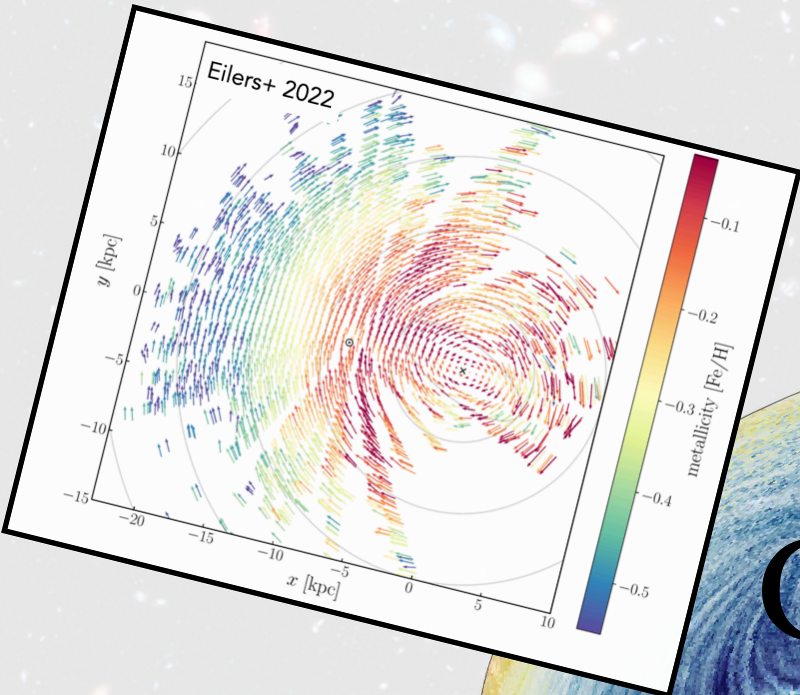
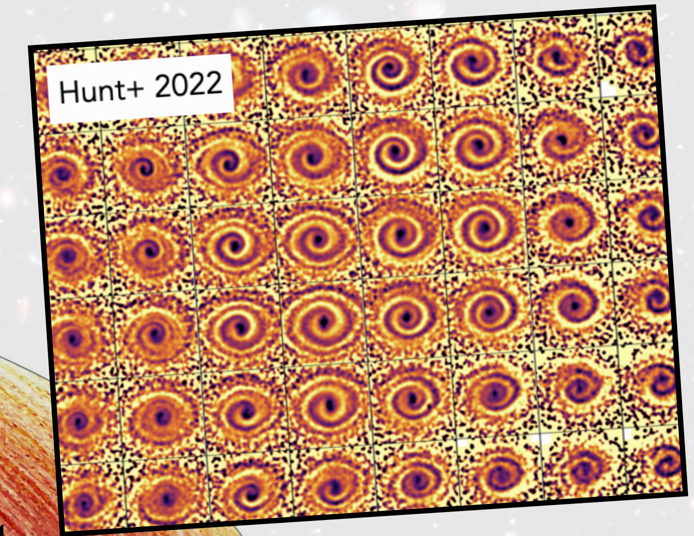




Galactic Kinematics & Statistical Stellar Ages

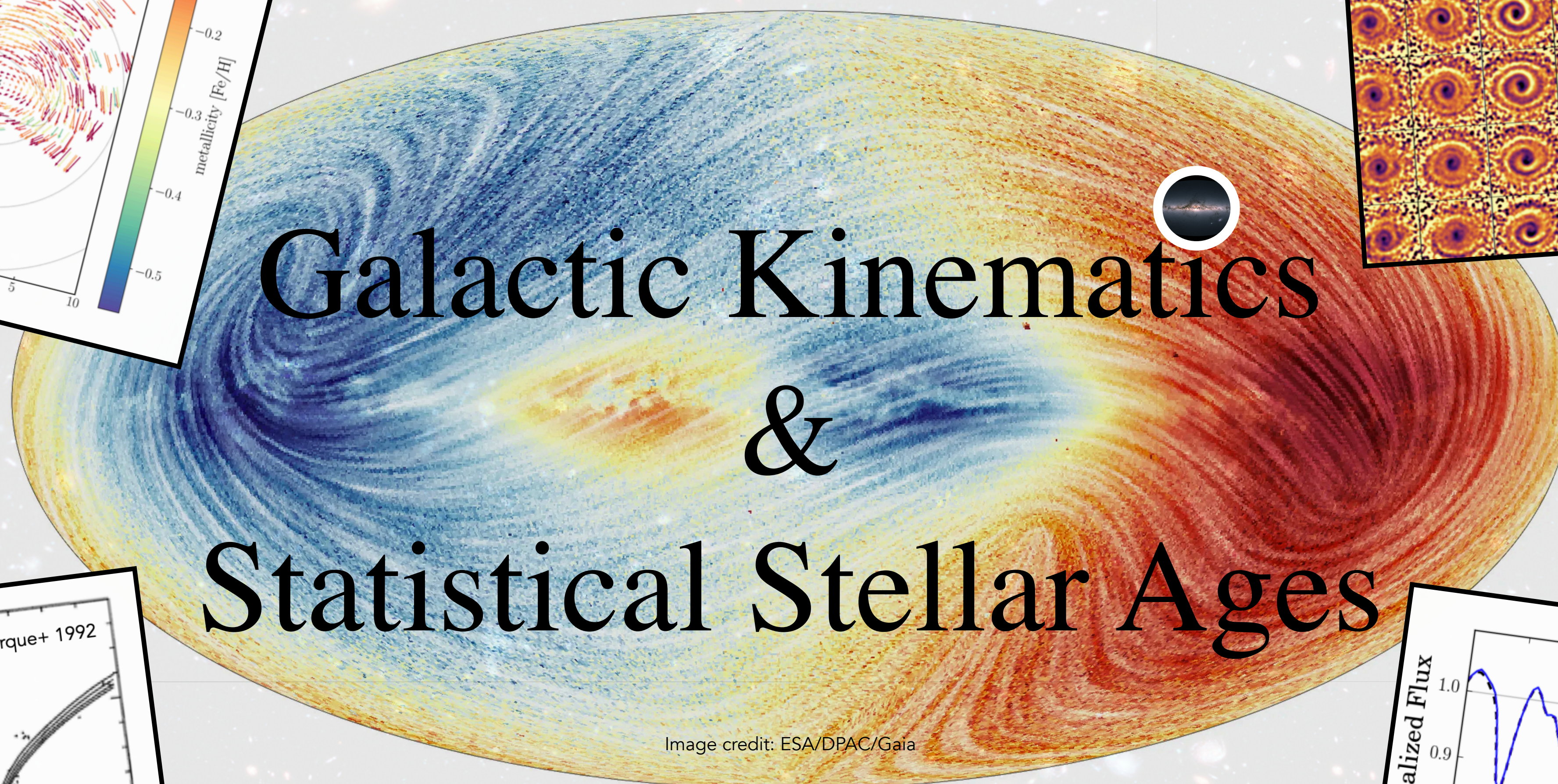
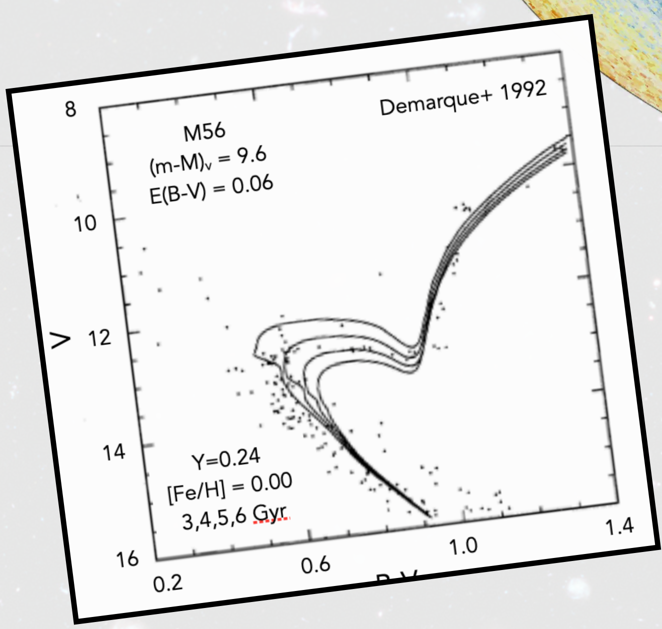
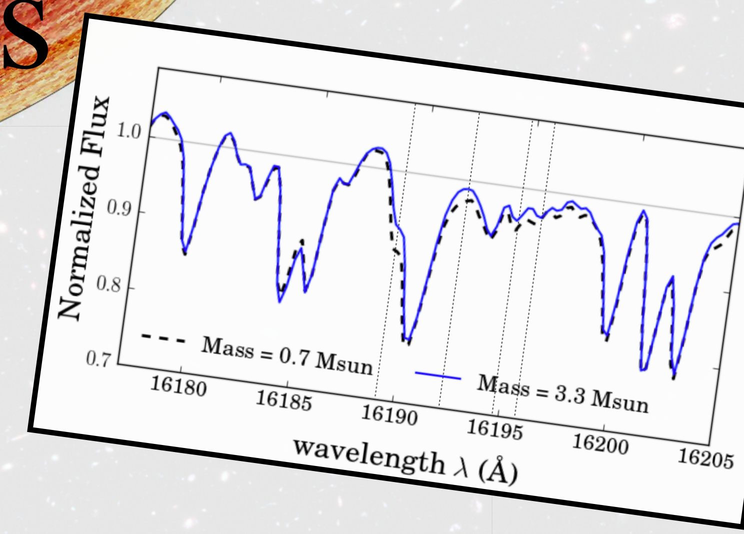


Image credit: ESA/DPAC/Gaia





Melissa Ness
Columbia University & Center for Computational Astrophysics, New York

Sagan workshop, July 2022

Outline

- The Milky Way Data Revolution
- The Populations in the Milky Way Galaxy in the Gaia era
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Circa 2004 — The Geneva Copenhagen survey

~17,000 G, F dwarfs in solar neighbourhood

- ages, proper motions, metallicities, velocities — Nordstrom+ 2004
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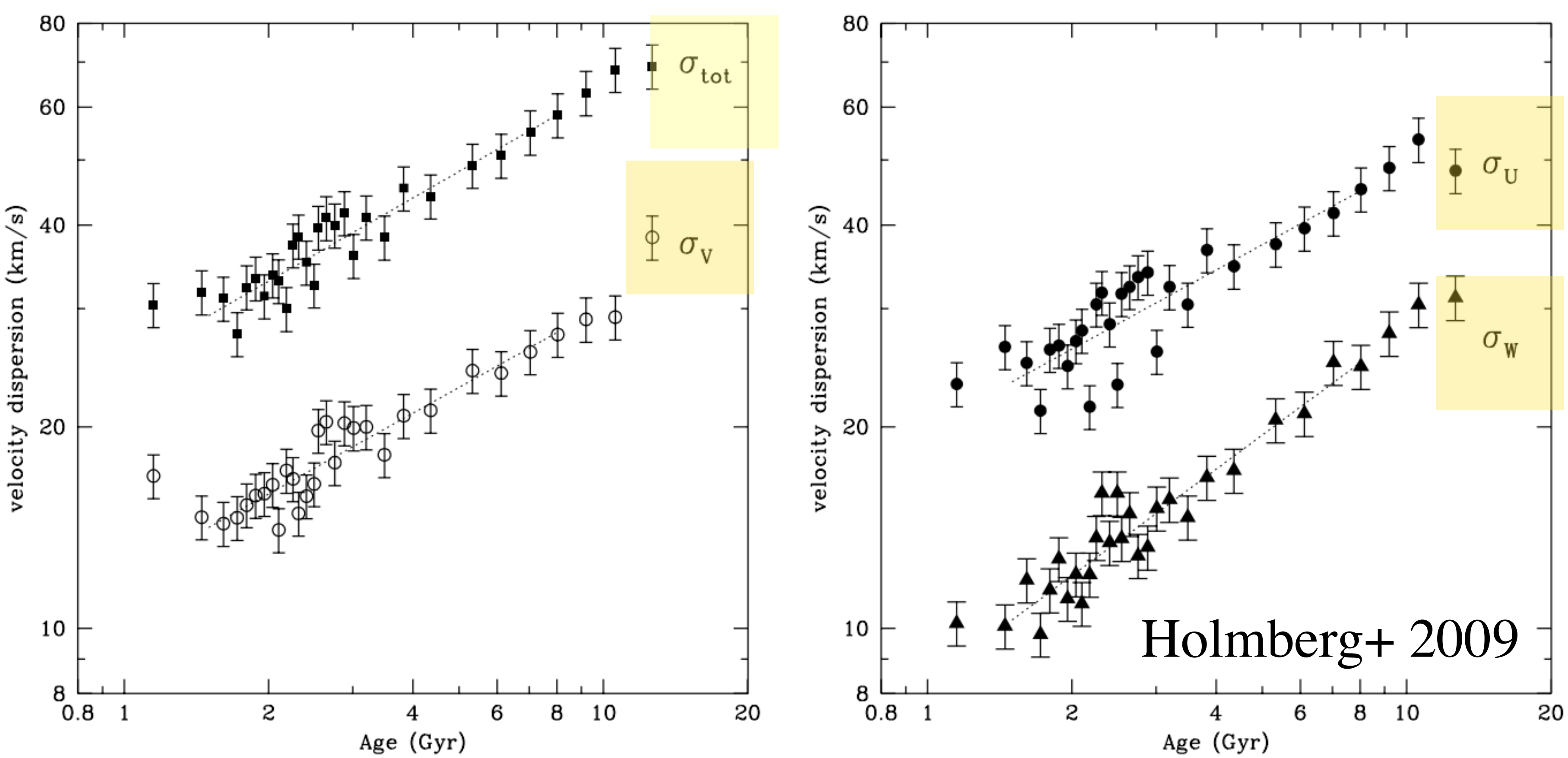

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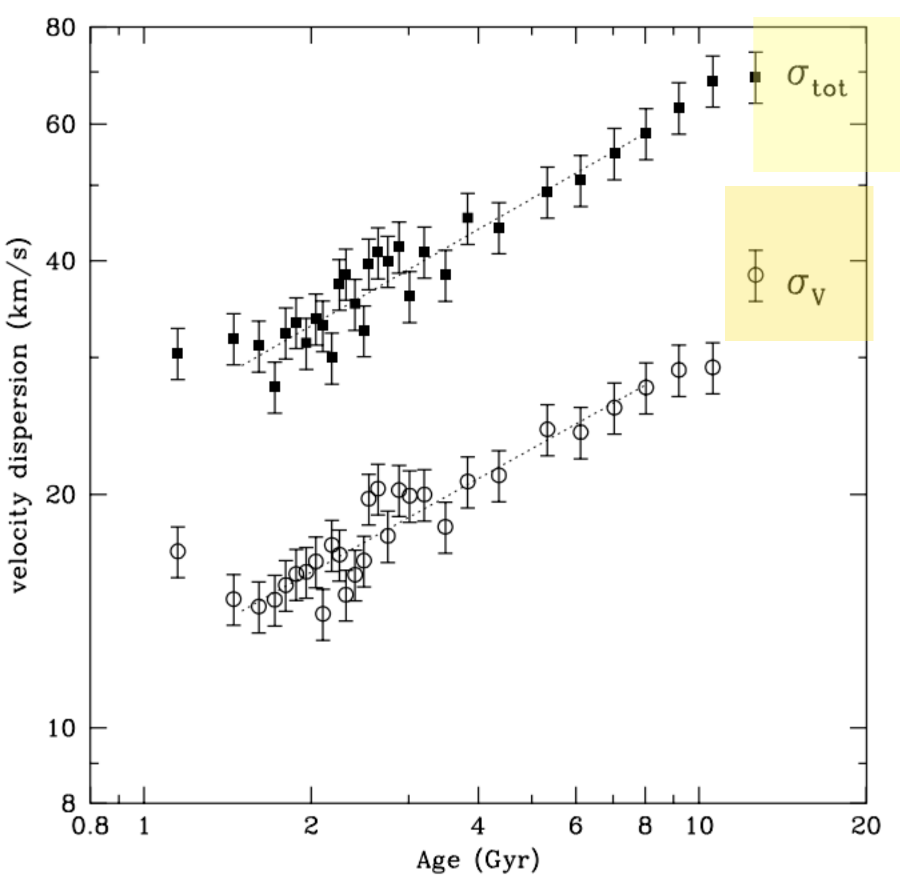

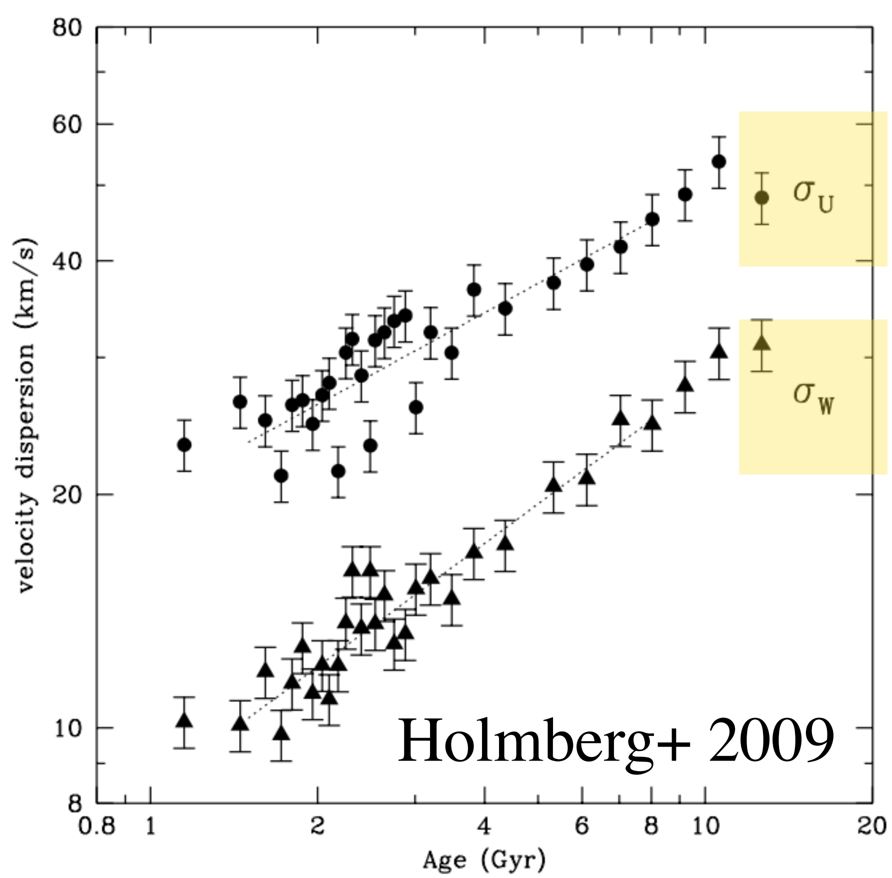

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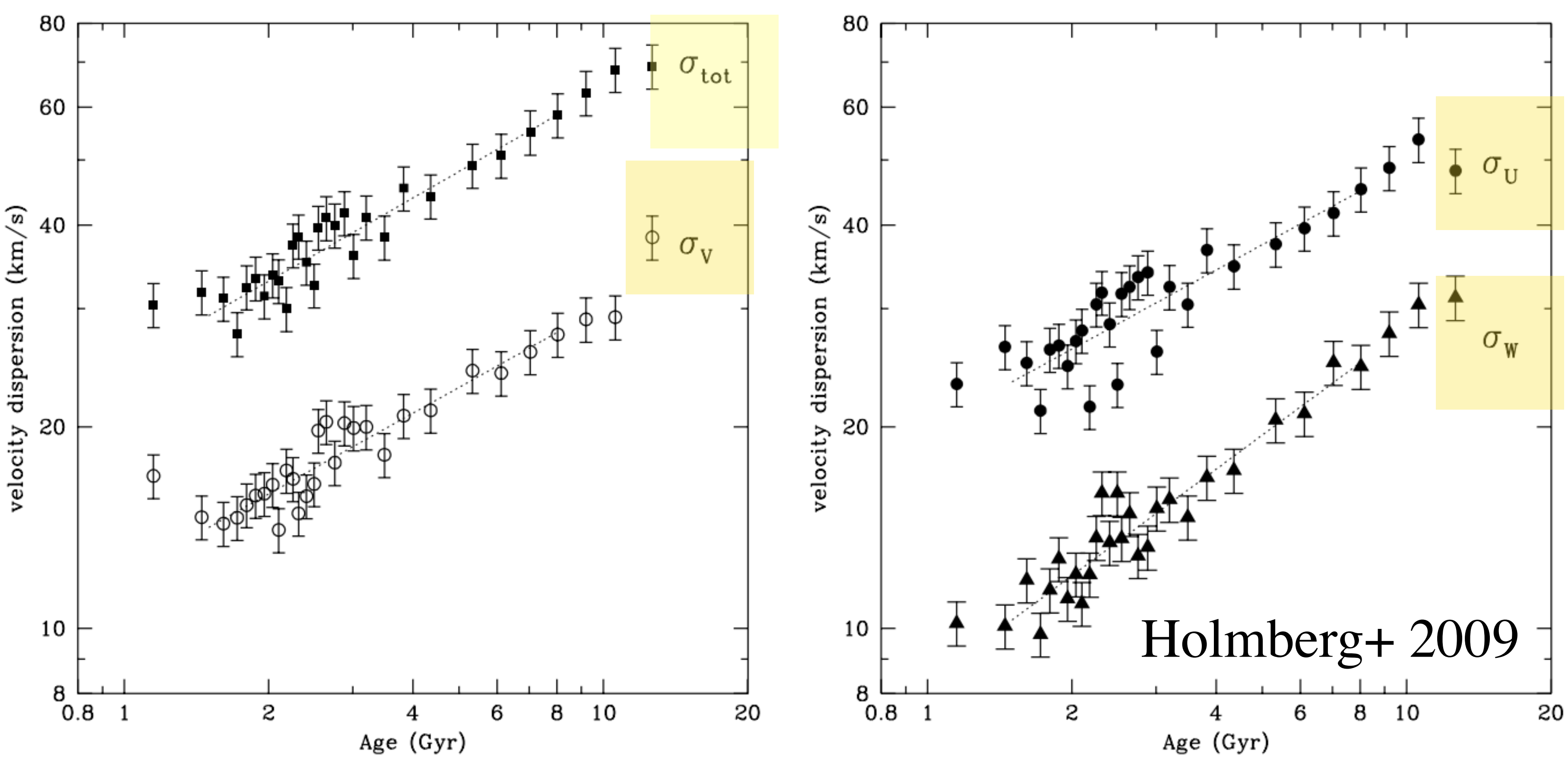

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"Unlikely to be superseded until the Gaia mission
(Perryman et al. 2001) and/or the RAVE project (Steinmetz 2003)"

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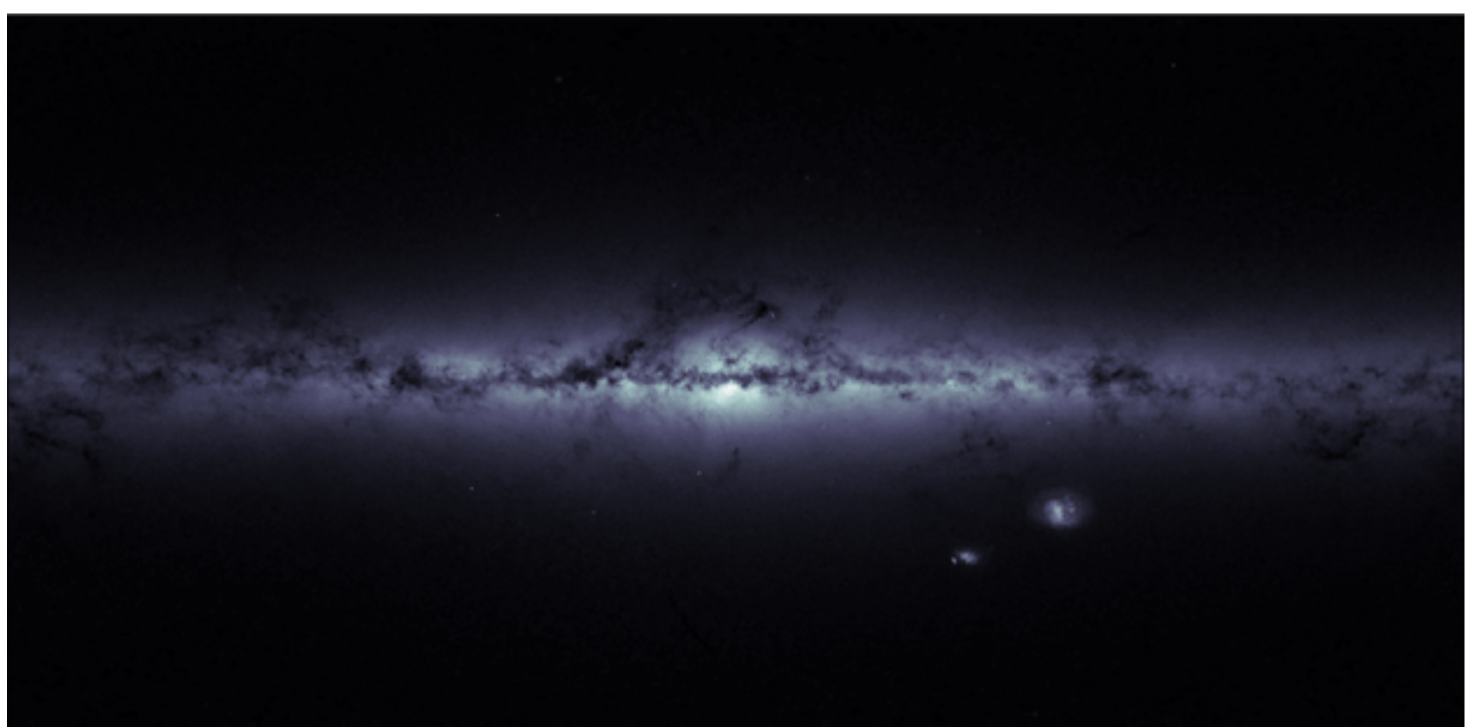

All sky-density map of the 1.1 billion sources in Gaia (ESA/Gaia/DPAC/U.Lisbon)

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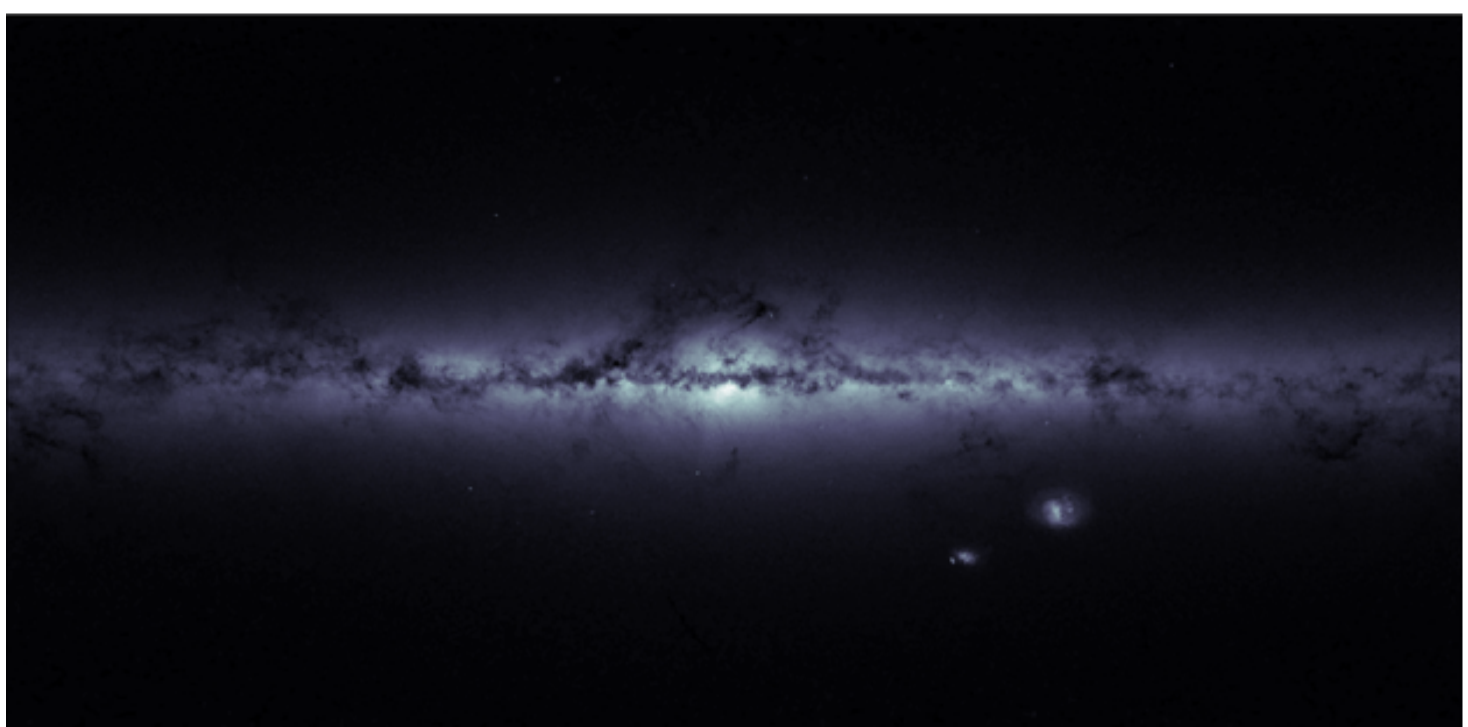

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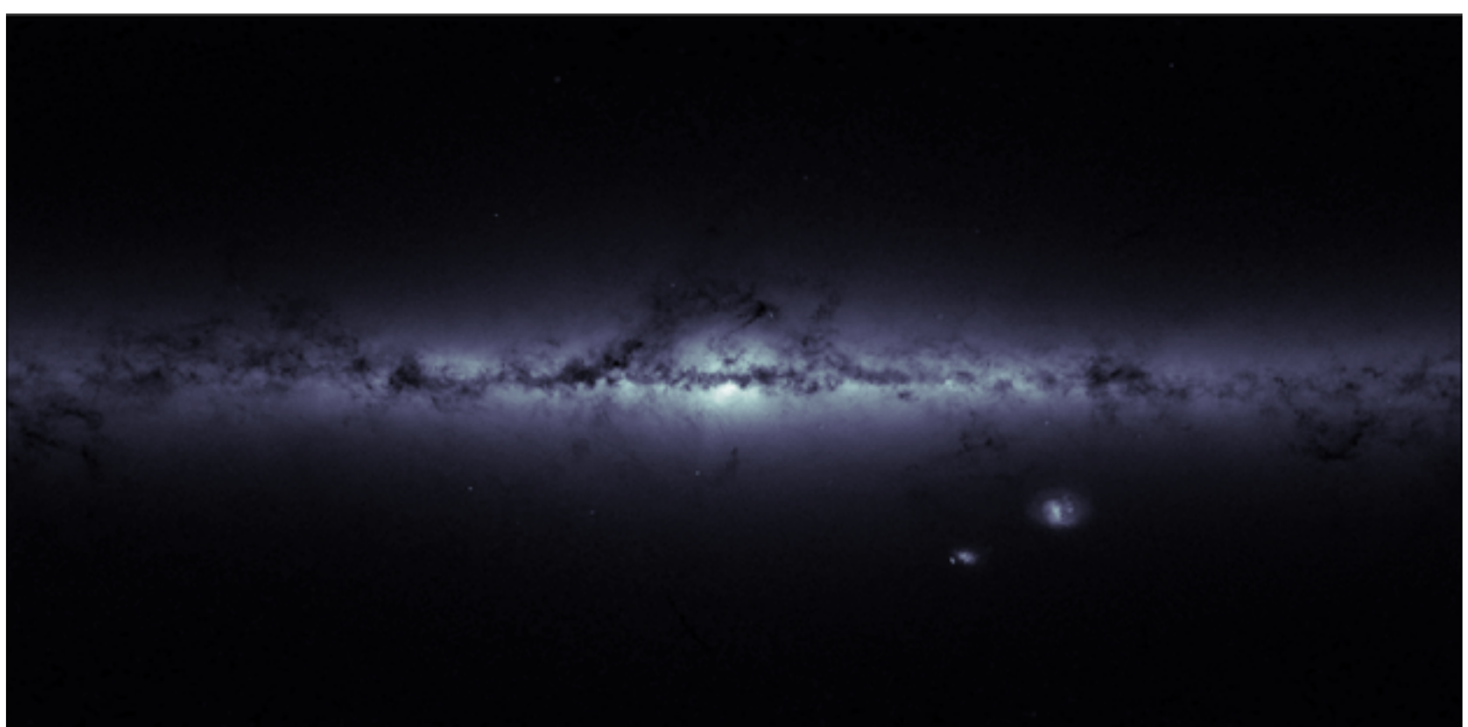

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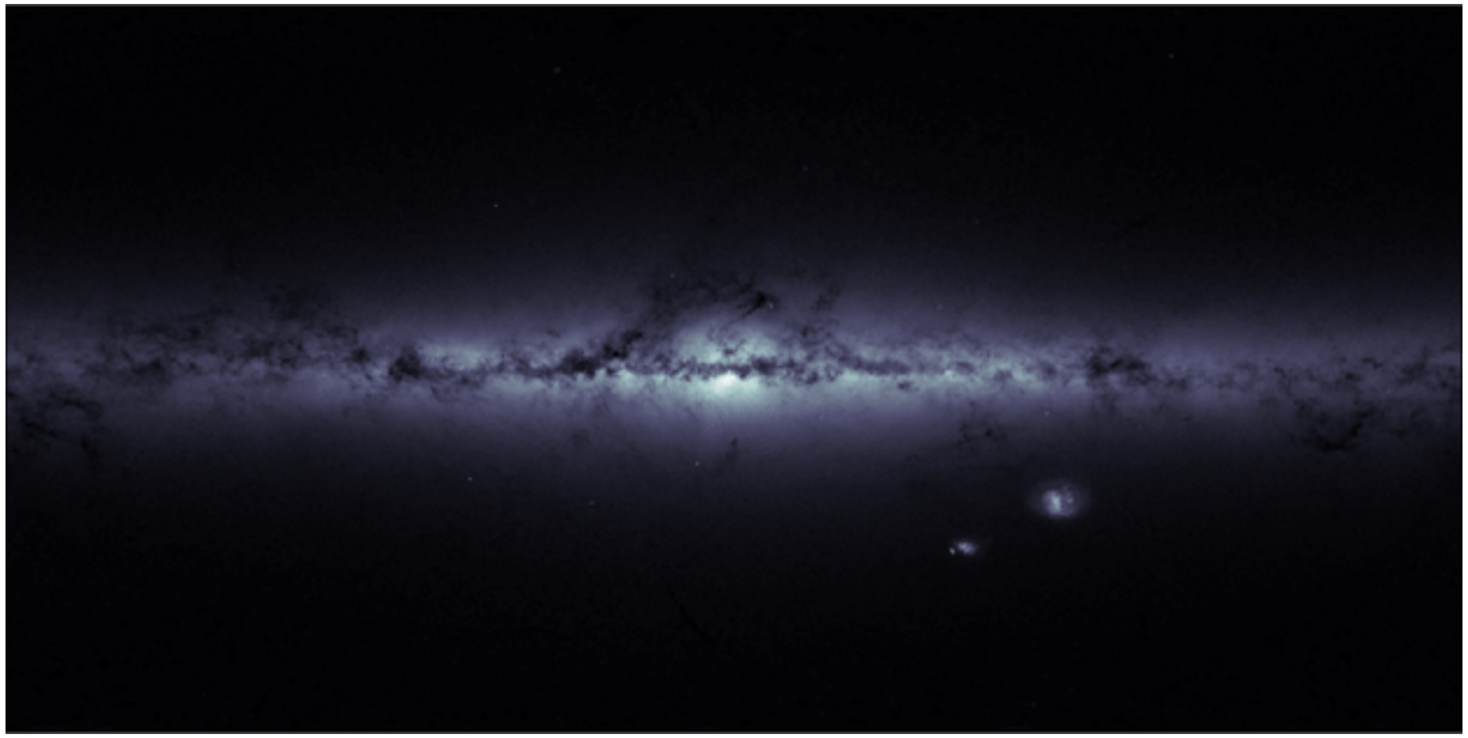
stellar spectra



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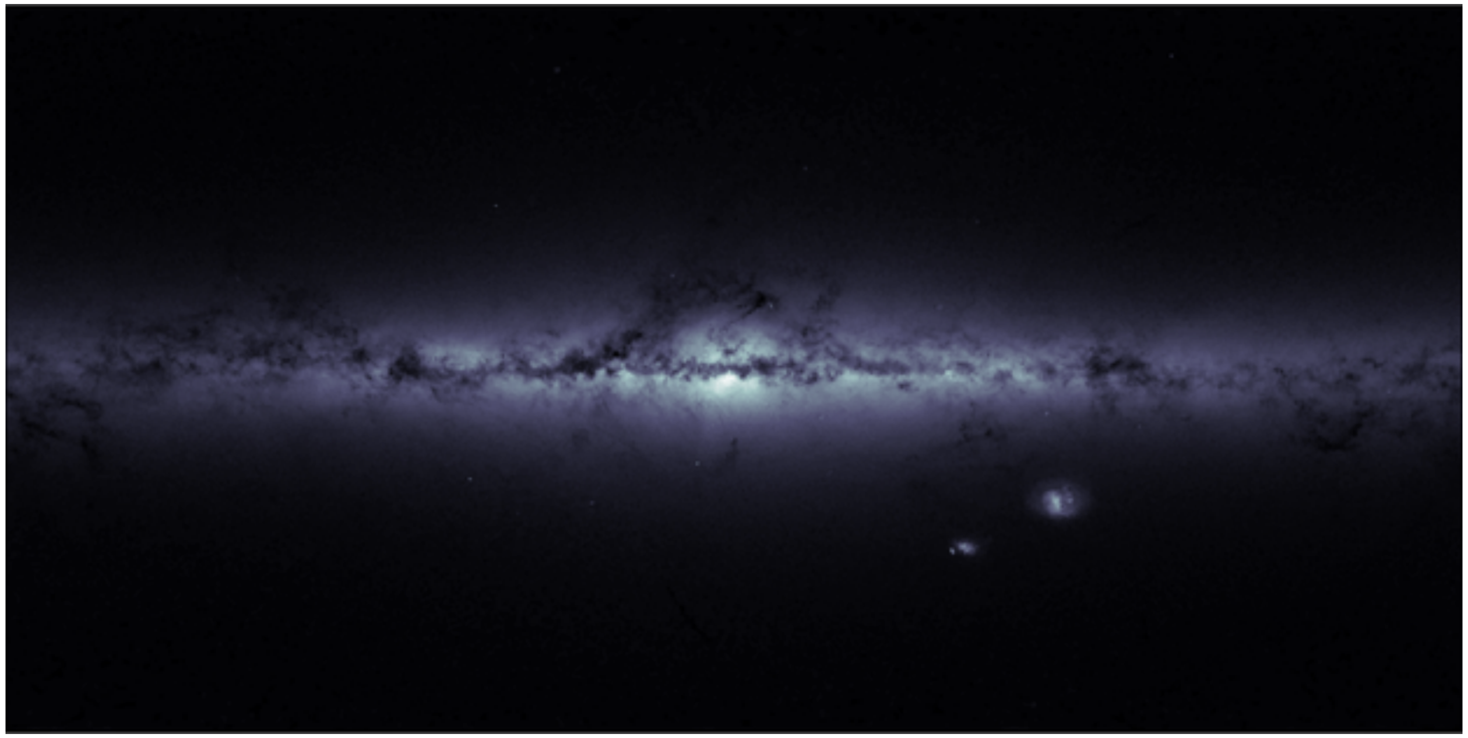

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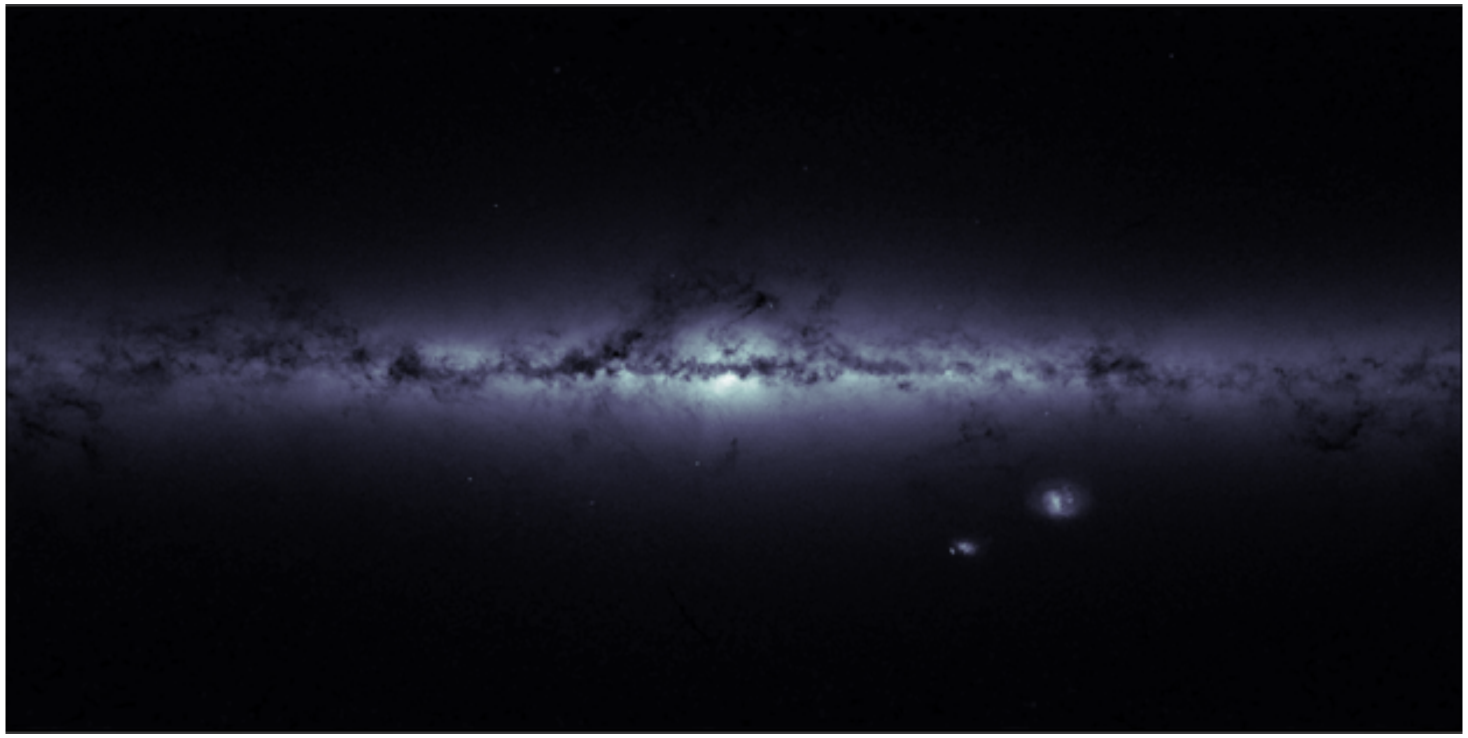

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The Milky Way in a cosmological context & stars as stellar-planetary architectures

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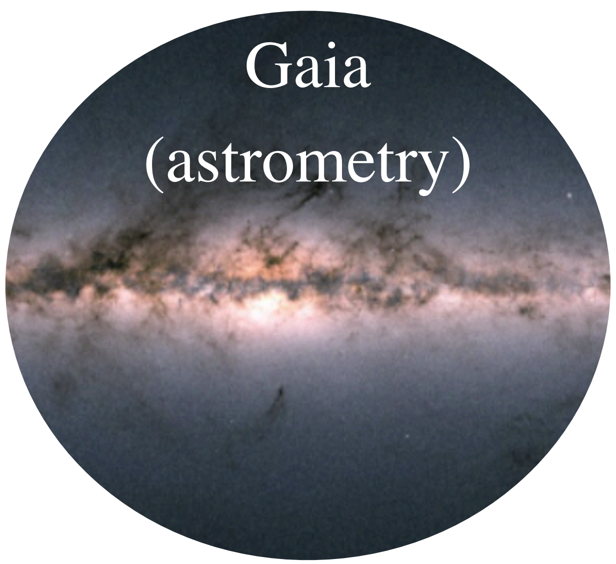

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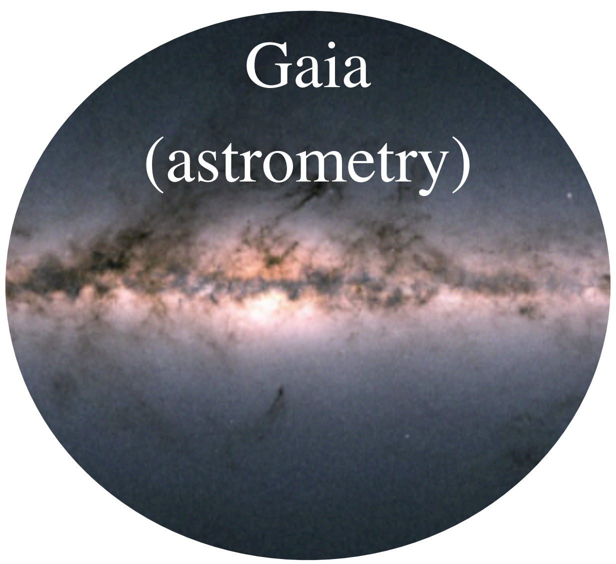

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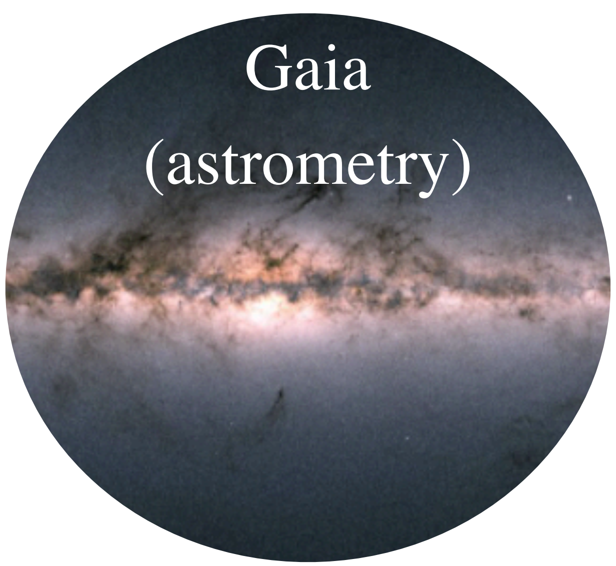

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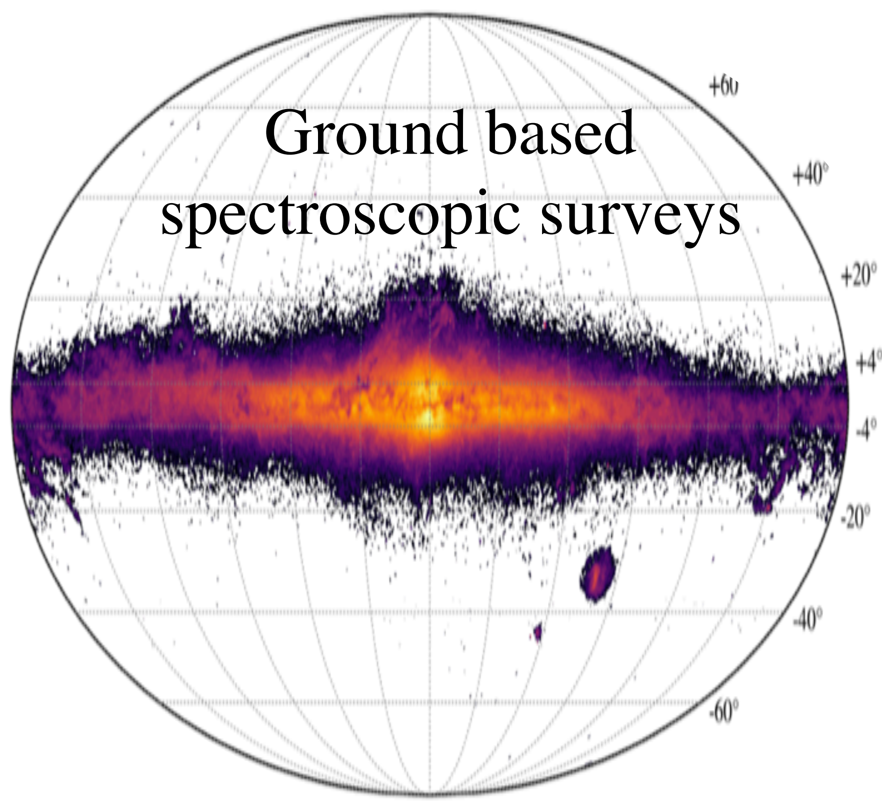

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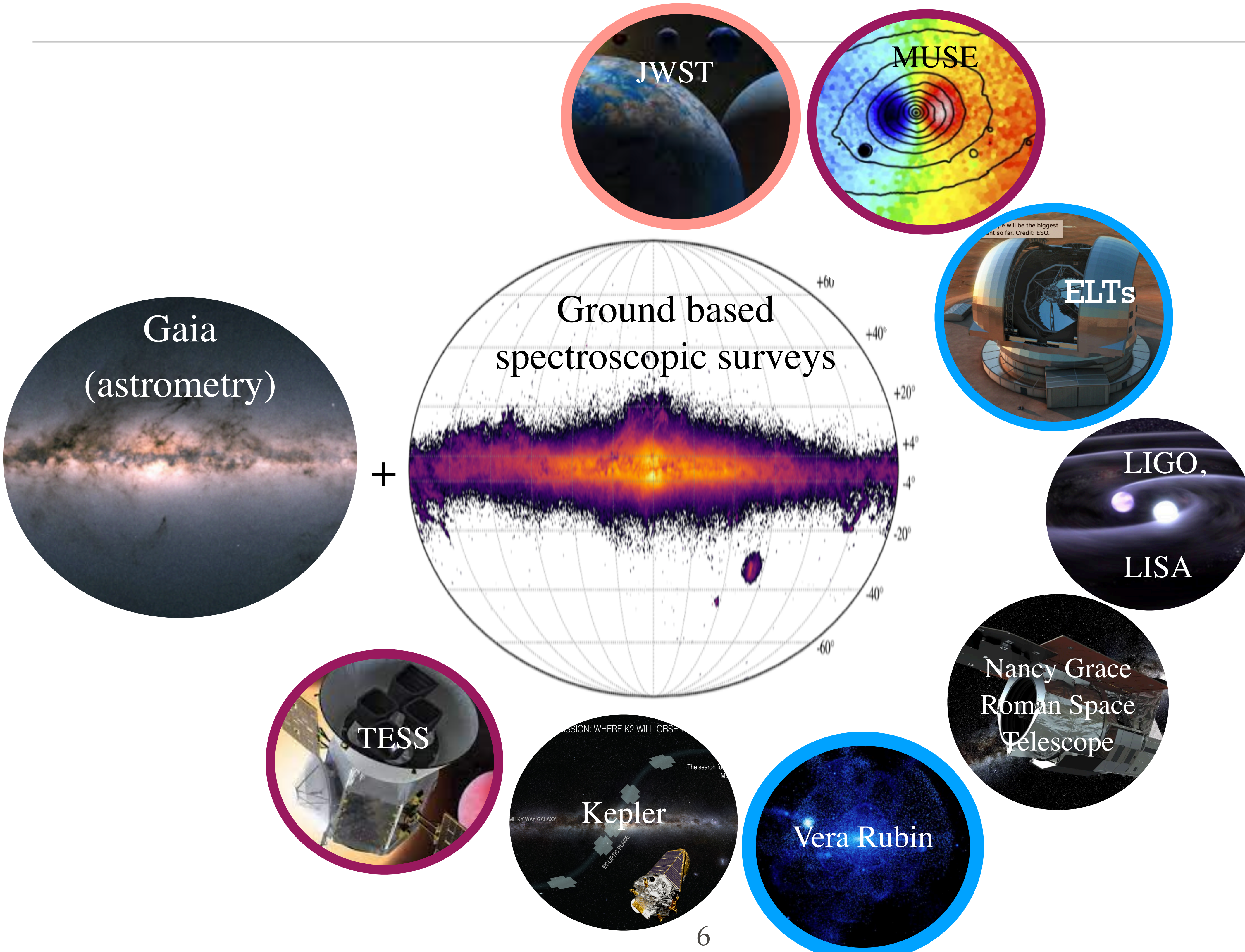

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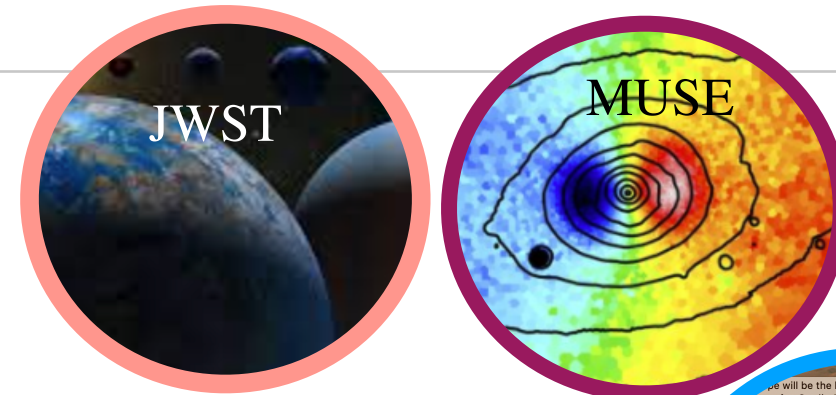
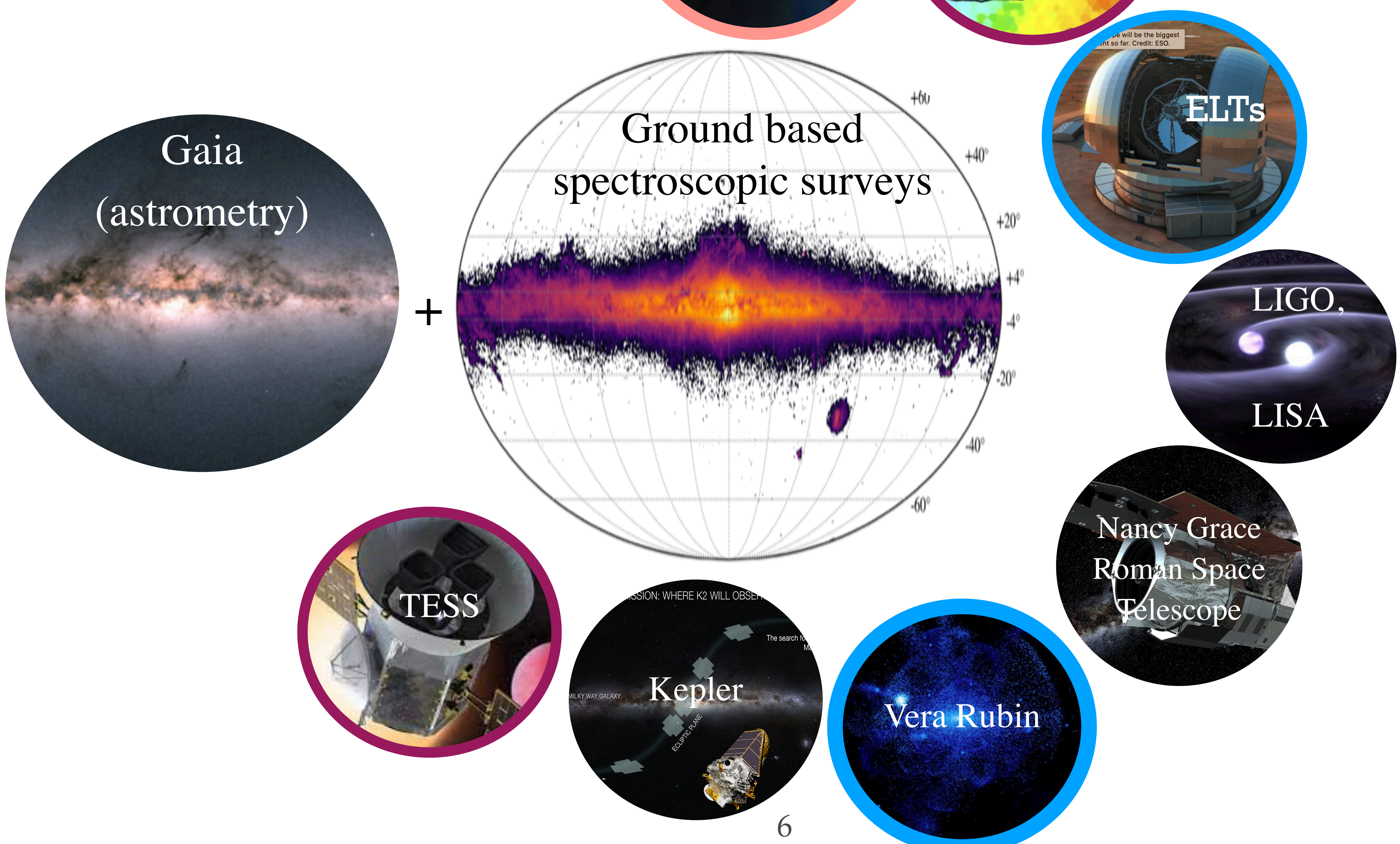


- An inventory of information across a huge range of spatial and temporal scales



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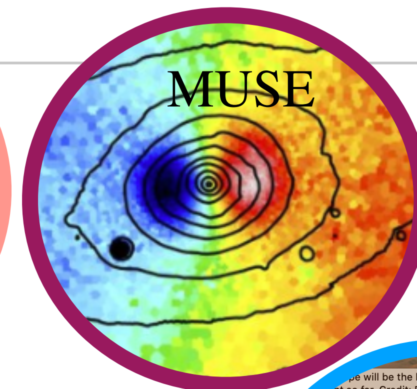

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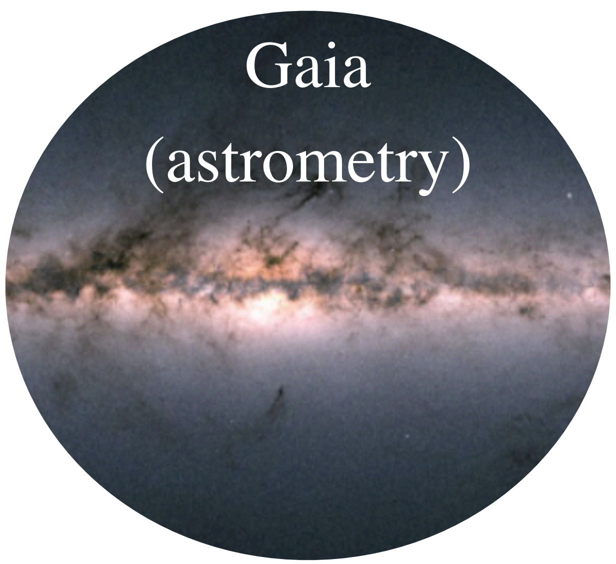

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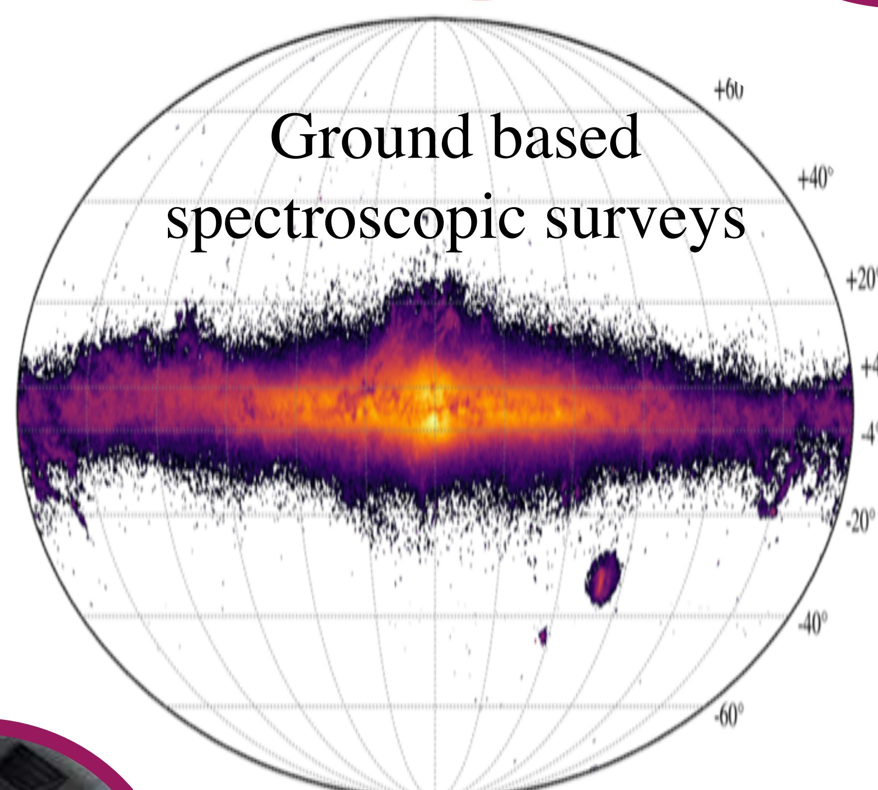

- Mapping (ages, velocities, metallicities)
  - Planets

Where is the Milky Way spectra coming from?

