Int. Symp. on “Simplicity, Symmetry and Beauty of Atomic Nuclei”
In Honor of Professor Akito Arima’s 88 year-old birthday 米寿
Shanghai, China, Sept. 26-28, 2018

Discovery of Neutron Star Merger and Supernova:

Impact on Element Genesis and Neutrino Physics

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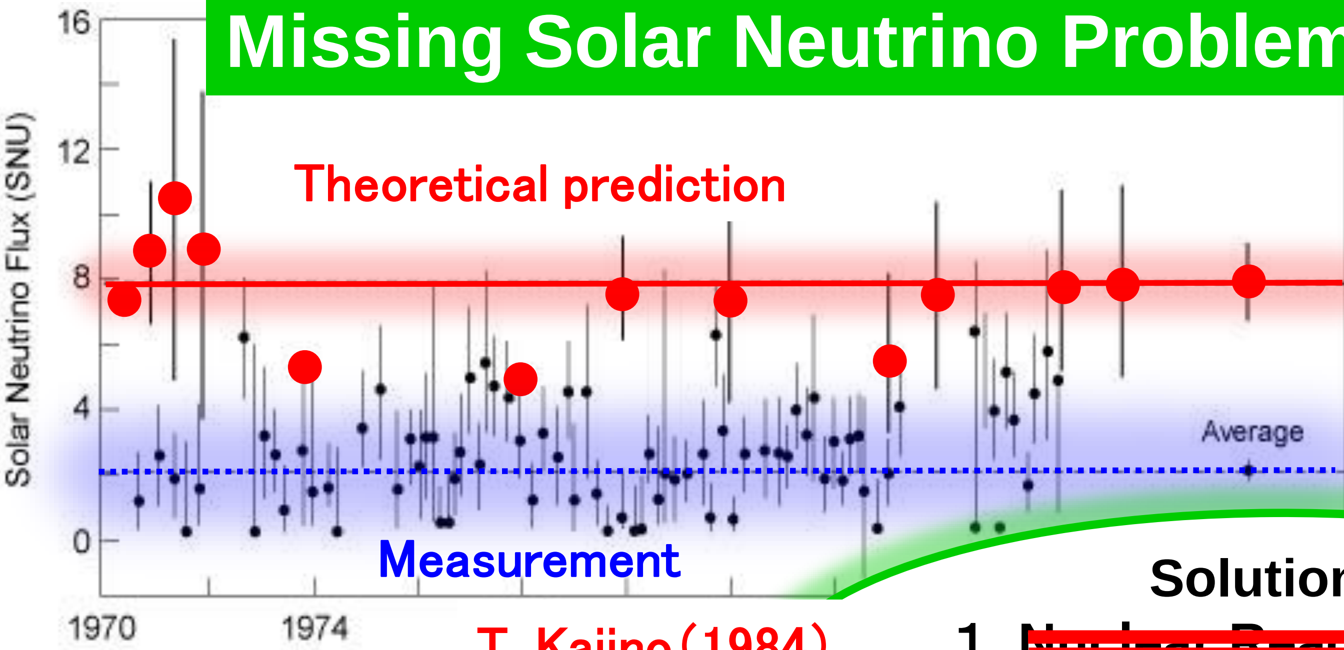
National Astronomical Observatory of Japan
The University of Tokyo

Missing Solar Neutrino Problem

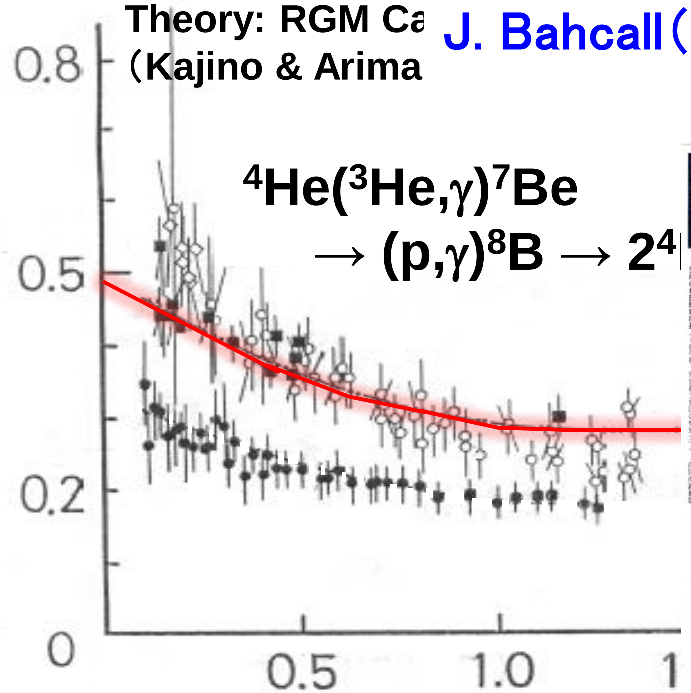


vis, Jr.
ysics

T. Kajino（1984）
J. Bahcall（1988）

Solution？
1.
2.
3. Unknown Neutrino Nature

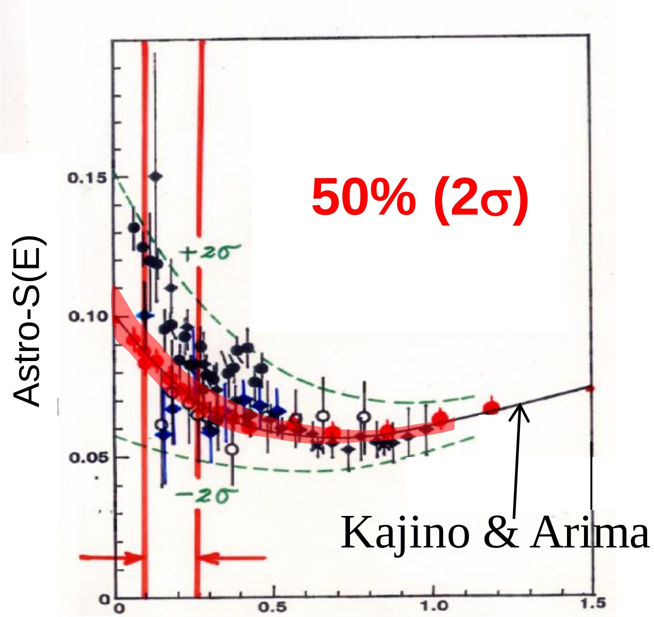
of Tokyo
(until 1993)

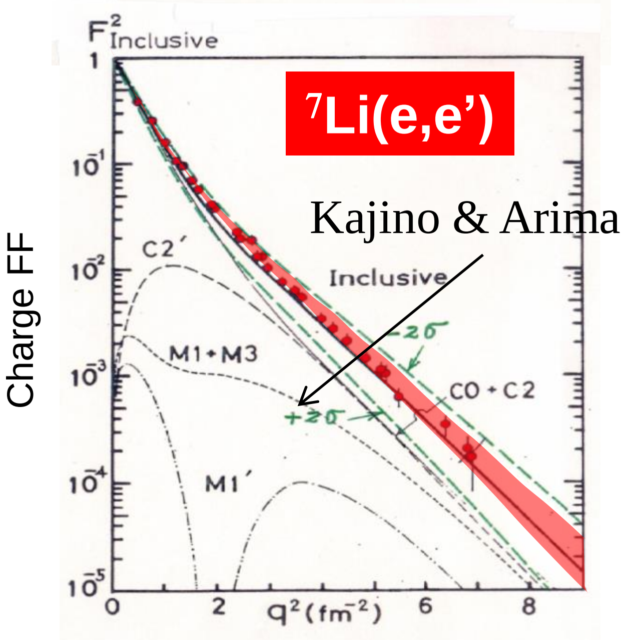


$^4He(^3He,\gamma)^7Be$
$\rightarrow (p,\gamma)^8B \rightarrow 2^4$


梶田氏ノーベル賞
物理学賞
ニュートリノ質量発見
宇宙の謎 解明に期待
スーパーカミオカンデで観測

$^4He(^3H,\gamma)^7Li$ ⟷ Mirror Conjugation ⟷ $^4He(^3He,\gamma)^7Be$



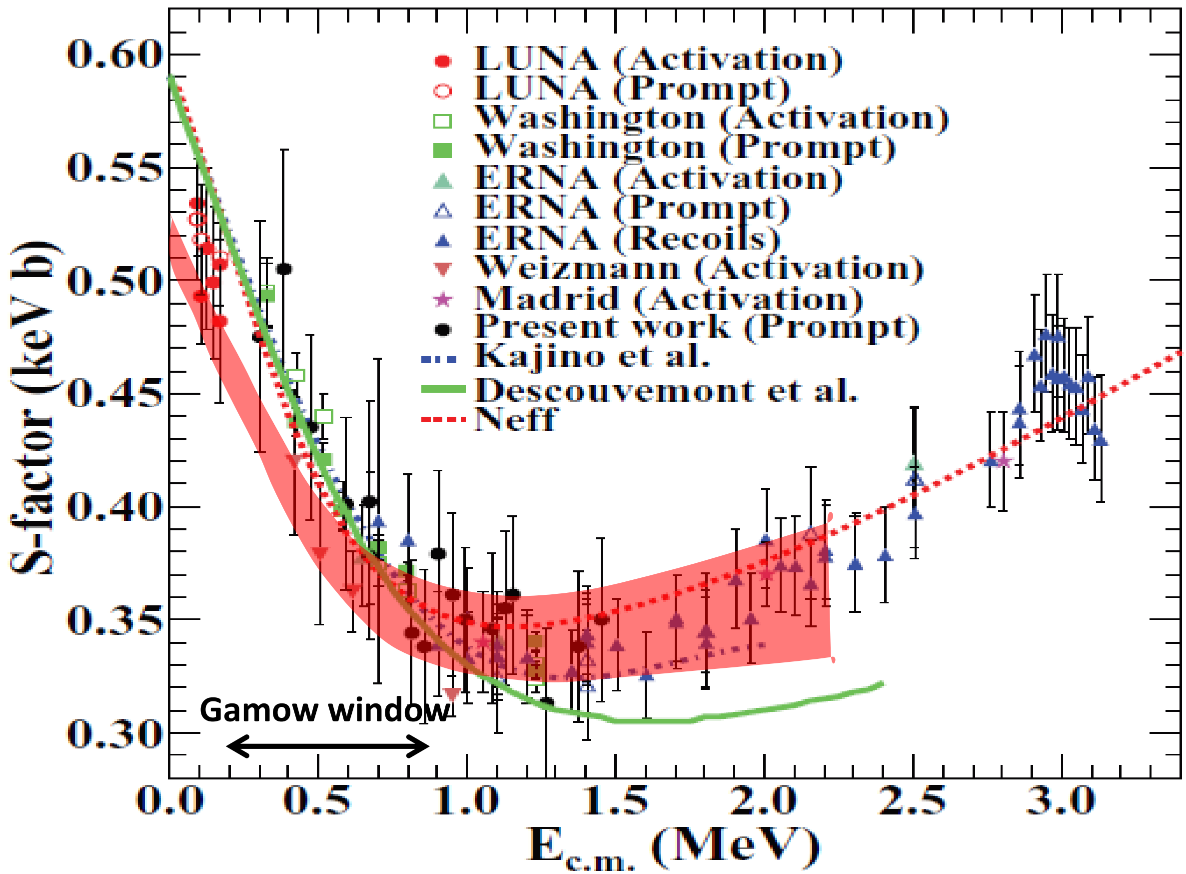


Adelberger, RMP 83 (2011),195.

