Observaitons of r-process enriched stars

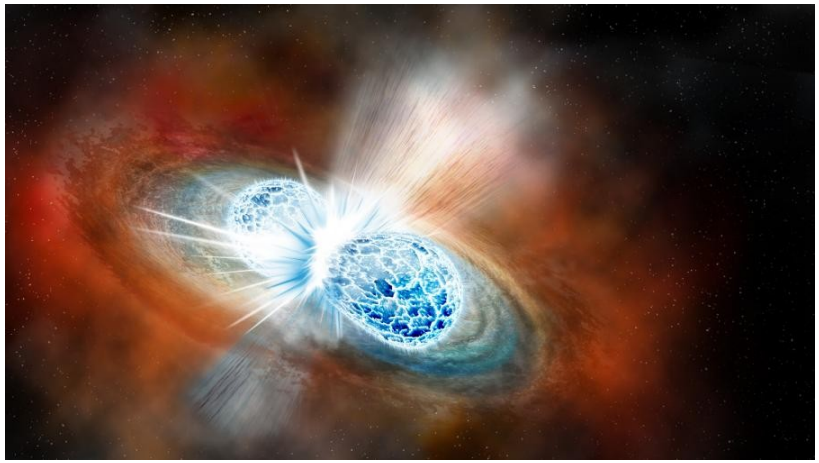
Terese T. Hansen

Sirens conference

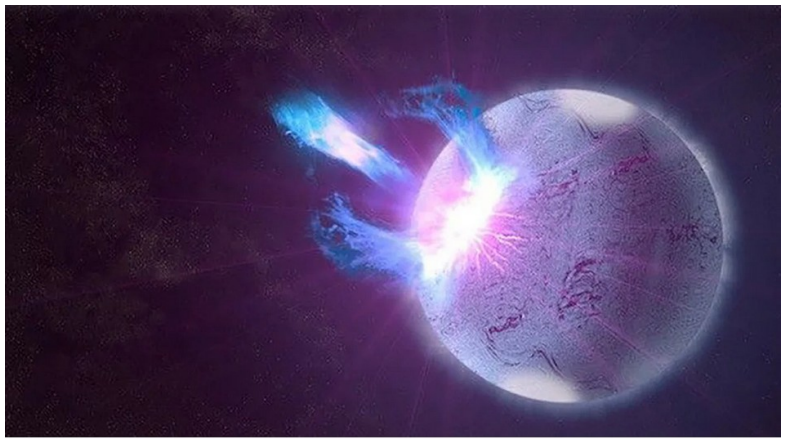
June 11, 2025

Astrophysical sites of the r-process ?

Neutron star mergers



Magnetar flare

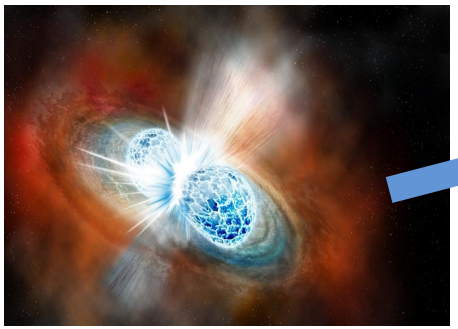


Exotic supernovae

Jet – supernovae **Collapsars** **Core-collapse**

Schramm+ 1974, Winteler+ 2012, Arcones+ 2011, Siegel+ 2018, Paten+ 2025

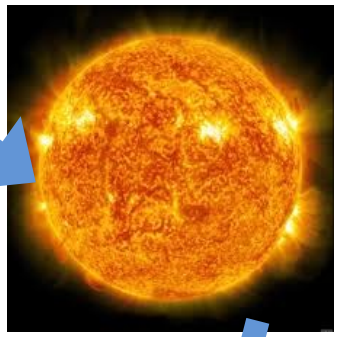
Nuclear astrophysics with stars

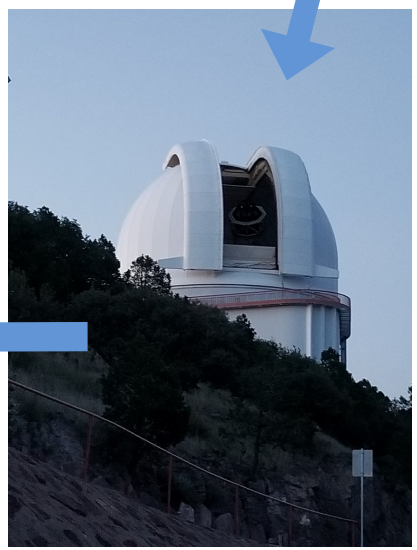


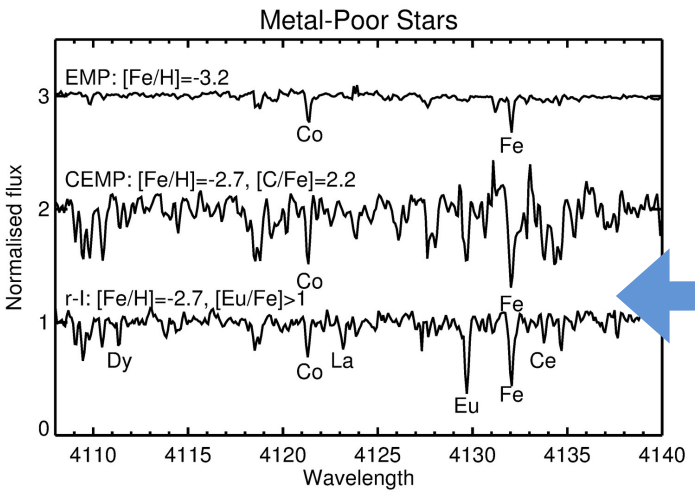
Nucleosynthesis event

Enriching interstellar medium

Low mass star we can observe today



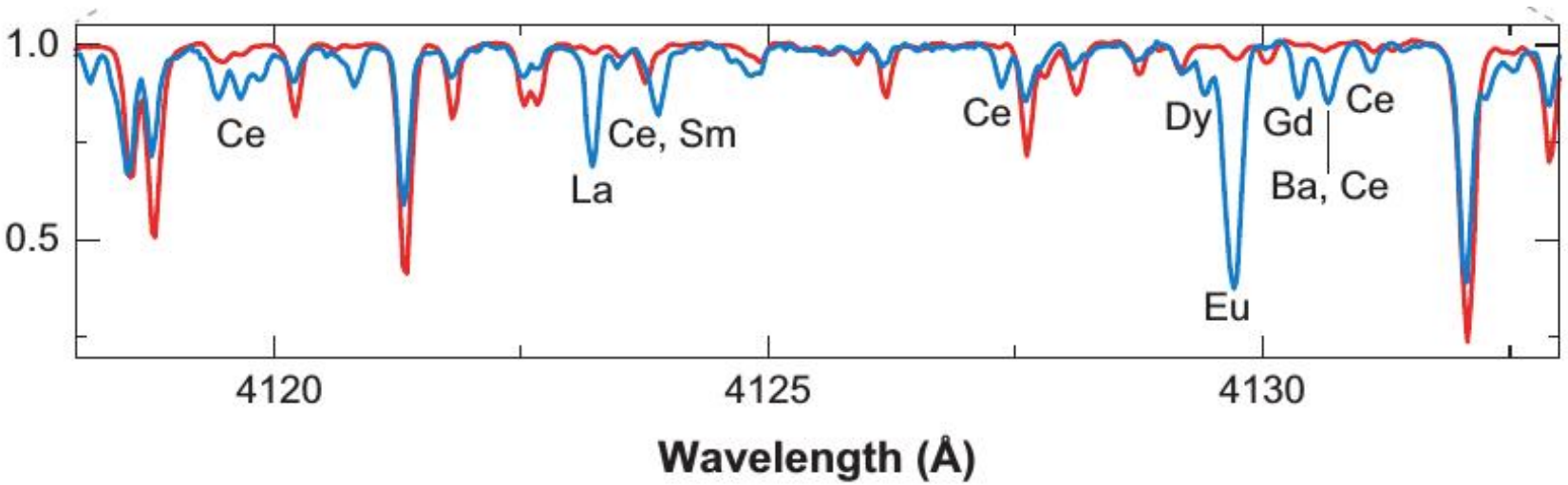




Measure stellar abundance of Eu <-> Eu produced in the nucleosynthesis event.

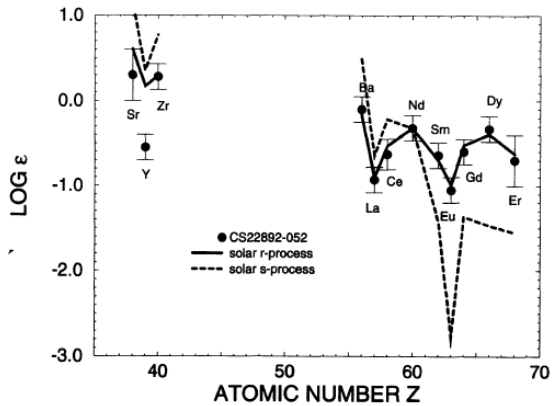
R-process enriched stars

- Stars with an r-process signature in their atmosphere, $[\mathrm{Ba/Eu}] < 0$
- Some are also enhanced - making it easier
  r-**I:** $0.3 < [\mathrm{Eu/Fe}] < 1.0$, $[\mathrm{Ba/Eu}] < 0$
  r-**II:** $[\mathrm{Eu/Fe}] > 1.0$, $[\mathrm{Ba/Eu}] < 0$

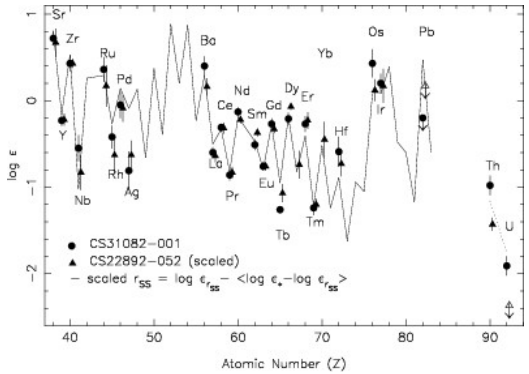


CS 22892−052 and HD 122563 Sneden+ 2008

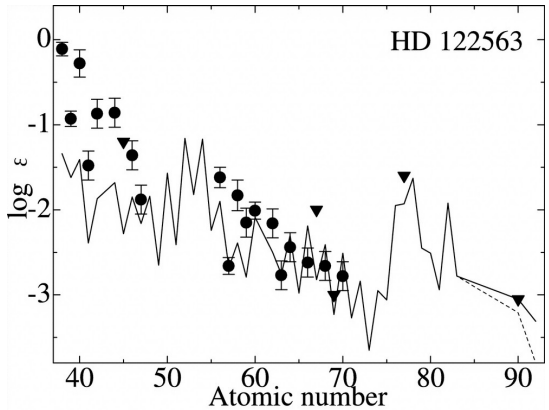
Some history - the hunt has begun



CS22892-052 first *r*-II star discovered (Cowan+ 1995)



