Constraints on the contributions of Neutron-Star Mergers and Supernovae to the r-Process

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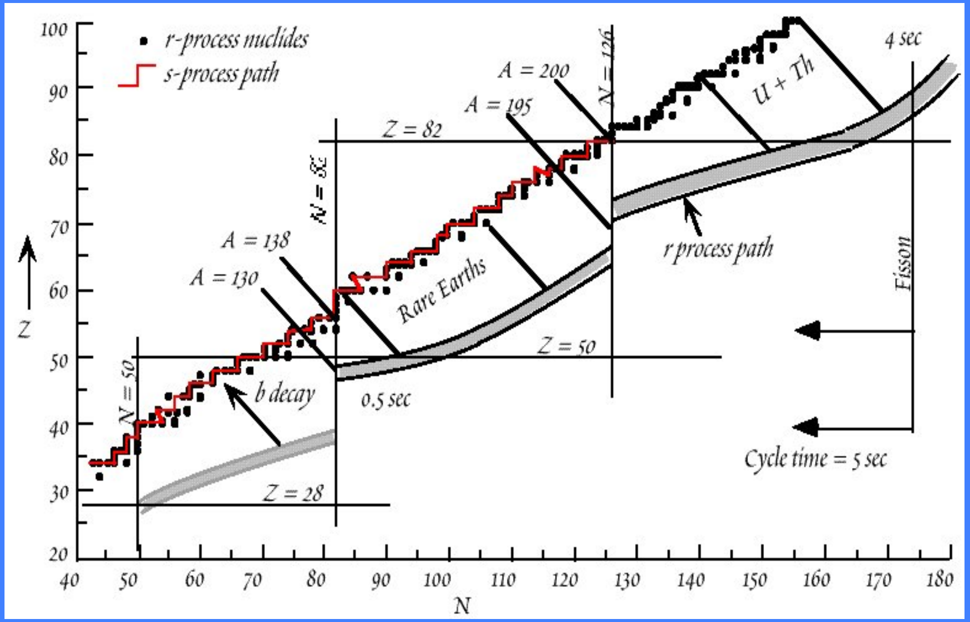
Shibagaki, Kajino, GJM, Chiba, Nishimura, Lorusso
ApJ, 816, 79 (2016)

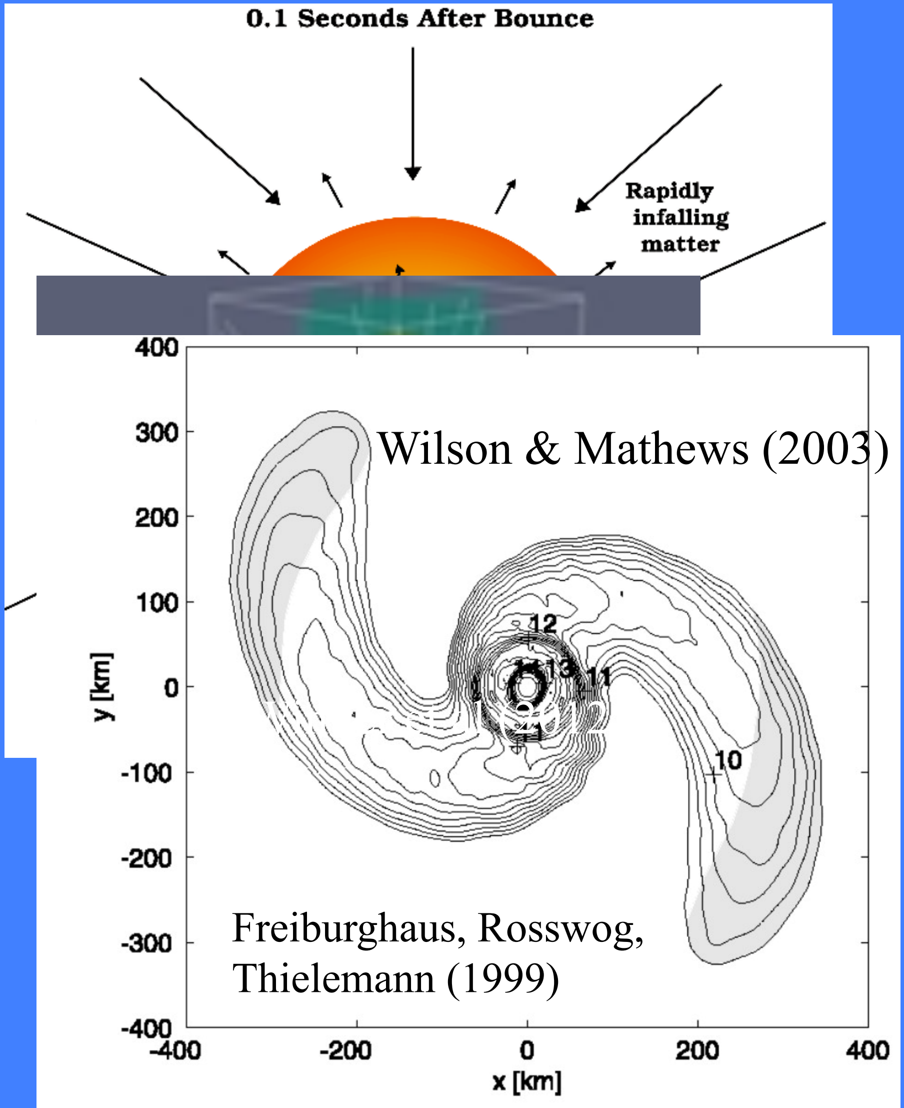
National Institute for Nuclear Theory program
INT 17-2b: *Observational Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers*
August 1, 2017



Which model is the site for the *r*-Process?

Neutrino Driven Winds in the High Entropy Supernova Bubble

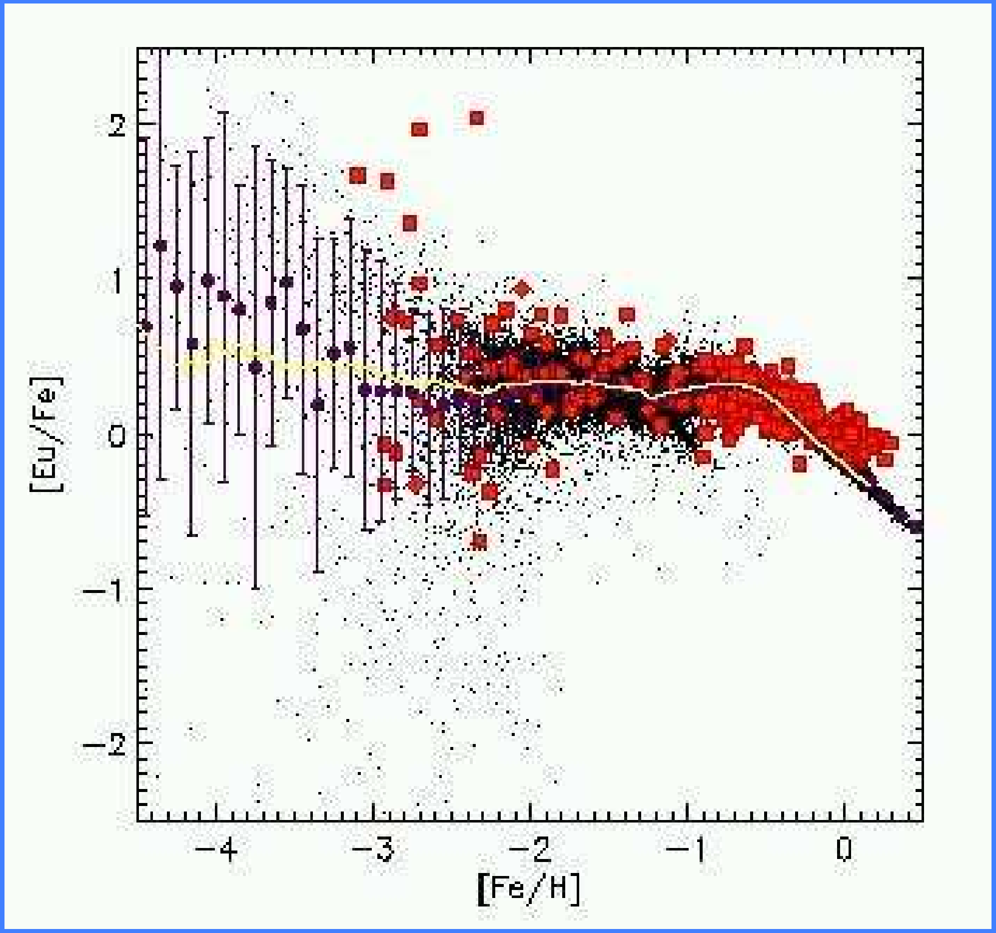
- Ejection of neutronized core material in a low-mass supernovae or MHD jets
- Neutron star mergers



Wilson & Mathews (2003)

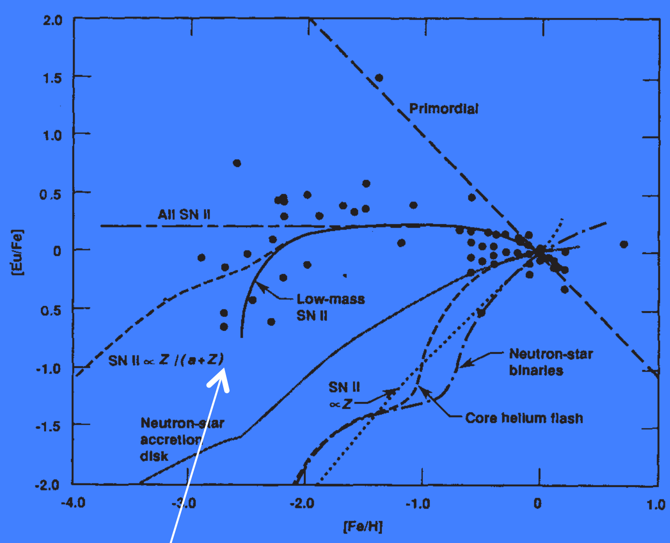
Freiburghaus, Rosswog, Thielemann (1999)

r-process material appears to arrive early consistent with a supernova origin



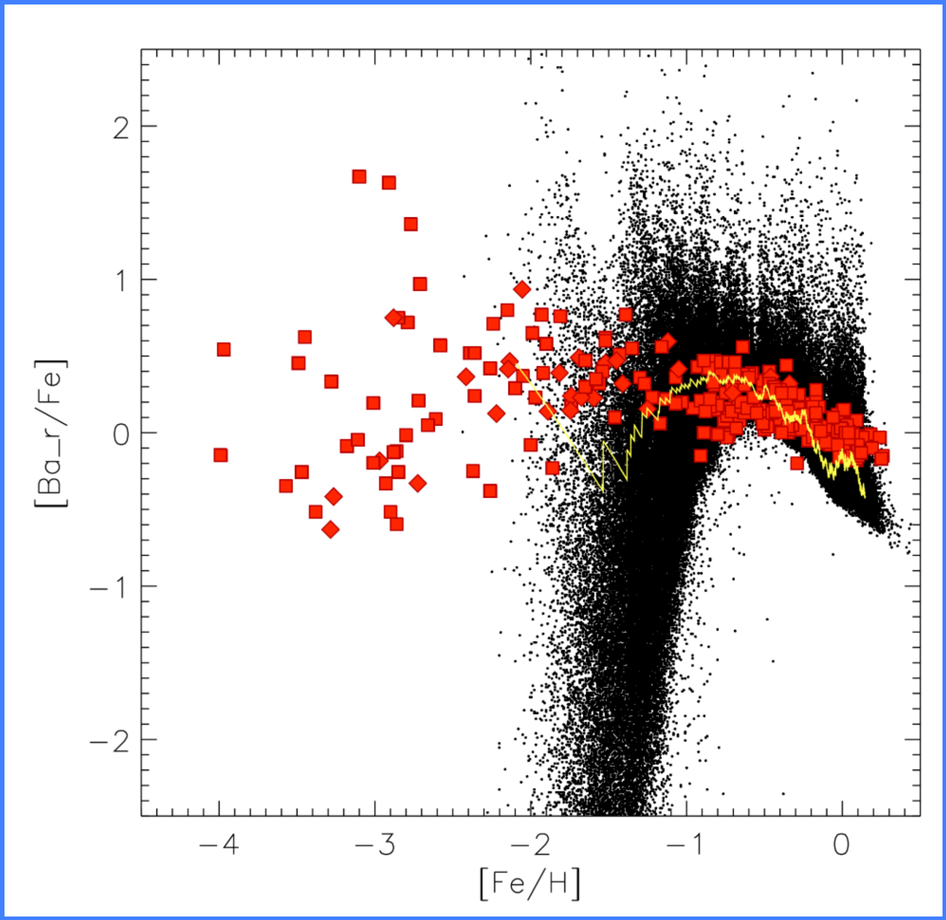
Argast et al. 2004 A&A

Mathews & Cowan, Sci. (1990)



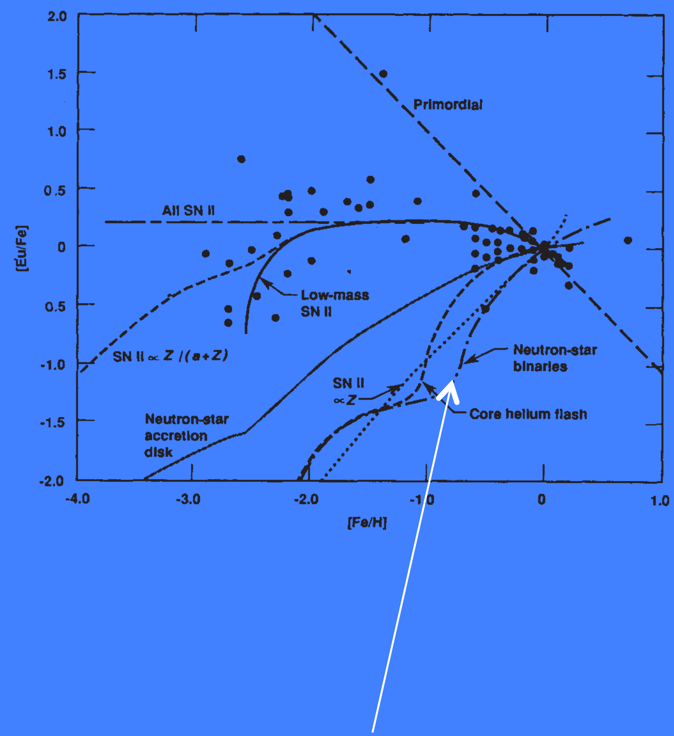
10-11 $M_\odot$ SNe

r-process in neutron star mergers is delayed at low metallicity



Argast et al. 2004 A&A

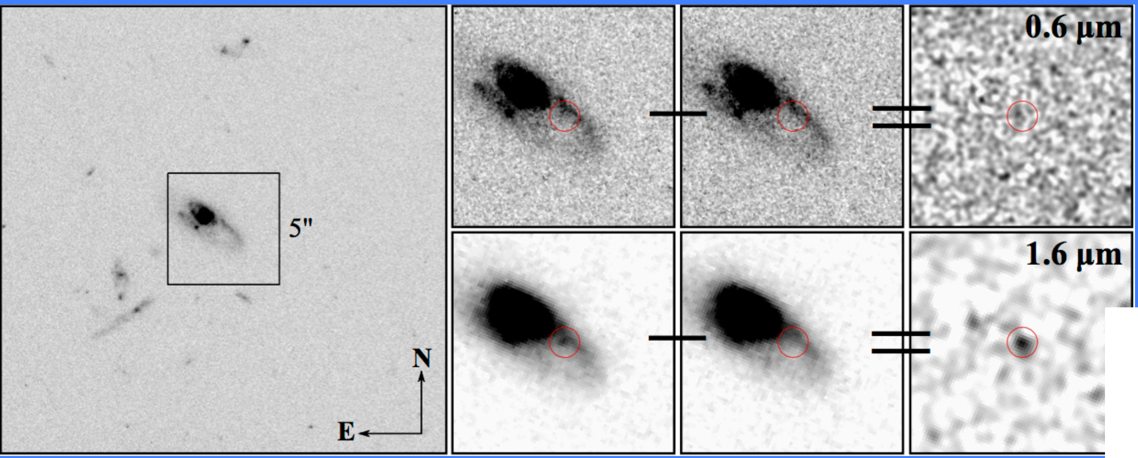
Mathews & Cowan, Sci. (1990)



