Galactic Archaeology in the Gaia era

Cristina Chiappini

Lecture II

AIP

XXV CCE at ON – Rio de Janeiro – Brazil

06-10 November 2023

Galactic Archaeology in the Gaia era

1. Mapping the Milky Way: Gaia, Spectroscopic Surveys and asteroseismology
2. The Galaxy is complex: finding debris and culprits of radial migration by combining ages, chemistry and kinematics
3. The galactic bulge I
4. The galactic bulge II and future outlook

3 important observational breakthroughs (2010-now)

Volume coverage & 6D phase space information & precision for ages & distances - extinction

1. **Asteroseismology for Red Giants** discovered in 2009 -> Masses and Radius for stars as far as 15 kpc! CoRoT, Kepler, K2, TESS and in the future PLATO

Precise distance and age for stars far away!
But pencil beam observations in few fields, low density

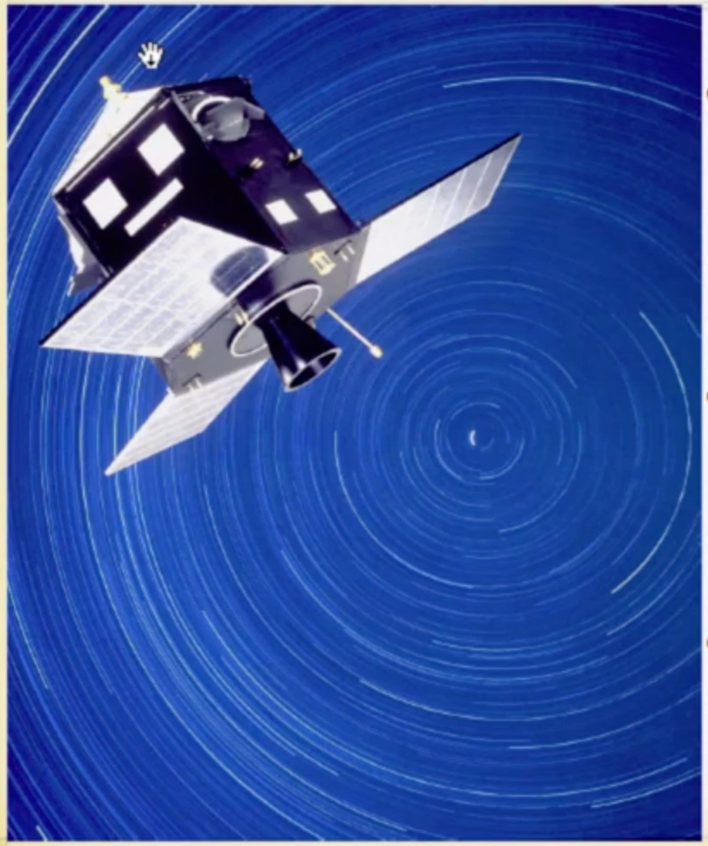
2. **Astrometry with high precision** -> Gaia - more precise than Hipparcos and large volume coverage – down to G ~ 20 , 1.7 billion targets!
Precise position and velocities -> **but need to work with complementary data (photometry and spectroscopy - Radial velocities and chemistry) in order to increase the studied volume.**

3. **APOGEE DR16-DR17 revealing the innermost MW region and more!**

2nd Revolution in Galactic Archaeology

Gaia (+complementary photometry and spectroscopy)

From Hipparcos to Gaia



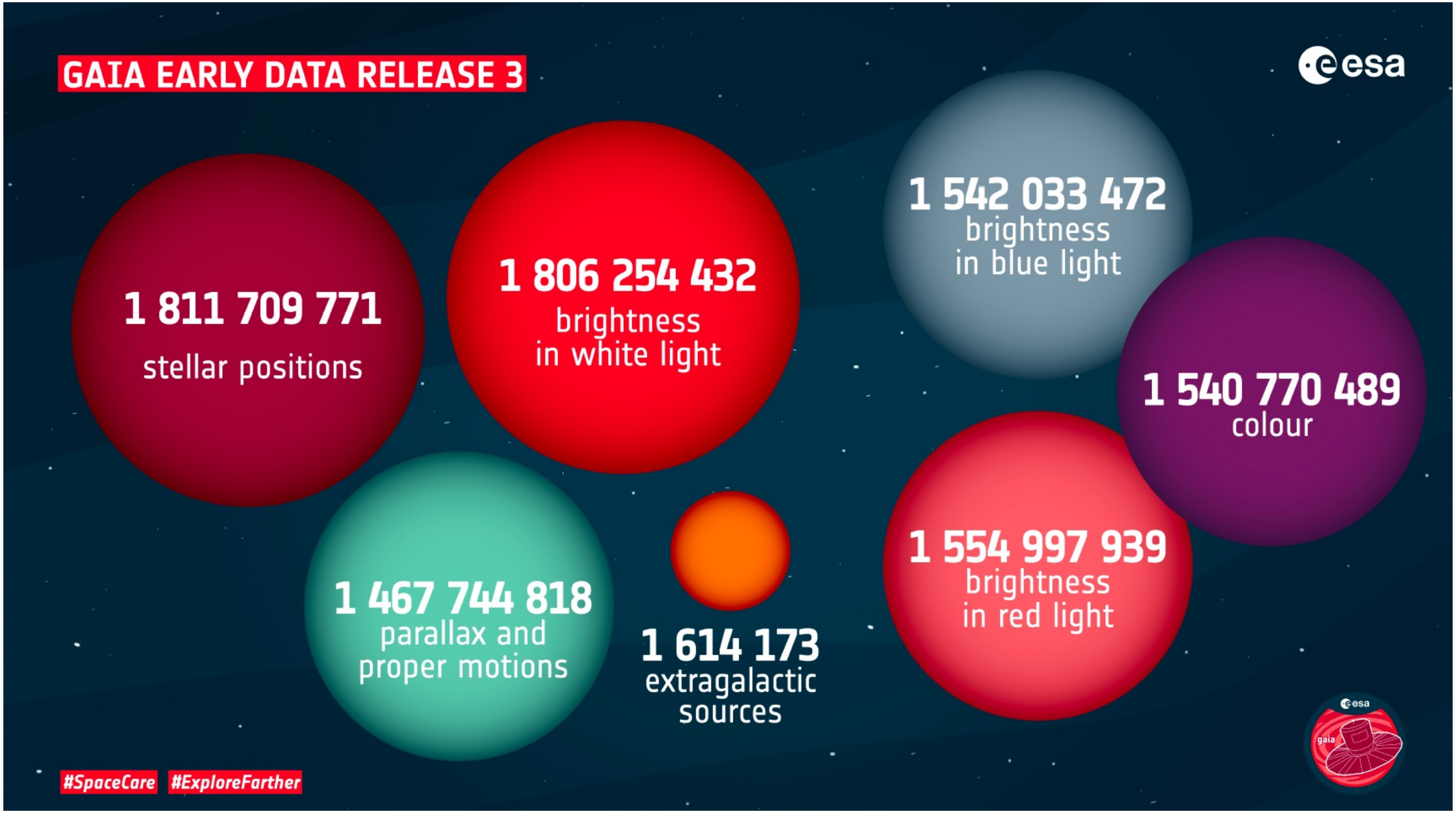
- The the first space astrometry mission was the Hipparcos satellite launched by ESA in 1989. It surveyed ~118,000 bright stars with 1-2 mas (yr^{-1}) accuracy.
- The catalogue (positions, parallaxes and proper motions) was, until recently, the main source of fundamental data for stars in the Solar neighbourhood.
- Gaia is 100 times more accurate and surveying ~1,700,000,000 objects across the galaxy.

Hobbs presentation at
ESA Voyage 2050
We need Gaia NIR

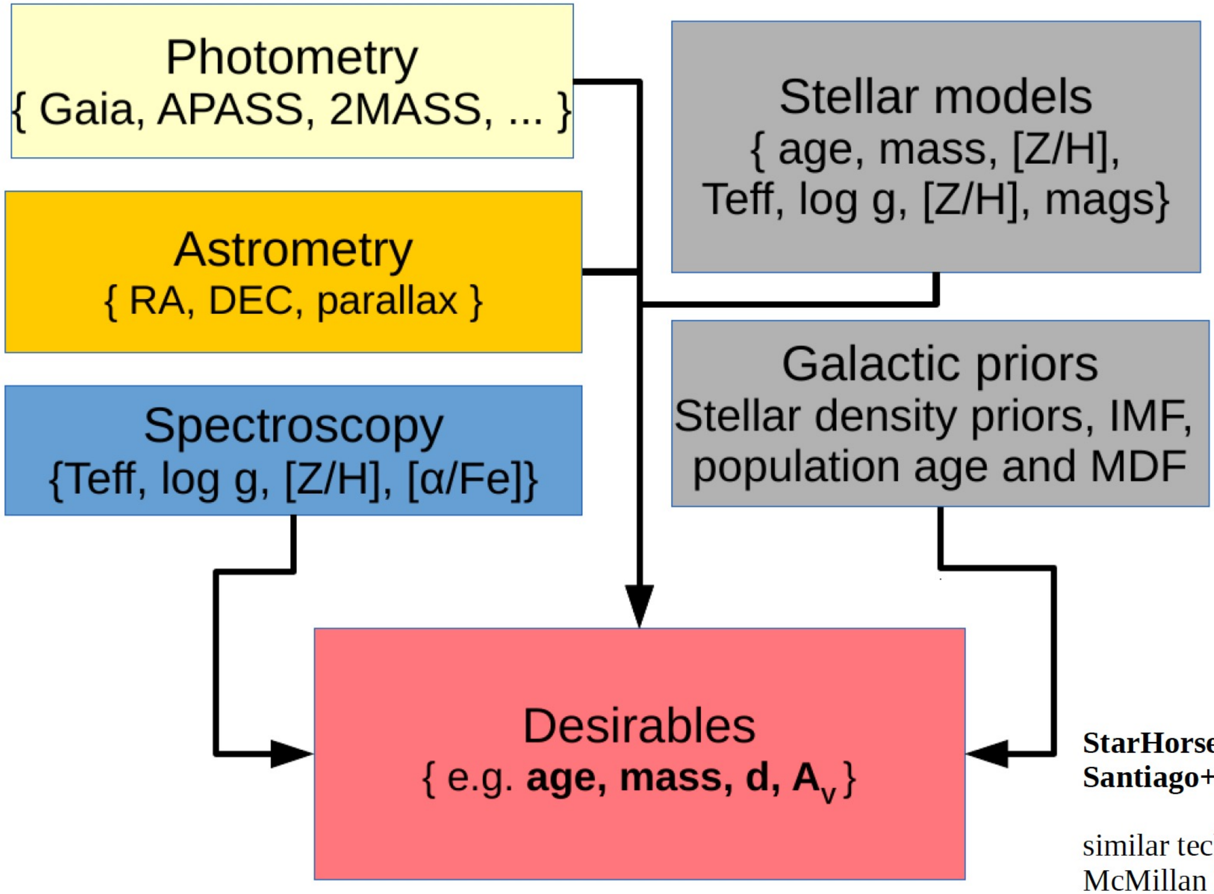
Gaia DR1 and then Gaia DR2 (2018) and EDR3 (2020), DR3 (2022)

Party at AIP

Gaia DR2 open!


GAIA EARLY DATA RELEASE 3
esa
1 811 709 771
stellar positions
1 806 254 432
brightness
in white light
1 542 033 472
brightness
in blue light
1 540 770 489
colour
1 467 744 818
parallax and
proper motions
1 614 173
extragalactic
sources
1 554 997 939
brightness
in red light
#SpaceCare
#ExploreFarther
esa
gaia

StarHorse: 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..

Credit: Slide from F. Anders

Gaia DR2 – Towards 3D map of the Galaxy: Gaia + Pan-STARRS1, 2MASS, and WISE all-sky maps

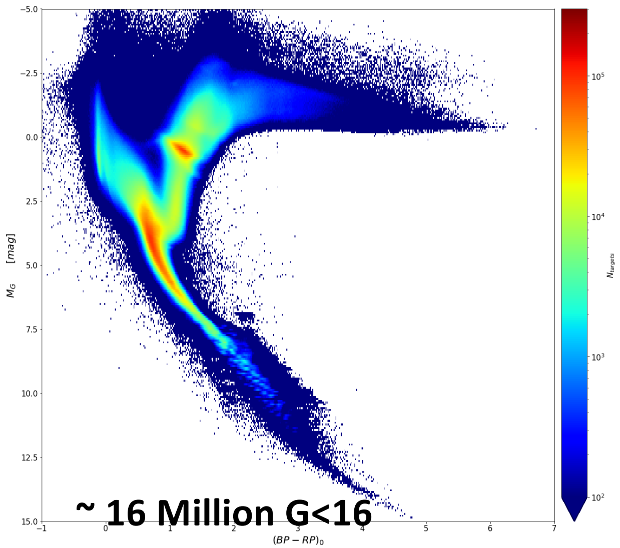
A&A 628, A94 (2019)
https://doi.org/10.1051/0004-6361/201935765

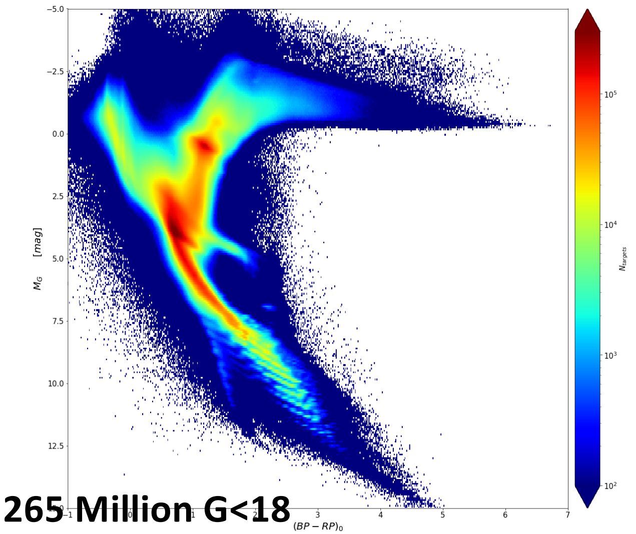
Astronomy & Astrophysics

Received 24 April 2019 / Accepted 27 June 2019

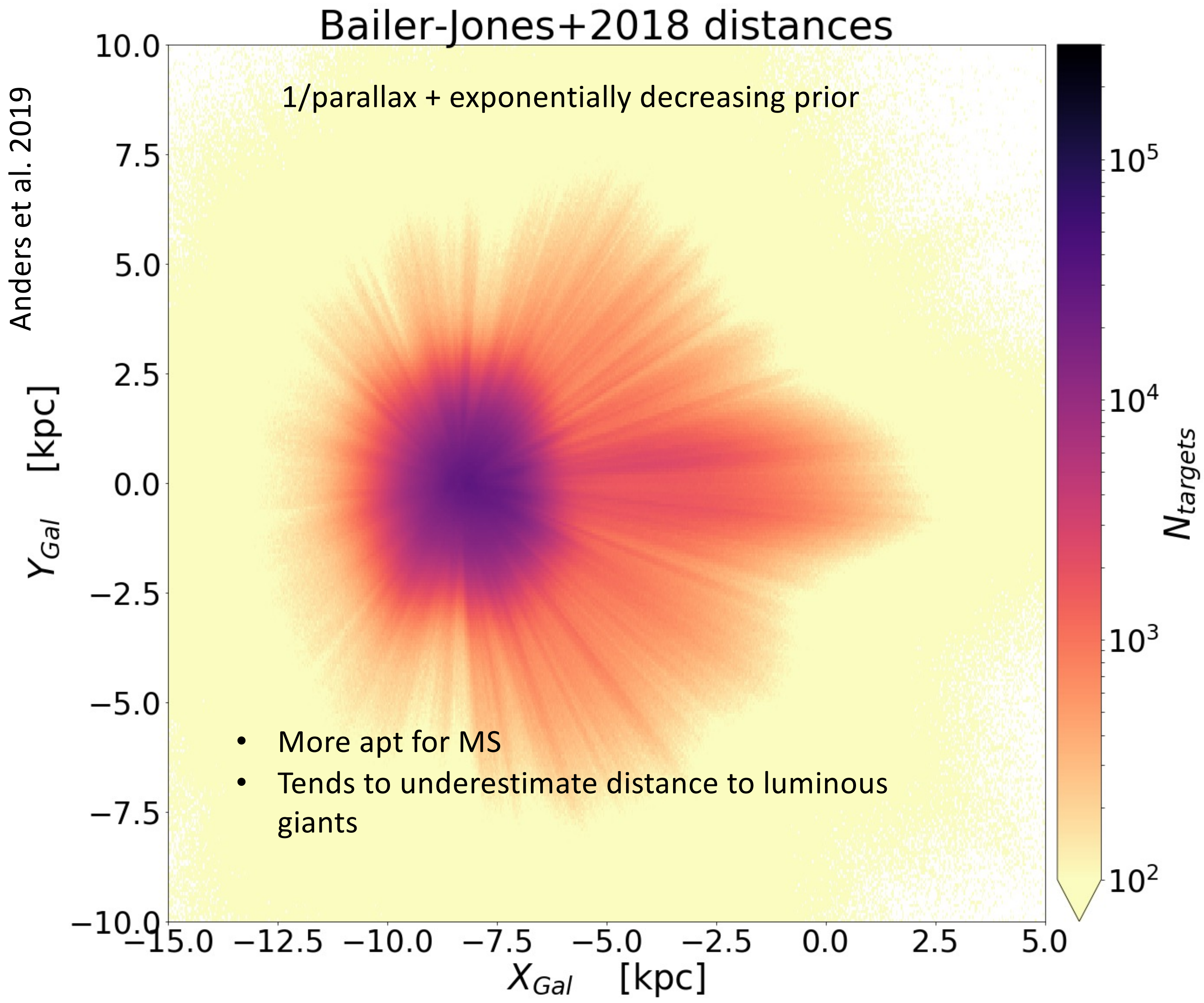
Photo-astrometric distances, extinctions, and astrophysical parameters for *Gaia* DR2 stars brighter than $G = 18$

F. Anders[1,2,3], A. Khalatyan[2], C. Chiappini[2,3], A. B. Queiroz[2,3], B. X. Santiago[4,3], C. Jordi[1], L. Girardi[5], A. G. A. Brown[6], G. Matijevič[2], G. Monari[2], T. Cantat-Gaudin[1], M. Weiler[1], S. Khan[7], A. Miglio[7], I. Carrillo[2], M. Romero-Gómez[1], I. Minchev[2], R. S. de Jong[2], T. Antoja[1], P. Ramos[1], M. Steinmetz[2], and H. Enke[2]





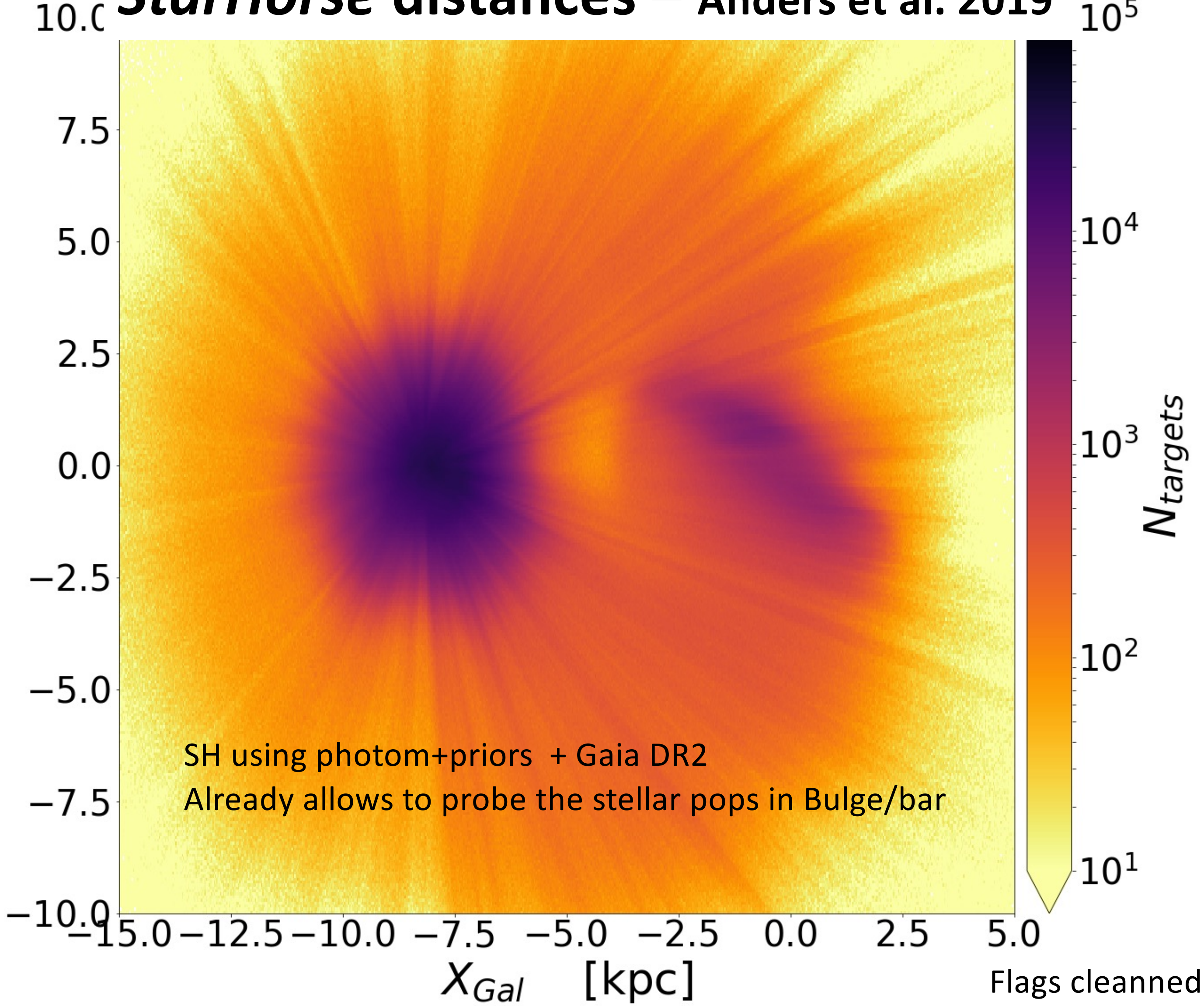
Extinction corrected CMDs


Bailer-Jones+2018 distances
1/parallax + exponentially decreasing prior
Anders et al. 2019
• More apt for MS
• Tends to underestimate distance to luminous giants
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

StarHorse distances – Anders et al. 2019

Infrared photometry (2MASS+WISE) breaks degeneracy between extinction and effective temperature

