

APOGEE



The Apache Point Observatory Galactic Evolution Experiment

Ricardo Schiavon

CS20, Boston, August 1st, 2018



APOGEE



Overview paper: Majewski, Schiavon et al. (2017)

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CrossMark

The Apache Point Observatory Galactic Evolution Experiment (APOGEE)

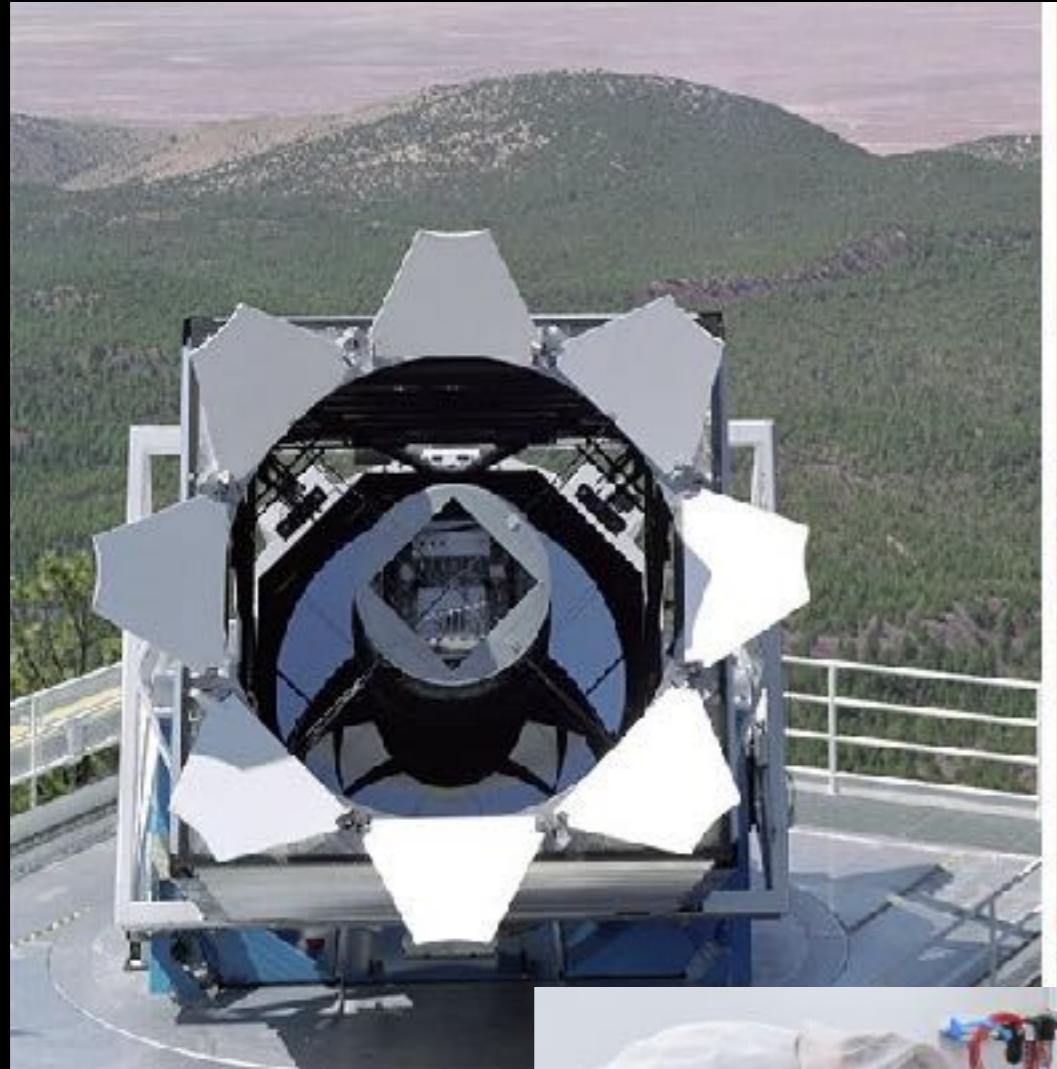
Steven R. Majewski¹, Ricardo P. Schiavon^{2,3}, Peter M. Frinchaboy⁴, Carlos Allende Prieto^{5,6}, Robert Barkhouser⁷, Dmitry Bizyaev^{8,9}, Basil Blank¹⁰, Sophia Brunner¹, Adam Burton¹, Ricardo Carrera^{5,6}, S. Drew Chojnowski^{1,11}, Kátia Cunha^{12,13},
¹⁴¹⁵¹⁶¹⁷¹⁸¹⁹²⁰²¹²²²³²⁴²⁵²⁶²⁷²⁸²⁹³⁰³¹³²³³³⁴³⁵³⁶³⁷³⁸³⁹⁴⁰⁴¹⁴²⁴³⁴⁴⁴⁵⁴⁶⁴⁷⁴⁸⁴⁹⁵⁰⁵¹⁵²⁵³⁵⁴⁵⁵⁵⁶⁵⁷⁵⁸⁵⁹⁶⁰⁶¹⁶²⁶³⁶⁴⁶⁵⁶⁶⁶⁷⁶⁸⁶⁹⁷⁰⁷¹⁷²⁷³⁷⁴⁷⁵⁷⁶⁷⁷⁷⁸⁷⁹⁸⁰⁸¹⁸²⁸³⁸⁴⁸⁵⁸⁶⁸⁷⁸⁸⁸⁹⁹⁰⁹¹⁹²⁹³⁹⁴⁹⁵⁹⁶⁹⁷⁹⁸⁹⁹¹⁰⁰¹⁰¹¹⁰²¹⁰³¹⁰⁴¹⁰⁵¹⁰⁶¹⁰⁷¹⁰⁸¹⁰⁹¹¹⁰¹¹¹¹¹²¹¹³¹¹⁴¹¹⁵¹¹⁶¹¹⁷¹¹⁸¹¹⁹¹²⁰¹²¹¹²²¹²³¹²⁴¹²⁵¹²⁶¹²⁷¹²⁸¹²⁹¹³⁰¹³¹¹³²¹³³¹³⁴¹³⁵¹³⁶¹³⁷¹³⁸¹³⁹¹⁴⁰¹⁴¹¹⁴²¹⁴³¹⁴⁴¹⁴⁵¹⁴⁶¹⁴⁷¹⁴⁸¹⁴⁹¹⁵⁰¹⁵¹¹⁵²¹⁵³¹⁵⁴¹⁵⁵¹⁵⁶¹⁵⁷¹⁵⁸¹⁵⁹¹⁶⁰¹⁶¹¹⁶²¹⁶³¹⁶⁴¹⁶⁵¹⁶⁶¹⁶⁷¹⁶⁸¹⁶⁹¹⁷⁰¹⁷¹¹⁷²¹⁷³¹⁷⁴¹⁷⁵¹⁷⁶¹⁷⁷¹⁷⁸¹⁷⁹¹⁸⁰¹⁸¹¹⁸²¹⁸³¹⁸⁴¹⁸⁵¹⁸⁶¹⁸⁷¹⁸⁸¹⁸⁹¹⁹⁰¹⁹¹¹⁹²¹⁹³¹⁹⁴¹⁹⁵¹⁹⁶¹⁹⁷¹⁹⁸¹⁹⁹²⁰⁰²⁰¹²⁰²²⁰³²⁰⁴²⁰⁵²⁰⁶²⁰⁷²⁰⁸²⁰⁹²¹⁰²¹¹²¹²²¹³²¹⁴²¹⁵²¹⁶²¹⁷²¹⁸²¹⁹²²⁰²²¹²²²²²³²²⁴²²⁵²²⁶²²⁷²²⁸²²⁹²³⁰²³¹²³²²³³²³⁴²³⁵²³⁶²³⁷²³⁸²³⁹²⁴⁰²⁴¹²⁴²²⁴³²⁴⁴²⁴⁵²⁴⁶²⁴⁷²⁴⁸²⁴⁹²⁵⁰²⁵¹²⁵²²⁵³²⁵⁴²⁵⁵²⁵⁶²⁵⁷²⁵⁸²⁵⁹²⁶⁰²⁶¹²⁶²²⁶³²⁶⁴²⁶⁵²⁶⁶²⁶⁷²⁶⁸²⁶⁹²⁷⁰²⁷¹²⁷²²⁷³²⁷⁴²⁷⁵²⁷⁶²⁷⁷²⁷⁸²⁷⁹²⁸⁰²⁸¹²⁸²²⁸³²⁸⁴²⁸⁵²⁸⁶²⁸⁷²⁸⁸²⁸⁹²⁹⁰²⁹¹²⁹²²⁹³²⁹⁴²⁹⁵²⁹⁶²⁹⁷²⁹⁸²⁹⁹³⁰⁰³⁰¹³⁰²³⁰³³⁰⁴³⁰⁵³⁰⁶³⁰⁷³⁰⁸³⁰⁹³¹⁰³¹¹³¹²³¹³³¹⁴³¹⁵³¹⁶³¹⁷³¹⁸³¹⁹³²⁰³²¹³²²³²³³²⁴³²⁵³²⁶³²⁷³²⁸³²⁹³³⁰³³¹³³²³³³³³⁴³³⁵³³⁶³³⁷³³⁸³³⁹³⁴⁰³⁴¹³⁴²³⁴³³⁴⁴³⁴⁵³⁴⁶³⁴⁷³⁴⁸³⁴⁹³⁵⁰³⁵¹³⁵²³⁵³³⁵⁴³⁵⁵³⁵⁶³⁵⁷³⁵⁸³⁵⁹³⁶⁰³⁶¹³⁶²³⁶³³⁶⁴³⁶⁵³⁶⁶³⁶⁷³⁶⁸³⁶⁹³⁷⁰³⁷¹³⁷²³⁷³³⁷⁴³⁷⁵³⁷⁶³⁷⁷³⁷⁸³⁷⁹³⁸⁰³⁸¹³⁸²³⁸³³⁸⁴³⁸⁵³⁸⁶³⁸⁷³⁸⁸³⁸⁹³⁹⁰³⁹¹³⁹²³⁹³³⁹⁴³⁹⁵³⁹⁶³⁹⁷³⁹⁸³⁹⁹⁴⁰⁰⁴⁰¹⁴⁰²⁴⁰³⁴⁰⁴⁴⁰⁵⁴⁰⁶⁴⁰⁷⁴⁰⁸⁴⁰⁹⁴¹⁰⁴¹¹⁴¹²⁴¹³⁴¹⁴⁴¹⁵⁴¹⁶⁴¹⁷⁴¹⁸⁴¹⁹⁴²⁰⁴²¹⁴²²⁴²³⁴²⁴⁴²⁵⁴²⁶⁴²⁷⁴²⁸⁴²⁹⁴³⁰⁴³¹⁴³²⁴³³⁴³⁴⁴³⁵⁴³⁶⁴³⁷⁴³⁸⁴³⁹⁴⁴⁰⁴⁴¹⁴⁴²⁴⁴³⁴⁴⁴⁴⁴⁵⁴⁴⁶⁴⁴⁷⁴⁴⁸⁴⁴⁹⁴⁵⁰⁴⁵¹⁴⁵²⁴⁵³⁴⁵⁴⁴⁵⁵⁴⁵⁶⁴⁵⁷⁴⁵⁸⁴⁵⁹⁴⁶⁰⁴⁶¹⁴⁶²⁴⁶³⁴⁶⁴⁴⁶⁵⁴⁶⁶⁴⁶⁷⁴⁶⁸⁴⁶⁹⁴⁷⁰⁴⁷¹⁴⁷²⁴⁷³⁴⁷⁴⁴⁷⁵⁴⁷⁶⁴⁷⁷⁴⁷⁸⁴⁷⁹⁴⁸⁰⁴⁸¹⁴⁸²⁴⁸³⁴⁸⁴⁴⁸⁵⁴⁸⁶⁴⁸⁷⁴⁸⁸⁴⁸⁹⁴⁹⁰⁴⁹¹⁴⁹²⁴⁹³⁴⁹⁴⁴⁹⁵⁴⁹⁶⁴⁹⁷⁴⁹⁸⁴⁹⁹⁵⁰⁰⁵⁰¹⁵⁰²⁵⁰³⁵⁰⁴⁵⁰⁵⁵⁰⁶⁵⁰⁷⁵⁰⁸⁵⁰⁹⁵¹⁰⁵¹¹⁵¹²⁵¹³⁵¹⁴⁵¹⁵⁵¹⁶⁵¹⁷⁵¹⁸⁵¹⁹⁵²⁰⁵²¹⁵²²⁵²³⁵²⁴⁵²⁵⁵²⁶⁵²⁷⁵²⁸⁵²⁹⁵³⁰⁵³¹⁵³²⁵³³⁵³⁴⁵³⁵⁵³⁶⁵³⁷⁵³⁸⁵³⁹⁵⁴⁰⁵⁴¹⁵⁴²⁵⁴³⁵⁴⁴⁵⁴⁵⁵⁴⁶⁵⁴⁷⁵⁴⁸⁵⁴⁹⁵⁵⁰⁵⁵¹⁵⁵²⁵⁵³⁵⁵⁴⁵⁵⁵⁵⁵⁶⁵⁵⁷⁵⁵⁸⁵⁵⁹⁵⁶⁰⁵⁶¹⁵⁶²⁵⁶³⁵⁶⁴⁵⁶⁵⁵⁶⁶⁵⁶⁷⁵⁶⁸⁵⁶⁹⁵⁷⁰⁵⁷¹⁵⁷²⁵⁷³⁵⁷⁴⁵⁷⁵⁵⁷⁶⁵⁷⁷⁵⁷⁸⁵⁷⁹⁵⁸⁰⁵⁸¹⁵⁸²⁵⁸³⁵⁸⁴⁵⁸⁵⁵⁸⁶⁵⁸⁷⁵⁸⁸⁵⁸⁹⁵⁹⁰⁵⁹¹⁵⁹²⁵⁹³⁵⁹⁴⁵⁹⁵⁵⁹⁶⁵⁹⁷⁵⁹⁸⁵⁹⁹⁶⁰⁰⁶⁰¹⁶⁰²⁶⁰³⁶⁰⁴⁶⁰⁵⁶⁰⁶⁶⁰⁷⁶⁰⁸⁶⁰⁹⁶¹⁰⁶¹¹⁶¹²⁶¹³⁶¹⁴⁶¹⁵⁶¹⁶⁶¹⁷⁶¹⁸⁶¹⁹⁶²⁰⁶²¹⁶²²⁶²³⁶²⁴⁶²⁵⁶²⁶⁶²⁷⁶²⁸⁶²⁹⁶³⁰⁶³¹⁶³²⁶³³⁶³⁴⁶³⁵⁶³⁶⁶³⁷⁶³⁸⁶³⁹⁶⁴⁰⁶⁴¹⁶⁴²⁶⁴³⁶⁴⁴⁶⁴⁵⁶⁴⁶⁶⁴⁷⁶⁴⁸⁶⁴⁹⁶⁵⁰⁶⁵¹⁶⁵²⁶⁵³⁶⁵⁴⁶⁵⁵⁶⁵⁶⁶⁵⁷⁶⁵⁸⁶⁵⁹⁶⁶⁰⁶⁶¹⁶⁶²⁶⁶³⁶⁶⁴⁶⁶⁵⁶⁶⁶⁶⁶⁷⁶⁶⁸⁶⁶⁹⁶⁷⁰⁶⁷¹⁶⁷²⁶⁷³⁶⁷⁴⁶⁷⁵⁶⁷⁶⁶⁷⁷⁶⁷⁸⁶⁷⁹⁶⁸⁰⁶⁸¹⁶⁸²⁶⁸³⁶⁸⁴⁶⁸⁵⁶⁸⁶⁶⁸⁷⁶⁸⁸⁶⁸⁹⁶⁹⁰⁶⁹¹⁶⁹²⁶⁹³⁶⁹⁴⁶⁹⁵⁶⁹⁶⁶⁹⁷⁶⁹⁸⁶⁹⁹⁷⁰⁰⁷⁰¹⁷⁰²⁷⁰³⁷⁰⁴⁷⁰⁵⁷⁰⁶⁷⁰⁷⁷⁰⁸⁷⁰⁹⁷¹⁰⁷¹¹⁷¹²⁷¹³⁷¹⁴⁷¹⁵⁷¹⁶⁷¹⁷⁷¹⁸⁷¹⁹⁷²⁰⁷²¹⁷²²⁷²³⁷²⁴⁷²⁵⁷²⁶⁷²⁷⁷²⁸⁷²⁹⁷³⁰⁷³¹⁷³²⁷³³⁷³⁴⁷³⁵⁷³⁶⁷³⁷⁷³⁸⁷³⁹⁷⁴⁰⁷⁴¹⁷⁴²⁷⁴³⁷⁴⁴⁷⁴⁵⁷⁴⁶⁷⁴⁷⁷⁴⁸⁷⁴⁹⁷⁵⁰⁷⁵¹⁷⁵²⁷⁵³⁷⁵⁴⁷⁵⁵⁷⁵⁶⁷⁵⁷⁷⁵⁸⁷⁵⁹⁷⁶⁰⁷⁶¹⁷⁶²⁷⁶³⁷⁶⁴⁷⁶⁵⁷⁶⁶⁷⁶⁷⁷⁶⁸⁷⁶⁹⁷⁷⁰⁷⁷¹⁷⁷²⁷⁷³⁷⁷⁴⁷⁷⁵⁷⁷⁶⁷⁷⁷⁷⁷⁸⁷⁷⁹⁷⁸⁰⁷⁸¹⁷⁸²⁷⁸³⁷⁸⁴⁷⁸⁵⁷⁸⁶⁷⁸⁷⁷⁸⁸⁷⁸⁹⁷⁹⁰⁷⁹¹⁷⁹²⁷⁹³⁷⁹⁴⁷⁹⁵⁷⁹⁶⁷⁹⁷⁷⁹⁸⁷⁹⁹⁸⁰⁰⁸⁰¹⁸⁰²⁸⁰³⁸⁰⁴⁸⁰⁵⁸⁰⁶⁸⁰⁷⁸⁰⁸⁸⁰⁹⁸¹⁰⁸¹¹⁸¹²⁸¹³⁸¹⁴⁸¹⁵⁸¹⁶⁸¹⁷⁸¹⁸⁸¹⁹⁸²⁰⁸²¹⁸²²⁸²³⁸²⁴⁸²⁵⁸²⁶⁸²⁷⁸²⁸⁸²⁹⁸³⁰⁸³¹⁸³²⁸³³⁸³⁴⁸³⁵⁸³⁶⁸³⁷⁸³⁸⁸³⁹⁸⁴⁰⁸⁴¹⁸⁴²⁸⁴³⁸⁴⁴⁸⁴⁵⁸⁴⁶⁸⁴⁷⁸⁴⁸⁸⁴⁹⁸⁵⁰⁸⁵¹⁸⁵²⁸⁵³⁸⁵⁴⁸⁵⁵⁸⁵⁶⁸⁵⁷⁸⁵⁸⁸⁵⁹⁸⁶⁰⁸⁶¹⁸⁶²⁸⁶³⁸⁶⁴⁸⁶⁵⁸⁶⁶⁸⁶⁷⁸⁶⁸⁸⁶⁹⁸⁷⁰⁸⁷¹⁸⁷²⁸⁷³⁸⁷⁴⁸⁷⁵⁸⁷⁶⁸⁷⁷⁸⁷⁸⁸⁷⁹⁸⁸⁰⁸⁸¹⁸⁸²⁸⁸³⁸⁸⁴⁸⁸⁵⁸⁸⁶⁸⁸⁷⁸⁸⁸⁸⁸⁹⁸⁹⁰⁸⁹¹⁸⁹²⁸⁹³⁸⁹⁴⁸⁹⁵⁸⁹⁶⁸⁹⁷⁸⁹⁸⁸⁹⁹⁹⁰⁰⁹⁰¹⁹⁰²⁹⁰³⁹⁰⁴⁹⁰⁵⁹⁰⁶⁹⁰⁷⁹⁰⁸⁹⁰⁹⁹¹⁰⁹¹¹⁹¹²⁹¹³⁹¹⁴⁹¹⁵⁹¹⁶⁹¹⁷⁹¹⁸⁹¹⁹⁹²⁰⁹²¹⁹²²⁹²³⁹²⁴⁹²⁵⁹²⁶⁹²⁷⁹²⁸⁹²⁹⁹³⁰⁹³¹⁹³²⁹³³⁹³⁴⁹³⁵⁹³⁶⁹³⁷⁹³⁸⁹³⁹⁹⁴⁰⁹⁴¹⁹⁴²⁹⁴³⁹⁴⁴⁹⁴⁵⁹⁴⁶⁹⁴⁷⁹⁴⁸⁹⁴⁹⁹⁵⁰⁹⁵¹⁹⁵²⁹⁵³⁹⁵⁴⁹⁵⁵⁹⁵⁶⁹⁵⁷⁹⁵⁸⁹⁵⁹⁹⁶⁰⁹⁶¹⁹⁶²⁹⁶³⁹⁶⁴⁹⁶⁵⁹⁶⁶⁹⁶⁷⁹⁶⁸⁹⁶⁹⁹⁷⁰⁹⁷¹⁹⁷²⁹⁷³⁹⁷⁴⁹⁷⁵⁹⁷⁶⁹⁷⁷⁹⁷⁸⁹⁷⁹⁹⁸⁰⁹⁸¹⁹⁸²⁹⁸³⁹⁸⁴⁹⁸⁵⁹⁸⁶⁹⁸⁷⁹⁸⁸⁹⁸⁹⁹⁹⁰⁹⁹¹⁹⁹²⁹⁹³⁹⁹⁴⁹⁹⁵⁹⁹⁶⁹⁹⁷⁹⁹⁸⁹⁹⁹⁹⁹⁹⁹

Steven R. Majewski¹, Ricardo P. Schiavon^{2,3}, Peter M. Frinchaboy⁴, Carlos Allende

APOGEE at a Glance

- Dual hemisphere spectroscopic survey of MW stellar populations
- Bright time SDSS-III/IV survey, 2011.Q2 to 2020.Q2
- Two *300 fiber*, $R \approx 22,500$, cryogenic spectrographs, large FOV
- H -band: 1510 – 1690 nm ($A_H/A_V \sim 1/6$)
- Typical $S/N = 100/\text{pixel}$ @ $H=12.2$ for 3-hr integration
- RV uncertainty spec < 500 m/s in 3 hr *Actual < 100 m/s in 1hr*
- Precision abundances for ≈ 20 *chemical elements* (including C, N, O, Fe, other α , odd-Z, a few neutron-capture)
- 5×10^5 , predominantly *giant stars*, probing *all Galactic populations, and those of their Local Group counterparts*

