Workshop on “The r-process and the nuclear EOS after LIGO’s third observing run” (INT 20R-1b), May 23-27, 2022

R-process in GW Objects, Supernovae, Collapsars & Neutron Star Mergers, and Galactic Chemo-dynamical Evolution

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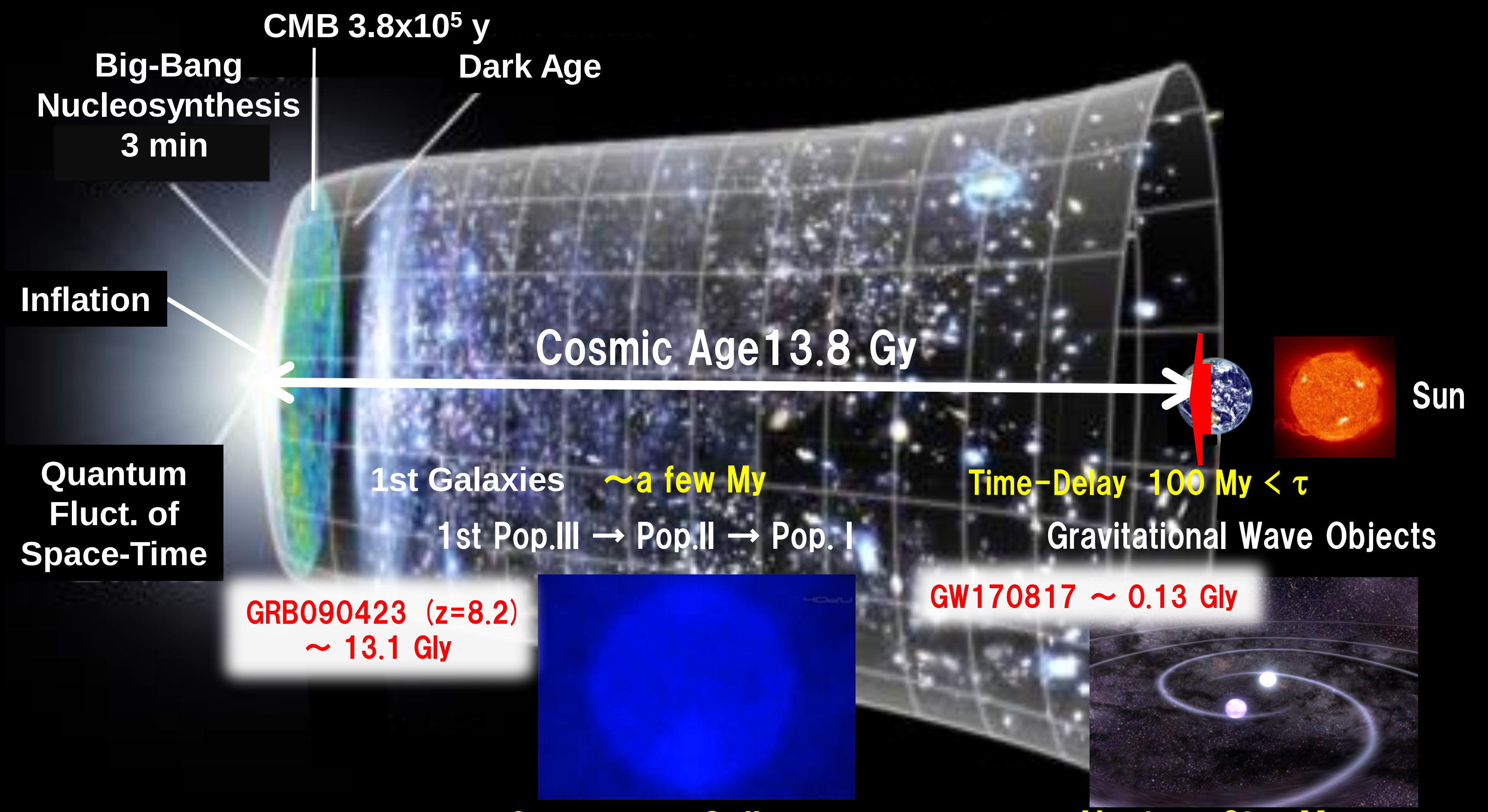
Origin of Heavy Nuclei in Cosmic & Galactic Evolution



CMB 3.8×10^5 y

Big-Bang Nucleosynthesis
3 min

Dark Age

Inflation

Quantum
Fluct. of
Space-Time

Cosmic Age 13.8 Gy

Sun

1st Galaxies ～a few My

1st Pop.III → Pop.II → Pop. I

Time-Delay 100 My < τ

Gravitational Wave Objects

GRB090423（z=8.2）
～ 13.1 Gly

GW170817 ～ 0.13 Gly

Supernova, Collapsar

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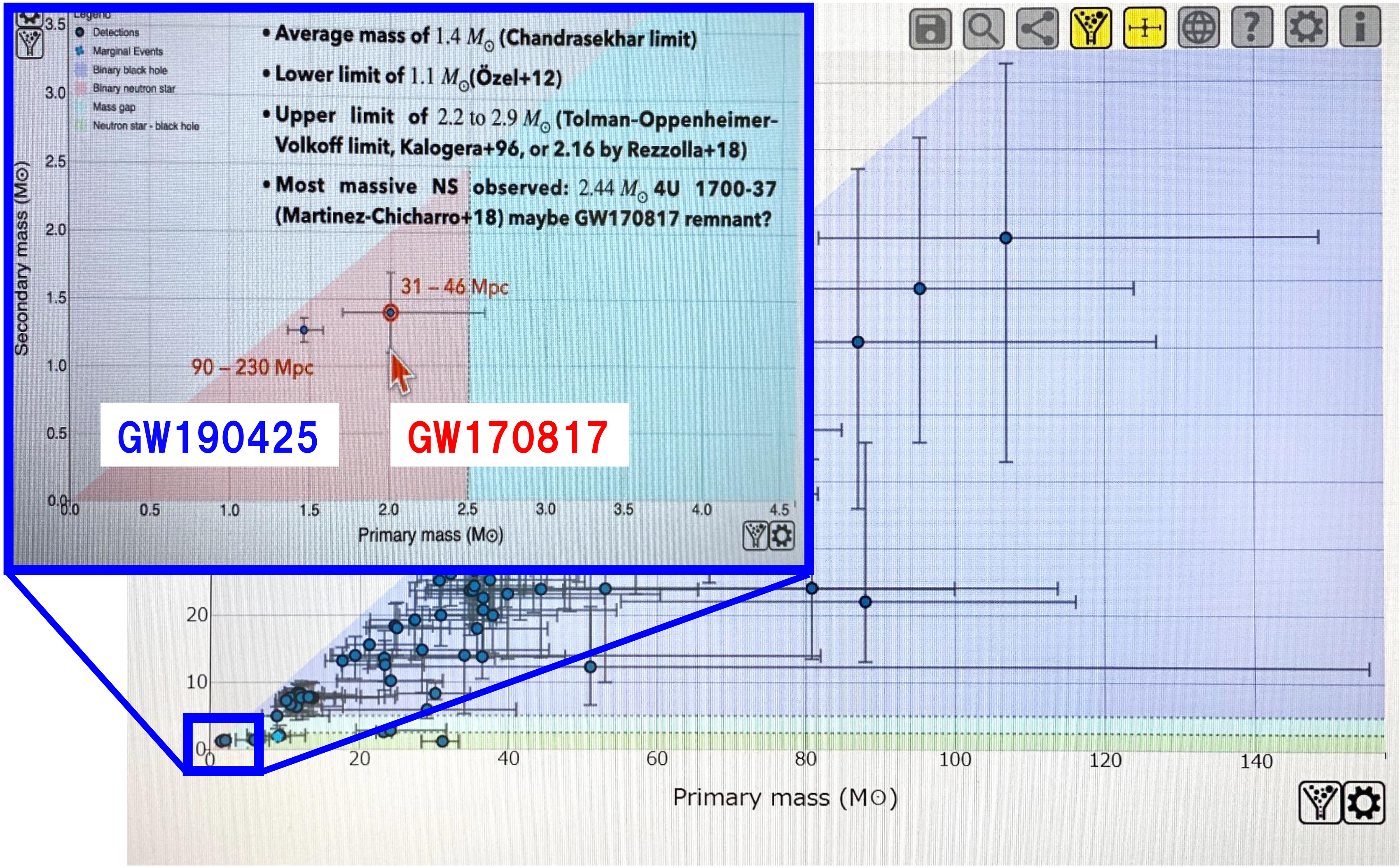
Neutron Star Merger

©NASA

LIGO-Virgo Compact Binary Catalogue



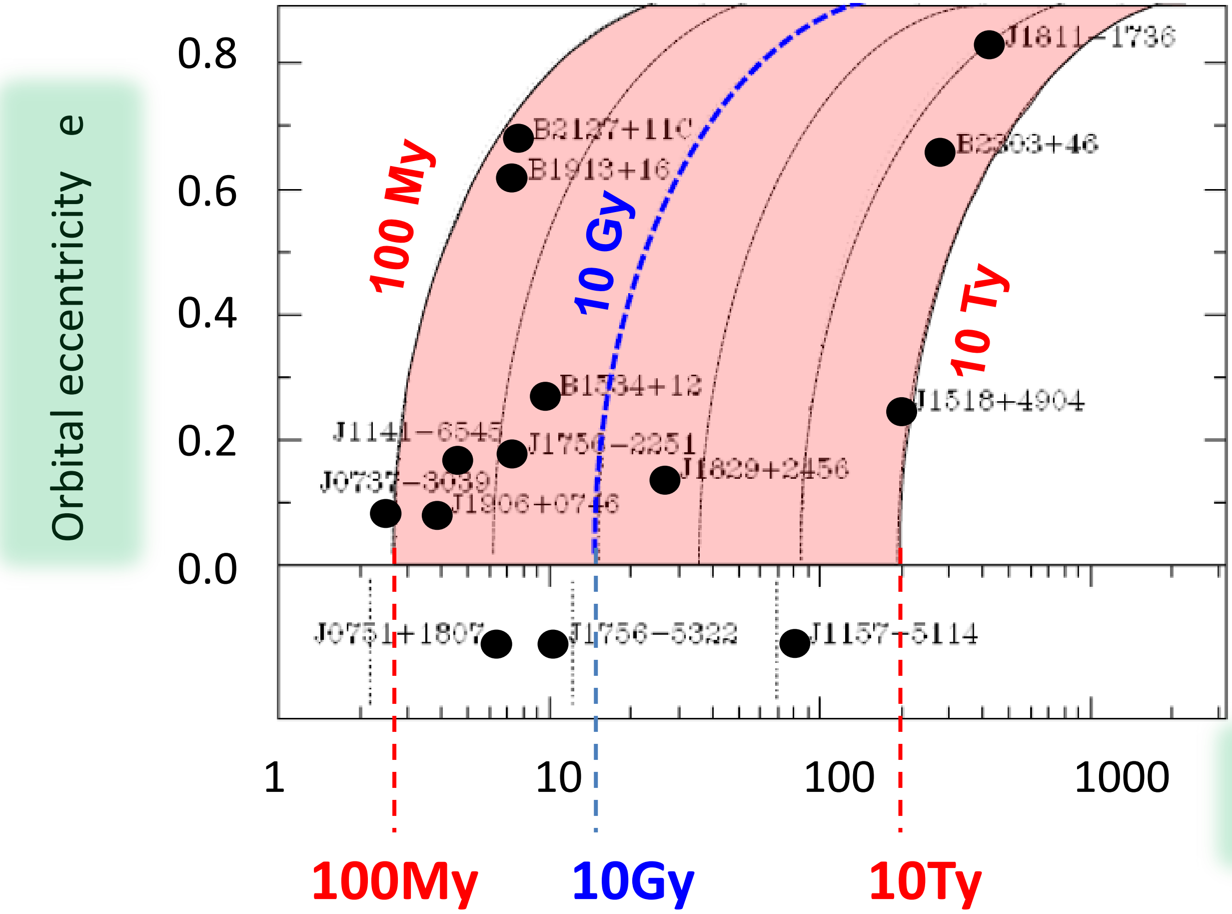
- Average mass of $1.4\ M_\odot$ (Chandrasekhar limit)
- Lower limit of $1.1\ M_\odot$(Özel+12)
- Upper limit of 2.2 to $2.9\ M_\odot$ (Tolman-Oppenheimer-Volkoff limit, Kalogera+96, or 2.16 by Rezzolla+18)
- Most massive NS observed: $2.44\ M_\odot$ 4U 1700-37 (Martinez-Chicharro+18) maybe GW170817 remnant?

https://catalog.cardiffgravity.org

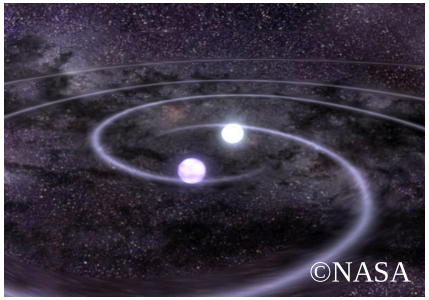
Expected Merger Time-Delay from Binary Pulsars

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

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



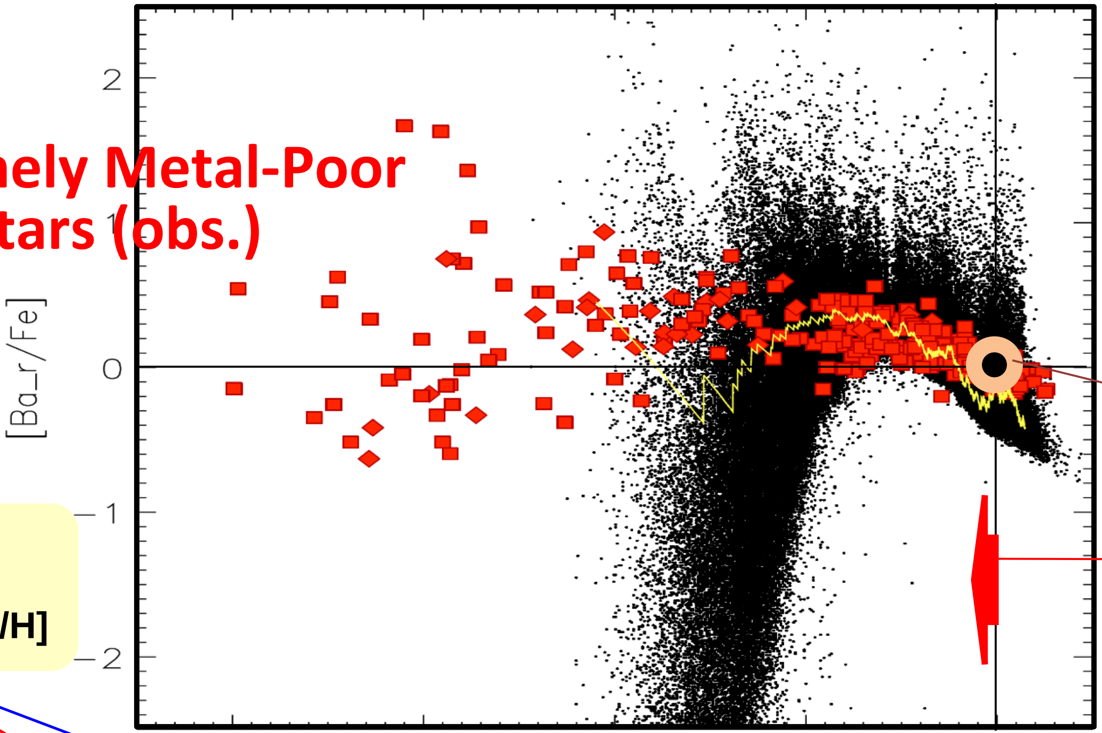
Orbital period P_b (hours)



GCE : No Dynamics!

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

τ_c = 100 My



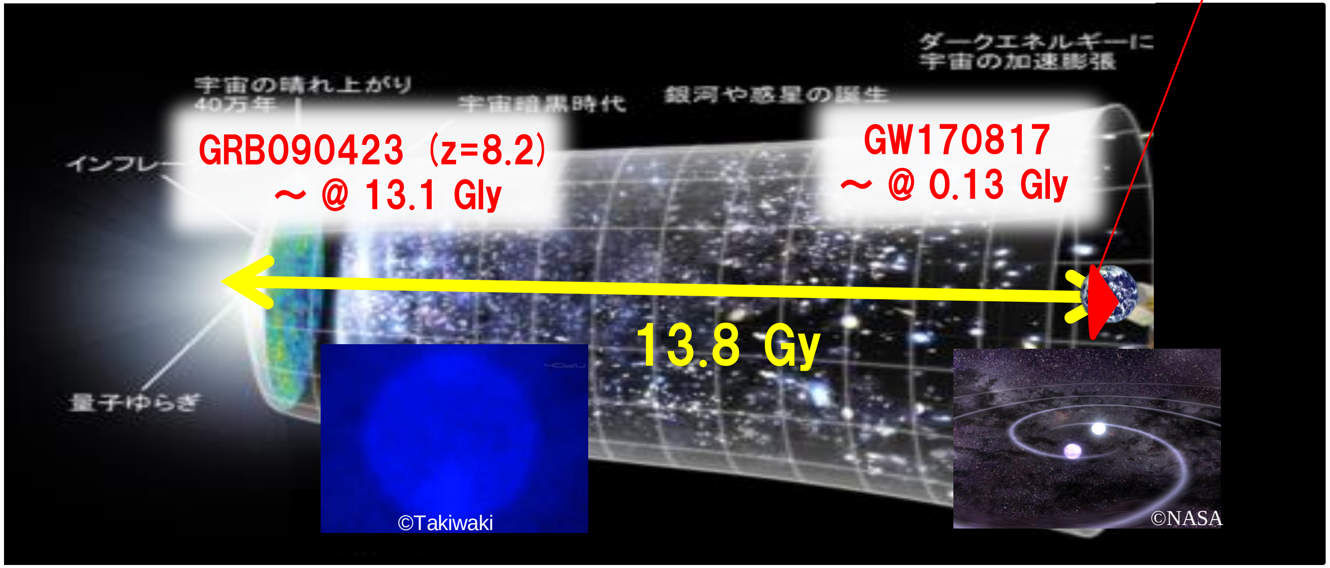
Extremely Metal-Poor Stars (obs.)

Sun (obs.)

