The environment of the r-process:

new advances enabled by the study of the orbits of r-process enhanced stars

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and
Joint Institute for Nuclear Astrophysics — Chemical Evolution of the Elements

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National Science Foundation
WHERE DISCOVERIES BEGIN

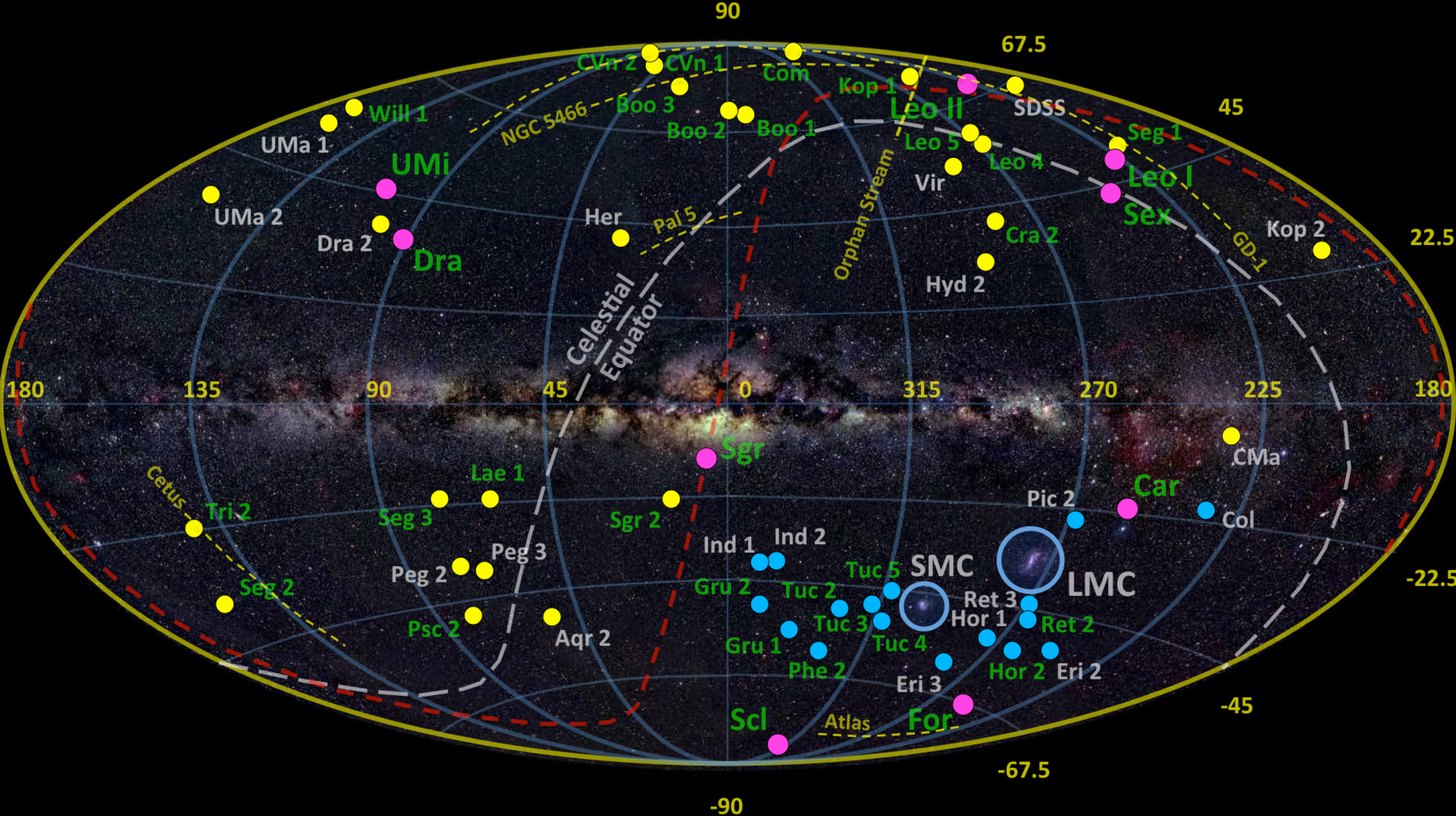
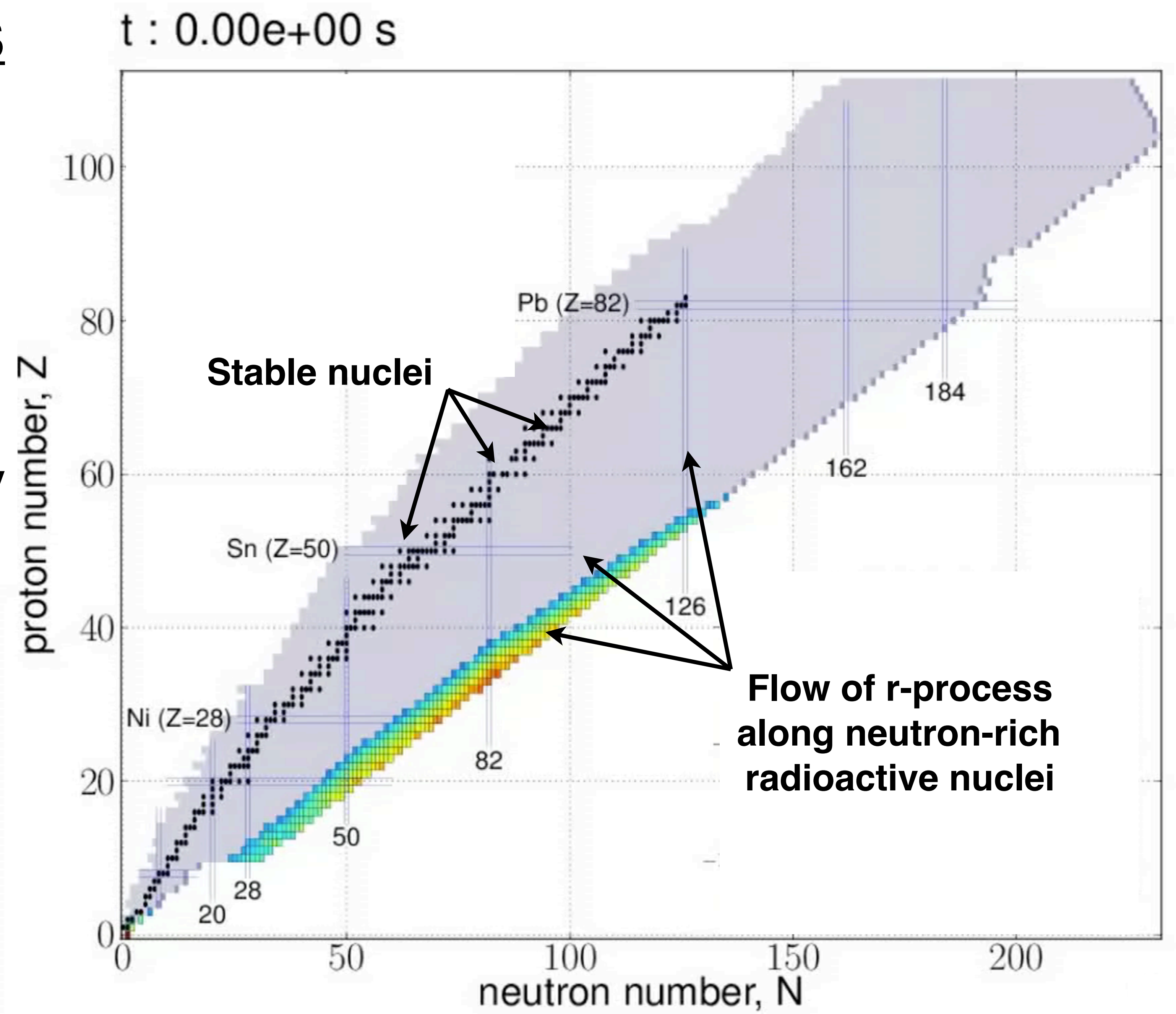


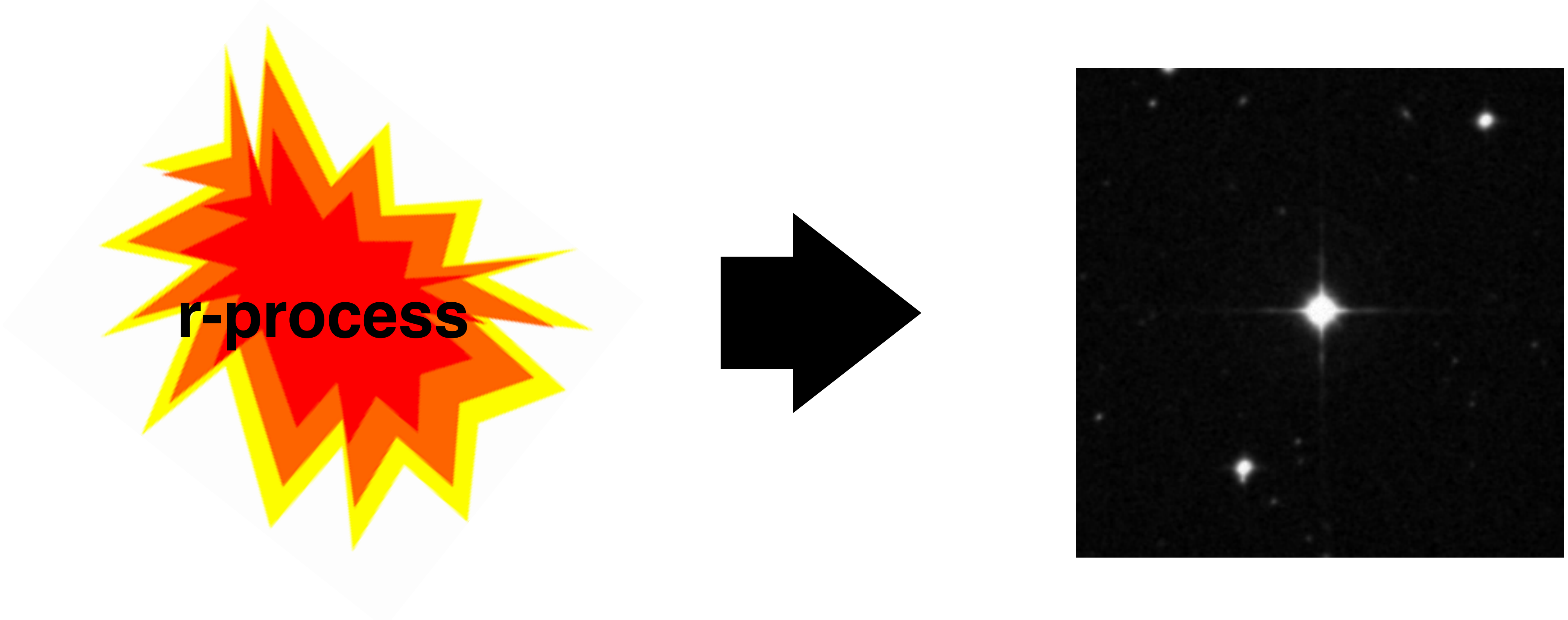
image: A. Mellinger (Central Michigan U.), M. Mateo (U. Michigan)

r-process nucleosynthesis

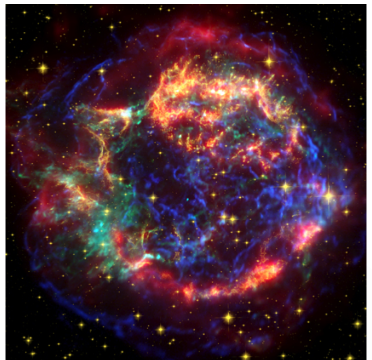
- **r**apid addition of neutrons
- explosive site
- $\sim 10^{22} - 10^{28}$ n cm^{-3}
- produced most heavy elements in the oldest stars
- produced about half of heavy elements found in the Sun



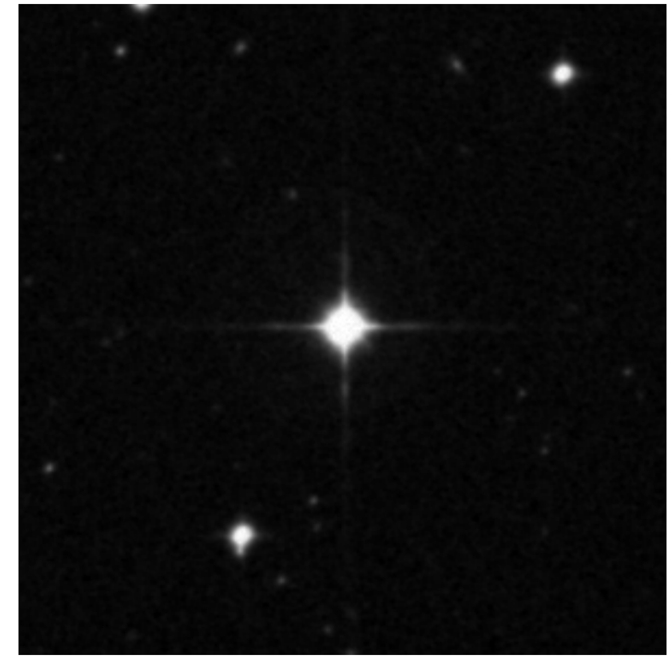
Burbidge, Burbidge, Fowler, & Hoyle, Rev. Mod. Phys., 29, 547 (1957) Korobkin et al., Mon. Not. Roy. Astron. Soc., 426, 1940 (2012)



