Chemical Enrichment in Ultra-faint Dwarf Galaxies

(UFDs)

Alex Ji
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Carina II and III
Ting Li, Josh Simon,
Jen Marshall, Ian Thompson,
Kathy Vivas, Andrew Pace,
Keith Bechtol, Alex Drlica-Wagner,
and the MagLiteS Collaboration

Reticulum II
Josh Simon, Ian Roederer,
Anna Frebel, Christian Johnson,
Mario Mateo, Ralf Klessen,
Gabriele Cescutti, and the M2FS team

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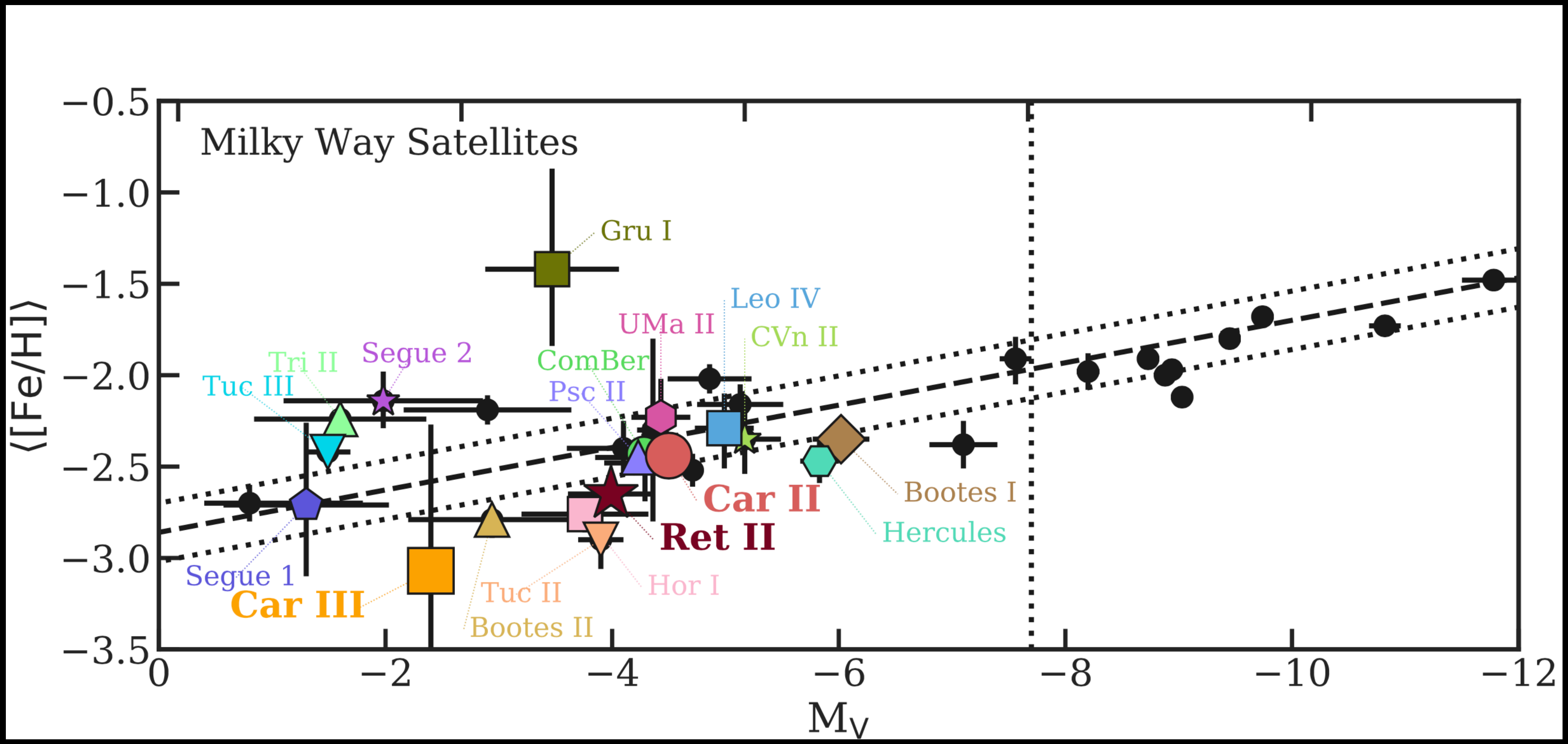
Ultra-faint Dwarf Galaxies: Independent Bursts of Early Star Formation

- Old: ~13 ± 1 Gyr age
- Metal-poor: [Fe/H] ≪ -2
- DM-dominated
- Lots of nearby UFDs (~50 known)

Biggest challenge: few stars. But we're making progress!



MZR line: Kirby+13
Galaxy data: Simon 19 compilation

Colored points = UFDs with detailed chemical abundances

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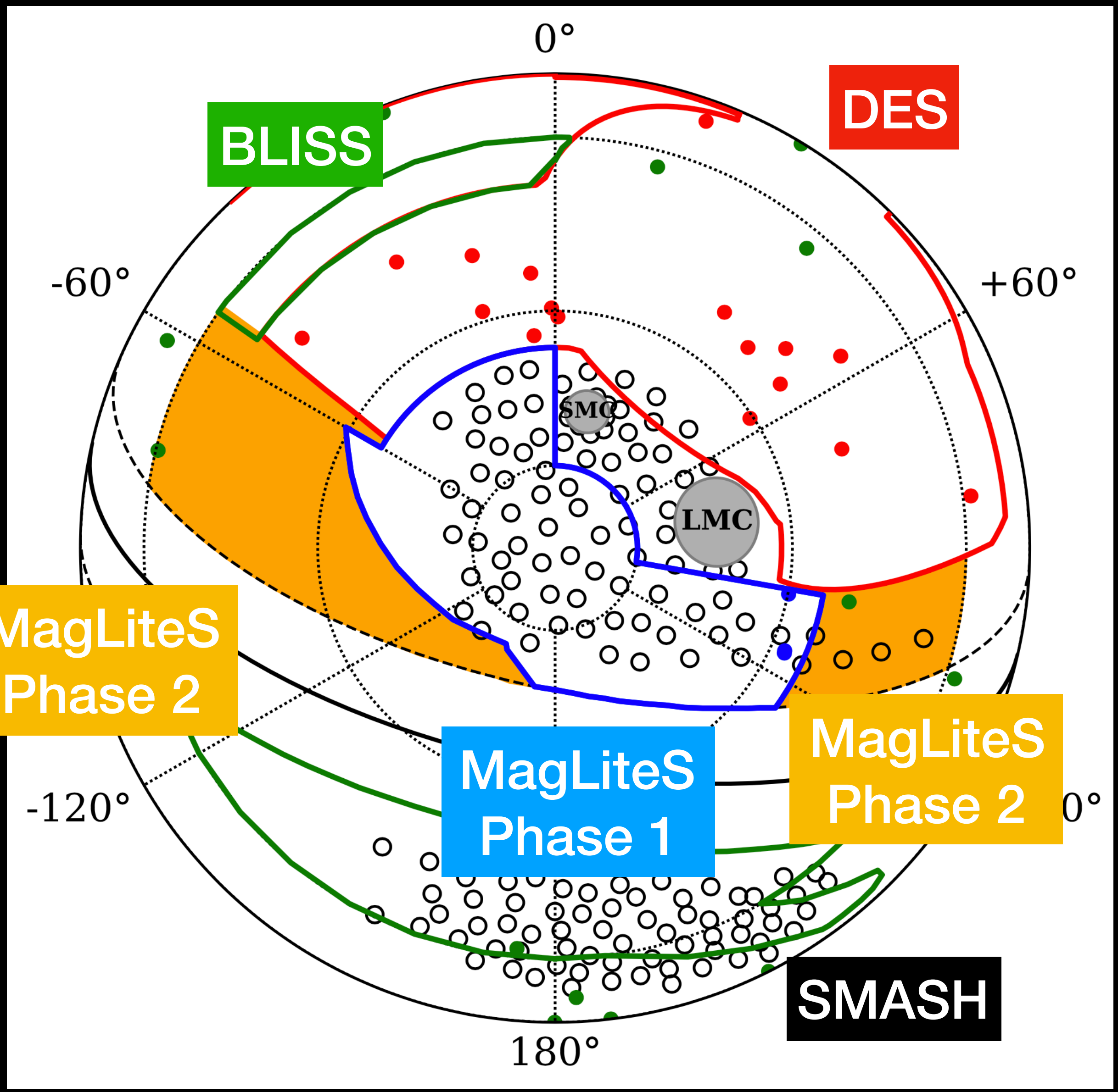
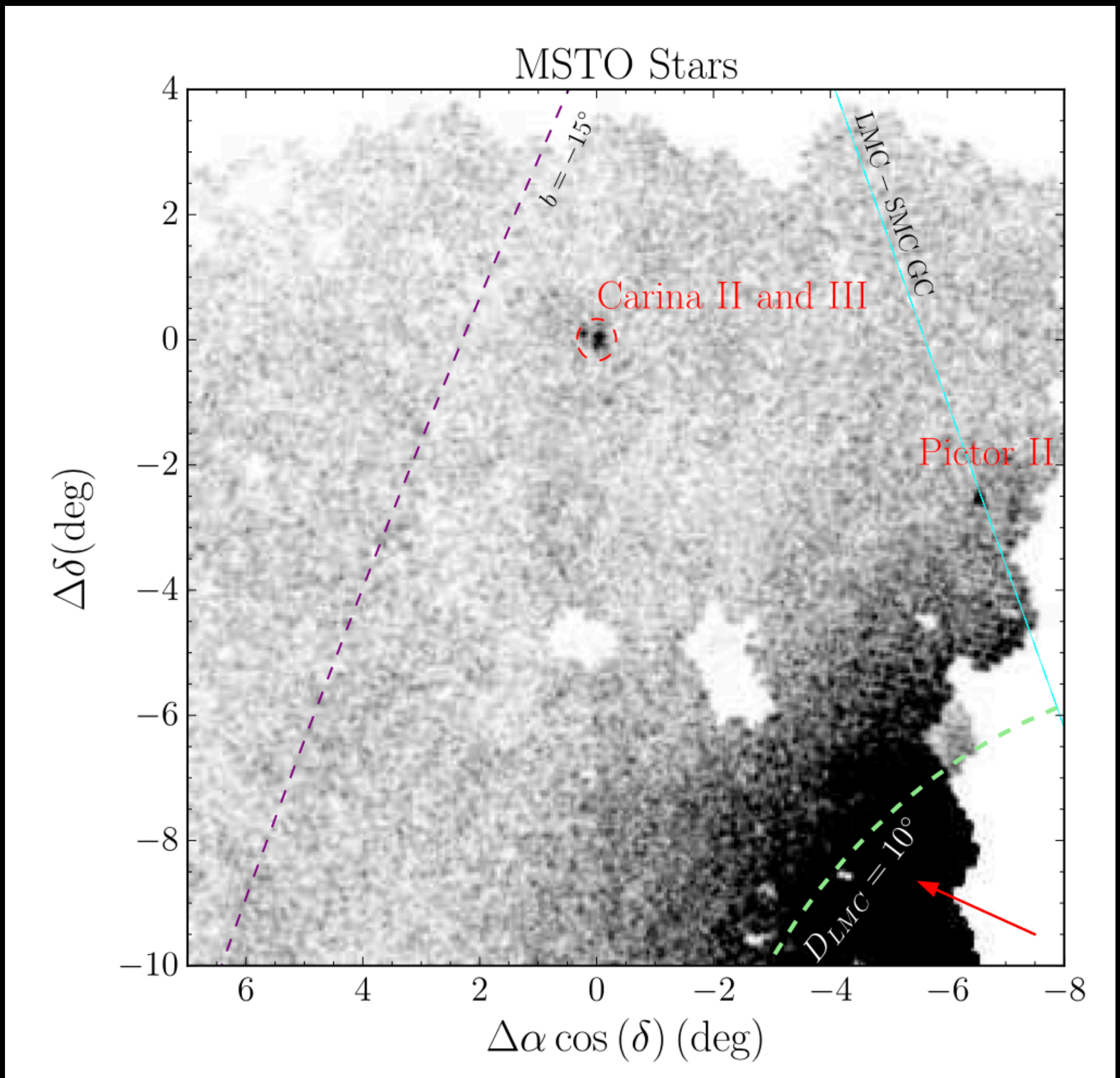
Outline

