Neutron Star Merger Contribution to R-process Abundance

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Neutron star merger and r-process nucleosynthesis

The merger scenario of r-process:
Lattimer & Schramm (1974)
“Black hole neutron star collisions”

The paper was submitted even before the discovery of Hulse-Taylor pulsar.

In a workshop at CCA Nov. 2017
Jim, “*This observation seems to have solved the long-standing mystery surrounding the origin of r-process elements*.”

GW170817 & AT2017gfo

- Kilonova mass estimate:

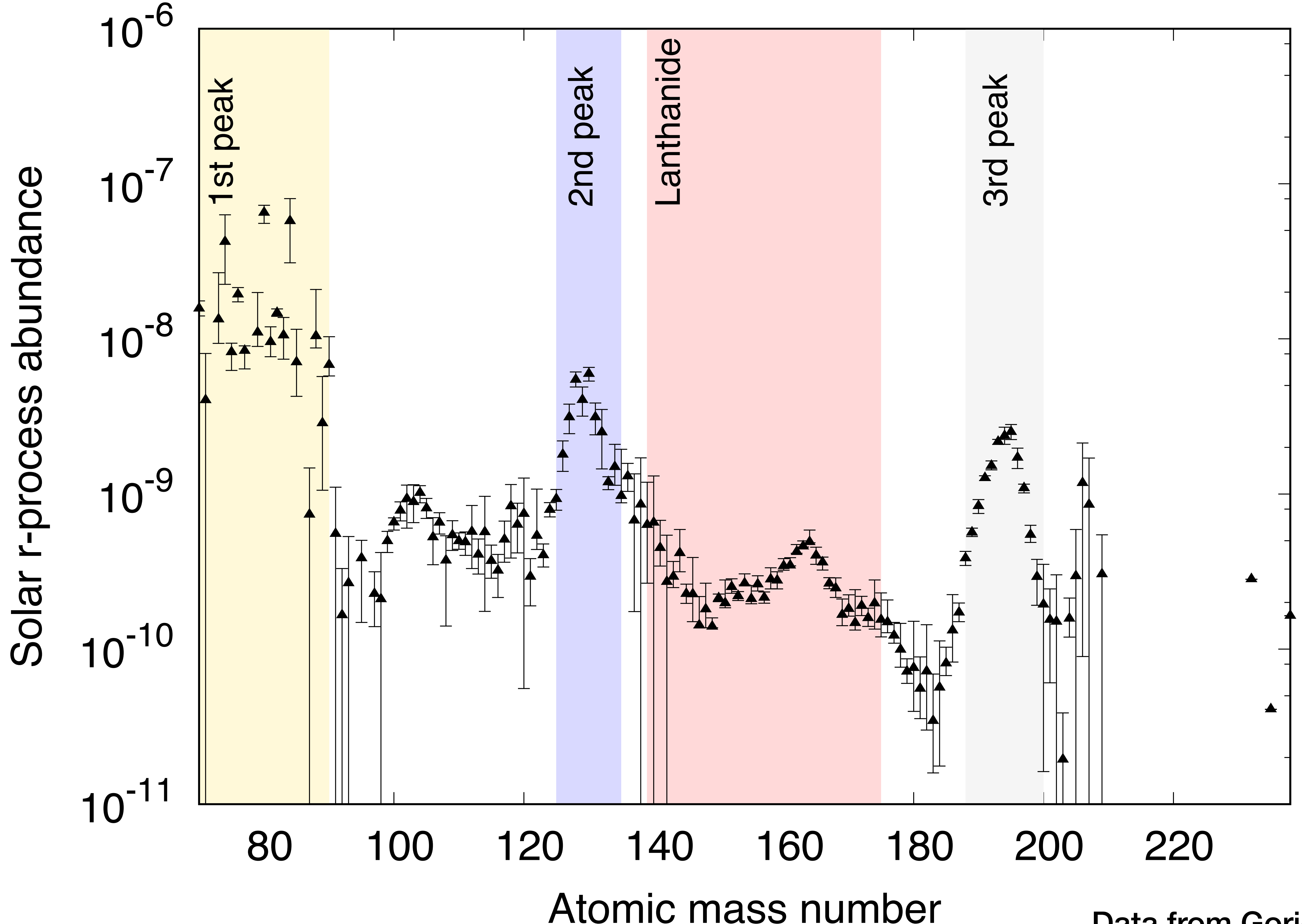
M_{ej}~0.04M_{sun} and X_{lan} ~ 0.01
+ ~0.01 M_{sun} and X_{lan} << 0.01
for the early blue emission.

- Event rate:

$R = 1540^{+3200}_{-1220}$ Gpc^{-3} yr^{-1}

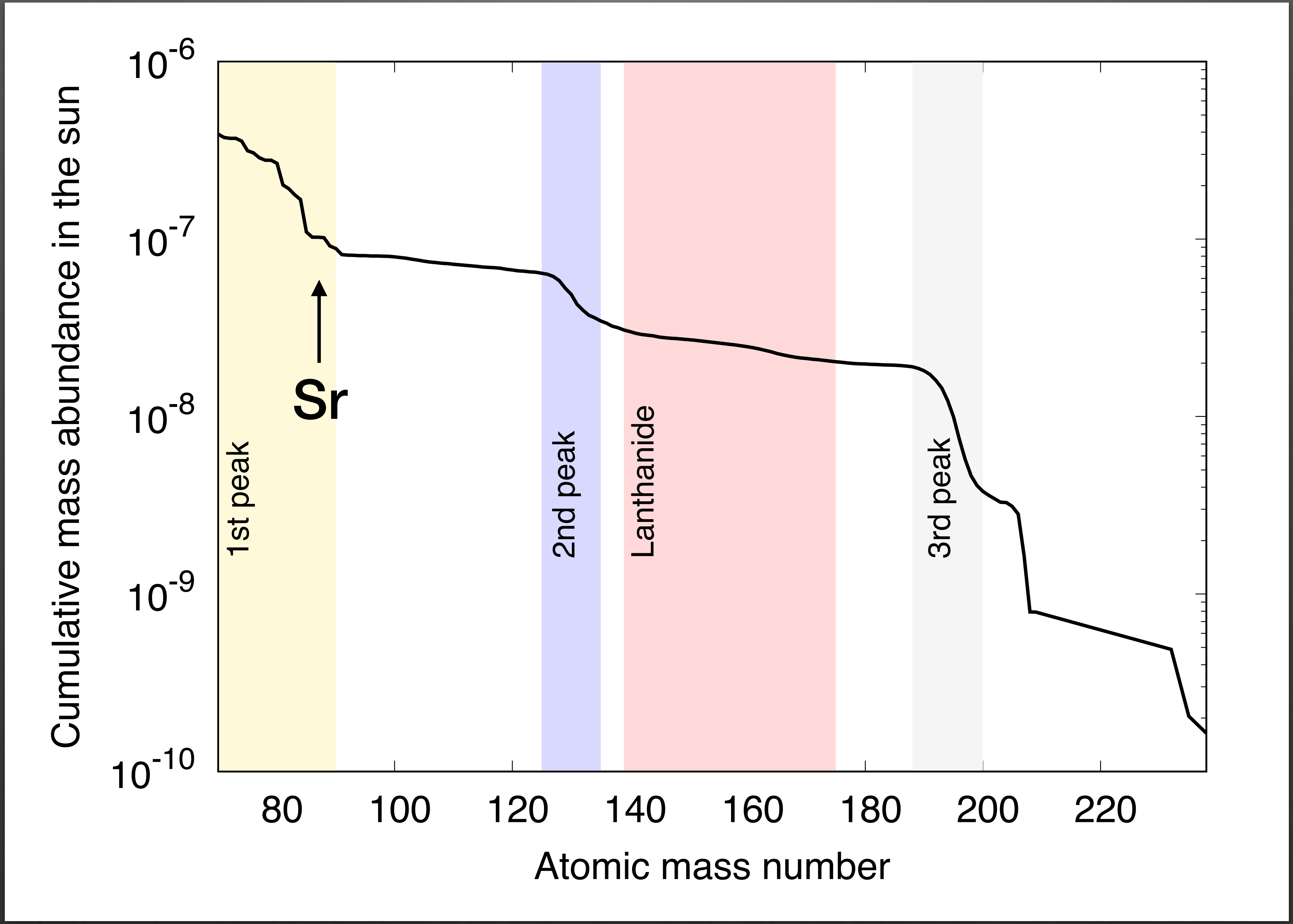
The host has currently very low star formation.
A long delay ~ 1 - 10 Gyr.

Solar r-process abundance



Data from Goriely 99

R-process elements in the Sun

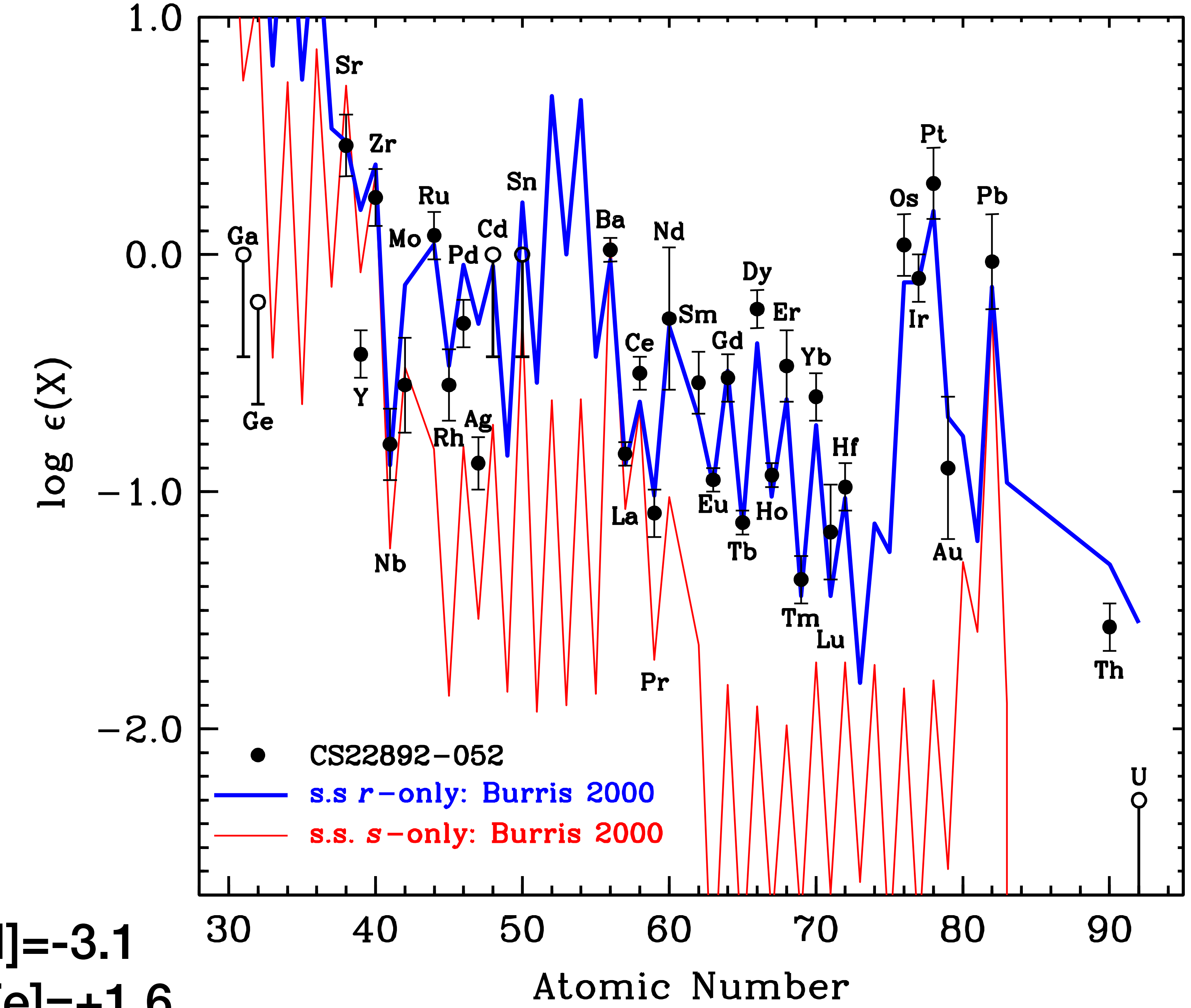


R-process mass ~ 10^{-7} - 5 x10^{-7}Msun.

