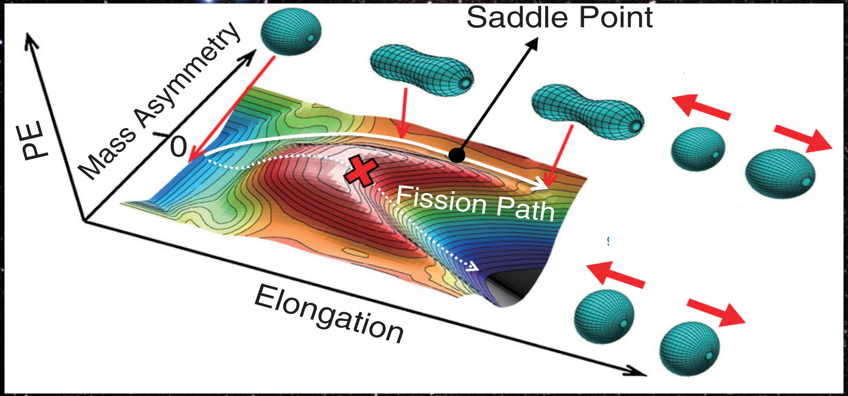
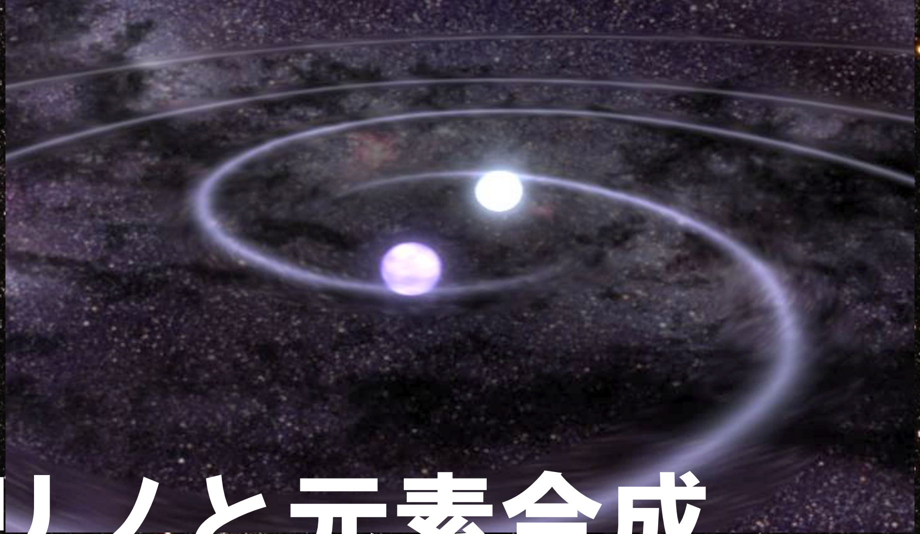


# 超新星ニュートリノと元素合成
# ー r プロセスー

S. Shibagaki[1, 2], T. Kajino[2, 1] G. J. Mathews[3] S. Chiba[4]
S. Nishimura[5], and G. Lorusso[5]

*1 University of Tokyo*
*2 National Astronomical Observatory of Japan*
*3 University of Notre Dame*
*4 Tokyo Institute of Technology*
*5 RIKEN*

# Condition for r-process

Neutron/Seed が高いほどr-processは起こりやすい！

- Expansion timescale (τ)
- Entropy (S)
- Electron fraction ($Y_e$)

Seed

Neutron

$$\frac{(S/230\,k_{\mathrm{B}}\,\mathrm{nucleon}^{-1})}{(Y_{\mathrm{e}}/0.40)(\tau/20\,\mathrm{ms})^{1/3}} \gtrsim 1, \qquad 0.38 \lesssim Y_{\mathrm{e}} \lesssim 0.46$$

Hoffman et al. (1997), Wanajo (2013)

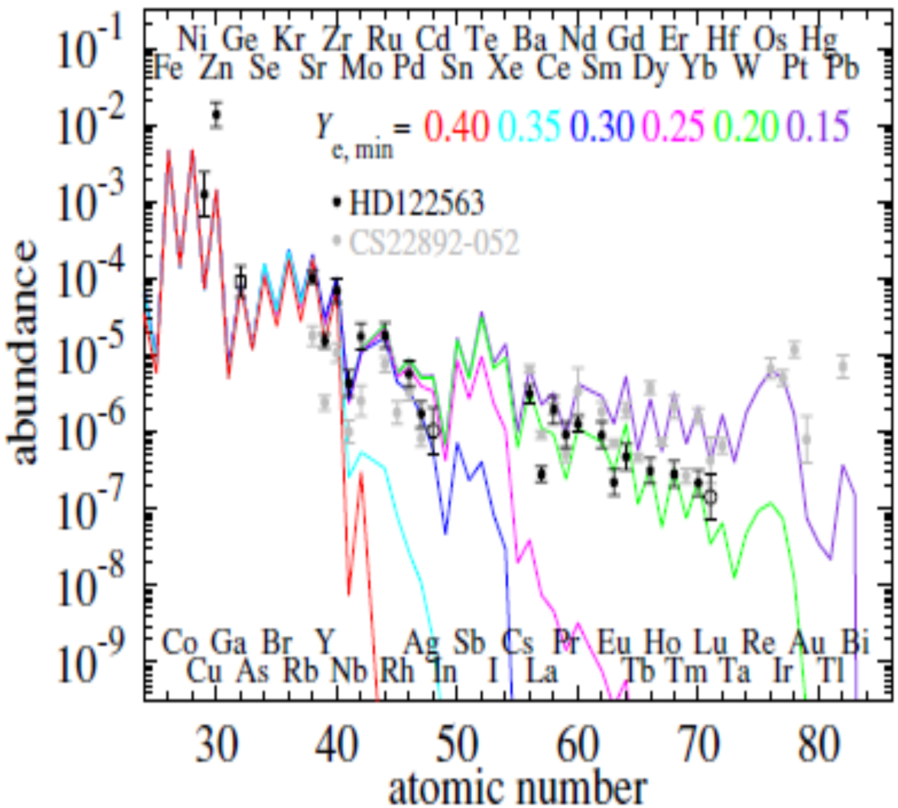
$$Y_{e,f} \approx \left(1 + \frac{L_{\overline{\nu}_e}}{L_{\nu_e}} \frac{\epsilon_{\overline{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\overline{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

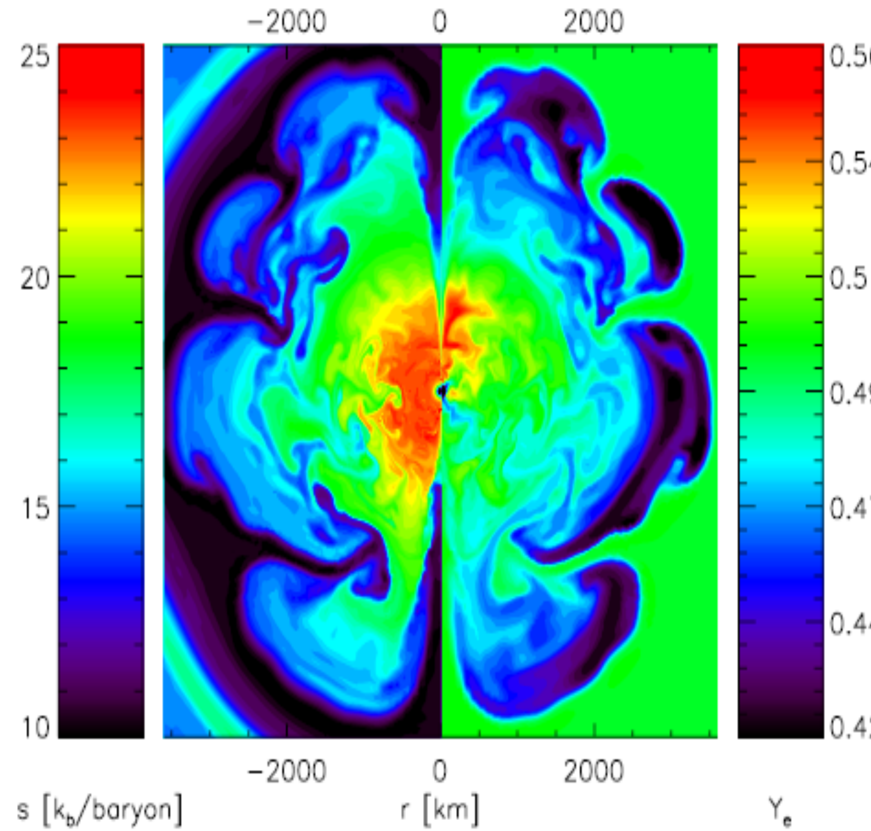
Qian and Woosley (1996)