- High-resolution abundances in 3 UFD galaxies:
  - Carina II + III: detailed abundances in two LMC satellites
  - Reticulum II: now with 30-40 member stars
- **Stay awake to learn about:**
  - The high-mass **initial mass function** (IMF)
  - UFD **gas dynamics**
  - If time: metal-free (**Pop III**) signatures

Carina II and III
LMC Satellite Galaxies Found by MagLiteS





Magellanic Satellites Survey (MagLiteS)
PI: Keith Bechtol

Torrealba et al. 2018
Carina II: M_V=-4.5, M_{star}~$10^4 M_\odot$
Carina III: M_V=-2.4, M_{star}~$10^3 M_\odot$

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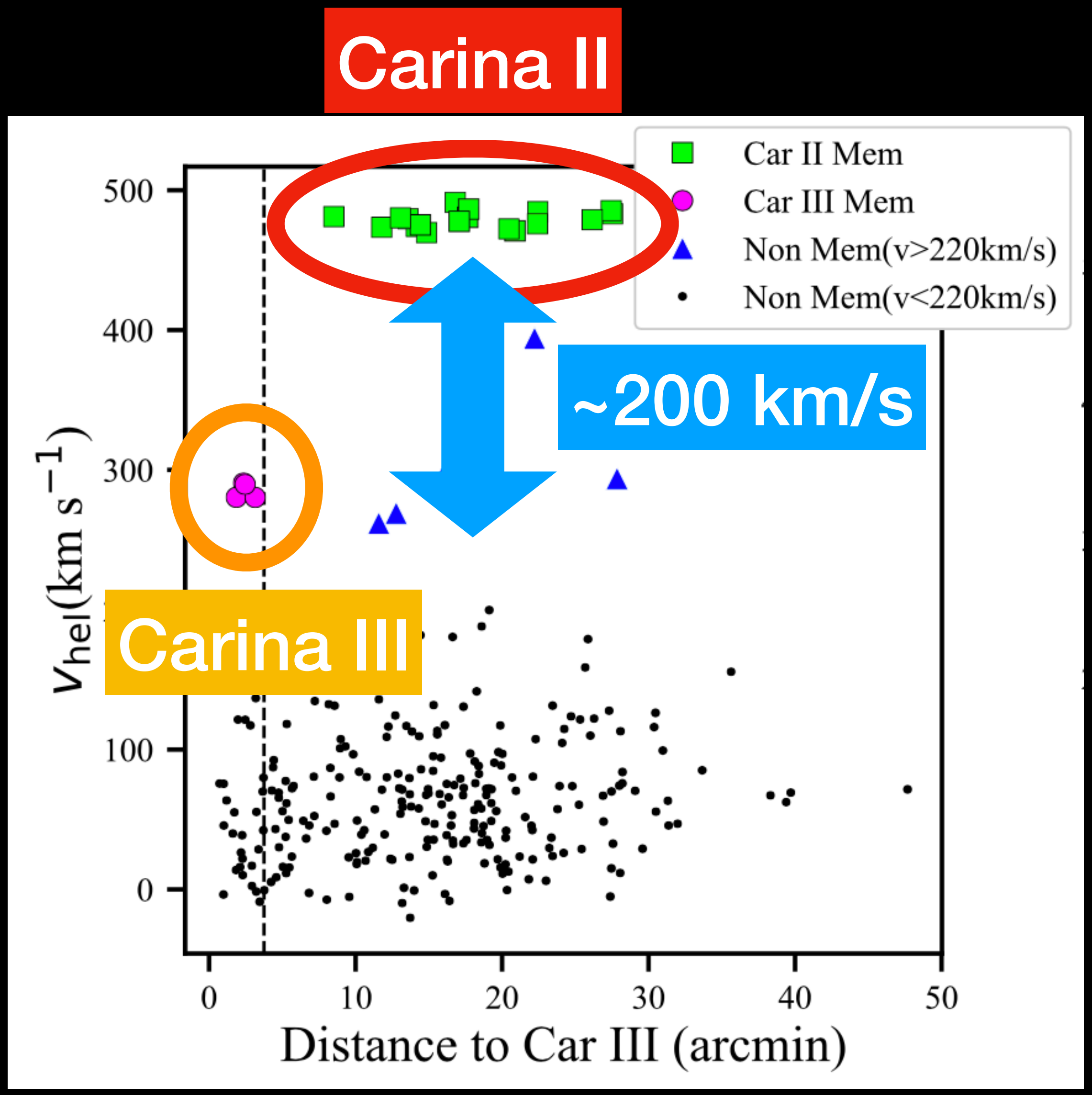
Carina II and III

LMC Satellite Galaxies Found by MagLiteS

- Dwarf galaxy sizes; resolved velocity and [Fe/H] dispersions
- Both associated with LMC (Kallivayalil+18, Erkal+Belokurov19) but *not* each other
- **New: R~30k Magellan/MIKE spectroscopy** (~22 elements) of
  -10 Car II stars (including 1 RRL)
  - 2 Car III stars
  - 3/12 stars have [Fe/H] < -3.5
  - Clearly UFD (not GC) abundances



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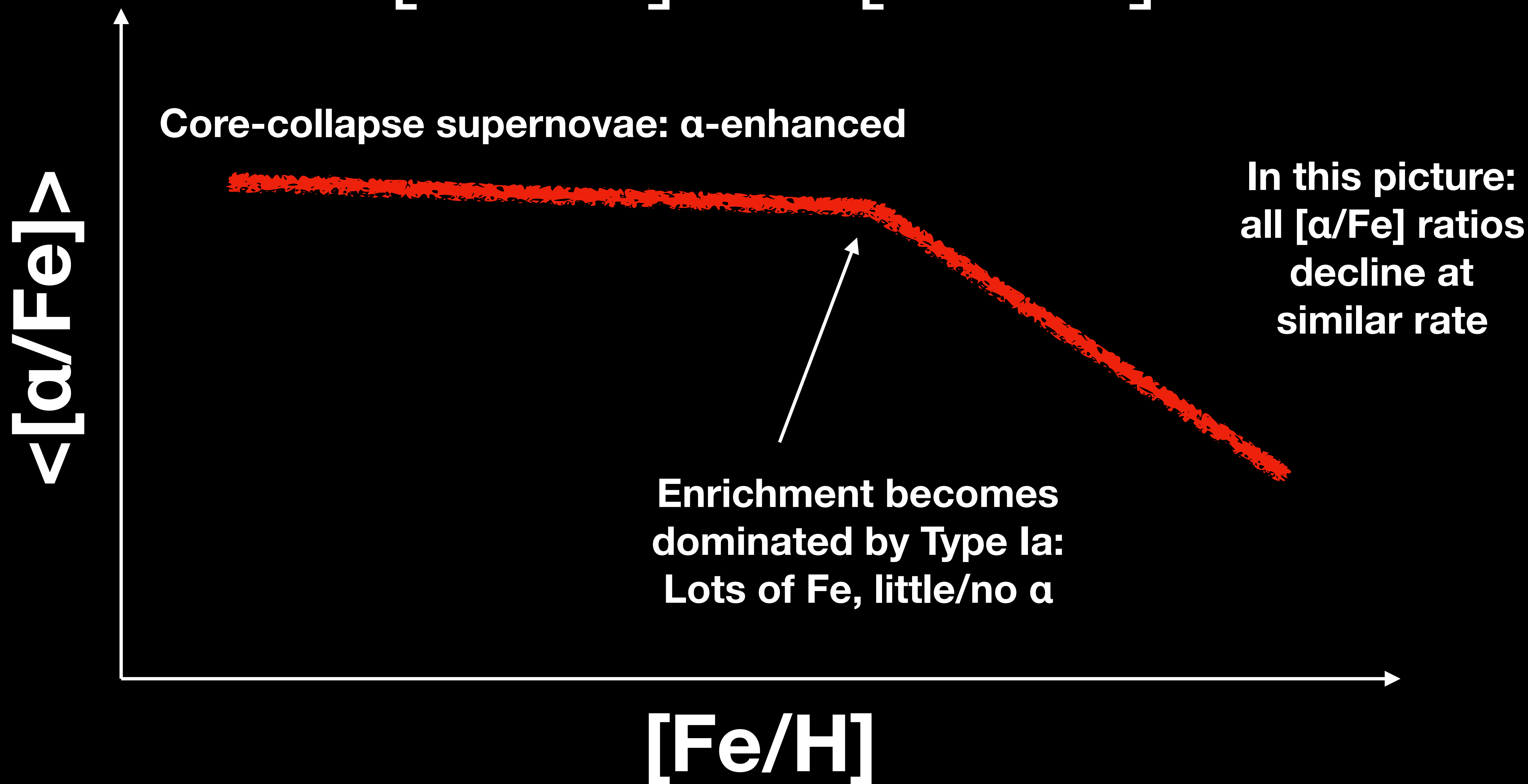
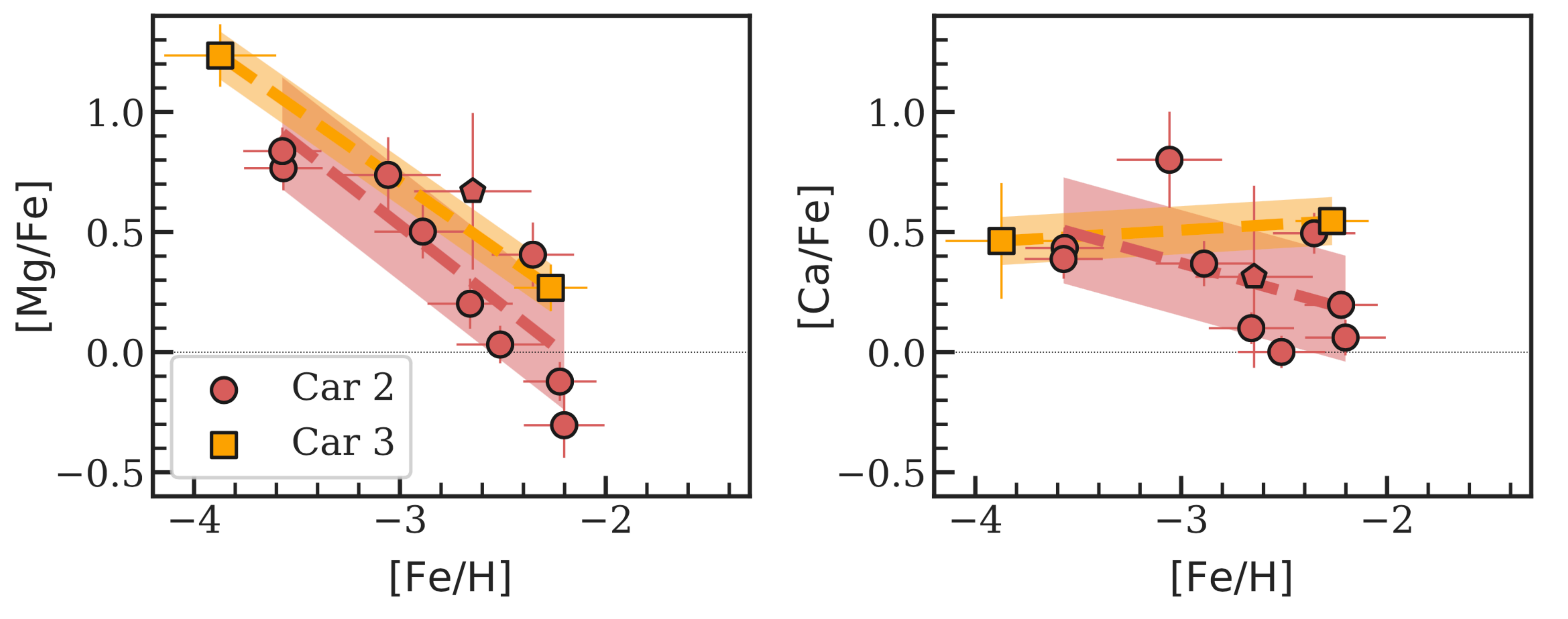
Torrealba et al. 2018, T. S. Li et al. 2018, Ji et al. in prep

