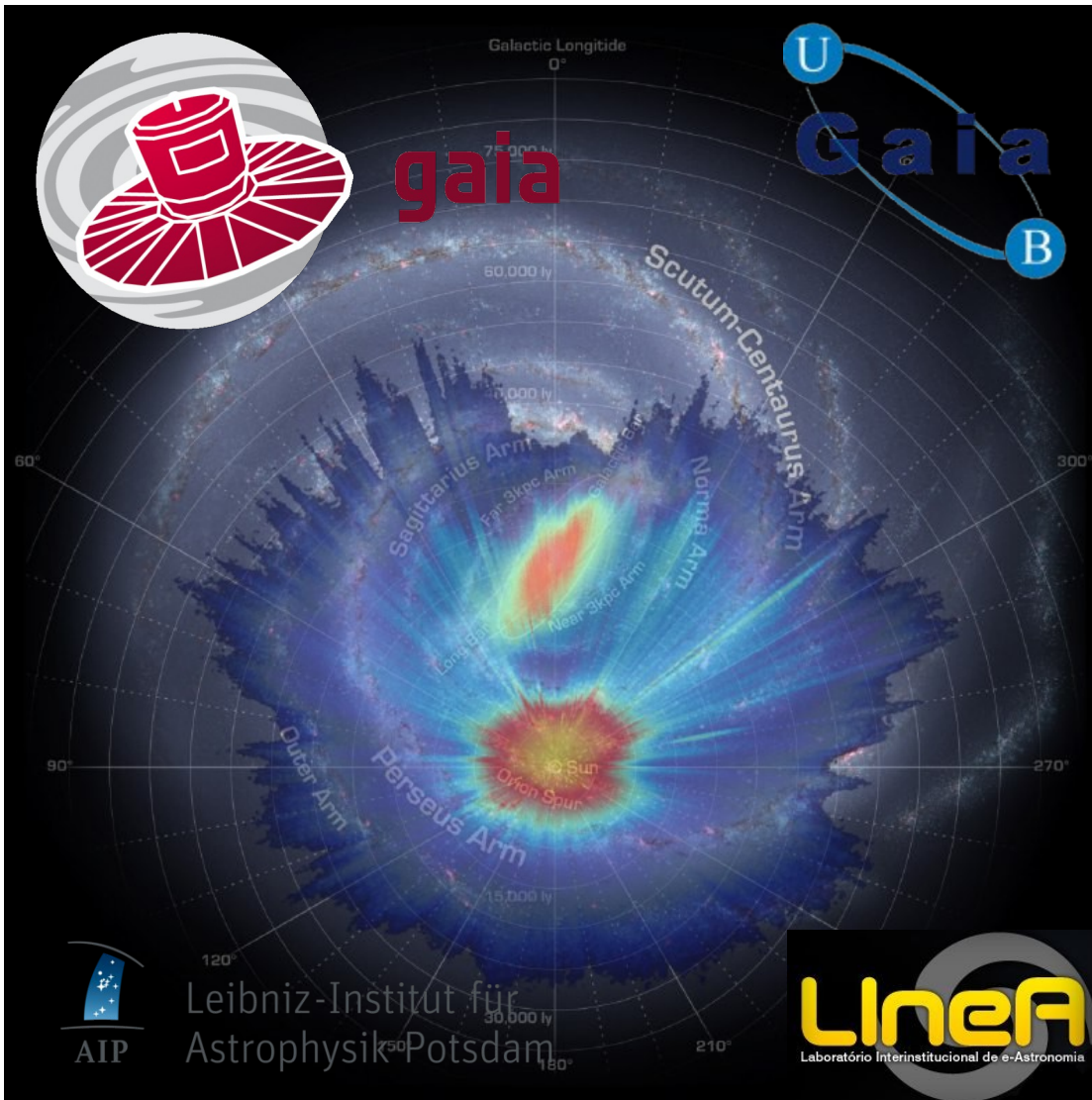
Determining distances and other stellar properties for millions of stars

Friedrich Anders (U Barcelona)

Cristina Chiappini, Arman Khalatyan,
Anna Barbara Queiroz (AIP)
Basilio X. Santiago (UFRGS)



UFRGS
UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

ICCUB
Institute of Cosmos Sciences

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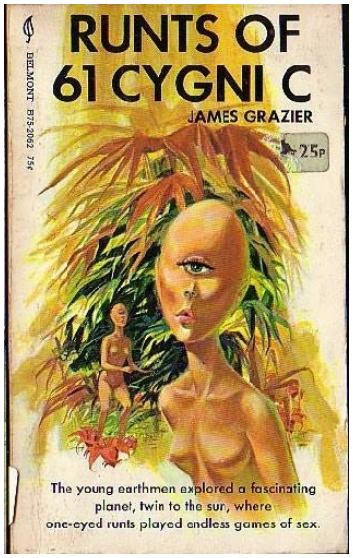
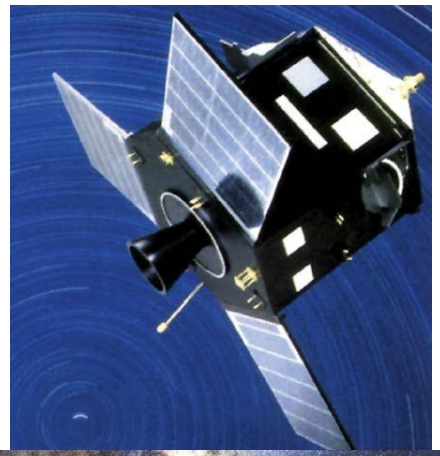
European Commission
Marie Skłodowska-Curie Actions

A short history of stellar distance measurements



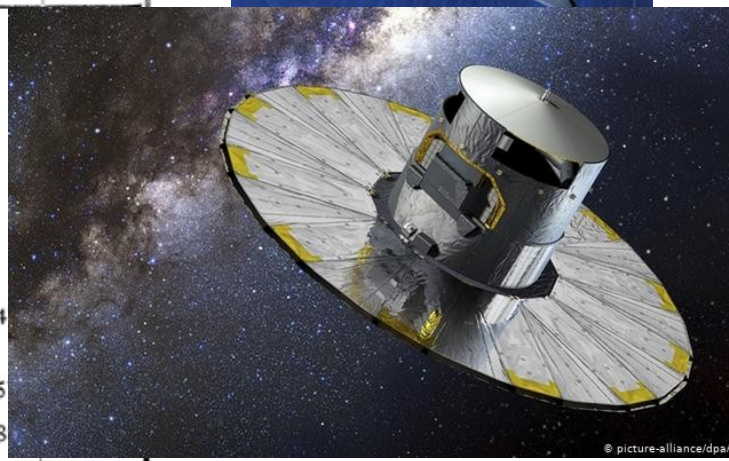
1838: first parallax measurement (Bessel)
1901: 58 parallaxes measured (Kapteyn)
1920s: first distance ladder controversy
1950s-today: main-sequence fitting for star clusters
1980s-2000s: statistical photometric distances to field stars
1990s-2010s: *Hipparcos* and its legacy: 100,000 stars with parallaxes (100
2000s-2010s: spectroscopic surveys (~ 10^6 stars)

2018: Gaia DR2 (~10^9 stars)

