Workshop on Fission Dynamics 2026, Chongqing in China, May 11-15, 2026

Fission and the Origin of Heavy Elements in the Universe

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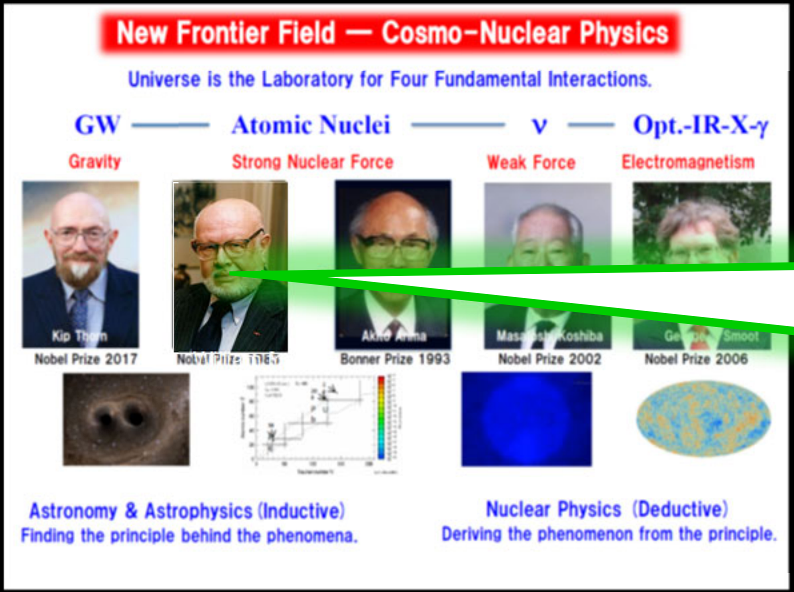
Beihang University, China

The University of Tokyo, National Astronomical Observatory of Japan



Universe is the Laboratory for Fundamental Physics

Taka …

Astrophysics and cosmology is a field which requires imagination.

Be brave enough to propose even crazy ideas.

Let's discuss together !

Because we are the collaborators !

William A. Fowler in 1987

Purpose

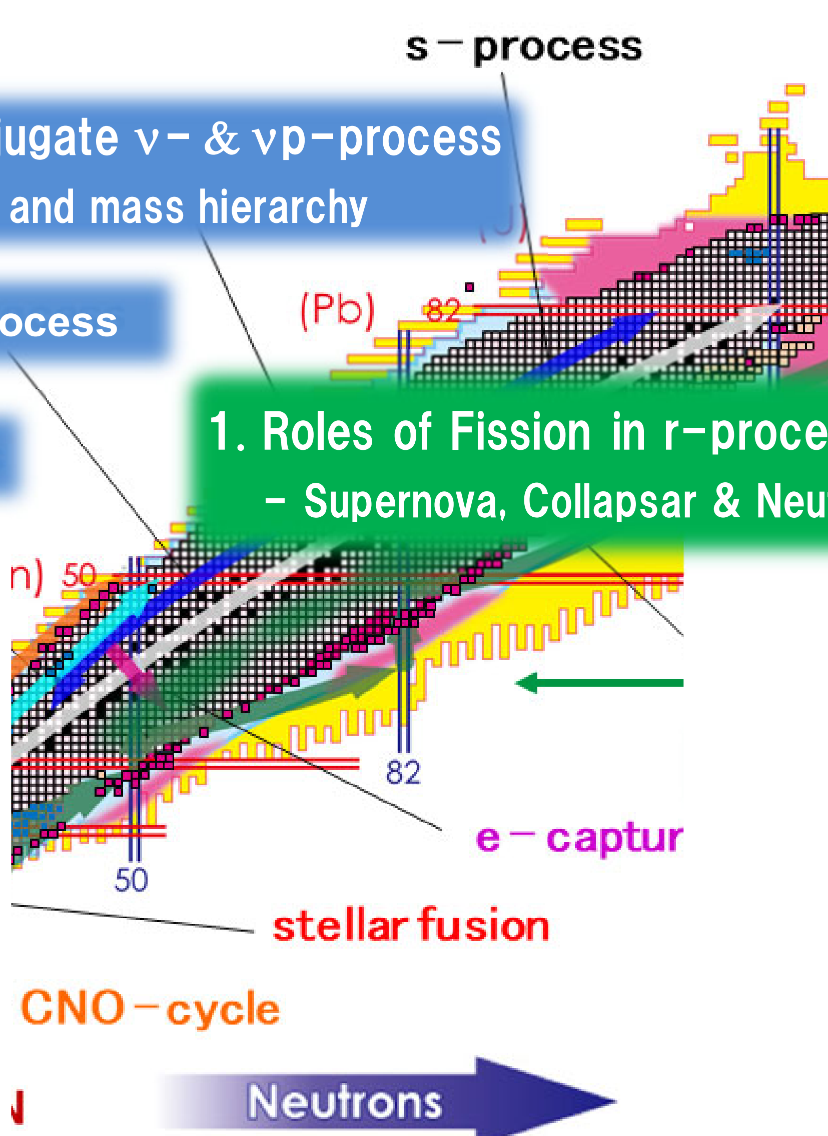
To elucidate the roles of Fission & νs in Explosive Nucleosynthesis

2. Roles of νs in conjugate ν− & νp−process

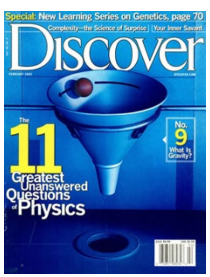
− ν flavor oscillation and mass hierarchy

1. Roles of Fission in r−process

− Supernova, Collapsar & Neutron−Star Merger ?



The 11 Greatest Unanswered Questions in Physics !



− What is the origin of Uranium ?

− Why do neutrinos have mass ?

The National Research Council's Board on Physics, USA (2002)

Go beyond

Origin of Elements in Stars
B2FH 1957

Margaret & Geoffrey Burbidge, William A. Fowler and Fred Hoyle (1957)

GW170817/SSS17a

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

GW170817/SSS17a

1. GW170817 (LIGO-Virgo) : $0.86 < M/M_\odot < 2.26$ → EoS

2. GRB170817A (Fermi-GBM) : 1.7 s → Central Engine

3. No ν–Signal: 10

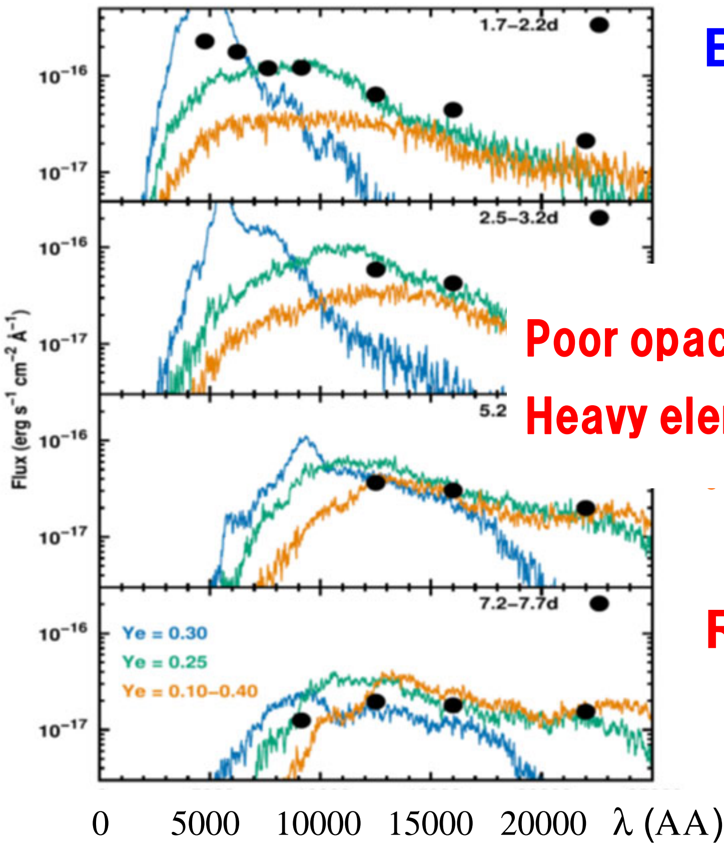
4. X-rays & Radio

5. Optical and Ne

Caution!

Today's astronomers' consensus:

No clear evidence for Lanthanoid in Neutron-Star-Merger !



Blue

Red

Poor opacity table !

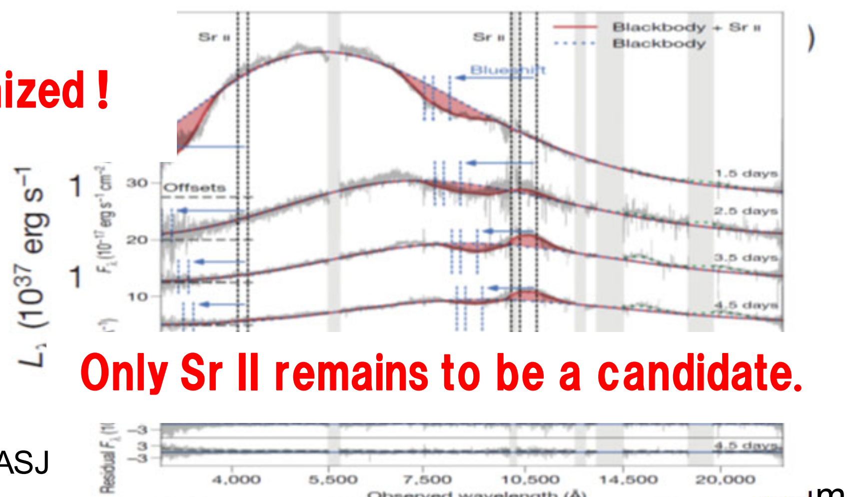
Heavy elements are ionized !

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

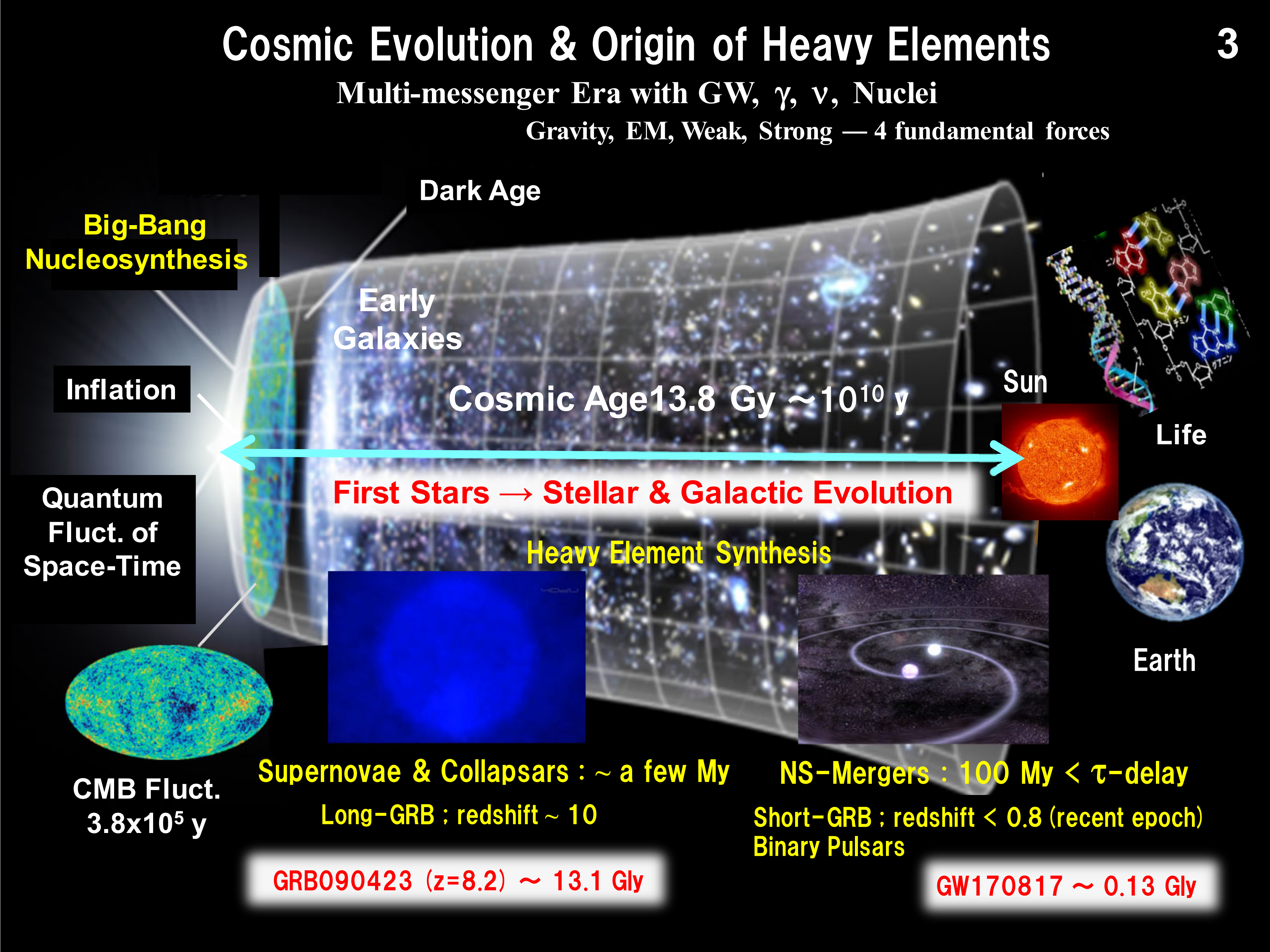
- ~~Color change over one week seems consistent with radioactive decay of r-elements. (Probably Lanthanoids)~~
- ~~Many neutral lines of heavy elements.~~

Watson et al., Nature 574 (2019), 497

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

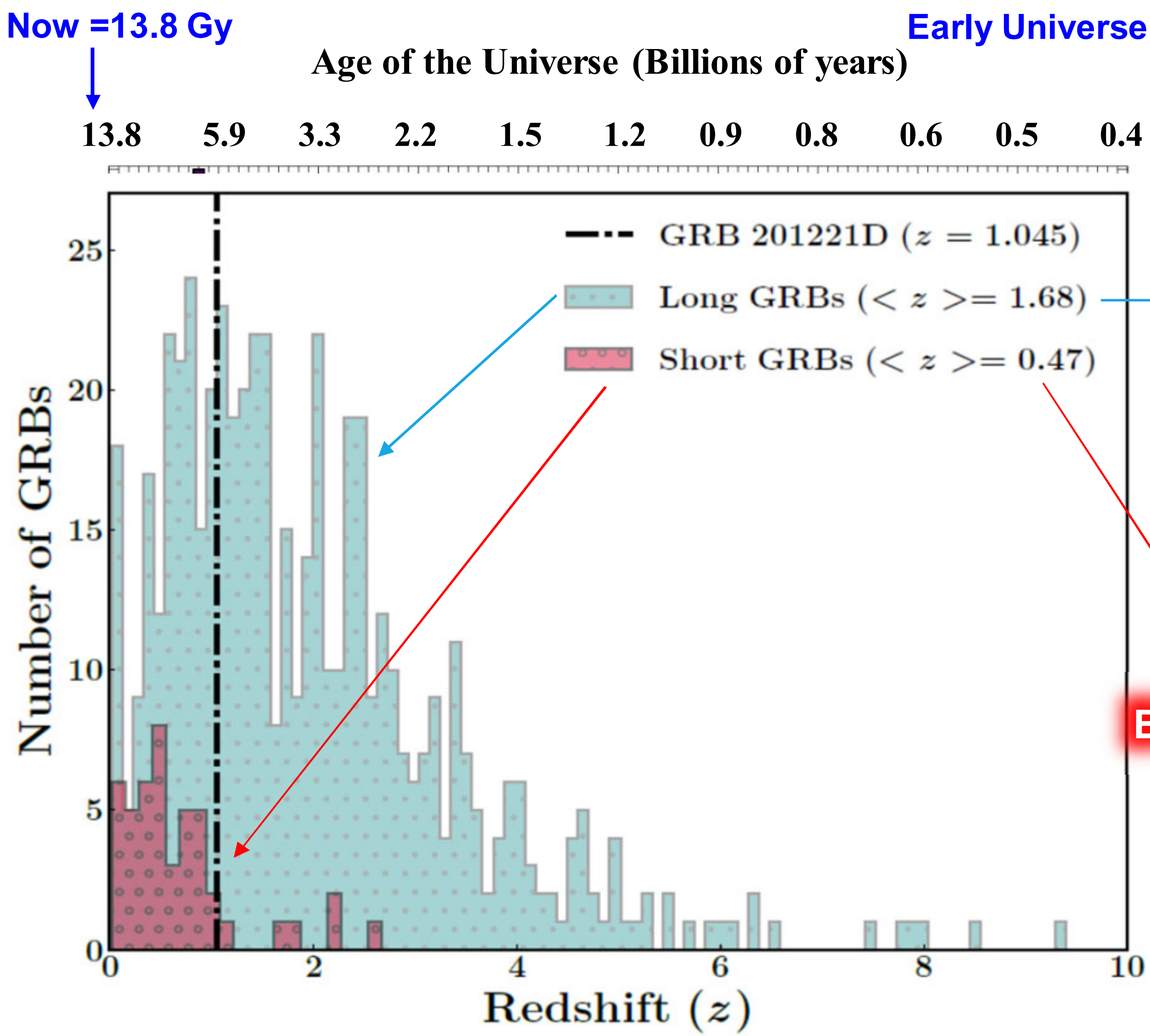


Only Sr II remains to be a candidate.


Cosmic Evolution & Origin of Heavy Elements
3
Multi-messenger Era with GW, γ, ν, Nuclei
Gravity, EM, Weak, Strong — 4 fundamental forces
Dark Age
Big-Bang Nucleosynthesis
Early Galaxies
Inflation
Cosmic Age13.8 Gy ~10¹⁰ y
Sun
Life
Quantum Fluct. of Space-Time
First Stars → Stellar & Galactic Evolution
Earth
Heavy Element Synthesis
CMB Fluct. 3.8x10⁵ y
Supernovae & Collapsars : ~ a few My
Long-GRB ; redshift ~ 10
NS-Mergers : 100 My < τ-delay
Short-GRB ; redshift < 0.8 (recent epoch)
Binary Pulsars
GRB090423 (z=8.2) ~ 13.1 Gly
GW170817 ~ 0.13 Gly

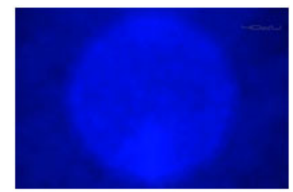
Redshift – Age relation of Gamma-Ray Bursts

Dimple, et al., MNRAS (2022) 516, Issue 1, pp.1-12



Central Engines of GRB

Collapsar



Over the entire history from the early Universe.