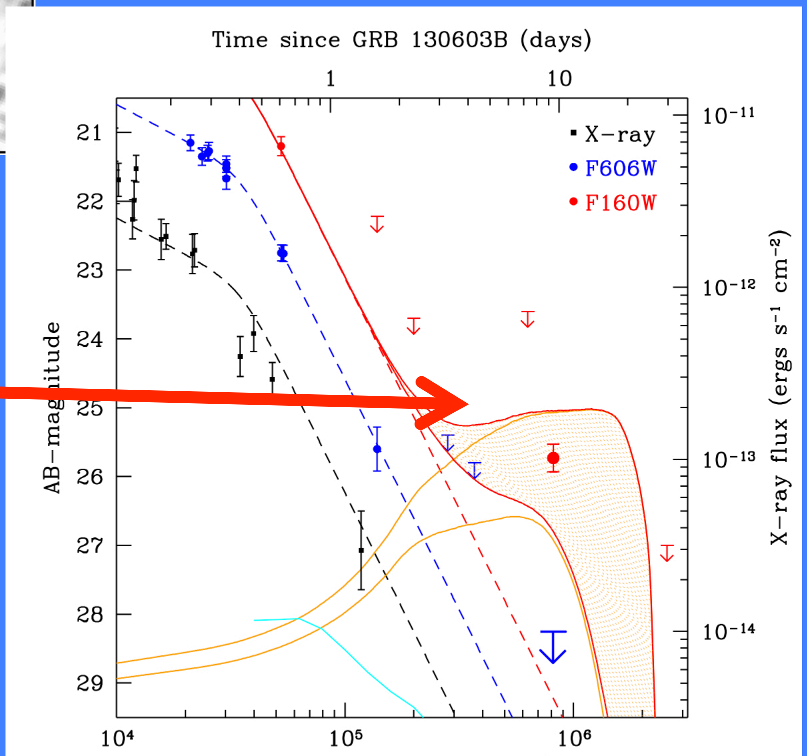
NSM

Evidence of r-Process in Neutron Star Mergers

Short Duration GRBs



The Kilonova

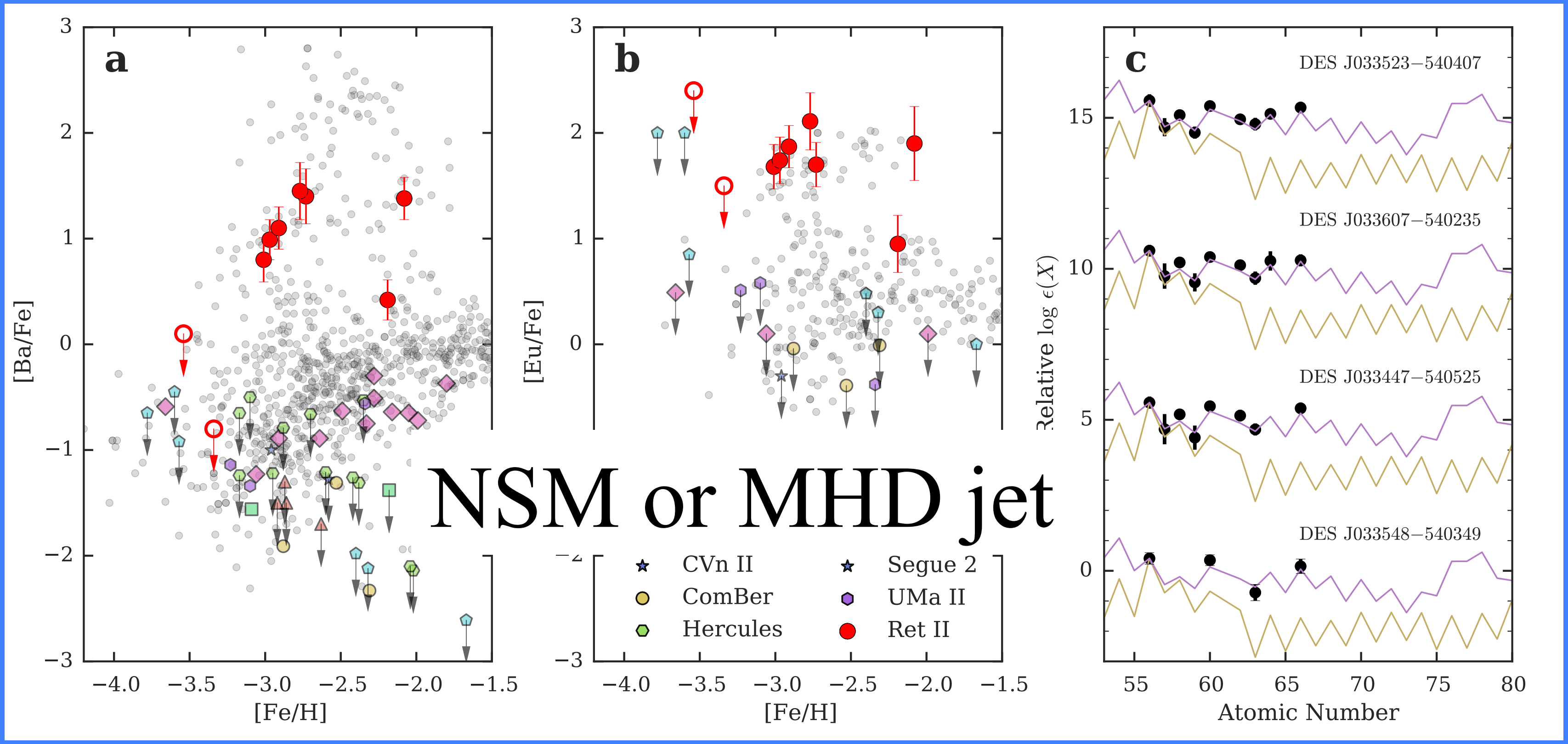


Tanvir, et al Nature (2013)

There is evidence for a rare (~10%) strong r-process contributor that produces the heaviest elements

- Reticulum II Dwarf Galaxy
- Actinide Boost Stars

Evidence of strong (~0.01 M$_\odot$) rare r-process enhancement in Reticulum II Dwarf Galaxy



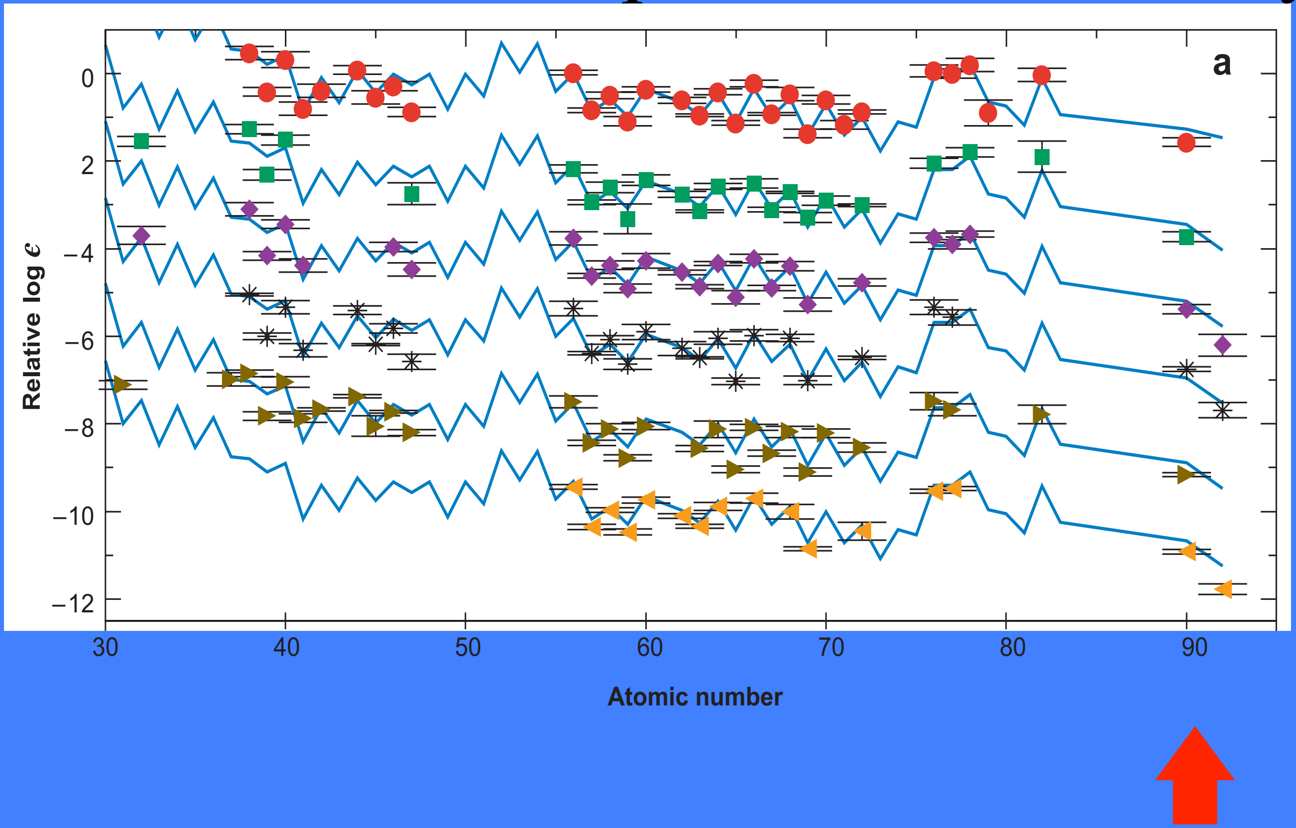
Ji, Frebel, Chiti, Simon, Nature, 531, 610 (2016); ApJ 830, 93 (2016)
Roderer et al. ApJ (2016)

1 out of 10 Dwarf galaxies ~10%

Actinide boost stars

Sneden+ 2008

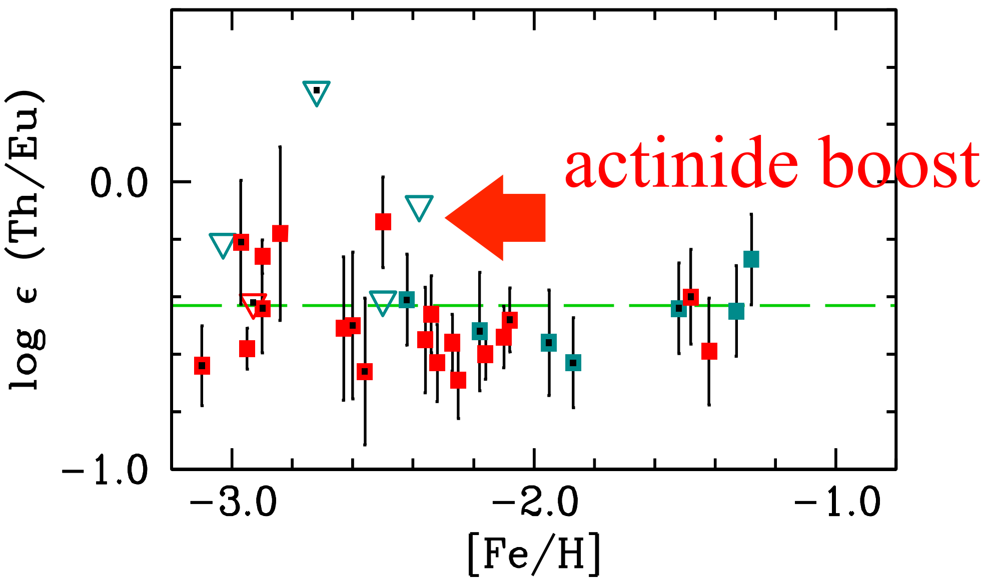
r-process Universality

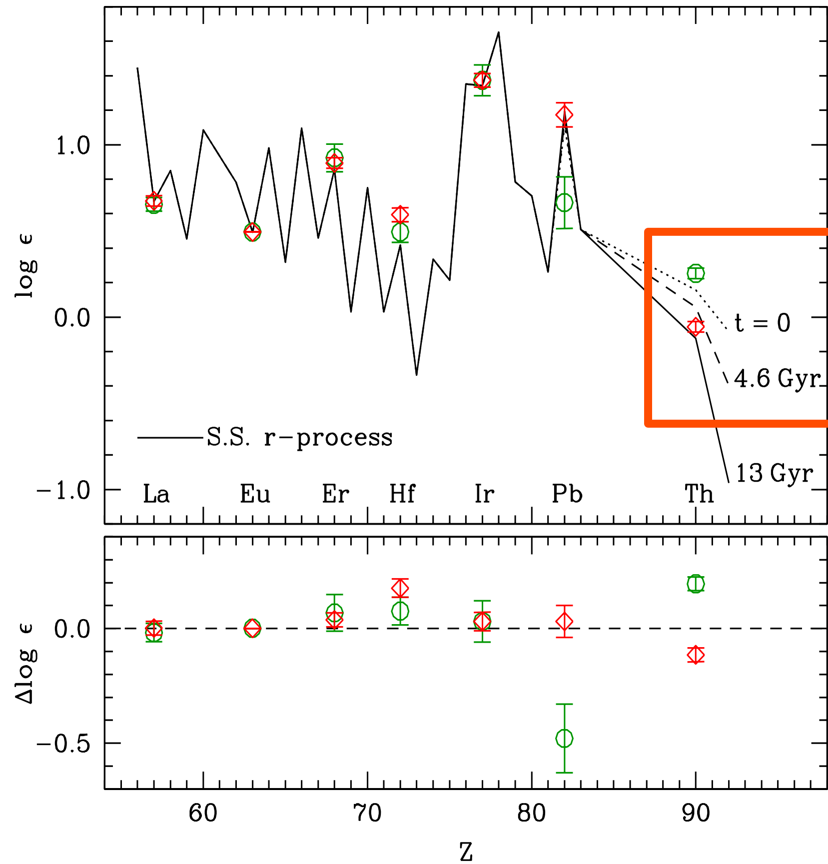


Does the universality hold up to the actinides??

Some MPH stars exhibit a very large Th abundance

Roederer et al. ApJ 698, 1963 (2009)





Can have apparent ages less than 0???

