

Lanthanide and actinide variation in metal-poor stars



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Ji, Drout, & (T.) Hansen 2019, arXiv:1905.01814

Shah, Ezzeddine, Holmbeck, Ji et al. 2026, arXiv:2604.12892

Alex Ji, University of Chicago

La and Ac variations in metal-poor stars

- The R-process Makes “Only Three Elements” (Two Ratios)
- The Lanthanide Fraction Distribution
- The Actinide-to-Lanthanide Distribution

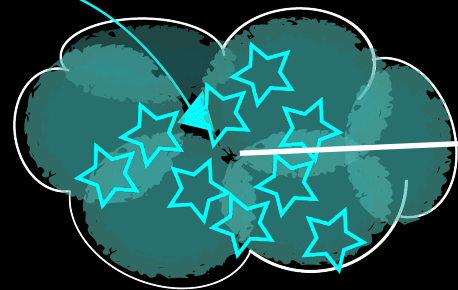
Stellar Archaeology

Chemical Enrichment:
~Individual Events

Metals



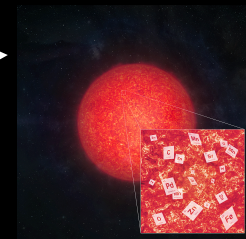
**Very Early
Neutron Star
Merger**



**Star forming
gas cloud**

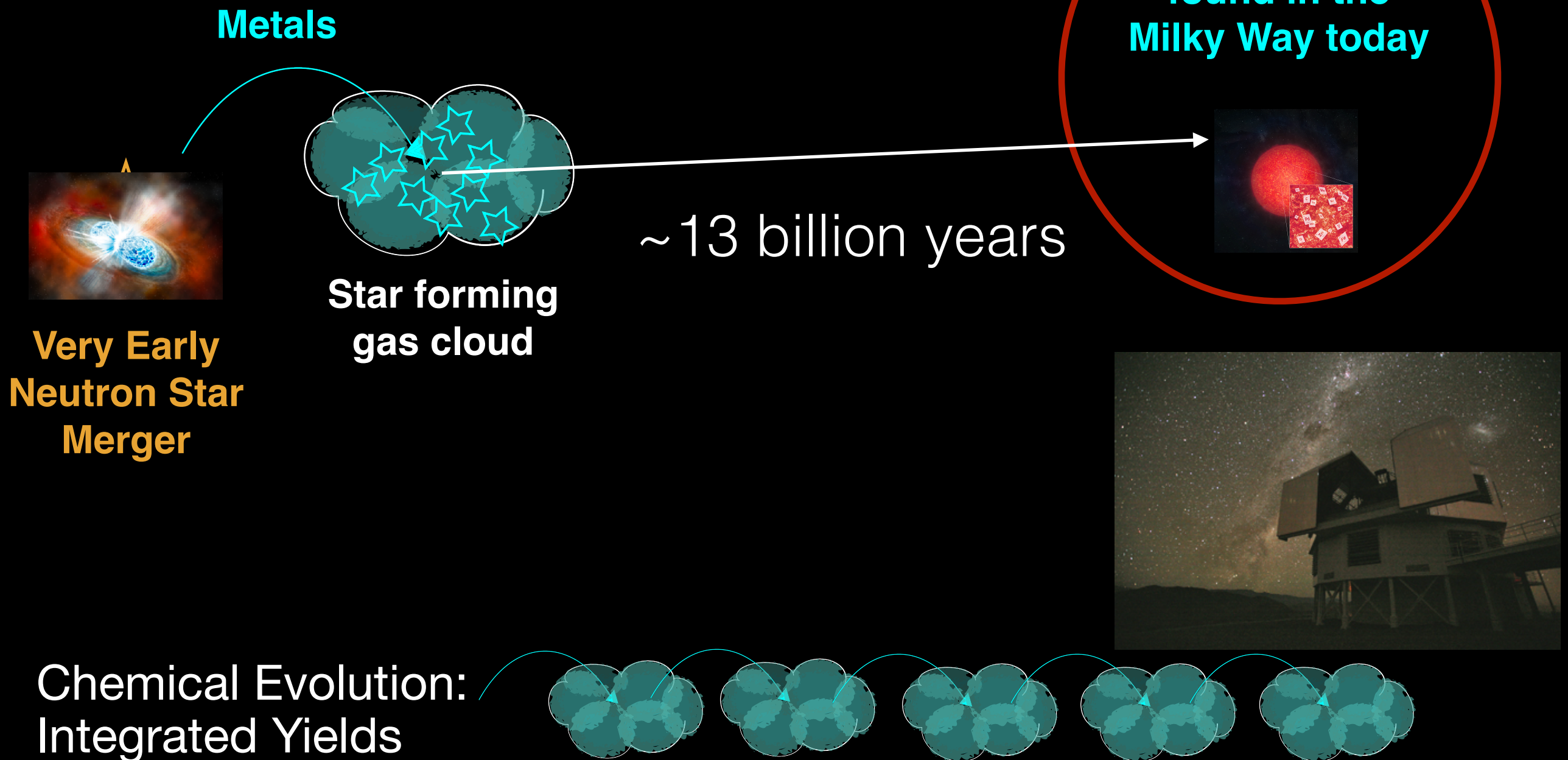
~13 billion years

**Metal-poor stars
found in the
Milky Way today**

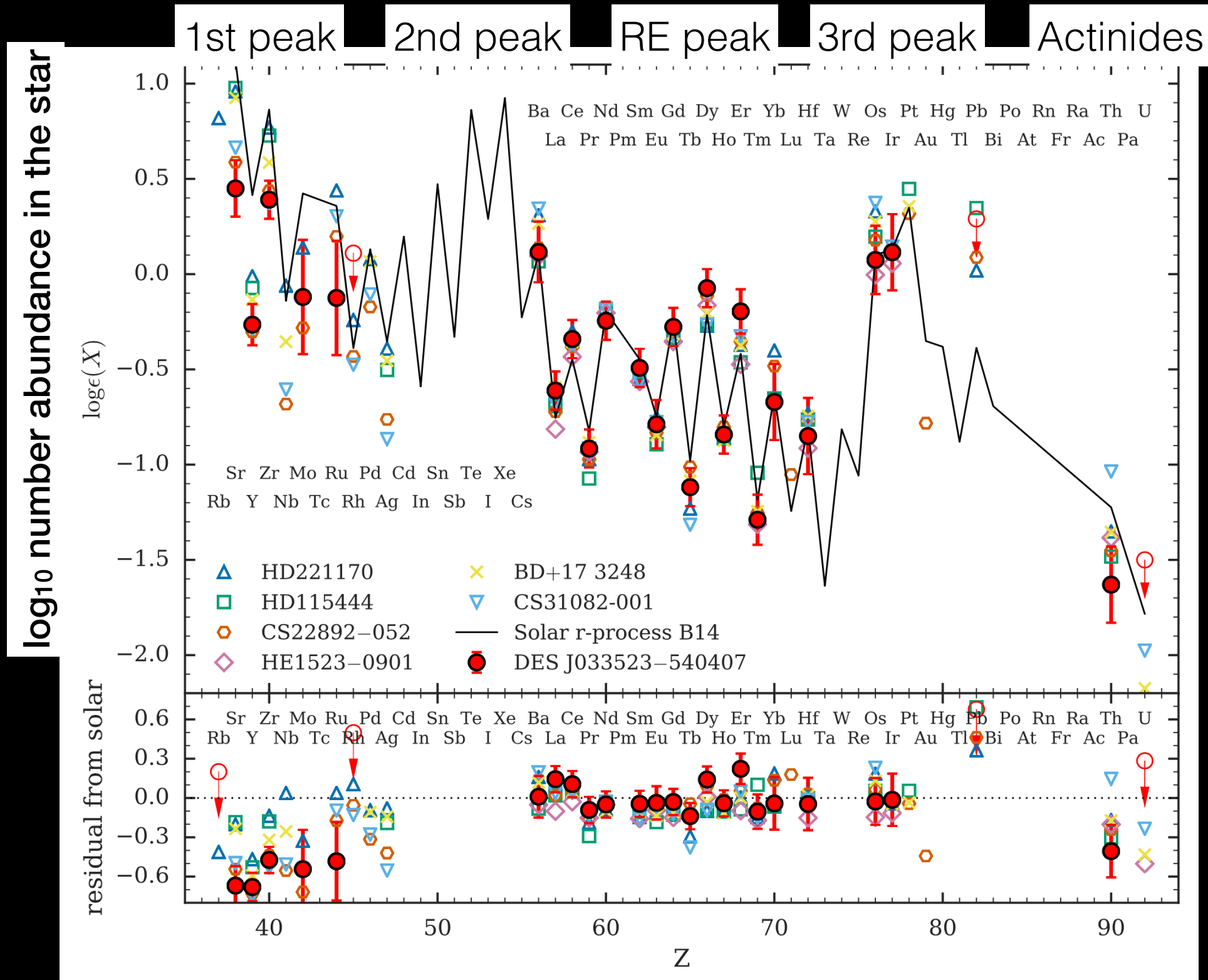


Stellar Archaeology

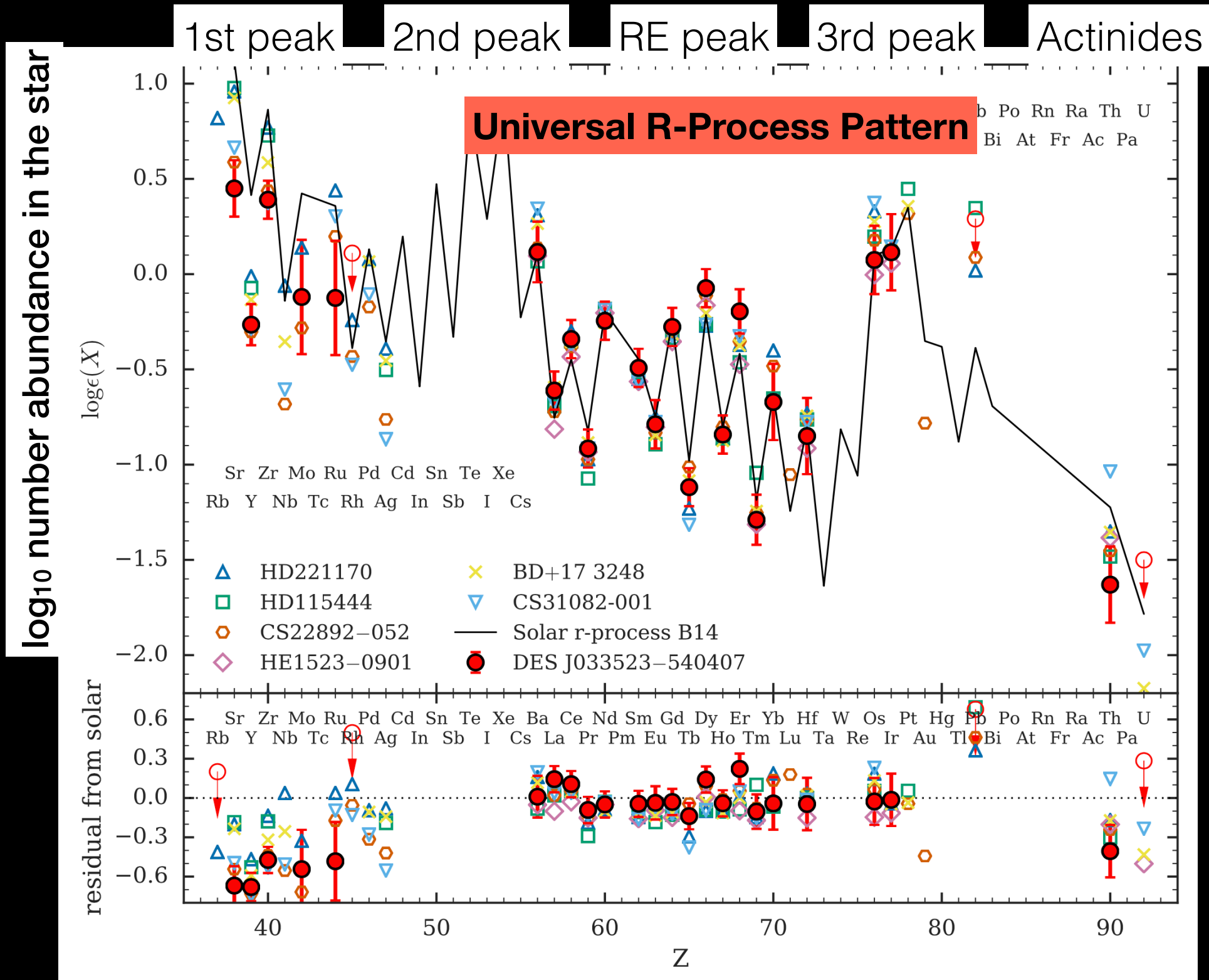
Chemical Enrichment:
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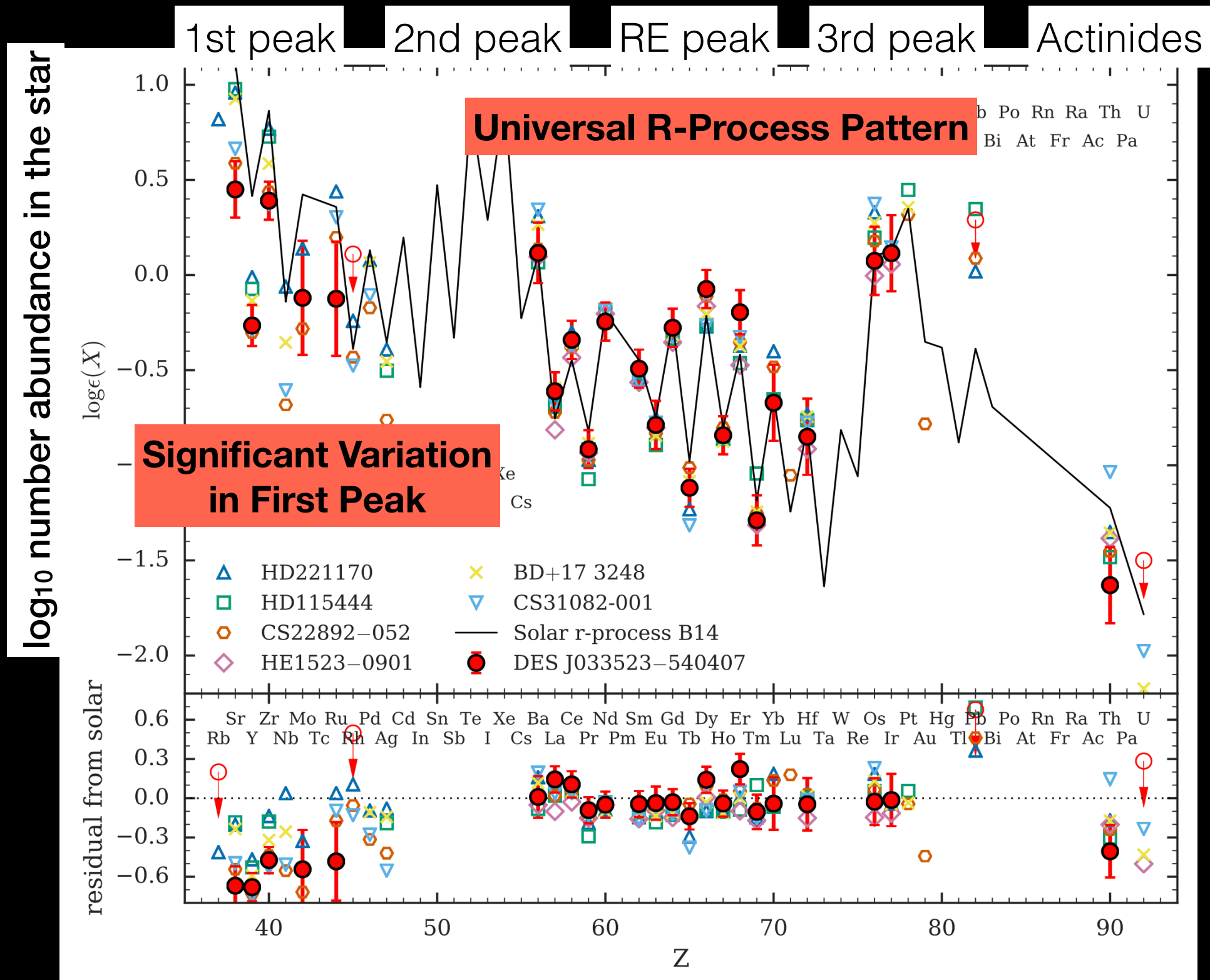
R-Process Lessons from Stellar Archaeology



