The Gaia mission, Gaia DR3, and science highlights from the Gaia data releases

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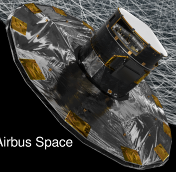
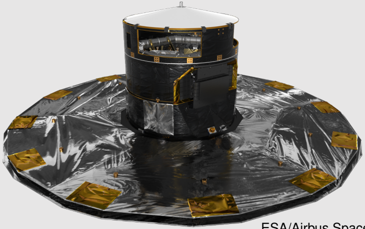

Airbus Space

ESA/Gaia/DPAC

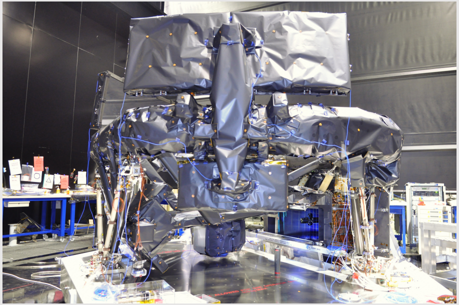
Gaia summary

- Astrometry and spectrophotometry for > 1 billion objects
- Radial velocities for > 100 million objects
- Survey
  - Complete to $G = 20.7$ ($V = 20$–22)
  - Observing programme: autonomous on-board detection and unbiased
  - Quasi-regular time-sampling over 5 years (~ 70 observations)
- Launch December 2013
- Operational at L2 since July 2014

- Gaia end-of-life estimated at early 2025
- Mission extended to end 2022
- With indicative approval to 2025

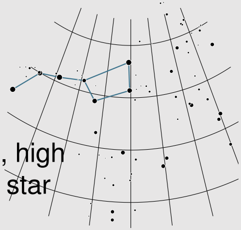


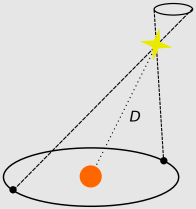
ESA/Airbus Space



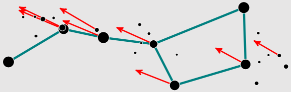
Gaia collects fundamental astronomical data

All-sky, complete, high accuracy star atlas

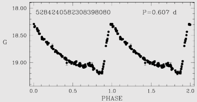


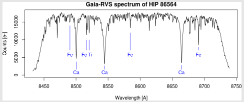


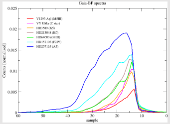
Parallaxes and proper motions

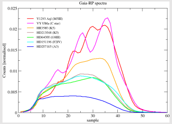


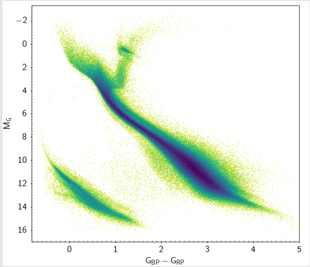
Astrometric, photometric, spectroscopic, radial velocity time series







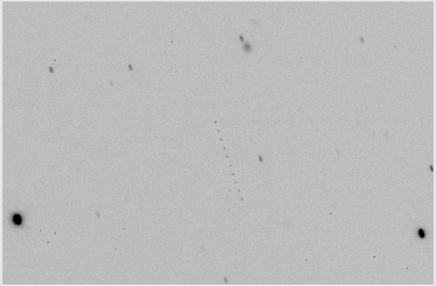




Astrophysical properties

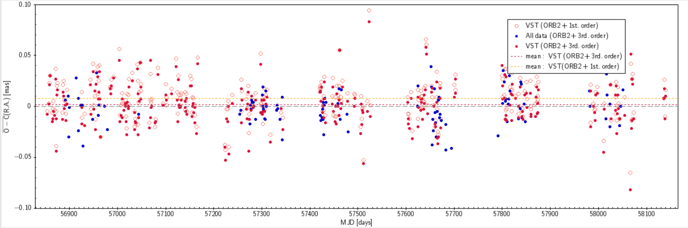
Optical tracking of Gaia

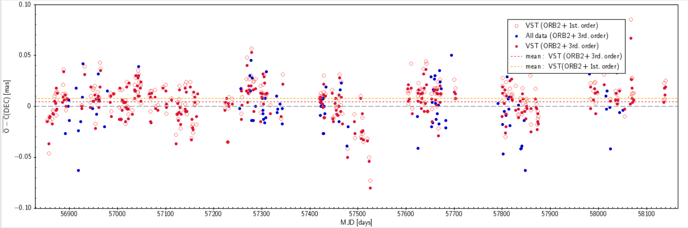
- Gaia orbit should be known to 150 m in position (solar system object parallaxes) and 2.5 mm/s in each velocity axis (aberration correction bright stars)
  - 1 mm/sec upper limit on systematic error!
- 20 mas accurate position of Gaia on the sky needed, every day
- Achieved through combination of ranging, Doppler, Delta-DOR (VLBI), and Ground Based Optical Tracking
  - Observations mainly from the VST (ESO 2013-2022, INAF since Q3 2022) and the Liverpool telescope
- GBOT essential to achieve orbit accuracy when Gaia is at low declination or performing Galactic plane scans



Gaia seen by ESO-VST on April 12 2015: image courtesy ESO/Martin Altmann

Optical tracking of Gaia





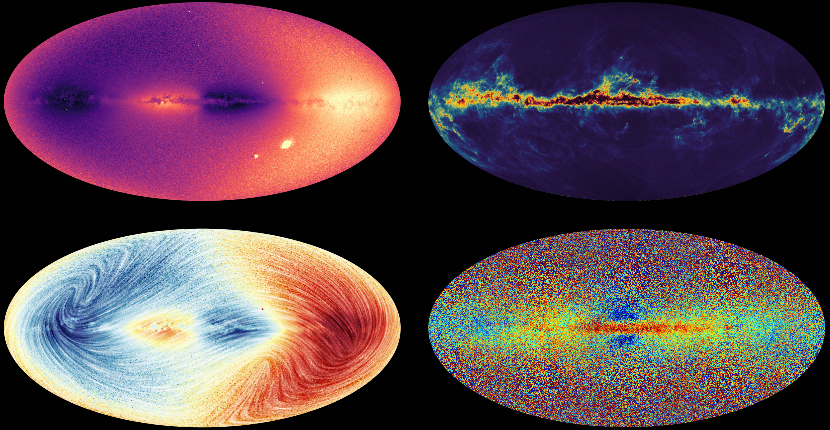
		$\overline{\mathbf{O-C}}$ (mas)	$\sigma_{\overline{\mathbf{O-C}}}$ (mas)
All	α	$+0.8$	19.2
	δ	$+3.3$	19.7
VST	α	$+1.7$	19.7
	δ	$+4.3$	17.2
LT	α	-1.4	17.2
	δ	$+0.5$	24.6

