International School of Nuclear Physics 41st Course
Star Mergers, GW, DM and Neutrinos in Nuclear, Particle and Astro-Physics and in Cosmology
Erice-Sicily, Sept. 16 – 24, 2019

# Impact of RIB Science and Neutrino Physics on Merger, Supernova, and Big-Bang Nucleosynthesis

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# GW170817 (Neutron Star Merger)

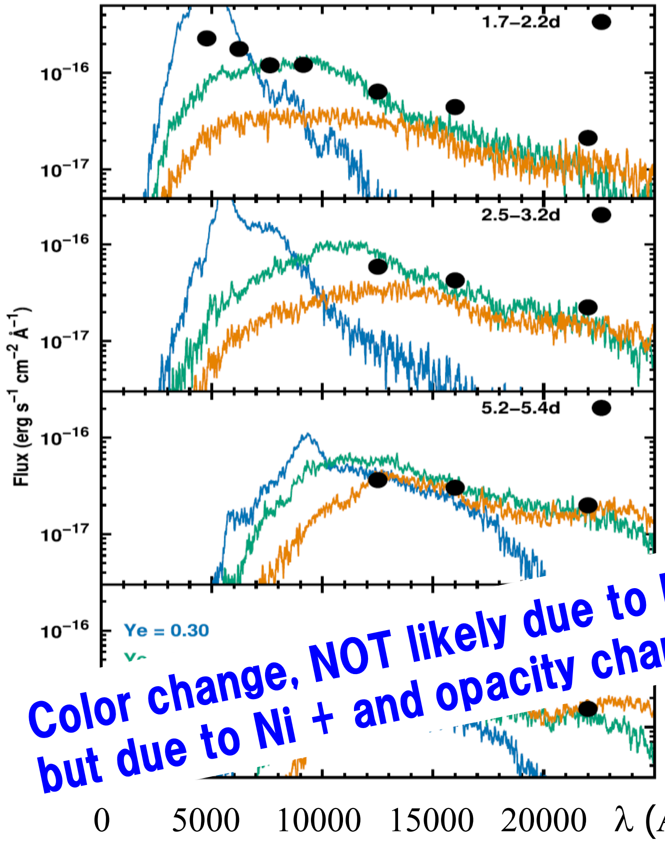
Abbott et al. (LIGO-Virgo), PRL 119, 16101 (2017)

1. GW170817 (LIGO-Virgo) : $0.86 < M/M_{\odot} < 2.26$
2. GRB170817A (Fermi-GBM) : 1.7 s
3. No ν–Signal: $10^{-6}$ weaker than SN1987A ($1.6 \times 10^{5}$ ly)
4. X-rays & Radio waves : Remnant NS or BH, not identified.
5. **Optical and Near-infrared : SSS17a (over 70 Telescopes)**


GW170817/SSS17a

◆ **Color change, consistent with radioactive decay of r-process elements, possibly Lanthanoids ?**

◆ ***No r-process element identified***




**Blue**

$Y_e$ = p/(p+n)

$Y_e$ = 0.30

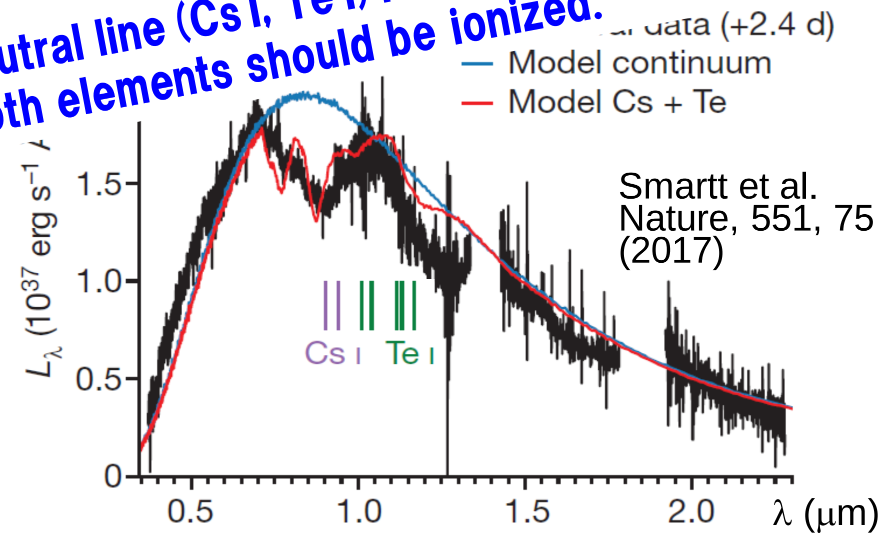
$Y_e$ = 0.25

$Y_e$ = 0.10-0.40

**Color change, NOT likely due to Lanthanoids but due to Ni + and opacity change !?**

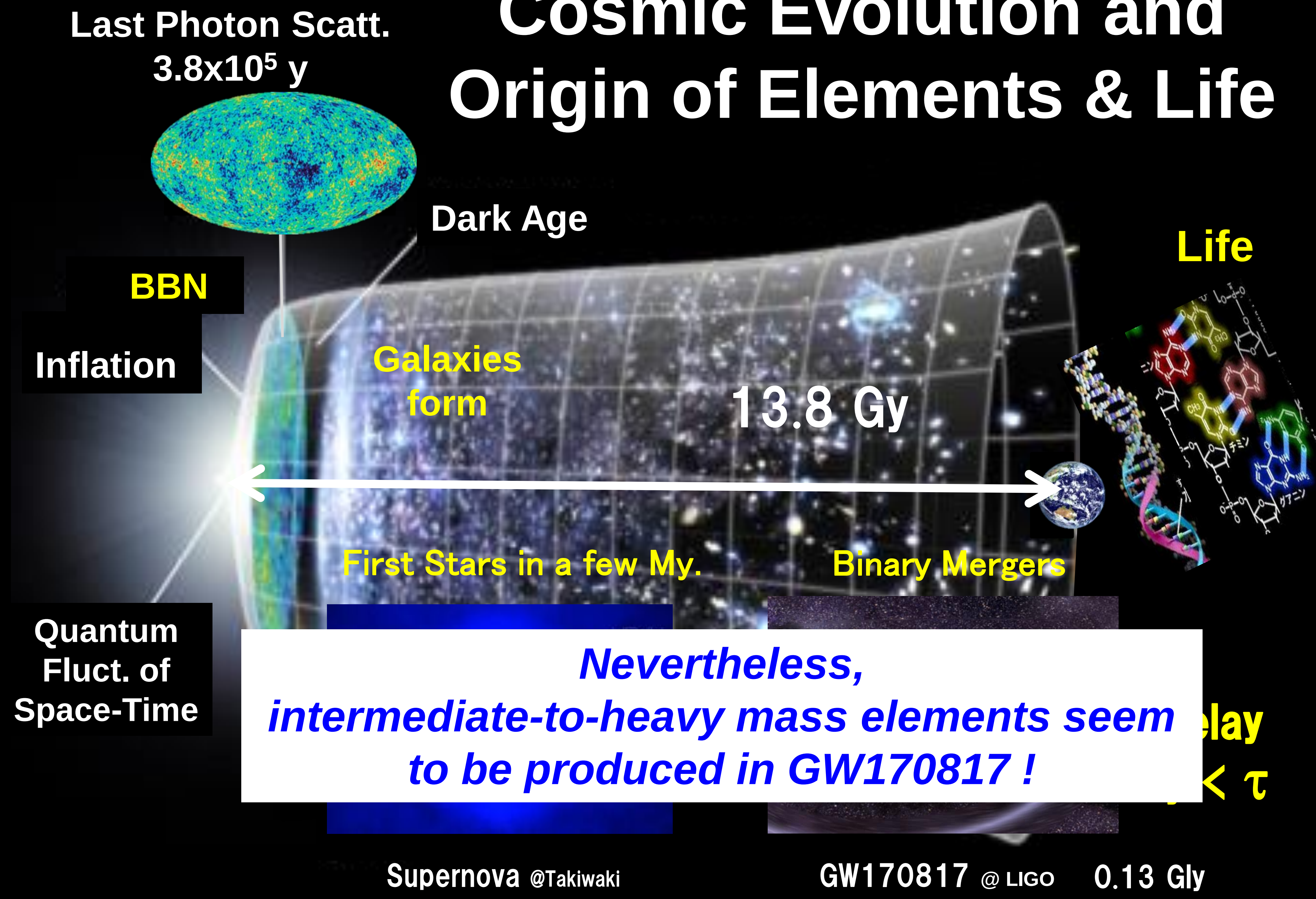
Tanaka et al. PASJ 00, 1-7 (2017)

**Neutral line (Cs I, Te I) is unreasonable ! Both elements should be ionized.**

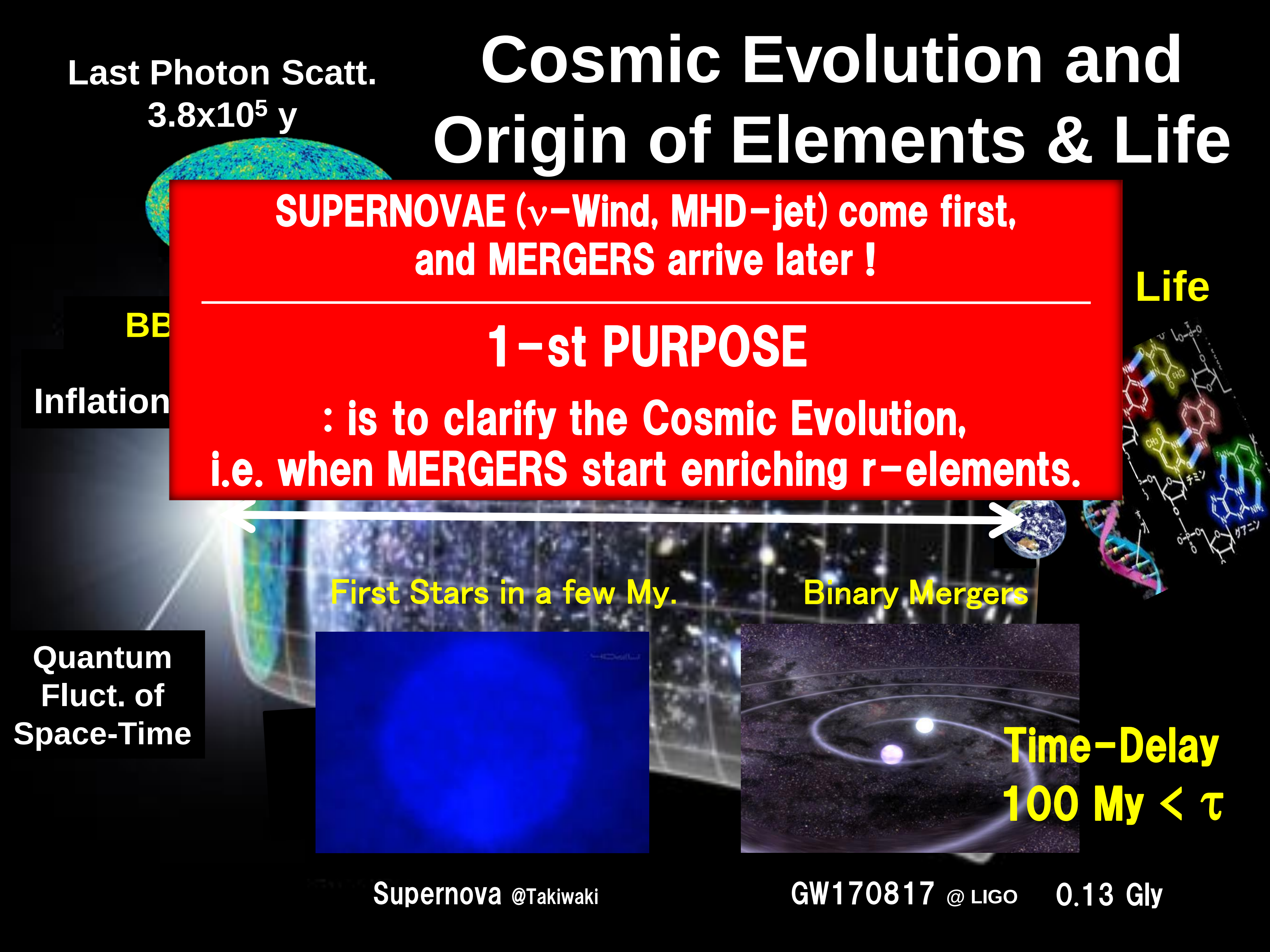



Smartt et al. Nature, 551, 75 (2017)

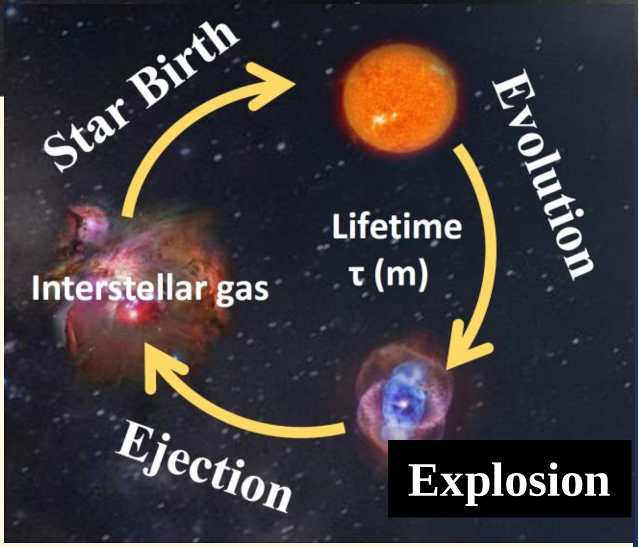
# Cosmic Evolution and Origin of Elements & Life




***Nevertheless,***
***intermediate-to-heavy mass elements seem to be produced in GW170817 !***


Cosmic Evolution and
Origin of Elements & Life
Last Photon Scatt.
3.8x10^5 y
SUPERNOVAE (ν-Wind, MHD-jet) come first,
and MERGERS arrive later !
1-st PURPOSE
: is to clarify the Cosmic Evolution,
i.e. when MERGERS start enriching r-elements.
Life
BB
Inflation
First Stars in a few My.
Binary Mergers
Quantum
Fluct. of
Space-Time
Time-Delay
100 My < τ
Supernova @Takiwaki
GW170817 @ LIGO
0.13 Gly

# Cosmic & Galactic Evolution




## Cosmic Gas- and Nuclear-Evolution

$$\dot{\sigma}_X = Inflow \cdot \delta_{X,gas} - \frac{\sigma_X}{\sigma_{gas}} \cdot B(\xi_{gas})$$

$$+ \int B(t-\tau(m))\,\phi(m)\,E_X(m)\,dm$$

*Stellar Birth Rate*

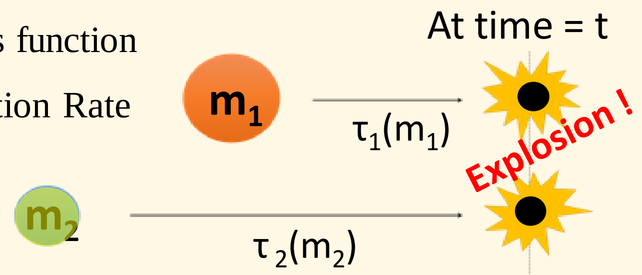
*X = Ejected Nucleus from SNe or NSM*

## Supernova Rate :

$$R_{SNII} = \int_{m_l}^{m_h} \phi(m)\,B(t-\tau(m))\,dm$$

$\Phi(m)$ : Initial mass function

$B(t)$ : Star Formation Rate

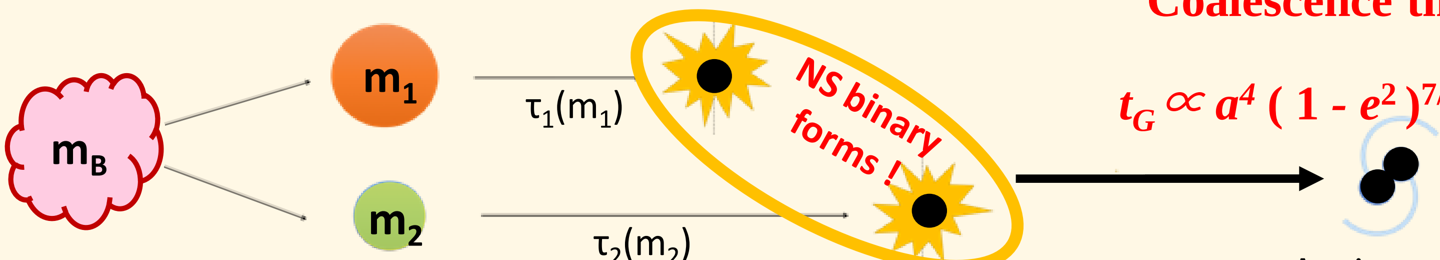



## Neutron Star Merger Rate :

$$R_{NSM} = \epsilon_{NSM} \int_{m_l}^{m_h} dM_B\,\phi(M_B) \int_{q_l}^{1} dq\,f(q) \int_{a_l}^{a_h} da\,P(a)\,B(t-\tau(m_2)-t_G)$$