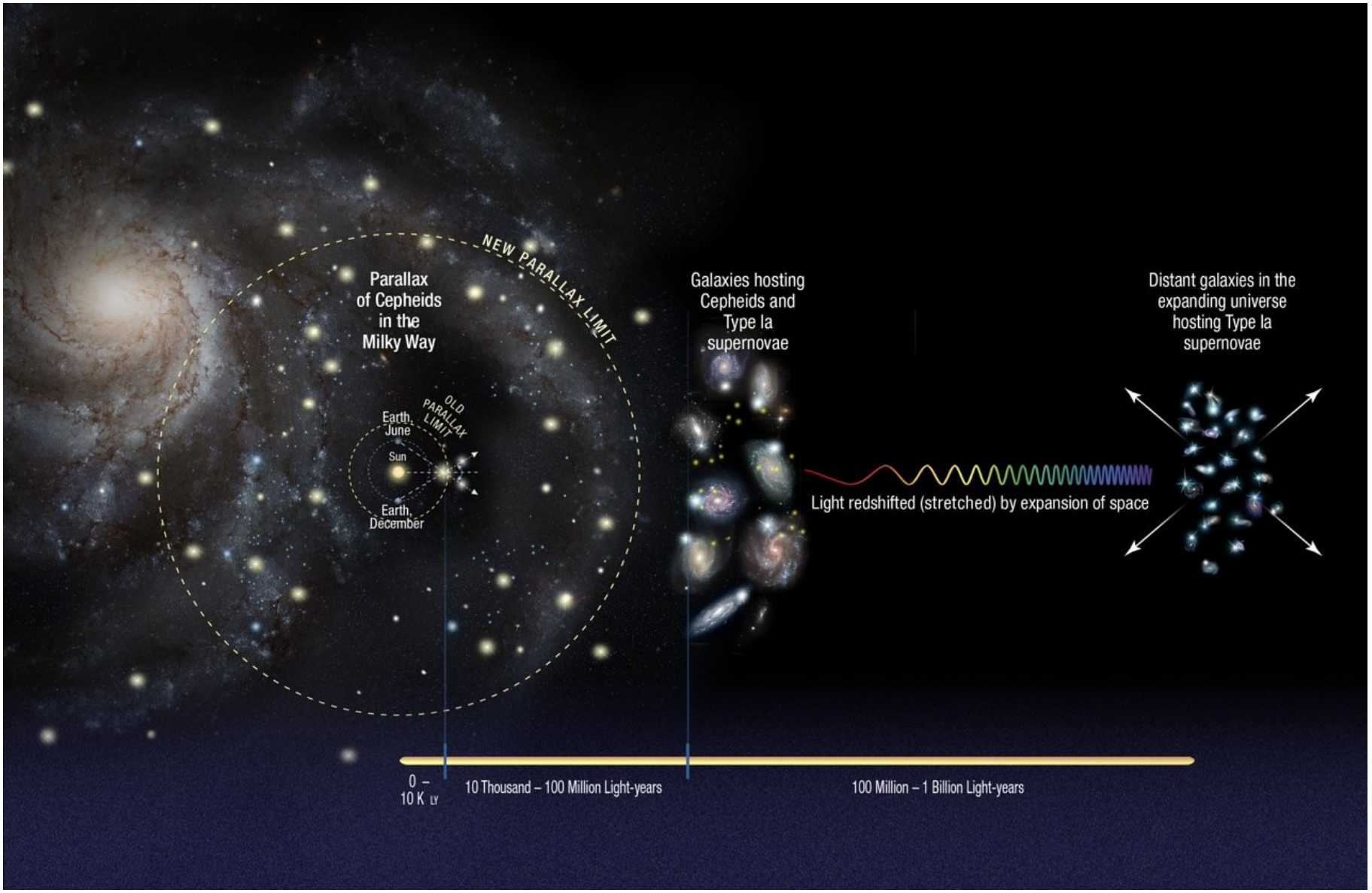


24 PARALLAX DETERMINATIONS. 25

No.	Star.	Mag.	Comp. *	Δ mag.	α 1900	δ 1900	Sp.	μ	ψ	$\pi_{aut.}$	r	Author.	$\pi_{abs.}$	Relat. weight.	$\pi_{adopt.}$	Abs. mag.	Lum.
					h m	° ′		″	°	″	″		″		″		
177	Lal. 23917	8·3	7·7		12 44·6	+ 1 45	G	0·68	183	+ 0·01 + ·025	± 0·049 18	Ch Y 2 Schl	+ 0·020 + ·031	1 5	× + 0·029		
178	δ Virginis	3·66	7·6		50·6	+ 3 56	Ma	0·481	263	— ·04	39	Ch Y 2	− ·030		— ·030		
179	Lal. 24414—'6	6·91	8·7		13 3·8	+ 5 46		0·72	175	— ·00	48	Ch Y 2	+ ·008		+ ·008		
180	Lal. 24504	8·5	8·6		6·4	+ 10 9		0·55	297	+ ·02	51	Ch Y 2	+ ·028		+ ·028		
181	43 Comae Ber.	4·32	8·5 7·4 8·5	— 0·3	7·2	+ 28 23	G	1·183	318	+ ·11 + ·08 + ·12	14 53 52	Pet 2 Fli Ch Y 2	+ ·118 + ·090 + ·128	7 1 1	× + ·116	4	
182	61 Virginis	4·80	5·4	— 0·6	13·2	— 17 45	G5	1·51	225	+ ·14	33	Fli	+ ·157		+ ·157	5	
183	Weisse$_2$ 13^h,241	9·3	7·6		14·9	+ 35 39	K**	0·92	154	+ ·07	52	Ch Y 2	+ ·080		+ ·080	8	



The parallax horizon: Gaia's transversal impact on astronomy



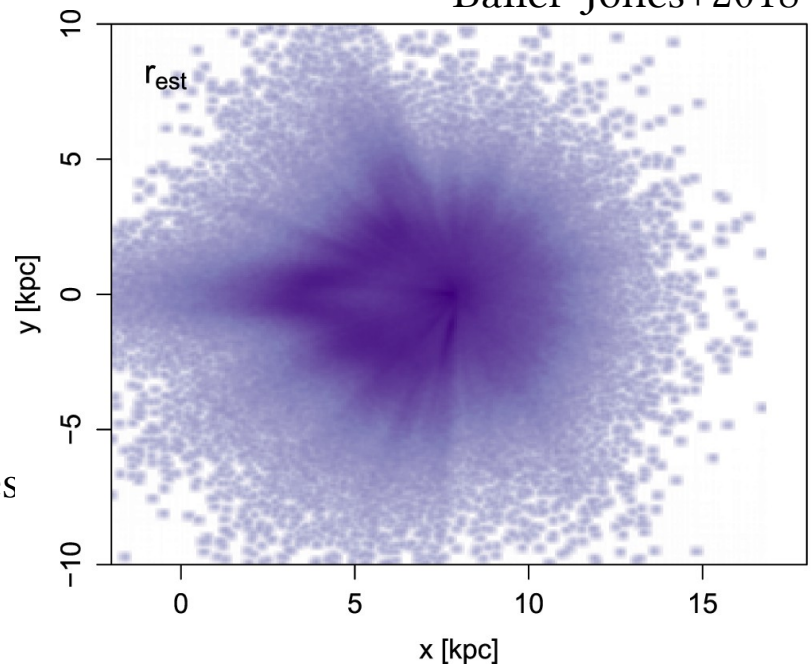
A new era: What Gaia DR2 brought us

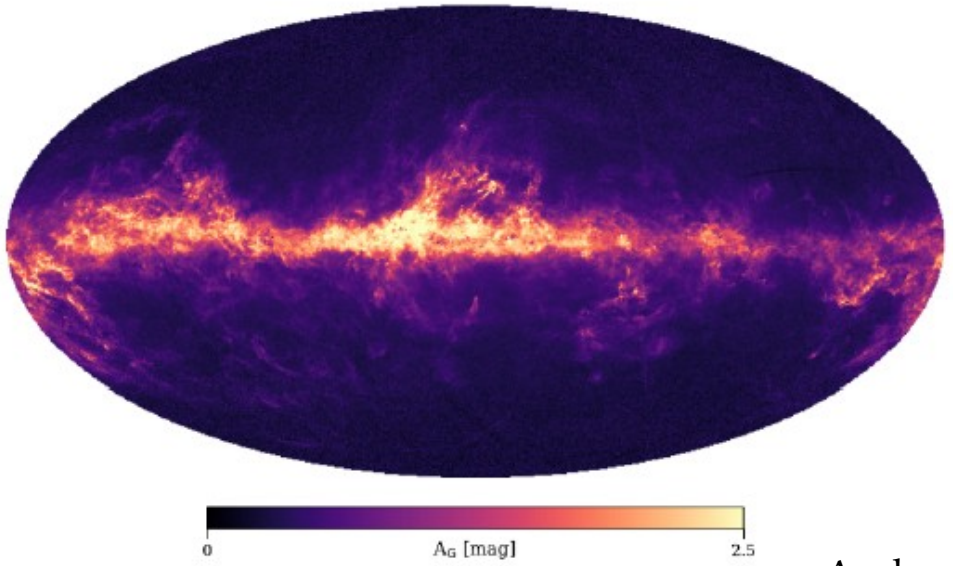
- 1.7 billion stars with 5D astrometric parameters
- New parallax horizon: **100 pc → 2 kpc**
- Radial velocities for 7M stars up to G < 12
- Extinction and temperatures for 80M stars
- ...

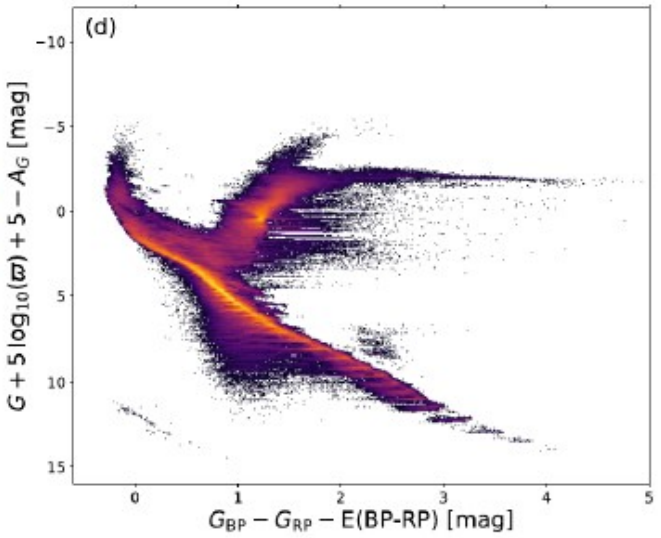
Coupled with spectroscopic surveys:

- High-precision chemical abundances, possibly also okay ages
- Distances for stars farther than 3 kpc
- Radial velocities for the fainter stars