R-processのためには
- Short expansion time
- High entropy
- Low electron fraction

# Weak r-process

Wanajo, Janka, Muller(2011)

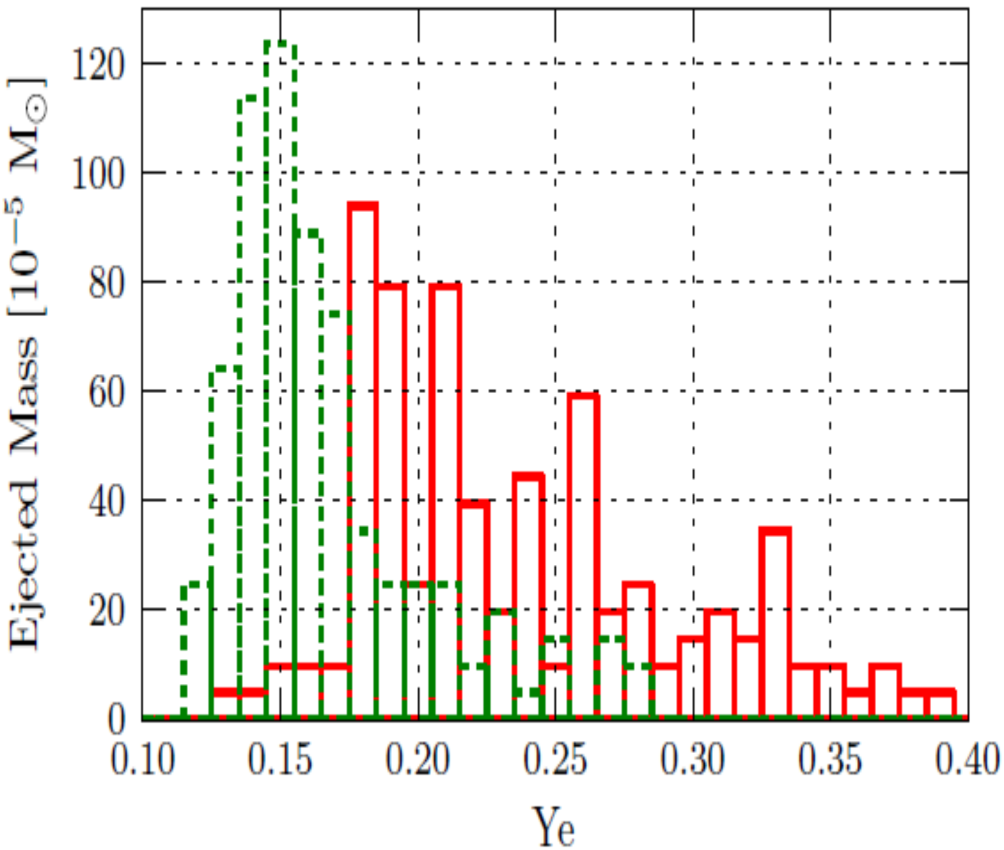


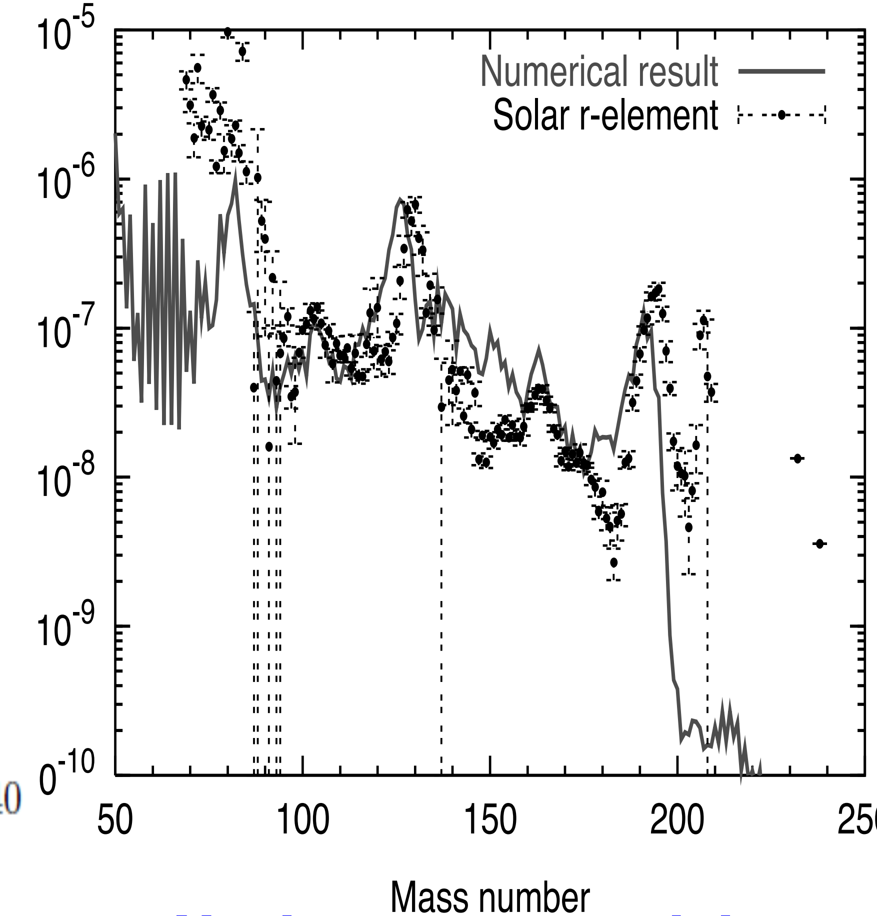




**ν-driven wind weak r-process may be possible to synthesize up to Cd**

# Magneto-hydrodynamic (MHD) Jet Supernova

S. Nishimura, et al., ApJ , 642, 410 (2006) ; T. Takiwaki, K.Kotake and K. Sato, ApJ 691, 1360 (2009); C. Winteler, et al., ApJ 750, L22 (2012).