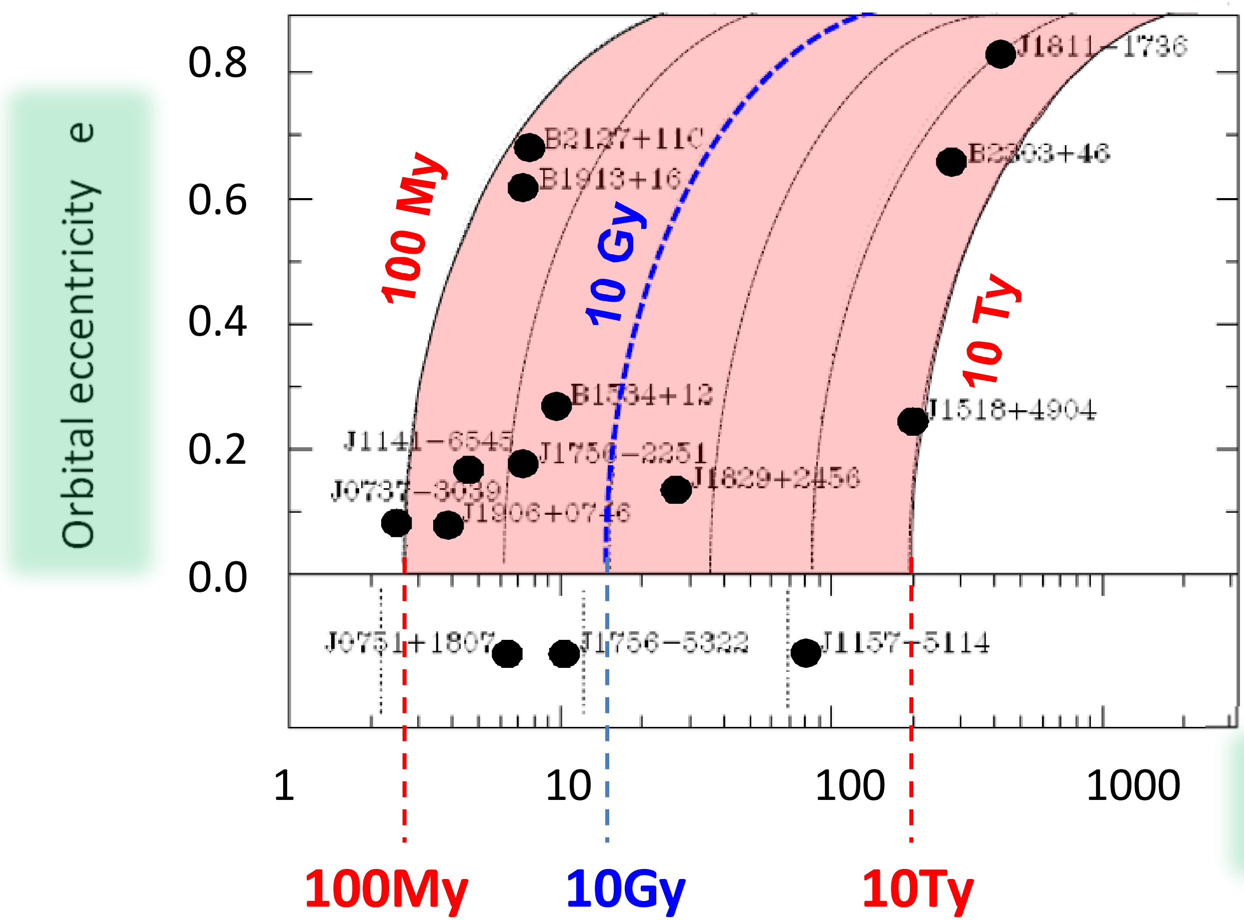
Binary Neutron-Star Merger

Only recently: 10 Gy < t

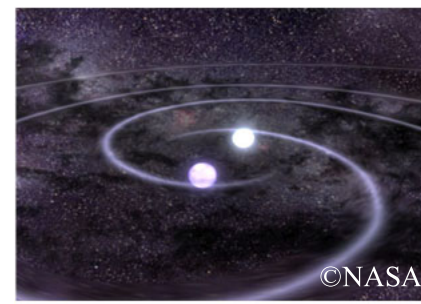
Binary Pulsars : Merger Time-Delay

General Relativity : $\tau_{delay} = 9.83\ \mathrm{Myr} \times \left(\frac{P_b}{\mathrm{hr}}\right)^{8/3} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1-e^2)^{7/2}$

14 BINARY PULSARS : Lorimer, Living Rev. Rel. 11(2008), 8; Beniamini+ (2019).



Orbital period P_b (hours)

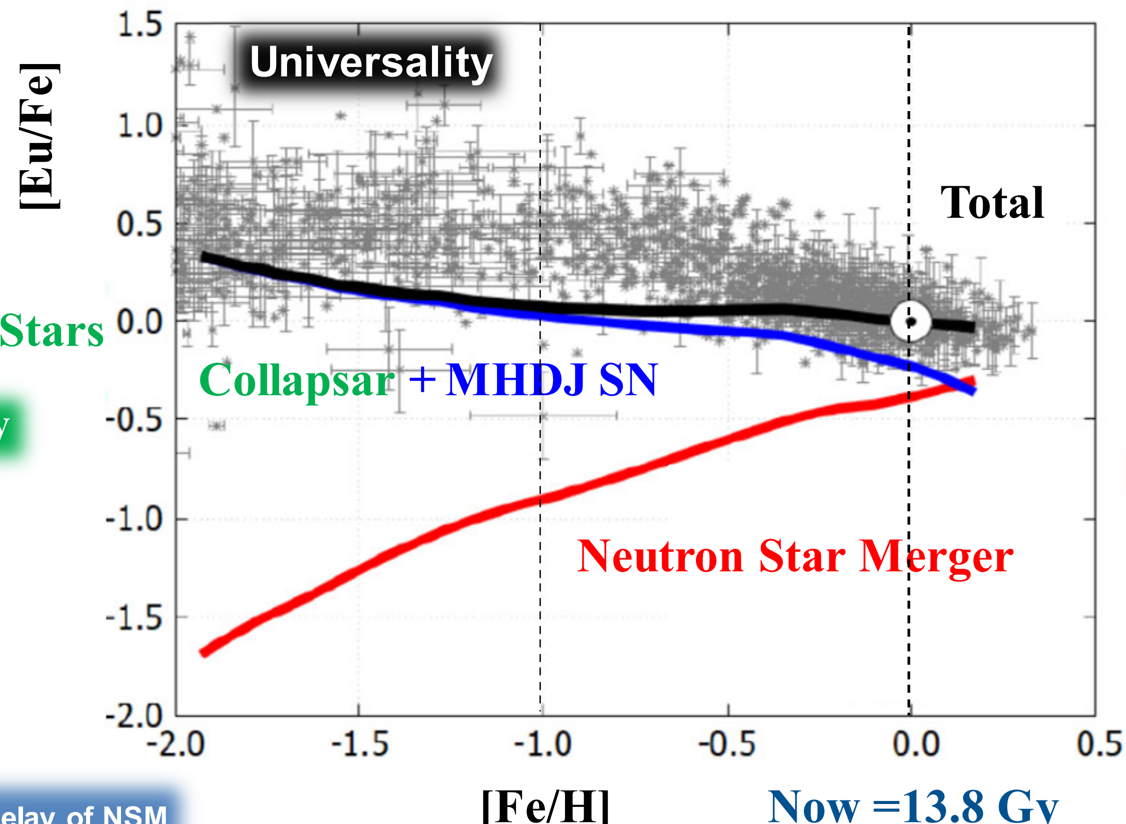


Cosmic & Galactic Chmeical Evolution (GCE) of r-Process Elements

Kim, Kim, He, Choi, Luo, Kajino, Tanihata, Diehl, ApJ 998 (2026), 253; He, Kajino, et al., ApJ Lett 966 (2024), L34; Yamazaki, He, Kajino, et al., ApJ 933 (2022), 112; Kobayashi, Karakas & Lugaro, ApJ 900 (2020), 179.

Single Massive Stars

τ_{life} ~ a few My



Observed Binary Pulsars = Binary NSs

→ 100 My < τ_{delay}

Lorimer, Living, Rev. Rel. 11(2008), 8; Beniamini (2019) ++

Now =13.8 Gy

Coalescence Time Delay of NSM

BB → 100 My

→ 1 Gy

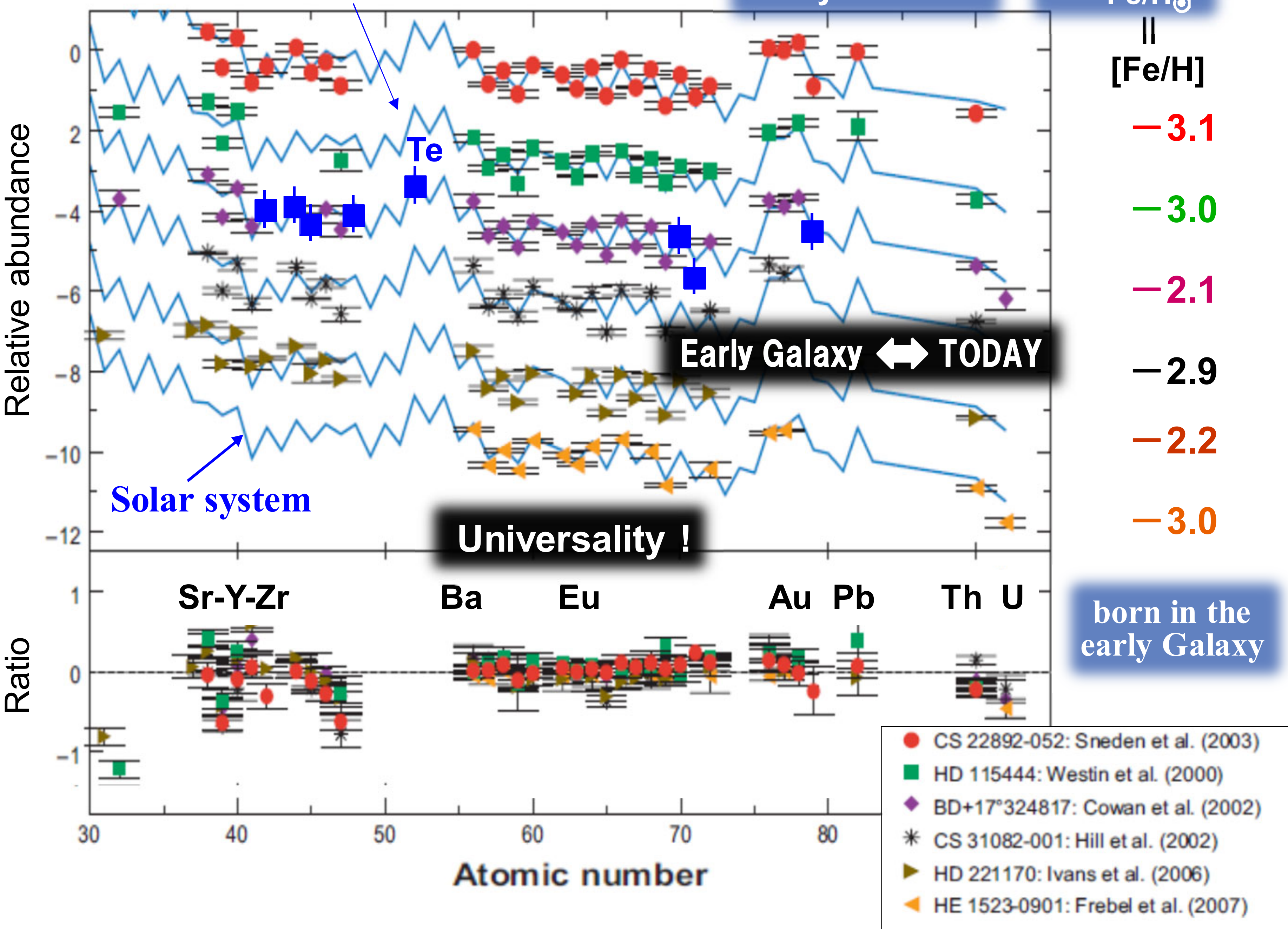
→ 10 Gy

$t/10Gy = 10^{[Fe/H]}$ ⟷ $[Fe/H] = \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$

Sneden, Cowan, Gallino, ARAA 46 (2008) 241.
HST-obs: Roederer et al., ApJ 747 (2012) L8.

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

$\log \frac{Fe/H_☆}{Fe/H_⊙} = [Fe/H]$

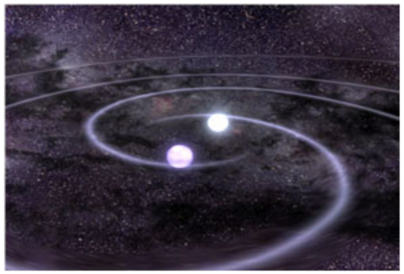


−3.1
−3.0
−2.1
−2.9
−2.2
−3.0

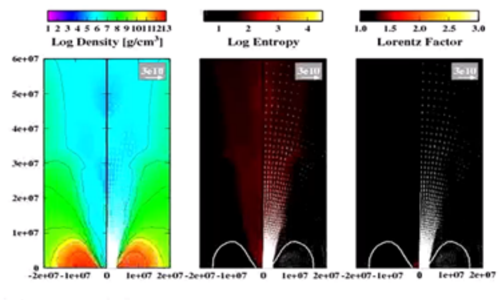
born in the early Galaxy

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

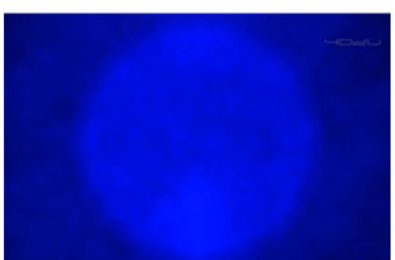
Neutron Star Merger



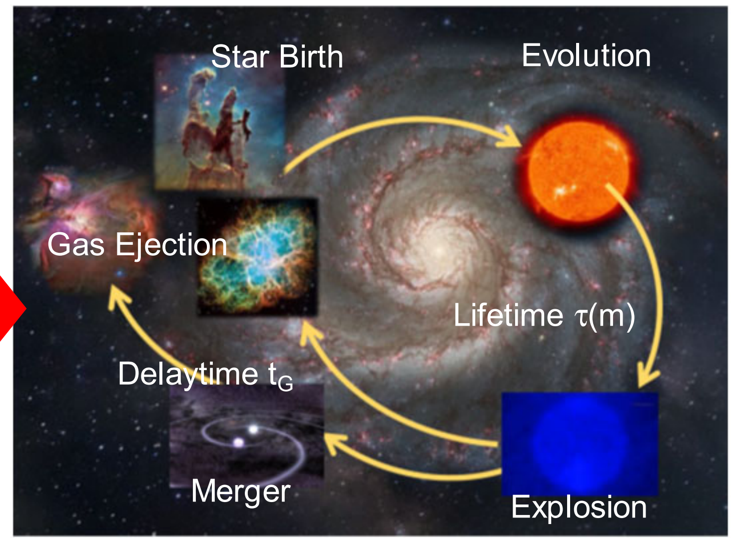
Collapsar Jet

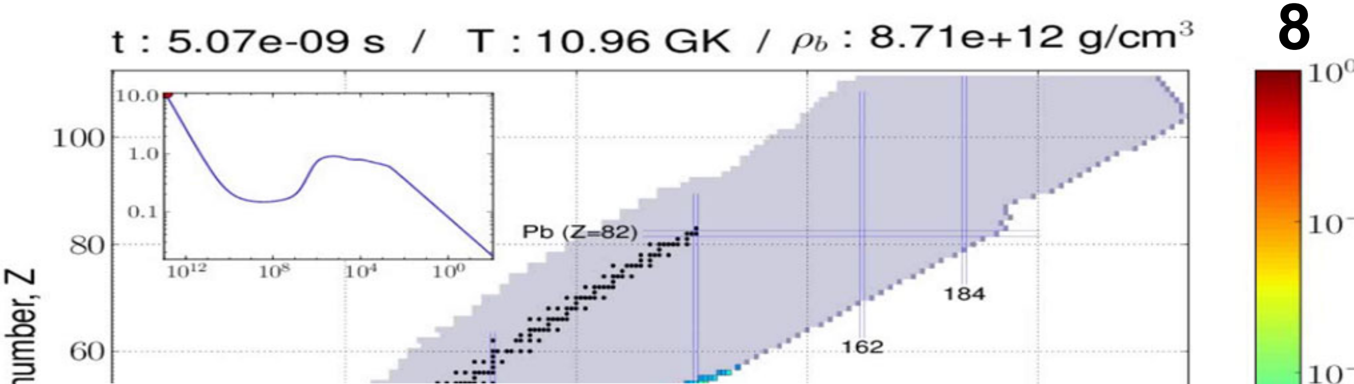


MHD Jet Supernova



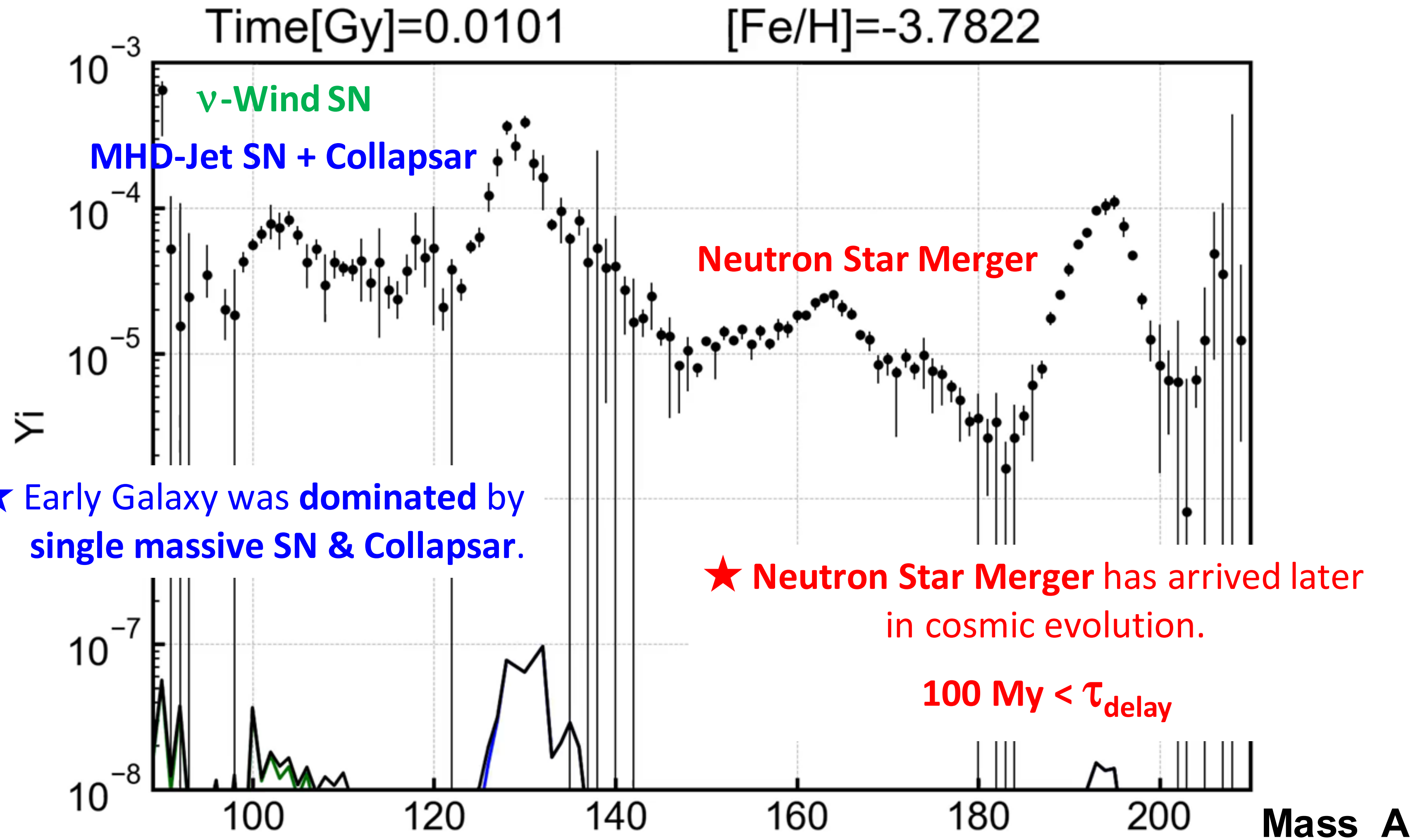
Cosmic & Galactic Evolution





Cosmic & Galactic Evolution, based on F. Timmes model

$t/10Gy = 10^{[Fe/H]}$ ⟷ $[Fe/H] = \log(N_{Fe}/N_H)_{\star} - \log(N_{Fe}/N_H)_{\odot}$