**Coalescence time delay**

$$t_G \propto a^4\,(1-e^2)^{7/2} = ?$$

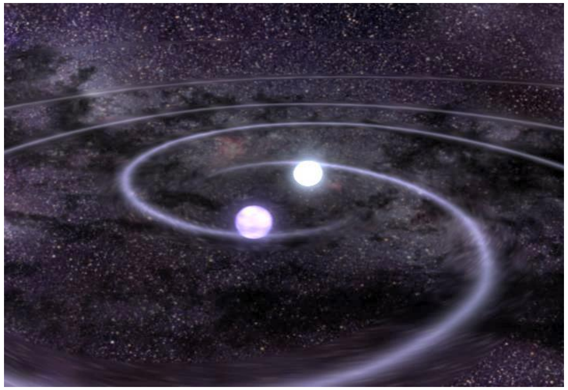



$q = m_2/m_1$

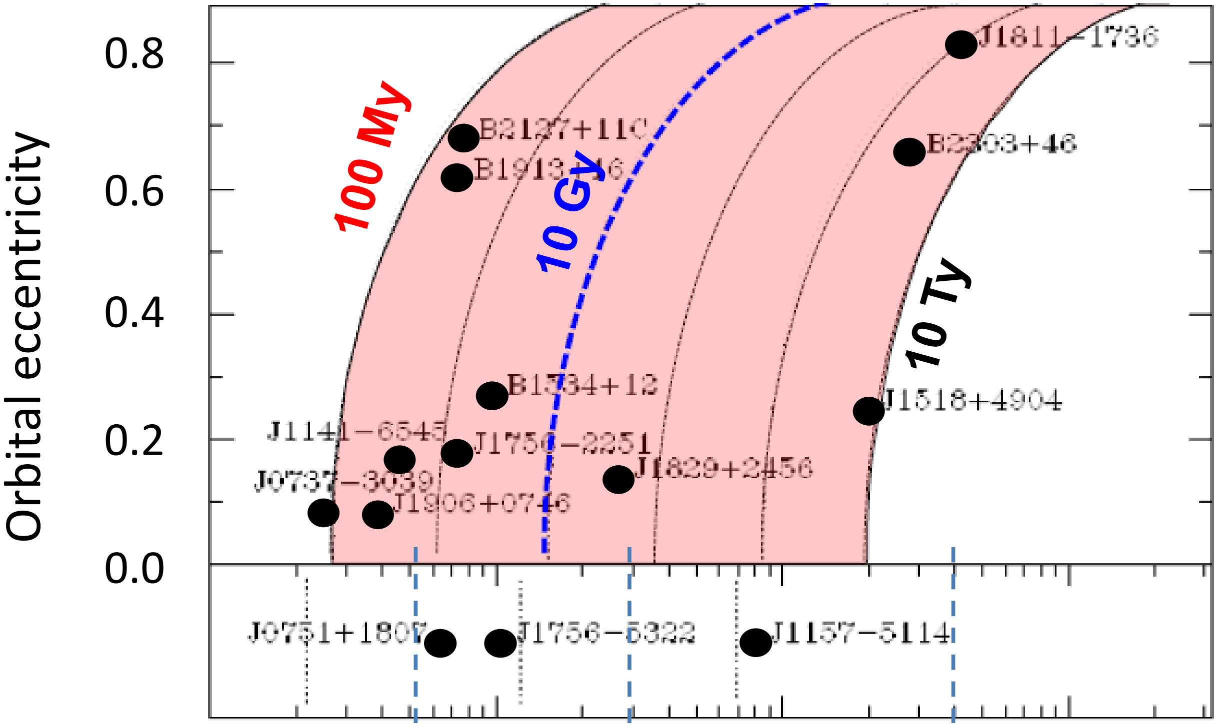
a = separation of NS-binary

# Merging Time Delay

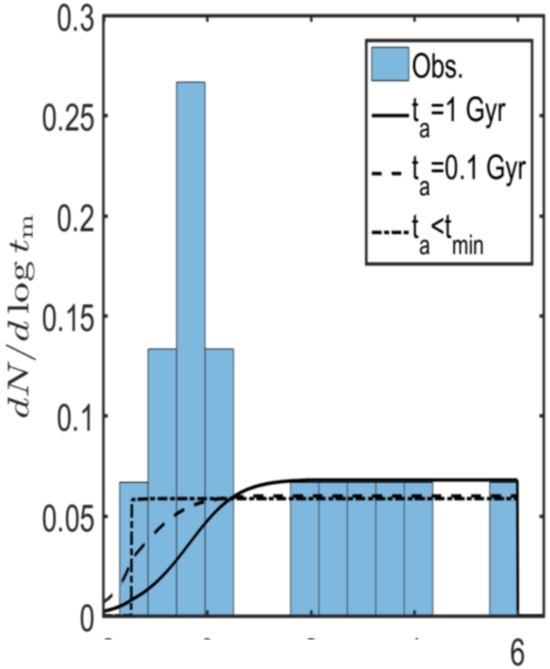
$$\tau_C \simeq 9.83 \times 10^6 \text{ yr} \left(\frac{P_b}{\text{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$$



**BINARY PULSARS** : Lorimer, Living Rev. Rel. 11(2008), 8.

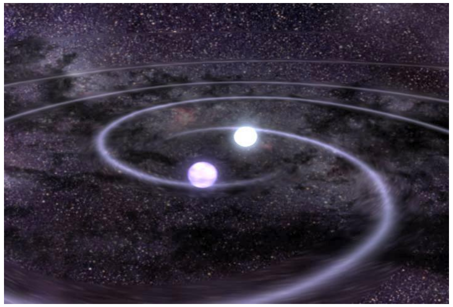


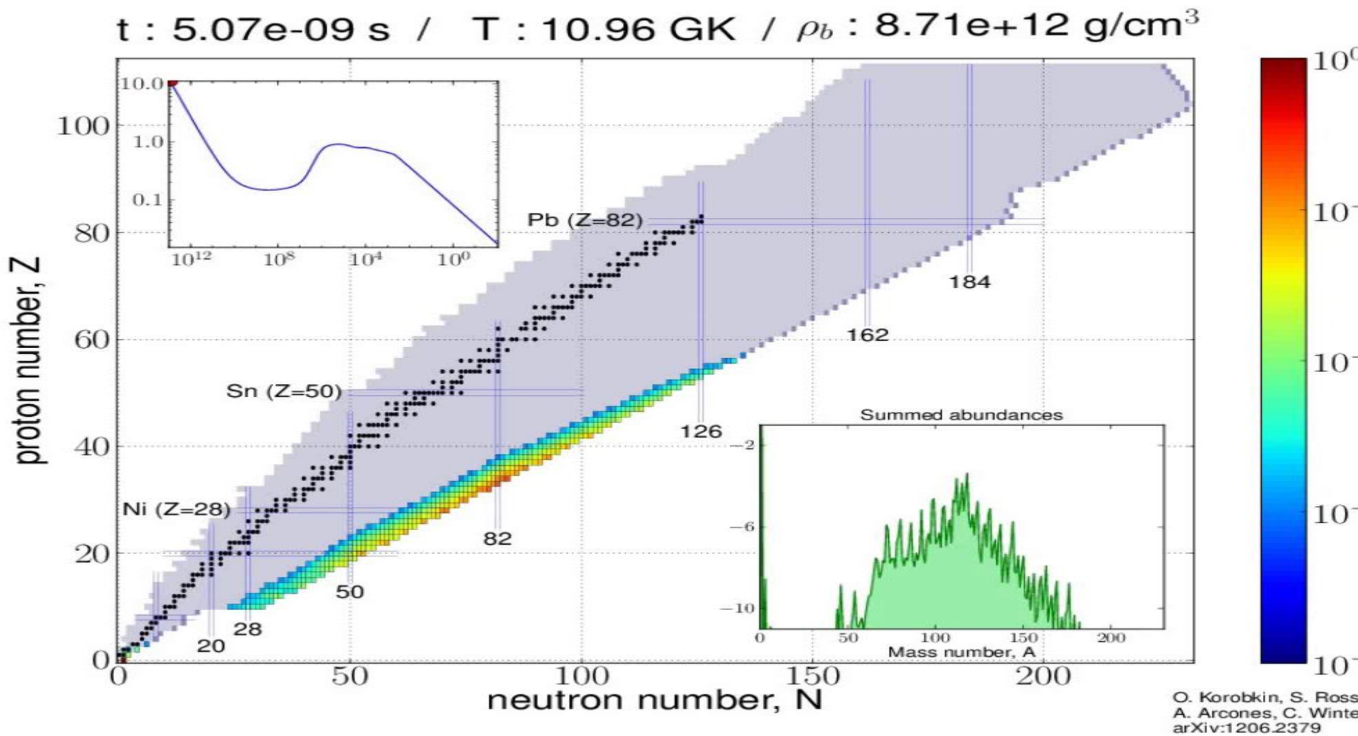

Beniamini+ (2019)




**Merging process is extremely slow due to very weak energy loss of GW radiation: 100My < $\tau_C$**

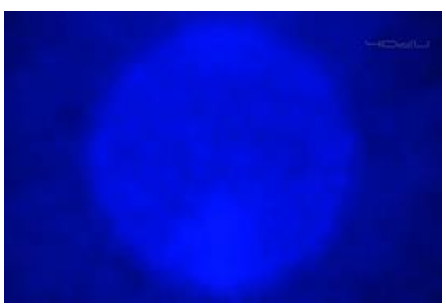
# Neutron Star Merger

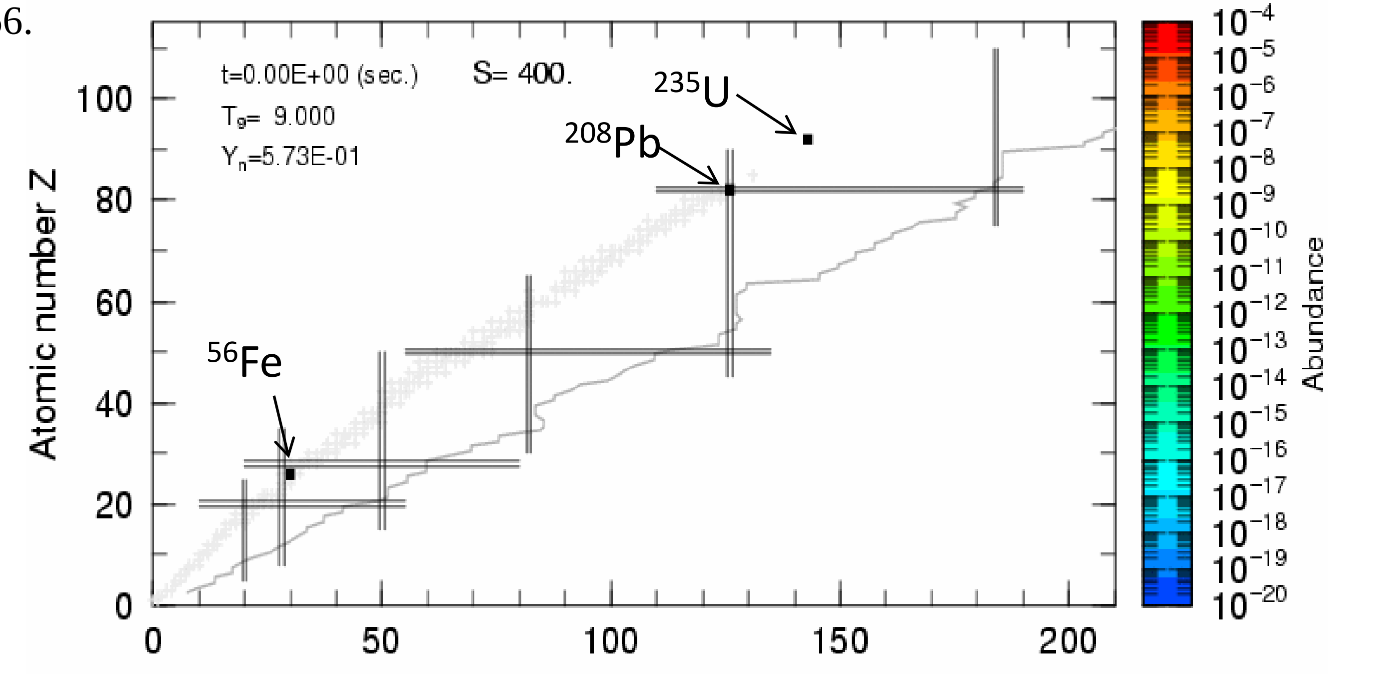





Kajino, Aoki, Balantekin, Diehl, Famiano, Mathews, Prog. Part. Nucl. Phys. 107 (2019) 109-166.

# Supernova (MHD Jet-SN)

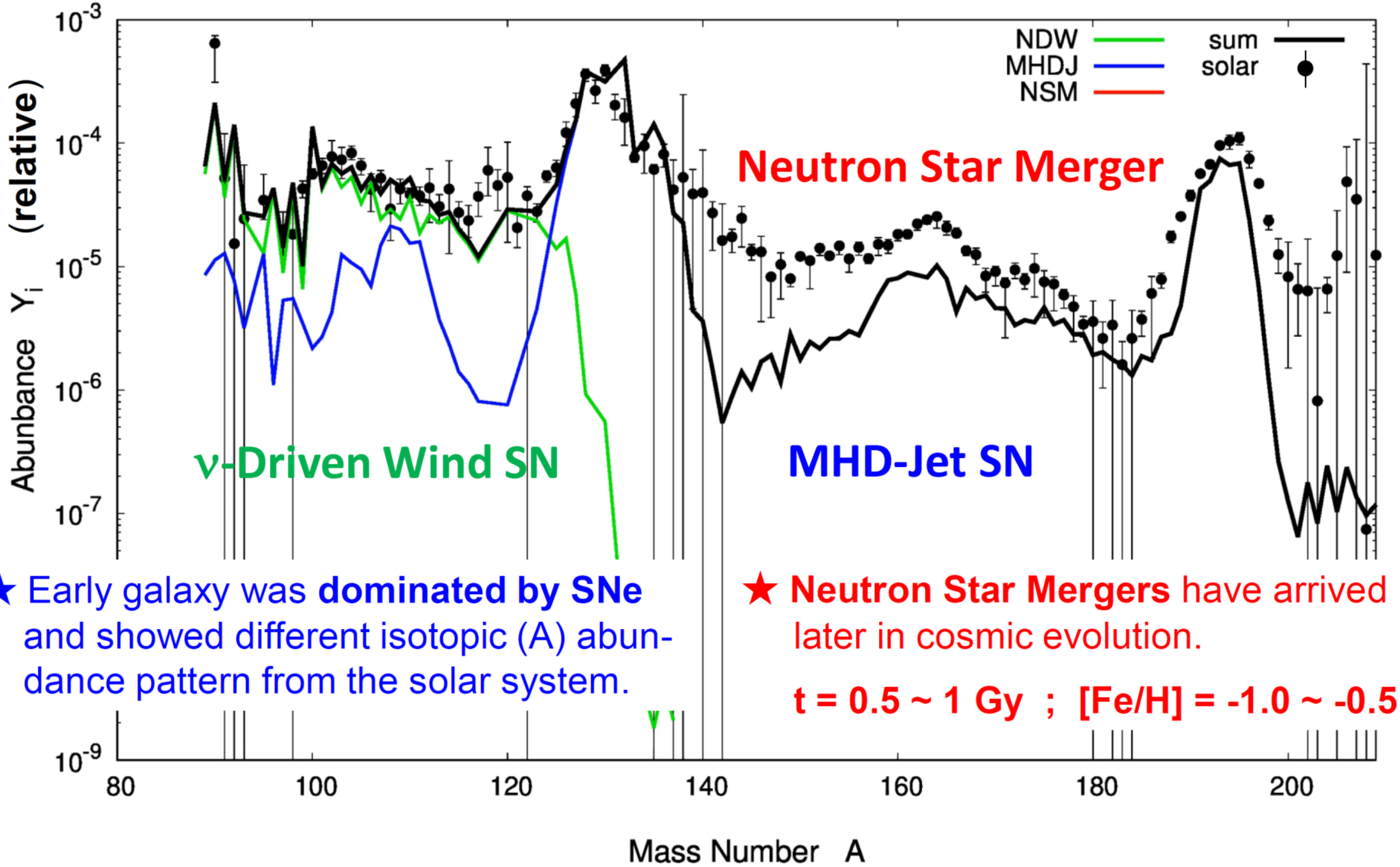




# MOVIE of Cosmic Evolution of r-Process Abundance

Yamazaki, Kajino, Mathews, Aoki, Tang, Shi et al., ApJ (2019).

**[Fe/H] : -3.0000**




★ Early galaxy was **dominated by SNe** and showed different isotopic (A) abundance pattern from the solar system.

