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Recent Progress in the Studies of Neutron Star Merger & Supernova and their Impact on Nuclear Physics

Taka Kajino 梶野 敏貴

Beihang University 北京航空航天大学

International Reearchs Centr for Big-Bang Cosmology and Element Genesis

National Astron. Observatory of Japan 国立天文台

The University of Tokyo 日本国東京大学

GW170817

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

GW170817 / SSS17a

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

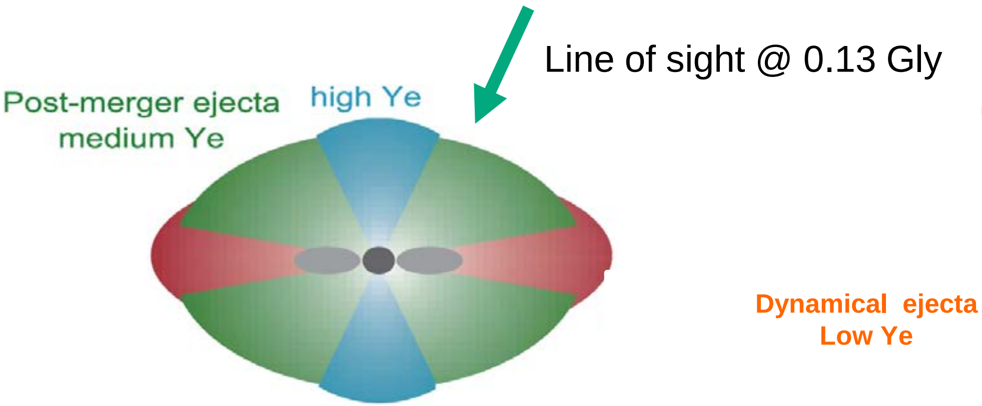
◆ **No r-element, identified.**

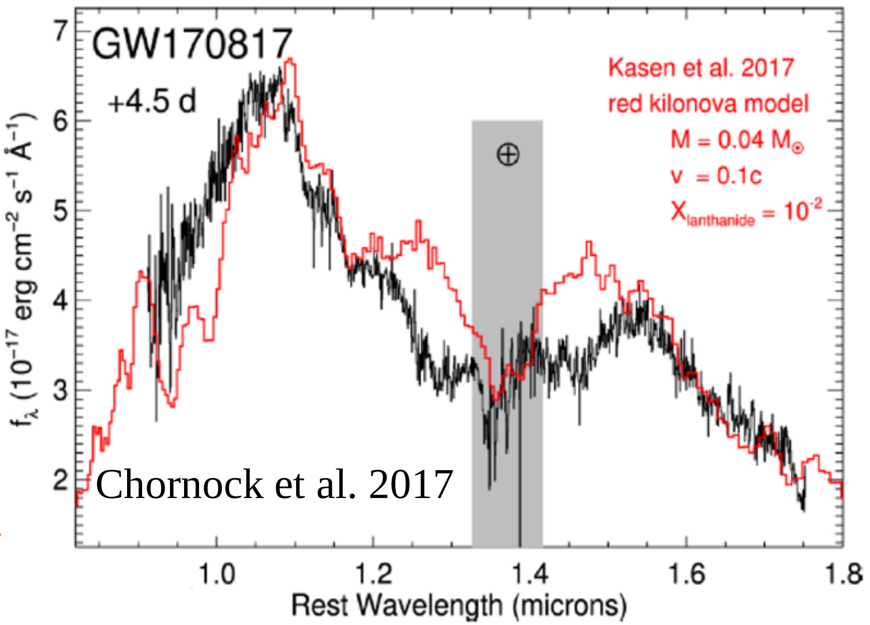
? Line of sight → Different Y_e
→ Complicated hydrodyn.

? Ejecta → Different velocities, blue shifts
→ Hundreds of r-elements

? Incomplete Opacity + too many r-elements
+ α, β, γ, fission dep.

◆ **Emission Energy, consistent with radioactive decay of r-elements !**





Purpose

1. How to distinguish r–process in Neutron Star Mergers (NSMs) vs. Core–Collapse Supernovae (CCSNe) ? Time scale ?

→ **Fission + masses, β-decay, (n, γ)**

→ **GW170817 vs. SiC-X Grains, Sediments**

→ **Actinide Boost Stars …**

CC-SNe = Magneto-Hydrodyn. Jet + ν-Heated Wind

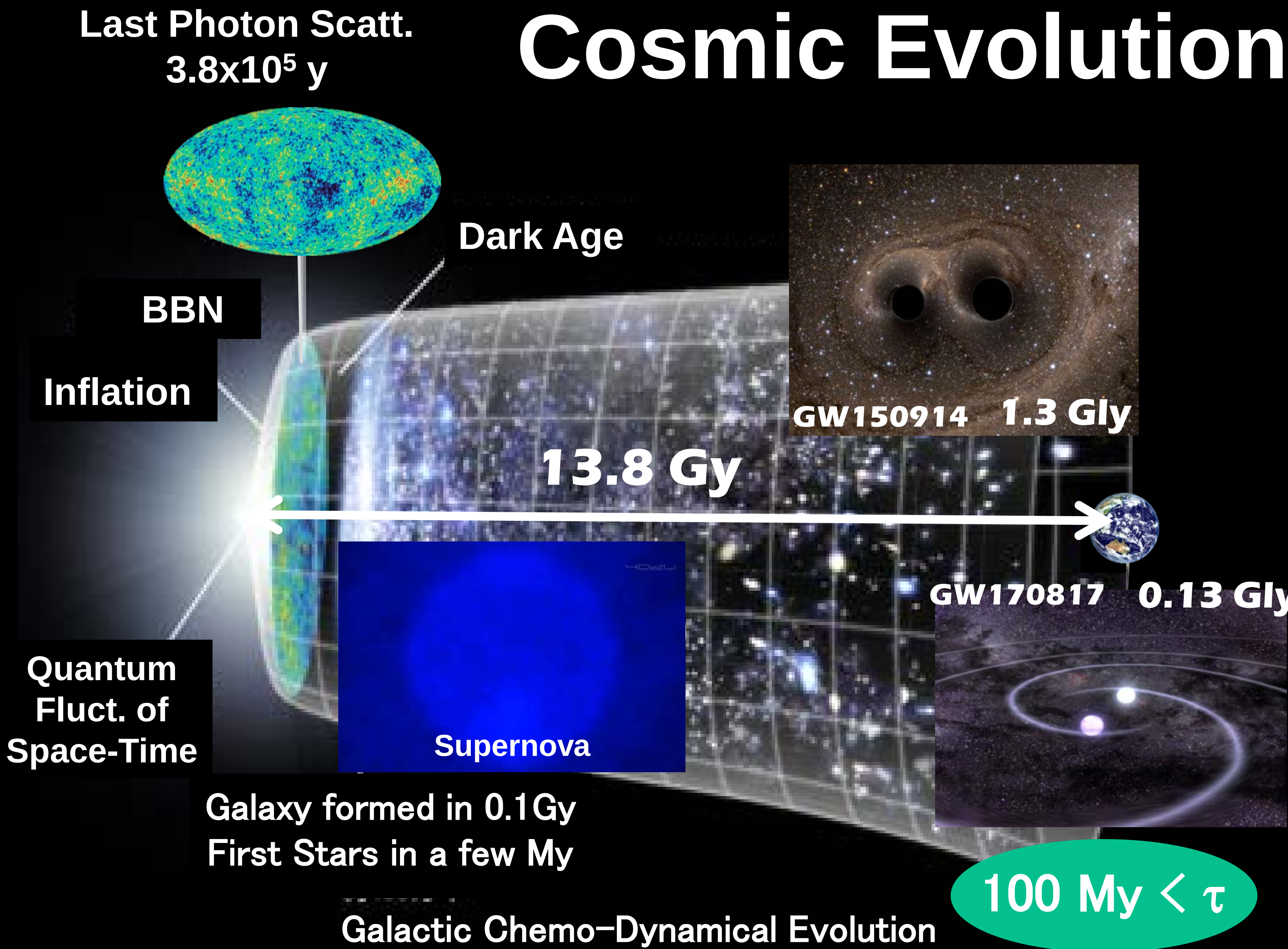
2. How to find the roles of ν–interactions and oscillations ?

