The Galactic Chemical Evolution of the Magellanic Clouds Reveal the *r*-process Enrichment Timescale

Kevin Schlaufman (JHU)
Henrique Reggiani (Carnegie Observatories)
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Josh Simon (Carnegie Observatories)
Alex Ji (University of Chicago)

INT Workshop 20R-1b: The *r*-process and the Nuclear EOS after LIGO-Virgo's Third Observing Run
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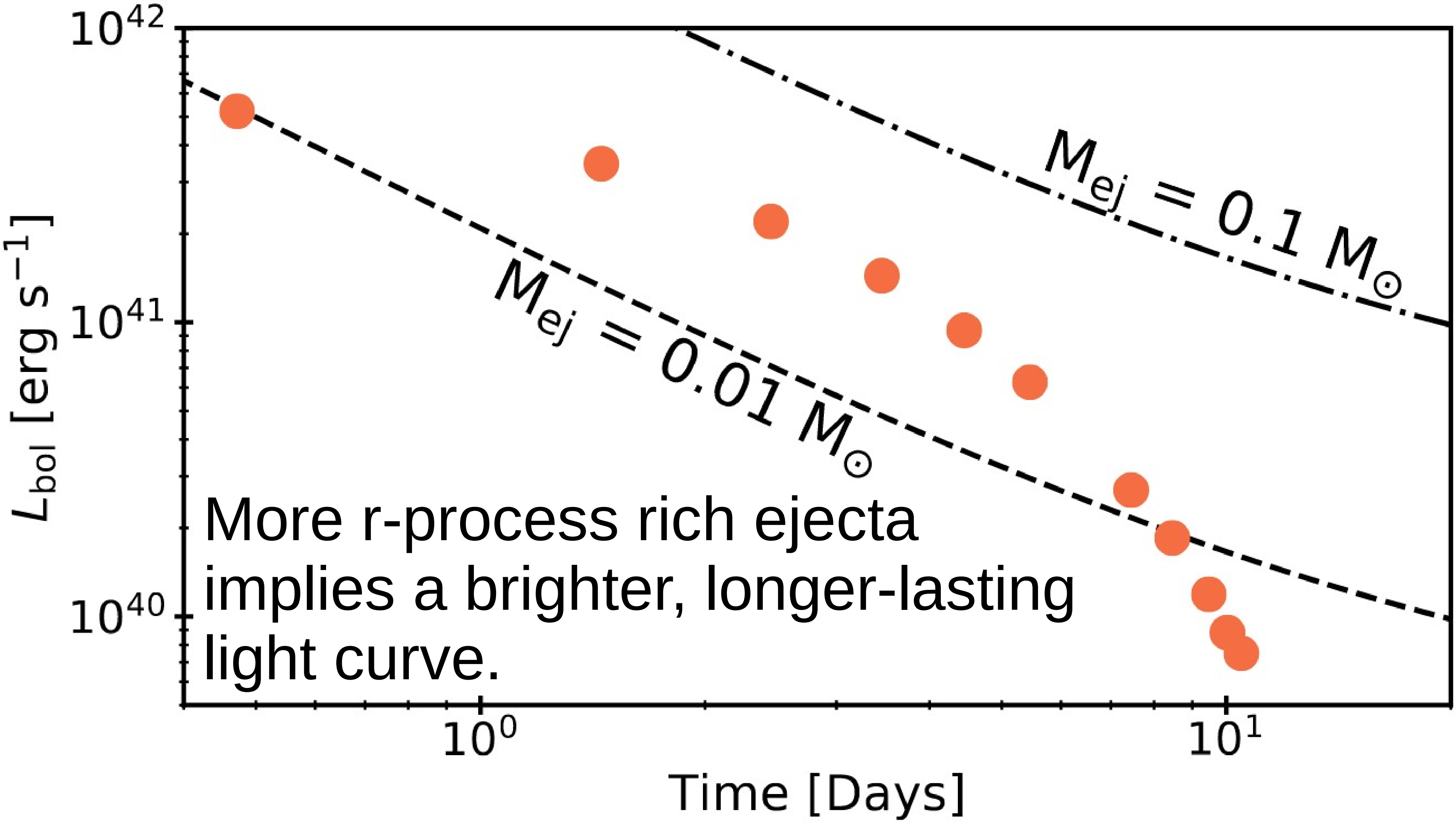
GW170817 *r*-process Insights

Kevin Schlaufman
27 May 2022



More r-process rich ejecta implies a brighter, longer-lasting light curve.

Cowperthwaite et al. (2017)

GW170817 *r*-process Insights

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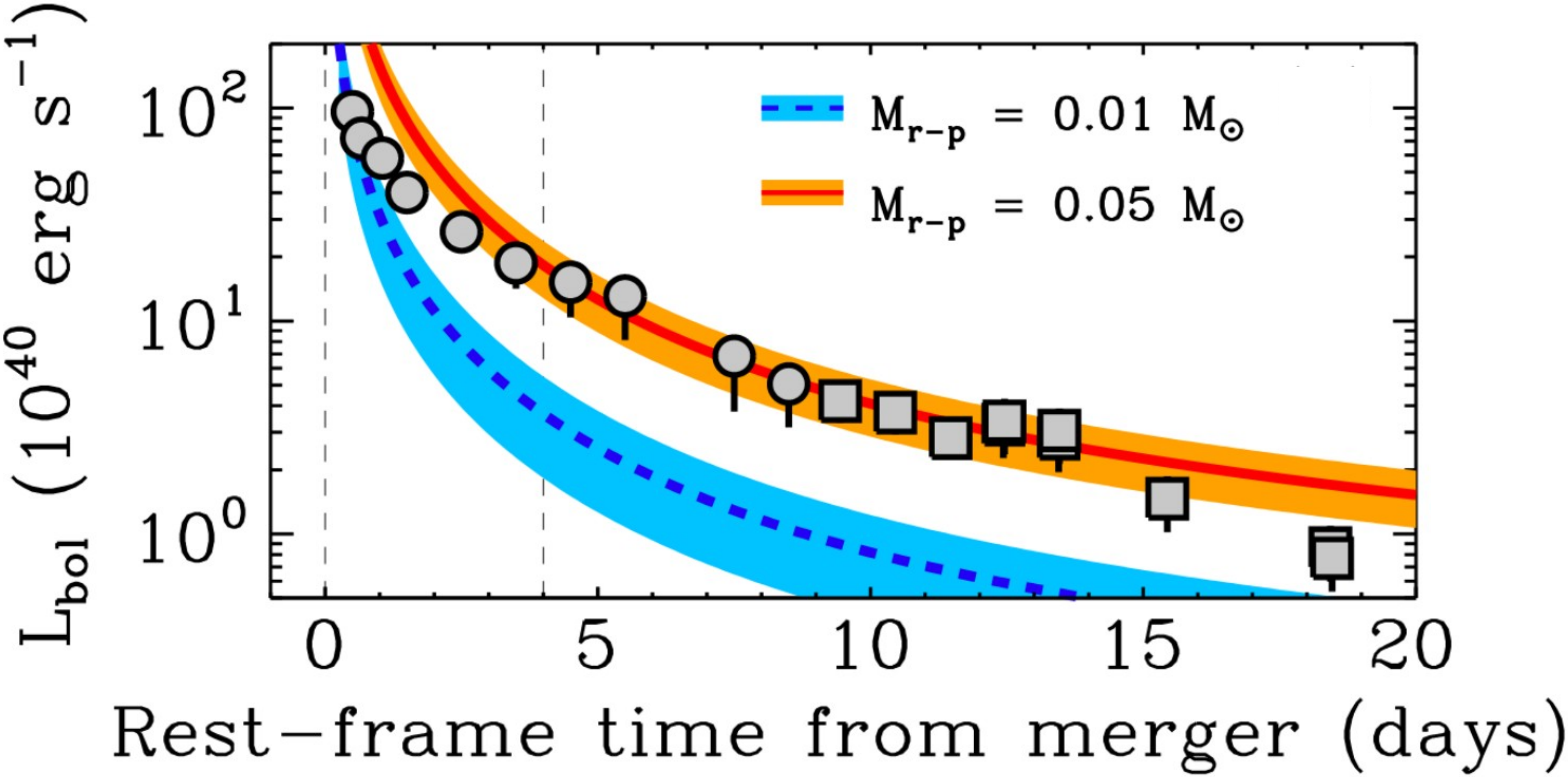

Drout et al. (2017)

GW170817 *r*-process Insights

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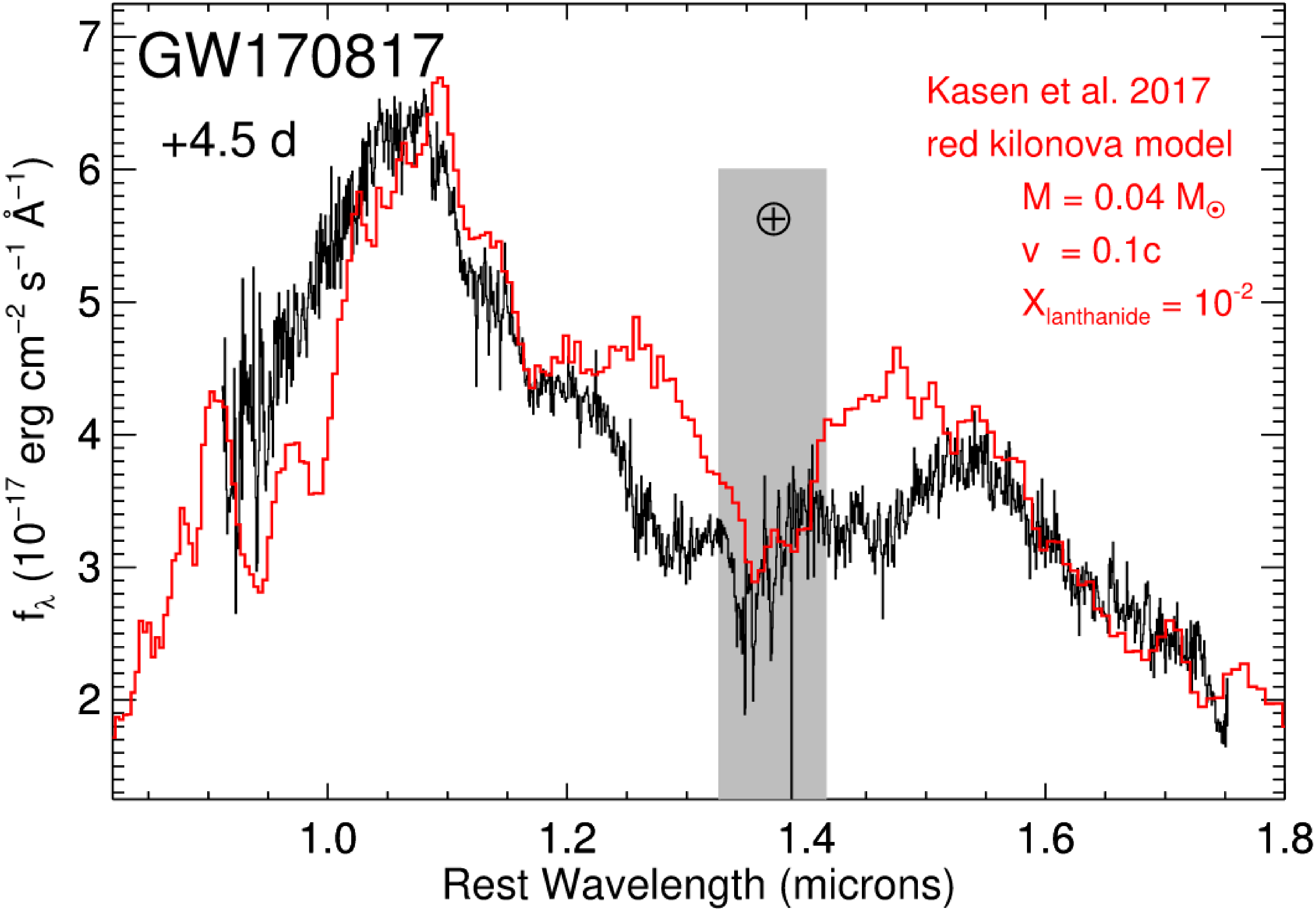

Chornock et al. (2017)

More to Come...

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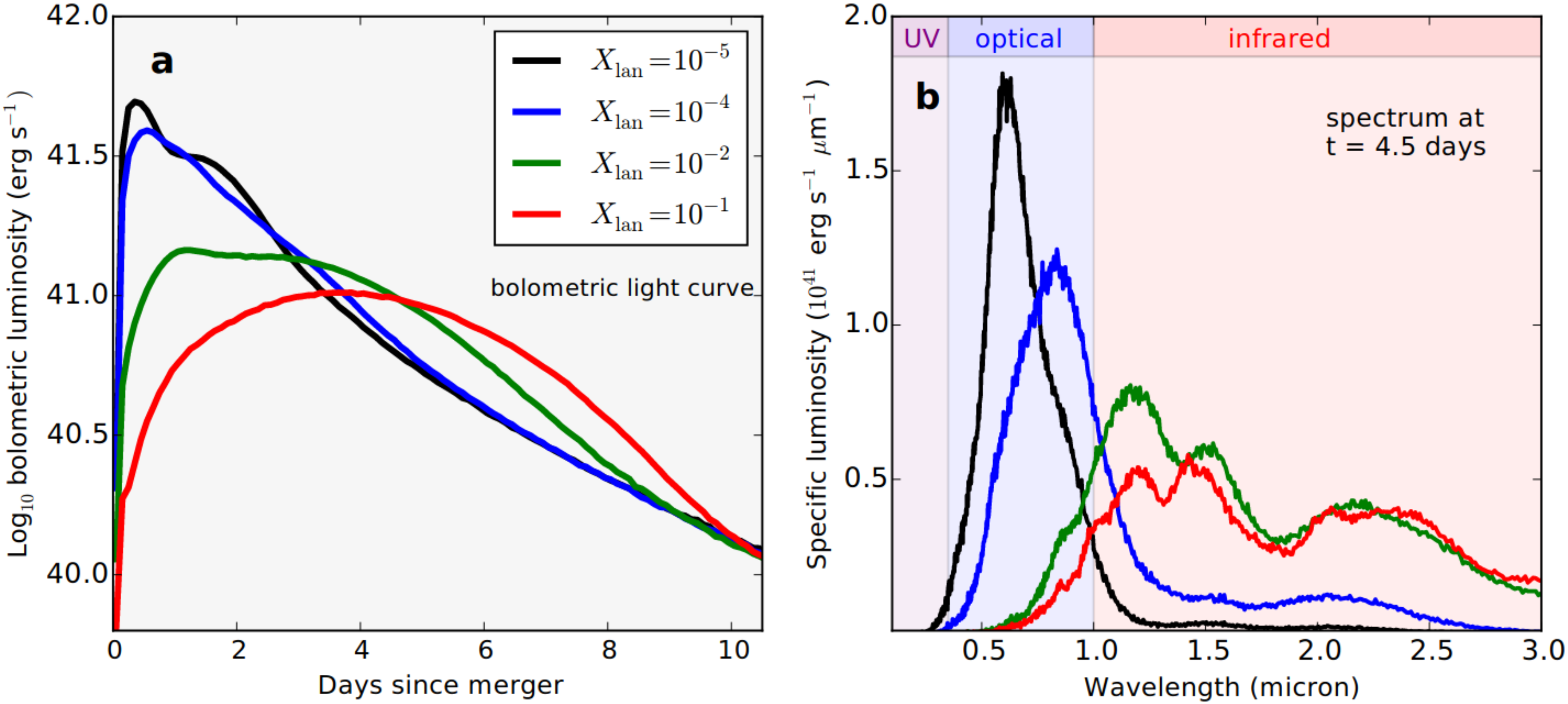

More lanthanides imply a higher opacity and therefore a less-peaked, longer-lasting light curve with a redder spectrum.

Kasen et al. (2017)

NS Mergers Make *r*-process

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GW170817 makes it clear that binary neutron star mergers produce *r*-process elements.

GW170817 does not by itself imply that all *r*-process nucleosynthesis comes from massive compact object mergers involving a neutron star.

