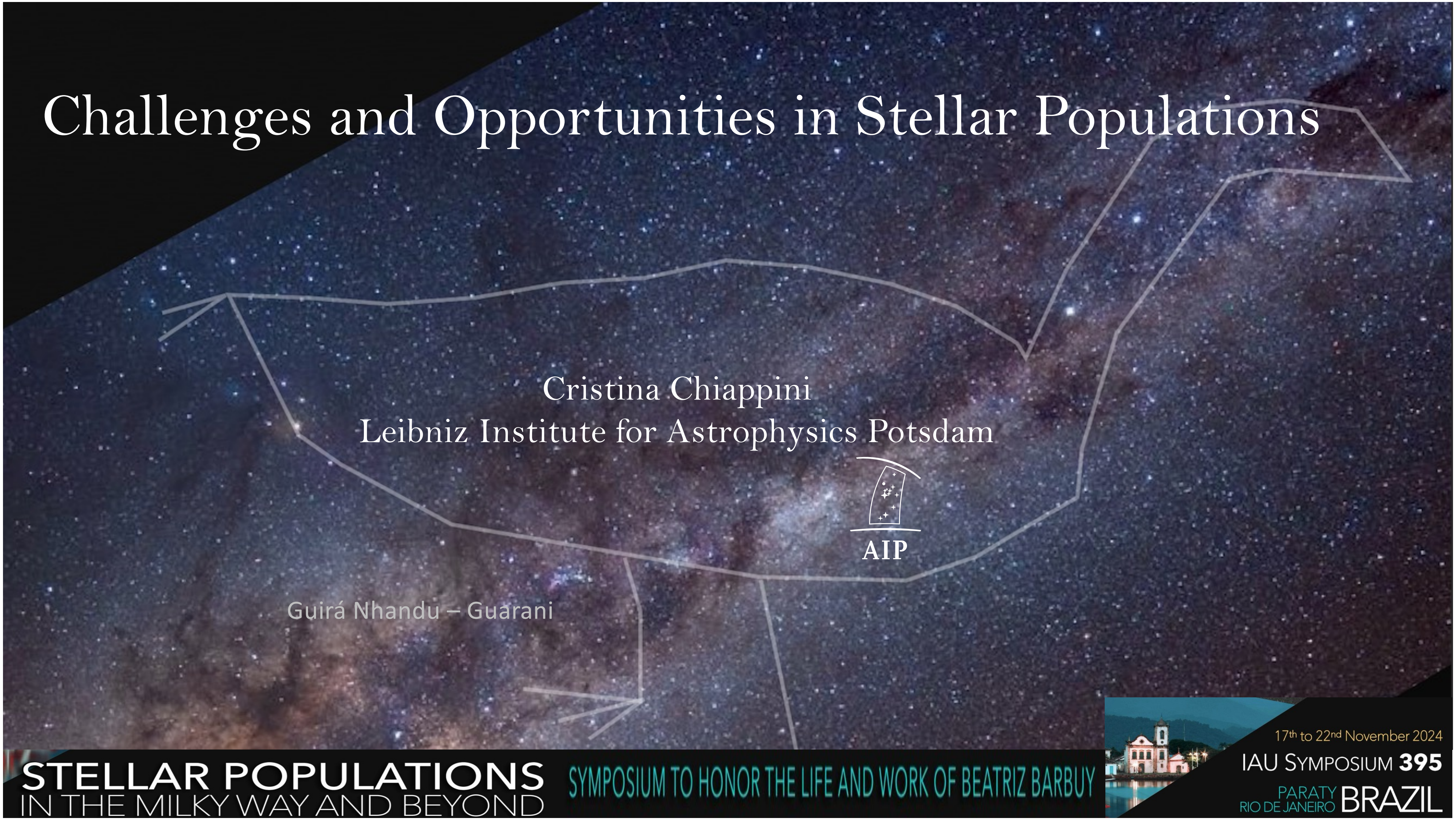
Challenges and Opportunities in Stellar Populations

Cristina Chiappini
Leibniz Institute for Astrophysics Potsdam
AIP



STELLAR POPULATIONS
IN THE MILKY WAY AND BEYOND
SYMPOSIUM TO HONOR THE LIFE AND WORK OF BEATRIZ BARBUY
17th to 22nd November 2024
IAU SYMPOSIUM 395
PARATY
RIO DE JANEIRO BRAZIL

1st Challenge

150 Abstracts on the morning of the deadline
More than 300 by the end of that day ☺

Supporting Divisions

- Division H Interstellar Matter and Local Universe (coordinating division)
- Division C Education, Outreach and Heritage
- Division G Stars and Stellar Physics
- Division J Galaxies and Cosmology

SOC

Jorge Meléndez (chair)
Cristina Chiappini (chair)
Aruna Goswami
Bruno Dias
Chris Sneden
Gary Da Costa
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Katia Cunha
Kim Venn
Livia Origlia
Lucimara Martins
Marina Trevisan
Monique Spite
Patricia Whitelock
Sara Lucatello
Thomas Bensby

What ?

Big thank you
Amasing program and posters

LOC

Bruno Castilho (chair)
Paula Coelho (chair)
Alan Alves-Brito (chair)
Giulia Martos
Giuliana Capistrano
Helio Rocha Pinto
Luan Ghezzi
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STELLAR POPULATIONS IN THE MILKY WAY AND BEYOND

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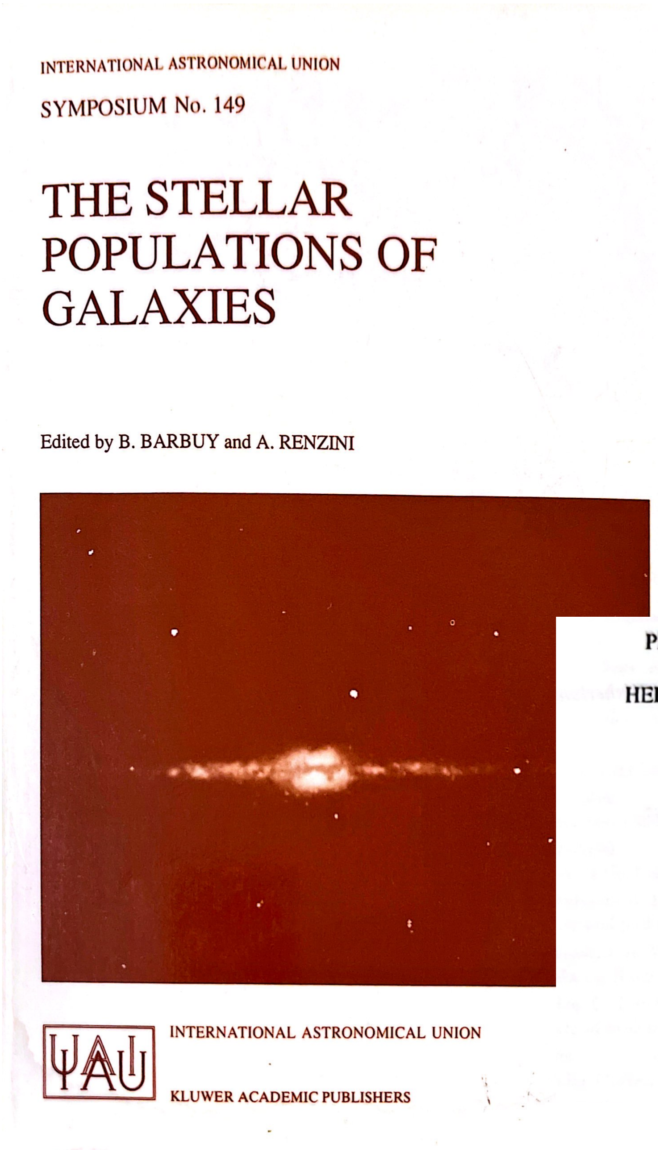

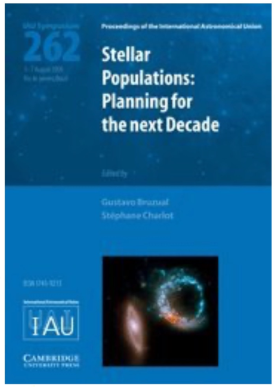

During General Assembly 2009 in Rio Bruzual & Charlot

PROCEEDINGS OF THE 149TH SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION, HELD IN ANGRA DOS REIS, BRAZIL, AUGUST 5–9, 1991

EDITED BY

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Instituto Astrônomico e Geofísico, Universidade de São Paulo, Brazil

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A. RENZINI
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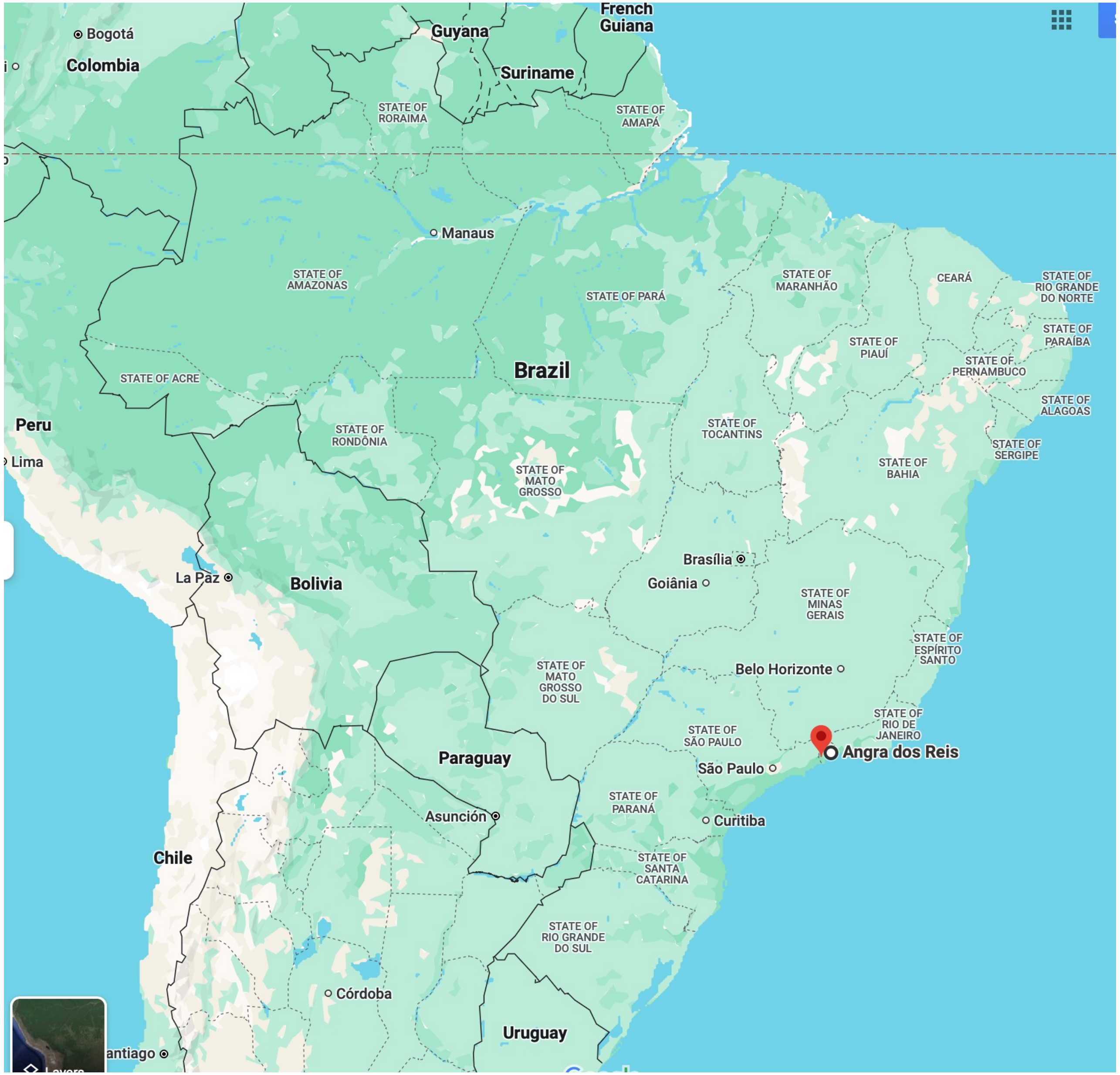
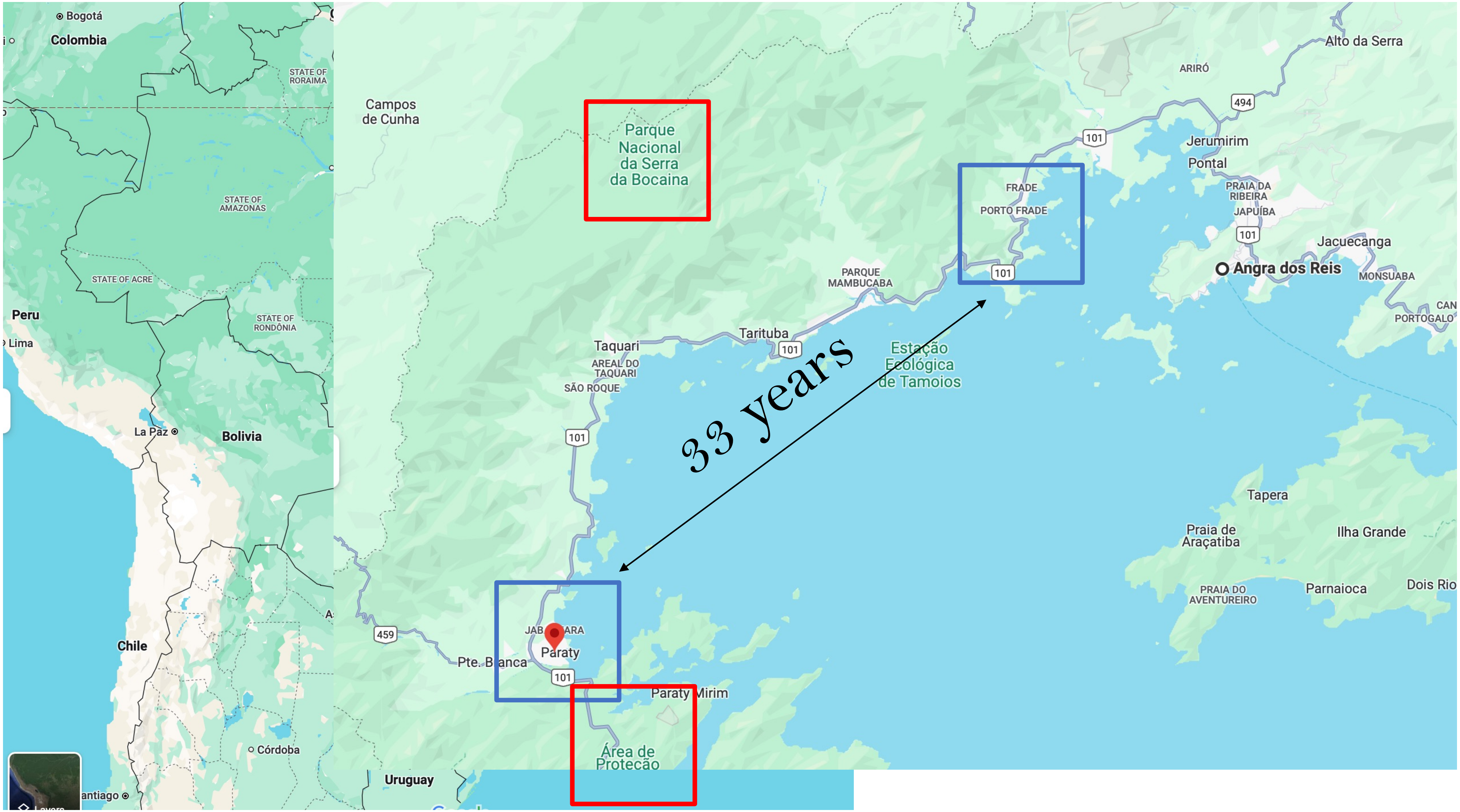

Bogotá
Colombia
Guyana
French Guiana
Suriname
STATE OF RORAIMA
STATE OF AMAPÁ
Manaus
STATE OF AMAZONAS
STATE OF PARÁ
STATE OF MARANHÃO
CEARÁ
STATE OF RIO GRANDE DO NORTE
STATE OF PARAÍBA
STATE OF PIAUÍ
STATE OF PERNAMBUCO
STATE OF ALAGOAS
STATE OF SERGIPE
Brazil
STATE OF ACRE
Peru
Lima
STATE OF RONDÔNIA
STATE OF MATO GROSSO
STATE OF TOCANTINS
STATE OF BAHIA
Brasília
Goiânia
La Paz
Bolivia
STATE OF MINAS GERAIS
STATE OF ESPÍRITO SANTO
Belo Horizonte
STATE OF MATO GROSSO DO SUL
STATE OF RIO DE JANEIRO
STATE OF SÃO PAULO
Angra dos Reis
Paraguay
São Paulo
Asunción
STATE OF PARANÁ
Curitiba
Chile
STATE OF SANTA CATARINA
STATE OF RIO GRANDE DO SUL
Córdoba
Uruguay

Welcome!