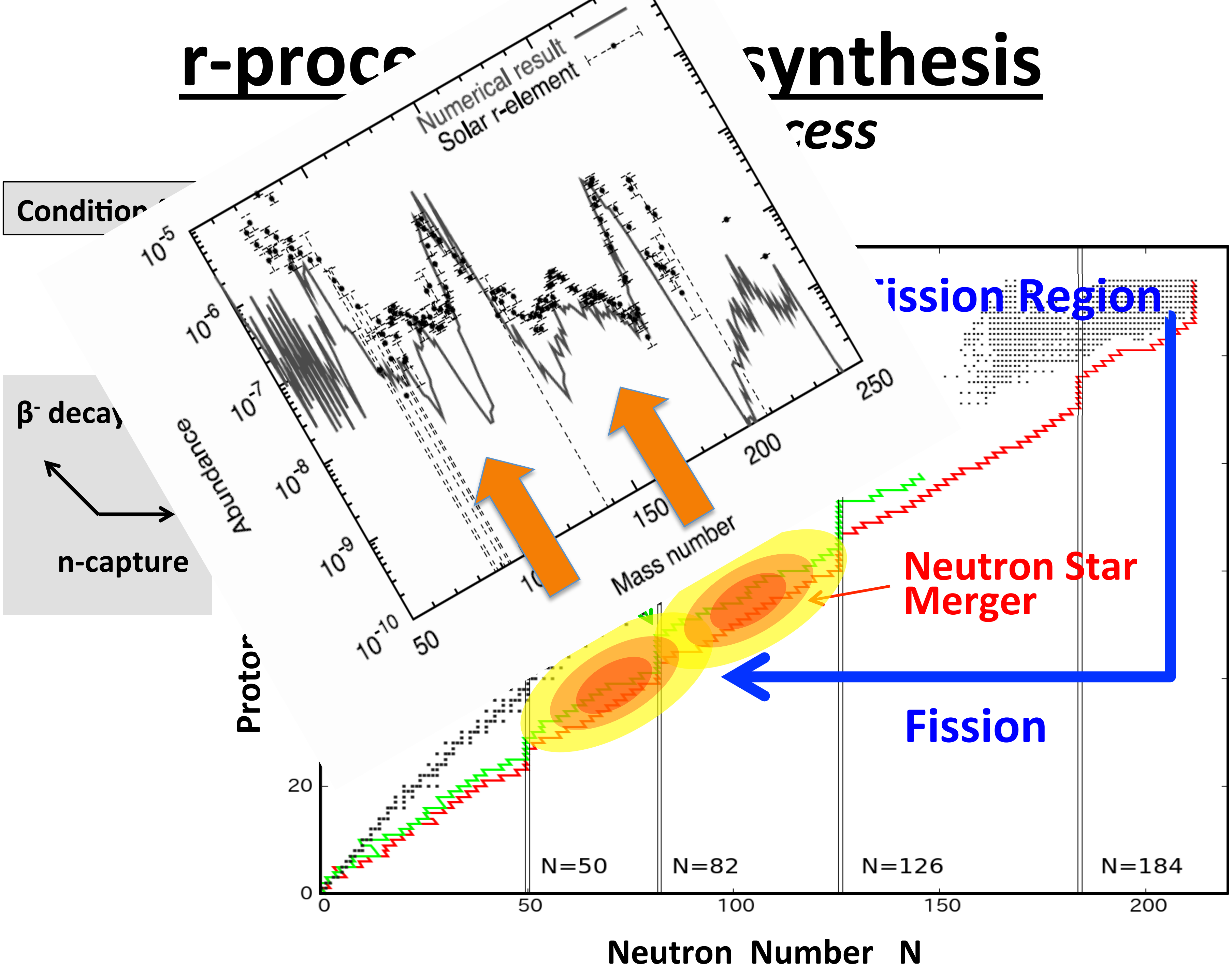




**Underproduction PROBLEM !** — **Possible Solutions**

- **Nuclear mass model**
- **Neutron Star Merger**

# r-proce synthesis

*cess*



Recent RIKEN β-Decay Experiment:
S. Nishimura et al., PRL 106, 052502 (2011).

# Nuclear Models — sensitive to Fissi

## One of the Best Mod

### Nuclear Mass Model :

KTUY Model

Fission Barrier, $Q_\beta$

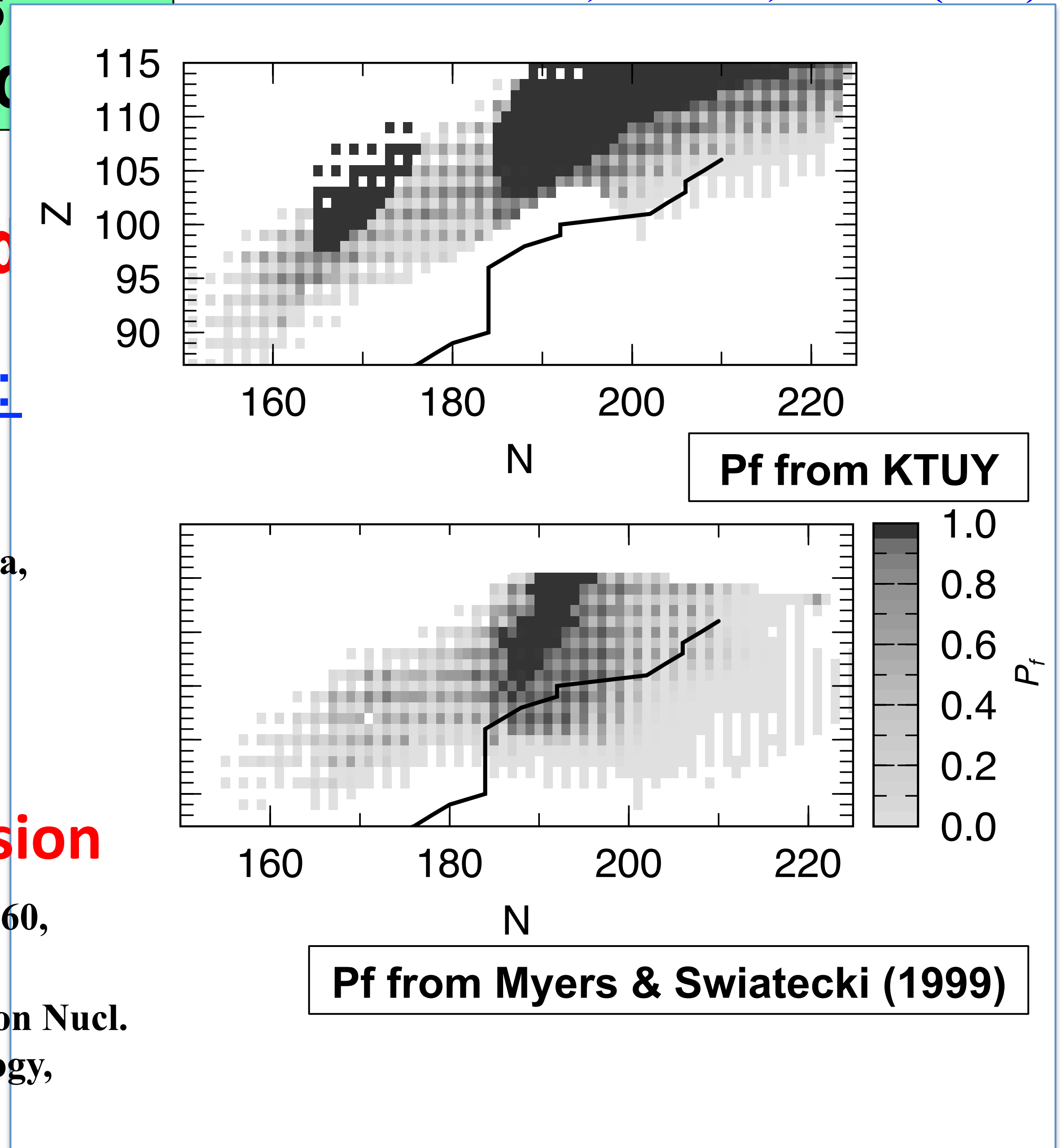
Koura, Tachibana, Uno, Yamada, PTP 113, 305 (2005).

### Reaction Rates:

α-decay, β-decay, fission

H. Koura, AIP Conf. Proc. 704, 60, (2004).

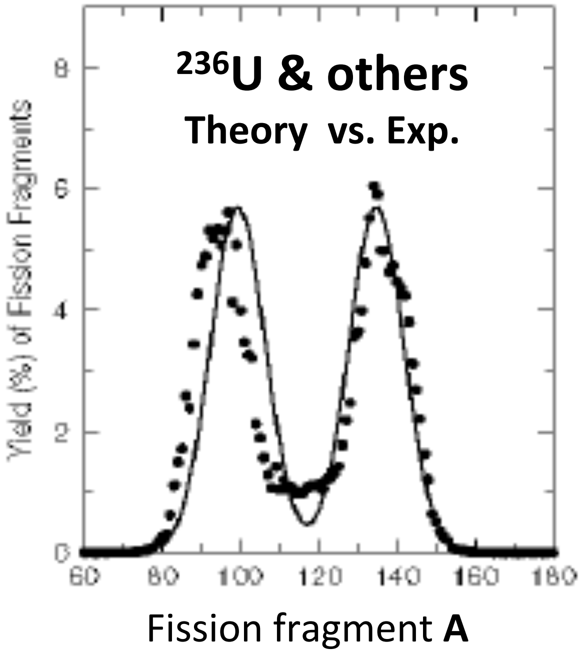
M. Ohta et al., Proc. Int. Conf. on Nucl. Data for Science and Technology, Nice, France, (2007).

