Precise photo-astrometric distances, extinctions, and stellar parameters for 150 million stars in Gaia DR2

ICCUB Seminar, 28.03.2019

Friedrich Anders

Arman Khalatyan, Cristina Chiappini, Anna Queiroz (AIP)

Outline

- Galactic Archaeology
- A short history of stellar distances
- *Gaia* DR2
- The `StarHorse` code
- Future plans

Bio

Physics student @ TU Dresden 2007-13
Erasmus student @ UAM 2010/11
ESA Trainee @ ESAC 2011
PhD thesis @ AIP/UP 2013-17
Visiting scientist @ IAG/USP 2016
Postdoc @ AIP 2017-2018
Marie Curie @ ICCUB since 02/2019

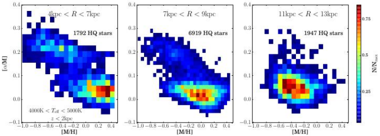


What I did in my thesis

APOGEE Galactic science

Chemodynamics of the Milky Way.
I. The first year of APOGEE data

F. Anders[1,2], C. Chiappini[1,3], B. X. Santiago[3,4], H. J. Rocha-Pinto[3,5], L. Girardi[3,6], L. N. da Costa[3,7], M. A. G. Maia[3,7], M. Steinmetz[1], I. Minchev[1], M. Schultheis[8], C. Boeche[9], A. Miglio[10], J. Montalbán[11], D. P. Schneider[12,13], T. C. Beers[14,15], K. Cunha[7,16], C. Allende Prieto[17], E. Balbinot[3,4], D. Bizyaev[18], D. E. Brauer[1], J. Brinkmann[18], P. M. Frinchaboy[19], A. E. García Pérez[20], M. R. Hayden[21], F. R. Hearty[20,12], J. Holtzman[21], J. Johnson[22], K. Kinemuchi[18], S. R. Majewski[20], E. Malanushenko[18], V. Malanushenko[18], D. L. Nidever[23], R. W. O'Connell[20], K. Pan[18], A. C. Robin[24], R. P. Schiavon[25], M. Shetrone[26], M. F. Skrutskie[20], V. V. Smith[14], K. Stassun[27], G. Zasowski[28]



Stellar distances & ages

Spectro-photometric distances to stars:
A general-purpose Bayesian approach

Basílio X. Santiago[1,2], Dorothée E. Brauer[3], Friedrich Anders[3,2], Cristina Chiappini[3,2], Anna B. Queiroz[1,2], Léo Girardi[4,2], Helio J. Rocha-Pinto[5,2], Eduardo Balbinot[1,2], Luiz N. da Costa[6,2], Marcio A.G. Maia[6,2], Mathias Schultheis[7], Matthias Steinmetz[3], Andrea Miglio[8], Josefina Montalbán[9], Donald P. Schneider[10,11], Timothy C. Beers[12], Peter M. Frinchaboy[13], Young Sun Lee[14], and Gail Zasowski[15]

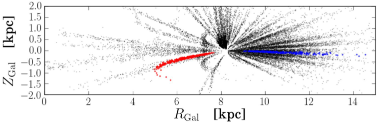
StarHorse: A Bayesian tool for determining stellar masses, ages, distances, and extinctions for field stars

A. B. A. Queiroz,[1,2★] F. Anders,[3,2] B. X. Santiago,[1,2] C. Chiappini,[3,2] M. Steinmetz,[3] M. Dal Ponte,[1,2] K. G. Stassun,[4] L. N. da Costa,[2,5] M. A. G. Maia,[2,5] T. C. Beers,[6] J. Crestani,[1,2] J. G. Fernández-Trincado,[7,8] D. A. García-Hernández,[9] A. Roman-Lopes,[10] O. Zamora,[9]

CoRoT-APOGEE project

Galactic archaeology with asteroseismology and spectroscopy:
Red giants observed by CoRoT and APOGEE

F. Anders[1,2], C. Chiappini[1,2], T. S. Rodrigues[2,3,4], A. Miglio[5], J. Montalbán[4], B. Mosser[6], L. Girardi[2,3], M. Valentini[1], A. Noels[7], T. Morel[7], J. A. Johnson[8], M. Schultheis[9], F. Baudin[10], R. de Assis Peralta[6], S. Hekker[11,12], N. Themeßl[11,12], T. Kallinger[13], R. A. García[14], S. Mathur[15], A. Baglin[6], B. X. Santiago[2,16], M. Martig[17], I. Minchev[1], M. Steinmetz[1], L. N. da Costa[2,18], M. A. G. Maia[2,18], C. Allende Prieto[19,20], K. Cunha[18], T. C. Beers[21], C. Epstein[8], A. E. García Pérez[19,20], D. A. García-Hernández[19,20], P. Harding[22], J. Holtzman[23], S. R. Majewski[24], Sz. Mészáros[25,26], D. Nidever[27], K. Pan[23,28], M. Pinsonneault[8], R. P. Schiavon[29], D. P. Schneider[30,31], M. D. Shetrone[32], K. Stassun[33], O. Zamora[19,20], G. Zasowski[34]



Galactic Archaeology with CoRoT and APOGEE:
Creating mock observations from a chemodynamical model

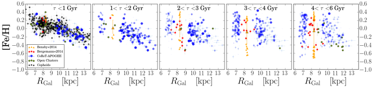
F. Anders[1,2], C. Chiappini[1,2], T. S. Rodrigues[2,3,4], T. Piffl[1], B. Mosser[5], A. Miglio[6], J. Montalbán[4], L. Girardi[3], I. Minchev[1], M. Valentini[1], and M. Steinmetz[1]

Young [α/Fe]-enhanced stars discovered by CoRoT and APOGEE:
What is their origin?

