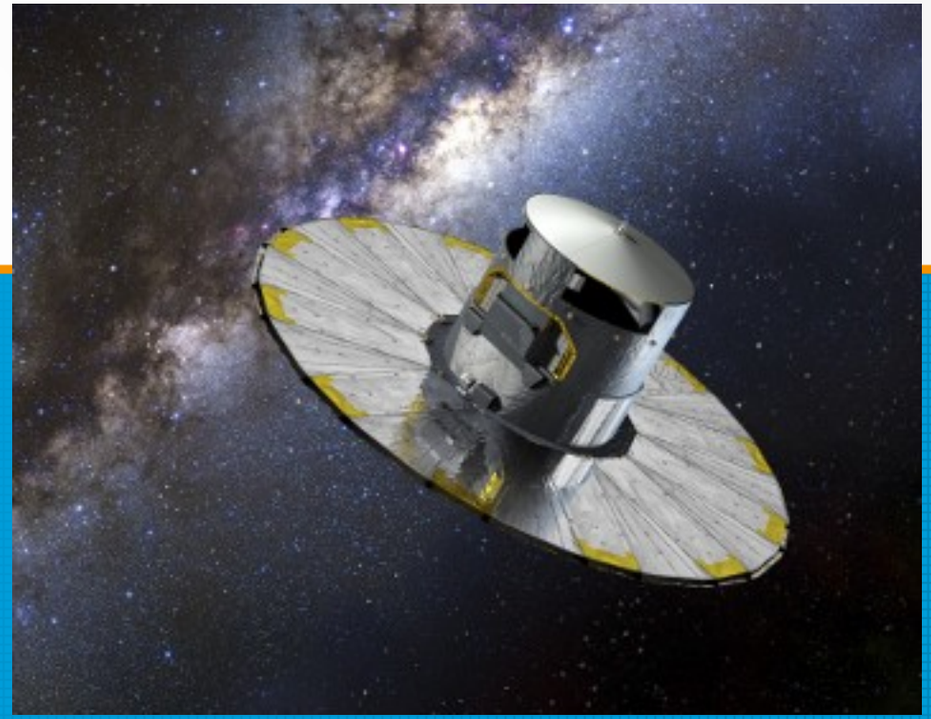
Exploring the Milky Way: Statistical analysis of Gaia data

Maria Süveges & Jan Rybizki
MPI for Astronomy (Heidelberg)
Graduate Days of the HGSFP
8 – 12 October 2018



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Lecture plan – week

- Monday (Jan): Gaia/data overview, first exploration
  - Data access, data cleaning, CMD, nearby stars, MW structure, Hyades cluster
- Tuesday (Maria): Time-series analysis, Gaia epoch photometry
  - Lightcurves from uneven and sparse sampling, variable stars
- Wednesday (Jan): Science case: Stellar encounters
  - RV data, Error sampling, orbit integration, completeness analysis, follow-up
- Thursday (Jan): Bayesian inference: Distances and masses
  - From parallax to distances, stellar parameters from CMD, Priors, MCMC
- Friday (Maria): Classification of variable stars

Lecture plan - today

- Gaia mission overview
- Gaia DR2 data sets overview
- MW structure / stellar physics (CMD / HRD)
- Data access/exploration, TAP, pyvo, topcat
- Data cleaning: quality indicators, sanity checks
- Nearby stars, volume complete sample
- Hyades, metallicity, age from stellar models

Prerequisites

- Astronomy background? Python background? PhDs/Master?
- Ask questions! Pair up. Discuss.
- Input slides → Jupyter notebooks (explanations on the fly)
- Maria's part will be more lecture style
- Access course material:
  - jupyter server (https://jupyter.kip.uni-heidelberg.de)
  - Data will be online and can be downloaded using the provided scripts
  - At the end everything will be on a github repository

Gaia Satellite

- Launched on the 19th of December 2013
- Nominal end 2019 after 5 years of operations
- Operated by ESA
- The Gaia Data Processing and Analysis Consortium (DPAC) are responsible for processing the raw data, which will be published in Gaia catalogue

Orbit and data transfer

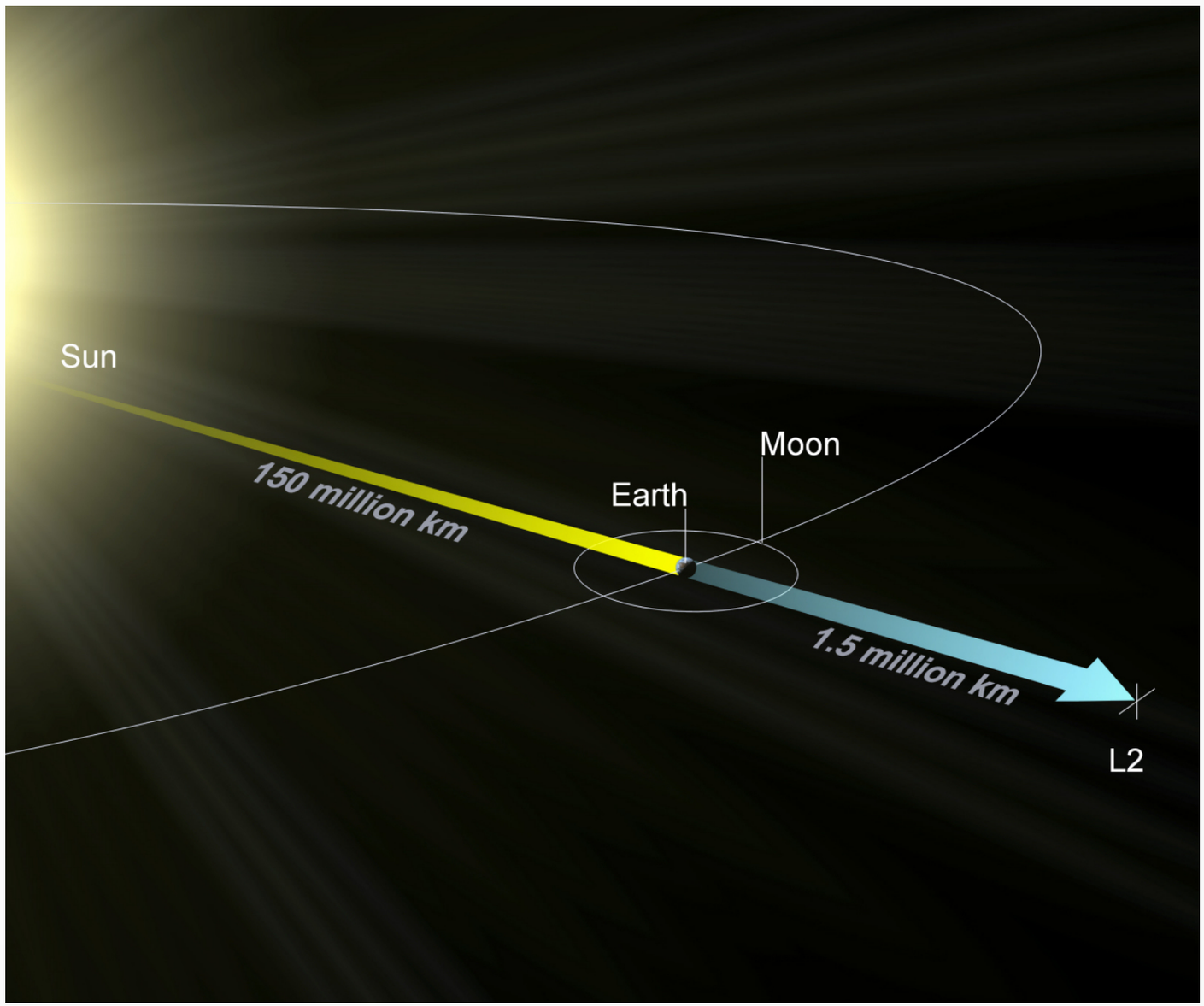
Lissajous-type orbit around L2

On average: 2mio stars per hour

High density >1mio/deg^2

50 GB per day, 8 hours connection

Downlink: up to 7.62 Mbit/s
Spain, Australia, Argentina
35 m radio telescopes,
X- band (7145-8500 MHz)



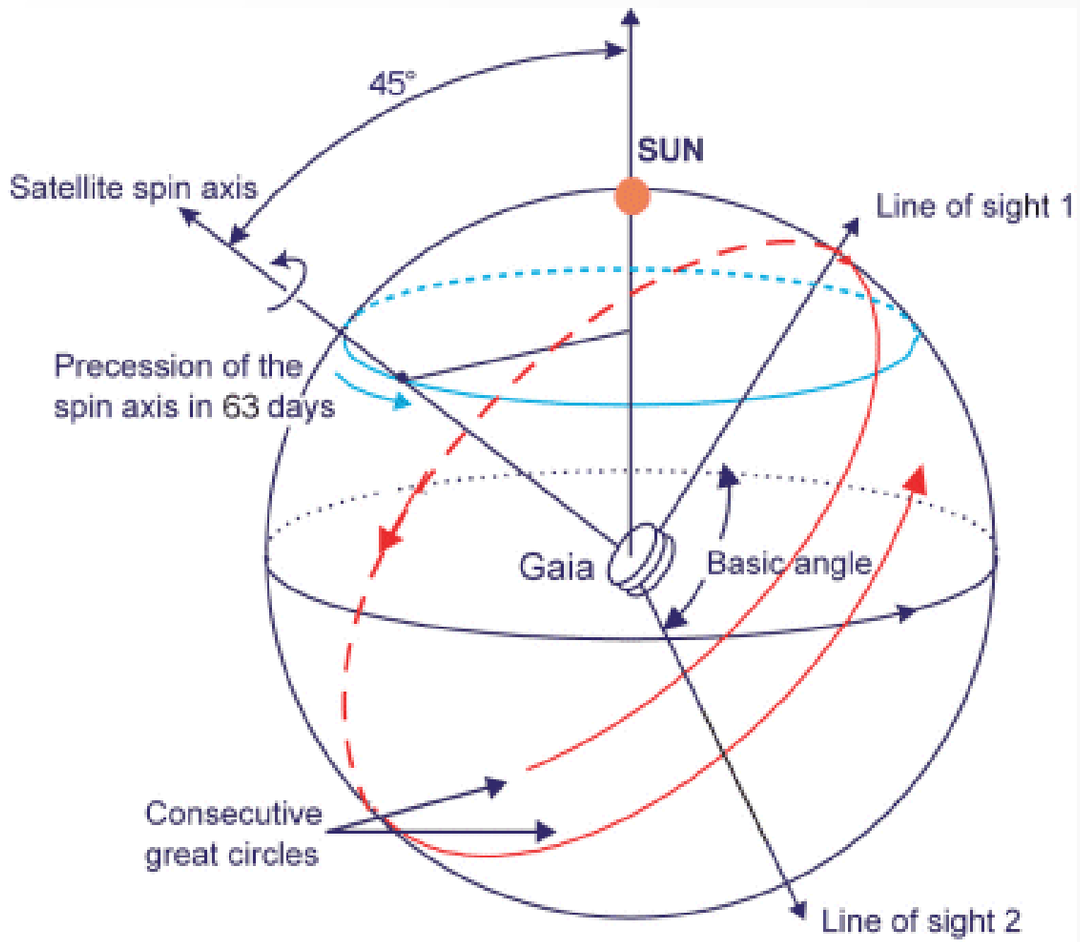
Credit: NASA/ESA

Scanning law

Rotation 1° per minute
→ 6hours full circle

Unequal sampling of sources across the sky
→ Marias lecture (animation) tomorrow

On average each source will be visited 70 times
Some more than 250 times others less than 30



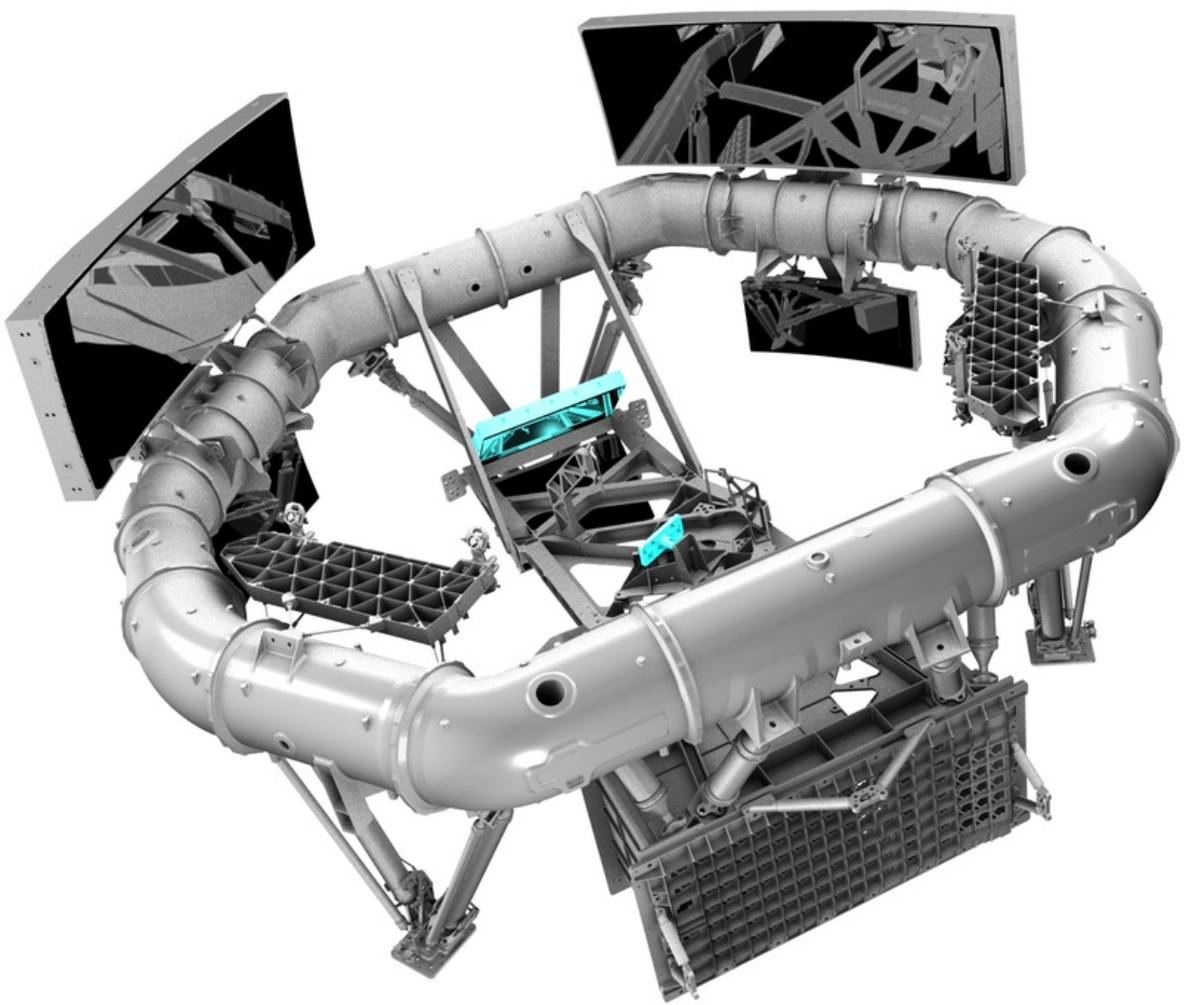
Credit: ESA

Telescope

Basic angle is 106.5°
→ most sources will be visited with 106.5 minutes separation and some also at 360 after first detection

