Galactic Archaeology in the Gaia era

Cristina Chiappini

Lecture VI

AIP

XXV CCE at ON – Rio de Janeiro – Brazil
06-10 November 2023

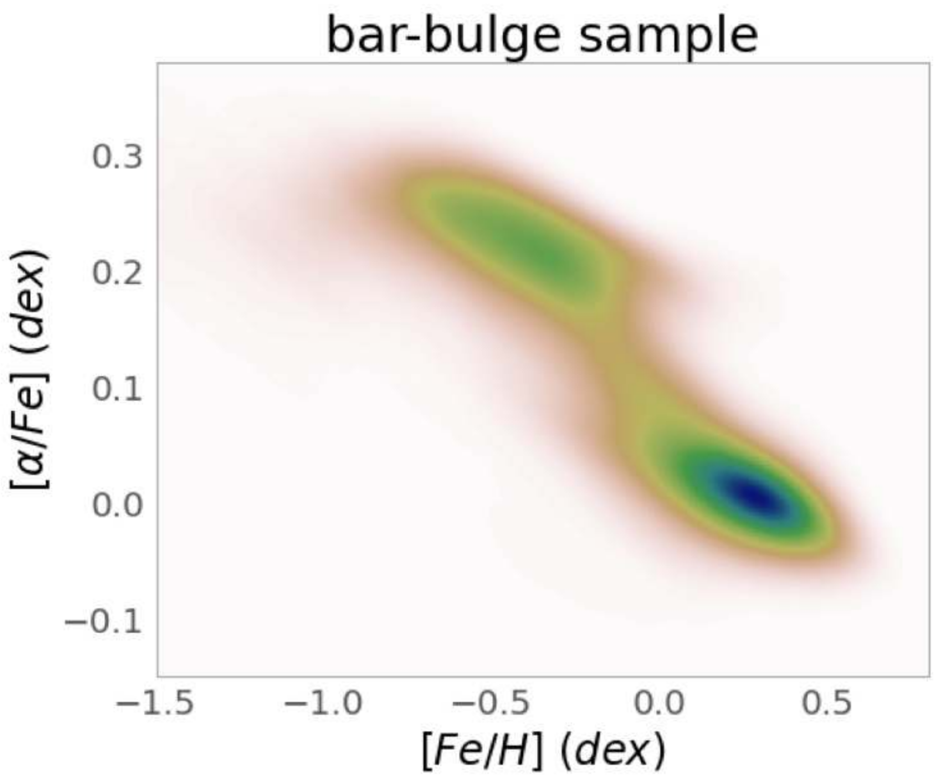
Galactic Archaeology in the Gaia era

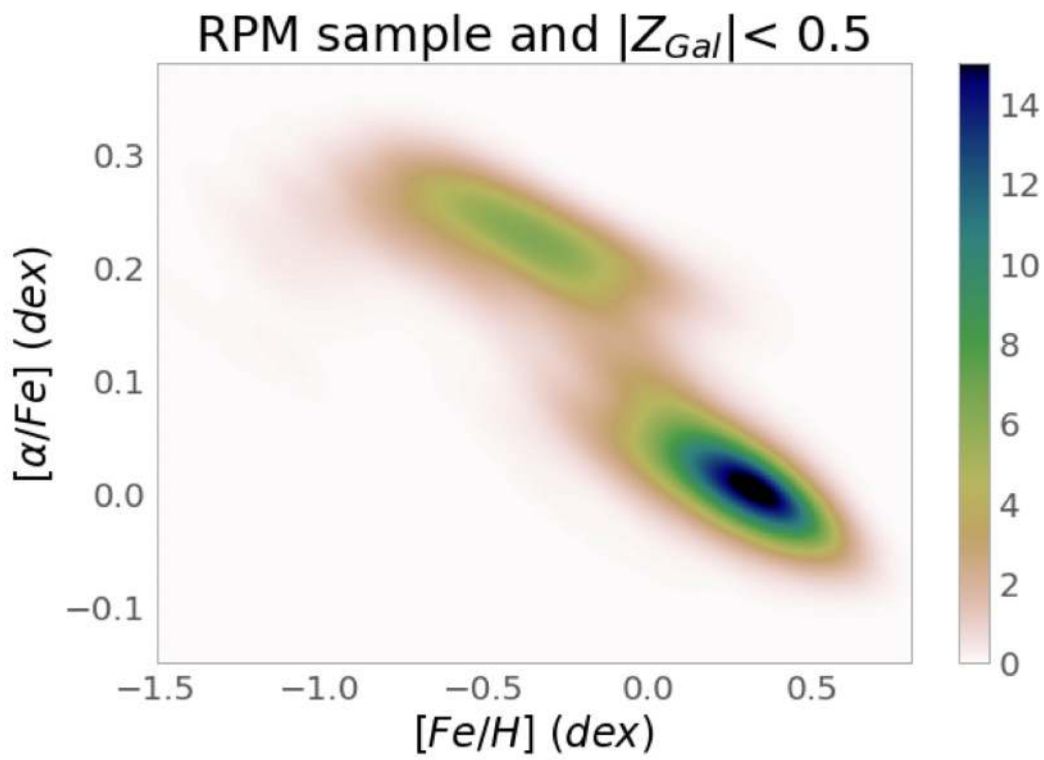
1. Mapping the Milky Way: Gaia, Spectroscopic Surveys and asteroseismology
2. The Galaxy is complex: finding debris and culprits of radial migration by combining ages, chemistry and kinematics
3. The galactic bulge I
4. The galactic bulge II and future outlook

Pushing APOGEE to the maximum – Bulge

26,500 stars

3,800 stars (around 8000 if relaxing Z)

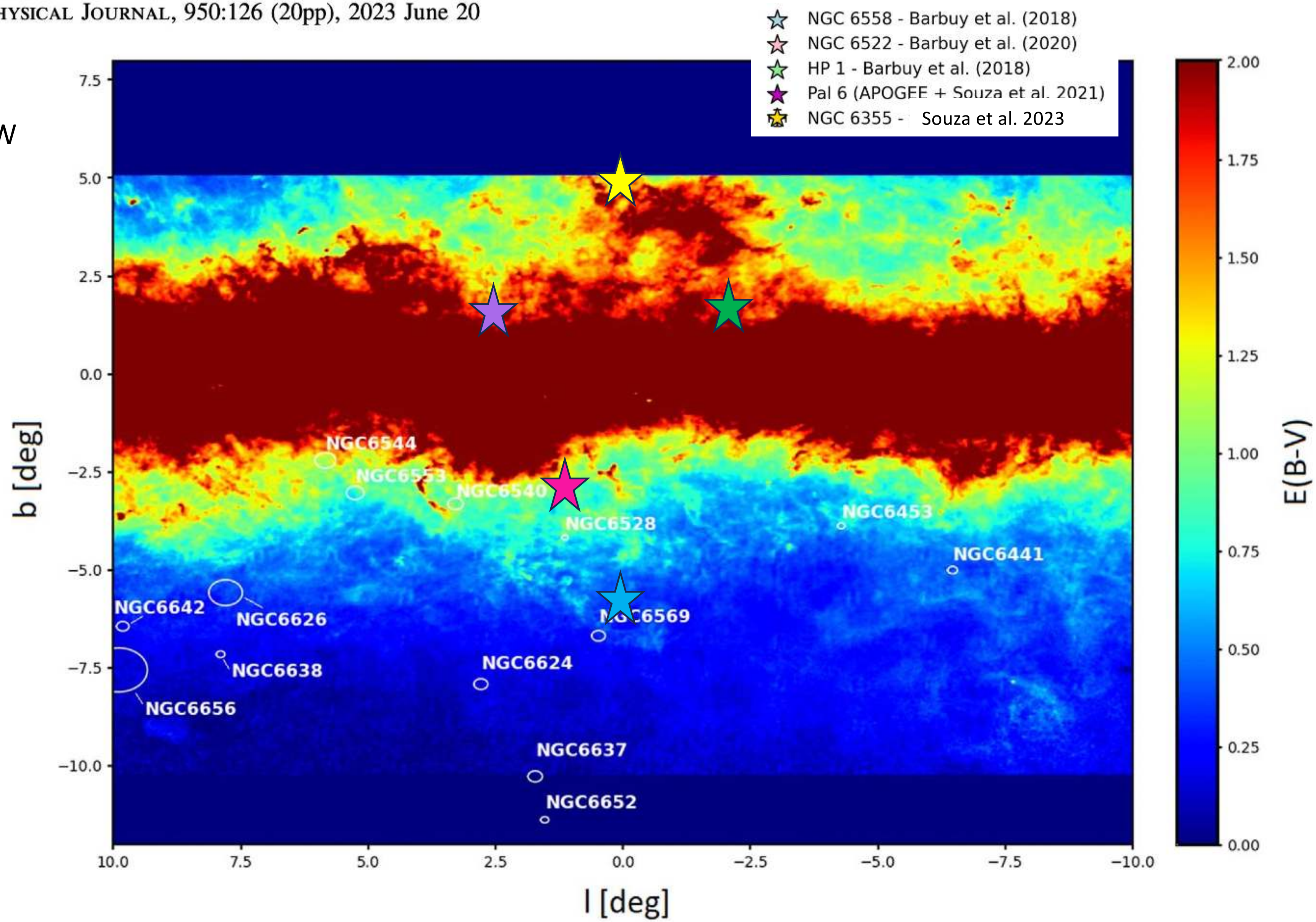




Queiroz, CC et al. 2021

Less foreground using EDR3 better proper motions + orbital analysis possible!

GCs view
Oldest MW



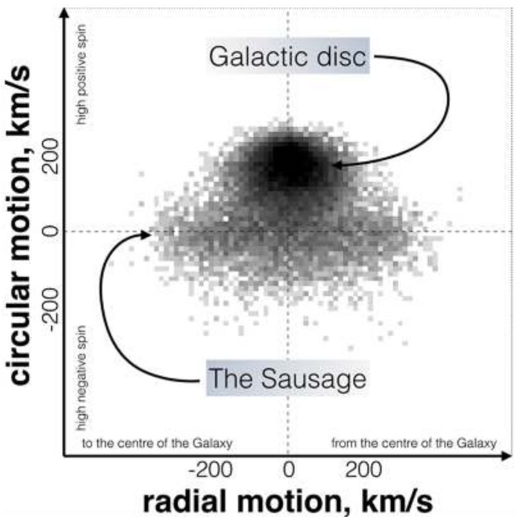
Are these GCs born in situ?

Small Detour

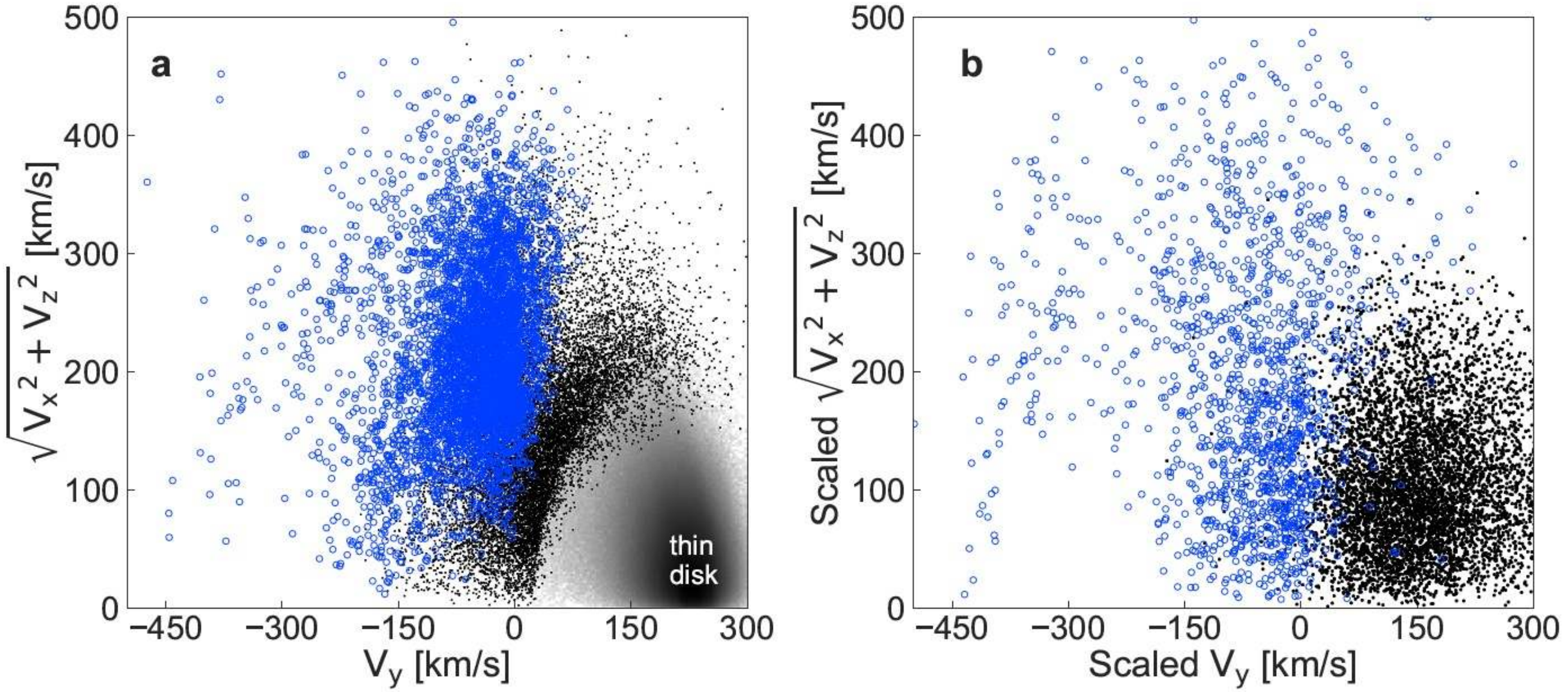
Many are the science enabled by such a large dataset, with 6-D (position + velocities) + n-D (chemistry) + age

Lots going on in the Halo but this lecture does not cover this part. See Helmi 2020 and references there in + Browse papers tha quote that paper ☺

Halo = Debris?
Past Accretion History



Belokurov et al. 2018



Helmi et al. 2018

Need distances + RVs + Chemistry + Ages

Halo (local) dominated by retrograde population remanescent of an impact with Gaia-Enceladus around 10 Gyr ago. Similar to simulation of large impact with MW like galaxy (20% mass ratio merger)

A lot of activity in this field thanks to Gaia + asteroseimology (ages)+ Spectroscopy - booming literature

Helmi 2020 review + Naidu et al 2020,2021 + Gallart et al. 2019 + Montalban et al. 2021 + Borre et al. 2022 + Limberg et al. 2021, 2022, Sestito et al. 2020,2021, Aguado et al. 2021, Perrotoni et al. 2022, Limberg et al. (2023), Balbinot et al. (2023), Dodd et al. (2023)

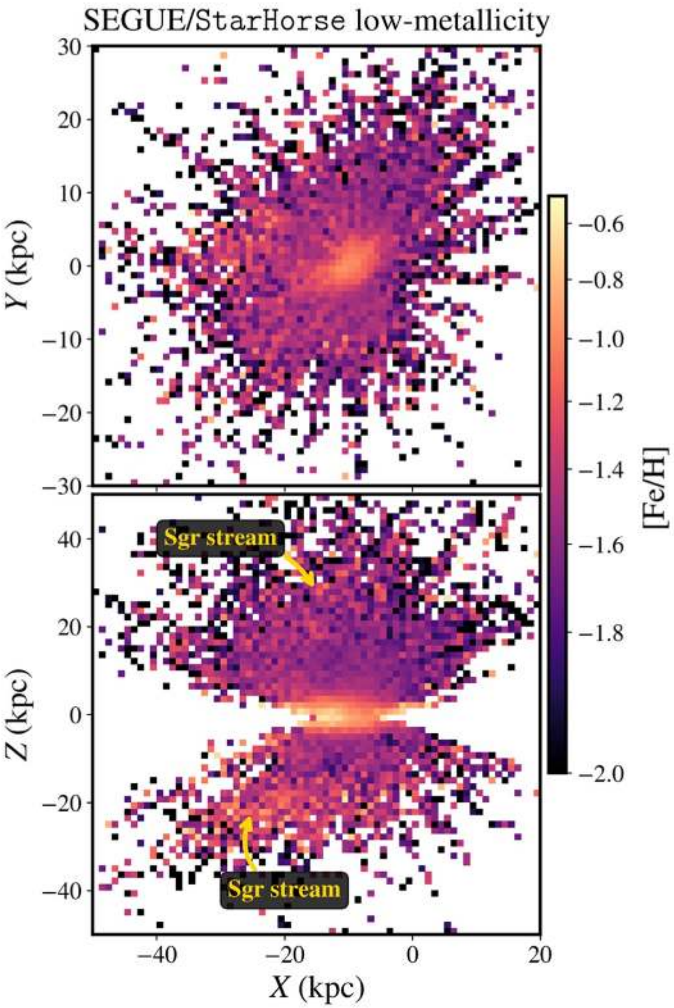


Figure 1. Cartesian Galactocentric projections of the SEGUE/StarHorse low-metallicity sample. Top: (X, Y). Bottom: (X, Z). Spatial bins are color coded by their mean [Fe/H] values. The attentive reader may notice the footprint of the Sgr stream as metal-rich trails at $|Z| \gtrsim 20$ kpc.