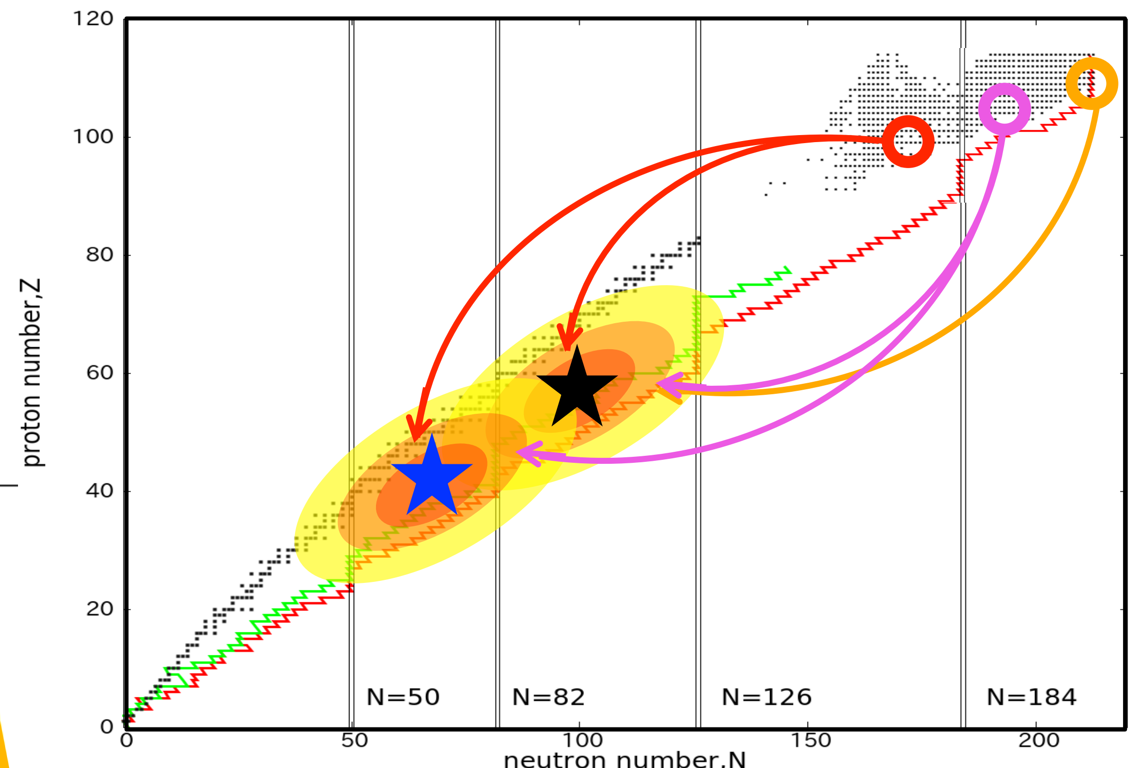


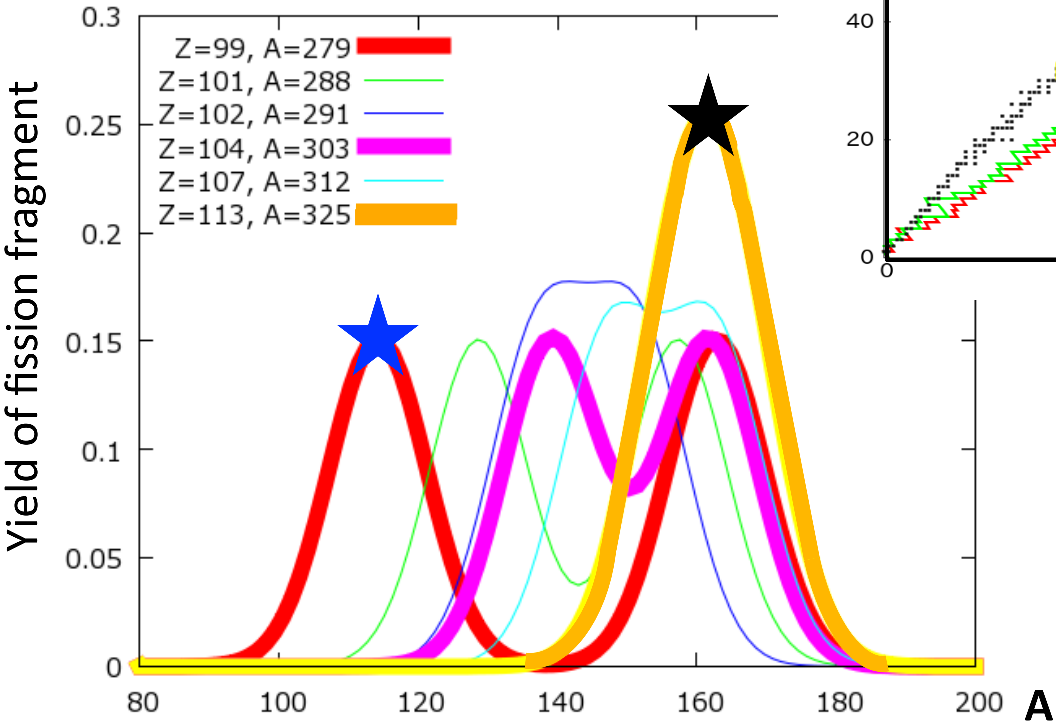

Mass Number

# Fission Fragment Mass Distribution

M. Ohta et al., Proc. Int. Conf. on NDST, Nice, France, (2007)
S. Chiba et al., AIP Conf. Proc. 1016, 162 (2008).




Unimodal or Bimordal FFD:

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

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

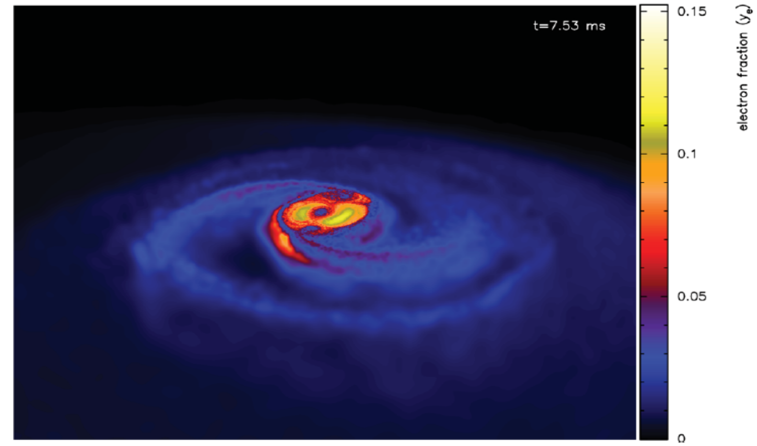
$$A_L = (1-\alpha)(A_p - N_{loss})/2$$

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

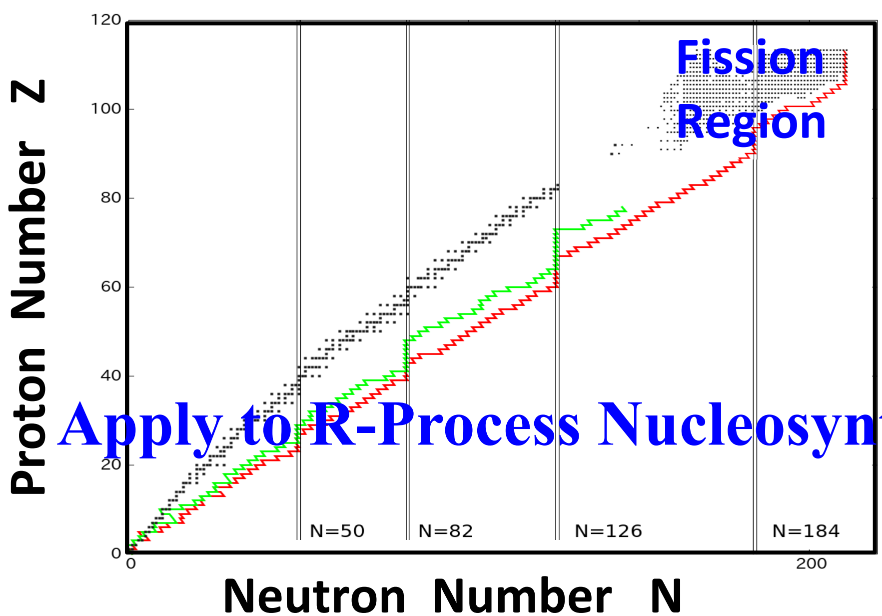
# Fluid Data for Neutron Star Merger

## 1.0M$_\odot$ NS - 1.0M$_\odot$ NS Binary Merger Simulation

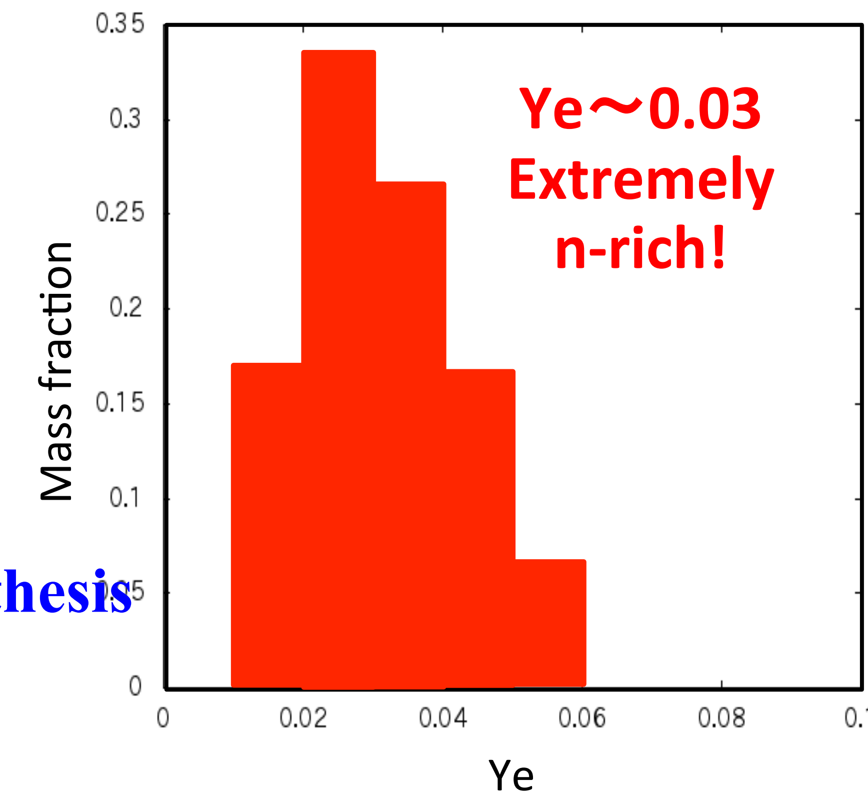
Korobkin et al., MNRAS 426 (2012), 1940,
Piran et al., MNRAS 430 (2013), 2121,
Rosswog et al., MNRAS 430 (2013), 2585.



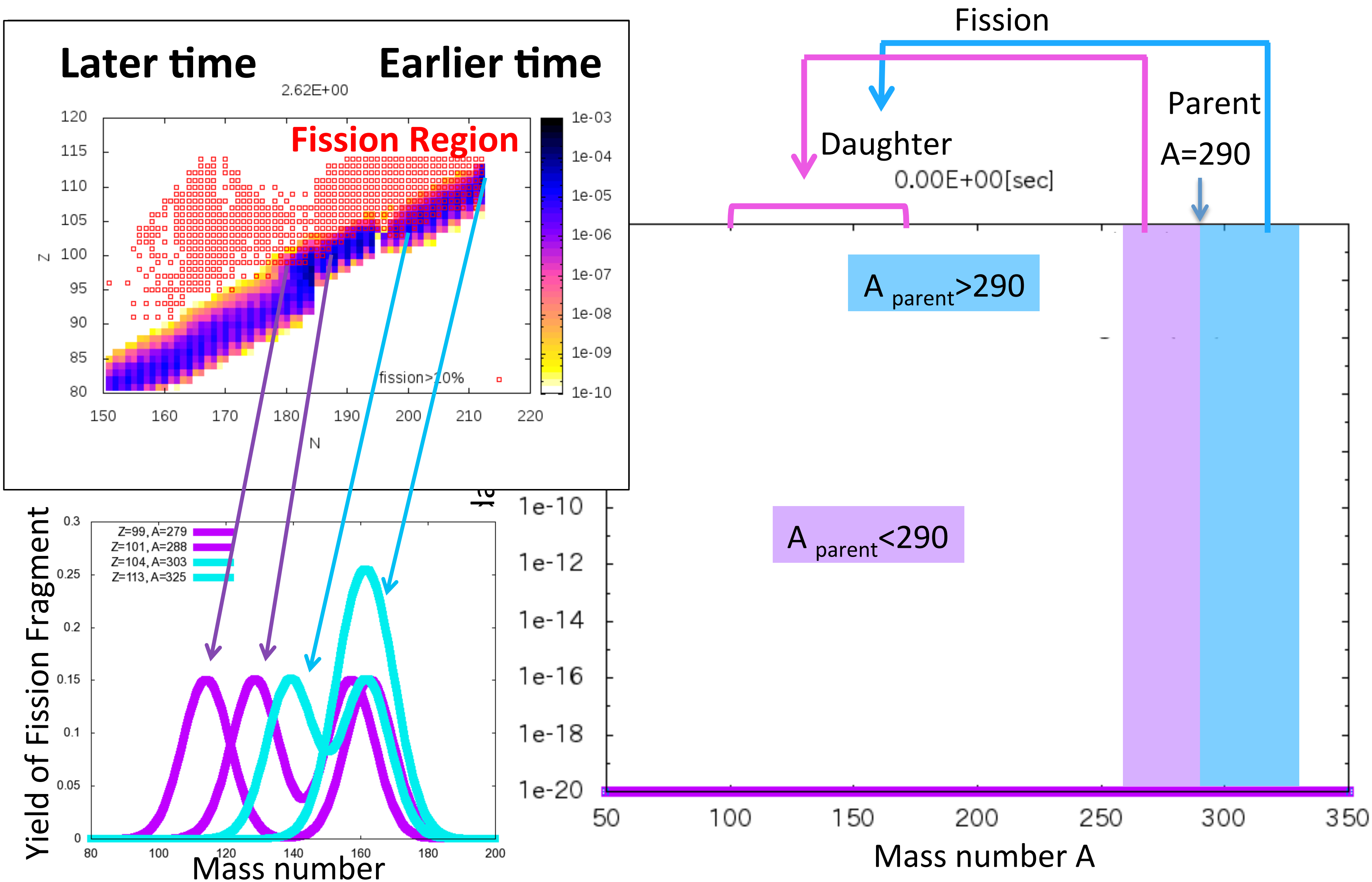

Smoothed particle hydrodynamic simulation
Newtonian gravity
Neutrino Leakage scheme
Shen et al. (1998) Equation of State