★ Early Galaxy was **dominated** by **single massive SN & Collapsar.**

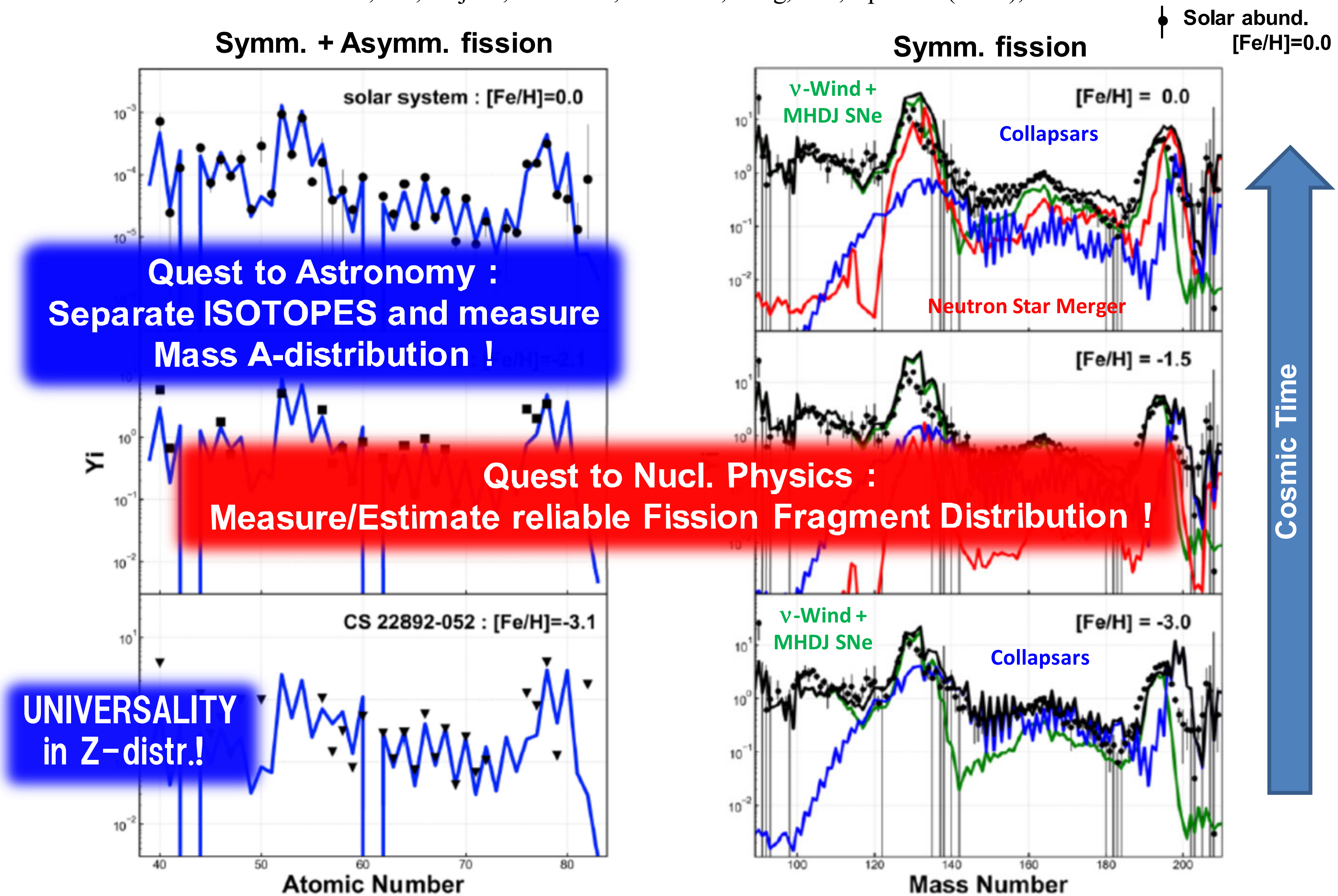
★ **Neutron Star Merger** has arrived later in cosmic evolution.

100 My < τ_{delay}

Yamazaki, He, Kajino, et al., ApJ 933 (2022), 112; Kim, Kim, He, Choi, Luo, Kajino, Tanihata, Diehl, ApJ 998 (2026), 253

Galactic Chemical Evolution

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.



Galactic Chemical Evolution

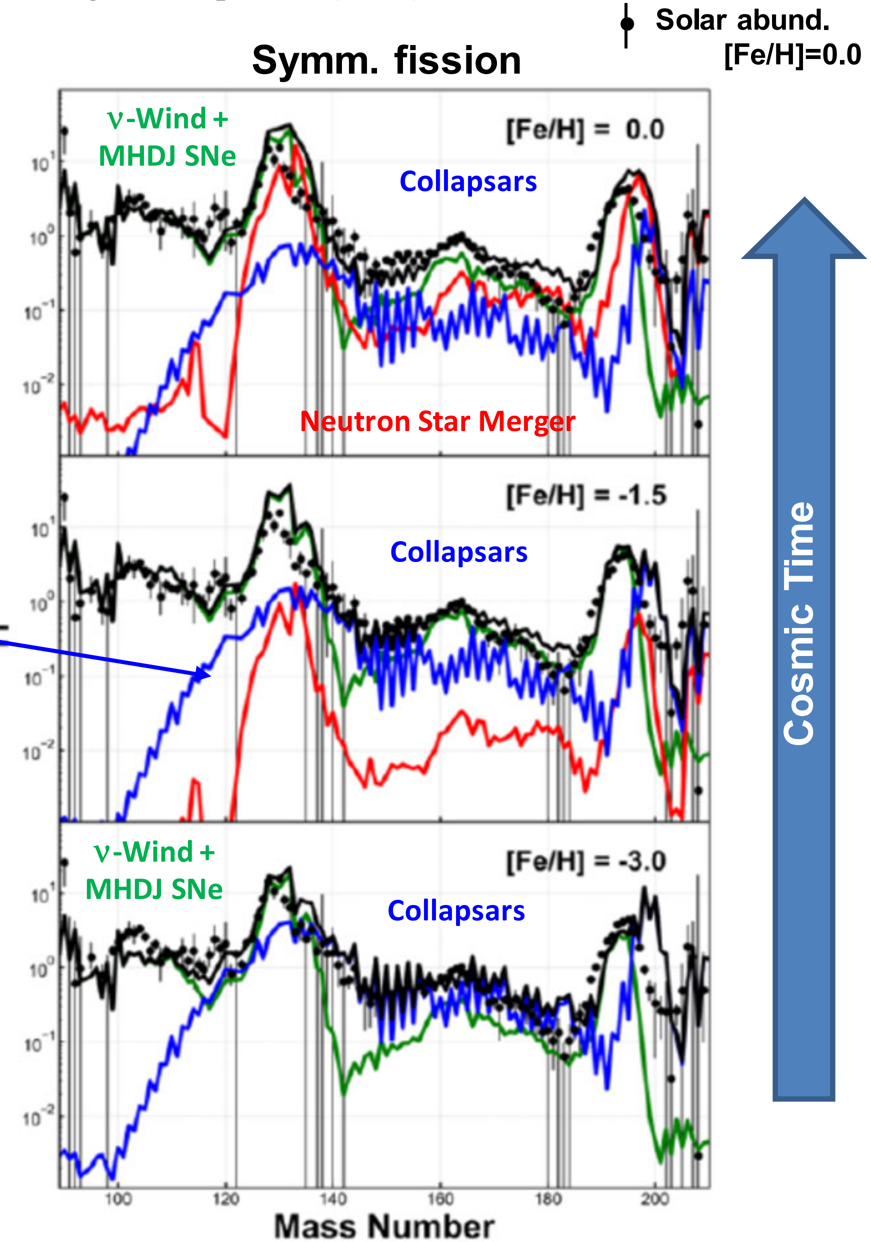
Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.

He, Kajino, Kusakabe, Zhou, Koura, Chiba, Li and Lin, ApJ Lett 966 (2024), L34;
He, Lin, Luo, Kajino and Li, ApJ 1000 (2026), 177.

Discovery of New Process in Collapsar (BH forming supernova)

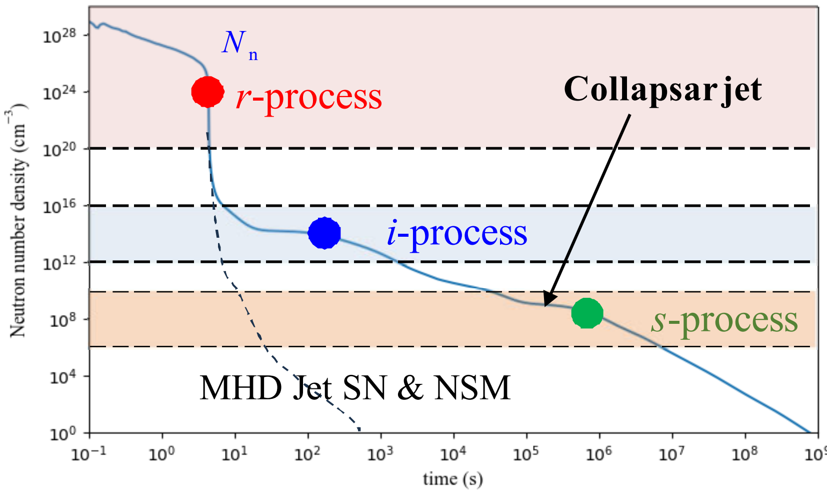
Three n-capture processes can coexist.

- **r (rapid)**
- **i (intermediate)**
- **s (slow)**



Coexistence of r-, i-, s-processes in Collapsar r-process

He, Kajino, Kusakabe, Zhou, Koura, Chiba, Li and Lin, ApJ Lett 966 (2024), L34; He, Lin, Luo, Kajino & Li, ApJ 1000 (2026), 177.



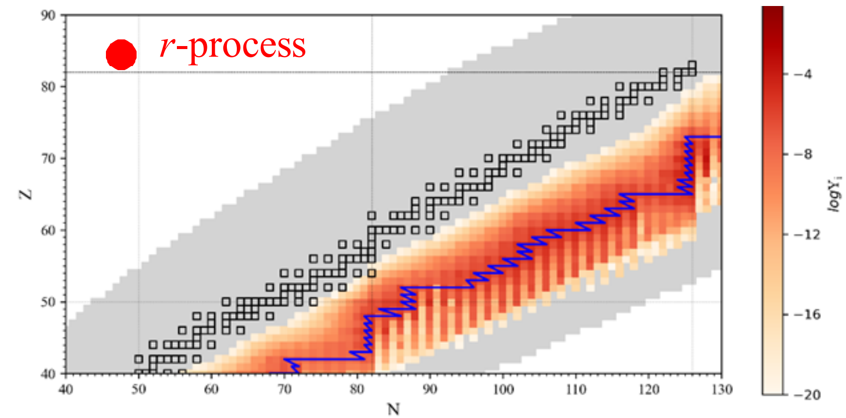
	$N_n\ (\mathrm{cm}^{-3})$
r-process:	$>10^{20}$
i-process:	$10^{12} \sim 10^{16}$
s-process:	$10^{6} \sim 10^{10}$

Fissions Neutrons from ^{276}Rf, ^{260}Fm & Trans-Uranium Isotopes for i-process

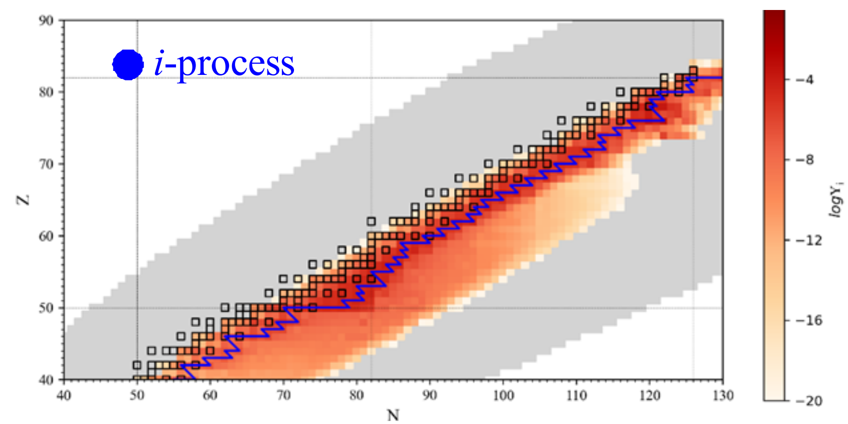
(n, γ) collision time **Expansion time-scale**

$$\tau_{(n,\gamma)} = \frac{1}{\rho Y_n N_A \langle \sigma v \rangle} < \tau_{dyn} = -\left(\frac{d \ln T_9}{dt}\right)^{-1}$$

time(s) = 4.5; T_9 = 0.86; ρ(gcc) = 1.8×10^2; Y_n = 1.6×10^{-6}; N_n(cm^{-3}) = 1.8×10^{20}



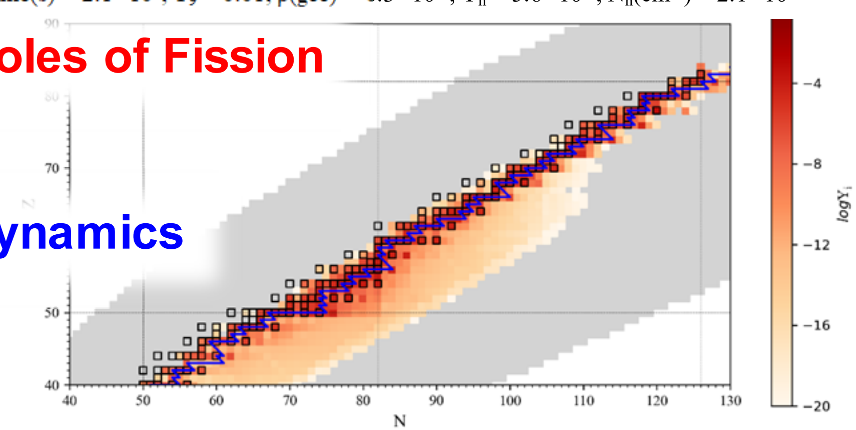
time(s) = 3.8×10^2; T_9 = 0.056; ρ(gcc) = 5.1×10^{-2}; Y_n = 7.7×10^{-10}; N_n(cm^{-3}) = 2.4×10^{13}



time(s) = 2.1×10^6; T_9 = 0.01; ρ(gcc) = 6.3×10^{-9}; Y_n = 5.6×10^{-9}; N_n(cm^{-3}) = 2.1×10^7

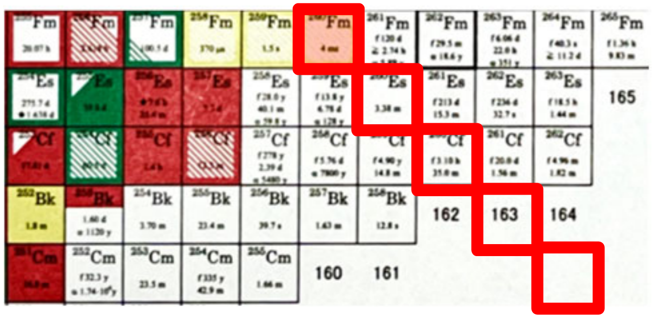
Roles of Fission

Dynamics



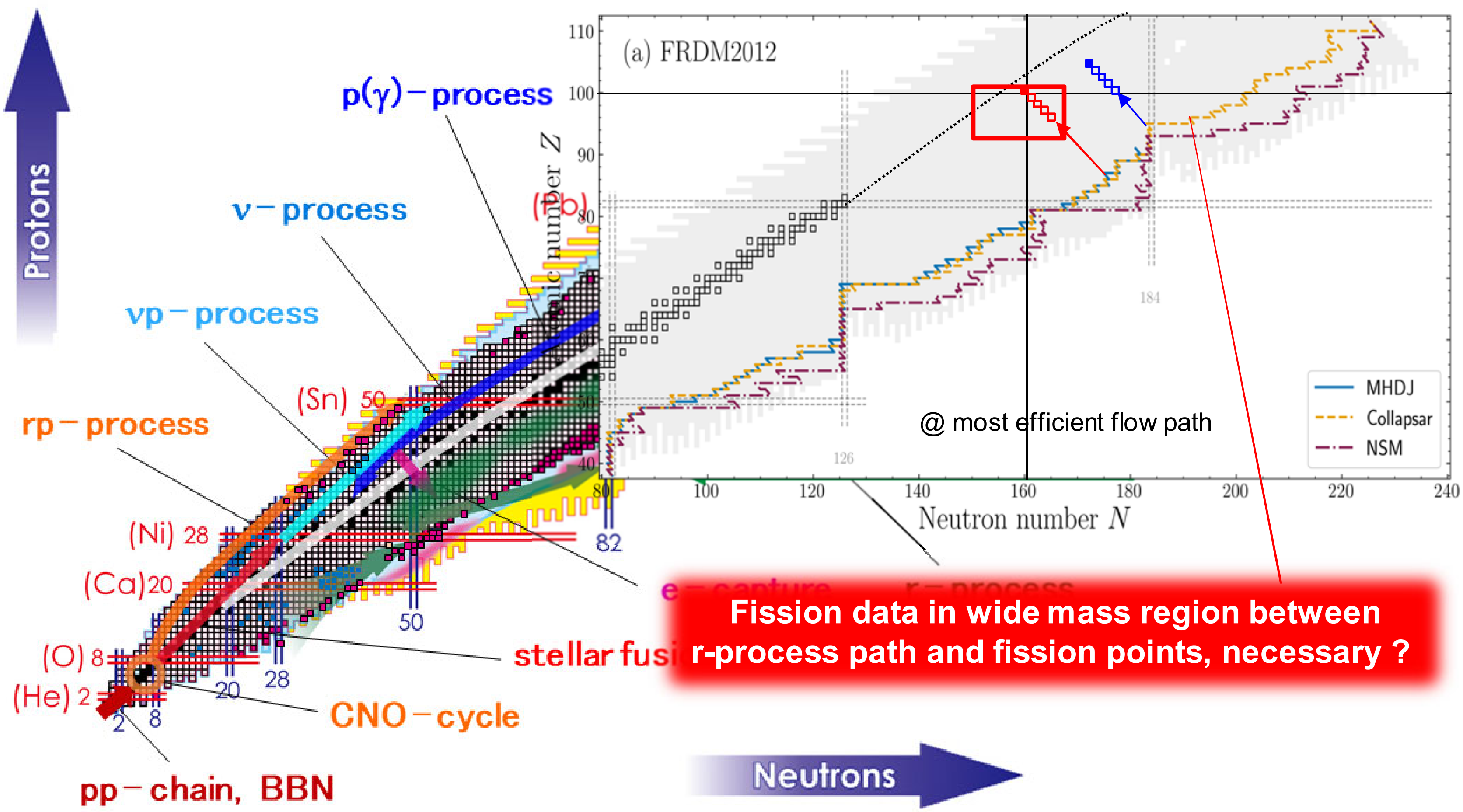
He, Kajino, Kusakabe, Zhou, Koura, Chiba, Li and Lin, ApJ Lett 966 (2024), L34; He, Lin, Luo, Kajino and Li, ApJ 1000 (2026), 177.

