International Workshop on
Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16), RCNP Osaka University, Sept. 29-30, 2016

Impact of Neutrino Interactions and Electron Captures in Supernova Nucleosynthesis

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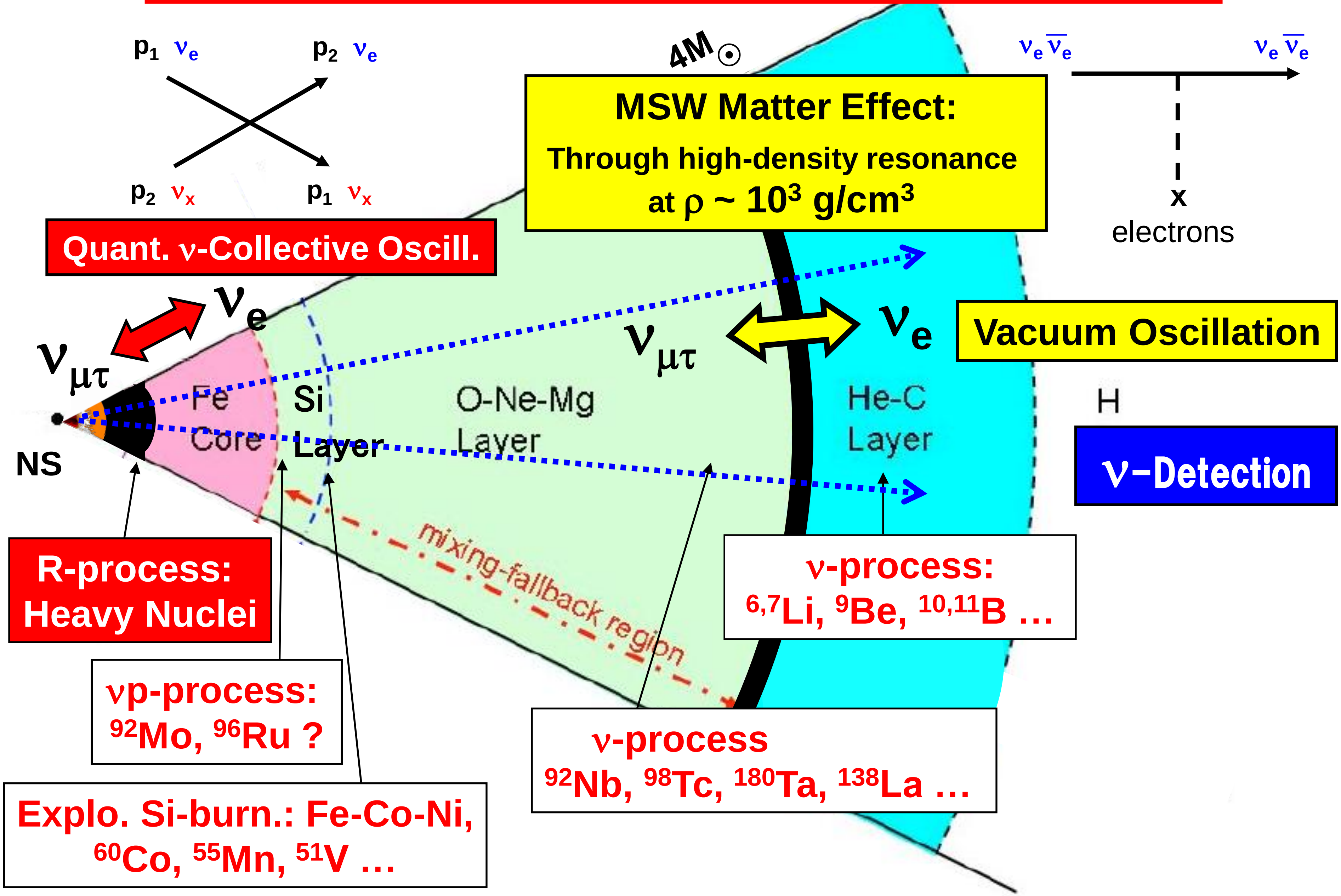
ν-Oscillation and SN II Nucleosynthesis



Elemental Constraints on SN ν's and Hierarchy!

^{180}Ta/^{138}La, ^{92}Nb (CC-ν) ➡ $T\nu_e = T\overline{\nu_e}$ = 4 MeV

Hayakawa, et al., Phys. Rev. C81 (2010) 052801®; Phys. Rev. C82 (2010) 058801.
Hayakaw,a et al., Astrophys. J. Lett. 778 (2013) L1.

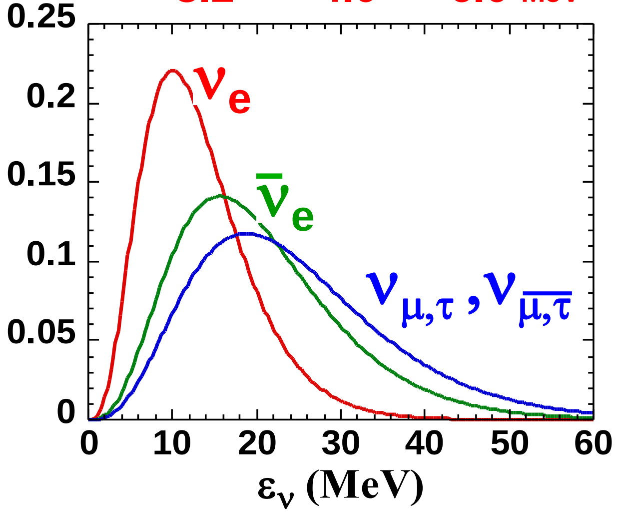
GCE; ^{6,7}Li-^{9}Be-^{10,11}B & Meteoritic ^{11}B/^{10}B (NC-ν) ➡ $T\nu_{x=\mu,\tau}$ = 6 MeV

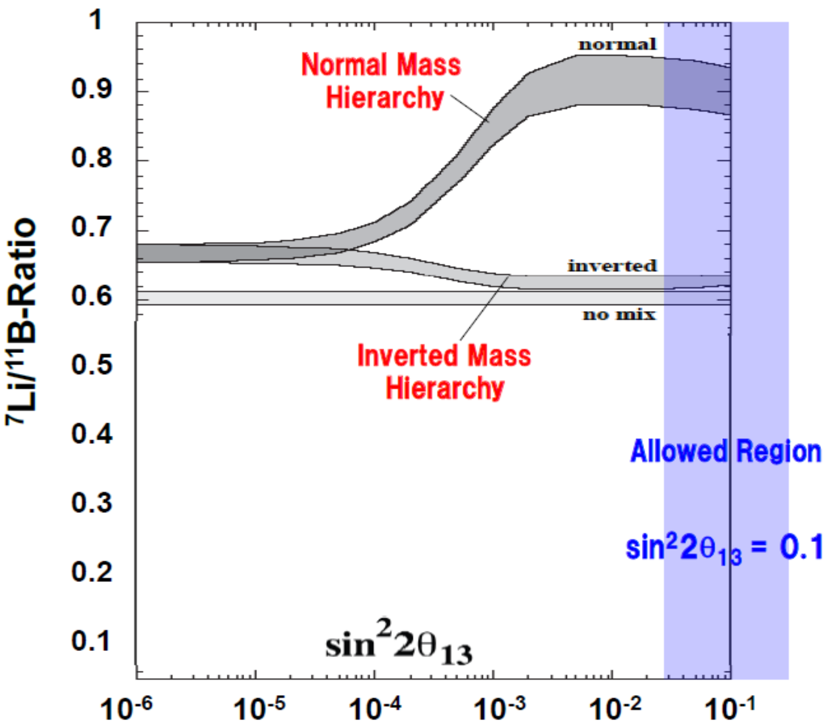
Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005) 231101.
Suzuki & Kajino, J. Phys. G37 (2010), 055101.

R-process (neutron-richness) ➡ $T\nu_e$ = 3.2 MeV, $T\overline{\nu_e}$ = 4 MeV

Otsuki, Tagoshi, Kajino and Wanajo, Astrophys. J. 533 (2000) 424.
Rosuss,o et al., Phys. Rev. Lett. 114 (2015) 192501.

$T(\nu_e) < T(\overline{\nu_e}) < T(\nu_x)$
3.2 4.0 6.0 MeV





ν-mass Hierarchy

Mathews, Kajino, Aoki, Fujita & Pitts, PR D85 (2012) 105023.

Suzuki and Kajino, J. Phys.G40 (2013), 083101.

Unknown ν-A Weak Interaction Cross Sections

★ ν-beam experiment is not available !

★ EM-PROBE (Hadronic CEX, γμ-ind. reactions) !

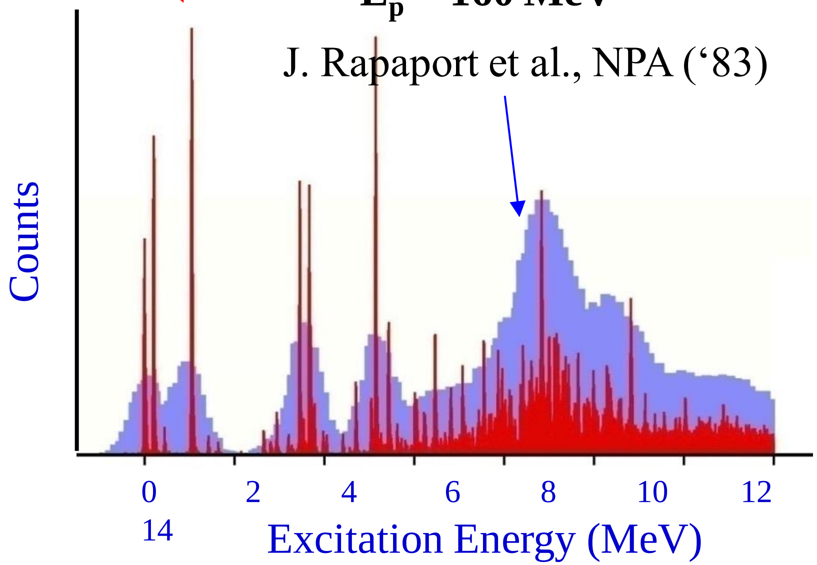
Similarity of Electro-Magnetic & Weak Interactions

^{58}Ni(^{3}He, *t*)^{58}Cu
E = 140 MeV/u

Y. Fujita et al., EPJ A 13 ('02) 411.
Y. Fujita et al., PRC 75 ('07)

^{58}Ni(*p*, *n*)^{58}Cu
E_p = 160 MeV

J. Rapaport et al., NPA ('83)



EM-current = $\vec{V}$, Weak-current = $\vec{V}$ - $\vec{A}$

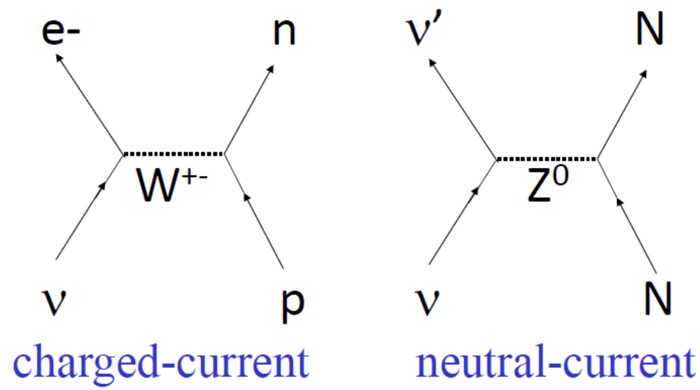
$$\vec{V} \approx g_V^{IV} \frac{i}{2m}\vec{\sigma}\times\vec{q} + \frac{g_V}{2m}(\vec{p}+\vec{p}\,')$$

$$\vec{A} \approx g_A\vec{\sigma}$$

Weak operator in non-relativistic limit

Gamow-Tellar operator = $\vec{\sigma}\tau_{\pm}$

Spin-Multipole operator $= [\vec{\sigma}\times Y(L)]^{J}\tau_{\pm}$

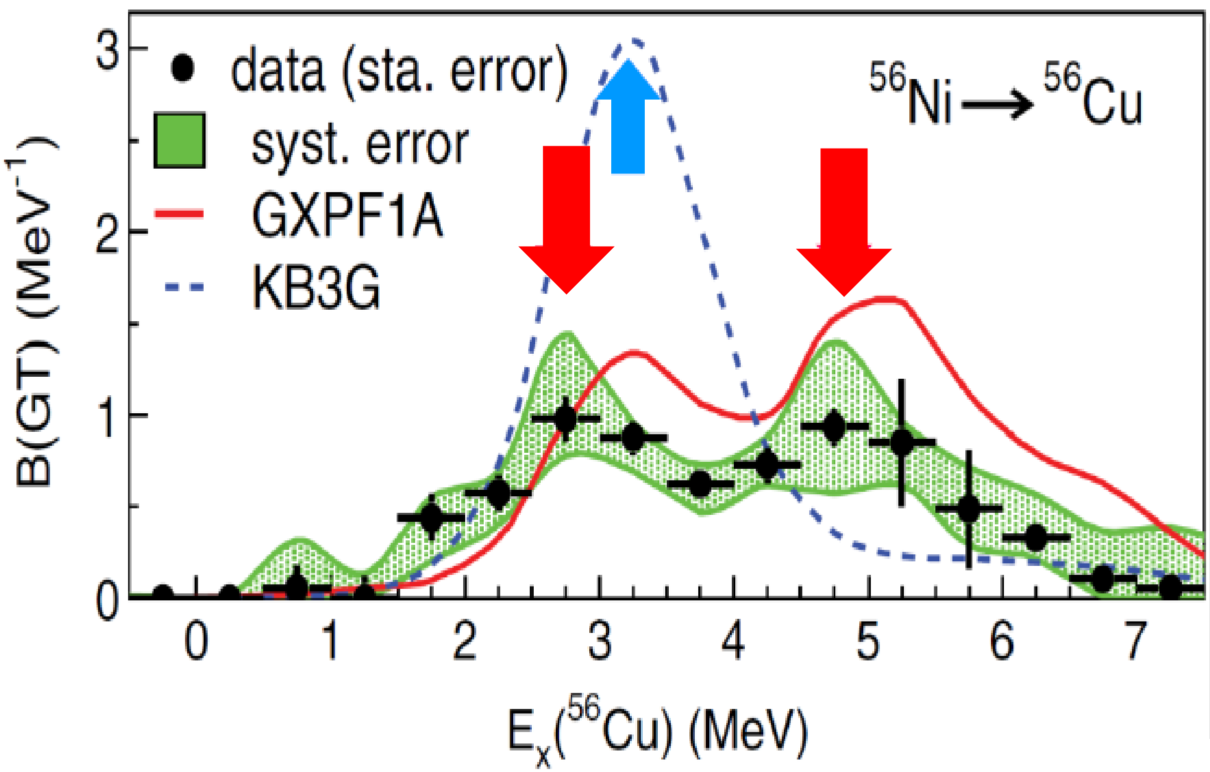


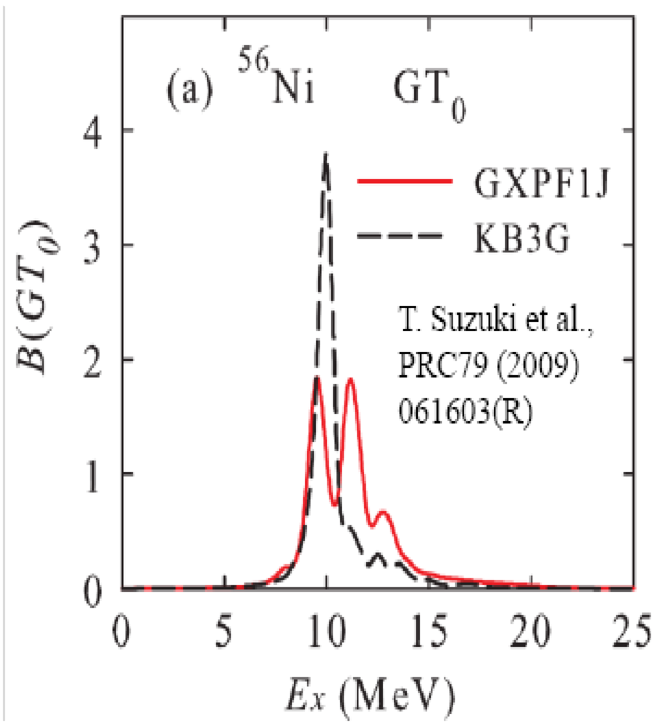
Selected for a Viewpoint in *Physics*
PRL **107**, 202501 (2011) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2011