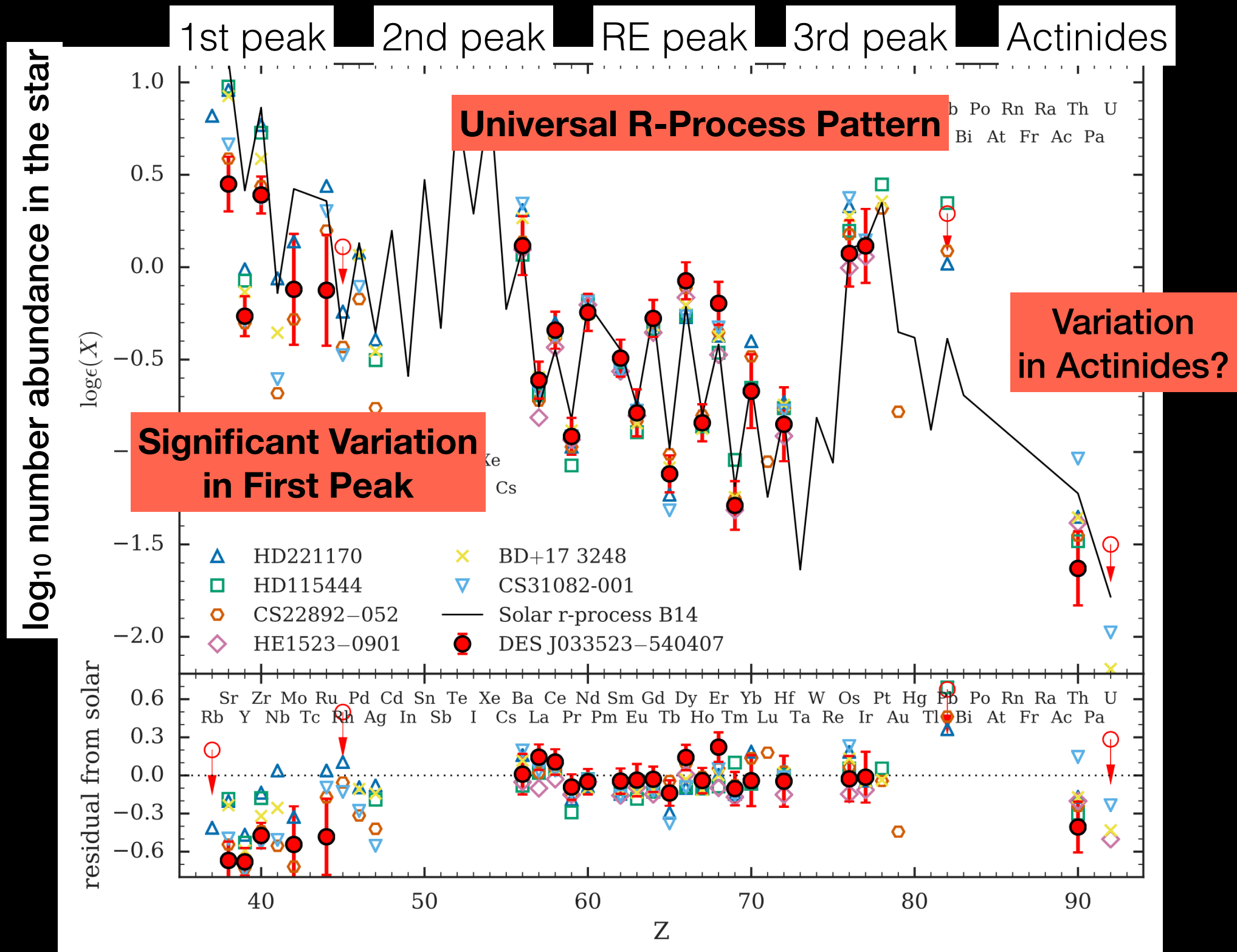
R-Process Lessons from Stellar Archaeology



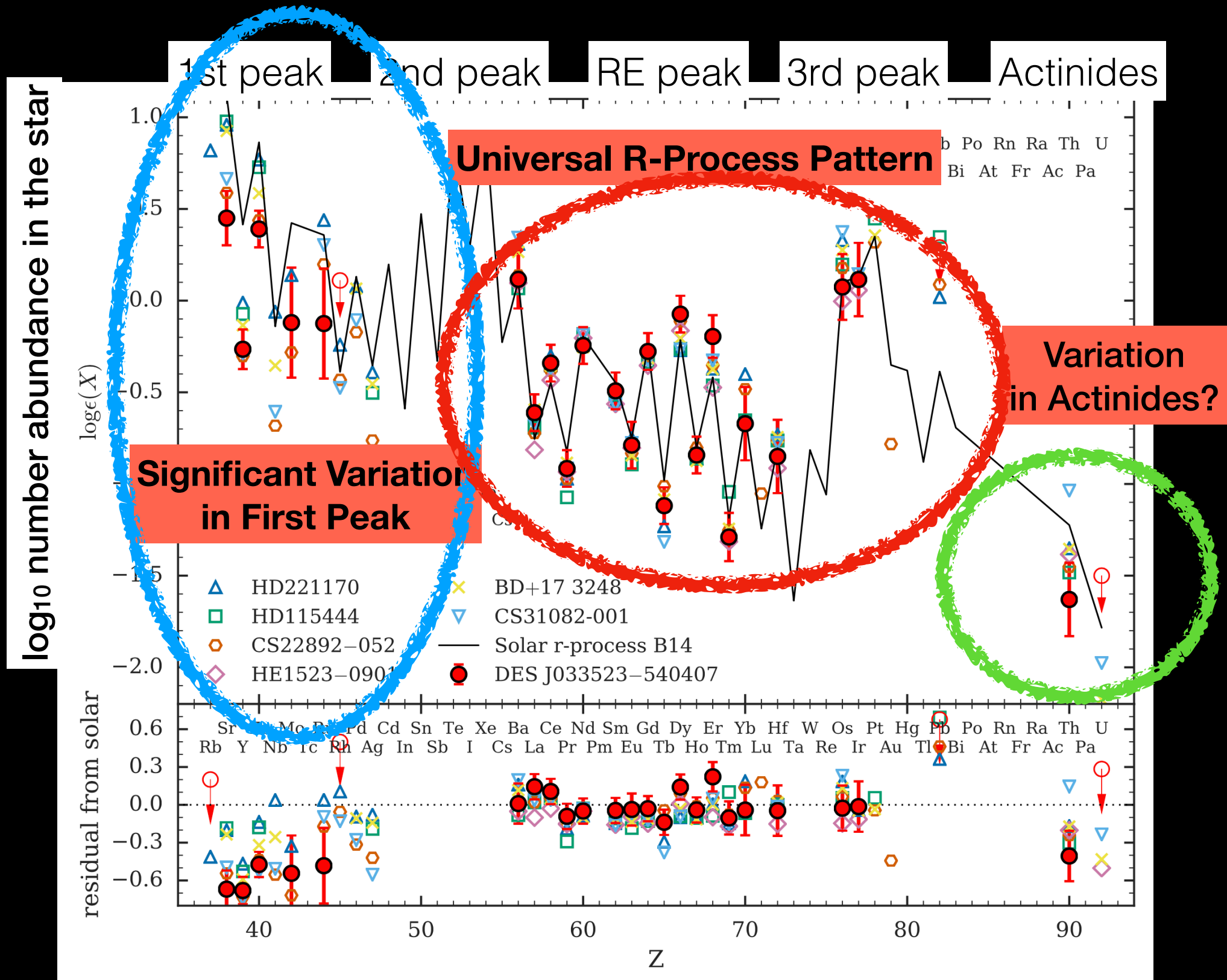
R-Process Lessons from Stellar Archaeology



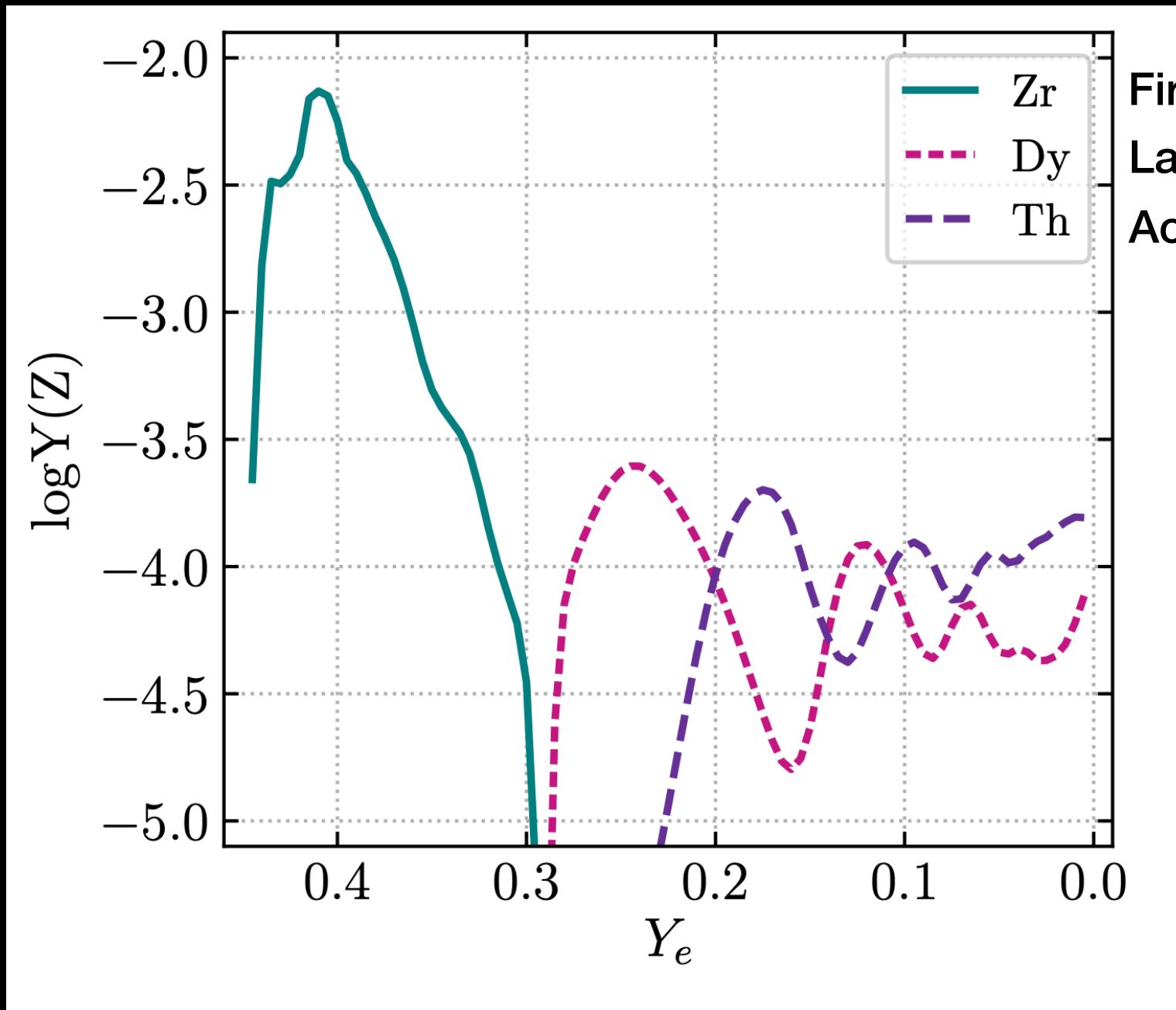
R-Process Lessons from Stellar Archaeology



R-Process Lessons from Stellar Archaeology



Three R-Process Elements ~Correspond to Electron Fraction



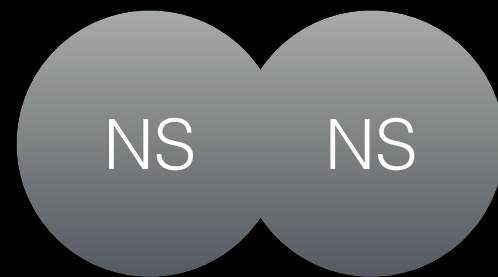
First Peak (Sr, Y, Zr)

Lanthanide (Eu, Dy)

Actinide (Th, U)