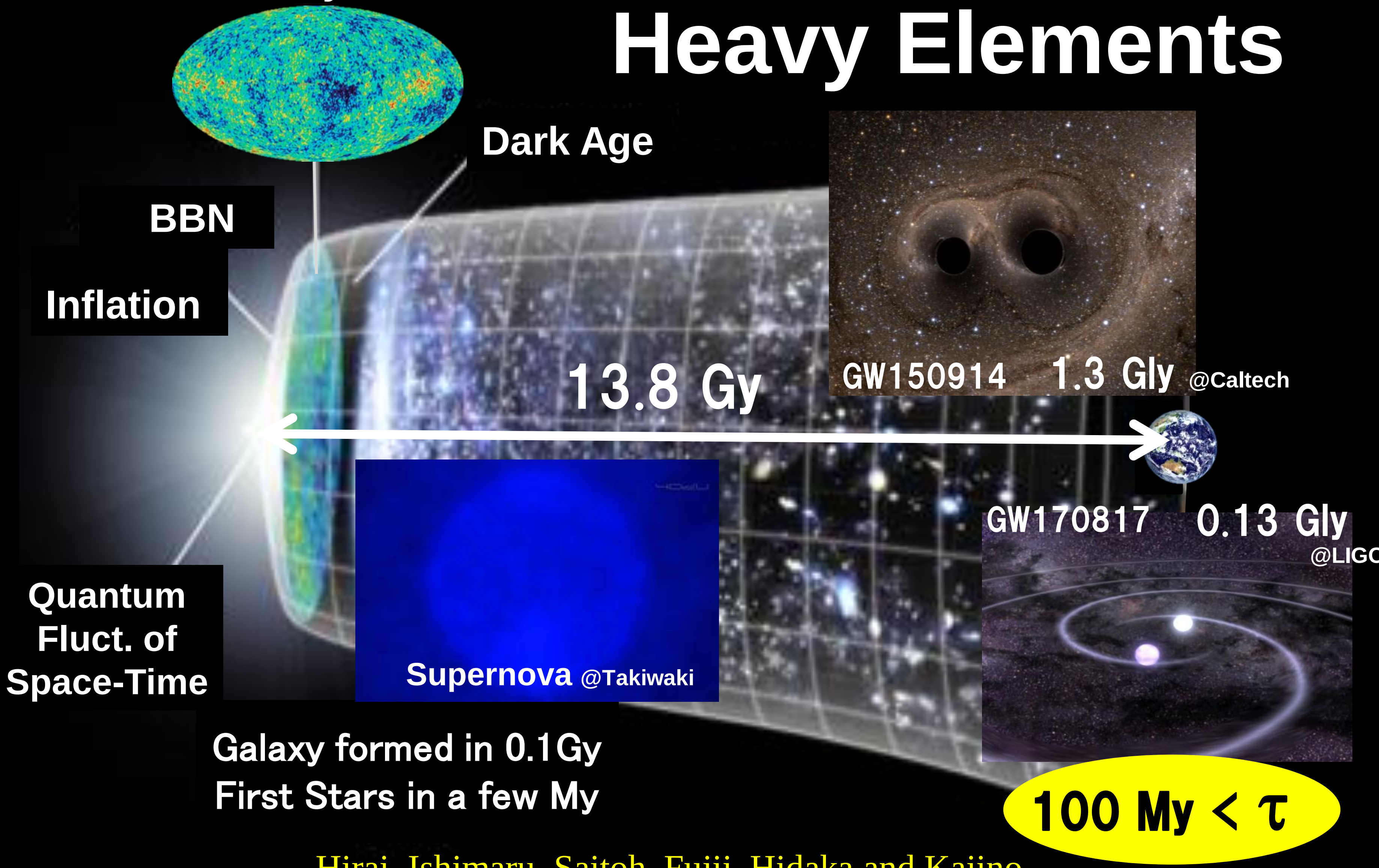
5% (1σ), uncertain !

Kajino & Arima, PRL 52 (1984), 739; NP A413 (1094), 323; NP A460 (1986), 559; ApJ 319 (1987), 531

Still to be studied precisely !

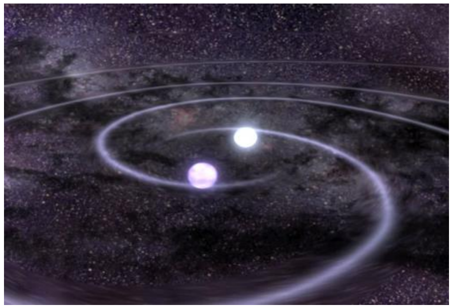


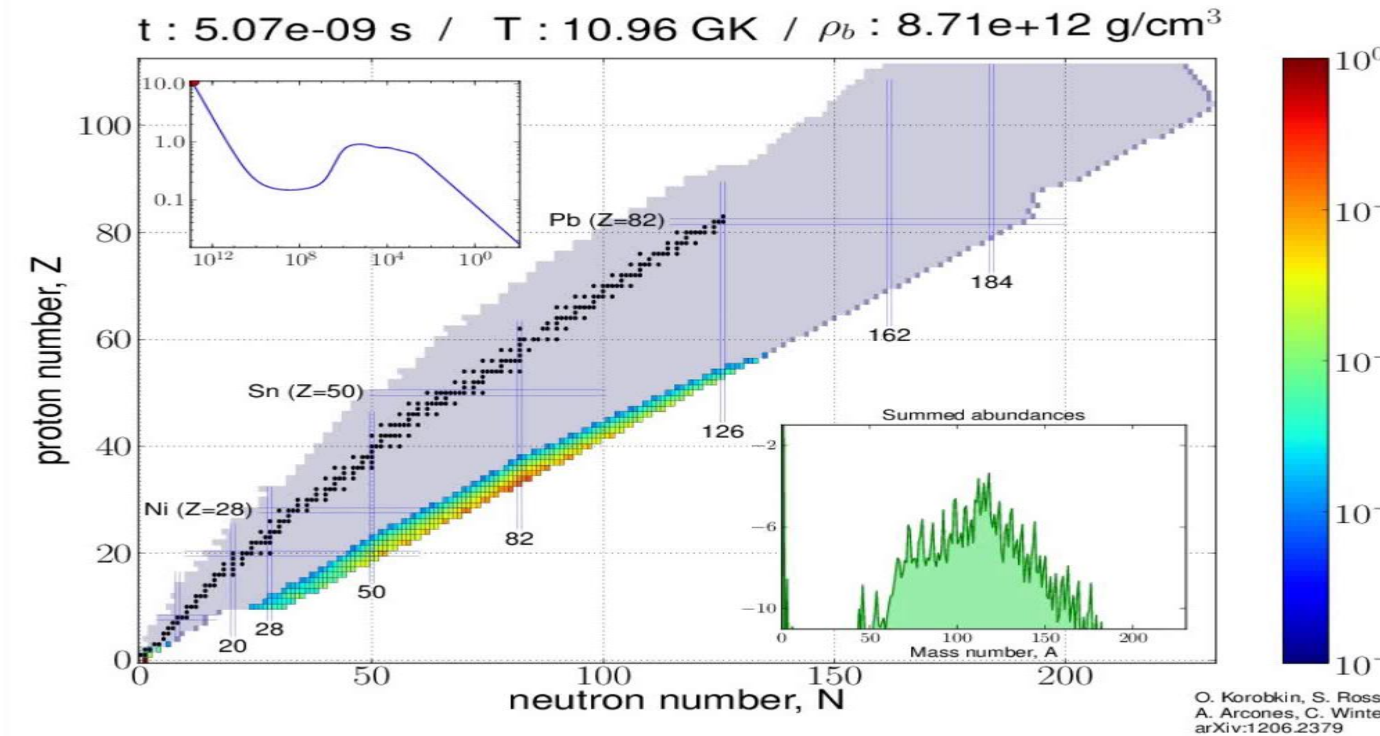
Cosmic Evolution & Heavy Elements



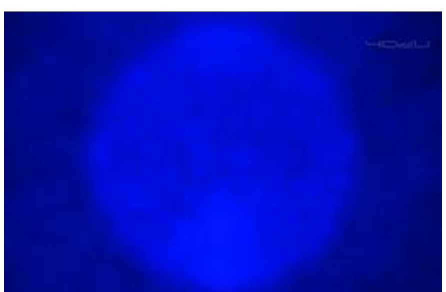
Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino,
ApJ 814 (2015), 41; MNRAS 466 (2017), 2474.