Yield/Occurrence Degeneracy

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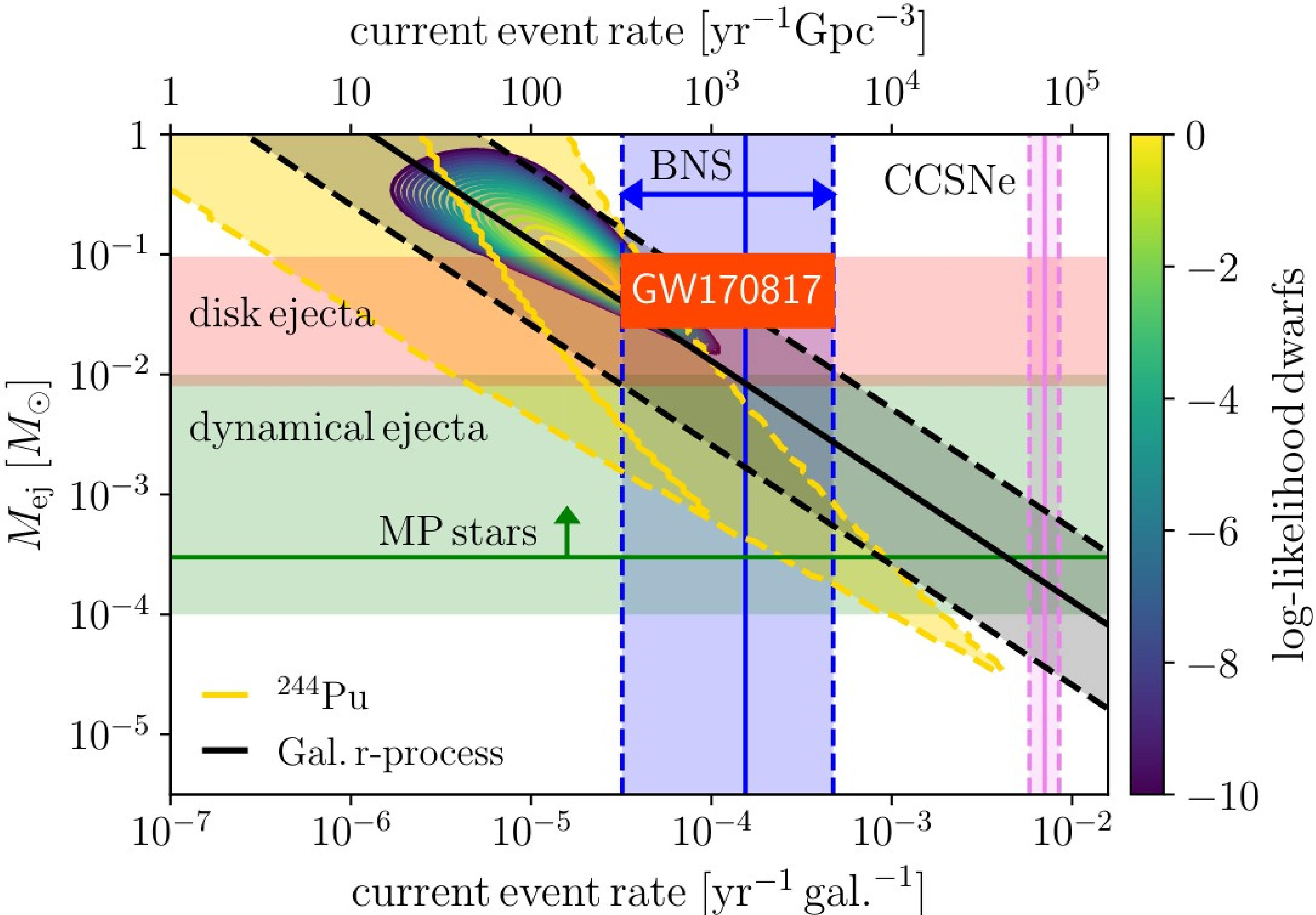

Siegel (2019)

Two New *r*-process Constraints

Kevin Schlaufman

(1) The most neutron-capture poor star requires a low-yield source of *r*-process elements (Casey & Schlaufman 2017).

(2) The chemical evolution of the Magellanic Clouds require a prolific source of *r*-process elements that are produced with a significant time delay after the era of the first core-collapse supernovae in those stellar populations (Reggiani et al. 2021).

Universality of the *r*-process

Kevin Schlaufman
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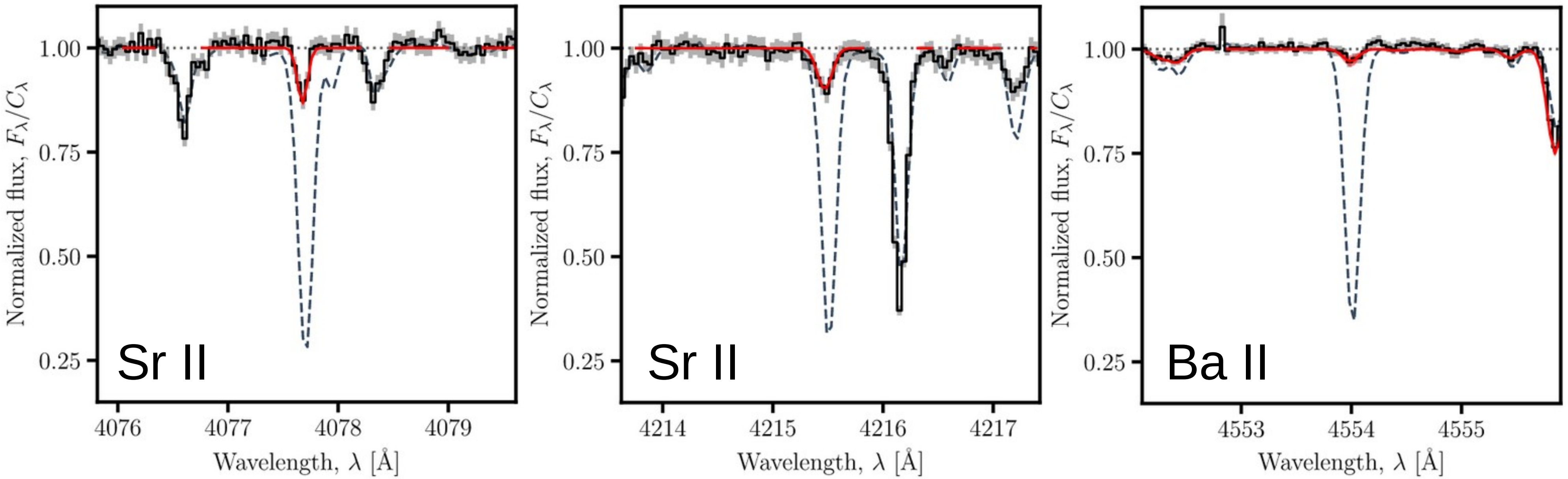
Casey & Schlaufman (2017)



2MASS J15111324-2130030 is the most neutron-capture-poor star ever observed.

Its Sr and Ba lines are 100x weaker than HD 126587, a standard extremely metal-poor star with similar photospheric parameters and solar [Sr/Fe] & [Ba/Fe].

Definition of [X/Y]

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27 May 2022

$$[\mathrm{X/Y}] \equiv \log_{10}\left(\frac{N_{\mathrm{X}}}{N_{\mathrm{Y}}}\right)_{*} - \log_{10}\left(\frac{N_{\mathrm{X}}}{N_{\mathrm{Y}}}\right)_{\odot}$$

$$N_{\mathrm{H},\odot} \equiv 12.00$$

Key points:

(1) Relative to solar abundances

(2) Logarithmic

Useful values:

(1) $N_{\mathrm{O,Sun}} = 8.69$

(2) $N_{\mathrm{Mg,Sun}} = 7.55$

(3) $N_{\mathrm{Fe,Sun}} = 7.46$

(4) $N_{\mathrm{Eu,Sun}} = 0.52$

Asplund et al. (2021)

Universality of the *r*-process

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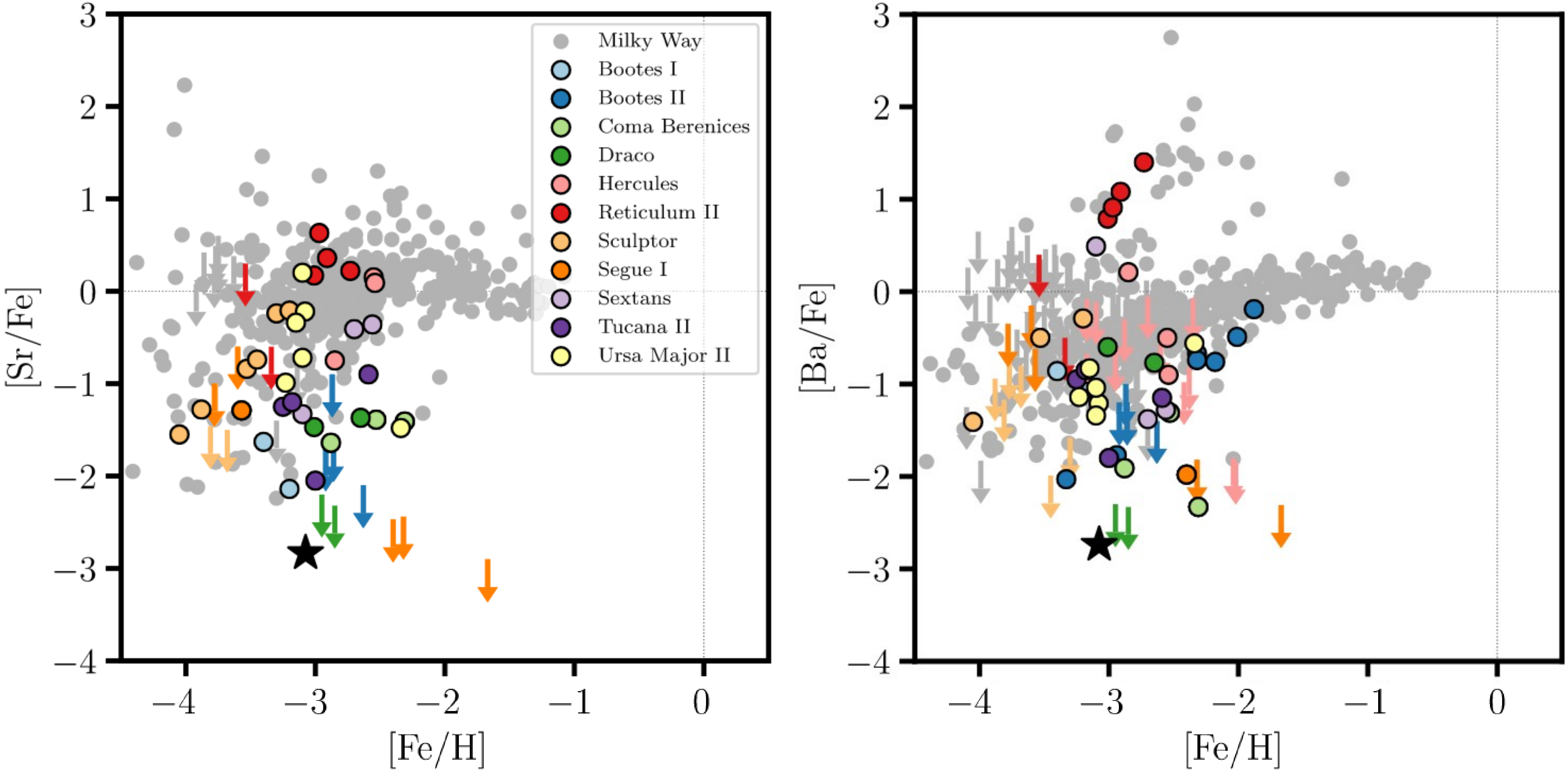
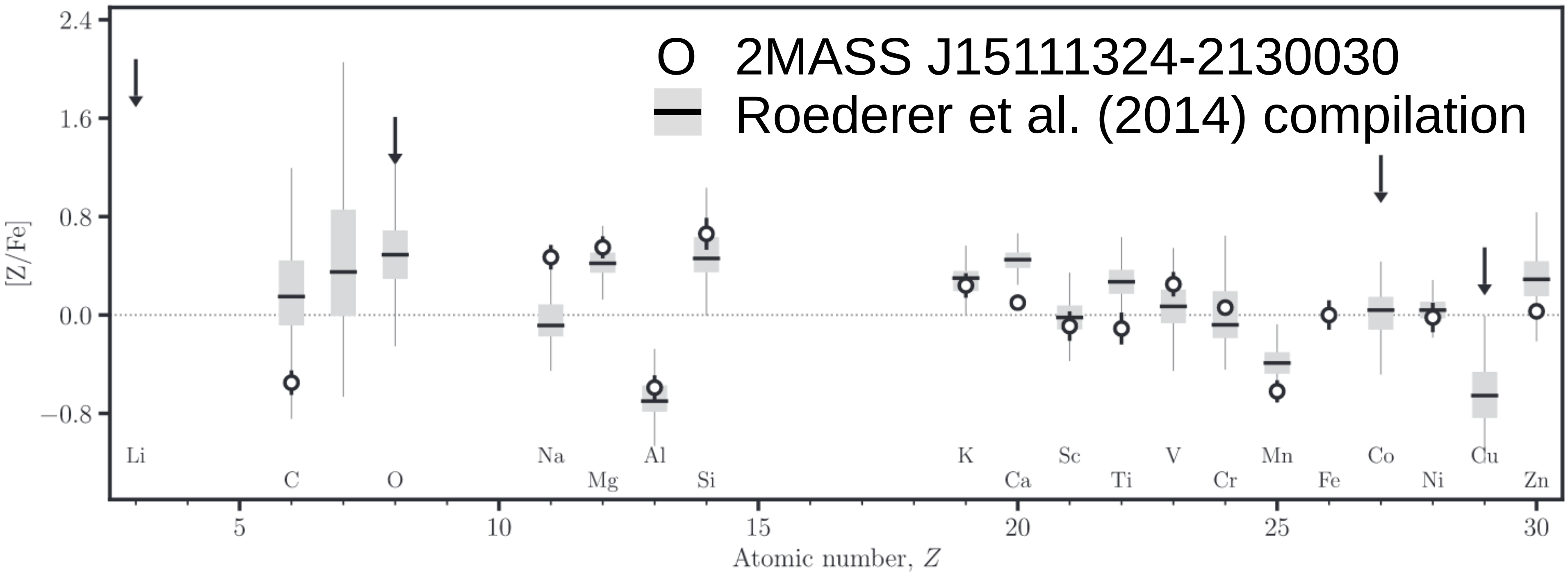
Casey & Schlaufman (2017)



2MASS J1511-2130 is the most neutron-capture-poor star ever observed.

Universality of the *r*-process

Casey & Schlaufman (2017)



2MASS J1511-2130 has ordinary α, light odd *Z*, and iron-peak elemental abundances.

Universality of the *r*-process

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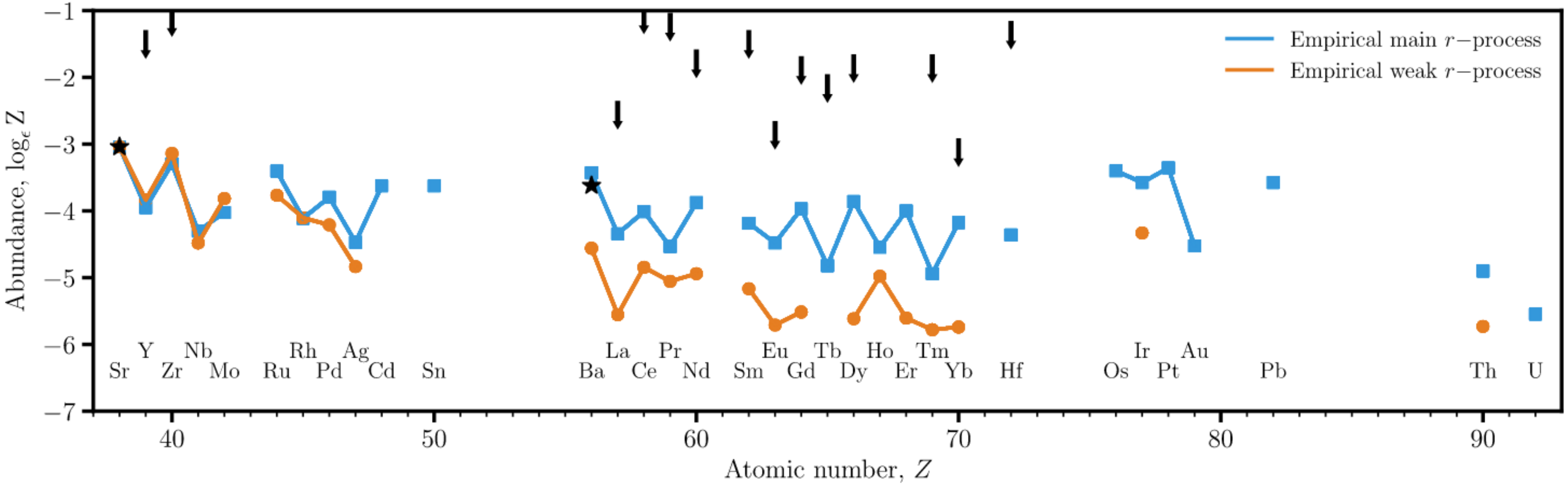
27 May 2022
Casey & Schlaufman (2017)



2MASS J1511-2130 has [Sr/Ba] = -0.11 +/- 0.14, fully consistent with the solar *r*-process [Sr/Ba] = -0.25.