→ **ν-induced Nucleosynthesis ⇔ CEX**

→ **ν-Oscillations, Hierarchy**

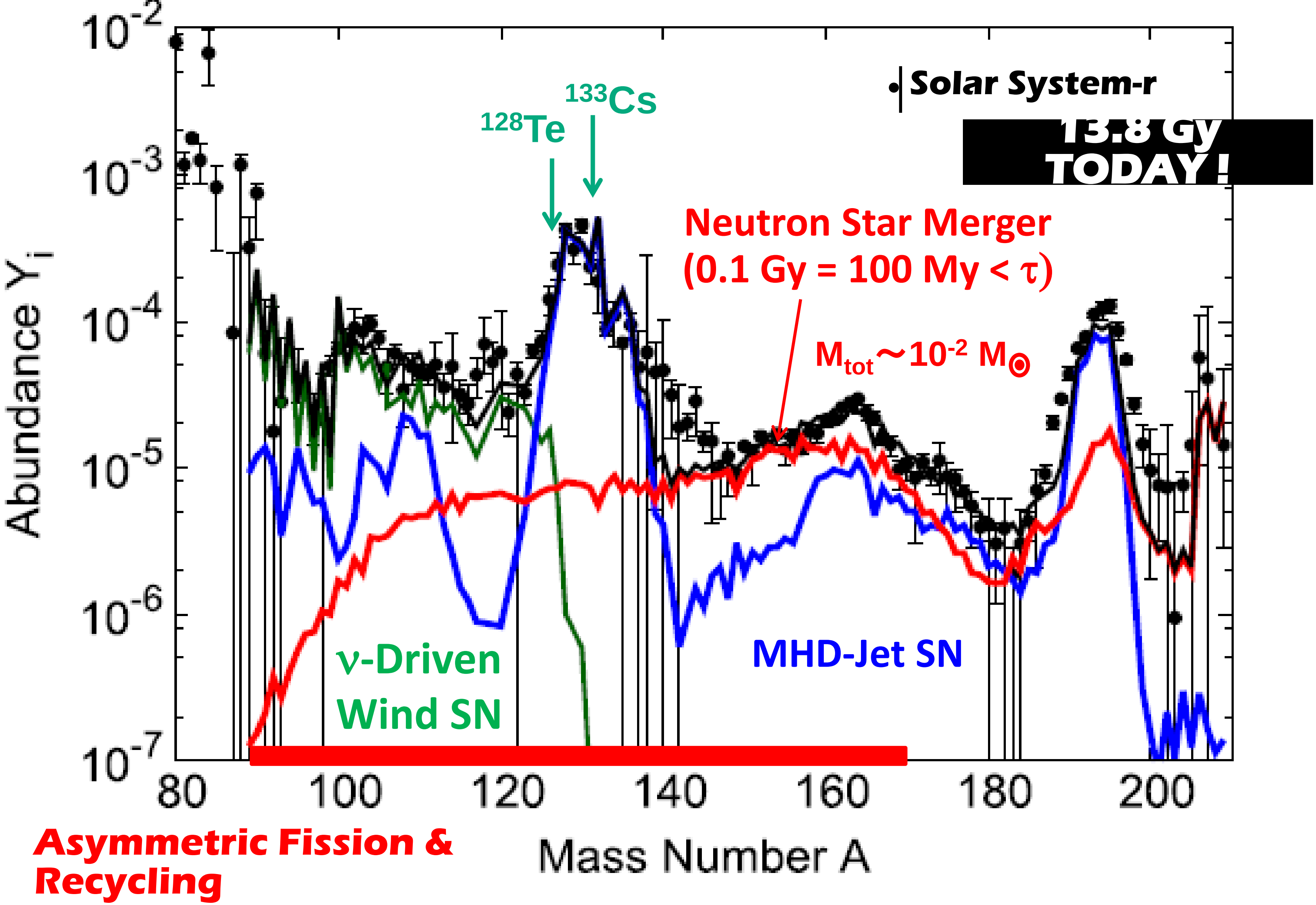
→ **Origin of Amino Acid Chirality**

Cosmic Evolution



Solar System r-Process Abundance

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



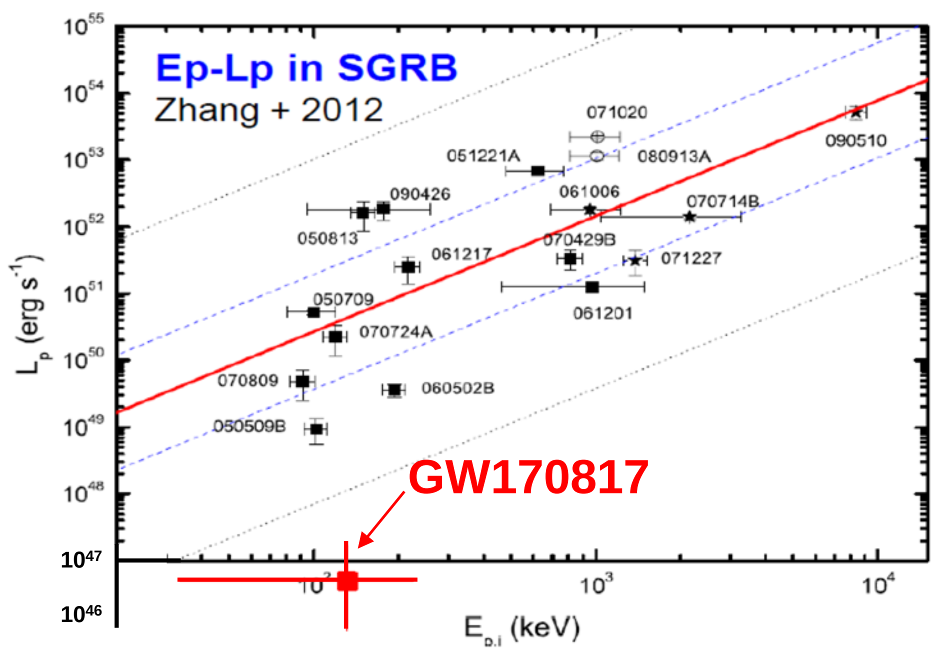
Observed event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]				
νSN (Weak r)	=	7.4×10^{-4}	x	(1.9 ± 1.1) [a]
MHD Jet SNe	=	0.6×10^{-2}	x	$((0.03 \pm 0.02) \times (1.9 \pm 1.1))$ [b]
Binary NSMs	=	$(2 \pm 1) \times 10^{-2}$	x	$(1\text{-}28) \times 10^{-3}$ [c]

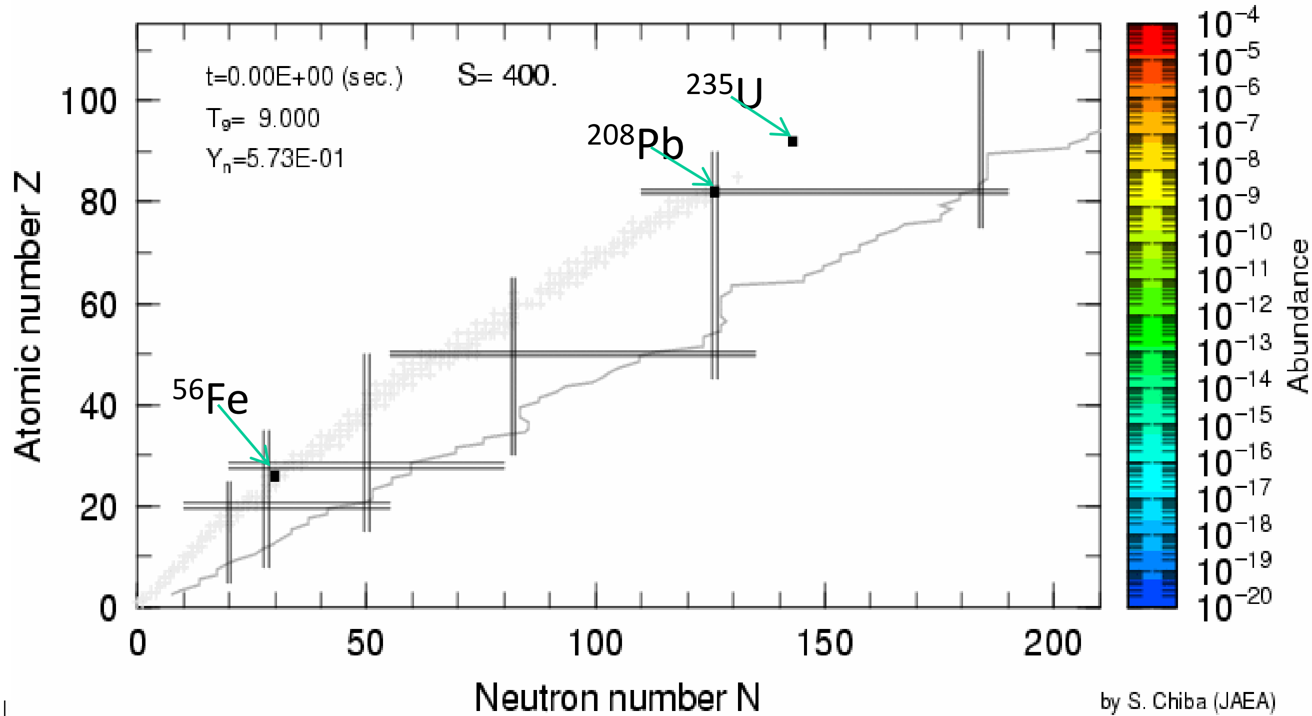
Observations	a	1.9 ± 1.1	Diehl, et al., Nature 439, 45 (2006).
	b	0.03 ± 0.02	Winteler, et al., ApJ 750, L22 (2012).
Obs. Estimate	c	$(1\text{-}28) \times 10^{-3}$	Kalogera, et al., ApJ 614, L137 (2004).

GW170817 is a clear evidence indicating that the central engine of the SGRB is binary NSM !

Why faint ?