Today: focus on [α/Fe] vs [Fe/H]



α-elements: O, Mg, Si, Ca, Ti

[α/Fe] declines in both Car II, III but *not* the same amount for Mg, Ca



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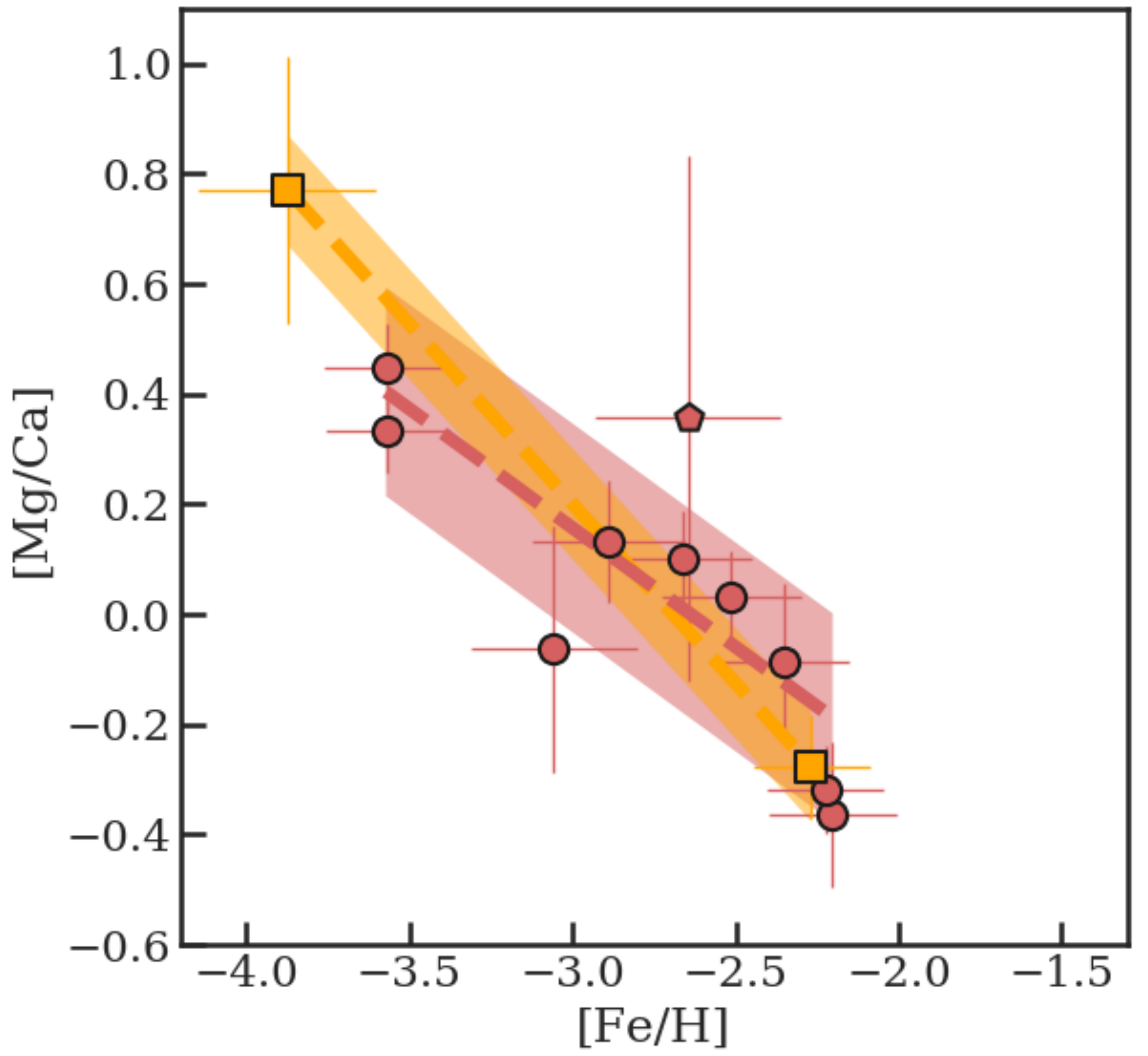
Ji et al. in prep



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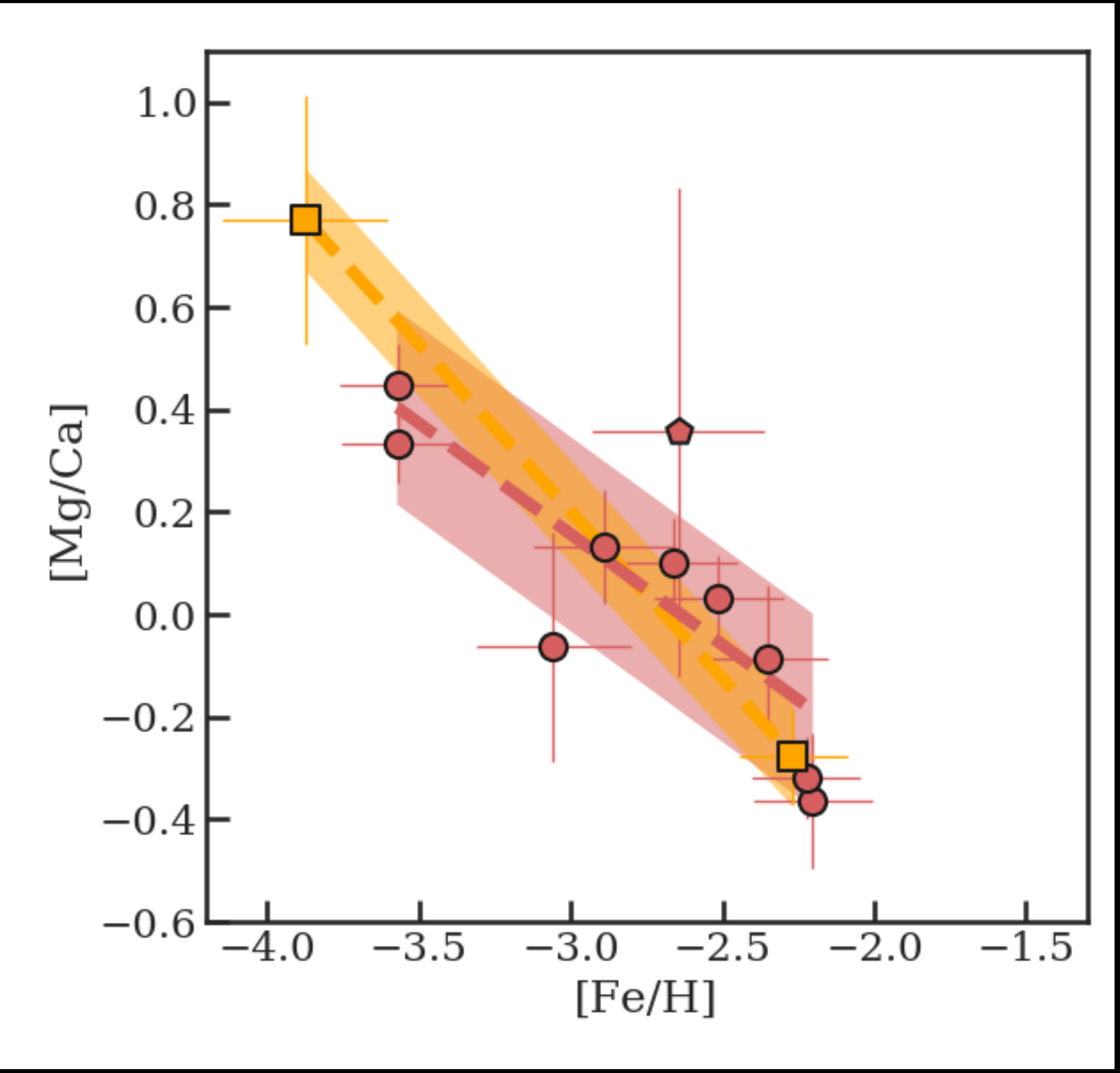
[Mg/Ca] corresponds to CCSN initial mass

e.g. McWilliam et al. 2013



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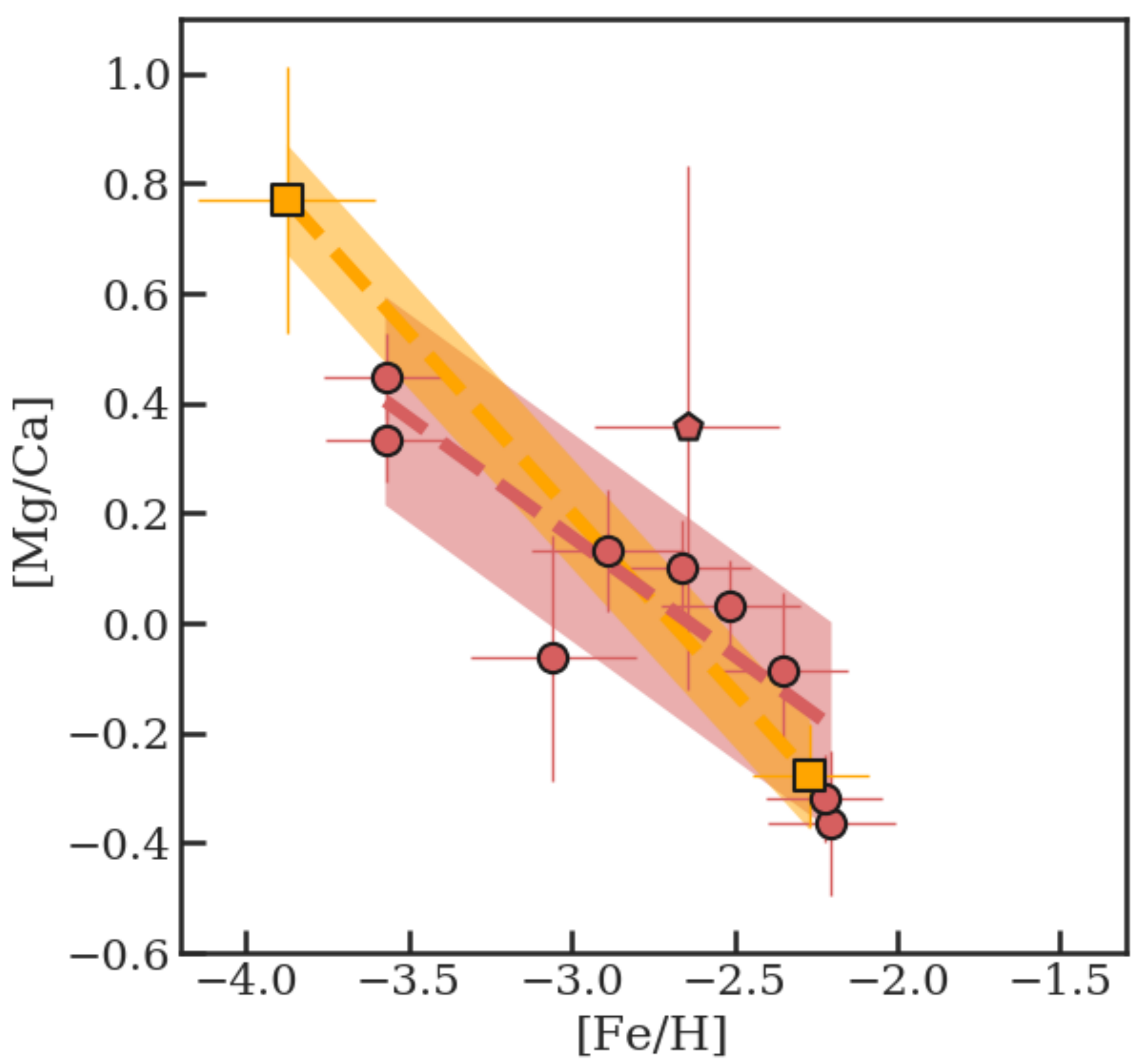