- Millions of spectra from a multitude of surveys — different λ, Resolution, spatial coverage:
  - Completed/current: APOGEE, GALAH, Gaia-ESO, RAVE, *Gaia*, LAMOST, SEGUE
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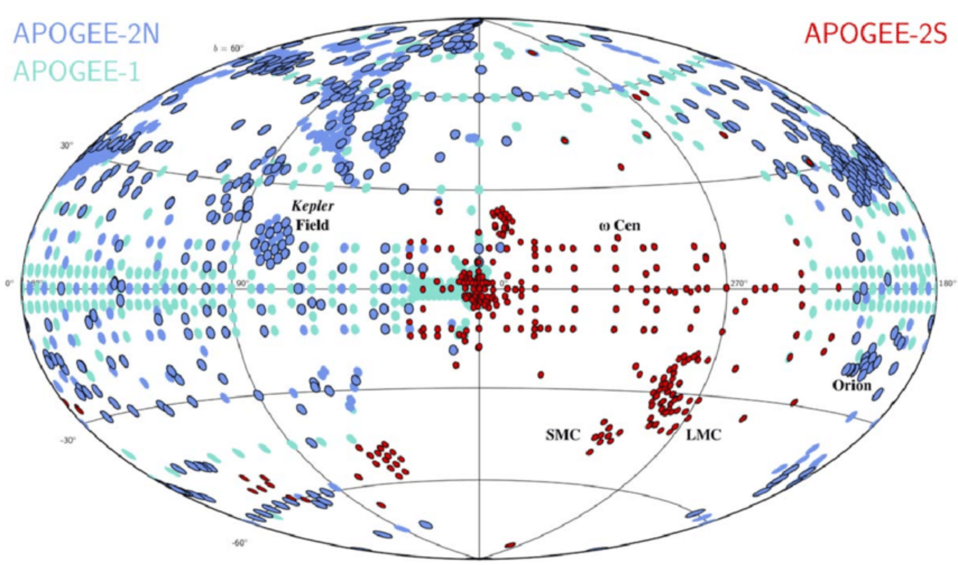

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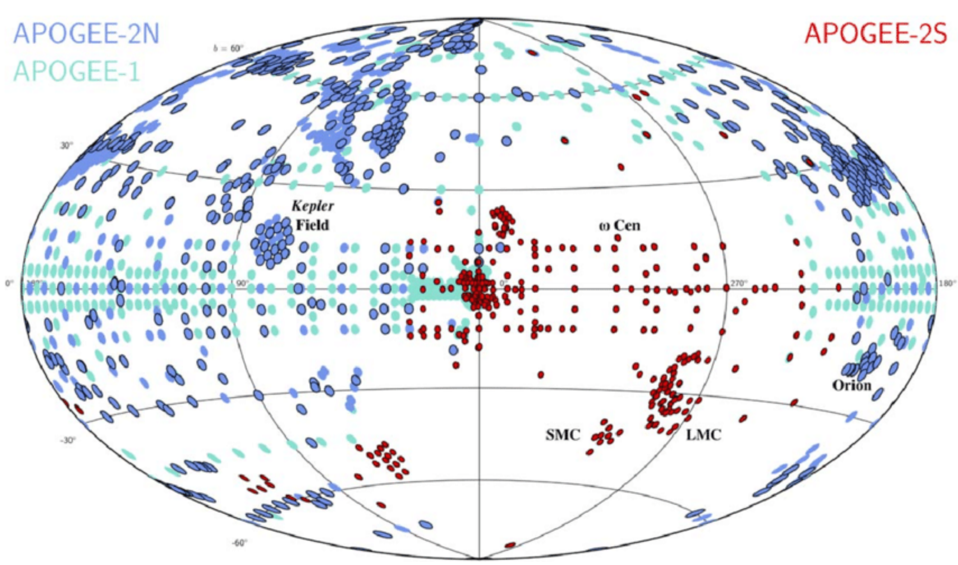

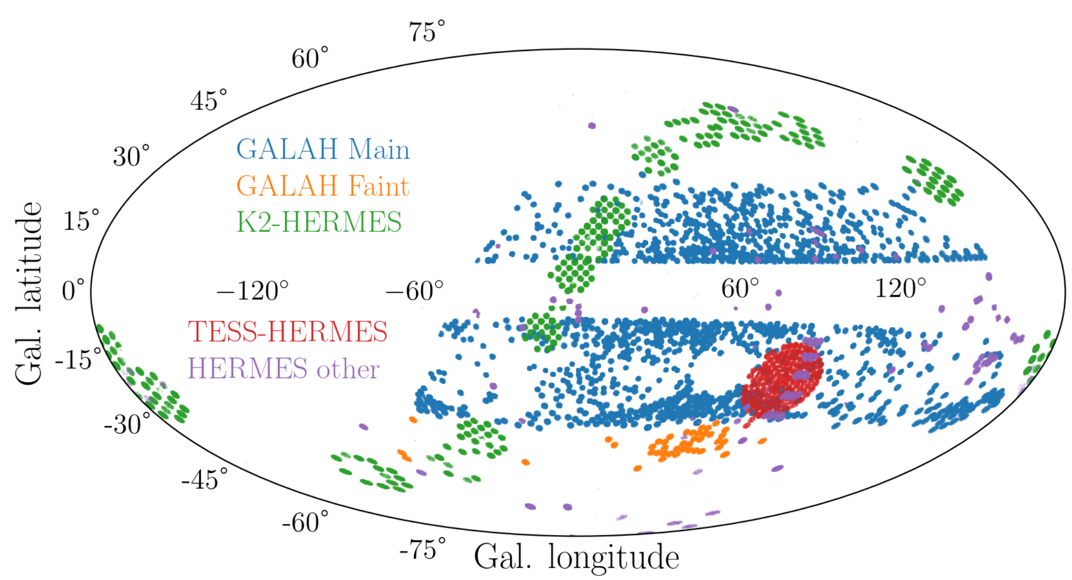

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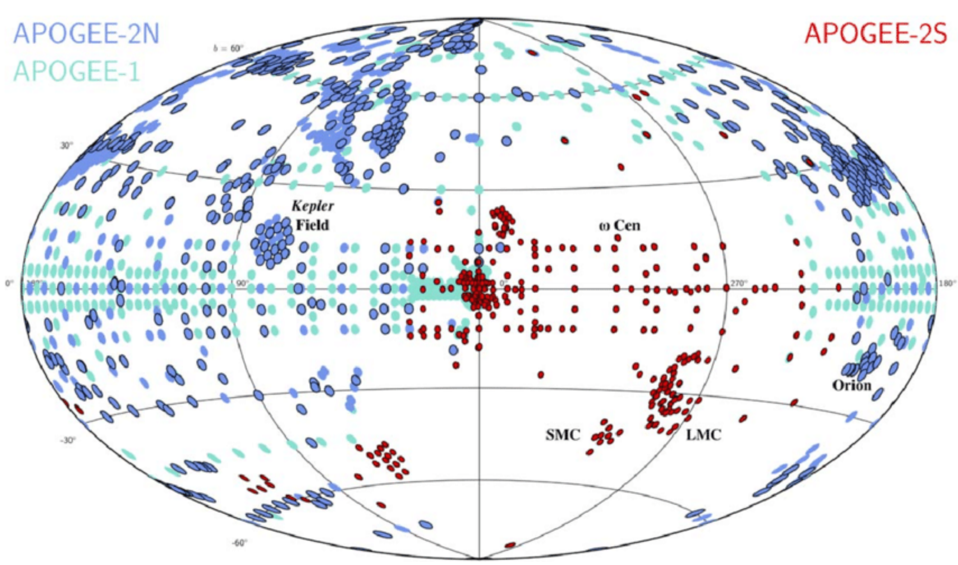

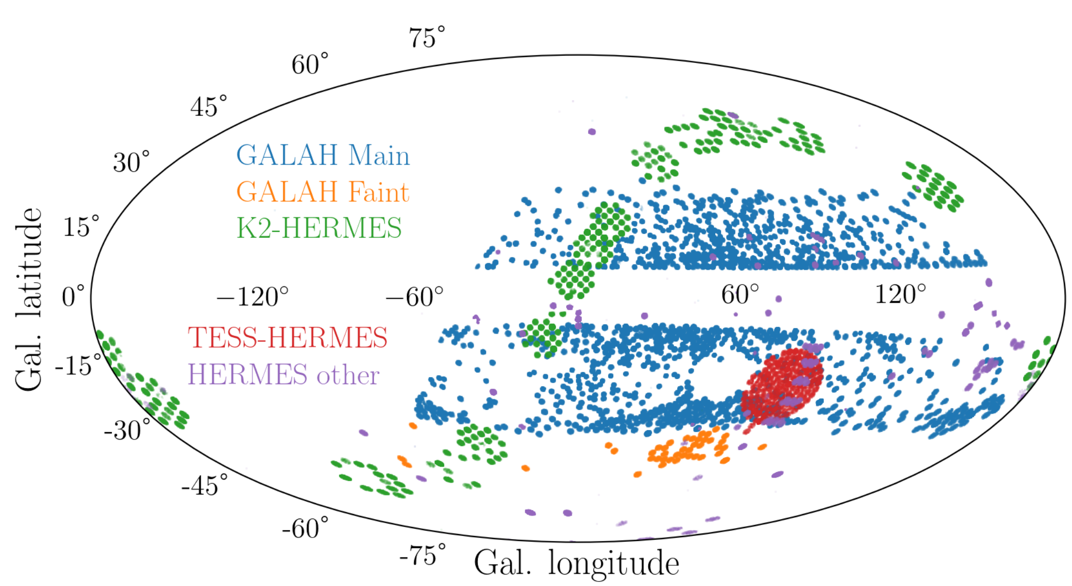

- Deliverables from spectra:
  - V_{rad}
  - **Teff, logg, [Fe/H] (stellar parameters) & [X/Fe] (chemical compositions)**

SDSS V Milky Way Mapper - 5 million stars across the Milky Way

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- A holistic view of the Galaxy — P.I. Juna Kollmeier (see Kollmeier et al., 2017)
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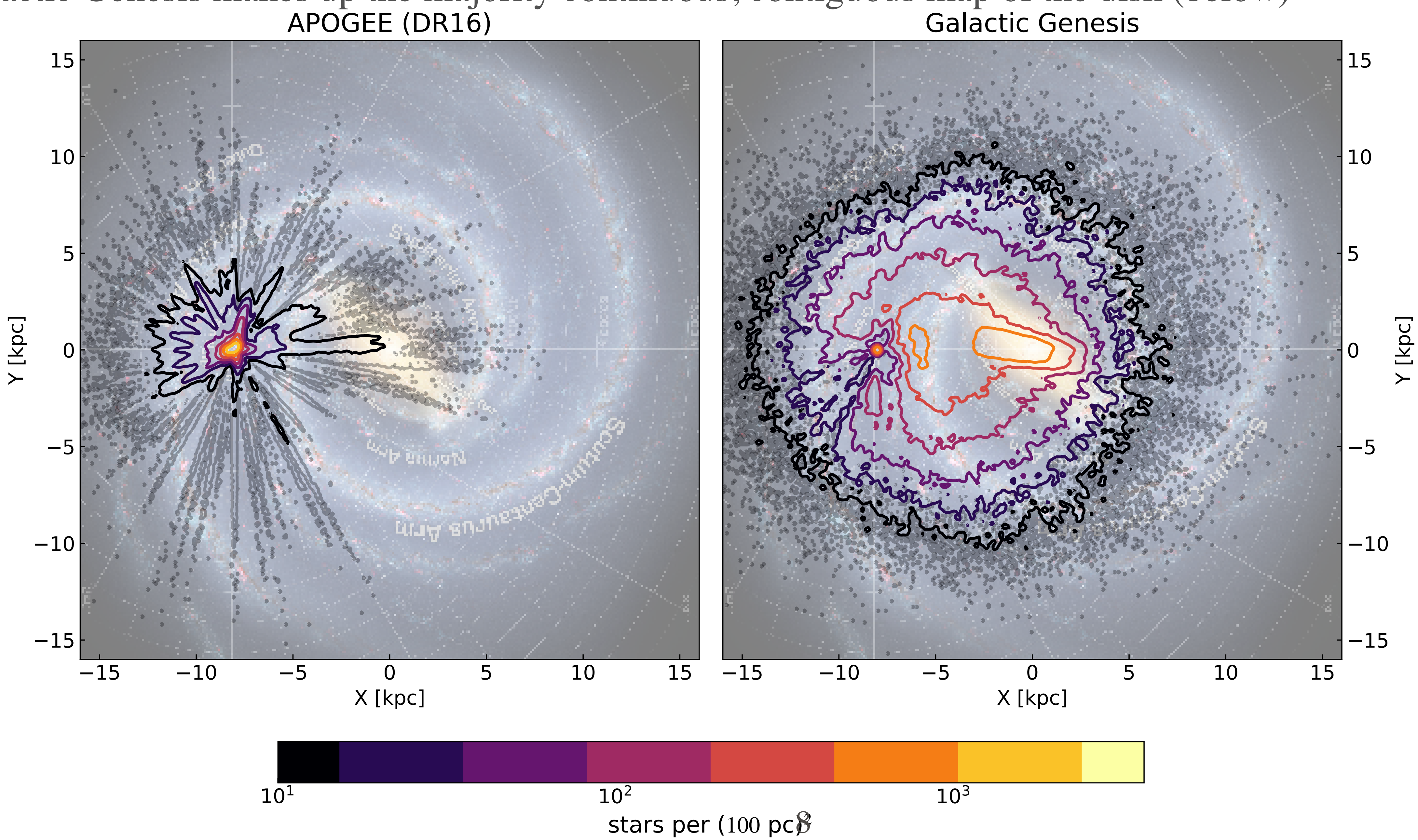

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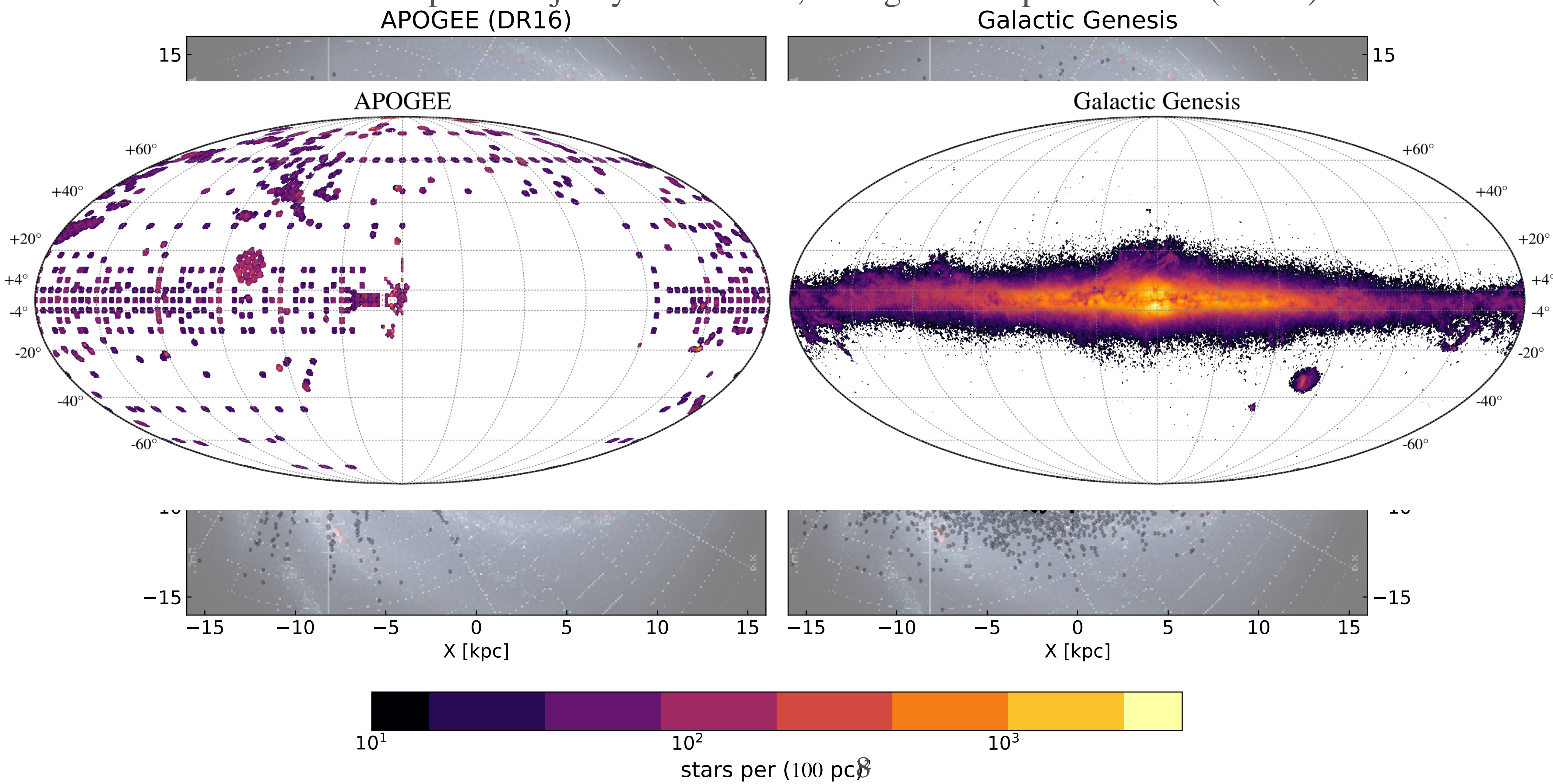

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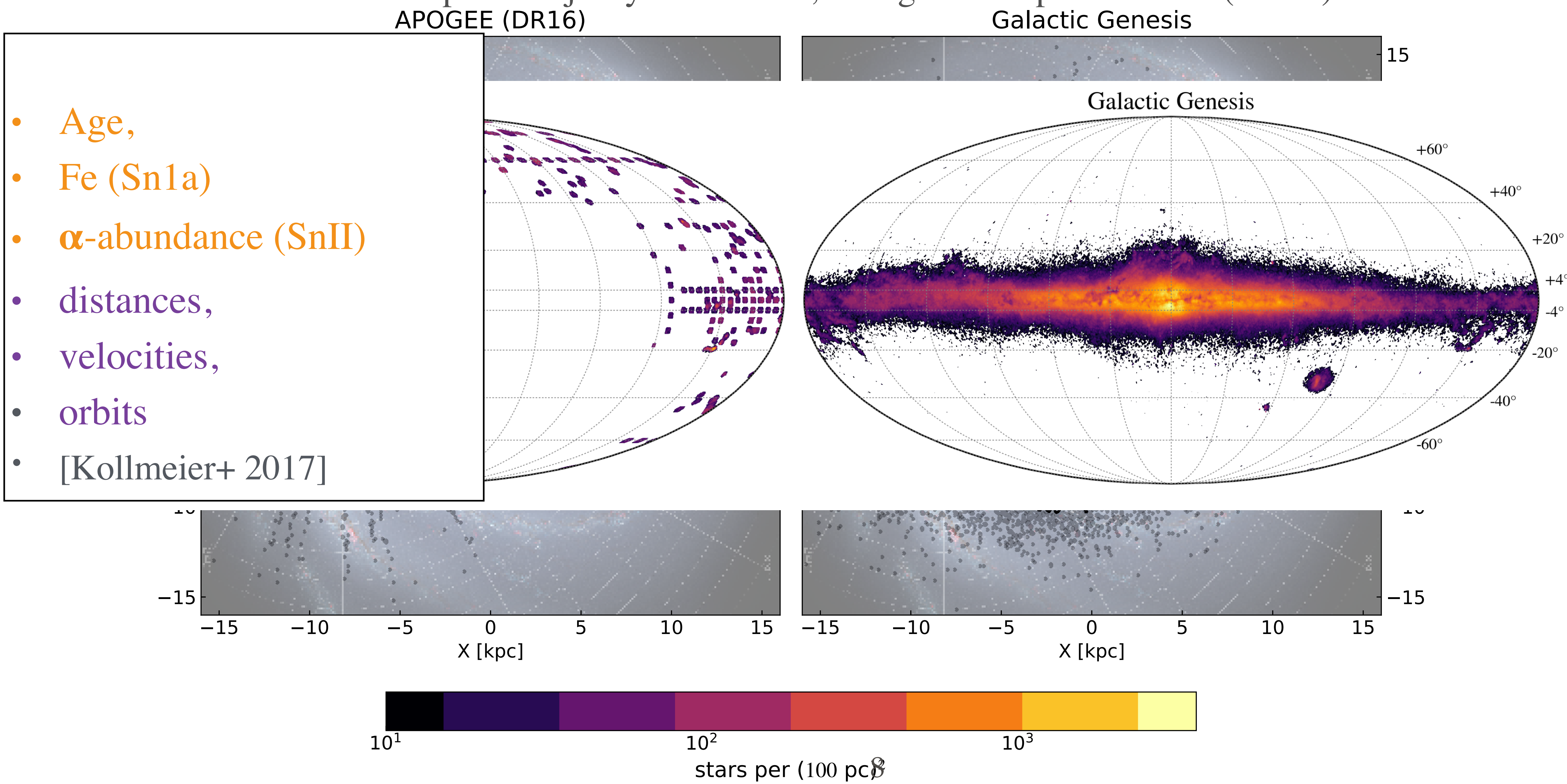

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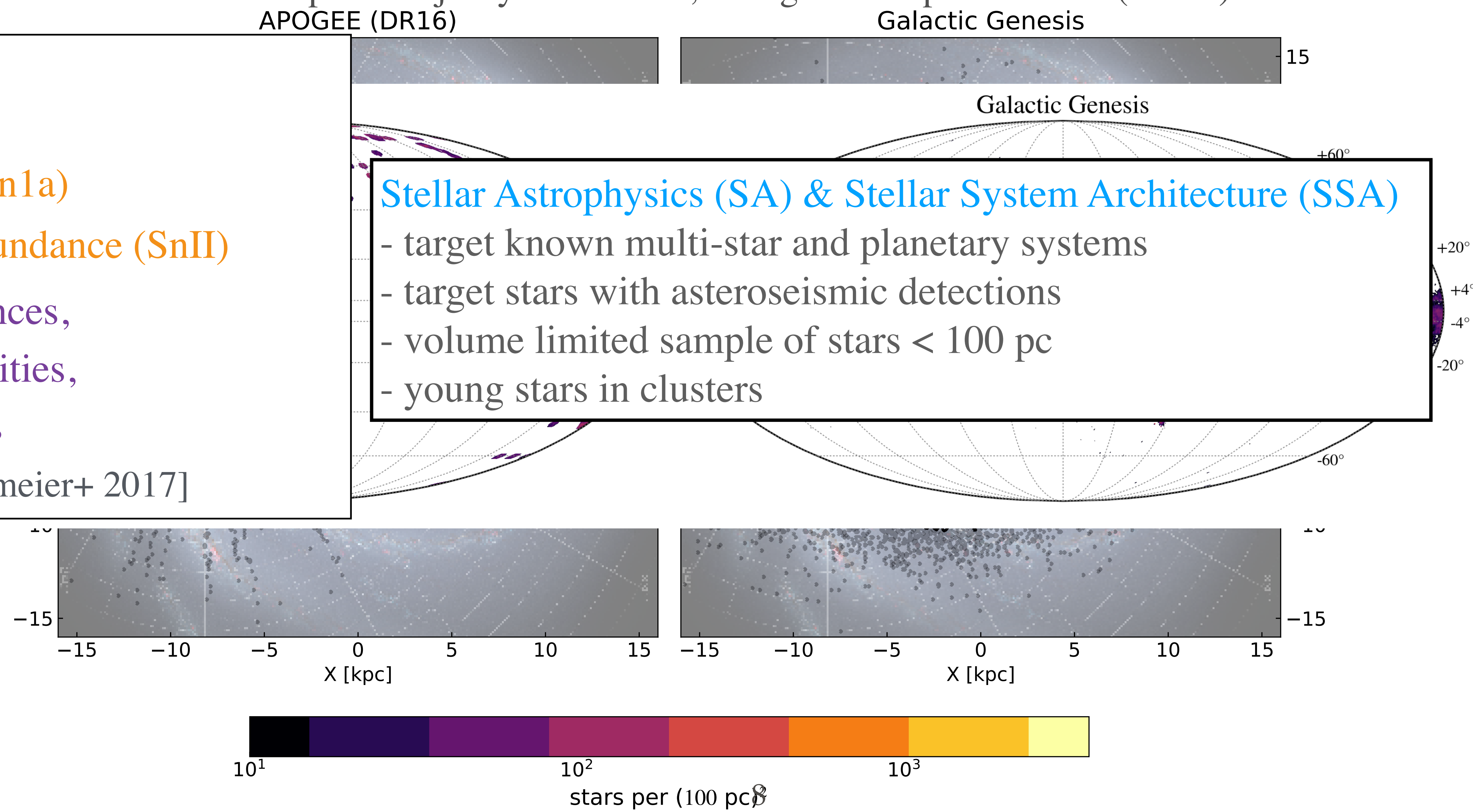

- Age,
- Fe (Sn1a)
- **α**-abundance (SnII)
- distances,
- velocities,
- orbits
- [Kollmeier+ 2017]

Stellar Astrophysics (SA) & Stellar System Architecture (SSA)

- target known multi-star and planetary systems
- target stars with asteroseismic detections
- volume limited sample of stars < 100 pc
- young stars in clusters

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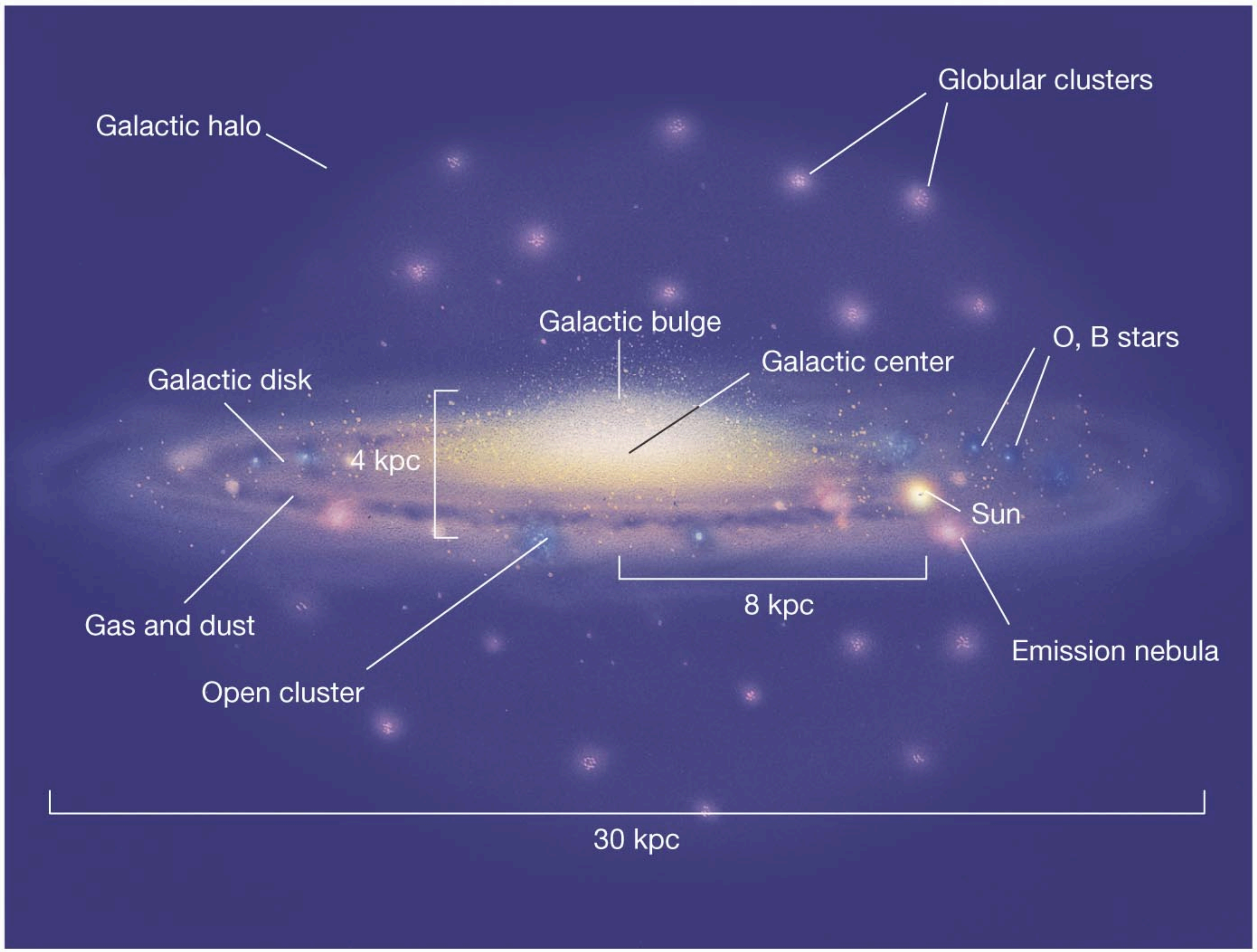
Milky Way Architecture



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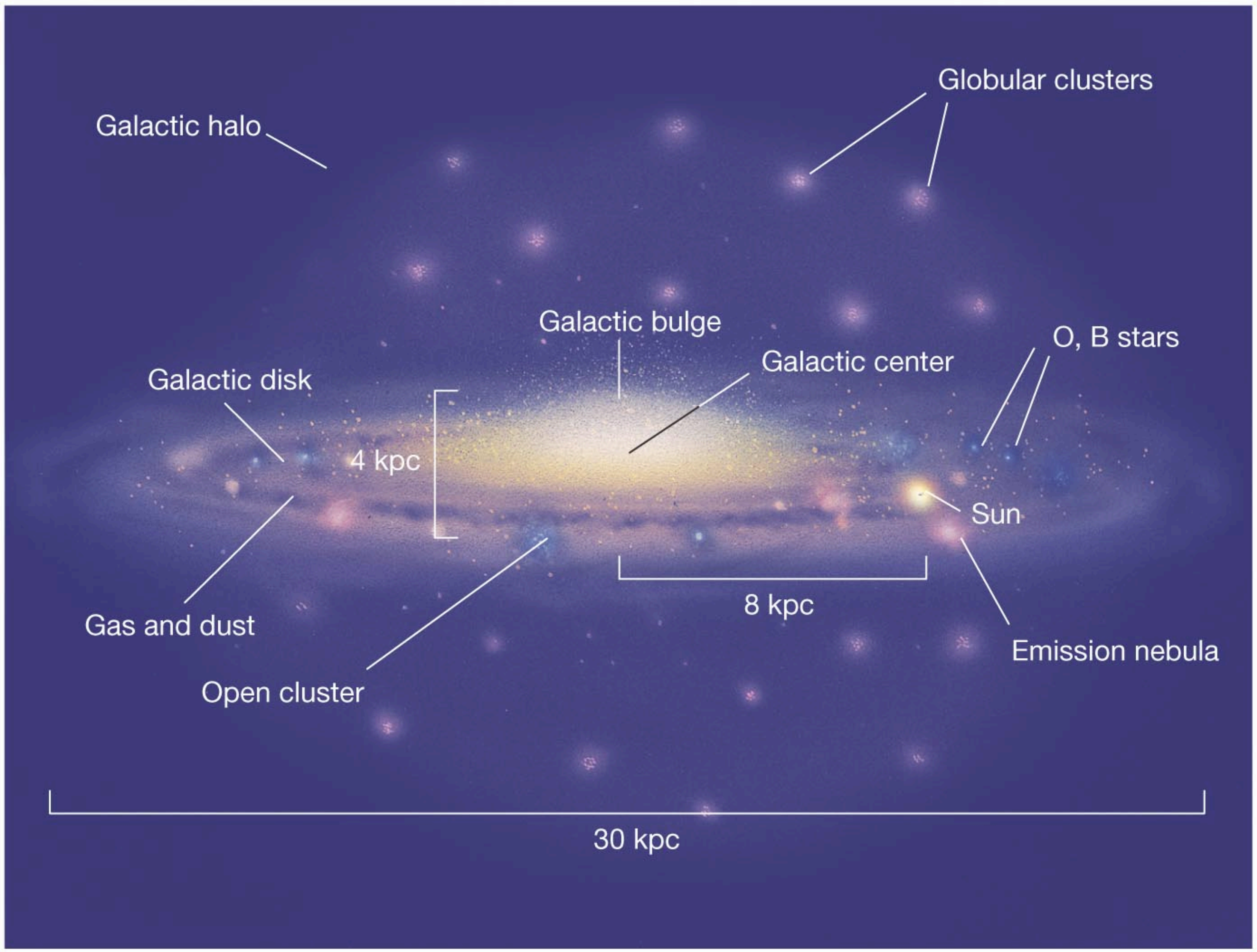

Different populations show different abundances and have different orbital properties

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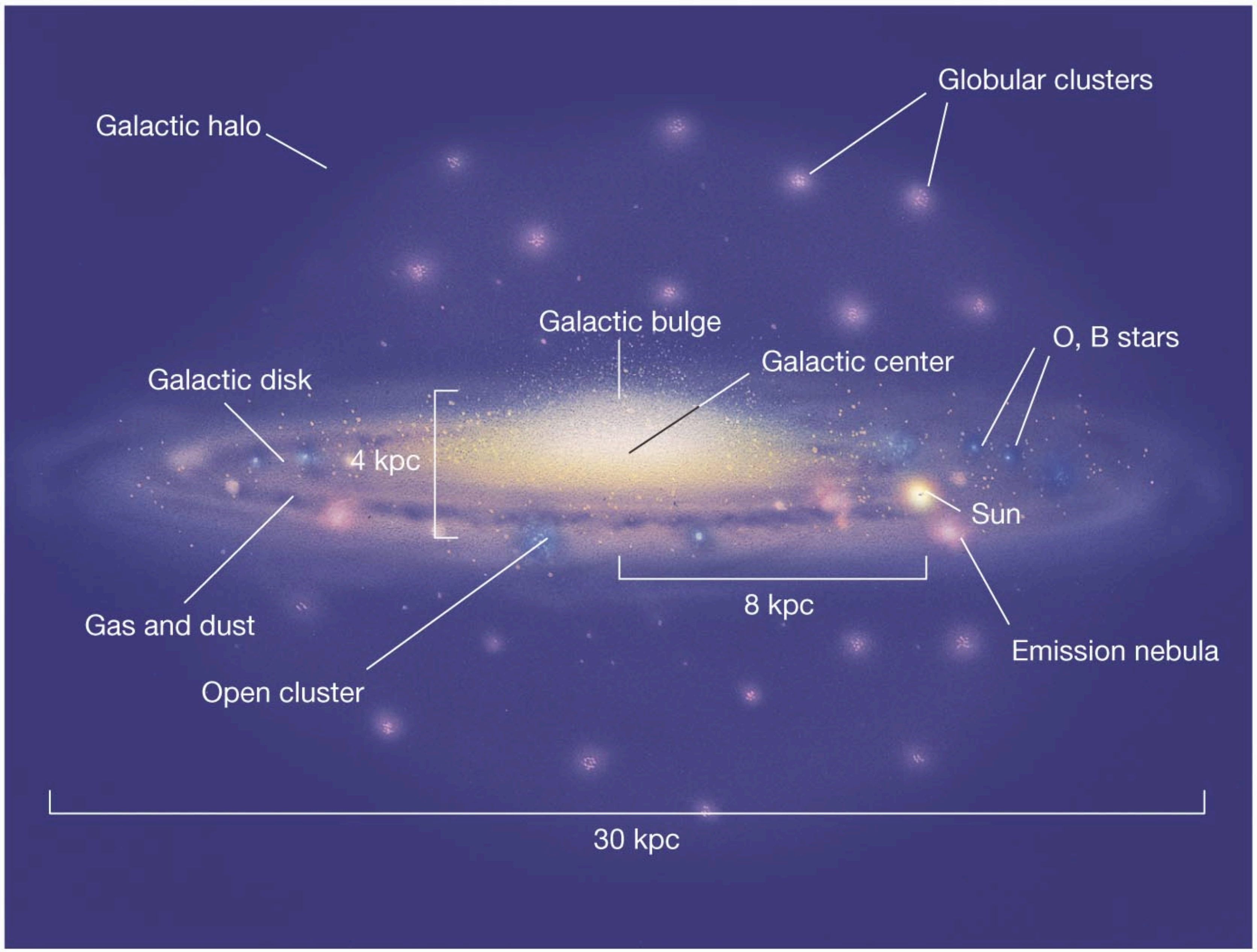


Different populations show different abundances and have different orbital properties

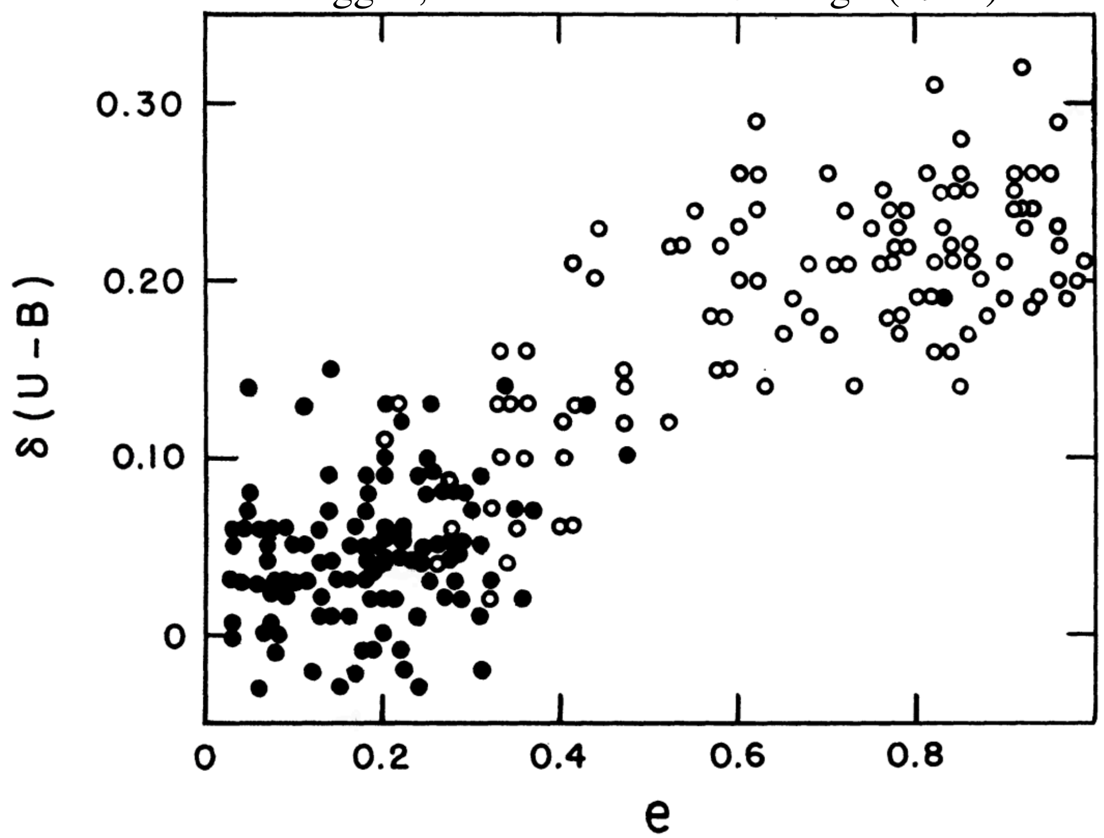
Stellar halo
1% of stellar mass but time capsule of early formation

Disk
75 % of stellar mass and record of assembly process

Bulge
24% of stellar mass and signature of formation events

The stellar halo

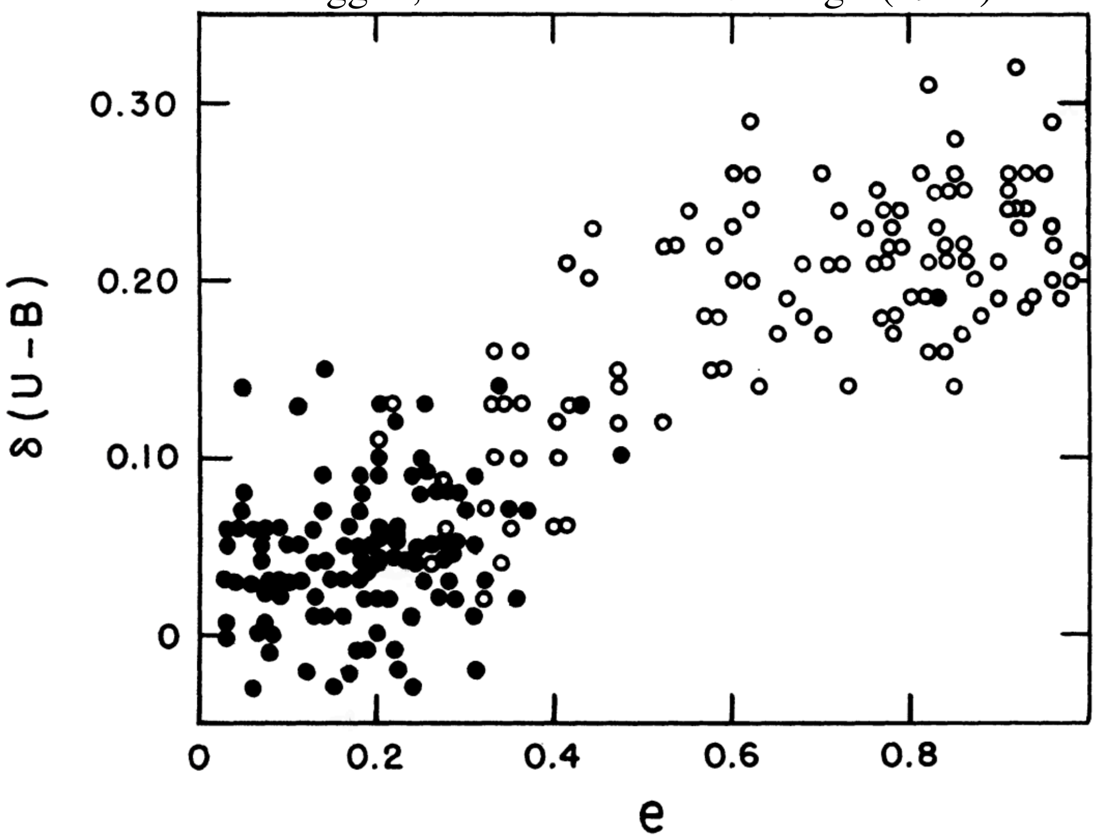
Eggen, Linden-Bell and Sandage (1962)



The stellar halo

More eccentric

Eggen, Linden-Bell and Sandage (1962)



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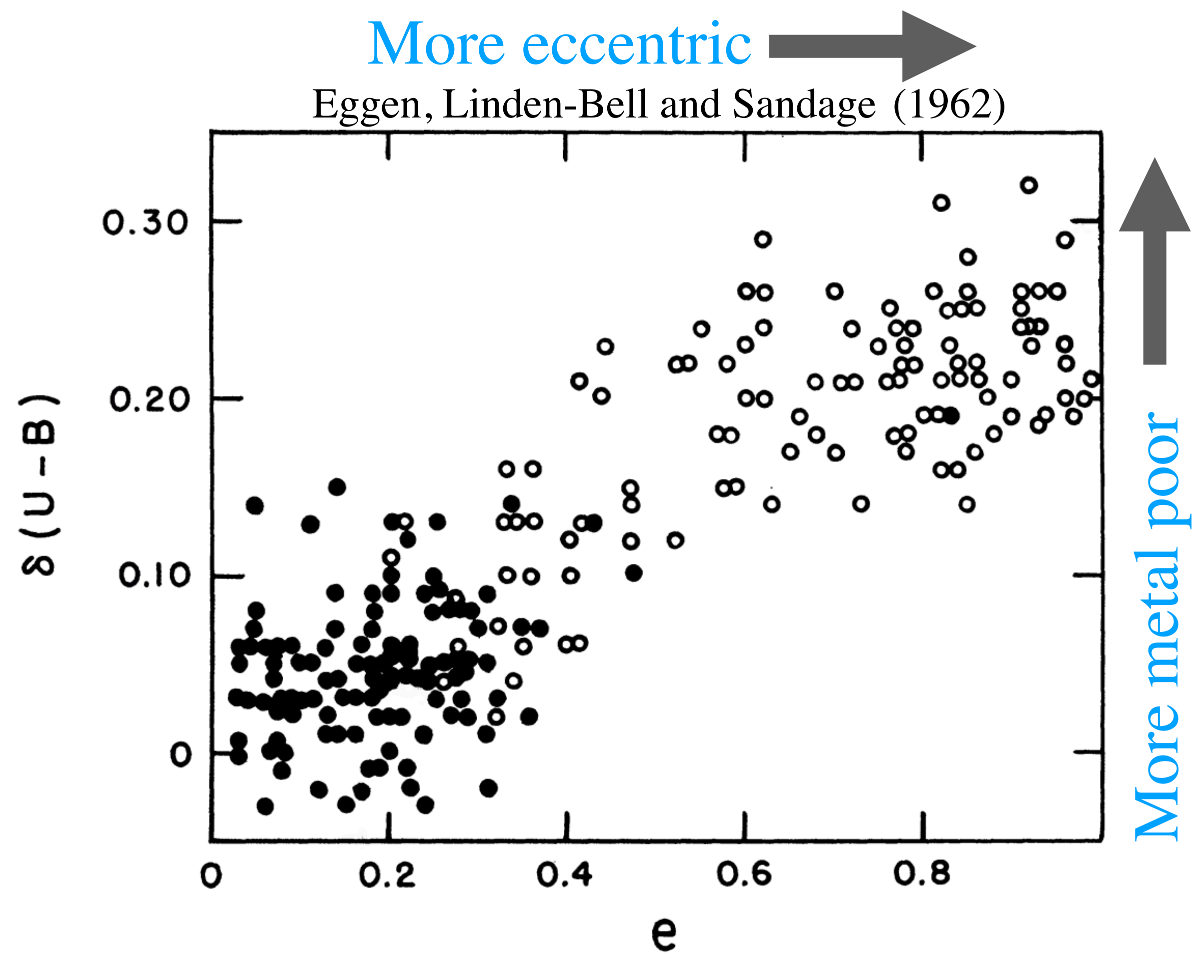
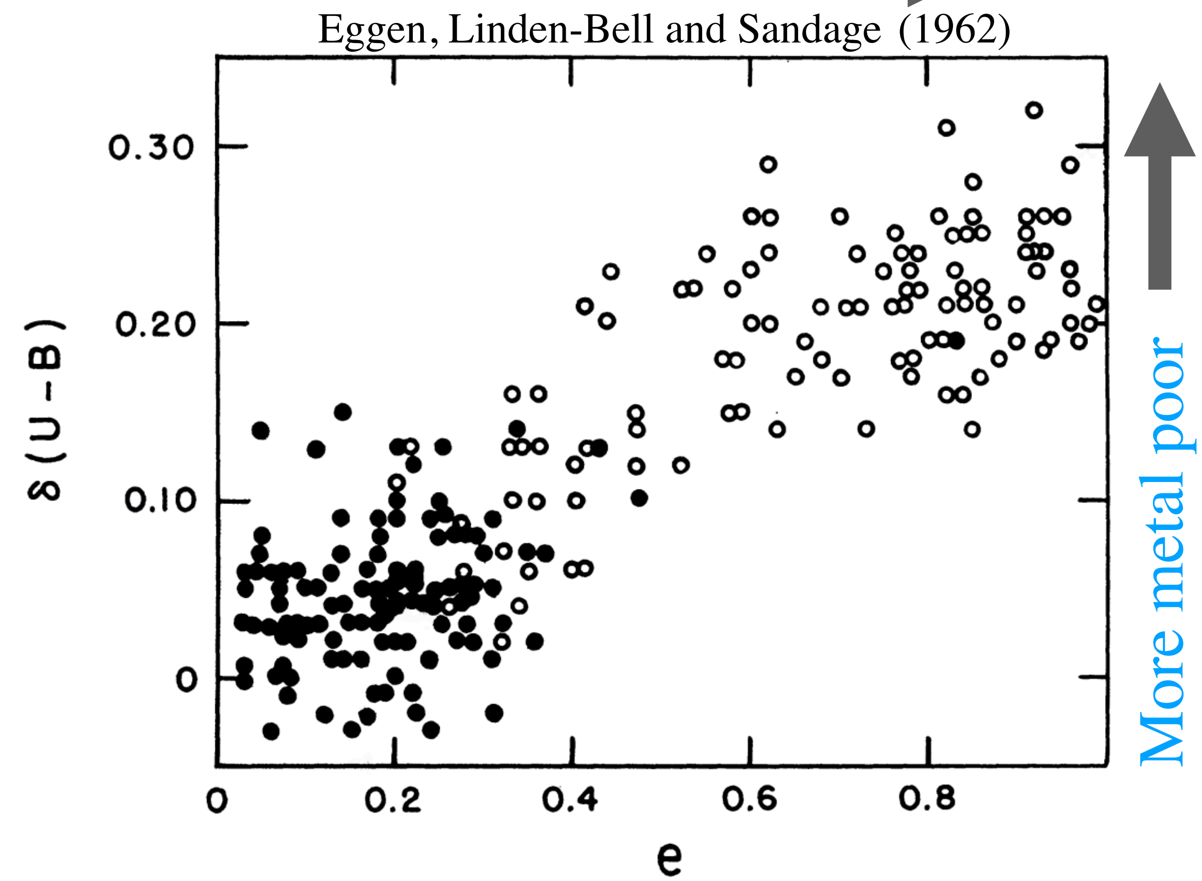


The stellar halo

Gaia+spectroscopic surveys -> substructure &
'in-situ' and 'accreted'

More eccentric



The stellar halo

Gaia+spectroscopic surveys -> substructure &
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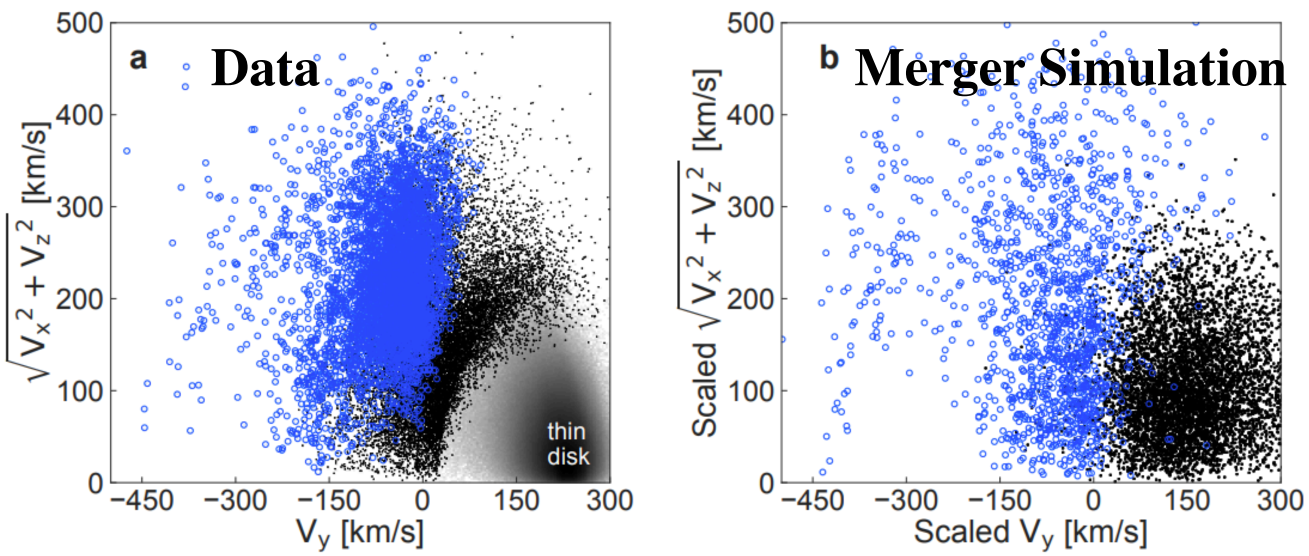
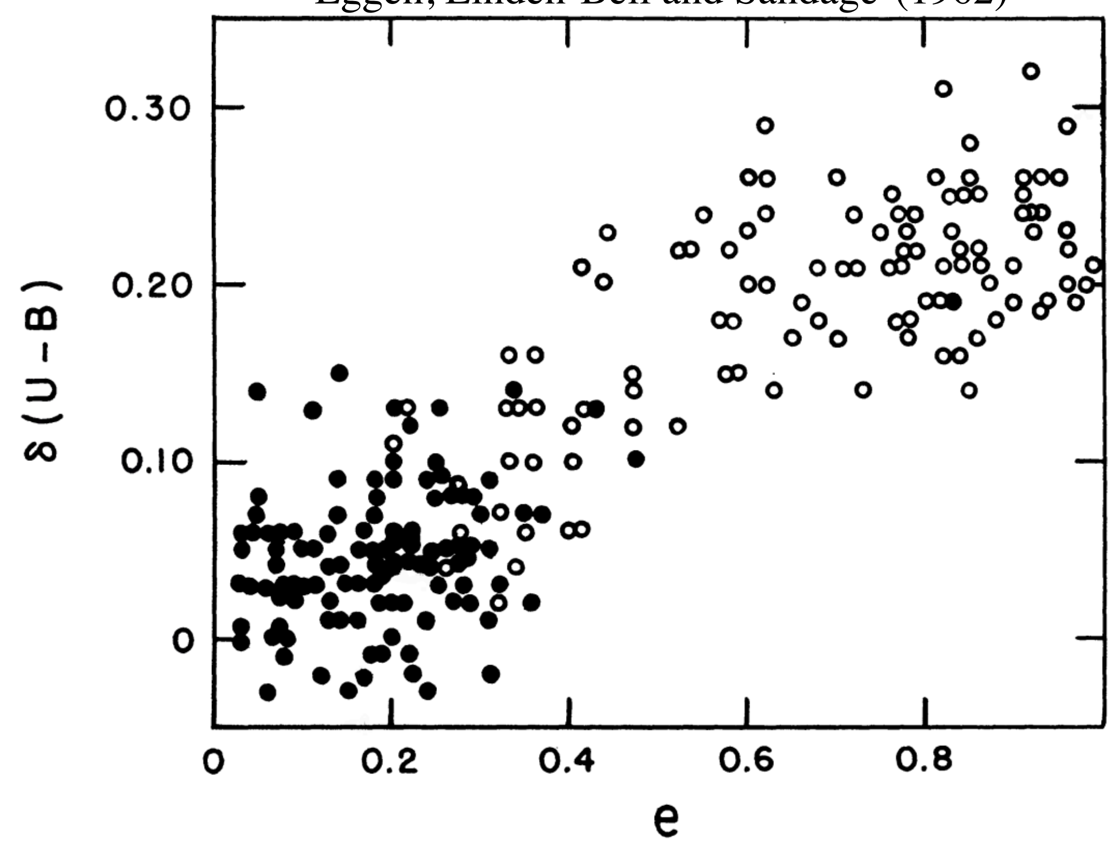
Helmi+ 2018: **Gaia-Encedaleus or Saussage**
(see also Belokurov+ 2018, Myeong+ 2018, Deason+ 2018)



Also noted by Nissen & Schuster (2010)

More eccentric

Eggen, Linden-Bell and Sandage (1962)



More metal poor

Industry in identifying & understanding halo field structures

e.g. Feuillet+ 2021, di Matteo + 2019, Buder+ 2022, Lane+ 2022, Bird+ 2021, An+ 2021, Das+ 2020, Deason+ 2019, Mackereth+ 2019

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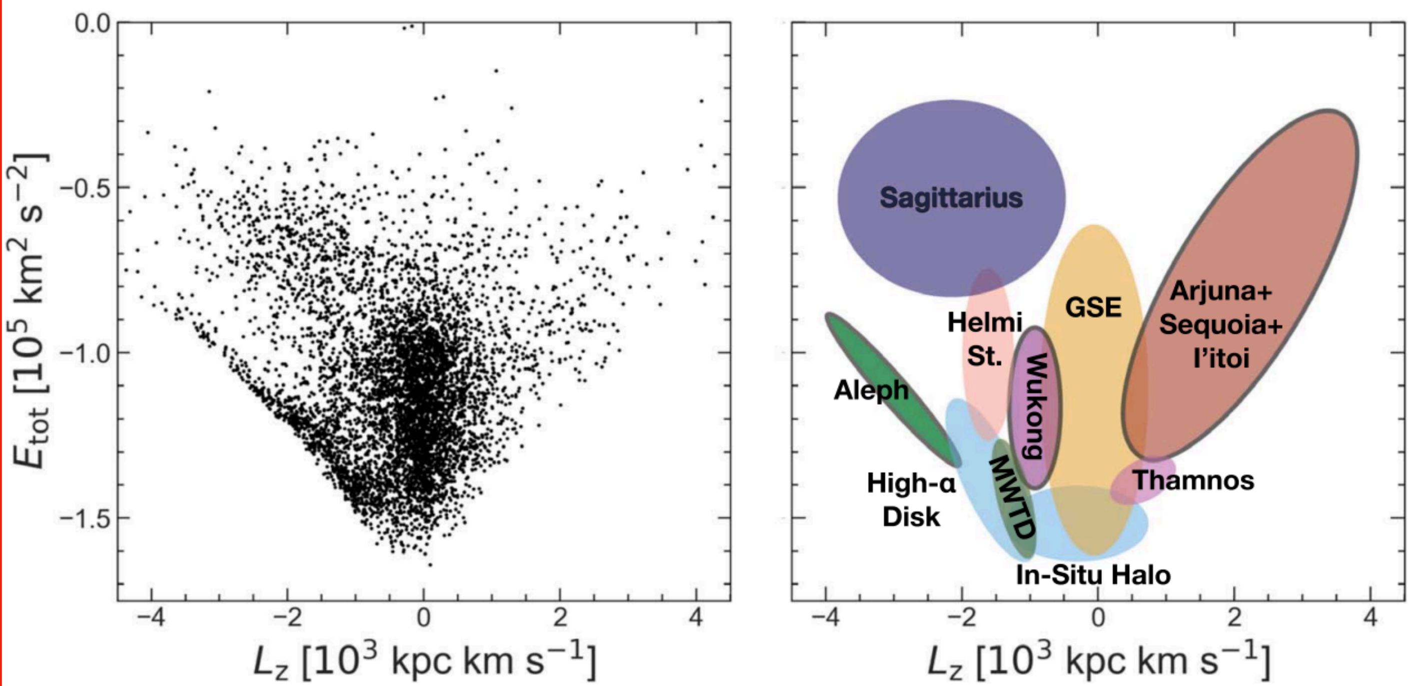
The MW halo is almost entirely composed of substructure
Naidu+ 2020, (H3 spectroscopic survey + Gaia) —



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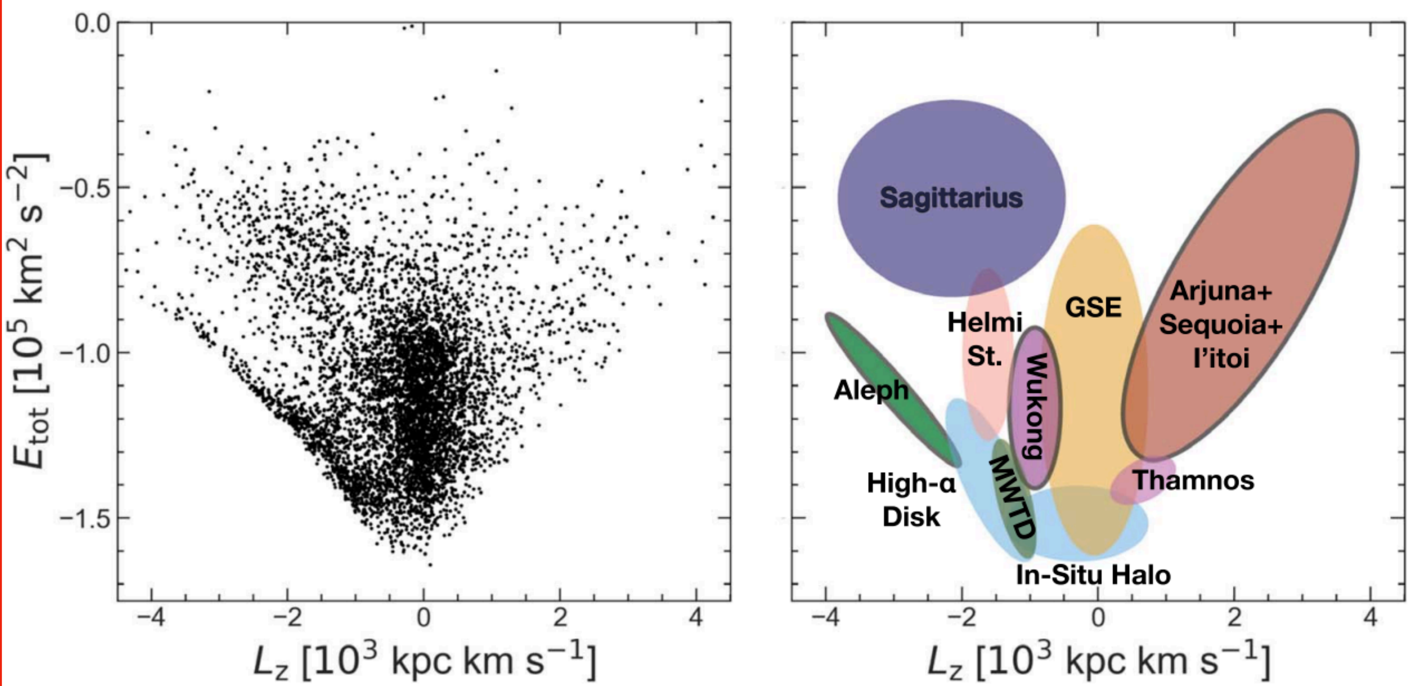
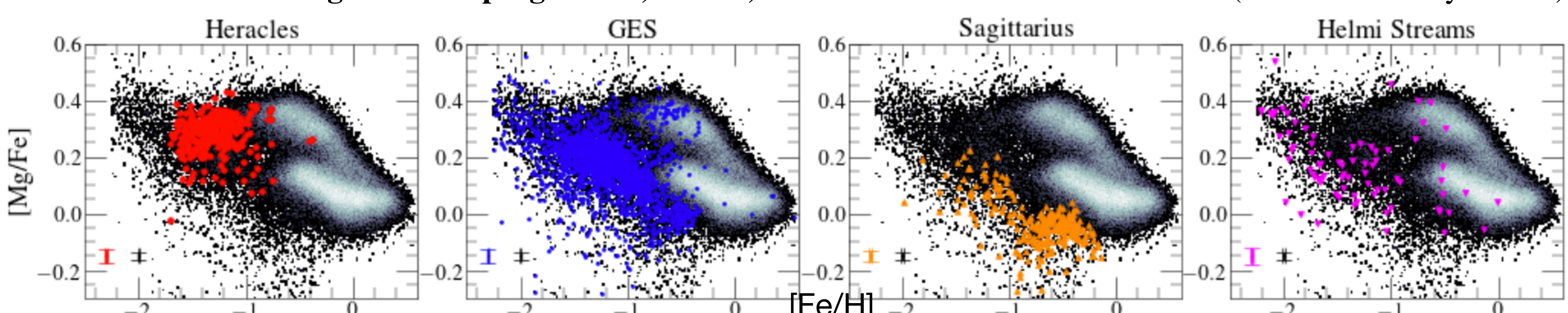


Abundances to organise into progenitors, ex-situ, in-situ and related — Horta+ 2022 (APOGEE survey + Gaia)



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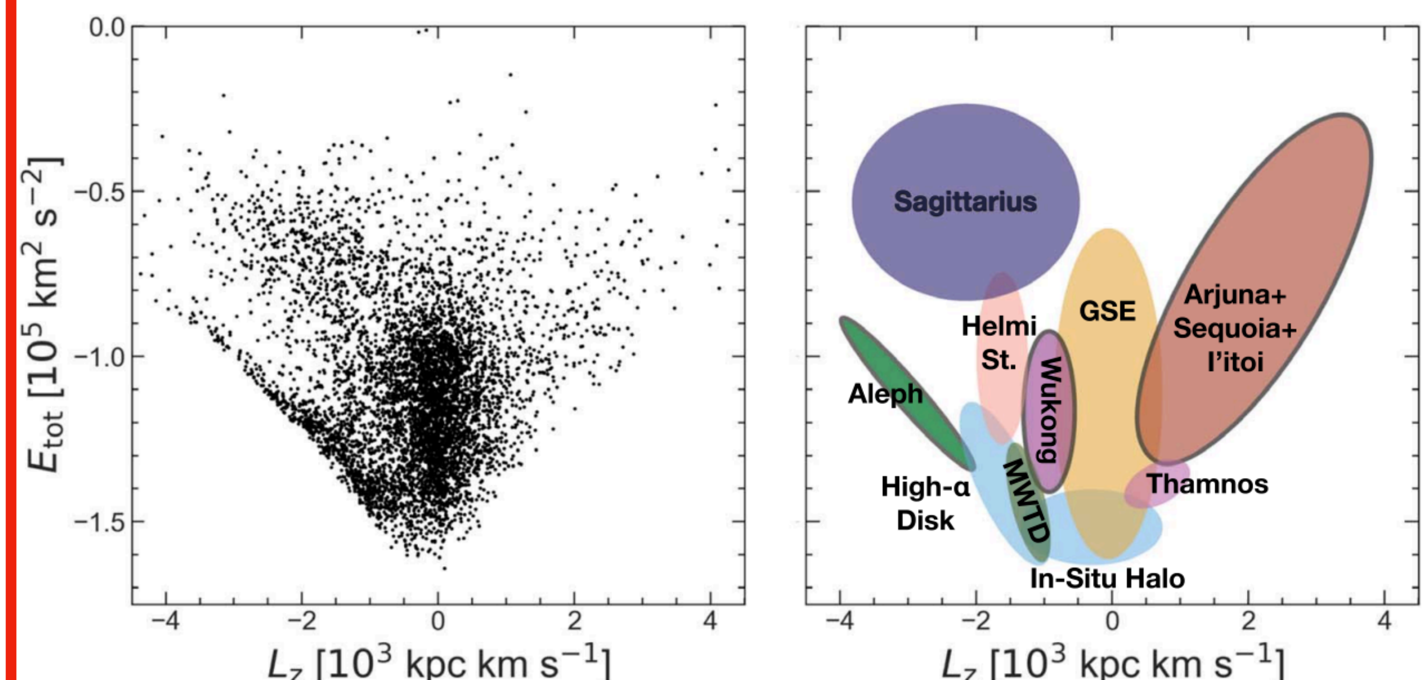
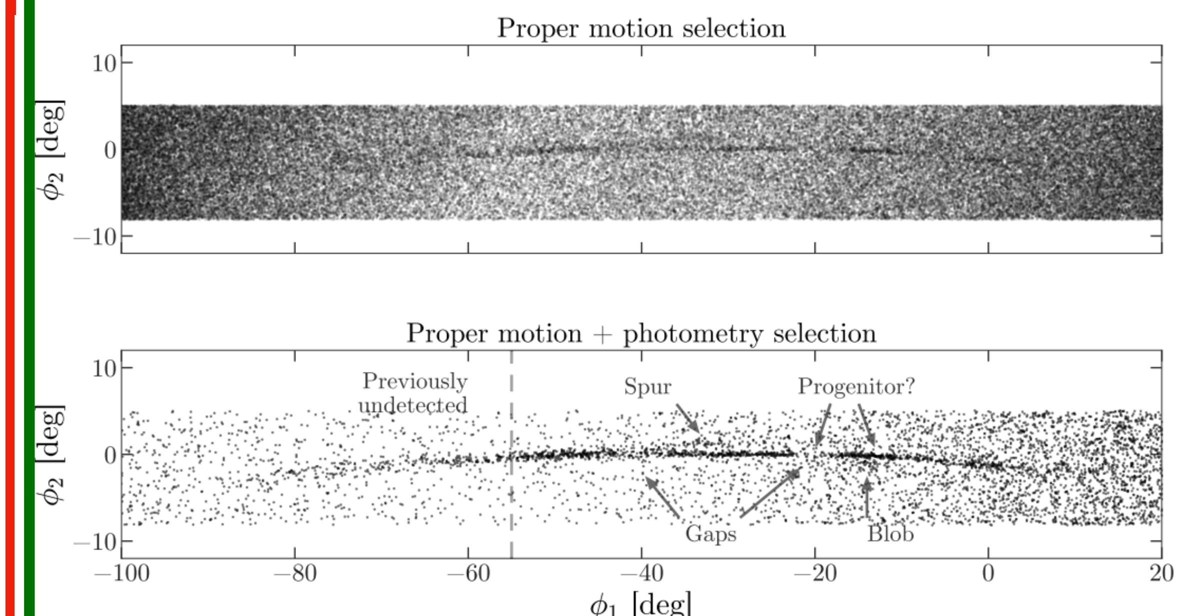
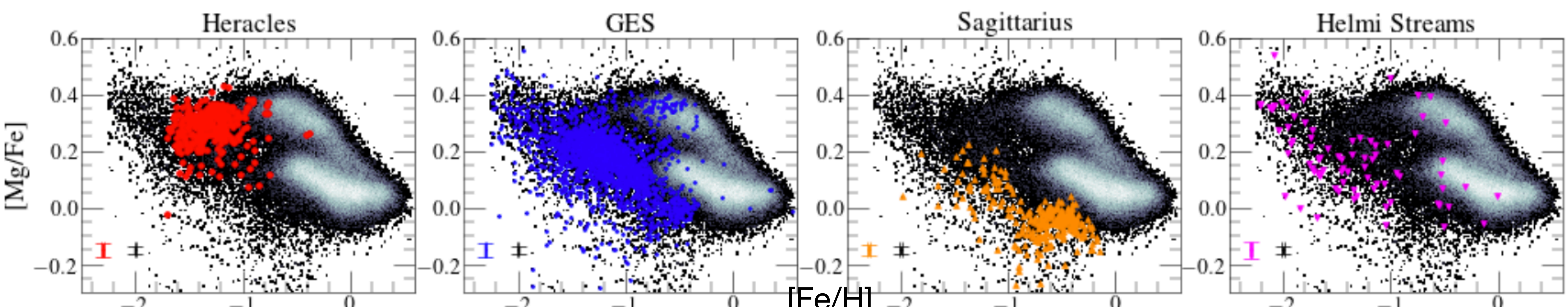


Streams and possible dark-matter sub halo interaction:
GD1 (PANSTARRS and GAIA)— Price-Wheelan & Bonaca 2018, Bonaca+ 2018, (also see Banik & Bovy + 2019)

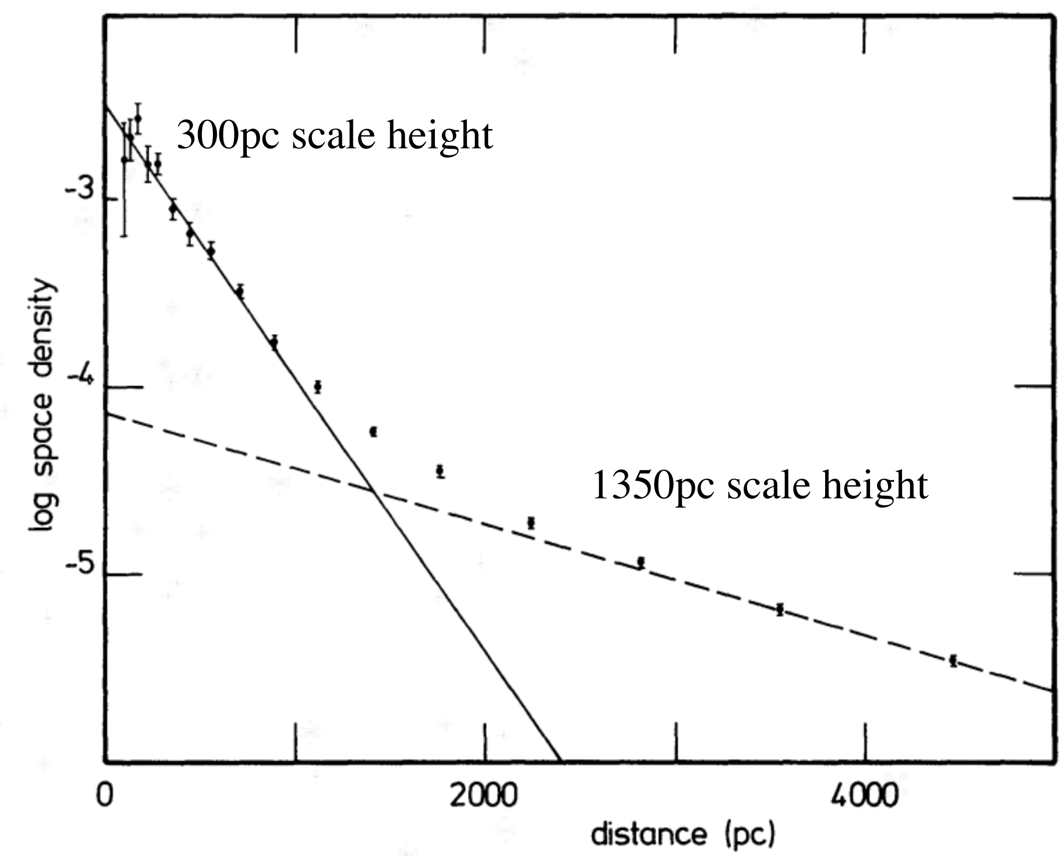


Abundances to organise into progenitors, ex-situ, in-situ and related — Horta+ 2022 (APOGEE survey + Gaia)



