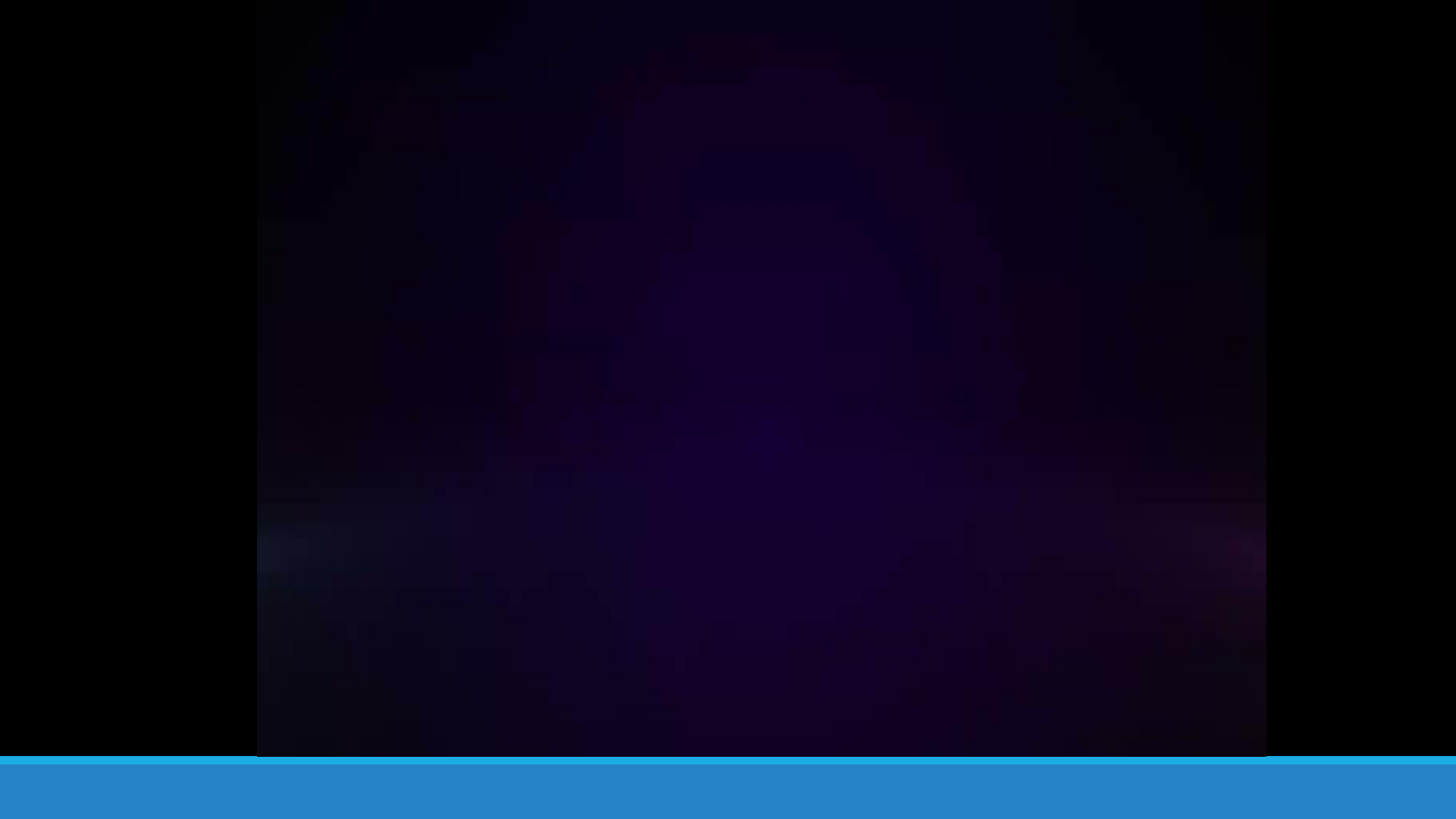




# A scientific guide to Gaia Astrophysical Parameters

23 March 2023

organized by Coordination Unit 8





A C

ATHENS

# General Stellar Parametrizer from Photometry (GSP-Phot)

---

Rene Andrae

MPIA Heidelberg, Germany

# Overview

---

- **Gaia satellite: observables**
- Gaia DR3: catalogue contents
- GSP-Phot in a nutshell
- scientific validation and user advice
- next steps

# Gaia satellite: observables

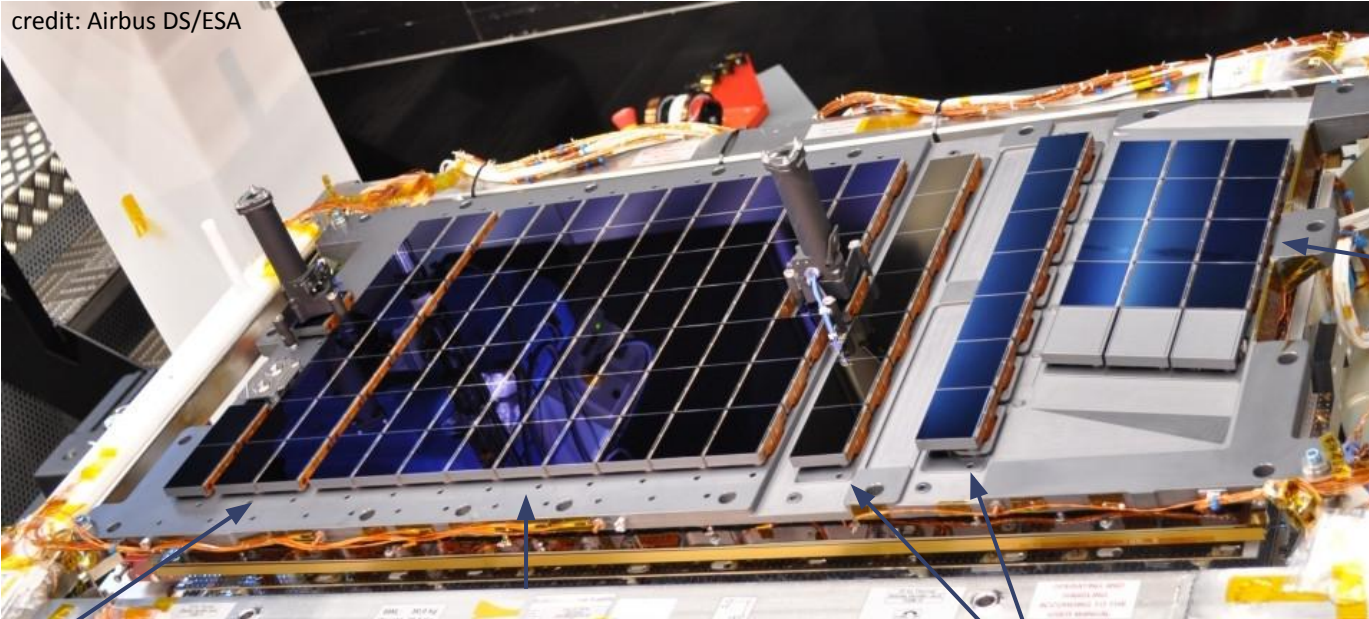
---

credit: Airbus DS/ESA



- launch: Dec 2013
- start nominal mission: summer 2014
- end nominal mission: summer 2019
- mission extension until Q1 2025
- DR3: June 2022, 34 months of data
- DR4: not before end of 2025,  
66 months of data (all from nominal mission)
- DR5: all data, including mission extension

