Gaia's low-resolution BP/RP spectra and its use for stellar characterisation

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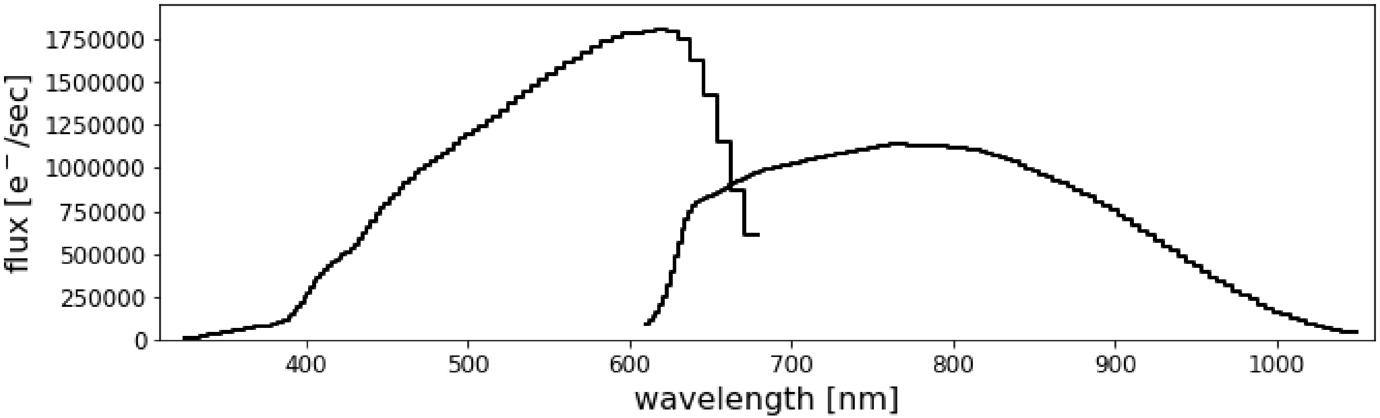
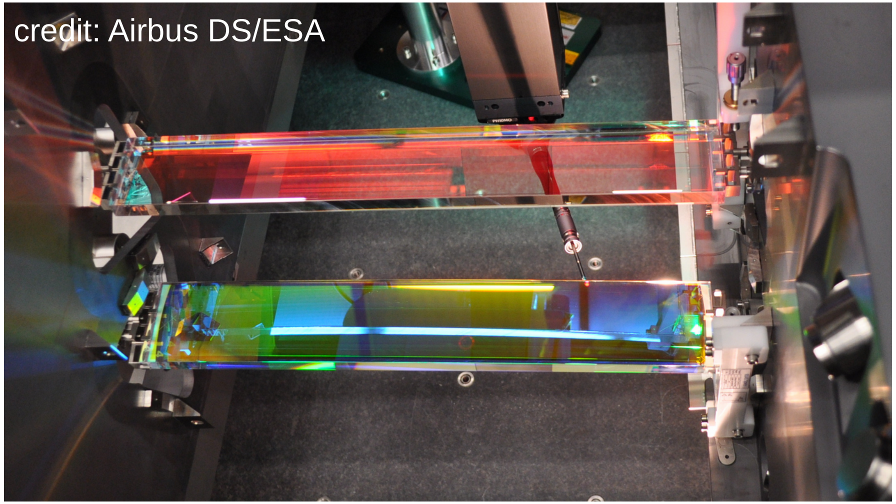
Overview

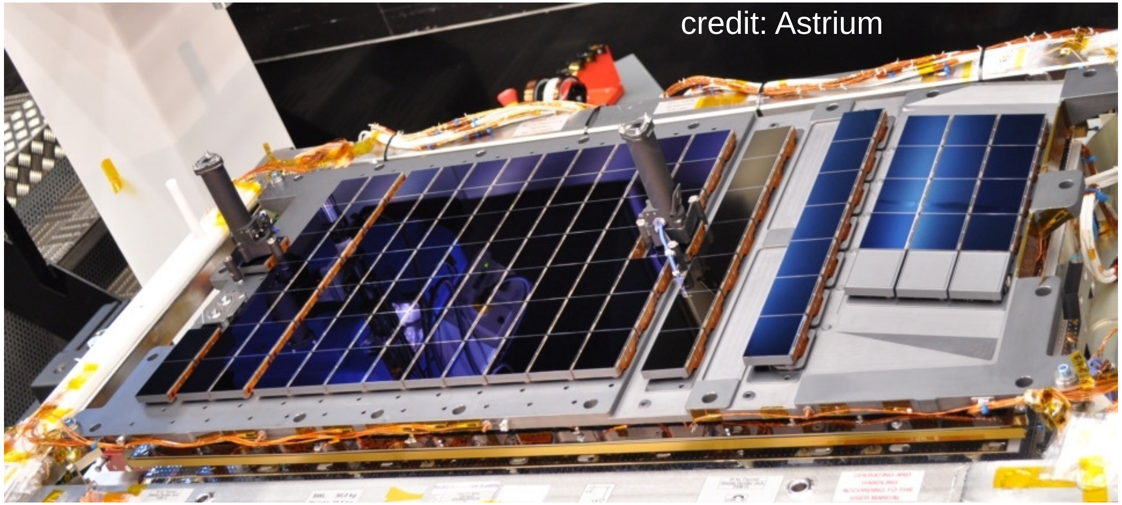
1) **XP spectra and their formats**
2) Stellar parameters from forward modelling
3) Current limitations of forward modelling
4) Inverse modelling: metal-poor heart of the Milky Way

XP instruments



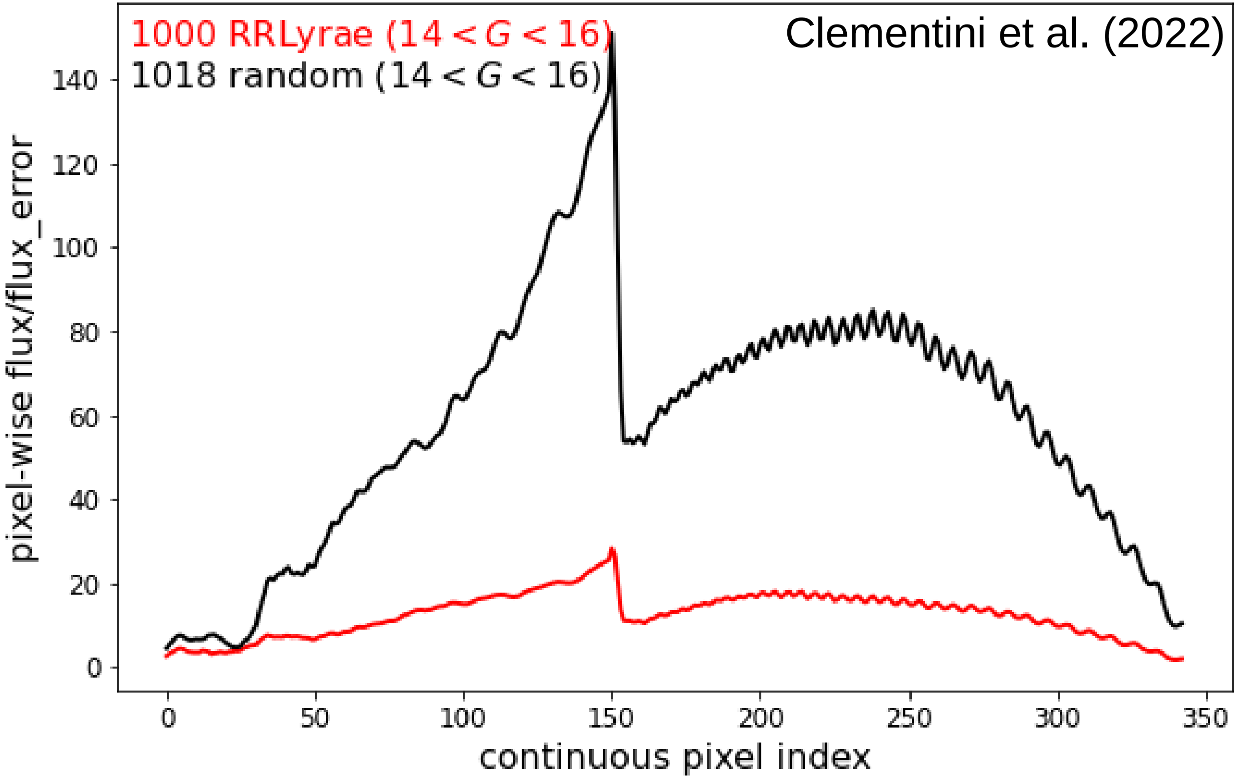
- 18 Sco = solar twin
- G ~ 5.3 mag
- BP/RP = 2 prism spectra





XP spectra basics

- all details: Carrasco et al. (2021), De Angeli et al. (2022)
- time-averaged mean spectra from ~40 epochs
  => variability "absorbed" into errors => lower SNR



XP spectra basics

- goal: combine ~40 epoch spectra for each source
- problem: instrument ages over time
- no two epoch spectra ever have the same wavelength sampling!
- cannot “just stack” epoch spectra