Gamow-Teller Transition Strengths from ^{56}Ni

M. Sasano,[1,2] G. Perdikakis,[1,2] R. G. T. Zegers,[1,2,3] Sam M. Austin,[1,2] D. Bazin,[1] B. A. Brown,[1,2,3] C. Caesar,[4] A. L. Cole,[5] J. M. Deaven,[1,2,3] N. Ferrante,[6] C. J. Guess,[7,2] G. W. Hitt,[8] R. Meharchand,[1,2,3] F. Montes,[1,2] J. Palardy,[6] A. Prinke,[1,2,3] L. A. Riley,[6] H. Sakai,[9] M. Scott,[1,2,3] A. Stolz,[1] L. Valdez,[1,2,3] and K. Yako[10]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[2]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*





MYSTERY of Type Ia Supernovae

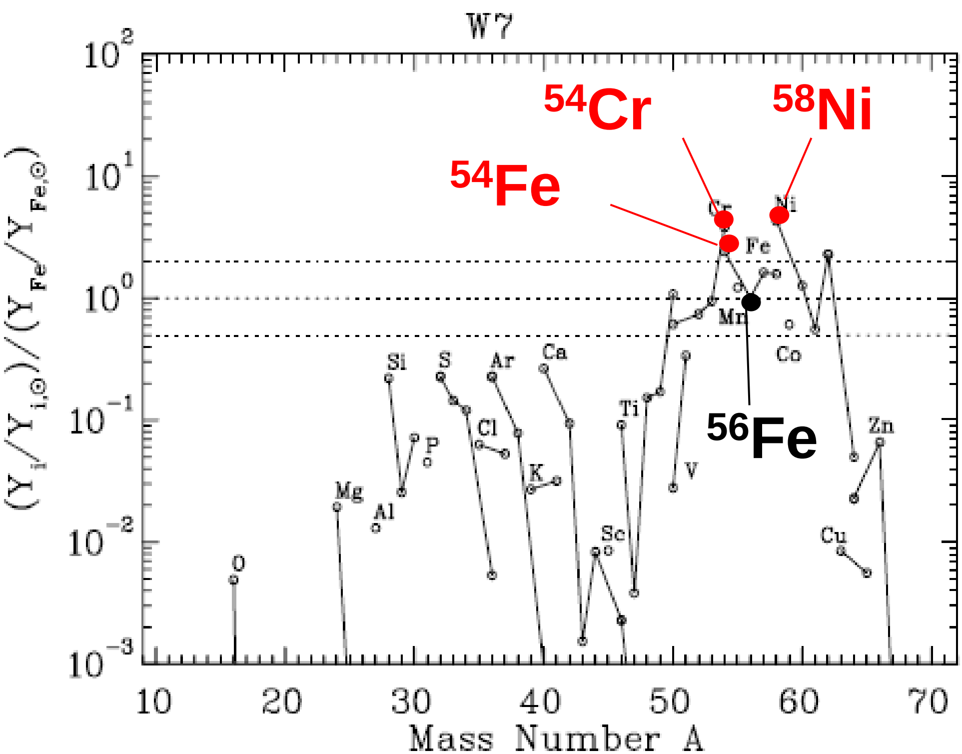
Iwamoto, Nonmoto, Thielemann et al., ApJS 125, 439 (1999)

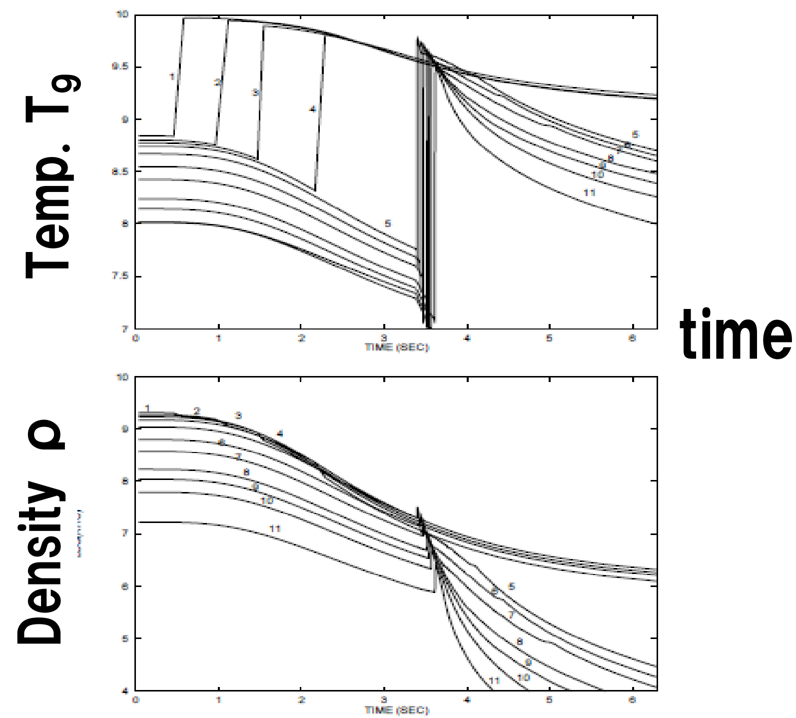
Initial condition of SN Ia : C-O white dwarf, $M=1.0M_{\odot}$, Central; $\rho_9=2.12$, $T_c=1\times10^7$K

and ignition densities to put new constraints on the above key quantities. The abundance of the Fe group, in particular of neutron-rich species like ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{54,58}Fe, and ^{58}Ni, is highly sensitive to the electron captures taking place in the central layers. The yields obtained from such a slow central

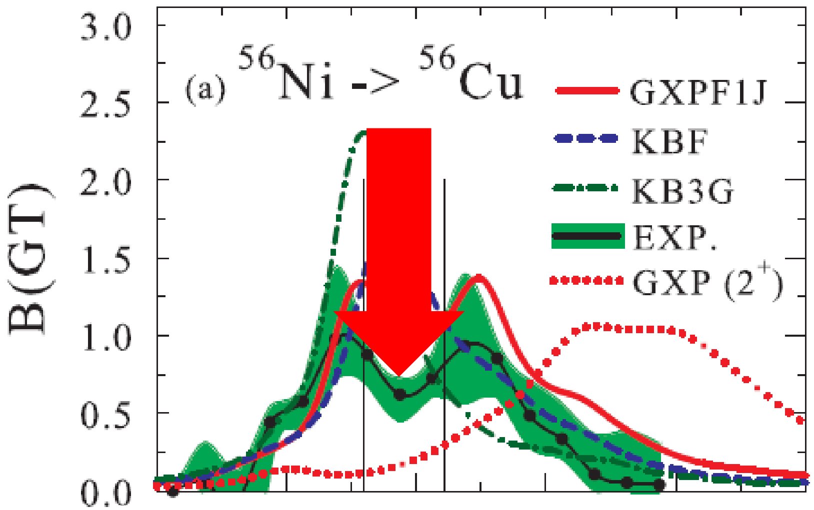
OVERPRODUCTION of n-excess Isotopes ^{54}Cr, ^{54}Fe, ^{58}Ni, etc. →

IMMATURED SM e-capture rates (Fuller-Fowler-Newton, '81-82)?
or
Deflagration vs. Detonation burning?





Modern Shell Model Cal. of B (GT) and e-Capture Rate



KB3G model

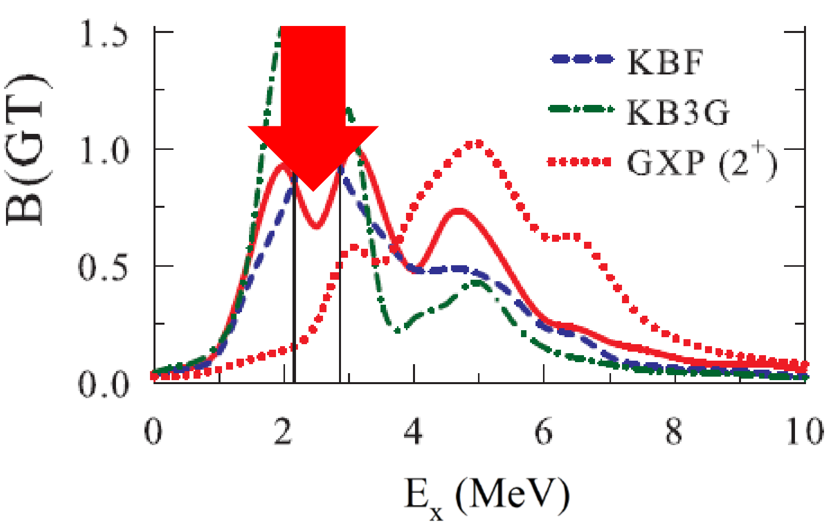
Caurier et al., Rev. Mod. Phys. 77, 427 (2005).

GXPF1J model

Honma et al., PR C65 (2002); C69 (2004);
Suzuki, Honma, Mao, Otsuka, Kajino, PR C83 (2011).

$$B_{ij}(GT) = \left(\frac{g_A}{g_V}\right)^2_{\text{eff}} \frac{\langle j || \sum_k \boldsymbol{\sigma}^k \boldsymbol{t}^k_{\pm} || i \rangle^2}{2J_i + 1}$$

GT-quenching ⇔ Quenched e-captures
⇔ Increase of Ye→0.5 (p～n) in SN explosion
⇔ Decrease of Neutron-Excess Isotopes



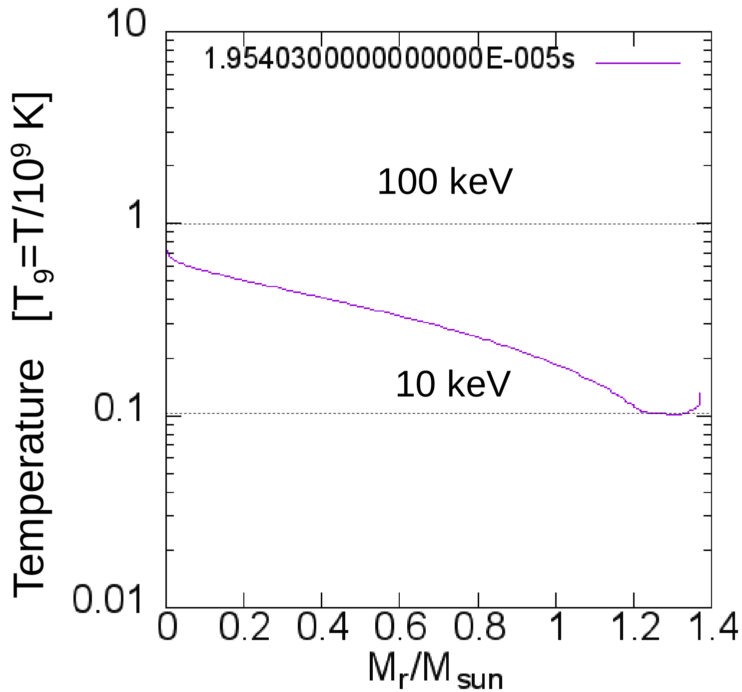
$$\times \int_{\omega_{\min}} \omega p (Q_{ij} + \omega)^2 F(Z, \omega) S_e(\omega) d\omega,$$

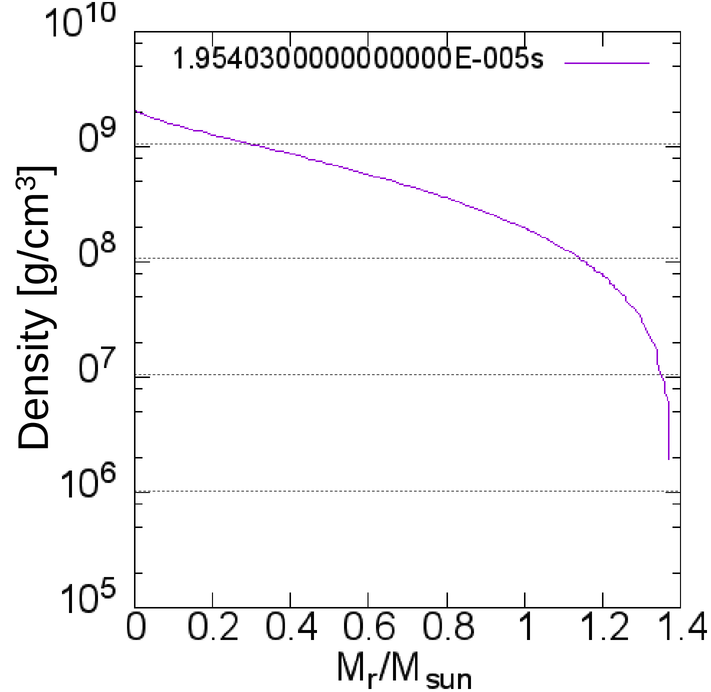
$$Q_{if} = (M_p c^2 - M_d c^2 + E_i - E_f)/m_e c^2,$$