# Gaia satellite: observables



RVS

104 x 42cm

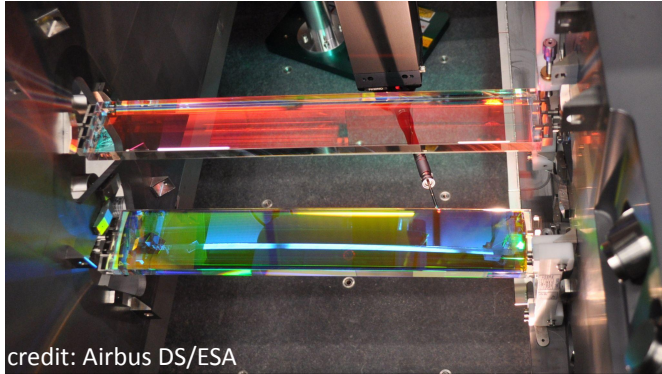
10s to cross

Sky Mapper:  
source detection

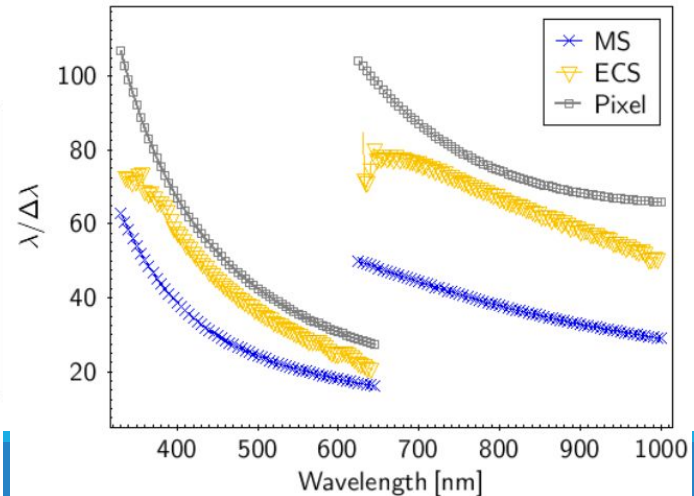
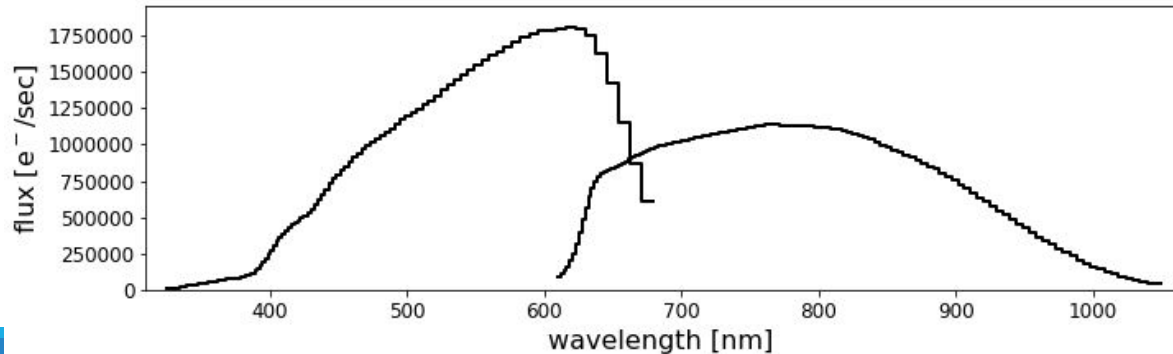
astrometric CCDs: position, parallax,  
proper motion + apparent G

BP + RP

# Gaia satellite: observables



- 2 prisms: BP + RP = XP
- optical + NIR wavelength, resolution 20-60  
([Montegriffo et al. 2022](#))



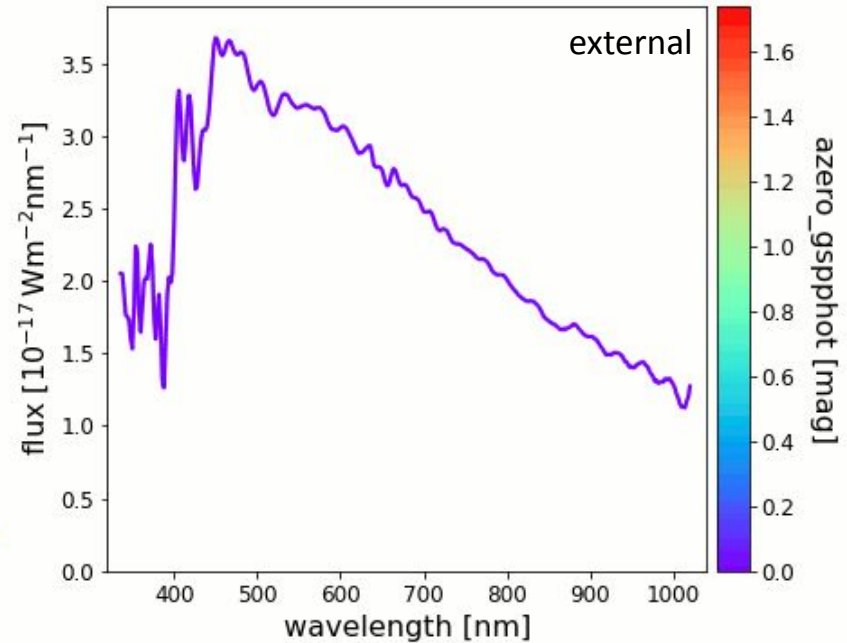
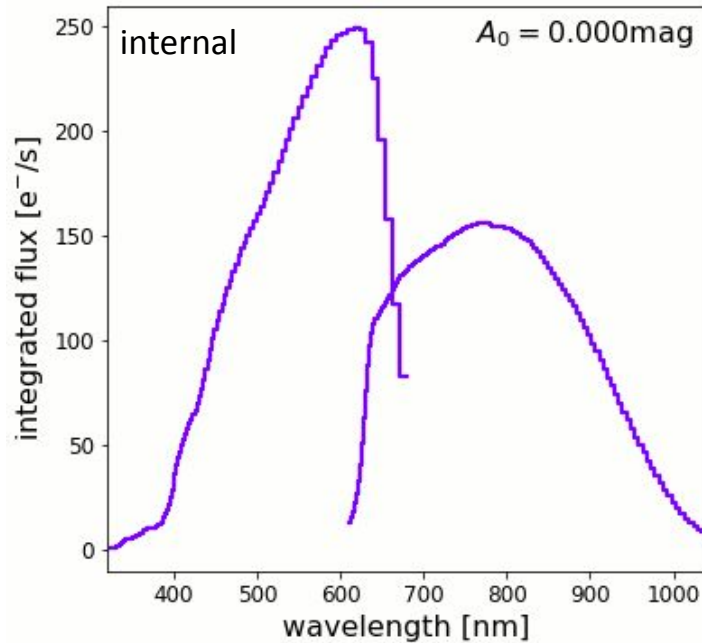


# Gaia satellite: observables

---

- XP spectra = time-averaged mean spectra of 40 epoch spectra (beware of variable stars)
- pixel sampling of epoch spectra varies ... continuous function needed ... basis expansion
- XP spectra come in 4 different formats:
  1. 55 coefficients per BP+RP (“xp\_continuous”, [Carrasco et al. 2021](#), [De Angeli et al. 2022](#))
  2. internally calibrated sampled spectra (not public)
  3. externally calibrated sampled spectra (“xp\_sampled”, [Montegriffo et al. 2022](#))