2.5 m SDSS telescope at
Apache Point Observatory



2.5 m du Pont telescope at Las
Campanas Observatory



The APOGEE-N
spectrograph

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Why APOGEE makes a difference

High resolution

*

Near Infrared

*

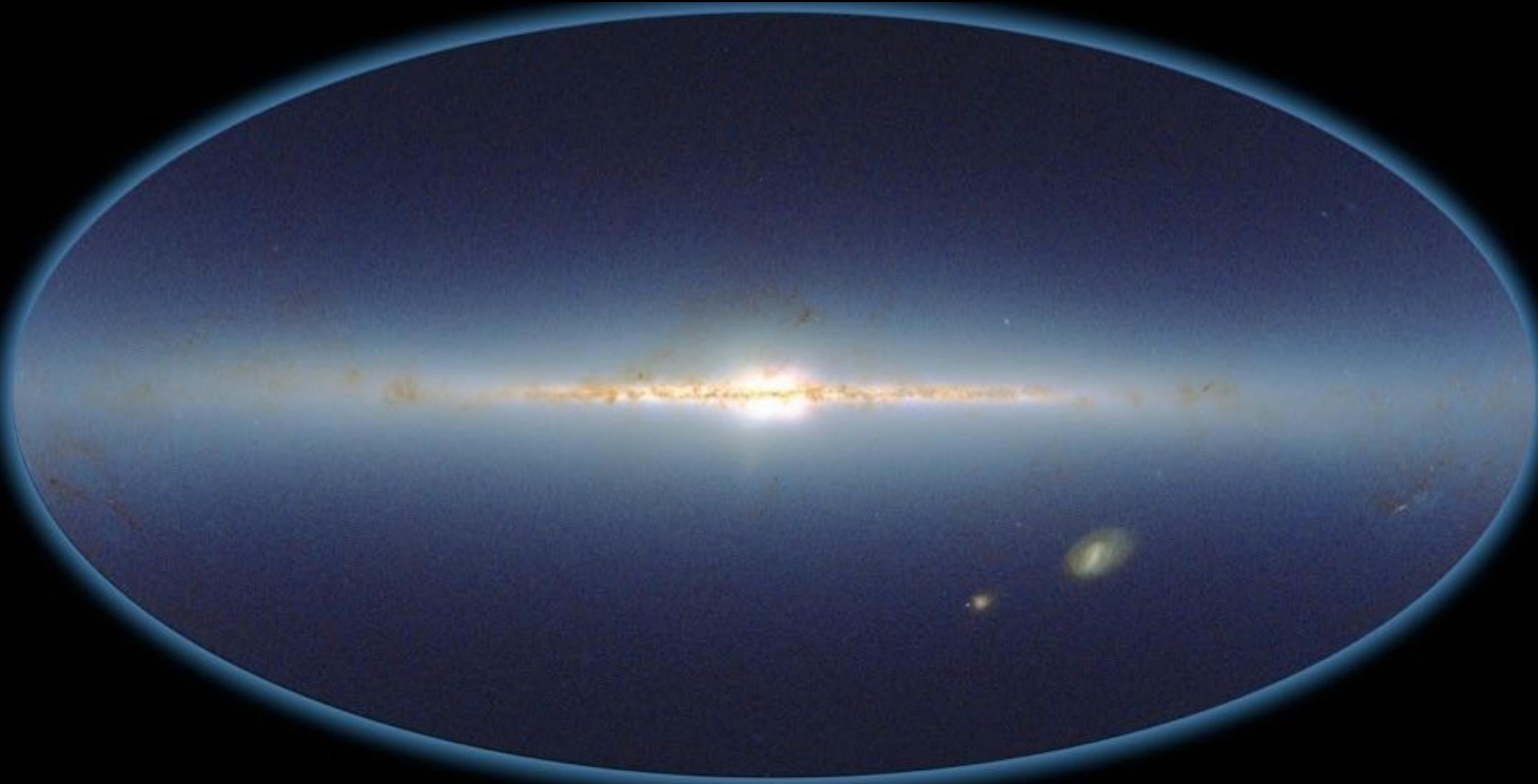
4-5x10⁵ giant stars

Optical Sky



© 2009 Axel Mellinger

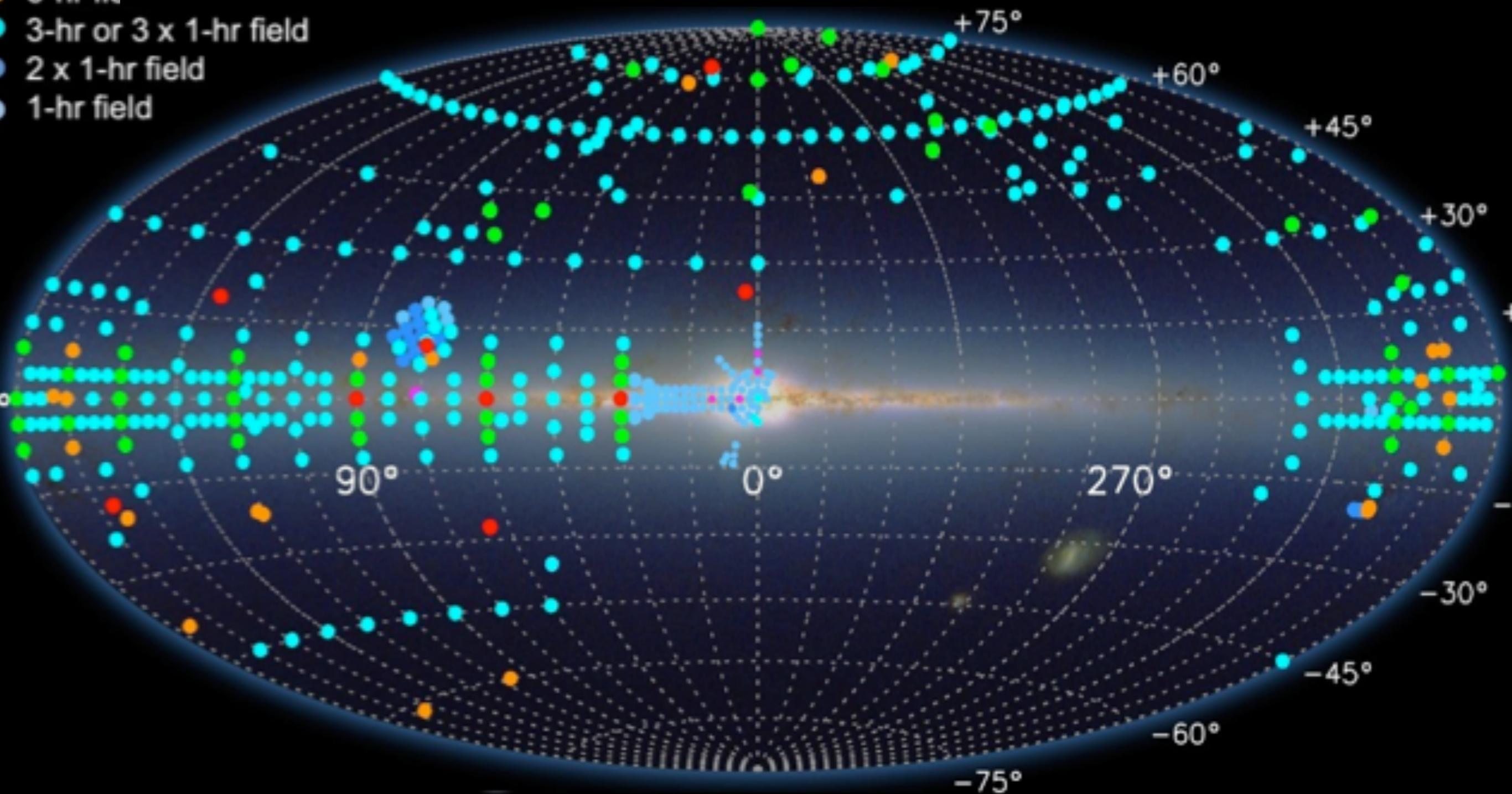
Near-Infrared Sky



The Two Micron All Sky Survey
Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

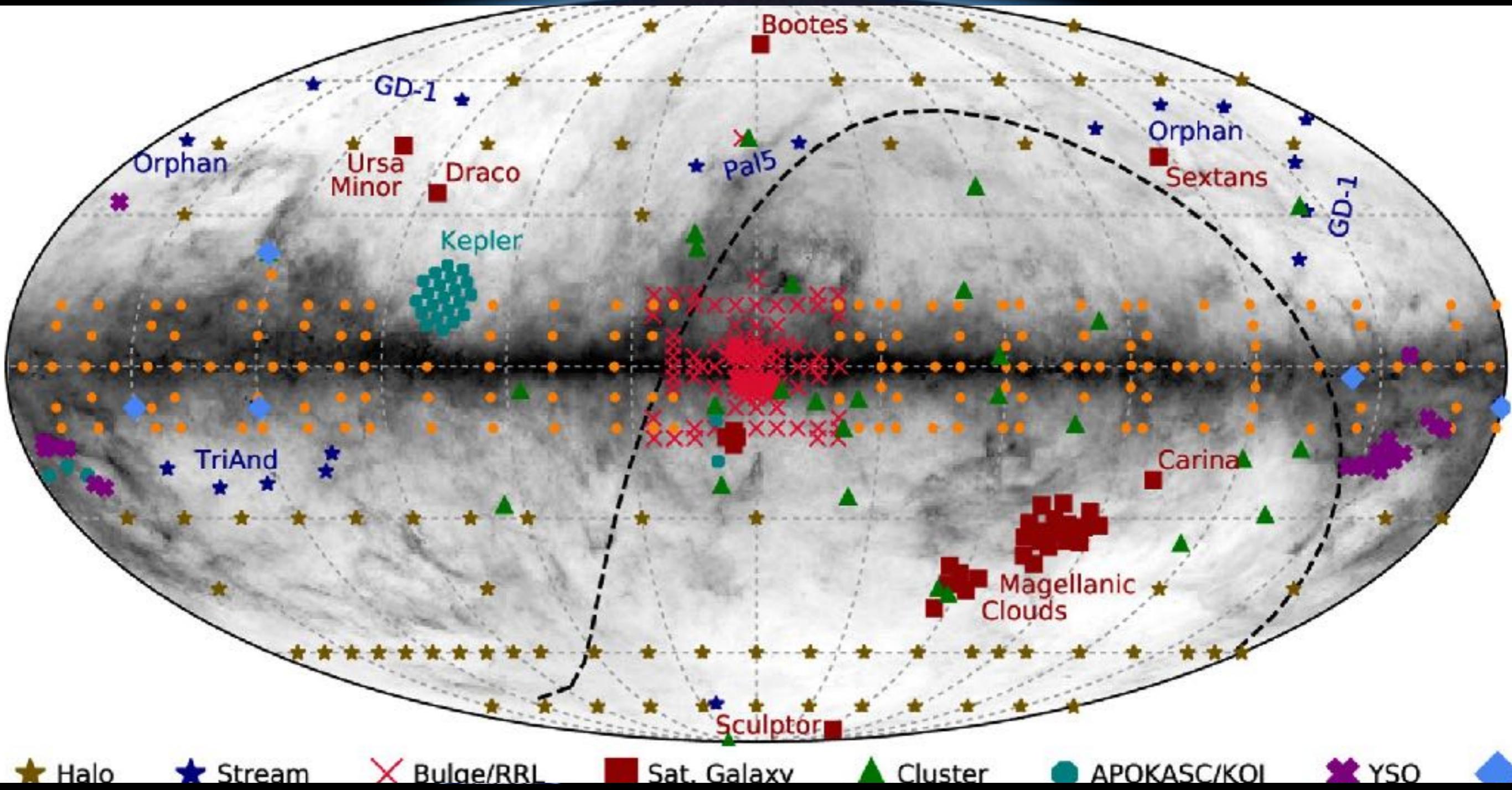
Comm
24-hr f
12-hr f
6-hr fie
3-hr or 3 x 1-hr field
2 x 1-hr field
1-hr field

APOGEE Footprint



APOGEE DR12 coverage

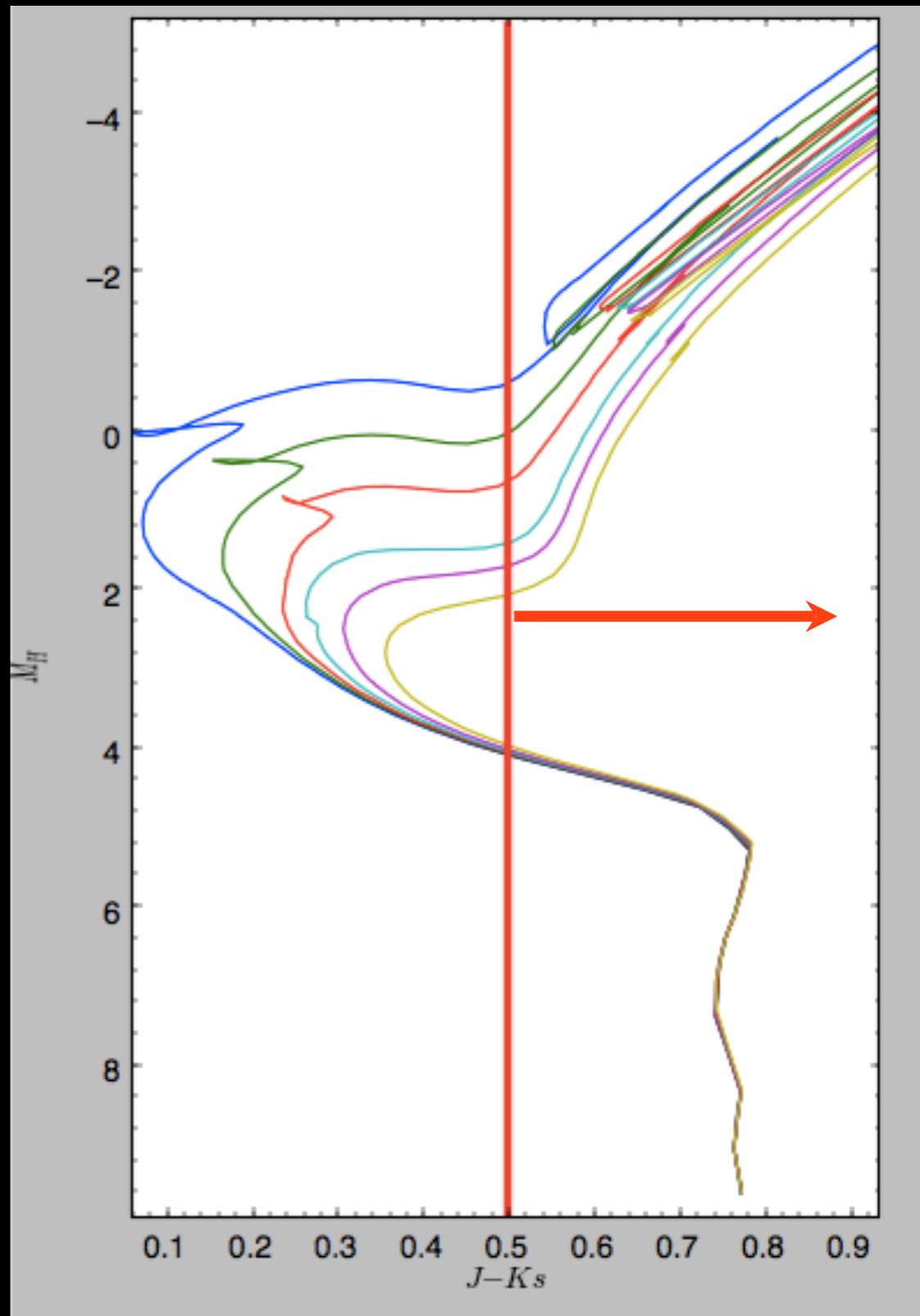
APOGEE 2 Footprint



APOGEE 2 Field plan - Zasowski et al. (2017)

Target Selection

- Main sample is selected from 2MASS (MIR from Spitzer and WISE for dereddening)
- $(J-K)_0 \geq 0.5, 7 < H < 13.8 \Rightarrow$ giants (RGB, AGB, RC) are 80% of the sample
- Open and globular clusters targeted for science and calibration purposes
- Ancillary science programs cover a variety of science targets (young Galactic clusters, M dwarfs, M31 GCs in integrated light)
- For details, see Zasowski et al. (2013,



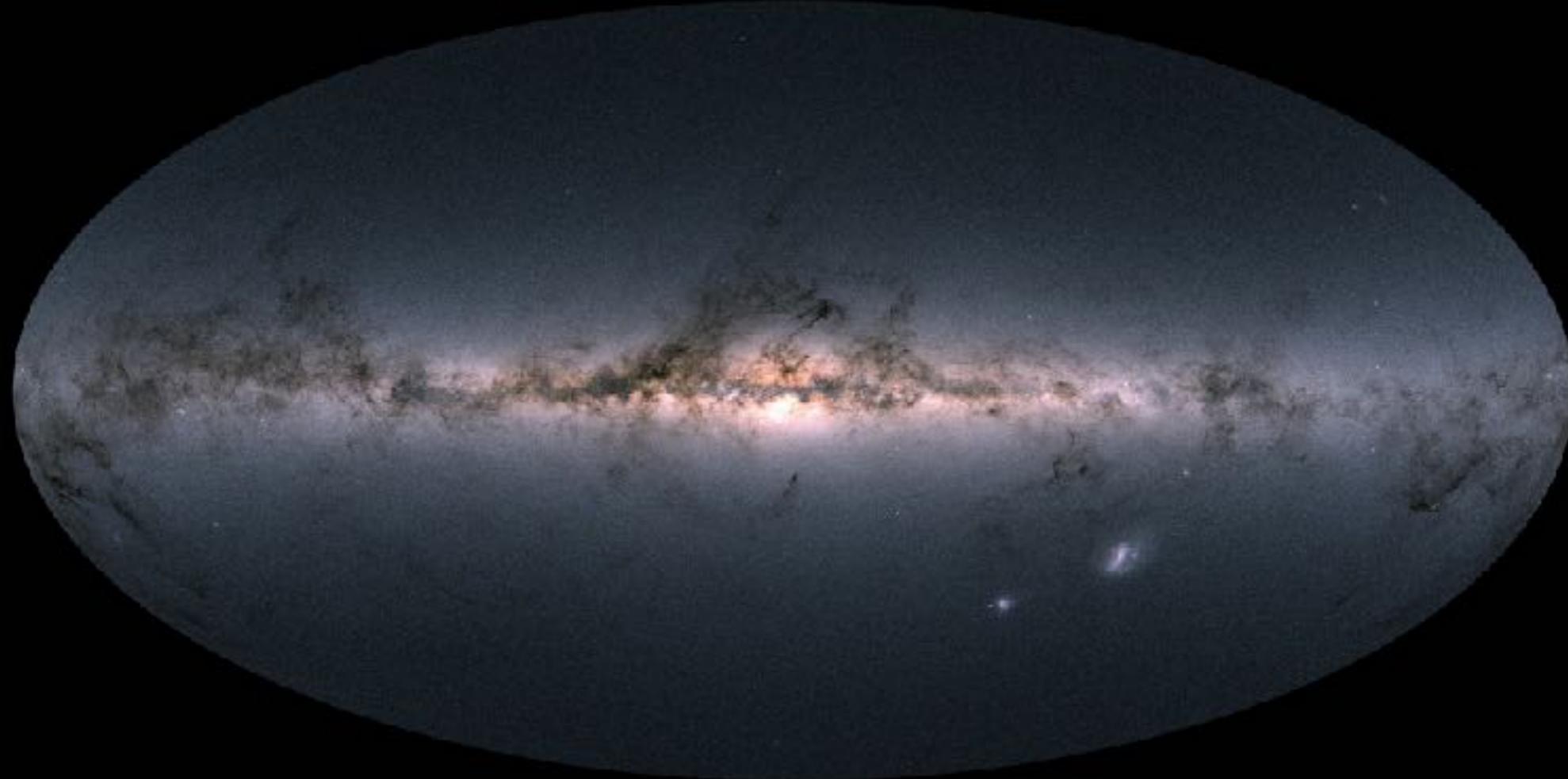
APOGEE Scientific Footprint

- Galactic Archaeology
- Local Group galaxies
- Stars
- Stellar Clusters
- Interstellar Medium
- Sub-stellar Companions
- Spectral Analysis

APOGEE Scientific Footprint

- Galactic Archaeology
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- 
- Disk
Bulge
Halo

Galactic Archaeology



The Questions:

- What is the current “structure” of the Galaxy?
- What was the history leading up to it?
- What does that teach us about galaxy formation

Galactic Archaeology



The Questions:

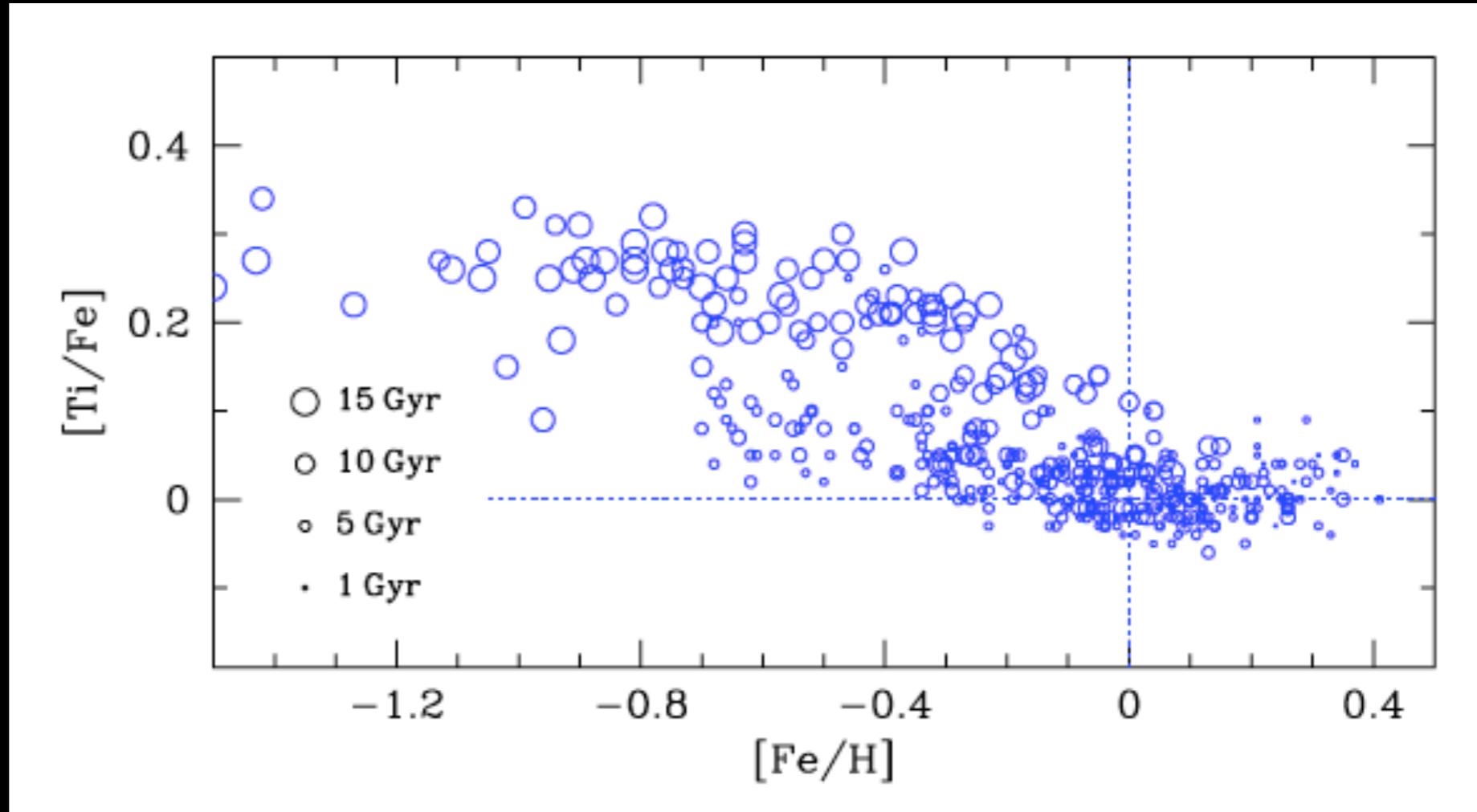
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Is the Galaxy a typical galaxy?