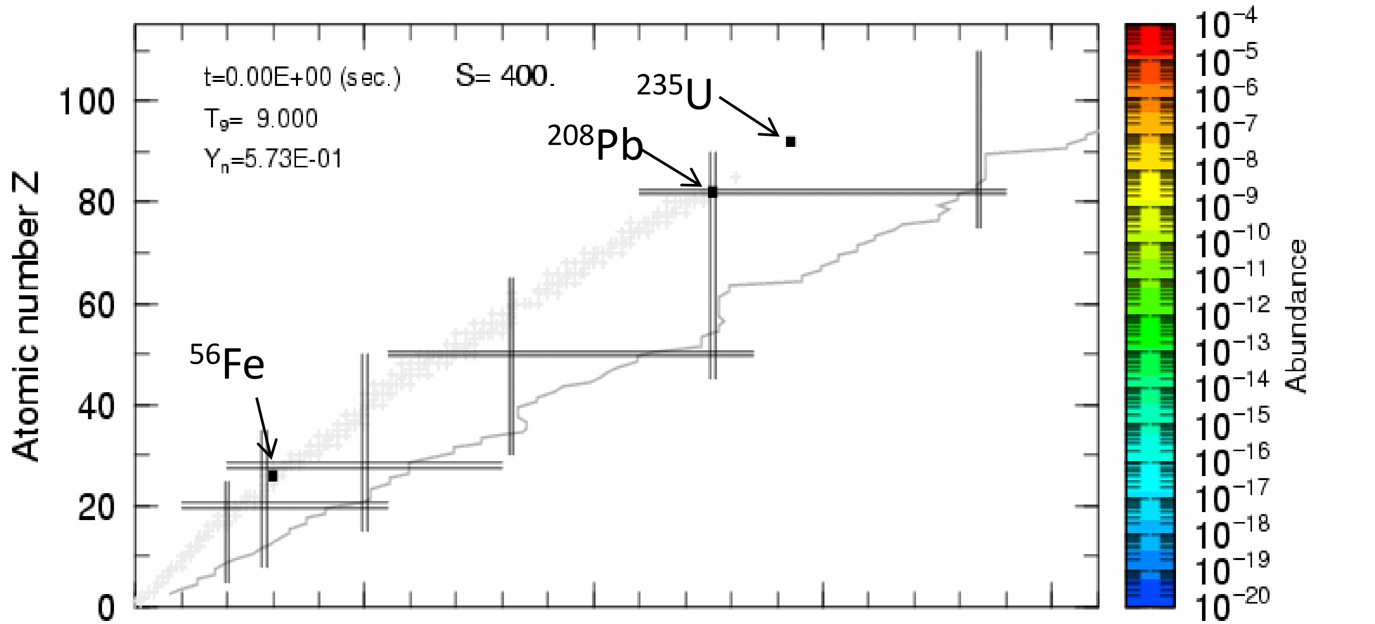
Neutron Star Merger





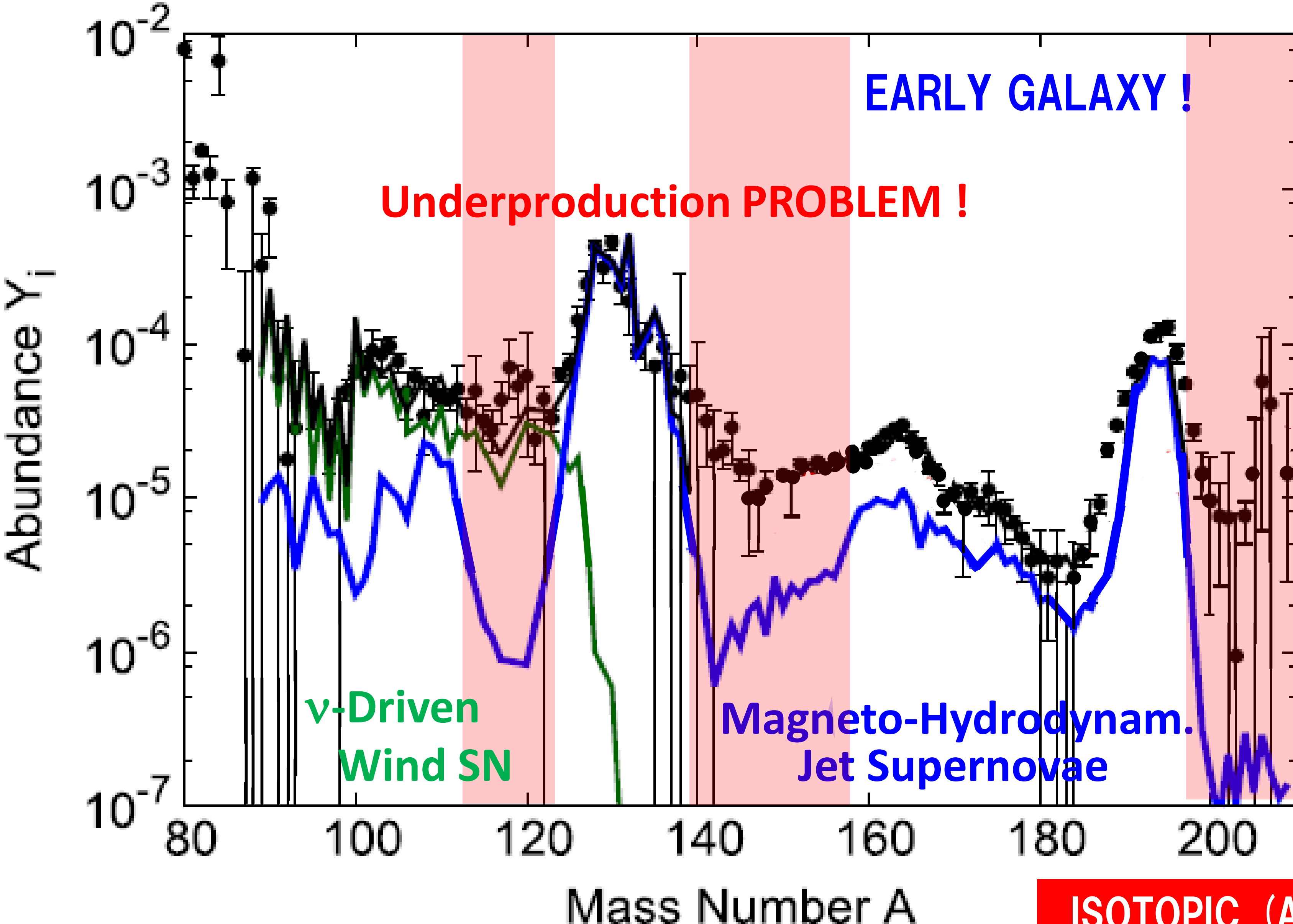
Supernova (MHD Jet)





EVOLUTION of the r-Process Abundance

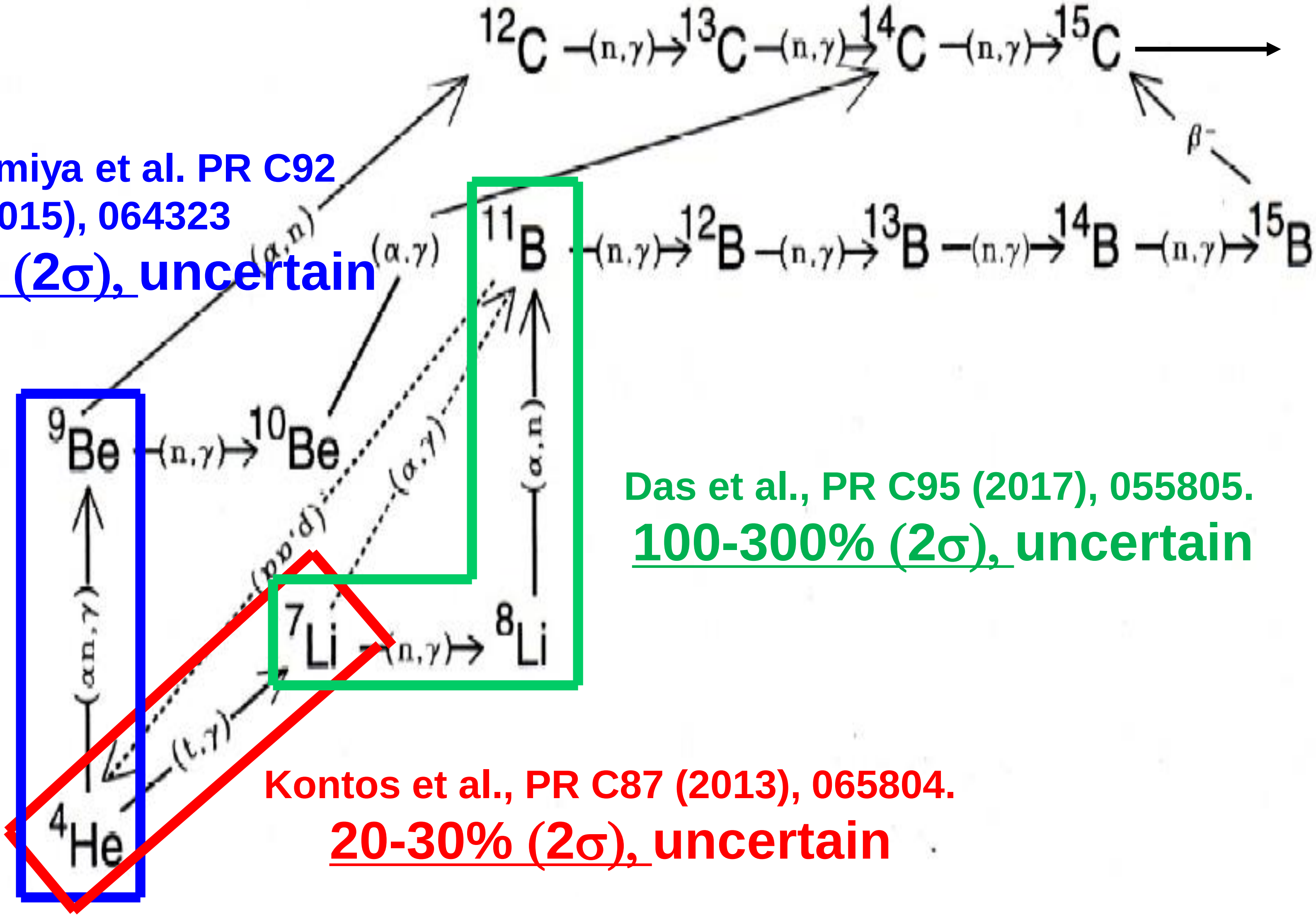
Kajino & Mathews (2017), Review of Prpgress in Physics 80 , 084901.



ISOTOPIC (A) !

SUPERNOVA R-Process: Important Reactions

Factor x2 change → 10-100 difference in 1st Peak r-Elements !



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.

20-30% (2σ), uncertain

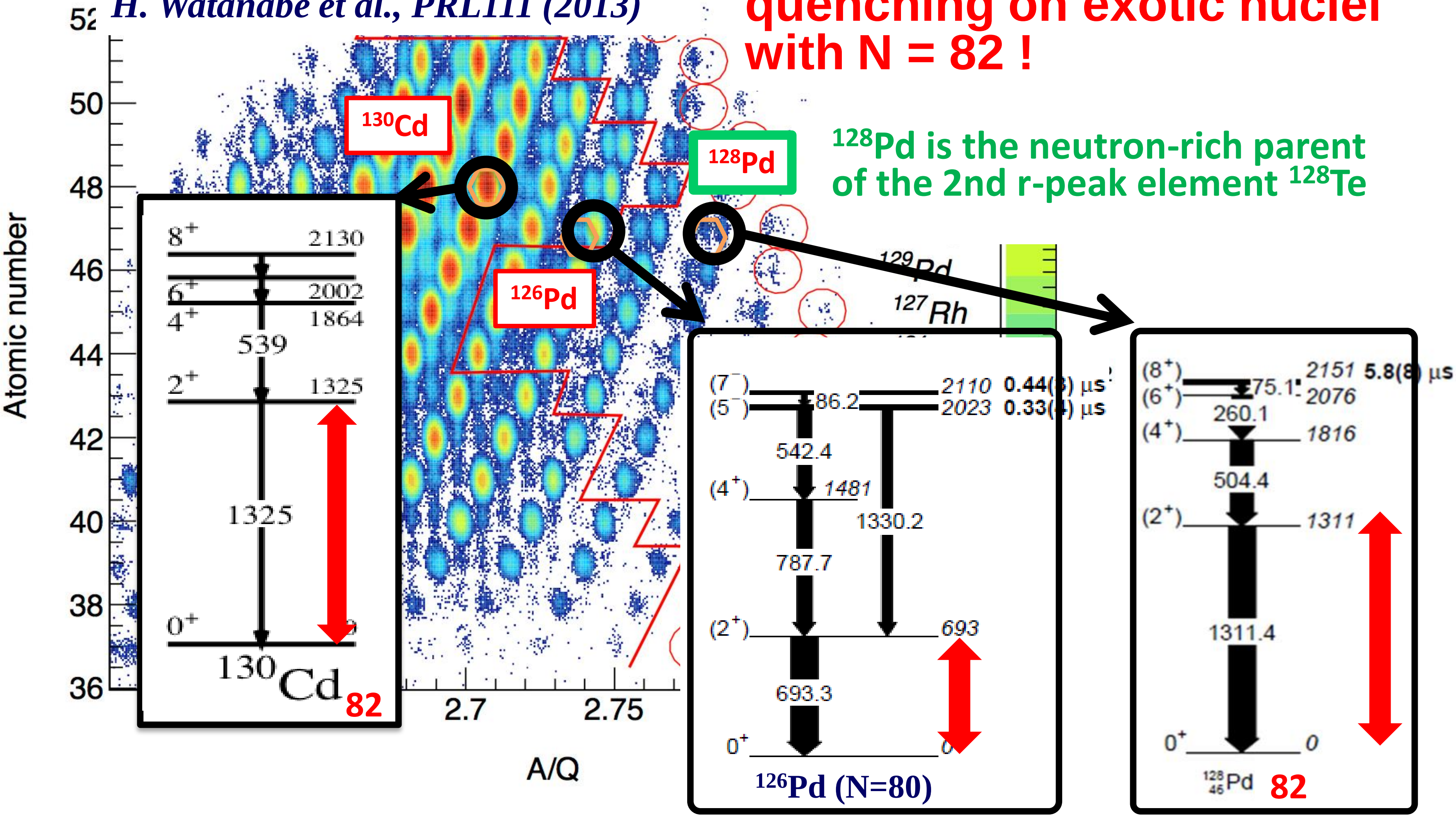
RIKEN-RIBF : Decay Spectroscopy around A = 100-145