# Gaia satellite: observables

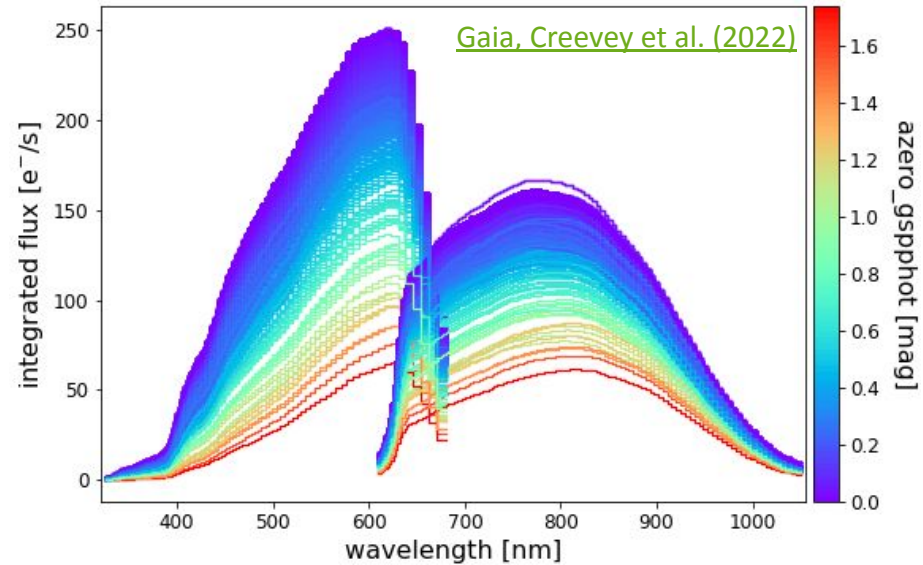
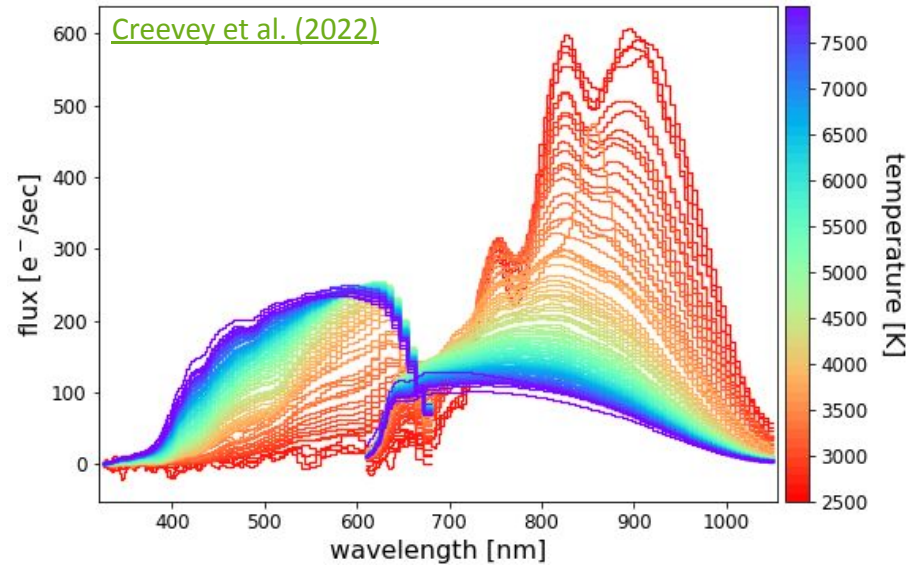


# Gaia satellite: observables

---

- XP spectra = time-averaged mean spectra of 40 epoch spectra (beware of variable stars)
- pixel sampling of epoch spectra varies ... continuous function needed ... basis expansion
- XP spectra come in 4 different formats:
  1. 55 coefficients per BP+RP (“xp\_continuous”, [Carrasco et al. 2021](#), [De Angeli et al. 2022](#))
  2. internally calibrated sampled spectra (not public)
  3. externally calibrated sampled spectra (“xp\_sampled”, [Montegriffo et al. 2022](#))
  4. synthesised photometry ([Gaia, Montegriffo et al. 2022](#), [GaiaXPy](#))
- choice of format = feature selection (e.g. [Rix et al. 2022](#))

# Gaia satellite: observables



# Overview

---

- Gaia satellite: observables
- **Gaia DR3: catalogue contents**
- GSP-Phot in a nutshell
- scientific validation and user advice
- next steps

# Gaia DR3: catalogue contents

The screenshot shows the Gaia archive website interface. At the top, there is a navigation bar with "EUROPEAN SPACE AGENCY" and "ABOUT ESAC" links. Below this is the "gaia archive" logo and a menu with "HOME", "SEARCH", "SINGLE OBJECT", "VISUALISATION", and "HELP". The main content area has tabs for "Basic", "Advanced (ADQL)", and "Query Results". A search input field contains the text "gaia". To the left of the search field is a sidebar with a list of categories, including "Other", "Gaia Data Release 1", "Gaia Data Release 2", "Gaia Data Release 3", "Astrophysical parameters", "Auxiliary", "Cross match", "Extra-galactic", "Non-single stars", "Performance verification", "Reference frame", "Science alerts", "Simulation", "Solar system", "Spectroscopy", and "Gaia Early Data Release 3". The "Gaia Data Release 3" category is expanded, showing sub-items like "galadr3.gaia\_source", "galadr3.gaia\_source\_lite", "galadr3.xp\_summary", and "Variability". On the right side of the search field, there is a "Job name:" input field and a table with one row containing the number "1". Below the table, there is a message "No results found" and a table header with "Status" and "Job". At the bottom of the page, there is a pagination control showing "1-1 of 0".

- all DR3 data in the [Gaia archive](#)
- ADQL queries

# Gaia DR3: catalogue contents

The screenshot shows the Gaia archive website interface. At the top, there is a dark red header with the text "gaia archive" and navigation links: HOME, SEARCH, SINGLE OBJECT, VISUALISATION, HELP. Below the header, there are tabs for "Basic", "Advanced (ADQL)", and "Query Results". The main content area is divided into two columns. The left column contains a list of parameters, with "has\_xp\_continuous" and "has\_xp\_sampled" highlighted by a red box. The right column contains a "Job name:" input field, a "Query Results" section with "No results found", and a table with columns "Status" and "Job".

- all DR3 data in the [Gaia archive](#)
- ADQL queries
- gaia\_source, gaia\_source\_lite:  
has\_xp\_continuous='true'  
has\_xp\_sampled='true'
- get XP spectra via DataLink

# Gaia DR3: catalogue contents

EUROPEAN SPACE AGENCY ABOUT ESAC SIGN IN

## gaia archive

HOME SEARCH SINGLE OBJECT VISUALISATION HELP

Basic **Advanced (ADQL)** Query Results

gaia


Other  
Gaia Data Release 1  
Gaia Data Release 2  
Gaia Data Release 3  
gaiadr3.gaia\_source  
gaiadr3.gaia\_source\_lite  
Astrophysical parameters  
Auxiliary  
Cross match  
Extra-galactic

Job name:

```
1 SELECT TOP 10
2 source_id
3 FROM gaiadr3.gaia_source_lite
4 WHERE has_xp_continuous='true'
```

Ctrl+Space for query autocompletion

Reset Form Submit Query

Status	Job	Creation date	Num. rows	Size	
✓	16793052028190	20-Mar-2023, 10:40:02	10	1 KB	



# Gaia DR3: catalogue contents

The screenshot shows the Gaia archive website interface. The top navigation bar includes 'EUROPEAN SPACE AGENCY' and 'ABOUT ESAC'. Below this is the 'gaia archive' logo and a menu with 'HOME', 'SEARCH', 'SINGLE OBJECT', 'VISUALISATION', and 'HELP'. The main content area has tabs for 'Basic', 'Advanced (ADQL)', and 'Query Results'. A search box contains the text 'gaia'. Below the search box, there are icons for 'Other', 'Gaia Data Release 1', 'Gaia Data Release 2', and 'Gaia Data Release 3'. Under 'Gaia Data Release 3', there are sub-items: 'gaiadr3.gaia\_source', 'gaiadr3.gaia\_source\_lite', and 'Astrophysical parameters'. The 'Astrophysical parameters' item is highlighted with a red box. Below this, there are sub-items: 'gaiadr3.astrophysical\_parameters' and 'gaiadr3.astrophysical\_parameters\_supp'. A list of parameters is shown below, including 'source\_id', 'libname\_best\_gspphot', 'teff\_gspphot\_marcs', 'teff\_gspphot\_marcs\_lower', 'teff\_gspphot\_marcs\_upper', 'logg\_gspphot\_marcs', 'logg\_gspphot\_marcs\_lower', 'logg\_gspphot\_marcs\_upper', 'mh\_gspphot\_marcs', 'mh\_gspphot\_marcs\_lower', 'mh\_gspphot\_marcs\_upper', 'distance\_gspphot\_marcs', 'distance\_gspphot\_marcs\_lower', 'distance\_gspphot\_marcs\_upper', 'azero\_gspphot\_marcs', and 'azero\_gspphot\_marcs\_lower'. On the right side, there is a 'Job name:' input field, a table with one row containing the number '1', and a 'No results found' message. Below this, there is a table with columns 'Status' and 'Job'. At the bottom, there is a pagination control showing '1-1 of 0'.