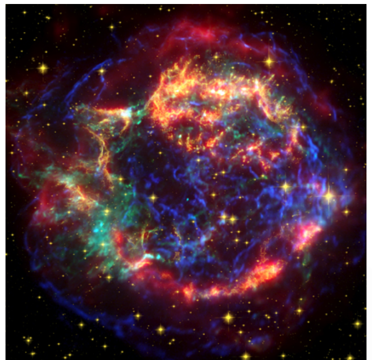
images: DSS



SN (from theory):
~10^{-5} $M_{\odot}$ of r-process material



images: DSS
NASA/CXC



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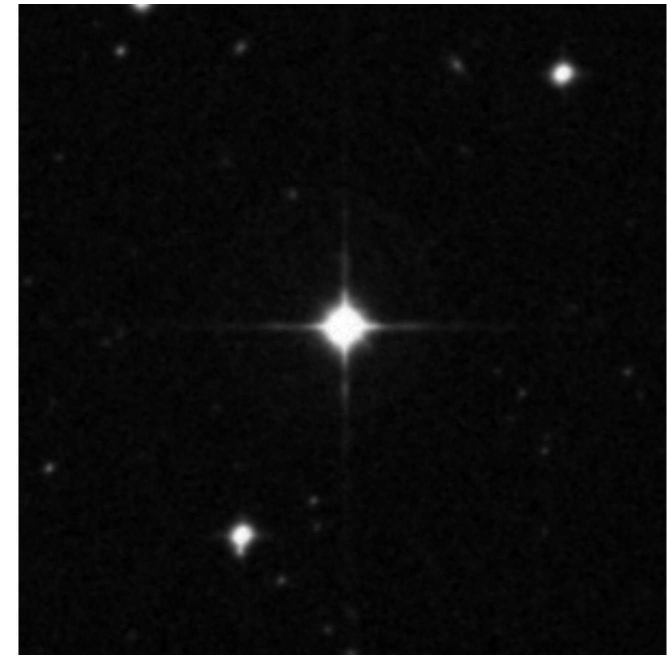
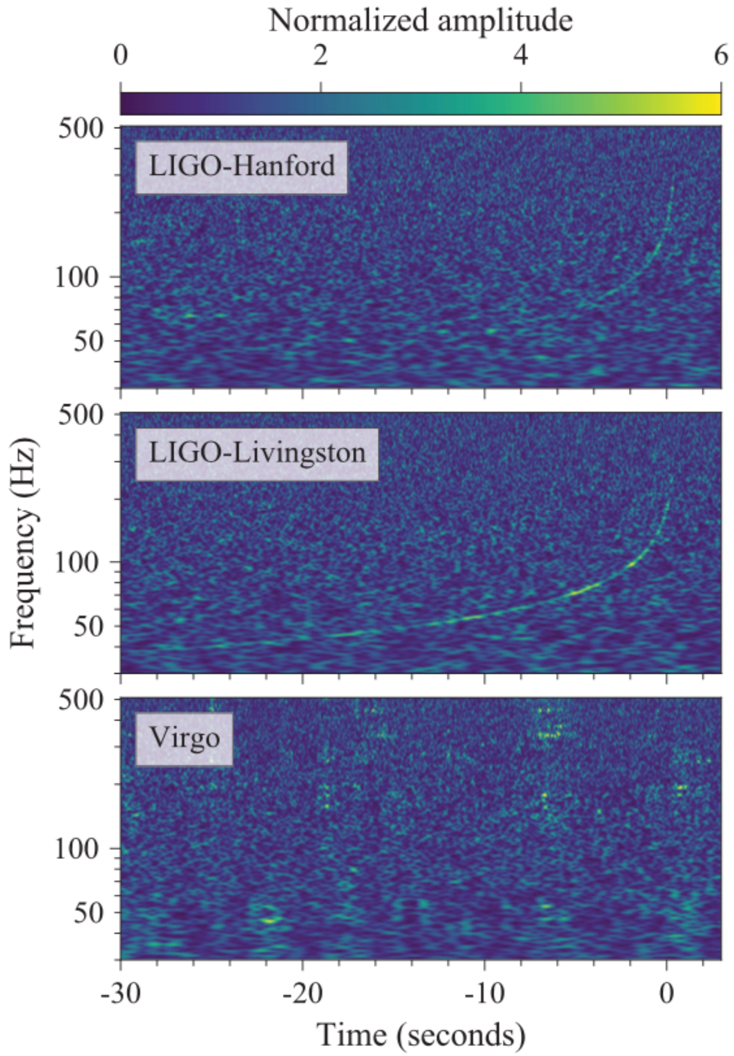


NSM (from theory):
~10^{-2} $M_\odot$ of r-process material
1 event per ~$10^{3\text{-}4}$ SN

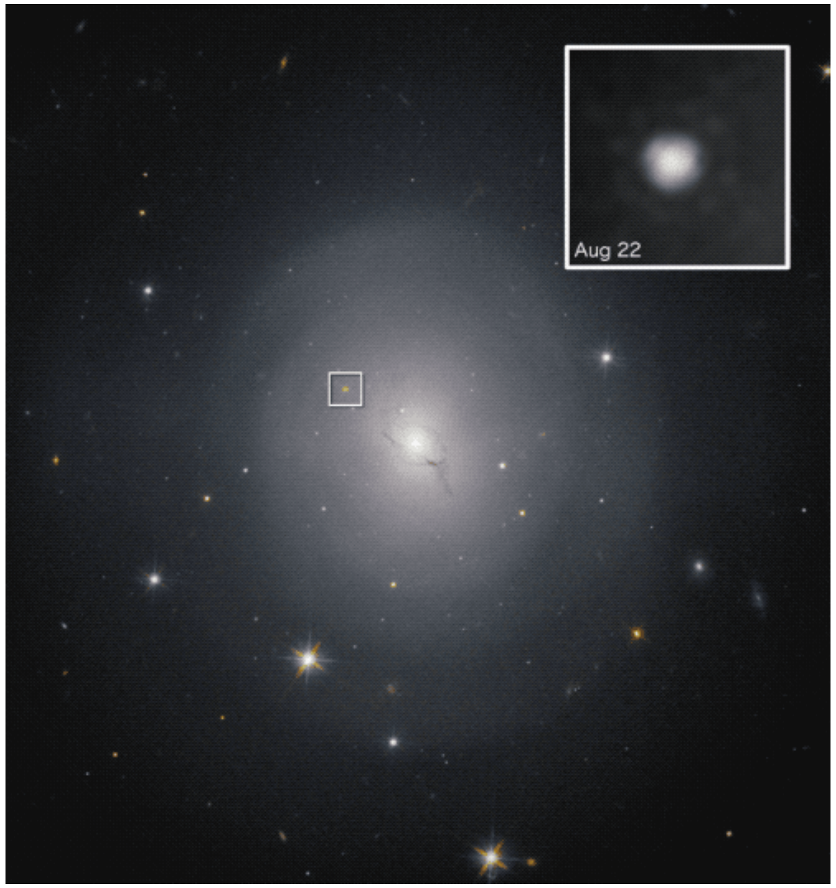
images: DSS
NASA/CXC
Carnegie Institution for Science

The binary neutron star merger GW170817 produced a **kilonova**, which is a light curve powered by the radioactive decay of a few 10^{-2} $M_\odot$ of r-process elements.

gravitational wave signal



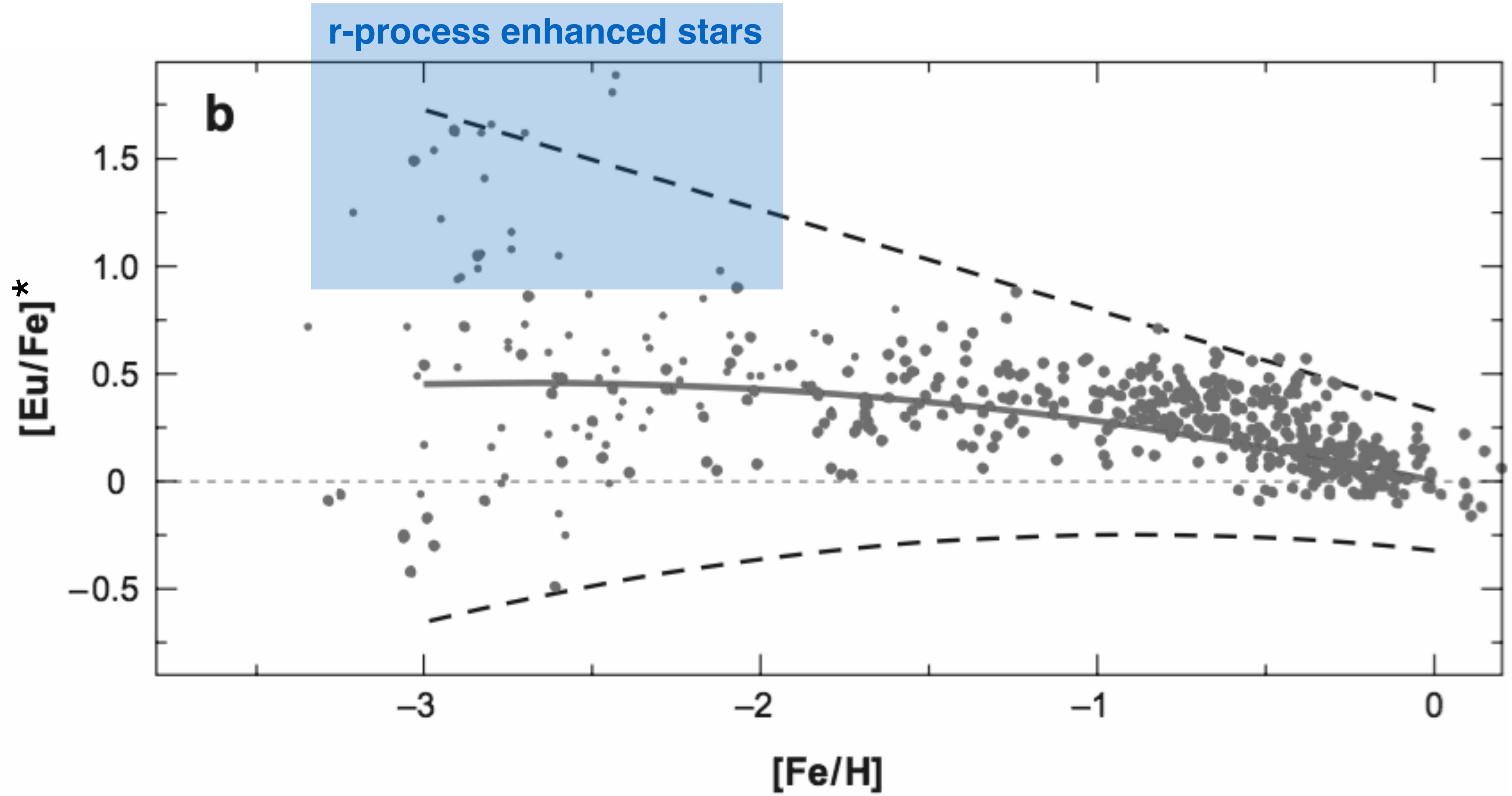
electromagnetic signal



LIGO Scientific Collaboration and Virgo Collaboration, Abbott et al., Phys. Rev. Lett., 119, 161101 (2017)