Tension with GW170817-like Event

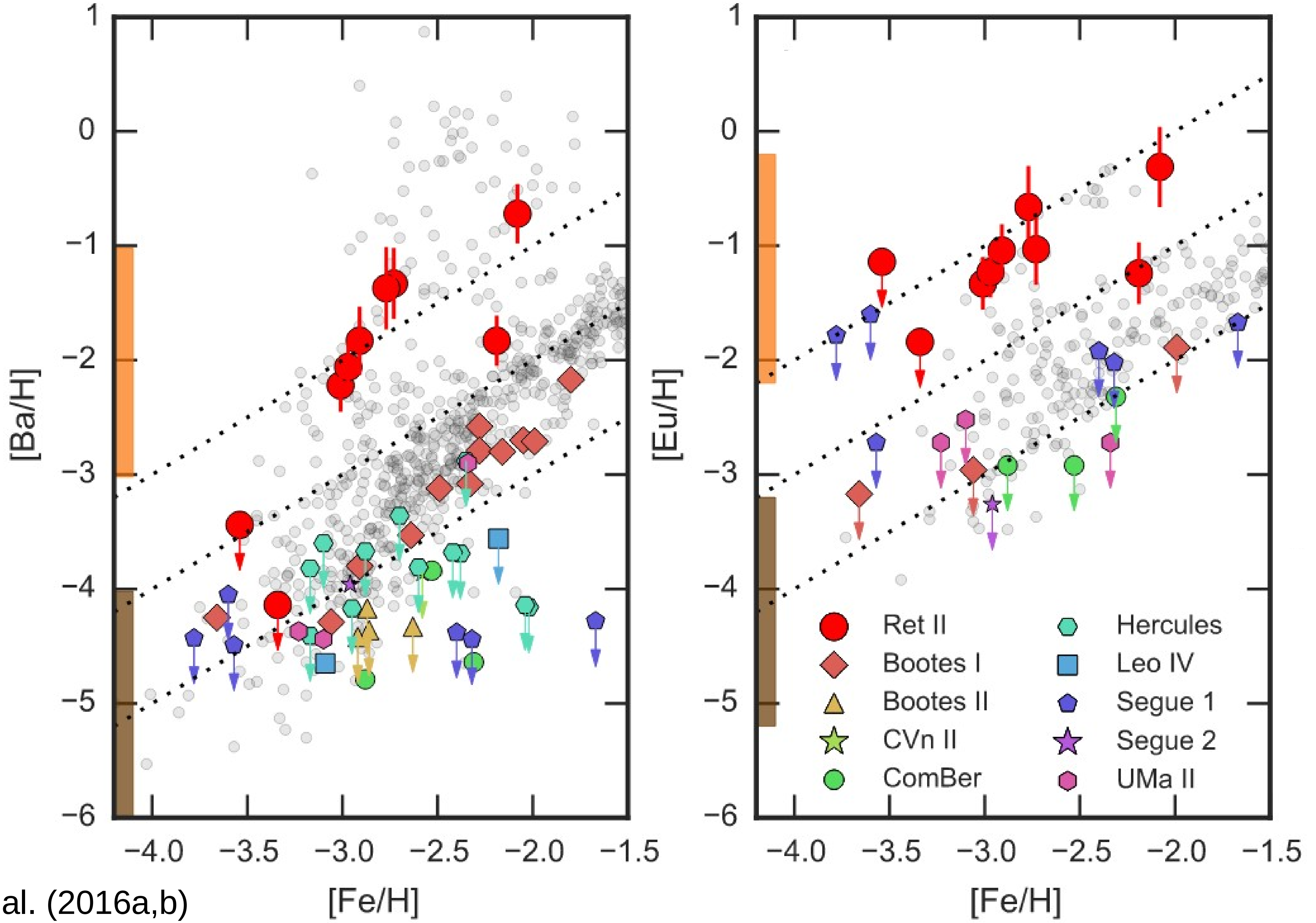
Casey & Schlaufman (2017)

2MASS J1511-2130 has about 5 x 10^{-14} M_{Sun} of strontium. GW170817 produced about 10^{-2} M_{Sun} of neutron-capture elements. Therefore:

(1) Since strontium is the most abundant element in the solar *r*-process pattern by a factor of two, 2MASS J1511-2130 has a total mass in neutron-capture elements of about 10^{-13} M_{Sun}.

(2) A cold gas mass of 10^{11} M_{Sun} would be necessary to dilute a GW170817-like yield down to the level observed in 2MASS J15111-2130. This is the entire gas content of the Milky Way.

Reticulum II



Ji et al. (2016a,b)
Roederer et al. (2016)

Tension with Reticulum II

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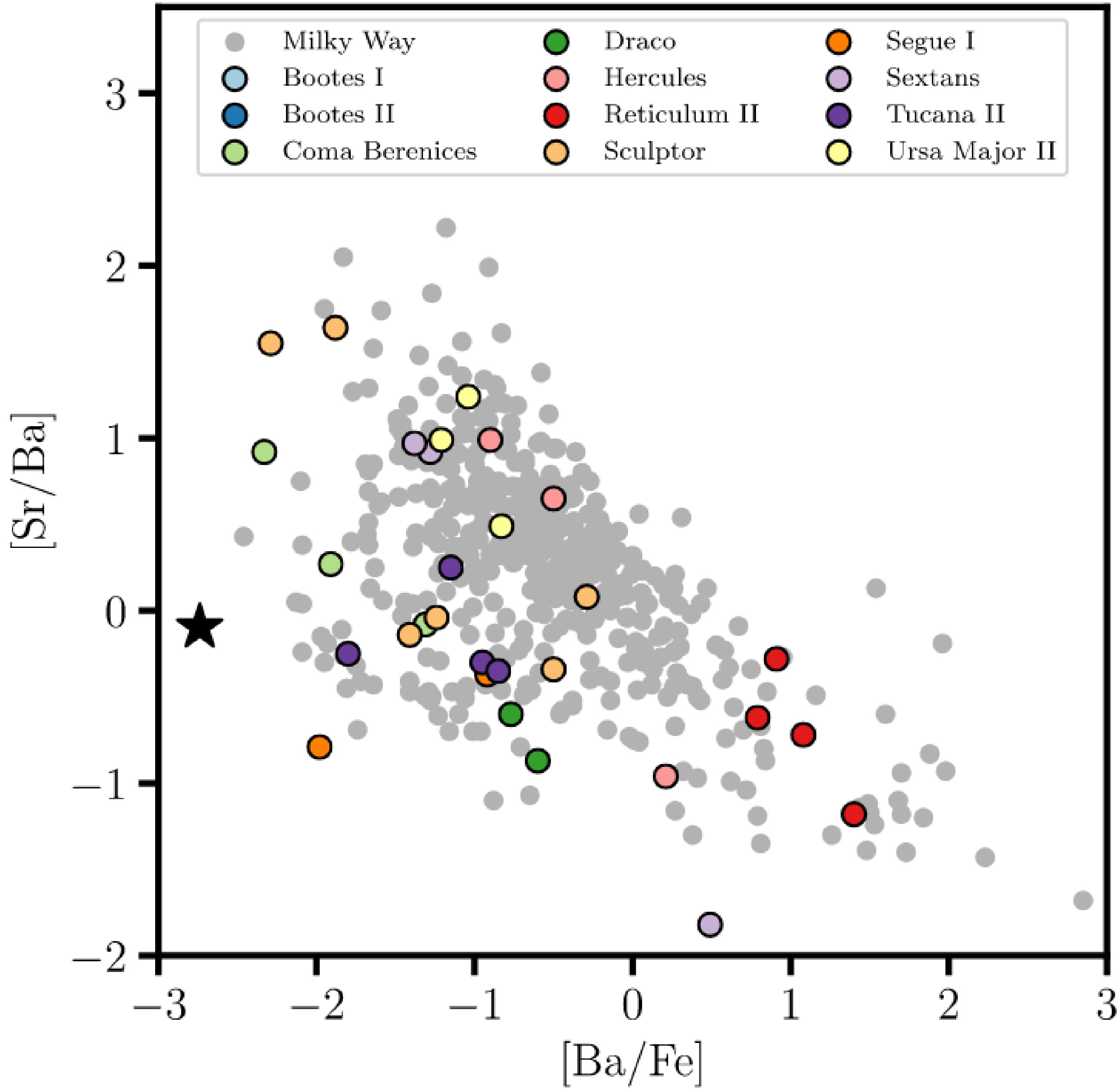
Casey & Schlaufman (2017)



Nucleosynthesis *t*-scale Diagnostics

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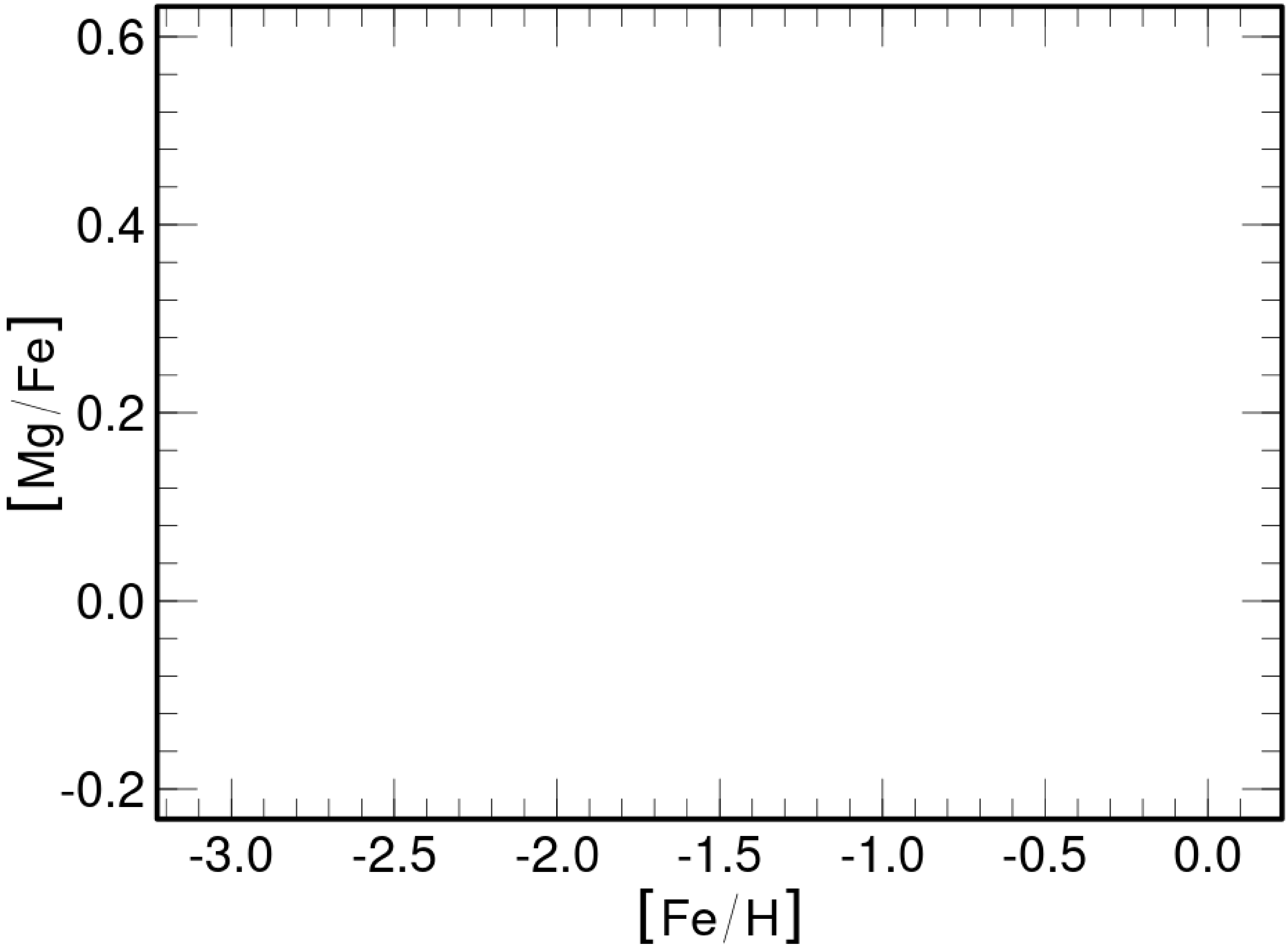

Nucleosynthesis *t*-scale Diagnostics

(1) The inference of magnesium and iron abundances in stellar photospheres is usually straightforward at all metallicities.

(2) Magnesium is mostly produced in hydrostatic carbon & neon burning and ejected into the interstellar medium by core collapse supernovae.

(3) Iron is mostly produced as radioactive nickel in oxygen or silicon-rich environments with $T \approx 4 \times 10^9$ K and low neutron excesses, either in core collapse (a little) or thermonuclear supernovae (a lot).

Nucleosynthesis *t*-scale Diagnostics

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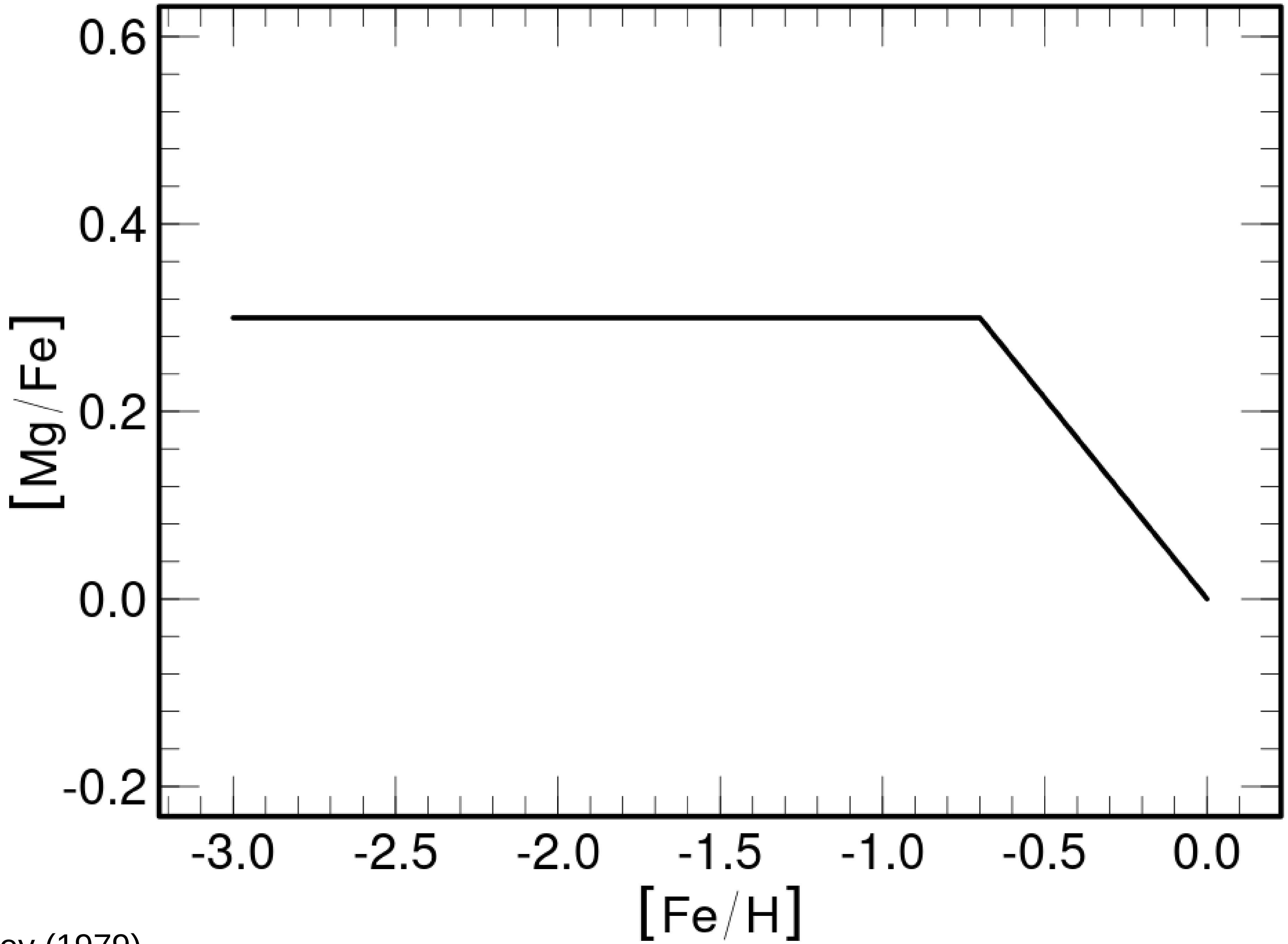
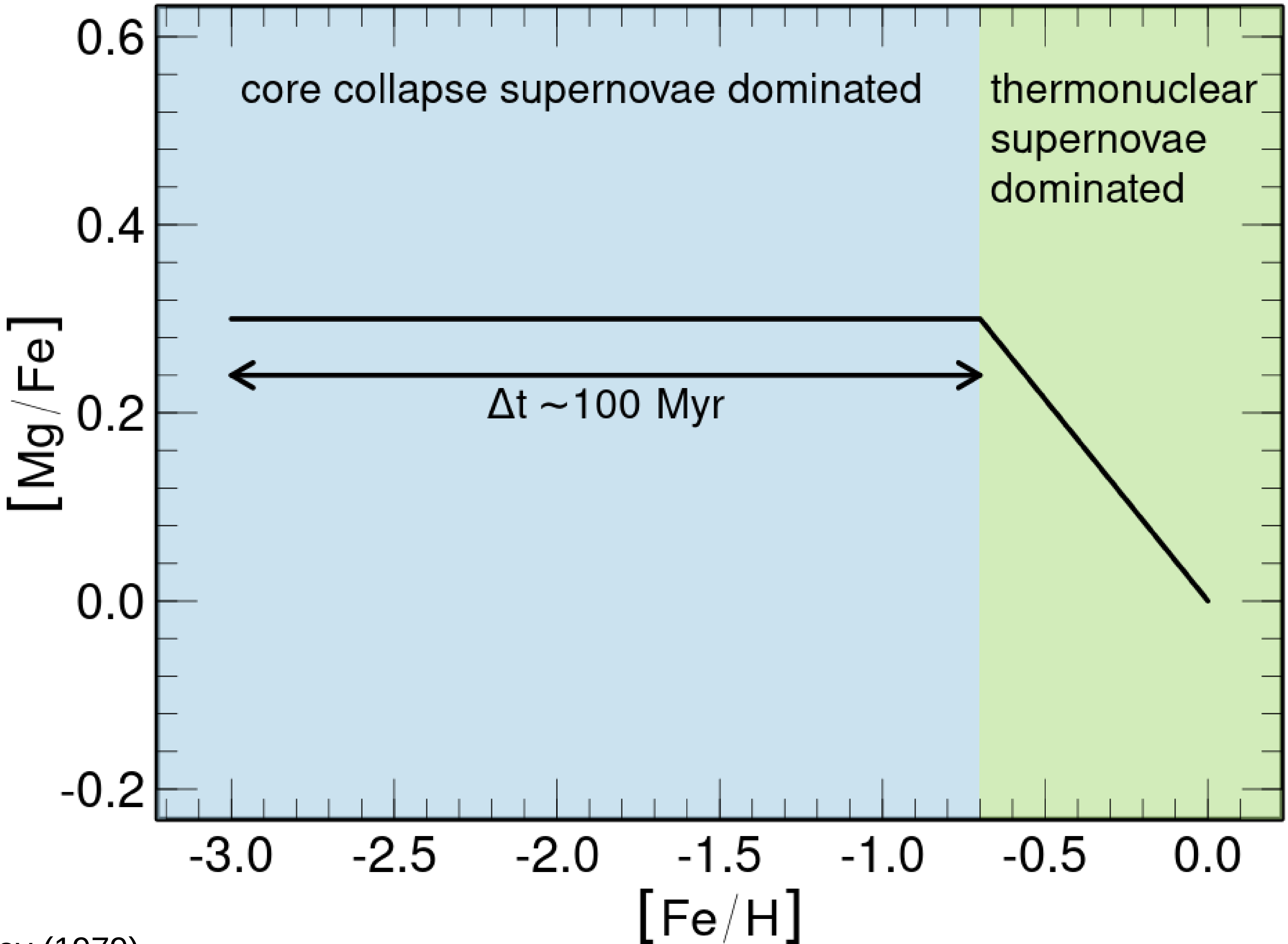