Gaia Data Release 3, June 13 2022

Gaia DPAC

esa

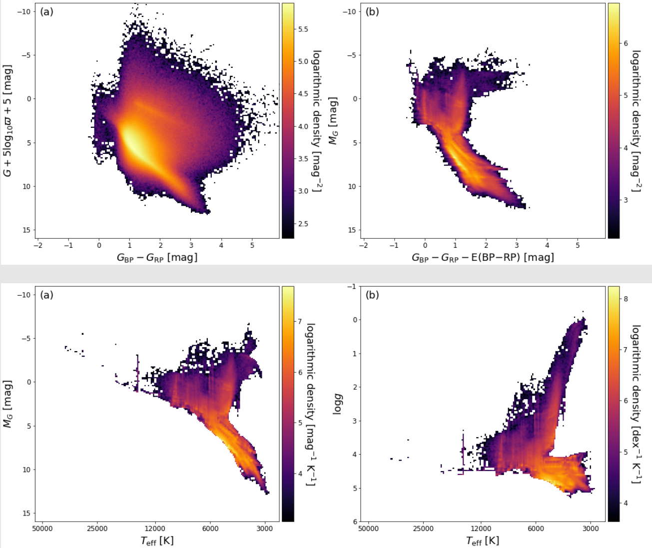
GAIA: EXPLORING THE MULTI-DIMENSIONAL MILKY WAY



www.esa.int

Credit: ESA/Gaia/DPAC

Astrophysical parameters for 471 million stars

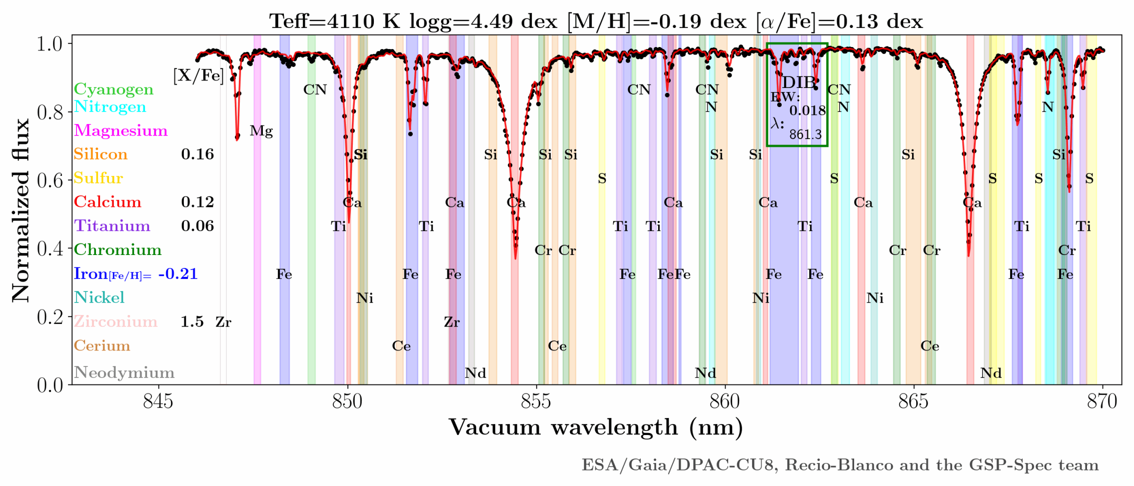


- $T_{\rm eff}$, $\log g$, [M/H], A_G, $E(G_{BP} - G_{RP})$, stellar radius, distances from BP/RP spectra
- mass, age, evolutionary stage (128 million stars)
- $2500 < T_{\rm eff} < 55\,000$ K
- $0 < A_G < 10$
- $G < 19$

See webinar on Gaia DR3 astrophysical parameters

Creevey et al, arXiv:2206.05864; Fouesneau et al, arXiv:2206.05992; Andrae et al, arXiv:2206.06138

Astrophysical parameters and chemical compositions from RVS spectra



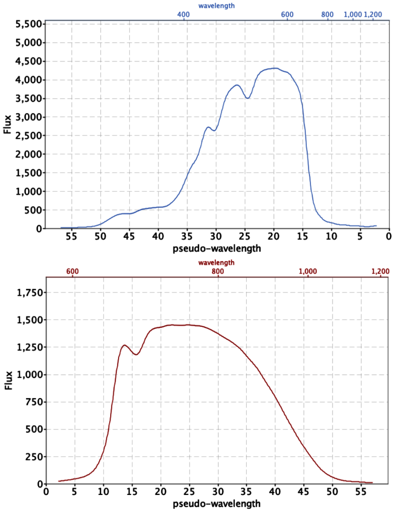
- Astrophysical parameters for 5.6 million sources, DIB parameters for 472 000 sources
- chemical abundances for 2.5 million sources (up to 13 species)
- Spectra for 1 million sources, covering a range of SNR

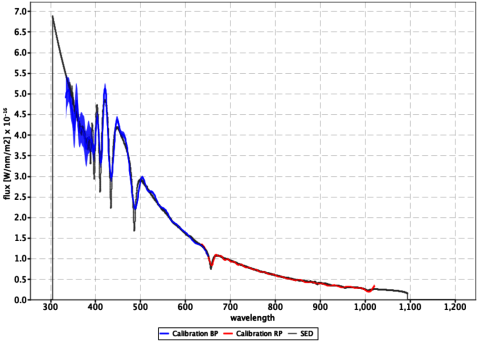
Recio-Blanco et al, arXiv:2206.05541

Low resolution spectra

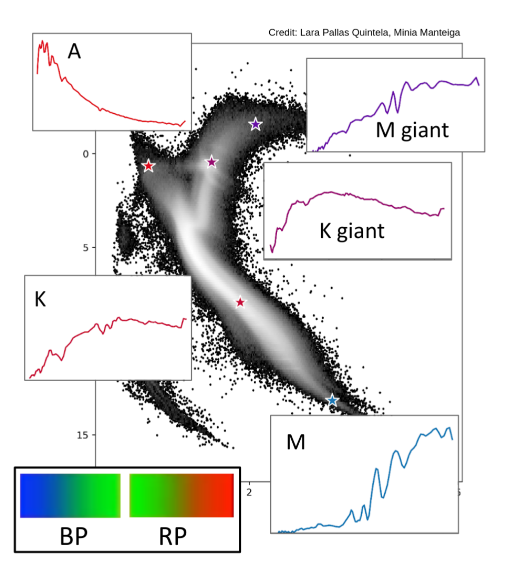
219 million BP/RP spectra, mostly at $G < 17.65$