**Apply to R-Process Nucleosynthesis**

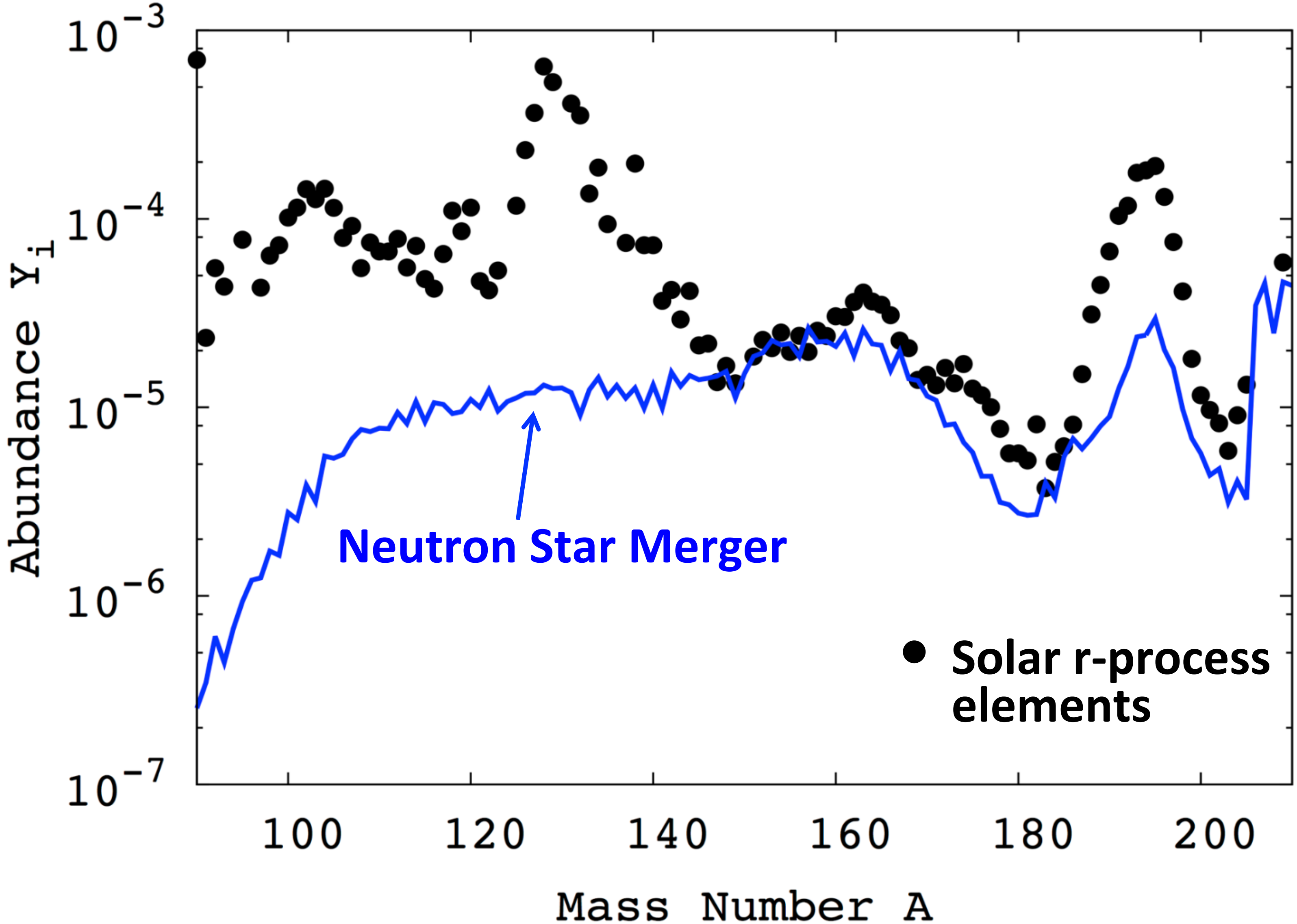


# Abundance Evolution of Neutron Star Merger (MOVIE)



# Elemental Abundances of Neutron Star Merger

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso, submitted (2015)



# Magneto-hydrodynamic (MHD) Jet Supernova

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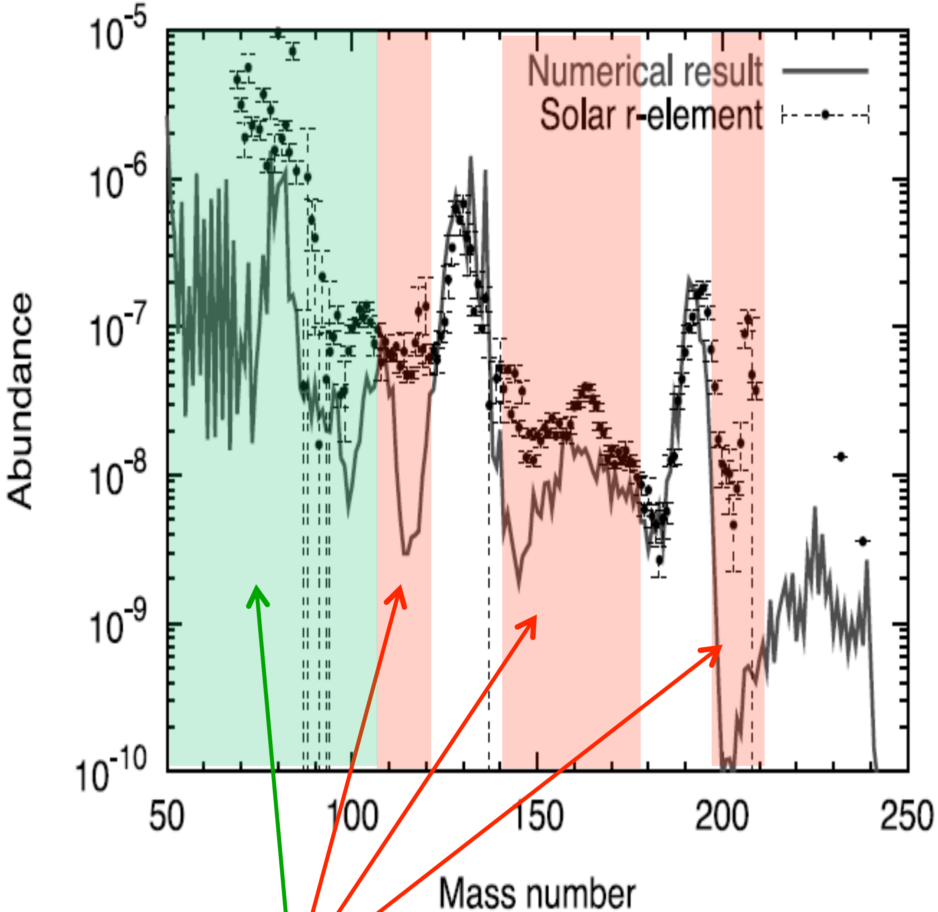
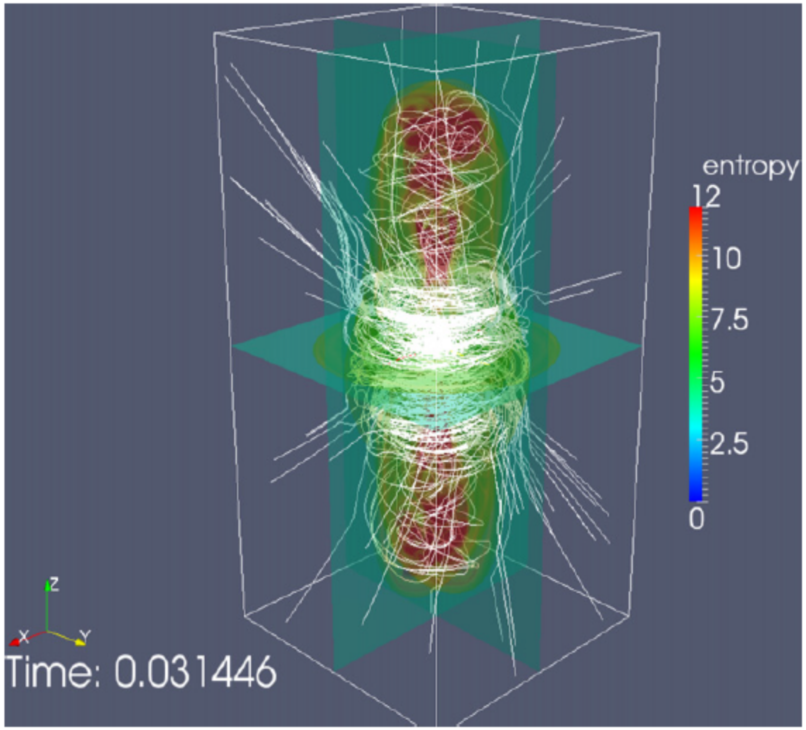



Underproduction PROBLEM !

