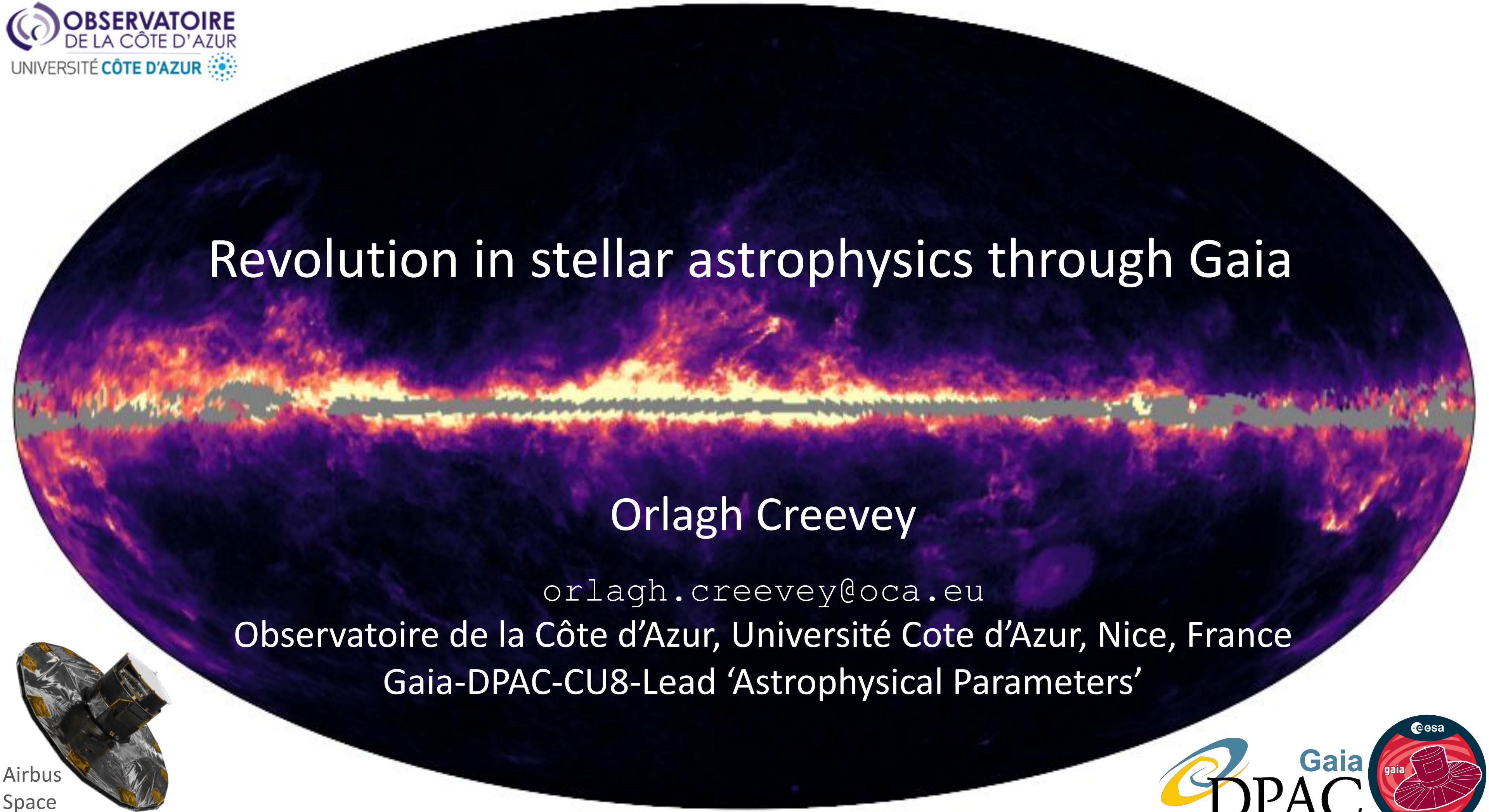

Revolution in stellar astrophysics through Gaia

Orlagh Creevey

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Gaia-DPAC-CU8-Lead 'Astrophysical Parameters'

Airbus Space

Outline

- Importance of stellar parameters for exoplanetary characterisation

- From the colour-magnitude diagram (CMD) to the HR diagram
  - Why the HR diagramme
  - Gaia observables
  - RVS spectra
  - BP/RP spectra
  - Spectral energy distributions: Temperatures, extinction, bolometric corrections
  - Gaia Results: Effective temperatures, luminosities, surface gravities, extinction, metallicities

- From the HR diagram to stellar masses and ages
  - Inferring stellar ages from the HR diagram
  - Key role of the stellar mass
  - Masses and Ages in Gaia DR3
  - Exoplanetary characterisation

- Key points

Why do we care about stellar parameters for exoplanets

- Mass, radius, and effective temperature (Teff) of the planet host dictate the size and density of the planet, and amount of irradiation of the planet receives ("too hot, too cold, just right").
- How fast does it spin, what about magnetic storms?
- Age:
  - Can we explain the known exoplanets distribution given our current knowledge of solar system evolution?
  - Has the system evolved long enough to be able to sustain life, and what kind of life? Is it like our Solar System?

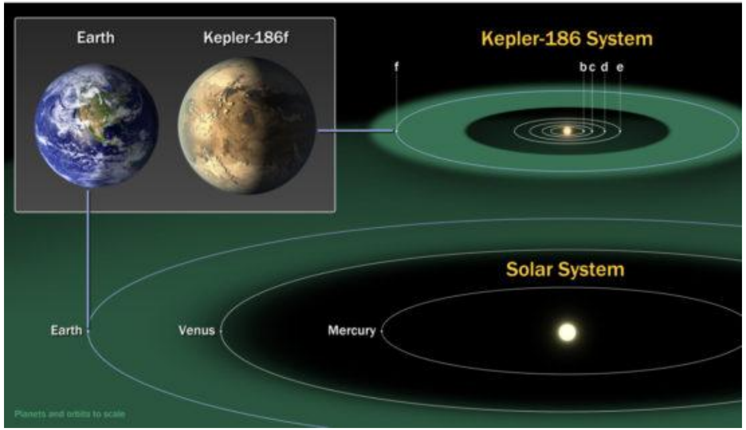

Image credit: NASA

Image credit: NASA/JPL-Caltech/Lizbeth B. De La Torre; adapted by O. Creevey

True physical characteristics of stars from measurements

- Teff
  - Teff is a definition(!) but even so we can not hold a thermometer to its surface
- Diameter
  - Stellar surface is generally not resolved like the Sun or the Moon or the solar system planets when photographed by a telescope or a space observatory
  - See talk by R. Ligi's (and G. Schaefer) on interferometry
- Mass
  - Resolved orbits of binary stars give masses
  - Single stars (most stars) can not be directly measured
- Age
  - See also talks by M. Ness and M. Kounkel
  - Can you tell my age from my surface characteristics?

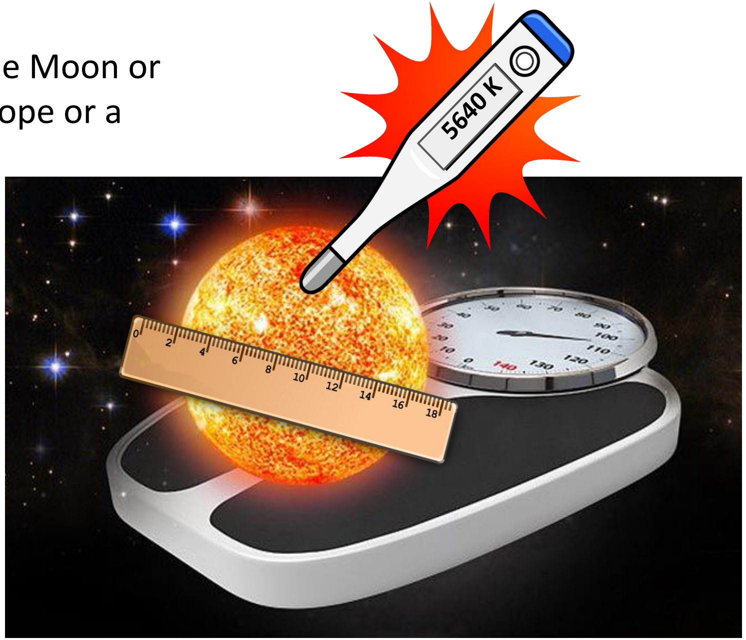

Image credits: Michael Schmelzer, Vanderbilt University; Ilustoon (thermometer); Clipart Library (ruler);

What is an observation and what is an inferred physical quantity?

- A true observation is a measurement of something
  - Amount of light, colours of stars, position on the sky, spectrum of star, light variations over time, interferometric visibilities
  - If we measure it over and over again we can define a “measurement error”
- Some quantities can be extracted directly from the measurements
  - radial velocities, oscillation frequencies, distances, orbits, rotation periods, chromospheric excess
- Inferred physical quantities use an assumption or a model along with the measurements
  - Teff
    - a spectrum and models of a stellar atmosphere
    - colours and a Teff-colour relation
  - Age
    - whatever measurements are available and stellar evolution models (my talk)
- In general, for most single stars, Teff, radius, mass, age are often <u>inferred quantities</u> and so we must <u>consider the assumptions in the model and account for this in our interpretation</u>
- Gaia Data Release 3 provides us for the first time with all of the “basic measurements” along with a catalogue of “inferred physical quantities” for a half billion objects (assumed to be stars)*

*Gaia DR3 contains 1.8 billion measurements and 0.5 billion physical quantities (G<19); it does not provide interferometric visibilities

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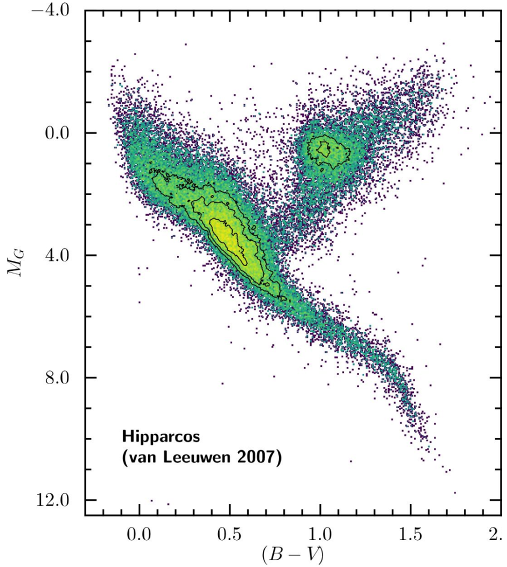
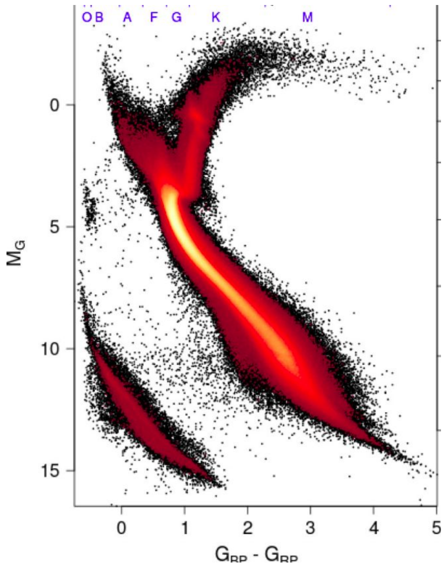
A colour-magnitude diagramme (CMD) pre Gaia DR3