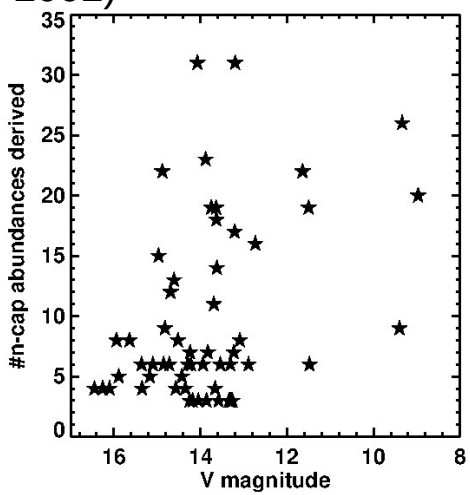
CS31082-001 first U detection, actinide boost star (Hill+ 2002)



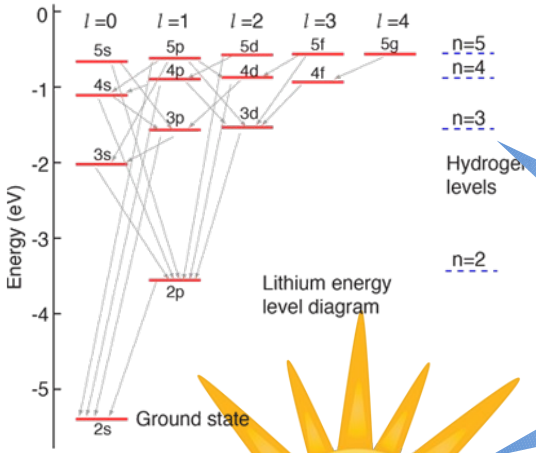
HD122563 – low Eu star (Honda+ 2006)

- HERES Survey (Barklem 2005) 8 new *r*-II stars and 35 new r-I stars out of 253 stars

~60 *r*-II stars known in 2016
Abundances spread over >20 publications. (saga database +JINABase)



Stellar abundance analysis

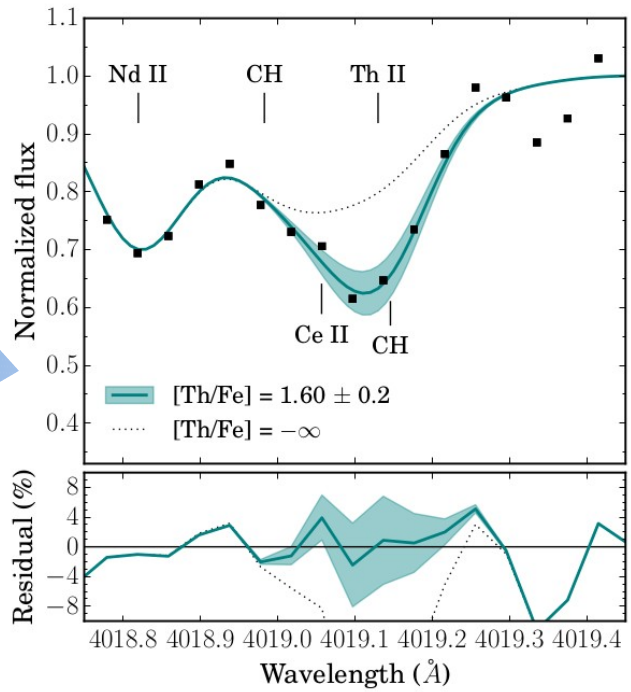


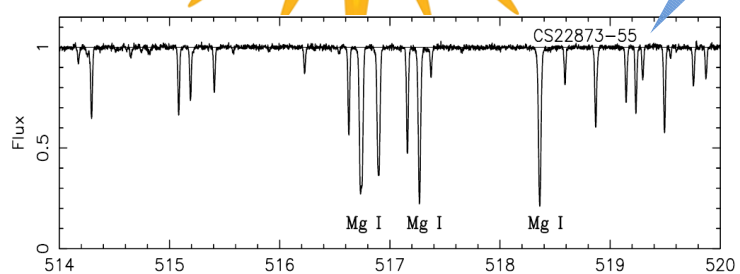
Teff, log g
Vmic, [Fe/H]

Radiative

Transfer

Code

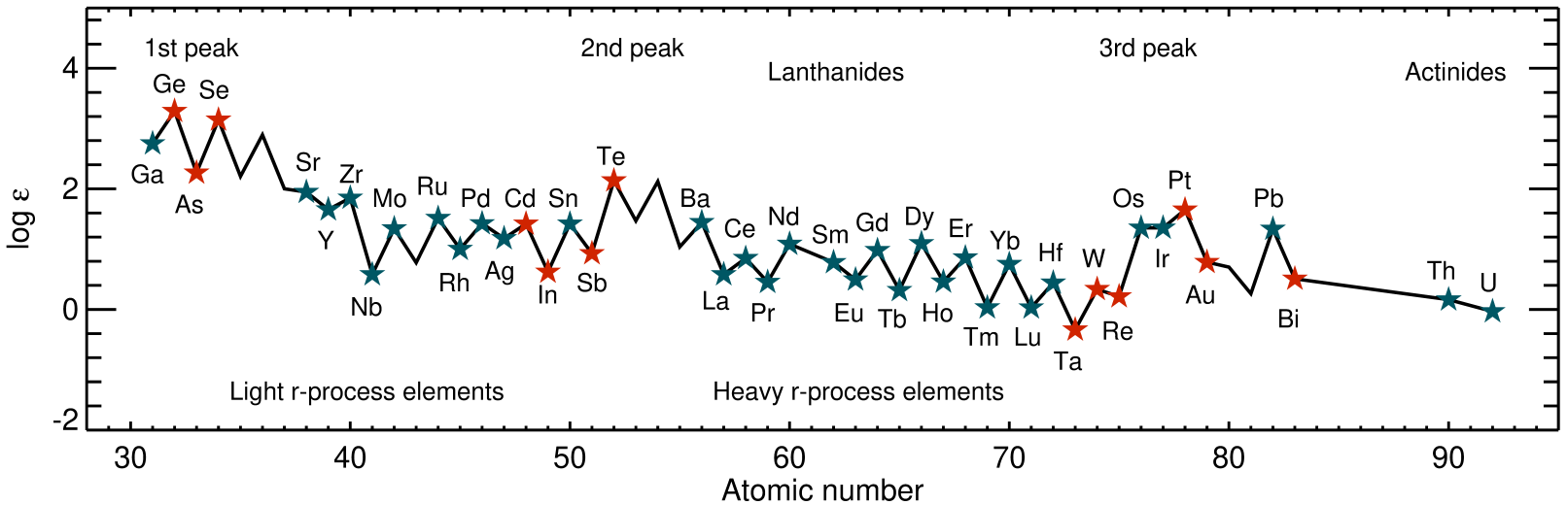




$$[\mathrm{X/Y}] = \log\left(\frac{\mathrm{N(X)}}{\mathrm{N(Y)}}\right)_* - \log\left(\frac{\mathrm{N(X)}}{\mathrm{N(Y)}}\right)_\odot$$

$$\log_\epsilon(\mathrm{X}) = \log(\mathrm{N(X)/N(H)}) + 12$$

What n-cap elements can we get?

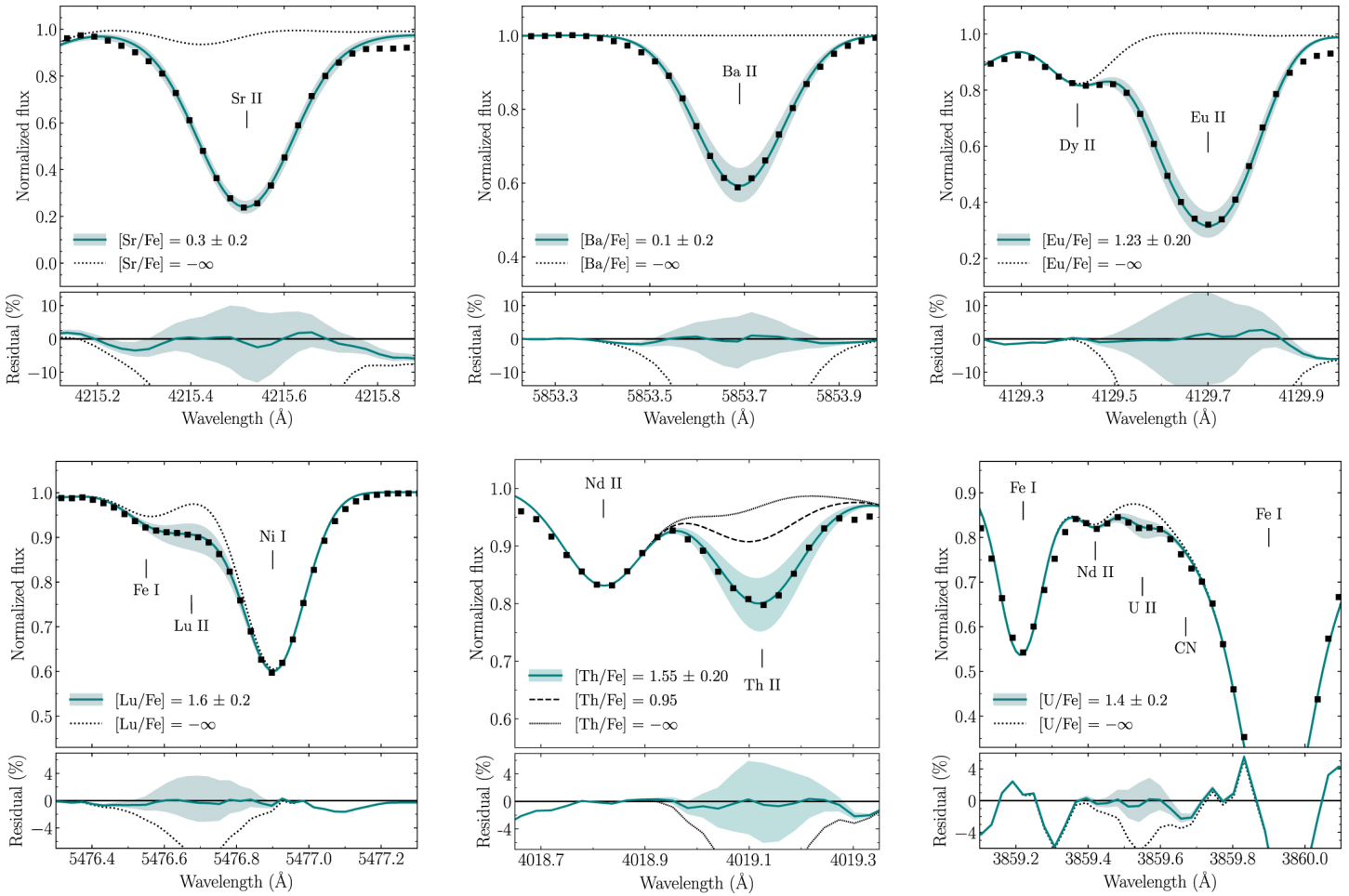


Ground, Space

$>$ 30 neutron-capture elements from ground based spectra!

