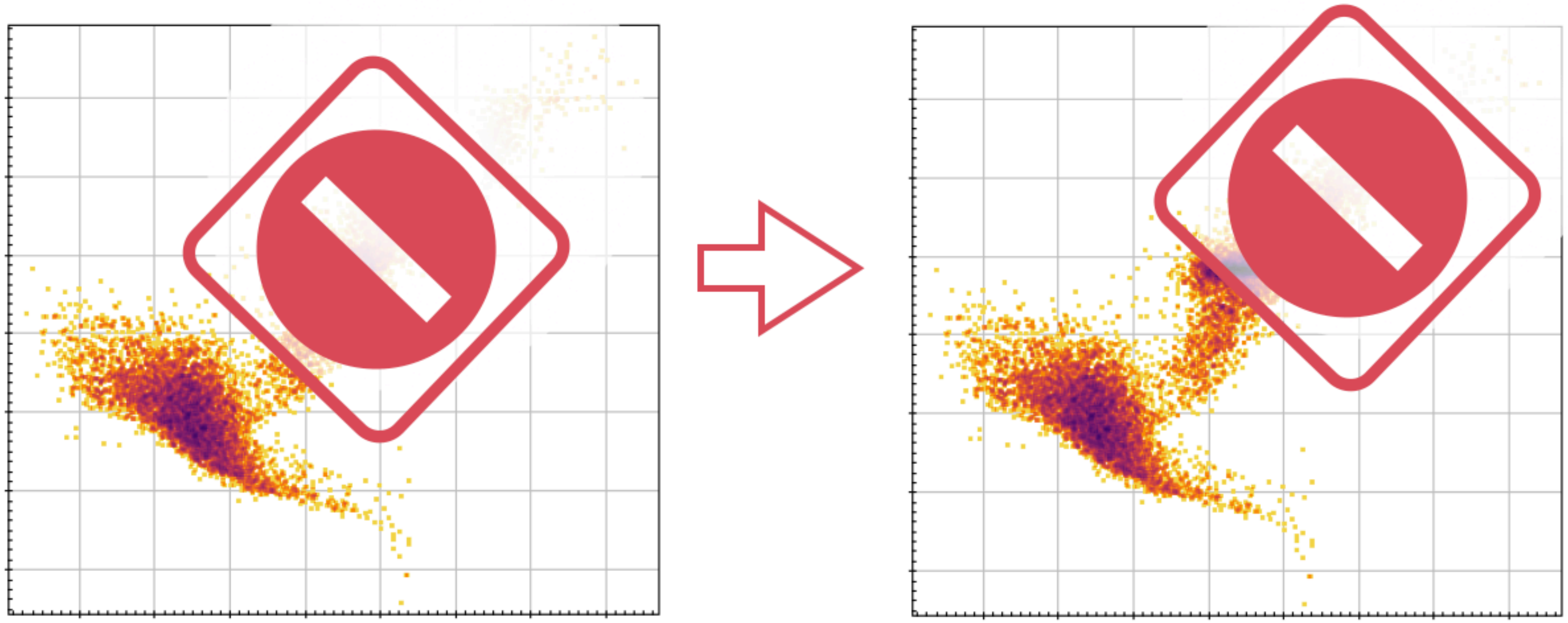
Asteroseismology with CoRoT, Kepler, K2 and TESS: impact on Galactic Archaeology



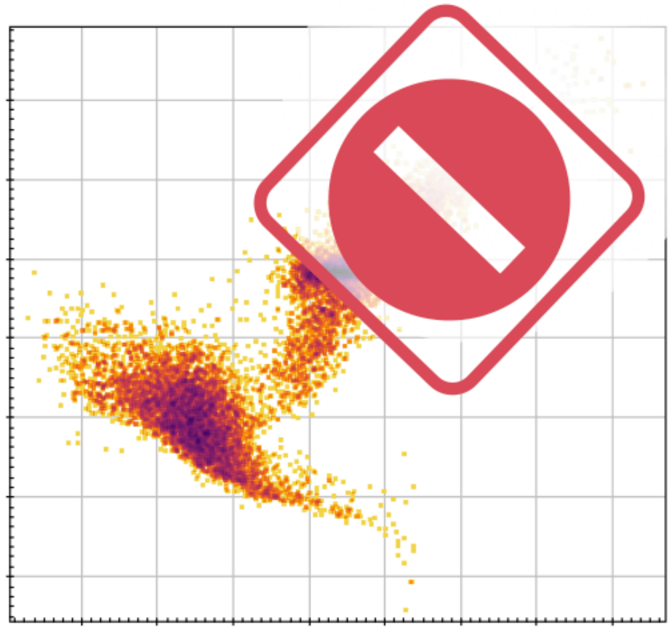
Miglio's talk

CRISTINA CHIAPPINI

Leibniz-Institut fuer Astrophysik Potsdam

PLATO PIC, Padova 09/2019

Plato *as it is* : a Legacy Mission for Galactic Archaeology



Miglio’s talk

AIP

CRISTINA CHIAPPINI

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PLATO PIC, Padova 09/2019

The PLATO 2.0 Mission

28.02.2014

H. Rauer[1,2], C. Catala[3], C. Aerts[4], T. Appourchaux[5], W. Benz[6], A. Brandeker[7], J. Christensen-Dalsgaard[8], M. Deleuil[9], L. Gizon[10,25], M.-J. Goupil[3], M. Güdel[11], E. Janot-Pacheco[12], M. Mas-Hesse[13], I. Pagano[14], G. Piotto[15], D. Pollacco[16], N.C. Santos[17], A. Smith[18], J.-C., Suárez[19], R. Szabó[20], S. Udry[21], V. Adibekyan[17], Y. Alibert[6], J.-M. Almenara[9], P. Amaro-Seoane[22], M. Ammler-von Eiff[23], M. Asplund[42], E. Antonello[24], W. Ball[25], S. Barnes[26], F. Baudin[5], K. Belkacem[3], M. Bergemann[27], G. Bihain[26], A.C. Birch[10], X. Bonfils[40], I. Boisse[17], A.S. Bonomo[28], F. Borsa[24], I.M. Brandão[17], E. Brocato[29], S. Brun[30], M. Burleigh[31], R. Burston[10], J. Cabrera[1], S. Cassisi[33], W. Chaplin[34], S. Charpinet[35], C. Chiappini[26], R.P. Church[36], Sz. Csizmadia[1], M. Cunha[17], M. Damasso[15,28], M.B. Davies[36], H.J. Deeg[37], R. F. Díaz[21], S. Dreizler[25], C. Dreyer[1,2], P. Eggenberger[21], D. Ehrenreich[21], P. Eigmüller[1], A. Erikson[1], R. Farmer[39], S. Feltzing[36], F. de Oliveira Fialho[38], P. Figueira[17], T. Forveille[40], M. Fridlund[1], R.A. García[30], P. Giommi[41], G. Giuffrida[29,41], M. Godolt[1], J. Gomes da Silva[17], T. Granzer[26], J.L. Grenfell[1], A. Grotsch-Noels[43], E. Günther[23], C.A. Haswell[39], A.P. Hatzes[23], G. Hébrard[44], S. Hekker[10,45], R. Helled[46], K. Heng[6], J.M. Jenkins[47], A. Johansen[36], M.L. Khodachenko[48], K.G. Kislyakova[48], W. Kley[49], U. Kolb[39], N. Krivova[10], F. Kupka[50], H. Lammer[48], A.F. Lanza[14], Y. Lebreton[3], D. Magrin[51], P. Marcos-Arenal[4], P.M. Marrese[29,41], J.P. Marques[25], J. Martins[17], S. Mathis[30], S. Mathur[52], S. Messina[14], A. Miglio[34], J. Montalban[43], M. Montalto[17], M.J.P.F.G. Monteiro[17], H. Moradi[53], E. Moravveji[4], C. Mordasini[54], T. Morel[43], A. Mortier[17], V. Nascimbeni[15], R.P. Nelson[60], M.B. Nielsen[25], L. Noack[32], A.J. Norton[39], A. Ofir[25], M. Oshagh[17], R.-M. Ouazzani[3], P. Pápics[4], V. C. Parro[55], P. Petit[56], B. Plez[57], E. Poretti[24], A. Quirrenbach[58], R. Ragazzoni[51], G. Raimondo[33], M. Rainer[24], D.R. Reese[43], R. Redmer[59], S. Reffert[58], B. Rojas-Ayala[17], I.W. Roxburgh[60], S. Salmon[43], A. Santerne[17], J. Schneider[3], J. Schou[10], S. Schuh[10], H. Schunker[10], A. Silva-Valio[61], R. Silvotti[28], I. Skillen[62], I. Snellen[63], F. Sohl[1], S.G. Sousa[17], A. Sozzetti[28], D. Stello[69], K. G. Strassmeier[26], M. Švanda[64], Gy. M. Szabó[20,65], A. Tkachenko[4], D. Valencia[66], V. Van Grootel[43], S.D. Vauclair[35], P. Ventura[29], F.W. Wagner[1], N.A. Walton[67], J. Weingrill[26], S.C. Werner[68], P.J. Wheatley[16], K. Zwintz[4]

Furthermore, the mission has the potential to detect exomoons, planetary rings, binary and Trojan planets. The planetary science possible with PLATO 2.0 is complemented by its impact on stellar and galactic science via asteroseismology as well as light curves of all kinds of variable stars, together with observations of stellar clusters of different ages. This will allow us to improve stellar models and study stellar activity. A large number of well-known ages from red giant stars will probe the structure and evolution of our Galaxy. Asteroseismic ages of bright stars for different phases of stellar evolution allow calibrating stellar age-rotation relationships. Together with the results of ESA's Gaia mission, the results of PLATO 2.0 will provide a huge legacy to planetary, stellar and galactic science.

Galactic Archaeology strives to reconstruct the past history of the Milky Way from the present day kinematical and chemical information.

Why is it Challenging ?

- Complex mix of populations with large **overlaps in parameter space** (such as Velocities, Metallicities, and Ages) **& small volume sampled by current data**

- **Stars move away from their birth places** (migrate radially, or even vertically via mergers/interactions of the MW with other Galaxies).

- **Many are the sources of migration**!

- Most of information **was confined to a small volume**

Key: **VOLUME COVERAGE & AGES**

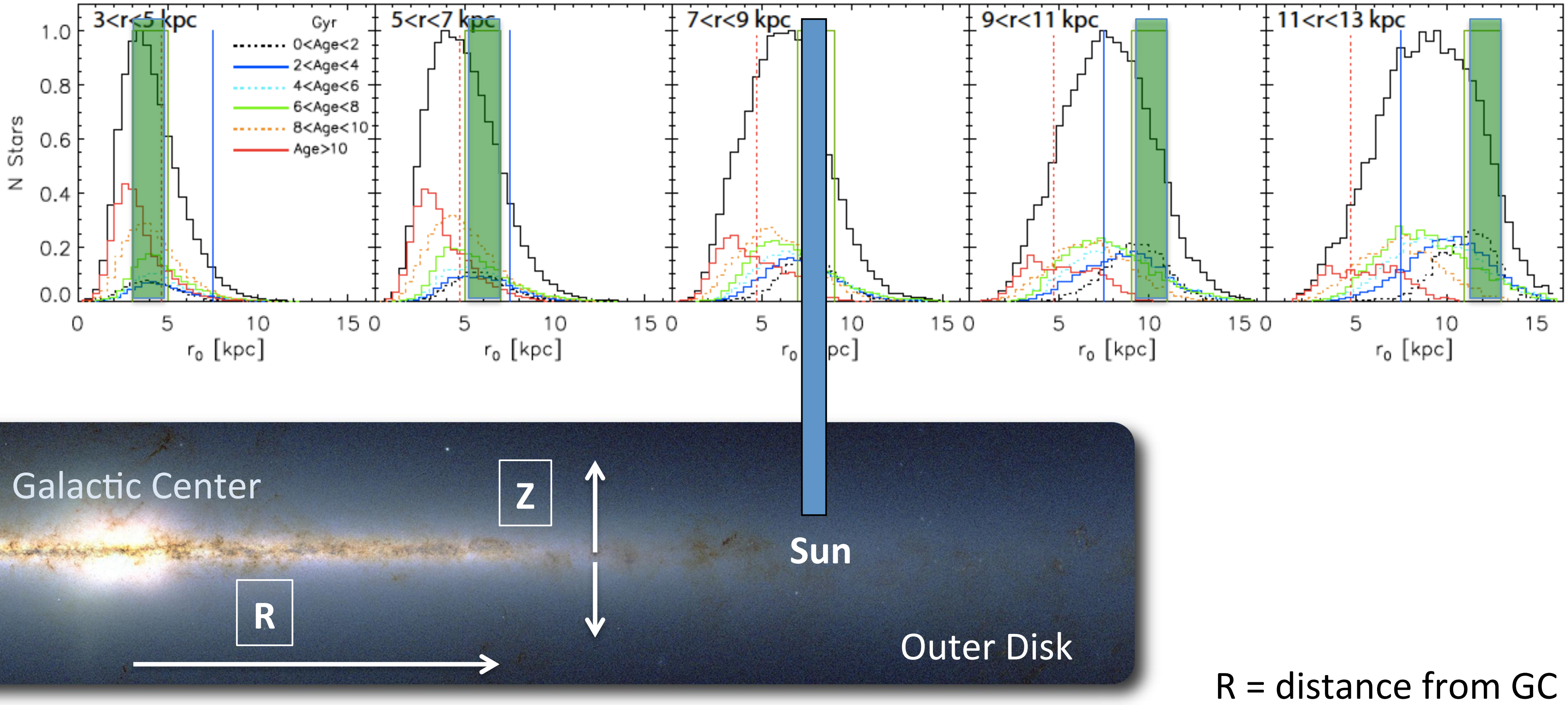
Miglio, Chiappini et al. 2017
Chiappini et al. 2018 IAU 334

Quantifying the impact of radial migration

The R_{birth} mix !

Stars that today (R_now) are in the green bins, came from different R0=birth

Radial Migration Sources = bar/spirals + mergers + Inside-out formation (gas accretion)



R = distance from GC

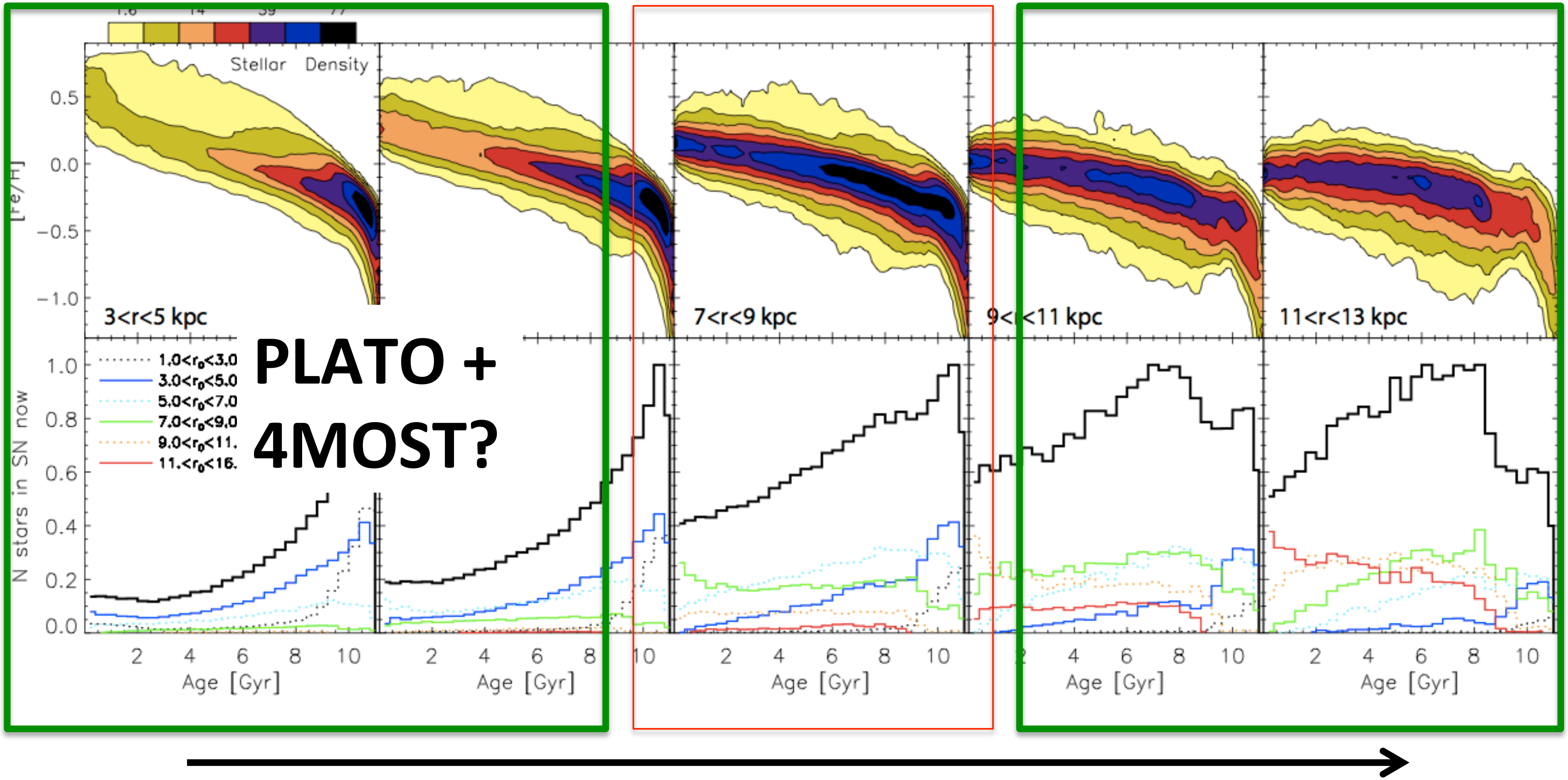
Minchev, Chiappini, Martig 2013, 2014 - MCM I + II A&A A&A 558 id A09, A&A 572, id A92