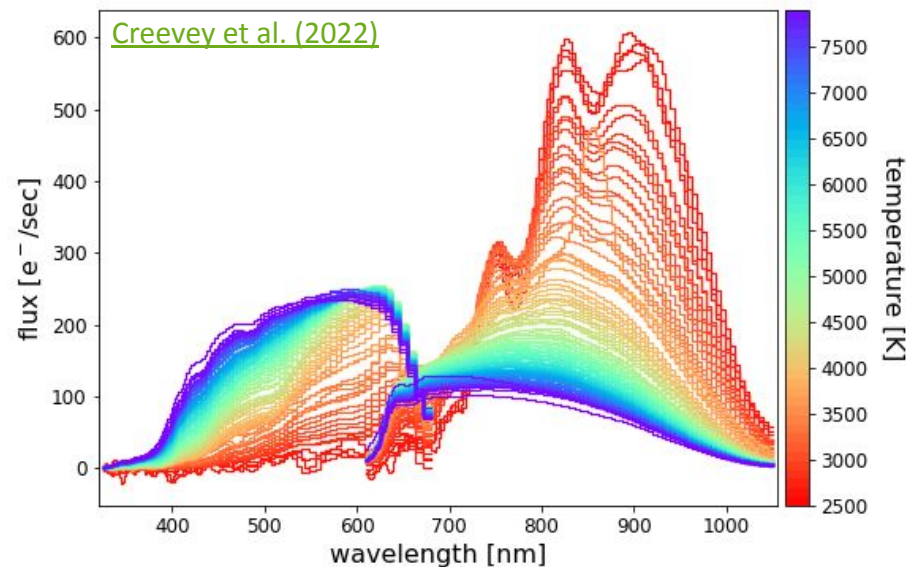
- all DR3 data in the [Gaia archive](#)
- ADQL queries
- gaia\_source, gaia\_source\_lite:  
has\_xp\_continuous='true'  
has\_xp\_sampled='true'
- get XP spectra via DataLink
- astrophysical\_parameters
- astrophysical\_parameters\_supp

# Overview

---

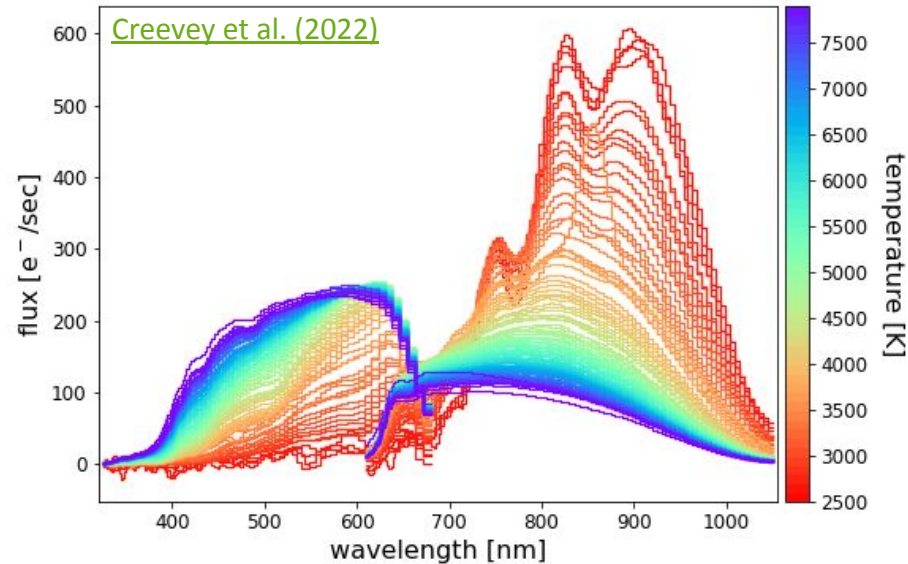
- Gaia satellite: observables
- Gaia DR3: catalogue contents
- **GSP-Phot in a nutshell**
- scientific validation and user advice
- next steps

# GSP-Phot in a nutshell



- goal: estimate stellar parameters from XP spectra
  - temperature,  $\log g$ ,  $[M/H]$
  - A0, AG ABP, ARP, E(BP-RP)
  - MG, radius, distance
- more observables: parallax, apparent G
- DR3: 471M stars with  $G < 19$  ([Andrae et al. 2022](#))

# GSP-Phot in a nutshell



- 4 SED libraries with different Teff ranges:
  - MARCS: 2500K - 8000K
  - PHOENIX: 3000K - 10.000K
  - A stars: 6000K - 20.000K
  - OB stars: 15.000K - 55.000K
- “best” library recommended (= max. log-posterior)
- best results in astrophysical\_parameters (e.g. `teff_gspphot`)
- 4 library results in `astrophysical_parameters_supp` (e.g. `logg_gspphot_marcs`, `azero_gspphot_ob`)

# GSP-Phot in a nutshell

- model SEDs scale as:

$$\vec{m} \sim \sigma_B T_{eff}^4$$

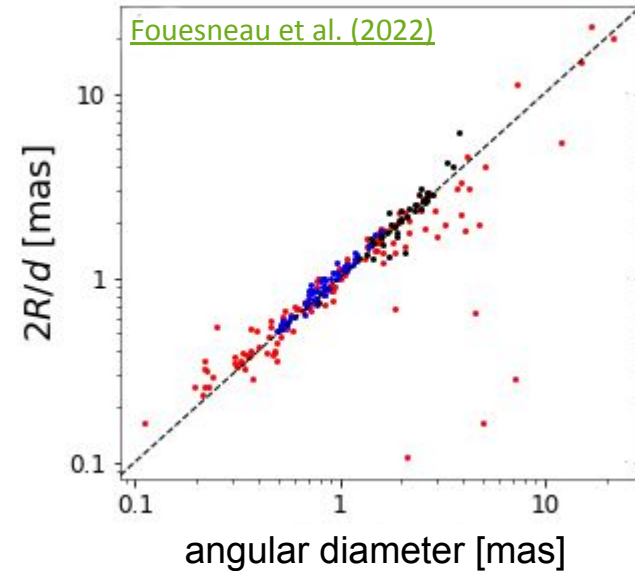
- XP spectra not normalised, i.e. they scale as:

$$\vec{x}\vec{p} \sim \left( \frac{\text{radius}}{\text{distance}} \right)^2 \sigma_B T_{eff}^4$$

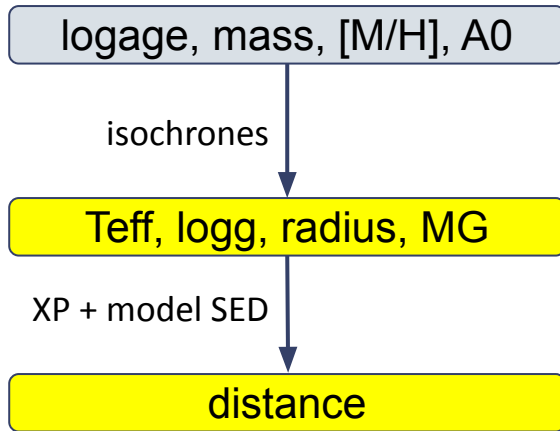
- PARSEC isochrone's radius + least-squares fit for XP amplitude:

$$a = \left( \frac{\text{radius}}{\text{distance}} \right)^2$$

- (radius/distance) is very well constrained from XP spectra



# GSP-Phot in a nutshell



- actual MCMC fit parameters: log-age, mass, [M/H], A0
- chi2 from fitting XP spectrum with model SED
- chi2 from parallax:

$$\chi_{\varpi}^2 = \left( \varpi - \frac{1/d}{\sigma_{\varpi}} \right)^2$$

- chi2 from apparent G magnitude:

$$\chi_G^2 = \left( \frac{G - M_G - A_G - 5 \log_{10} d + 5}{\sigma_G} \right)^2$$

- total chi2 = XP + parallax + G
- priors from GDR3 mock ([Rybizki et al. 2020](#)):
  - Hertzsprung-Russel diagram
  - distance prior
  - extinction prior