Left: 43 546 stars from the Hipparcos catalogue with parallax precision better than 20% (Gaia coll. Brown et all. 2016)
Middle: 4 million stars by filtering on parallax (10%) and on interstellar medium dust properties (Gaia coll. Babusiaux et al. 2018)

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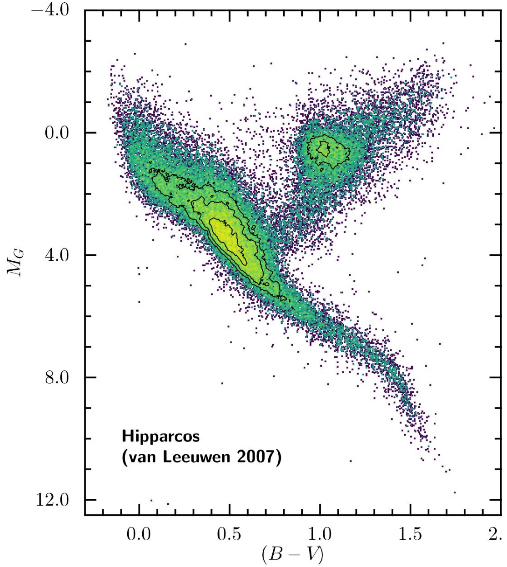

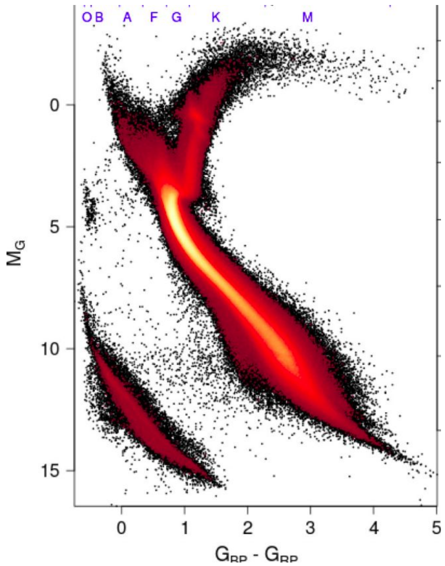

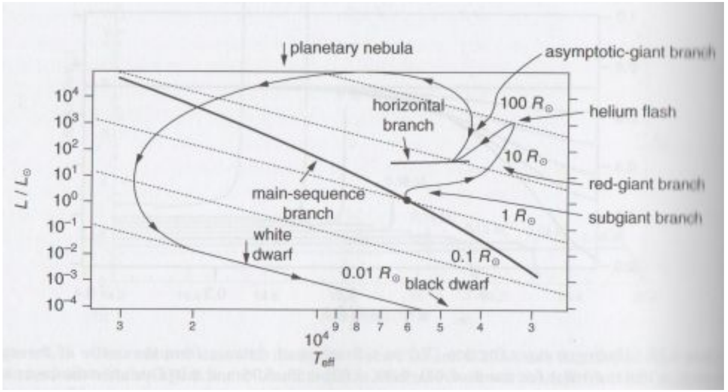

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Right: Evolution track of a one solar mass star (*Stellar Astrophysics*, Le Blanc)

Gaia revolution in stellar observations

- Gaia measurements are <u>time series</u> of:
  - Positions of stars
  - ‘G’ band photometry
  - Low resolution spectro-photometry from the Blue and Red Prism
  - High resolution (R~11,000) spectra from the Radial Velocity Spectrometer

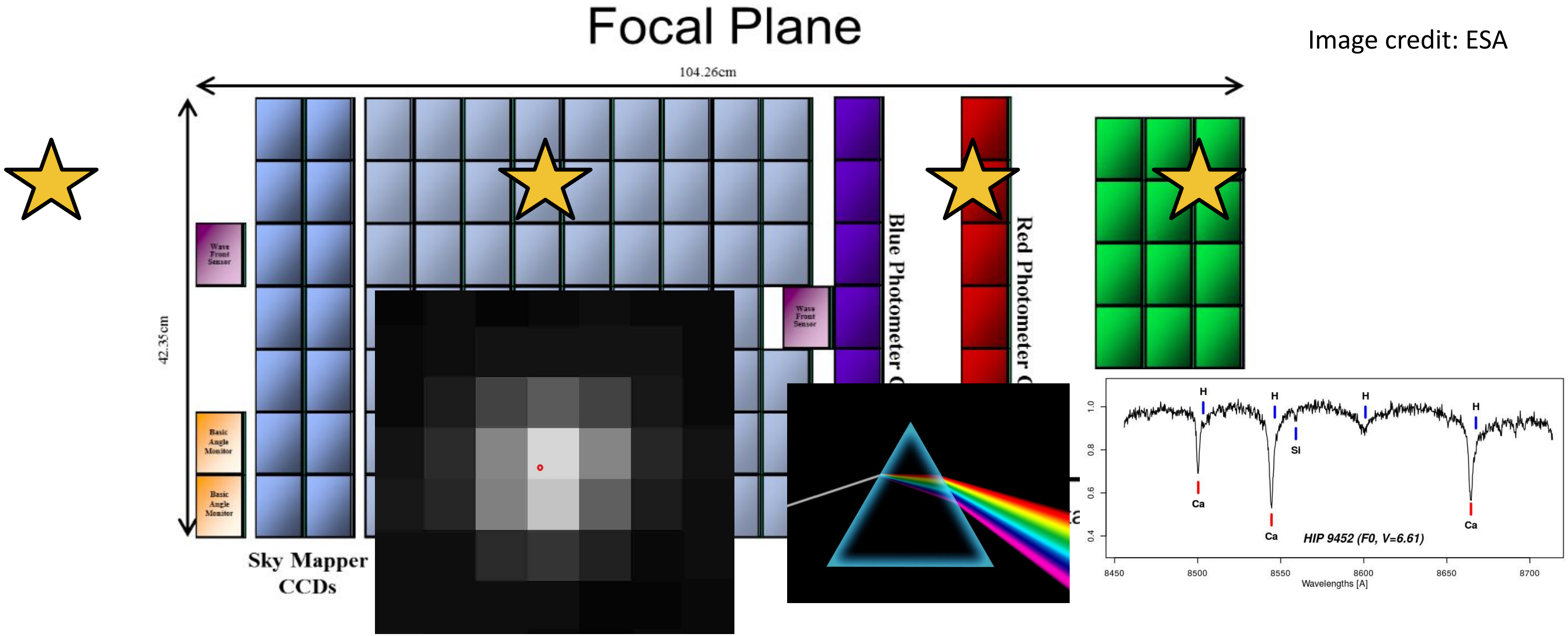

Image credit: ESA

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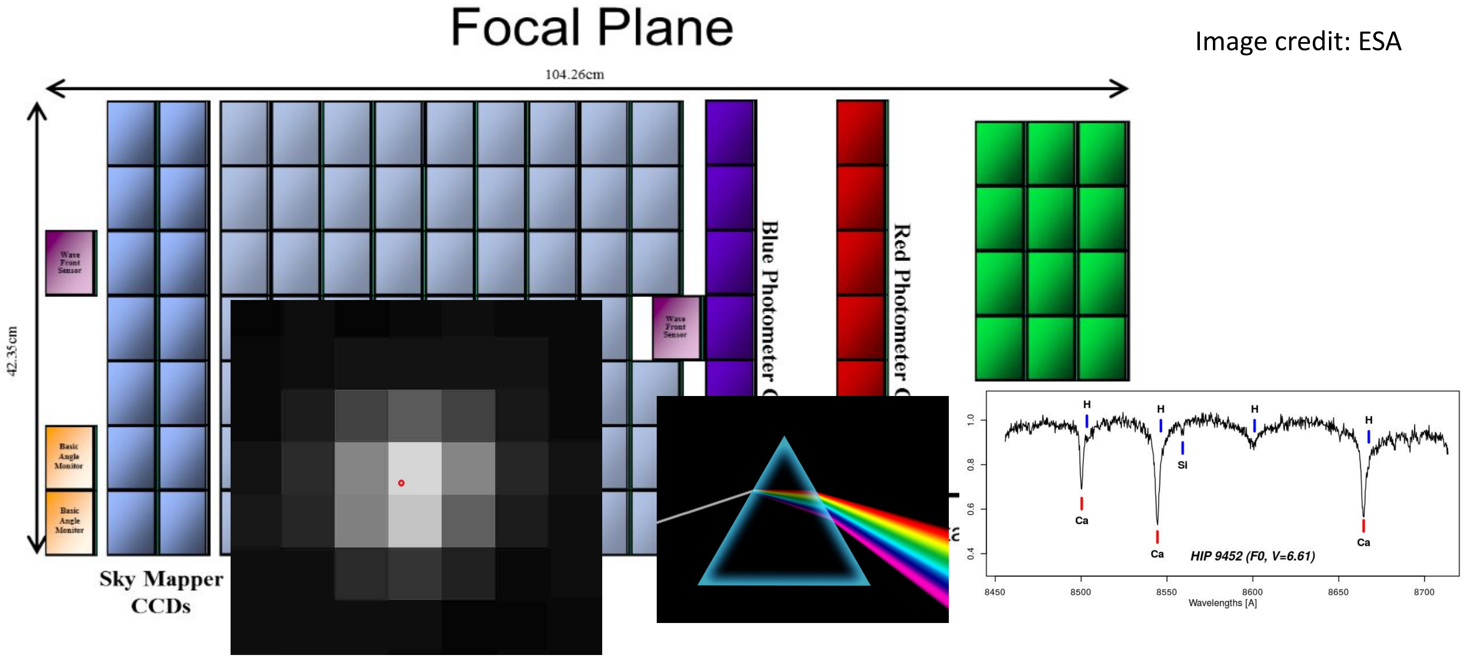

Image credit: ESA

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- These are converted to
  - Astrometric solution (proper motions, parallax, positions)
  - Mean and time-resolved ‘G’ magnitude (with zeropoint and passbands)
  - Mean and time-resolved BP/RP also give ‘G_{BP}’ and ‘G_{RP}’ integrated photometry (therefore $G_{BP} - G_{RP}$, with zeropoints and passbands)
  - Mean and time-resolved BP/RP spectra (“coefficients”)
  - Mean and time-resolved RVS spectra

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  - **Mean** and time-resolved **RVS spectra** note: time-resolved for variable objects + GAPS only

Gaia revolution in stellar observations and astrophysics

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    - Based on model assumptions and adopted methods
    - Spectroscopic parameters: Teff, surface gravity (log g), metallicity [M/H], abundances e.g. [Fe/H], line broadening mostly due to rotation (vsini), chromospheric emission (activityindex)
    - Evolutionary parameters: radius, mass, age, evolution index
    - Rotation period: from time-series where ‘variability’ is detected