optical image credit: HST/NASA/ESA

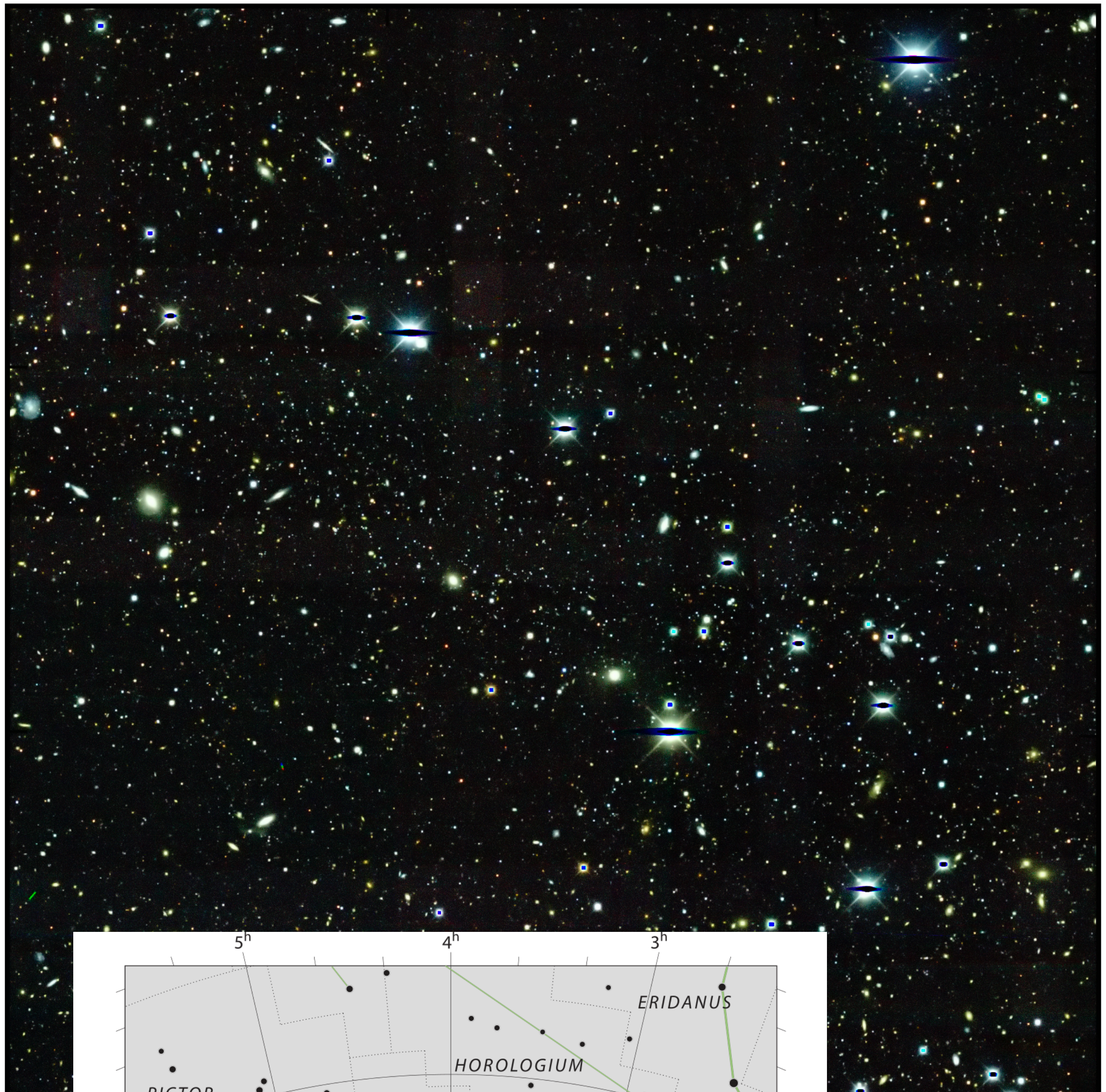
ENVIRONMENT

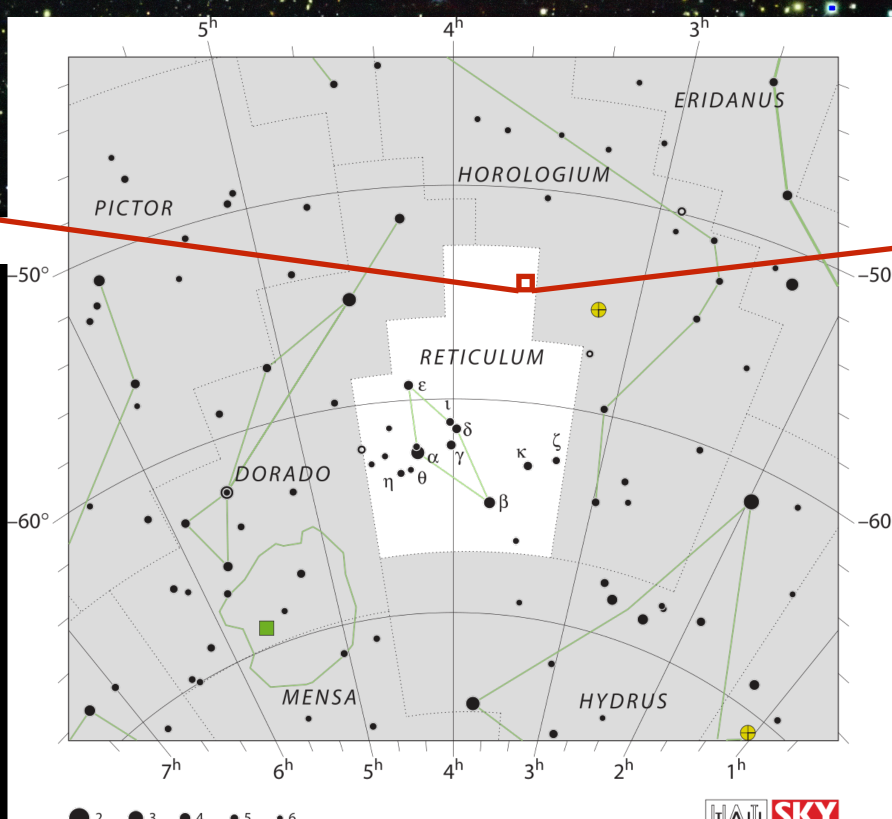


Sneden, Cowan, & Gallino, Ann. Rev. Astron. Astrophys., 46, 241 (2008)

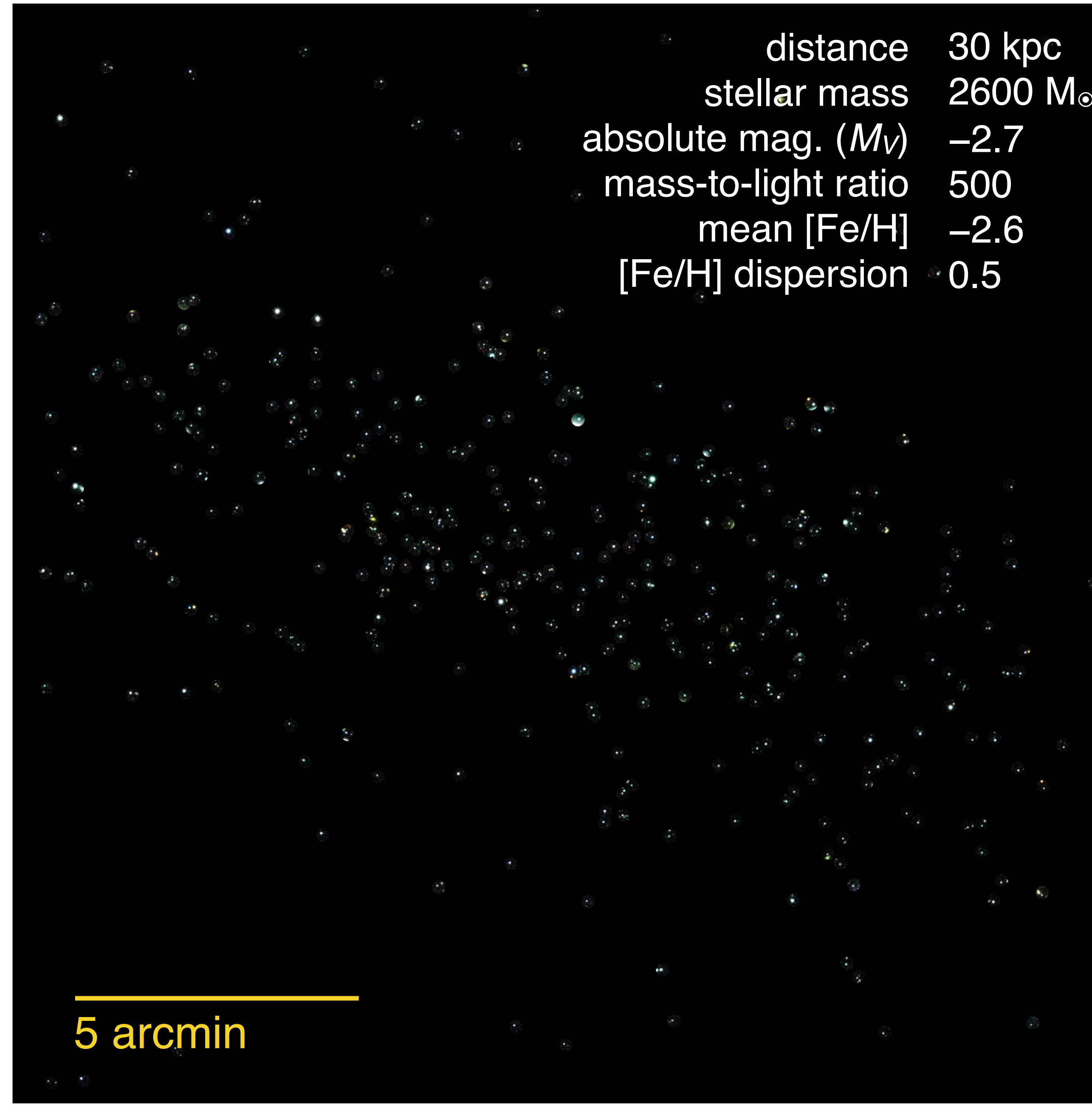
* [Eu/Fe] = $\log_{10}(N_{Eu})_{STAR} - \log_{10}(N_{Eu})_{SUN}$ — [Fe/H]
(think of this as the level of r-process enhancement in a star)

All stars and background galaxies





Stars in the Reticulum II galaxy only



images:
Fermilab / Dark Energy Survey
IAU / Sky and Telescope

properties:
Koposov et al., Astrophys. J. 805, 130 (2015)
Bechtol et al., Astrophys. J. 807, 50 (2015)
Walker et al., Astrophys. J. 808, 108 (2015)

5% of stars in the **Milky Way halo** are r-process enhanced

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0% of stars in **other UFD galaxies** are r-process enhanced

5% of stars in the **Milky Way halo** are r-process enhanced

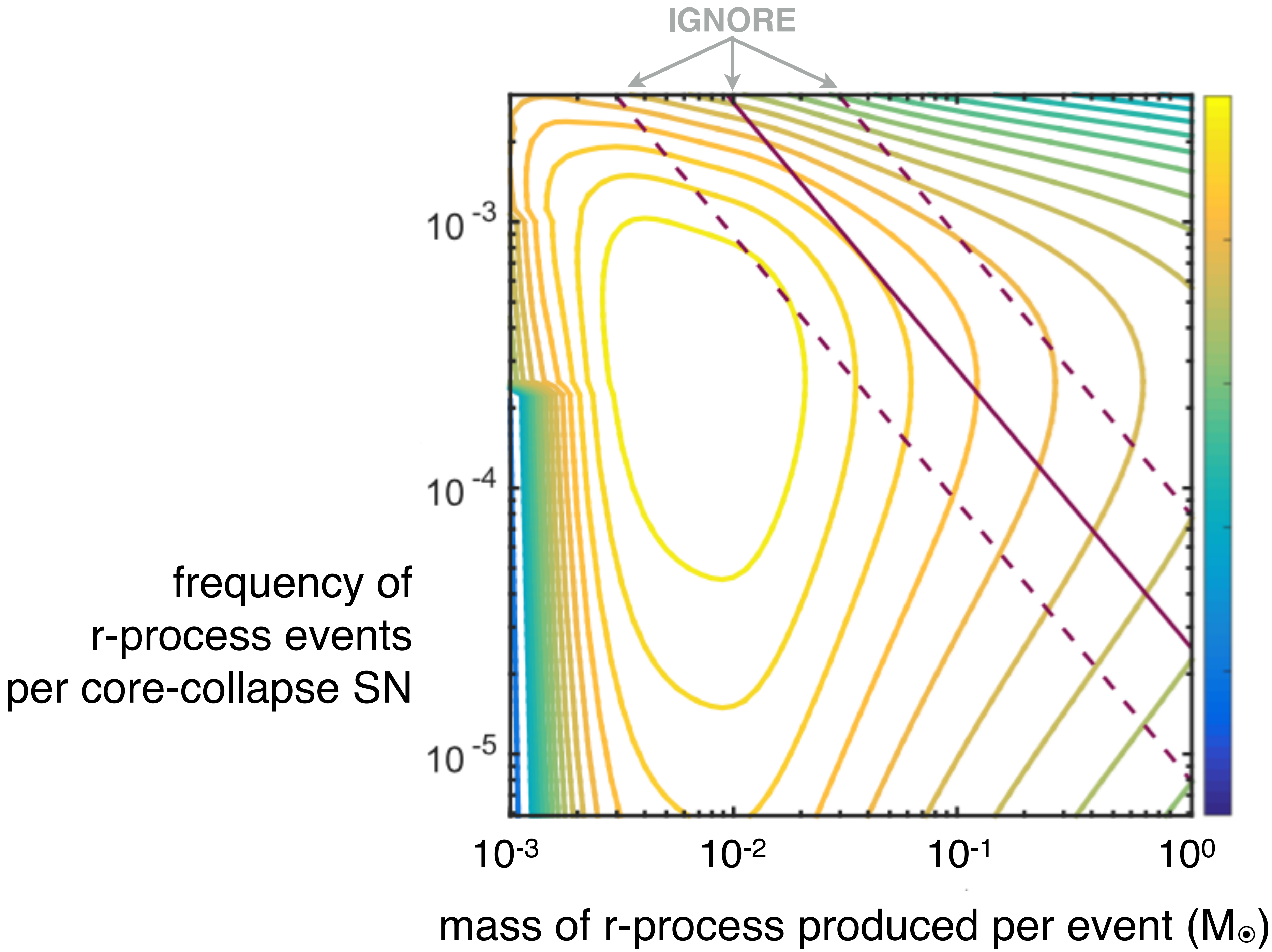
0% of stars in **other UFD galaxies** are r-process enhanced