GW170817 @ 0.13 Gly

t/10Gy ≈ $10^{[Fe/H]}$

−∞	−4	−3	−2	−1	0	[Fe/H]
Big-Bang	1My	10My	100My	1Gy	13.8Gy	time



Supercomputer Simulation of Binary Neutron Star Mergers
Galactic Chemo-Dynamical Evolution

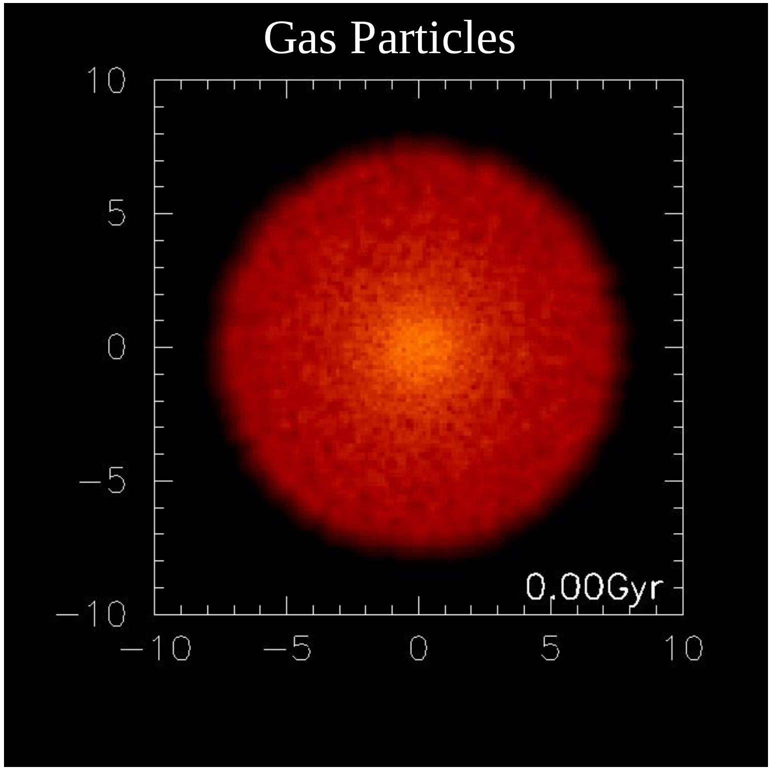
N-Body/SPH Simulation of Dwarf Spheroidal

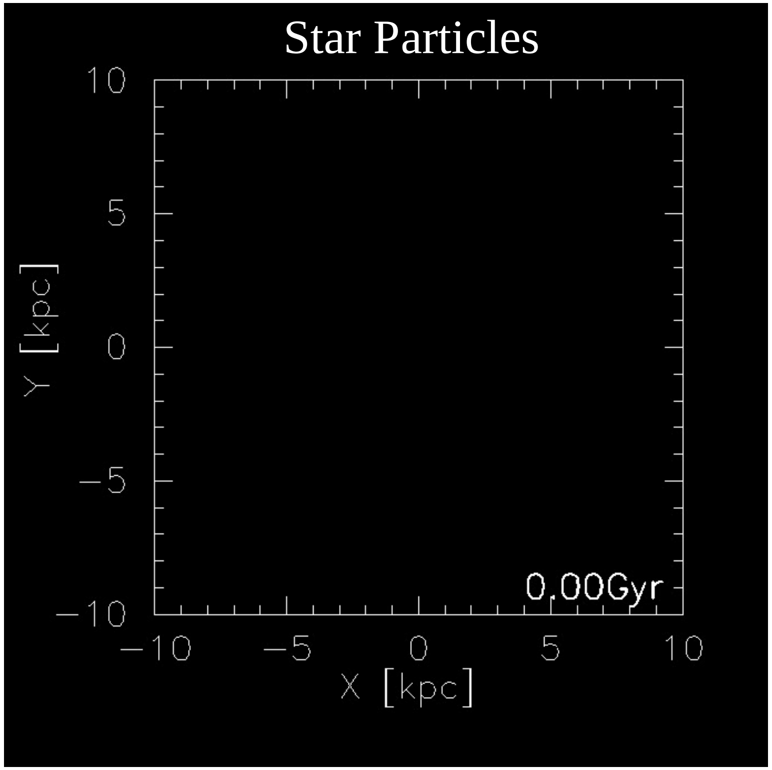
Gas, DMs & Stars

Star forms in SFR at $T < 10^4$K, $v < 0$, $n_H > 100\ \mathrm{cm}^{-3}$ → 100pc, Gas mixing

NSMs(τ_c=0.1Gy, Ba)+ SNe(1My, Fe) : $M_{tot} = 7\mathrm{x}10^8\ M_{sun}$, $N_i = 5\mathrm{x}10^5$ particles, $M_\bigstar = 100M_{sun}$

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


Gas Particles

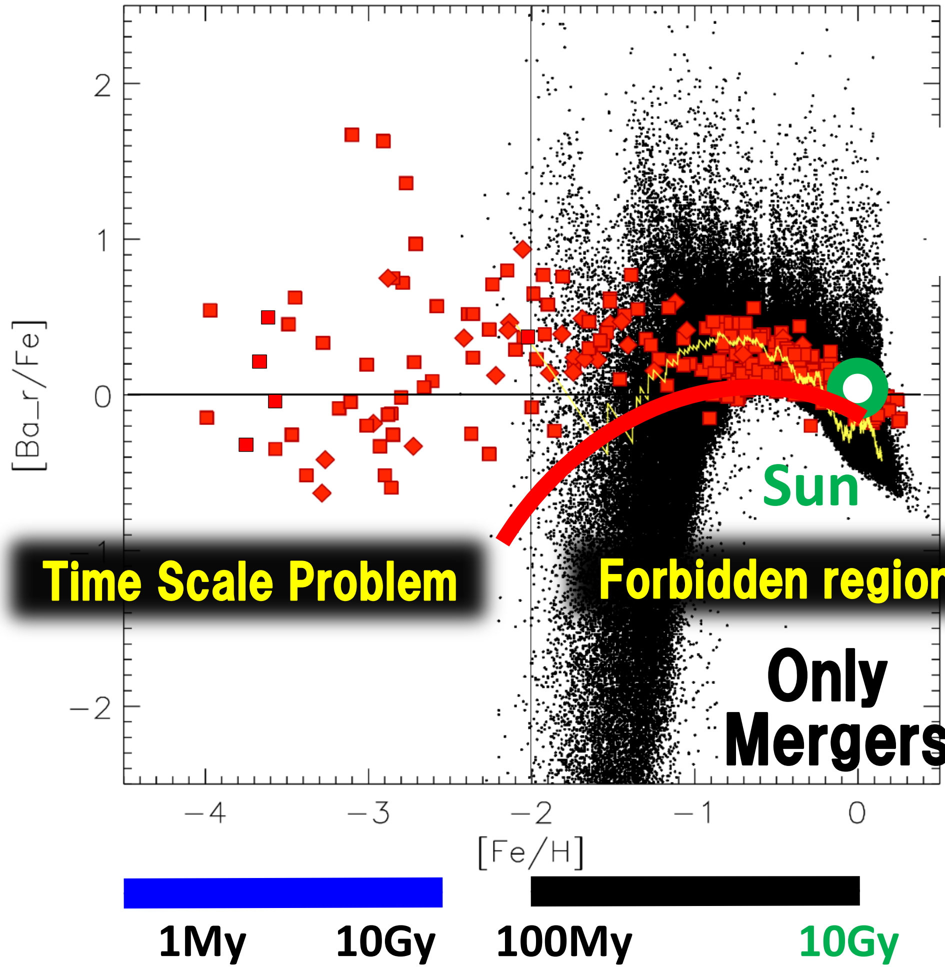

Star Particles

N-Body/SPH Simulation of Chemo-Dynamical Evolution of Dwarf Spheroidal (Building Blocks of MW Halo)

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

τ_c = 100My

W/O N-body Dynamics & Gas mixing



Time Scale Problem

Forbidden region

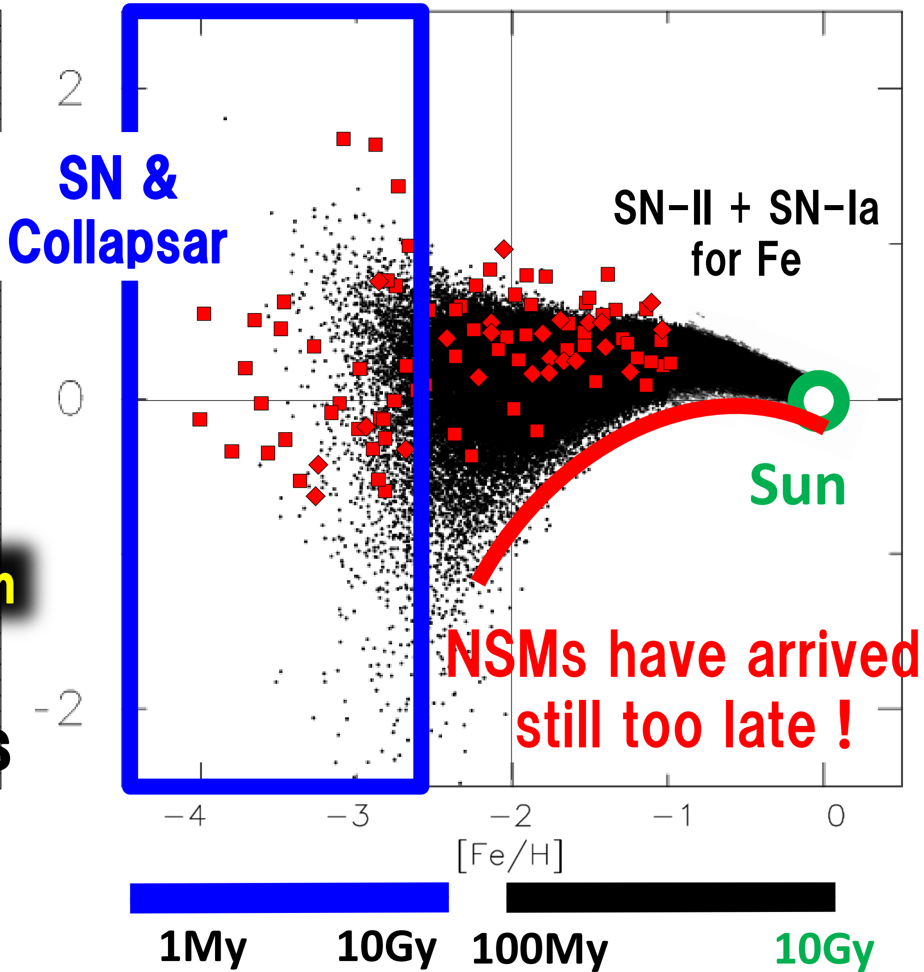
Sun

Only Mergers

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

τ_c = 100My

With N-body Dynamics, Gas mixing



SN & Collapsar

SN-II + SN-Ia for Fe

Sun

NSMs have arrived still too late !

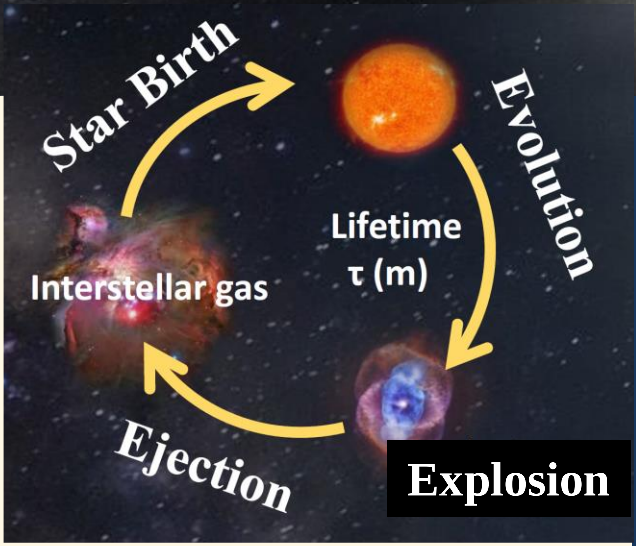
Purpose

:- to elucidate “when” and “how” the neutron star mergers, CCSNe and Collapsars have contributed differently to the r-process over the entire history of Galactic evolution.

:- to elucidate coupling among nuclear physics, neutrino physics and astronomy in the studies of r-process.

Contents

Cosmic & Galactic Evolution



Cosmic Gas- and Nuclear-Evolution

$$\dot{\sigma}_X = Inflow \cdot \delta_{X,gas} - \frac{\sigma_X}{\sigma_{gas}} \cdot \underline{B(\xi_{gas})} + \int \underline{B(t-\tau(m))\,\phi(m)\,E_X(m)}\,dm$$

Stellar Birth Rate

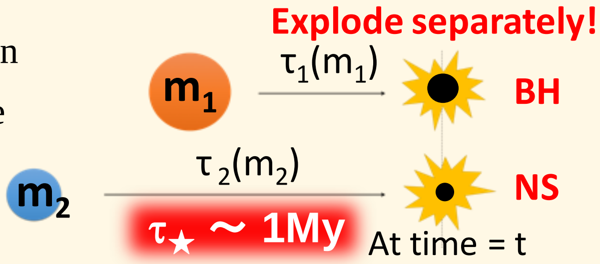
X = Ejected Nucleus from SNe or NSM

CCSN & Hypernova/Collapsar 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

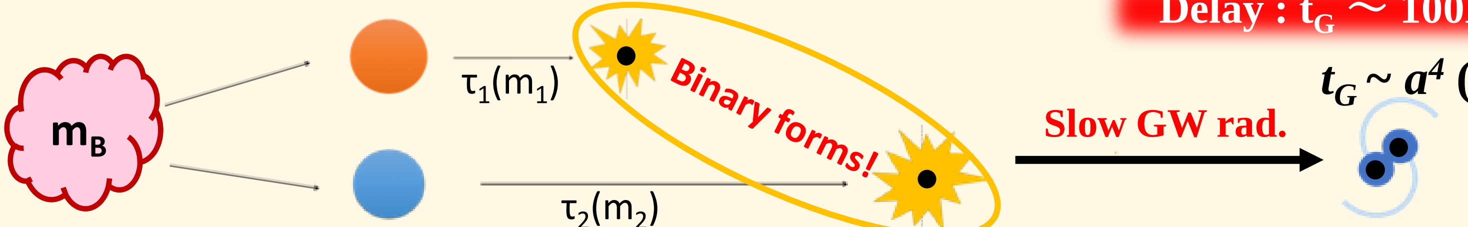


Binary Neutron Star Merger Rate :

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

Delay : $t_G \sim$ 100My–10Ty

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



$q = m_2/m_1$

a = separation of binaries

At time = t

Observed EVENT RATES

Contribution = Ejected Mass [$M_\odot$] x Event Rate [/Galaxy/Century]

νSN (Weak r) = 7.4×10^{-4} x (1.9 ± 1.1) [a]

MHD Jet SNe = 0.6×10^{-2} x $((0.03 \pm 0.02) \times (1.9 \pm 1.1))$ [b]

* **Binary NSMs (Short-GRB)** = $(2 \pm 1) \times 10^{-2}$ x $(1\text{-}28) \times 10^{-3}$ [c]

* **Collapsars (Failed SN)** = Assuming the same for MHD Jet SNe

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Observations	a	1.9±1.1*	Diehl, et al., Nature 439, 45 (2006). *1.3±0.6 (2018)
	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).

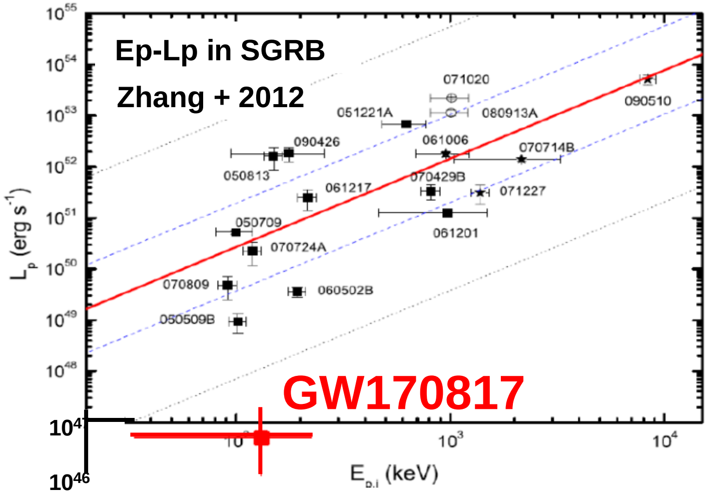
＊ Binary NSM ← Central engine of short GRB

- GW170817: Why faint？
- Jet inclination and beaming < 5° ？

＊ Collapsar (BH) ←Failed Supernovae, Long GRB

Yamazaki et al. (2022); Harikae et al. (2009, 2010); Nakamura et al. (2015),

c.f. Siegel et al. (2019) assumed: Super-Luminous SN
Hypernova (Long GRB)

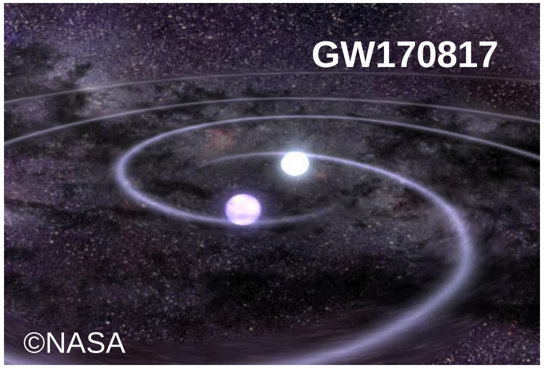


Ep-Lp in SGRB
Zhang + 2012

Astrophysical Sites for R-Process

BINARY Stars

Neutron Star Merger



©NASA

Time Delay : 100 My < τ < 10 Ty

Lorimer, Living Rev. Rel. 11(2008), 8.
Beniamini+ (2019), Timmes+ (1995)

Failed SN → Collapsar

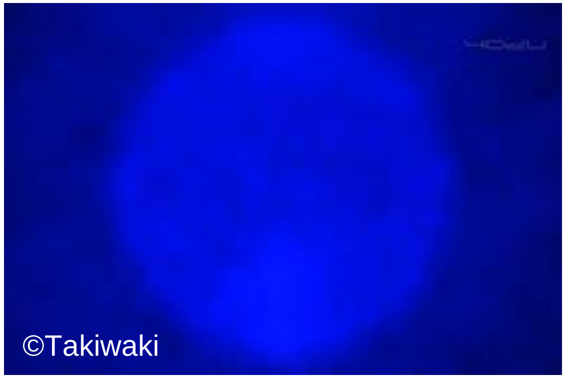
MacFadyen, Woosley, ApJ 524 (1999), 262; Nakamura, Kajino, Mathews, Sato & Harikae, A&Ap 582 (2015), A34; Yamazaki, et al. (2022).

Super-Luminous SN/Hypernova

Siegel, Barnes & Metzger, Nature 569 (2019), 243.

SINGLE Star

CCSN II : ν-DW & MHD Jet



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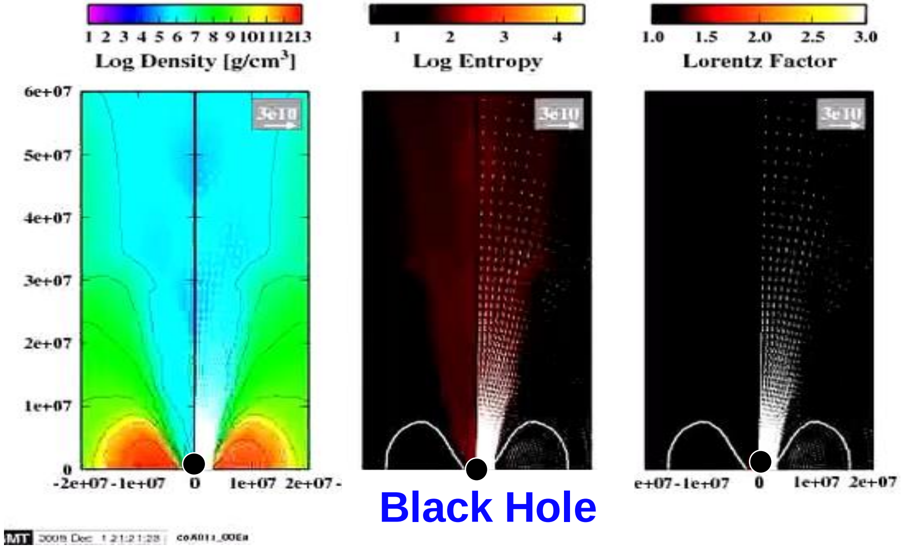
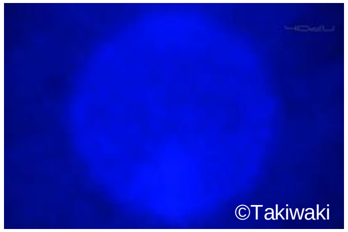
Neutron Star

Collapsar Jet



Black Hole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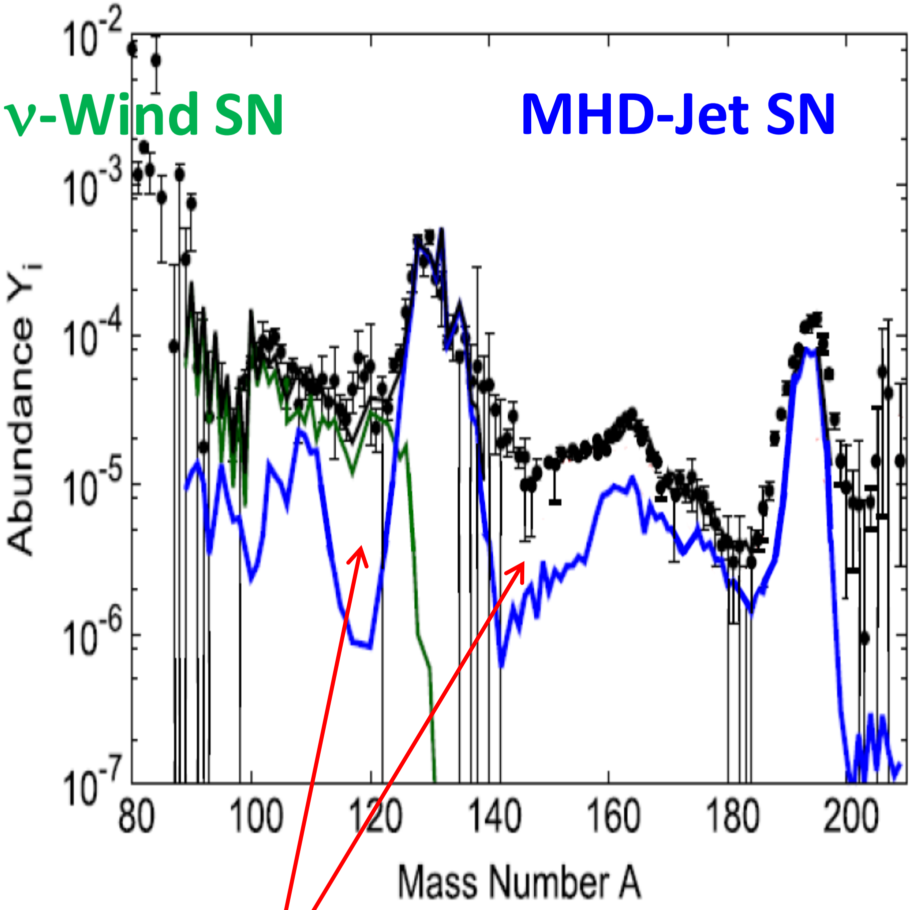
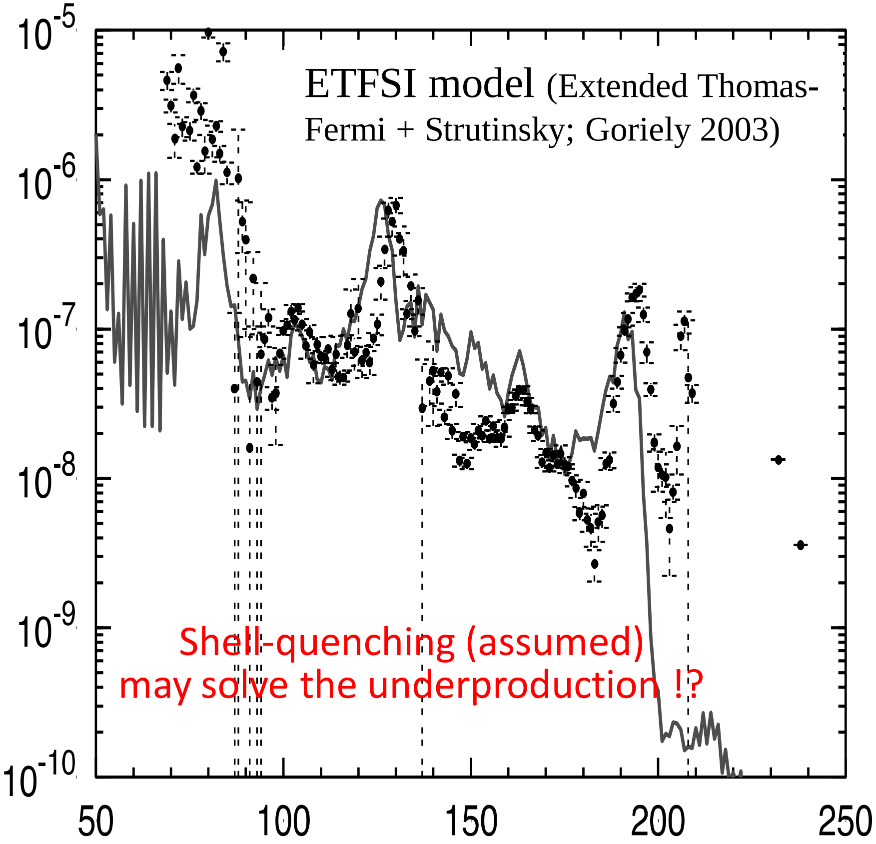
1. Supernovae (ν-driv. Wind & MHDJet)

Shibagaki, Kajino, Mathews, Chiba, Nishimura, Lorusso, ApJ 816, 79; Kajino & Mathews (2017), ROPP 80, 084901; Kajino, Aoki, Balantekin, Dihel, Famiano, Mathews (2019), PPNP 107, 109.