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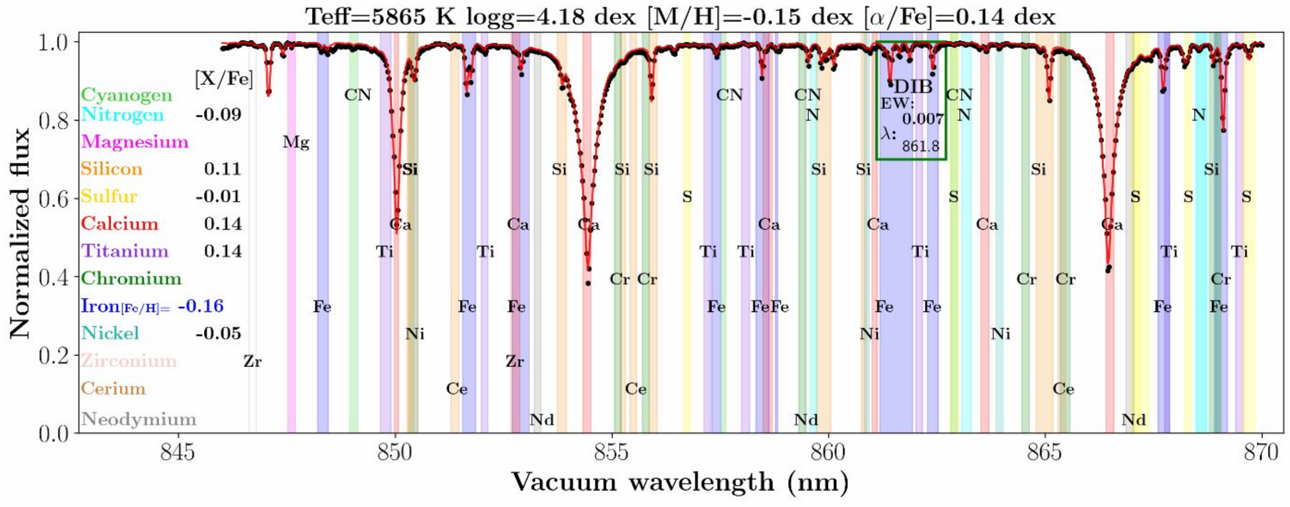
RVS spectra: spectroscopic parameters and abundances

- The RVS spectra are used to derive radial velocities (3rd velocity component)
- They also contain a rich amount of astrophysical information: teff, log g , [M/H], alpha-abundance, individual chemical species (Fe, Mg, Ca, …) and even the diffuse interstellar band (DIB) feature which is related to the interstellar medium
- 1 million spectra published



ESA/Gaia/DPAC-CU8, Recio-Blanco and the GSP-Spec team

RVS high-resolution spectra : Teff, log g and [M/H]

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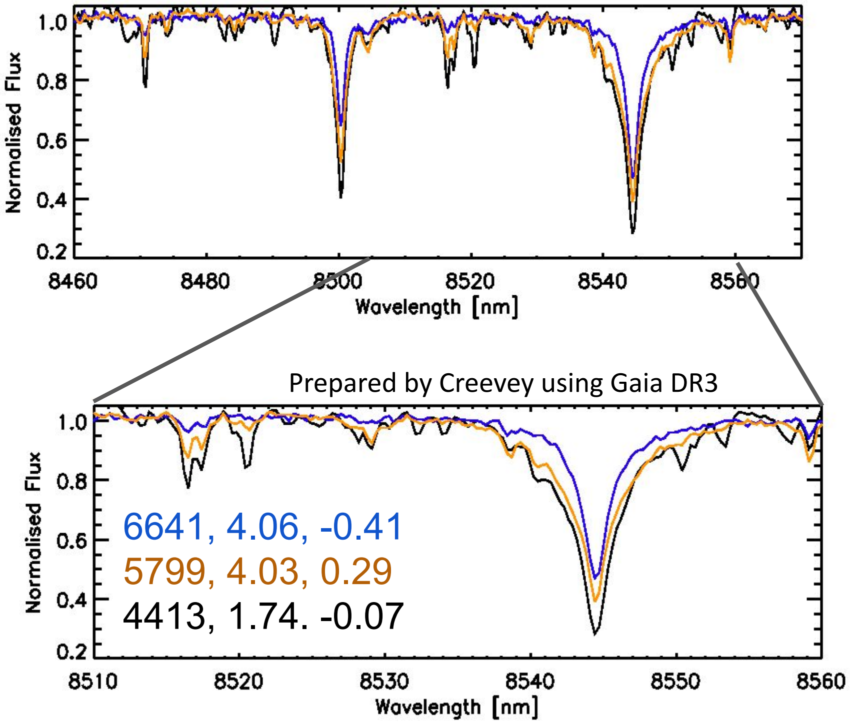
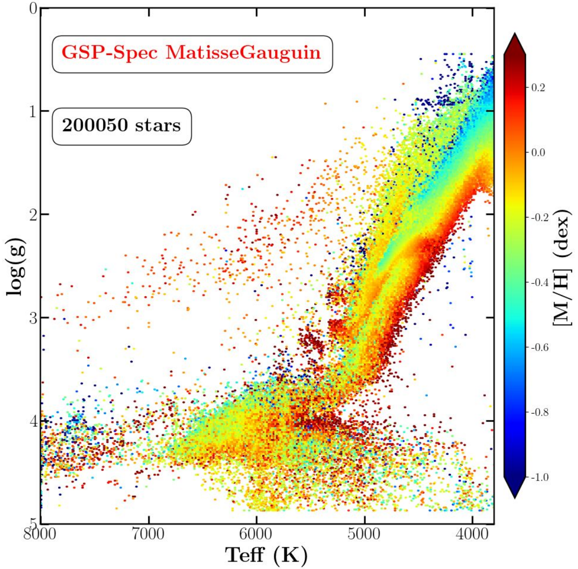
- Distribution of Teff and logg in Gaia DR3 using RVS-derived parameters (Kiel diagramme)





Recio-Blanco et al. 2022 A&A

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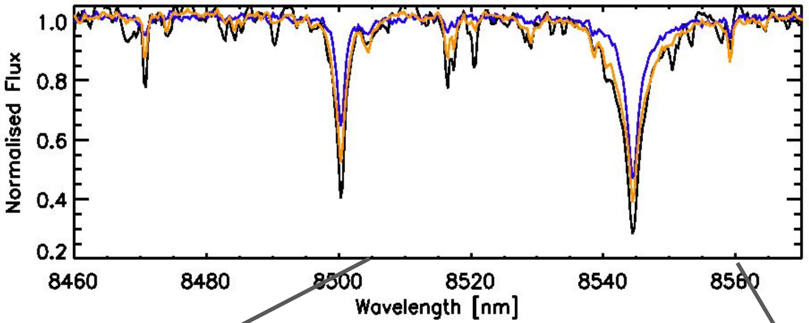
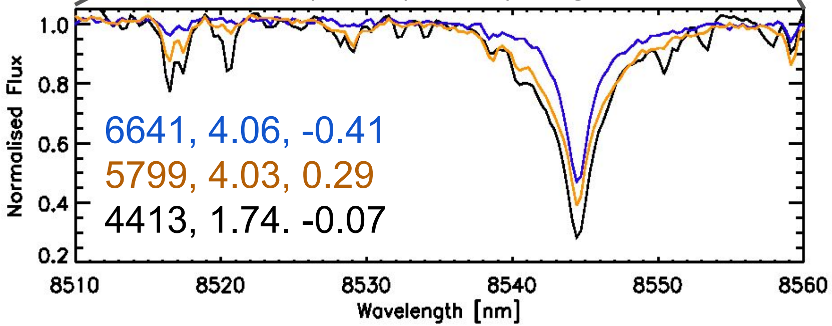
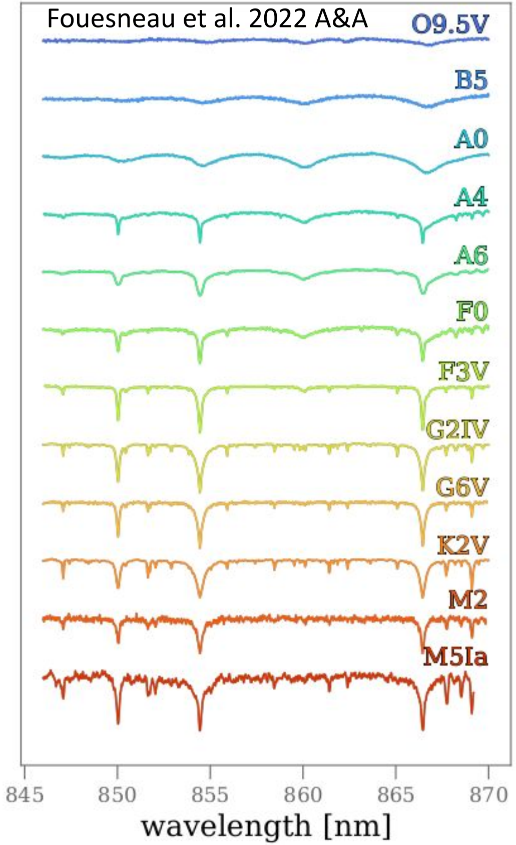


Prepared by Creevey using Gaia DR3



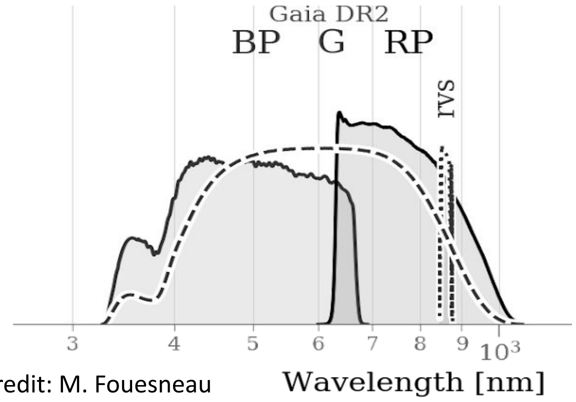
Fouesneau et al. 2022 A&A



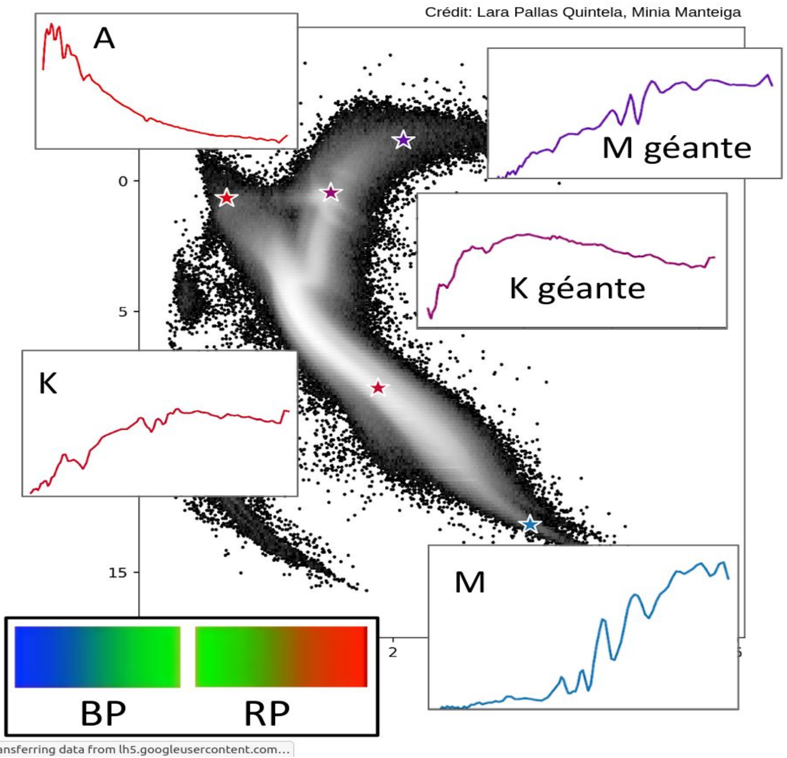
Low-resolution spectra: BP and RP

- Gaia produces BP and RP spectra, and these provide information about intensity distribution across wavelength (220 million published)

- The figure on the right shows examples of the flux distribution across the 330 – 1050 nm wavelength
  BP: 330nm – 680 nm
  RP: 640nm – 1050 nm