Tool for working with the spectra: https://gaia-dpci.github.io/GaiaXPy-website/



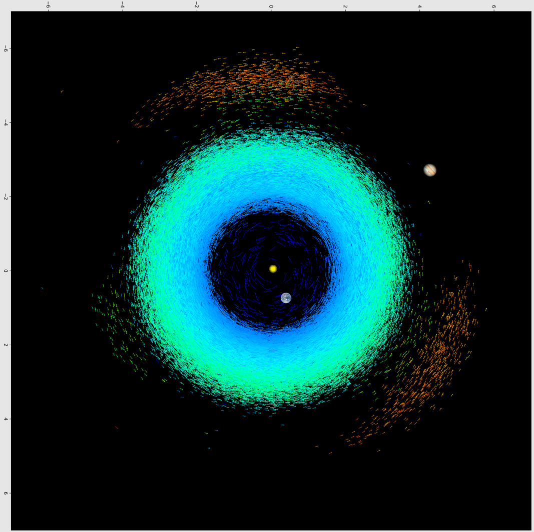


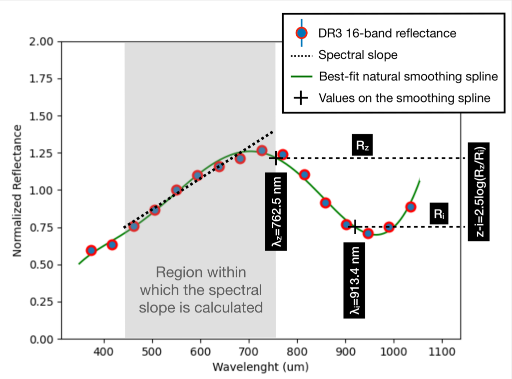
Low resolution spectra



De Angeli et al, arXiv:2206.06143; Montegriffo et al, arXiv:2206.06205

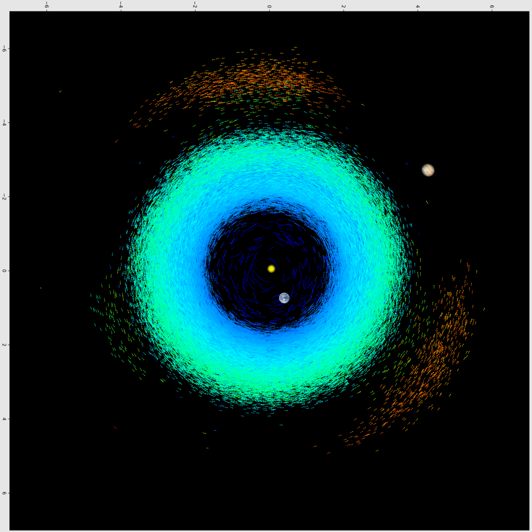
Reflectance spectra of solar system small bodies

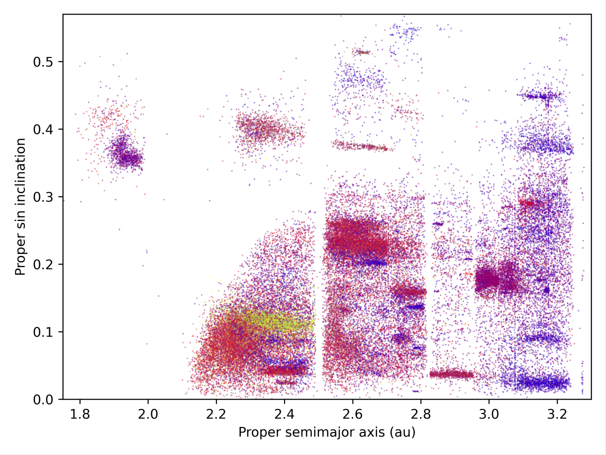




Gaia Collaboration, Gallucio et al; Tanga et al, arXiv:2206.05561

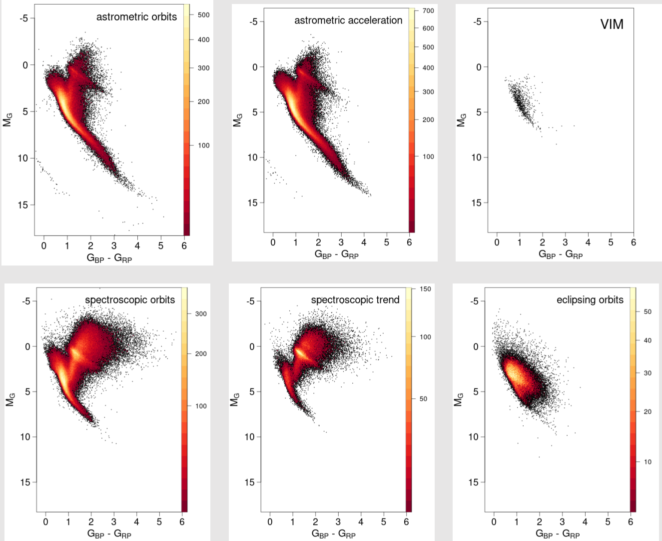
Reflectance spectra of solar system small bodies





Gaia Collaboration, Gallucio et al; Tanga et al, arXiv:2206.05561

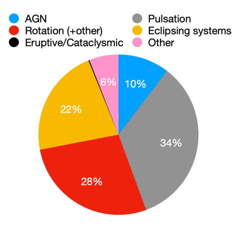
Non-single stars



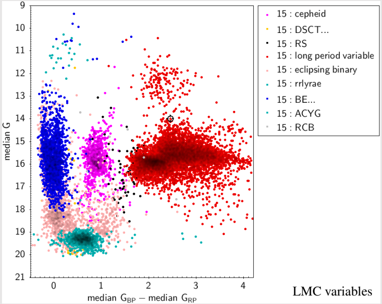
- Catalogue of ∼ 800 000 binary stars
- Astrometric, spectroscopic, eclipsing, combined solutions
  - including sub-stellar companions (dozens of candidate exoplanets, see `https://www.cosmos.esa.int/web/gaia/exoplanets`)

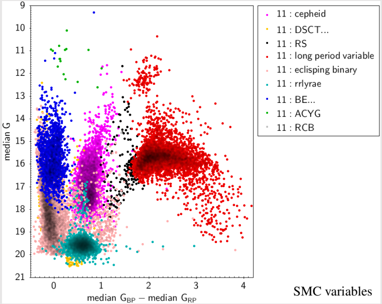
Gaia Collaboration, Arenou et al, arXiv:2206.05595

Variable sources



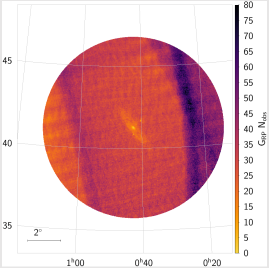
- 10.5 million variable sources with light curves
- 24 variability types
- DPAC papers: see list at https://www.cosmos.esa.int/web/gaia/dr3-papers



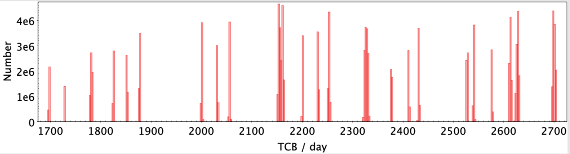


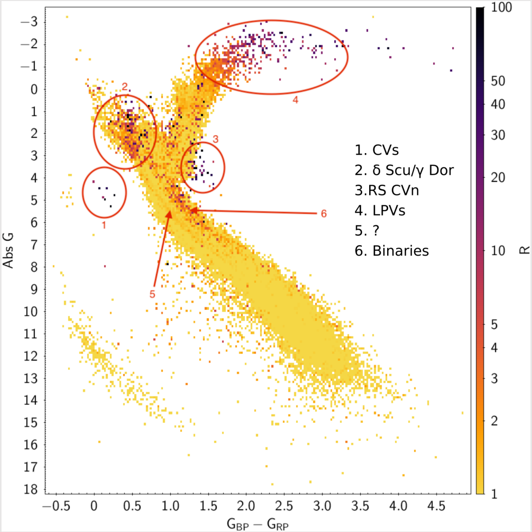
Gaia Andromeda Photometric Survey (GAPS)

- G/ G_{BP}/ G_{RP} time series for all 1.3 million sources in 5.5° radius around M31
- Well populated Milky Way CMD, M31 sources



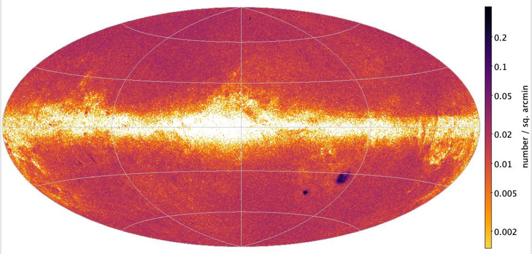
- Diversity of scanning conditions
- Validate searches for variables using `gaia_source` fields
- Taster for Gaia DR4