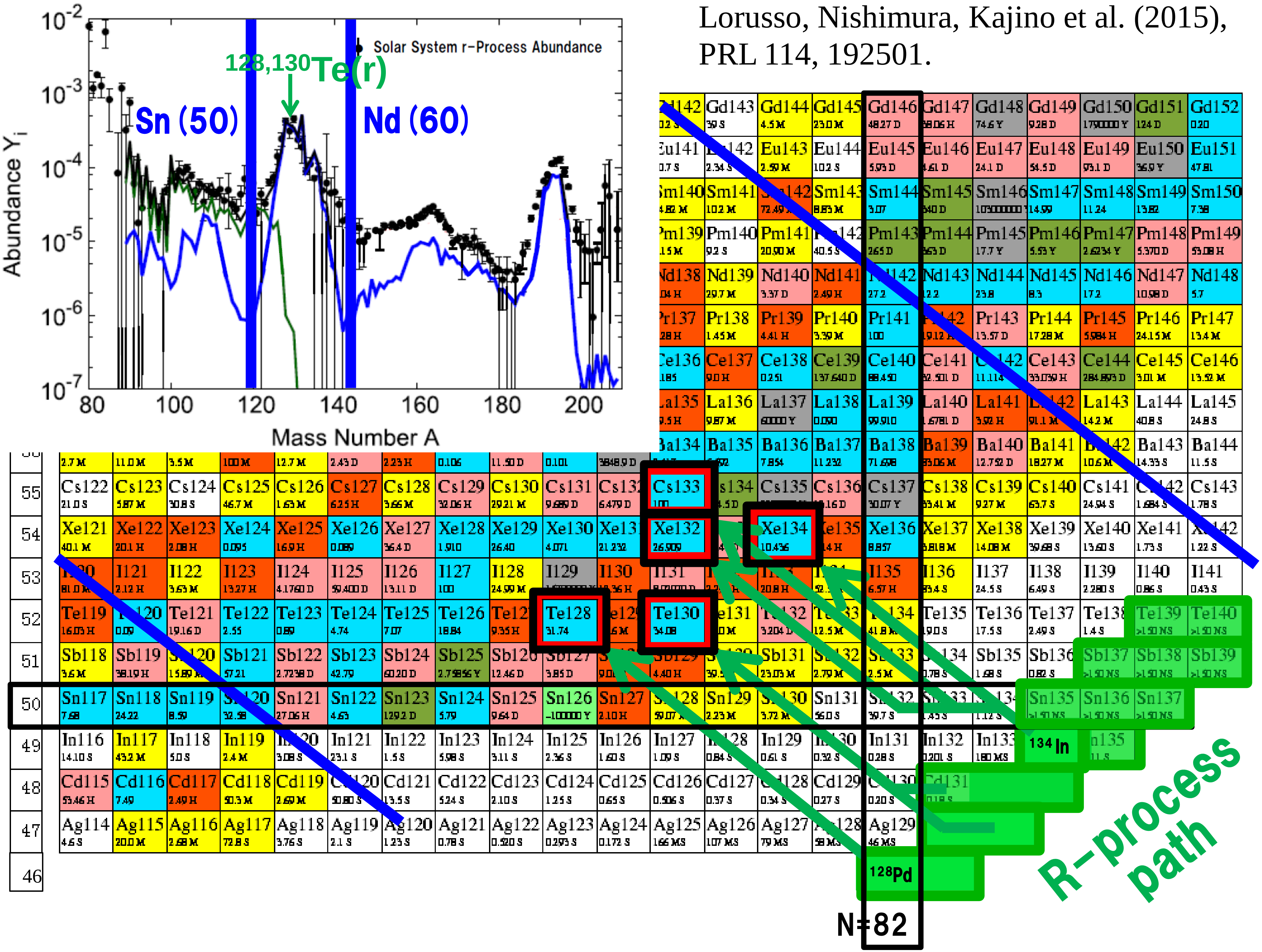
ETFSI model (Extended Thomas-Fermi + Strutinsky; Goriely 2003)

Shell-quenching (assumed)
may solve the underproduction !?

Underproduction → Possible Solution

- **1. Nucl. Phys. – Shell Quenching ?**
- **2. Astro. – Another Site ?**
  (Merger or Collapsar ?)

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



												d142 0.2	Gd143 39 S	Gd144 4.5 M	Gd145 23.0 M	Gd146 48.27 D	Gd147 38.06 H	Gd148 74.6 Y	Gd149 9.28 D	Gd150 1790000 Y	Gd151 124 D	Gd152 0.20
												u141 0.7 S	142 2.34 S	Eu143 2.59 M	Eu144 10.2 S	Eu145 5.93 D	Eu146 4.61 D	Eu147 24.1 D	Eu148 54.5 D	Eu149 93.1 D	Eu150 36.9 Y	Eu151 47.81
												m140 4.82 M	Sm141 10.2 M	142 72.49	Sm143 8.83 M	Sm144 3.07	Sm145 340 D	Sm146 103000000	Sm147 14.99	Sm148 11.24	Sm149 13.82	Sm150 7.38
												m139 15 M	Pm140 9.2 S	Pm141 20.90 M	142 40.5 S	Pm143 265 D	Pm144 363 D	Pm145 17.7 Y	Pm146 5.53 Y	Pm147 2.6234 Y	Pm148 5.370 D	Pm149 53.08 H
												d138 04 H	Nd139 29.7 M	Nd140 3.37 D	Nd141 2.49 H	142 27.2	Nd143 12.2	Nd144 23.8	Nd145 8.3	Nd146 17.2	Nd147 10.98 D	Nd148 5.7
												r137 28 H	Pr138 1.45 M	Pr139 4.41 H	Pr140 3.39 M	Pr141 100	142 19.12	Pr143 13.57 D	Pr144 17.28 M	Pr145 5.984 H	Pr146 24.15 M	Pr147 13.4 M
												e136 185	Ce137 9.0 H	Ce138 0.251	Ce139 137.640 D	Ce140 88.450	Ce141 32.501 D	142 11.114	Ce143 33.039 H	Ce144 284.893 D	Ce145 3.01 M	Ce146 13.52 M
												a135 9.5 H	La136 9.87 M	La137 60000 Y	La138 0.090	La139 99.910	La140 1.6781 D	La141 3.92 H	142 91.1 M	La143 14.2 M	La144 40.8 S	La145 24.8 S
	2.7 M	11.0 M	3.5 M	100 M	12.7 M	2.43 D	2.23 H	0.106	11.50 D	0.101	3848.9 D	a134	Ba135 6.592	Ba136 7.854	Ba137 11.232	Ba138 71.698	Ba139 83.06 M	Ba140 12.752 D	Ba141 18.27 M	142 10.6 M	Ba143 14.33 S	Ba144 11.5 S
55	Cs122 21.0 S	Cs123 5.87 M	Cs124 30.8 S	Cs125 46.7 M	Cs126 1.63 M	Cs127 6.25 H	Cs128 3.66 M	Cs129 32.06 H	Cs130 29.21 M	Cs131 9.689 D	Cs13 6.479 D	Cs133 100	s134 .5 D	Cs135	Cs136 .16 D	Cs137 30.07 Y	Cs138 33.41 M	Cs139 9.27 M	Cs140 63.7 S	Cs141 24.94 S	142 1.684 S	Cs143 1.78 S
54	Xe121 40.1 M	Xe122 20.1 H	Xe123 2.08 H	Xe124 0.095	Xe125 16.9 H	Xe126 0.089	Xe127 36.4 D	Xe128 1.910	Xe129 26.40	Xe130 4.071	Xe13 21.232	Xe132 26.909		Xe134 10.436	e135 4 H	Xe136 8.857	Xe137 3.818 M	Xe138 14.08 M	Xe139 39.68 S	Xe140 13.60 S	Xe141 1.73 S	142 1.22 S
53	20 81.0	I121 2.12 H	I122 3.63 M	I123 13.27 H	I124 4.1760 D	I125 59.400 D	I126 13.11 D	I127 100	I128 24.99 M	I129	I130 12.36 H	I131		20.8 H	52.	I135 6.57 H	I136 83.4 S	I137 24.5 S	I138 6.49 S	I139 2.280 S	I140 0.86 S	I141 0.43 S
52	Te119 16.03 H	120 0.09	Te121 19.16 D	Te122 2.55	Te123 0.89	Te124 4.74	Te125 7.07	Te126 18.84	Te12 9.35 H	Te128 31.74	e129 6 M	Te130 34.08	e131 0 M	132 3.204	133 12.5 M	134 41.8	Te135 19.0 S	Te136 17.5 S	Te137 2.49 S	Te138 1.4 S	Te139 >1 50 NS	Te140 >1 50 NS
51	Sb118 3.6 M	Sb119 38.19 H	120 15.89	Sb121 57.21	Sb122 2.7238 D	Sb123 42.79	Sb124 60.20 D	Sb125 2.75856 Y	Sb126 12.46 D	3.85 D	9.01	4.40 H	39.5	Sb131 23.03 M	2.79 M	2.5 M	134 0.78 S	Sb135 1.68 S	Sb136 0.82 S	Sb137 >1 50 NS	Sb138 >1 50 NS	Sb139 >1 50 NS
50	Sn117 7.68	Sn118 24.22	Sn119 8.59	120 32.58	Sn121 27.06 H	Sn122 4.63	Sn123 129.2 D	Sn124 5.79	Sn125 9.64 D	Sn126 ~100000 Y	Sn127 2.10 H	128 59.07	Sn129 2.23 M	130 3.72 M	Sn131 56.0 S	32 39.7 S	33 1.45 S	134 1.12 S	Sn135 >1 50 NS	Sn136 >1 50 NS	Sn137 >1 50 NS	
49	In116 14.10 S	In117 43.2 M	In118 5.0 S	In119 2.4 M	20 3.08 S	In121 23.1 S	In122 1.5 S	In123 5.98 S	In124 3.11 S	In125 2.36 S	In126 1.60 S	In127 1.09 S	128 0.84 S	In129 0.61 S	130 0.32 S	In131 0.28 S	In132 0.201 S	In133 180 MS	134 In	n135		
48	Cd115 53.46 H	Cd116 7.49	Cd117 2.49 H	Cd118 50.3 M	Cd119 2.69 M	120 50.80 S	Cd121 13.5 S	Cd122 5.24 S	Cd123 2.10 S	Cd124 1.25 S	Cd125 0.65 S	Cd126 0.506 S	Cd127 0.37 S	128 0.34 S	Cd129 0.27 S	130 0.20 S	Cd131					
47	Ag114 4.6 S	Ag115 20.0 M	Ag116 2.68 M	Ag117 72.8 S	Ag118 3.76 S	Ag119 2.1 S	Ag120 1.23 S	Ag121 0.78 S	Ag122 0.520 S	Ag123 0.293 S	Ag124 0.172 S	Ag125 166 MS	Ag126 107 MS	Ag127 79 MS	128 58 MS	Ag129 46 MS						
46																^{128}Pd						

~~Shell Quenching~~ ?

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

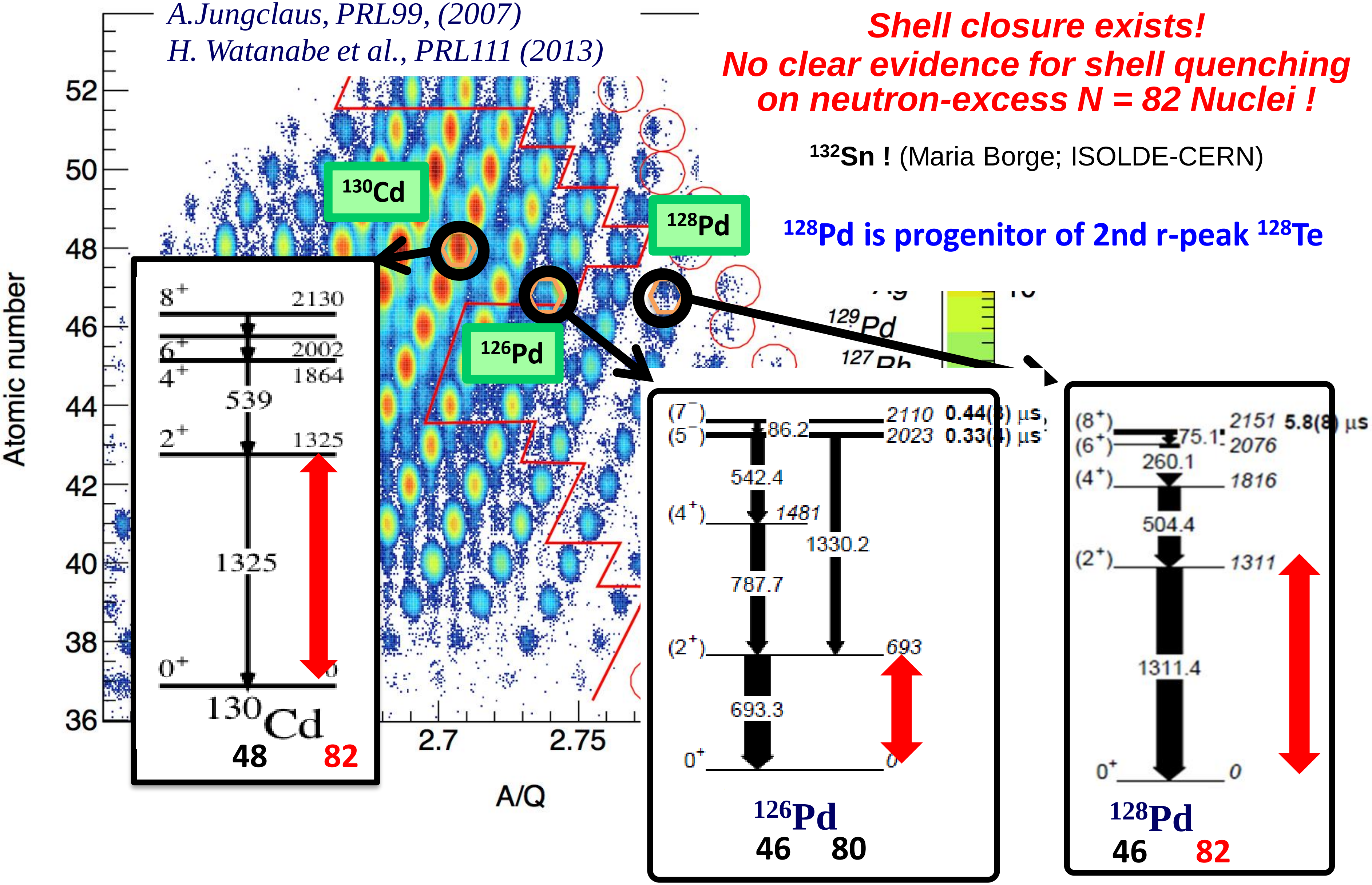
G. Lorusso et al., PRL 114 (2015), 192501.

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

Shell closure exists!
No clear evidence for shell quenching on neutron-excess N = 82 Nuclei !

^{132}Sn ! (Maria Borge; ISOLDE-CERN)

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

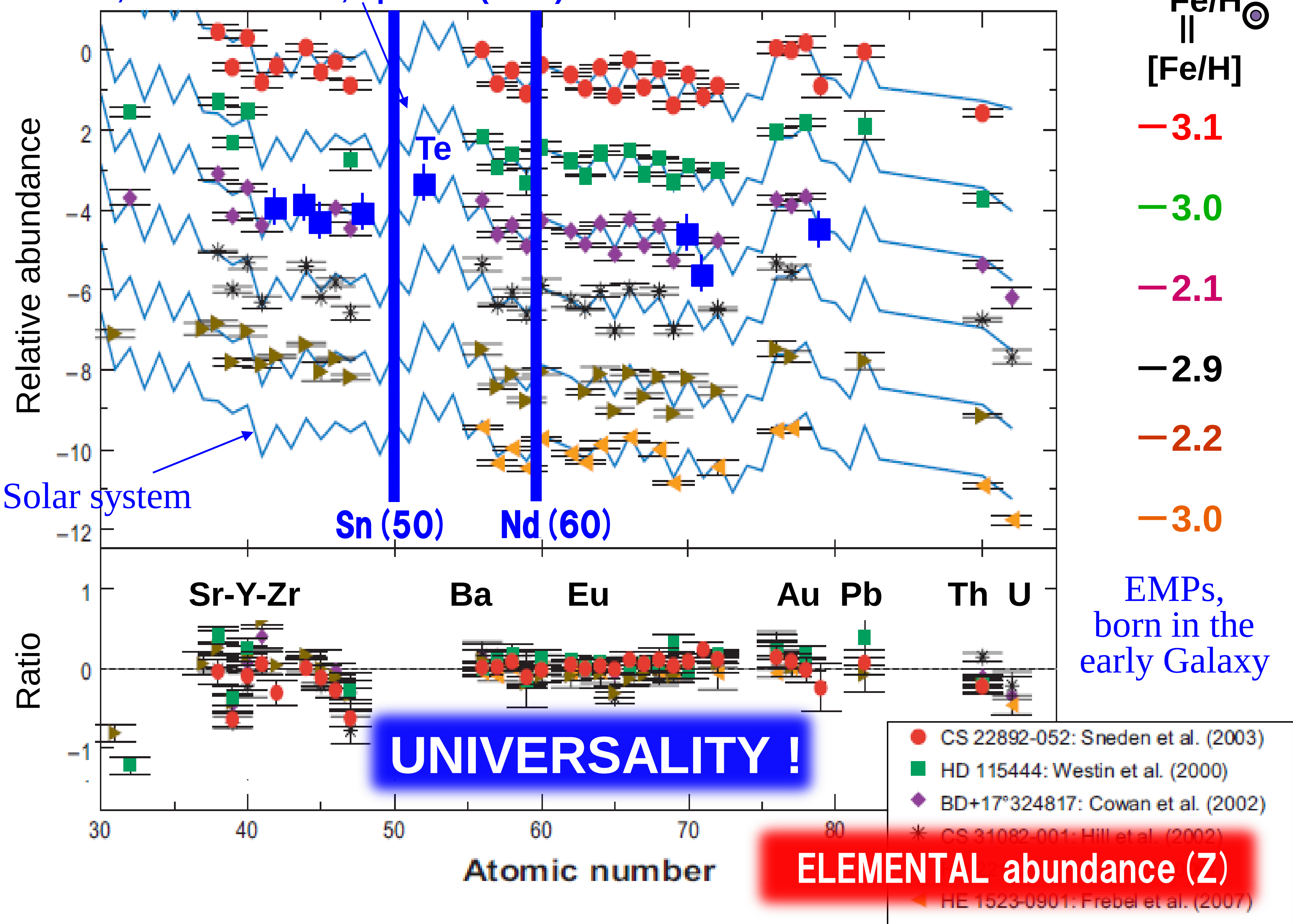


Sneden, Cowan, Gallino, ARAA 46 (2008) 241.