Two ways to expand volume for GA

- Gaia + complementary photometric information (but no ages for far away stars) – **also useful for PIC!**
- Asteroseismology of RGs (with ages!) - **also useful for core science PLATO (miglio's talk)**

The properties at different places in the disk: AMR

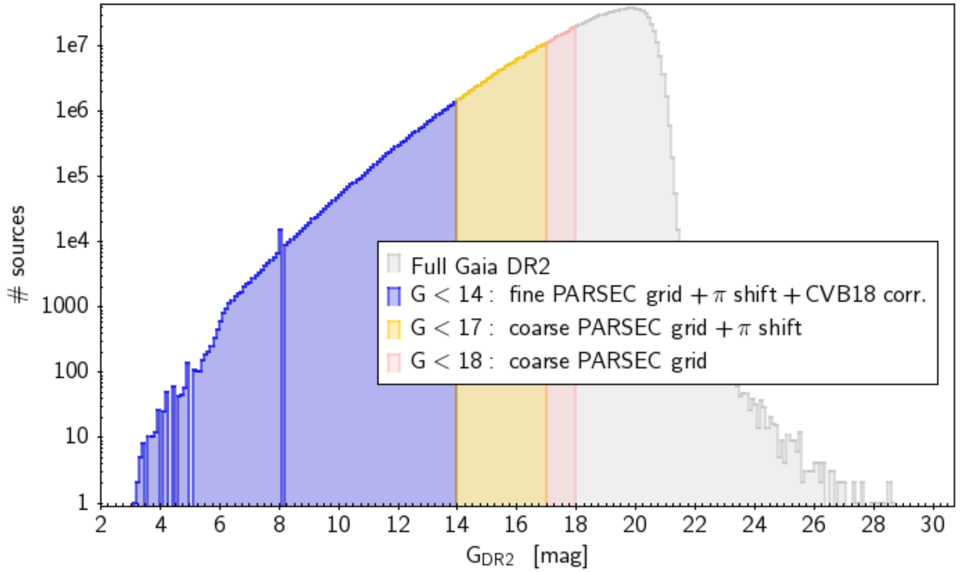
CoRoT, Gaia+, K2 + APOGEE **Kepler, TESS, K2, Gaia** **CoRoT, Gaia+, K2 + APOGEE**

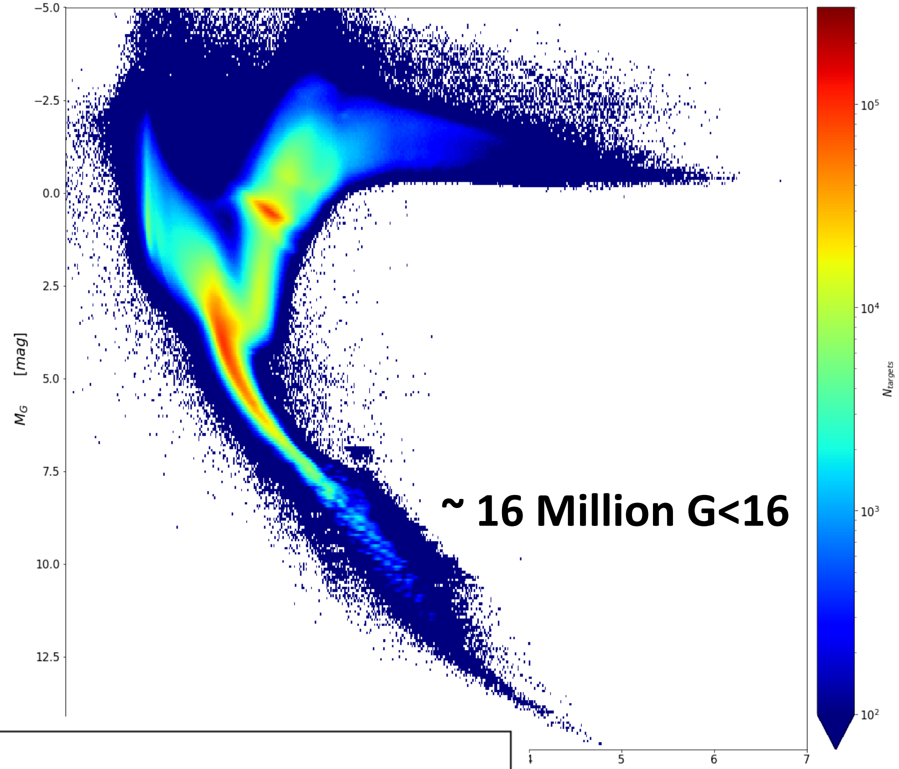


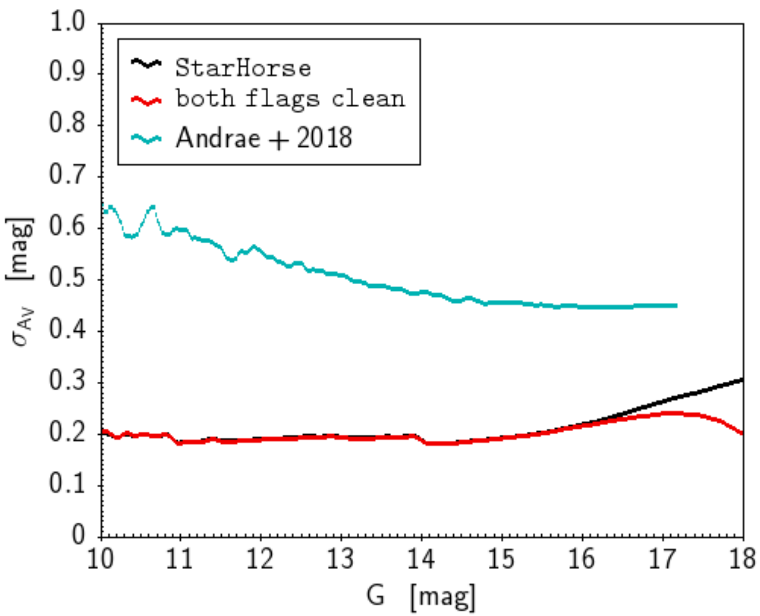
Prediction: AMR Scatter increases towards outer regions

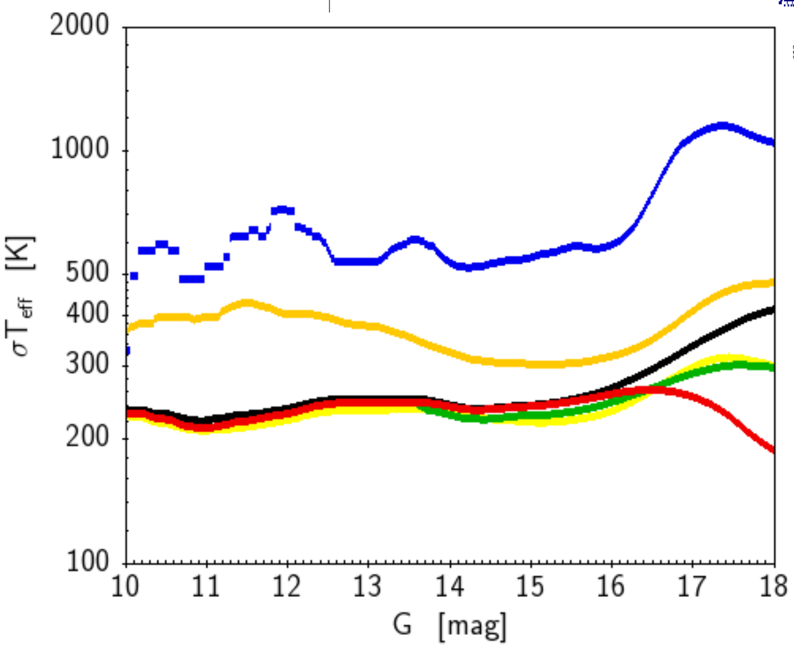
Age scatter increasestowars outer regions

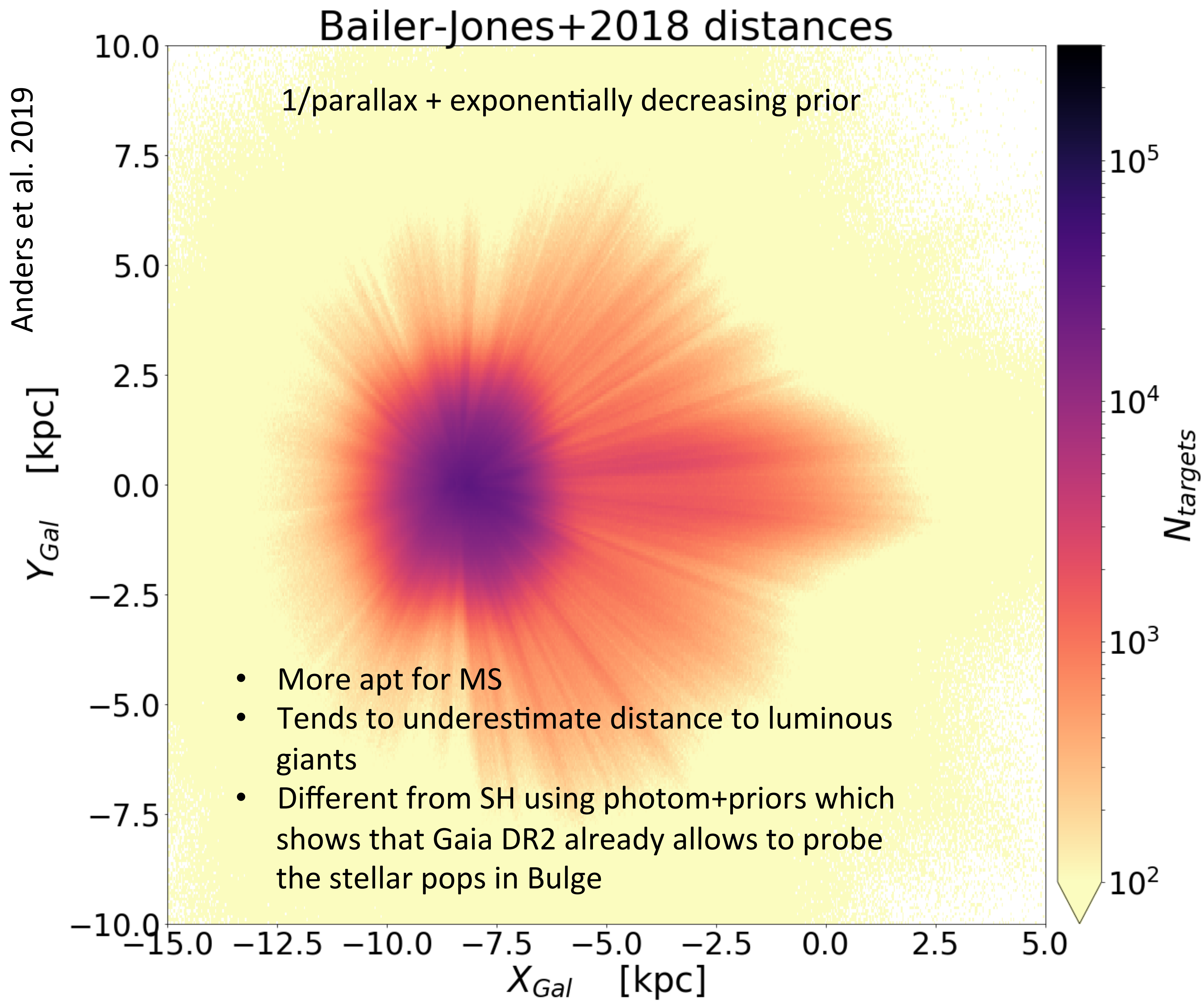
Extracting the best from GaiaDR2 - Anders et al. 2019 – see ESA PR





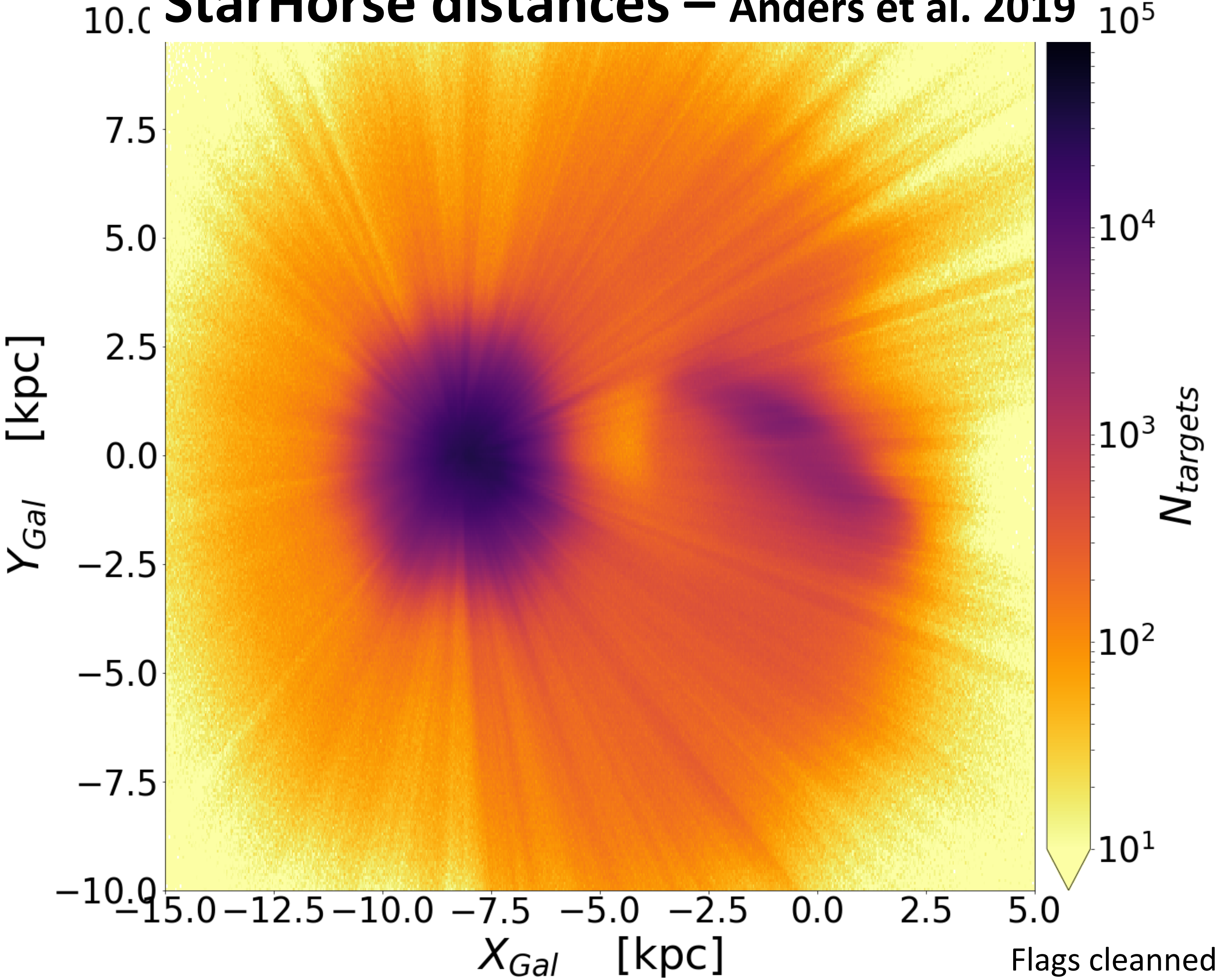






Bailer-Jones+2018 distances
1/parallax + exponentially decreasing prior
Anders et al. 2019
Y_{Gal} [kpc]
X_{Gal} [kpc]
$N_{targets}$
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
−15.0
−12.5
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
10^5
10^4
10^3
10^2
• More apt for MS
• Tends to underestimate distance to luminous giants
• Different from SH using photom+priors which shows that Gaia DR2 already allows to probe the stellar pops in Bulge