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flux of epoch spectrum

maximum decomposition order

$$f(u) = \sum_{k=0}^{54} c_k b_k(u)$$

pixel coordinate

continuous basis function

expansion coefficient

XP spectra and their formats

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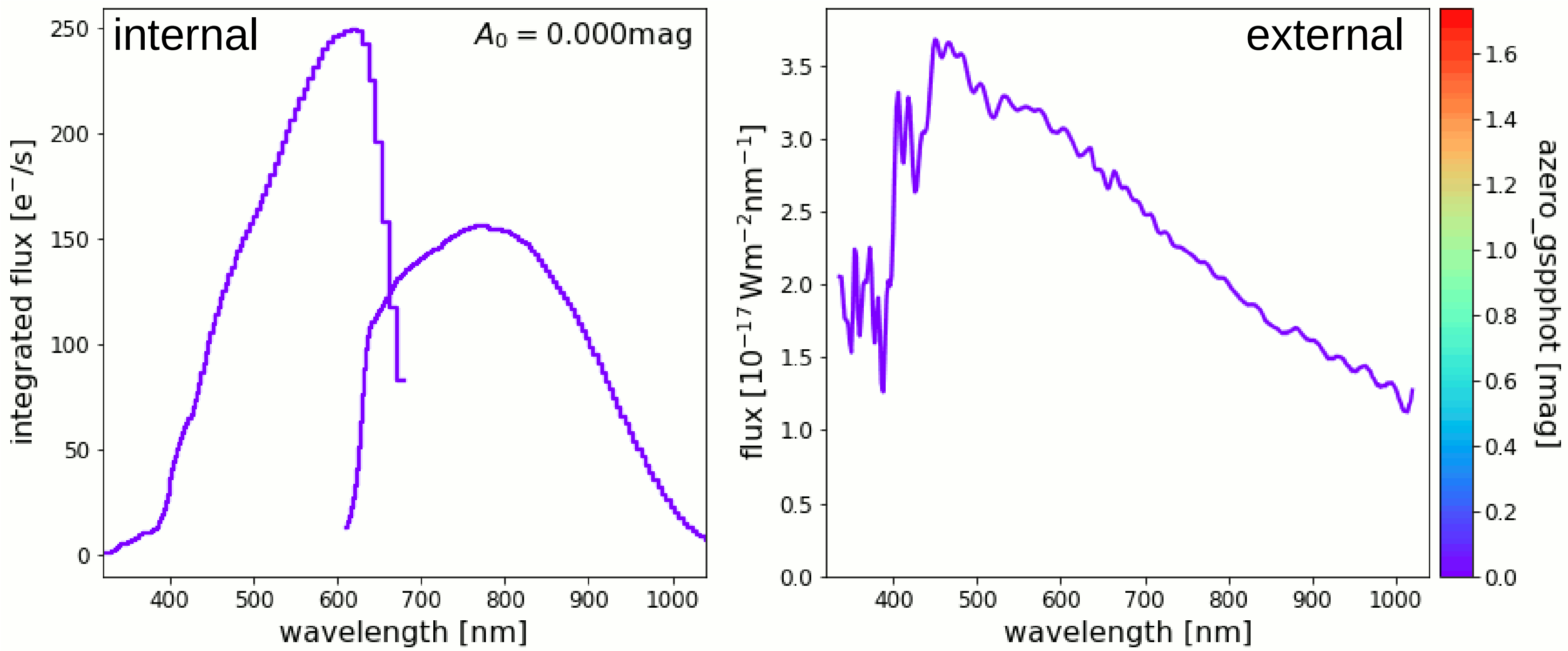
2) internally calibrated sampled spectra (GaiaXPy)

3) externally calibrated sampled spectra ("xp_sampled", GaiaXPy, Montegriffo et al. 2022a)



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1) 2 x 55 coefficients for BP + RP (“xp_continuous”, De Angeli et al. 2022)

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4) alternative: generate synthetic photometry (Gaia Collaboration, Montegriffo et al. 2022)

DR3: 220 million coefficients + covariance matrix
(G < 17.65 mag + QSOs + galaxies + ultra-cool dwarfs)

Aside: Inverting BP/RP covariance matrices

- 55 coefficients … covariance matrices are large
- inverse covariance matrices needed for inference:

$$\chi^2 = (\vec{c} - \vec{m})^T \cdot C^{-1} \cdot (\vec{c} - \vec{m})$$

- standard inversion can be numerically unstable:

```
C_inv = scipy.linalg.inv(C)
```

- use Cholesky decomposition for inversion:

```
L = scipy.linalg.cholesky(C, lower=True)
L_inv = scipy.linalg.solve_triangular(L, numpy.identity(55), lower=True)
C_inv = numpy.dot(L_inv.T, L_inv)
```

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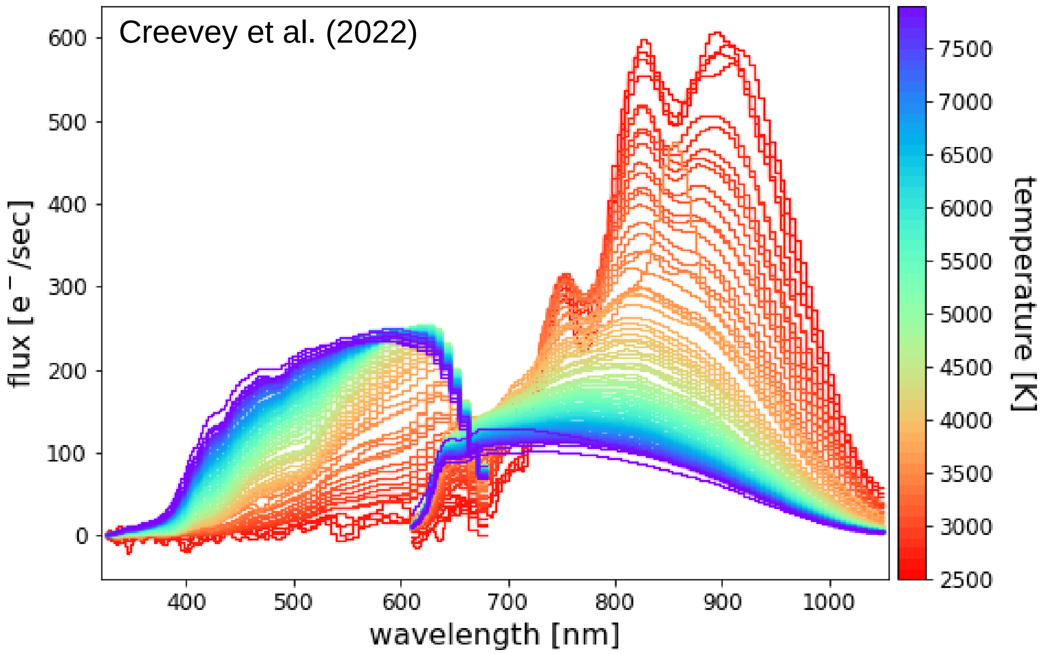
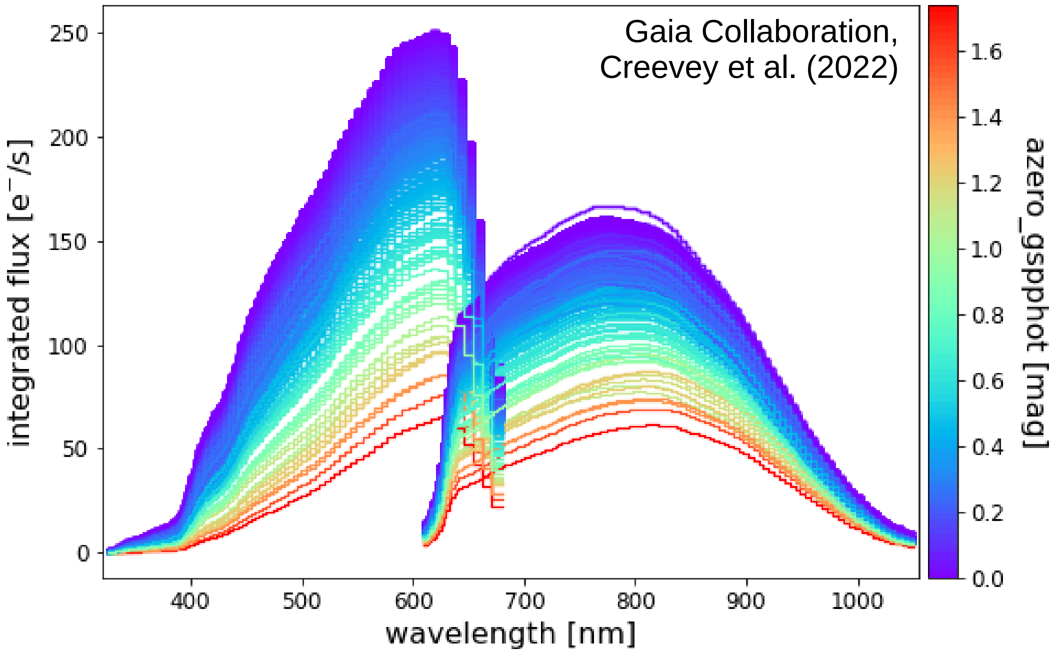
XP spectra vs temperature + extinction