But what can we really get?

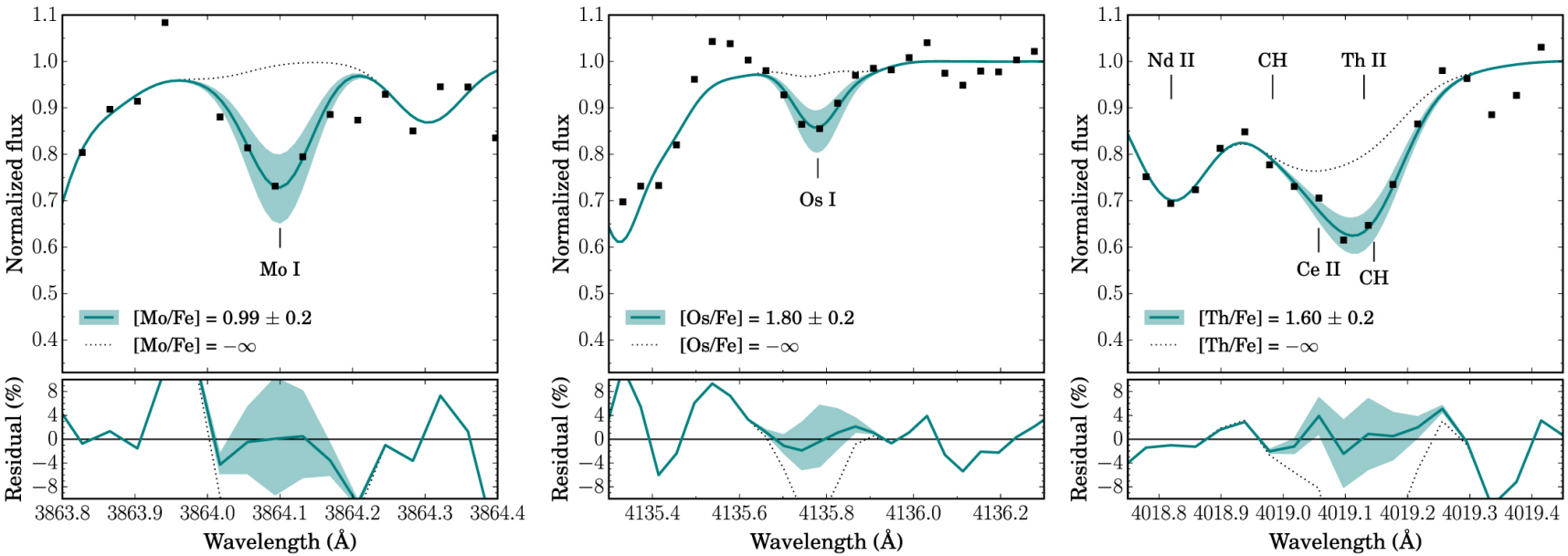
[Eu/Fe]= 1.28, R=60000, SNR=90 at 4100, V=10



Holmbeck+ 2020

But what can we really get?

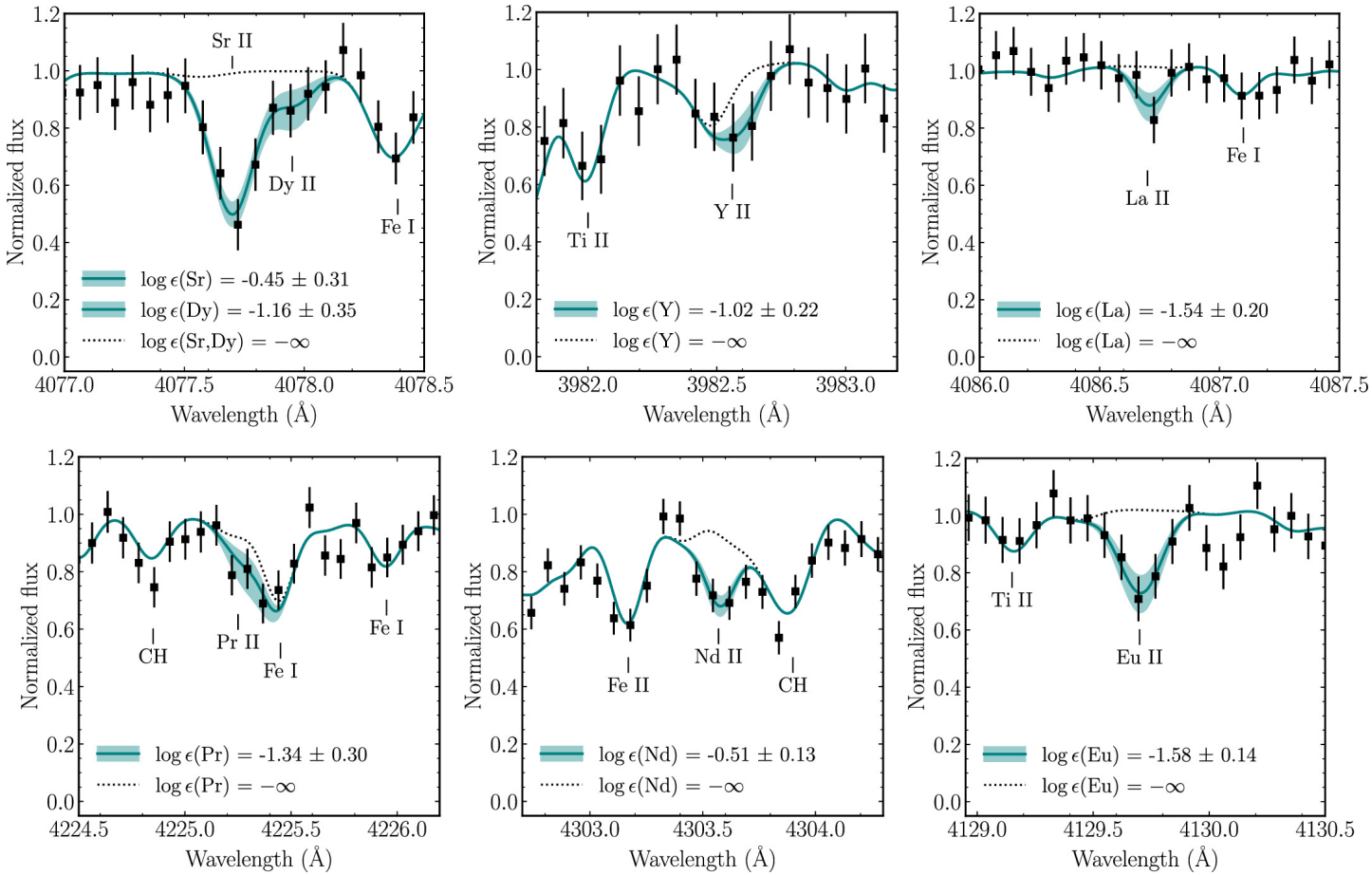
[Eu/Fe]= 1.18, R=35000, SNR=25 at 4500, V=17



Hansen+ 2021

But what can we really get?

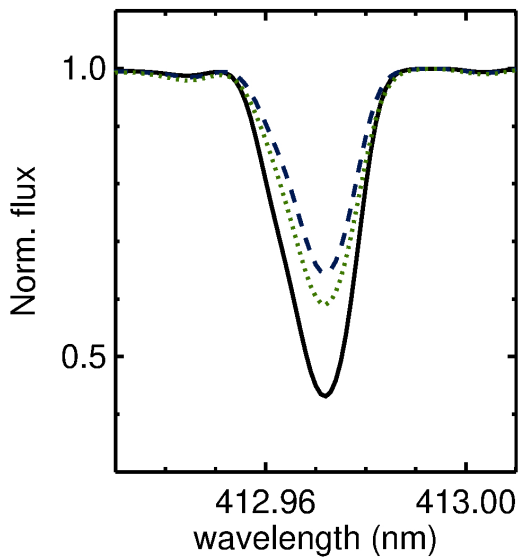
[Eu/Fe]= 0.36, R=28000, SNR=20 at 4500; V=18.5



Hansen+ 2024

Scatter in abundances for CS22892-052

Teff	Logg	[Fe/H]	[Eu/Fe]	loge(Eu)	R / SNR	Ref
4760	1.30	-2.87	1.30	-1.05	22000/	McWilliam 1995
4850	1.50	-2.80	1.34	-0.94	40000/	Norris 1997
4690	1.15	-3.24	1.44	-1.28	41000/270	Roederer 2014
4850	1.60	-3.03	1.48	-1.03	47000/130	Francois 2007
4922	1.90	-2.61	1.48	-0.90	20000/50	Ren 2012
4884	1.81	-2.95	1.53	-0.90	20000/46	Barklem 2005
4790	1.60	-2.91	1.53	-0.86	90000/60	Honda 2004
4800	1.50	-3.10	1.62	-0.96	45000/200	Roederer 2009
4800	1.50	-3.10	1.63	-0.95	60000/100	Sneden 2003
4800	1.50	-3.12	1.66	-0.95	45000/200	Cowan 2005
4710	1.50	-3.20	1.75	-0.93	60000/150	Sneden 2000