**Metal-poor stars probe
 Y_e distribution of the early
r-process site**

NSMs eject material in many ways

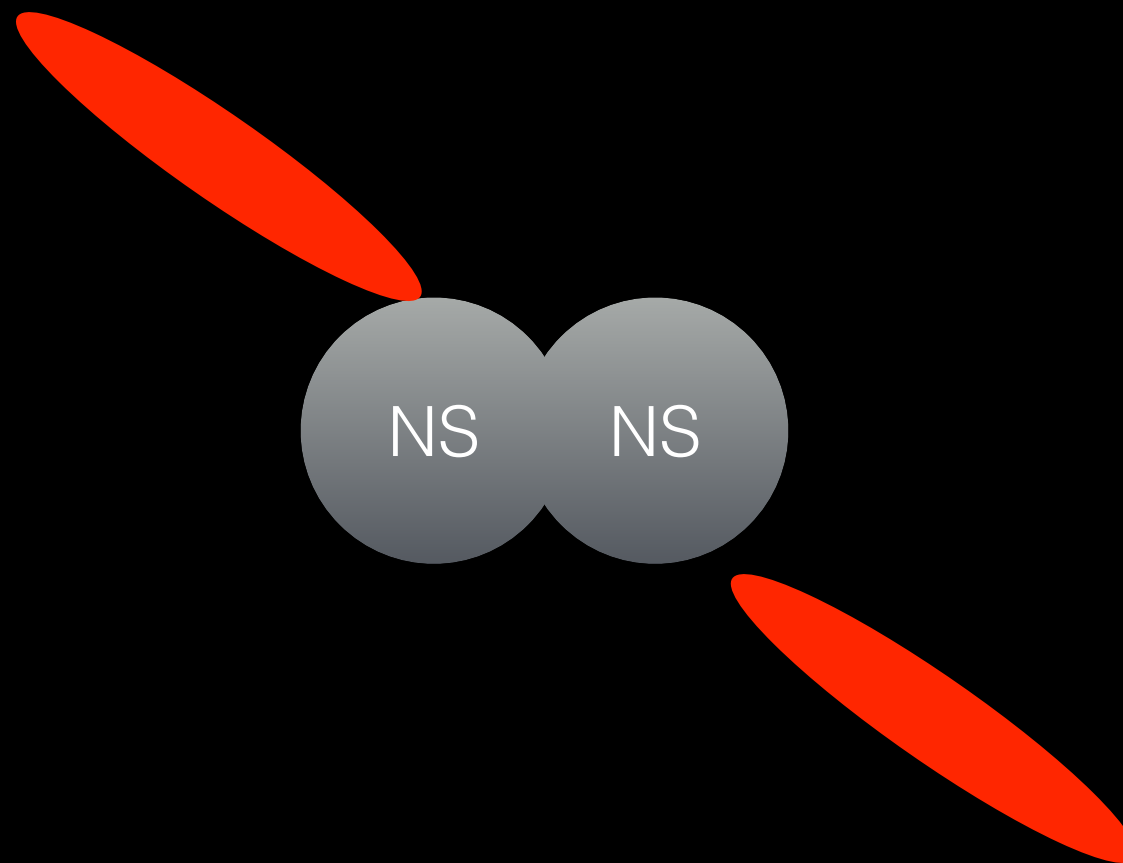


Blue: neutron-poor, **light** 1st-peak r-process elements

Red: neutron-rich, **heavy** 2nd+3rd peak r-process elements

see e.g. Metzger 2017, whole discussion yesterday

NSMs eject material in many ways



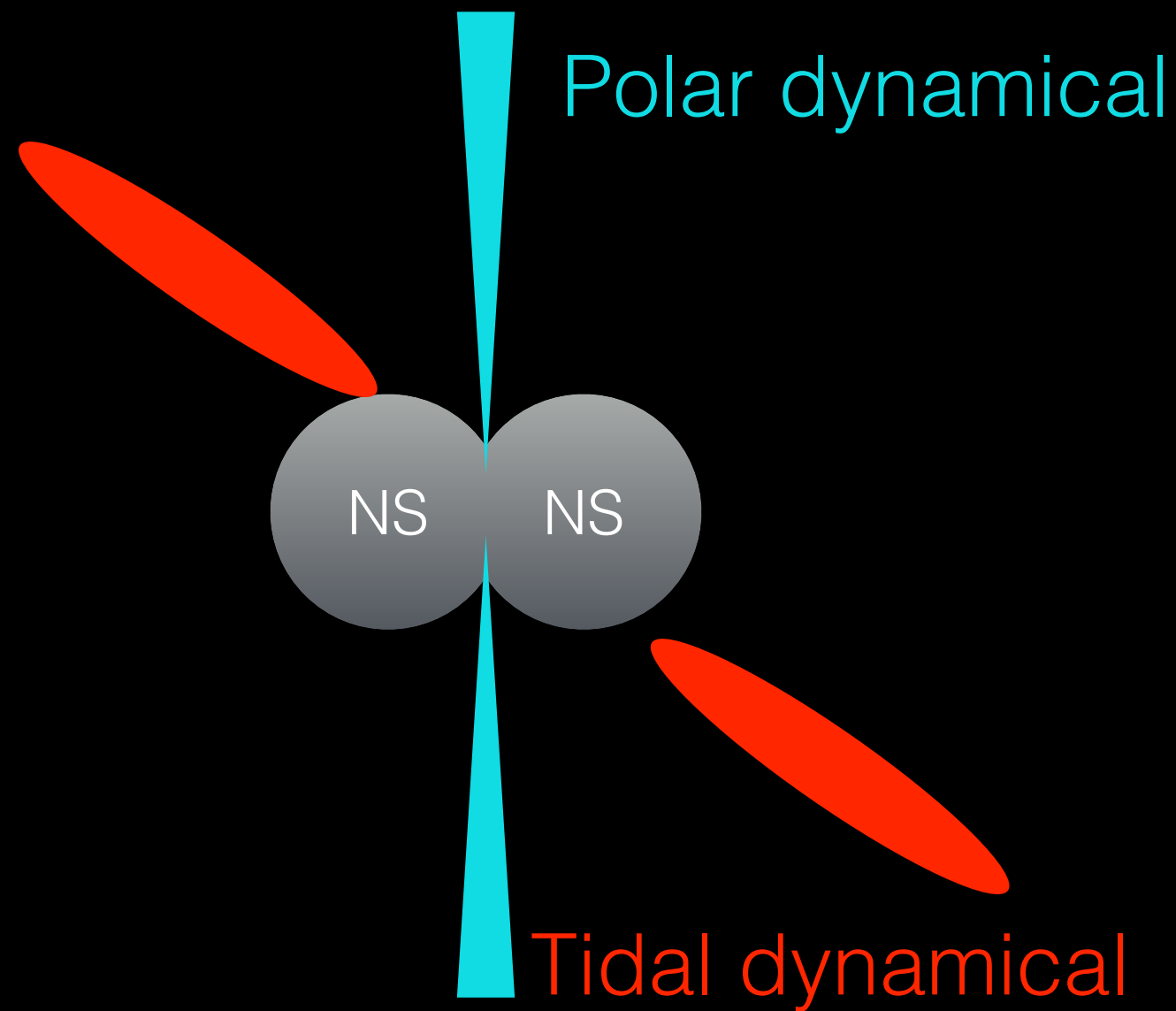
Tidal dynamical

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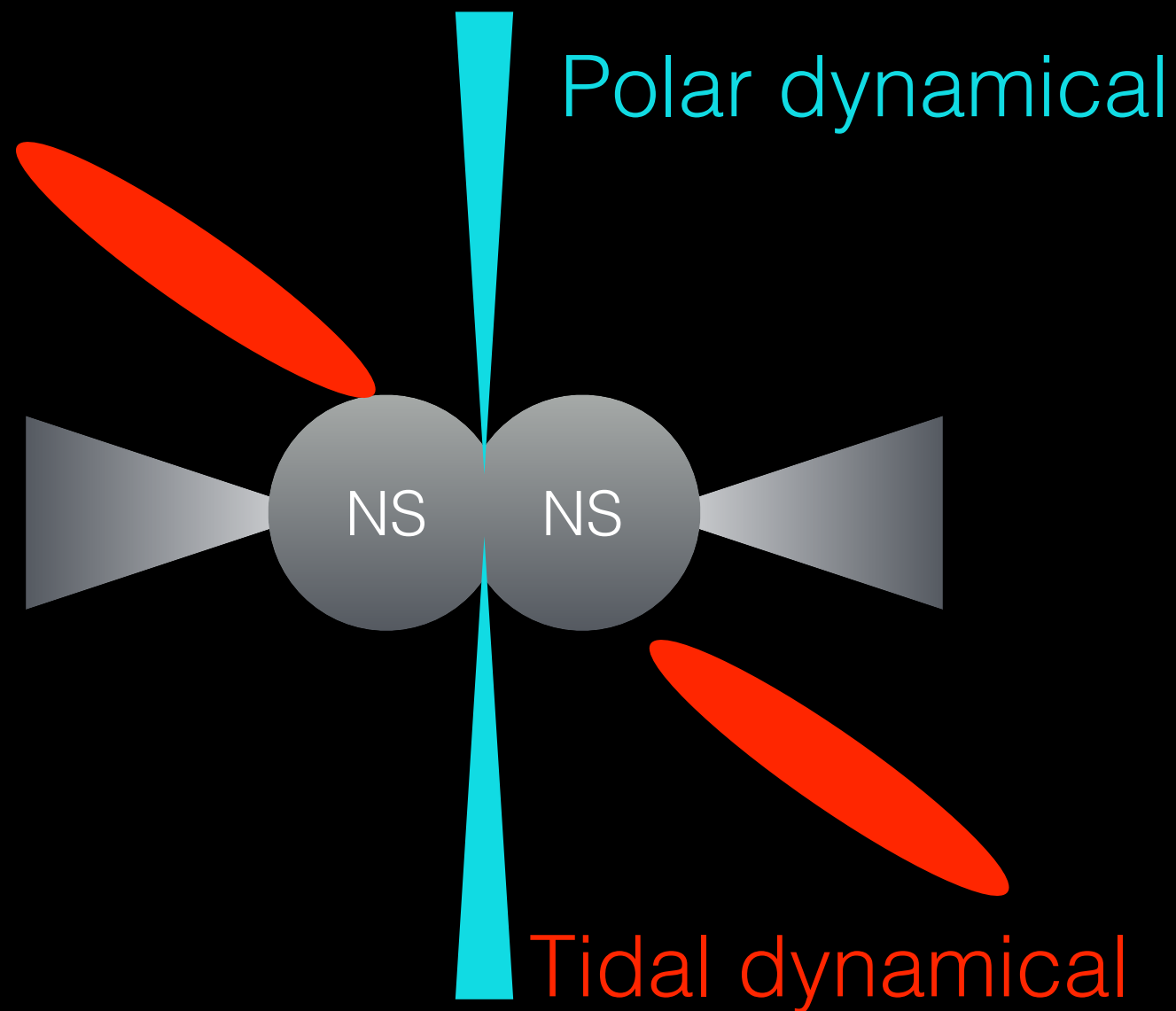


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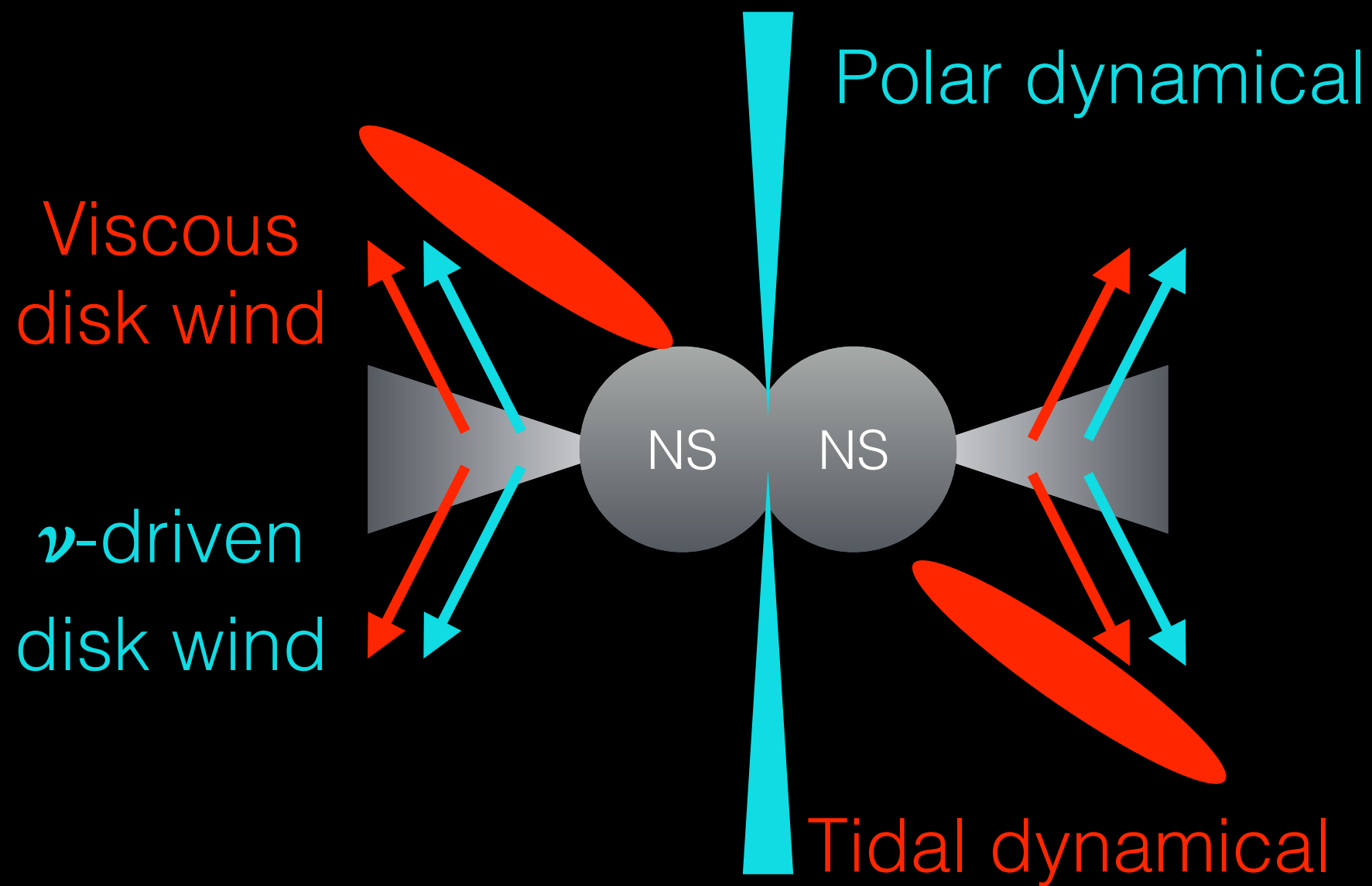