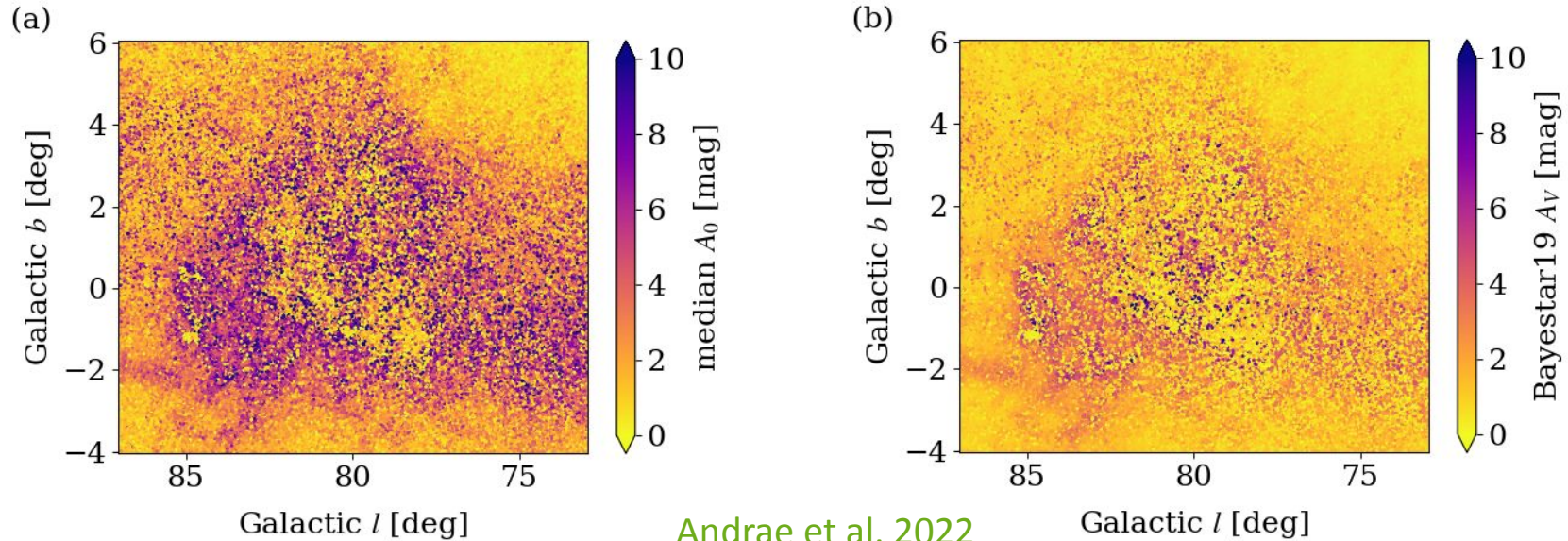
# Overview

---

- Gaia satellite: observables
- Gaia DR3: catalogue contents
- GSP-Phot in a nutshell
- **scientific validation and user advice**
- next steps

# scientific validation and user advice

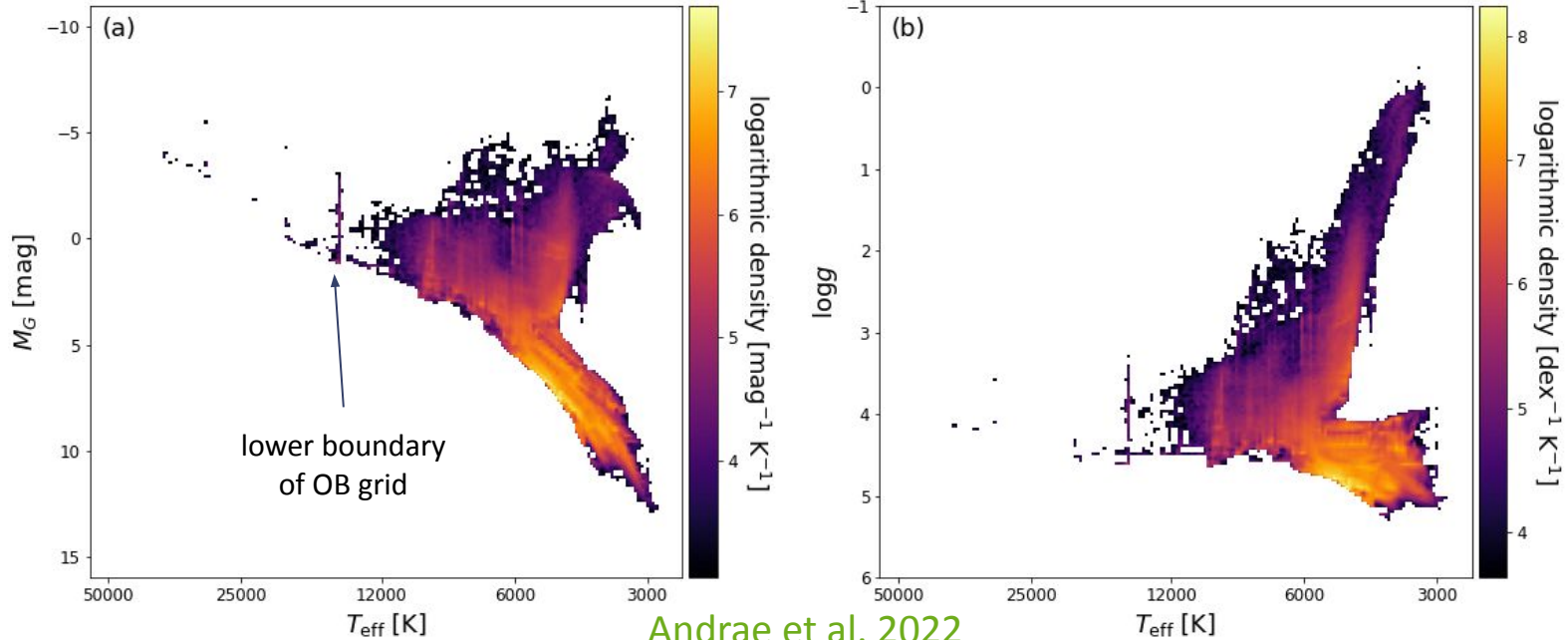
- Cygnus X1: GSP-Phot (a) shows more structure than BayesStar19 (b)





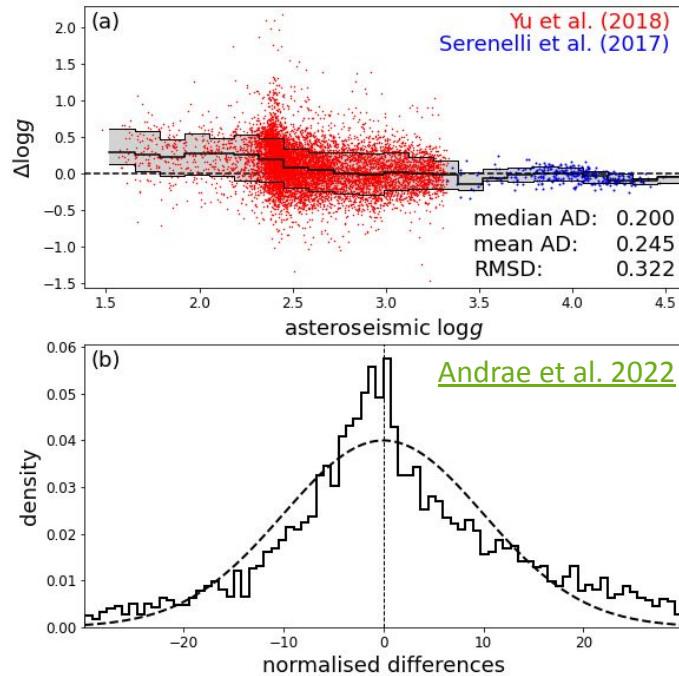
# scientific validation and user advice

- HRD and Kiel diagram look OK ... but still some artefacts



[Andrae et al. 2022](#)