Credit: M. Fouesneau



Spectral energy distribution: dependence on Teff

- The radiance of a star across different wavelengths (spectral distribution) depends on its temperature
- We can use the Planck Blackbody radiation law to describe this distribution
- Three main points to notice:
  - peak intensity wavelength (see also Wien's Law)
  - amount of radiation (higher temperature, more radiance)
  - spectral distribution shape (more peaky or flatter)
- This energy is the amount emitted at the surface per second (luminosity), but stars are generally at different distances so the flux received on Earth depends on the distance

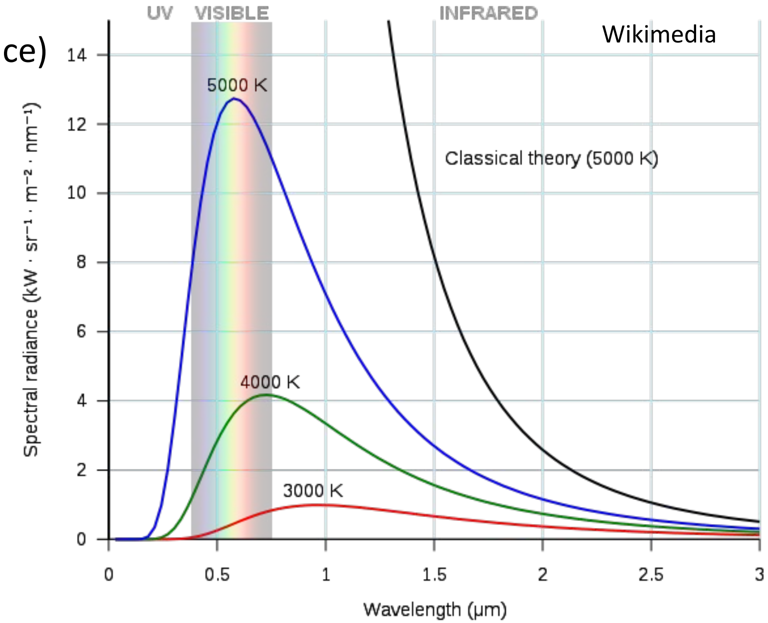


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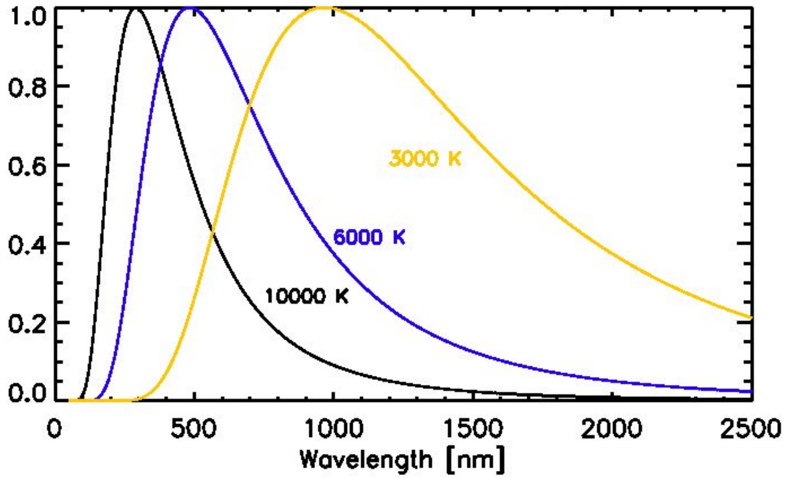
Figure produced by O. Creevey



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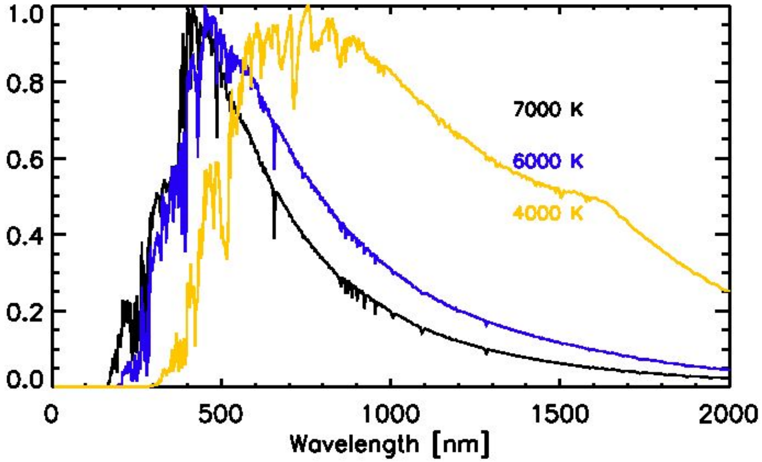
- "Real" stars using models are not as simple and also depend on [M/H] and log g

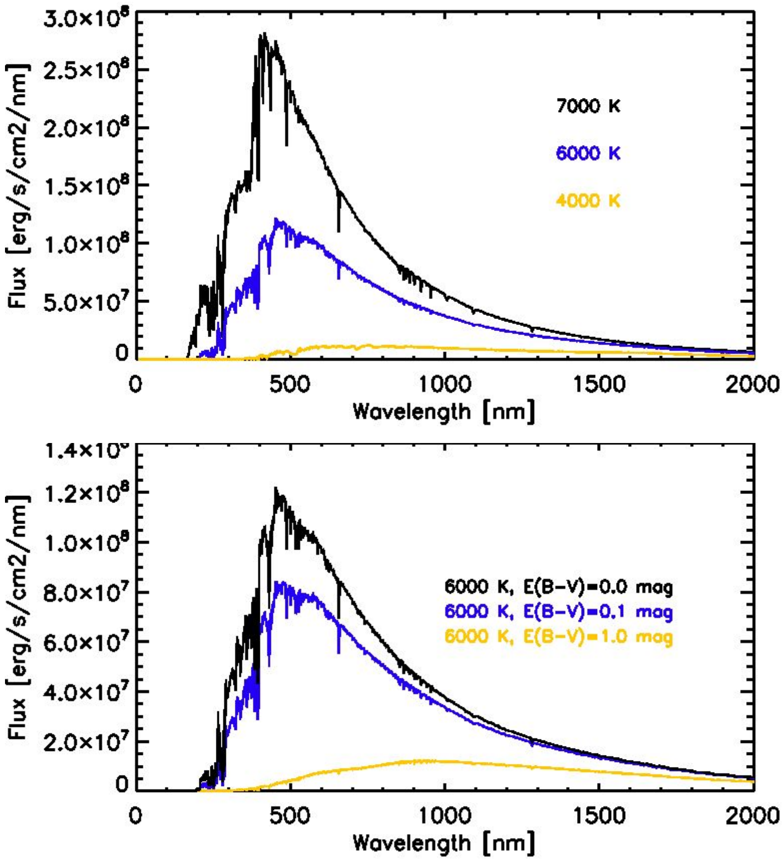
Figure produced by O. Creevey



Spectral energy distribution: ‘real’ flux and extinction

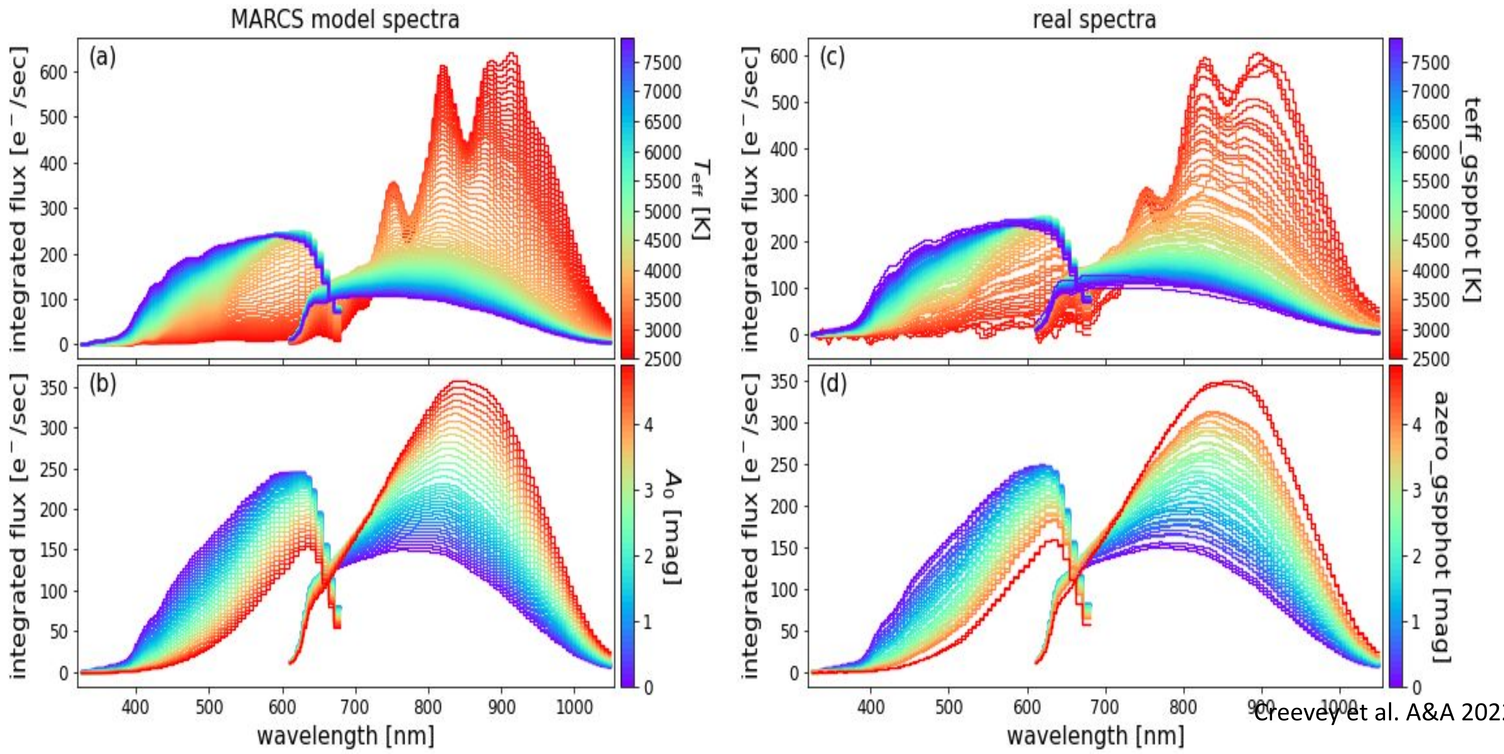
- Spectral energy distribution depends on Teff, logg, [M/H]
- Amount received at Earth depends on distance
- The gas and dust between us and the star attenuate the light received from the star.
  - The star will appear dimmer
  - We call this extinction Aλ
  - Blue light is affected more than red light so the spectral shape will change
  - We also call it interstellar absorption or ‘reddening’
  - A_{BP} - A_{RP} = E(BP-RP) ‘reddening’
- Now we must consider
  - Teff (logg, [M/H])
  - Distance
  - extinction

Figure produced by O. Creevey



GDR3 results from BP/RP spectra: Teff and extinction

- Gaia DR3 contains 470 million estimates of Teff, AG, logg, [M/H] derived from the BP/RP spectra (the spectra have been rescaled to an apparent magnitude of G=15.)