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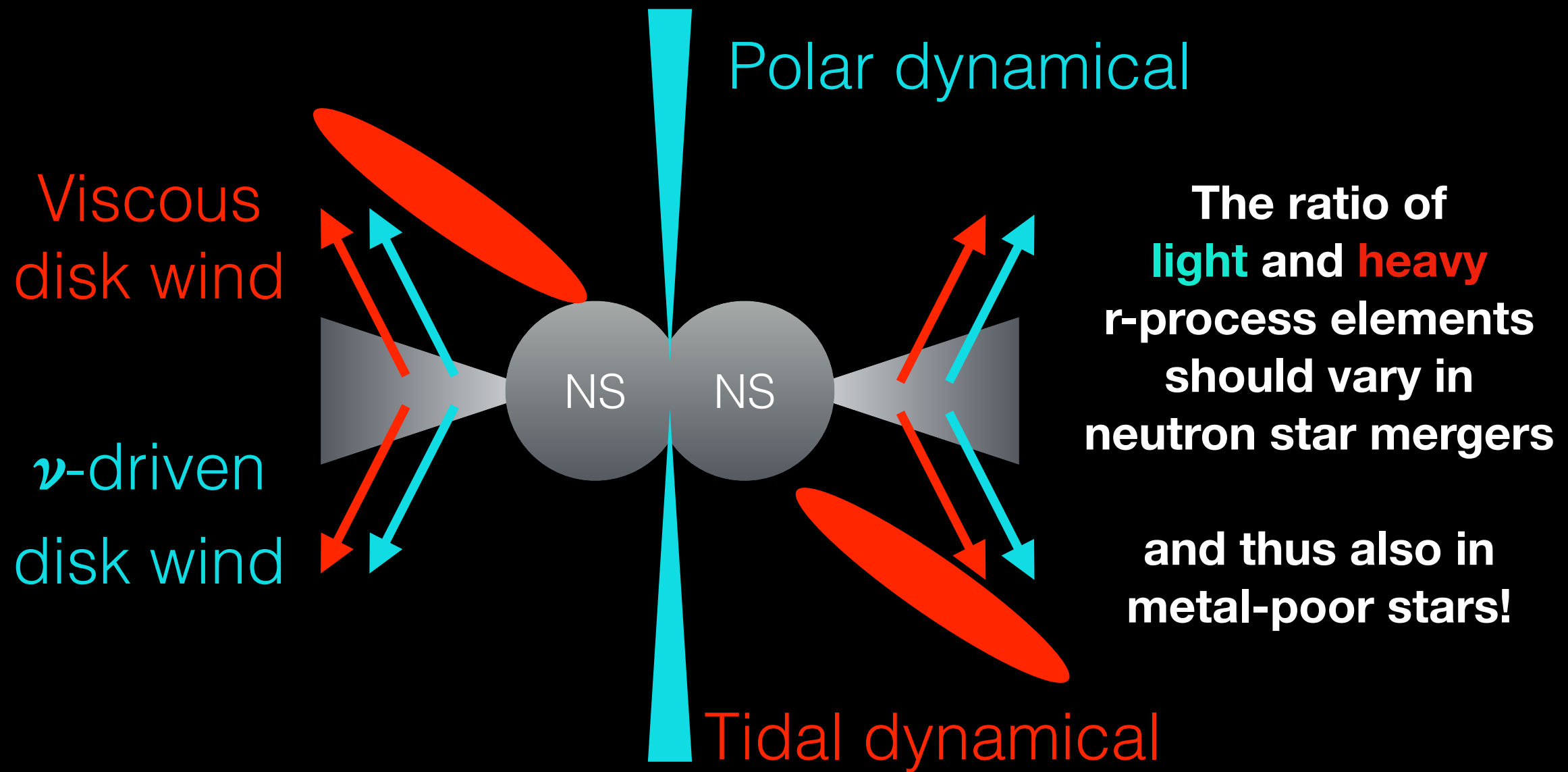


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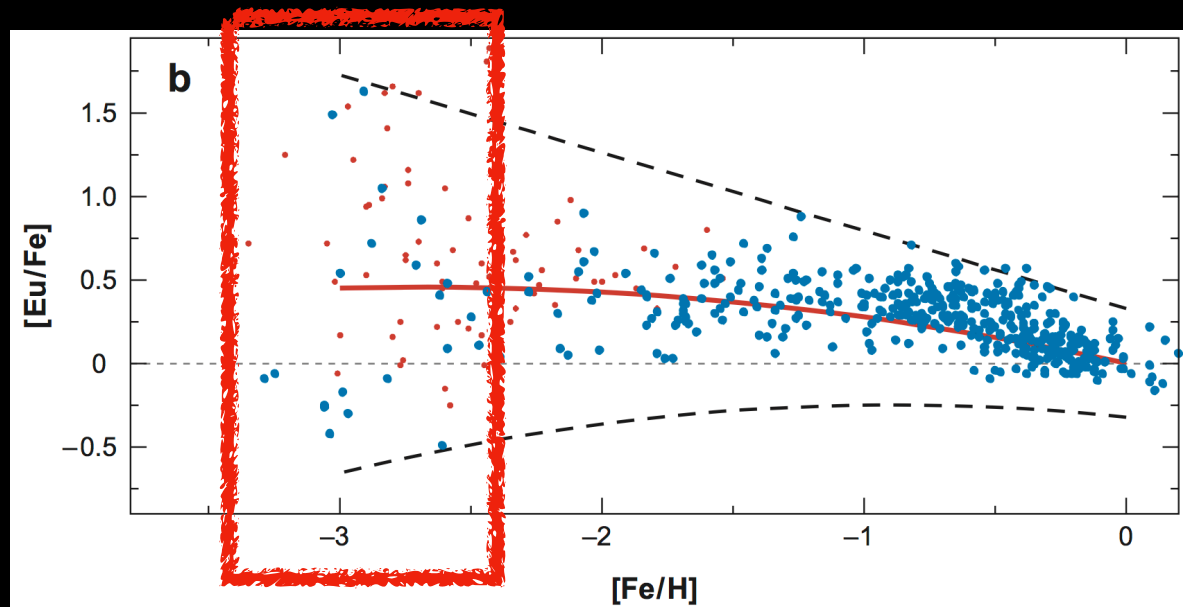
Varying R-Process Abundances in Stars Corresponds to Different Kilonova (or Neutron Star Merger) Compositions

The *lanthanide fraction* $X_{\text{La}} \sim 0.1 \text{ heavy}/(\text{heavy}+\text{light})$
is measurable in both stars and kilonovae



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Measure X_{La} in existing
metal-poor Milky Way stars
(assume each star = 1 neutron star merger)

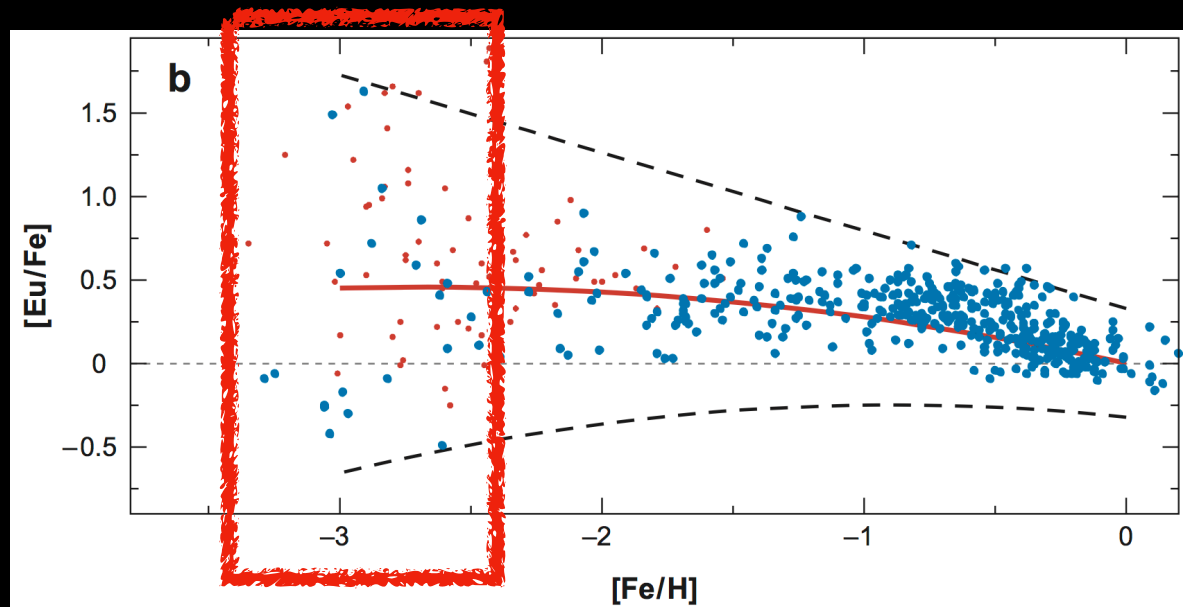
Figure: Sneden et al. 2008



Ji, Drout, & Hansen 2019

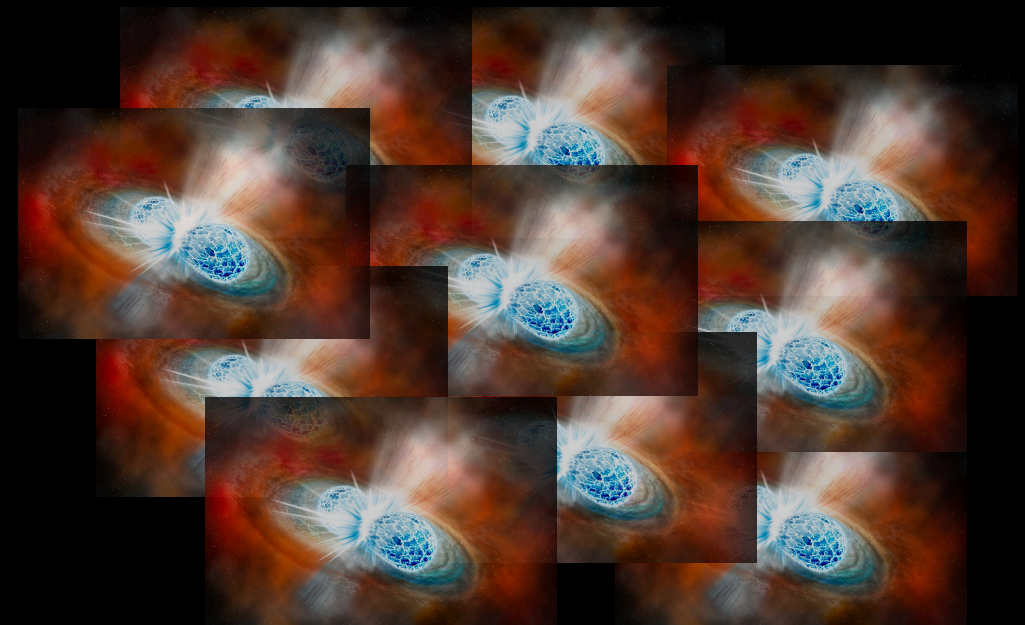
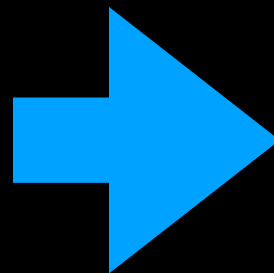
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Figure: Sneden et al. 2008



Predict X_{La} for future kilonovae

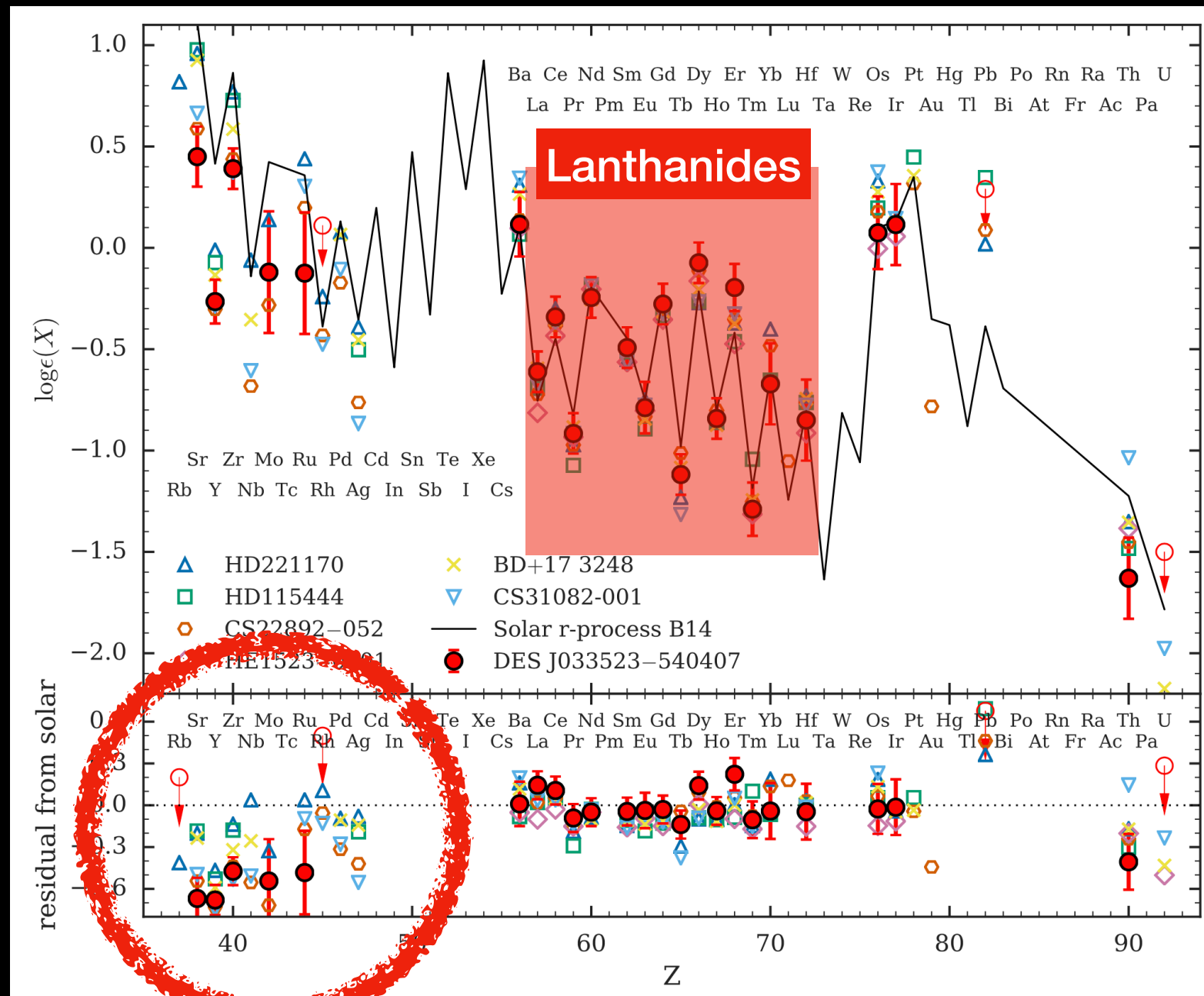


Ji, Drout, & Hansen 2019

Determining X_{La} in metal-poor stars

We do not measure all elements: extrapolate with the solar r-process pattern

$$X_{\text{La}} \sim 0.1 \text{ heavy}/(\text{heavy} + \text{light})$$

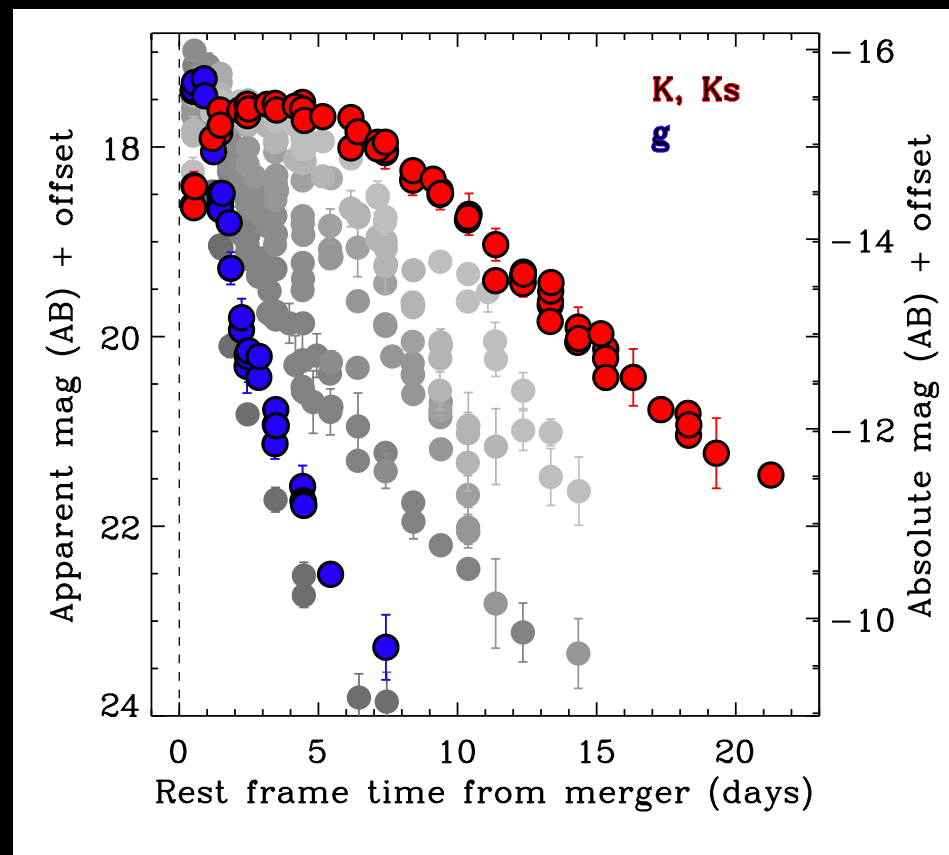


This scatter
->
different X_{La}

(We use Arnould+2007 solar pattern as fiducial model, split 1st-2nd peak at $A=115$)