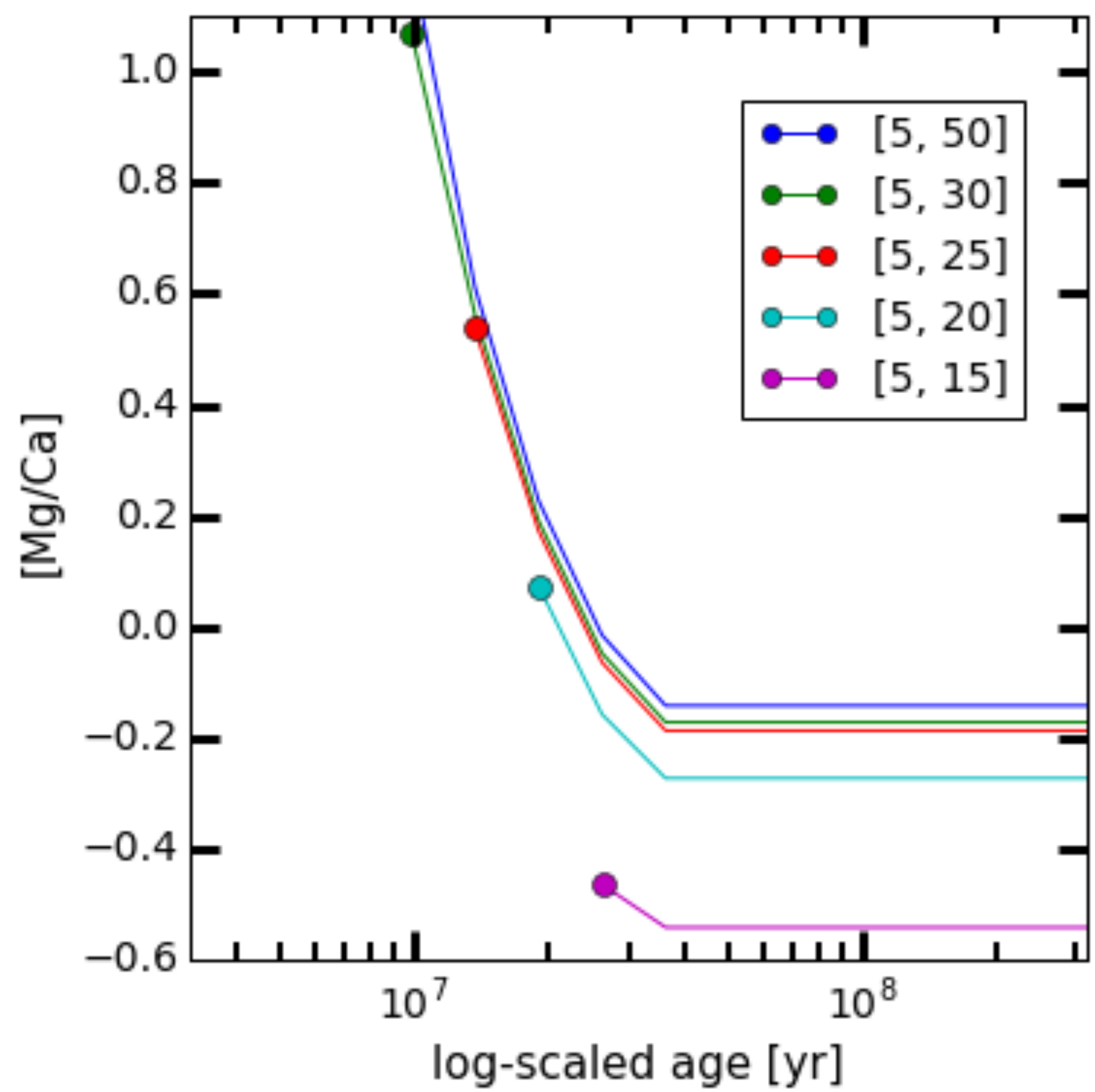

Yields from NuGrid: Ritter + Cote 2016 http://nugrid.github.io/NuPyCEE/

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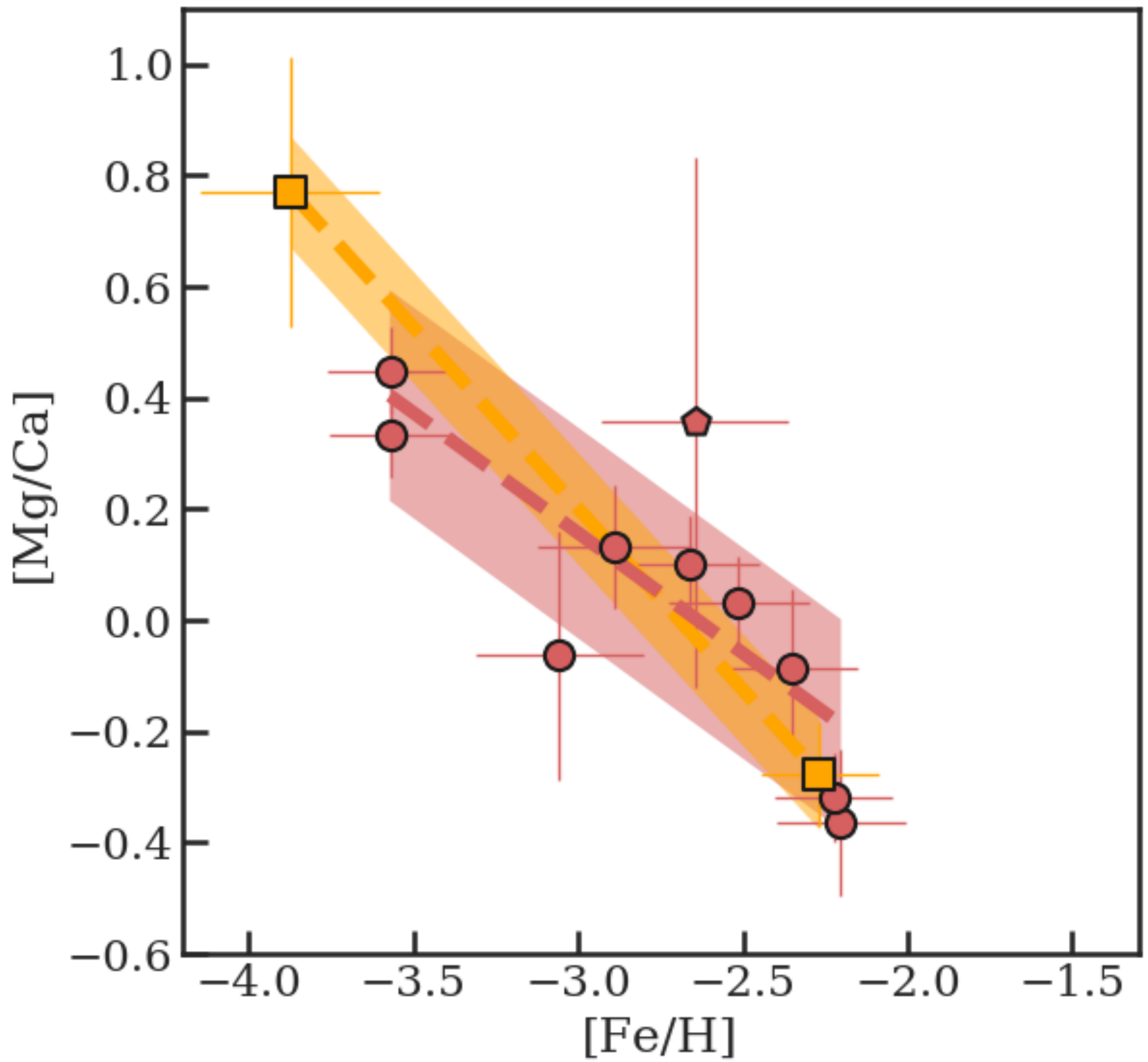