The Astrophysical Journal, 946:66 (15pp), 2023 April 1 https://doi.org/10.3847/1538-4357/acb694

Phase-space Properties and Chemistry of the Sagittarius Stellar Stream Down to the Extremely Metal-poor ([Fe/H] $\lesssim -3$) Regime

Guilherme Limberg[1,2,3], Anna B. A. Queiroz[4,5], Hélio D. Perottoni[1,6], Silvia Rossi[1], João A. S. Amarante[6,7,14], Rafael M. Santucci[8,9], Cristina Chiappini[4,10], Angeles Pérez-Villegas[11], and Young Sun Lee[12,13]
[1] Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Departamento de Astronomia, SP 05508-090, São Paulo, Brasil;

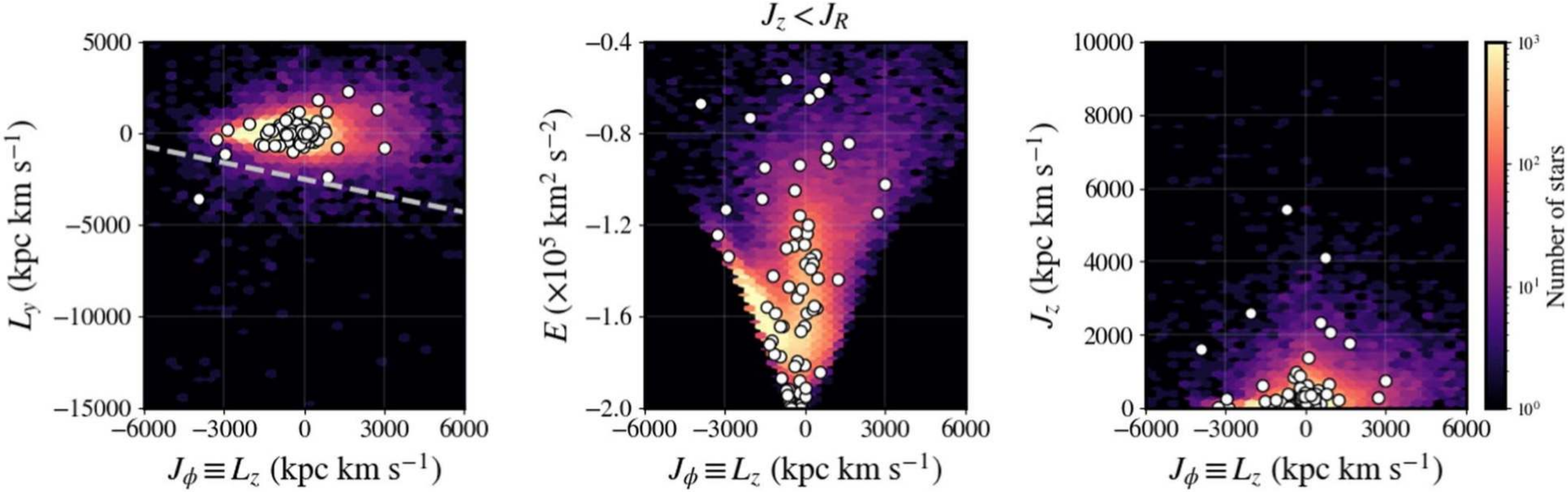
$$L_x = YV_z - ZV_y$$
$$L_y = ZV_x - XV_z$$
$$L_z = XV_y - YV_x,$$

$$L = \sqrt{L_x^2 + L_y^2 + L_z^2}.$$

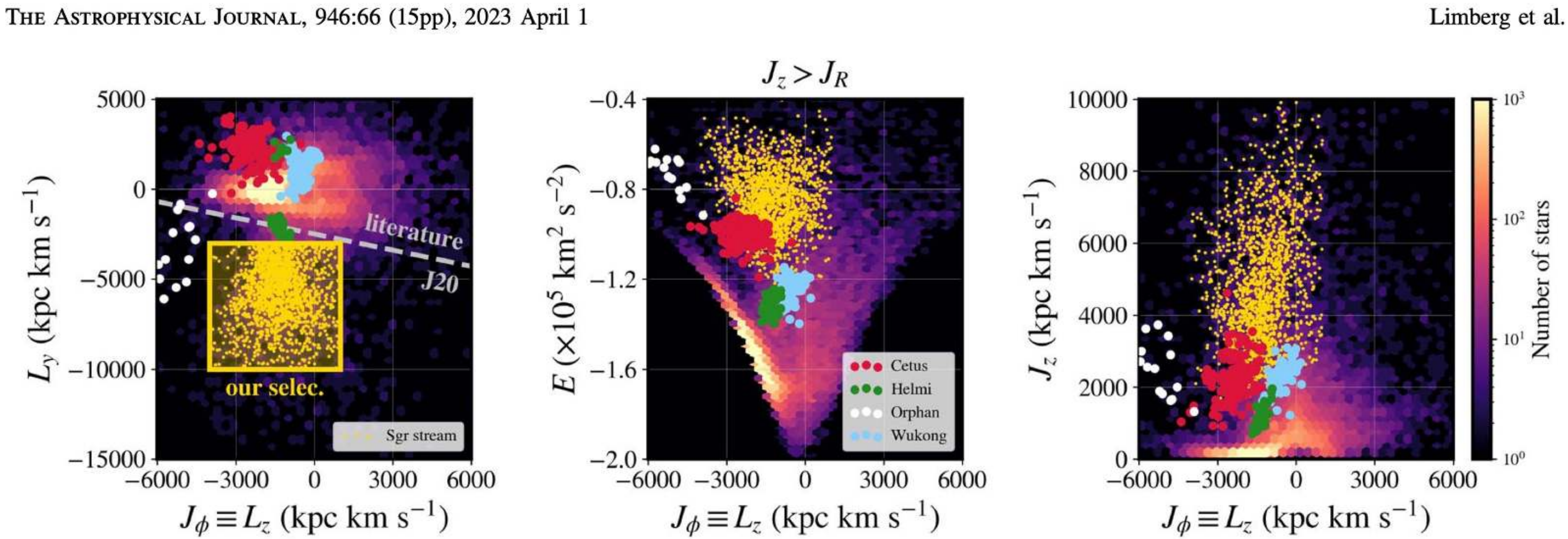
+

For the entire SEGUE/StarHorse low-metallicity sample, we also compute other dynamical parameters, such as orbital energy (E) and actions ($\boldsymbol{J} = (J_R, J_\phi, J_z)$ in cylindrical frame). The azimuthal action is equivalent to the vertical component of angular momentum ($J_\phi \equiv L_z$) and we use these nomenclatures interchangeably. In order to obtain these quantities, orbits are integrated for 10 Gyr forward with the AGAMA package

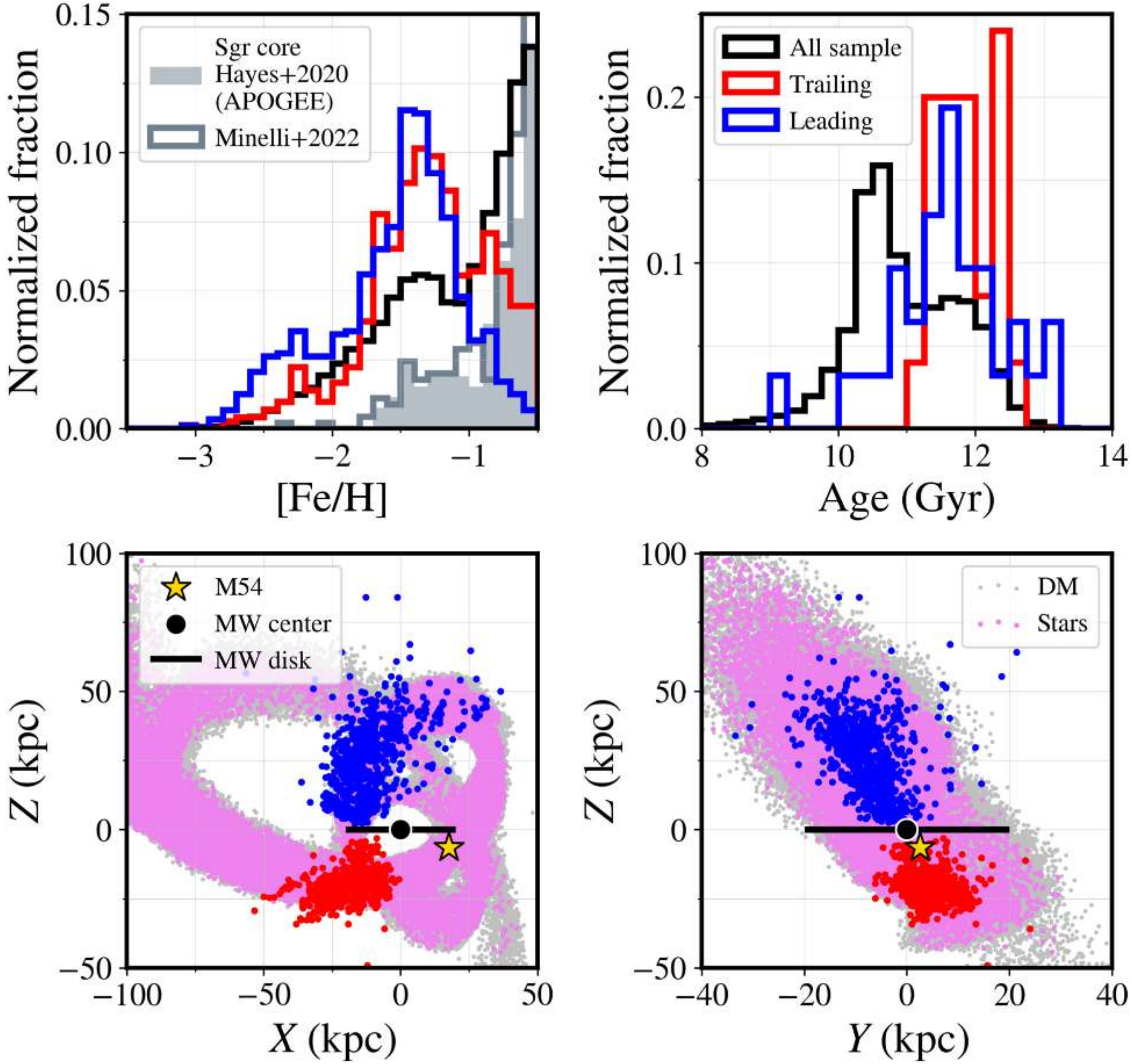
$J_z < J_R$ (predominantly radial orbits)



$J_z > J_R$ (predominantly polar orbits)



- SEGUE + Gaia + SH distances: Selection doubles number of known Sagitarius members at low metallicities
- ~1600 stream members, including >200 VMP star, 7 GCs
- Leading arm more metal-poor by 0.2 dex and older by 1 Gyr with respect to trailing arm. Gradient prior to disruption?


Sgr core
Hayes+2020
(APOGEE)
Minelli+2022
Normalized fraction
[Fe/H]
All sample
Trailing
Leading
Age (Gyr)
M54
MW center
MW disk
Z (kpc)
X (kpc)
DM
Stars
Y (kpc)

Many are the science enabled by such a large dataset, with 6-D (position + velocities) + n-D (chemistry) + age

- SEGUE + Gaia + SH distances: Selection doubles number of known Sagitarius members at low metallicities
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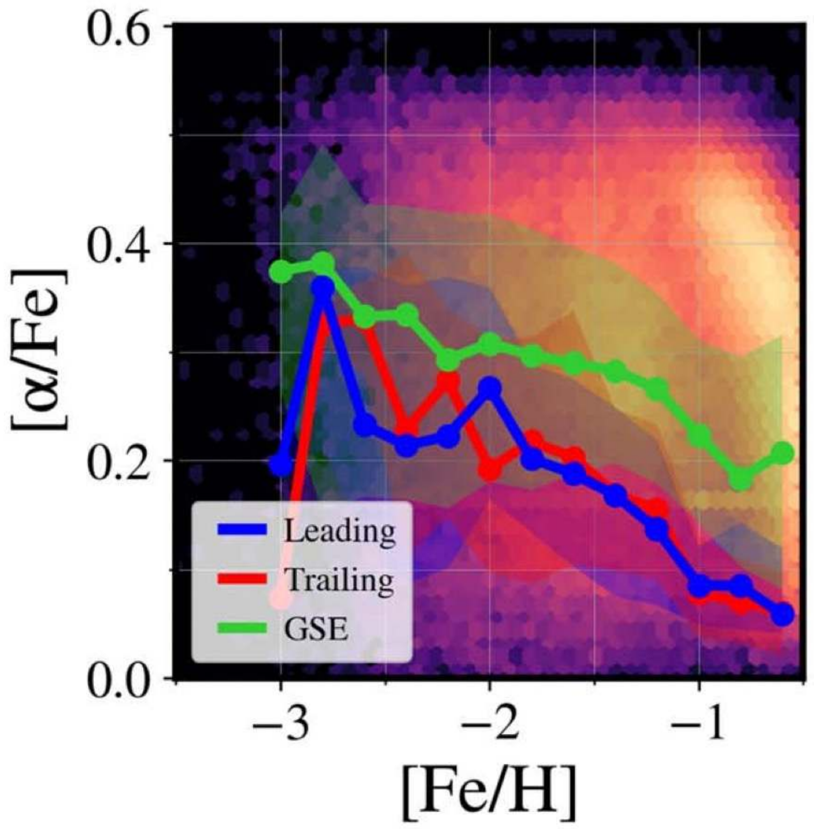


- We provide the first age estimates for individual stars in the Sgr stream thanks to a a subsample of 56 turnoff/subgiant stars in this substructure.
- Overall median age of 11.7+0.3 Gyr - similar to thick disk age (maybe older)
- We confidently (>3σ) identify CEMP stars in the Sgr stream.

End Detour

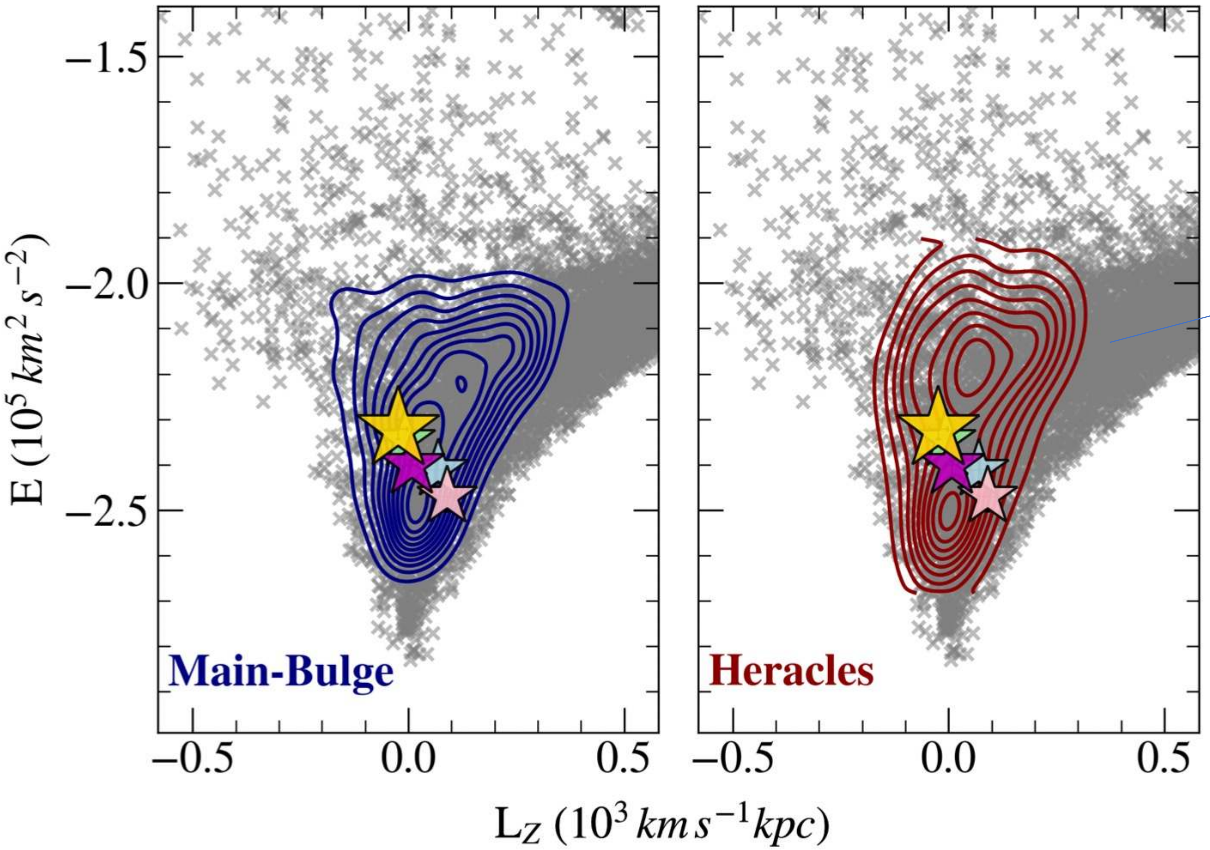
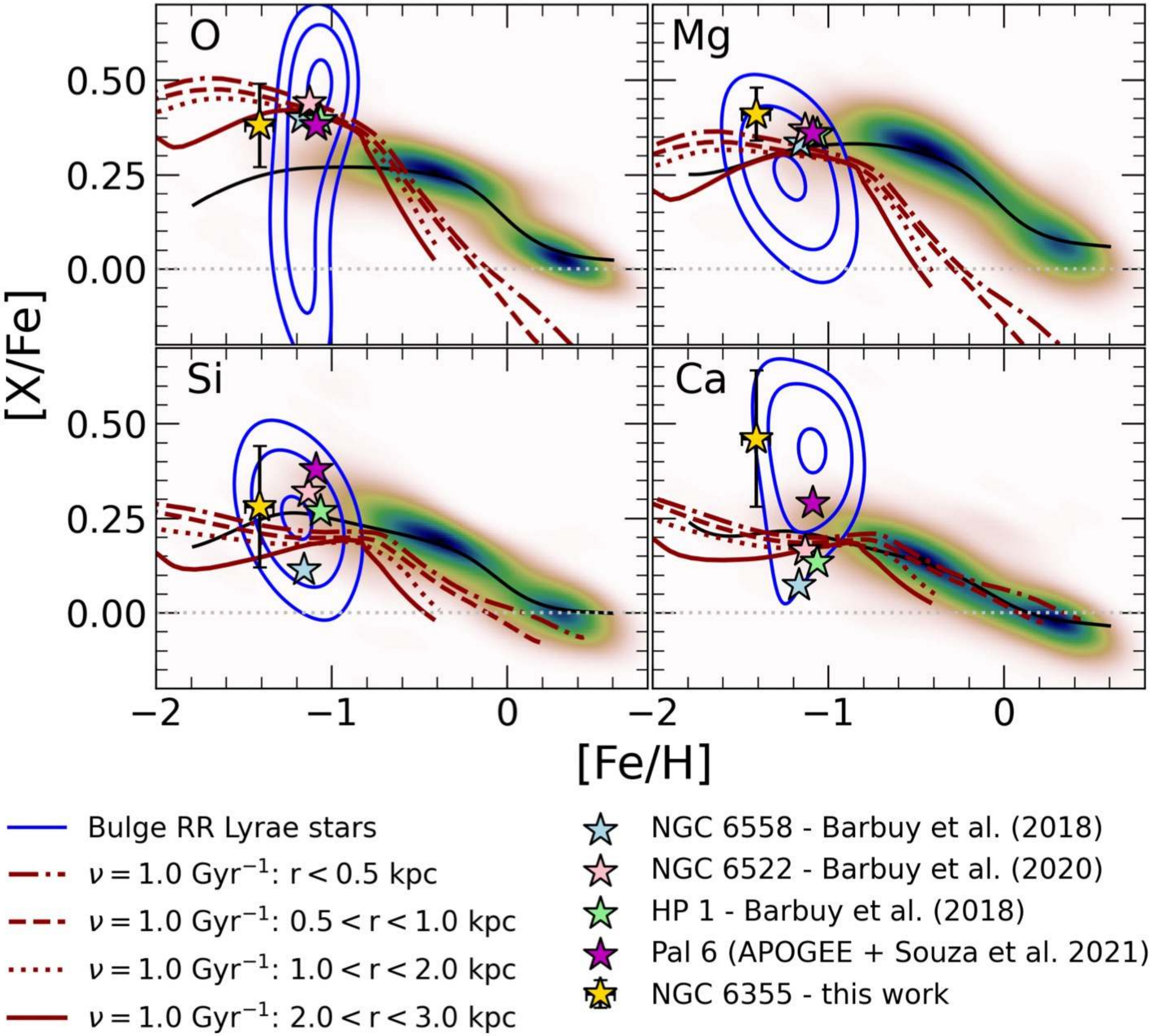


Fig. 26. IOM space for the bulge stars selected by Horta et al. (2021). The left panel shows the contours for the main-bulge progenitor stars. The right panel shows the contours of the Heracles progenitor. The stars are coulored as in Fig. 19.