Chronometer Pair	P.R. at Time "zero"	log(P.R.)	"Standard" Stars With log ϵ (La/Eu) < +0.25: Observed Mean (dex)	No. Stars	Age (Gyr)	Age Spread (Gyr)	Stars With Actinide Boost: Observed Mean (dex)	No. Stars	Age (Gyr)	Age Spread (Gyr)
Th/La	0.585	−0.233	−0.67 ± 0.03 (σ=0.10)	16	20.4 ± 4.1	4.7	−0.37 ± 0.03 (σ=0.05)	4	6.4 ± 4.3	2.3
Th/Eu	0.463	−0.334	−0.56 ± 0.03 (σ=0.08)	16	10.6 ± 4.1	3.7	−0.24 ± 0.03 (σ=0.06)	4	−4.4 ± 4.3	2.8
Th/Er	0.236	−0.627	−0.91 ± 0.04 (σ=0.11)	12	13.2 ± 4.3	5.1	−0.66 ± 0.08 (σ=0.17)	4	1.5 ± 5.5	7.9
Th/Hf	0.648	−0.188	−0.61 ± 0.05 (σ=0.13)	8	19.7 ± 4.5	6.1	−0.26 ± 0.06	1	3.4 ± 5.7	...
Th/Ir	0.0677	−1.169	−1.42 ± 0.06 (σ=0.15)	8	11.7 ± 4.8	7.0	−1.12 ± 0.16 (σ=0.18)	2	−2.3 ± 8.8	8.4
Th/Pb	0.111	−0.955	−1.21 ± 0.23 (σ=0.32)	2	> 9.9	11.	−0.43 ± 0.25	1	...	...

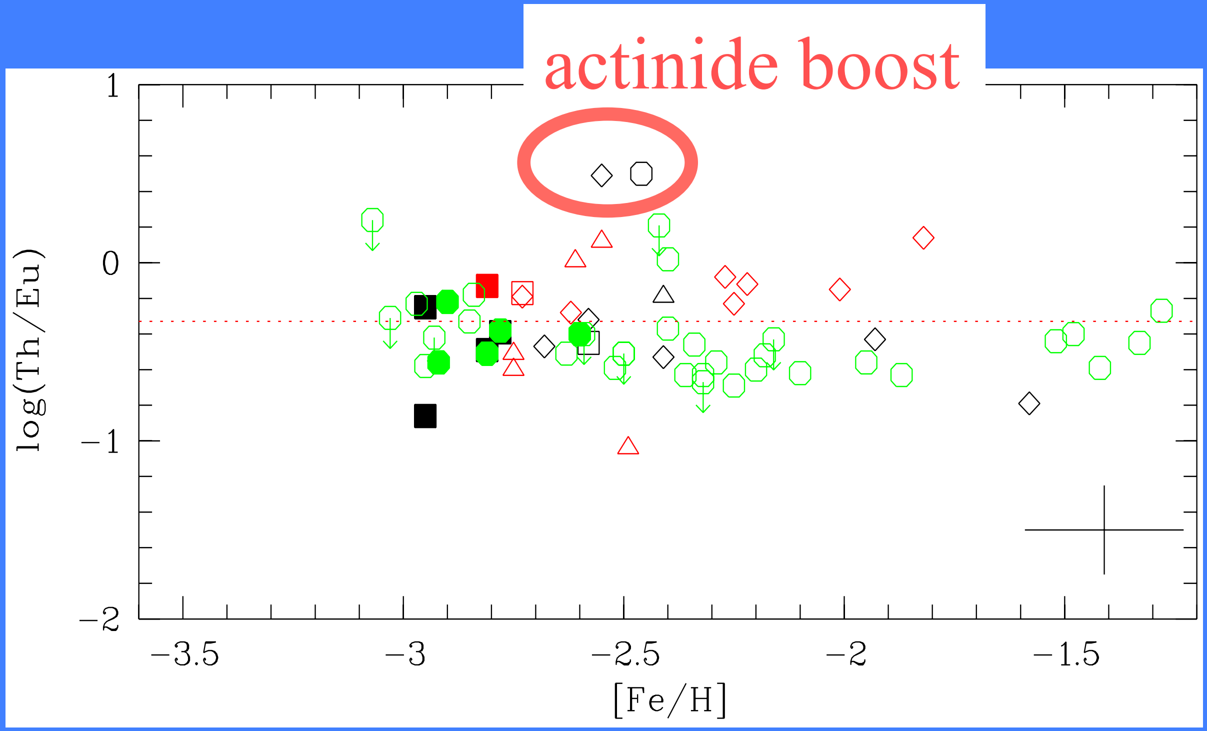
Roederer et al. ApJ 698, 1963 (2009)

Ren et al. A&A 537, A118 (2012)

Hamburg/ESO R-process enhanced star survey (HERES)

Th abundance detected for 17 metal-poor stars

=> ~10% actinite boost stars.



black: detected
red: upper limit
green: literature

Ret-II =>

Ejects a large amount of r-process material

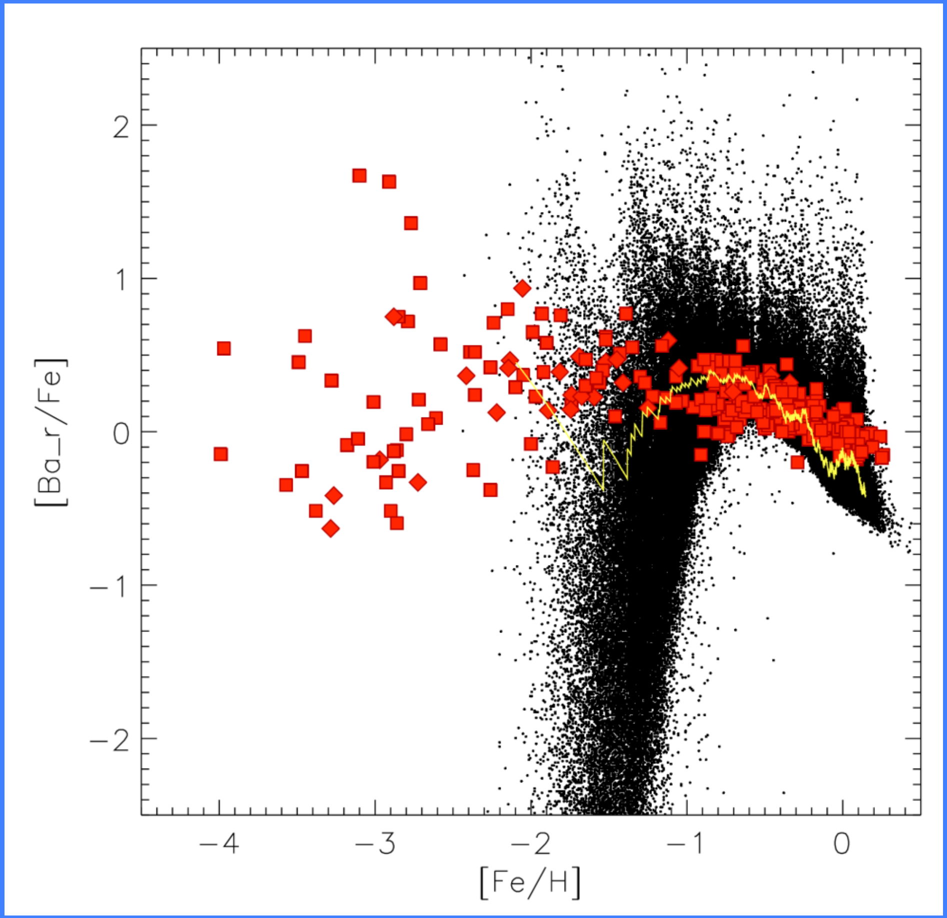
Actinide Boost Stars =>

Rare event (~10%)

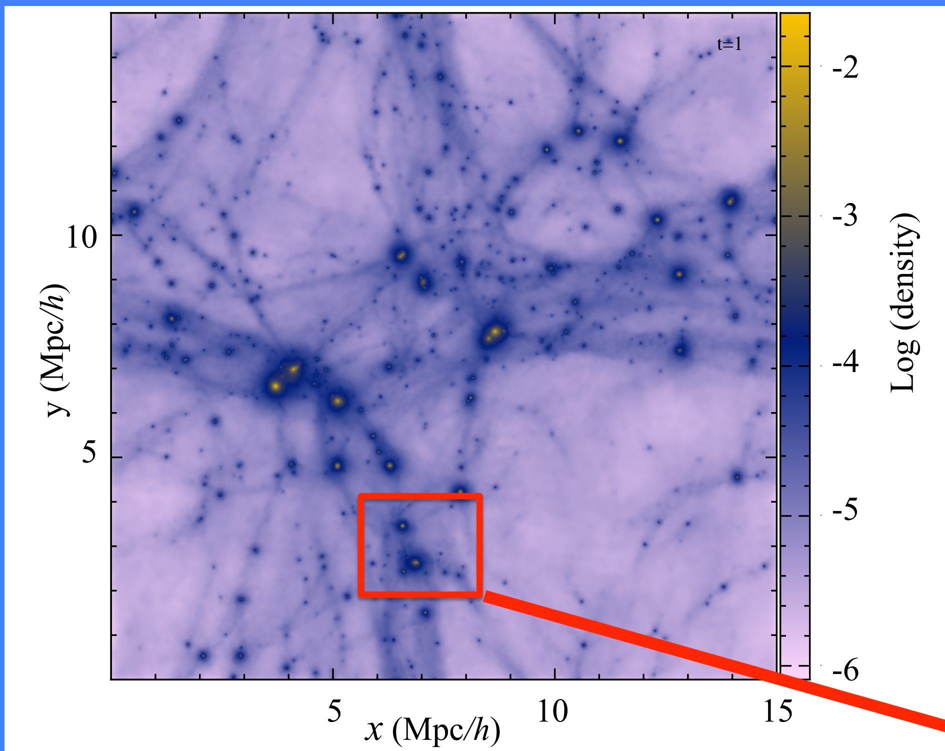
Undergoes fission recycling

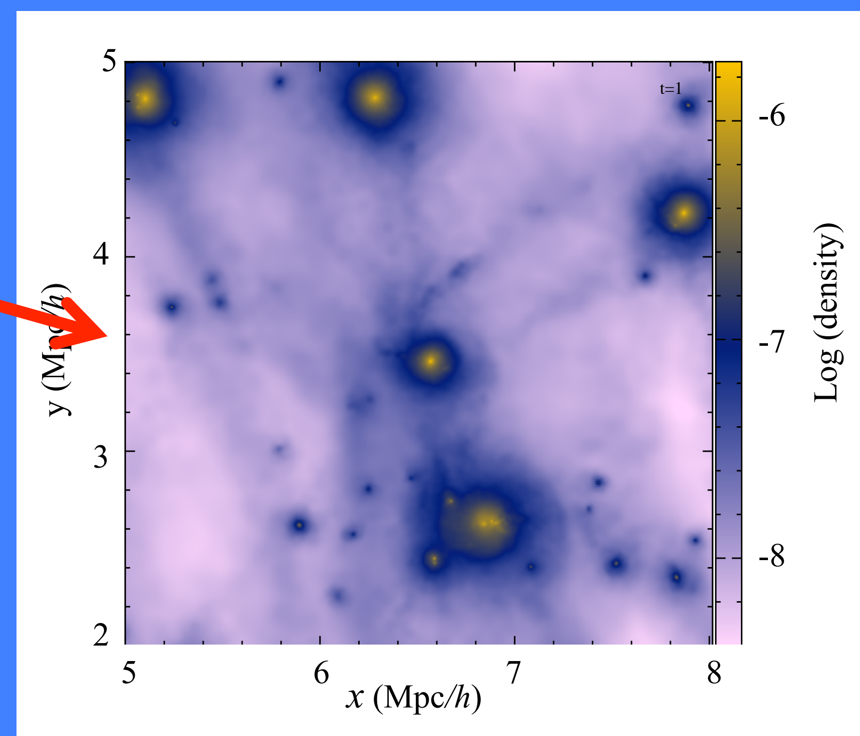
Postulate: These events are the NSMs

How can NSMs appear at low metallicity?



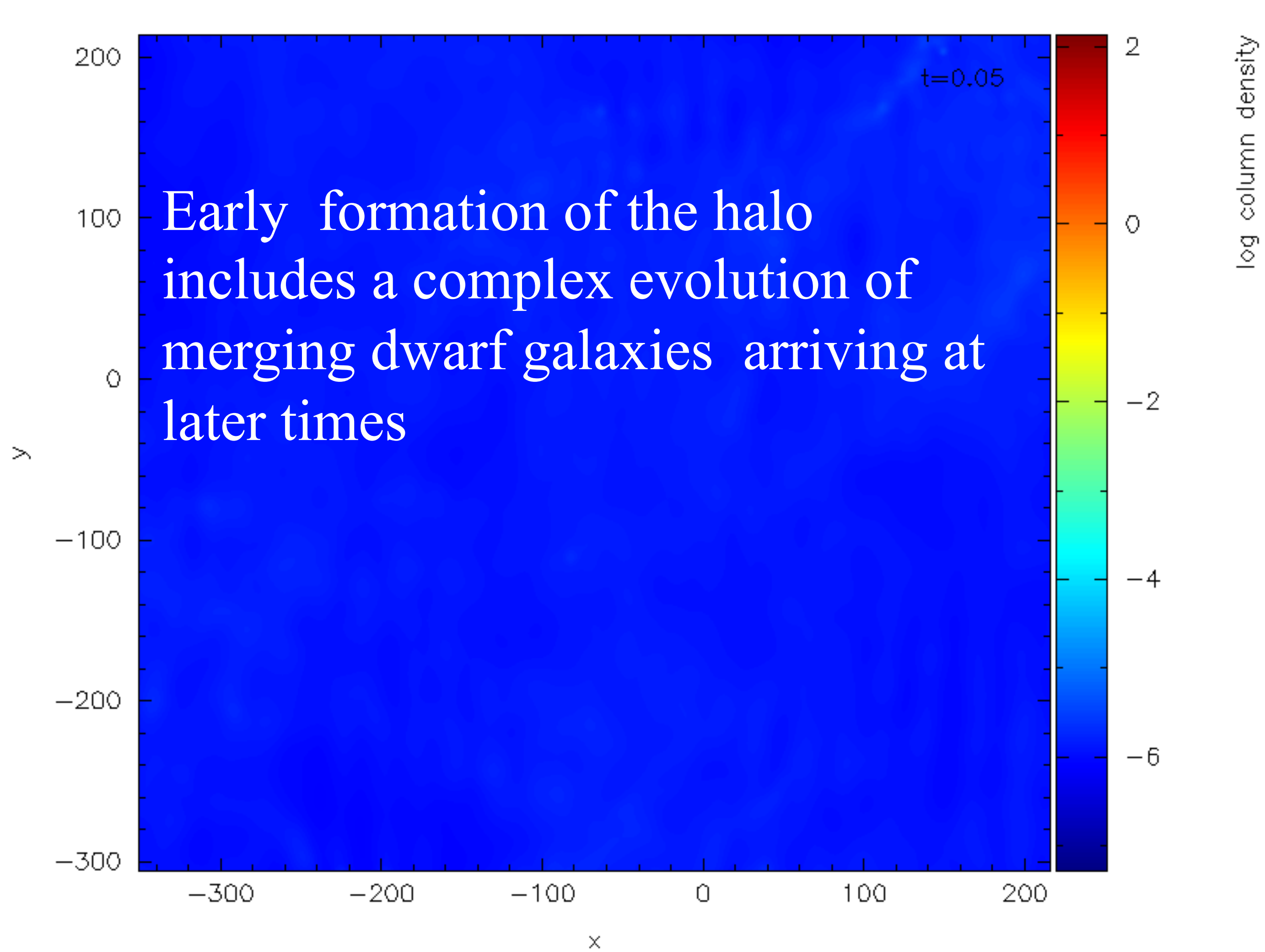
Arrival of r-process material in the halo requires chemo-dynamical modeling of the Local Group





Mathews et al. MPLA (2014)

At least some metal-poor r-process material in the halo arrives via merging of halo dwarf galaxies