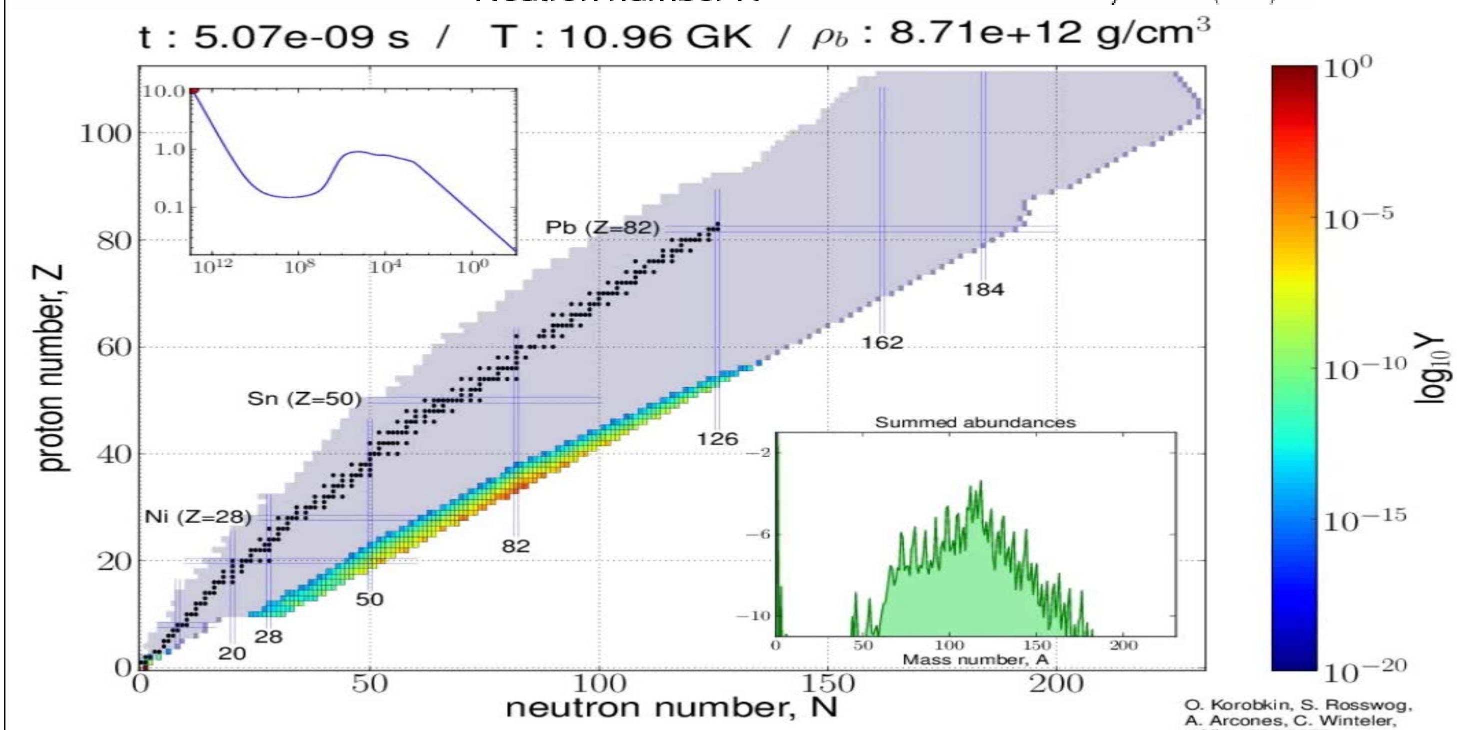


SN



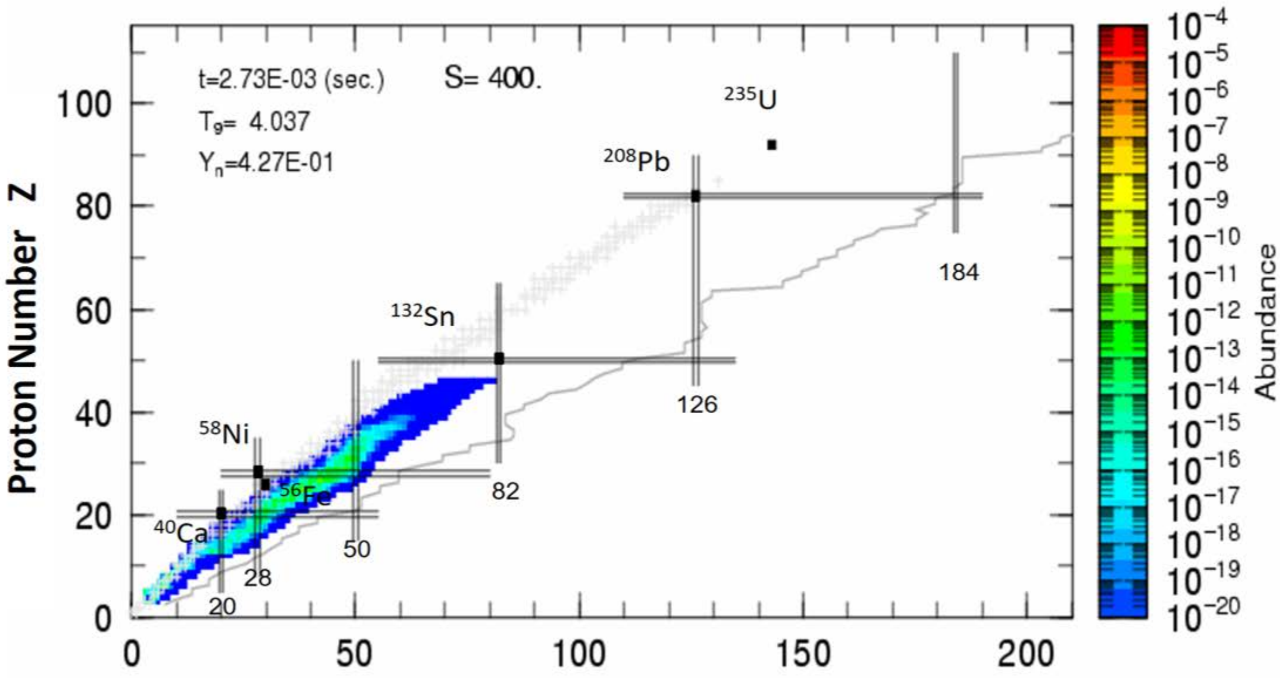
t=0.00E+00 (sec.)
S= 400.
T9= 9.000
Yn=5.73E-01
235U
208Pb
56Fe
Atomic number Z
Neutron number N
Abundance
by S. Chiba (JAEA)

NS Merger



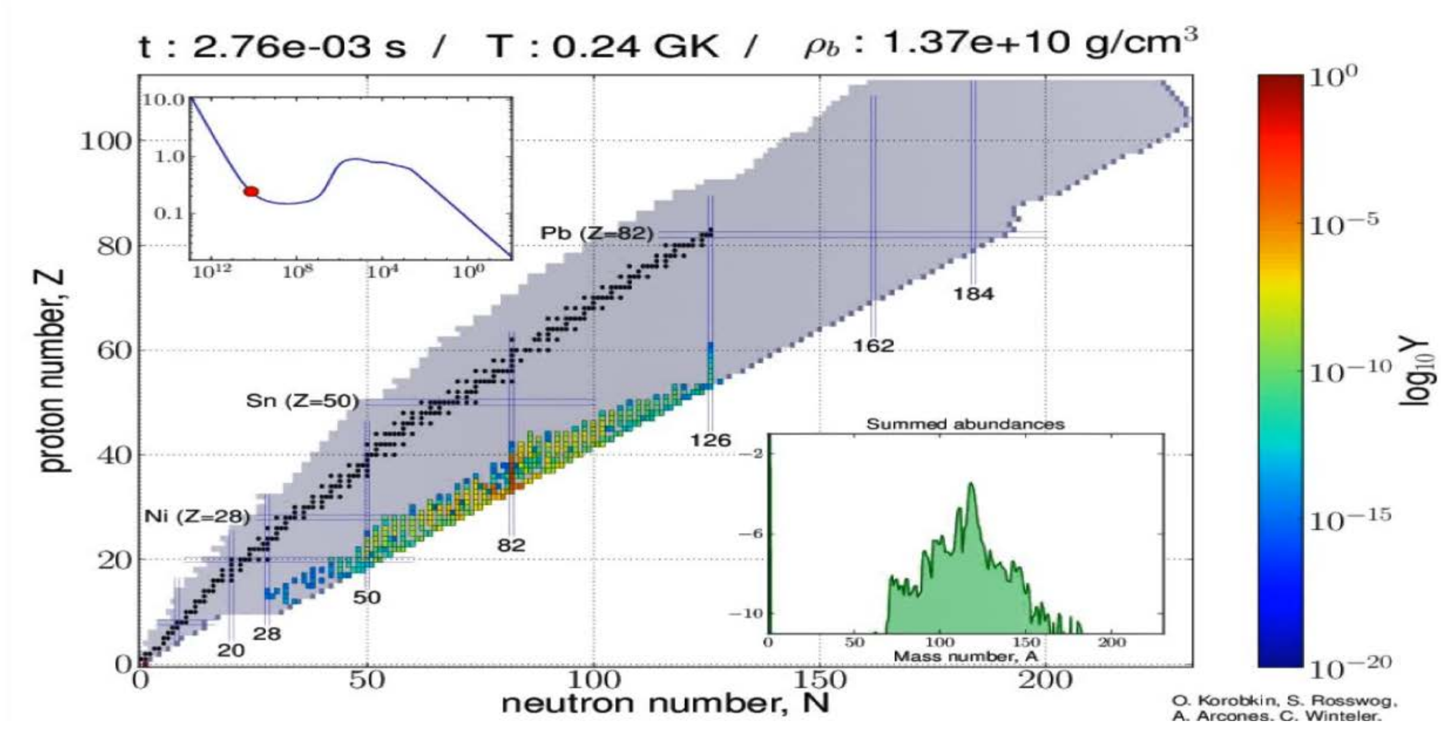
t : 5.07e-09 s / T : 10.96 GK / ρb : 8.71e+12 g/cm3
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
184
162
126
82
50
28
20
Summed abundances
Mass number, A
proton number, Z
neutron number, N
log10Y
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler,

