Int. Conf. on Origin of Matter and Evolution of Galaxies
IBS, Daejeon Korea, June 26-29, 2017

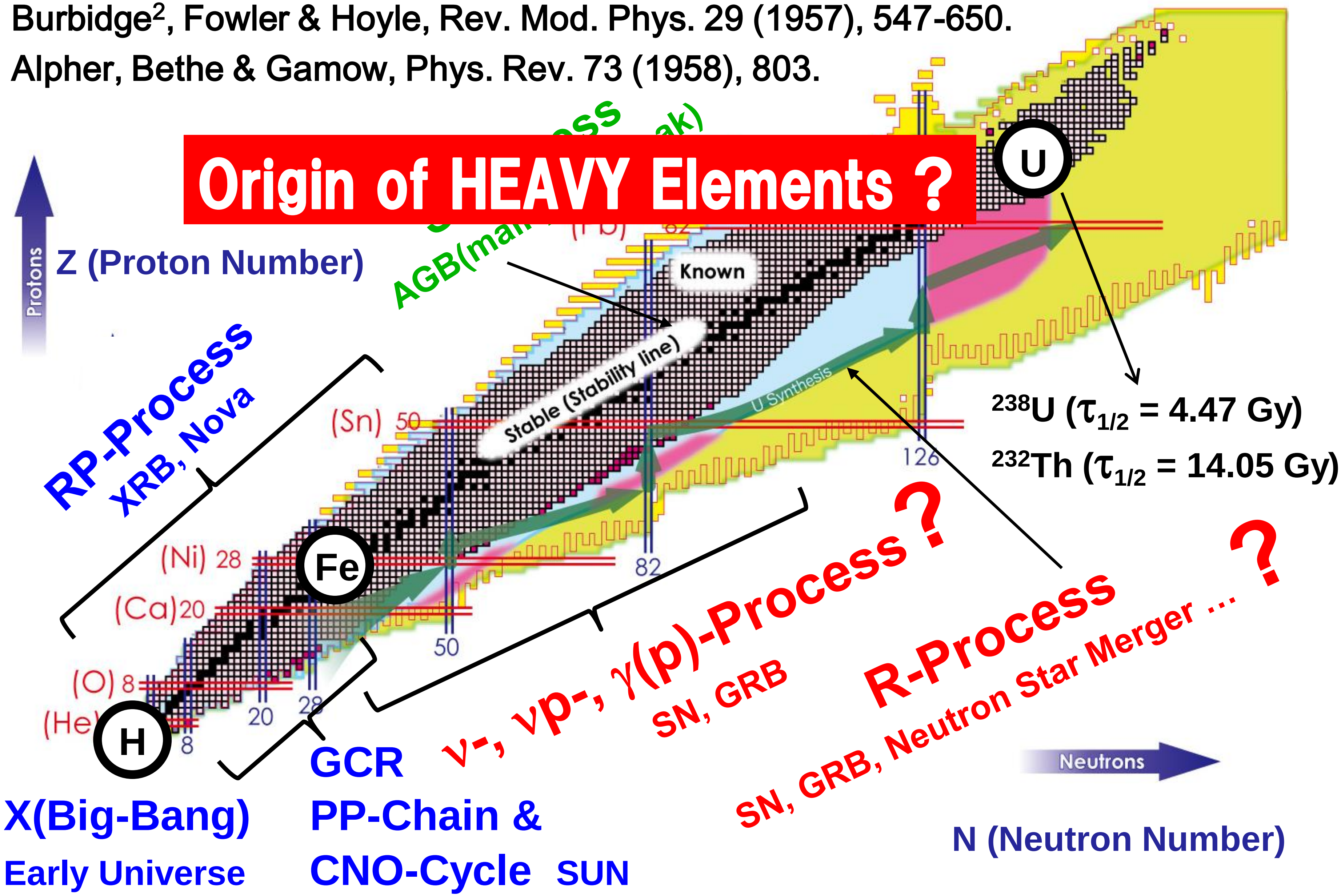
Solving the Mystery of r-Process and νp-Process

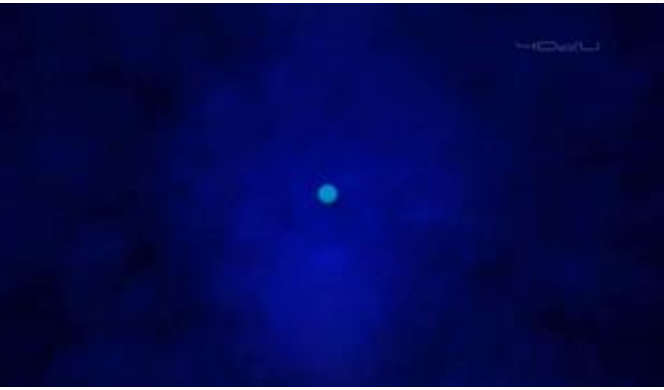
Taka KAJINO

National Astronomical Observatory of Japan
The University of Tokyo
Beihang University, Int. Cent. Big-Bang Cosmology & Element Genesis

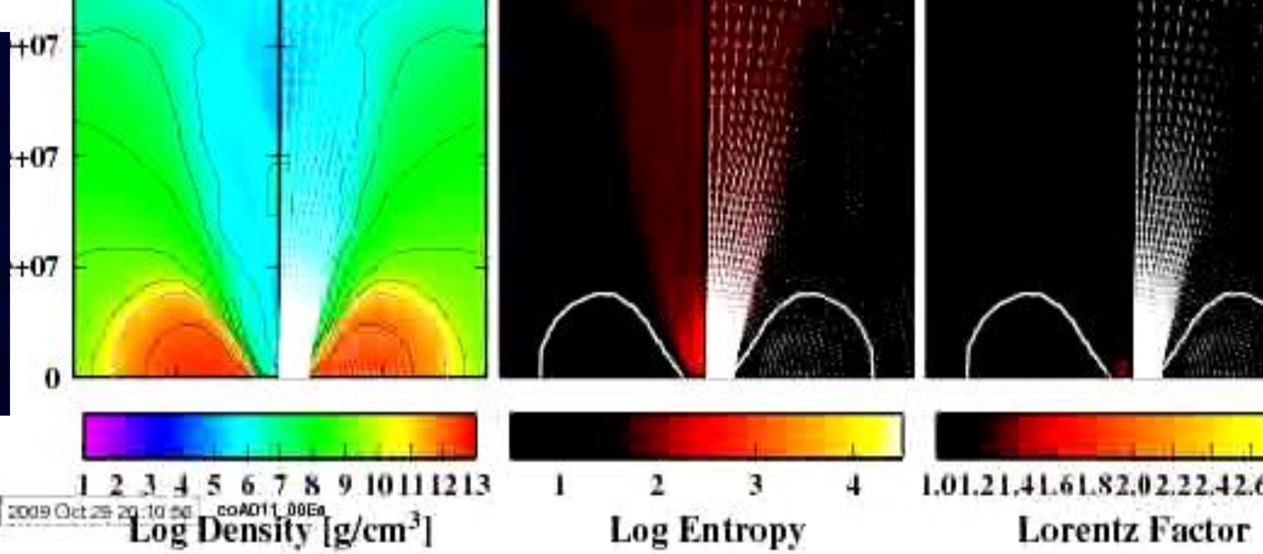
Element Genesis from Nuclear Processes in Cosmos

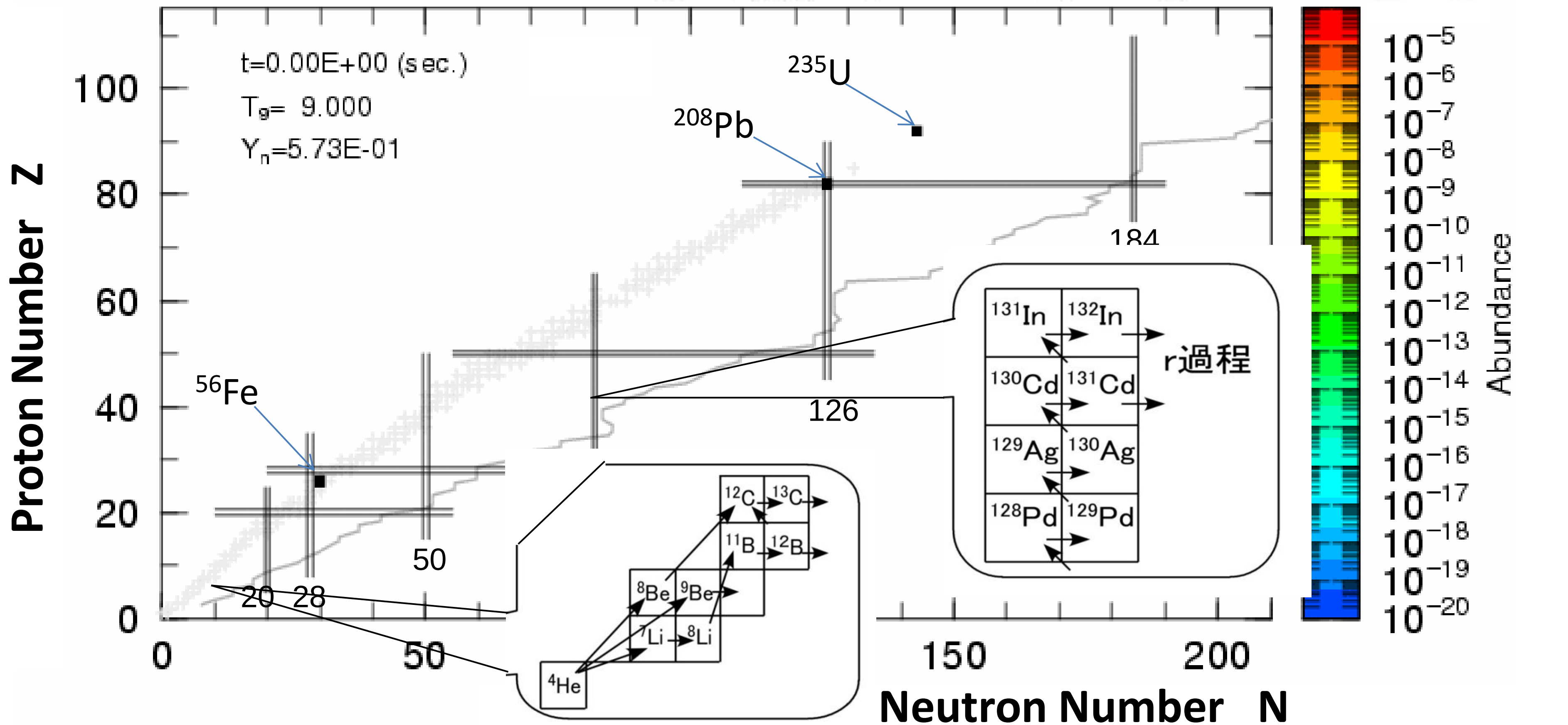
Burbidge^2, Fowler & Hoyle, Rev. Mod. Phys. 29 (1957), 547-650.
Alpher, Bethe & Gamow, Phys. Rev. 73 (1958), 803.





MHD-Jet Supernova

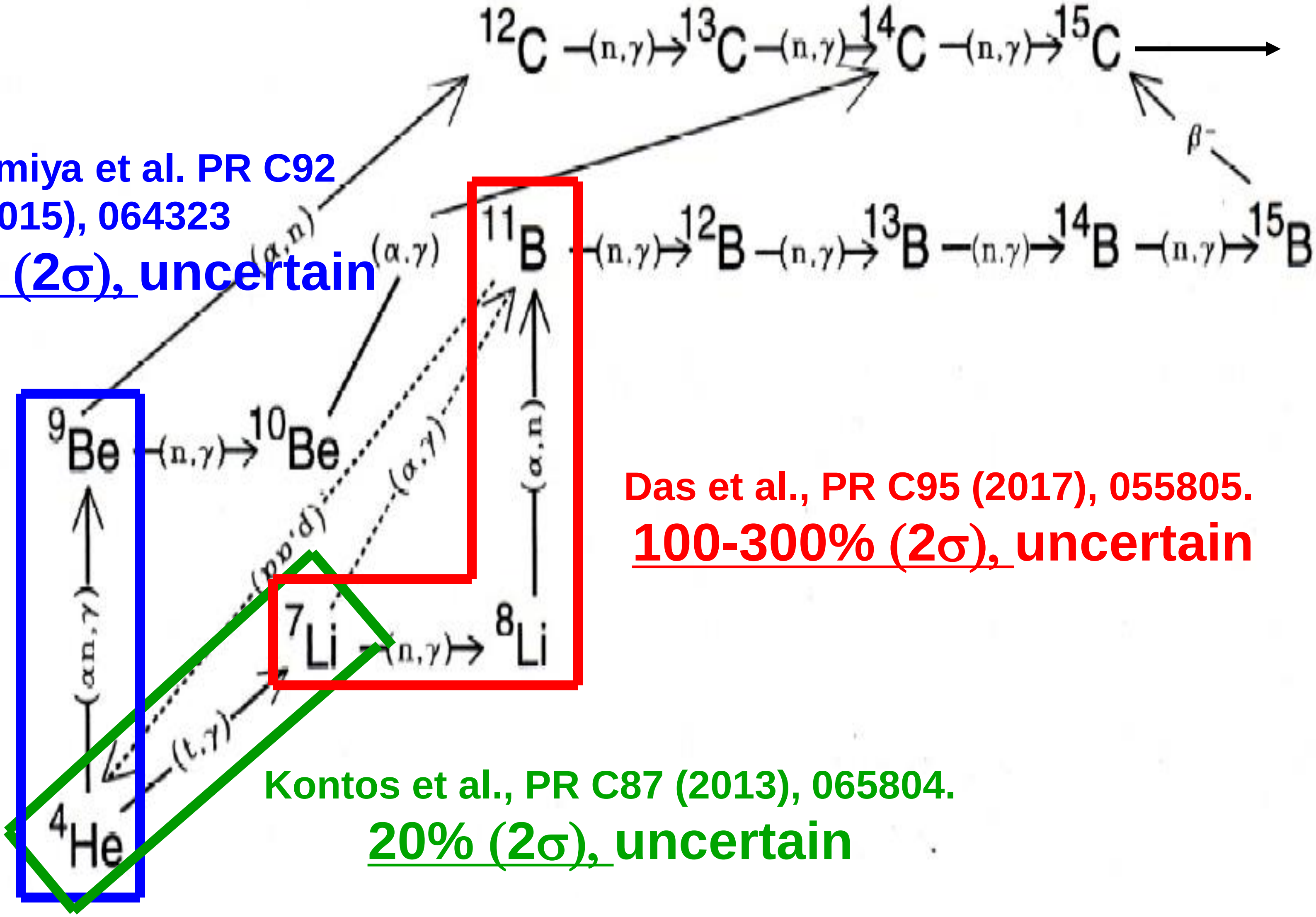




Important Reaction Flows, affecting R-Process

Factor x2 change could lead to 10^{1-2} difference in r-elements !