→ Improves extinction by a factor of 2 than using DR2 alone



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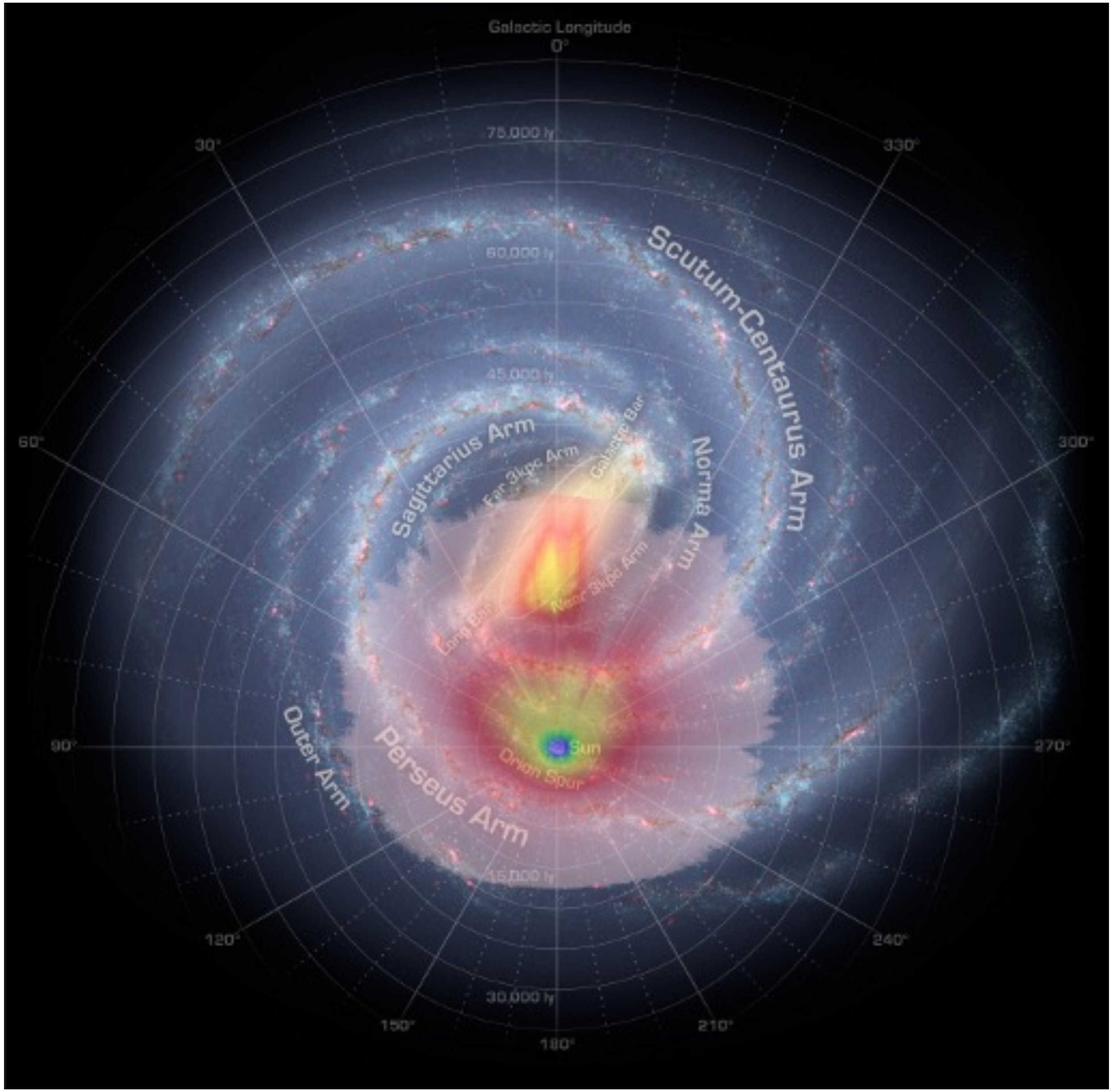
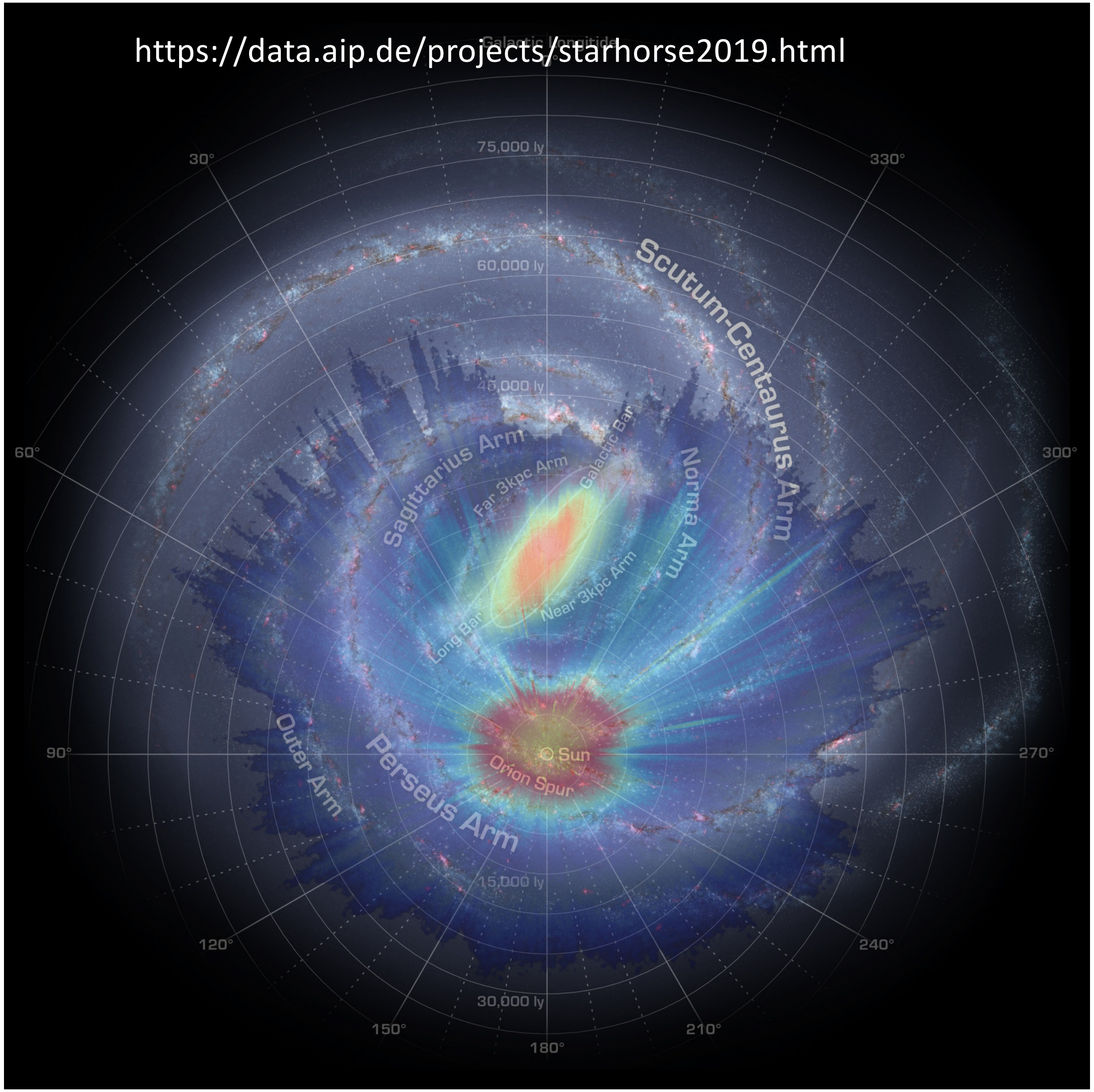


Gaia simulated
End of Mission

Goal: 3D-Map of the MW

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]



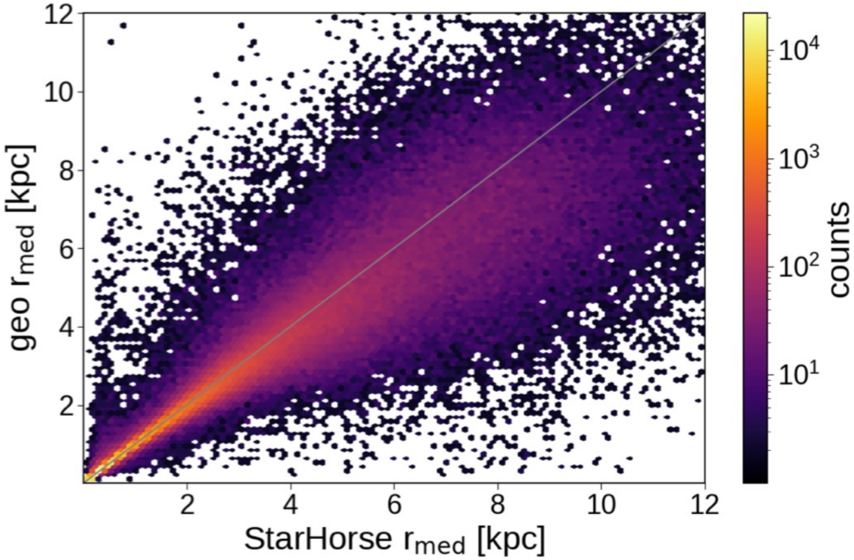
Gaia DR2 + *StarHorse*
Observed
3D (distances and extinctions for
>200 Million stars
(Anders et al. 2019)

Gaia + Photometry

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

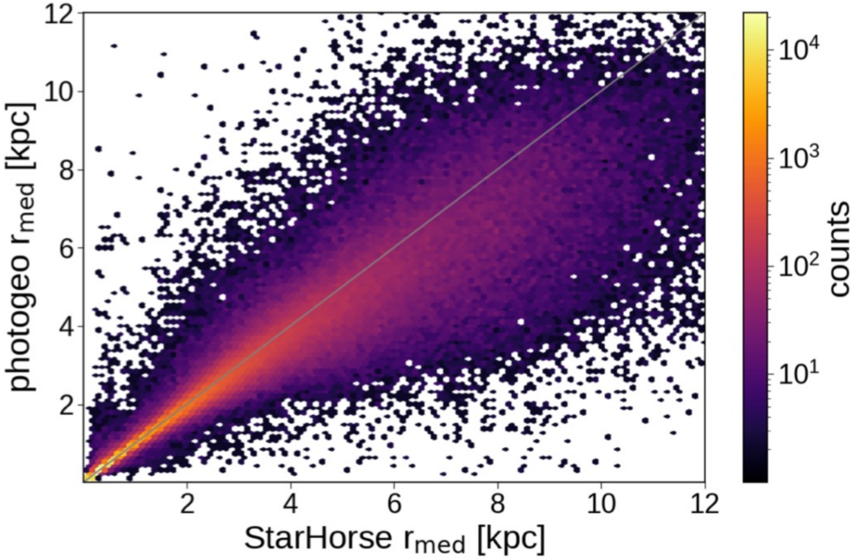
Source:A. Khalatyan/StarHorse Team – Density map of ~200 million stars – May 2019

Gaia EDR3: Bailer Jones et al. 2021
1.47 billion stars



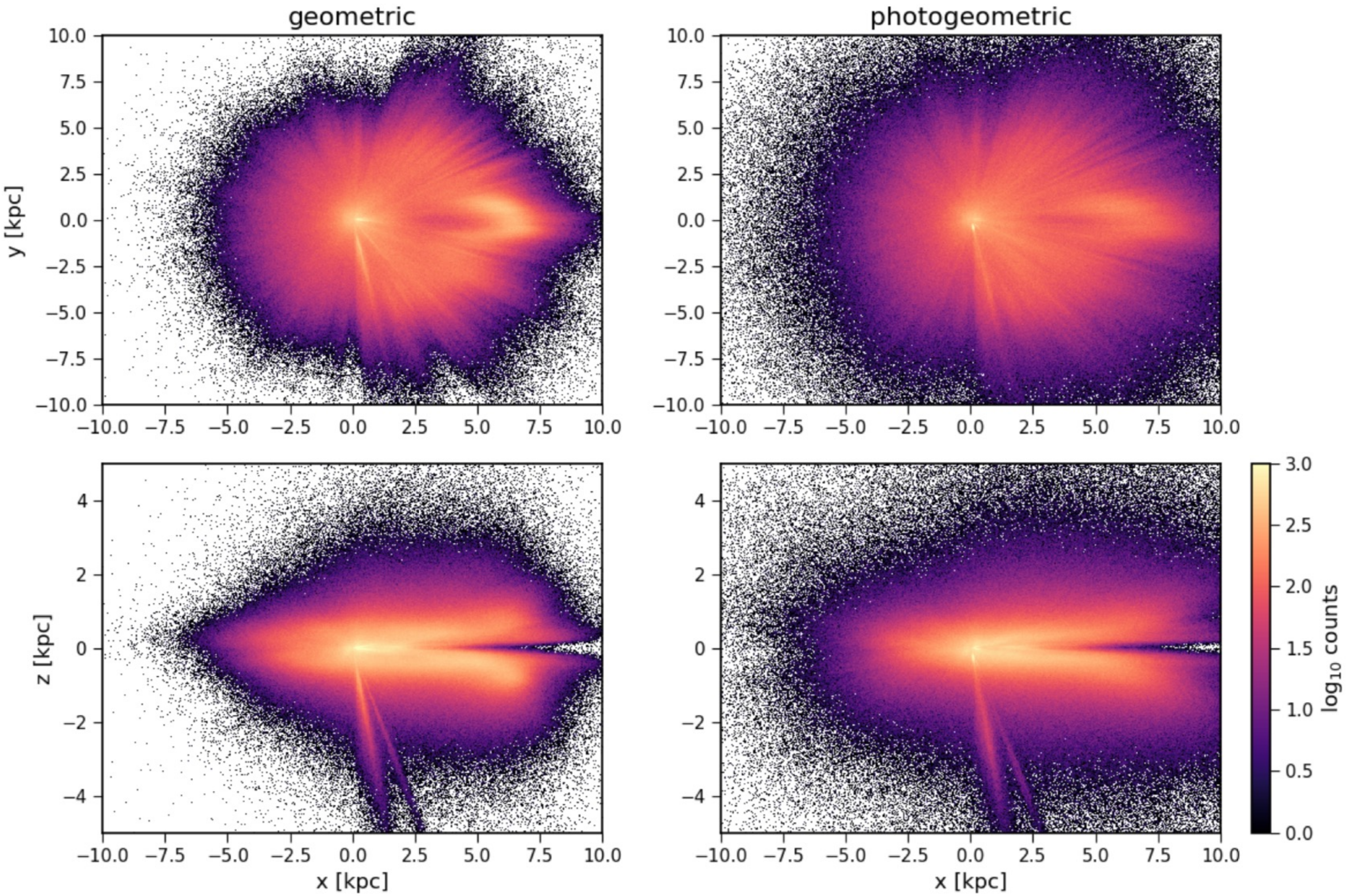
fractional bias = 0.00
rms of deviations = 0.30

Comparison of *StarHorse* distance estimates from Queiroz et al. (2020) to Bailer-Jones et al. 2021 geometric (top) and photogeometric (bottom) for around 300 000 common stars



fractional bias = -0.01
rms of deviations = 0.22

Gaia EDR3 Bailer Jones et al. 2021



Very similar to Anders et al. 2019 results using only Gaia DR2 where bar was already seen but now for more data

StarHorse2021: The Gaia EDR3 edition

Anders+2022 arXiv:2111.01860

Changes w.r.t. Anders+2019:

- EDR3 **Parallaxes** are **20% more precise** (Gaia Collaboration+2021), systematics are drastically reduced (Lindegren+2021)
- Problematic parallaxes identifiable by EDR3 **fidelity flag** (Rybizki+2021)
- Flag-cleaning more straightforward and less stars are affected
- Going fainter: **G<18.5** → **350M stars**
- Inclusion of **SkyMapper** data to cover the Southern hemisphere with *griz*
- Updated PARSEC stellar models including atomic diffusion and better post-RC tracks (Pastorelli+2019)
- Updated some priors (bar angle, **3D extinction map**, new **Local Group priors** for MCs & Sgr)
- Code speed-up, less dense model grid, & new computing cluster: **improved CO_2 footprint (factor ~6)**
- Now also approximation of the **joint posterior PDF for each star** available

Credit Anders

StarHorse Team 2021

+ Basilio Santiago!

StarHorse2021 (Anders et al. 2022)

Run for G > 18.5

- 400 M input stars
- 350 M converged
- **316 M with good flags**

https://data.aip.de/projects/starhorse2021.html

Anders, Khalatyan, et al.: `StarHorse` parameters for *Gaia* EDR3 stars

Density Distributions

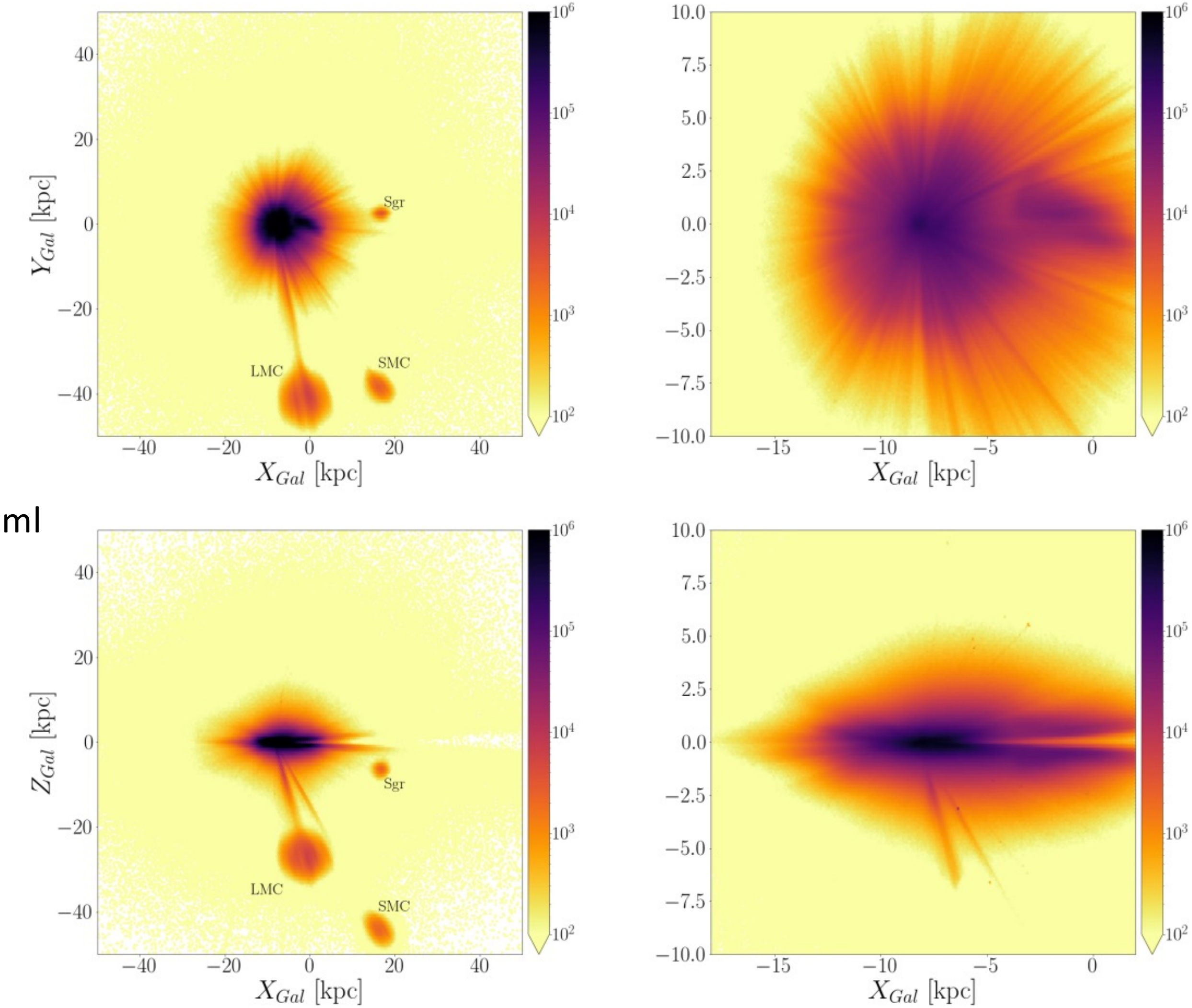


Photo-astrometric distances, extinctions, and astrophysical parameters for Gaia EDR3 stars brighter than G = 18.5

Anders, Khalatyan, et al. (2021)

Accessing the catalogue

ADQL queries:

- gaia.aip.de ADQL query interface
- StarHorse2021-specific examples in Appendix C of the paper
- Gaia ADQL tutorial

TAP queries with TOPCAT:

- TAP instructions for https://gaia.aip.de/tap/ (scroll down for TOPCAT-specific instructions)
- TOPCAT TAP access manual
- TOPCAT homepage

TAP queries with python / pyvo:

- starhorse_db (access ing the SH2021 data works in the same way as with the SH2019 dataset)
- cmd_from_db: launch binder Launch on Google Colab
- cmd_from_db_chunking: launch binder Launch on Google Colab
- TAP instructions for https://gaia.aip.de/tap/

Please use this DOI to cite the data:

doi:10.17876/data/2021_1

The data were published with this article:

Anders et al. (2021)

Download

For questions please contact:

Contact

F.Anders
Universitat de Barcelona (ICCUB)
fanders AT icc.ub.edu
A.Khalatyan
Leibniz-Institut fuer Astrophysik Potsdam (AIP)
akhalatyan AT aip.de
C.Chiappini
Leibniz-Institut fuer Astrophysik Potsdam (AIP)
cristina.chiappini AT aip.de

Gaia EDR3 + Spectroscopic Surveys

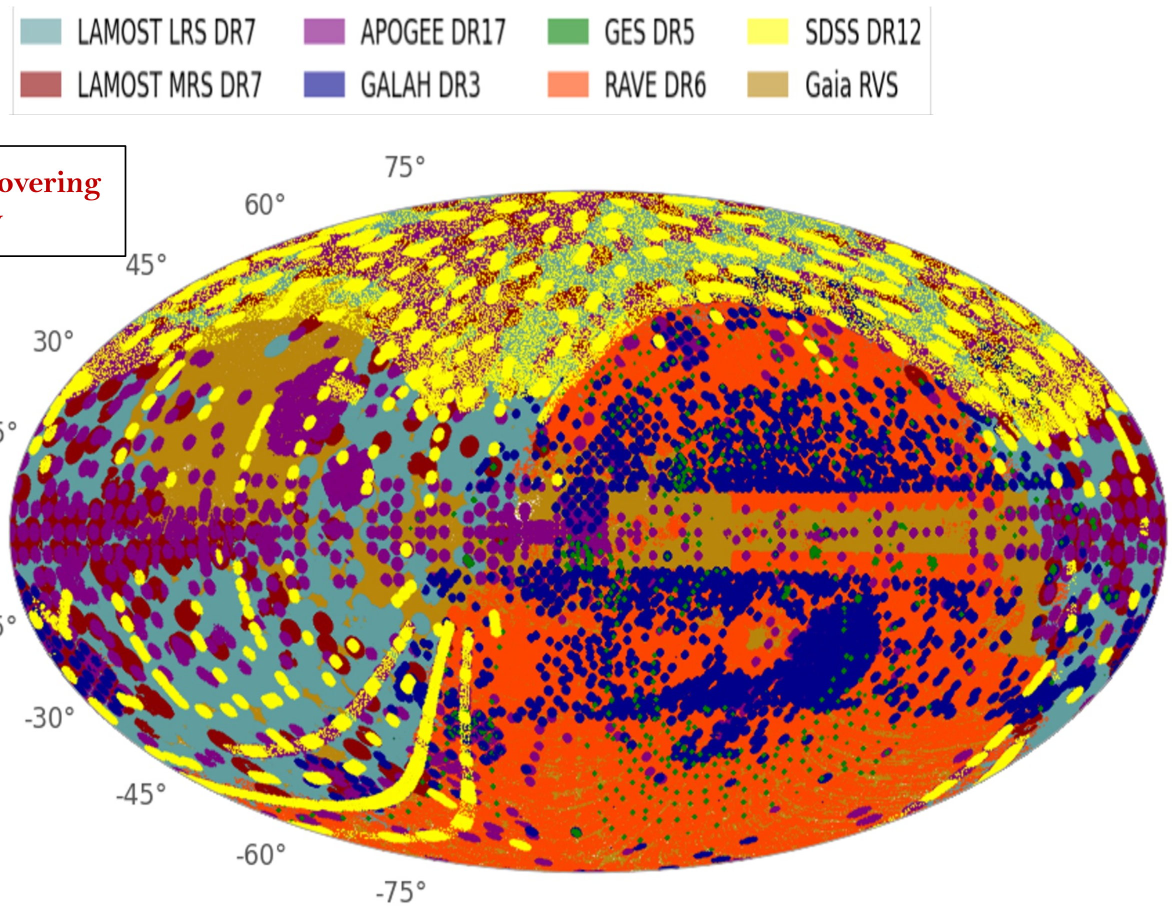
Spectroscopic Surveys at present: around 11 million sources covering all major components of the Galaxy with spectroscopy

Gaia EDR3 parallaxes (all surveys have more than 70% good Gaia parallaxes coverage)

Photometry: Pan-STARRS (visual Northern Hemisphere); Skymapper (visual Southern Hemisphere); 2mass (all sky infrared); allwise (all sky infrared)