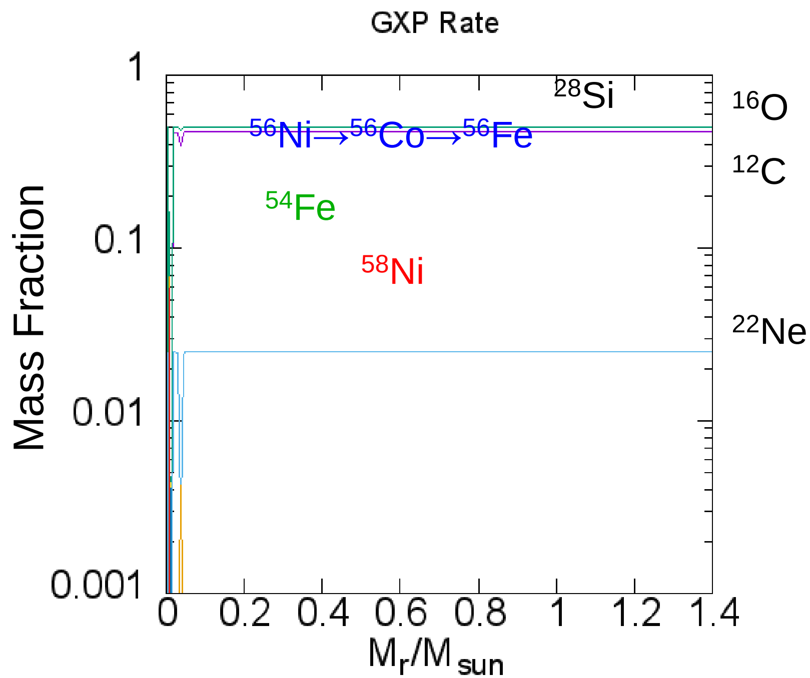
$$W_i = (2J_i + 1) e^{-E_i/kT} / \sum_i (2J_i + 1) e^{-E_i/kT},$$

$$\rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar}\right)^3 \int_0^\infty (S_e - S_p) p^2 \, dp,$$

$$S_e = \frac{1}{\exp\left(\frac{E_e - \mu_e}{kT}\right) + 1}, \quad \mu_p = -\mu_e.$$







Explosive Nucleosynthesis in Type Ia Supernova (Single Degenerate)

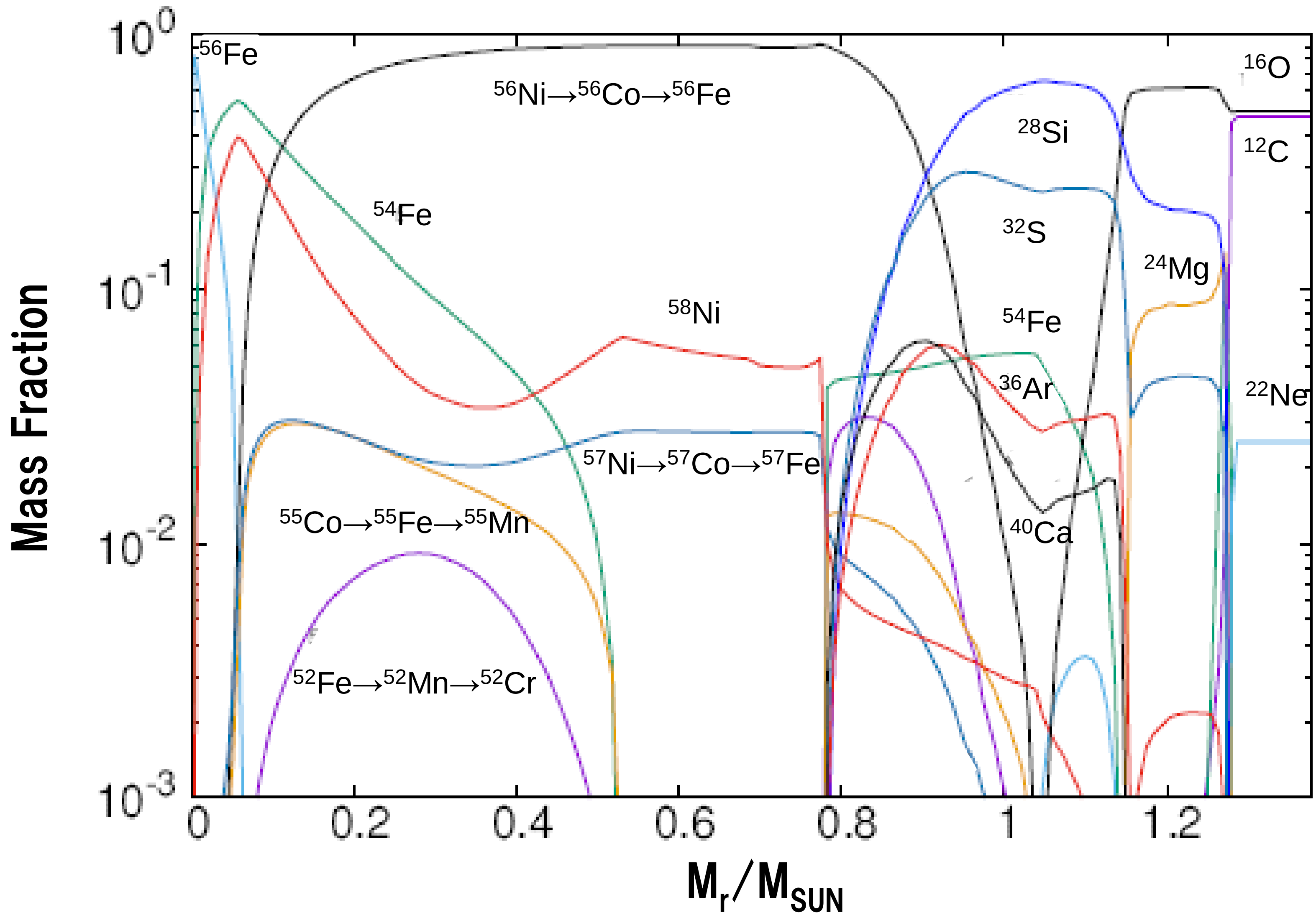
Slow-Deflagration (W7 model)

Mori, Famiano, Kajino, Suzuki, Otsuka, Nomoto and Iwamoto, ApJ (2016), submit.

Final Yields as a function of M_r (just after explosion at 1 min)

Slow-Deflagration (W7 model)

Mori, Famiano, Kajino, Suzuki, Otsuka, Nomoto, and Iwamoto, ApJ (2016), submitted.



Nucleosynthesis in Type Ia Supernovae：

"Overproduction" of Neutron-Excess Isotopes ^{54}Cr, ^{54}Fe, ^{58}Ni / ^{56}Fe

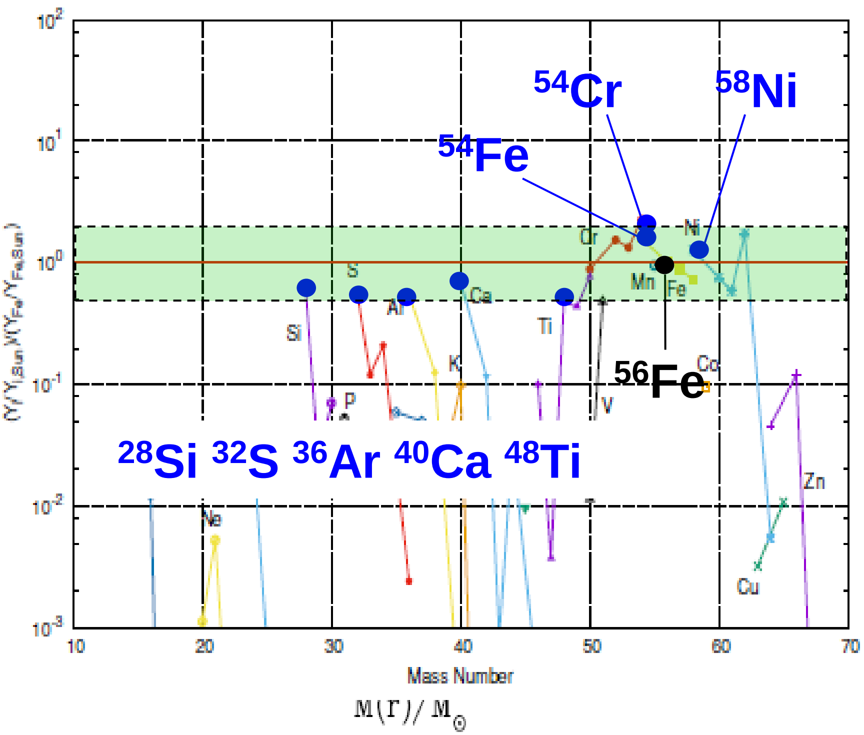
"Underproduction" of α-elements (p=n) ^{28}Si, ^{32}S, ^{36}Ar, ^{48}Ti / ^{56}Fe

Can CEX Reactions data for GT strength solve these Problems ?

Delayed-Detonation (DD2 model)

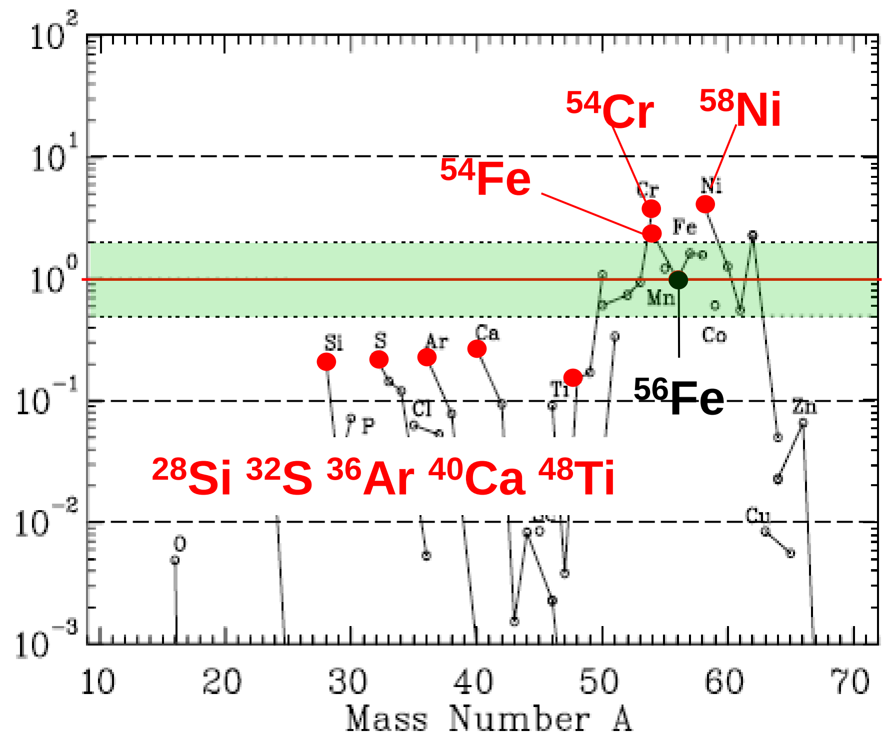
Mori, Famiano, Kajino, Suzuki, Otsuka, Nomoto, and Iwamoto, ApJ (2016), submitted.

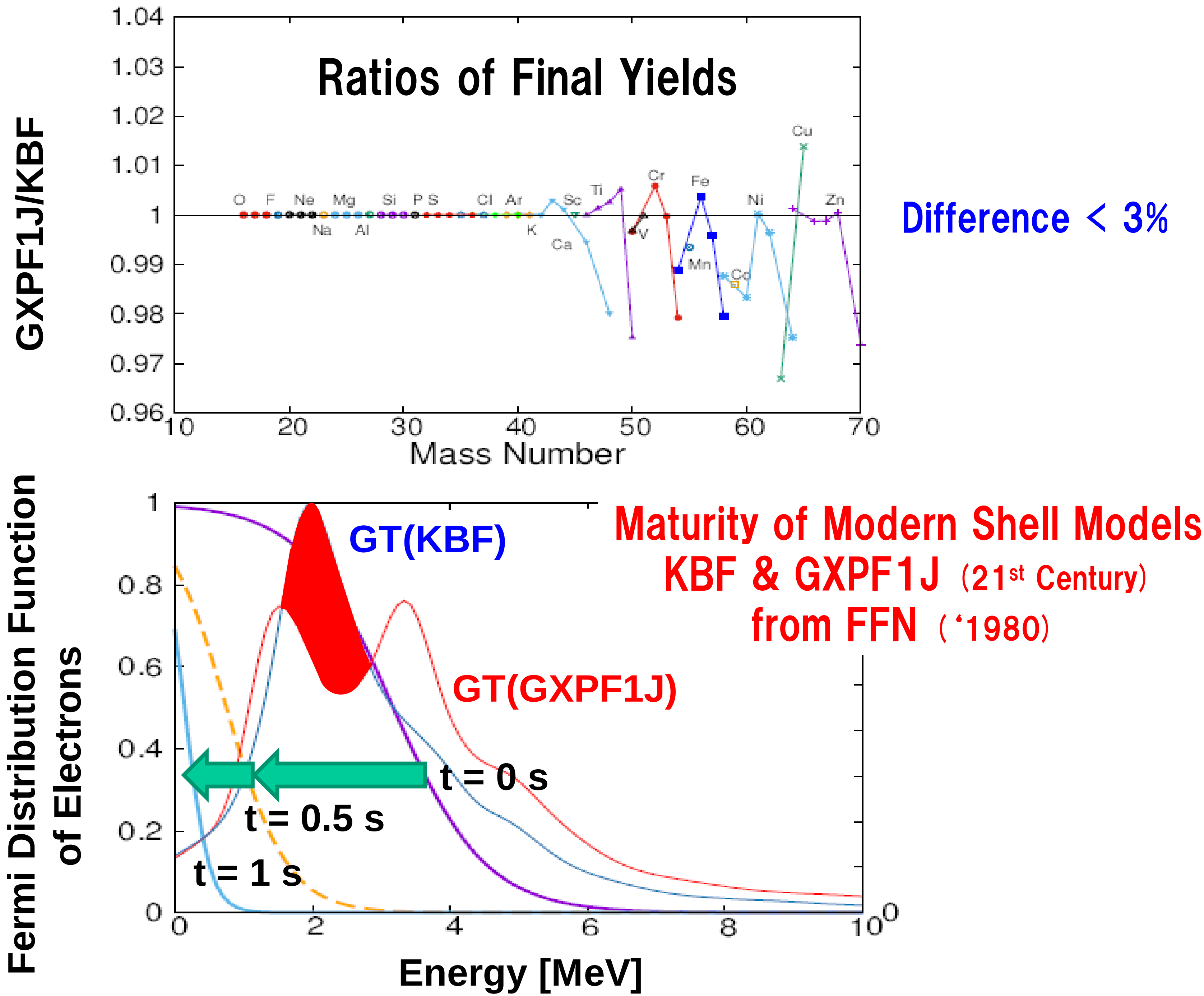
e-capt. rates : Suzuki et al. (GXPF1J)



Slow-Deflagration (W7 model)

Improved e-capt. rates from FFN (1981-1982), but similar to Iwamoto et al., ApJ. S125, 439 (1999).