Tinsley (1979)

Nucleosynthesis *t*-scale Diagnostics



Tinsley (1979)

Nucleosynthesis *t*-scale Diagnostics

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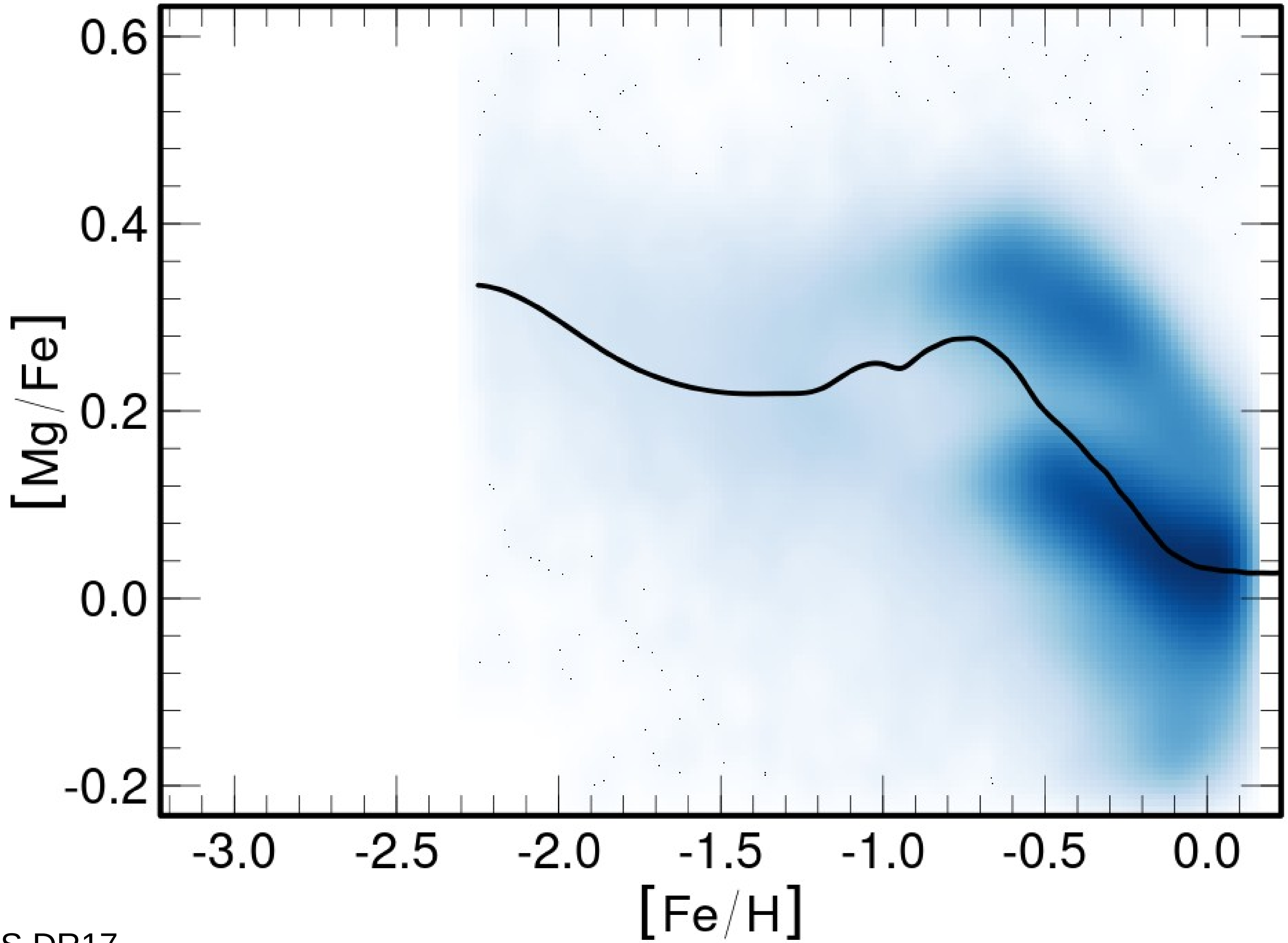

SDSS DR17

Nucleosynthesis *t*-scale Diagnostics

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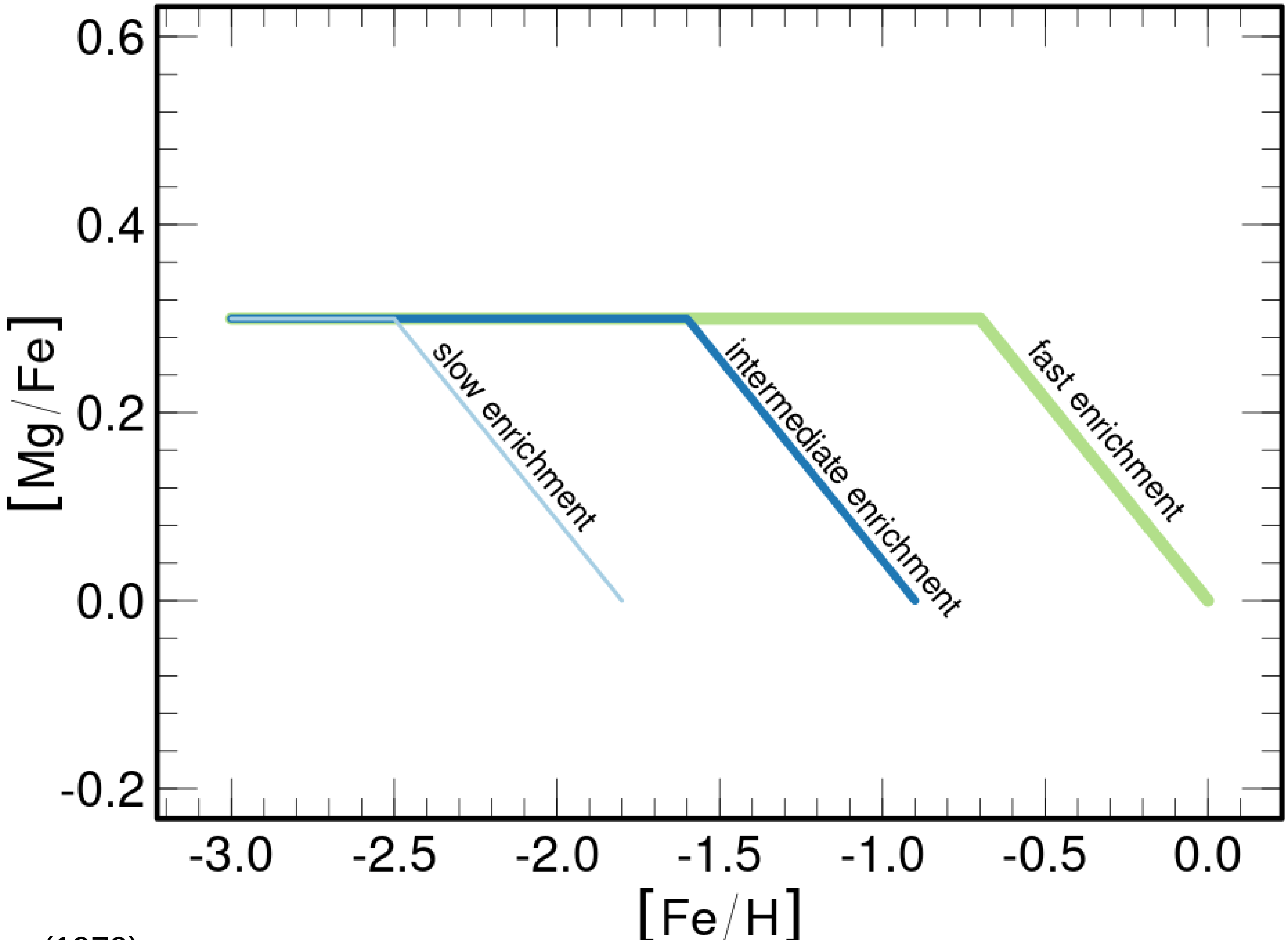

Tinsley (1979)

Nucleosynthesis *t*-scale Diagnostics

This is true of all massive galaxies:

(1) any element X produced promptly in massive stars or their supernovae, before the era of the first thermonuclear supernovae, will have significantly positive [X/Fe] at low [Fe/H].

(2) any element Y produced more slowly than the core-collapse supernova timescale, during or after the era of the era of the first thermonuclear supernovae, will have lower [Y/Fe] at low [Fe/H].

MW and its Satellite Galaxies

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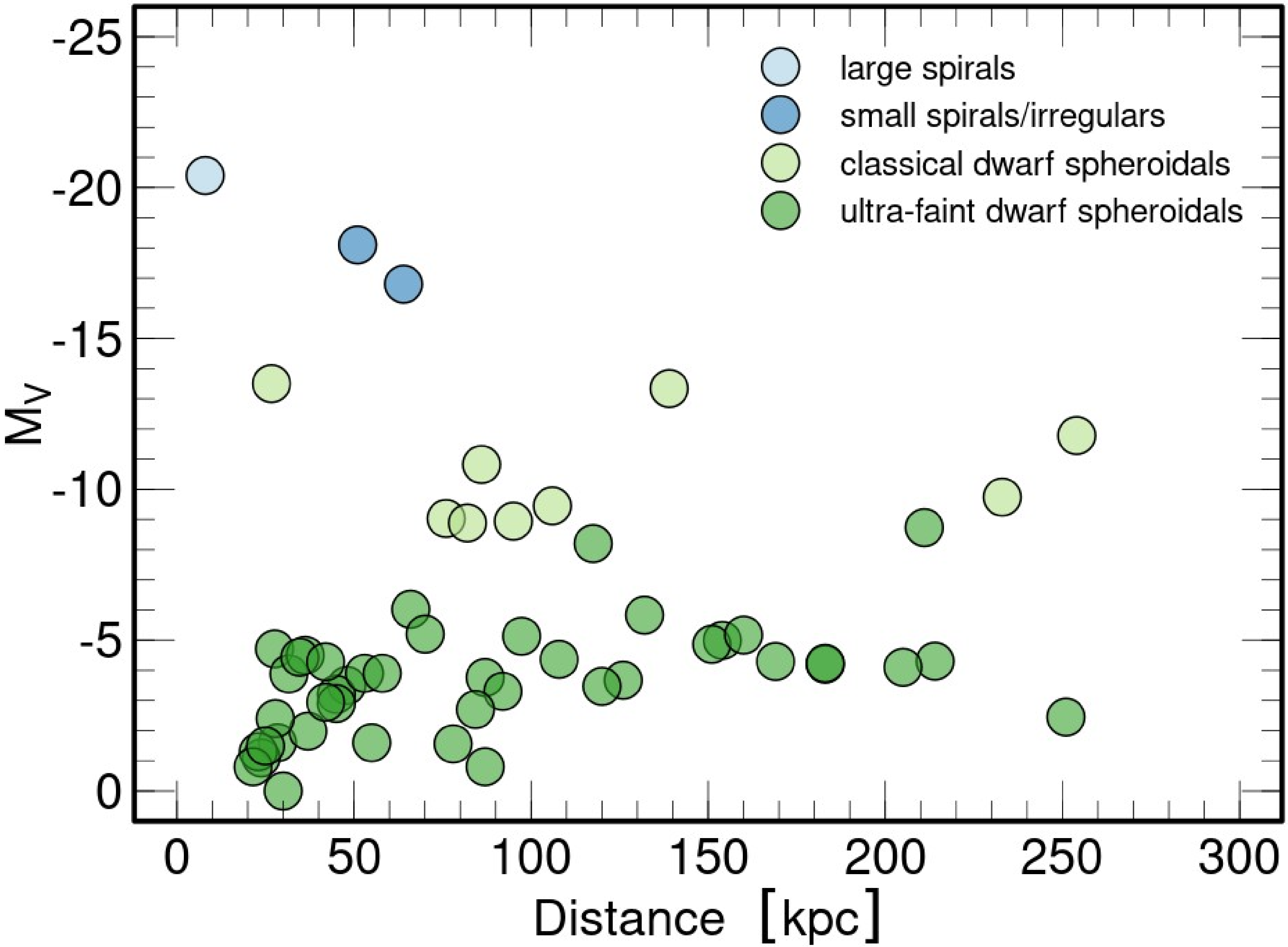
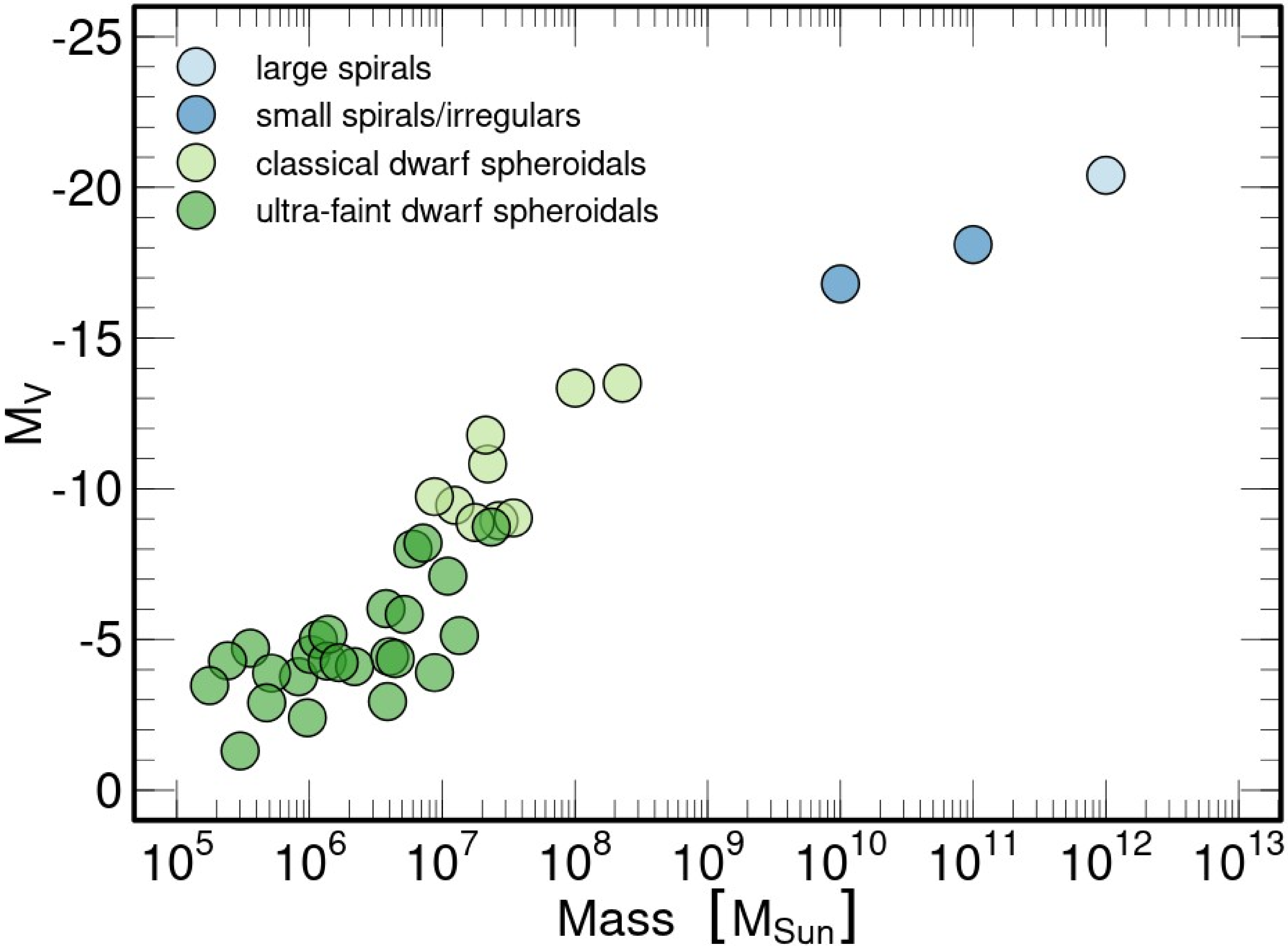
27 May 2022