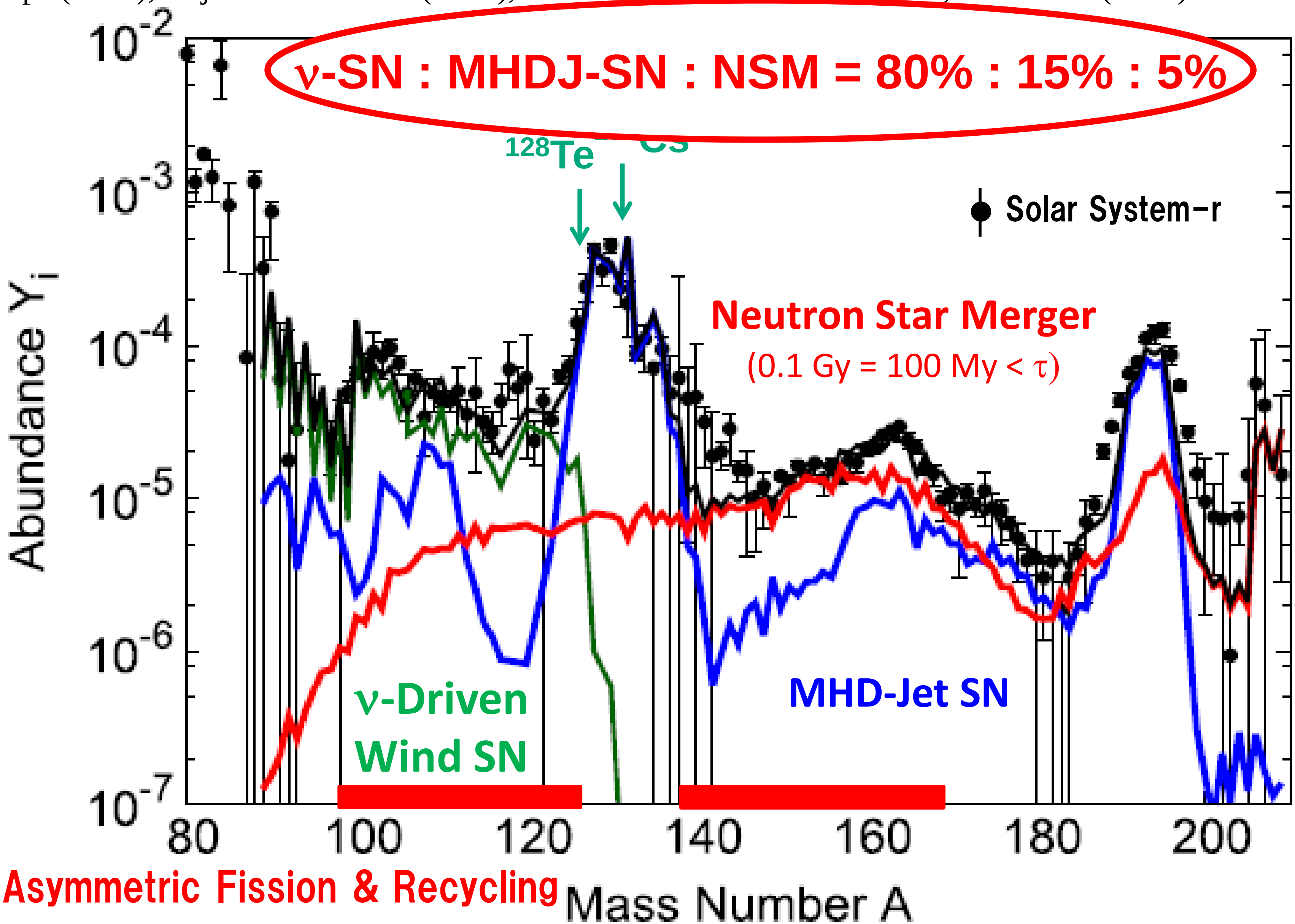
★ **Neutron Star Mergers** have arrived later in cosmic evolution.

**t = 0.5 ~ 1 Gy ; [Fe/H] = -1.0 ~ -0.5**

# Solar System r-Process Abundance

**13.8 Gy TODAY !**

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2018); Kajino & Mathews (2017), ROPP 80 , 084901: Kajino et al., PPNP 107 (2019) 109.



## ● Observed Galactic "Event Rates" were adopted.

| | Ejected Mass [M⊙] | x | Event Rate [/Galaxy/Century] | | |
|---|---|---|---|---|---|
| νSN (Weak r) | = 7.4 x $10^{-4}$ | x | (1.9±1.1) [a] | | 80% |
| MHD Jet SNe | = 0.6 x $10^{-2}$ | x | ((0.03±0.02) x (1.9±1.1)) [b] | | 15% |
| Binary NSMs | = (2±1) x $10^{-2}$ | x | (1-28)x$10^{-3}$ [c] | (Short GRB) | 5% |

| | | | |
|---|---|---|---|
| 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 | (1-28) x $10^{-3}$ | Kalogera, et al., ApJ 614, L137 (2004). |

GW170817 confirmed that a progenitor central-engine of short GRB is a binary Neutron Star Merger (NSM) !

## ● R-Process in S.S. from both Supernova and Merger.

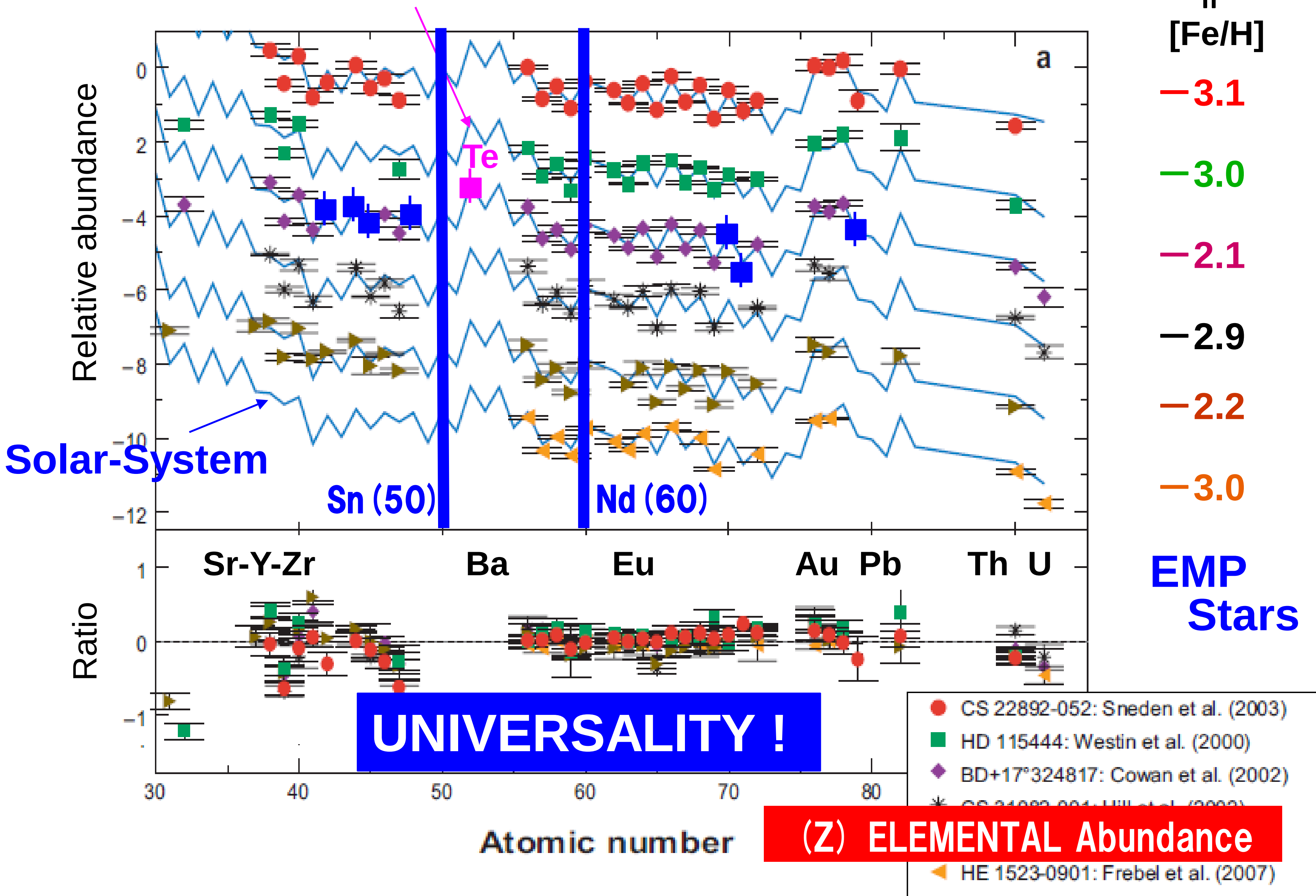
Universality ?

How to distinguish Merger from SN ?

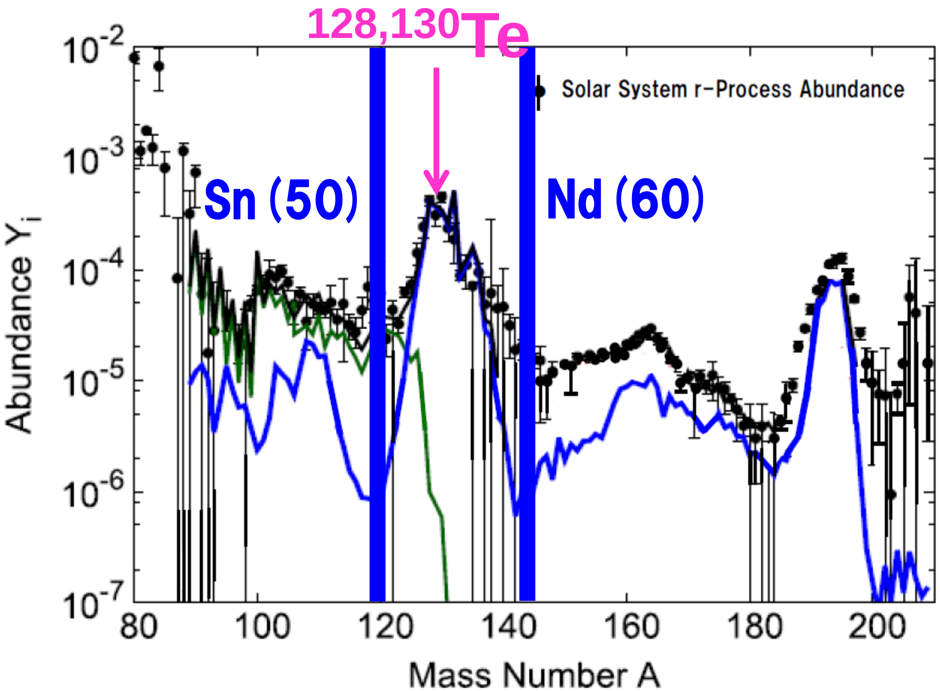
Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

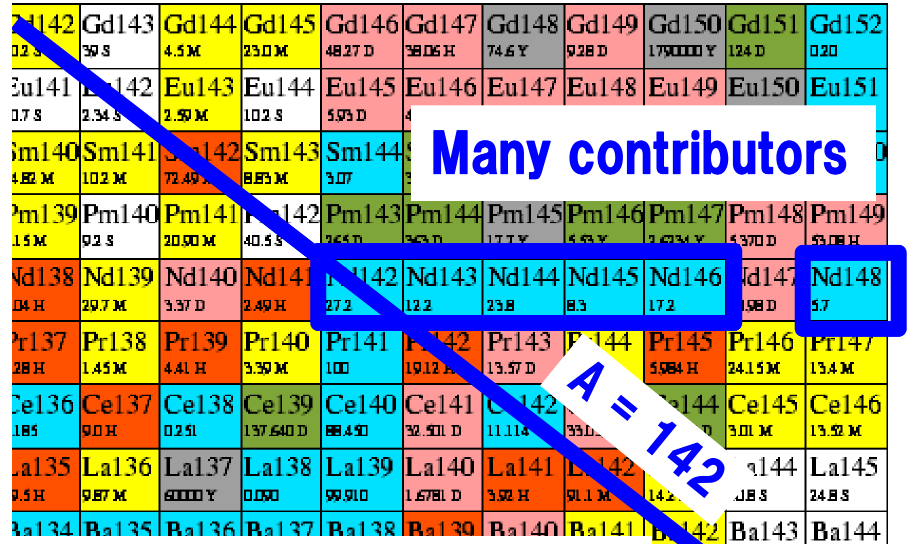
HST-obs., Roederer et al., ApJ 747 (2012) L8.

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

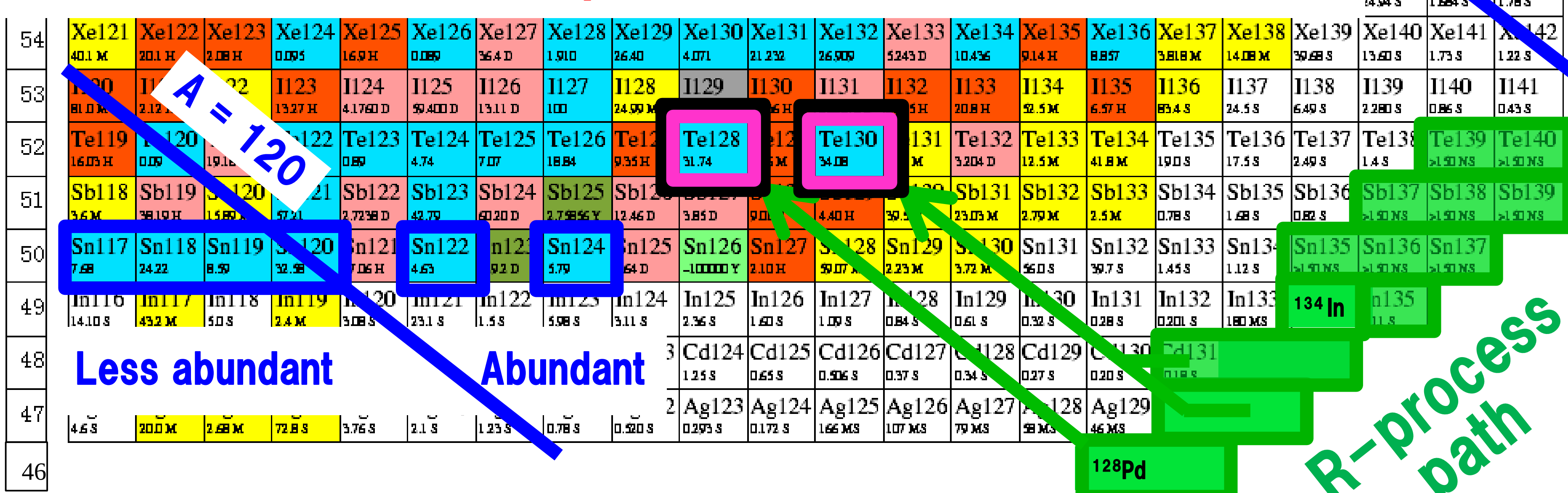


Lorusso, Nishimura, Kajino et al. (2015), PRL 114, 192501.