Determining X_{La} in Kilonovae

Kilonovae have *red* and *blue* components

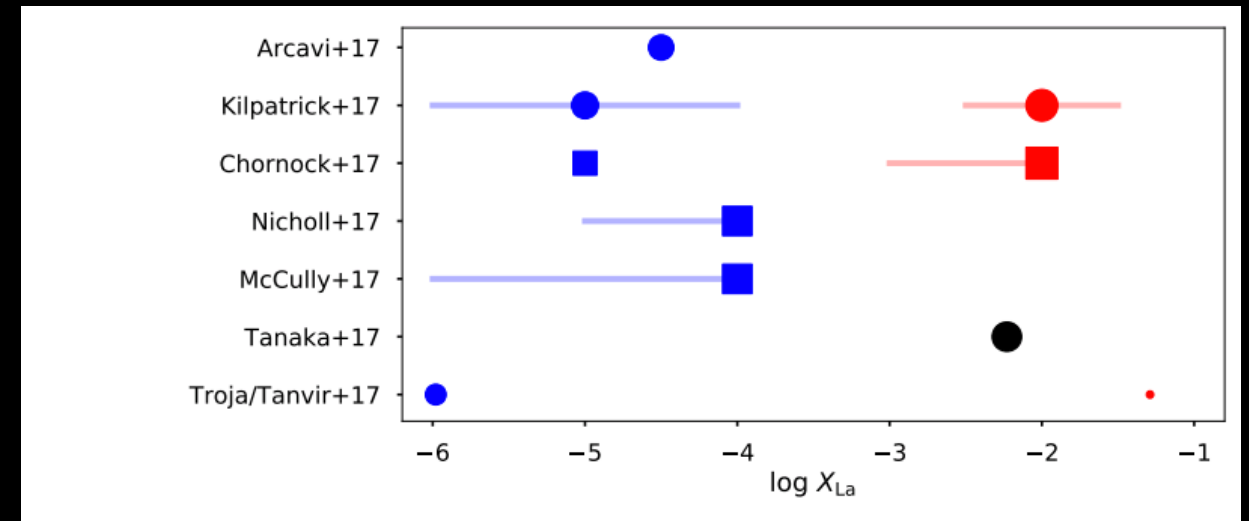


At least two mass components:
 blue = La-poor (low opacity)
 red = La-rich (high opacity)

Stars probe the **sum** of
 all components

Drout et al. 2017

Lanthanide fractions in GW170817



Vary by $\sim 5\times$ in ejected
 mass but all agree
 $\log X_{\text{La}} \sim -2.2 \pm 0.5$

Periodic Table of the Elements

1	2																	18
H	He																	He
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18			
Li	Be	B	C	N	O	F	Ne									Ne		
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34			
Na	Mg	Al	Si	P	S	Cl	Ar									Ar		
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50			
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se			
51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66			
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te			
67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82			
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb			
83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98			
Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No			
101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116			
Uuq	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo									Uuo		
117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132			
Uus	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo									Uuo		

Determining X_{La} in Kilonovae

Kilonovae have *red* and *blue* components

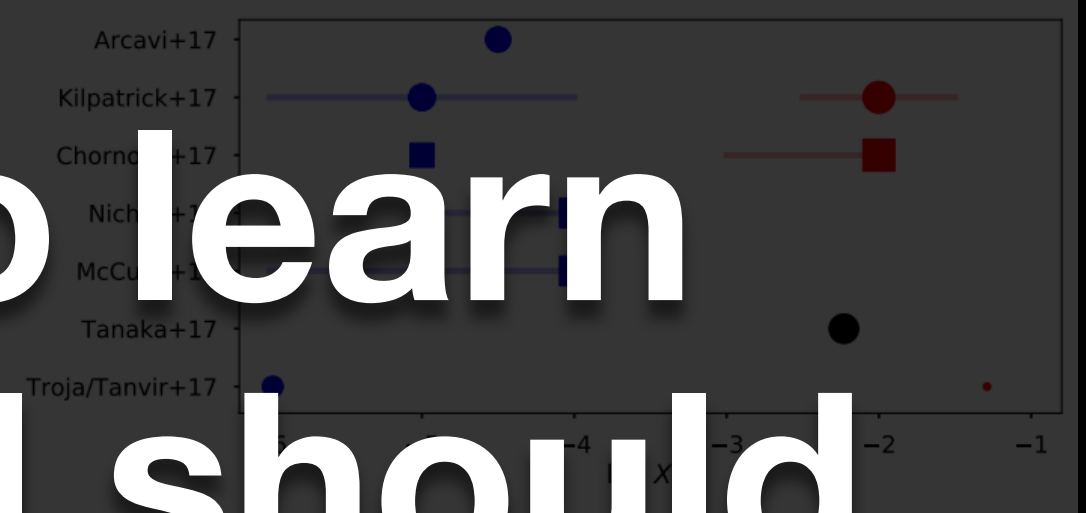
Hoping to learn
here what I should
do instead!!

At least two mass components:
blue = La-poor (low opacity)
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Stars probe the **sum** of
all components

Drout et al. 2017

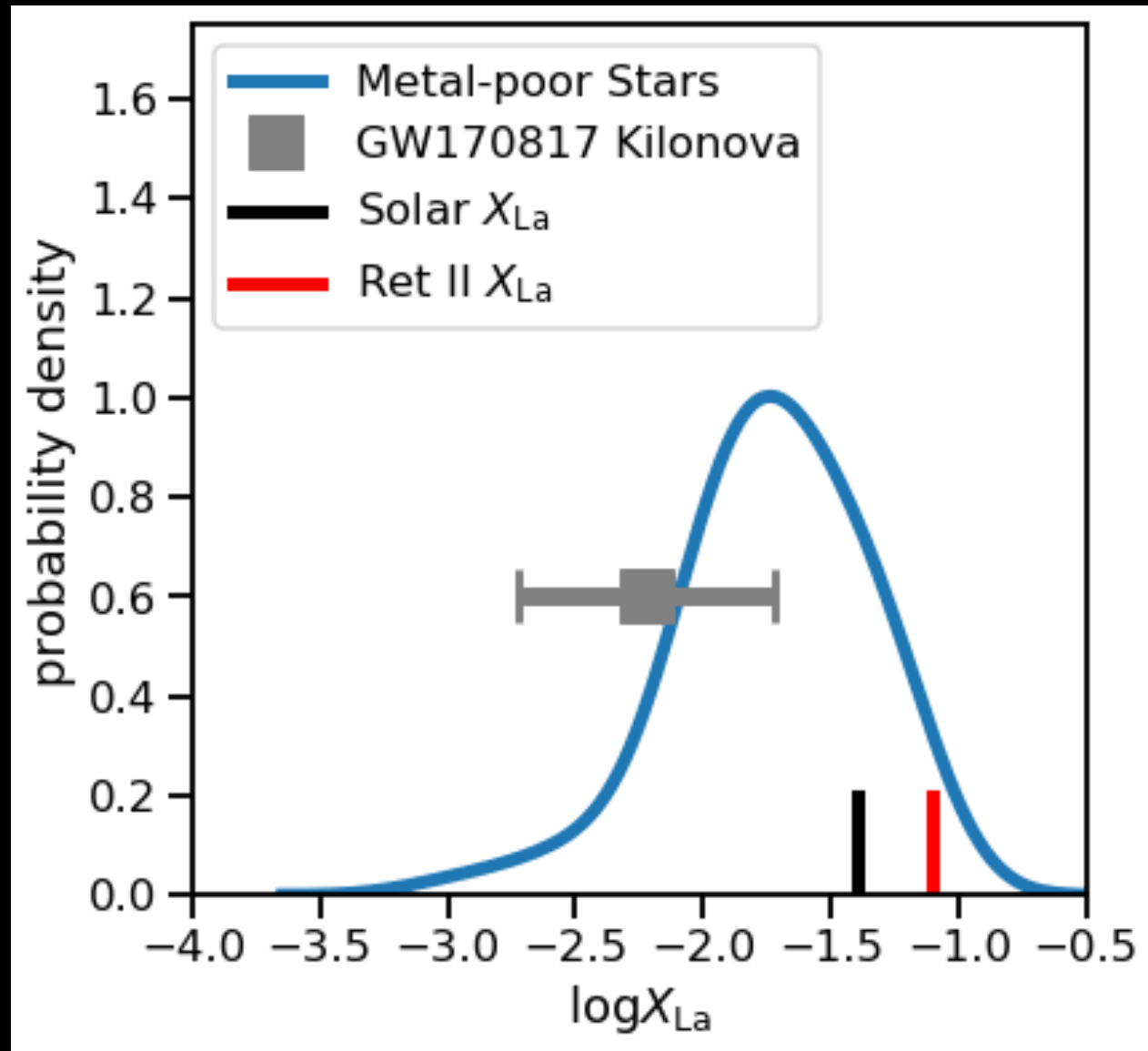
Lanthanide fractions in GW170817



Vary by $\sim 5\times$ in ejected
masses but all agree
 $\log X_{\text{La}} \sim -2.2 \pm 0.5$

A standard periodic table of elements. The lanthanide and actinide series are highlighted with red borders at the bottom of the table.

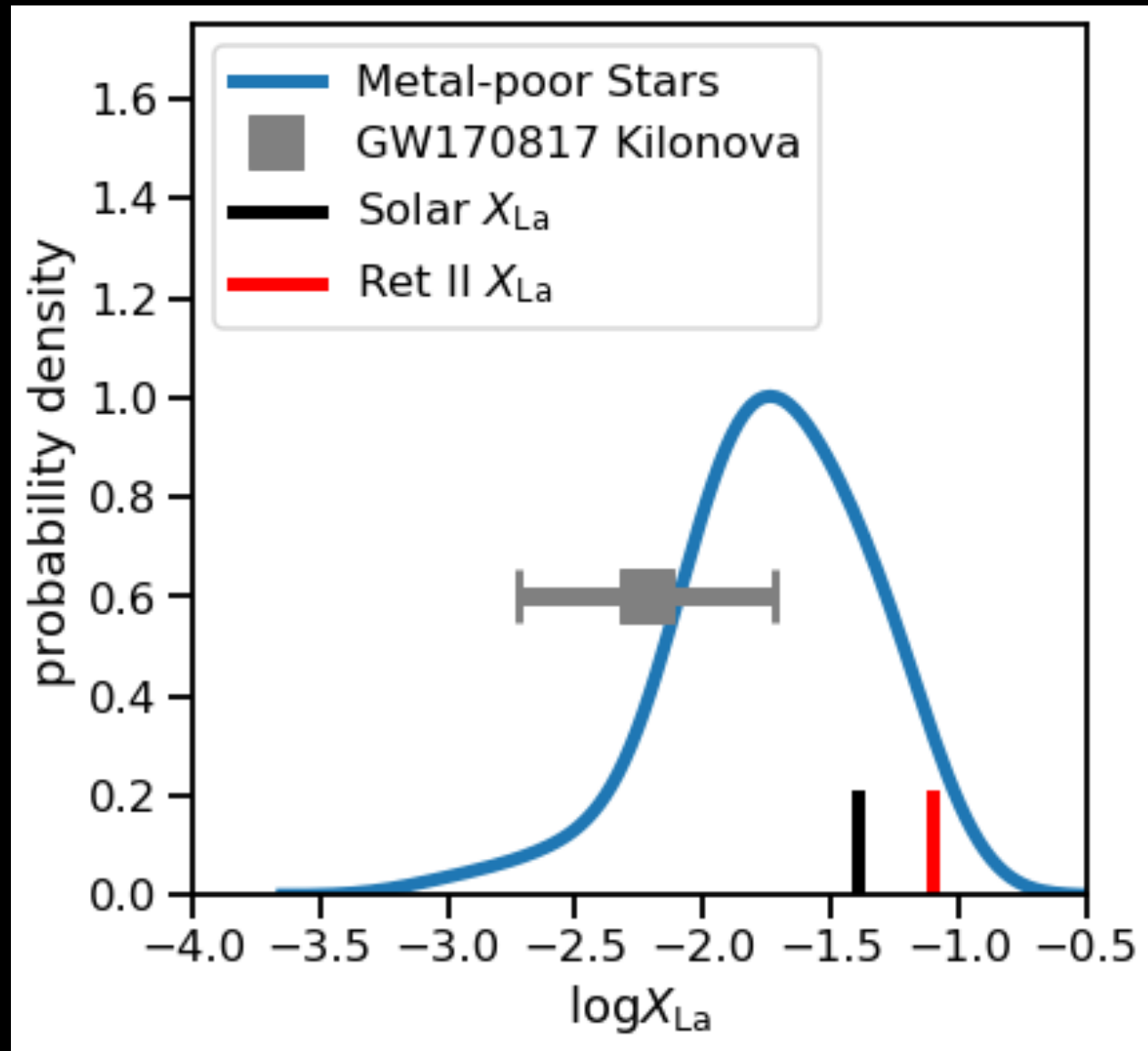
Lanthanide Fraction Comparison



$$\langle \log X_{\text{La}} \rangle = -1.7$$

1σ spread of 0.5 dex (obs error is ~ 0.2 dex)