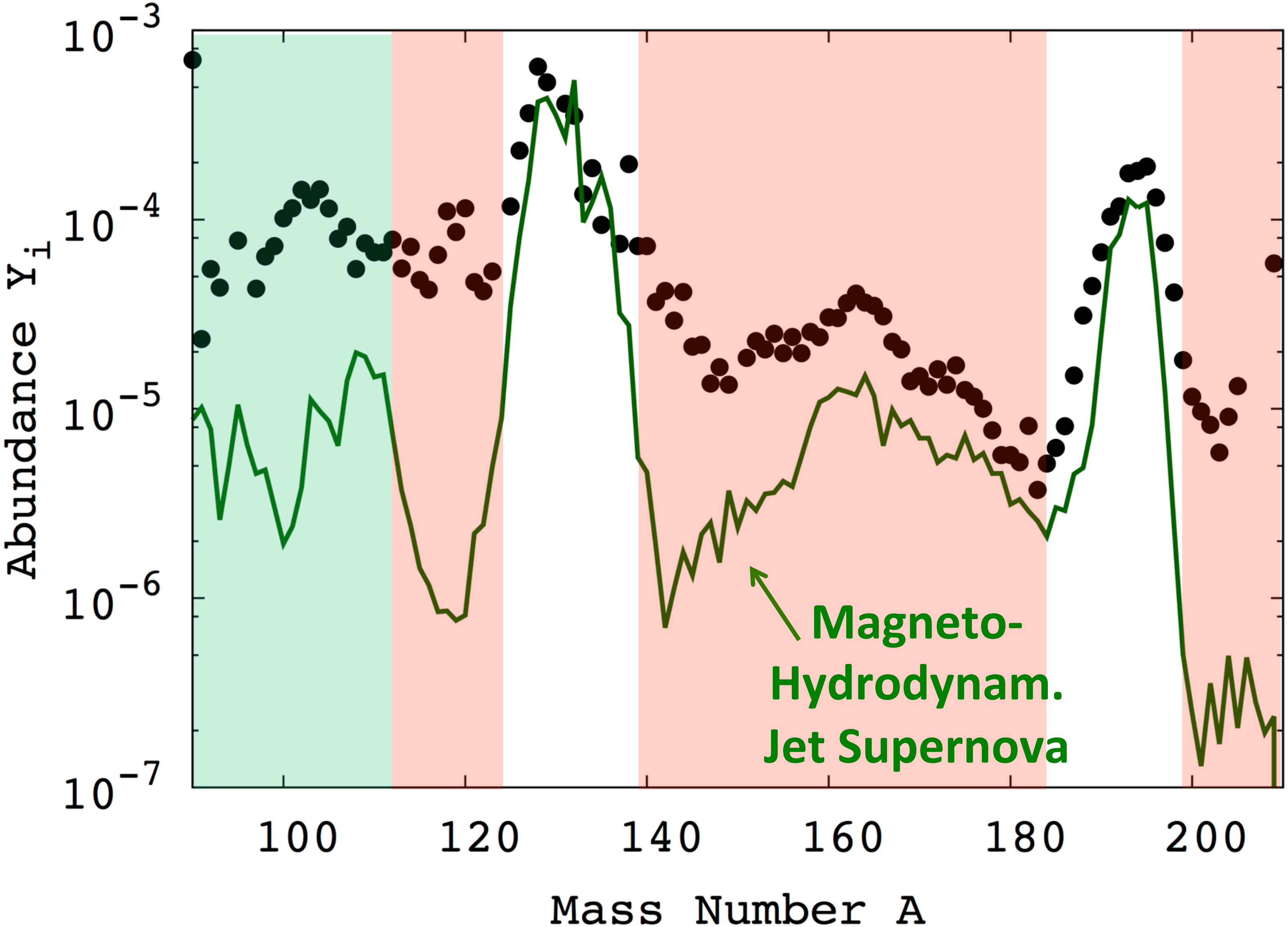
Possible Solutions

Nuclear mass model

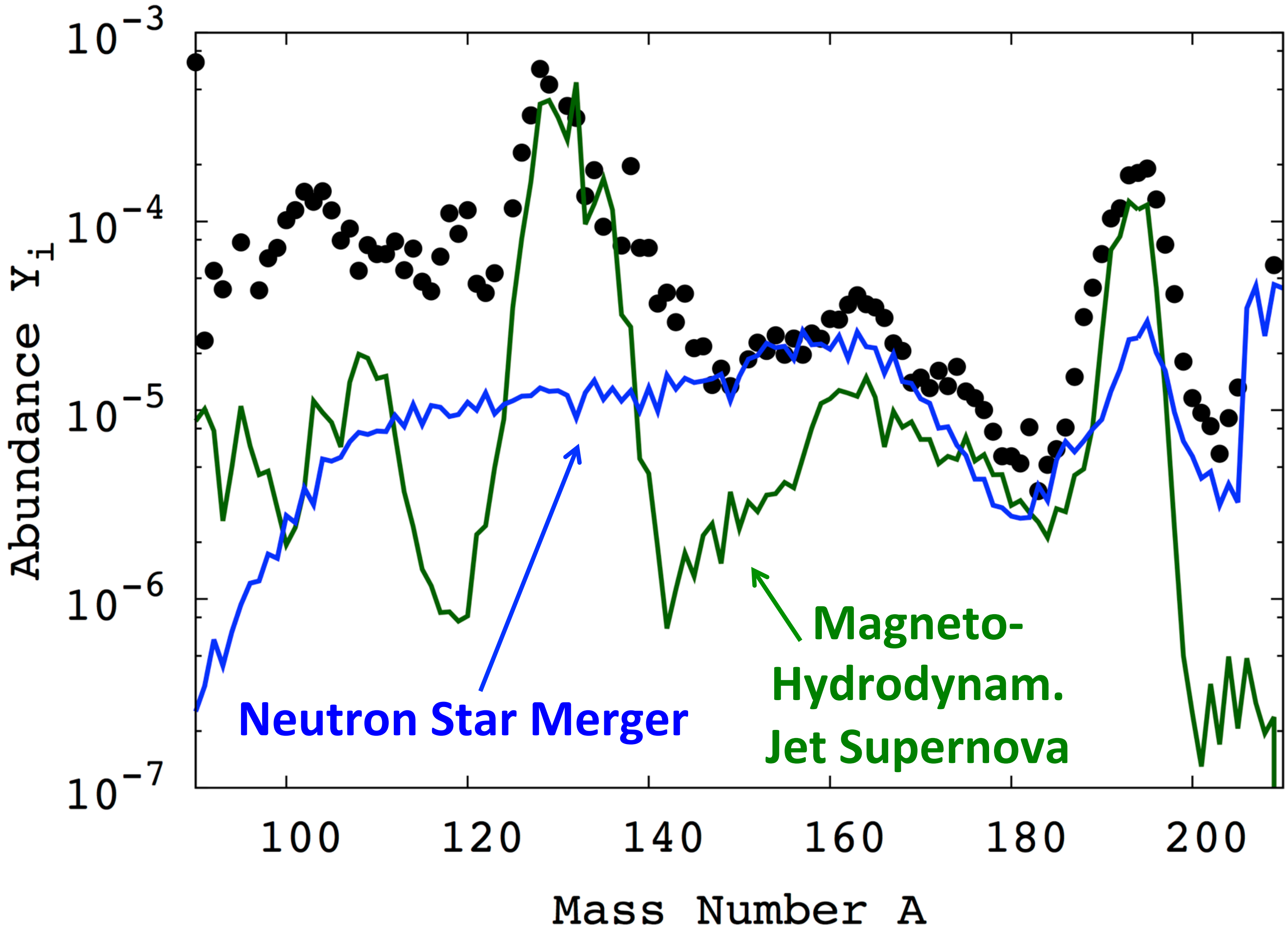
Neutron Star Merger

# Recipe to reproduce solar r-elements

Underproduction PROBLEM !