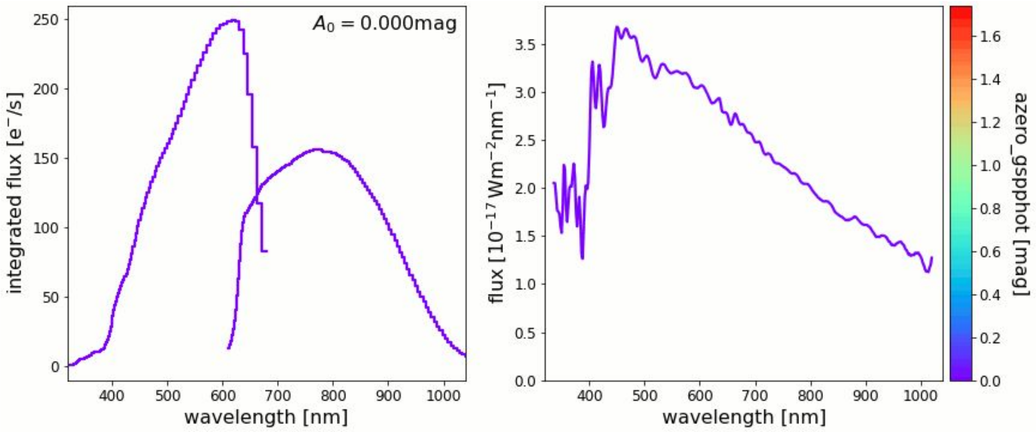


Creevey et al. A&A 2022

GDR3 results from BP/RP spectra: effect of extinction

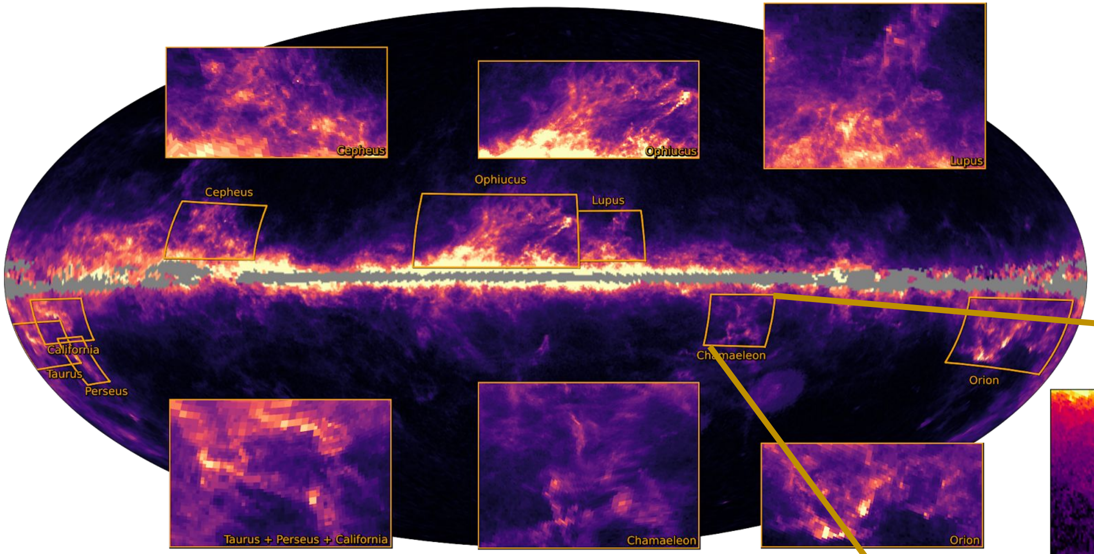
- By selecting 'identical' stars but with different amounts of extinction, we can investigate the impact of the dust on the spectral distribution

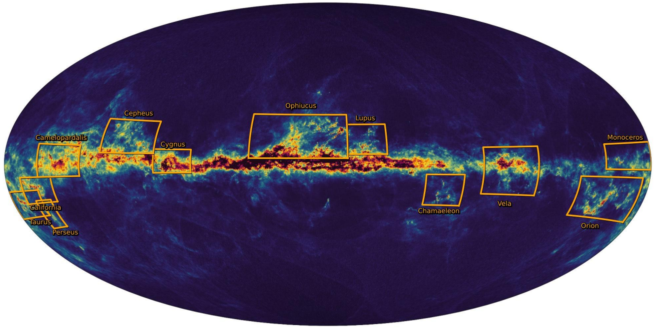
- The following are a selection of solar analogues i.e. similar Teff, log g, radius, mass to the Sun, with different values of extinction. Left are the the internally-calibrated spectra, right are flux-calibrated spectra.

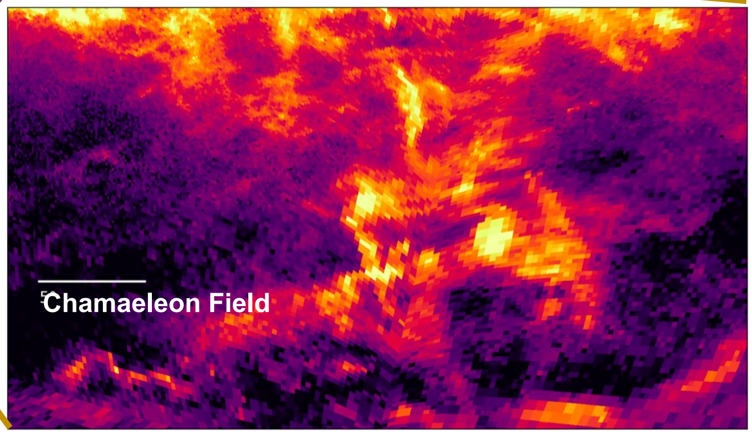


Gaia coll. Creevey et al. A&A 2022

GDR3 results from BP/RP spectra: mapping the 2D and 3D extinction







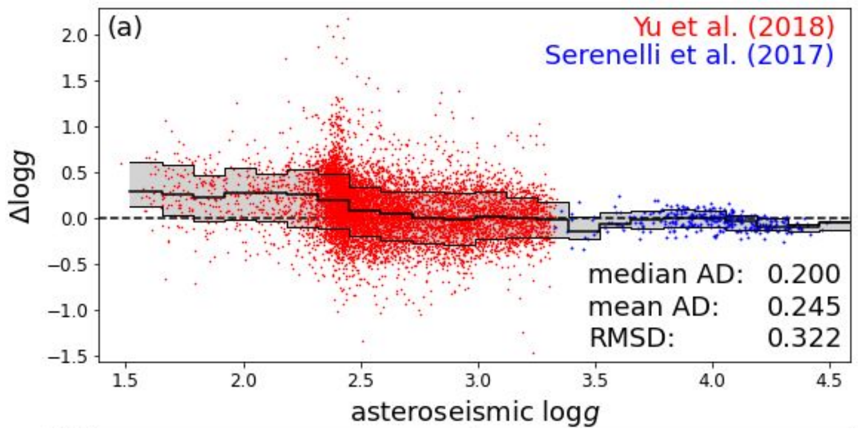
Delchambre et al. 2022 A&A; Acknowledgement Thavisha Dharmawadena (projections); Creevey et al. 2022, A&A (Chamaeleon field)

See also: a 3D Galaxy fly-through

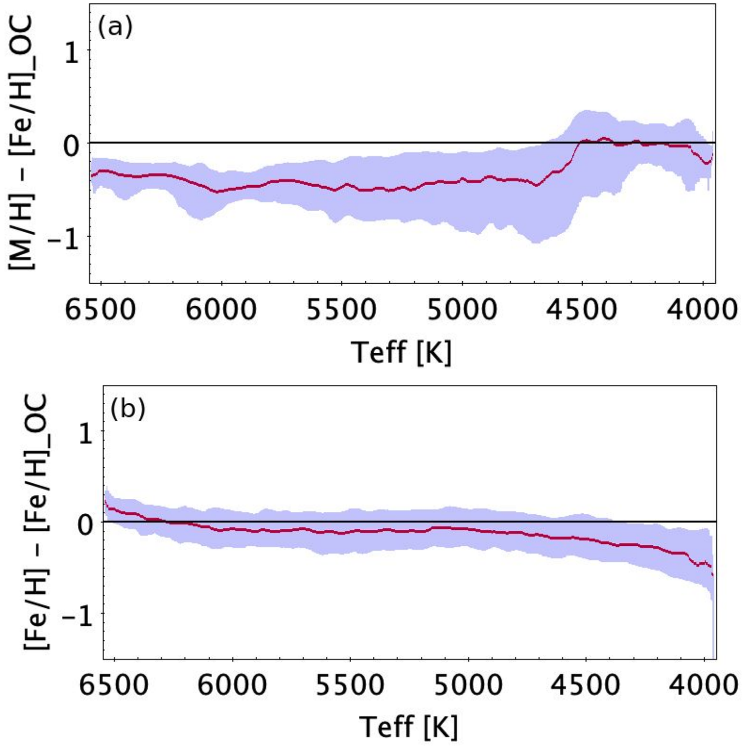
The 2D TGE uses a minimum number of giants beyond 10 kpc as tracers of extinction, hence the missing values along the disc.

GDR3 results from BP/RP spectra: log g and metallicity

- Comparison of logg_gspphot with asteroseismology
- Comparison of metallicity before and after calibration



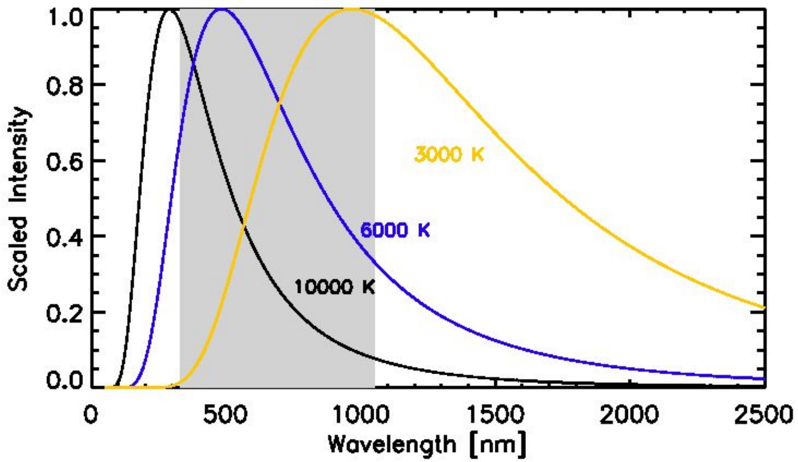
Andrae et al. 2022



Spectral energy distribution: luminosity

- G magnitude only covers some of the spectral range (see D. Huber's talk)
- Anything outside of the grey area can be "estimated" from models and this missing flux is called the bolometric correction (BC)
- BC depends on Teff, logg, [M/H]