The Nearby Stellar Disk

Bensby et al. 2014

- Precision abundances for 714 F-G dwarfs
- $R = 40,000\text{-}110,000$
- Solar neighborhood

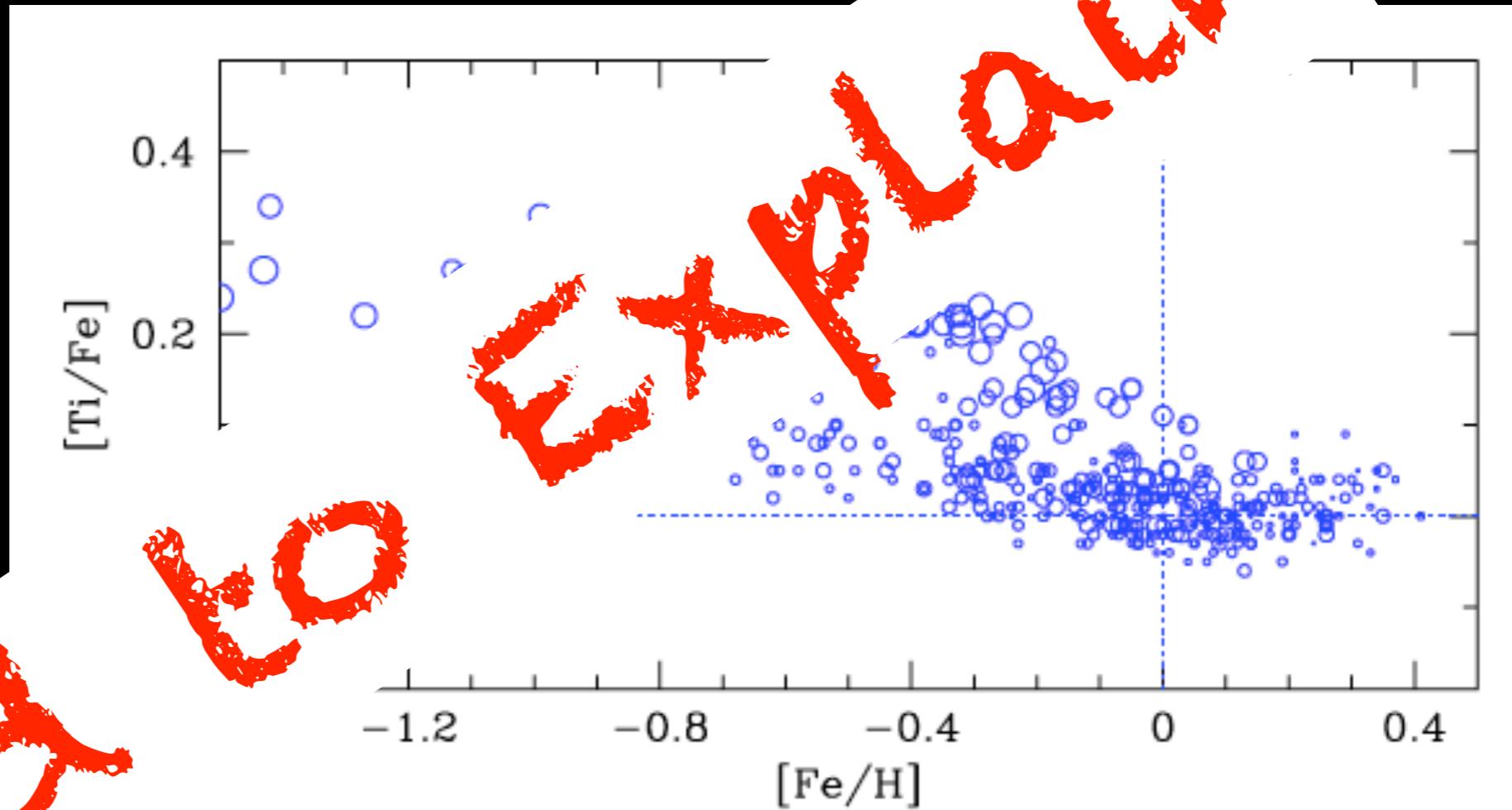


- A bimodal distribution in $[\alpha/\text{Fe}]$ (at constant $[\text{Fe}/\text{H}]$)
- High α stars older, higher z_{MAX} , shorter $R_{\text{MEAN}} \Rightarrow$ Inner (thick) disk
- Low α stars younger, lower z_{MAX} , longer $R_{\text{MEAN}} \Rightarrow$ reach Outer disk

The Nearby Stellar Disk

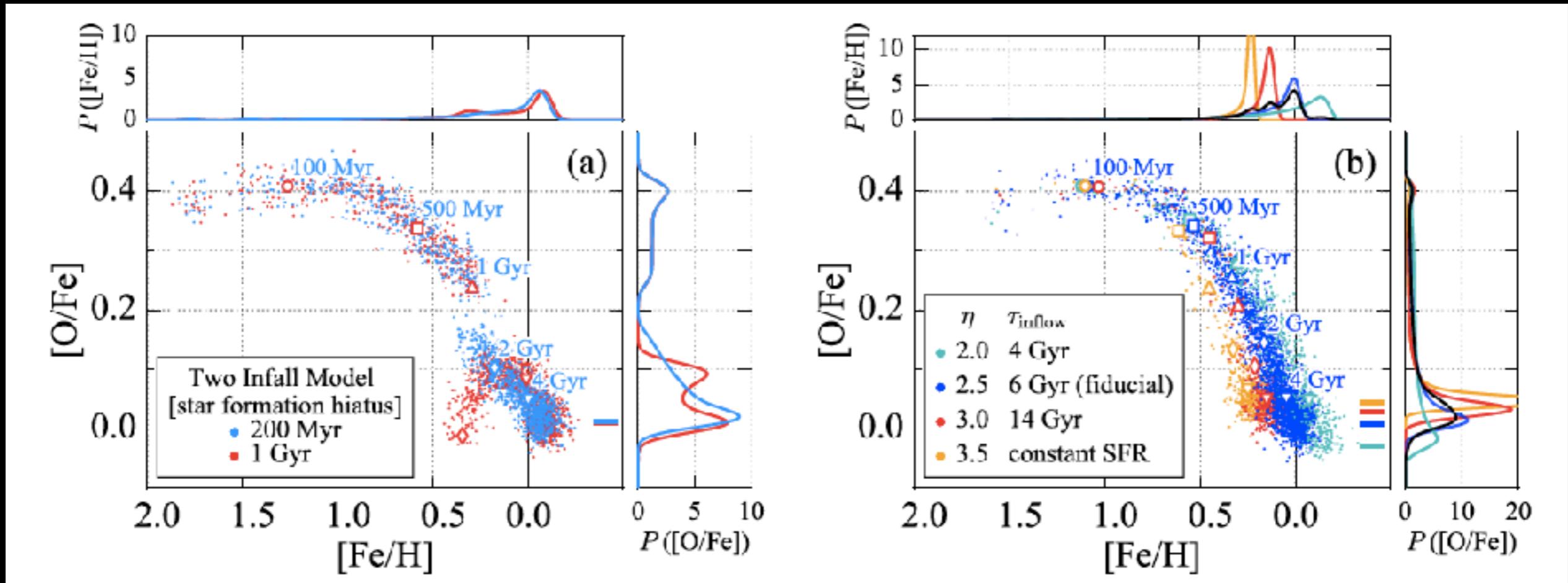
Bensby et al. 2014

- Precision abundances for 714 F-G dwarfs
- $R = 40,000\text{-}110,000$
- Solar neighborhood



- A **blue** **HOT** **band** in $[\alpha/{\rm Fe}]$ (at constant $[{\rm Fe}/{\rm H}]$)
- High α stars older, higher z_{MAX} , shorter $R_{\text{MEAN}} \Rightarrow$ Inner (thick) disk
- Low α stars younger, lower z_{MAX} , longer $R_{\text{MEAN}} \Rightarrow$ reach Outer disk

“Reverse Engineering” Disk Formation

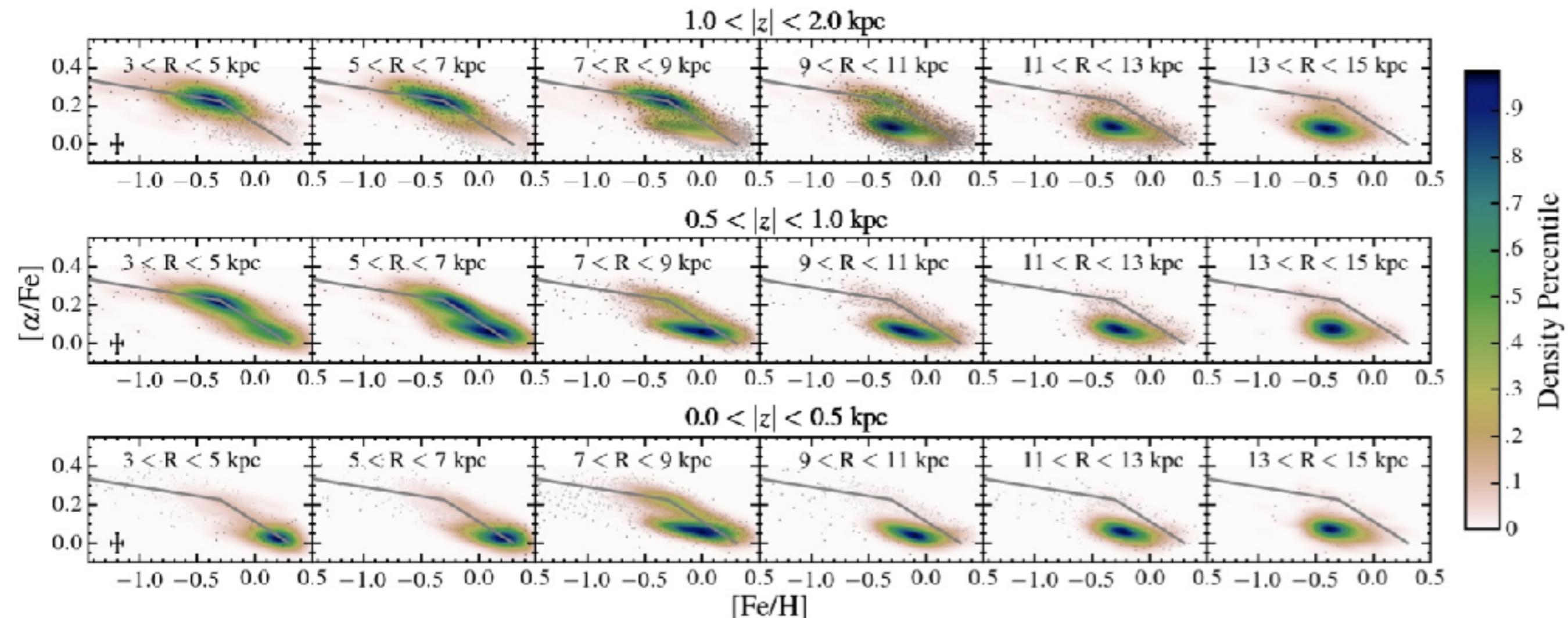


Andrews et al. 2017

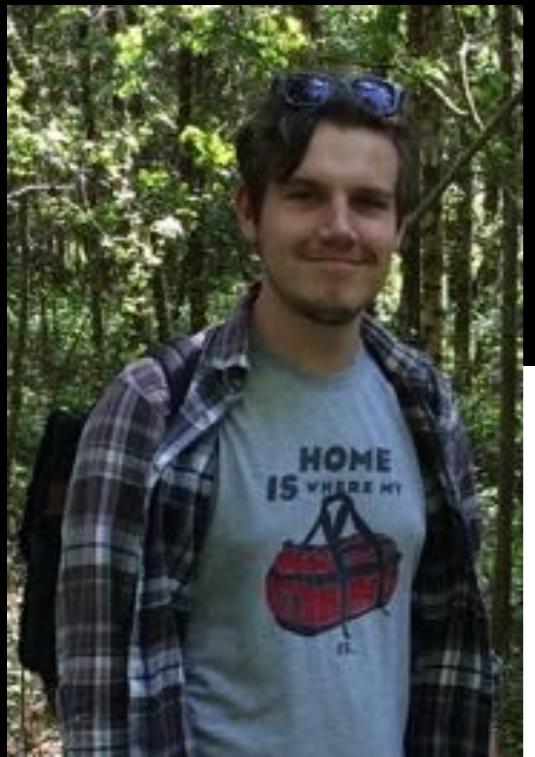
- Devise SFH and chemical enrichment history to produce observations
- Two-infall model (Chiappini et al. 2001), radial migrations (e.g., Schönrich & Binney 2009, Loebman et al. 2011)
- Match data for solar neighborhood with varying degree of success

The Disk According to APOGEE

Hayden et al. 2015

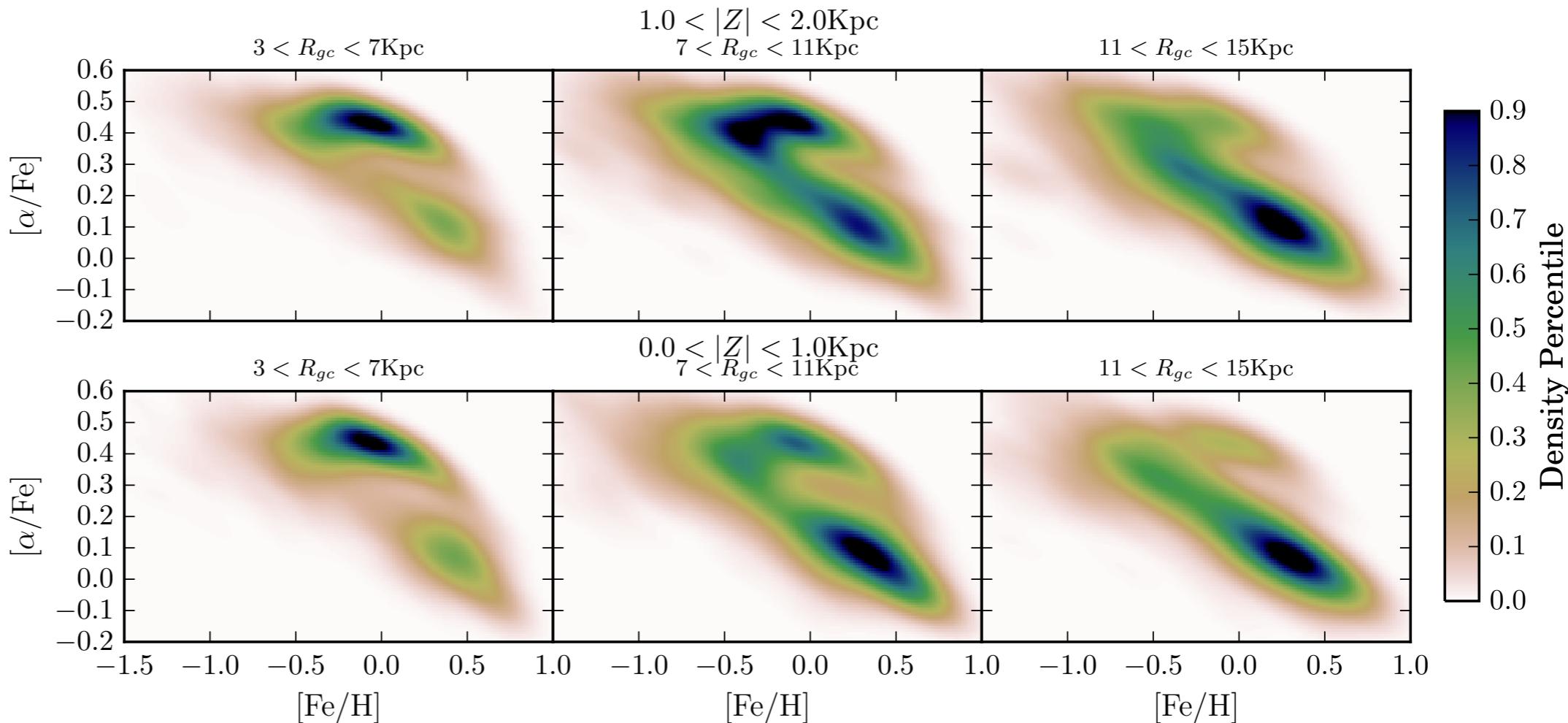


- Study [Fe/H] and [α/Fe] for ~70,000 stars along RGB
- Data from DR12. Note bimodal [α/Fe].
- $3 < R_{\text{GC}} < 15 \text{ kpc}, |z| < 2 \text{ kpc}$
- See also Hasselquist et al. (2018)



APOGEE vs EAGLE

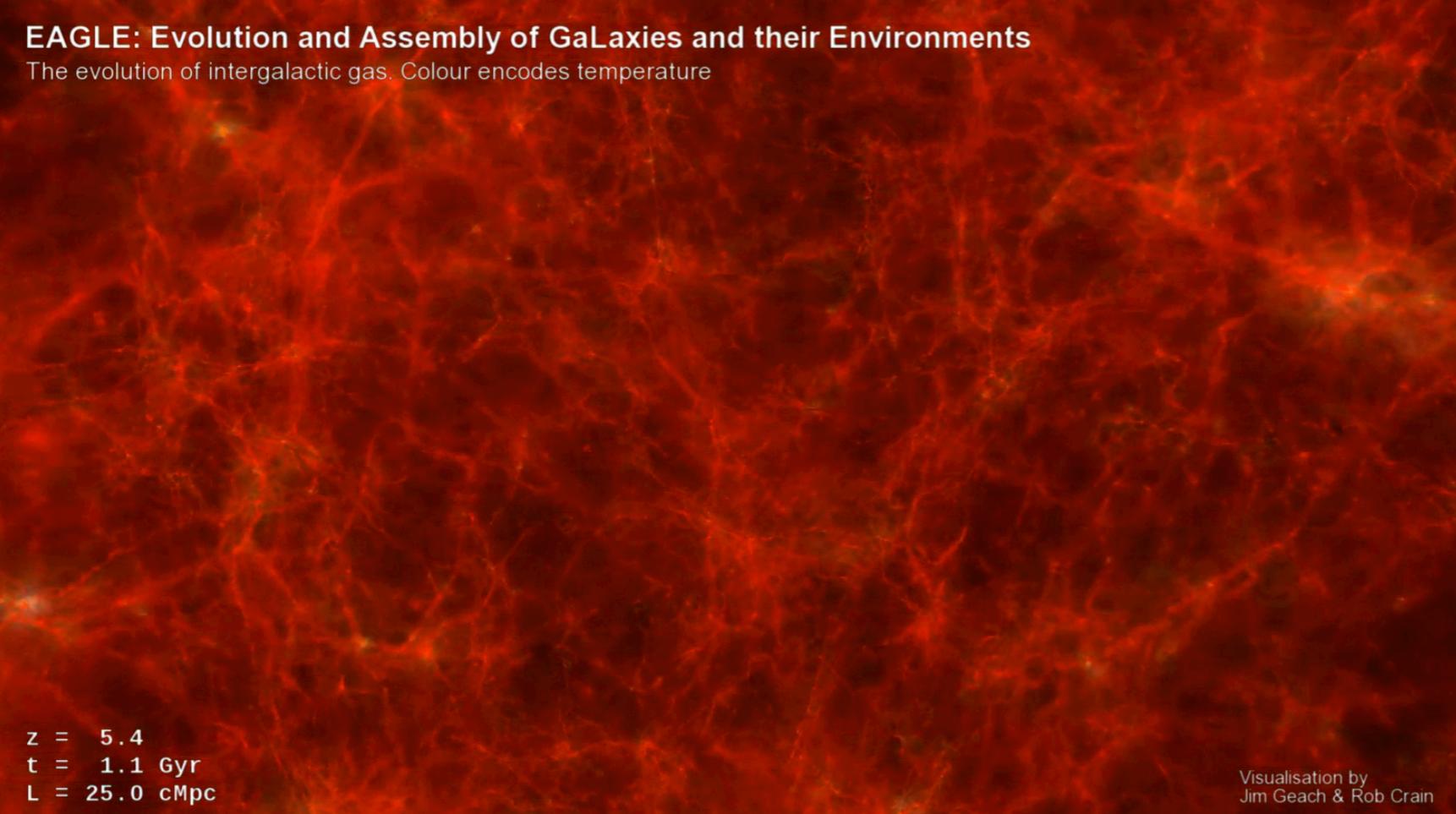
Mackereth, Crain, Schiavon



- Understanding bimodality in light of state-of-the-art cosmological numerical simulations
- Some MW-like galaxies show bimodality in the simulations

EAGLE: Evolution and Assembly of GaLaxies and their Environments

The evolution of intergalactic gas. Colour encodes temperature



The EAGLE project

Schaye+ 2015, Crain+2015

Cosmological simulations
of the galaxy population.