Kim et al., (2017), on-going project at RAON/RISP/IBS.



Utsunomiya et al. PR C92 (2015), 064323

30-50% (2σ), uncertain

Das et al., PR C95 (2017), 055805.

100-300% (2σ), uncertain

Kontos et al., PR C87 (2013), 065804.

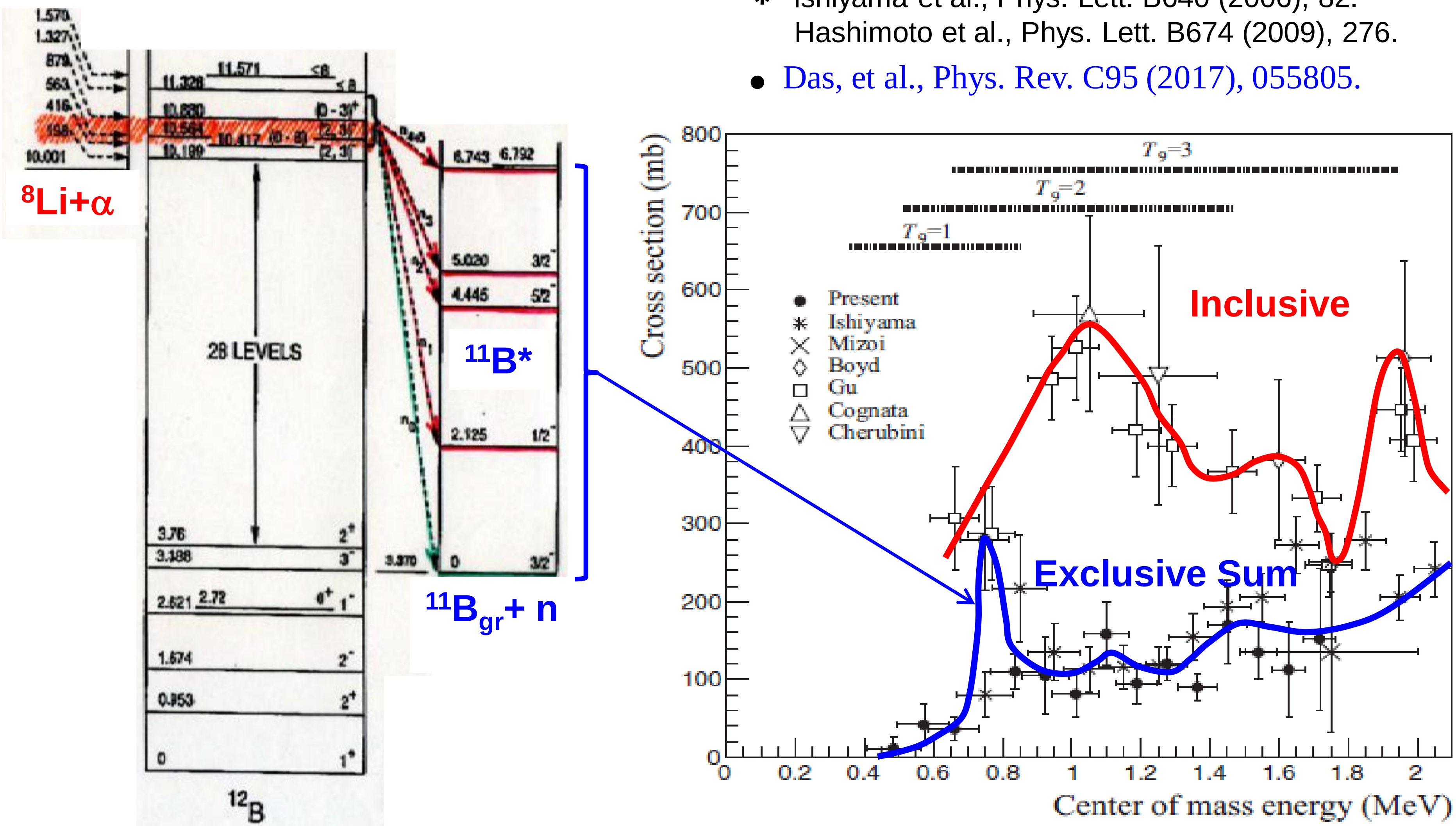
20% (2σ), uncertain

$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

Discrepancy
Inclusive > Exclusive Sum ?

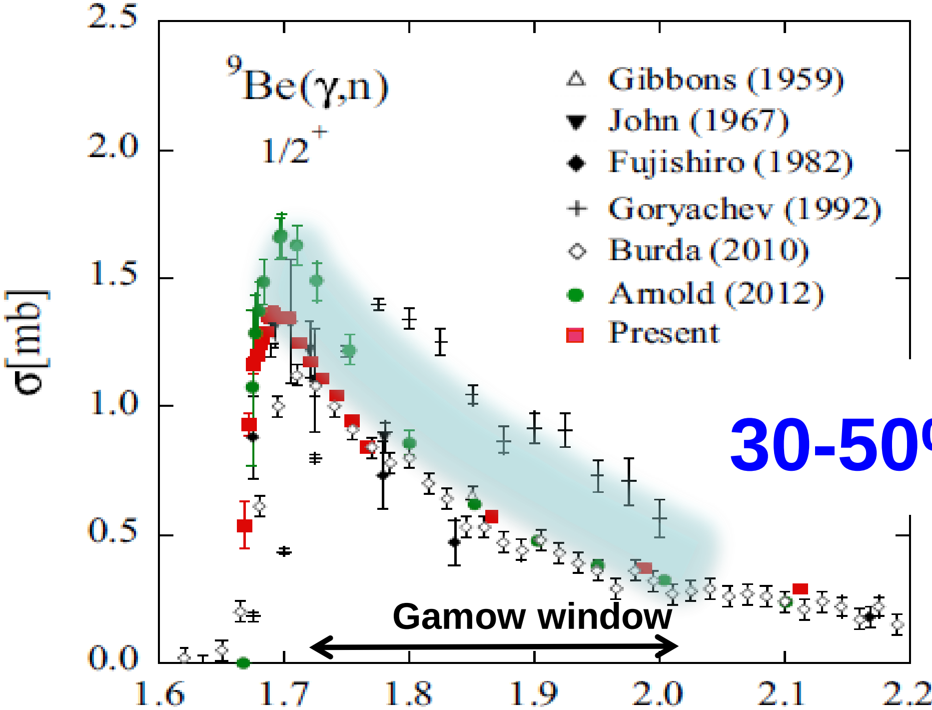
100-300% (2σ), uncertain !

- ◇ Boyd et al. Phys. Rev. Lett. 68 (1992), 1283.
- △ LaCognata et al., Phys. Lett. B664 (2008), 157.
- □ Gu et al., Phys. Lett. B343 (1995), 31.
- ∗ Ishiyama et al., Phys. Lett. B640 (2006), 82.
  Hashimoto et al., Phys. Lett. B674 (2009), 276.
- ● Das, et al., Phys. Rev. C95 (2017), 055805.



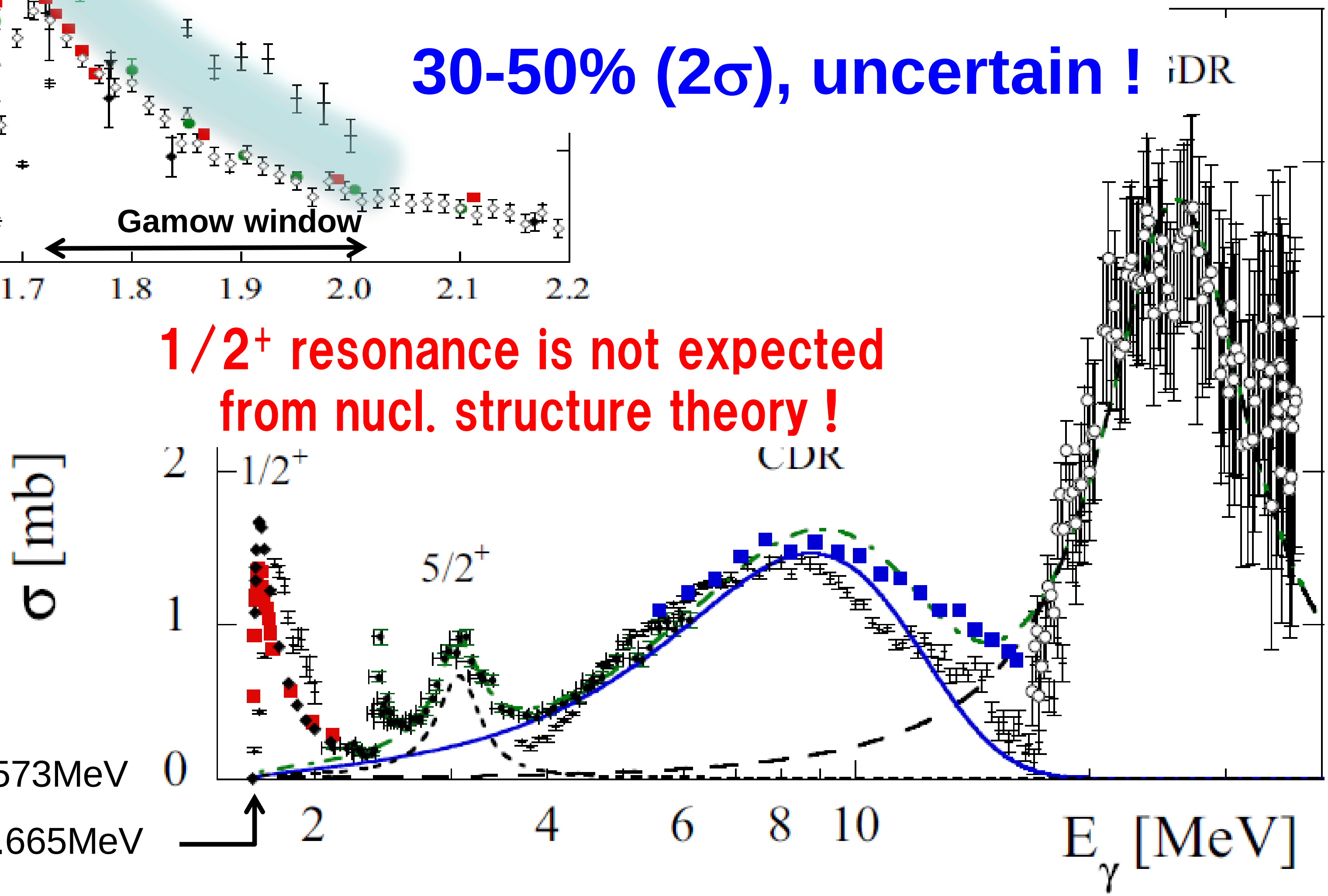
$^{9}Be(\gamma,n)2\alpha$

Utsunomiya et al.,
PRC92 (2015), 064323.



30-50% (2σ), uncertain !

1/2⁺ resonance is not expected from nucl. structure theory !



$E_{th}(n+2\alpha)$=1.573MeV

$E_{th}(n+^{8}Be)$=1.665MeV

$^{4}He(^{3}He,\gamma)^{7}Be$

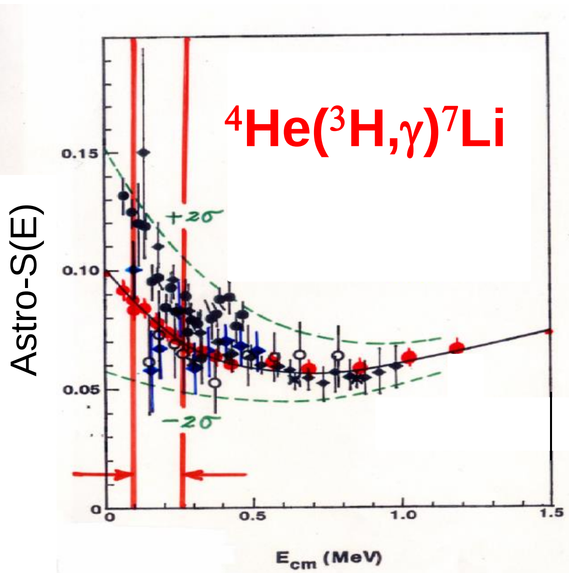
E.G. Adelberger, Rev. Mod. Phys. 83 (2011), 195.