Too old, phase-space mixed

Difficult to disentangle accreted events from in situ stars at low Energies – Need Chemistry + AGE



Souza et al. 2023

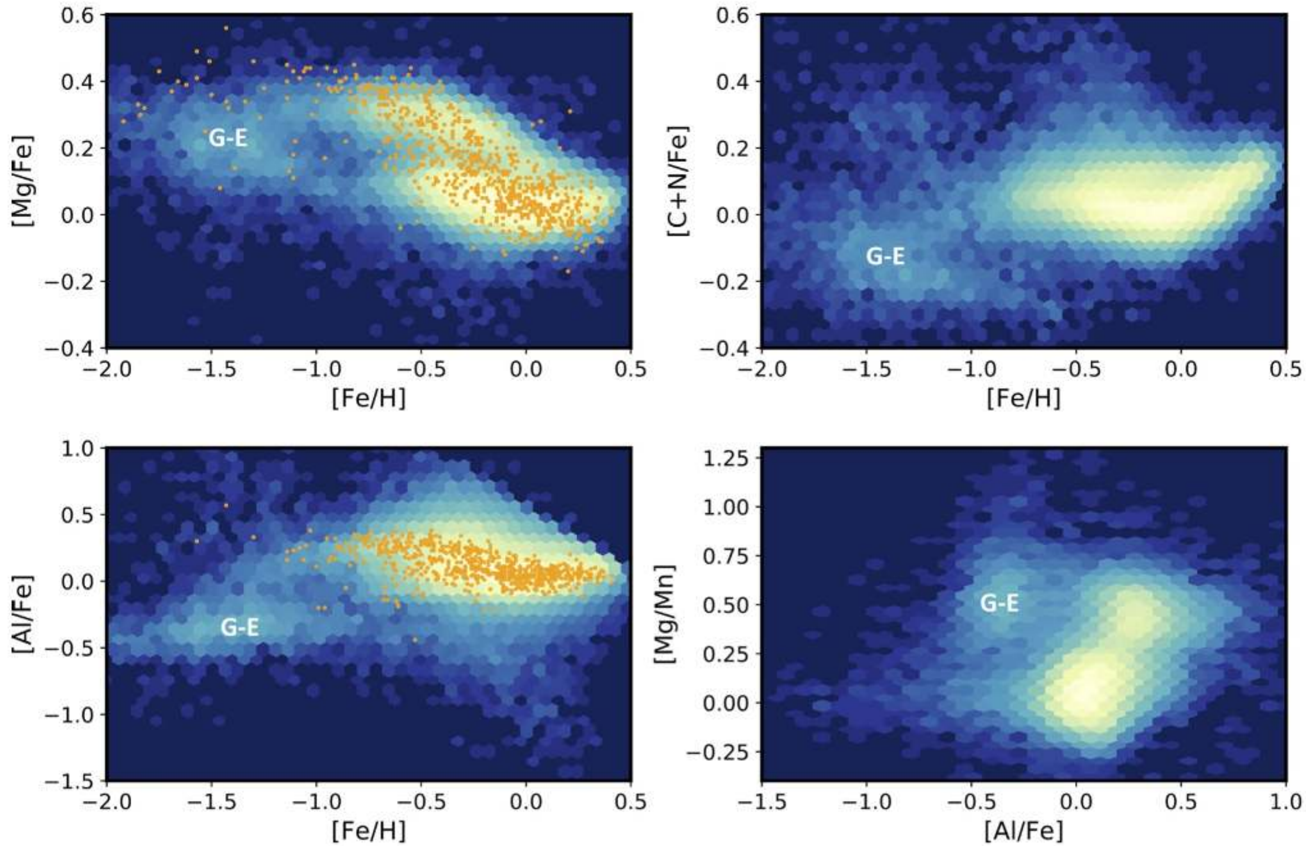
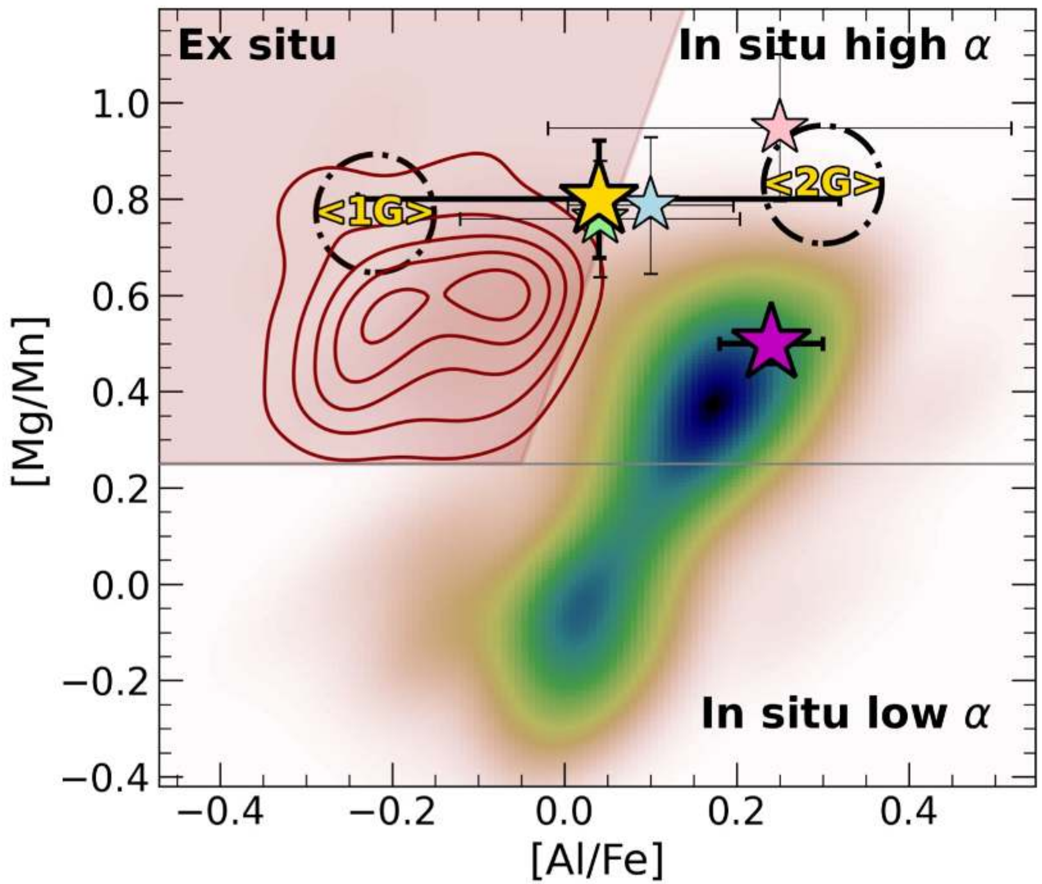


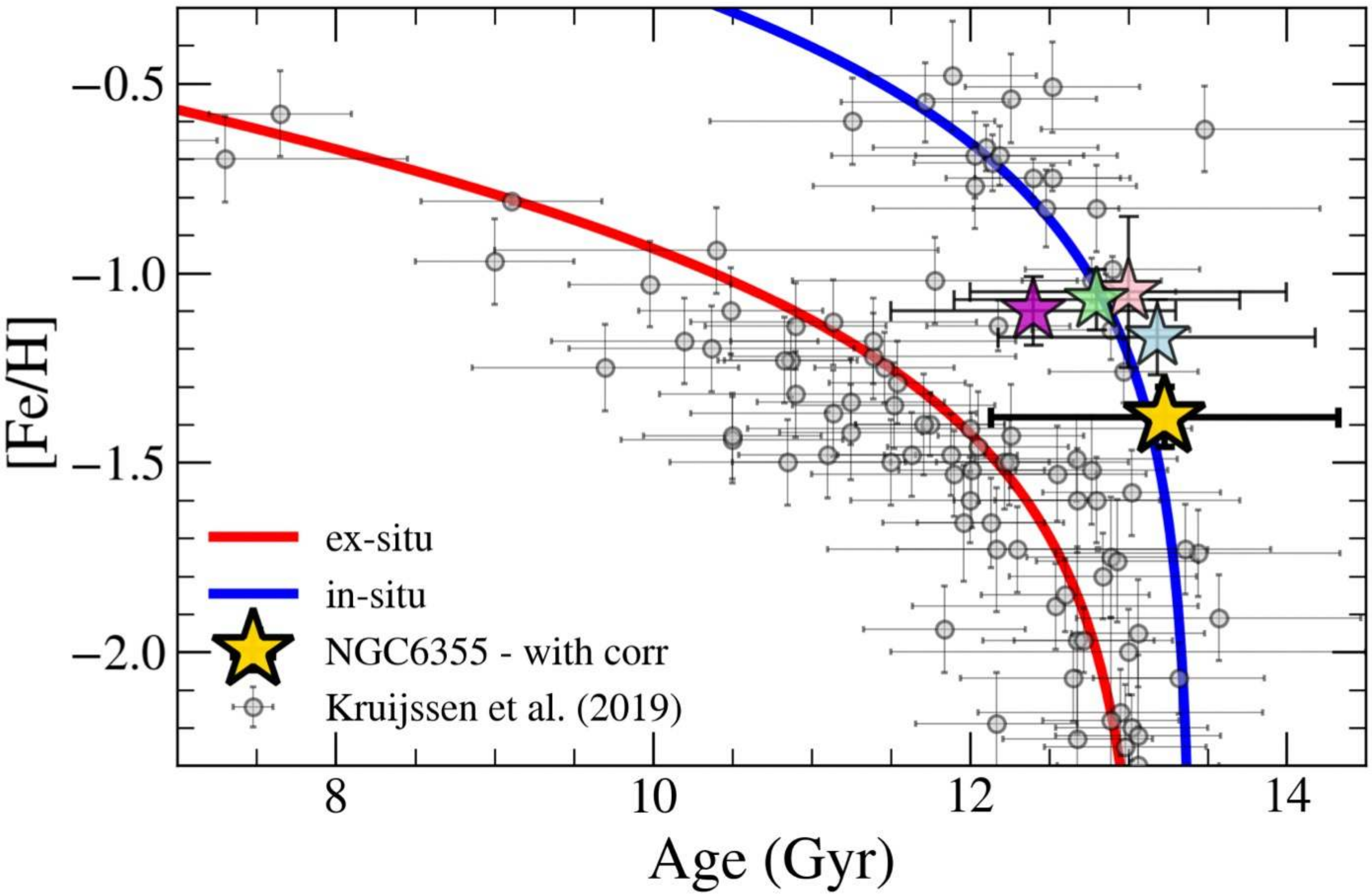
Figure 17

Two-dimensional abundance distribution of APOGEE DR14 stars in different chemical abundance planes. The filled orange circles correspond to kinematically-selected disk stars from Bensby et al. (2014). Note the presence of Gaia-Enceladus (marked as "G-E" in all panels), and its clear distinction from the thick disk, not only in [Mg/Fe] vs [Fe/H] but also in lighter elements such as [Al/Fe] and [C+N/Fe]. *Credits: Adapted from Das et al. (2020), their Fig. 3.*

Helmi 2020 ARAA

We found that two of the four stars are Al-depleted and N-normal, while the others are N- and Al-rich.
The detection of MPs was confirmed through the (anti-)correlations Al-N/Na (Mészáros et al. 2020), and Na-O (Carretta et al. 2009a).





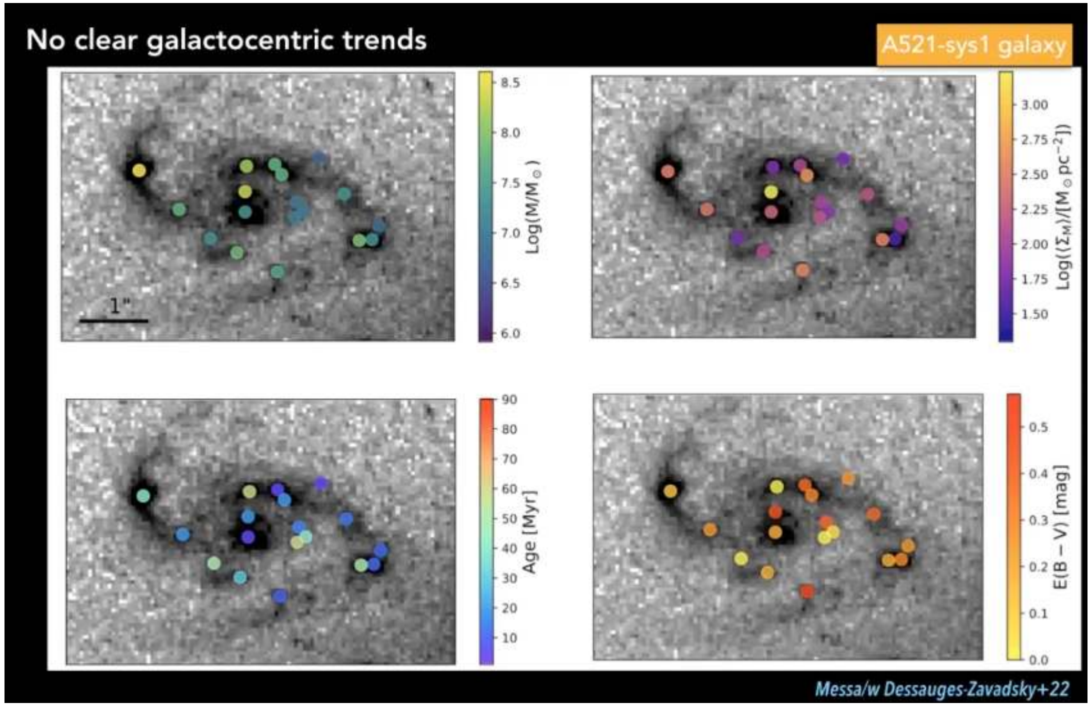
−0.5
−1.0
−1.5
−2.0
[Fe/H]
8
10
12
14
Age (Gyr)
ex-situ
in-situ
NGC6355 - with corr
Kruijssen et al. (2019)

Pristine building blocks burried in disk/debris

Oldest Bulge stars and non-tipical globular clusters

Where are the local counterparts of SF clumps seen at high redhifts? Are we seen burried past accretion events?

Star forming clumps at high-z (HDF+Lensing)



Why study them? Formed in situ – Very large SFEs

Typical masses – 10^7 Msun

Do clumps contribute to bulge growh?

Article

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

https://doi.org/10.1038/s41586-023-06028-1

Received: 13 December 2022

Qian-Fan Xing[1], Gang Zhao[1,2] ✉, Zheng-Wei Liu[2,3,4], Alexander Heger[5,6], Zhan-Wen Han[2,3,4], Wako Aoki[7,8], Yu-Qin Chen[1,2], Miho N. Ishigaki[7,8], Hai-Ning Li[1] & Jing-Kun Zhao[1]

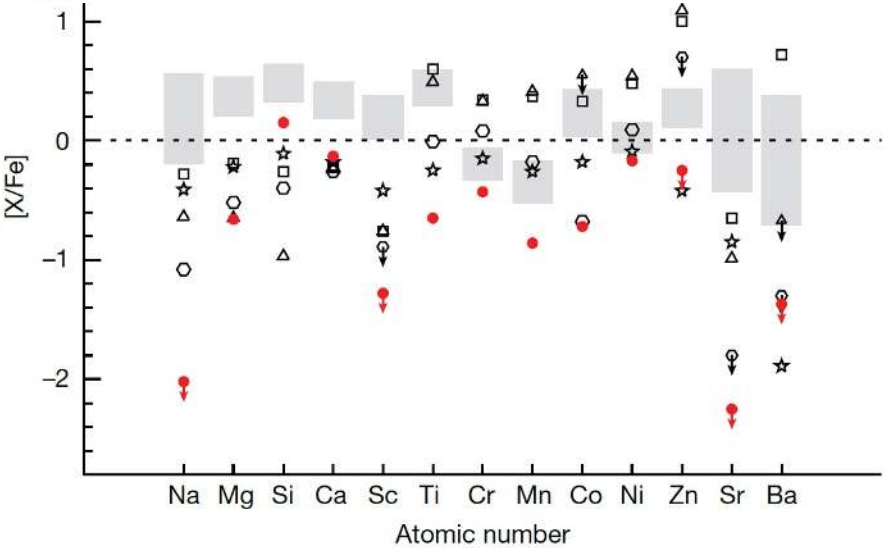
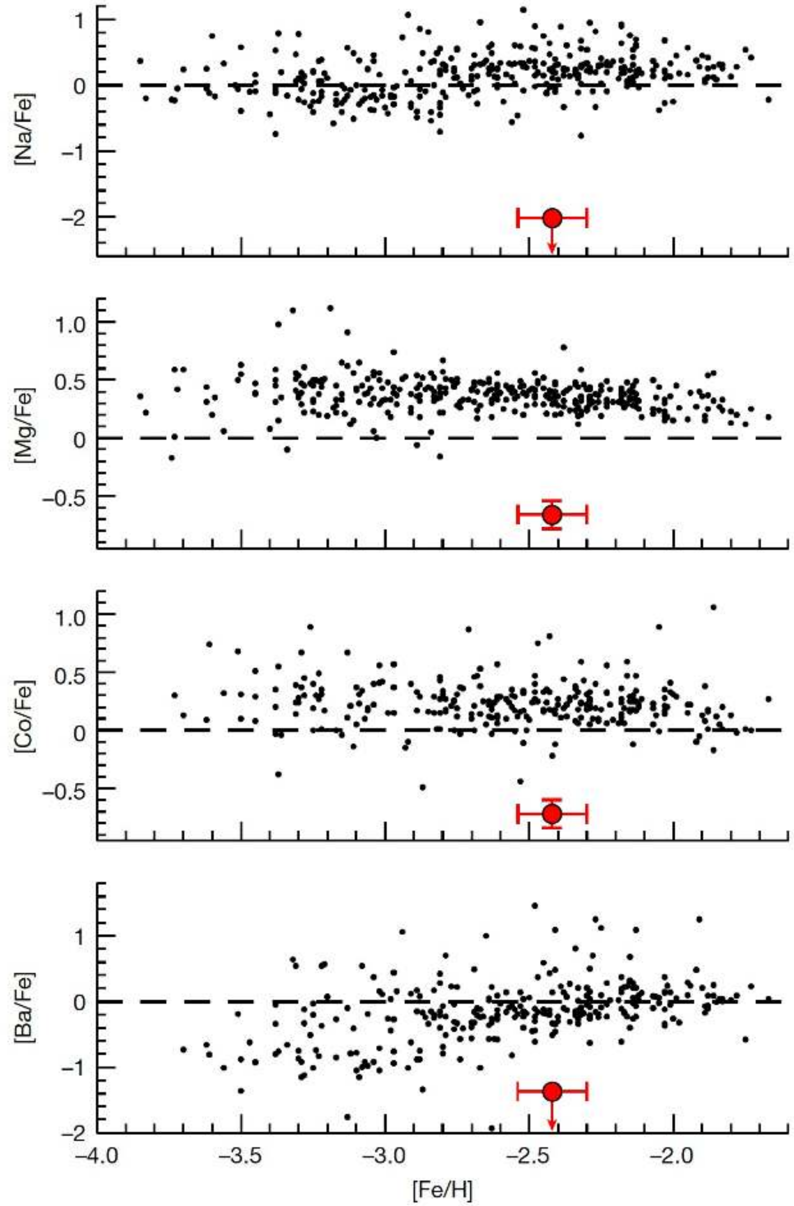