SN



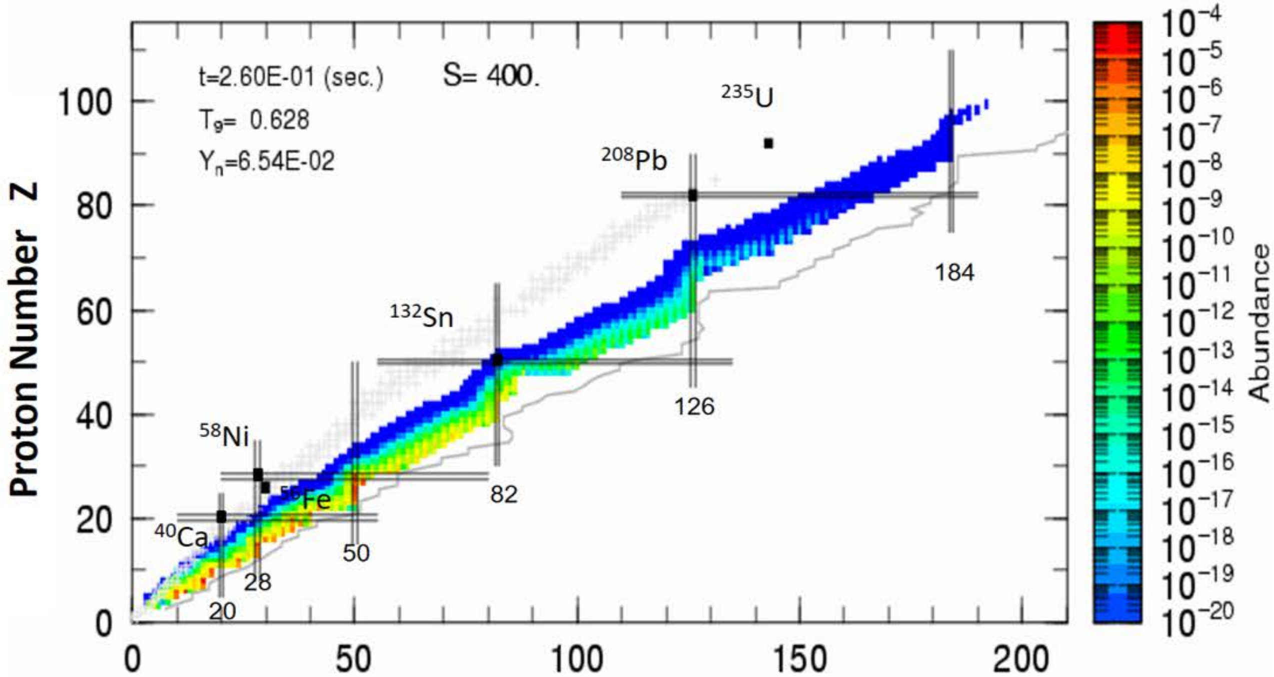
t=2.73E-03 (sec.)
S= 400.
T_9= 4.037
Y_n=4.27E-01
Proton Number Z
Abundance
^{235}U
^{208}Pb
^{132}Sn
^{58}Ni
^{56}Fe
^{40}Ca
184
126
82
50
28
20

NS Merger

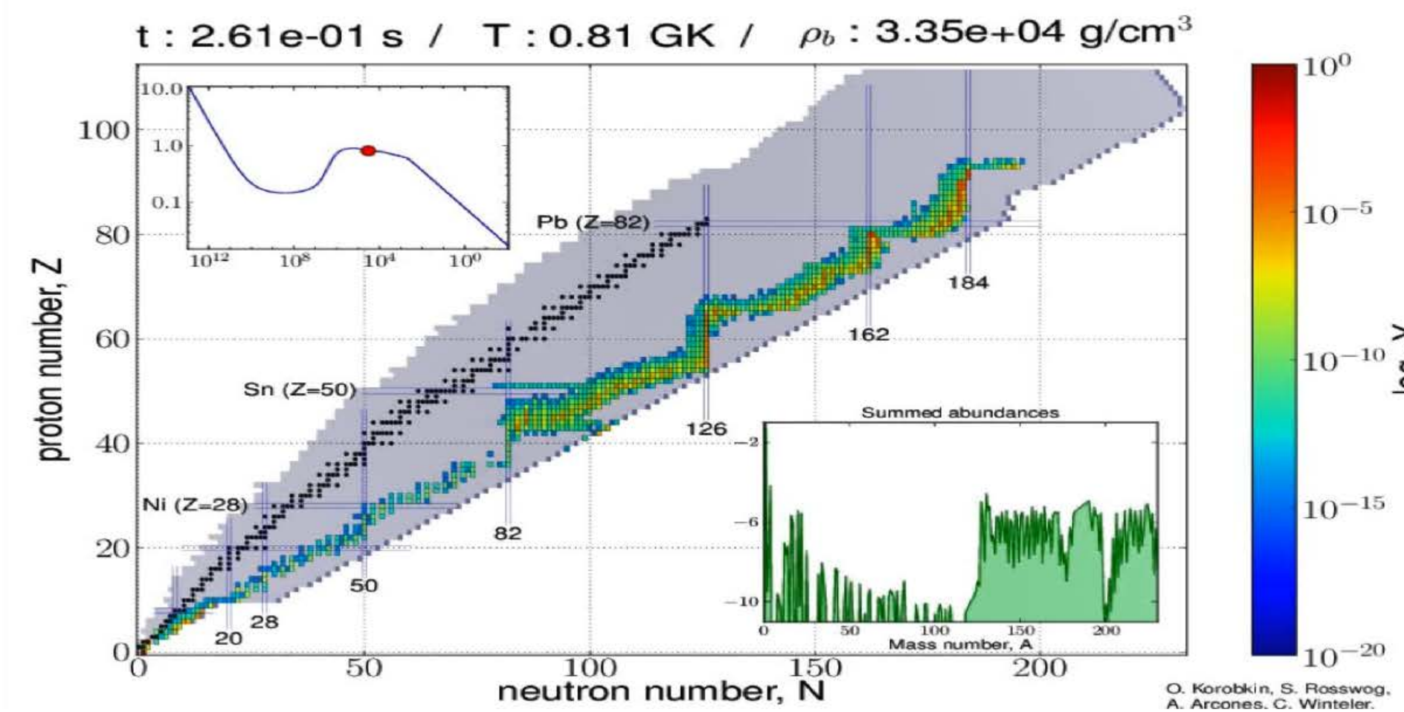


t : 2.76e-03 s / T : 0.24 GK / ρ_b : 1.37e+10 g/cm^3
proton number, Z
neutron number, N
$\log_{10}$ Y
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
184
162
126
82
50
28
20
Summed abundances
Mass number, A
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler.