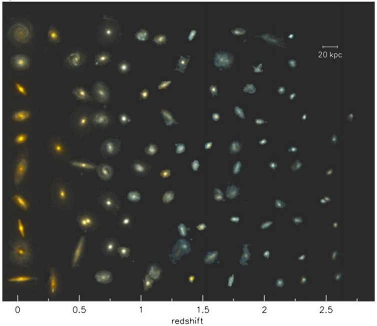
C. Chiappini[1,2], F. Anders[1,2], T. S. Rodrigues[2,3,4], A. Miglio[5], J. Montalbán[4], B. Mosser[6], L. Girardi[2,3], M. Valentini[1], A. Noels[7], T. Morel[7], I. Minchev[1], M. Steinmetz[1], B. X. Santiago[2,8], M. Schultheis[9], M. Martig[10], L. N. da Costa[2,11], M. A. G. Maia[2,11], C. Allende Prieto[12,13], R. de Assis Peralta[6], S. Hekker[14,15], N. Themeßl[14,15], T. Kallinger[16], R. A. García[17], S. Mathur[18], F. Baudin[19], T. C. Beers[20], K. Cunha[11], P. Harding[21], J. Holtzman[22], S. Majewski[23], Sz. Mészáros[24,25], D. Nidever[26], K. Pan[22,27], R. P. Schiavon[28], M. D. Shetrone[29], D. P. Schneider[30,31], K. Stassun[32]

Red giants observed by CoRoT and APOGEE:
The evolution of the Milky Way's radial metallicity gradient

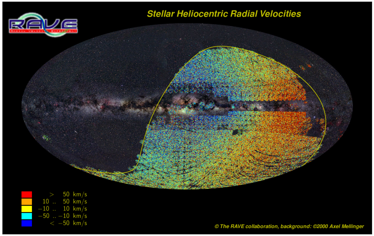
F. Anders[1,2], C. Chiappini[1,2], I. Minchev[1], A. Miglio[3], J. Montalbán[4], B. Mosser[5], T. S. Rodrigues[2,4,6], B. X. Santiago[2,7], F. Baudin[8], T. C. Beers[9], L. N. da Costa[2,10], R. A. García[11], D. A. García-Hernández[12,13], J. Holtzman[14], M. A. G. Maia[2,10], S. Majewski[15], S. Mathur[16], A. Noels-Grotsch[17], K. Pan[18,15], D. P. Schneider[19,20], M. Schultheis[21], M. Steinmetz[1], M. Valentini[1], O. Zamora[12,13]



The Milky Way in the context of galaxy evolution



Milky-Way-like galaxies at higher redshift: van Dokkum et al. 2013



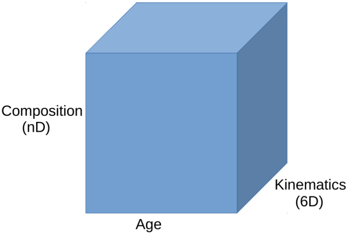
RAVE Collaboration; background image by A. Mellinger

Martig et al. (2012) simulation, movie courtesy of I. Minchev

Galactic Archaeology

- Combination of chemical evolution theory with stellar dynamics & cosmology – *how did the MW form and evolve?*
- Main observational question: how can we infer the star-formation, chemical-enrichment, accretion, and radial migration histories of the MW?
- Use empirical chemo-kinematical relations as well as forward modelling (Population synthesis, chemical evolution, pure dynamical + full chemodynamical models)
- Stars as Time Capsules: combine spectral analysis, photometry & astrometry

Dissecting the Age-kinematics-abundance hypercube

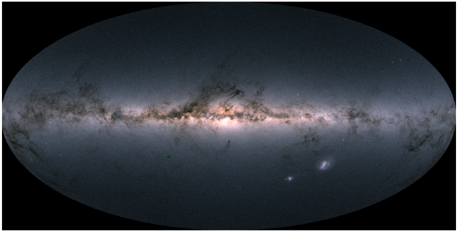


- Galactic models make predictions for the distribution of stars in this multi-dim. space (or its subspaces)
- Basic problem of Galactic Archaeology: dimensionality reduction
- *Single out the most robust and telling slices of this hypercube to constrain models for a given dataset*

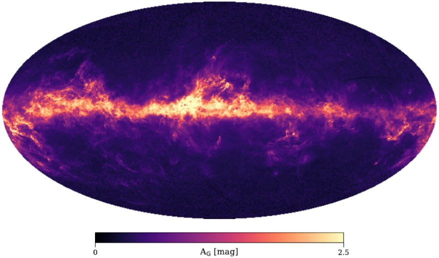
A short history of stellar distance measurements

- 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 pc volume)
- 2000s-2010s: spectroscopic surveys ($\sim 10^6$ stars)

A new era: What *Gaia* DR2 brought us



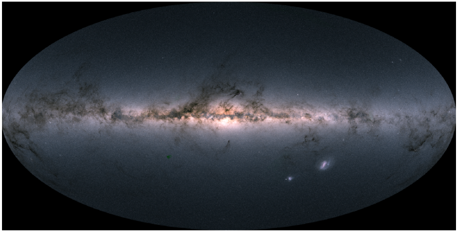
Gaia Collaboration, Brown, et al. (2018)



Andrae et al. (2018)

- 1.7 billion stars with 5D astrometric parameters!
- Improved precision and accuracy with respect to DR1, less correlated uncertainties: $\sigma_{\varpi} < 0.15$ mas up to $G = 18$
- 3-band photometry for 1.3 billion stars
- Extinction and temperatures for 80 million stars
- Radial velocities for $\sim 7 \cdot 10^6$ stars up to $G \lesssim 12$

A new era: What *Gaia* DR2 brought us



Gaia Collaboration, Brown, et al. (2018)

- 1 billion stars with 5D astrometric parameters!
- New parallax horizon: 100 pc $\longrightarrow \sim$ 2 kpc
- Radial velocities for $\sim 7 \cdot 10^6$ stars up to $G < 12$

Coupled with spectroscopy:

- High-precision chemical abundances, possibly also precise stellar ages!
- Distances and ages for stars farther than $\sim$ 3 kpc
- Radial velocities for the fainter stars

Leaving the solar vicinity with *Gaia* + spectroscopic surveys

Stellar distances computed with `StarHorse` (Queiroz, Anders et al. 2018). Movie courtesy of G. Matijevič (AIP).