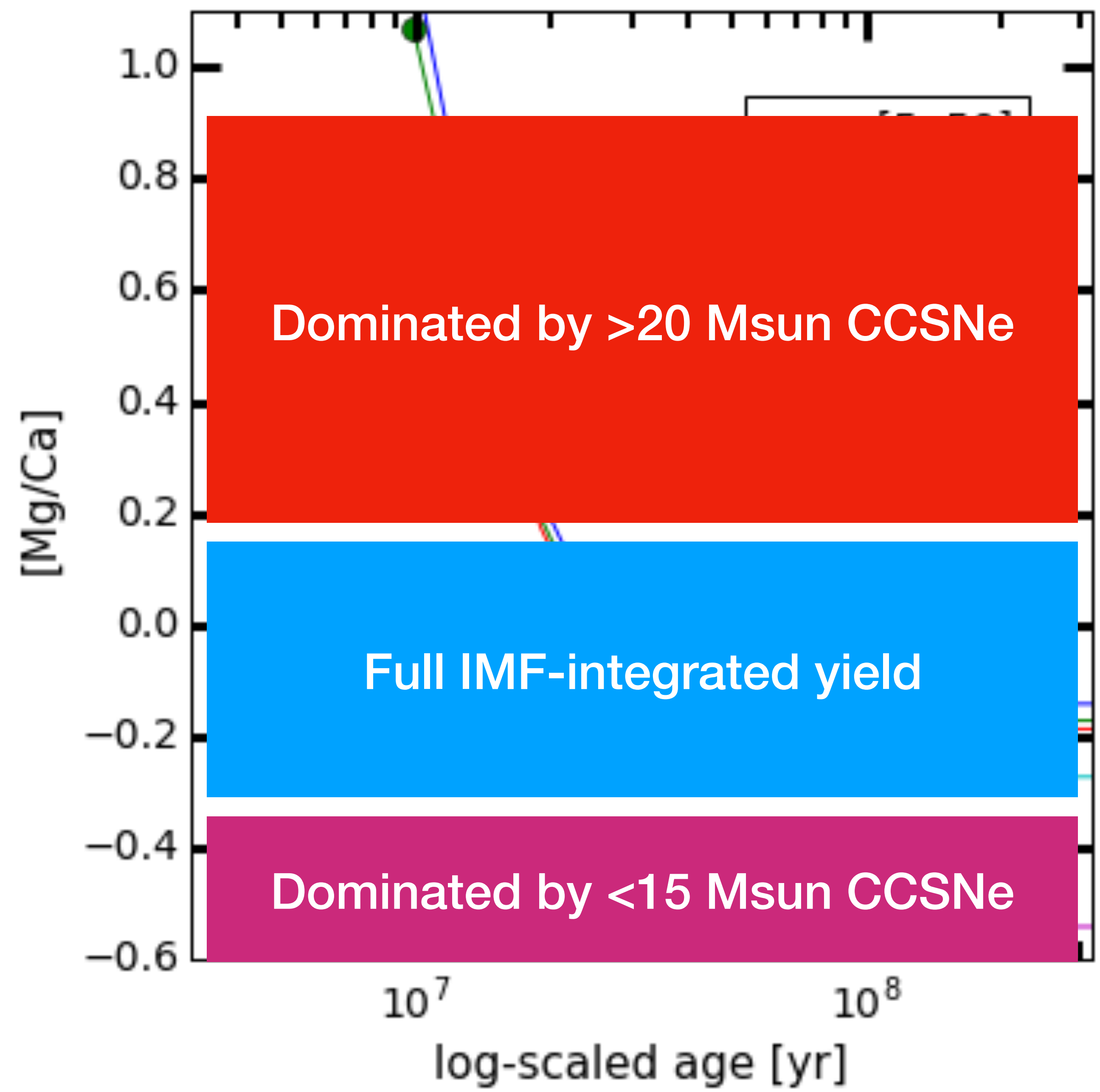

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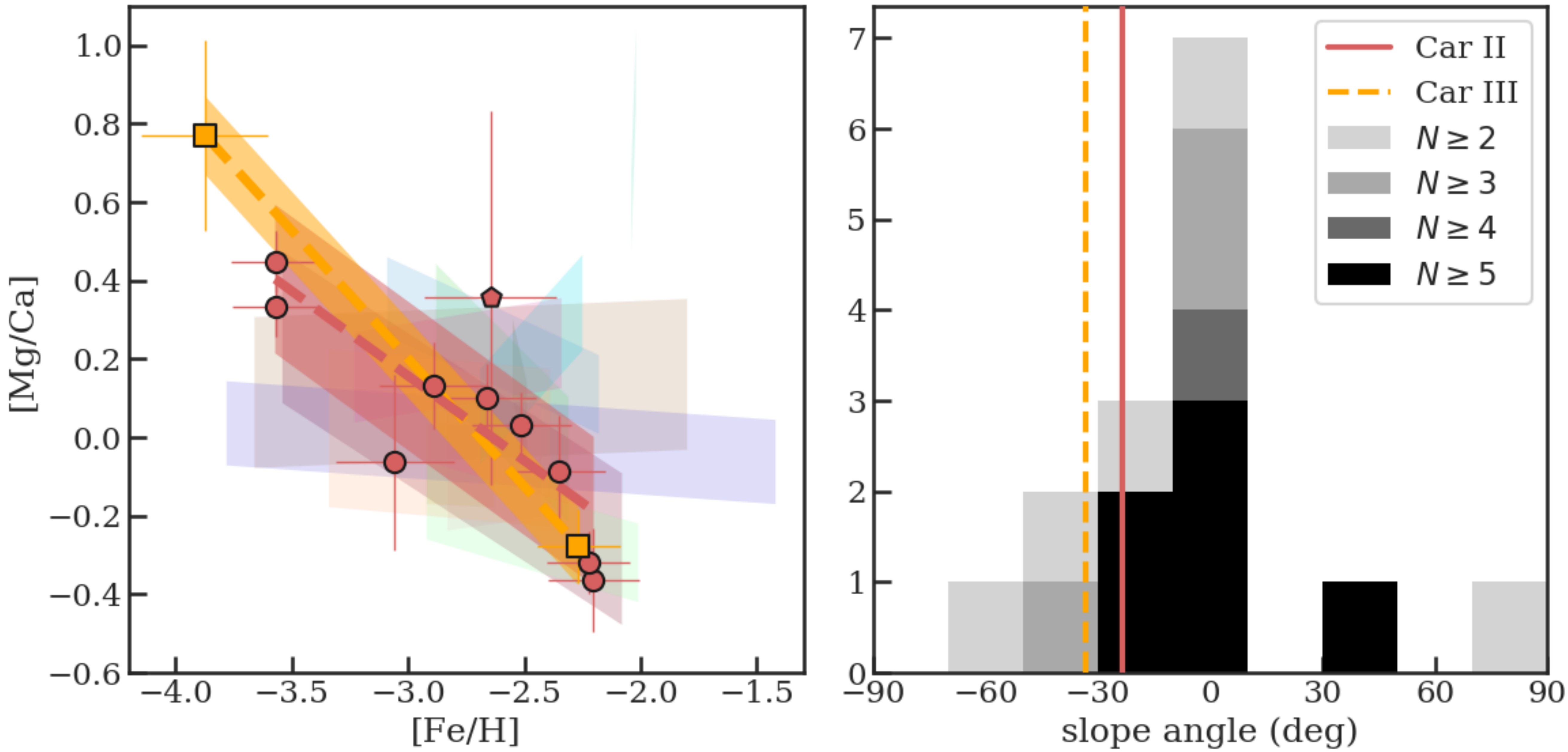
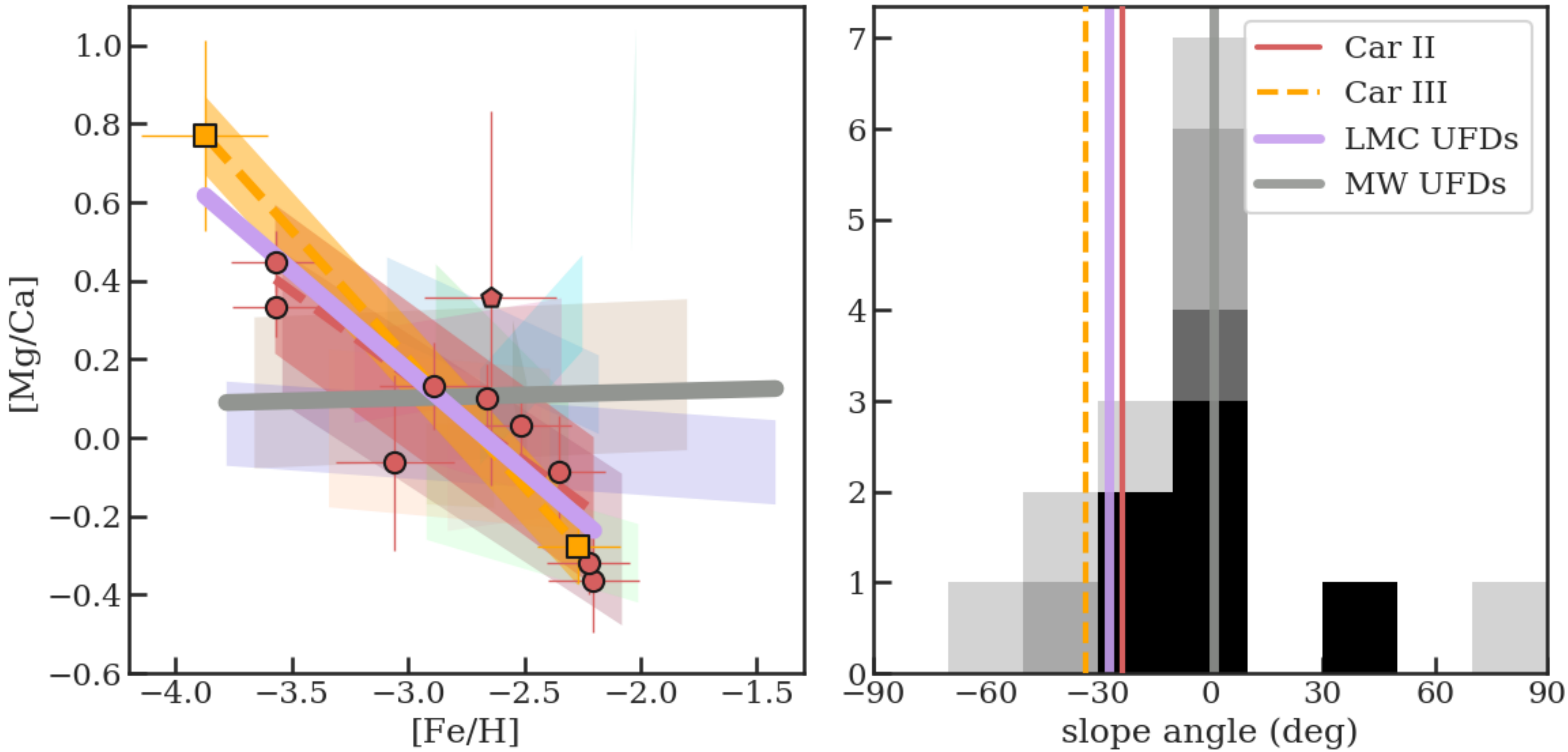
[Mg/Ca] slope varies in UFDs



Ji et al. in prep

LMC and MW UFDs have different [Mg/Ca] slopes



LMC UFDs = Car II, Car III, Hor I

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Ji et al. in prep

α-elements in Car II and III

- **Not all α-elements behave the same.**
  In Car II, [Mg/Ca] clearly varies by a factor of ~5

- Possible explanations:
  - Stochastic IMF sampling
  - Systematic IMF variation
  - Inhomogeneous metal mixing
  - Type Ia SNe with high Ca yields

- LMC satellites* have stronger [Mg/Ca] variations:
  Environment-dependent abundance signature?

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*Car II currently dominates LMC satellite stars

Nucleosynthesis

Nuclear physics
Stellar evolution
Supernovae
Stellar populations

$$[X / H]$$

Normally, X and H are highly degenerate

Hierarchical galaxy formation
Gas accretion and expulsion
Metal mixing
Star formation

Galaxy Formation

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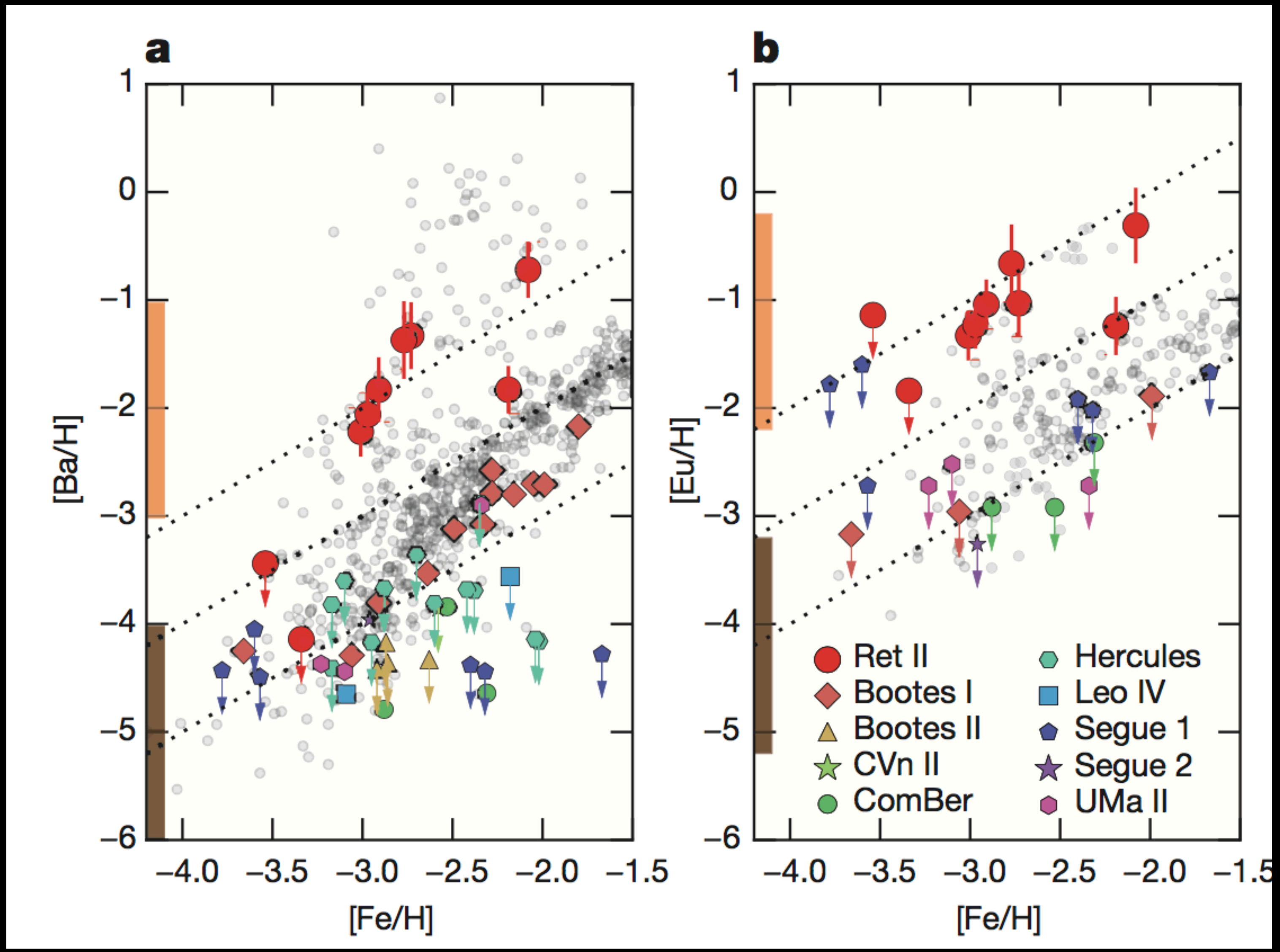
Use the *r*-process galaxy Reticulum II to measure inhomogeneous metal mixing