80% of stars in the **UFD galaxy Ret II** are r-process enhanced

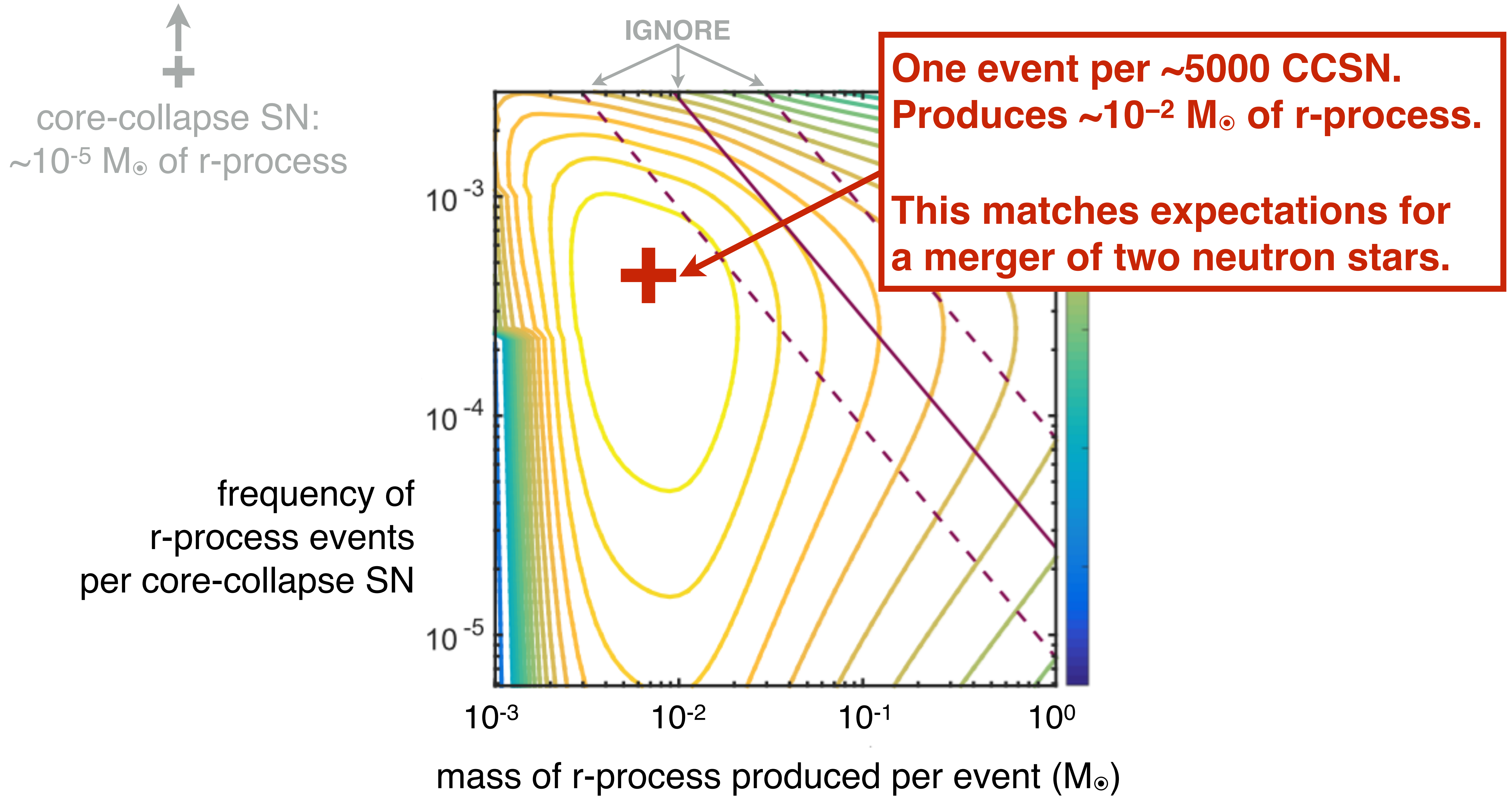
Two r-process enhanced UFD galaxies are known:
Reticulum II
Tucana III

10-15% of known **UFD galaxies** are r-process enhanced

Ret II: Ji et al., Astrophys. J., 830, 93 (2016); Roederer et al., Astron. J., 151, 82 (2016)
Tuc III: Hansen et al., Astrophys. J., 838, 44 (2017); Marshall et al., Astrophys. J., subm. (arXiv:1812.01022)



Beniamini et al., Astrophys. J., 832, 149 (2016) [plus annotations]
see also Ji et al., Nature, 531, 610 (2016)



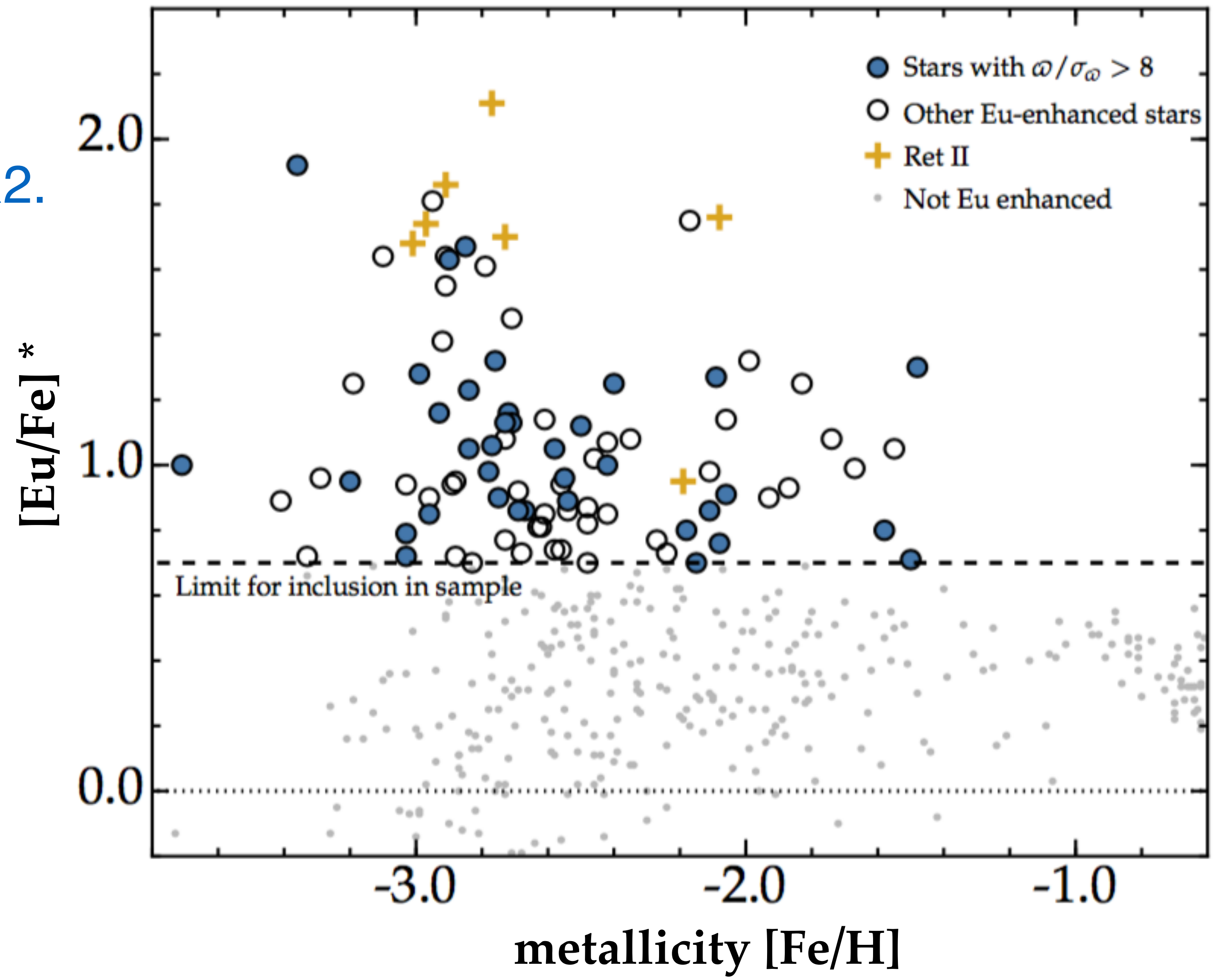
Beniamini et al., Astrophys. J., 832, 149 (2016) [plus annotations]

see also Ji et al., Nature, 531, 610 (2016)

There are 83 **r-process-enhanced stars** ([Eu/Fe] > +0.7) known in the **Milky Way field**.

- Stars with good distances from *Gaia* DR2.

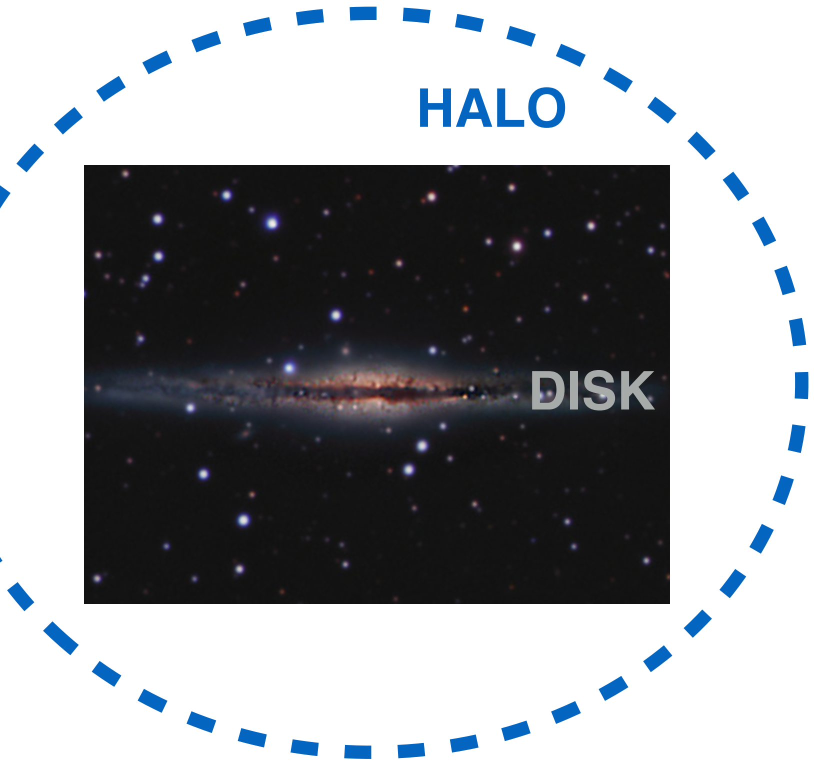
- calculate 6D positions and velocities
- adopt a Milky Way potential
- compute orbits, angular momenta, specific energies, etc.

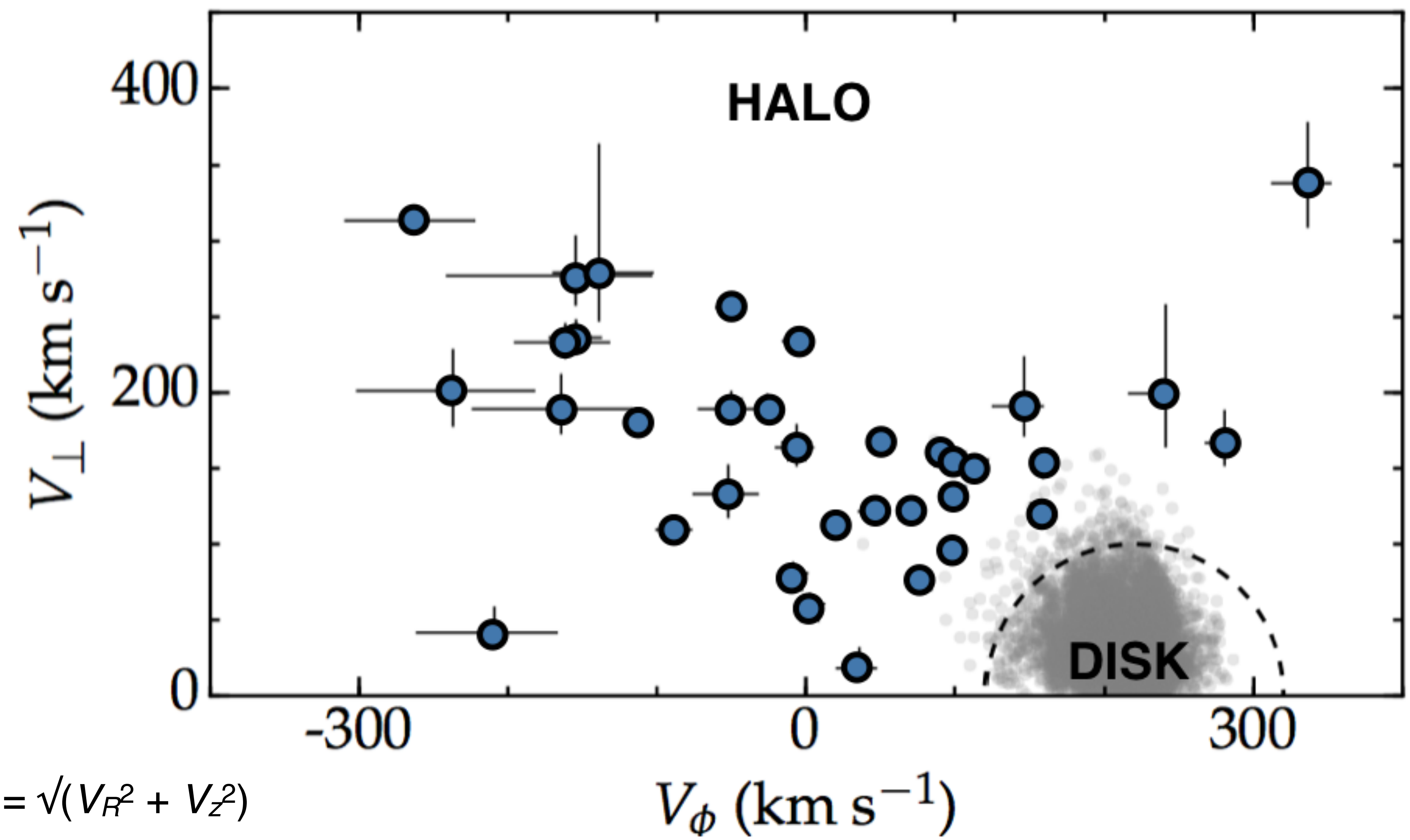


Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

* $[Eu/Fe] = \log_{10}(N_{Eu})_{STAR} - \log_{10}(N_{Eu})_{SUN} - [Fe/H]$
(think of this as the level of r-process enhancement in a star)

Highly r-process-enhanced stars are not part of the Milky Way disk.