- all XP spectra re-scaled to G = 15
- A0 < 0.05 mag
- -0.2 < [M/H] < 0
- 3.25 < logg < 3.75

- all XP spectra re-scaled to G = 15 + AG
- solar-analog candidates

Exploiting absolute fluxes of XP spectra

- XP spectra are **not** normalised
- observed XP spectra scale as: $\vec{s} \sim \left(\frac{R}{d}\right)^2 \sigma_B T_{eff}^4$

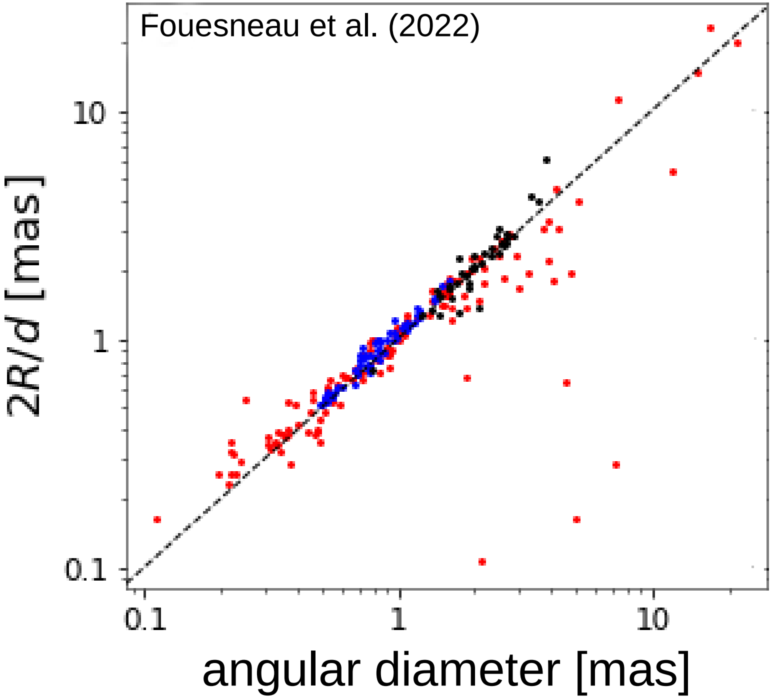
radius

distance

- model SEDs scale as: $\vec{m} \sim \sigma_B T_{eff}^4$
- fit for model amplitude:

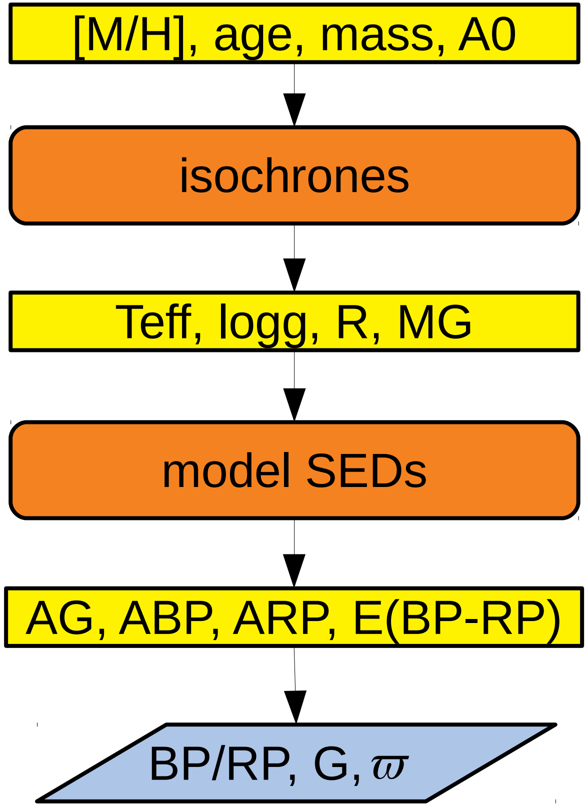
$$\chi^2_{BP/RP} = (\vec{s} - a\vec{m})^T \cdot C_s^{-1} \cdot (\vec{s} - a\vec{m}) \quad \Rightarrow \quad a = \left(\frac{R}{d}\right)^2$$

- R/d very well constrained
- even if distance biased, R/d still good



GSP-Phot in a nutshell

- General Stellar Parametriser from Photometry (Andrae et al. 2022)
- stellar parameters for 471 million stars
- PARSEC isochrones (1.2S Colibri S37)



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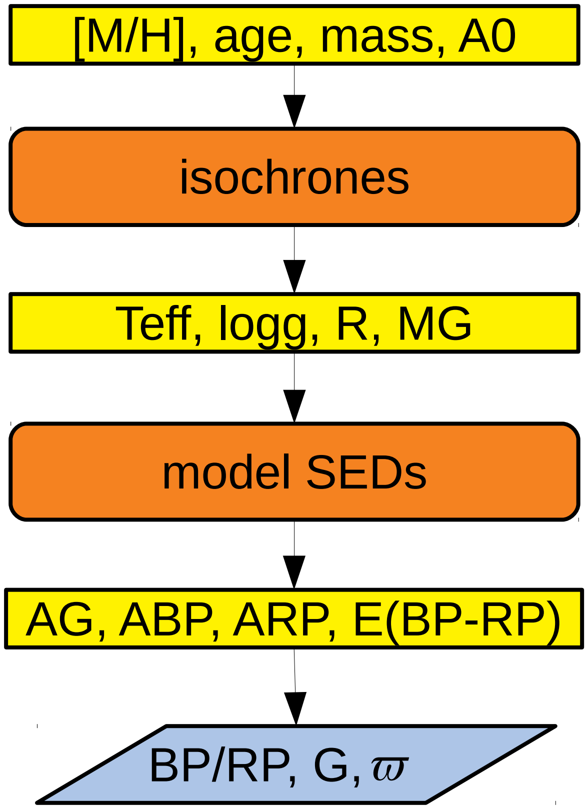
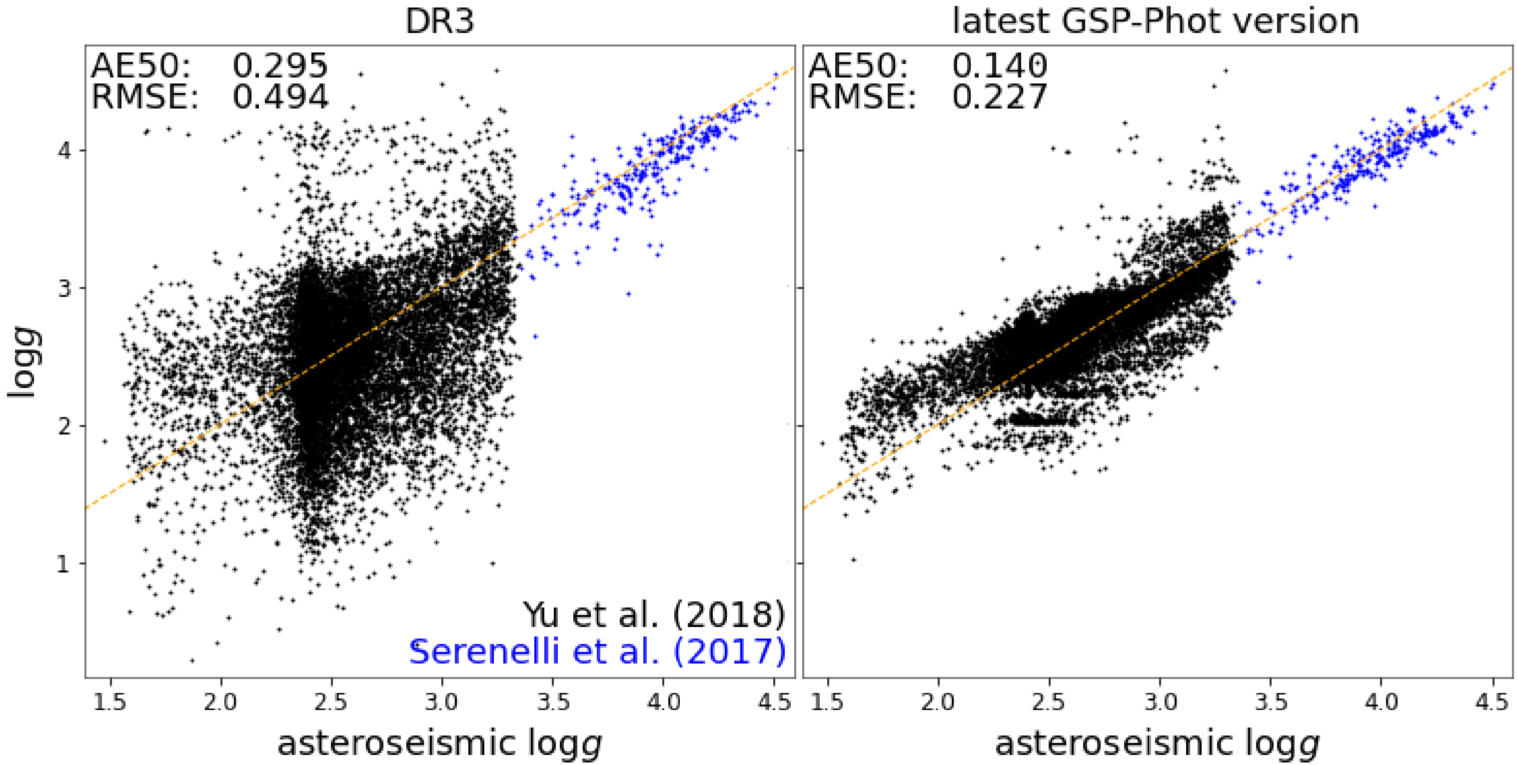
- General Stellar Parametriser from Photometry (Andrae et al. 2022)
- stellar parameters for 471 million stars
- PARSEC isochrones (1.2S Colibri S37)
- BP/RP spectrum: Teff, logg, A0, [M/H], $a = \left(\frac{R}{d}\right)^2$
- parallax: $\chi^2_{\varpi} = \left(\varpi - \frac{1/d}{\sigma_{\varpi}}\right)^2$
- apparent magnitude: $\chi^2_G = \left(\frac{G - M_G - A_G - 5\log_{10} d + 5}{\sigma_G}\right)^2$
- MCMC inference on priors and