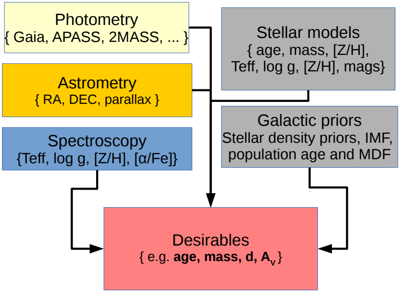
The StarHorse code

Spectro-photometric distances to stars: A general purpose Bayesian approach

Basílio X. Santiago[1,2], Dorothée E. Brauer[3], Friedrich Anders[3,2], Cristina Chiappini[3,2], Anna B. Queiroz[1,2], Léo Girardi[4,2], Helio J. Rocha-Pinto[5,2], Eduardo Balbinot[1,2], Luiz N. da Costa[6,2], Marcio A.G. Maia[6,2], Mathias Schultheis[7], Matthias Steinmetz[3], Andrea Miglio[8], Josefina Montalbán[9], Donald P. Schneider[10,11], Timothy C. Beers[12], Peter M. Frinchaboy[13], Young Sun Lee[14], and Gail Zasowski[15]

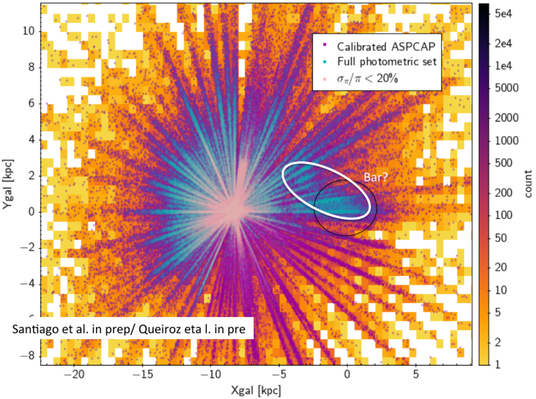
StarHorse: A Bayesian tool for determining stellar masses, ages, distances, and extinctions for field stars

A. B. A. Queiroz,[1,2]* F. Anders,[3,2] B. X. Santiago,[1,2] C. Chiappini,[3,2] M. Steinmetz,[3] M. Dal Ponte,[1,2] K. G. Stassun,[4] L. N. da Costa,[2,5] M. A. G. Maia,[2,5] T. C. Beers,[6] J. Crestani,[1,2] J. G. Fernández-Trincado,[7,8] D. A. García-Hernández,[9] A. Roman-Lopes,[10] O. Zamora,[9]



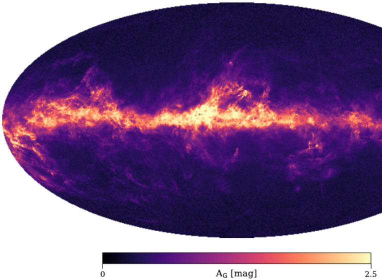
- Code grew with necessities: from simple Bayesian distances in Fortran to flexible multi-purpose `python` code
- Bayesian parameter estimation by comparing data to stellar models (default: PARSEC 1.2S)
- Priors: stellar density, age distribution, and metallicity distribution for main Galactic components (2 discs, halo, bulge)

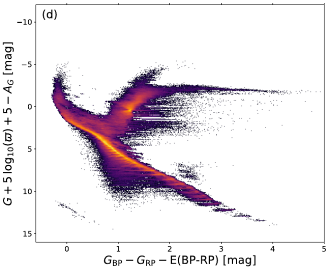
Leaving the solar vicinity with *Gaia* + APOGEE (pre-DR16)



- Typical uncertainties: $\sigma_d/d \sim 5\%$ (10% beyond GDR2 parallax sphere), $\sigma_{A_V} \sim 0.08$ mag with PanSTARRS-1, 0.2 mag without
- Clear overdensity in the bar region (almost direct imaging!)

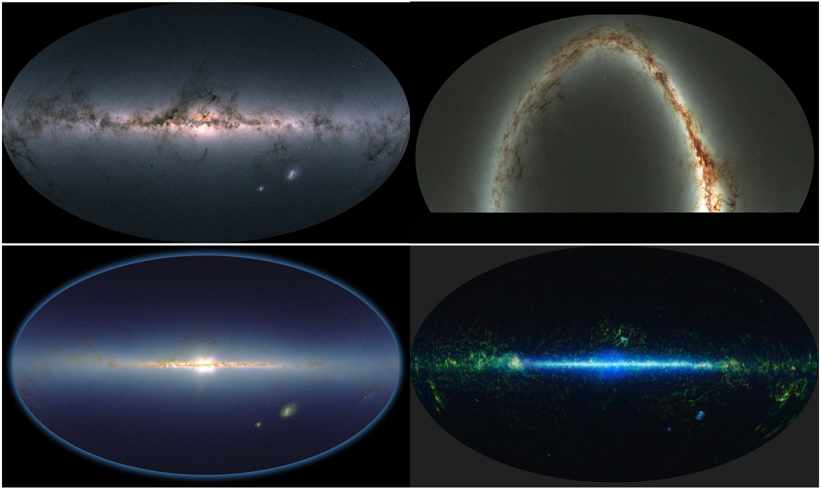
But what about the other billion *Gaia* stars?





- First try: CU8/APSIS results for 80 million stars (Andrae+2018)
- "substantially better results are likely achievable when combining [GDR2] with other data"