Figures produced by O. Creevey



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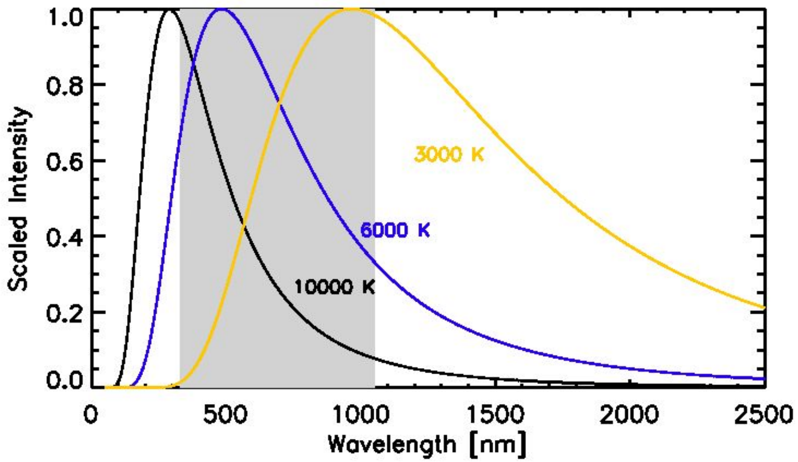
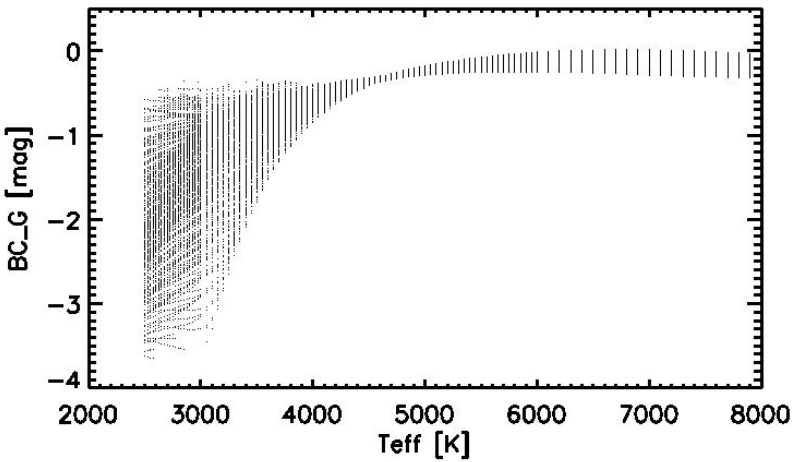
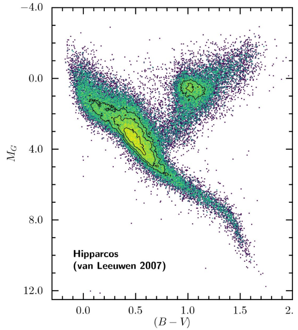
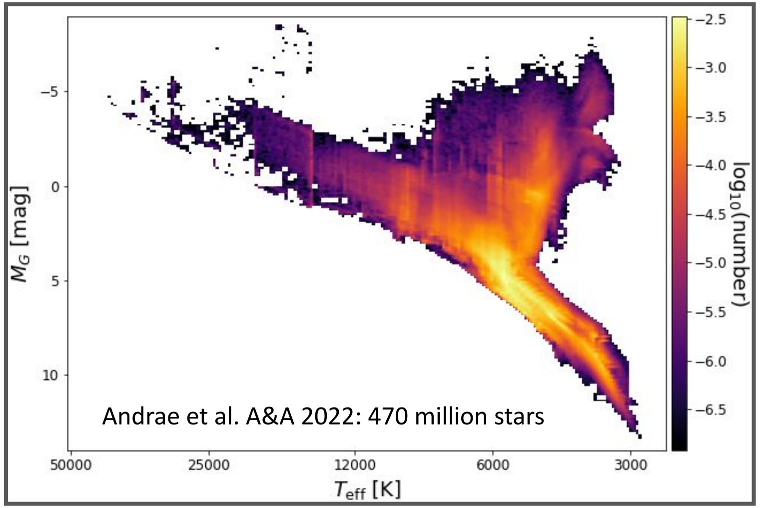


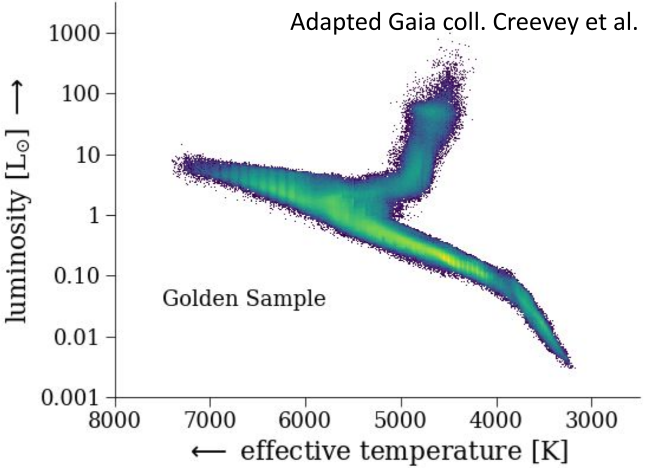


GDR3 results: Luminosity

- Intrinsic luminosity needs:
  - distance (parallax, spectrogeometric, …)
  - flux in G band (‘G’ magnitude)
  - extinction (AG, ABP, ARP, A0, E(BP-RP))
  - BC, BC needs Teff, [MH], log g





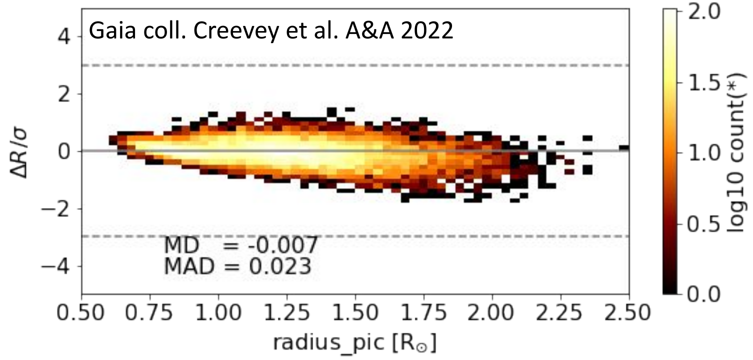


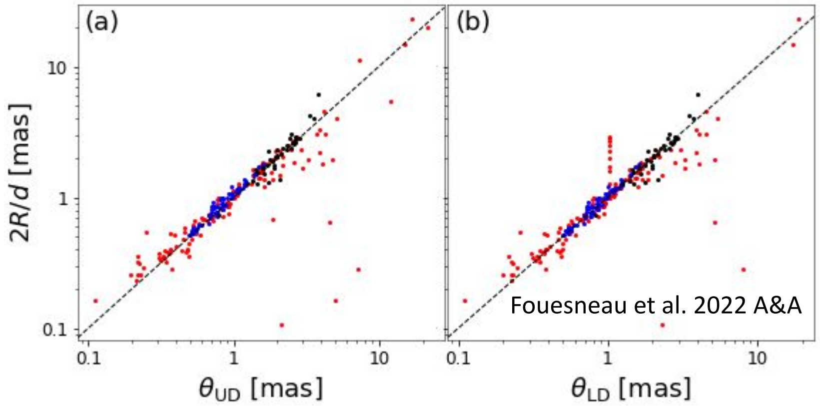
Adapted Gaia coll. Creevey et al. A&A 2022

GDR3 results: Radius

- Two different estimates in Gaia
  - radius_flame: use the Stefan-Boltzmann Law
  - radius_gspphot: use the amplitude of the BP/RP spectra and distance (needs evolution models coupled to BP/RP spectra models)

$$L_\star = 4\pi R_\star^2 \sigma T_{\rm eff}^4$$

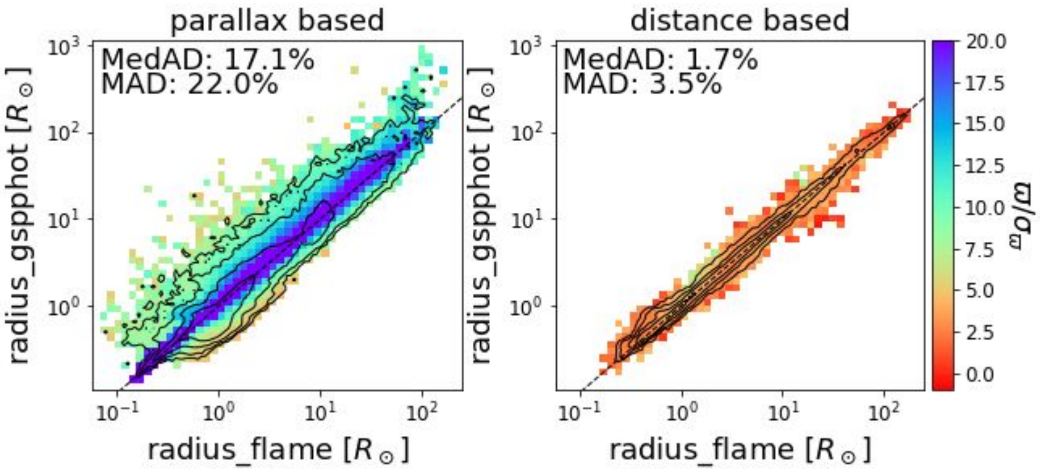




GDR3 results: Radius

- Two different estimates in Gaia
  - radius_flame: use the Stefan-Boltzmann Law
  - radius_gspphot: use the amplitude of the BP/RP spectra and distance (needs evolution models coupled to BP/RP spectra models)

GDR3 Online documentation, Ulla et al. 2022



Outline

- Importance of stellar parameters for exoplanetary characterisation

- From the colour-magnitude diagram (CMD) to the HR diagram
  - Why the HR diagram
  - Gaia observables
  - RVS spectra
  - BP/RP spectra
  - Spectral energy distributions: Temperatures, extinction, bolometric corrections
  - Gaia Results: Effective temperatures, luminosities, surface gravities, extinction, metallicities

- From the HR diagram to stellar masses and ages
  - Inferring stellar ages from the HR diagram
  - Key role of the stellar mass
  - Masses and Ages in Gaia DR3
  - Exoplanetary characterisation

- Key points

Inferring ages from a HR diagram

- Typical approach for deriving ages of (single) stars
  - Lum + error
  - Teff + error
  - [M/H] + error

- 18 Sco – bright and well measured

- Classical Teff, Lum, [M/H] (pre-Gaia) 'good measurements'
  - σ(Lum) = 0.04 Lsun
  - σ(Teff) = 70 K
  - σ[M/H] = 0.06

- Use stellar evolution tracks or isochrones and find those that fall within the error bar

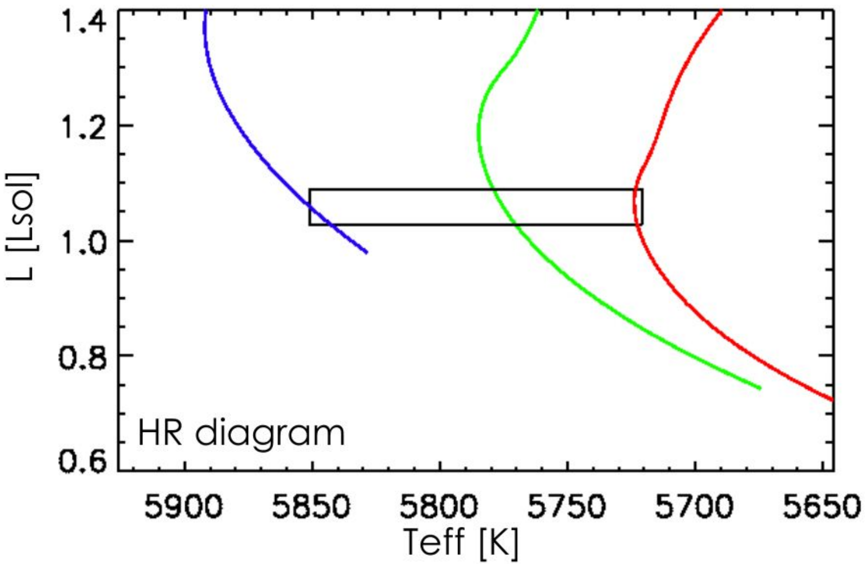


Figure produced by O. Creevey

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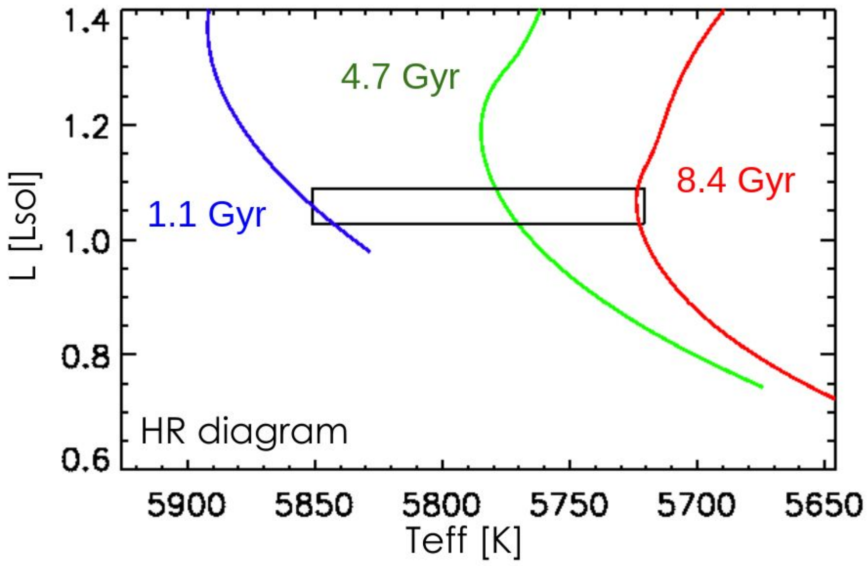