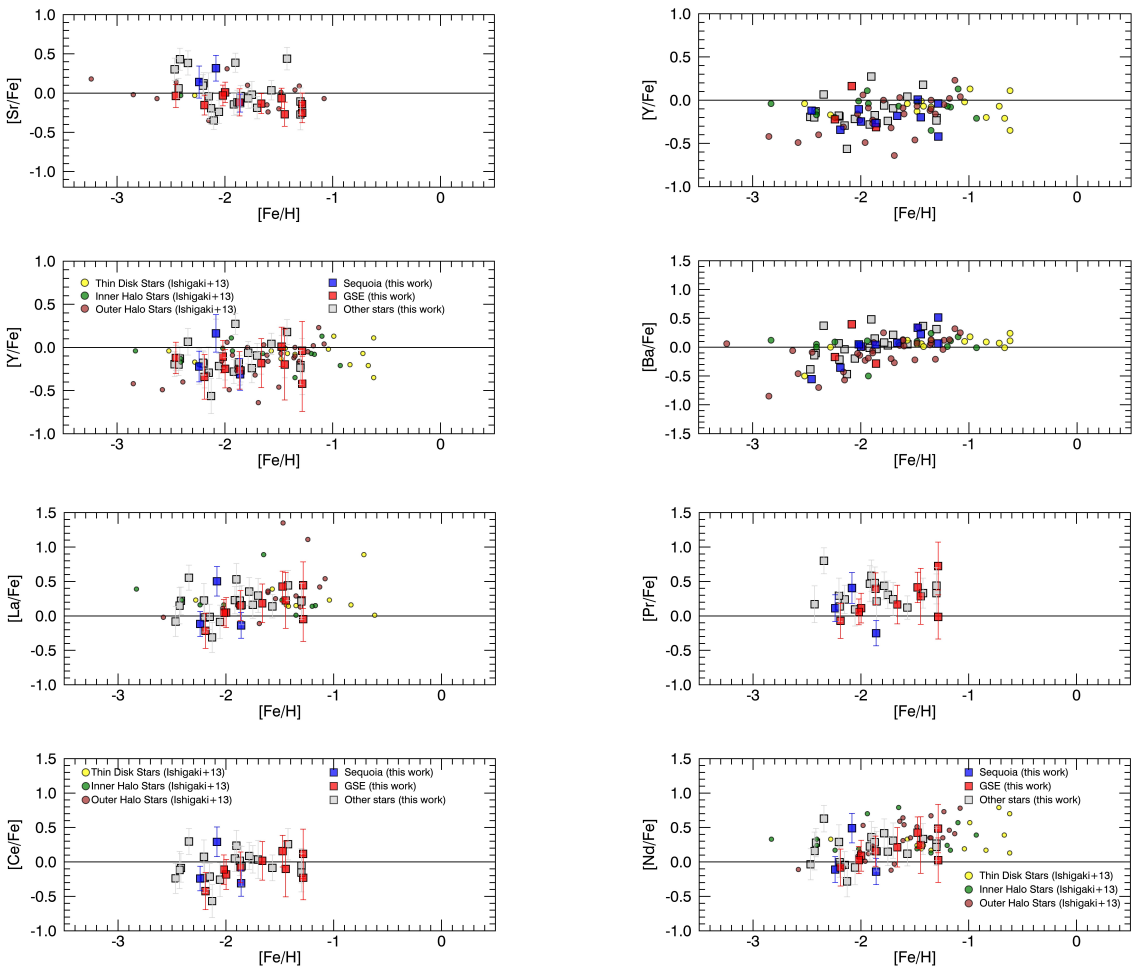
→ Caution when using data from large compilations like SAGA and JINABase.

Okay, so what is next

- Most observations and analysis have focused on finding the most metal-poor, most r-process enhanced stars, resulting in single star analysis from many sources.
- Focus is now moving to better statistics for all r-process enrichment levels and better metallicity coverage.
- Homogeneous analysis of larger samples.
- Also focus on stellar birth environment.

MINCE (Measuring at Intermediate metallicity Neutron-Capture Elements)

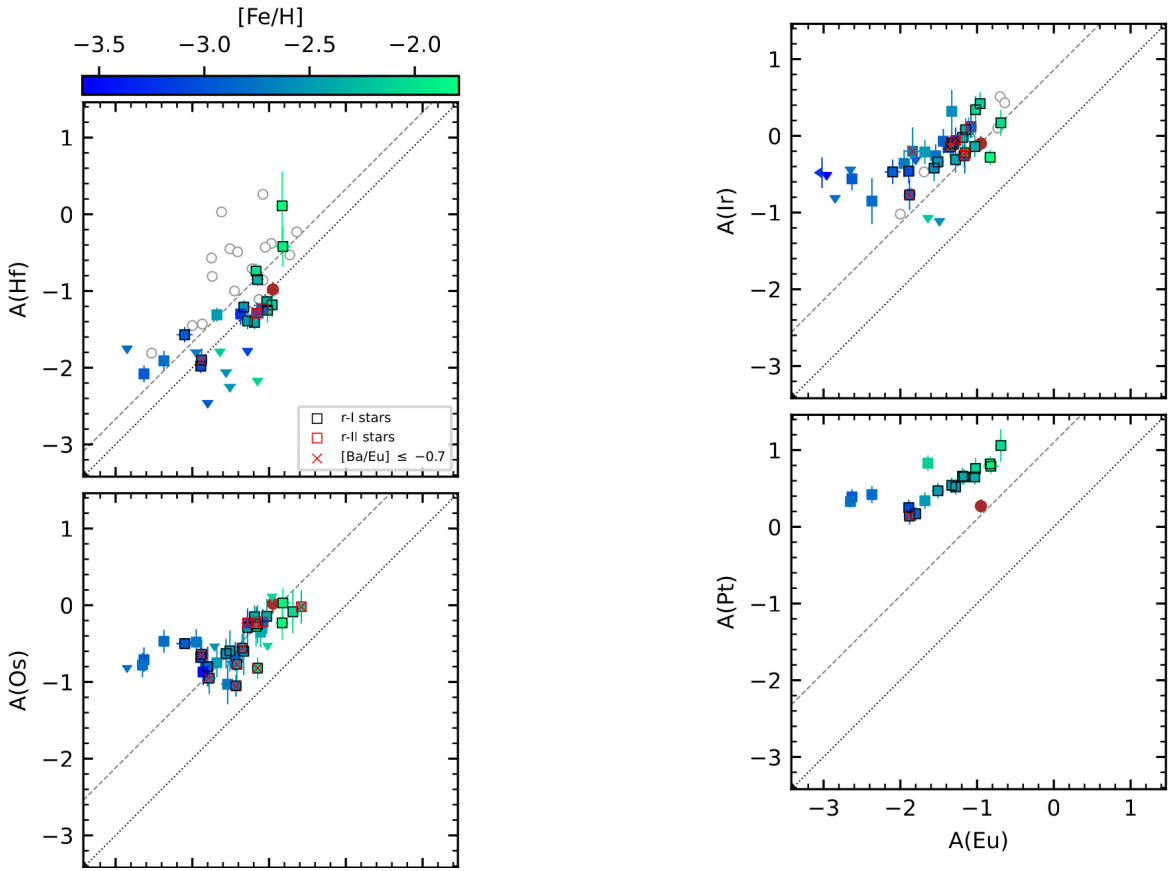
Probing a new metallicity range and tracing the stellar birth environment. See talk by Francesca Lucertini



Francois+ 2024

CERES (Chemical Evolution of R-process Elements in Stars)

Homogeneous analysis of stars with a range of r-process enrichment levels. See talk by Linda Lombardo



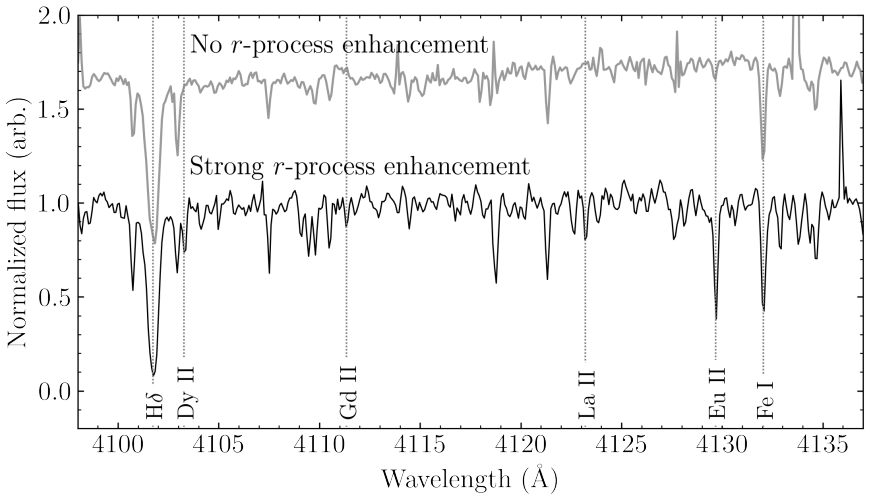
Puls+ 2025

R-Process Alliance

1) A large sample of metal-poor stars for robust r-process enhancement statistics.

2) A large sample of r-process enriched stars sufficiently bright to detect all elements needed to study the variations in the r-process.

- **Bright**, $V < 13.5 \rightarrow$ can observe many stars in short time
- **Cold**, $4000 < \mathrm{T_{eff}} < 5500 \rightarrow$ Get Sr, Ba, and Eu abundances or good upper limits
- **Metal poor**, $[\mathrm{Fe/H}] < -2 \rightarrow$ Only few nucleosynthesis events

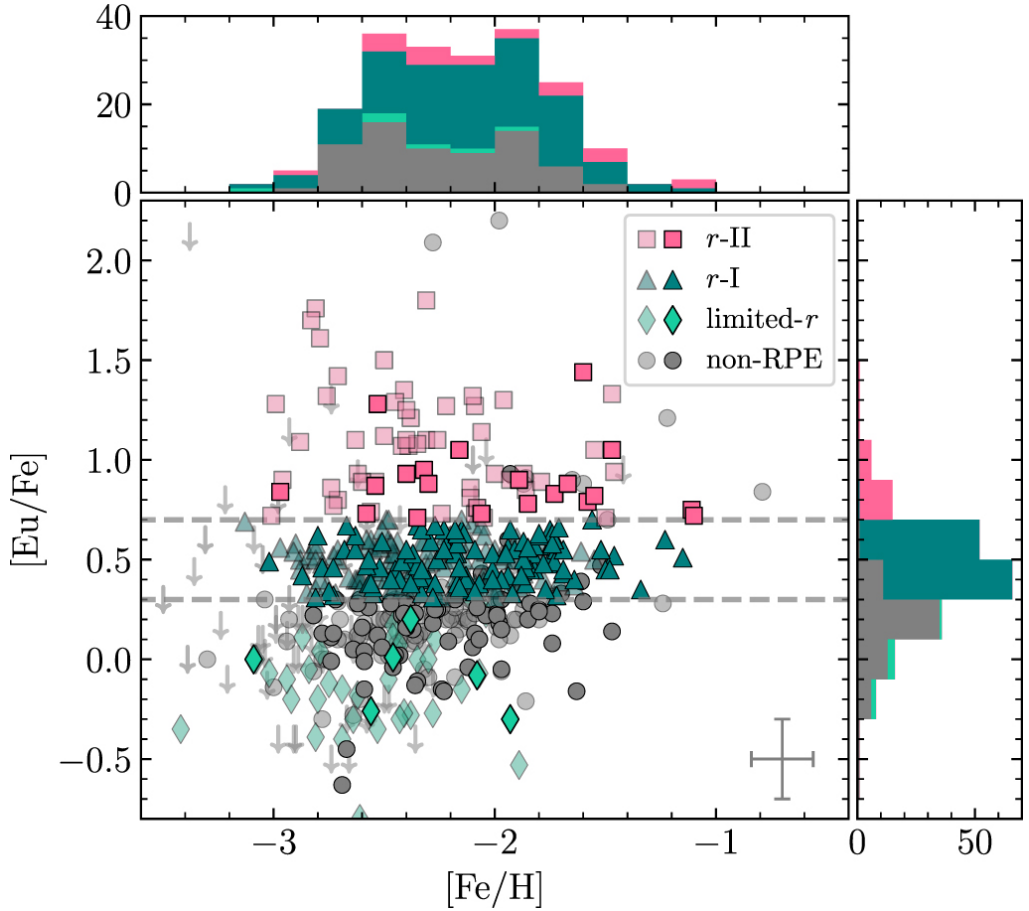


R ~25000, S/N~30 4100A

RPA - Current results

747 stars with $[\mathrm{Eu/Fe}]$ abundances before RPA, we have added 600 in DR1-5, including 70 r-II stars. Next stop 2000!