$X_{lan, solar-r}$ ~ 0.1 (A>100) - 0.025 (A>70)

R-process abundances of r-rich extremely low metal stars (2 kinds)

Sneden + 03



[Fe/H]=-3.1
[Eu/Fe]=+1.6

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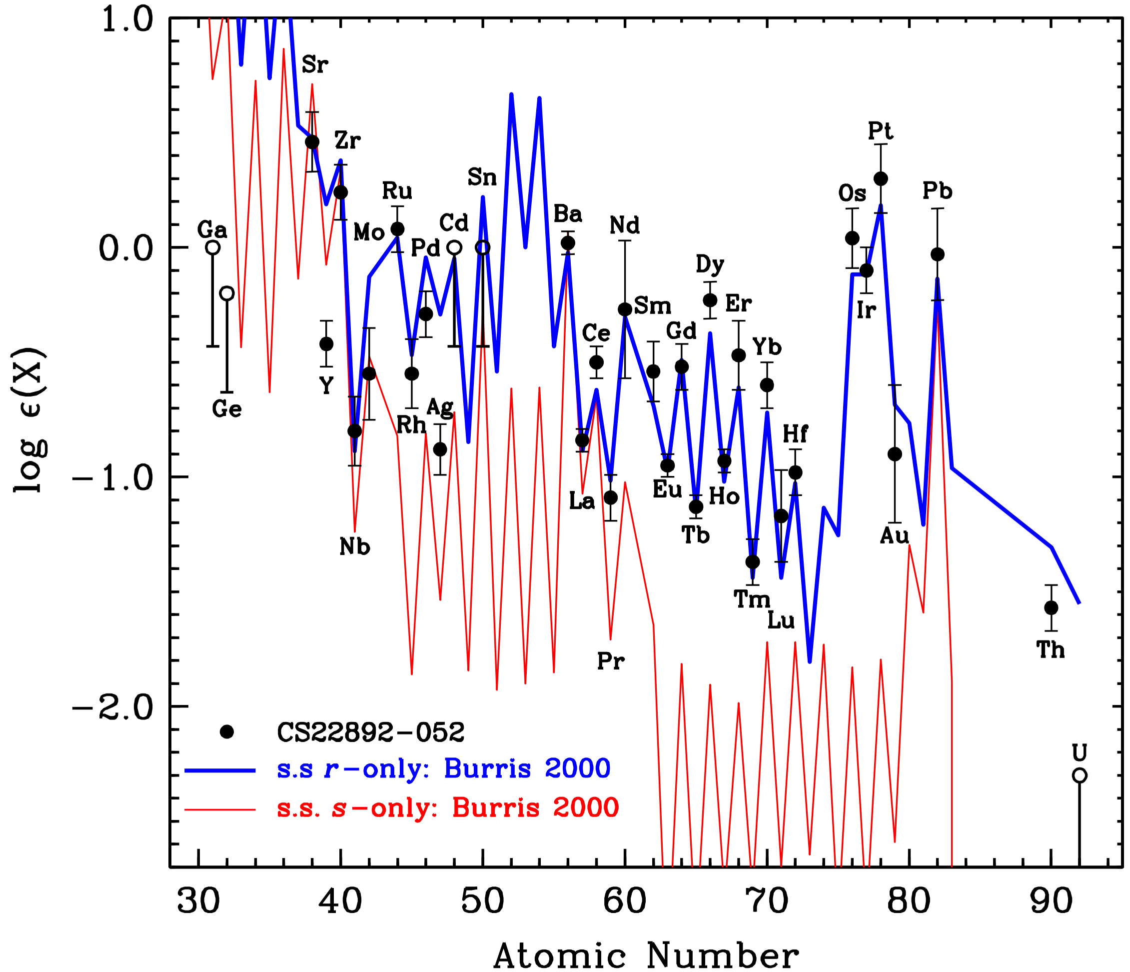
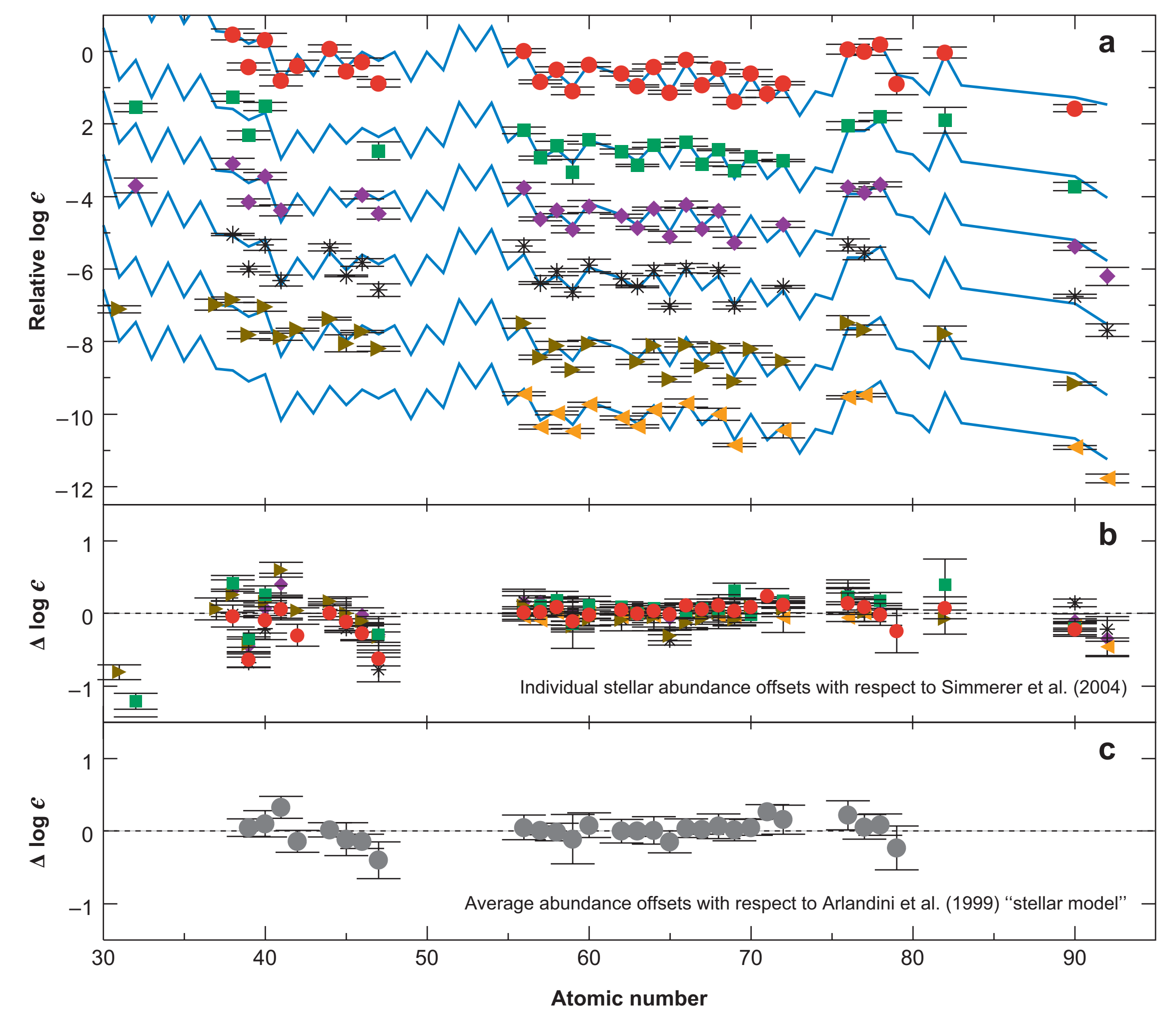
Sneden + 03