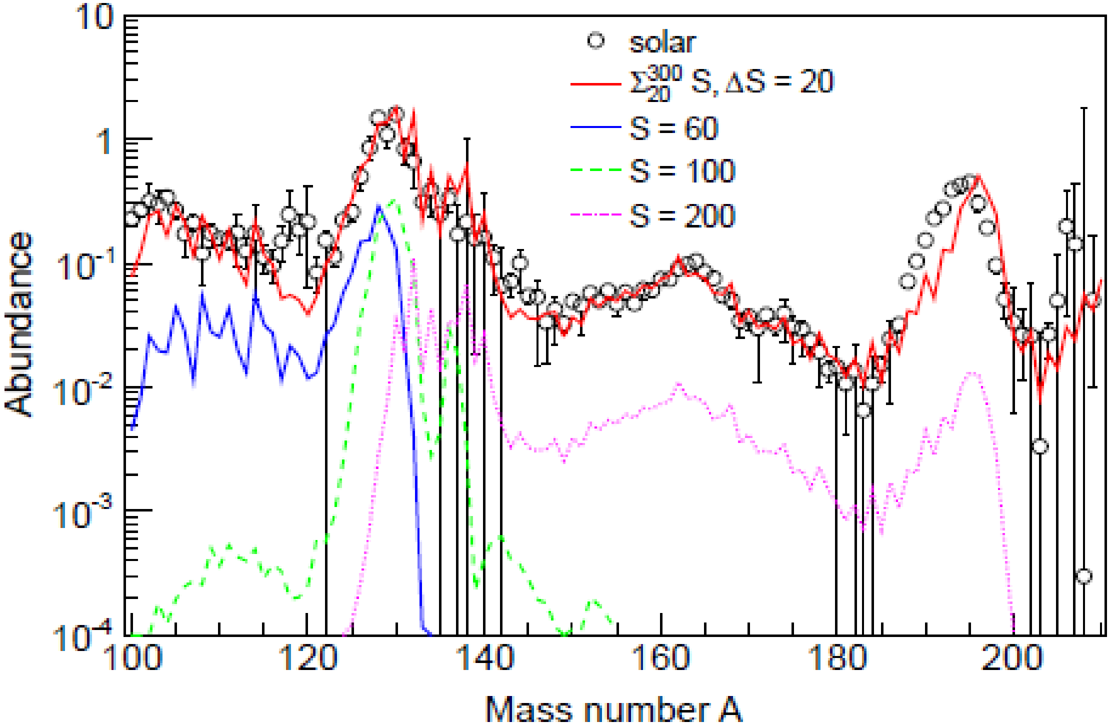




Ratios of Final Yields
GXPF1J/KBF
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
10
20
30
40
50
60
70
Mass Number
O F Ne Mg Si P S Cl Ar Sc Ti Cr Fe Ni Zn Cu
Na Al K Ca V Mn Co
Difference < 3%
Maturity of Modern Shell Models
KBF & GXPF1J (21st Century)
from FFN ('1980)
Fermi Distribution Function
of Electrons
GT(KBF)
GT(GXPF1J)
t = 0 s
t = 0.5 s
t = 1 s
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
Energy [MeV]

ν's plays CRITICAL ROLES in CCSNe
in Nucleosynthesis & Explosion Dynamics

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



Several numerical supernova simulations suggest;

$Y_e > 0.5$.

Roberts, Reddy and Shen (PRC86, 065803, 2012) pointed out

$Y_e < 0.5$ (neutron-rich) !

in ν-transport cal's by taking account of nucleonic potential plus Pauli-blocking effects.

Otsuki, Tagoshi, Kajino and Wanajo, ApJ 533 (2000), 424; Wanajo, Kajino, Mathews and Otsuki, ApJ 554 (2001), 578.

Neutron-rich condition for successful r-process: $Y_e << 0.4$

$\nu_e + n \rightarrow p + e^-$

$\overline{\nu}_e + p \rightarrow n + e^+$

$$Y_e = \frac{p}{n+p} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \times \frac{\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

$\varepsilon_\nu = 3.15\ T_\nu$

$T_{\nu e} = 3.2$ MeV, $T_{\overline{\nu e}} = 4$ MeV

Where is astro. site of the r-process ?

Core-Collapse Supernovae?

MHD-Jet
Nishimura, et al., ApJ 642, 410 (2006).
Fujimoto, et al., ApJ 680, 1350 (2008).
Winteler, et al., ApJ 750, L22 (2012).
Nishimura et al., ApJ, 810, 109 (2015)

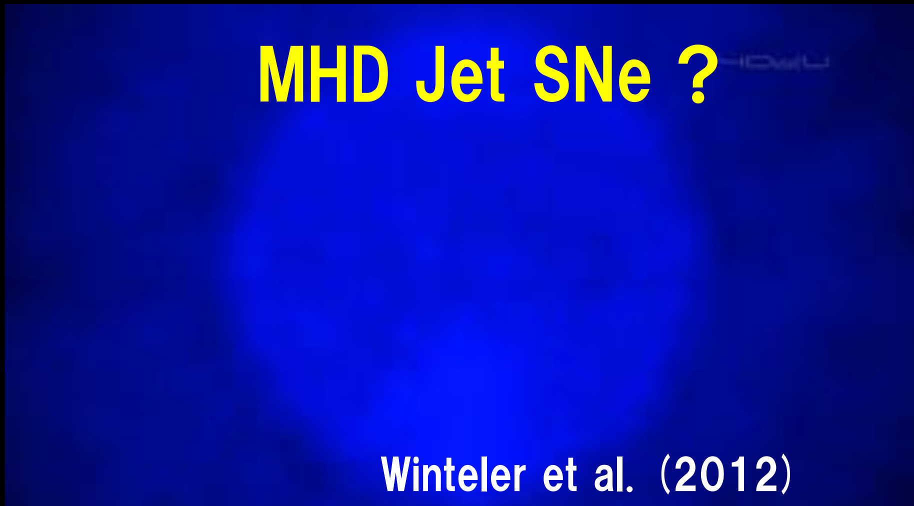
ν-DW ?
Woosley, et al., ApJ 433, 229 (1994). +

Long-GRB
Nakamura, et al, A&Ap 582 A34 (2015)

τ =1-10My

Underproduction, off peaks ?

ν's ? Explo. Condition (Ω, B) ?



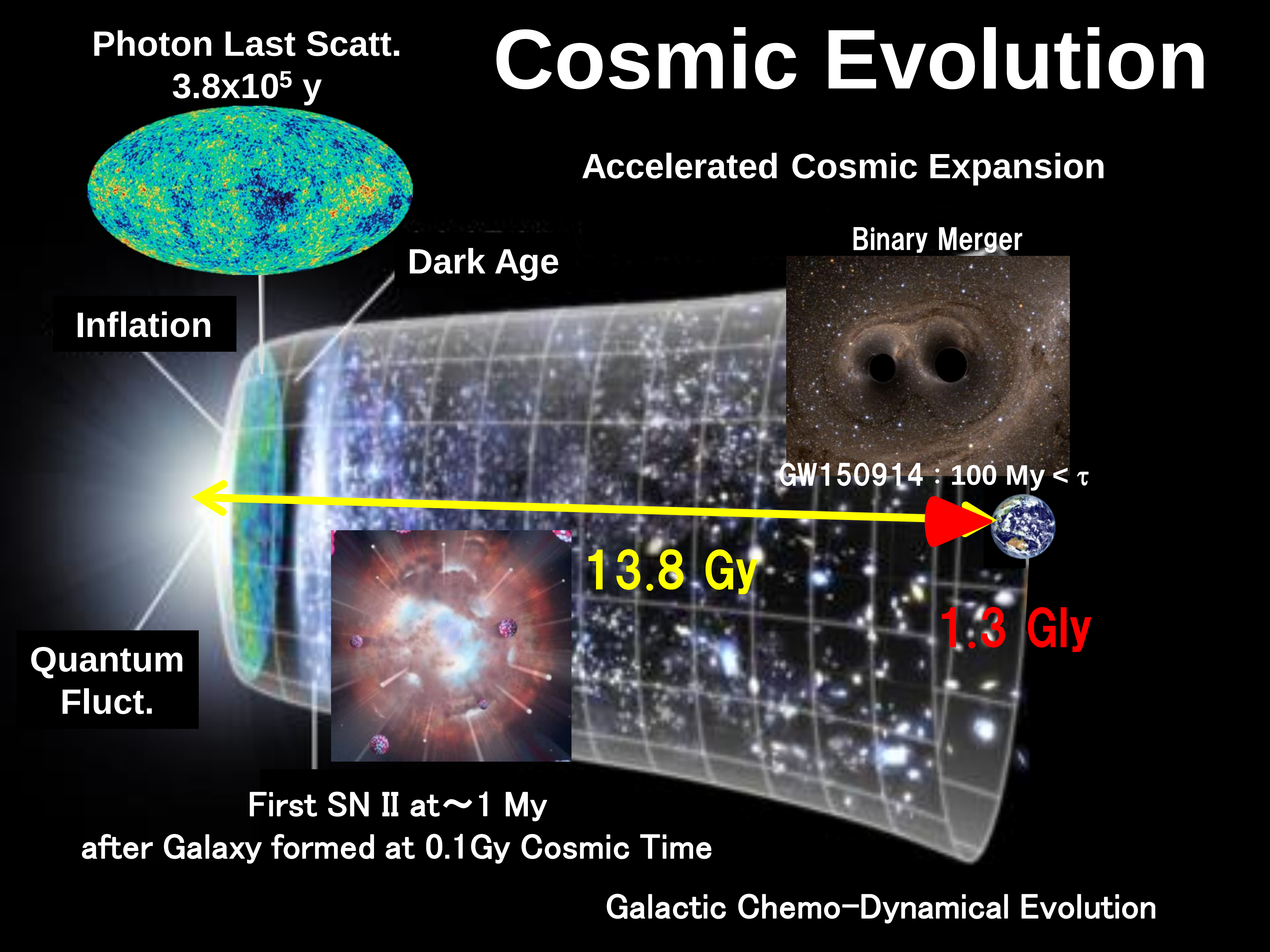
Binary Neutron-Star Mergers?

Goriely, et al., ApJ 738, L32 (2011).
Korobkin, et al., MNRAS 426, 1940 (2012).
Rosswog, et al., MNRAS 430, 2585 (2013).
Goriely, et al., PRL 111, 242502 (2013), (2015).
Piran, et al., MNRAS 430, 2121 (2013).
Wanajo, et al., ApJ 789, L39 (2014).

100My $\leq \tau_c \leq$ 10Ty

Binary NSs arrive too late ?

Time Scale Problem ?

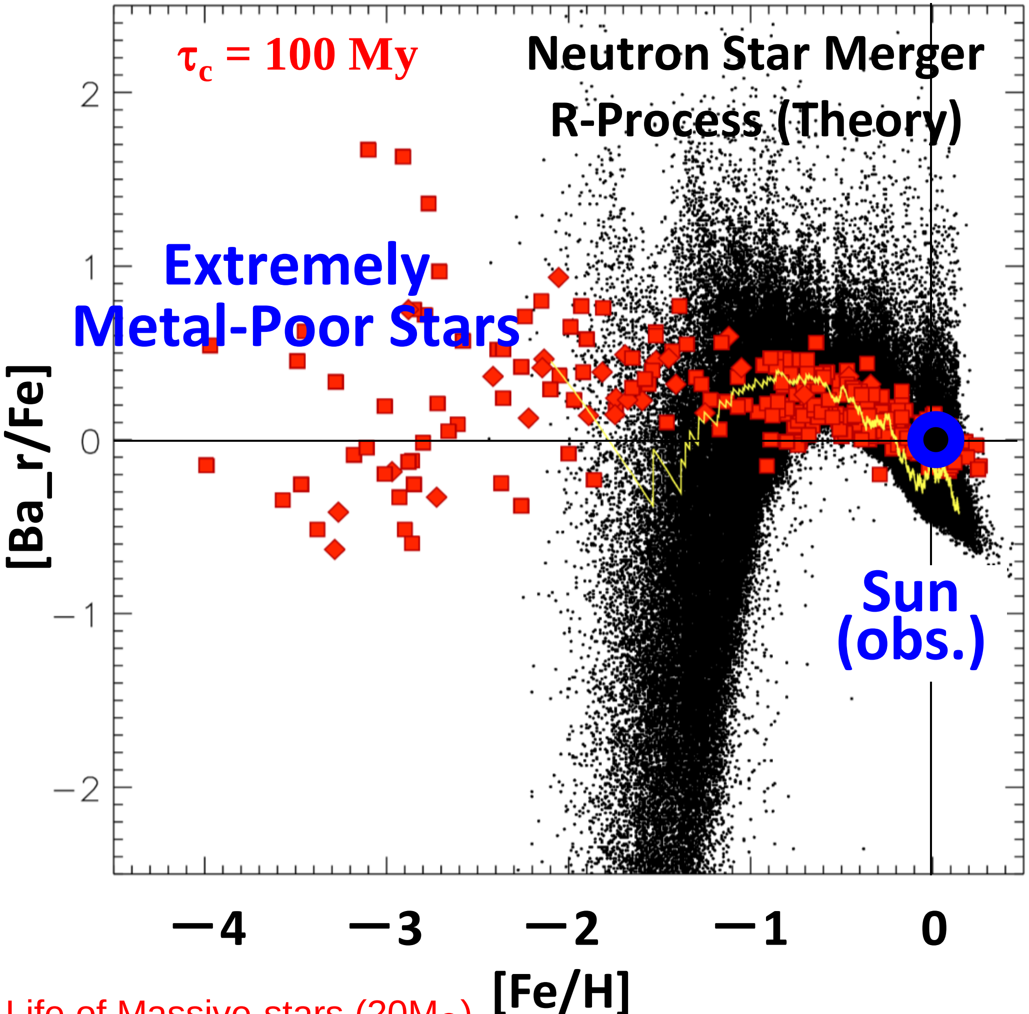

Cosmic Evolution
Photon Last Scatt.
3.8x10^5 y
Accelerated Cosmic Expansion
Binary Merger
Dark Age
Inflation
GW150914 : 100 My < τ
13.8 Gy
1.3 Gly
Quantum
Fluct.
First SN II at～1 My
after Galaxy formed at 0.1Gy Cosmic Time
Galactic Chemo-Dynamical Evolution

Wanderman & Piran (2014), τ_C = 4 Gy (arXiv:1405.5878)

Time Scale Problem

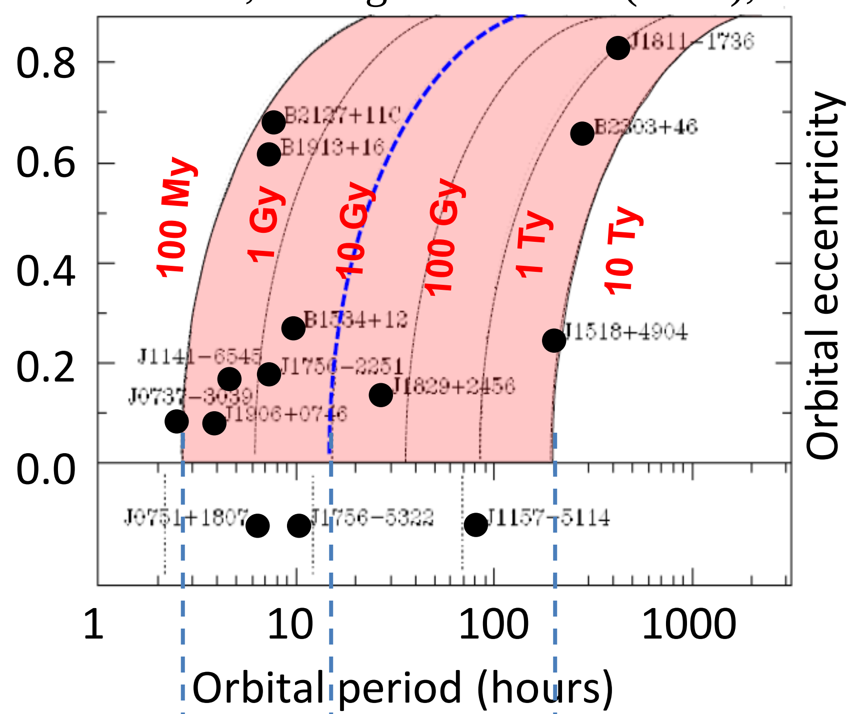
Argast, et al., A&A 416 (2004), 997,
Wehmeyer et al., MNRAS 452 (2015), 1970.