The Milky Way disk

"Thin" and "Thick" disk
Gilmore & Reid 1983



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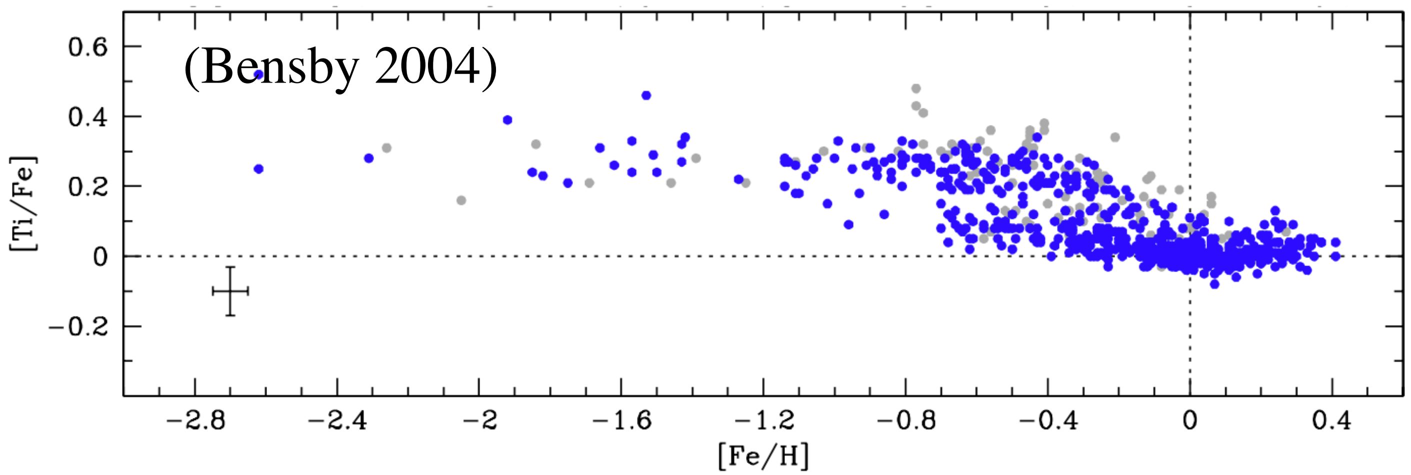

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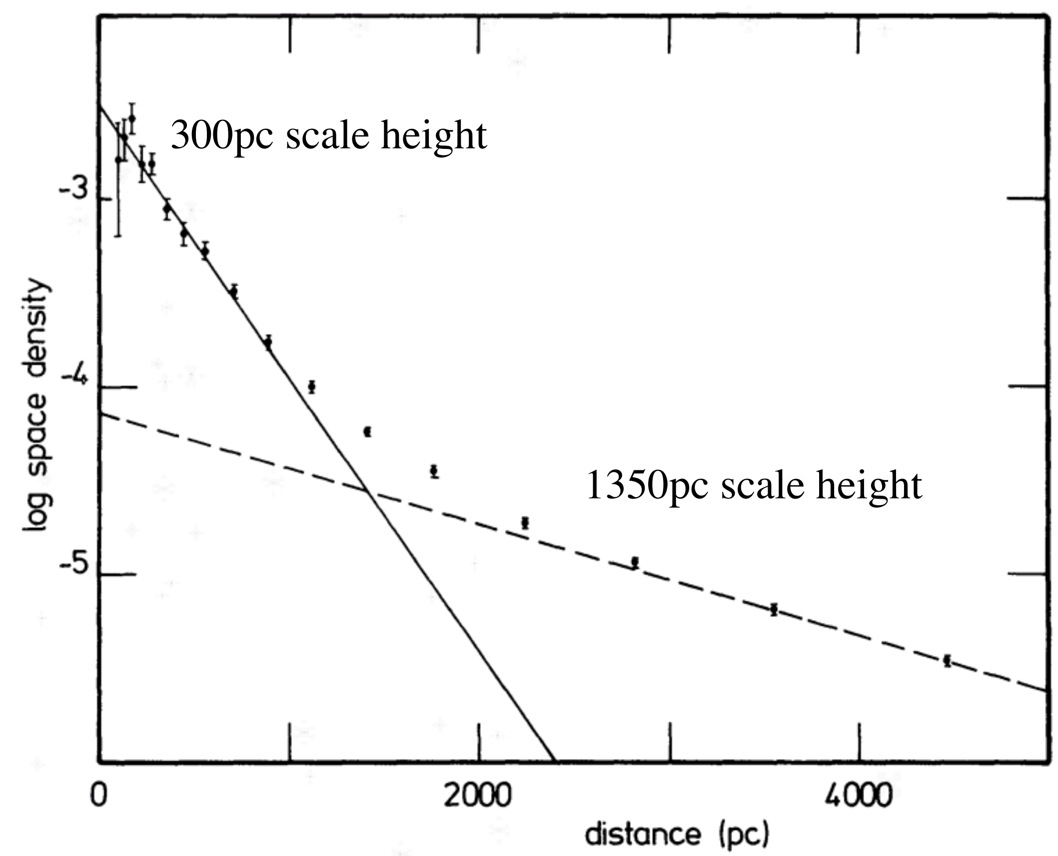

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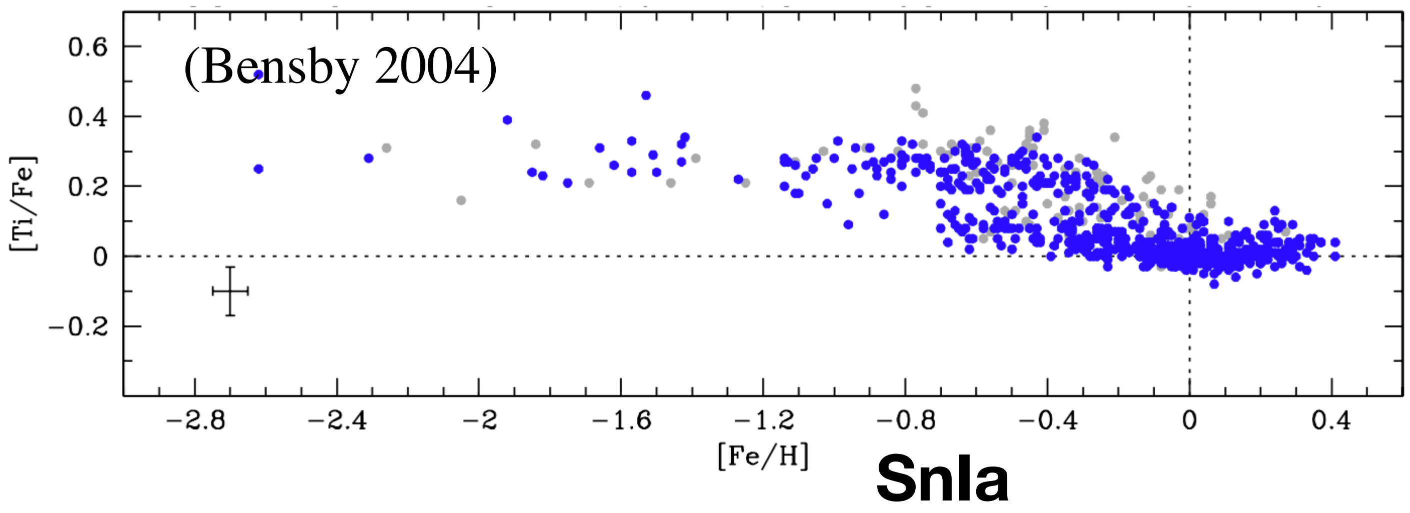

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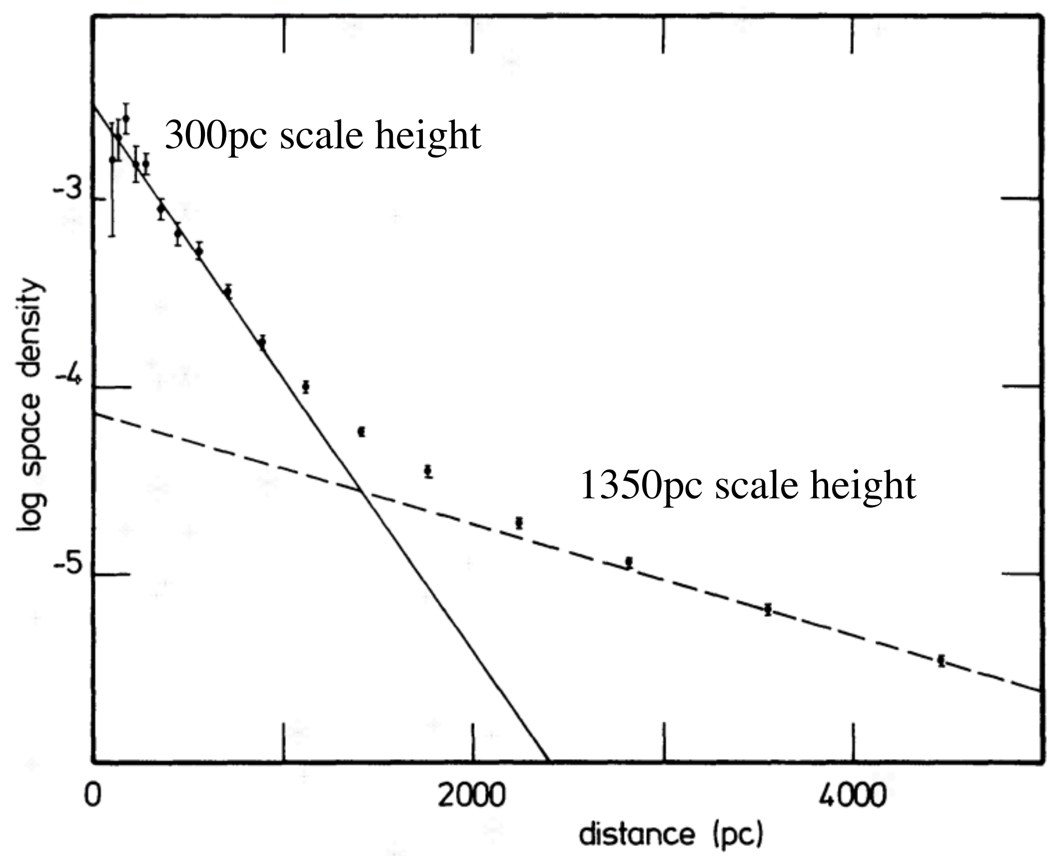

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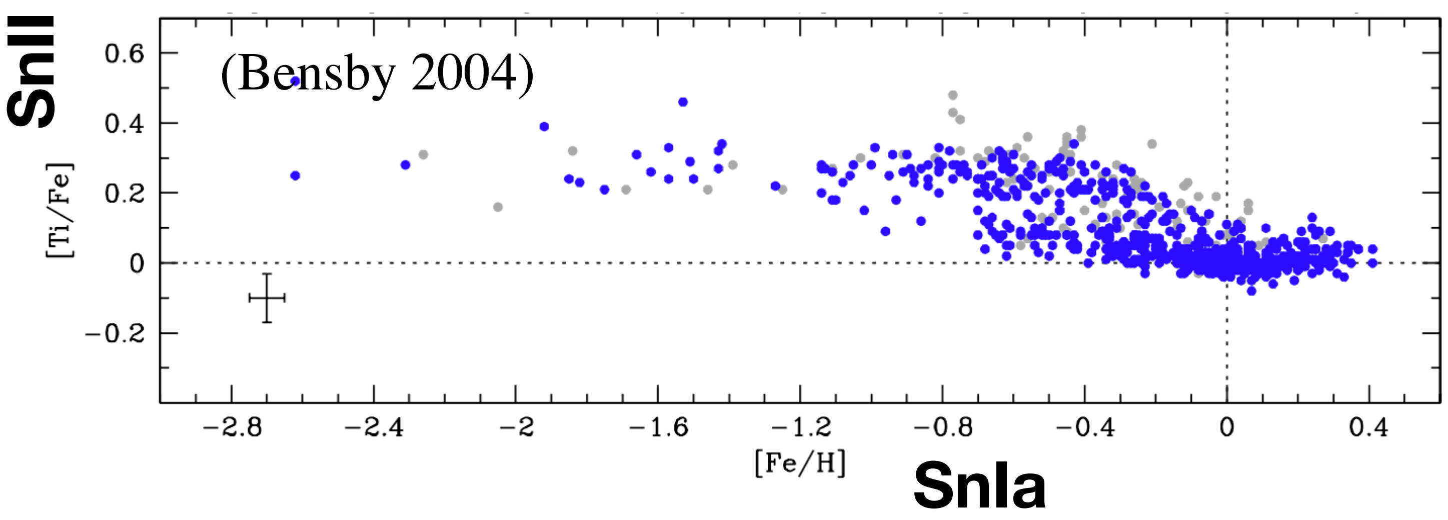

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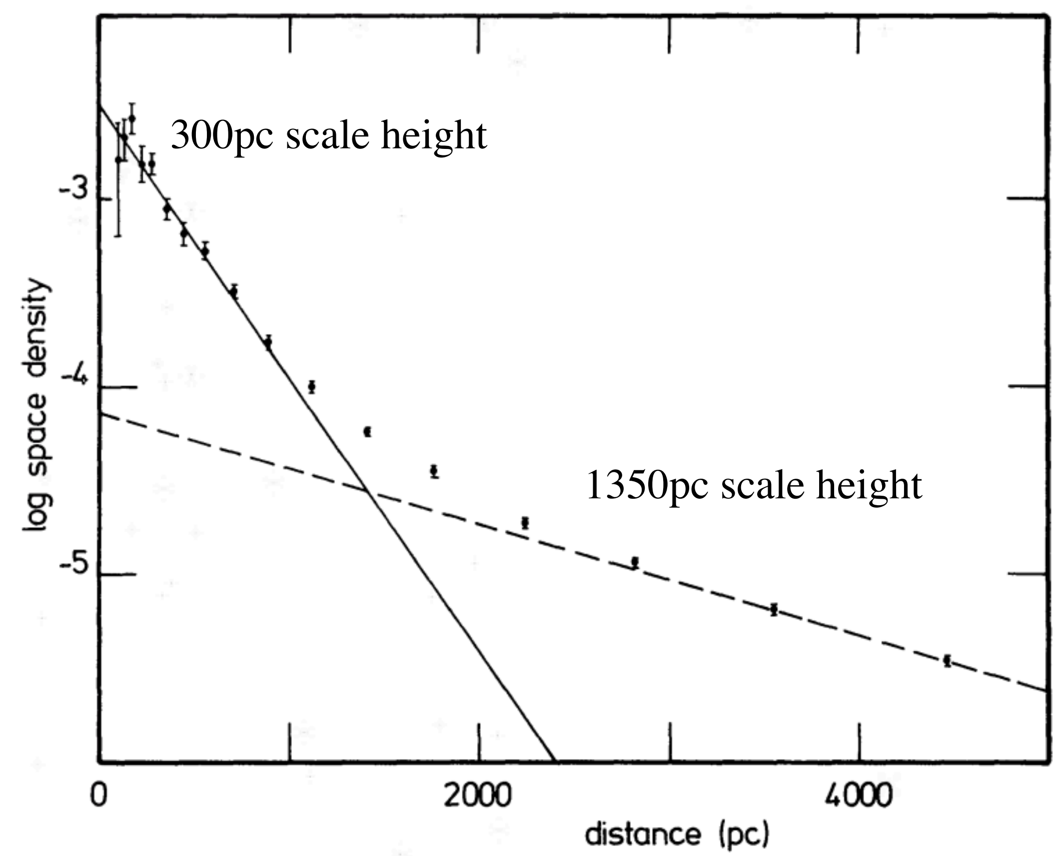

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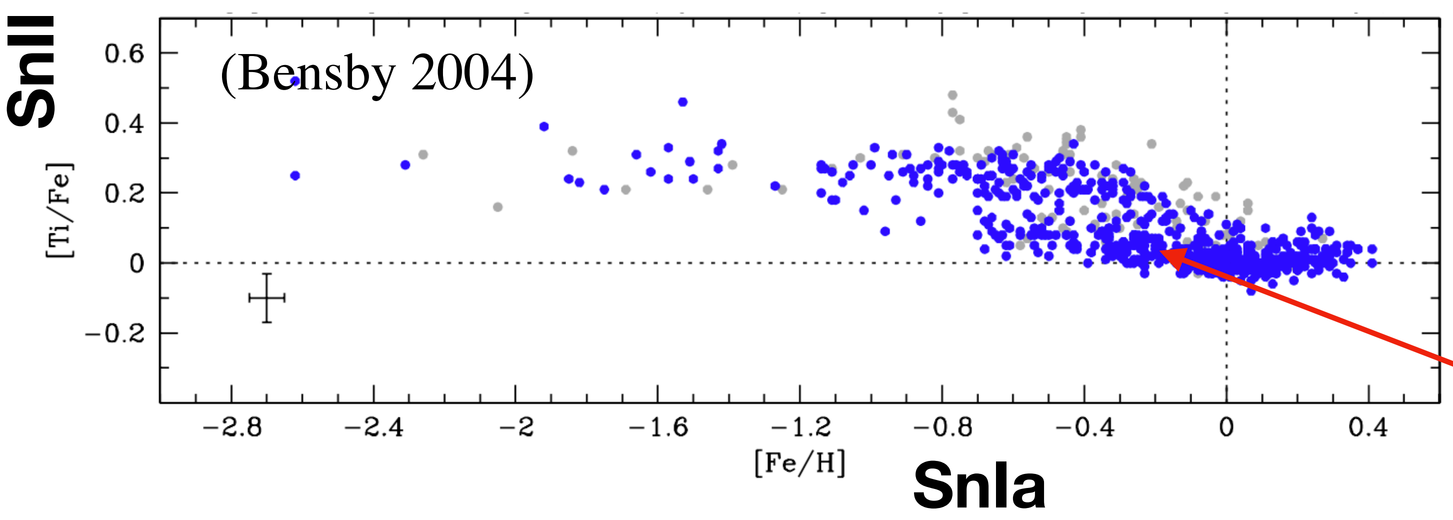

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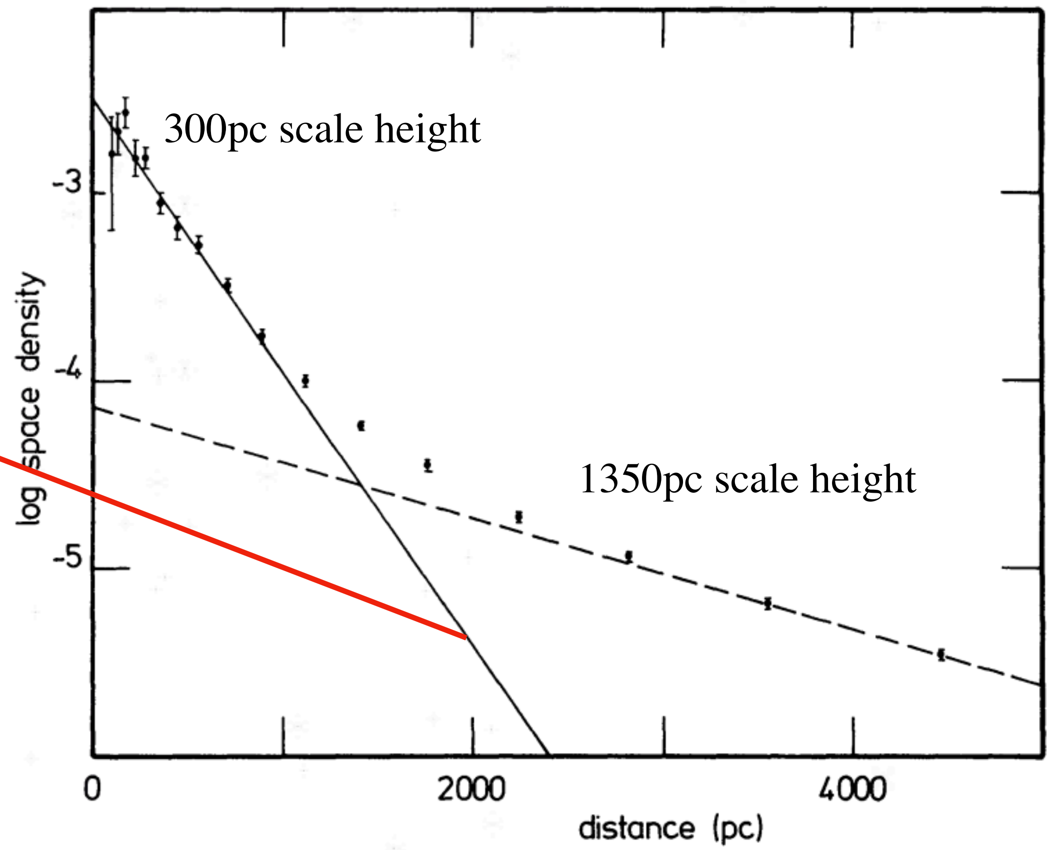

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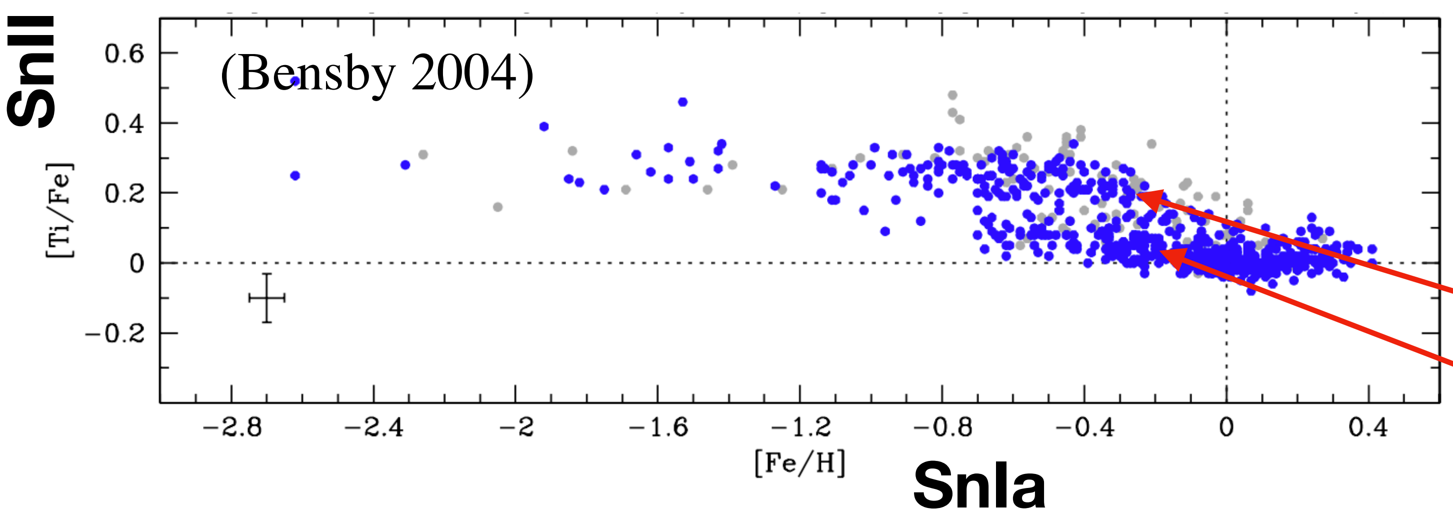

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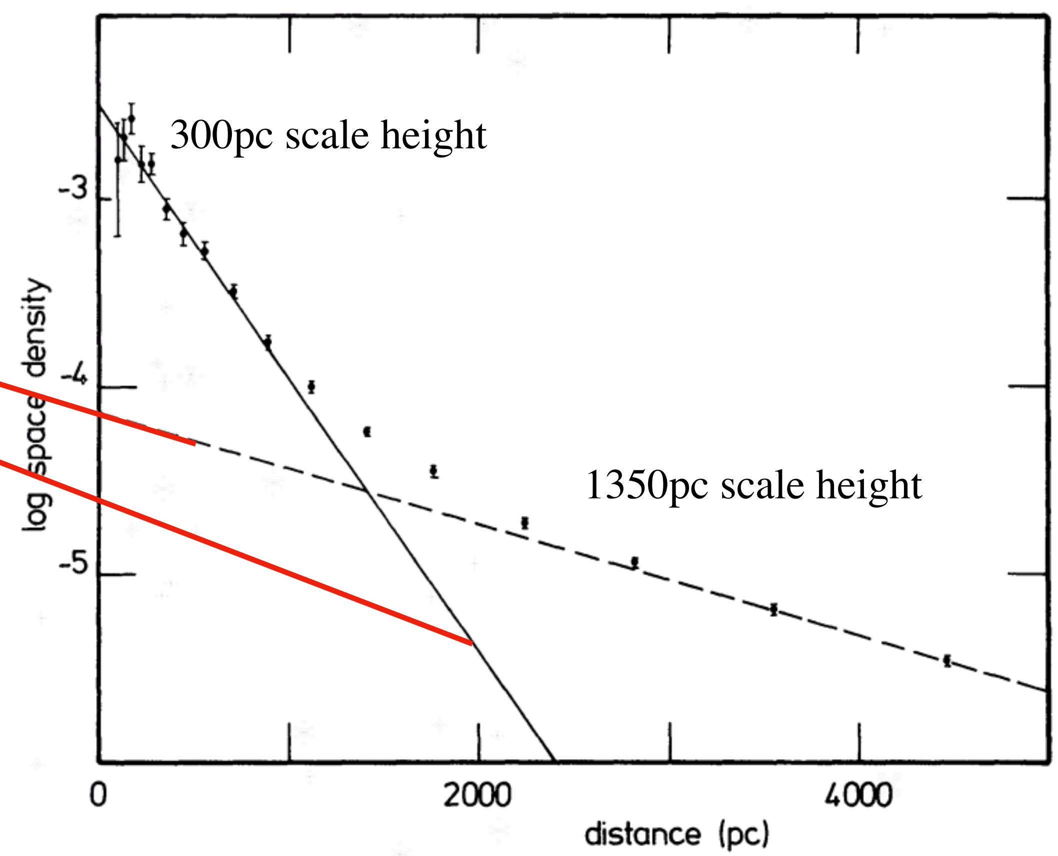
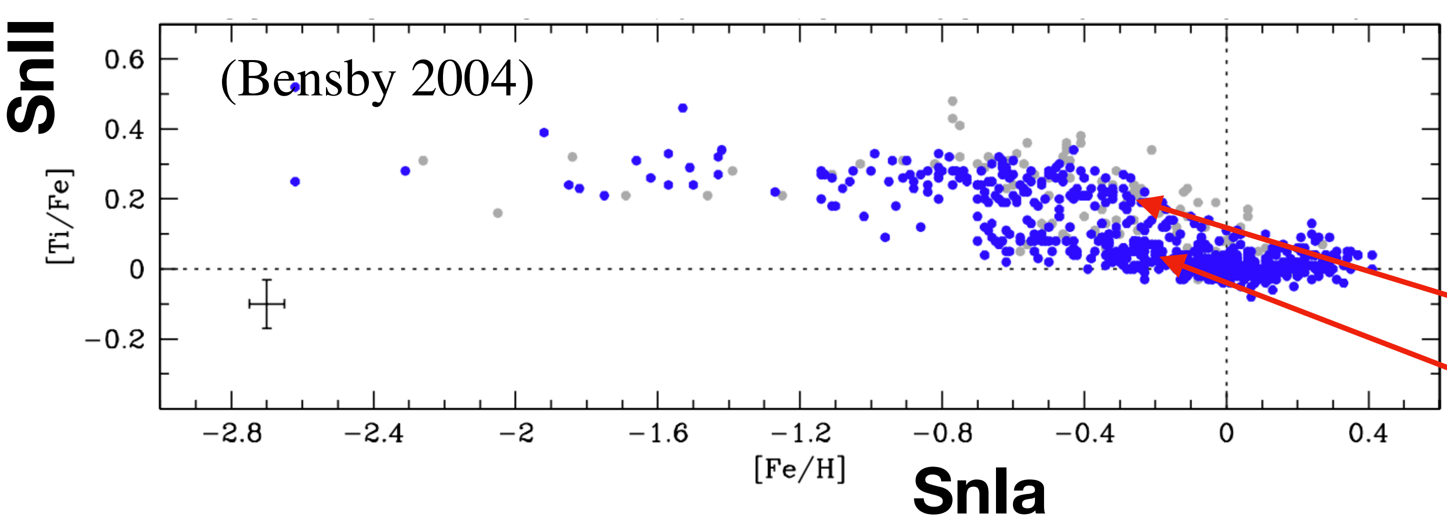


The Milky Way disk

"High" and "Low" alpha-disks (fast v slow star formation)
(see also Fuhrmann 1998, Gratton+ 2000, Tautvaisine+ 2001, Soubrian+ 2003, Reddy+ 2003)



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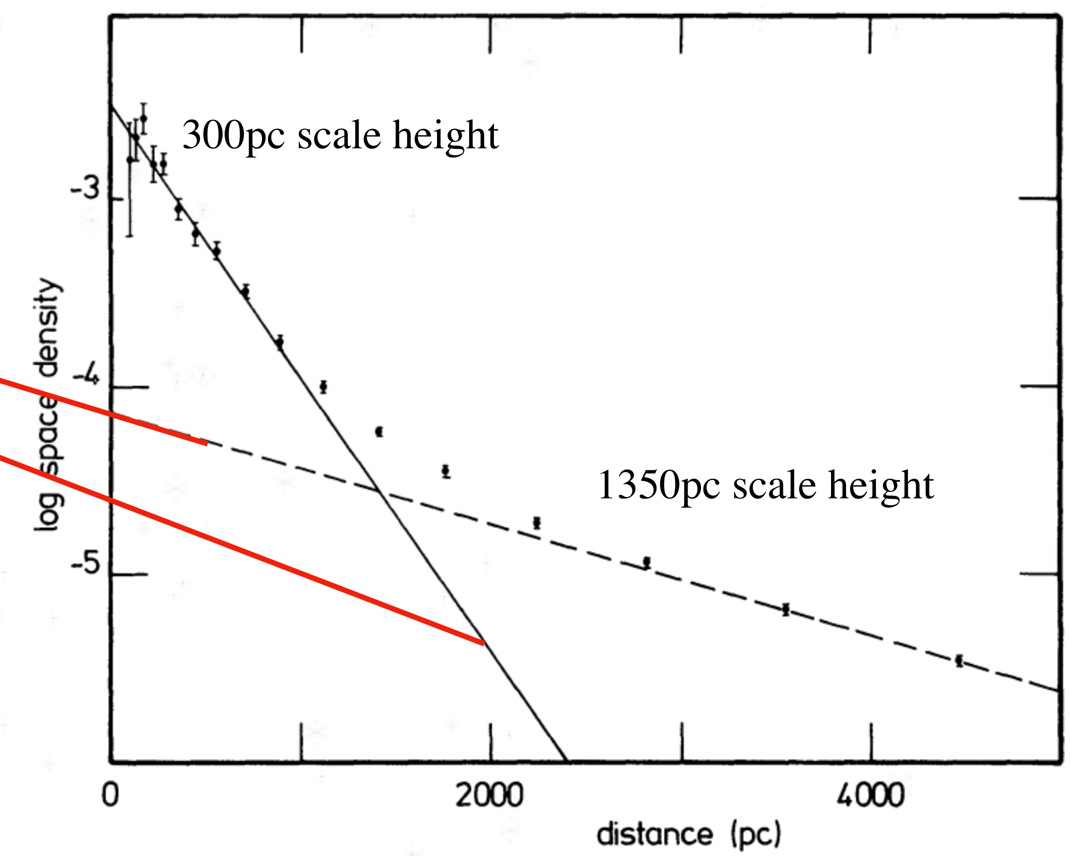

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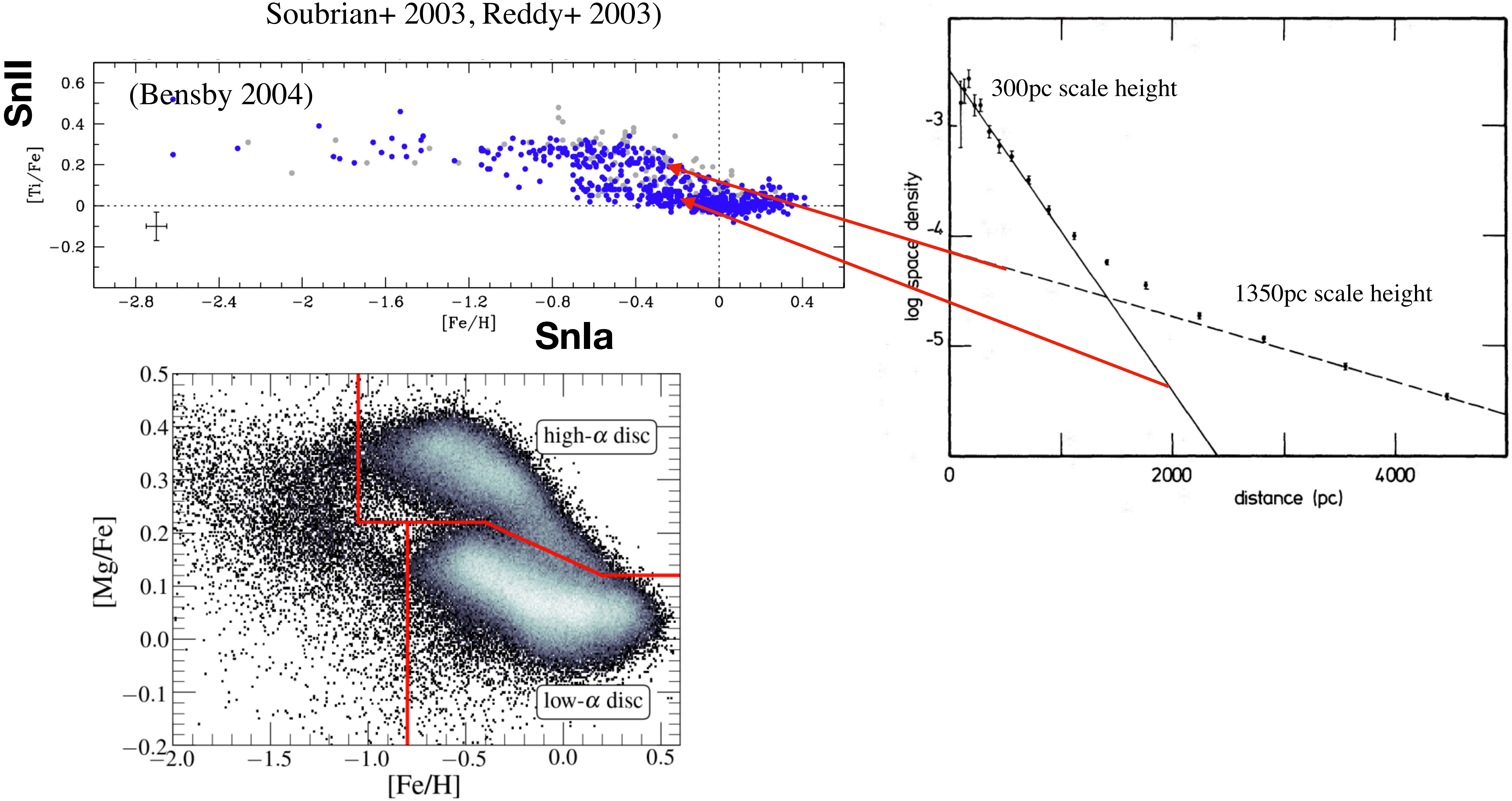

From APOGEE DR17 (Horta+ 2022)

Empirical landscape of the Milky Way disk-bulge

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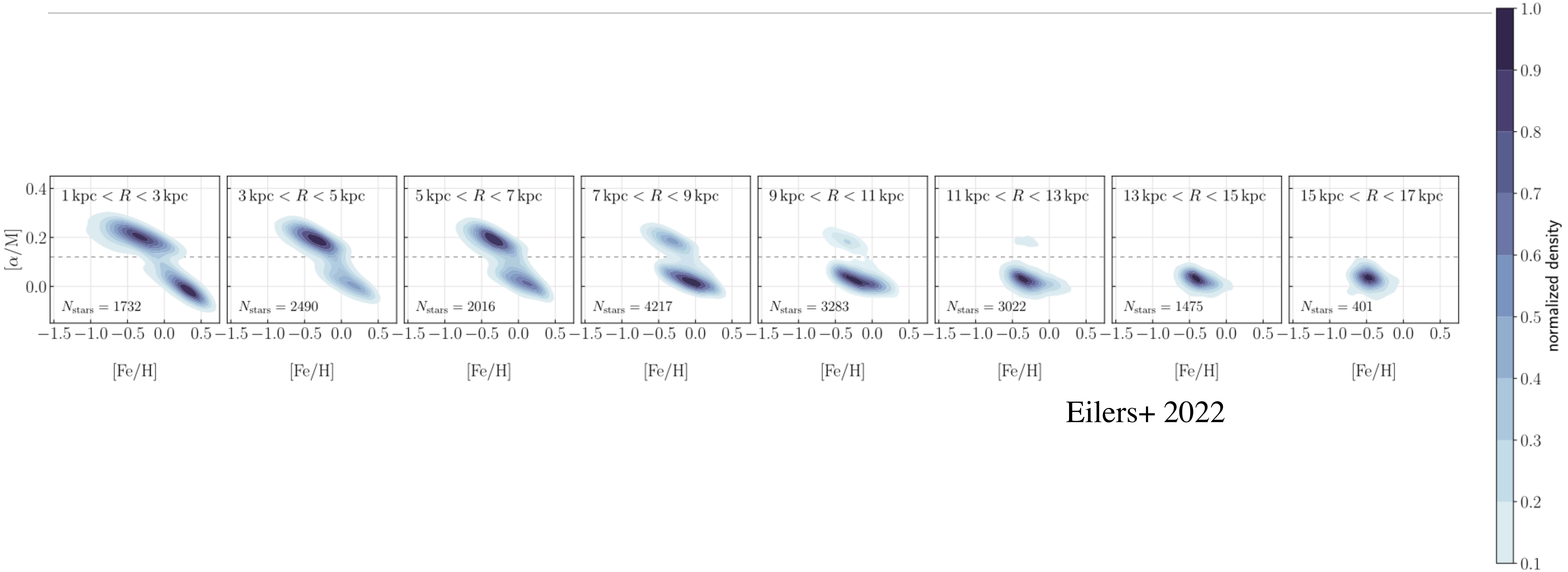

Eilers+ 2022

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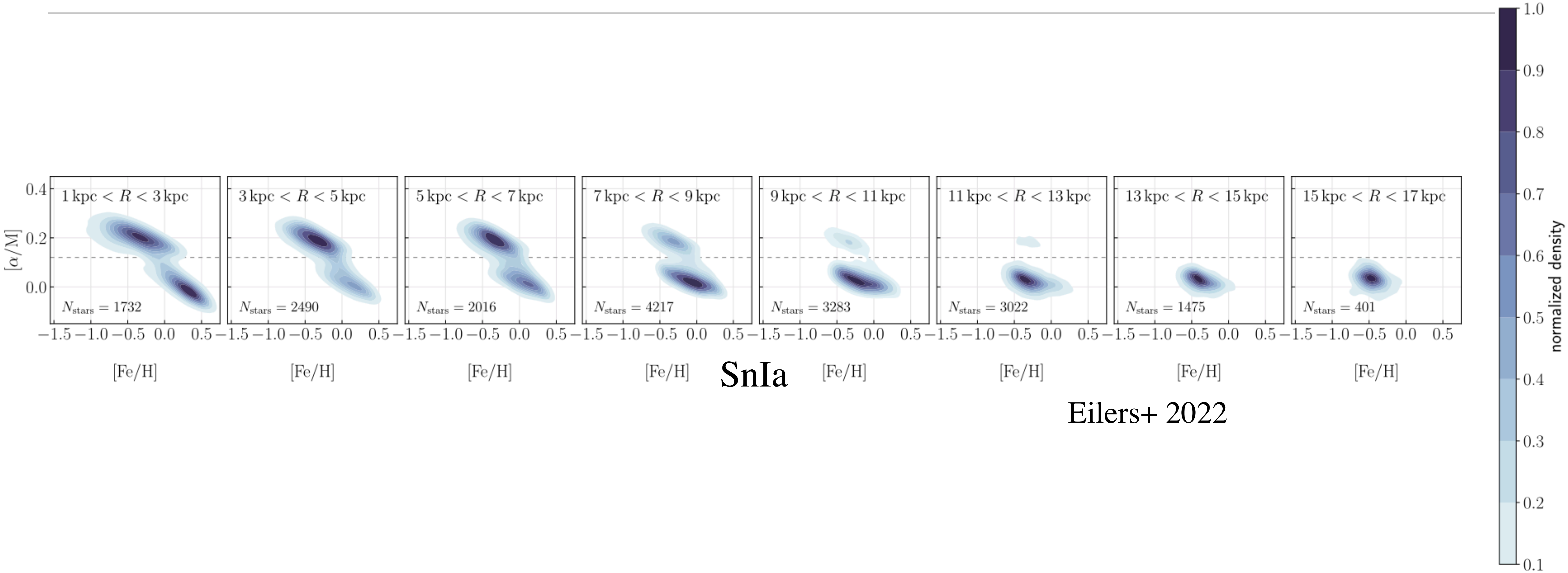

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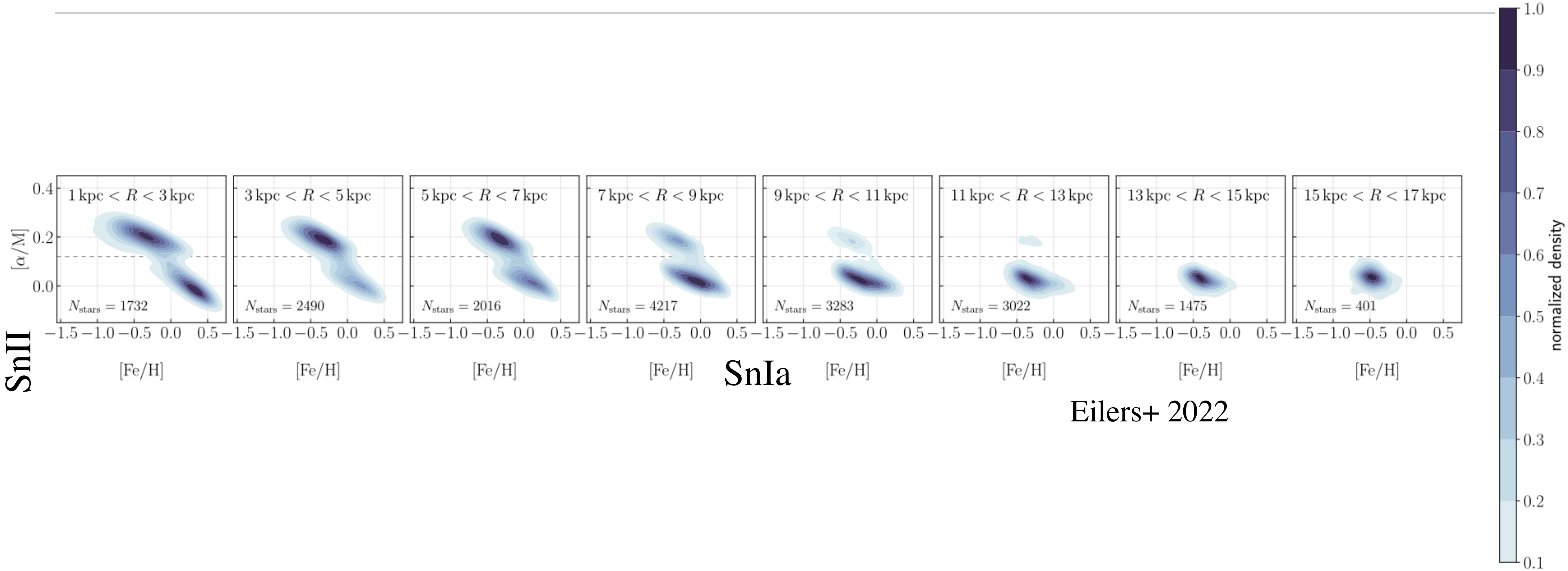

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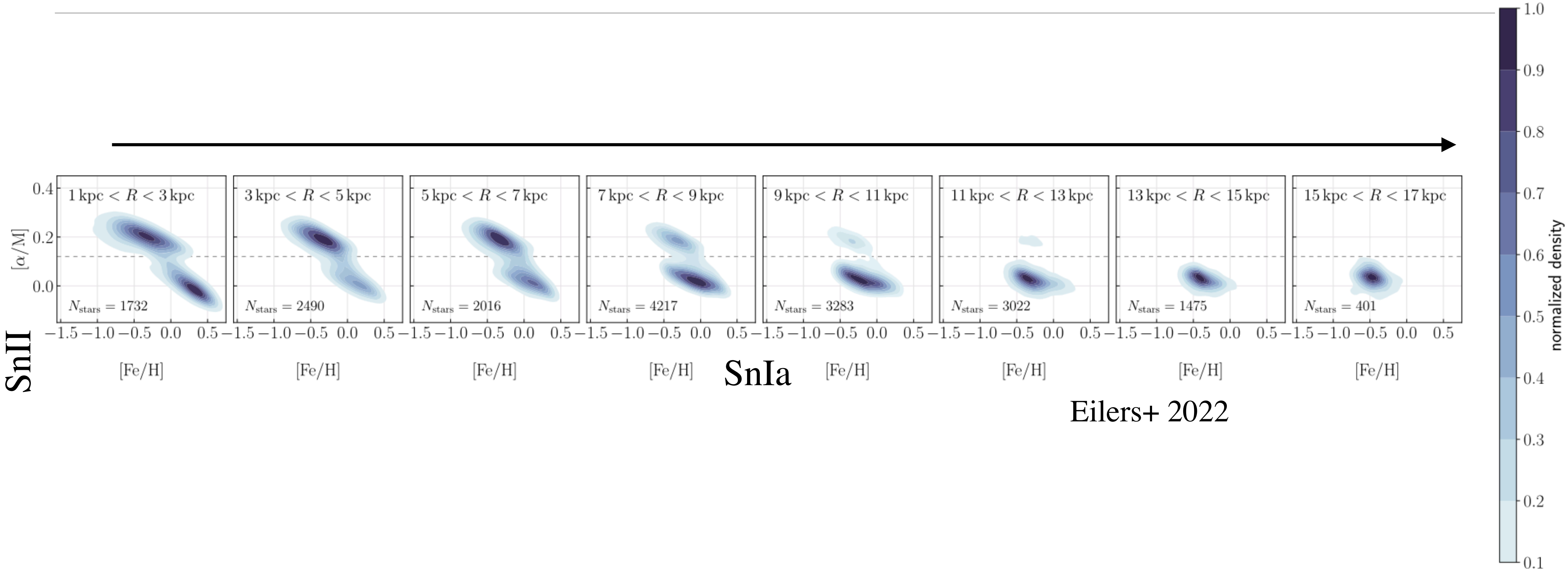

Eilers+ 2022

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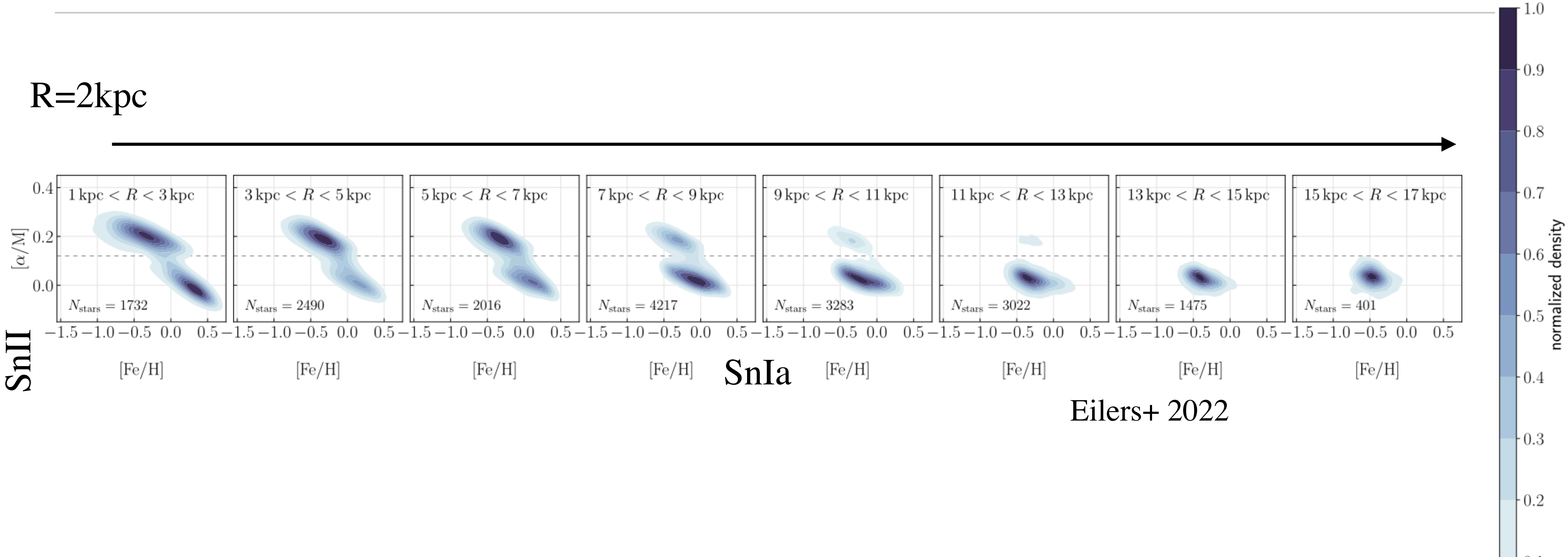
R=2kpc



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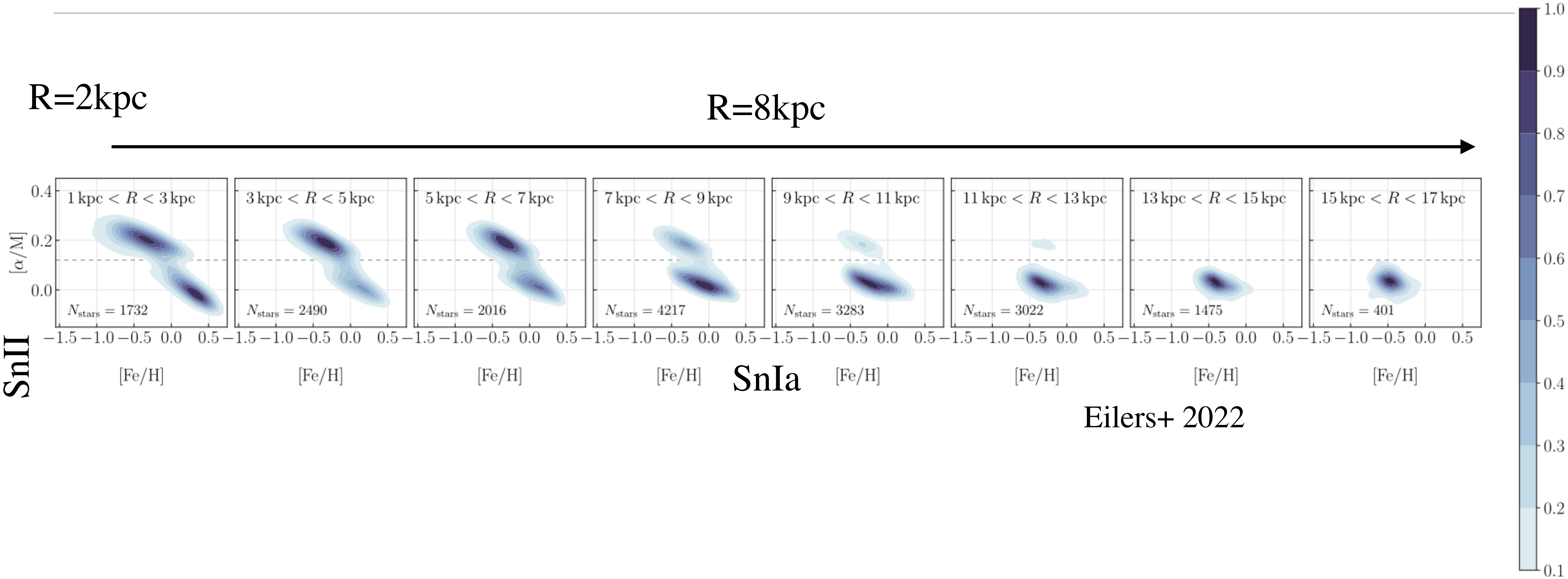

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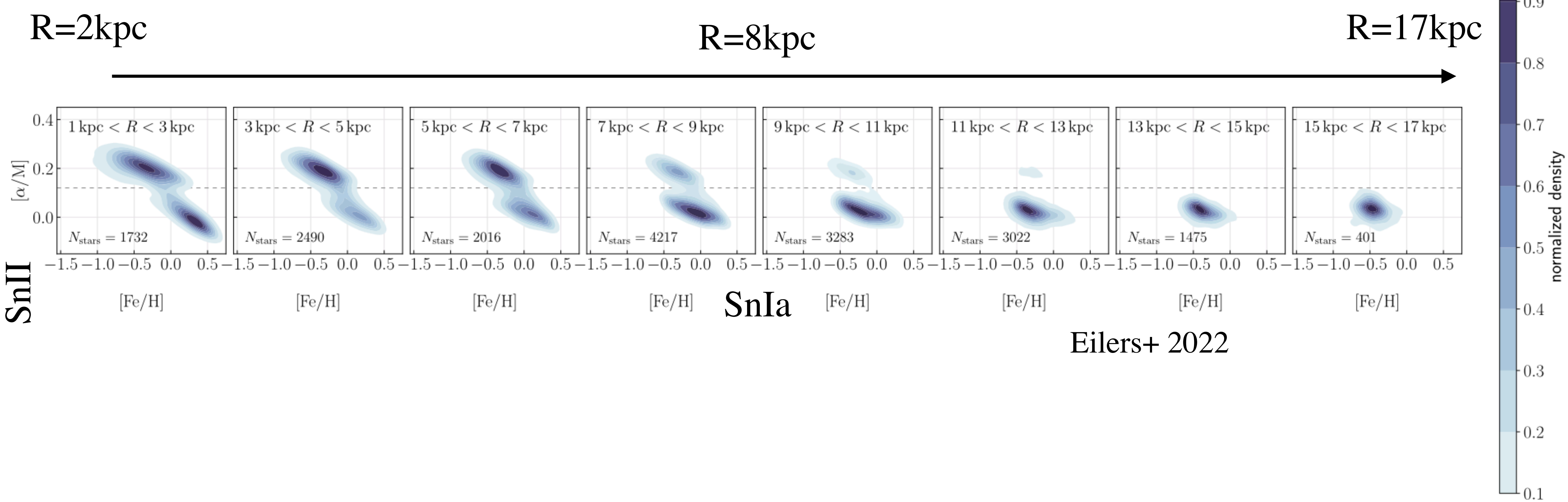

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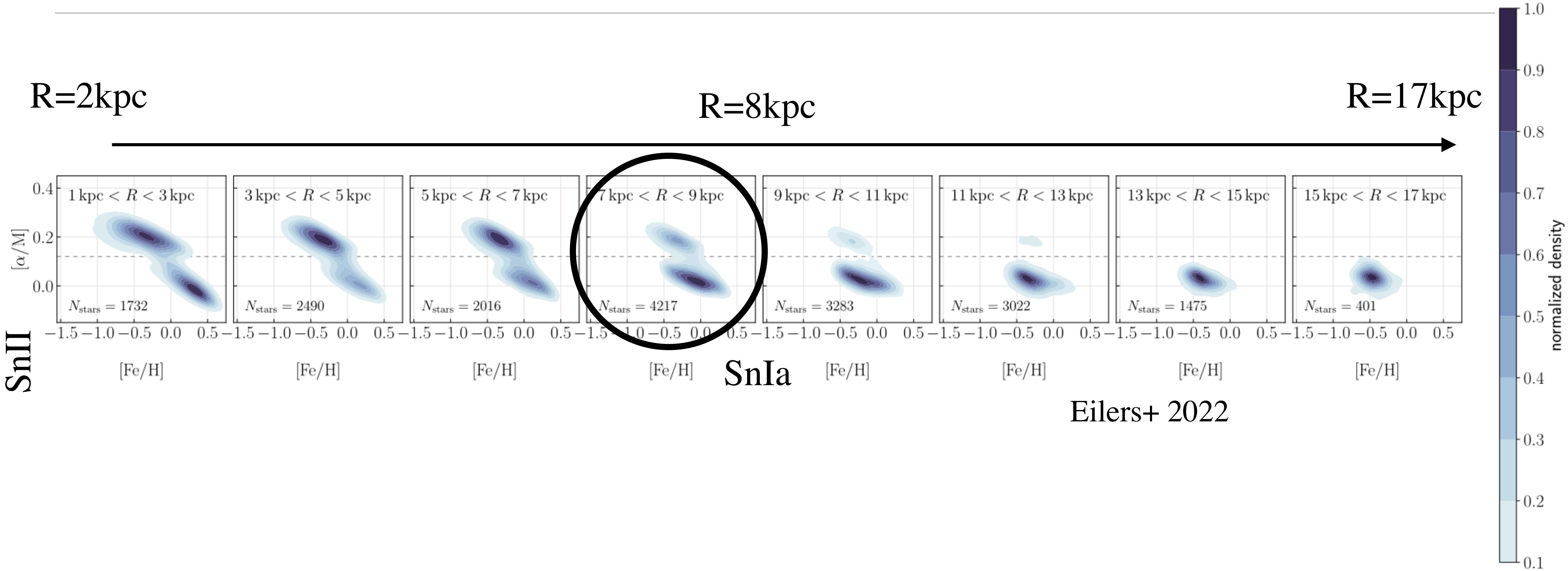

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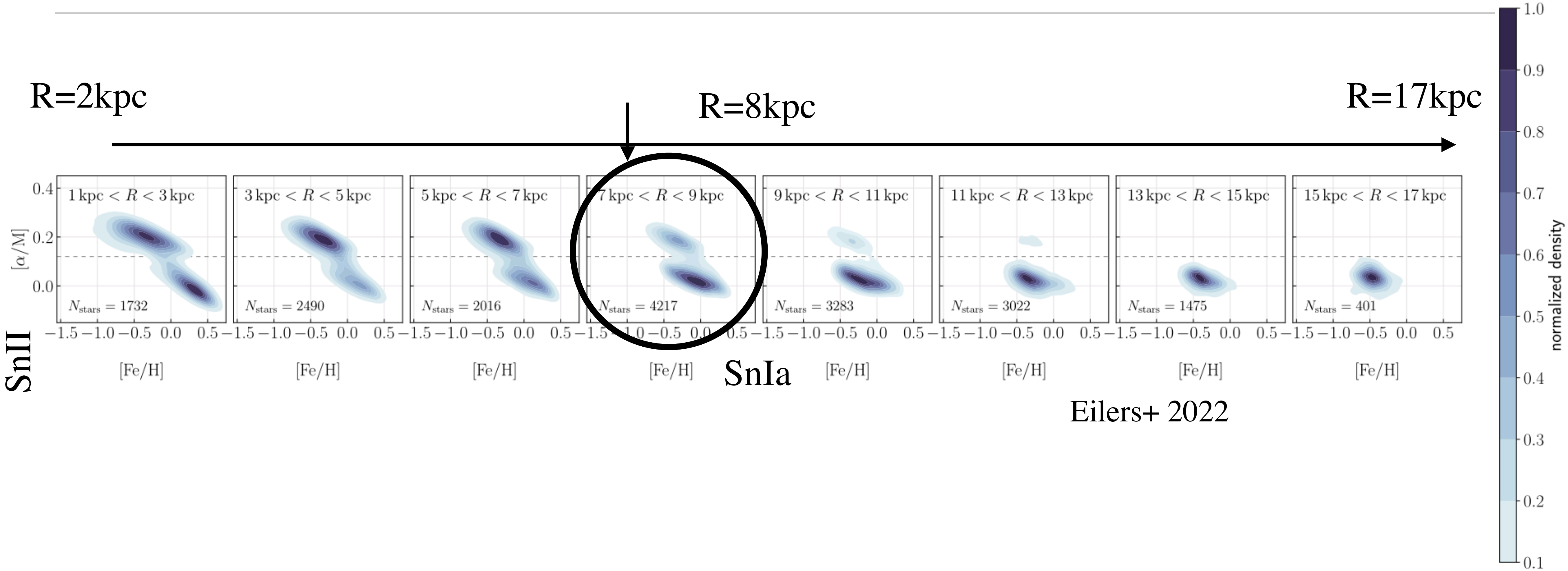

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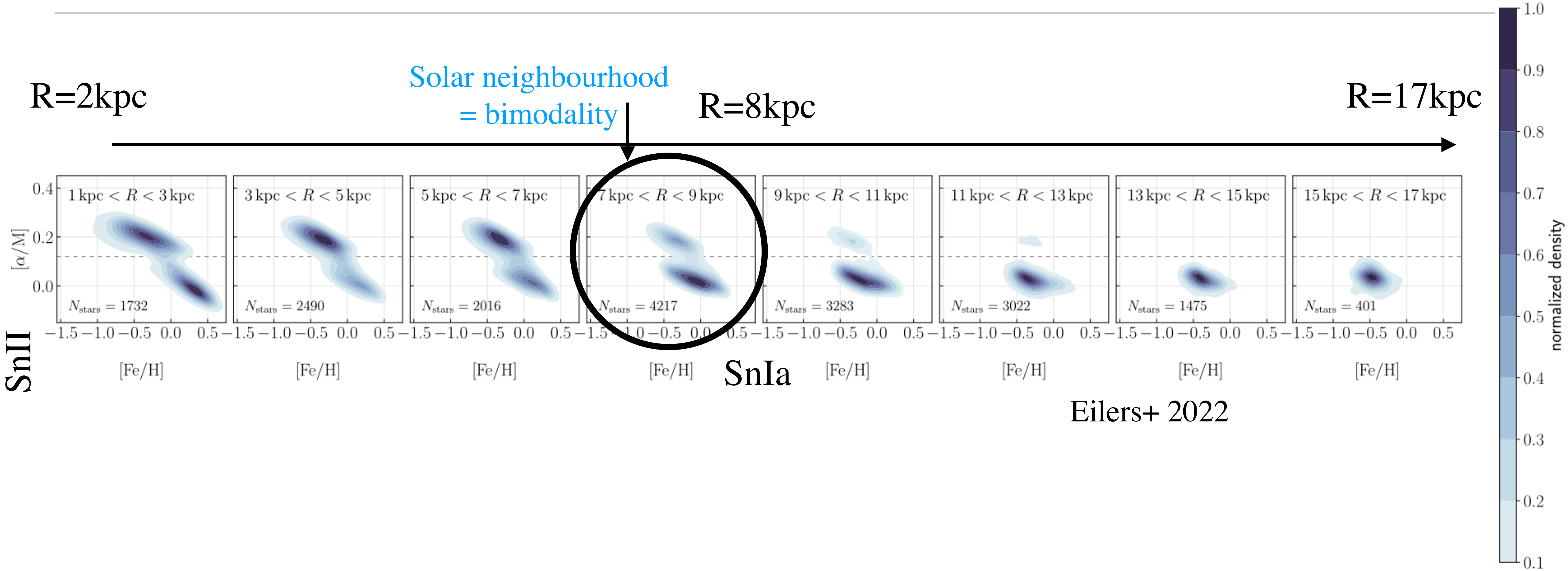

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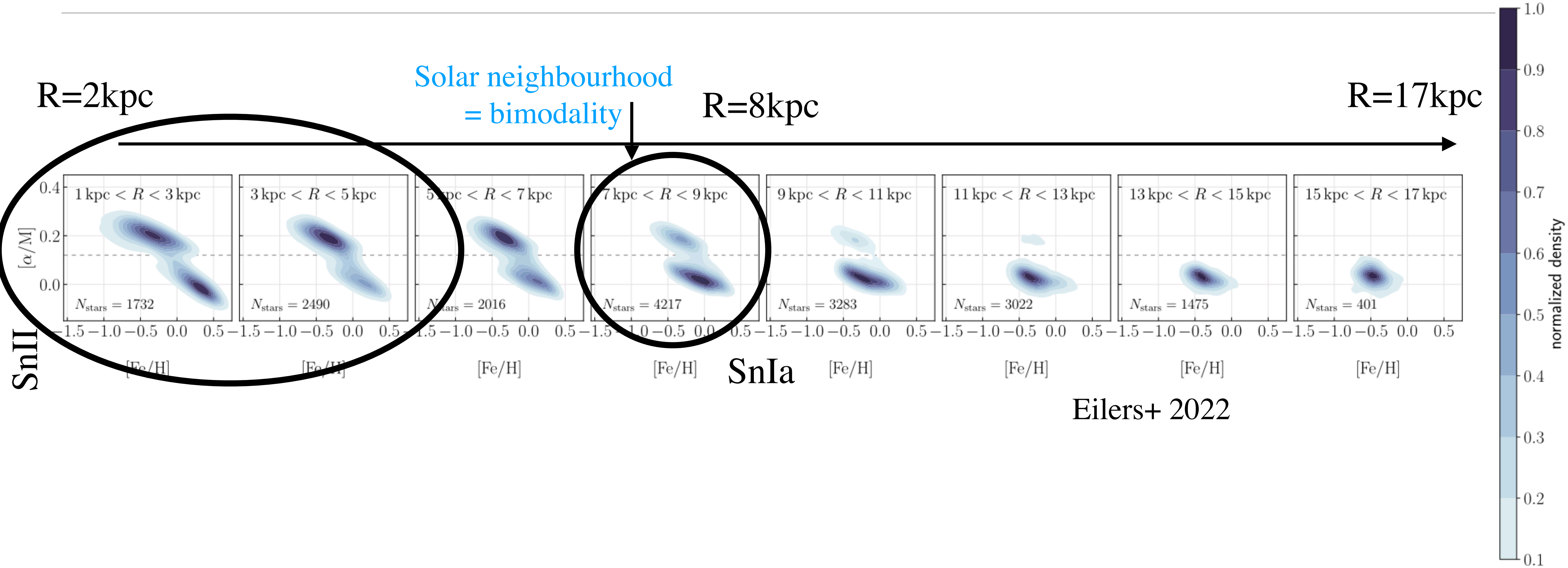

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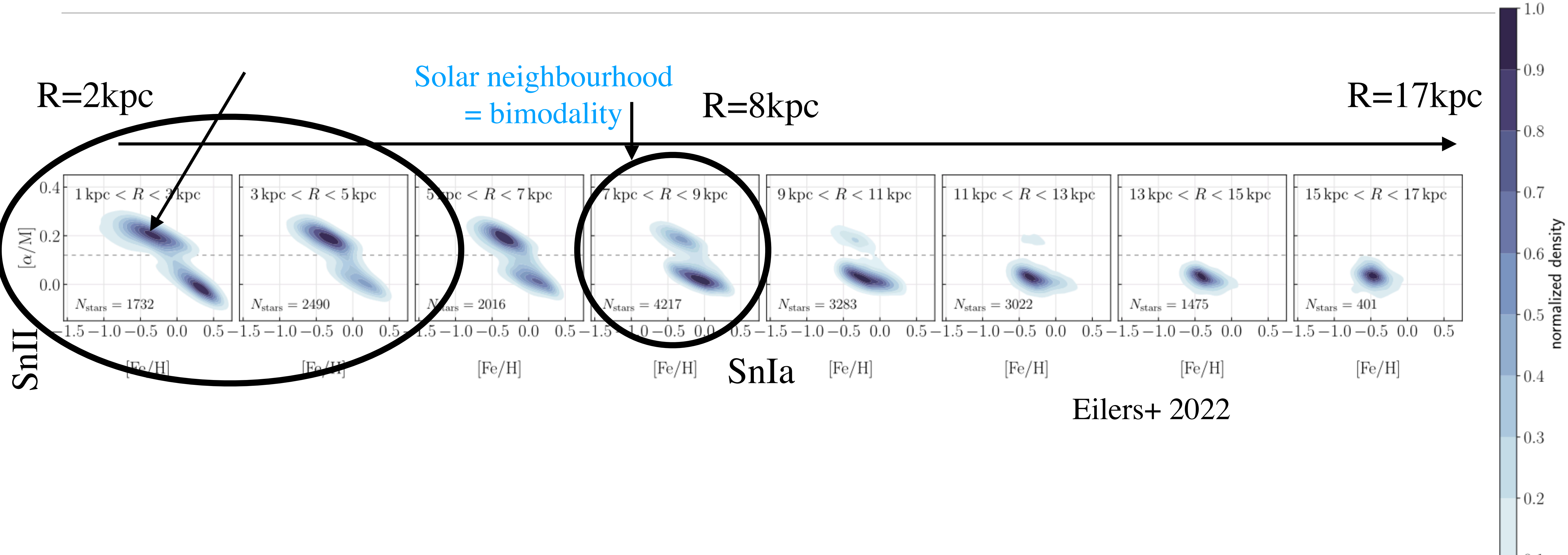

