The GaiaUnlimited Project

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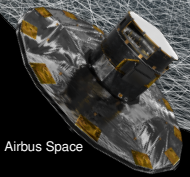
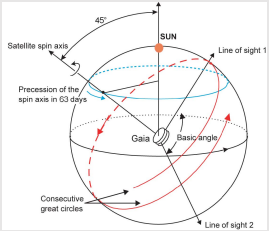
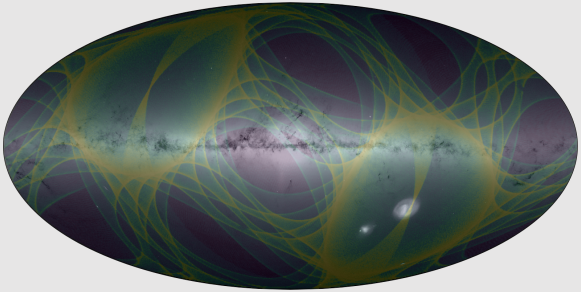


Airbus Space

ESA/Gaia/DPAC

Gaia selection function elements





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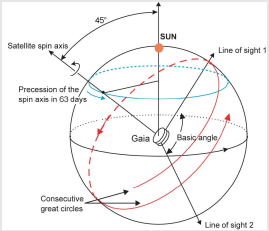
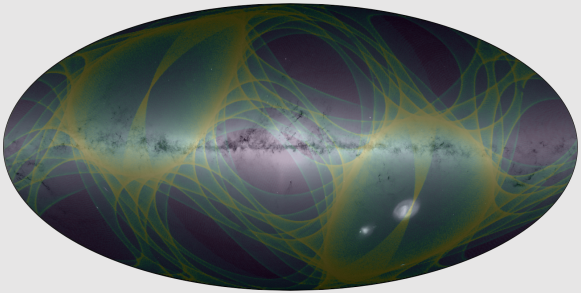
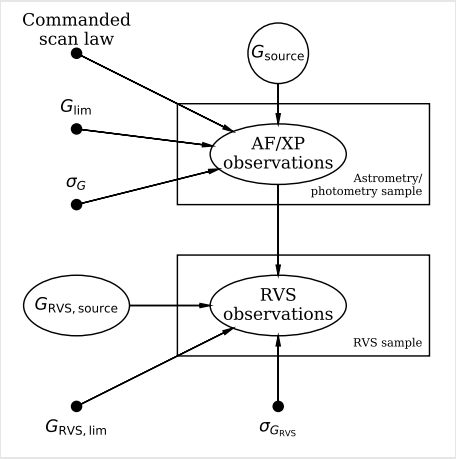
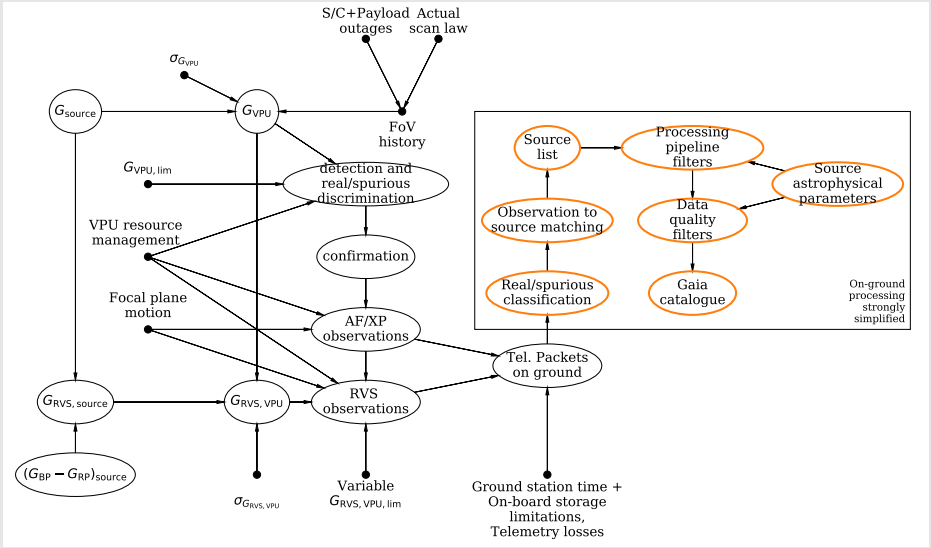