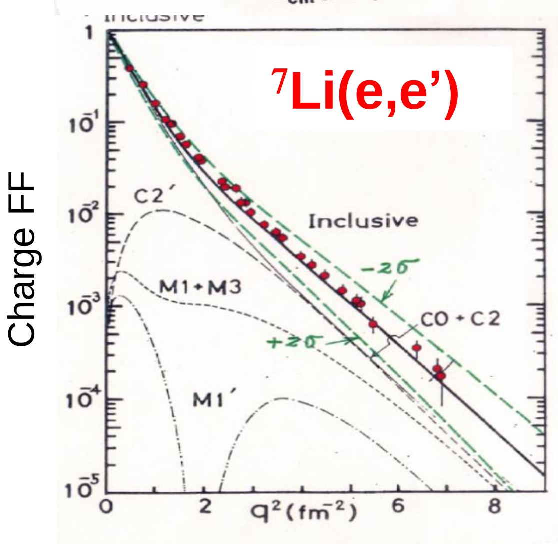
5% (1σ), uncertain !

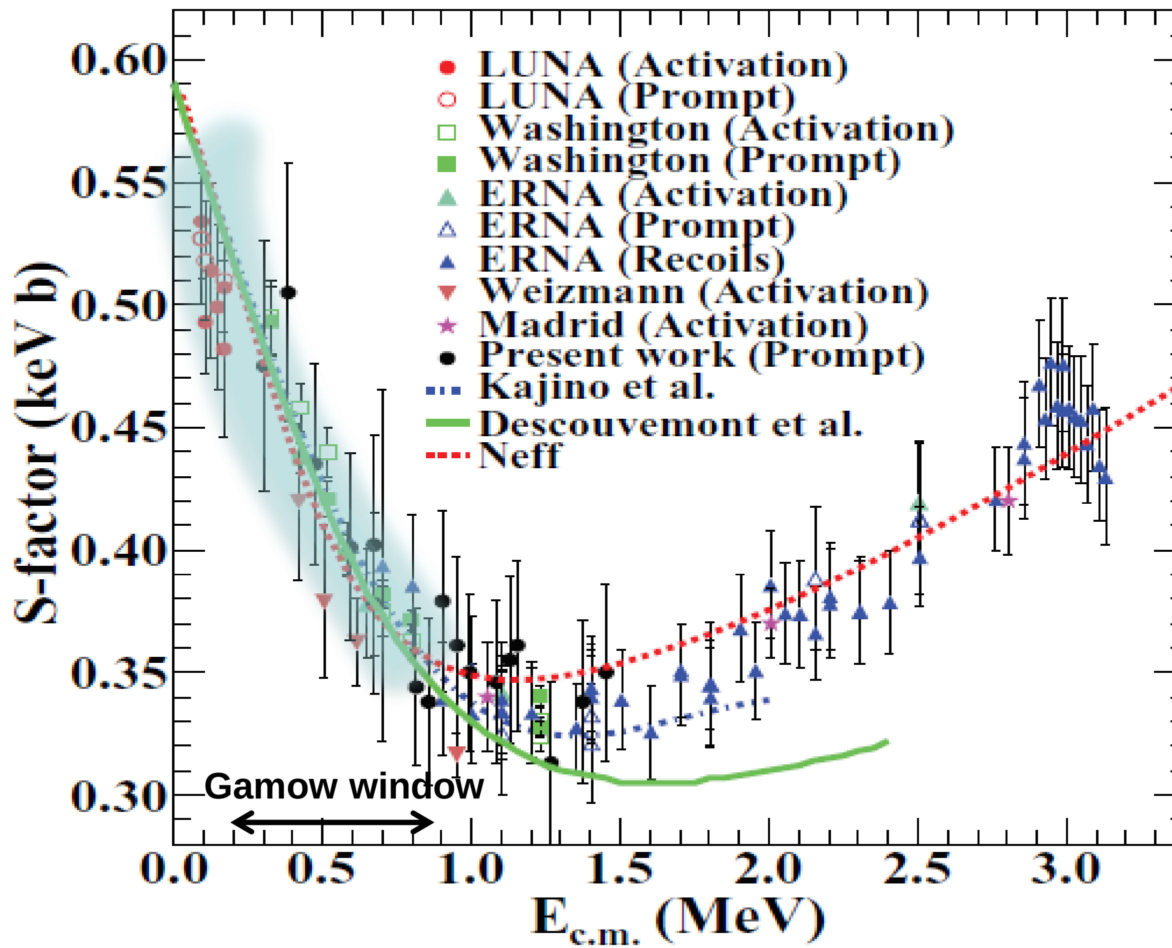
A. Kontos et al., PRC87 (2013), 065804.

20% (2σ), uncertain !

Charge Conjugation
^{7}Be and ^{7}Li

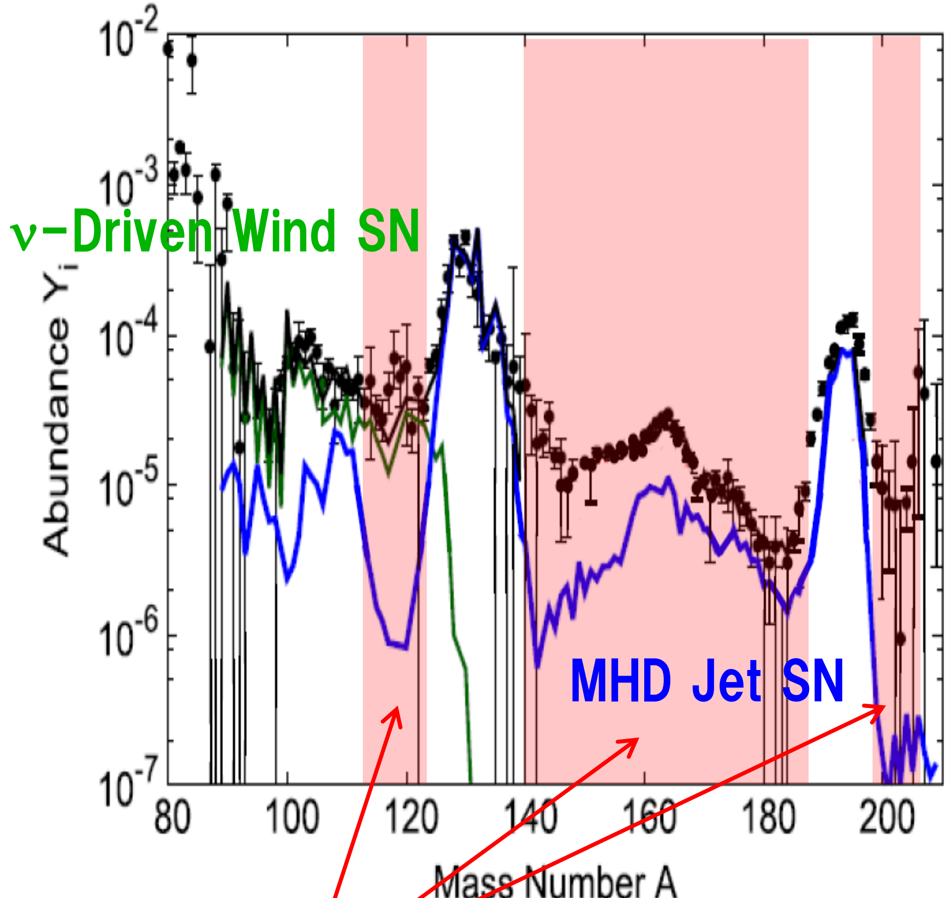


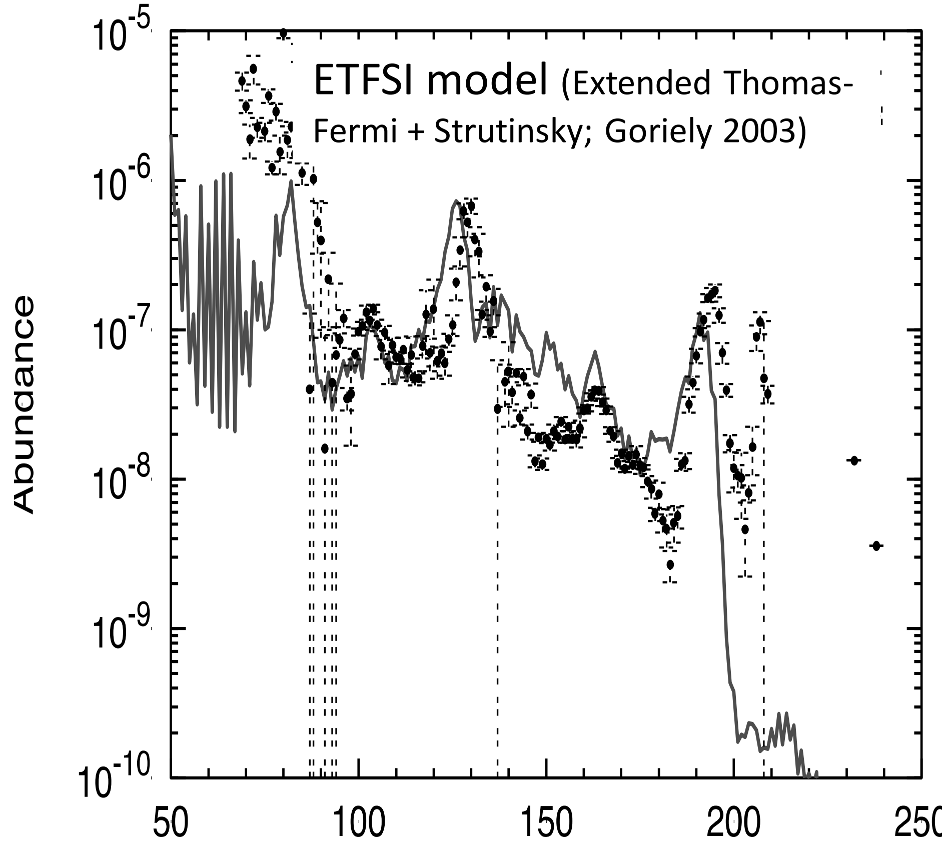




Magneto-Hydrodynamic Jets (MHDJ-SN)

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**

Nucl. Phys. − Shell Quenching ?
or
Another Site (NSM) ?

RIKEN-RIBF : Decay Spectroscopy around A = 100-145

G. Lorusso et al., PRL 114 (2015), 192501.

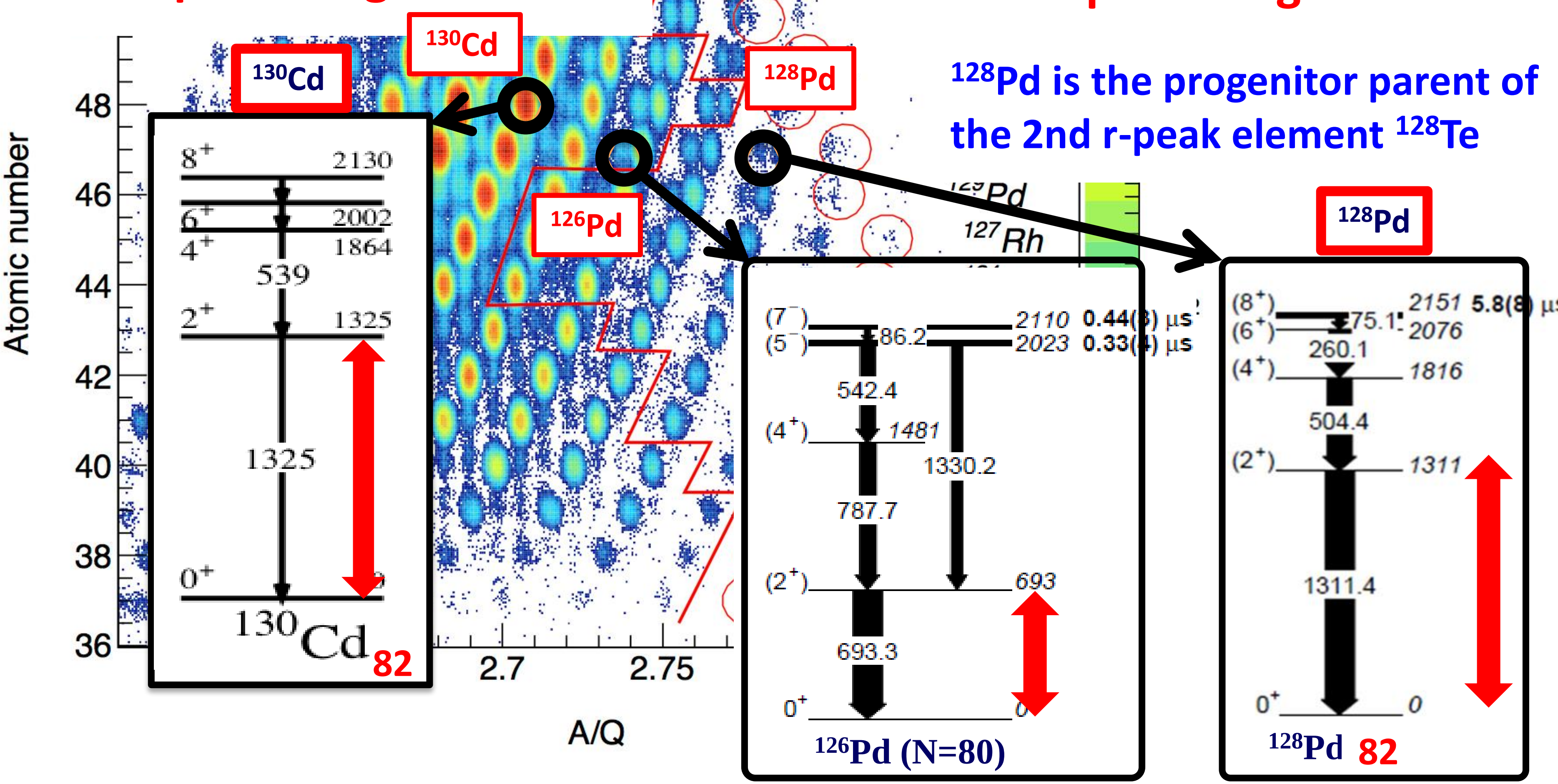
A.Jungclaus, PRL99, (2007)

No clear evidence for shell quenching on N=82!