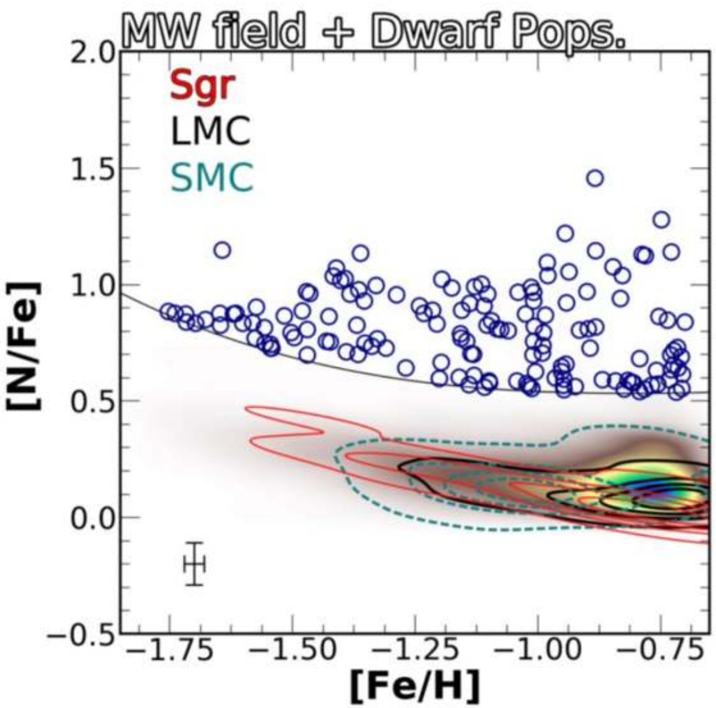
Fig. 2 | Abundance pattern of J1010+2358. The red circles denote J1010+2358. The open symbols indicate four previously known metal-poor stars with sub-solar [Mg/Fe] ratios. The abundances of these α-poor metal-poor stars ($-2.46 \leq$ [Fe/H] ≤ -1.91) have been well studied on the basis of high-resolution spectroscopic analysis[15,16]. The shaded regions indicate abundances of other metal-poor stars from the literature[10,11]. The arrows represent the upper limits.



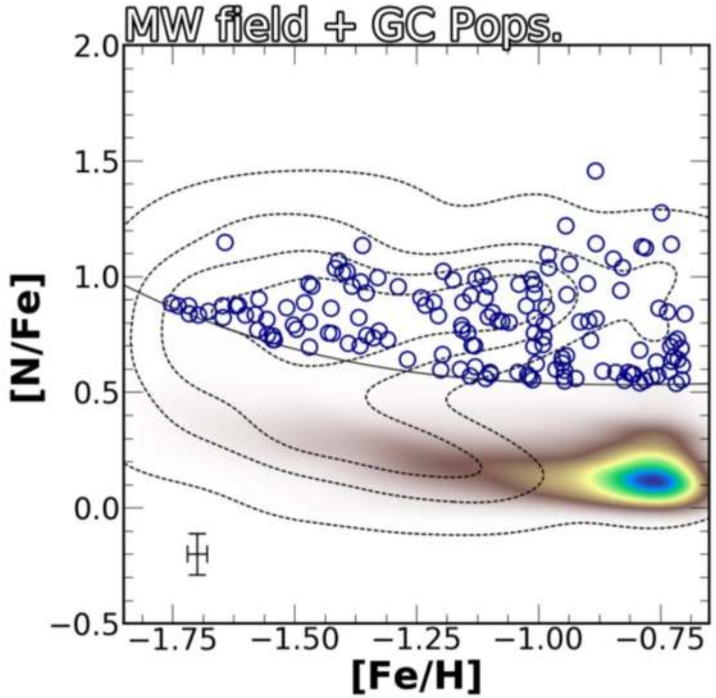
Caveats: Rare populations with especial chemical signatures

(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

A&A 673, A123 (2023)
https://doi.org/10.1051/0004-6361/202346048

Astronomy & Astrophysics

NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-020-17649-9

Unveiling the chemical fingerprint of phosphorus-rich stars

I. In the infrared region of APOGEE-2*

Maren Brauner[1,2], Thomas Masseron[1,2], Domingo A. García-Hernández[1,2], Marco Pignatar
Kate A. Womack[5], Maria Lugaro[3,4,7,8], and Christian R. Hayes[9]

ele-
s a
pri-
de-

Discovery of P-rich & moderate metal-poor (1/10th solar iron) & correlation with Si/Fe (H-Band)

Strong overabundance in the α-element Si but normal Ca and S abundances!

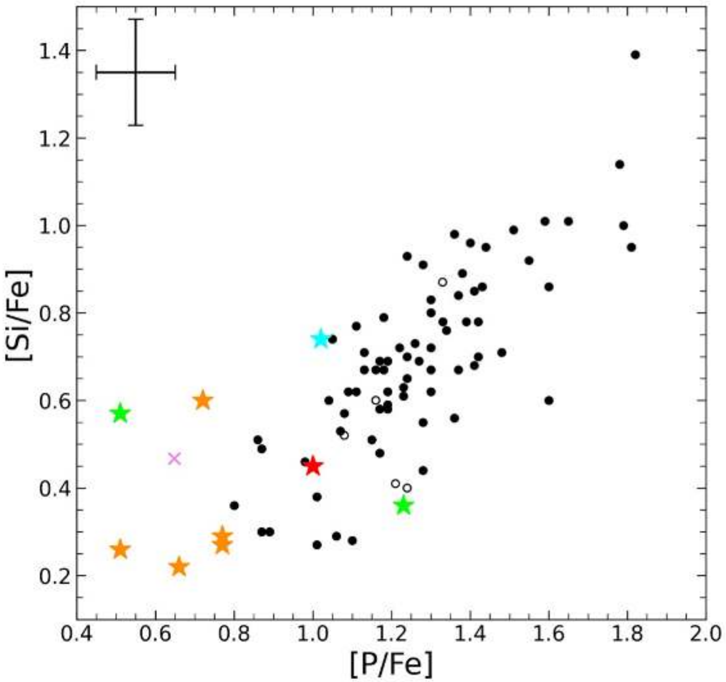
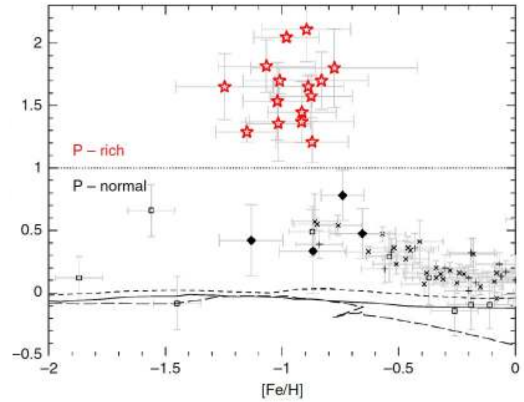


Fig. 3. Abundances in the [Si/Fe] vs. [P/Fe] plane. The symbols are the same as in Fig. 2. The error bar represents the typical standard deviation of the elements listed in Table D.2. No background stars are displayed because the reliability of the P abundances obtained by the automatic calculation is limited (see Appendix C for further justifications).



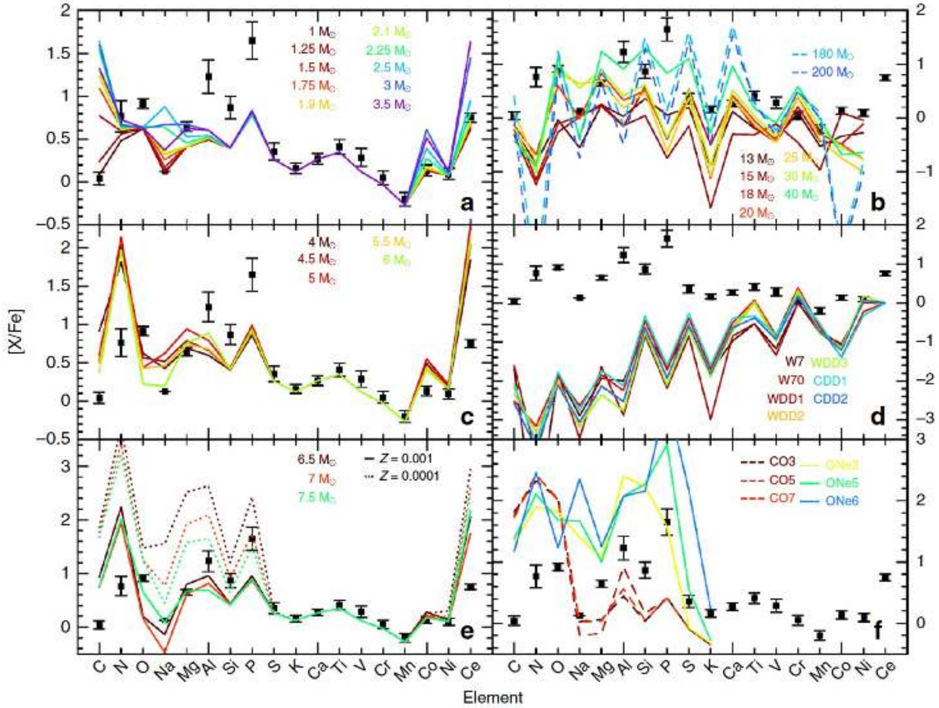


Fig. 6 P-rich stars versus nucleosynthesis predictions. Median chemical abundance pattern of the P-rich stars (black squares) against the several moc prediction patterns (colored lines), where [X/Fe]=log10(n(X)/n(Fe))-log10(n(X)/n(Fe))$_{\odot}$. Error bars show the star-to-star abundance rms scatter. **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 speci 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$_{\odot}$.

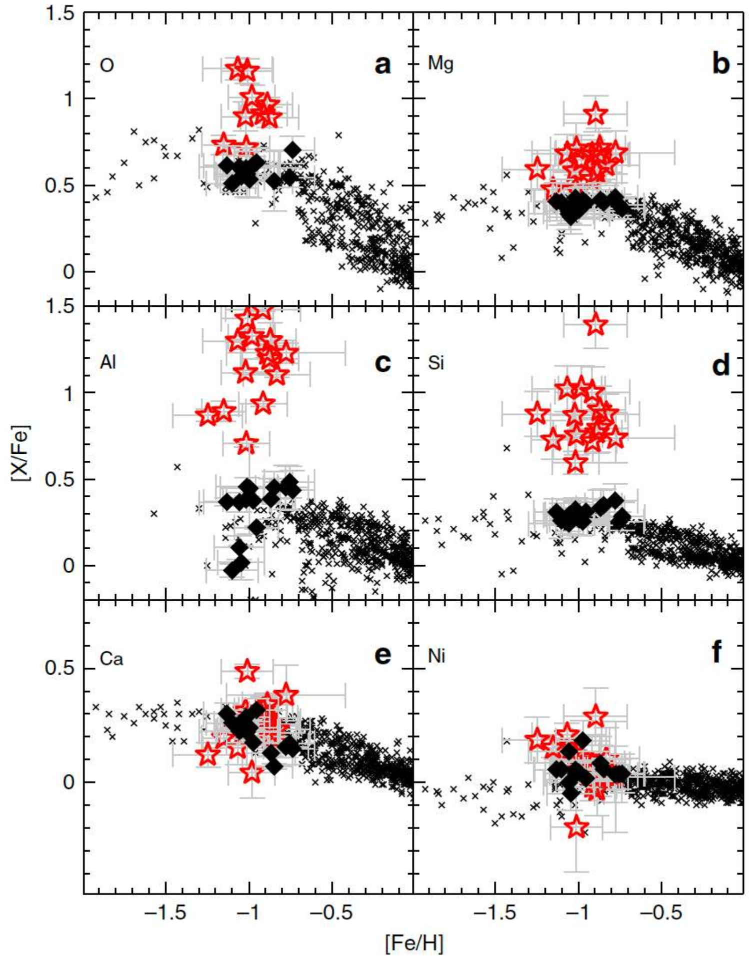


Fig. 9 Elemental abundances as a function of metallicity. a Oxygen, **b** magnesium, **c** aluminum, **d** silicon, **e** calcium, **f** nickel. The red stars and black diamonds show the P-rich and P-normal stars, respectively, while the black crosses correspond to the optical literature values for field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

Main Challenges

Many more statistically significant *rare* samples, with age, velocities and positions information, even in previously almost unexplored regions of the MW

- Need for (new)stellar models beyond standard cases – able to test not only yields but their dependency with other parameters
- Test timescales for different scenarios of Type-Ia, neutron-star mergers…
- Extract abundances and stellar parameters from huge datasets
- We are seeing stars born far away but that are now here

Need for investments in Stellar Evolution Theory + Dealing with advanced methods (ML?) to address large datasets

Where next?

4MIDABLE-LR

Science Motivation in one sentence: **Gaia spectroscopic follow-up of disk & bulge**
Preparing to take off from the local volume and expand **chrono-chemo-kinematic maps**

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

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]

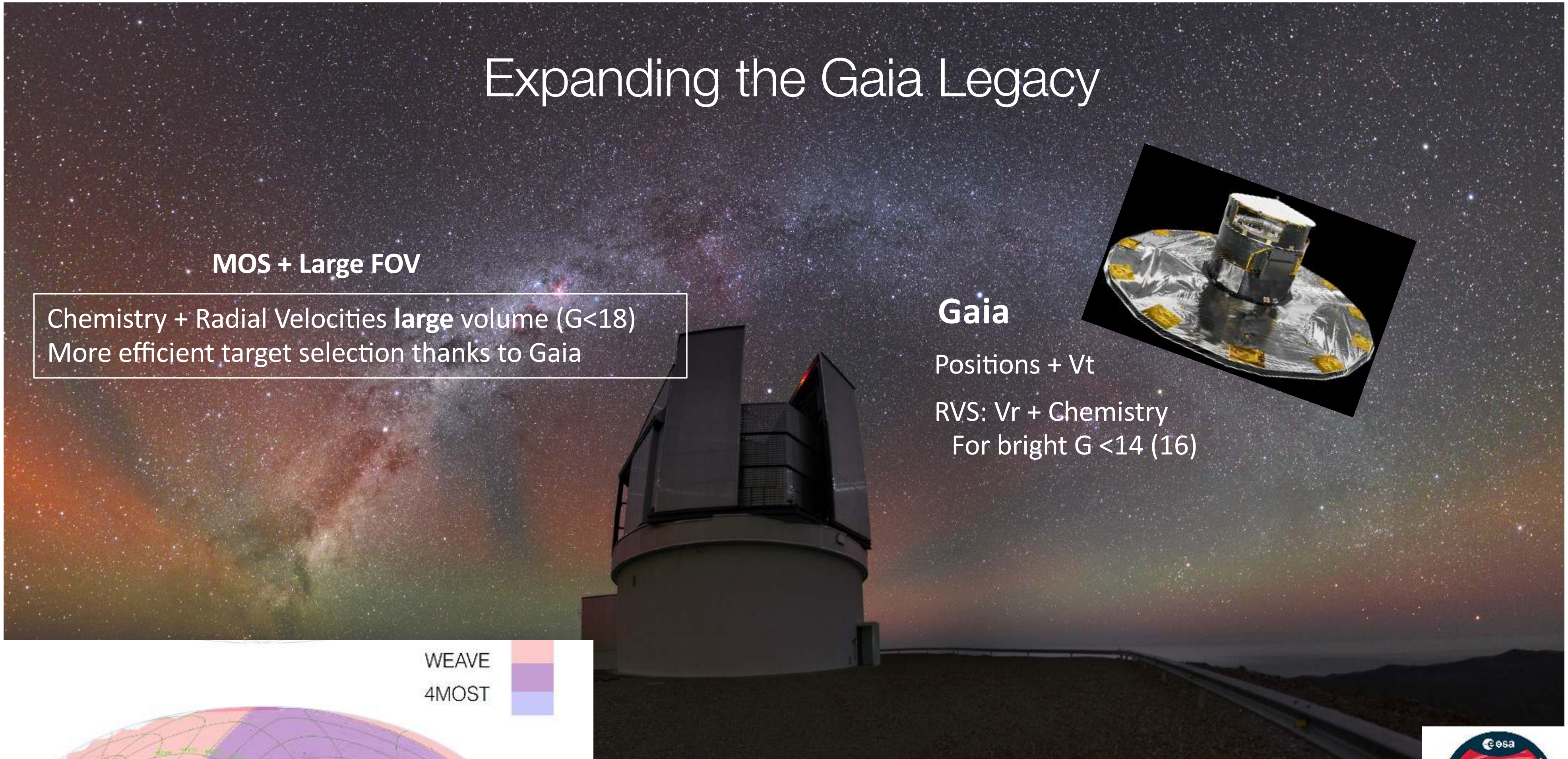
Discoveries still focused on small volume/bright/low extinction