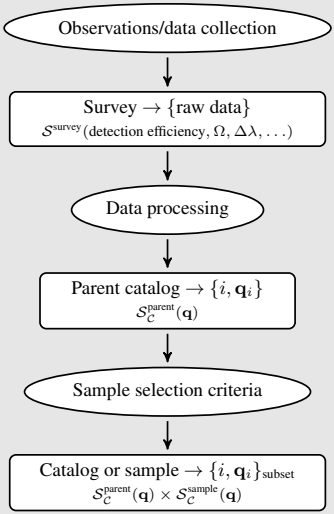




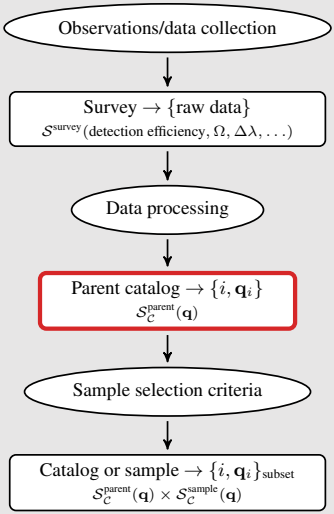
Gaia selection function elements



GaiaUnlimited approach to selection function



GaiaUnlimited approach to selection function



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

GaiaUnlimited provides:

- 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, full photometry, radial velocity, RUWE $< x$, ...
- Selection functions for Gaia combined with other surveys
  - Photometric and spectroscopic surveys (e.g. AllWISE, APOGEE)
- Examples of specific Gaia selection functions
  - For example: binaries, Red Clump stars, metal poor Red Giants
- Basic principles in Rix et al. (2022), arXiv:2106.07653

Availability of tools and data

- Website: https:/gaia-unlimited.org
- Github repository: https://github.com/gaia-unlimited
  - Code and notebooks with worked examples
- Documentation: https://gaiaunlimited.readthedocs.io
  - Including tutorials and links to worked examples

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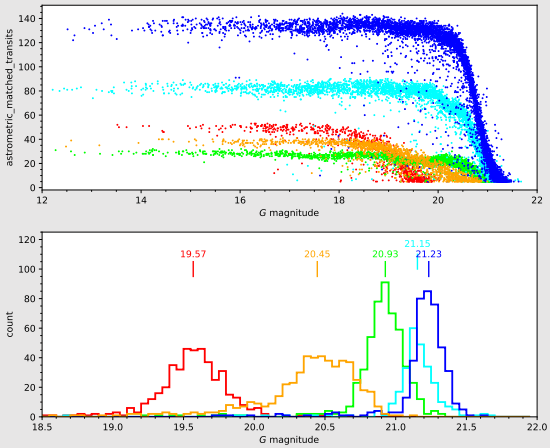
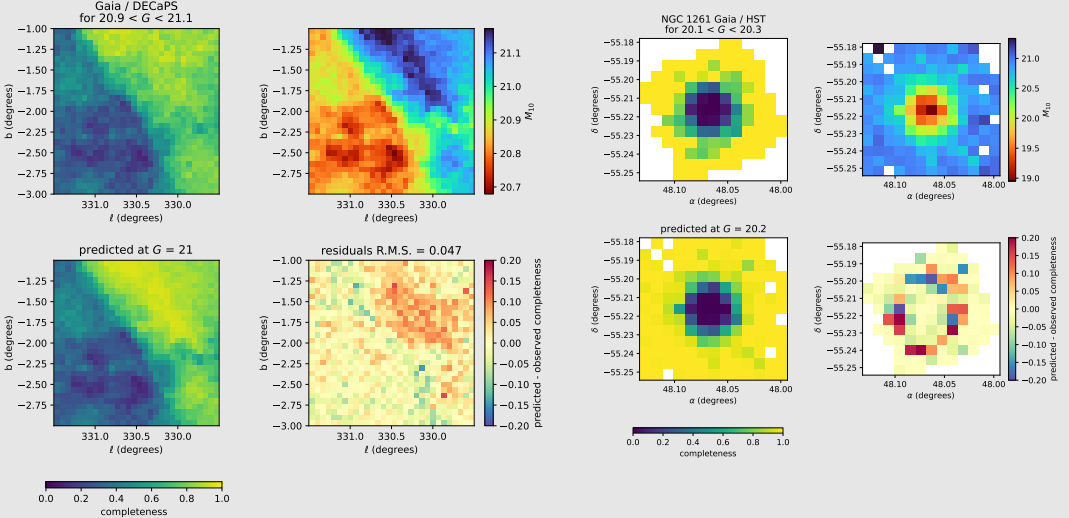
Empirical model of parent survey selection function