$[Fe/H]=-3.1$
$[Eu/Fe]=+1.6$

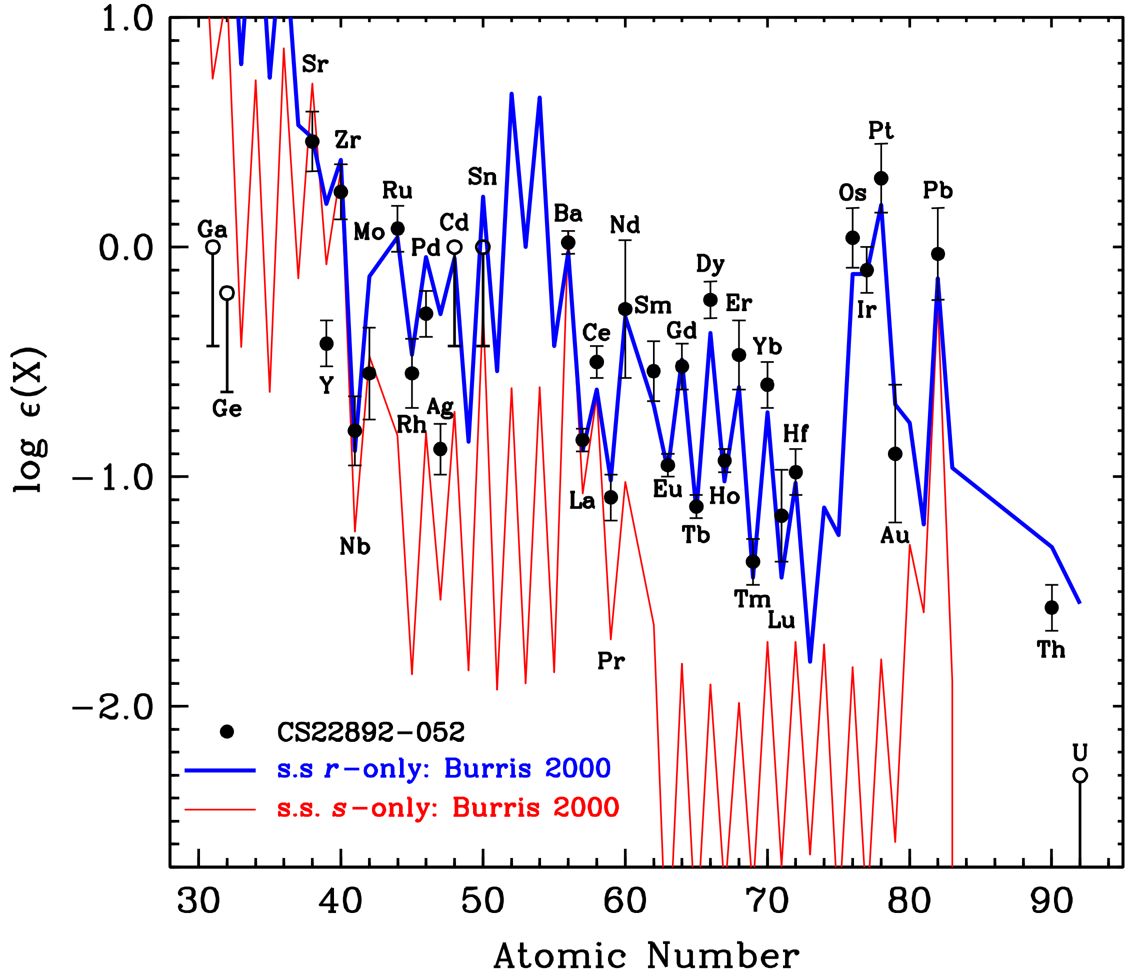
Sneden + 08



Variation Universality

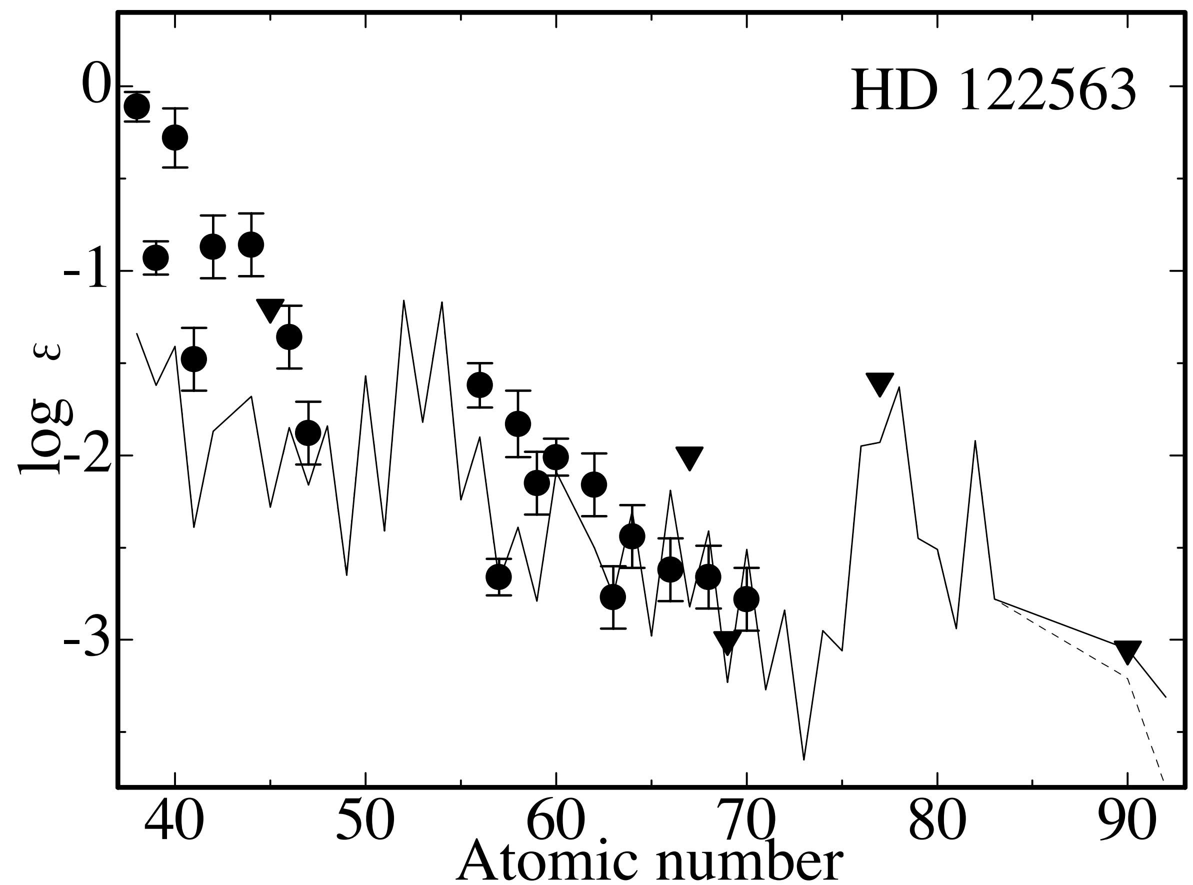
R-process abundances of r-rich extremely low metal stars (2 kinds)

Sneden + 03



[Fe/H]=-3.1
[Eu/Fe]=+1.6

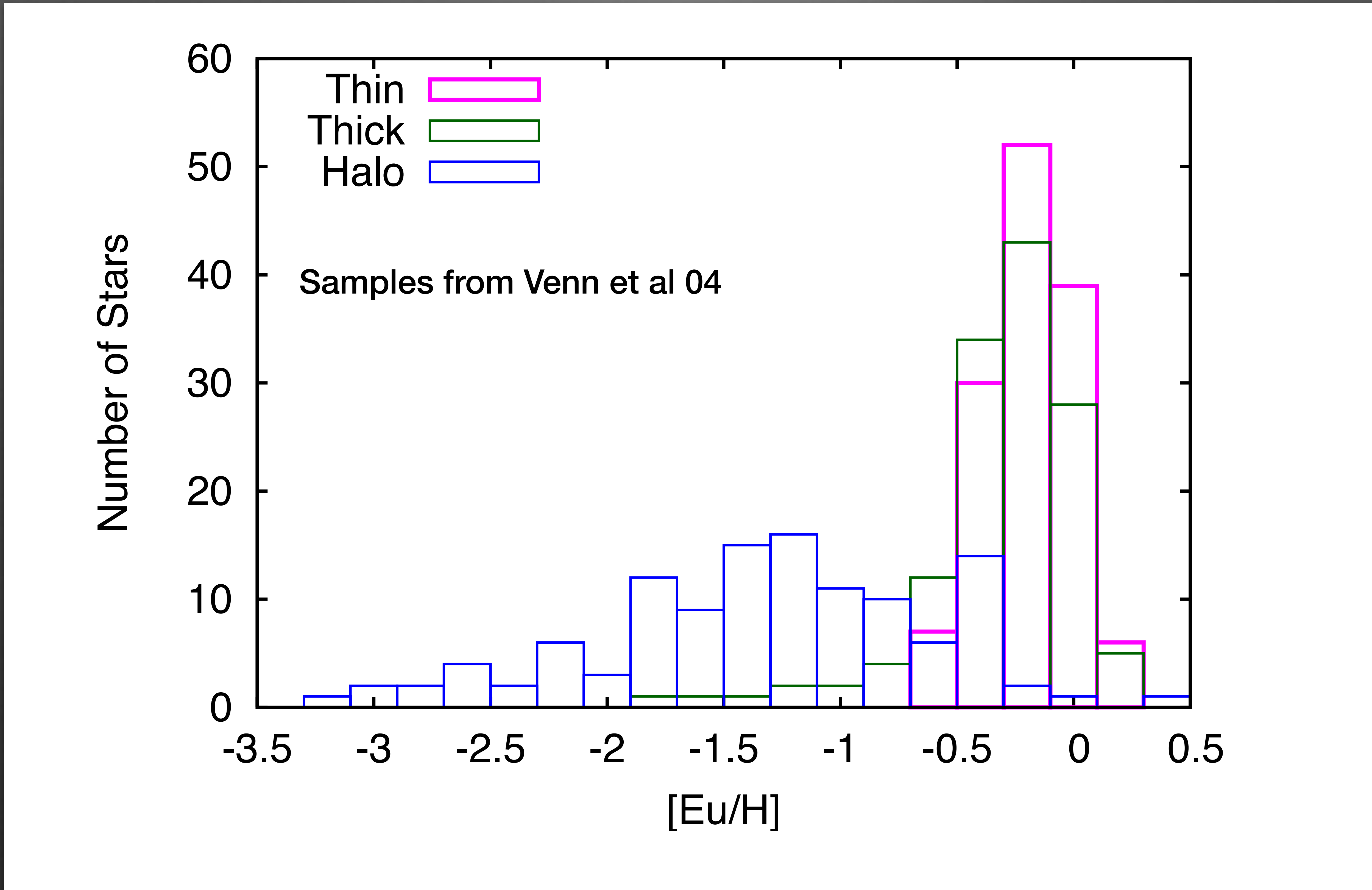
Honda + 06



[Fe/H]=-2.7
[Eu/Fe]=-0.83

R-process events have a variation in 1st/2nd peak
Two different sources for light and heavy r-processes?

Nearby stars



R-process elements in the Milky Way

Eichler, Livio, Piran, Schramm 1989

The mass of the Galactic disk ~ 6 x 10^{10} Msun.

(McMillan 2011)

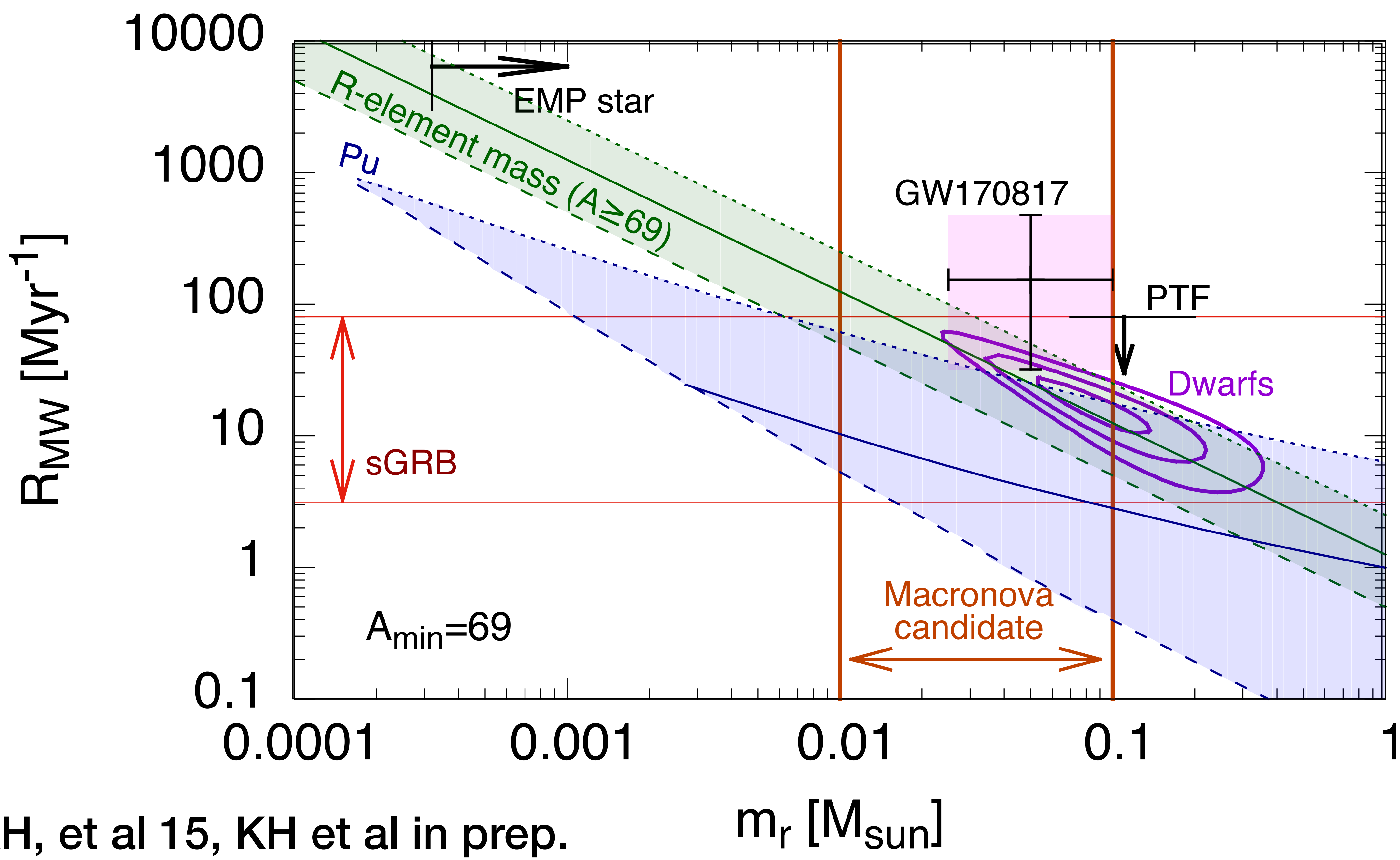
Assuming that the solar abundance is the typical,
The mass of r-process (A>69)~ 2.3 x 10^4 Msun,
(A>90) ~ 5000 Msun.