$$\chi^2 = \chi^2_{BP/RP} + \chi^2_{\varpi} + \chi^2_G$$



GSP-Phot in a nutshell

- GSP-Phot results in DR3: benchmark
- DR3 processing ended July 2021
- many lessons learned from 1 year of validation for DR3



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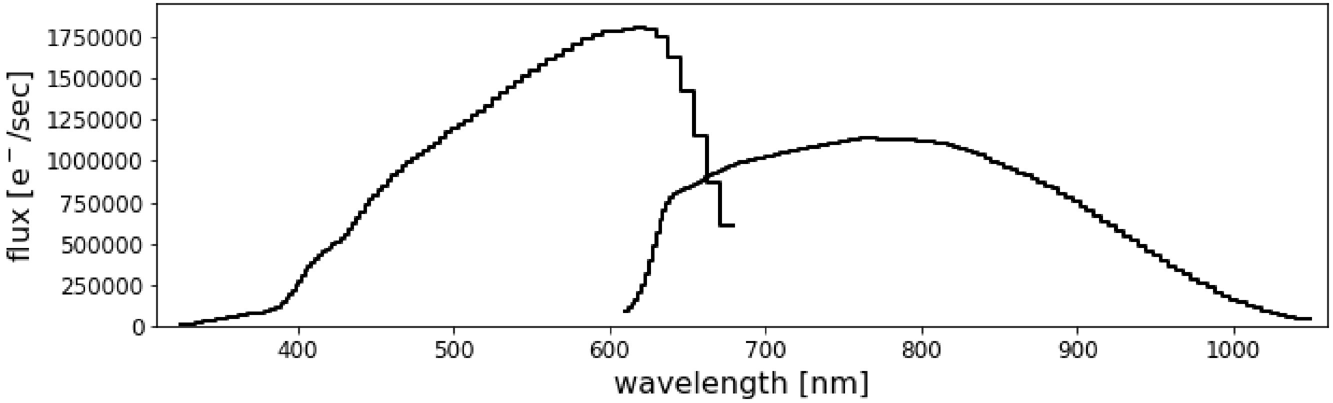
Returning to XP spectrum of 18 Sco



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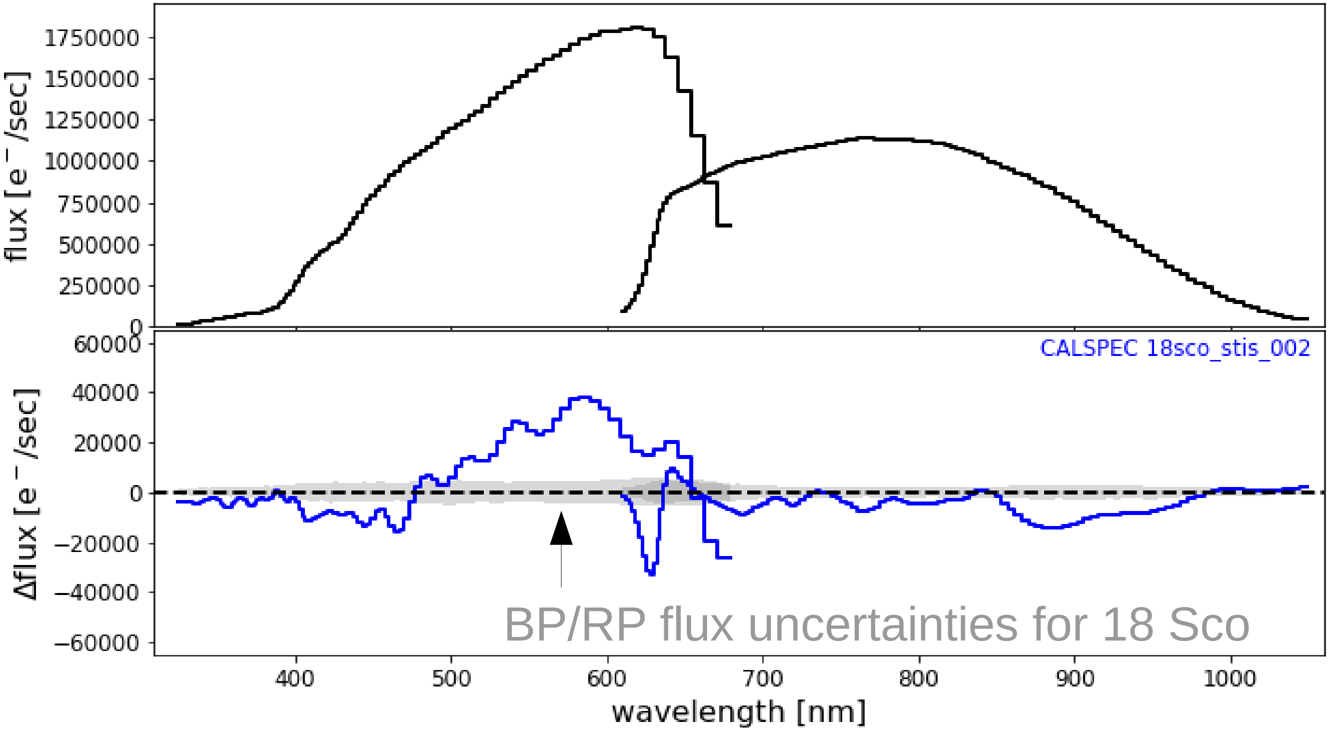

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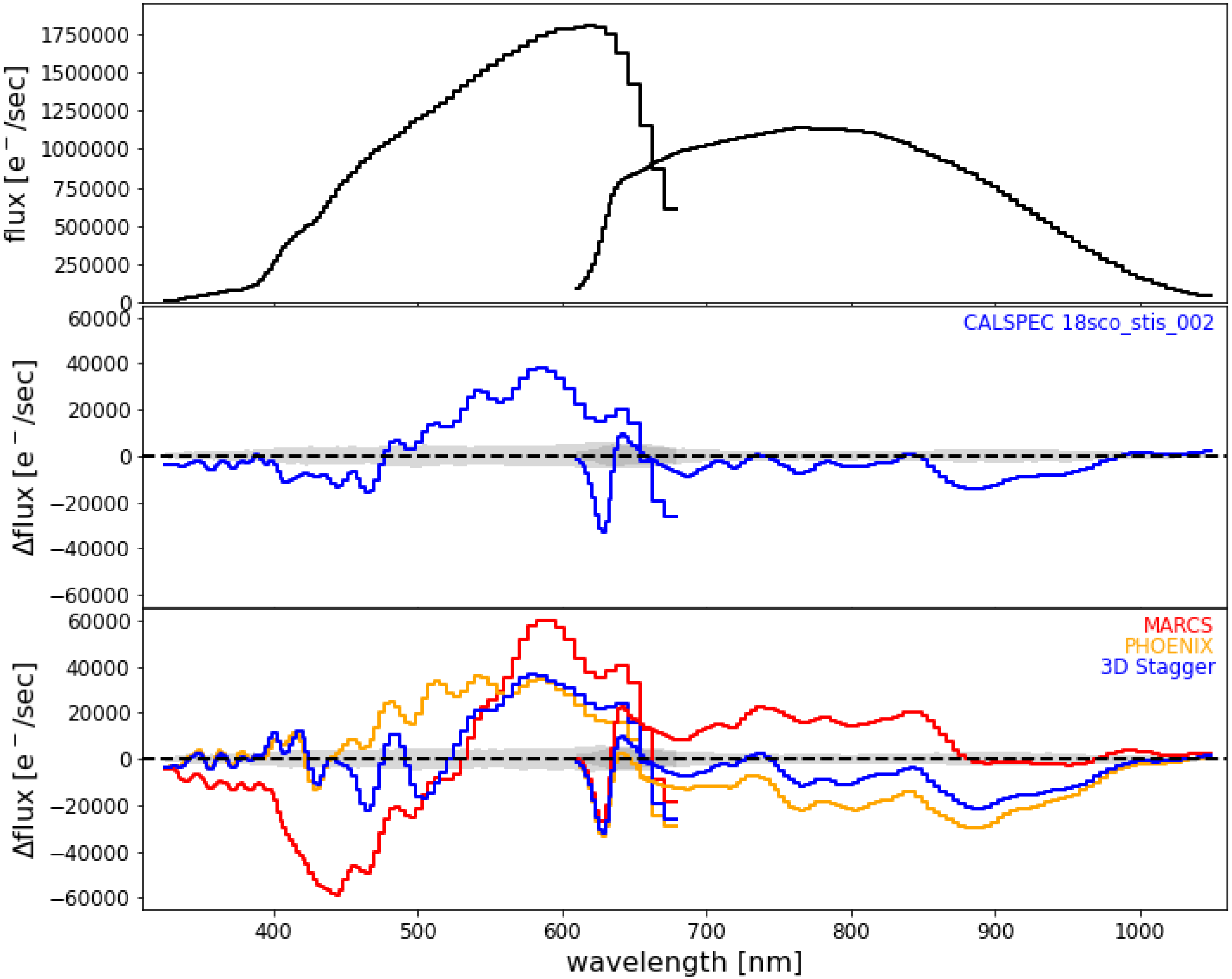