- M10: median magnitude of sources with less than 10 `astrometric_matched_transits`
- Correlates well with survey completeness level
- Basis for emprical model of selection function $\mathcal{S}(\ell, b, G)$
- Calibrated on DECaPS survey of Galactic plane
- Cantat-Gaudin et al. (2023), arXiv:2208.09335

Empirical model of parent survey selection function



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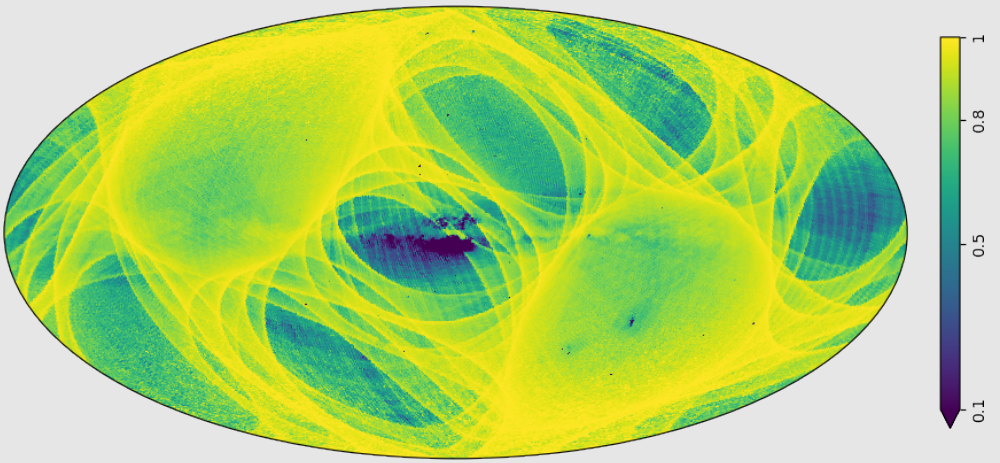

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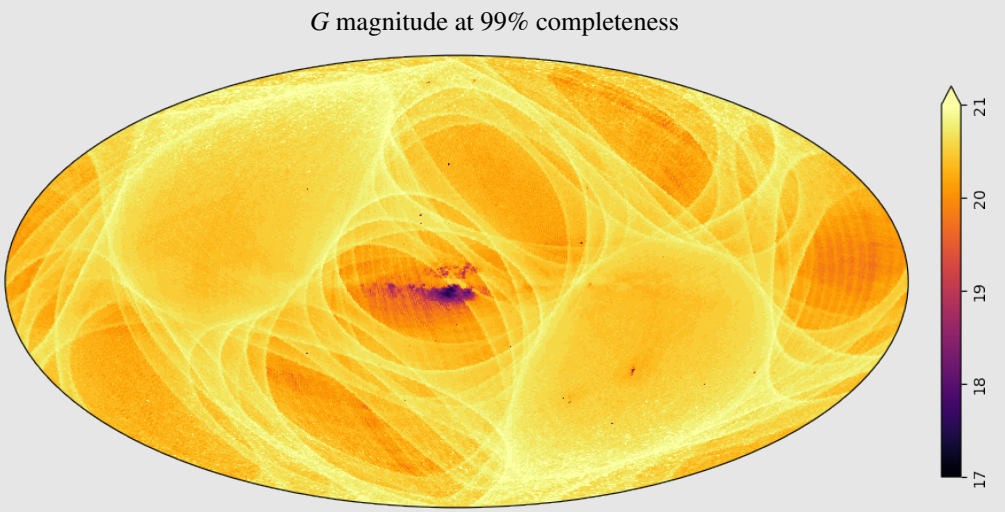
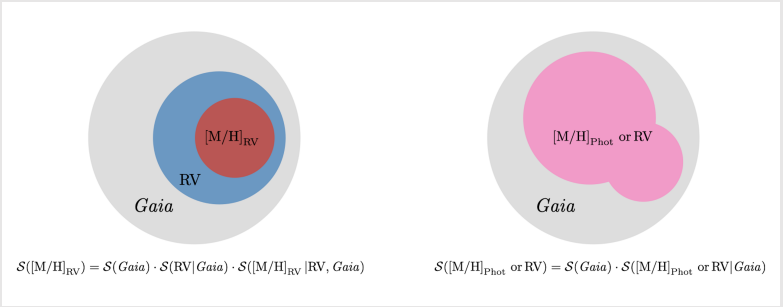