Bogotá
Colombia
STATE OF RORAIMA
STATE OF AMAZONAS
STATE OF ACRE
Peru
Lima
STATE OF RONDÔNIA
La Paz
Bolivia
Chile
Córdoba
Uruguay
Campos de Cunha
Parque Nacional da Serra da Bocaina
Taquari
AREAL DO TAQUARI
SÃO ROQUE
Tarituba
PARQUE MAMBUCABA
FRADE
PORTO FRADE
Estação Ecológica de Tamoios
33 years
Alto da Serra
ARIRÓ
Jerumirim
Pontal
PRAIA DA RIBEIRA
JAPUÍBA
Jacuecanga
Angra dos Reis
MONSUABA
PORTOGALO
Tapera
Praia de Araçatiba
Ilha Grande
PRAIA DO AVENTUREIRO
Parnaioca
Pte. Branca
Paraty
Paraty Mirim
Área de Proteção
101
459
494

3 Decades

90's - 2020's

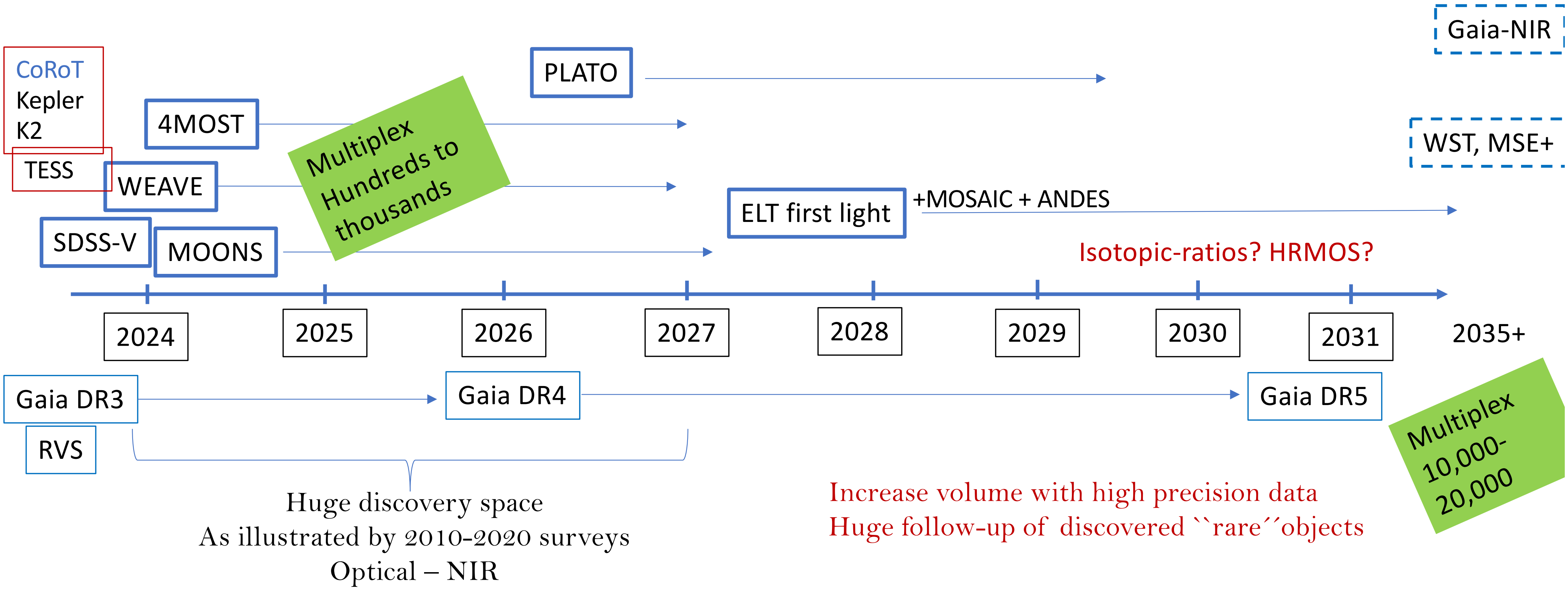
- Hubble 1990 – Globular Clusters – Multiple Populations
- Hipparcos (1989-1993) + first spectroscopic surveys (Geneva-Copenhagen)
- VLTs began construction in 1991, first observations 1998, UVES 1999 first light
- UVES – First Stars Large Program 2000 – Cayrel et al. 2001 – HARPS 2003
- Fiber-fed spectrographs (FLAMES-GIRAFFE, SDSS/SEGUE & RAVE)
- Integral Fields – boost information beyond MW
- Asteroseismology of red giants – precise ages for far away stars CoRoT 2006 (+Kepler, K2, TESS)
- Large spectroscopic Surveys DESI LAMOST GALAH GaiaESO APOGEE
- APOGEE enournous role in the Bulge
- Gaia – DR2/DR3 – REVOLUTION & RVS
- Boom in observations of variable stars (Cepheids, RRLyrae…)
- Bulge – Globular Clusters + Imaging (VVV + BDBS)
- Transition from hundreds to thousands fiber fed spectrographs 4MOST WEAVE
- Machine learning as a necessary tool to tackle large/complex datasets (big data)
- Expansion of spectra libraries (inclusion of metal poor, IR, ….)
- Plus MOONS, Euclid, JWST, Roman, PLATO, ELT (and instruments)
- Numerical simulations of galaxy formation (more obs. Constraints)
- More complex population synthesis models

2030's – 2050's

Many of us already working towards facilities starting 2030-2050 (Gaia-NIR, WST, Asteroseismic in dense fields, JASMINE, HRMOS, MSE …)

Timescales 2024 to 2030-2031

Transformation on MW and other Galaxies data – Taking spectroscopic surveys to a next level



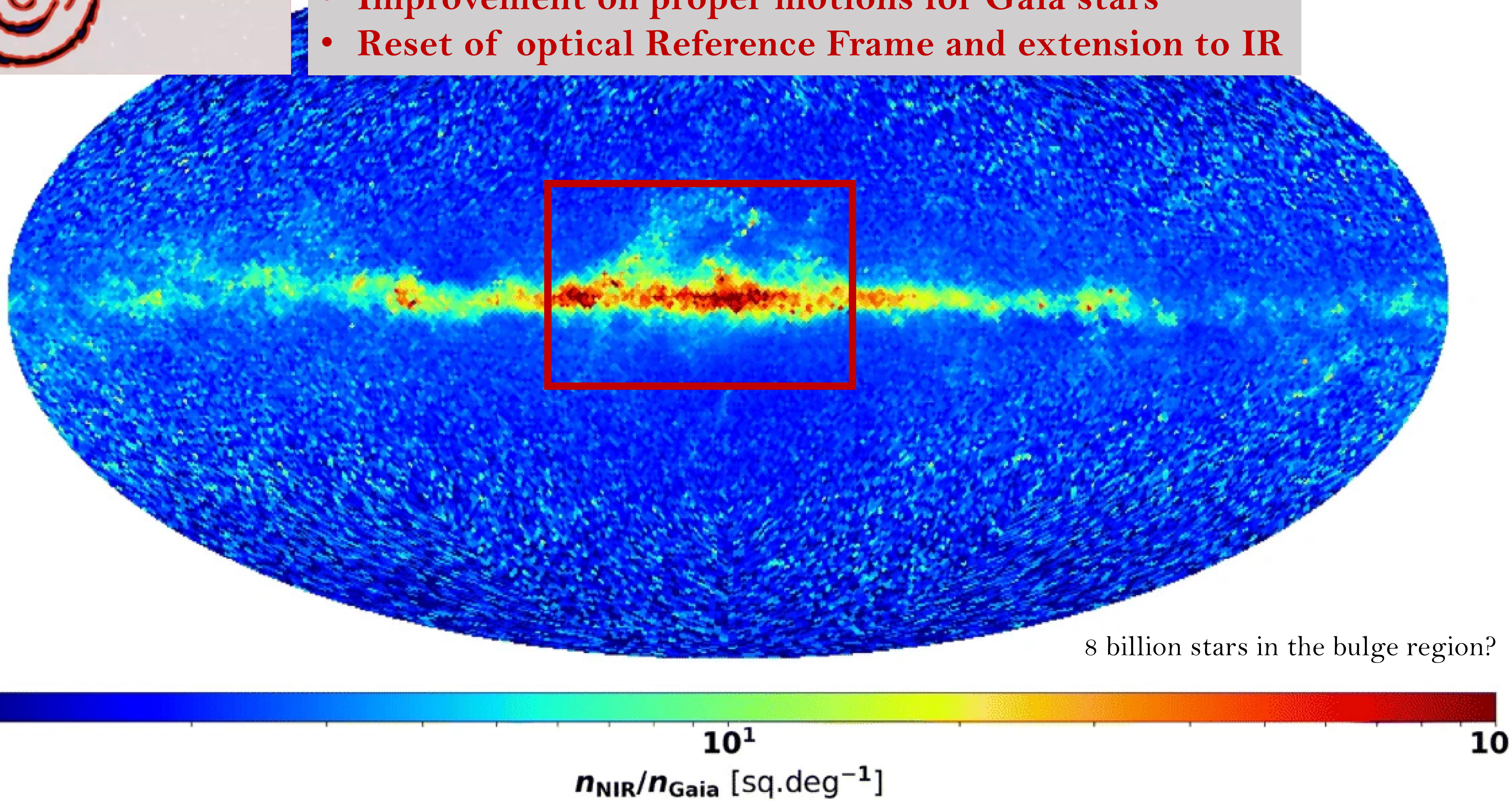
Challenges increase
2030's – 2050's

- Large collaborations – require a lot of time spent in organising, communication
- Expensive projects – long duration between idea -> real data in hands (20 yrs)
- Computer science skills to address complex datasets (machine learning as black box?)
- Early career work recognition in large projects (opportunity but also challenge)
- Increased number of artificial satellites – how to protect our sky?
- Global warming & sustainability issues on the way we work
- Not inclusive (still)
- Political difficulties – budgets not stable even for the basics (e.g. fellowships) specially in global South
- Efficiently use all the data coming `now´´ (2025-2035) to prepare the now-next (2035-2050)

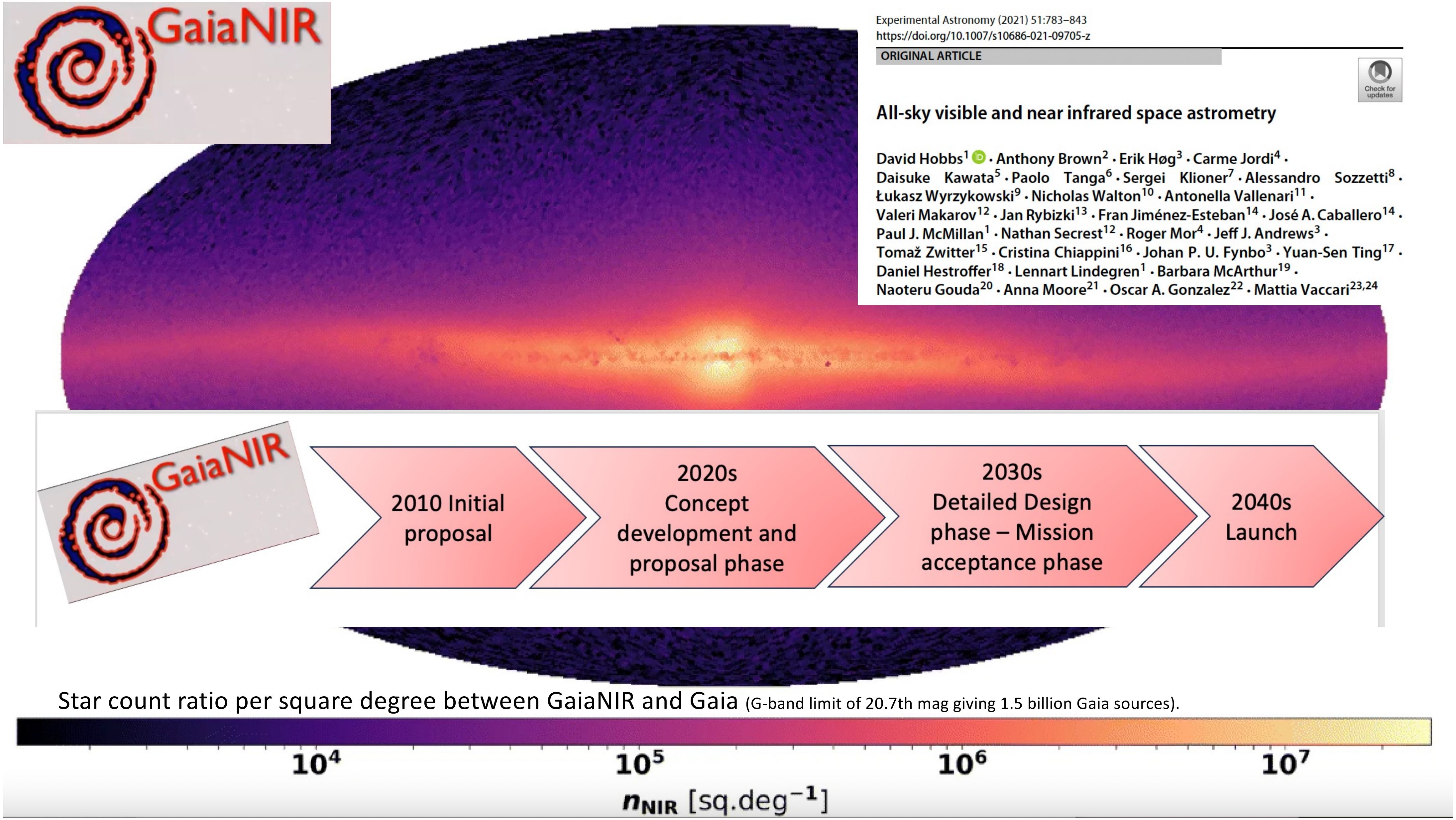
Each of us contribute in different fronts also to address these challenges

GaiaNIR

- **Probing hiding regions of the MW**
- **Improvement on proper motions for Gaia stars**
- **Reset of optical Reference Frame and extension to IR**



8 billion stars in the bulge region?


GaiaNIR
Experimental Astronomy (2021) 51:783–843
https://doi.org/10.1007/s10686-021-09705-z
ORIGINAL ARTICLE
Check for updates
All-sky visible and near infrared space astrometry
David Hobbs[1] · Anthony Brown[2] · Erik Høg[3] · Carme Jordi[4] · Daisuke Kawata[5] · Paolo Tanga[6] · Sergei Klioner[7] · Alessandro Sozzetti[8] · Łukasz Wyrzykowski[9] · Nicholas Walton[10] · Antonella Vallenari[11] · Valeri Makarov[12] · Jan Rybizki[13] · Fran Jiménez-Esteban[14] · José A. Caballero[14] · Paul J. McMillan[1] · Nathan Secrest[12] · Roger Mor[4] · Jeff J. Andrews[3] · Tomaž Zwitter[15] · Cristina Chiappini[16] · Johan P. U. Fynbo[3] · Yuan-Sen Ting[17] · Daniel Hestroffer[18] · Lennart Lindegren[1] · Barbara McArthur[19] · Naoteru Gouda[20] · Anna Moore[21] · Oscar A. Gonzalez[22] · Mattia Vaccari[23,24]
GaiaNIR
2010 Initial proposal
2020s Concept development and proposal phase
2030s Detailed Design phase – Mission acceptance phase
2040s Launch
Star count ratio per square degree between GaiaNIR and Gaia (G-band limit of 20.7th mag giving 1.5 billion Gaia sources).
10^4
10^5
10^6
10^7
n_{NIR} [sq.deg^{-1}]

Topics included

1. The Galactic halo populations: chemical composition and kinematics of in situ and accreted stars; halo globular clusters.
2. The populations of the inner Galaxy: bulge, halo, disk, bar and mixed populations from spectroscopic and photometric surveys; bulge stellar clusters.
3. The Galactic disk populations: chemical composition and kinematics of thick and thin disk stars; open clusters; tracers of present-day abundances.
4. Gaia DR3; spectroscopic and photometric surveys for the study of stellar populations.
5. Methods for the determination of atmospheric stellar parameters and chemical abundances. Spectral libraries for population synthesis.
6. Chemical evolution of Milky Way-like galaxies from cosmological simulations.
7. Resolved and unresolved extragalactic stellar populations.
8. New developments in astronomical instrumentation for stellar populations studies.