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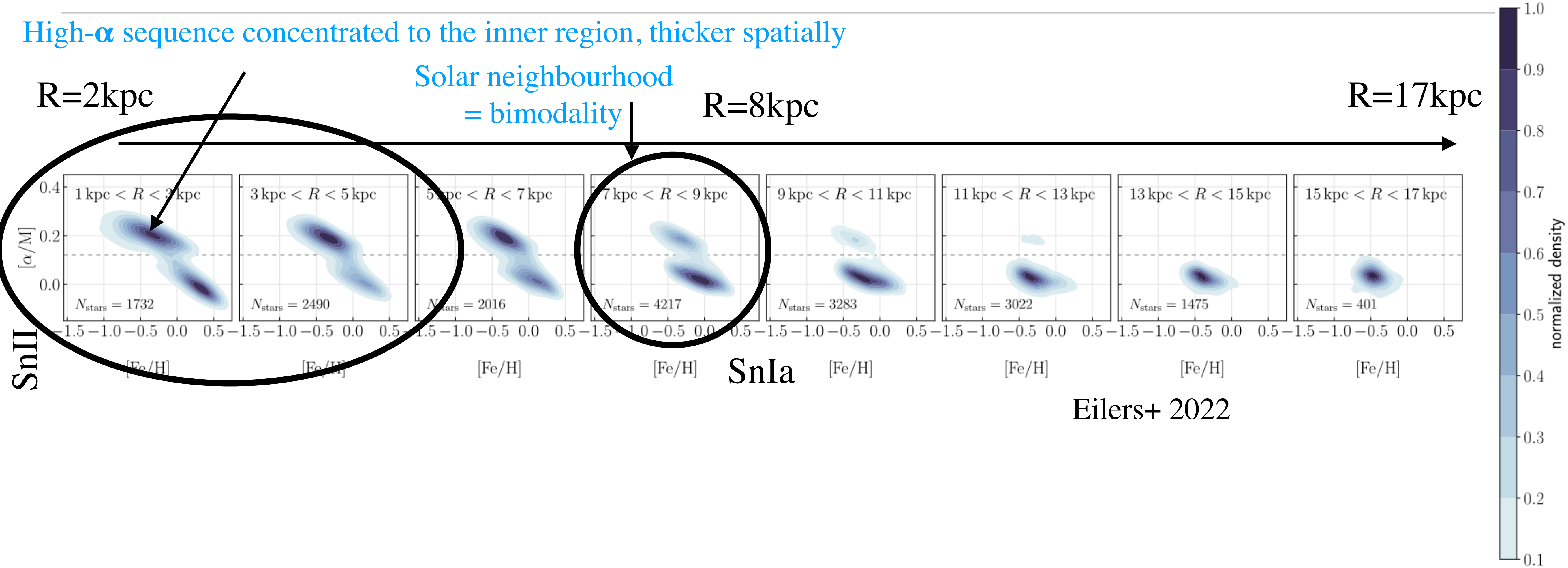

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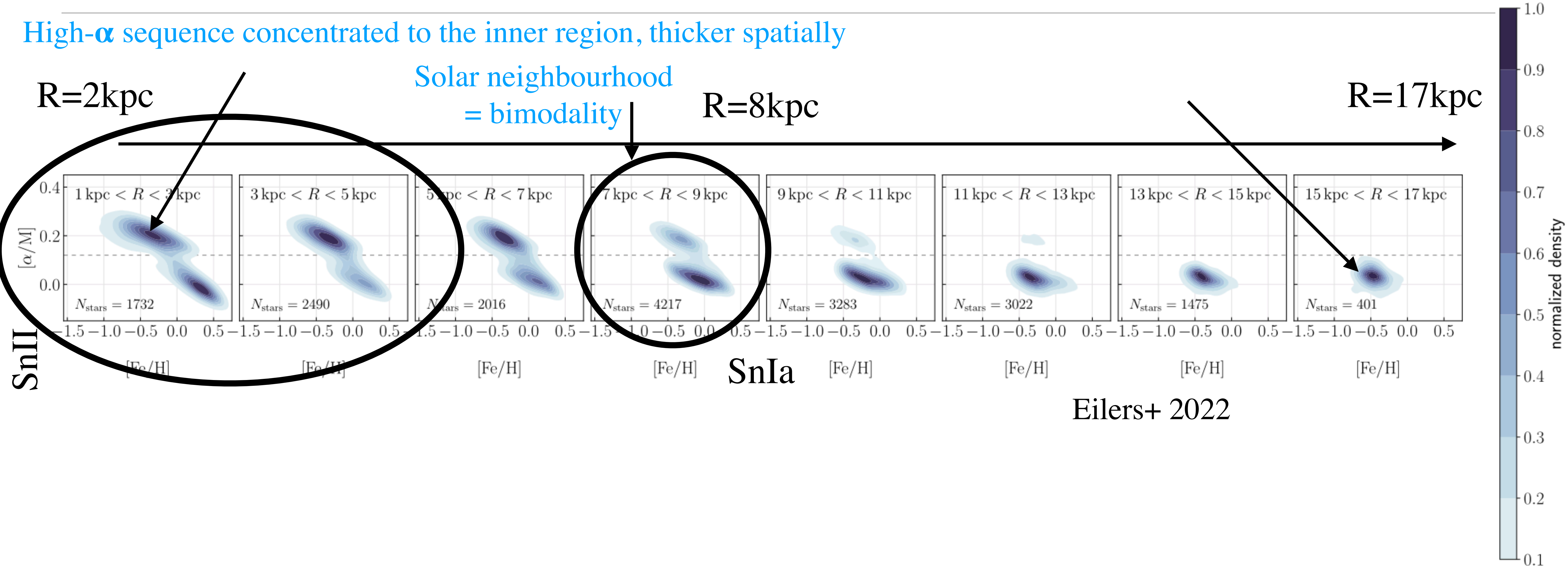
High-α sequence concentrated to the inner region, thicker spatially



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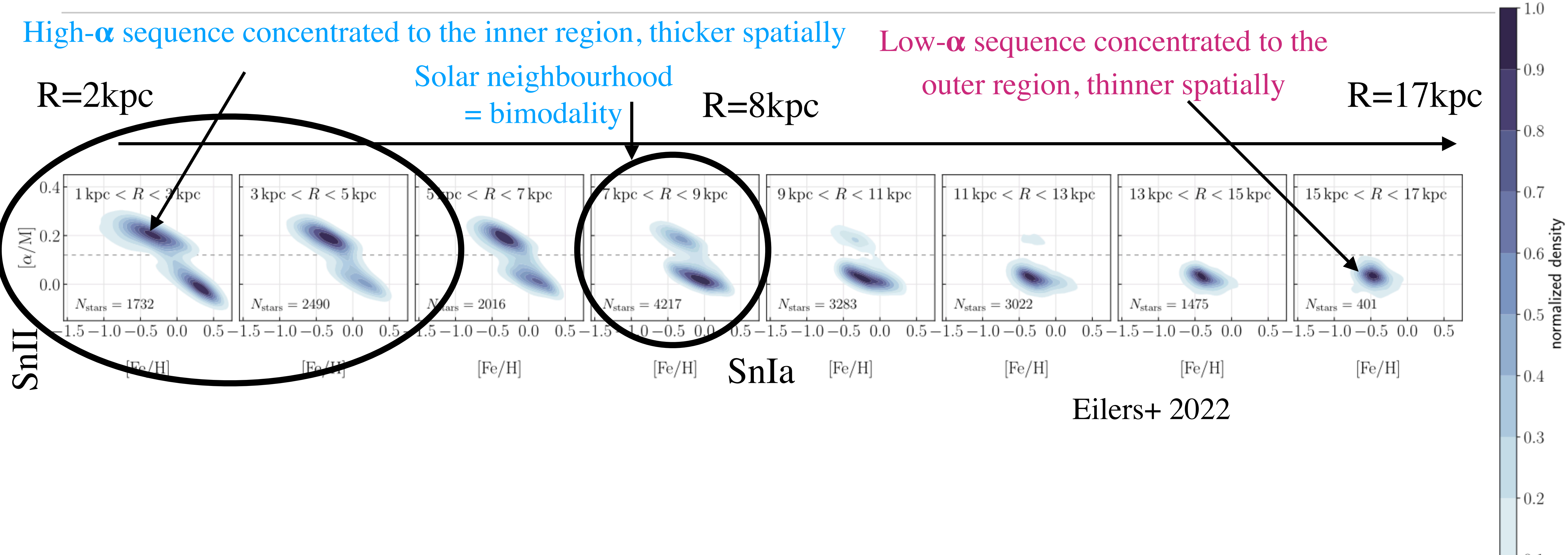

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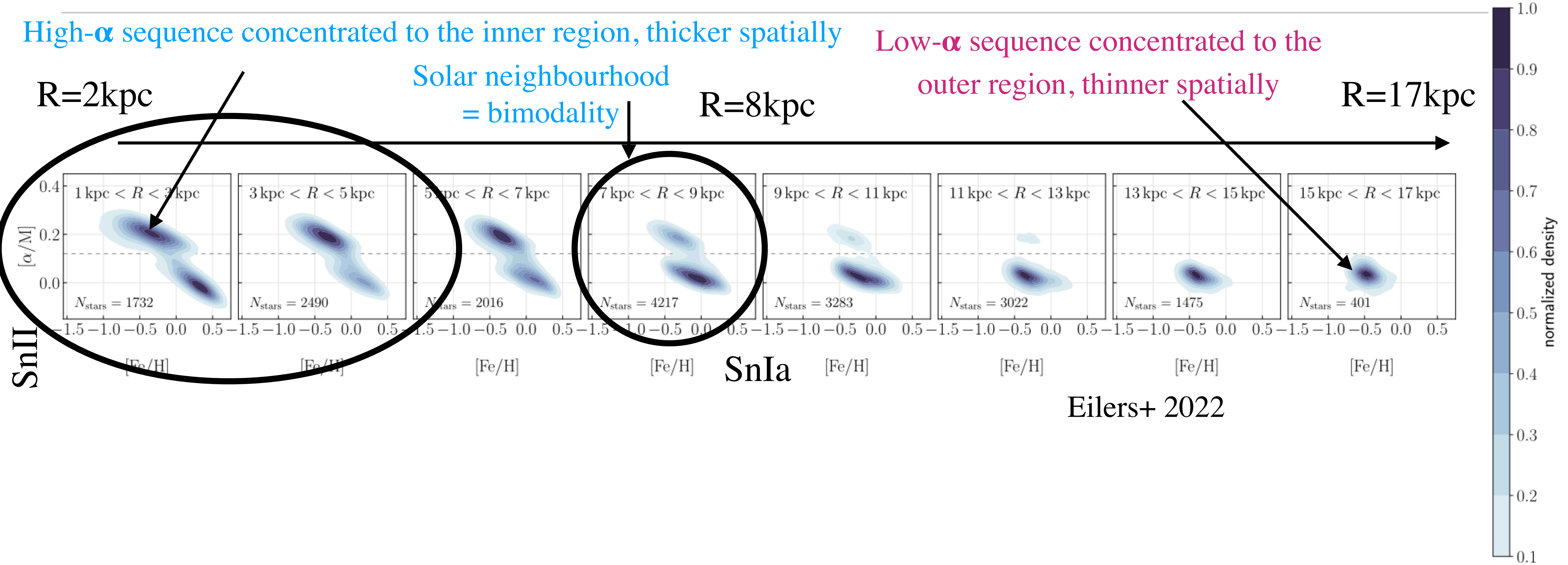

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Also see Nidever+ 2014, Bovy+ 2015, Hayden+ 2015, Queiroz+ 2020, Eilers+ 2021, Sharma+ 2022, Johnson+ 202

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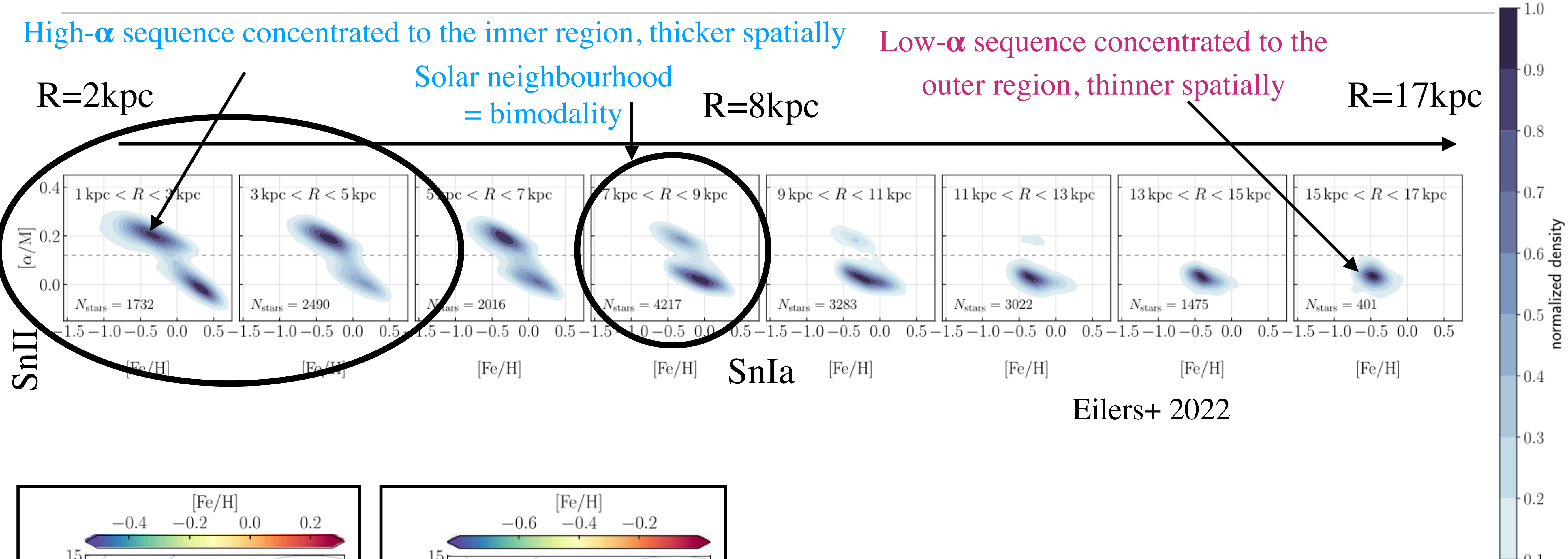

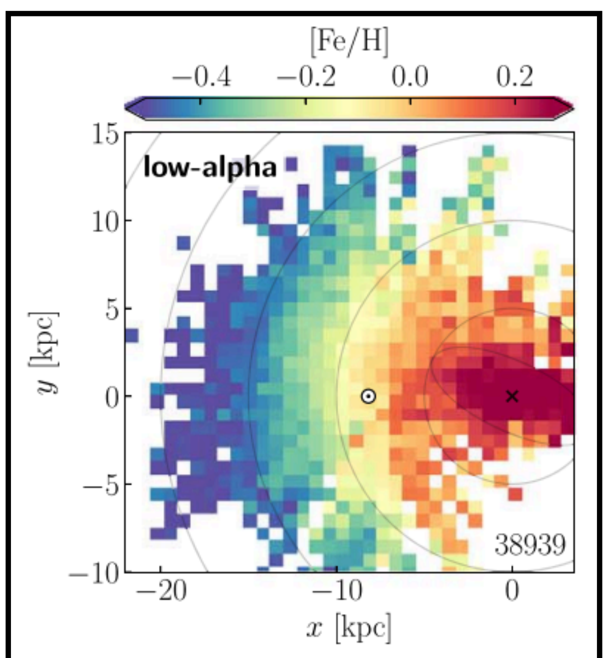

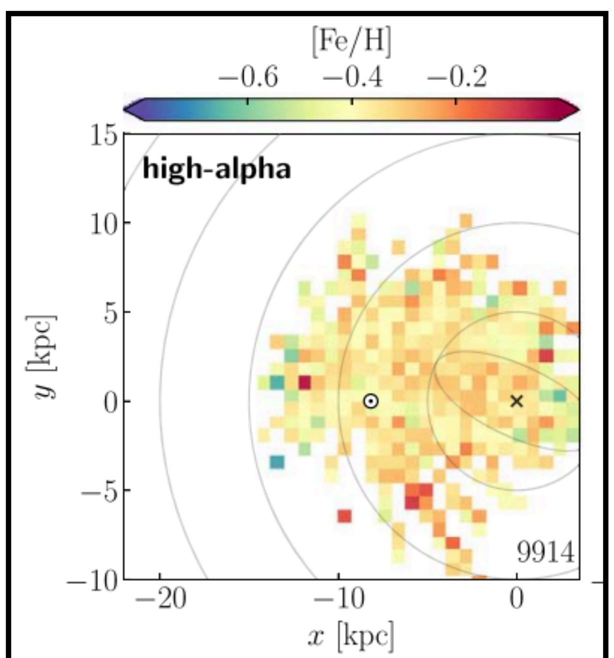

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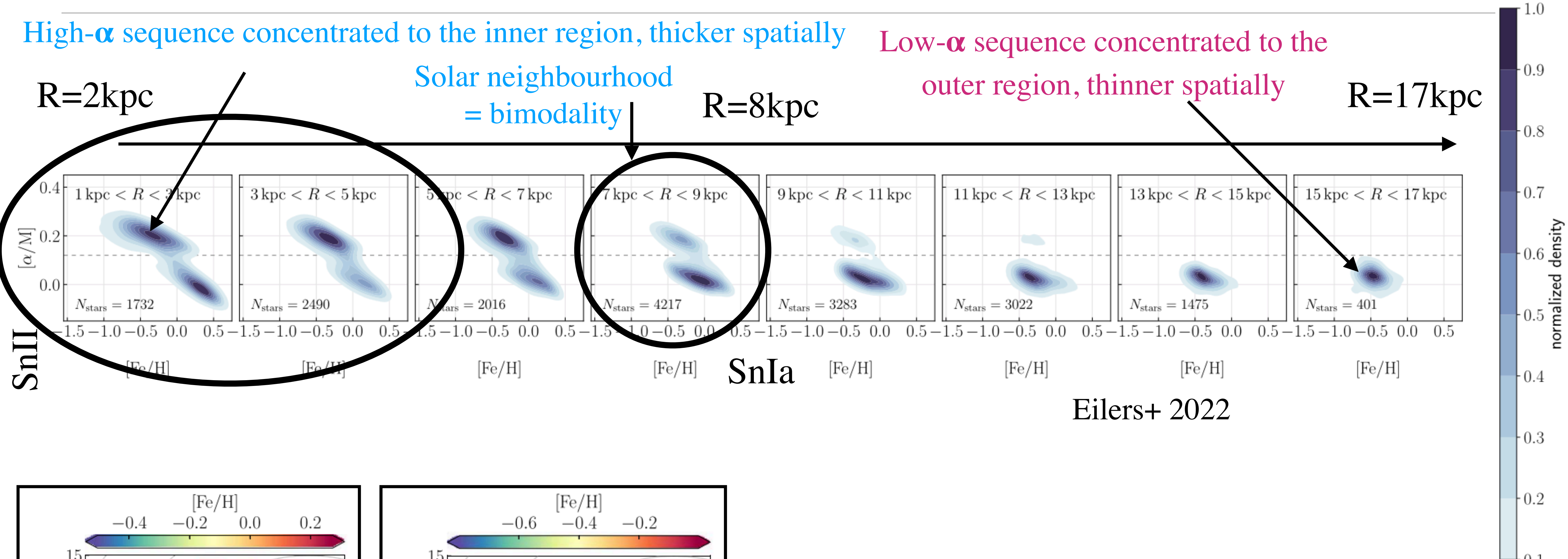

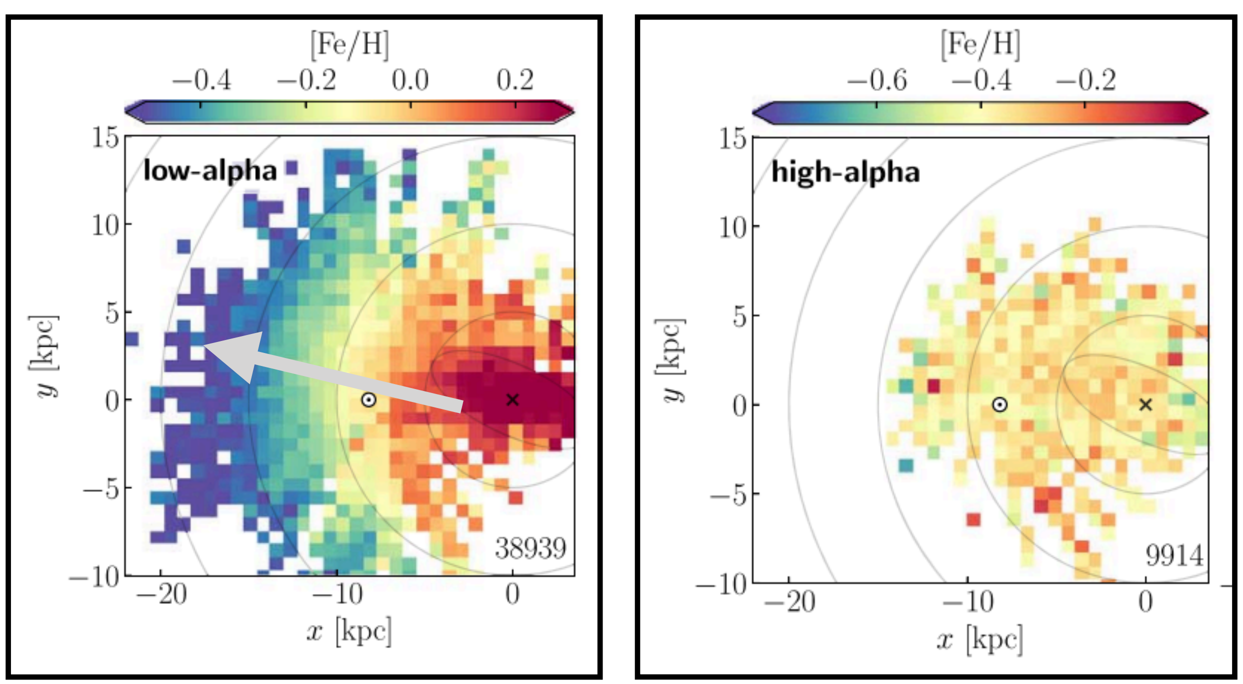

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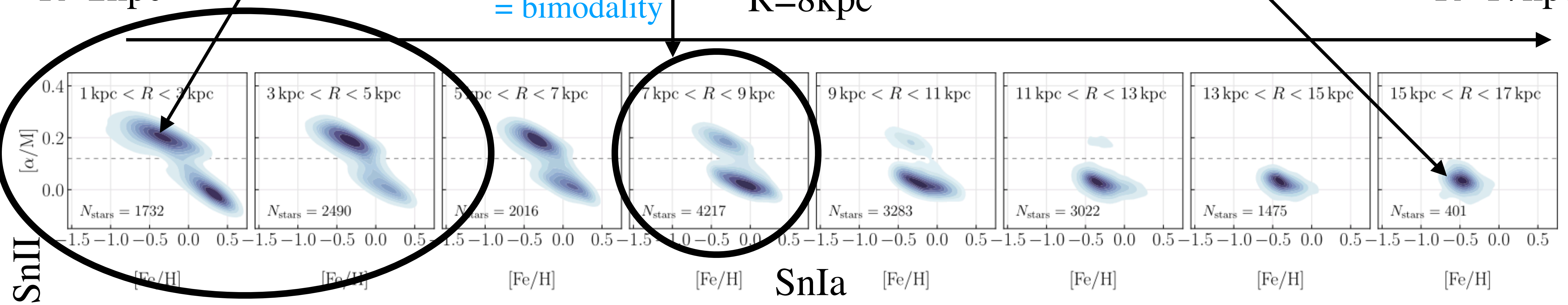
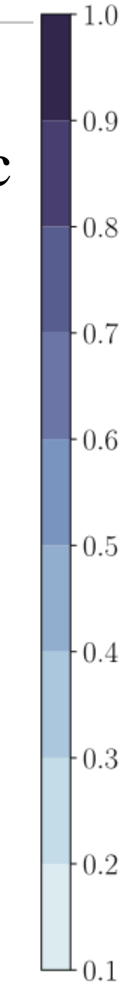
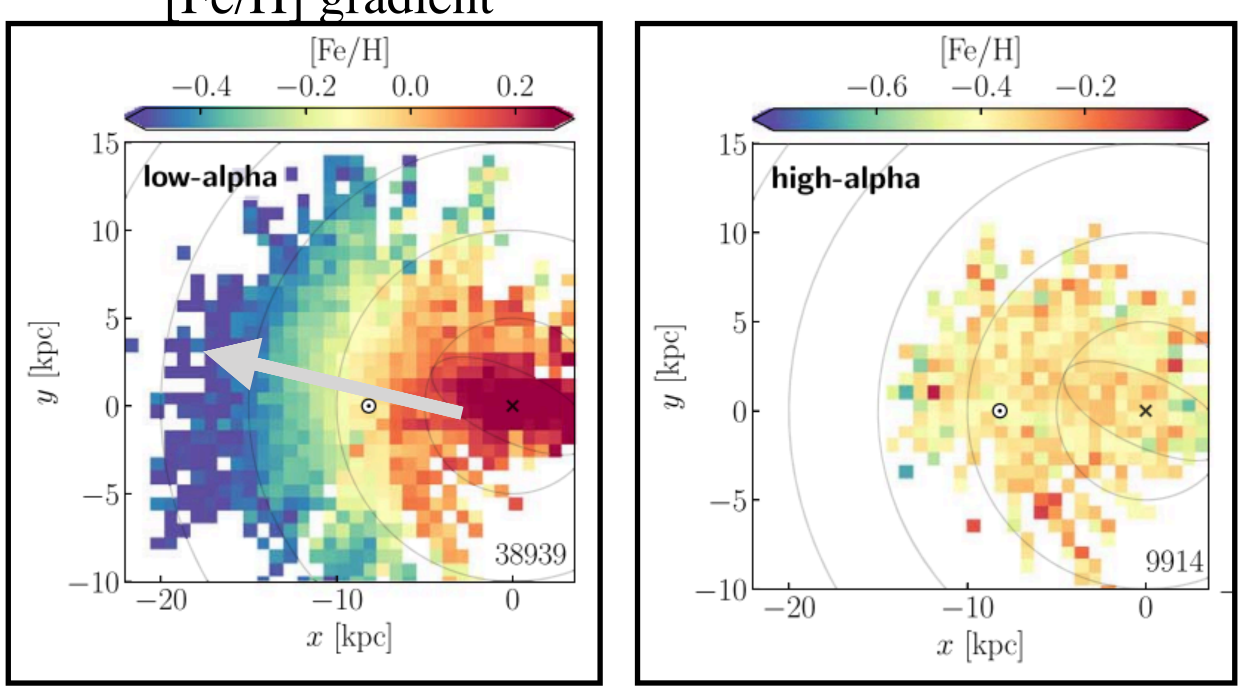




Eilers+ 2022

[Fe/H] gradient



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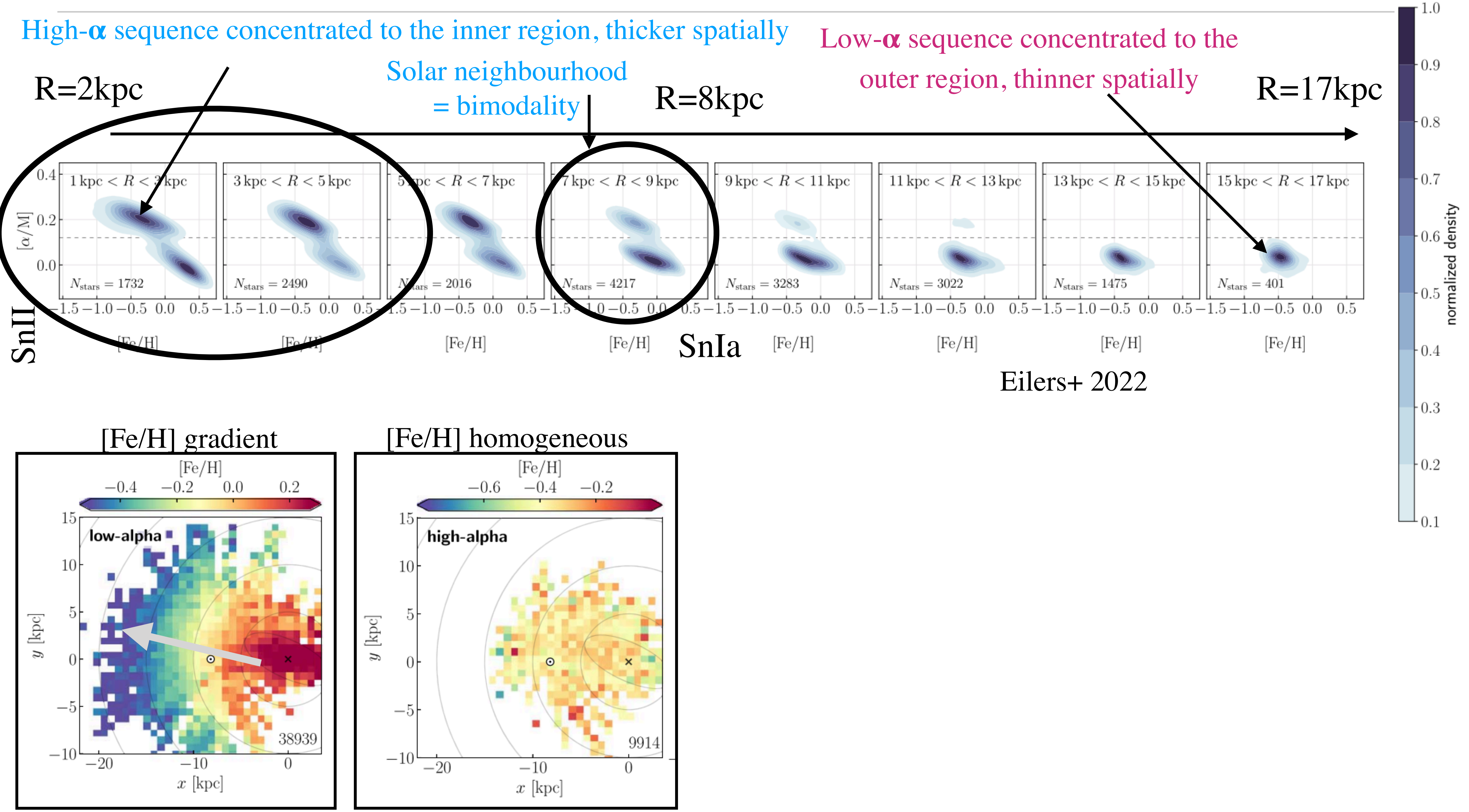

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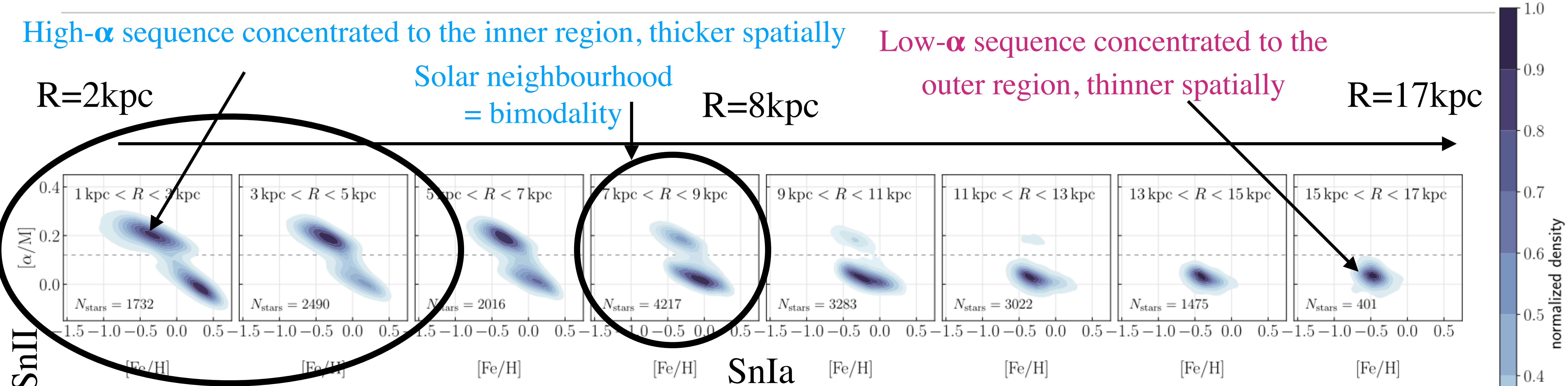

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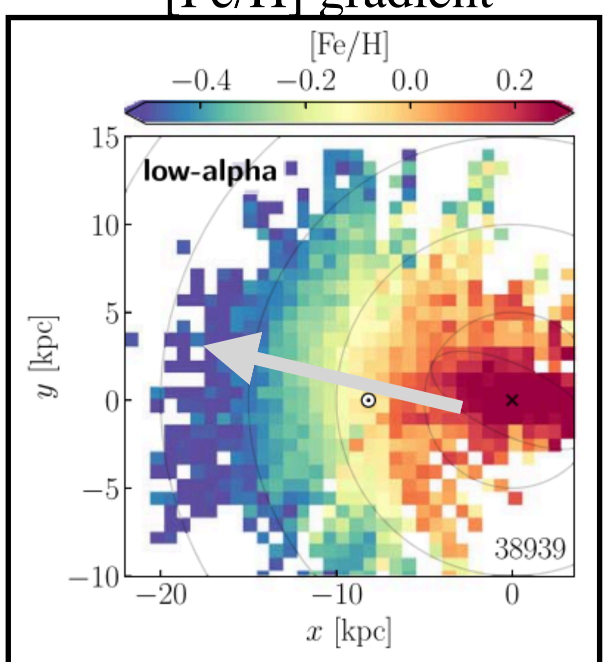
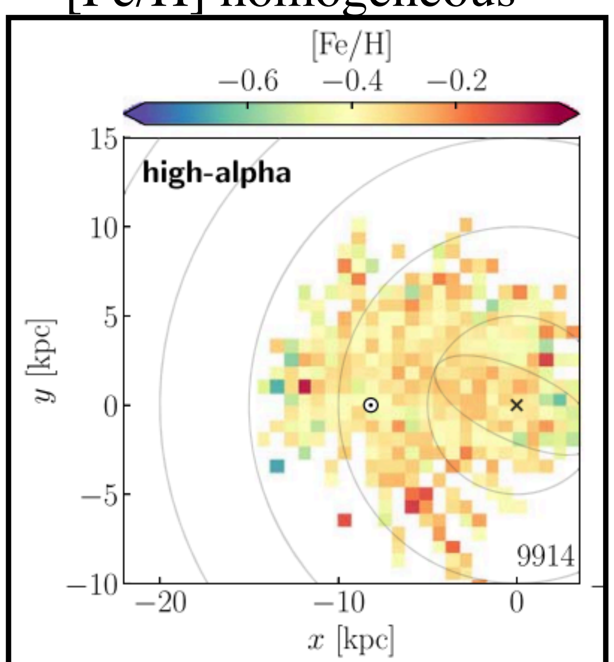
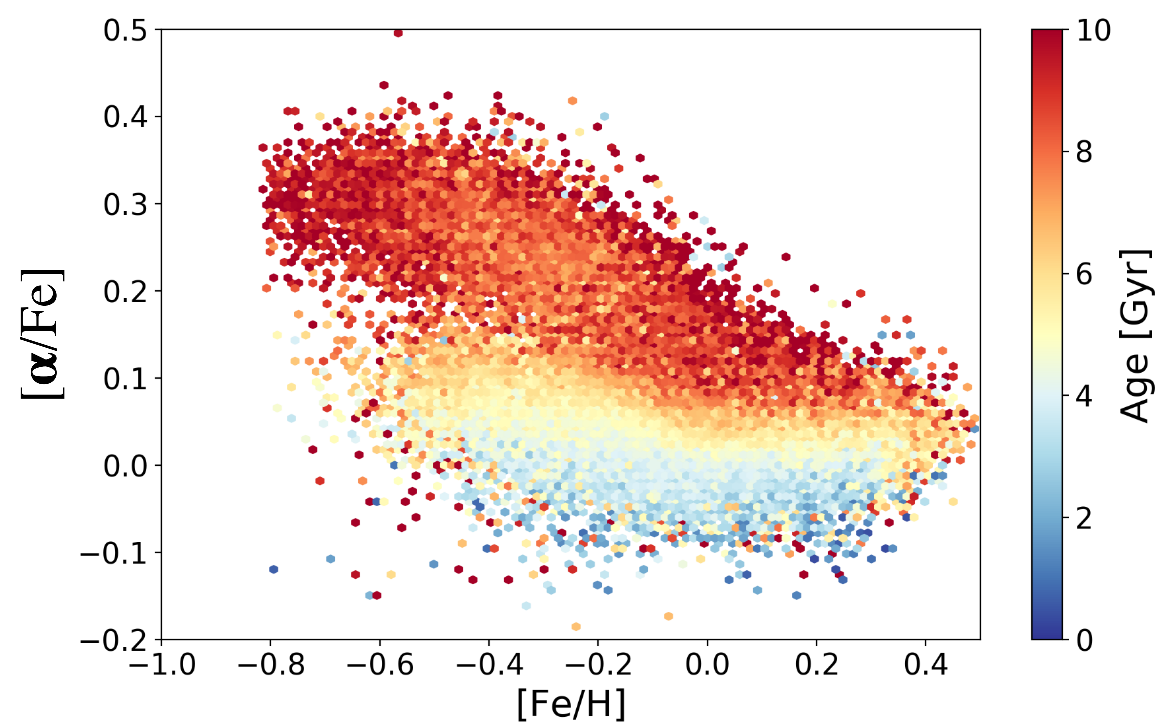


[Fe/H] homogeneous





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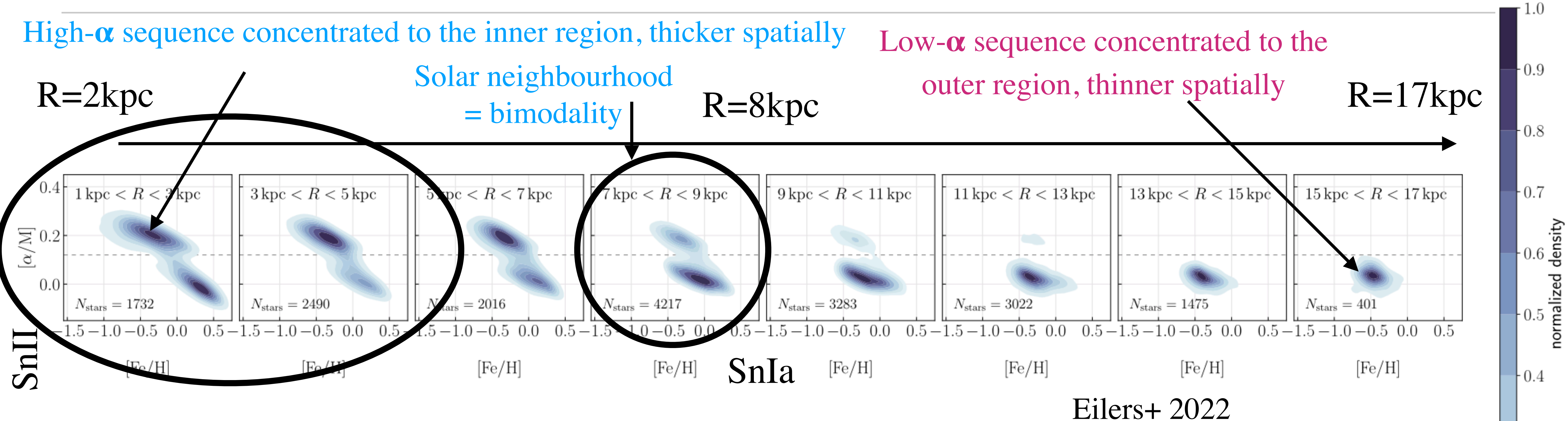

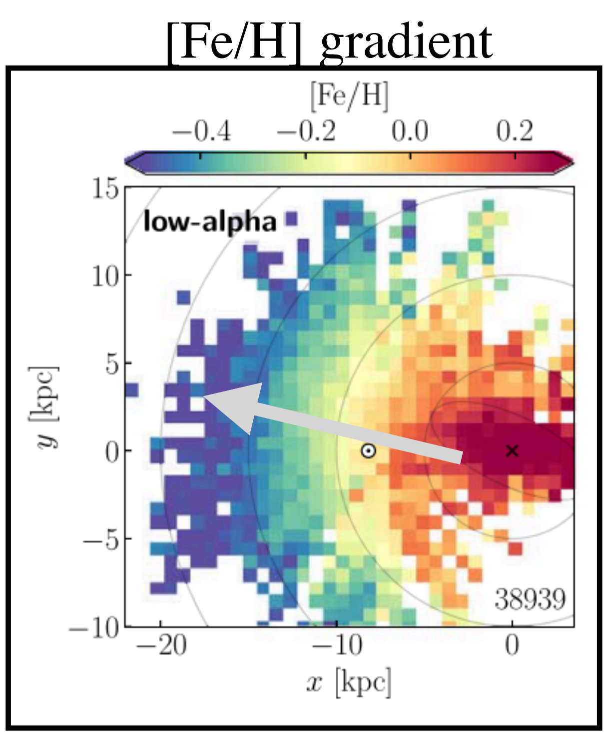

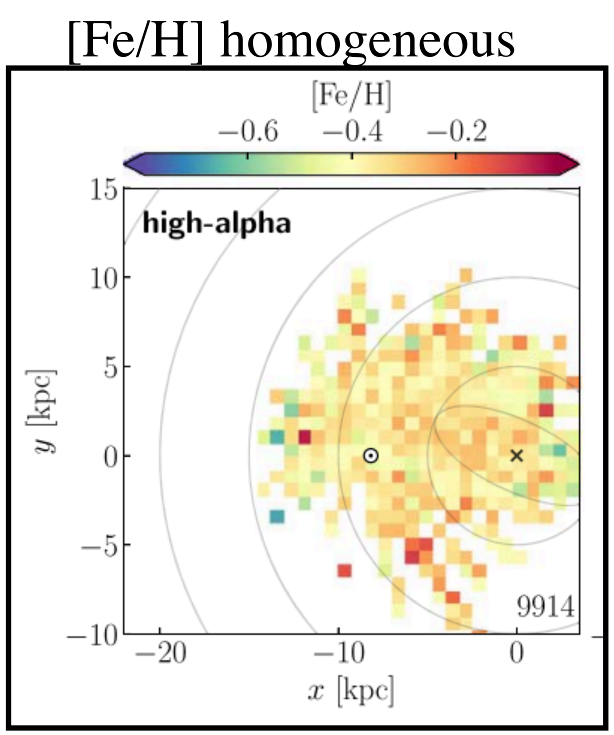

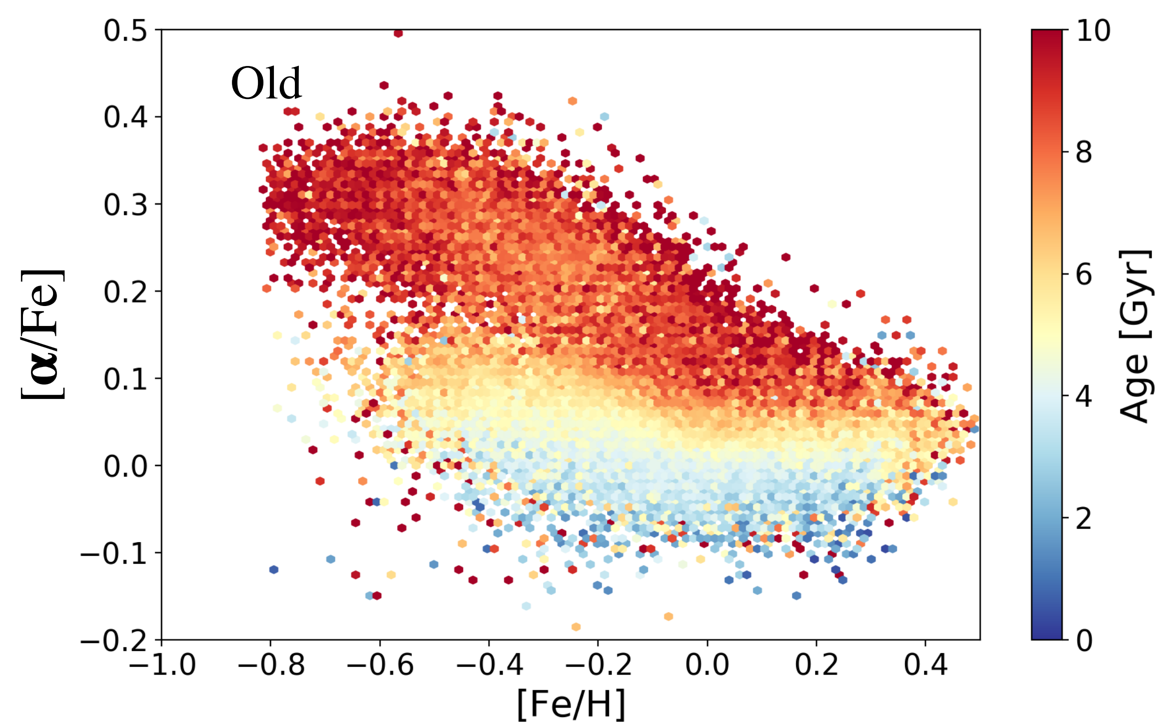

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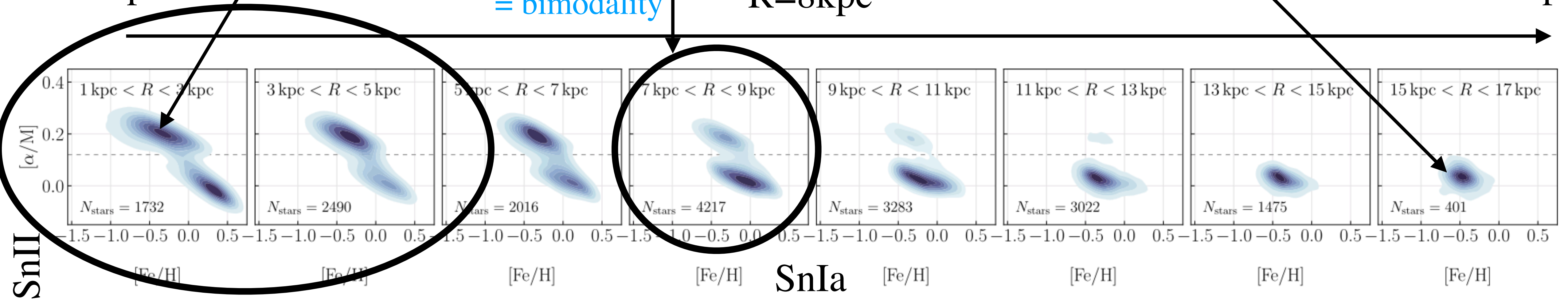

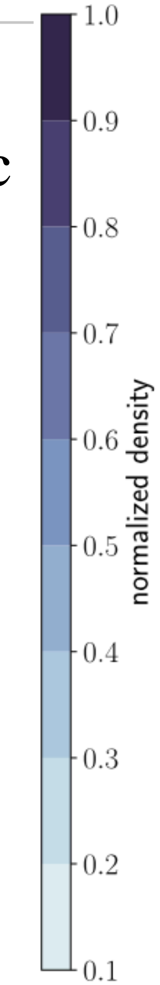

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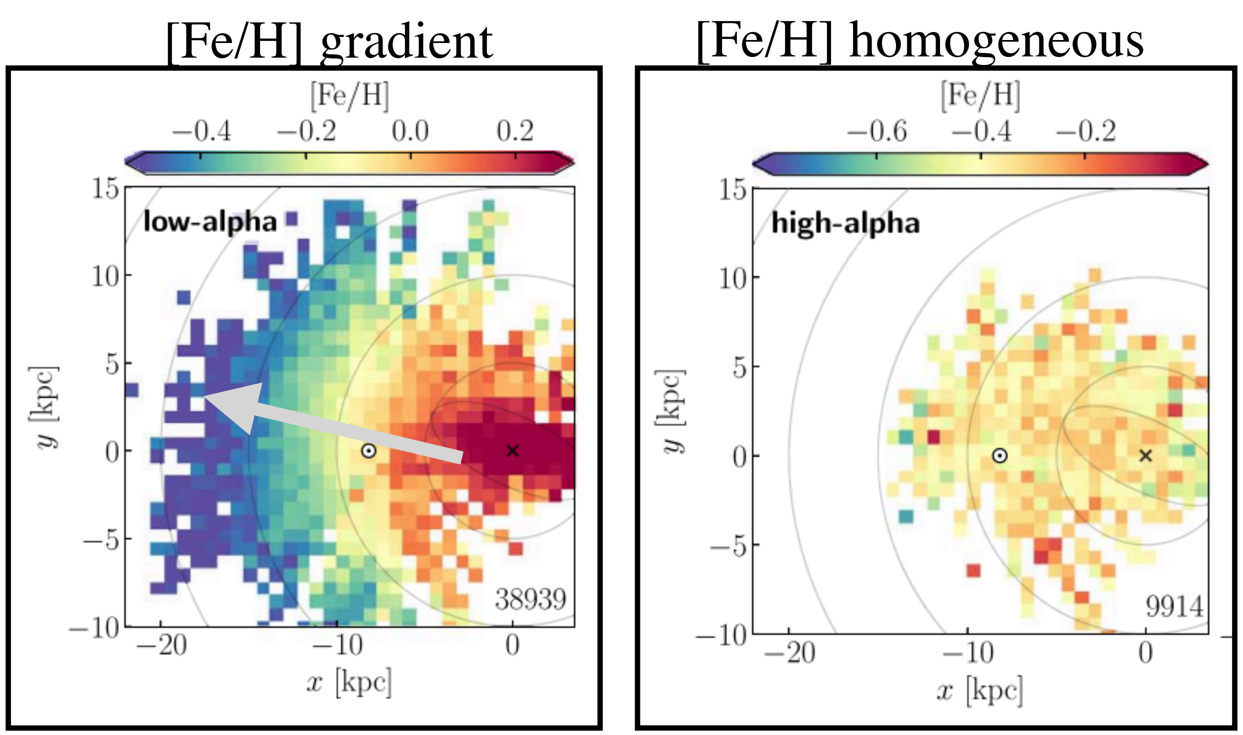

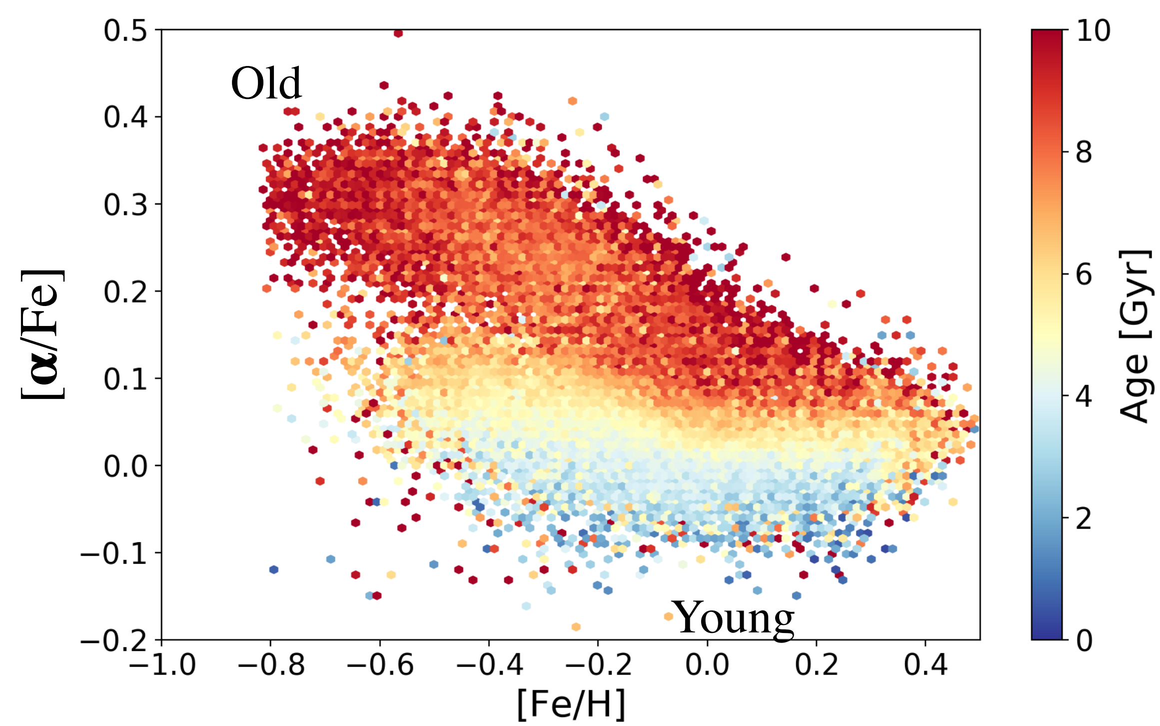

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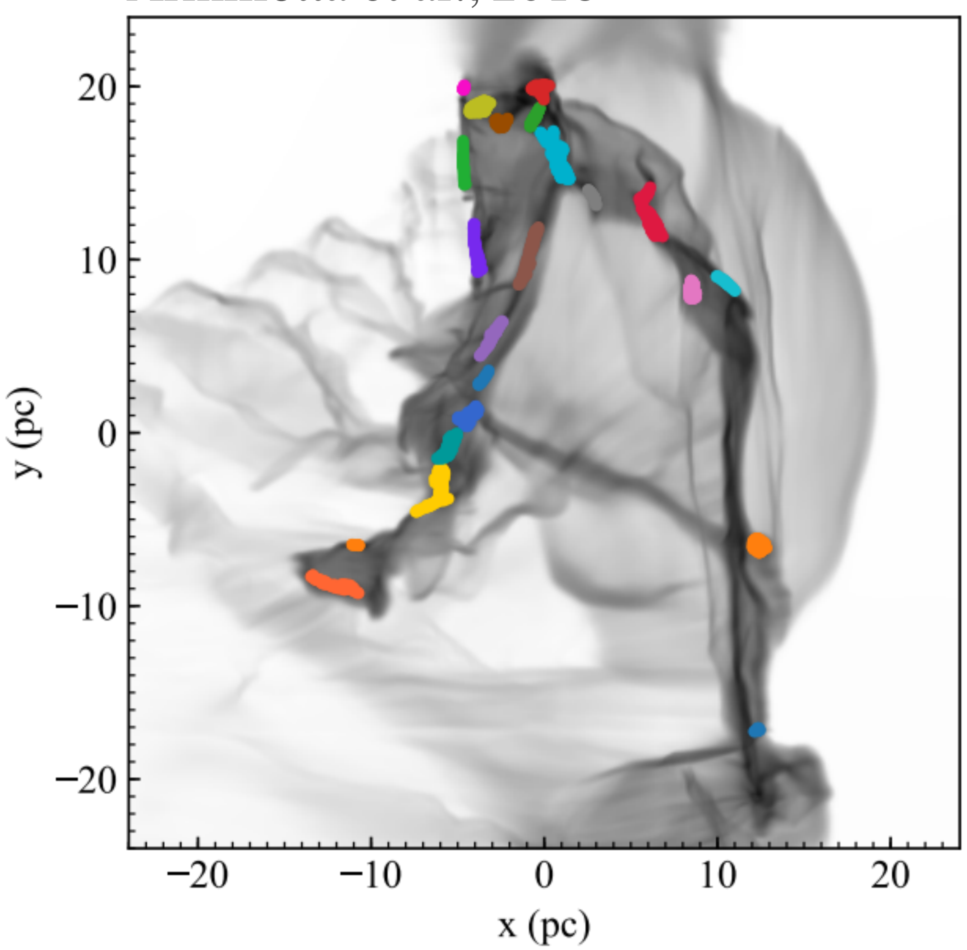
In the disk, stars are born…and move over time…

- Stars form in clusters, with presumably identical abundances

Armillotta et al., 2018



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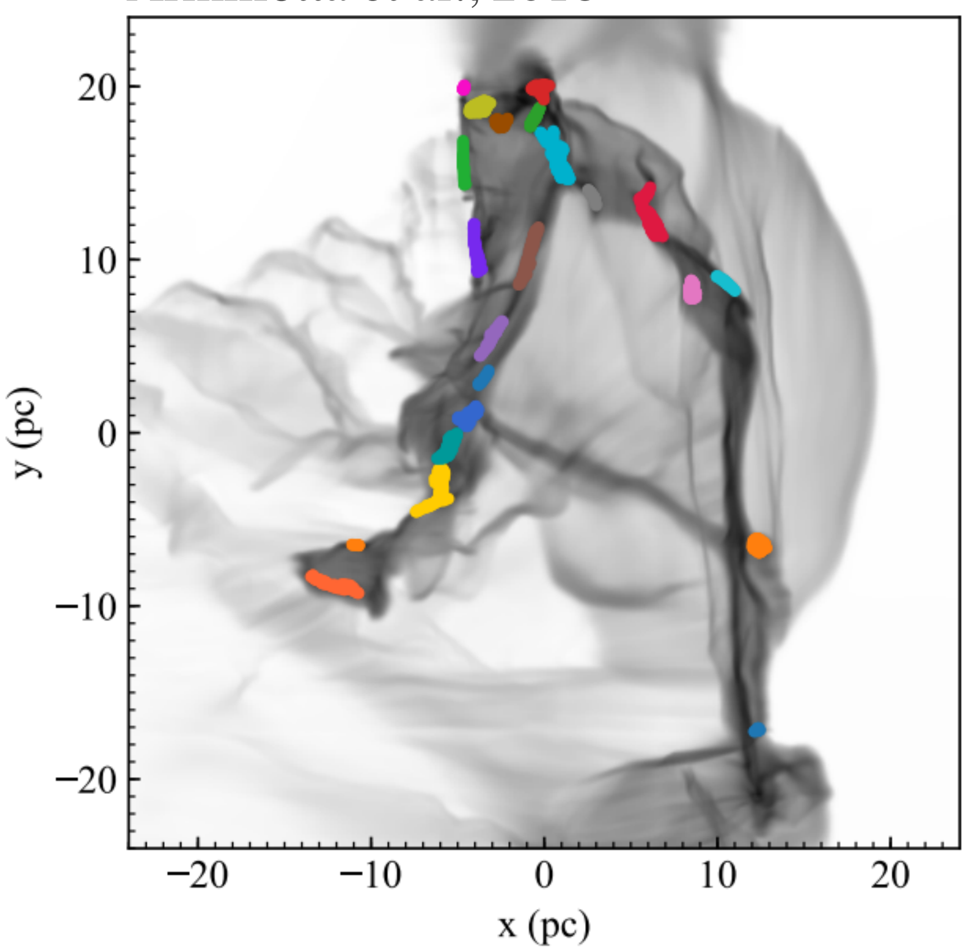

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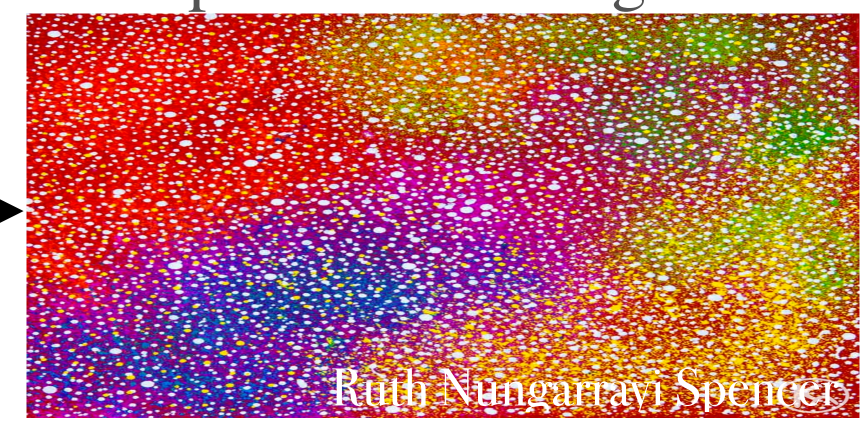

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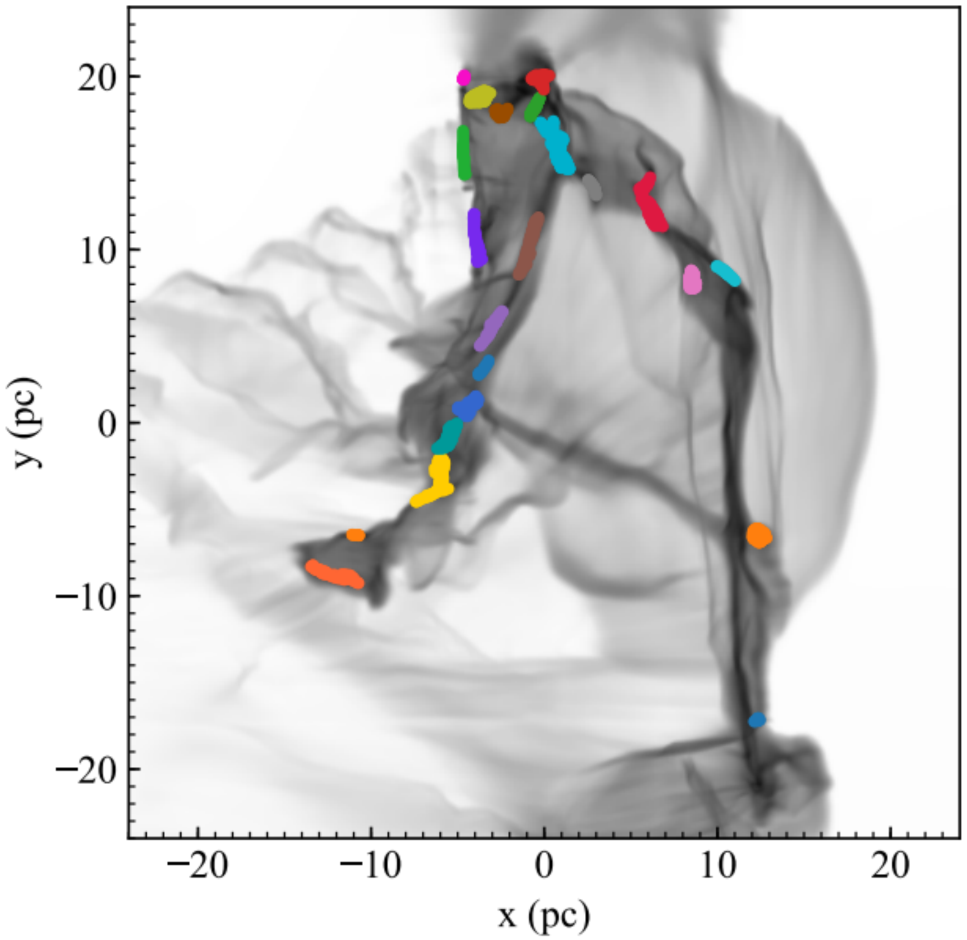

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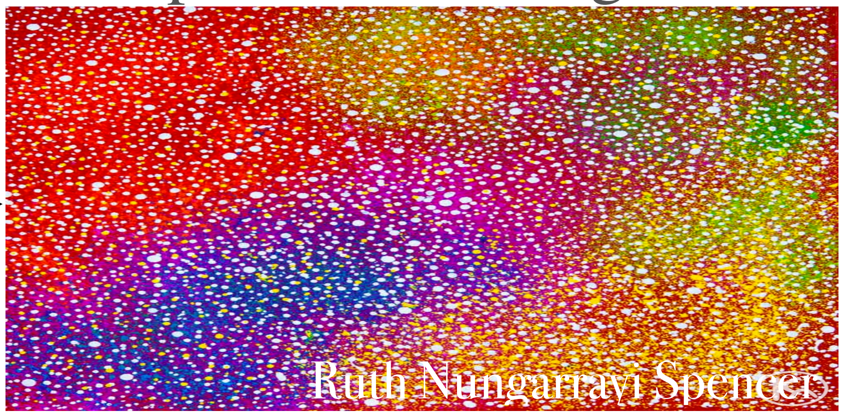

- one prospect to trace back disk assembly — **chemical tagging** (Bland-Hawthorn & Freeman 2010)
- identify individual stars across the disk from the same birth sites using large vector of chemical abundances

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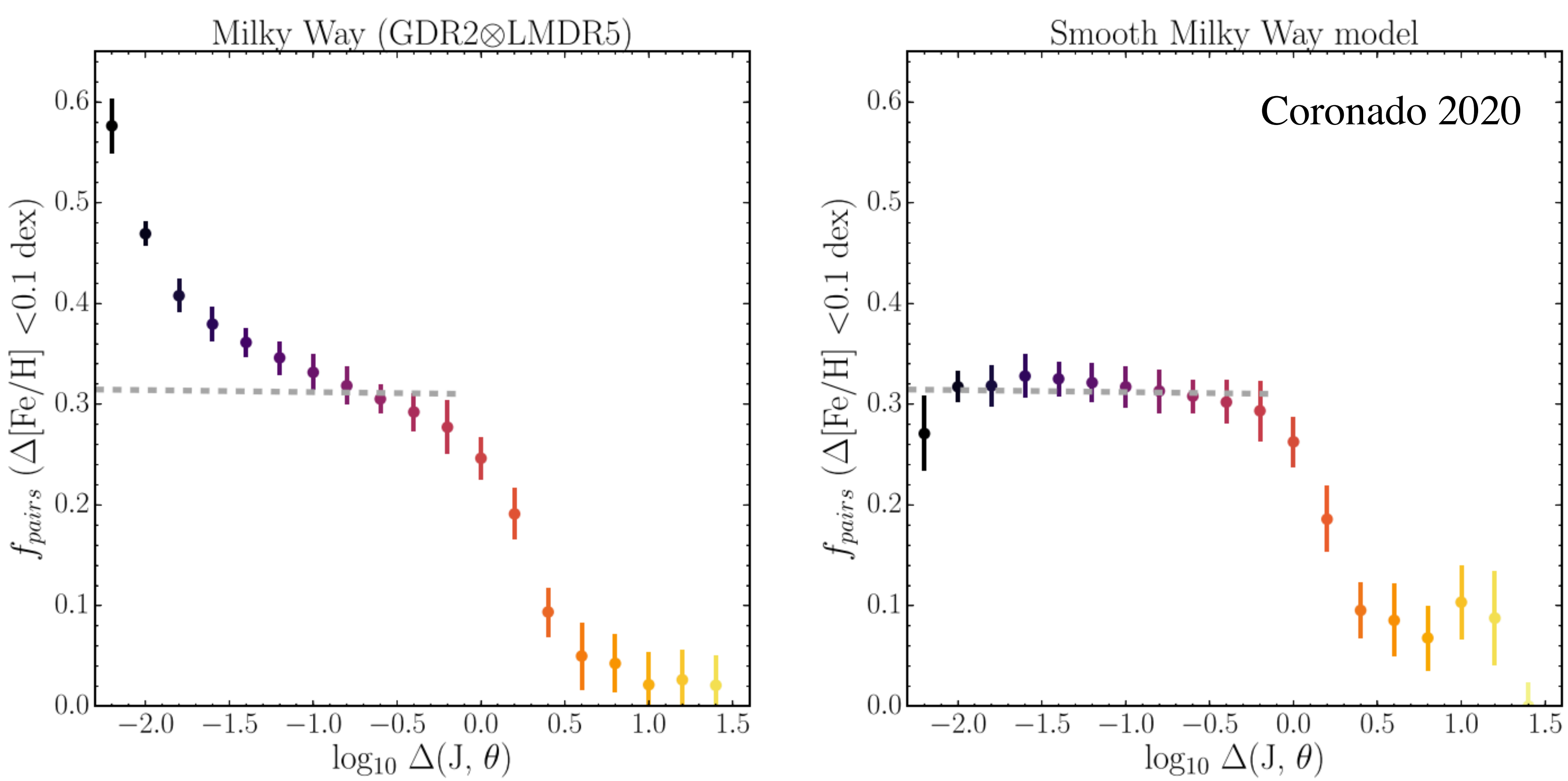