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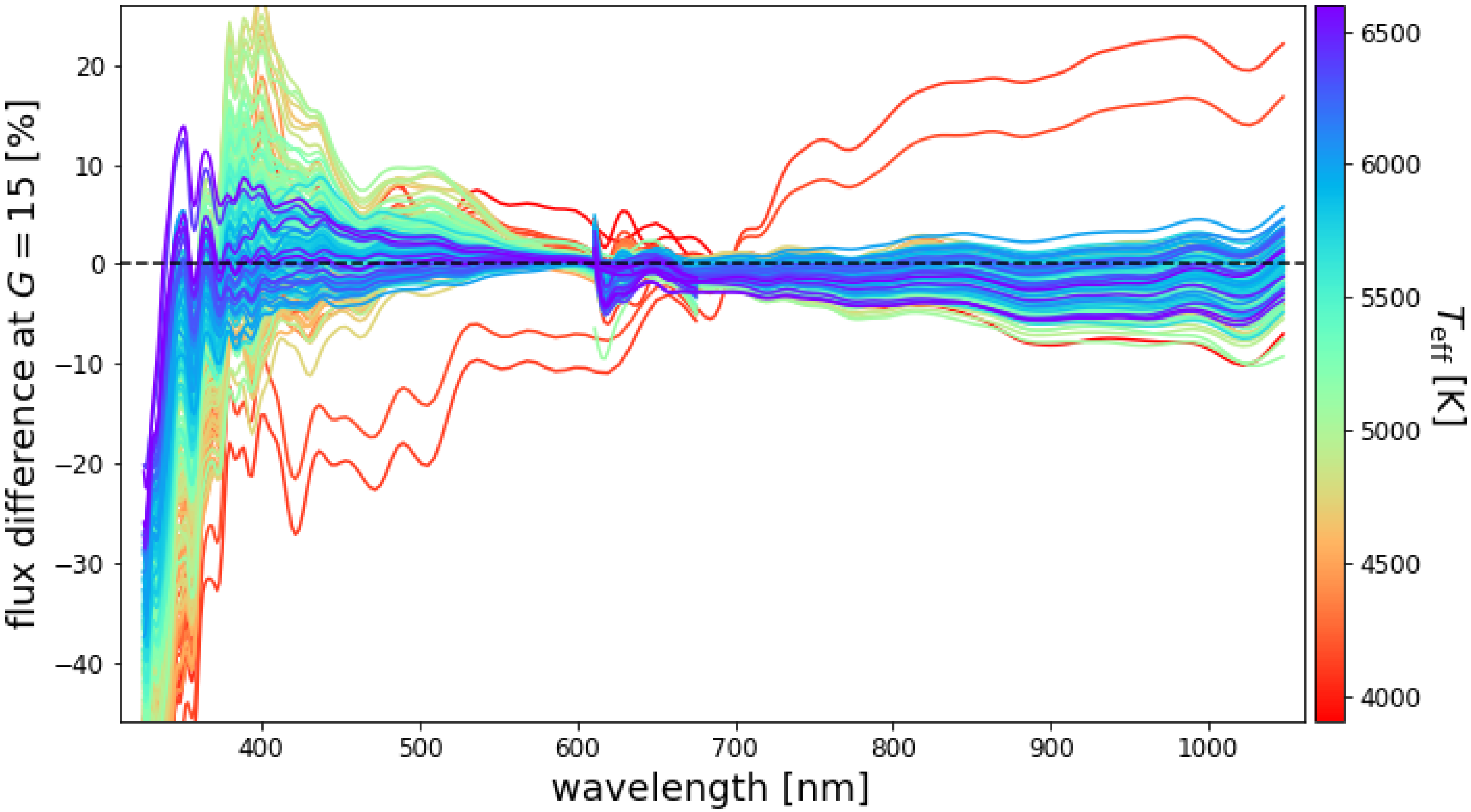
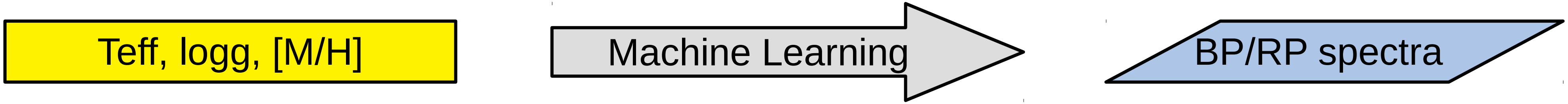
- model SEDs of Sun: more systematics
- systematics easily detectable in XP

Systematics with MARCS simulations

- systematics due to XP instrument model … not due to MARCS
- especially below 400nm => poor [M/H] from GSP-Phot



Forward-model emulation



- limited by systematics: XP instrument model + stellar SEDs + isochrones
- may take years to improve SEDs or isochrones
- empirical approach: real XP spectra + known stellar parameters
  - The Payne (e.g. Ting et al 2019): neural nets
  - Starfish (Czekala et al 2015): Gaussian process
  - The Cannon (e.g. Ness et al. 2015): 2nd-order polynomial
- disadvantage: inherit systematics from literature parameters

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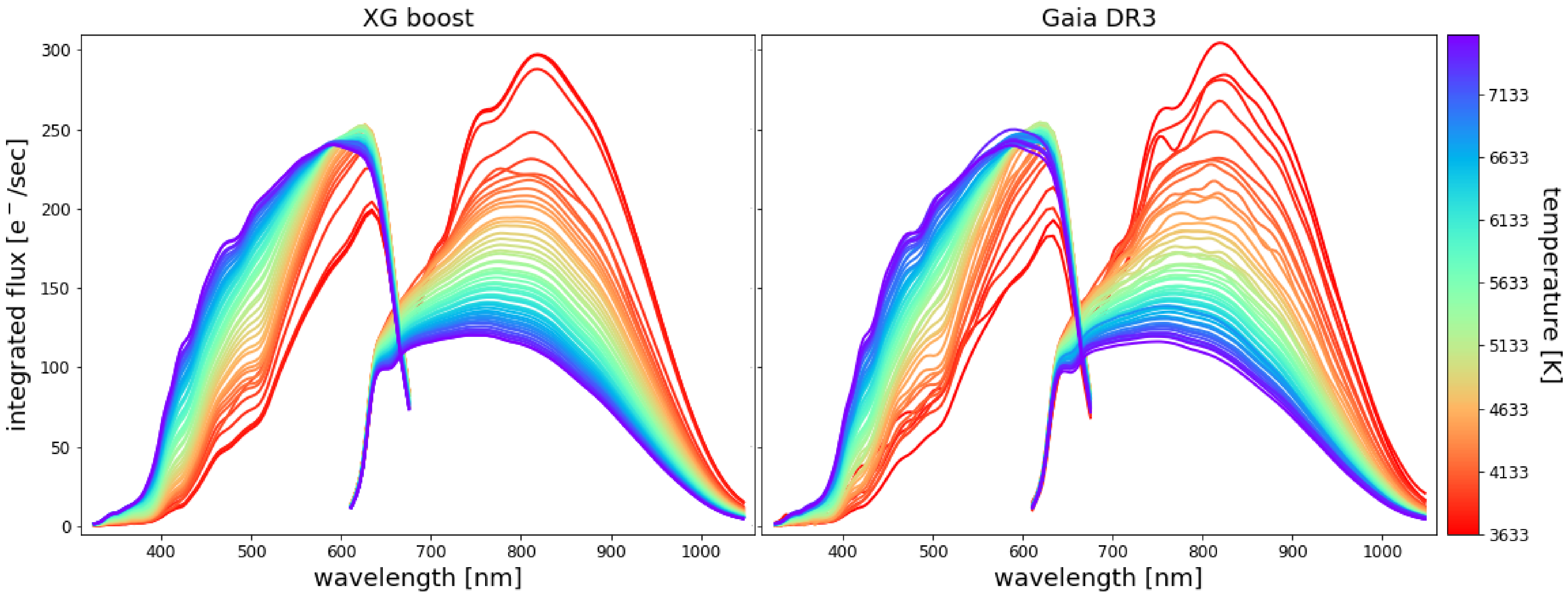