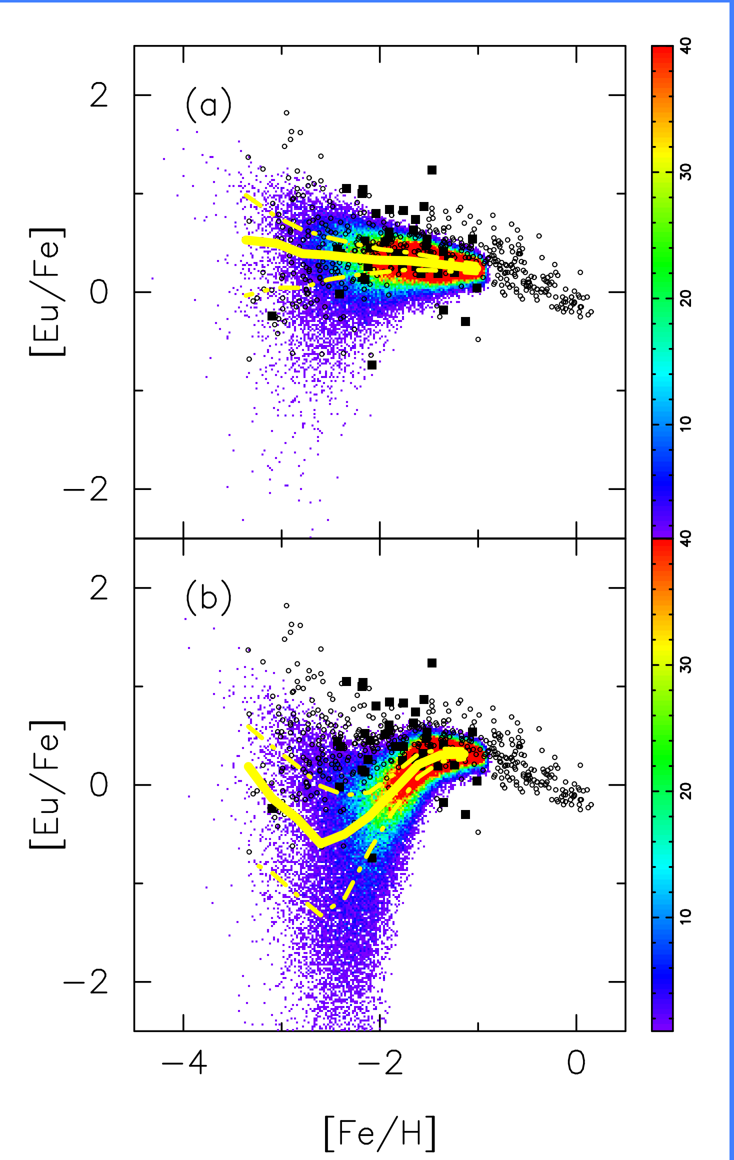


Zhao & Mathews (2012)

Neutron star merger r-process in dwarf galaxies can apper at low metallicity

Hiria, et al. ApJ (2015)

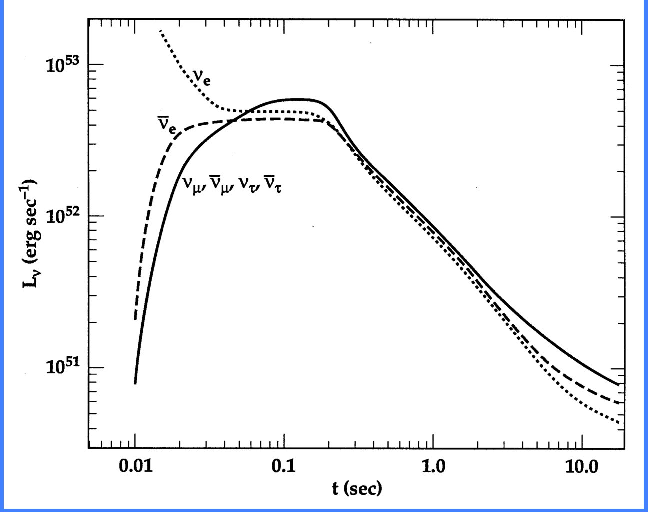
τ(merger) = 10 Myr



In dwarf galaxies, metallicity growth time scale can be much longer
=> Lower metallicity
=> Reticulum II NSM event could have been delayed

τ(merger) = 500 Myr

Problem with the Neutrino Heated Wind r-Process

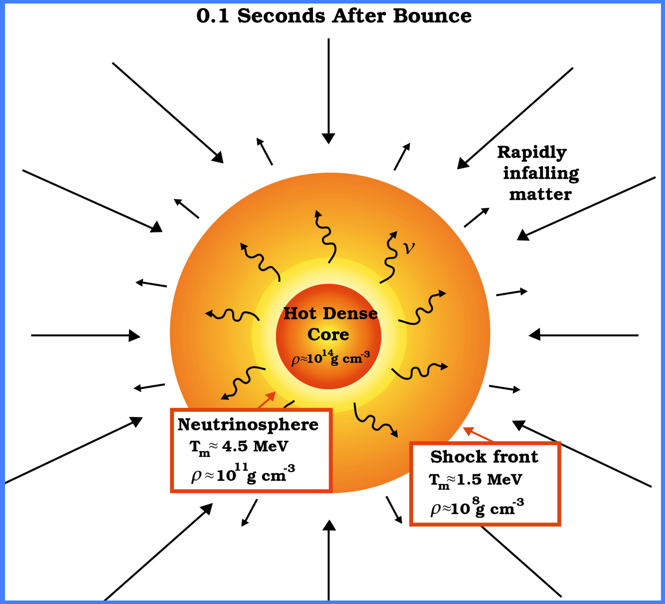


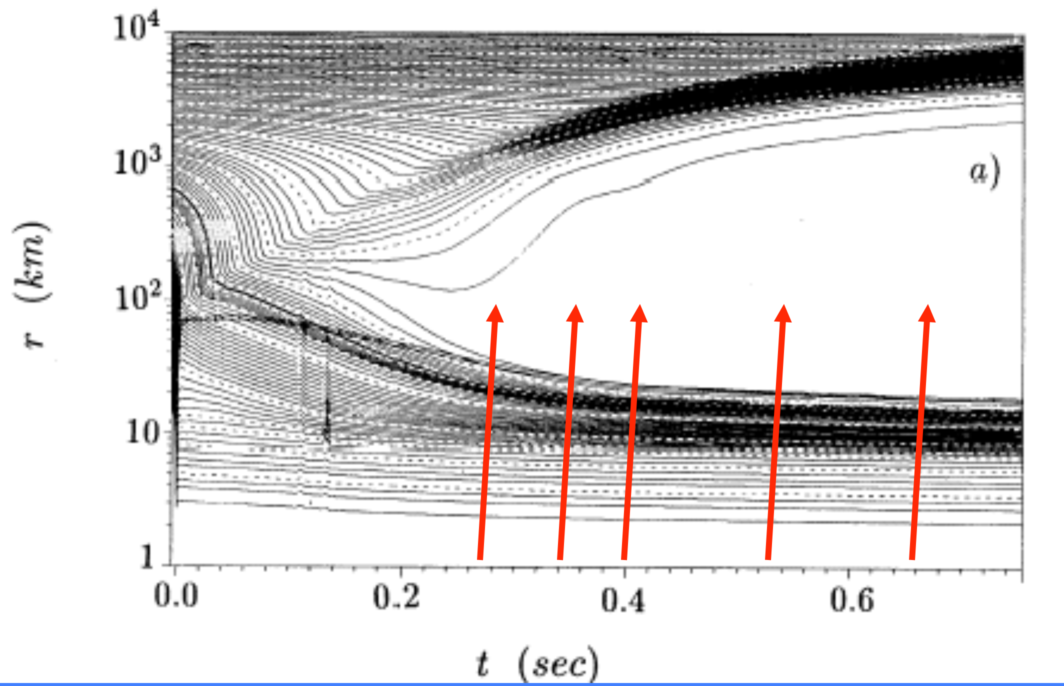
Neutrino Luminosity $\sim 10^{53}$ erg/sec

Neutrino Heating Produces a high entropy bubble

$S = \int dt\ (dQ/dt)/T$

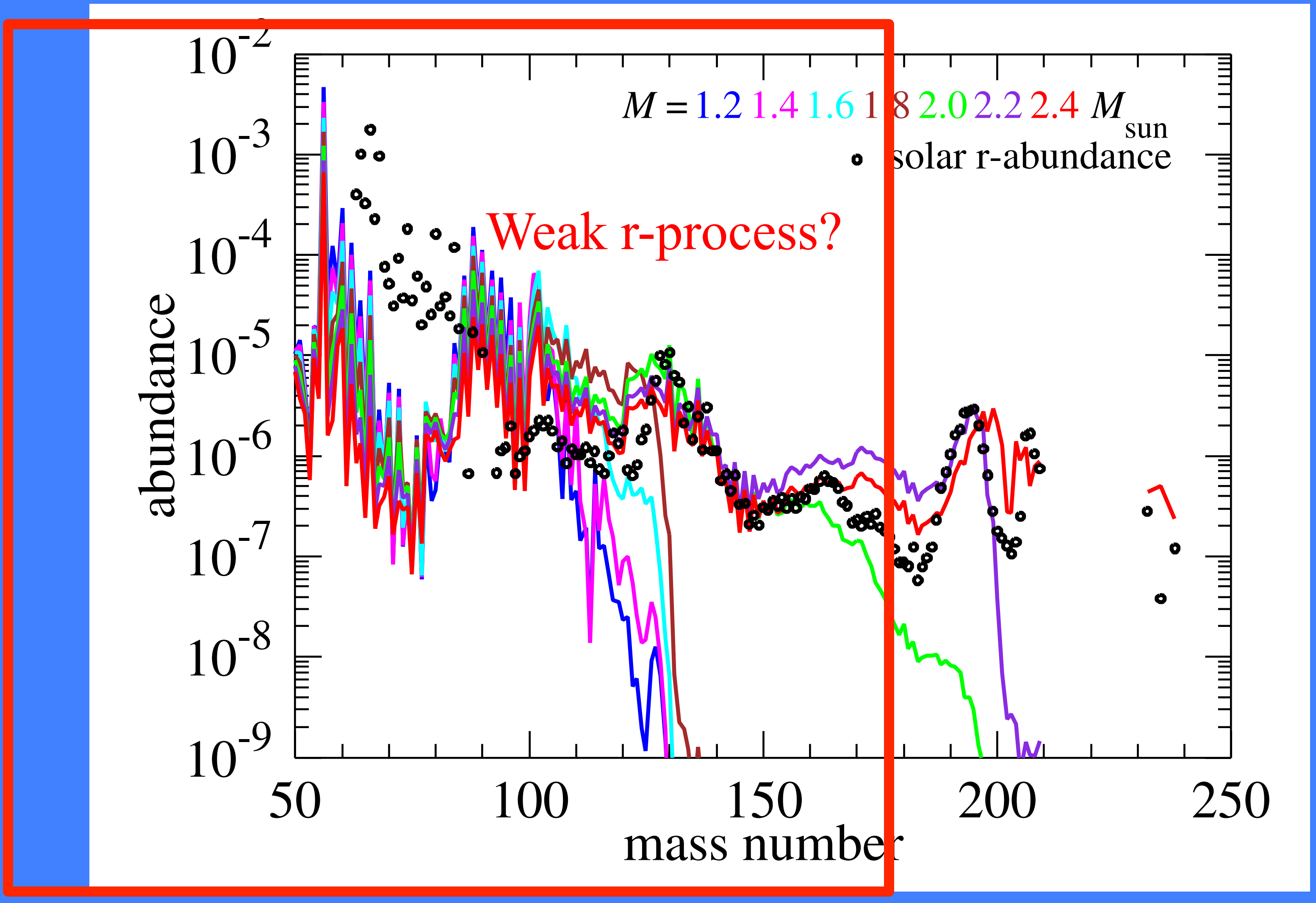
Woosley, GJM, et al.(1994)





Not enough neutrons for the heaviest *r*-process nuclides

S. Wanajo, ApJL, L22 (2013)



Most likely the NDW only produces the light r-process elements

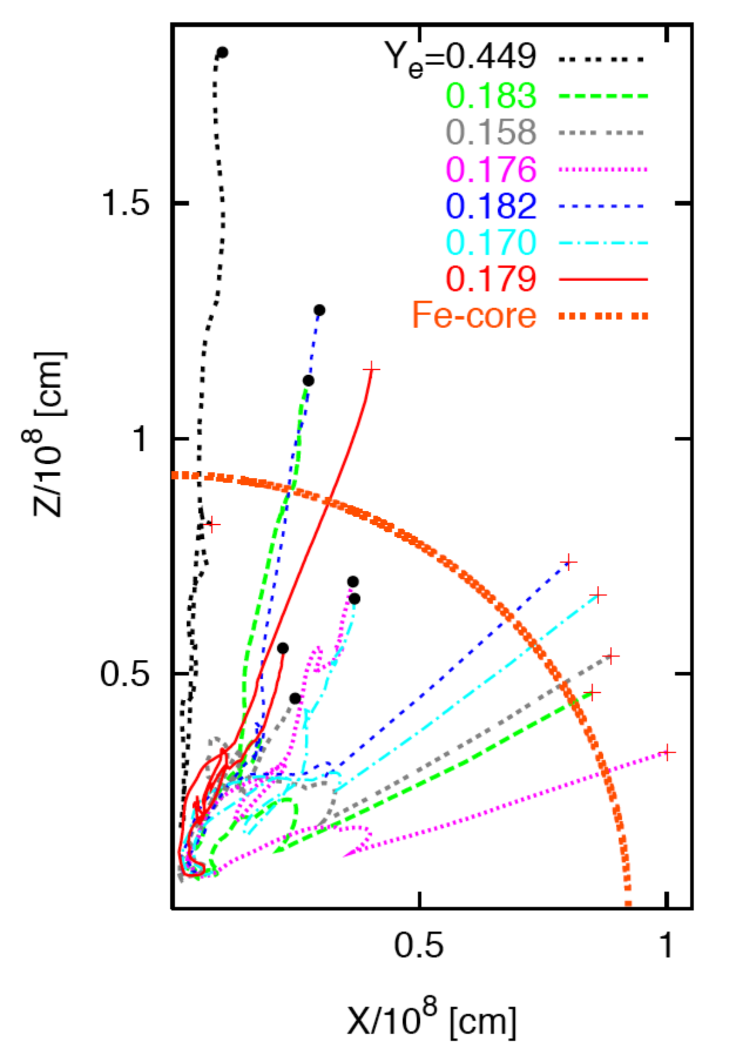
What can make heavier r-process elements?