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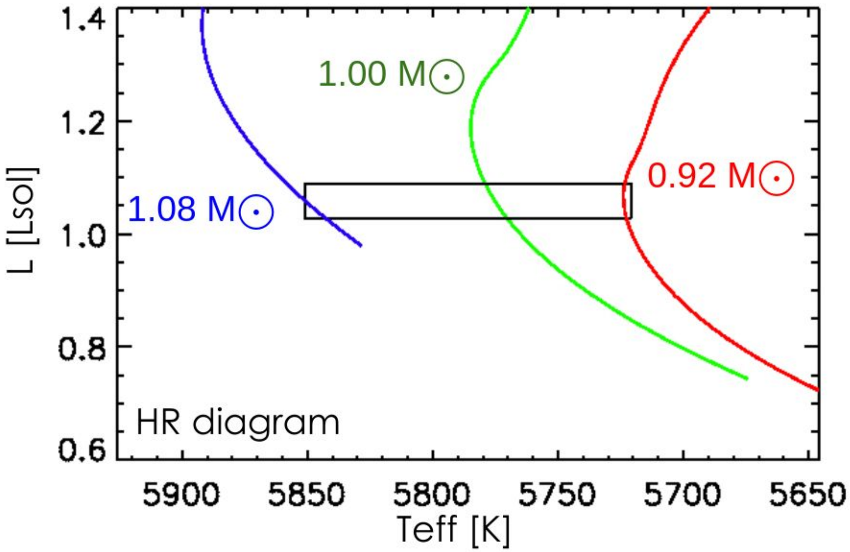
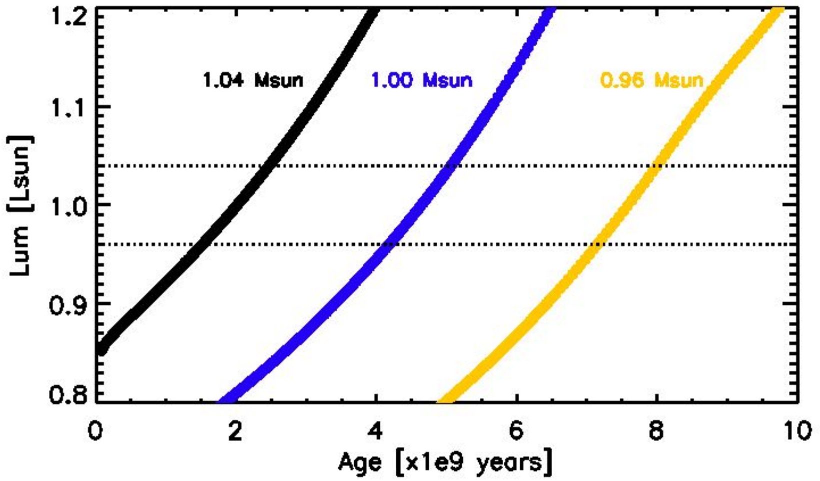


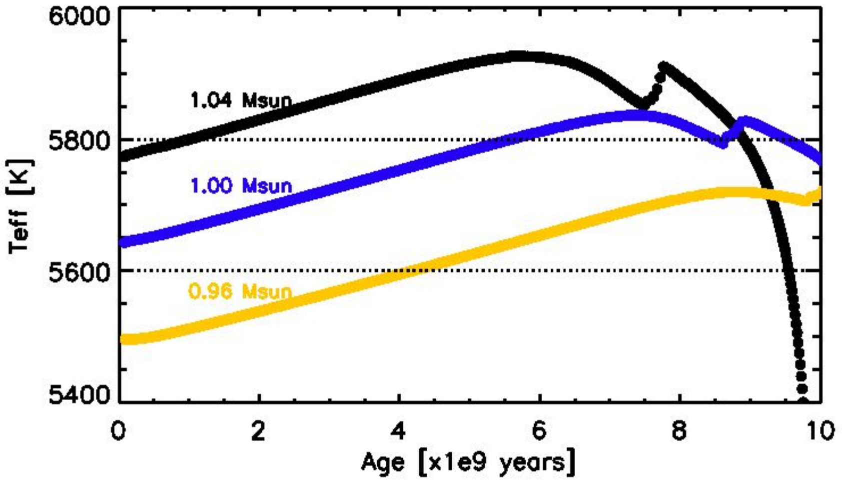
Figure produced by O. Creevey

Why we care about the stellar mass (apart from knowing exoplanets)

- The mass of the star is the key quantity that determines its structure and evolution speed
  - Higher mass = higher pressure in center = higher T in center = higher nuclear reaction rates
  - Evolution speed is determined by the nuclear reactions
    - Things change slowly in lower mass stars (live for billions of years)
    - Things change rapidly in high mass stars (live fast die young!)

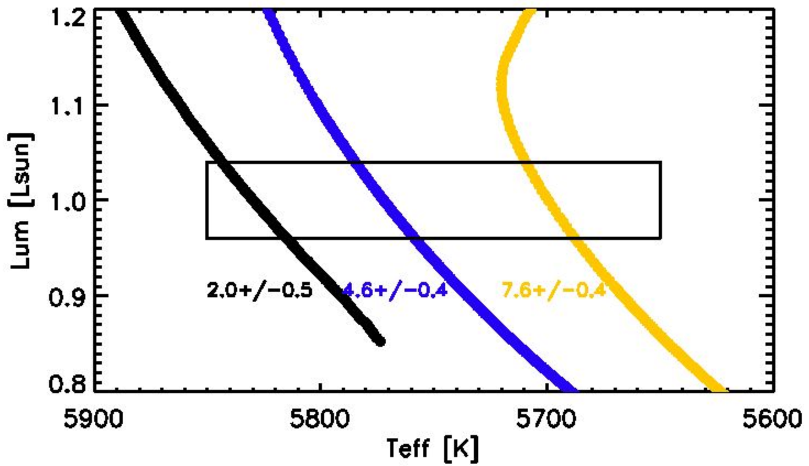
Figures produced by O. Creevey





Mass is the key to knowing the age

- The mass of the star is the key quantity that determines the structure of the star
- Age varies from 1.5 to 8.0 billion years even though the mass differs by 0.08 Msun
- An independent radius measurement can help!
    - 0.98 +/- 0.01 Rsun
    - 1.00 +/- 0.01 Rsun
    - 1.03 +/- 0.01 Rsun



Masses of stars in Gaia DR3

- Single Stars
  - log g and radius for 470 million stars
  - Using stellar models for 130 million stars
- Binary systems
  - New catalogue of binary masses for ~200,000 stars

Gaia coll. Arenou et al. A&A 2022

Fouesneau et al. A&A 2022

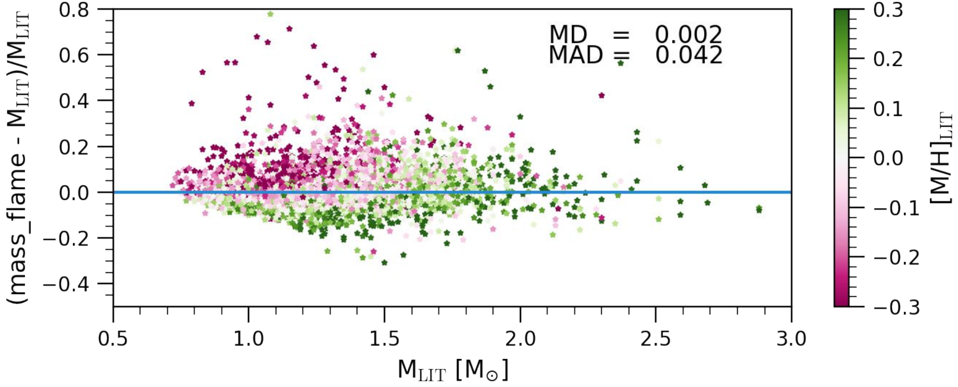


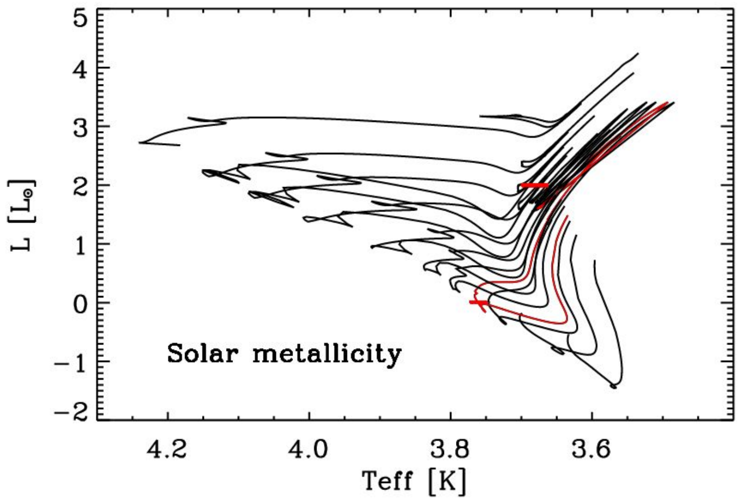
Table 3. Content of the Catalogue of masses.

Combination Method	Number	$\mathcal{M}_1$	$\mathcal{M}_2$	F_2/F_1
Orbital+SB2	23	✓	✓	✓
EclipsingSpectro(SB2)	3	✓	✓	
Eclipsing+SB2	53	✓	✓	
AstroSpectroSB1+M1	17578		✓	✓
Orbital+SB1+M1	1513		✓	✓
EclipsingSpectro+M1	71		✓	
Eclipsing+SB1+M1	155		✓	
SB2+M1	3856		✓	
Orbital+M1	111792		lower/upper	
SB1+M1	60271		lower	

Notes. The full table is available in the *Gaia* table `binary_masses`.