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

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

$$\mathrm{Log}\,\frac{\mathrm{Fe/H}_{\star}}{\mathrm{Fe/H}_{\odot}} = [\mathrm{Fe/H}]$$



−3.1
−3.0
−2.1
−2.9
−2.2
−3.0

EMPs,
born in the
early Galaxy

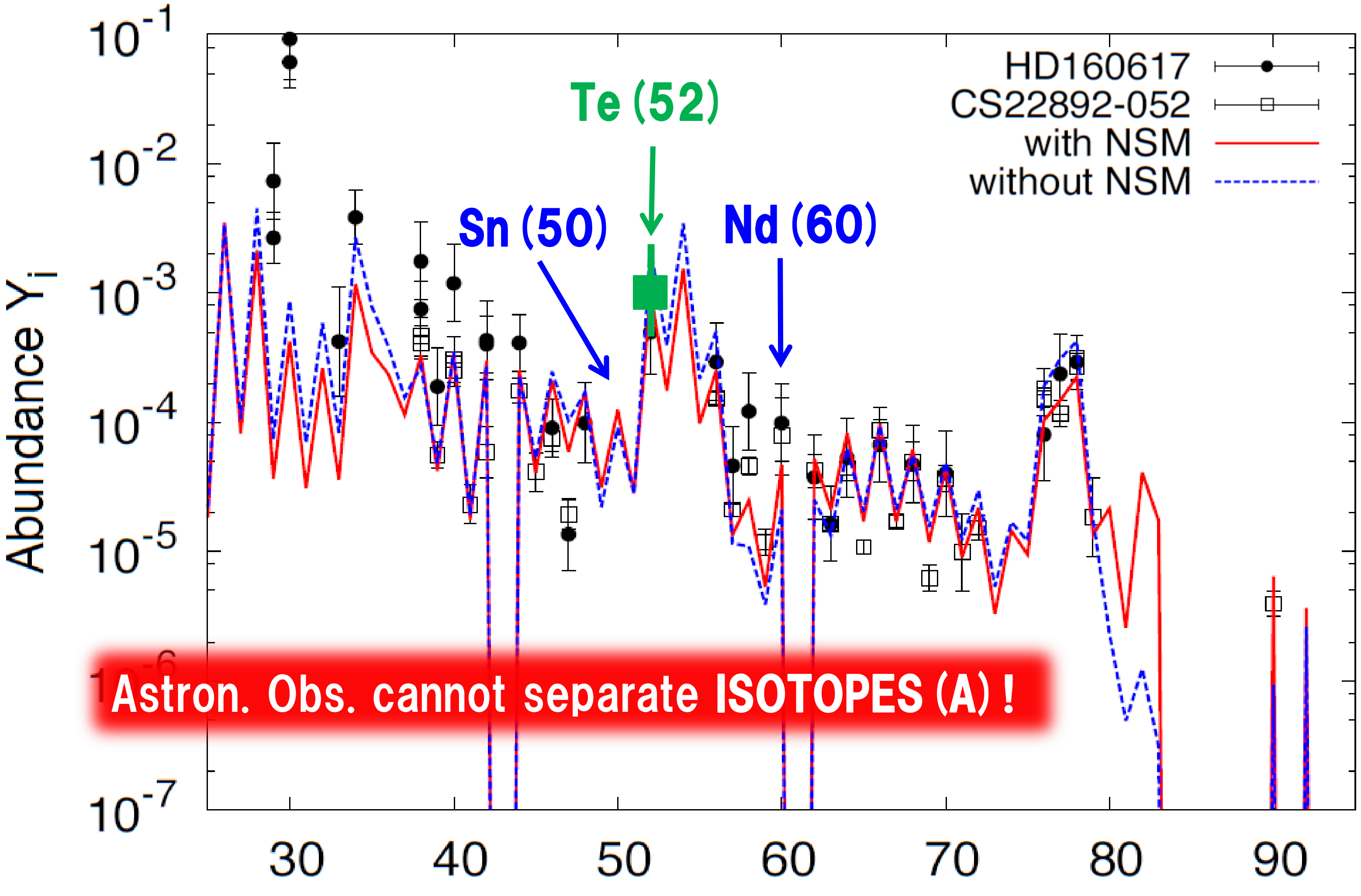
UNIVERSALITY !

ELEMENTAL abundance (Z)

UNIVERSALITY !

Early Galaxy ⟷ TODAY

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

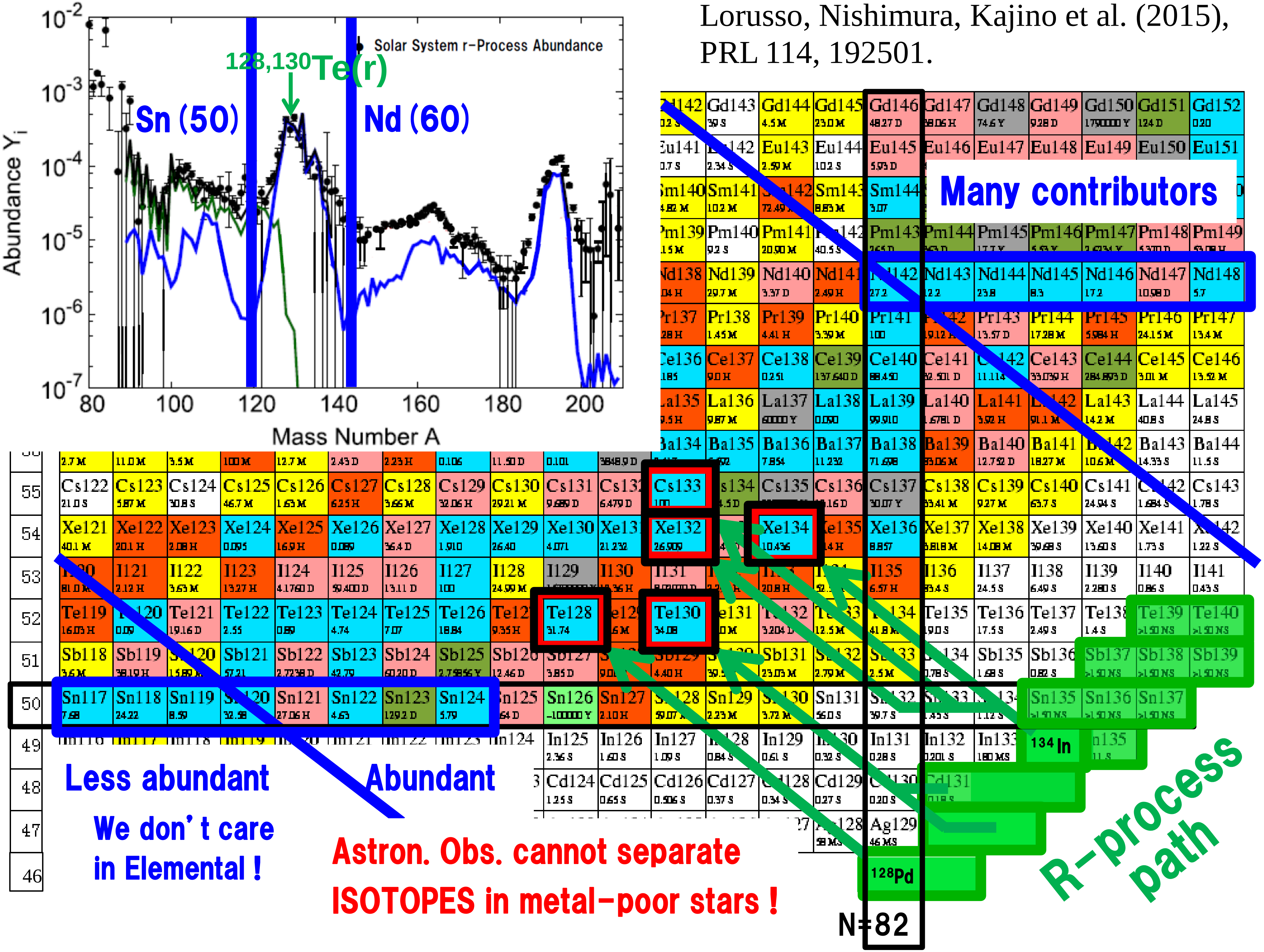


Astron. Obs. cannot separate ISOTOPES (A) !

Atomic Number Z

ELEMENTAL abundance (Z)

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



Many contributors

Less abundant

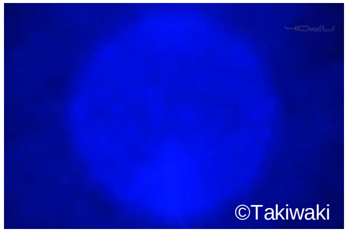
Abundant

We don't care in Elemental !

Astron. Obs. cannot separate ISOTOPES in metal-poor stars !

R-process path

N=82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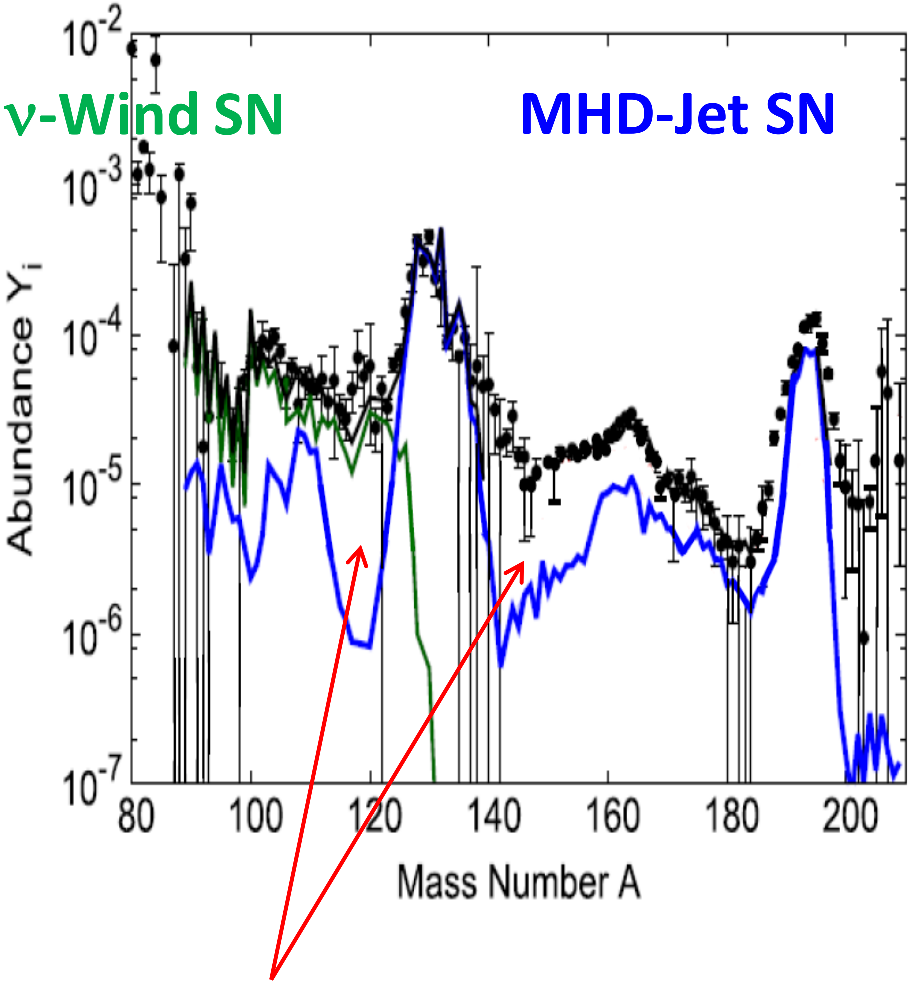
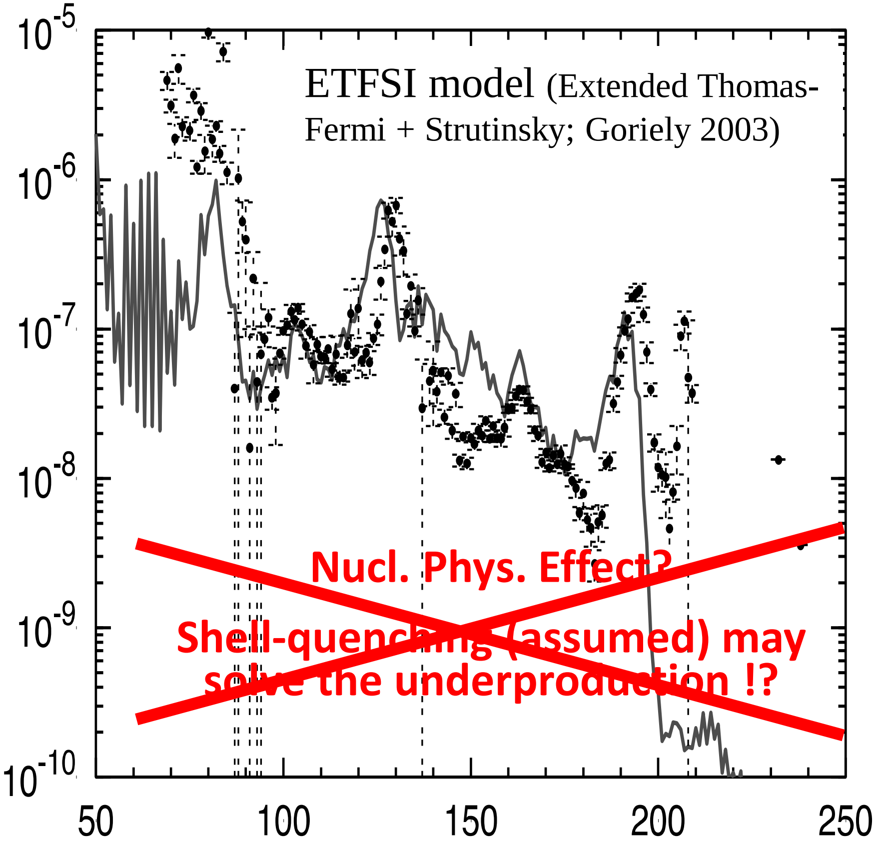
1. Supernovae (ν-driven & MHD Jet)

Shibagaki, Kajino, Mathews, Chiba, Nishimura, Lorusso, ApJ 816, 79; Kajino & Mathews (2017), ROPP 80, 084901; Kajino, Aoki, Balantekin, Dihel, Famiano, Mathews (2019), PPNP 107, 109.





ETFSI model (Extended Thomas-Fermi + Strutinsky; Goriely 2003)

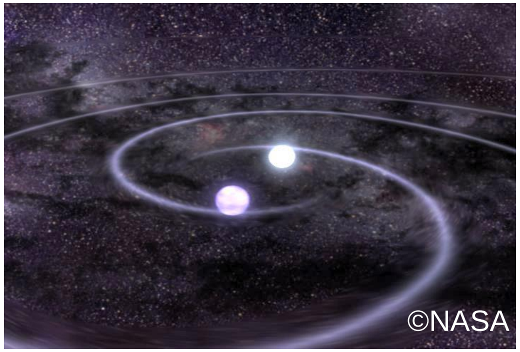
Nucl. Phys. Effect?

Shell-quenching (assumed) may solve the underproduction !?

Underproduction → Possible Solution

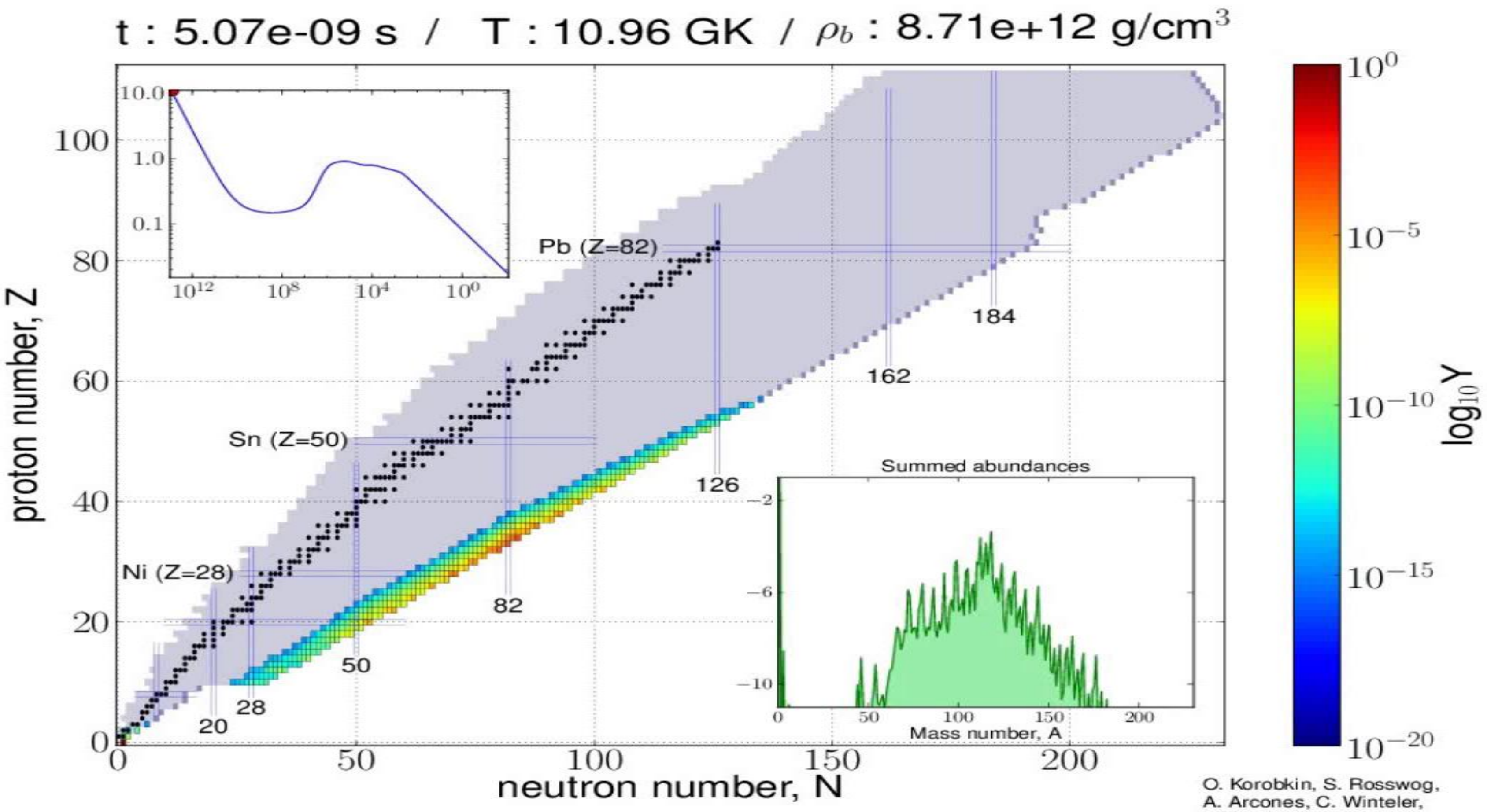
~~1. Nucl. Phys. – Shell Quenching ?~~

2. Astro. – Another Site ?
(Merger or Collapsar ?)



2. Neutron Star Merger

Shibagaki, Kajino, Mathews, Chiba, Nishimura, Lorusso, ApJ 816, 79;
Kajino & Mathews (2017), ROPP 80, 084901;
Kajino, Aoki, Balantekin, Dihel, Famiano, Mathews (2019), PPNP 107, 109.



O. Korobkin, S. Rosswog,
A. Arcones, C. Winteler,
arXiv:1206.2379

Shape Parametrization

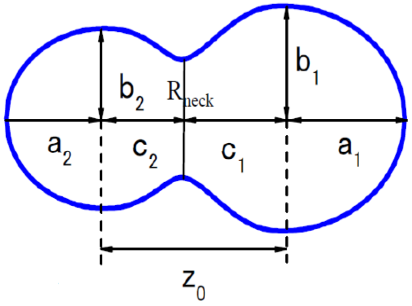
Quantum Tunneling → Dynamical Fission → 3D & 4D Lengevin Eq.

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)

Shape parametrization

Two-center model

(Maruhn and Greiner, Z. Phys. 251(1972) 431)



Collective coordinates (3 or 4 dynamical variables)

$$\{q\}_{3D} = \{ZZ_0, \delta, \alpha\} \qquad \{q\}_{4D} = \{ZZ_0, \delta_1, \delta_2, \alpha\}$$

★ $ZZ_0 = \dfrac{z_0}{R}$ Elongation

R : Radius of compound nucleus $= 1.2 A_{CN}^{1/3}$

★ $\delta_i = \dfrac{3(a_i - b_i)}{2a_i + b_i}$ Deformation $(\delta_1 =/ \delta_2 \rightarrow$ 4D Lengevin Eq.)