An ejecta mass of 0.01Msun => 500 - 2300 /Gpc^3/yr

(see also Qian 2001, Bauswein +14, KH+15, Rosswog+17)

Galactic Rate - Mass/event

Total r-process mass ~ Rate x Mass/event x 10 Gyr (23000Msun for A>69)



KH, et al 15, KH et al in prep.

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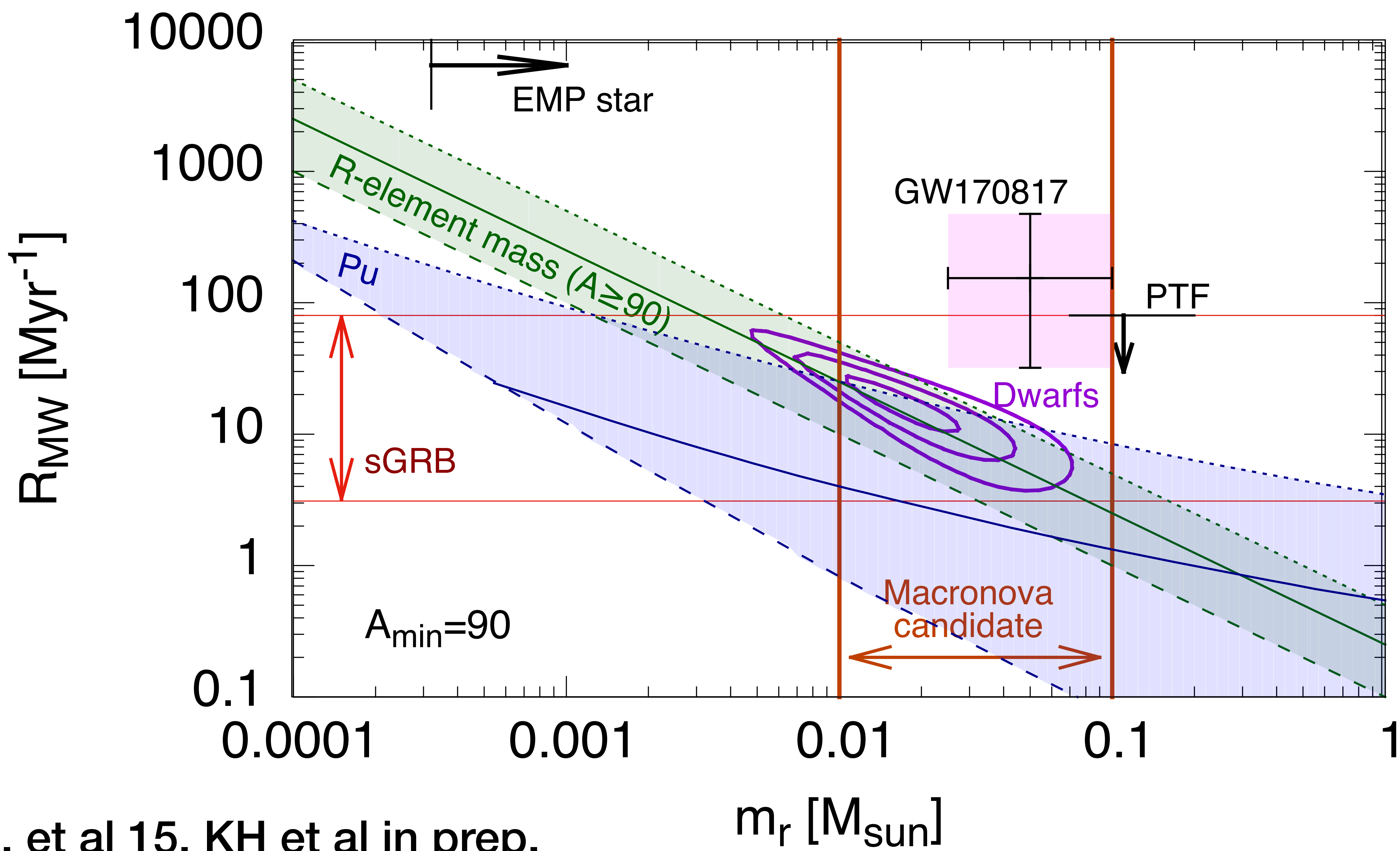
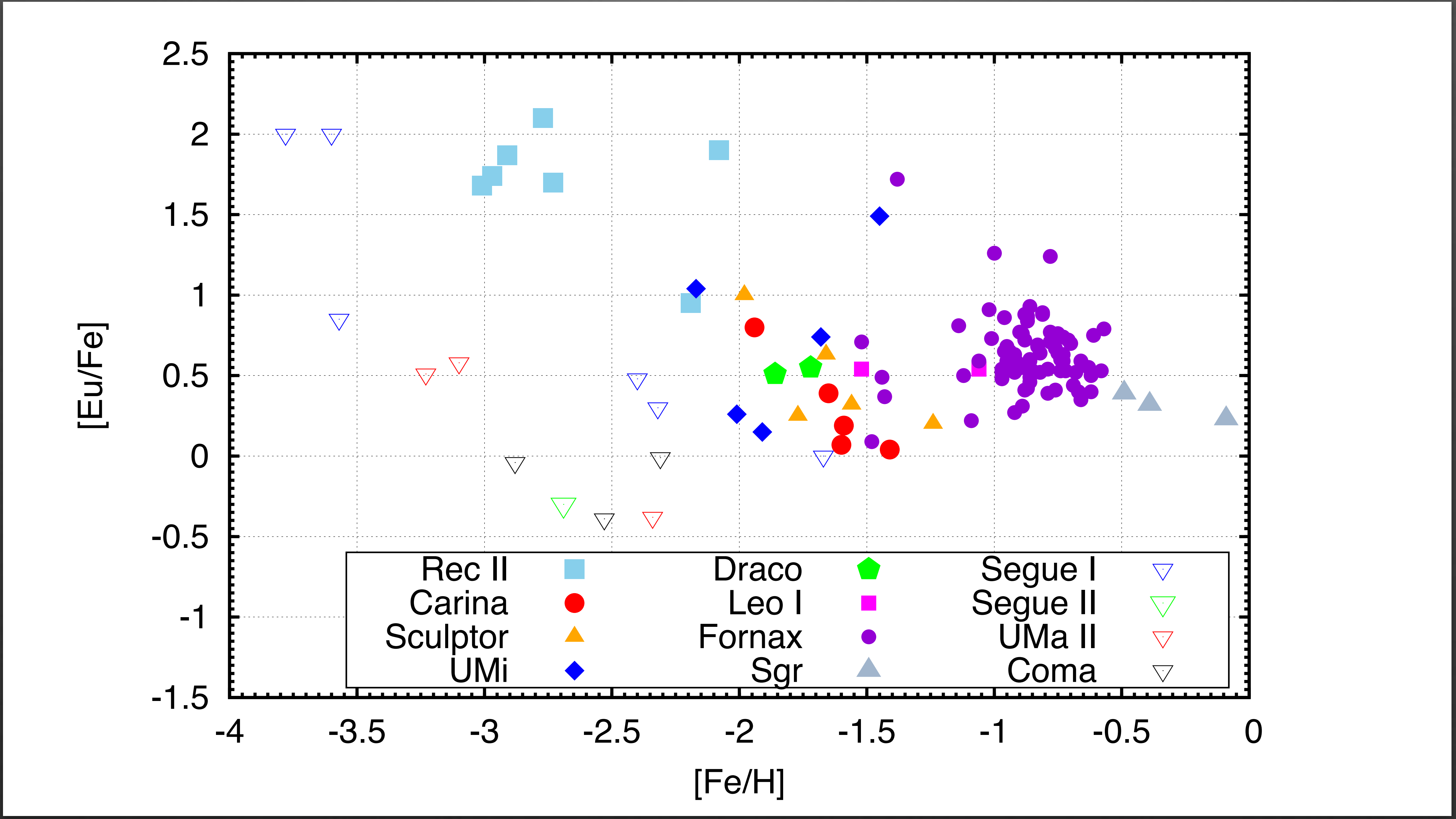


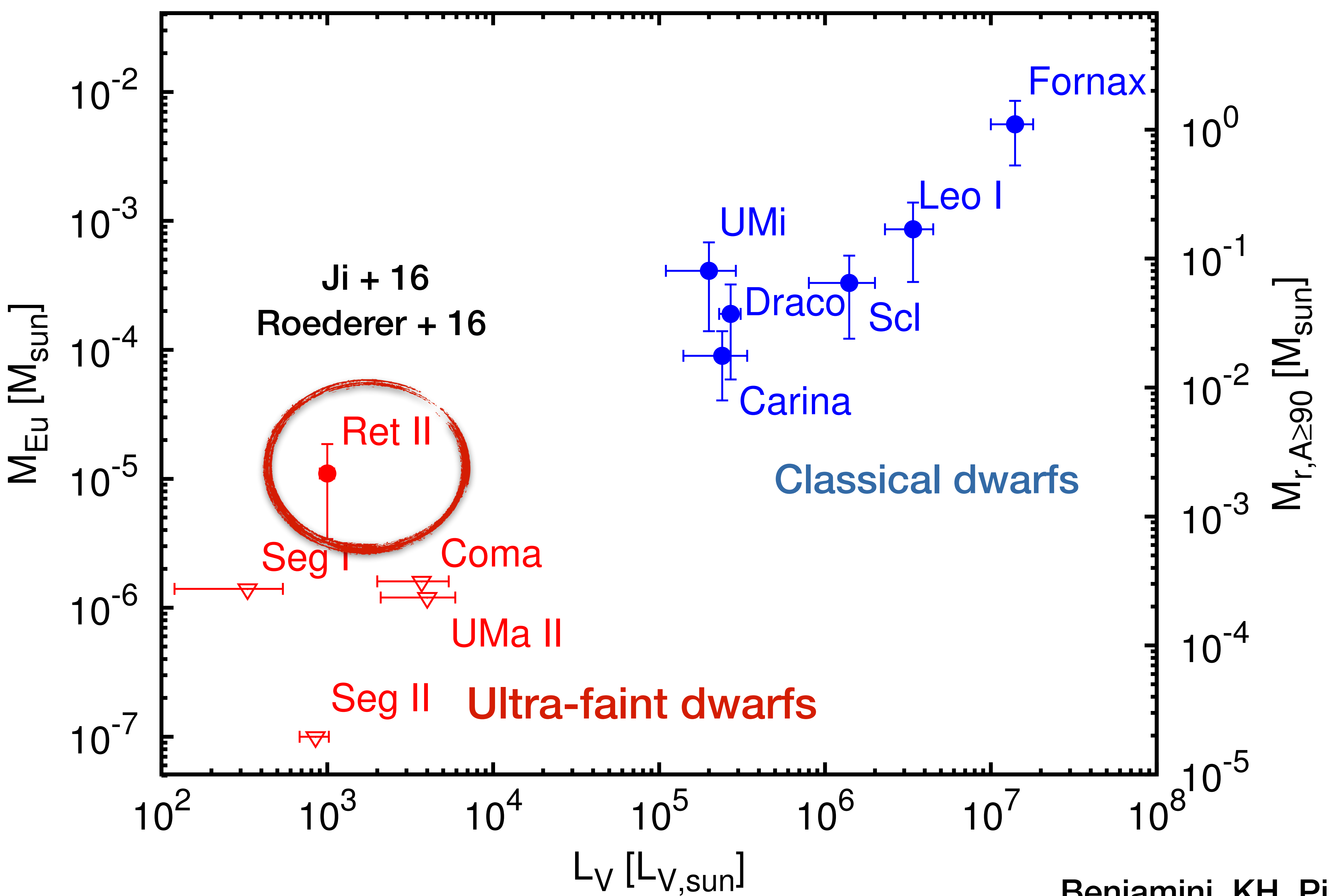
KH, et al 15, KH et al in prep.