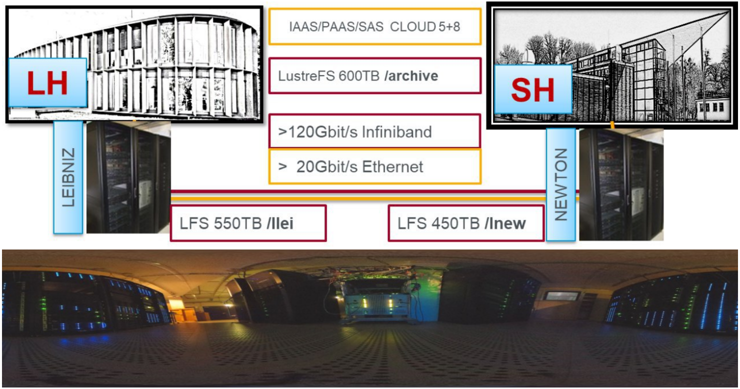
Combining GDR2 with photometric surveys



AIP e-science infrastructure used

Arman in action

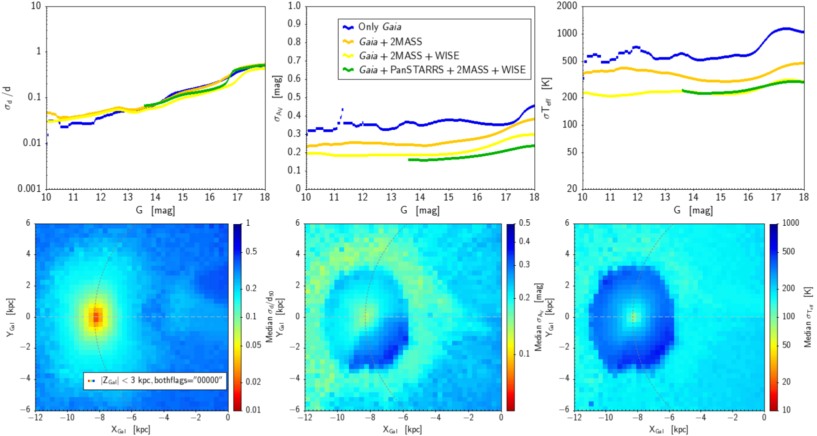
- `StarHorse` implemented to run in parallel on `newton` (1000 cores)
- Takes 1 sec/star for sparse isochrone grid ($G > 14$, 270M), 20 sec/star for fine grid ($G < 14$, 16M)
- Total: 164,000 CPU hours (19 years on single core...)



Statistics

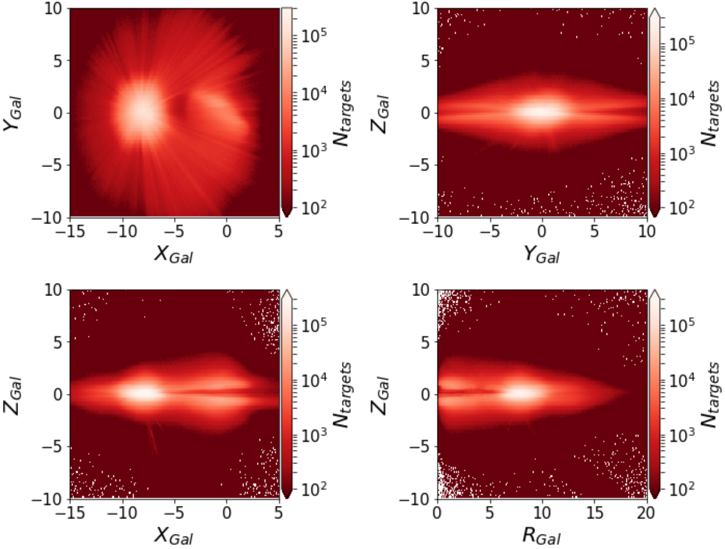
Reference	Survey(s)	#	σ_d/d	σ_{A_V}	$\sigma_{T_{\rm eff}}$
Queiroz+2018	GDR1 + spectra	2M	15 %	0.08 mag	–
Mints+2018	GDR1 + spectra	3M	15 %	0.12 mag	–
Sanders&Das 2018	GDR2 + spectra	3M	12 %	–	–
Bailer-Jones+2018	GDR2 ($G \lesssim 21$)	1330M	25 %	–	–
Andrae+2018	GDR2 ($G \leq 17$)	80M	–	0.5 mag	324 K
StarHorse	GDR2X ($G < 18$)	285M			
converged		265M	28 %	0.25 mag	310 K
$\varpi^{\rm cal}/\sigma_{\varpi}^{\rm cal} > 5$		103M	9 %	0.20 mag	265 K
SH_GAIAFLAG="000"		232M	26 %	0.24 mag	305 K
SH_OUTFLAG="00000"		151M	13 %	0.22 mag	250 K
both flags		136M	13 %	0.22 mag	250 K
All photometry		34M	12 %	0.18 mag	220 K
GDR2+2MASS+WISE		52M	9 %	0.21 mag	230 K
GDR2+2MASS		28M	17 %	0.28 mag	300 K
GDR2 only		2M	18 %	0.35 mag	390 K
$G \leq 14$		14M	5 %	0.20 mag	245 K
$14 < G \leq 16$		49M	12 %	0.20 mag	245 K
$16 < G \leq 17$		43M	16 %	0.23 mag	260 K
$17 < G \leq 18$		30M	14 %	0.24 mag	230 K

Resulting uncertainties ($d, A_V, T_{\rm eff}$)



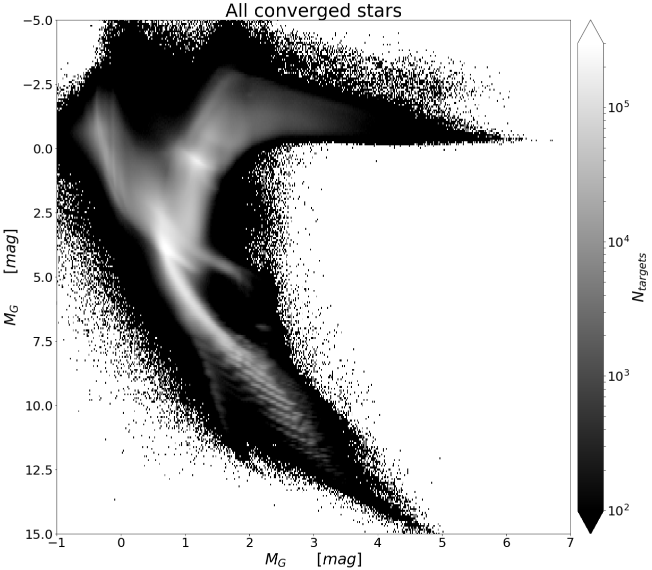
Anders et al. (in prep.)

StarHorse density maps



Anders et al. (in prep.)