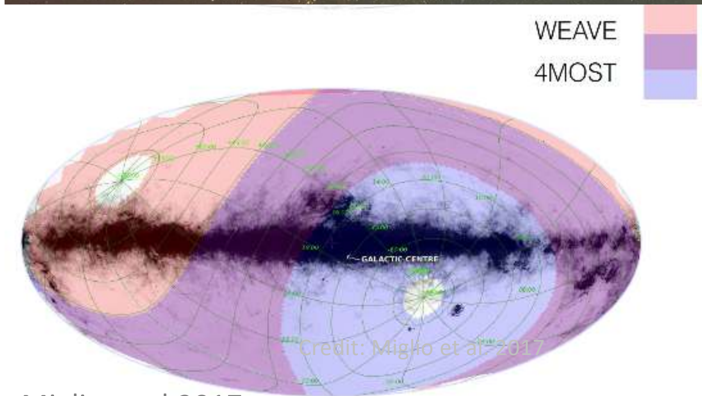
Gaia Enceladus

Helmi et al. 2018 with Gaia DR2 **+ APOGEE**
Belokurov et al. 2018, Gallart et al. 2019, Montalban et al. 2021

Explore the Gaia/ground synergies in the domain of Galactic Science and make recommendations: asteroseismology (PLATO) + massive multiplex spectrographs (4MOST, WEAVE, MOONS)

Expanding the Gaia Legacy

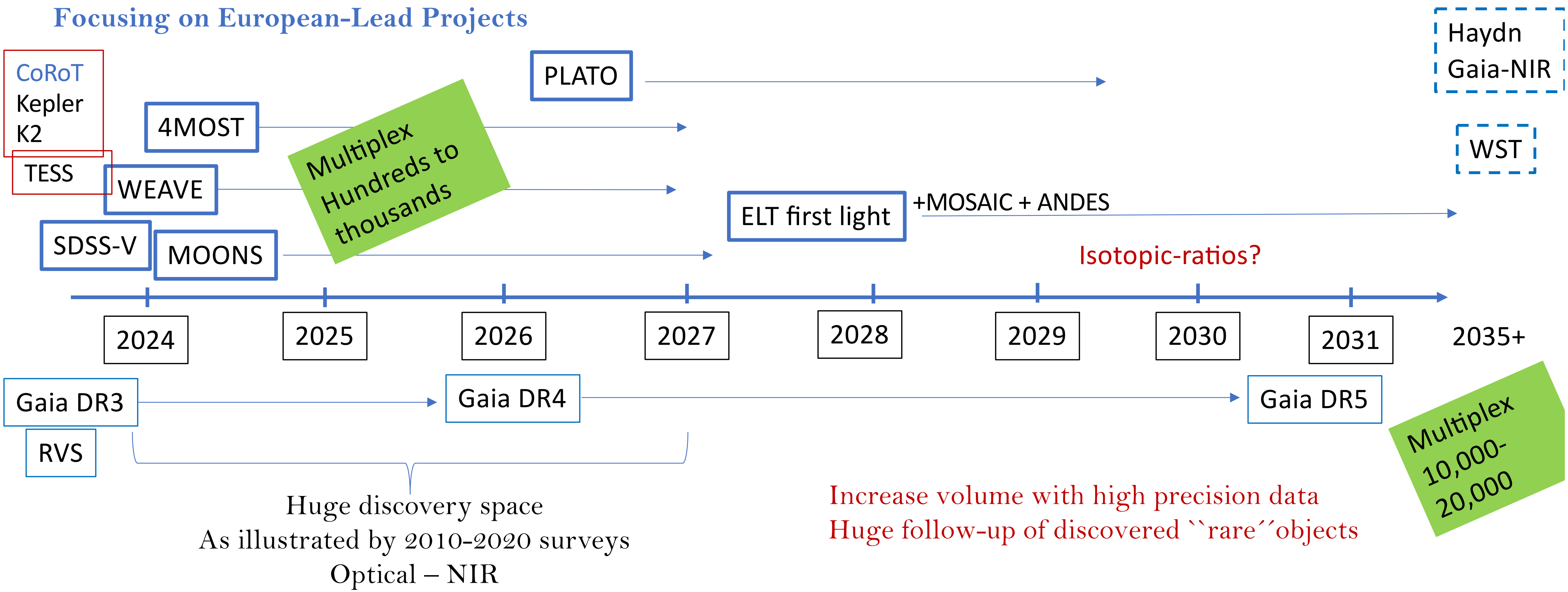




Miglio et al.2017

Timescales 2024 to 2030-2031

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



SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

3 Potential Scientific Themes for Medium Missions

3.1.8 High Precision Asteroseismology

Asteroseismology is one of the most powerful tools for probing the structure of stars. It uses the variability of the light from the star produced by its pulsation modes to constrain the interiors of stars. Its final aim is to determine the physical properties and the internal structure of stars, such as how temperature, pressure, density, speed of sound, and chemical composition vary with radius. In the last decade, the research field of asteroseismology has experienced a revolution with the operation of several space missions whose main aim has been the detection of exoplanets, for example *Kepler*.

A Medium mission designed to carry out pure asteroseismology would characterise stars in a wider range of (relatively homogeneous) stellar environments such as dwarf galaxies or the Galactic bulge, as well as Red Giant Branch stars that are relatively close to the Sun. Such missions would provide key information on stellar physics that would allow testing of stellar evolution models, especially when 2-D and 3-D modelling become widely implemented. Furthermore, and in combination with *Gaia* and large ground-based spectroscopic surveys, they would provide new insights into the star formation history and different phases of the assembly of the Milky Way.

HAYDN

High-precision AsteroseismologY of DeNse stellar fields

Andrea Miglio, Léo Girardi, Frank Grundahl, Benoit Mosser, Nate Bastian, Angela Bragaglia, Karsten Brogaard, Gaël Buldgen, William Chantereau, William Chaplin, Cristina Chiappini, Marc-Antoine Dupret, Patrick Eggenberger, Mark Gieles, Robert Izzard, Daisuke Kawata, Christoffer Karoff, Nadège Lagarde, Ted Mackereth, Demetrio Magrin, Georges Meynet, Eric Michel, Josefina Montalbán, Valerio Nascimbeni, Arlette Noels, Giampaolo Piotto, Roberto Ragazzoni, Igor Soszyński, Eline Tolstoy, Silvia Toonen, Amaury Triaud & Fiorenzo Vincenzo

— Show fewer authors

High-precision AsteroseismologY in DeNse stellar fields

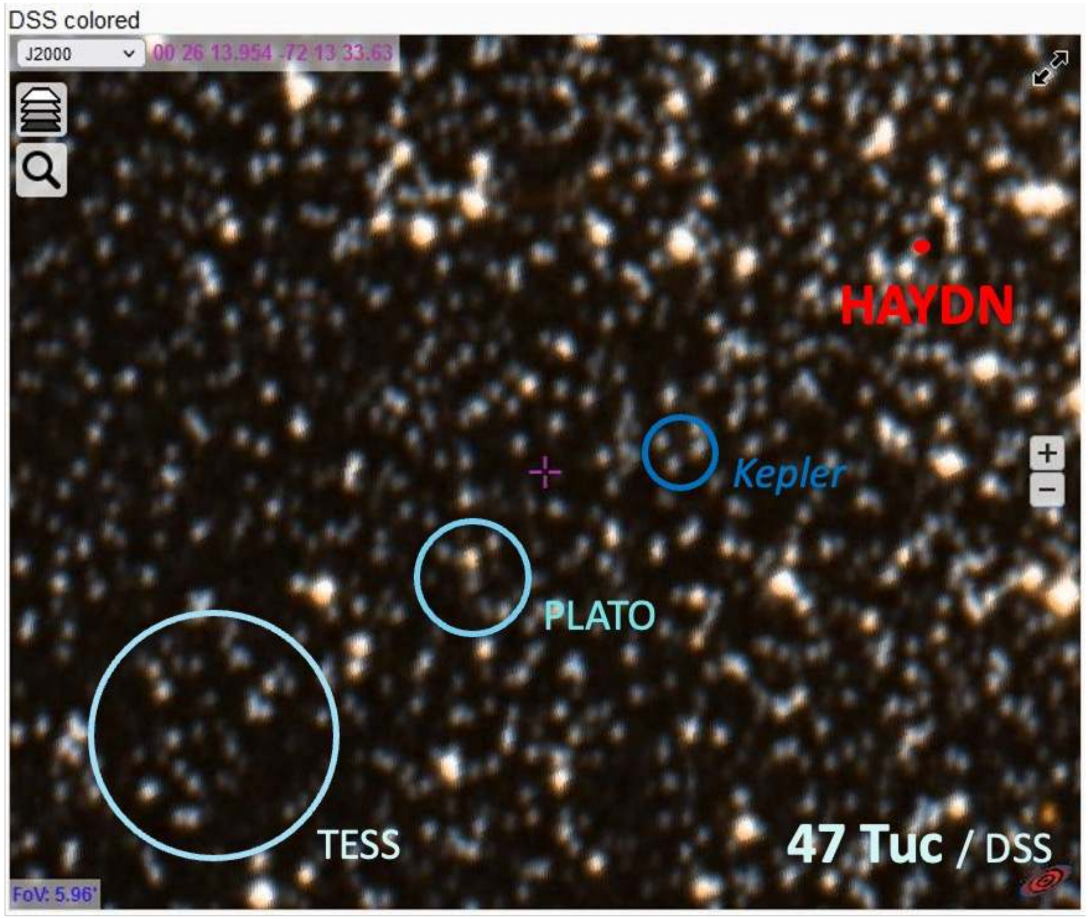
An ESA Voyage 2050 long-term plan proposal, HAYDN is a small/medium class space mission, which will improve our understanding of stellar astrophysics and the evolution of clusters, and elucidate the origins of the Milky Way bulge and nearby dwarf galaxies.

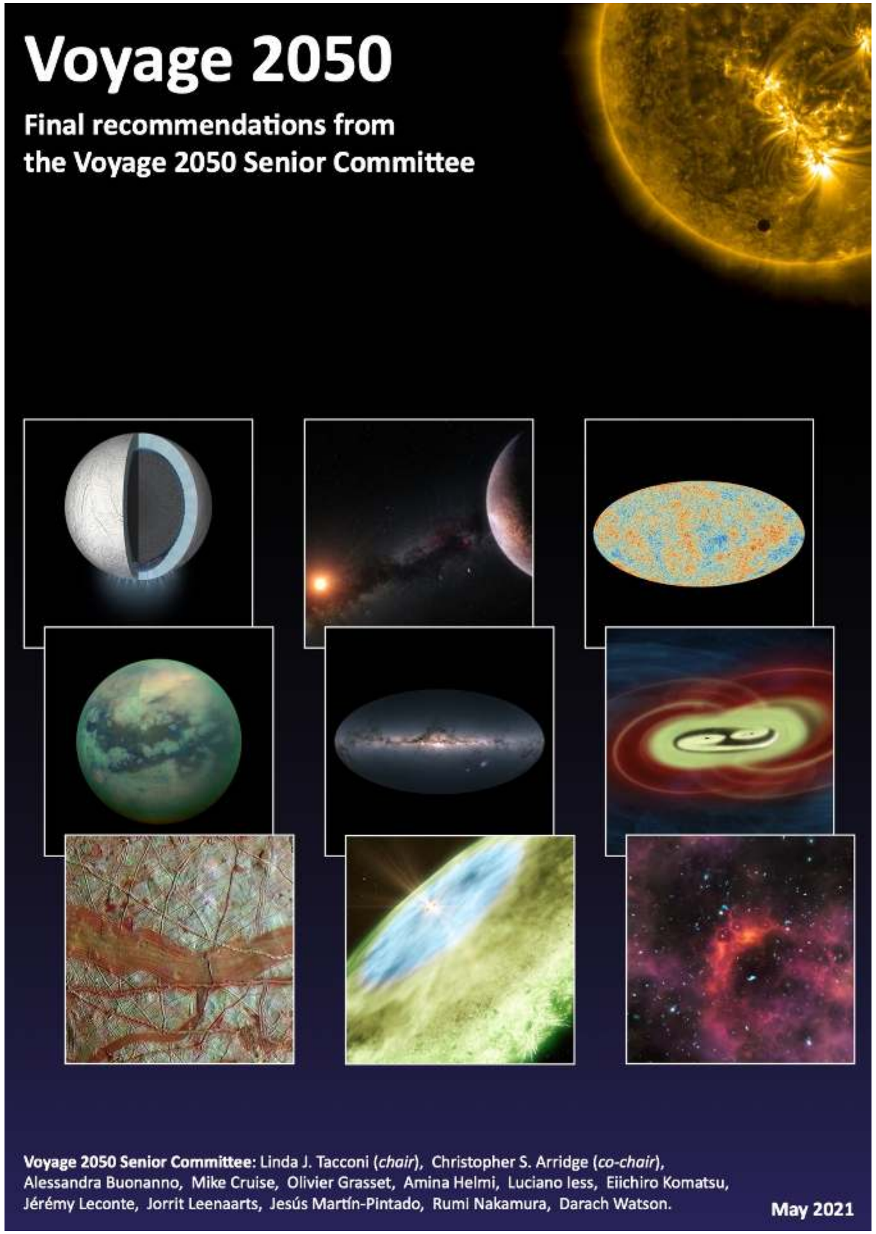
http://www.asterochronometry.eu/haydn/

H A Y D N

HAYDN benefits from the heritage of CoRoT, Eddington, PLATO, but with a PSF designed for the observation of dense stellar fields

Mission	PSF (arcsec)
CoRoT (seismo)	914
TESS	84
Kepler	21
PLATO	37
HAYDN	1.3





ESA call for proposals
Dec 2021

← Haydn Phase 1 proposal Feb 2022

← Haydn Phase 2 proposal July 2022

Selected for M7 further study
Nov 2022

UPDATE ON THE F2 AND M7 MISSION OPPORTUNITY

8 November 2022

At its November meeting, the Science Programme Committee (SPC) has selected ARRAKIHS as the mission candidate for the F2 mission opportunity, and has been informed that the following missions have been selected for further study for the M7 mission opportunity: CALICO, HAYDN, M-MATISSE, Plasma Observatory, and THESEUS.

Concurrent Design Facility ESA
8 sessions April/May 2023
Haydn

← Haydn cdf report 7/6 deadline
Workshop 14th/15th June

Review M7 for Phase A
Setember/2023

← Haydn in Phase A? **NO**
Maybe November 2023

Launch to L2 2035

HAYDN science and payload workshops: June 14th/15th 2023

- Science workshop: to establish and consolidate the L0 requirements, and the cases that are driving the L1 requirements
- Payload workshop: to converge on the baseline and back-up detector choice, and consolidating the optical design of the telescope.

Why dense fields?

HAYDN

Benchmarks for the calibration of the absolute stellar age scale

Benchmarks for the calibration of the cosmic distance scale

Formation history and chemical evolution of key building blocks of galaxies

Strong support of Stellar and Galactic communities (immediate impact)

Impact also in unresolved stellar populations (indirect)

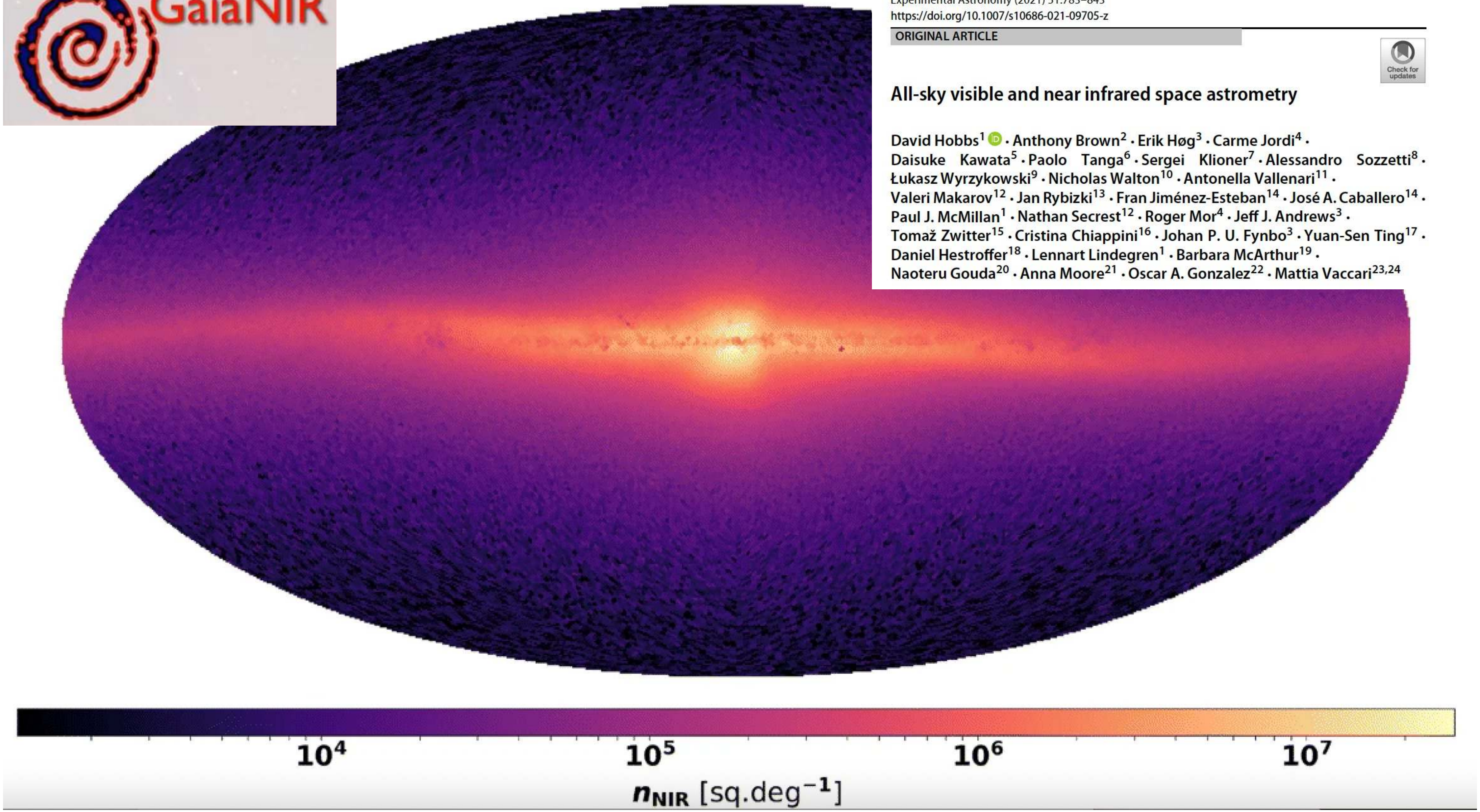
GaiaNIR

Experimental Astronomy (2021) 51:783–843
https://doi.org/10.1007/s10686-021-09705-z