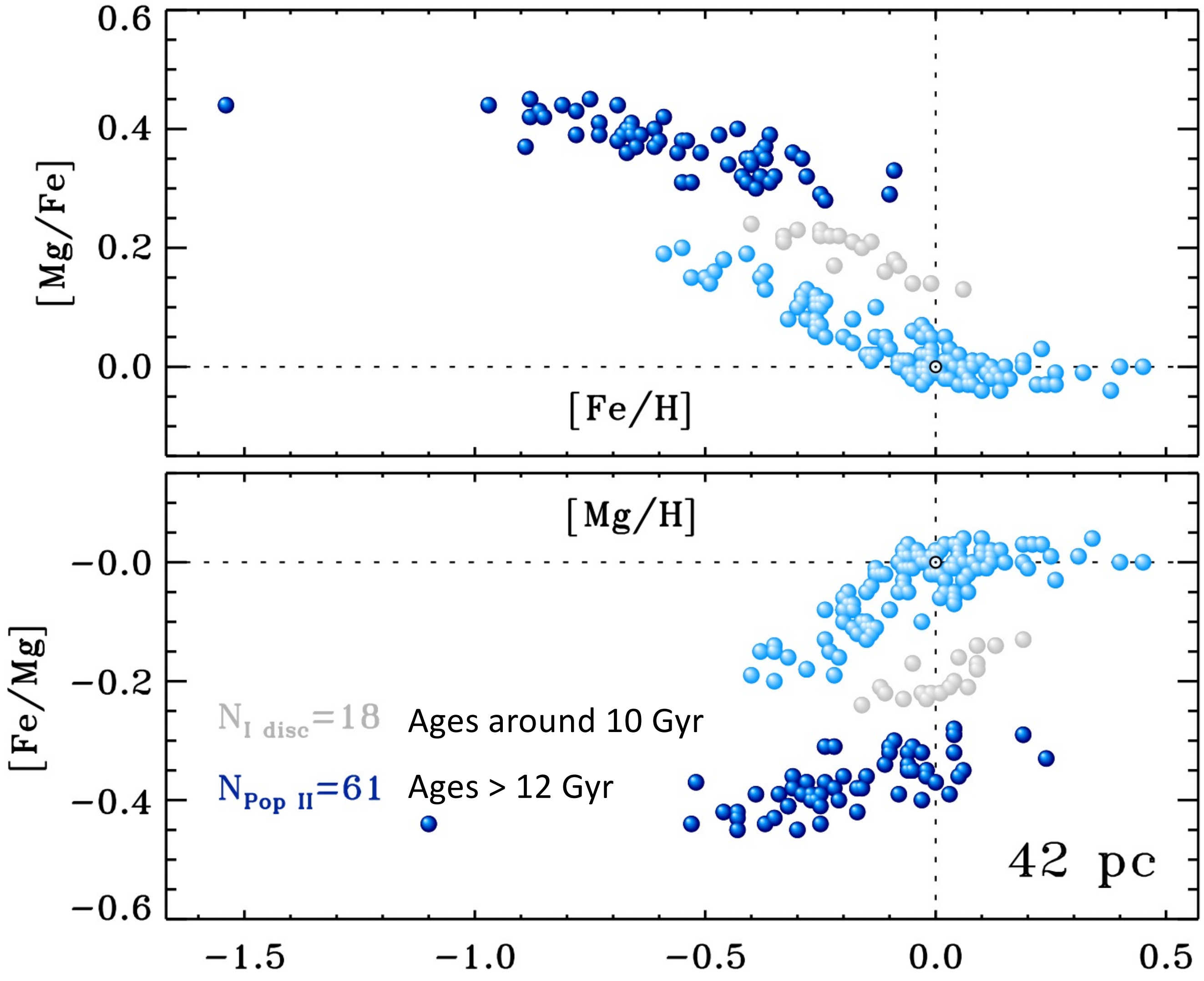
Challenge in the MW: Leaving the Solar Vicinity

Need precise distances
Need precise ages
Need precise chemistry

Challenge in the MW:

Mix of stellar populations even when using samples in very small volumes!

Stars move away from their birthplace



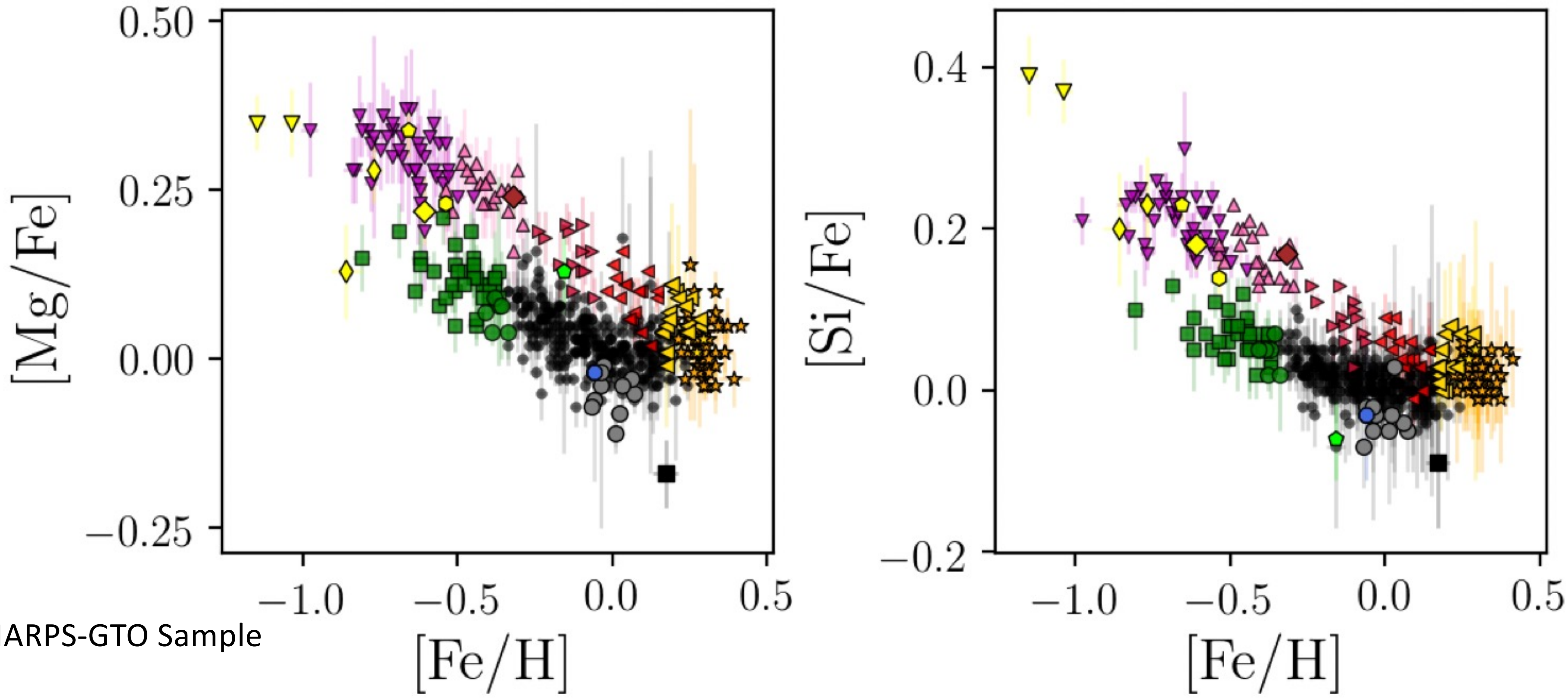
40 pc

Fuhrmann & Chiti 2021

``hints for multiple populations in the high-[α/Fe] population, and indications that the chemical evolution of the high-[α/Fe] metal-rich stars is connected with the super-metal-rich stars.´´

MSTO

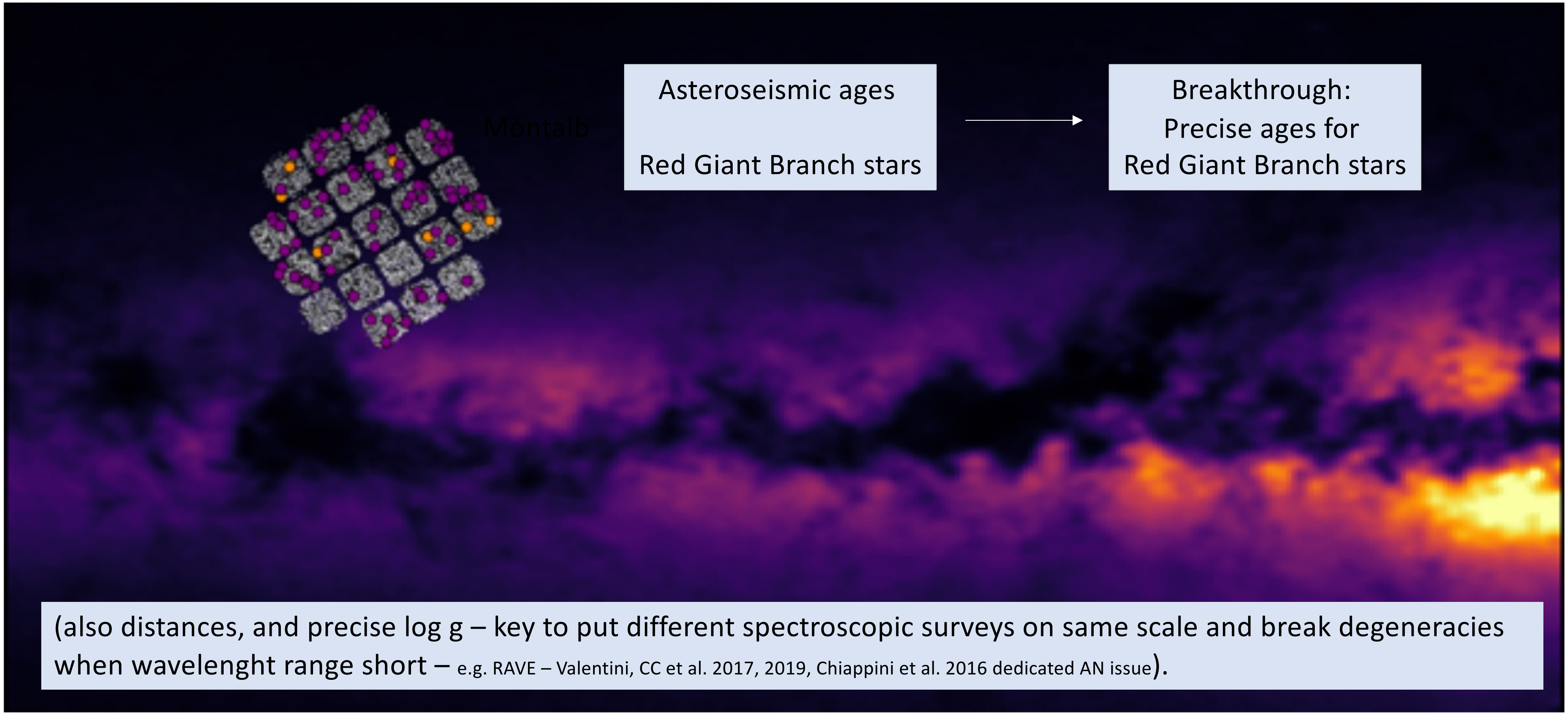
100 pc



With HARPS-GTO Sample

Anders et al. 2018 – tSNE* analysis of the chemistry space of the solar neighbourhood

*unsupervised non-linear dimensionality reduction technique

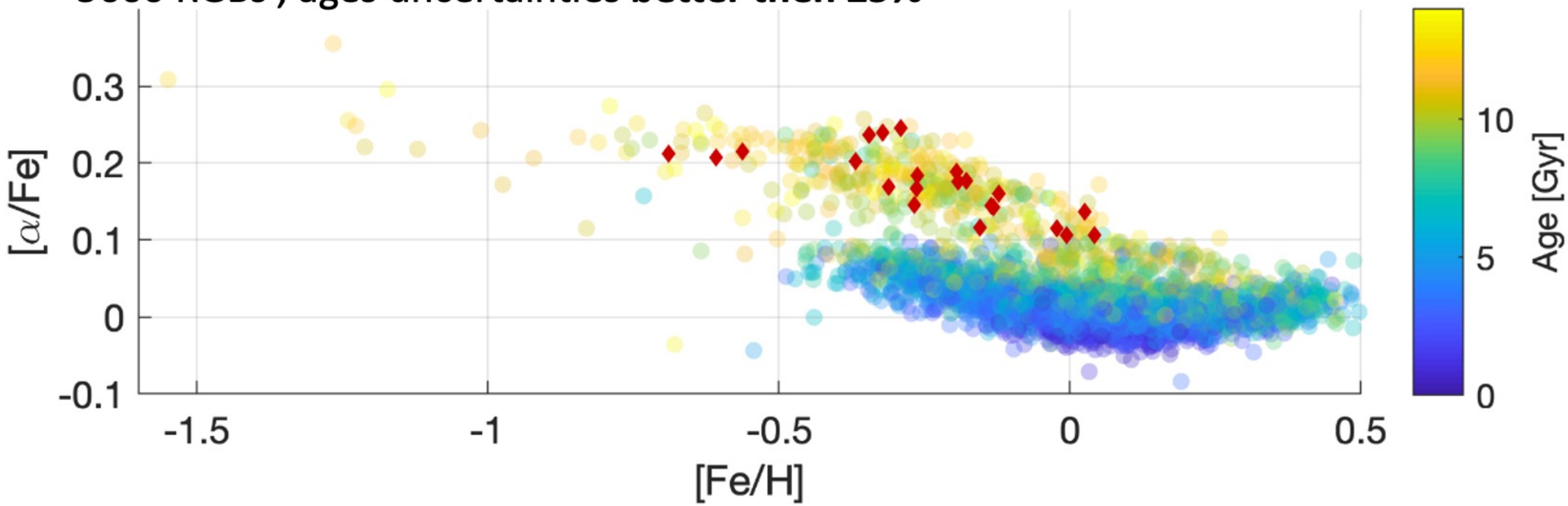


Milky Way stellar density map obtained with the StarHorse code using data from Gaia, superimposed with the field of view of the Kepler satellite on the left. The points are the APOGEE targets in the Kepler field. Of those, coloured in magenta are the older in situ stars, coloured in orange are the stars from Gaia Enceladus. Credit: Data: ESA-Gaia-DPAC, APOGEE-DR16, AIP/A. Queiroz & StarHorse Team

See Montalban et al. 2021 for high precision ages with Kepler + APOGEE + individual oscilations analysis

APOGEE + Kepler **Solar Circle 7.5-9.5 kpc** **Miglio, Chiappini et al. 2021**

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



Young alpha-rich – see Grisoni, CC et al. 2024 for K2 ages, Chiappini et al. 2015 for CoRoT ages, Martig et al. 2015 for Kepler