Lanthanide Fraction Comparison



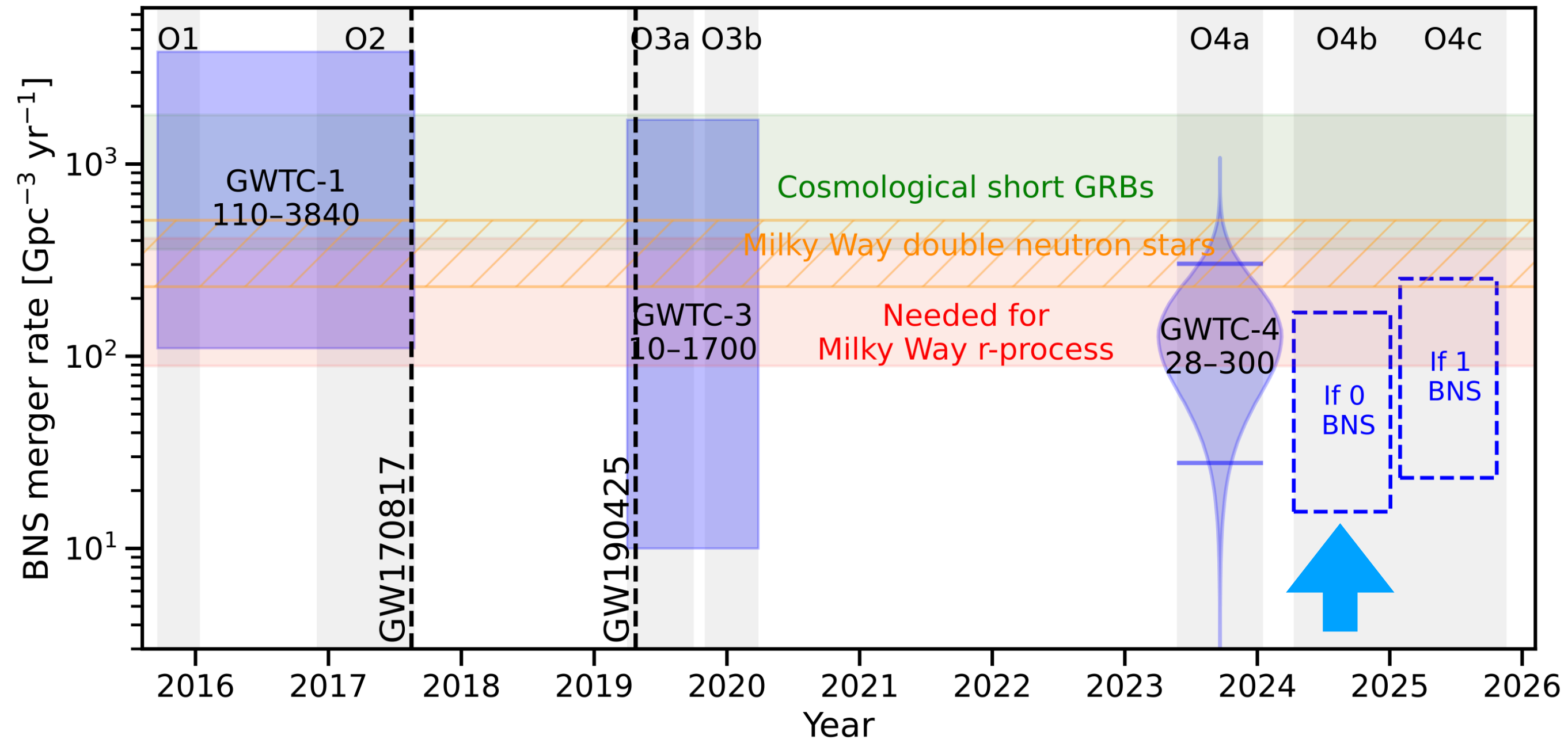
- [Early models]: GW170817 has $\log X_{\text{La}} \sim -2.2 \pm 0.5$
- Future kilonovae should mostly have higher X_{La}
- High- X_{La} KN are redder, probably eject less mass (shorter and fainter)

$$\langle \log X_{\text{La}} \rangle = -1.7$$

1σ spread of 0.5 dex (obs error is ~ 0.2 dex)

Updated LIGO NSM Rates

Sadly we may need to wait a while to do the comparison...



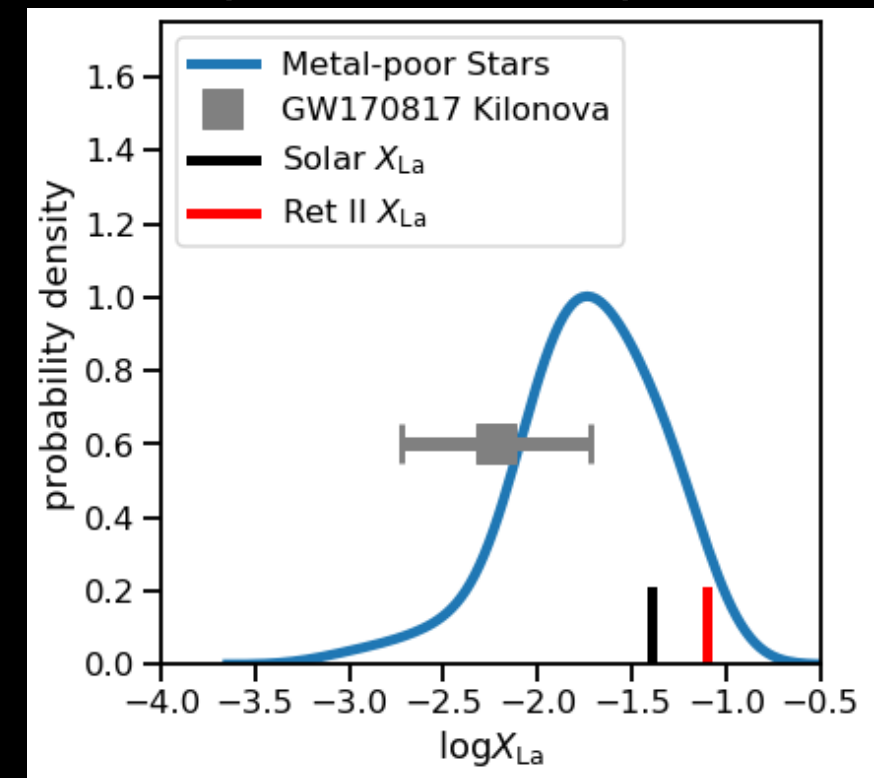
Ask Jillian about the GRBs

La and Ac variations in metal-poor stars

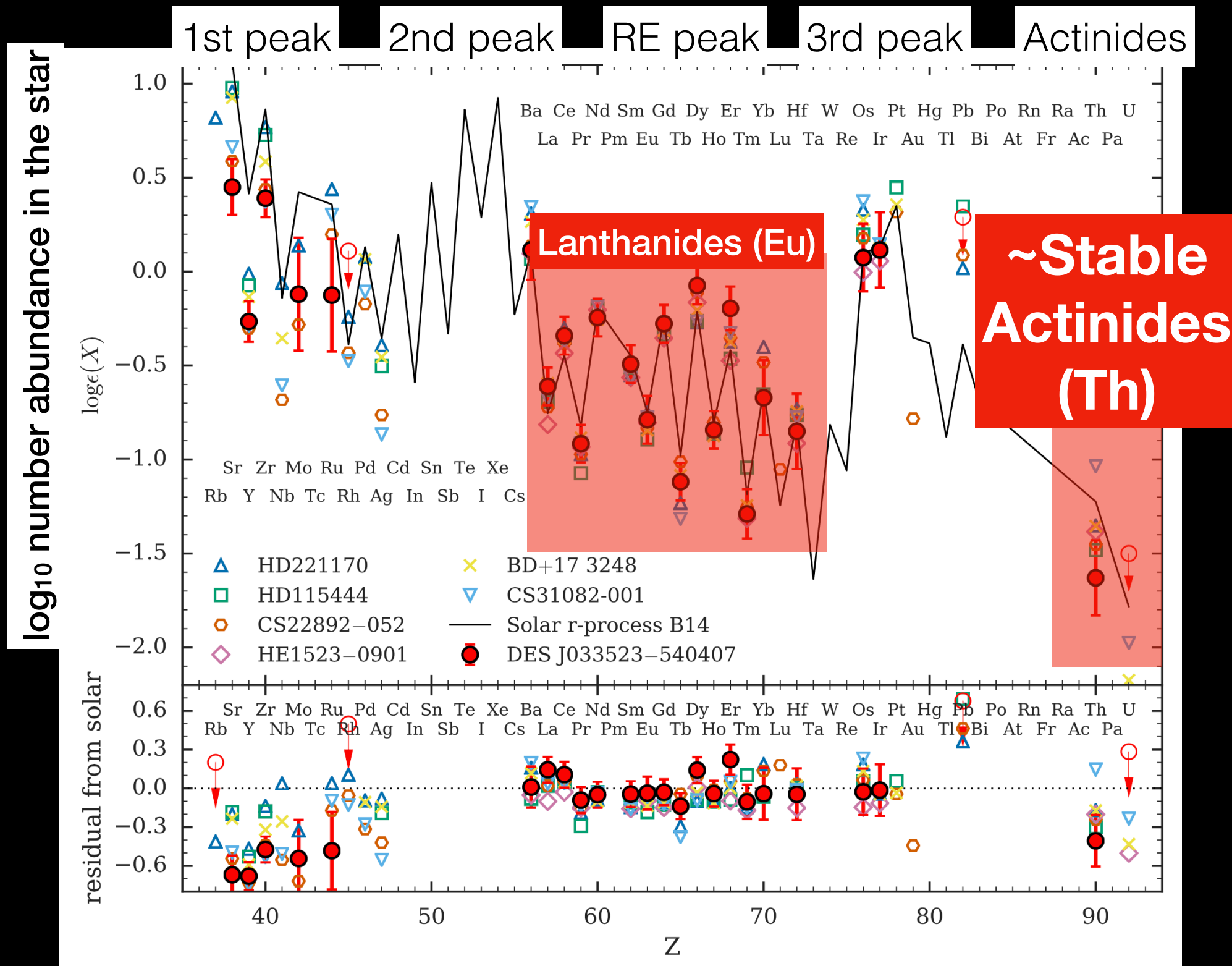
- The R-process Makes “Only Three Elements” (Two Ratios)
- The Lanthanide Fraction Distribution

$\log X_{\text{La}} \sim -1.7 \pm 0.5$
(Future kilonovae should be La-rich)

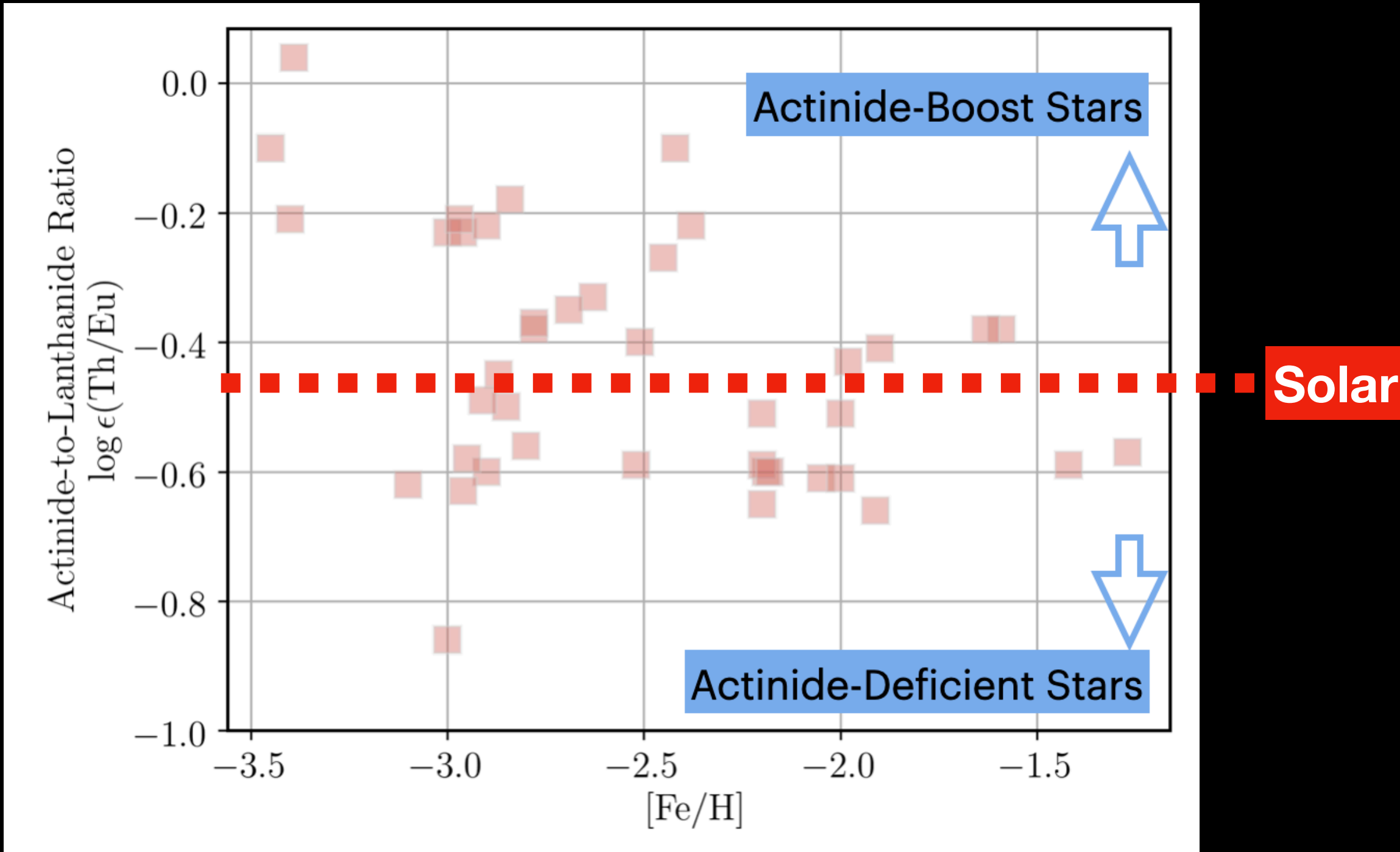
- The Actinide-to-Lanthanide Distribution



Measuring Actinides: Need Homogeneous Thorium



~45 Literature Th Abundances (~30 years)