R-process in Satellite Dwarf galaxies

Ji + 16 found an r-process enriched ultra-faint dwarf galaxy, Reticulum 2.
(see also Roederer + 16)

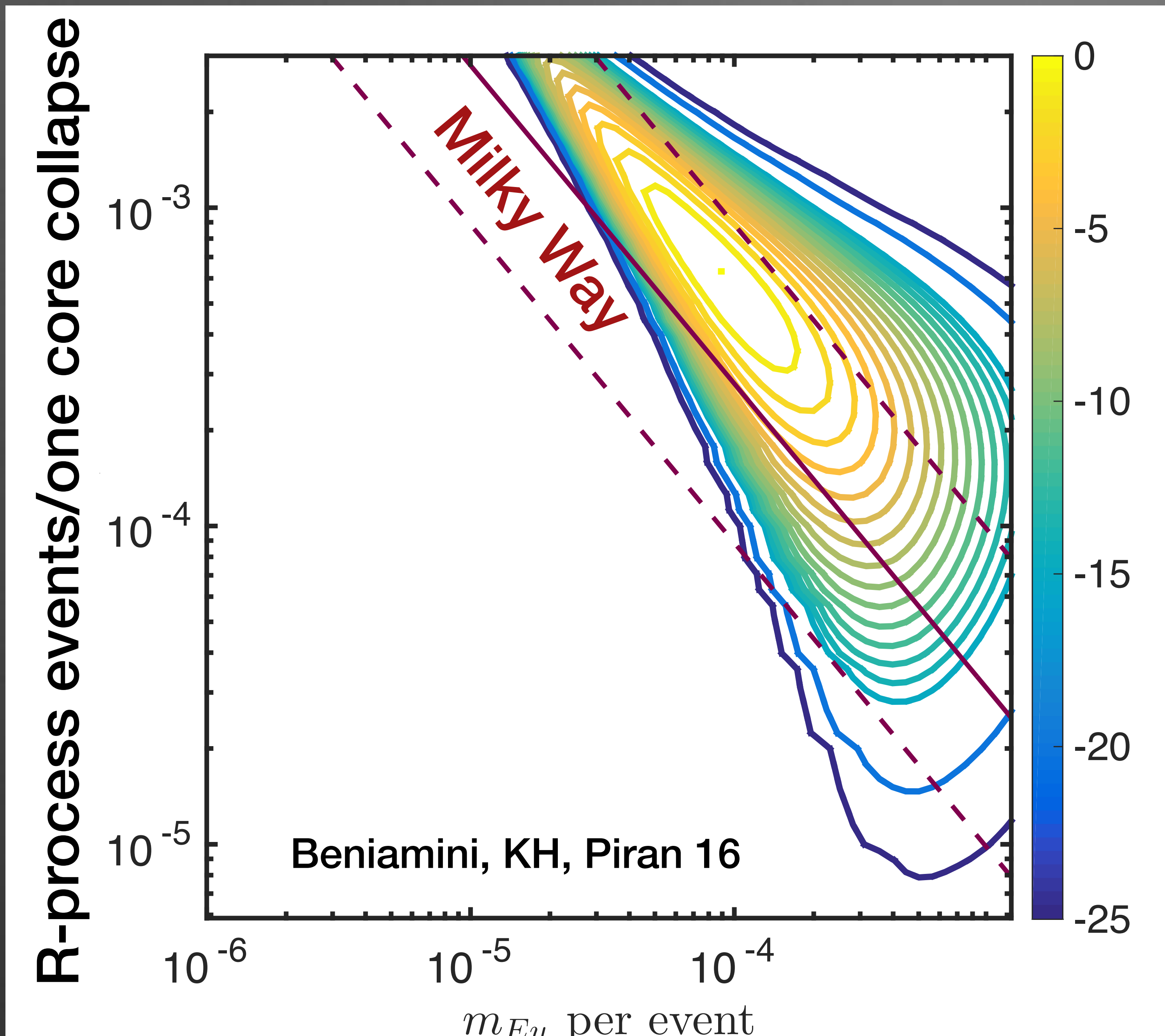


Eu mass in the Dwarfs



Beniamini, KH, Piran 16

R-process rate and Eu mass/event

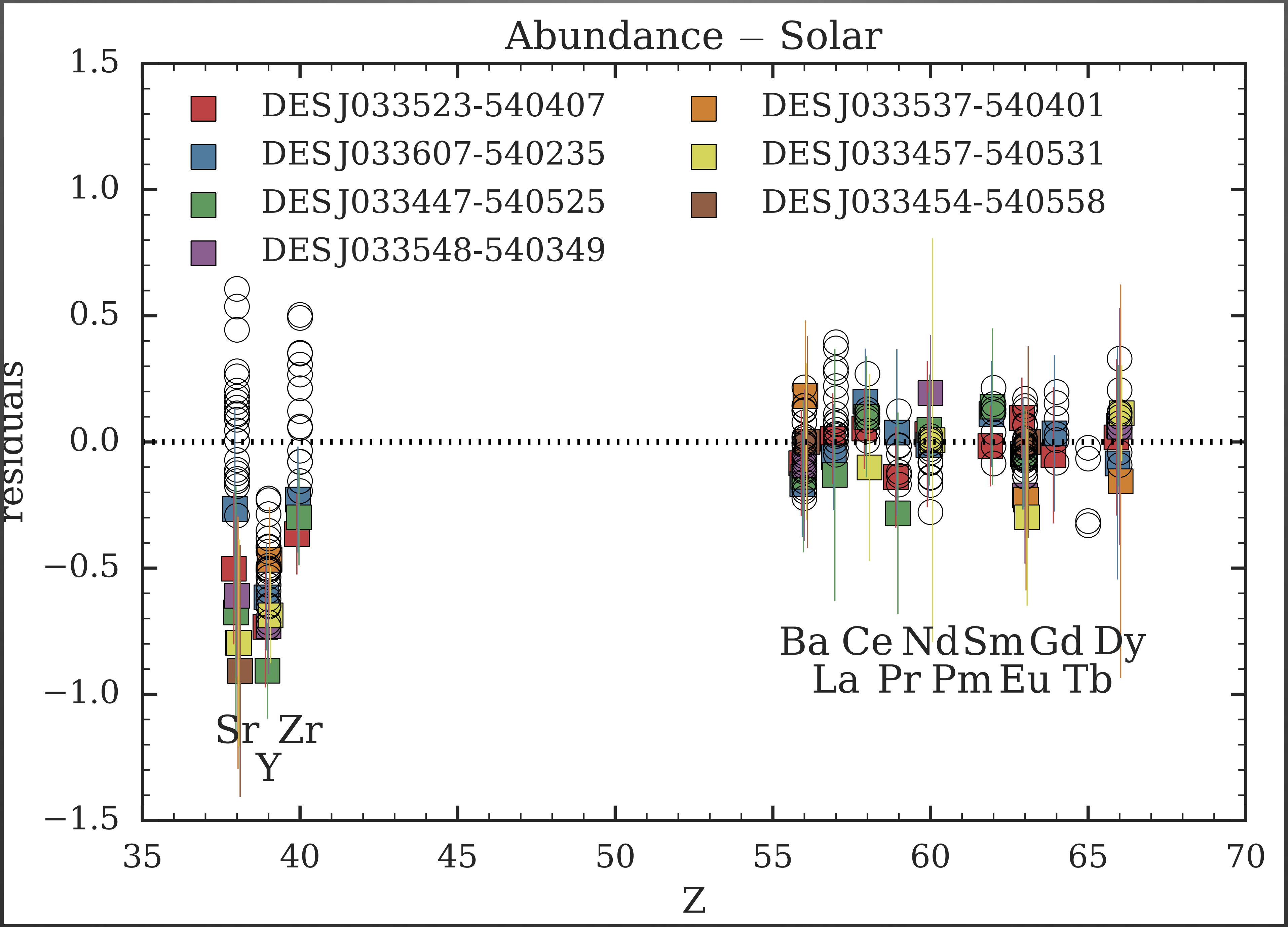


- An r-process event every 10^3 - 10^4 SNe.
- r-process elements ~0.008- 0.04 Msun.
- Some effects of natal kicks (the center of mass velocity after the Second SN is > 10km/s)

Note: the mass is scaled with the gas mass that contributes the chemical evolution.
Caveats: the mixing and escape fraction of Eu from a galaxy should be carefully studied.

Abundance of Ret 2

Ji et al 2016



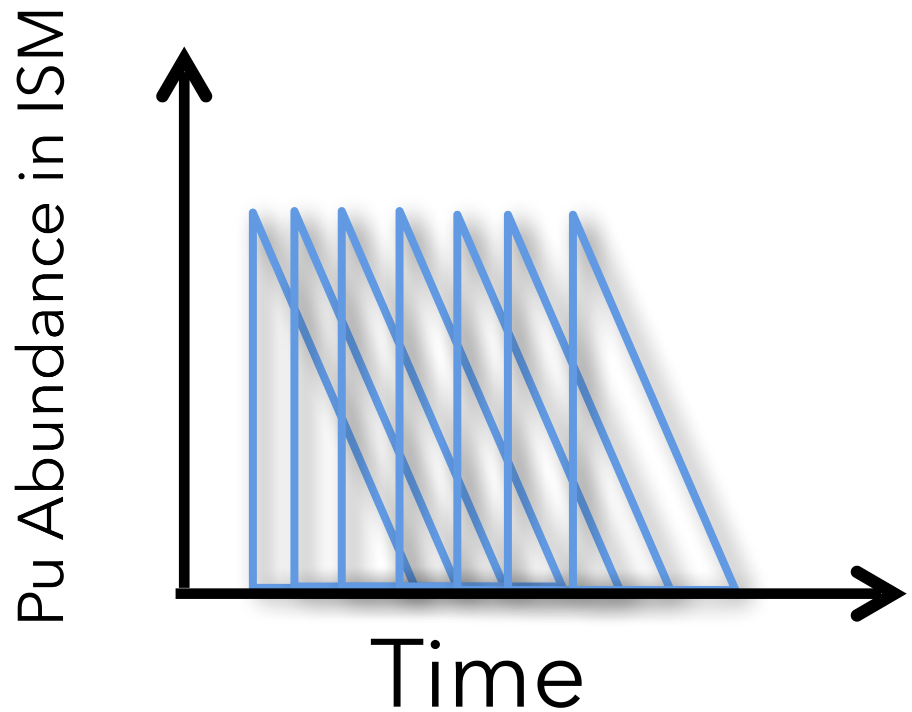
Abundance of radioactive elements in the ISM