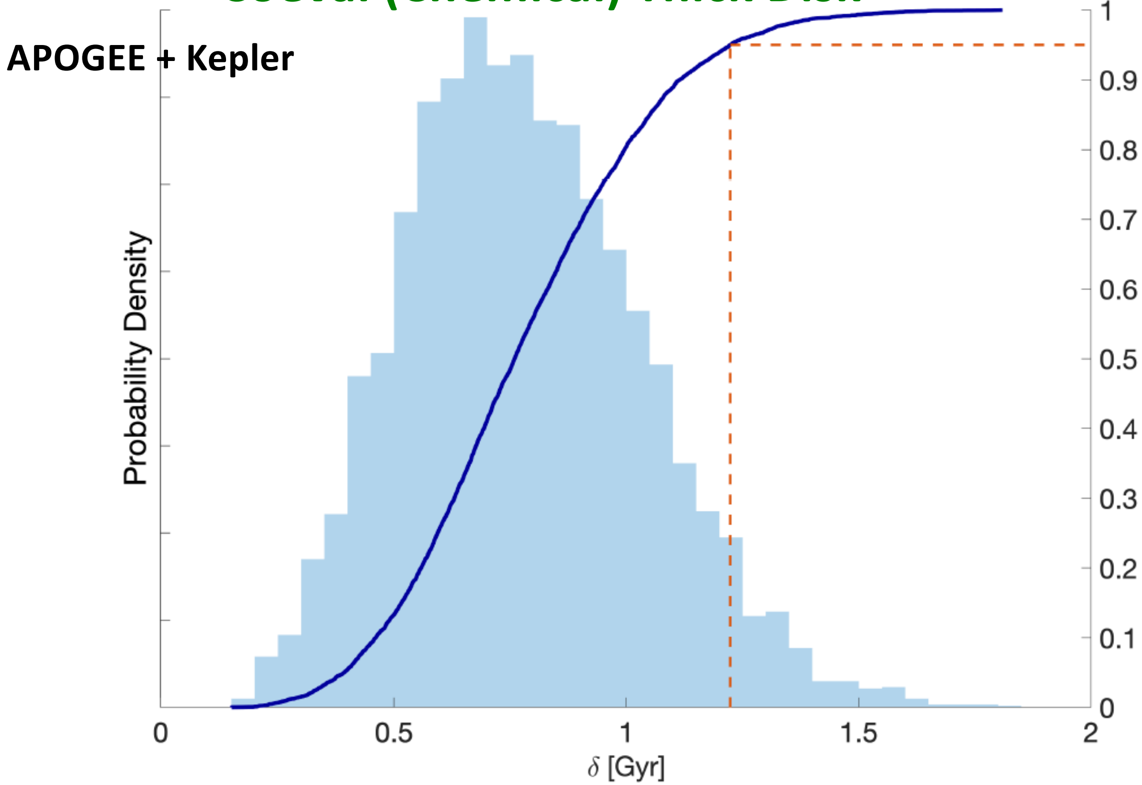
PLATO could have been a great opportunity for Galactic Archaeology!

Around 1-2 kpc

Check it out – Miglio, CC et al. (>100 authors) 2017

Coeval (Chemical) Thick Disk

Miglio, Chiappini et al. 2021



400 alpha-rich RGBs
Mean age 11Gyr

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.

Using dimensionality-reduction technique (t-distributed stochastic neighbour embedding; t-SNE

Table 4. Mean parameters of the genuine thick disk found in the different surveys.

Kinematic parameters checked a posteriori

Survey	Age (Gyr)	$\sigma_{\rm age}$ (Gyr)	V_ϕ (km s^{-1})	σ_{V_ϕ} (km s^{-1})
LAMOST DR7 MRS	11.4	1.3	189.	50
GALAH DR3	11.2	1.0	188.	41
APOGEE DR17	11.2	1.4	179.	45

Queiroz et al. 2023

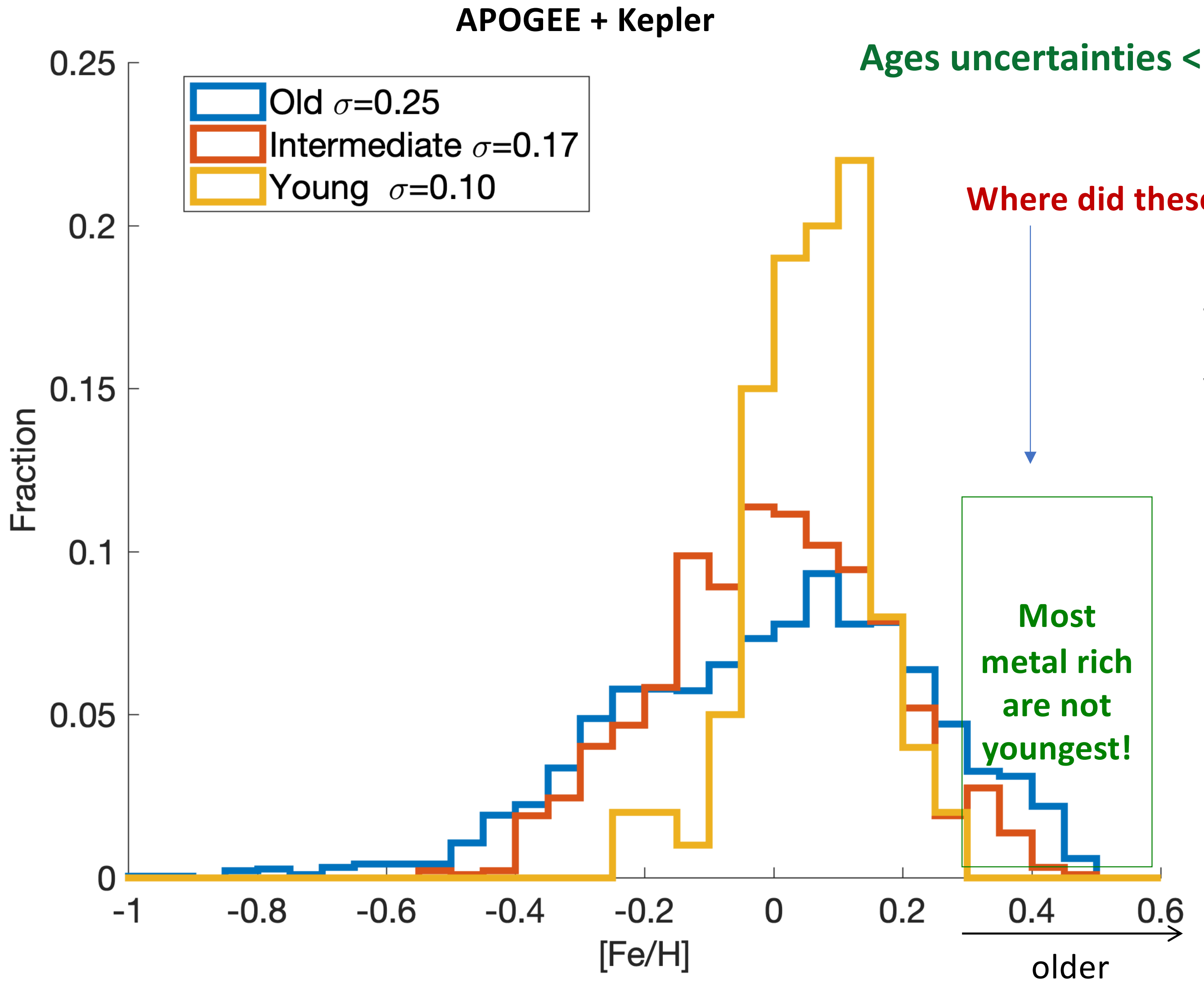
Note the agreement with a) ages inferred from seismology of red giant branch stars in Miglio et al. 2021 (previous slides) and b) the differerent surveys analysed here (different resolution) using subgiant stars.

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

At solar neighborhood ~1kpc

KEPLER and APOGEE and Gaia

Ages uncertainties < 25%



Where did these come from? Inner regions!

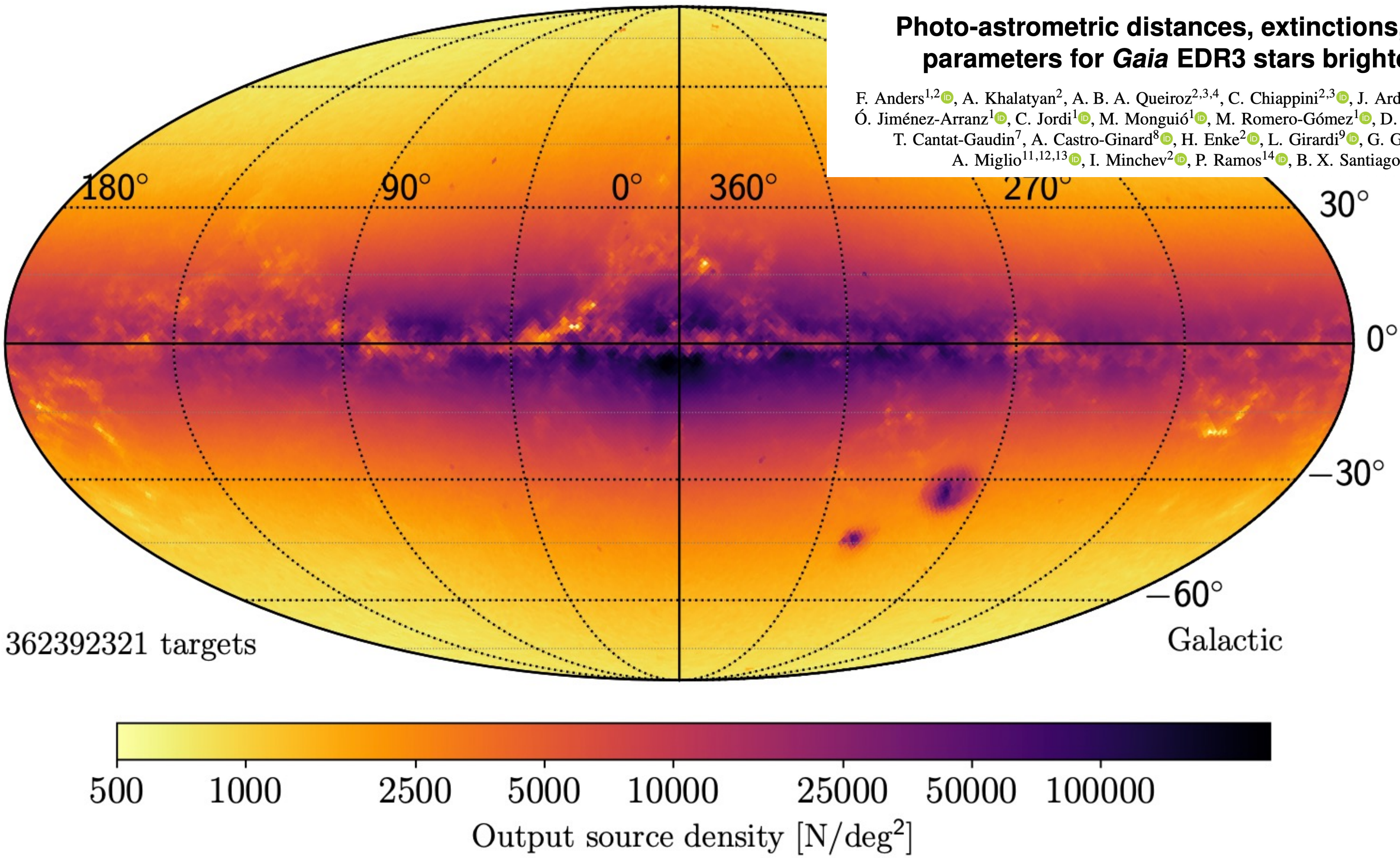
See also Anders et al. 2017a,b using CoRoT and Willet et al. 2023 using K2 for the impact of radial migraiton on the metallicity gradients

A&A 658, A91 (2022)
https://doi.org/10.1051/0004-6361/202142369

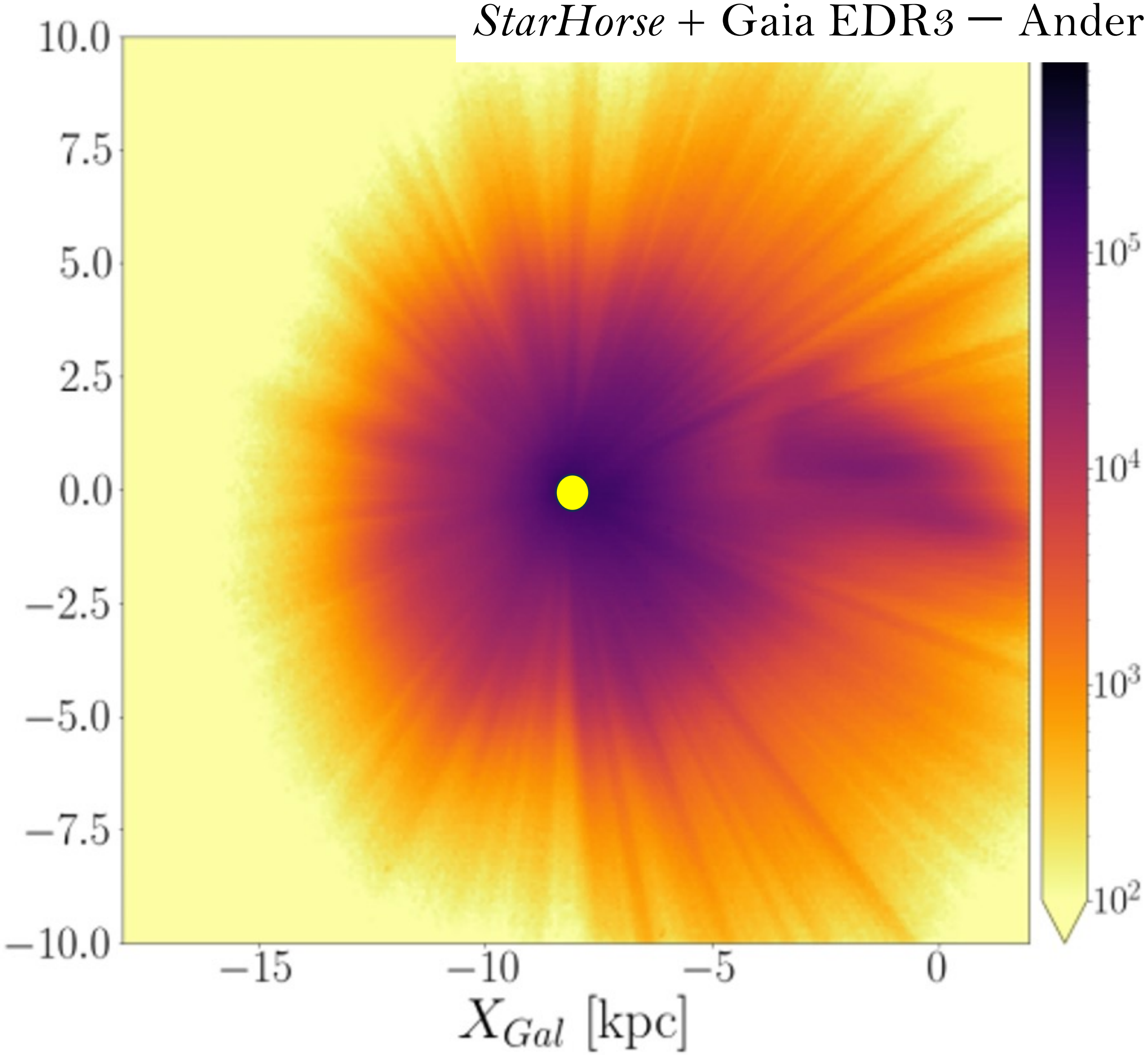
Astronomy & Astrophysics

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

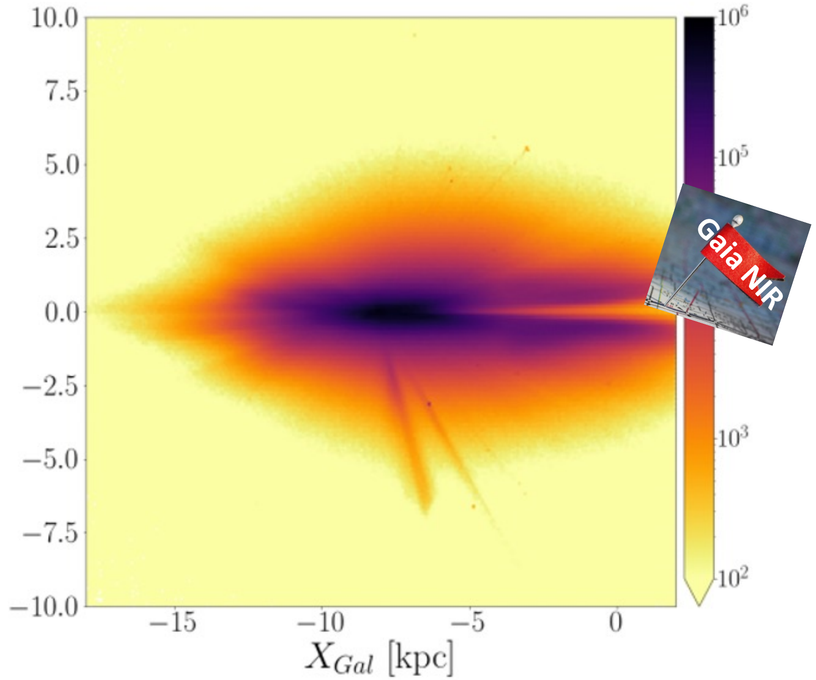
F. Anders[1,2], A. Khalatyan[2], A. B. A. Queiroz[2,3,4], C. Chiappini[2,3], J. Ardèvol[1], L. Casamiquela[5], F. Figueras[1], Ó. Jiménez-Arranz[1], C. Jordi[1], M. Monguió[1], M. Romero-Gómez[1], D. Altamirano[1], T. Antoja[1], R. Assaad[6], T. Cantat-Gaudin[7], A. Castro-Ginard[8], H. Enke[2], L. Girardi[9], G. Guiglion[2], S. Khan[10], X. Luri[1], A. Miglio[11,12,13], I. Minchev[2], P. Ramos[14], B. X. Santiago[15,3], and M. Steinmetz[2]