StarHorse distances – Anders et al. 2019



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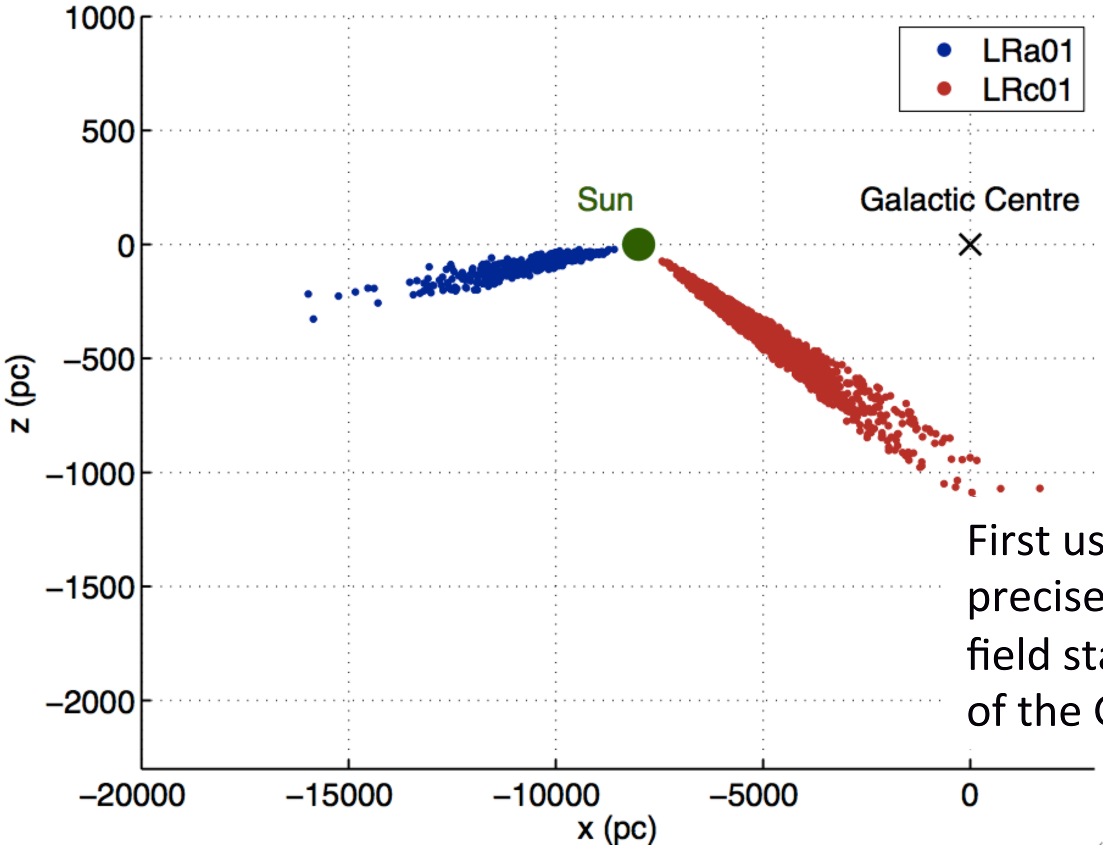
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 429, 423–428 (2013) doi:10.1093/mnras/sts345

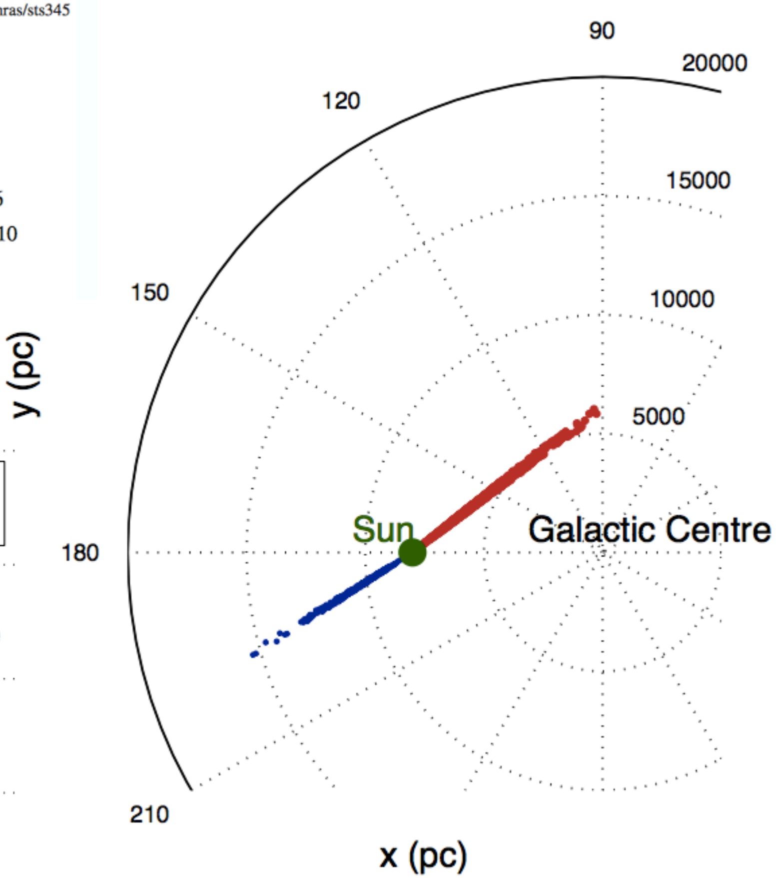
Galactic archaeology: mapping and dating stellar populations with asteroseismology of red-giant stars

A. Miglio,[1,2★] C. Chiappini,[3] T. Morel,[4] M. Barbieri,[5] W. J. Chaplin,[1] L. Girardi,[6] J. Montalbán,[4] M. Valentini,[4] B. Mosser,[7] F. Baudin,[8] L. Casagrande,[9] L. Fossati,[10] V. Silva Aguirre[11] and A. Baglin[7]

CoRoT

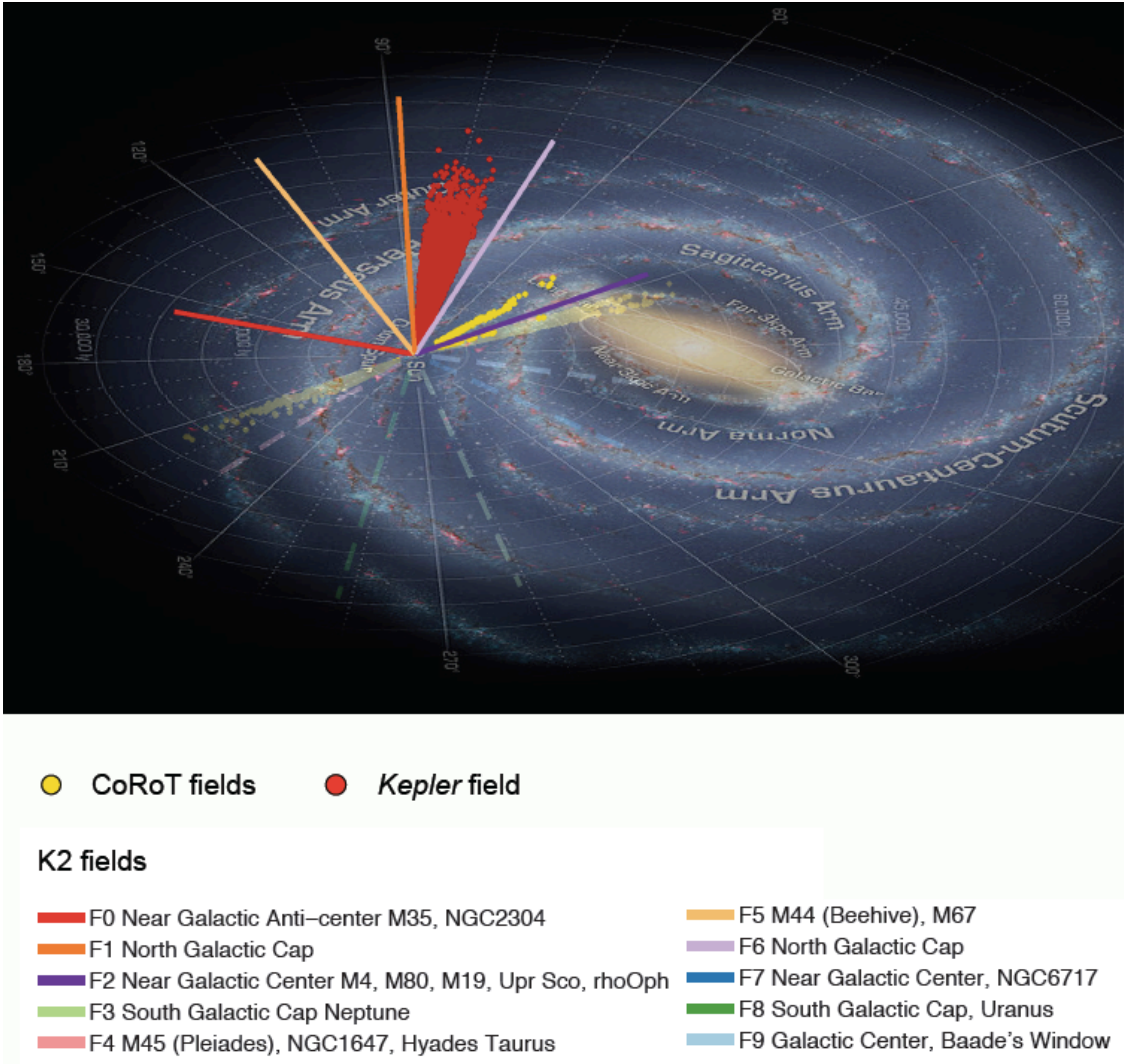
Different Mass Distributions -> Age vertical gradient





First use of asteroseismology to determine precise distances for a large (~2000) sample of field stars (giants) spread across nearly 15 kpc of the Galactic disc.

- Uncertainty on M ~ 10%
- Uncertainty on R ~ 3%


Sagittarius Arm
Norma Arm
Scutum-Centaurus Arm
Far 3kpc Arm
Galactic Bar
90°
120°
150°
180°
210°
240°
270°
300°
60°
CoRoT fields
Kepler field
K2 fields
F0 Near Galactic Anti–center M35, NGC2304
F1 North Galactic Cap
F2 Near Galactic Center M4, M80, M19, Upr Sco, rhoOph
F3 South Galactic Cap Neptune
F4 M45 (Pleiades), NGC1647, Hyades Taurus
F5 M44 (Beehive), M67
F6 North Galactic Cap
F7 Near Galactic Center, NGC6717
F8 South Galactic Cap, Uranus
F9 Galactic Center, Baade's Window

Seismology of RG – 5 selected highlights

With Seismic information from Solar-like oscillating giants

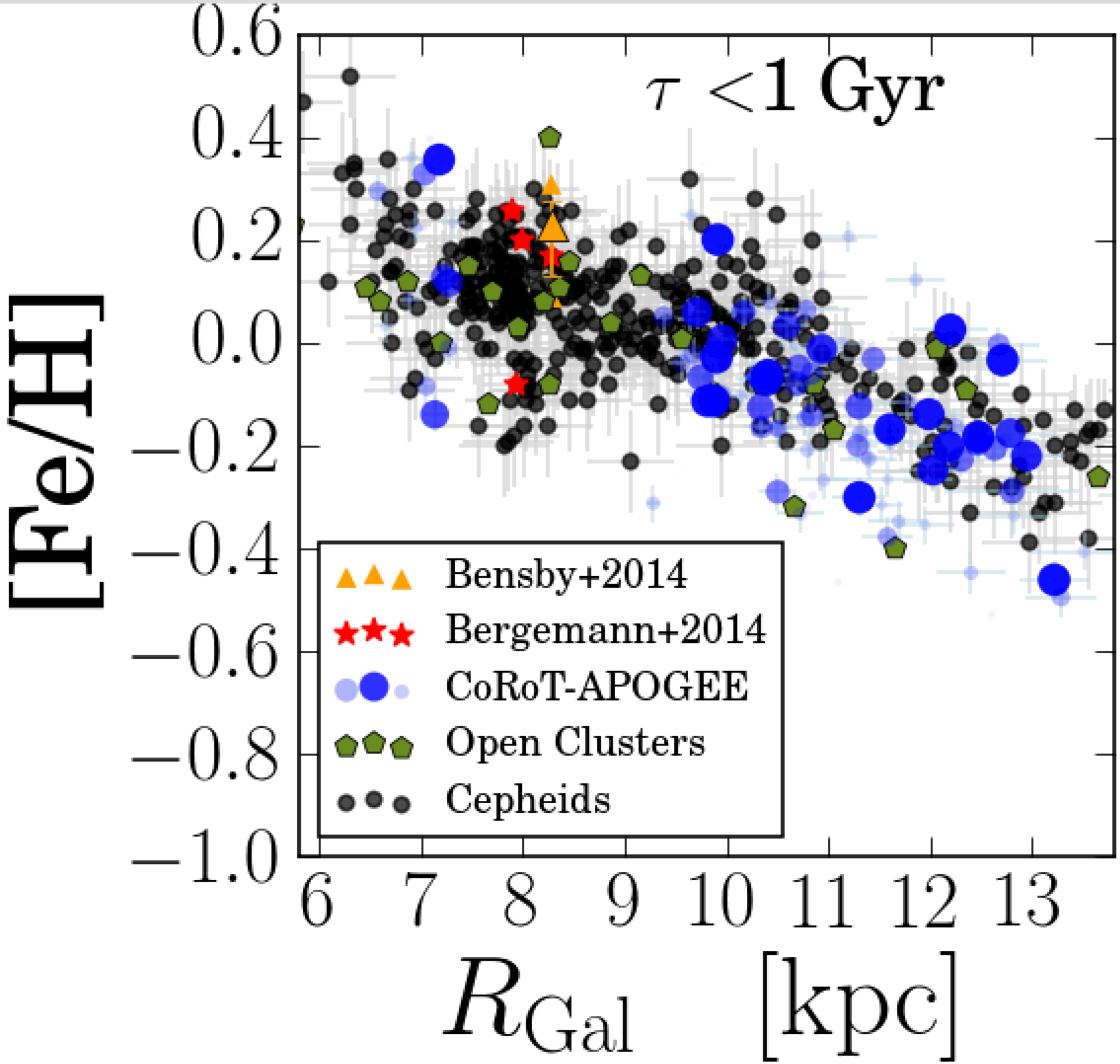
AGES to ~20-30% precision are already a breakthrough in the disk and halo if sampling different line of sights to large distances

Taste of it with CoRoT , K2 & Kepler

Main drawnback of CoRot & K2 -> Too low statistics for GA studies
Main drawnback of Kepler -> Short range in Galactocentric dist
TESS – too bright, too local

I. Quantifying Radial migration on the disk

With CoRoGEE and CoRoGES



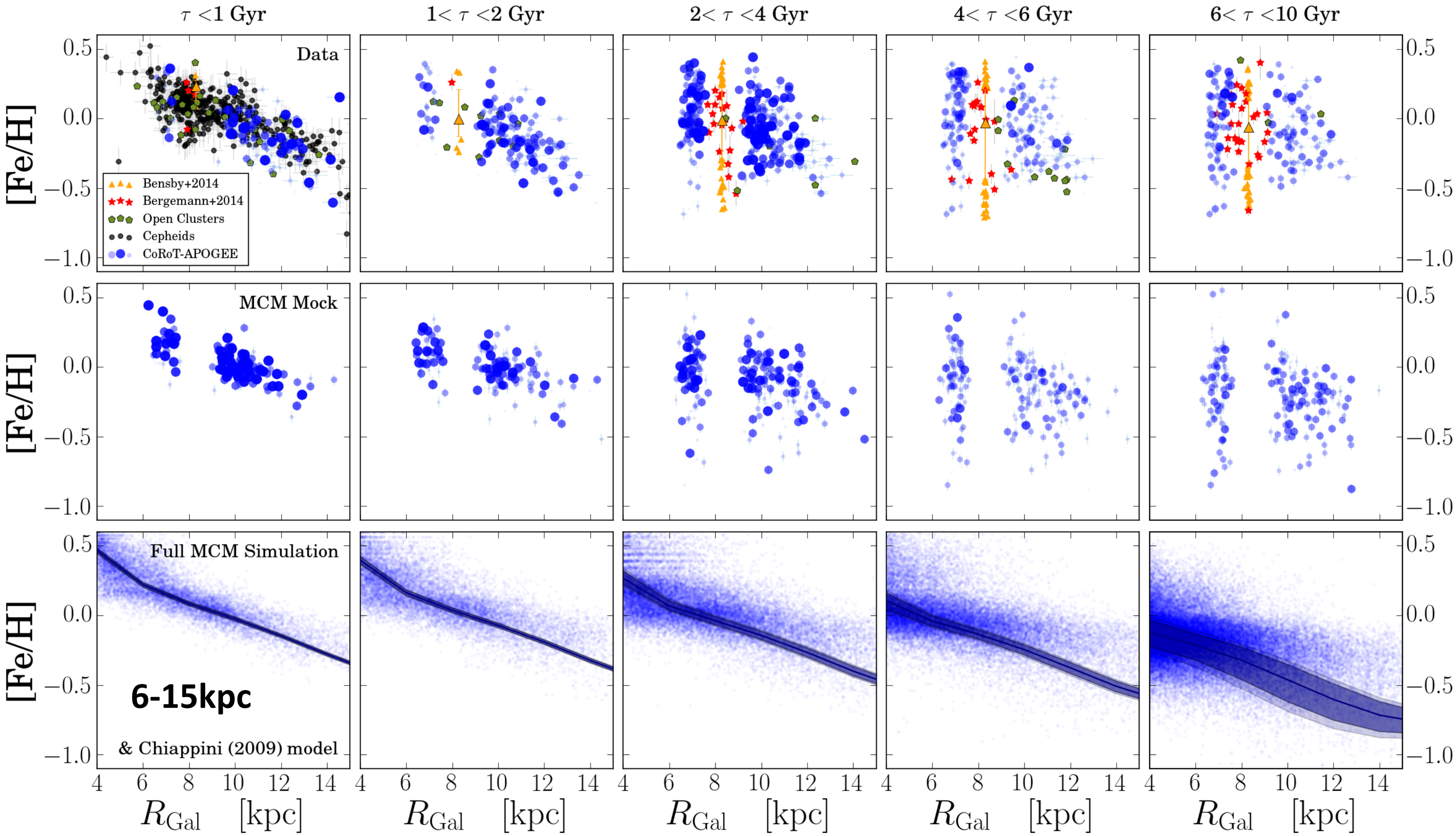
Anders et al. 2017b

Young Corot stars and young objects such as Cepheis and open clusters trace same gradients

CoRoGEE: Few % precision in distance out to 5kpc from us!