Unknown feedback
efficiencies **calibrated** to
reproduce observables.

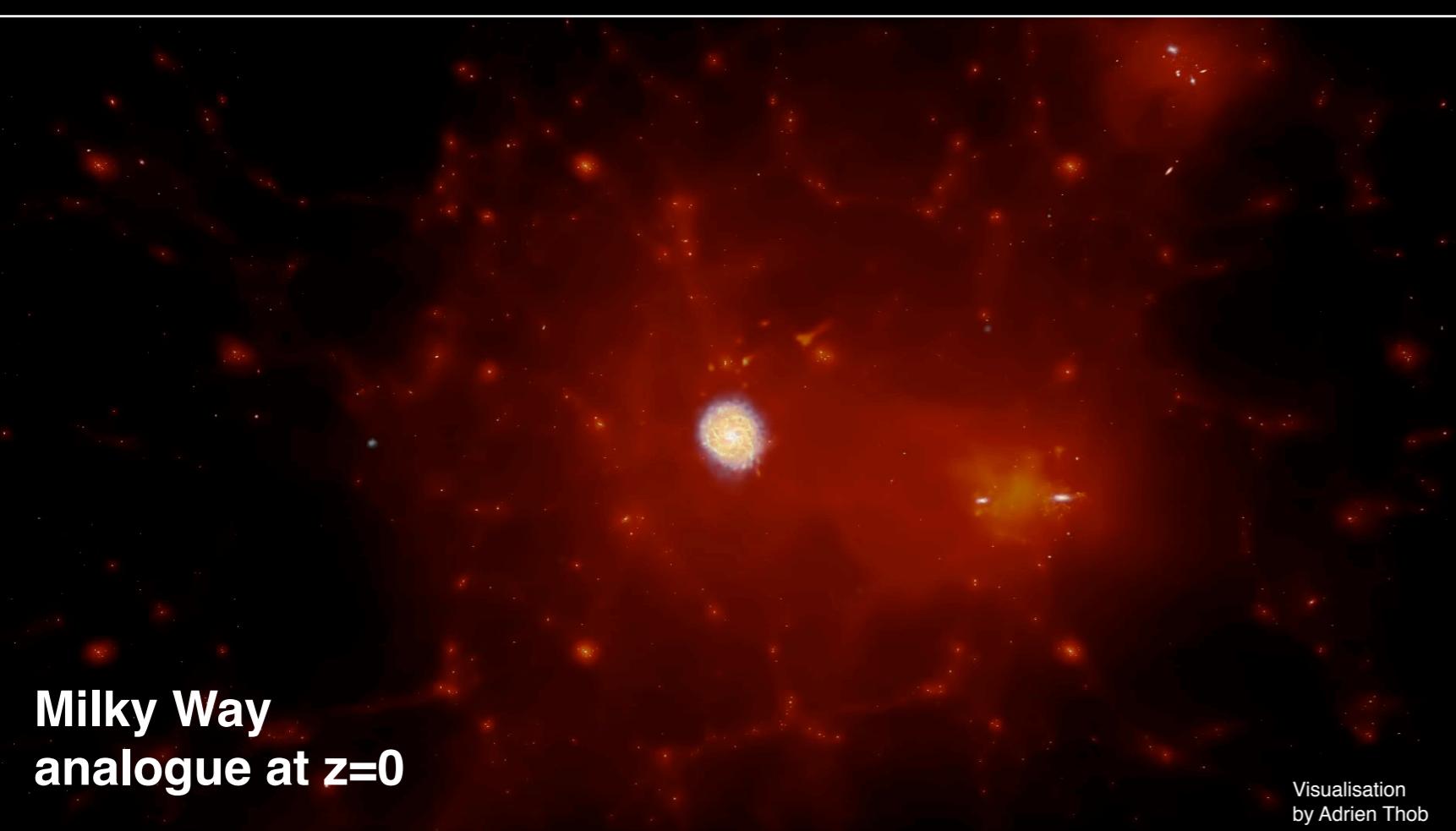
Largest run is a cubic
volume of $L=100$ cMpc

$\sim 200 \sim L^*$ galaxies, each
with 10,000 star particles.

Diverse formation
histories & environments

Abundances of 9 metal
species tracked, from:

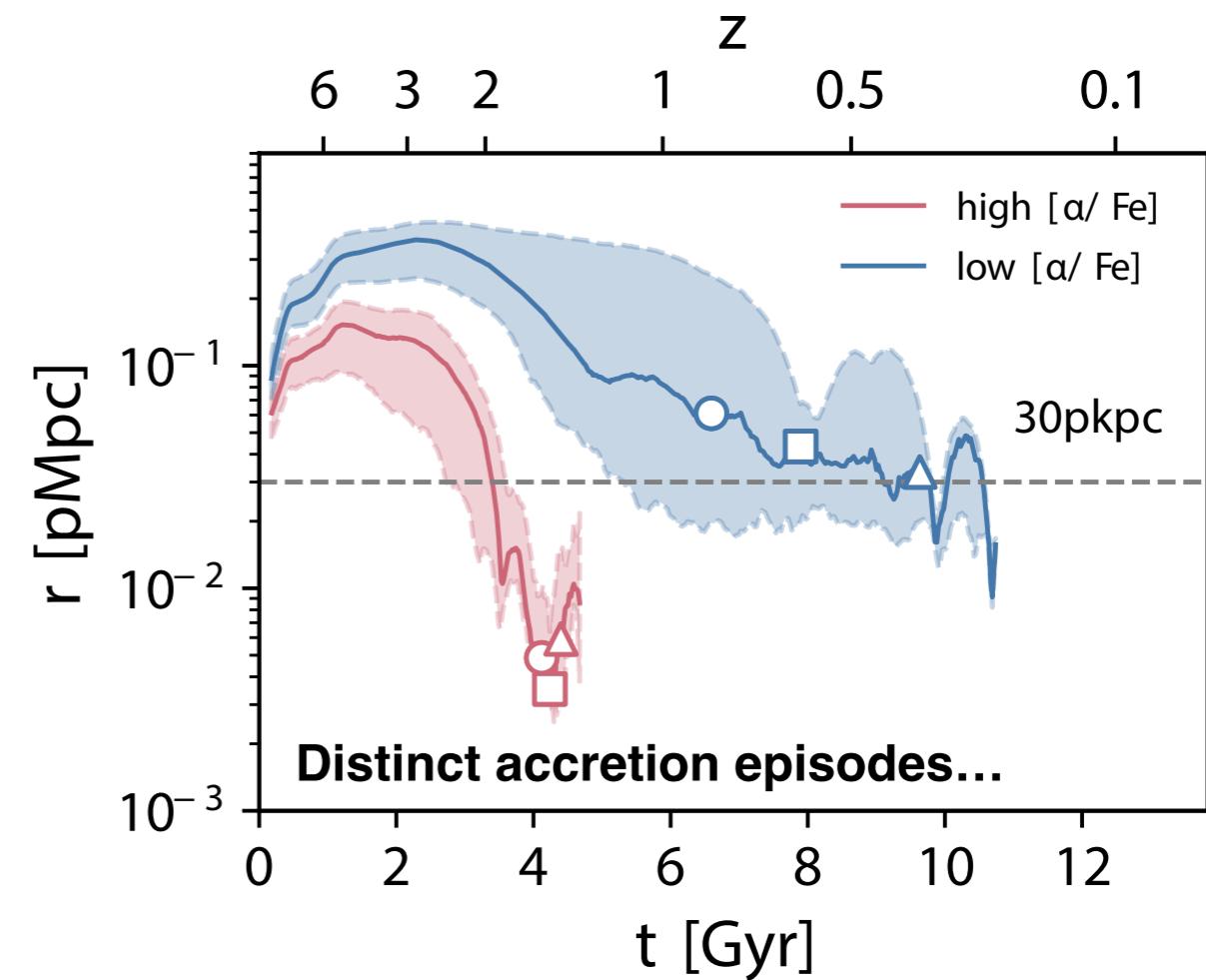
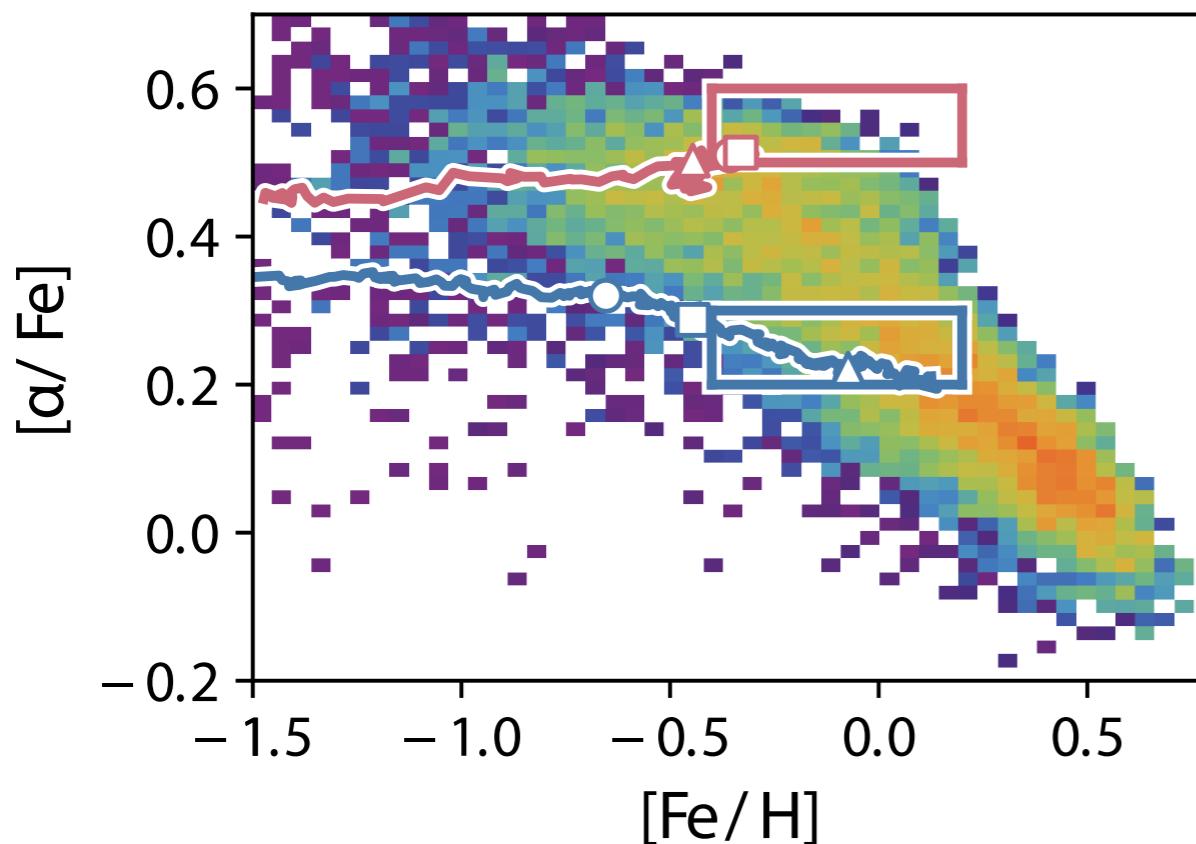
- AGB stars
- Type Ia SNe
- Type II SNe



Origin of high-/low- α according to EAGLE cosmological simulations

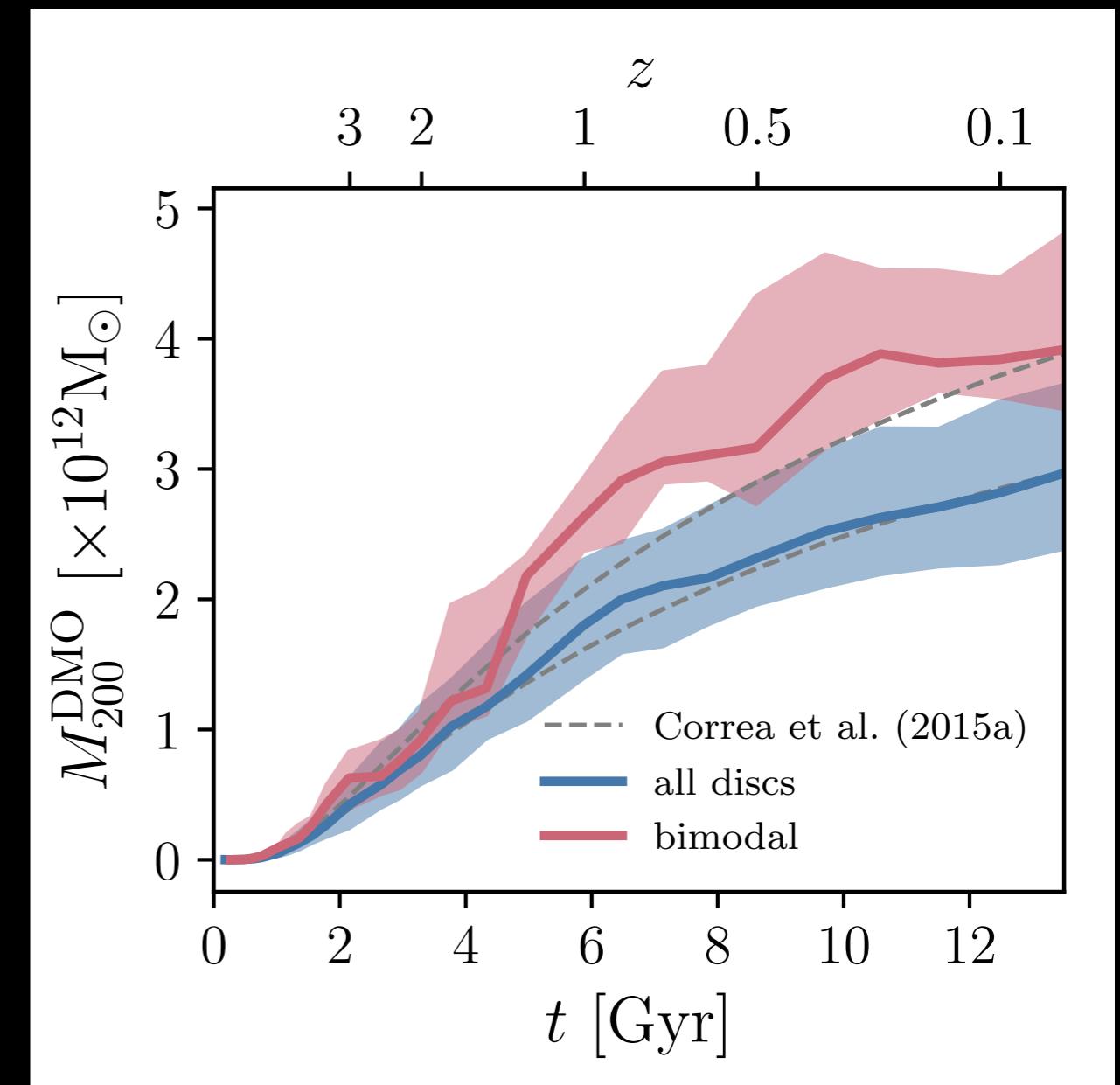
Mackereth, Crain, Schiavon, et al. (2018)

- High- and low- α populations evolve in chemical isolation
- No need to concoct schemes to explain chemical evolution



Accretion History

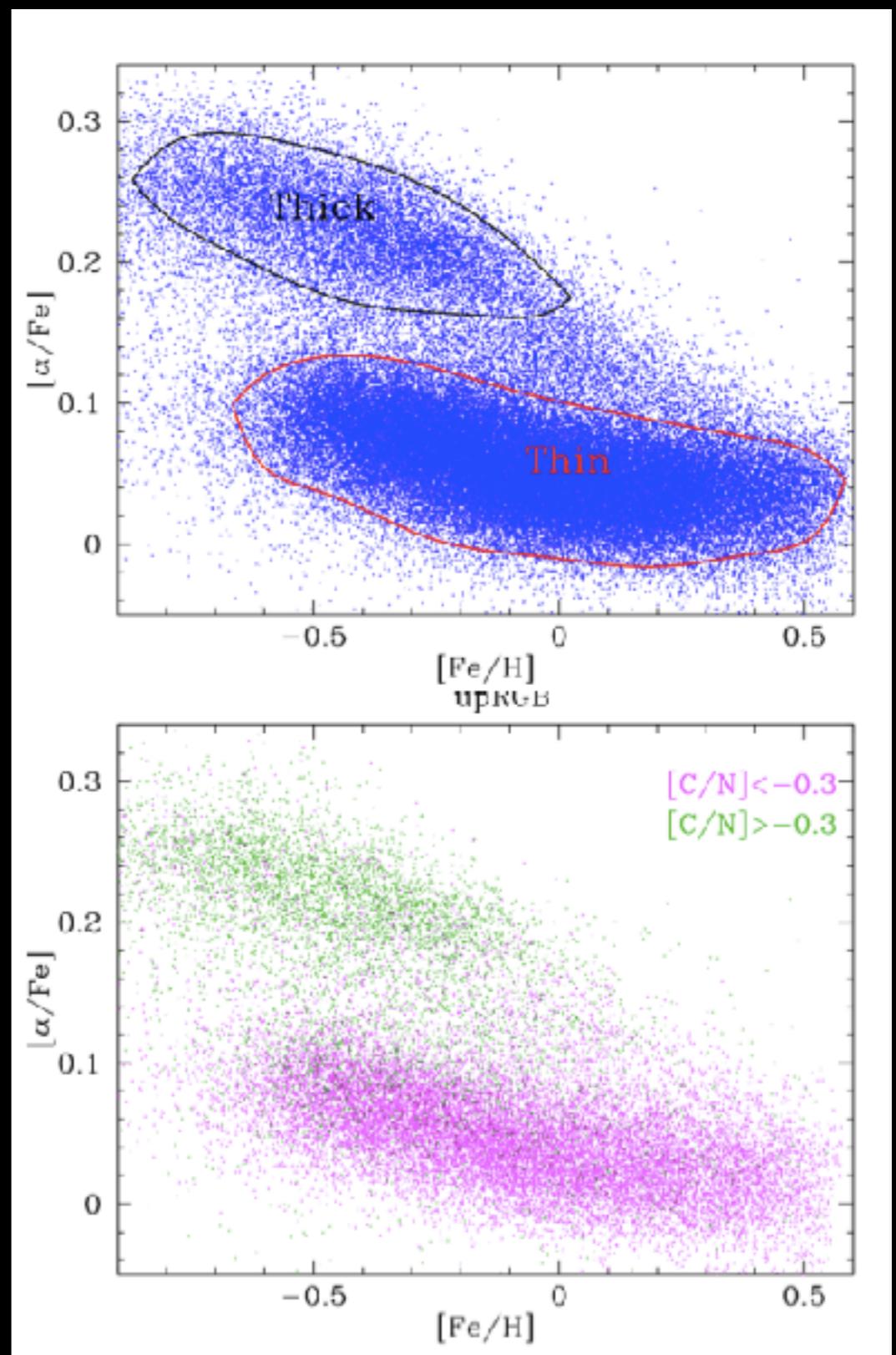
- Only 6/133 MW-like galaxies in EAGLE show bimodal $[\alpha/\text{Fe}]$ distributions
- The phenomenon seems to be associated with intense accretion activity at $1 < z < 2$
- The Milky Way may be a rare MW-like galaxy



Mackereth, Crain, Schiavon et al. (2018)

C/N and Mass of RGB stars

- High- α /thick disk and low- α /thin disk stars have markedly different [C/N] ratios
- This is a by-product of a combination of stellar evolution (mixing), chemical evolution (weakly) and *stellar mass*
- The mass of an RGB star is directly related to its age!