β-decay half-lives;
P. Moeller, et al. Phys. Rev. C67 (2003), 055802.



^{260}Fm (4.0ms) - fission
^{260}Es (149.5s)
^{260}Cf (**2111.3s**)
^{260}Bk (27.67s)
^{260}Cm (11.94s)

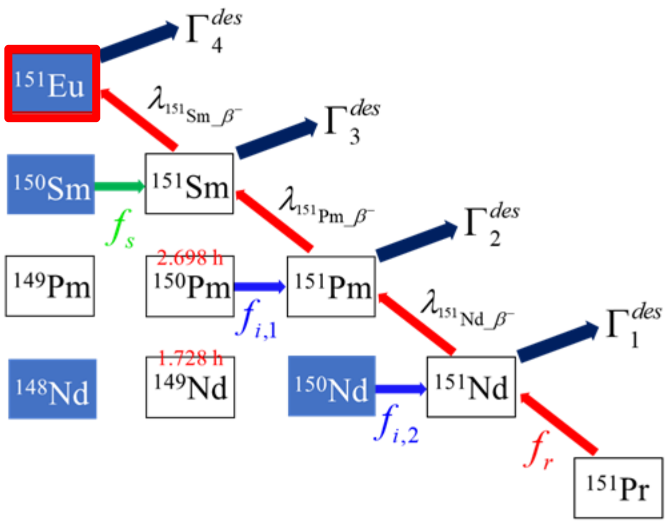
^{276}Rf (4.0ms) - fission
^{276}Lr (149.5s)
^{276}No (**262.3s**)
^{276}Md (14.53s)
^{276}Fm (7.756s)

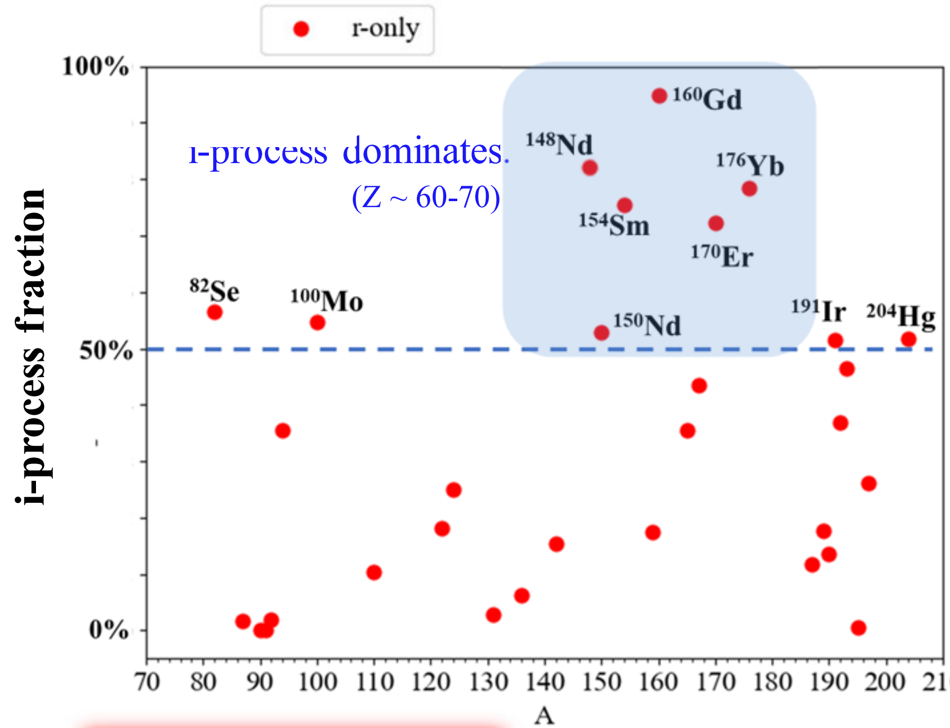


Fission data in wide mass region between r-process path and fission points, necessary ?

Contribution from *i*-process to the *r*-only nuclei

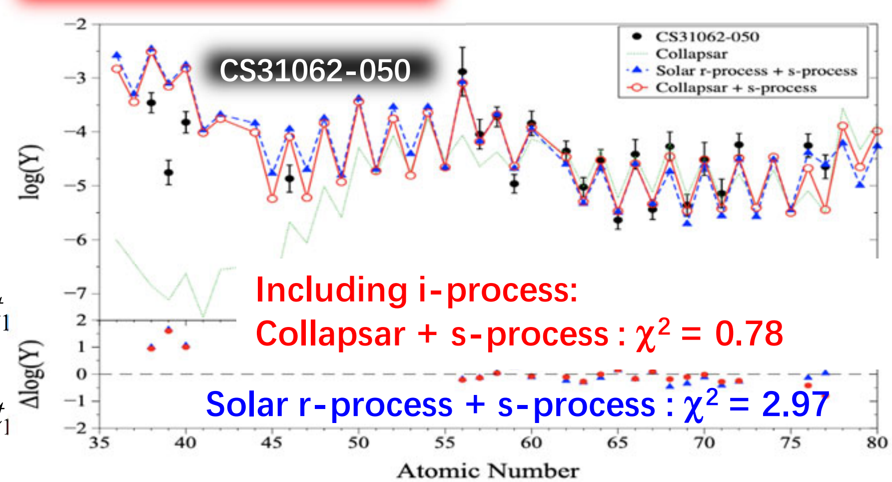
Astronomers
He, Kajino, et al. with Li & Lin,
ApJ Lett 966 (2024), L34.





Observational Signal

Hampel et al. (2016)



Theoretical Formulae:

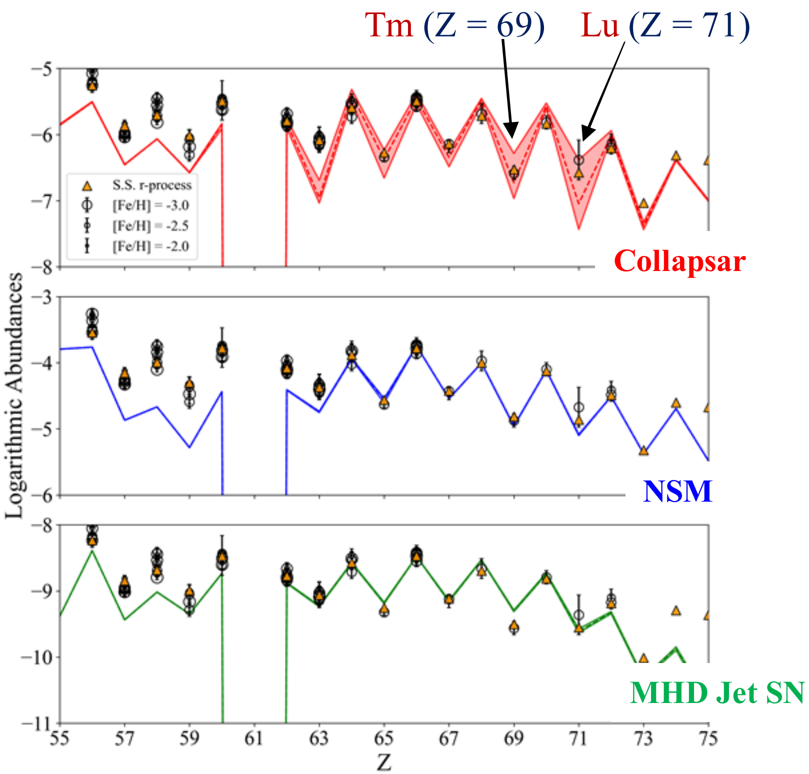
$$Y_s = \int_0^T dt P_4^{sur}(t;T)\left[\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^t d\tau f_s(\tau) P_3^{sur}(\tau;t)\right]$$

$$Y_i = \int_0^T dt_3 P_4^{sur}(t_3;T)\left\{\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^{t_3} dt_2\left[\lambda_{^{151}\mathrm{Pm}\_\beta^-}\int_0^{t_2} dt_1 \ldots t_2;t_3)\right\}$$

$$Y_r = \int_0^T dt_3 P_4^{sur}(t_3;T)\left\{\lambda_{^{151}\mathrm{Sm}\_\beta^-}\int_0^{t_3} dt_2\left[\lambda_{^{151}\mathrm{Pm}\_\beta^-}\int_0^{t_2} dt_1 \ldots\right.\right.$$

Observational & Experimental Verifications ?

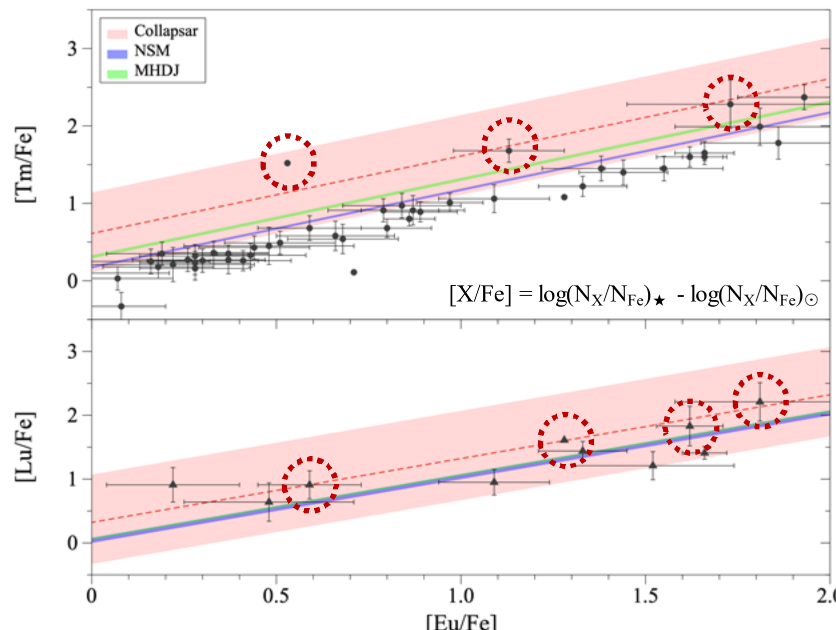
I. Observational Signal ?



Astronomers

He, Lin, Luo, Kajino & Li, ApJ 1000 (2026), 177.

[Tm/Eu] or [Lu/Eu], enhanced !



(SAGA database)

II. Precise Experimental Input ?

- **(n, γ) Reaction Rates**
- **Fission Frag. Distr.**

➢ Top 10 important (n,γ) reactions for **Tm**

^{175}Yb(n,γ)^{176}Yb, ^{153}Sm(n,γ)^{154}Sm, ^{151}Pm(n,γ)^{152}Pm, ^{172}Er(n,γ)^{173}Er, ^{175}Tm(n,γ)^{176}Tm, ^{166}Ho(n,γ)^{167}Ho, ^{151}Nd(n,γ)^{152}Nd, ^{152}Pm(n,γ)^{153}Pm, ^{149}Nd(n,γ)^{150}Nd, ^{147}Nd(n,γ)^{148}Nd

➢ Top 10 important (n,γ) reactions for **Lu**

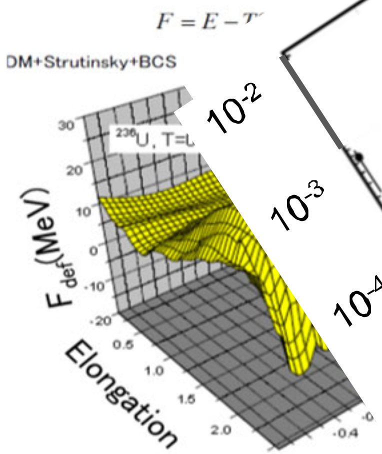
^{169}Er(n,γ)^{170}Er, ^{153}Sm(n,γ)^{154}Sm, ^{166}Dy(n,γ)^{167}Dy, ^{151}Pm(n,γ)^{152}Pm, ^{168}Ho(n,γ)^{169}Ho, ^{174}Tm(n,γ)^{175}Tm, ^{151}Nd(n,γ)^{152}Nd, ^{152}Pm(n,γ)^{153}Pm, ^{149}Nd(n,γ)^{150}Nd, ^{147}Nd(n,γ)^{148}Nd

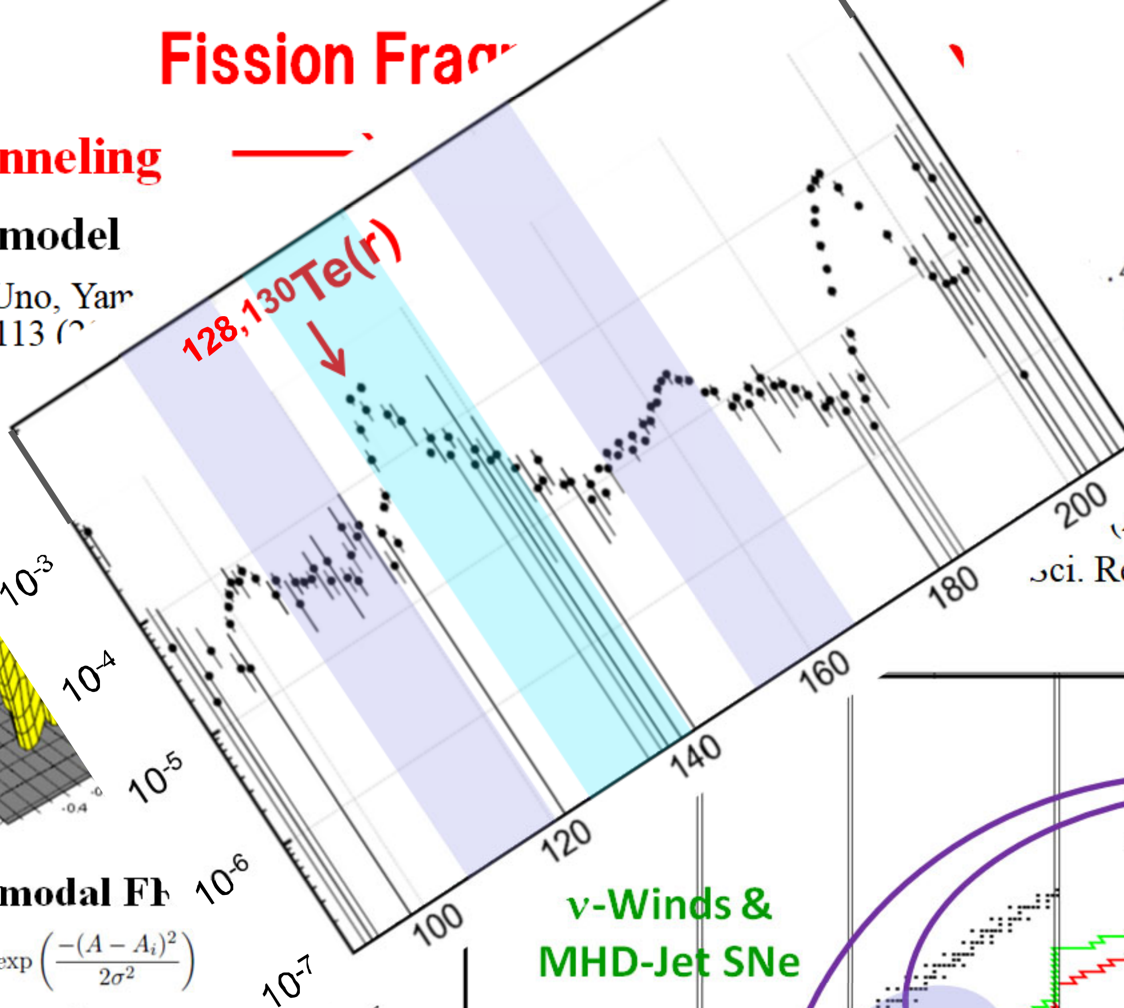
Fission Frag

Quantum Tunneling

KTUY - mass model

Koura, Tachibana, Uno, Yam
Prog. Theor. Phys. 113 (2





.4}={ZZ$_0$, α , δ$_L$, δ$_R$}

term   Wiener term

$^{-1})_{jk}p_k + g_{ij}R_j(t)$

(2018), 054331; Okumura
Sci. Reports, 9 (2019), 1525.