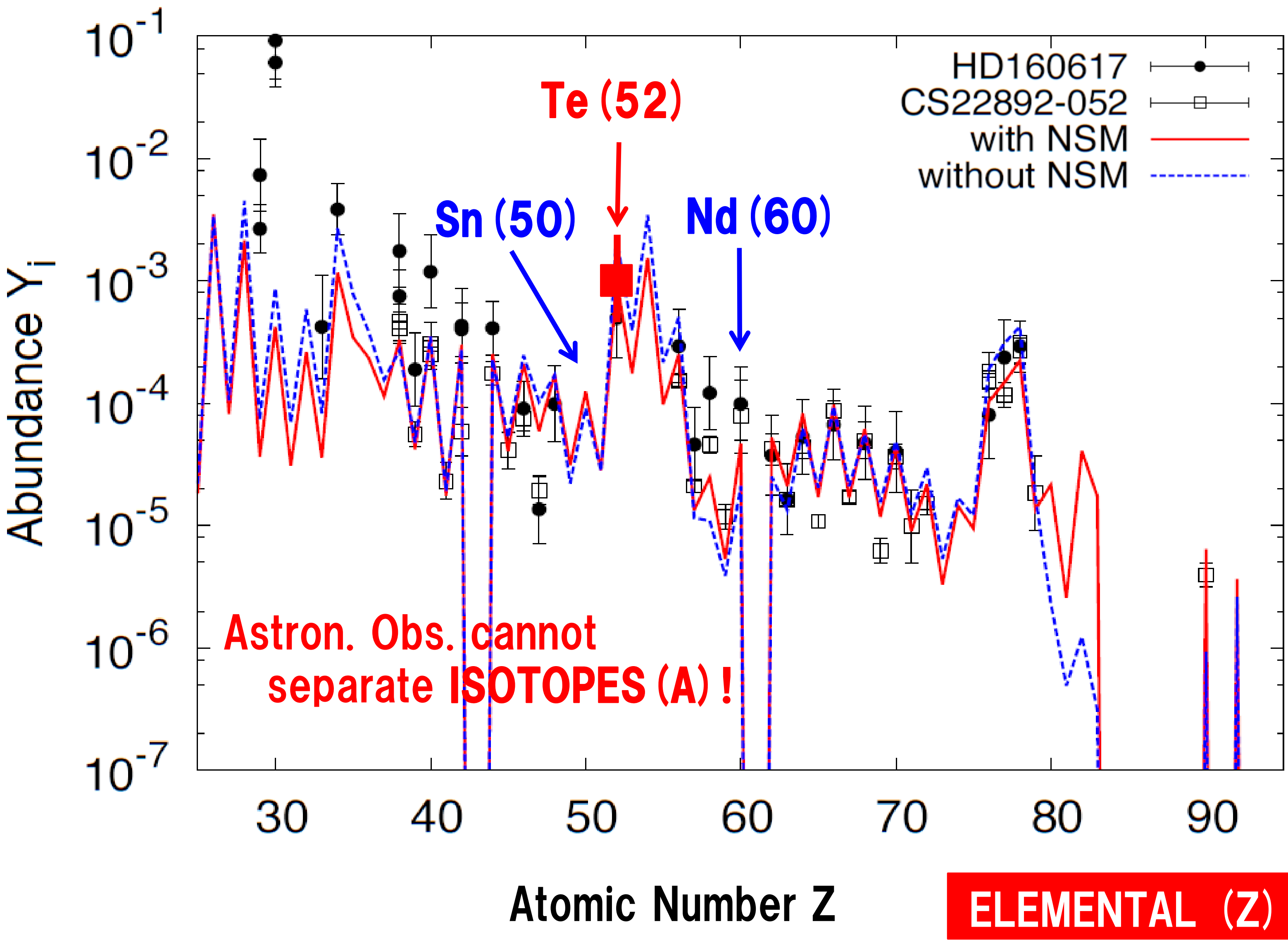

**Astron. Obs. cannot separate ISOTOPES in EMP stars !**



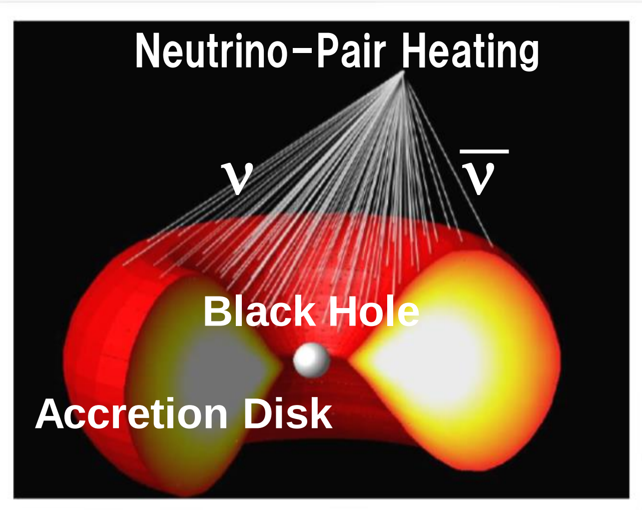
# UNIVERSALITY !

Early Galaxy ⟺ TODAY

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



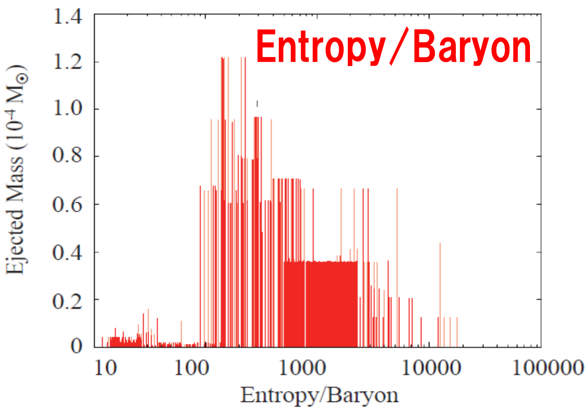

ELEMENTAL (Z)




~~Short-GRB = Neutron Star Merger~~

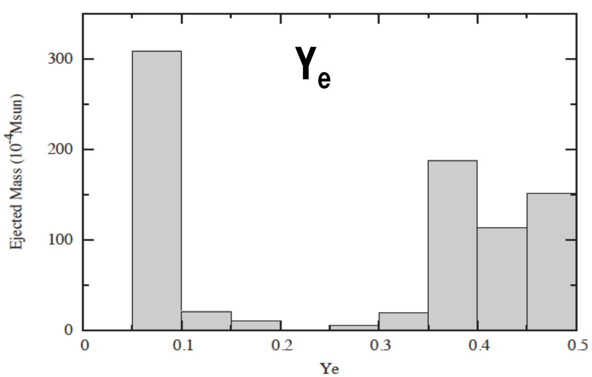
Siegel, Barnes & Metzger, Nature 569 (2019), 243:
Korobkin et al., arXiv: 1905.05089v1 [astro-ph.HE].

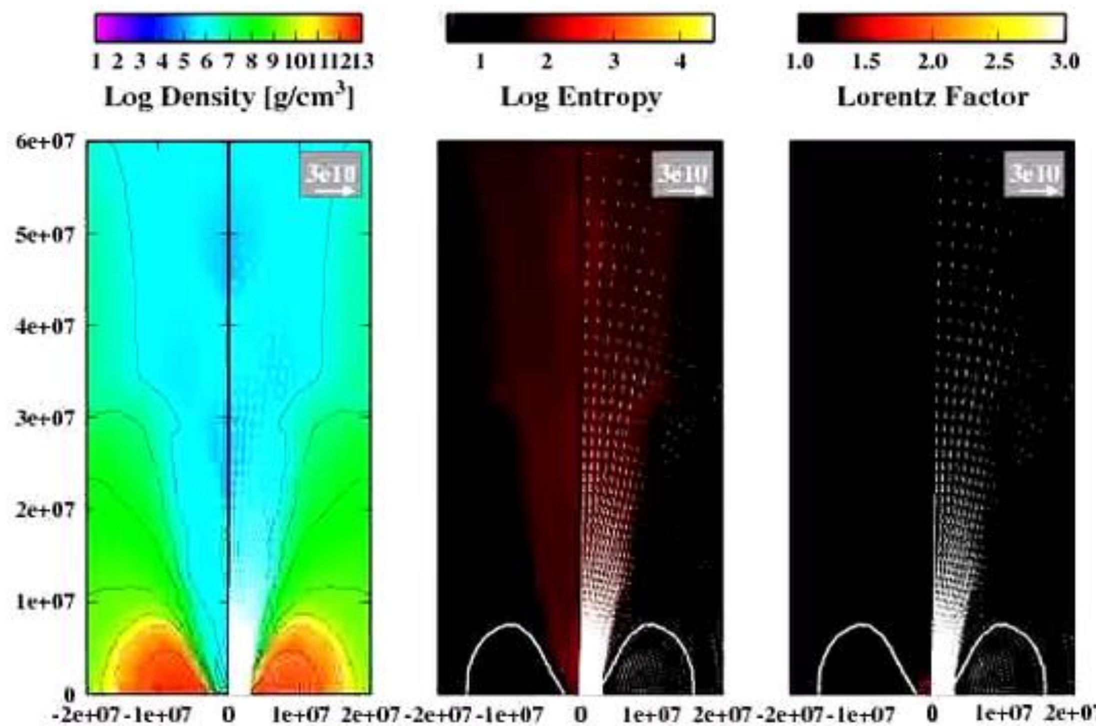
## Long-GRB = Collapsar (BH forms)




### Collapsar (2D-Hydro) Model

Harikae et al., ApJ 704 (2009), 354; ApJ 713 (2010) 304;
Nakamura, Kajino, Mathews, Sato, Harikae, A&Ap 582(2015), A34.

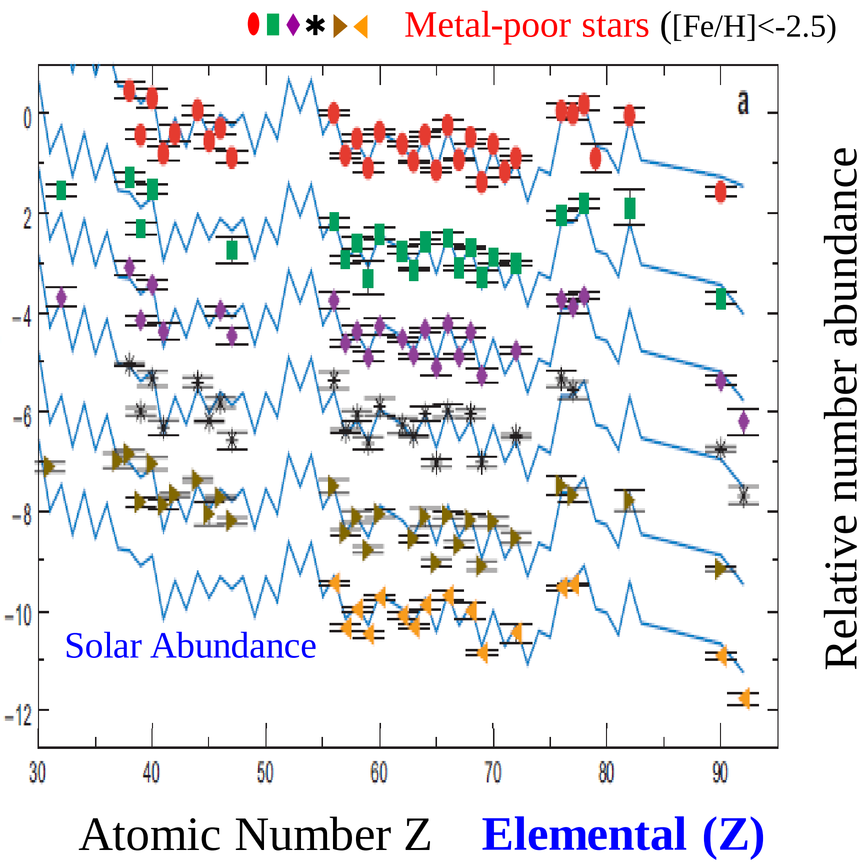


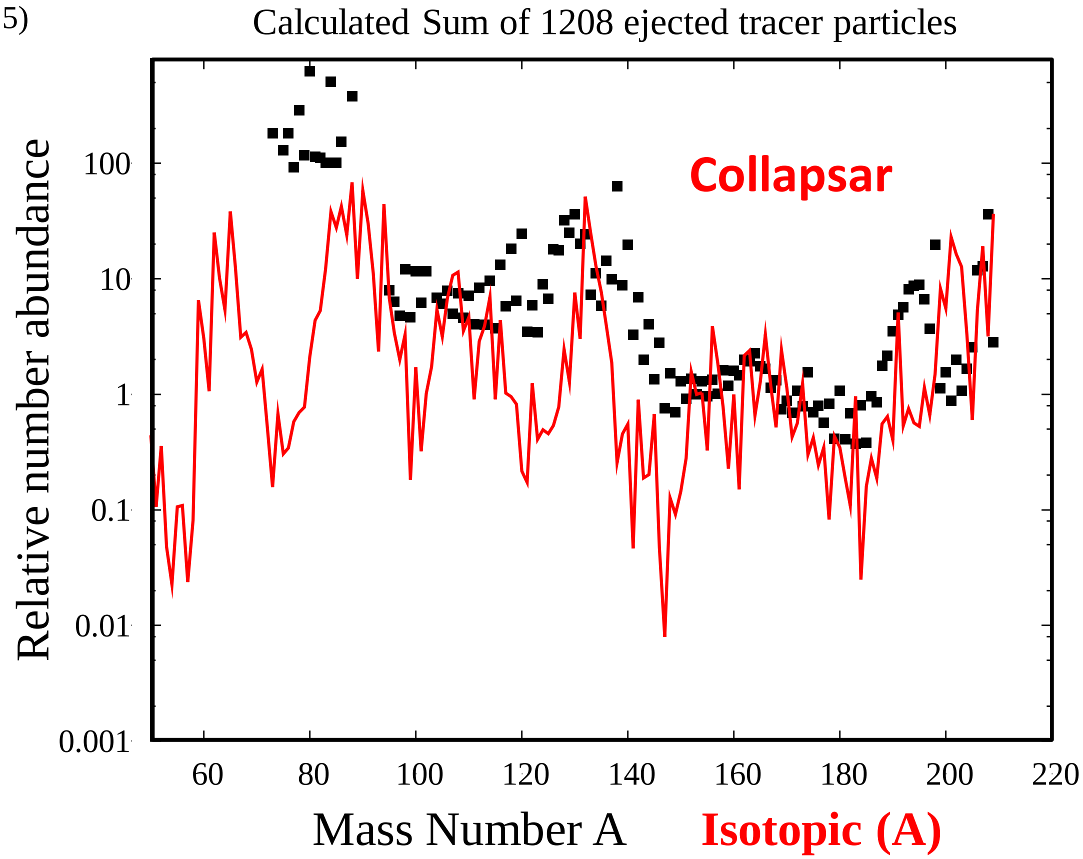
# Collapsar R-Process Long-GRB

Harikae et al., ApJ 704 (2009), 354; ApJ 713 (2010) 304;
Nakamura, Kajino, Mathews, Sato, Harikae, A&Ap 582(2015), A34.