Bailer-Jones+2018

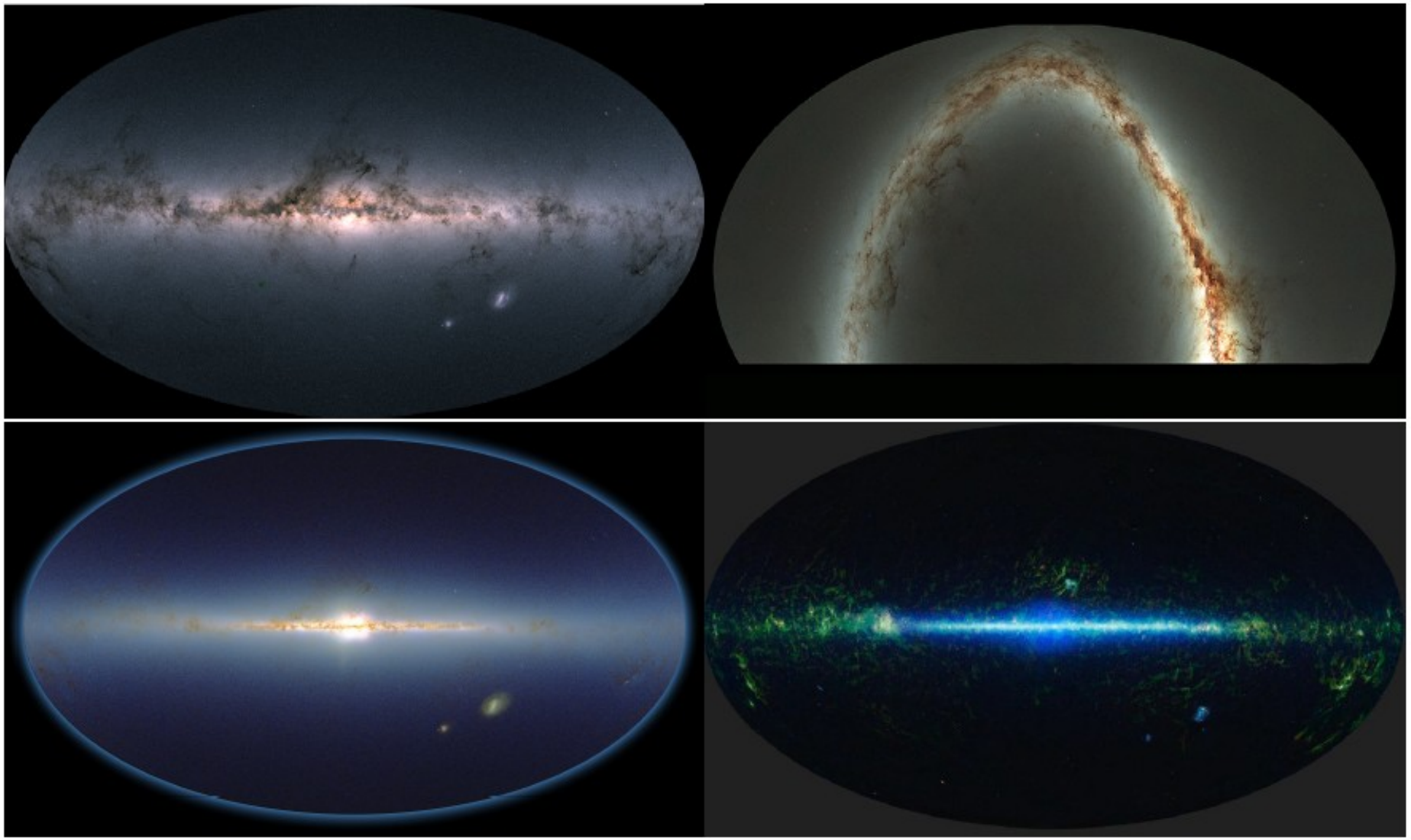






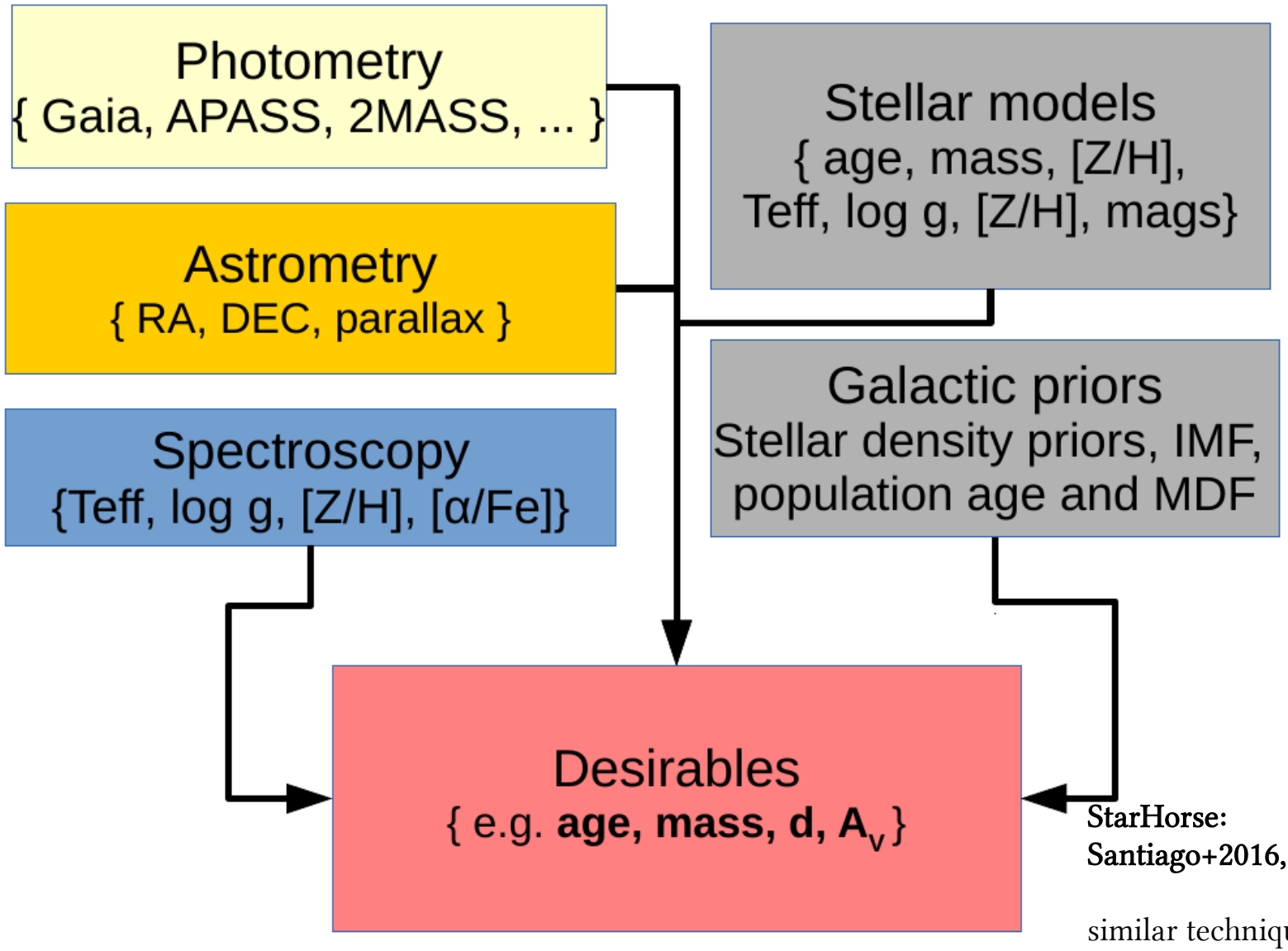
Andrae+2018

Combining Gaia with other surveys: StarHorse2019 project



Gaia DR2, Pan-STARRS1, 2MASS, and WISE all-sky maps

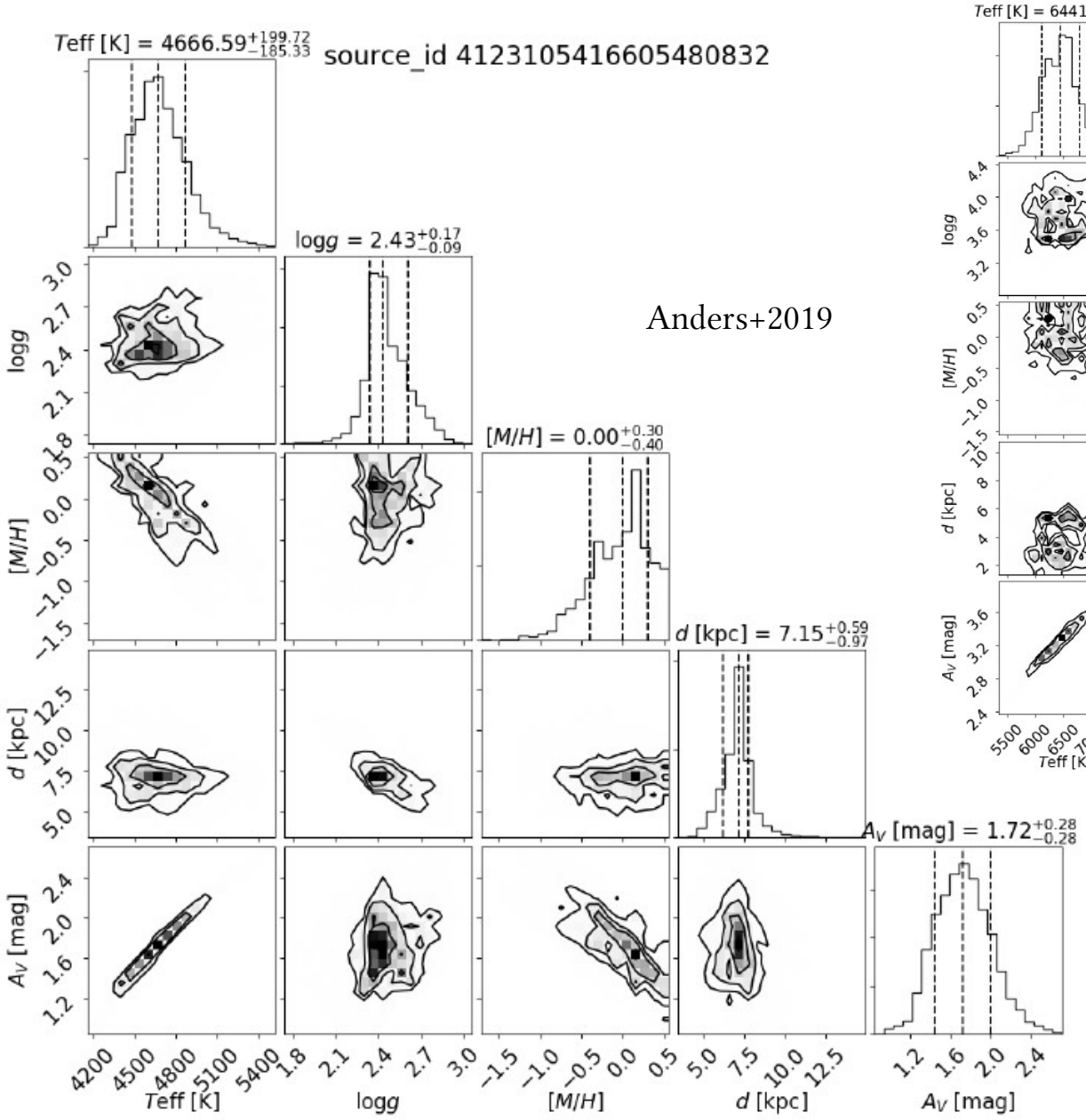
Bayesian inference of distances and stellar parameters