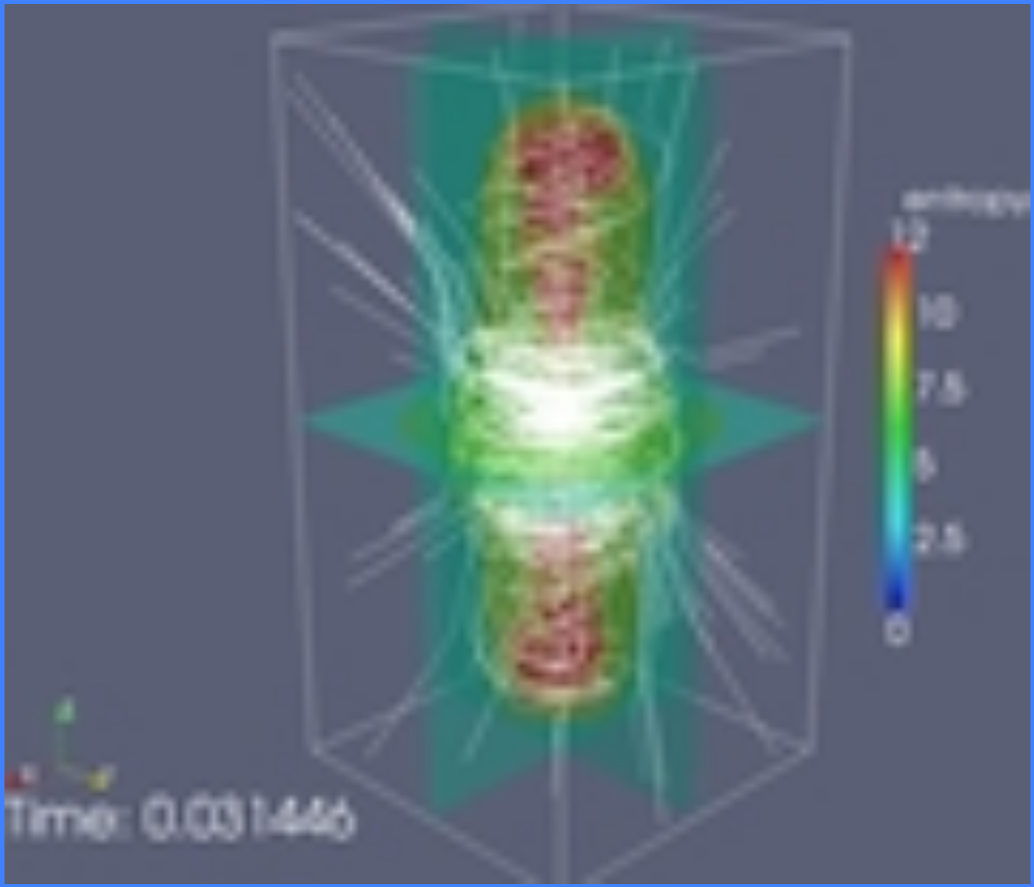
MHD jets?

Neutron star mergers?

MHD Jets from proto neutron stars ?

Nishimura et al (2005-2016)
Winteler et al (2012)
Nakamura et al.(2015)



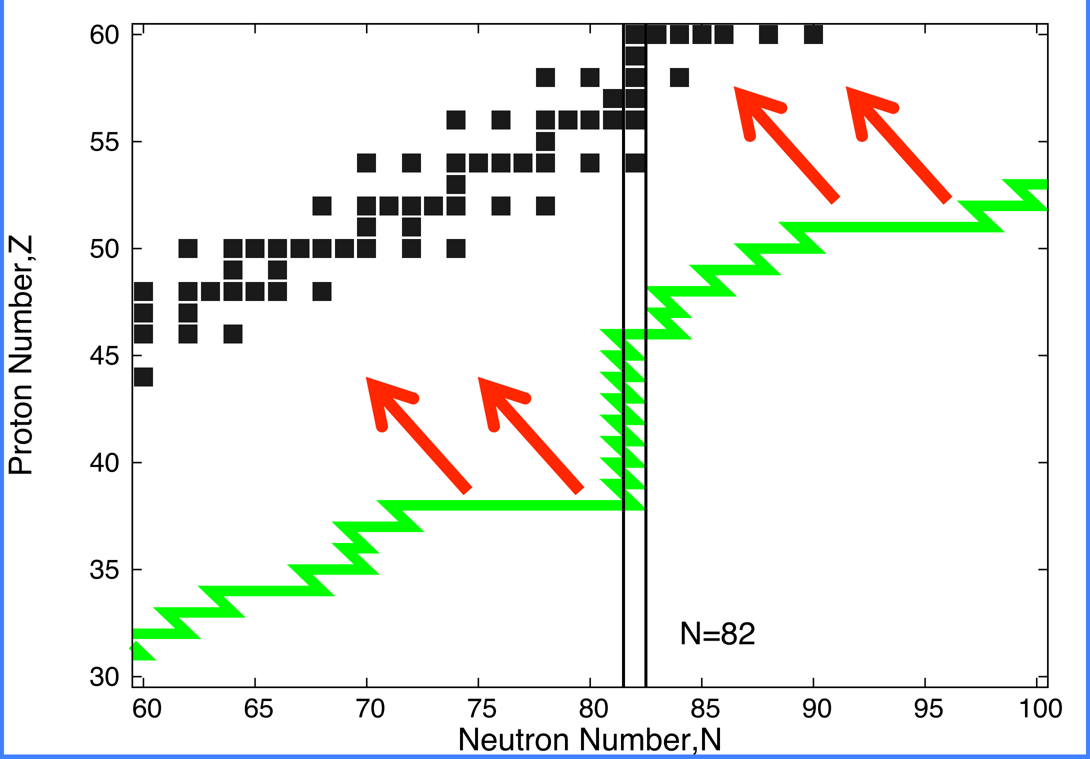


MHD jets are rare

- Small fraction of all SNe ~ 1%
  - High magnetic fields
  - High rotation

This is a general problem with jet models

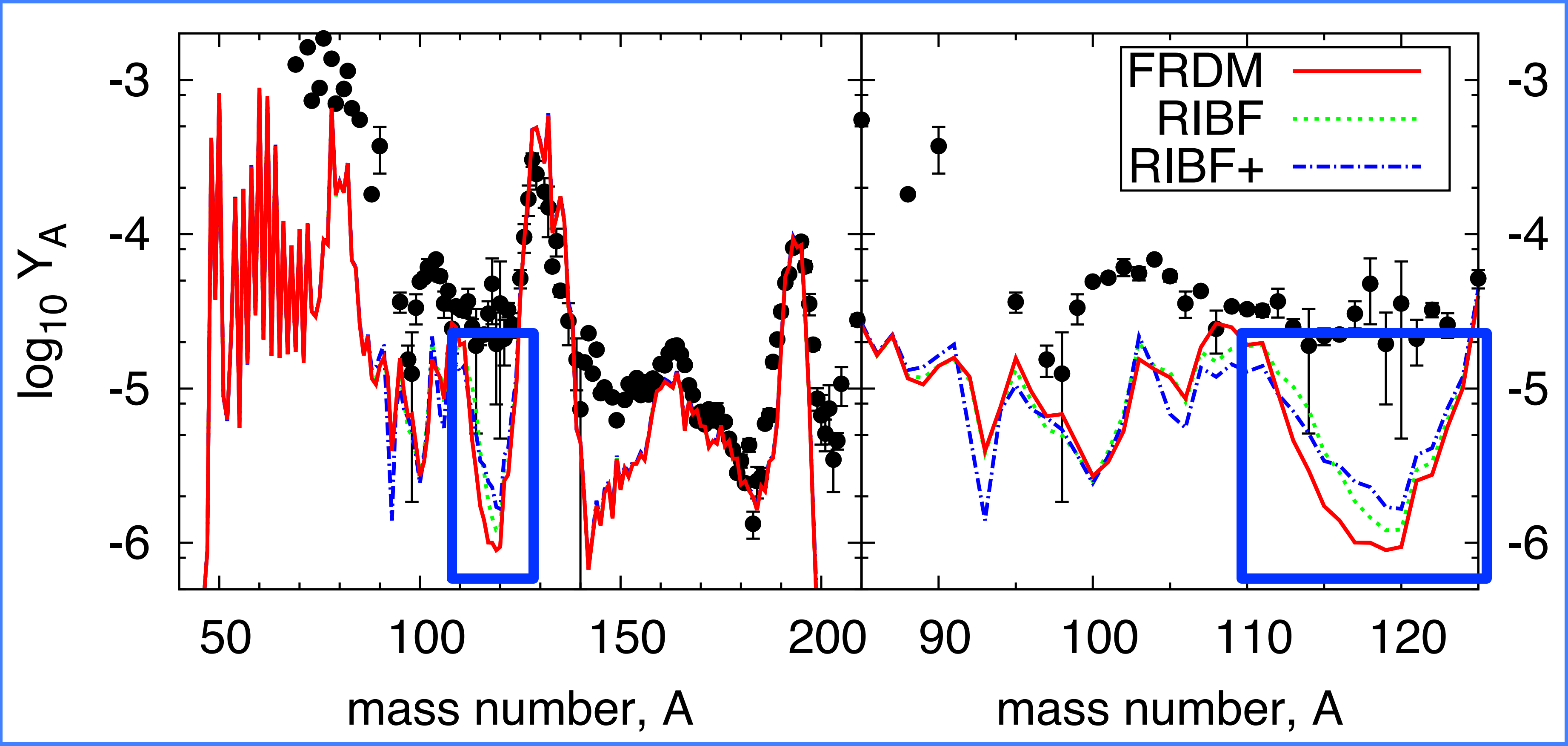
- Short timescale => rapid freezeout
- => bypass isotopes near closed nuclear shells



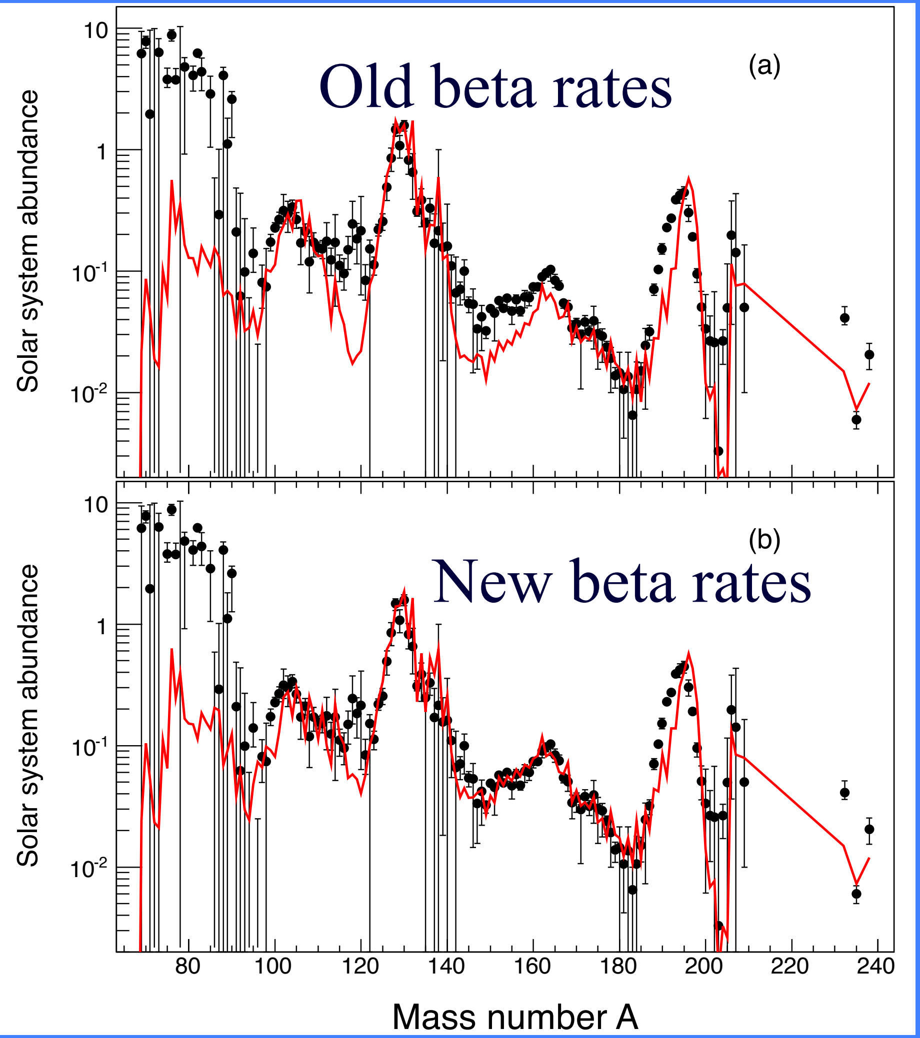
r-procss nucleosynthesis in the supernova MHD jet

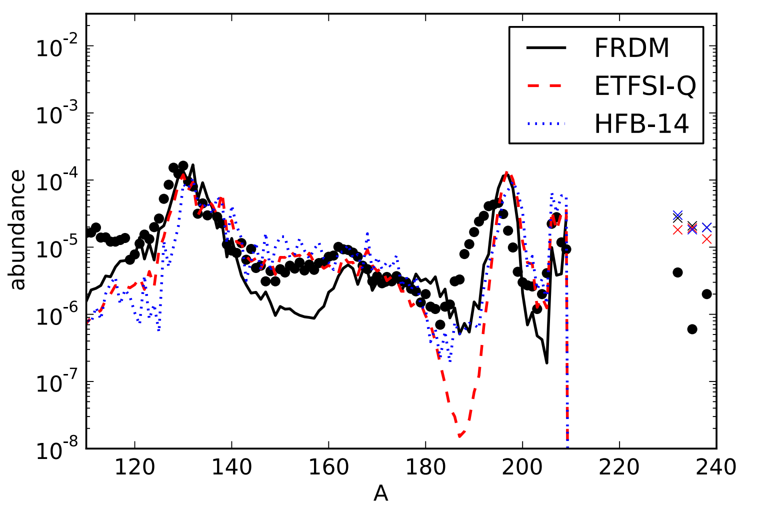
Nishimura, Kajino, GJM, Nishimura, Suzuki (2012) PRC, 85, 048801

38 neutron-rich isotopes including ^{100}Kr, $^{103-105}$Sr, $^{106-108}$Y, $^{108-110}$Zr, ^{111,112}Nb, $^{112-115}$Mo, and ^{116,117}Tc. Measured at RIKEN RIBF