## UNIVERSALITY
### Elemental (Z) Abundance Pattern




## Isotopic (A) Abundance Pattern



# Fission is sensitive to Nuclear Models

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

## (Japanese) KTUY M One of the Best Models!

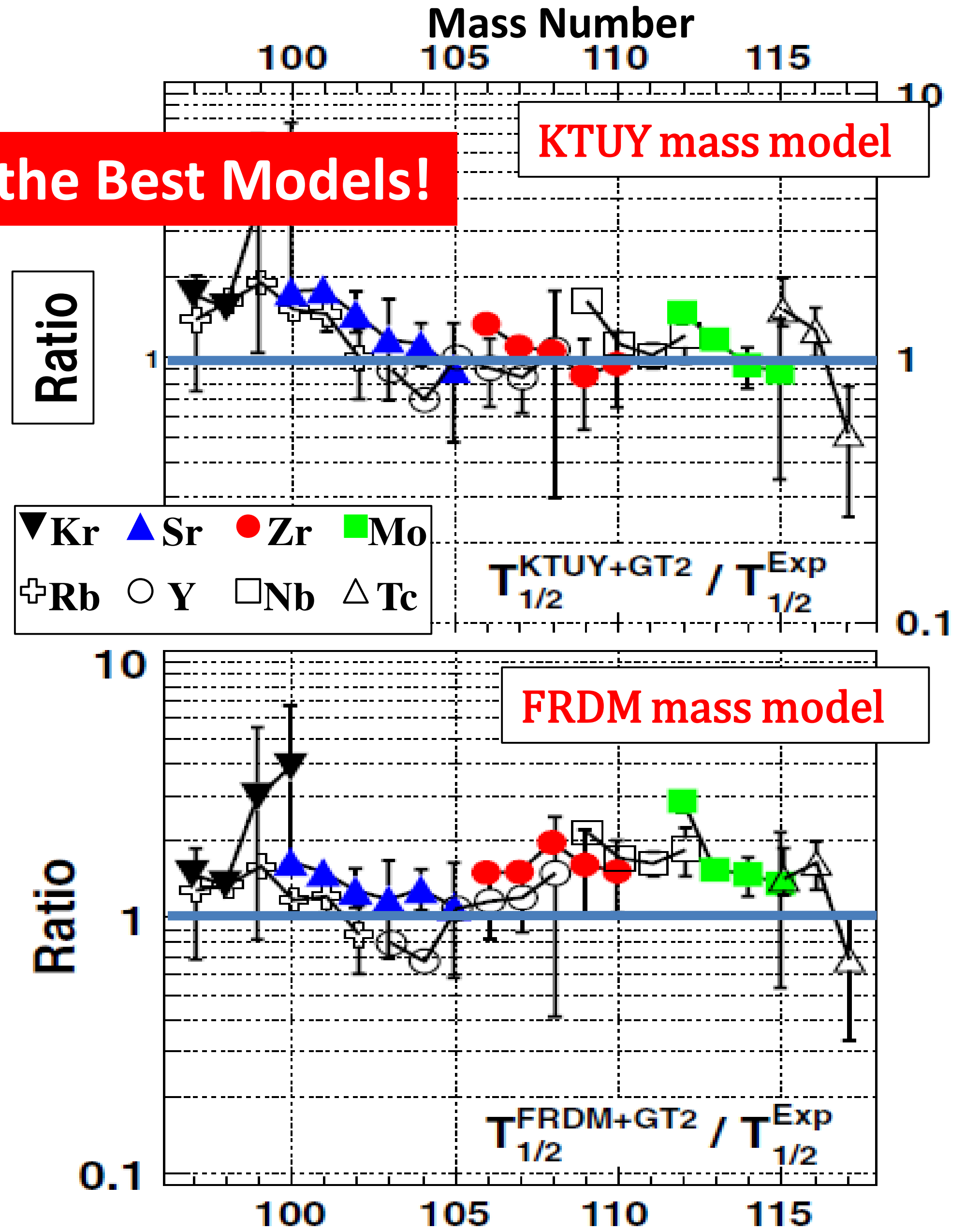
### Mass: Fission Barrier, $Q_\beta$

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

### Reactions: αβ-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).

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## FRDM Model

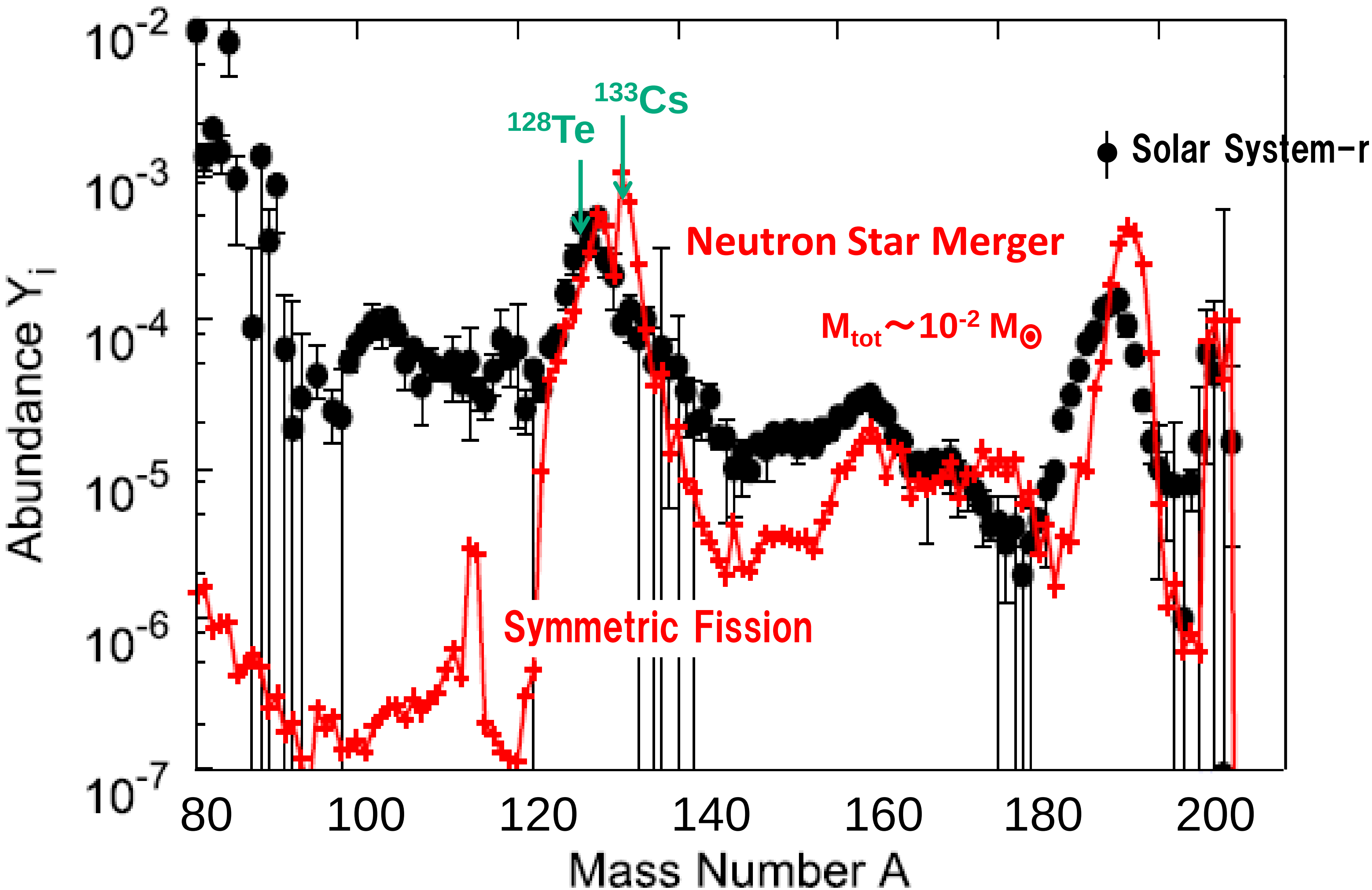
Möller, P., Myers, W. D., Sagawa, H., et al., PRL 108, 052501 (2012).

Möller, P., NIx, J. R., Myers, W. D., et al. ADNDT 59, 185 (1995).

# Merger r-Abundance, dep.t on Fission & Mass Formula !

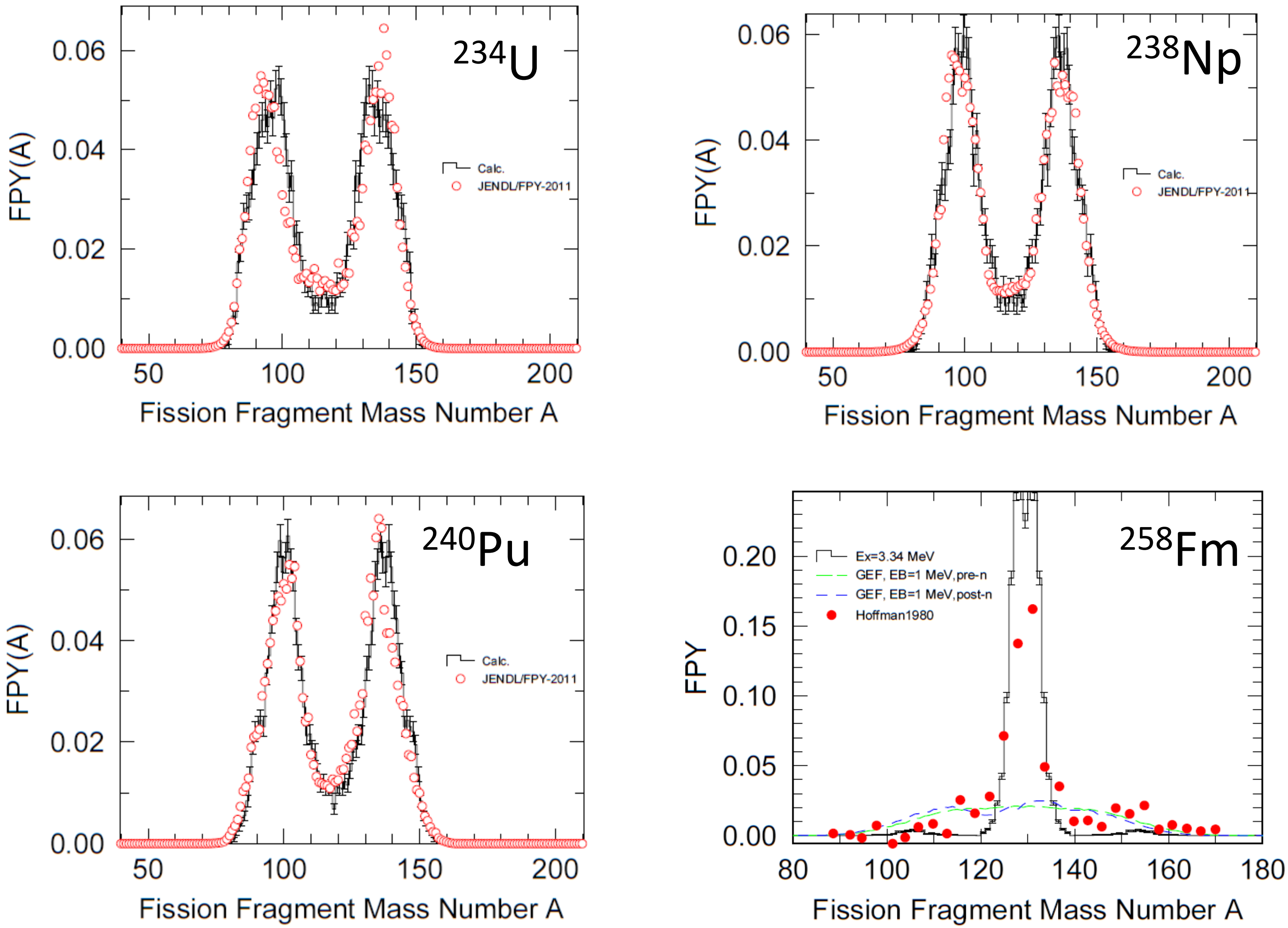
**Mass Formula: FRDM (Moeller & Kratz)**

Suzuki, Kajino, et al., ApJ 859 (2018), 133;
Shibagaki, Kajino, Mathews (2019).

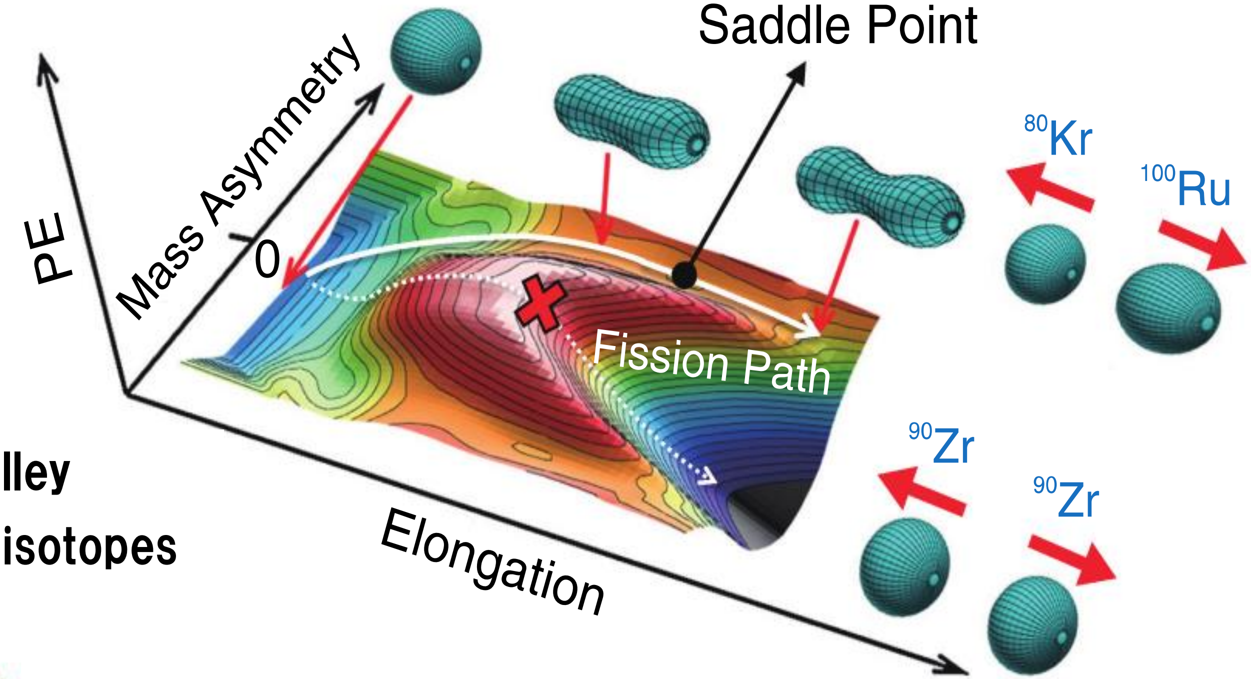


# Mass Distribution of Fission Fragments at Ex=20MeV

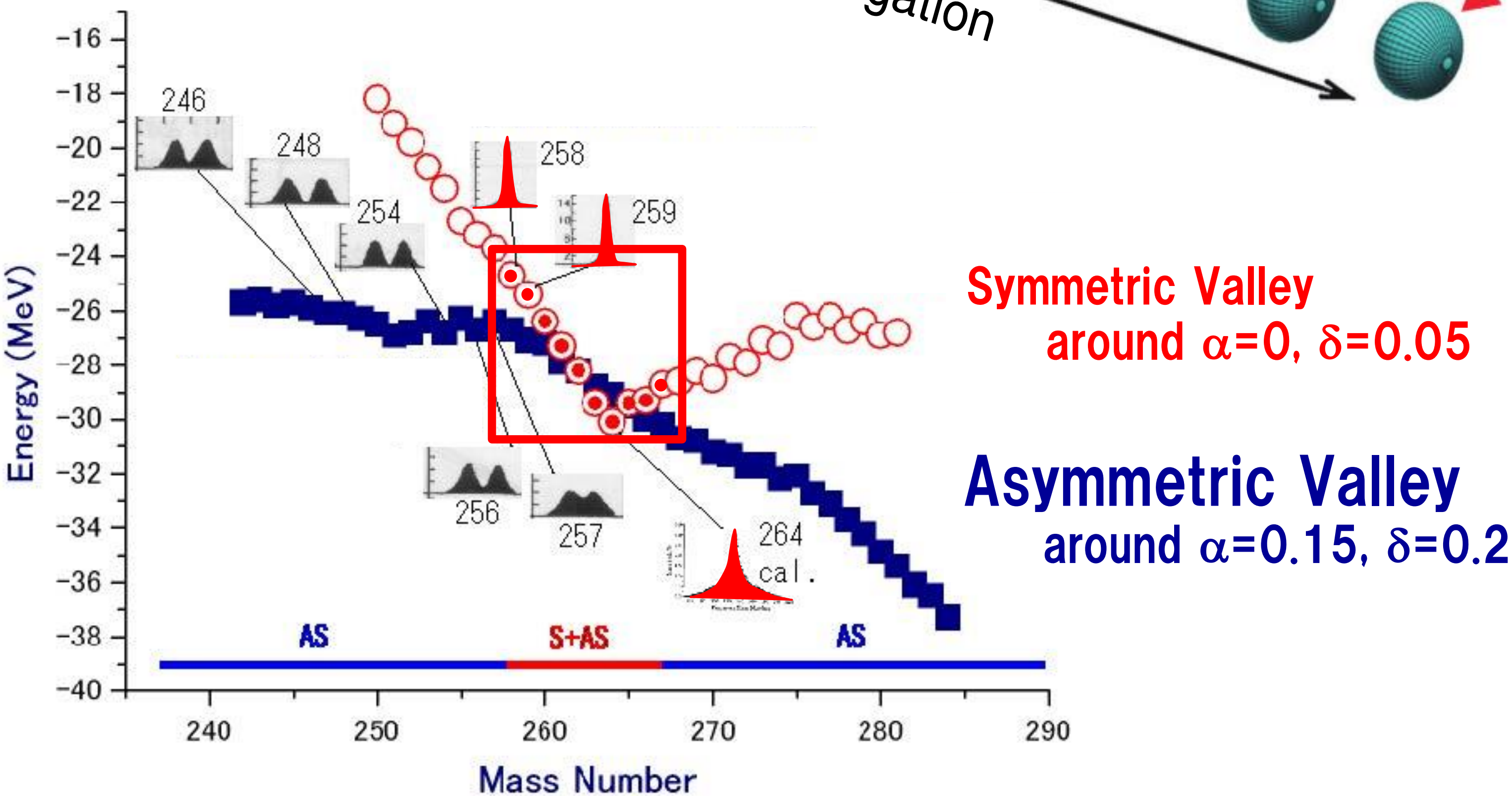
Ishizuka et al., Phys. Rev. C96 (2017), 064616; Ivanyuk et al., Phys. Rev. C97, 054331 (2018); Okumura et al., J. Nucl. Sci. Tech. 55, 1009 (2018); Usang et al., Sci. Reports, 9, 1525(2019)