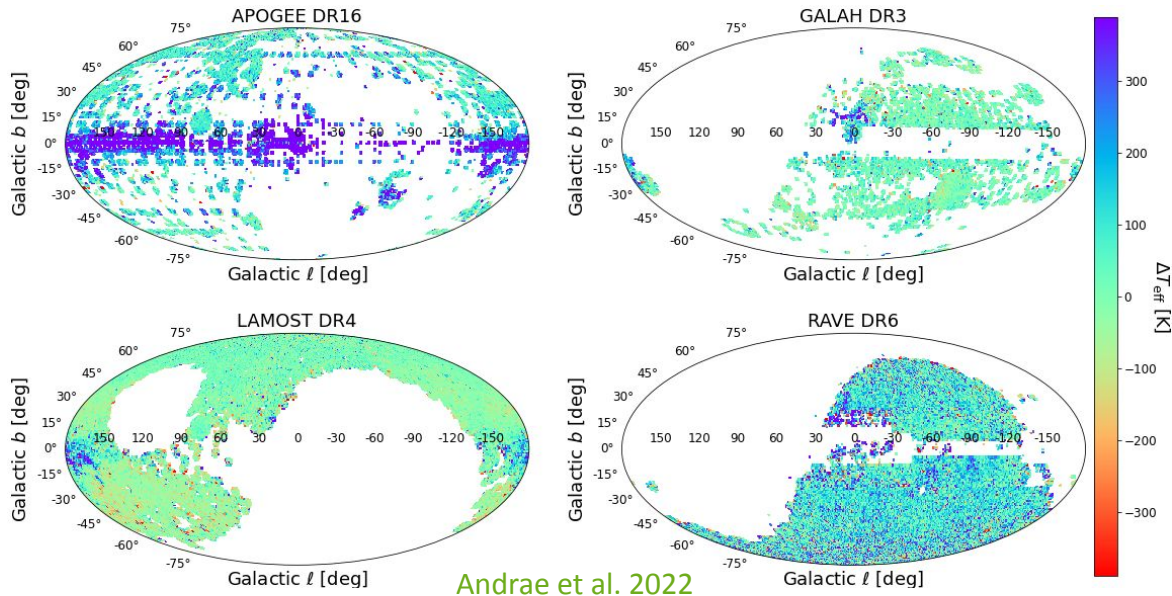
# scientific validation and user advice



- $\log g$  compares very well to asteroseismology (solar-like oscillators)
- $\log g$  uncertainties underestimated by factor 10

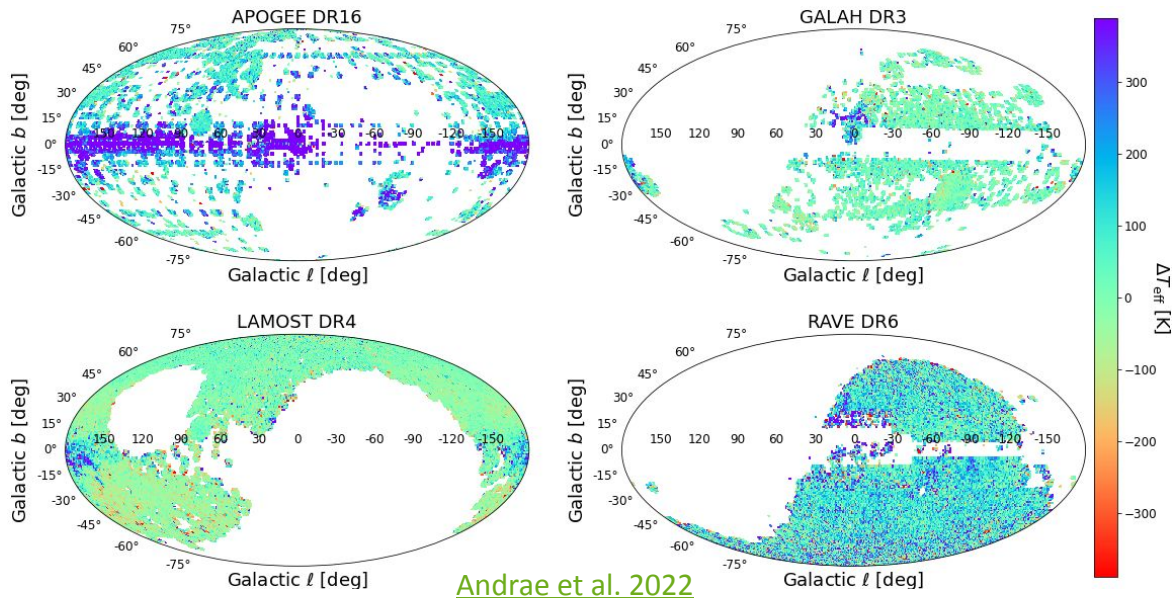
# scientific validation and user advice

- skymaps of Teff residuals show degeneracy with extinction



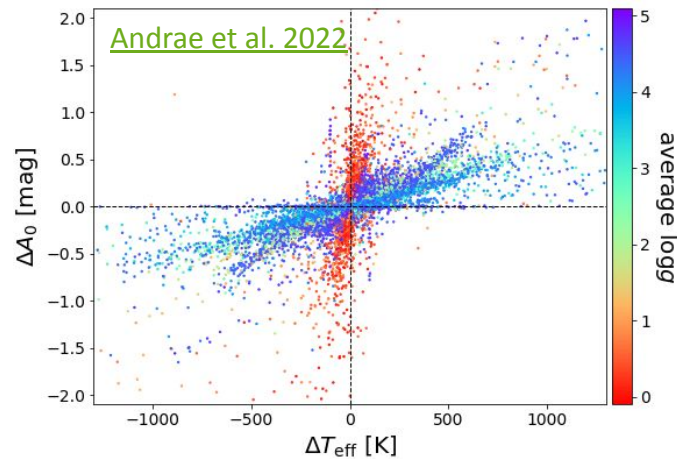
# scientific validation and user advice

- skymaps of Teff residuals show degeneracy with extinction



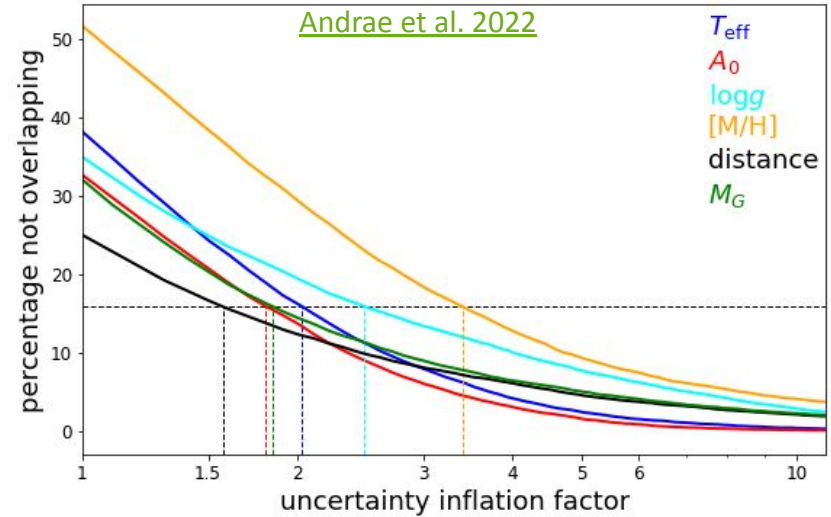
[Andrae et al. 2022](#)