StarHorse
Bayesian Spectrophotometric code

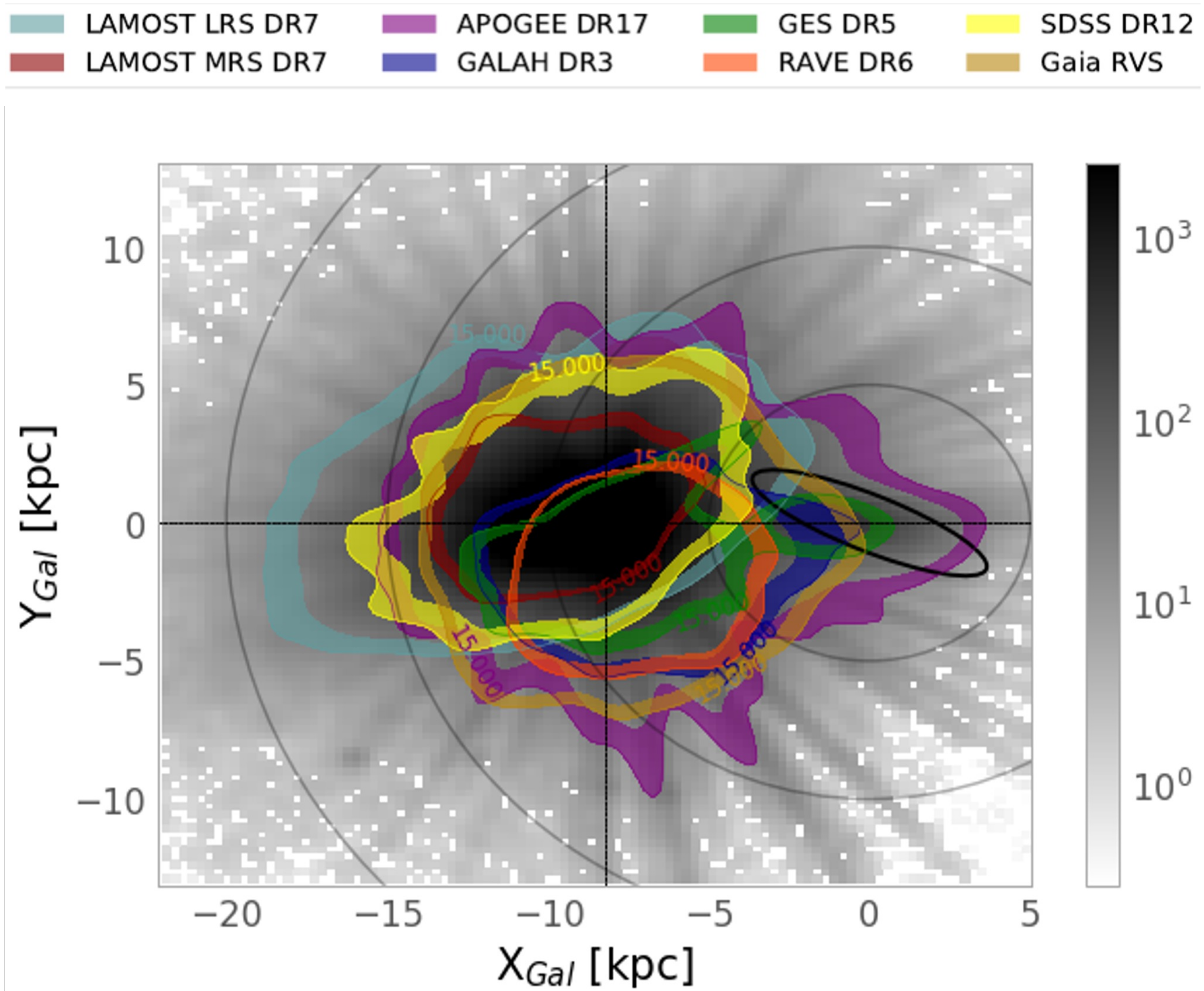
d, Av, *Teff, logg, [M/H], mass*



Queiroz et al. 2023 – Gaia EDR3 + Spectroscopic Surveys + Isochrone ages (MSTO & SGs)

Gaia + photometry + spectroscopy + SH

Precise Distances
are essential for
precise orbital
parameters
computation



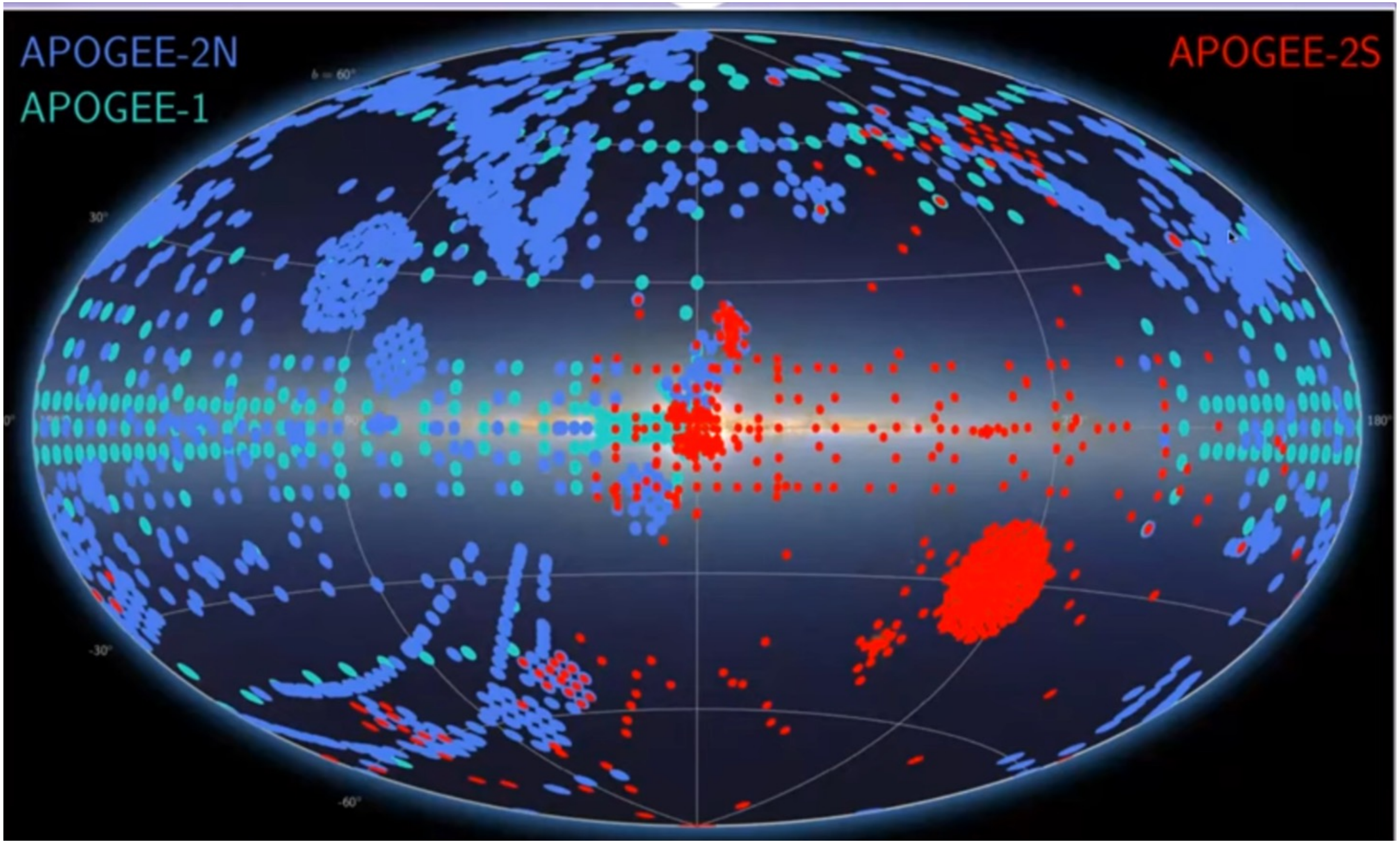
https://data.aip.de/projects/aqueiroz2023.html

Queiroz et al. 2023, 11 Million targets with distances, 2.5 Million with ages

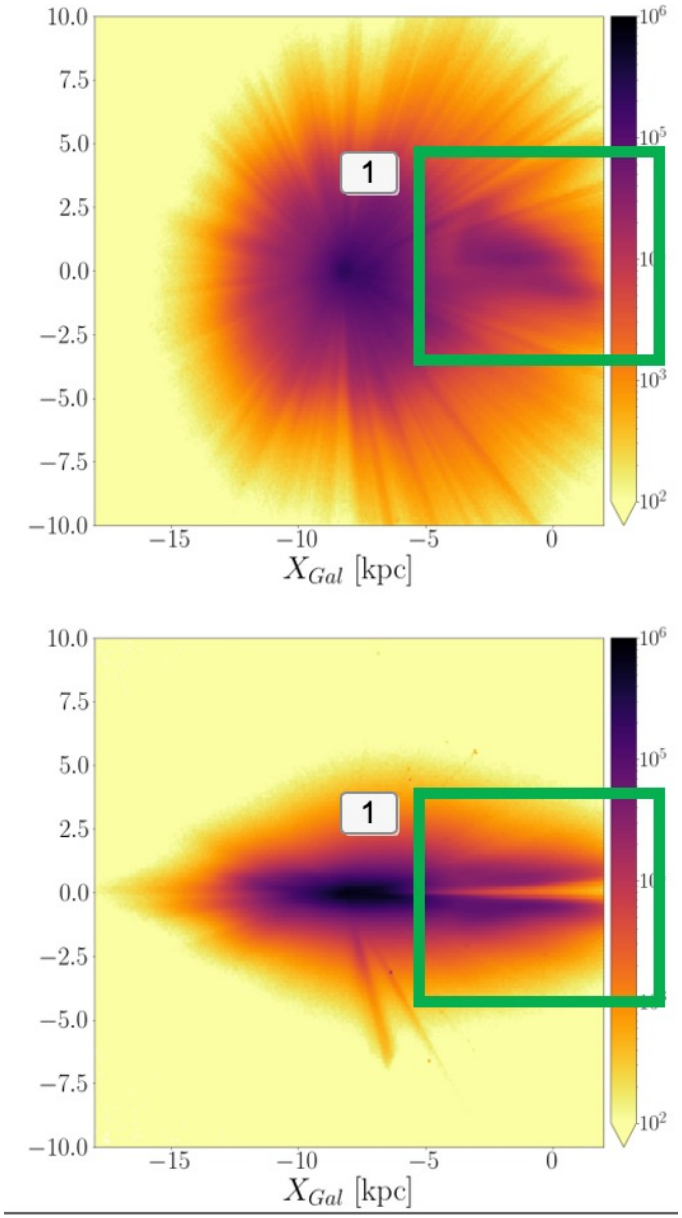
3rd Revolution in Galactic Archaeology

APOGEE

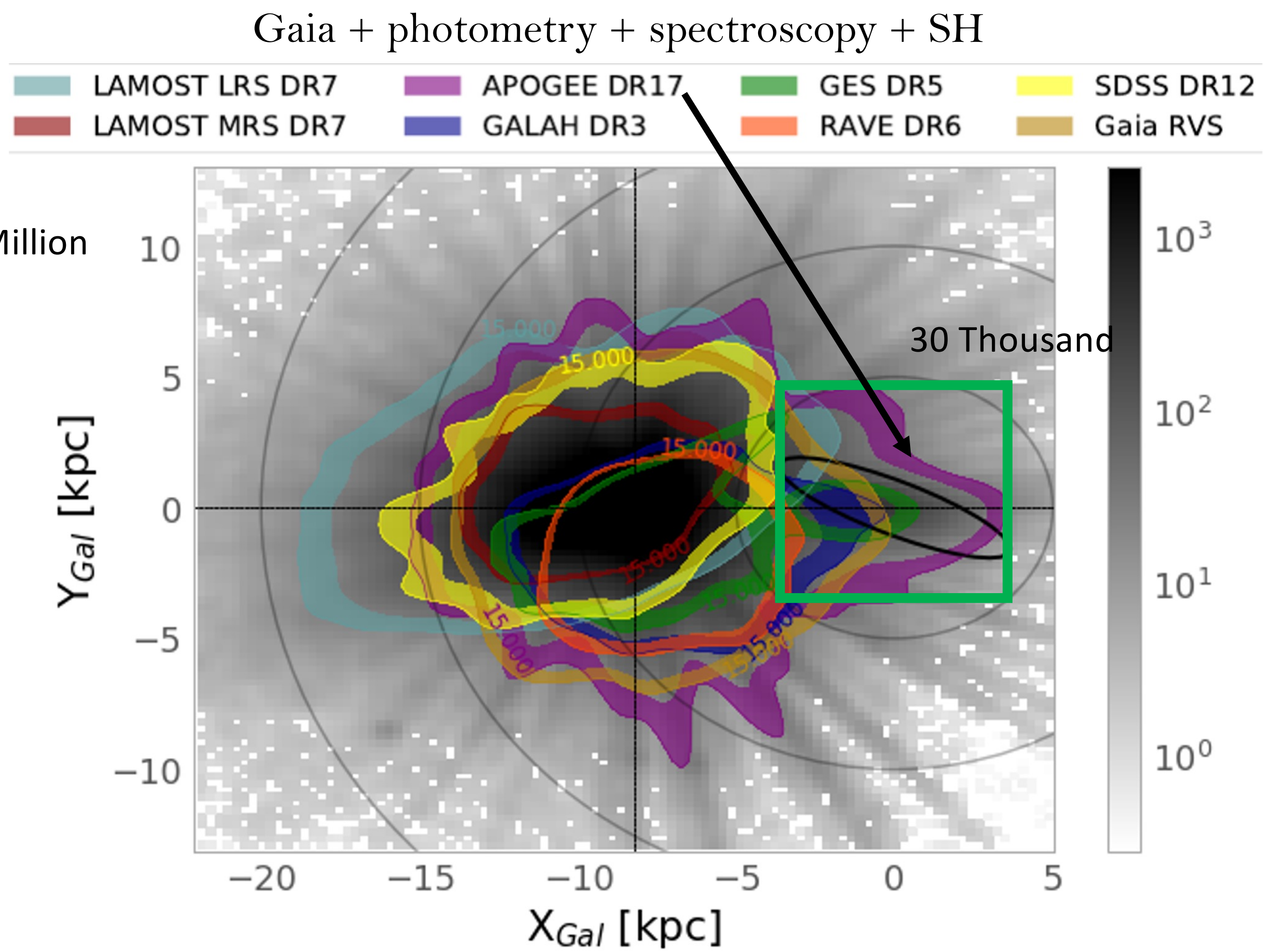
Majewsky et al. 2017



DR17 Abdurro’uf et al. 2022 ApJS, 259, 35, 39 pp.+VAC



30 Million



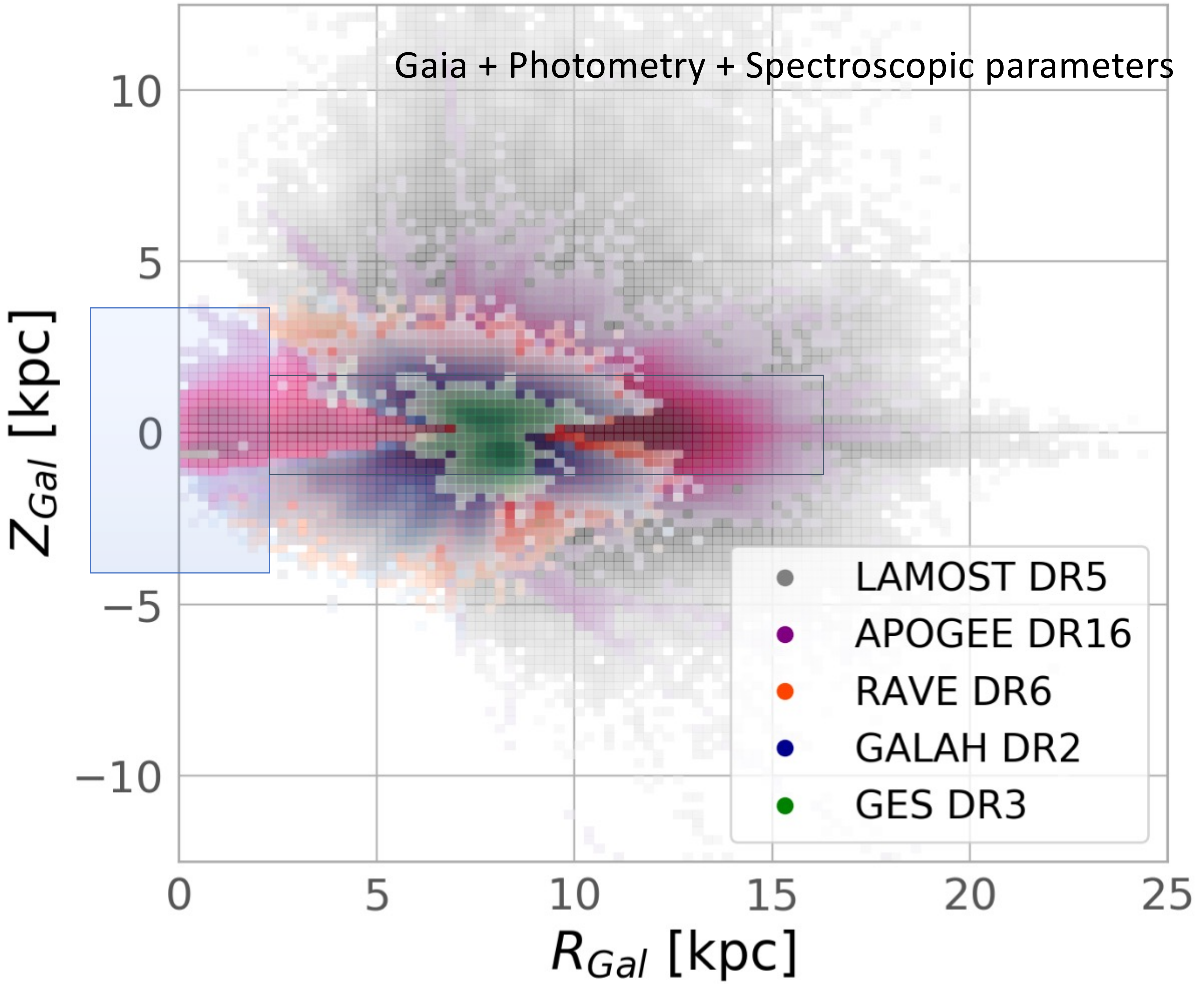
https://data.aip.de/projects/aqueiroz2023.html

Queiroz et al. 2023

Third breakthrough: APOGEE-DR16

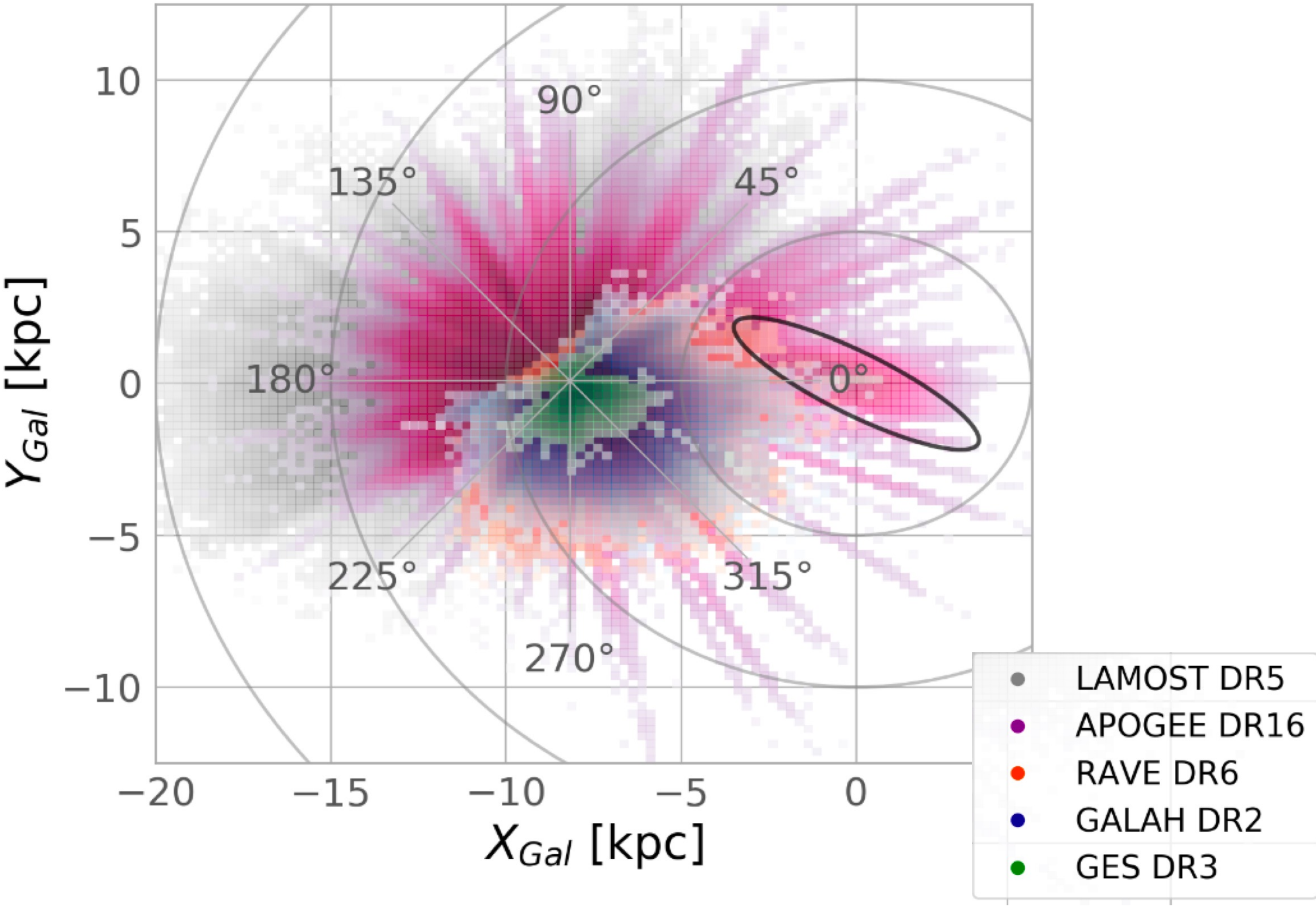
Queiroz et al. 2020

https://data.aip.de/projects/aqueiroz2020.html +Queiroz et al. 2022 in prep.