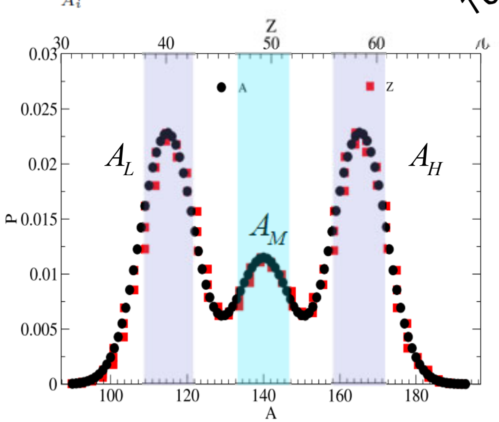
Bimordial or Trimodal FF

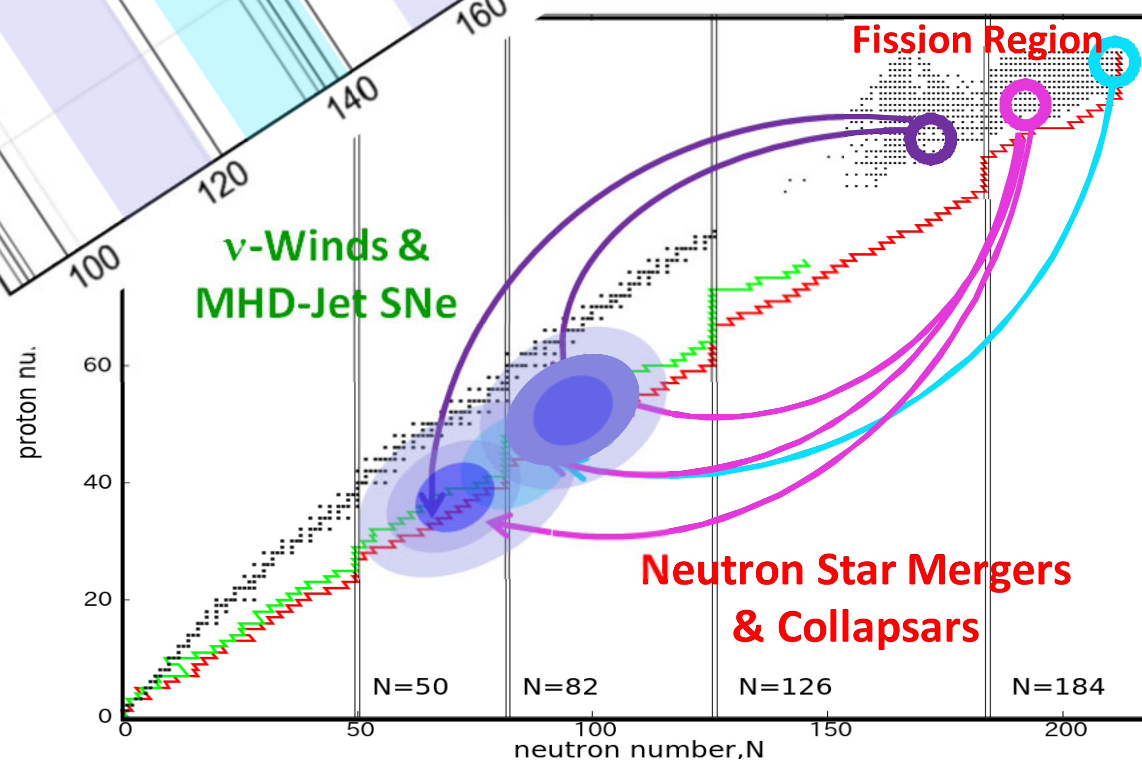
$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi\sigma}} W_i \exp\left(\frac{-(A-A_i)^2}{2\sigma^2}\right)$$

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

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

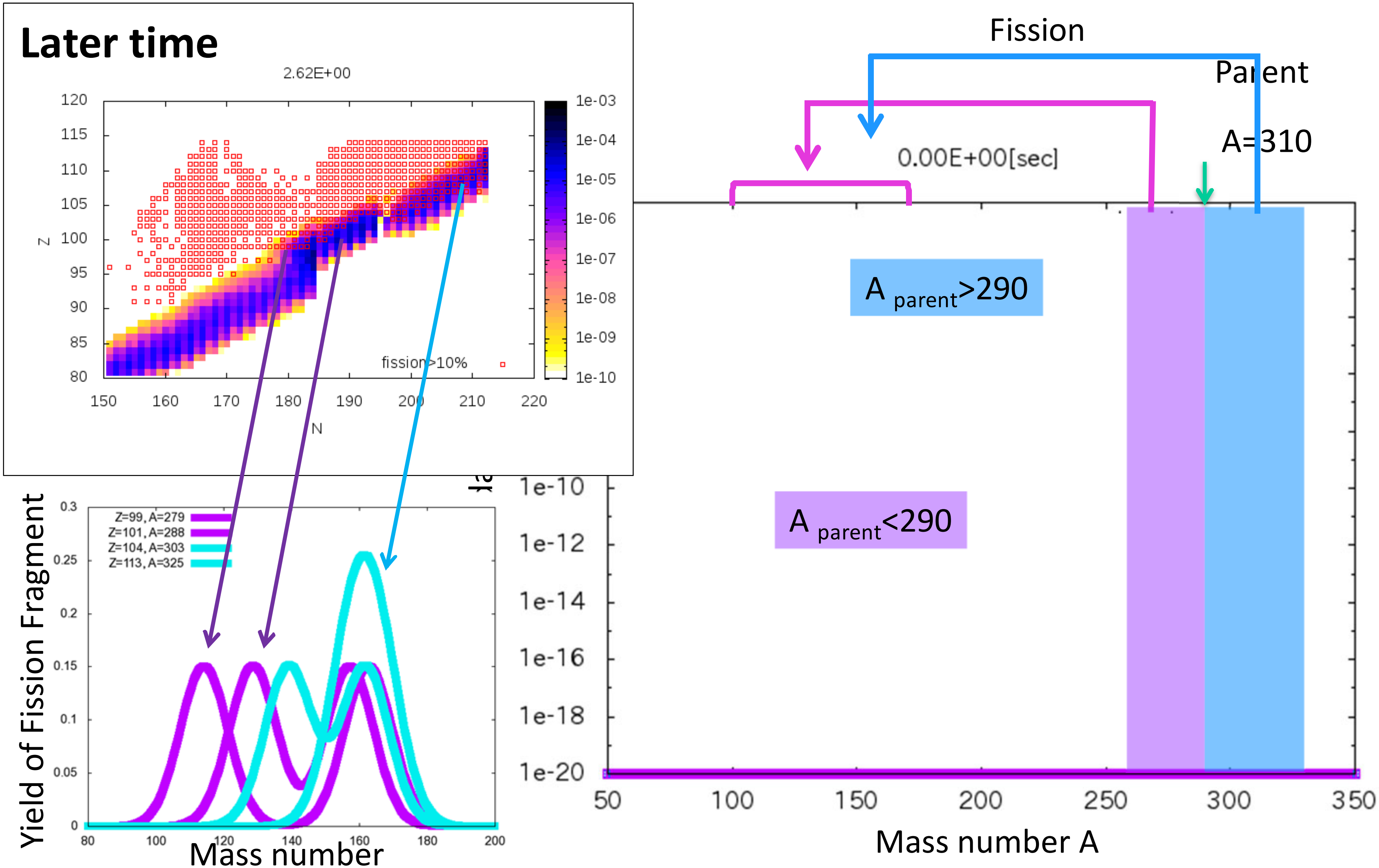
$A_M = (A_H + A_L)/2.$





Abundance Evolution of Fission Recycling

Collapsar Model: Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ 933 (2022), 112.



Nuclear Mass Models

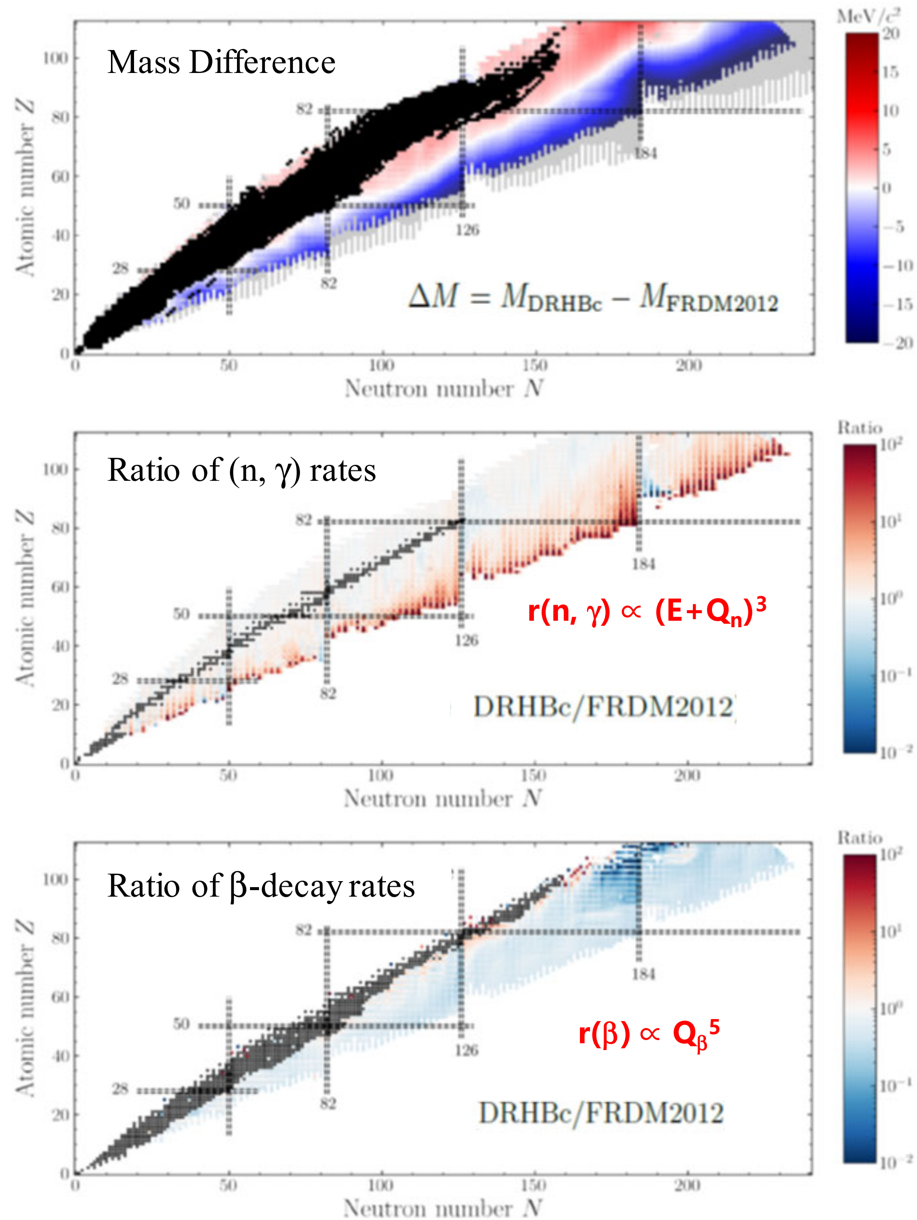
Choi, He, Kim, Kim, Kajino (2026), to be submitted.

Finite-Range Droplet Model (FRDM)

- Global nuclear mass model,
- Coupled macroscopic and microscopic theories.

Deformed Relativistic Hartree-Bogoliubov Theory in continuum (DRHBc)

- Axial deformation symmetry, considered,
- Meson-exchange interactions, included,
- Deformed relativistic Hartree-Bogoliubov eq. is solved in a Dirac Woods-Saxon basis,
- With contact interactions, applying to even-even, odd-*A*, and odd-odd nuclei.



Choi, Kim, He, Choi, Kim, Kajino,
Phys. Rev. C113 (2026), 024329,
Application to r-process with deep learning for nuclear masses in DRHBc.

Choi, He, kim, Kim, Kajino
Astrophys. J. (2026), to be submitted,
Application of DRHBc to r-process in MHDJ Supernova, Collapsar, and Neutron Star Merger.

TDDFT for Nuclear Fission/Fusion and Systematic DFT Calculations of Ground-state Properties

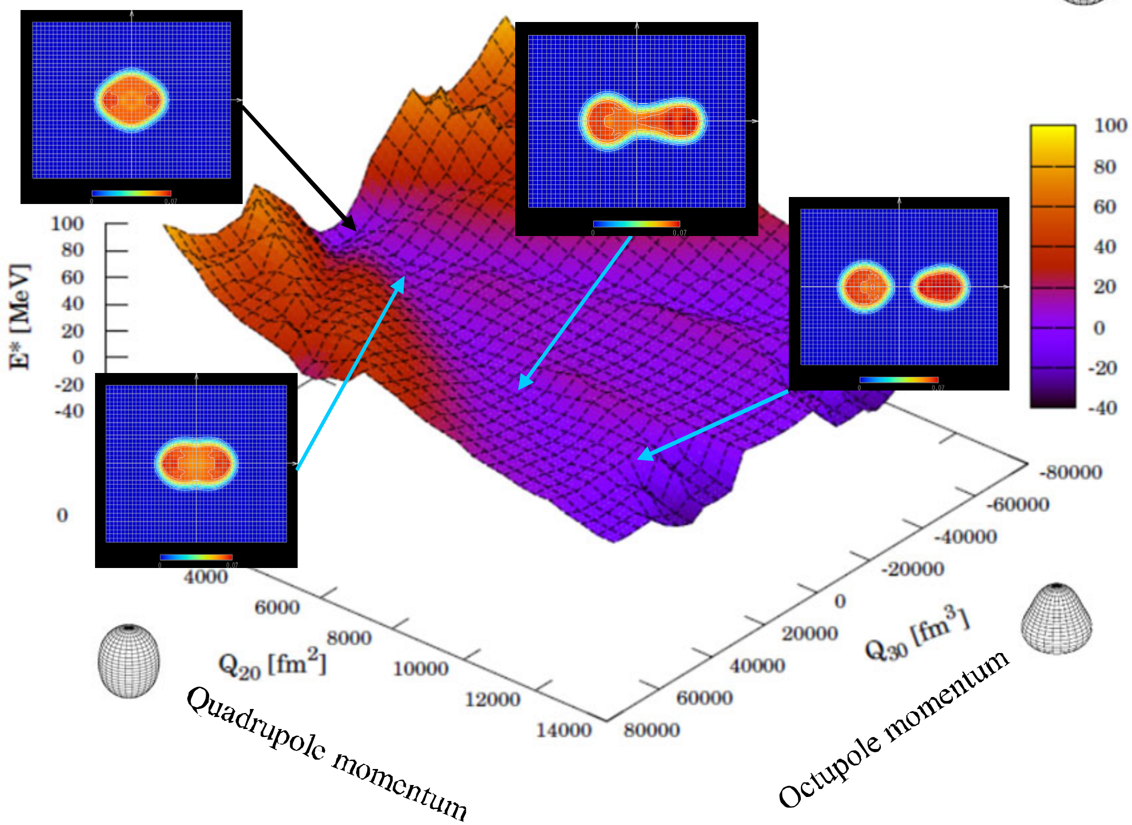
~ DFT applications on nuclear physics ~

Shuichiro Ebata (Saitama Univ.) & Takashi Nakatsukasa (Tsukuba Univ.)

S.Ebata, T.Nakatsukasa,
Phys. Scr. **92** (2017) 064005;
S. Ebata et al.,
Int. J. Mod. Phys. **E 32** (2023) 235003;
EPJ Web of Conf. **284** (2023) 04008

Large amplitude collective motion: Fission

Potential energy surface in Quadrupole-Octupole Collective space is obtained by the constraint 3D Skyrme HF+BCS (**Static calculation**).



About 60% nuclei are deformed!

- ✓ From the density distributions of fission fragments, their charge distributions are obtained.
- ✓ The charge distribution is important quantity to estimate neutron emission.
- ✓ The microscopic results can contribute to the nuclear engineering.

Courtesy from S. Ebata

TDDFT Results

Large amplitude collective motion: Fission

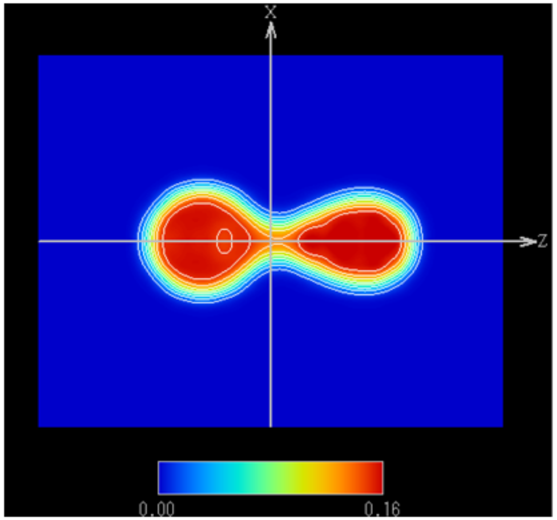
S. Ebata et al., Int. J. Mod. Phys. **E 32** (2023) 235003;
EPJ Web of Conf. **284** (2023) 04008.

Charge polarization(CP) of fission fragments (FFs)

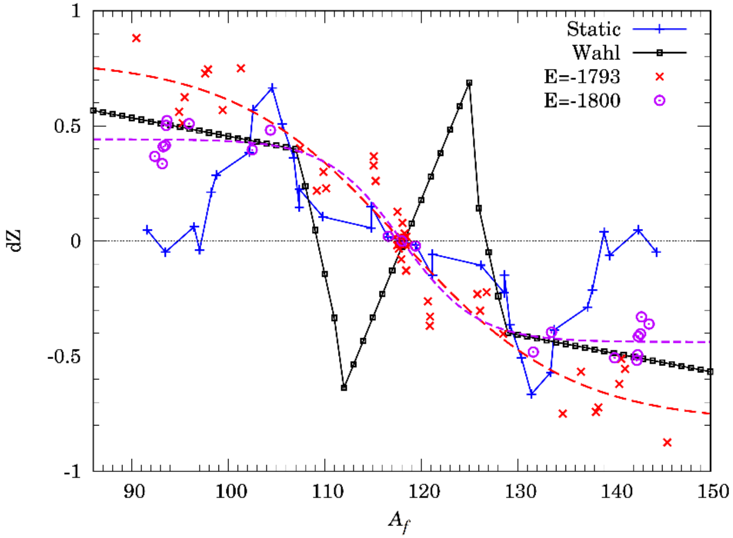
The distribution of atomic numbers in the FFs is an essential quantity to evaluate neutron emission from the FFs.

Prediction of the CP consistent with existing data is one of the reasons to justify the theoretical description of fission.

Time-evolution of nuclear density with the well deformed initial state.



Dynamic model calculation shows qualitatively consistent results with existing nuclear data.



Next stage is to connect the theoretical results to statistical decay calculations to confirm the neutron multiplicity of fission fragments.

Call for Systematic Prediction of FFD (TDDFT/TDGCM) for r-process!