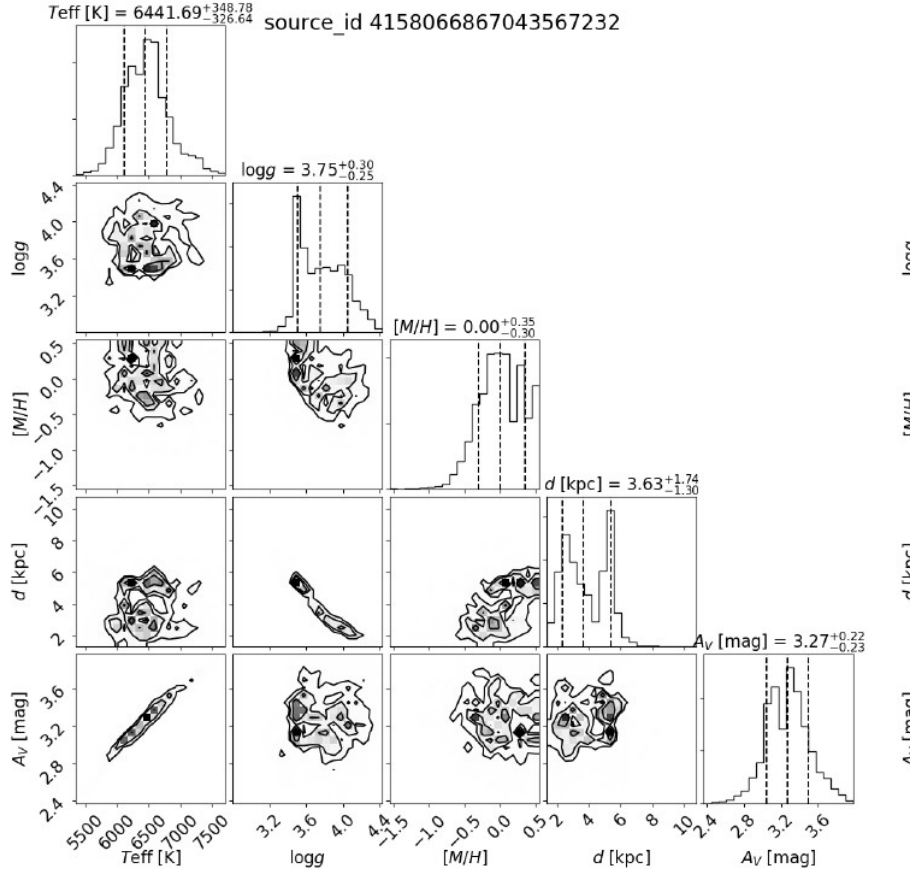
StarHorse:
Santiago+2016, Queiroz+2018

similar techniques used by Binney+2014, McMillan 2017, Mints&Hekker 2017, ...
Simpler techniques used by Gaia DPAC, Astraatmadja+2016, Bailer-Jones+2018..

StarHorse: joint posterior PDFs



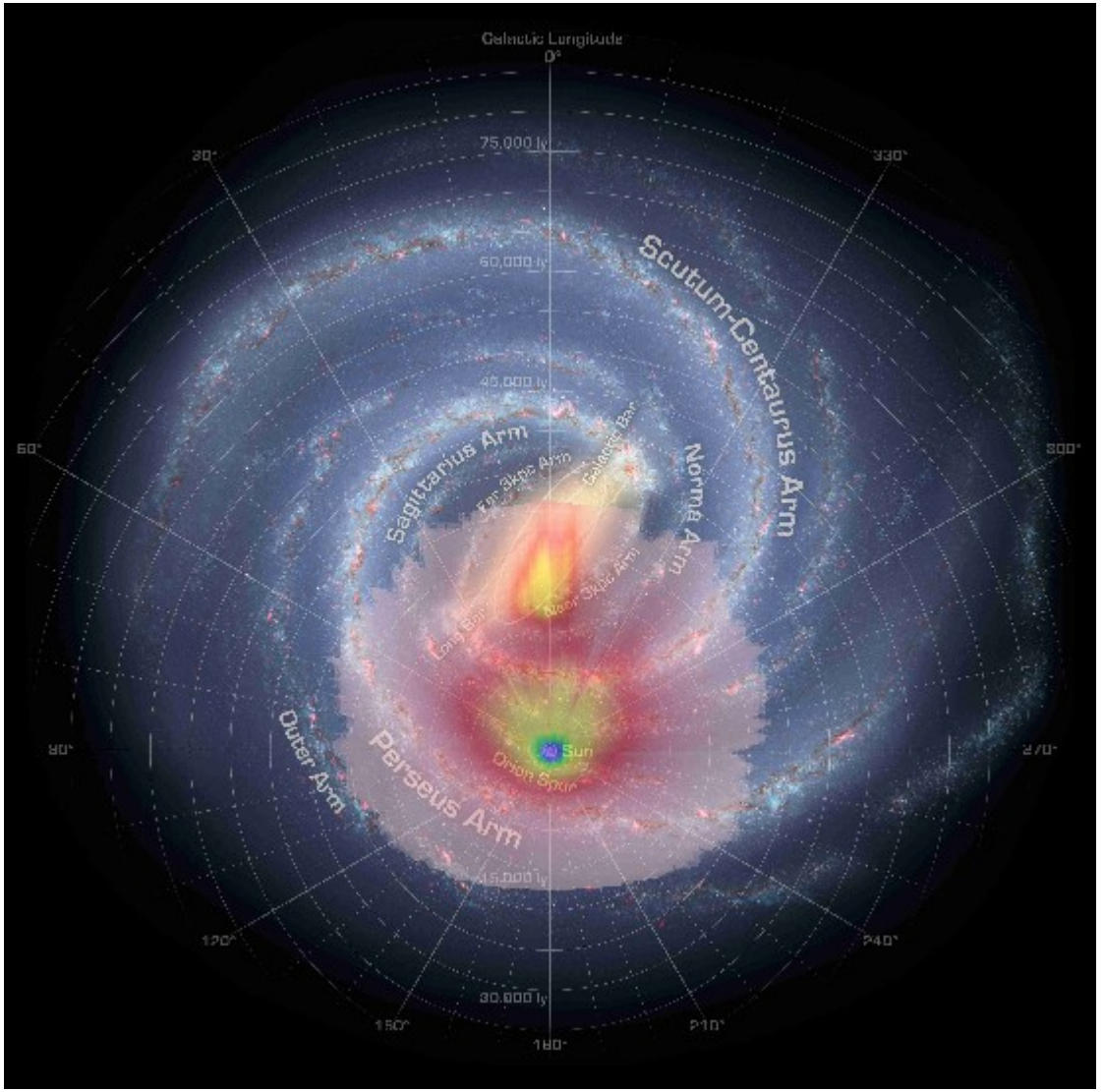
Anders+2019



The posteriors are seldom Gaussian, often multi-peaked, etc...

→ Uncertain results are flagged and should be used with care...

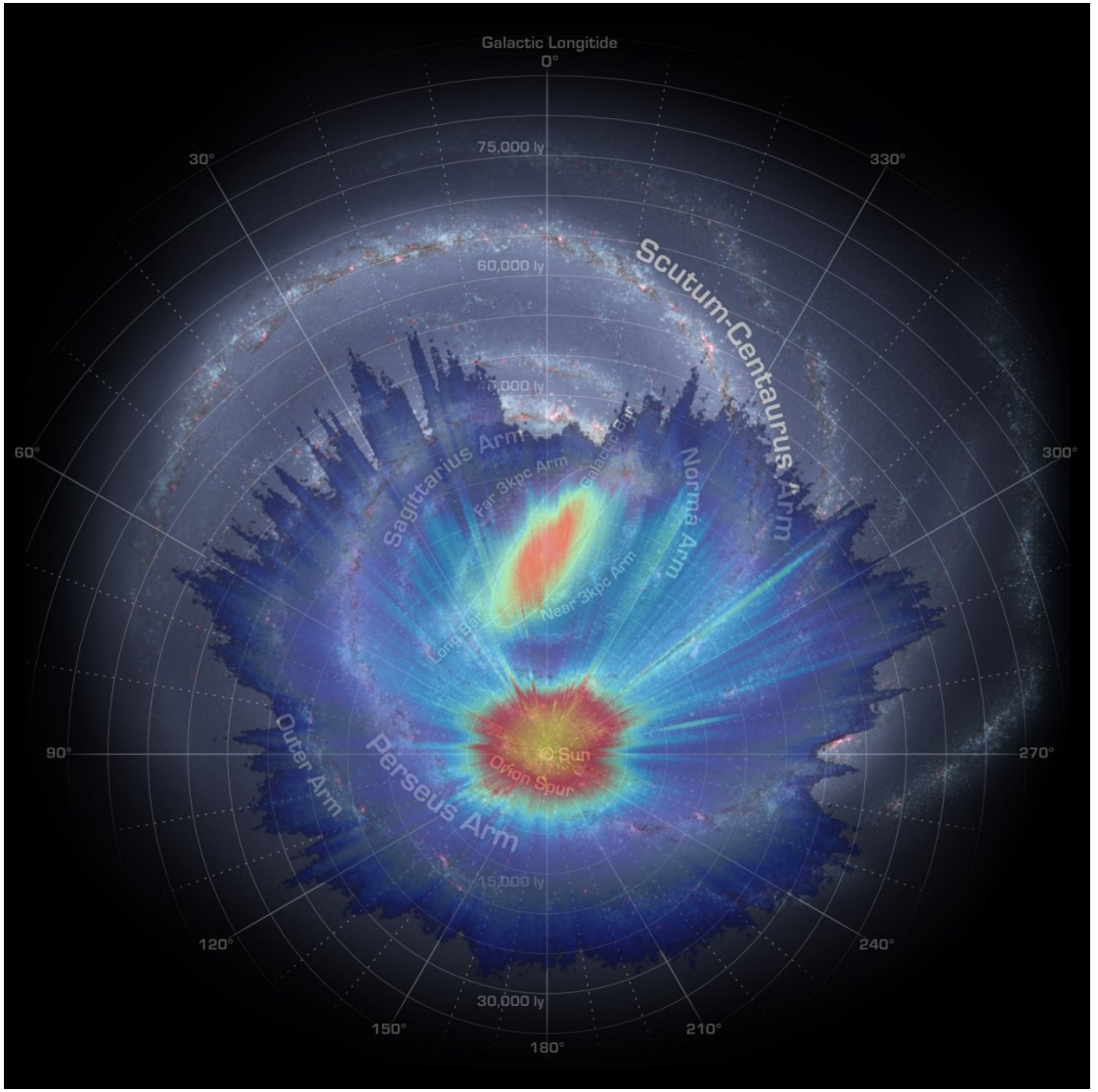
A sharpened view of the Galaxy



Gaia end-of-mission expectation in 2012.
Credit: X. Luri/ A. Robin

- Extension of the Gaia parallax horizon:
  More accurate distances for stars with imprecise parallaxes
- Masses and age estimates for stars with good parallaxes
- Better HRDs, more precise chemo-dynamics, stellar orbits, etc.