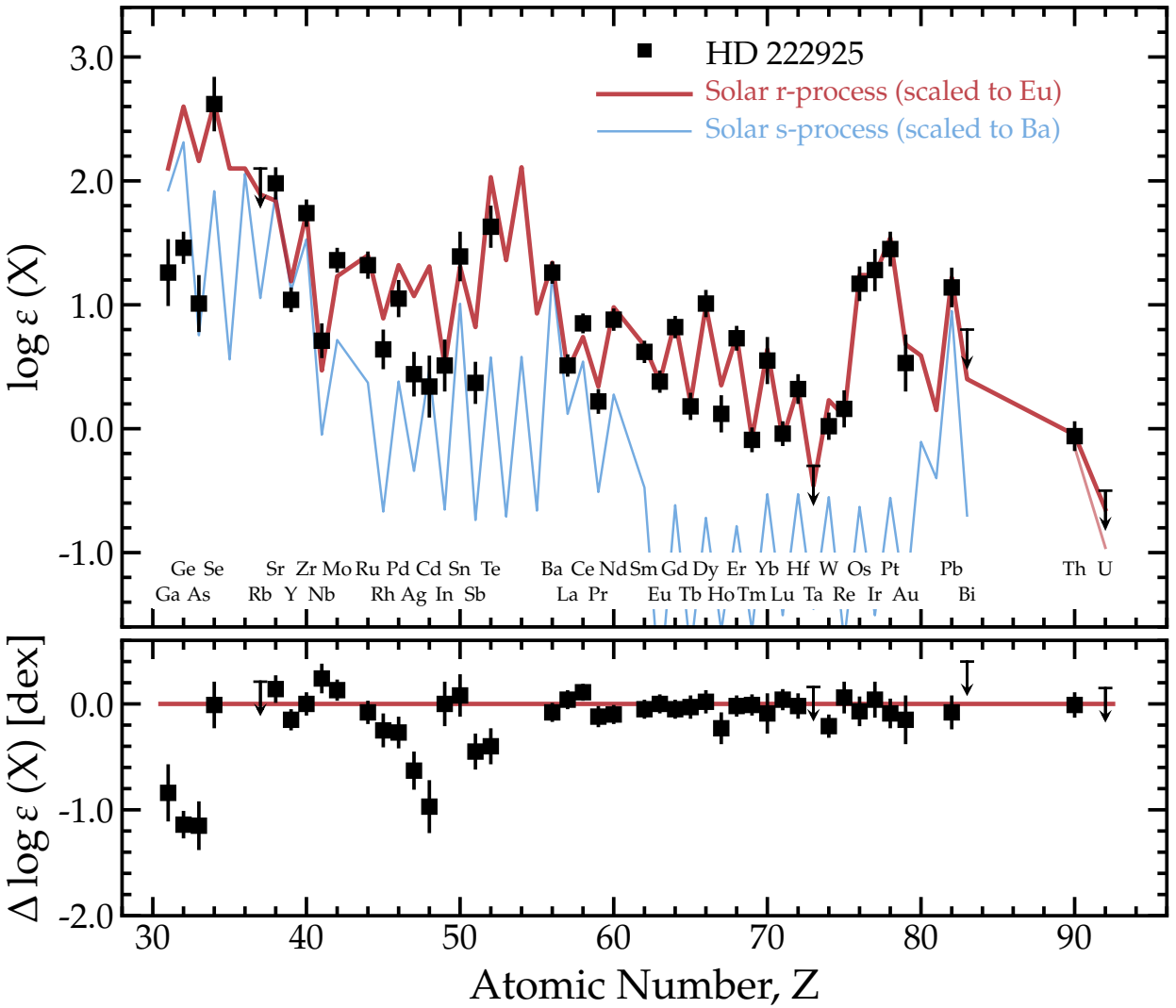
$\rightarrow$New data driven classification of r-II stars: $[\mathrm{Eu/Fe}] \geq 0.7$



