (Trampedach et al. 2014a; Ball 2021)
Overshooting	Exponential, increasing with mass.
$\alpha_{\rm MLT}$	Varying with $T_{\rm eff}$ and $\log(g)$, follows 3D grid (Trampedach et al. 2014b)
Scaling factor $k_{\alpha_{\rm MLT}}$	1.11
Mass loss	No
MLT_option	Henyey
Convection	Schwarzschild criterion
Diffusion	Yes

Table 2. Summary of parameters in MESA models for the isochrone shown in Figure 7. The isochrone is presented in A1

Empirical isochrones

- Good membership & Chemical abundances→Fiducial sequences vs relative ages

» calibrated on reference Ocs

depending on uncertainties on parallaxes,

binary fraction, extinction

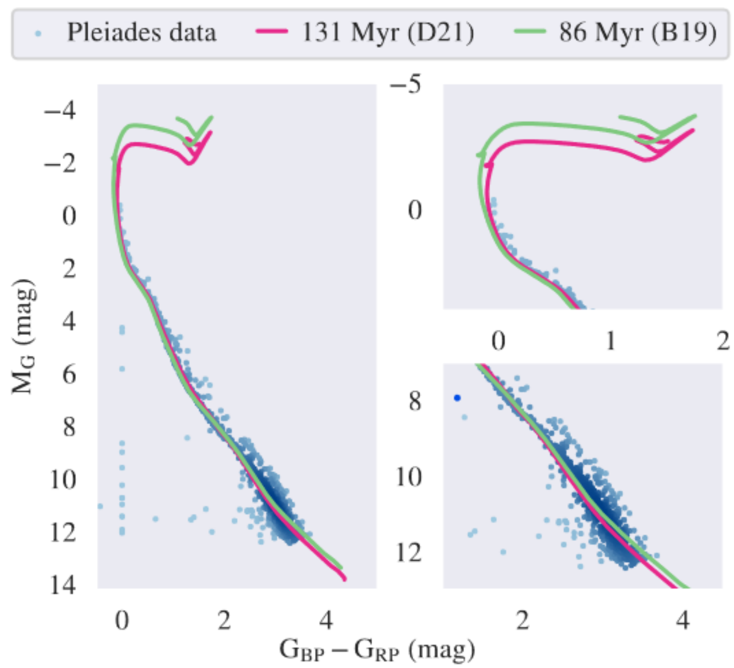


Fig. 1. Comparison between two different isochronal ages for the Pleiades cluster. The data points correspond to the *Gaia* DR2 cluster selection of Cantat-Gaudin & Anders (2020), and the isochrones were produced with PARSEC, using the parameters calculated in the respective works (Bossini et al. 2019; Dias et al. 2021), indicated by B19 and D21 in the figure legend, respectively.