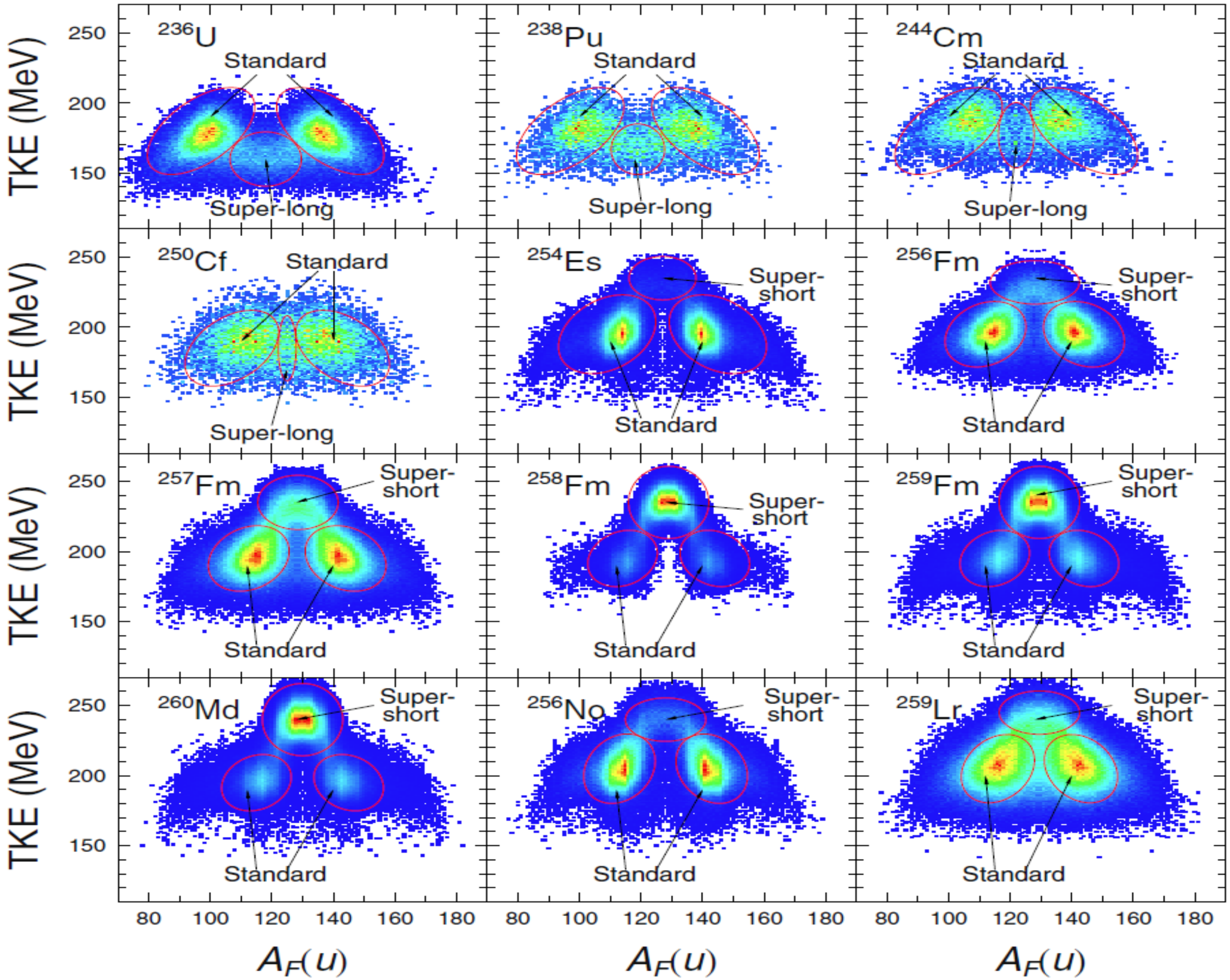


## Fission Path of Mercury




## Potential Depth of Fission Valley (near Scission Point) of Fm isotopes



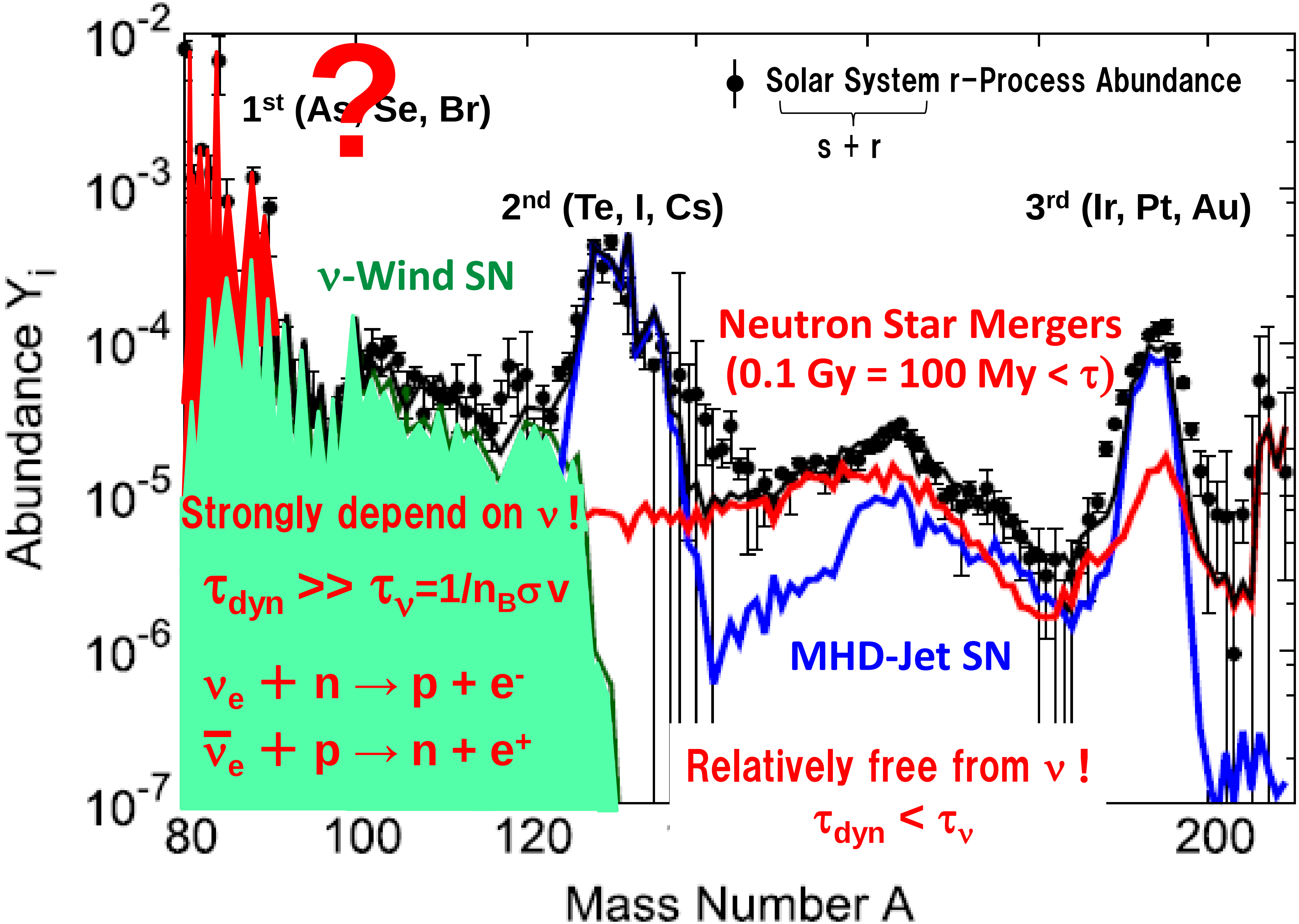



Correlation of mass number (horizontal axis) and total kinetic energy (vertical axis) of fission fragments from various fission nuclei calculated in 4D Langevin theory.

C. Ishizuka et al., Phys. Rev. C96 (2017), 064616; F.A. Ivanyuk et al., Phys. Rev. C97, 054331 (2018); S. Okumura et al., J. Nucl. Sci. Tech. 55, 1009 (2018); M.D. Usang et al., Sci. Reports, 9, 1525(2019)

# Solar System r-Process Abundance    Present time: t = 13.8Gy

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



# Why ν-Oscillation?

■ To establish "Standard" Cosmology & Physics: Why $\Omega_B + \Omega_{DM} + \Omega_\Lambda = 1$ ?

⇒ CMB including $m_\nu \neq 0$. ⇒ Go beyond "Standard Model"

$m_\nu \neq 0$ ; Unique Signal !

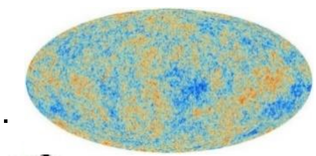
Higgs mechanism does not apply.

## How to know $m_\nu$ ?

■ **CMB Anisotropies + LSS**

$\sum m_\nu < 0.2$ eV ($2\sigma$, $B_\lambda$<2nG): WMAP-7yr + HST + CMASS + Magnetic Field

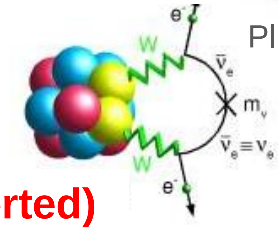
Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; PR D81 (2010), 103519.



Planck 2013

■ **0νββ in COUORE, NEMO3, EXO, KamLAND Zen**

$|\sum U^2_{e\beta} m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen

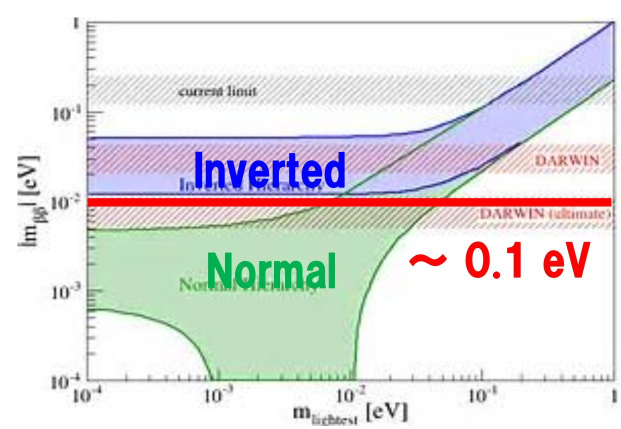



■ **ν-OSCILLATION** $\sum m_\nu$ = 0.05 eV (Normal) or 0.1 eV (Inverted)

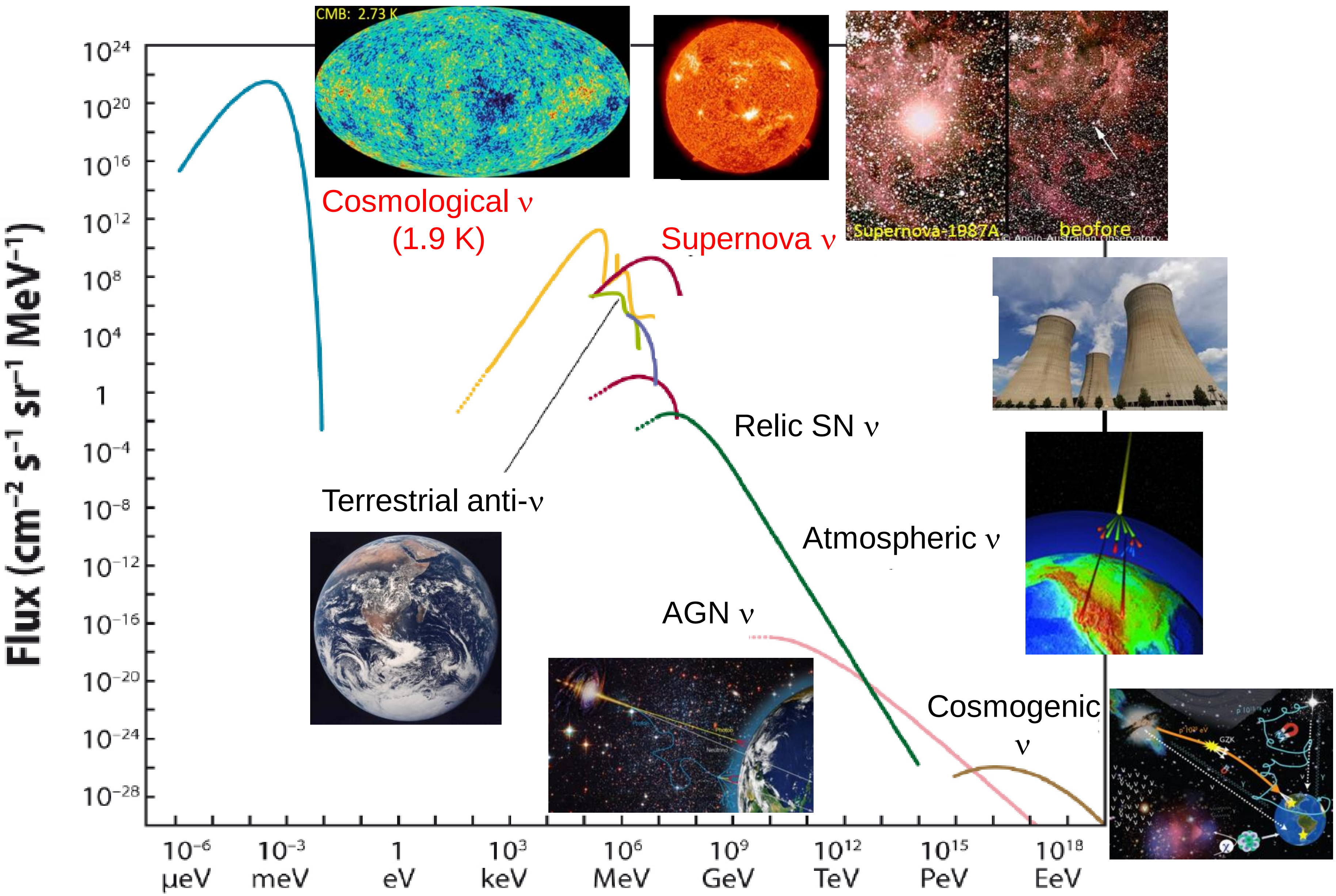
$$\Delta m^2_{12} = 7.9 \times 10^{-5} \mathrm{eV}^2 \quad |\Delta m^2_{23}| = 2.4 \times 10^{-3} = (0.05\ \mathrm{eV})^2$$

**2nd PURPPOSE**

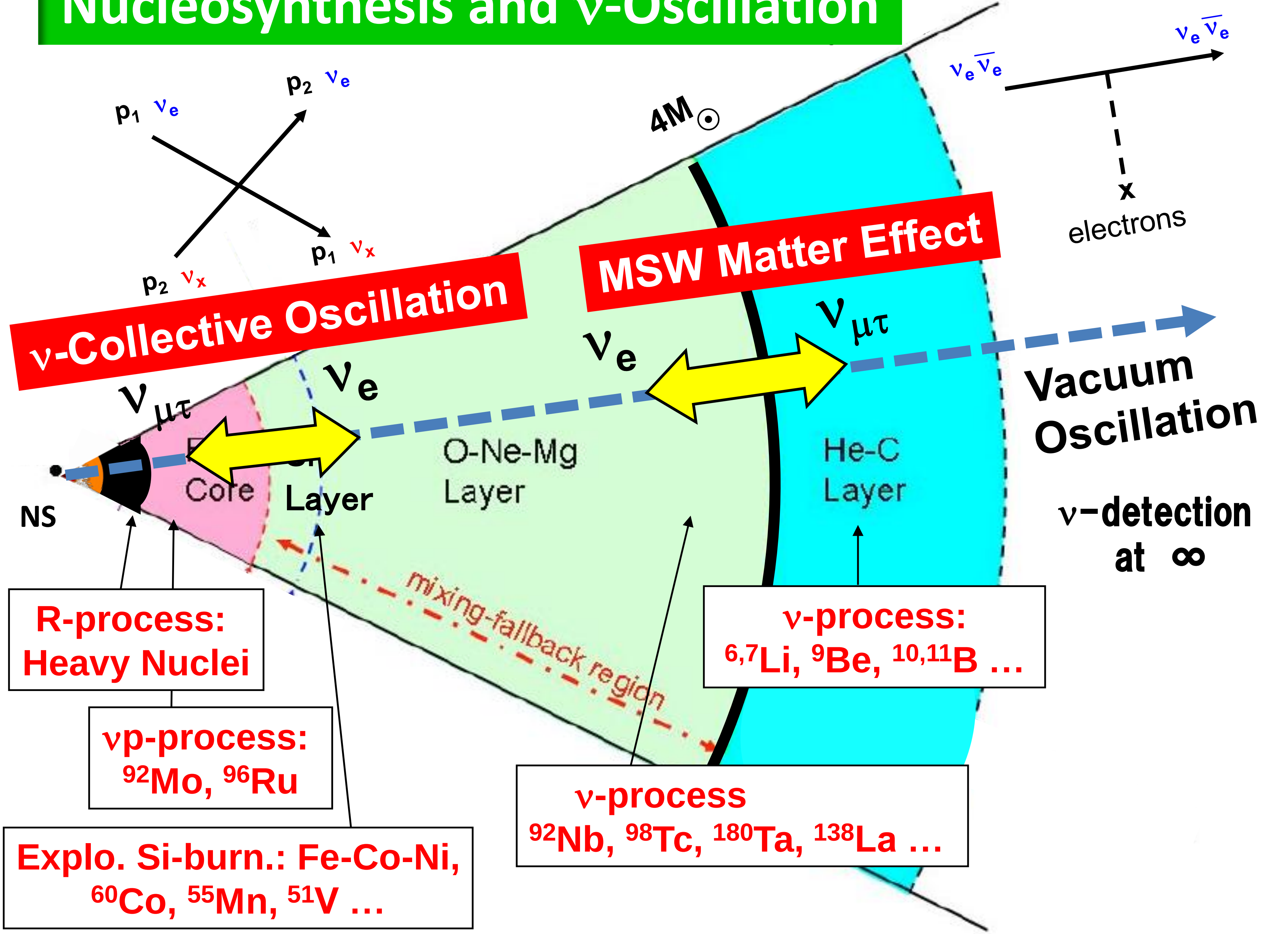
**:- to constrain ν-Mass Hiararchy from Supernova Nucleosynthesis**



# Neutrino Source in Nature and Culture



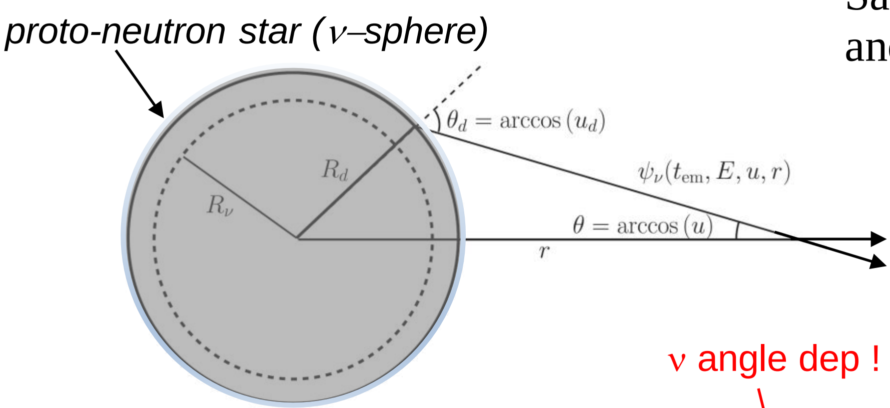
# Nucleosynthesis and ν-Oscillation



# MSW + Collective ν Oscillations — Self-interaction 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 D98 (2018), 083002.