Hansen+ 2018, Sakari+ 2018, Ezzeddine+ 2020, Holmbeck+ 2020, Bandyopadhyay+ 2024

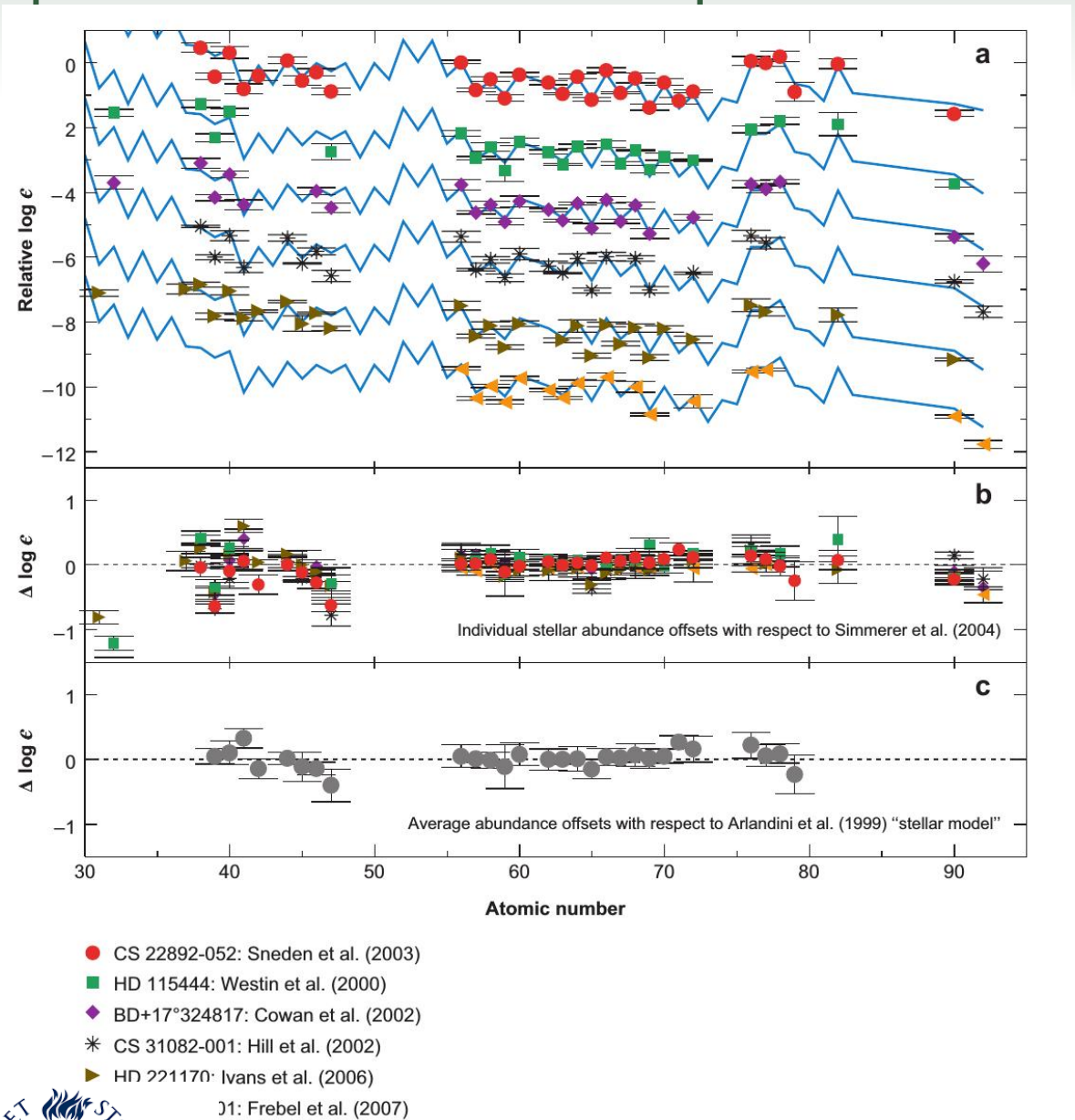
HD 222925 - The golden standard

$V = 9.02$, [Fe/H]=-1.46, [Eu/Fe]=1.32



Roederer, RPA+ 2022

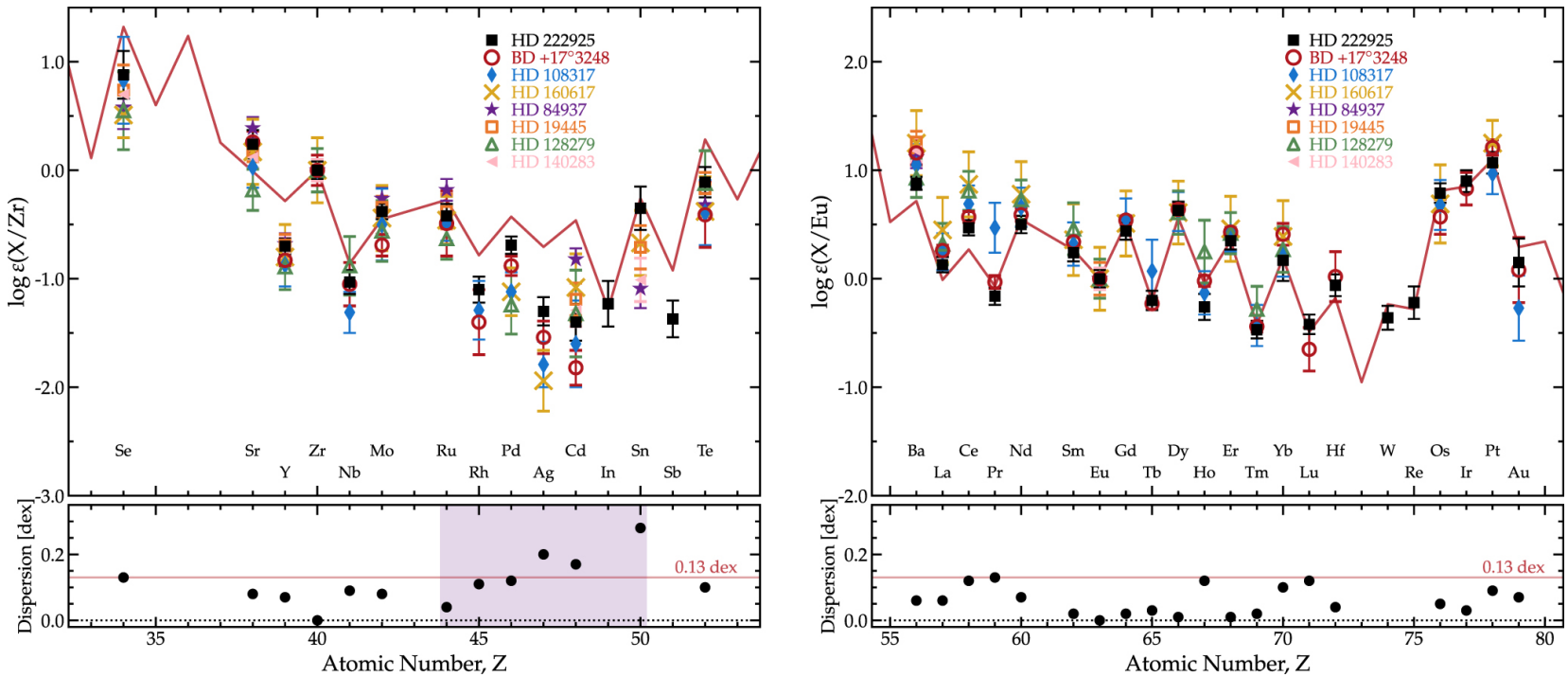
R-process enhanced star pattern



- Highly r-process enhanced stars are rare $\rightarrow$ 3-5%
- All show similar ratios for elements from Ba-HF $\rightarrow$ universal pattern.
- Scatter in light elements $\rightarrow$ multiple sites?
- Scatter in actinides $\rightarrow$ actinide boost.

Light element universality

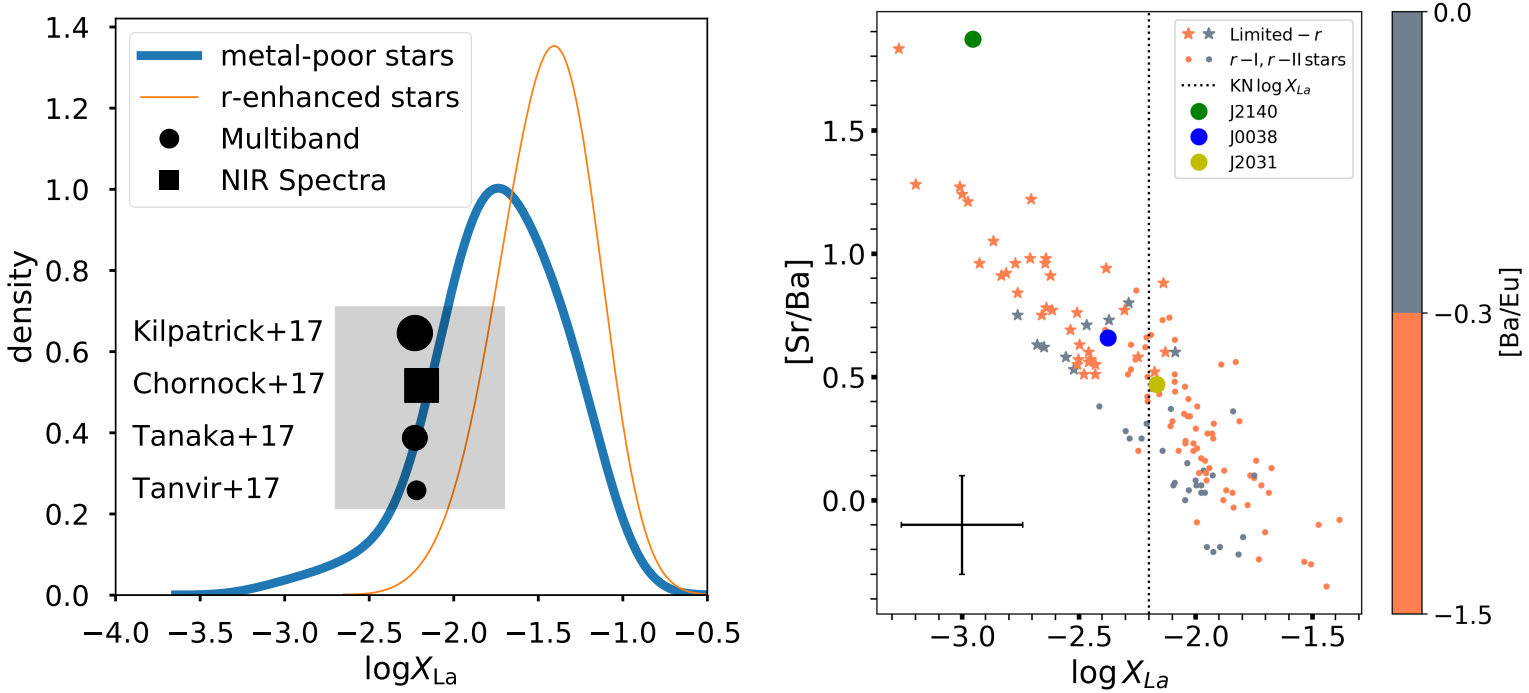
Stars with Se or Te detections, $-0.22 < [\mathrm{Eu/Fe}] < 1.32$



→ There is a universality in the production of the light elements similar to the heavy elements, but the ratio of light to heavy varies from star to star. Roederer, RPA+ 2022b

Lanthanide fractions of r-process stars as constraint on site

Select stars with $[\mathrm{Ba/Eu}] < -0.4$ and calculate $X_{La} = M_{lan}/M_{tot}$

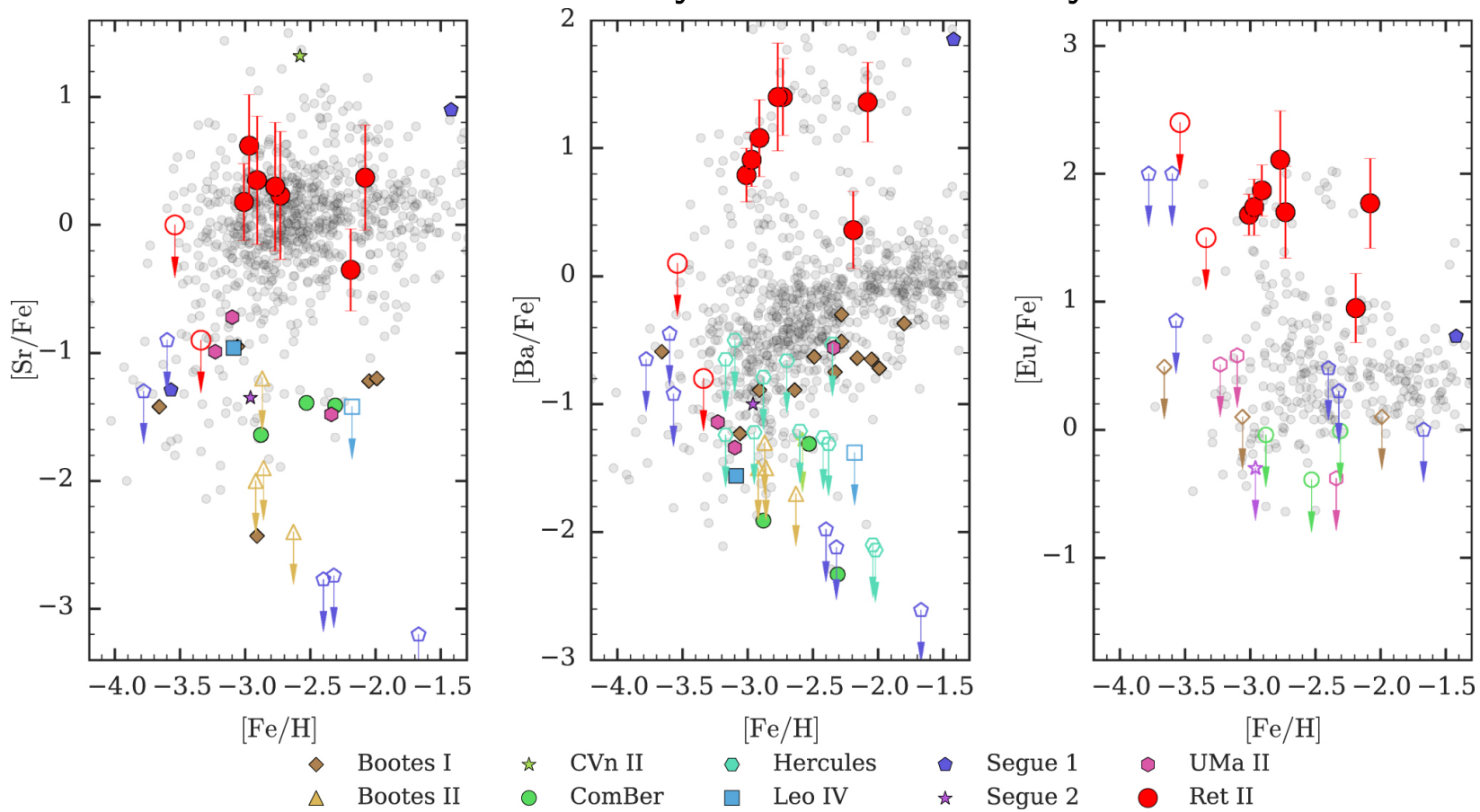


Ji+ 2019, Xylakis+ 2024

$\rightarrow$ 2017 kilonova match low Eu stars, to match high Eu stars
$\sim$10% of future kilonovae should have $X_{LA} > 10^{-1.5}$