First time mock chemodynamical models are compared with data with age info

First time quantifying radial migration effect on gradients! Anders et al. 2017b



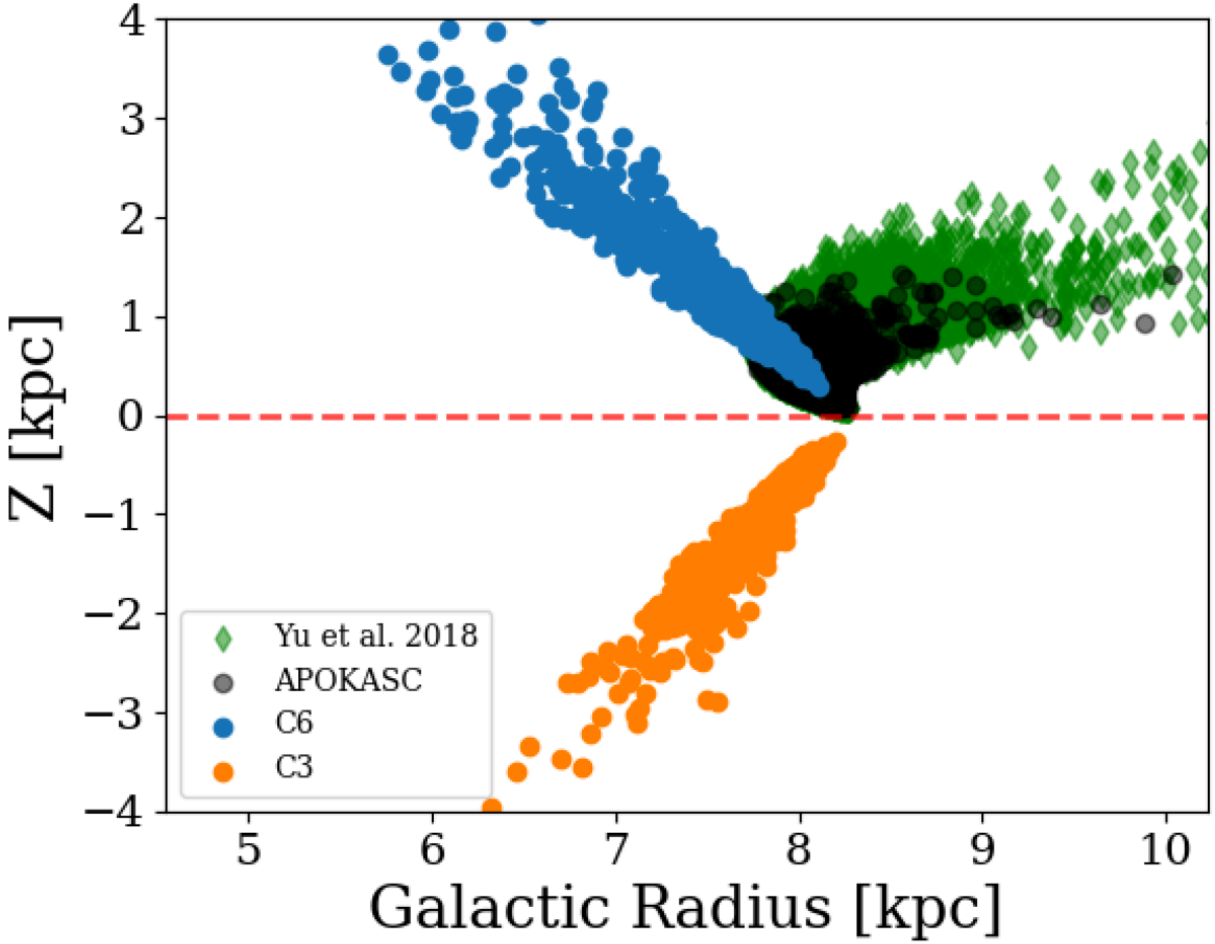
BUT Two low statistics – Only two fields – Not all targets with spectroscopic follow-up & poor coverage of inner disk

II. Age gradients above/below Galactic Mid-Plane

With K2 + APOGEE

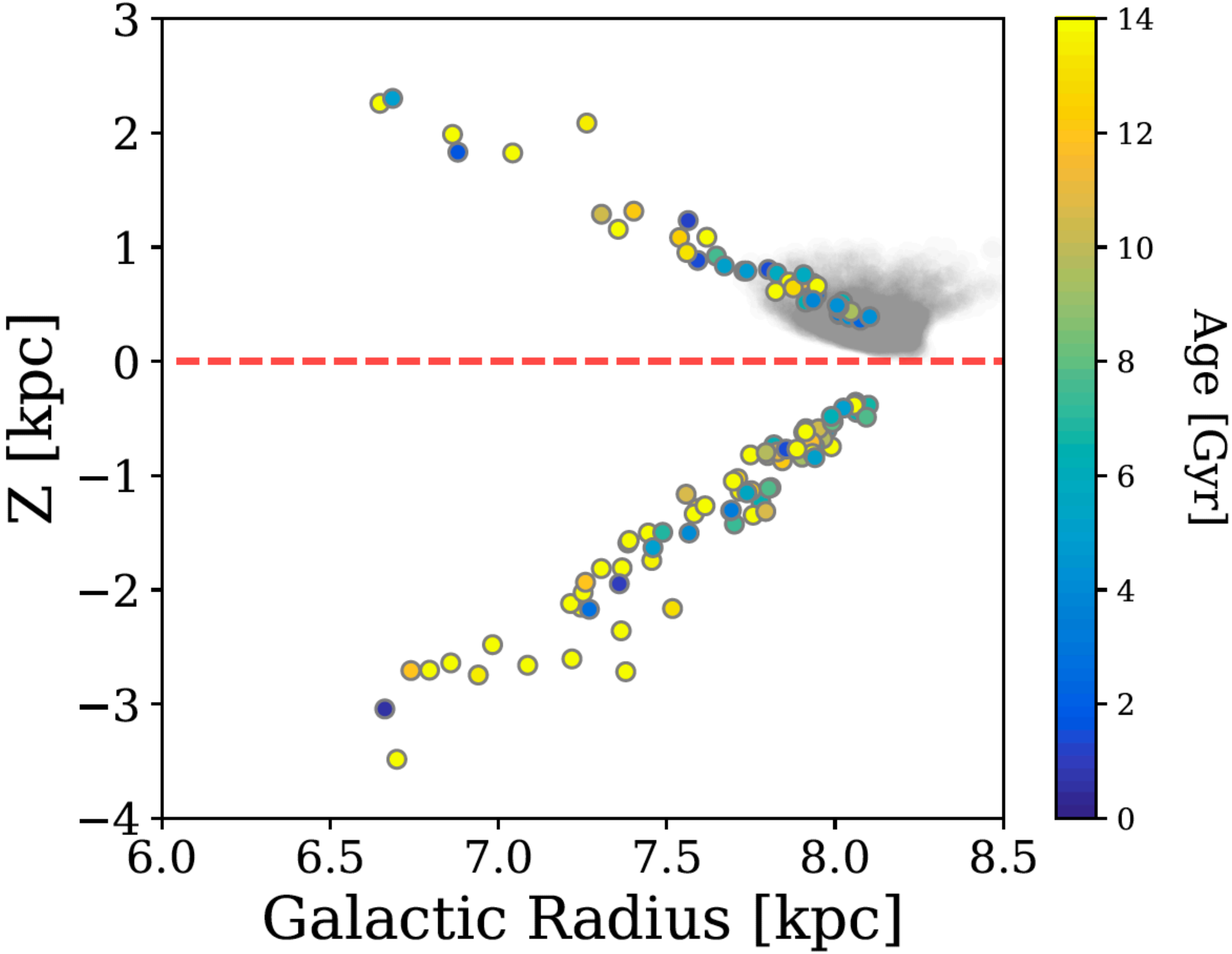
The K2 Galactic Caps Project - Going Beyond the *Kepler* Field and Ageing the Galactic Disc

B.M. Rendle[1,2★], A. Miglio[1,2], C. Chiappini[3], M. Valentini[3], G.R. Davies[1,2], B. Mosser[4], Y. Elsworth[1,2], R.A. García[5,6], S. Mathur[7,8,9], P. Jofré[10], C.C. Worley[11], L. Casagrande[12], L. Girardi[13], M.N. Lund[2,1], D.K. Feuillet[14], A. Gavel[15], L. Magrini[16], S. Khan[1,2], T.S. Rodrigues[13], J.A. Johnson[17,18], K. Cunha[19,20], R. L. Lane[21,22], C. Nitschelm[23], W.J. Chaplin[1,2]



APOKASC (black)
K2 campaign 3 (orange)
K2 campaign 6 (blue)

The sample of 16000 red giants from the Kepler survey (green diamonds, Yu et al. 2018) shows the full range of the Kepler field compared to the APOKASC sample

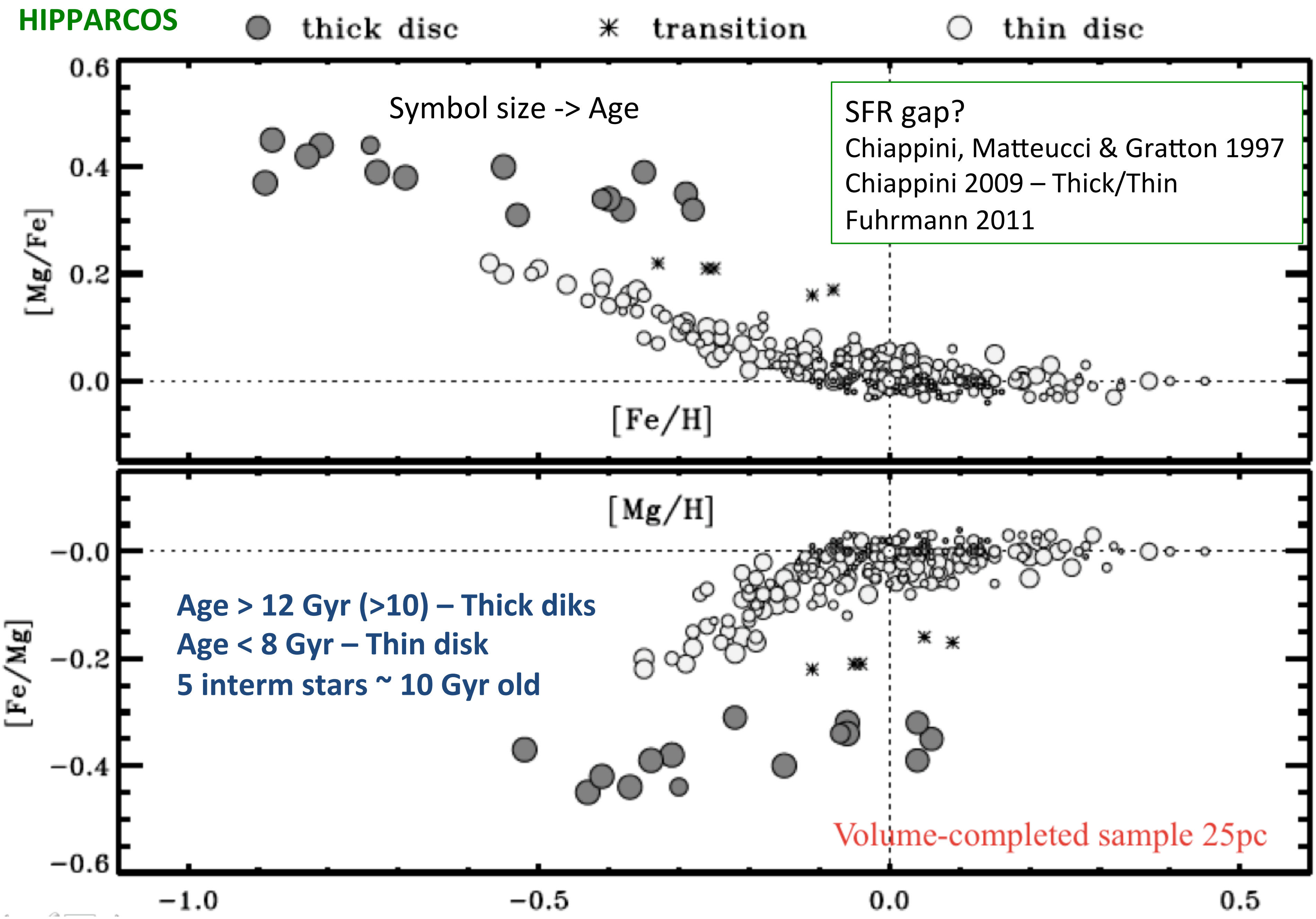


3
2
1
0
−1
−2
−3
−4
Z [kpc]
6.0
6.5
7.0
7.5
8.0
8.5
Galactic Radius [kpc]
14
12
10
8
6
4
2
0
Age [Gyr]