Focal length: 35m
Aperture: 1.45m x 0.5m
Field of view: 1.7° x 0.6°

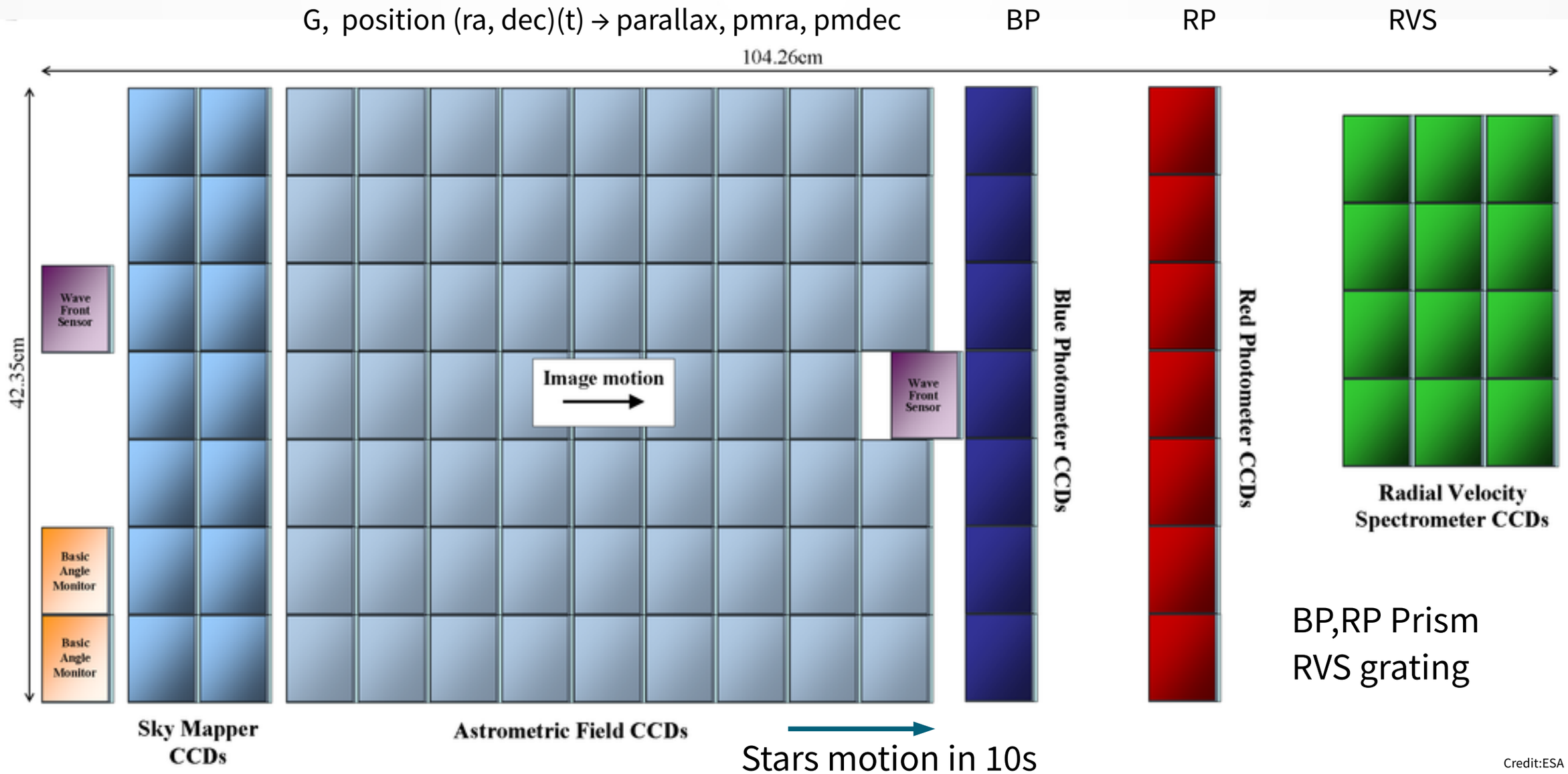
6mirrors, 4 is combiner



Credit: ESA/ASTRIUM

Focal plane

G, position (ra, dec)(t) → parallax, pmra, pmdec



Focal plane

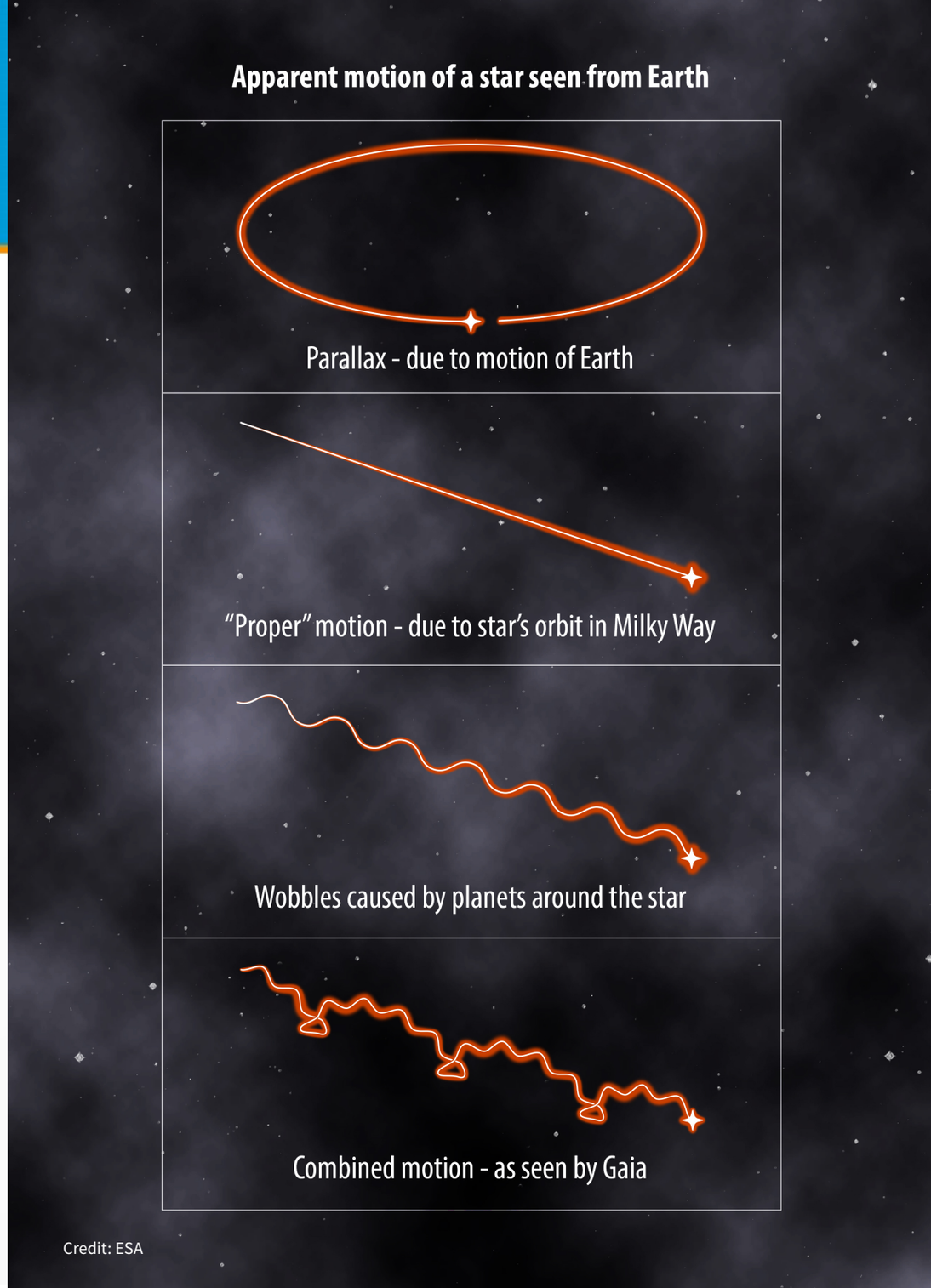
- TDI (time delay integration ~1ms) = pixel crossing time
- Bright stars TDI gates activated, shorten the integration time
- Along scan 4500 x 10µm , across scan 1966 x 30µm
- Operational temperature = -115°C
- 106 CCDs, almost 1 Gpixel

Measurements

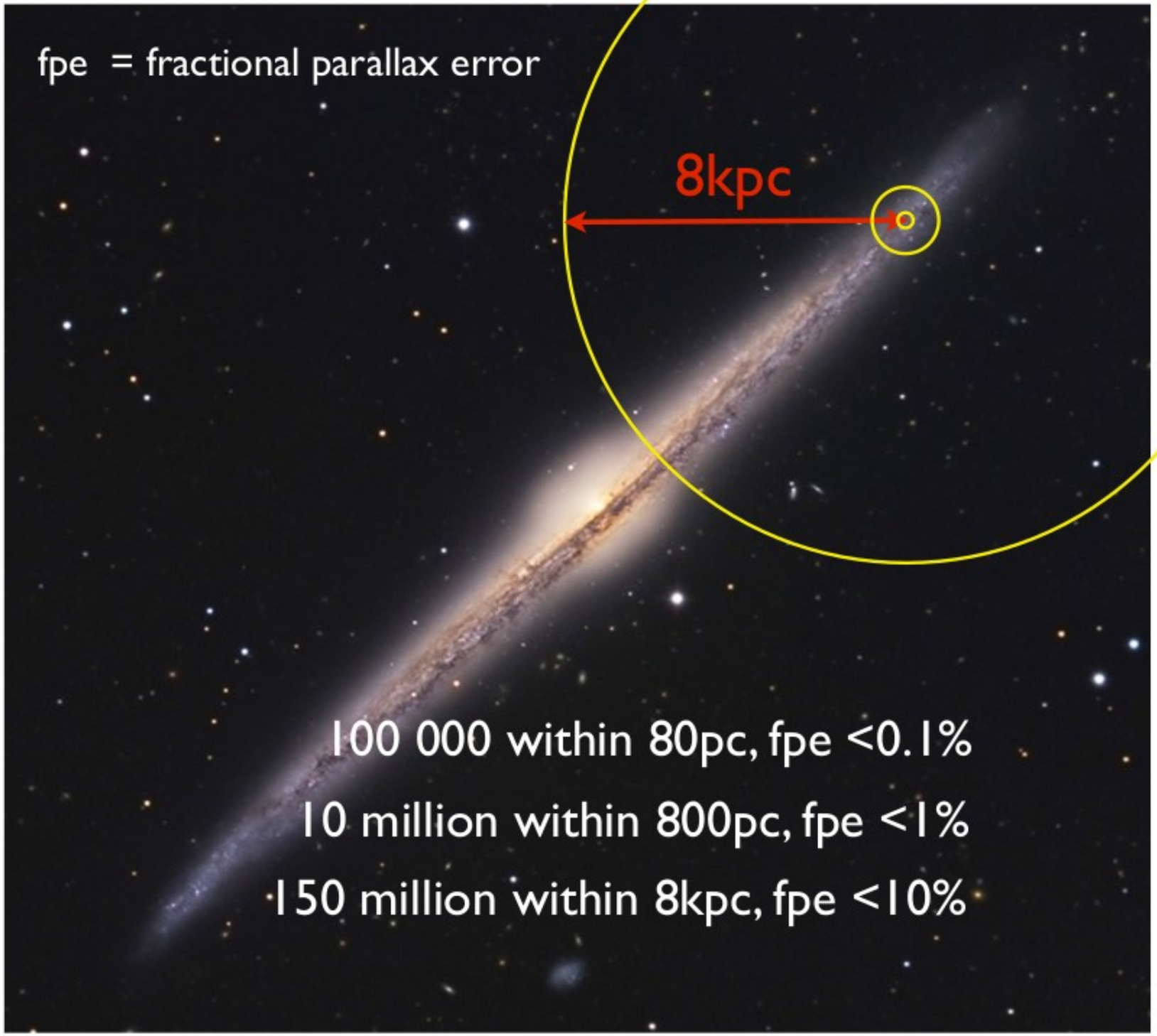
- Astrometry (today)
  - Position (ra, dec), parallax, proper motion (pmra, pmdec)
- Photometry (today)
  - G, G_BP, G_RP (also needed for chromaticity calibration)
  - continuous spectra (120 pixel) in the band 330-1050 nm (not part of DR2)
- Spectrometry (Wednesday)
  - high resolution, grating, narrow band: 845-872 nm, (only RVs published)
- Epoch data for all of these (Tuesday)