StarHorse extinction-corrected CMD



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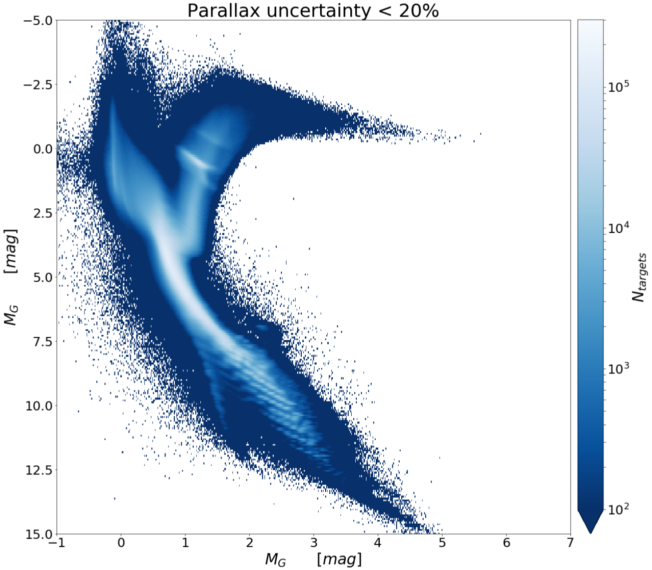
StarHorse extinction-corrected CMD



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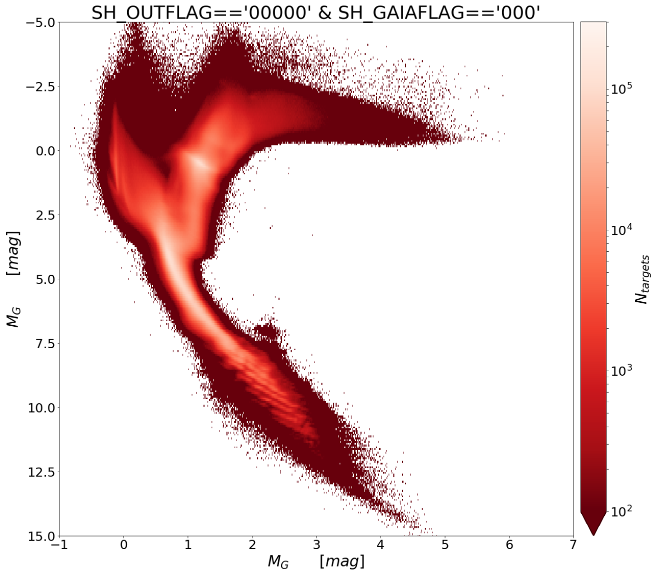
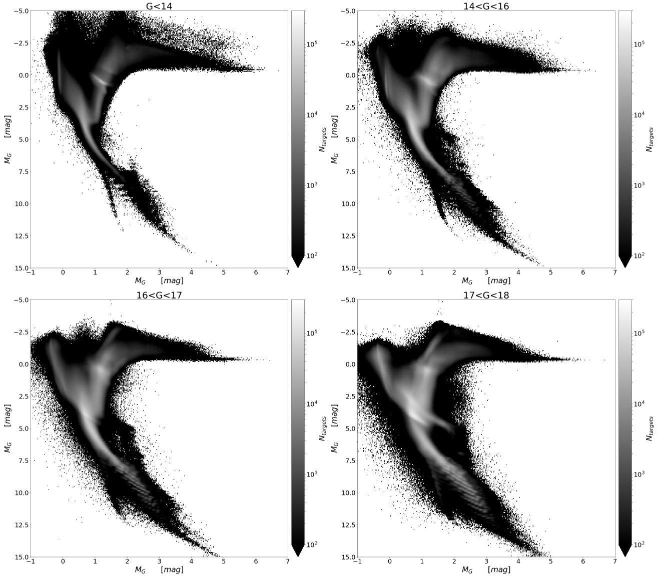
StarHorse extinction-corrected CMD



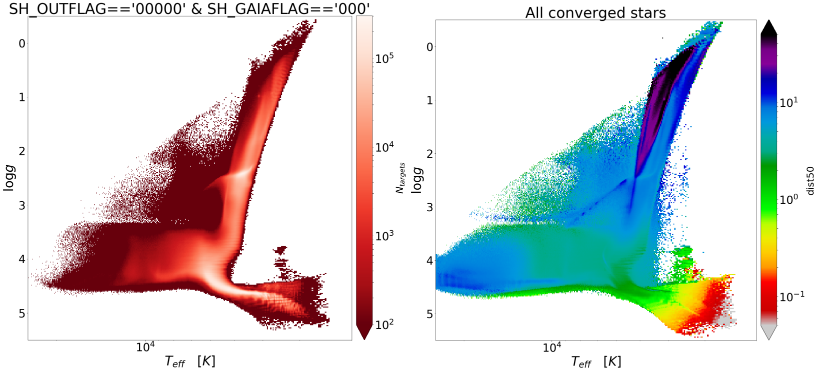
Anders et al. (in prep.)

StarHorse CMD - Magnitude bins



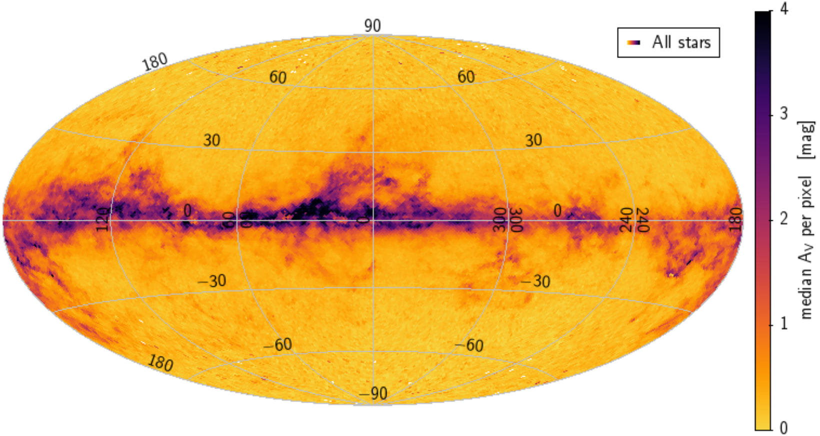
Anders et al. (in prep.)