DR16 Ahumada et al. 2020 +VAC, APOGEE Majewski et al. 2017, **DR17** Abdurro'uf et al. 2022 ApJS, 259, 35, 39 pp.+VAC

Queiroz, Anders, Chiappini et al. 2020 A&A 638, id. A76



Main points of our MW up to here

- We are now able to obtain chrono-chemical-kinematical maps over much larger volumes of the MW
- 6D phase space information is now available for a larger volume. But this volume will still extend in next years when large spectroscopic surveys will complement Gaia with RVs. 6D phase space information is crucial to identify substructure-streams-mergers and help dissecting the stellar populatios within our Galaxy (e.g. Bulge-inner Galaxy)
- Large multi-D information from chemistry will also complement Gaia – at different levels of precision and number of chemical elements. 6D + Chemistry is a lot more powerful to reconstruct building blocks of our Galaxy´s formation
- One more key dimension: Age – this will remain critical. Hopes on chemical clocks, asteroseismology of red giants and larger telescopes
- Very important is to combine the sharpest information on smaller volumes with a more holistic view of the Galaxy from less multi-D data - therefore the need to understand diferent datasets/techniques

Next steps: How to use this information (**Gaia+Spectroscopy+Photometry+Asteroseismology**) to learn about the MW formation and how this can impact how we model and observe other galaxies

The MW thin and thick disk

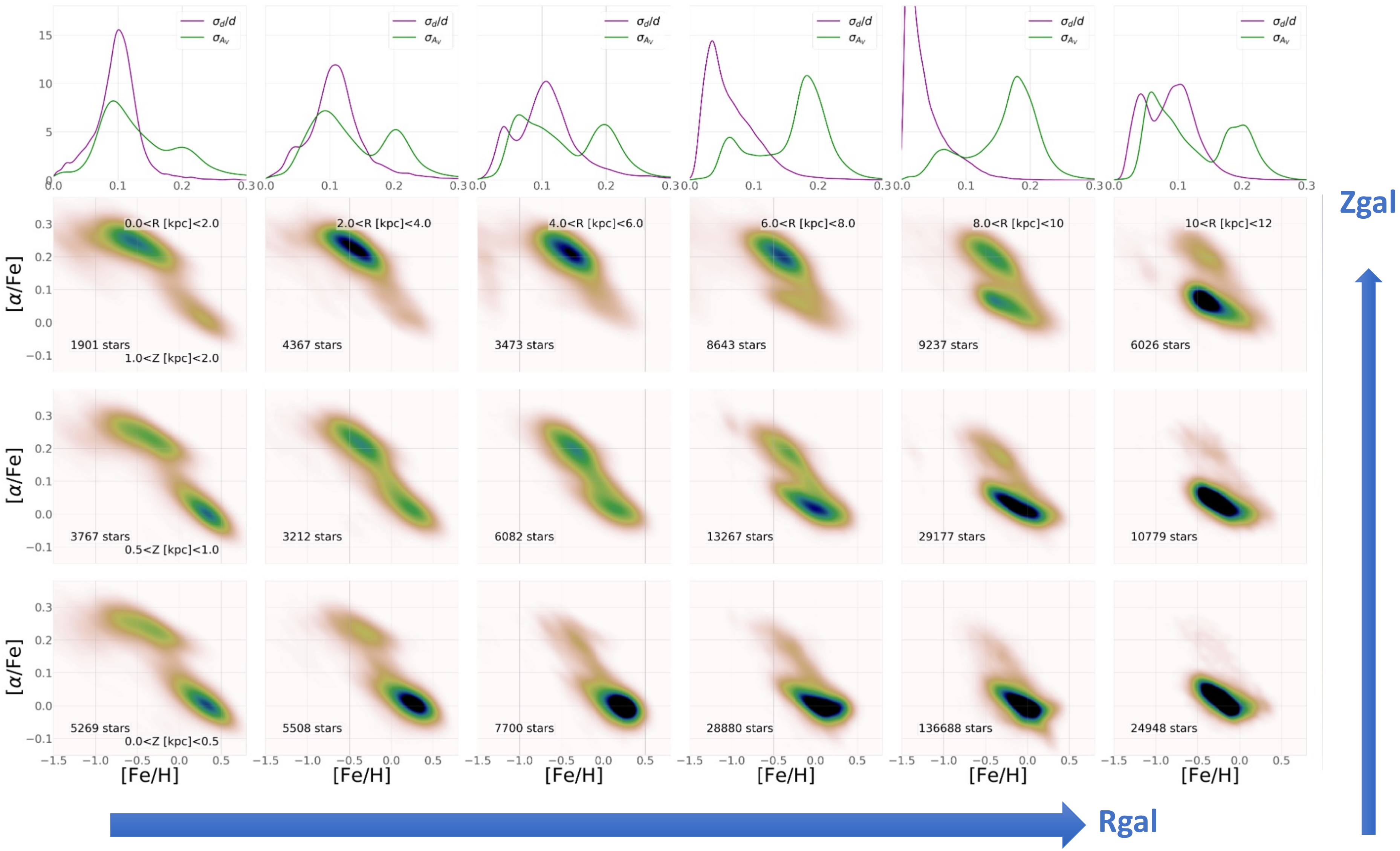
Inside out formation

Which thick disk?

Chemical – Genuine or Geometric?

Short scale lenght
Very old

Queiroz et al. 2020 – **APOGEE DR16** + Gaia DR2 + Complementary photometry



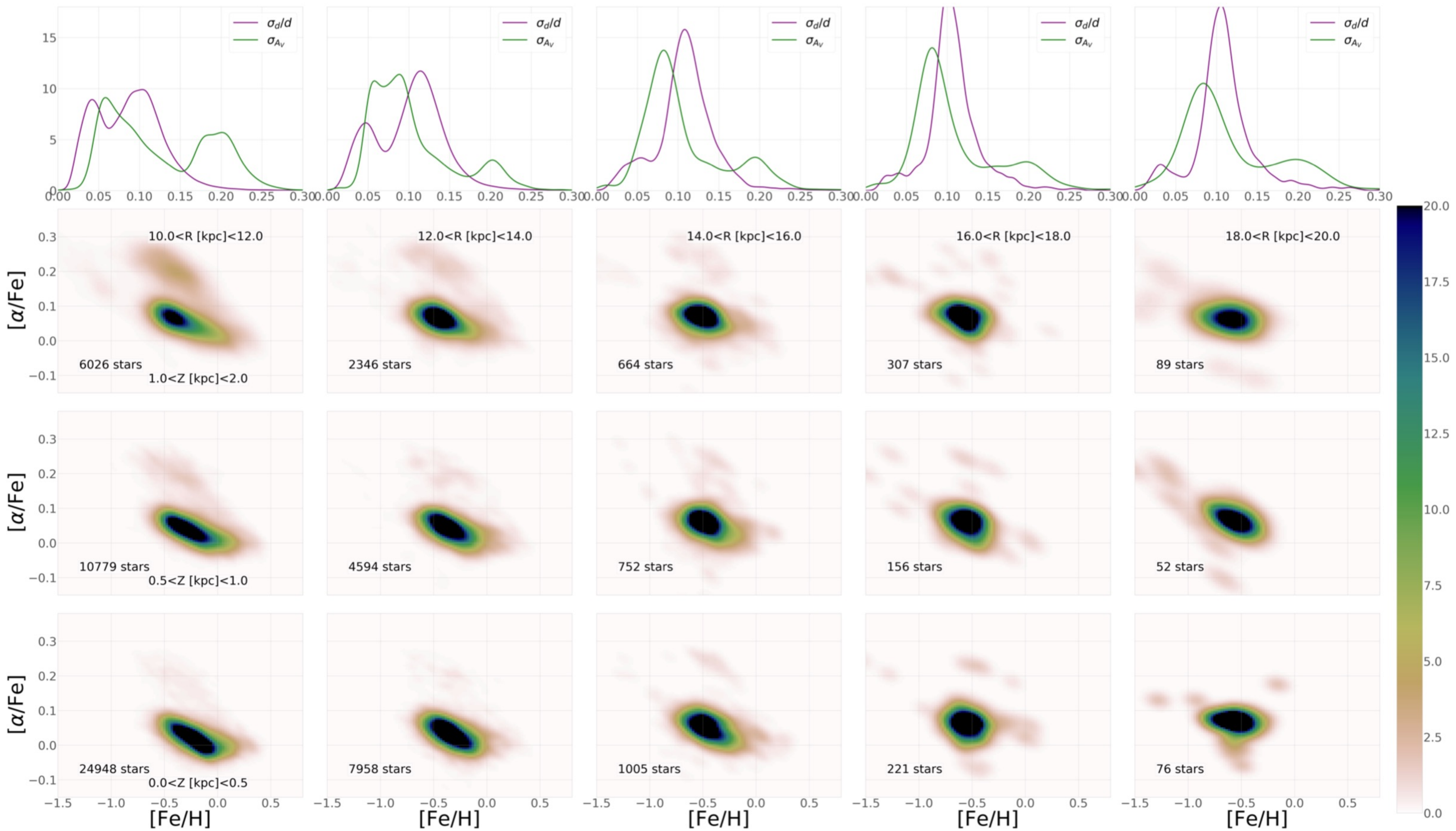
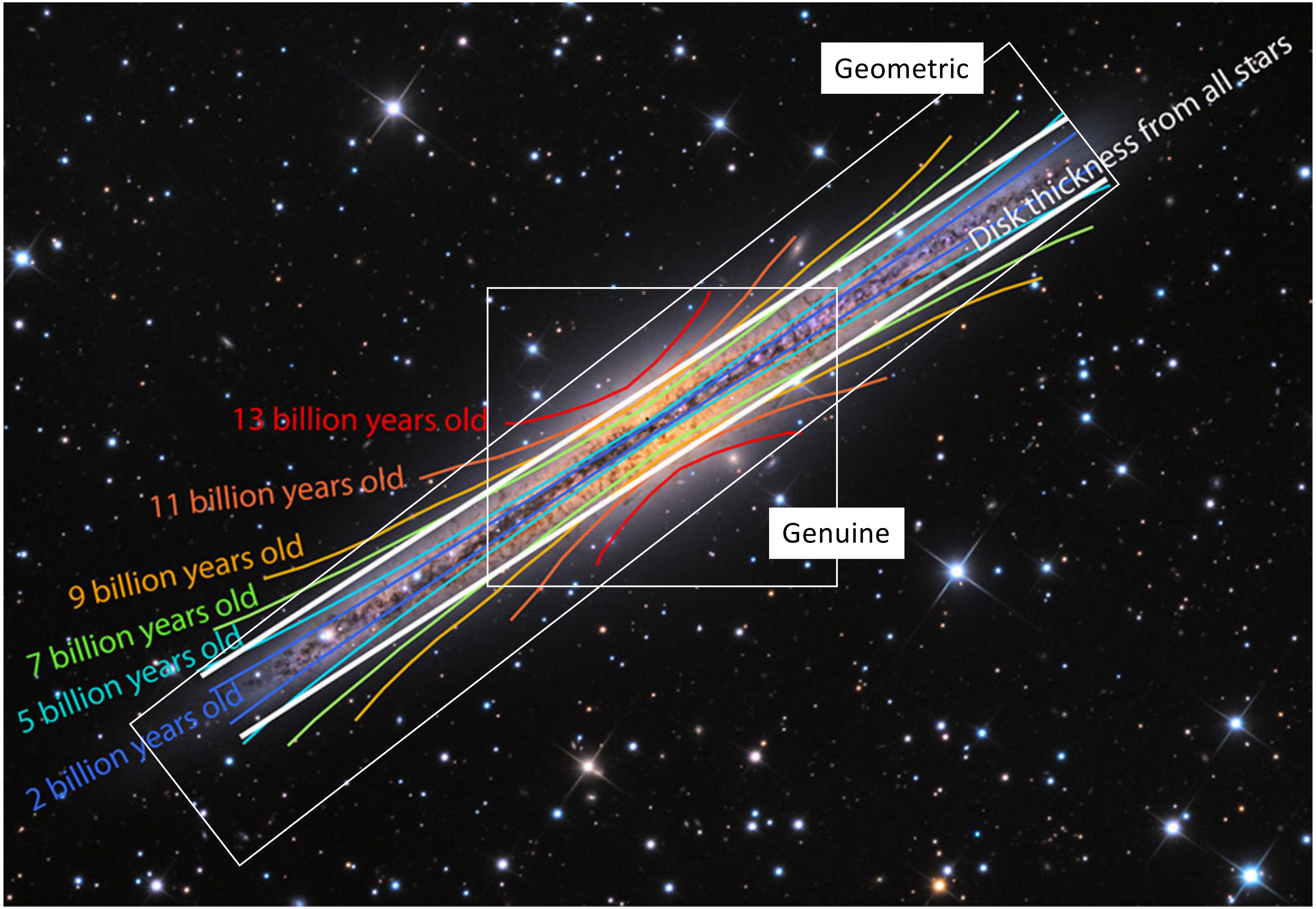


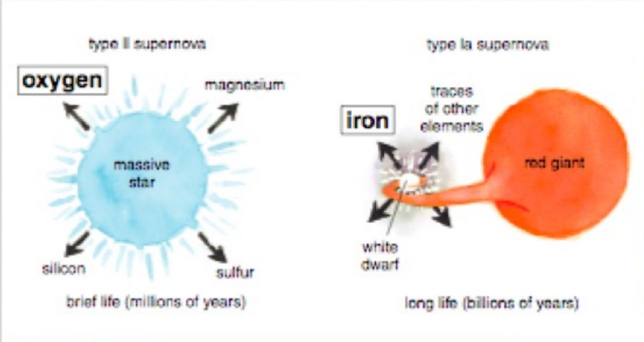
Fig. 7. Same as previous Figure, but now extending to the outer disk.



Minchev et al. 2015

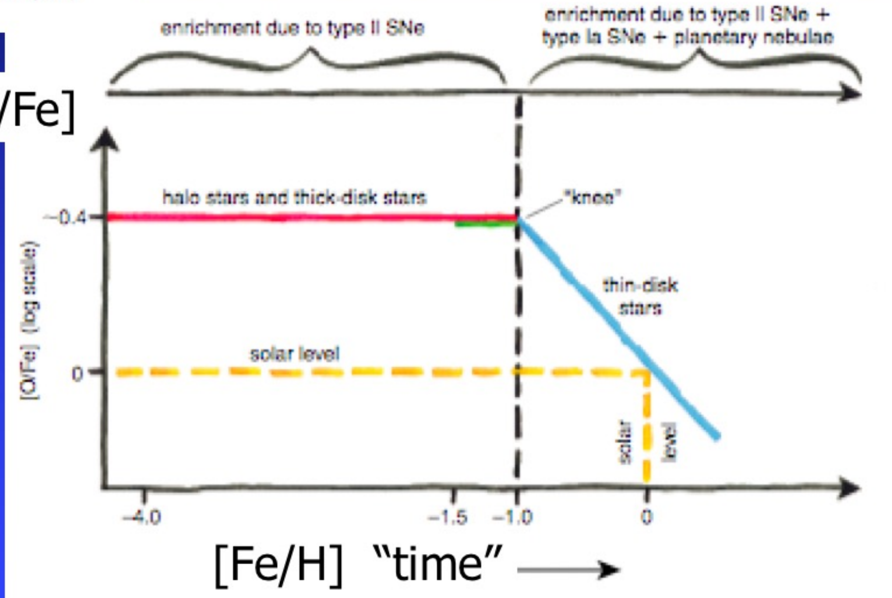
Quick detour: Chemical Clocks

M

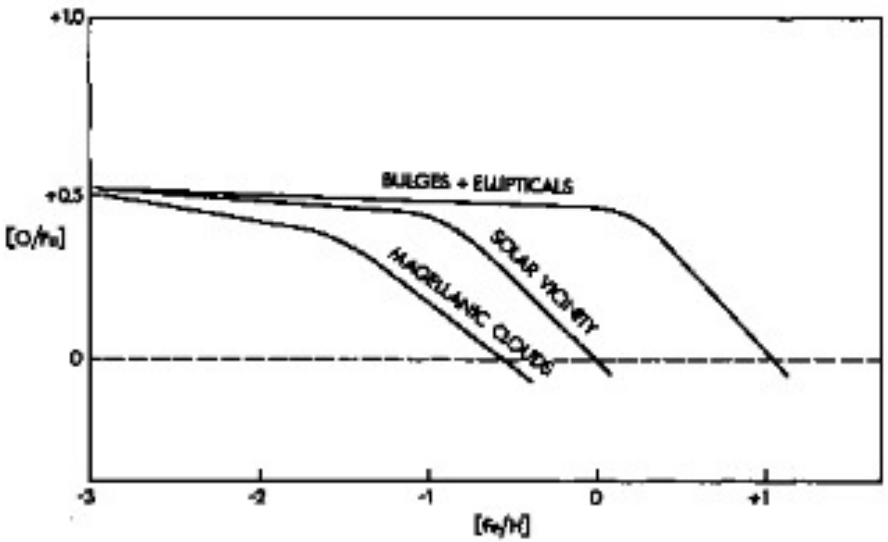


[O/Fe] x [Fe/H]

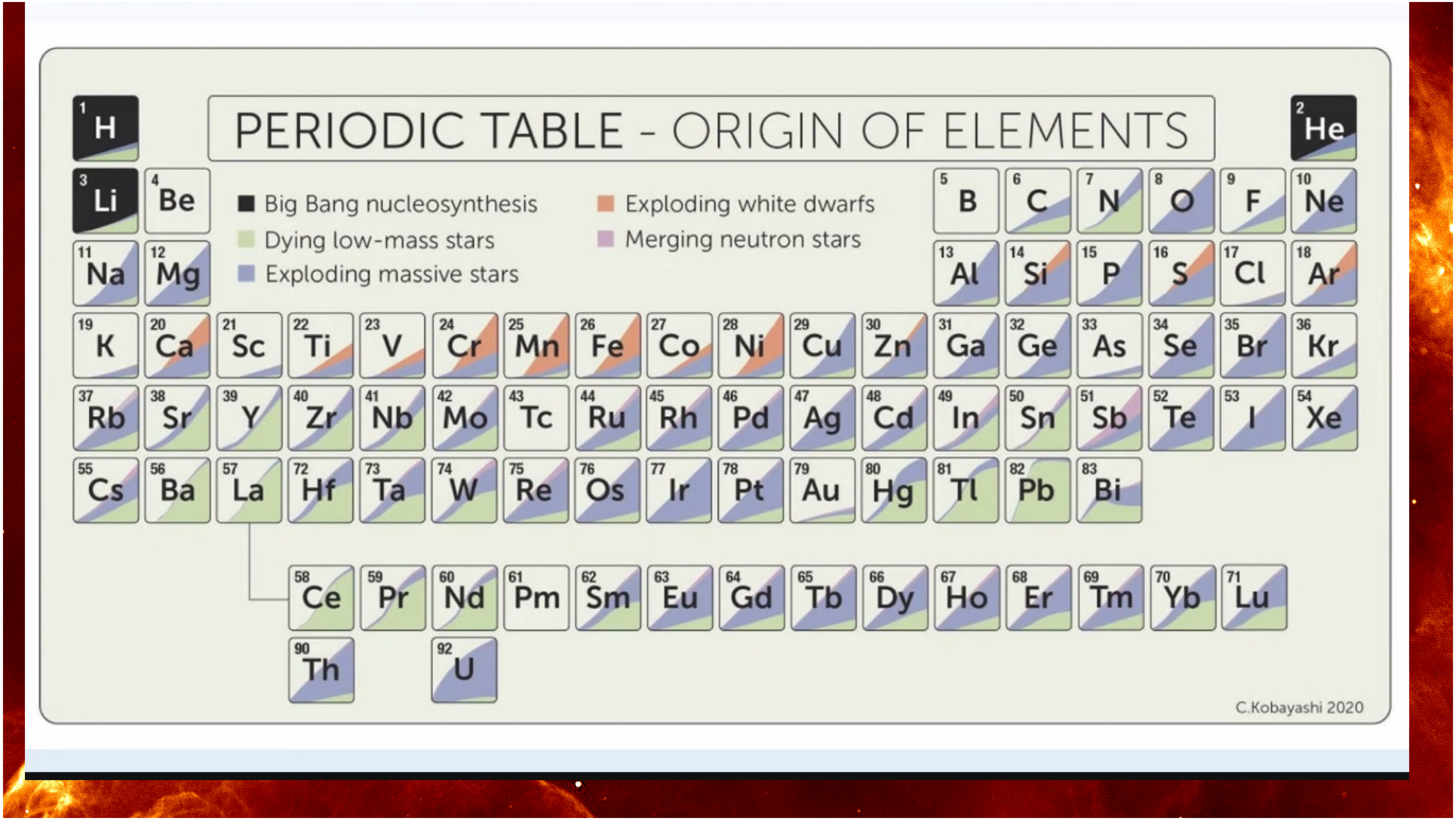
([X/H] = log(X/H) –log(X/H)_sun)

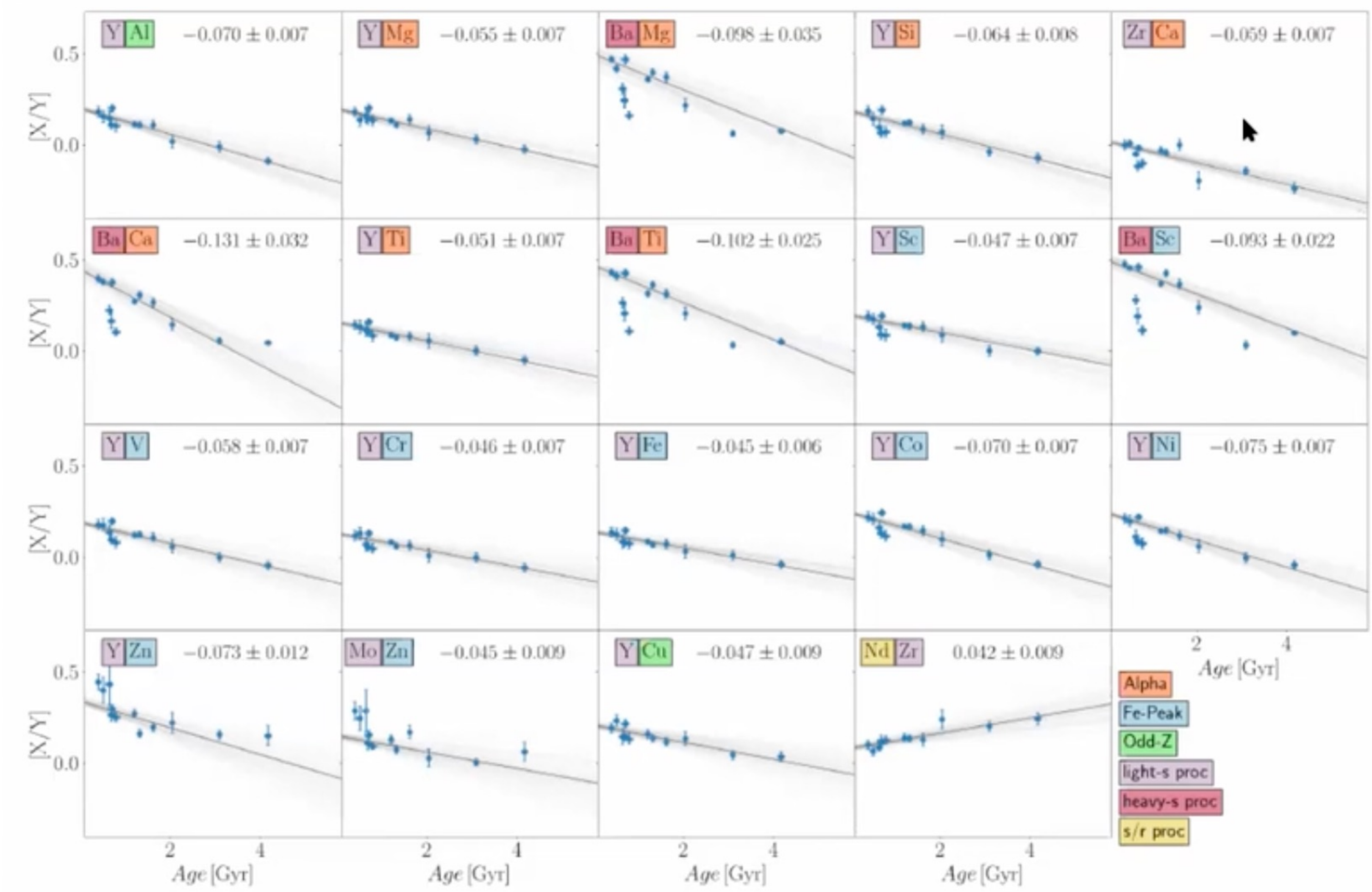


Chiappini 2004 S&T



Matteucci & Brocato, see Matteucci 2022

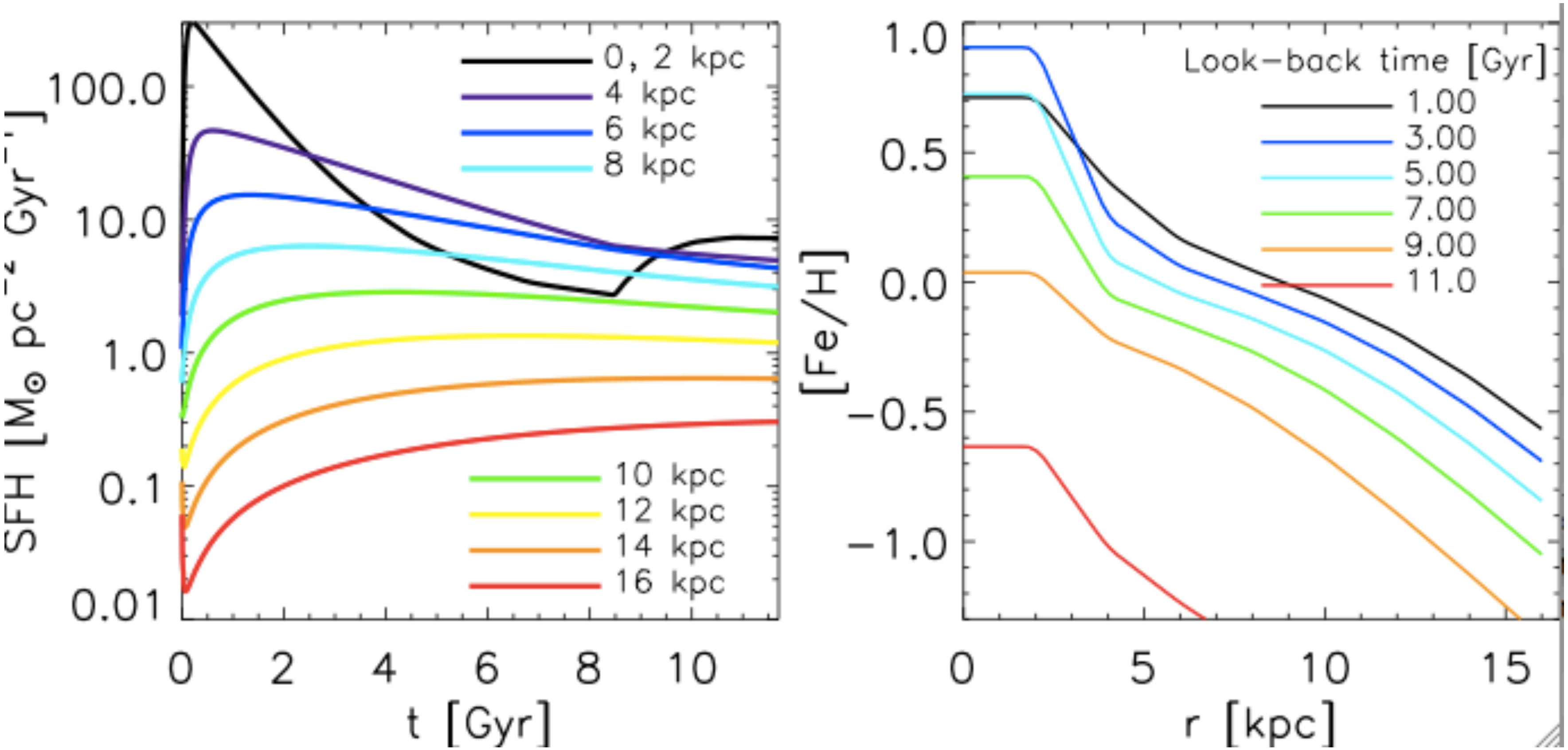

PERIODIC TABLE - ORIGIN OF ELEMENTS
Big Bang nucleosynthesis
Dying low-mass stars
Exploding massive stars
Exploding white dwarfs
Merging neutron stars
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57 La
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
92 U
C.Kobayashi 2020



Casamiquela et al 2021

Thin disk... Secular processes

The Challenge: Infer Star formation histories
... but stars move from their birthplaces...