Merging, too slow for GW rad.: 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



Life of Massive stars ($20M_\odot$)

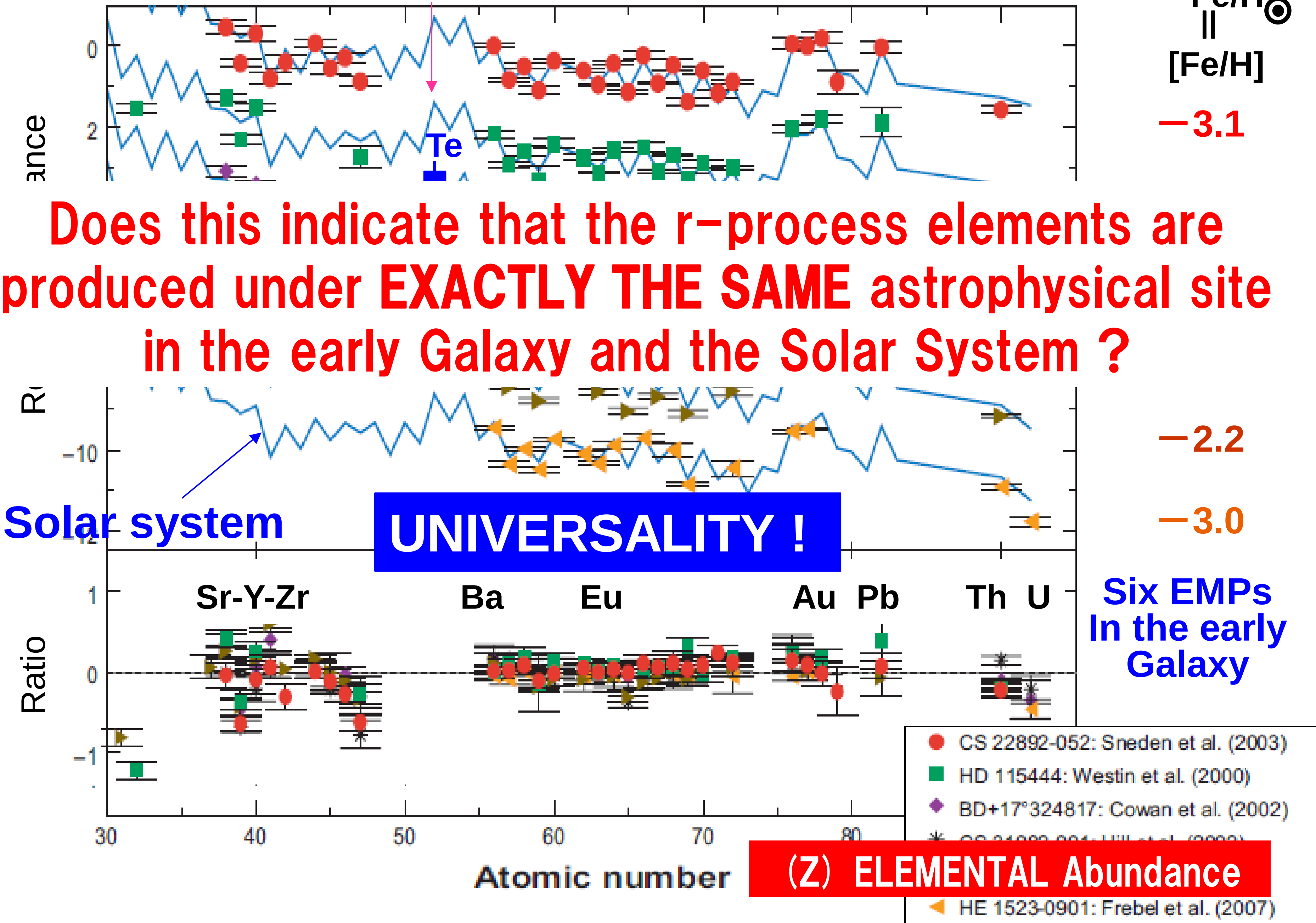
1My 10My **100My ・・・ 10Gy** **100My 10Gy 10Ty**

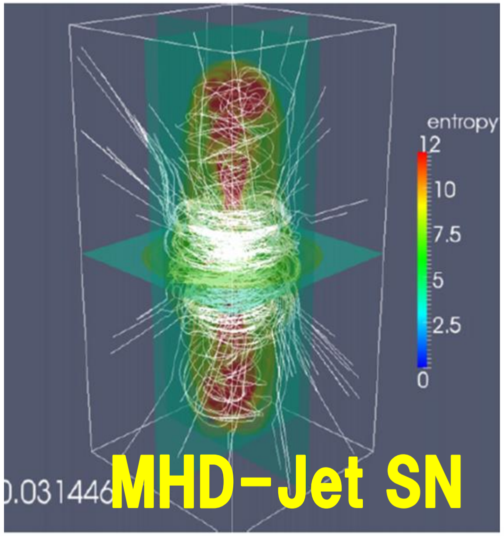
Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

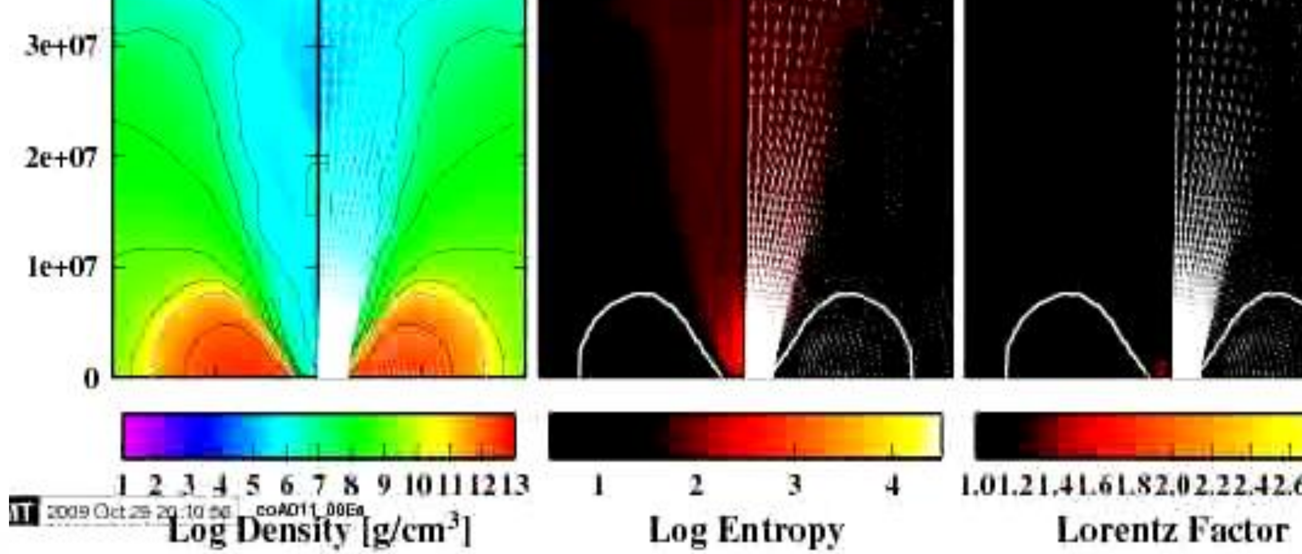
HST-obs., Roederer et al., ApJ 747 (2012) L8.

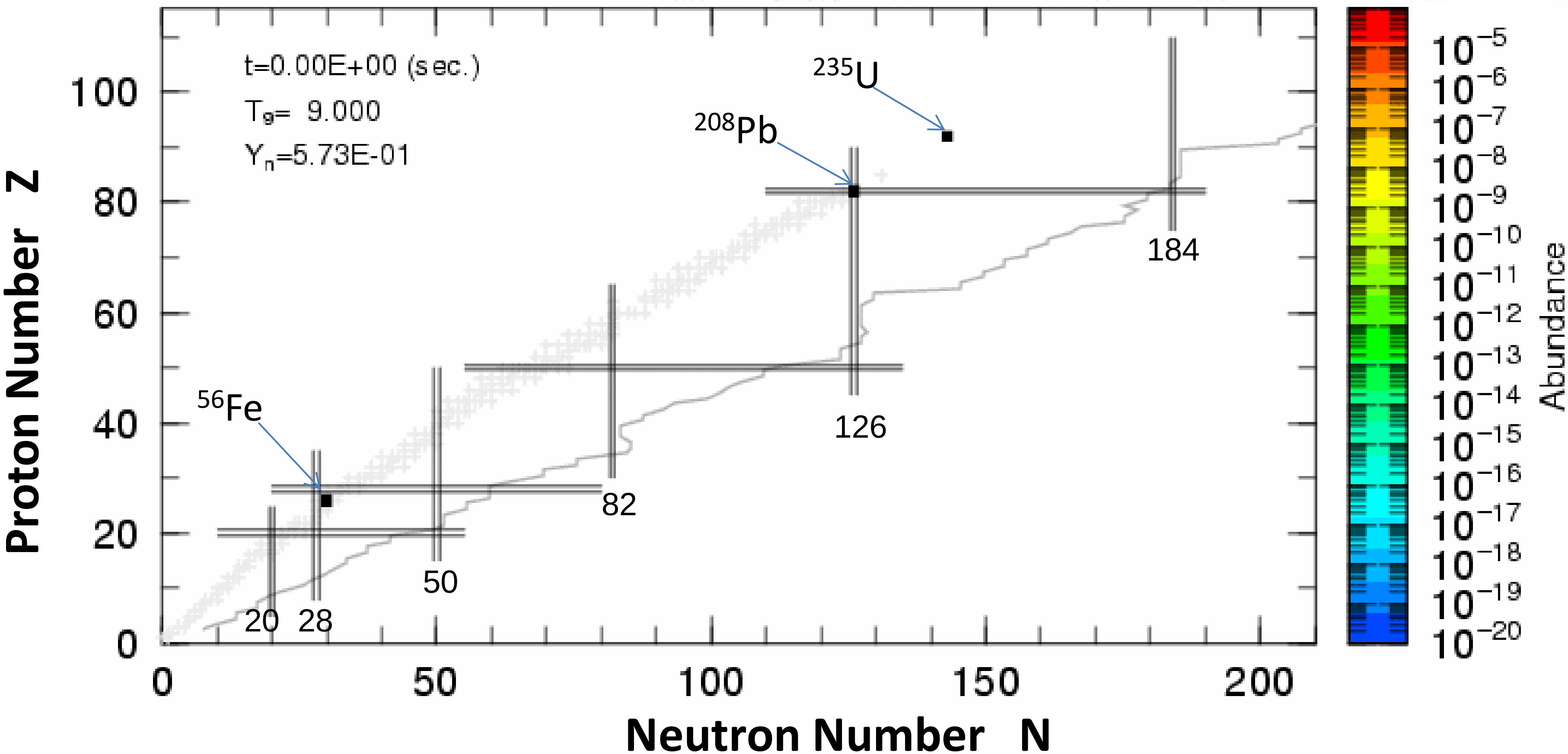
$$\frac{t}{10^{10}y} \fallingdotseq 10^{[Fe/H]} \qquad \mathrm{Log}\frac{Fe/H_{\star}}{Fe/H_{\odot}} = [Fe/H]$$

Does this indicate that the r-process elements are produced under EXACTLY THE SAME astrophysical site in the early Galaxy and the Solar System ?