MW and its Satellite Galaxies



MW Satellite Chemical Evolution

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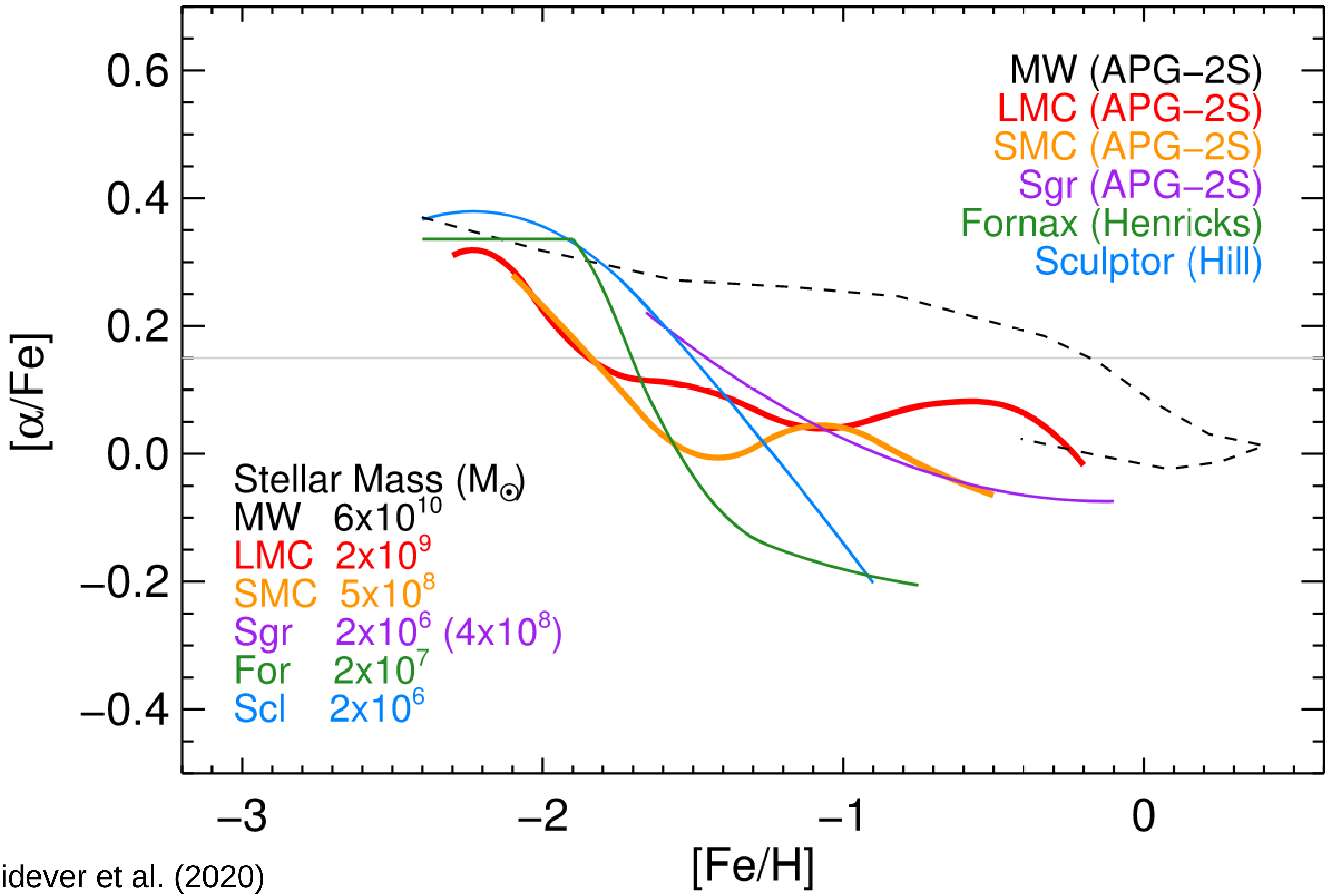

Nidever et al. (2020)

MW Satellite Chemical Evolution

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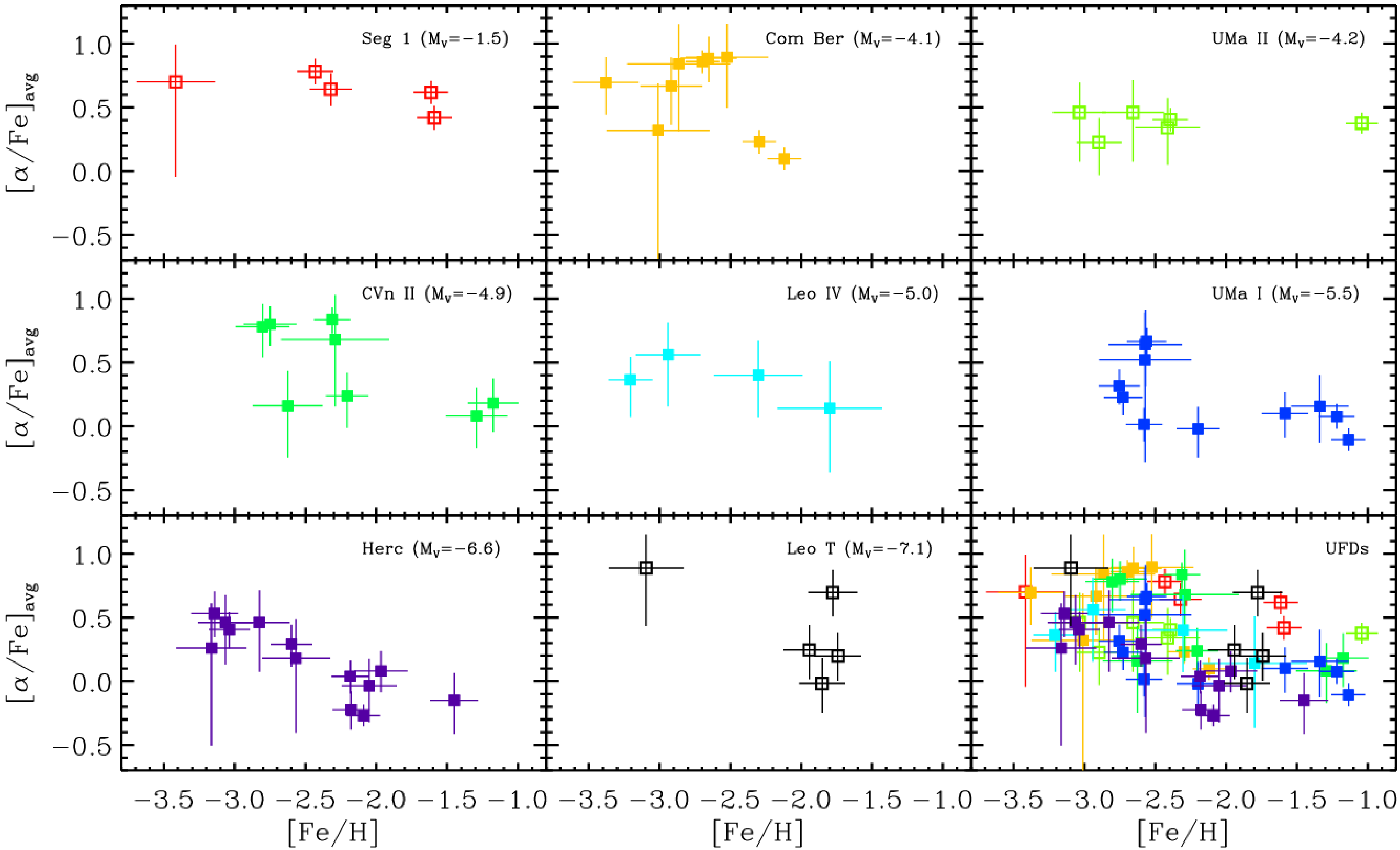

Vargas et al. (2013)

The Experiment

Reggiani et al. (2021)

If prolific *r*-process nucleosynthesis takes place mostly in low-occurrences event with timescales comparable to ordinary core-collapse supernovae—like collapsars or magnetorotationally powered supernovae—then the occurrence of *r*-process enhanced stars in the quickly enriched Milky Way and slowly enriched Magellanic Clouds should be similar.

The Experiment

Kevin Schlaufman
27 May 2022
Reggiani et al. (2021)

On the other hand, if prolific *r*-process nucleosynthesis occurs mostly in low-occurrences events with timescales longer than core-collapse supernovae but shorter than or comparable to thermonuclear supernovae—like mergers of neutron star—then the occurrence of *r*-process enhanced stars in the slowly enriched Magellanic Clouds should be be higher than in the quickly enriched Milky Way.

Abundance Distribution of Mg

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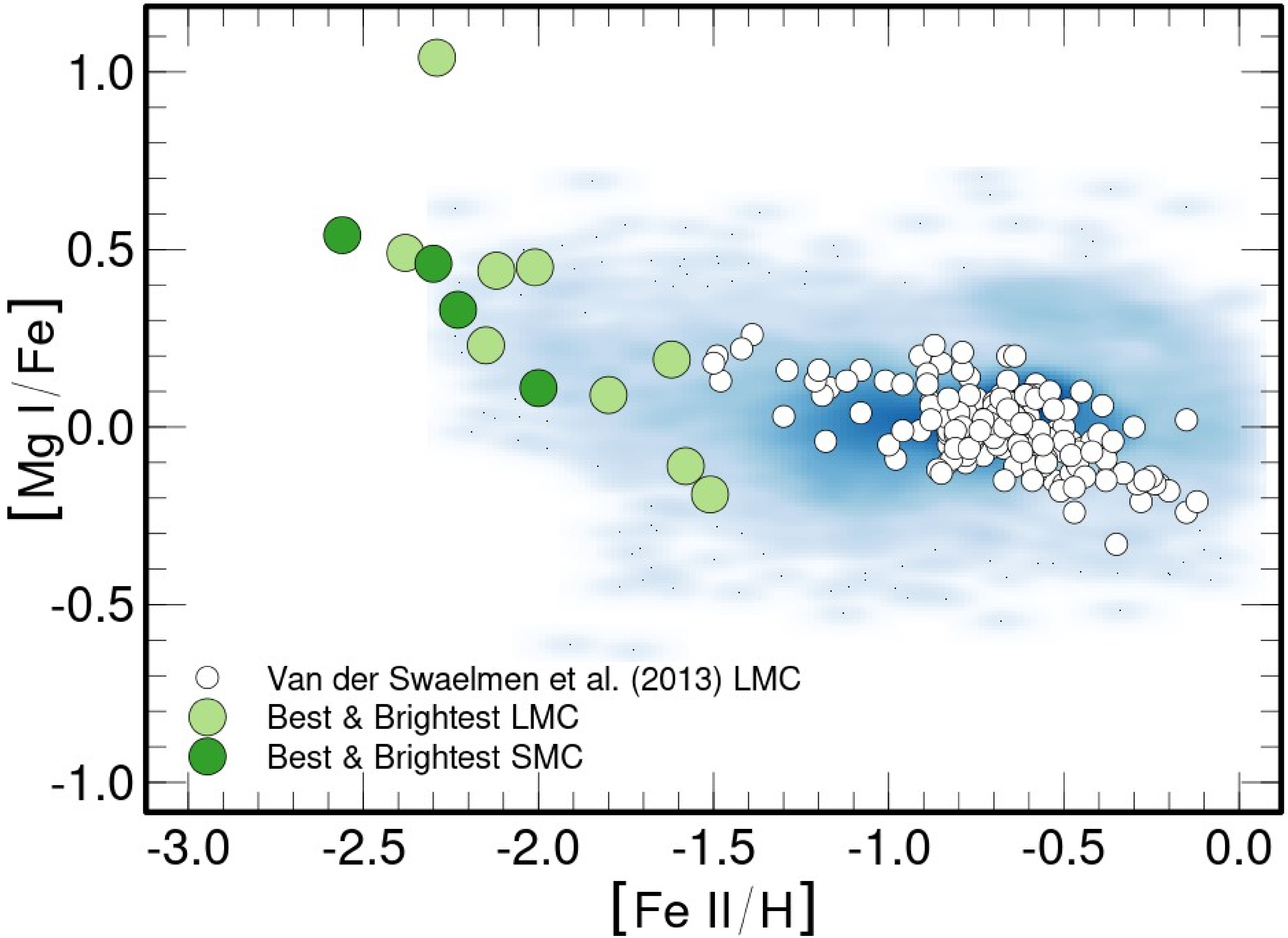
Reggiani et al. (2021)