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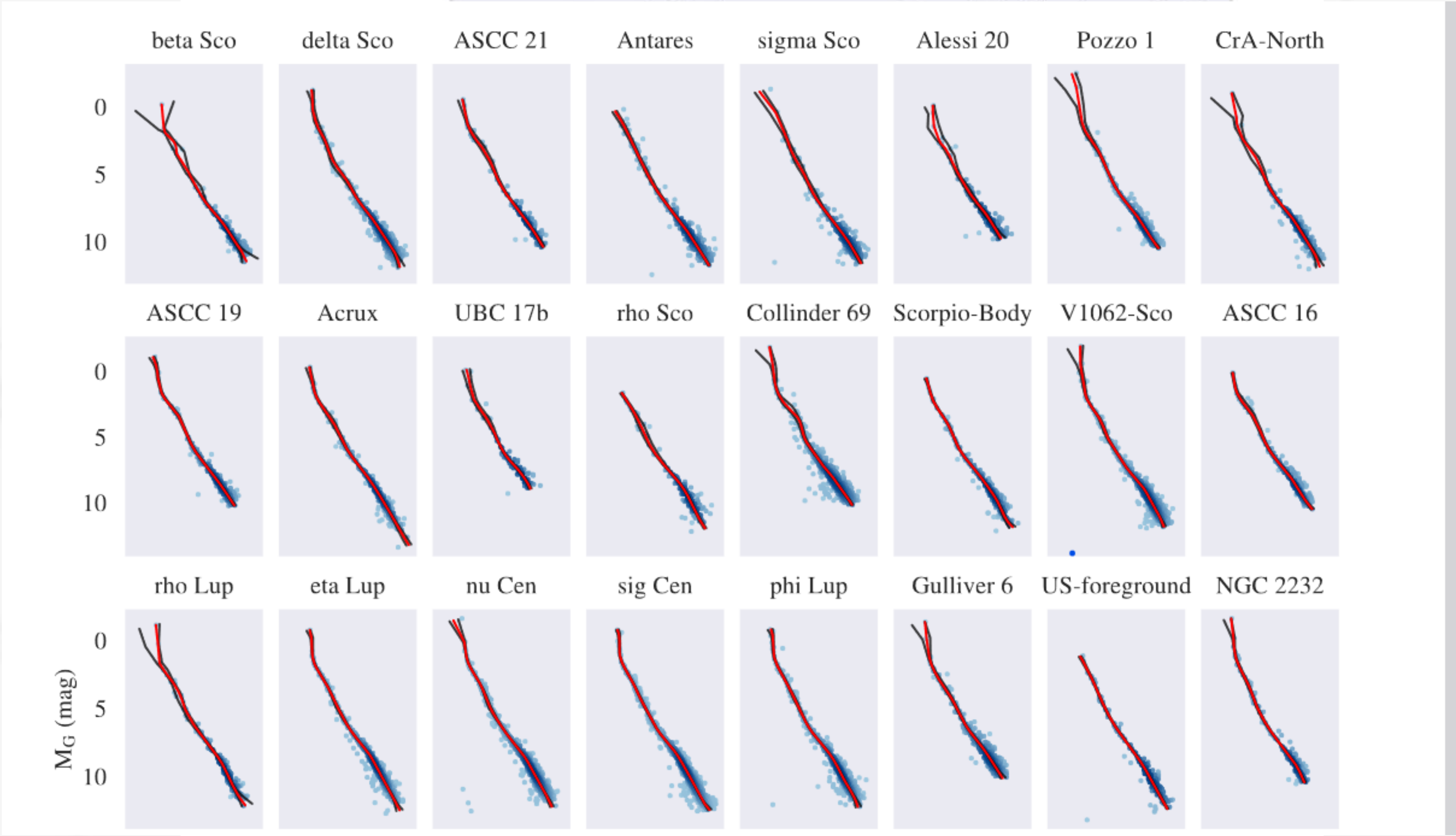
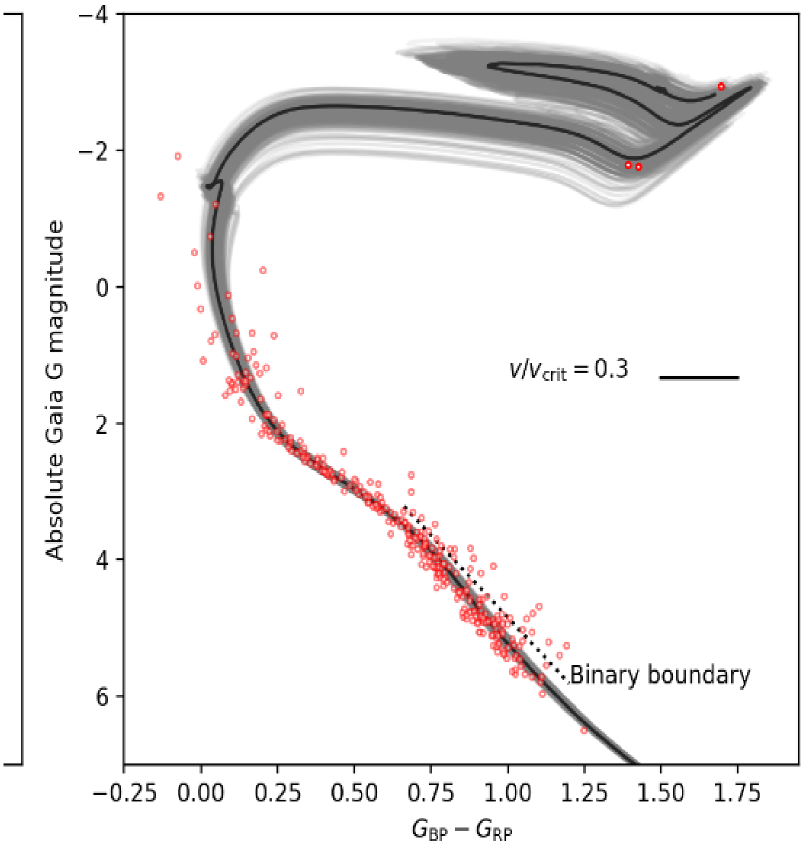
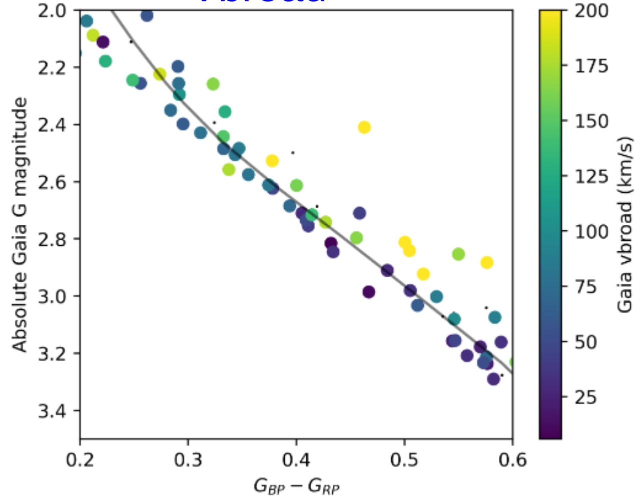


Coupling with asteroseismology



Vbroad



l rotation lead a star deviating from the main sequence. The ranges of the
: 3.5 mag. The stars are colour-coded by RUWE (showing binarity) and
k dots are stars without broadening values in the *Gaia* DR3 database.

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Fig. 1. Observed *Gaia* DR3 CMD of NGC 2516. Left panel: fits for isochrones with varying rotation rates. Isochrones with $v/v_{\rm crit} \leq 0.4$ effectively reproduce the observed data. Right panel: solid black isochrone represents the best-fitting result with $v/v_{\rm crit} = 0.3$. The grey background tracks collectively represent the uncertainty, which is determined using a set of 500 isochrones randomly selected from the Monte Carlo approach explained in the main text. The dotted line marks the boundary of the binary sequence.

Precise stellar parameters are needed as input to asteroseismology

- Age
- Mixing
- Mass loss in RGB
- Rotation→ (vbroad+gmode internal rotation)

→ Diego's talk