StarHorse *Kiel* diagrams



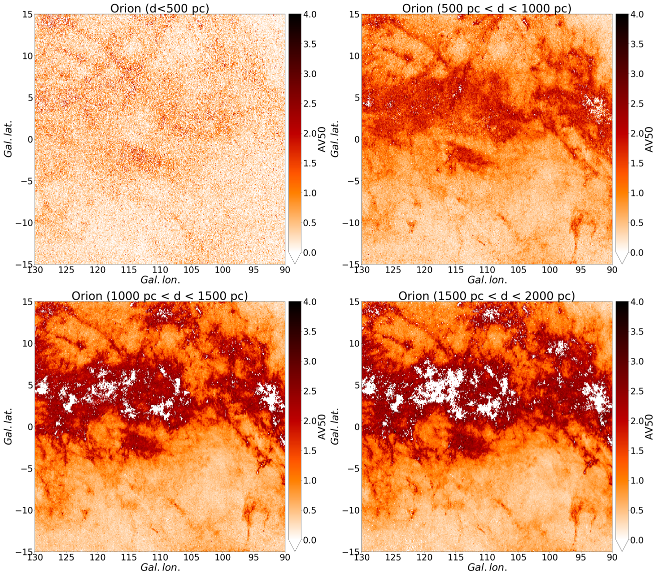
Anders et al. (in prep.)

StarHorse A_V maps



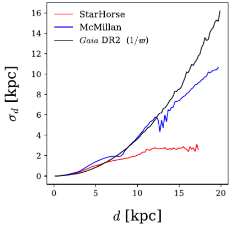
Anders et al. (in prep.)

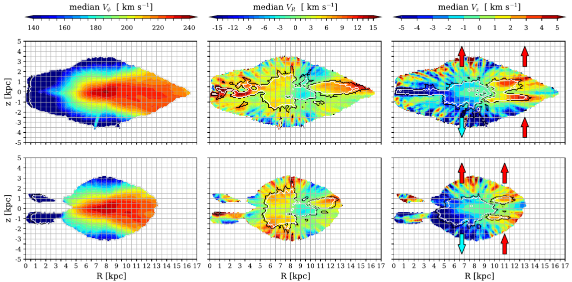
StarHorse A_V maps - Orion

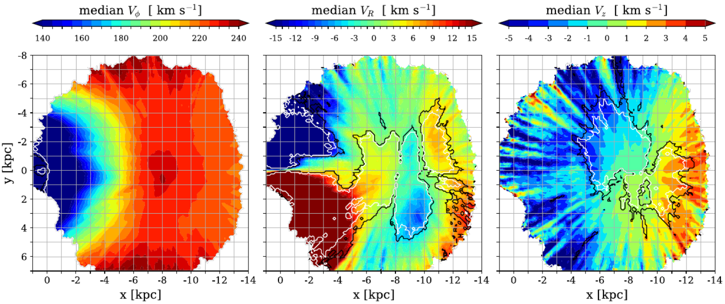


Anders et al. (in prep.)

First use cases: Galaxy dynamics

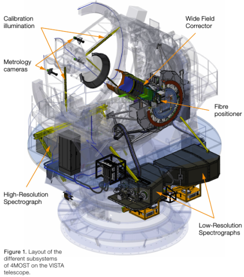


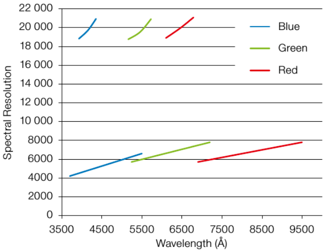


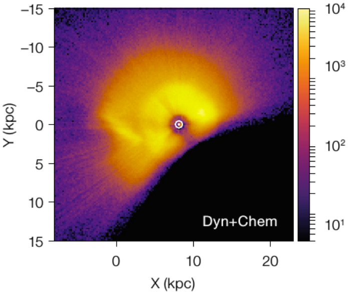


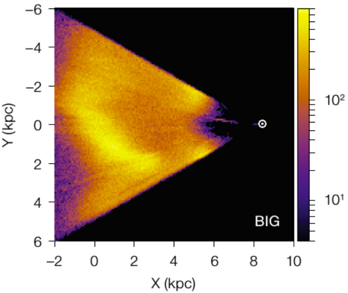
Carrillo et al. (2019)

First use cases: 4MOST survey planning



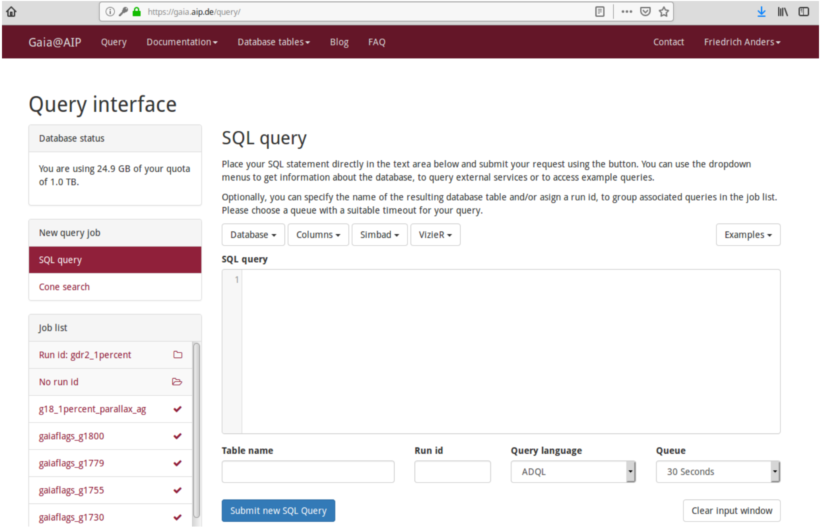




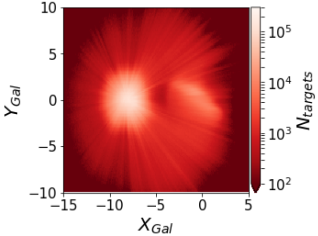


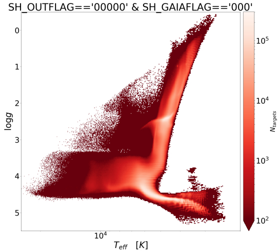
The ESO Messenger 175 (March 2019): de Jong et al. (2019), Chiappini et al. (2019)