Astrometry

- 1 arcsec (as) → 1 parsec (pc)
  - 30 arcmin ~ moon or sun diameter
  - 1 arcmin ~ eye's resolution
  - 1 as ~ human hair diameter in 10m
  - 20 μas ~ Gaia uncertainty (50 kpc)
- Proxima Centauri 1.3 pc → 0.77 as
- Bernard's Star has pm 10.3 as/yr
- Parallax uncertainty dependent on G and N_obs



Parallax

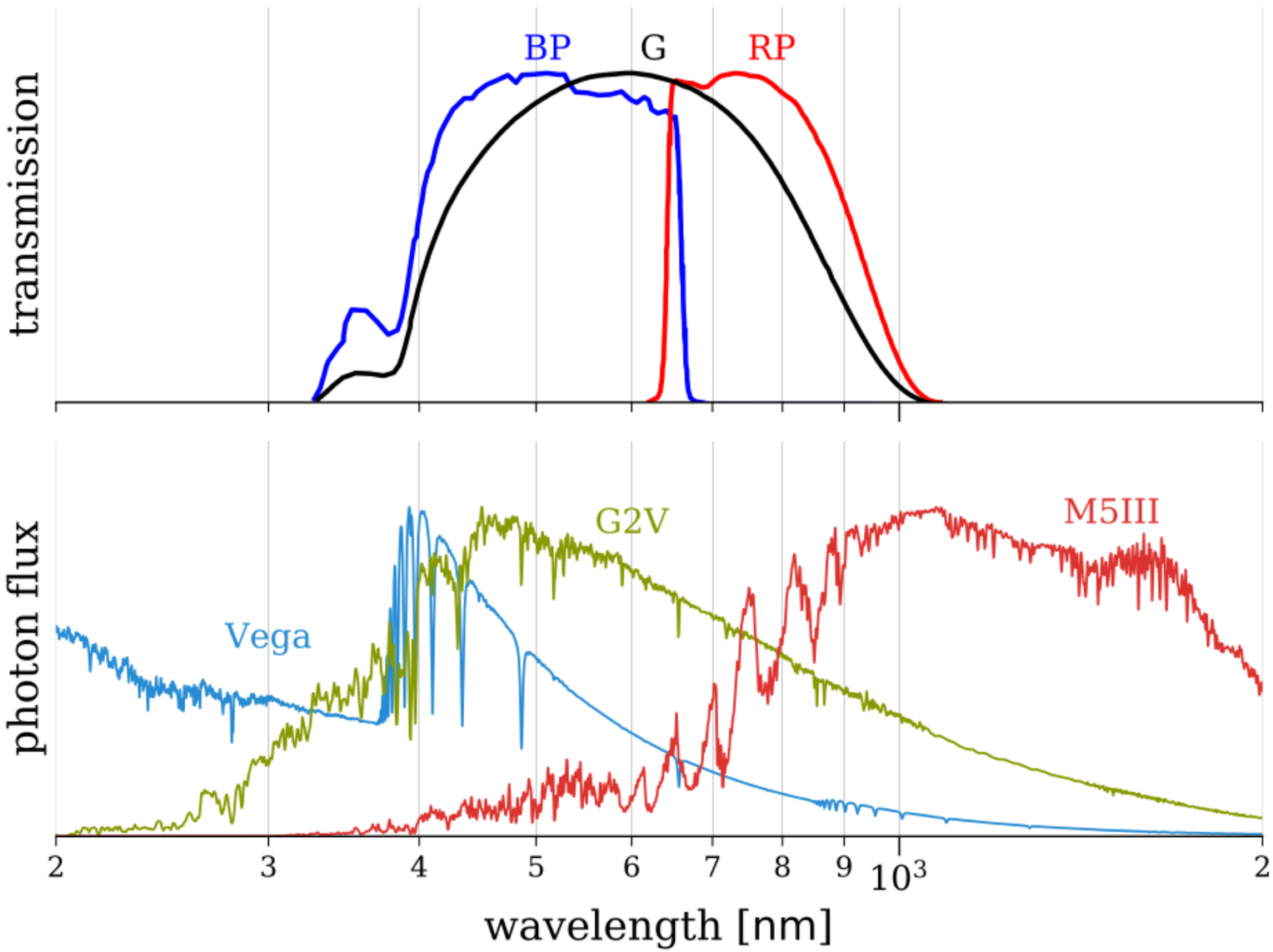


NGC4565 from panther-observatory.com

Slide: Coryn Bailer-Jones

Photometry

- Flux from different photometric bands
- G, BP, RP
- Given in Magnitudes
- Vega 9,600 °K
- G2V (Sun) 5,800 °K
- M5III 3,000 °K



Andrae et al.(2018)

Photometry

- Apparent magnitude (m = 2.5 x log10(F(d))
  - Sun -27
    Moon -13
    Rigel 0
    Pluto 14

Visible to typical human eye[1]	Apparent magnitude	Bright-ness relative to Vega	Number of stars brighter than apparent magnitude[2] in the night sky
Yes	−1.0	250%	1 (Sirius)
	0.0	100%	4
	1.0	40%	15
	2.0	16%	48
	3.0	6.3%	171
	4.0	2.5%	513
	5.0	1.0%	1602
	6.0	0.4%	4800
	6.5	0.25%	9100[3]
No	7.0	0.16%	14 000
	8.0	0.063%	42 000
	9.0	0.025%	121 000
	10.0	0.010%	340 000

Credit: Wikipedia

Photometry

- Apparent magnitude (m = 2.5 x log10(F(d))
  - Sun -27
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- Absolute magnitude (M = 2.5 x log10(F(10pc)))
  - Range for stars is ~ -10 to +17
  - Rigel -8
    Vega 0.5
    Sun 5
    Proxima Centauri 16

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  - Range for stars is ~ -10 to +17
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- Inverse square law: 2 x distance --> ¼ x brightness
  - Distance modulus: μ = m – M = 5 x log10(d) - 5
  - Sun in 100pc distance would be 10 mag (100 times fainter)
  - Sun in 1000pc distance would be 15 mag (10,000 times fainter)

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Credit: Wikipedia

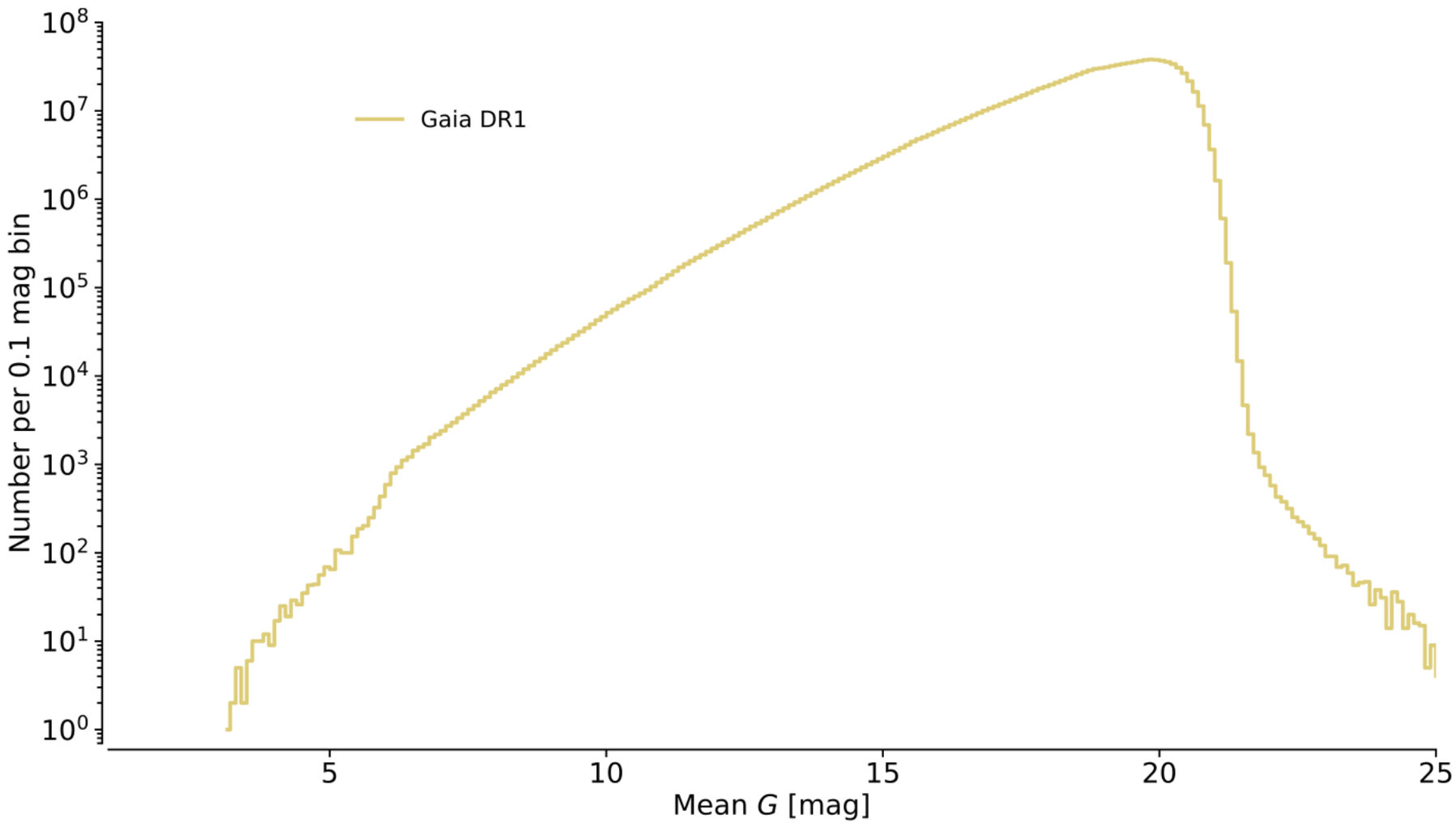
April 25 2018: a big step from Gaia DR1 to DR2

Data product	Gaia DR2	Gaia DR1
Total number of sources	1.69 billion	1.14 billion
Position, parallax, proper motion	1.33 billion	0.002 billion
Position only	0.36 billion	1.14 billion
Mean G	1.69 billion	1.14 billion
Mean G_{BP}, G_{RP}	1.38 billion	-
Median v_{rad} at $G_{RVS} < 12$ $\quad (G \lesssim 13)$	7.2 million	-
Astrophysical parameters at $G < 17$	77–161 million	-
Variable star light curves	551 thousand	3 thousand
Epoch astrometry/photometry for a pre-selected list of asteroids	14 thousand	-