Fission-Astrophys. Collab. Project, underway

TDDFT (S. Ebata) → Lengevin Simulation (Y. Aritomo) → r-process (T. Kajino)

Purpose

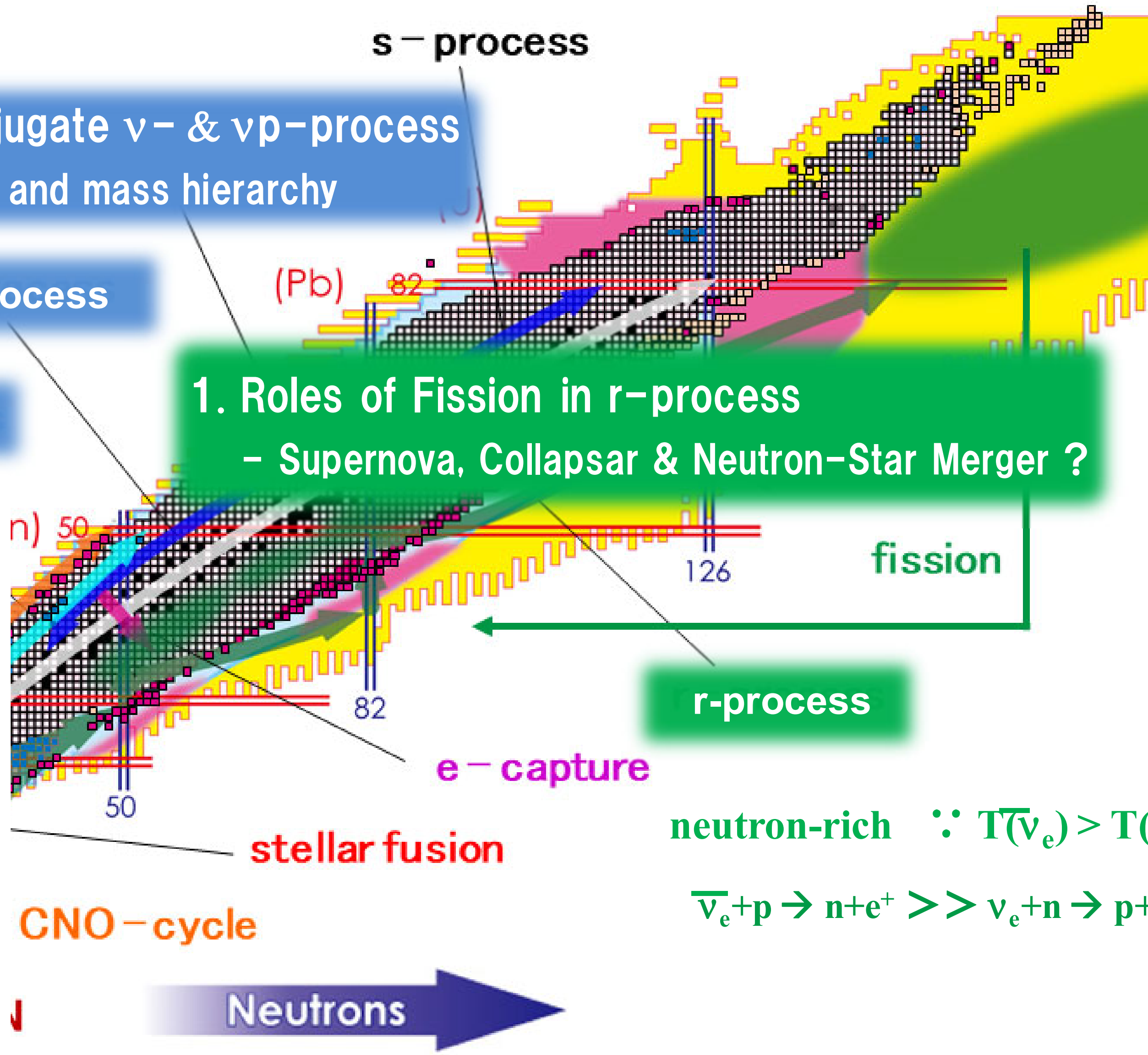
To elucidate the roles of Fission & νs in Explosive Nucleosynthesis

2. Roles of νs in conjugate ν− & νp−process
− ν flavor oscillation and mass hierarchy

ν-process

νp-process

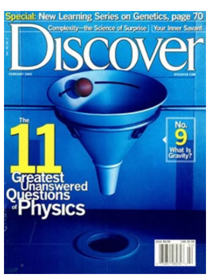
1. Roles of Fission in r−process
− Supernova, Collapsar & Neutron−Star Merger ?



neutron-rich ∵ $T(\bar{\nu}_e) > T(\nu_e)$

$\bar{\nu}_e + p \rightarrow n + e^+ \gg \nu_e + n \rightarrow p + e^-$

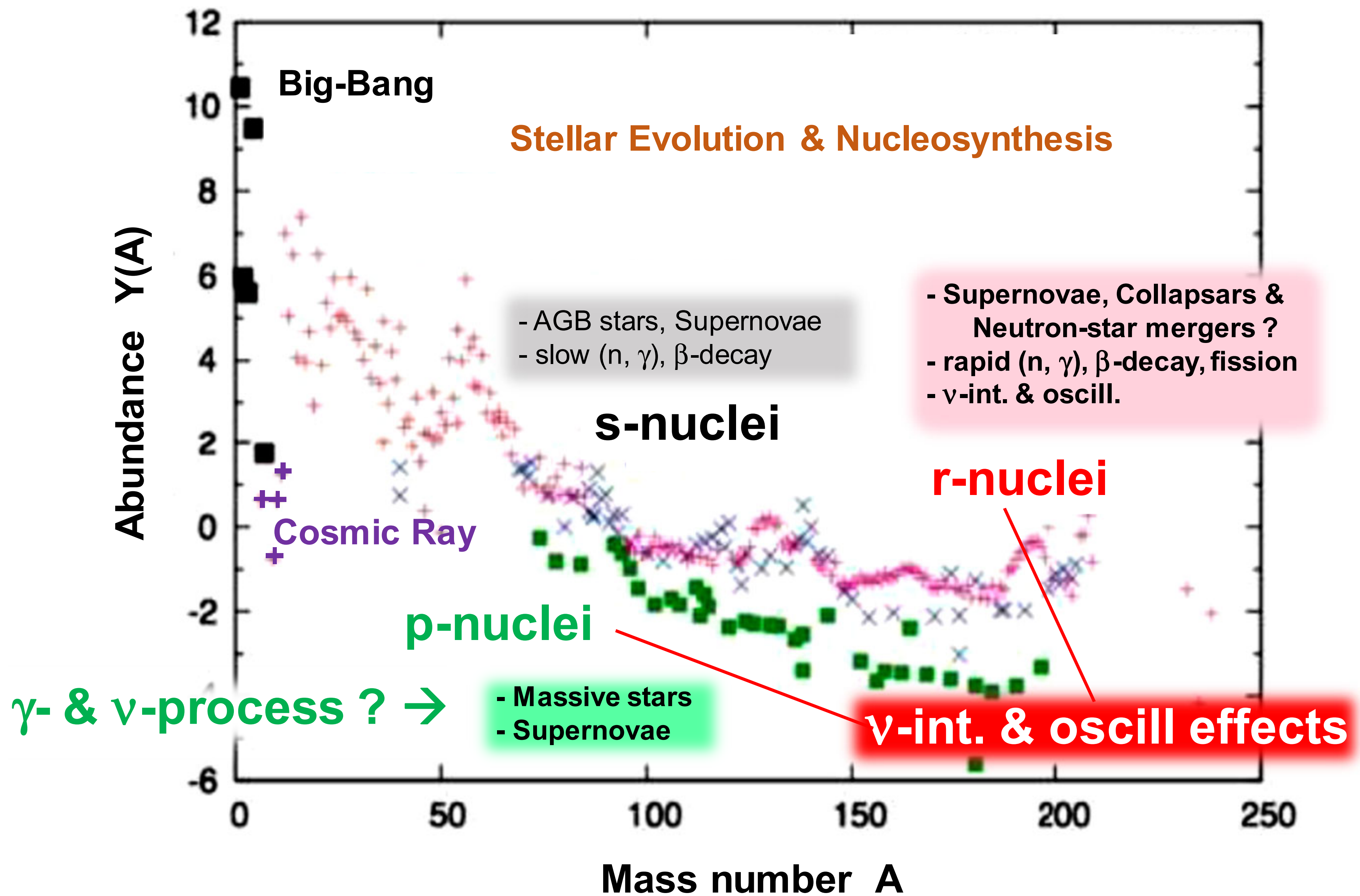
The 11 Greatest Unanswered Questions in Physics !



- What is the origin of Uranium ?
- Why do neutrinos have mass ?

The National Research Council's Board on Physics, USA (2002)

Solar-system Abundances



Origin of ^{92,94}Mo ^{96,98}Mo ?
Very abundant p-nuclei

■ Other p-nuclei ～ Isotopic fract. = 0.1 - 1%

Origin is SN γ-process !

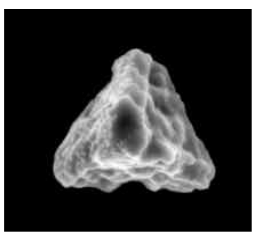
Isotopic fraction in %

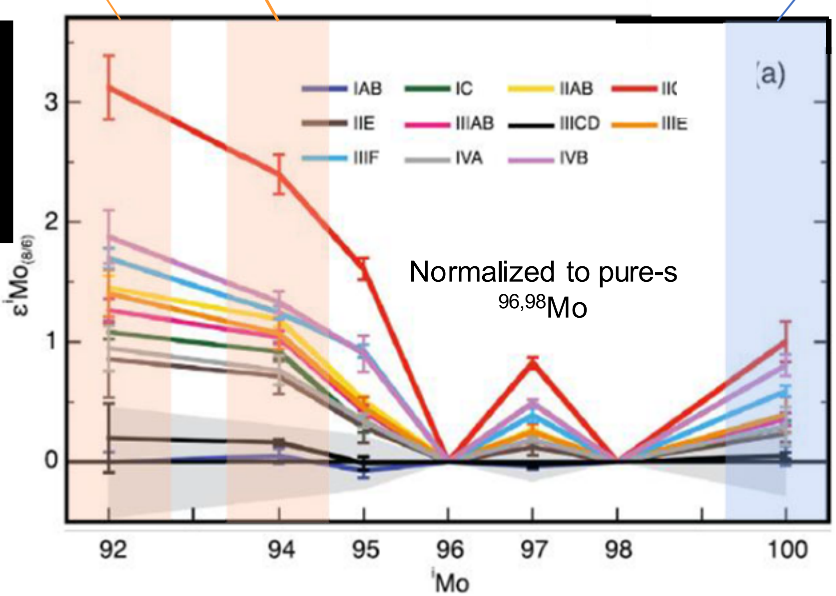
^{92}Mo	^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
14.53	9.15	15.84	16.67	9.6	24.39	9.82
100	99.1	0	0	0	0	0
0	0.9	69.6	100 (over)	63.7	82.2	4.5
0	0	30.4	0	36.3	17.8	95.5

Bisterzo et al., MNRAS 418, 284 (2011); ApJ. 787, 10 (2014).

Red = p-process
Green = s-process
Blue = r-process

Isotopic Anomaly





Mo isotopes

Poole, EPSL, 473, 215 (2017).

Correlated Anomaly in Meteorites between ^{92,94}Mo & ^{100}Mo

pure-p　pure-r

Origin in the same astrophysical site.

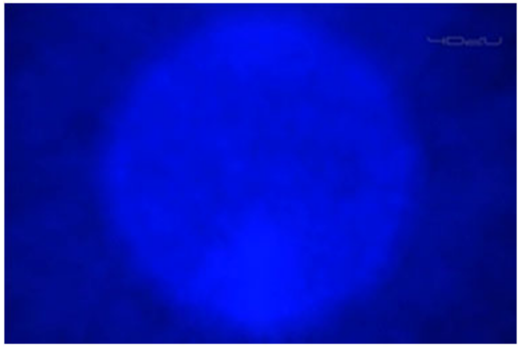
Hypernova/Collapsar

Sasaki, Yamazaki, Kajino et al., PL B851 (2024) 138581.

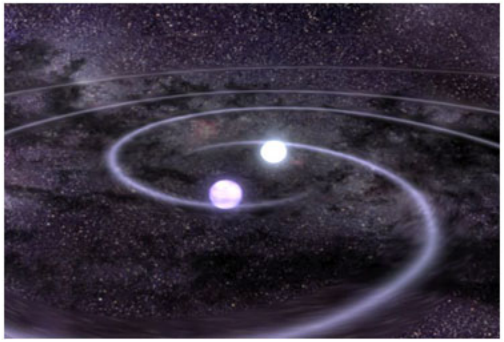
Can correlated anomaly between r-nuclei & ν-nuclei be seen in Neutron-Star-Merger ?

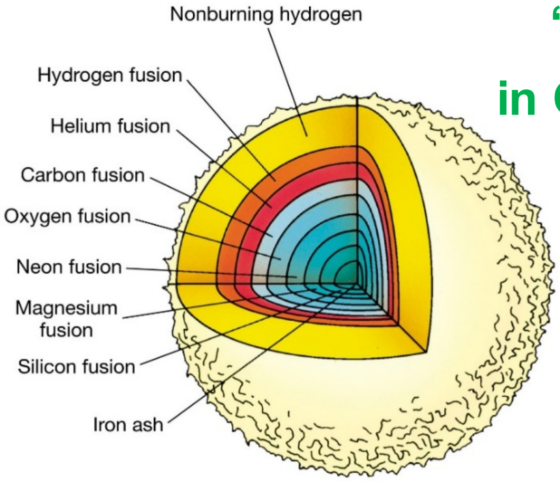
Single Massive Stars (SNe, HNe, Collapsars)

Neutron-Star Mergers



"r-process" in both Dynamical Ejecta





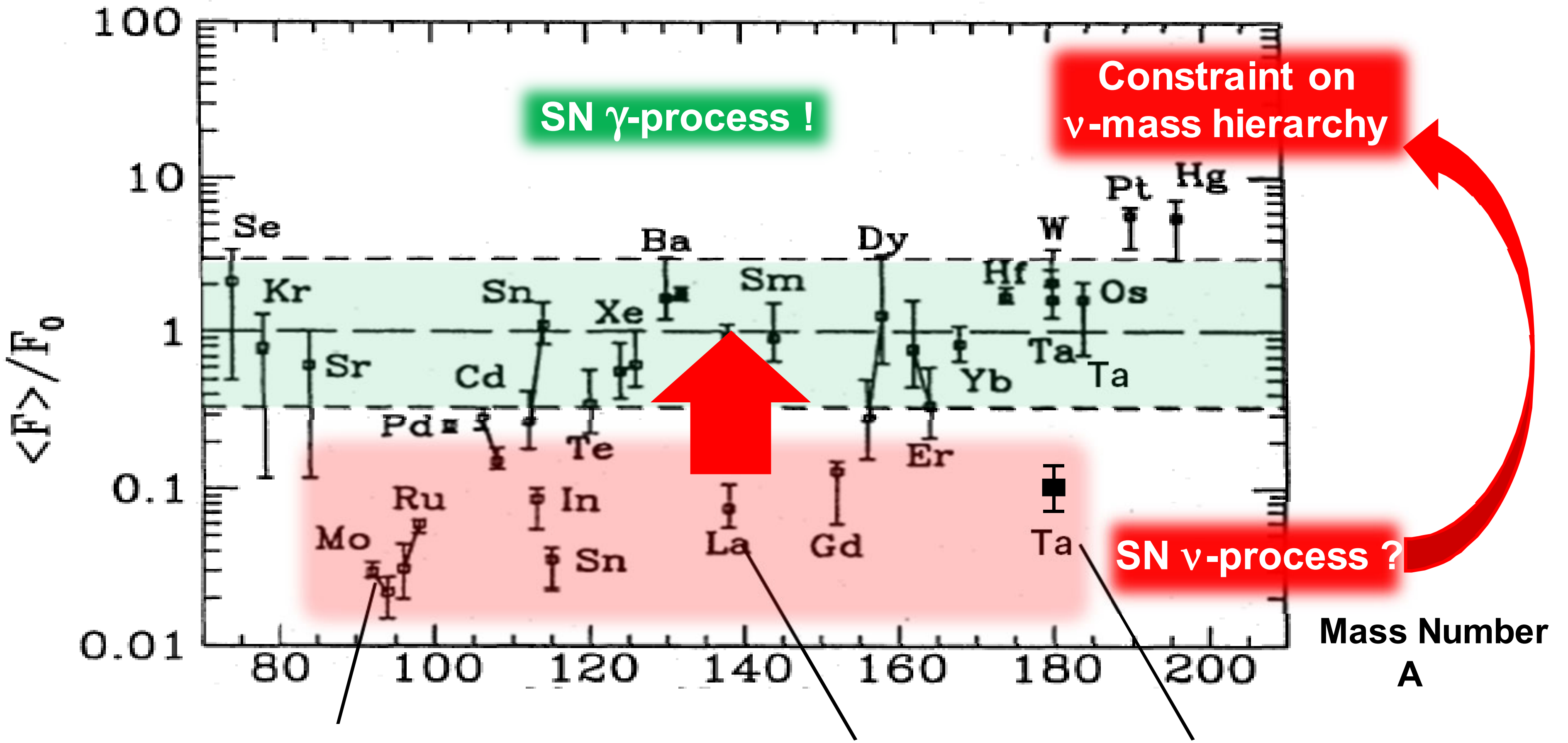
"ν-rocess" in Outer Layers

NO !

Origin of p-nuclei (n-deficient side) → γ-process ?

Rare isotopes

Rayet, M., Arnould, M., Hashimoto, M., Prantzos, N., Nomoto, A. & Ap. **298** (1995), 517.
M. Arnould Stephane Goriely, Phys. Rep. **384** (2003) 1–84.