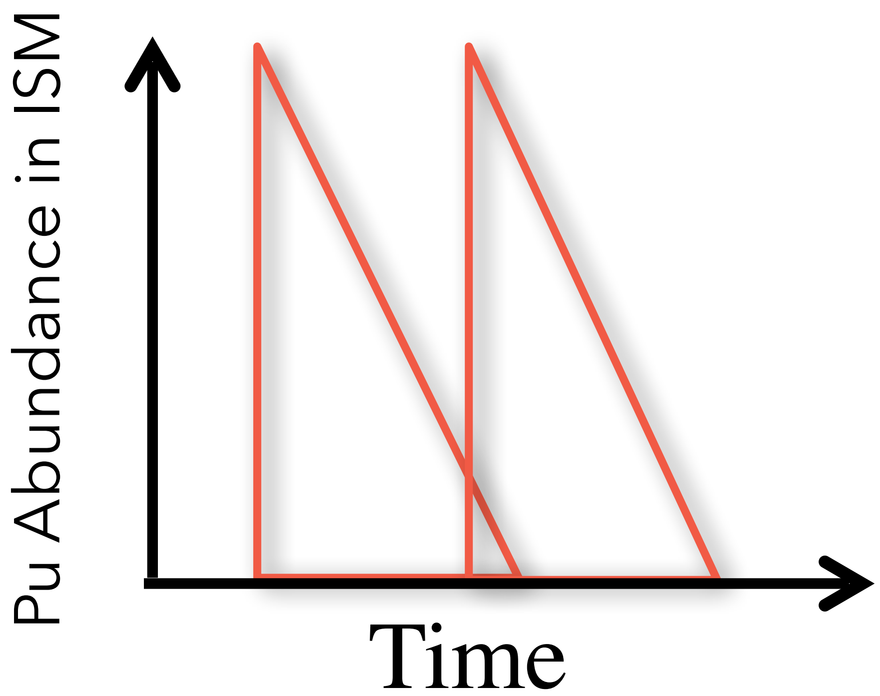
Supernova

=> High rate/low yield

Compact binary merger

=> Low rate/high yield





High median density
Small dispersion

Low median density
Large dispersion

$$\tau_{\rm mix} \approx 300\,{\rm Myr}\,(R/10\,{\rm Myr})^{-2/5}(\alpha/0.1)^{-3/5}$$

$$\times\,(v_{\rm t}/7\,{\rm km/s})^{-3/5}(H/0.2\,{\rm kpc})^{-3/5}$$

Radioactive nuclei in Meteorites

Long lived

Half-lives (Myr)

^{232}Th: 14000

^{235}U: 704

^{238}U: 4500

Short lived

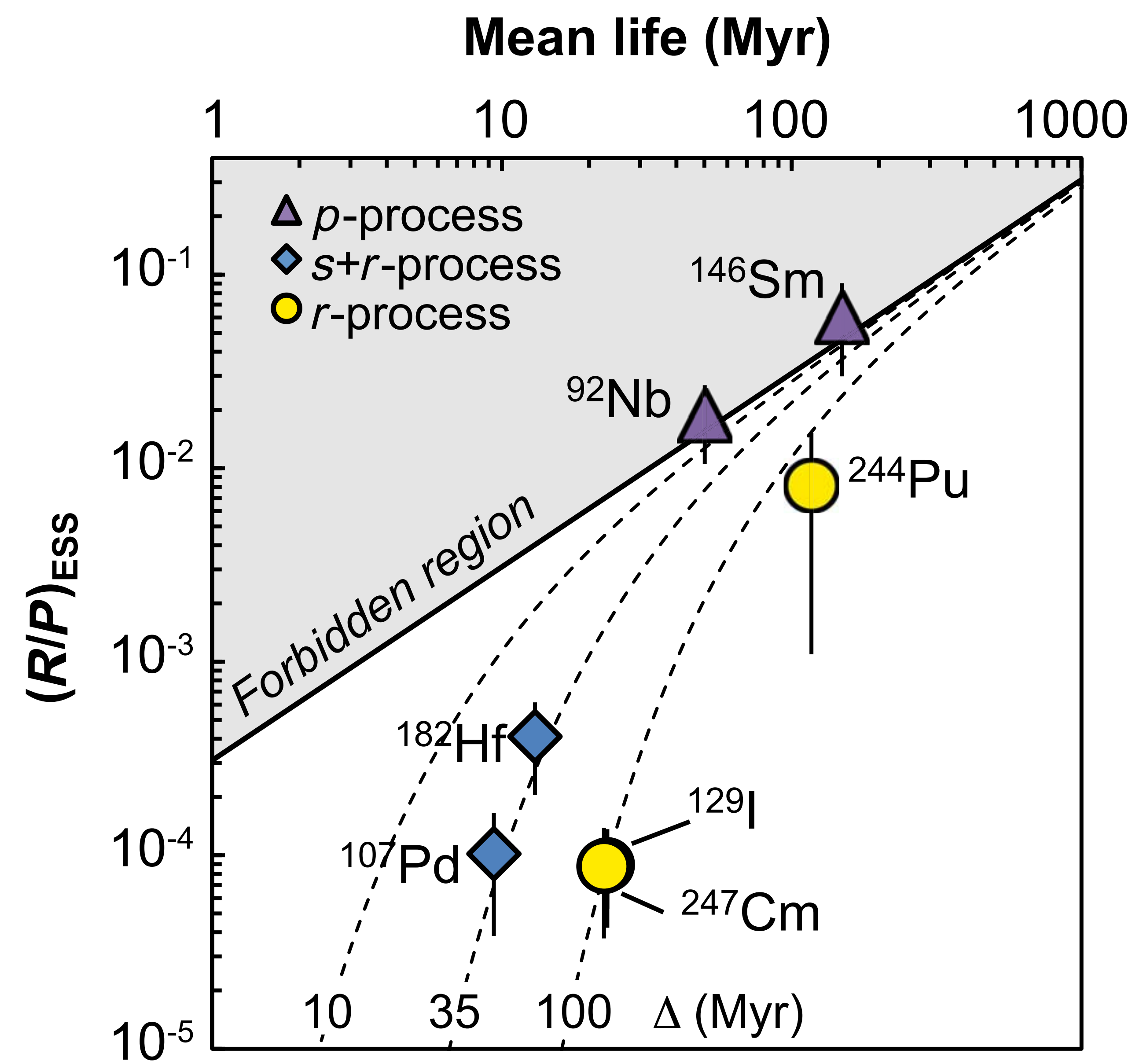
^{129}I: 15.7

^{244}Pu: 81

^{247}Cm: 15.6

used to exist in the early solar system

Comparable amounts of ^{238}U, ^{244}Pu, ^{247}Cm had been produced around 100 Myr before the Solar system formed.

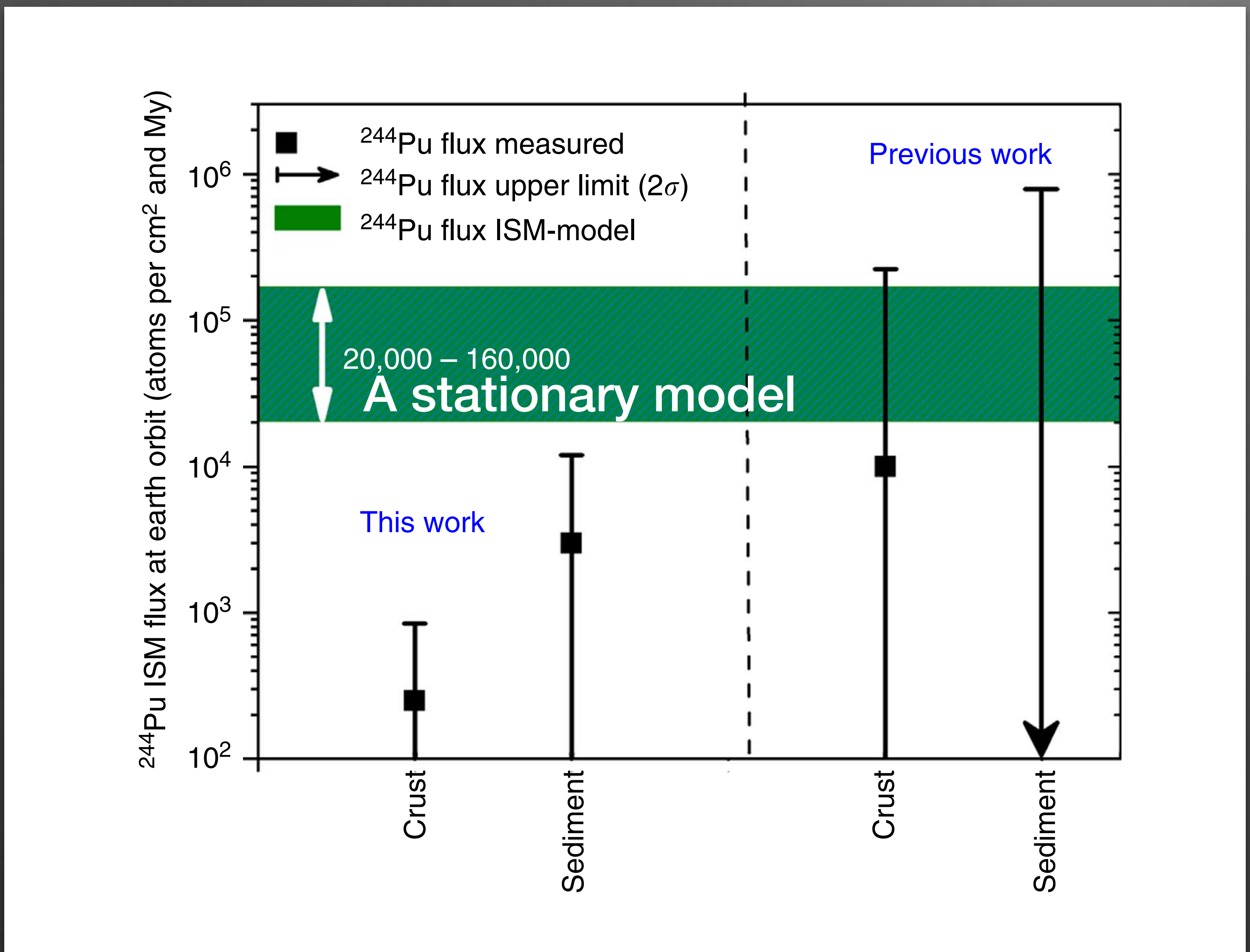


Tissot et al 2016

see also Turner et al 2007

Deep Sea ^{244}Pu measurement

Wallner et al 15, Paul et al 07



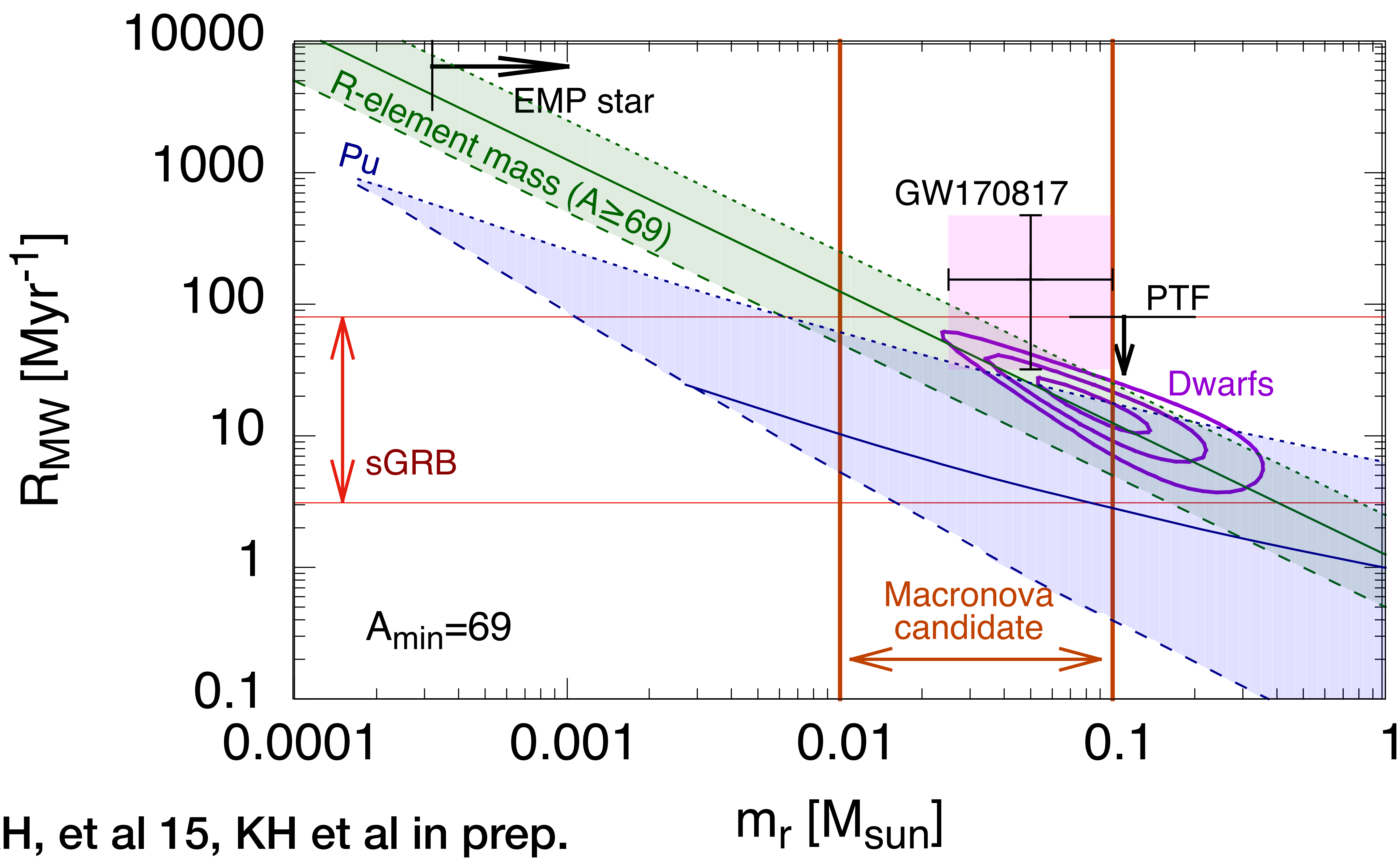
- Half life = 81 Myr
- Produced by r-process
- No ^{244}Pu currently survives from the early solar system.