Exact numbers and more info: `https://www.cosmos.esa.int/web/gaia/dr2`

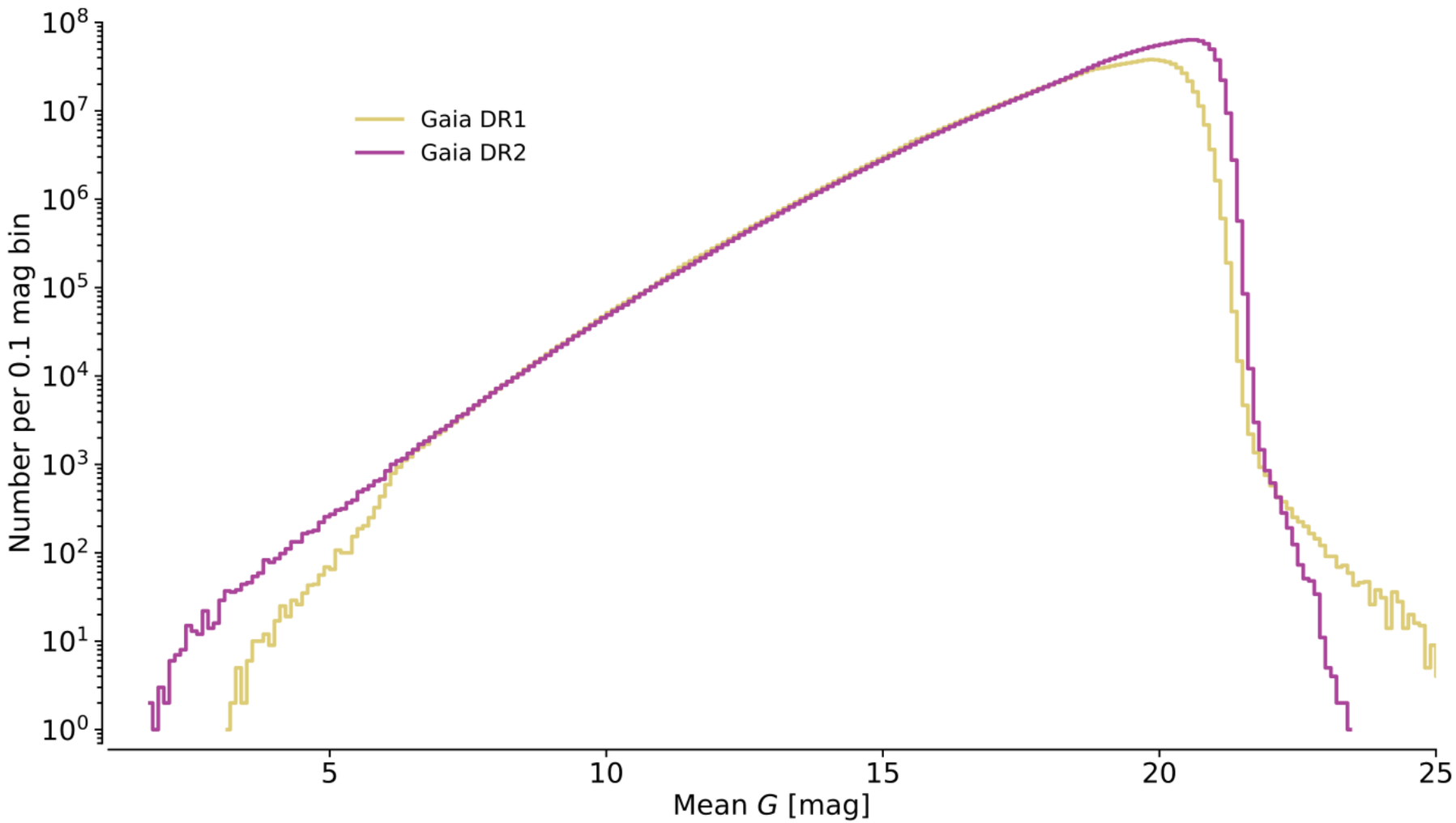
Slide: Anthony Brown

Magnitude distributions



Slide: Coryn Bailer-Jones

Magnitude distributions



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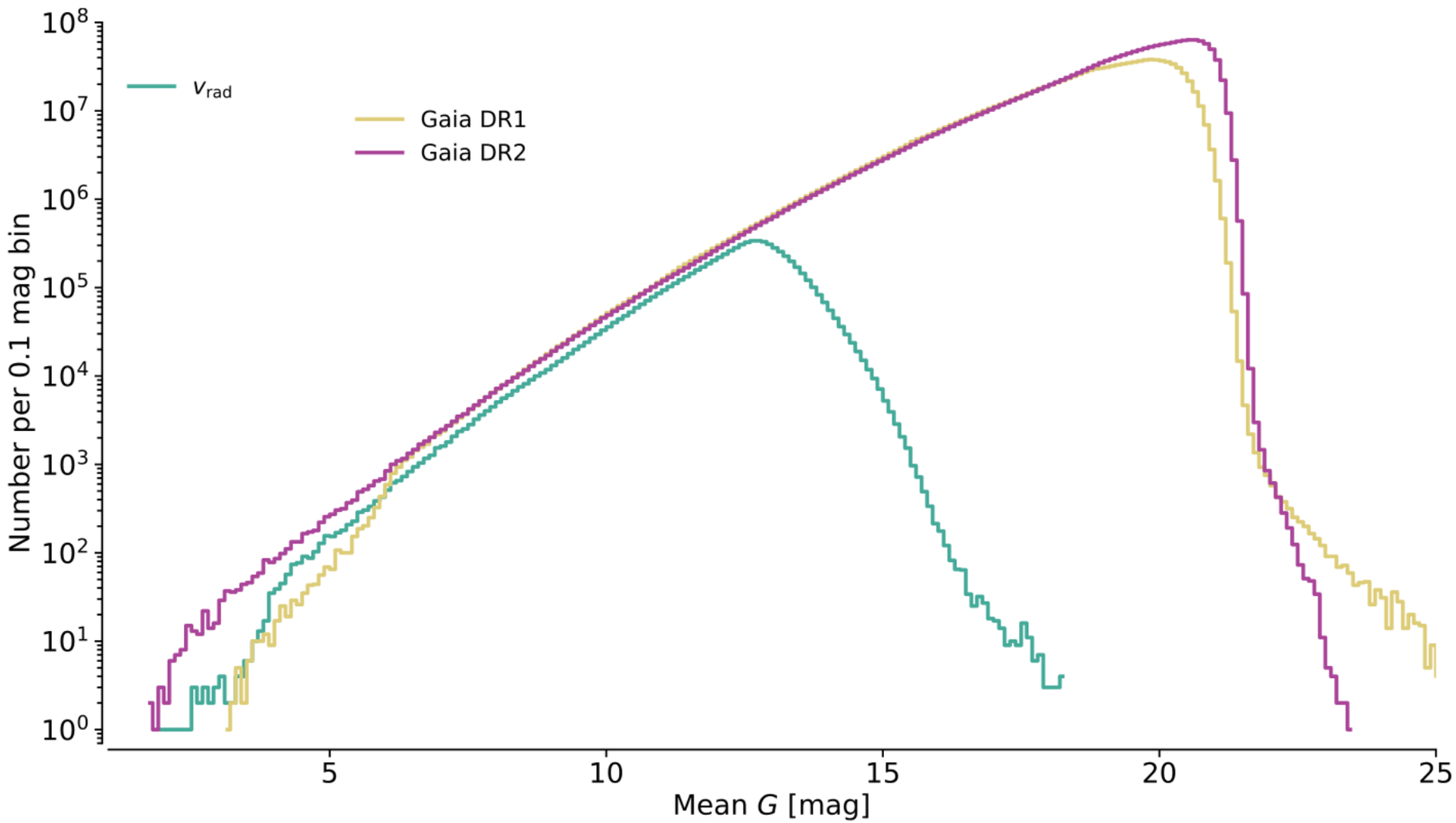

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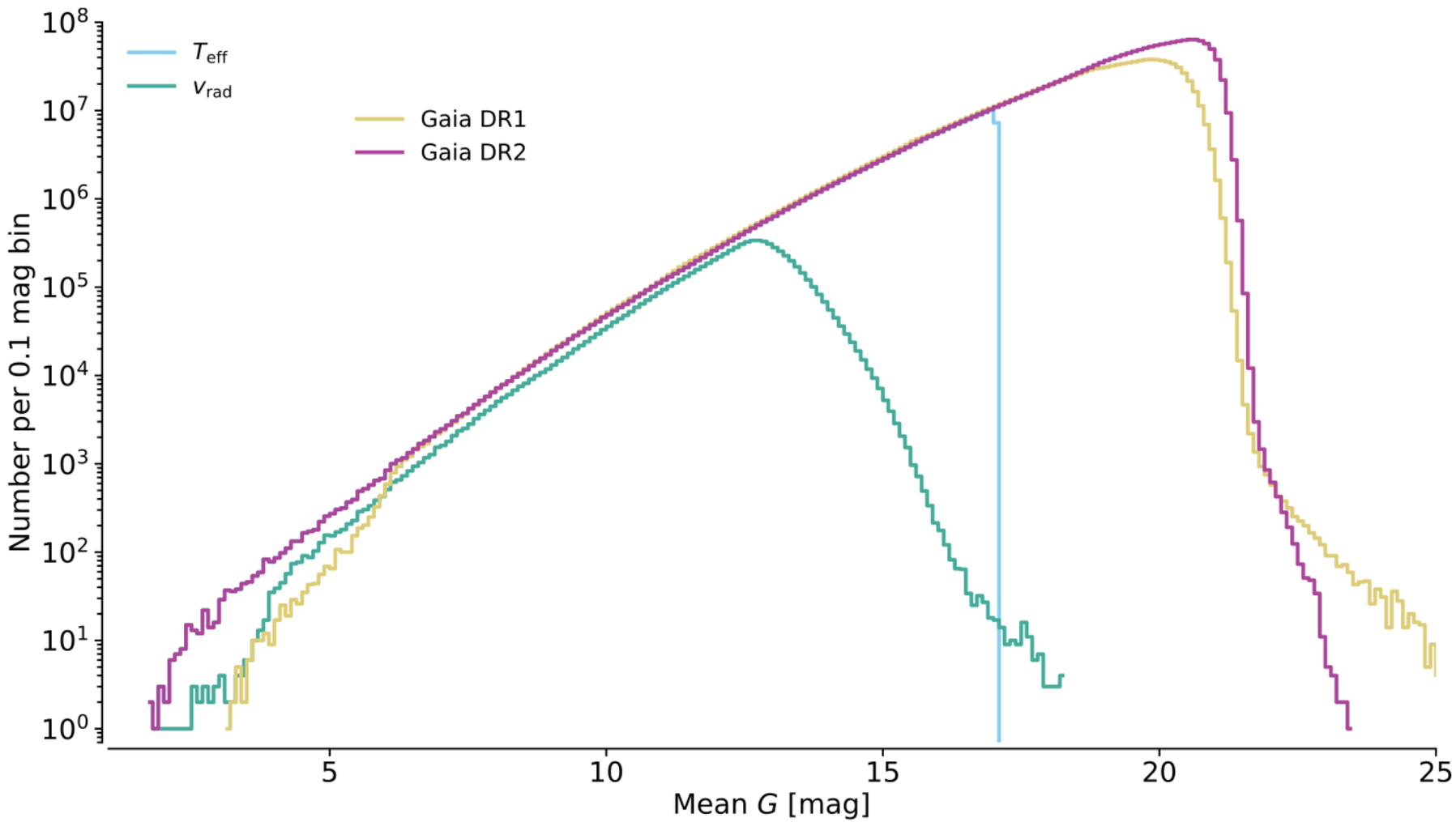

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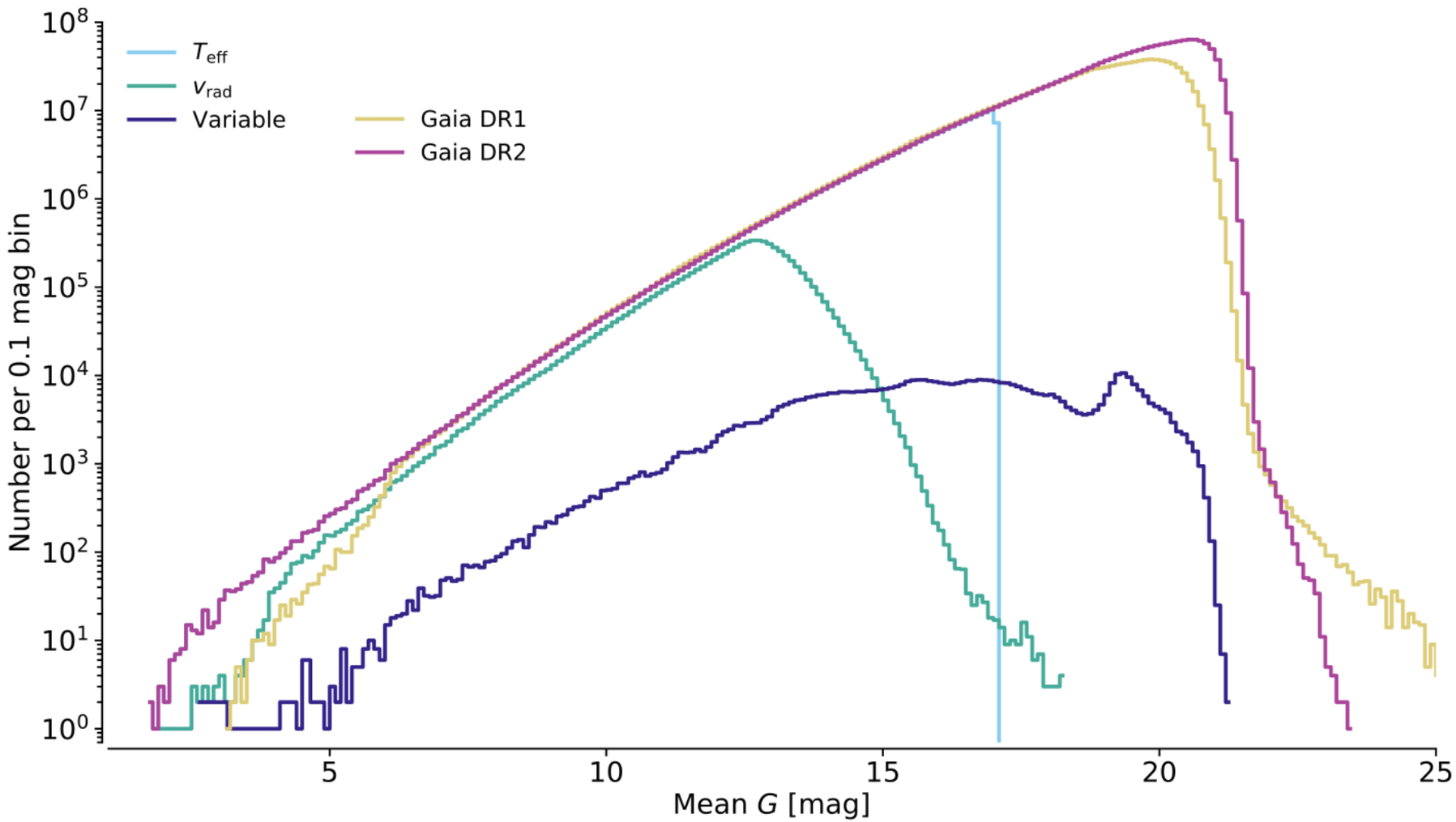