A sharpened view of the Galaxy



Gaia DR2 StarHorse view (22 months of data)
Credit: A. Khalatyan/F. Anders

- Extension of the Gaia parallax horizon: More accurate distances for stars with imprecise parallaxes
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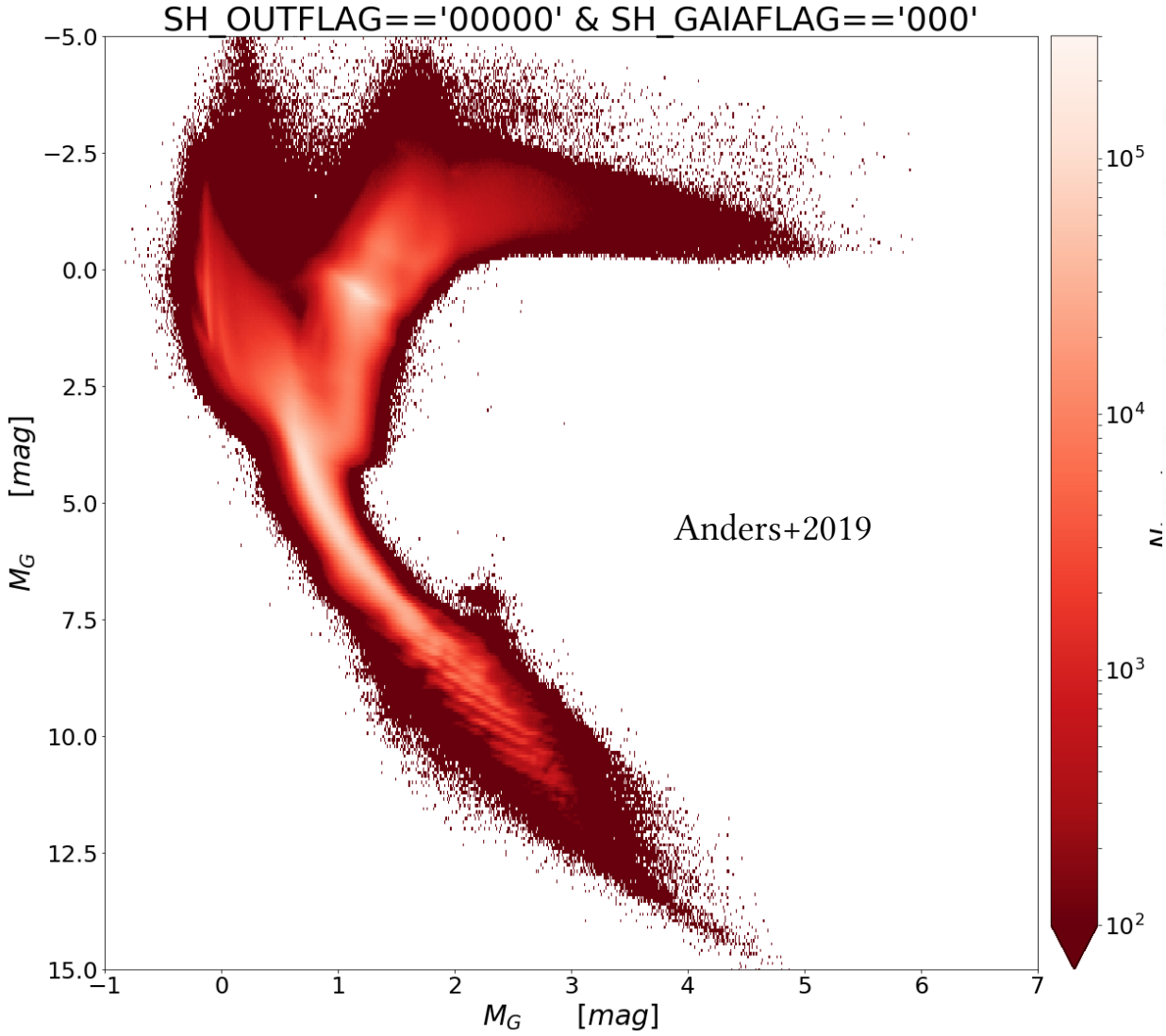
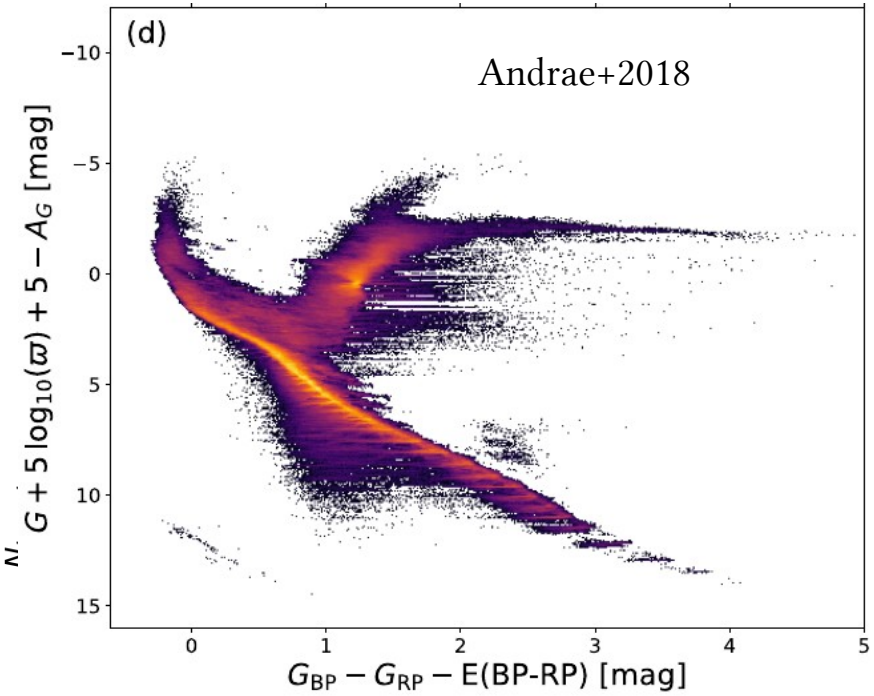
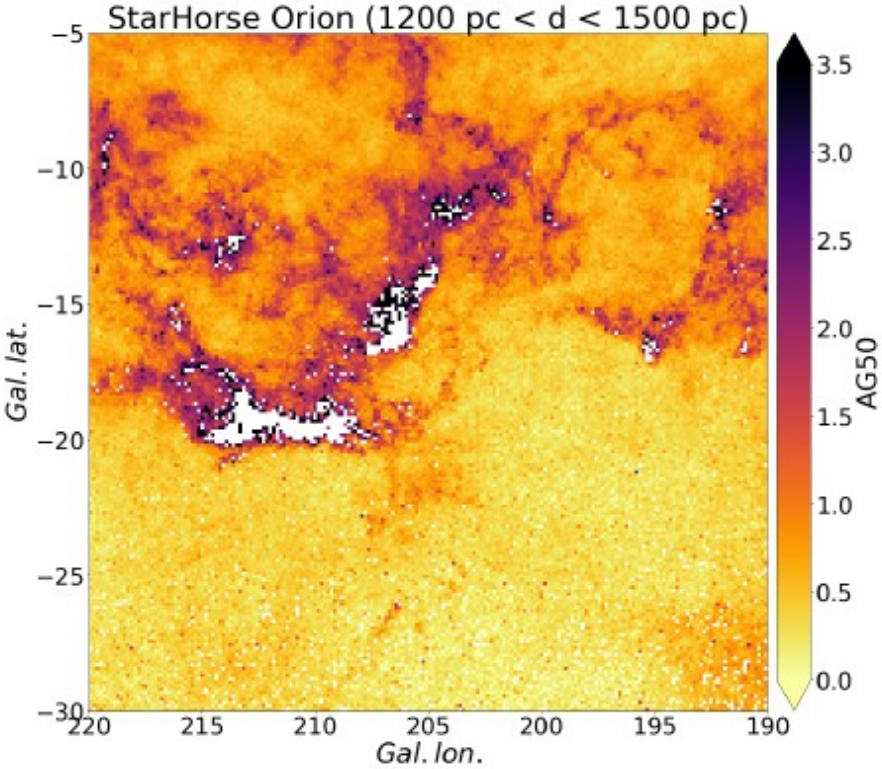
Improved HR diagrams with more stars