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

A.Jungclaus, PRL99, (2007)
H. Watanabe et al., PRL111 (2013)

No clear evidence for shell quenching on exotic nuclei with N = 82 !

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

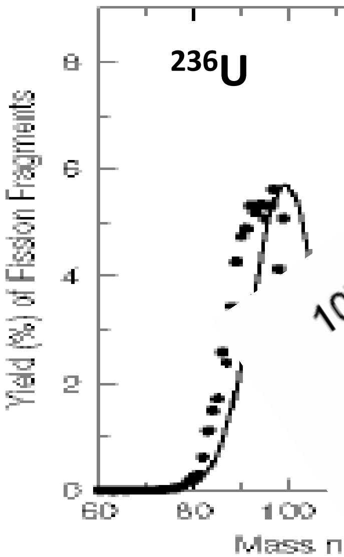


Important Nucl. P… Mergers

… sections !

…ibution !

…rance, (2007)



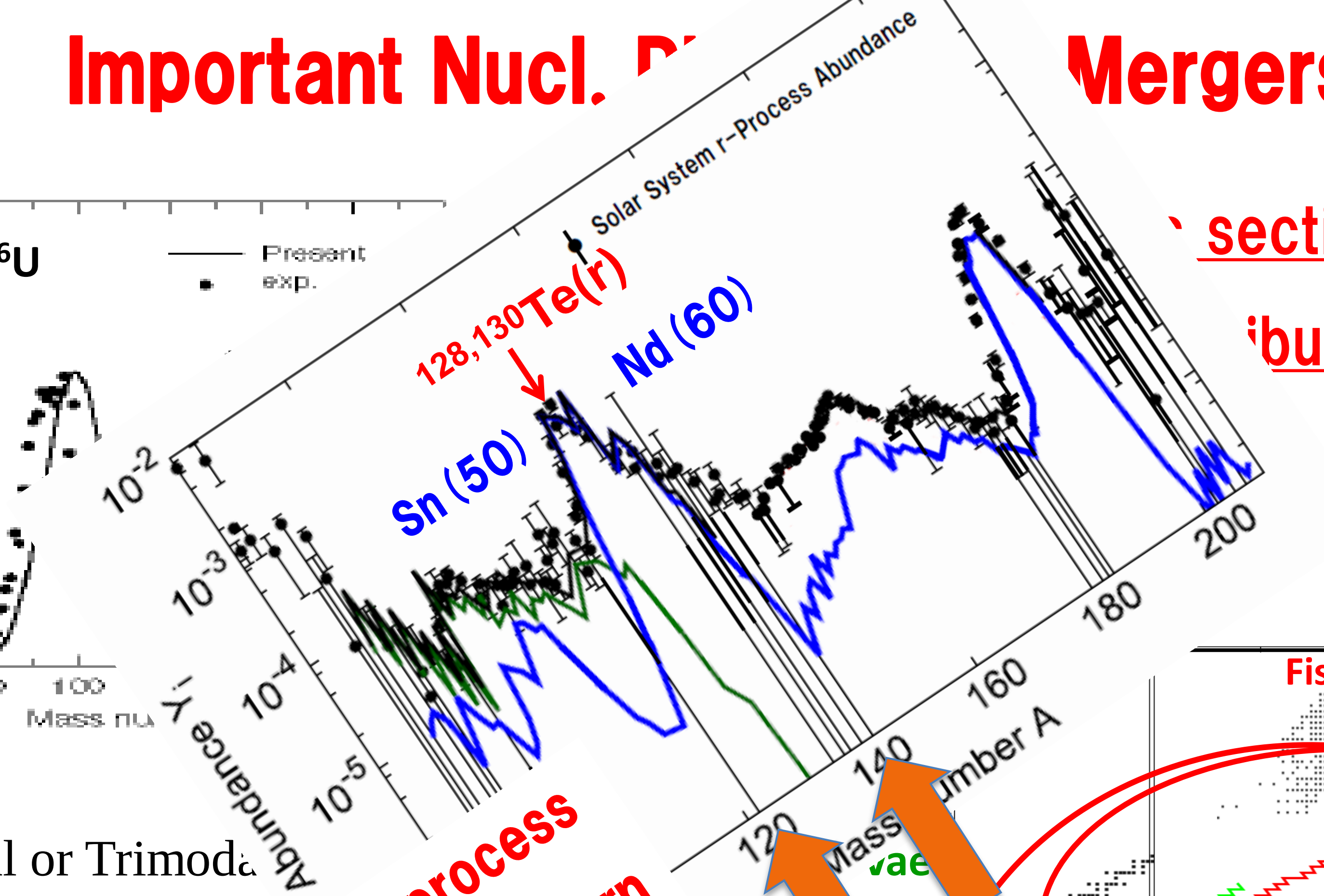
Bimordial or Trimoda…

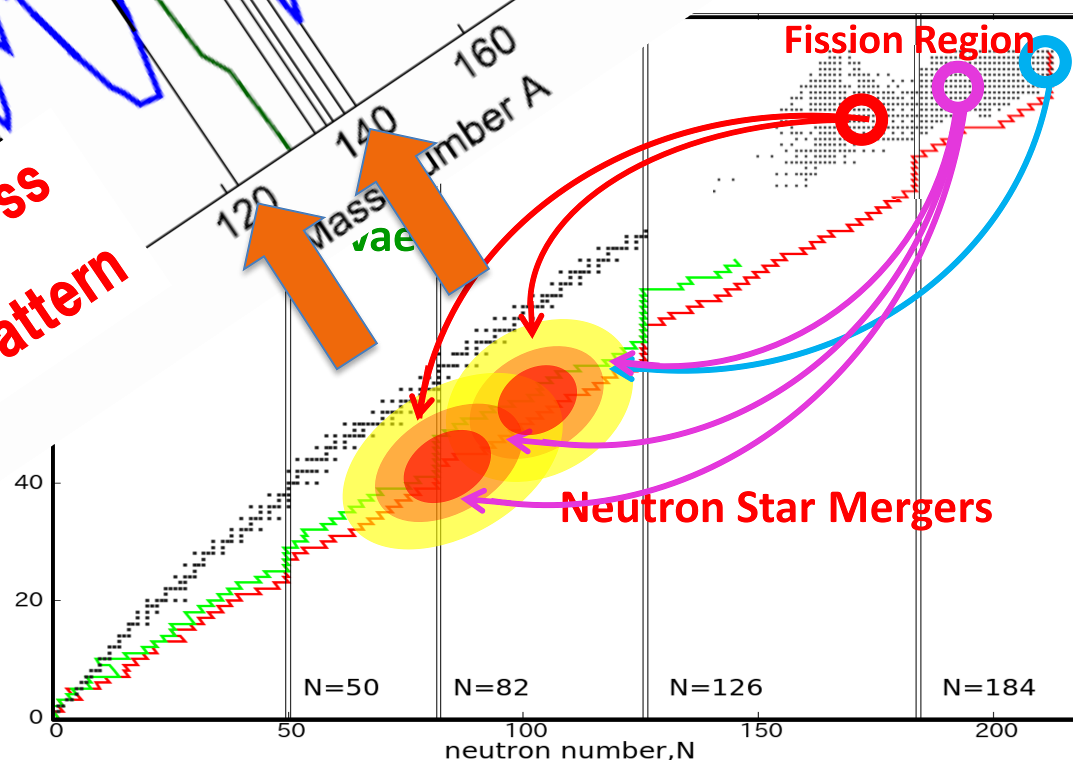
$$f(A,A_p)=\sum_{A_i}\frac{1}{\sqrt{2\pi\sigma}}W_i\exp(\ldots$$