Masseron & Gilmore (2015)

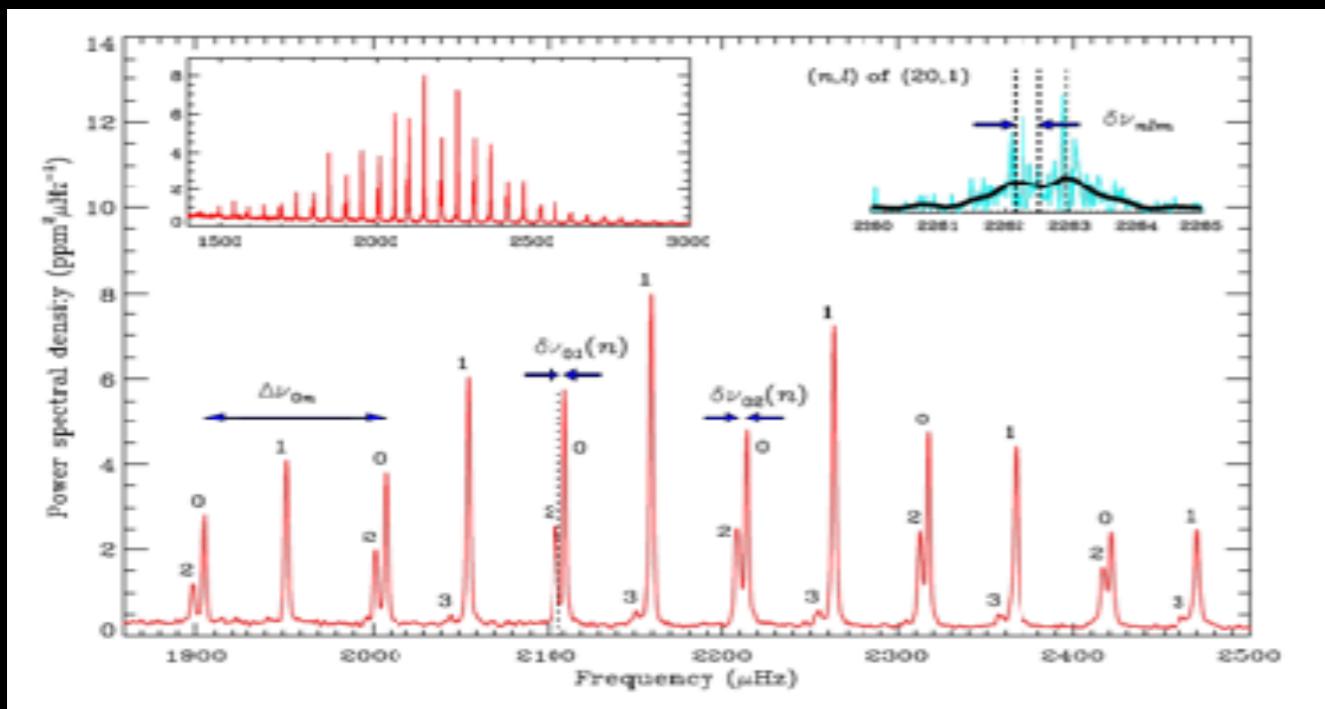
RGB masses from asteroseismology

Scaling Relations
+ Spectroscopy
= Mass and Age

$$\Delta\nu^2 \sim M/R^3$$

$$v_{\max} \sim M/R^2 T^{-1/2}$$

=> Can Solve For M and R



$$\frac{M}{M_\odot} \approx \left(\frac{\nu_{\max}}{\nu_{\max,\odot}} \right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot} \right)^{-4} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{3/2}$$
$$\frac{R}{R_\odot} \approx \left(\frac{\nu_{\max}}{\nu_{\max,\odot}} \right) \left(\frac{\Delta\nu}{\Delta\nu_\odot} \right)^{-2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{1/2}.$$

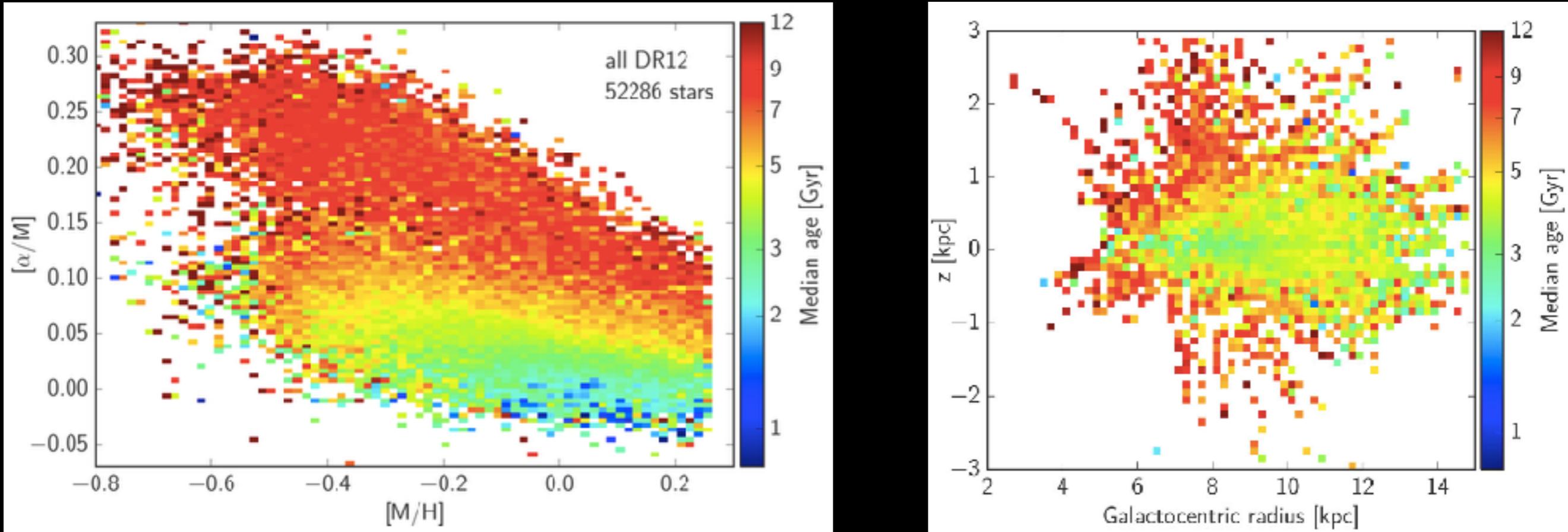
“Scaling Relations”

16 Cyg A Metcalfe+ 2012

See Pinsonneault et al. (2018), Epstein et al. (2014)

Ages of field stars

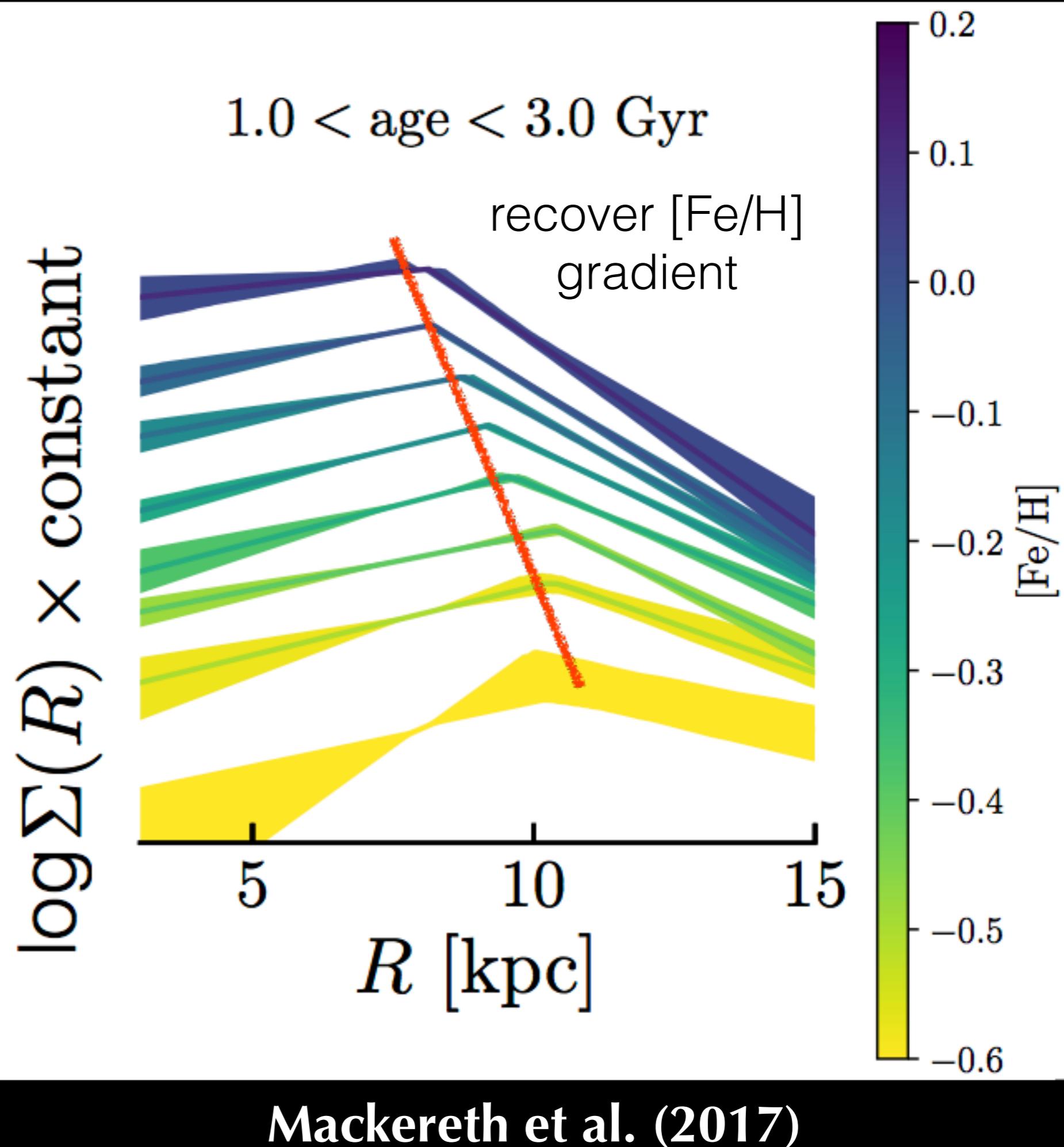
Martig et al. (2016)



- Use APOKASC sample to fit relation between Mass and [C/N] for fixed stellar parameters
- Invert relation to estimate masses (thus ages) for 52,000 stars
- High- α stars ~8-11 Gyr old. Interesting pattern in thin disk.
- Spatial distribution interesting, not corrected for selection function
- See also Ness et al. (2016)

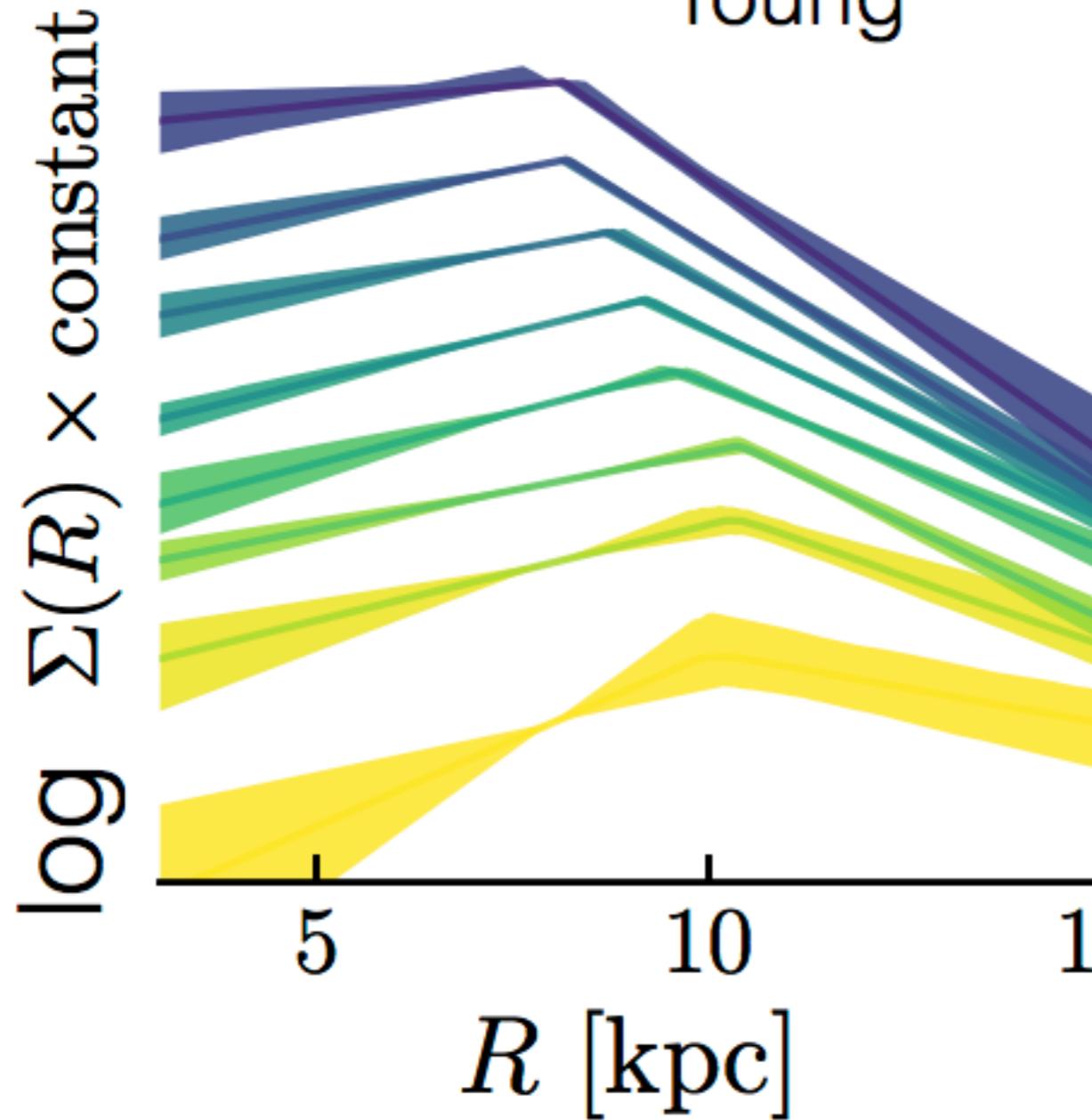
Low [a/Fe],
youngest
populations

Clear broken
exponential



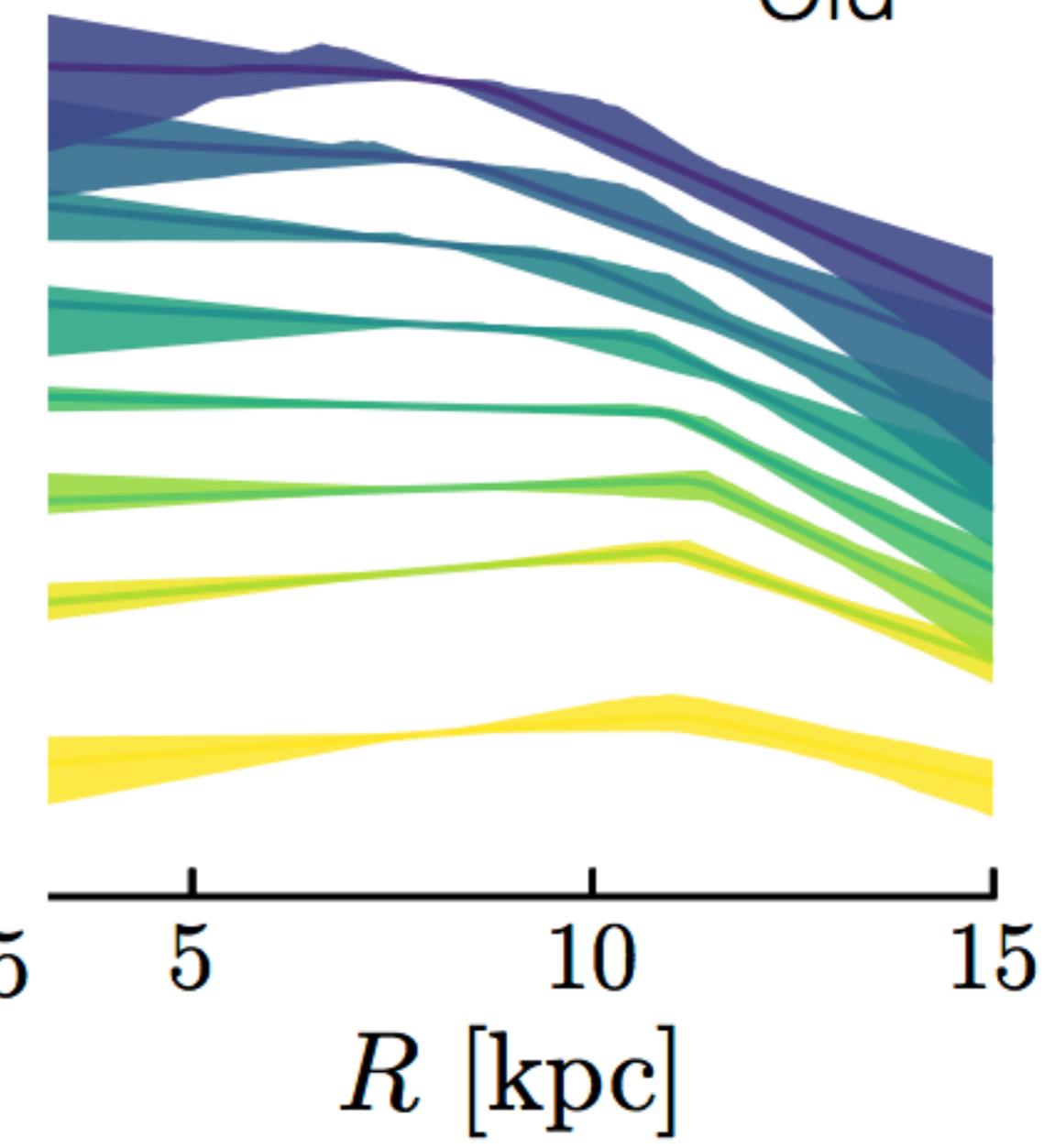
$1.0 < \text{age} < 3.0 \text{ Gyr}$

Young



$7.0 < \text{age} < 9.0 \text{ Gyr}$

Old



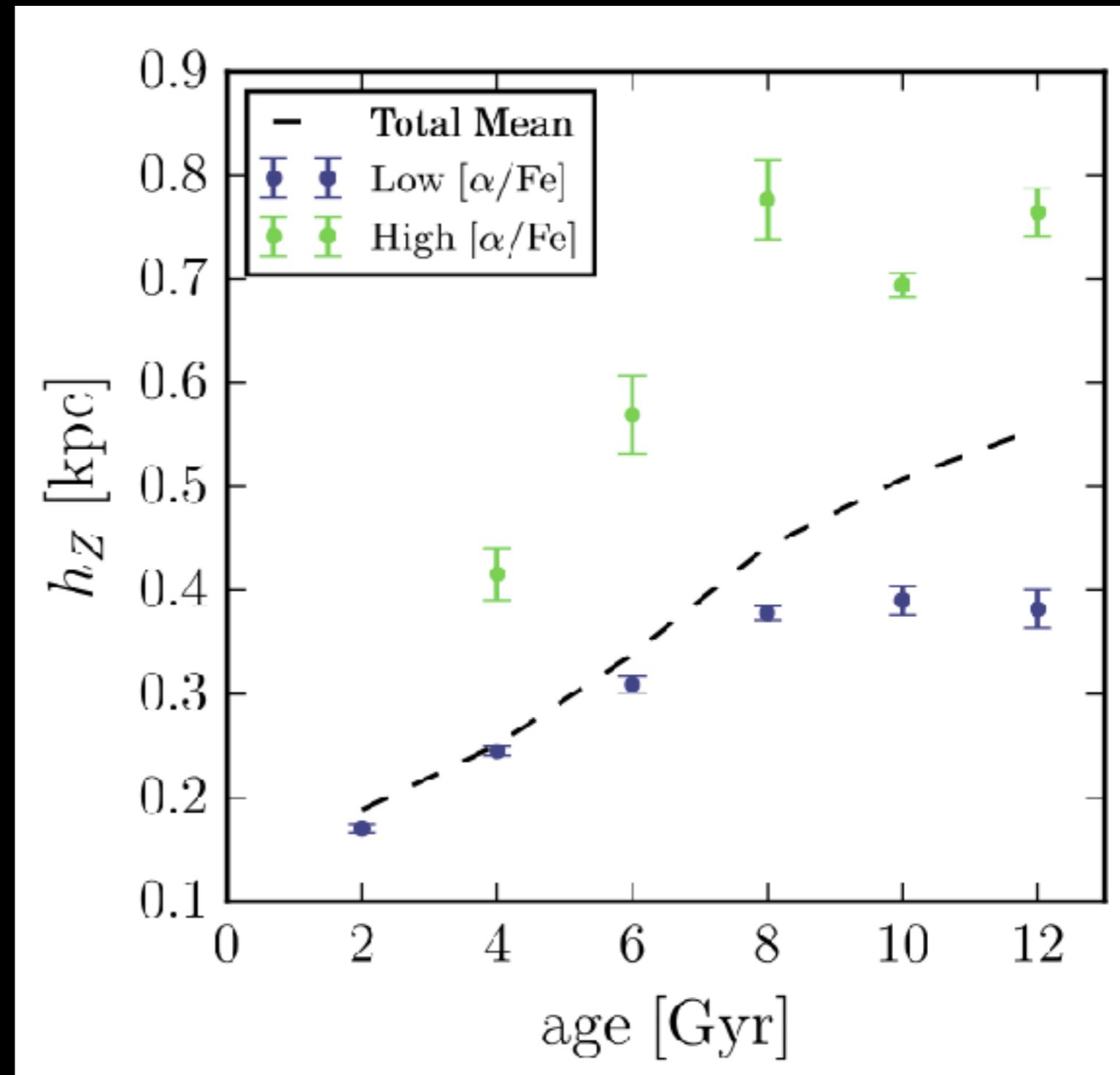
Profiles broaden
with age

Timescale of radial migration / disk heating?