StarHorse + Gaia EDR3 — Anders et al. 2022



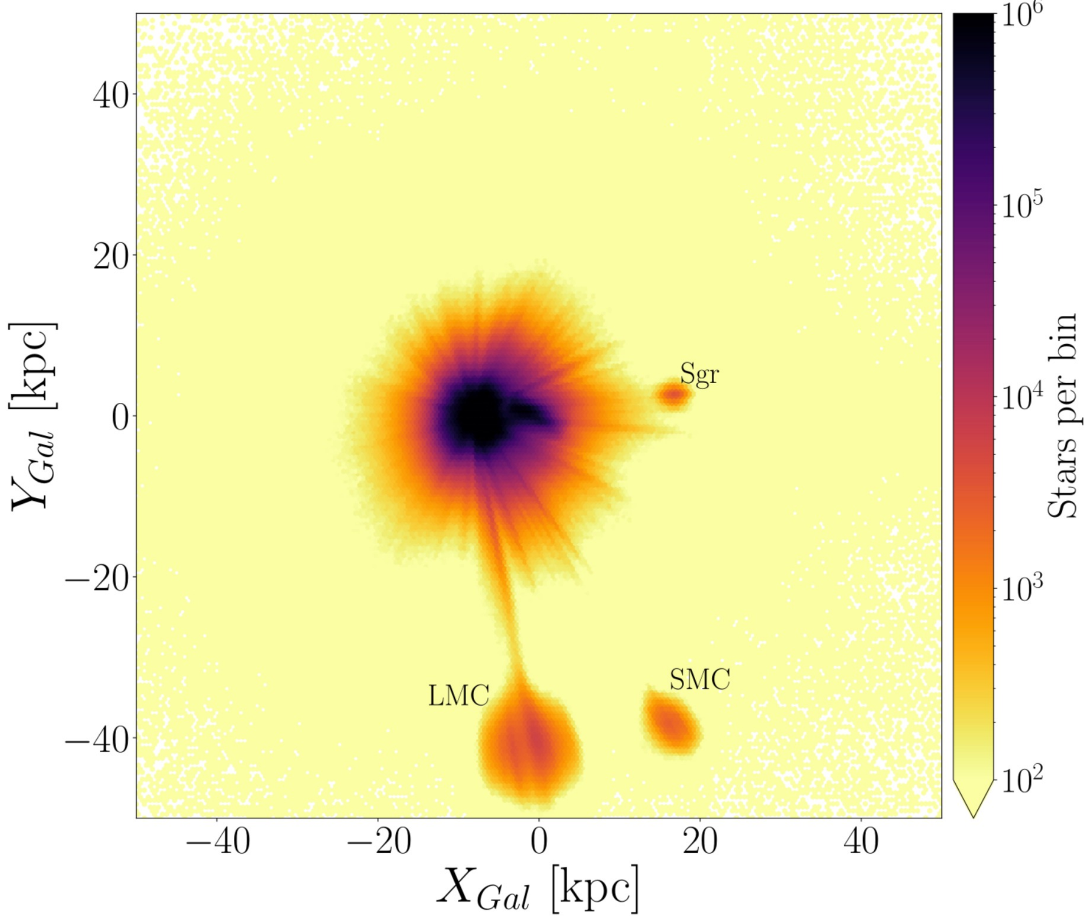
Run for G > 18.5



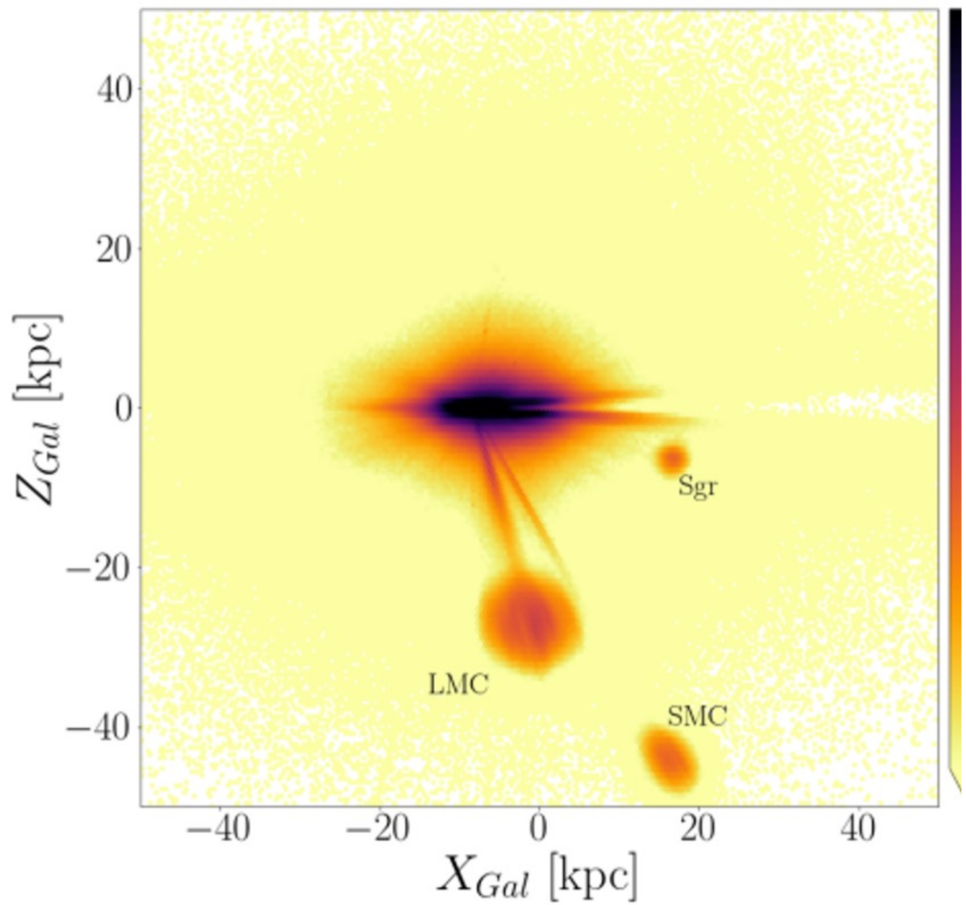
- 400 M input stars
- 350 M converged
- **316 M with good flags**

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

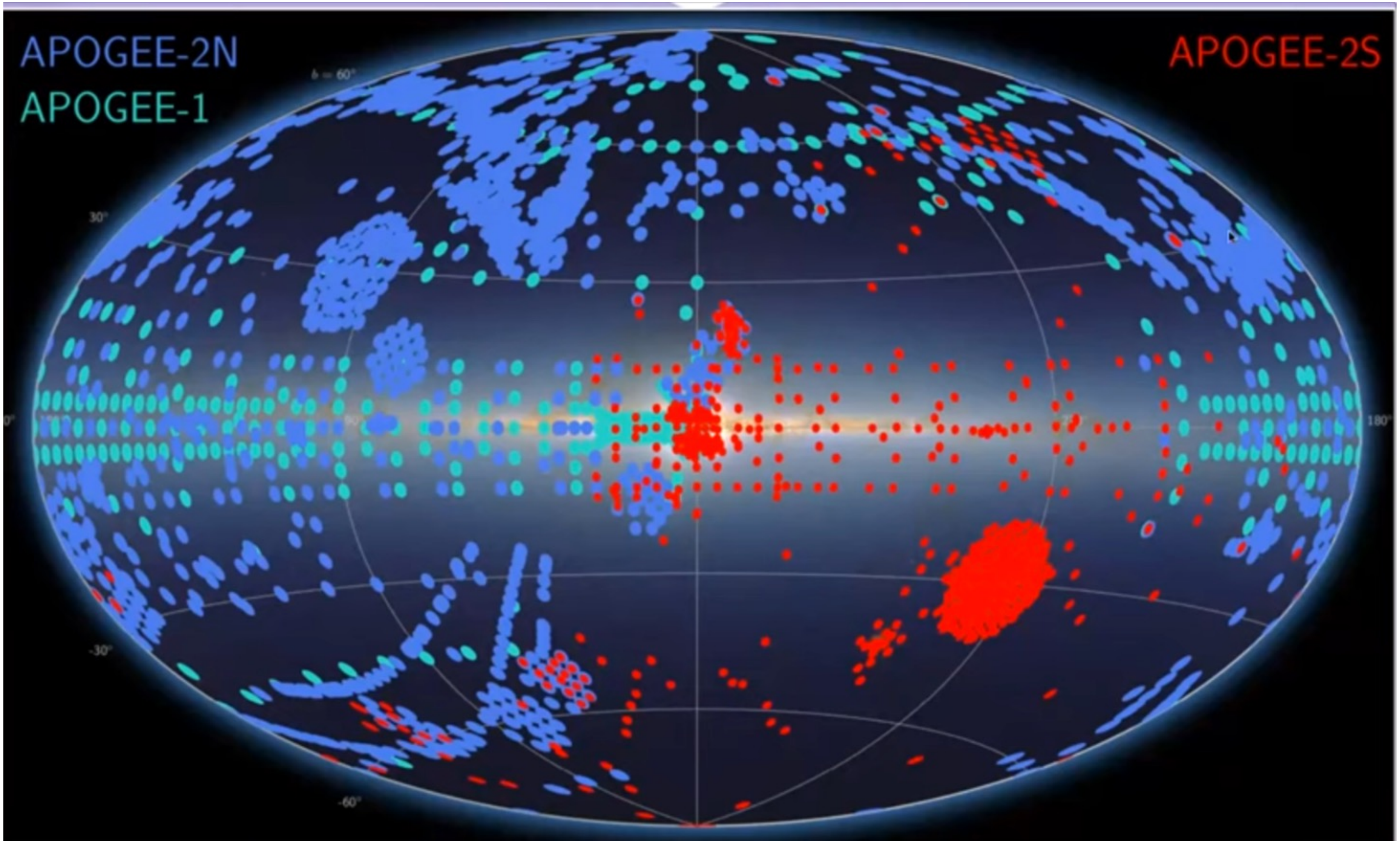
Now on a larger volume 40 kpc x 40 kpc (more tl



StarHorse EDR3 Galactocentric stellar density map
(Anders, F., et al., 2022, A&A, 658, A91)



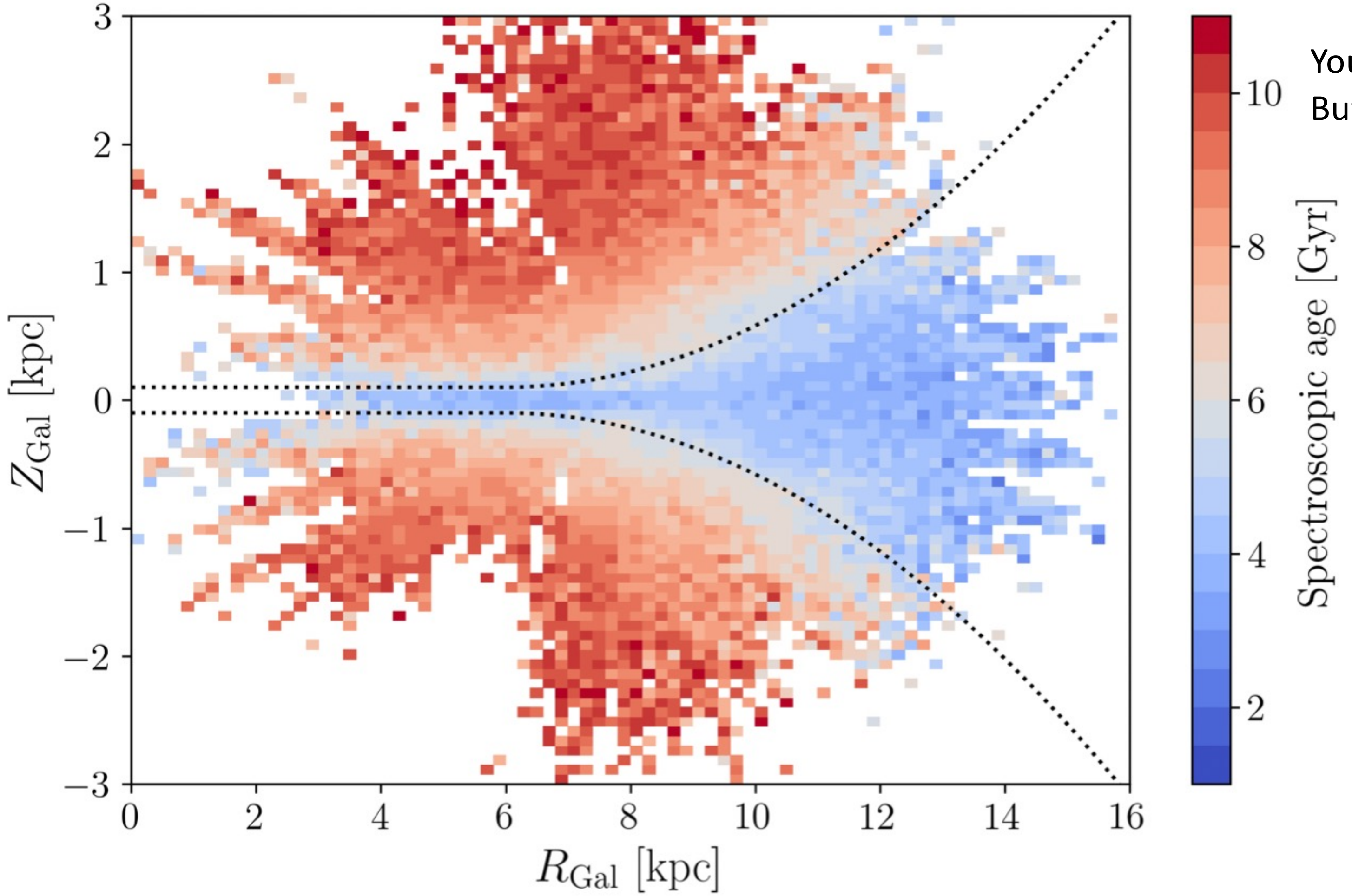
https://data.aip.de/projects/starhorse2021.html



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

Machine Learning!