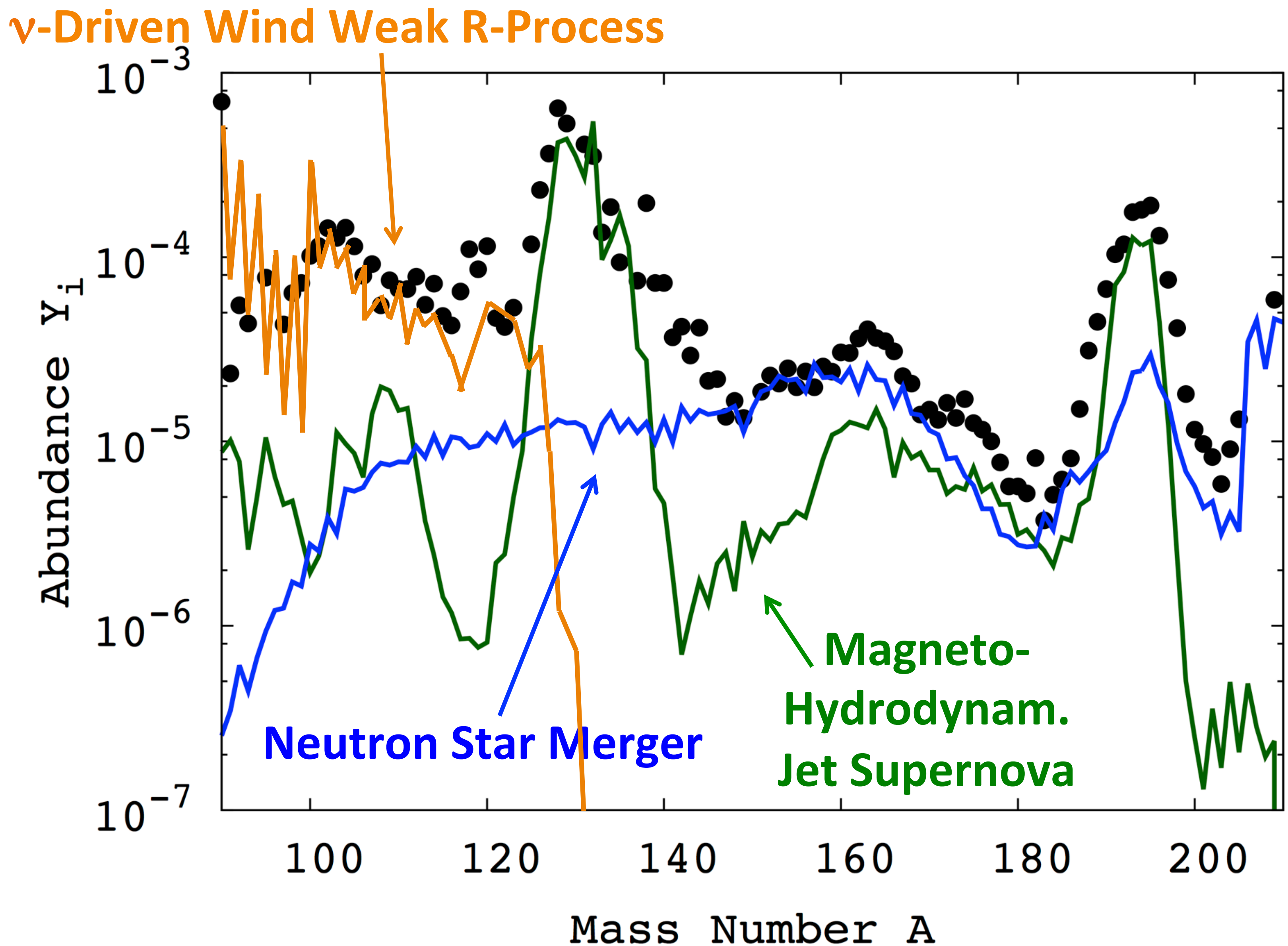


# Recipe to reproduce solar r-elements



# Recipe to reproduce solar r-elements

S. Wanajo, ApJ 770 (2013), L22.



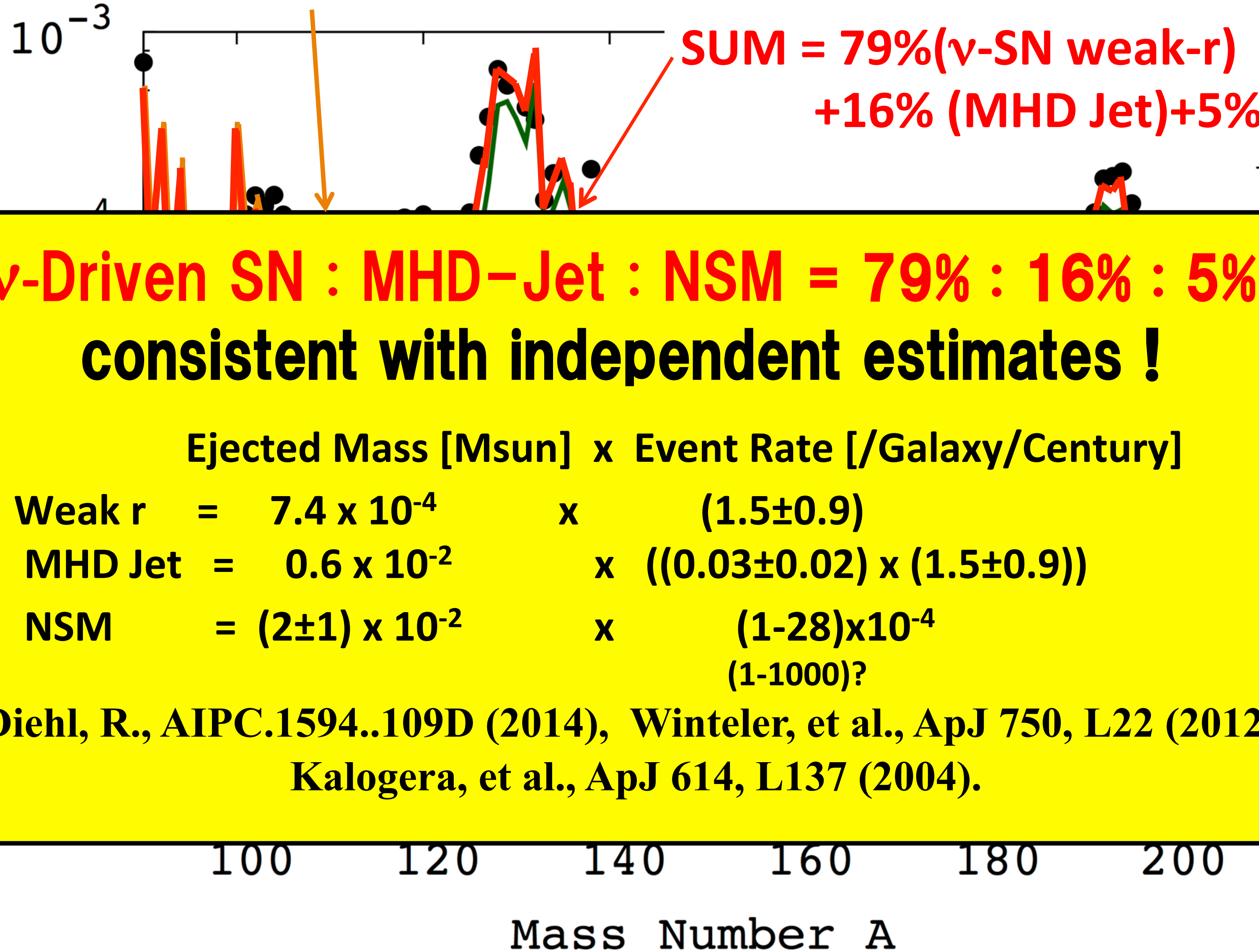
# Recipe to reproduce solar r-elements

S. Wanajo, ApJ 770 (2013), L22.

ν-Driven Wind Weak R-Process

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso, submitted (2015)

SUM = 79%(ν-SN weak-r) +16% (MHD Jet)+5%(NSM)




**ν-Driven SN : MHD-Jet : NSM = 79% : 16% : 5%**

**consistent with independent estimates !**

| | Ejected Mass [Msun] | x | Event Rate [/Galaxy/Century] |
|---|---|---|---|
| Weak r = | $7.4 \times 10^{-4}$ | x | $(1.5 \pm 0.9)$ |
| MHD Jet = | $0.6 \times 10^{-2}$ | x | $((0.03 \pm 0.02) \times (1.5 \pm 0.9))$ |
| NSM = | $(2 \pm 1) \times 10^{-2}$ | x | $(1\text{-}28) \times 10^{-4}$<br>(1-1000)? |

Diehl, R., AIPC.1594..109D (2014), Winteler, et al., ApJ 750, L22 (2012), Kalogera, et al., ApJ 614, L137 (2004).

# Summary

- There are 3 candidates for r-process sites.
  (MHD-Jet SN, NSM, $\nu$-driven wind SN)
- We construct the new nuclear reaction network code and apply to r-process nucleosynthesis of the binary neutron star merger.
- MHD-Jet SNe + NSMs + $\nu$-driven wind SNe can reproduce the solar r-elements.
- Fission fragment mass distribution (FFD) and fission barrier are critical to reproduce the elemental abundance around A = 160.

➡ Quest for nuclear mass models and FFDs is highly desirable.