R-process enhanced stars in ultra-faint dwarf galaxies

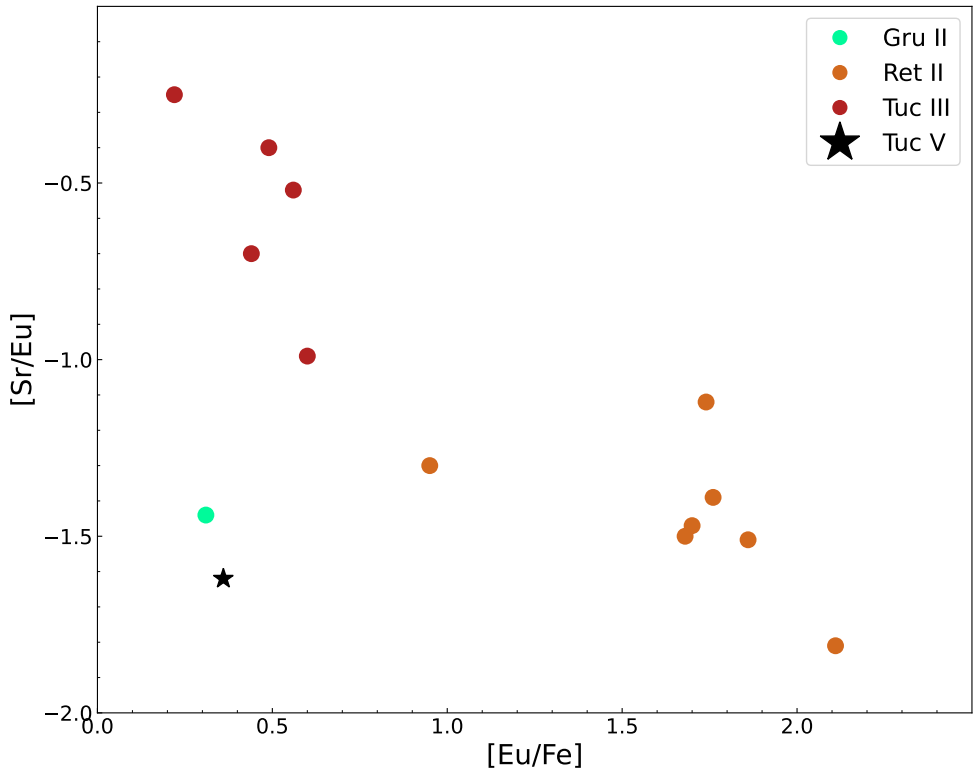
Reticulum II - 70% of the stars are r-process enhanced.
Enrichment event with a delay time of ∼500Myr



Ji+ 2016,2023, Simon+ 2023

R-process enhanced stars in ultra-faint dwarf galaxies

Also r-process enhances stars in Grus II, Tucana III, and Tucana V

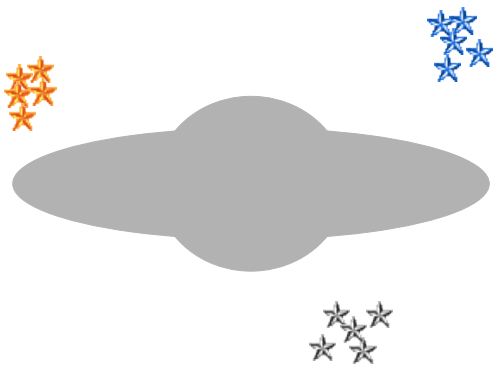


$\rightarrow$ similar ratios of light (Sr) to heavy (Eu) elements might suggests similar enrichment sites in Gru II, Ret II, and Tuc V, but we need more stars.

Hansen+ 2018,2020,2024

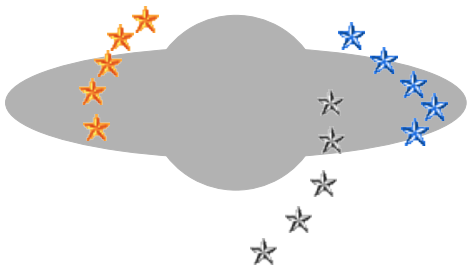
Substructures in and around the Milky Way

Dwarf Galaxies
Globular Clusters



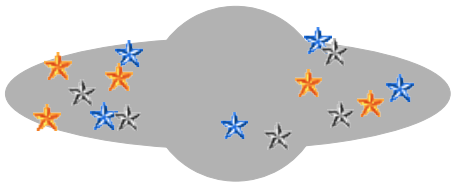
Spatially Coherent
Not disrupted

Stellar Streams



Spatially Coherent
Disrupted

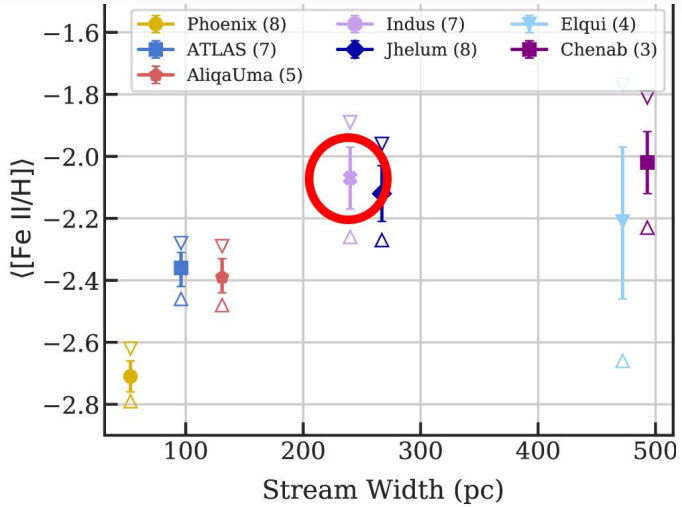
Accreted Substructure

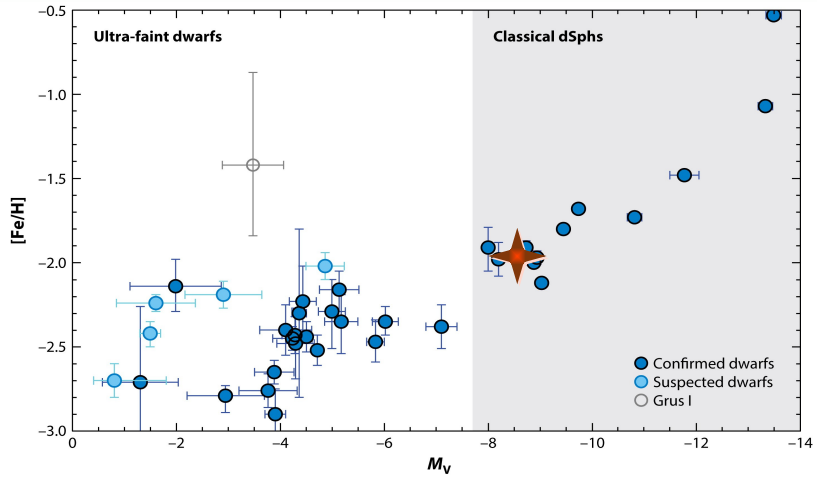


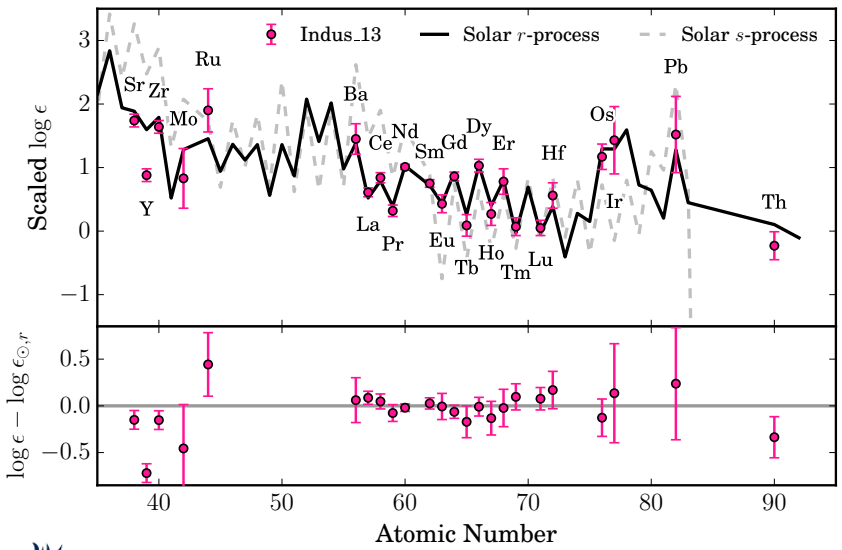
Incoherent
Fully Disrupted

R-process enhanced streams

Investigation of the Indus stream with S^5 collaboration.







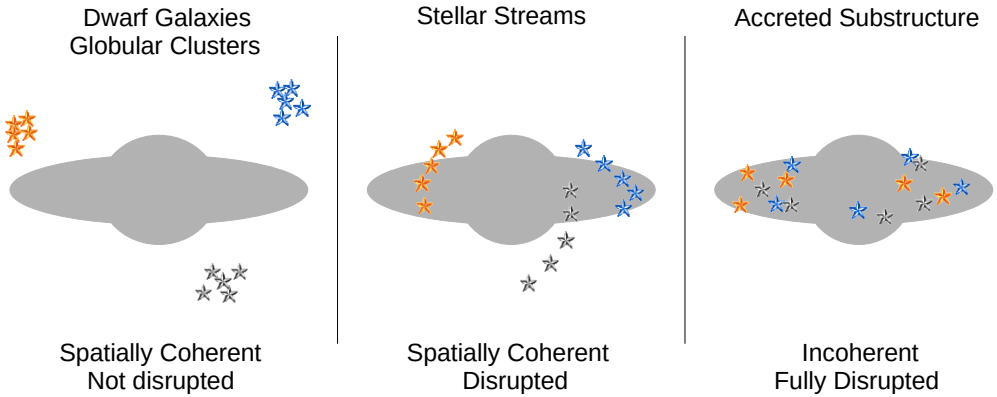
→ Star with $[\mathrm{Eu/Fe}] = 1.81$ born in a galaxy with a mass similar to Ursa Minor