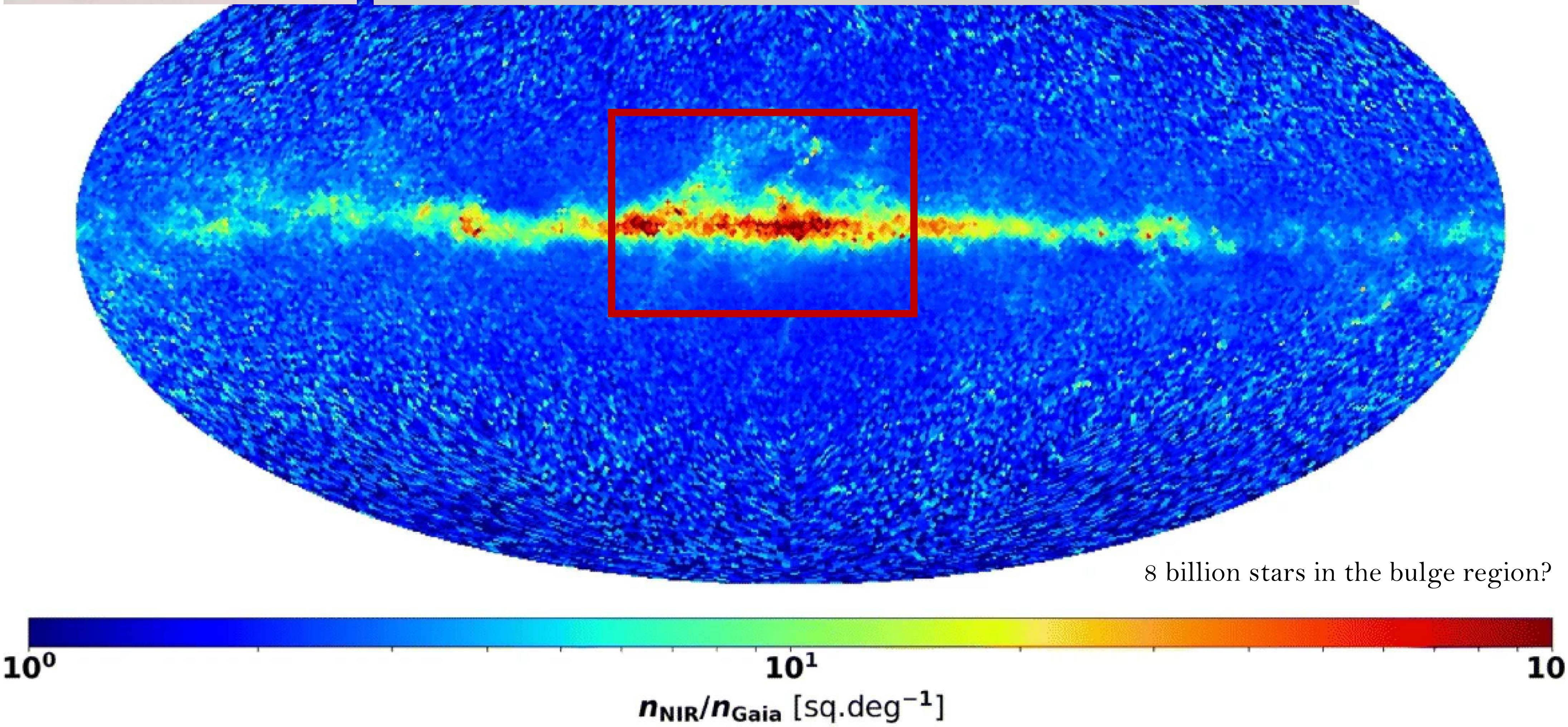
ORIGINAL ARTICLE

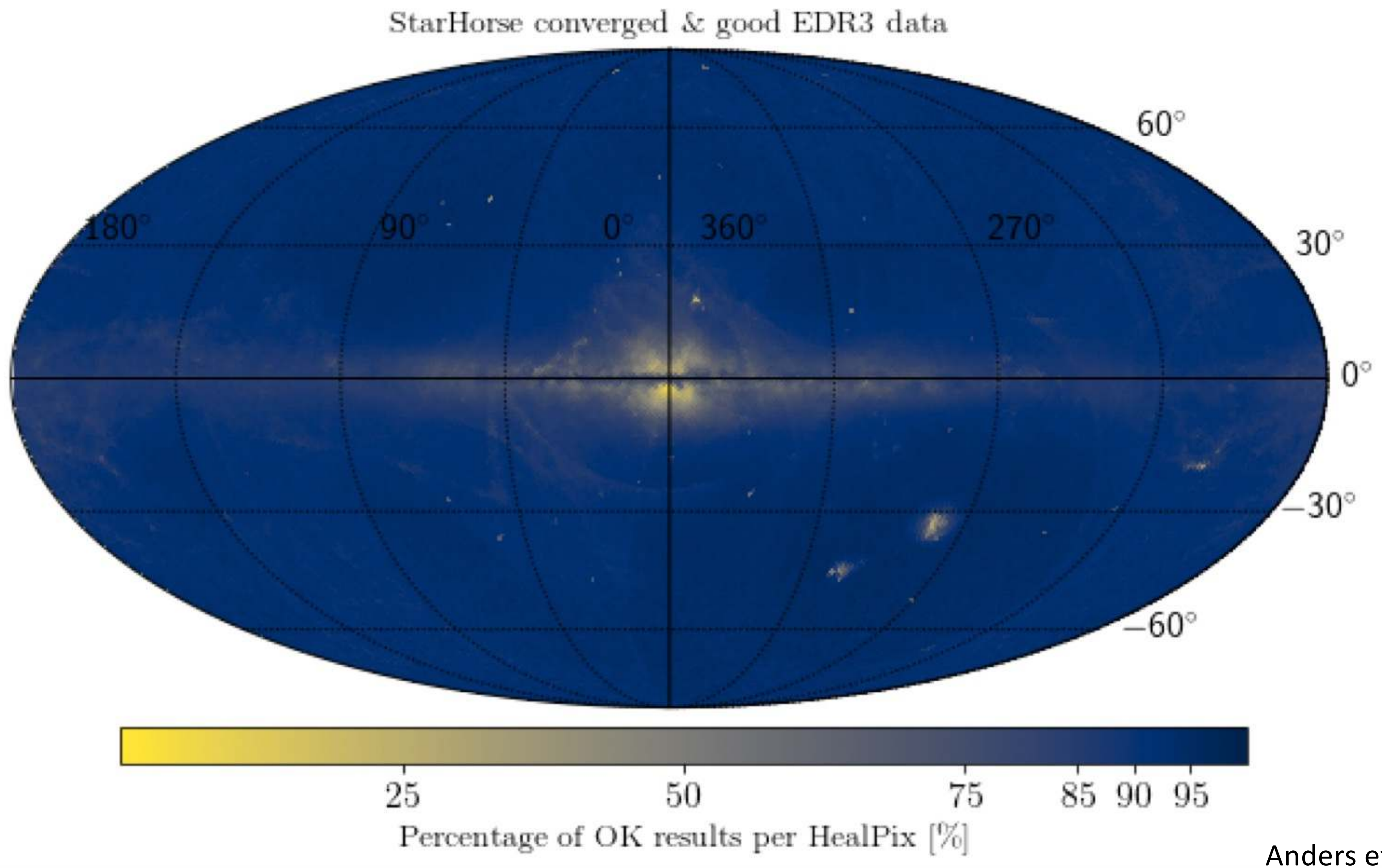
All-sky visible and near infrared space astrometry

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]



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





Anders et al. 2022

2010 Initial proposal → 2020s Concept development and proposal phase → 2030s Detailed Design phase – Mission acceptance phase → 2040s Launch

- NIR all-sky astrometry and photometry to penetrate the obscured regions and to observe intrinsically red objects with almost diffraction limited resolution;

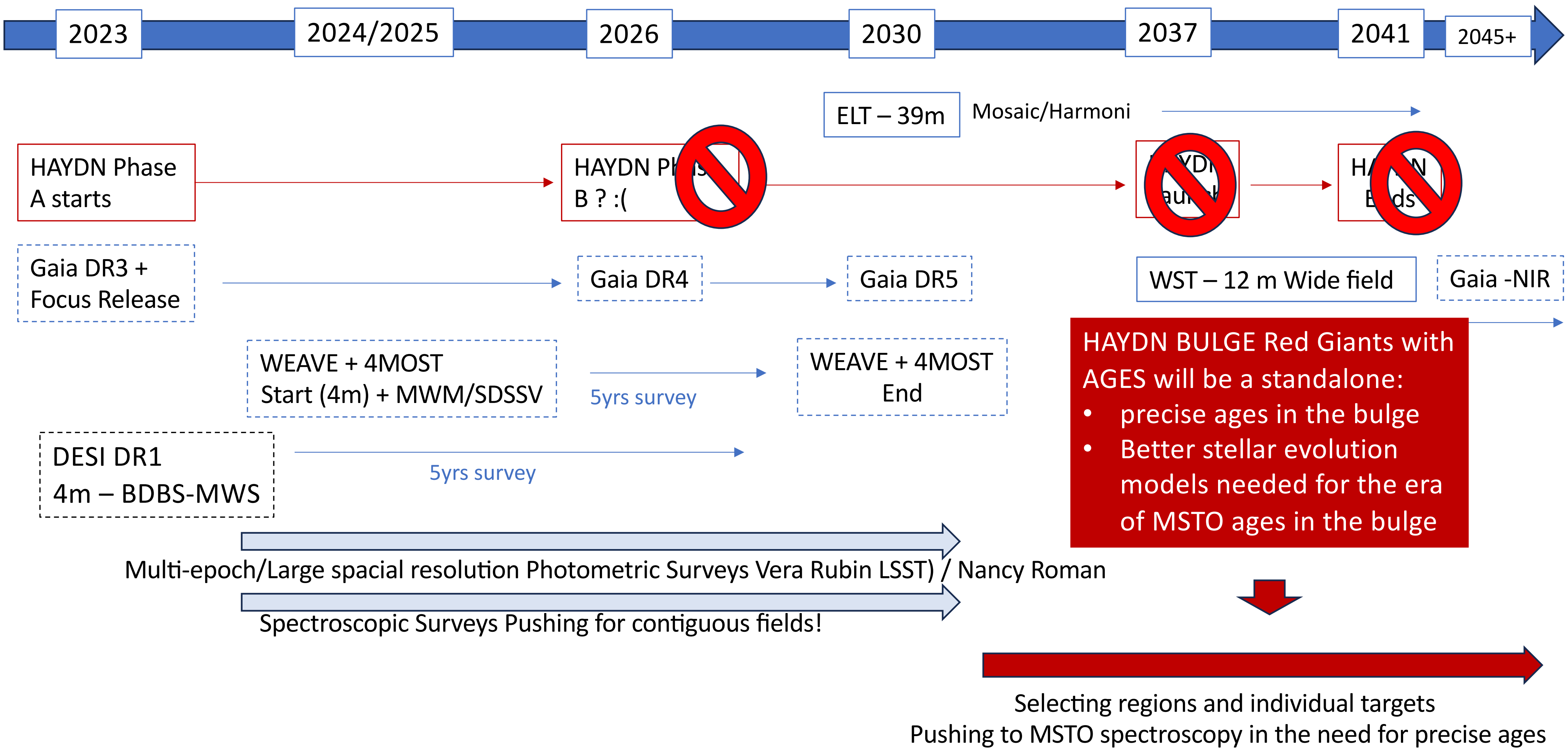
BULGE AND INNER-DISK!

- Improved proper motions with fourteen times smaller errors than from Gaia alone opening up new science cases, such as long period exoplanets and accurate halo measurements;
- Allow the slowly degrading accuracy of the Gaia reference frame, which will be the basis for future astronomical measurements, to be reset.

https://www.astro.lu.se/GaiaNIR

Hobbs et al. 2021

What happens from now to 2040 (Bulge) ? HAYDN at perfec time!



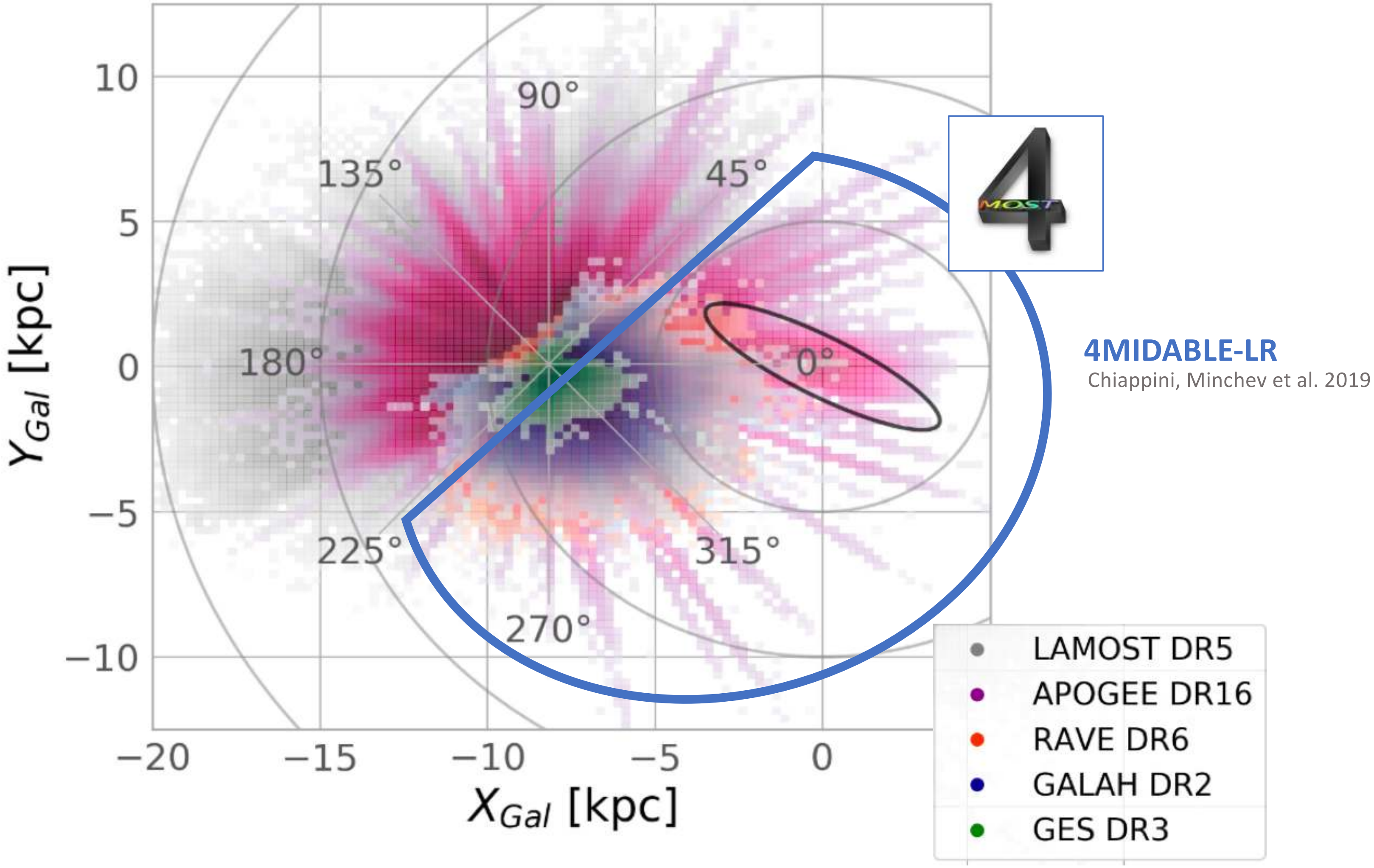
4MOST WEAVE MOONS SDSSV

- Will open interesting regions to focus with future facilities ELT
- Where to focus?
- How to connect with properties seen in nearby galaxies? (e.g. MUSE)
- CEMs will need to catch up with data – multi-components!