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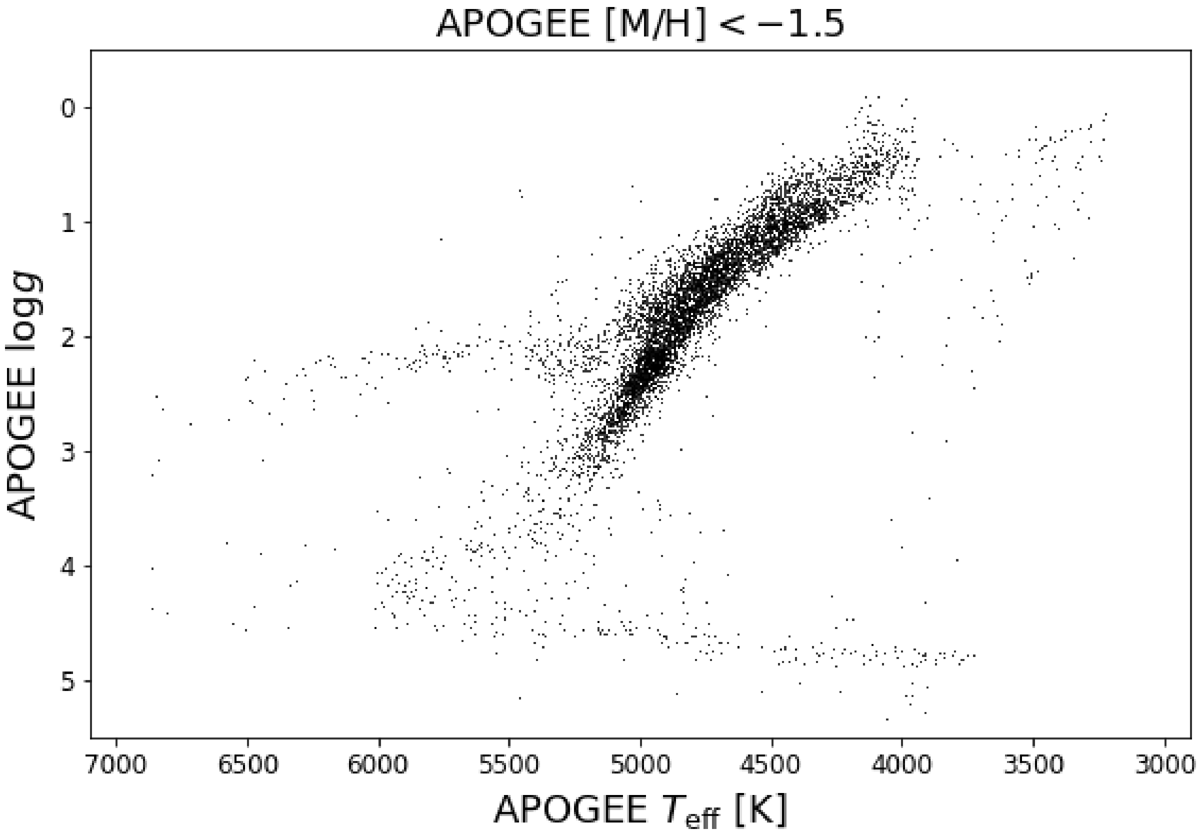
Inverse modelling

- “inverse modelling” = “data driven” = “empirical”
- pro: avoid systematics from XP instrument model
- cons:
    - inherit systematics from training sample
    - cannot exploit BP/RP amplitude
- normalise BP/RP spectra to common apparent G
- example: “The Poor Old Heart of the Milky Way” (Rix et al. 2022)

Poor Old Heart of the Milky Way

- APOGEE DR17 + XP spectra + G_{BP}<15.5 + AllWISE
- only giants, not Main Sequence



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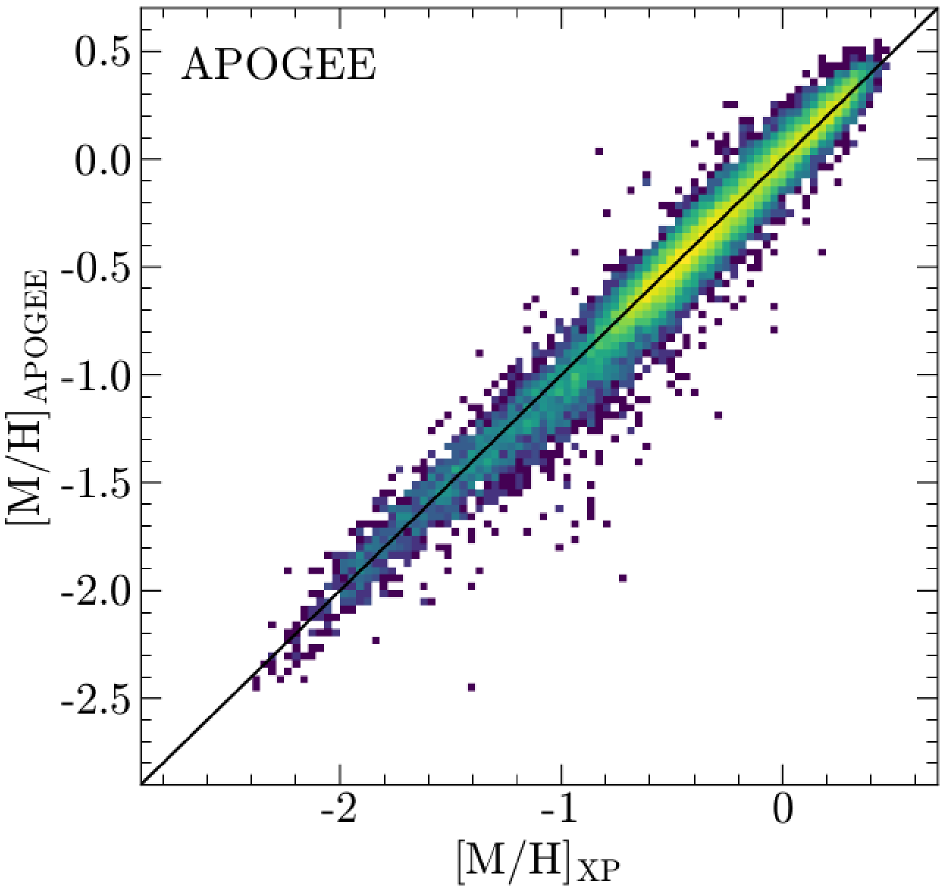

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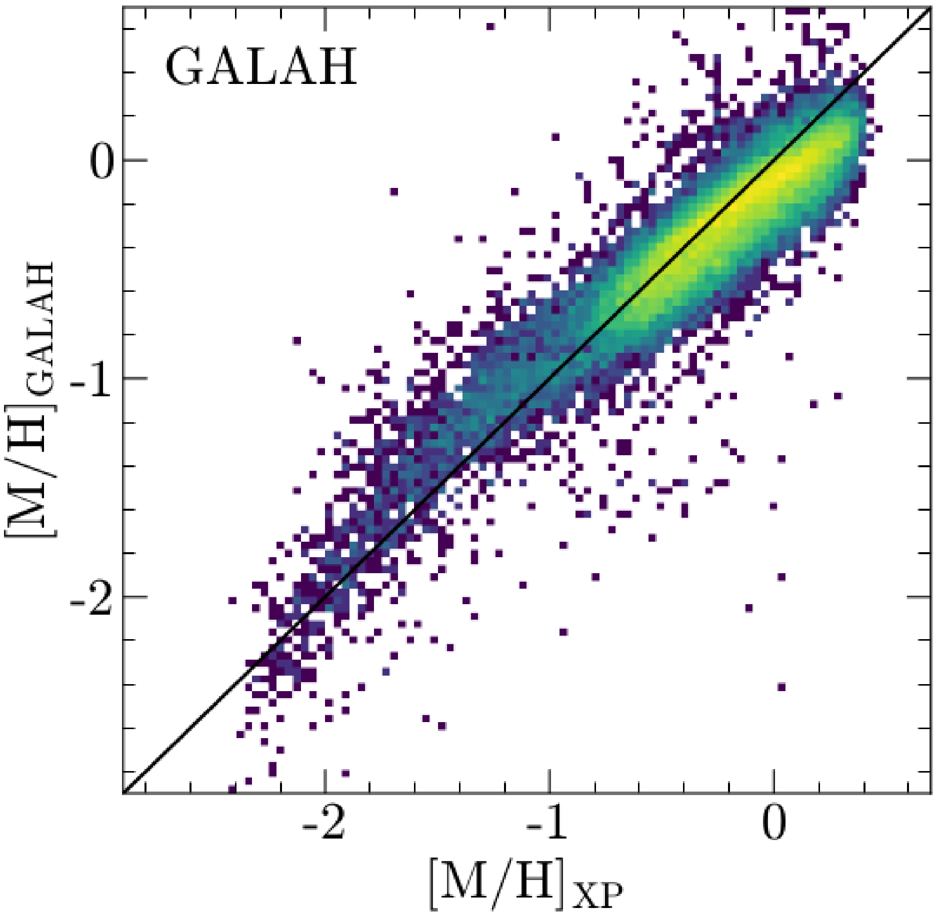