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

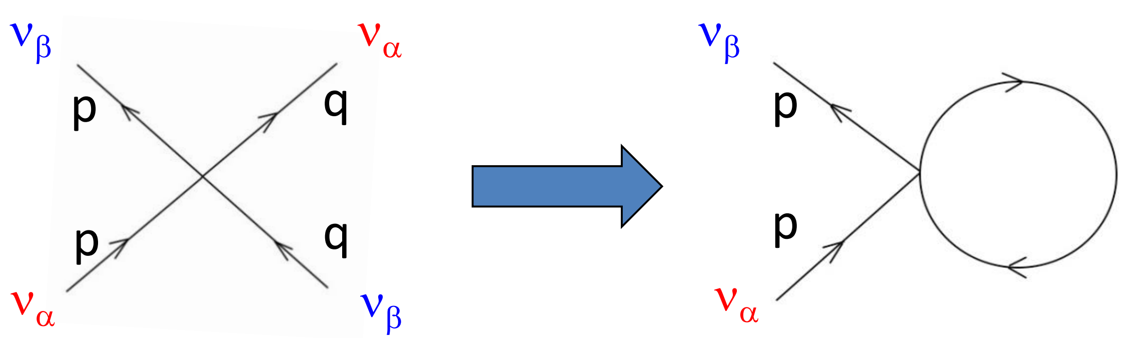



$$
\begin{cases}
i\dfrac{d\psi_\nu}{dt} = (H_{\rm v} + H_e + H_\nu)\psi_\nu(t_{\rm em}, E, u, r), \\
H_{\rm v} = U\dfrac{M^2}{2E}U^\dagger, & \textbf{Vacuum} \\
H_e = \sqrt{2}G_F n_e(r)\,\mathrm{diag}(1,0,0), & \textbf{MSW}
\end{cases}
$$

ν angle dep !

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

**Collective Oscill. due to self-interactions**



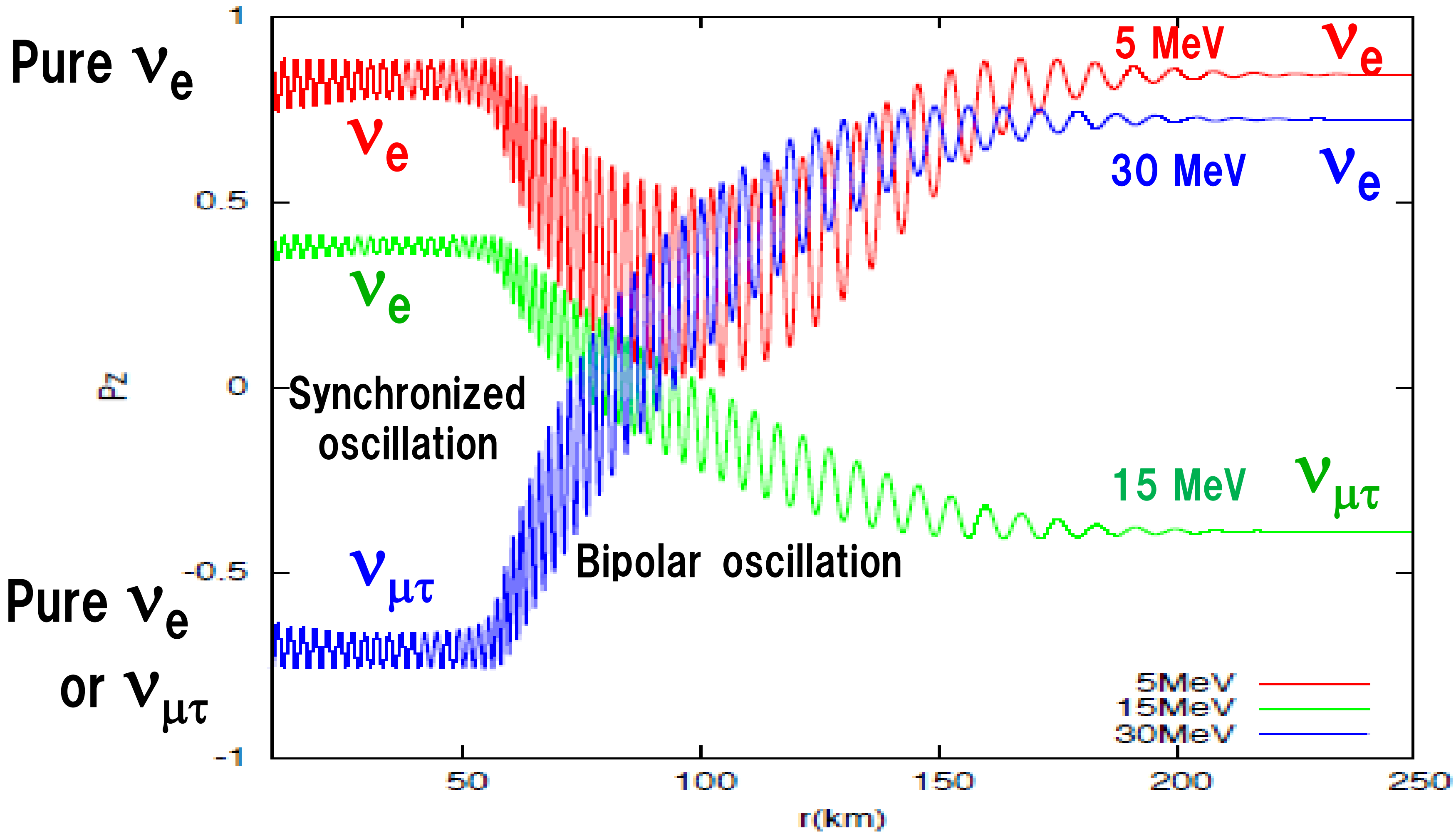

$\alpha, \beta$ = e, $\mu$, $\tau$

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

# Calculated Collective (Self-int.) ν Flavor Oscillation

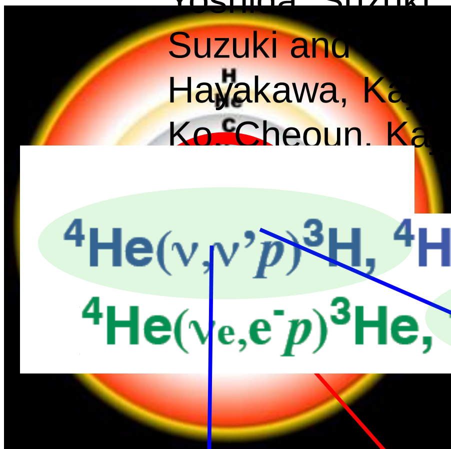
## Collective ν–Flavor Oscillation induces "Eneregy Spectral Split"

Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011.
Birol, Pehlivan, Balantekin & Kajino, PR D98 (2018), 083002.
Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin & Pehlivan, PR D96 (2017), 043013.



# $^{7}Li$ and $^{11}B$ are produced in the He/C Shell

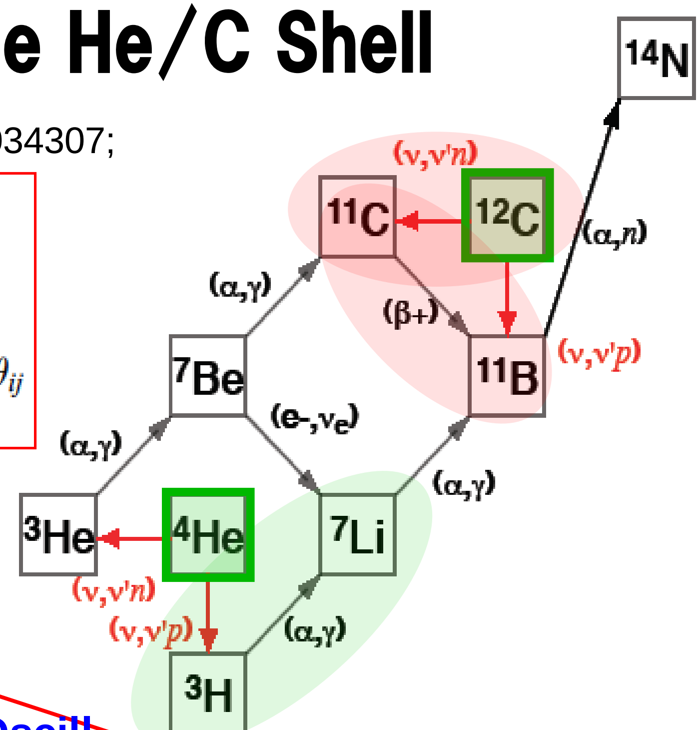
Suzuki, Chiba, Yoshida, Kajino and Otsuka, PRC74 (2006), 034307;
Yoshida, Suzuki, Chiba, Kajino, et al., ApJ 686 (2008), 448;
Suzuki and Kajino, J. Phys. G40 (2013), 083101;
Hayakawa, Kajino et al., PRL 121 (2018), 102701;
Ko, Cheoun, Kajino et al. (2019), submitted.

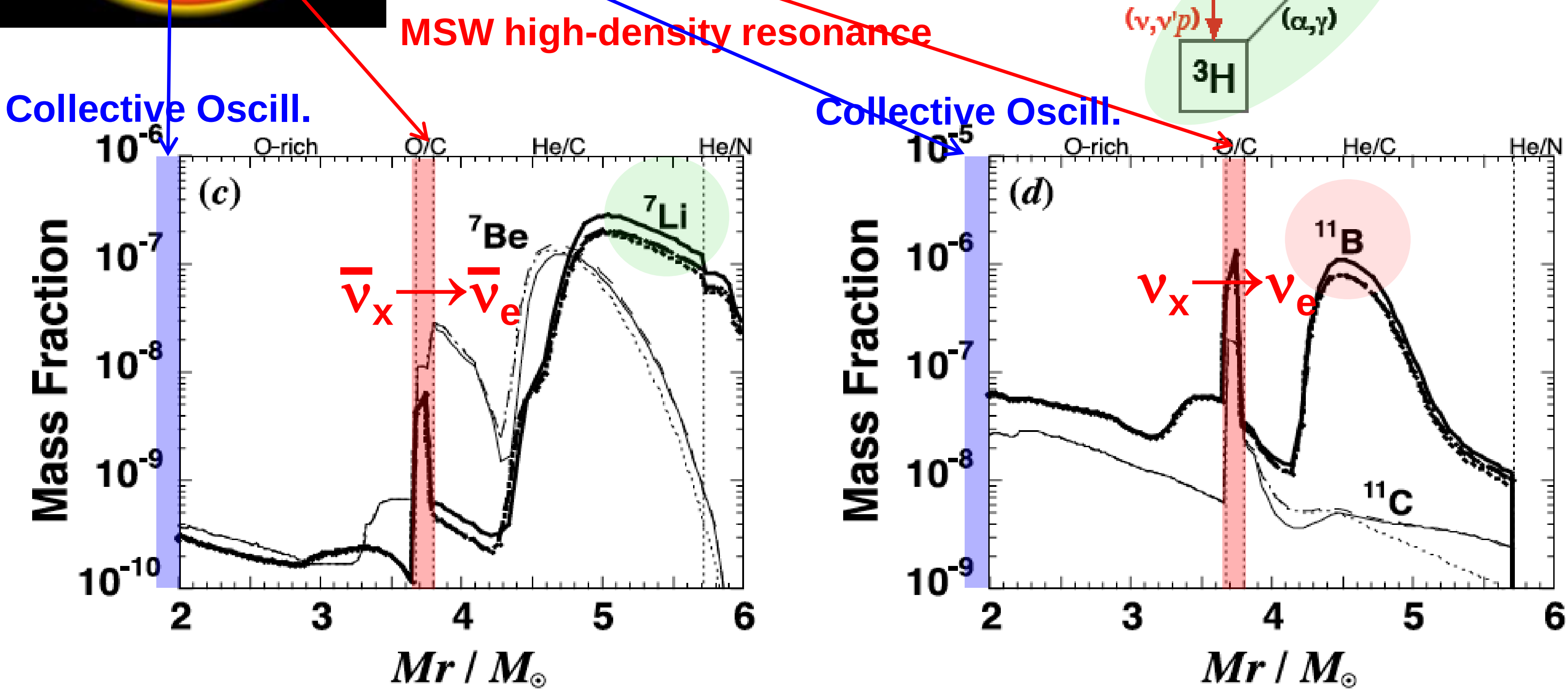


$$\rho_{res} Y_e = \frac{m_u \Delta m^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu} \quad [\mathrm{g\ cm^{-3}}]$$
$$= 6.55 \times 10^6 \left(\frac{\Delta m^2_{ji}}{1\ \mathrm{eV}^2}\right)\left(\frac{1\ \mathrm{MeV}}{\varepsilon}\right) \cos 2\theta_{ij}$$

$^{4}He(\nu,\nu' p)^{3}H$, $^{4}He(\nu,\nu' n)^{3}He$, $^{12}C(\nu,\nu' p)^{11}B$

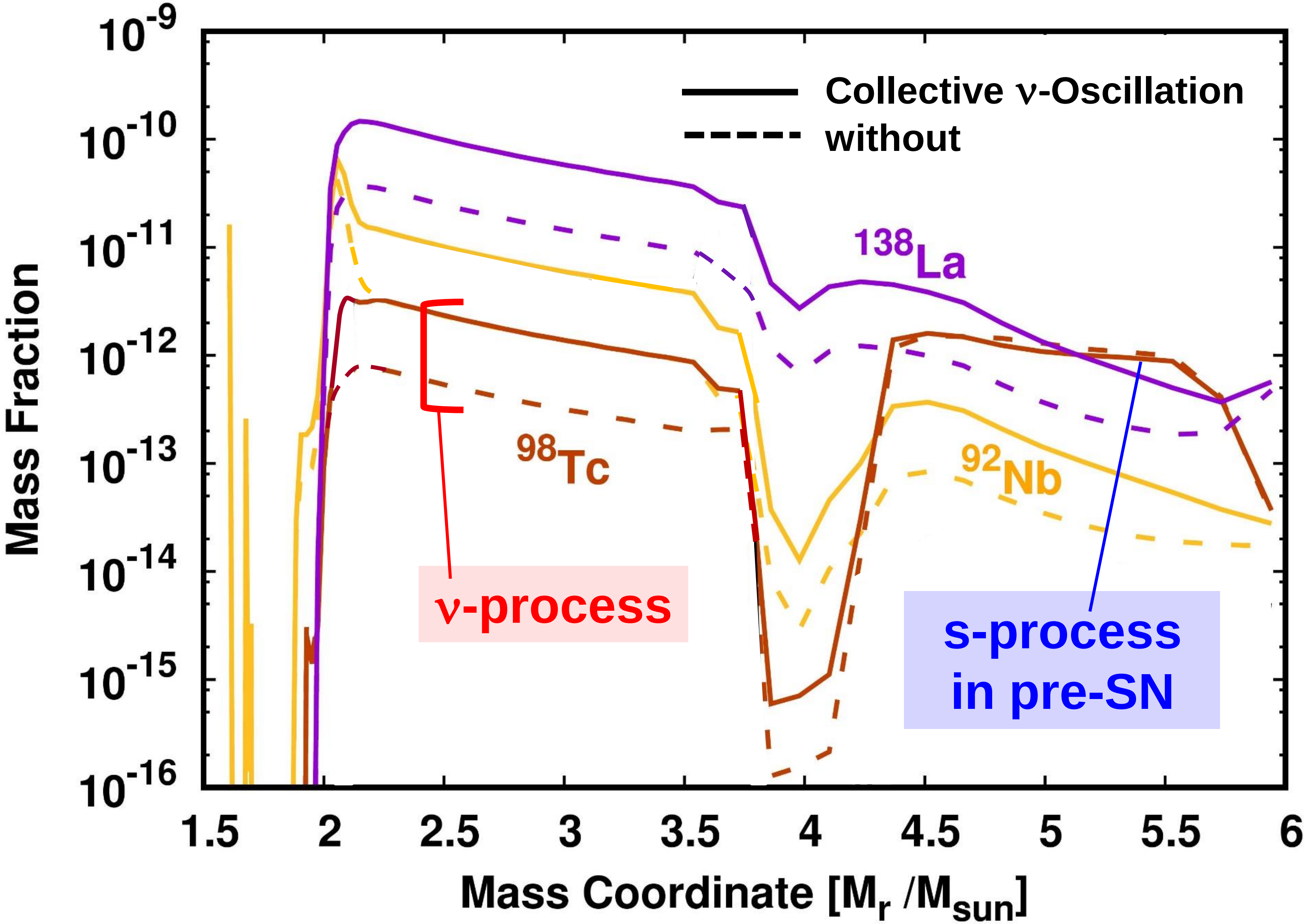
$^{4}He(\nu_e,e^- p)^{3}He$, $^{4}He(\bar{\nu}_e,e^+ n)^{3}H$, $^{12}C(\nu_e,e^- p)^{11}C$,