- Most Ret II stars enriched by a single neutron star binary merger
- All r-process elements deposited at one time: [r/H] distribution traces metal mixing



Barium:
- good dynamic range
- easy to measure

Europium:
- traces r-process
- hard to measure

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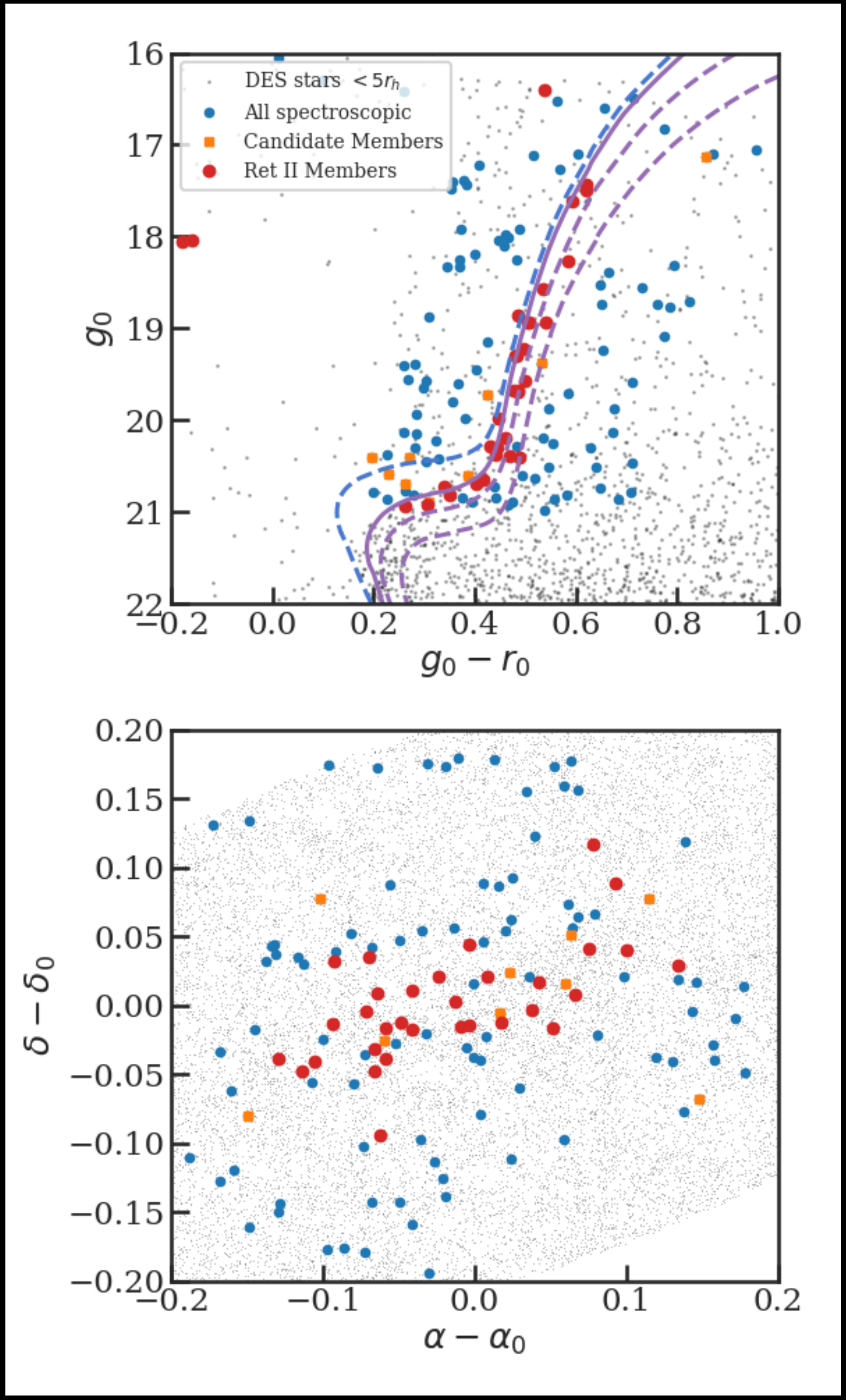
Ji et al. 2016

New Ret II Observations

- Goal: measure [Ba/H] scatter
- 12 hours FLAMES
  + 14 hours M2FS
  around strong Ba line
- 32 clear members
  + 9 candidates
  17+2 [Ba/H] measurements
- Confirms previous velocity and metallicity dispersions:
  σ_V=2.7±0.4 km/s
  σ_{Fe}=0.25±0.07 dex



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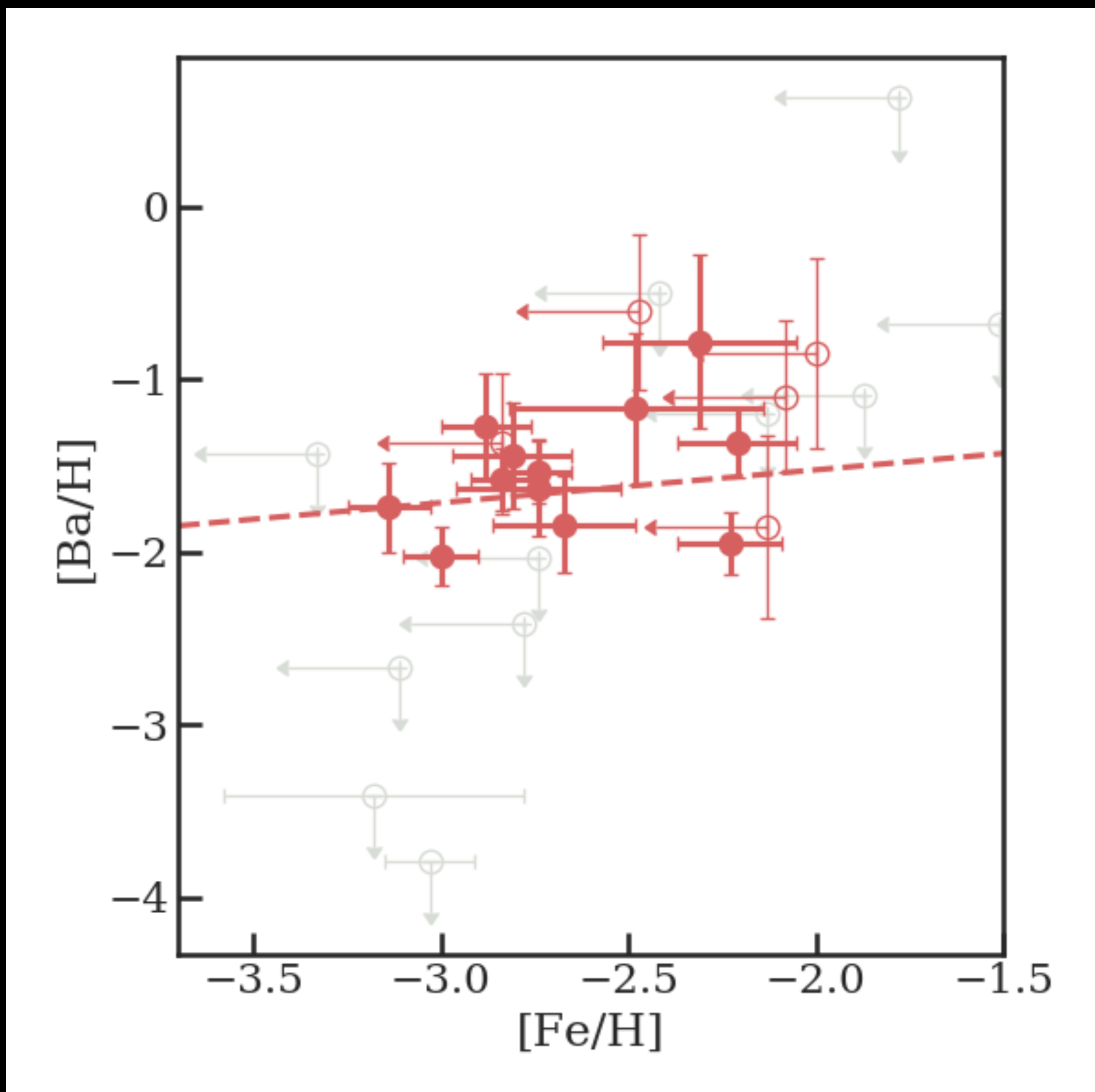
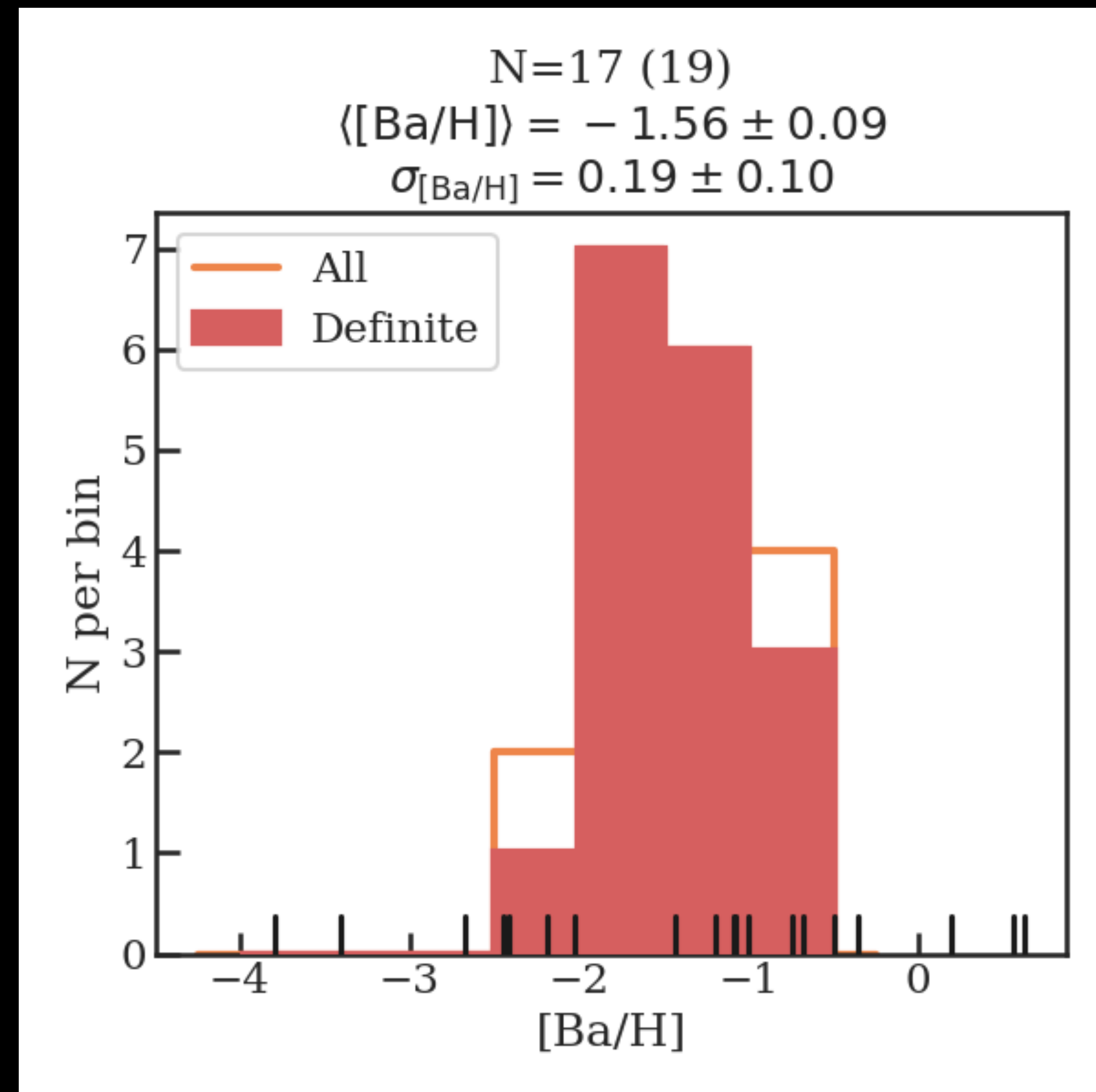
Well-mixed metals in Ret II