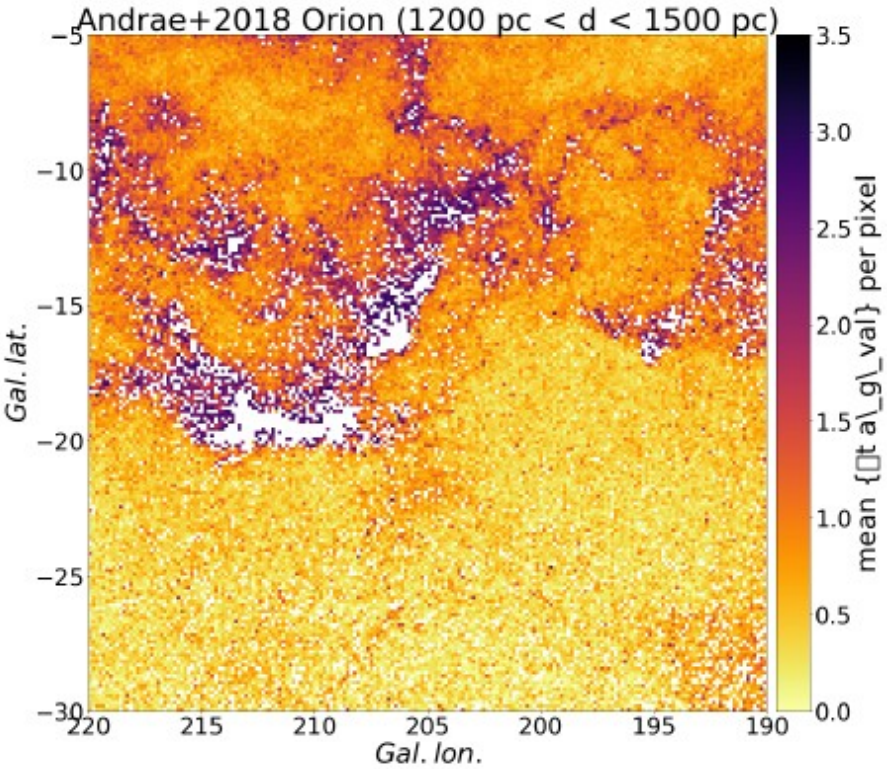




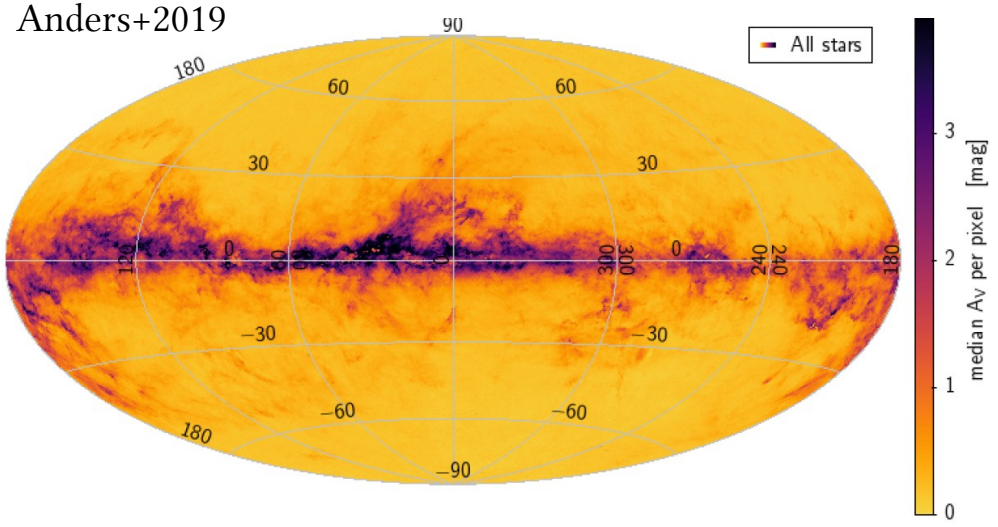
- Infrared photometry breaks degeneracy between extinction and effective temperature ⟶ Nicer dereddened CMDs

Improved extinction maps with more stars



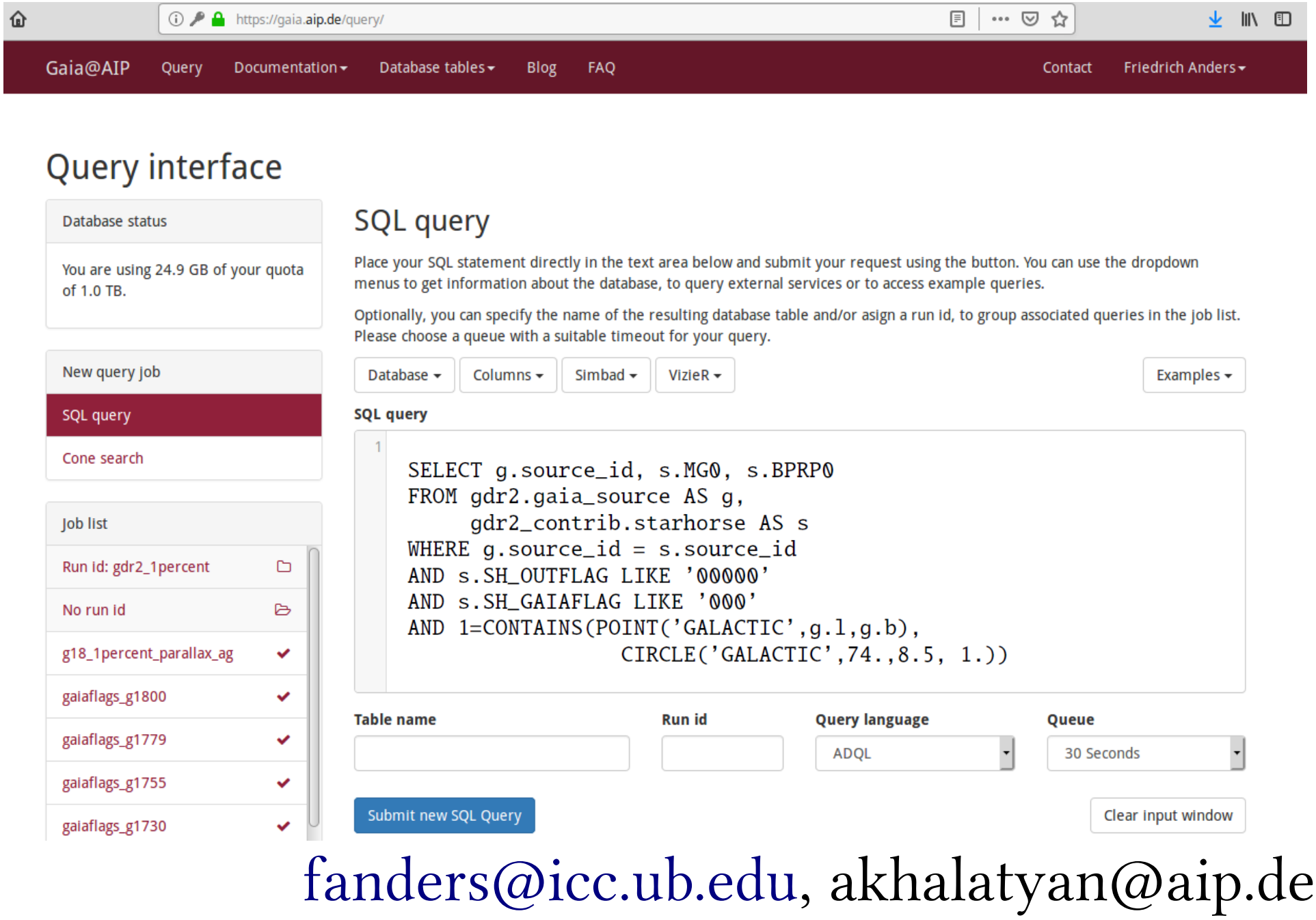


Anders+2019



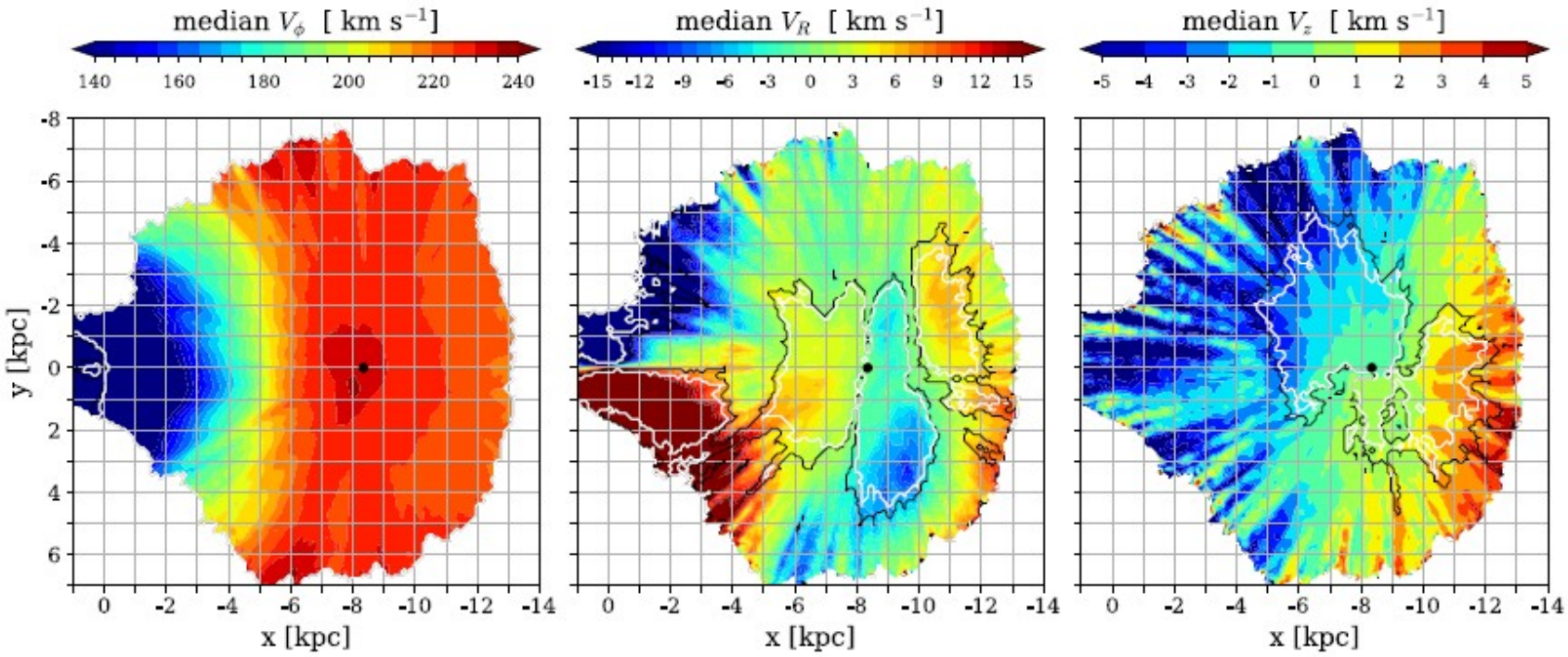
- Infrared photometry breaks degeneracy between extinction and effective temperature ⟶ 2-3 times better extinction precision