- XP split-epoch sample ([De Angeli et al. 2022](#))
- Teff-A0 degeneracy



# scientific validation and user advice

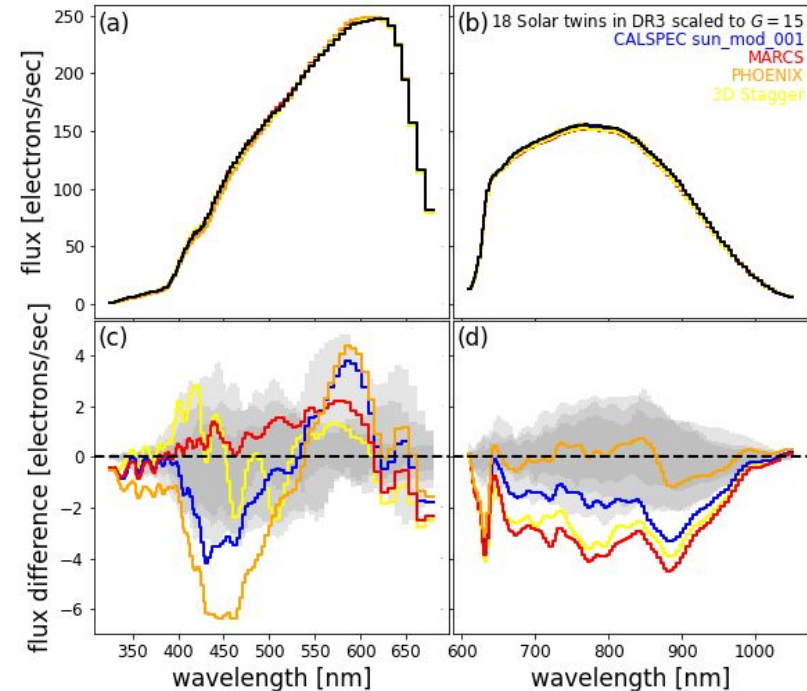
- uncertainties systematically too small
- systematic underestimation of distances for parallax SNR < 10 (overly harsh distance prior)
- outliers (MCMC initialisation)



# scientific validation and user advice

[Andrae et al. 2022](#)

- uncertainties systematically too small
- systematic underestimation of distances for parallax SNR < 10 (overly harsh distance prior)
- outliers (MCMC initialisation)
- heavily biased [M/H]:
  - caused by model mismatch (e.g. solar twins)
  - XP *does* contain information about [M/H] (e.g. [Rix et al. 2022](#), [Andrae et al. 2023](#))
- empirical forward model achieves good uncertainties ([Zhang et al. 2023](#))



# Overview

---

- Gaia satellite: observables
- Gaia DR3: catalogue contents
- GSP-Phot in a nutshell
- scientific validation and user advice
- **next steps**

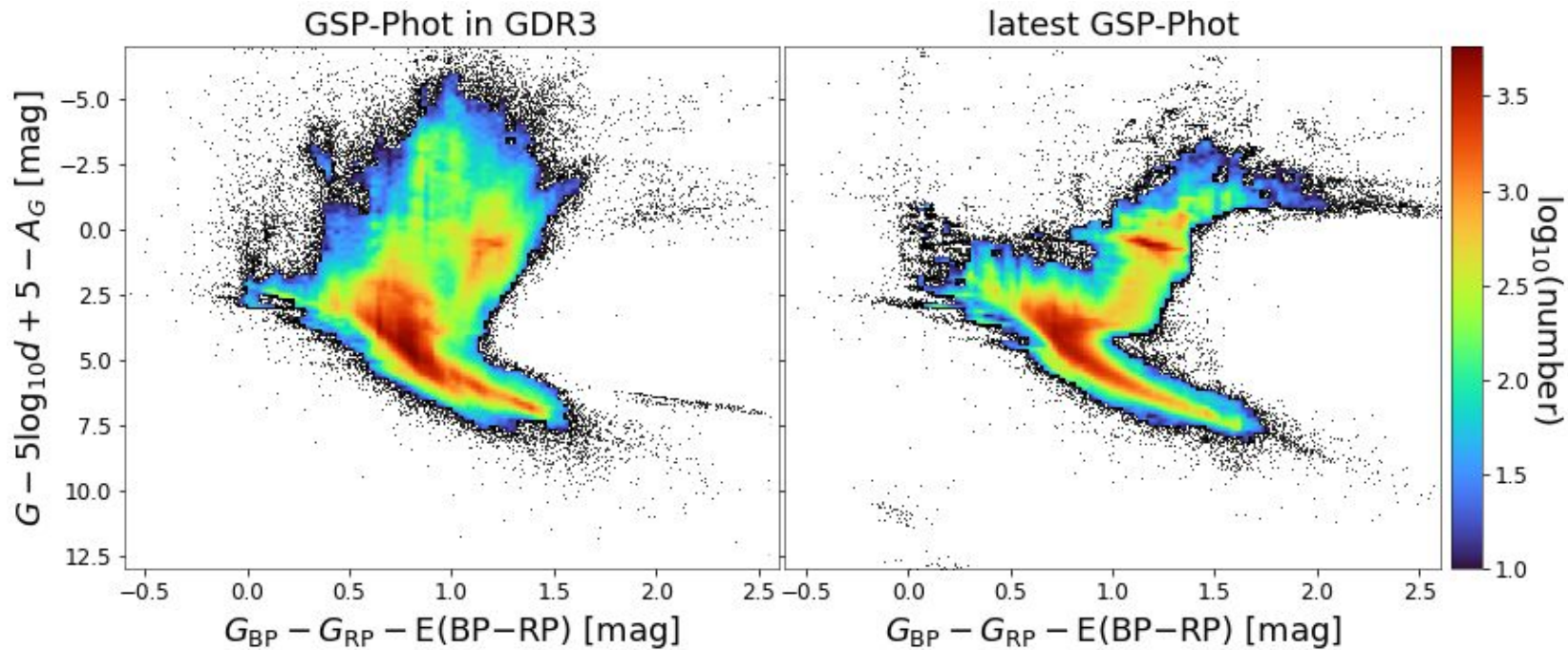
# next steps

---

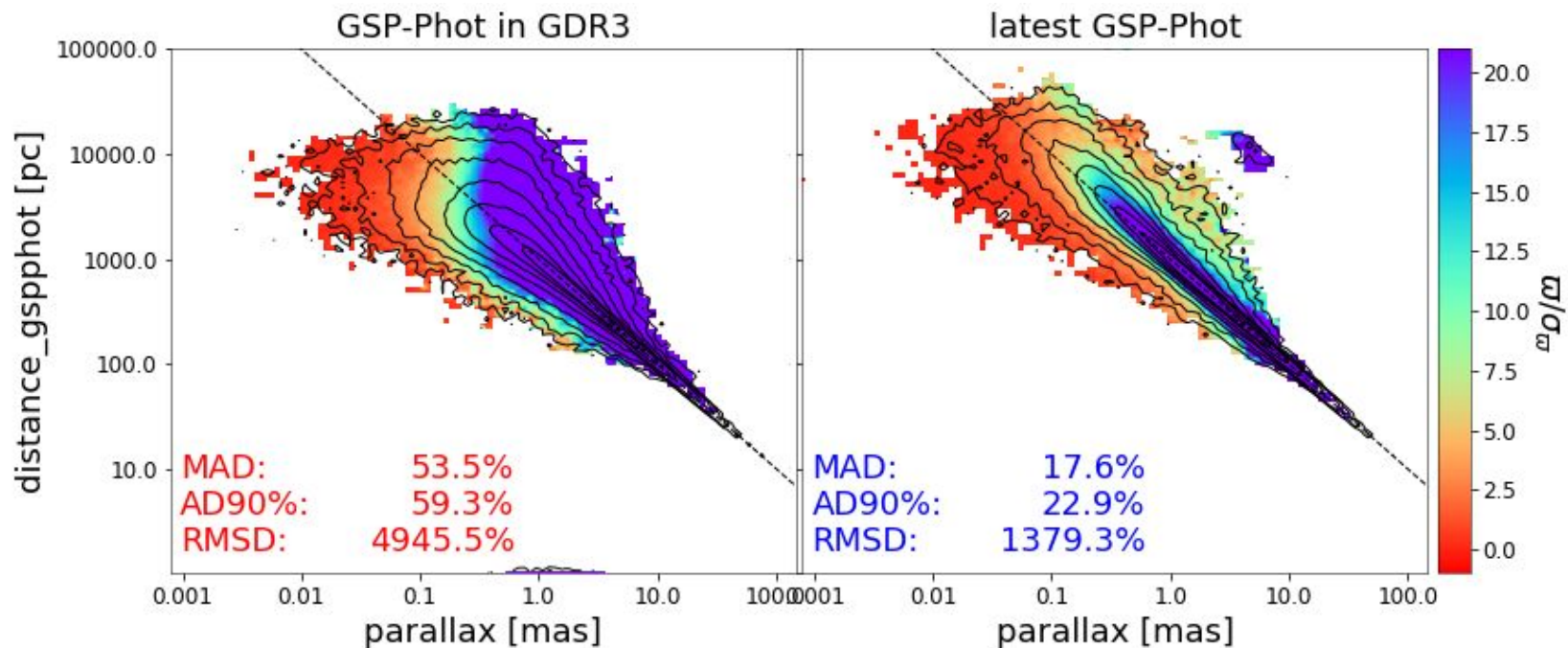
- GSP-Phot for DR4:
  - better distance prior (healpix-wise quantiles from [Rybizki et al. 2020](#))
  - better initial guess + differential evolution preceding MCMC
  - isochrone interpolation over evolutionary state (not initial mass)
  - empirical re-calibration of models
  - use full XP covariance (not just diagonal elements as in [Andrae et al. 2022](#))
  - many small details
  - better XP spectra, better XP models, better parallaxes
- upcoming re-processing of all 220M XP spectra published in DR3