A reasonable model for inhomogeneous mixing:
lognormal hydrogen dilution mass
Mean ~10^6 M_{sun}, Scatter ~0.2 dex

Ji et al. in prep

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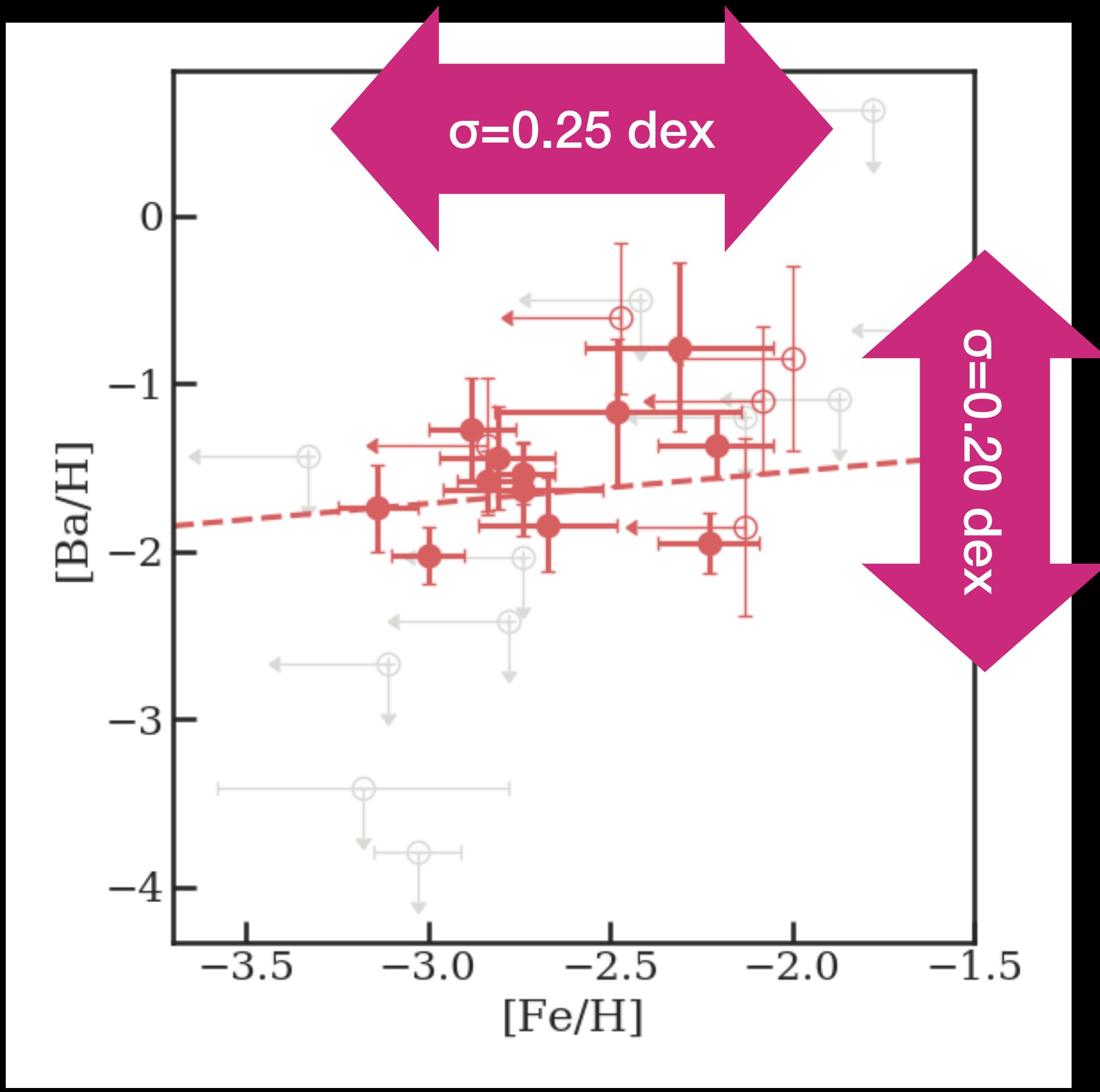

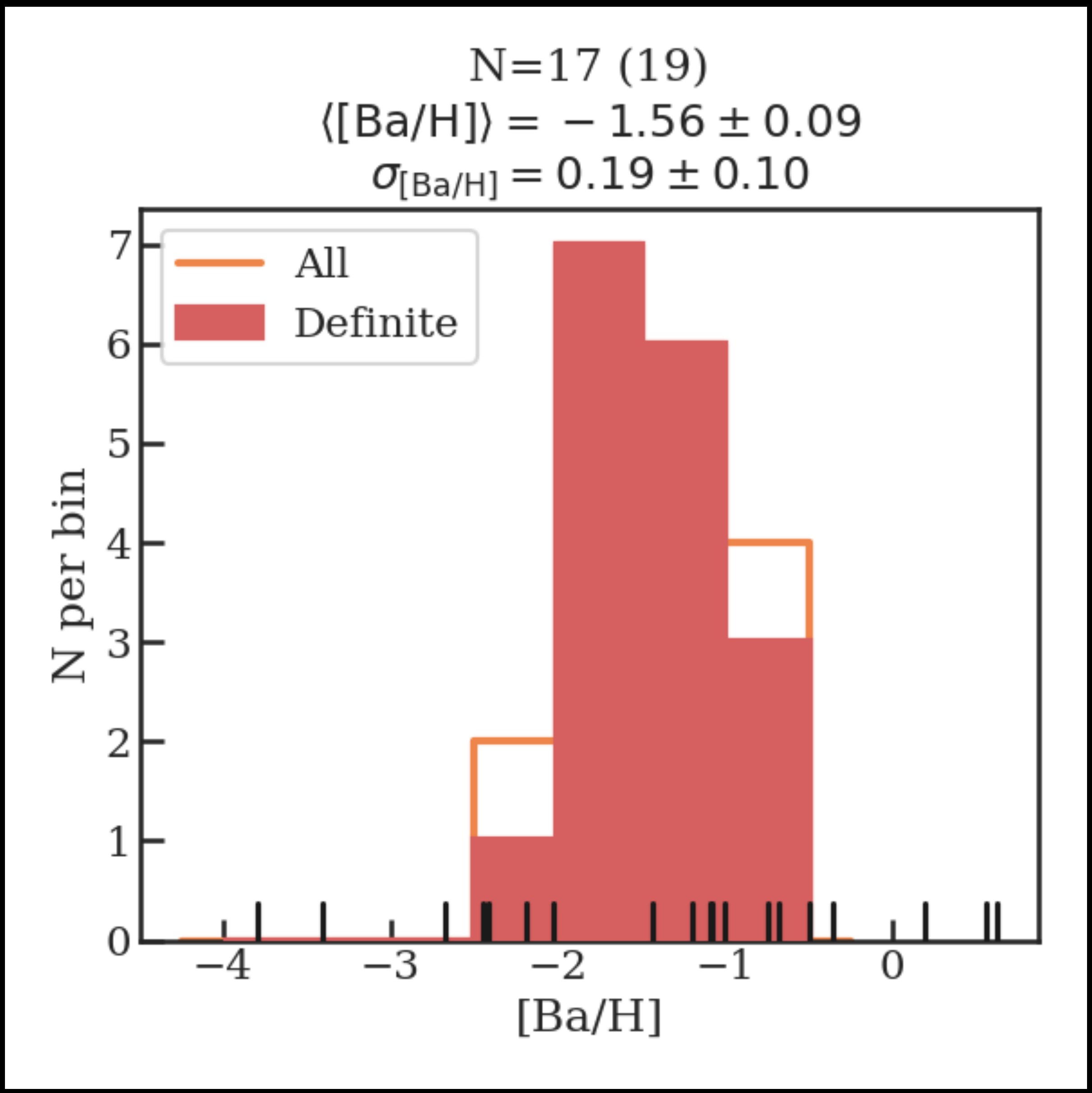

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Ji et al. in prep

Ret II Takeaways

- 32 Ret II members + 9 candidates confirm previous velocity and metallicity dispersions

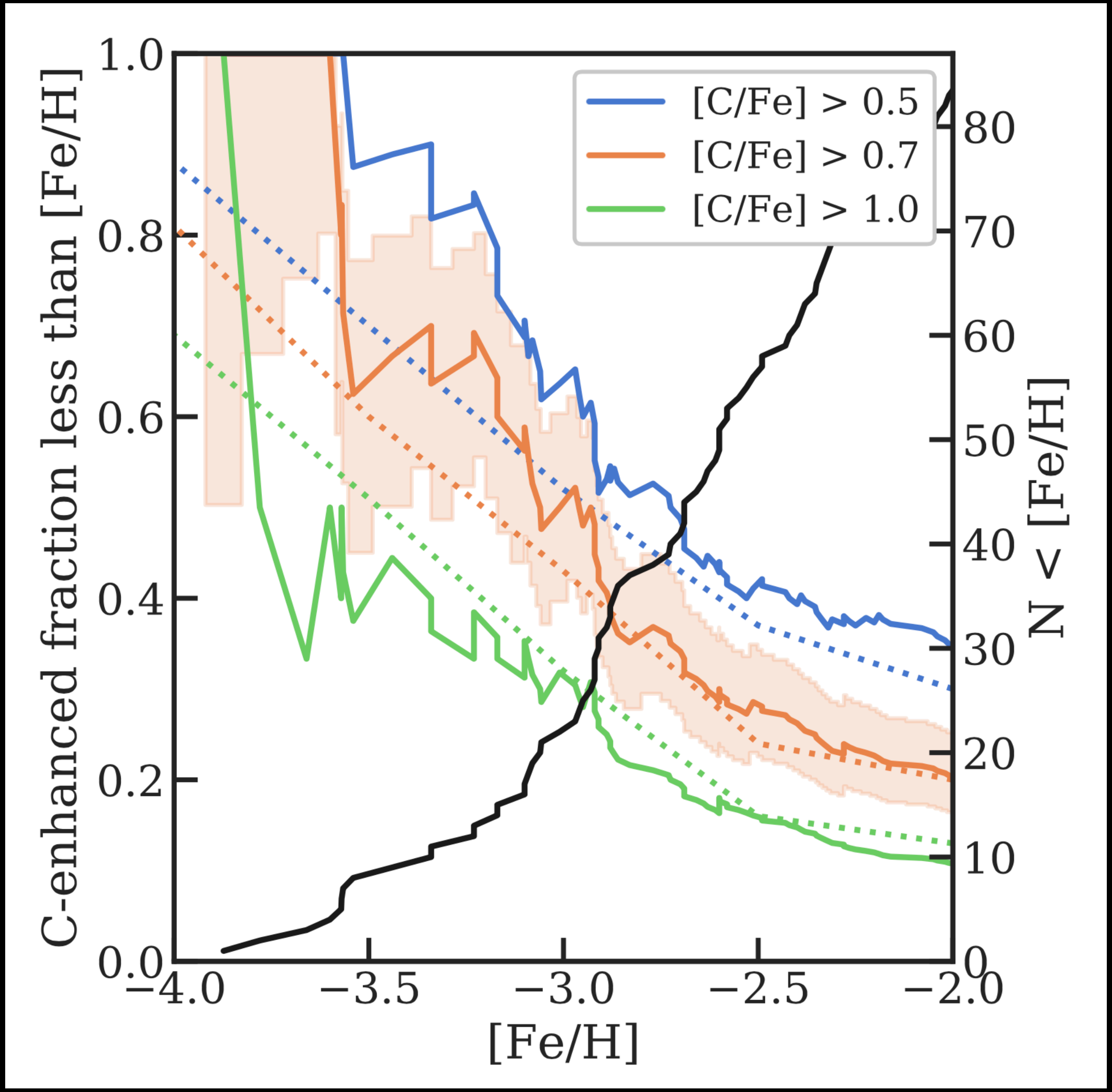
- The r-process material is well-mixed in Ret II:
  - Can attribute ~0.2 dex [X/H] scatter to inhomogeneous metal mixing in UFDs