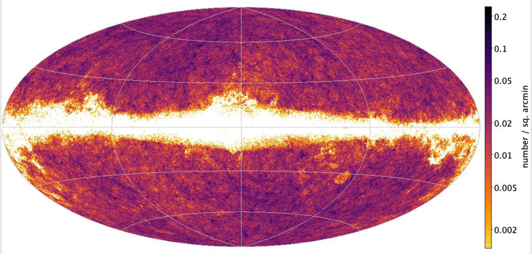


The extragalactic content

Quasar purer candidates: 1.9 million, 95% pure



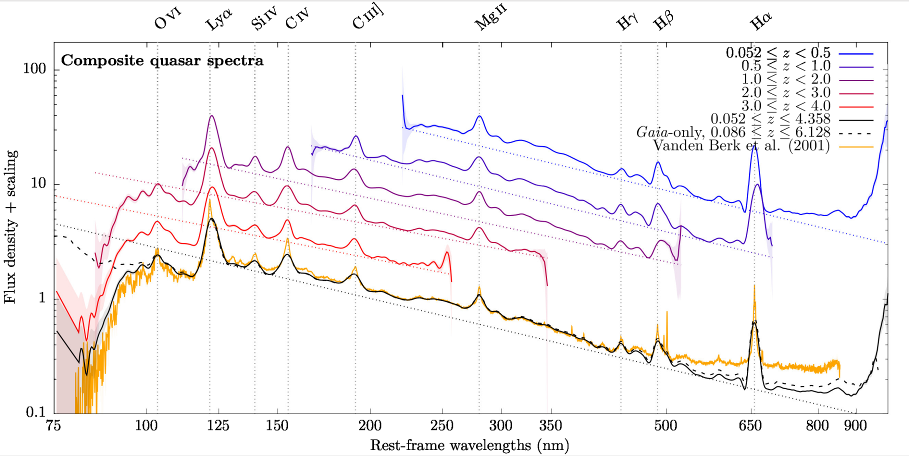
Galaxies purer candidates: 2.9 million, 94% pure



- Various Gaia data products and algorithms can be used to find galaxies and quasars
- BP/RP spectra and astrometry, surface brightness profiles to find galaxies and host galaxies for quasars
- Large set of ‘candidates’: objects that could be galaxies or quasars

Gaia Collaboration, Bailer-Jones et al, arXiv:2206.05681

The extragalactic content

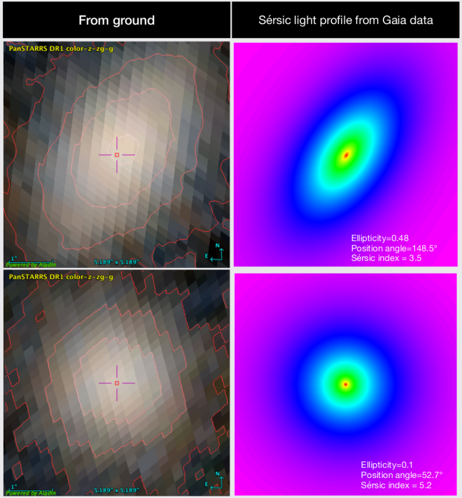


- Gaia observes QSOs from various epochs in the Universe
- ‘Composite spectrum’ from the individual observations as a kind of ‘reference’

Gaia Collaboration, Bailer-Jones et al, arXiv:2206.05681

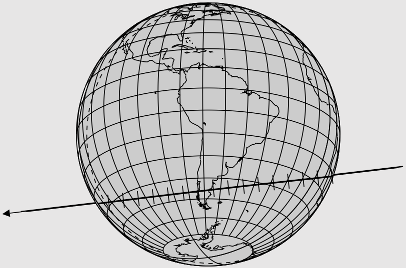
The extragalactic content

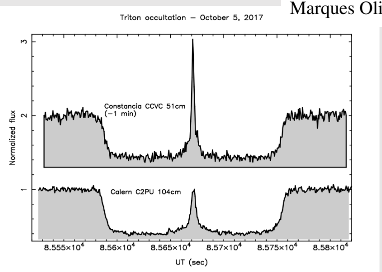
- Use Gaia data to give us an idea of what galaxies look like
- Synthetic image from fitting parameters to the Gaia light profiles.
- Comparing to images taken from Earth, we can see more details in the Gaia 'images'.
- There are almost 1 million such 'images' in DR3



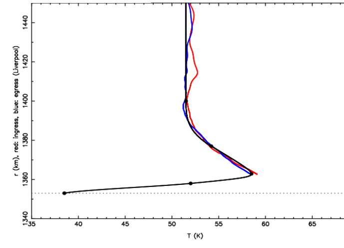
Gaia Collaboration, Bailer-Jones et al, arXiv:2206.05681

Gaia's impact on solar system exploration

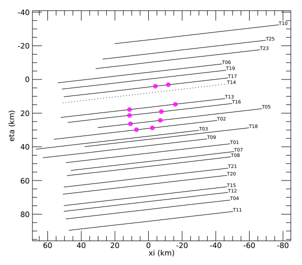




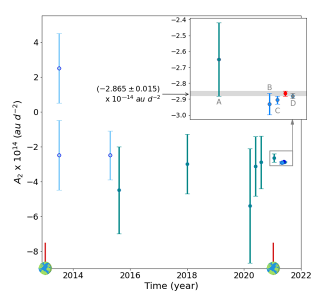
Marques Oliveira et al 2018/2019



Buie et al 2020, AJ, arXiv:2001.00125

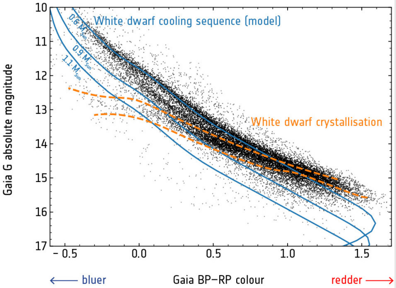


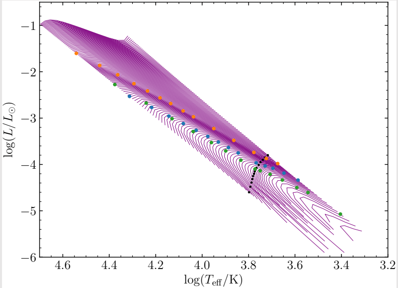
NASA/JHU-APL/SWRI



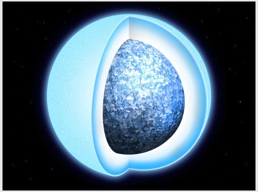
Apophis Yarkovsky acceleration
P. Tanga, Gaia Image of the Week 2021.03.29

White dwarf interiors



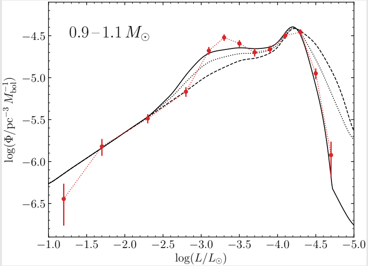


Tremblay et al., 2019, Nature 565, 203

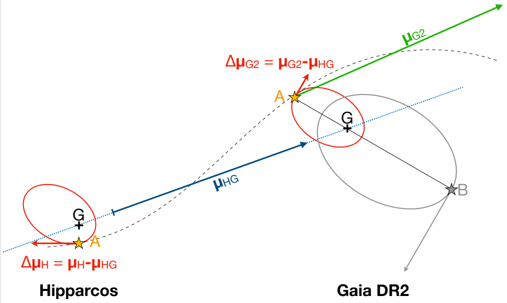


- Clear evidence for crystallization of C/O WD interiors
  - mass dependent pile-up of WDs along cooling track
- Detailed luminosity function modelling suggests:
  - ^{16}O sedimentation
  - ^{22}Ne sedimentation, perhaps through clusters of ^{22}Ne in liquid C/O plasma