SN

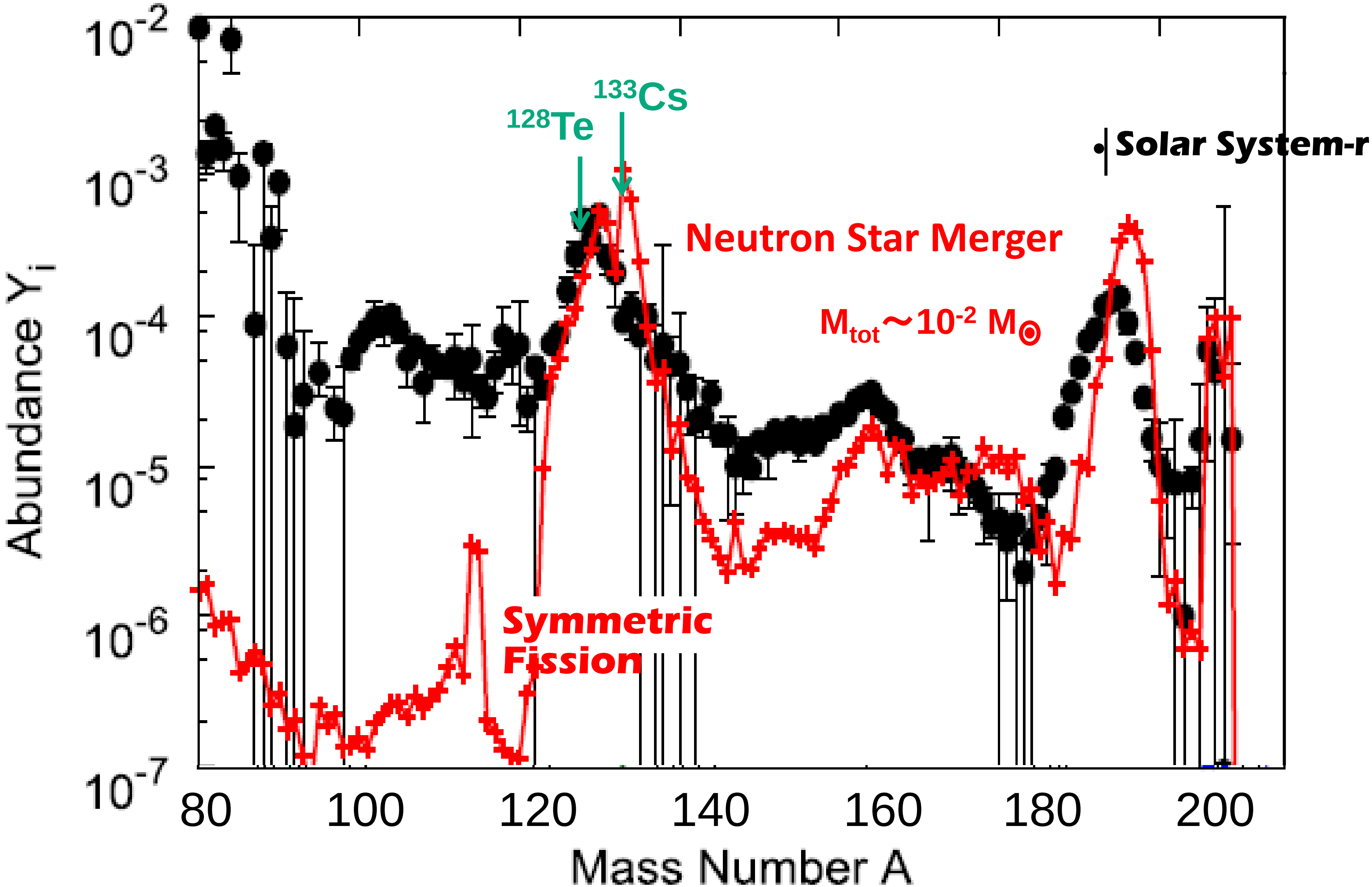

t=2.60E-01 (sec.)
S= 400.
T9= 0.628
Yn=6.54E-02
235U
208Pb
132Sn
58Ni
56Fe
40Ca
20
28
50
82
126
184
Proton Number Z
Abundance

MS Merger


t : 2.61e-01 s / T : 0.81 GK / ρb : 3.35e+04 g/cm3
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
Summed abundances
Mass number, A
proton number, Z
neutron number, N
log10 Y
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler.

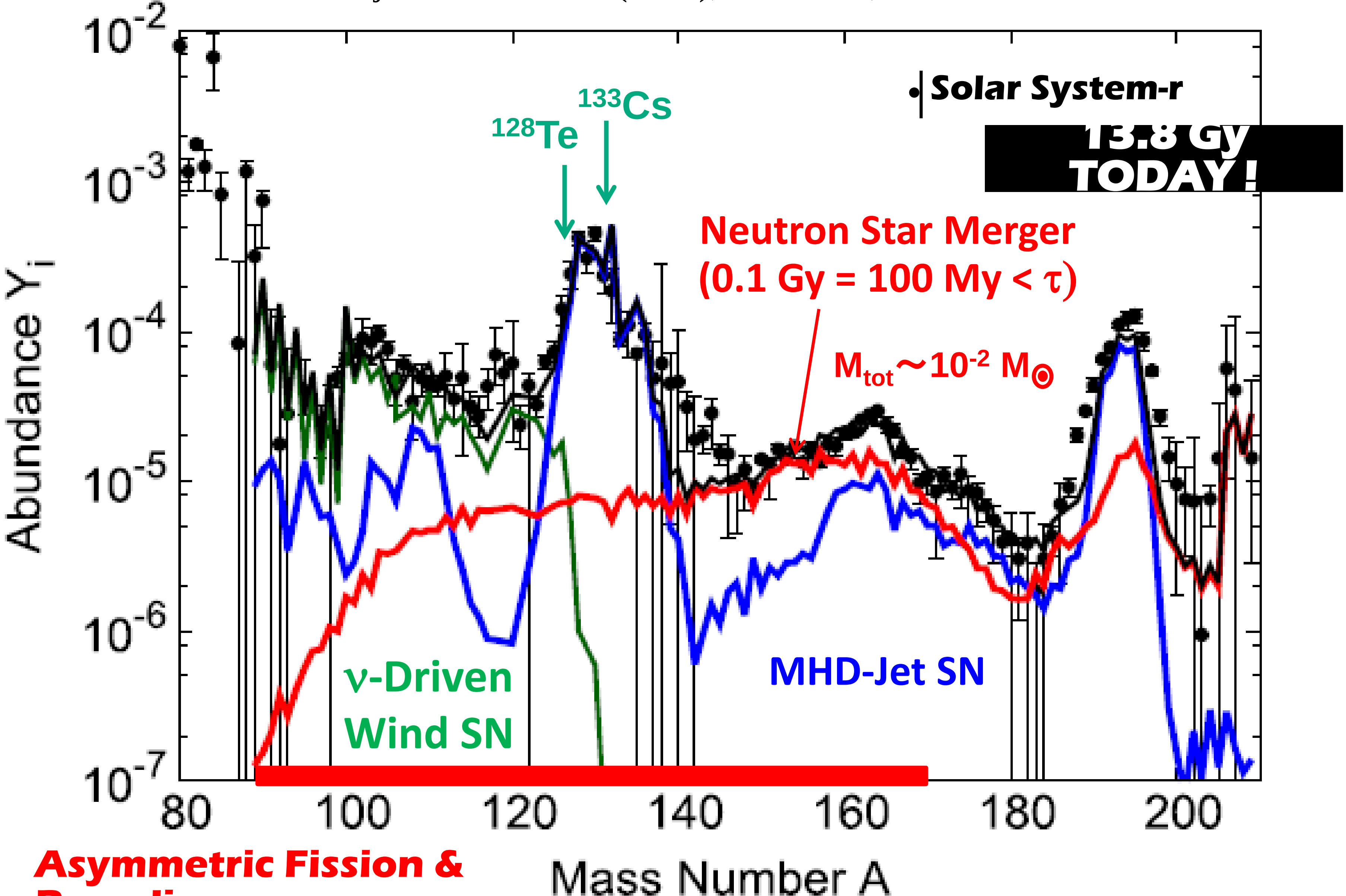
Challenge of Nucear Physics — Fission & Mass Formula

Mass Formula: FRDM (Moeller & Kratz) Shibagaki, Kajino, Mathews (2018)