Data access: gaia.aip.de

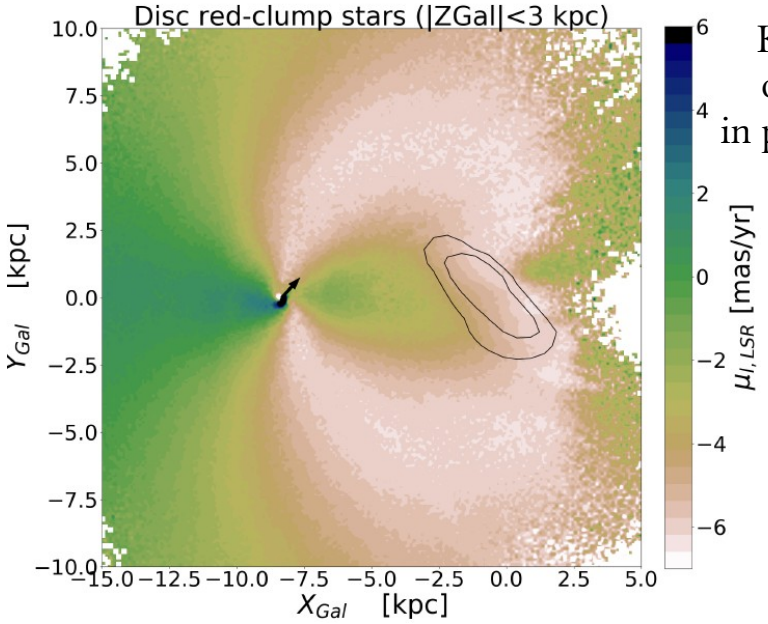


fanders@icc.ub.edu, akhalatyan@aip.de

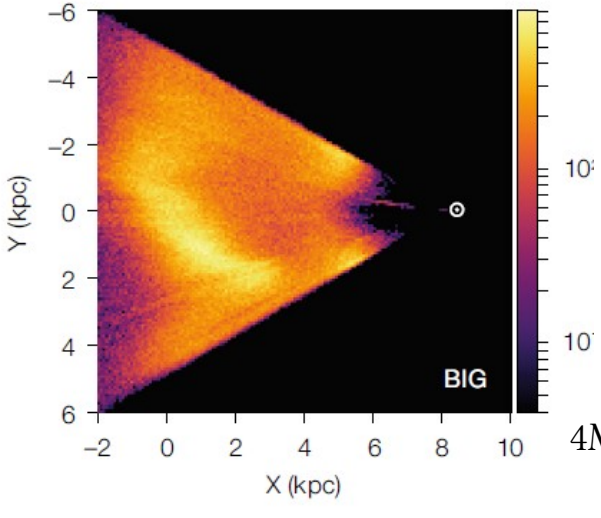
First science applications



6D Kinematics of the Galactic disc:
Carrillo+2019

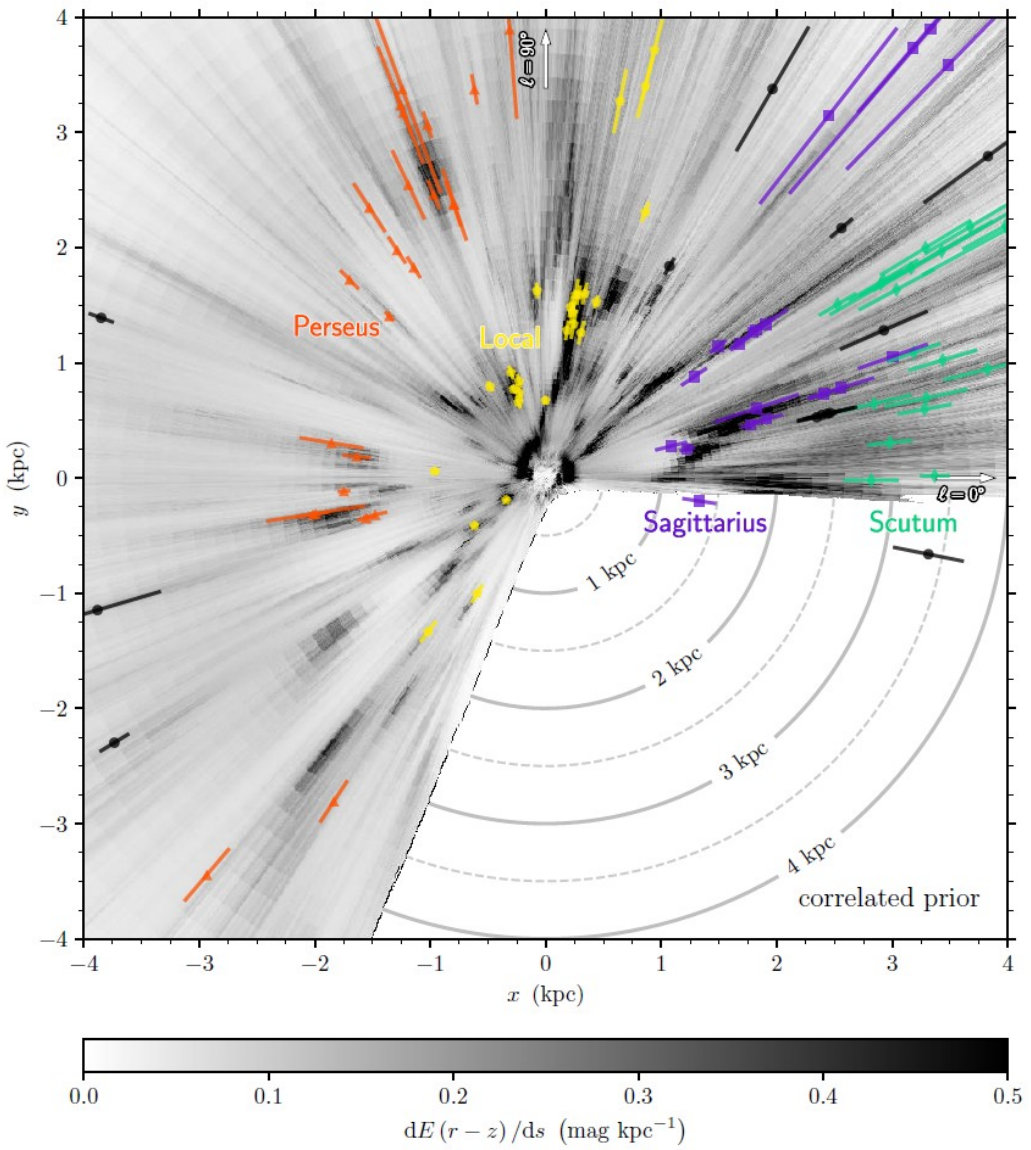


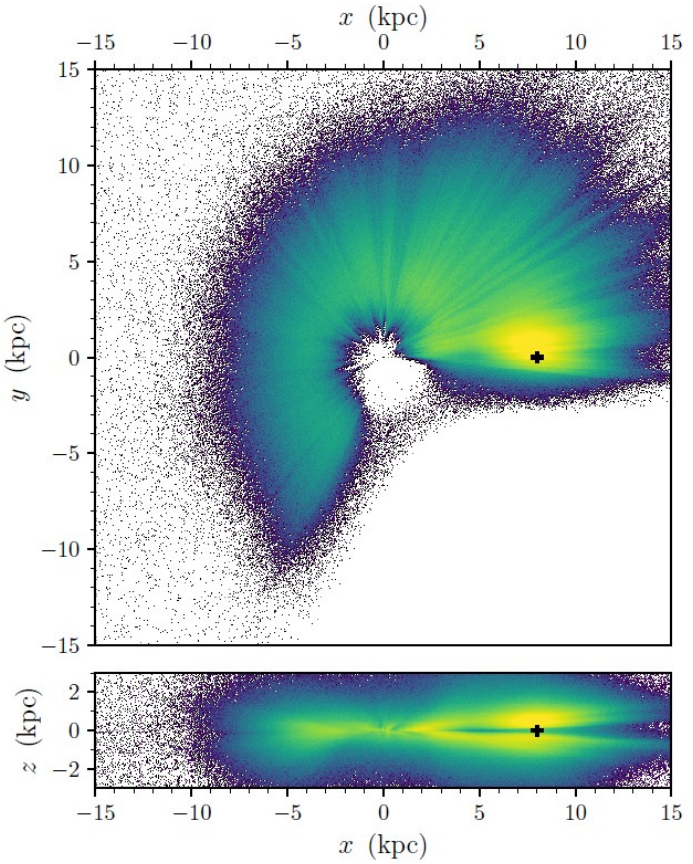
Kinematic imprint
of the Galactic bar
in proper motion spa
Anders+2019



4MOST survey planning:
Chiappini+2019

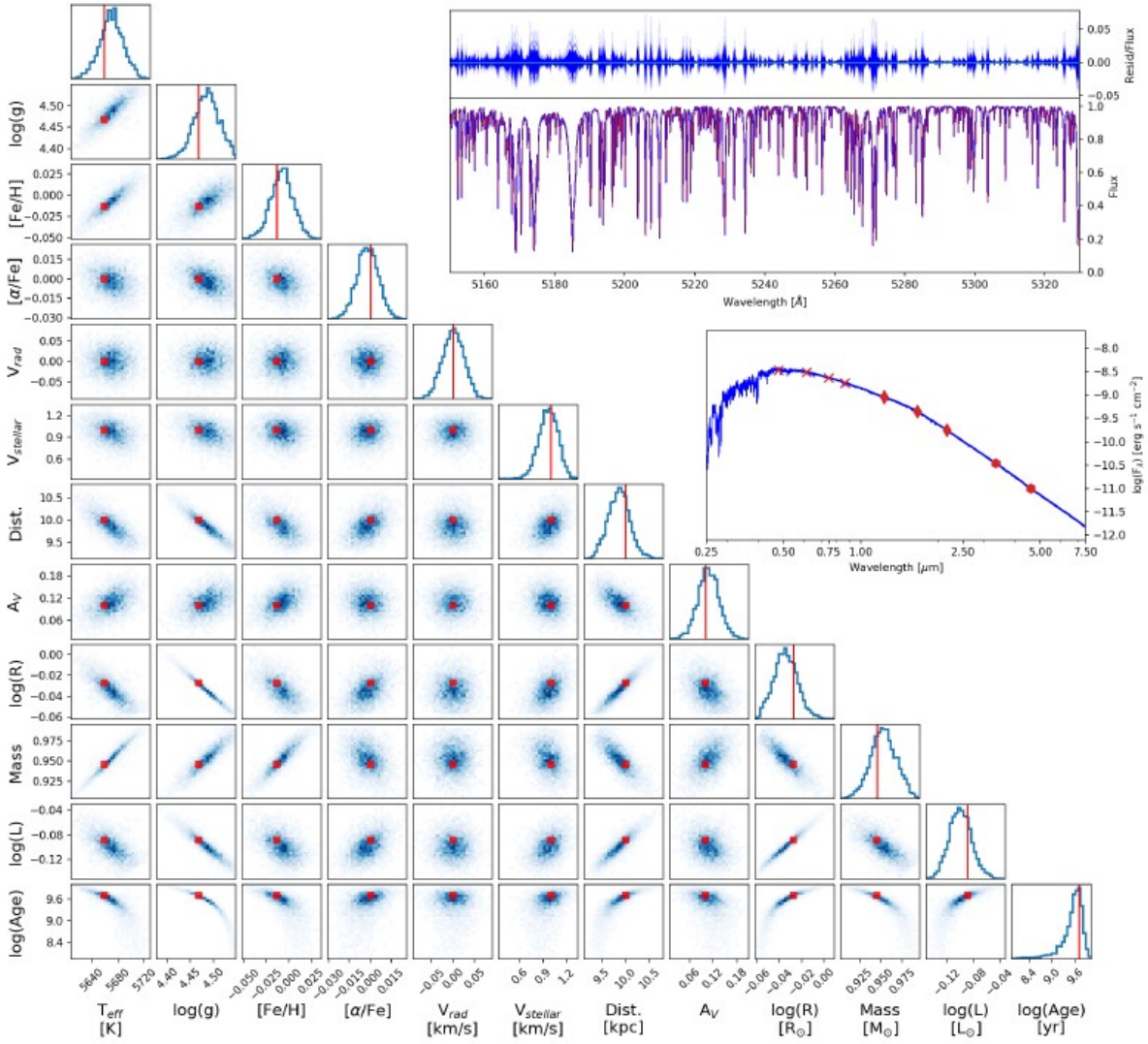
The future: Beyond „trad.“ Bayesian isochrone fitting