$$A_H=(1+\alpha)(\ldots$$

$$A_L=\ldots$$

$$A_M\ldots$$

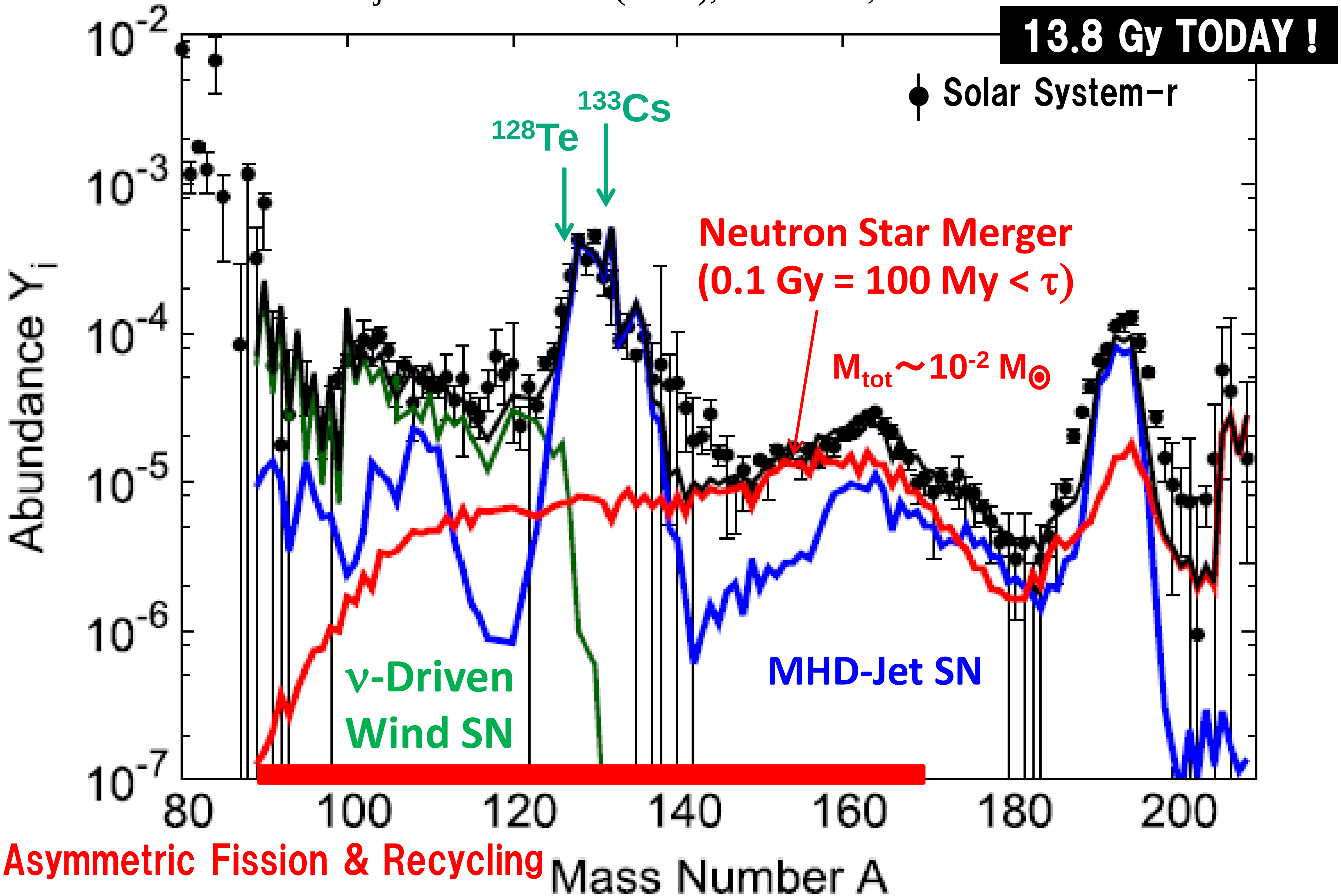


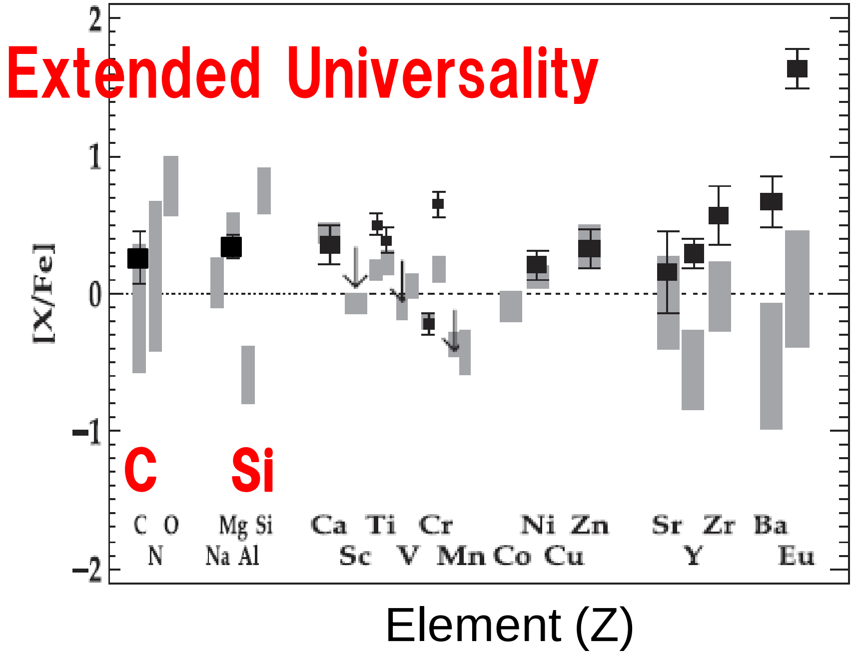


Fission recycling and r-process (n,γ) & β-decay for smoothing abundance pattern

Solar System r-Process Abundance

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2018);
Kajino & Mathews (2017), ROPP 80 , 084901.



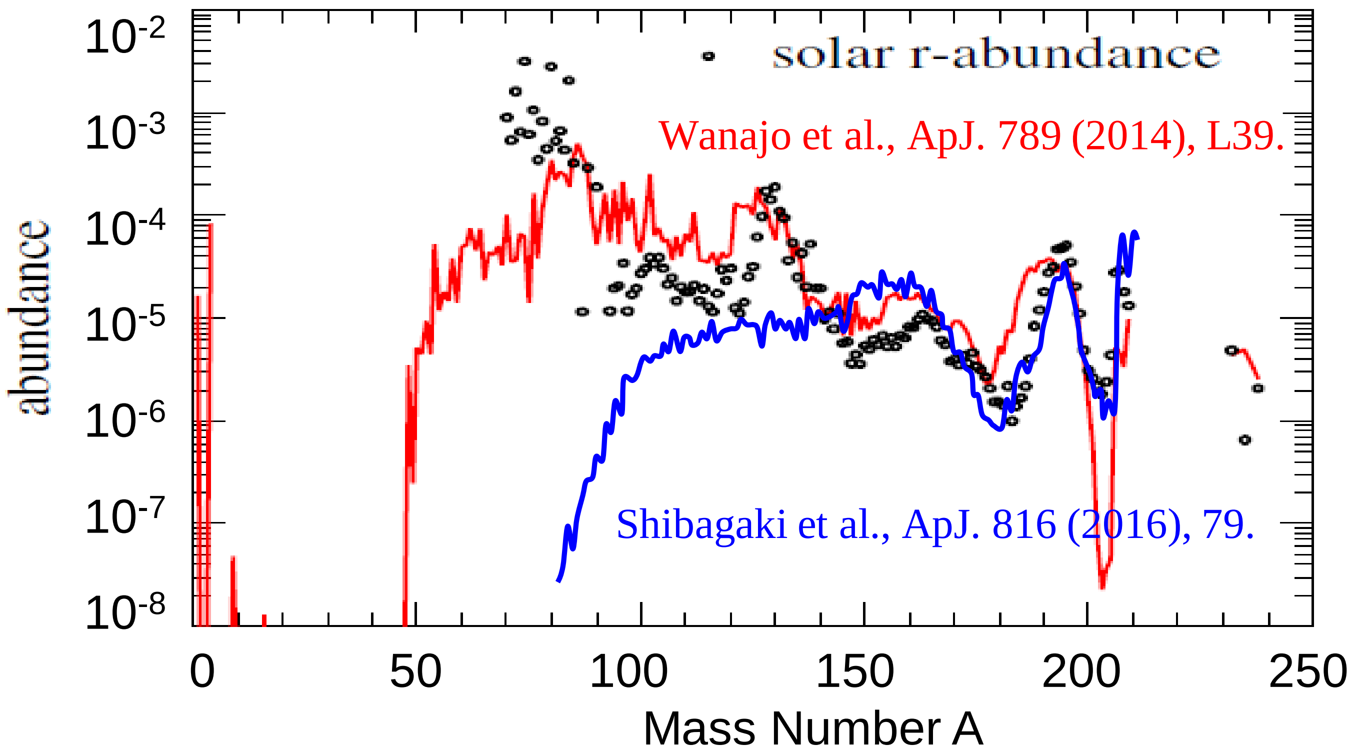


Ultra-Faint Dwarf Galaxy: Ret. II

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.

NSM can not produce A<80 enough !



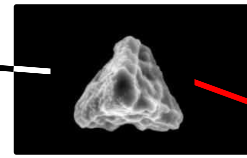
Goriely, et al., ApJ 738, L32 (2011); Korobkin, et al., MNRAS 426, 1940 (2012); Bauswein, et al., ApJ 773, 78 (2013); Rosswog, et al., MNRAS 430, 2585 (2013); Goriely, et al., PRL 111, 242502 (2013), (2015): Piran, et al., MNRAS 430, 2121 (2013).

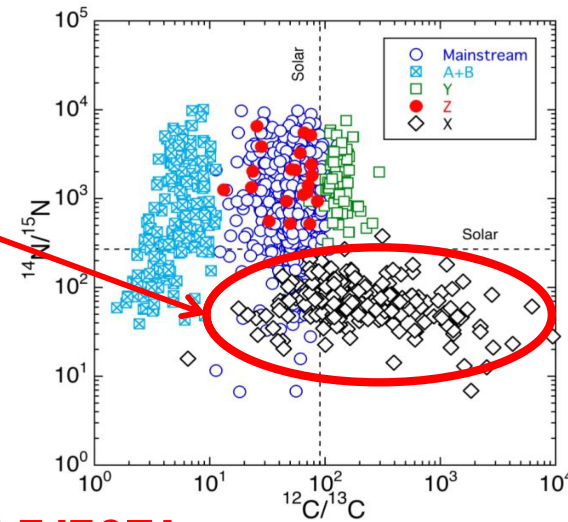
“r-process” Elements, found in SiC X-Grains

◎ Supernova Grains e.g. Murchison Meteorite

Courtesy of S. Amari

SiC X-grains





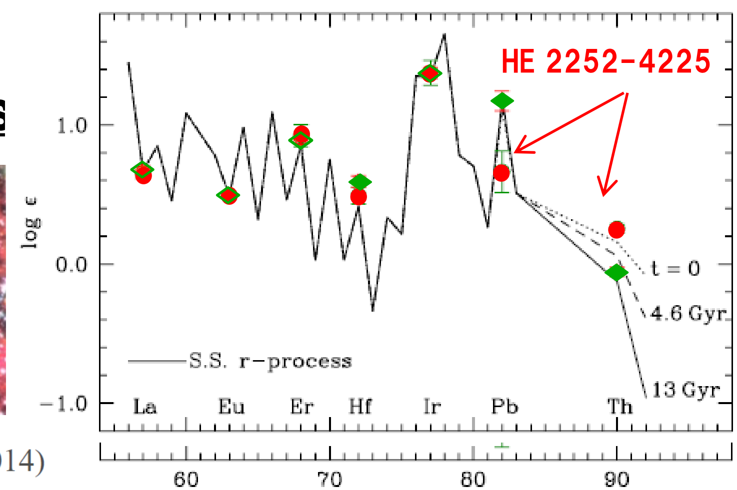
- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)

Pre-solar SiC X-grains condense & form from **SN EJECTA.**

- ■ SiC X-grain including r-elements ⟶ NSM/SN event rates !
- ■ Extended universality & actinide boost ⟶ both NSM & SN !