III. Constraining Galactic Assembly from Solar Neighb. Data – the [alpha/Fe] – age relation

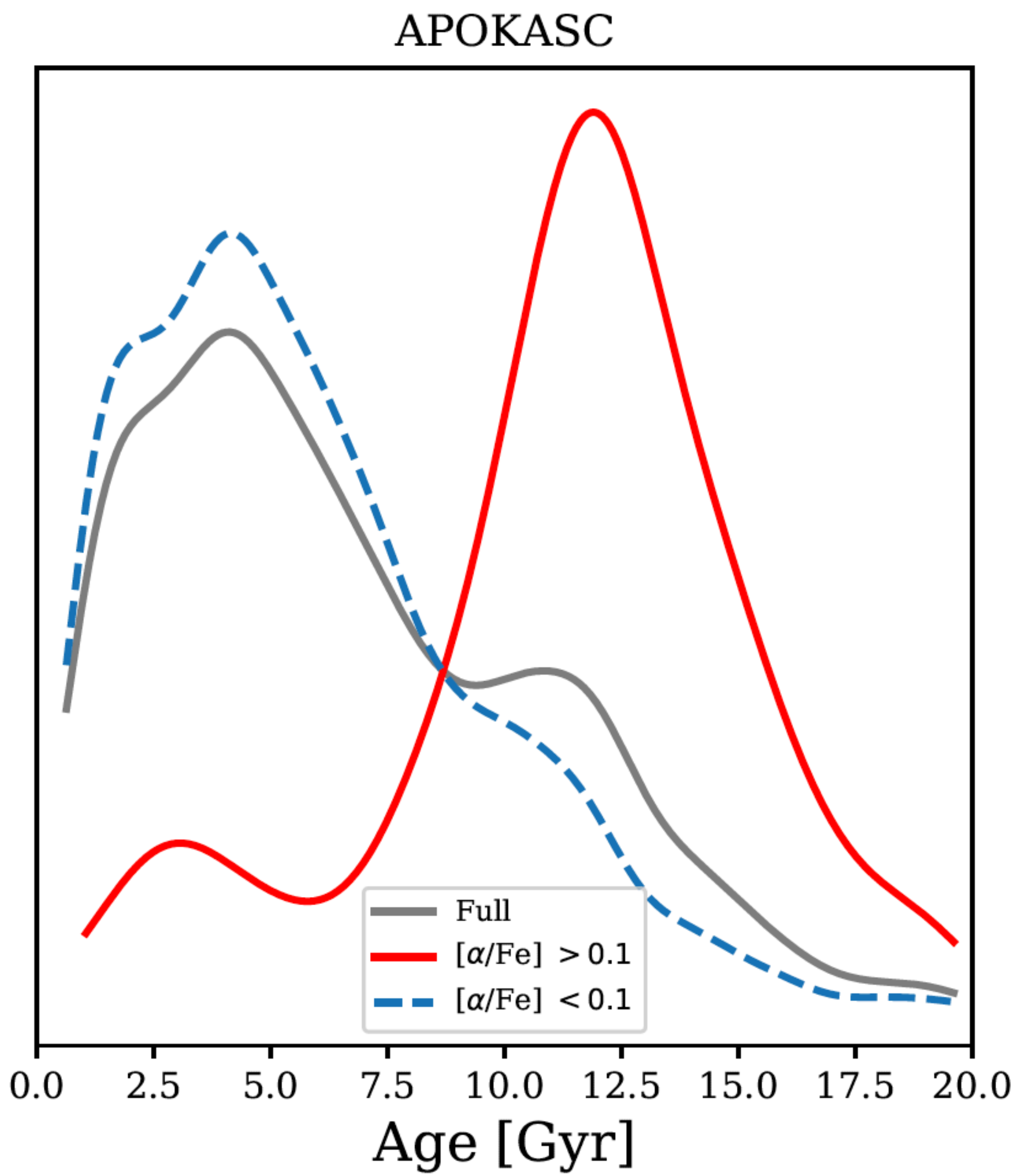
With Kepler + APOGEE

Subgiants – precise ages + stellar parameters + chemistry (Fuhrmann 1998-2011)



APOKASC ages from Miglio et al .(in prep)

- For alpha-rich we used Δν obtained from individual frequencies from radial modes
- Then we adopt the bayesian code PARAM (Rodrigues et al.2017) with this Δν without assuming scaling relations
- ~5000 RGBs , ages uncertainties better then 25% (better than for K2 – where we used 35%)



TAKE HOME MESSAGE 1:

For now seismo had a great impact on GA as:

- calibrators -> better gravities leading to more precise temperatures and abundances
- Already breakthrough in GA even with without pre-prepared and optimized RG catalogues. But if we do not do a specific RG Target Selection we will again have most of targets within 3kpc distance.

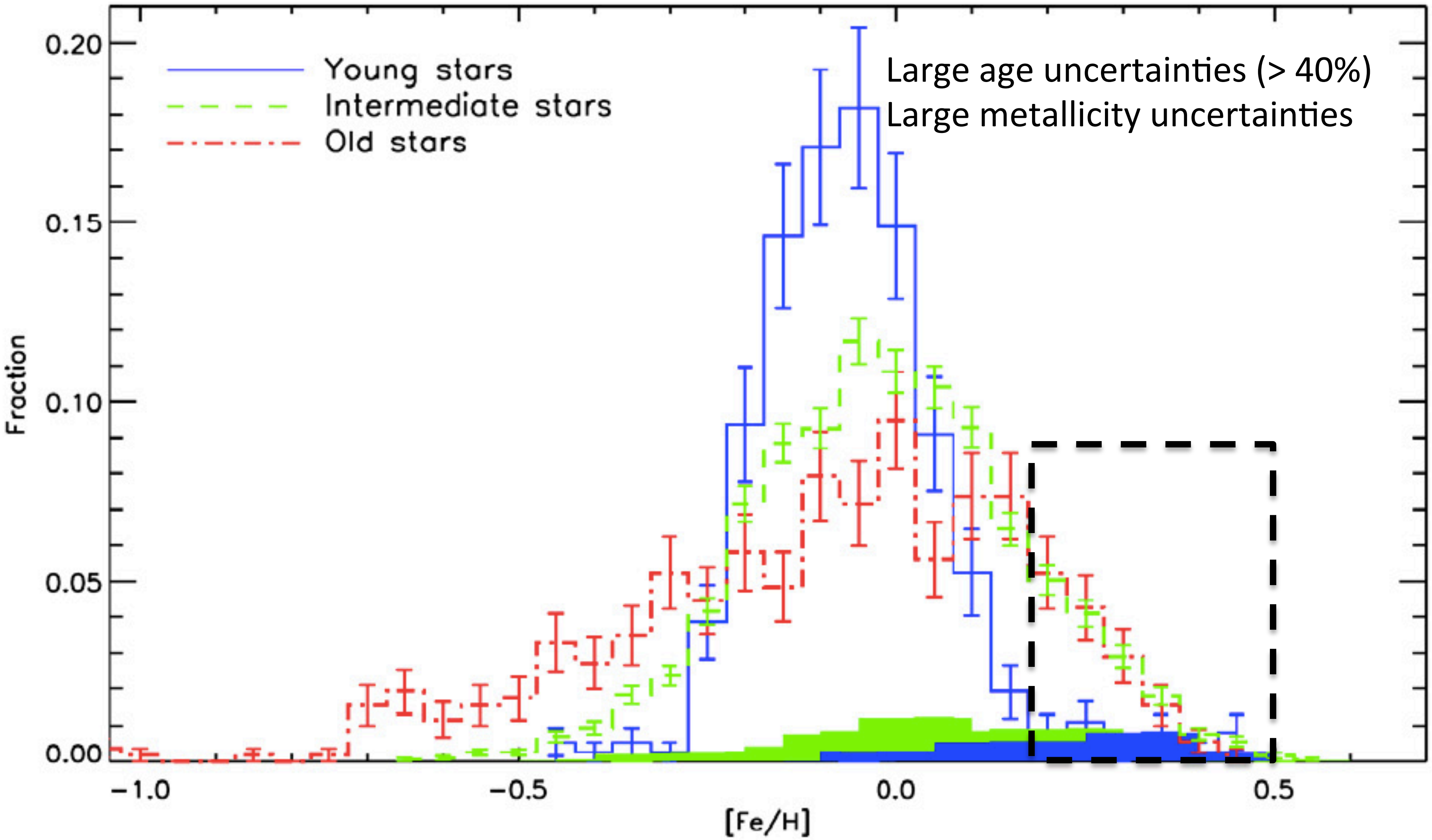
WHAT DO WE NEED? To be able to produce RG targets which will cover larger volumes [especially towards inner parts 2kpc-5kpc galactocentric distances] – good synergy with 4MOST

IV. Quantifying Radial migration in the local volume (d < 100 pc)

With Kepler + APOGEE

Within Hipparcos volume 100 pc

Casagrande et al. 2011 – Geneva Copenhagen Survey - ages



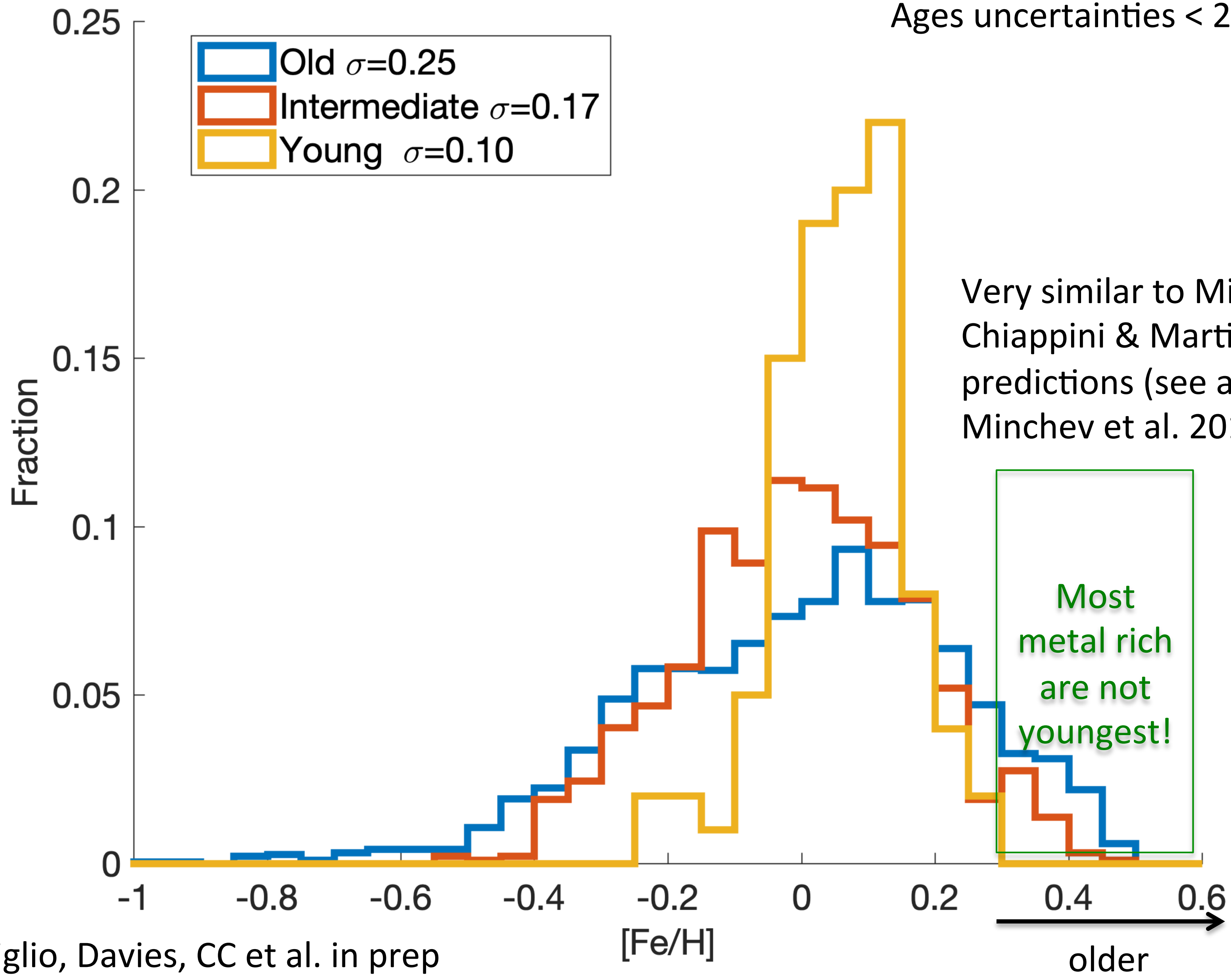
Metal-rich tail of the local MDF is composed mainly by **old + interm. age stars**

Large scatter in the local Age-Metallicity relation (Nordstrom et al. 2004, Holberg et al. 2007)

At solar neighborhood ~1kpc

With APOKASC ages PARAM

Ages uncertainties < 25%



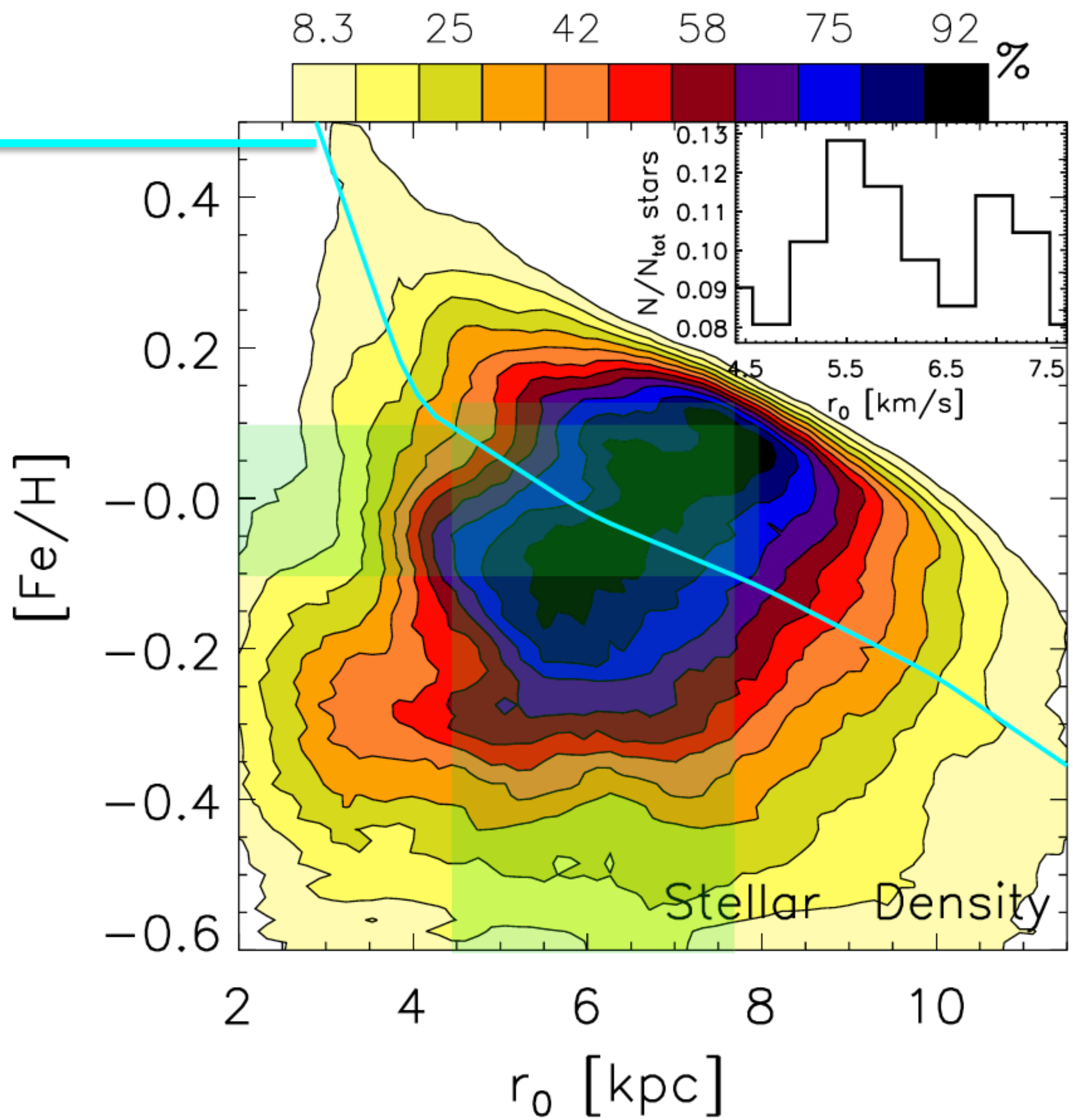
Very similar to Minchev, Chiappini & Martig 2013 predictions (see also Minchev et al. 2018)

Miglio, Davies, CC et al. in prep

Birth Radii-[Fe/H] plane for local stars

Where was the Sun born? Today at Rga = 8.3 kpc, born at ~6kpc?

Metallicity gradient of solar age stars (in birth radii)



Density probability of birth radii of Solar analogs

Could it be more probable to find Earth-Sun like systems 1 or 2 kpc towards the inner MW?

Even the most local volumes have "intruders"

TAKE HOME MESSAGE 2: What happens in the Hipparcos volume (100 pc) depends on mergers+ bar – stars migrating from the innermost regions (that will be inside your PIC). A joint Planet/GA mission will allow to put the planet hunt into Galactic context.

Proof of concept (Anders, CC et al. 2018): Dimensionality reduction technique t-SNE applied to the HARPS high-resolution sample of Delgado-Mena et al. 2017) – d < 100 pc

V. Asteroseismology impact in constraining earliest phases of Galaxy Assembly and Nature of the First stars

The metal-poor regime

Table 1 Selected r-process enhanced metal-poor stars for which ages have been determined by means of nucleochronometry.