A thin disk only model

A&A 558, A9 (2013)
DOI: 10.1051/0004-6361/201220189

Astronomy & Astrophysics

Chemodynamical evolution of the Milky Way disk

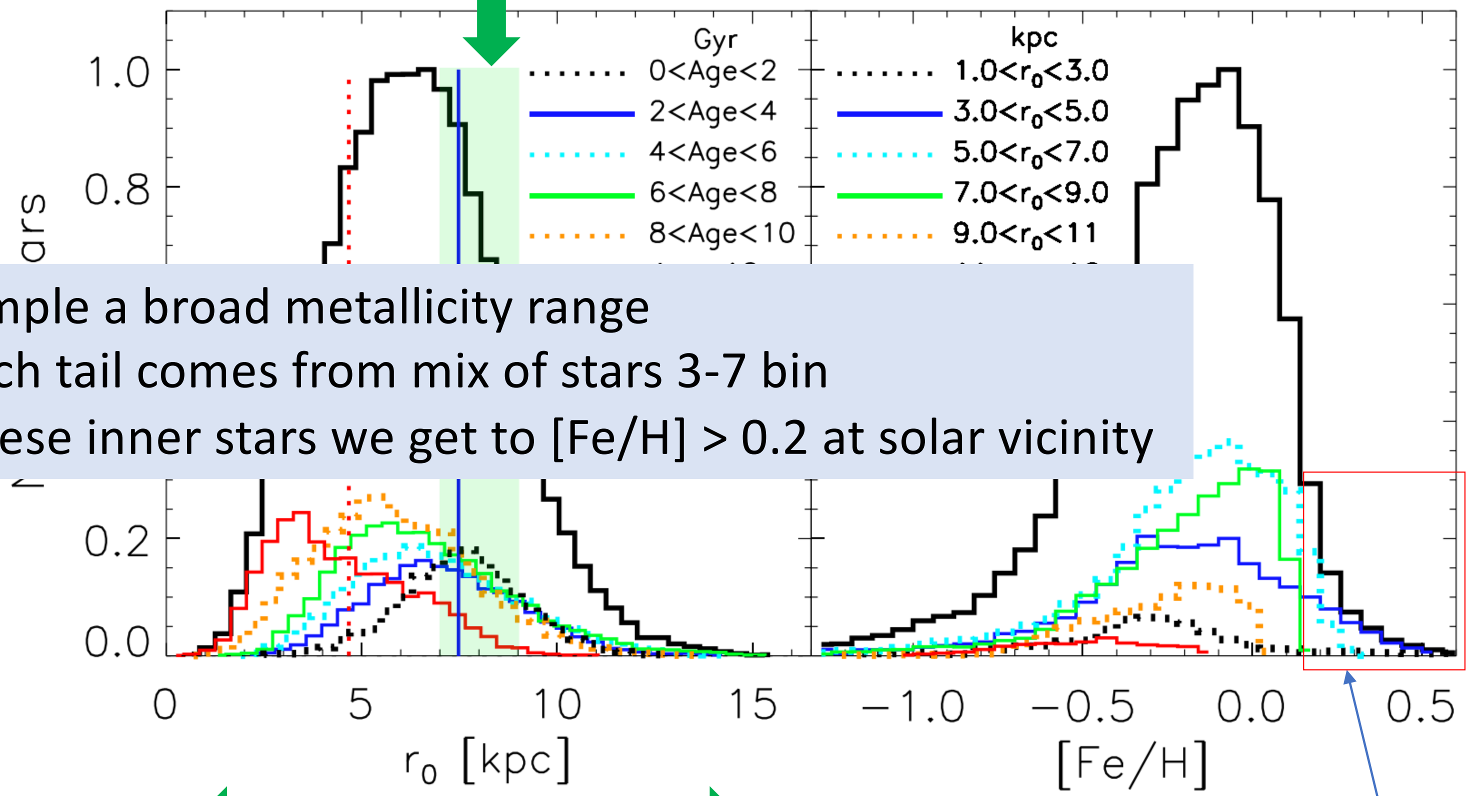
I. The solar vicinity*

I. Minchev[1], C. Chiappini[1], and M. Martig[2]

[1] Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: iminchev1@gmail.com
[2] Centre for Astrophysics & Supercomputing, Swinburne University of Technology, PO Box 218, VIC 3122 Hawthorn, Australia

Received 8 August 2012 / Accepted 1 July 2013

Stars currently around the Sun...



Old stars sample a broad metallicity range
The metal rich tail comes from mix of stars 3-7 bin
Only with these inner stars we get to [Fe/H] > 0.2 at solar vicinity

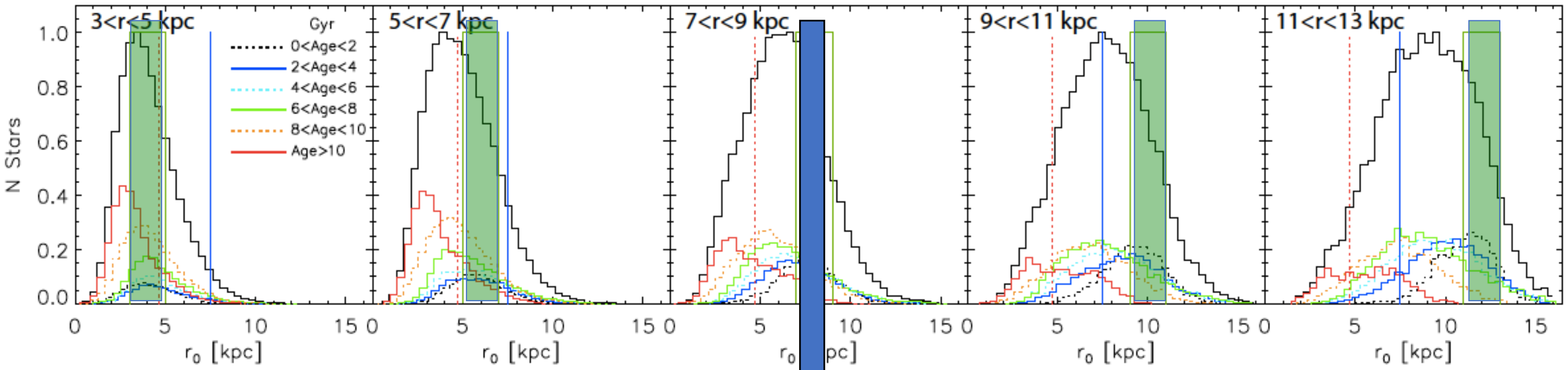
came from different regions in the Galaxy?

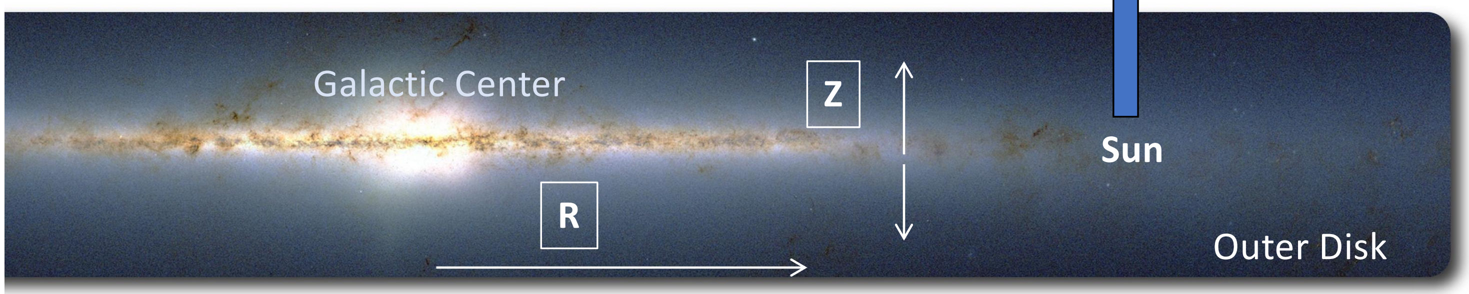
Are the most metal rich born at Ro < 5-7 kpc?
If yes, they are not the youngest...

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)