◎ Direct Spect. Obs.: Actinide-boost stars

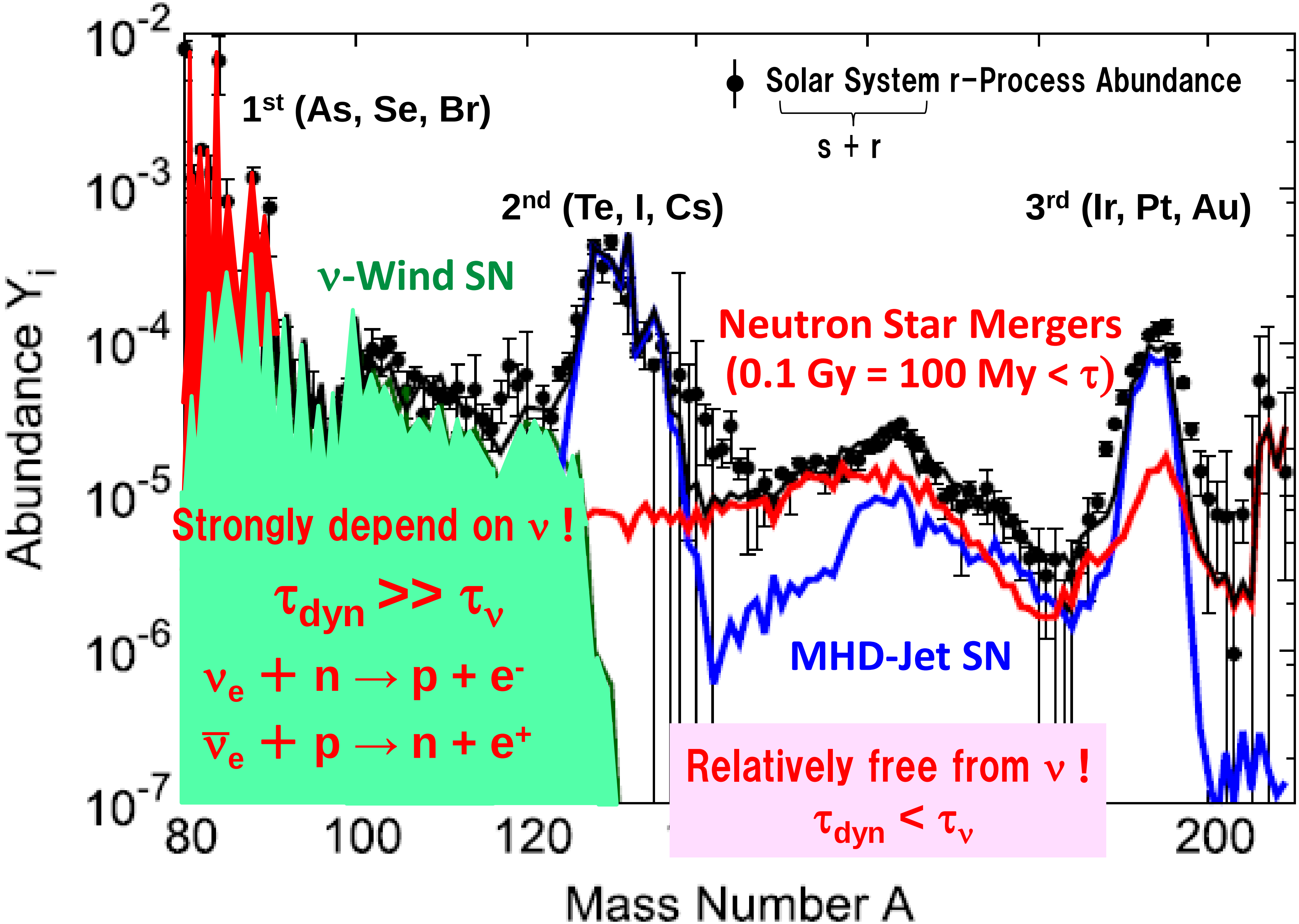
Simultaneous direct detection of C, Si & r-elements is highly desirable !



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

Solar System r-Process Abundance **Present Epoch: t = 13.8Gy**

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2017); Kajino & Mathews (2017), ROPP 80, 084901.

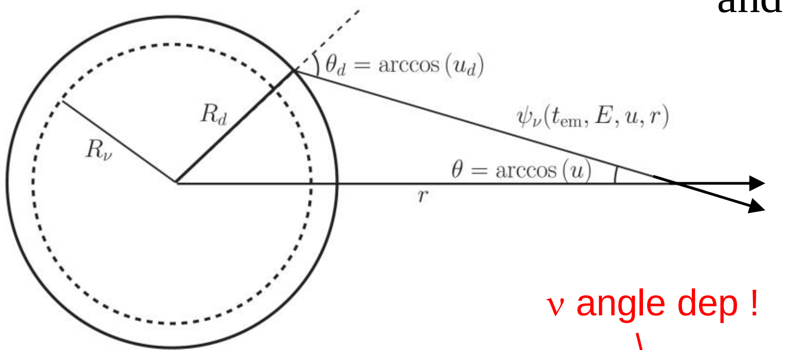


Collective ν Oscillation — Many-Body Quantum Effect

Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101; Fogli, Lisi, Marrone & Mirizzi, JCAP 12 (2007) 010; Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011; PR D (2018), in press.

Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin and Pehlivan, PR D96 (2017), 043013

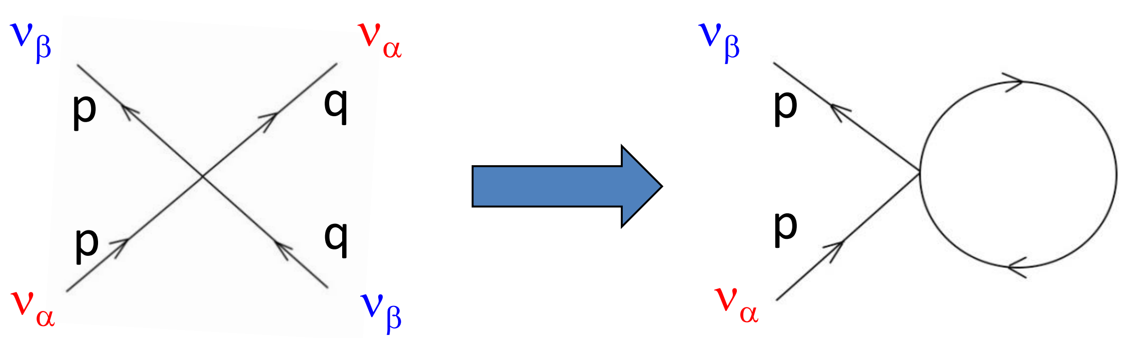
proto-neutron star (ν Sphere)



$$\begin{cases} i\dfrac{d\psi_\nu}{dt} = (H_{\rm v} + H_e + H_\nu)\psi_\nu(t_{\rm em}, E, u, r), \\ H_{\rm v} = U\dfrac{M^2}{2E}U^\dagger, \\ H_e = \sqrt{2}G_F n_e(r)\,{\rm diag}(1,0,0), \end{cases}$$

ν angle dep !

$$H_\nu = \sqrt{2}G_F\sum_\alpha \int dE' d\Omega' \underline{(1 - uu')}\left[\frac{d^2 n_{\nu_\alpha}}{dE' d\Omega'}\rho_{\nu_\alpha}(t'_{\rm em}, E', u', r) - \frac{d^2 n_{\bar\nu_\alpha}}{dE' d\Omega'}\rho^*_{\bar\nu_\alpha}(t'_{\rm em}, E', u', r)\right].$$