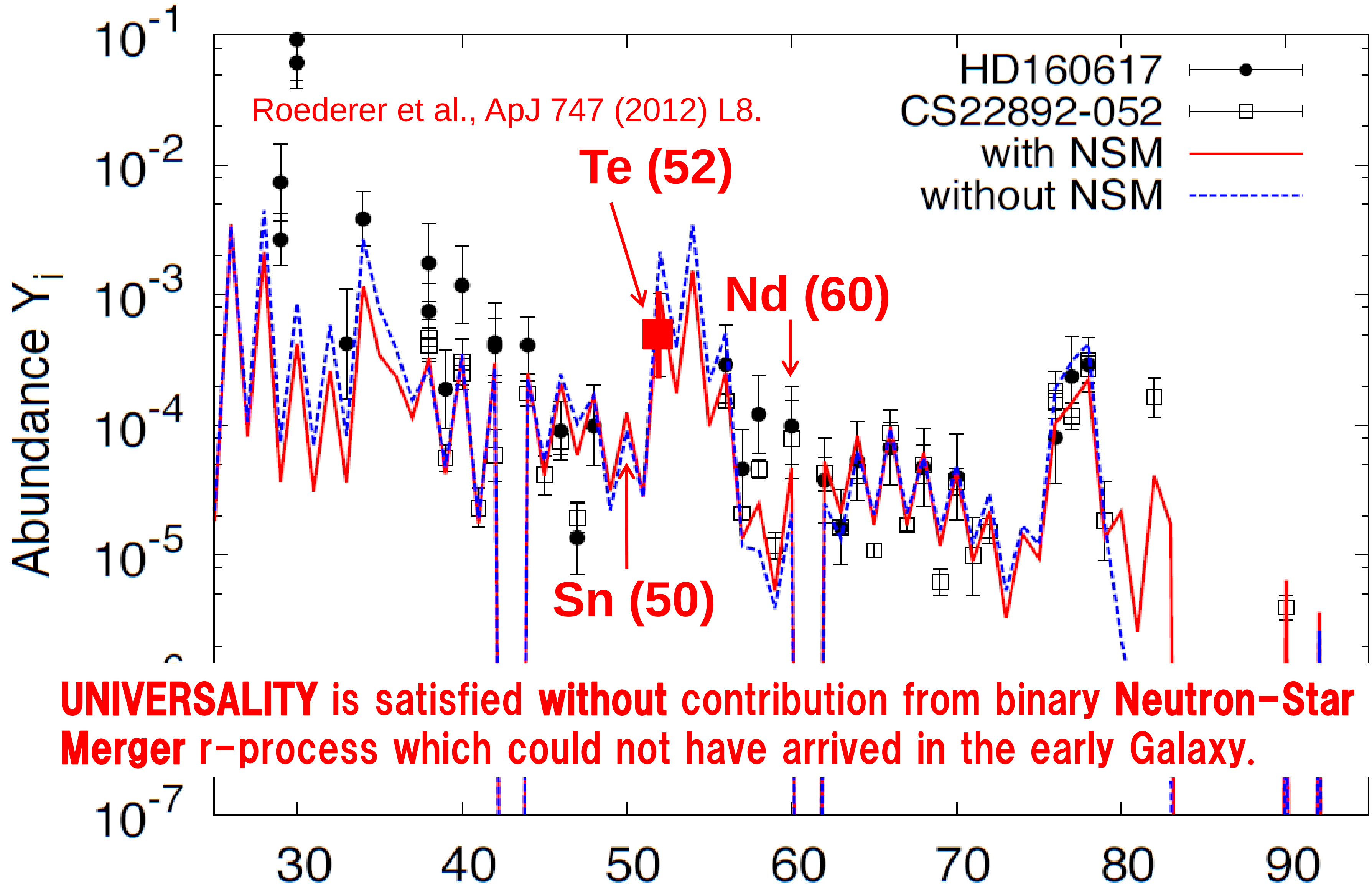

entropy
12
10
7.5
5
2.5
0
.031446
MHD-Jet SN


3e+07
2e+07
1e+07
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Log Density [g/cm³]
1 2 3 4
Log Entropy
Lorentz Factor


t=0.00E+00 (sec.)
T9= 9.000
Yn=5.73E-01
235U
208Pb
56Fe
184
126
82
50
20
28
Proton Number Z
Neutron Number N
0
20
40
60
80
100
0
50
100
150
200
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
Abundance

UNIVERSALITY !

Early Galaxy !



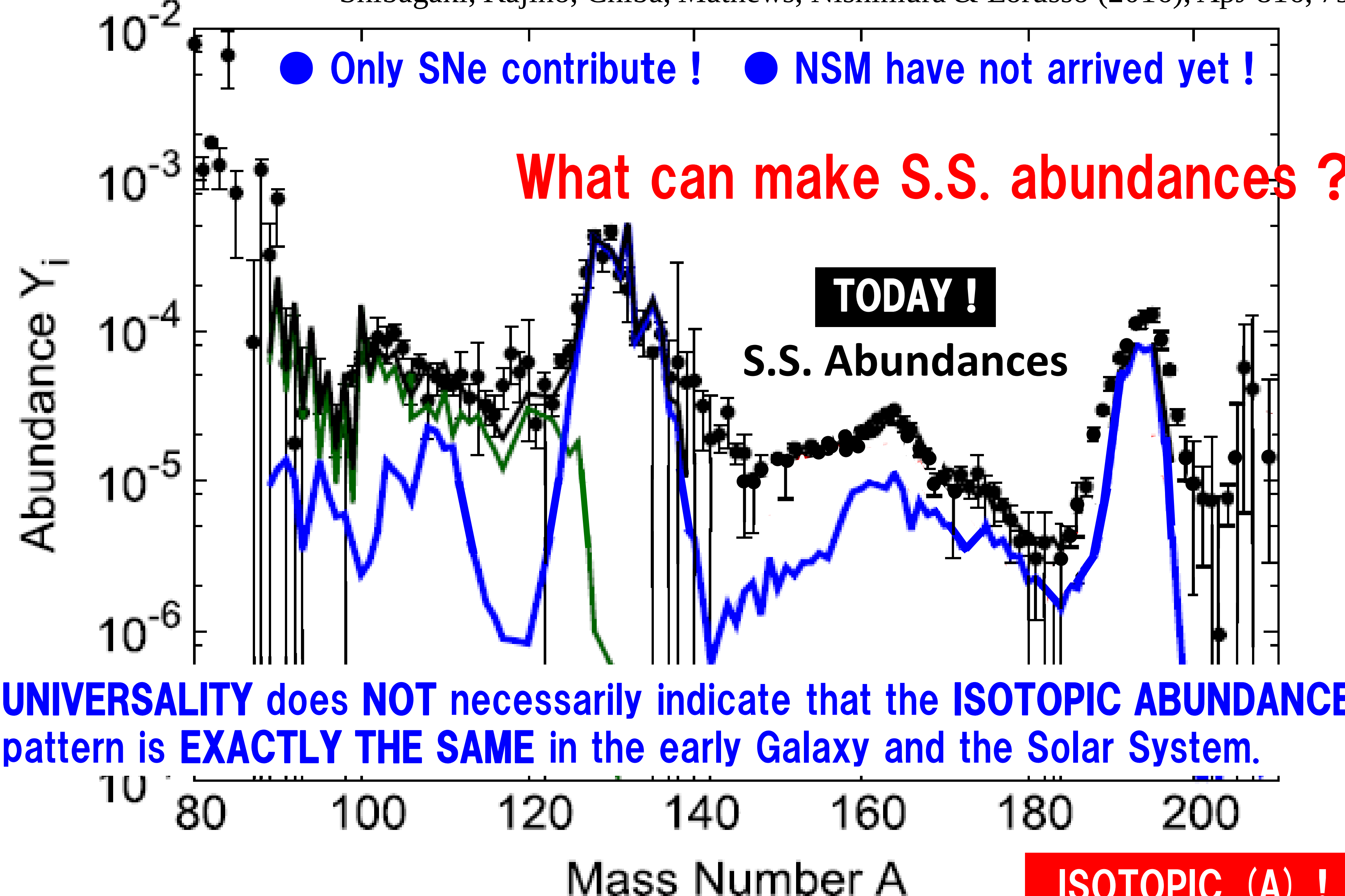
UNIVERSALITY is satisfied **without** contribution from binary **Neutron-Star Merger** r-process which could not have arrived in the early Galaxy.

Astron. Obs. Doesn't separate ISOTOPES ! Atomic Number Z **ELEMENTAL (Z)**

Solar System r-Process Abundance

Early Galaxy !

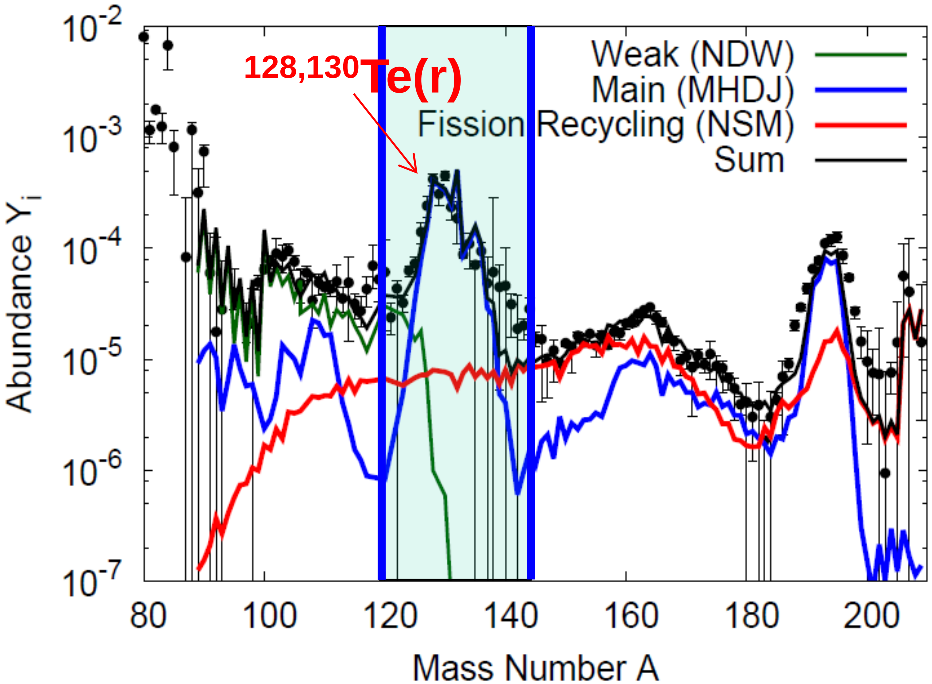
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.

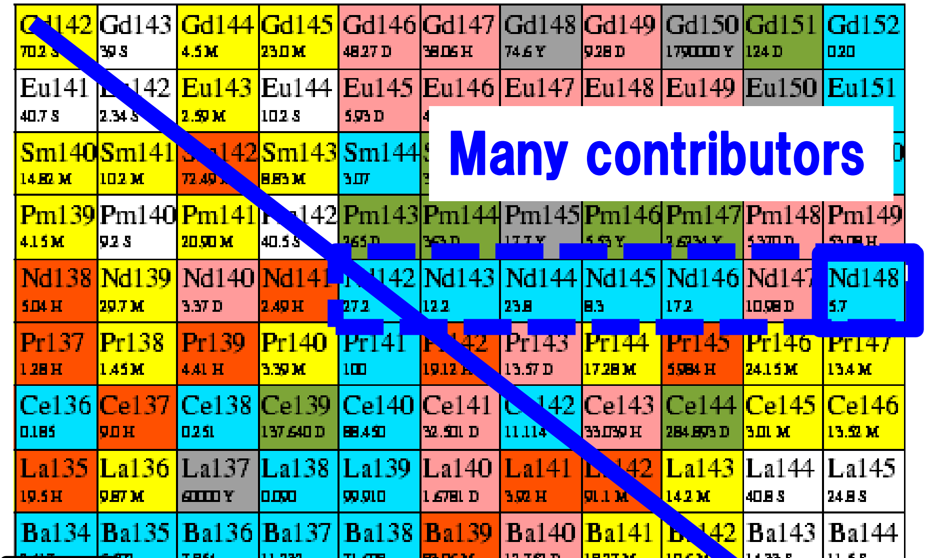


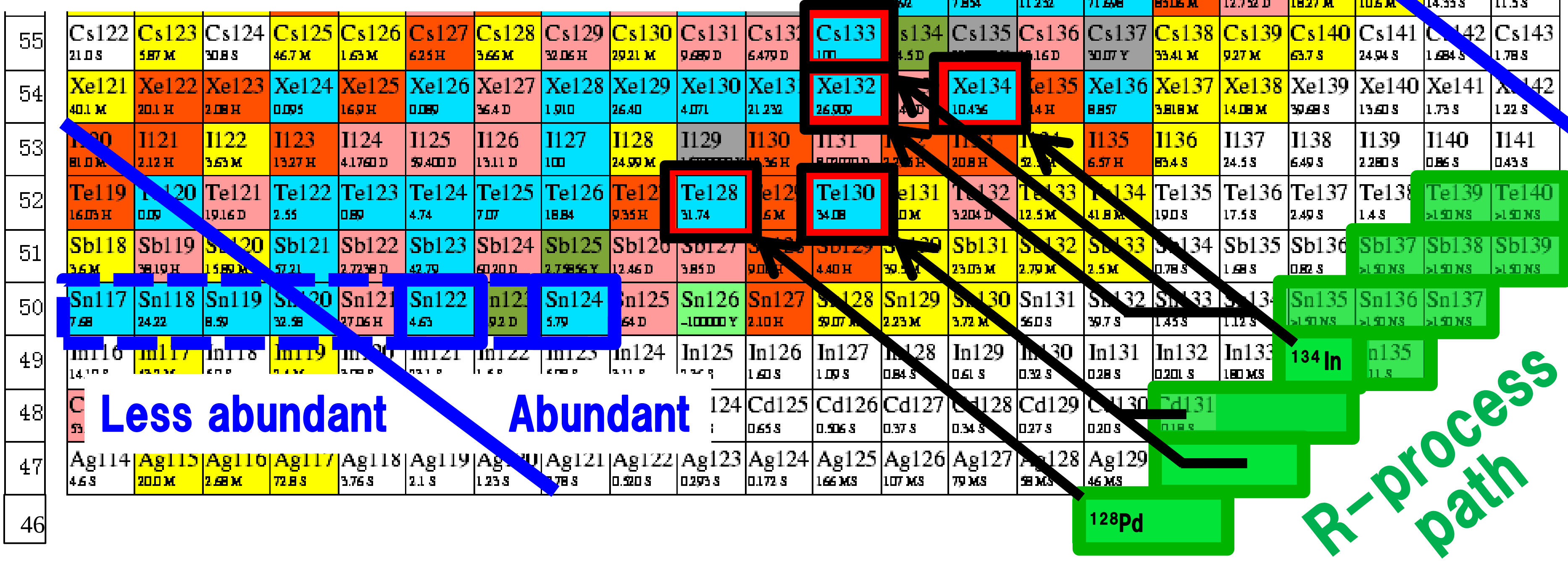
UNIVERSALITY does **NOT** necessarily indicate that the **ISOTOPIC ABUNDANCE** pattern is **EXACTLY THE SAME** in the early Galaxy and the Solar System.

ISOTOPIC (A) !

Lorusso et al. with Kajino (2015), PRL 114, 192501. (COSNAP + RIKEN Collab.)