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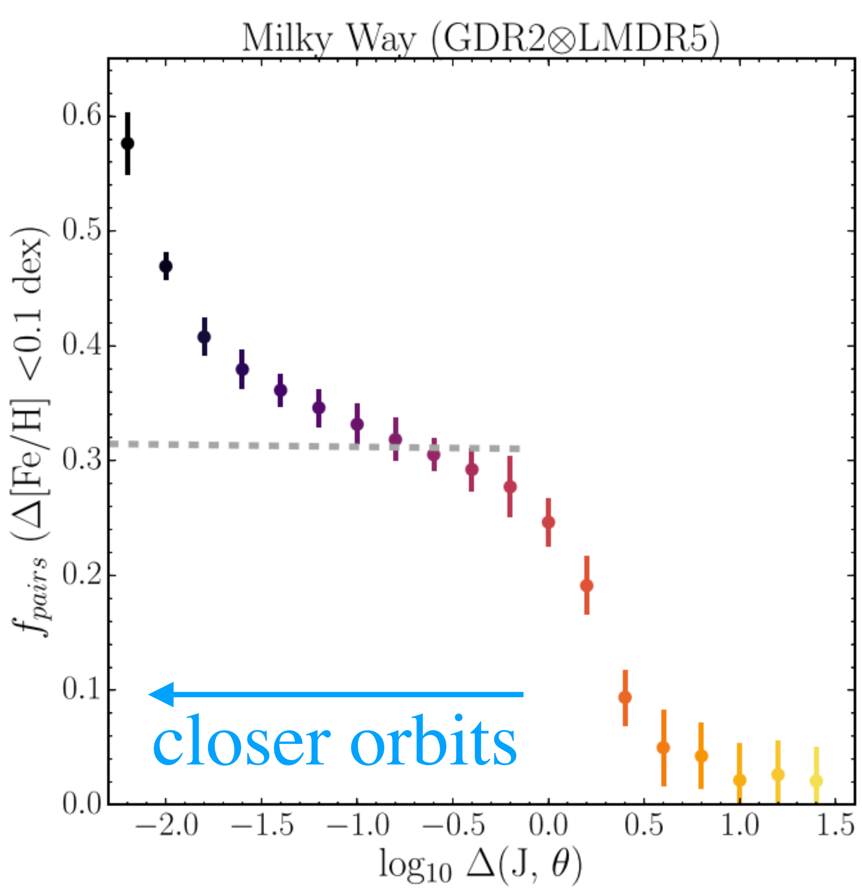

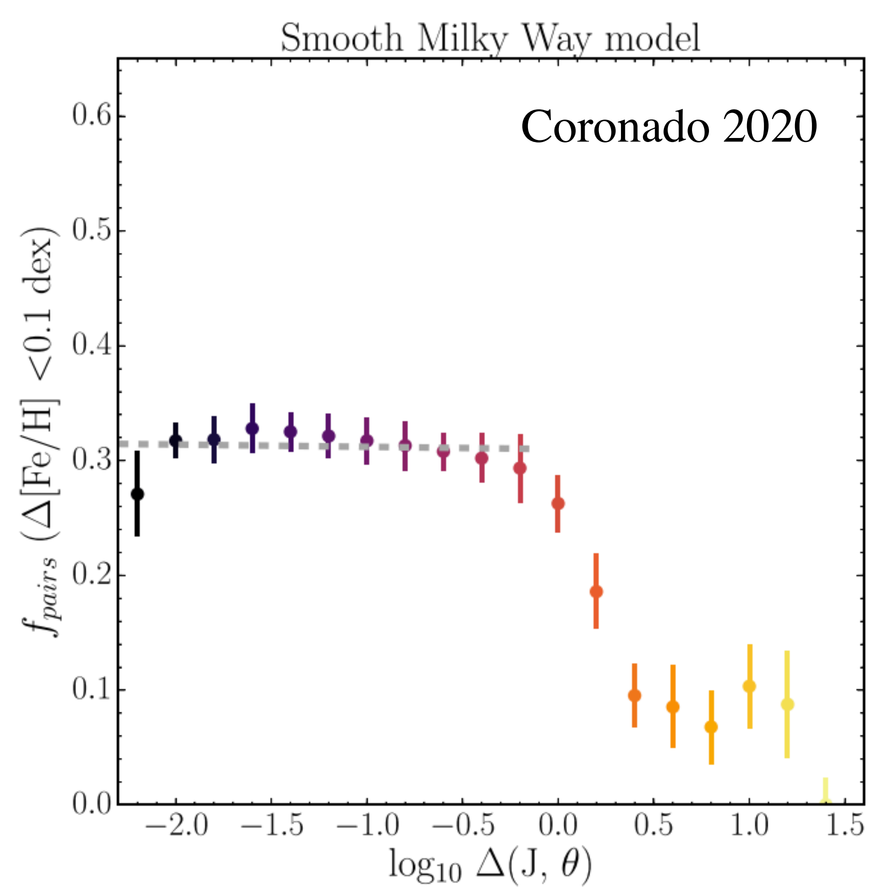

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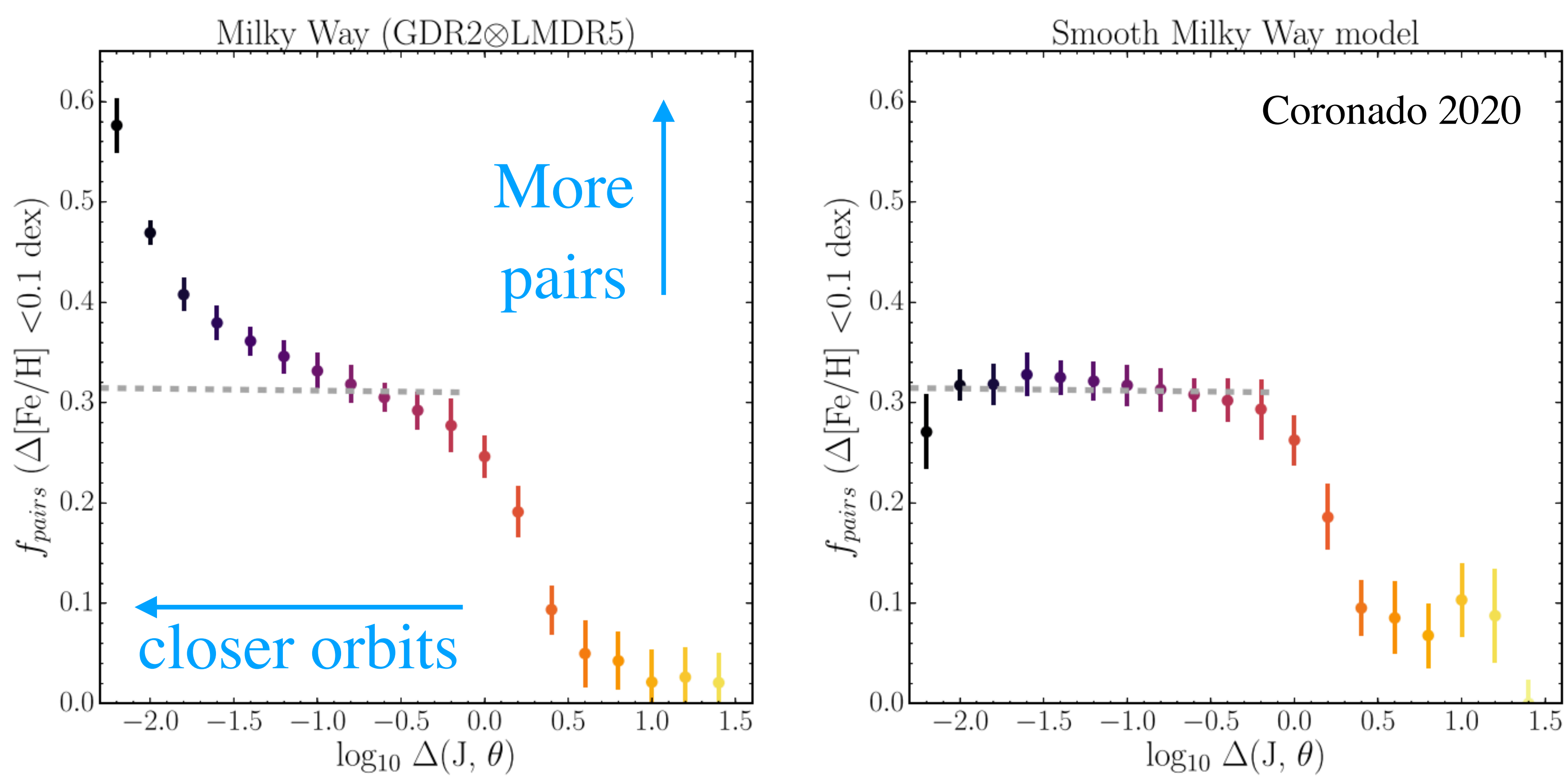

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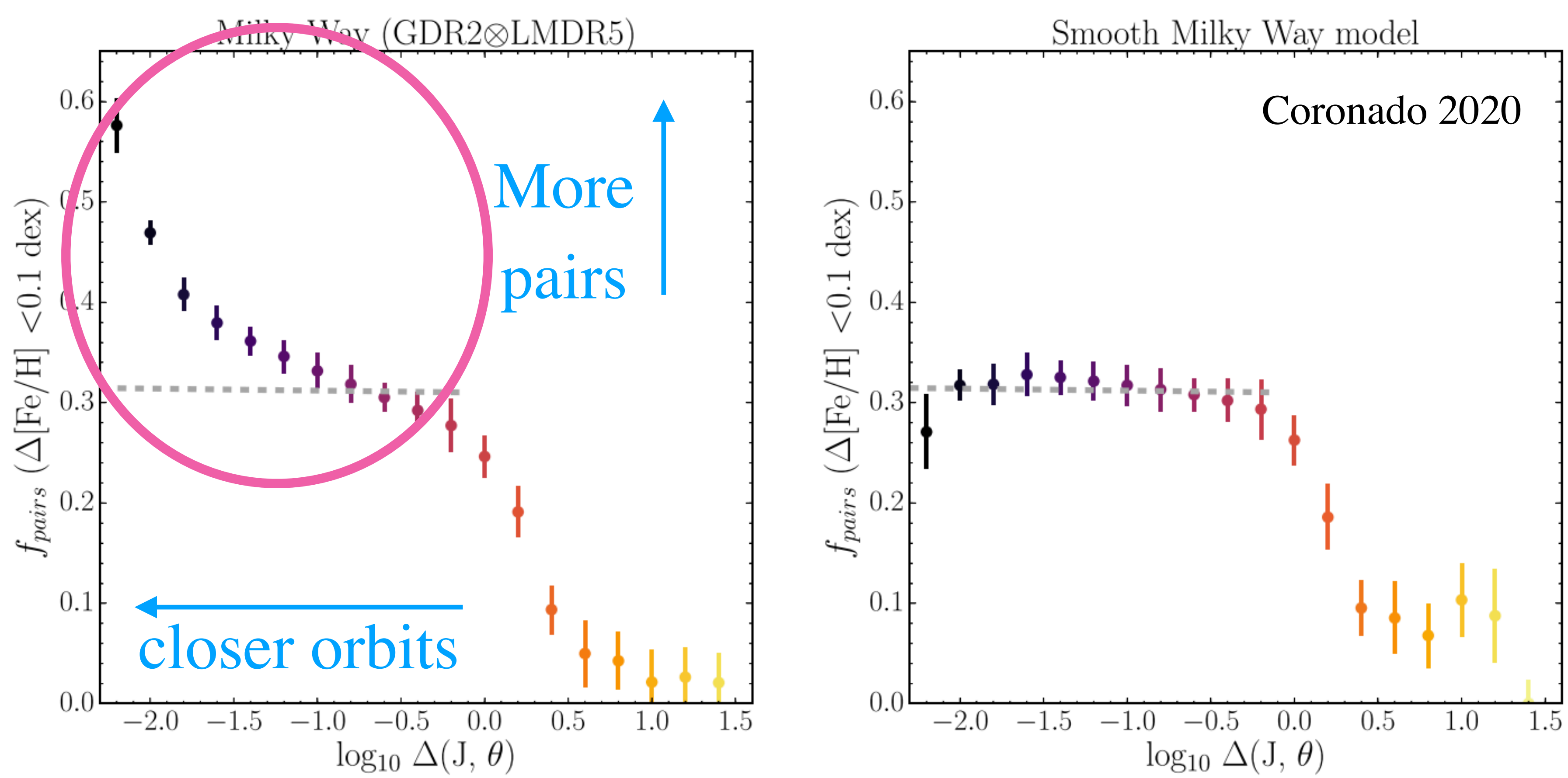

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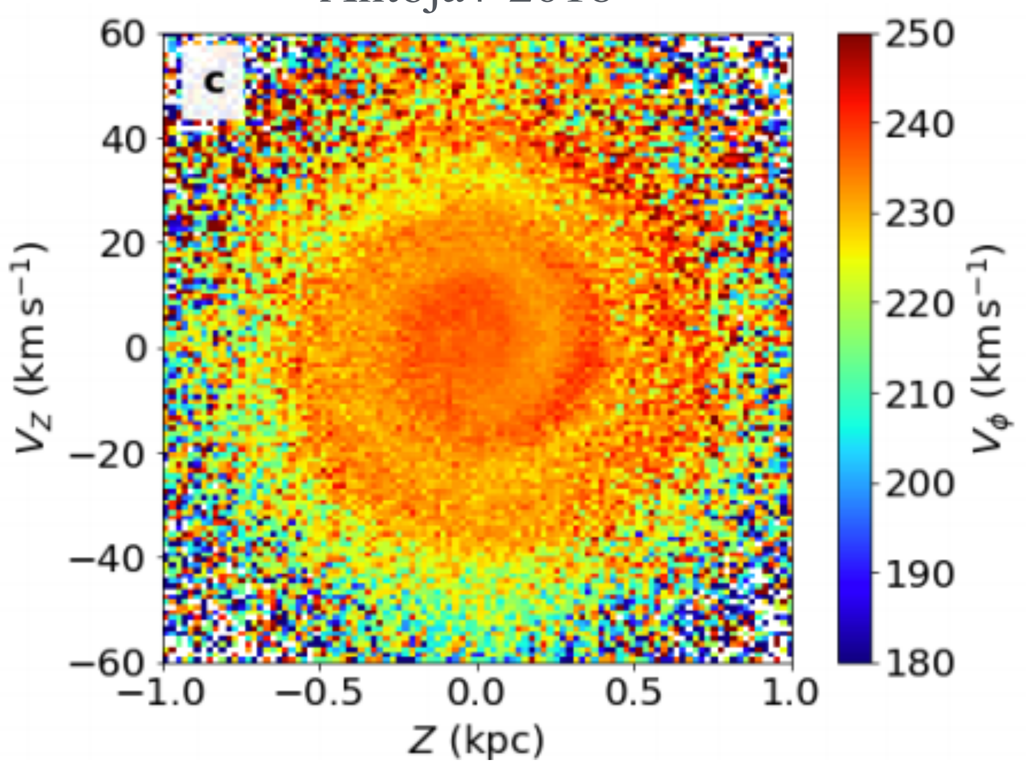

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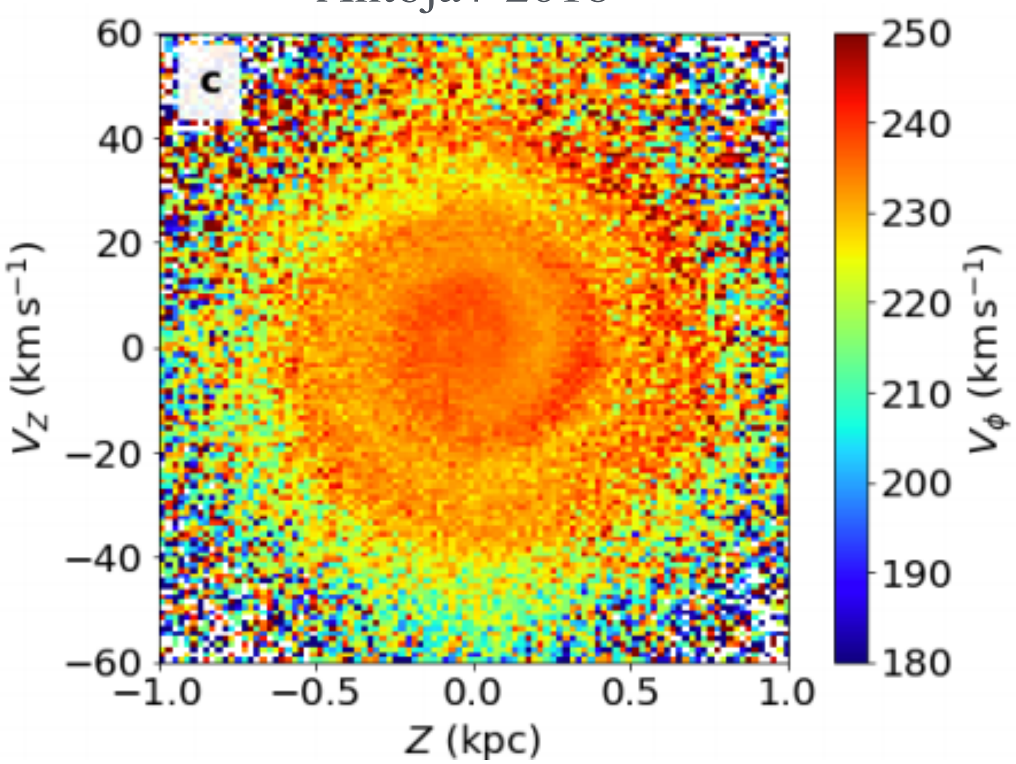

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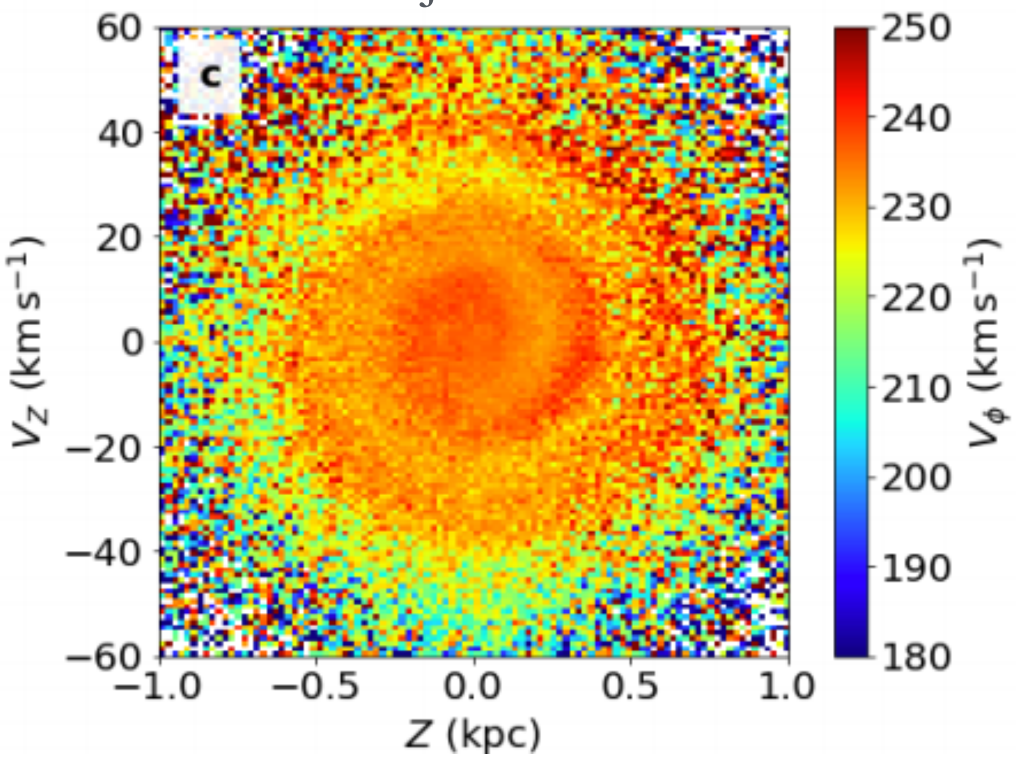

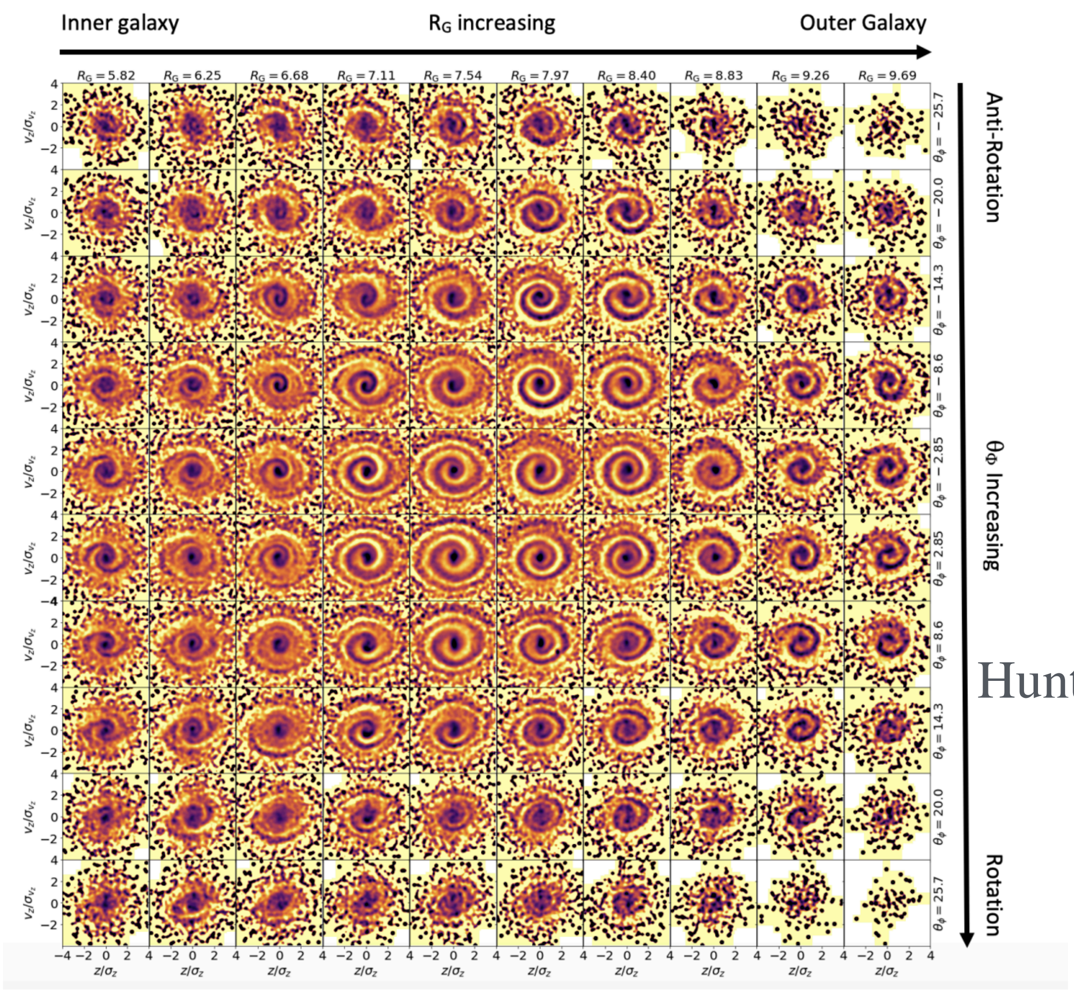

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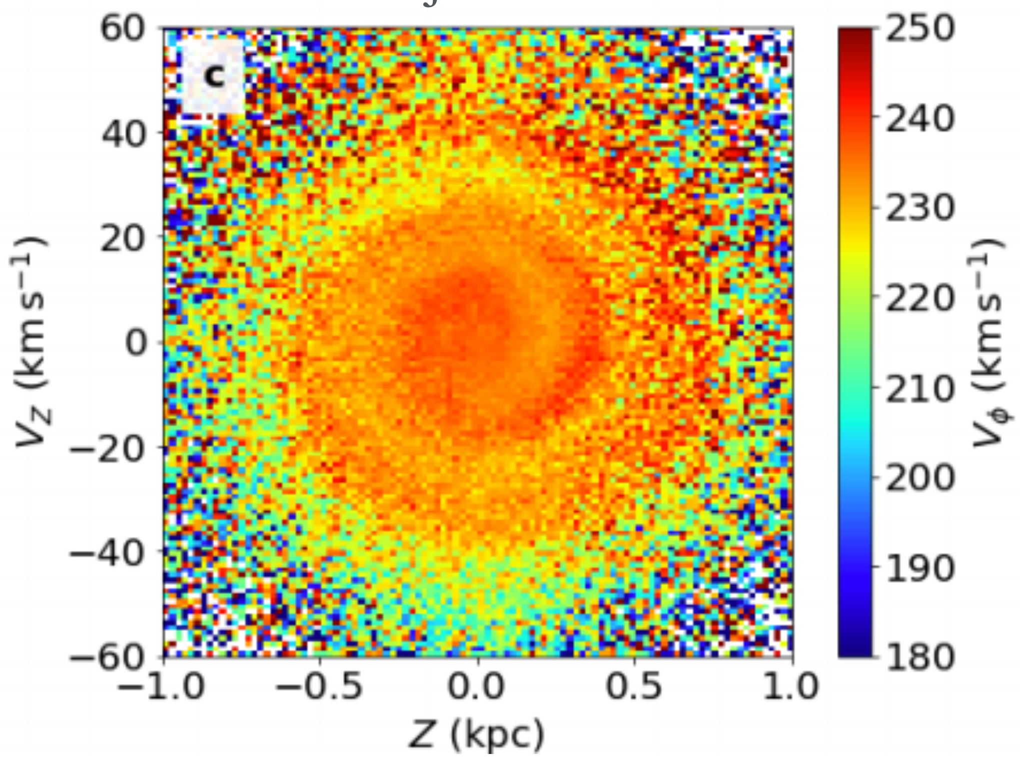

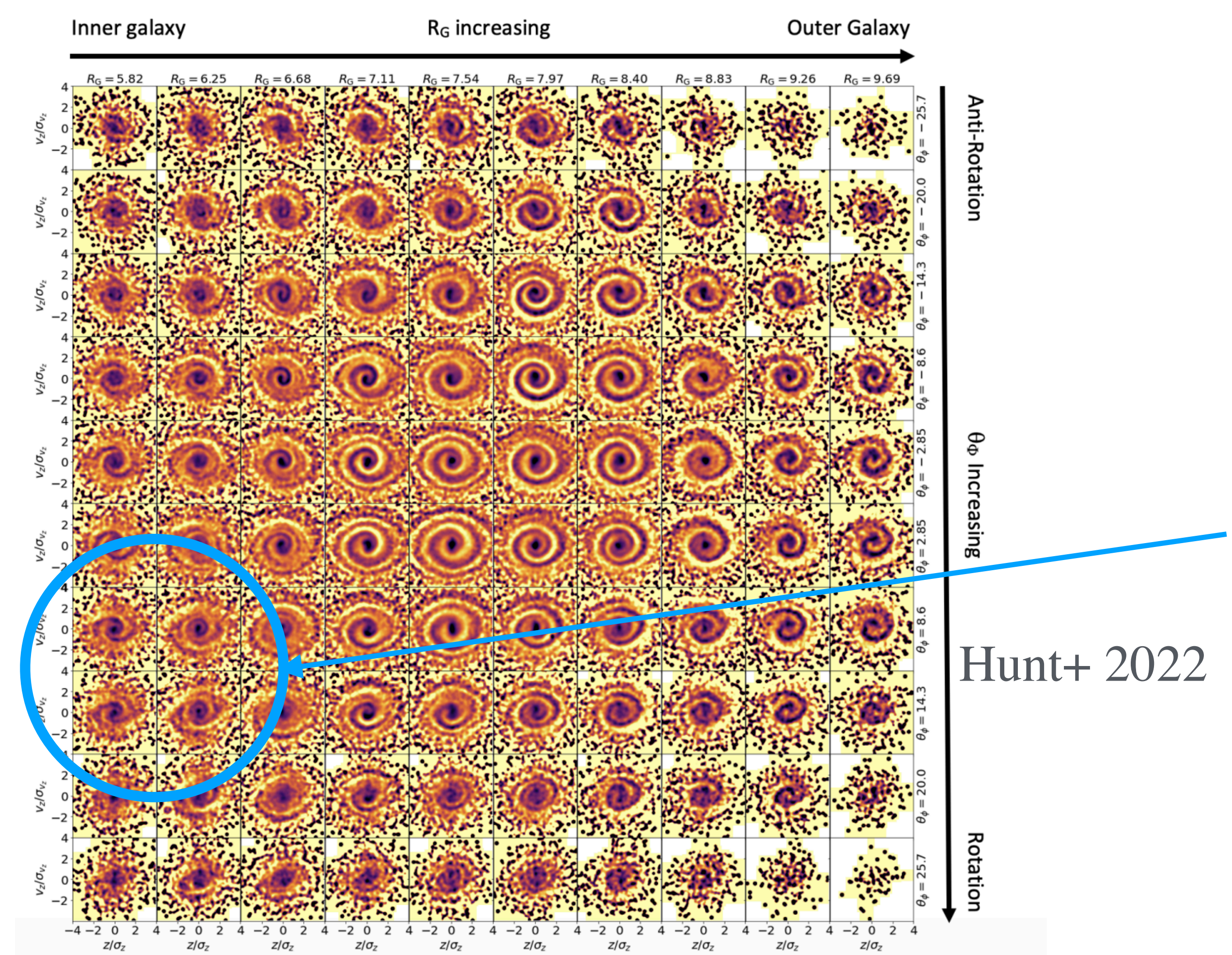

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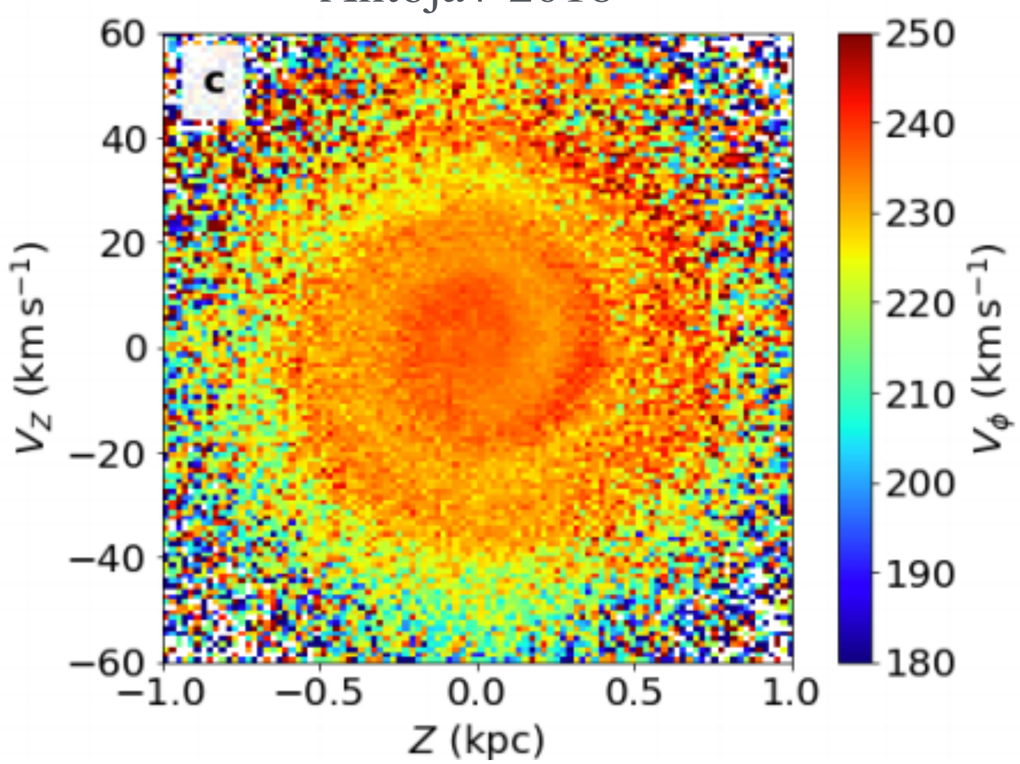

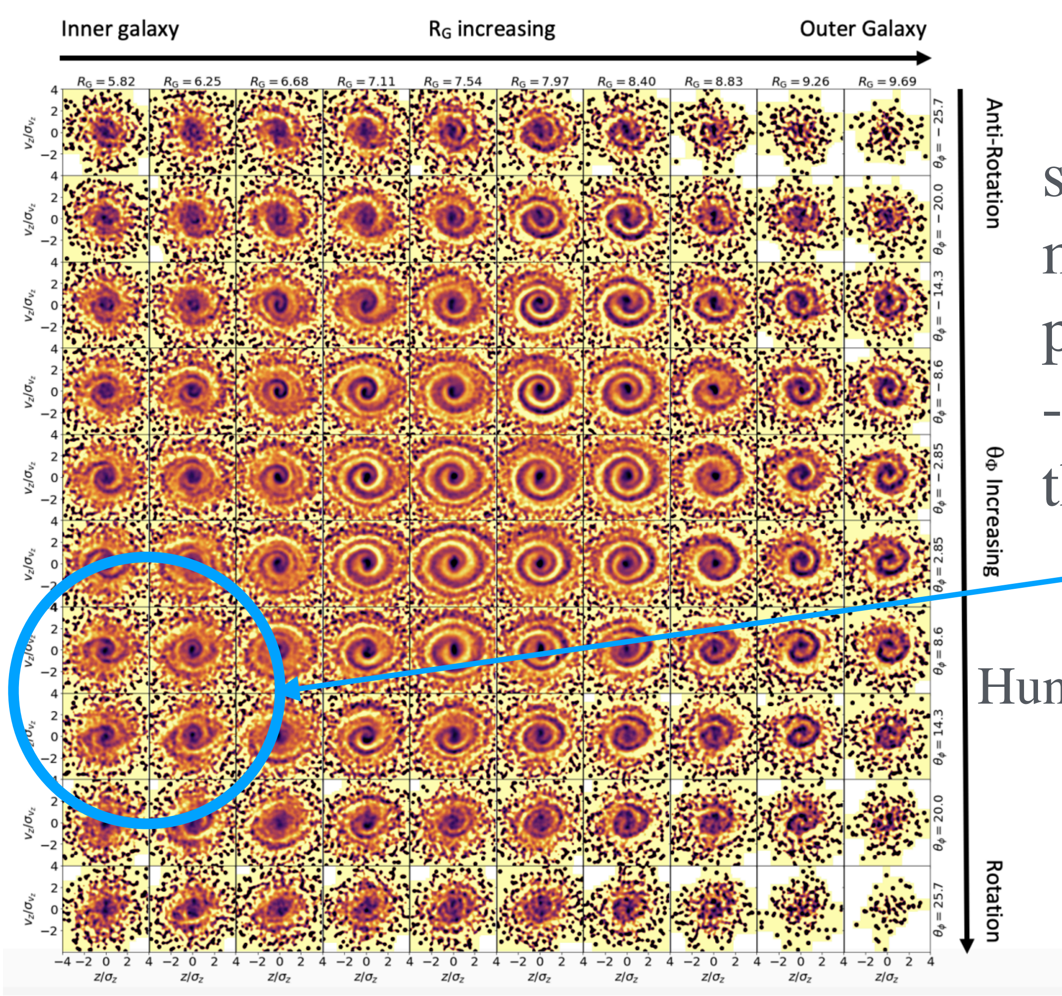

signatures of multiple perturbations
-in the inner galaxy there are two arms

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Simulations predict a bulge formed from the disk will be boxy/X-shaped

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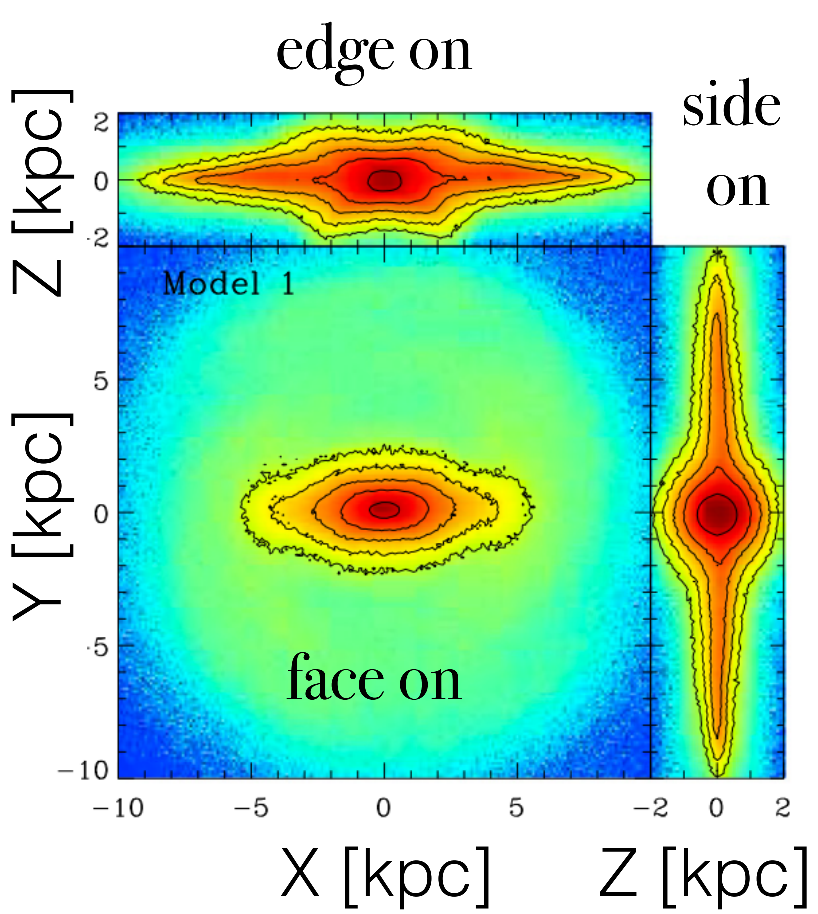

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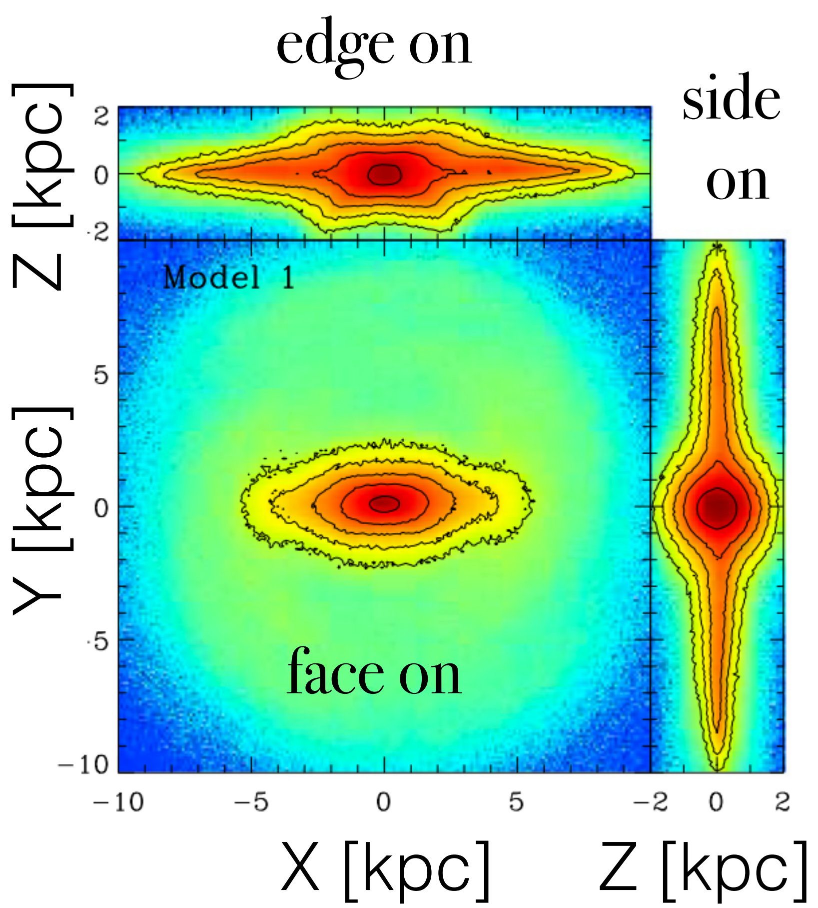

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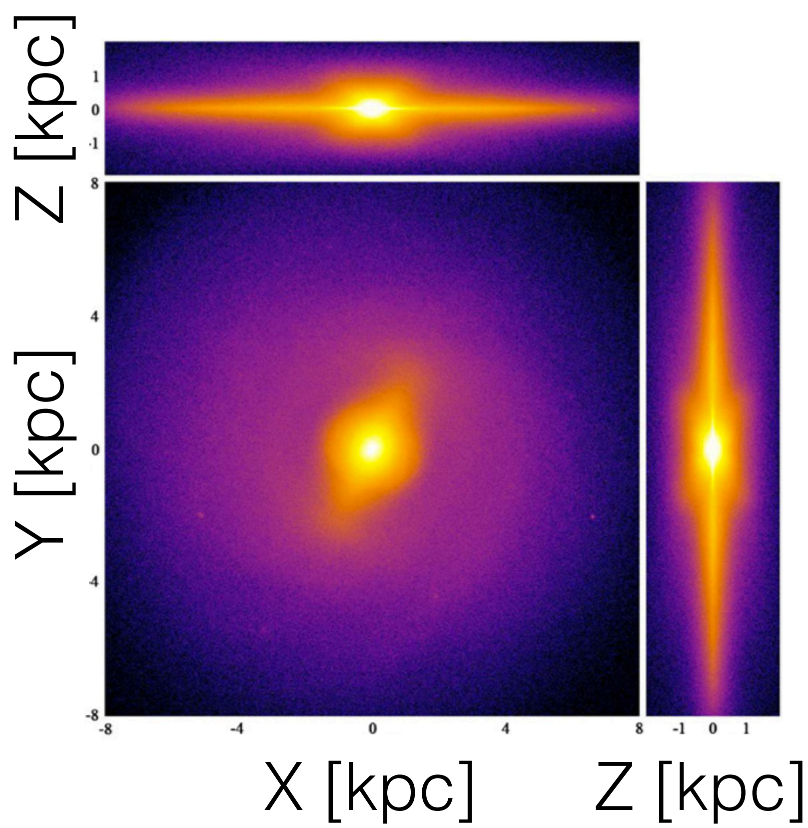

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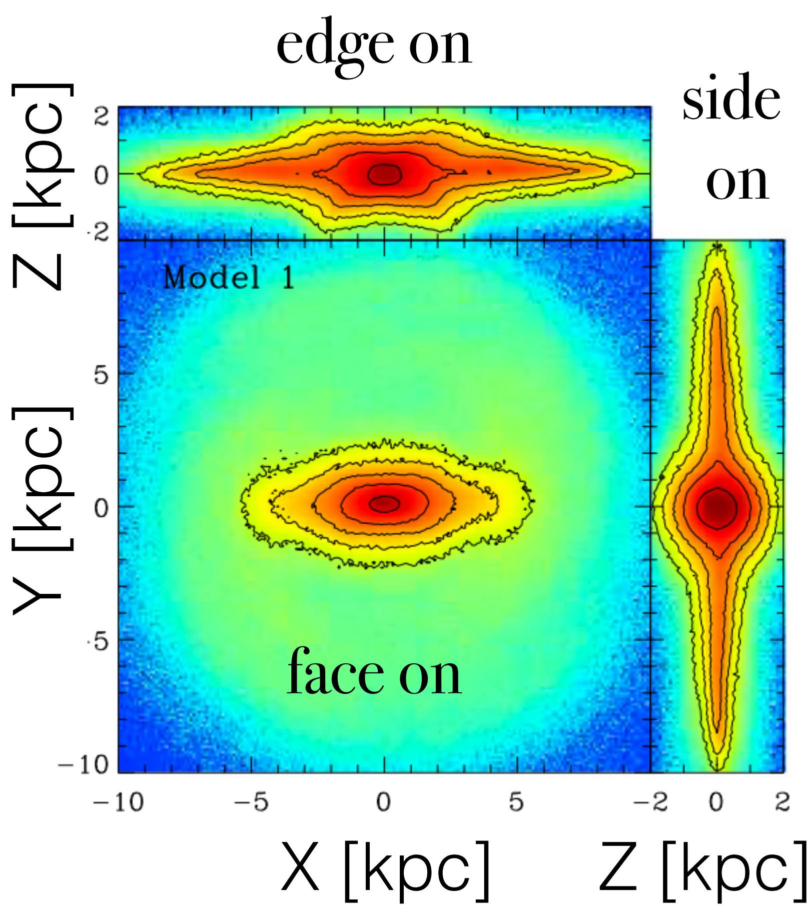

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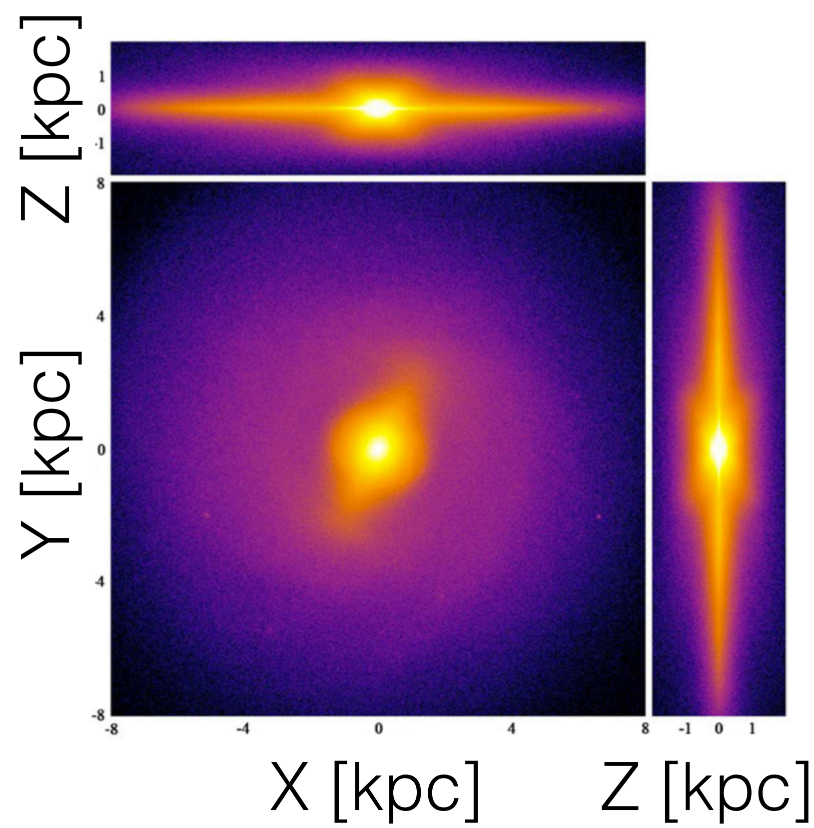

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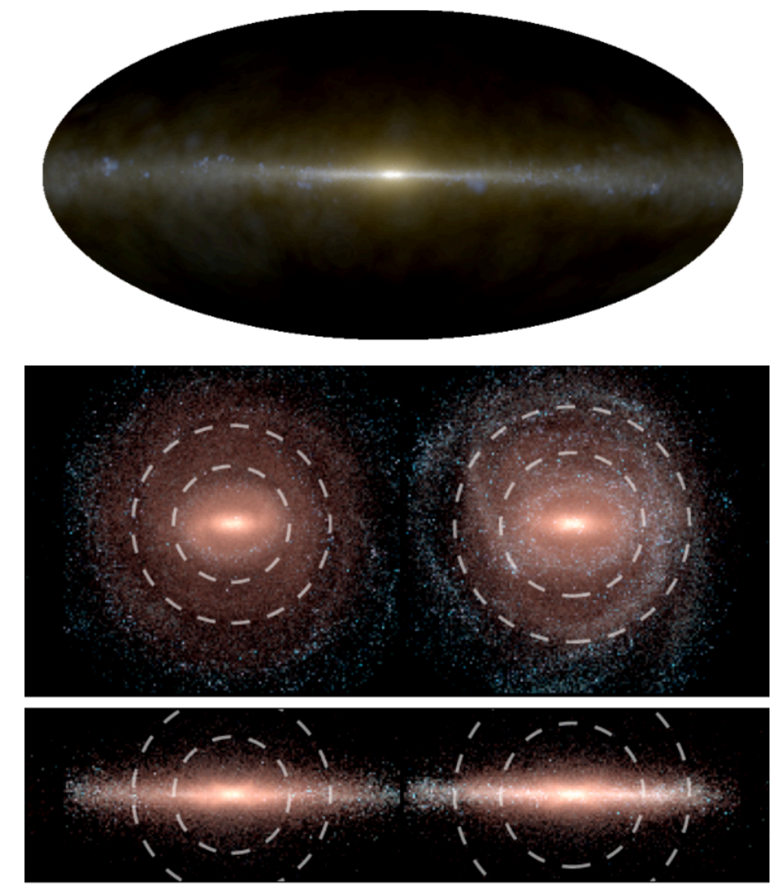

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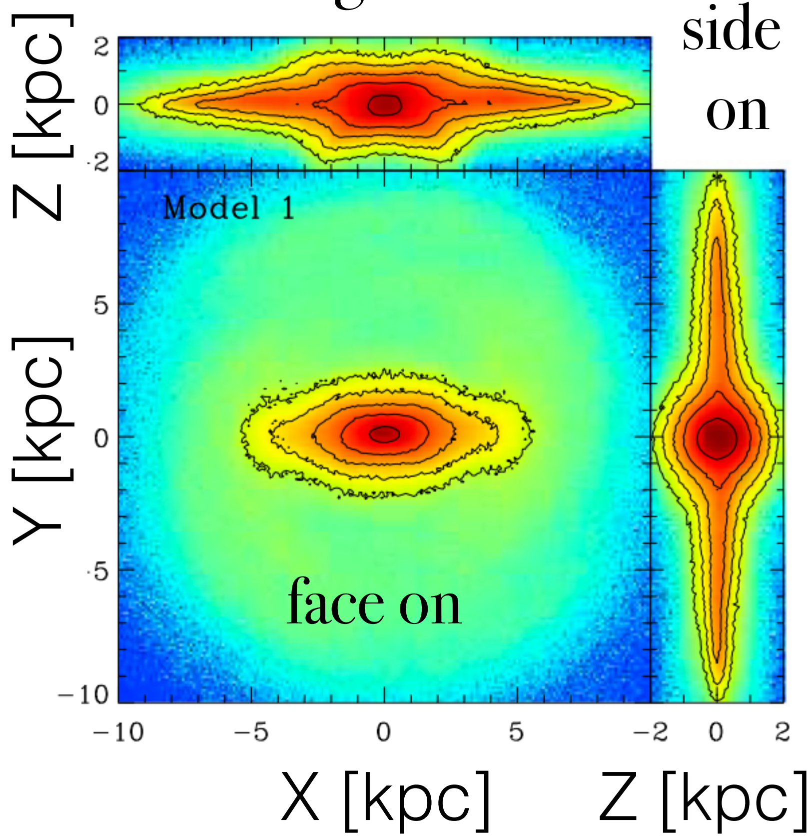

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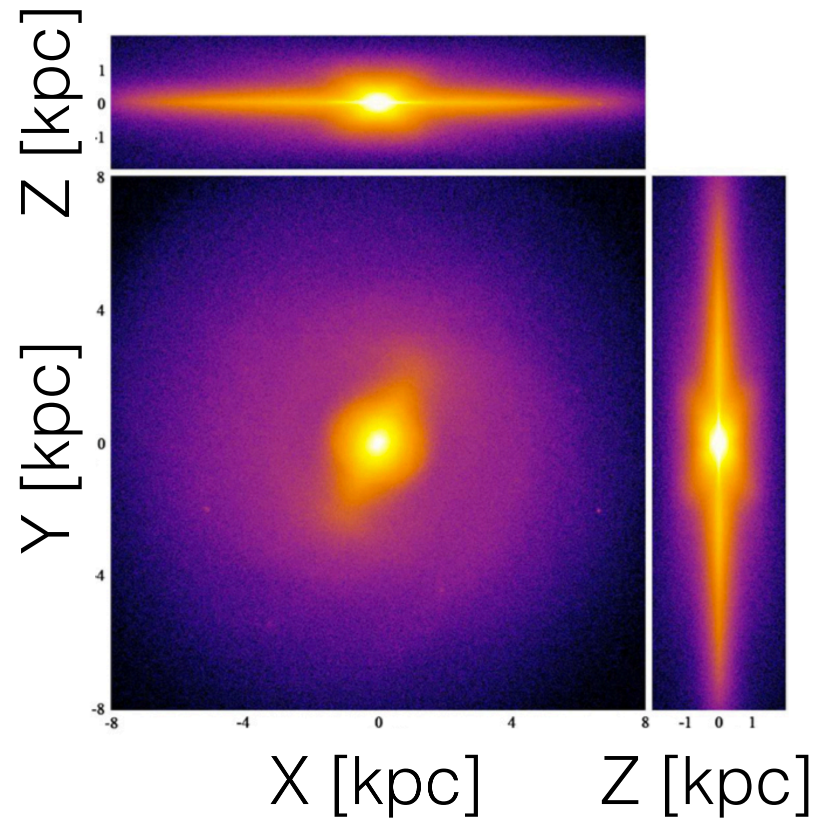

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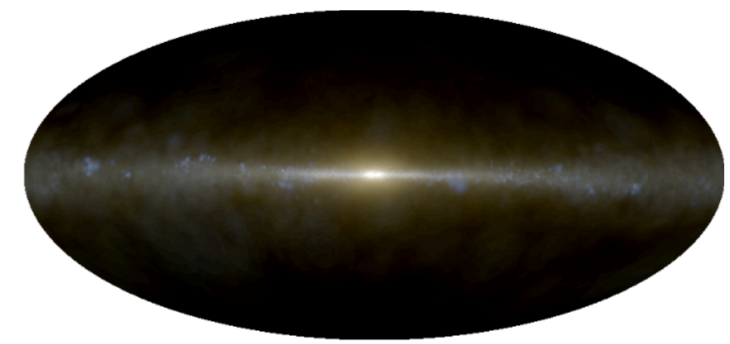

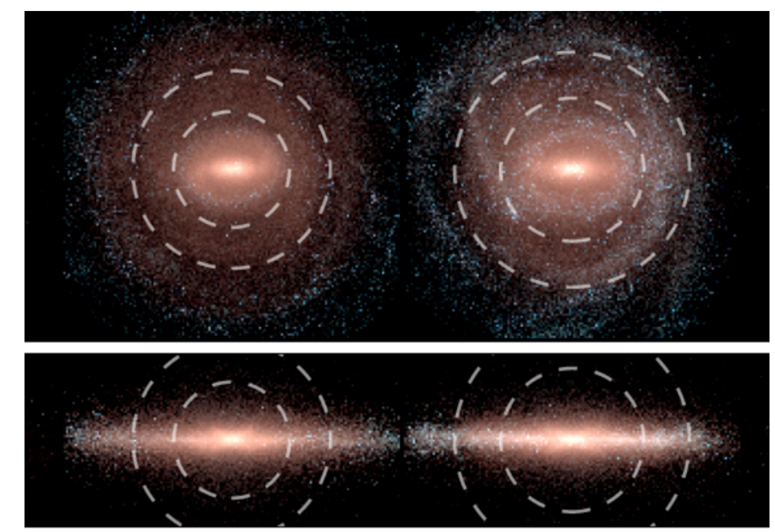

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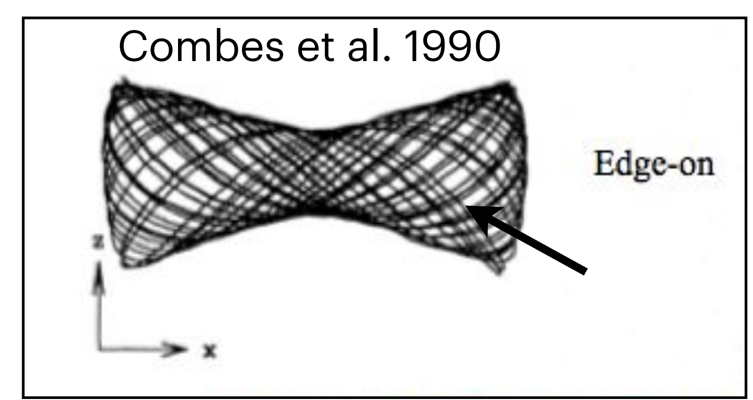
& a consequence of orbit families from dynamical instabilities



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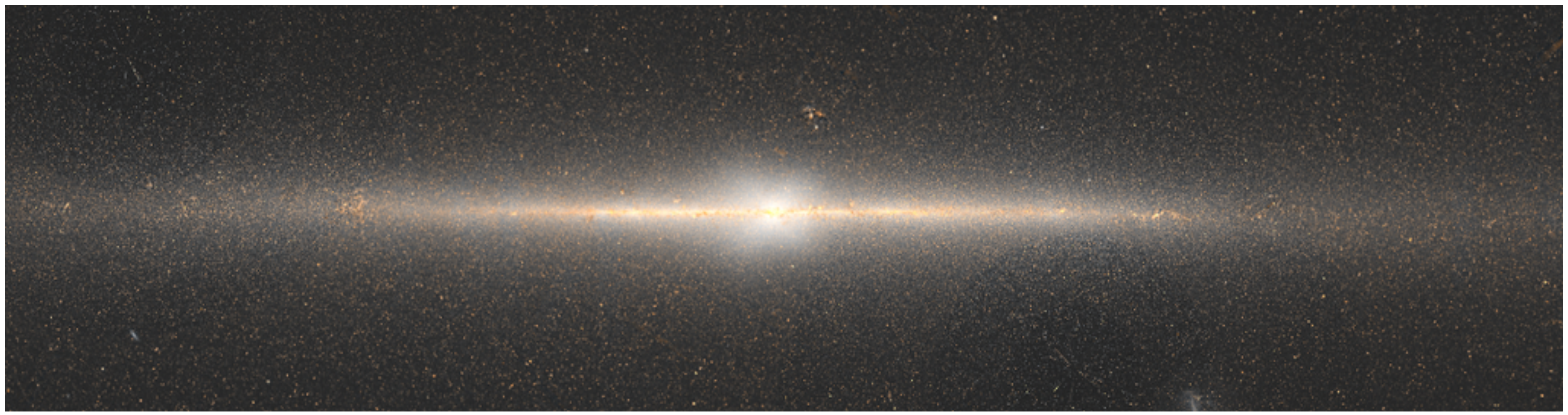
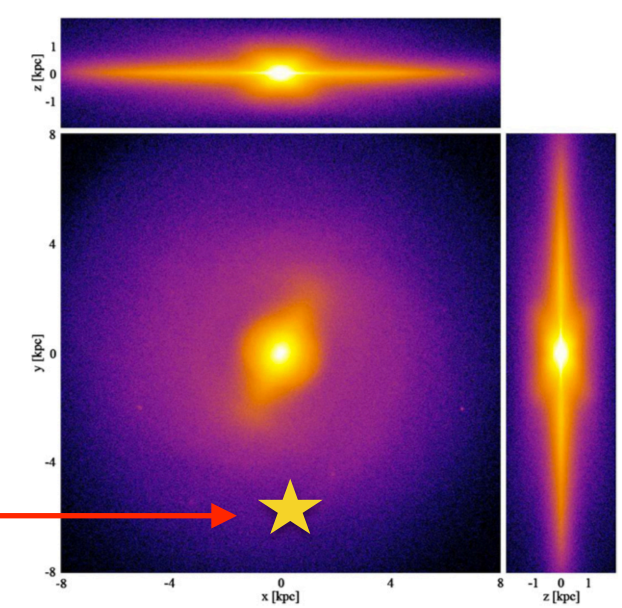


image credit: (Lang - unwise **photometry**)

*Milky Way bulge is 27 degrees with respect to our line of sight



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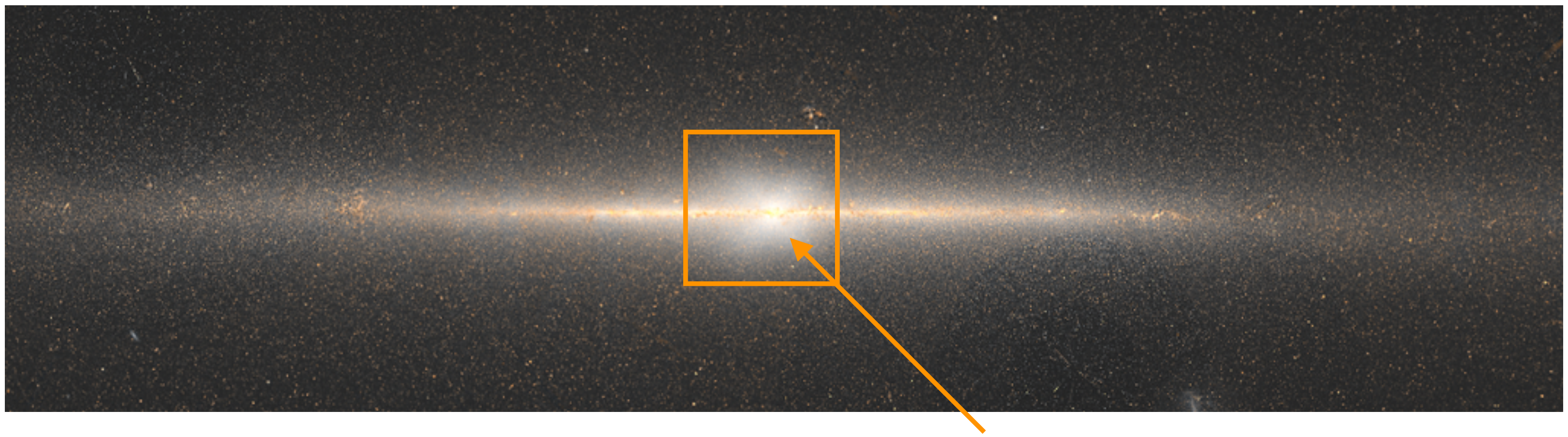

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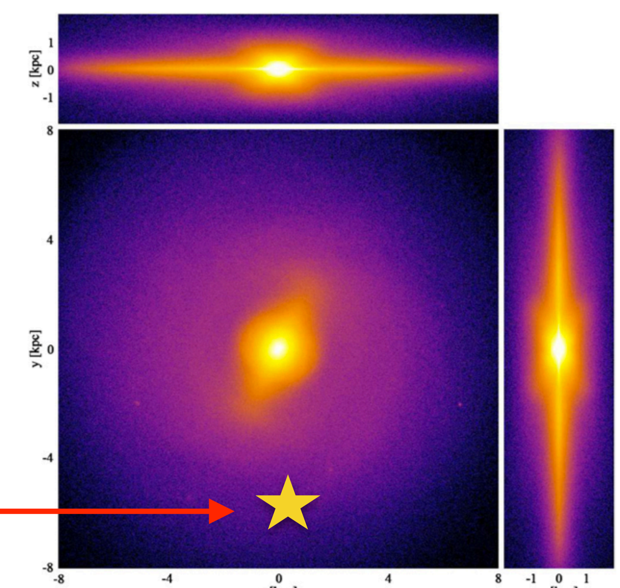

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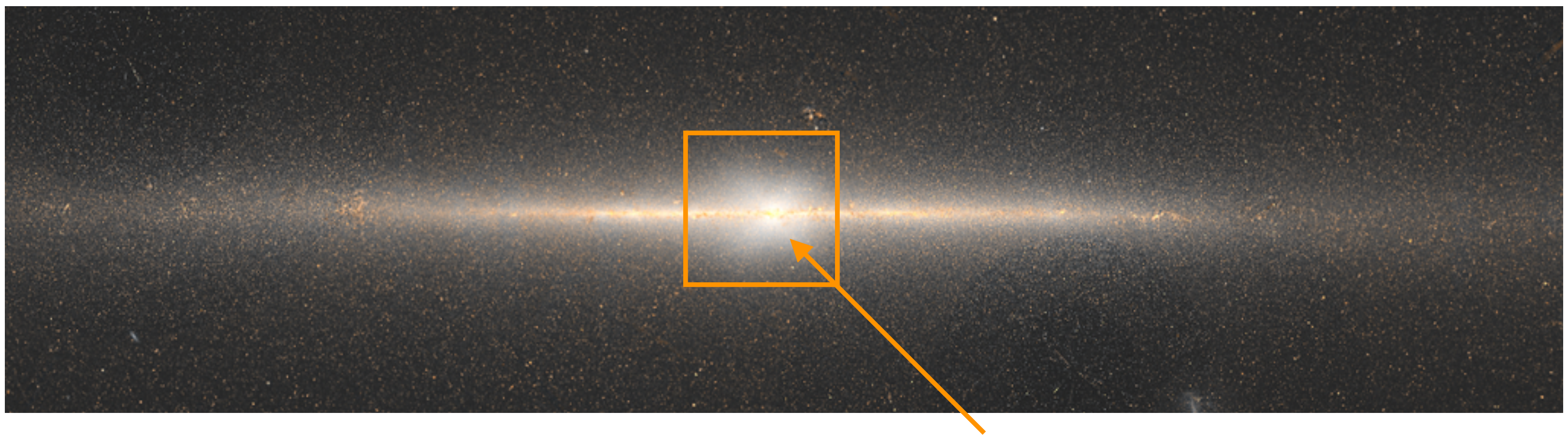