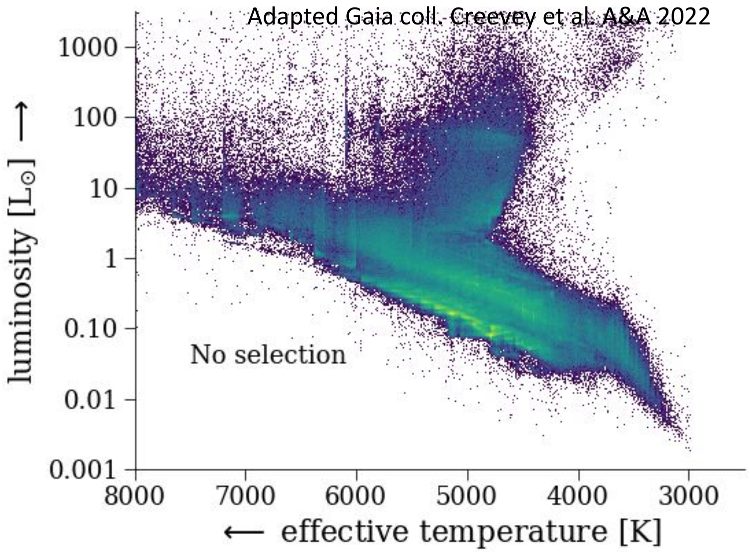
Ages of stars in Gaia DR3

- In Gaia DR3 120 million stellar ages have been estimated
- Use stellar evolution approach with a grid of models (BASTI, Hidalgo et al. 2018, right figure)
- Main-sequence - Tip Redgiant branch; 0.5-10.0 Msol
- Mass, age (and evolutionary stage) are derived at the same time using L, Teff, [M/H]
- (caveat: remember sources of possible errors!)



Ages of stars in Gaia DR3

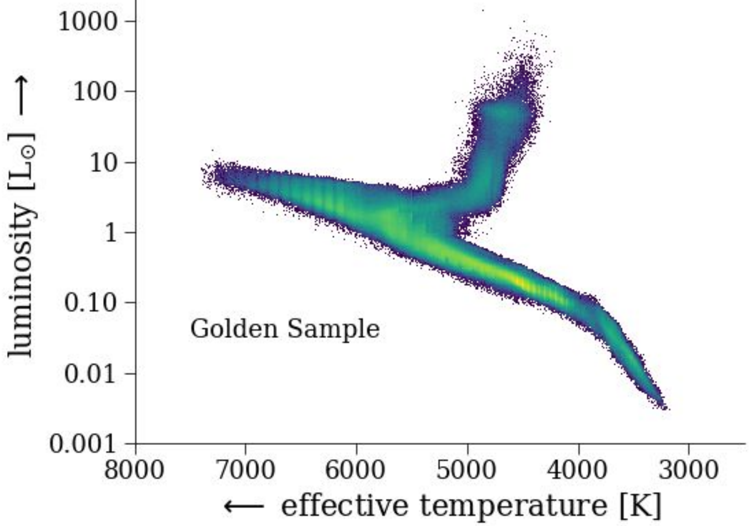
- Golden Sample from Gaia coll. Creevey et al. 2022 showing a selection of high quality astrophysical parameters, colour-coded by number of sources

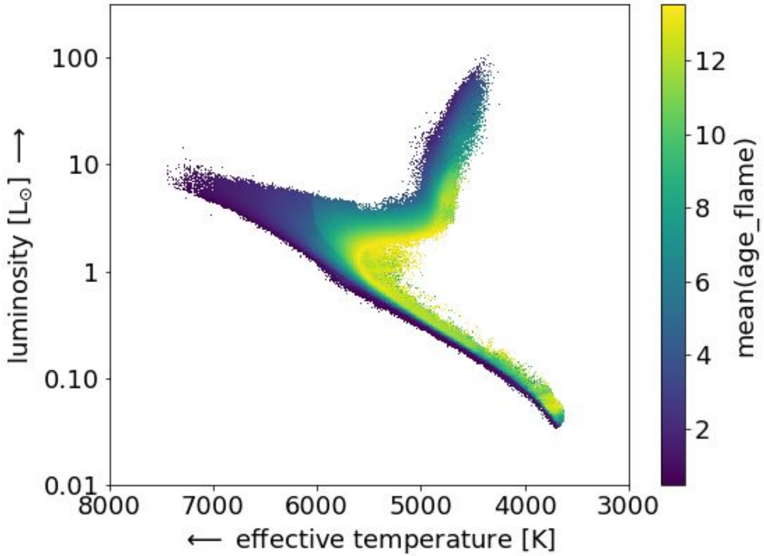


Ages of stars in Gaia DR3

- Golden Sample from Gaia coll. Creevey et al. 2022 showing a selection of high quality astrophysical parameters, colour-coded by number of sources
- Same diagram colour-coded by age – easily identify the main sequence and post-MS

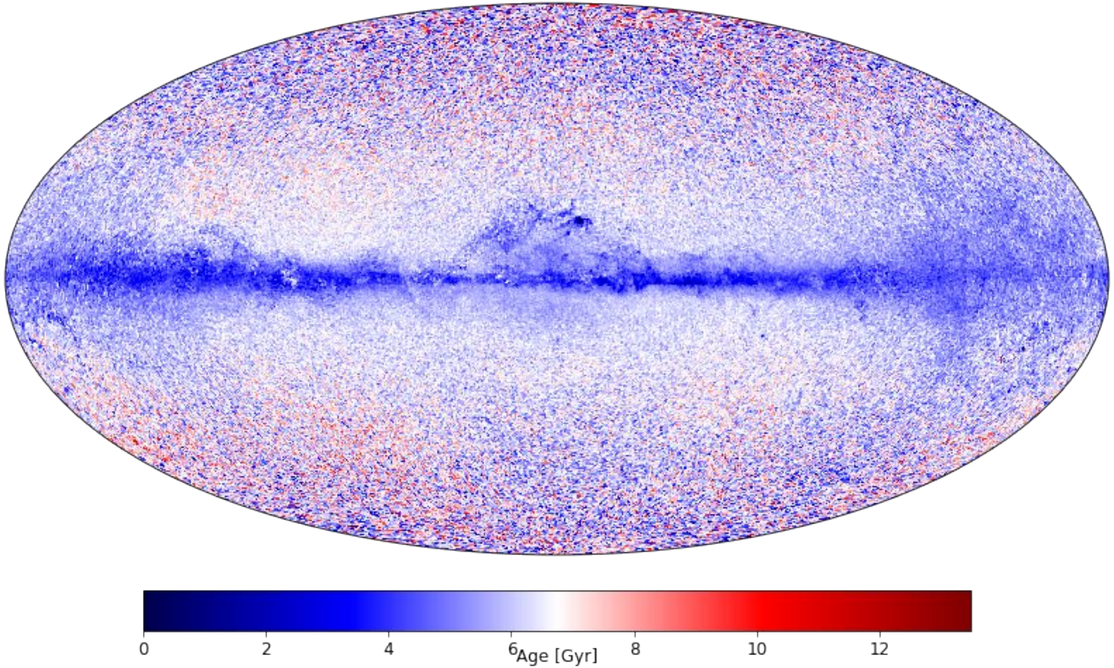
Adapted Gaia coll. Creevey et al. A&A 2022





Ages of stars in Gaia DR3

- Galactic projection showing distribution of ages in the Galaxy



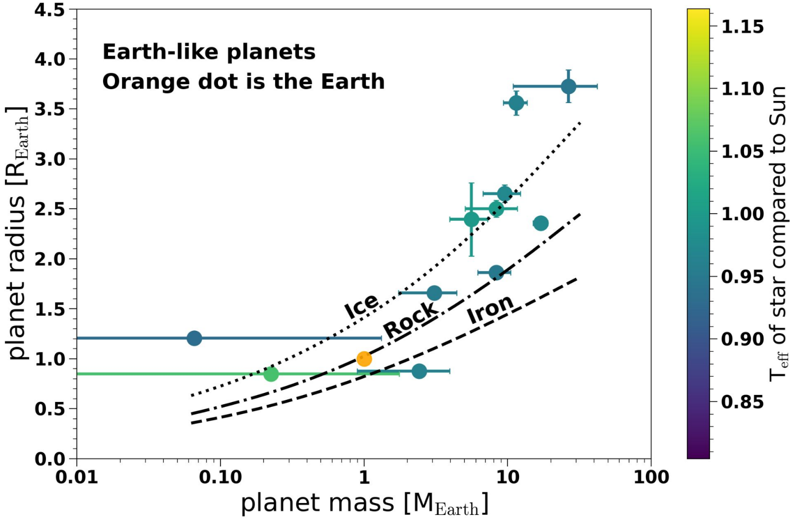
Credit: ESA/Gaia/DPAC; O Creevey & M. Fouesneau

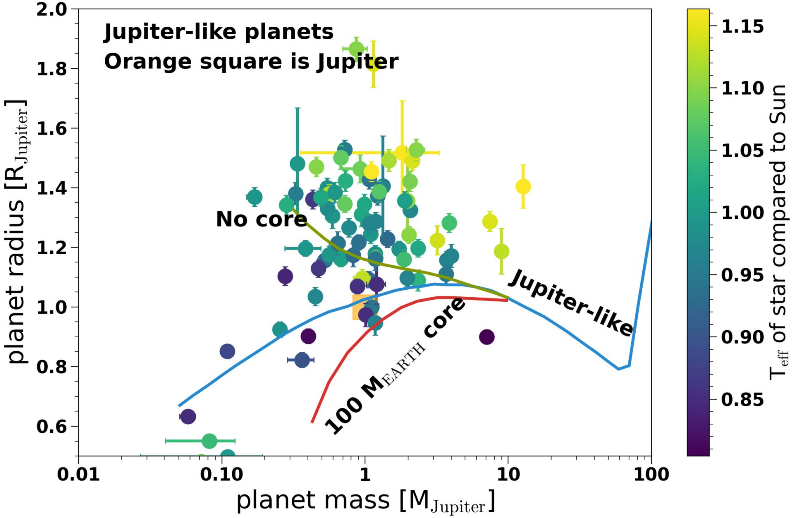
Masses, radii and ages of exoplanets using Gaia DR3

- Cross-match the Golden Sample with known exoplanet host stars
- Use the astrophysical parameters from Gaia DR3 (teff, radius, mass, age)

$$d_{tr} = \left(\frac{R_p}{R_\star}\right)^2 \qquad M_p \sin(i) = \frac{M_\star^{2/3} P^{1/3} K (1-e^2)^{0.5}}{(2\pi G)^{1/3}}$$

Adapted Gaia coll. Creevey et al. A&A 2022





A few words before finishing

- 218 million spectral types in Gaia DR3 produced by our team based on the spectra
- Chromospheric activity index from the Ca IR III can indicate youth in stars (but look also at their positions in the HR diagram)
- Interest in binaries for stellar masses is also to improve our stellar physics so that we can give you better models!
- Do not forget a very important message also given by Dan: there are systematics in stellar evolution. But with precise “observables” and measuring things in different ways we refine our knowledge of the physics of stellar interiors and evolution
- Metallicities for low-metal stars: calibration tool is proposed, see: Gaia software tools
- Want to know more on Gaia stellar parameters:
  - Scientific Apsis papers on Astrophysical Parameters, on ADS

Webinar on CU8 APs

CU8 highlights and what we do

Navigate through the multi-D Gaia

What to retain from this lecture

- We care about the host stars and in particular their fundamental parameters mass, age, radius, teff; we need these to characterise the planet
- Radius, teff, lum “observable” (almost!) while mass, age “unobservable” (except binaries with full solutions)
- We need to go through the observables to get to age
- Observables are complicated too; Gaia provides many other types of observations to help us get there in particular the RVS (1 M) and BP/RP spectra (220 M), and photometry (1.6 B, not only astrometry)
- The age depends on many physical assumptions and it is critically dependent on the mass of the star
- Precision in the HR diagram is important. This translates directly to precision on mass and age.
- Gaia provides you with the way to choose your best targets and even gives you the astrophysical parameters (teff, log g, extinction, [M/H], radius, luminosity, mass, age). Now you can combine these with other data to get even more information about radius, mass and ages of exoplanets

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Thank you for your attention!