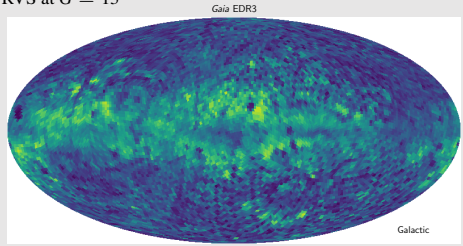
Selection functions for subsets of the Gaia catalogue



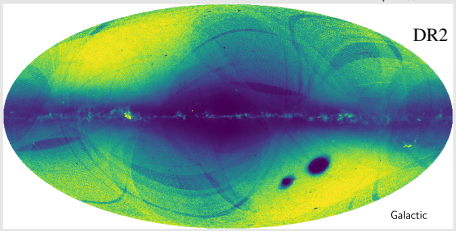
- $\mathcal{S}_{\mathcal{C}}^{\text{subset}}(\boldsymbol{q}) = \mathcal{S}_{\mathcal{C}}(\boldsymbol{q} \mid \boldsymbol{q} \text{ in parent}) \times \mathcal{S}_{\mathcal{C}}^{\text{parent}}(\boldsymbol{q})$
- Model $\mathcal{S}_{\mathcal{C}}(\boldsymbol{q} \mid \boldsymbol{q} \text{ in parent})$ as binomial process with probability p
- Estimate p as $(k+1)/(n+2)$: k number of sources with $\boldsymbol{q}$ in given bin (sky, magnitude, colour, etc) and n total number of sources in parent catalogue
- Details in Castro-Ginard et al. (2023), arXiv:2303.17738

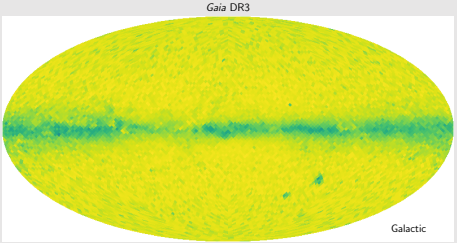
Selection functions for subsets of the Gaia catalogue

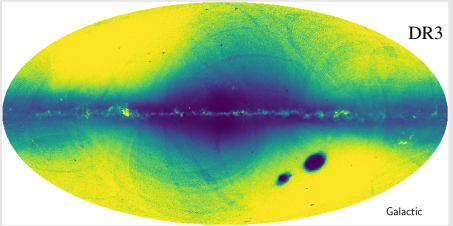
RVS at $G = 13$



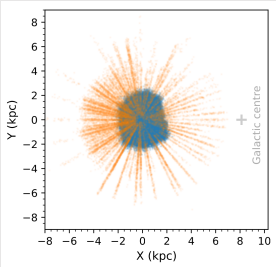
$\varpi > 0.1$ and $\varpi/\sigma_\varpi > 5$