Results soon available at GDR2 mirror: gaia.aip.de

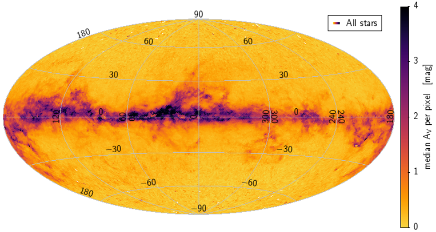


Plans for the fellowship I - Publish StarHorse paper + catalogue

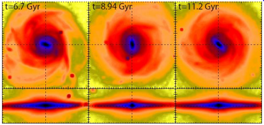


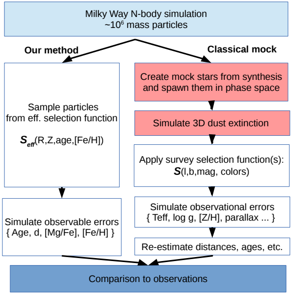


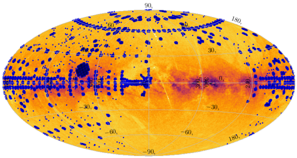
- Provide Gaia value-added catalogues (d, A_V, $T_{\rm eff}$, $\log g$, $[\mathrm{M/H}]$, M_*) for *Gaia* DR2 + photometry using StarHorse (Anders et al., in prep.)



Plans for the fellowship II - *Gaia* mock catalogues



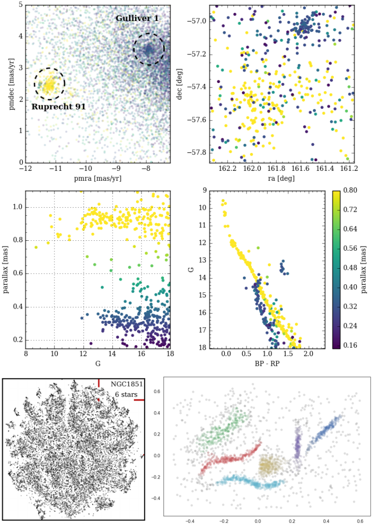




- Create a code- and database to create Gaia-like mock observations of state-of-the-art MW models (as done for the small CoRoGEE dataset in Anders et al. 2016
- This approach allows to correct for geometric and stellar-population survey biases, and to treat models and data in the exact same way

Plans for the fellowship III - Data mining with *Gaia DR2*

New open clusters found in GDR2 (Cantat-Gaudin et al. 2018)



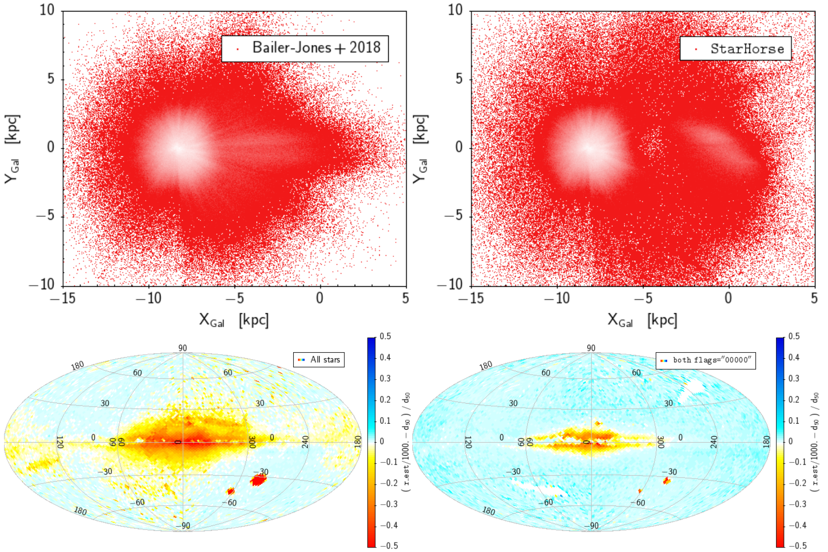
t-SNE (Fig. from Kos et al. 2017) + HDBSCAN

- *Gaia* DR2 is subject to less covariance issues - an ideal playground for data mining!
- Promising first results from work in progress with *Gaia* DR1/TGAS: Coupling dimensionality reduction techniques with novel clustering algorithms yields new clusters & moving groups!
- Many more clusters and dynamical features to be discovered with DR2
- Machine-learning also most useful for Galactic Archaeology: chemical/chemo-kinematical tagging will be possible with the DR2 + sectroscopic surveys