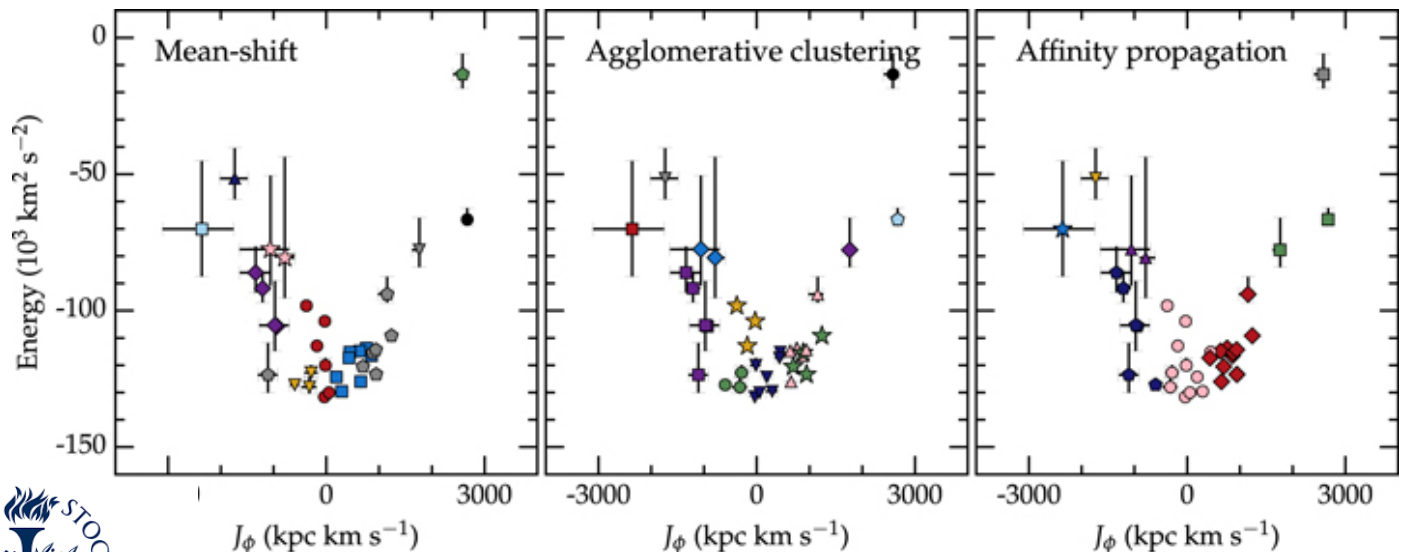
See Asa talk for more on classical dwarf galaxies

(Hansen+ 2021, Ji+ 2021, Simon 2019).

Substructures in and around the Milky Way

Most of the r-II stars are accreted (Roederer+ 2018)



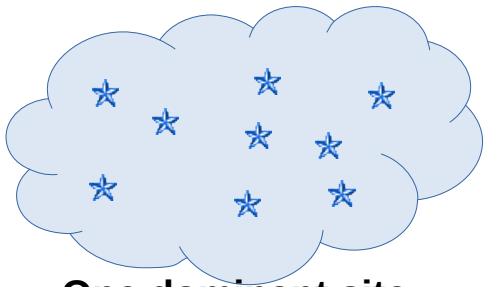


Combining abundances and Gaia

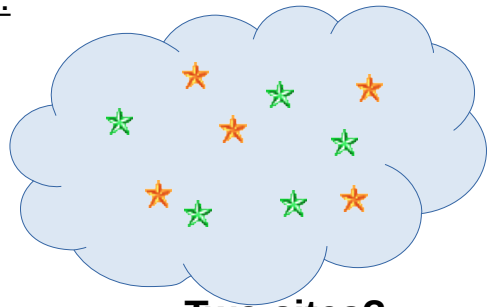
Different r-process production sites:

=[Sr/Eu]=0 =[Sr/Eu]>0 = [Sr/Eu]<0 = non r-enhanced

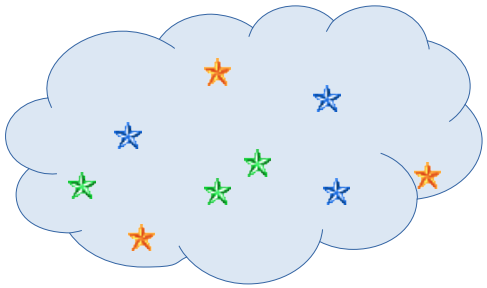
Frequency of production sites:



One dominant site

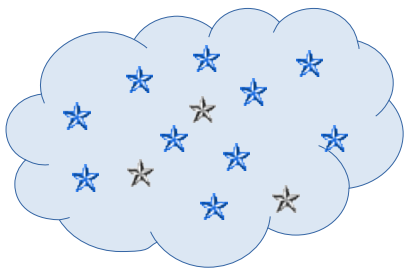


Two sites?

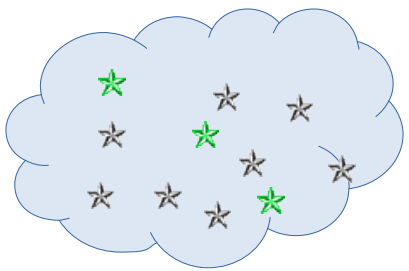


Everything together

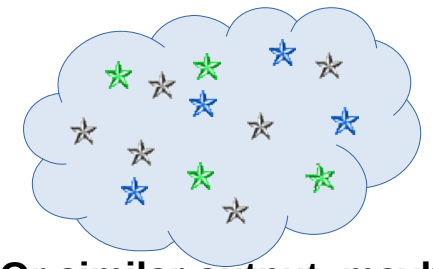
Prolificness of production sites:



One site that is always very prolific?



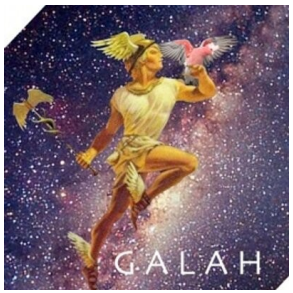
Another site not so much?

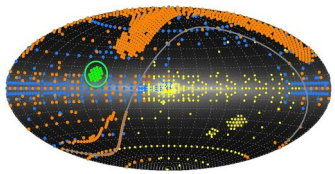


Or similar output, maybe depending on the size of the system

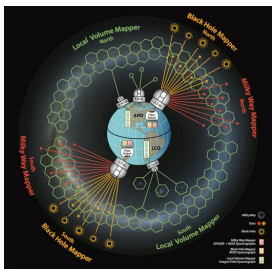
Future - surveys and new telescopes/instruments

Current surveys

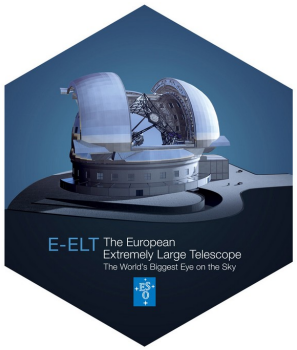




Upcoming surveys



New telescopes/instruments

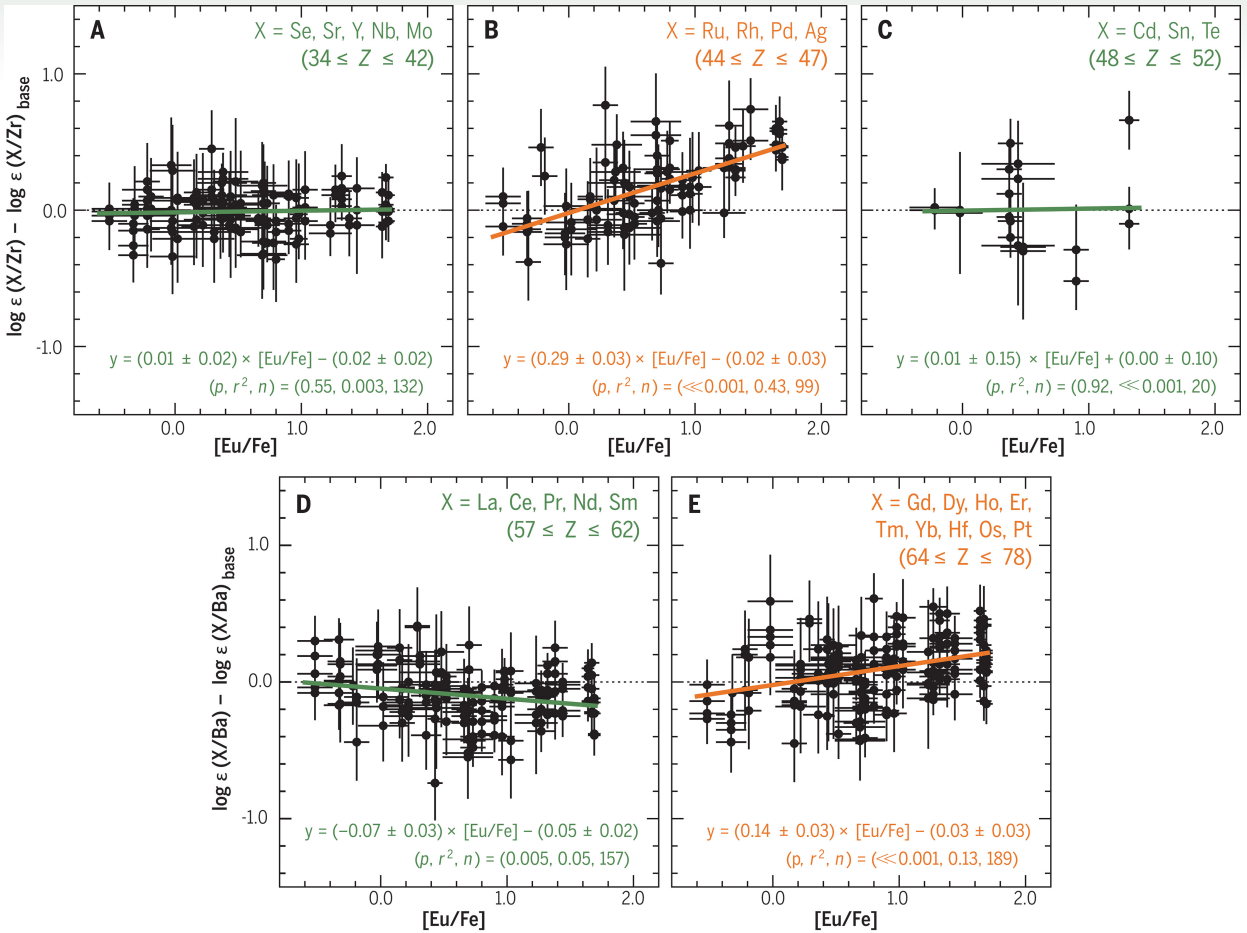


ANDES, G-CLEF, HRMOS, CUBES

Summary

- r-process enriched stars has been known for 30 years.
- Past focus on most metal-poor and most r-process enhanced, leading to single star analysis.
- New work from CERES, MINCE, and RPA has a focus on all levels of enrichment, broad metallicity range, and homogeneous analysis.
- New definition of r-II stars at [Fe/Eu]> 0.7 and possible universality amoung light r-process elements.
- Future will bring more stars and options for exploring stellar birth environments.

Fission fragments



Light r-process elements Ru, Rh, Pd, and Ag, and heavy r-process elements Gd, Dy, Ho, Er, Tm, Yb, Hf, Os, and Pt seems to be affected by fission fragment deposition (Roederer, RPA+ 2023).