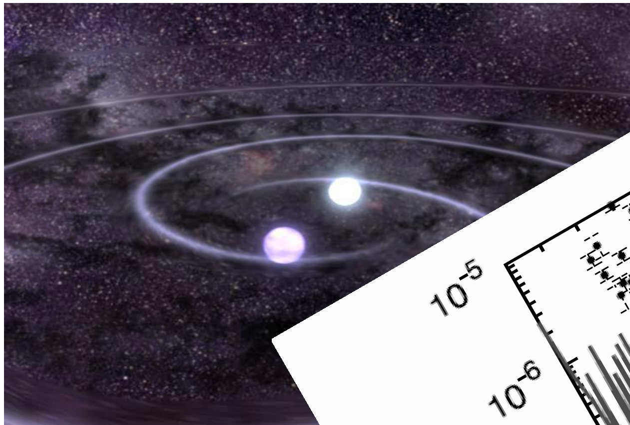
H. Watanabe et al., PRL111 (2013)

No clear evidence for shell quenching on N=82 !

^{128}Pd is the progenitor parent of the 2nd r-peak element ^{128}Te



Binary Neutron S... ers

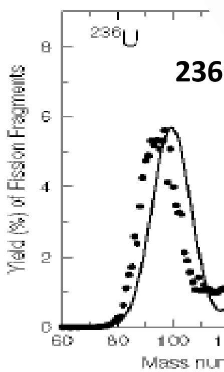


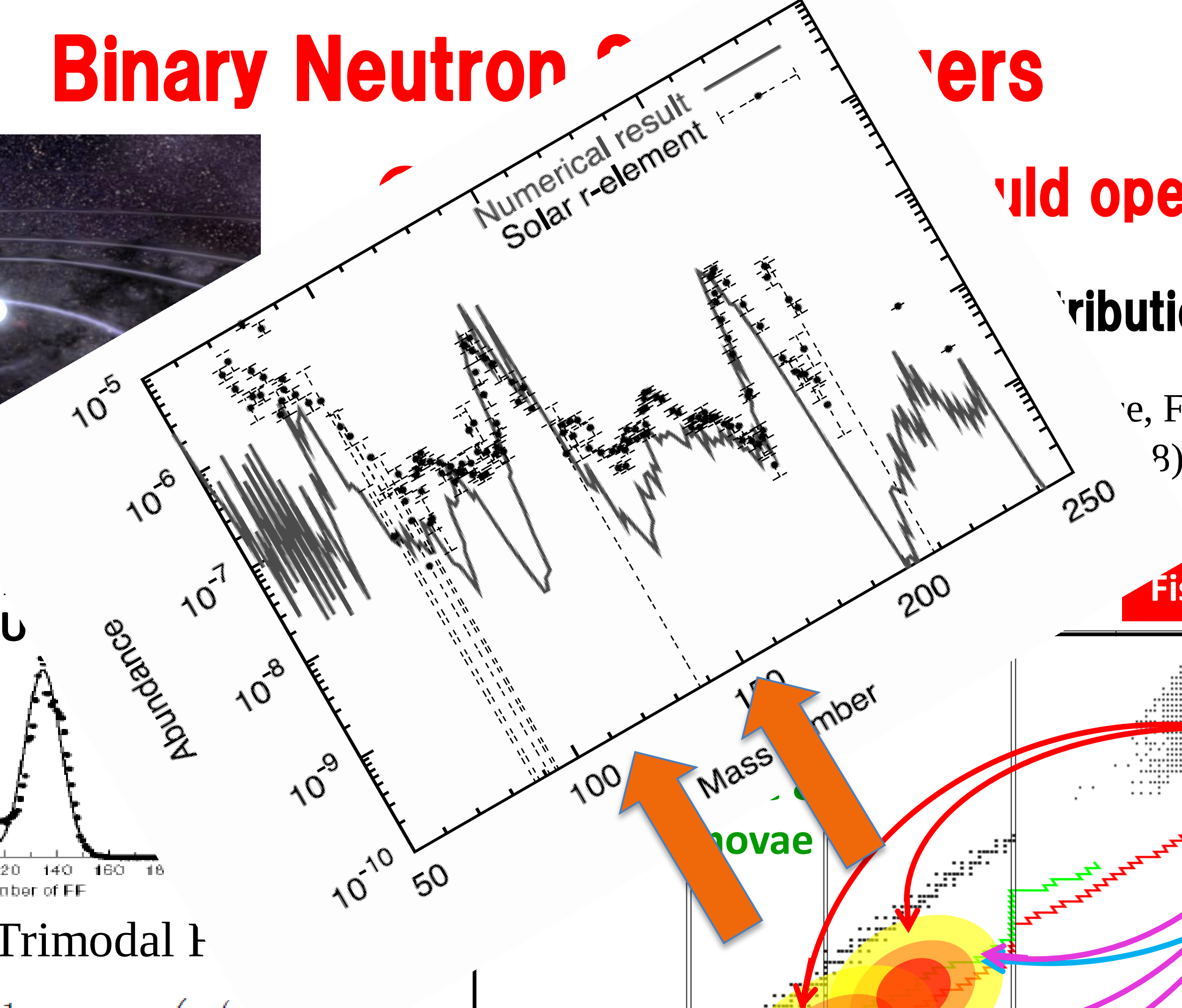
...uld operate!

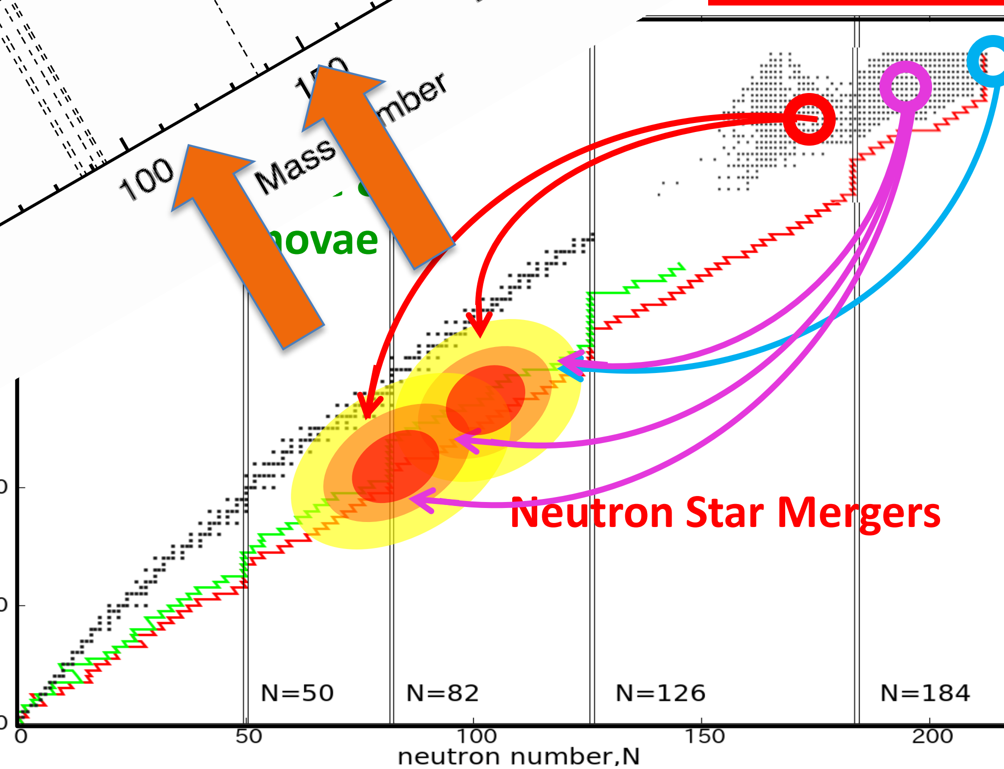
...ribution

...e, France, (2007)

...8).







Bimordial or Trimodal I...

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

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

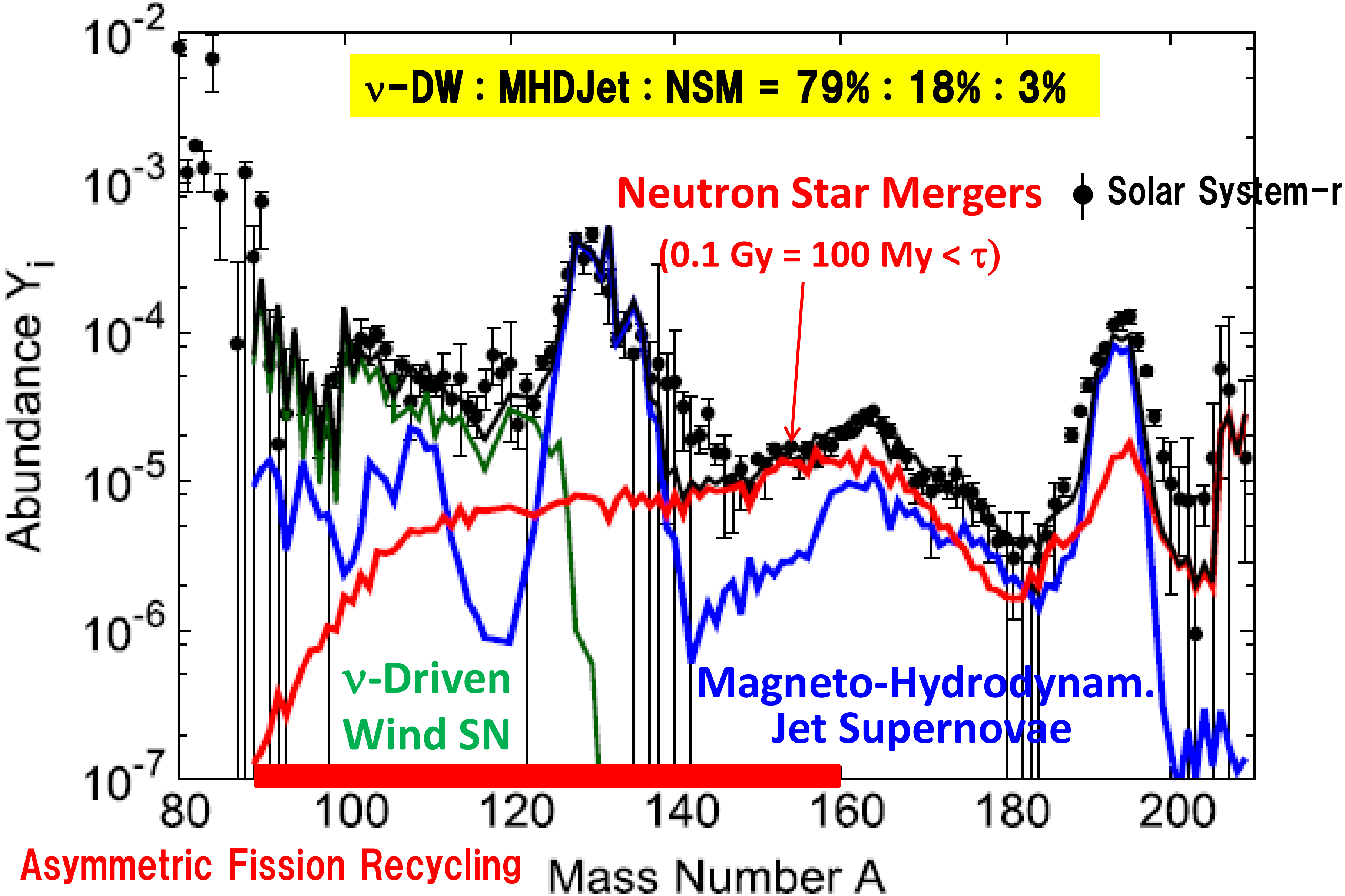
$$A_L = (1-\alpha)(A_p - N_{loss})/2$$

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

Solar System r-Process Abundance

Present t = 13.8Gy

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.