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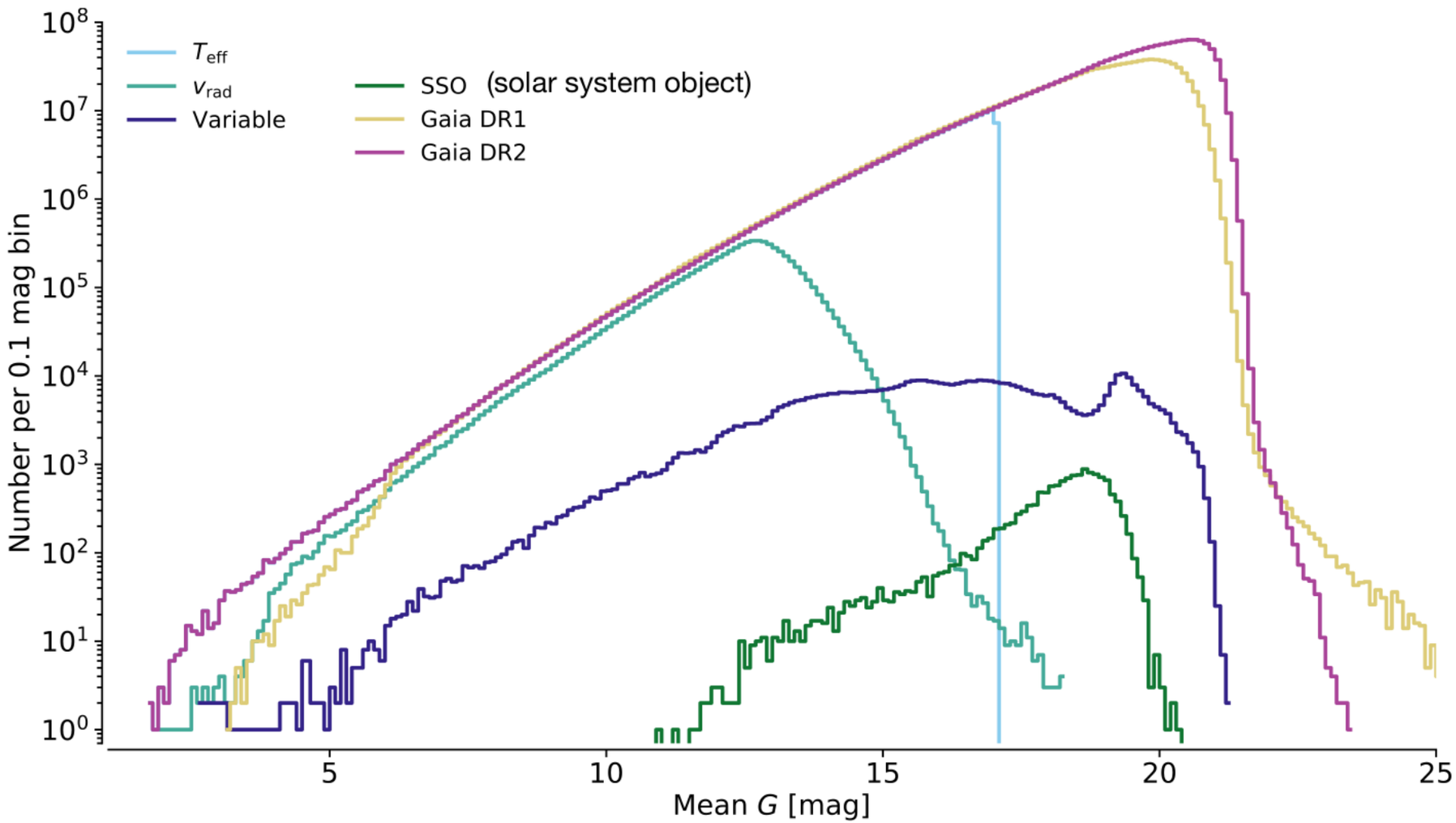

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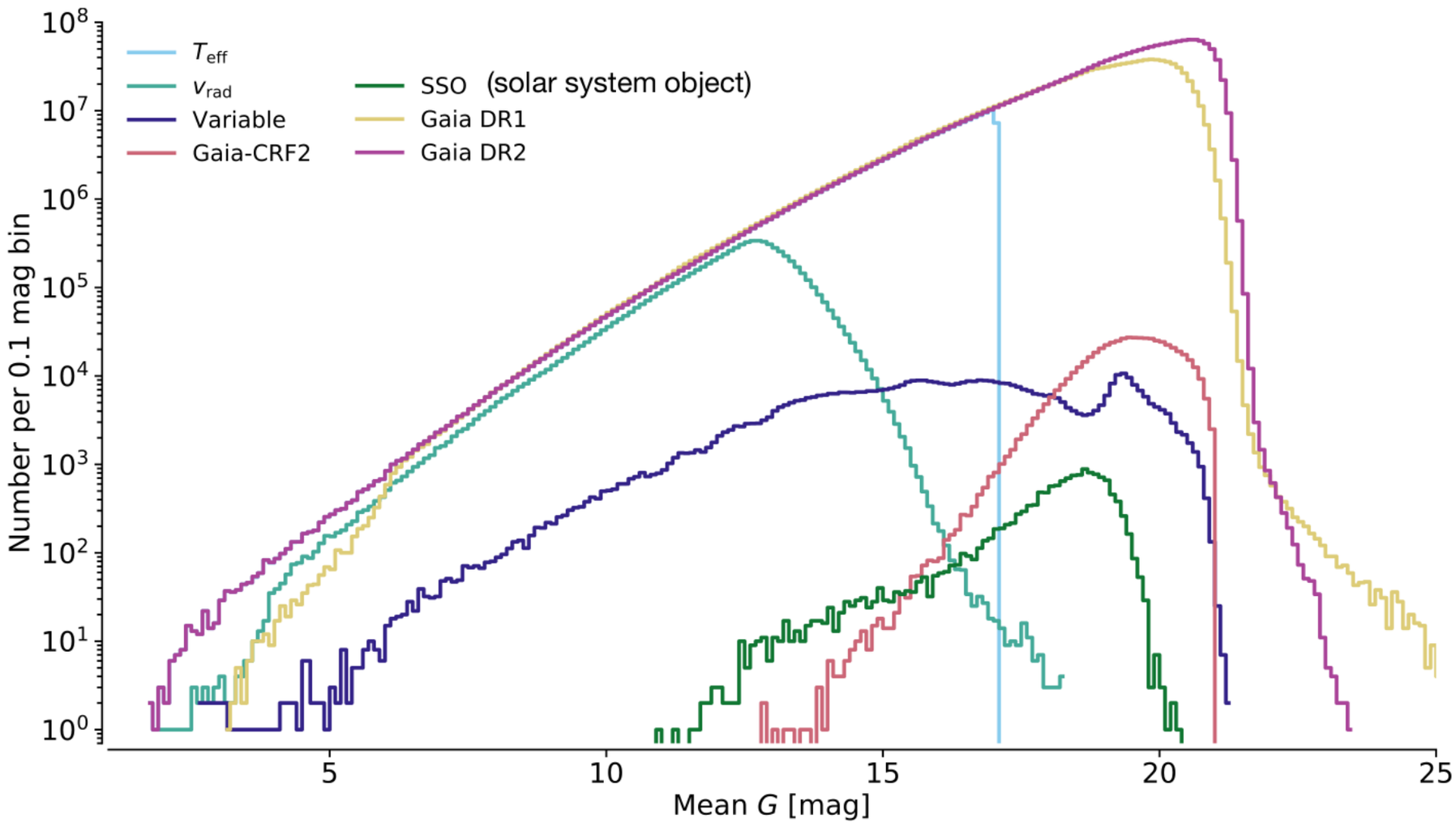

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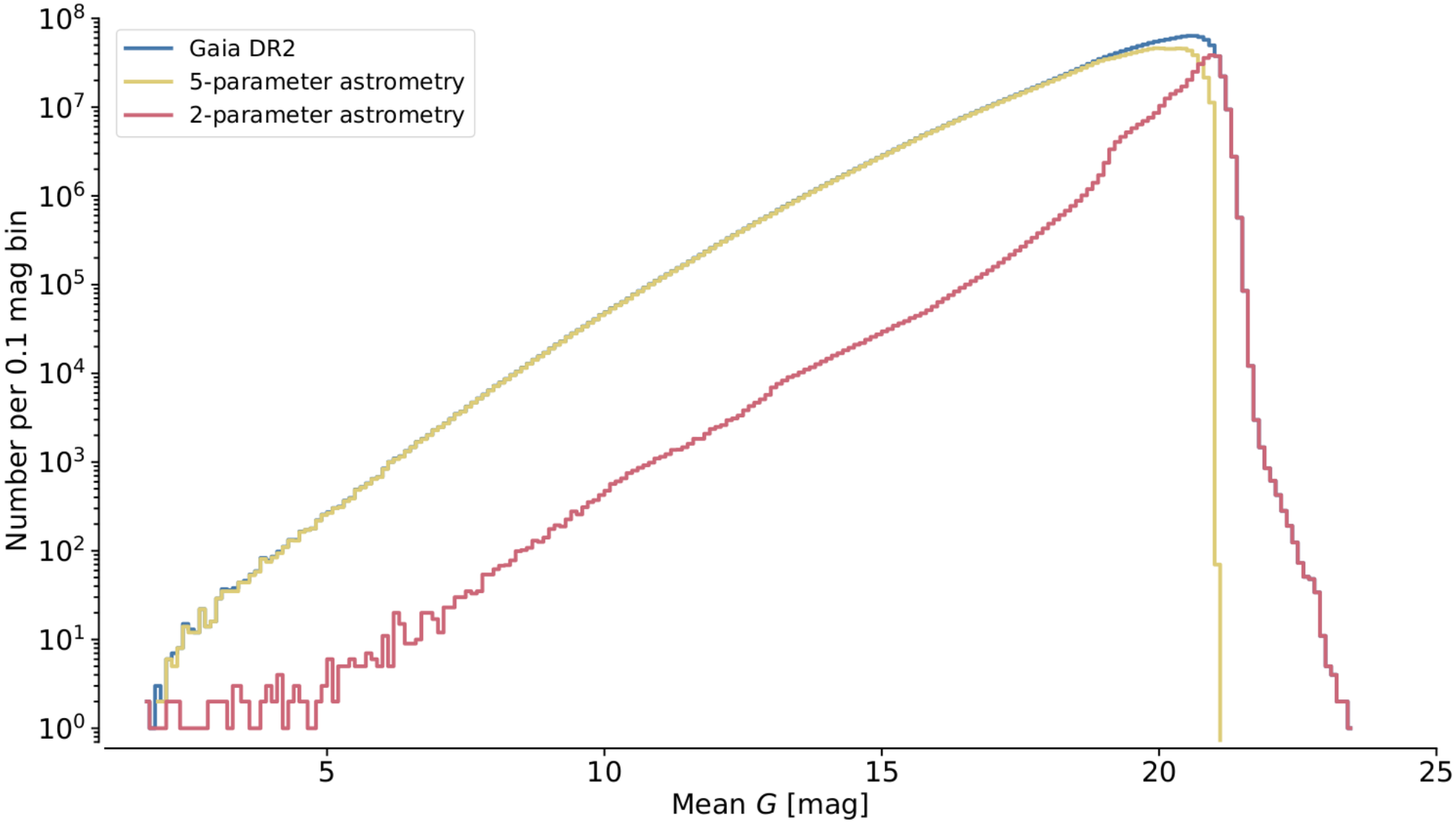
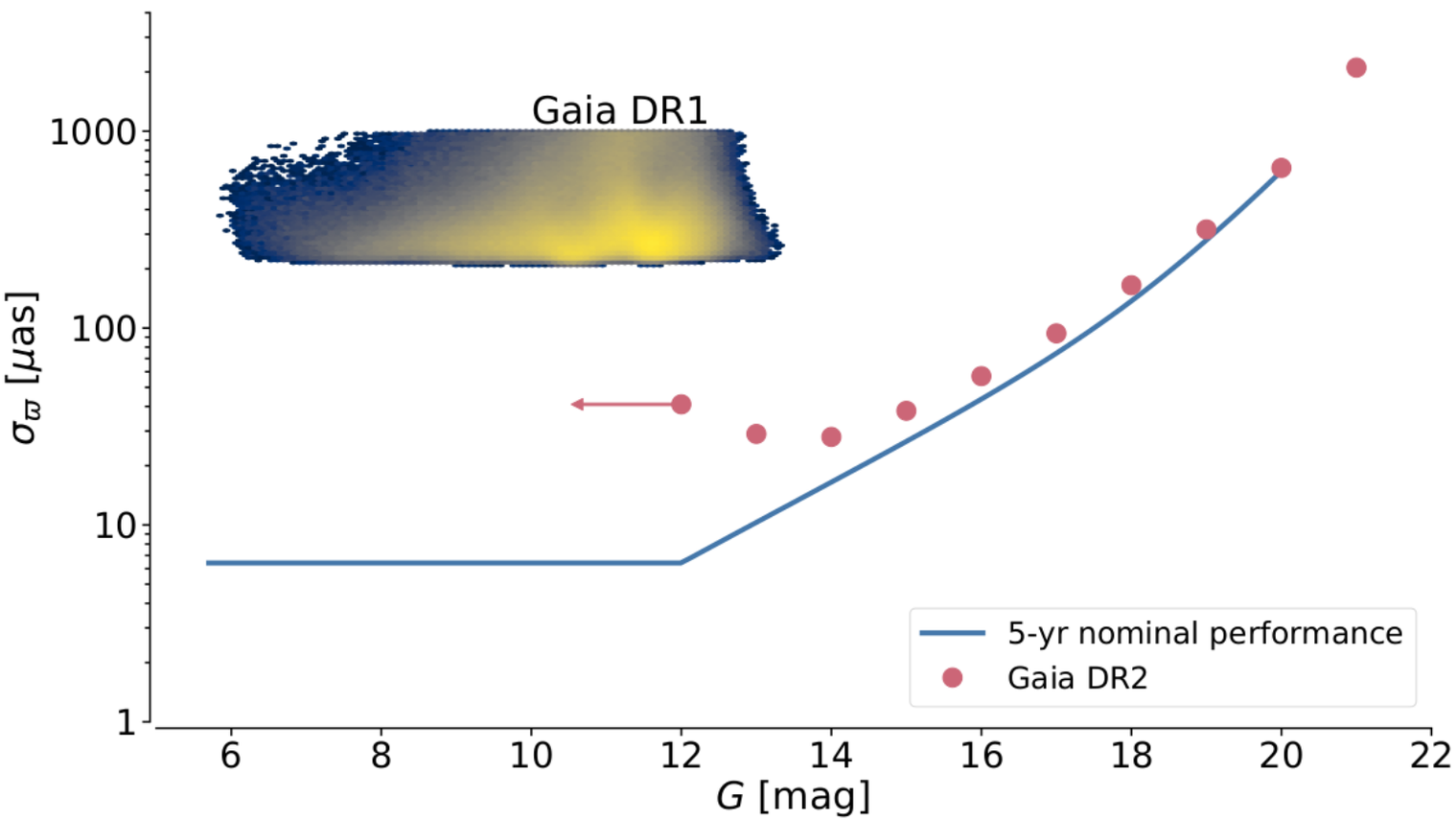
Source counts