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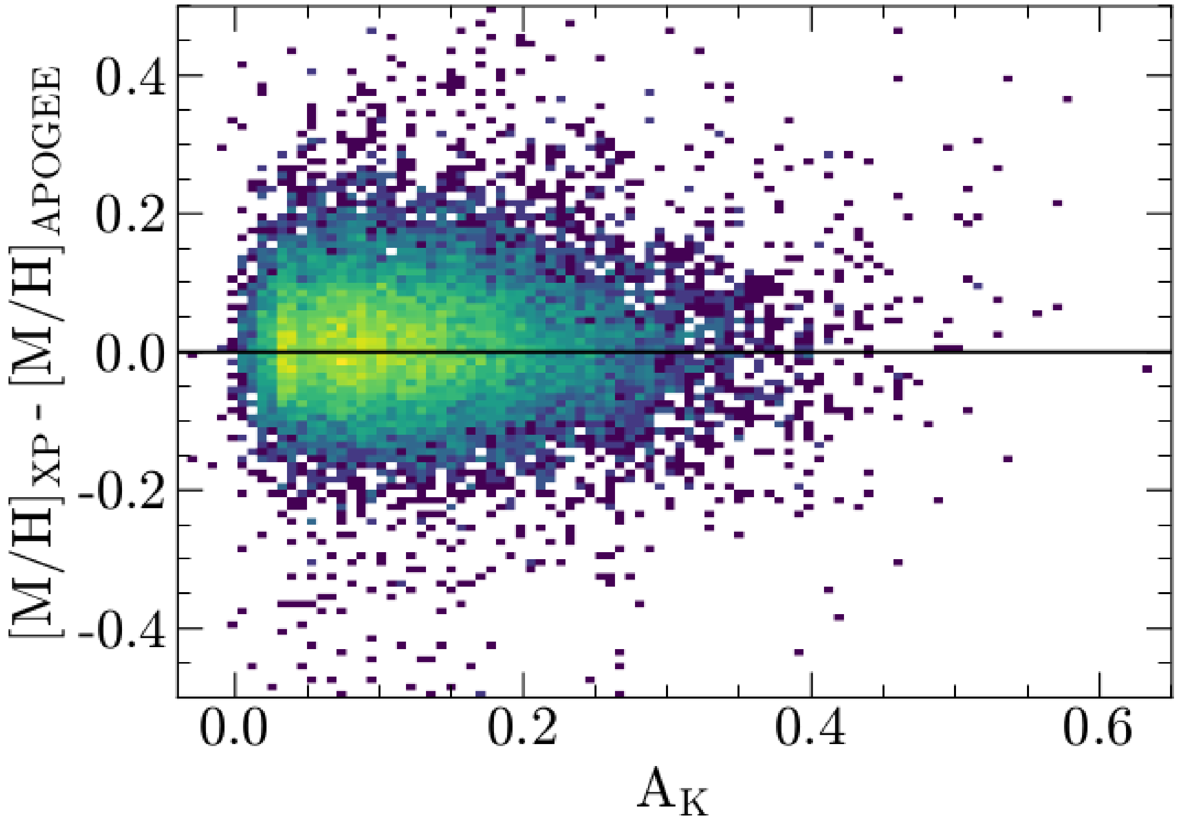

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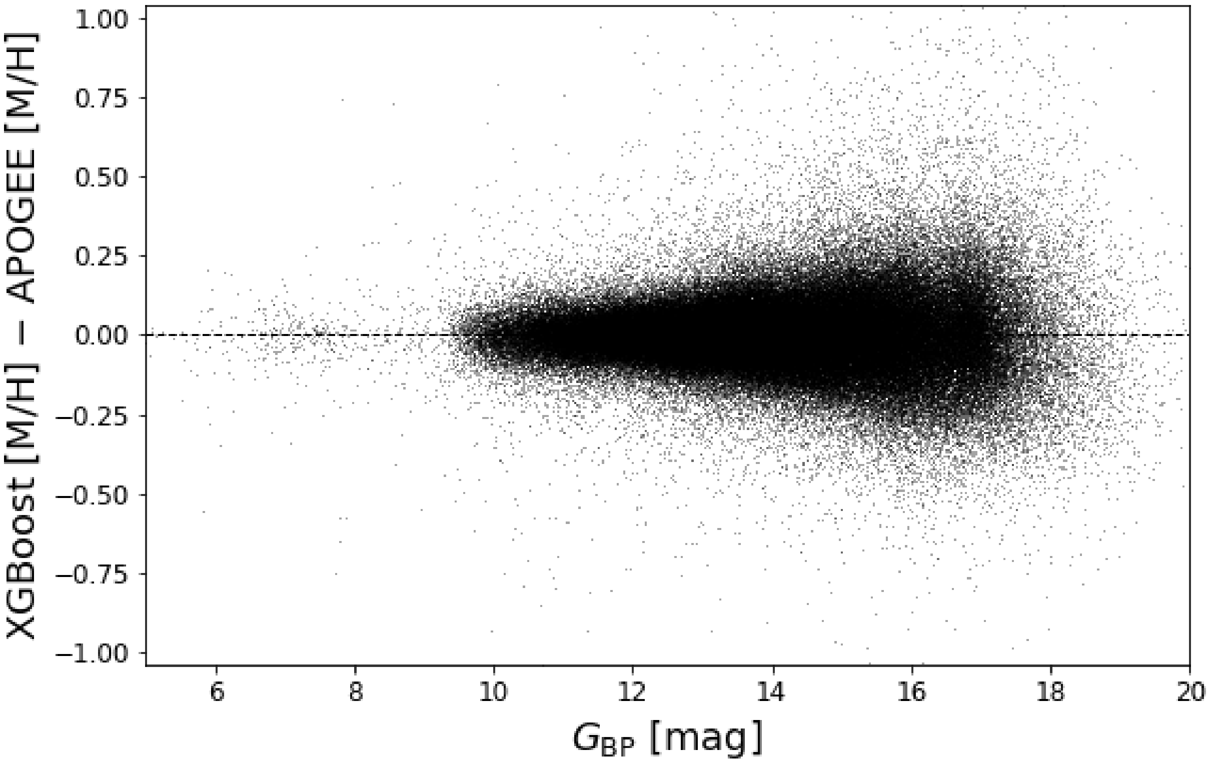
- robust against dust
- robust beyond G_{BP}=15.5



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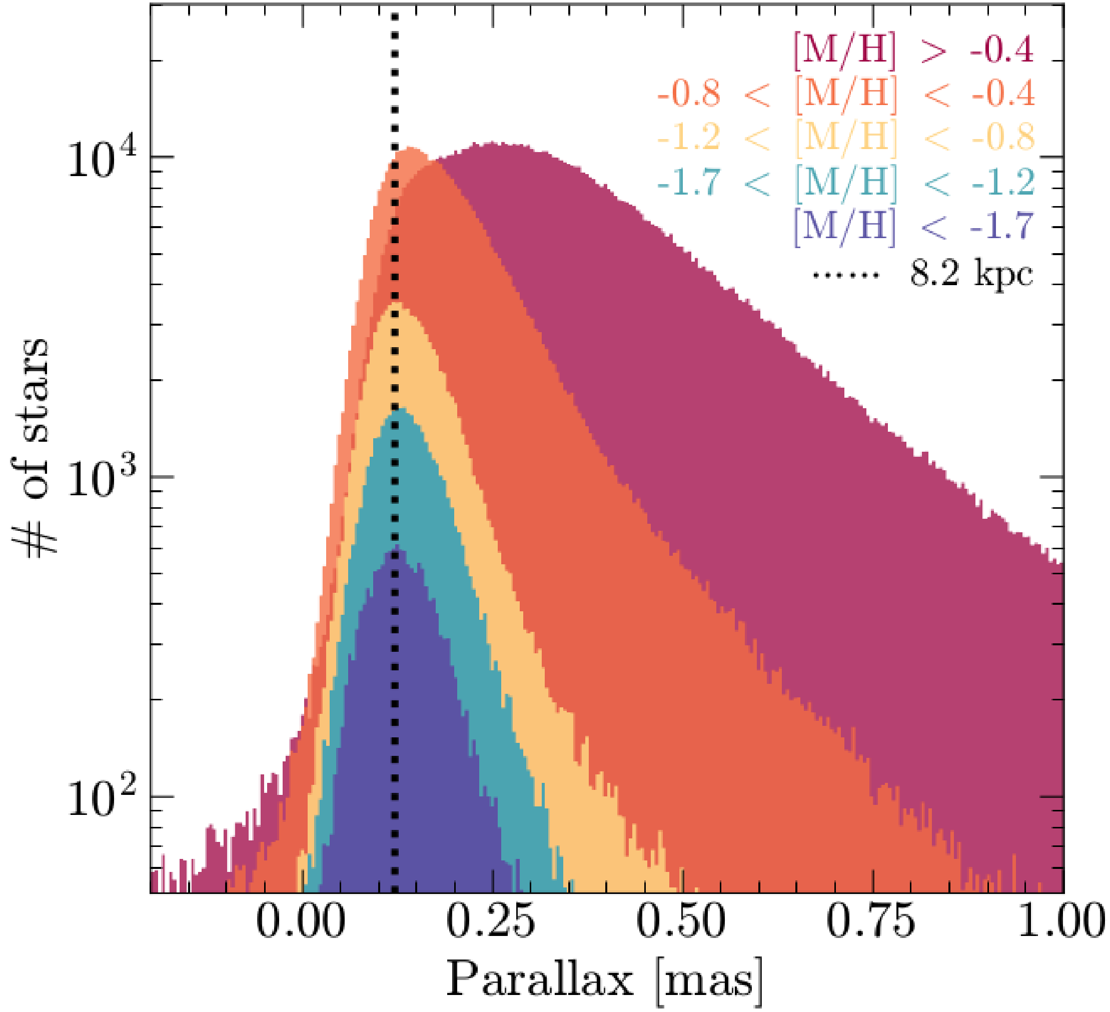