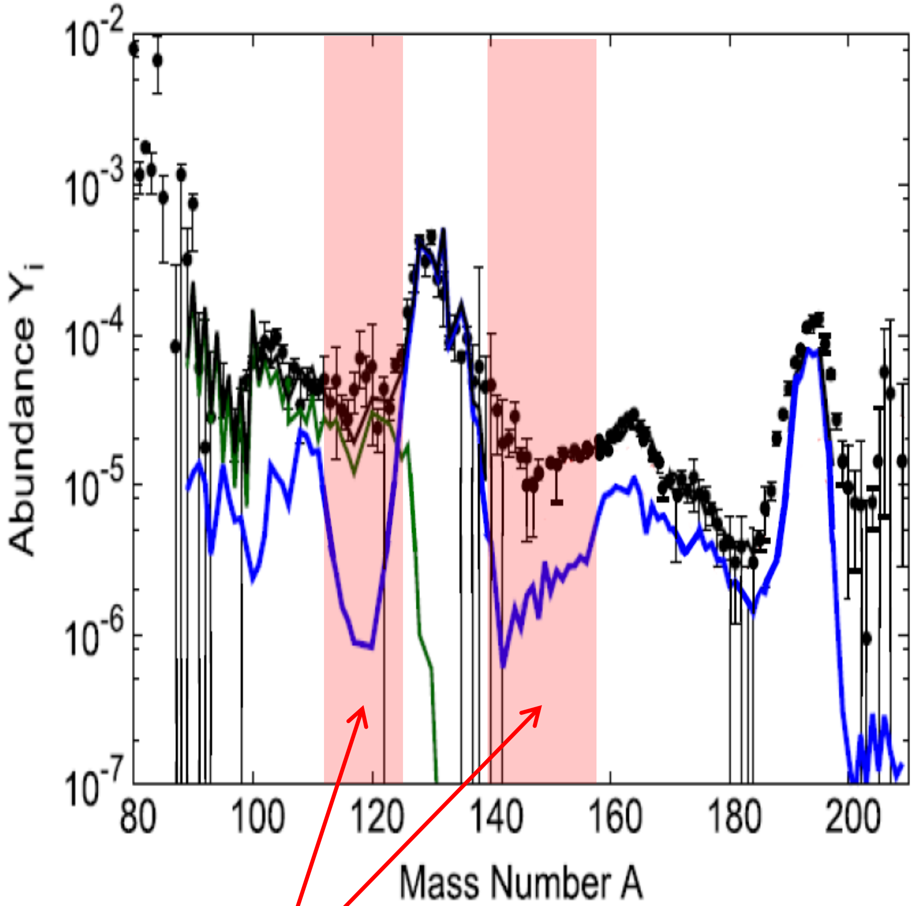


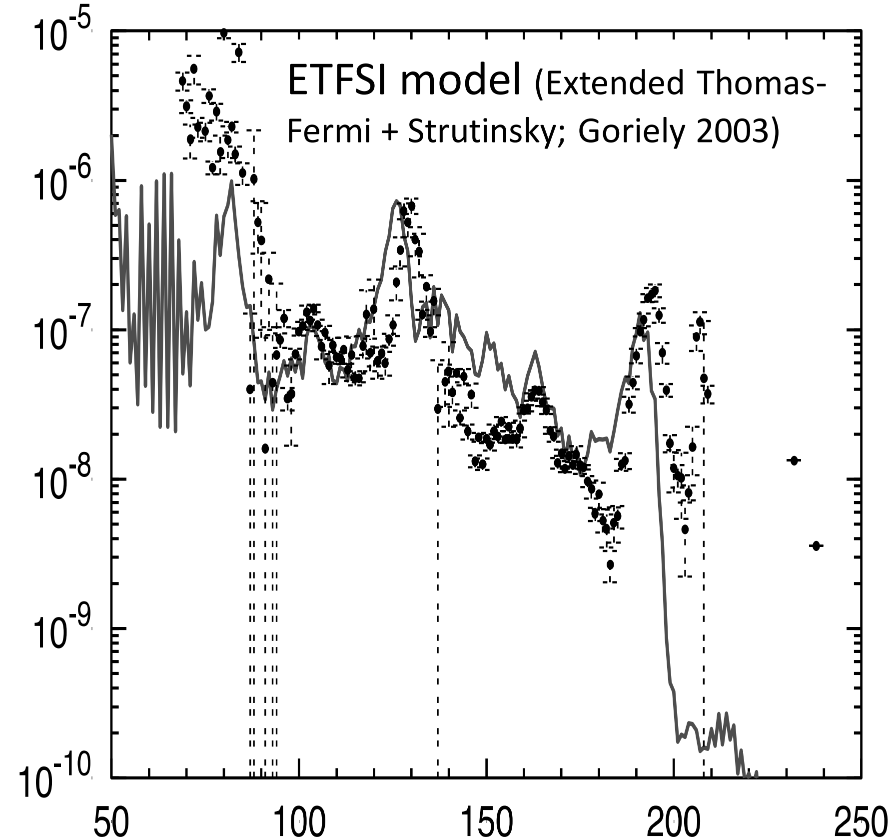




CCSN: Magneto-Hydrodynamic Jets

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 ?**

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

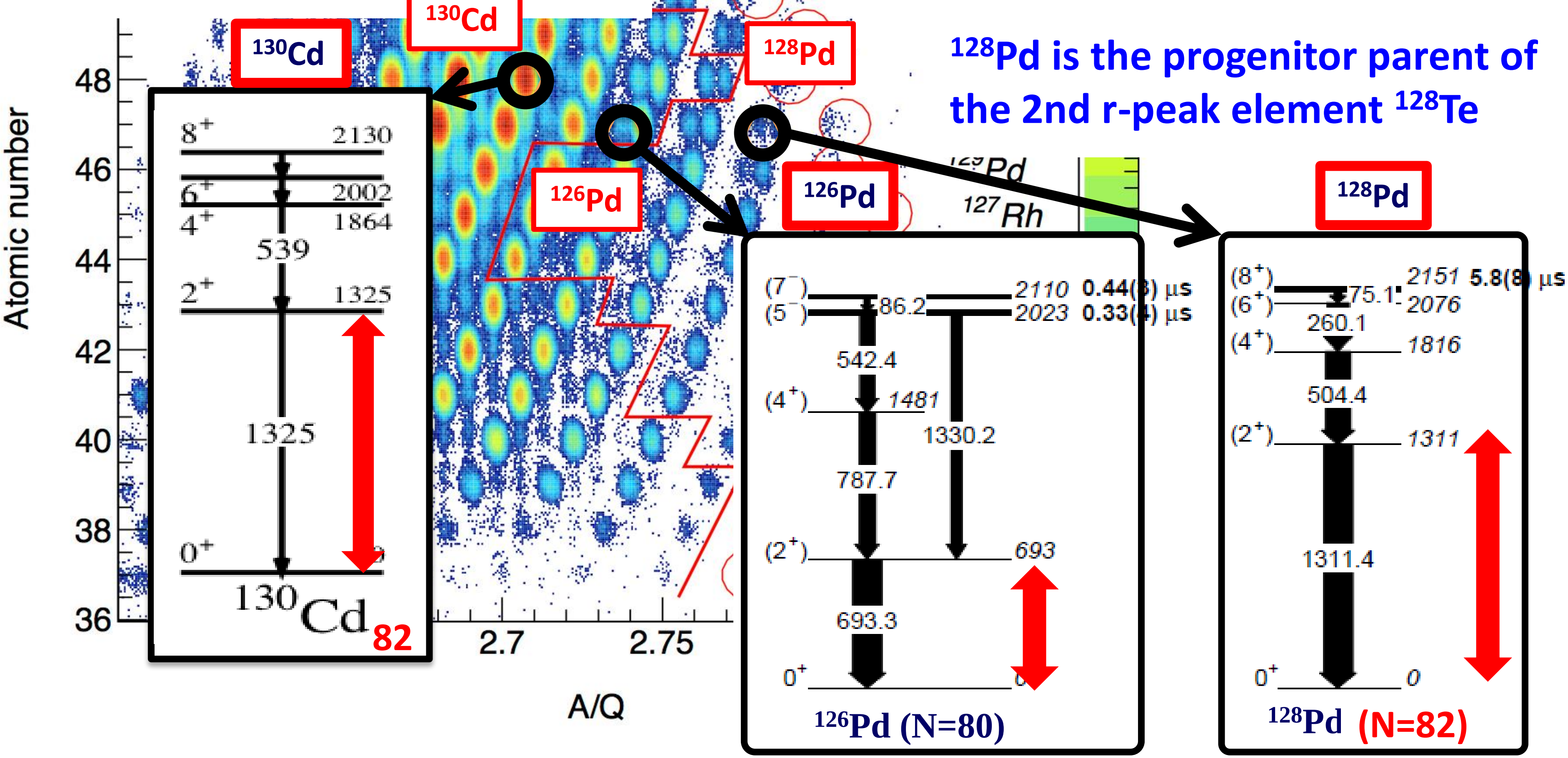
G. Lorusso et al., PRL 114 (2015), 192501.

A.Jungclaus, PRL99, (2007)

No evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

No evidence for shell quenching on N=82 !



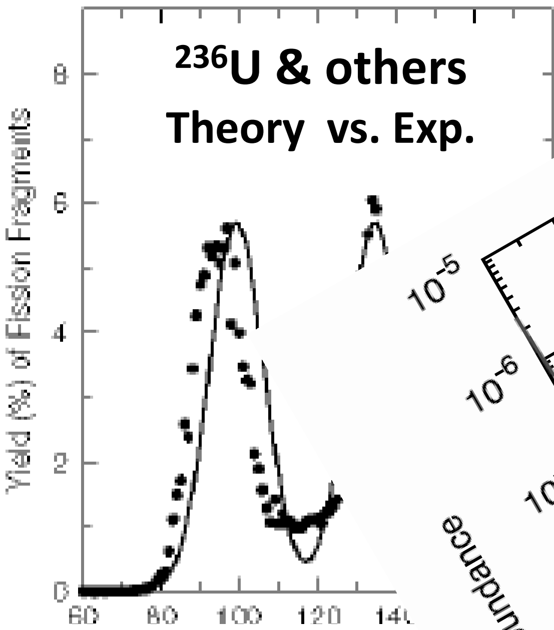
MHD-Jet SNe vs. Binary … Star Mergers

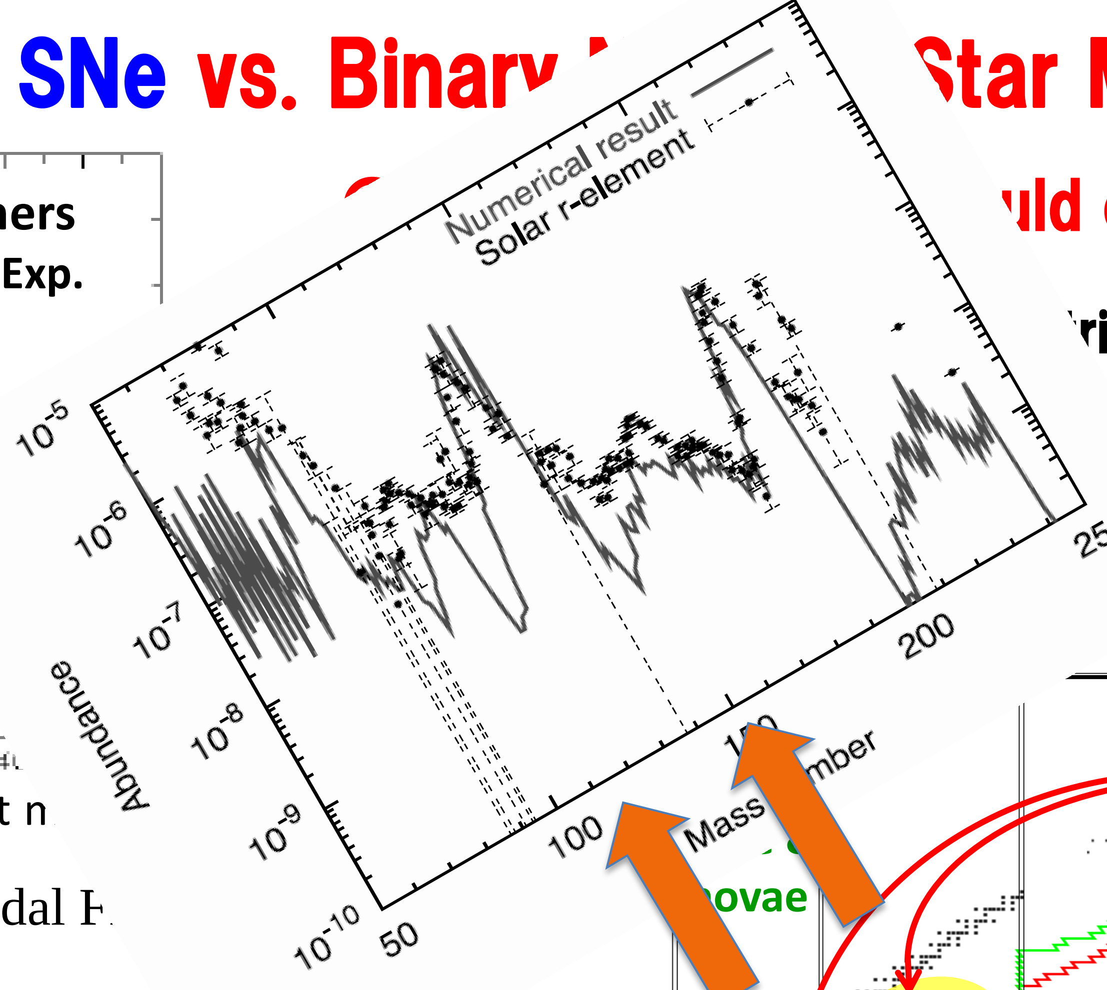
…uld operate!

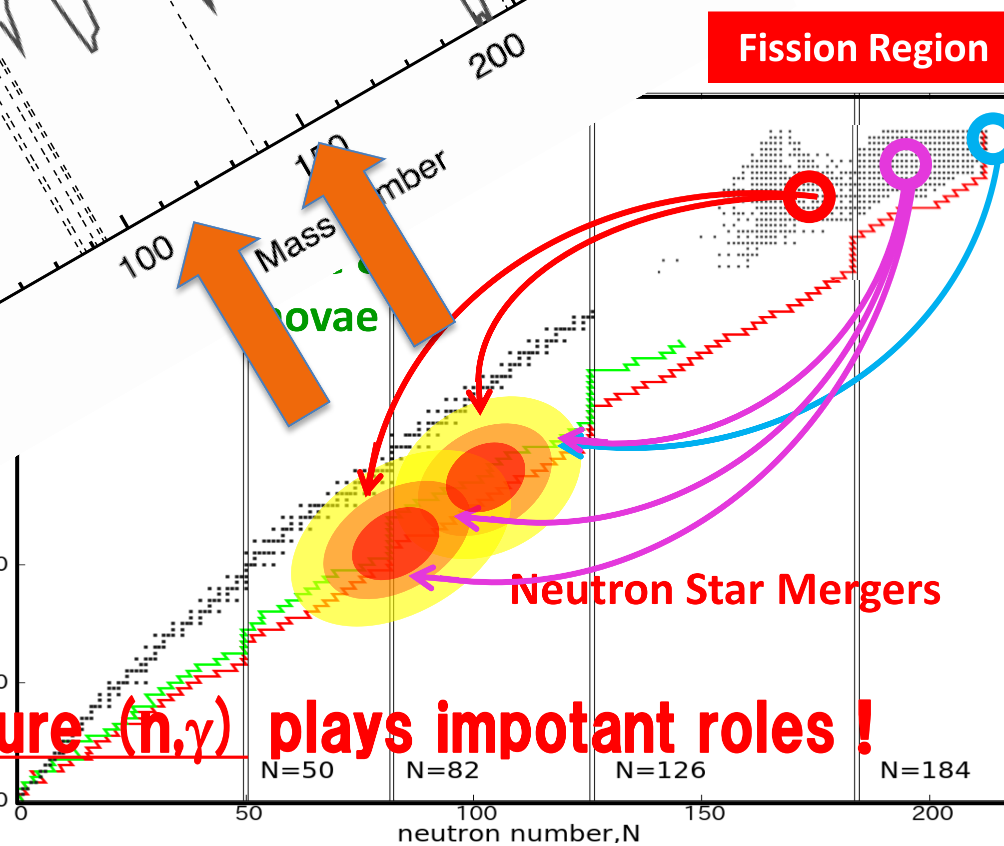
…ribution

…e, France, (2007)

…8).