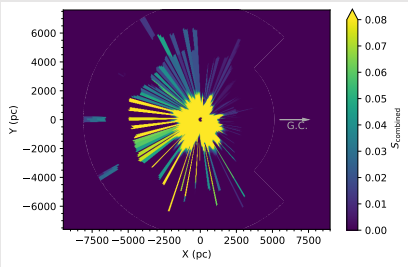


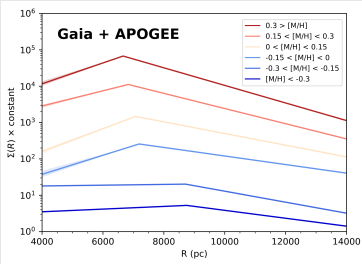


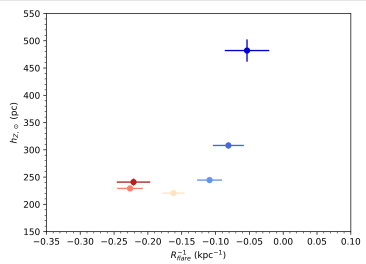


Milky Way disk with Gaia-GSP-Spec/APOGEE combination





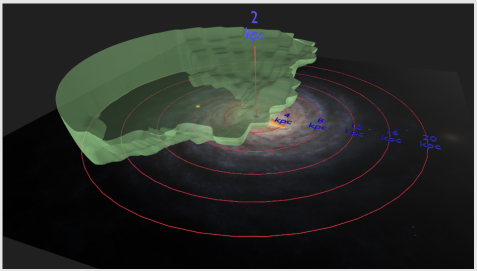


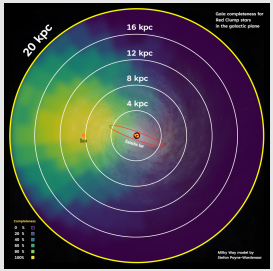


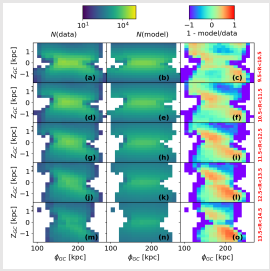
- Selection functions constructed for Red Clump stars: APOGEE DR17, GSP-Spec, and combination
- Joint sample used to study density profile of mono-abundance populations in different metallicity ranges
- Density profiles steepen with metallicity
- Metallicity-dependent flaring of $[\alpha/\mathrm{Fe}] < 0.1$ disk

Cantat-Gaudin et al,
arXiv:2401.05023

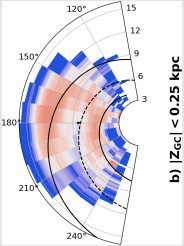
The disk in Red Clump stars from Gaia+AllWISE





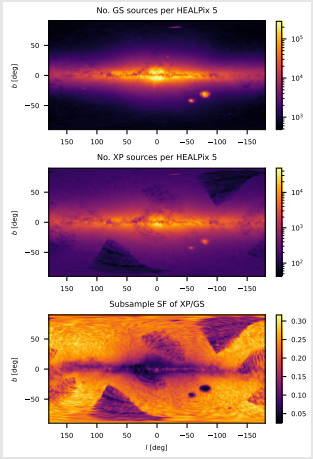


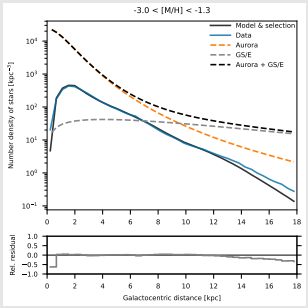
- Construction of combined Gaia+AllWISE selection function for Red Clump stars
- Disk structure for this sample: flared thin disk + shorter/thicker disk with no flare
- Outer disk shows clear signs of the warp
- Model + selection function residuals near disk plane show hints of spiral arms