Observed Galactic event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]

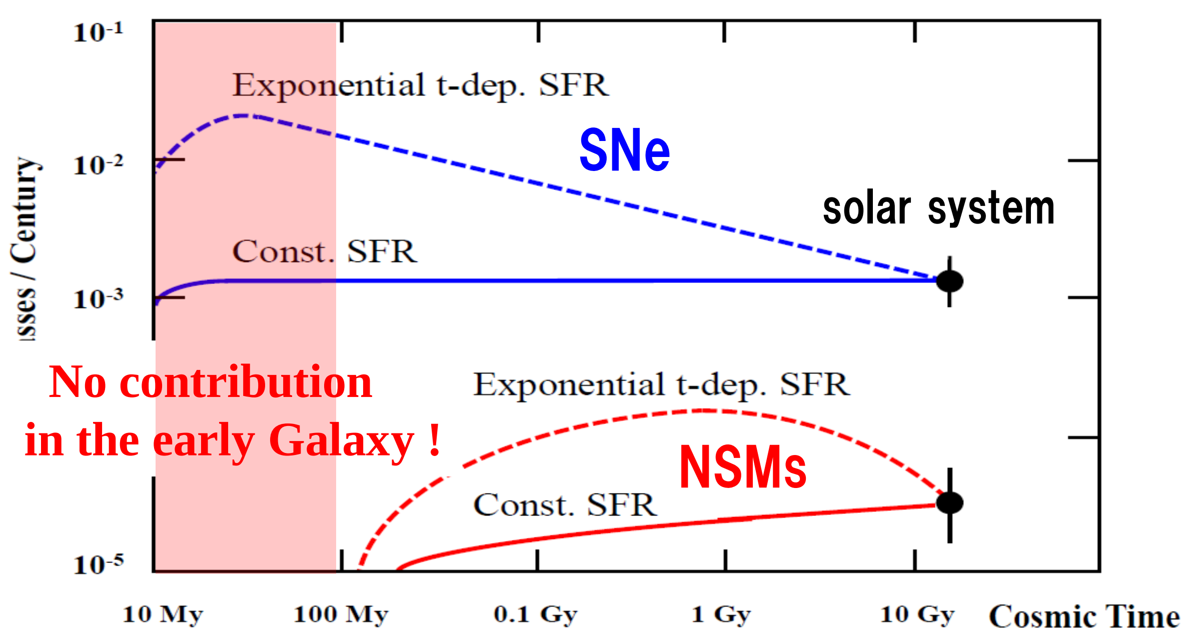
νSN (Weak r)	=	7.4×10^{-4}	x	(1.9 ± 1.1) [a]
MHD Jet SNe	=	0.6×10^{-2}	x	$((0.03 \pm 0.02) \times (1.9 \pm 1.1))$ [b]
Binary NSMs	=	$(2 \pm 1) \times 10^{-2}$	x	$(1\text{-}28) \times 10^{-3}$ [c]

Observations	a	1.9 ± 1.1	Diehl, et al., Nature 439, 45 (2006).
	b	0.03 ± 0.02	Winteler, et al., ApJ 750, L22 (2012).
Obs. Estimate	c	$(1\text{-}28) \times 10^{-3}$	Kalogera, et al., ApJ 614, L137 (2004).

Event rates including Binary Evolution

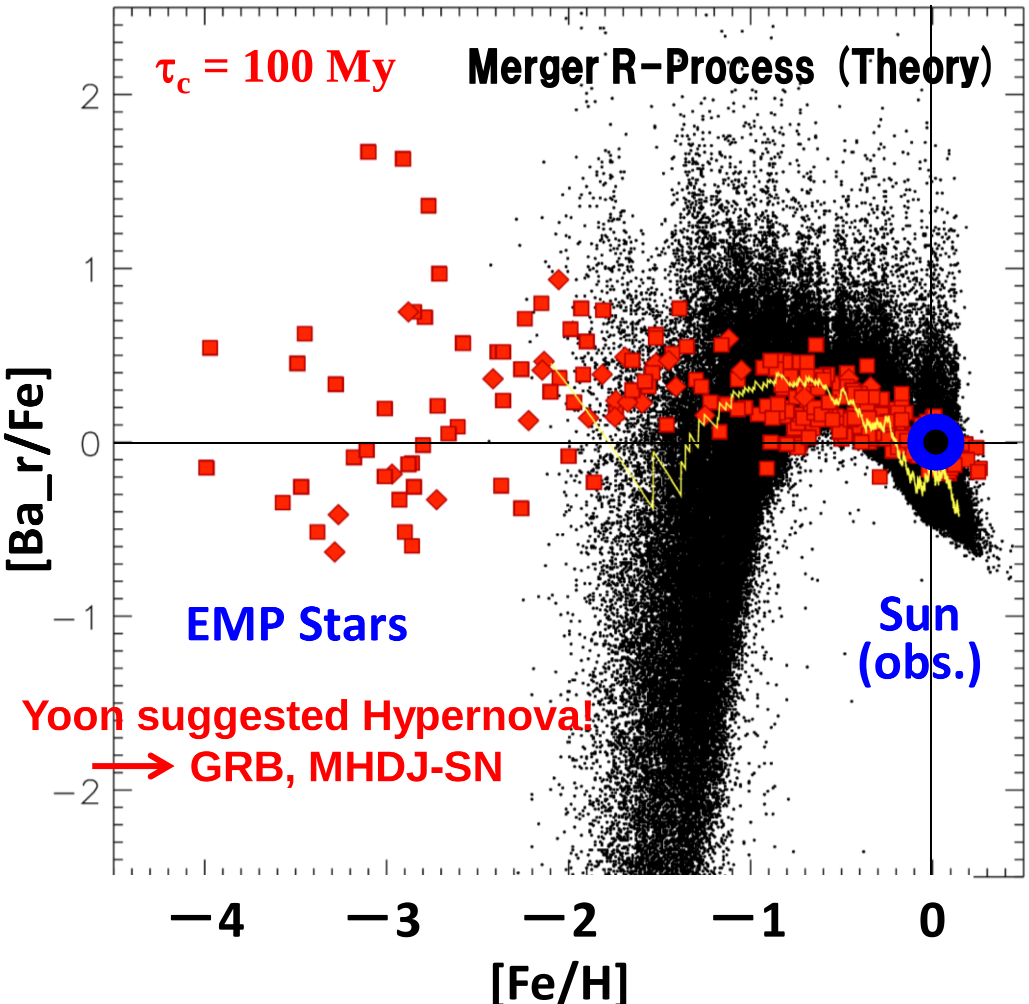
Kajino & Mathews, Rep. Prog. Phys. **80** (2017) 08490; Mathews & Kajino, (1987).

Time Scale Problem in Neutron Star Mergers



Time Scale Problem

Argast, et al., A&A 416 (2004), 997,
Wehmeyer et al., MNRAS, 452 (2015), 1970.



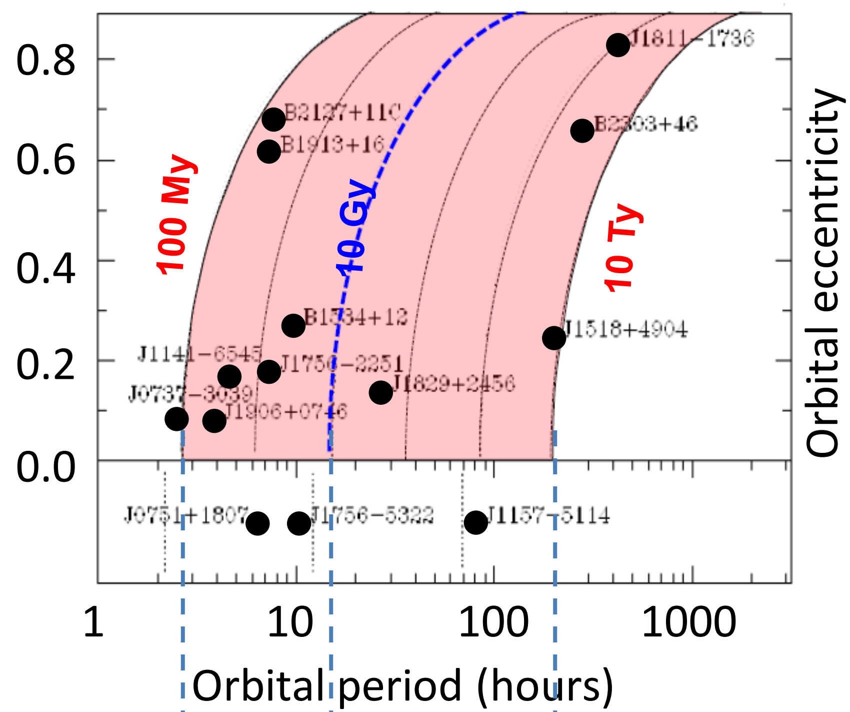
τ_{life} (10-30M$_\odot$)

1My 10My 100My ・・・ 10Gy

Binary merger process, too slow for GW radiation: 100My<τ_C

$$\tau_c \simeq 9.83 \times 10^6 \text{ yr} \left(\frac{P_b}{\text{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$$

Lorimer, Living Rev. Rel. 11(2008), 8.



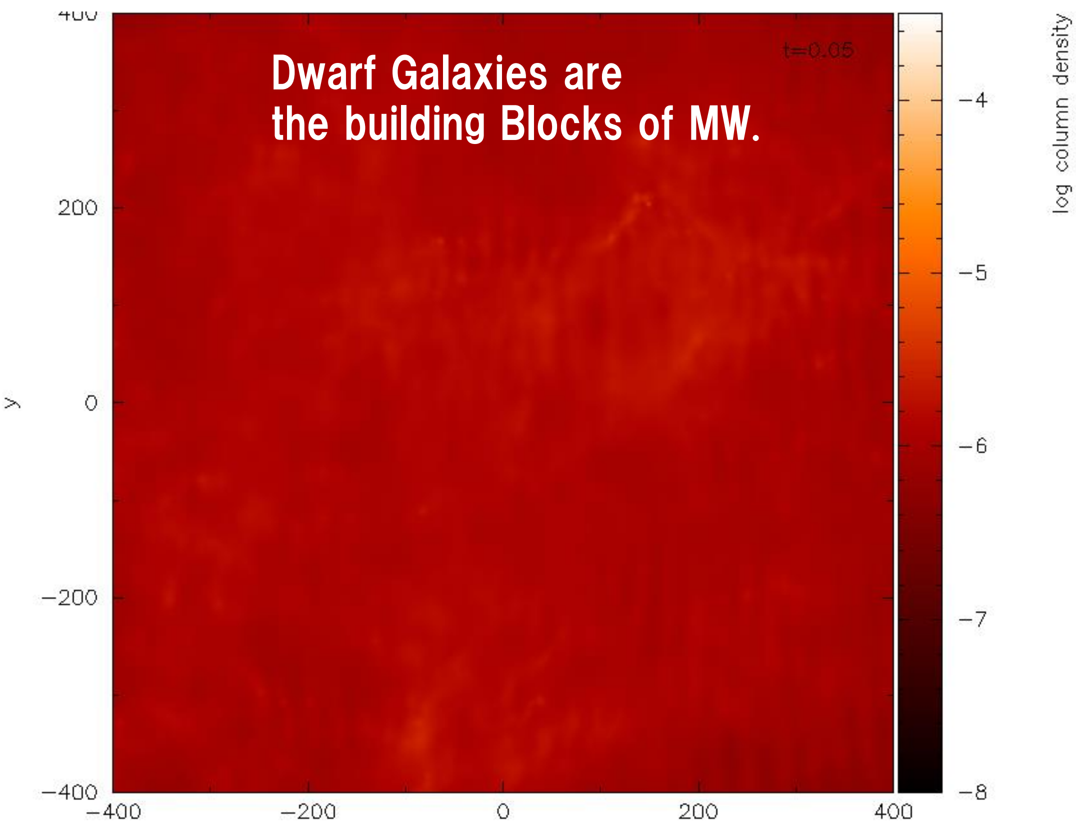
100My 10Gy 10Ty

SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution

Komiya & Shigeyama, ApJ 830, 10 (2016).

Mixing of r-elements between neighboring Dwarf Galaxies is limited to only 0.001-0.1% for [Fe/H] < -3.5.

Mathews et al., MPL A29 (2014), 1430012-118.

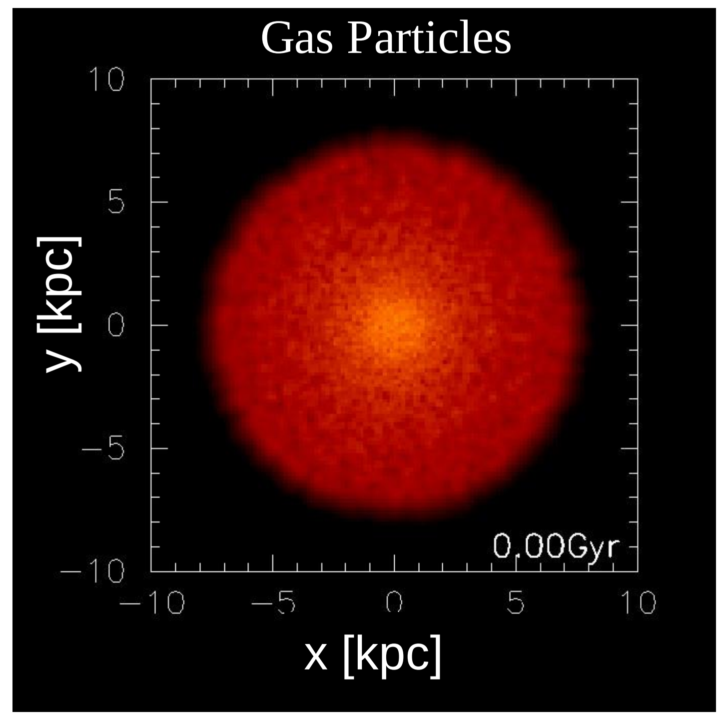


Evolution of Single Dwarf Galaxy

N-Body/SPH Simulation DM + GAS + Star Particles with GAS-MIXING in the star forming region.

Hirai et al., ApJ 814 (2015), 41; MNRAS 466 (2017) 2474.