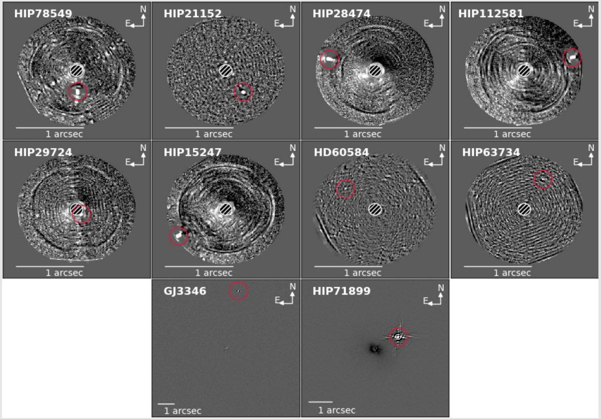
  Cheng et al, arXiv:1905.12710; Bauer et al, arXiv:2009.04025



Improving direct imaging efficiency

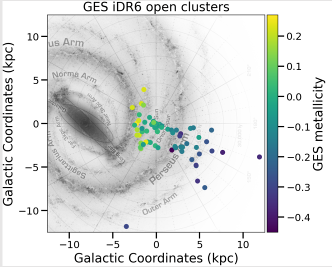


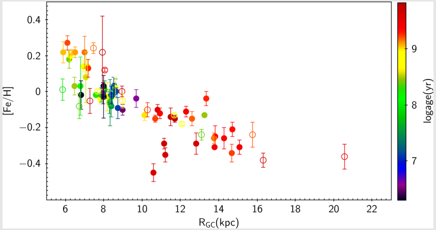
Kervella et al (2019, 2022)
Brandt (2018, 2021)
Snellen & Brown (2018)

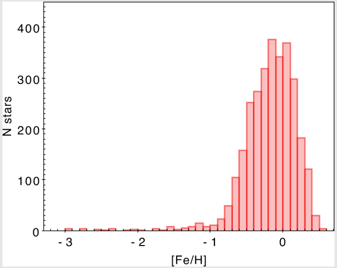


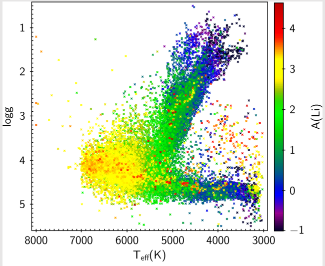
Bonavita et al (2022)

Gaia-ESO survey







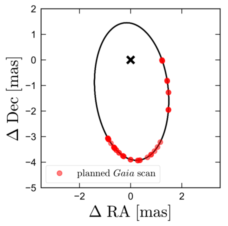


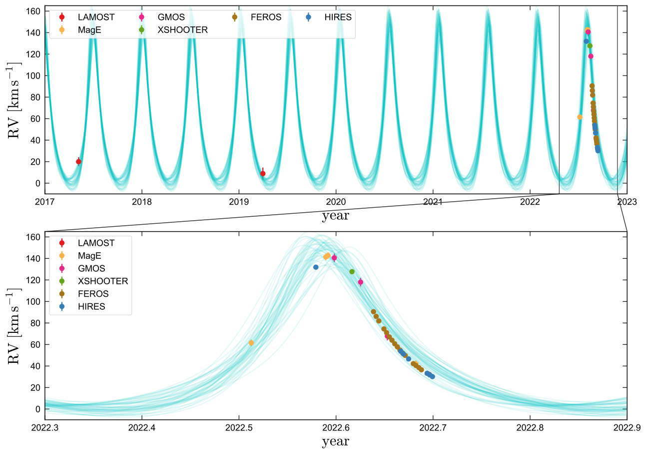
- Illustrations of DR5 and science potential in Randich et al. (2022)
- Interesting features on open cluster [Fe/H] gradients vs. age
- Good coverage in [Fe/H] of Milky Way stars in UVES parallel sample
- Lithium measurements with good coverage HR diagram

Gaia BH1

- BH candidate identified through high value of $4\pi/(P^2G)(a_0/\varpi)^3$
- Astrometric solution was considered doubtful by DPAC
  - Period three times Gaia spin axis precession period, high σ_{a_0}, σ_ϖ
- RV follow-up validates Gaia solution
  - RV curve alone sets lower limit of 5 $M_\odot$ on M_2
- $9.8 \pm 0.2\ M_\odot$ black hole orbited by solar type star!
- Independently discovered by Chakrabarti et al (arXiv:2210.05003)

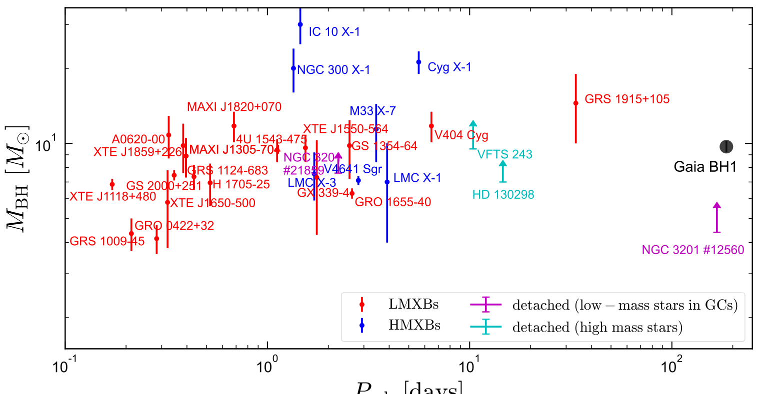
$$P_{\rm orb} = 185.63 \pm 0.05 \text{ d}$$
$$a = 1.41 \pm 0.01 \text{ au}$$
$$e = 0.454 \pm 0.005$$





El Badry et al., arXiv:2209.06833

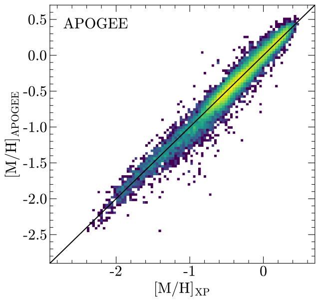
Gaia BH1

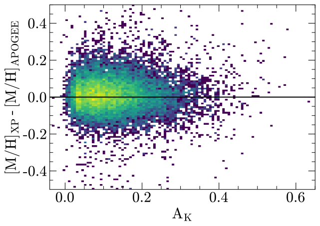


El Badry et al., arXiv:2209.06833

- Unique system among the known black holes: solar type star on wide orbit around dormant BH
- Evolutionary path to make such systems is unclear
- Gaia DR4 may uncover dozens more cases