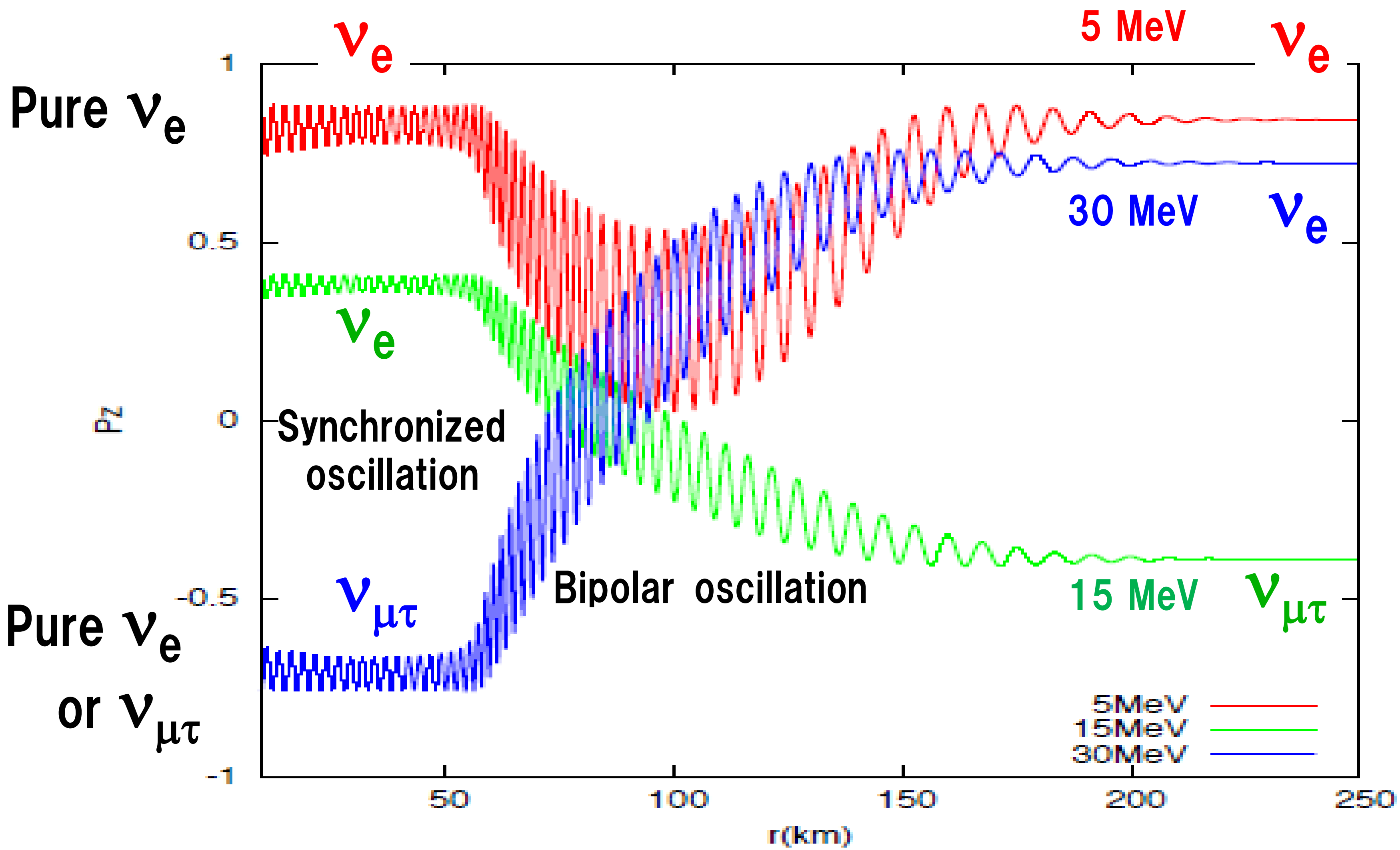


$\alpha, \beta = e, \mu, \tau$

10^{48} ν's with 3-flavors & multi-angles ! → **Mean Field Approx.**

Calculated ν Flavor Oscillation

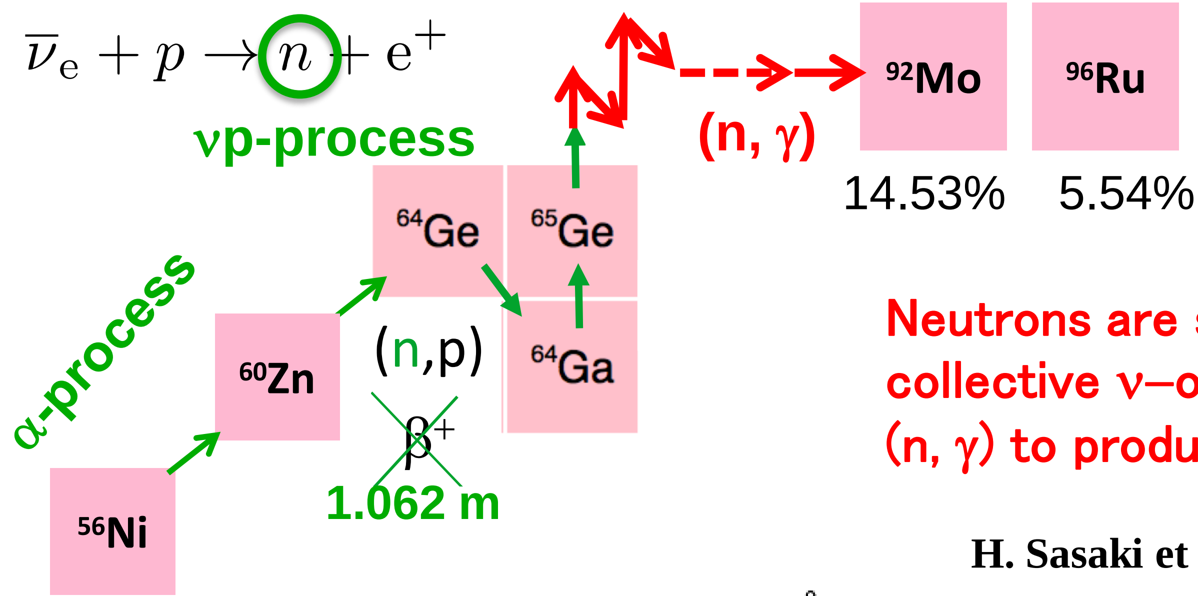
Energy spectra swap!



Ordinary νp−process

C. Freohlich, et al., PRL 96 (2006), 142502.

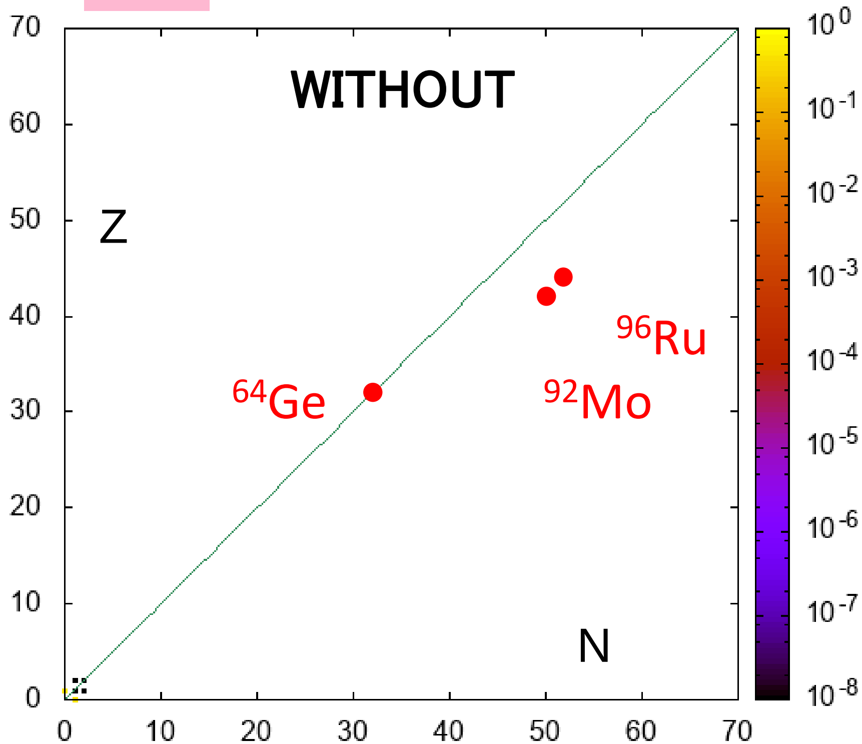
$$\overline{\nu}_e + p \rightarrow n + e^+$$

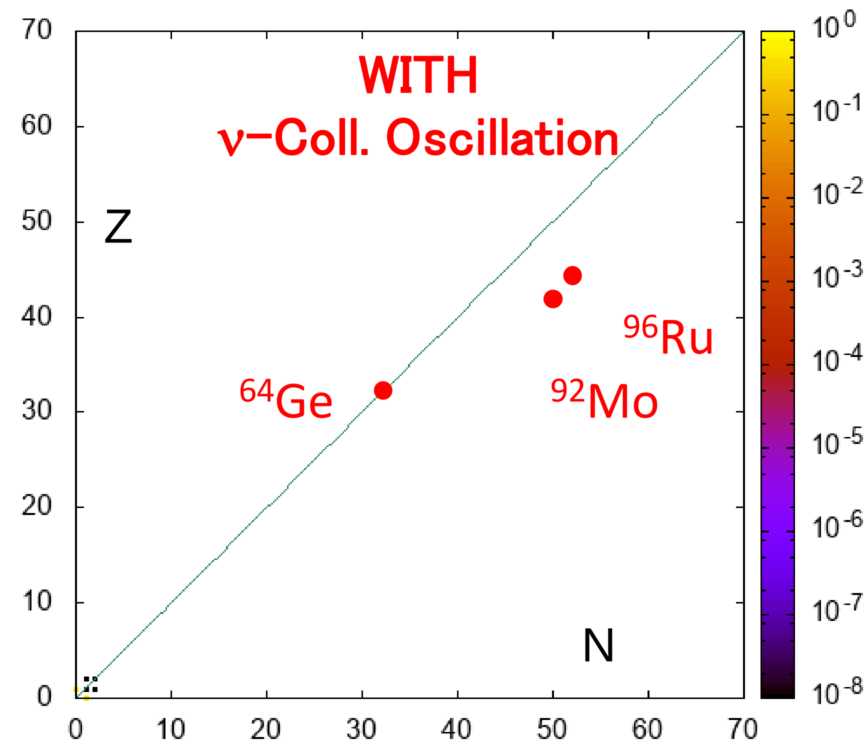


Isotopic ratio of p-nuclei ~ 0.1-1%

Neutrons are supplied continuously by collective ν−oscillations, followed by (n, γ) to produce ^{92,94}Mo, ^{96,98}Ru!

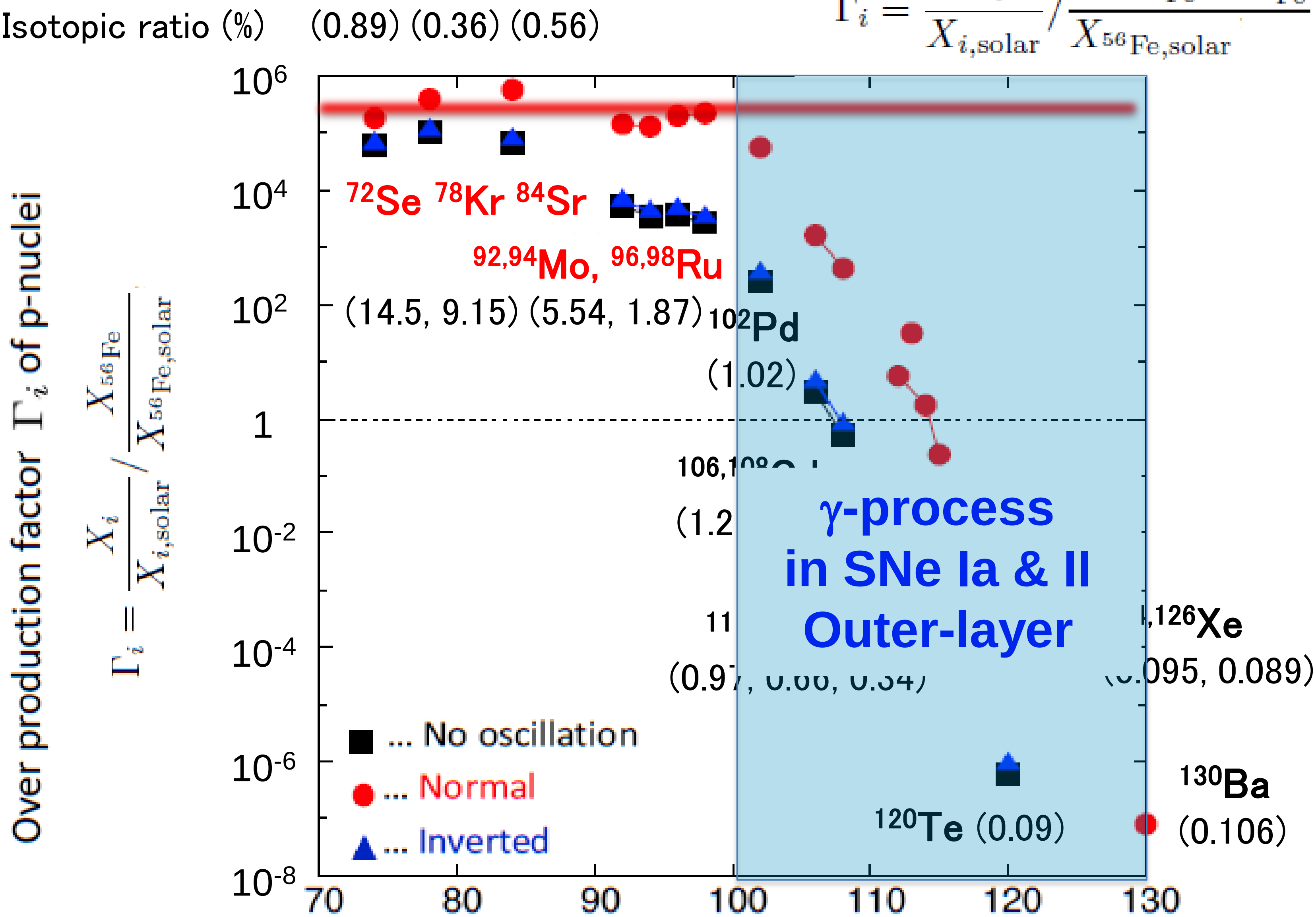
H. Sasaki et al. PR D96 (2017), 043013.