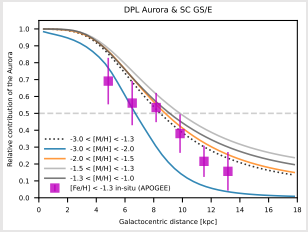


Khanna et al,
arXiv:2410.22036

Aurora and Gaia-Enceladus from XP-based RGB sample



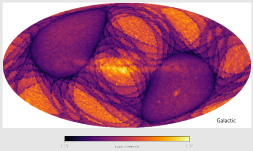




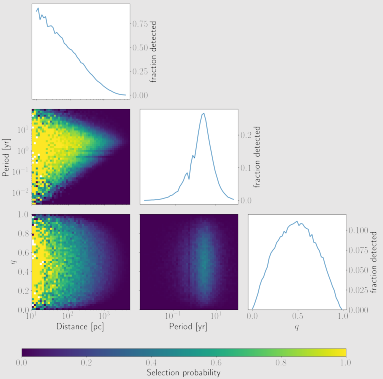
Kurbatov et al,
arXiv:2410.22250

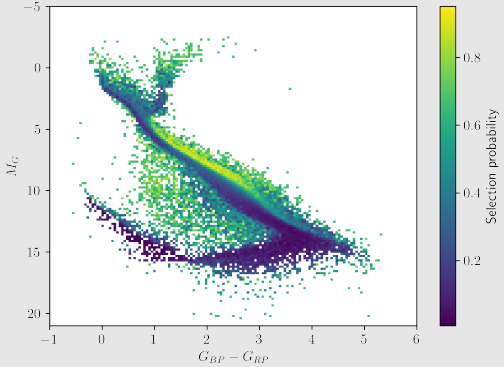
- Metal poor RGB stars, selection function: $G < 16$, $\varpi > 4\sigma_{\varpi}$, metallicities from XP spectra
- Density + luminosity function + extinction model for Aurora and Gaia-Enceladus populations
- Model predicts observables, accounting for selection function and parallax uncertainties
- Fairly complex model available in Python/Jupyter from GaiaUnlimited repository

Binaries selected on the basis of RUWE



- Sky-dependent RUWE threshold for selecting candidate binary stars
- Translation to selection effects on underlying binary orbital parameters
- Tools available to simulate selection effects for your favourite binary population





Castro-Ginard et al,
arXiv:2404.14127

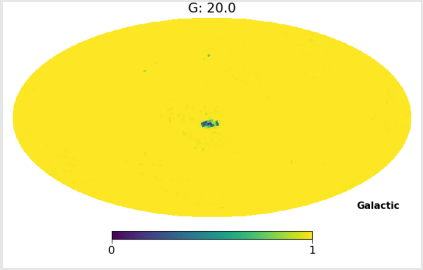
Statistical model of parent selection function for Gaia DR4

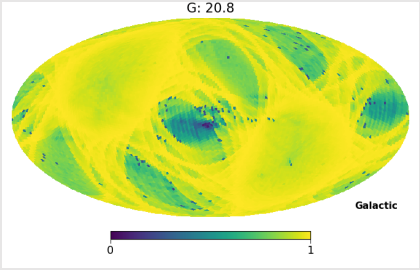
- Detection of sources by Gaia is considered a coin-flipping experiment with effective detection probability θ which varies with (ℓ, b, G) (Boubert & Everall 2020)
- Probability of k detections out of n field of view transits across a source:

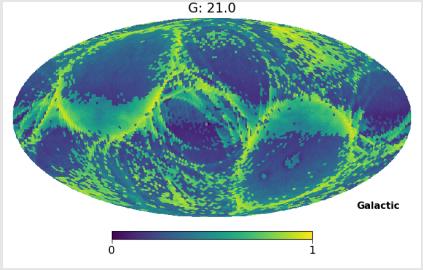
$$p(k \mid n, \theta) = \binom{n}{k} \theta^k (1-\theta)^{n-k}$$

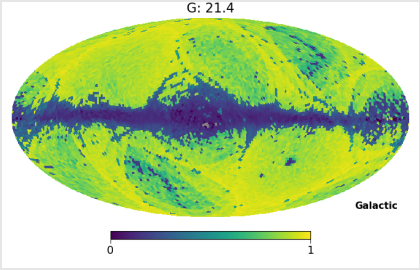
- k is the number of times a source is detected (in either Gaia field of view)
  - `astrometric_matched_transits`
  - Implicitly accounts for observation gaps, discarded data, and crowded fields
- n is the number of times that source crossed one of Gaia's fields of view
  - as predicted by Gaia Observation Scheduling Tool (GOST)
- Infer $\theta(\ell, b, G)$ from values of k and n per HEALPix and magnitude bin (and take into account $k \geq 5$)
- Following preliminary results **for DR3** are by Alfred Castro Ginard