Abundance Distribution of Eu

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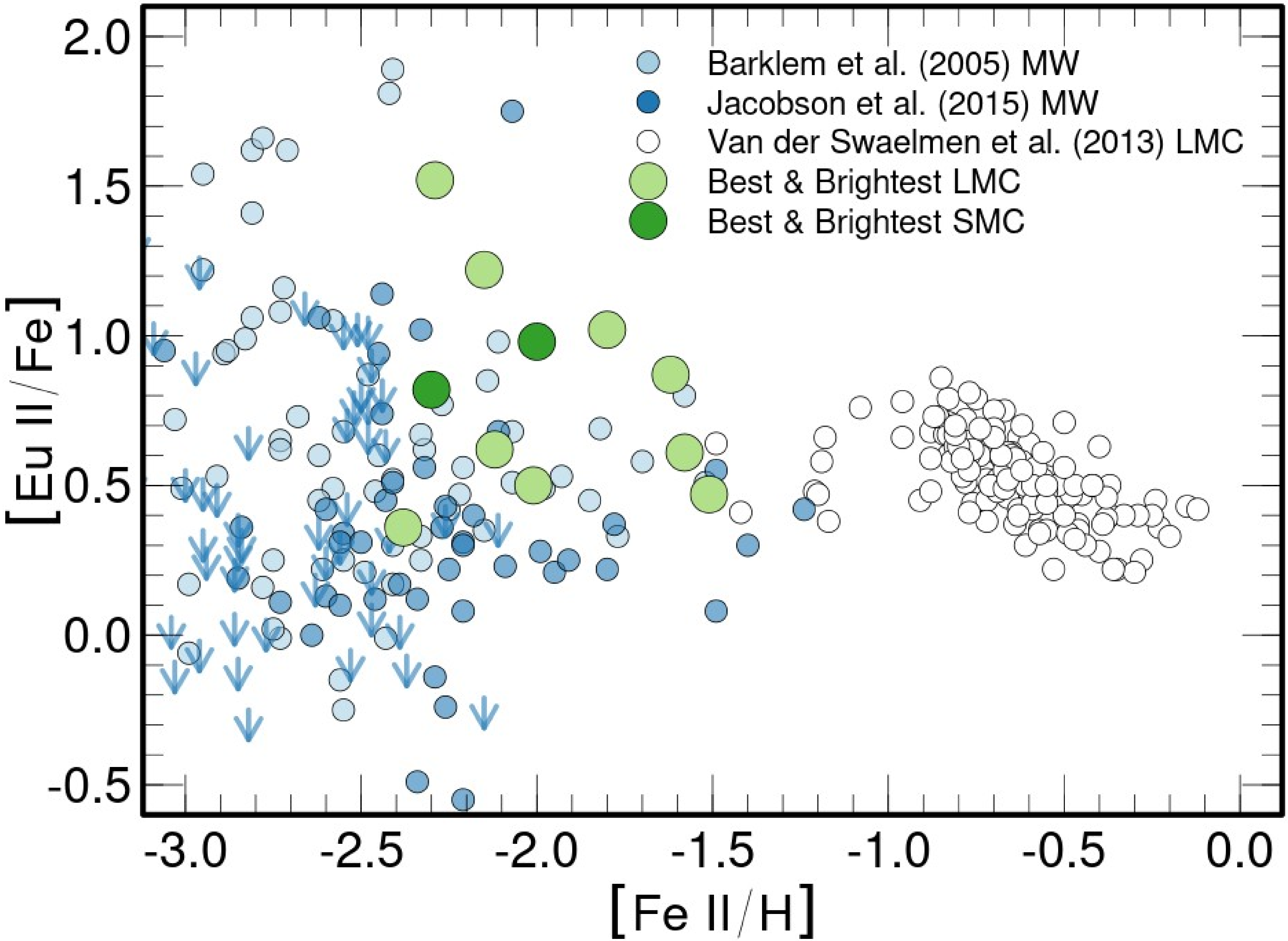
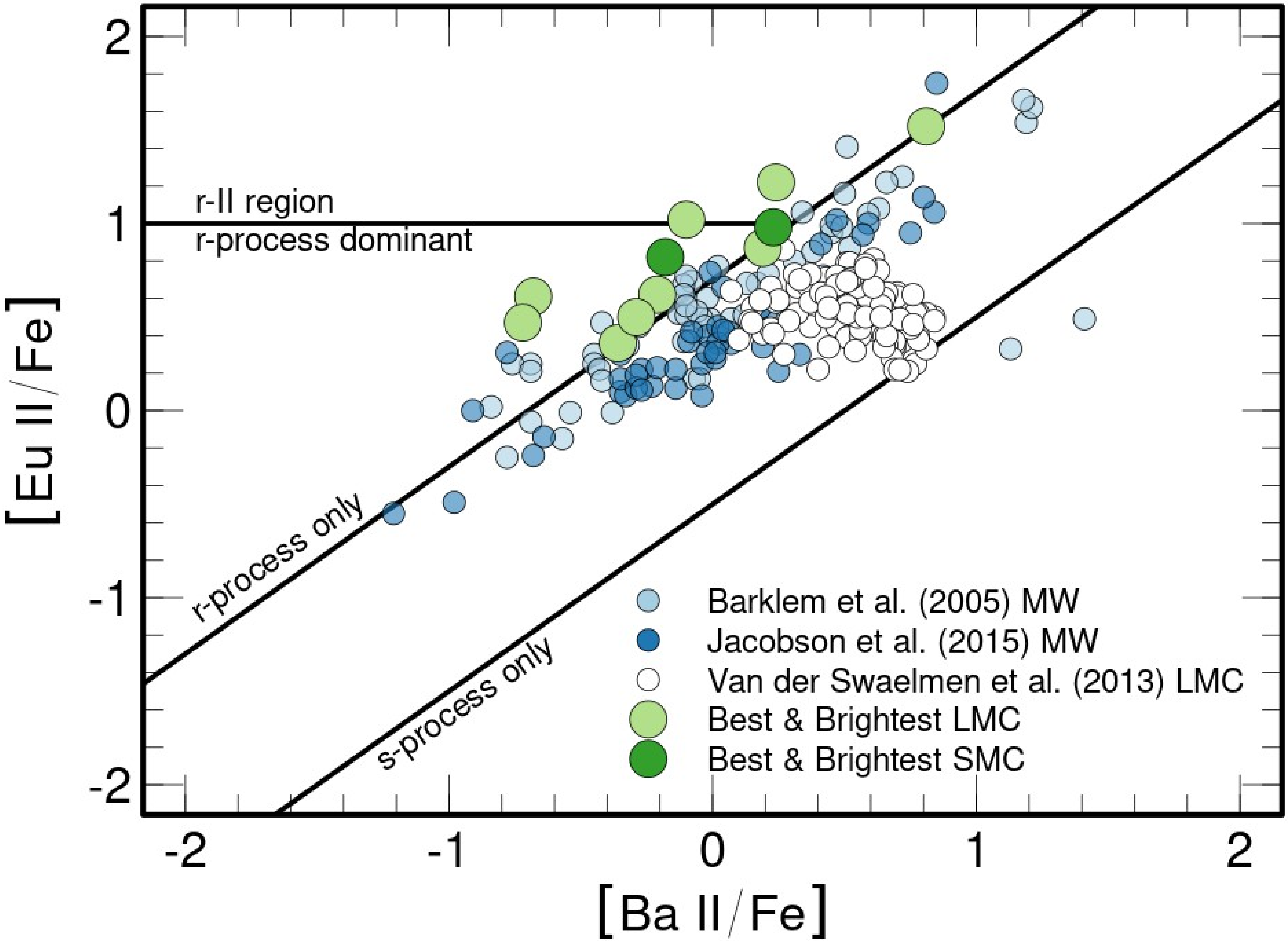
27 May 2022
Reggiani et al. (2021)



Signature of *r*-process

Reggiani et al. (2021)



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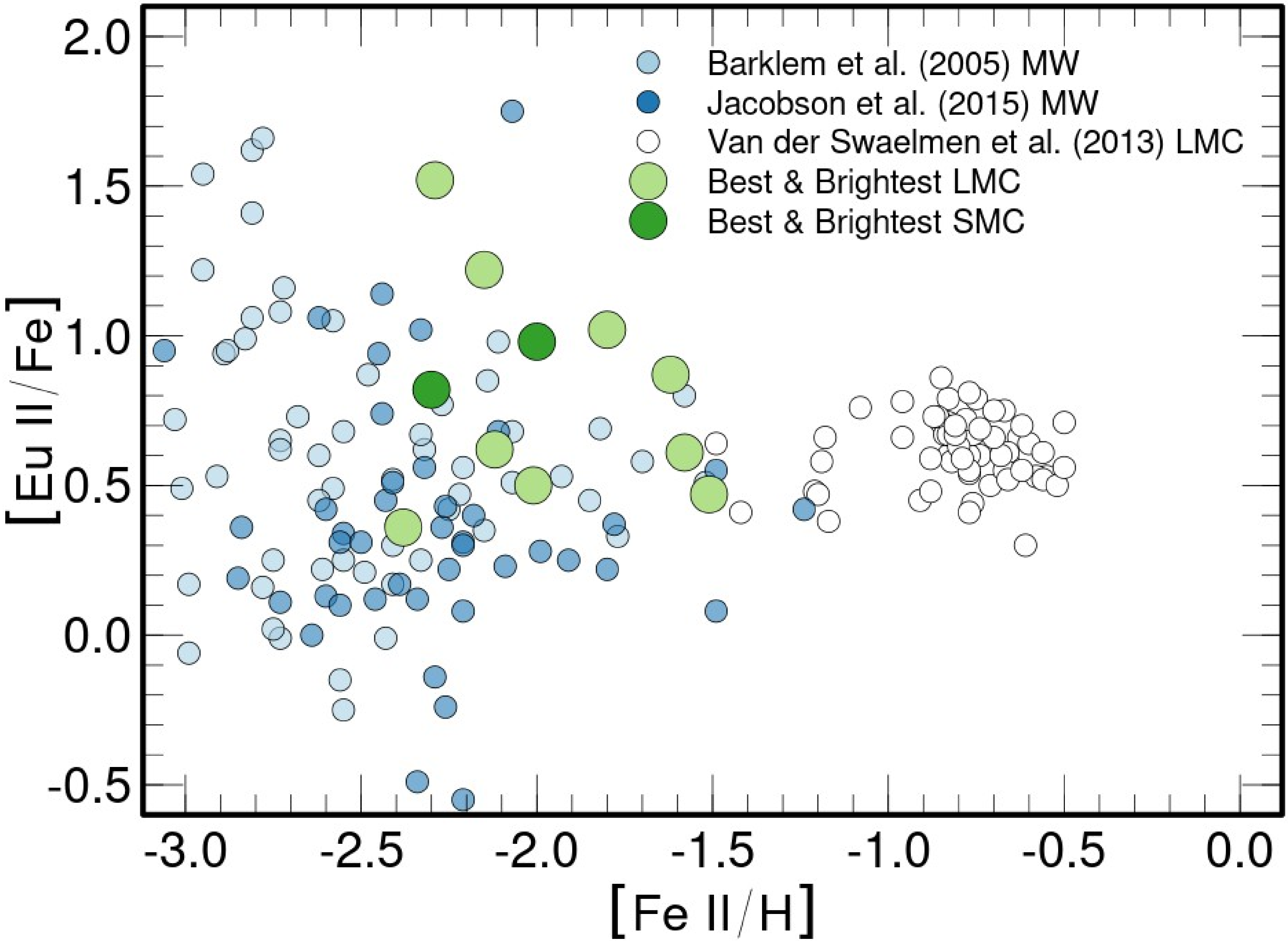
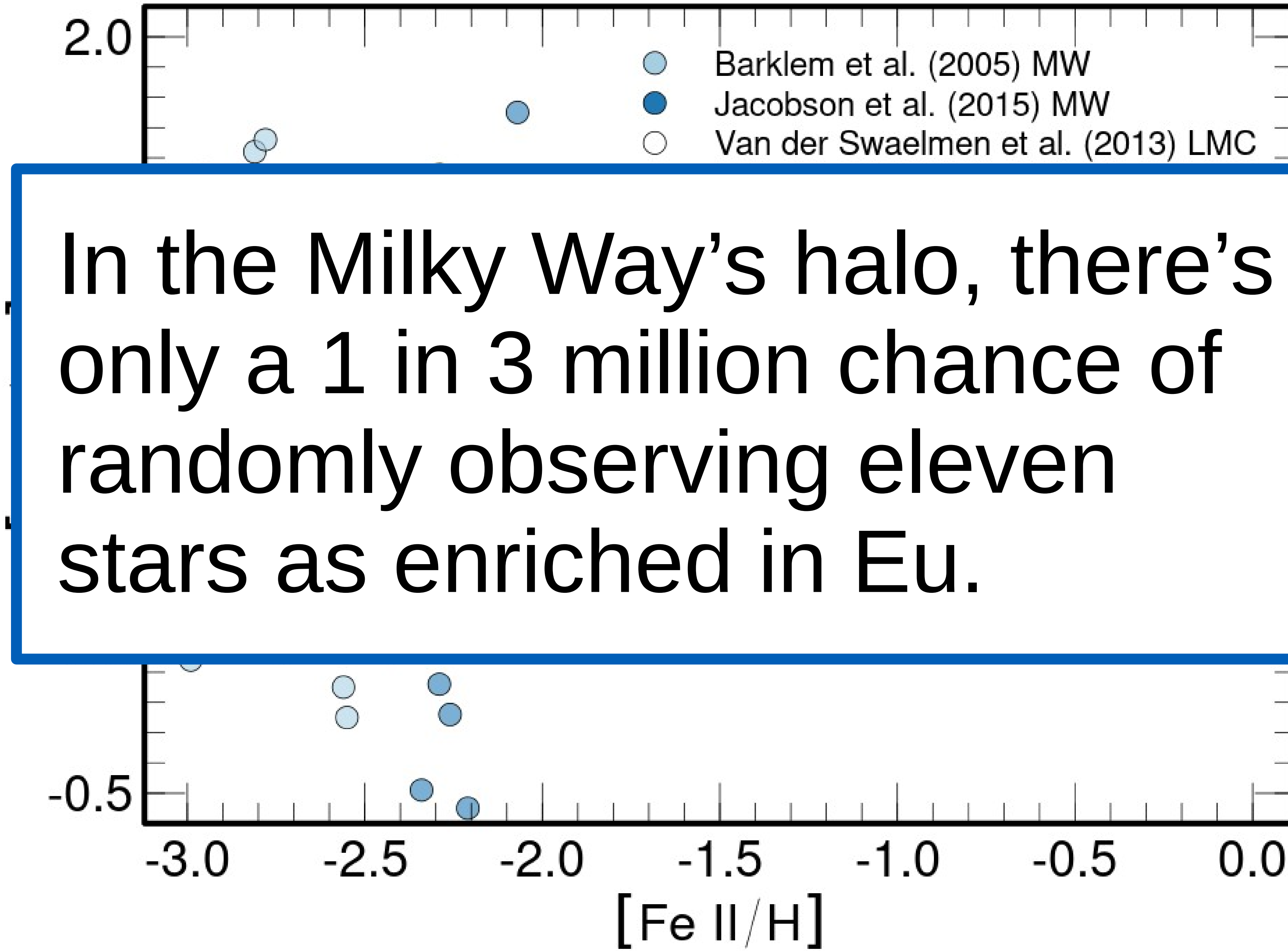


Signature of *r*-process

Reggiani et al. (2021)



In the Milky Way's halo, there's only a 1 in 3 million chance of randomly observing eleven stars as enriched in Eu.

r-process Enriched Stars

Kevin Schlaufman
27 May 2022
Reggiani et al. (2021)

***r*-I** +0.3 < [Eu/Fe] < +1.0 and [Eu/Ba] > 0
***r*-II** [Eu/Fe] > +1.0 and [Eu/Ba] > 0

	***r*-I (%)**	***r*-II (%)**
Milky Way	14	3
Magellanic Clouds	94^{+4}_{-9}	38^{+14}_{-13}

Beers & Christlieb (2005)
Barklem et al. (2005)

Conclusions

(1) There is a low-yield *r*-process channel, perhaps associated with ordinary core-collapse supernovae.

(2) The high occurrence of *r*-process enhanced stars in the slowly chemically enriched Magellanic Clouds relative to the quickly enriched Milky Way supports a prolific source of the *r*-process that starts to operate after the era of the first core-collapse supernovae in a stellar population.