Gaps depend upon ejection time scale ***and beta decay rates***



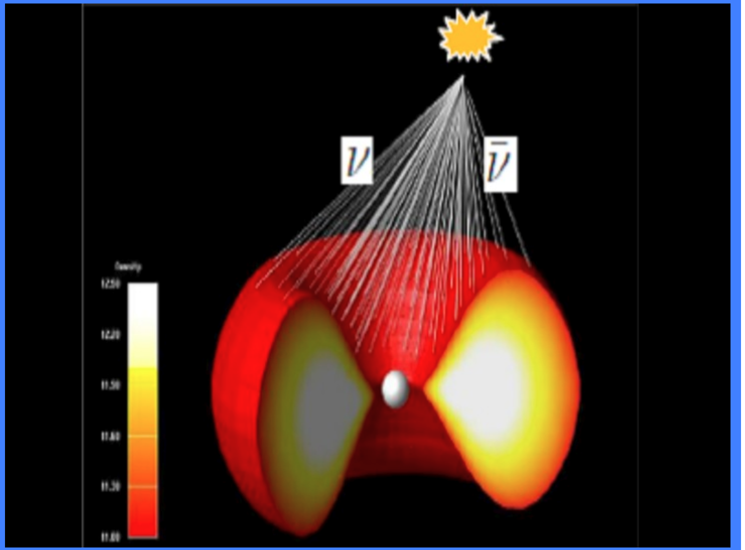


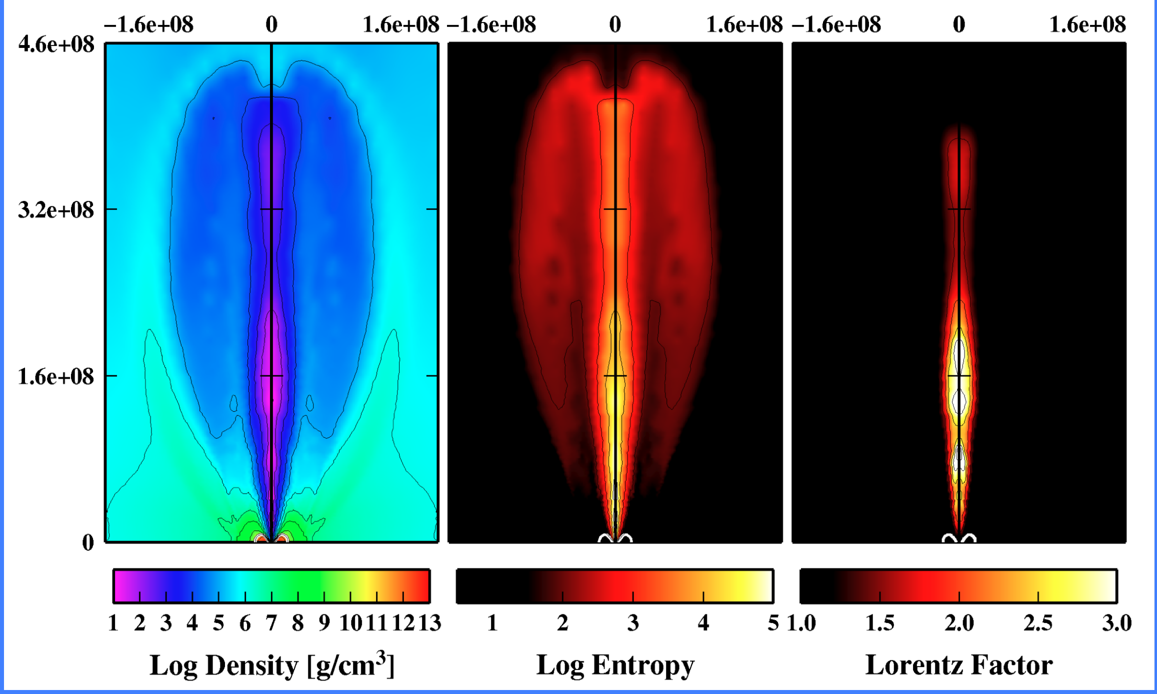
Eichler et al. (2015)

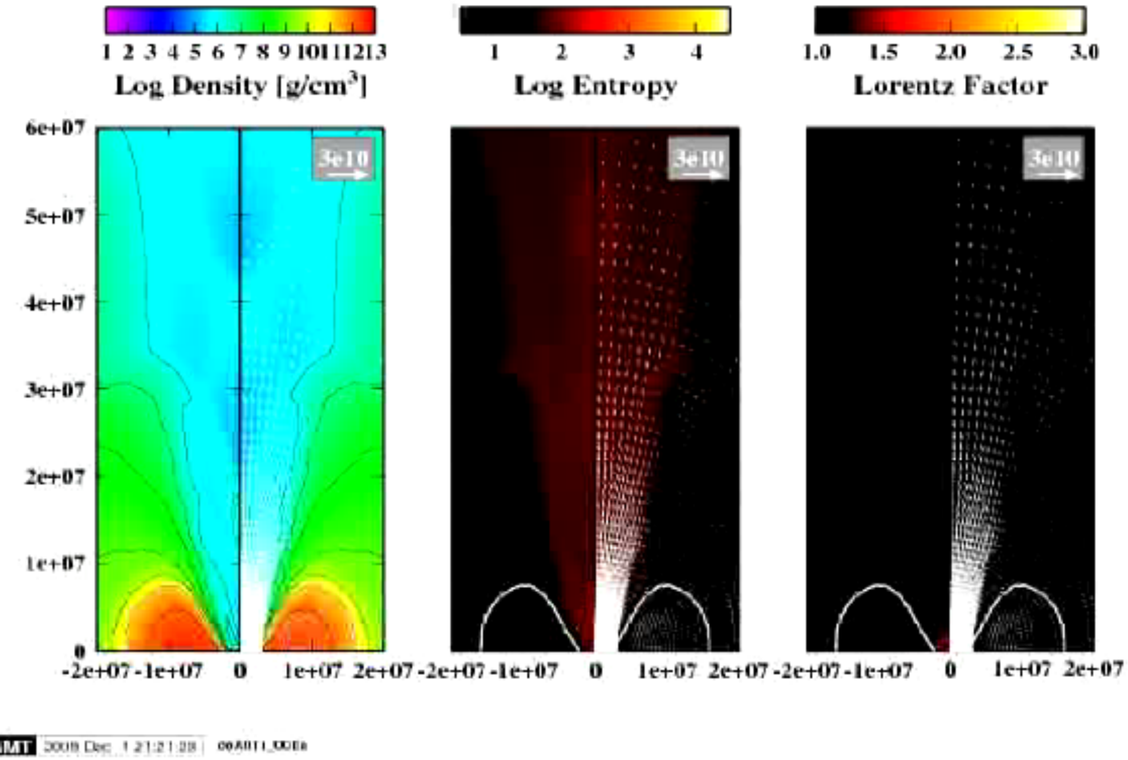
Lorusso et al. (2015)

R-PROCESS NUCLEOSYNTHESIS IN THE MHD+NEUTRINO-PAIR HEATED COLLAPSAR JET

K. Nakamura, S. Sato, S Harikae, T. Kajino and GJM, A&A, 582, 234 (2015)



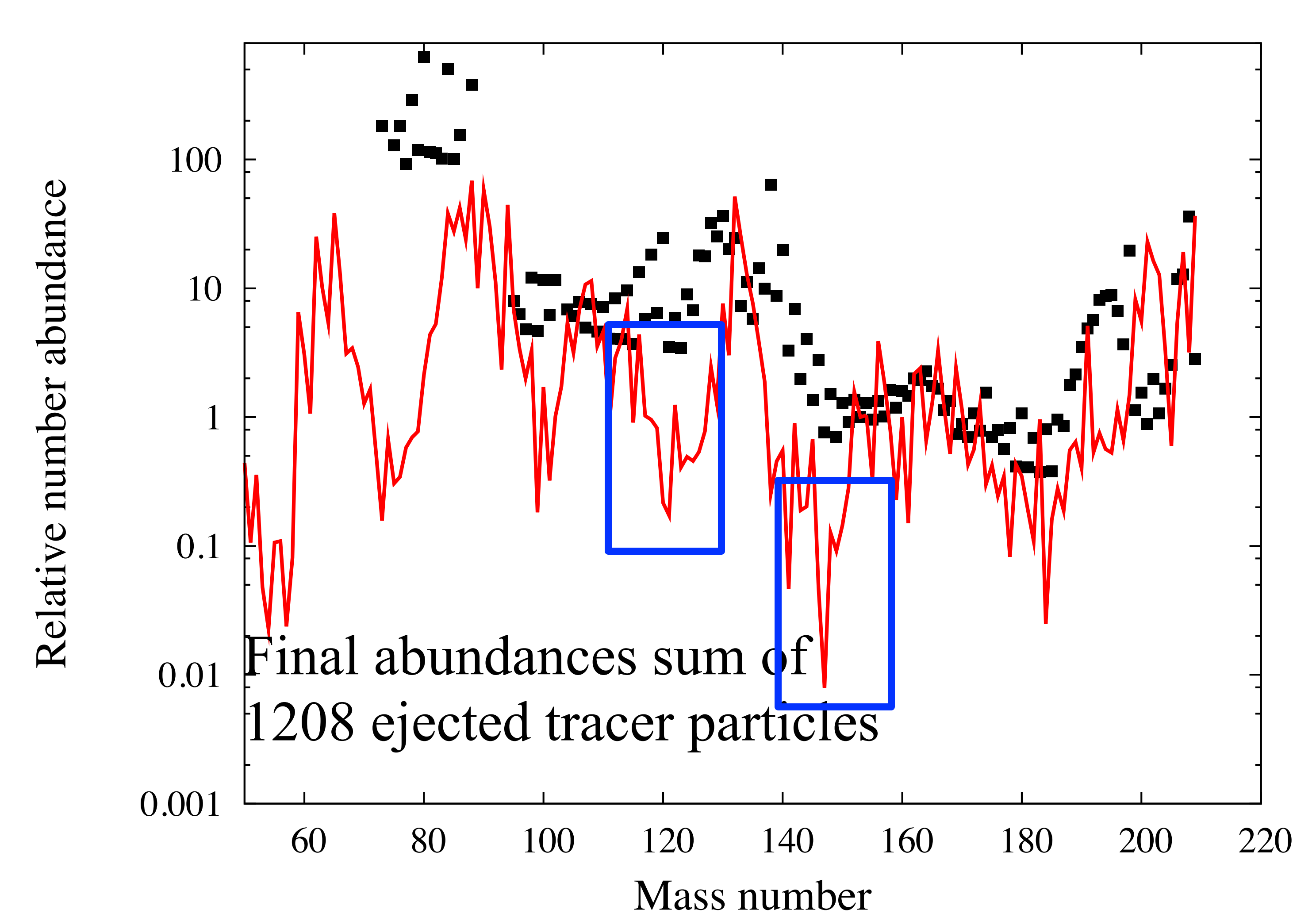




1 2 3 4 5 6 7 8 9 10 11 12 13
Log Density [g/cm3]
1 2 3 4
Log Entropy
1.0 1.5 2.0 2.5 3.0
Lorentz Factor
6e+07
5e+07
4e+07
3e+07
2e+07
1e+07
0
3e10
-2e+07 -1e+07 0 1e+07 2e+07

R-Process in the collapsar jet?

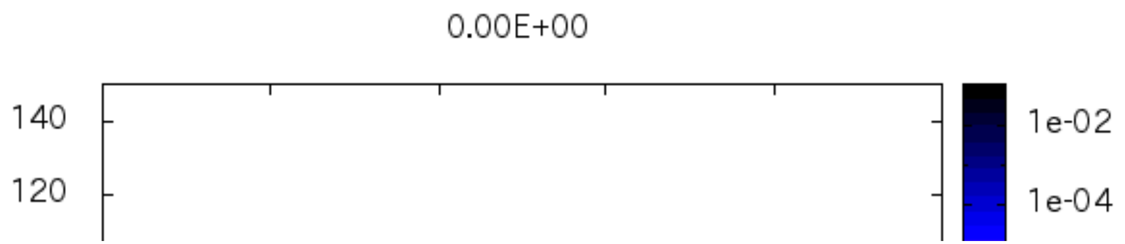
K. Nakamura, S. Sato, S Harikae, T. Kajino, and GJM, A&A (2015)



May need a process to fill in above and below r-process peaks

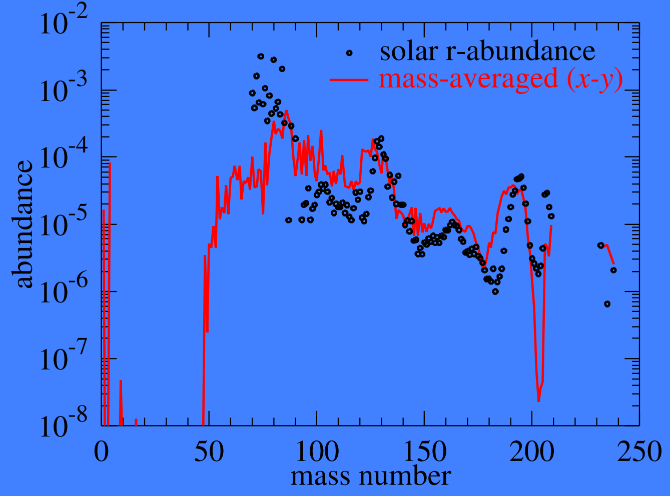
- Fission recycling in neutron star mergers

Shibagaki, Kajino, GJM et al, ApJ (2016)

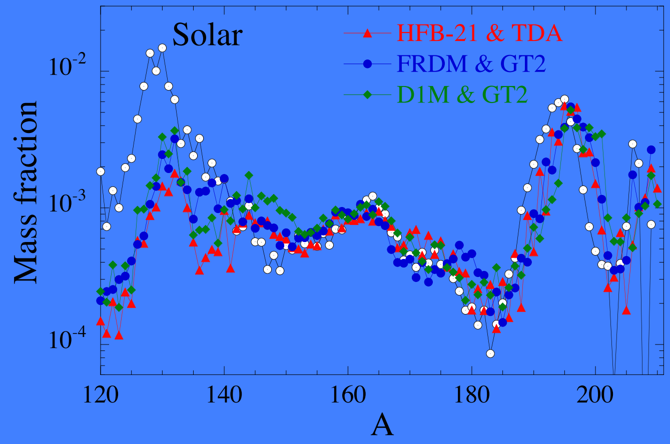


Key Nuclear Physics Issue:
Fission barriers and mass distributions near the termination of the r-process path

Neutron star mergers can produce solar r-process abundance distributions, but this depends upon fission barriers and fragment mass distributions



Wanajo et al. ApJ (2014)



Goriely et al. PRL (2013)