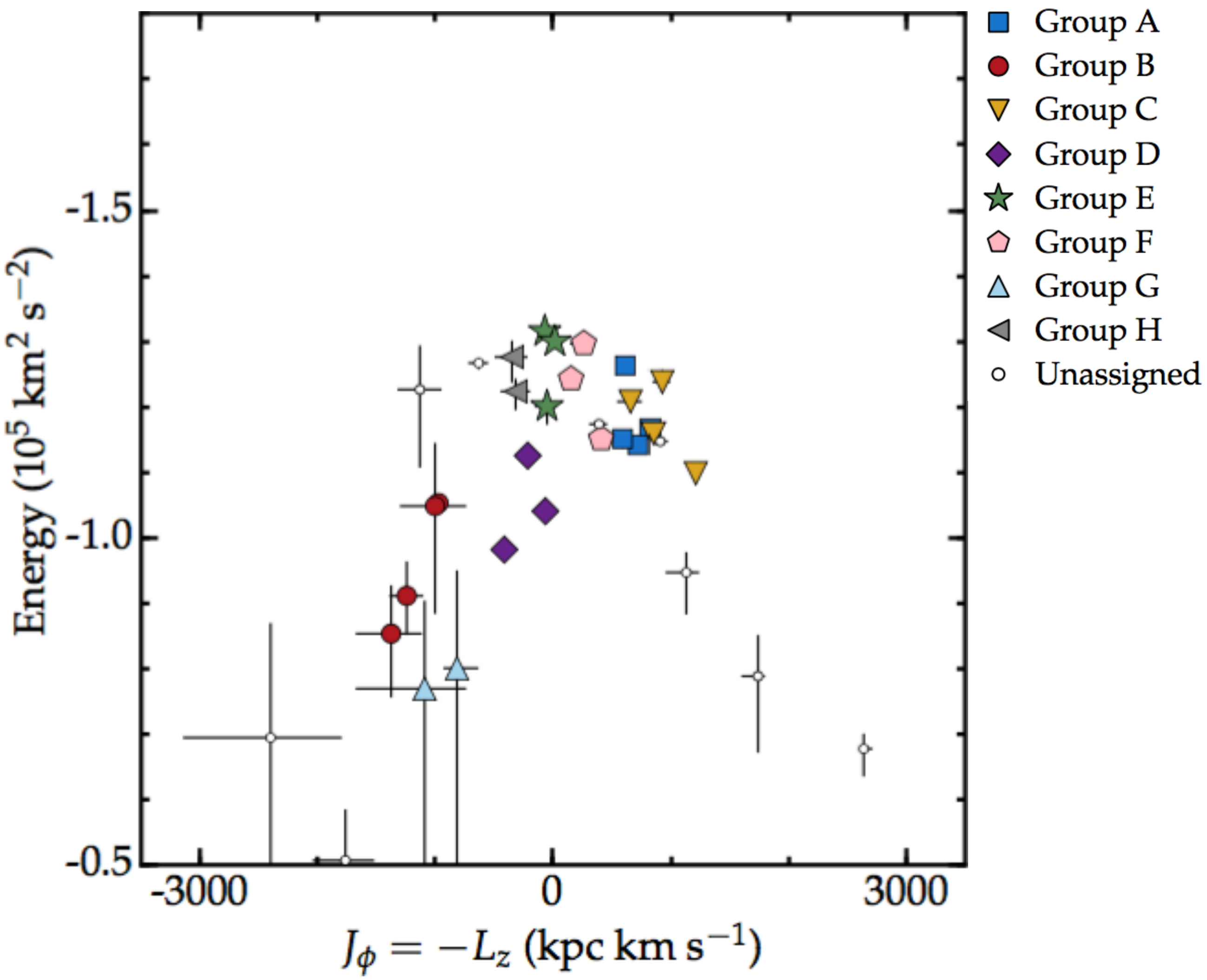
$V_\perp = \sqrt{(V_R^2 + V_z^2)}$

$V_\phi > 0 \longrightarrow$ prograde

image: R. Pommier, via Sky & Telescope

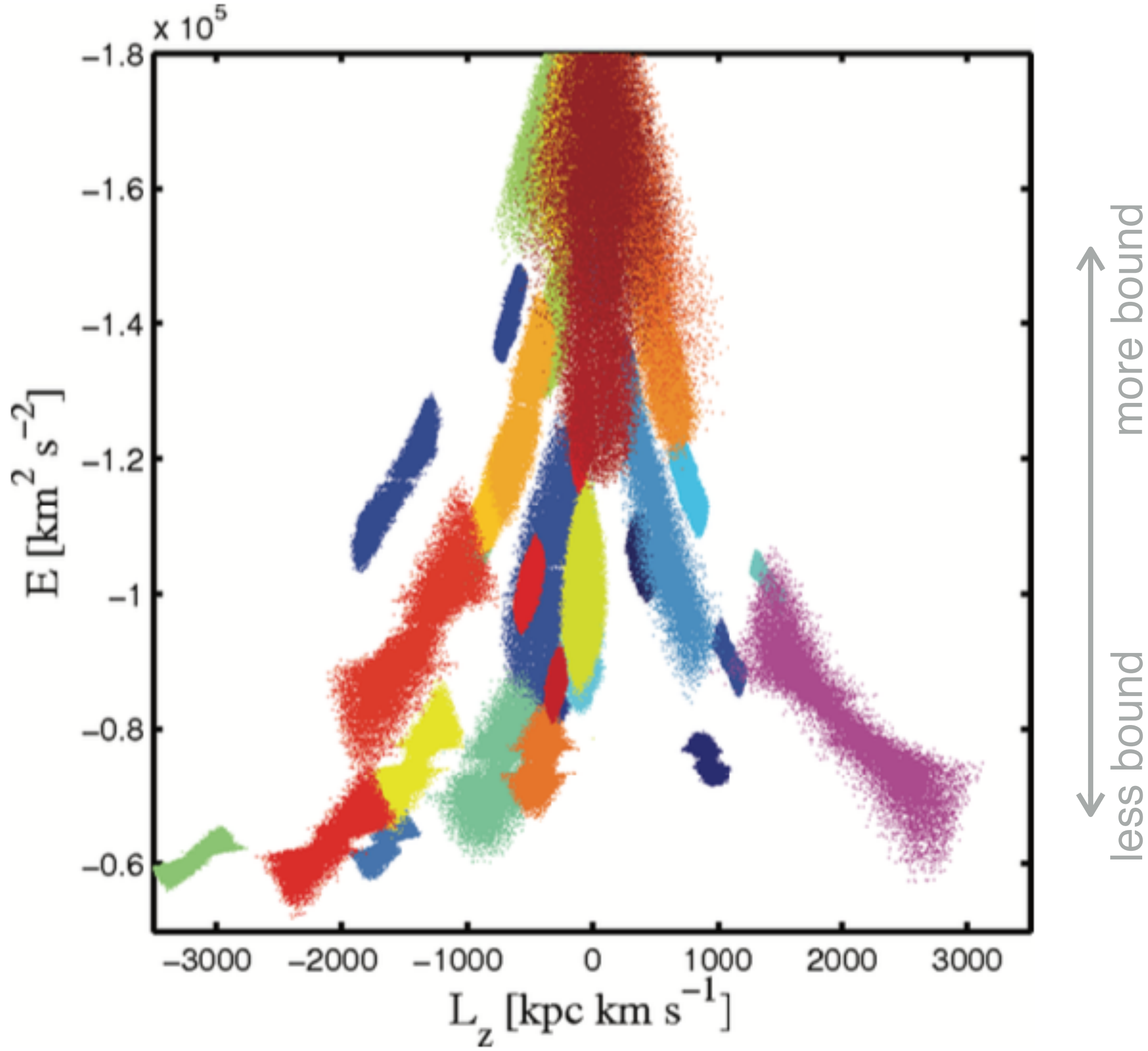
Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

Observations: each symbol/color represents r-process enhanced stars found by three clustering methods applied to the energy (*E*) and integrals of motion (J_R, J_ϕ, J_z)



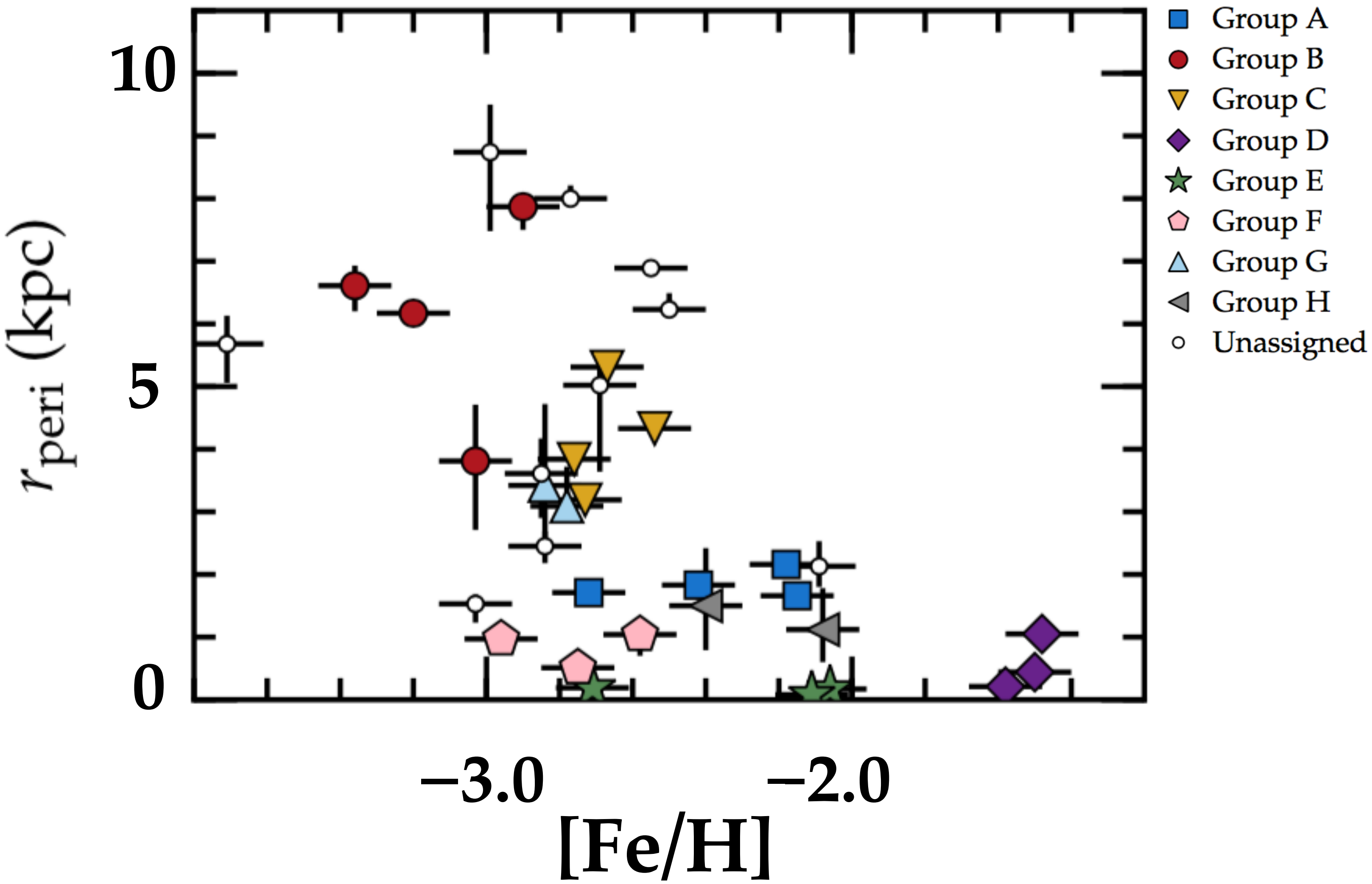
Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

Simulations: each cloud of points represents stars from one disrupted satellite, 10 Gyr later



Gómez et al., Mon. Not. Roy. Astron. Soc., 408, 935 (2010)

All candidate groups show a small metallicity dispersion,
even though chemistry played no role in the clustering analysis.



Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

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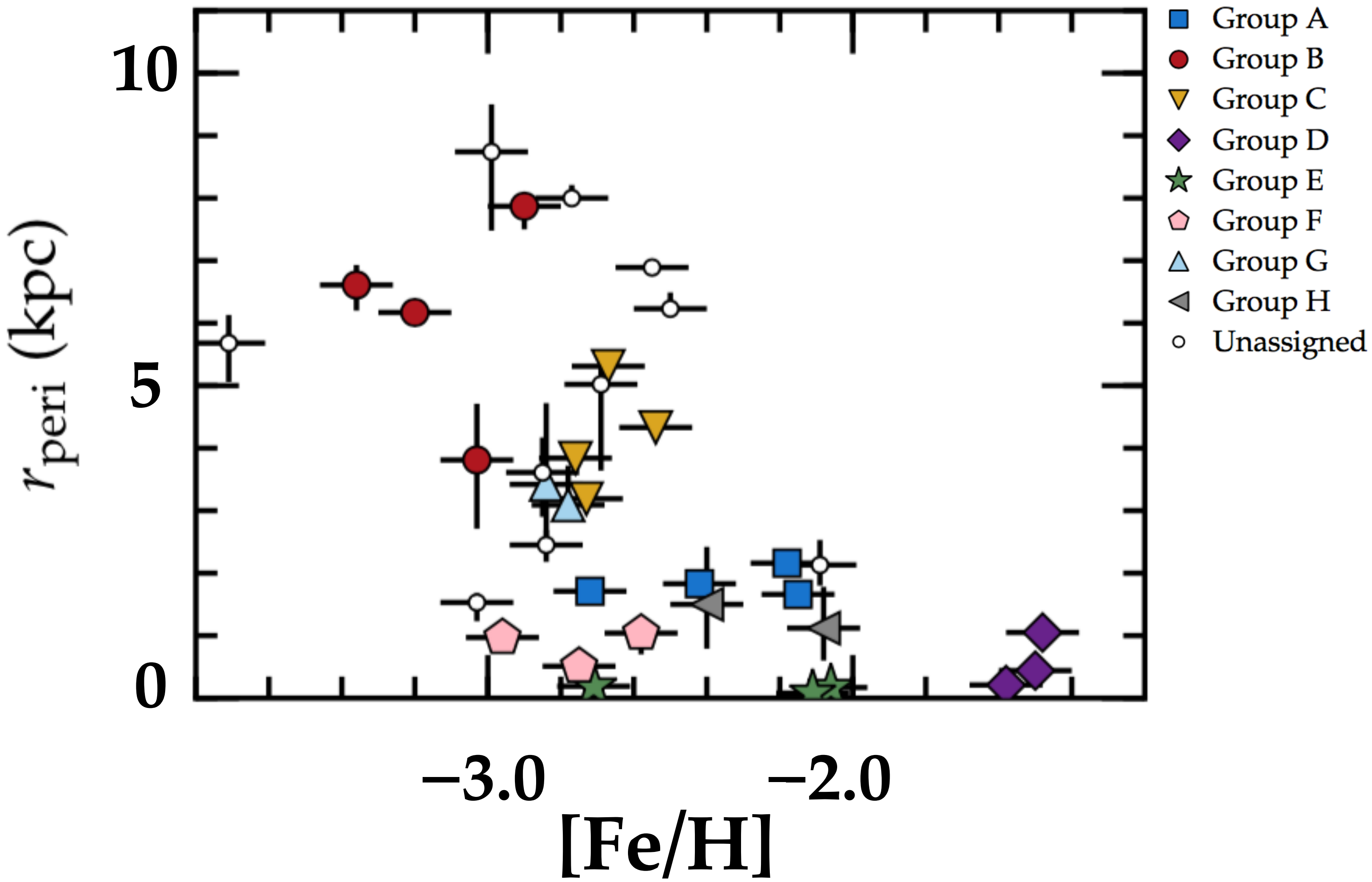
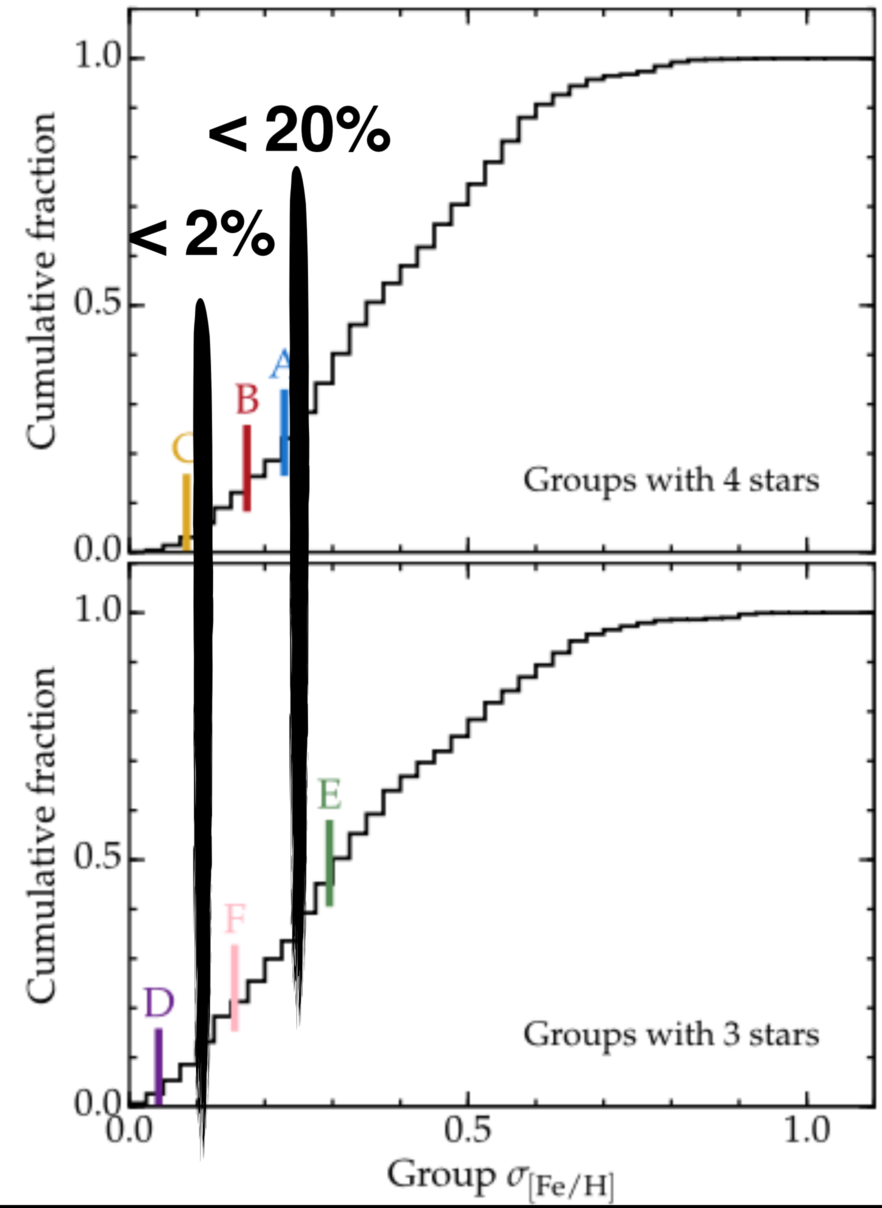
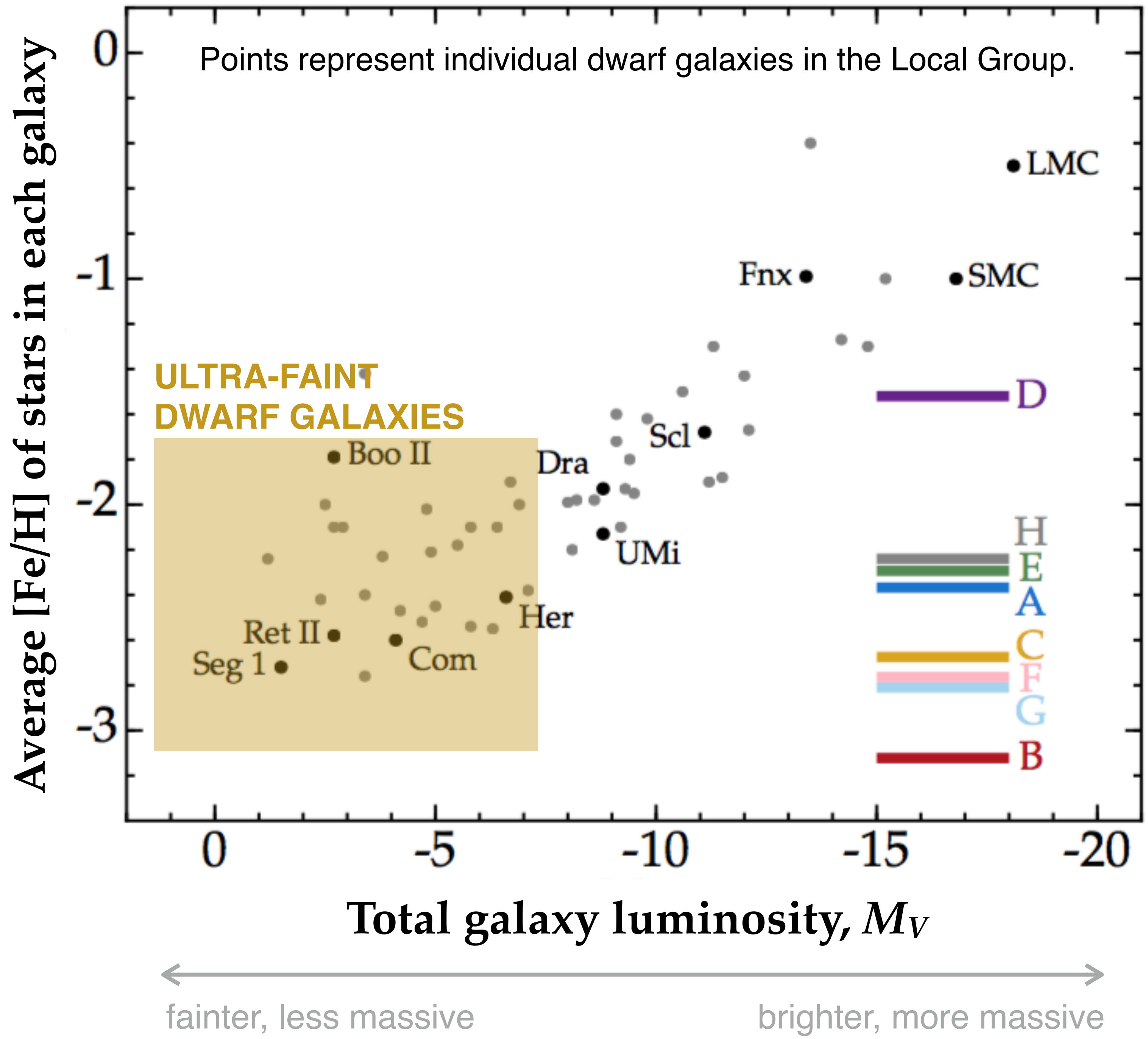




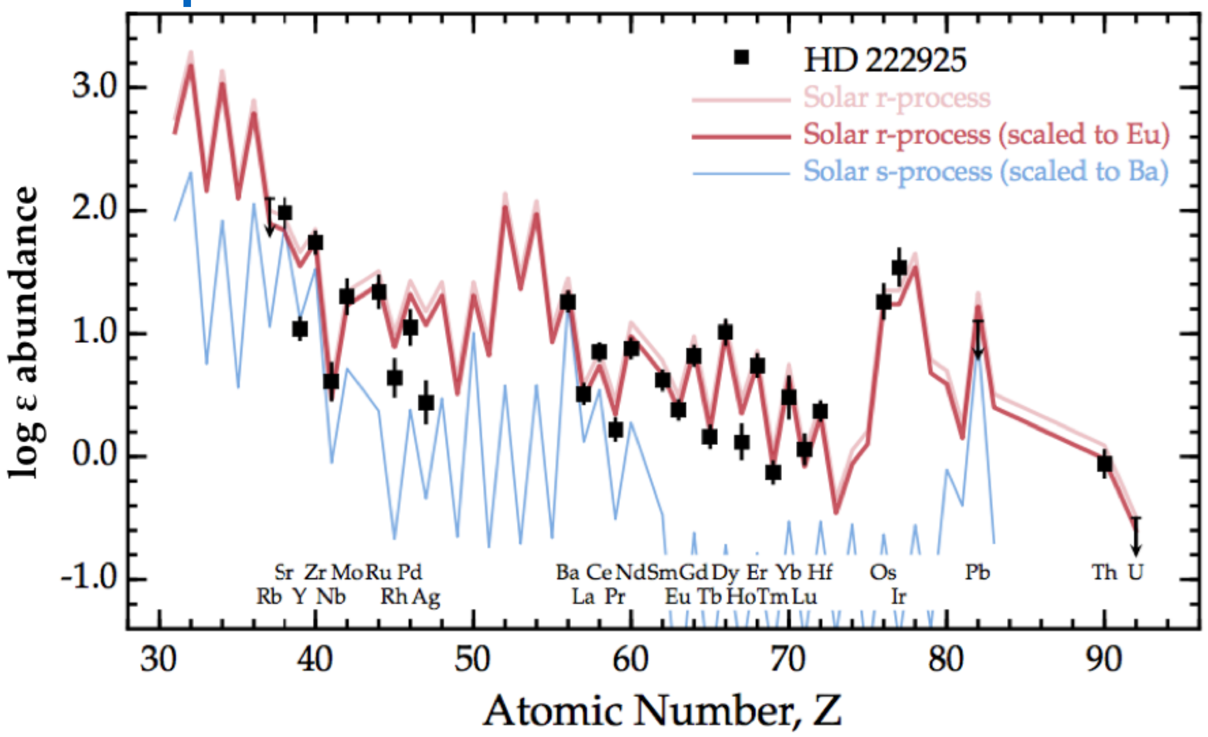
Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)



Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

Luminosity-metallicity relation for dwarf galaxies from, e.g.,
Kirby et al., Astrophys. J. Lett., 685, L43 (2008)
Walker et al., Astrophys. J., 819, 53 (2016)

r-process enhanced stars like this…

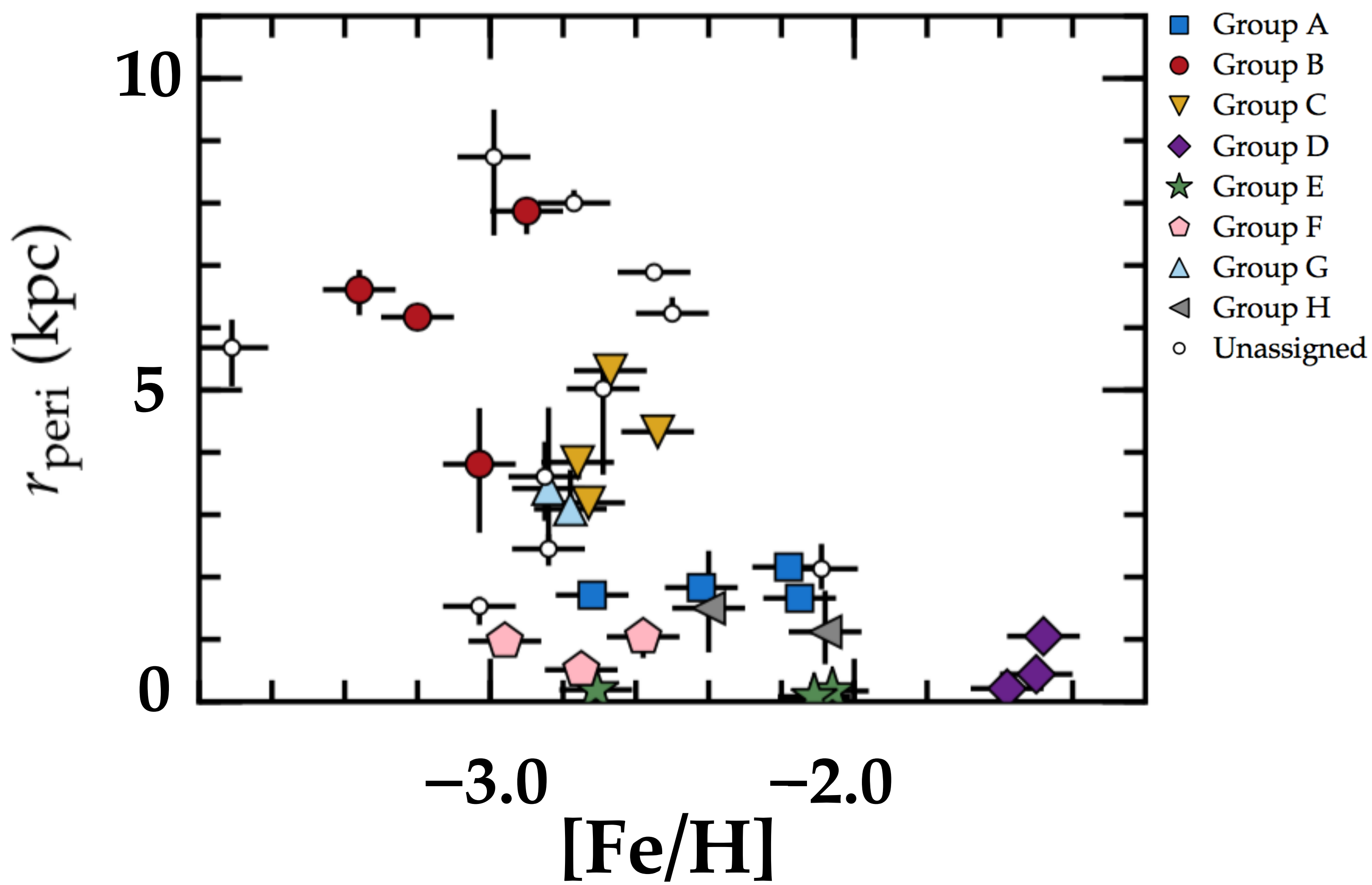


…came from UFD galaxies like this.