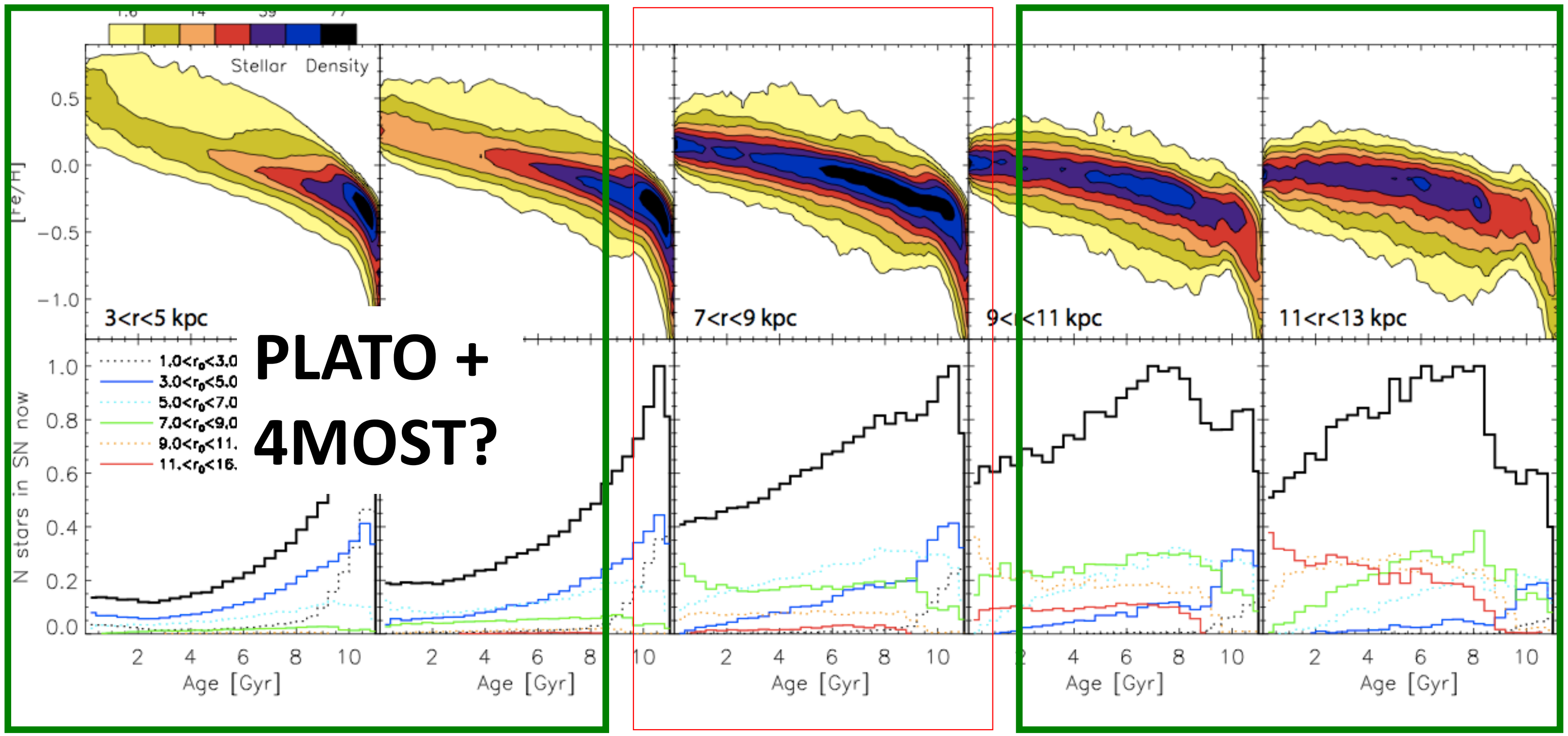


R = distance from GC

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

The properties at different places in the disk: AMR

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

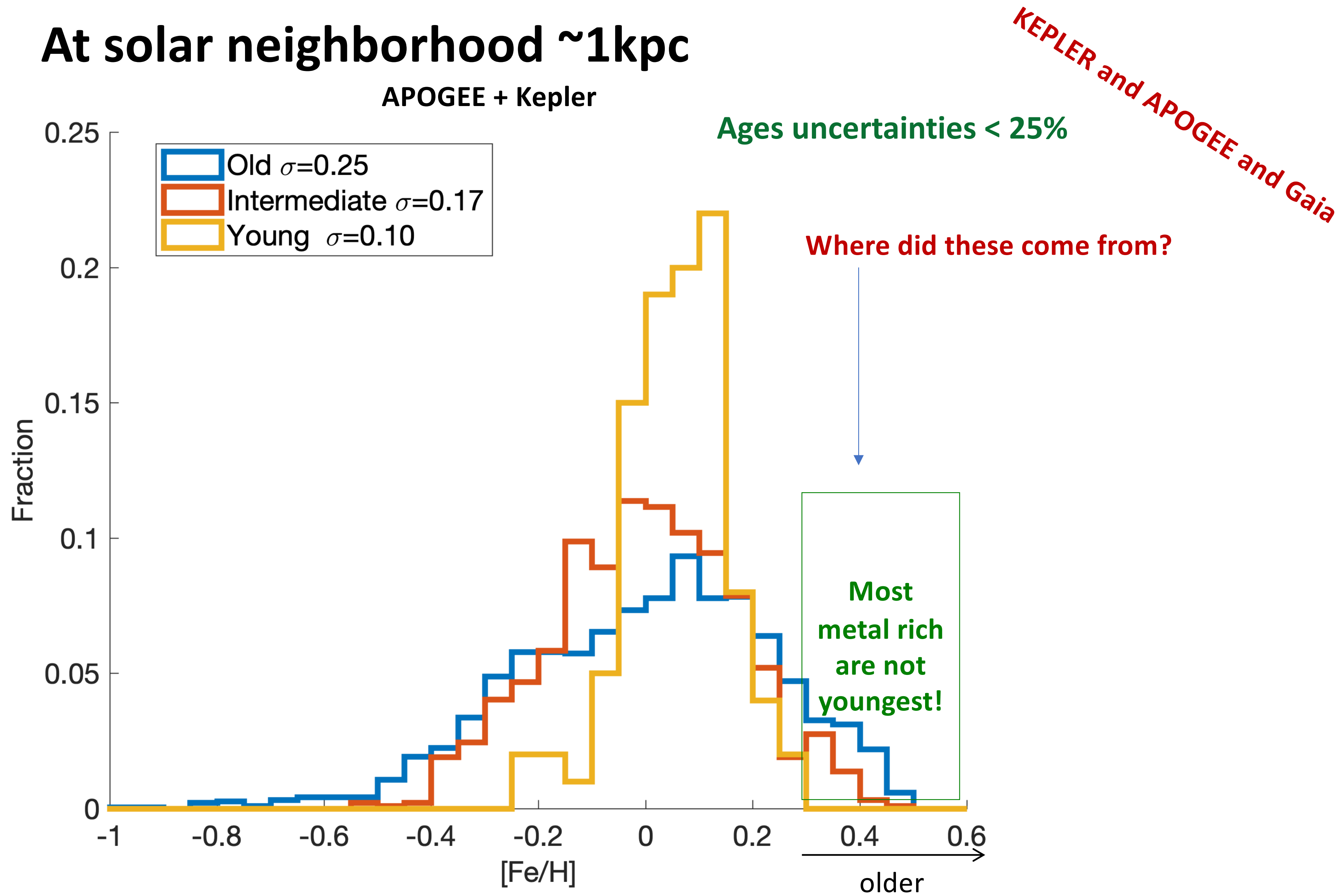


Prediction: AMR Scatter increases towards outer regions

Age scatter increases towars outer regions

Minchev, Chiappini & Martig 2013; Minchev, Chiappini, Martig 2014

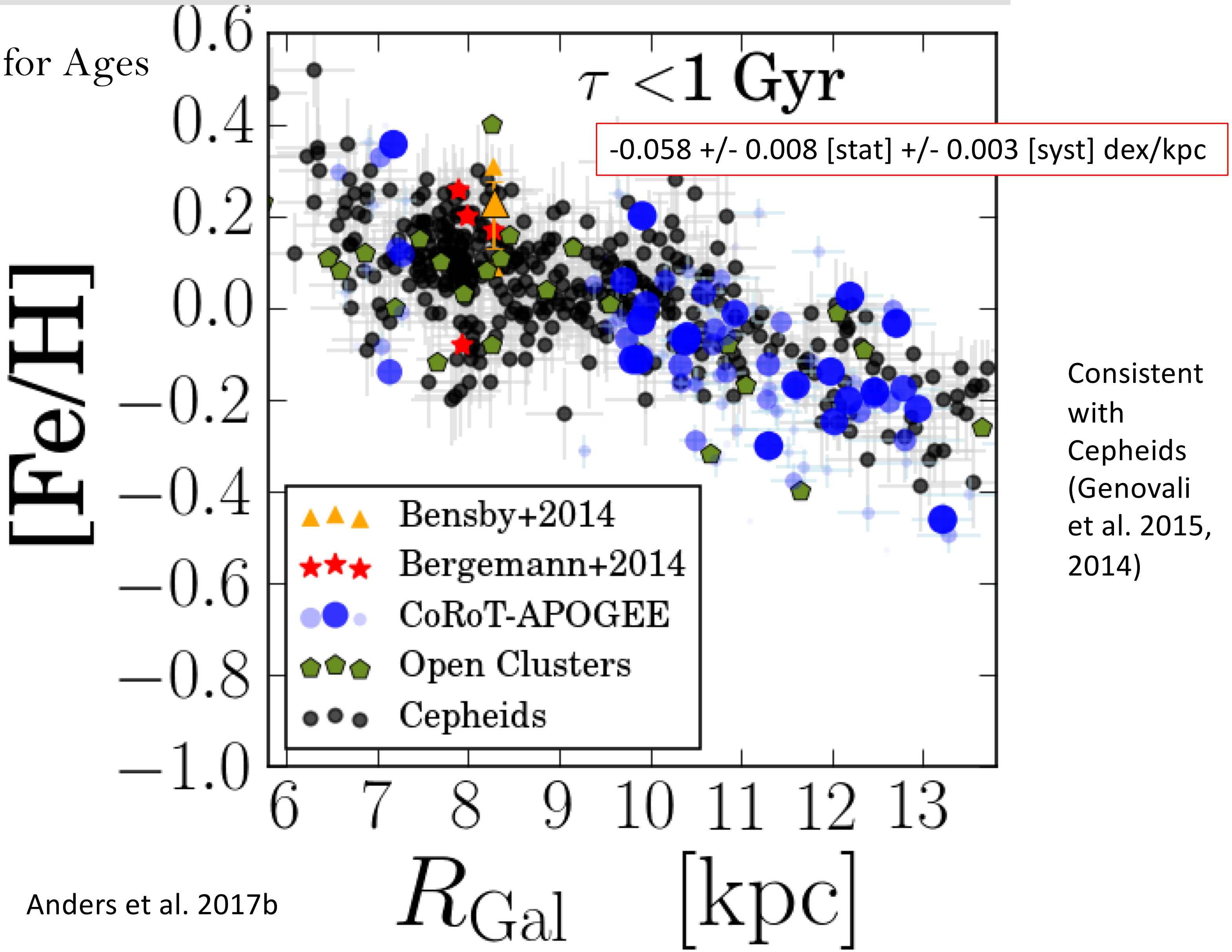
At solar neighborhood ~1kpc



Miglio al. 2021 – also Casagrande et al. 2011, Trevisan et al. 2011

Abundance Gradients in the disk
“observing” radial migration

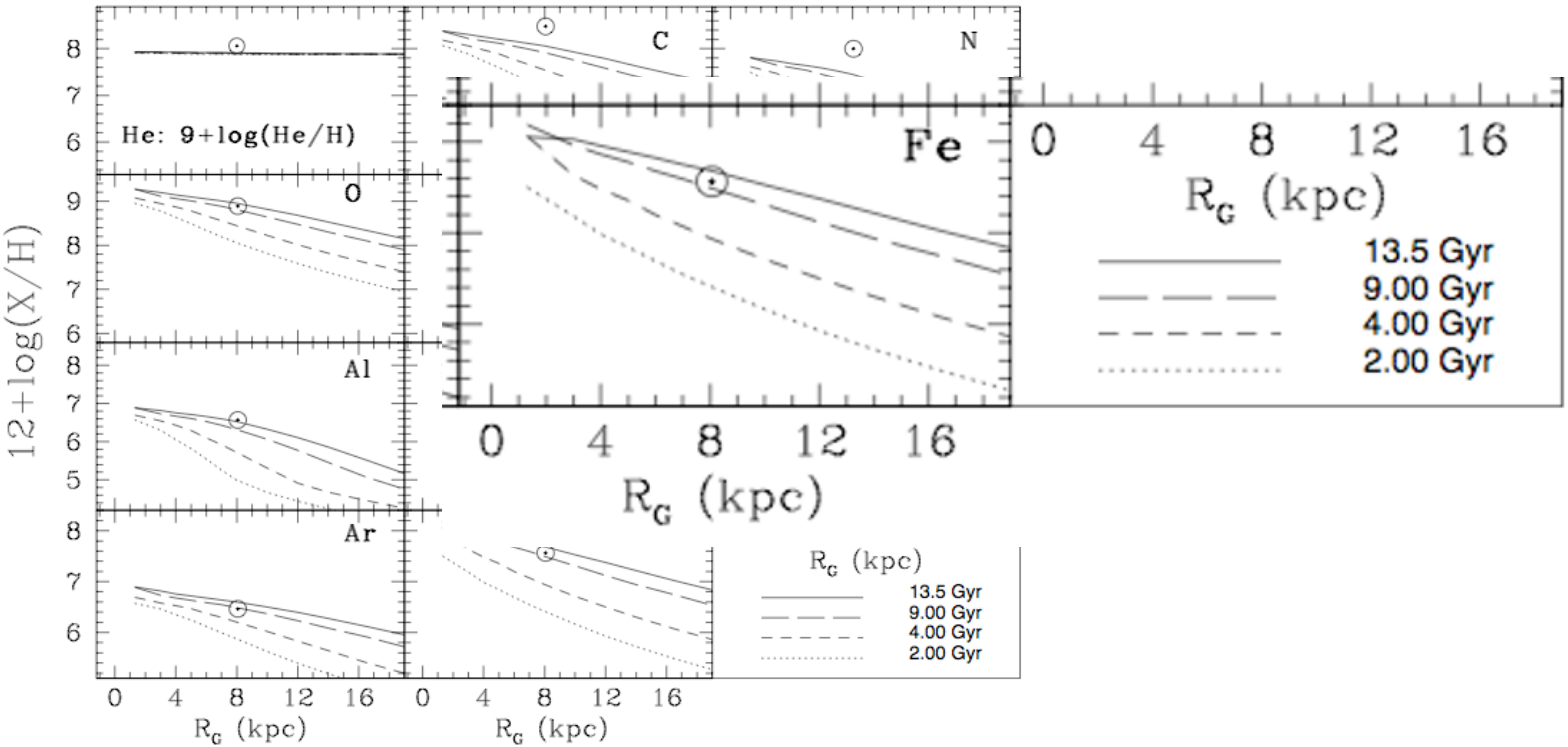
Seismology for Ages

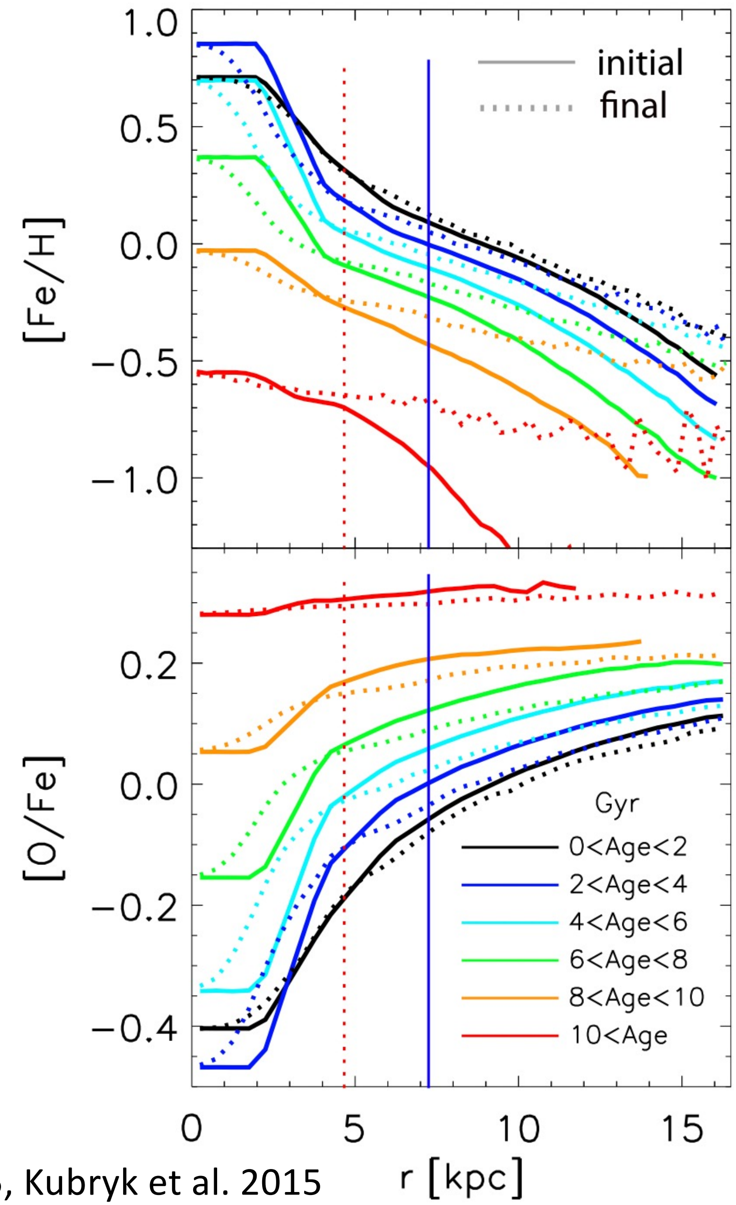


Anders et al. 2017b

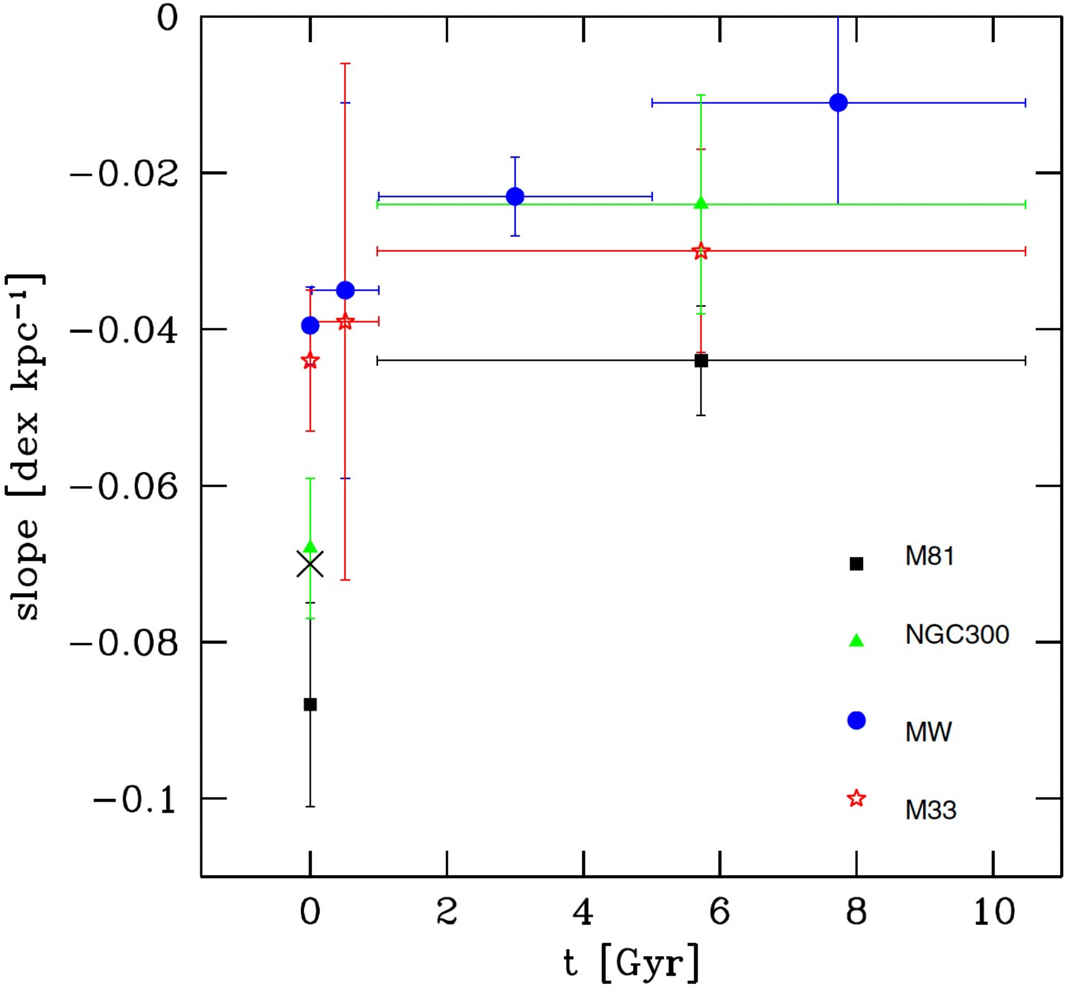
Consistent with Cepheids (Genovali et al. 2015, 2014)

Hou et al. 2000





Minchev et al. 2013, Minchev et al. 2015, Kubryk et al. 2015



Pilkington et al. 2012 shows with disk galaxies hydrodynamic simulations that:

``We find that the majority of the models predict radial gradients today which are consistent with those observed in late-type disks, but they evolve to this self-similarity in different fashions, despite each adhering to classical “inside-out” growth´´

Fig. 30 Evolution of the metallicity gradient in the MW and in a few additional galaxies as a function of lookback time, based on different metallicity tracers probing the gas phase at different epochs. This diagram shows that gradients become steeper, more negative, as time flows. Image reproduced with permission from Stanghellini et al. (2014), copyright by ESO

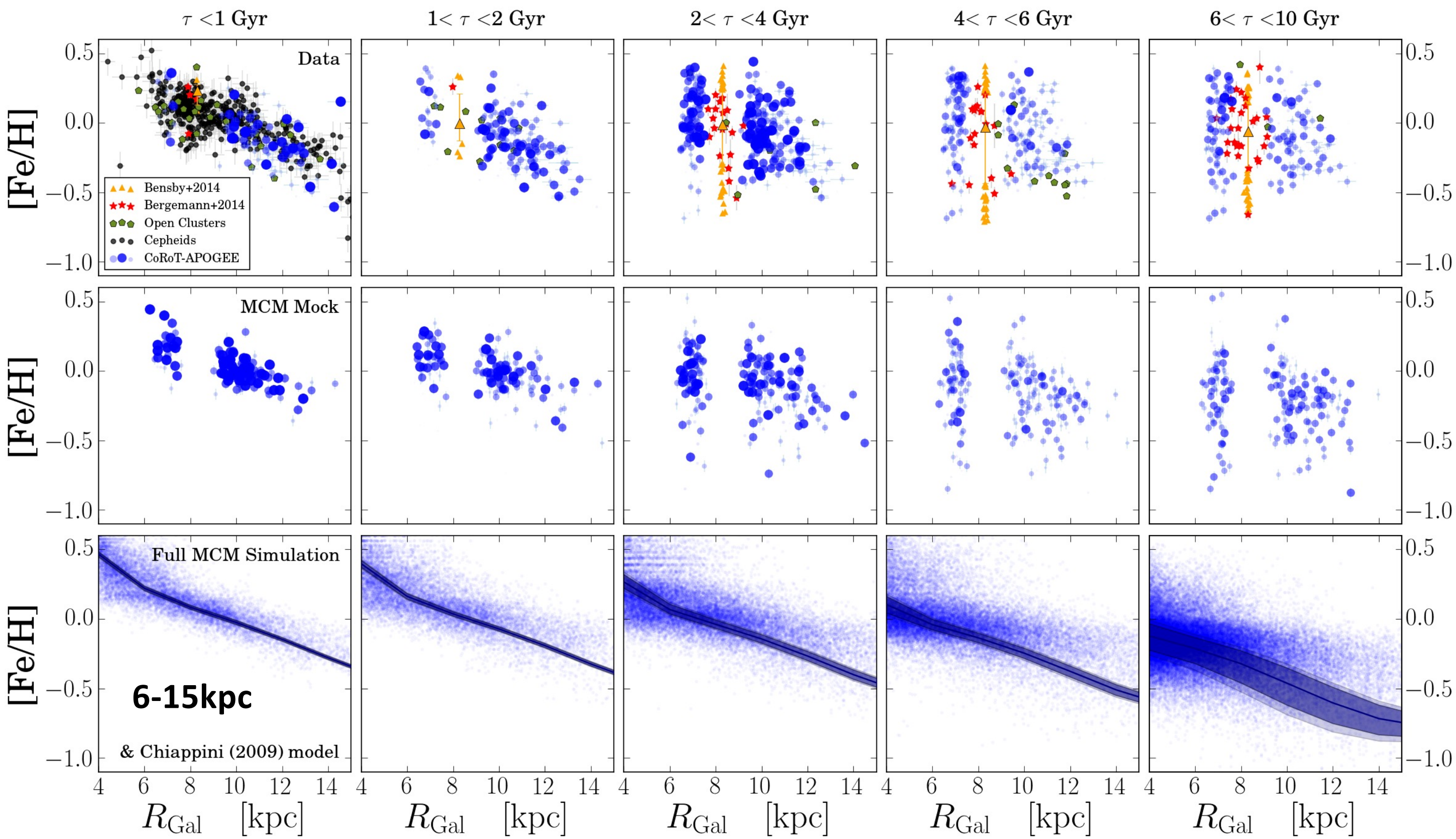
From Maiolino & Mannucci 2019

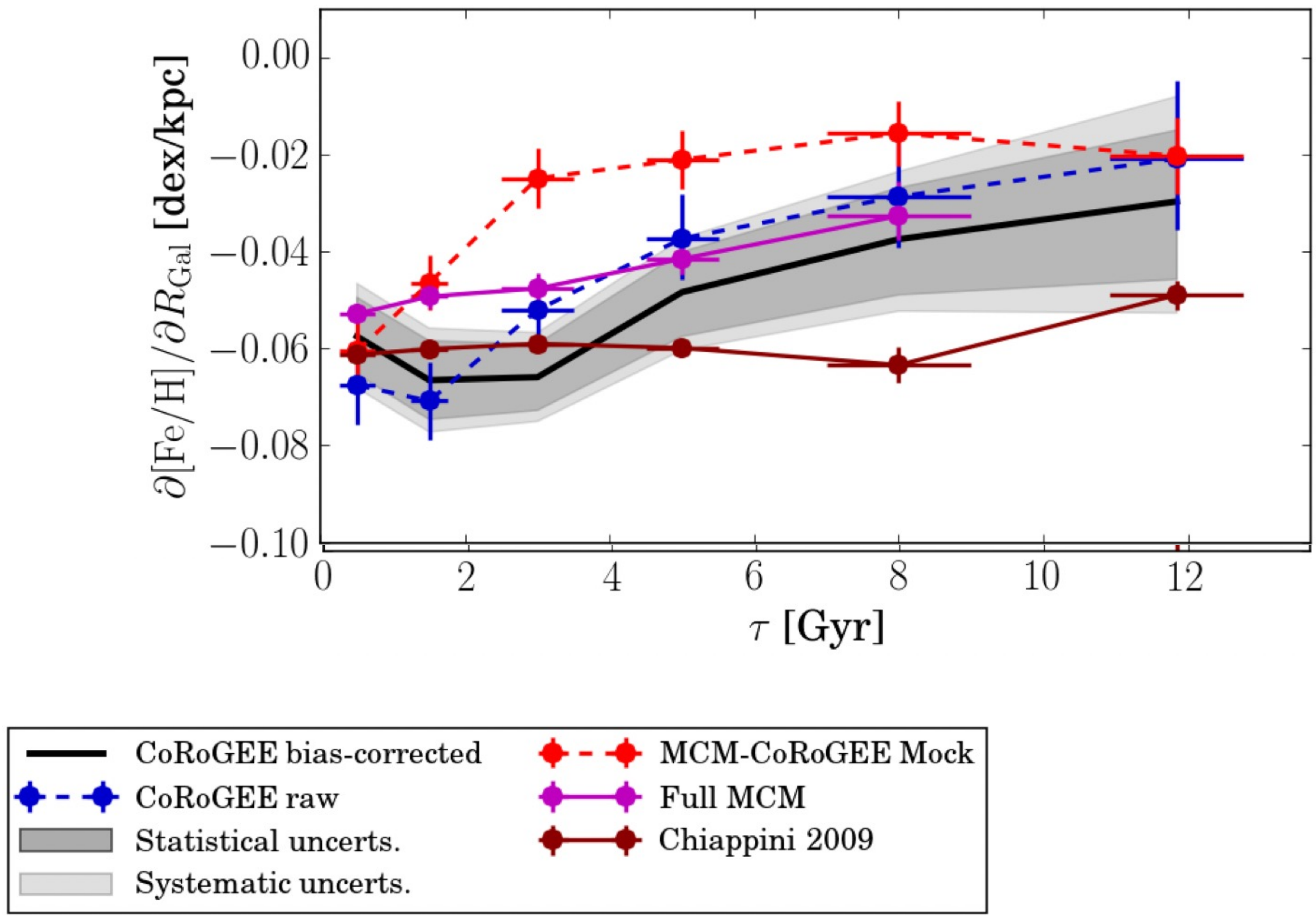
Also different initial conditions:
Pre-enrichment Chiappini et al. 2001

First time quantifying radial migration effect on gradients

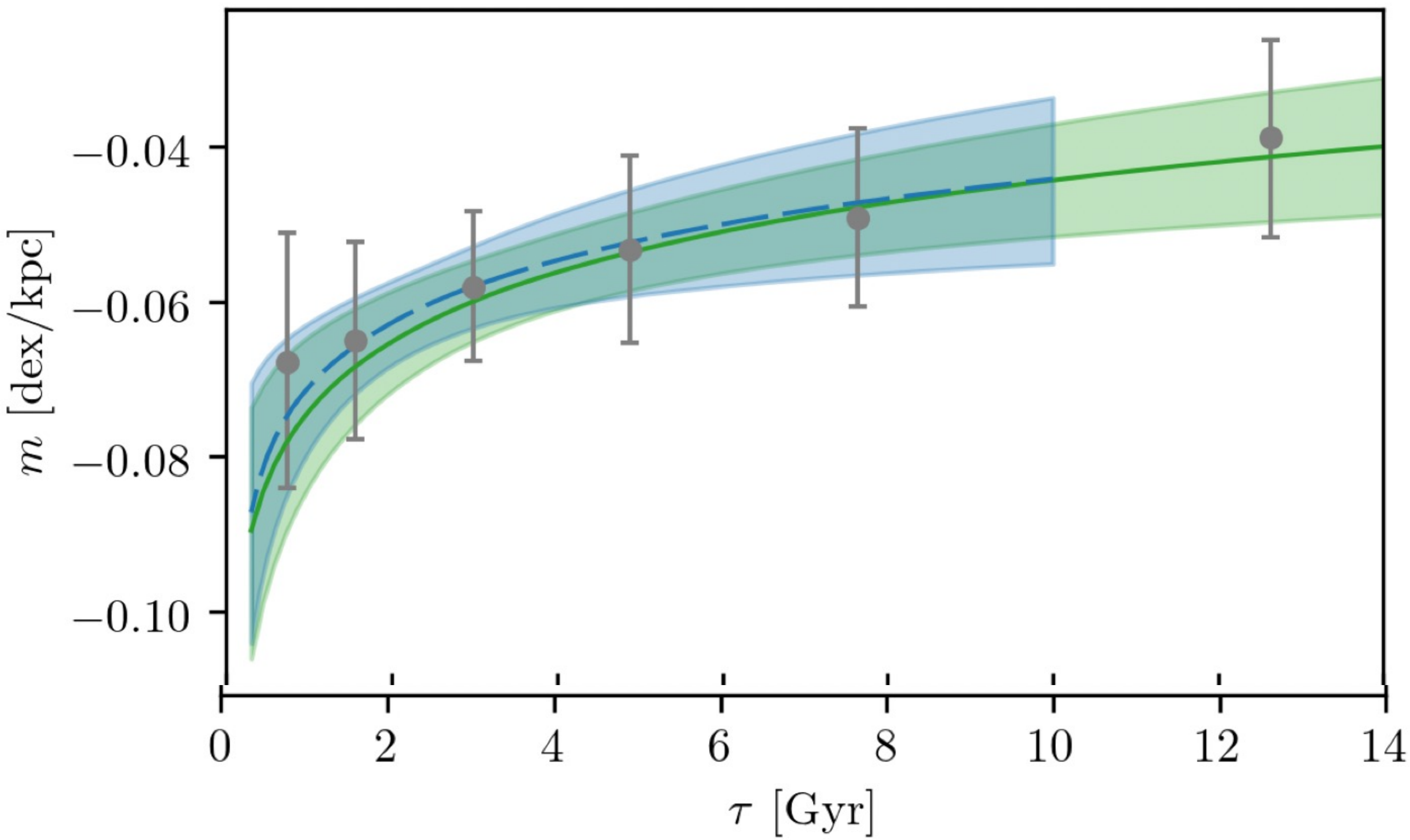
Anders et al. 2017b

CoRoT and APOGEE

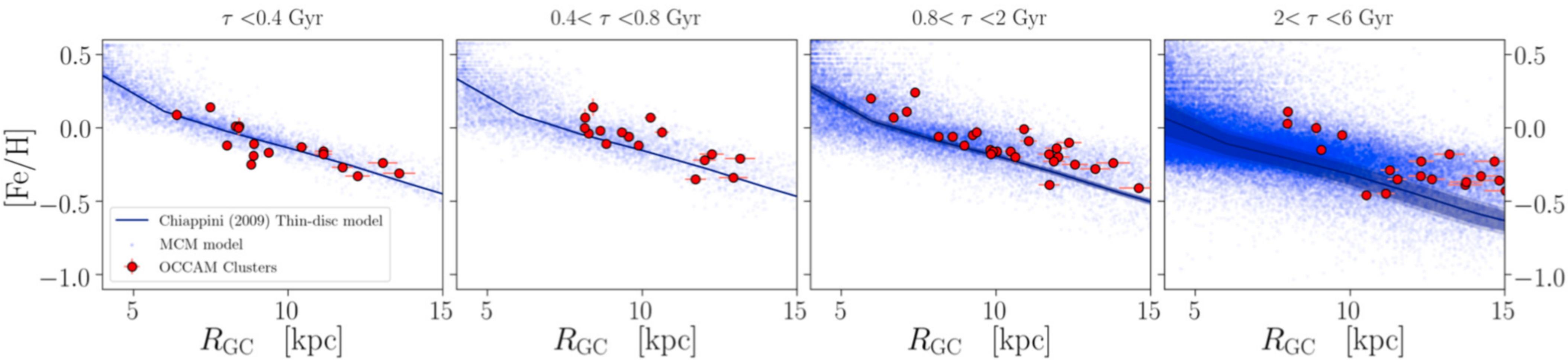




0.00
−0.02
−0.04
−0.06
−0.08
−0.10
0
2
4
6
8
10
12
$\partial[\mathrm{Fe/H}]/\partial R_{\mathrm{Gal}}$ [dex/kpc]
τ [Gyr]
CoRoGEE bias-corrected
CoRoGEE raw
Statistical uncerts.
Systematic uncerts.
MCM-CoRoGEE Mock
Full MCM
Chiappini 2009