3D : $\delta_1 = \delta_2 = \delta$ 4D : δ_1, δ_2 are independent

★ $\alpha = \dfrac{A_1 - A_2}{A_1 + A_2}$ Mass asymmetry

A_1 : mass of the right fragment

A_2 : mass of the left fragment

$\varepsilon = 0.35$ neck parameter : fixed

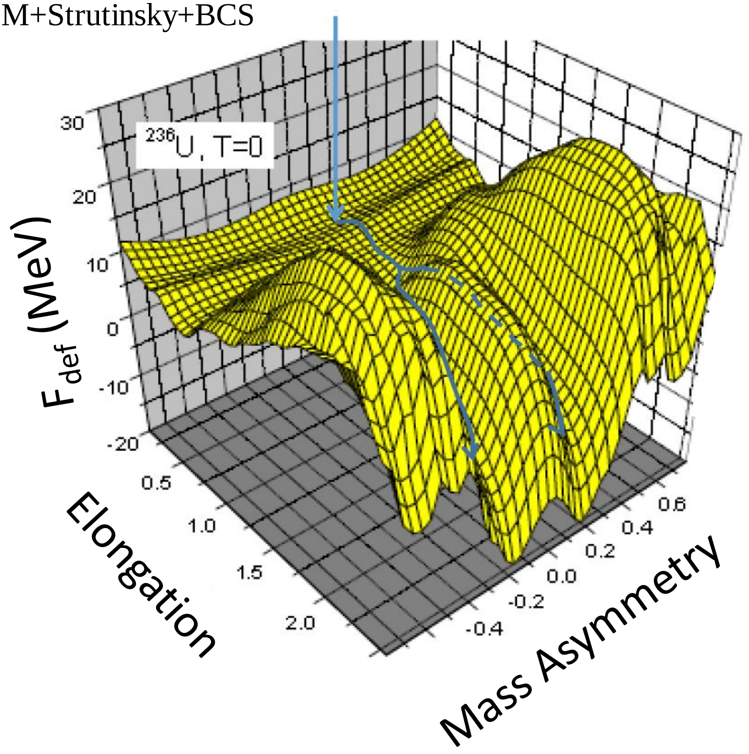
volume conservation condition is applied

Quantum Tunneling
WKB

Free energy surface F

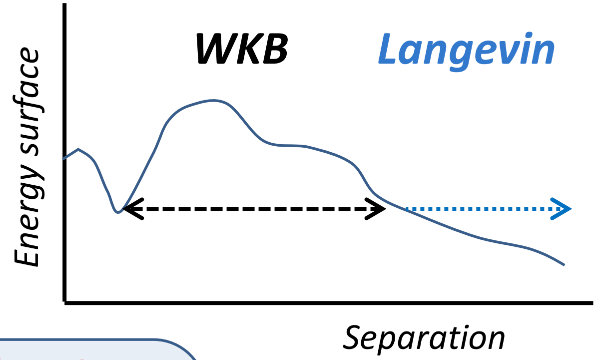
$$F = E - TS = E\,(at\, T = 0)$$

FRDM+Strutinsky+BCS



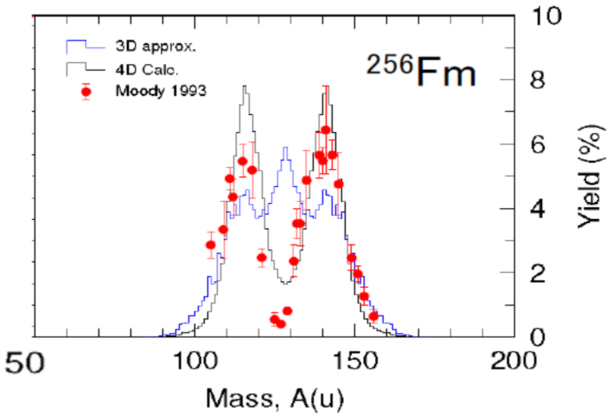
Dynamical Fission → 3D & 4D Lengevin Eq.

Ishizuka, Chiba et al., Phys. Rev. C96 (2017), 064616.



4 Collective Coordinates $\{q_i : i = 1..4\}=\{ZZ_0 , \alpha , \delta_L , \delta_R\}$

$$\begin{cases} \dfrac{dp_i}{dt} = -\overset{\text{Drift term}}{\dfrac{\partial F}{\partial q_i}} - \dfrac{1}{2}\dfrac{\partial}{\partial q_i}(m^{-1})_{jk}p_j p_k - \overset{\text{Friction term}}{\gamma_{ij}(m^{-1})_{jk}p_k} + \overset{\text{Wiener term}}{g_{ij}R_j(t)} \\ \dfrac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j \end{cases}$$



F: Helmholtz' free energy, $F = E - TS$

2-center Woods-Saxon model

q_i: Nuclear shape motion

p_i: Momentum conjugate to q_i

m_{ij}: Inertia tensor

γ_{ij}: friction tensor

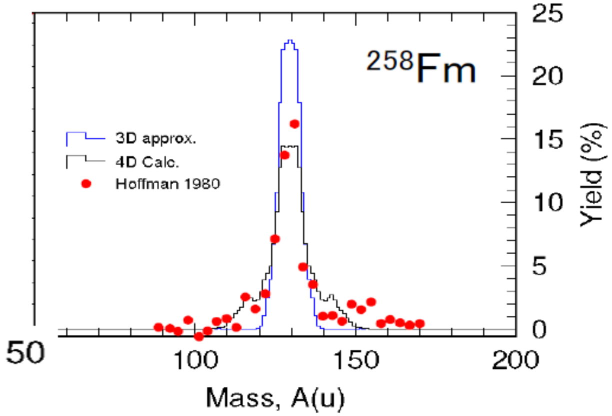
Hydrodynamical model

$g_{ij}g_{ij} = \gamma_{ij}T$: Fluctuation dissipation theorem

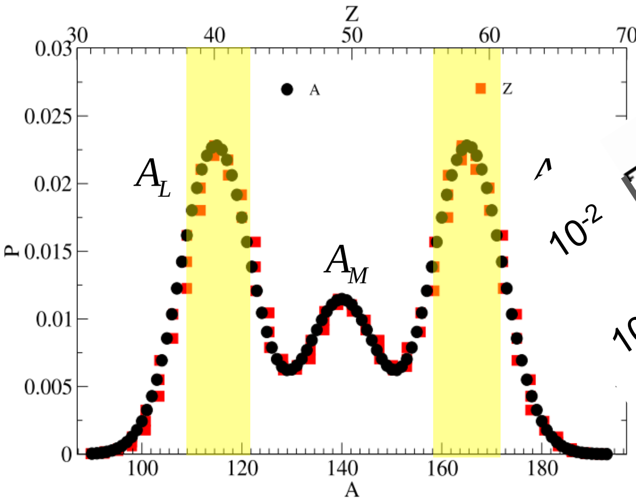
(+Einstein relation)

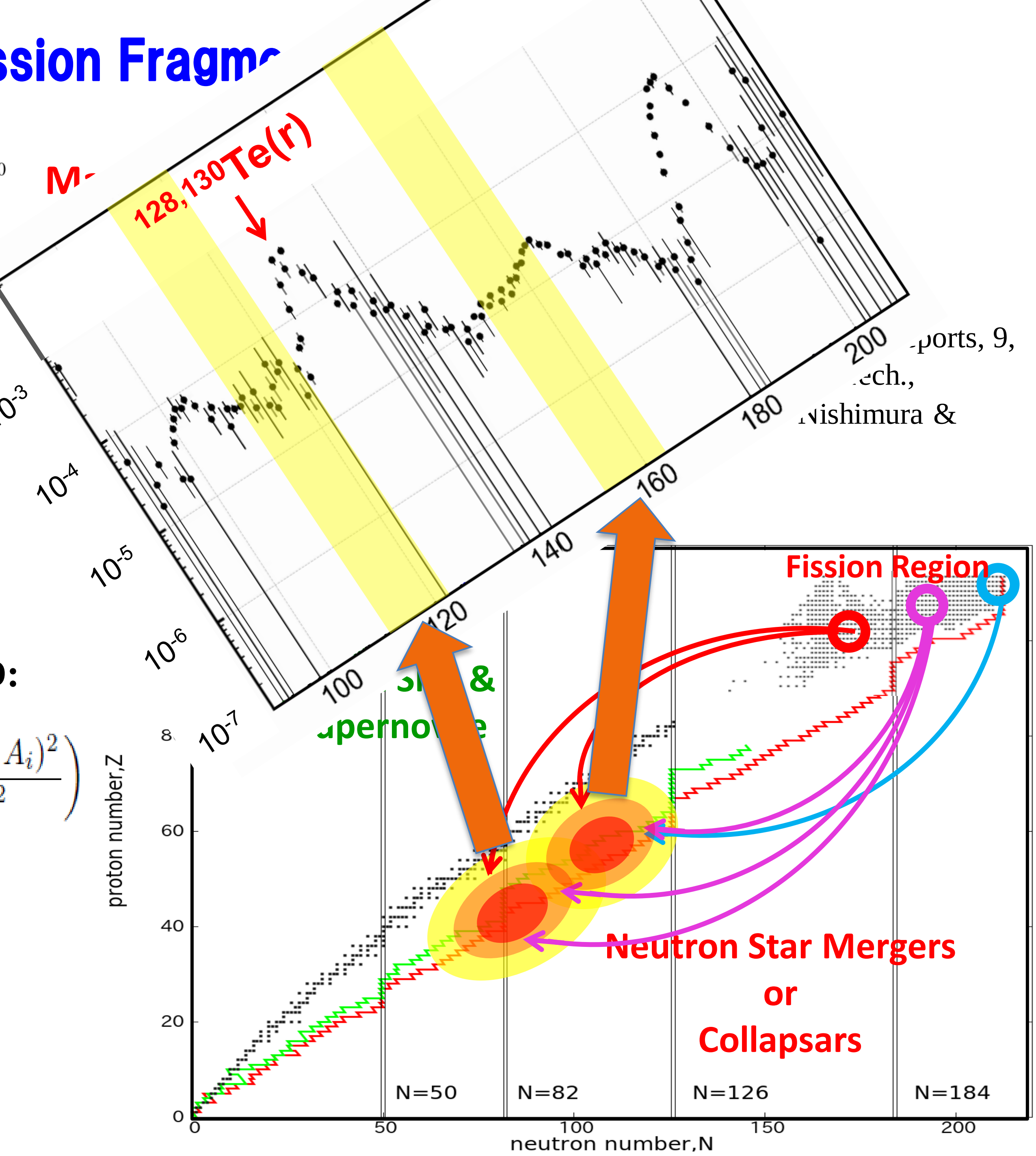
$$T = \sqrt{\frac{E^* - \frac{1}{2}m_{ij}p_i p_j - E_{rot}}{a}}$$

E^* : Total excitation energy of the system



Fission Fragm





Bimordial or Trimodal FFD:

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

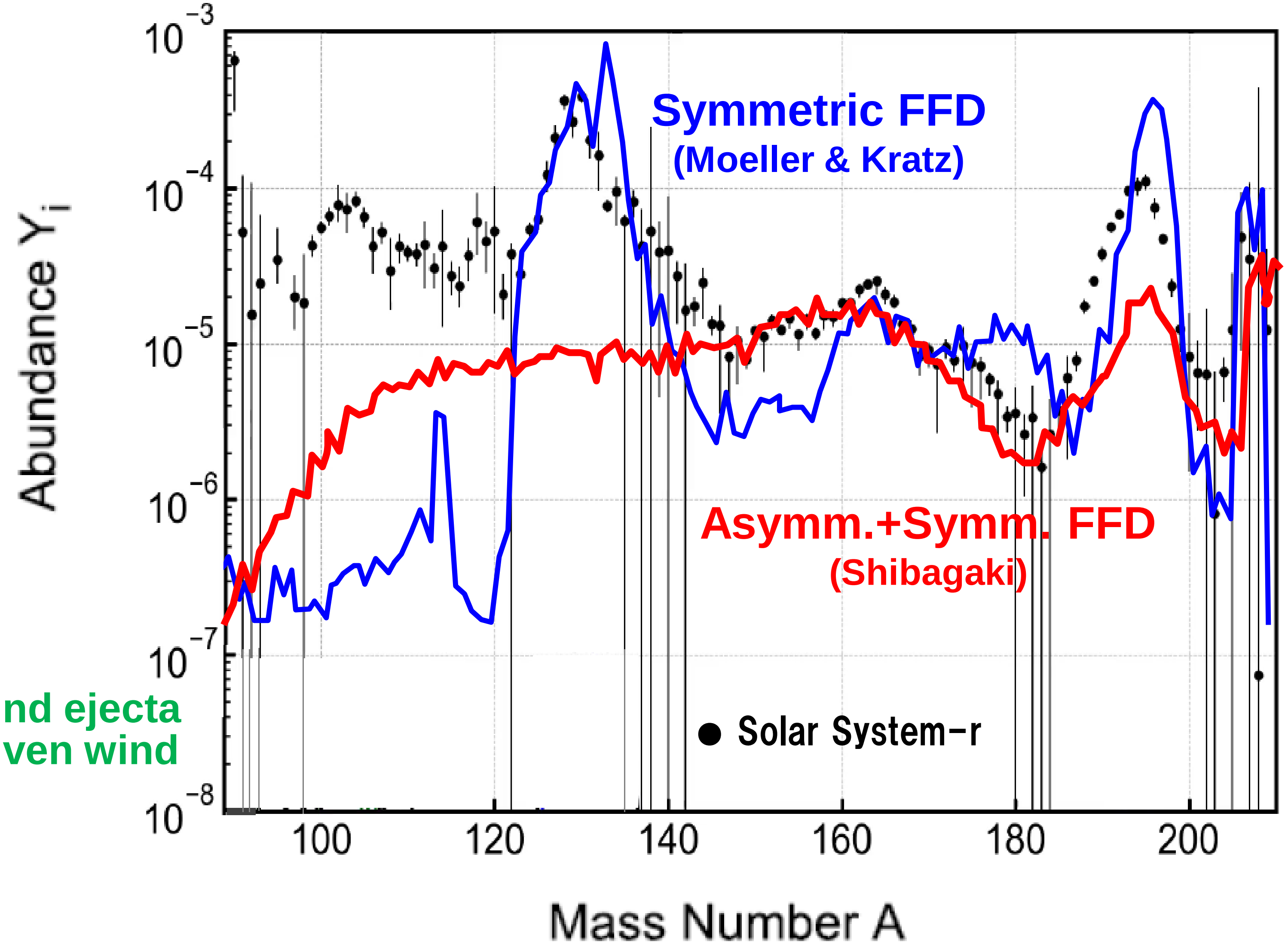
$$A_H=(1+\alpha)(A_p-N_{loss})/2$$

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

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

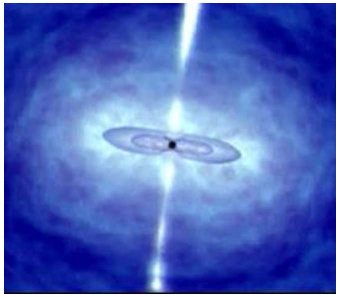
Neutron Star Merger r-Process

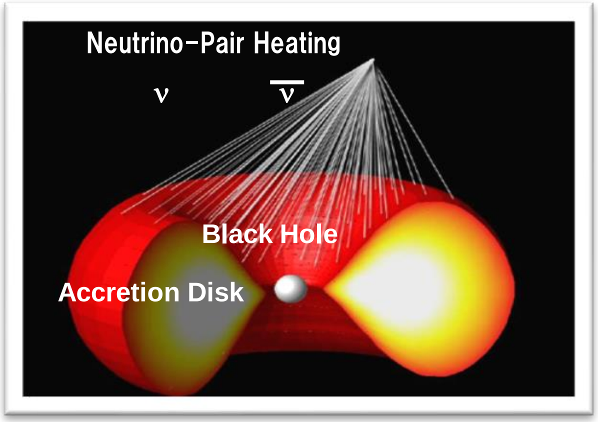
Shibagaki, Kajino, Mathews, Chiba, Nishimura, Lorusso, ApJ 816, 79; Suzuki, et al., ApJ 859 (2018), 133; Kajino & Mathews (2017), ROPP 80, 084901; Kajino, Aoki, Balantekin, Dihel, Famiano, Mathews (2019), PPNP 107, 109.



Disc wind ejecta
～ ν-driven wind

3. Collapsar Jet





Numerical Hydrodynamic Model

MacFadyen, Woosley, ApJ 524 (1999), 262;
Nagataki et al., ApJ 659 (2007), 512.

2D Collapsar Hydrodynamic Model

Takiwaki et al., ApJ 691 (2009), 1360;
Harikae et al., ApJ 704 (2009), 354; ApJ 713 (2010) 304;

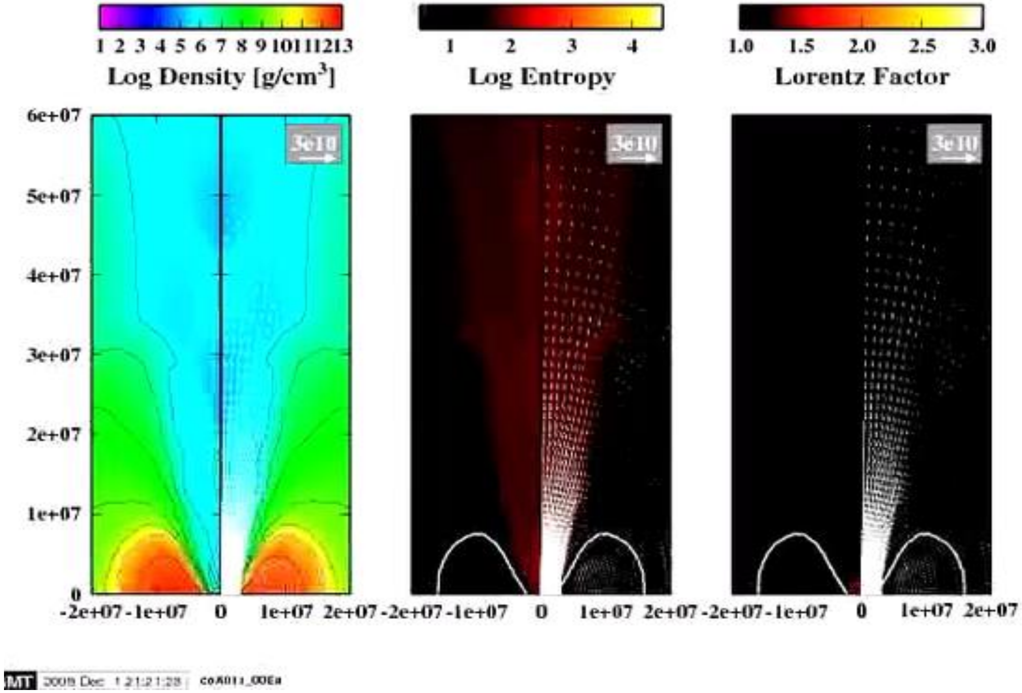
Nakamura, Kajino, Mathews, Sato, Harikae, A&Ap 582 (2015), A34.

- **Collapsar = Failed Supernova**
- Produces a **Black Hole** and
  a high temperature **Accretion Disk**.
- **MHD + ν-heating triggers Energetic Jet**.
- A Model of central engine for Long-GRB

≠

Hypernova = Super-Luminous SN

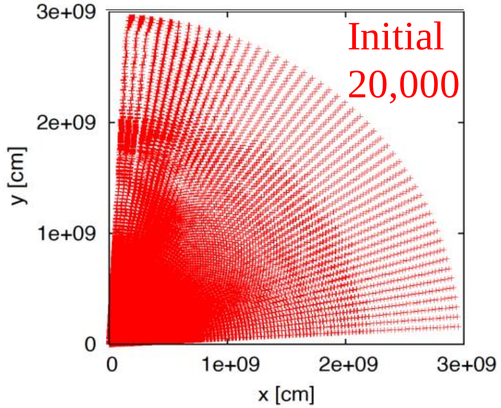
Siegel, Barnes & Metzger,
Nature 569 (2019), 243.