Roederer et al., Astrophys. J., 865, 129 (2018)

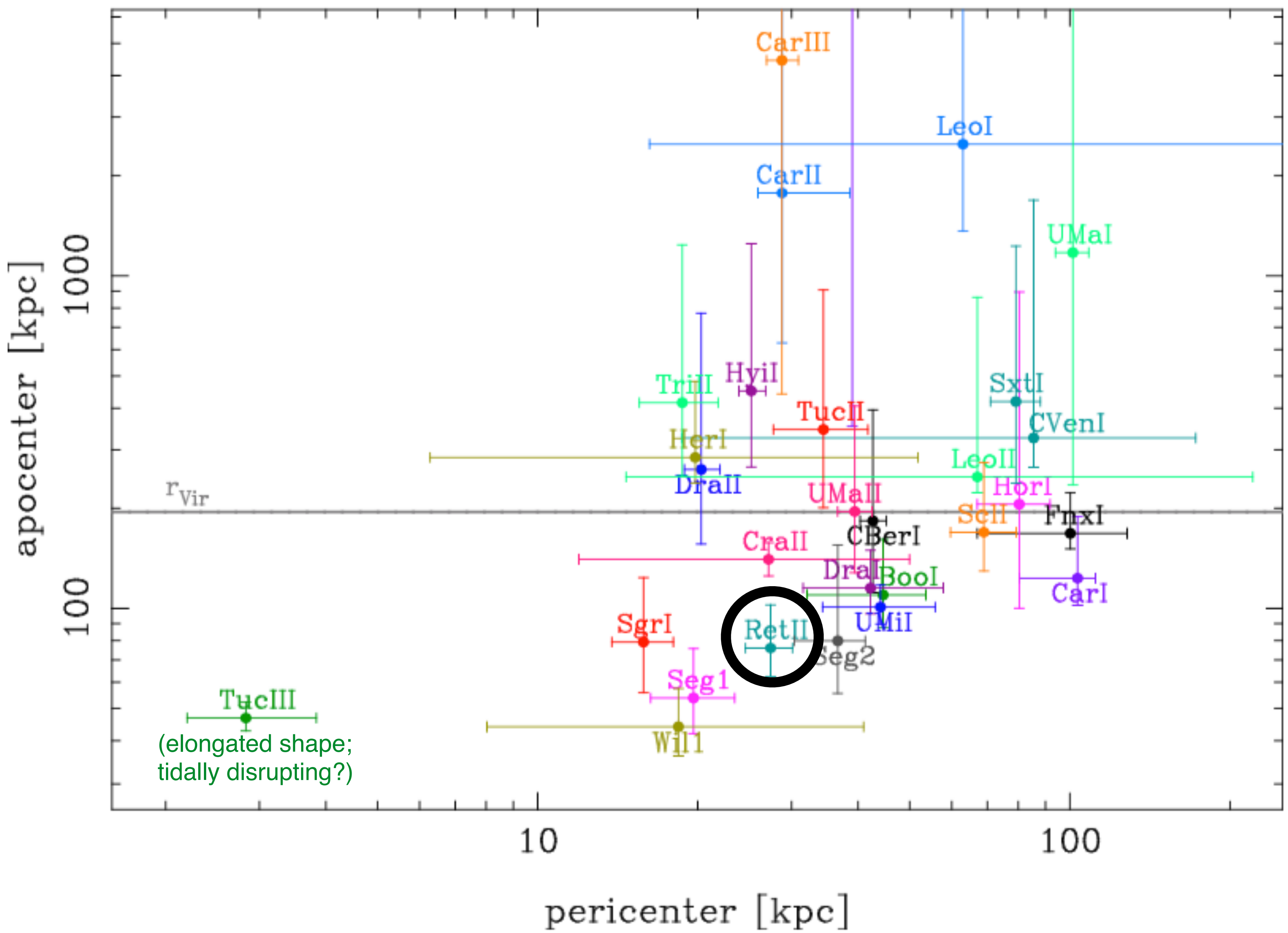
Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)
see also: Xing et al., Nature Astron. (2019)

The **r-process enhanced stars** have **small** orbital pericenters (< 8 kpc).



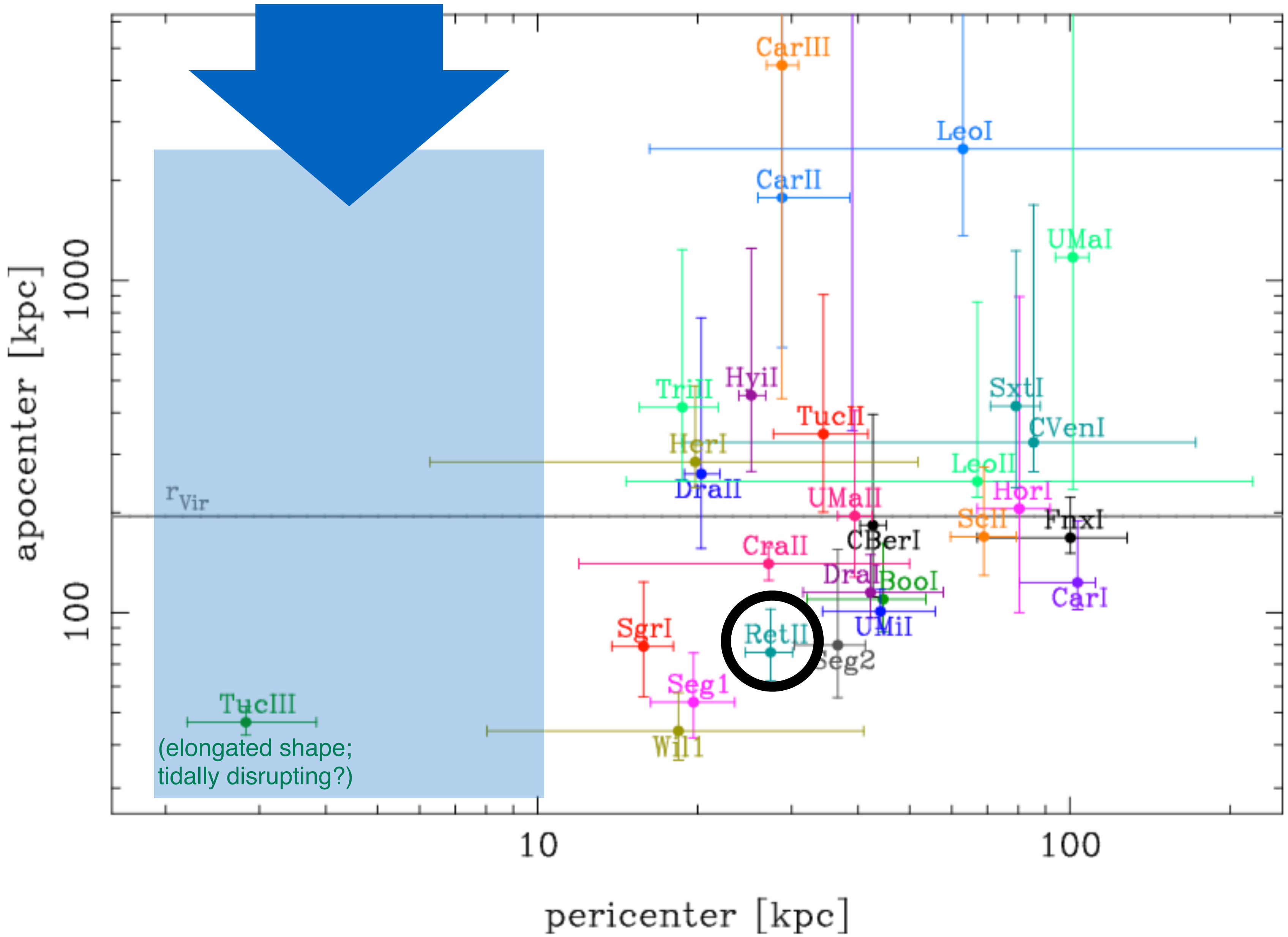
Roederer, Hattori, & Valluri, Astron. J., 156, 179 (2018)

The **surviving UFD galaxies** all have **large** orbital pericenters (> 20 kpc).



Fritz et al., Astron. Astrophys., 619, A103 (2018)

HYPOTHESIS: the **r-process enhanced UFD galaxies** with small orbital pericenters became the **r-process enhanced field stars** of today.



Fritz et al., Astron. Astrophys., 619, A103 (2018)

RPA R-Process Alliance

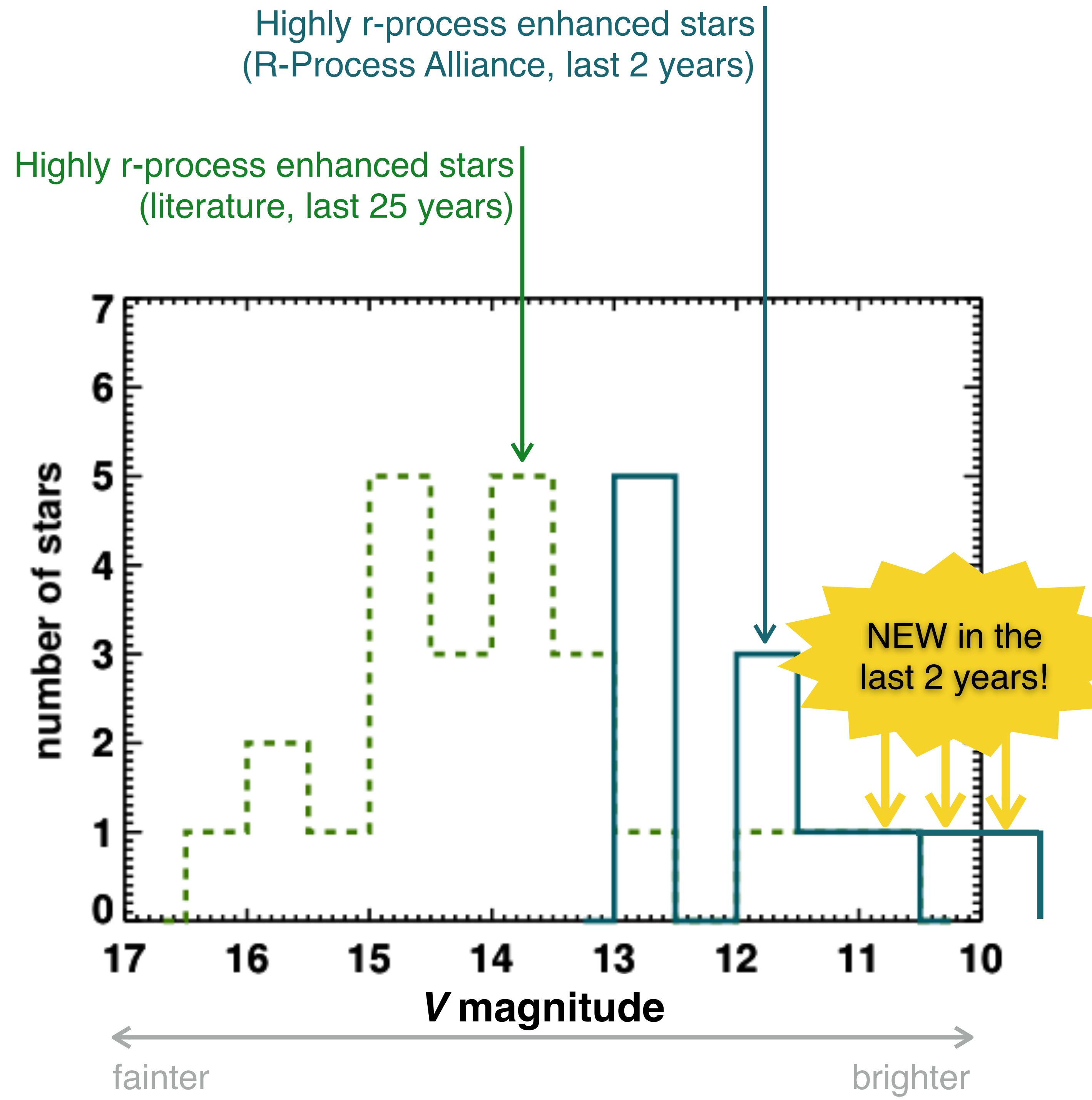
a multi-stage, multi-year effort to provide observational, theoretical, and laboratory constraints on the nature and origin of the astrophysical r-process