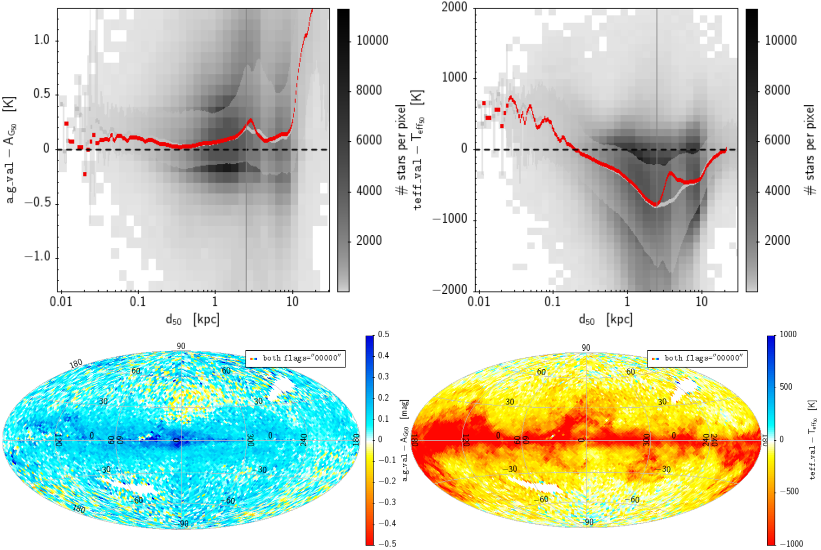
Calibrations

Parameter	Parameter regime	Calibration choice	Reference
ϖ	$G < 14$	parallax $+ 0.05$ mas	Zinn+2018, Lindegren 2
	$14 < G < 16.5$	parallax $+ (0.1676 - 0.0084 \cdot$ phot_g_mean_mag) mas	Lindegren 2018, linear i
	$G > 16.5$	parallax $+ 0.029$ mas	Arenou+2018 Lindegren
σ_ϖ	$G < 11$	$1.2 \cdot$ parallax_error	Lindegren 2018
	$11 < G < 15$	$(0.22 \cdot$ phot_g_mean_mag $- 1.22) \cdot$ parallax_error	Lindegren 2018, linear i
	$G > 15$	$(\mathrm{e}^{-(\texttt{phot\_g\_mean\_mag} - 15)} + 1.08) \cdot$ parallax_error	Lindegren 2018
G	$G < 6$	phot_g_mean_mag $+ 0.0271 \cdot (6 -$ phot_g_mean_mag)	Maiz&Weiler 2018
	$6 < G < 16$	phot_g_mean_mag $- 0.0032 \cdot$ (phot_g_mean_mag $- 6$)	Maiz&Weiler 2018
	$G > 16$	phot_g_mean_mag $- 0.032$	Maiz&Weiler 2018
G_{BP}	$G < 10.87$	using bright G_{BP} filter curve	Maiz&Weiler 2018
	$G > 10.87$	using faint G_{BP} filter curve	Maiz&Weiler 2018
g_{PS1}	$G > 14$	g_mean_psf_mag $- 0.020$	Scolnic+2015
r_{PS1}		r_mean_psf_mag $- 0.033$	Scolnic+2015
i_{PS1}		i_mean_psf_mag $- 0.024$	Scolnic+2015
z_{PS1}		z_mean_psf_mag $- 0.028$	Scolnic+2015
y_{PS1}		y_mean_psf_mag $- 0.011$	Scolnic+2015
σ_{mag}	*Gaia*, 2MASS, WISE	$\max\{\sigma_{\mathrm{mag,source}}, 0.03\mathrm{mag}\}$	
	PanSTARRS-1	$\max\{\sigma_{\mathrm{mag,source}}, 0.04\mathrm{mag}\}$	

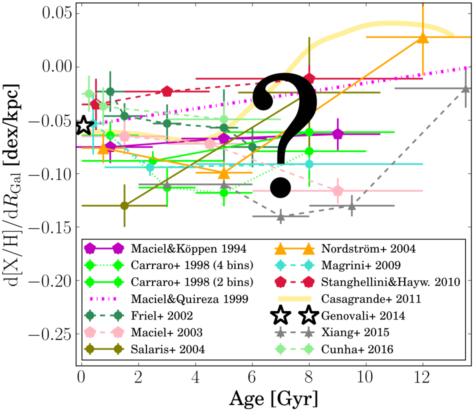
Comparison to Bailer-Jones+2018



Comparison to Andrae+2018

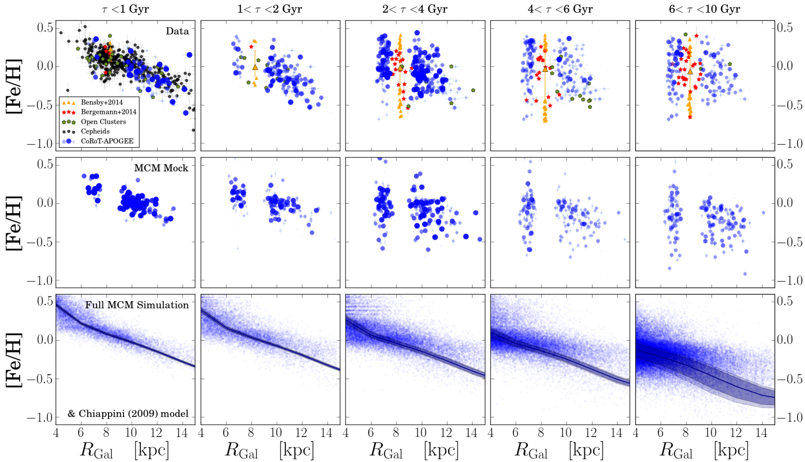


Evolution of the radial abundance gradients

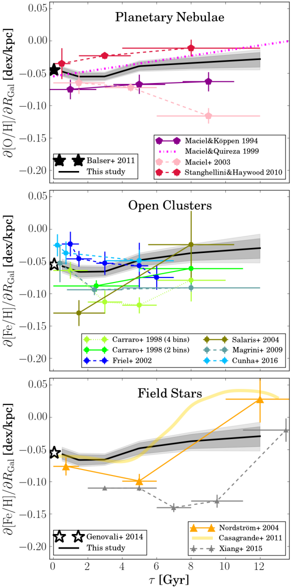


- 20-year dispute in chemical-evolution theory *and* observations: did the gradient flatten or steepen with time?
- How much did radial migration smear out the gradient over time?
- Consequences on the MW disc initial conditions + accretion/enrichment history

Evolution of the radial abundance gradients



Quantifying the gradient evolution



Anders et al. (2017b)

- Classical tracers suffer from low number statistics and unknown selection biases (OCs) or uncertain age and distance estimates (PNe)
- Results in very good agreement with young Cepheids & HII regions
- Gradient slope of 1–4 Gyr population marginally steeper than youngest population
- Radial mixing smears out the gradient of the older populations $\longrightarrow$ main driver of the gradient evolution for $\tau \gtrsim 2$ Gyr
- Our analysis relied on just 400 stars and already supersedes OC and PNe results – just the beginning of the fruitful synergy between seismology and spectroscopy