Bimordial or Trimodal F…

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

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

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

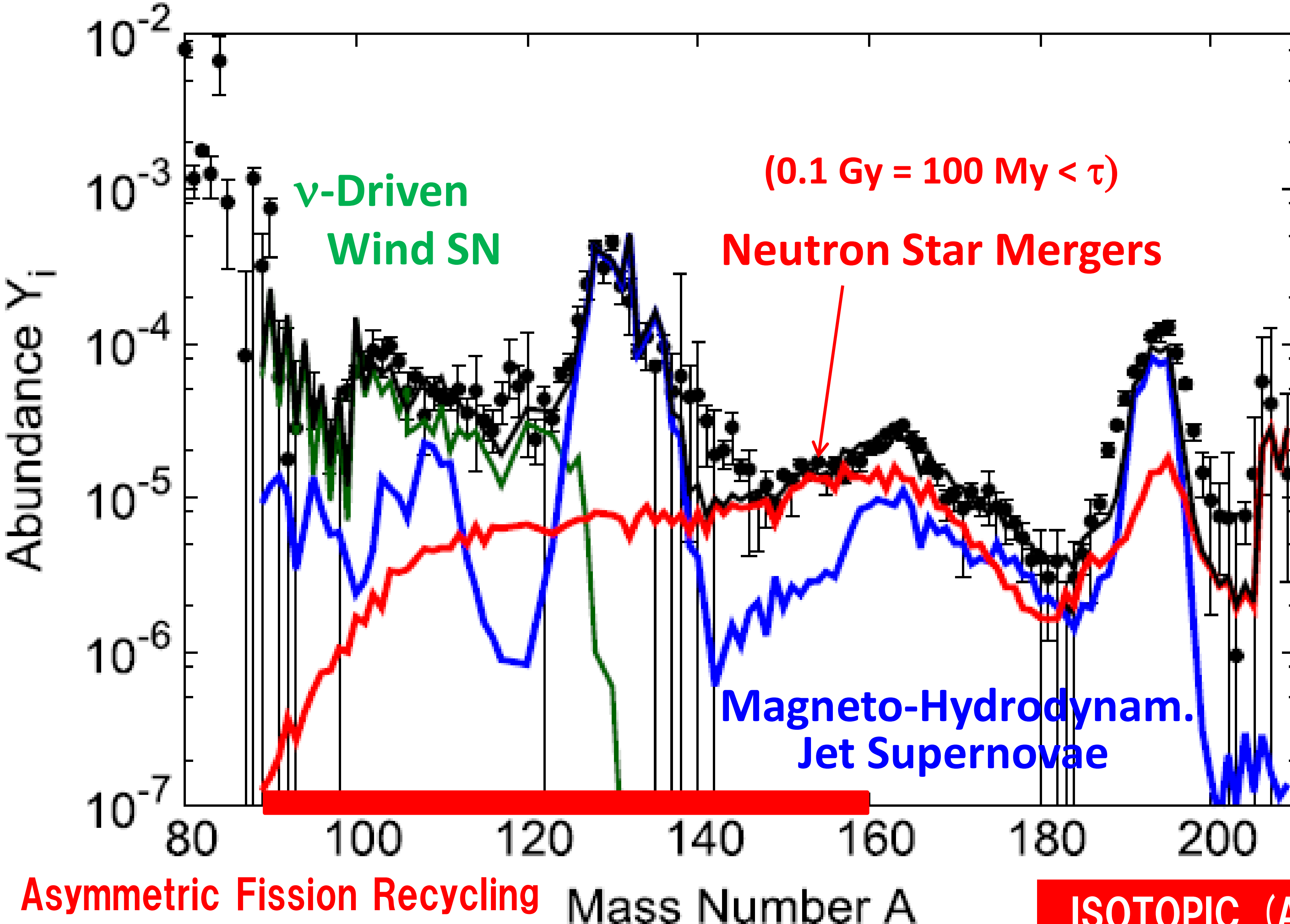
$$A_M = (A_H + A_L)/2$$

◎ Neutron capture (n,γ) plays impotant roles !

Solar System r-Process Abundance

TODAY t = 13.8Gy

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



Asymmetric Fission Recycling

ISOTOPIC (A) !

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±0.02) x (1.9±1.1)) [b]
Binary NSMs	=	$(2\pm1) \times 10^{-2}$	x	$(1\text{-}28)\times10^{-3}$ [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).

Galactic Evolution including Binary Evolution

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

Ejection rate of species i into the ISM

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

Production rate of newly synthesized species i into the ISM

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

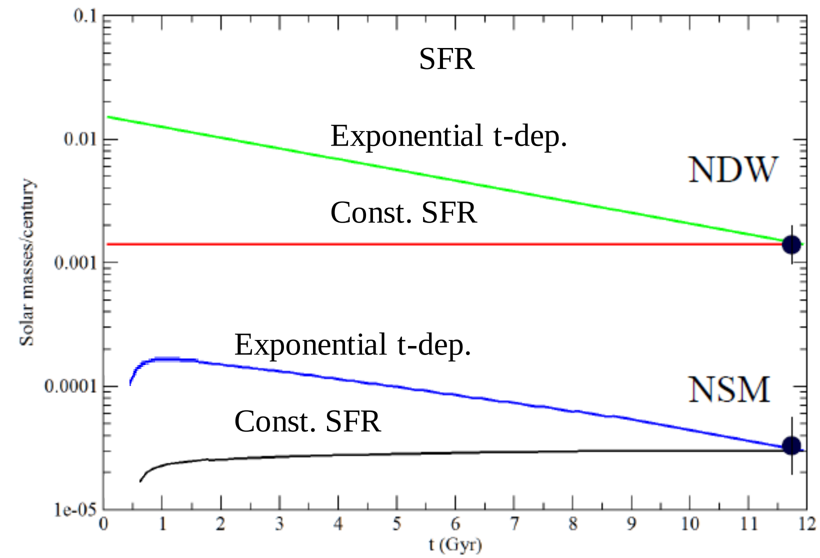
$$P_{rNSM}(t) = m_r(NSM)R_{NSM} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

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

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

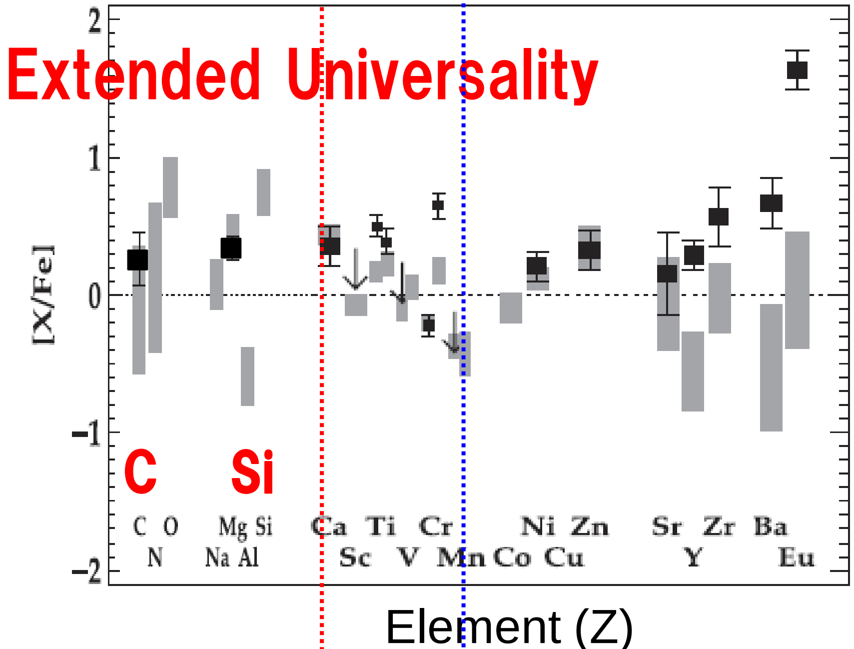
$$R_{NSM} = \int_{m_l}^{m_h} dM_B\,\varphi(M_B) \int_{q_l}^{1} dq f(q) \int_{a_l}^{a_u} da P(a)\psi(t - \tau_{m2} - t_G)$$

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

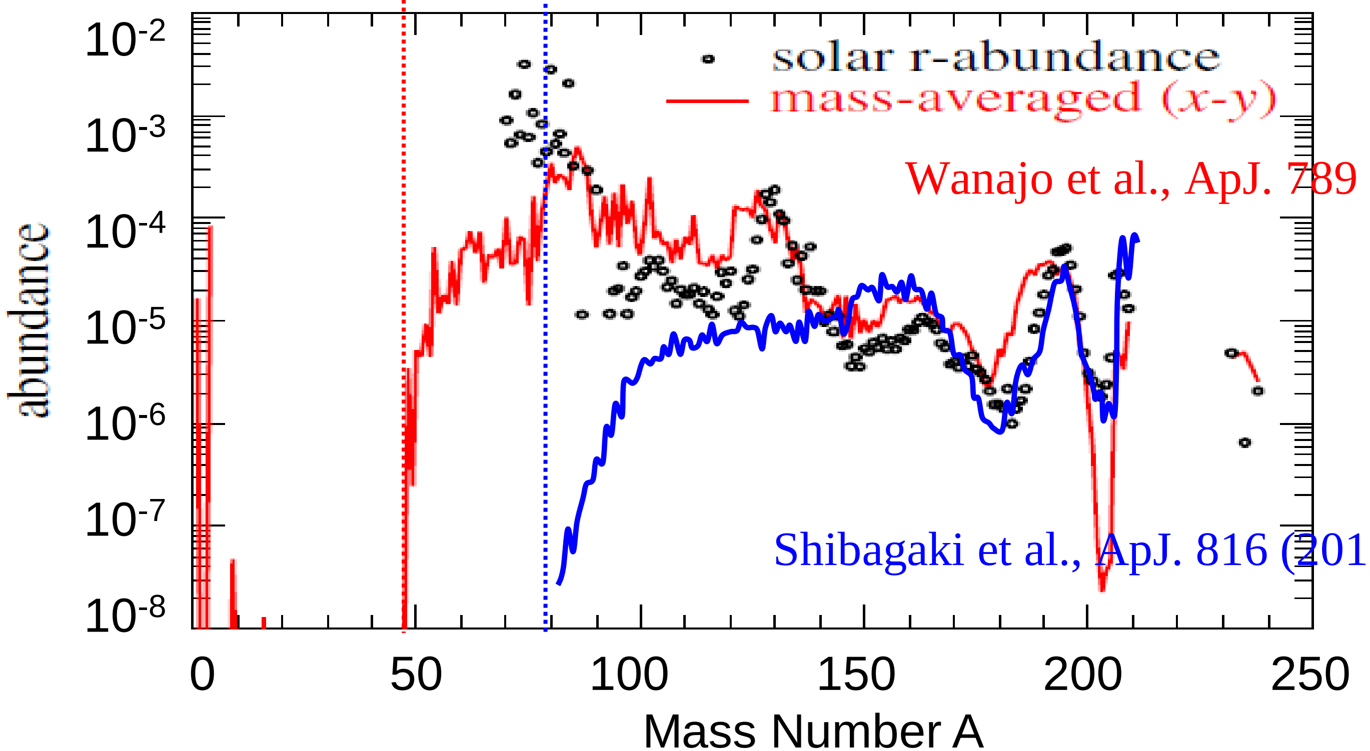


Ultra-Faint warf Galaxy: Ret. II

Ian U. Roederer et al., ApJ. 151 (2016), 82.



Neutron Star Merger r-process cannot produce A < 50 !

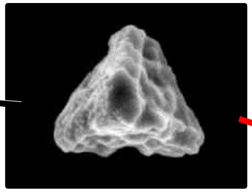


Theor. Cal.
NSM r-Process

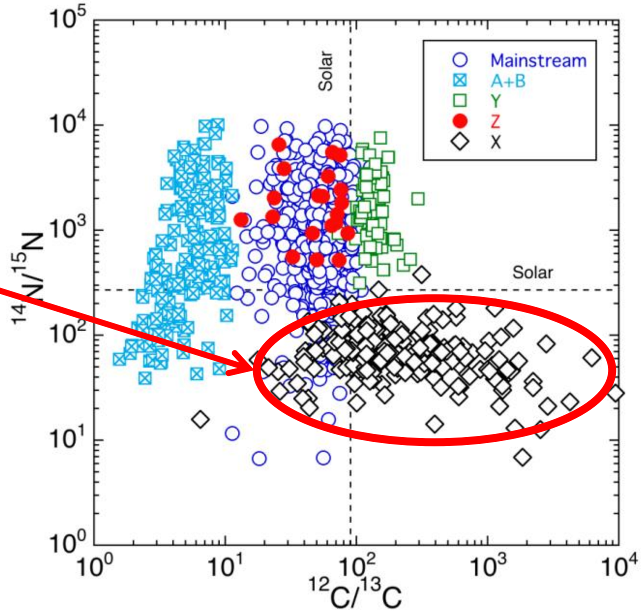
QUEST for Cosmo-Chemistry

Supernova Grains

SiC X-grains



H. Yurimoto, S. Amari



SiC X-grains are made of CC-SN Dust !

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}$=7x10^5yr), ^{44}Ti ($t_{1/2}$=60yr)

Pre-solar grains (S. Amari) :- Grains condensed and formed in stellar outflow or stellar (SN) ejecta, were incorporated into meteorites.

- ■ Universality manifests in [r/C-Si-Fe] = 0 ⟶ SNe
- ■ Even inhomogeneity/scatter exists in [r/C-Si-Fe] ⟶ SNe
- ■ SiC X-grain including r-elements ⟶ NSM ?

However, if pre-solar grains formed after mixing between ejecta and ISM, then we cannot distinguish SNe/NSMs.

SUMMARY

- Electron Captures in SN Ia

A new shell model Hamiltonian GXPF1J well describes the spin responses (GT strengths) in pf-shell nuclei .

Modern GXPF1J shell model Hamiltonian gives more quenched e-capture rates than KB3G, KBF and FFN, and can solve the overproduction problem in neutron-excess iron-group nuclei in delayed-detonation SN Ia explosion.

- Origin of R-Process Elements

Both CCSNe and binary NSMs are necessary, but their roles in cosmic evolution and isotopic abundance patterns are different.

R-process in CCSNe (MHD Jet & neutrino-driven) satisfies the universality in the early Galaxy. Binary Neutron-Star Mergers (NSMs) have arrived too late (time-scale problem) but gradually contribute to the S.S..

It is highly desirable to study the weak interactions & neutrino oscillations in CCSN and NSM nucleosynthesis.