$M_{tot} = 7x10^8 M_{sun}$, $N_i = 5x10^5$ particles,
$M_\star = 100 M_{sun}$



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

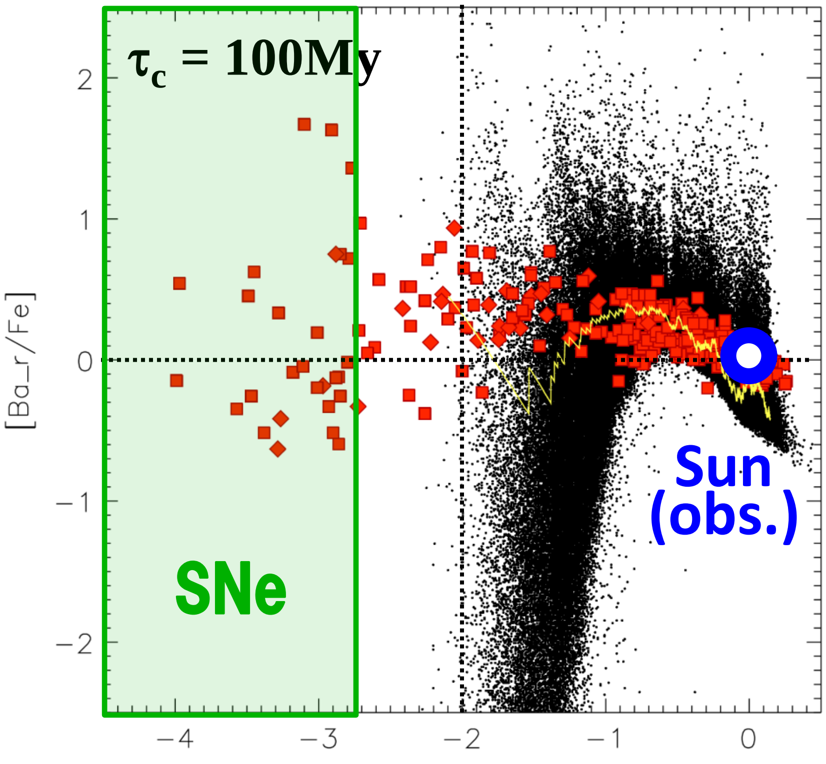
N-Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.
SNe = Metals ; NSM (τ_c=100My) = r-process elements. (n_H >100 cm^{-3} → ~10-100pc)

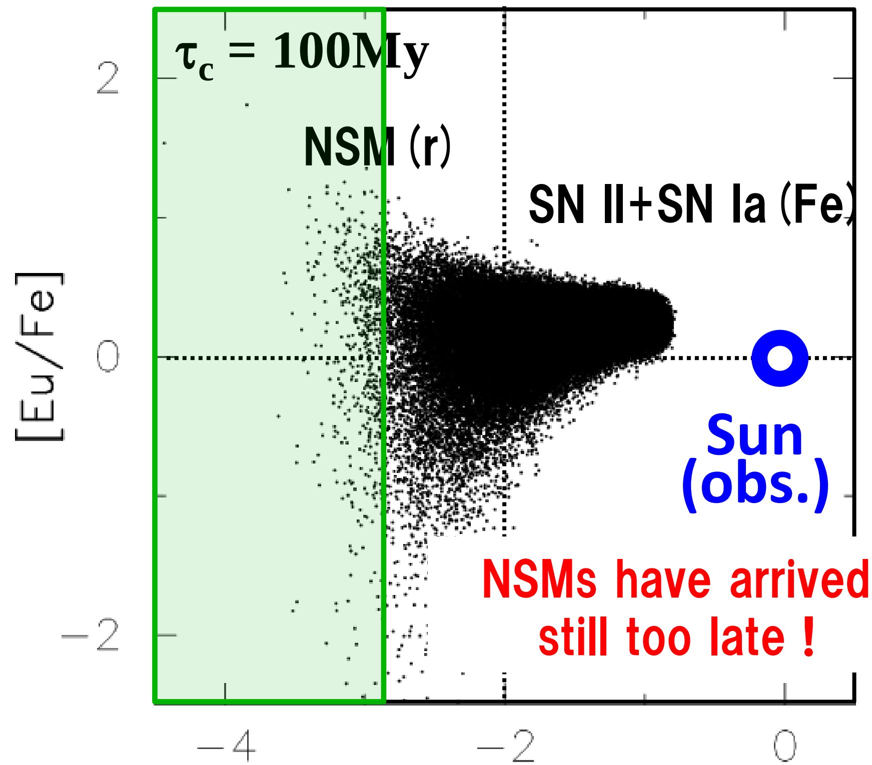
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino, ApJ 814 (2015), 41; MNRAS 466 (2017), 2474.

Without GAS MIXING

With GAS MIXING



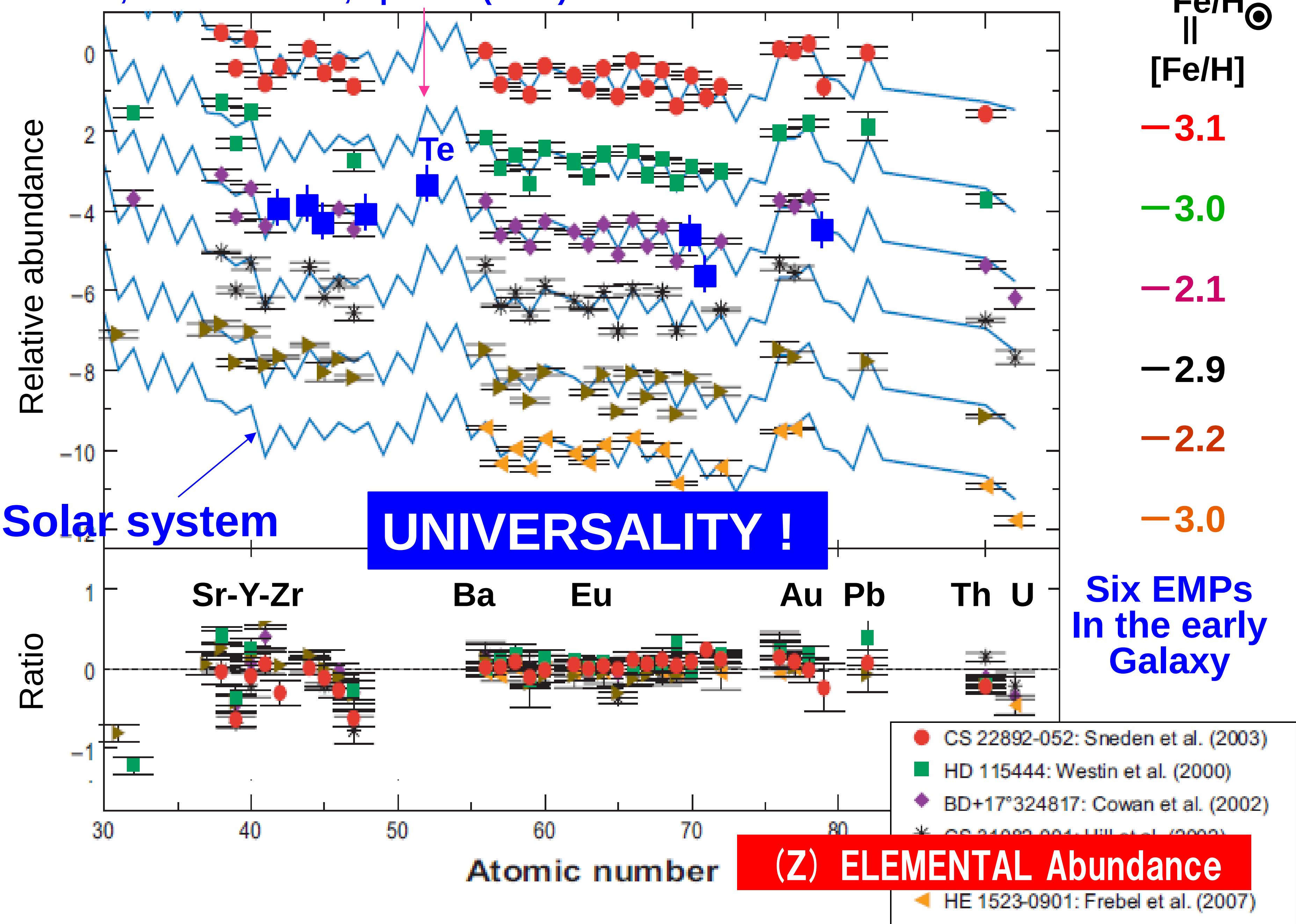


Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

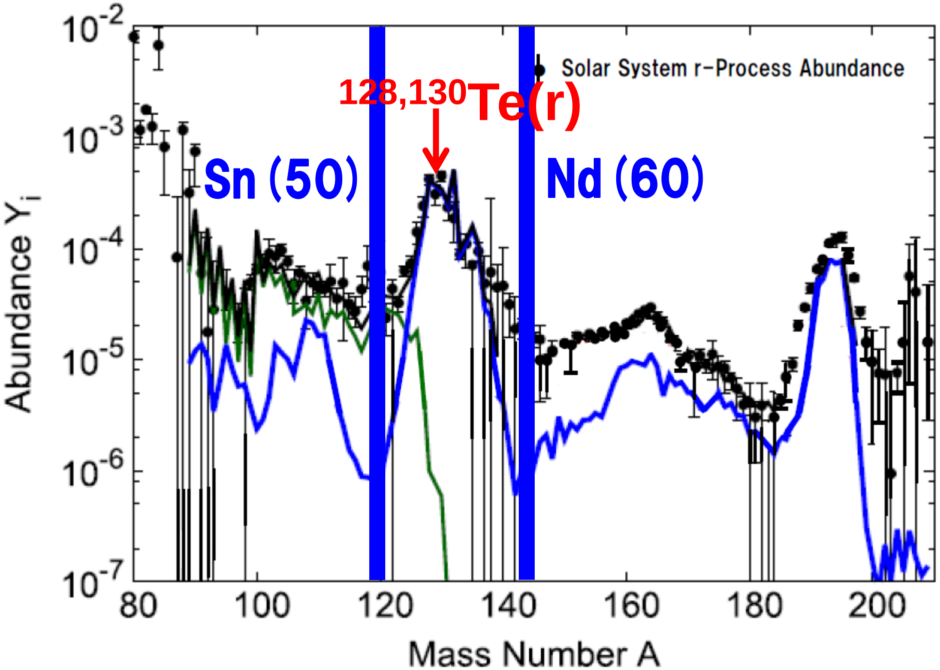
HST-obs., Roederer et al., ApJ 747 (2012) L8.

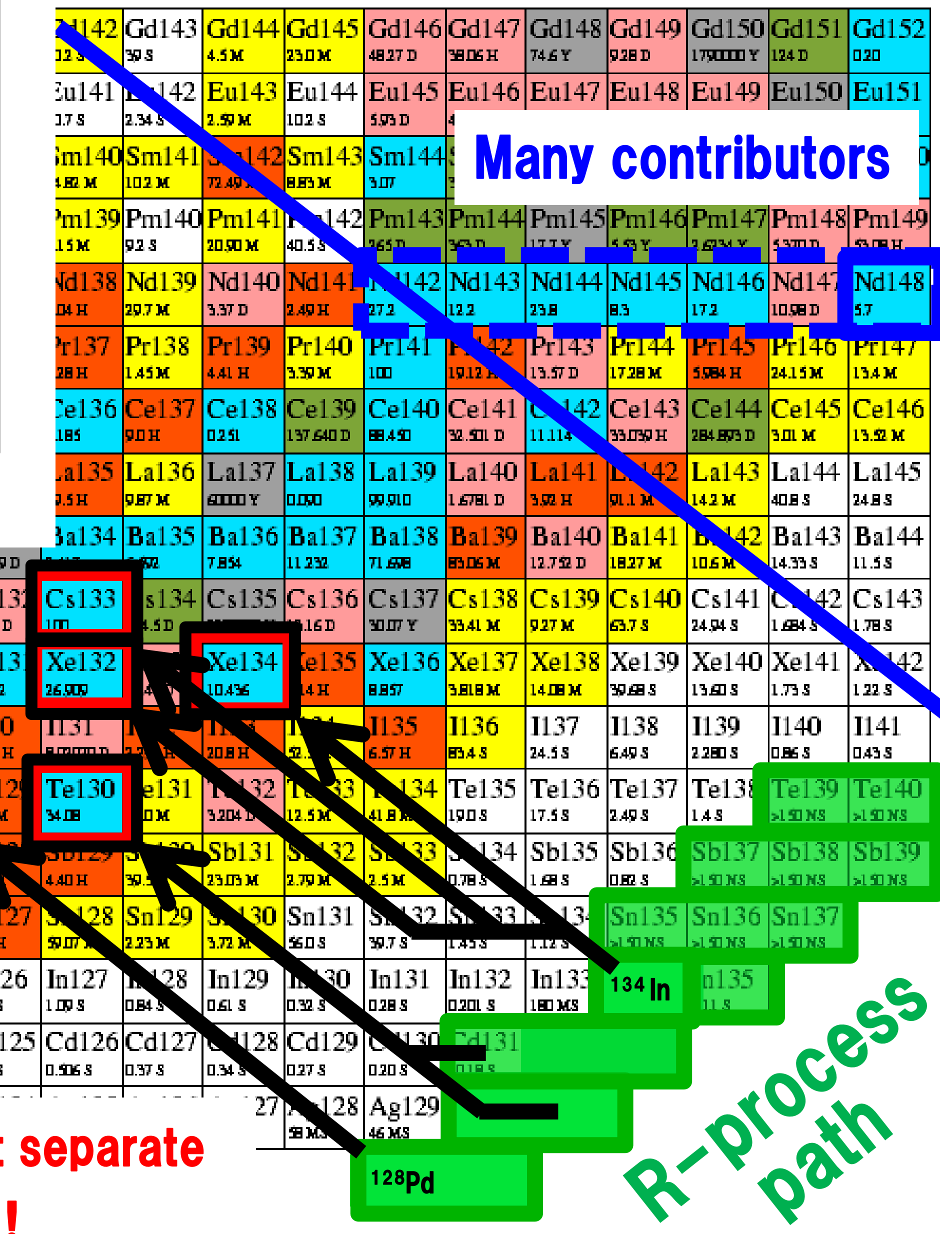
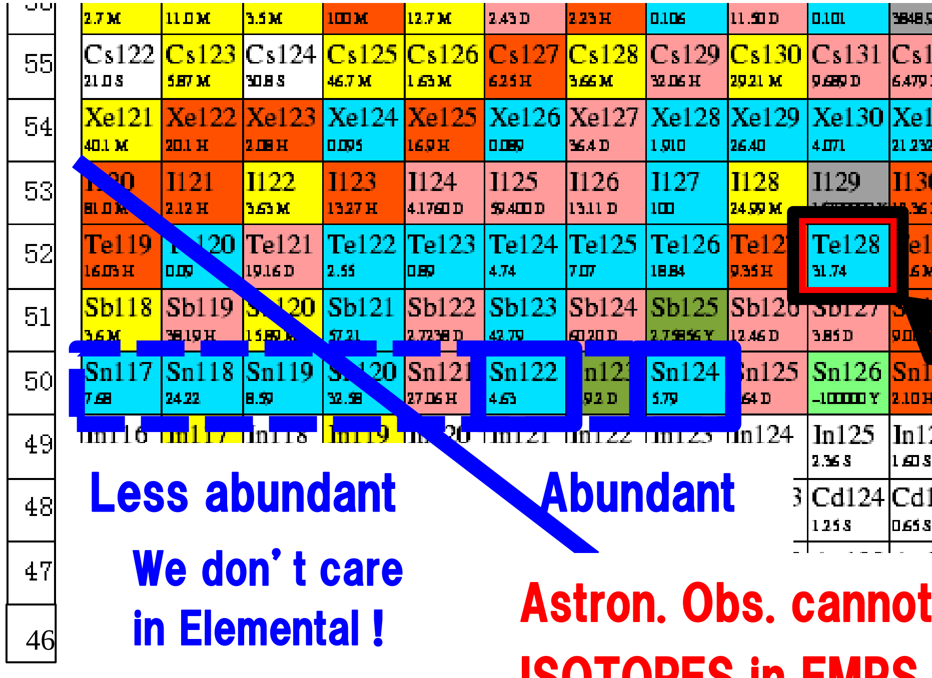
$$\frac{t}{10^{10}y} \fallingdotseq 10^{[Fe/H]}$$