The poor old heart of the Milky Way

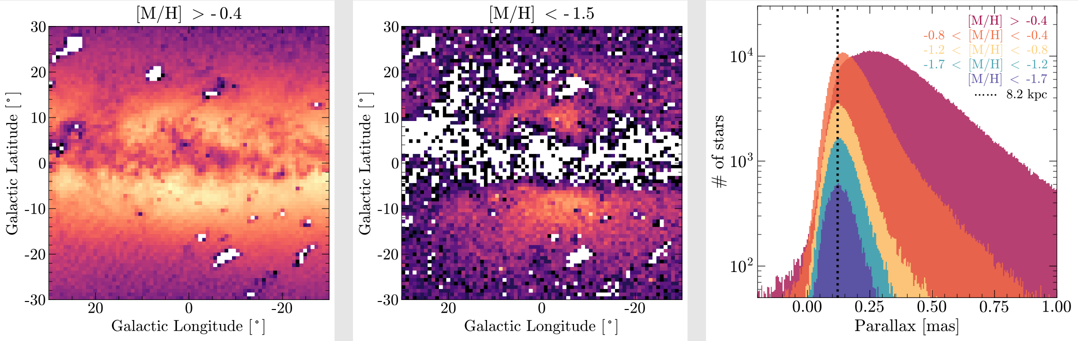




- Metallicity estimates from XP spectra for bright ($G_{BP} < 15.5$) giants
  - Machine learning (XGBoost) trained on APOGEE data
  - XP spectra coefficients, synthetic colours from XP, AllWISE
  - Validated against GALAH, LAMOST, GSPSpec (Gaia RVS)
- XP spectra contain robust metallicity information!
- See also Belokurov et al. arXiv:2208.11135, Lucey et al. arXiv:2206.08299

Rix et al. arXiv:2209.13992

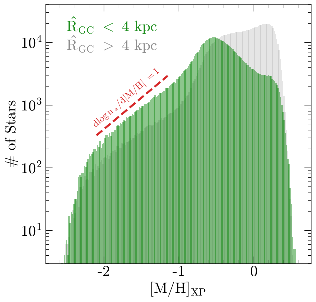
The poor old heart of the Milky Way

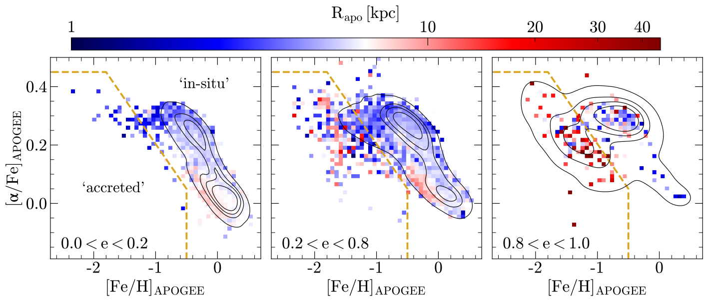


Rix et al. arXiv:2209.13992

- Sample of giants in 30 degree radius around galactic centre, $\varpi < 1$
- Metal poor population very centrally concentrated: $\sigma_{r_{GC}} \sim 2.7$ kpc
- Mass in stars at [M/H] < -1.5 at least $5 \times 10^7\ M_\odot$, probably more than $10^8\ M_\odot$

The poor old heart of the Milky Way





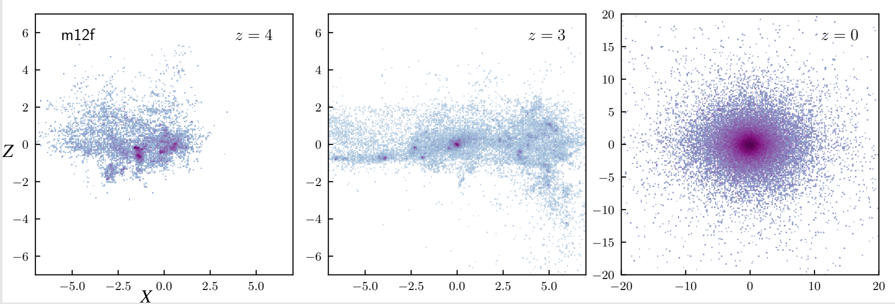
Rix et al. arXiv:2209.13992

Analysis of orbits and abundances of population near Galactic centre

- Metal poor population dominated by stars on small-apocentre orbits
- Stars with large eccentricities and apocentres were accreted (Gaia-Enceladus)
- Metal poor population is rich in α elements
  - points to origin of the stars in massive, rapidly self-enriching, object

The poor old heart of the Milky Way

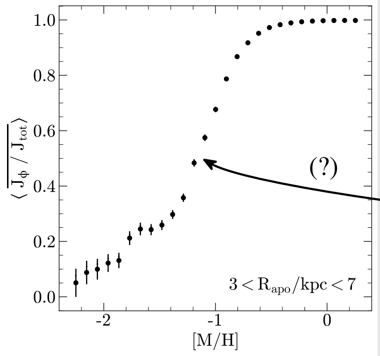
Young stars — Same stars at $z = 0$



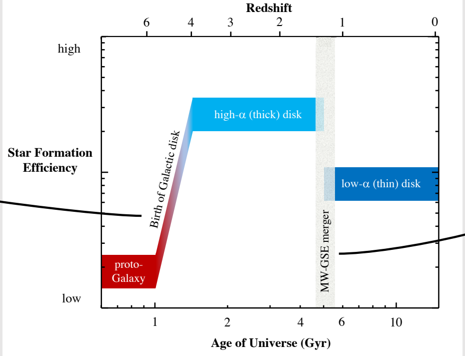
Belokurov & Kravtsov, arXiv:2203.04980

- Metal poor population near Galactic centre represents the proto-galaxy
- Formed at $\tau \gtrsim 12.5$ Gyr ago, or $z \gtrsim 5$
  - formation was before onset of thick disk formation (see Xiang & Rix, 2022, Nature)
  - probably the same object as the proposed ancient merger Heracles/Kraken/Koala
- The same population was found recently in the volume closer to the sun (Belokurov & Kravtsov, arXiv:2203.04980; Conroy et al., arXiv:2204.02989)