- ^{244}Pu is accreted on Earth from ISM.

- The flux is less than the expectation by a factor of 100.

Galactic Rate - Mass/event

Total r-process mass ~ Rate x Mass/event x 10 Gyr
(5000Msun for A>90)



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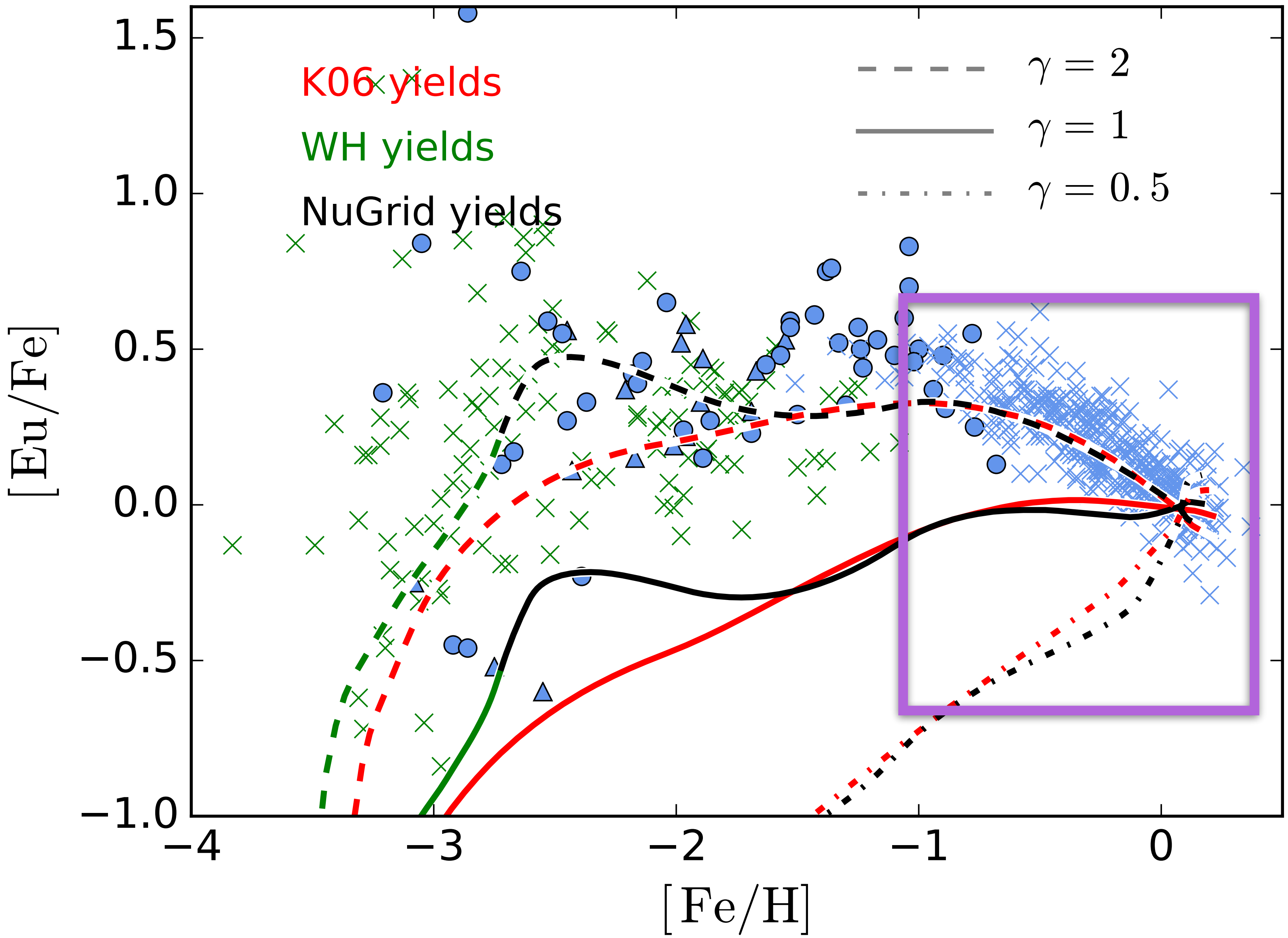
A problem on r-production history of the MW

1 zone model

Cote+ 17



$$\frac{\#\text{r-process event}}{\#\text{ccSNe + SNe Ia}}$$

Delay time distribution ~ $\Delta t^{-\gamma}$,

but 1540^{+3200}_{-1220} Gpc^{-3} yr^{-1} with Δt ~ 1 - 10Gyr

Heating rate

R-process heating rate: $Q \sim t^{-1.3}$

(Metzger et al 10, Goriely et al 11, Roberts et al 11, Korobkin et al 12

The original Li & Paczinski:
Many (β-unstable) nuclear spices => $dN/dt \sim 1/t$ => $Q \sim f/t$

Lifetime (decay probability) of beta decay:
phase space volume of e^- and $\nu \sim p_e^3\, p_\nu^3$ + energy conservation

A correction is needed:

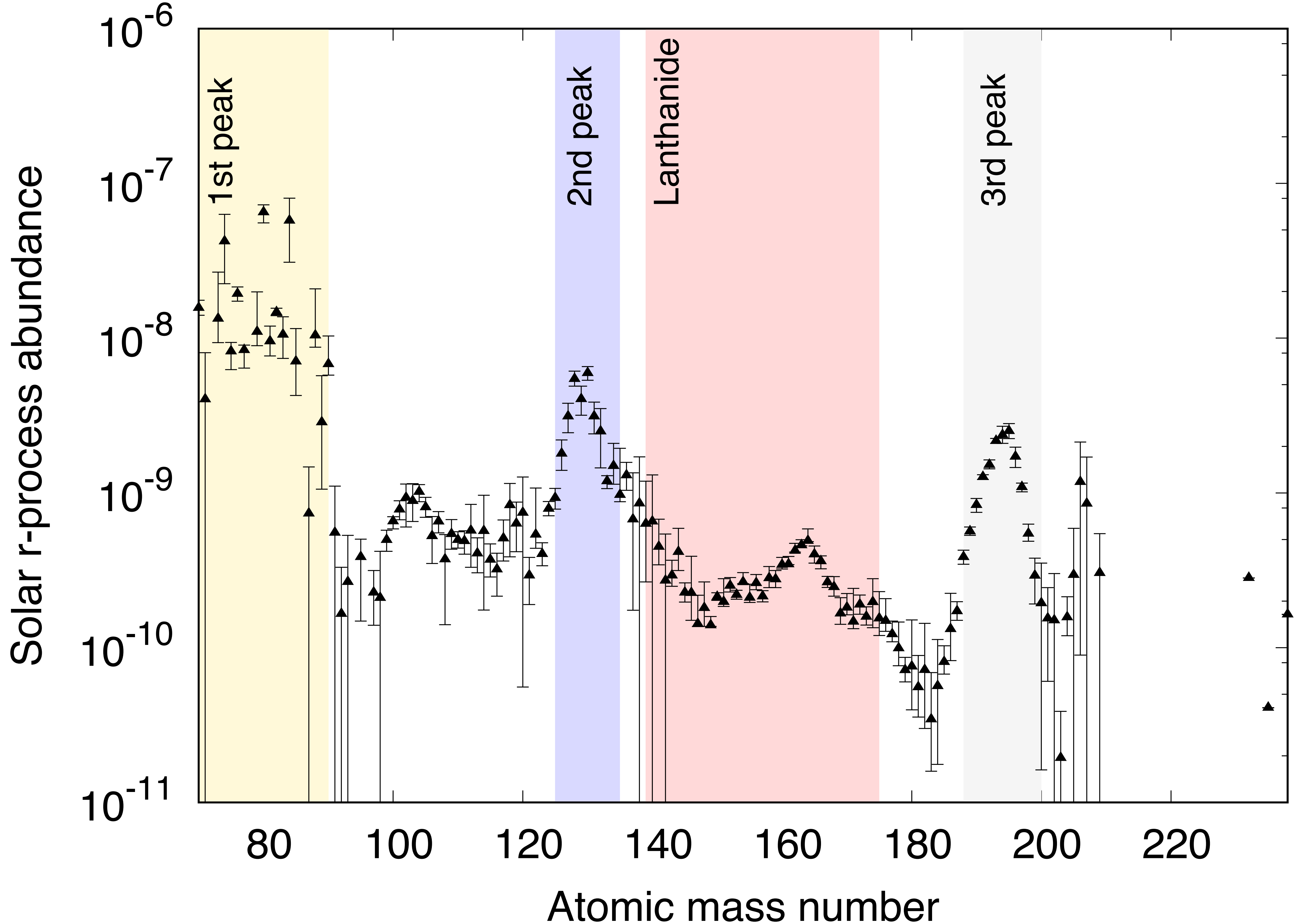
Lifetime $\sim E^{-5}$ ($E>m_e$) => $Q \sim t^{-1.2}$