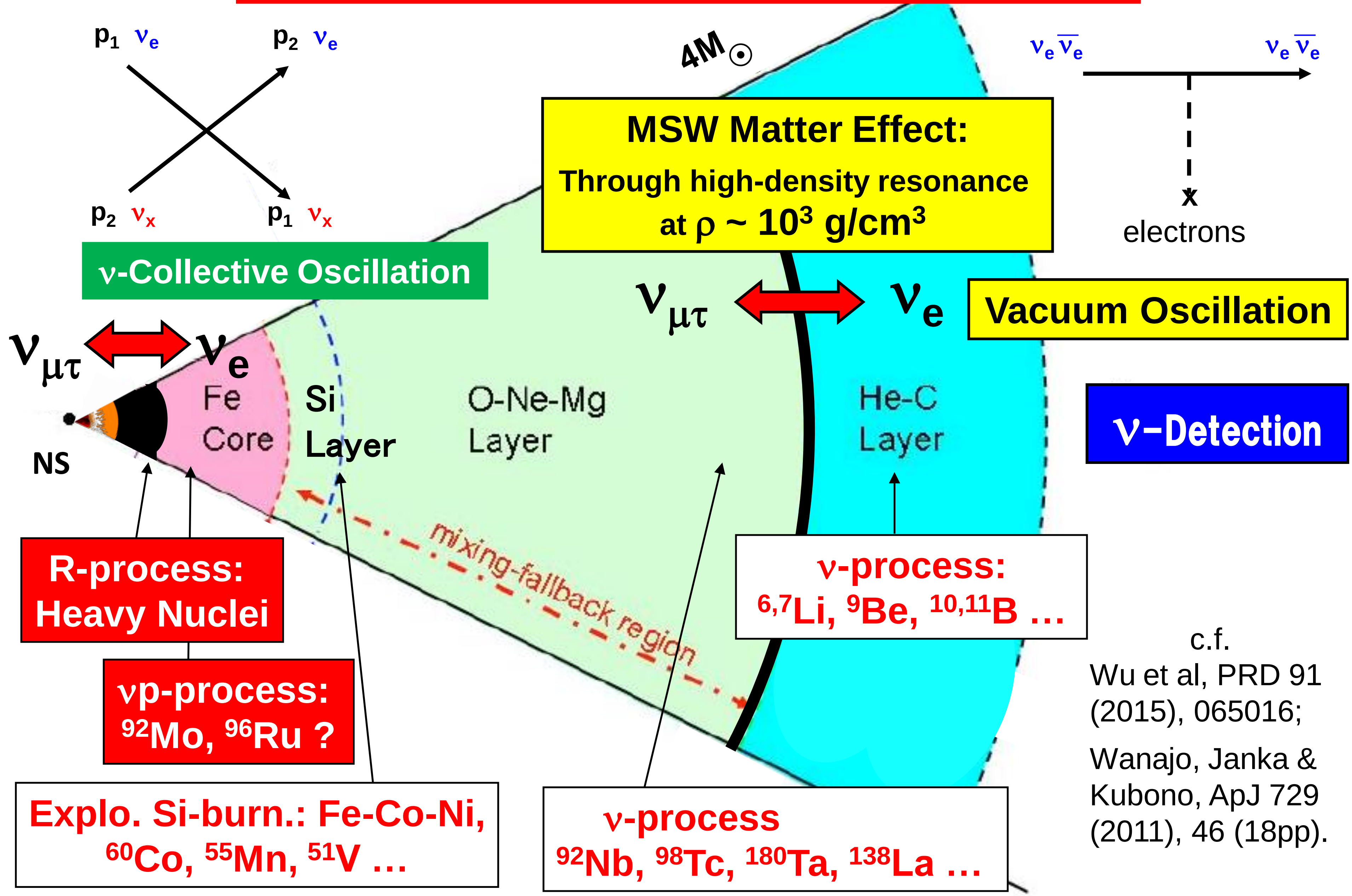
P–Nuclei

$$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} \Big/ \frac{X_{^{56}\mathrm{Fe}} + X^{\mathrm{Si\text{-}burn.}}_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}}$$



Sasaki et al. PR D96 (2017), 043013.
Wanajo, Kubono, Janka, 729 (2011) 46 (18 pp).

ν-Oscillation and Nucleosynthesis

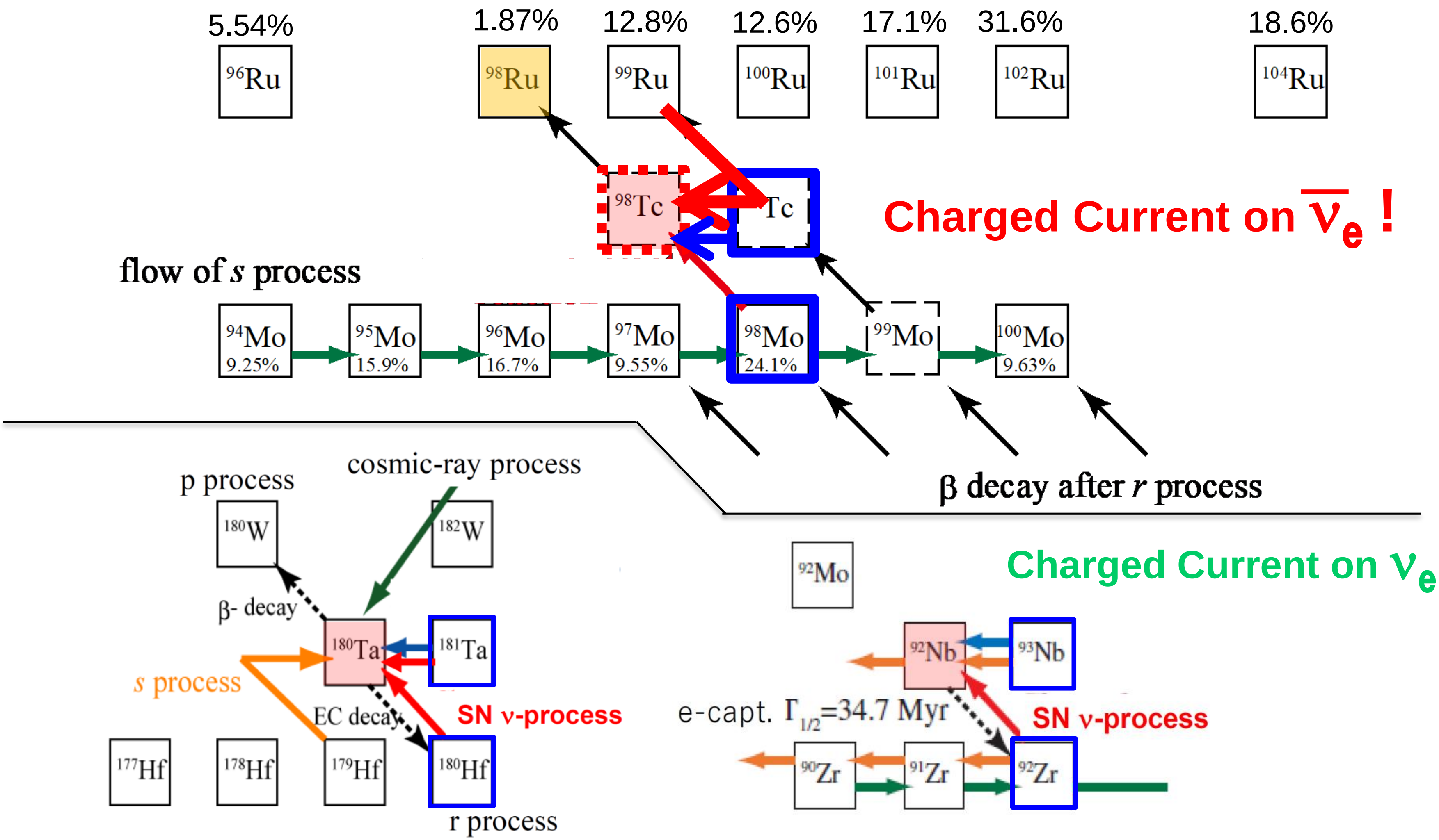


c.f.
Wu et al, PRD 91 (2015), 065016;
Wanajo, Janka & Kubono, ApJ 729 (2011), 46 (18pp).

^{98}Tc is sensitive to $\overline{\nu}_e$-spectrum !

Hayakawa, Kajino et al., PRL 121 (2018), 102701.

^{98}Tc decays to ^{98}Ru in 4.2×10^6 y, and meteoritic ^{98}Ru-isotope anomaly in is expected.



Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272; Heger et al., PL B606 (2005), 258; Hayakawa, Kajino et al., PR C81 (2010), 052801®; PR C82 (2010), 058801; ApJL 779 (2013), L1; Suzuki & Kajino, JoP G40 (2013), 083101; Kajino, Mathews & Hayakawa, JoP G41 (2014) 044007 ++

Summary

- **Neutron Star Merger R-process**, confronts Time Scale Problem:
  in the early Galaxy :- CCSNe (both MHDJ- & ν-Wind)
  in the Solar-System :- Neutron Star Mergers contrinute + CCSNe

  → **Fission Recycling & Fragment Mass Distr. + masses, β-decay, (n, γ)**

- **Supernova (ν-Wind) proves:**
  :- Origin of Abundant p-Nuclei ($^{92,94}Mo$, $^{96,98}Ru$ …)
  → **Mechanism of ν-Self Interacting Collective Oscillations**

  :- ν-Mass Hierarchy
  → **Nuclear Weak Structure of ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc, ^{7}Li, ^{11}B …**

- Origin of Amino-Acid Chirality:

  → **Broken-Symmery of ν_e & $\bar{\nu}_e$+$^{14}N(1^+)$ Interaction under Strong B-Fields**

Neutron Star Meregrs, Supernovae = Multi Messenger

→ GWs, Lights, Elements and Neutrinos

→ DAWN of Nuclear Astrophysics

Beihang University

1000 Talents Plan
Foreign Expert

Int. Res Center for Big-Bang Cosmology and Element Genesis

Grant Mathews

Baha Balantekin

理論

Cosmology,
Nucl Astrophys.
Neutrino Phys.
Bio Astron.

天文観測

Opt-, Xγ-Spect.
Neutrino Astron.
GW.

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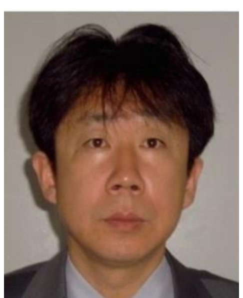

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