- applied to giants only!
- parallaxes of metal-poor giants peak at 8.2 kpc
- older than the old thick disk (Xiang & Rix 2022)

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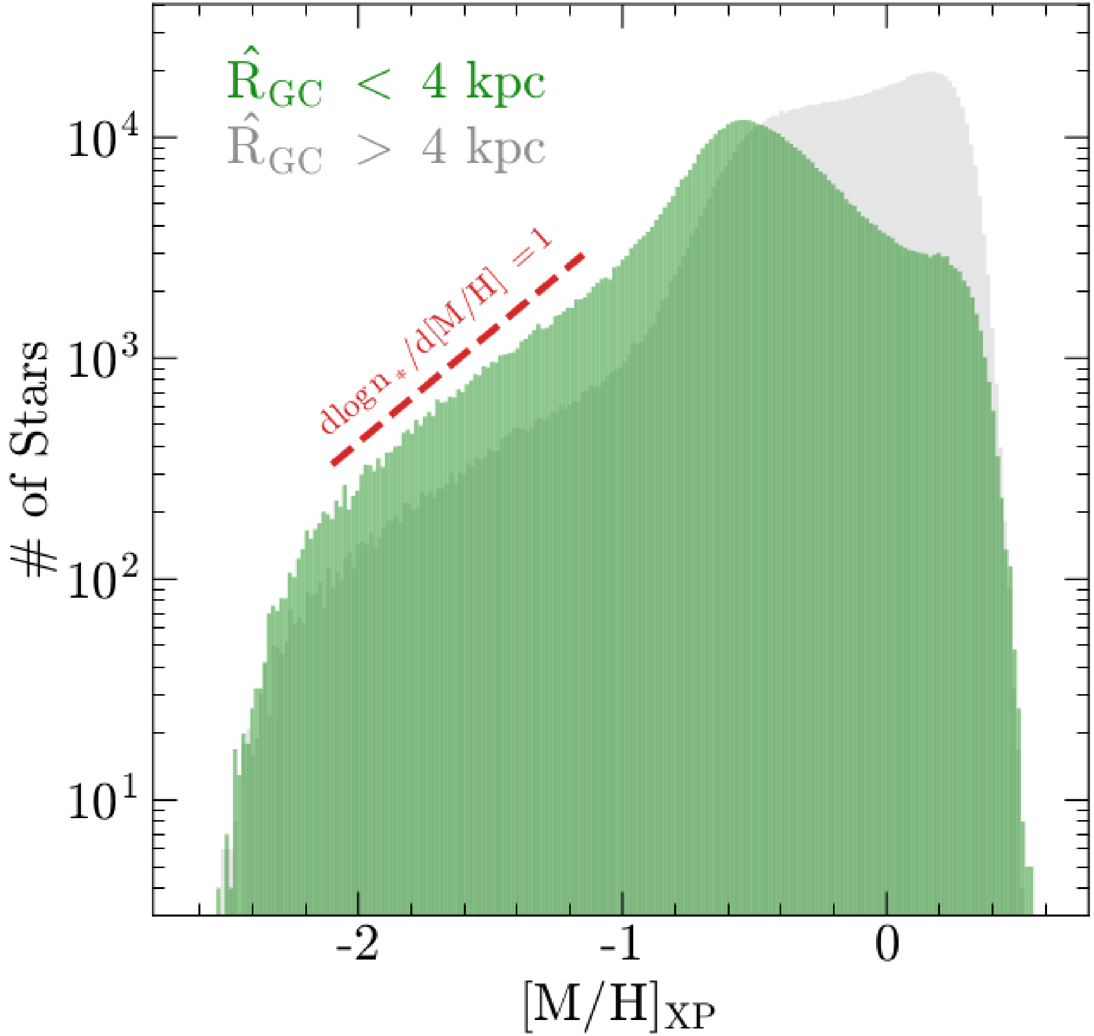

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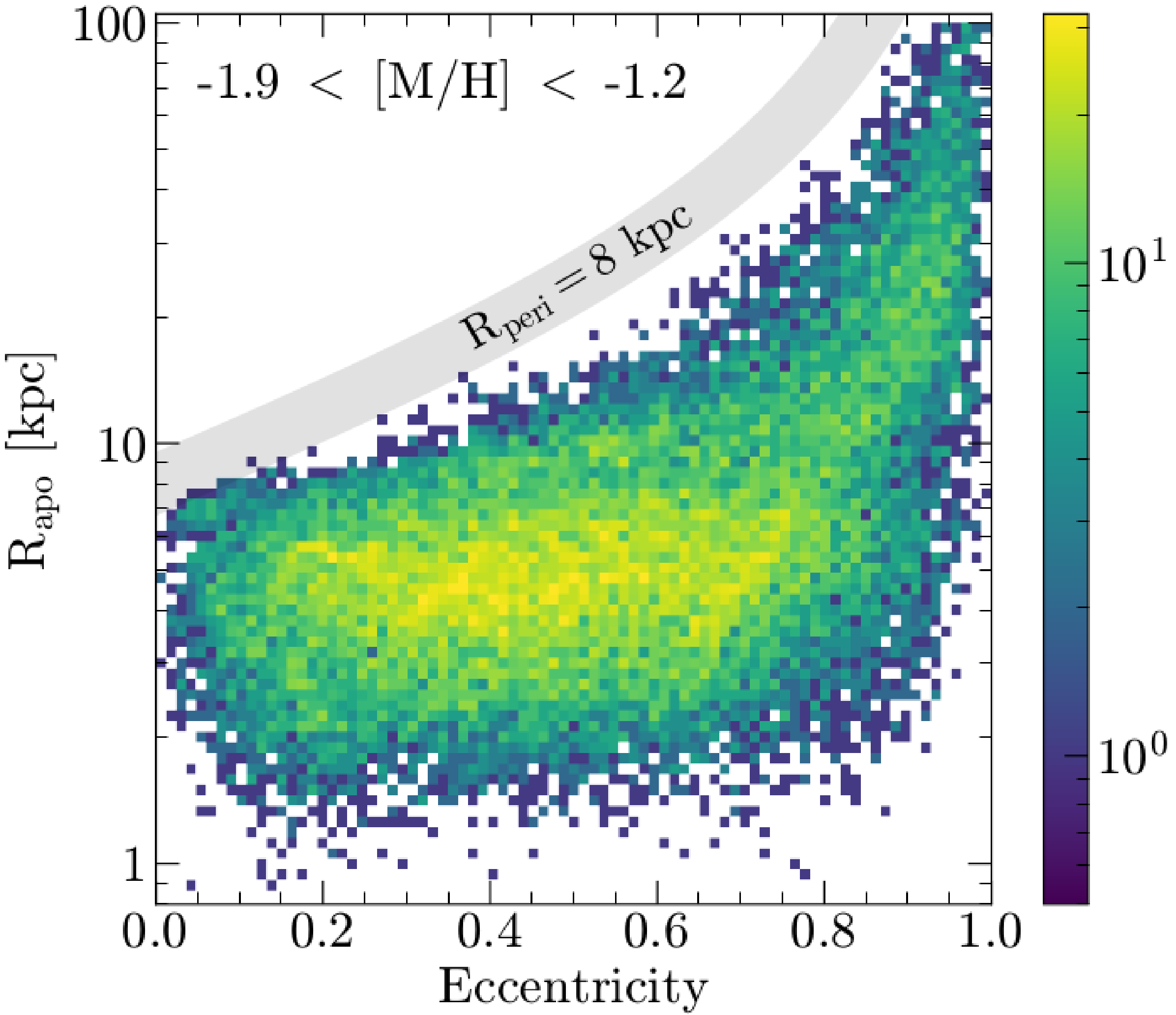

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- older than the old thick disk (Xiang & Rix 2022)
- slope of 1 between -2 and -1 (large gas supply)
- orbits show tight bound
- some accreted GSE members

Summary

- 220 million XP spectra in Gaia DR3
- 3 different formats + photometry: “feature selection”
- XP spectra come with absolute flux levels: $a = (R/d)^2$
- forward modelling limited by model systematics
- Machine Learning can extract [M/H] from XP spectra
- no obvious limitations from XP spectra quality