$\sim E^{-3.5}$ ($E<m_e$) => $Q \sim t^{-1.29}$

$\sim E^{-3}$ ($Z\alpha>\beta^2$) => $Q \sim t^{-1.33}$

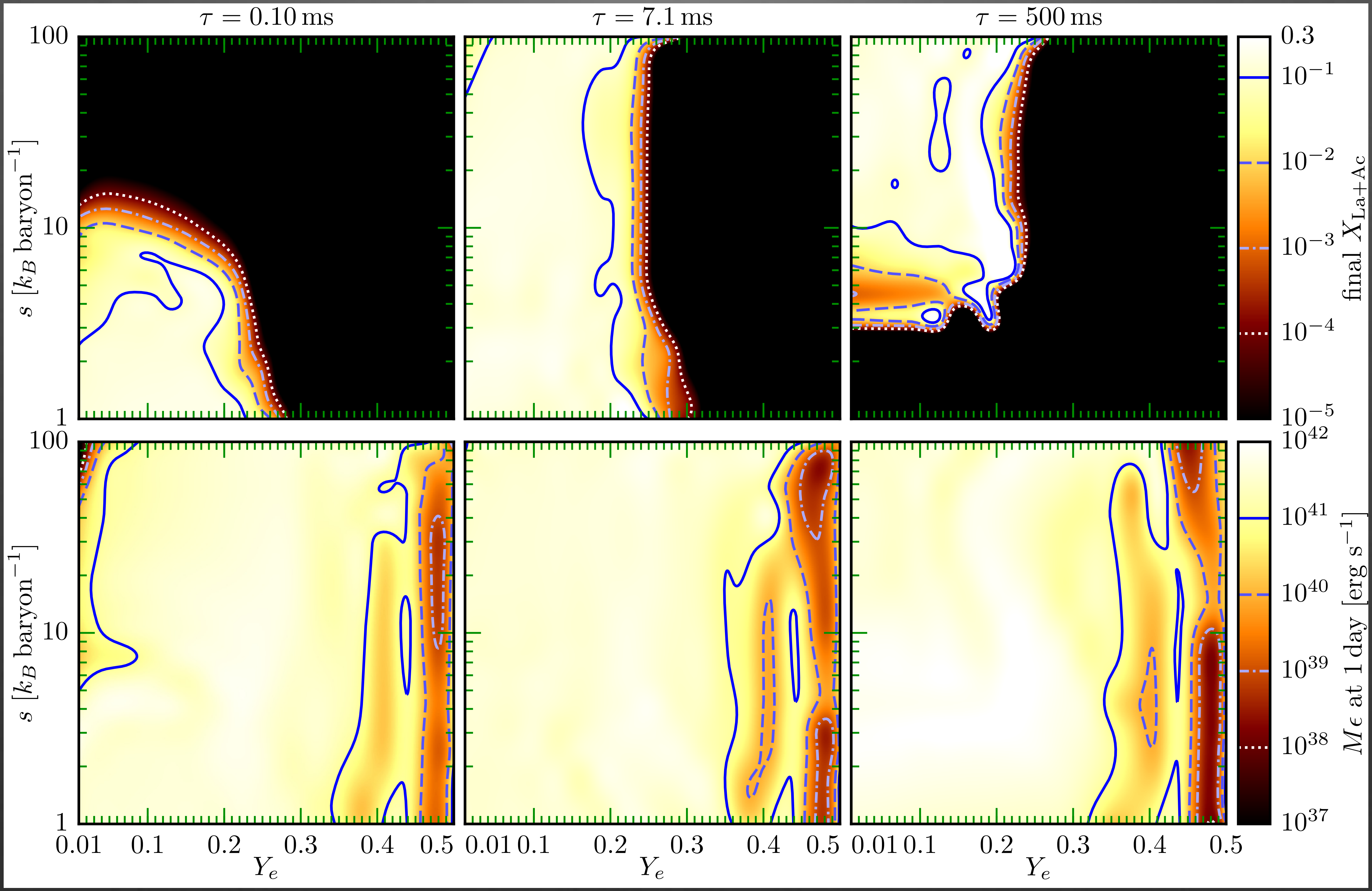
KH, Sari, Piran 17

Solar r-process abundance

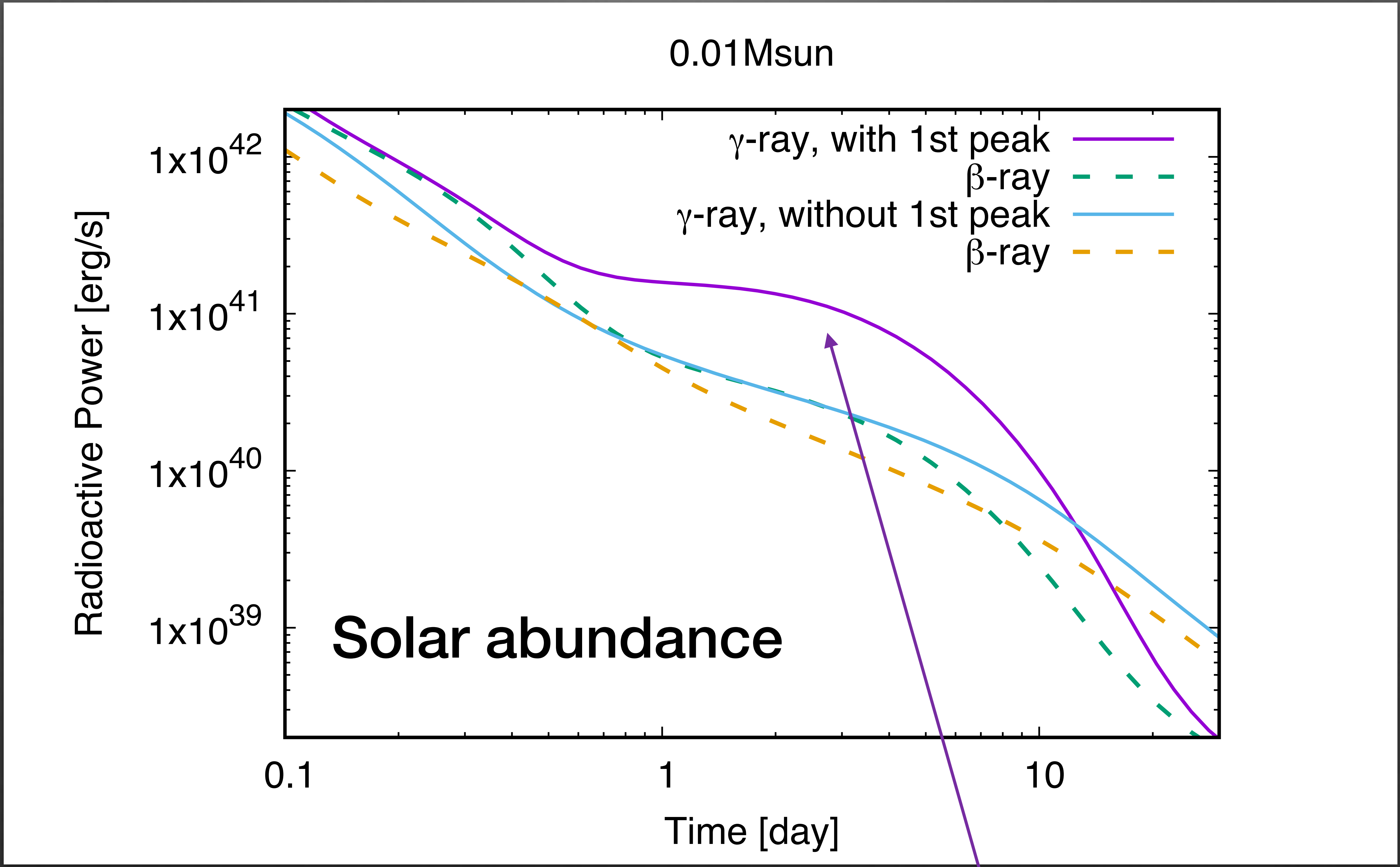


Heating rate & Composition

Lippuner & Roberts 15



Caveat: Heating rate depends on the composition



^{72}Zn ($t_{1/2}$=46.5h) -> ^{72}Ga ($t_{1/2}$=14.1h) -> ^{72}Ge

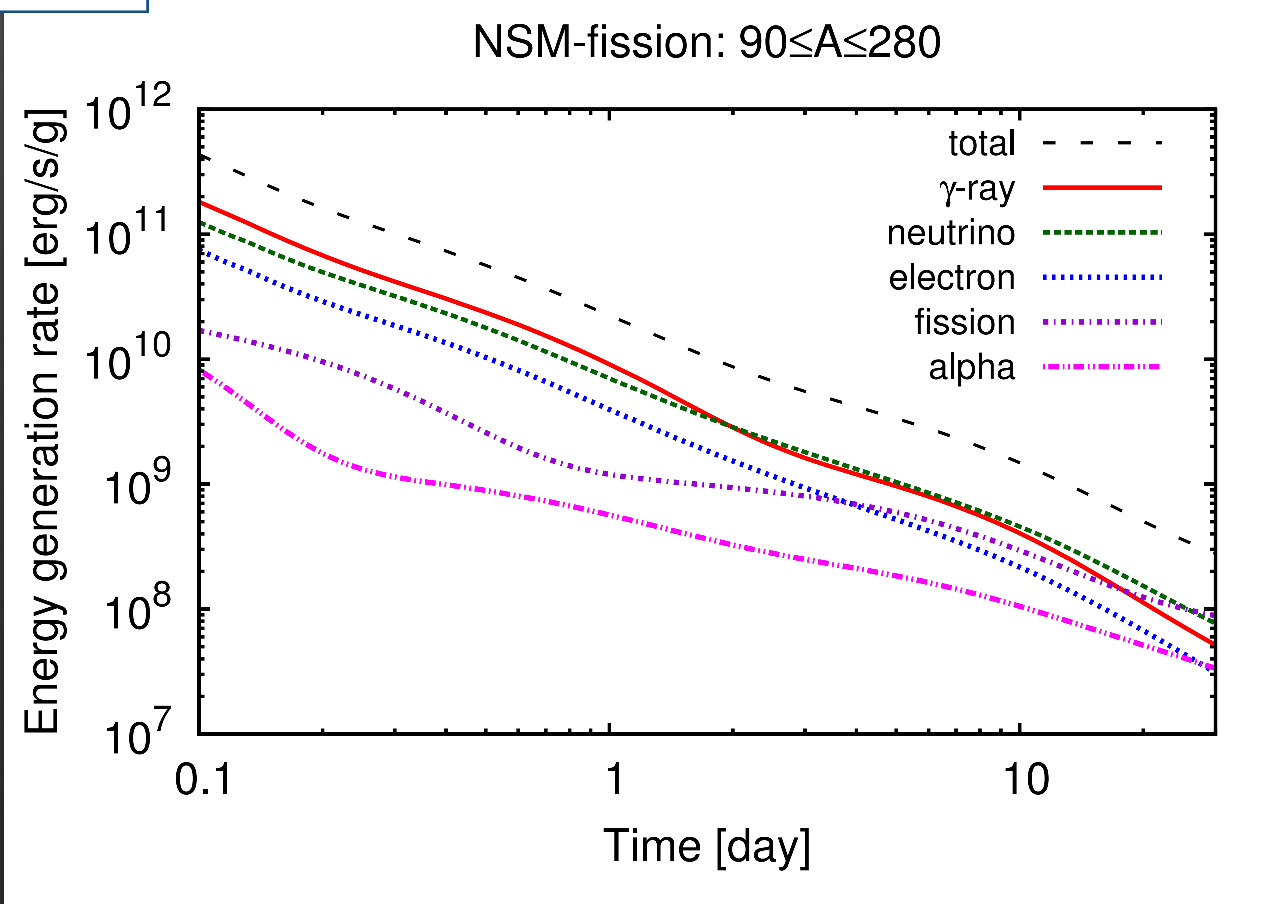
Decay products: Transuranium elements

type	MeV/decay	ε_{th} (1week)	comment
α	~5	~0.5	A>~200
β	~1	~0.5	-
γ	~1	<0.1	-
ν	~1	0	-
fission	~100	~0.8	A>~230

- alpha decay and spontaneous fission may be important.

  KH+16, Barnes+16, Wollaeger +17

- Given inefficient heating of gamma rays and Electrons, and uncertainties in alpha, fission, We should use the early light curve to estimate The ejecta mass.



Summary

- The amount, X_{lan}, and rate inferred from GW170817 suggest that neutron star mergers have produced the solar abundance r-process elements for stars in the Milky Way disk. (including the 1st peak)

    What does X_{lan} really mean ?
    Can be some lanthanides hidden in slow ejecta?

- These are consistent with dwarfs and ^{244}Pu measurements.

- X_{lan} of r-rich extreme metal poor stars fluctuates.

- The heating rate of the material $X_{lan} << 0.1$ may different from a widely used one 1.0e10 erg/s/g $(t/day)^{-1.3}$.