Star	α (J2000)	δ	V	$B-V$	$T_{\rm eff}$ (K)	log g	[Fe/H]	Age (Gyr)	References
CS 29497-004	00 28 06.9	−26 03 04	14.03	0.71	5013	2.1	−2.85	14.8 ± 3.6	Hill et al. 2016
CS 31082-001	01 29 31.1	−16 00 45	11.67	0.77	4825	1.5	−2.90	14.0 ± 2.4	Hill et al. 2002
HE 1523−0901	15 26 01.1	−09 11 39	11.50	0.87	4630	1.0	−2.95	13.2 ± 2	Frebel et al. 2007
BD +17°3248	17 28 14.5	+17 30 36	9.37	0.66	5200	1.8	−2.0	13.8 ± 4	Cowan et al. 2002
CS 22892-052	22 17 01.5	−16 39 26	13.18	0.78	4800	1.5	−3.10	14.2 ± 3	Sneden et al. 2003
HD 221170	23 29 28.8	+30 25 58	7.66	1.08	4510	1.0	−2.19	11.7 ± 2.8	Ivans et al. 2006

Christlieb (2016, AN, 337, 931)

- Uncertainties -> at least 2 Gyrs (uncertain production rates)
- Require very high S/N and resolution (R > 60 000) -> limited to bright (V<12) stars
- Require large enhancement in r-process elements

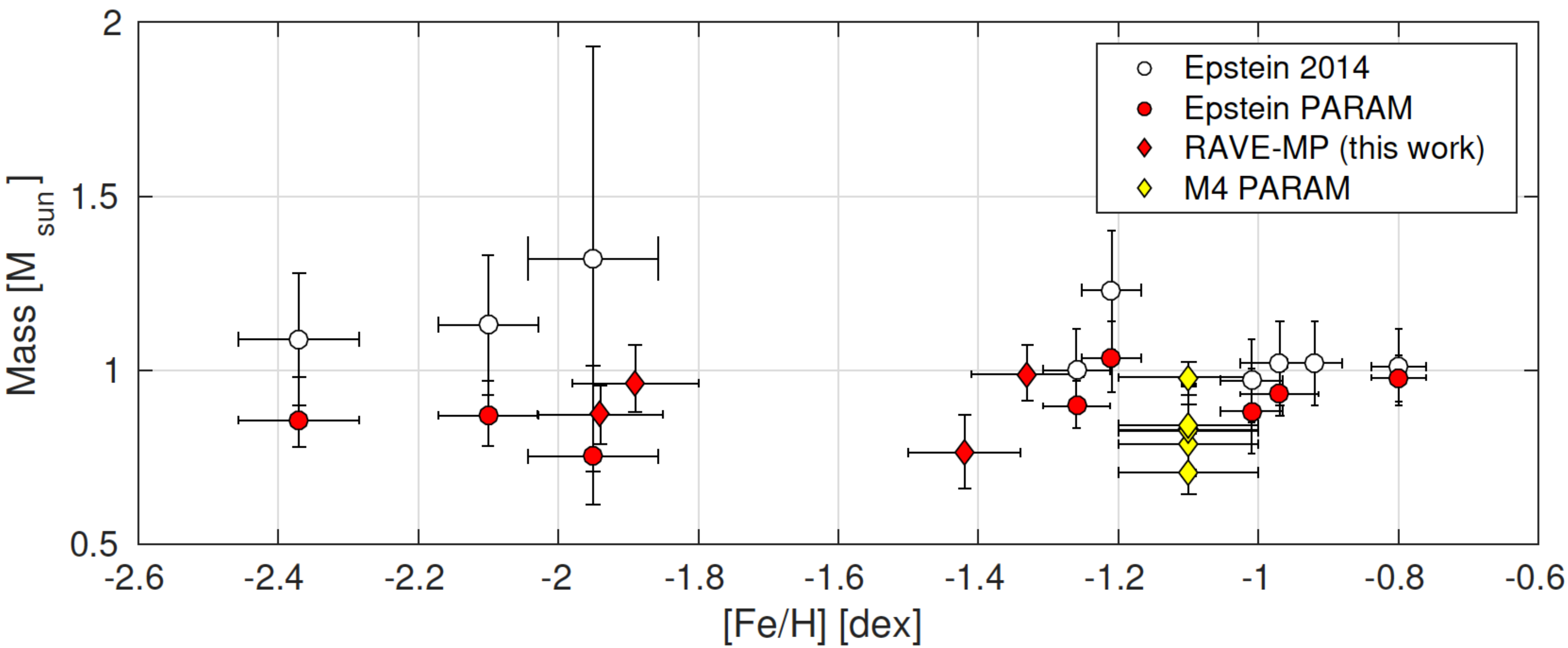
Rare objects: about one in a million stars in the Solar neighborhood – not applicable to large samples of stars

A&A 627, A173 (2019)

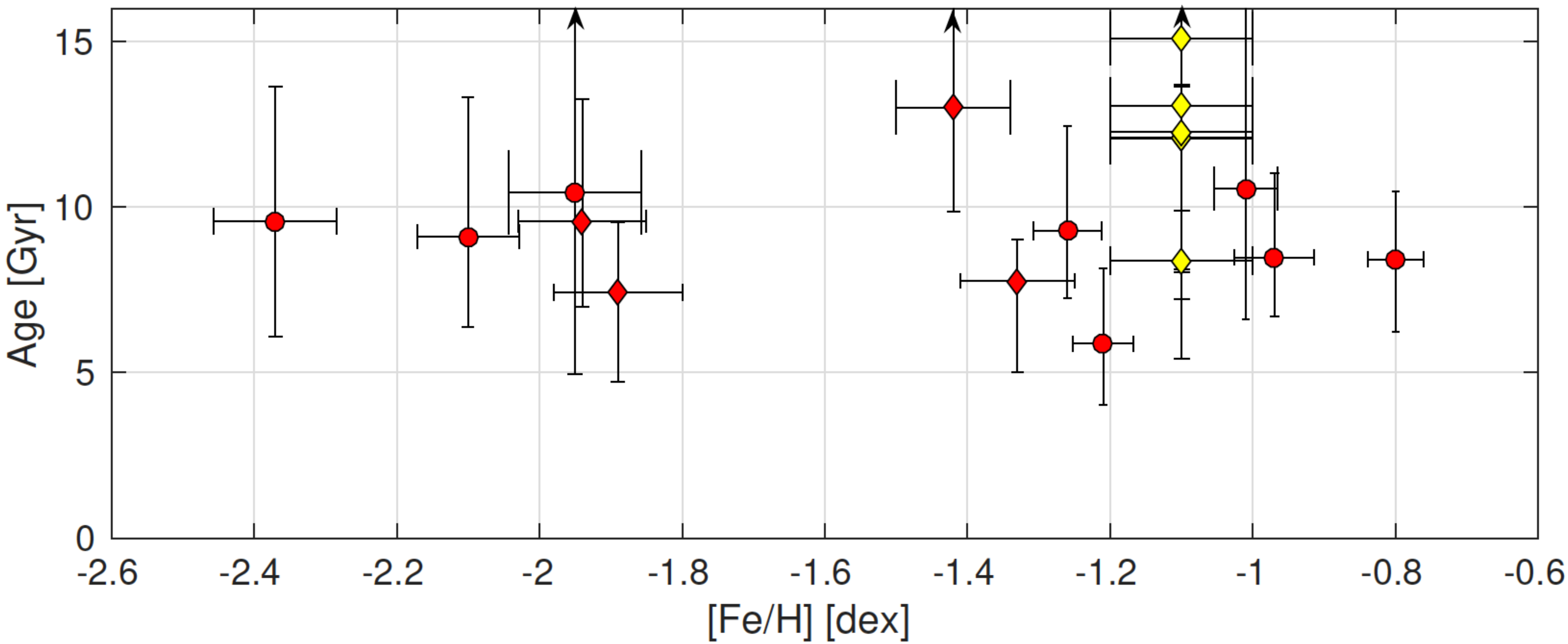
Masses and ages for metal-poor stars

A pilot programme combining asteroseismology and high-resolution spectroscopic follow-up of RAVE halo stars*,**

M. Valentini[1], C. Chiappini[1], D. Bossini[2,3], A. Miglio[4,5], G. R. Davies[4,5], B. Mosser[6], Y. P. Elsworth[4,5], S. Mathur[7,8], R. A. García[9,10], L. Girardi[2], T. S. Rodrigues[2], M. Steinmetz[1] and A. Vallenari[2]



Asteroseismology: opens a new window into halo/thick disk ages



New proposal ESO (deadline tomorrow) with 45 new metal-poor stars with seismic information

By the time PLATO on sky we will have lists of metal poor stars fully characterized – to get AGES

TAKE HOME MESSAGE 3: Seismo for GA and early nucleosynthesis

The large spectroscopic surveys will find many of the rare metal-poor stars. These will have 4MOST and WEAVE spectra.

“PLATO follow-up” of our metal-poor bright giants offer the only way of unveiling the history of the busy earliest phases of galaxy assembly (e.g. Enceladus – Helmi et al. 2018 – Nature).

WHAT DO WE NEED? Knowing the PLATO field 2 years before launch (but already now) prepare metal-poor RG catalogue on time.

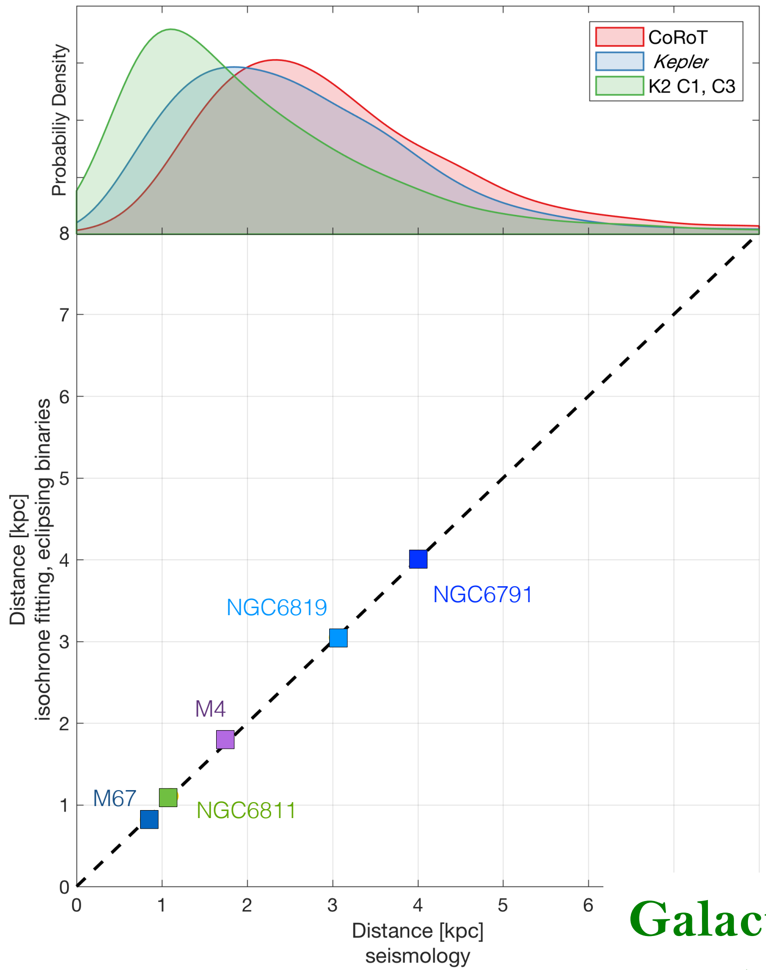
Summary: Major impact of seismology of RG on GA

- Precise distances out to 15 kpc
- Precise log g enabling high precision chemical analysis thanks to more robust determination of T_{eff}, and putting different surveys on same scale (Valentini et al. 2017, 2019) - Benchmarks
- Ages for far away giants lowering the uncertainties from ~100% to 20% (hopes to improve to ~10% set up timeline of events in early MW history & ages for metal-poor)
- Identification of sub-populations of star within PIC – help characterizing stars for PLATO core-science and Galactic Archaeology
- Constrain gaia parallax shifts (Khan et at 2019)

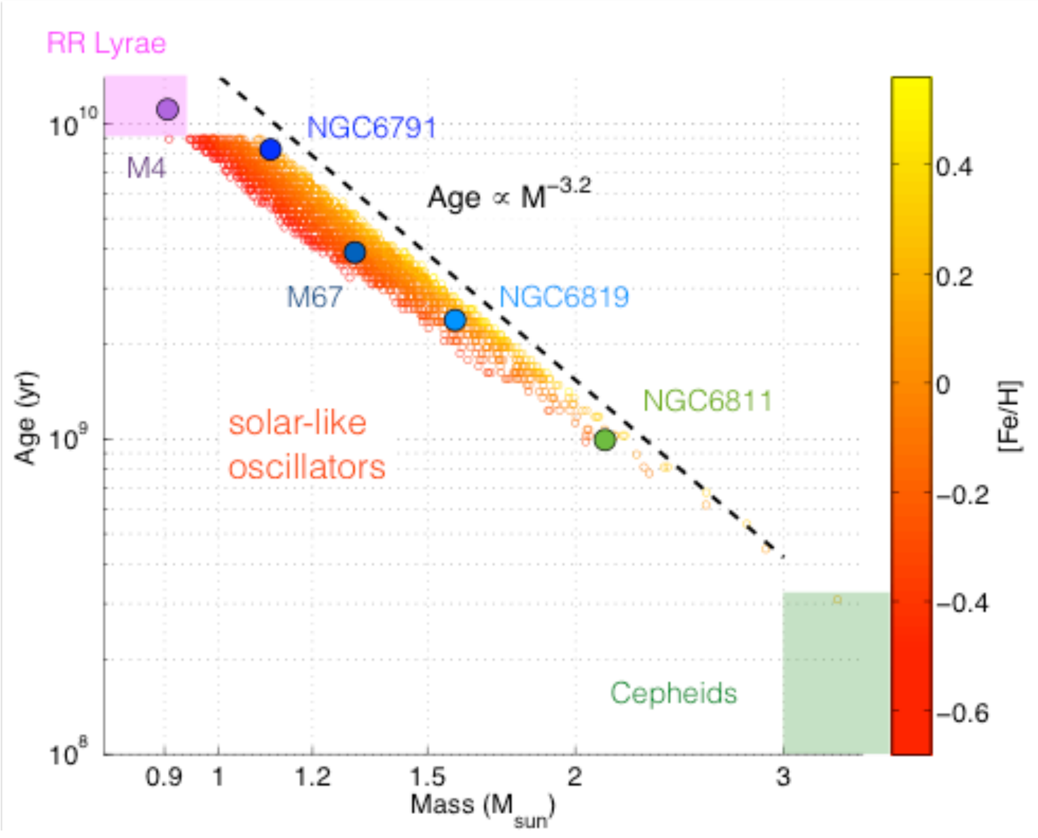
BENCHMARK stars

Followed-up by all spectroscopic surveys

Distances to a few % uncertainty!



Masses to Ages with ~ 20-30 % uncertainties



Galactic Archaeology EU community (>200) strong support to PLATO (with RGs)

See Miglio, Chiappini et al. 2017 AN and refs therein

Seismology of Red Giants for GA

Galactic Archaeology EU community (>200)
strong support to PLATO (with RGs)

- Precise distances, masses and ages beyond the solar vicinity and **beyond capabilities of Gaia + spectroscopic surveys**
- **Key impact for metal-poor science**
- **Sampling different line of sights (if not possible anymore, at least field that give a good baseline in galactocentric distance – especially in South)**
- **Outer Bulge/Inner-Galaxy – key to obtain ages - Barbuy, Chiappini, Gerhard 2018, ARAA 56, 223**

We (=large European community) therefore strongly endorse PLATO's current design and proposed observational strategy, and conclude that PLATO, as it is, will be a legacy mission for Galactic archaeology and an opportunity not to be missed. But we need 1) selected RGs, 2) field choice that gives good R galactocentric range.