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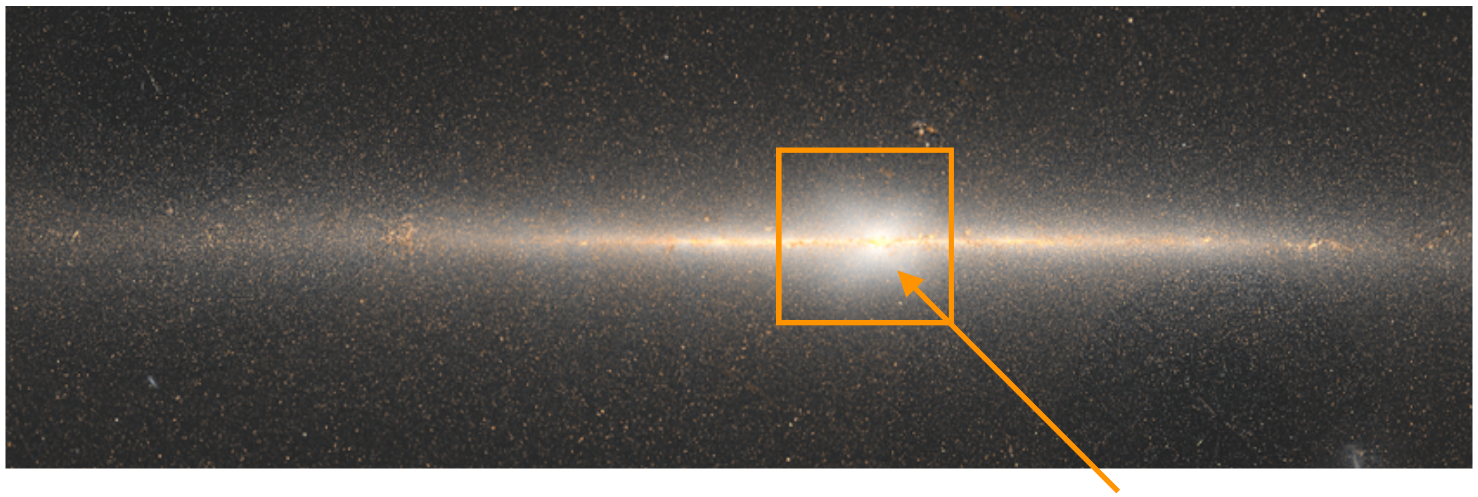

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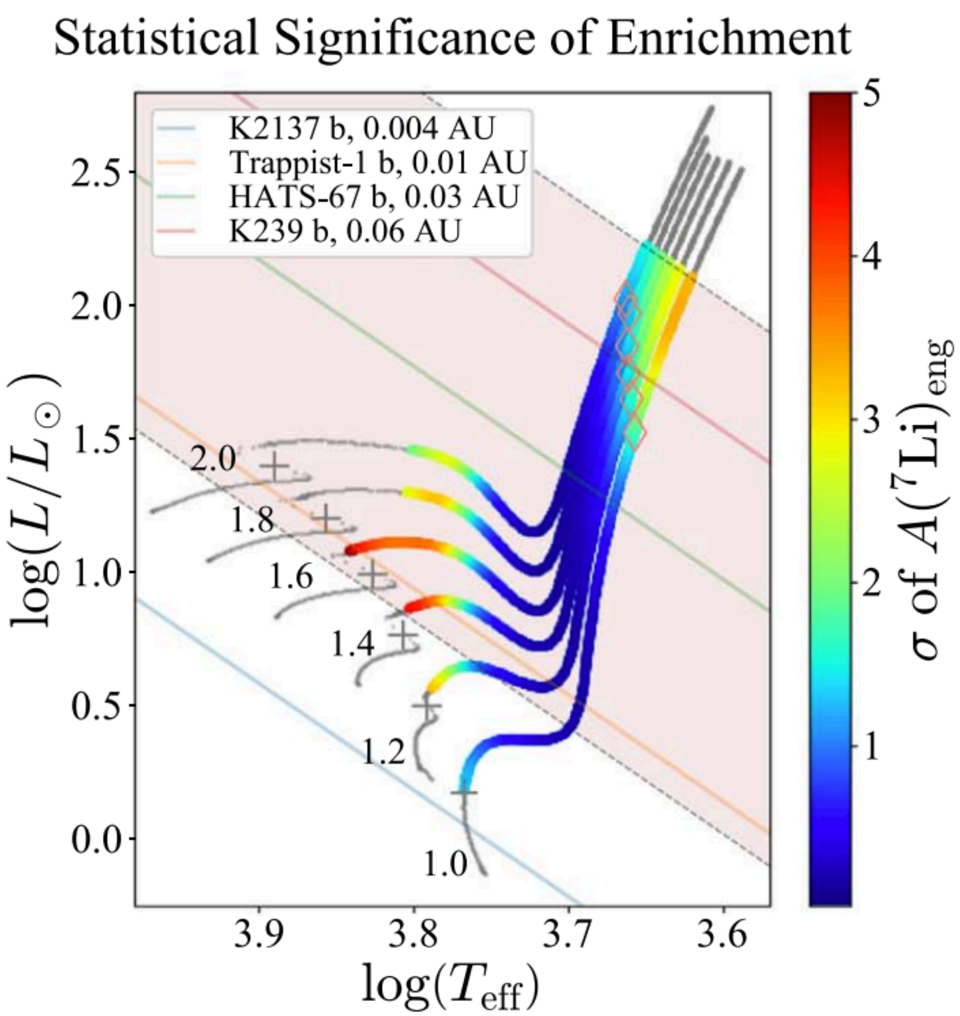

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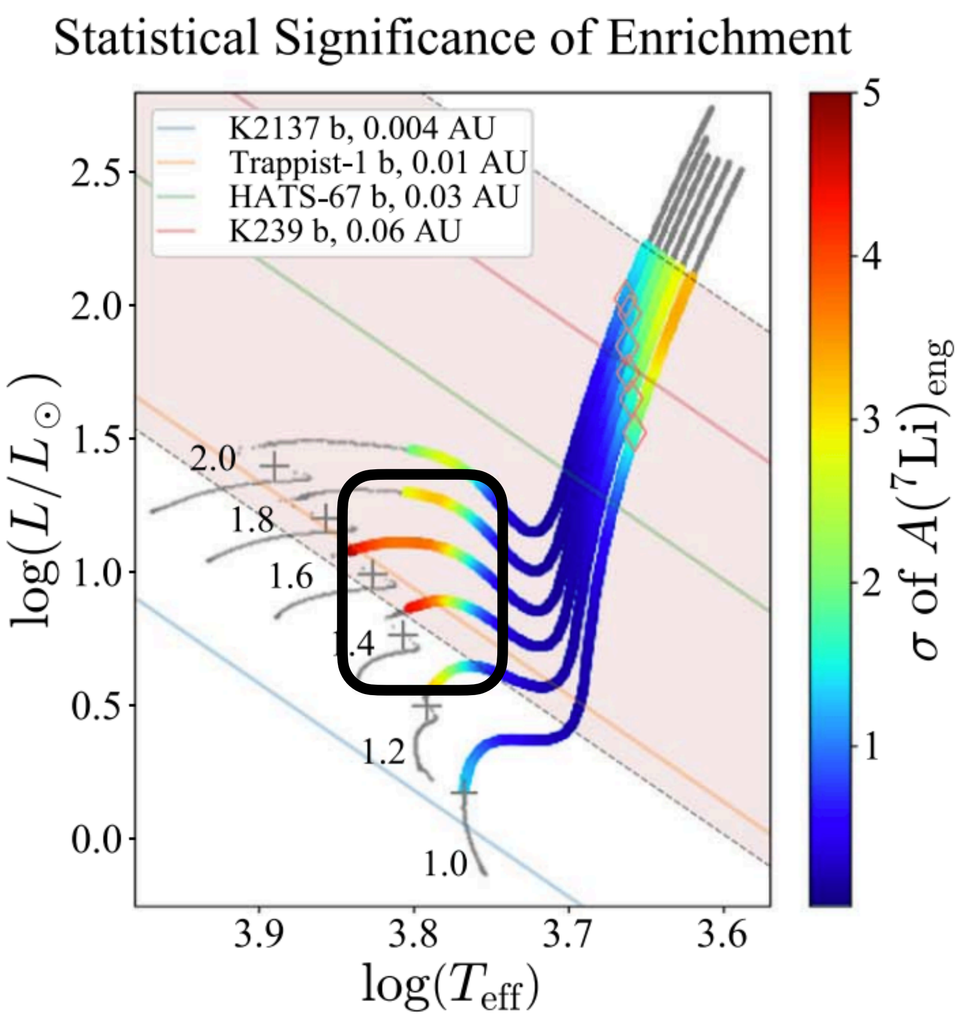

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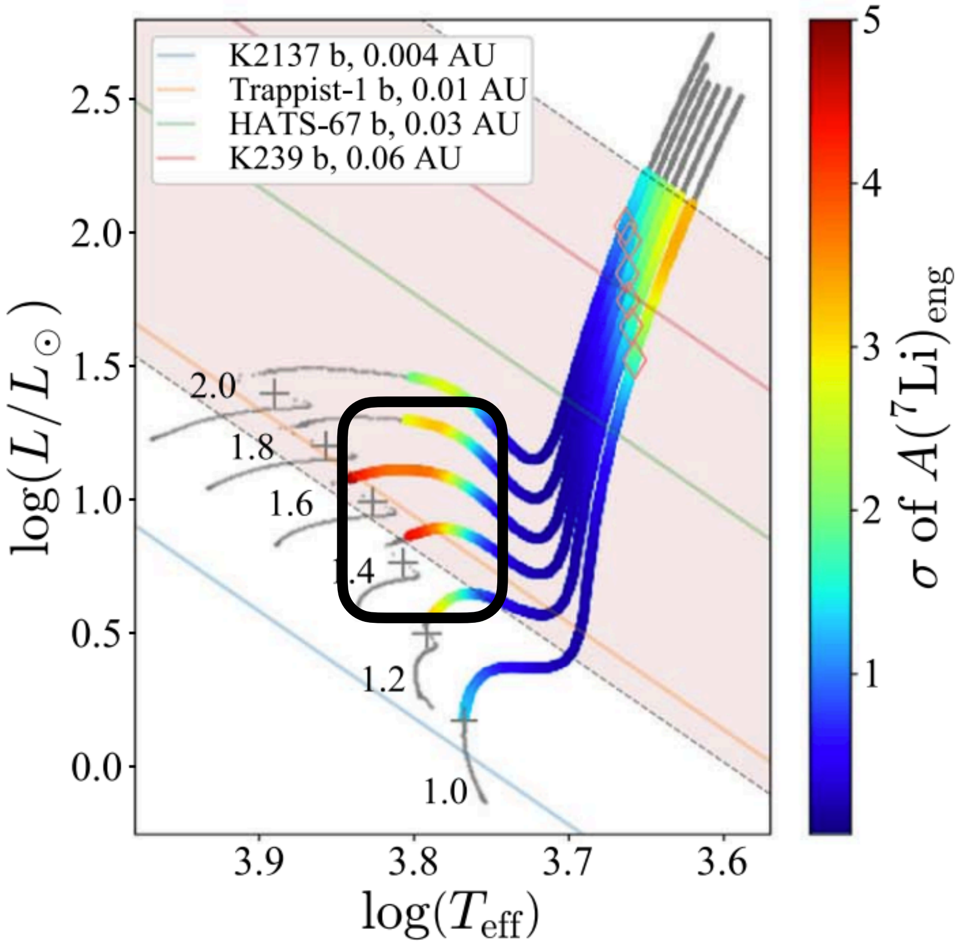

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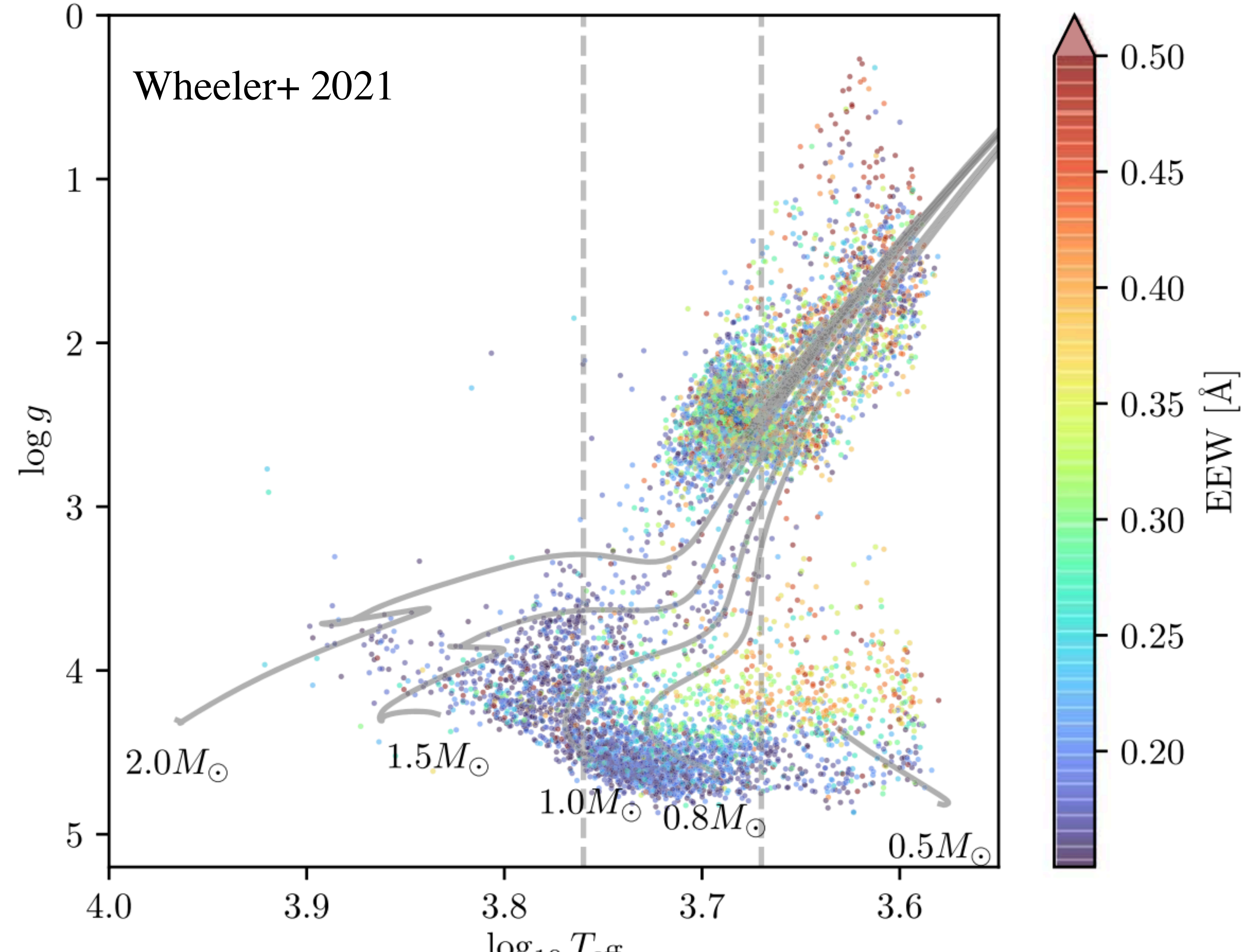

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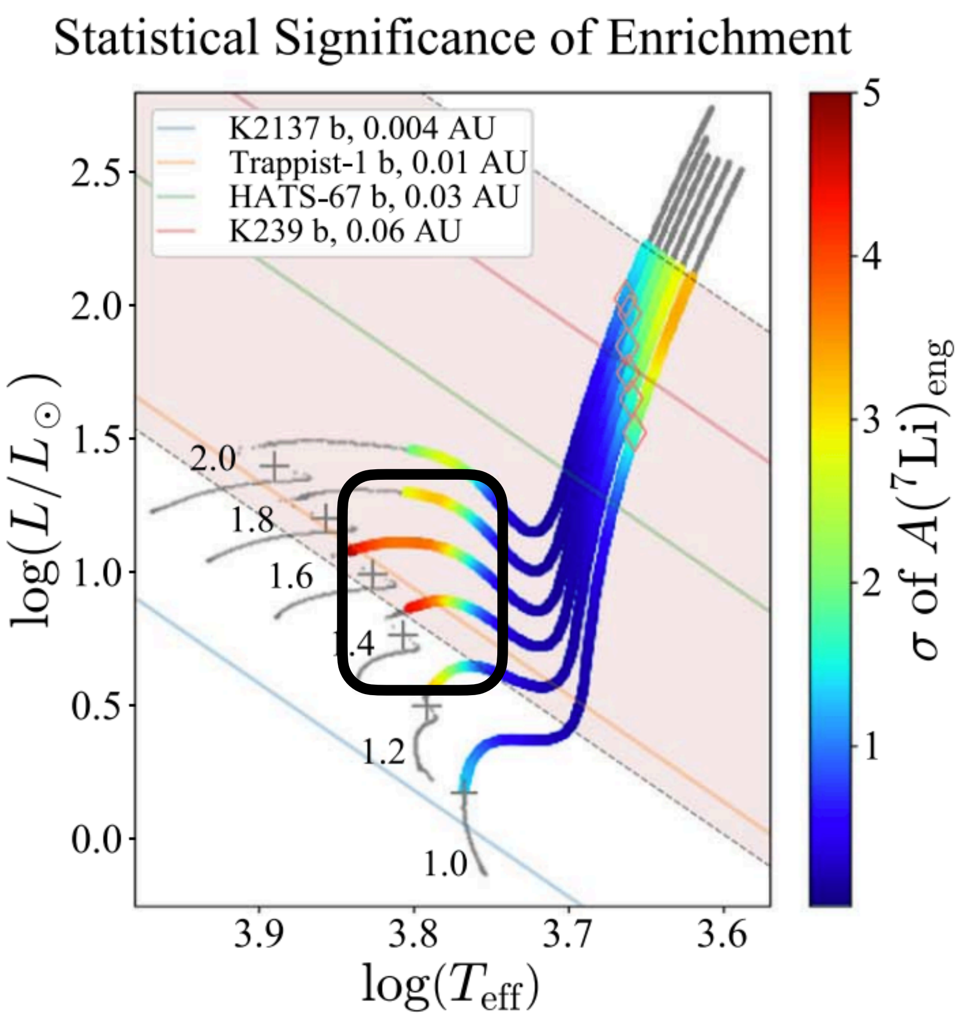

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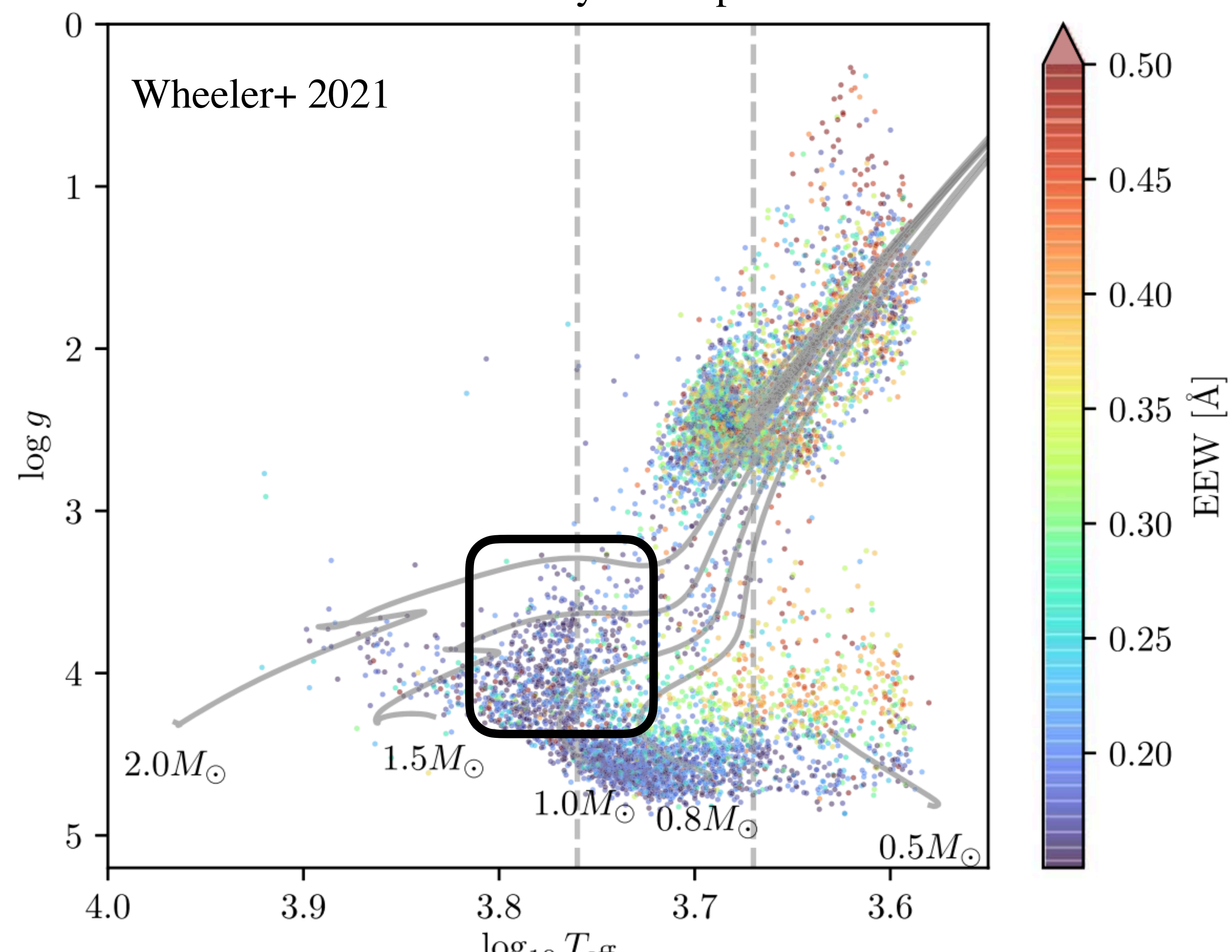
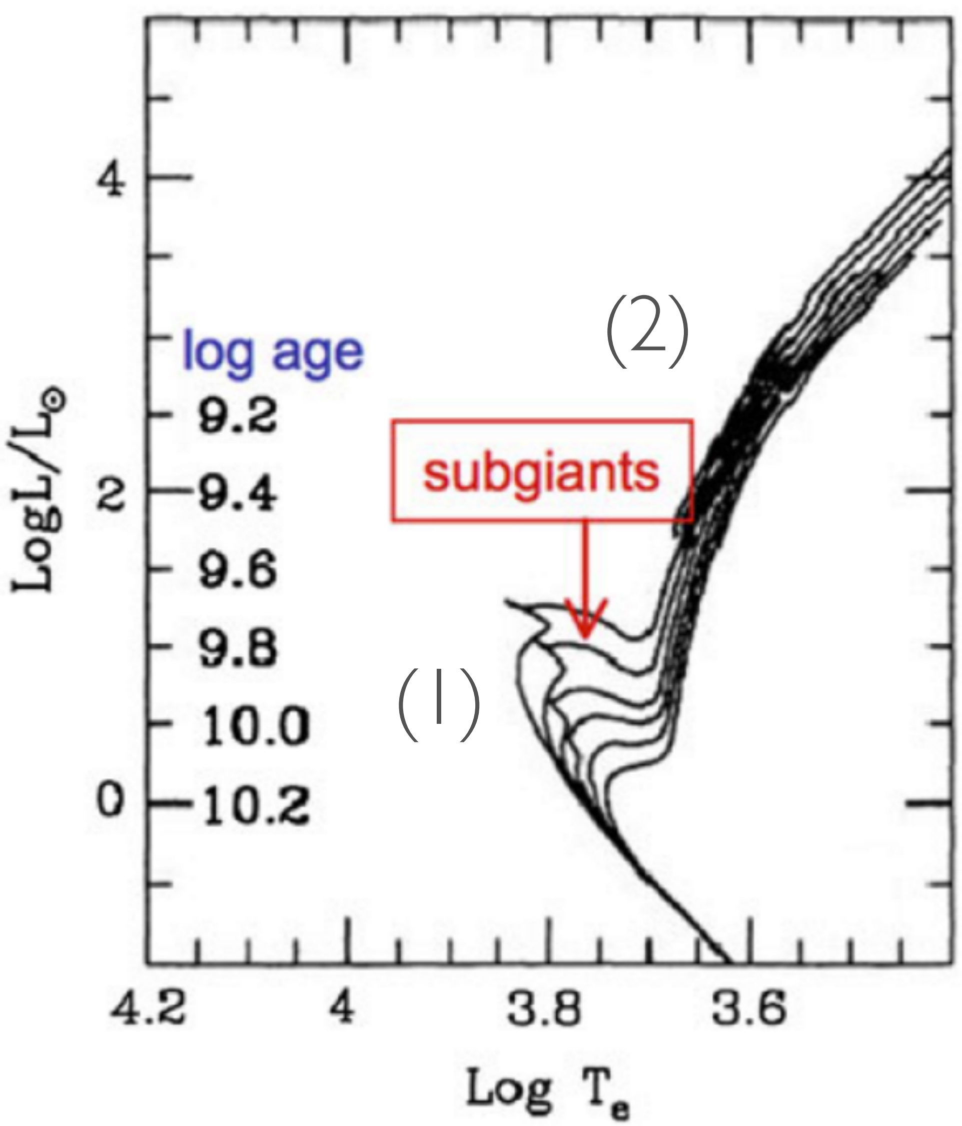


Outline

- The Milky Way Data Revolution
- The Populations in the Milky Way Galaxy in the Gaia era
- Statistical Stellar Ages

How are ages typically measured?

(also see talk by Marina Kounkel)



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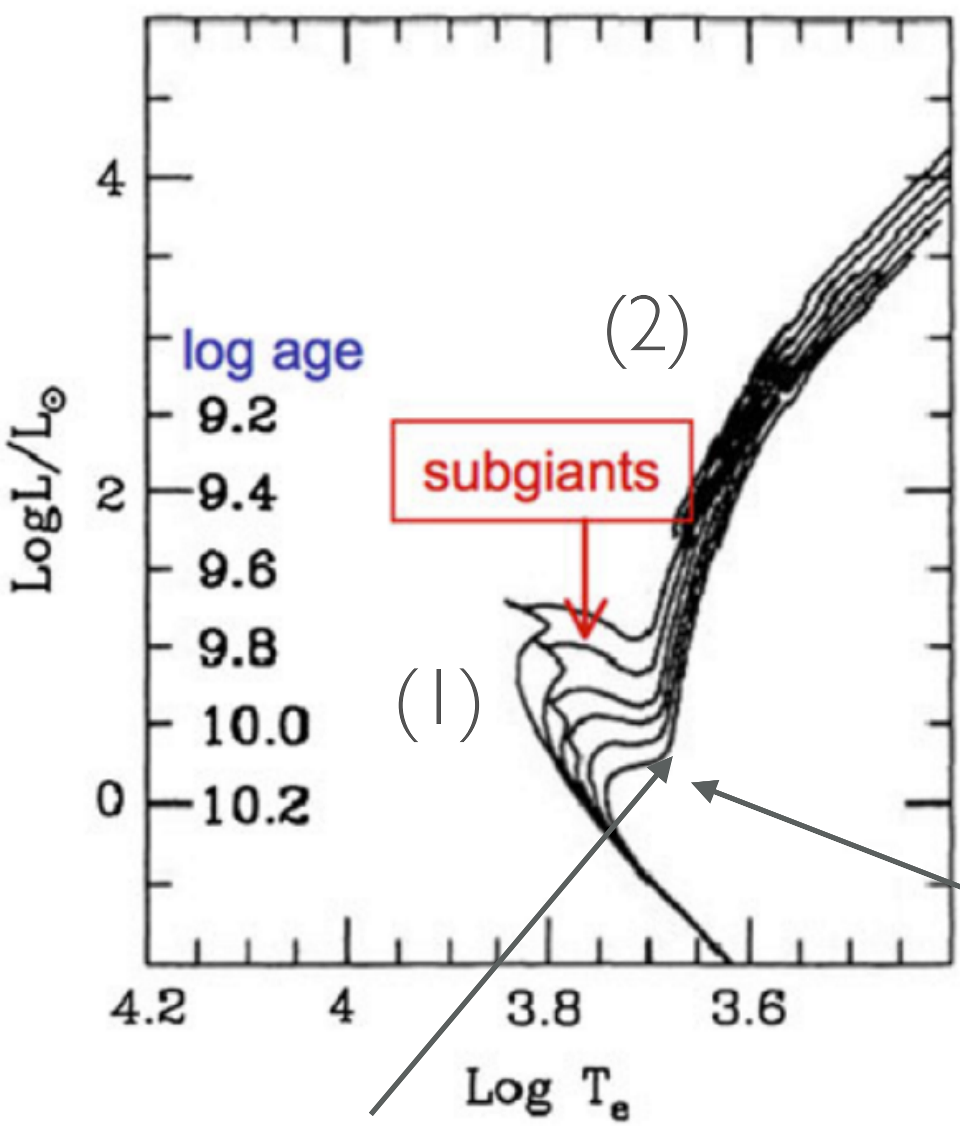

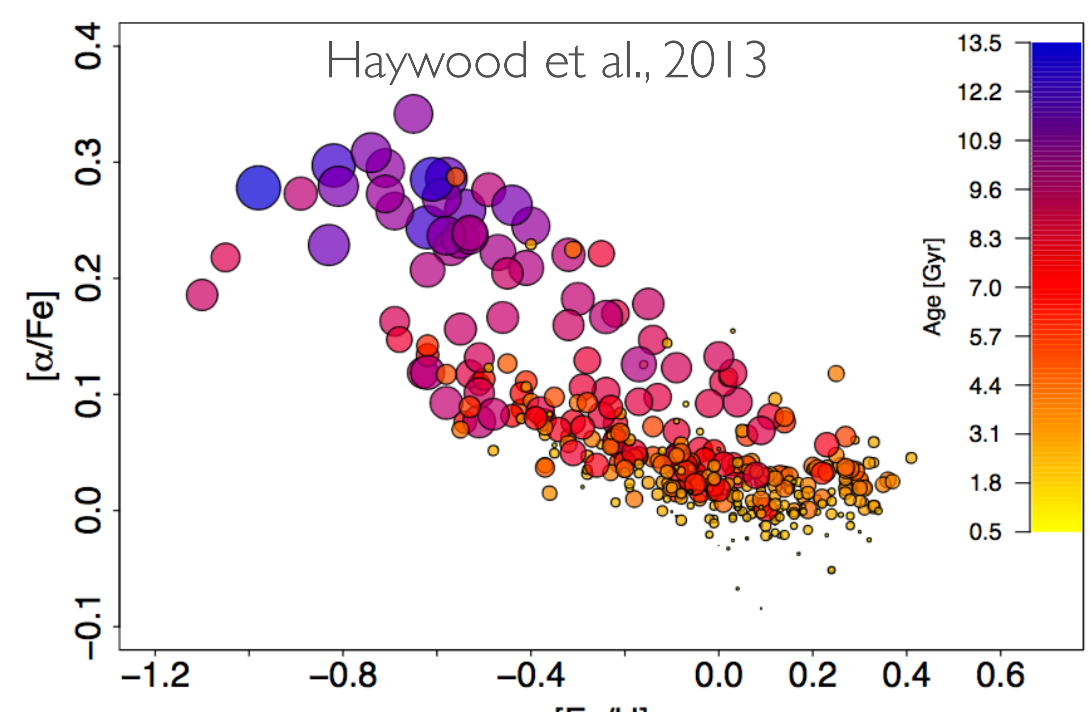

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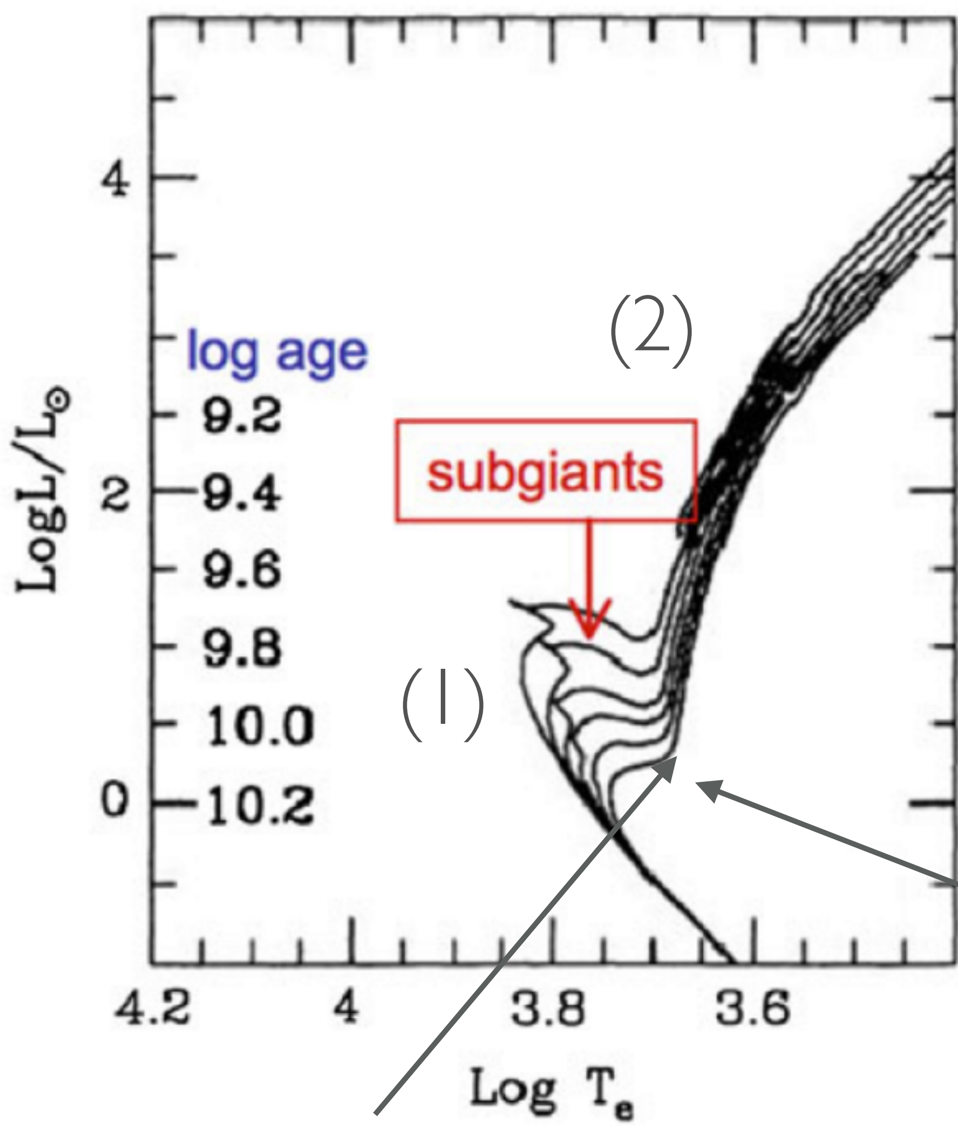

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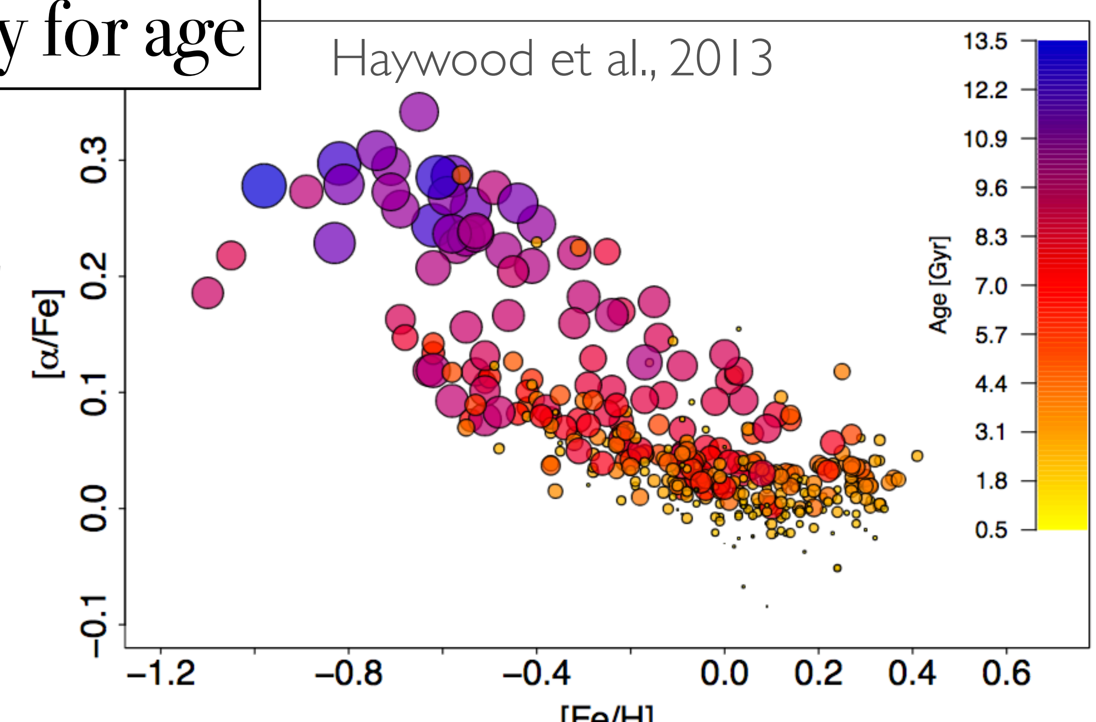

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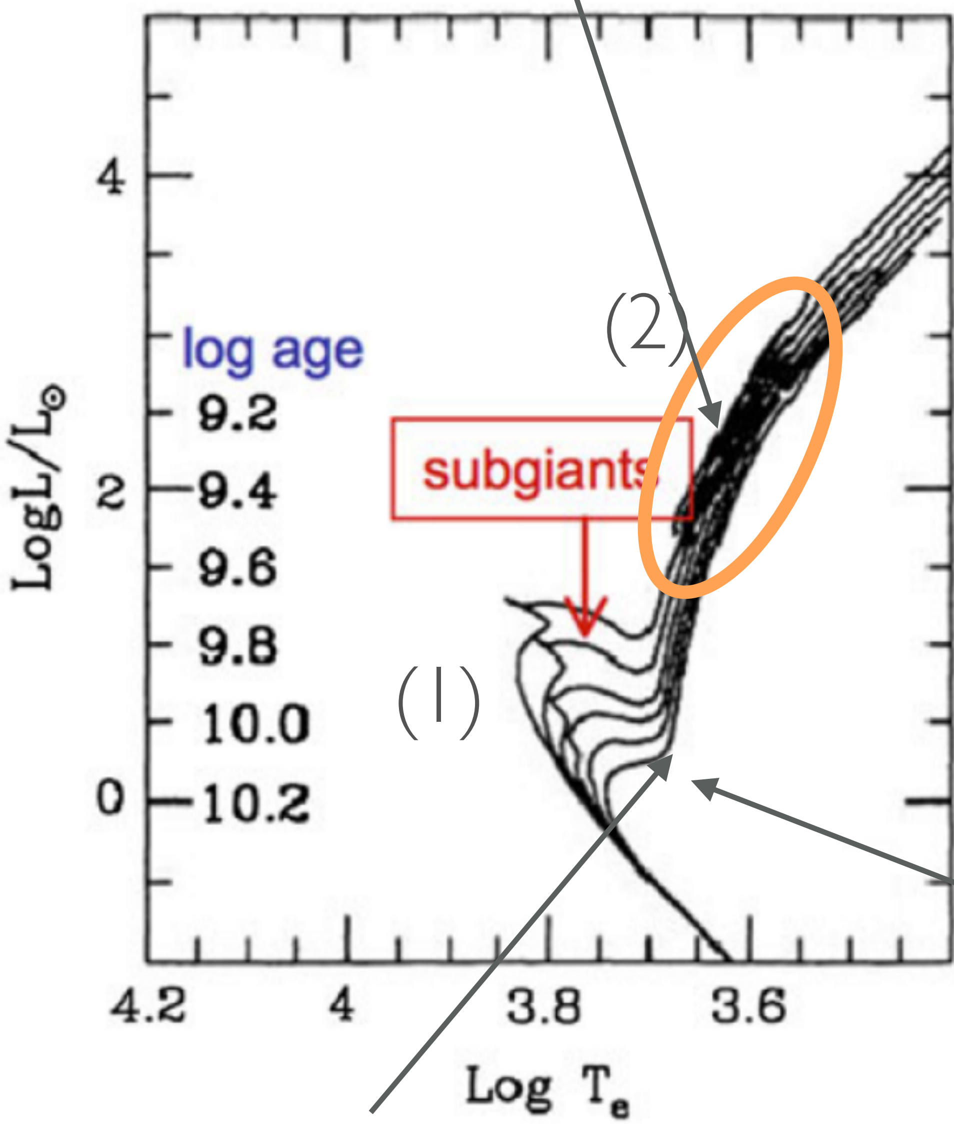

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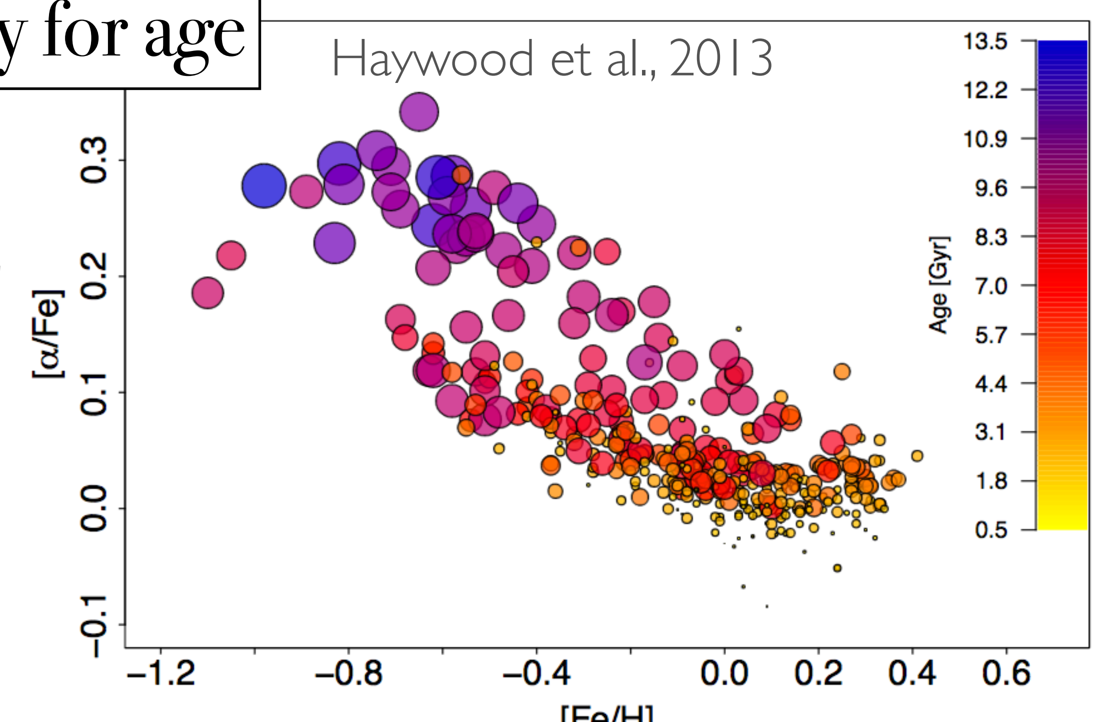

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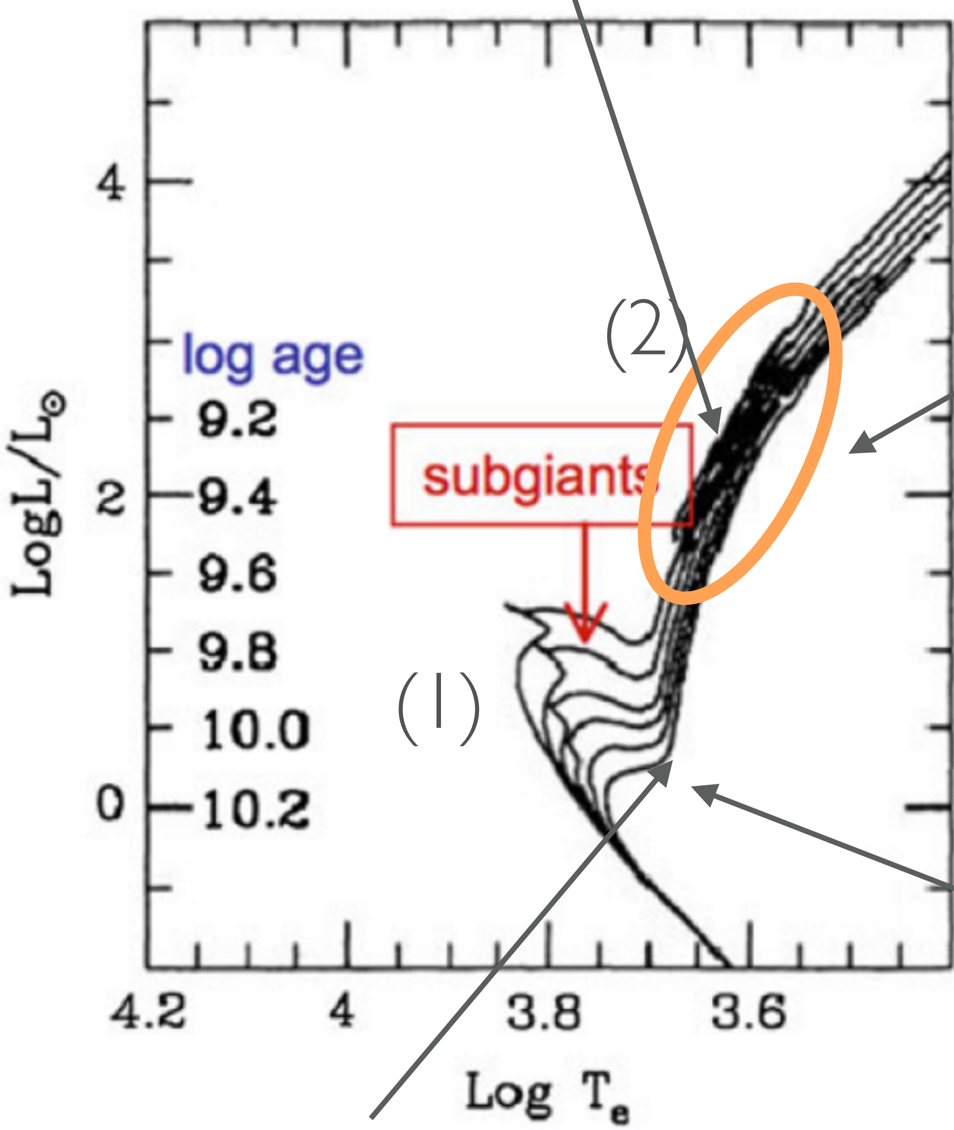
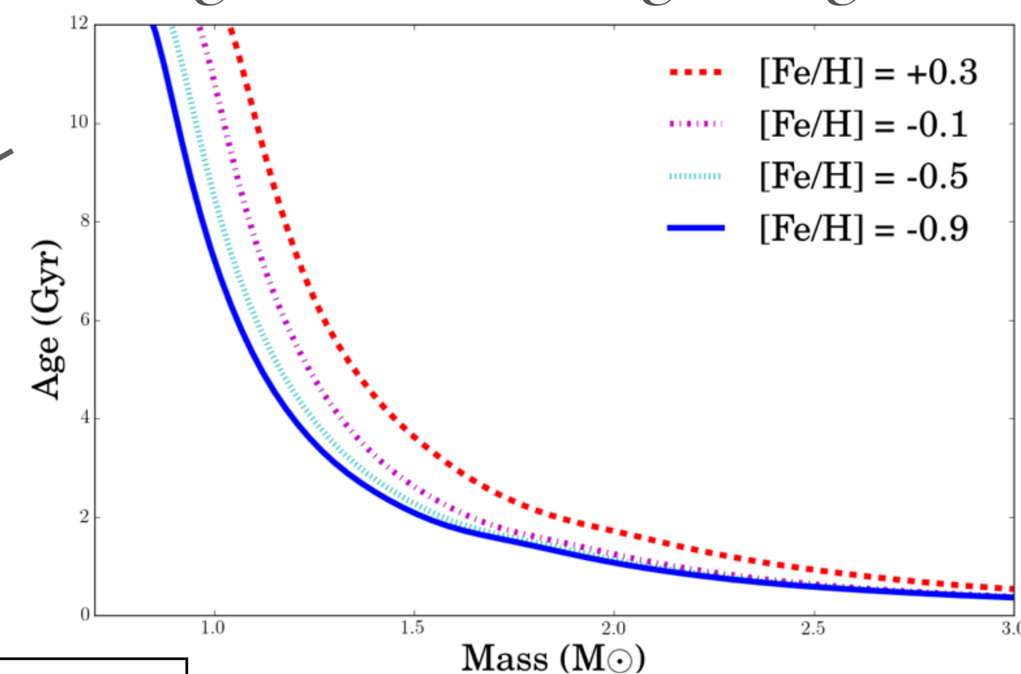
giant masses ⟶ giant ages





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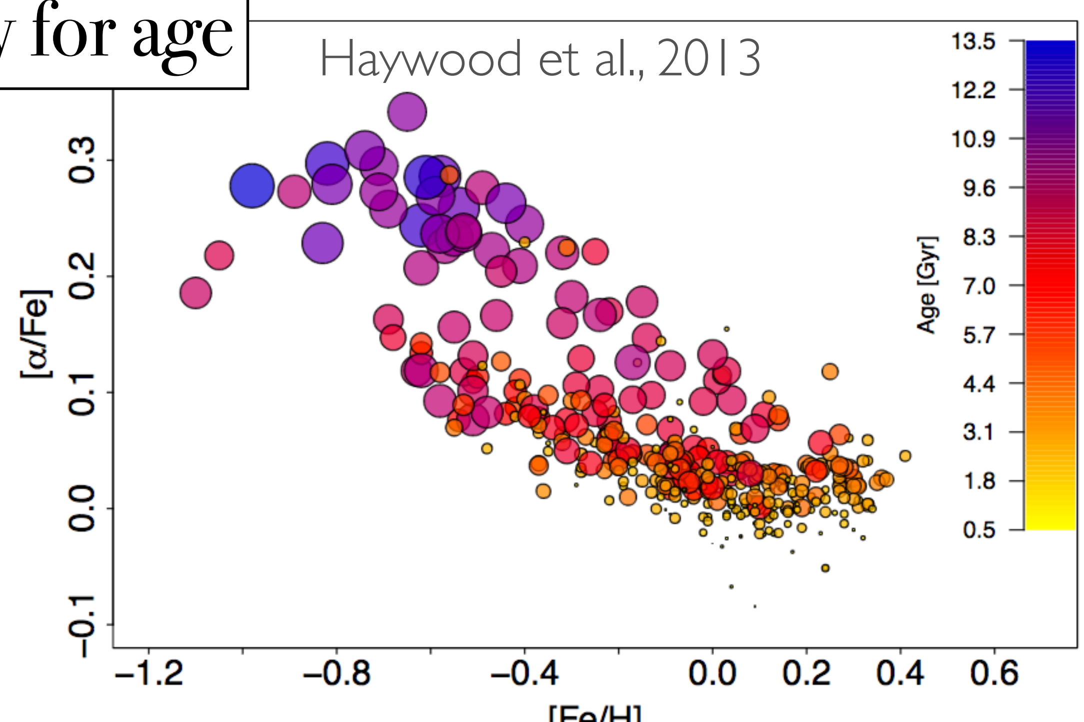

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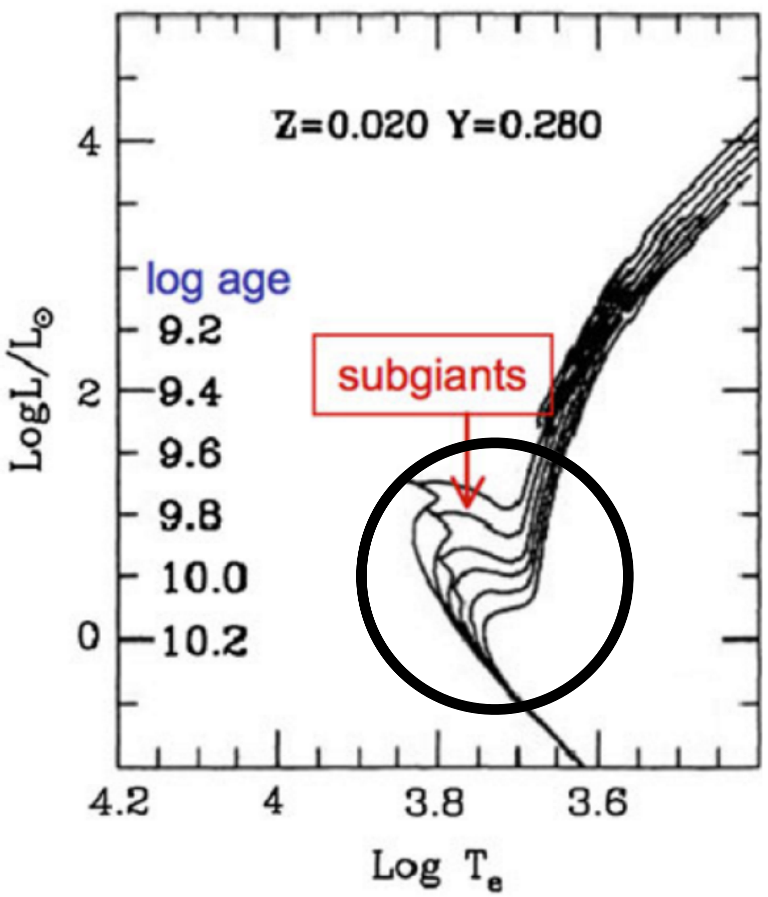

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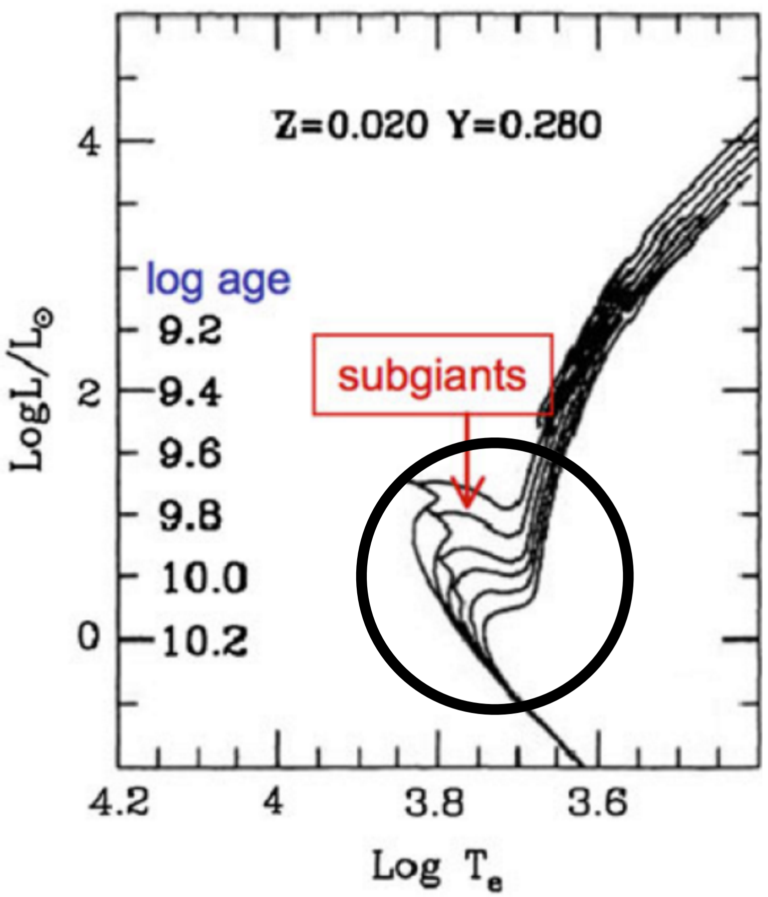

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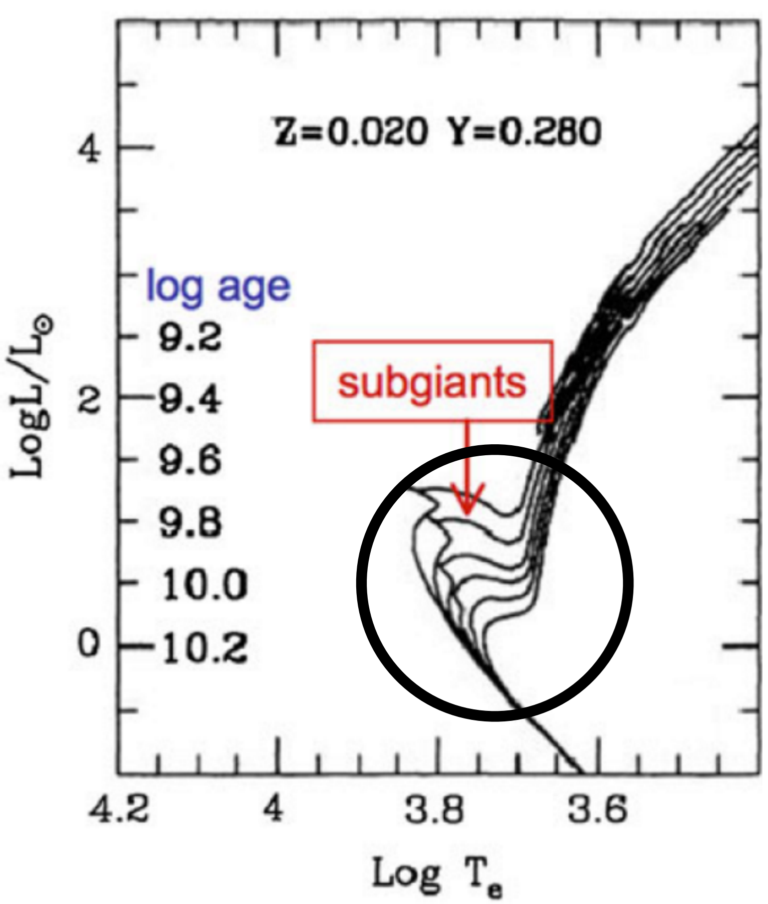

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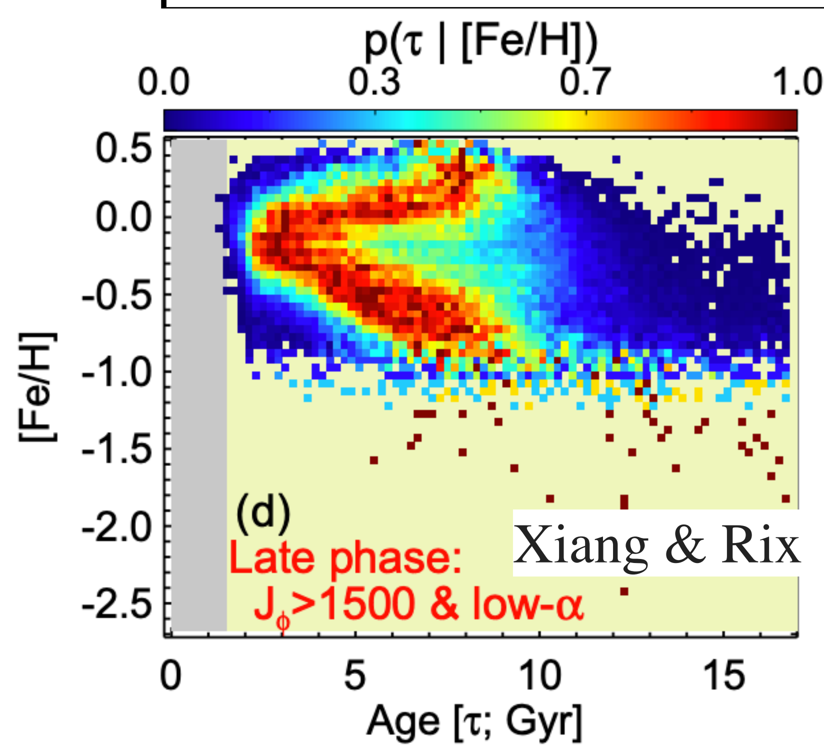

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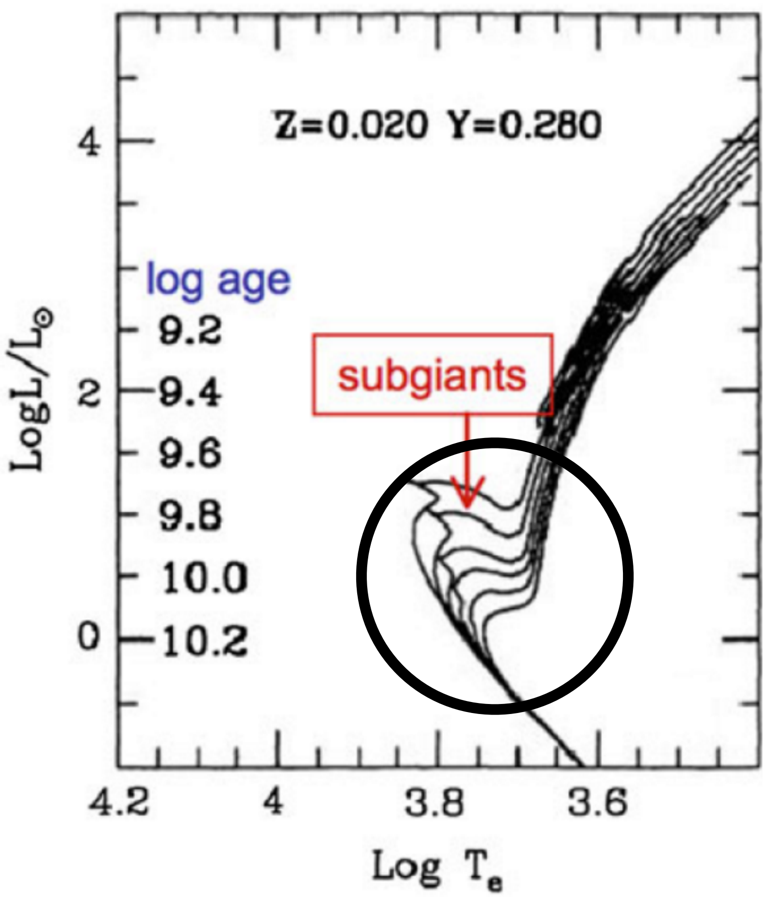

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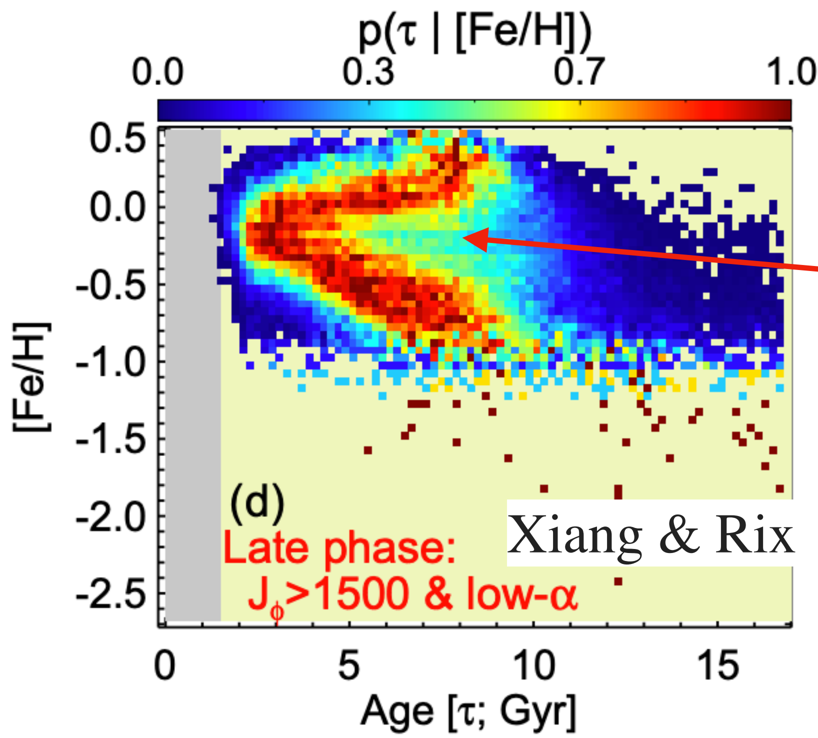

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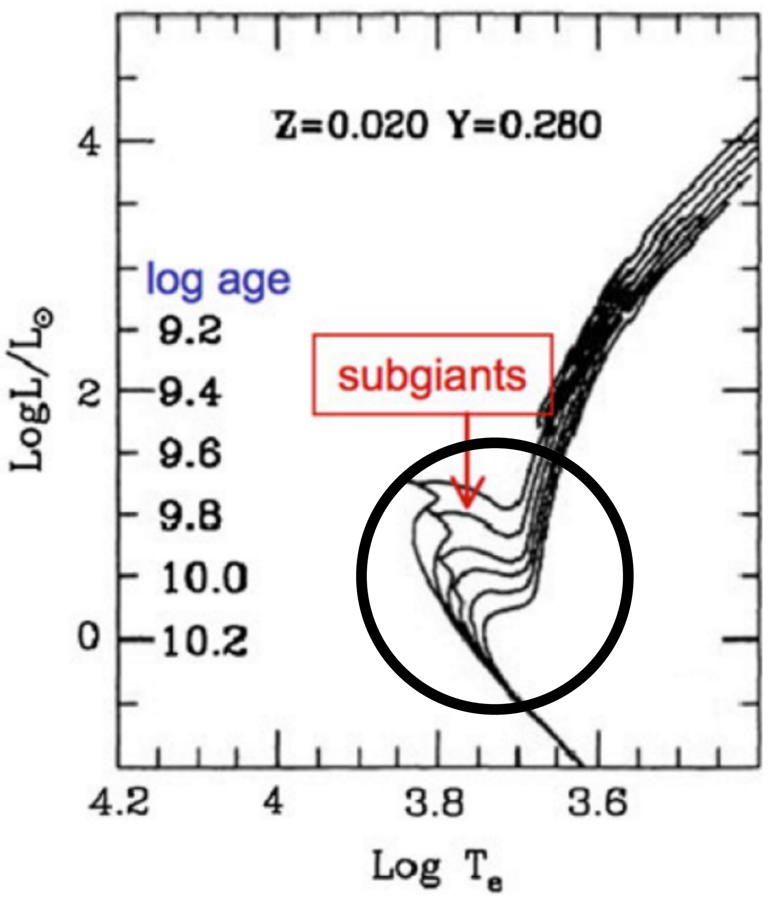

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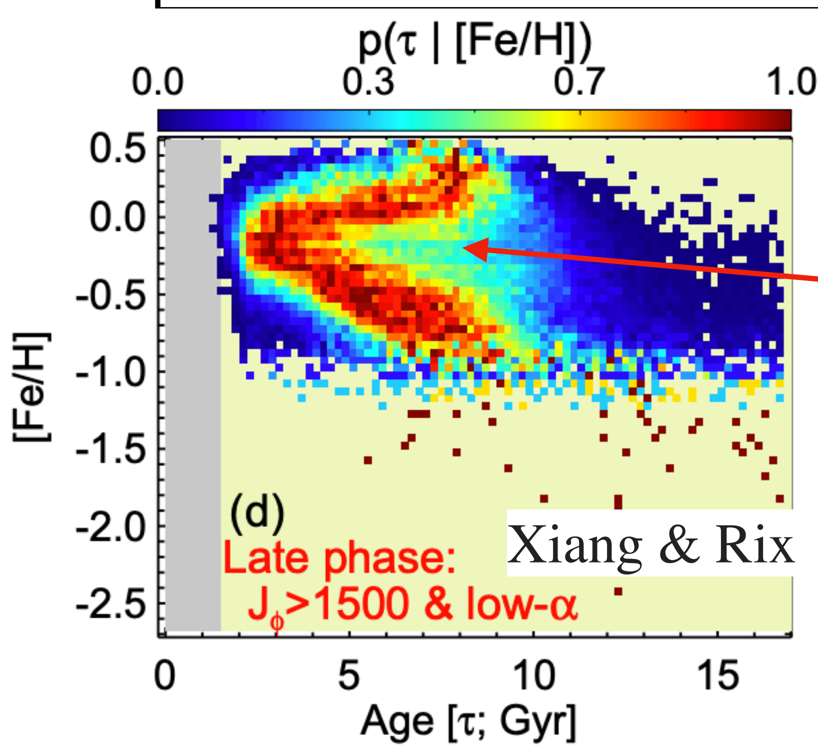