4MIDABLE-LR

PIs Cristina Chiappini and Ivan Minchev

Goal: Complement Gaia – Reaching the next step in Galactic Archaeology – Focus: Inner disk and bulge



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

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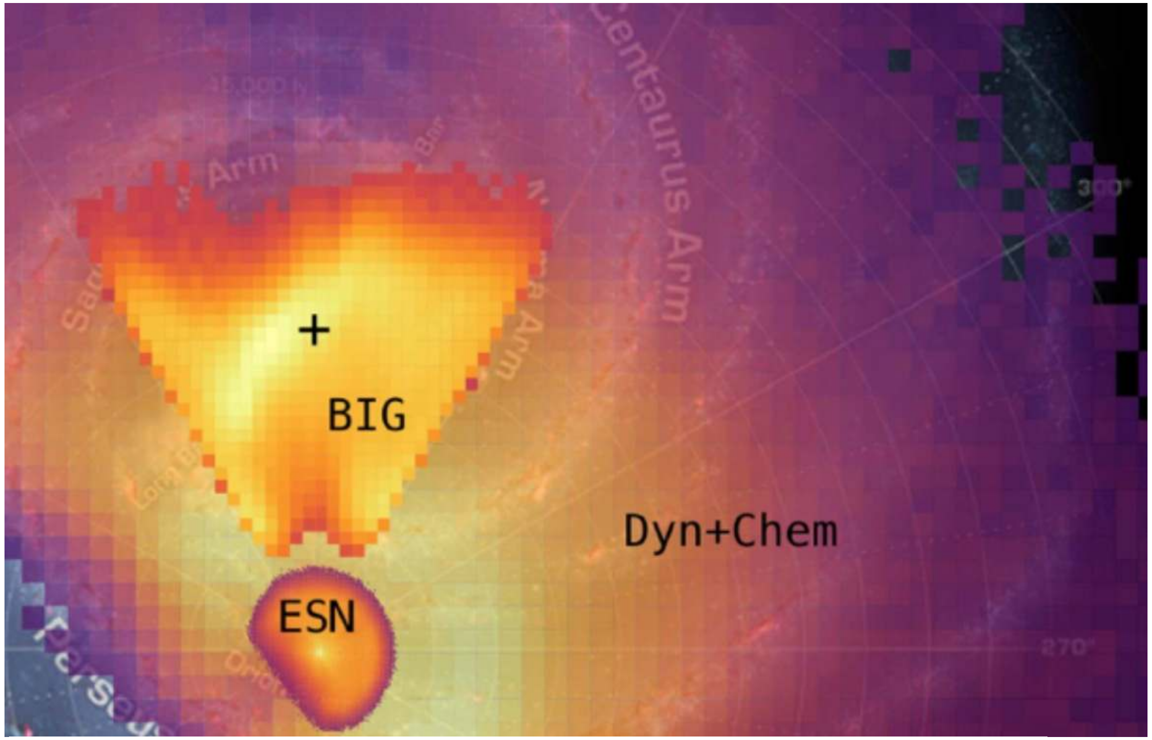
Nils Ryde[7]
Hans-Walter Rix[8]
Nicholas Walton[11]
Maosheng Xiang[8]
Daniel Zucker[12]
and the 4MIDABLE-LR Team



Surveys
DOI: 10.18727/0722-6691/5122

4MOST Consortium Survey 3: Milky Way Disc and Bulge Low-Resolution Survey (4MIDABLE-LR)

Chiappini, Minchev et al. 2019 The Messenger 175 – March 2019

First light 2024

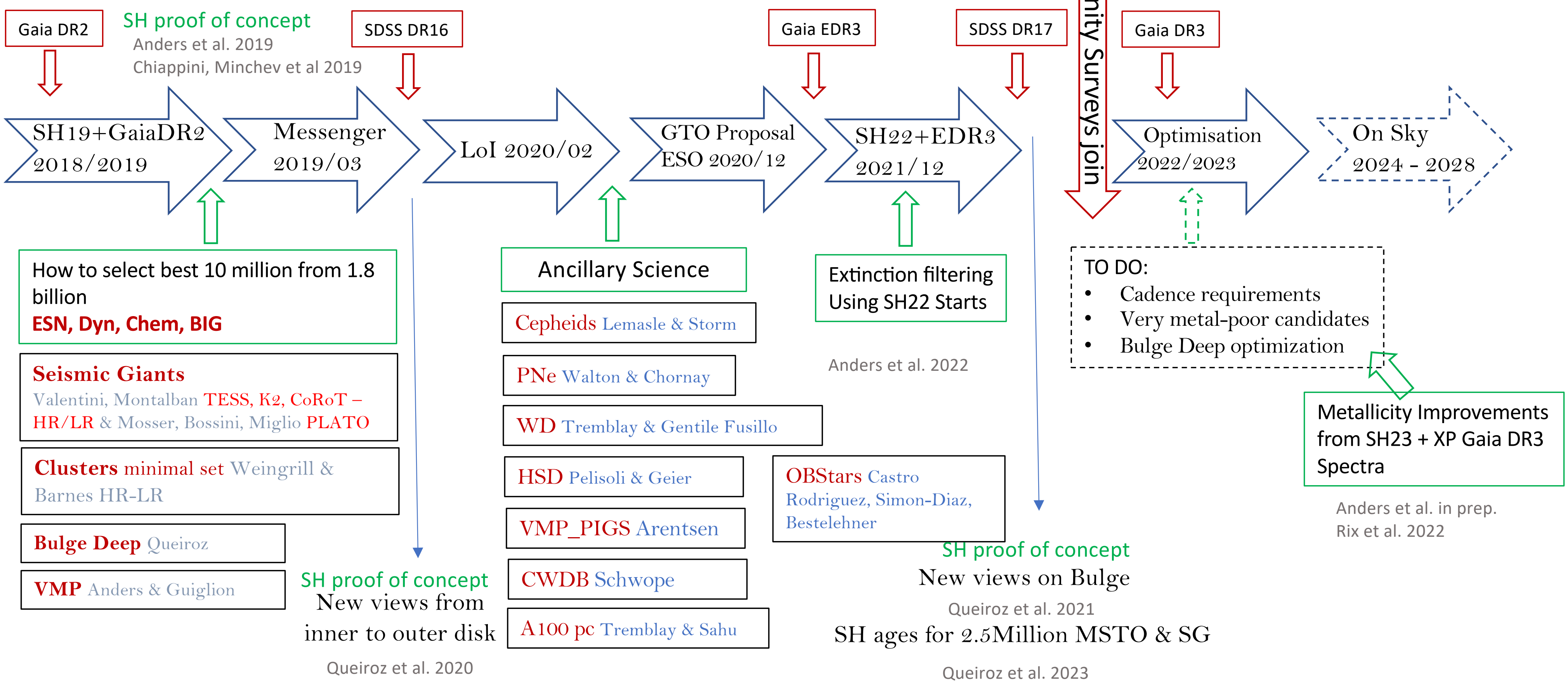
Current list of 66 members

Anders, Arentsen, Asplund, Bailer-Jones, Balbinot, Barnes, Bensby, Bergemann, Bestenlehner, Bossini, Casagrande, Casey, Castro Rodriguez, Cescutti, Chiappini, Chornay, Church, Dorsch, Farihi, Feltzing, Foesneau, Fragkoudi, Geier, Gentile Fusillo, Gehrard, Grebel, Guiglion, Helmi, Hobbs, Jin, Khalatyan, Khoperskov, Kordopatis, Lemasle, Lind, McMillan, Miglio, Mikolaitis, Minchev, Monari, Montalban, Mosser, Nepal, Pelisoli, Queiroz, Ratcliffe, Rau, Rix, Ryde, Sahu, Schneider, Schwope, Sharma, Simon-Diaz, Starkenburg, Steinmetz, Storm, Sun, Traven, Tremblay, Valentini, Walton, Weingrill, Xiang, Yong, Zucker


MIDABLE-LR
MOST
josefina montalban

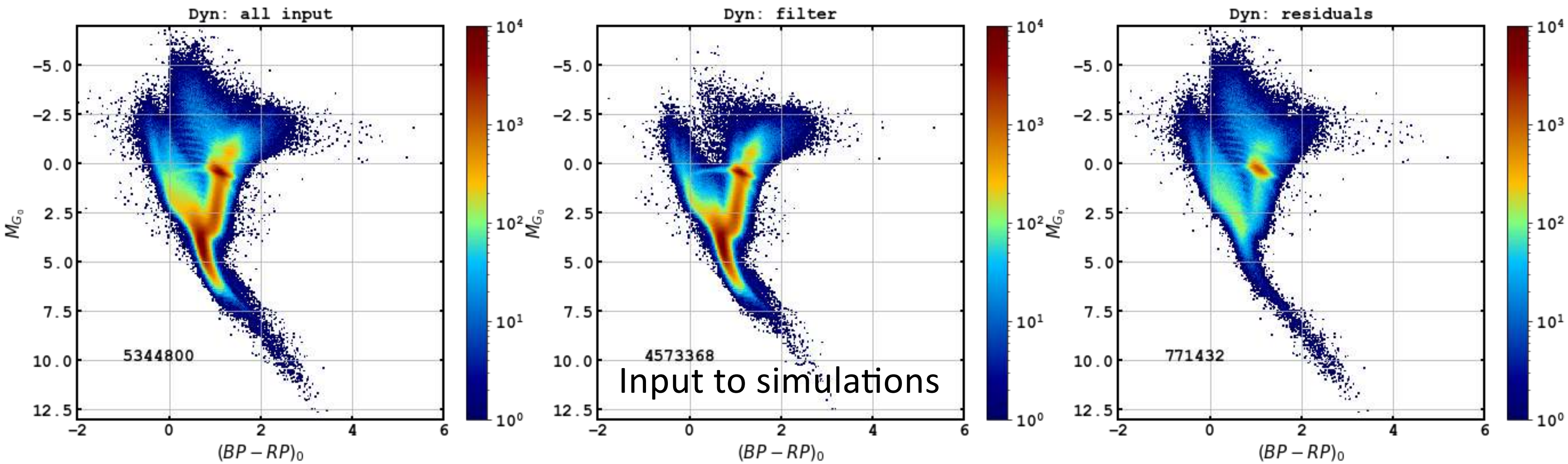
Milestones 4MIDABLE-LR

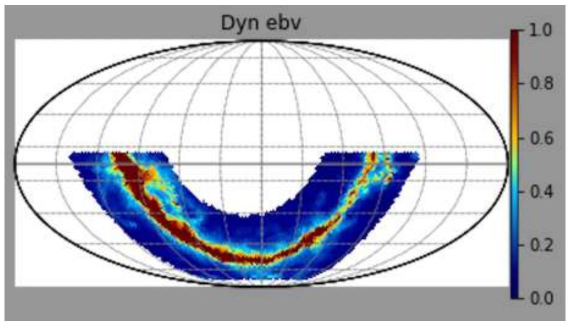
Chiappini & Minchev

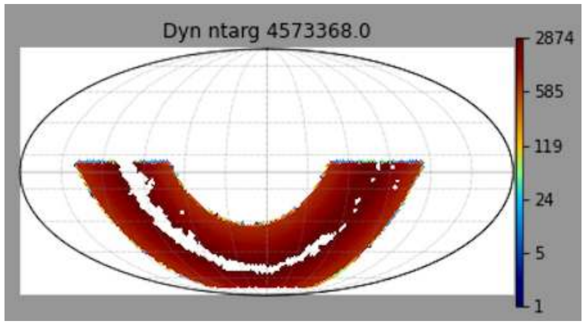


Dyn

Ingestion_20221024 - ebv_min = 0.8

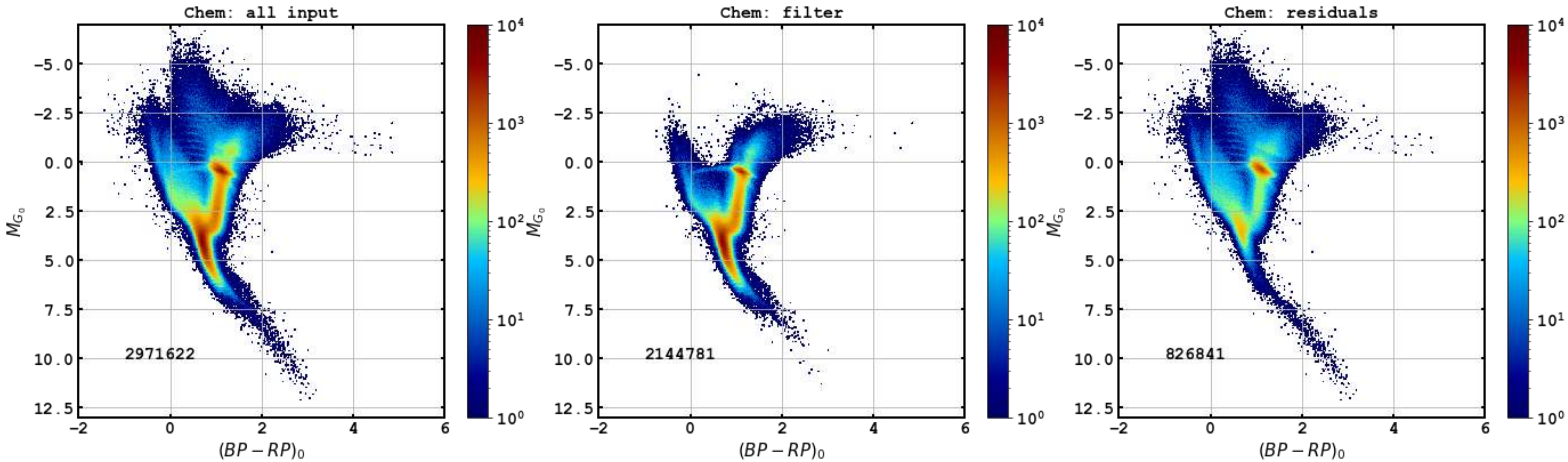


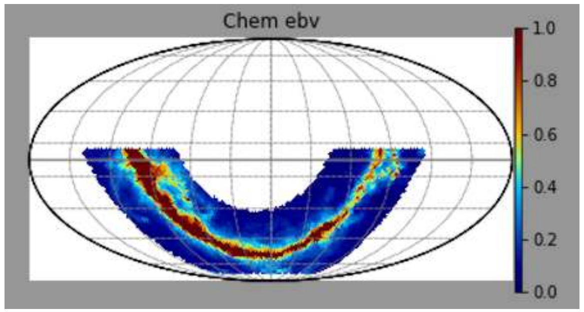


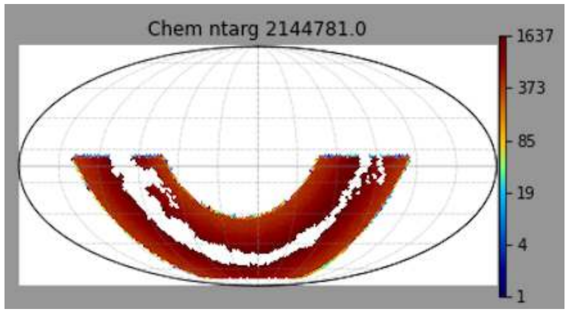


Chem

Ingestion_20221024 - ebv_min = 0.5





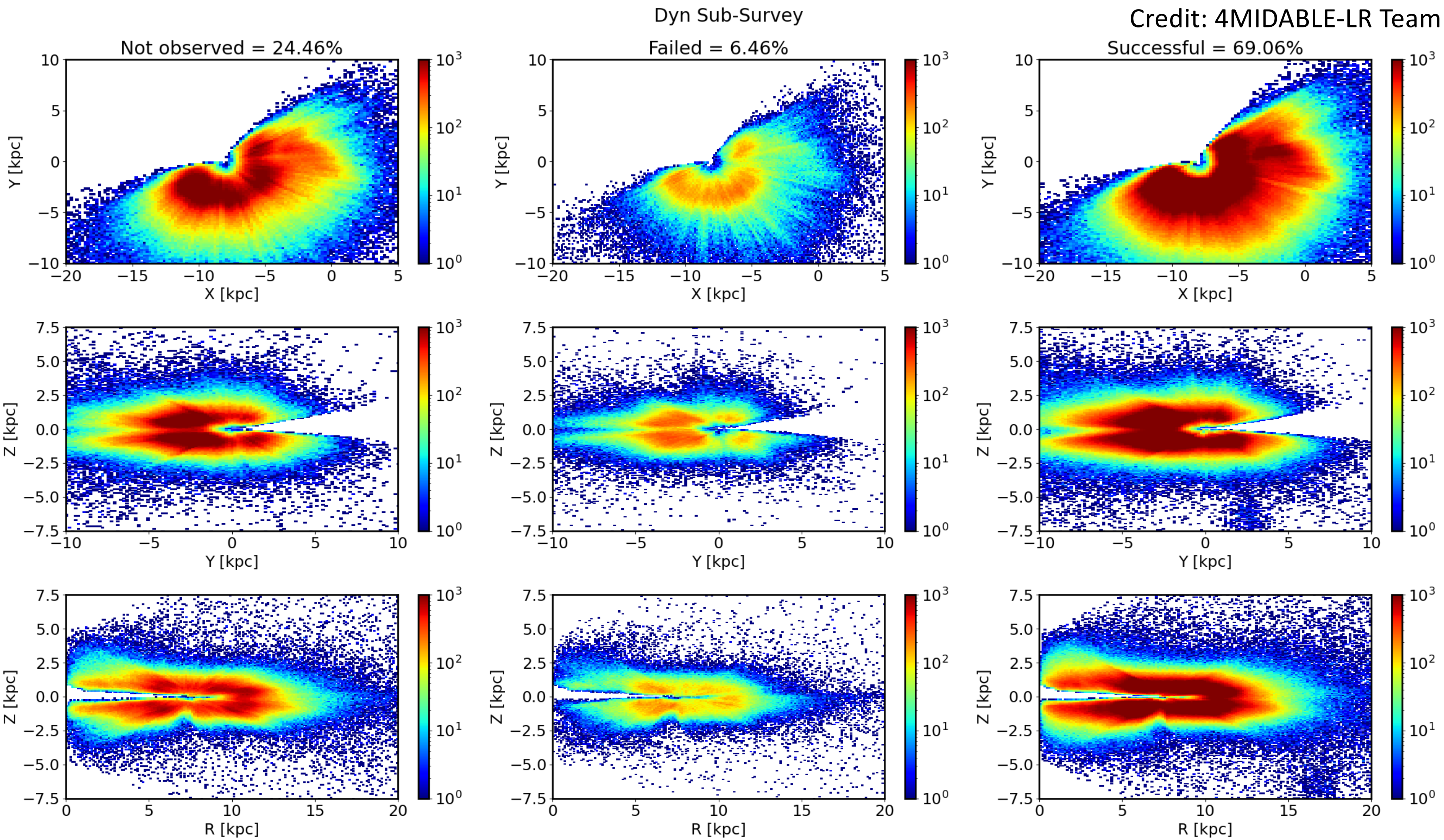


29% completed - E(B-V) = 0.8

37% (fobs > 0.9) – E(B-V) = 0.5

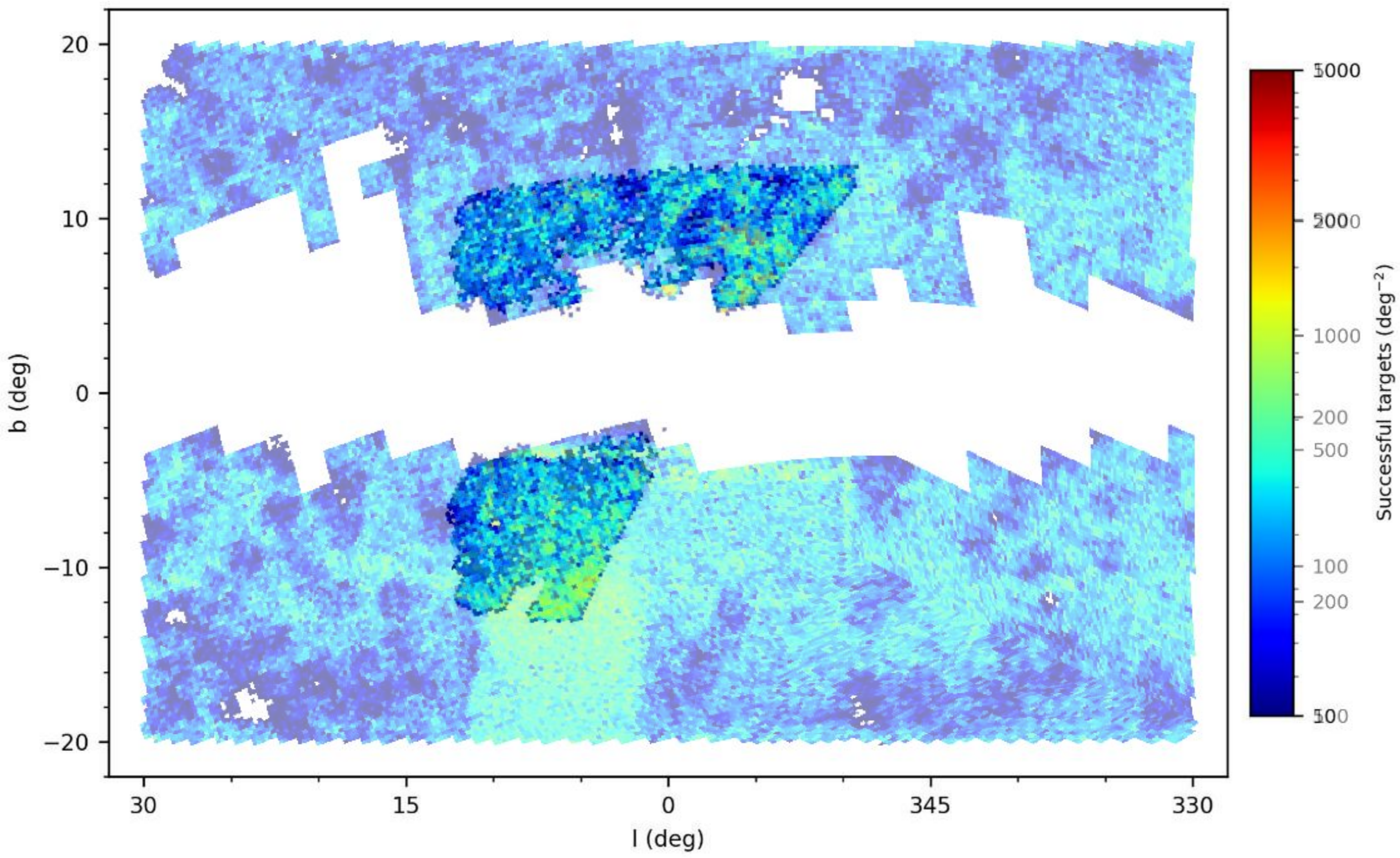
Decrease in Nstars with Tmax > 120 min

More than 1M not observed


Dyn Sub-Survey
Credit: 4MIDABLE-LR Team
Not observed = 24.46%
Failed = 6.46%
Successful = 69.06%
X [kpc]
Y [kpc]
Z [kpc]
R [kpc]
10^0
10^1
10^2
10^3