Evolution of disk scale-height, h_z

Scale-height of both
high- and low- α disks
in solar annulus
evolved steadily with
time

Fundamental
constraint on models
for the formation of
the thick disk



$1 < |z| < 1.5 \text{ kpc}$

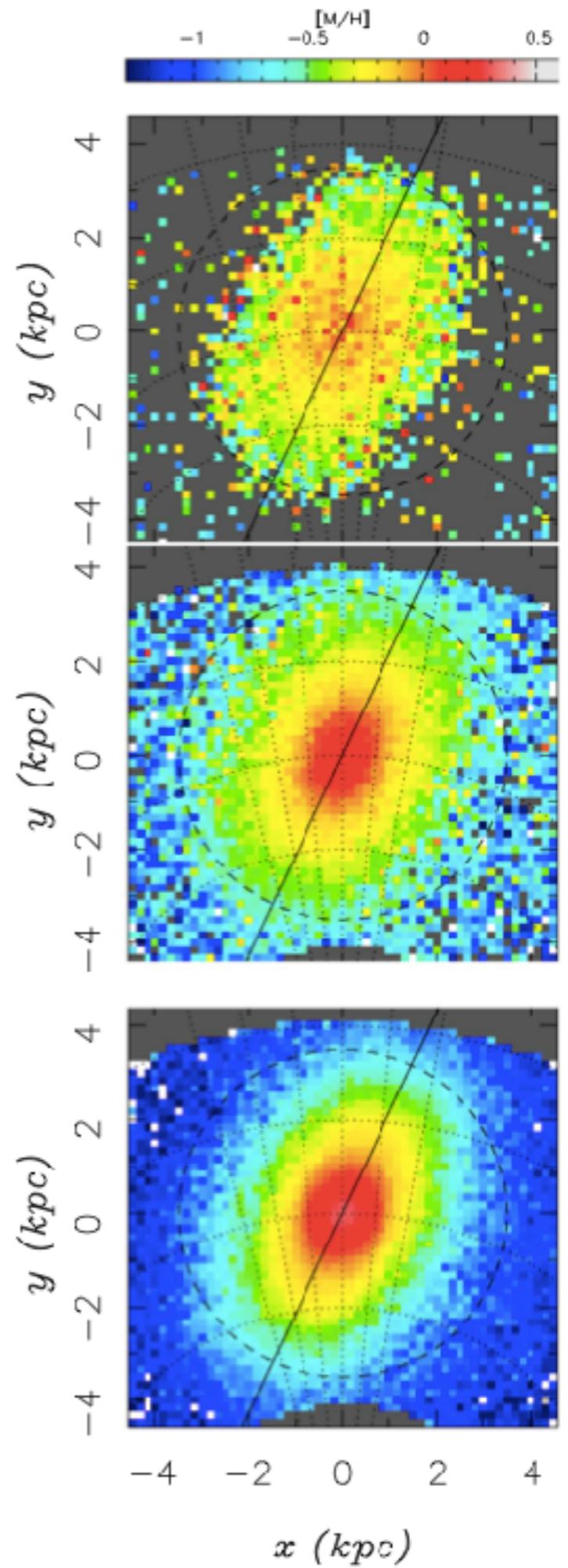
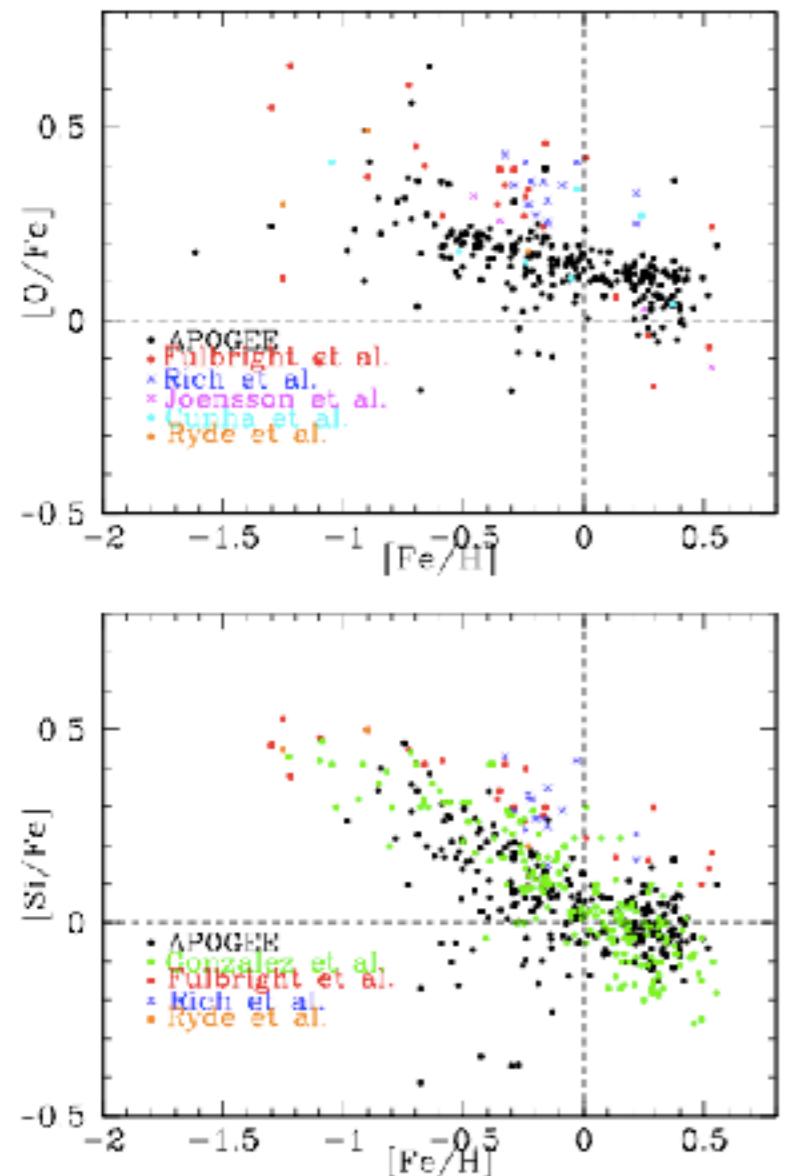
$0.5 < |z| < 1 \text{ kpc}$

$0 < |z| < 0.5 \text{ kpc}$

The Bulge

Schultheis et al. 2017, García-Pérez et al. 2018

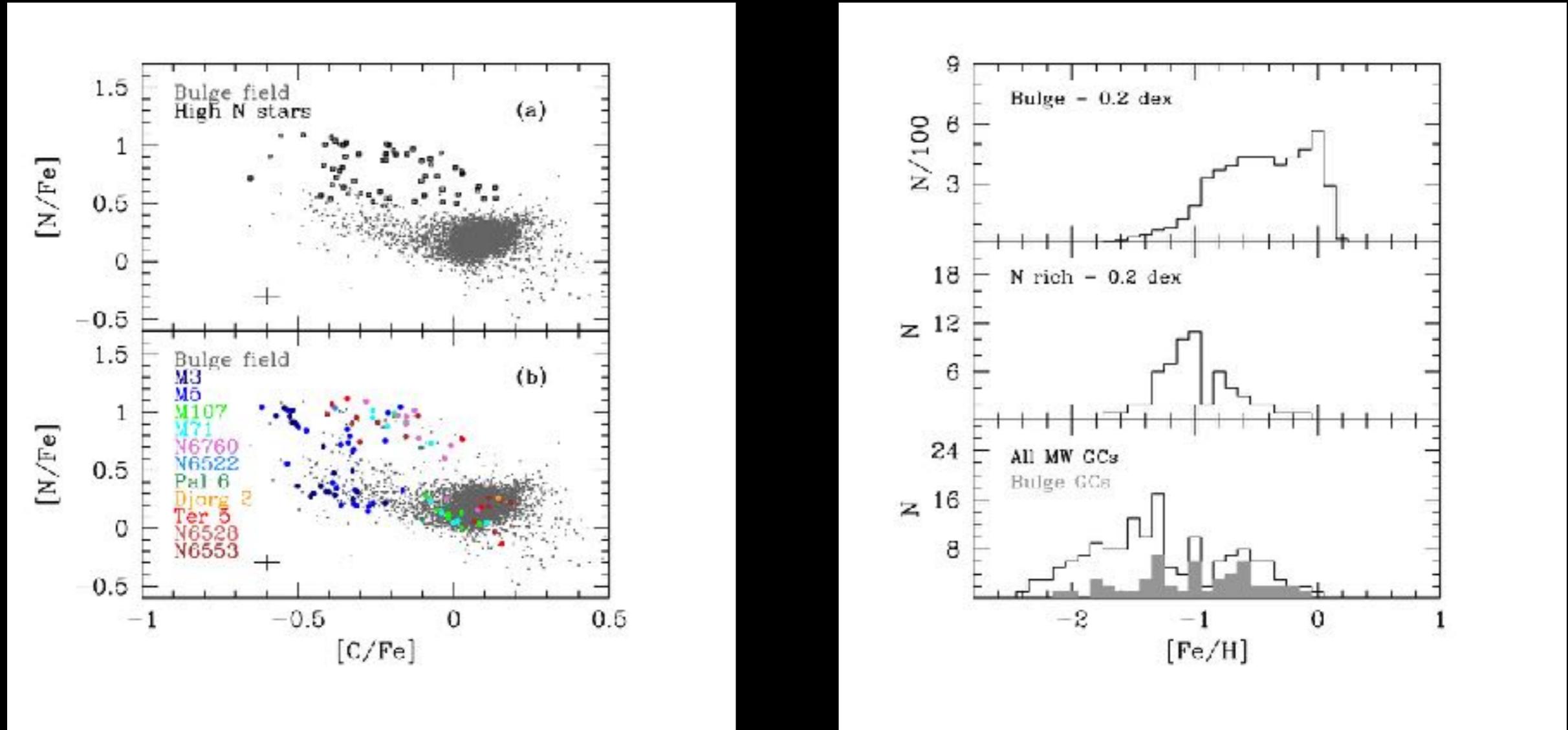
M. Schultheis et al.: Baade's window and APOGEE



- Mapping spatial structure and detailed chemical composition of bulge stellar populations

Dissolved Globular Clusters

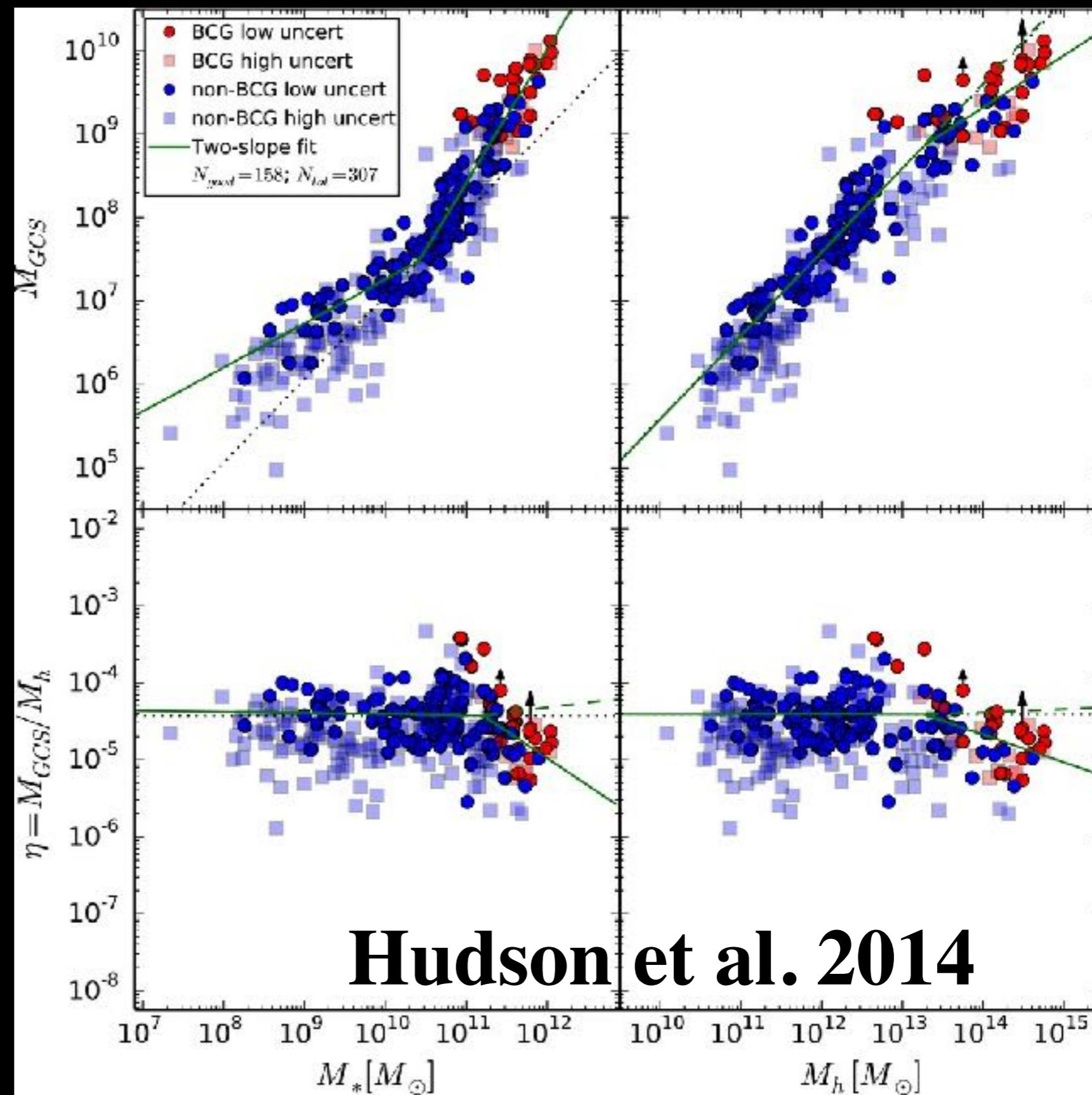
Schiavon et al. 2017



- Stars discovered in the Inner Galaxy with GC abundance patterns (C,N,Mg,Al)
- GC destruction deposited 25% of halo stellar mass at $R_{GC} < 2$ kpc ($10^8 M_{\odot}$)
- Corresponds to 6-8 times the mass of the entire existing Galactic GC system
- See also Martell et al. (2017), Fernandez-Trincado et al. (2017)

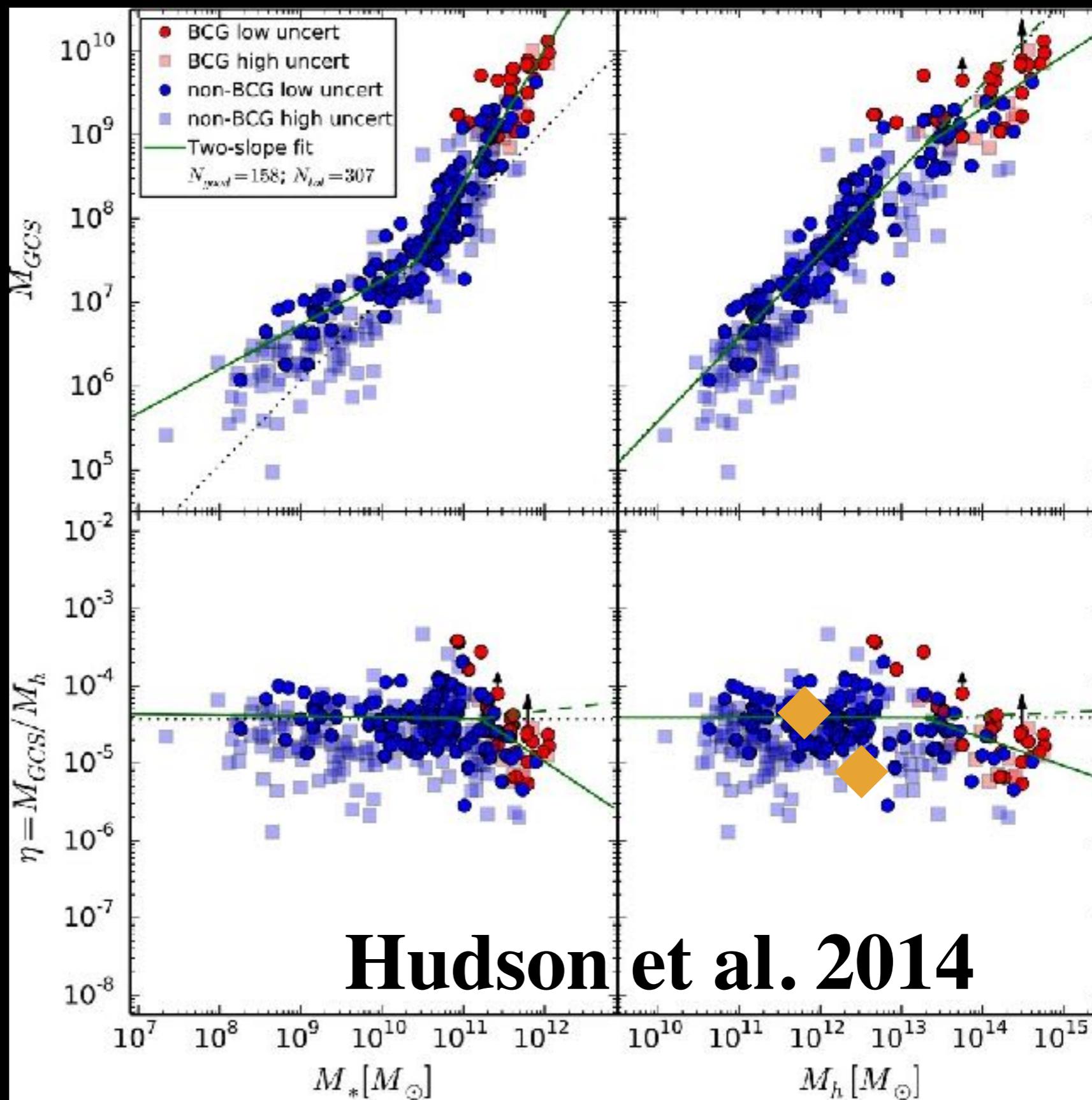
GCs and DM halos

- Total mass in GC systems scales with the total mass of the system
- Only stellar population found to behave that way
- Suggestion that it formed early, before feedback processes became important



GCs and DM halos

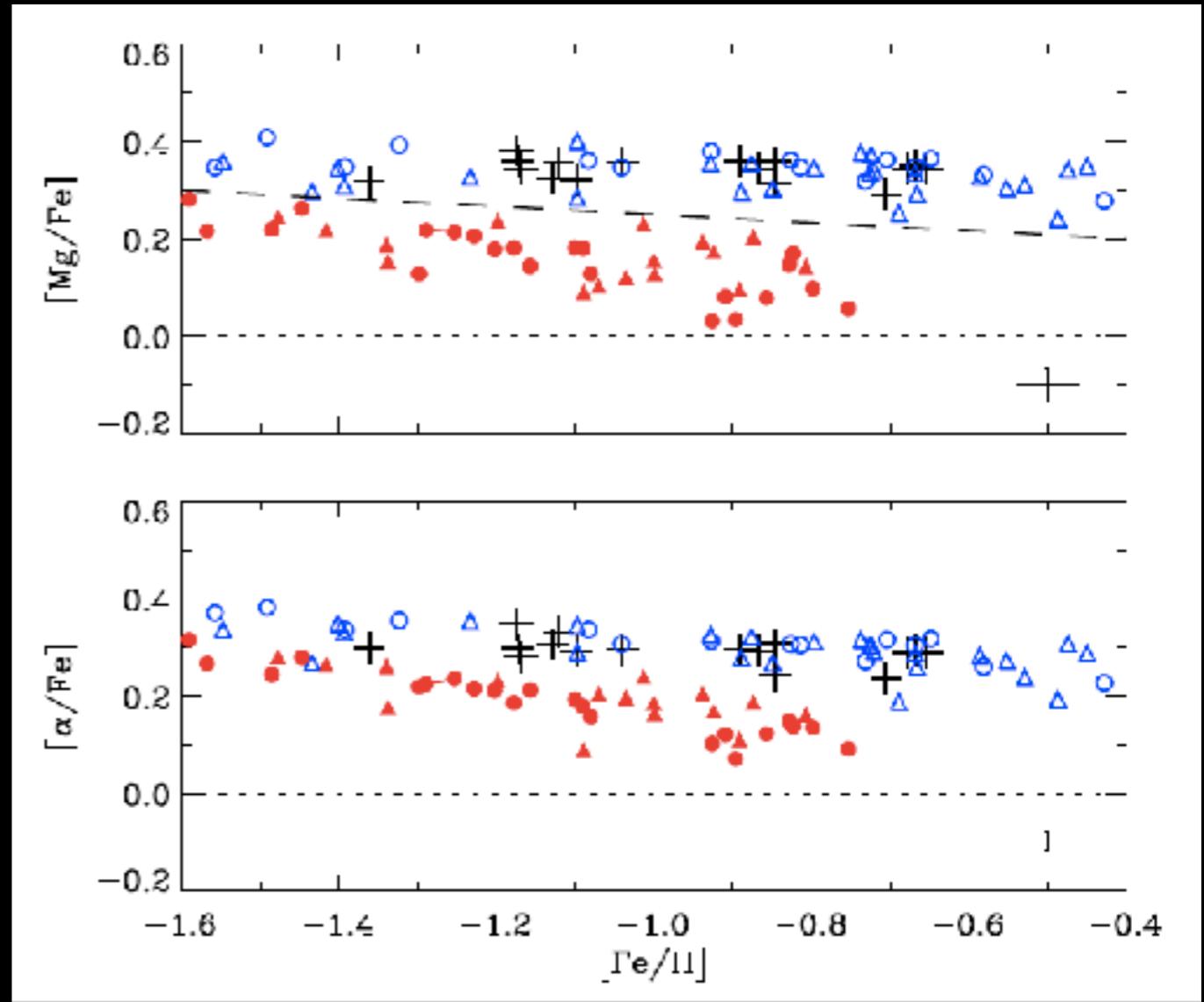
- $\eta = M_{GC}/M_{TOT}$
- $\eta = (4 \pm 1) \times 10^{-5}$
- $\eta_{MW} = 9 \times 10^{-6} - 5 \times 10^{-5}$