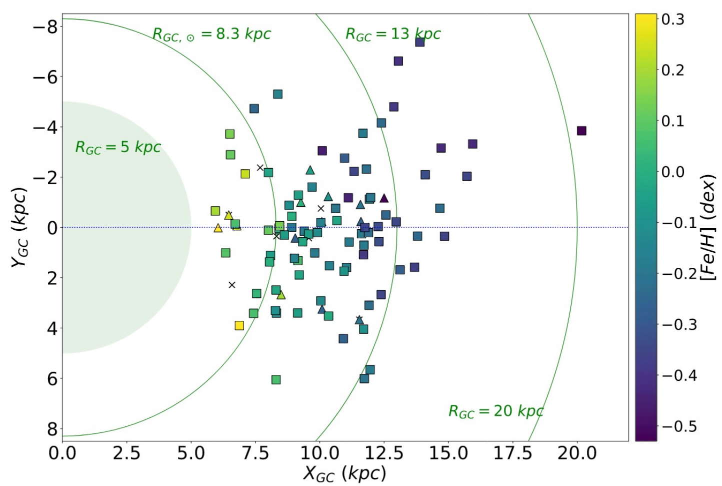


Willet et al. 2023 – K2 sample

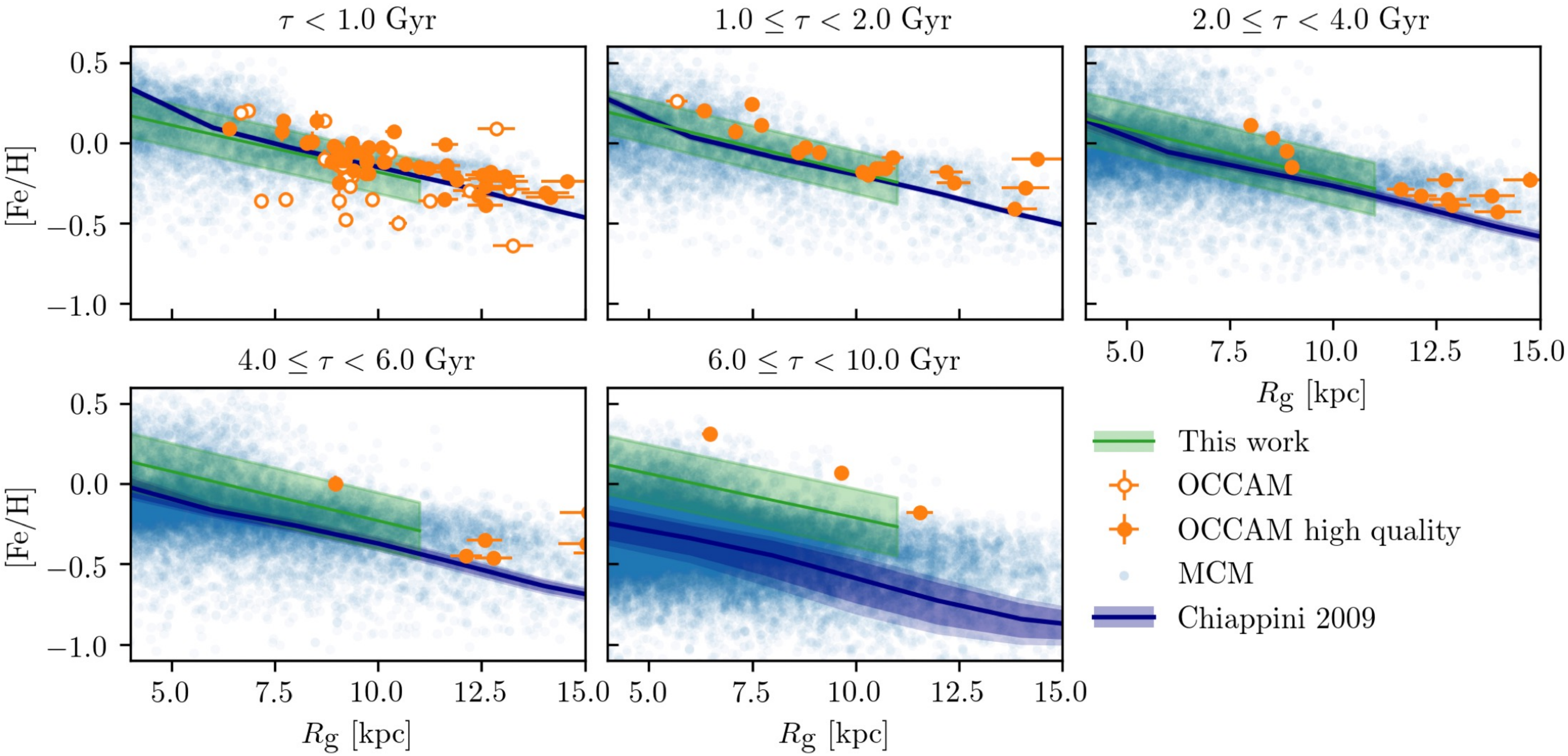


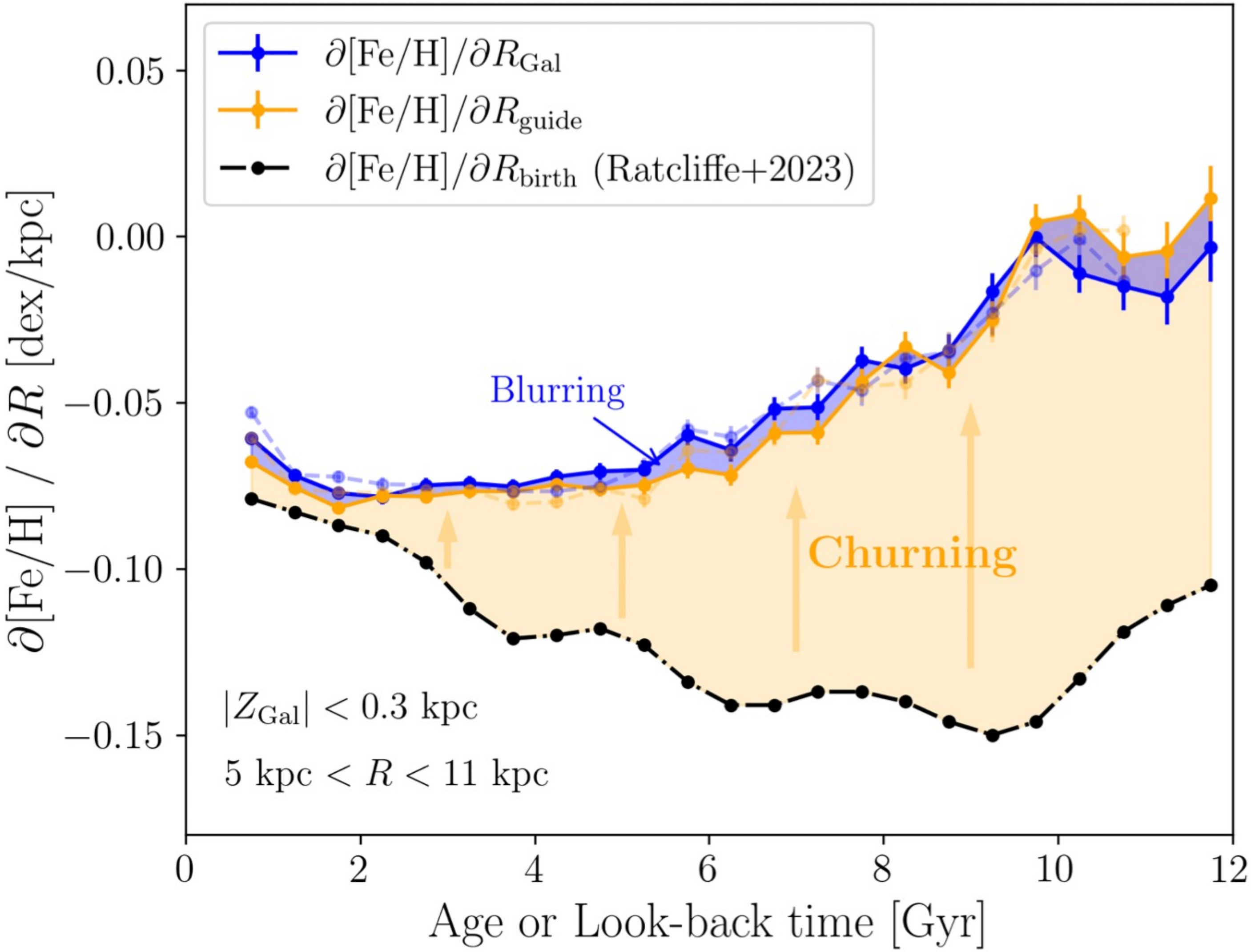
Myers et al. 2022 (APOGEE)

THE ASTRONOMICAL JOURNAL, 164:85 (17pp), 2022 September



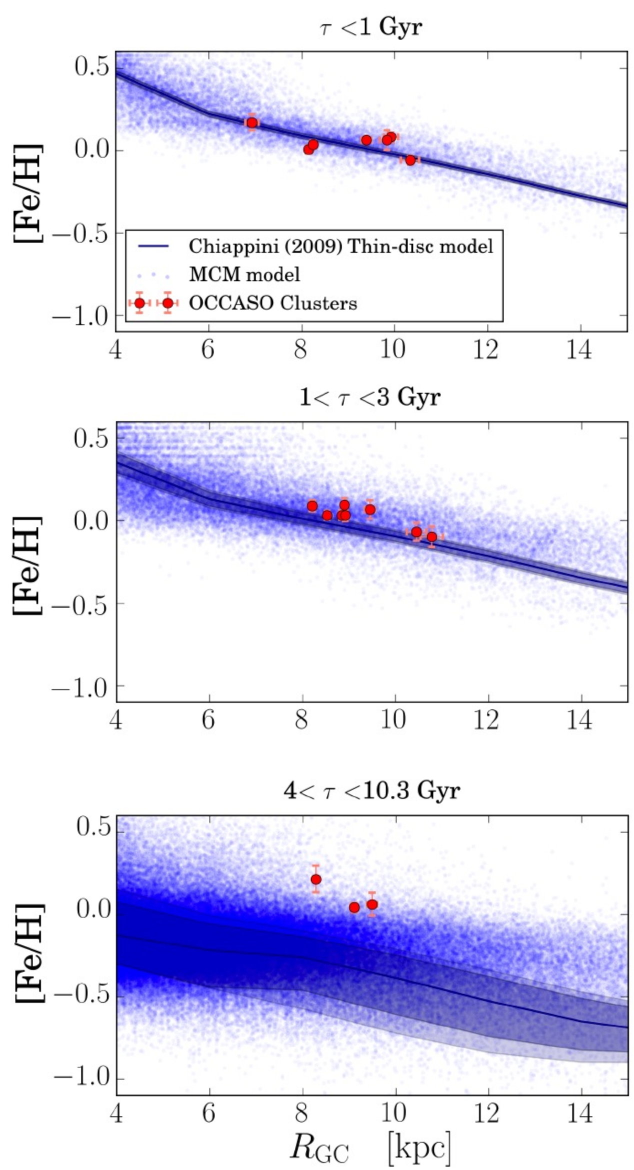
K2 and APOGEE





Anders et al. 2023

OCCASO Survey – Casamiquela et al. 2017, 2019



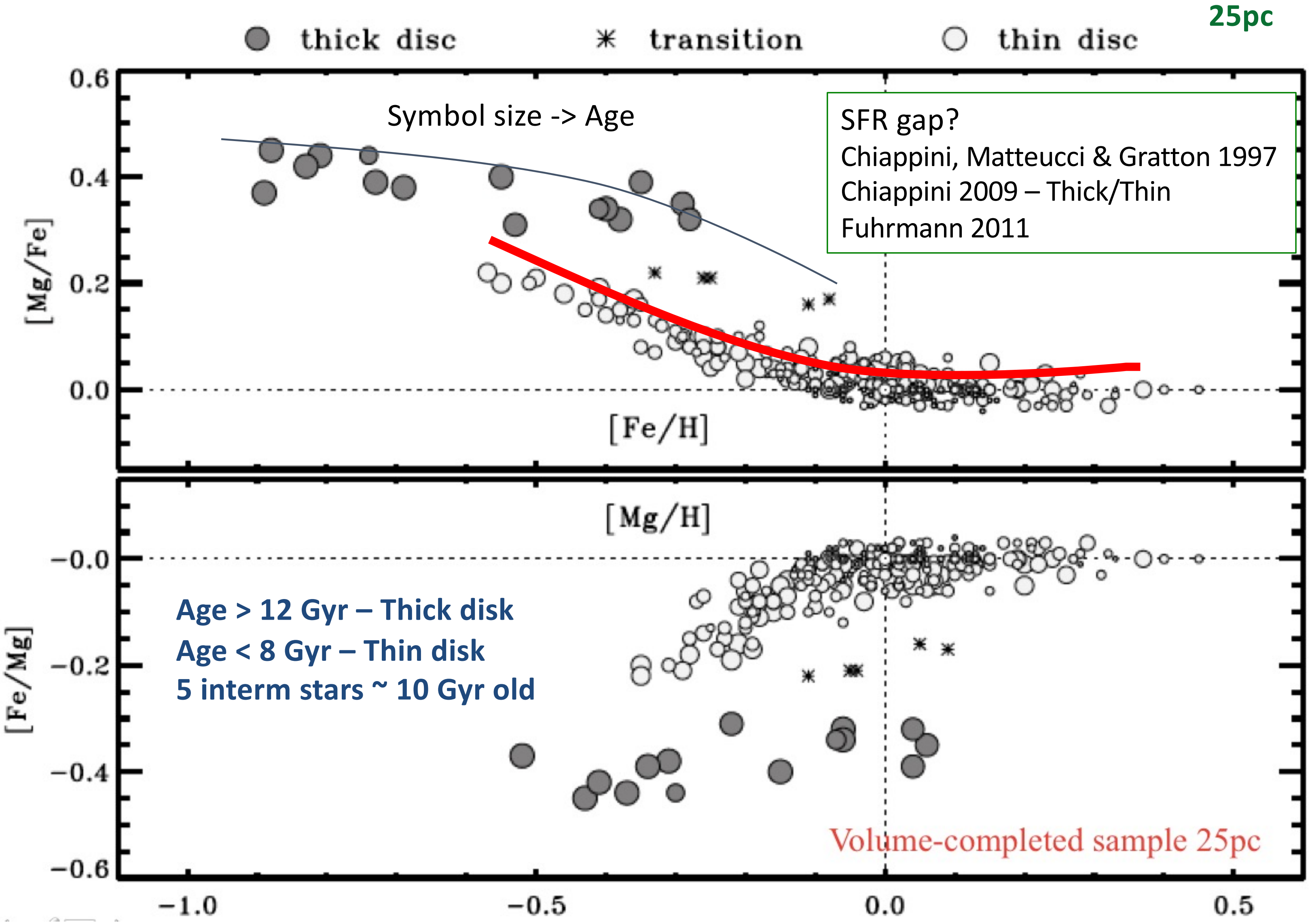
Explaining how older open clusters can be more metal rich than younger ones at a given galactocentric distance

Radial Migration

THE [ALPHA/FE] VS. AGE RELATION
Star Formation Gap/Quenching?

From the Hipparcos volume d < 100 pc to the solar circle d < 1-2 kpc and more

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

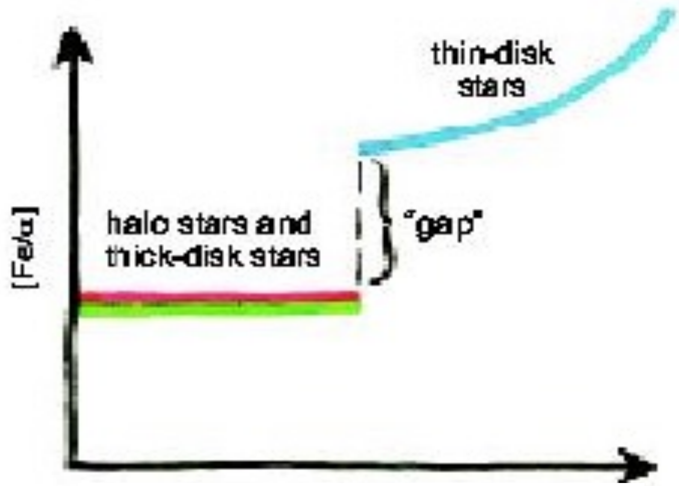


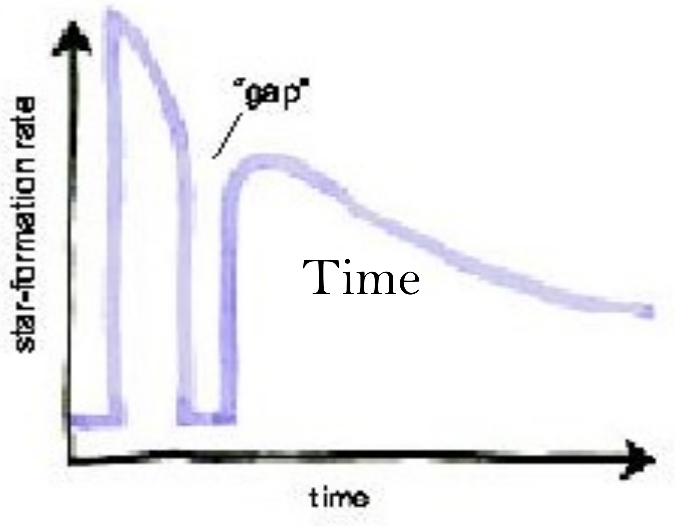
Discontinuity in the [Alpha/Fe] vs. [Fe/H]

Two infall model (Chiappini, Matteucci & Gratton 1997) – Two main gas accretion phases (also suggested by some modern simulations of MW Galaxy in cosmological context – e.g. Grand et al. 2018, Mackreth et al. 2018, Noguchi 2018, see also Combes 2018 IAU 334 summary + more recent results)

[Fe/α]

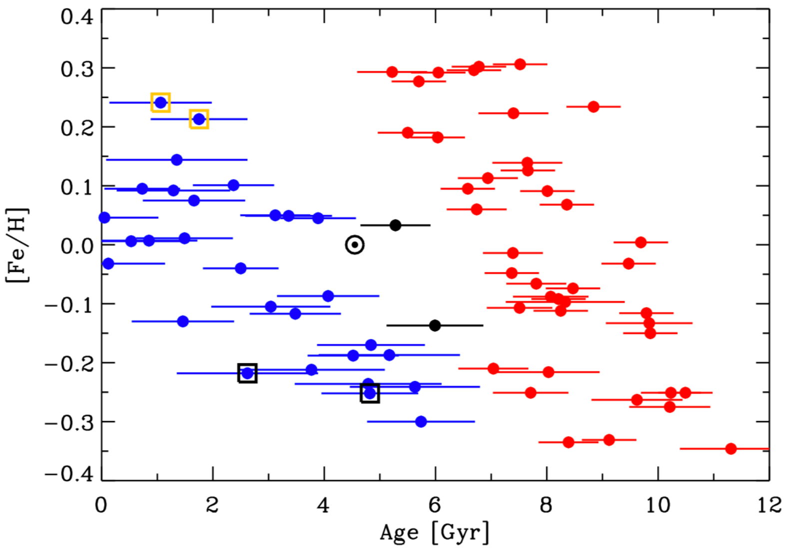
Star Formation History





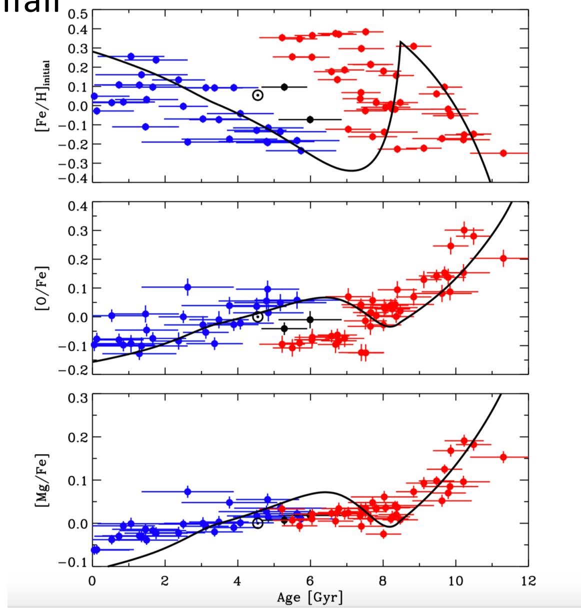
[α/H] (by instance O)

(Chiappini 2001 Am.Sci. & see also Sky & Telescope 2004)



High-precision chemical abundances have been determined from HARPS spectra of **72 nearby solar-type stars and precise ages** were derived by comparing spectroscopic effective temperatures and luminosities based on *Gaia* DR2 distances to ASTEC isochrones.

two Infall



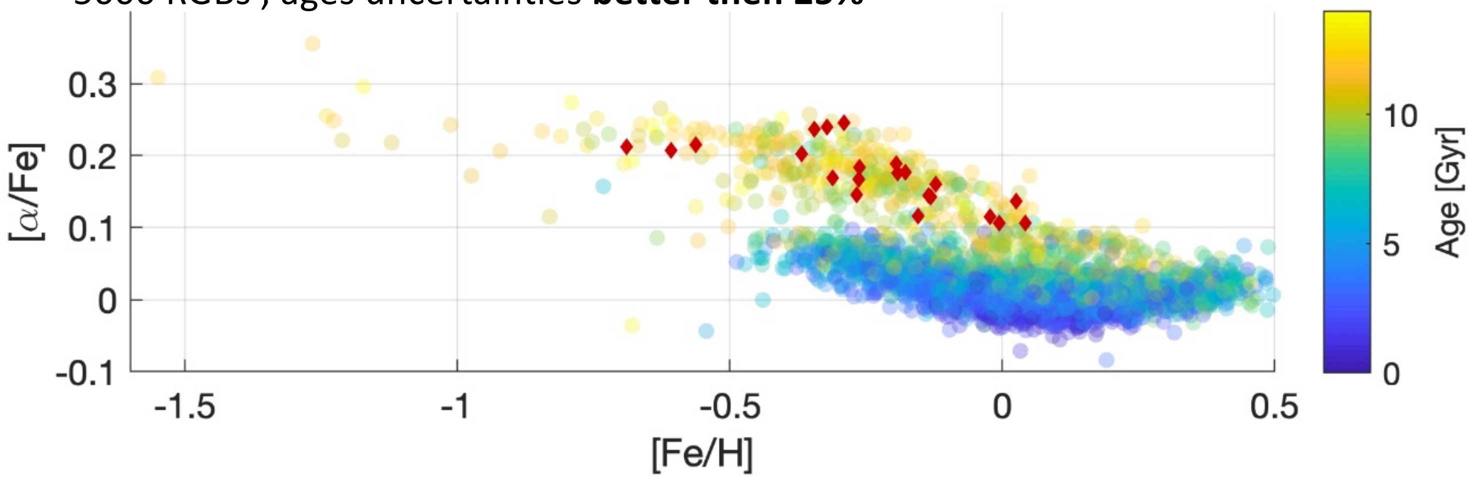
Nissen et al. 2020

$$[\mathrm{Y/Mg}] = 0.179\,(\pm 0.007) - 0.0383\,(\pm 0.0010)\cdot \mathrm{Age\,[Gyr]}.$$

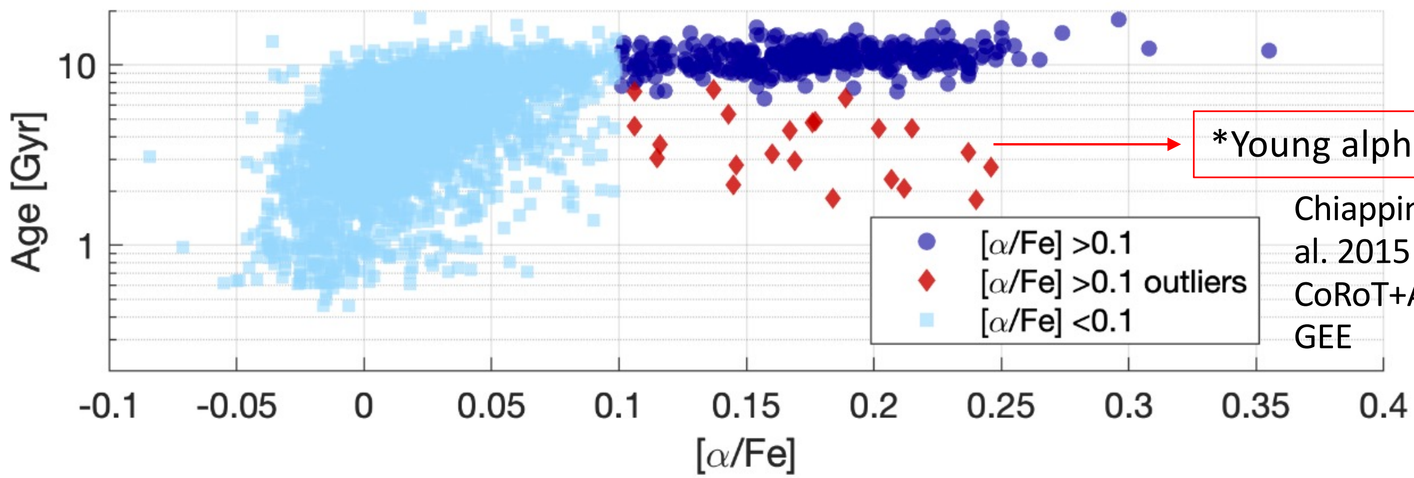
APOGEE + Kepler **Solar Circle 7.5-9.5 kpc**

~5000 RGBs , ages uncertainties **better then 25%**

Miglio, Chiappini et al. 2021



VERY LOW AGE-SCATTER FOR CHEMICAL THICK DISK



*Young alpha rich

Chiappini et al. 2015 in CoRoT+APOGEE

Also seen in Kepler+APOGEE (Martig et al. 2015)