Slide: Anthony Brown

Astrometric performance Gaia DR2



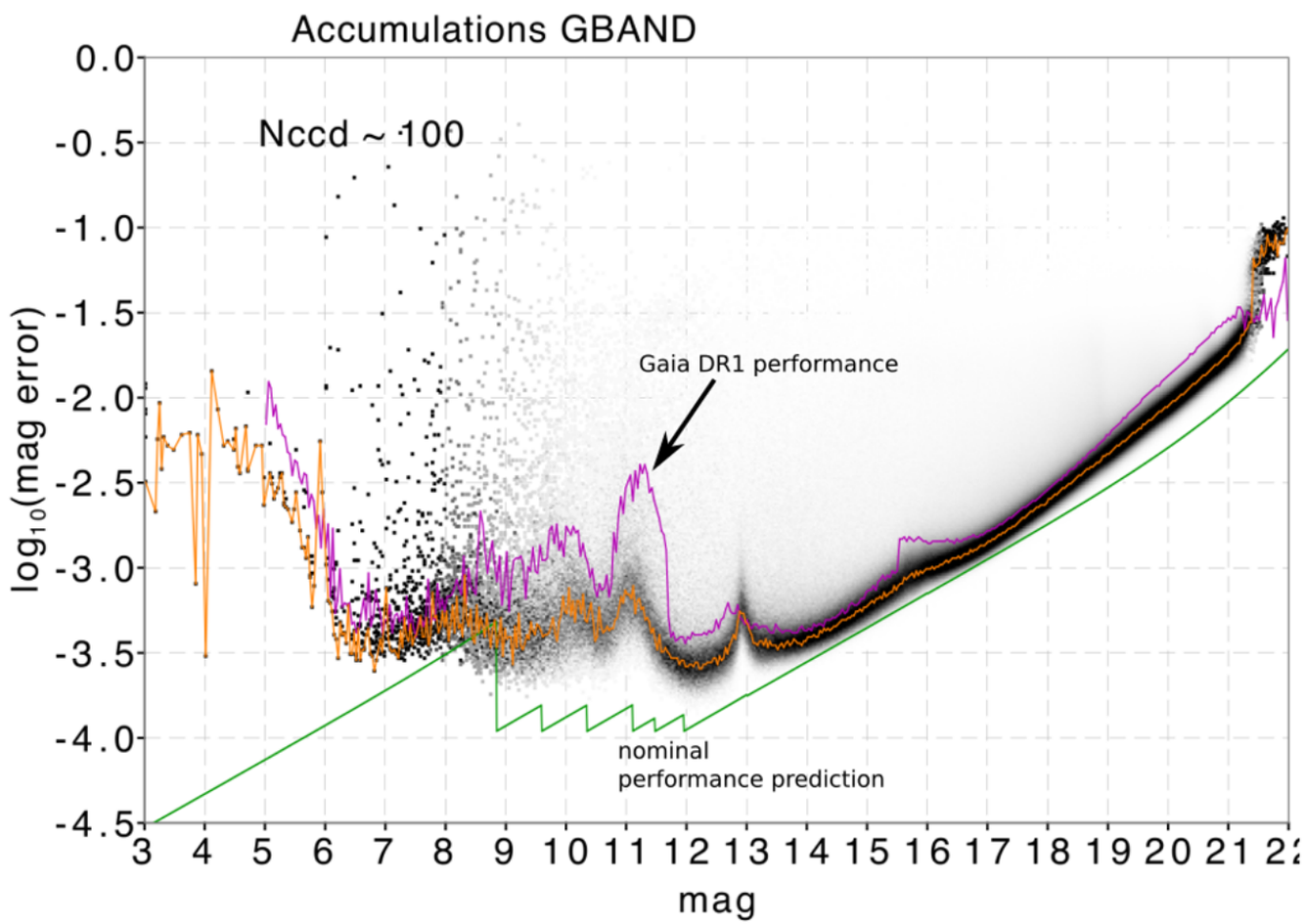
Typical parallax precision

$G = 15$	0.02–0.04 mas
$G = 17$	0.1 mas
$G = 20$	0.7 mas
$G = 21$	2.0 mas

- Systematic errors below 0.1 mas
- Spatial correlations at ~ 1 and ~ 20 degree scales
- Bright star performance calibration limited