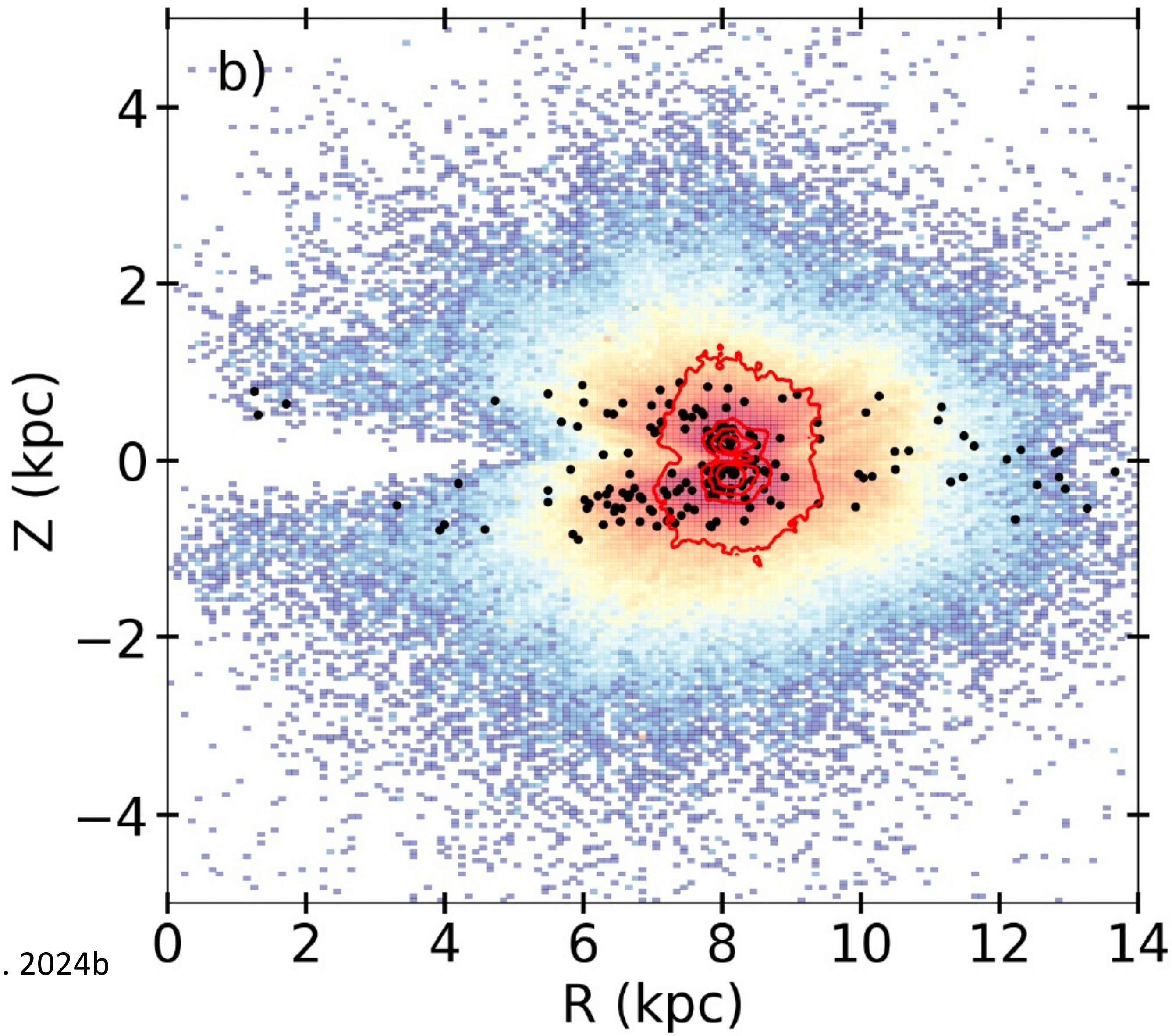
Around 180 000 APOGEE red giants
XGBoost trained on RGs of Miglio et al. 2021 with Kepler and APOGEE



You can learn a lot on a global way
But…

Anders et al. 2023 (see also Ciuca et al. 2021, Leung et al. 2023, Imig et al. 2023, Stone-Martinez et al. 2024)

Machine Learning!



RVS-CNN (Guiglion et al. 2024)
Using DR3 XP information

Black points: metal-poor stars with thin disk orbits!

AGE sample (MSTO+SG)
Almost 200 000 stars!
Very precise SH distances!

Nepal, CC et al. 2024b

A&A, 691, A98 (2024)
https://doi.org/10.1051/0004-6361/202451427

Astronomy & Astrophysics

Machine Learning!

Metal-poor and super metal rich candidates

Transferring spectroscopic stellar labels to 217 million *Gaia* DR3 XP stars with SHBoost

A. Khalatyan[1], F. Anders[2,3,4,⋆], C. Chiappini[1], A. B. A. Queiroz[5,6], S. Nepal[1,7], M. dal Ponte[8], C. Jordi[4], G. Guiglion[9,10,1], M. Valentini[1], G. Torralba Elipe[11,12,13], M. Steinmetz[1], M. Pantaleoni-González[14,15], S. Malhotra[2,3,4], Ó. Jiménez-Arranz[16,2,3,4], H. Enke[1], L. Casamiquela[17], and J. Ardèvol[2,3,4]

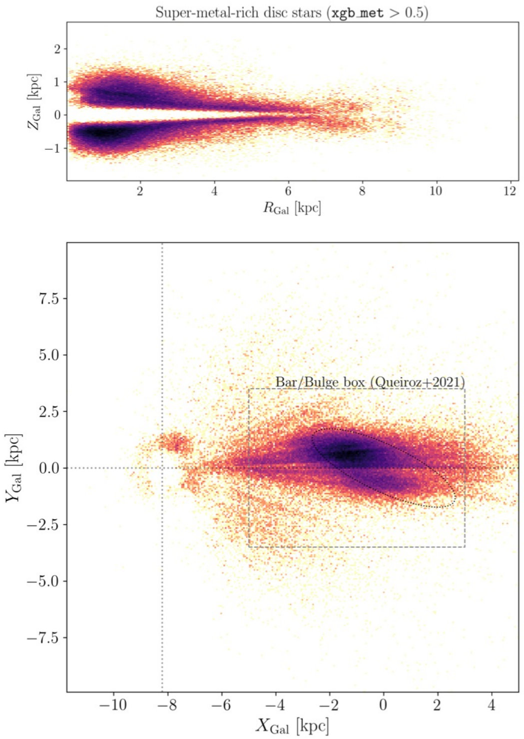


Fig. 12. Galactic maps of super-metal-rich stars (xgbdist_met > +0.5). The lower panel shows a top-down view of the Galaxy, marking the solar position (dotted lines), the approximate extent of the Galactic bar (ellipse), and the bulge and bar region studied by Queiroz et al. (2021).

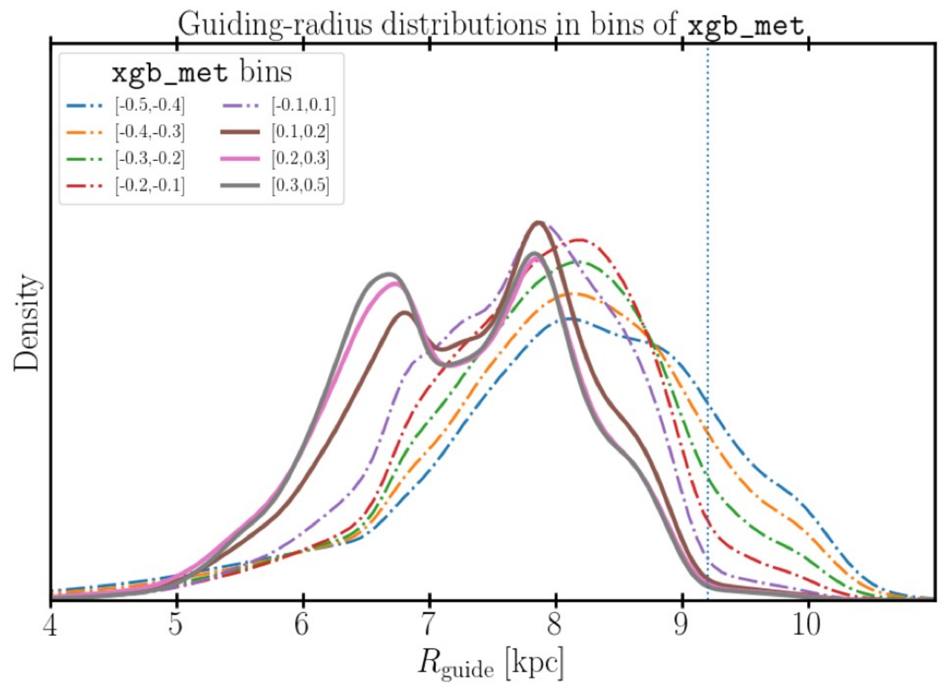


Fig. 13. Guiding-radius distributions of the XP sample with radial velocities from *Gaia* RVS, in bins of xgbdist_met. The curves of SMR stars are highlighted as thicker lines. The dotted vertical line at R_{guide} highlights the point after which the density of metal-rich stars reaches a floor, which might possibly be related to the outer Lindblad resonance of the Galactic bar.

Third challenge

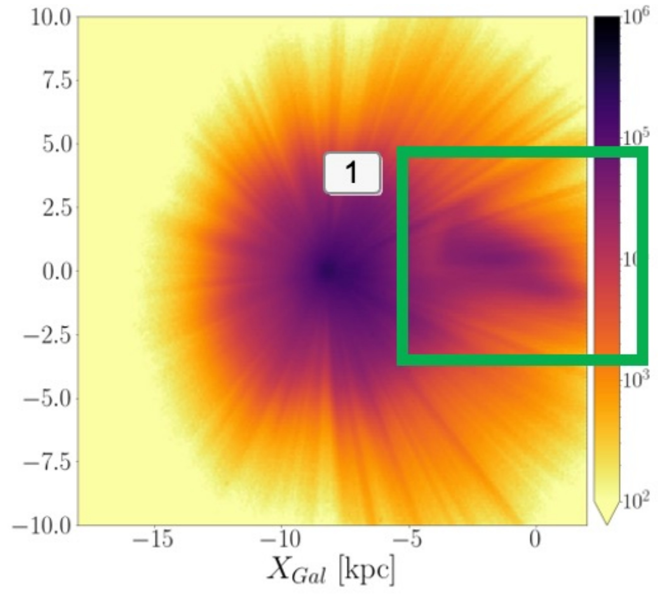
Annual Review of Astronomy and Astrophysics

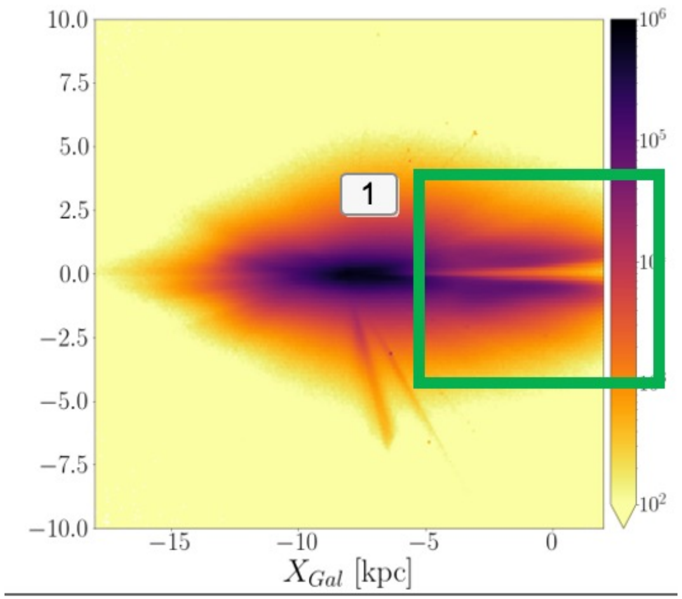
Chemodynamical History of the Galactic Bulge

Beatriz Barbuy,[1] Cristina Chiappini,[2] and Ortwin Gerhard[3]

We will need to understand the innermost regions of the MW

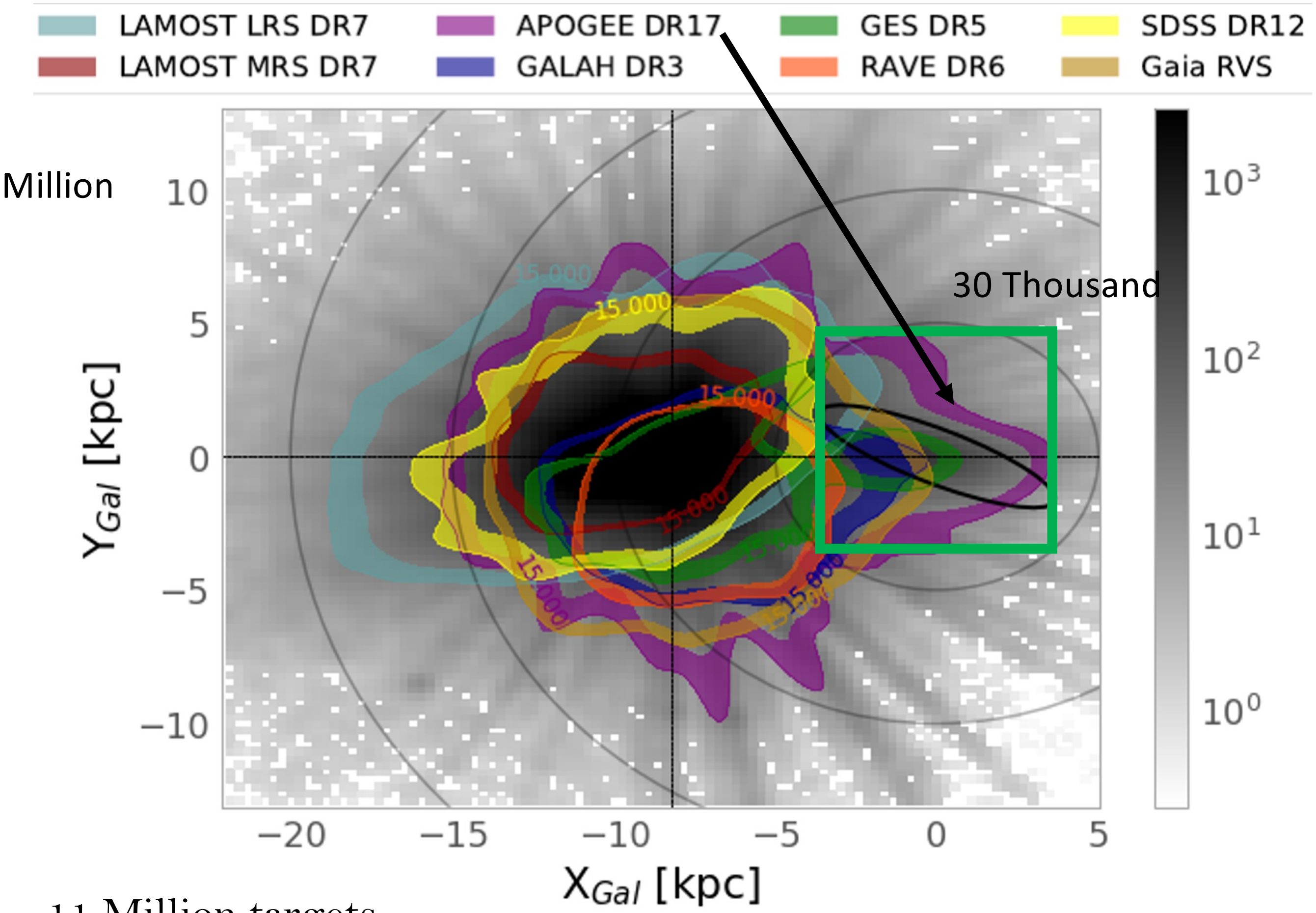
Revolution with Gaia and APOGEE after 2018