# ν-process Nucleosynthesis : $^{92}$Nb, $^{98}$Tc, $^{138}$La

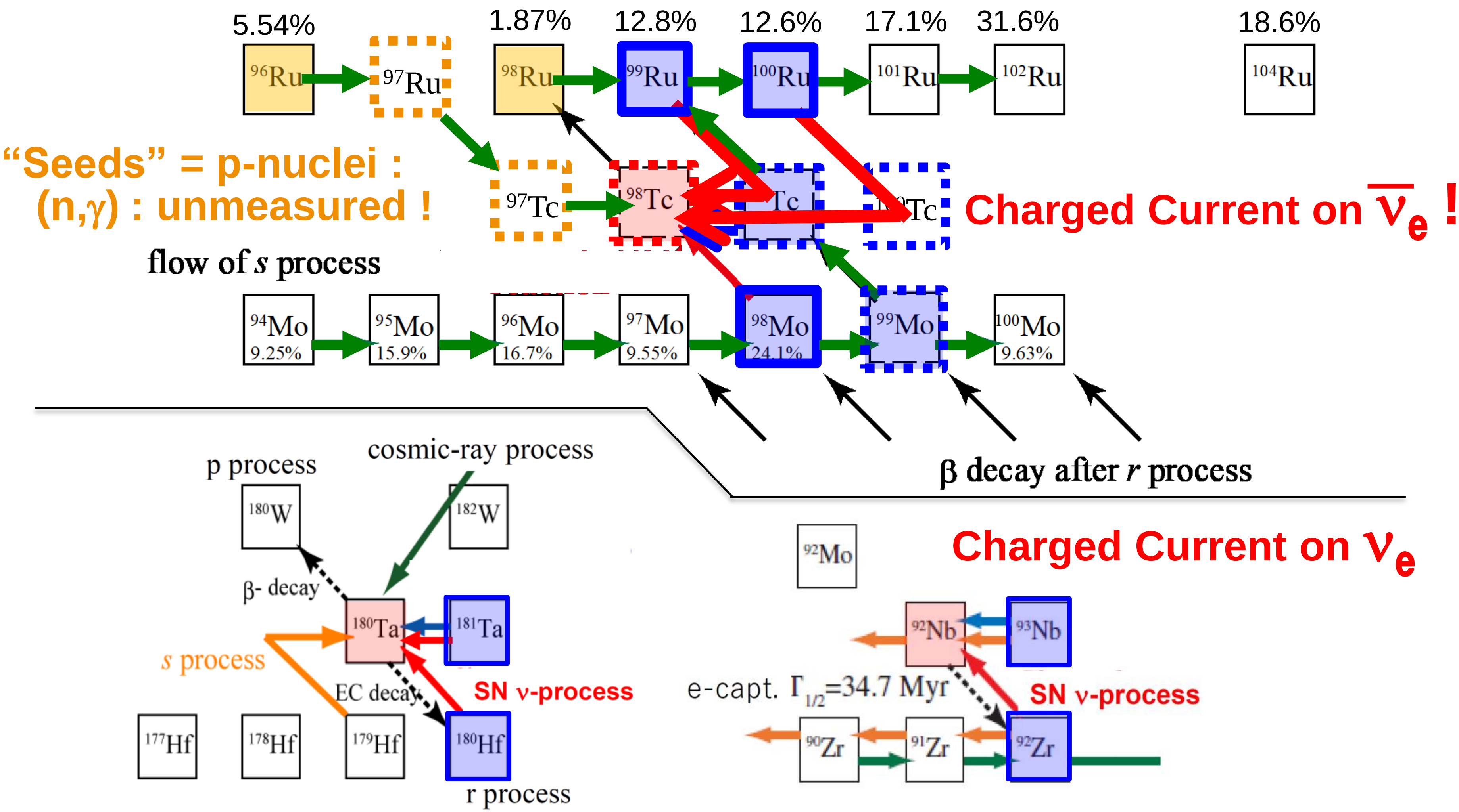
Hayakawa, Kajino et al., PRL 121 (2018), 102701; Ko, Cheoun, Kajino et al. (2019), submitted.



# $^{98}$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 is expected.**

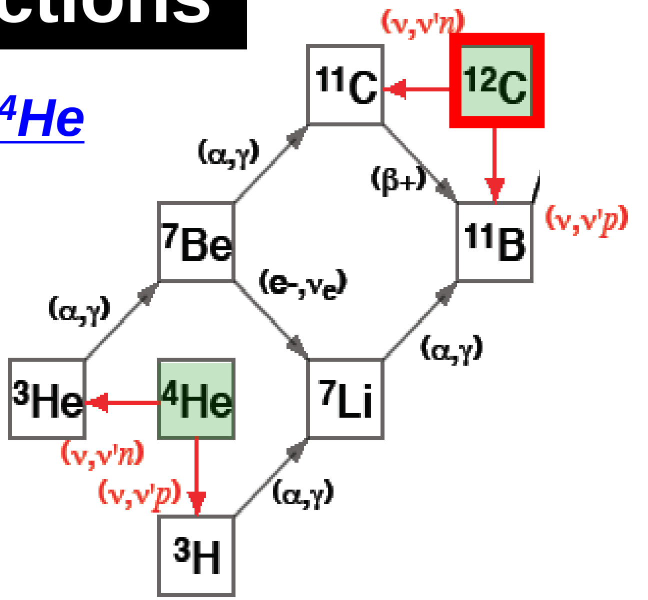



Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272; Heger et al., PL B606 (2005), 258;
Hayakawa, Kajino et al., PR C81 (2010), 052801®; PR C82 (2010), 058801; ApJL 779 (2013), L1; Kajino, Mathews & Hayakawa, JoP G41 (2014) 044007; Suzuki & Kajino, JoP G40 (2013), 083101; ++

# ν–Nucleus Cross-Sections

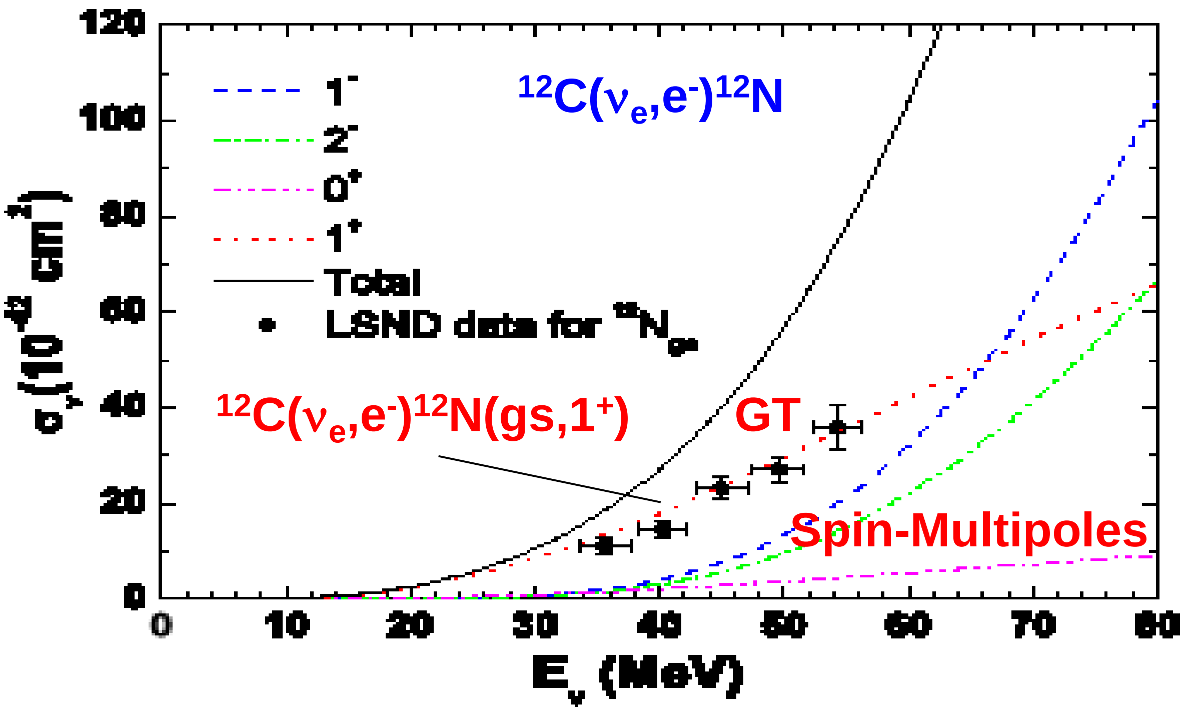
## Shell Model Cal. with NEW Hamiltonian: ν-$^{12}$C, $^{4}$He

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307,
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003),
Suzuki and Kajino, J. Phys. G40 (2013), 083101.




**$^{12}$C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.**

- μ-moments of p-shell nuclei
- GT strength for $^{12}$C→$^{12}$N, $^{14}$C→$^{14}$N, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections



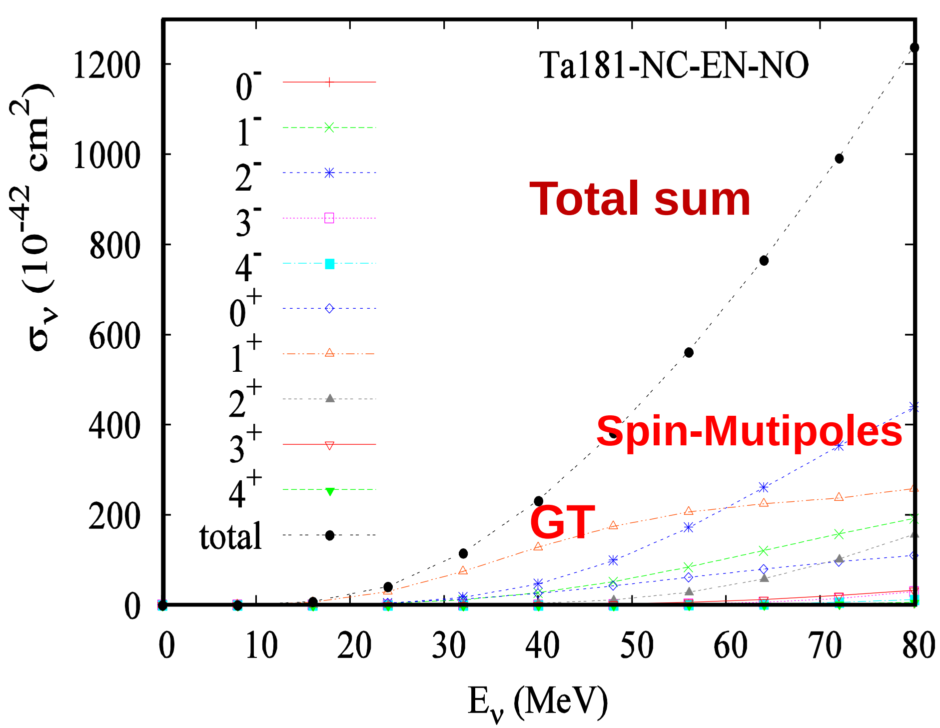
# ν–Nucleus Cross-Sections

## QRPA cal.: *ν* -$^{180}$*Ta*, $^{138}$*La*, $^{98}$*Tc*, $^{92}$*Nb*, $^{42}$*Ca* + $^{12}$*C*, $^{4}$*He…*

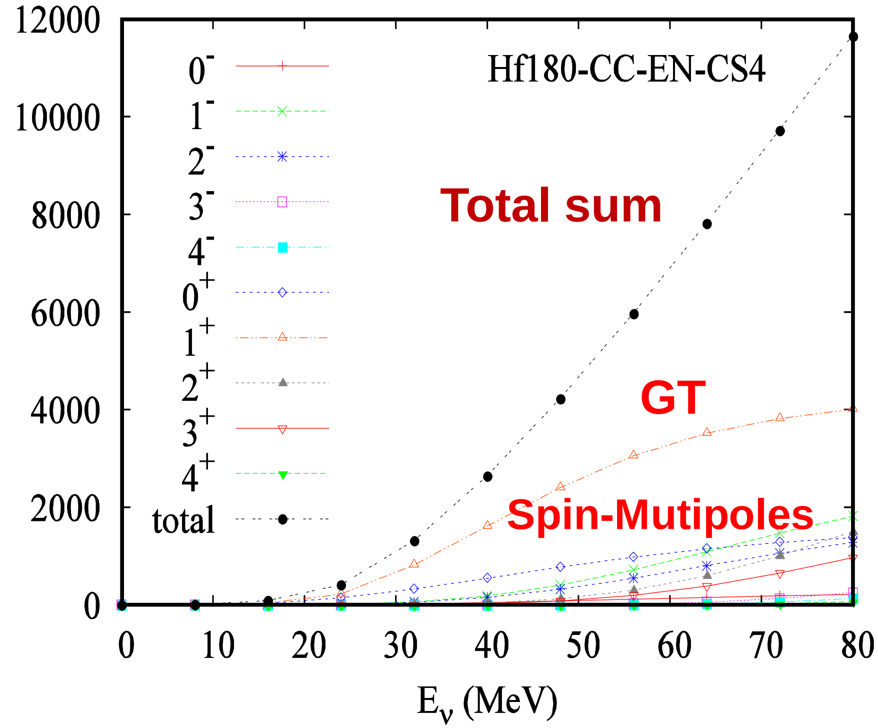
Cheoun, Ha, Hayakawa, Kajino & Chiba, PRC82 (2010), 035504;
Cheoun, Ha, Kim, & Kajino, J. Phys. G37 (2010) 055101;
Cheoun, Ha & Kajino, PRC 83 (2011), 028801

**Need GT + Spin-Multipole transitions !**

**$^{181}$Ta + ν → $^{180}$Ta + n + ν' (NC)**




**$^{180}$Hf + ν → $^{180}$Ta + e$^{-}$ (CC)**



★ ν-beam is not yet available !

★ EW-PROBE γ, e, μ & Hadronic CEX reactions !

# Similarity between Electro-Magnetic & Weak Interactions

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

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

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

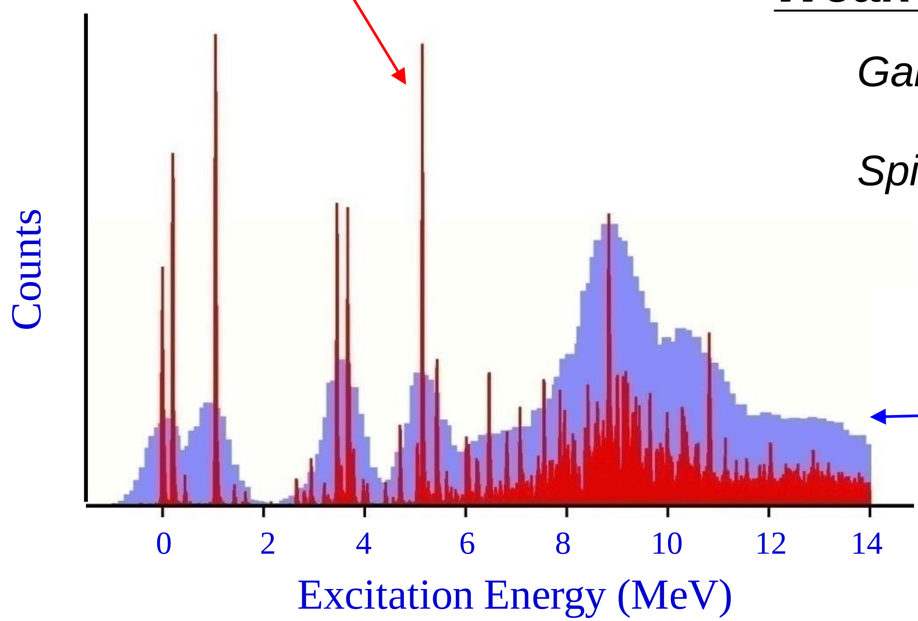
***Weak operator in non-relativistic limit***

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

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

**$^{58}$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)

# Conclusion

- R-proc elements in the Early Galaxy were dominated by Supernovae. Neutron Star-Mergers have arrived later in cosmic evolution.

- Supernova $\nu$-Process Nucleosynthesis
  :- is a good probe of $\nu$-Quantum Coll. Oscillations and MSW Effect.
  :- constrains $\nu$-MASS HIERARCHY.

## Recent Progress,

based on SYNERGY among Astrophysics, Astronomy & Nucl-Part. Physics

↓

GW — $\nu$ — Opt.-IR-X-$\gamma$ — "Baryons (Nuclei)"

**Dawn of Multi-Messenger Astronomy & Nuclear Astrophysics**