Slide: Anthony Brown

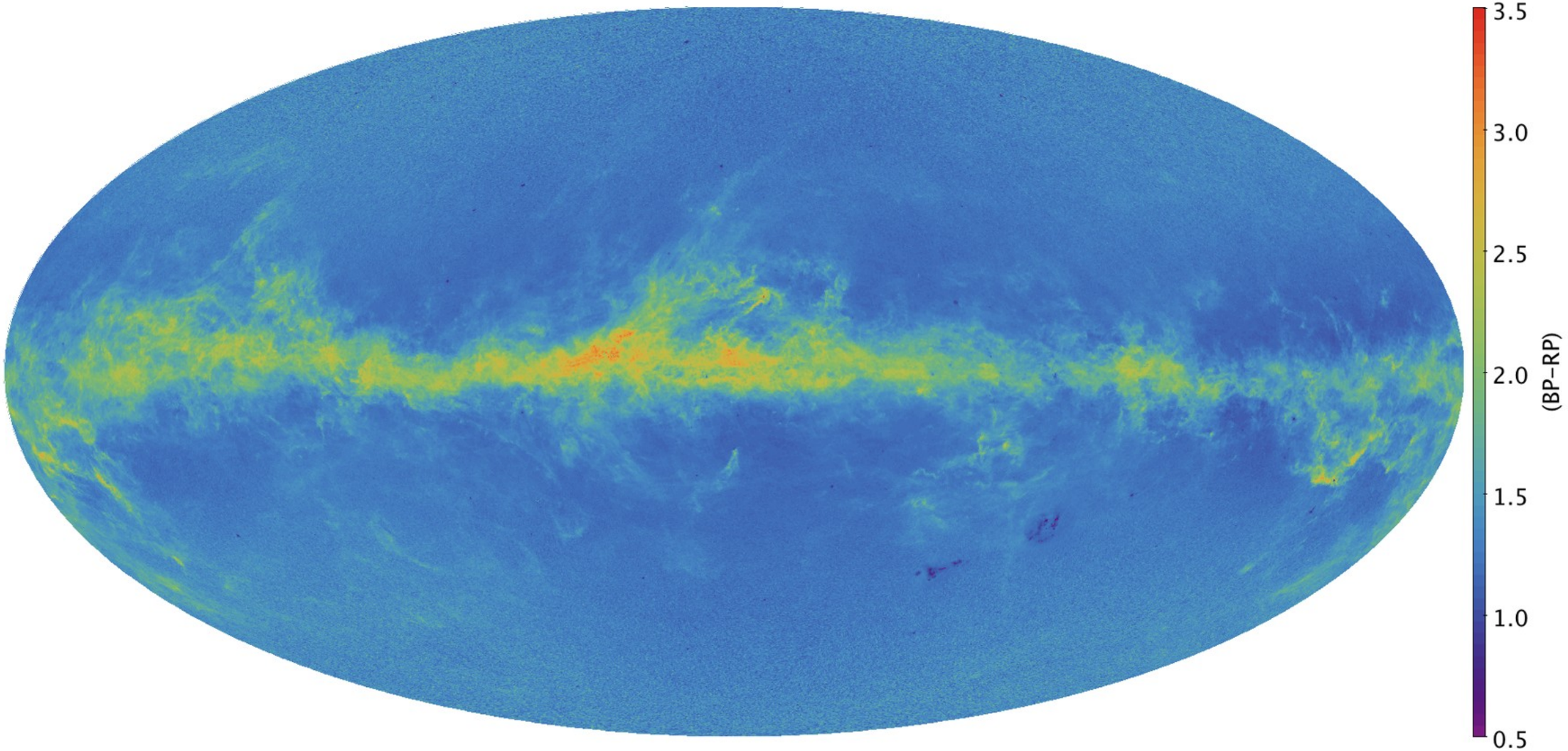
Photometric performance Gaia DR2



- *G*-band scatter for sources observed ~ 100 times

Slide: Anthony Brown

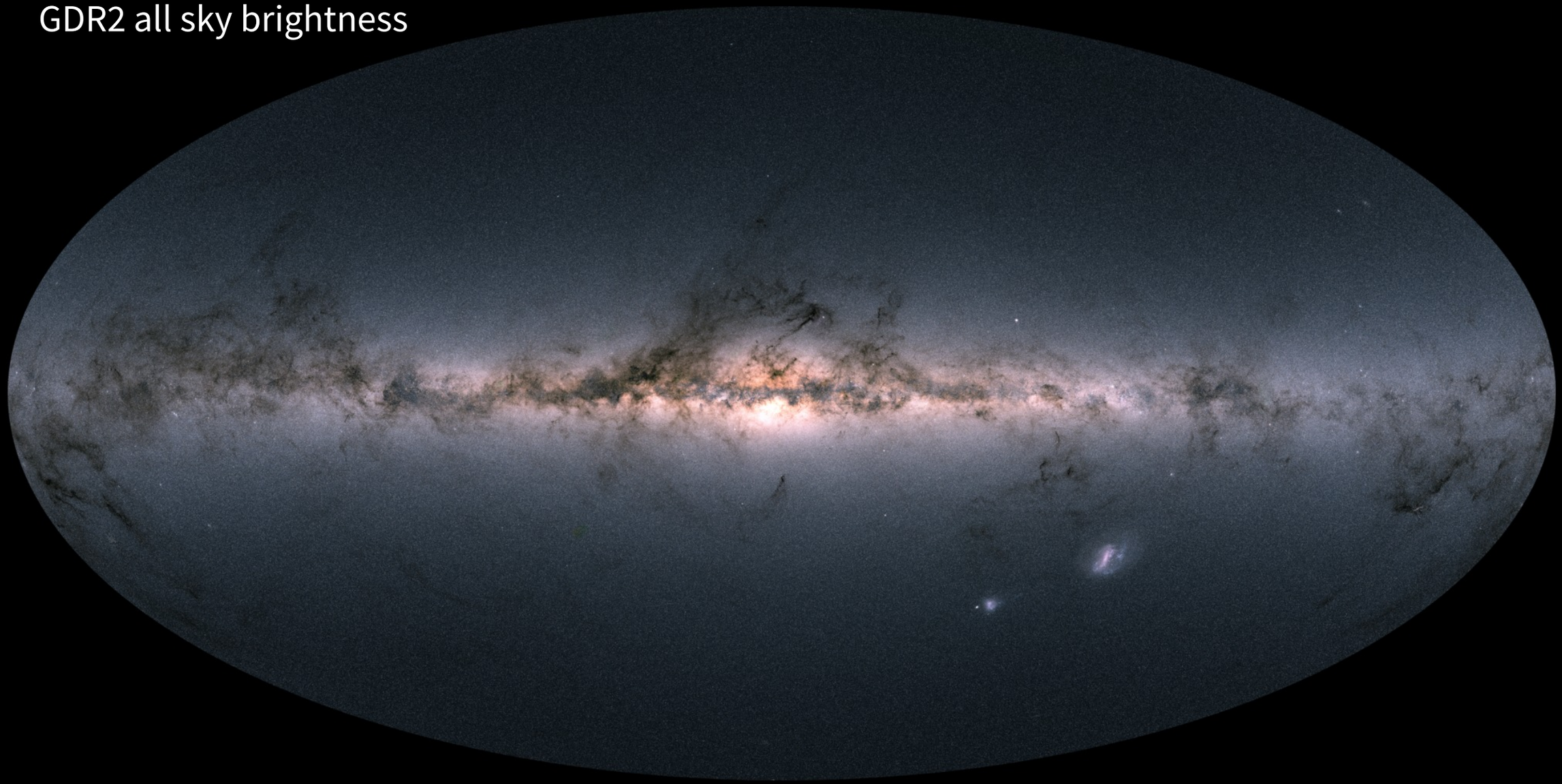
Photometric performance Gaia DR2



Mean colour of the Gaia DR2 sky

Slide: Anthony Brown

GDR2 all sky brightness

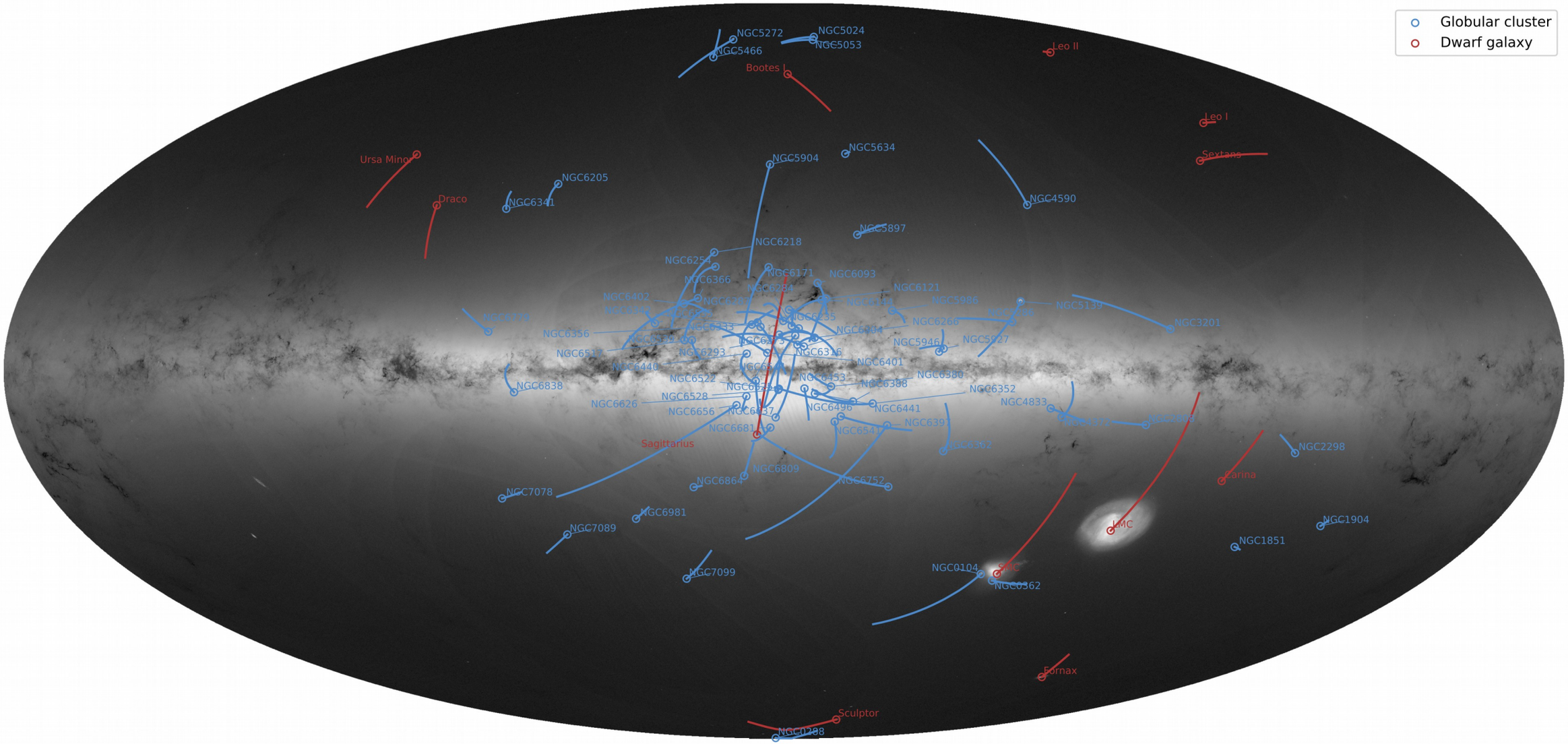


Credit: ESA

Objectives / Science

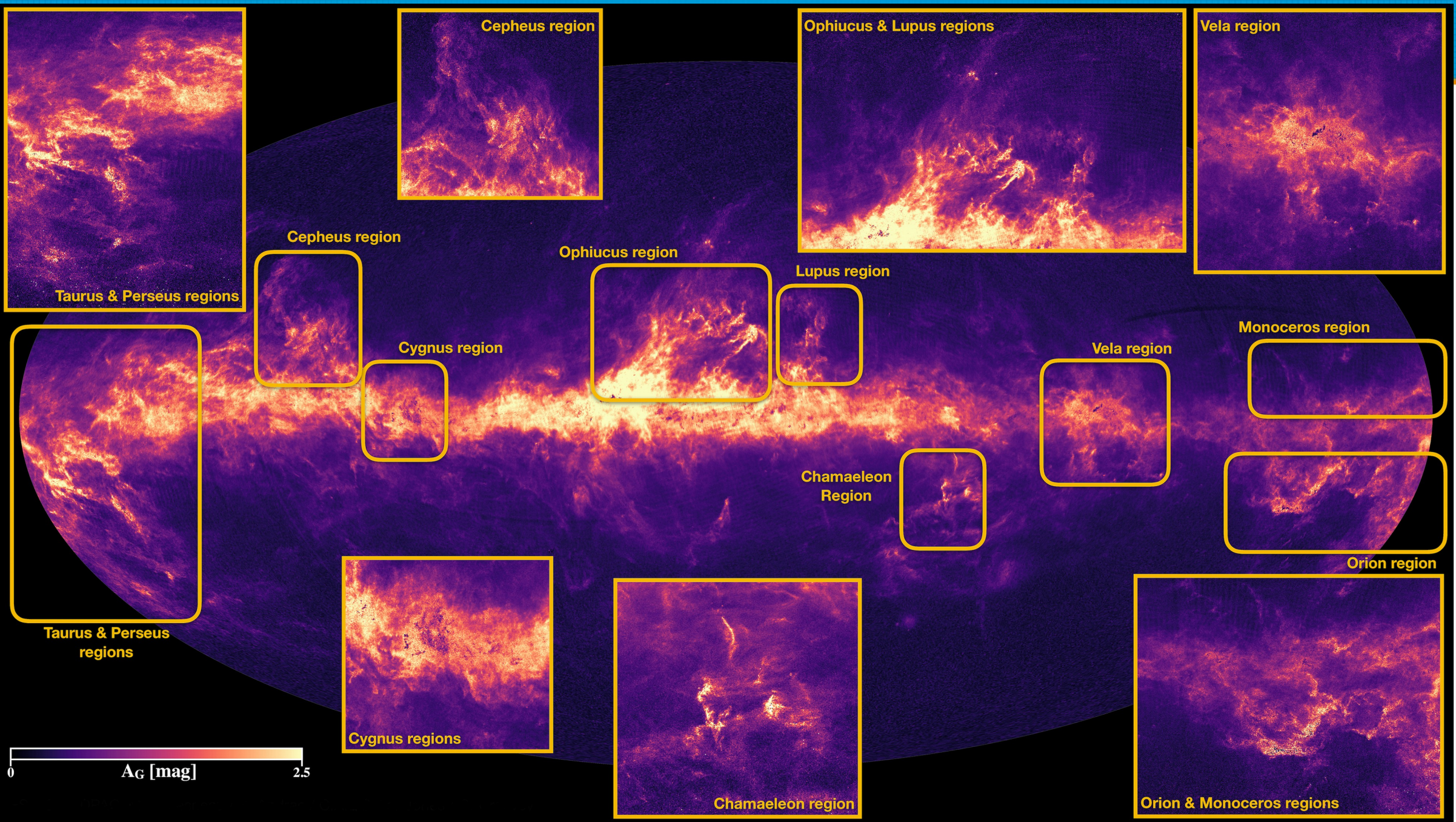
- MW structure / evolution
- Stellar physics
- Exoplanets
- Microlensing
- Asteroids
- Galaxies and quasars
- Variable stars

GDR2 Science

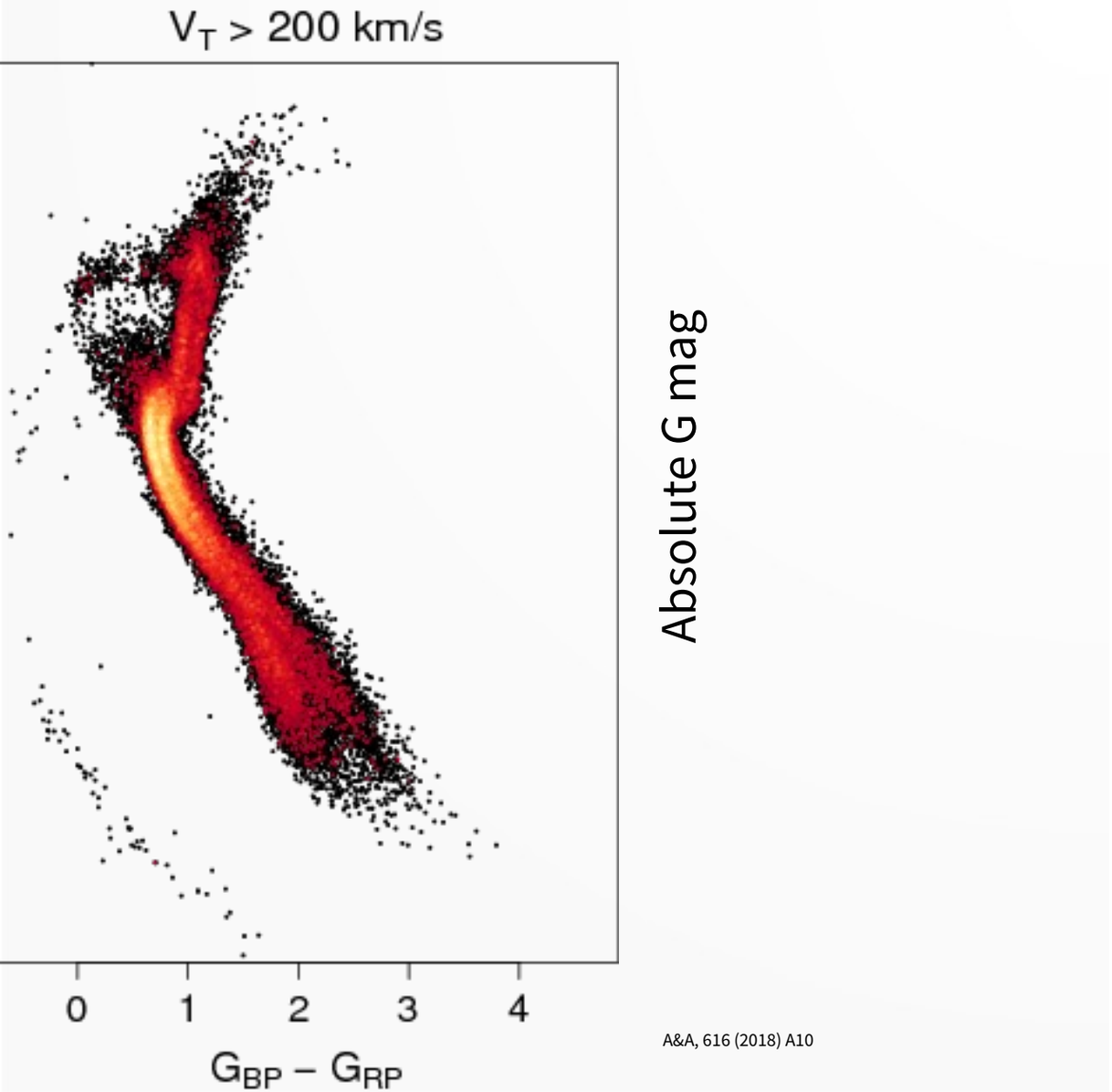


GDR2 Science

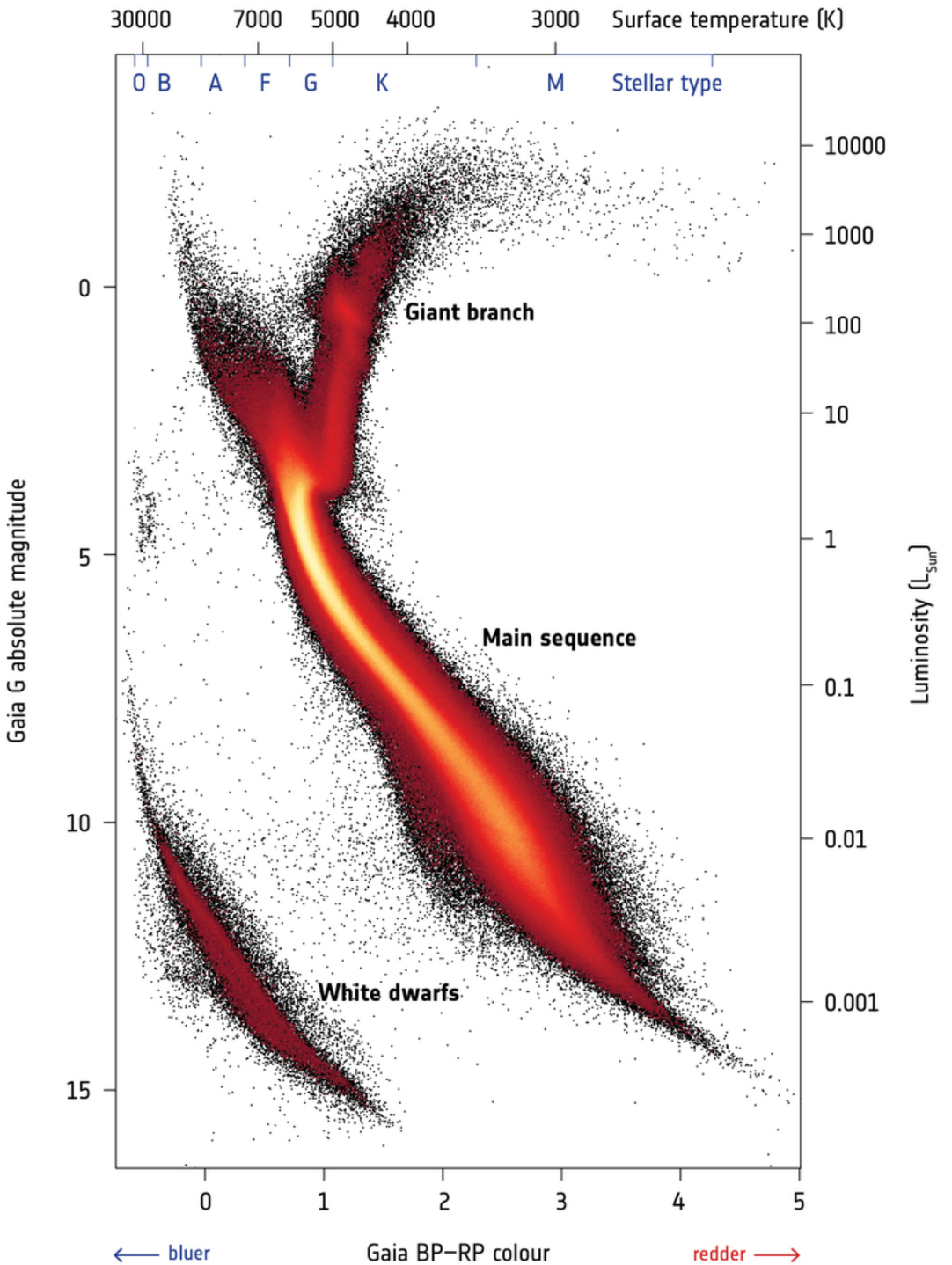
Credit: M. Fouesneau / R. Andrae / C.A.L Bailer-Jones / O. Creevey



GDR2 Science



A&A, 616 (2018) A10



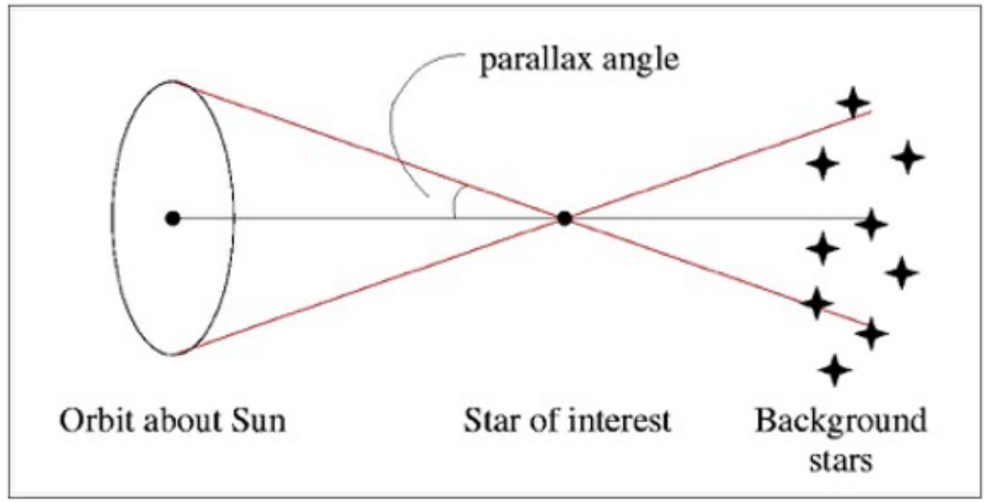
Preparation for after coffee break

- Can all enter the Shuttle (name: hgsfpXX, pw: hgsfp2018)?