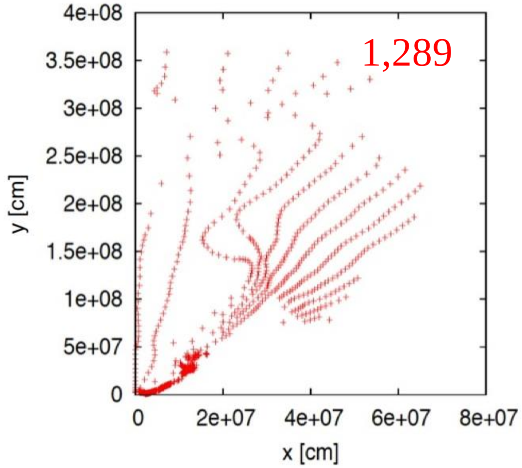


Modeling the r-process

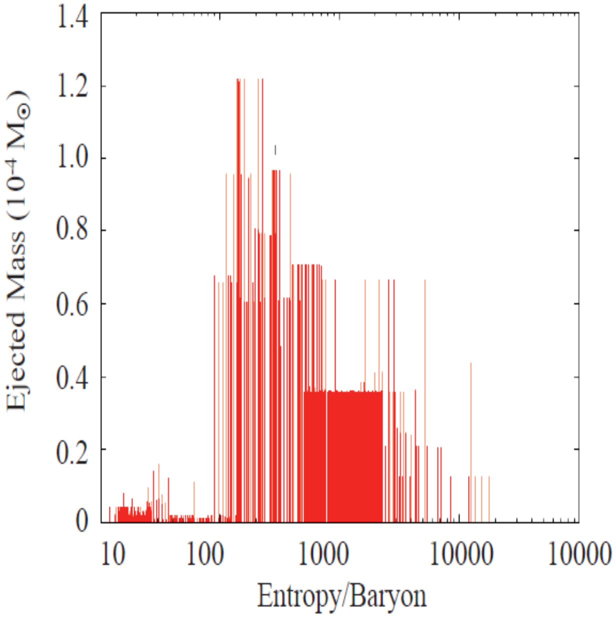
Surman et al. 2008; Fujimoto et al. 2008; Ono et al. 2012;
Nakamura, Kajino, Mathews, Sato, Harikae, A&Ap 582 (2015), A34.

- **Extend the jet beyond the MHD+neutrino pair heating using 2D hydo** (Takiwaki et al., 2009; Harikae et al., 2009).
- **Attach 20,000 tracer particles to evolve the flow of material into the accretion disk and out into the jet.**
- **1,289 trajectories are ejected with positive energy.**

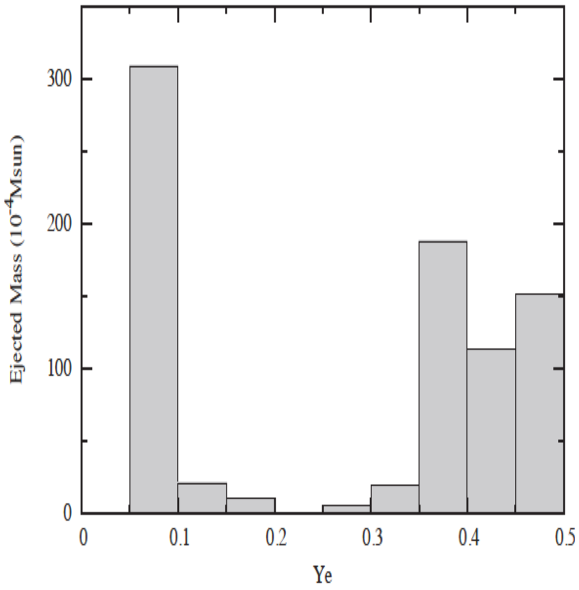




Entropy distribution



Y_e distribution

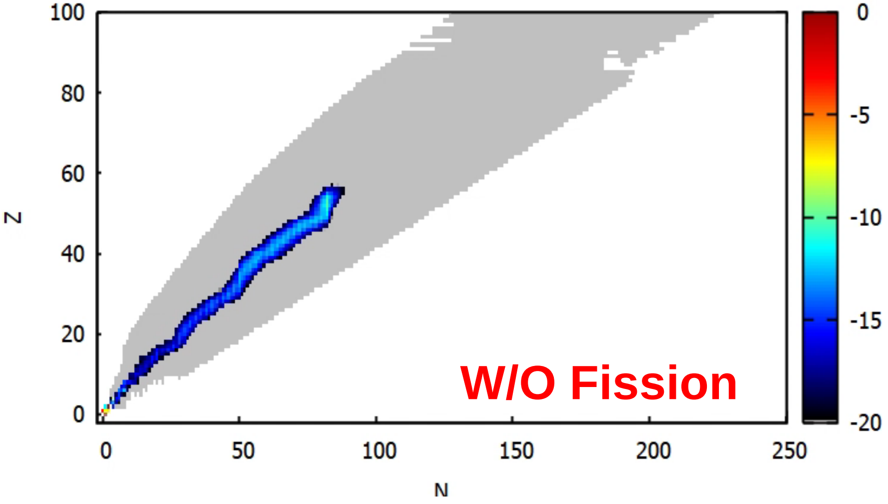


Collapsar Jet r-process

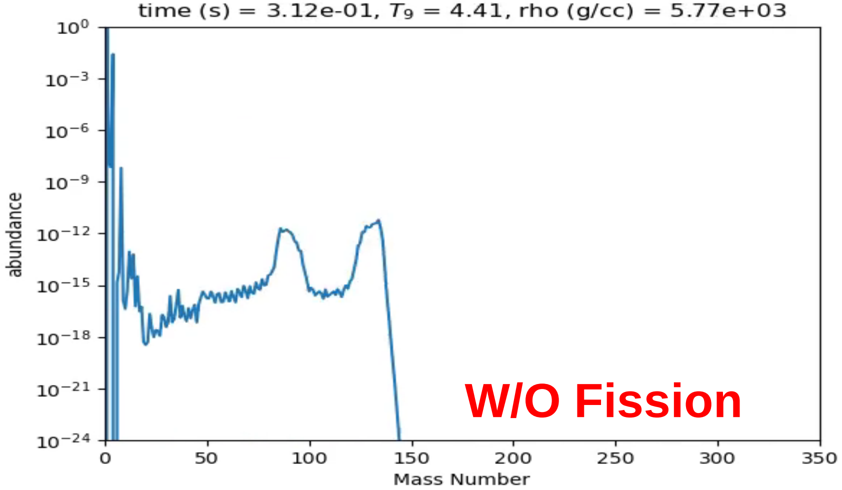
Fission Effect

Zhenyu He, M. Kusakabe, T. Kajino, G. Mathews, Y. Yamazaki, et al., (2022).

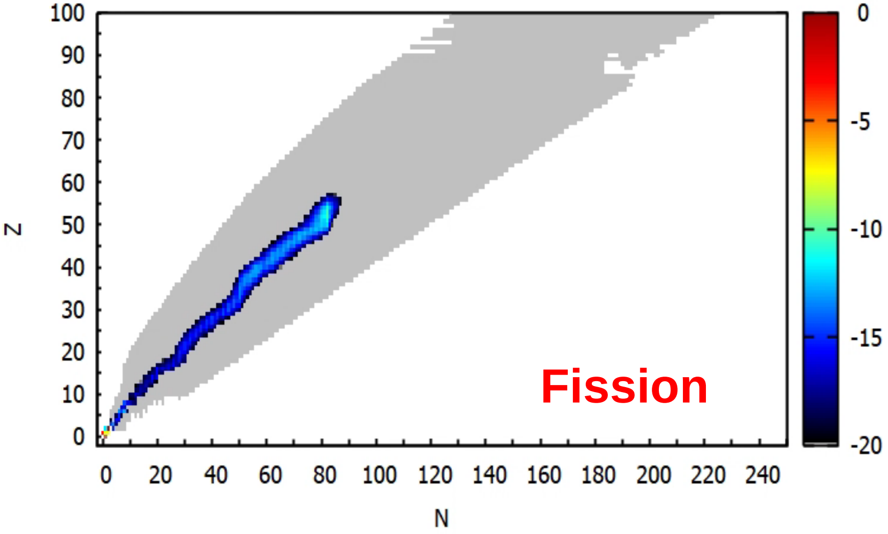
time(s) = 3.8641E-01; t9 = 3.8903; rho(gcc) = 4.3707E+03; Ye = 0.0504; Yn = 0.8994



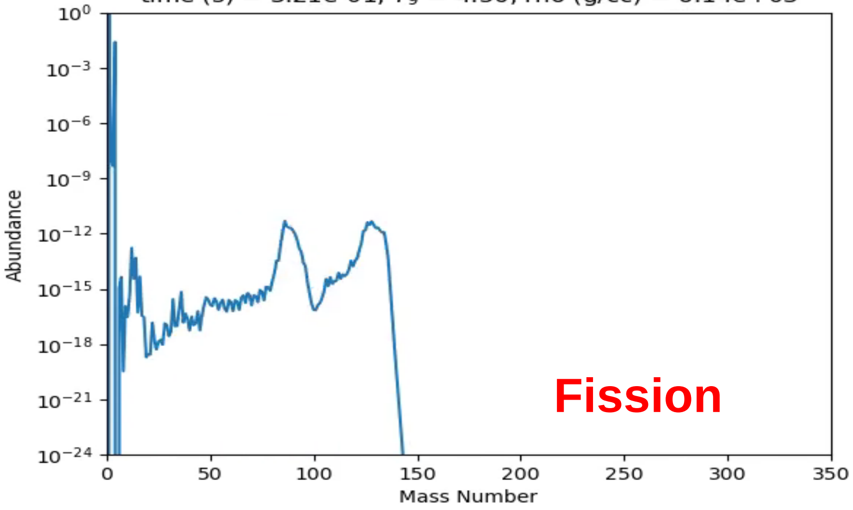
time (s) = 3.12e-01, T_9 = 4.41, rho (g/cc) = 5.77e+03



time(s) = 3.7343E-01; t9 = 4.1059; rho(gcc) = 4.8898E+03; Ye = 0.0504; Yn = 0.8995



time (s) = 3.21e-01, T_9 = 4.50, rho (g/cc) = 6.14e+03



Strong Magnetic Field : $B \neq 0$

Relativistic Fermi-Dirac Screening of β-decays
Landau Quantization

Relativistic Fermi-Dirac Screening Effect on e's ($B = 0$)

$$n = -\frac{e}{4\pi}\int_0^\infty d^3p\left[\frac{1}{e^{(E-\mu-e\phi)/T}+1} - \frac{1}{e^{(E+\mu+e\phi)/T}+1}\right]$$

Relativistic Screening ($B \neq 0$) with **Landau Quantization**

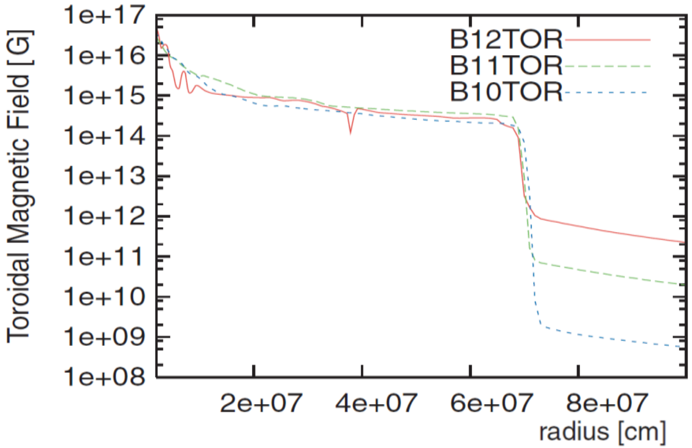
$$n = -\frac{eB}{2\pi^2}\sum_{\nu=0}^{\infty} g_\nu \int_0^\infty dp_z\left(\left[\exp\left(\frac{\sqrt{p_z^2+m_e^2+2\nu eB}-\mu-e\phi}{T}\right)\right.\right.$$

Poisson-Boltzmann Equation ($B \neq 0$)

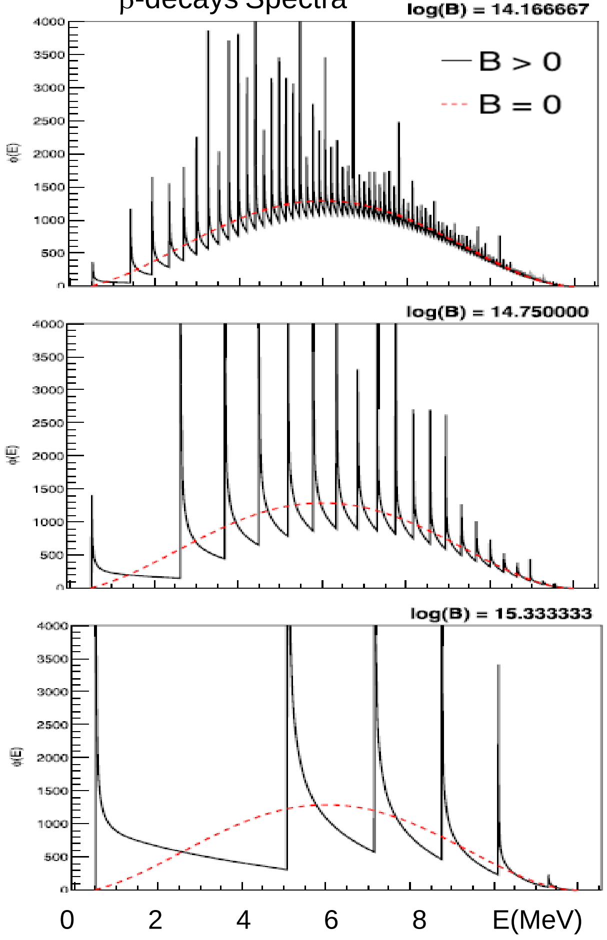
$$\nabla^2\phi(r) = -4\pi Z e\delta^3(\mathbf{r}) - 4\pi\sum_{z>0} z e n_z \exp\left[-\frac{ze\phi_r}{T}\right] + 4\pi$$

$$+\frac{eB}{\pi}\sum_{n=0}^{\infty} g_n \int_0^\infty dp\left[\frac{1}{\exp\left[\frac{\sqrt{E^2+2neB}-\mu-e\phi_r}{T}\right]+1} - \frac{}{\exp}\right.$$

$$-\frac{eB}{\pi}\sum_{n=0}^{\infty} g_n \int_0^\infty dp\left[\frac{1}{\exp\left[\frac{\sqrt{E^2+2neB}-\mu}{T}\right]+1} - \frac{}{\exp\left[\sqrt{E}\right.}\right.$$

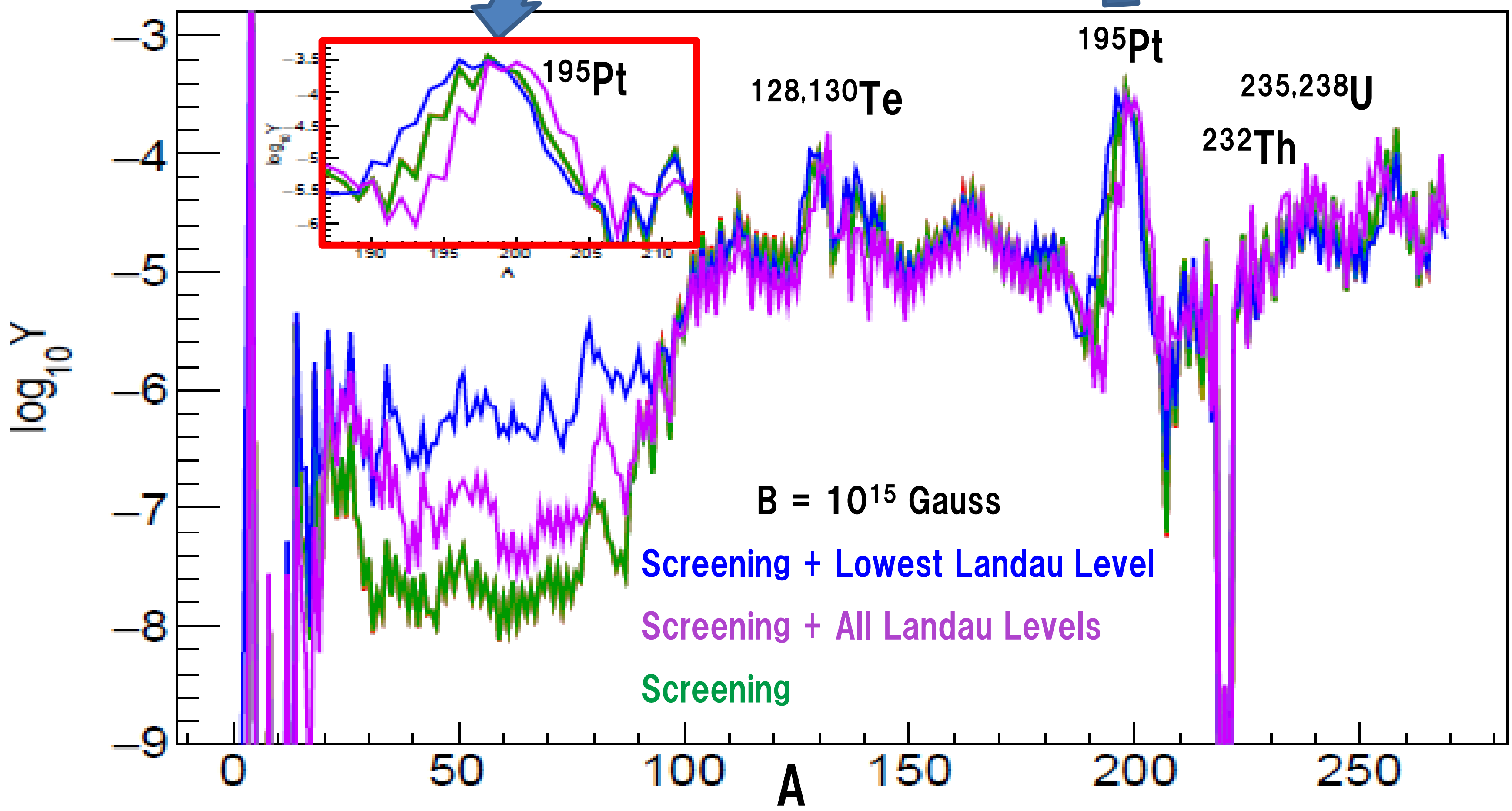


β-decays Spectra



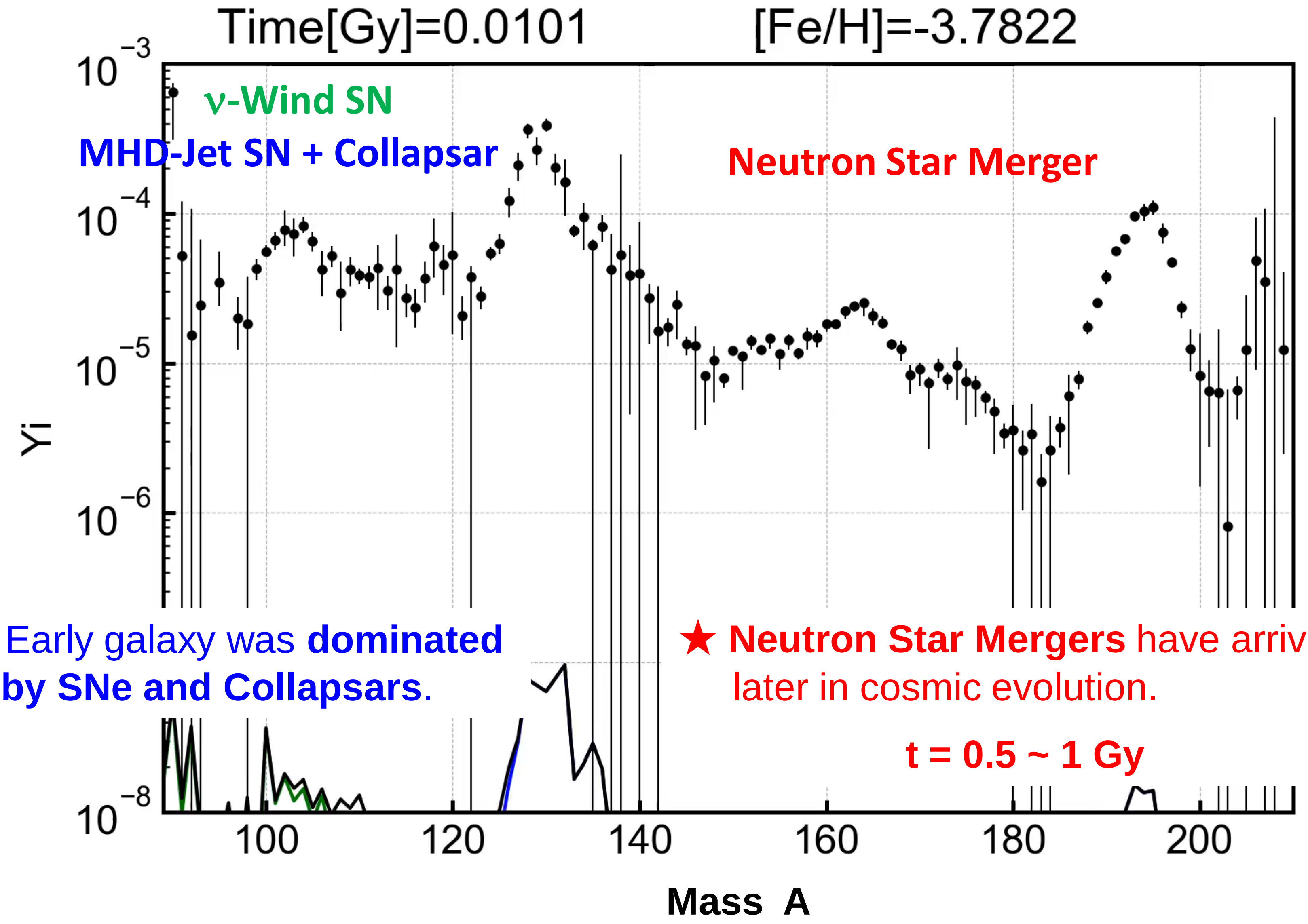
Strong Magnetic Field Effect on COLLAPSAR r-process

Famiano, Balantekin, Kajino, Kusakabe, Mori, Luo, ApJ **898** (2020), 163.
Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ (2022), in press.
Zhenyu He, M. Kusakabe, T. Kajino, G. J. Mathews, Y. Yamazaki, et al., (2022).