Solar System r-Process Abundance

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

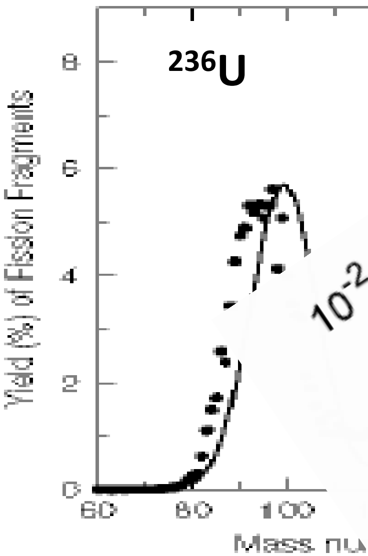


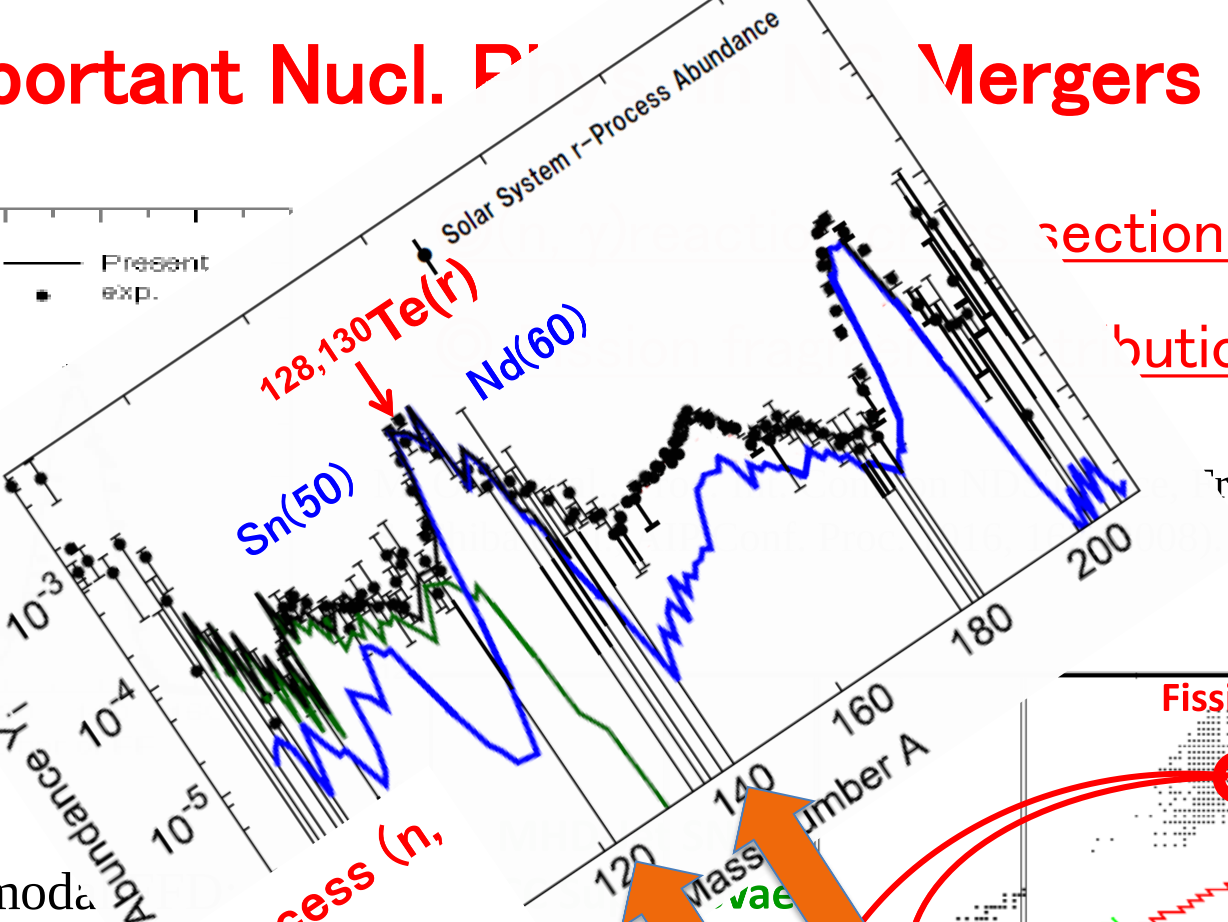
Important Nucl. P... Mergers

...section !

...bution !

...rance, (2007)





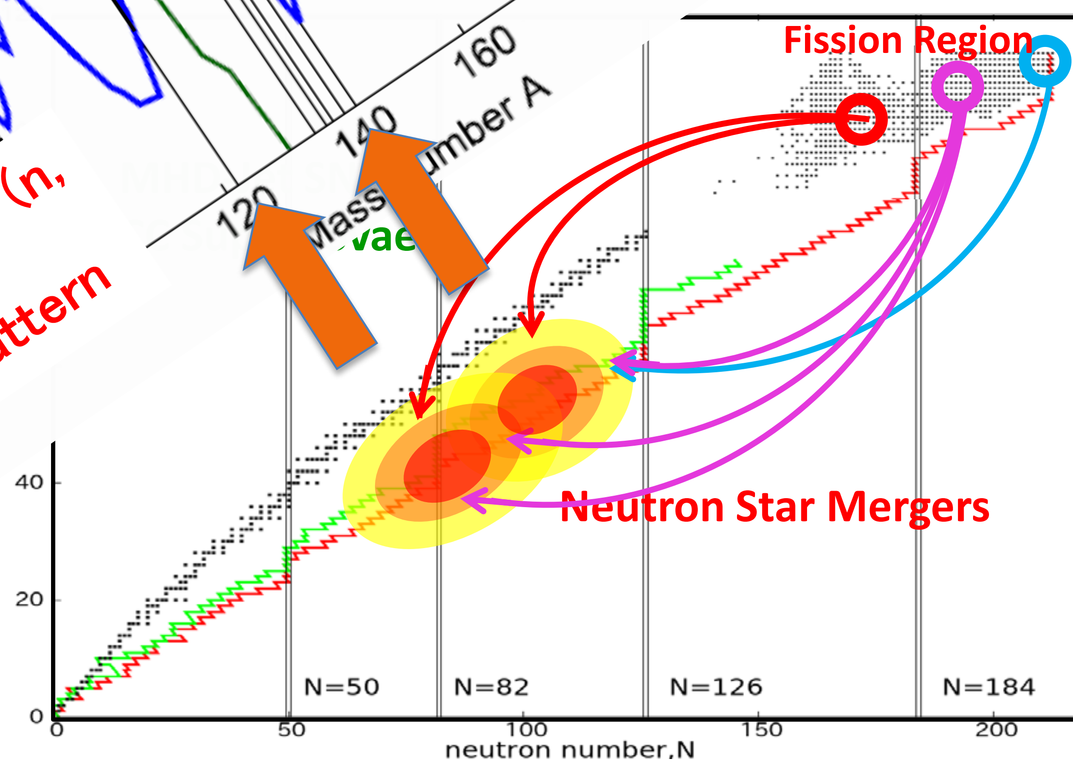
Bimordial or Trimoda...

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

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

$A_L = \ldots$

$A_M \ldots$



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

Fission is sensitive to Nuclear Models

KTUY Model

One of the Best Models!

Mass: Fission Barrier, Q_β

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

Reactions: αβ-decay, fission

H. Koura, AIP Conf. Proc. 704, 60, (2004).

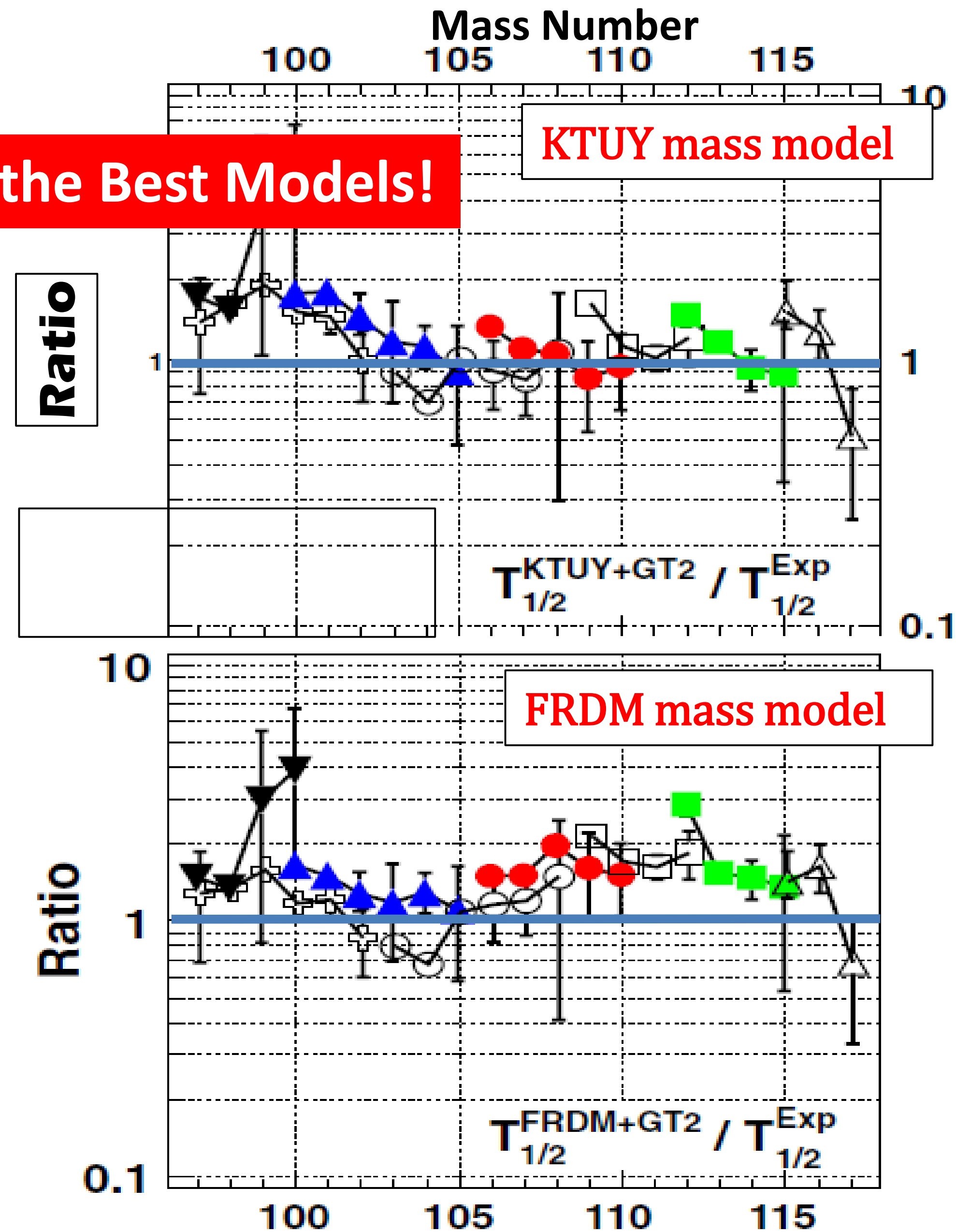
M. Ohta et al., Proc. Int. Conf. on Nucl. Data for Science and Technology, Nice, France, (2007).