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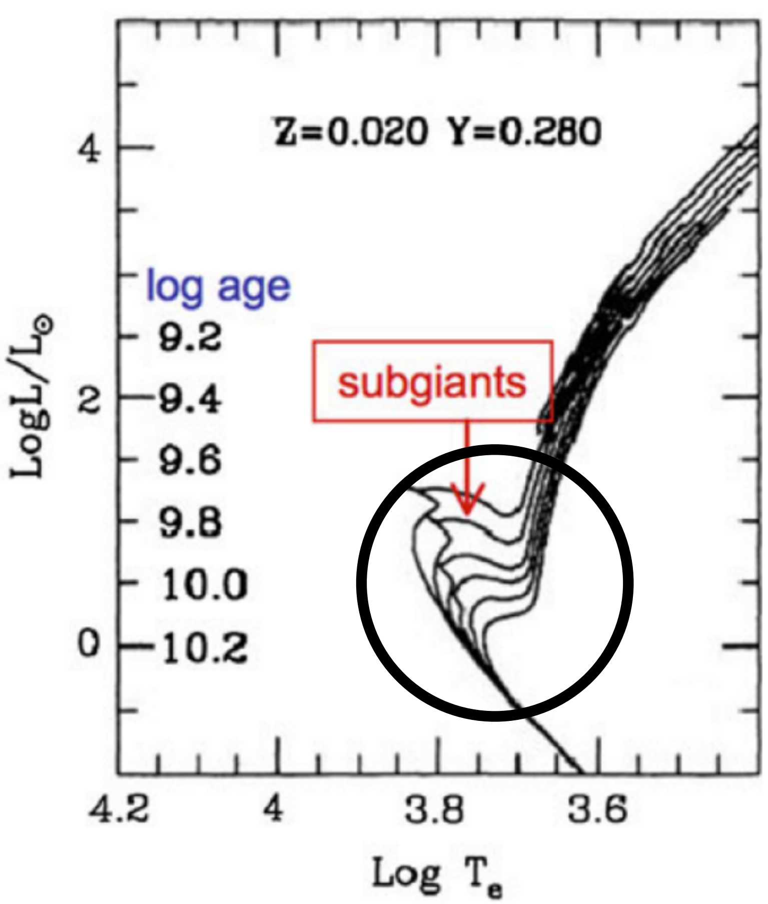

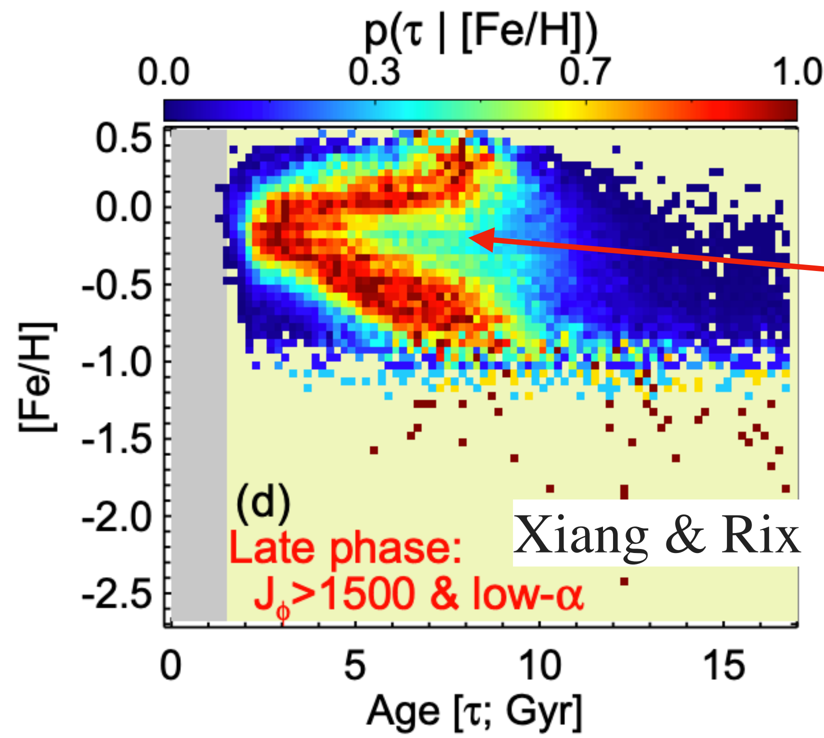

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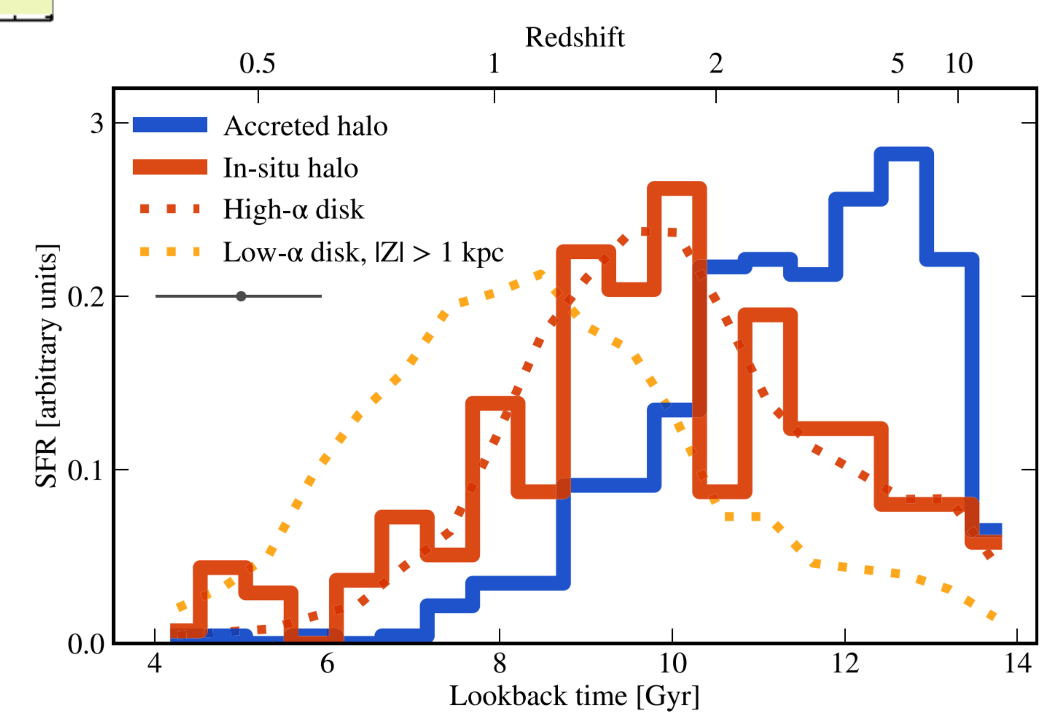

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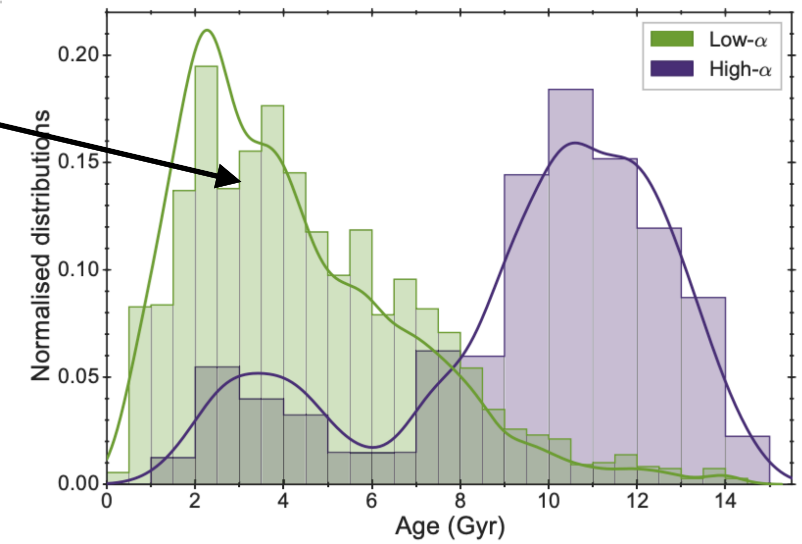

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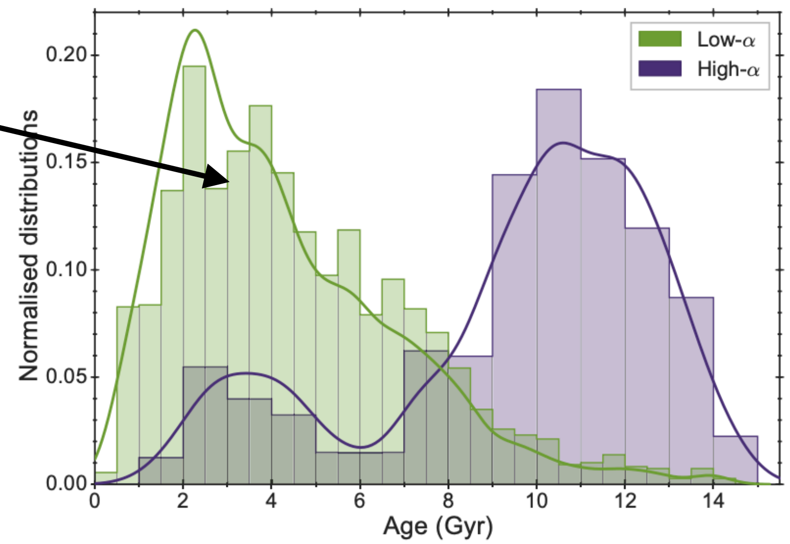

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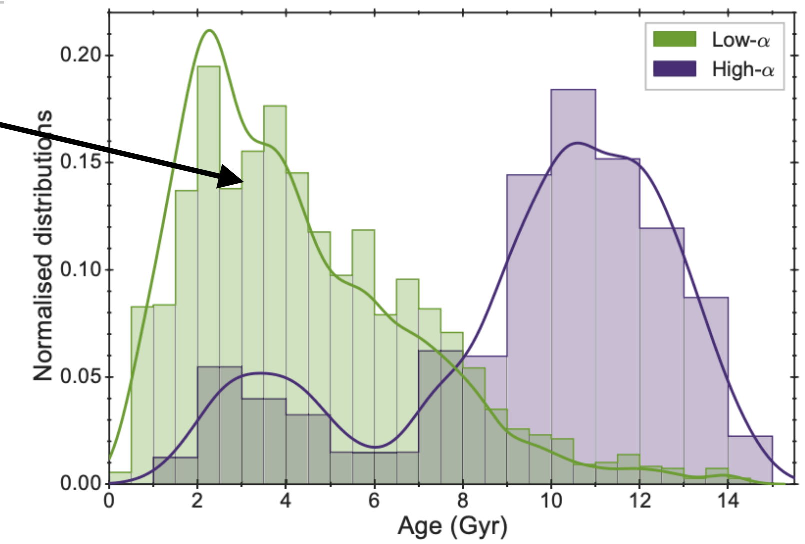

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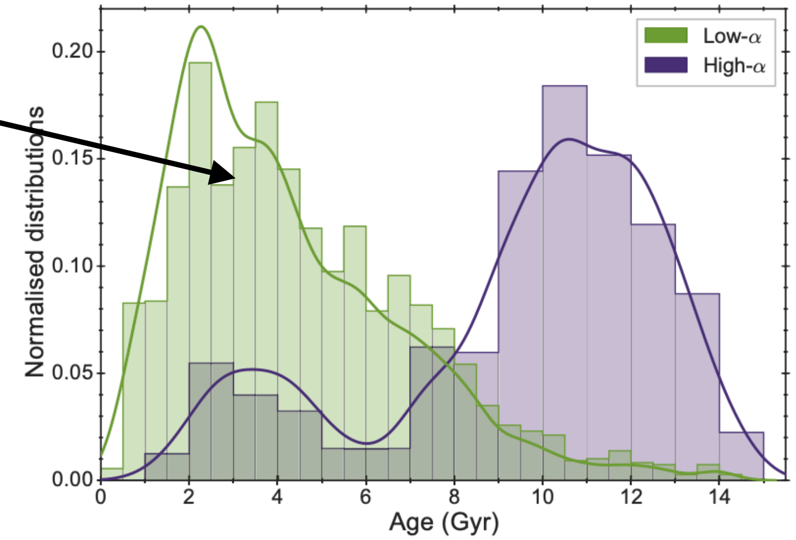

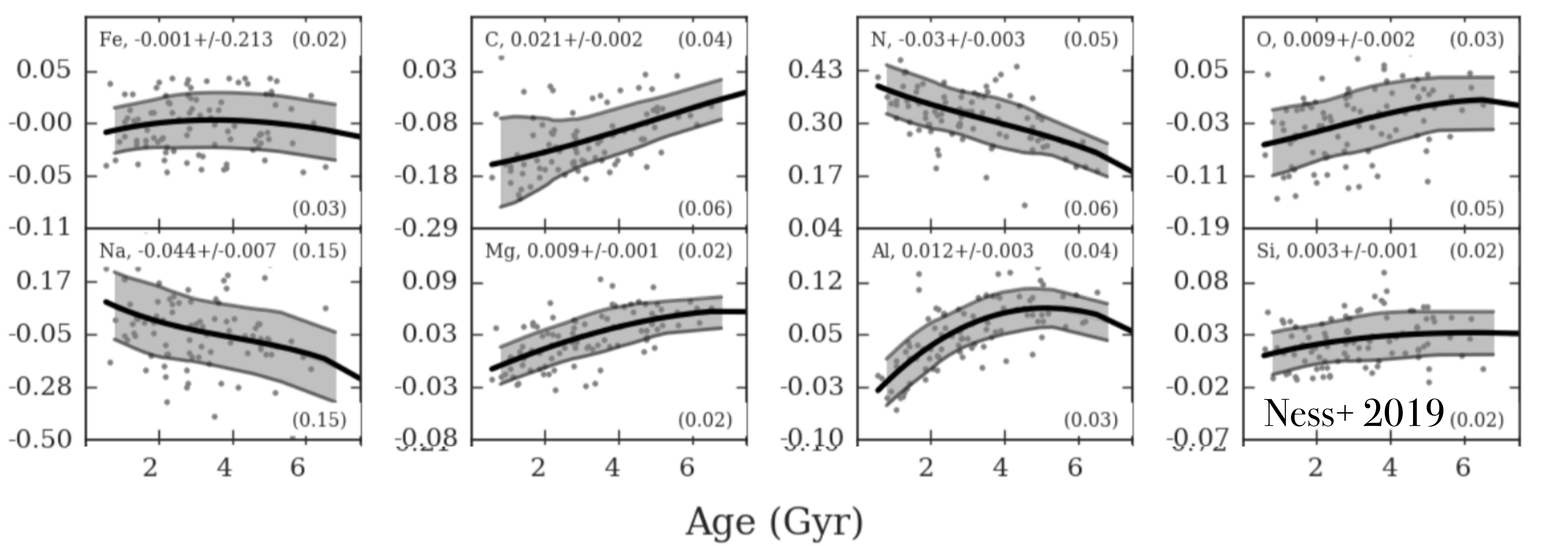

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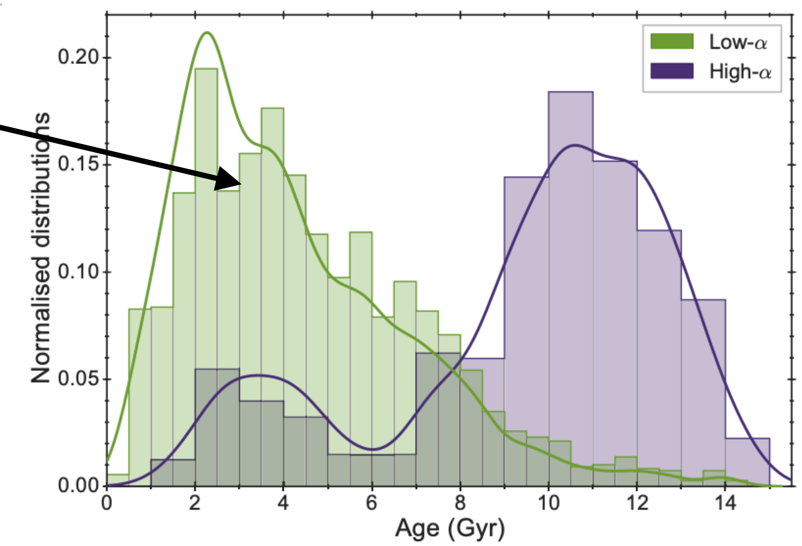

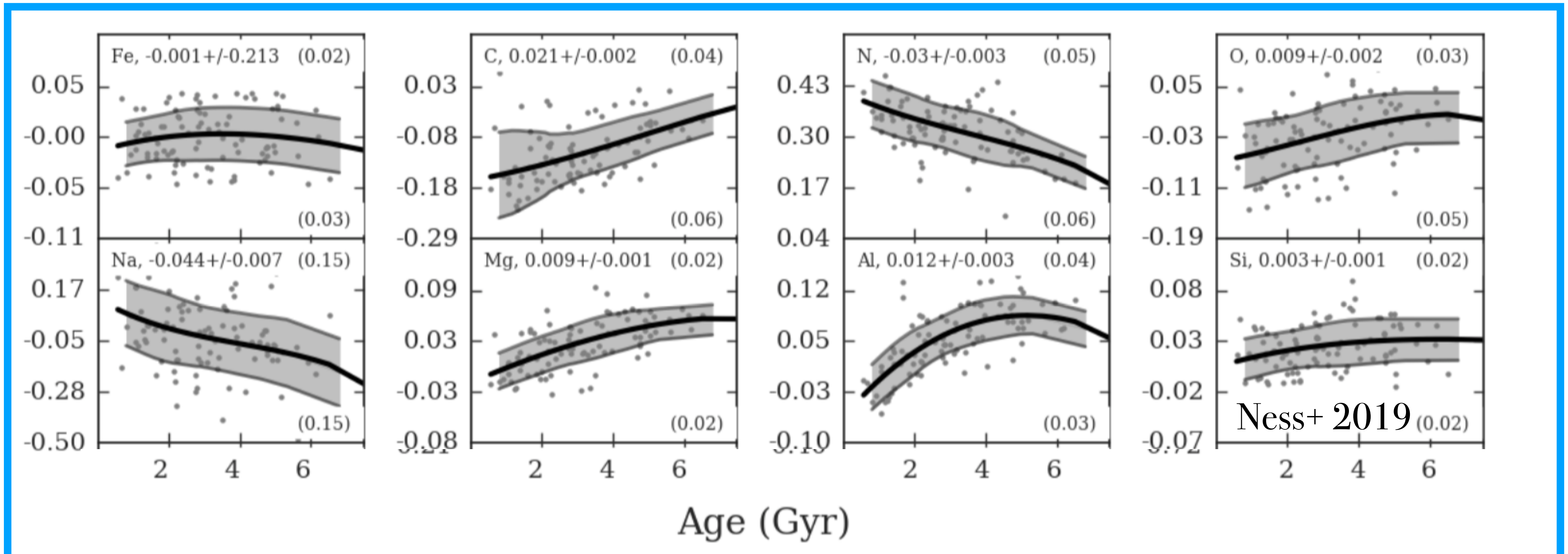

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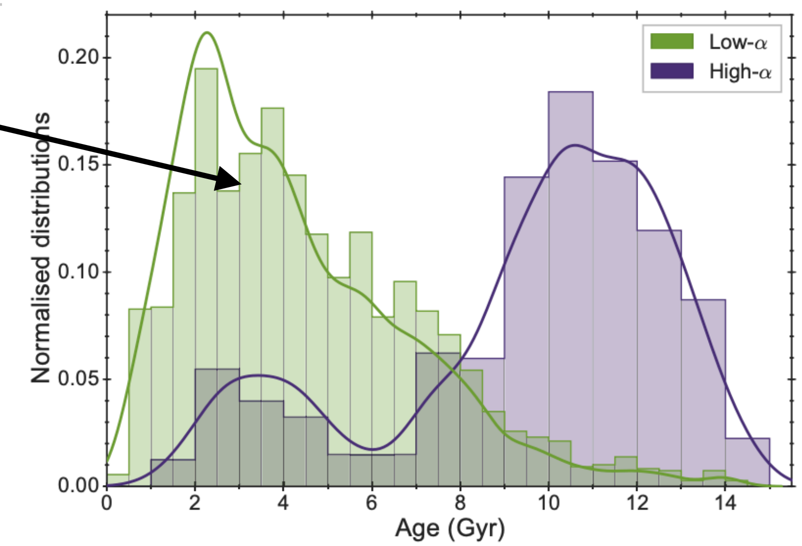

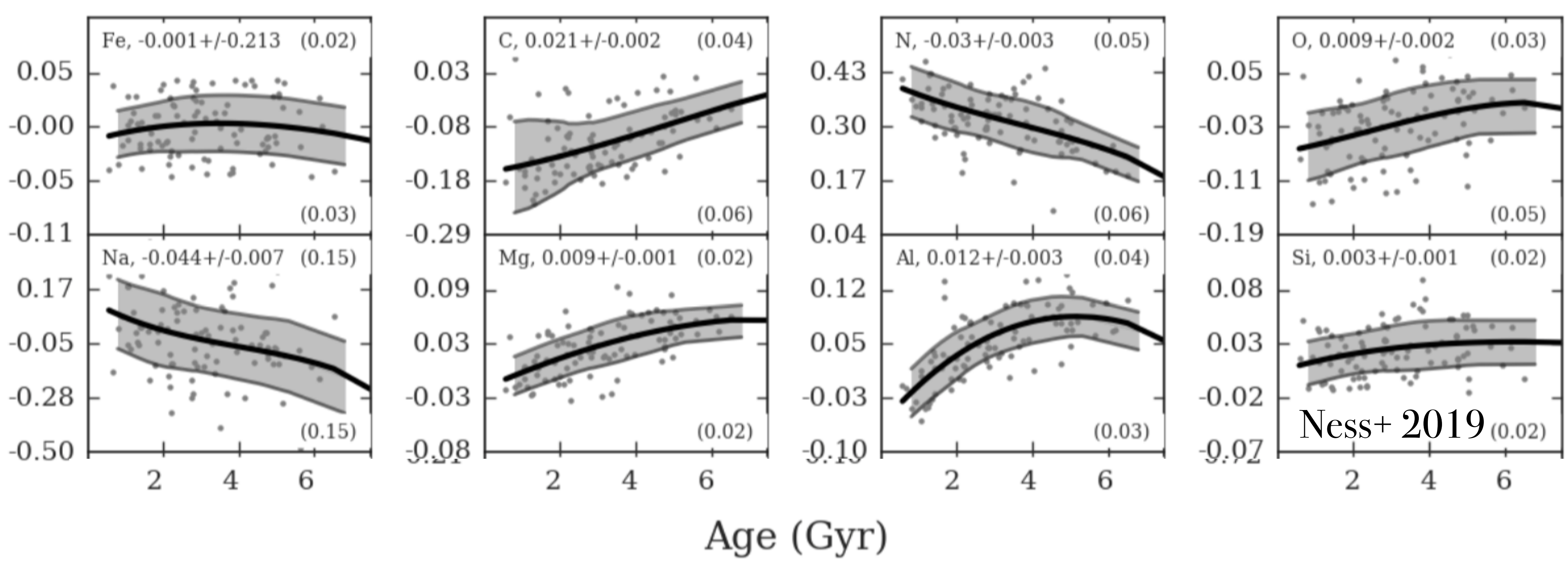

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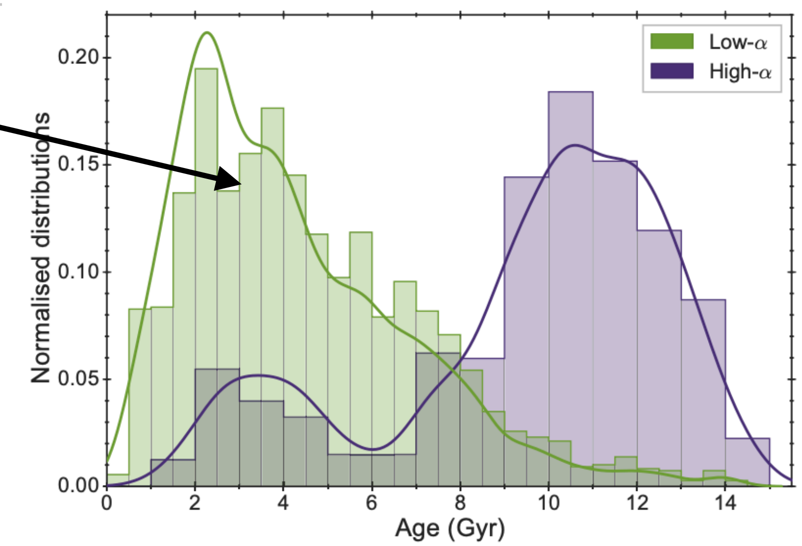
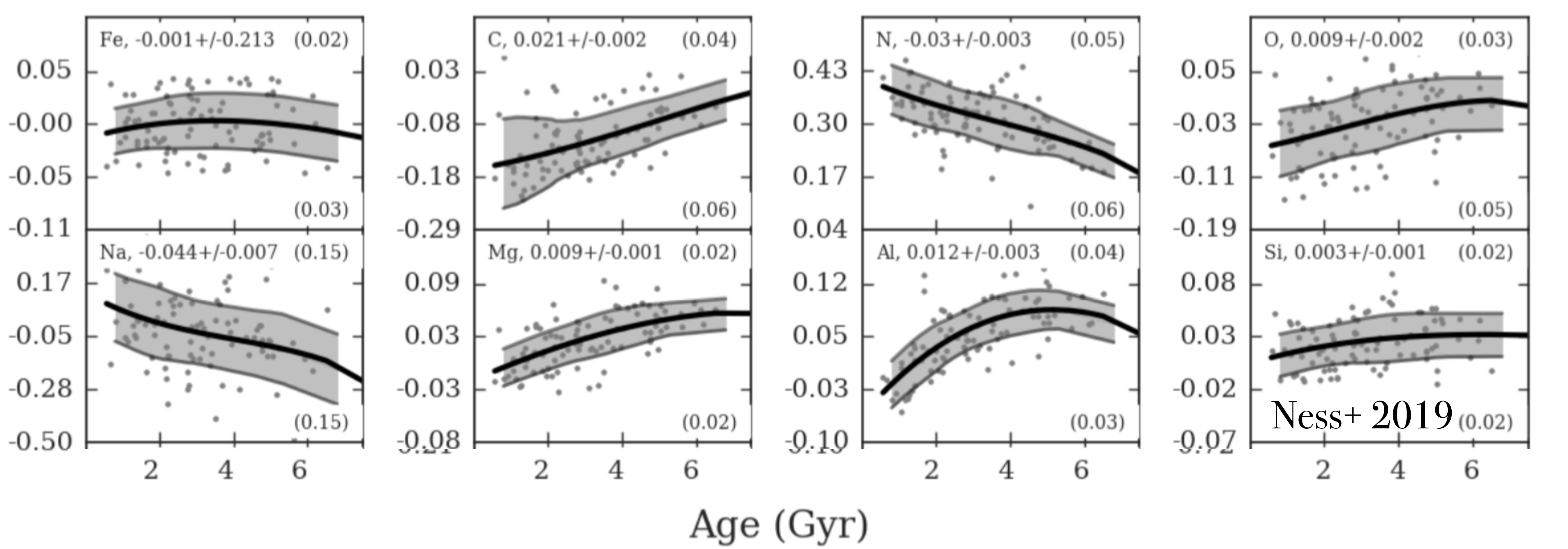
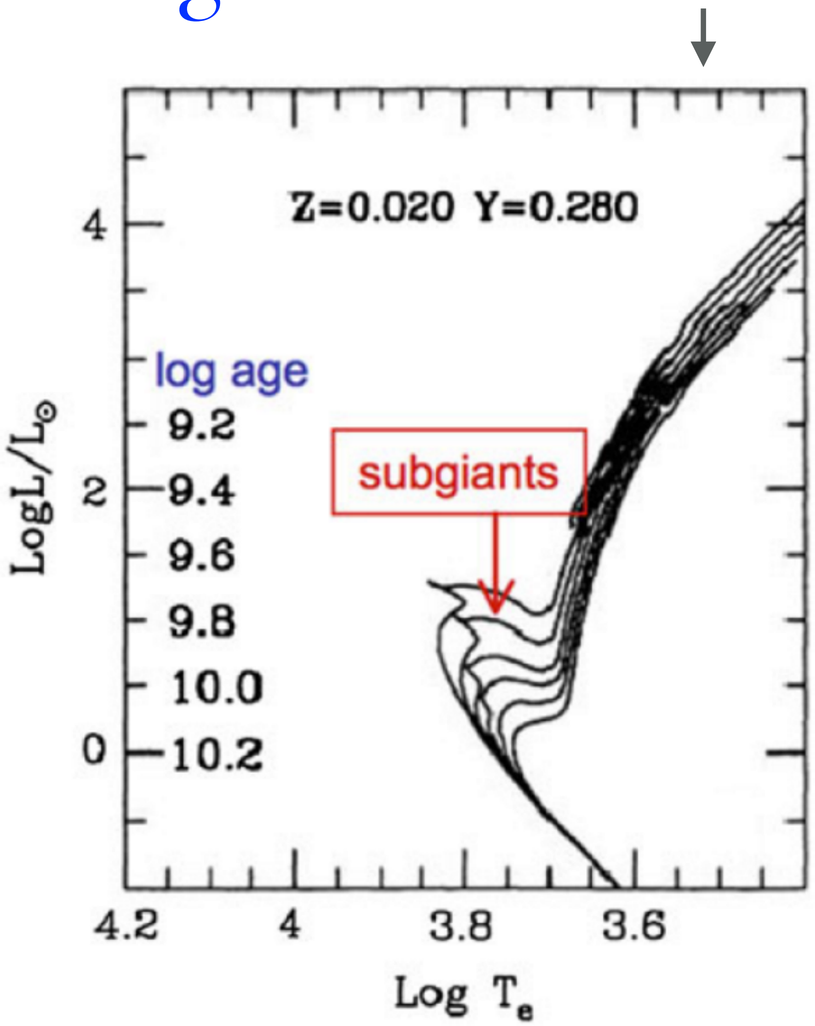




- invert age-abundance gradients —> to get ages, given abundances —> also see
- Moya+ 2022
- Feuillet+2018, Hayden+2021, Sharma+ 2021

We can now measure ages for giants spectroscopically

regime change:
from stars in the solar neighbourhood....



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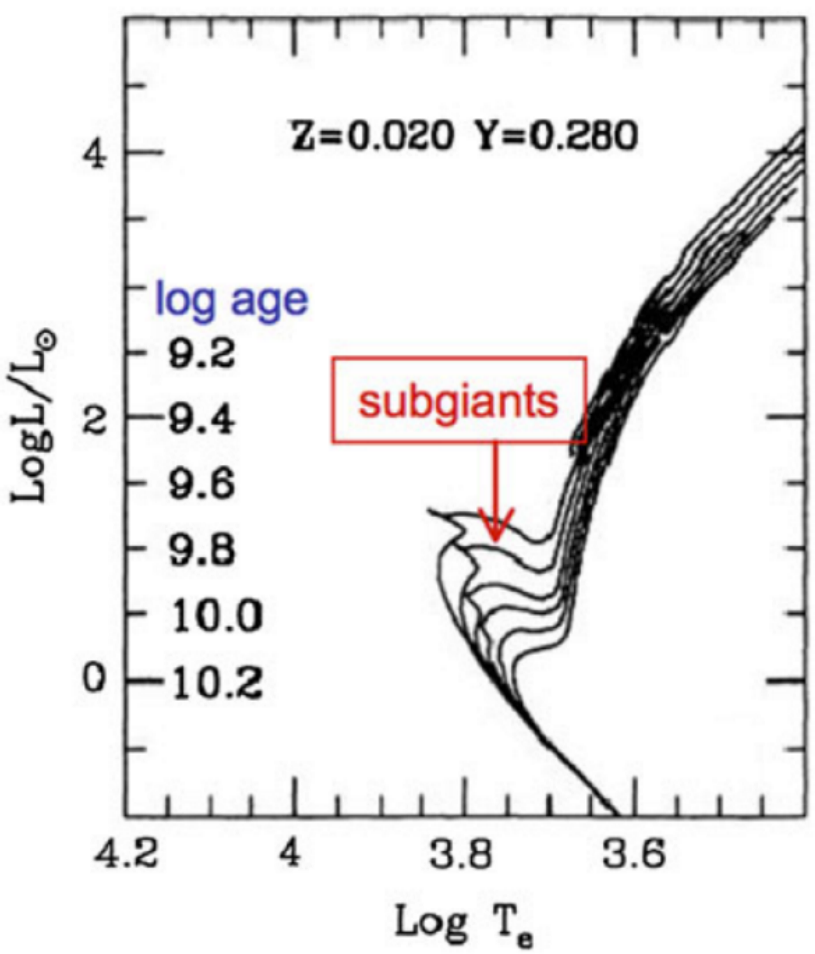

large, vast maps

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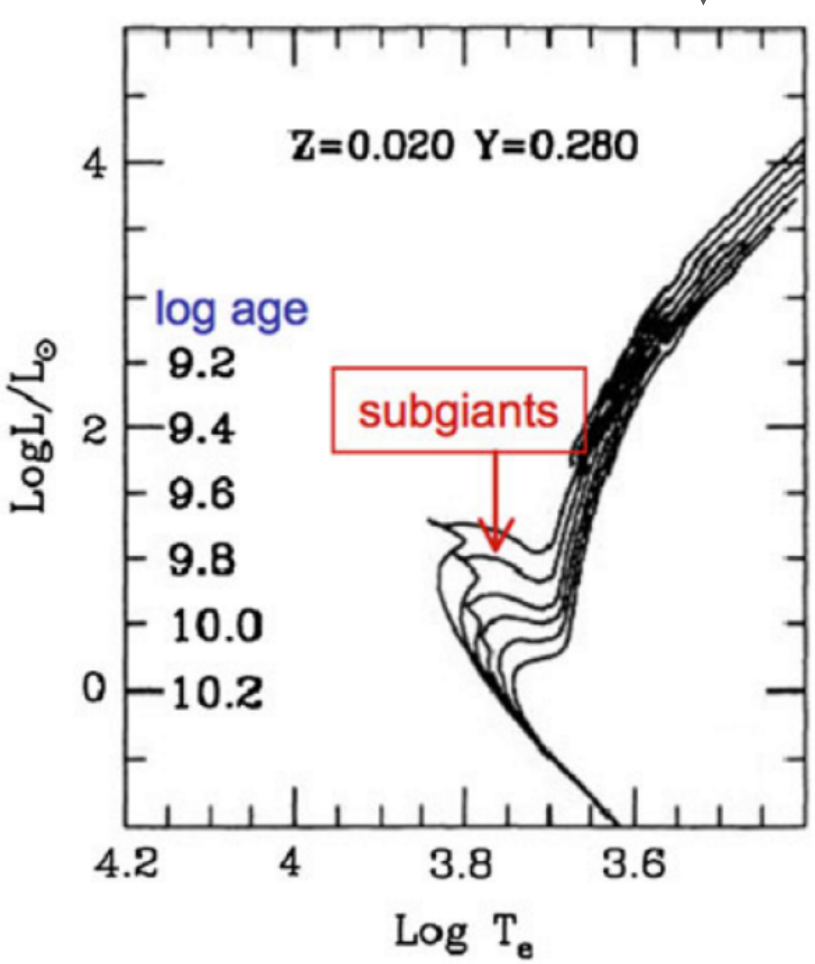

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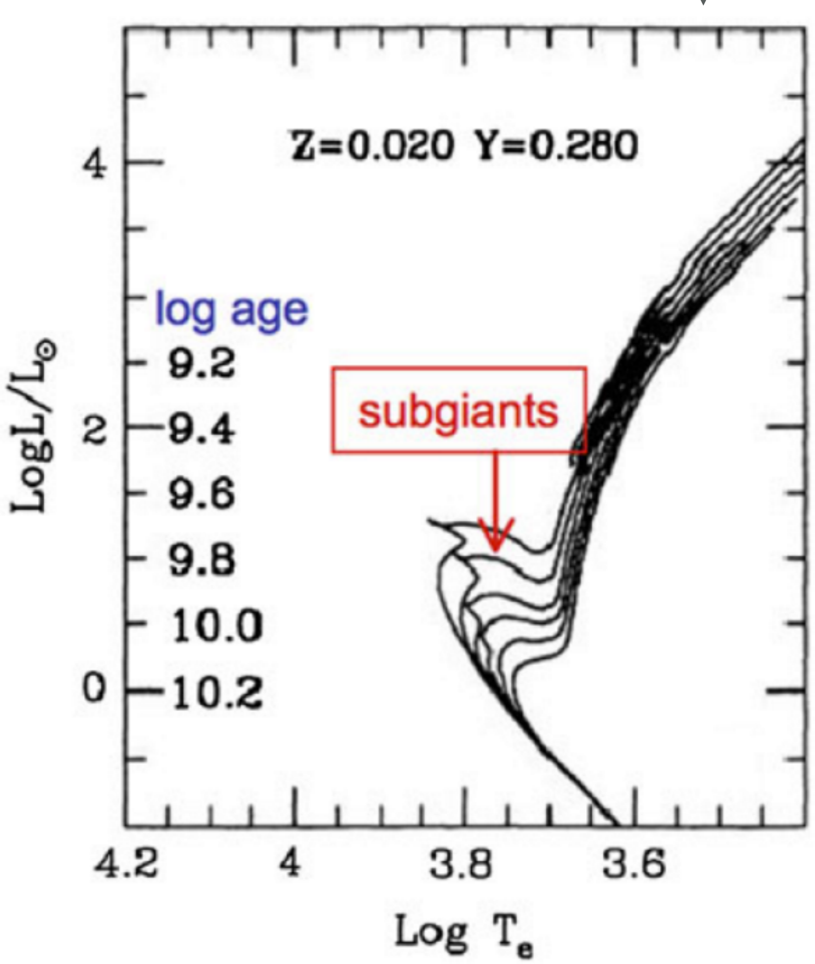

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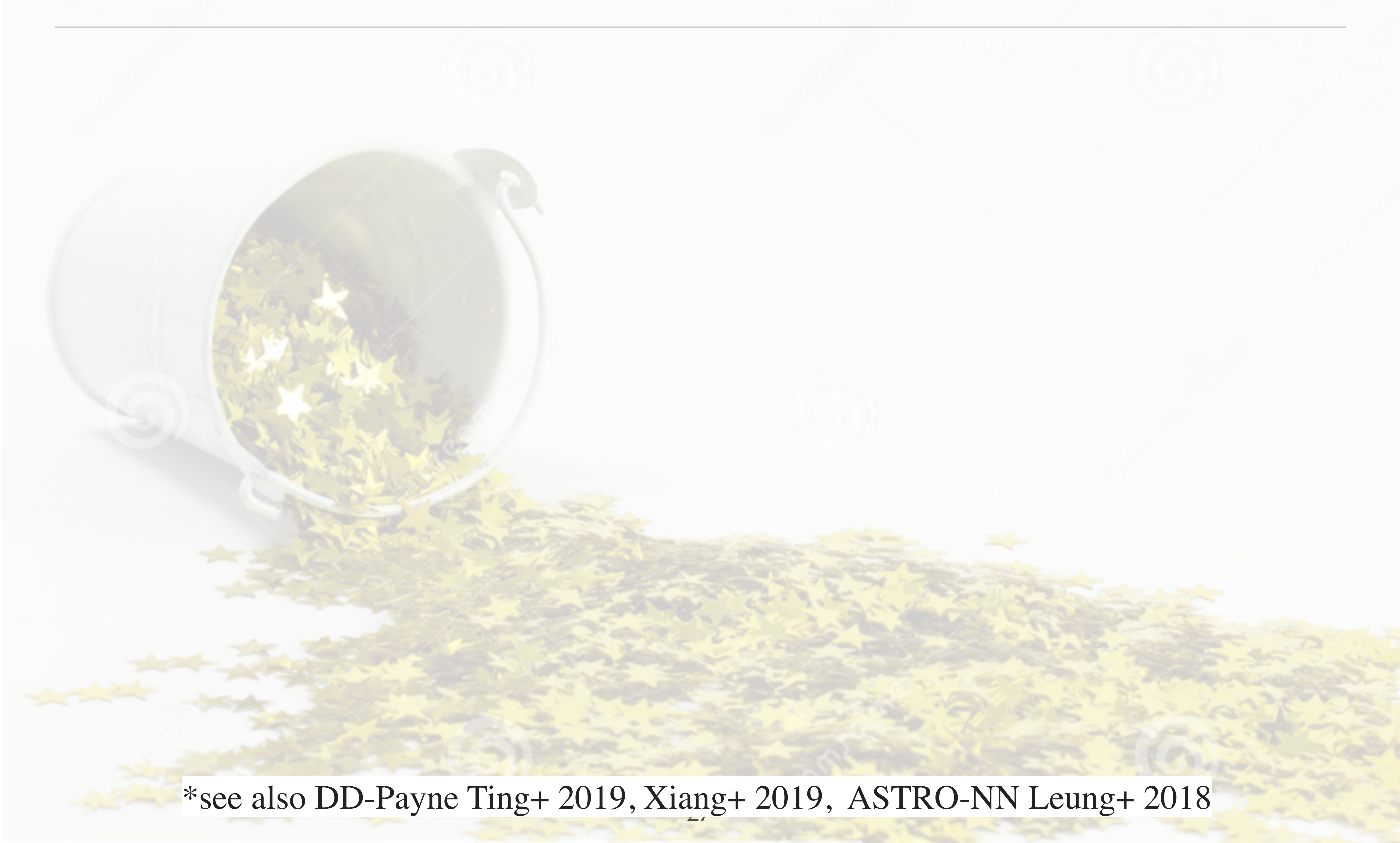
An incomplete list…

Wu+ 1998, Prugniel+ 2011+ 2011 Ness+ 2015, 2016, Ho+ 2017, 2018, Casey+ 2017, 2019, Ting+2019, Leung+ 2018, Buder+ 2018, Hogg+ 2019, Eilers+ 2019, Birky+ 2020, Behmard+ 2020, Casagrande+ 2019, Xiang+2020, Lucey+ 2020, Sayeed+2021, de Mijolla+2021, Feeney+ 2021, Green+ 2021, Galgano+ 2020, Feeney+ 2020, Blancato+2020, Leung 2019, Deacon+ 2019, Sit+2020, Wheeler+ 2020, Wylie+ 2021, Hawkins+ 2017, 2021, Lu+ 2021, Ciuca+ 2021

How *The Cannon* works on spectra (and other data-driven label transfer)



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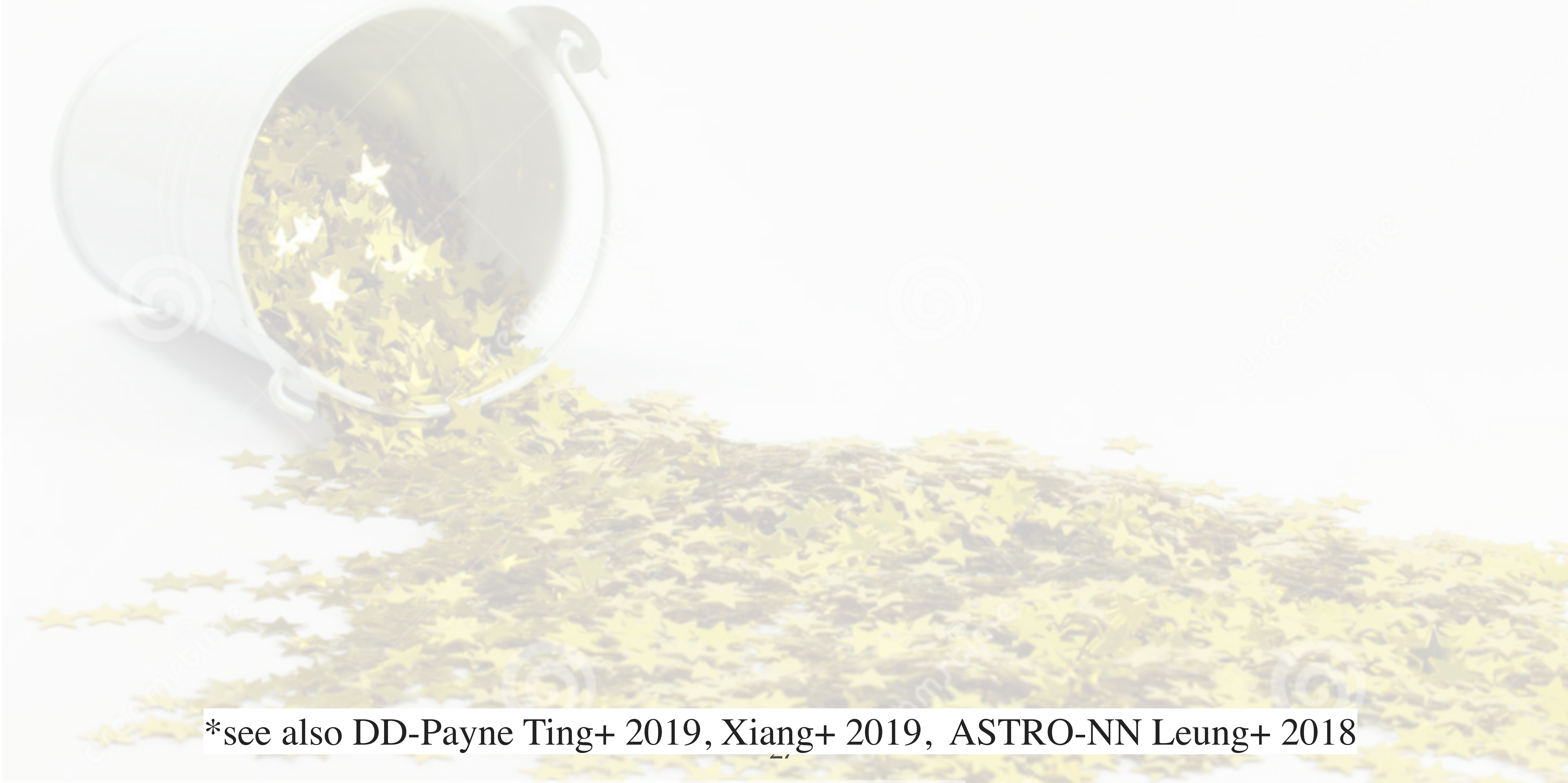

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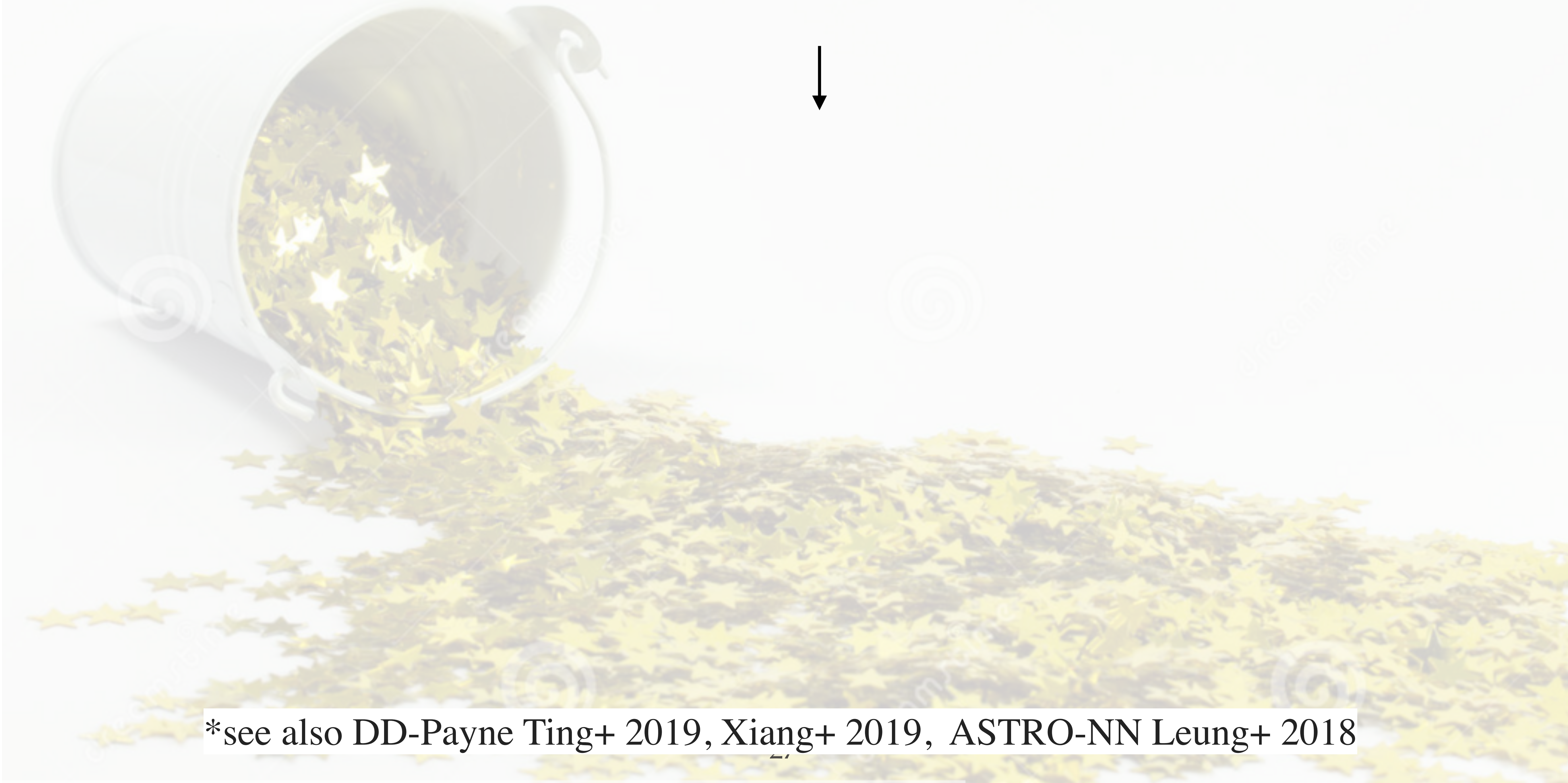

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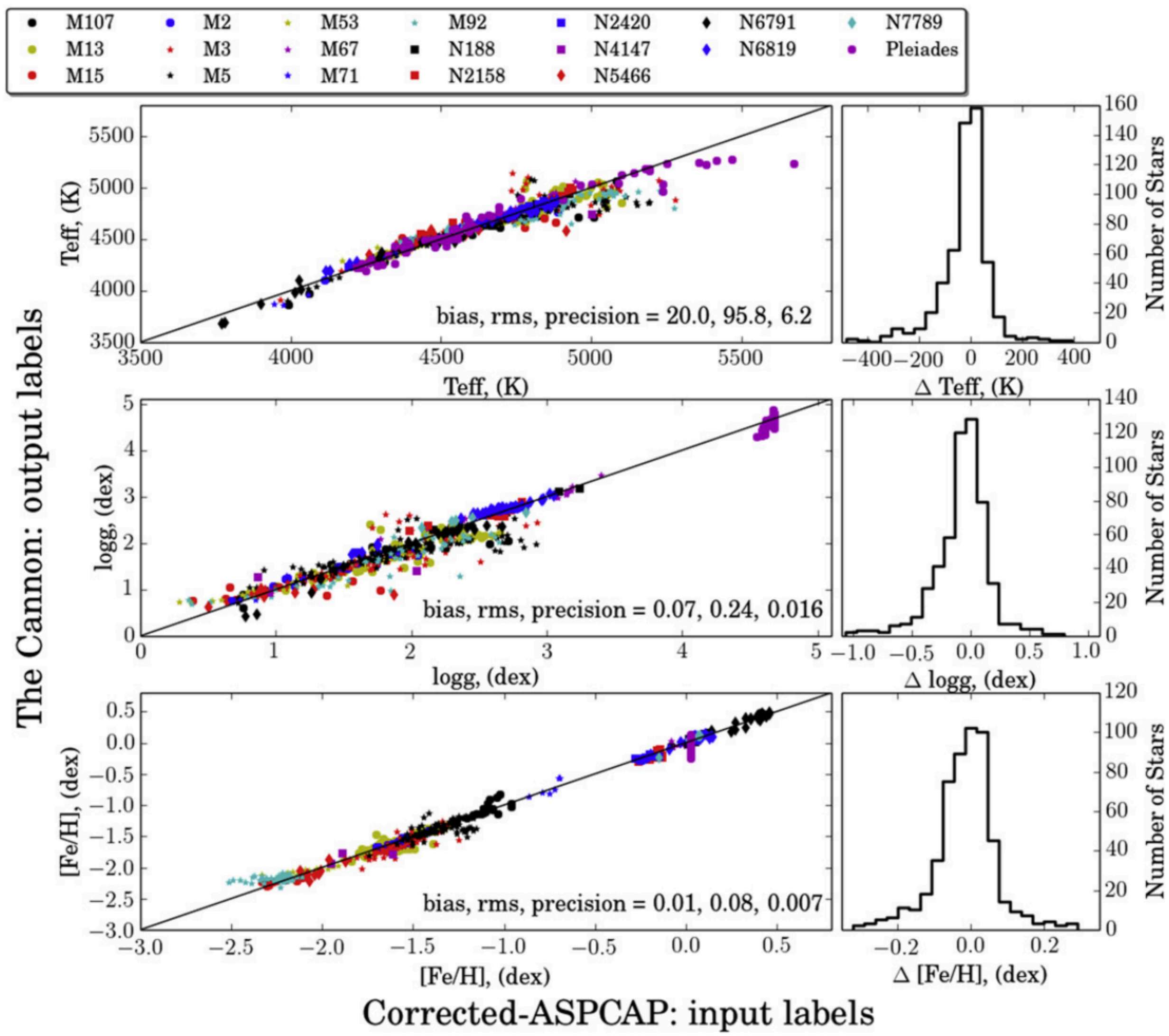

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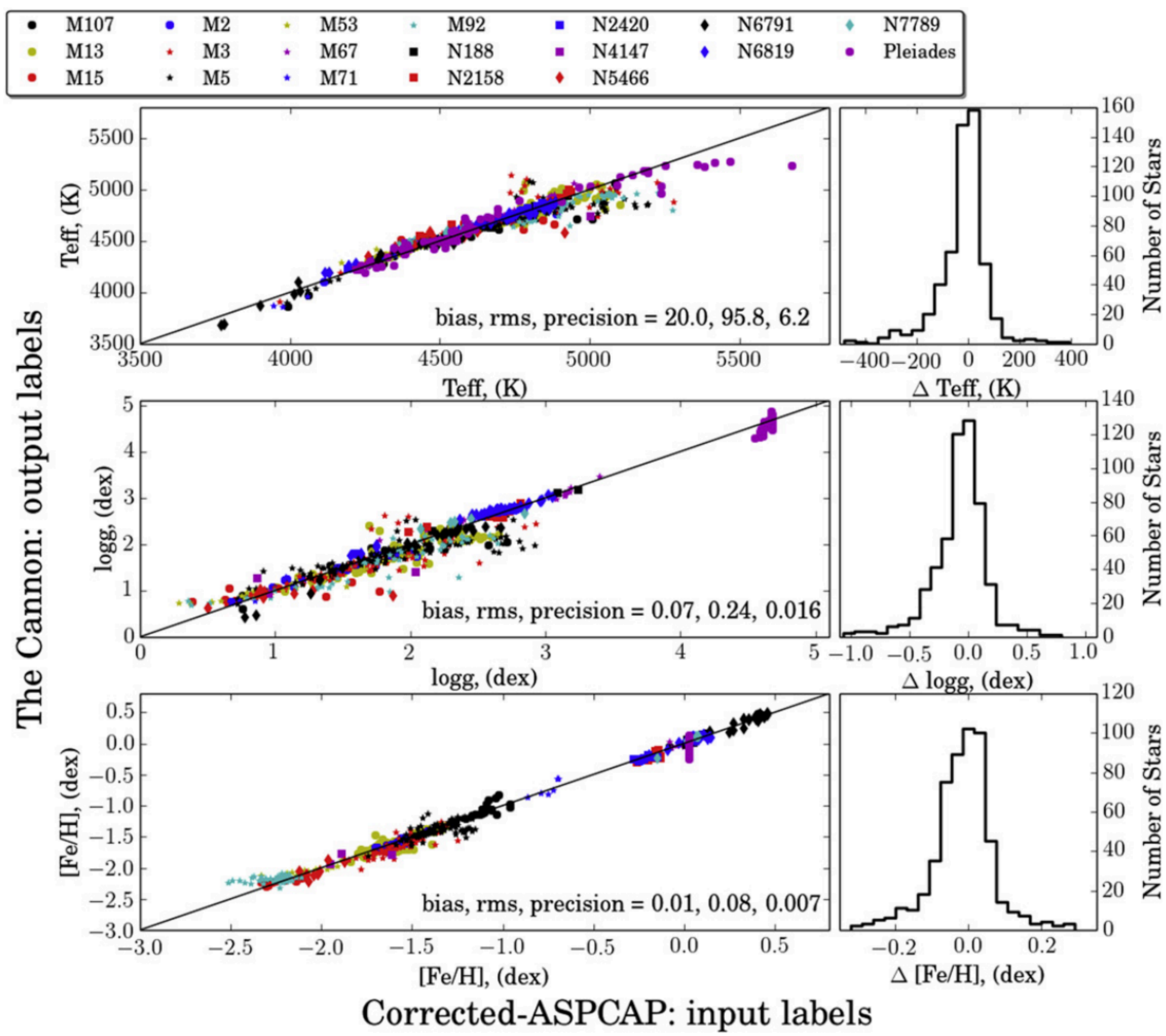

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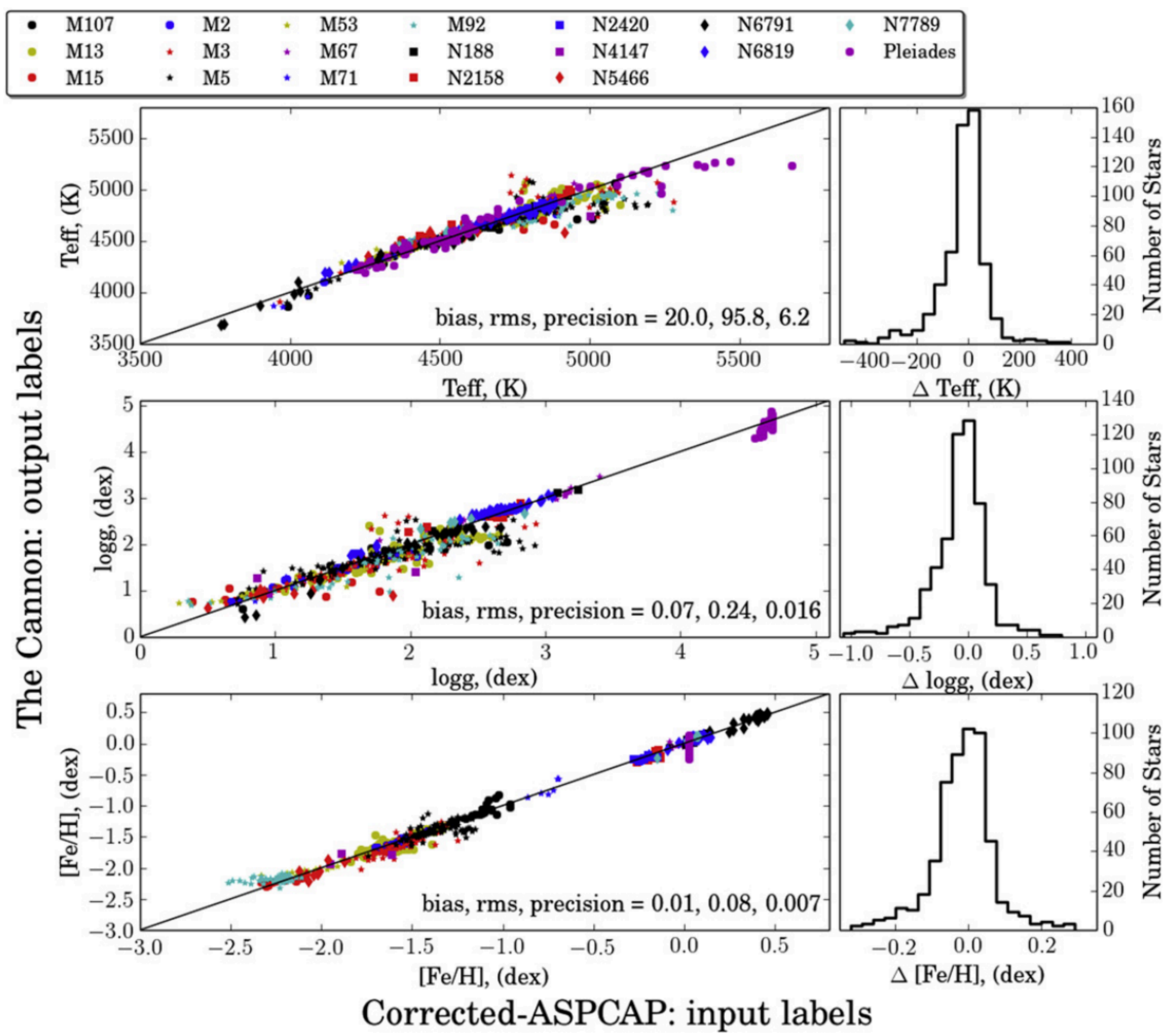

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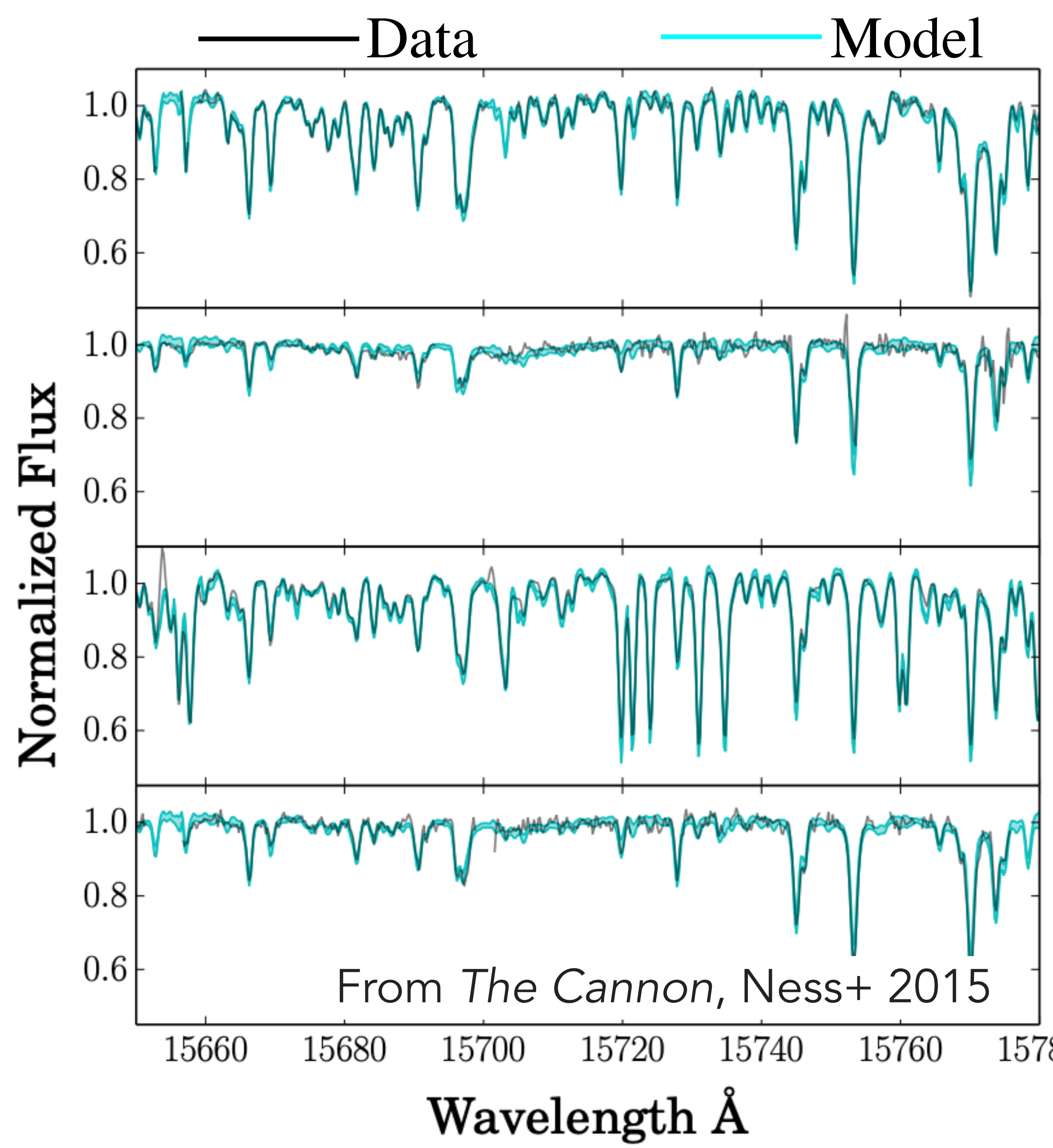