$$\log \frac{Fe/H_{☆}}{Fe/H_{\odot}} = [Fe/H]$$



Lorusso, Nishimura, Kajino et al. (2015), PRL 114, 192501.

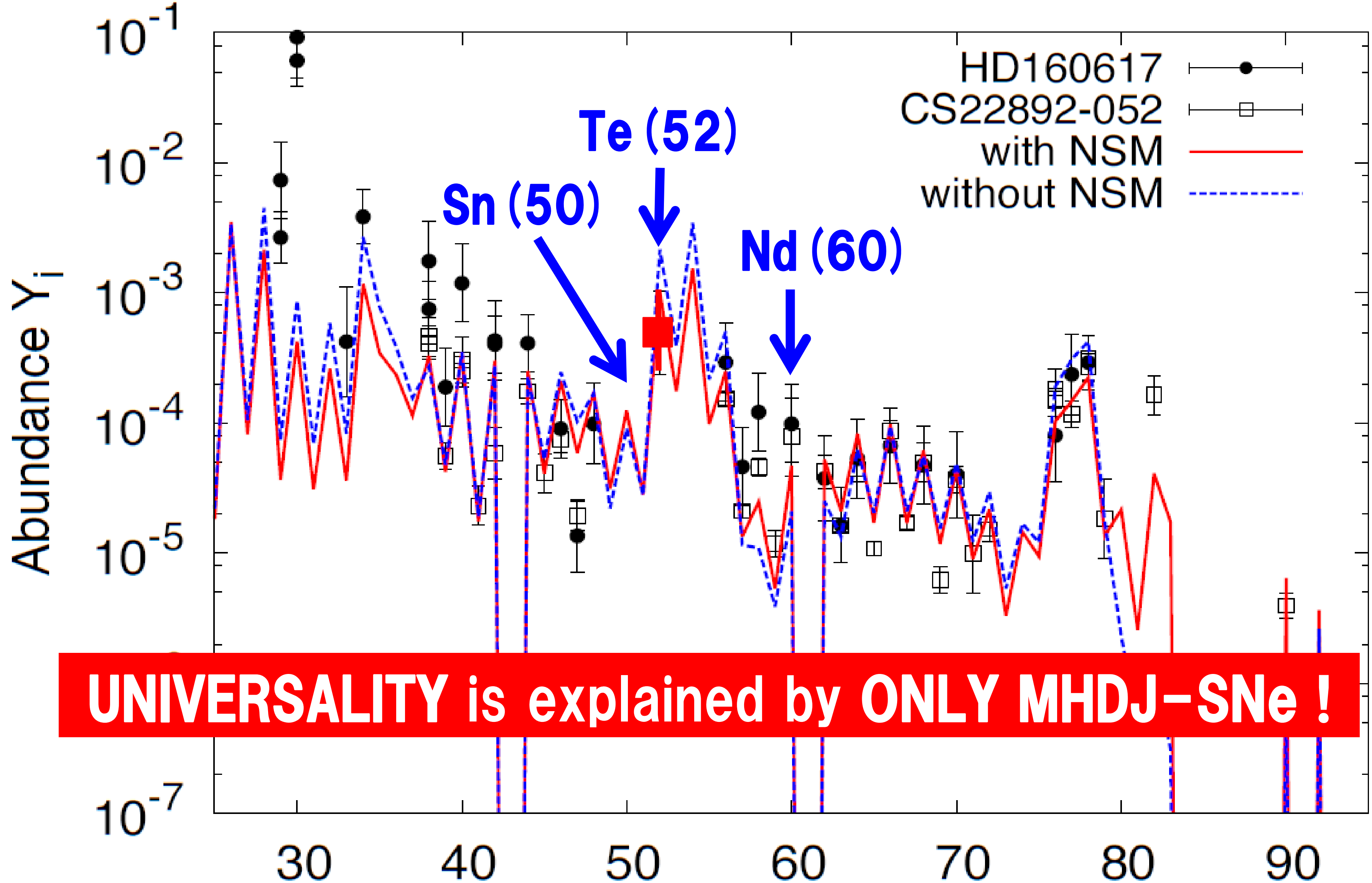


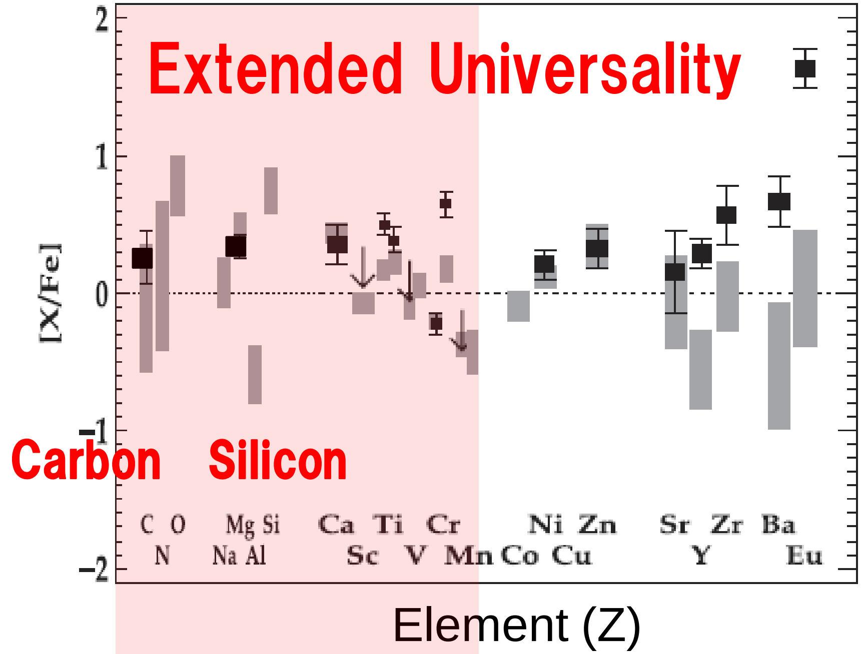
UNIVERSALITY !

Early Galaxy !

Shibagaki et al., ApJ. 816 (2016),79; Mathews & Kajino & Mathews, ROPP **80** (2017) 08490.



Astron. Obs. cannot separate ISOTOPES ! **Atomic Number Z** **ELEMENTAL (Z)**

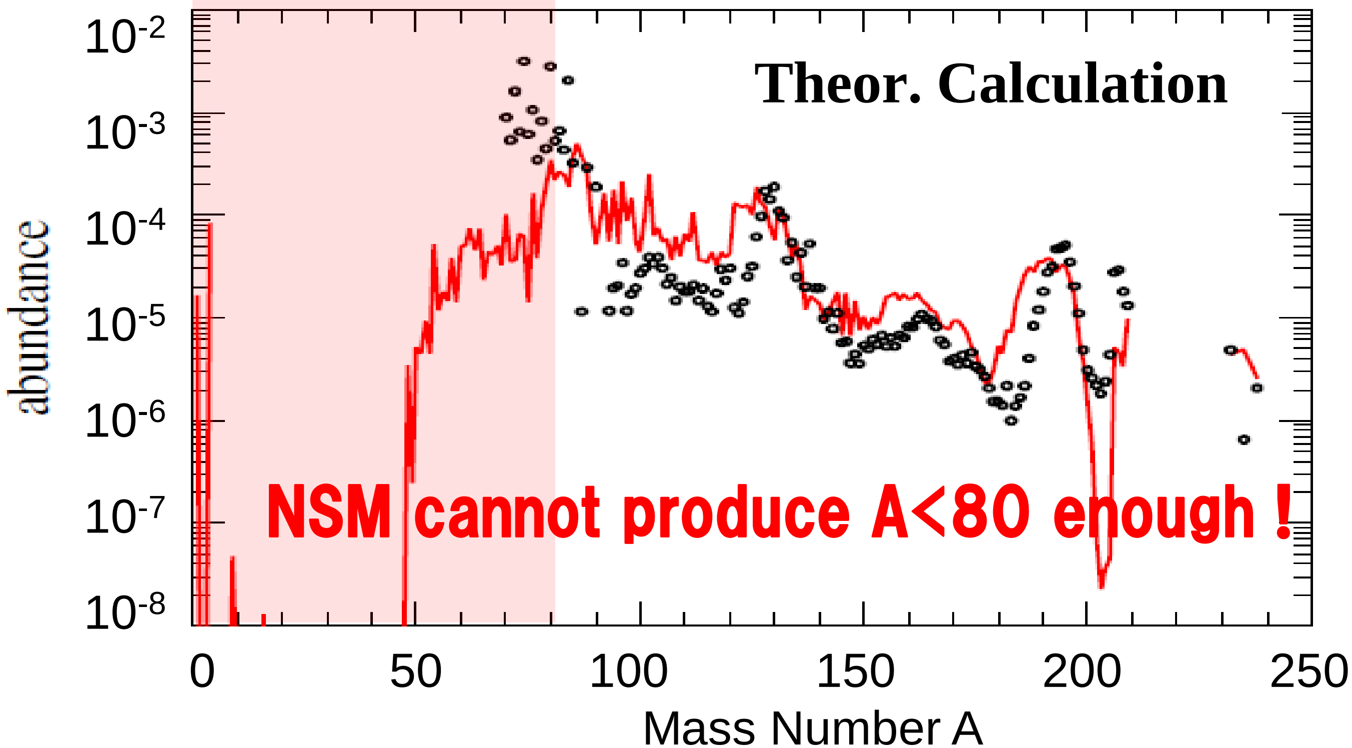


Ultra-Faint warf Galaxy: Ret. II

Astron. Observation

Ian U. Roederer et al., ApJ. 151 (2016), 82;
P. Ji Alexander, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610.

Wanajo et al., ApJ. 789 (2014), L39.
Shibagaki et al., ApJ. 816 (2016), 79; (2017)



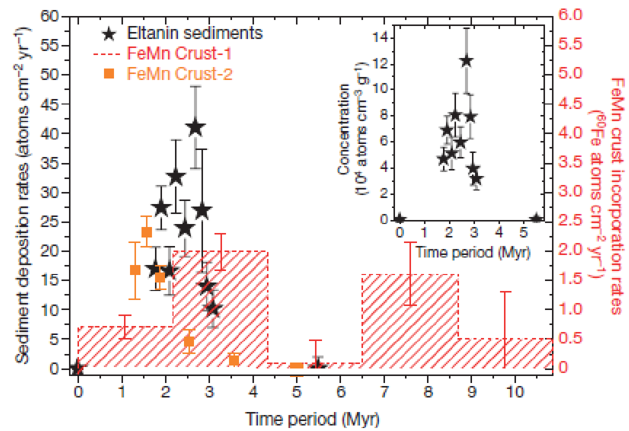
Goriely, et al., ApJ 738, L32 (2011); Korobkin, et al., MNRAS 426, 1940 (2012); Bauswein, et al., ApJ 773, 78 (2013); Rosswog, et al., MNRAS 430, 2585 (2013); Goriely, et al., PRL 111, 242502 (2013), (2015): Piran, et al., MNRAS 430, 2121 (2013).

Deep Sea Sediments & EMPS points DUALITY of SN & NSM !