Statistical model: preliminary results for Gaia DR3



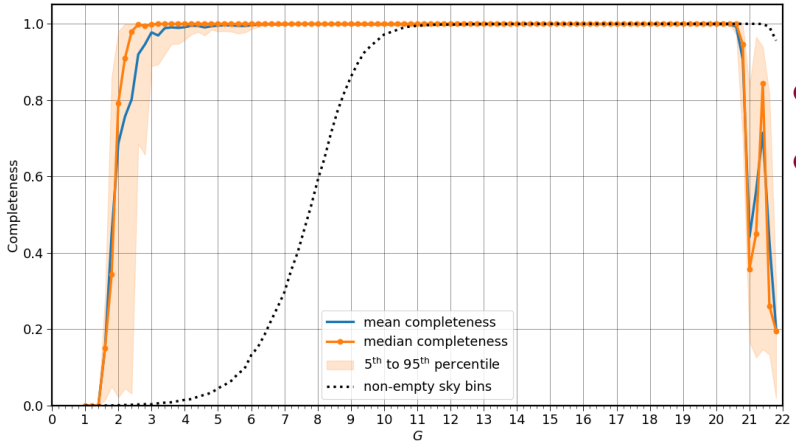






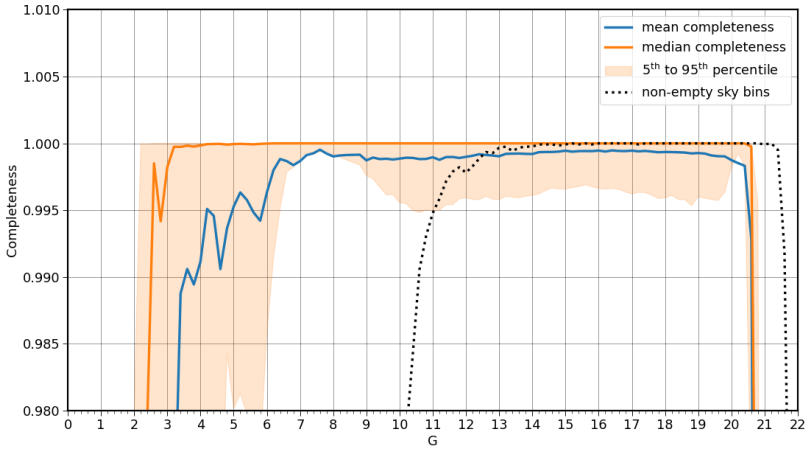
?

Statistical model: preliminary results for Gaia DR3



- Unexpected dip/ peak at $G > 21$
- Due to galaxies or QSO/AGN with too faint flux estimates
  - Mismatch PSF vs. galaxy image
  - Missing flux outside observation window

Statistical model: preliminary results for Gaia DR3



To do for Gaia DR4(+)

- Filter out extended galaxies and QSO/AGN or limit selection function to $G \leq 21$
- Improve statistical model to account for differences between GOST and the actual Gaia scanning law
  - Tests are underway with n as latent variable with prior informed by GOST
  - Speed-up of inference process
- Determine selection function for Gaia DR4

SPACIOUS: Computational opportunities and challenges

- Extensive use of the SPACIOUS/Spark platform
  - Automated task scheduling for parallelization
  - Efficient access to data (k for 2 billion sources, n for $\sim 2 \times 10^5$ sky pixels, ~ 100 magnitude bins)
- Numpyro + JAX for speed up of MCMC does not work on Spark
  - Use Dask instead?
- Time consuming step is a specific integral in likelihood calculation
  - Currently trying out evaluation of integral by neural network trained on pre-computed samples

GaiaUnlimited team

GaiaUnlimited postdocs

- Tristan Cantat-Gaudin (MPIA Heidelberg)
- Alfred Castro-Ginard (Leiden)
- Shourya Khanna (INAF-Torino)
- Evgeny Kurbatov (Cambridge)

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- Andy Everall (Cambridge)
- Semyeong Oh (IoA Cambridge)
- Zuzanna Kostrzewa-Rutkowska (Leiden)

- Anthony Brown (Leiden, PI)
- Vasily Belokurov (IoA Cambridge)
- Andy Casey (Monash)
- Ron Drimmel (INAF-Torino)
- Morgan Fouesneau (MPIA Heidelberg)
- David Hogg (NYU/ Flatiron/ MPIA Heidelberg)
- Adrian Price-Whelan (Flatiron)
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- Richard Smart (Torino)
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- Hans-Walter Rix (MPIA Heidelberg)