Accreted vs “In situ” Halo

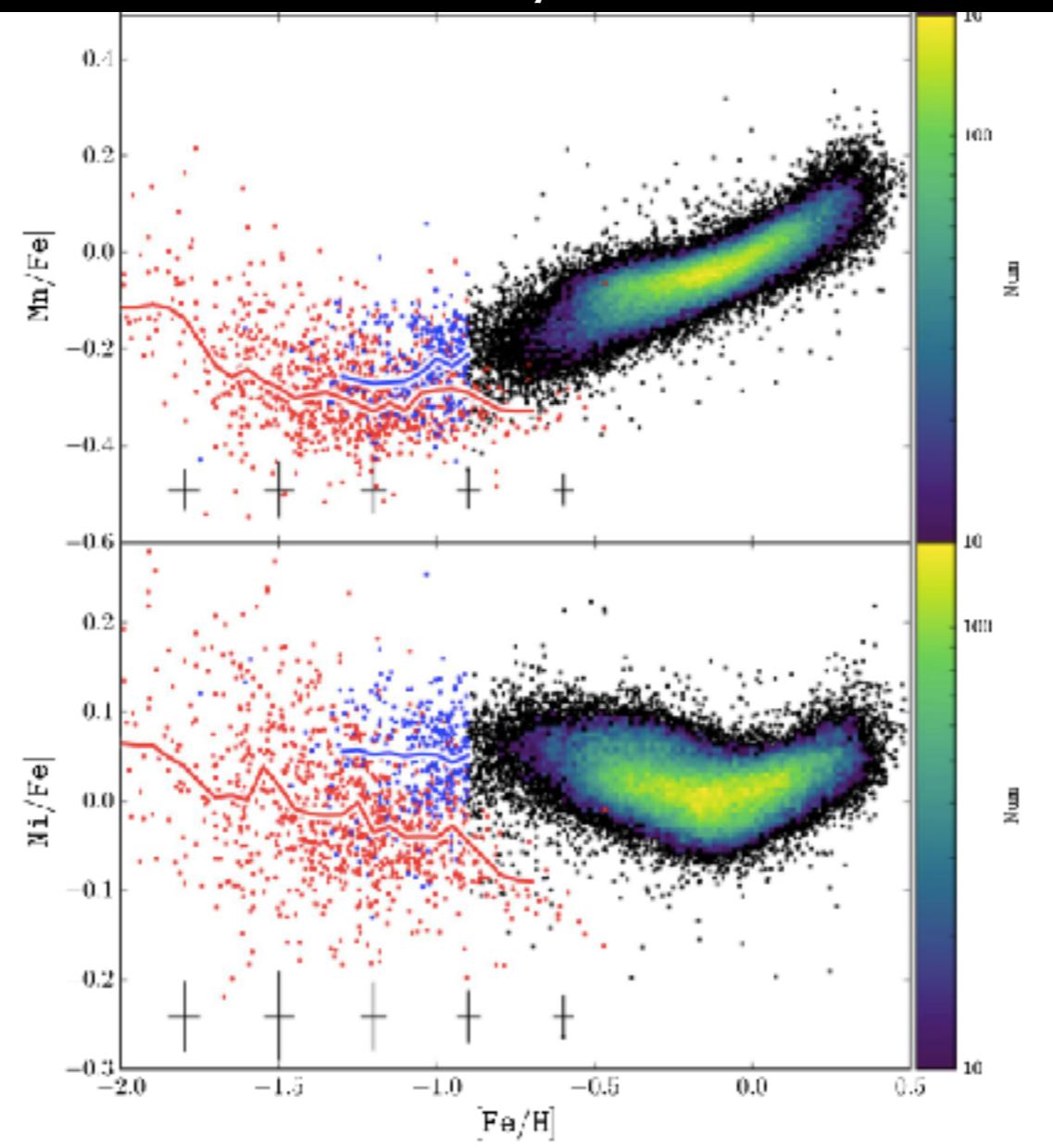
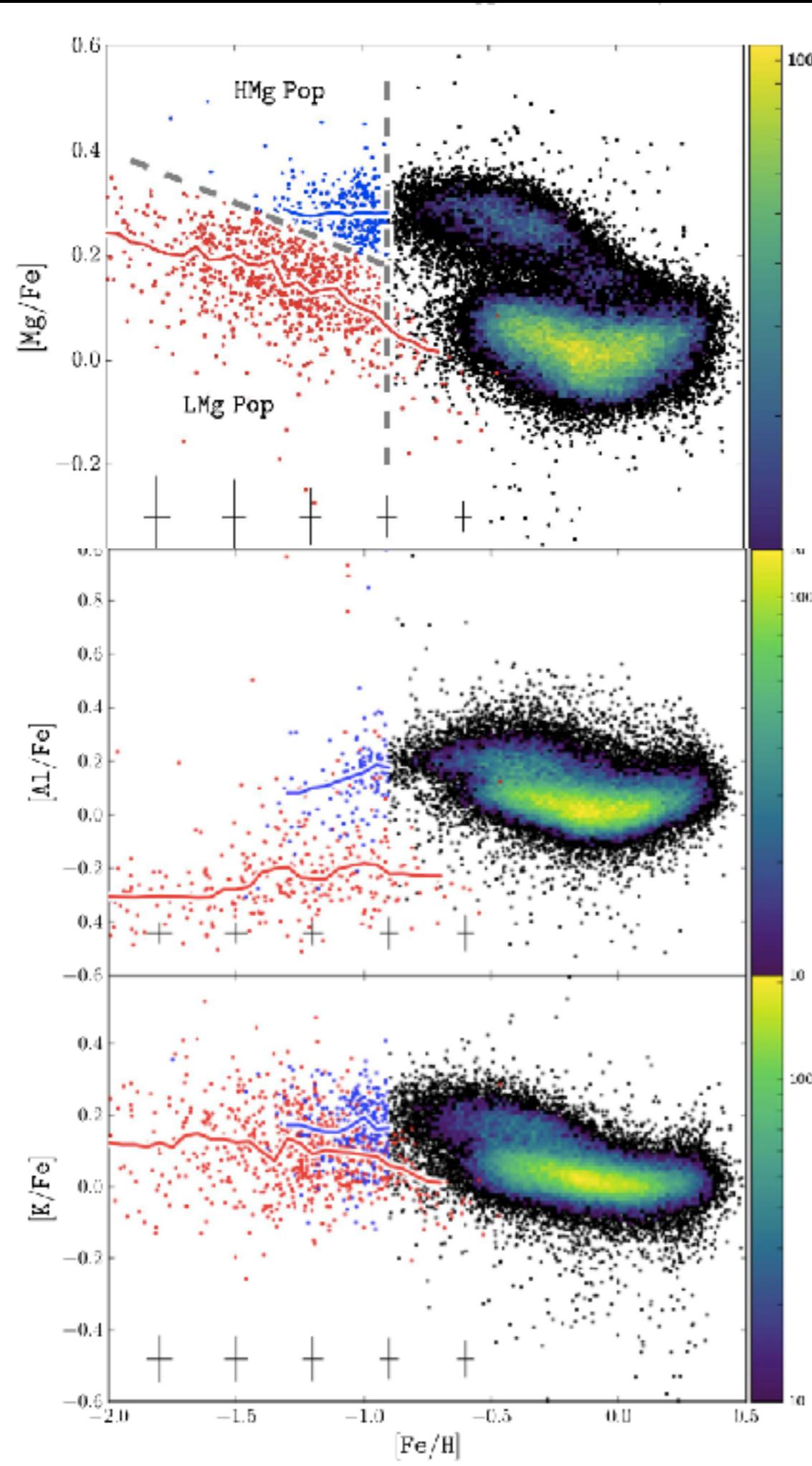
Nissen & Schuster (2010)

- Precision abundances for 94 F-G dwarfs
- $R = 40,000\text{-}54,000$
- Distance $< 335 \text{ pc}$
- A bimodal distribution in $[\alpha/\text{Fe}]$
- High α stars mostly on prograde orbits => Puffed up disk/bulge
- Low α stars mostly on retrograde orbits => Accreted



Abundance Patterns

Hayes et al. (2018)

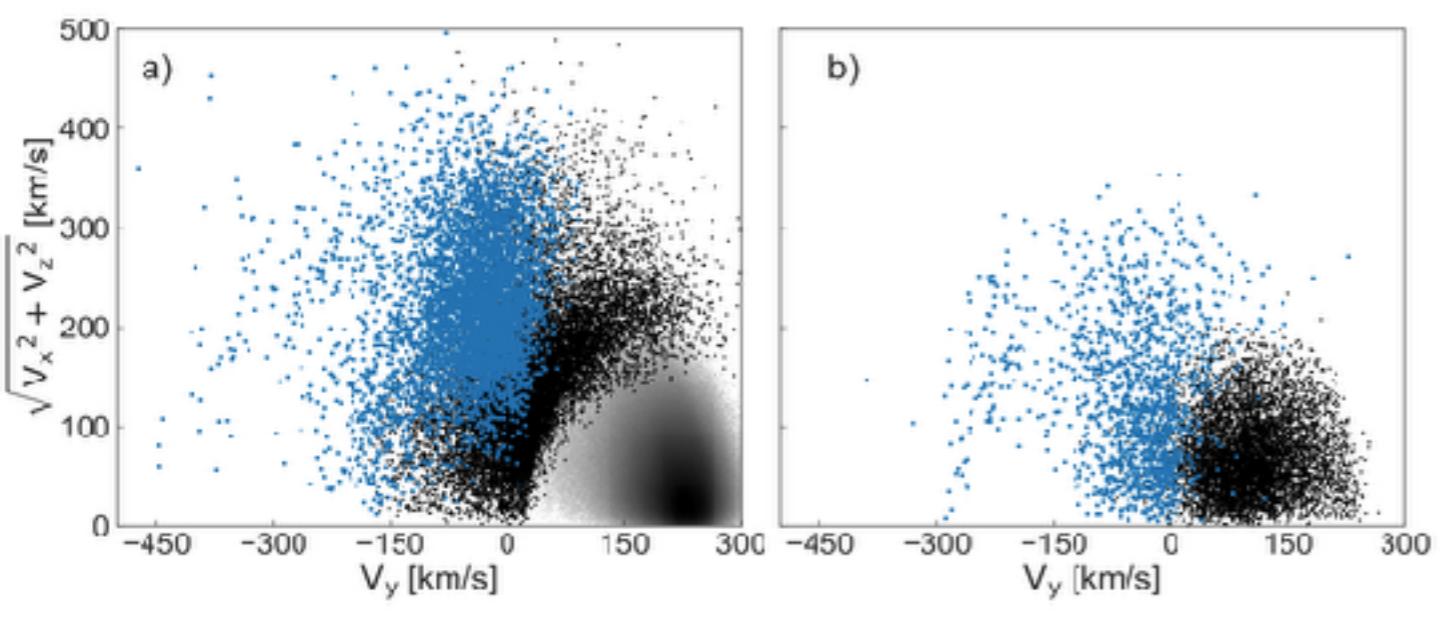


Abundance pattern of low α stars indeed similar to that of dwarf galaxies

See also Fernandez-Alvar et al. (2018)

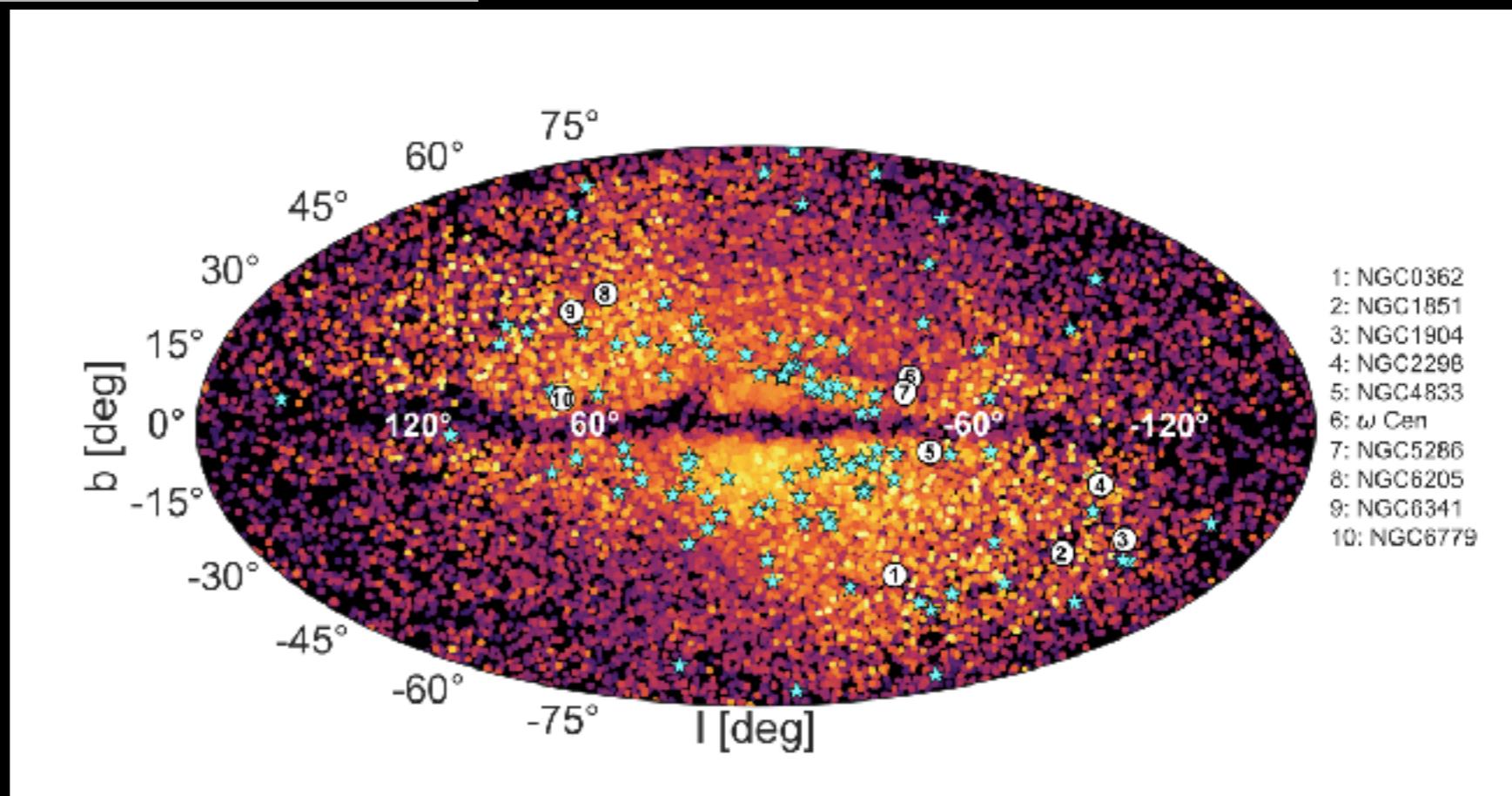
Gaia-Enceladus

Helmi et al. (2018), Kopelman et al. (2018)



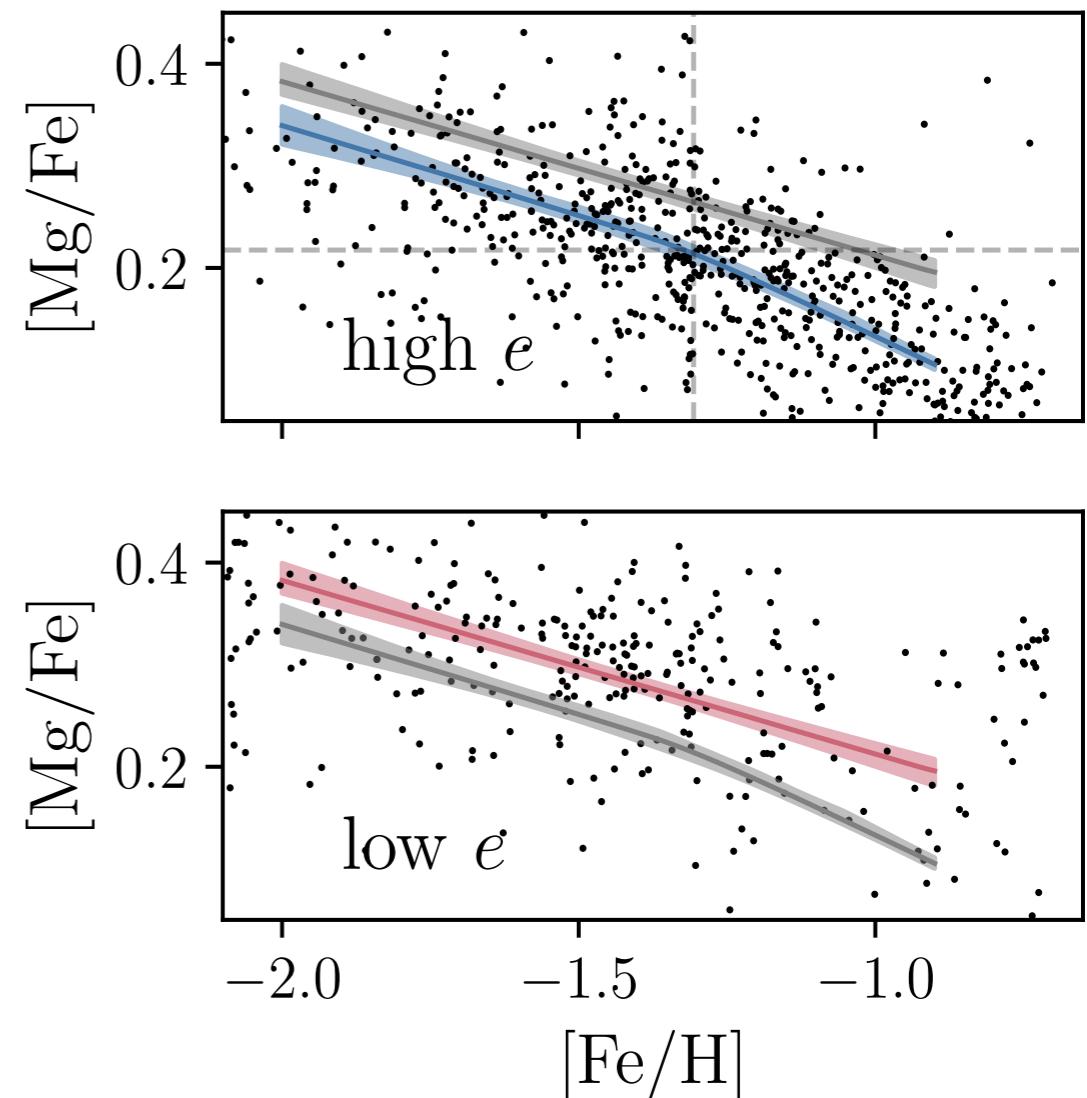
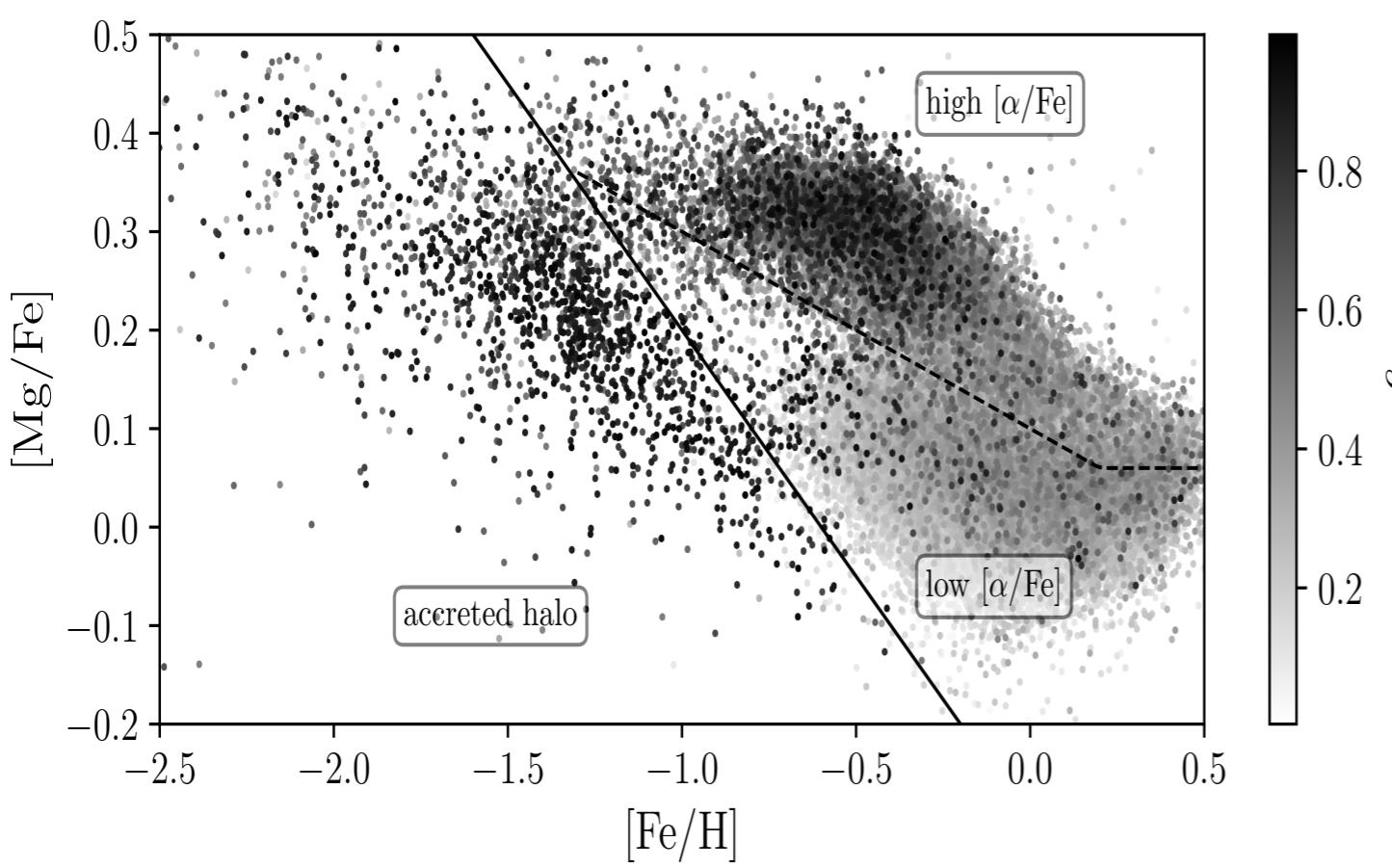
- Gaia DR2 reveals a large population of retrograde stars within 2.5 kpc of Sun
- Low- α abundances (APOGEE)
- Single accretion event

- Distribution on the sky of potential G-E members
- Progenitor system mass estimated at $6 \times 10^8 M_{\text{Sun}}$



See Also Belokurov et al. (2018), Deason et al. (2018)