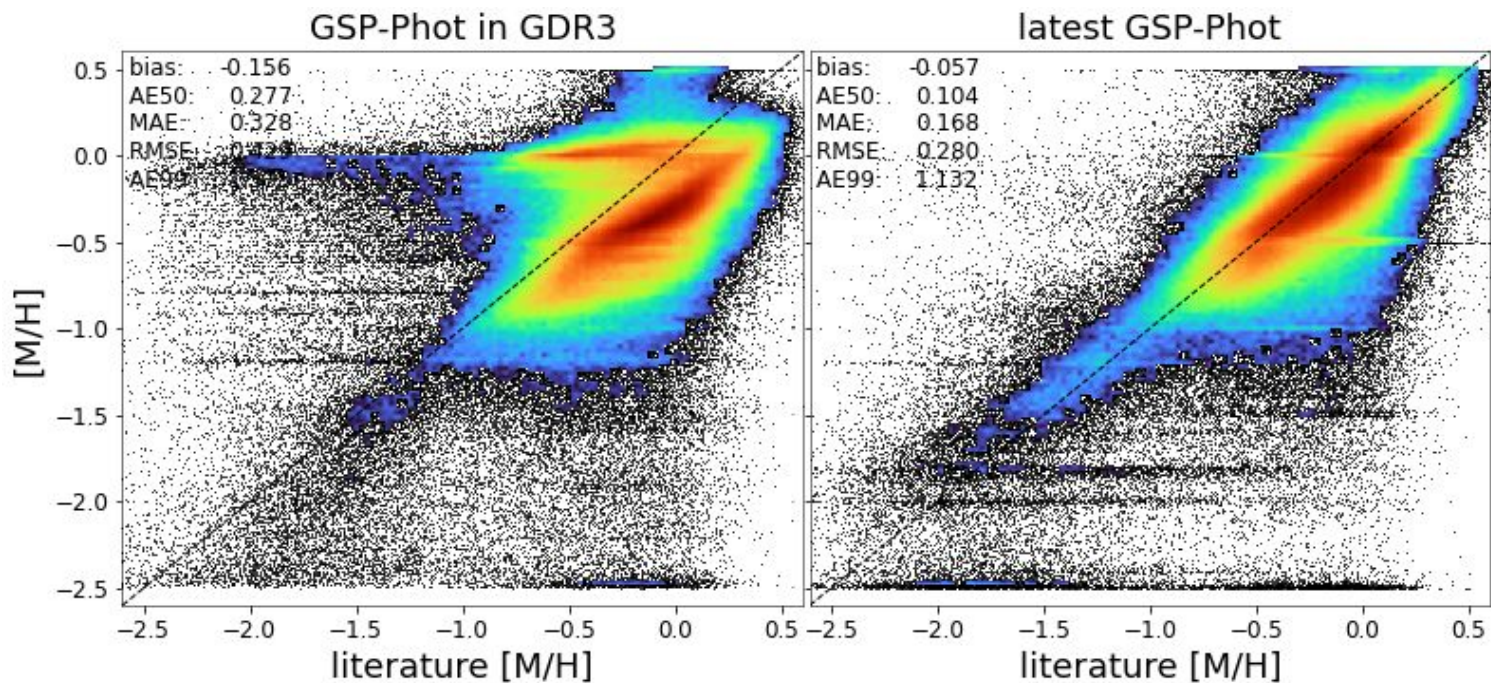
# next steps



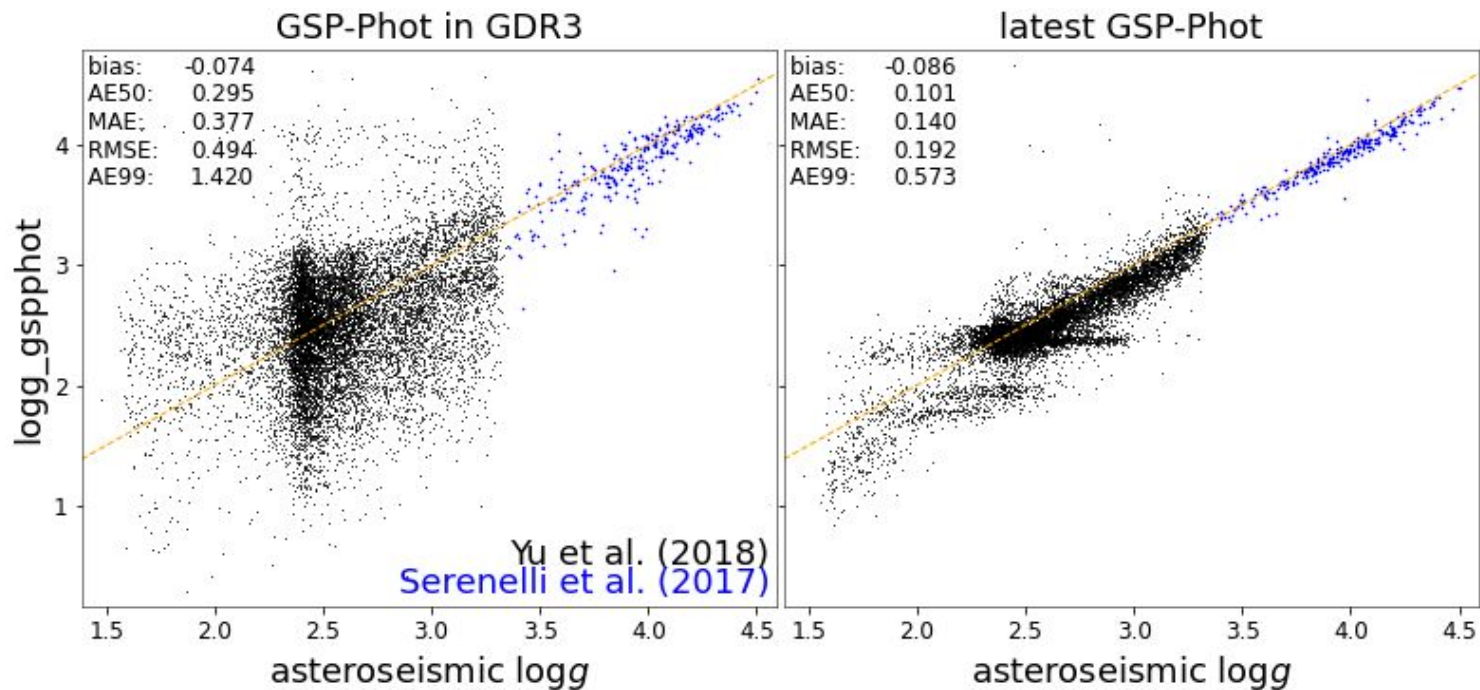
# next steps



# next steps



# next steps



# Summary

---

- GSP-Phot = stellar parameters from XP spectra + G + parallax
- 471M results in Gaia DR3: astrophysical\_parameters table in [Gaia archive](#)
- limitations: [M/H] not usable, distances too low for parallax SNR<10, outliers, uncertainties systematically too small
- substantially better GSP-Phot results on 220M public XP spectra coming soon