Cosmic & Galactic Evolution of R-Process Nuclei

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ (2022), in press. (arXiv:2102.05891)



★ Early galaxy was **dominated by SNe and Collapsars.**

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

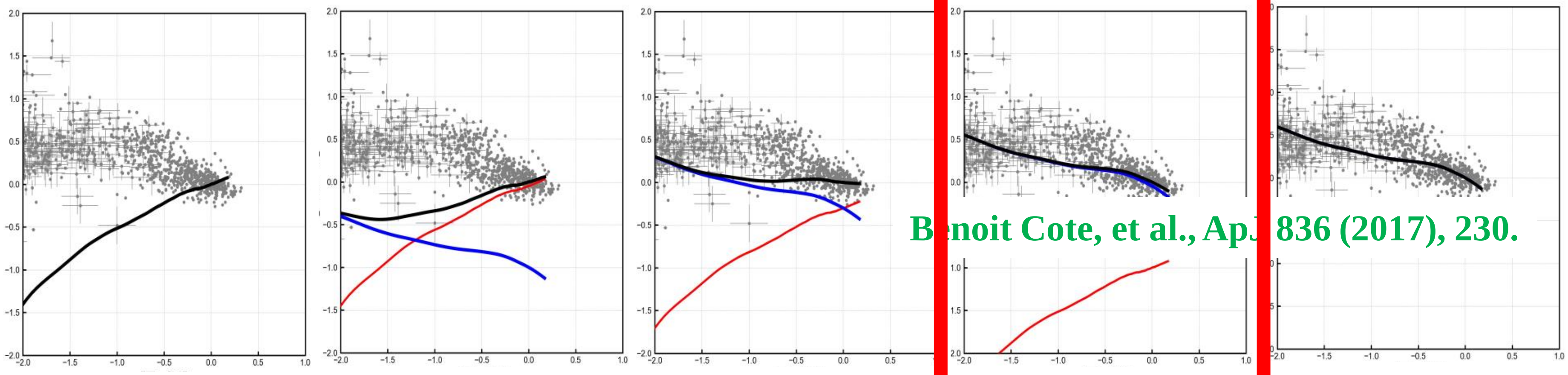
t = 0.5 ~ 1 Gy

Milky Way : Coalescence Time Delay of NSM

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ (2022), in press. (arXiv:2102.05891)

NSM (τ_C=0.1 Gy)

100% **90%** **50%** **10%** **0%**



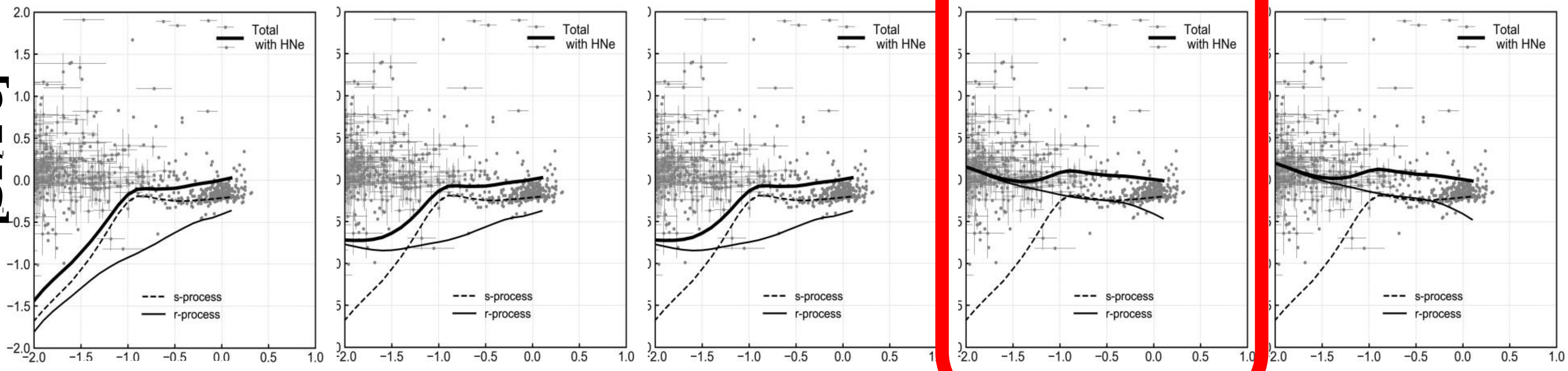
[Eu/Fe]

[Fe/H]

Benoit Cote, et al., ApJ 836 (2017), 230.

10% **50%** **90%** **100%**

CCSN + Collapsar

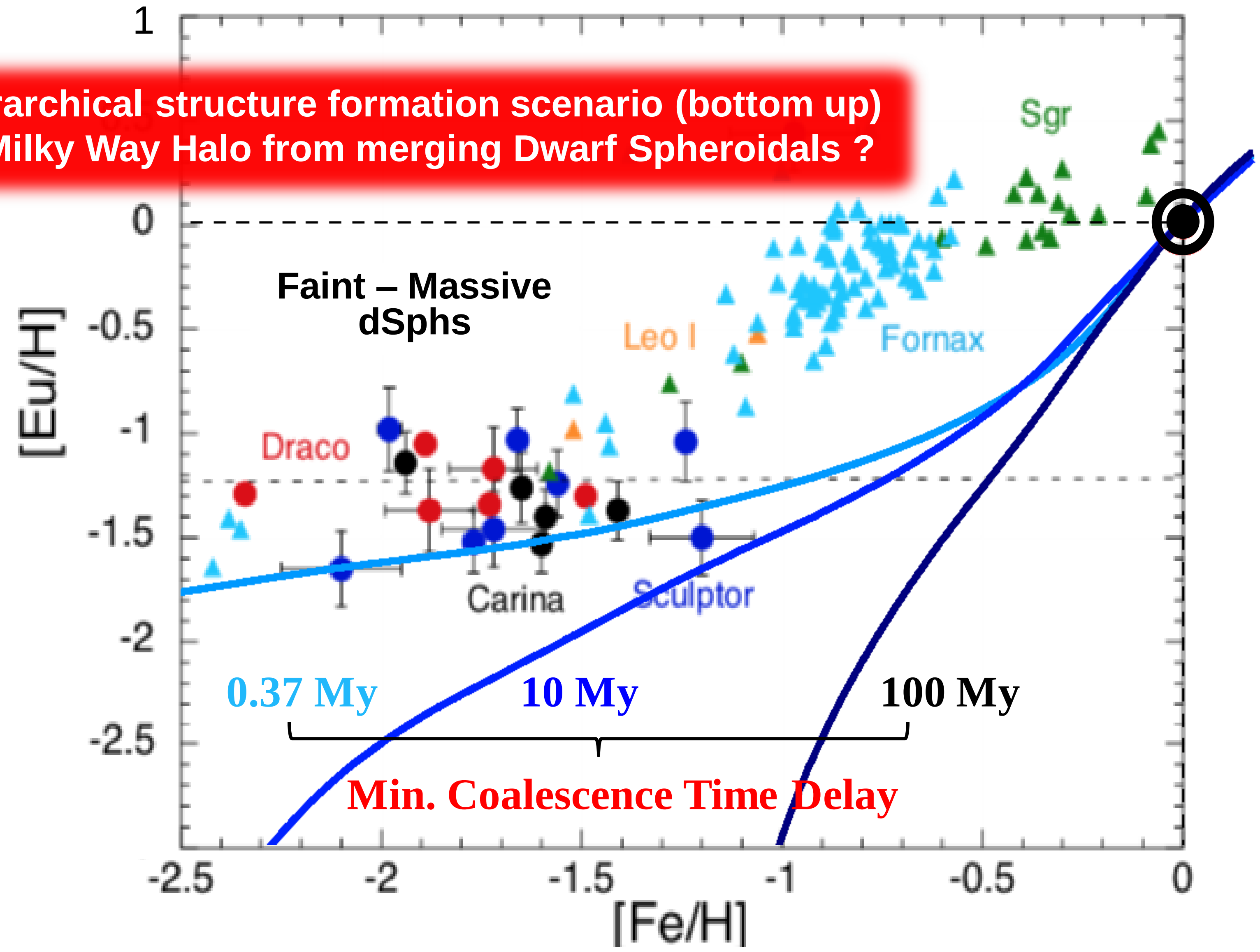


[Sr/Fe]

[Fe/H]

Dwarf Spheroidals

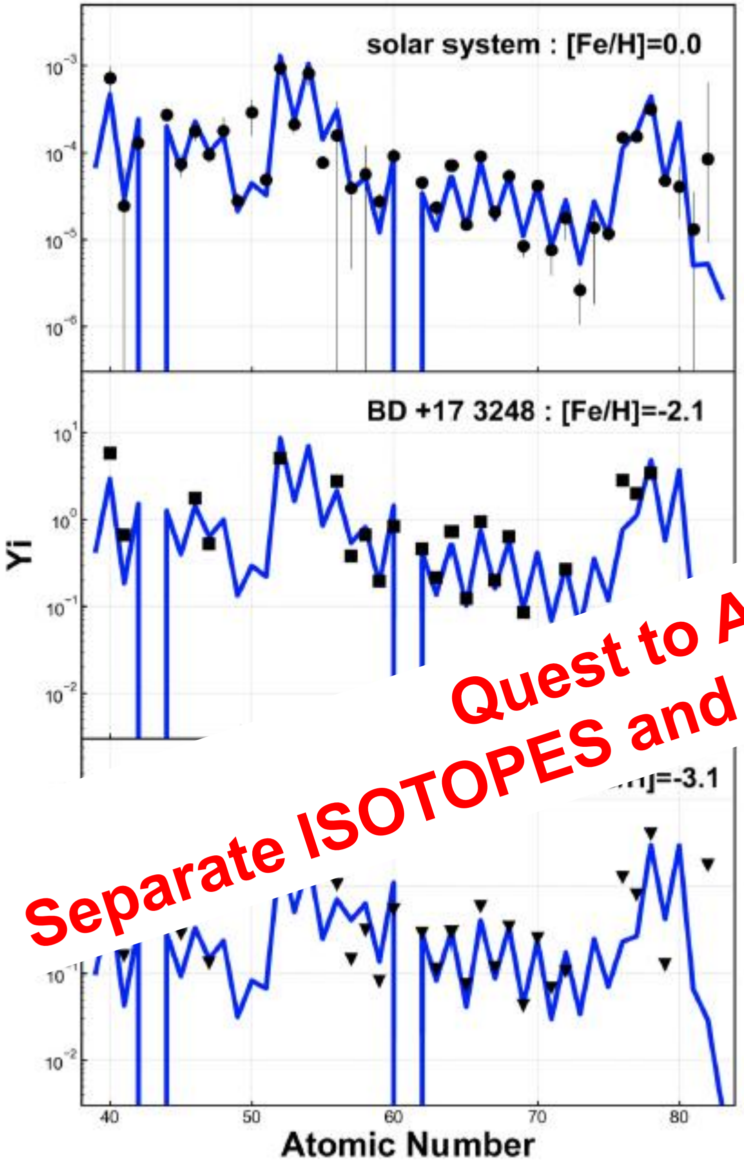
Yamazaki, He, Kajino, Mathews, Tang, Shi, Famiano et al. (2022), ApJ, in press.



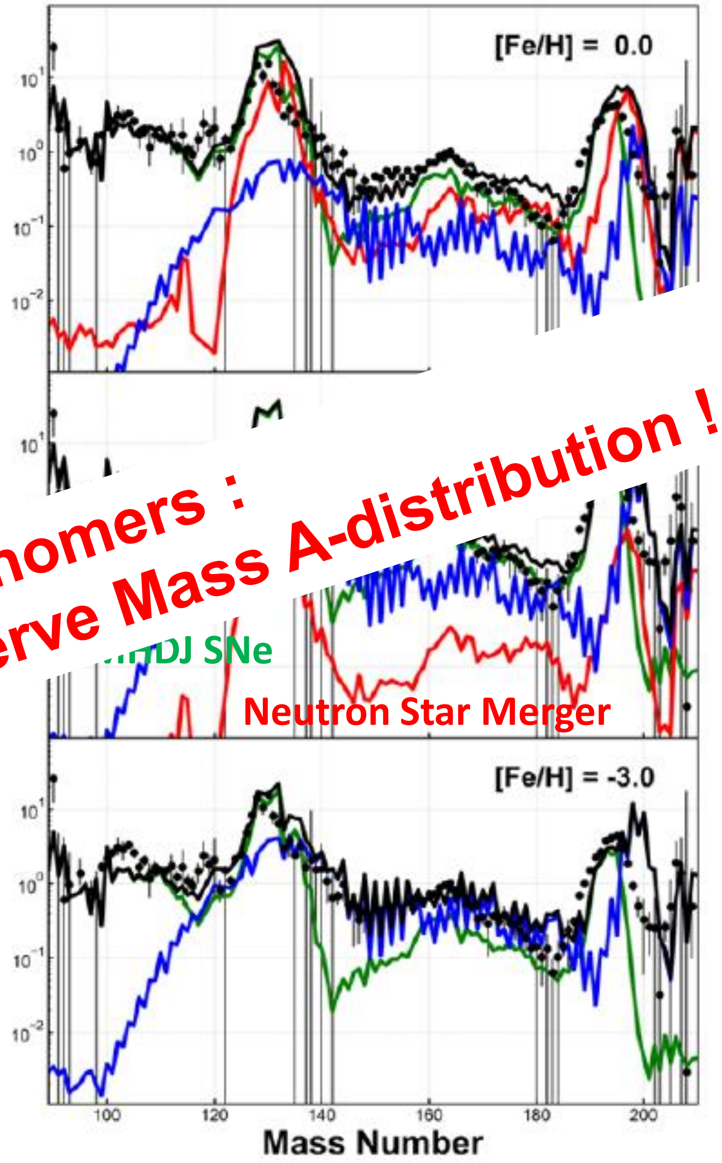
Hierarchical structure formation scenario (bottom up) of Milky Way Halo from merging Dwarf Spheroidals ?

Galactic Chemical Evolution

Yamazaki, He, Kajino, Mathews, Famiano, Tang, Shi, ApJ (2022), in press. (arXiv:2102.05891)



Symm. & Asymm. fission



Symm. fission

Quest to Astronomers :

Separate ISOTOPES and observe Mass A-distribution !

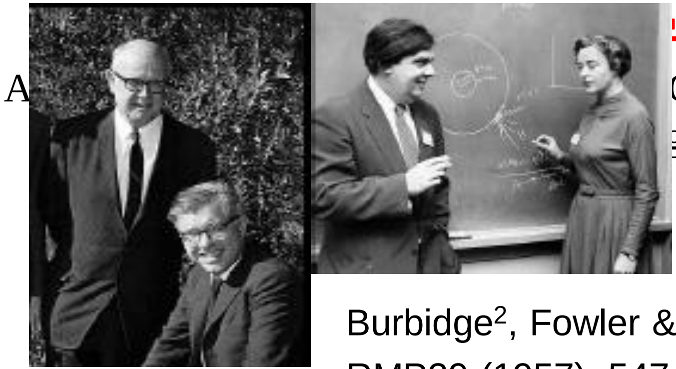
宙核物理进展

A

Guo, Hahn, Liu, Liu,

g, Wang, We

Origin of p-nuclei and the roles of νp-process

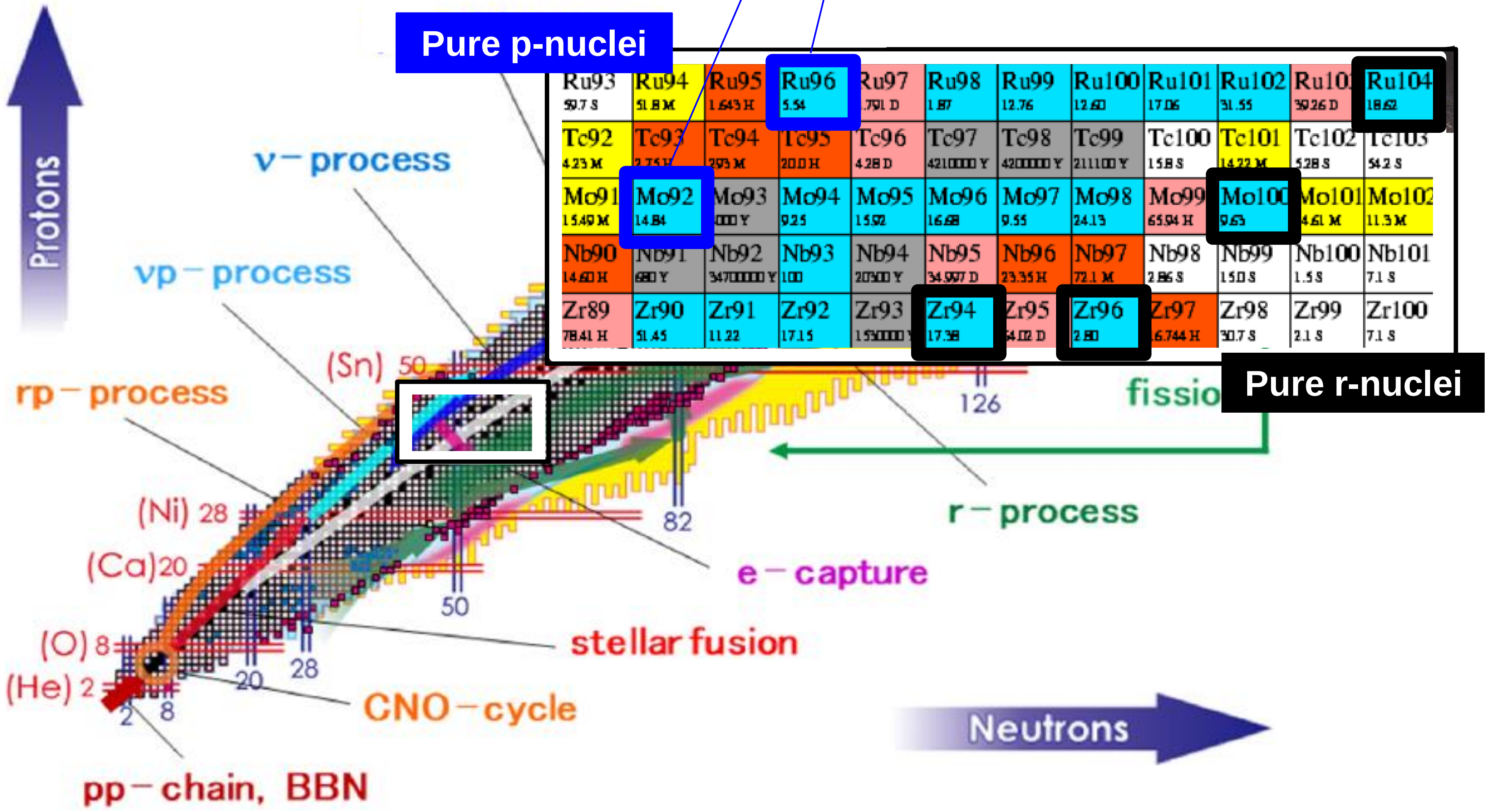


Burbidge^2, Fowler & Hoyle
RMP29 (1957), 547.