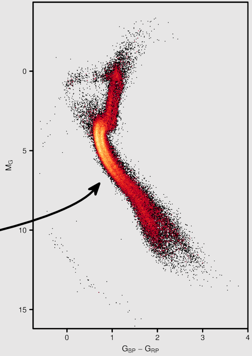
Milky Way formation picture



Rix et al., arXiv:2209.13992

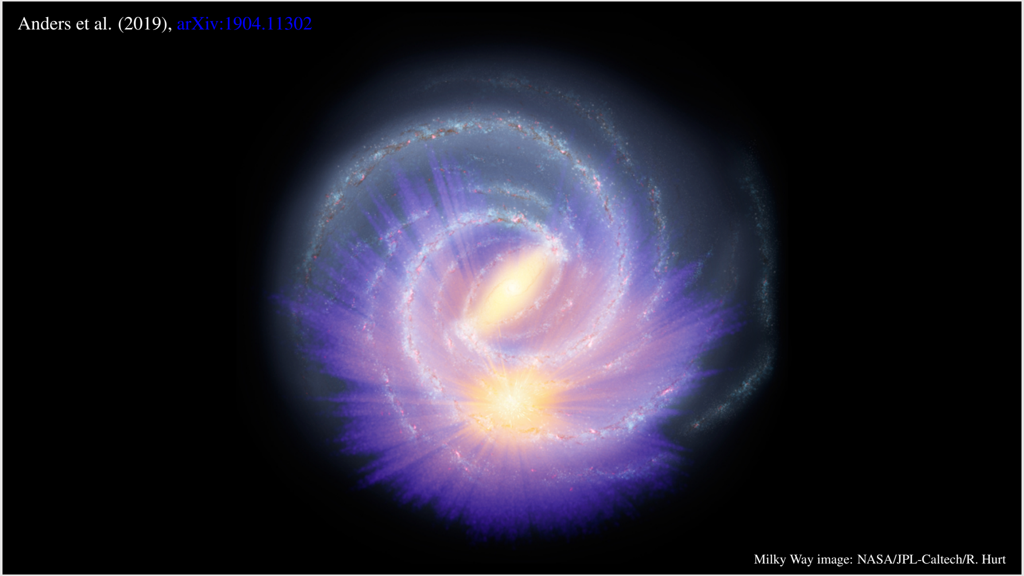


Conroy et al., arXiv:2204.02989

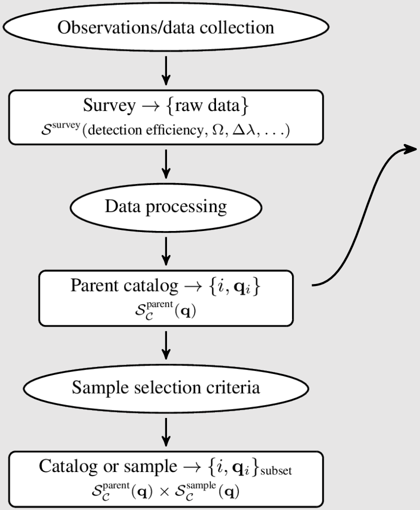


Gaia Collaboration, Babusiaux et al. 2018

GaiaUnlimited: the Gaia survey selection function



GaiaUnlimited: the Gaia survey selection function



$\mathcal{S}_{\mathcal{C}}(\boldsymbol{q}_i)$: probability that source i with observables $\boldsymbol{q}_i$ is contained in catalogue or sample $\mathcal{C}$

GaiaUnlimited will provide:

- Selection function of parent Gaia catalogue
  - all sources with $\boldsymbol{q}_i = \{\alpha_i, \delta_i, G_i, \ldots\}$
- Selection function for subsets
  - 5-parameter astrometry, radial velocity, RUWE $< x$, ...
- Selection functions for combinations of Gaia and other surveys
  - Photometric and spectroscopic surveys
- Examples of specific Gaia selection functions
  - For example: binaries, Cepheid variables

References: Rix et al., 2021; Cantat-Gaudin et al., 2022

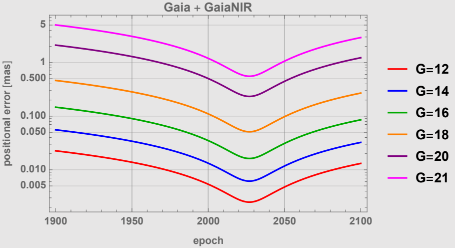
Web: https://github.com/gaia-unlimited/gaiaunlimited; https://gaia-unlimited.org/

GaiaNIR proposal

ESA Voyage 2050 Senior Committee recommendation: Focus on ‘Characterisation of Temperate Exoplanets’ and ‘Galactic Ecosystem with Astrometry in the Near-infrared’

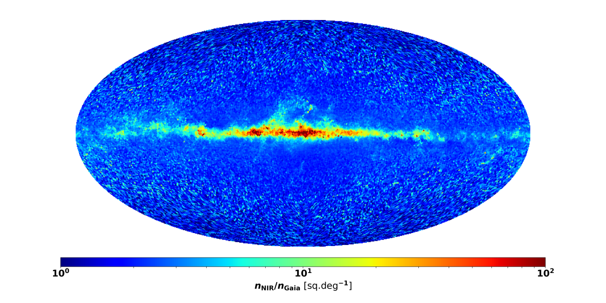
- GaiaNIR: Gaia-type mission covering optical to near-IR
  - overlap with Gaia wavelength range; long time baseline proper motions accurate to better than few μas yr^{-1}
  - dense phase space sampling of obscured regions
  - direct observations of link between star formation and Milky Way structure and dynamics
  - synergy with SDSS-V, Roman telescope, Euclid, . . .
  - reference maintenance
- Challenges
  - TDI/drift-scanning in the near-infrared
  - if not possible, how to realize a revolving scanning mission without TDI-capable detectors
- See https://ui.adsabs.harvard.edu/abs/2021ExA...tmp...16H

NASA/ESA/CSA/STScI; J. DePasquale (STScI), A.M. Koekemoer (STScI), A. Pagan (STScI)



Hobbs et al. 2021

What will GaiaNIR observe?



- Star count ratio between GaiaNIR and Gaia gives 5 times more stars for a H-band limit of 20th mag and 6 times more stars for a K-band limit of 20th mag
  - About 10 or 12 billion stars for H or K-band cut-offs.
- The star count ratio in the disk is uncertain due the extinction model used (older models give a ratio of 3 instead of 5)
- This uncertainty is a key science case in itself that cannot be resolved by Gaia alone

GaiaNIR detector status

Options for TDI operation are Gaia-like CCDs with wavelength range extended to $\sim$ 1400–1800 nm, or Avalanche Photodiodes (APDs) operating over range 800–2500 nm (up to 3500 nm)

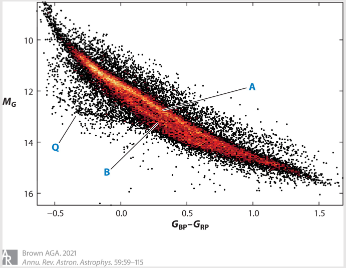
- For Gaia CCDs we reproduce the nominal Gaia accuracy
- For HgCdTe linear avalanche photodiode arrays (APDs) we get better astrometric performance for several reasons
  - Reverting back to optimal scanning law parameters (e.g. sun aspect angle, scan rate, etc.)
  - Broader wavelength range more than compensates for longer observing wavelength
  - Lower read noise and lower background noise are game changers for astrometry!
- Instead of going to longer (i.e. to 3500 nm) wavelengths it may better to go fainter
- The combinations of these improvements results in a new mission that can outperform Gaia!
- Radial velocity spectrograph possible with APD detectors and slow scan rate for part of the mission
  - could give a revolutionary deep all-sky astrometric and RV/chemistry survey!

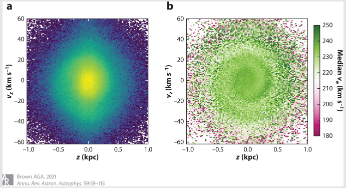
Community building to start soon: get in touch if you want to contribute