- Green+2019: used Gaussian processes to measure the 3D extinction structure + distances + stellar parameters simultaneously

The future: Beyond „trad.“ Bayesian isochrone fitting



- Cargile+2019: use neural networks to fit spectra, photometry, and astrometry to determine stellar parameters + distances + extinction simultaneously

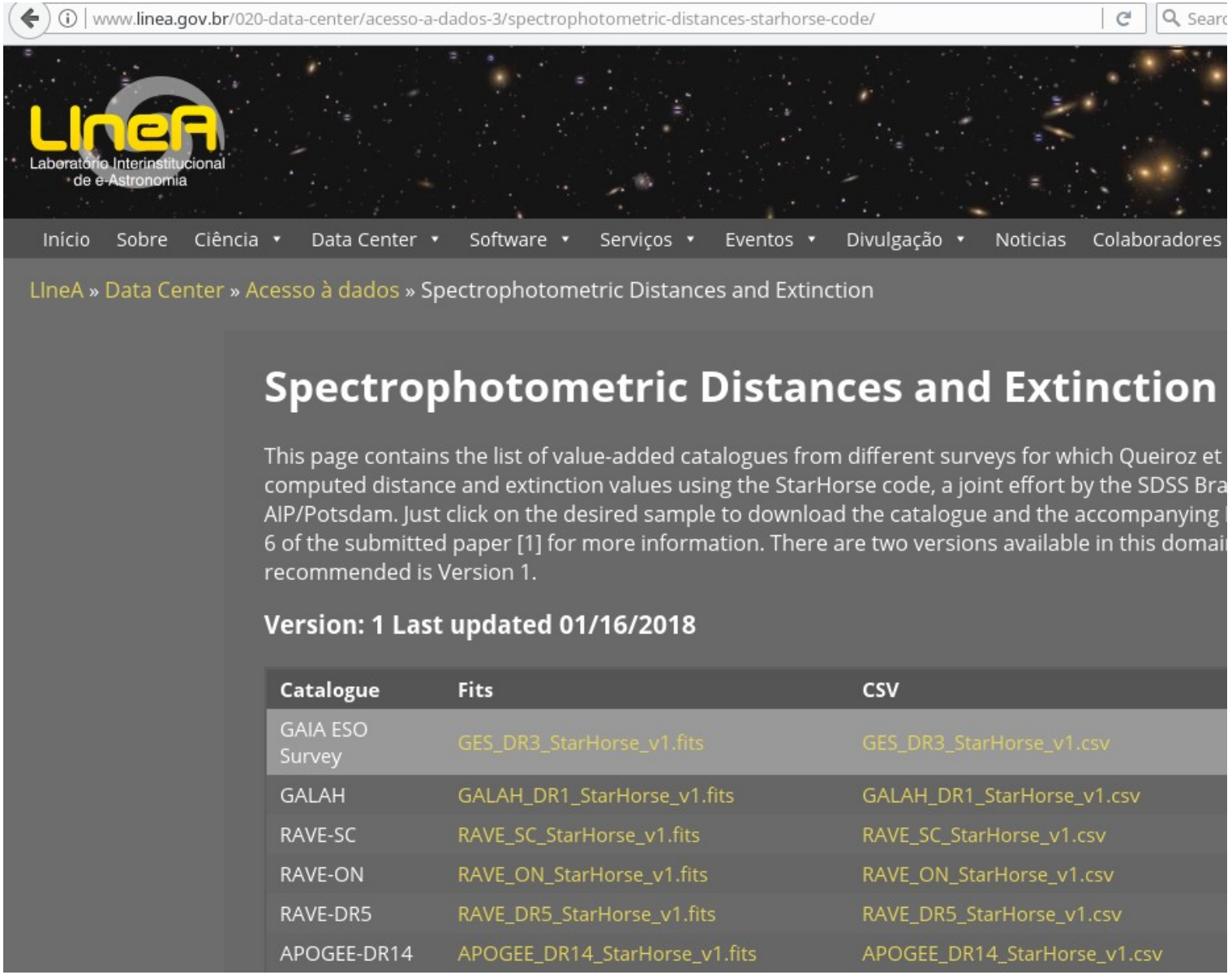
Summary: available StarHorse results

- **Gaia DR1 + {APOGEE DR14, RAVE DR5, GALAH DR1, GES DR3}**: high-quality masses, distances and extinctions for ~1M stars. Results available via **linea.gov.br**
- **Gaia DR2 + photometry:** stellar parameters, distances & extinctions for G < 18: Results available via **gaia.aip.de**
- **Gaia DR2 + {APOGEE DR16, RAVE DR5, GALAH DR2, GES DR3, LAMOST DR5}**: **Very soon!** Stellar parameters, distances, extinctions for 3M stars

Some caveats

- Accuracy of our approach is limited by systematics in stellar models. Most important: binarity effects.
- Photometric zeropoints and transmission curves matter..
- Spatial variations in the extinction law are not taken into account...
- Different stellar parameter scales for different spectroscopic surveys...
- Extragalactic stellar populations (MCs, Sagittarius, etc) are not included in the prior...

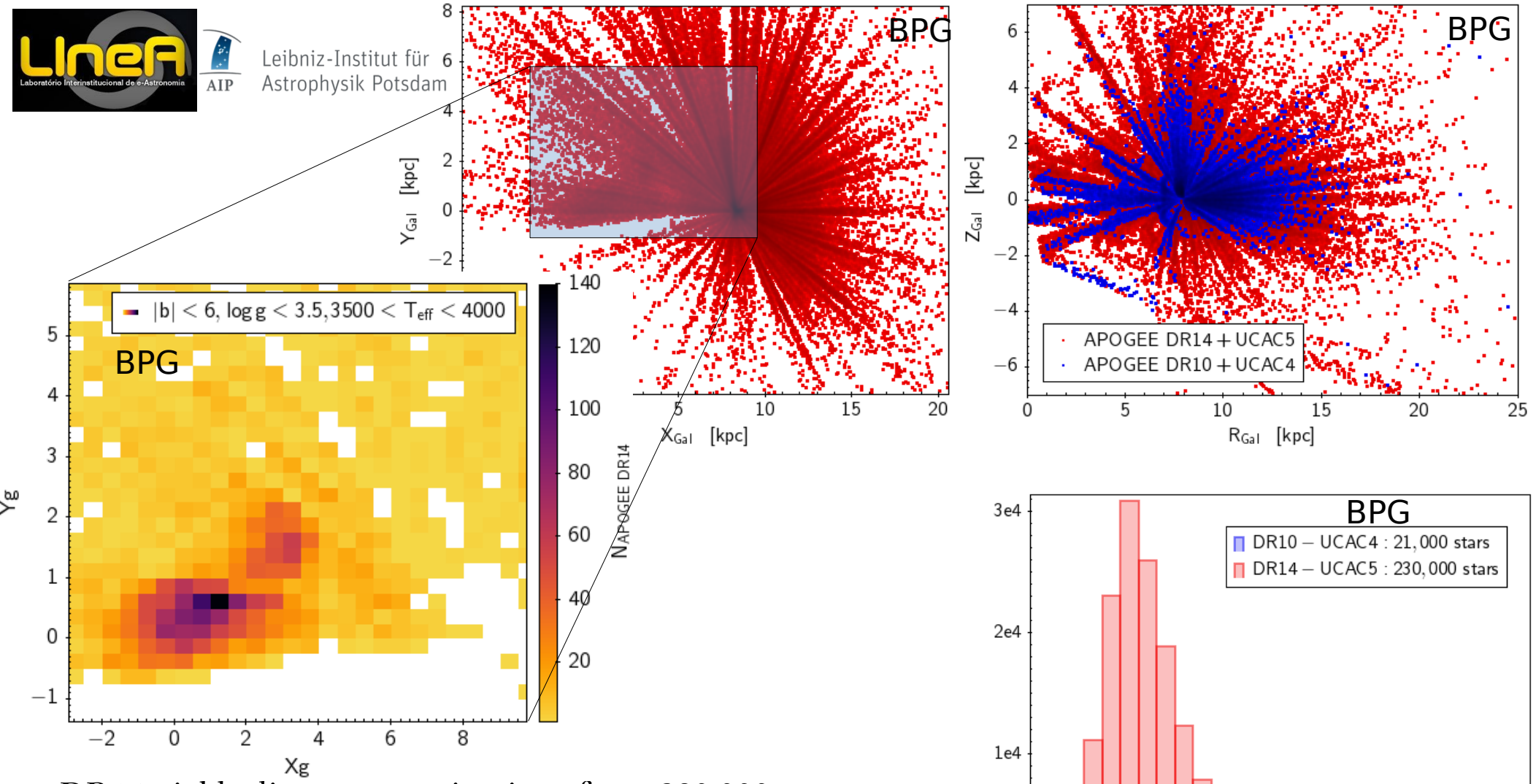
Coming up next:
Gaia DR2 + spectroscopic surveys results



Queiroz+ (in prep.):

Gaia DR2 +
{ APOGEE DR16,
RAVE DR5,
GALAH DR2,
GES DR3,
LAMOST DR5 }

Taking a closer look at the bar with APOGEE



- DR16 yields distances+extinctions for > **380,000 stars**
- Median precision for giants 12% in distance, 0.07 mag in A(V)
- Effects of the Galactic bar are clearly seen in the data (Fragkoudi+2017, Bovy+2019, Queiroz+in prep.)