Backup

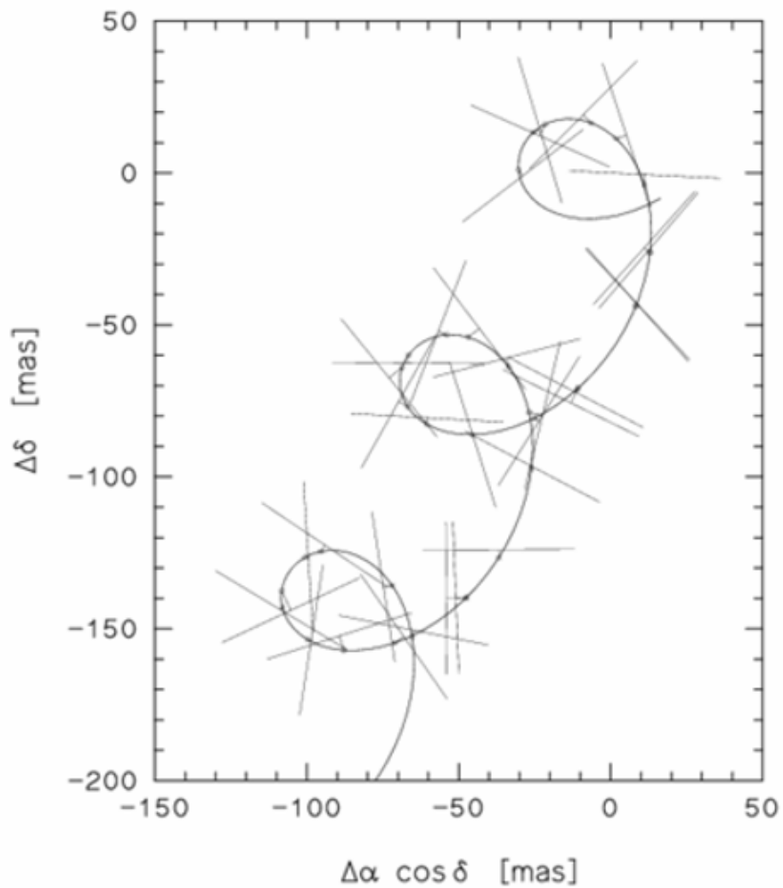
Astrometry

Gaia orbits Sun to create parallax effect



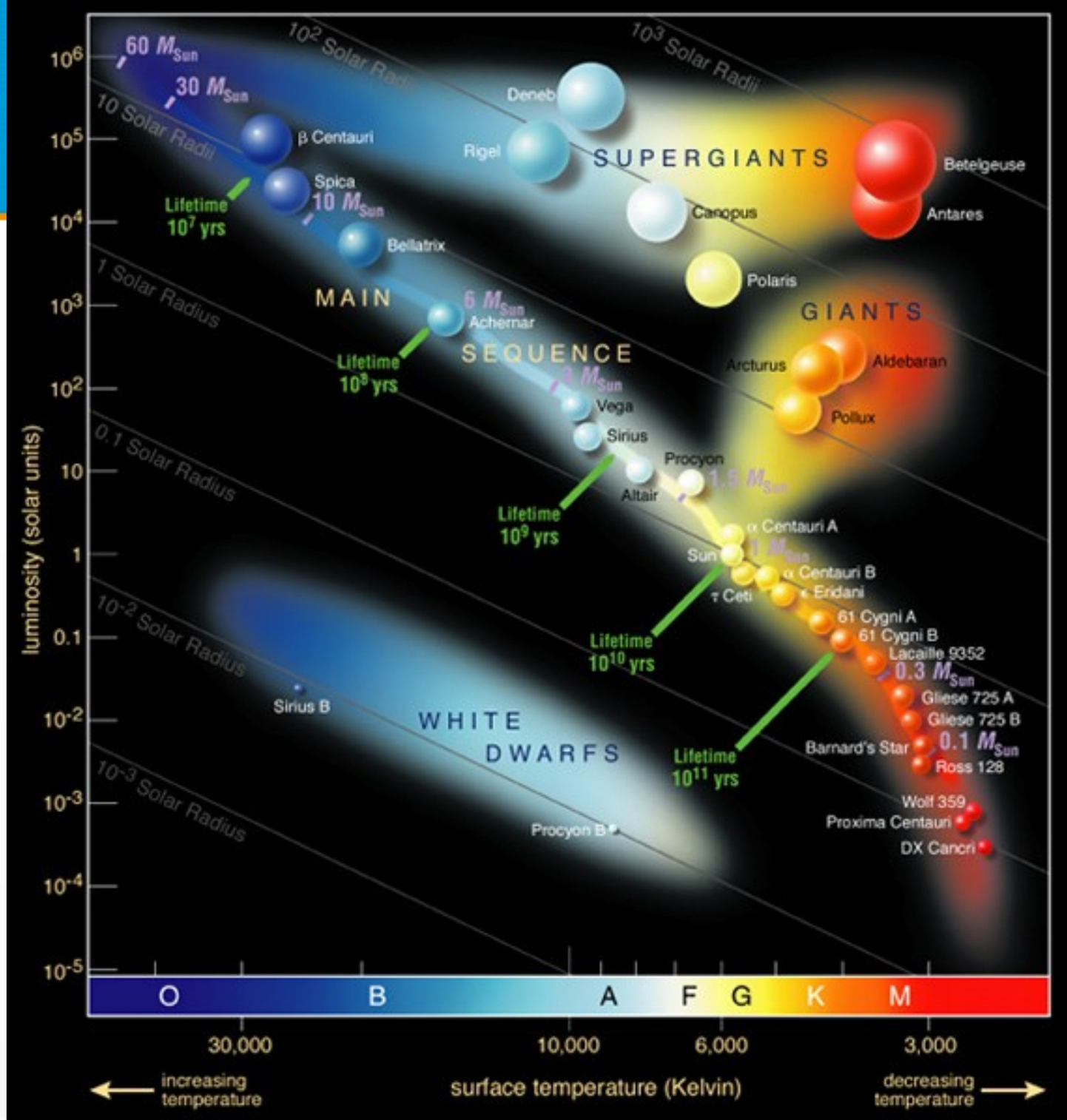
Six dimensions of phase space

- positions: right ascension, declination
- distance (from parallax)
- tangential velocities (from proper motions and parallax)
- radial velocity



Slide: Coryn Bailer-Jones

HRD

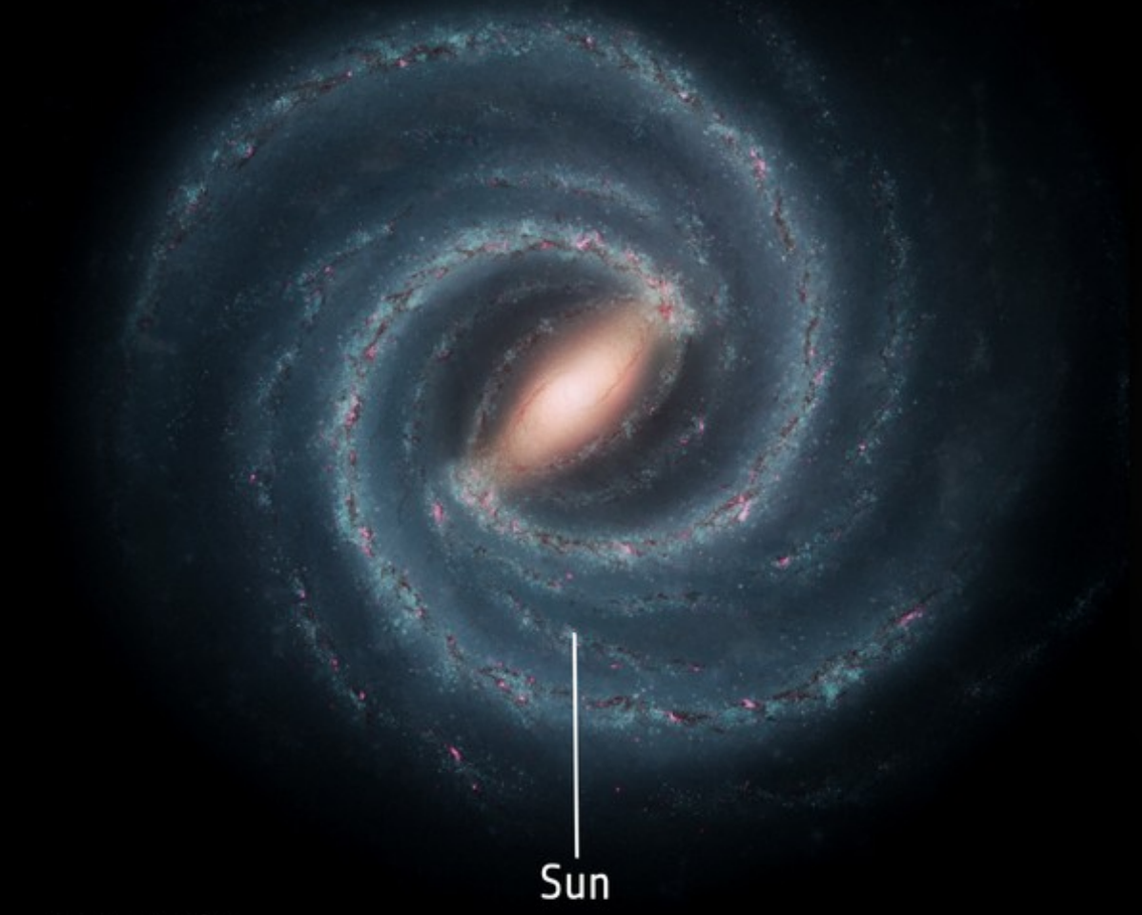


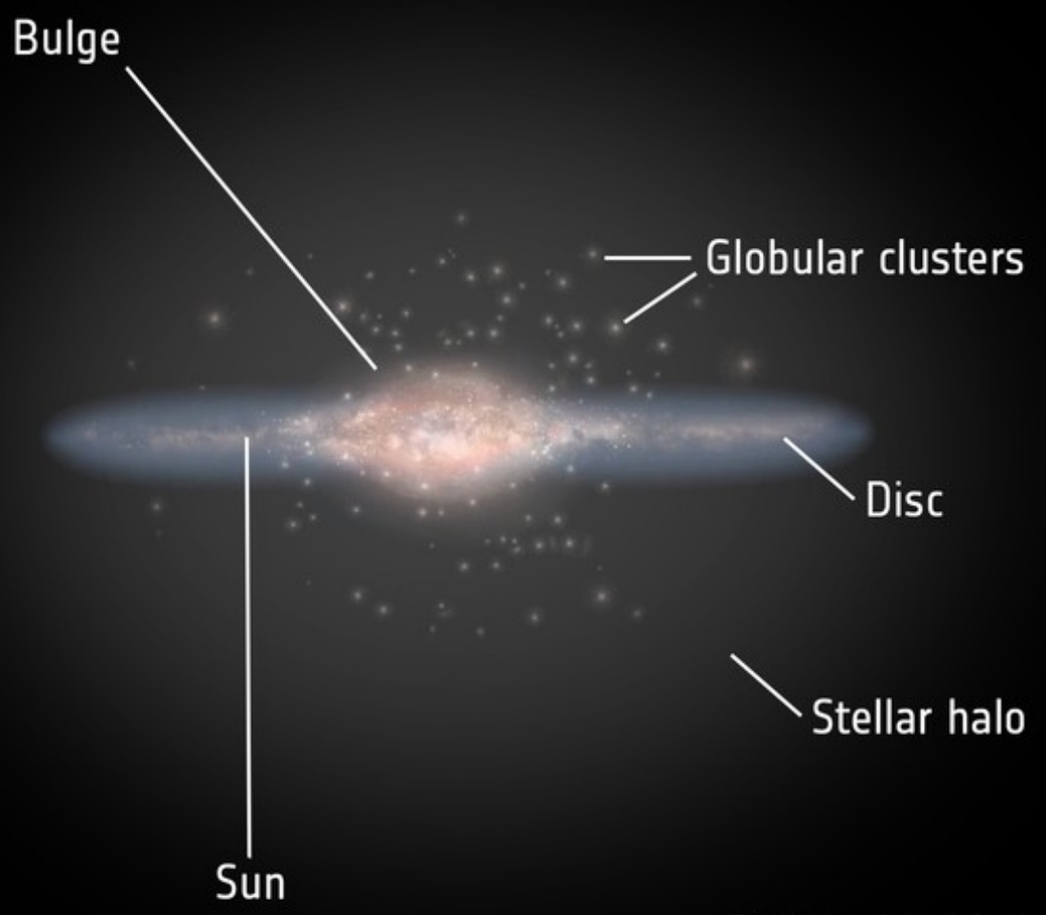
Credit: ESO

MW

→ ANATOMY OF THE MILKY WAY

esa





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European Space Agency