More detailed presentation: https://doi.org/10.5281/zenodo.7068309

The impact of Gaia

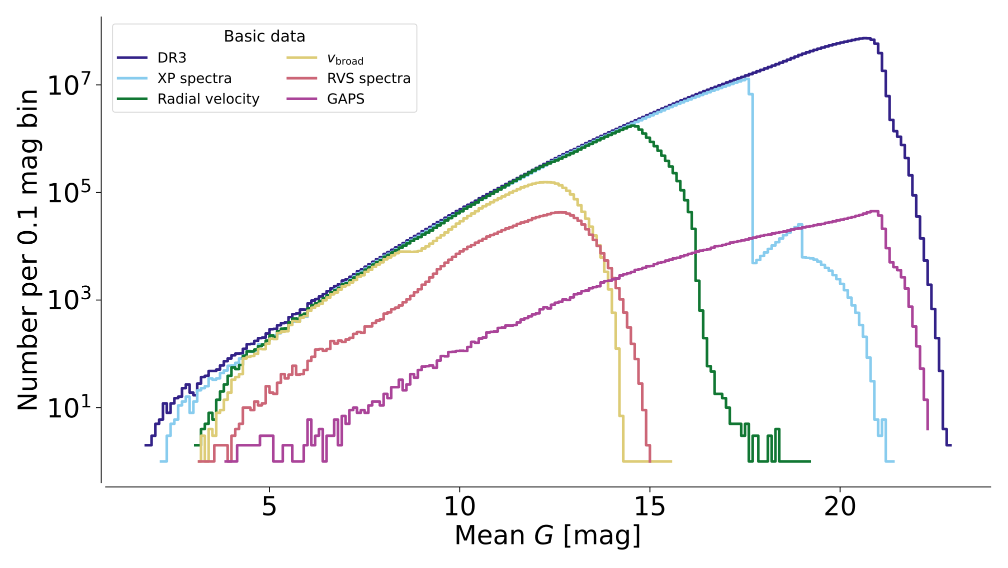
- Gaia is revolutionizing astronomy through a vast set of **easily available fundamental data**
- Definitive demonstration of the **power of an all-sky, high spatial resolution, high astrometric and photometric accuracy survey**
- **Dense sampling of Galactic phase space** at high astrometric,photometric,and radial velocity precisions
  - uncovering subtle features in phase space and the observational HR diagram
  - enabling Galactoseismology
- The celestial reference frame provided by **Gaia enables the accurate astrometric and photometric calibration of past, current, and future sky surveys**
- Accurate star map with parallaxes and proper motions allows for **vast improvements in stellar occultation campaigns**
  - shape measurements of Kuiper-belt objects at < 1 km resolution, limits on atmospheres
  - enhanced spacecraft navigation and mission planning



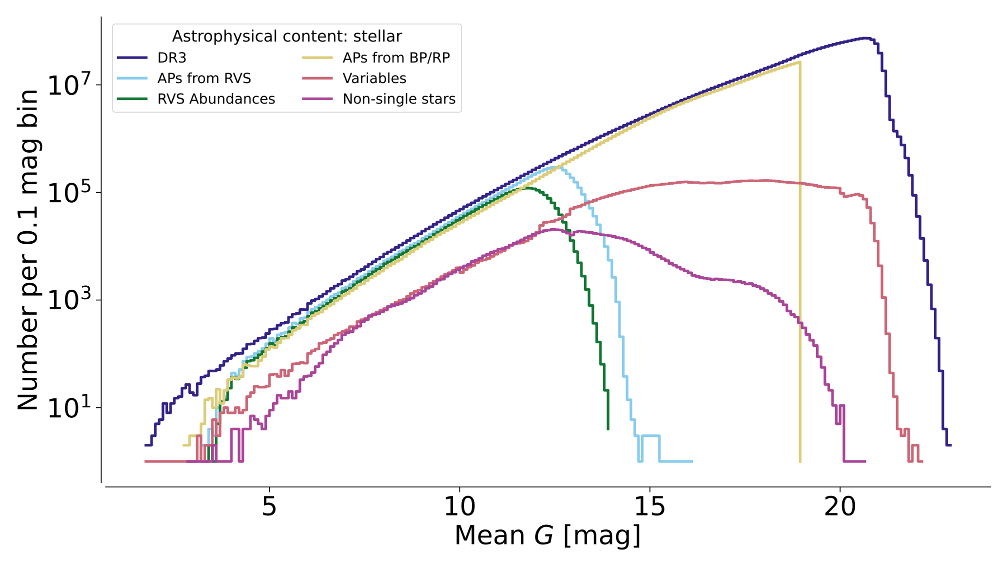


Gaia data is brought to you by

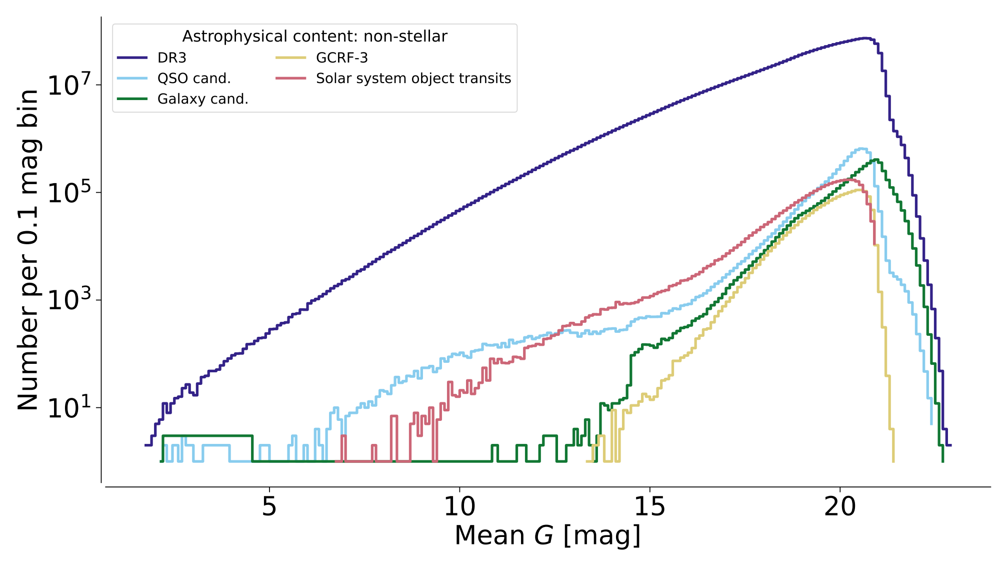
Magnitude distribution Gaia DR3 of data products



Magnitude distribution Gaia DR3 of data products



Magnitude distribution Gaia DR3 of data products



Be aware of...

- **Gaia DR3 papers and Documentation**
- Overview pages: https://www.cosmos.esa.int/web/gaia/data-release-3
- DR3 sample selection choices
  - magnitude distribution and limits, sky coverage, specifically selected lists of sources
- Caveats on data quality
- Data quality indicators $\longrightarrow$ there are many!
- Corrections/calibrations not included in the Gaia DR3 archive (see the papers for details)
  - Calibrations of radial velocities for specific types of stars
  - Calibrations of astrophysical parameters
- Multi-dimensional data (time series, spectra, MCMC samples) accessible via DataLink interface
- Software tools
- Auxiliary data not included in archive
- Pre-computed cross-matches to large surveys

Resources

- Gaia DR3 papers: https://www.cosmos.esa.int/web/gaia/dr3-papers
  - Read at least the overview (Gaia Collaboration, Vallenari et al) and validation (Babusiaux et al) papers
- Gaia DR3 documentation https://gea.esac.esa.int/archive/documentation/GDR3/index.html
  - See executive summary for compact overview of contents and papers, and archive table index
  - See chapter 20 for detailed data model
- Auxiliary data: https://www.cosmos.esa.int/web/gaia/dr3-auxiliary-data
- Software tools: https://www.cosmos.esa.int/web/gaia/dr3-code
- Known issues arising after publication of release: https://www.cosmos.esa.int/web/gaia/dr3-known-issues
- Manipulate BP/RP spectra and calculate synthetic photometry: https://gaia-dpci.github.io/GaiaXPy-website/
- Tutorial on accessing DataLink products: https://www.cosmos.esa.int/web/gaia-users/archive/datalink-products
- Credit and citation instructions: https://gea.esac.esa.int/archive/documentation/GDR3/Miscellaneous/sec_credit_and_citation_instructions/