FRDM Model

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

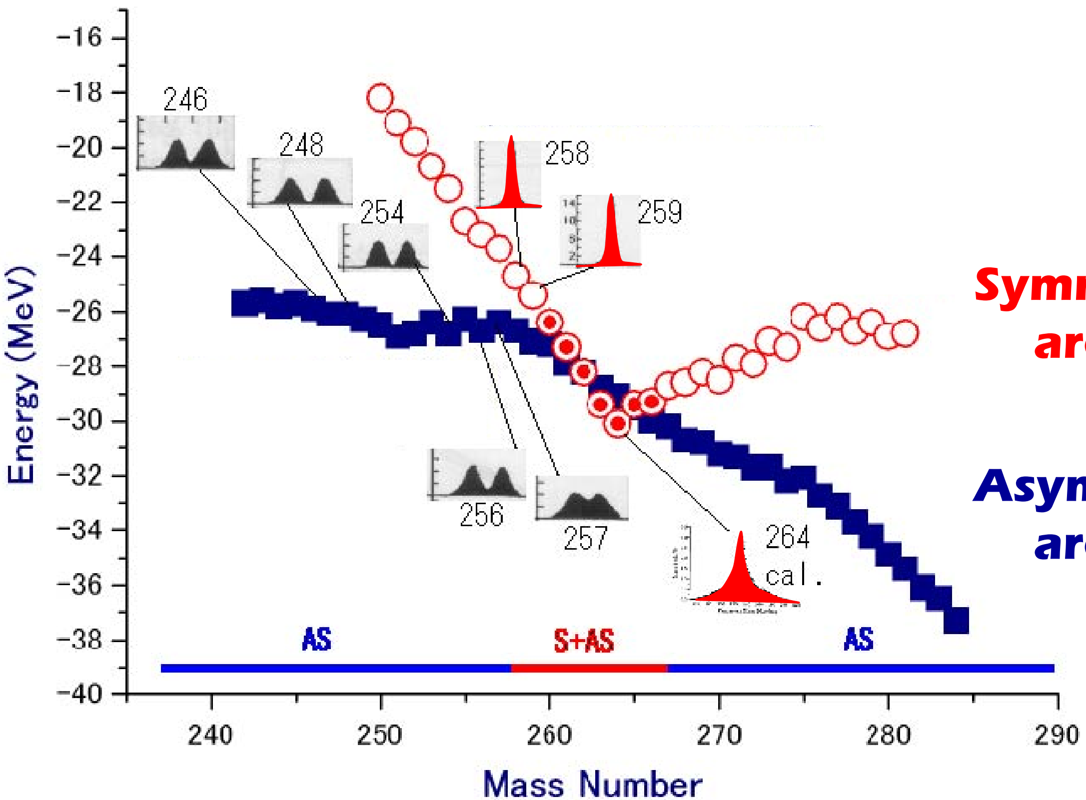
Möller, P., NIx, J. R., Myers, W. D., et al. ADNDT 59, 185 (1995).

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



Fission Path of Mercury

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



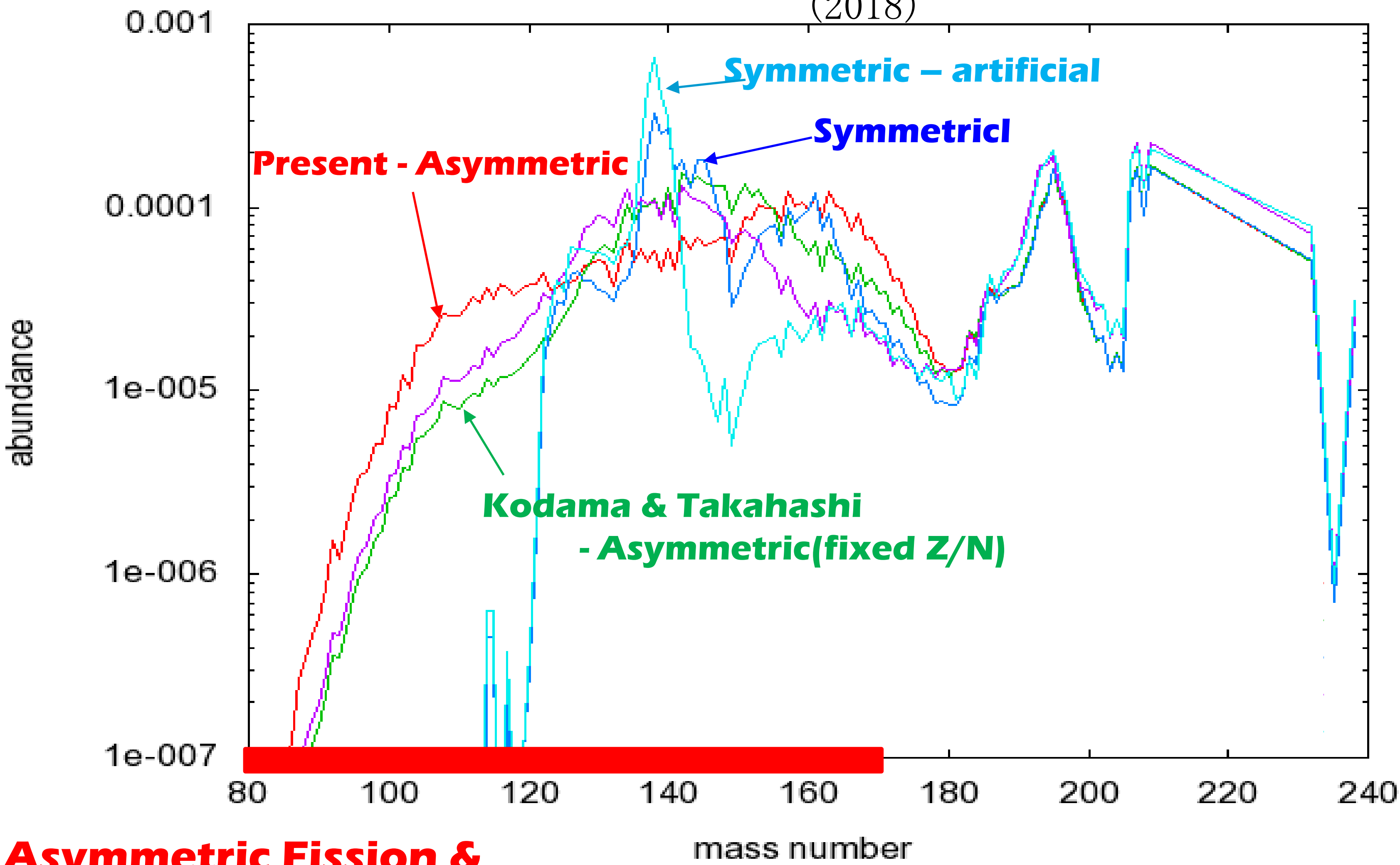
Symmetric Valley around α=0, δ=0.05

Asymmetric Valley around α=0.15, δ=0.2

Symmetric fission makes sharp 2nd & 3rd peaks.

Asymmetric fission & recycling wash out the 2nd peak, still keeping the REE hill and the 3rd peak.

Shibagaki, Kajino, Mathews (2018)



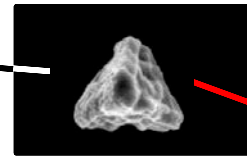
Asymmetric Fission & Recycling

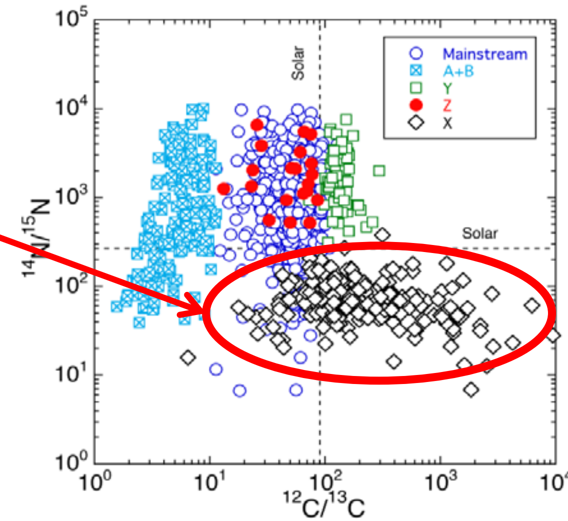
"r–process" Elements, found in SiC X–Grains

◎ Supernova Grains e.g. Murchison Meteorite

Courtesy of S. Amari

SiC X–grains





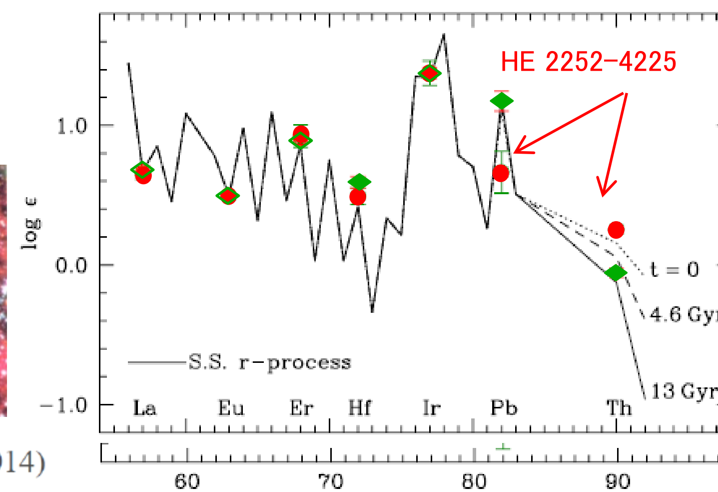
- Enhanced ^{12}C ($^{12}C/^{13}C$ > Solar), Enhanced ^{28}Si
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}$=60yr)

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

- ■ SiC X–grain including r–elements → NSM/SN event rates !
- ■ Extended universality & actinide boost → Both NSM & SN !