The APOGEE view



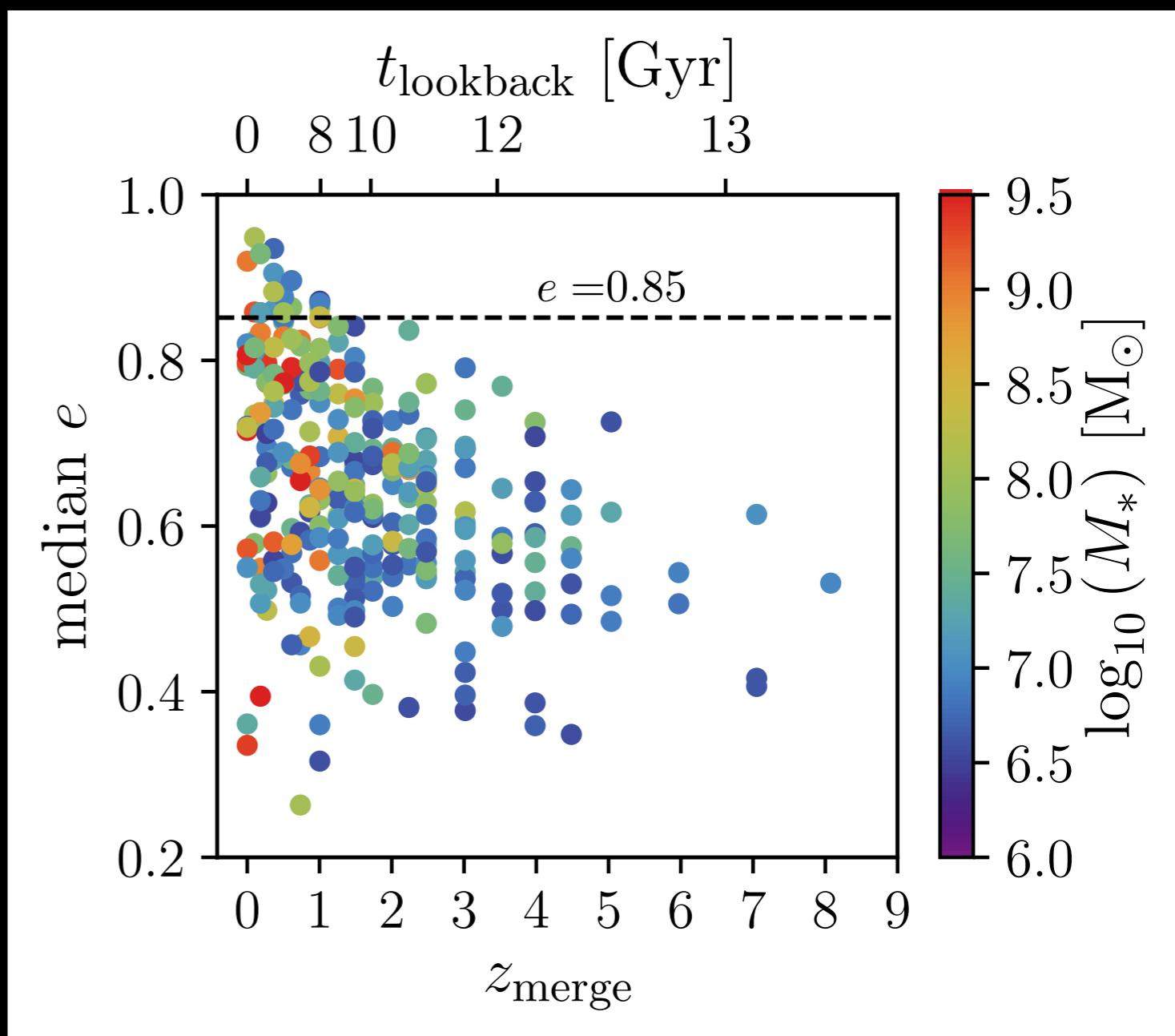
Mackereth et al. (2018b)

- **Discovery of an accreted population with very high eccentricity (e)**
- **Makes up for 2/3 of all APOGEE-Gaia sample**
- **Presence of a “knee” in Mg-Fe plane suggests massive system (MC-like)**
- **Low e population shows no “knee” => mix of stellar populations**

The EAGLE view

Mackereth et al. (2018b)

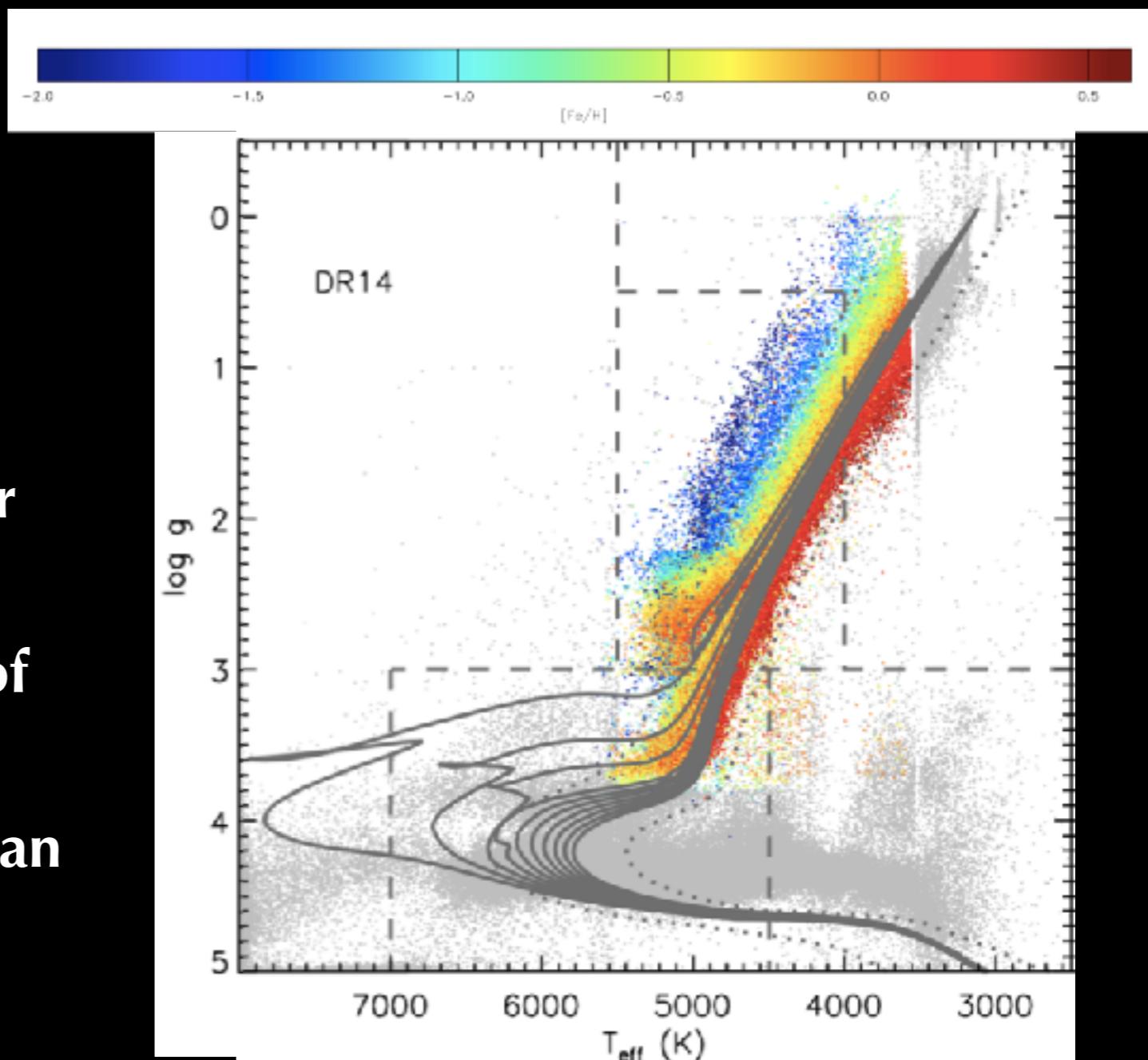
- The EAGLE simulations show that only systems accreted at $z < 1.5$ have such high eccentricity distributions
- Due to cosmology, such systems tend to be more massive (up to $10^9 M_{\odot}$)
- Such accretion events happen for only 3/22 of MW-like galaxies. They are rare.



M Dwarfs

Souto et al. (2018, 2017)

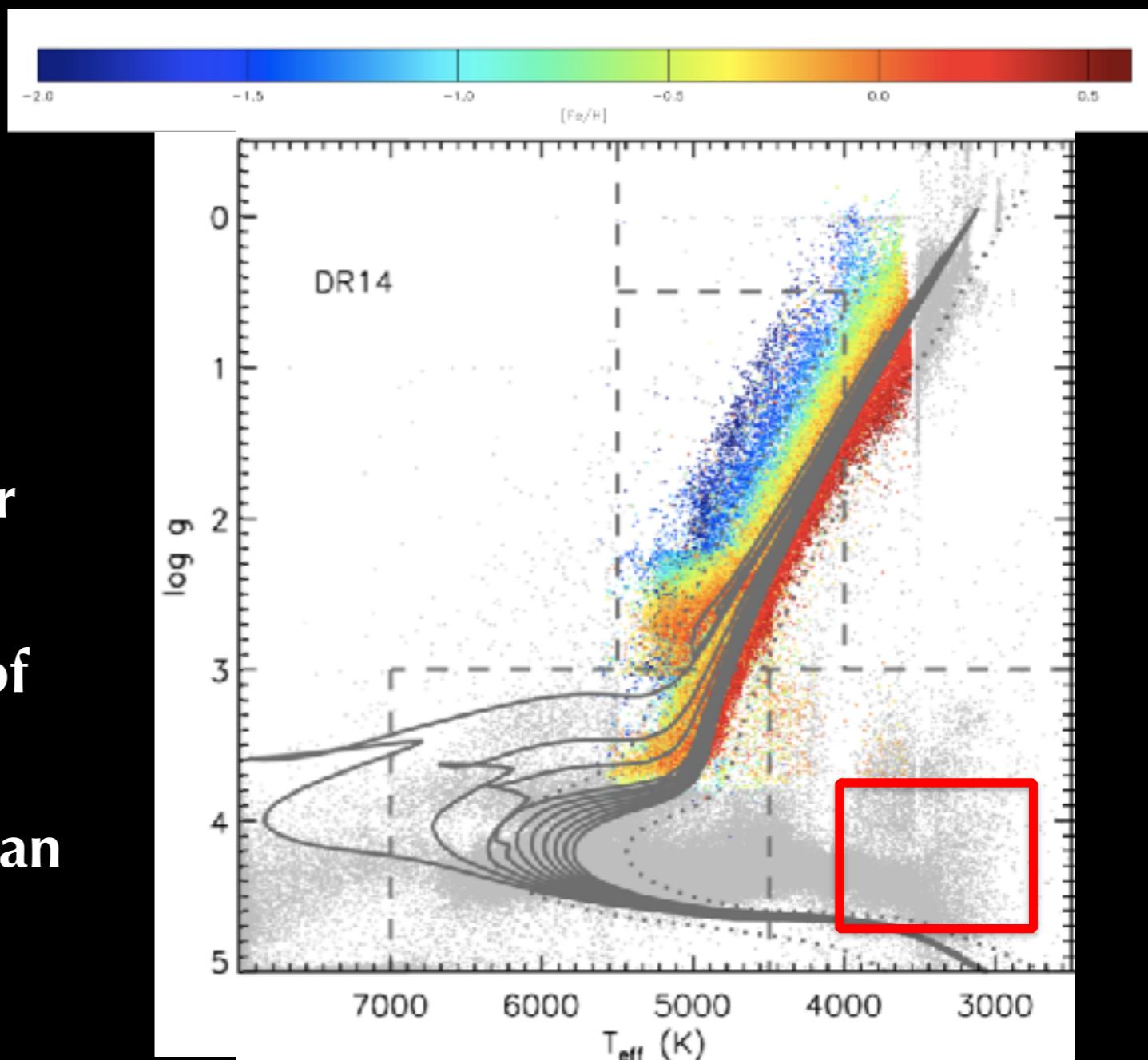
- Contain most of the stellar mass
- Least studied among cool stars
- Important in search for extra-solar Earths
- TESS and Plato will discover lots of those
- APOGEE has amassed spectra for an astounding 12,000 M dwarfs.



M Dwarfs

Souto et al. (2018, 2017)

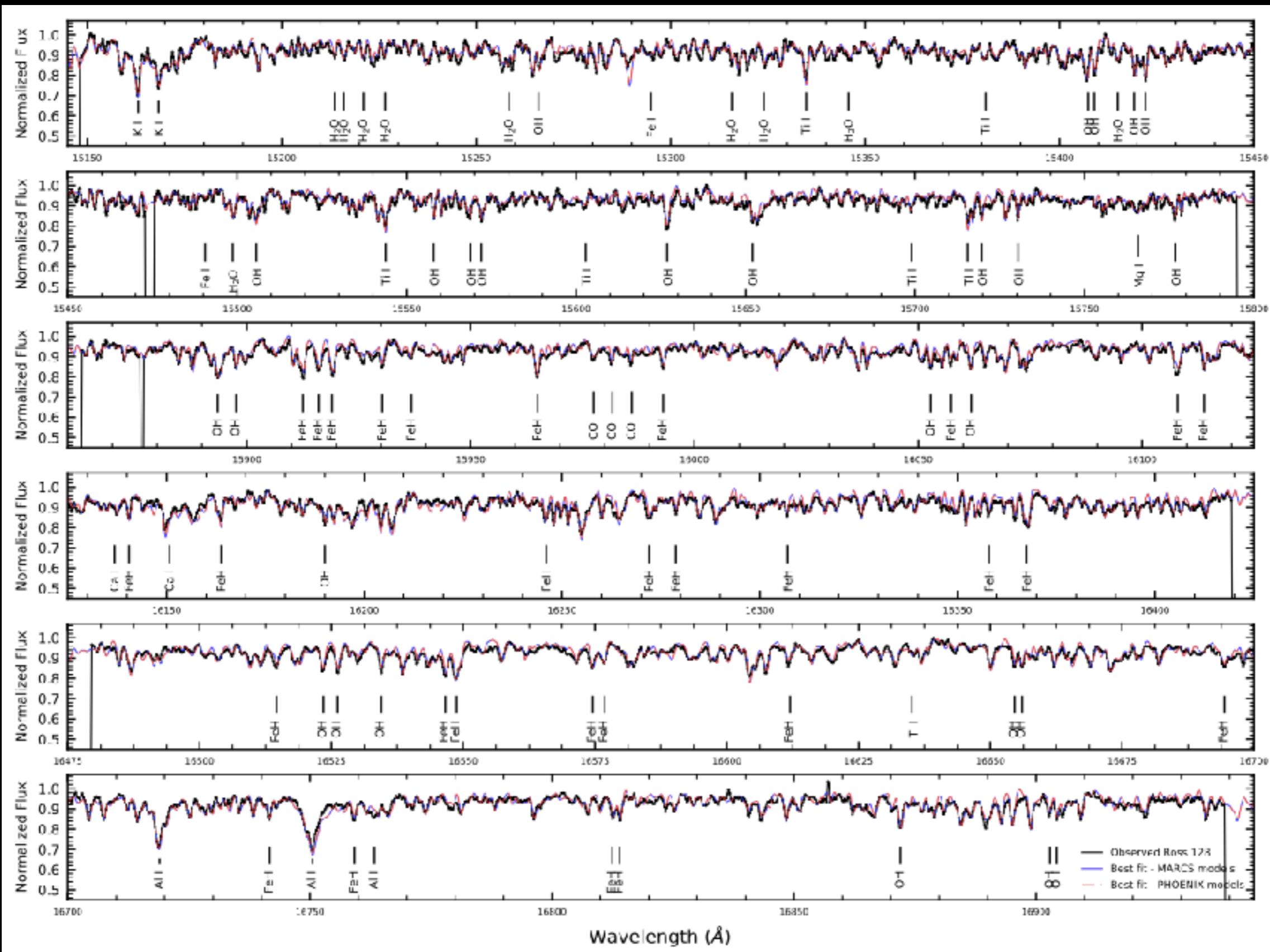
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Spectrum synthesis of Ross 128 — Souto et al. (2018)

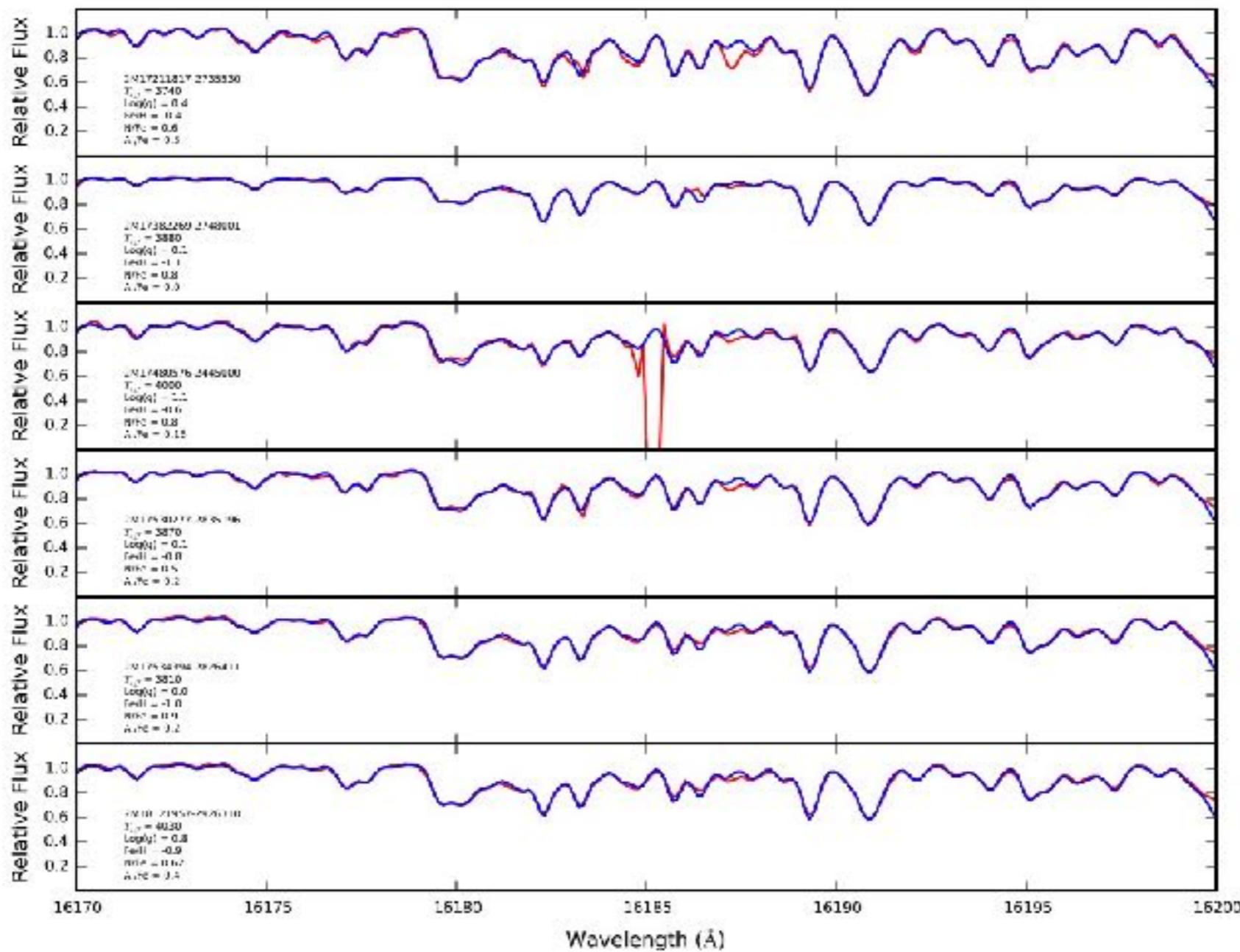
Teff = 3200 K log g = 5 near solar metallicity

Abundances of C, O, Mg, Al, K, Ca, Ti, and Fe



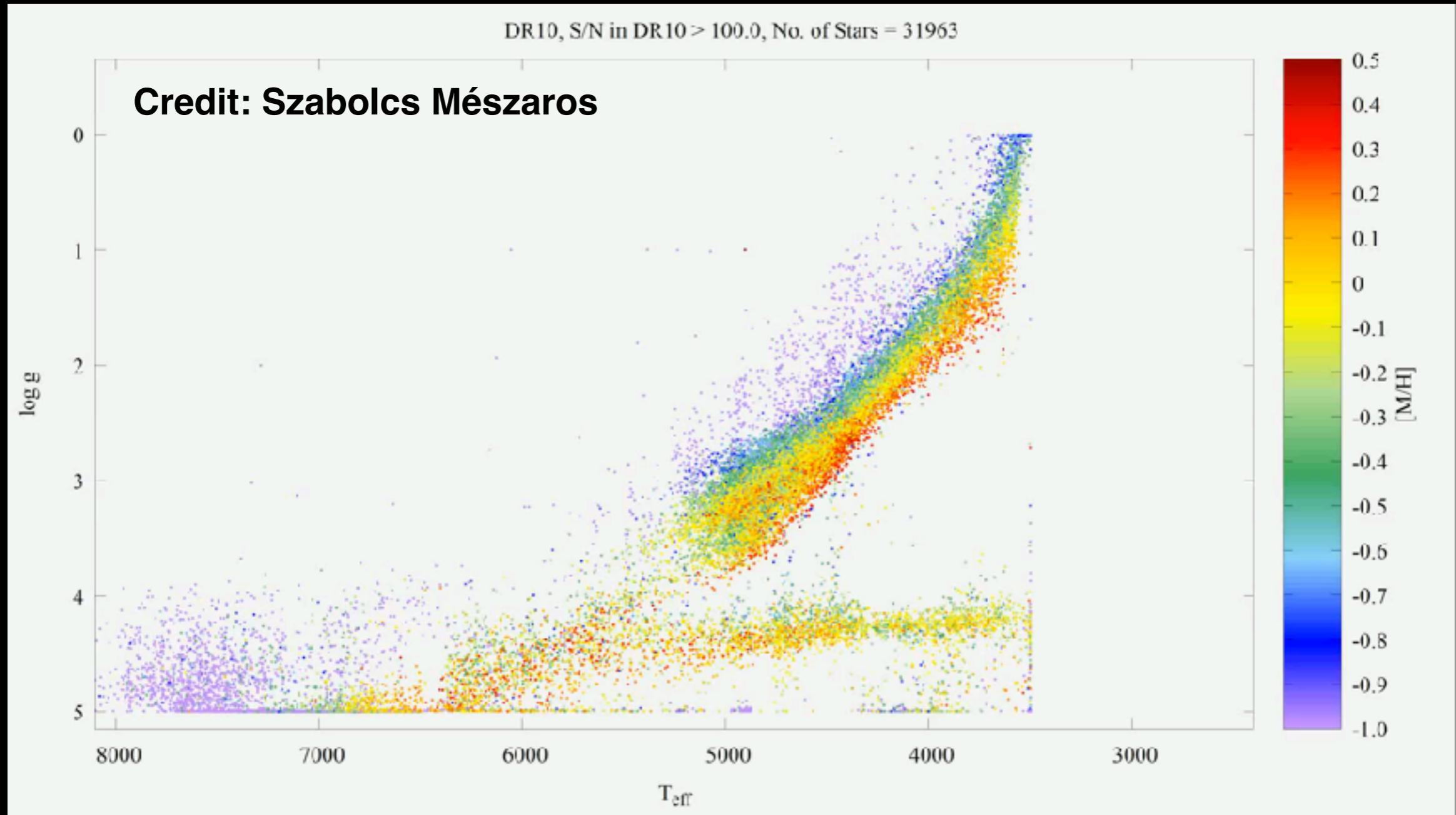
ASPCAP

Example: spectral fits around CO lines



For details, see Holtzman et al. (2015), García Pérez et al. (2017), Majewski et al. (2017)

The Evolution of APOGEE Stellar Parameters



Download DR14 data from: <https://www.sdss.org/dr14/irspec/>
See Holtzman et al. (2018) and Jönsson et al. (2018)