30 Million

Gaia + photometry + spectroscopy + SH



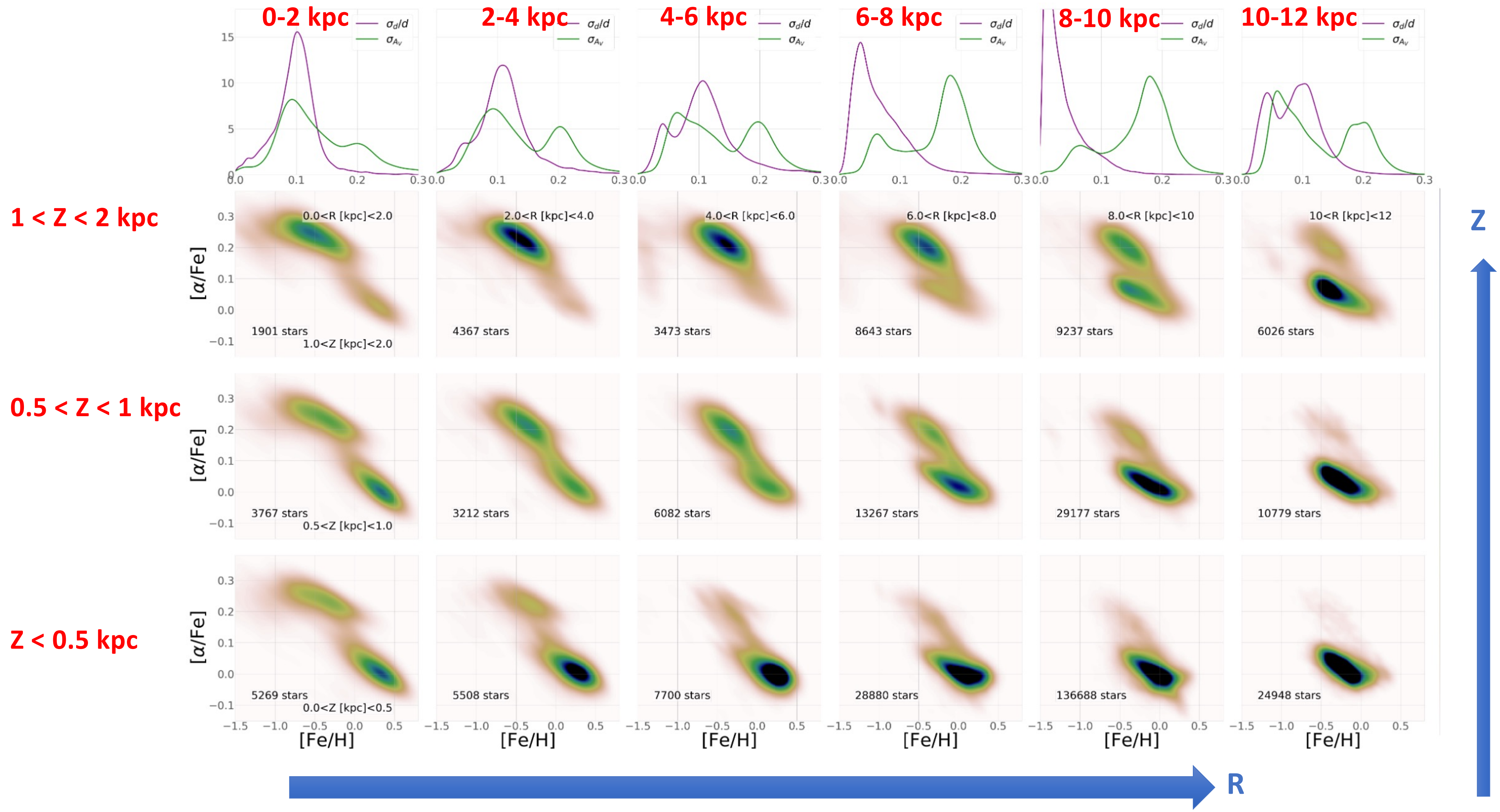
- 11 Million targets with distances
- 2.5 Million with ages (MSTO+SGs)

Queiroz et al. 2023, See also Limberg et al. 2023

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

FULL DISC

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



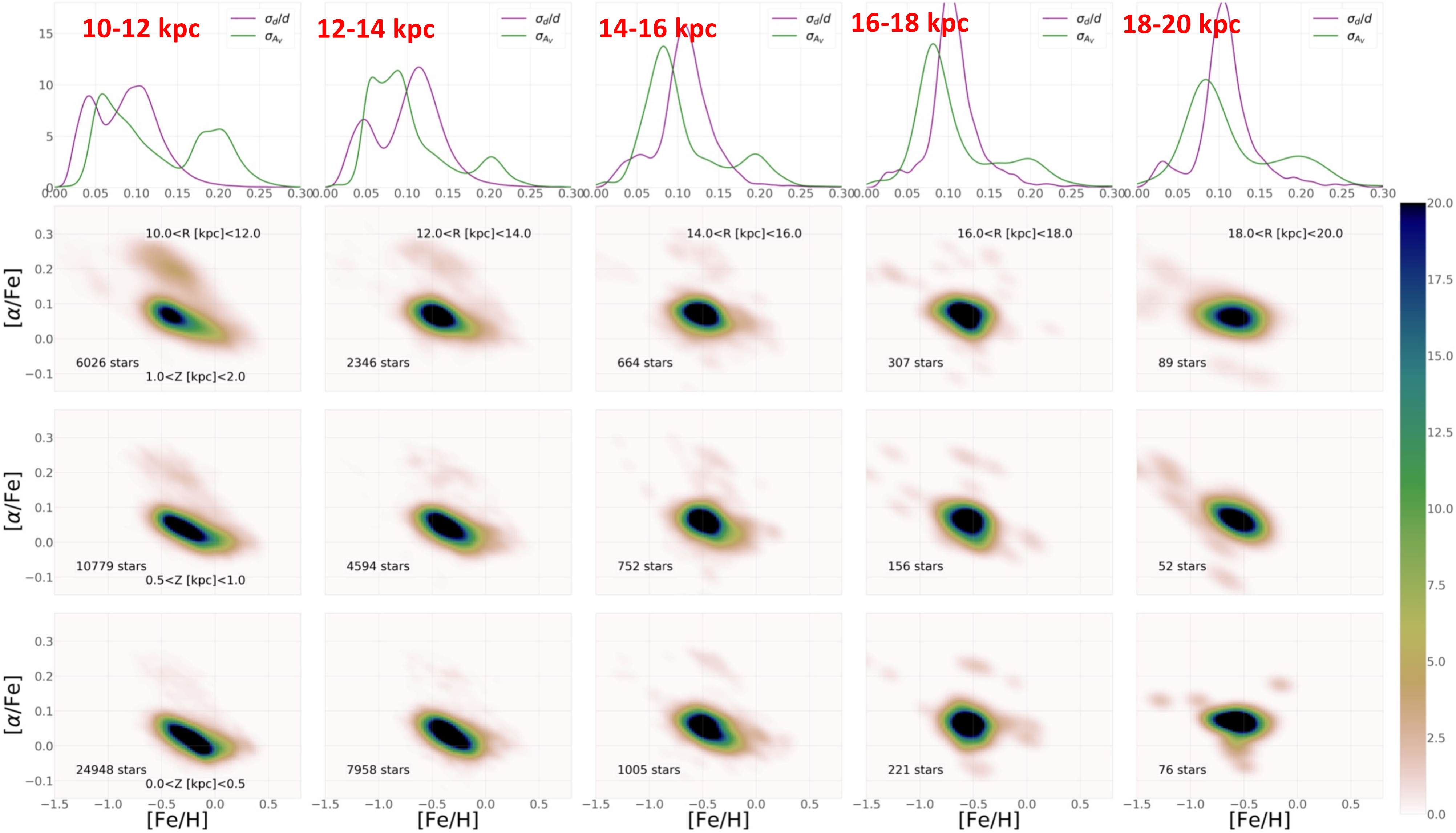
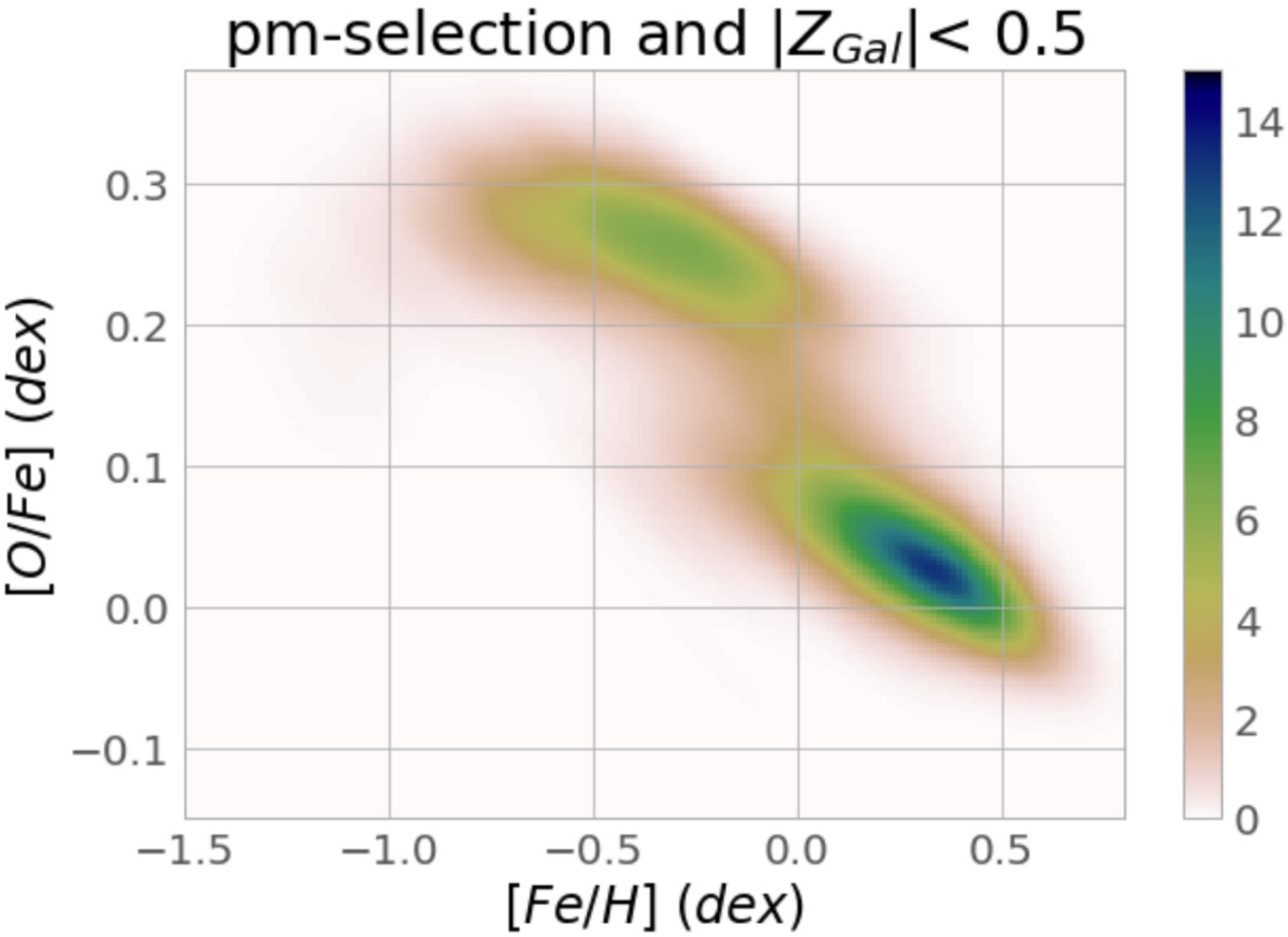


Fig. 7. Same as previous Figure, but now extending to the outer disk.

Queiroz, CC, Perez-Villegas et al. 2021 – APOGEE DR16+ + Gaia **EDR3** + Complementary photometry

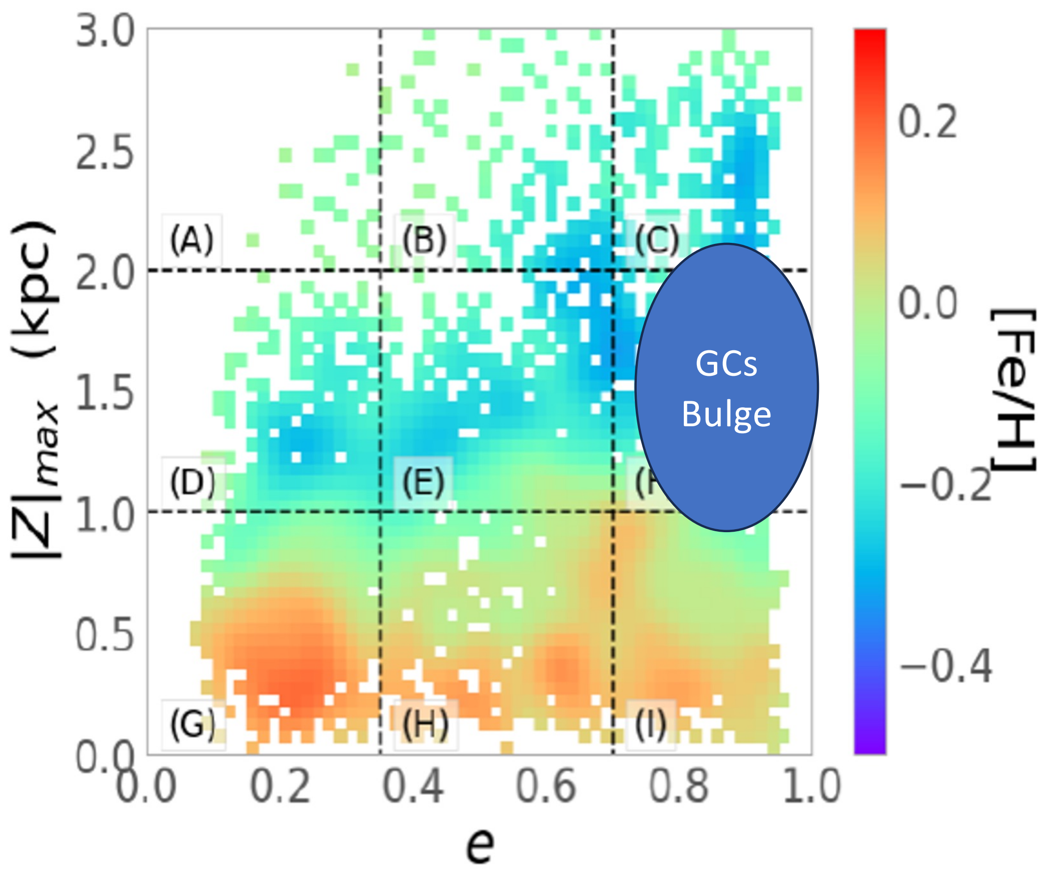
INNER kpcs



7D+

We can finally make an orbital space analysis but for around 8000 stars...
(from box of 30Million -> 30Thousand – Thousands...)

INNER kpcs



Queiroz et al. 2021

Inner thick disk + Inner thin disk + old spheroidal bulge

4th Challenge

Need large statistics
Finding outliers and important sub-populations not well represented in small local samples

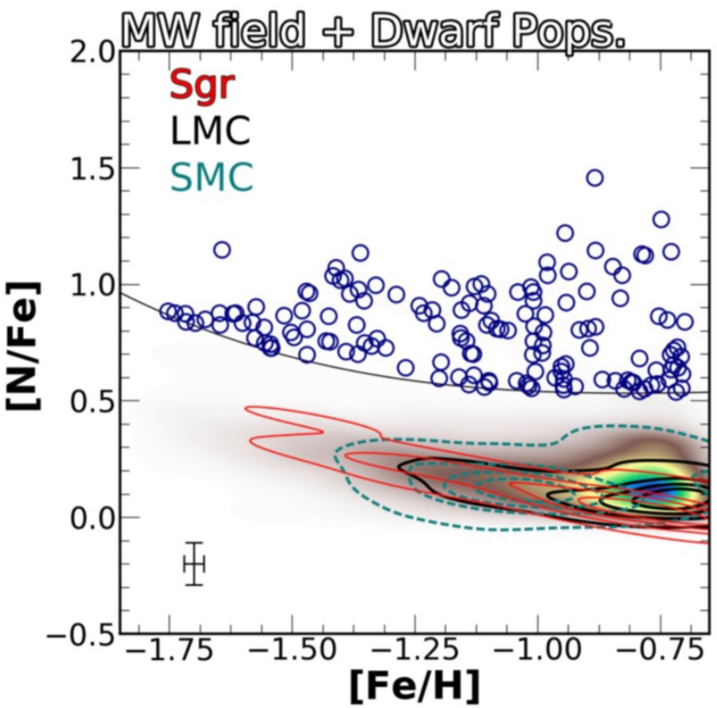
Extract chemical information in lower resolution for large datasets – 4MIDABLE-LR survey (see Chiappini, Minchev et al. 2019)

Machine learning…

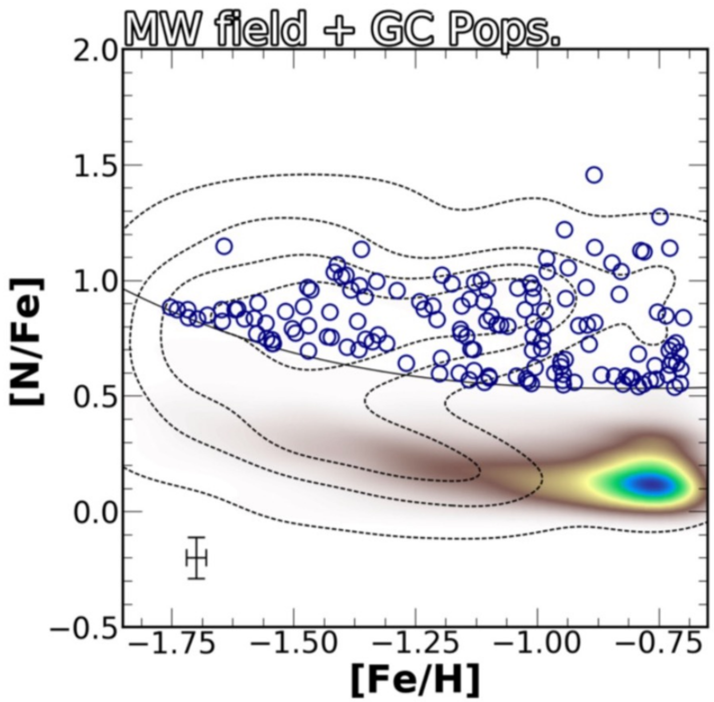
Caveats: Rare populations with especial chemical signatures

(Schiavon et al. 2017, Masseron et al. 2020, Fernandez-Trincado et al. 2017, 2022, Maren et al. 2023):

N-rich, Al-rich, Si-rich, P-rich, R-process rich, Na-rich and s-process rich stars...