Bulge Inner Disk (BIG) + Pristine Inner Galaxy + Bulge Deep + VMP Bulge+Disk (Gaia DR3-XP + SH)

4MIDABLE-LR



Ongoing *optimization at target level, but area, mag range and Ntargets will not change*

Key aspect: large wavelengh coverage (as e.g. SEGUE) but mid-resolution (as e.g. RAVE)

4MIDABLE-LR

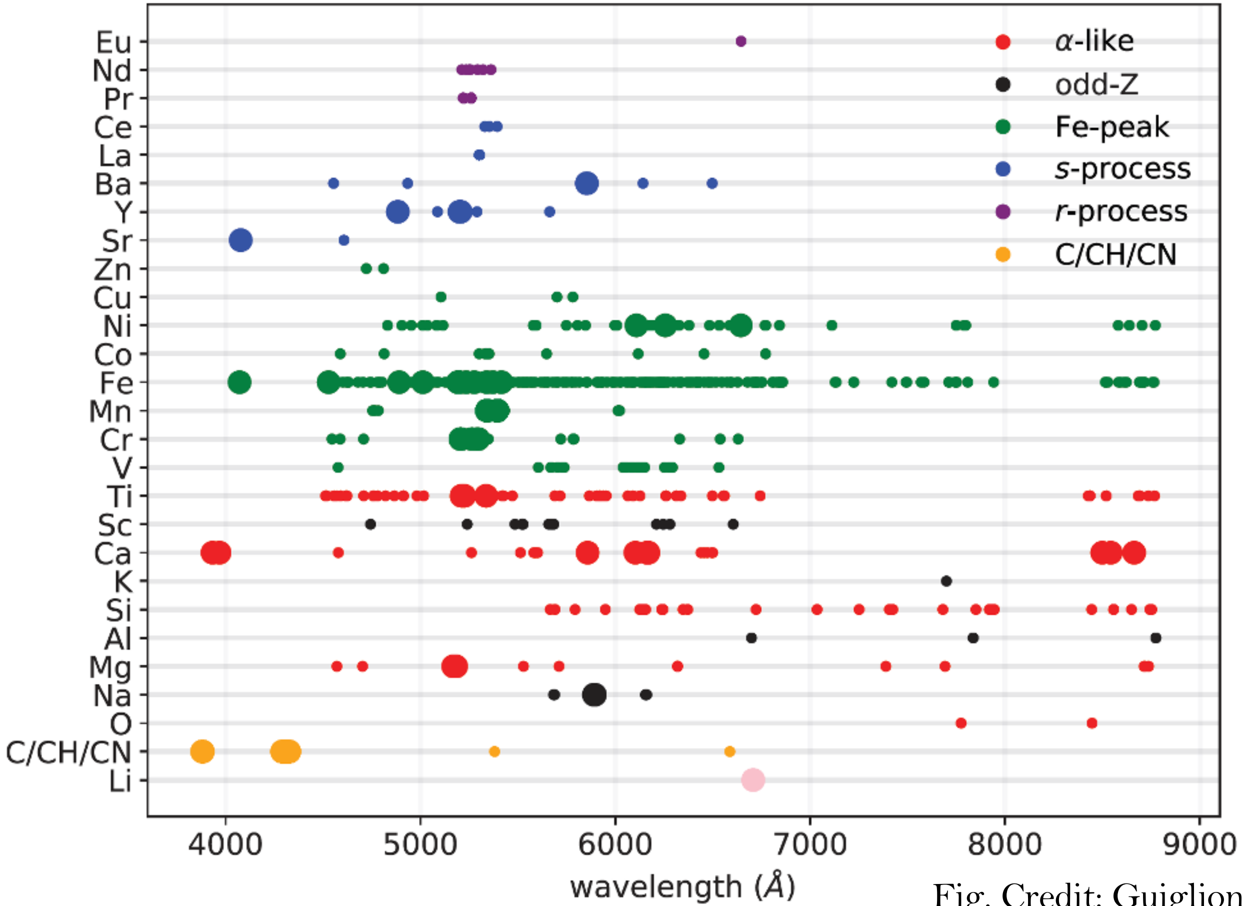


Fig. Credit: Guiglion

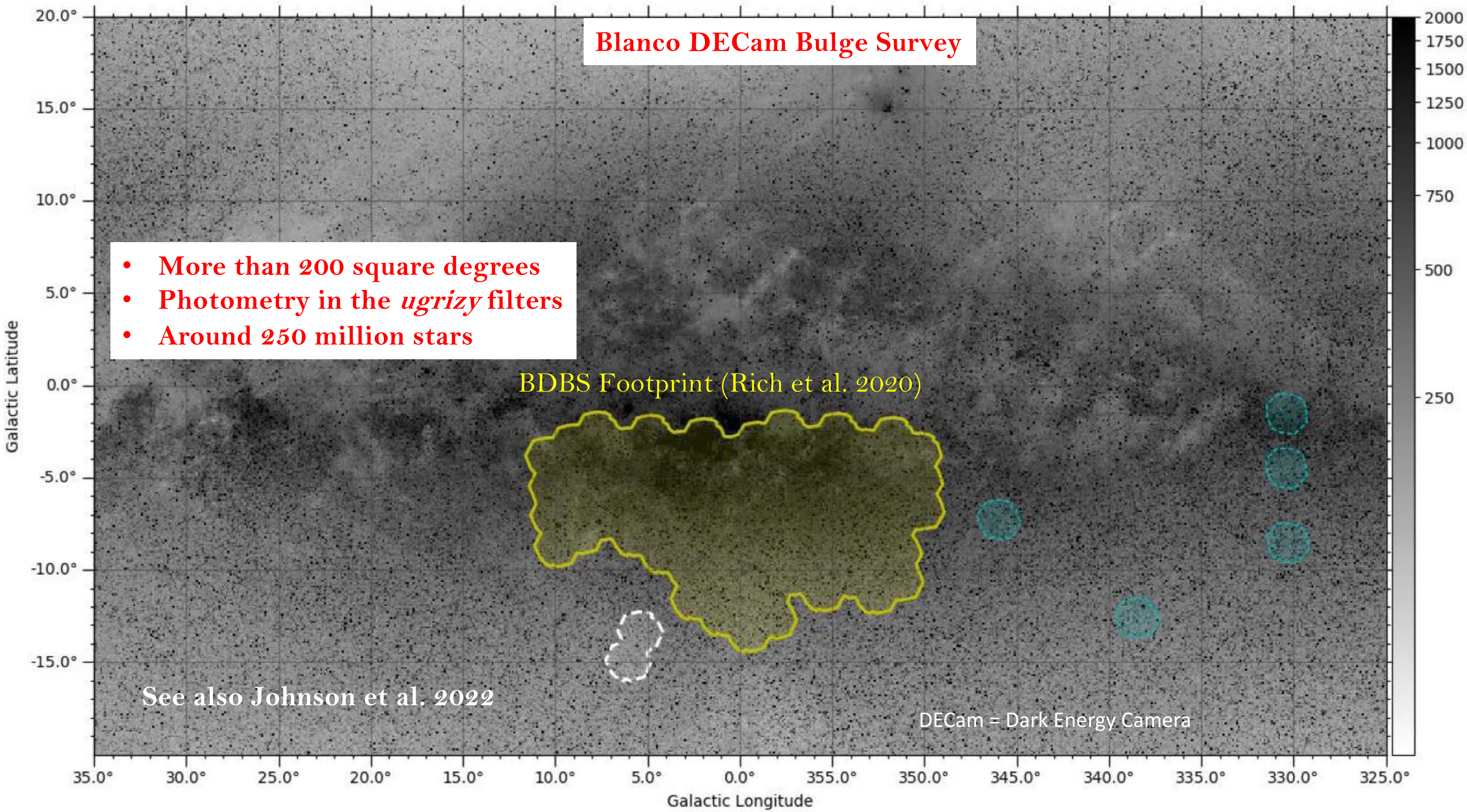
4MIDABLE-LR Team tests with different pipelines/methods

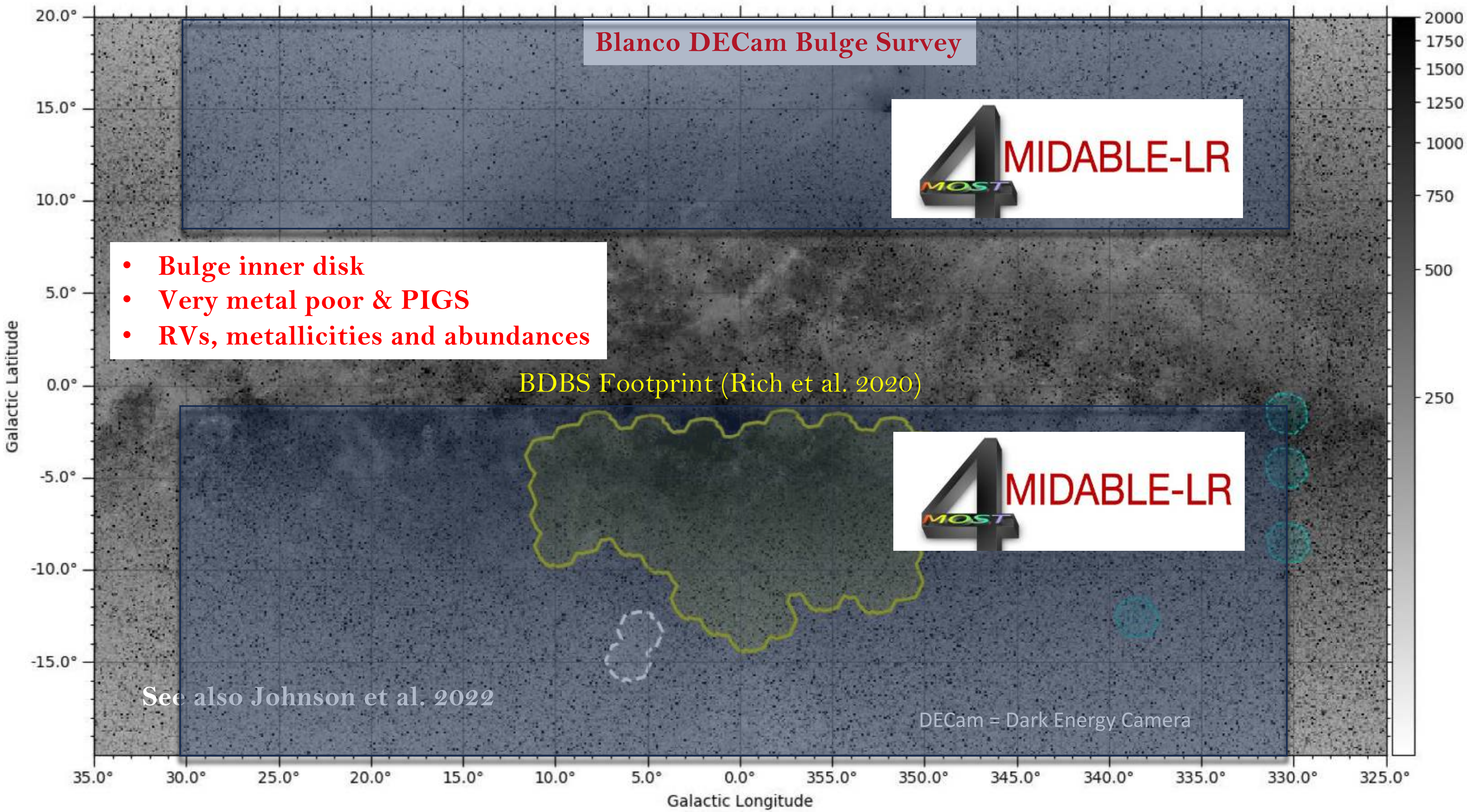
Several nucleosynthetic families

Exploring ML approaches to infer abundances from LR spectra

Guiglion et al. (2020), Nepal et al. (2023), Ambrosch et al. (2023), Guiglion et al. (2023) using CNN (convolution neural network) – we applied to RAVE, GES, Gaia-RVS.

Definitively not only a RV survey!


Blanco DECam Bulge Survey
• More than 200 square degrees
• Photometry in the ugrizy filters
• Around 250 million stars
BDBS Footprint (Rich et al. 2020)
See also Johnson et al. 2022
DECam = Dark Energy Camera
Galactic Latitude
Galactic Longitude
20.0°
15.0°
10.0°
5.0°
0.0°
-5.0°
-10.0°
-15.0°
35.0°
30.0°
25.0°
20.0°
15.0°
10.0°
5.0°
0.0°
355.0°
350.0°
345.0°
340.0°
335.0°
330.0°
325.0°
2000
1750
1500
1250
1000
750
500
250


Blanco DECam Bulge Survey
4MOST
MIDABLE-LR
• Bulge inner disk
• Very metal poor & PIGS
• RVs, metallicities and abundances
BDBS Footprint (Rich et al. 2020)
4MOST
MIDABLE-LR
See also Johnson et al. 2022
DECam = Dark Energy Camera
Galactic Latitude
Galactic Longitude
20.0°
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335.0°
330.0°
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2000
1750
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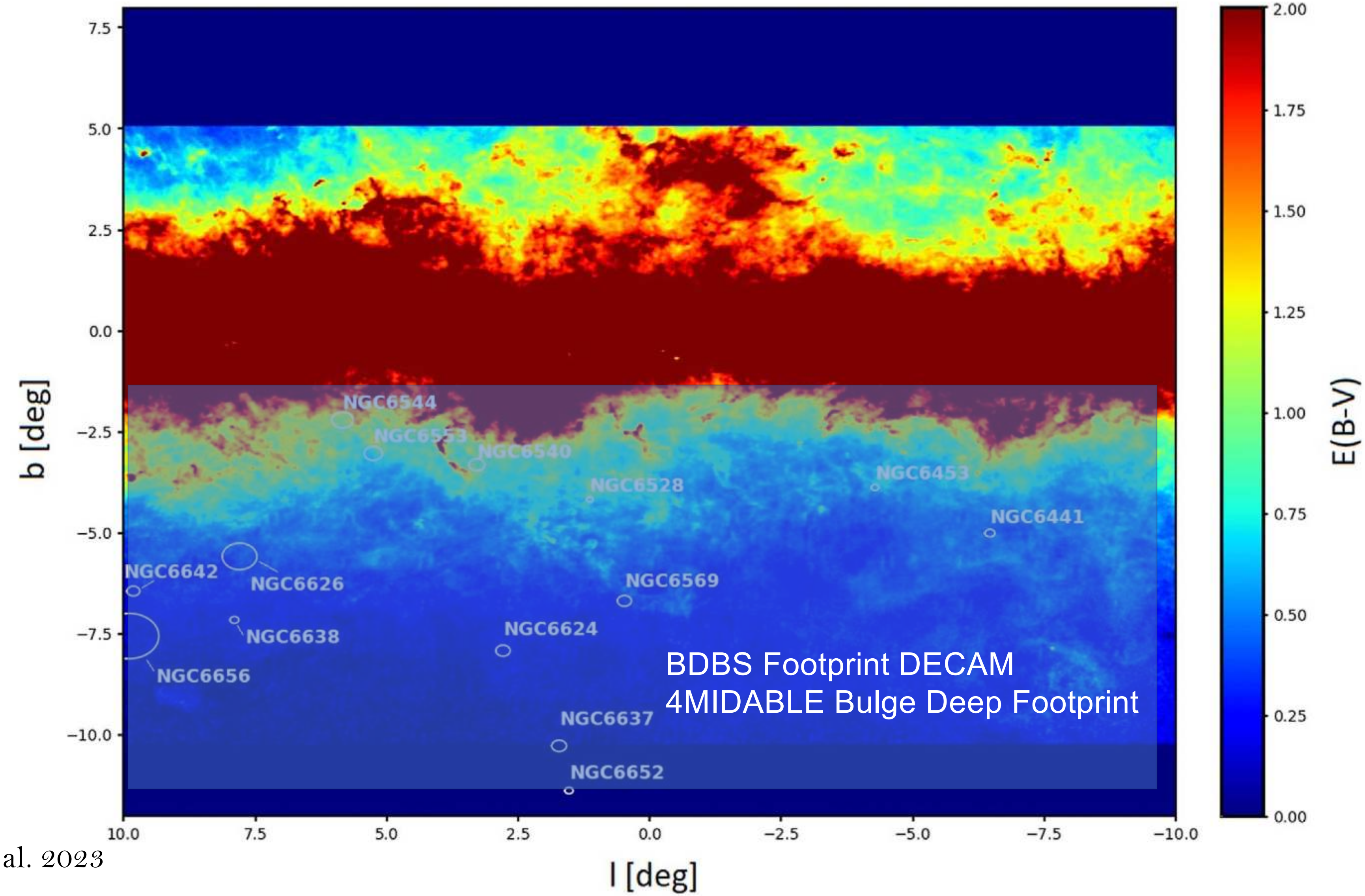

Kader et al. 2023

My main take point

It is an amazing time to be an early career researcher

OBRIGADA! GRAZIE! MERCI! DANKE! GRACIAS! THANKS!