- If the [Ba/H] trend is flat over large [Fe/H] range:
  - lack of pristine gas accretion?

What is the Pop III initial mass function?

- Two approaches using Pop II star abundances:
  - **Carbon-enhanced (CEMP) fraction:**
    Empirical signature likely associated with Pop III stars
  - **Direct model fits:** use grid of Pop III CCSN yields to fit detailed stellar abundances of the most Fe-poor stars ([Fe/H] < -3.5)
- UFD stars are great for this from theory side:
  minimize galaxy formation degeneracies (but expensive)
- **Carina II/III have 3 of the 9 most Fe-poor stars in UFDs**

The CEMP fraction of UFD stars matches the MW stellar halo



colored dotted lines: halo CEMP fraction
colored solid lines: UFD CEMP fraction

Note: the most Fe-poor stars in a given UFD have similar [C/Fe]

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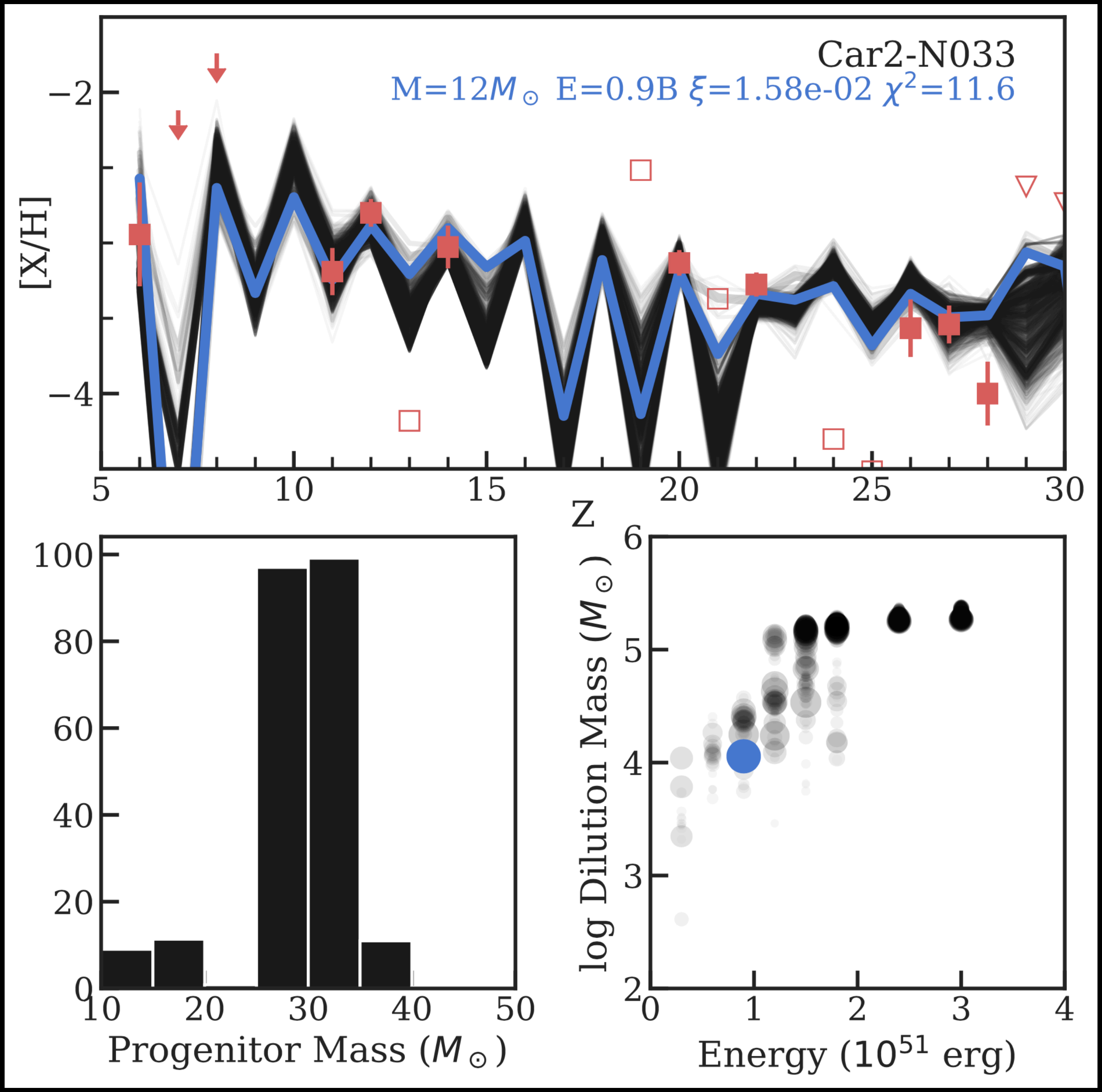
Ji et al. in prep

Pop III CCSN Yields Can Fit Most Fe-poor UFD stars

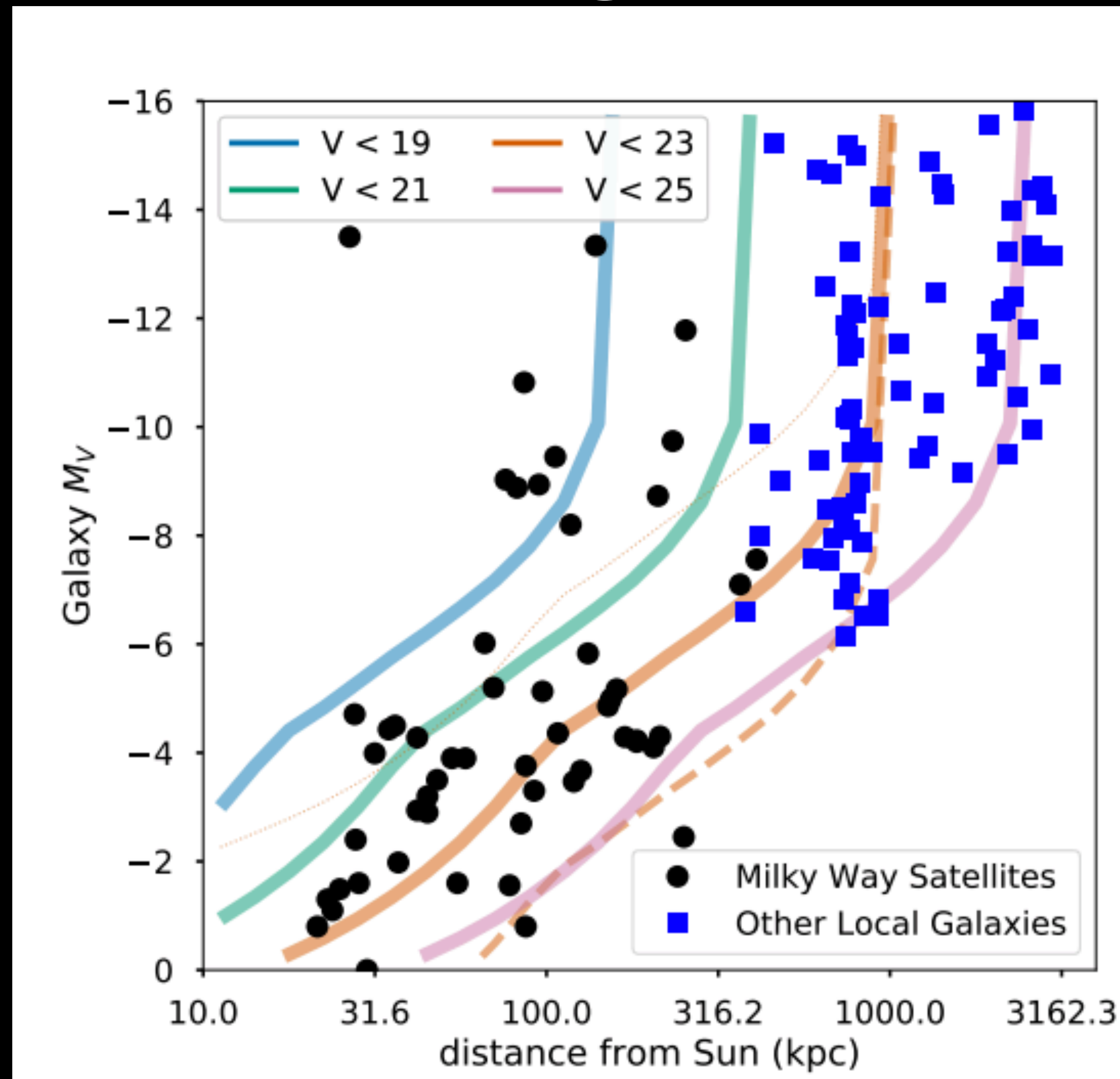


- Two stars in Carina II, one star in Carina III with [Fe/H] ~ -3.5
- Most-likely moderate energy ~30 M_{sun} SNe (Heger+Woosley 2010)
- Likely ***not*** external enrichment (unless the 1SN assumption is broken)

The future: how many stars are accessible per galaxy?

Current Capability	ELT Capability
100 stars HRS 1000 stars LRS	Only 1h obs. needed
(10 stars HRS) 100 stars MRS	100 stars HRS 1000 stars MRS
(<1 star HRS) (10 stars MRS)	(10 stars HRS) 100 stars MRS
(<1 star MRS)	(10 stars MRS)

Assuming ~1 night per field (need multiobject spectroscopy) and old metal-poor stellar pop



Ji et al. 2019, Astro 2020 Decadal Survey White Paper

Summary

- Magellanic satellite galaxies Carina II and III:
  Strongly decreasing [Mg/Ca] vs [Fe/H] trend
  Signatures of IMF variation? Environment dependence?

- Reticulum II: empirical measurement of metal mixing
  Can attribute ~0.2 dex *stellar* [X/H] scatter to inhomogeneous metal mixing in UFDs

- Pop III star signatures in UFDs do not appear to differ from the MW halo