^{92,94}Mo, ^{96,98}Ru

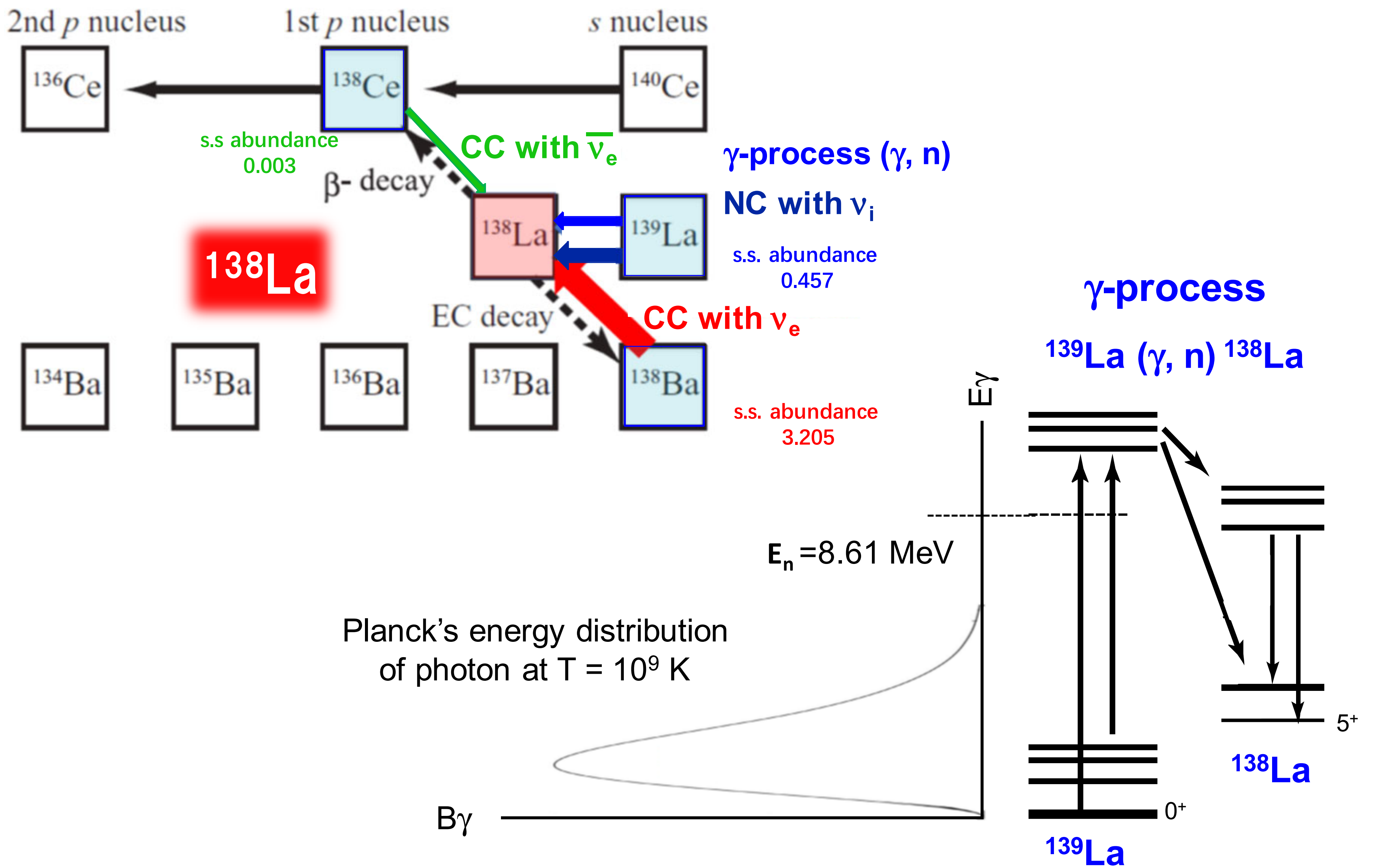
^{138}La ^{139}La
0.089% 99.91%

^{180}Ta ^{181}Ta
0.012% 99.988%

Why $^{138}Ba(\nu, e^-)^{138}La$ dominates over $^{139}La(\gamma, n)^{138}La$?

Weak - process

EM - process

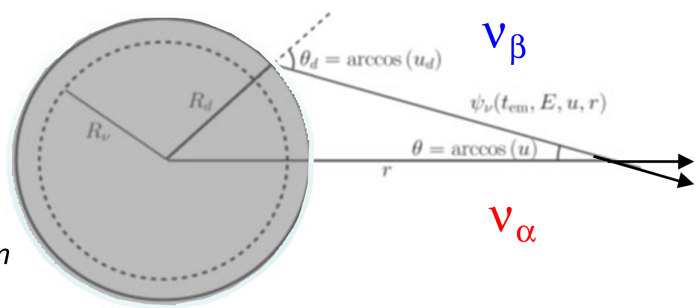


ν-flavor Oscill. due to MSW + νν-Quantum Coll. Many-Body Effect

Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011; PR D98 (2018), 083002; Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101; Fogli, Lisi, Marrone & Mirizzi, JCAP 12 (2007) 010; Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin, Pehlivan, PR D96 (2017), 043013; Yao, Kajino, Luo et al. (2025), ApJ 980, 247.

proto-Neutron Star

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



ν-sphere ~20km

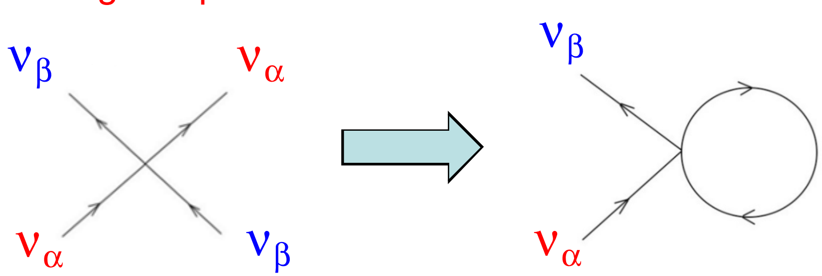
GWS standard model

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

Collective flavor oscillation in coherent ν-ν scattering

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

ν angle dep !



10^{58} ν's with 3-flavors & multi-angles !

Mean Field Approx.

Unified Electroweak Theory
Nobel Prize 1979

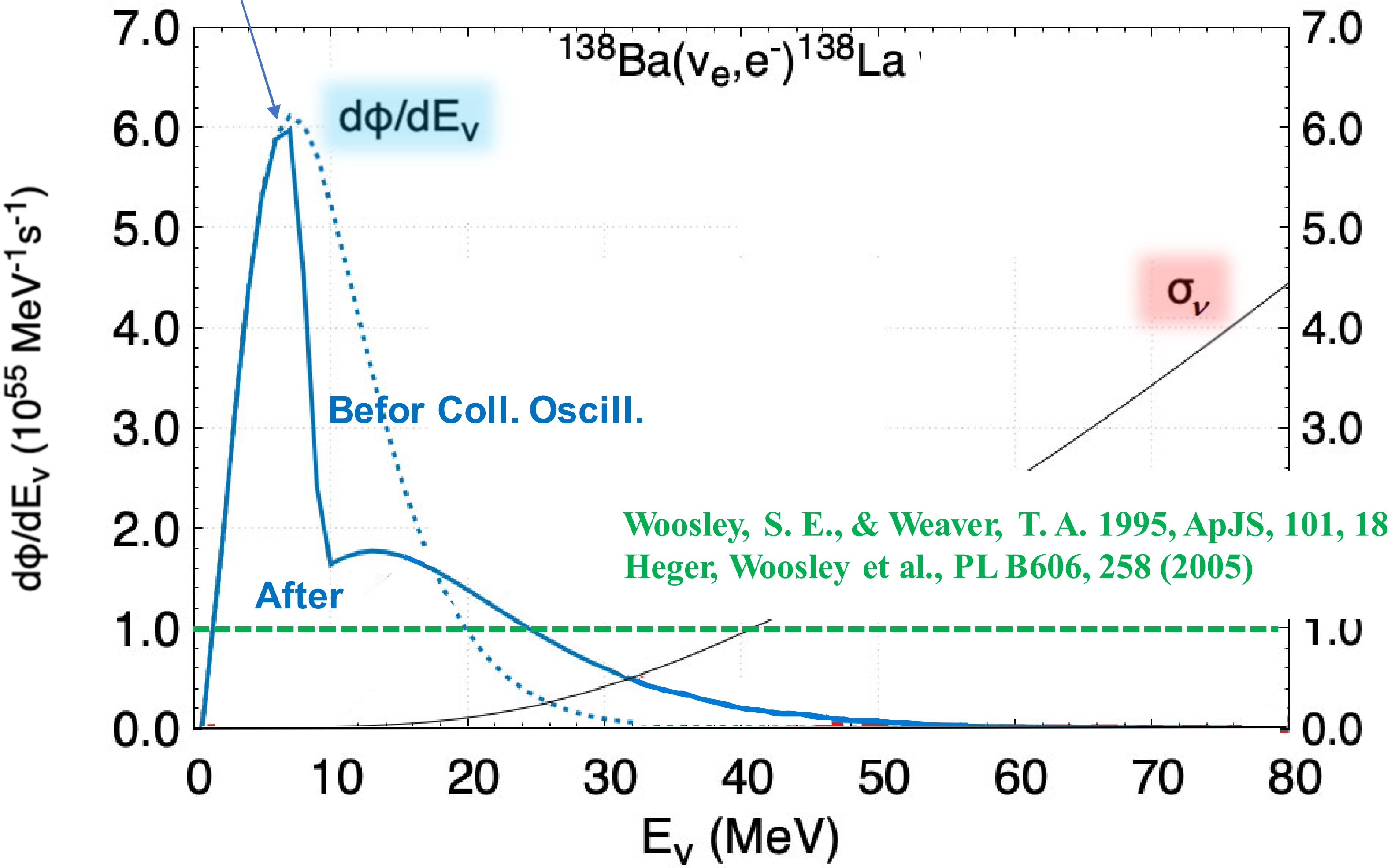
Steven Weinberg   Sheldon Glashow   Abdus Salam

$^{138}Ba(\nu_e, e^-)^{138}La$

Yao, Kajino, Luo et al. (2025), ApJ 980, 247;
Yao, Luo, Kajino, Hayakawa, Yamaguchi, Tang, Gao, Liu (2025), CPC 49, 084003.

ν-Energy Spectral Change due to Collective Oscill. (Mean-field approx.)

Inverted case



Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181;
Heger, Woosley et al., PL B606, 258 (2005)

$^{138}Ba(\nu_e, e^-)^{138}La$

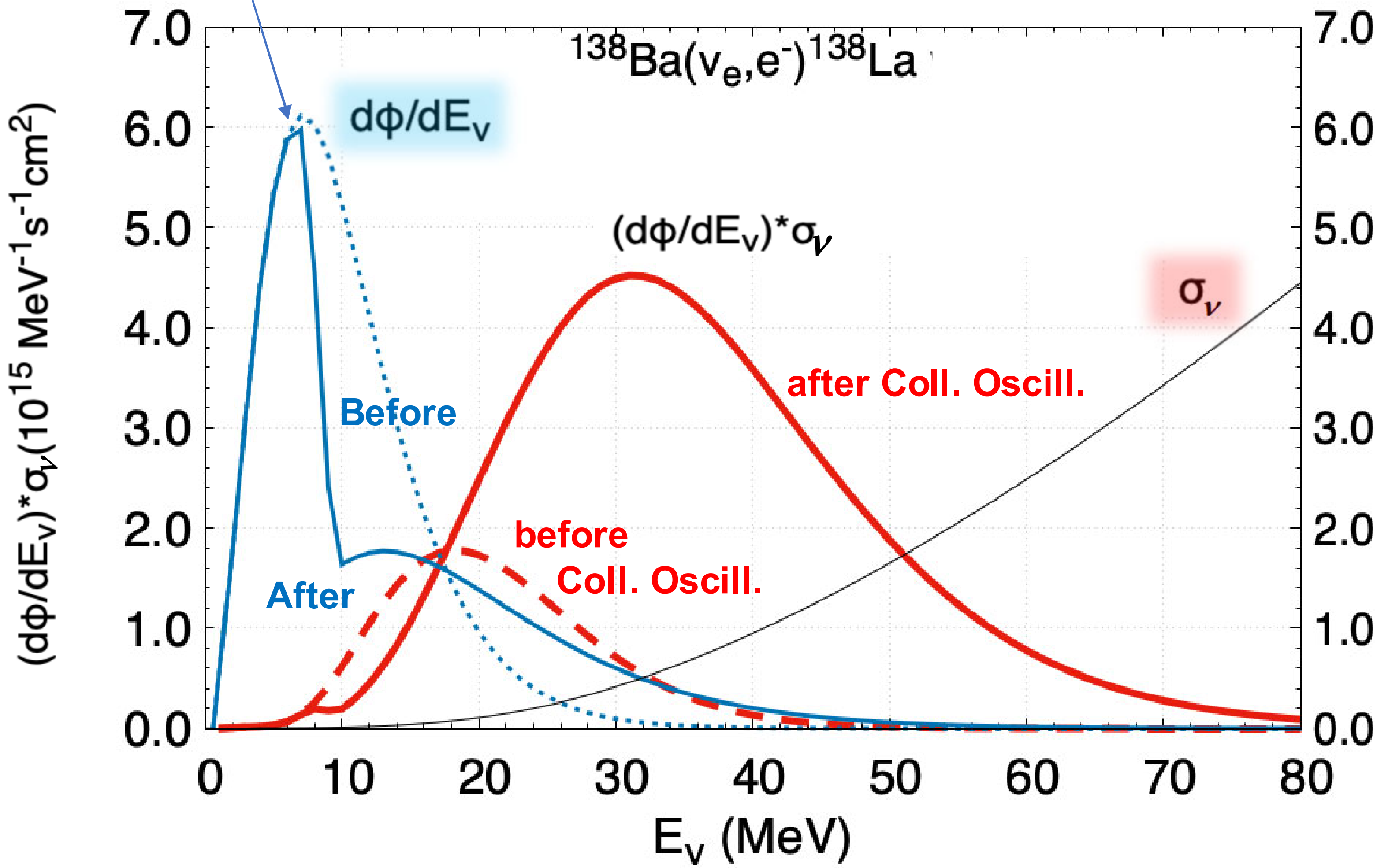
$$dn_{^{138}La}/dt = \langle d\phi_\nu/dE_\nu \, \sigma_\nu c \rangle_R \, n_{^{138}Ba}$$

$d\phi_\nu/dE_\nu \propto$ ν–spectrum

$\sigma_\nu \propto E_\nu^{\,2}$

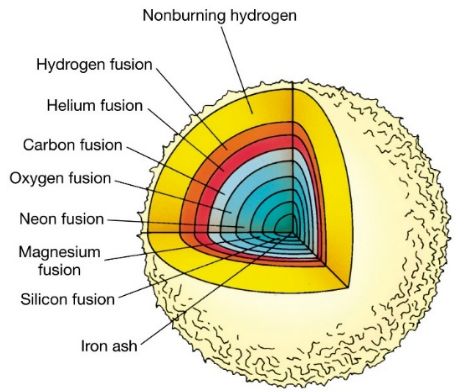
ν-Energy Spectral Change due to Collective Oscill. (Mean-field approx.)

Inverted



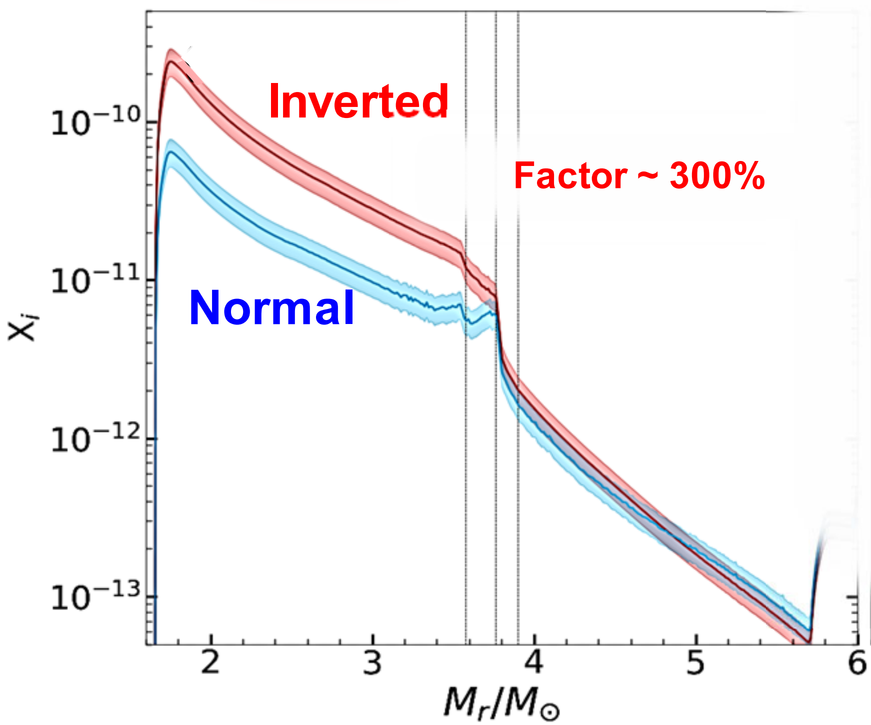
Calculated Result

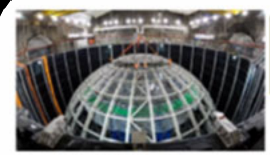
Yao, Kajino, Luo et al. (2025), ApJ 980, 247.
Yao, Luo, Kajino, Hayakawa, Yamaguchi, Tang, Gao, Liu (2025), CPC 49, 084003.



Difference between normal and inverted hierarchy in ^{138}La is more than **factor of 3 (> 300%)!**

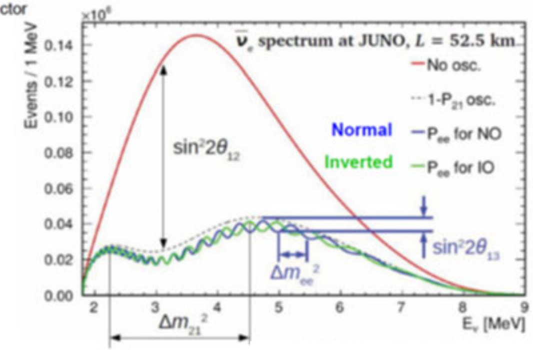
^{138}La





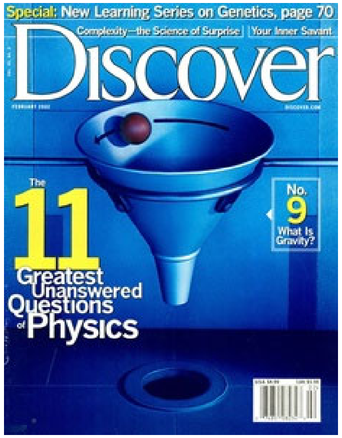
Jiangmen Underground Neutrino Observatory (JUNO) http://juno.ihep.cas.

JUNO ν-detector



JUNO
±3% (4σ) C.L. — 5 years

11 Unsolved Mysteries of Physics in the 21st Century



US Academy of Science selected 11 greatest unanswered questions in modern physics:

Q3 How were the heavy elements made?

Q4 Why do neutrinos have mass?

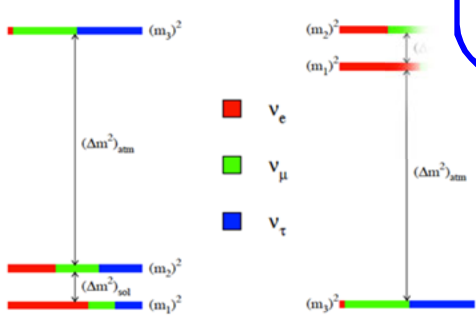
Finite ν-mass, the only unique evidence to go "beyond the standard model".

Why Neutrinos and Element Genesis?

(1) ~~Mass,~~ (2) Hierarchy, (3) ~~δ_{CP}~~ Di

?