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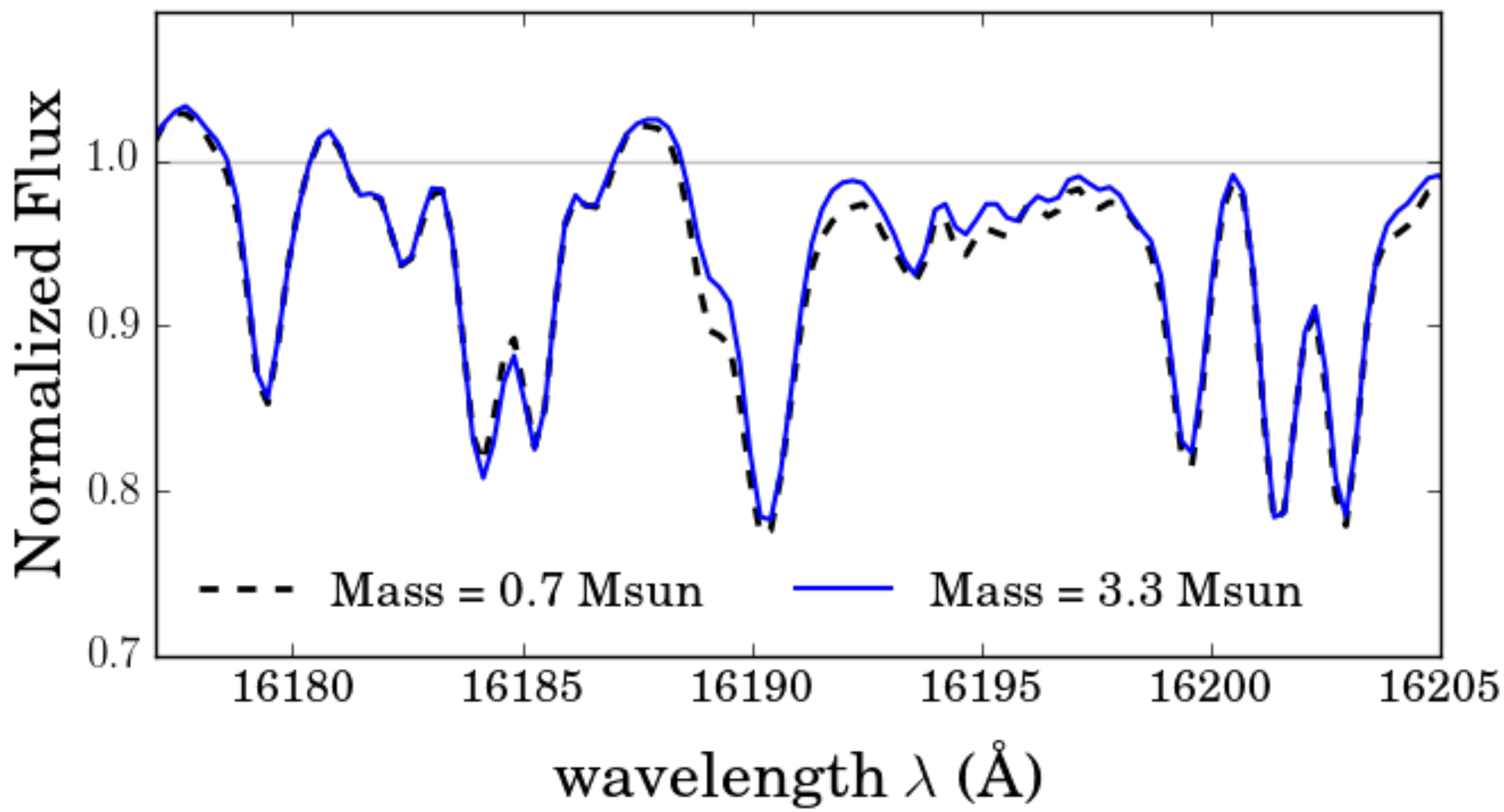
Go from mass to age with stellar evolution models

Origin of mass information



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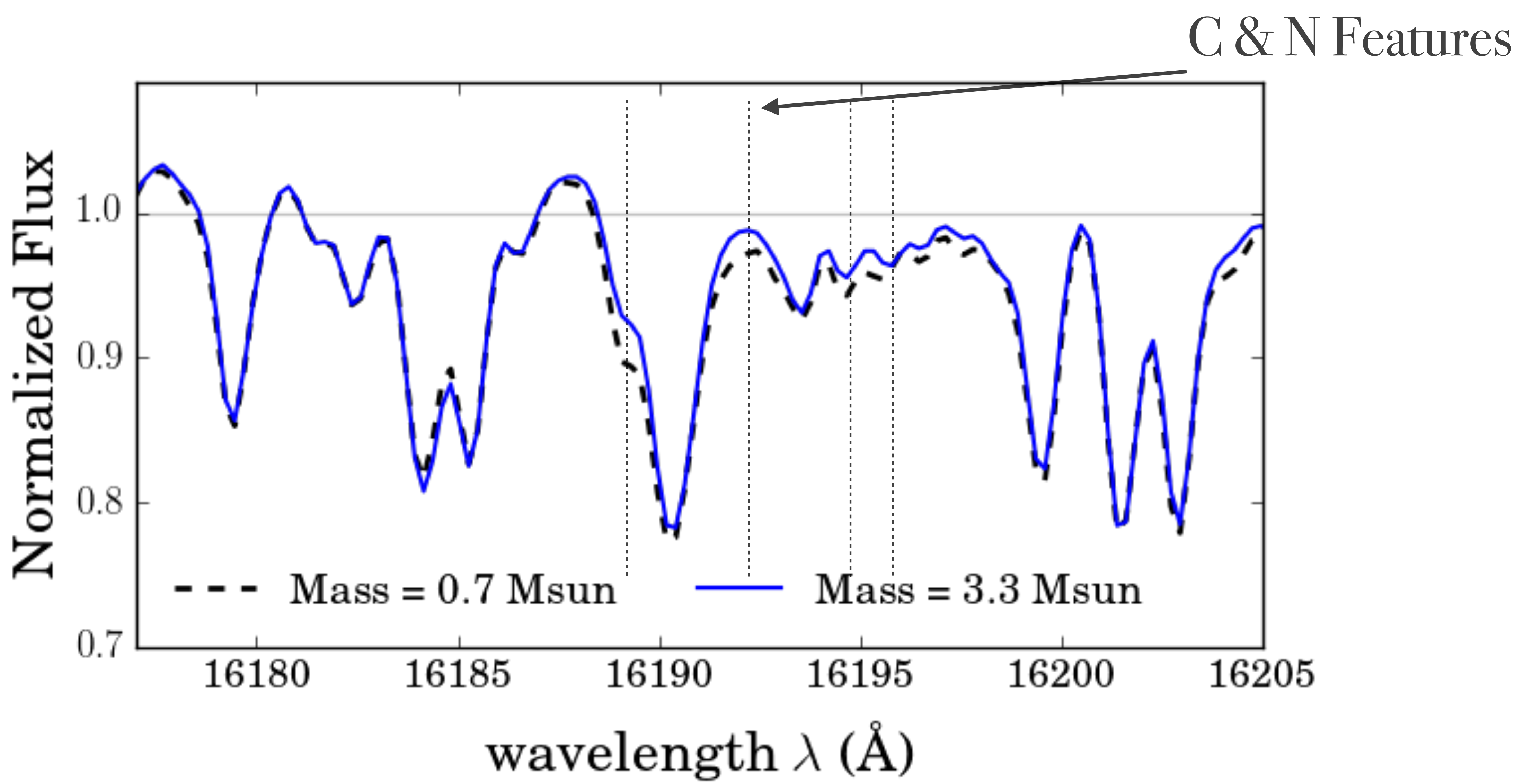

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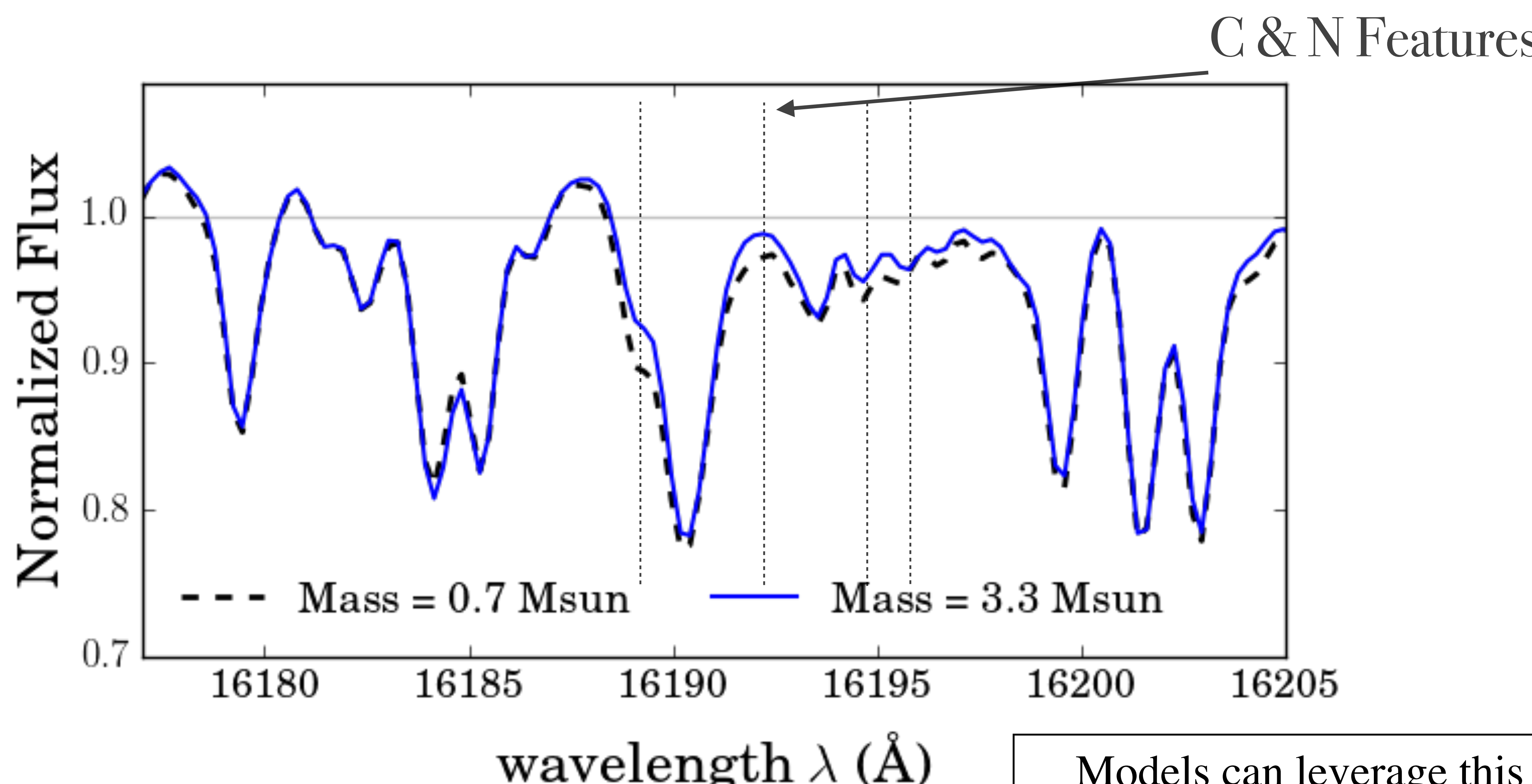

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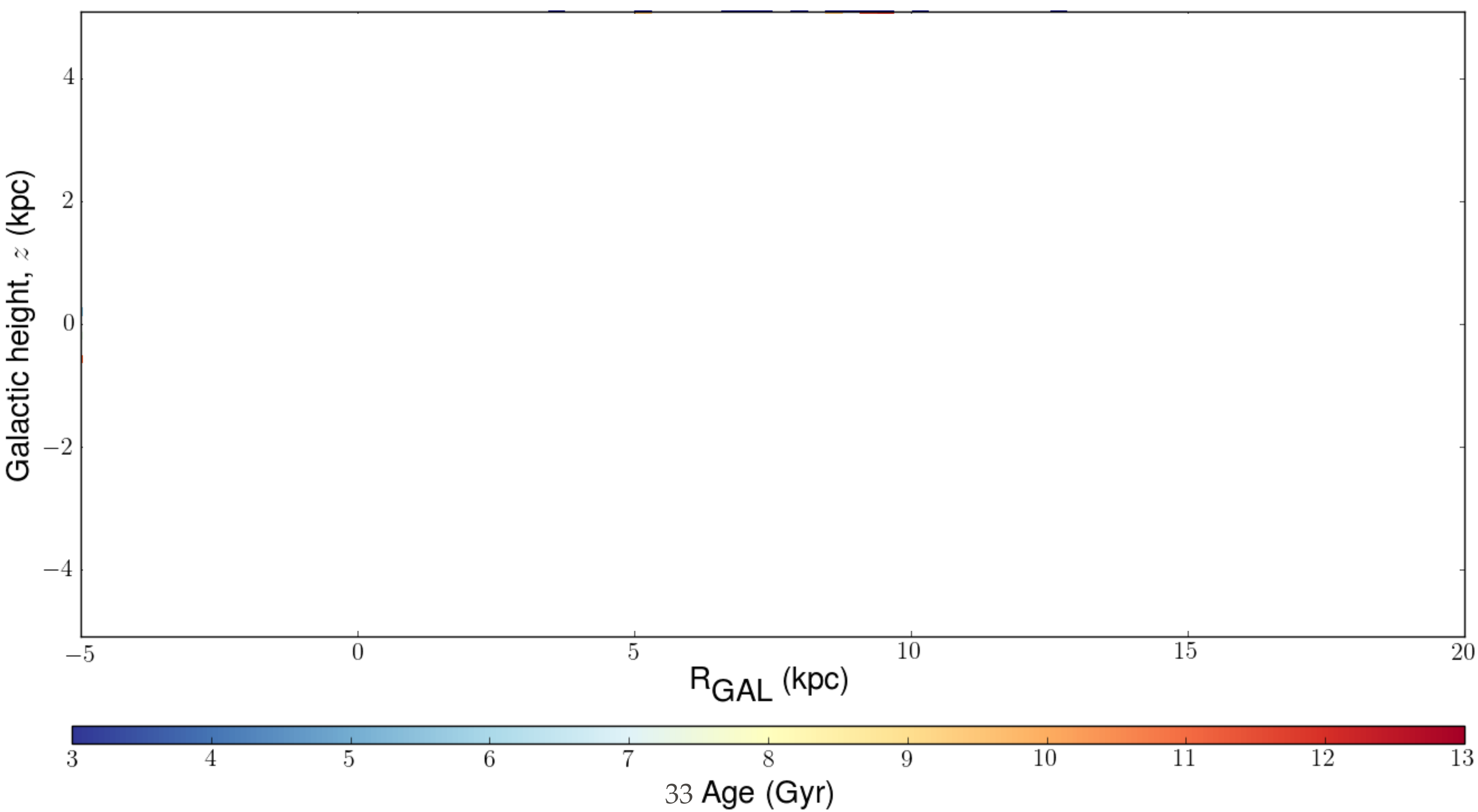
Models can leverage this indirectly or directly using [C/N/]-age calibration with asteroseimic stars or clusters

e.g. Spoo+ 2022, Casali+ 2017, Martig+ 2016

Ages: inside out formation and flaring of the disk

75,000 stars from APOGEE DR16



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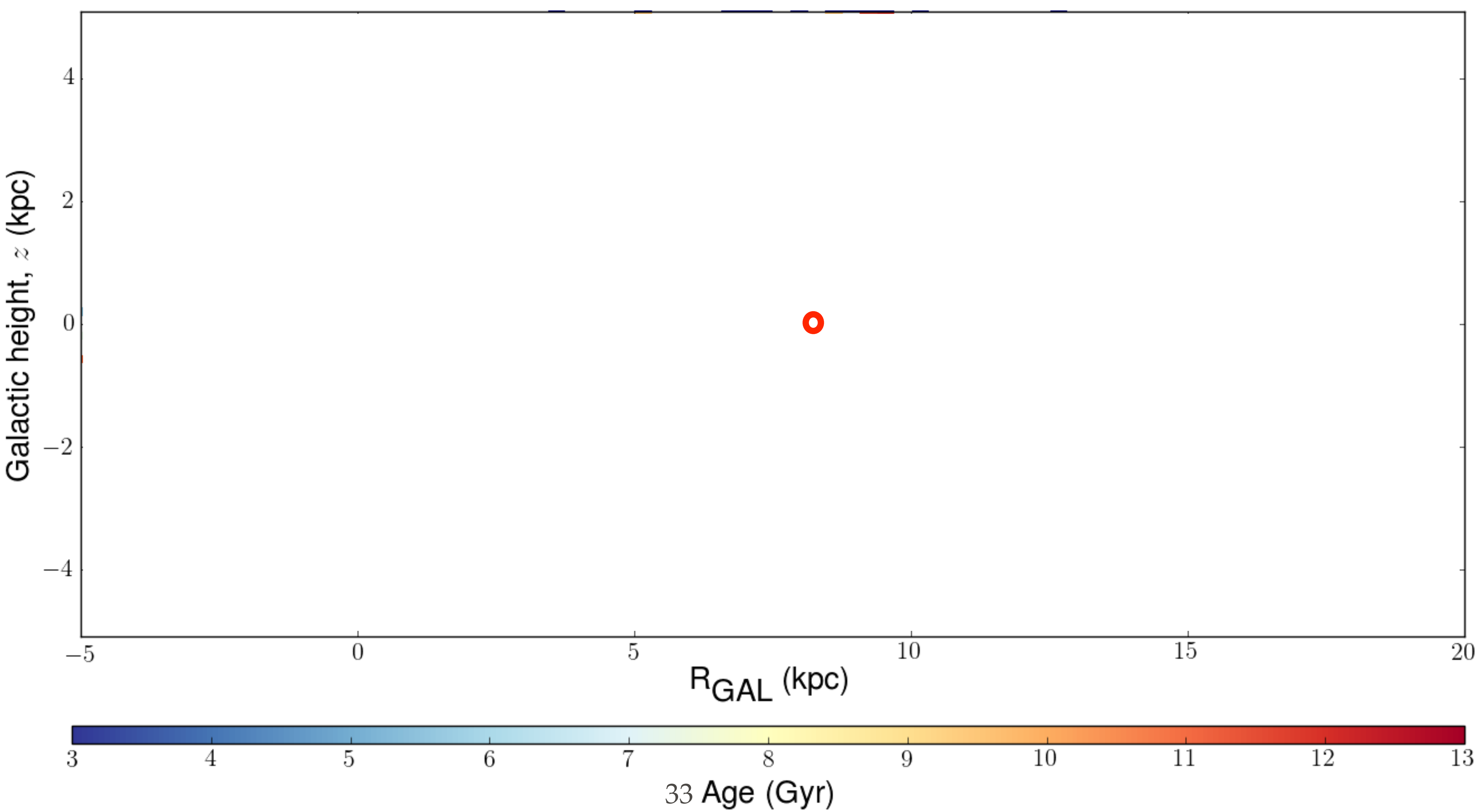

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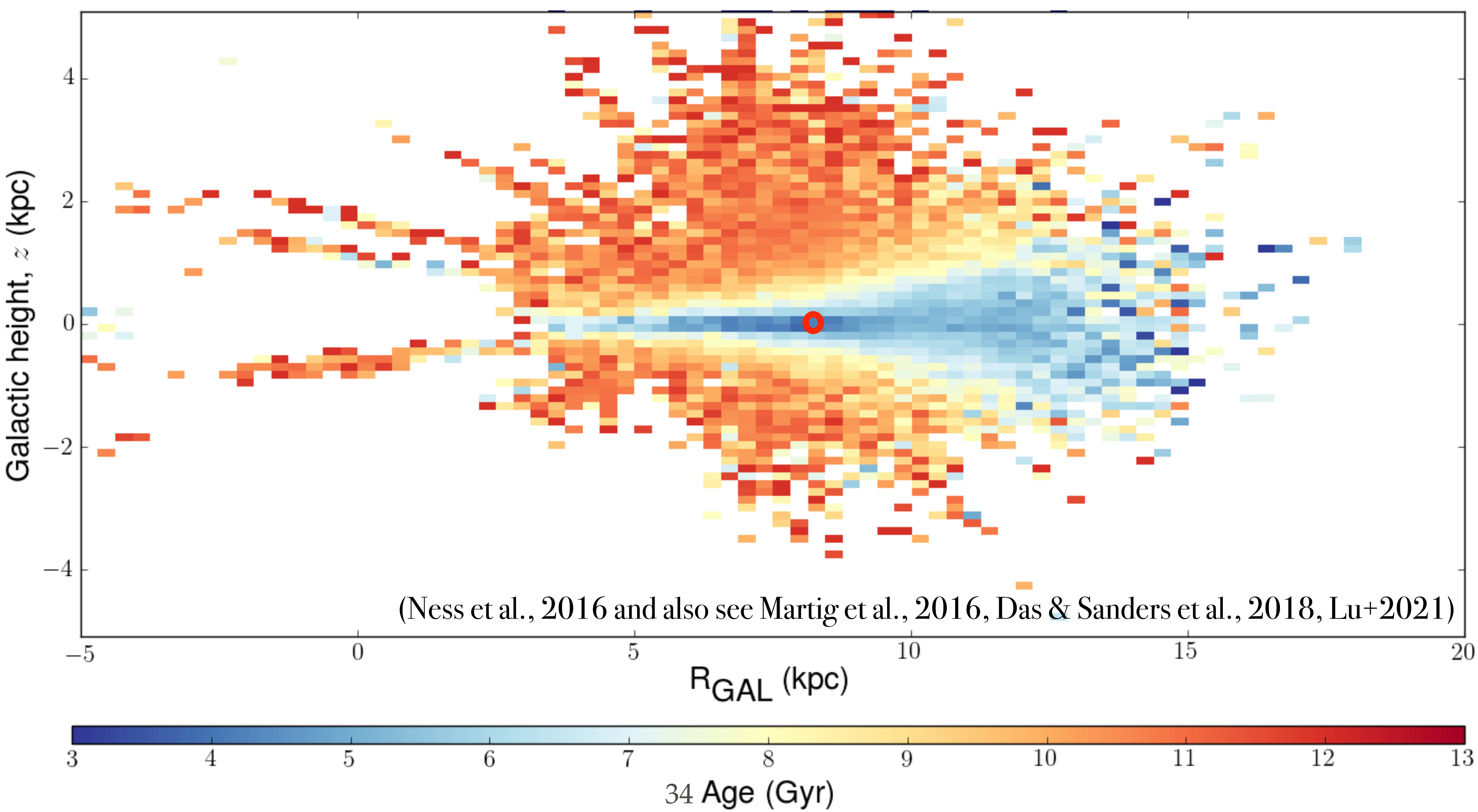

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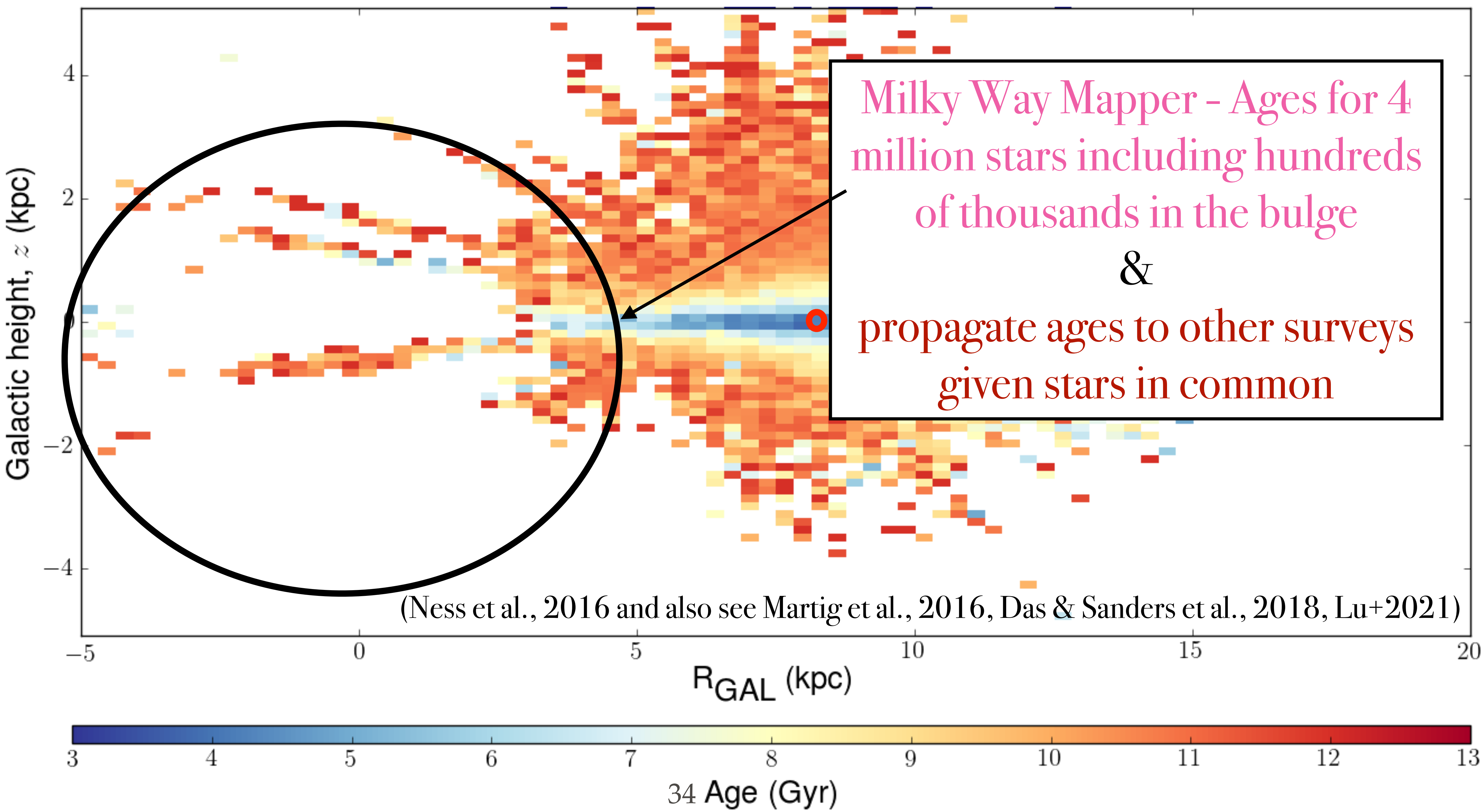

Putting everything together - ages are key

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Reconstructing

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Reconstructing

- Measure **radial migration & inside-out formation** of the disk (e.g. Frankel+ 2018,2019)
- **Modelling the joint abundance-age-spatial** distribution across the disk (e.g. Sharma+ 2021)
- Measuring **dynamical heating** across the Milky Way (e.g. Mackereth+ 2019, Ting+ 2019)

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- The relationship between **orbits and abundances and ages** (e.g. Gaia-Collaboration 2022, Viscasillas-Vazquez+ 2022, Manea+ 2022, Espinoza-Rojas+ 2021, Lu+ 2021, Hayden+ 2020, Gandhi+ 2019, Beane+ 2018)

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Signatures

- **Age-metallicity** relations across the disk (e.g. Xiang+ 2022, Lu+ 2021, Feuillet+ 2019)
- **Age dating the disk z-vz spiral** from a perturbing impulse (e.g. Bland-Hawthorn+ 2019)
- **Age dating the bulge compared to the disk** (e.g. Bovy+ 2019, Sit+ 2020, Hasselquist+ 2020, Surot+ 2019, Valenti+ 2018)

Planet engulfment signatures: hidden in abundances of mono-age-metallicity groups?

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open clusters with 20 measured abundances

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where the indices n and n' denote the two stars, i the elements, and x_{ni} the measurements with uncertainty σ_{ni}.

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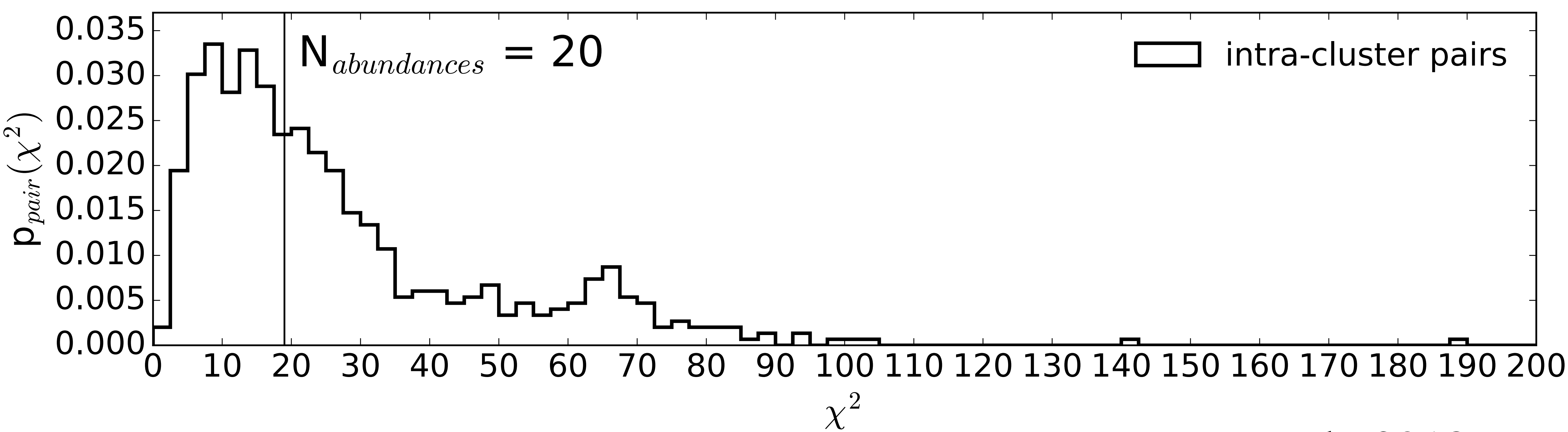

Ness et al., 2018

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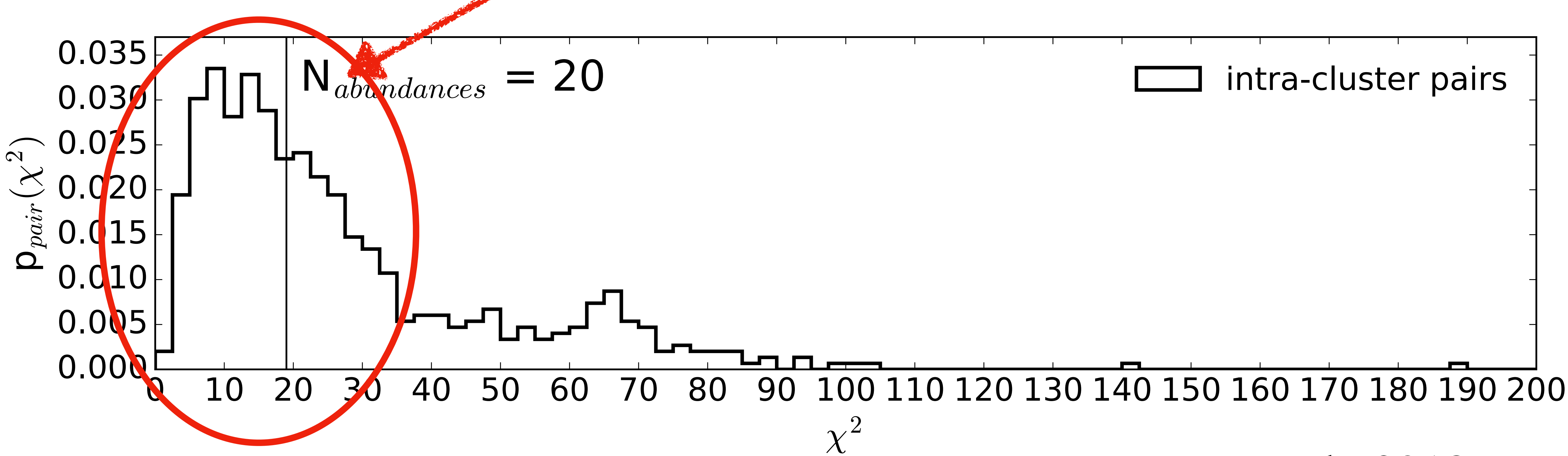

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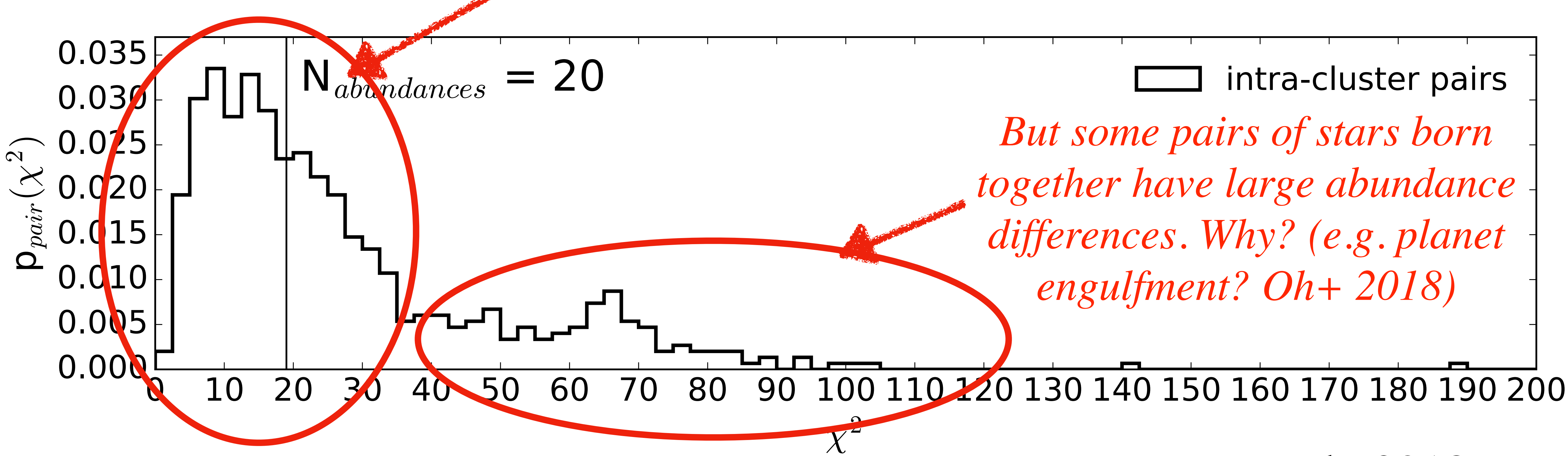
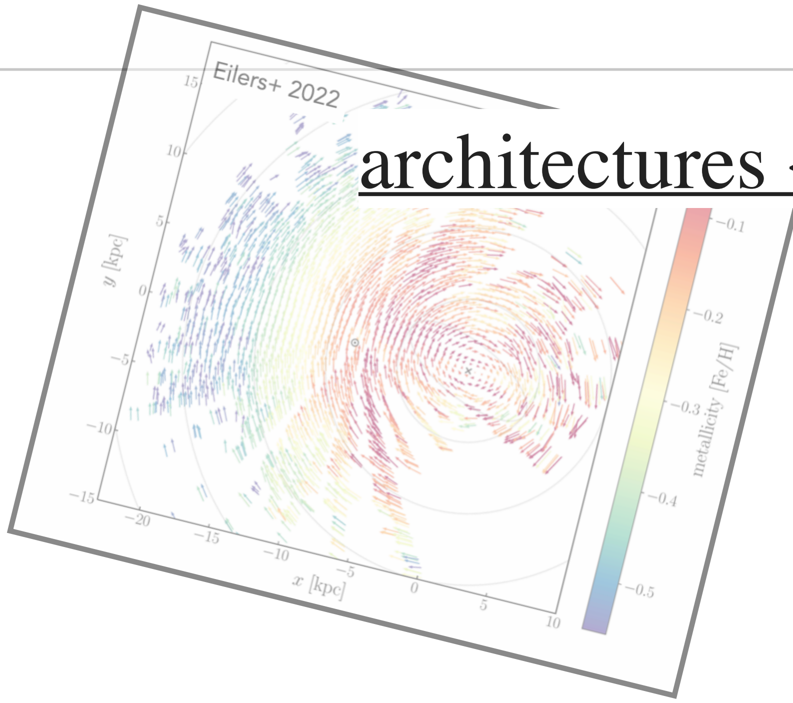


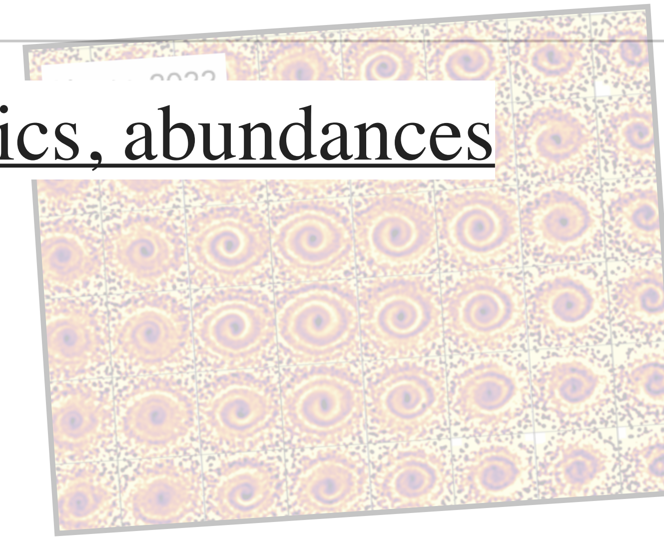
But some pairs of stars born together have large abundance differences. Why? (e.g. planet engulfment? Oh+ 2018)

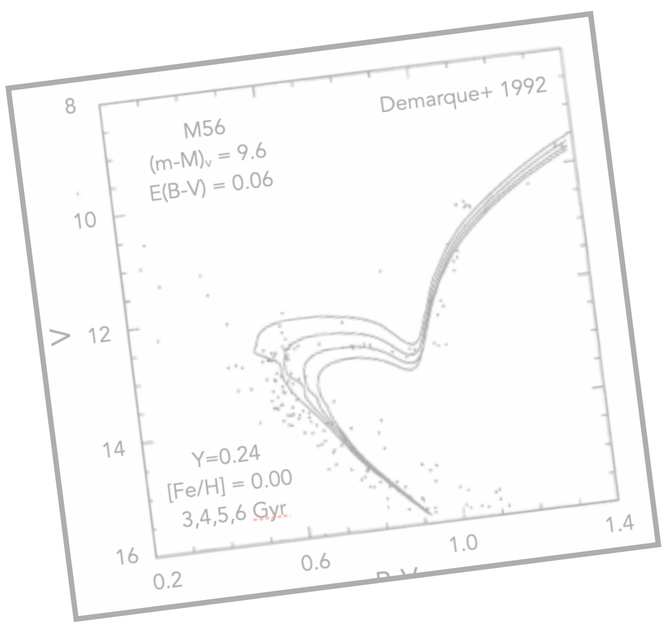
Ness et al., 2018

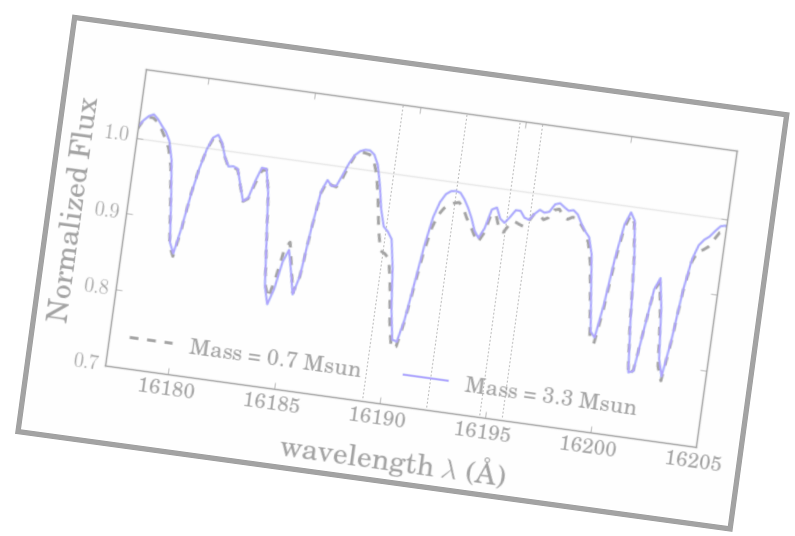
Next Frontiers

<u>architectures <- ages, kinematics, abundances</u>









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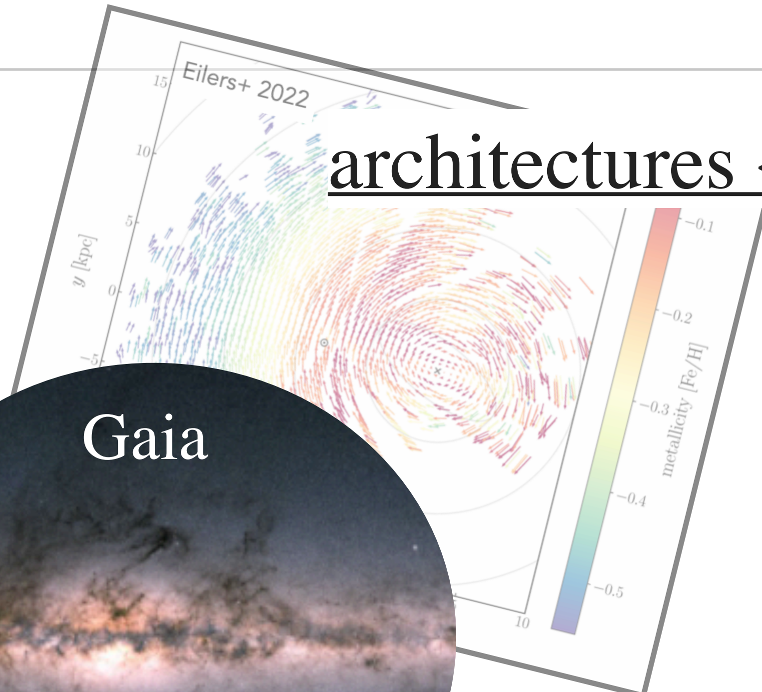

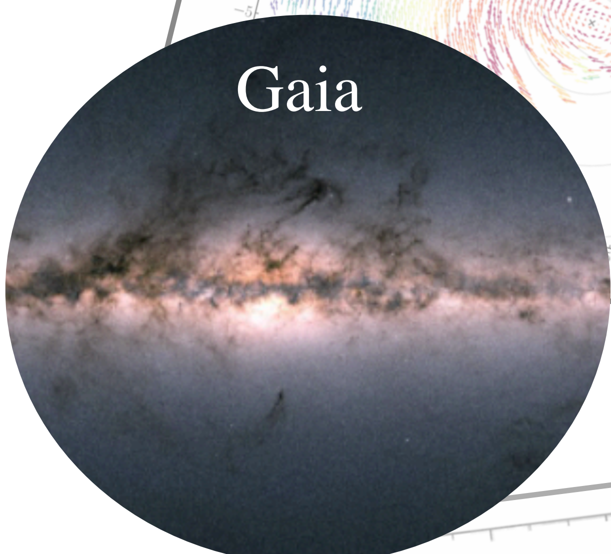

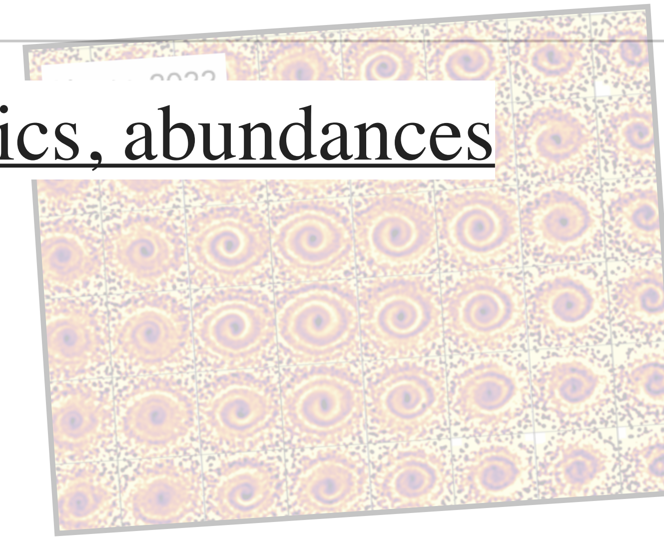

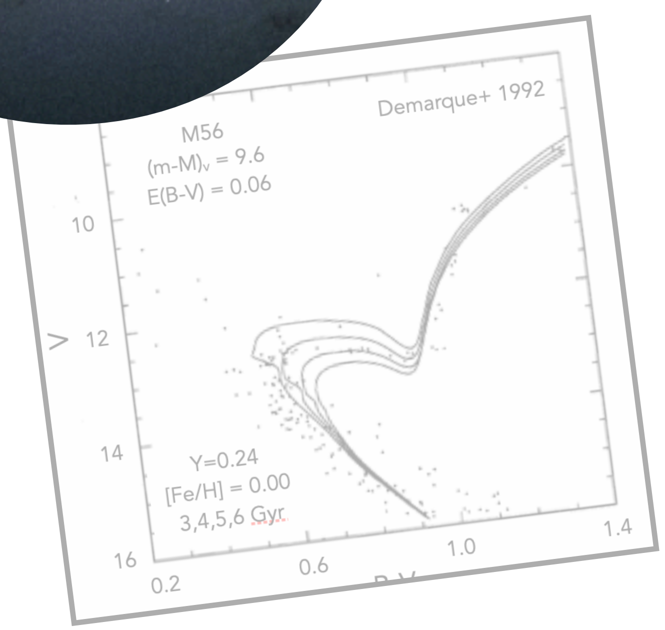

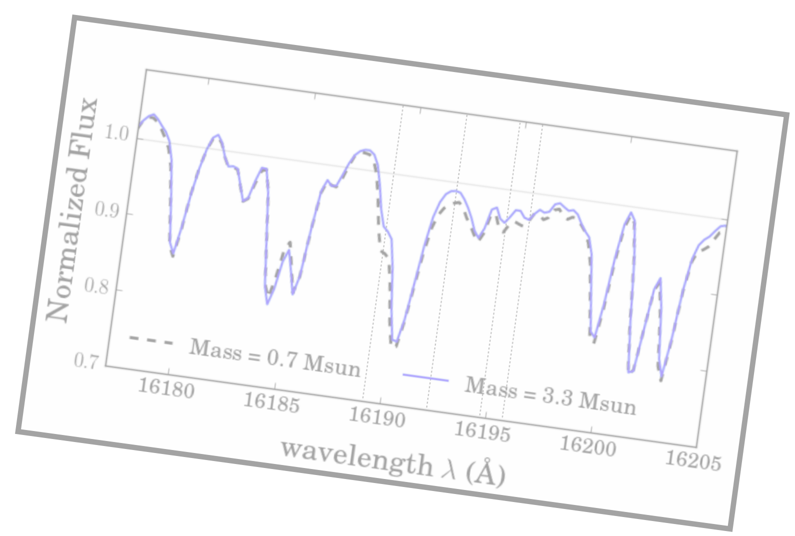

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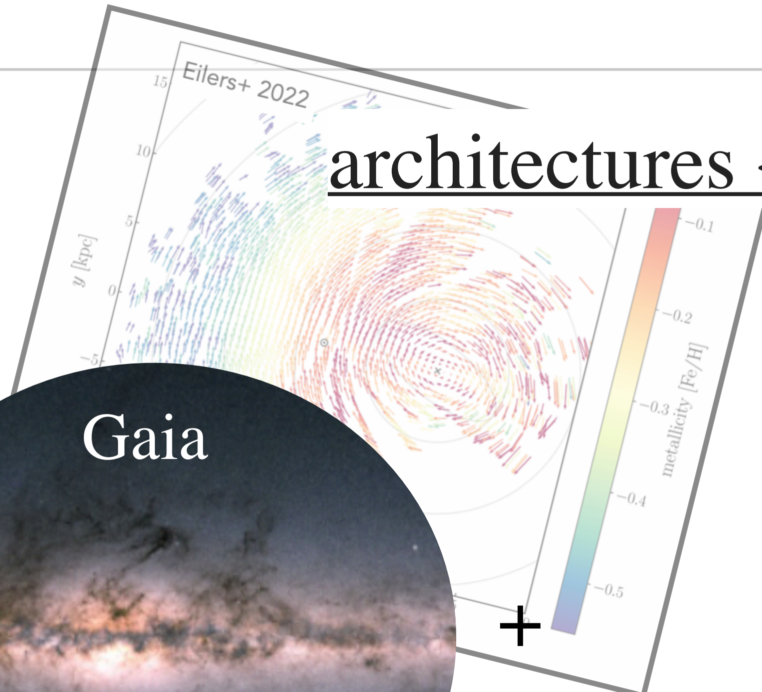

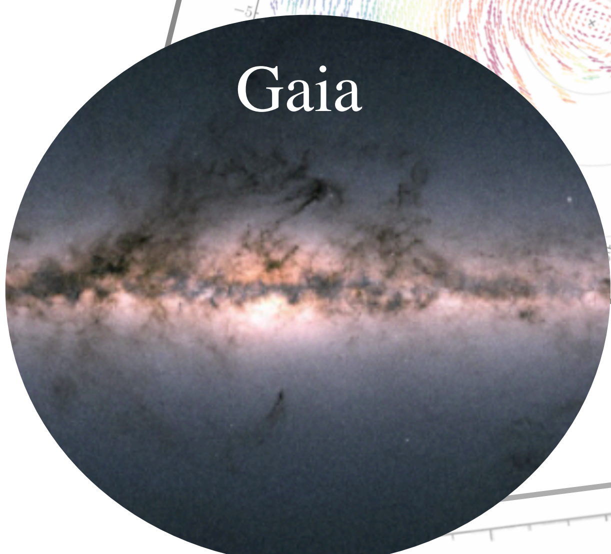

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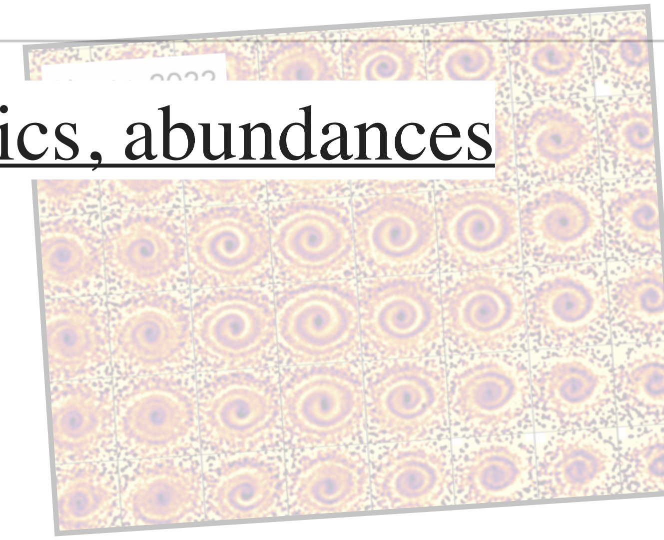

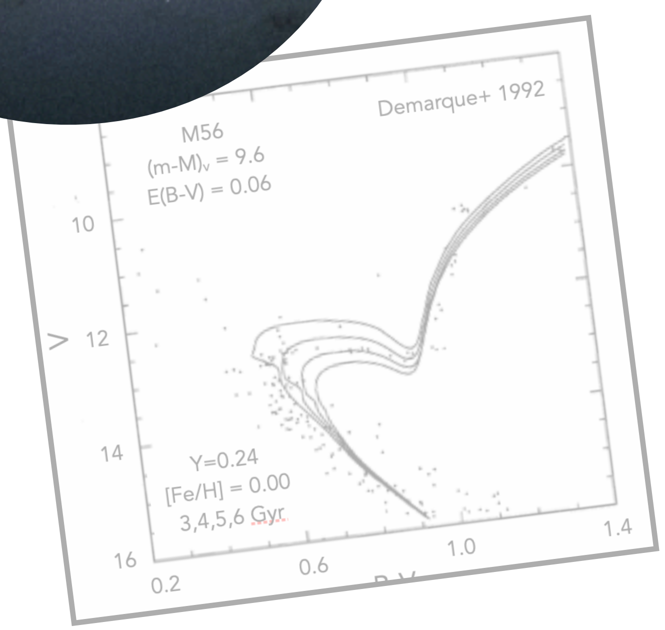

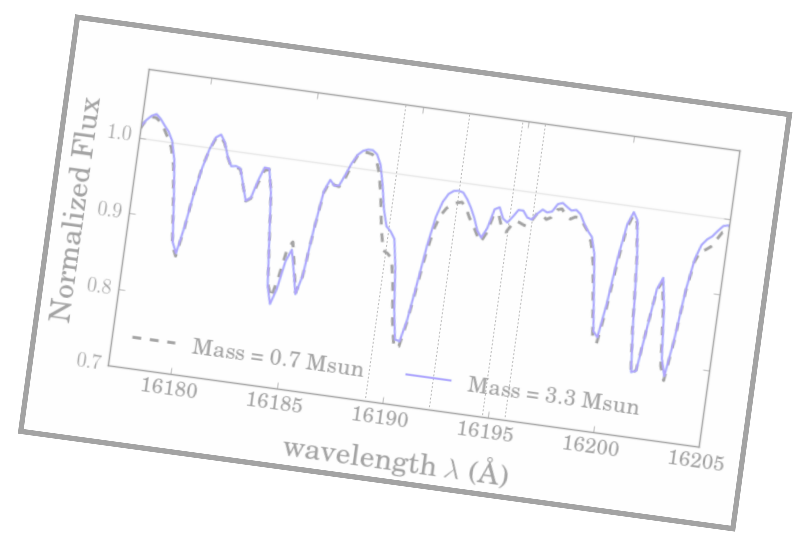

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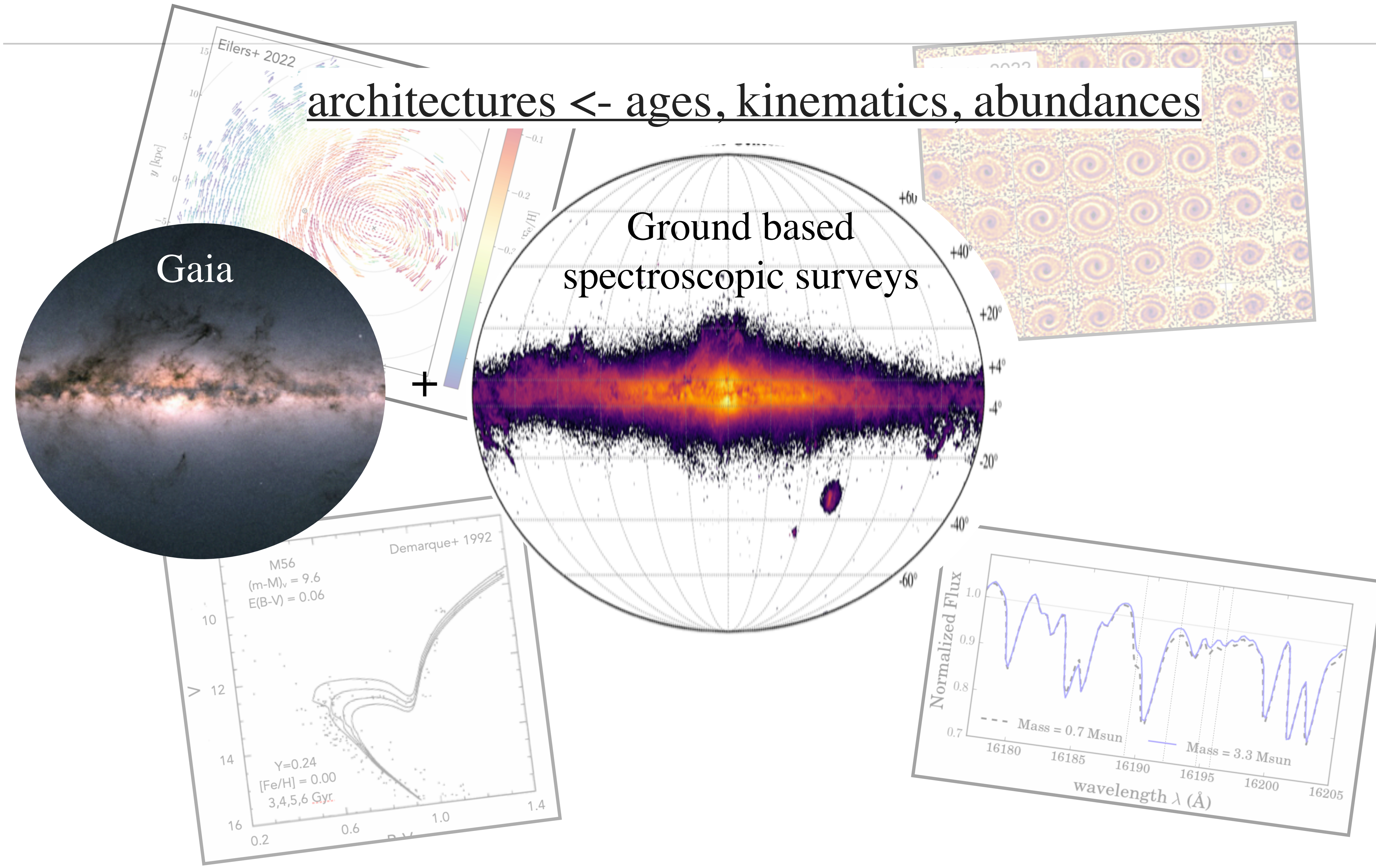
<u>architectures <- ages, kinematics, abundances</u>



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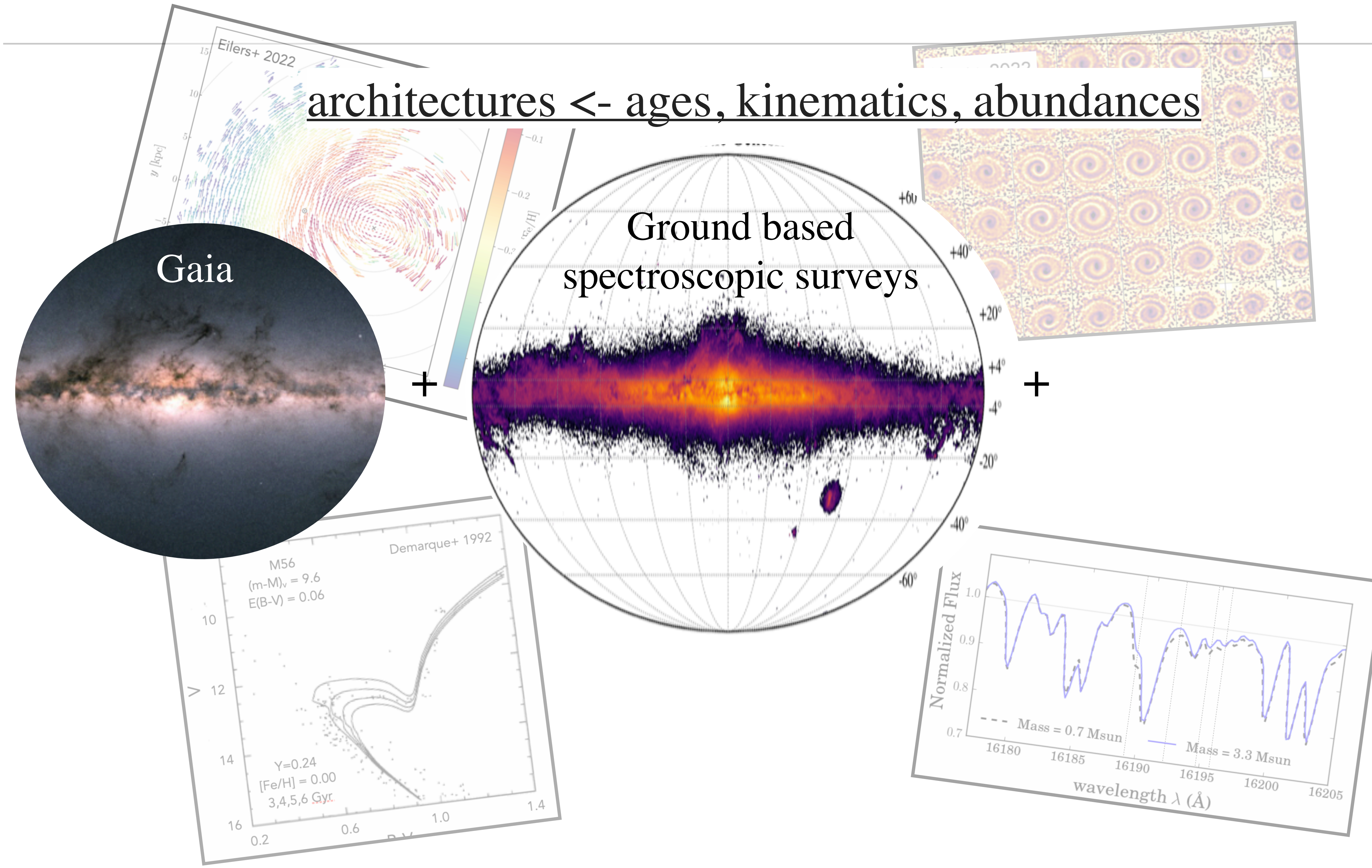
<u>architectures <- ages, kinematics, abundances</u>

Gaia + Ground based spectroscopic surveys +



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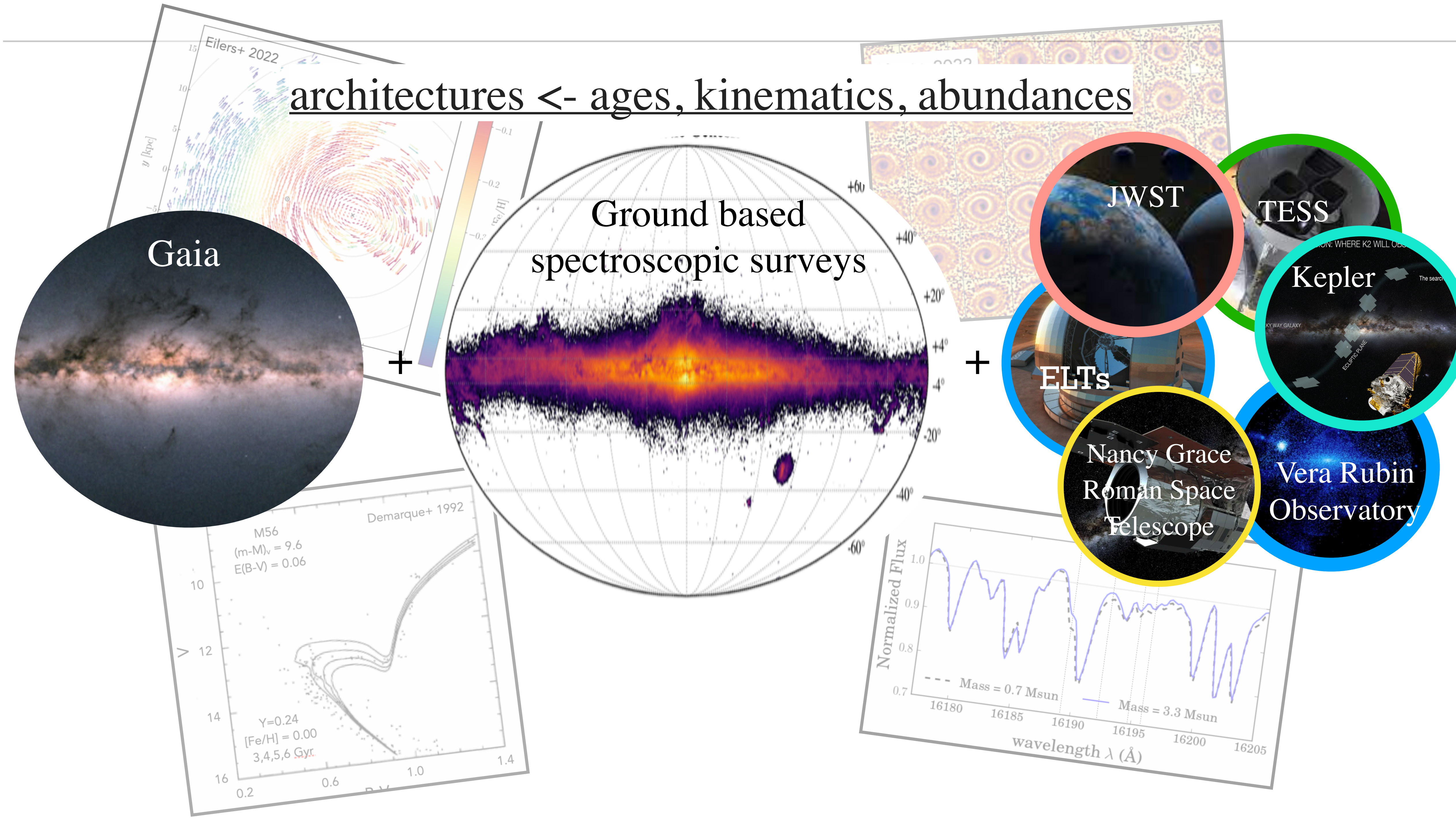

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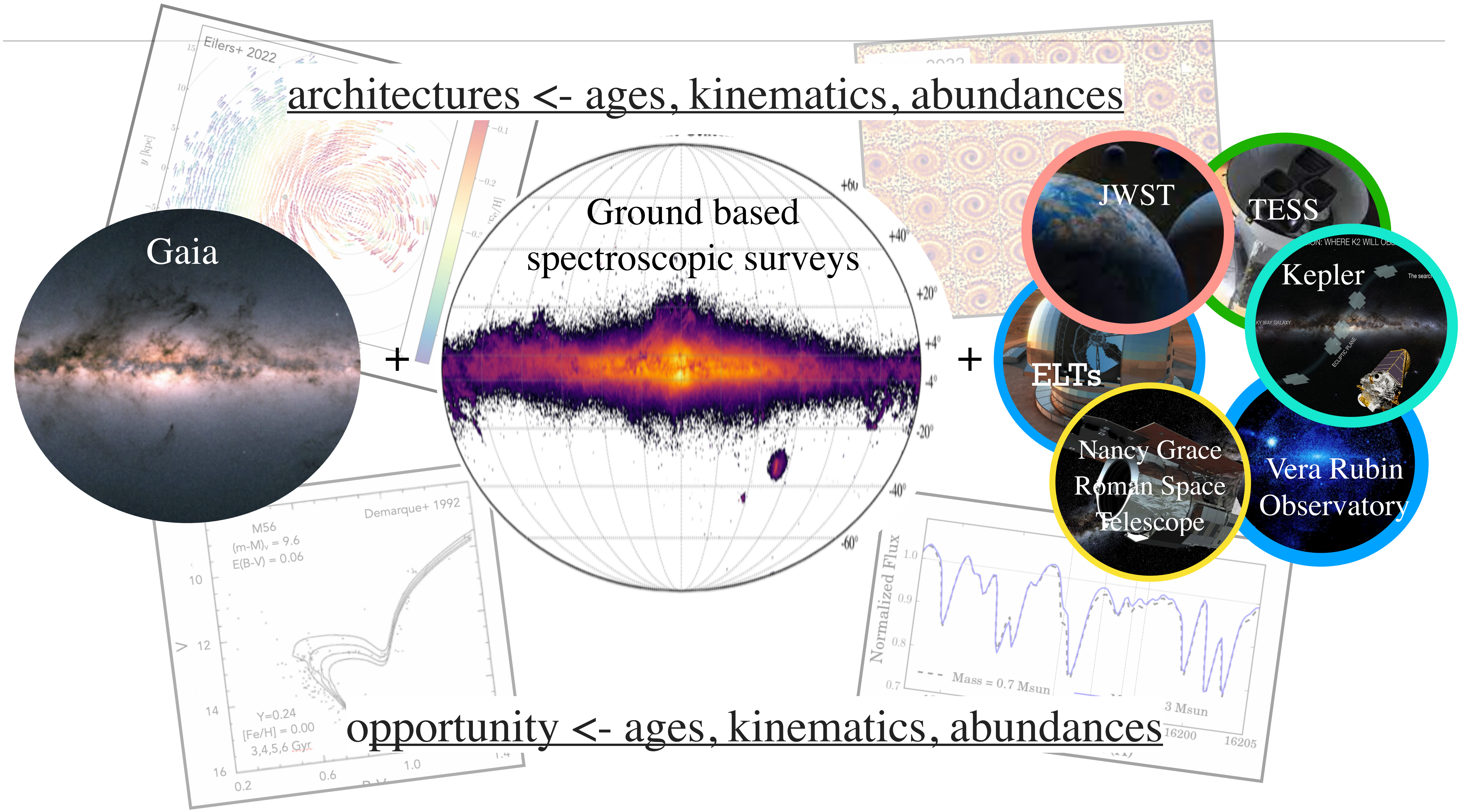
architectures <- ages, kinematics, abundances



opportunity <- ages, kinematics, abundances