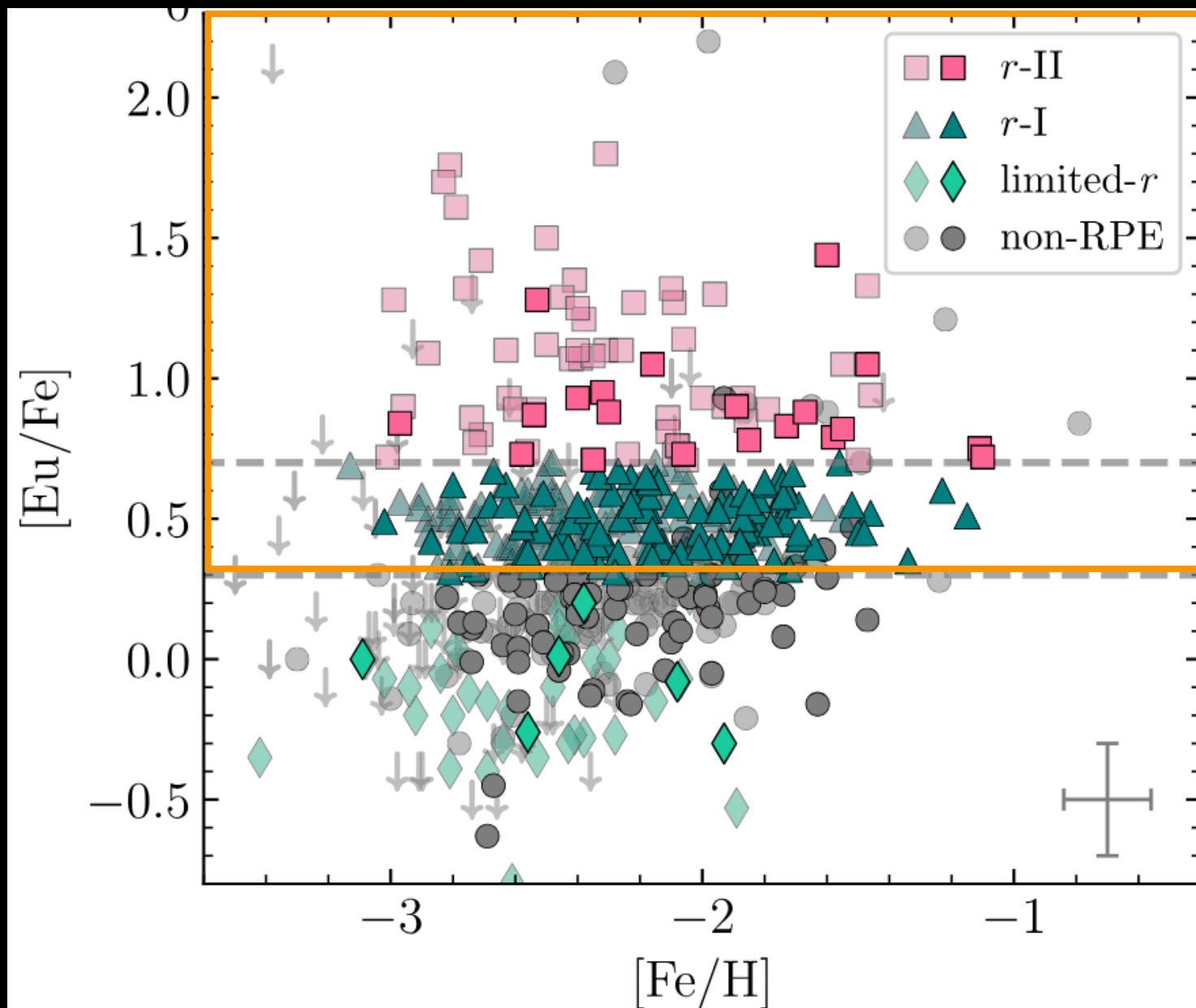


R-Process Alliance (RPA) Thorium

47 new homogeneous Th measurements



Shivani Shah
Florida -> NC State



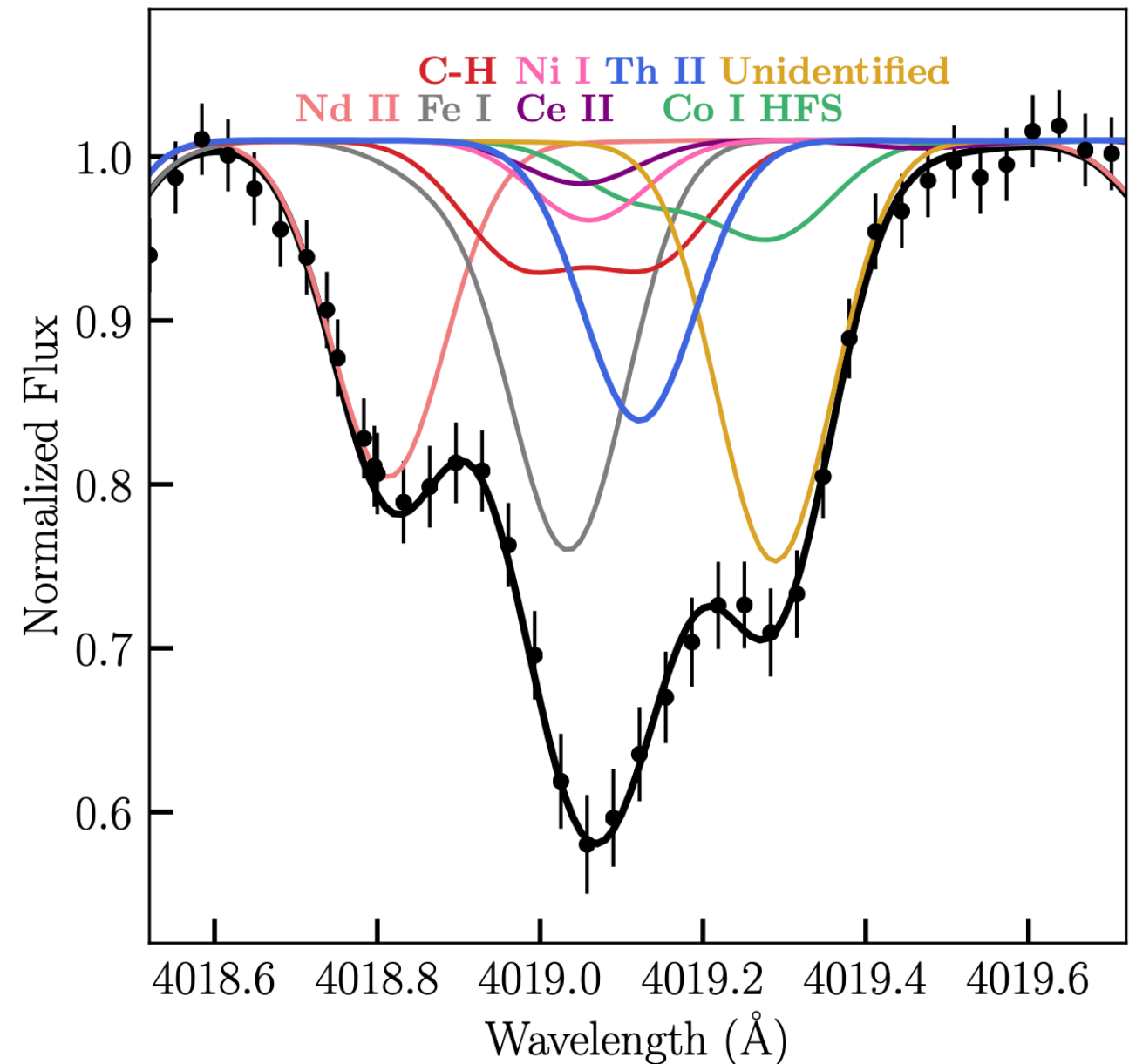
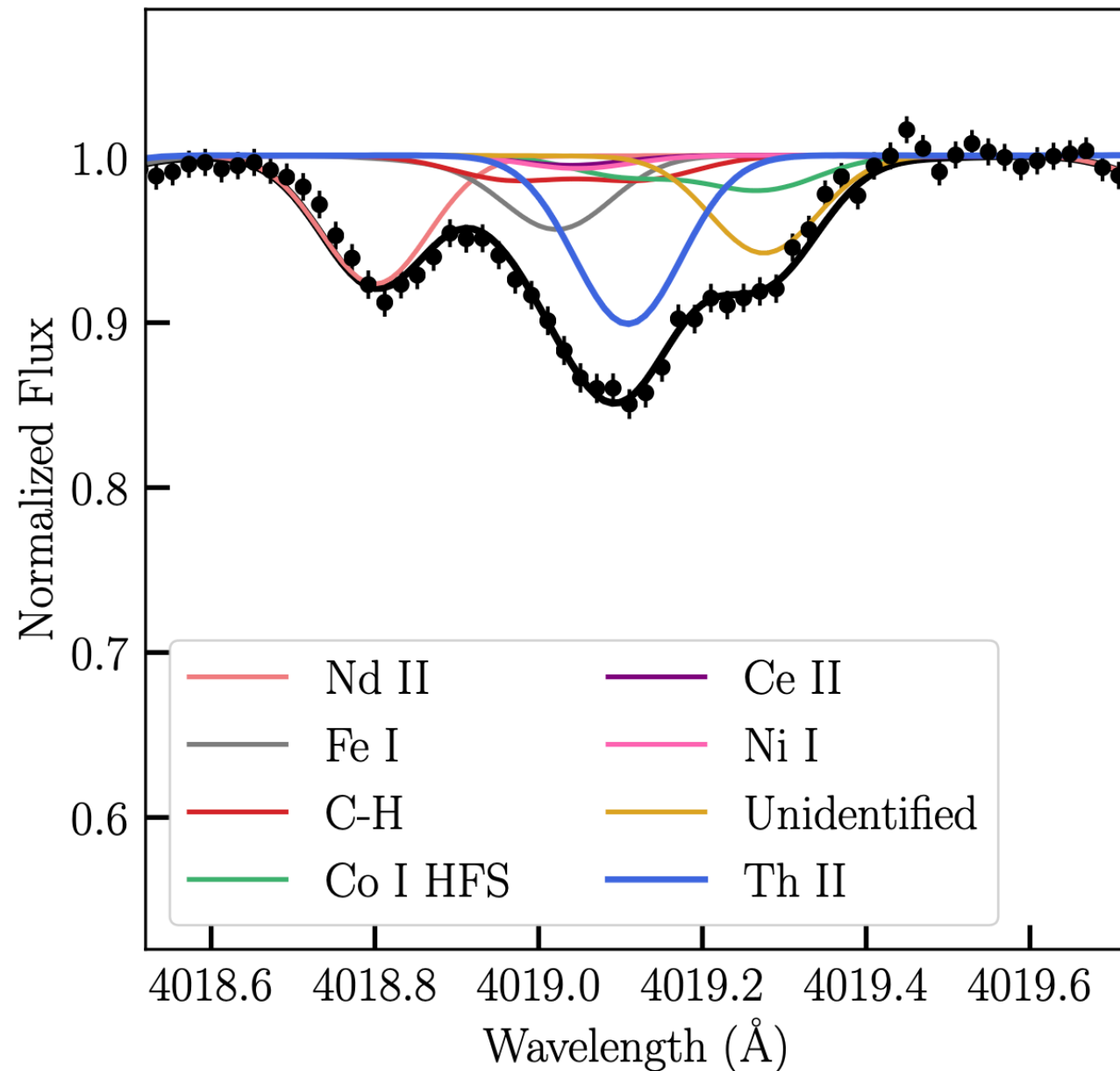
500 star base sample
(2000 stars coming)

Moderate $[\text{Eu}/\text{Fe}] > 0.3$

Moderate-high SNR
(>90 per res element
at Th line)

Detailed uncertainty
determination

Measuring Thorium is Hard

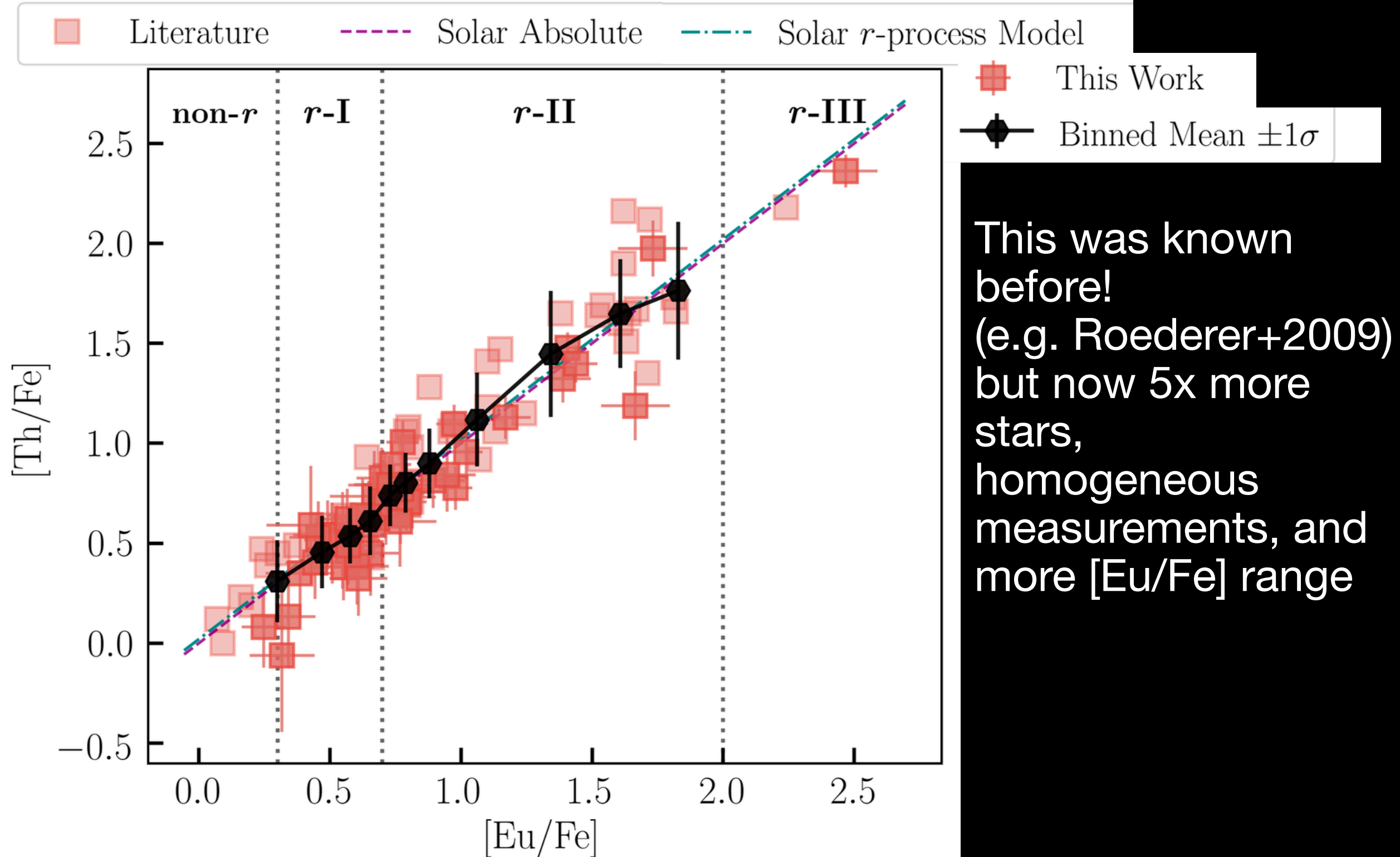


There is still an unidentified line. (HELP!)