^{92}Mo 14.53%

^{96}Ru 5.54%

All other p-nuclei ~ 0.1-1%



Pure p-nuclei

Ru93 59.7 S	Ru94 51.8 M	Ru95 1.643 H	Ru96 5.54	Ru97 .791 D	Ru98 1.87	Ru99 12.76	Ru100 12.60	Ru101 17.06	Ru102 31.55	Ru10 39.26 D	Ru104 18.62
Tc92 4.23 M	Tc93 2.75 H	Tc94 293 M	Tc95 20.0 H	Tc96 4.28 D	Tc97 4210000 Y	Tc98 4200000 Y	Tc99 211100 Y	Tc100 15.8 S	Tc101 14.22 M	Tc102 5.28 S	Tc103 54.2 S
Mo91 15.49 M	Mo92 14.84	Mo93 4000 Y	Mo94 9.25	Mo95 15.92	Mo96 16.68	Mo97 9.55	Mo98 24.13	Mo99 65.94 H	Mo100 9.63	Mo101 4.61 M	Mo102 11.3 M
Nb90 14.60 H	Nb91 680 Y	Nb92 34700000 Y	Nb93 100	Nb94 20300 Y	Nb95 34.997 D	Nb96 23.35 H	Nb97 72.1 M	Nb98 2.86 S	Nb99 15.0 S	Nb100 1.5 S	Nb101 7.1 S
Zr89 78.41 H	Zr90 51.45	Zr91 11.22	Zr92 17.15	Zr93 1530000 Y	Zr94 17.38	Zr95 4.02 D	Zr96 2.80	Zr97 16.744 H	Zr98 30.7 S	Zr99 2.1 S	Zr100 7.1 S

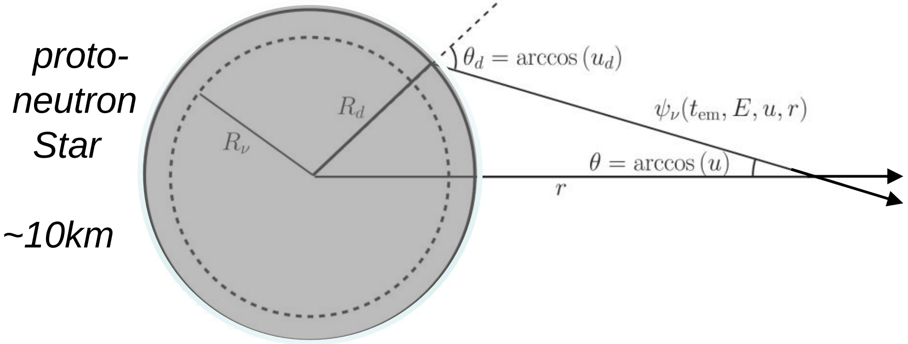
Pure r-nuclei

Collective + MSW ν Oscillations — Many Body Quantum 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 and Pehlivan, PR D96 (2017), 043013

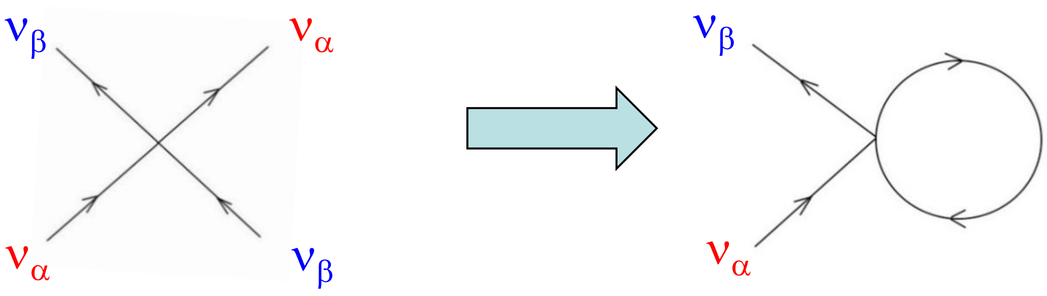
ν–sphere



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

Collective flavor oscillation in coherent ν-ν scattering

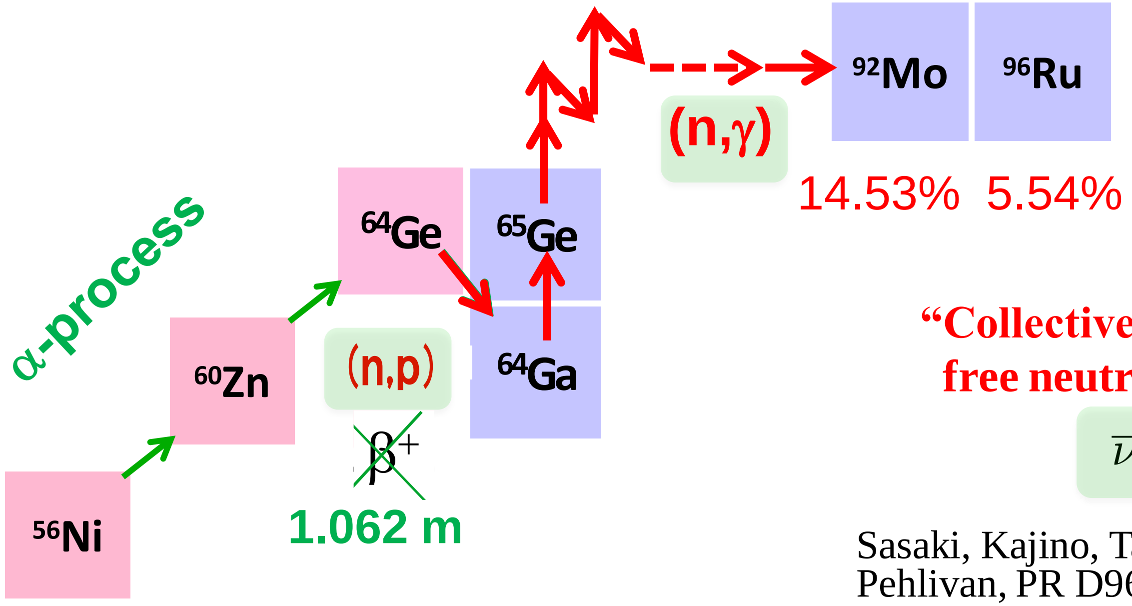
$$\boxed{H_\nu} = \sqrt{2}G_F\sum_\alpha\int dE'\underset{\text{ν angle dep !}}{\underline{d\Omega'(1-uu')}}\left[\frac{d^2n_{\nu_\alpha}}{dE'd\Omega'}\rho_{\nu_\alpha}(t'_{\rm em}, E', u', r) - \frac{d^2n_{\bar{\nu}_\alpha}}{dE'd\Omega'}\rho^*_{\bar{\nu}_\alpha}(t'_{\rm em}, E', u', r)\right].$$



α, β = e, μ, τ

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

νp−process including Collective Oscillation in Supernova



α-process

^{56}Ni

^{60}Zn

^{64}Ge

^{65}Ge

^{64}Ga

(n,p)

$\cancel{\beta^+}$

1.062 m

(n,γ)

^{92}Mo

^{96}Ru

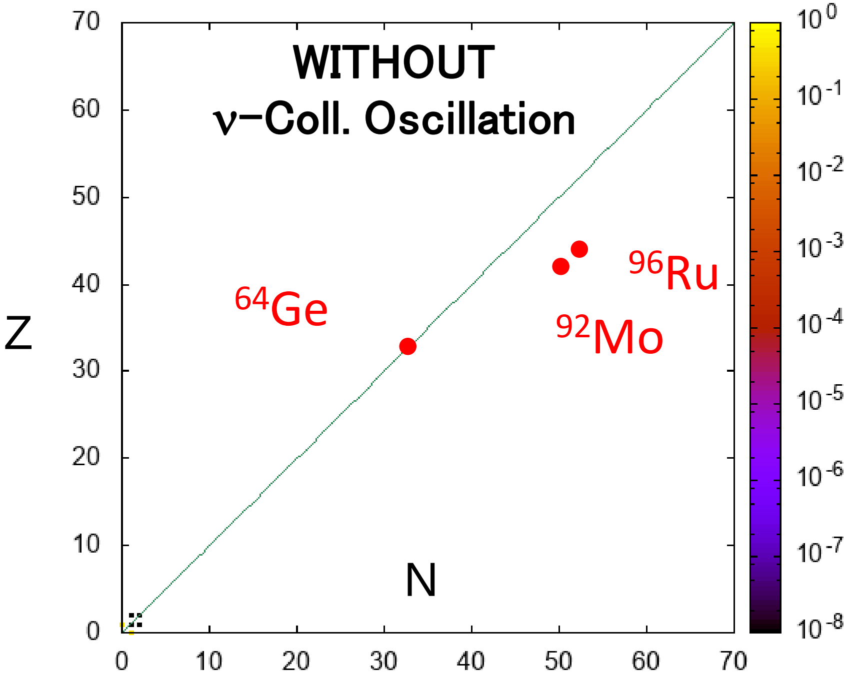
14.53% 5.54%

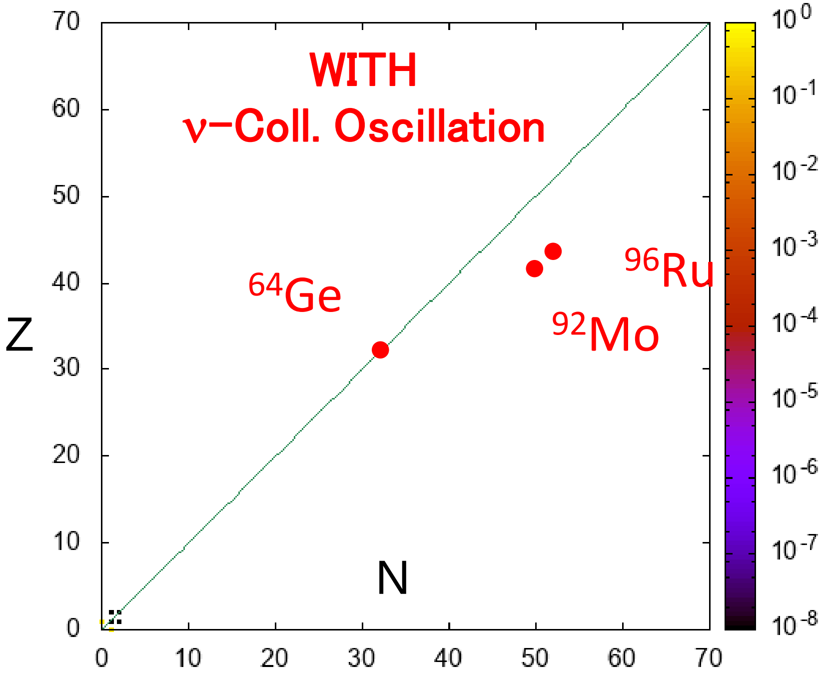
Isotopic ratio of p-nuclei
~ 0.1-1%

“Collective ν-oscillation” produces free neutrons continuously.

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

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



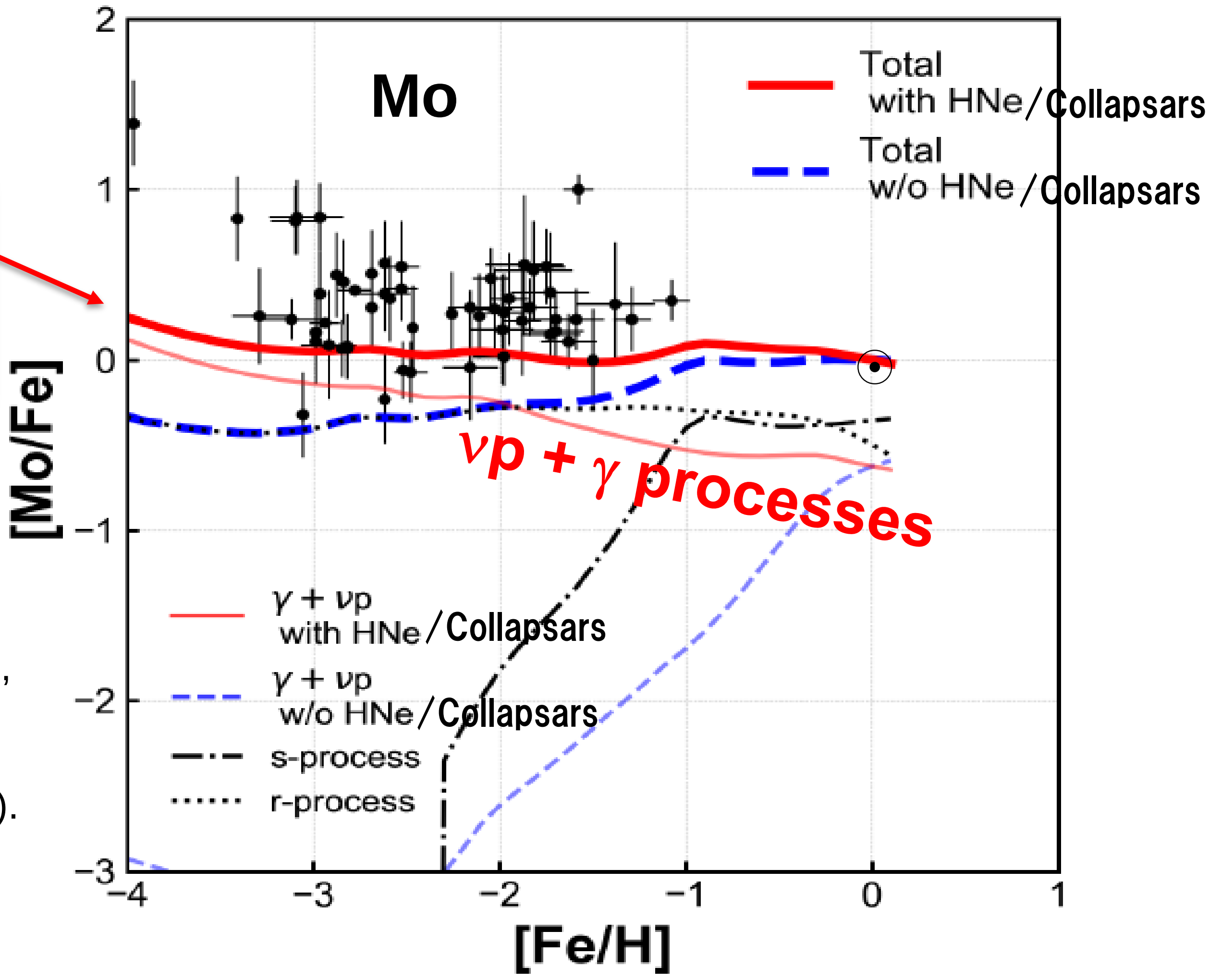


Cosmic & Galactic Chem. Evolution

Mo	^{92}Mo	^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
	p	**p** + s	**s**	s + **r**	**s**	s + **r**	**r**
	14.53%	9.15%					

νp-process

in Collapsar + MHDJ-SN

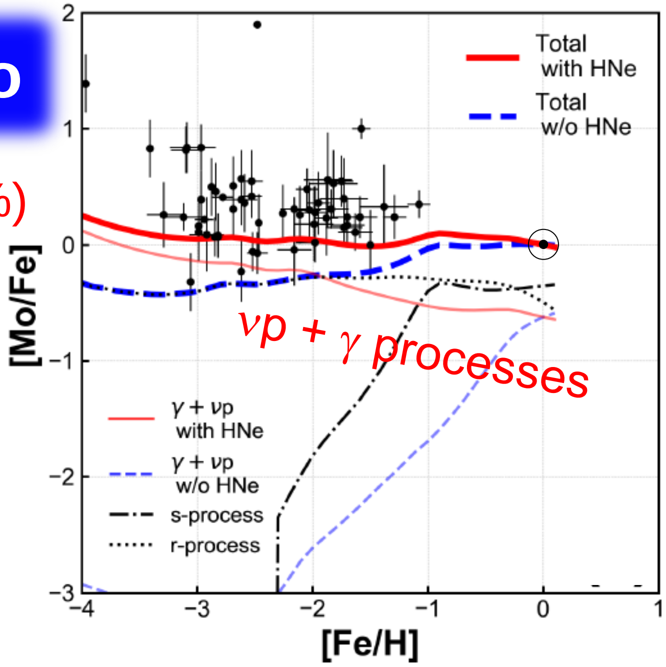


νp + γ processes

Sasaki, Yamazaki, Kajino, Kusakabe, Hayakawa, Cheoun,Ko, Mathews, ApJ 924 (2022), 29 (7 pp).

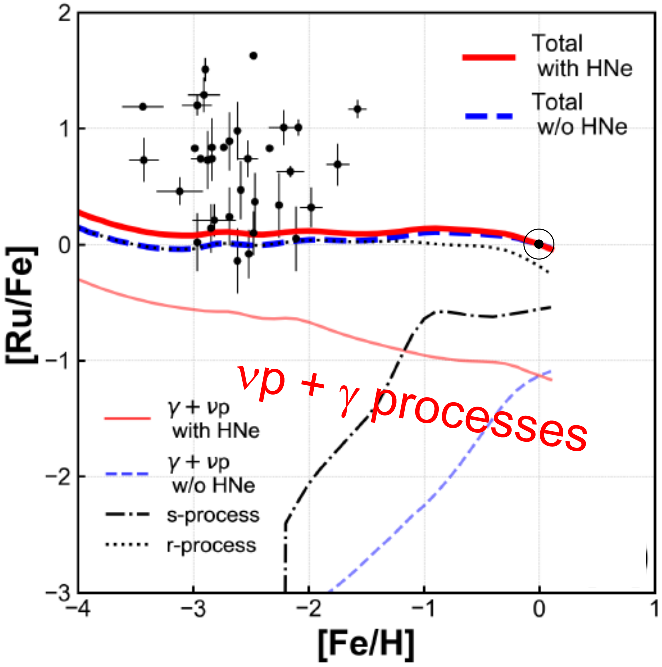
$^{92\text{-}100}$Mo

(p= 23.7%)



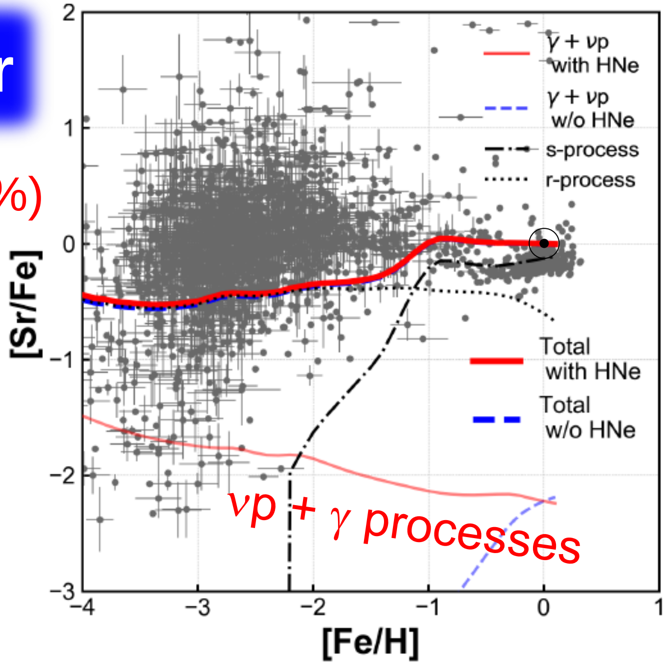
$^{96\text{-}104}$Ru

(p= 7.4%)



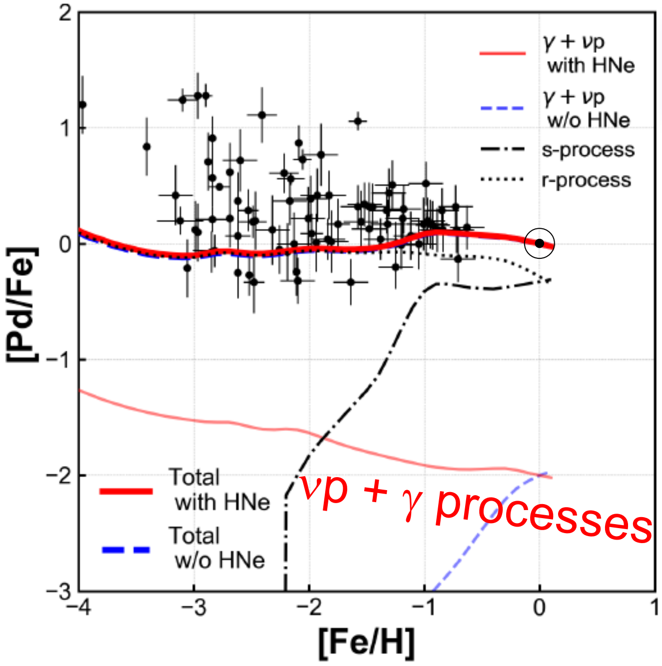
$^{84\text{-}88}$Sr

(p= 0.56%)



$^{102\text{-}110}$Pd

(p= 1.02%)



Summary

1. Galactic Chemical Evolution R-process Elements

Supernovae and **collapsars** are the main sites for the heavy element production over the entire history of galactic evolution. **Neutron star mergers** have arrived later and contribute partially to the solar-system elements.

2. Origin of ^{92,94}Mo and ^{96,98}Ru

Origin of abundant p-nuclei ^{92,94}Mo and ^{96,98}Ru in the early Galaxy is dominated by the **νp-process** in **collapsar** nucleosynthesis.

3. Isomers in R-process

New isomer in ^{127}Cd could affect the 2nd r-process peak though the β-decay and β-delayed one & two neutron emissions from ^{128}Ag. This effect is **independent** of astrophysical models of **supernova, collapsar or neutron star merger.**

4. Origin of ^{180}Ta/^{138}La, ^{92}Nb and ^{98}Nb

Solar system ^{180}Ta and ^{138}La are explained consistently by supernova ν-process. Intra and inter **isomer-intermediate-ground** transitions of ^{180}Ta is found to be critical.

5. Flavor Oscillation and the ν-mass Hierarchy

Supernova **ν-process** of ^{7}Li and ^{11}B is quantitatively the most sensitive probe of the **ν-flavor oscillation** in high-density matter and could constraint the **ν-mass hierarchy**.