Galaxies Differ in Many Ways

Kevin Schlaufman
27 May 2022

Chemical evolution has many independent variables:

(1) Mass
(2) gravitational potential depth/escape velocity
(3) ability to fully sample stellar initial mass and binary property distributions
(4) ability to accrete unenriched gas from the cosmic web

Infrared Metal-poor Star Selection

Kevin Schlaufman
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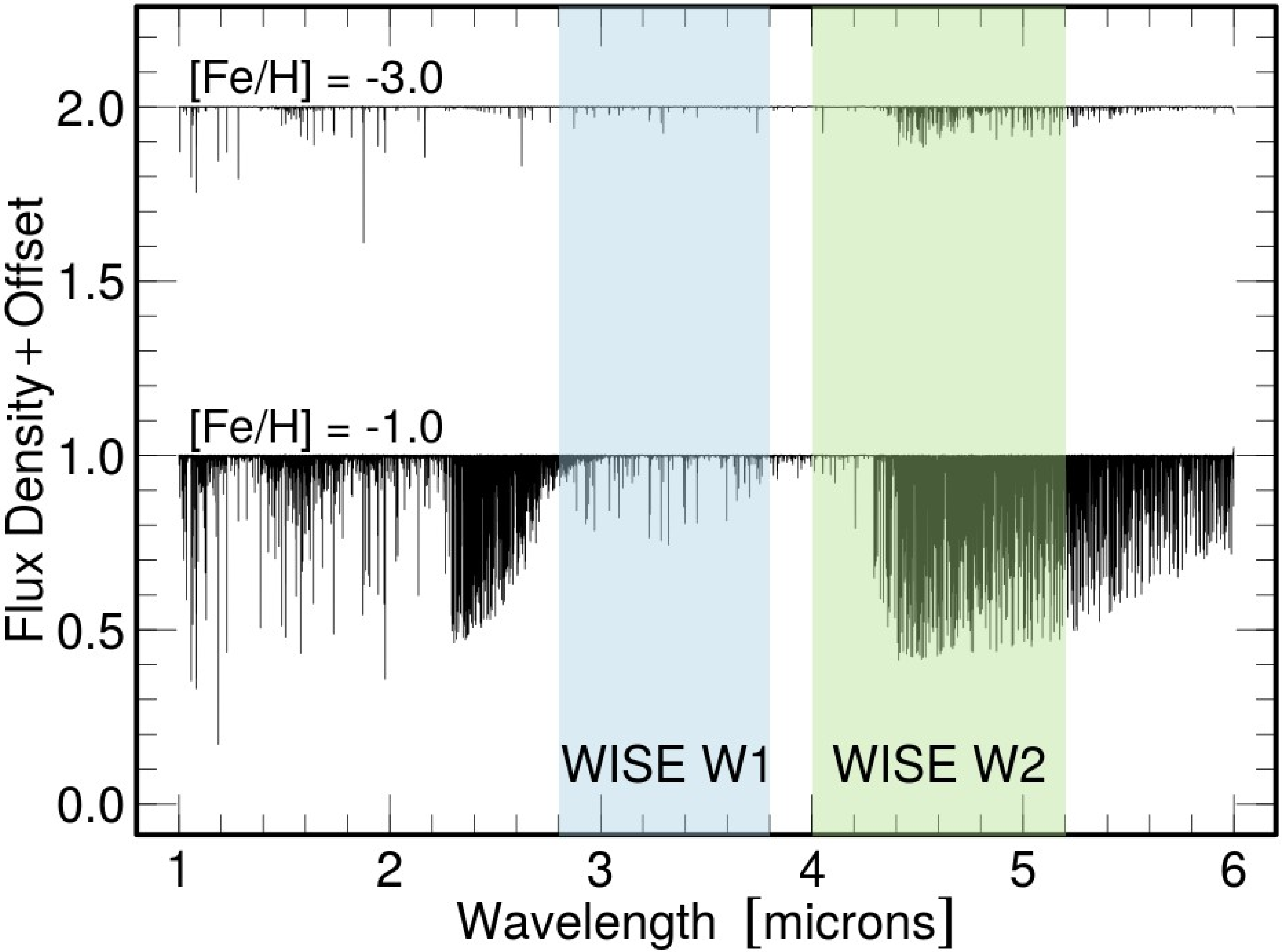
Schlaufman & Casey (2014)



Infrared Metal-poor Star Selection

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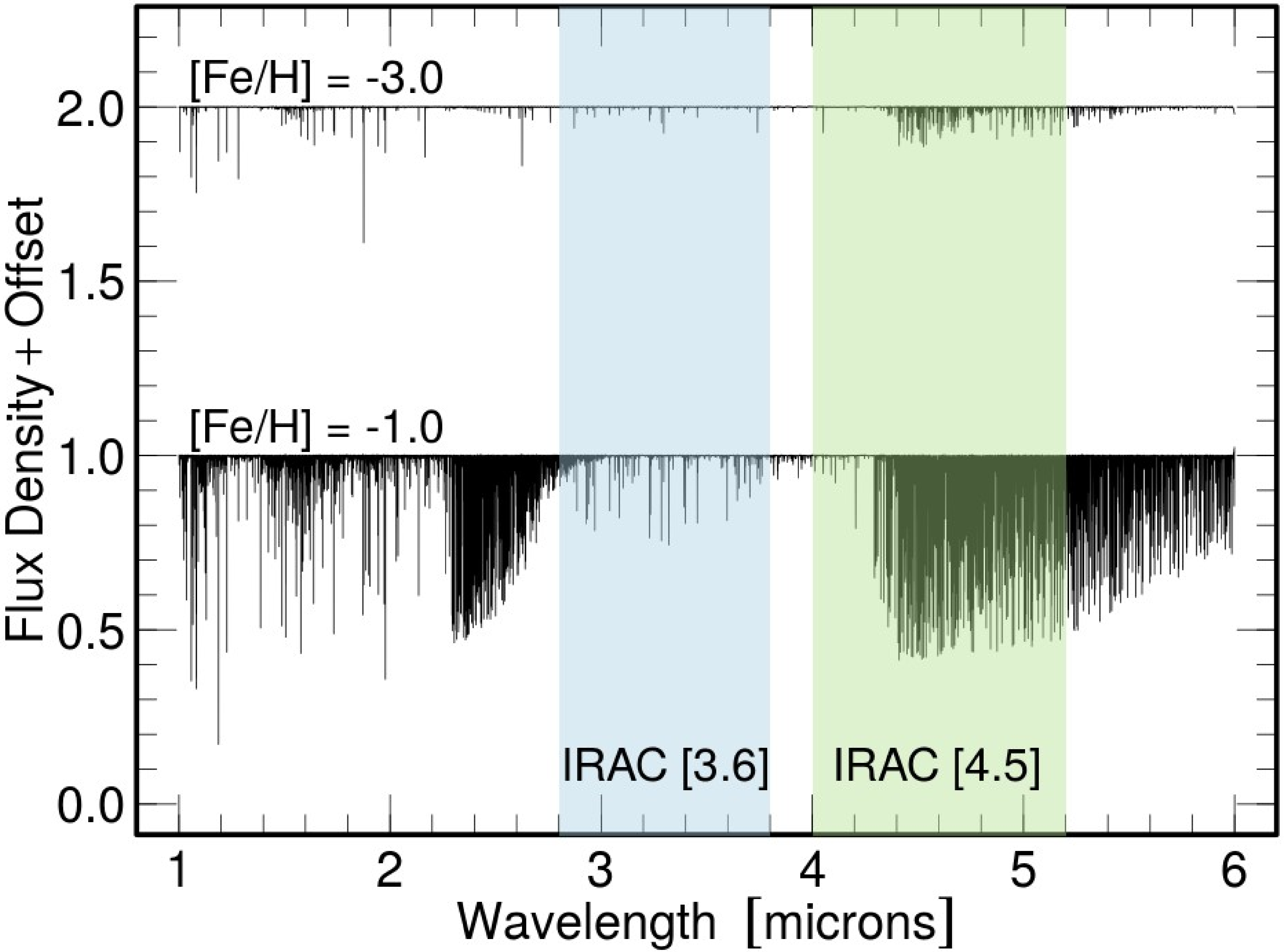

Spitzer/SAGE LMC Map

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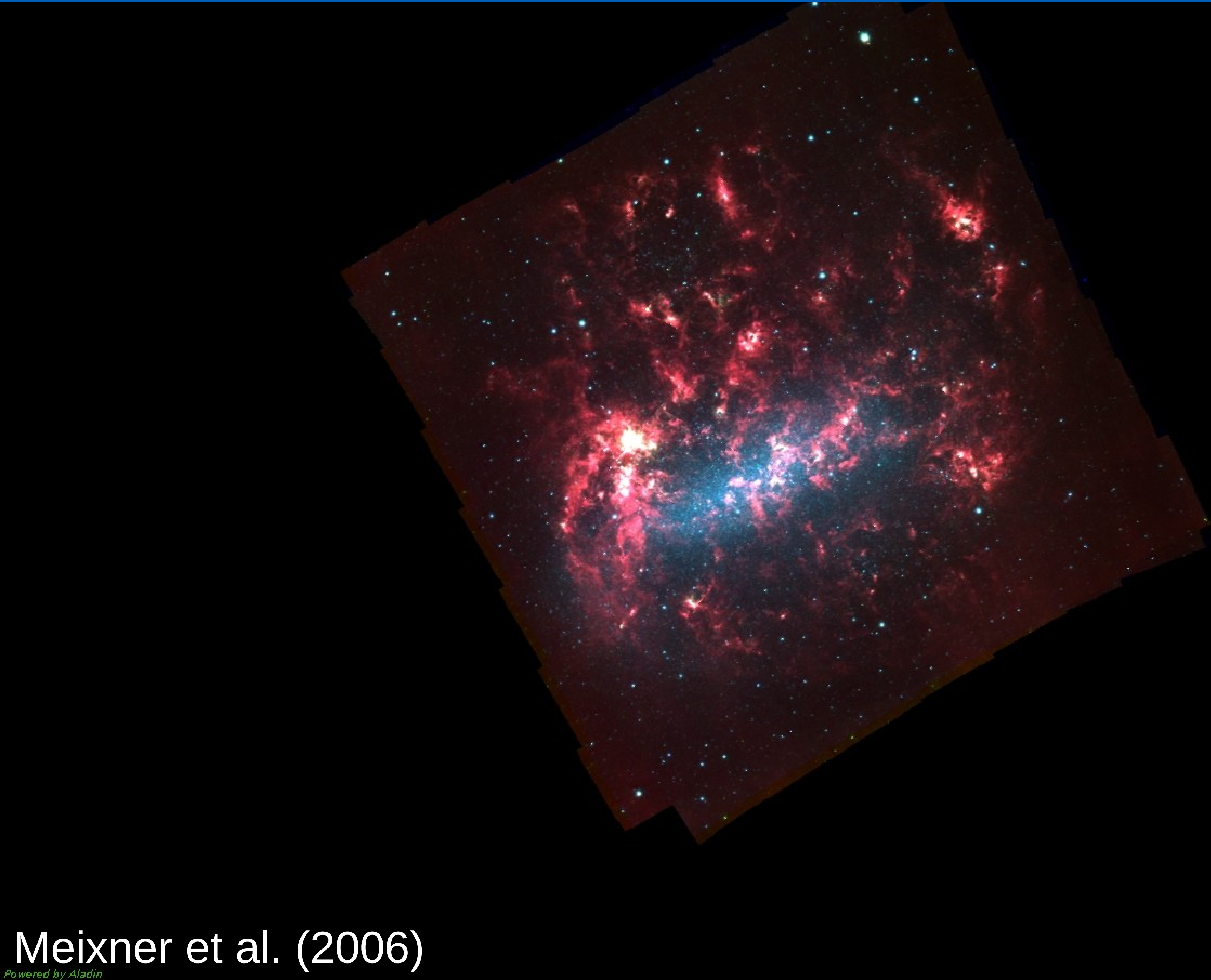

Meixner et al. (2006)

Spitzer/SAGE LMC Map

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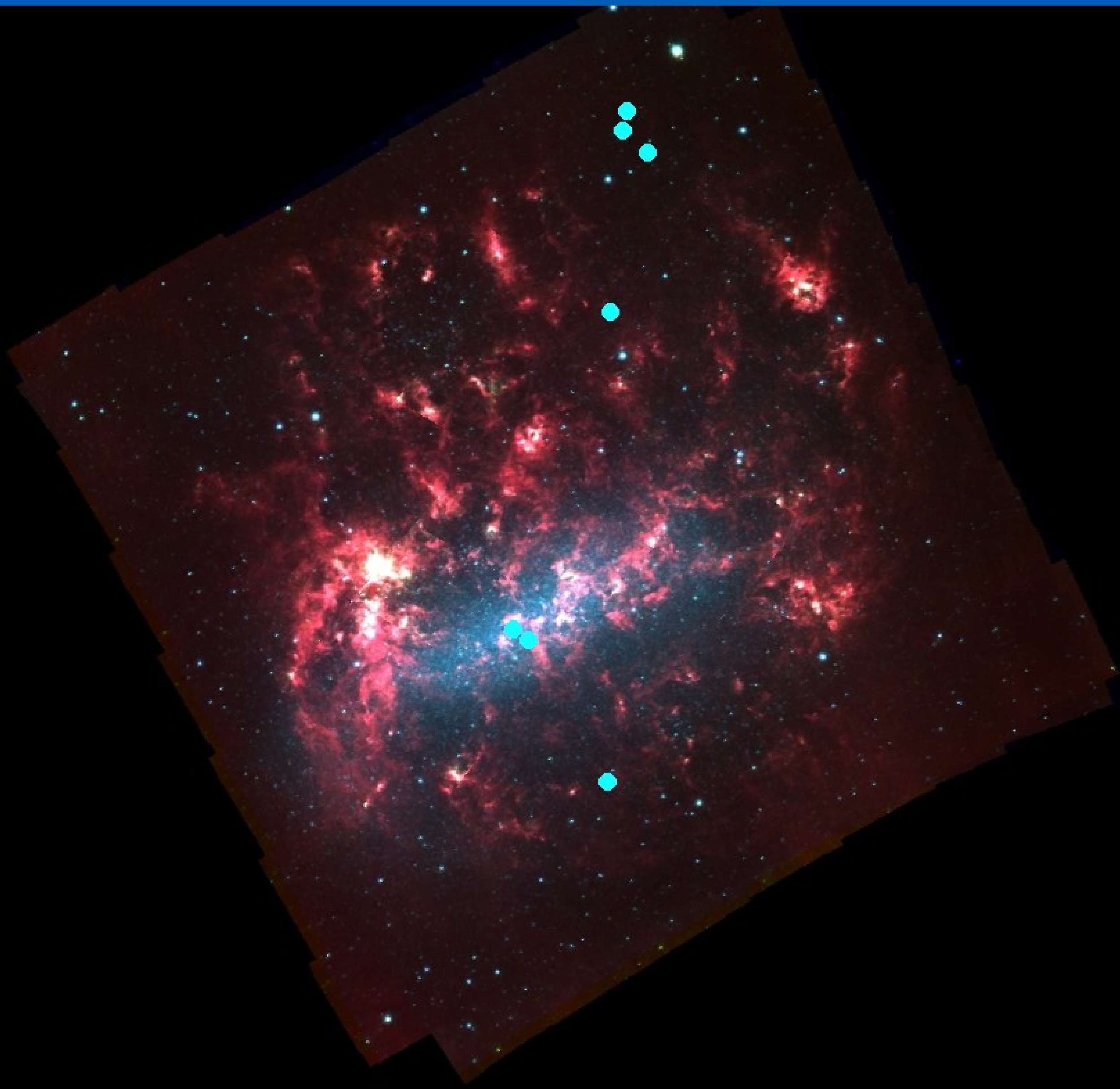

Meixner et al. (2006)

MC *r*-process Enhanced Stars

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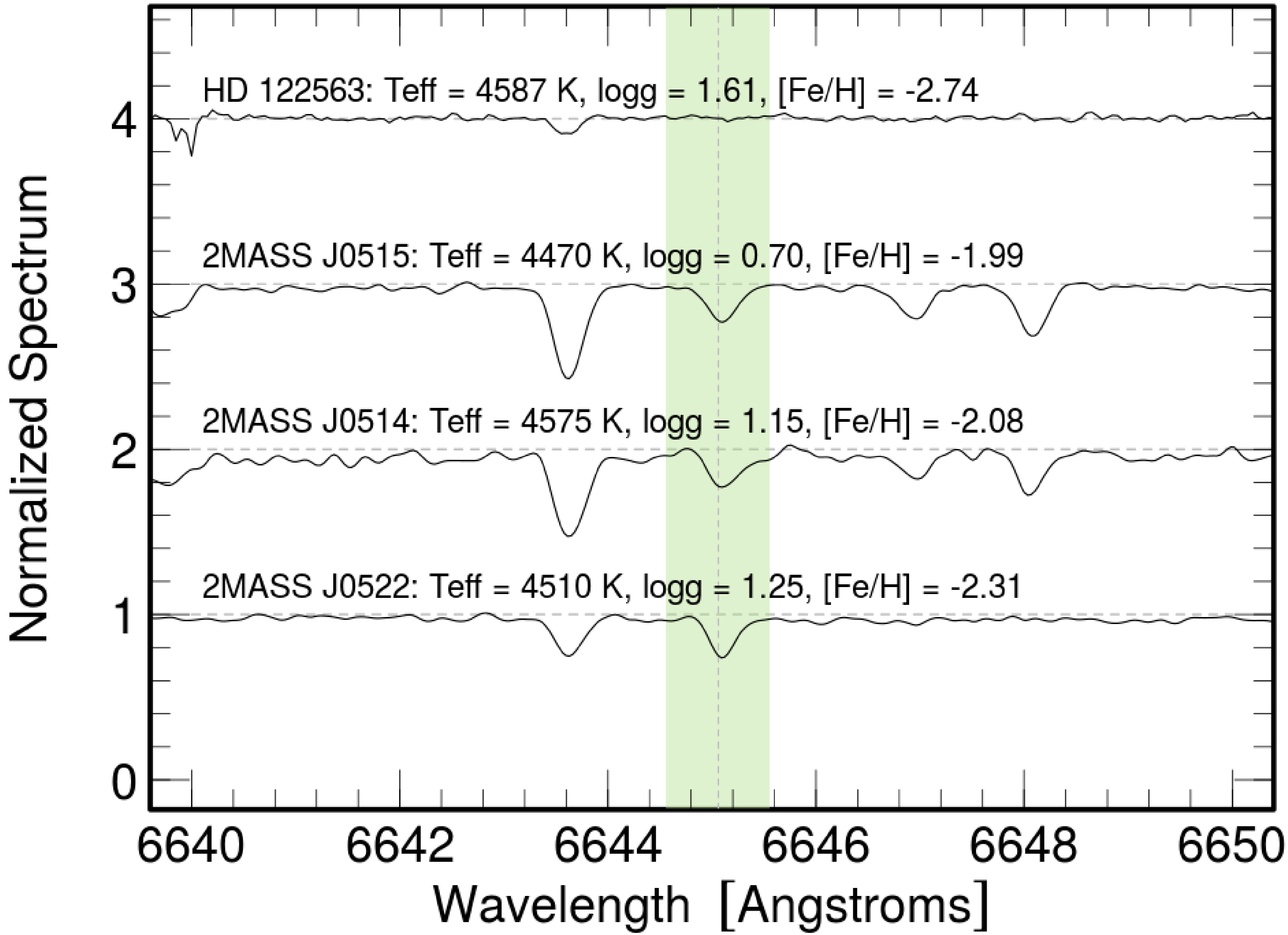
Reggiani et al. (2021)