Chemical thick disk formation in less than 1.25 Gyr

Coeval (Chemical) Thick Disk

Miglio, Chiappini et al. 2021

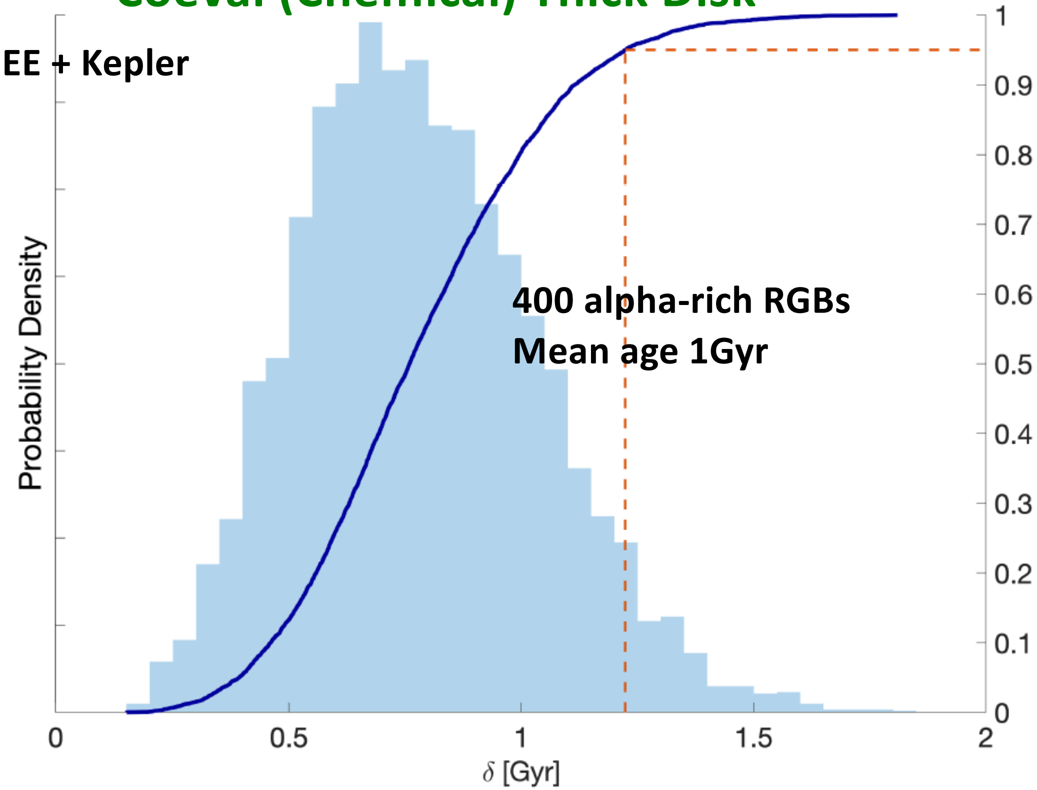
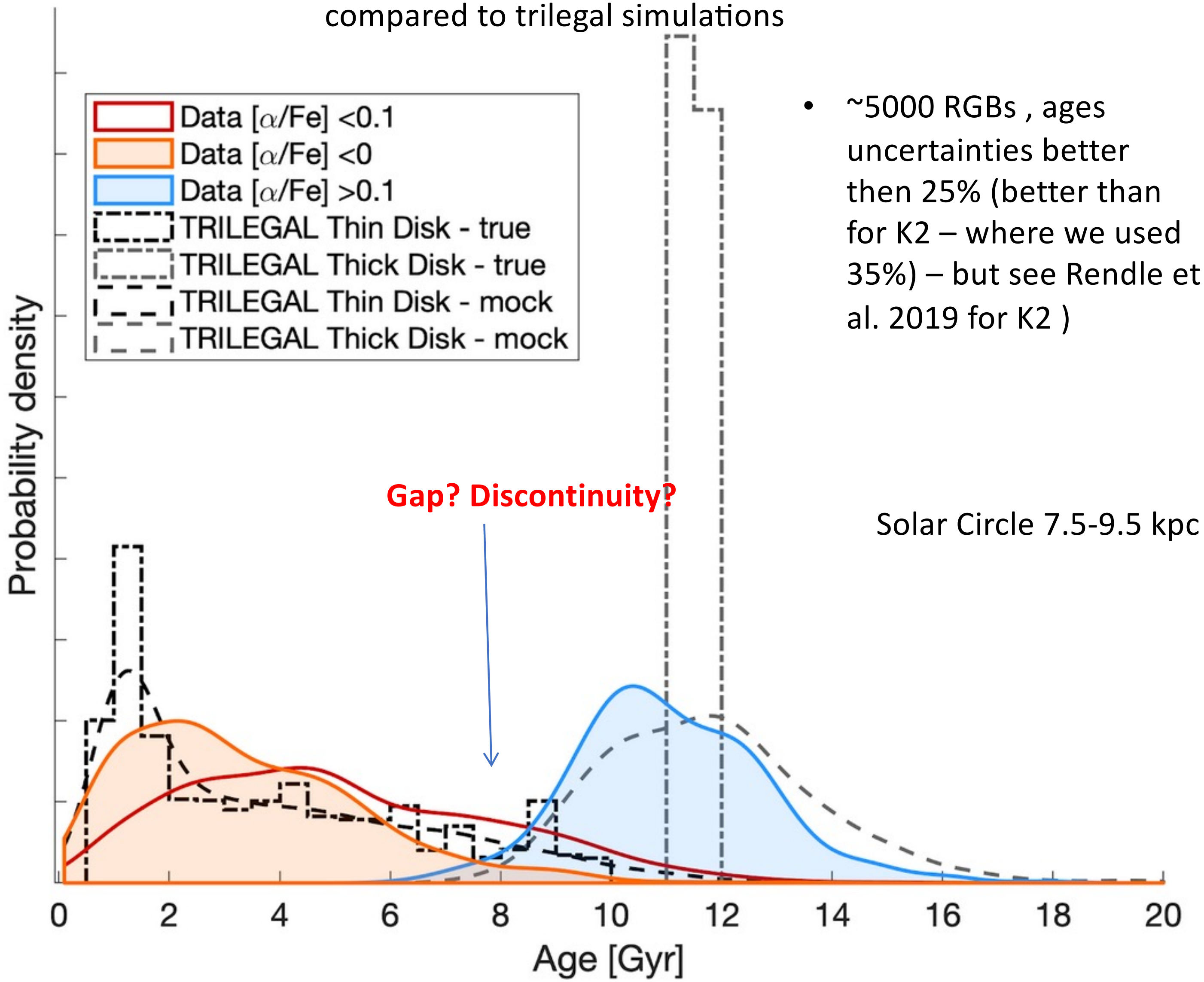


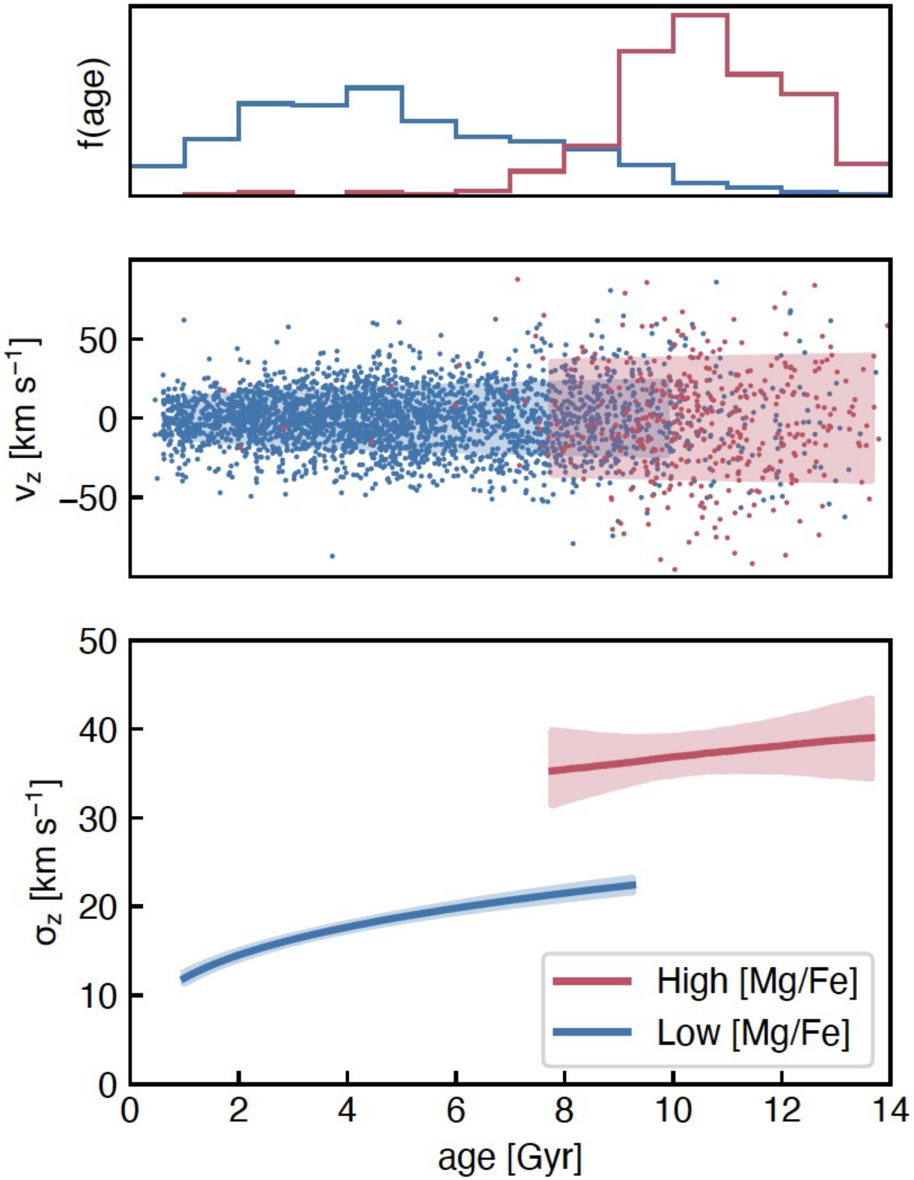
Fig. 12. Posterior probability distribution function of the age spread of the high-α population in the sample (R1, see Table 1), resulting from the statistical model described in Appendix B. The cumulative distribution function is shown as a solid line and indicates that the 95% credible interval for the intrinsic age spread corresponds to $\delta \lesssim 1.25$ Gyr. Results from all the modelling runs are reported in Table 1.

Kepler + APOGEE DR14 ages 25% or better precision from Miglio et al. (2021) compared to trilegal simulations



- ~5000 RGBs , ages uncertainties better then 25% (better than for K2 – where we used 35%) – but see Rendle et al. 2019 for K2)

Solar Circle 7.5-9.5 kpc



Thick & thin disks seem discrete populations (from precise data at solar circle!).

Can start to be seen only with ages more precise than 20-25%.

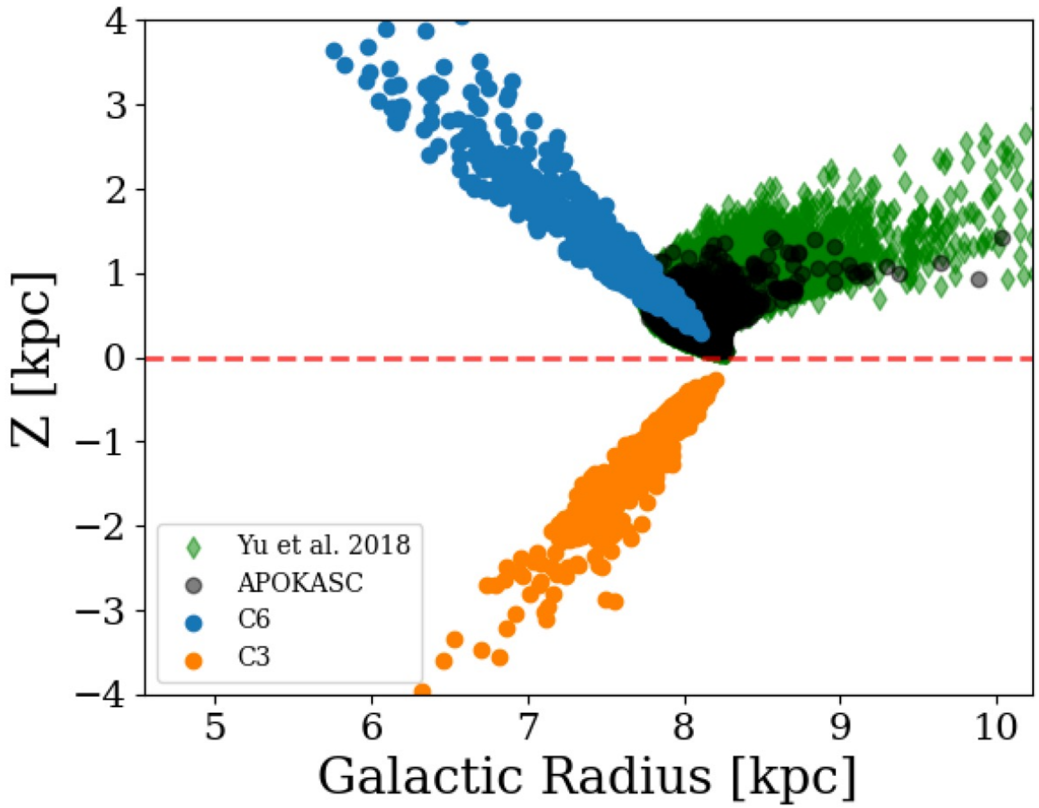
Miglio, Chiappini et al. 2021

Is there a bimodality in age? And with height from mid-plane?

With Kepler and 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]

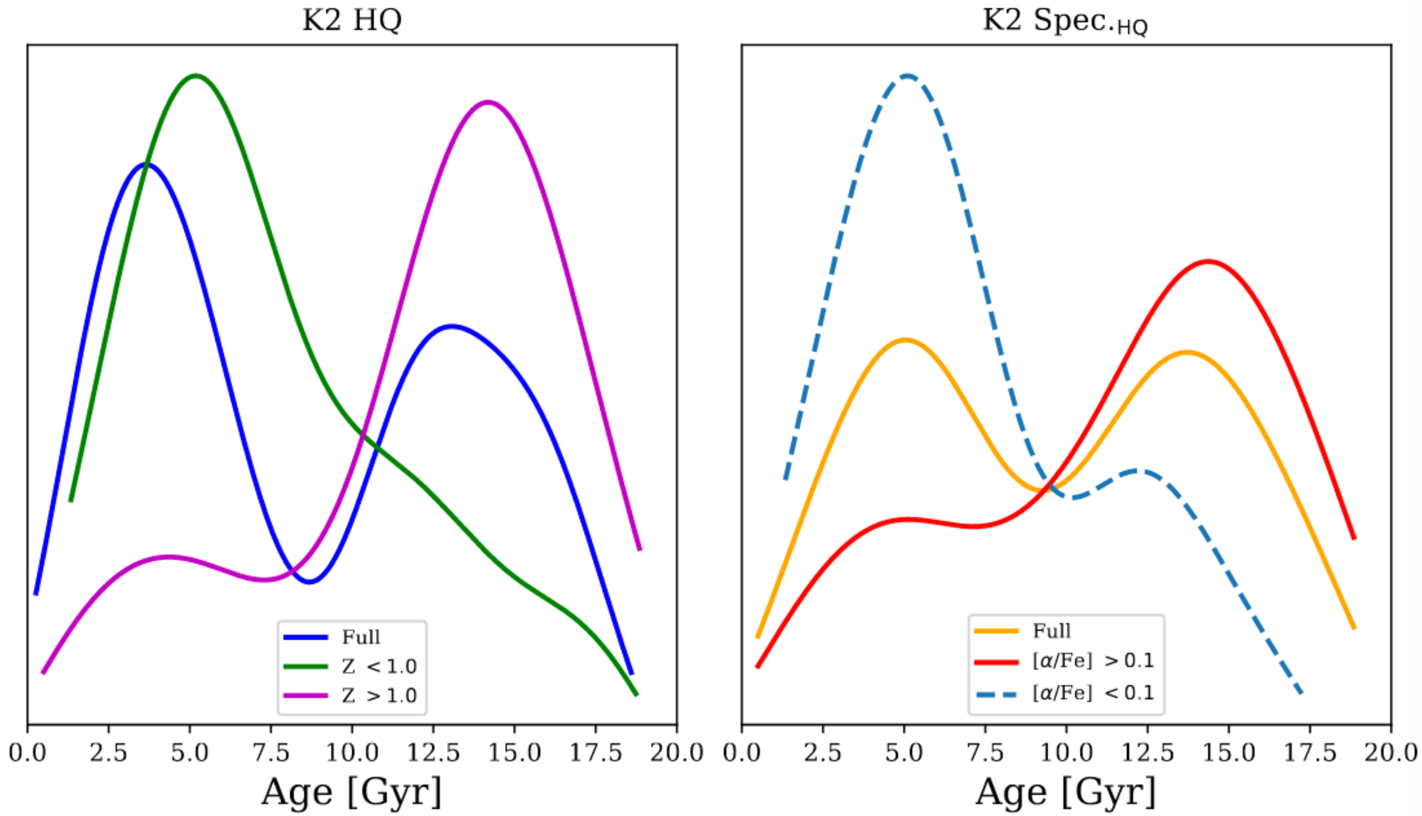


APOKASC (black)
K2 campaign 3 (orange)
K2 campaign 6 (blue)

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

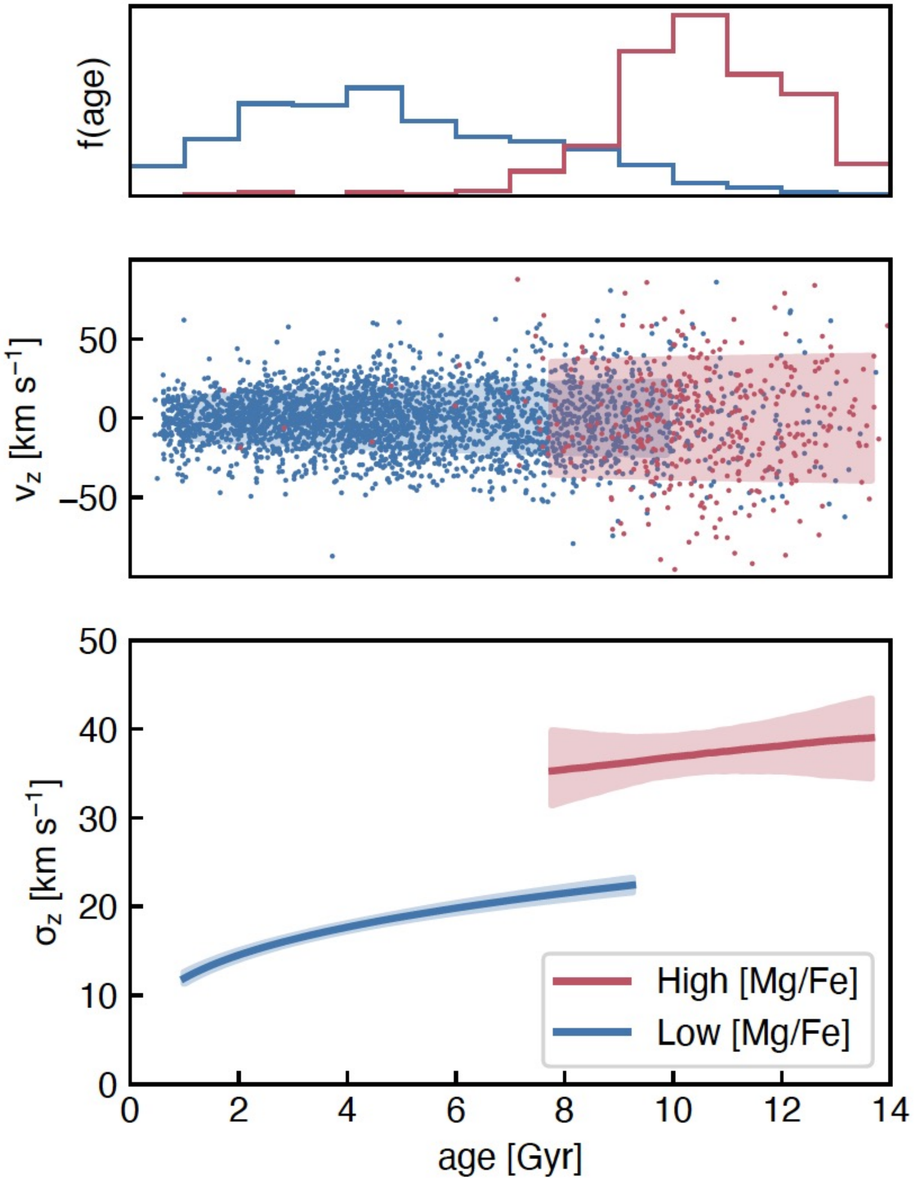
Age probability denstity distributions

With K2 age precision ~30-35% with/without spectroscopic information



Rendle et al. 2019

Is there a bimodality in kinematics?

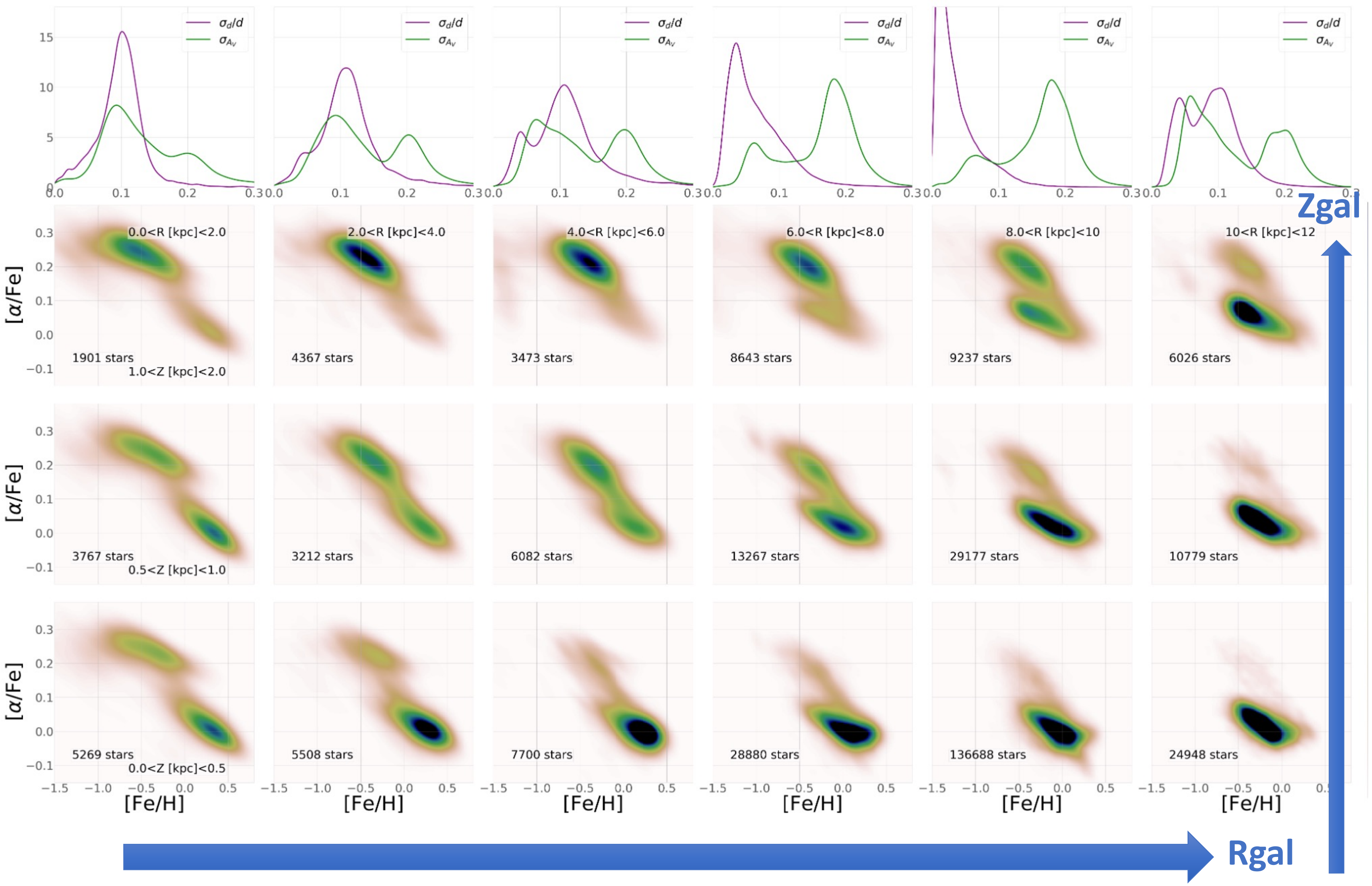


Thick & thin disks seem discrete populations (from precise data at solar circle!).

Does the bimodality extend to inner most regions?

Queiroz et al. 2020 – **APOGEE DR16** + Gaia DR2 + Complementary photometry

Inner disk – not one sequence, but two, extending into bulge



Queiroz et al. 2020 – **APOGEE DR16** + Gaia DR2 + Complementary photometry

Inner disk – not one sequence, but two, extending into bulge