Key Nuclear Physics Issue: Termination of the r-process path

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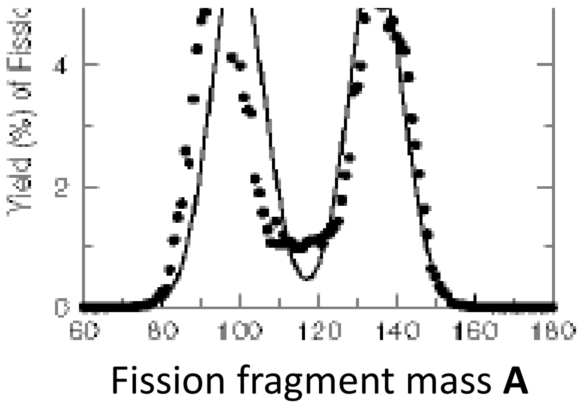
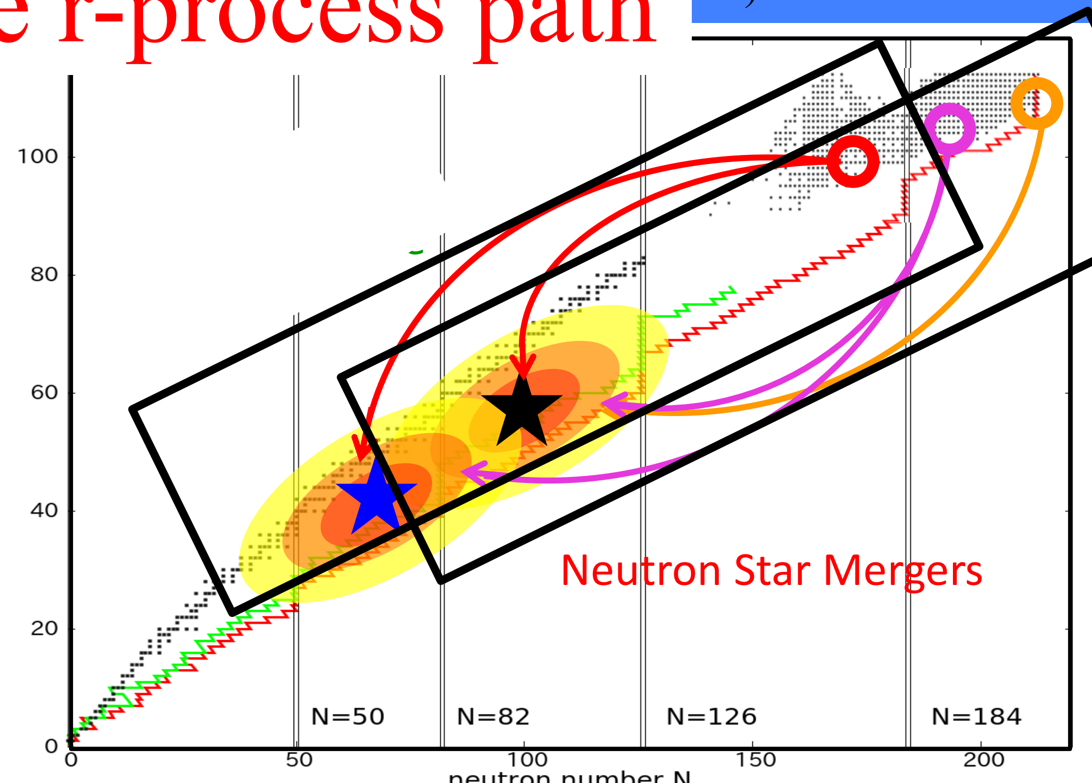
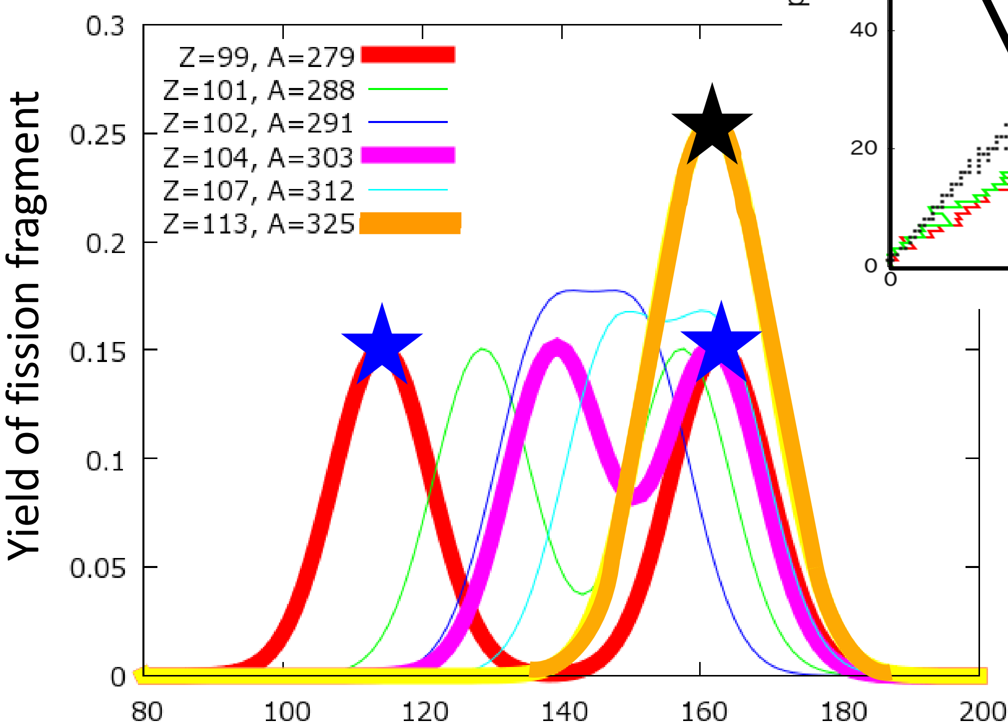
ce, France, (2007)

)08).







Bimordial or Trimodal FFD:

$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi}\sigma} W_i \exp\left(\frac{-(A - A_i)^2}{2\sigma^2}\right)$$

$$A_H = (1+\alpha)(A_p - N_{loss})/2$$

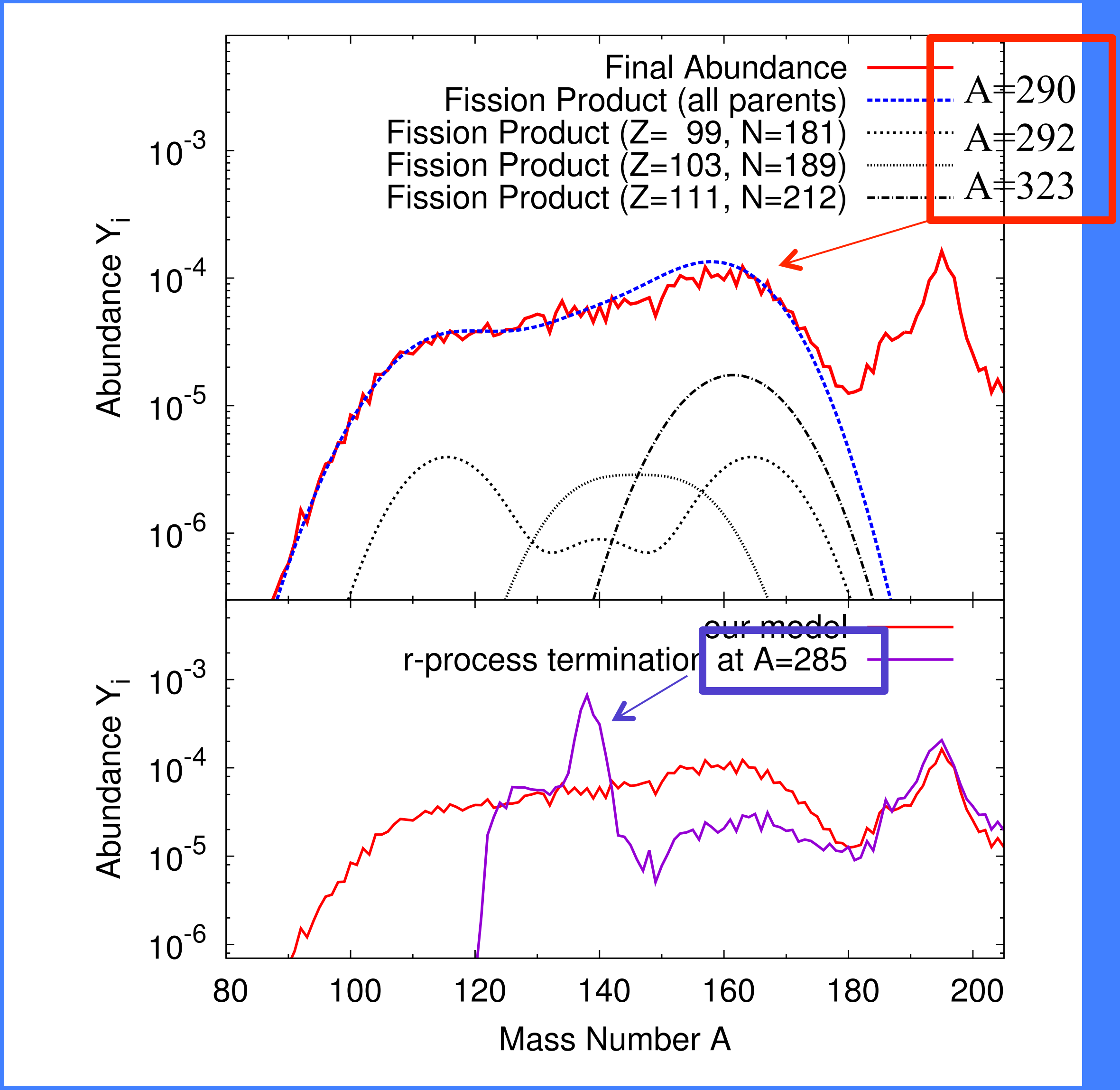
$$A_L = (1-\alpha)(A_p - N_{loss})/2$$

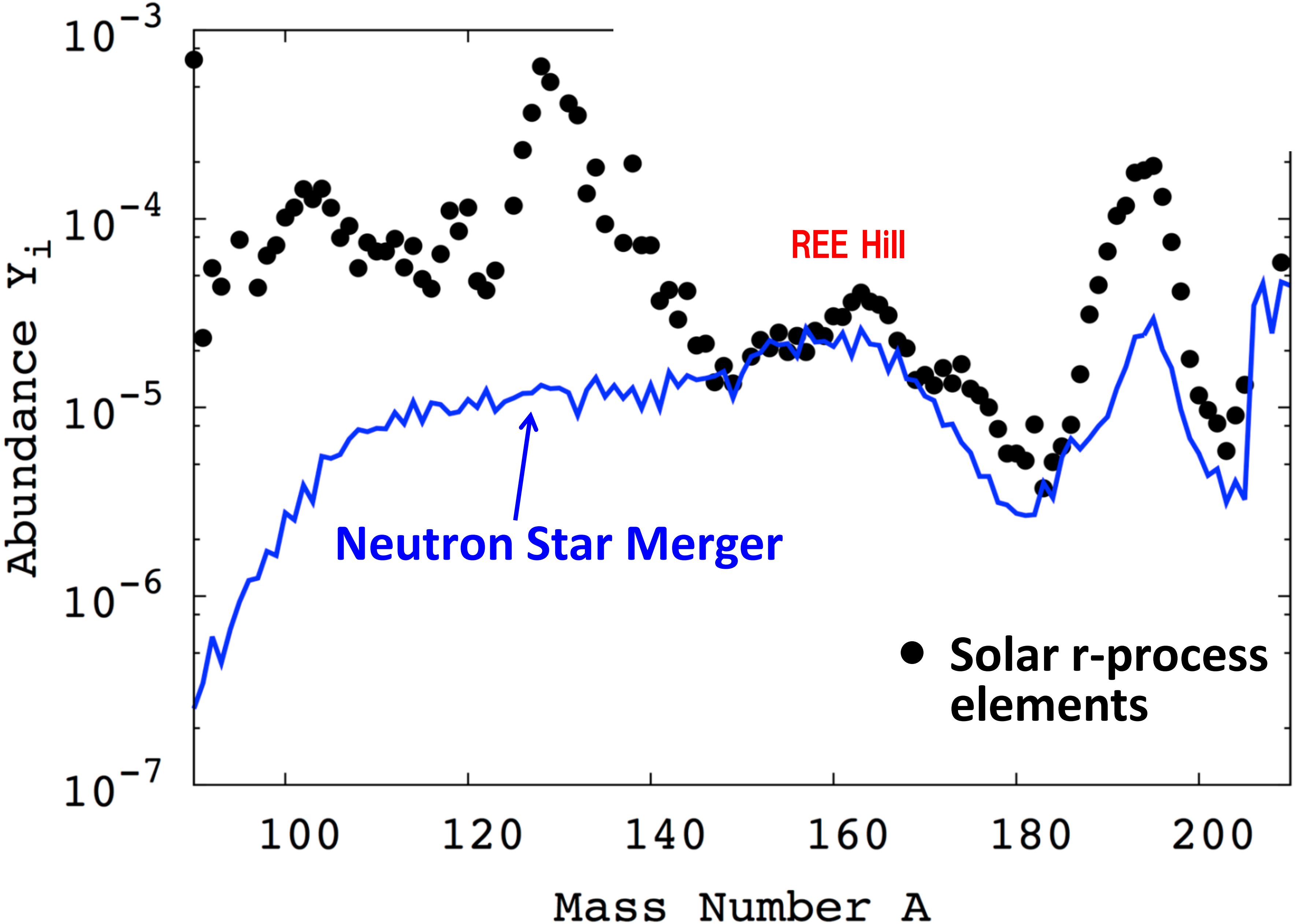
$$A_M = (A_H + A_L)/2.$$

Fission Fragment mass **A**

r-process yields are sensitive to the termination of the r-process by beta-induced fission

Shibagaki, Kajino, GJM et al, ApJ, 816, 79 (2016)





10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Abundance Y_i
REE Hill
Neutron Star Merger
Solar r-process elements
100
120
140
160
180
200
Mass Number A

Each possibility has advantages and disadvantages => One must consider the galactic chemical evolution r-process contributions from all three sites

$$\frac{dM_i}{dt} = P_i(t) + E_i(t) + X_{in} f_{in}(t) - X_i[f_{out}(t) + B(t)]$$

Ejection rate of species i into the ISM

$$E_i(t) = \int_{m(t-\tau_m)}^{m_h} (m_i) X_i(t - \tau_m)(m - m_r - m_i)\phi(m)\psi(t - \tau_m) dm$$

Production rate of newly synthesized species i into the ISM

$$P_{Fe}(t) = m_{Fe}(Ia)R_{Ia} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

$$P_{rNSM}(t) = m_r(NSM)R_{NSM} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

$$P_{rNDW}(t) = m_r(NDW)R_{SNII}$$

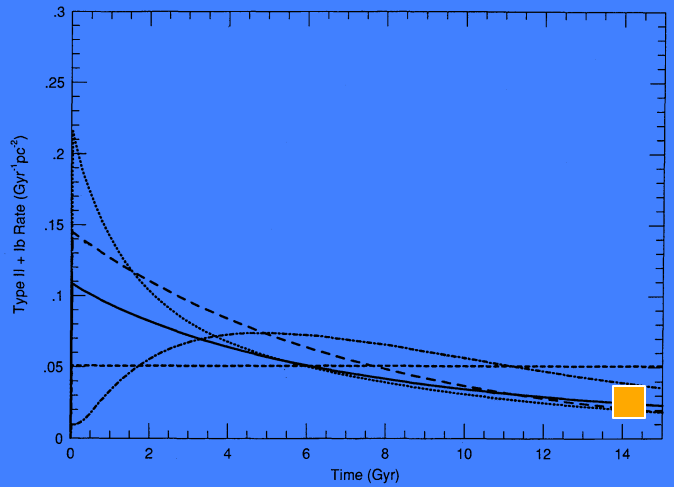
$$P_{rMHDJ}(t) = m_r(MHDJ)\epsilon_{MHDJ}R_{SNII}$$

$$R_{NSM} = \int_{m_l}^{m_h} dM_B \phi(M_B) \int_{q_l}^{1} dq f(q) \int_{a_l}^{a_h} da P(a) \psi(t - \tau_{m2} - t_G)$$

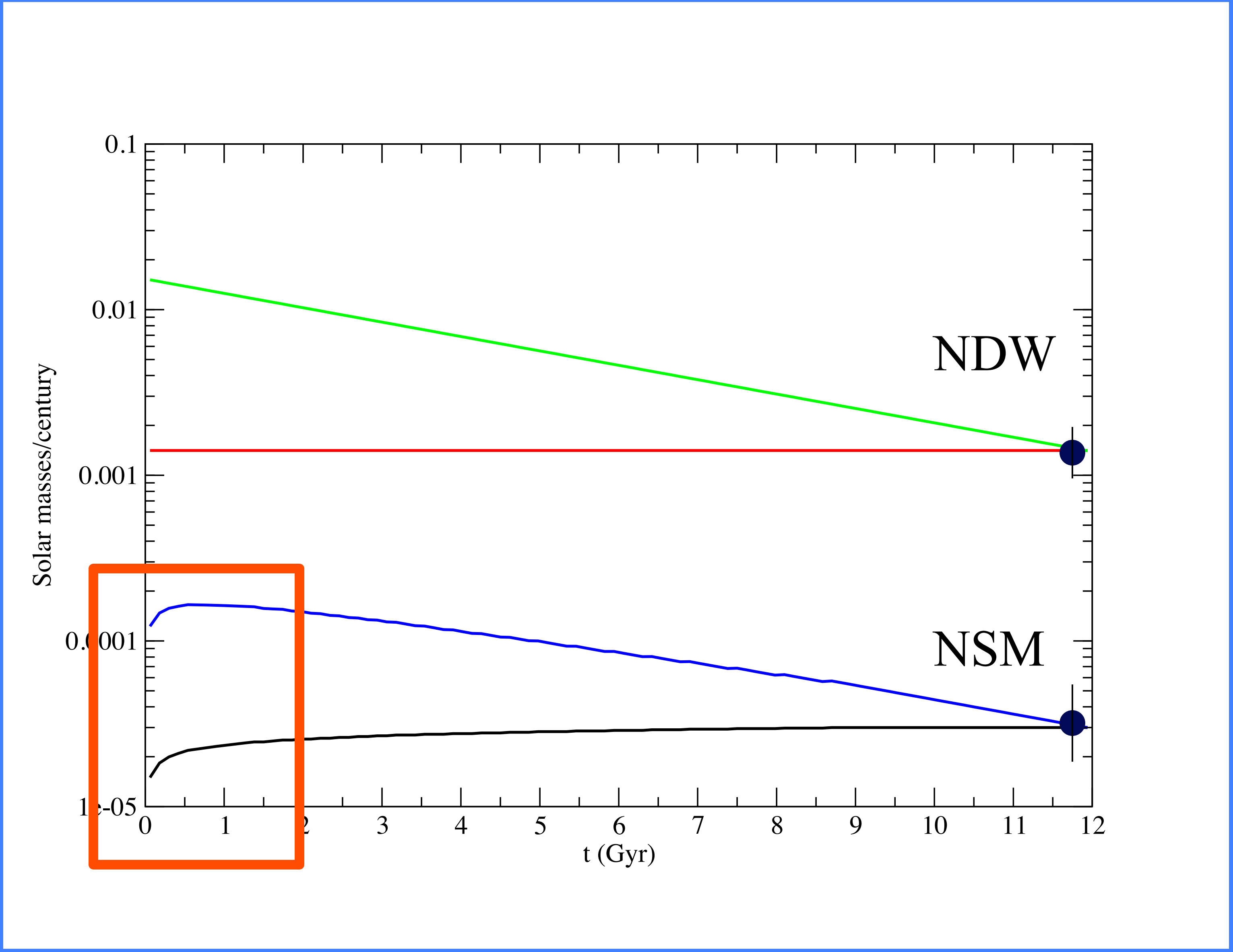
$$R_{SNII} = \int_{m_l}^{m_h} \phi(m)\psi(t - \tau_m) dm$$