Fernandez-Trincado et al. 2022



See also Belokurov and Kravtsov 2023, arXiv:2306.00060

Article

A metal-poor star with abundances from a pair-instability supernova

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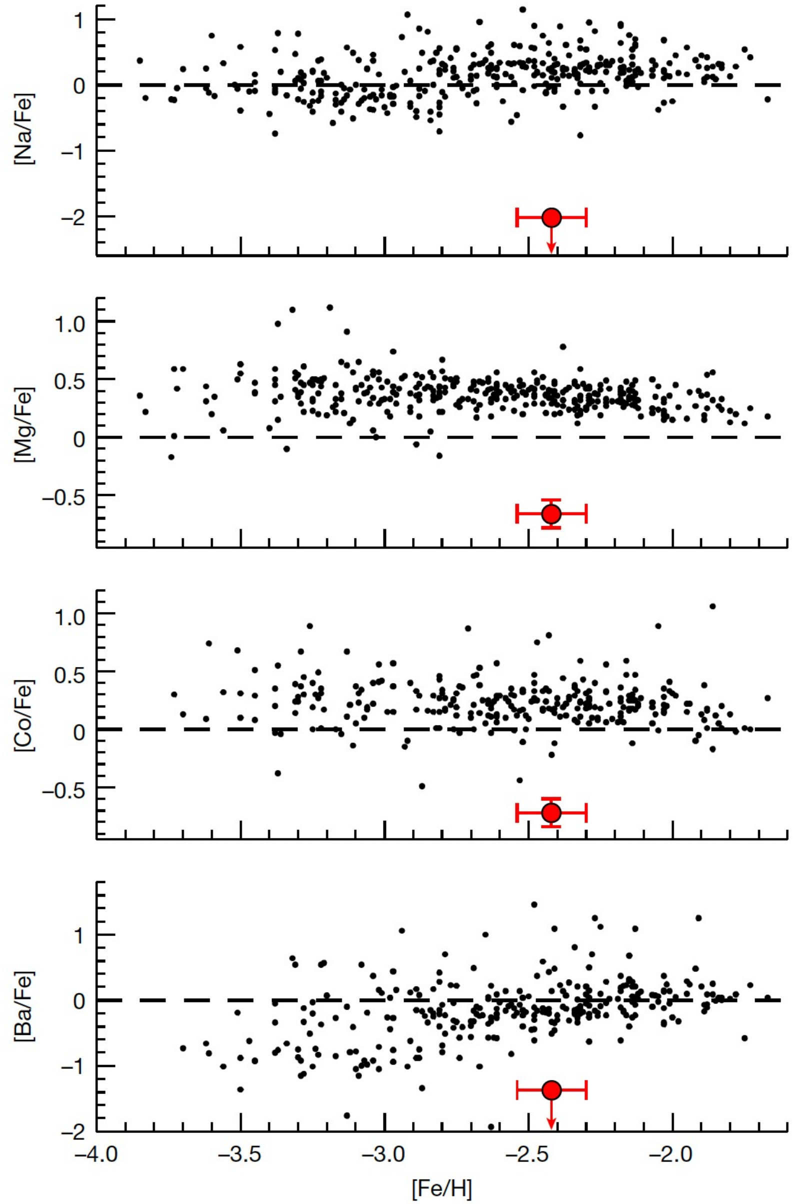


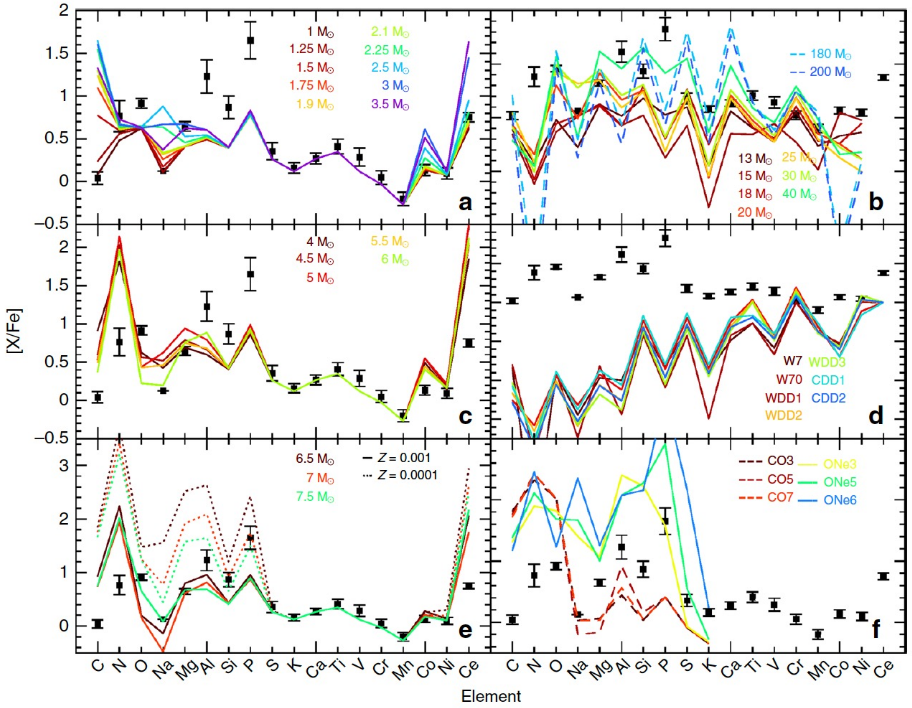


Fig. 6 P-rich stars versus nucleosynthesis predictions. Median chemical abundance pattern of the P-rich stars (black squares) against the several mod prediction patterns (colored lines), where [X/Fe]=log10(n(X)/n(Fe))-log10(n(X)/n(Fe))$_{\odot}$. Error bars show the star-to-star abundance rms scatter. **a** Tl low-mass AGB subpanel shows the yields[20] for a metallicity of $Z = 0.004$ (Fe/H] ~−0.7) and various initial masses [1.0–3.0]M$_{\odot}$ in a rainbow fashio (steps of 0.5 M$_{\odot}$), the redder being the lower masses. **b** In the core collapse supernova (SNII) subpanel, we show standard models (i.e. without any specit effect like rotation or O-C mergers) where the mass range is [13–40]M$_{\odot}$ and metallicity such that $Z = 0.001$ ([Fe/H] ~−1.3)[22]. In the same subpanel, tl pair-instability supernovae (PISN) yields[62] are represented by dashed lines for masses of 180 and 200 M$_{\odot}$. **c** The initial masses of the intermediate-ma AGB predictions[20] (intM-AGB) range from 3.5 to 6 M$_{\odot}$ with $Z = 0.004$ (or [Fe/H]~−0.7). **d** The SN Type Ia (SNIa) yields[63] cover all values in centr densities (1.37×10^9–2.12×10^9 g cm^{-3}) and deflagration speeds (1.5%–5% of sound speed) provided by the authors. **e** Theoretical predictions for supe AGB stars[64] (S-AGB) at two metallicities ($Z = 0.001$, 0.0001 or [Fe/H] ~−1.3, −2.3; continuous and dotted lines, respectively) and three initial mass (6.5, 7.5 and 8.0 M$_{\odot}$) are displayed. **f** Finally, we display the only solar metallicity ($Z = 0.014$ or [Fe/H] ~0.0) novae yields available in the literature[65] wi CO core WDs (dashed lines) and ONe WDs (continuous lines) with the same mass range of [0.85–1.15]M$_{\odot}$.

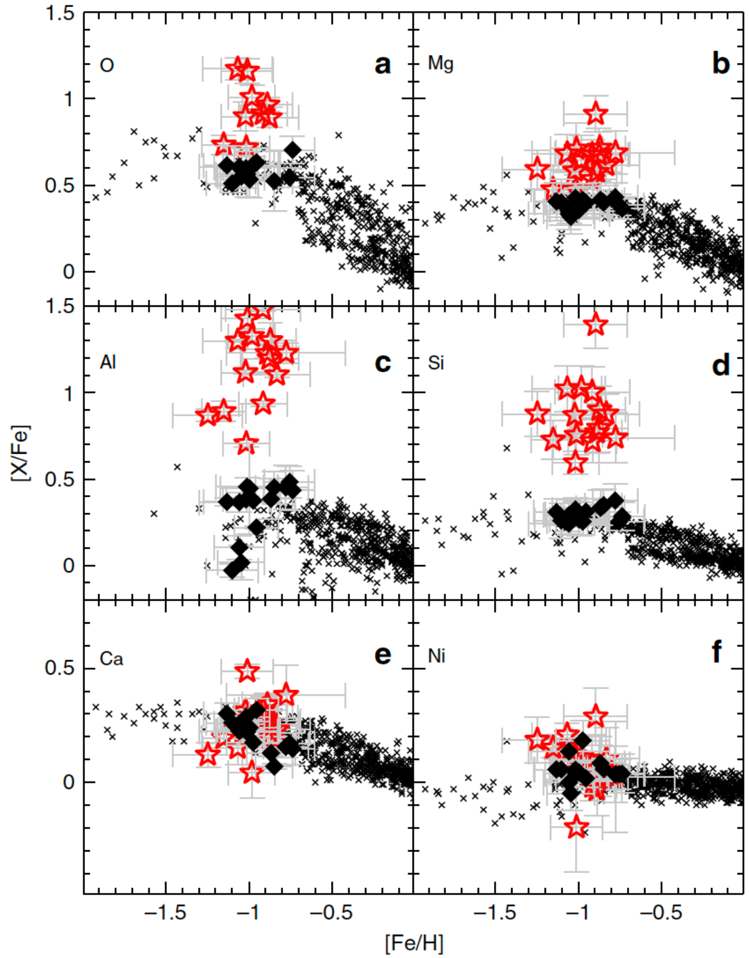


Fig. 9 Elemental abundances as a function of metallicity. a Oxygen, **b** magnesium, **c** aluminum, **d** silicon, **e** calcium, **f** nickel. The red stars and black diamonds show the P-rich and P-normal stars, respectively, while the black crosses correspond to the optical literature values for field dwarf stars[48]. Error bars indicate our measurement uncertainties such as displayed in Supplementary Tables 3 and 4.

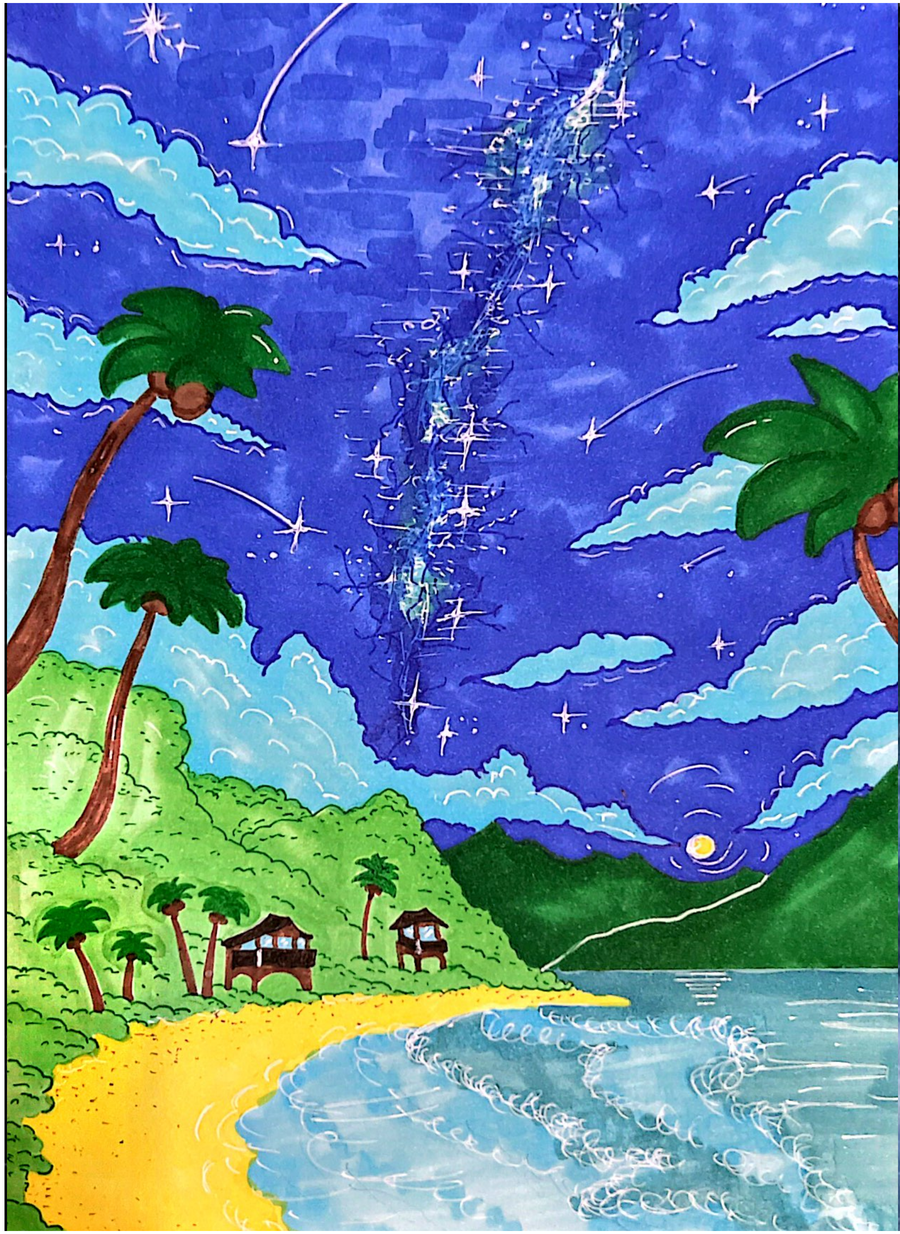
Field of Stellar Populations in a critical moment

(i) the emergence of a huge data set of detailed chemistry, ages, and precision kinematics for millions of stars supplied by the Gaia satellite and ground-based spectroscopic surveys, enabled by improvements on model atmospheres, atomic and molecular line data, NLTE line formation, stellar ages, and automatic spectral analysis codes

(ii) the successful operation of JWST, which is delivering snapshots of various stages of galaxy evolution over a wide range of redshifts showing the very early settle of disks;

(iii) a new generation of cosmological numerical simulations yielding realistic predictions of the detailed properties of Milky Way-like galaxies.

Time for us to build build a holistic picture of galaxy formation and think on future instruments in the next decadeS.



Lets enjoy the time together!

Thank you!