Tim Beers*	(Notre Dame)
Maddie Cain	(MIT)
Julio Chaname	(P. U. Católica)
Rana Ezzeddine*	(Florida)
Anna Frebel*	(MIT)
Maud Gull	(MIT)
Terese Hansen*	(Texas A&M)
Erika Holmbeck	(Notre Dame)
Jennifer Marshall	(Texas A&M)
Maria Paz Sepúlveda	(P. U. Católica)
Vini Placco*	(Notre Dame)
Kaitlin Rasmussen	(Notre Dame)
Ian Roederer*	(Michigan)
Charli Sakari*	(San Francisco St.)
Rafael Santucci	(U. F. de Goiás)
Chris Sneden	(Texas)
Sandro Villanova	(Concepción)
Devin Whitten	(Notre Dame)

This is a loose affiliation and will likely grow as the project moves into later phases

* Core member

R-Process Alliance

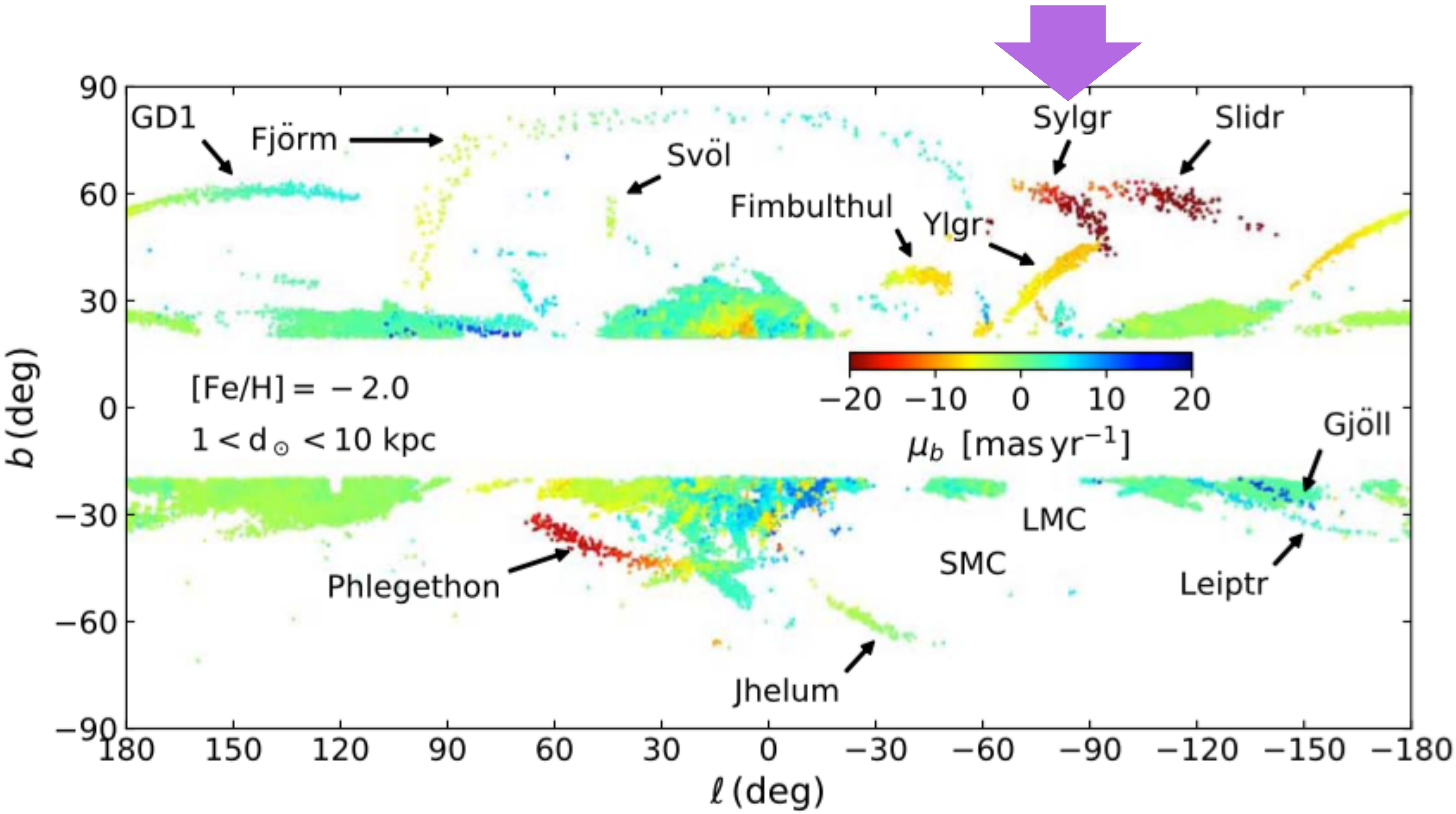


Hansen et al., Astrophys. J., 858, 92 (2018)

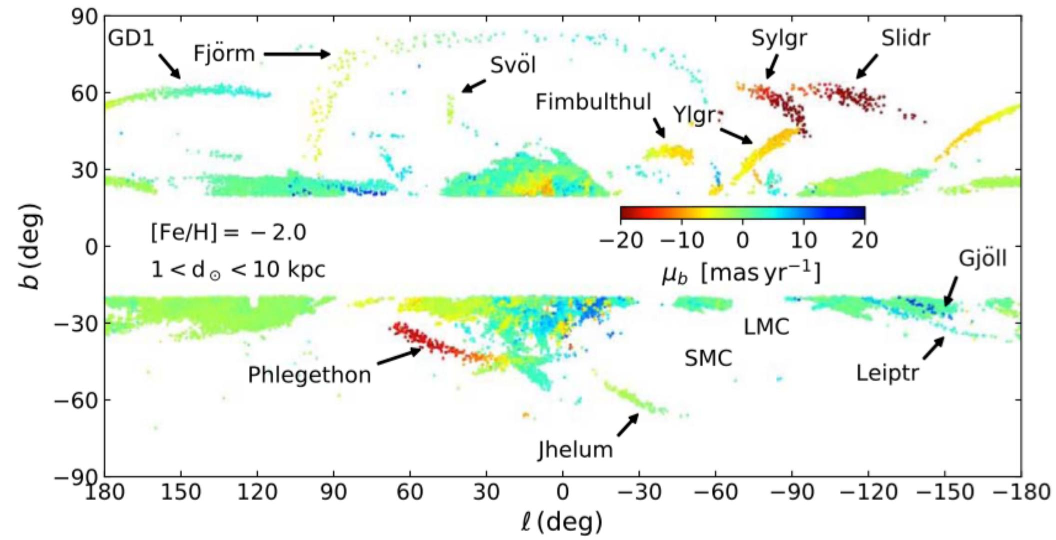
R-Process Alliance

- environmental dependence of the r-process
- precise r-process occurrence frequencies
- associate element-by-element yield patterns with physics and sites
- chemically tag early Milky Way halo assembly

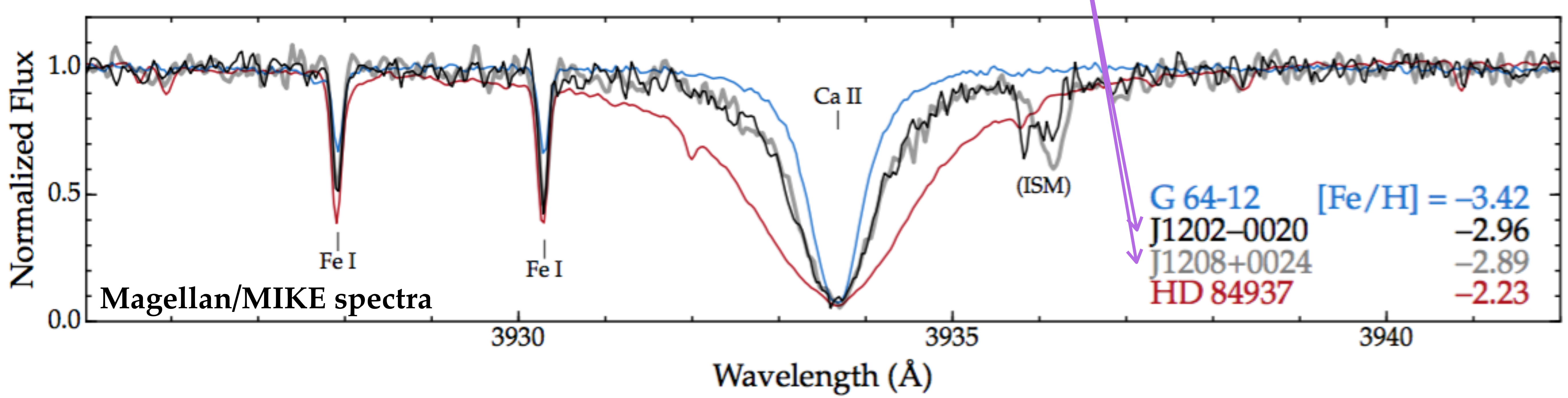
Sylgr: a thin, stellar stream discovered recently by Ibata et al. using Gaia DR2.



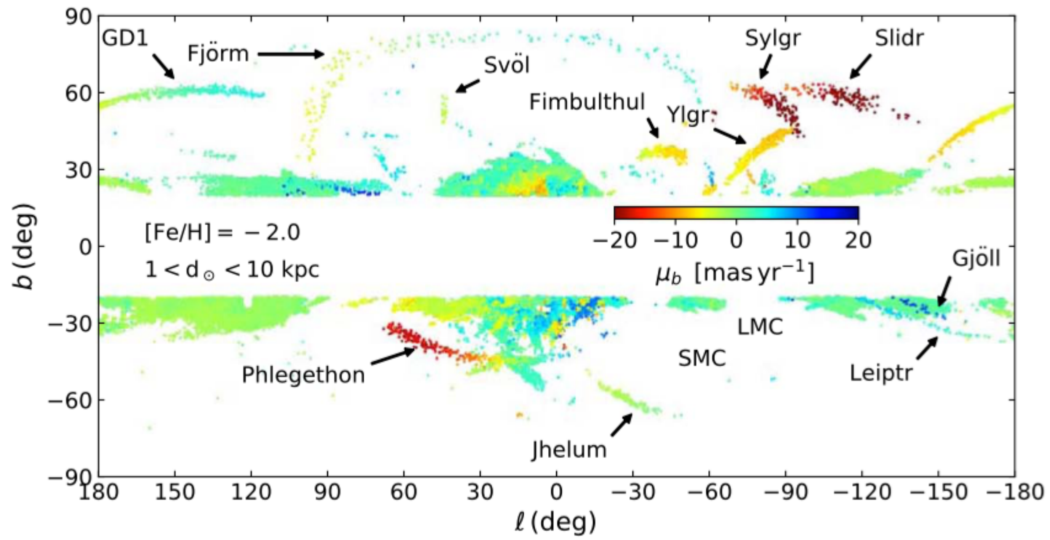
Ibata et al., Astrophys. J., 872, 152 (2019)



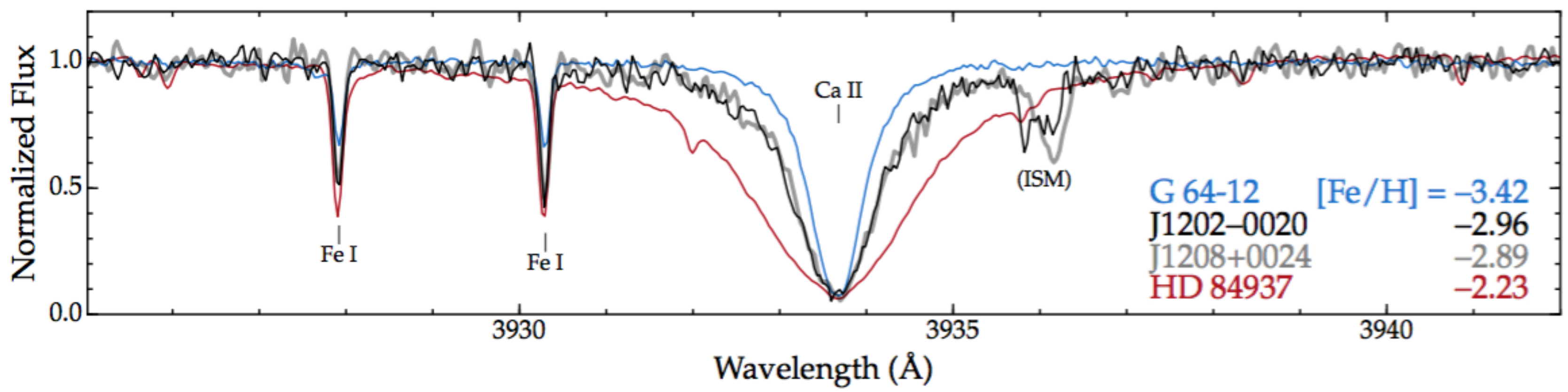
We observed two stars in the Sylgr stream.
They have identical compositions,
and both have [Fe/H] = −2.9.



Ibata et al., Astrophys. J., 872, 152 (2019)
Roederer & Gnedin, Astrophys. J., submitted



Sylgr stream: dense progenitor, [Fe/H] = –2.9



If the progenitor was a **dwarf galaxy**, the stream probably represents its densest part, like a **nuclear star cluster**.

If the progenitor was a **globular cluster**, it would have been (by far) the **most metal-poor globular cluster known**.

Ibata et al., Astrophys. J., 872, 152 (2019)
Roederer & Gnedin, Astrophys. J., submitted

[redacted]