We can provide help on:

- PIC characterization of targets using Gaia
- 4MOST spectroscopy (if PIC targets known by 2024 – we can still observe all of them ***before*** PLATO goes online

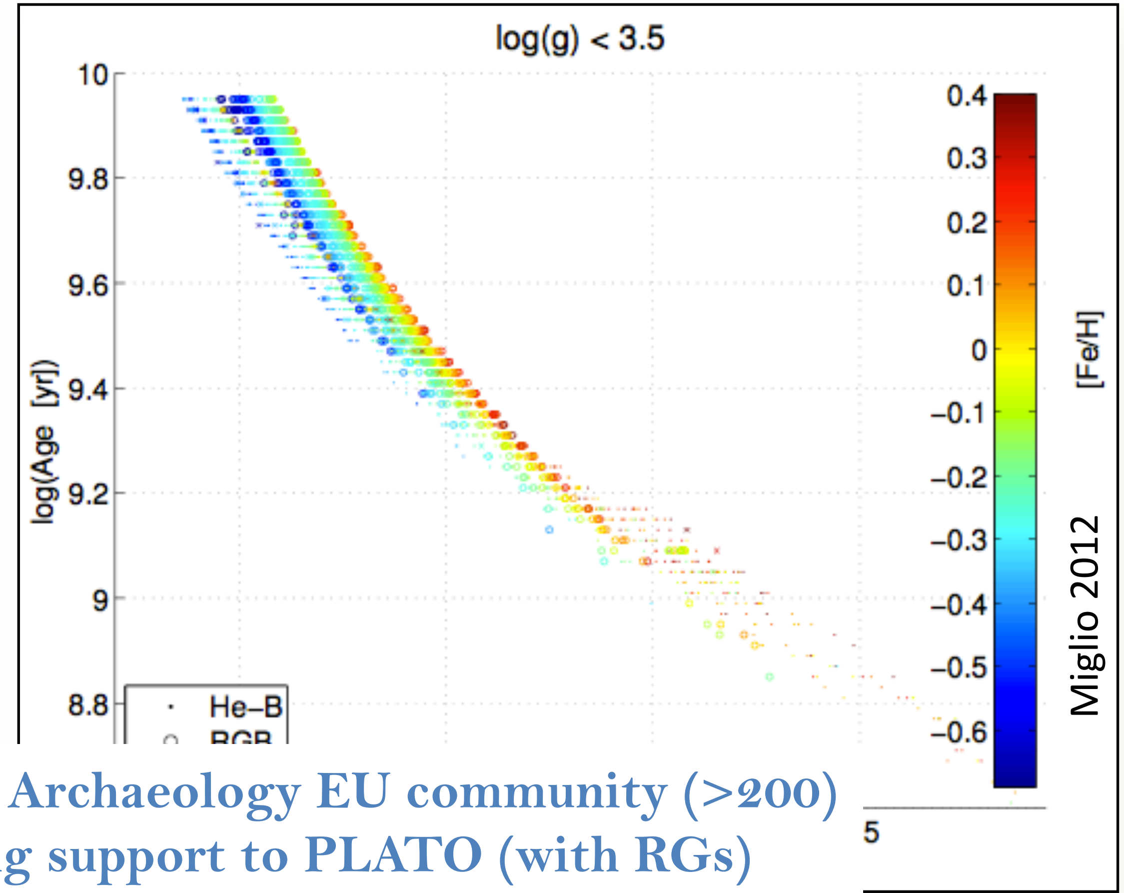
PLATO would then take fully advantage of the investments being done by ESA/ESO and would be the most efficient mission, both in finding Earth-like planets and unveiling the MW assembly history, helping constraining radial migration, and putting the planets into a galactic context (as it was the goal spelled out in Rauer et al. 2014)

The ESA–ESO Working Group on Galactic Populations, Chemistry and Dynamics

The Messenger 134 – December 2008

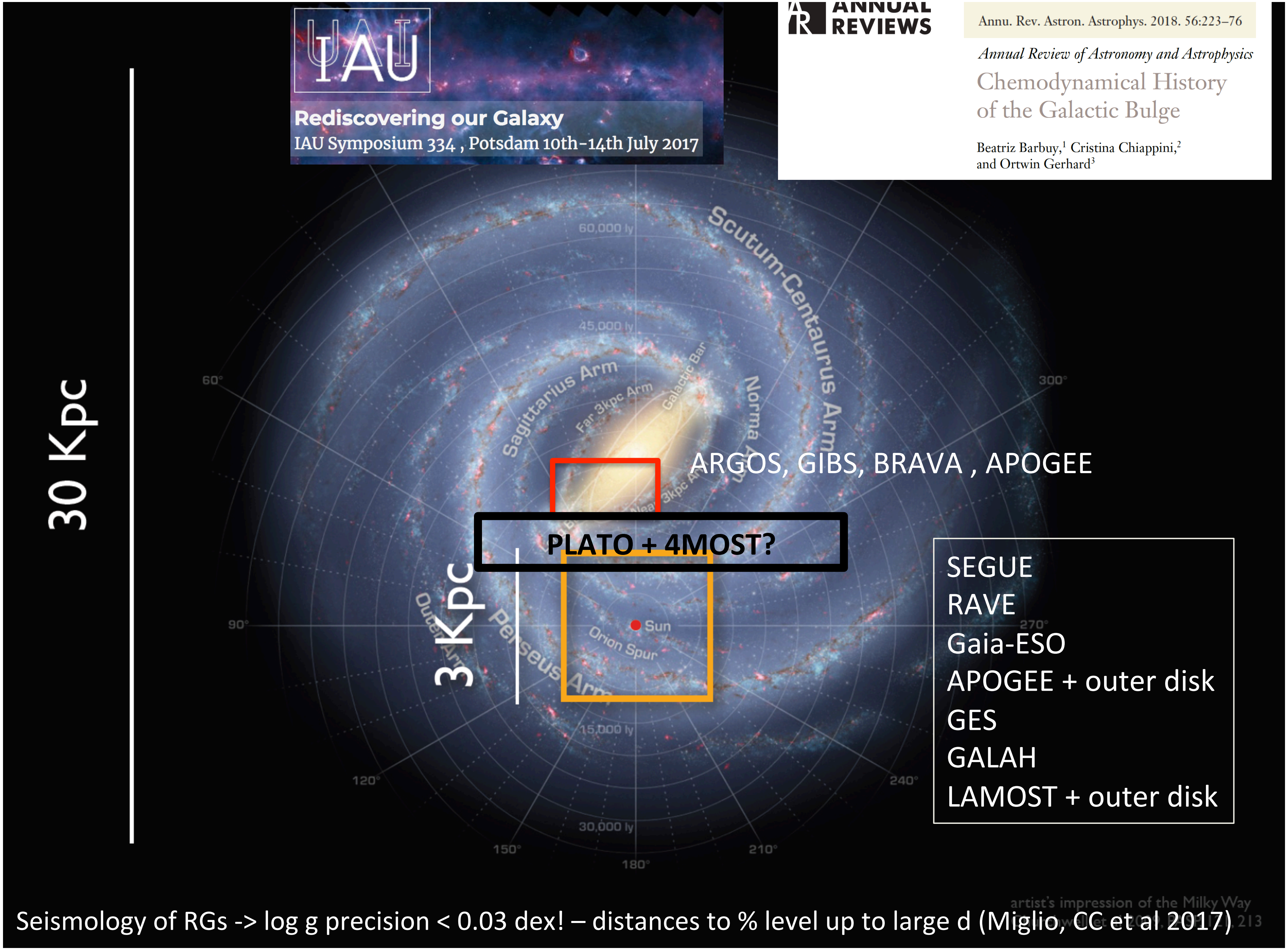
Asteroseismology

Catherine Turon[1]
Francesca Primas[2]
James Binney[3]
Cristina Chiappini[4]
Janet Drew[5]
Amina Helmi[6]
Annie Robin[7]
Sean G. Ryan[5]



Galactic Archaeology EU community (>200) strong support to PLATO (with RGs)

Recommendation to ESA by WG4 (Turon et al. 2008) :"Asteroseismology is a major tool to complement Gaia with respect to age determinations. ESA should encourage the community to prepare for a next-generation mission, which would sample the different populations of the Galaxy much more widely than CNES-ESA's CoRoT and NASA's Kepler"


IAU
Rediscovering our Galaxy
IAU Symposium 334 , Potsdam 10th-14th July 2017
ANNUAL REVIEWS
Annu. Rev. Astron. Astrophys. 2018. 56:223–76
Annual Review of Astronomy and Astrophysics
Chemodynamical History of the Galactic Bulge
Beatriz Barbuy,[1] Cristina Chiappini,[2] and Ortwin Gerhard[3]
30 Kpc
3 Kpc
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Perseus Arm
Orion Spur
Sun
ARGOS, GIBS, BRAVA , APOGEE
PLATO + 4MOST?
SEGUE
RAVE
Gaia-ESO
APOGEE + outer disk
GES
GALAH
LAMOST + outer disk
Seismology of RGs -> log g precision < 0.03 dex! – distances to % level up to large d (Miglio, CC et al 2017)
artist's impression of the Milky Way

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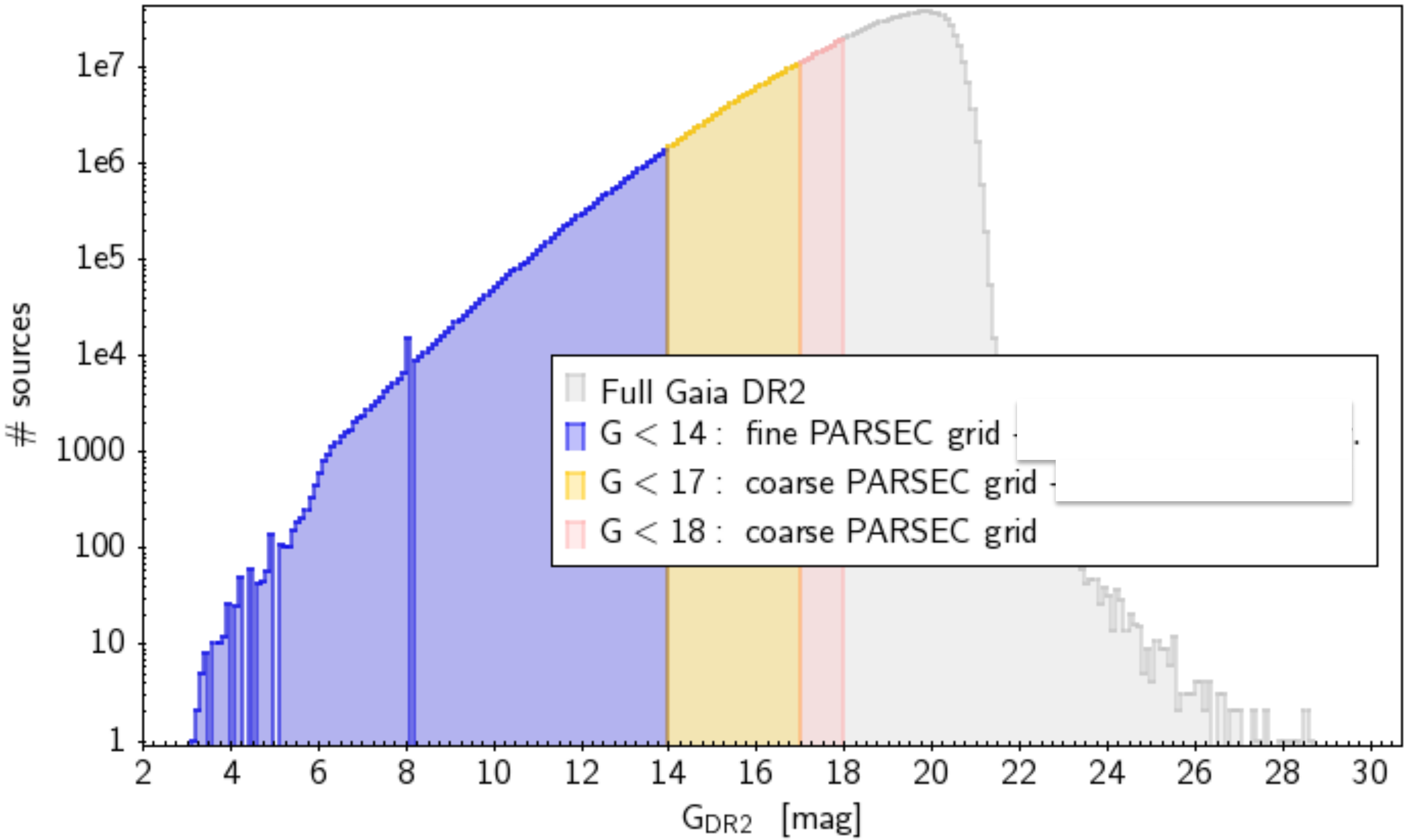
Star Horse Run Parallax + Photometry



Tests have shown SH could improve on Gaia DR2 results for G < 18

*e-science support & AIP computational resources greatly acknowledged

See Shan et al. 2019

Need too:

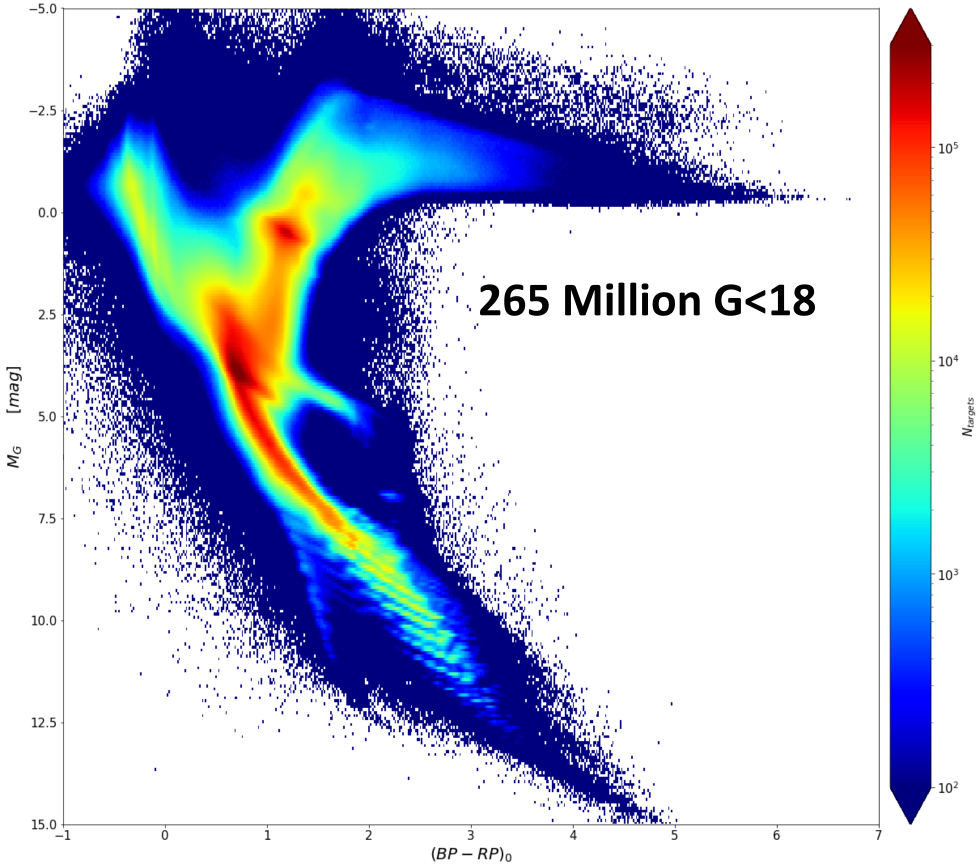
- a) take care of parallax shift (how? Seismic is key here too)
- b) parallax errors inflation
- c) transmission curves correction

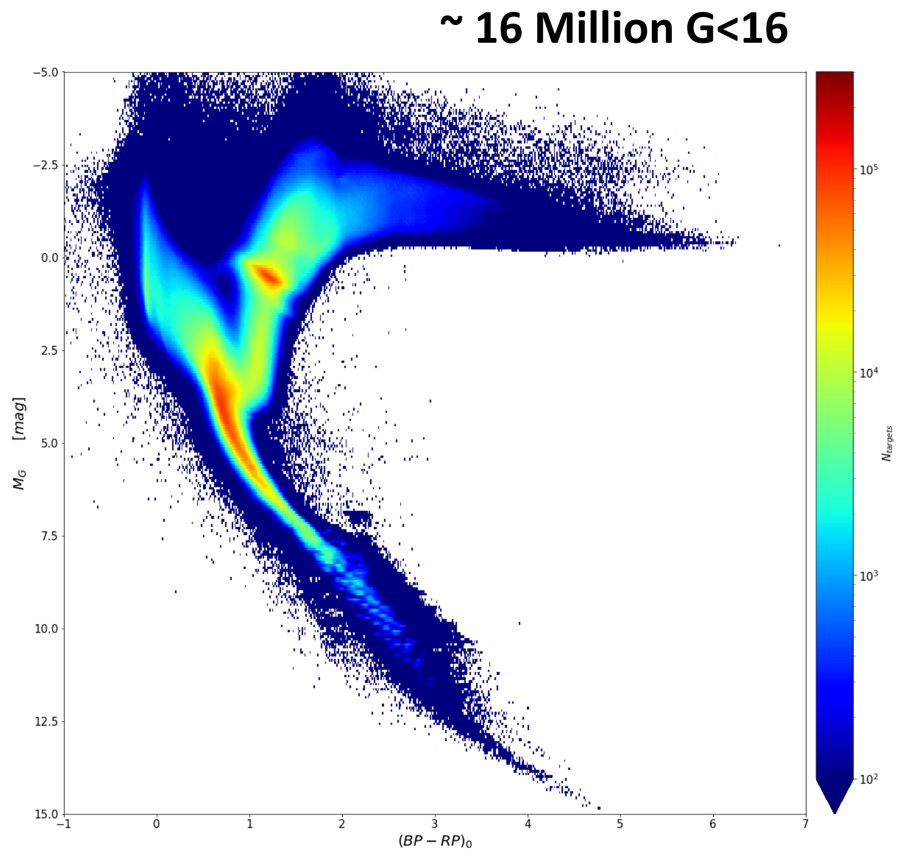
Table 2. Summary of the calibrations and data curation applied for the fiducial `StarHorse` run.