~ 0.05 eV



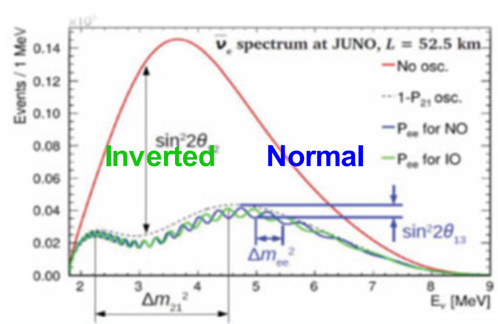
$\Delta m^2_{12} = 7.9 \times 10^{-5} eV^2$

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

Any observables in flavor oscillations do not depend on δ_{CP} when

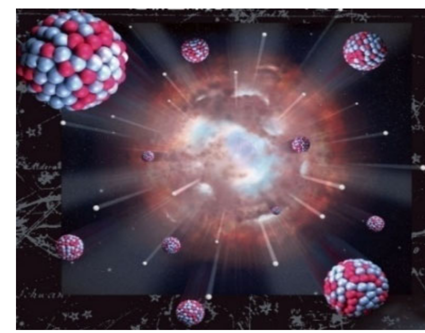
$E\nu_e < E\bar{\nu}_e < E\nu_\mu, \bar{\nu}_\mu = E\nu_\tau, \bar{\nu}_\tau$.

(Yokomakura et al., Phys. Lett. B544, 286)



< a few % precision is required!

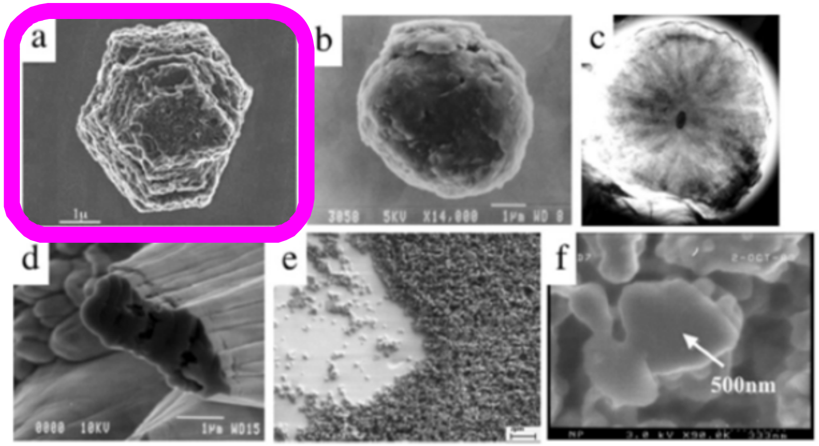
ν-oscillations at high density



Supernova : $E\nu_e < E\bar{\nu}_e < E\nu_\mu = E\nu_\tau$

Factor ~ 3 (300%) sensitivity !

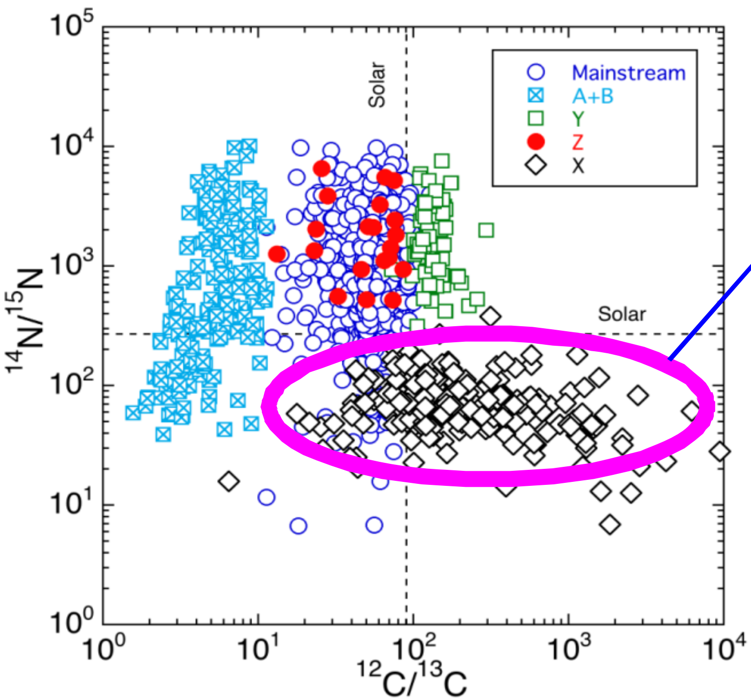
Nucleosynthesis constrains ν-Hierarchy with SUPERNOVA Grains



Pre-solar dust grains scanning e-micrographs

E. Zinner (2008), **Meteorite** Scientist

(a) Silicon-carbide
(b) Graphite,
(c) Graphite slice with inner TiC grain,
(d) Aluminum oxide, (e) Spinel, (f) Silicate



Characteristics of SiC X-Grains

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar)
- Enhanced ^{28}Si ($^{28}Si/^{29,30}Si$ > Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)

Probe of SN ν−Flavor Oscillations

MSW effect:

Mathews, Kajino, Aoki & Fujiya, PR D85, 105023 (2012),
Kajino, Mathews, Hayakawa, J. Phys. G41 (2014), 044007

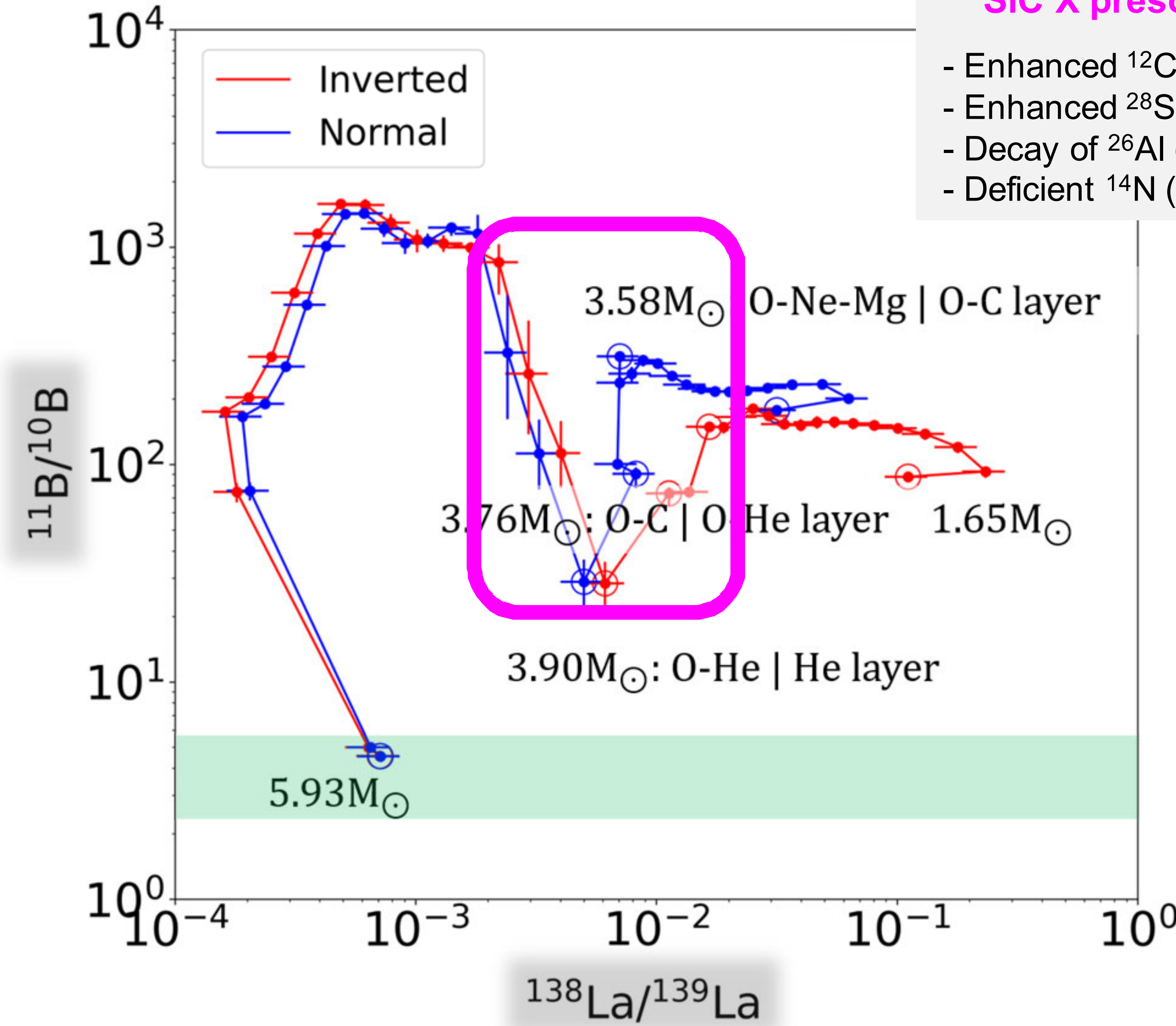
Collective + MSW effects:

Yao, Kajino, Luo, et al., ApJ 980, 247 (2025)

Obs. Test — SN grain (SiC X)

Yao, Kajino, Luo et al. (2025), ApJ 980, 247.
Yao, Luo, Kajino et al. (2025), CPC 49, v9.
Luo, He, Kajino et al. (2026), to be submit.

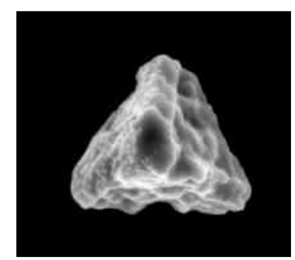
Isotopic Correlation $^{138}La/^{139}La$ vs. $^{11}B/^{10}B$



SiC X presolar grains → SN grain

- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar)
- Enhanced ^{28}Si ($^{28}Si/^{29,30}Si$ > Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)

SiC-X grains (SN grains), largely mixed with ISM (~ solar composition)



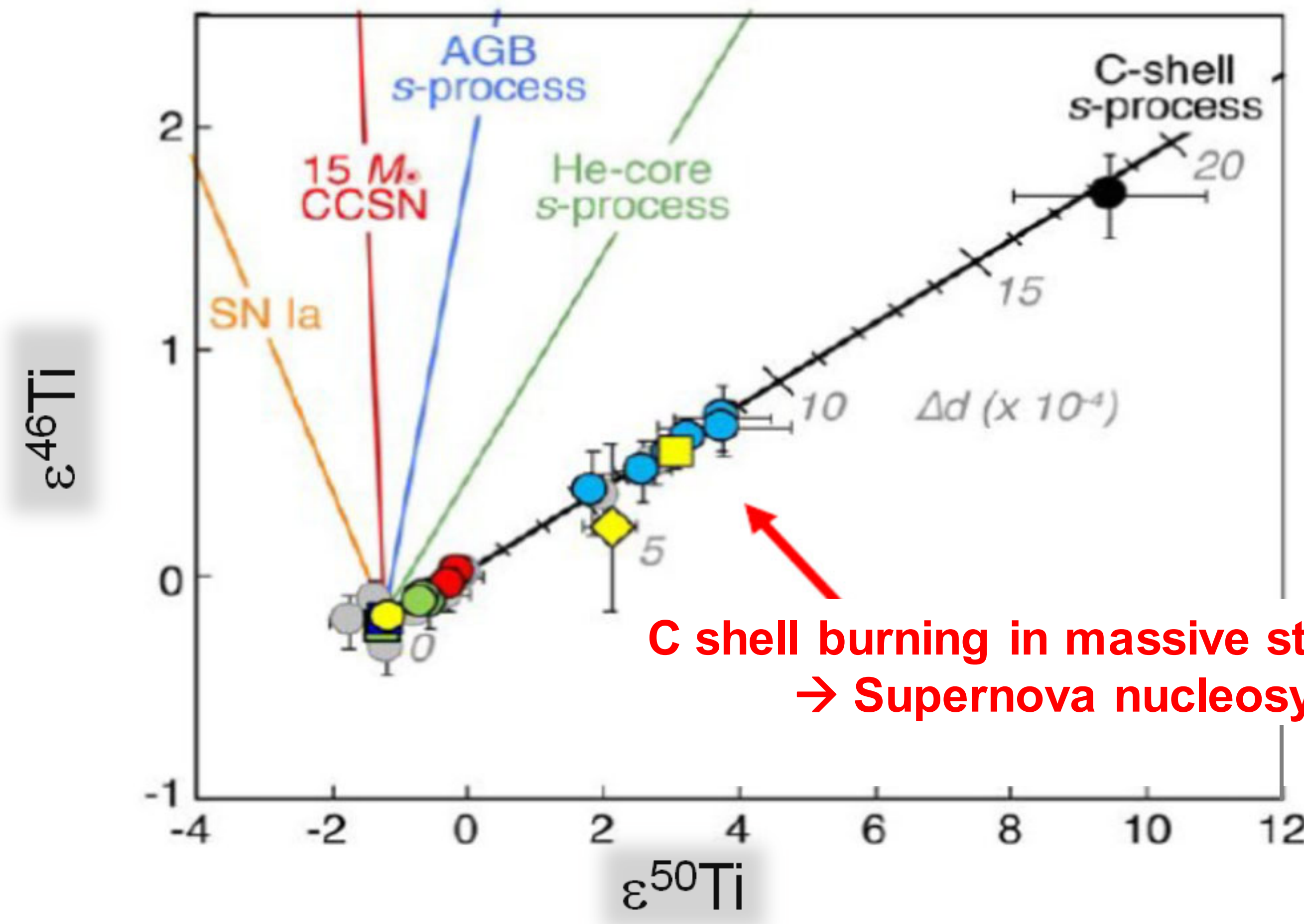
Fujiya, Hoppe, Ott, ApJ 730 (2011), L7; Hoppe, Lodders, Strebel, et al., ApJ 551 (2001), 478.

Obs. Test No. 2 — CAIs

Luo, Yao, Kajino, Hayakawa, et al. (2026), to be submitted.

δTi - δLa Correlation in Ca-Al rich Inclusions (CAIs)

T. Iizuka, et al. ApJL 979 (2025), L29.

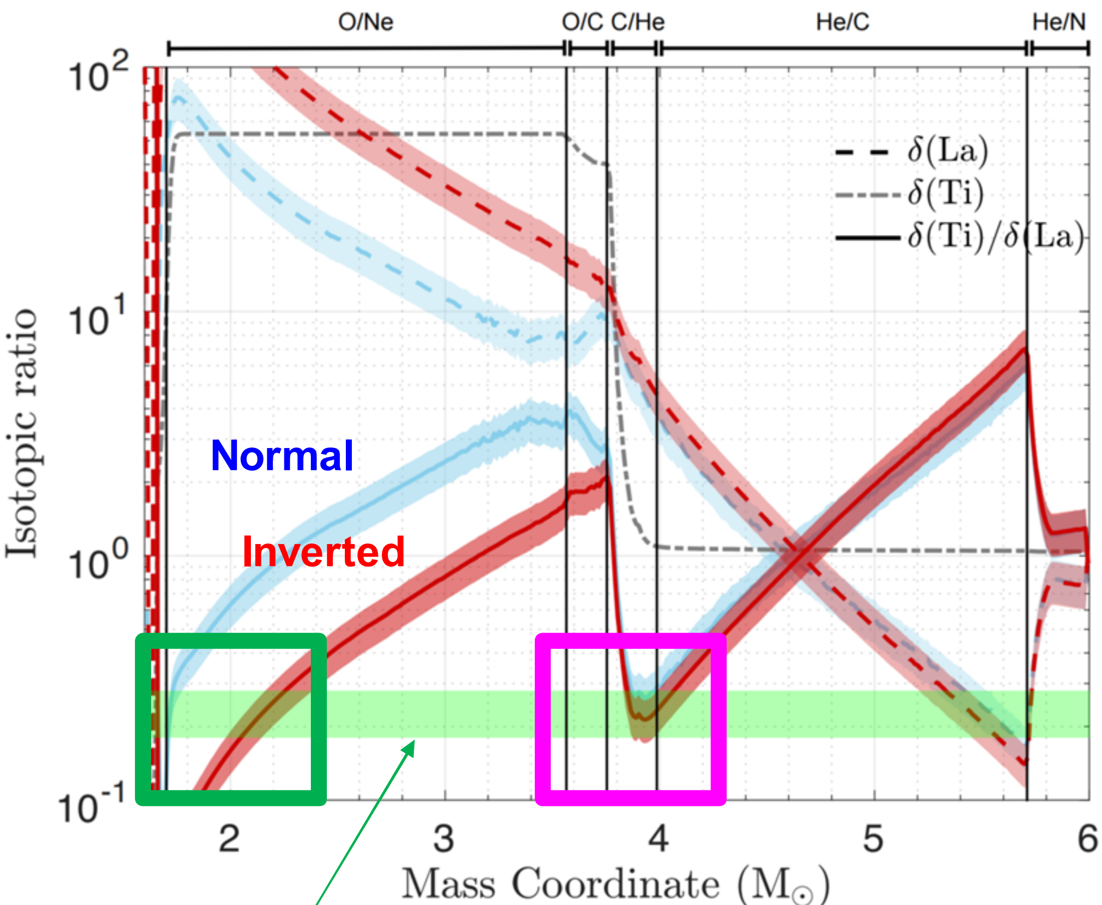


C shell burning in massive stars
→ Supernova nucleosynthesis

Calculated δTi - δLa correlation

Luo, Yao, Kajino, Hayakawa, et al. (2026), to be submitted.

Comparison between measurement and model



Constraint from measured CAIs

$$\delta(Ti) \equiv f(Ti)\,\frac{(^{50}Ti/^{48}Ti)_{SN}}{(^{50}Ti/^{48}Ti)_{\odot}}$$

$$f(Ti) = \frac{X_{SN}(Ti)\cdot m_{eject}}{X_{CAI}(Ti)_{CAI}\cdot m_{CAI}}$$

$$\delta(La) \equiv f(La)\,\frac{(^{138}La/^{139}La)_{SN}}{(^{138}La/^{139}La)_{\odot}}$$

$\delta(Ti)/\delta(La)$ under normal and inverted hierarchies

Green band is the coefficient of correlation.

Summary

1. Cosmic & Galactic Chem. Evolution

- **Single Massive Stars (MHDJ SNe & Collapsars)** dominate r-process over the cosmic evolution, while **NSMs** come later. → **More astronomical observations, required.**

2. Origin of r-process Nuclei and Roles of Fission

- **Fission** takes the key in different **A-distribution among** MHDJ SN, Collapsars, and NSMs.
  → **Fission Fragment Distribution, required !**
  → **Consistency with Mass Model (DDFT), desirable !**
- **r-, i- and s-processes can coexist in Collapsar nucleosynthesis.**
  → **Fission neutrons and (n, γ) rates, required !**

Collaboration between Fission Physics and Astrophys., highly desirable !

3. Origin of ν-process Nuclei

- **SN ν/νp-process** could be a sensitive probe to **constrain still unknown ν-mass hierarchy**.
  → **Meteoritic anomaly search, required!**
  → **Nuclear-weak & (n, p) rates (GT + forbidden), required !**