Question:
**What should we find for
Th/Eu distribution?**

- (A) Varies Between Stars**
- (B) Similar Between Stars**

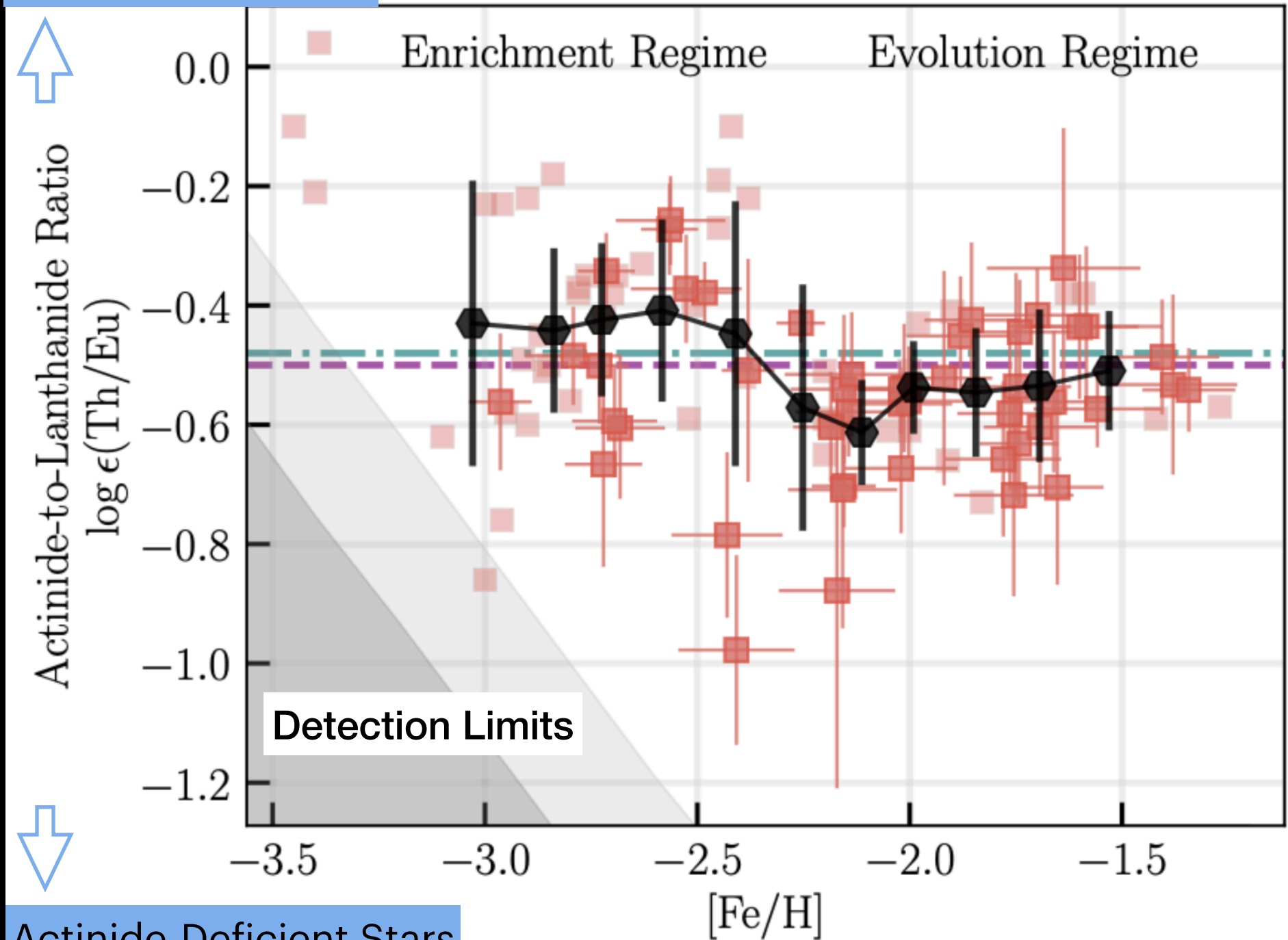
Th/Fe vs Eu/Fe: nearly 1-1



This was known before!
(e.g. Roederer+2009)
but now 5x more stars,
homogeneous measurements, and
more $[\text{Eu}/\text{Fe}]$ range

Th/Eu ratio ~flat vs metallicity

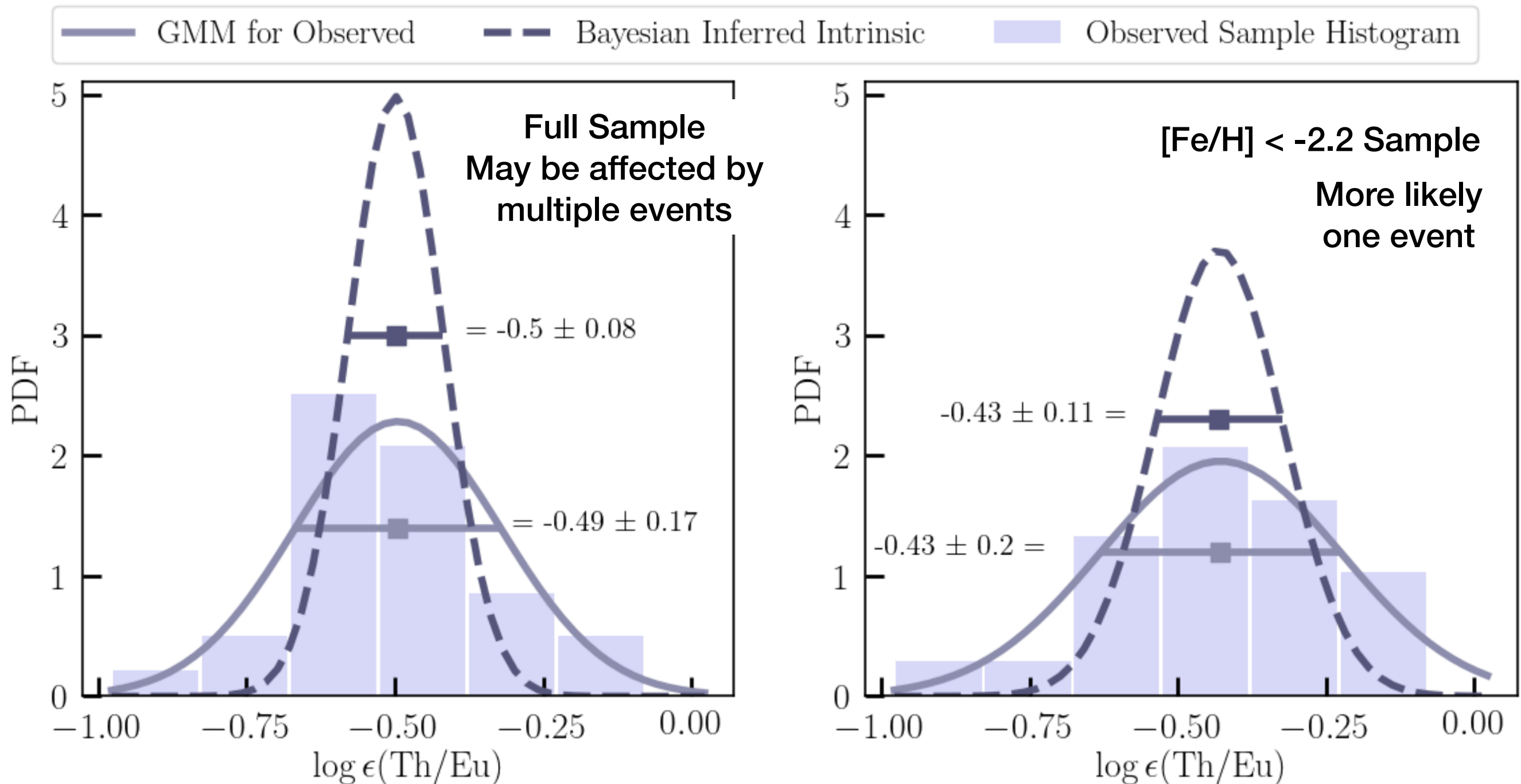
Actinide-Boost Stars



Actinide-Deficient Stars

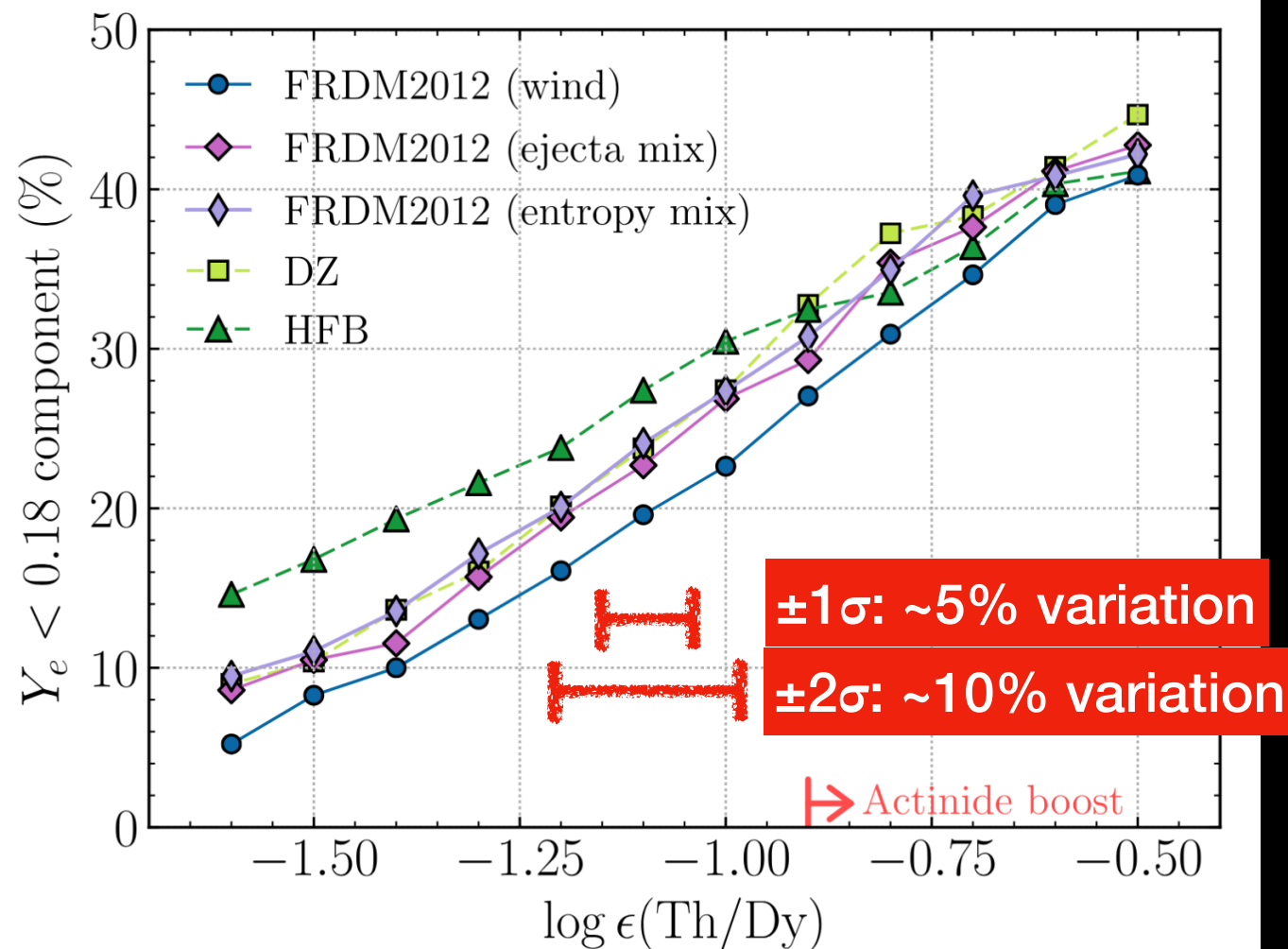
Narrow Intrinsic Dispersion 0.11 ± 0.04 dex (17-40%)

(~5% of events are outliers)



What does this mean for early r-process?

It seems hard to get narrow Th/Eu



- Th / Eu ratio is very sensitive to Y_e
- Different Y_e distributions give different total Th / Eu
- R-process sites seem like they should have varying Y_e distributions (e.g. ratio of dynamical to disk ejecta)

Holmbeck et al. 2019

Shah et al. 2026

What does this mean for early r-process?

It seems hard to get narrow Th/Eu

- All r-process events make very similar Y_e distribution?
 - (e.g. everything is a NS-BH tidal tail)
- Fission cycling homogenizes Th/Eu?
 - (if it's the dominant mass component, seems hard)
- Your idea here?

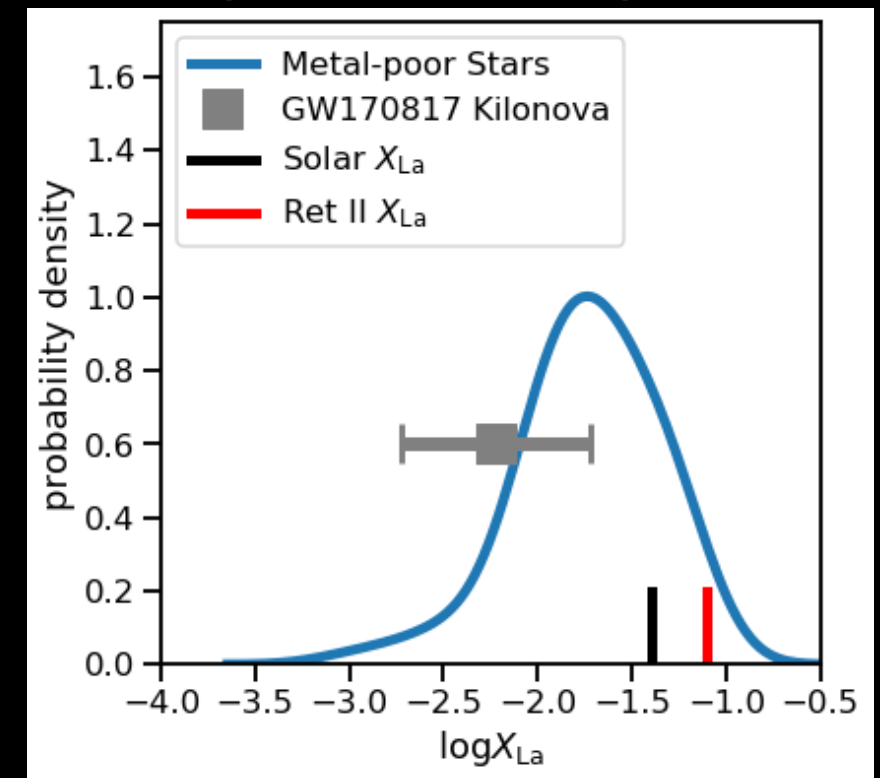
Some Caveats

- Only looking at Th detections.
 - No low Th limits expected, but we need to check
- Only looking at $[\text{Eu}/\text{Fe}] > 0.3$.
 - Maybe lower Eu has more scattered Th?
- Th variation due to age variation
- Relatively metal-rich: maybe already sampling multiple events
- 1D LTE analyses for metal-poor red giants

La and Ac variations in metal-poor stars

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- The Lanthanide Fraction Distribution

$\log X_{\text{La}} \sim -1.7 \pm 0.5$
(Future kilonovae should be La-rich)



- The Actinide-to-Lanthanide Distribution

$\log \text{Th}/\text{Eu} \sim -0.43 \pm 0.11$
Very narrow: how do you get this??