Abundance Distribution of Eu

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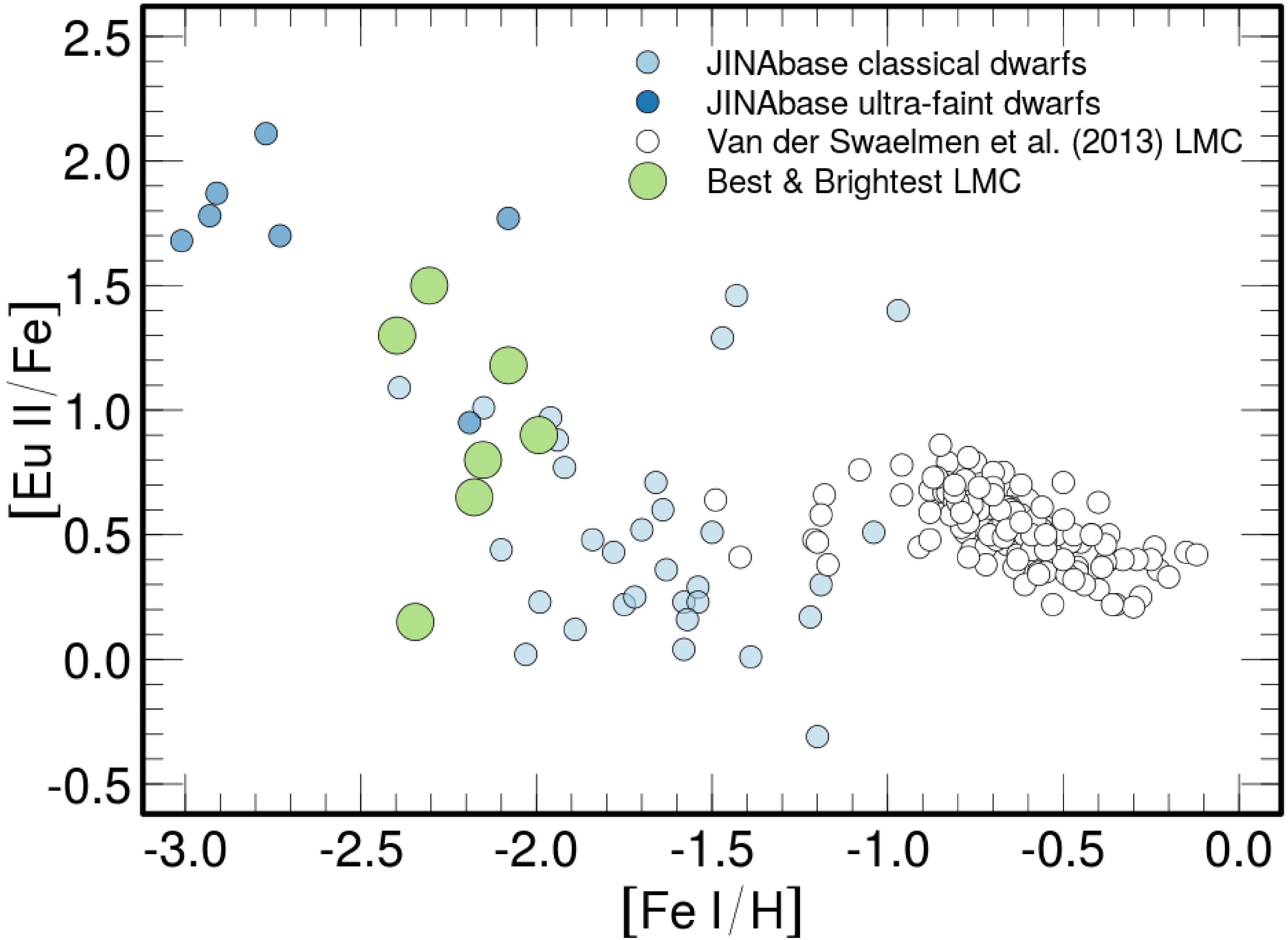
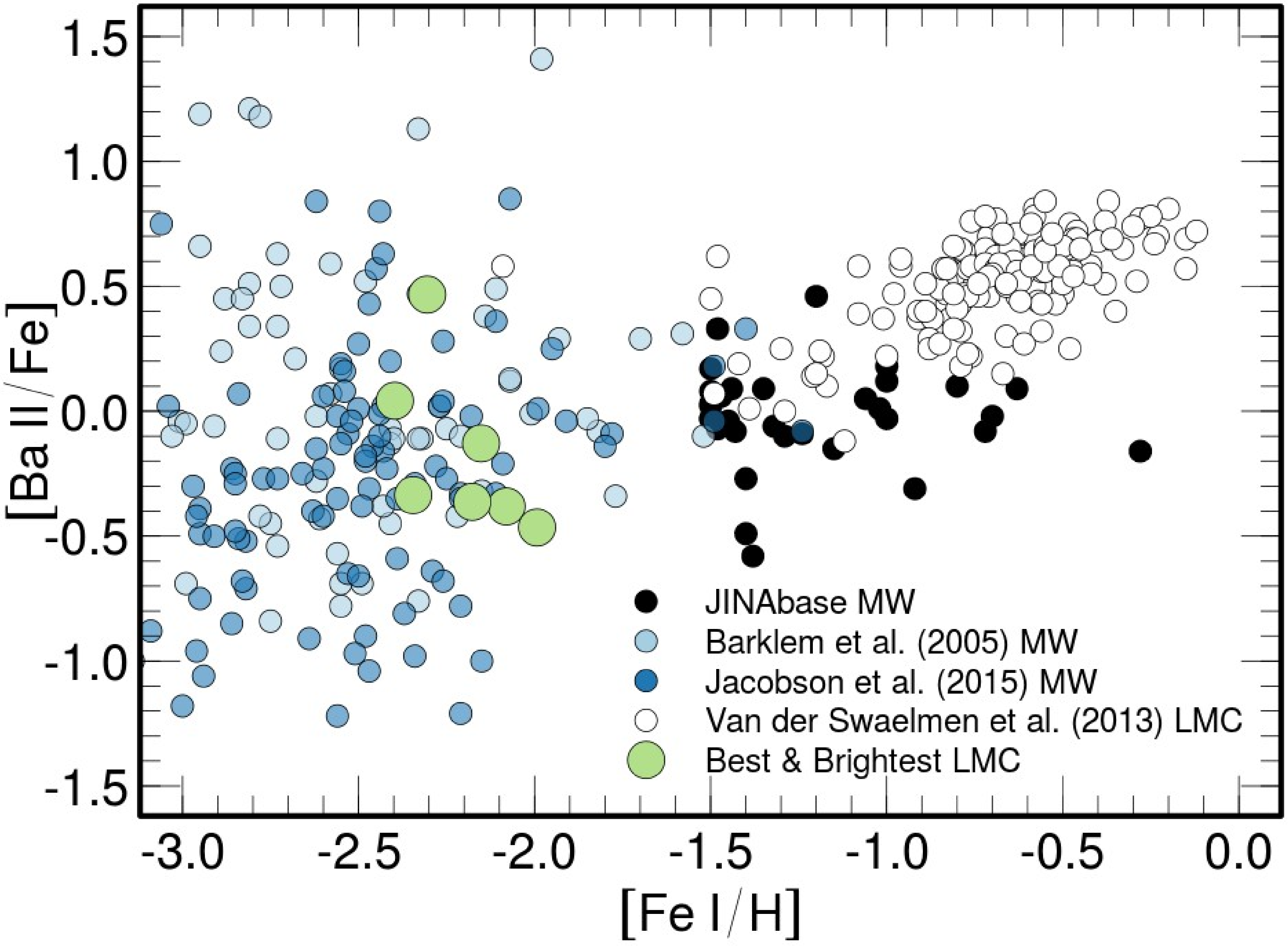
Reggiani et al. (2020, in prep)



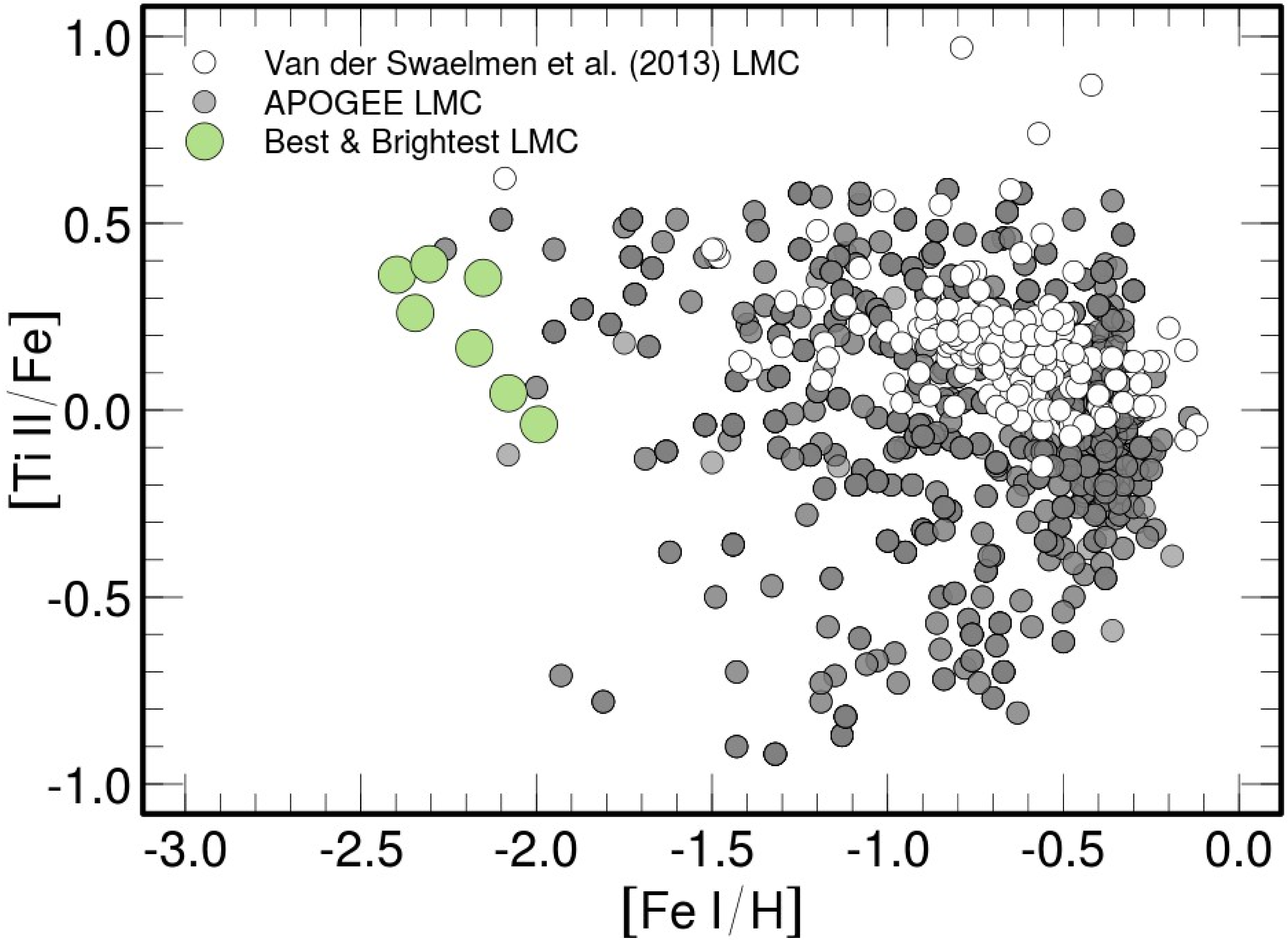
Abundance Distribution of Ba

Reggiani et al. (2021)



Abundance Distribution of Ti

Reggiani et al. (2021)



LMC Chemical Evolution

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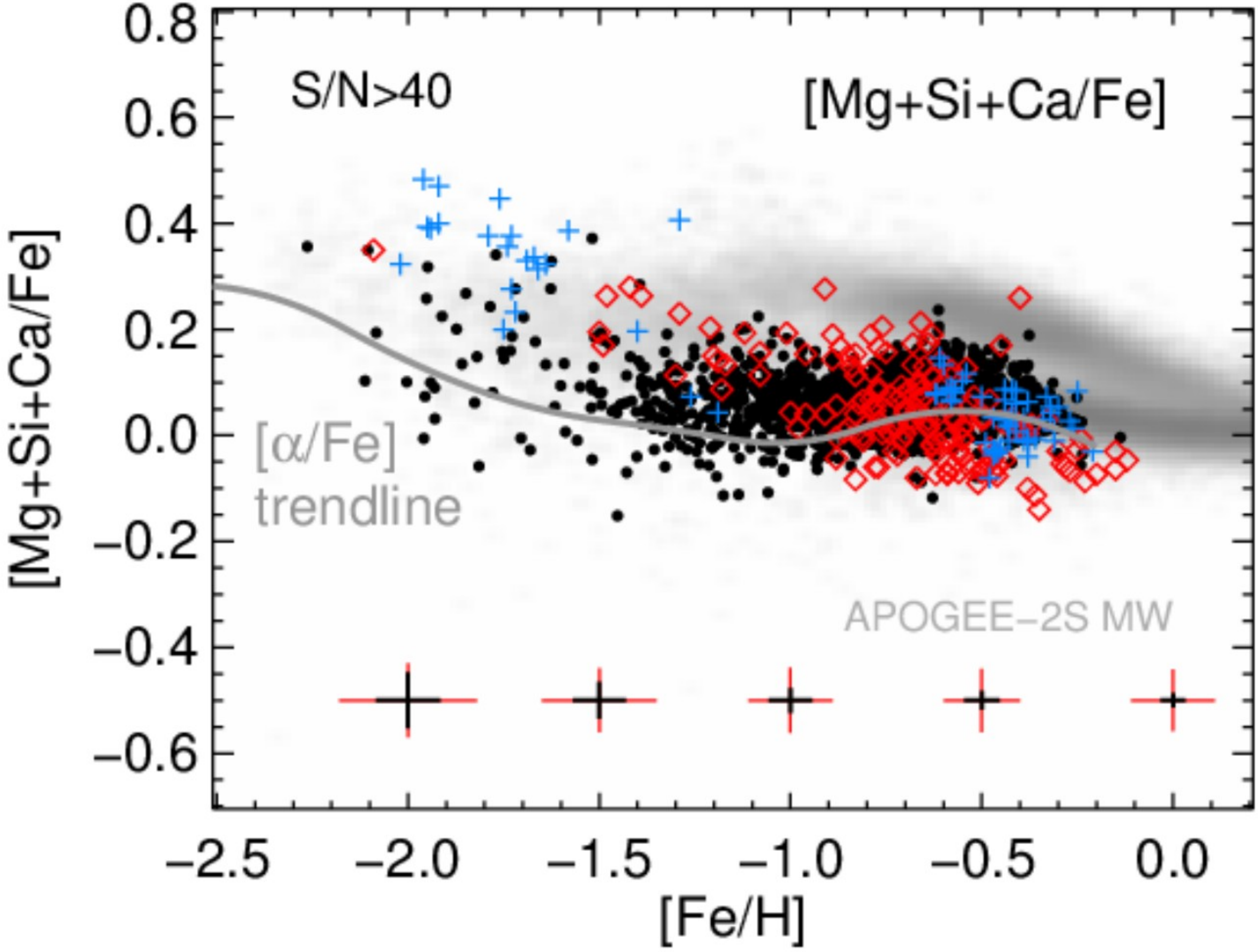

Nidever et al. (2020)