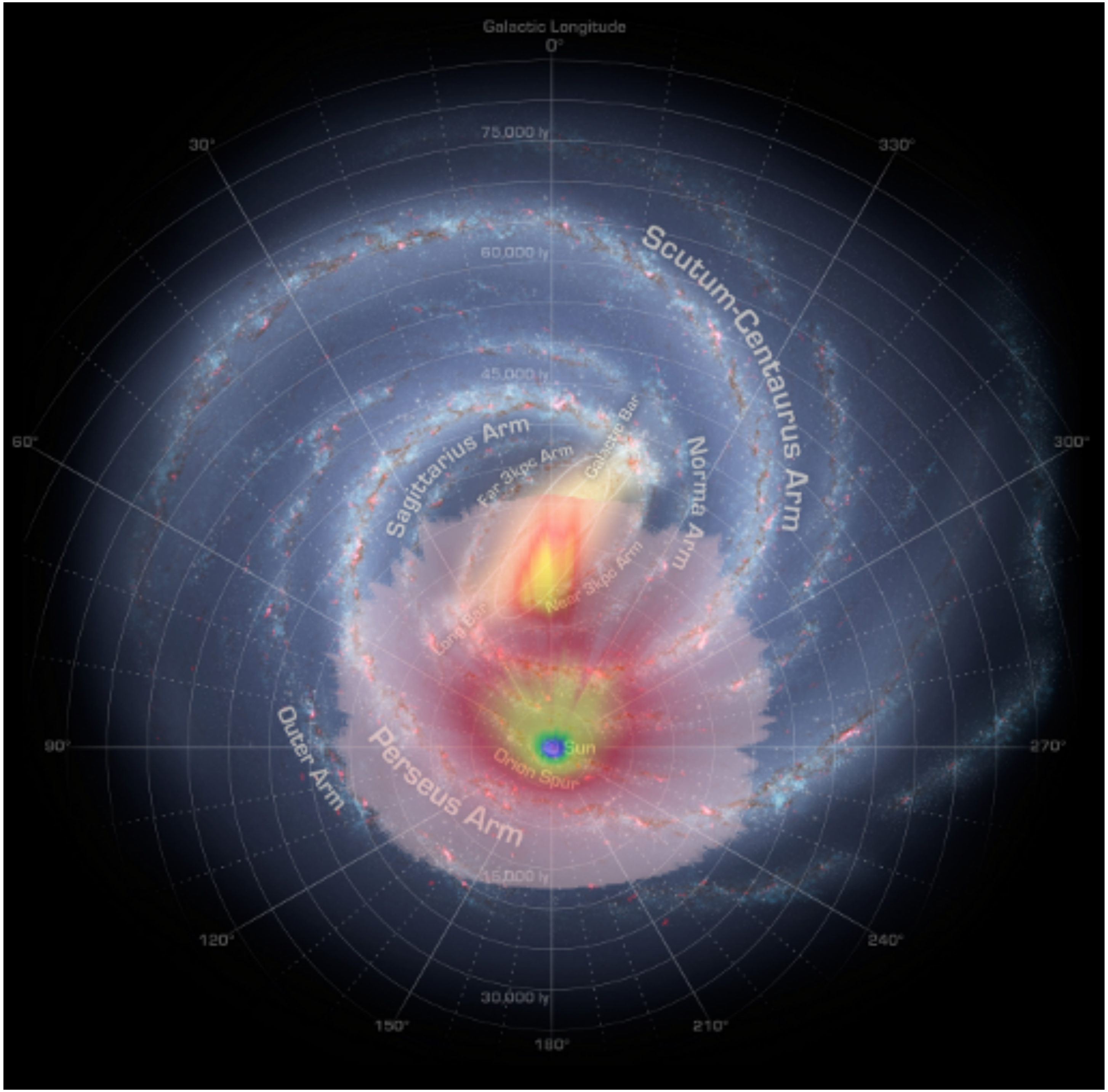
Parameter	Parameter regime	Calibration choice	Reference
ϖ	$G < 14$	`parallax` + 0.05 mas	Zinn et al. (2018); Lindegren (2018)
	$14 < G < 16.5$	`parallax` + (0.1676 − 0.0084 · `phot_g_mean_mag`) mas	Lindegren (2018), linear interpolation
	$G > 16.5$	`parallax` + 0.029 mas	Arenou et al. (2018); Lindegren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

Anders et al. 2019

Extinction corrected CMDs



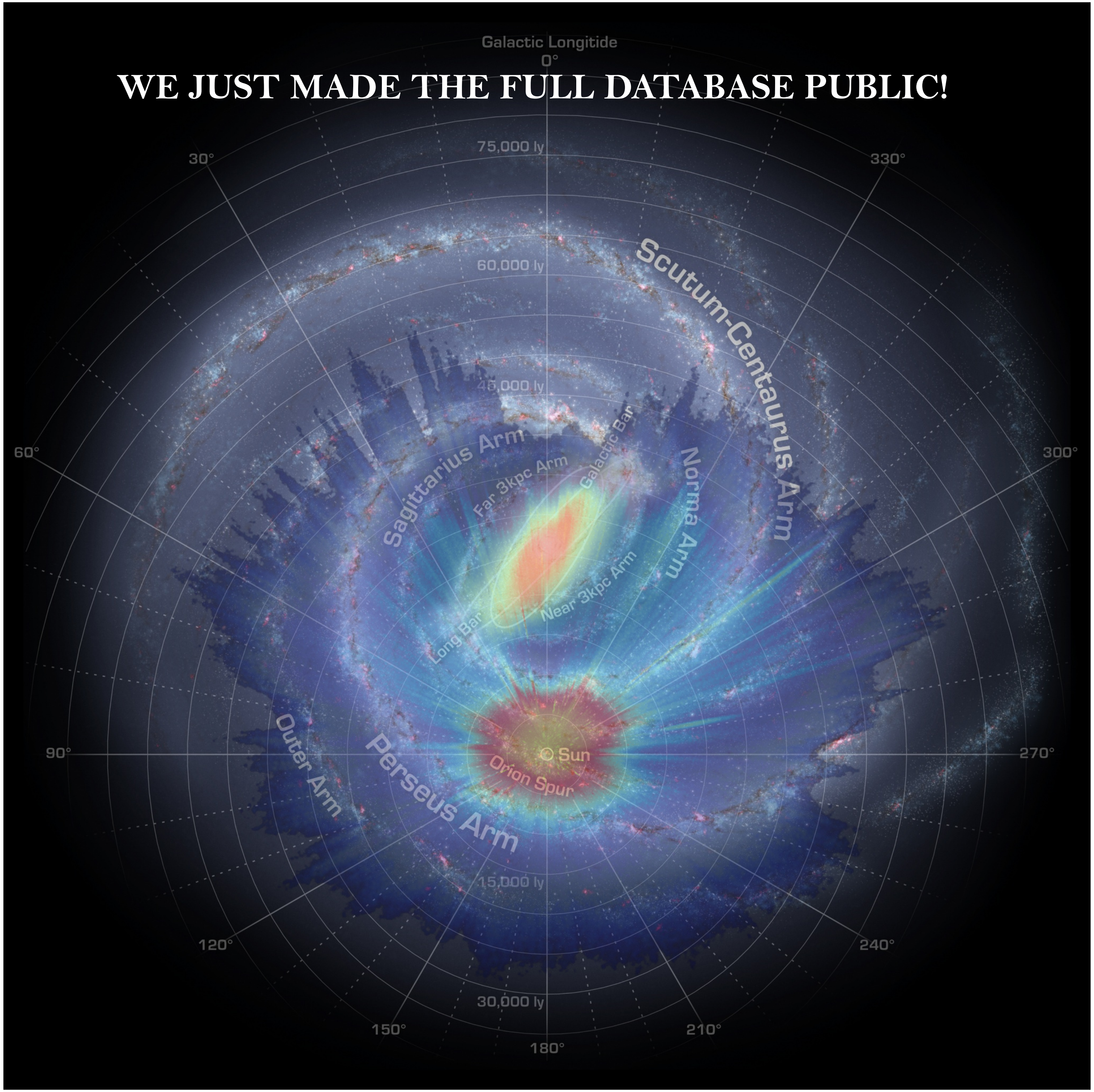




Gaia simulated
End of Mission

Source: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)
Published: November 8, 2017

Source: X. Luri & the DPAC-CU2. Simulations based on an adaptation for Gaia of the Besançon galaxy model (A. Robin et al.)
[Published: 10/08/2011]



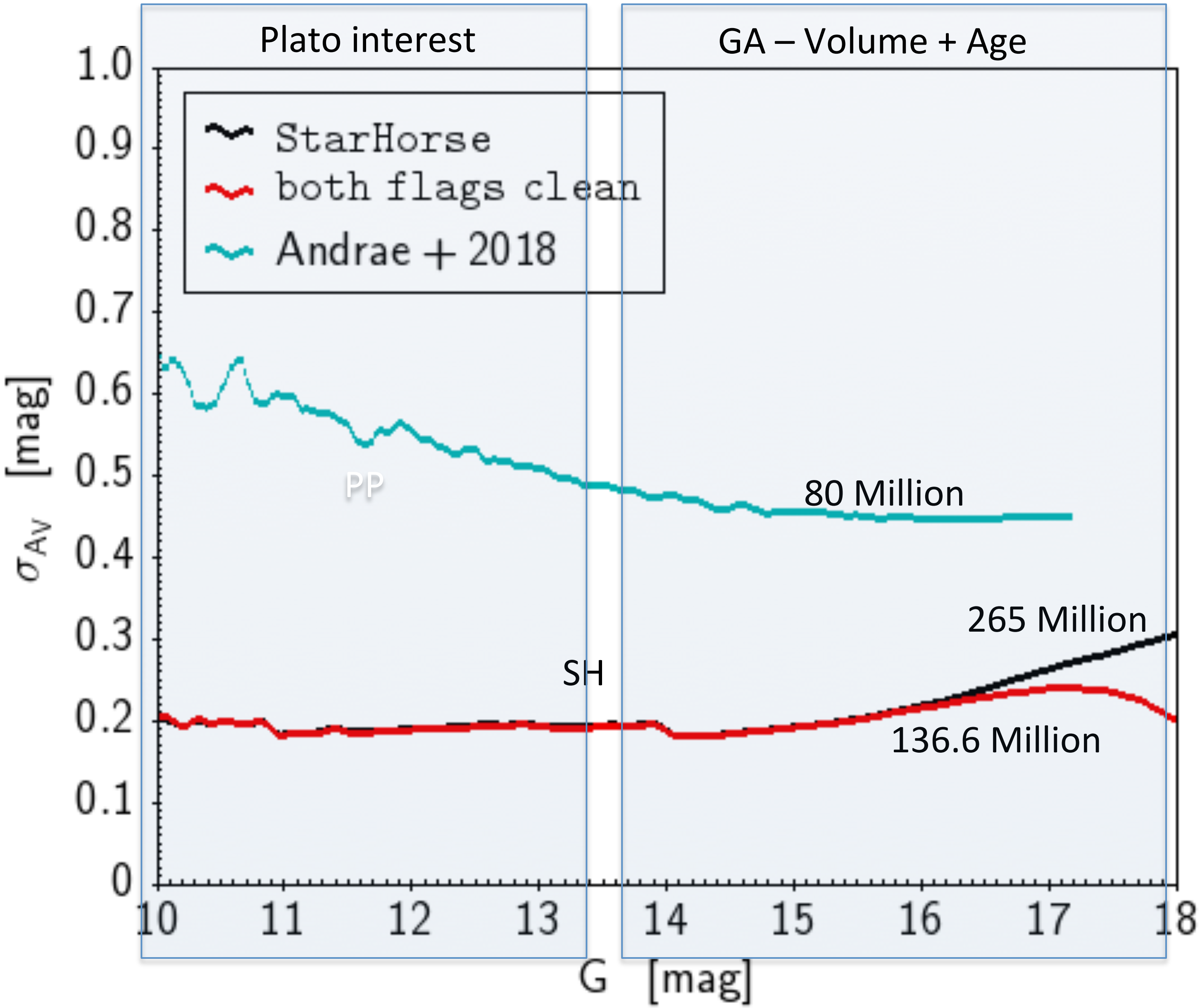
Gaia Observed 3D (distances and extinctions for ~200 Million stars (Anders et al. 2019)

We made public on https://gaia.aip.de/

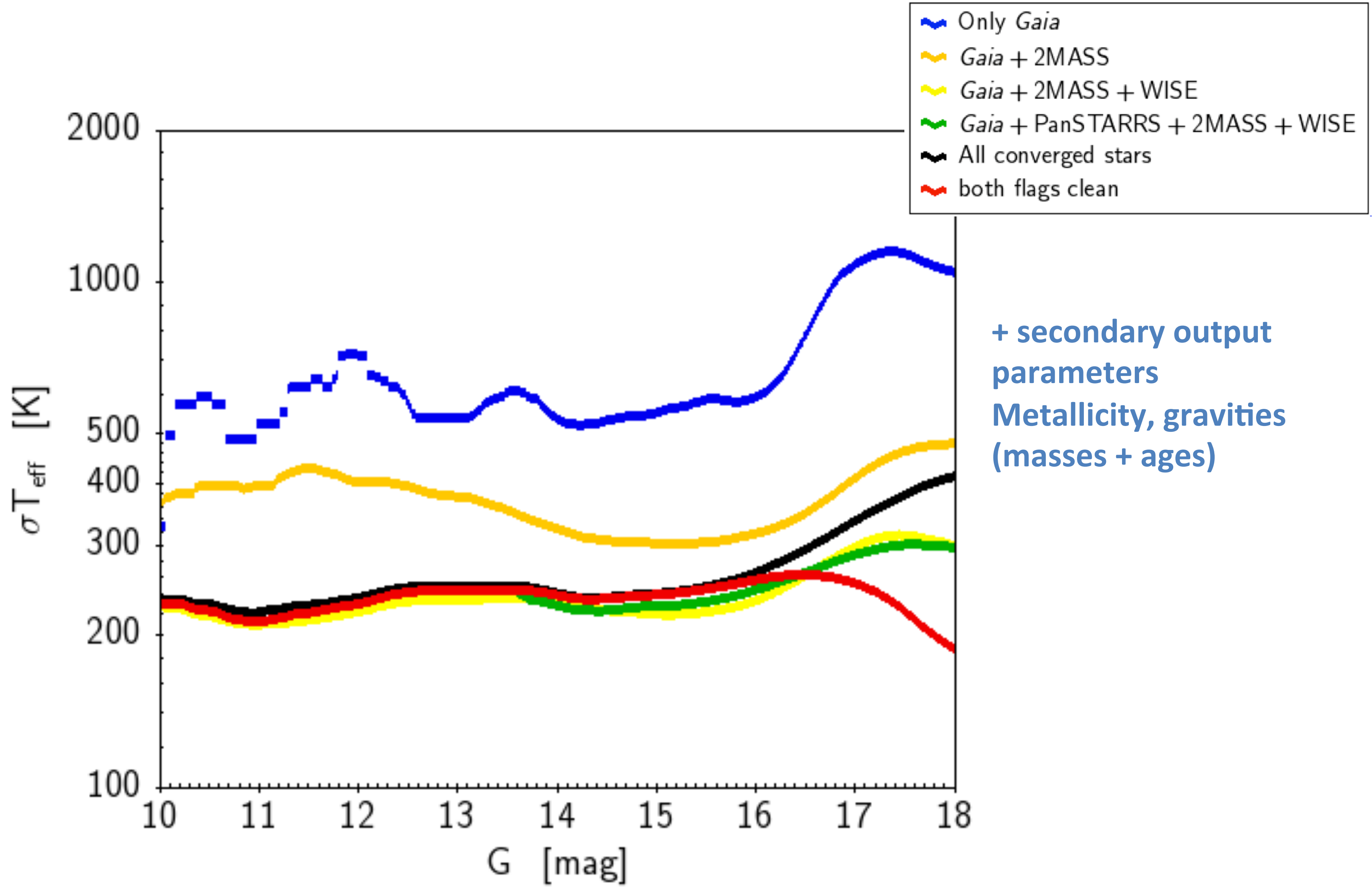
And on ESA with DR3

Source: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)
Published: November 8, 2017

Source:A. Khalatyian/ StarHorse Team – Density map of ~200 million stars – May 2019



Plato interest
GA – Volume + Age
StarHorse
both flags clean
Andrae + 2018
PP
80 Million
265 Million
SH
136.6 Million
σ_{AV} [mag]
G [mag]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
11
12
13
14
15
16
17
18



+ secondary output parameters
Metallicity, gravities
(masses + ages)