^{244}Pu/^{60}Fe in Earth's Deep Sea Sediments → NSM/MHDJ : SNe = 1 : 100

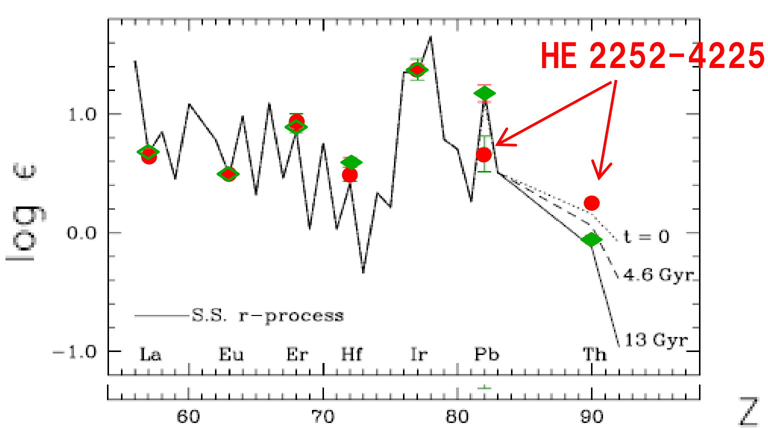
NSM, MHDJ —— ^{244}Pu (80.8 My) : Wallner et al., Nature Comm. 6 (2015), 1-9; NPA8 (2017)
ν-DW ———— ^{60}Fe (2.62 My) : Wallner et al. Nature 532 (2016), 69.

Over 25 My

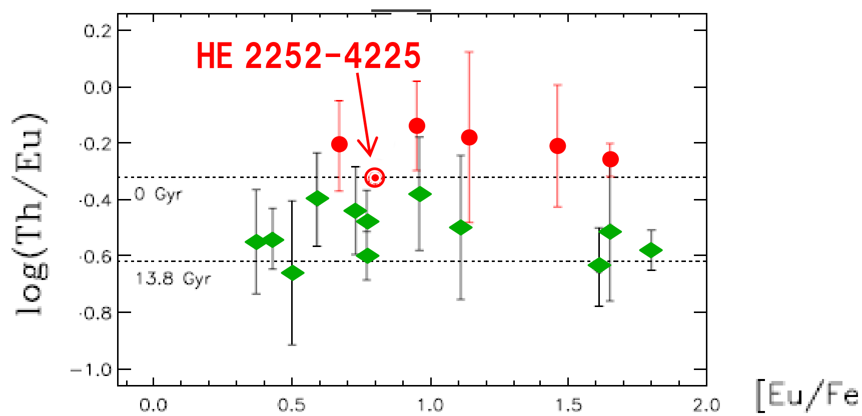


Actinide Boost EMP Stars needs "Fission-Recycling R-process in NSMs".

Mashonkina et al. A&A 569, A43 (2014)



Roederer et al. ApJ 698, 1963 (2009)
Hill et al., arXiv:1608.07463v1

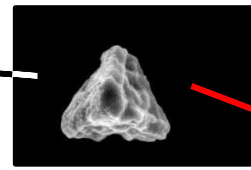


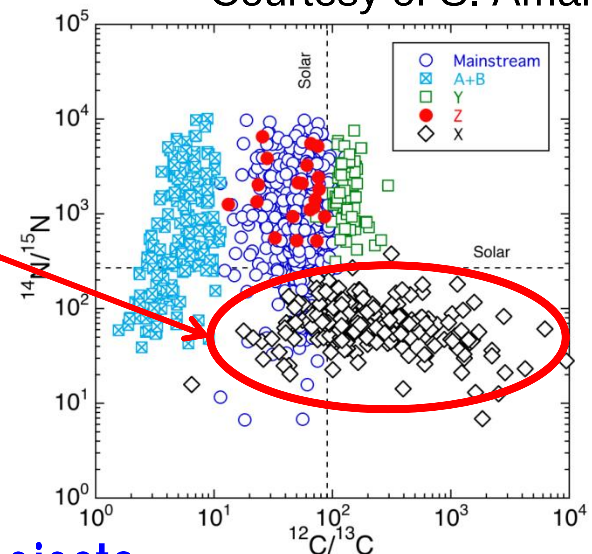
SiC X-Grain including heavy "r-process" elements, HARD to form from NSM Ejecta !

◎ Supernova Grains e.g. Murchison Meteorite

Courtesy of S. Amari

SiC X-grains





- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)

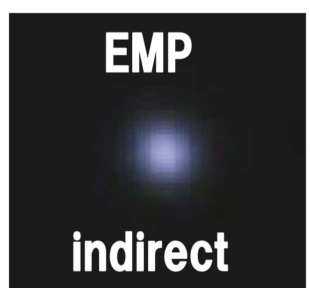
Pre-solar X-grains condense and form in SN ejecta.

■ SiC X-grain including r-elements ⟶ NSM ? SN !

■ If extended Universality manifests in [r/C-Si-Fe] = 0 ⟶ SN !

◎ Spectr. Astron. Obs.

Direct detection of C, Si & r-elements simultaneously !



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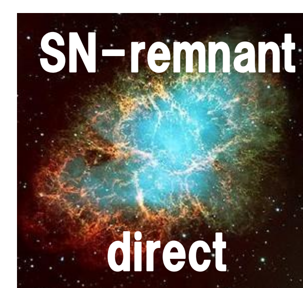
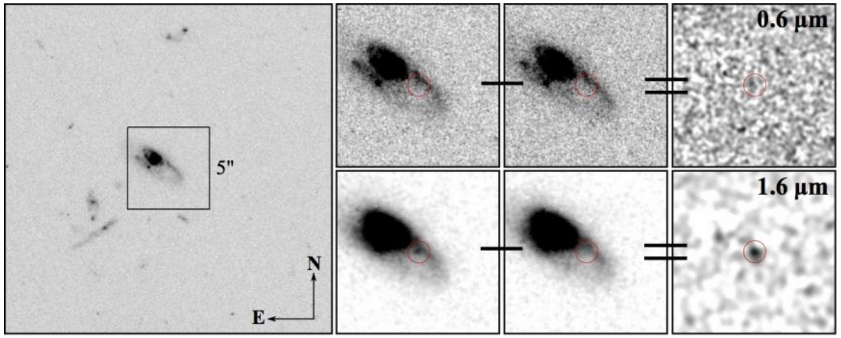


Another DIFFICULTY for Binary Neutron Star Mergers

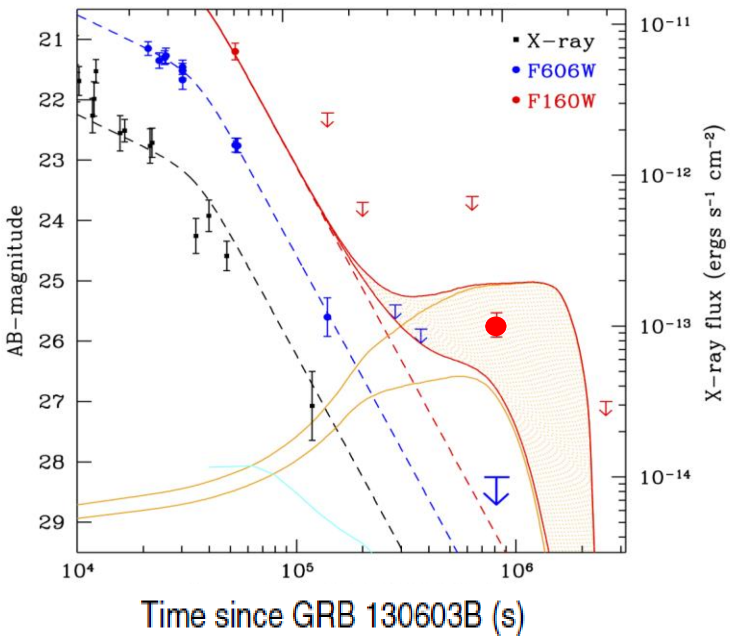


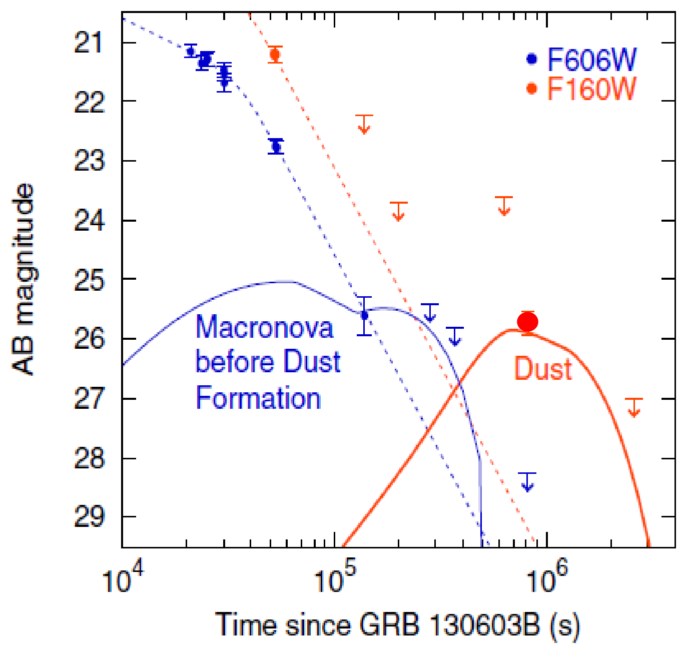
Macronova (Kilonova)

Tanvir, Levan, Fruchter, et al., Nature 500, 547 (2013)

Dust is hard to form for deficient C, Si and other lighter elements.

Takami, Nozawa & Ioka, ApJ 786, L5 (2014).



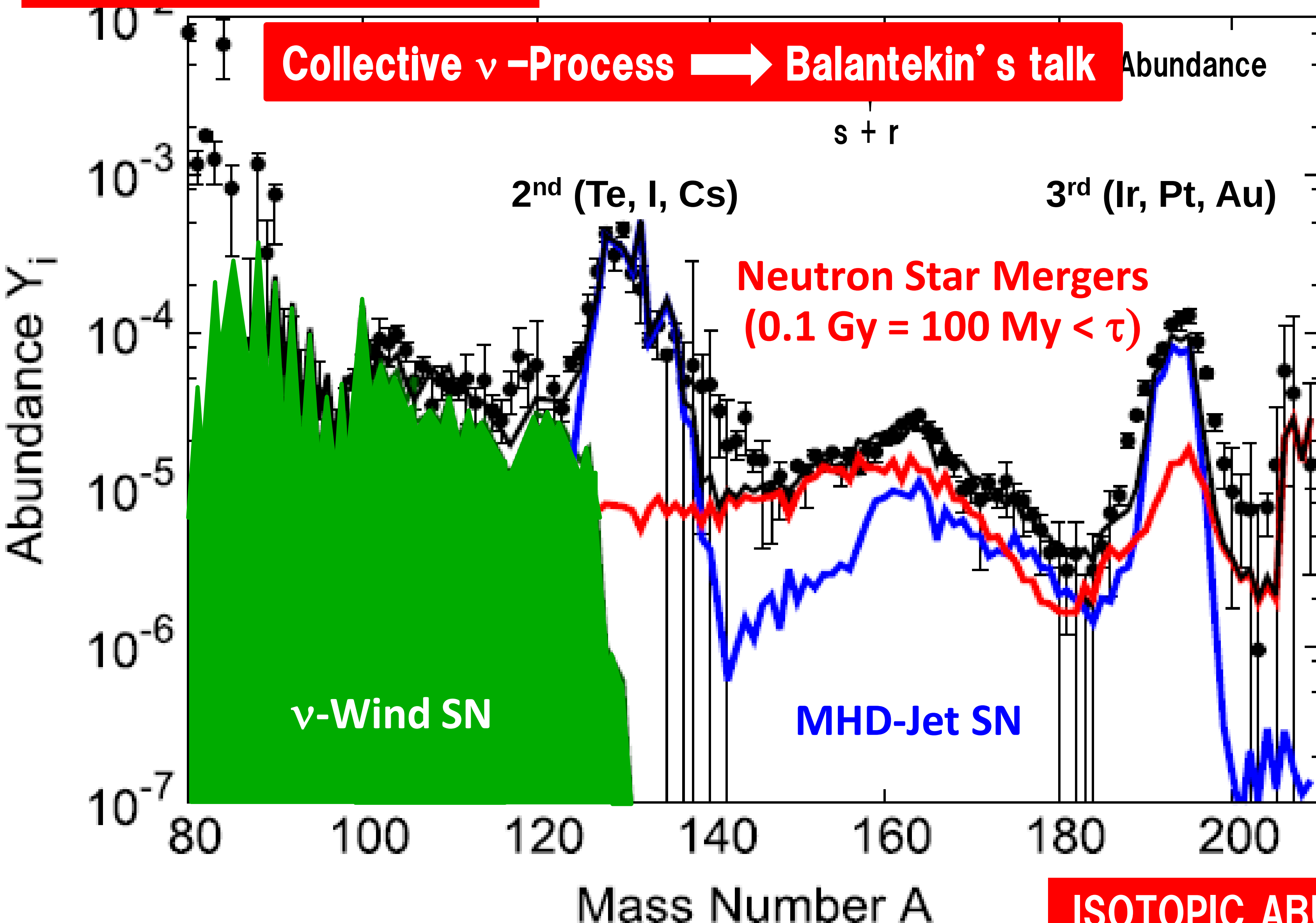


Dust formation, even more difficult when one includes "modern better (complete) opacity" table for heavy actinide elements.

Solar System r-Process Abundance

Solar Sys. t = 13.8Gy

New process, required ? athews, Nishimura & Lorusso (2016), ApJ 816, 79.



ISOTOPIC ABUND.

SUMMARY

Solar-system abundances of the r-process elements consists of both SNe and NSMs contributions.

- MHD-Jet SNe make the r-process peaks, but robust sh… cause deficiency above and below the peaks.
- Asymmetric fission recycling in NSM r-p…
- Early Universe is dominated b…

Abundant … produced in the prot…

- … like $^{64}Ge(n,p)^{64}Ga$ takes the key.
- ν … in 3 flavor multi-angle Hamiltonian should be solved exa… this new process.
- Obse…vational evidence in astronomy or meteorite is required.