Normalization

- R(SNII) = 1.9±1.1/Century - Diehl, et al., Nature 439, 45 (2006).
- ε(MJDJ) =Fraction of SNe that make MHD jets = ~ 1% Winteler, et al., ApJ 750, L22 (2012).
- R(NSM) (1-28) x 10^{-3} /Century - Kalogera, et al., ApJ 614, L137 (2004).



mass ejection rate



Relative contribution to the Solar-System r-process material from NDW, MHD-jets, and neutron-star mergers?

Ejected Mass

- ***m_r(NDW)*** = 7.4×10^{-4} $M_\odot$
  - Wanajo et al (2013)
- ***m_r(MHDJ)*** ε(MJDJ) = 0.6×10^{-2} $M_\odot \times (0.03 \pm 0.02)$
  - Winteler et al. (2012)
- ***m_r(NSM)*** = $(2 \pm 1) \times 10^{-2}$ $M_\odot$

$$f_{Fission} \approx \frac{\mathrm{R_{NSM} M_{r,NSM}}}{\epsilon_{MHDJ} \mathrm{R_{CCSN} M_{r,MHDJ}}}$$

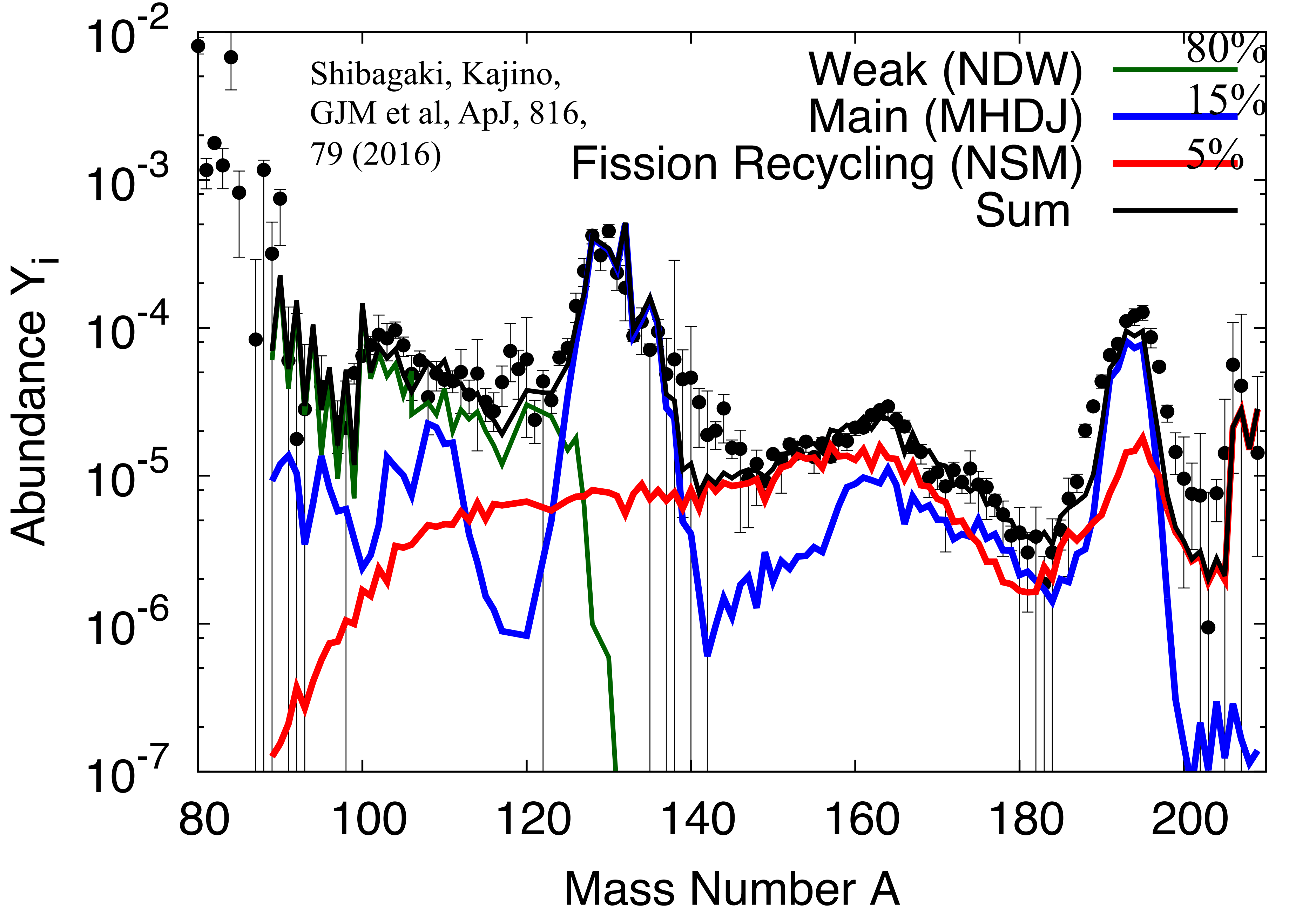
=>

NDW ~80% :

MHDJ ~15% :

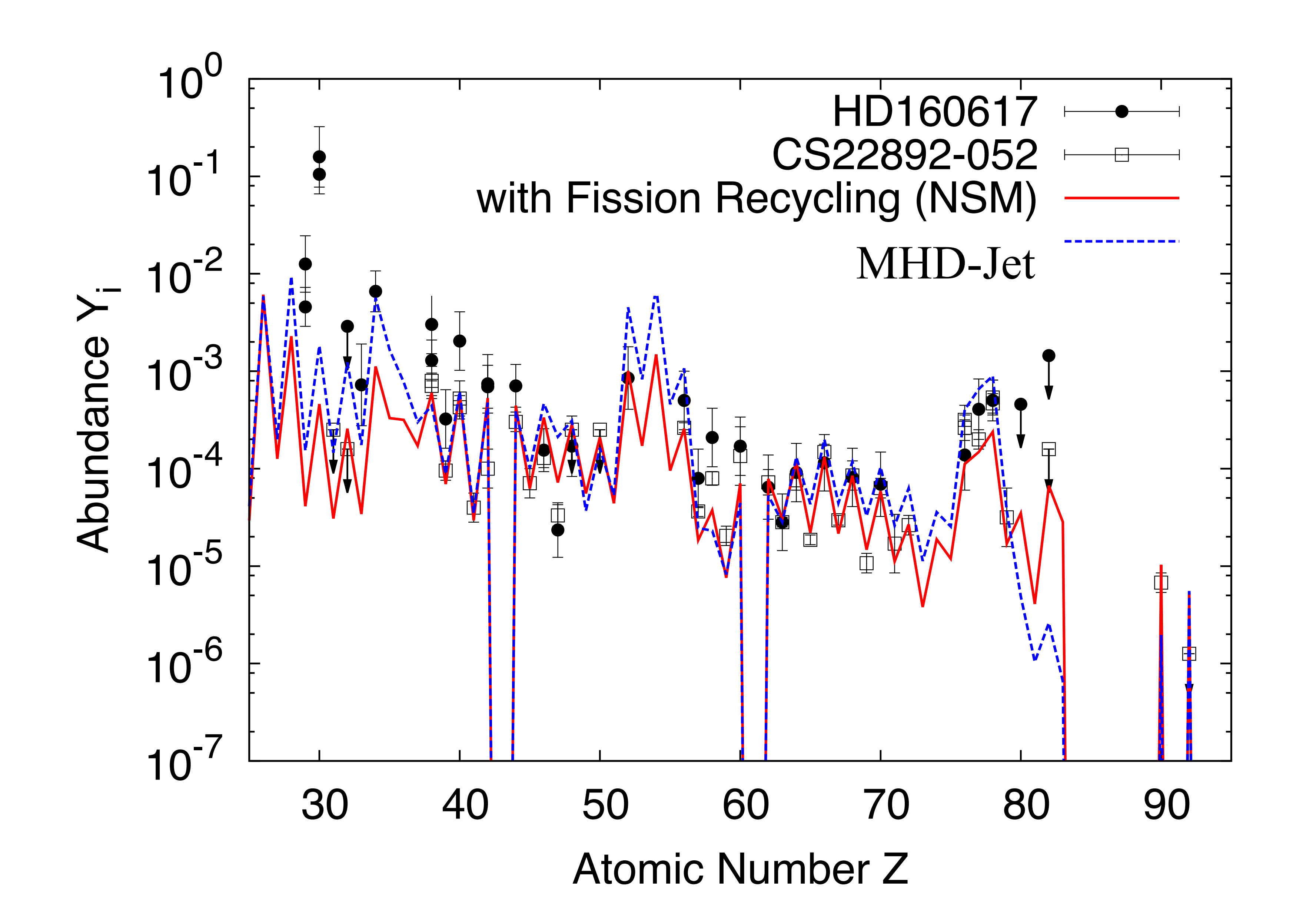
NSM ~5%

$$f_{Weak} \approx \frac{\mathrm{R_{CCSN} M_{r,Weak}}}{\epsilon_{MHDJ} \mathrm{R_{CCSN} M_{r,MHDJ}}}$$

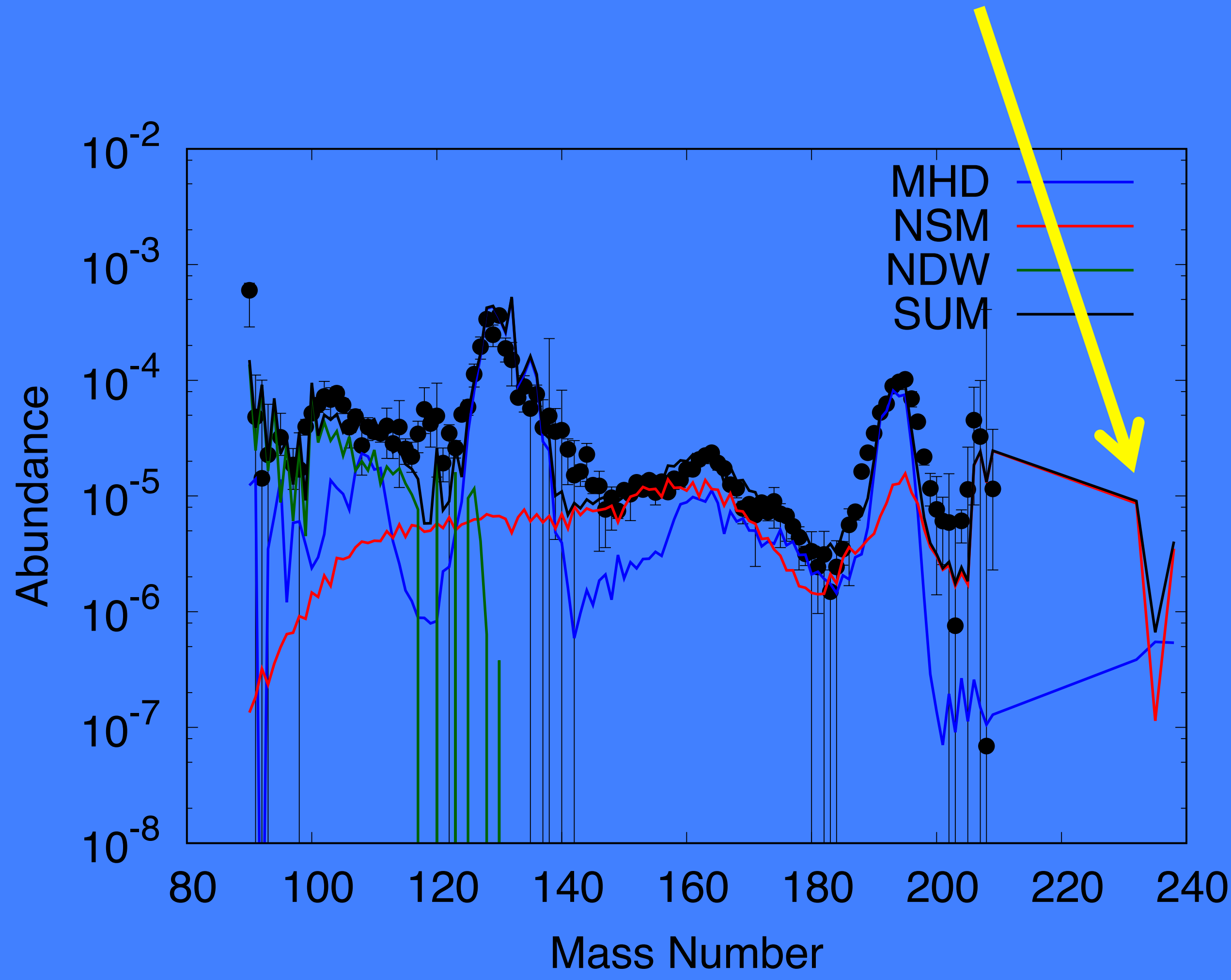


Shibagaki, Kajino,
GJM et al, ApJ, 816,
79 (2016)
Weak (NDW) 80%
Main (MHDJ) 15%
Fission Recycling (NSM) 5%
Sum
Abundance Y_i
Mass Number A
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
80
100
120
140
160
180
200

Universality at low metallicity?



Actinide Boost



Is Ret-II a NSM or a Jet?

- [Ba/Eu] - NSM ~ -1
- [Ba/Eu] - MHDJ ~ 0.3

- [Ba/Eu] - Ret-II ~ -0.4-0.8
  - Looks like a NSM

Conclusions

- All three candidates contribute to the solar r-process abundances:
  - NDW, MHD jets, NS mergers
  - 80% , 15% , 5%
- The relative contributions of each environment may be discernable from the shortcomings of each model
- Fission barriers and beta induced fission rates crucial for A = 280-300
- [Ba/Eu] may be a crucial test for a fission recycling distribution