◎ Direct Spect. Obs.: Actinide–boost stars

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



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

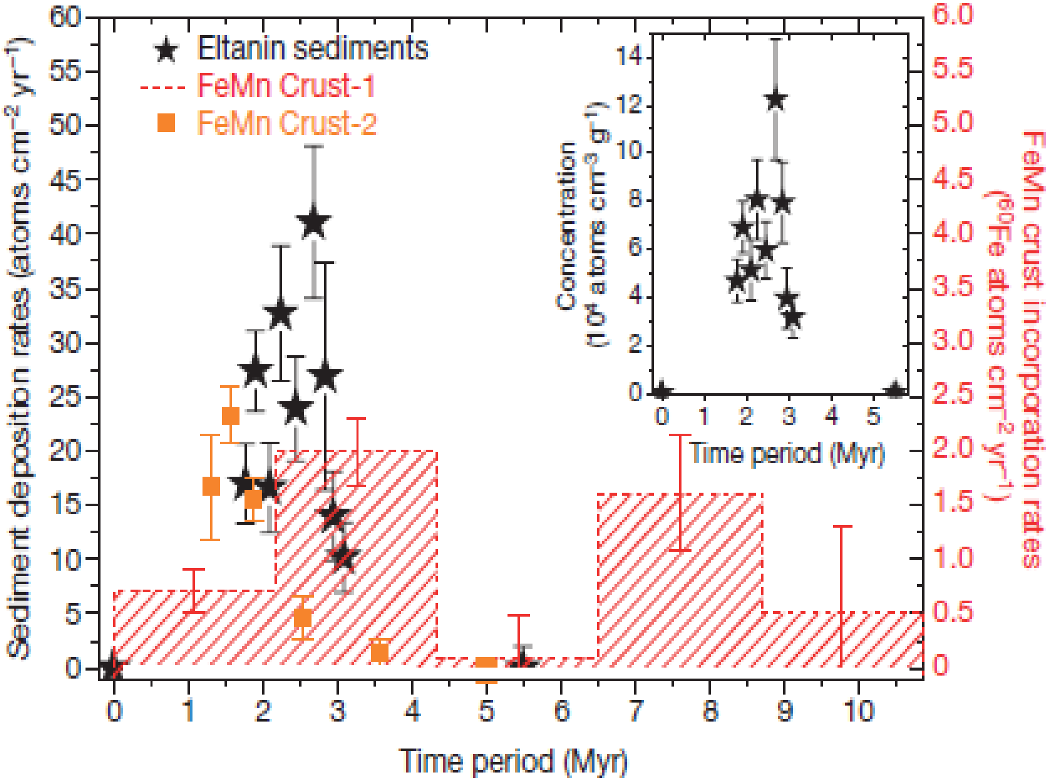
Deep Sea Sediments & EMPS points DUALITY of SN & NSM

$^{244}Pu/^{60}Fe$ in Earth's Deep Sea Sedim~~ents~~ NSM/MHDJ : SNe = 1 : 100!

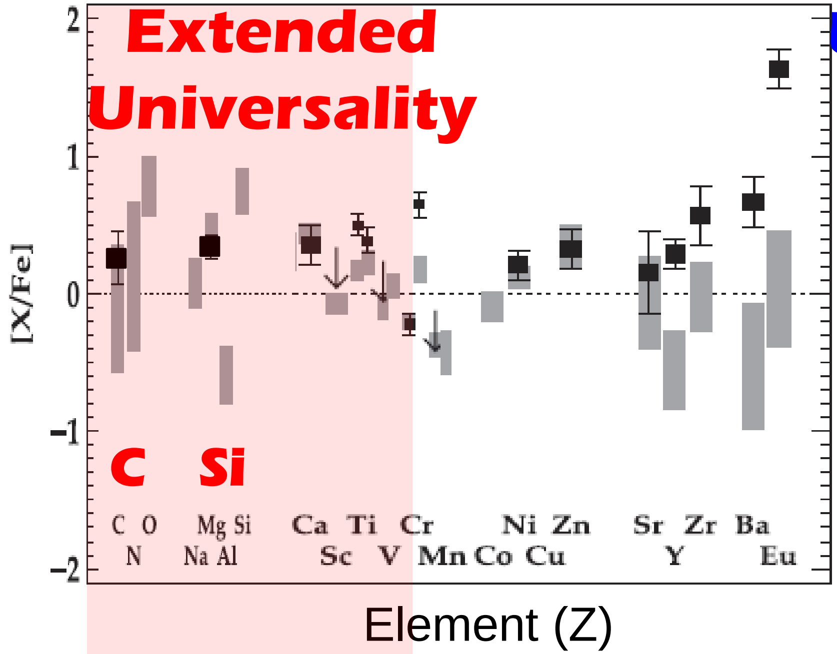
Over 25 My

NSM, MHDJ ^{244}Pu(80.8 My): Wallner et al., Nature Comm. 6 (2015), 1-9; NPA8 (2017)

ν-DW ^{60}Fe(2.62 My): Wallner et al. Nature 532 (2016), 69.



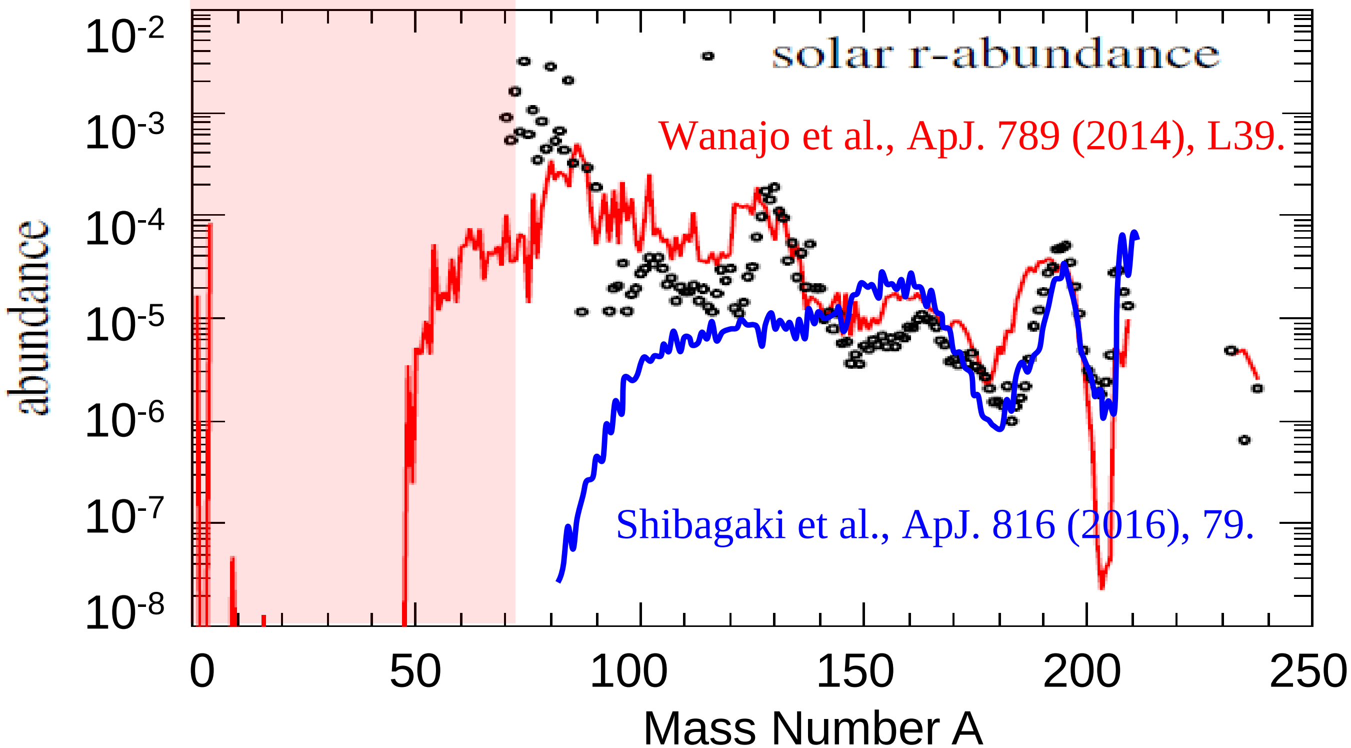
Ultra-Faint Dwarf Galaxy: Ret. II



Astron. Observation

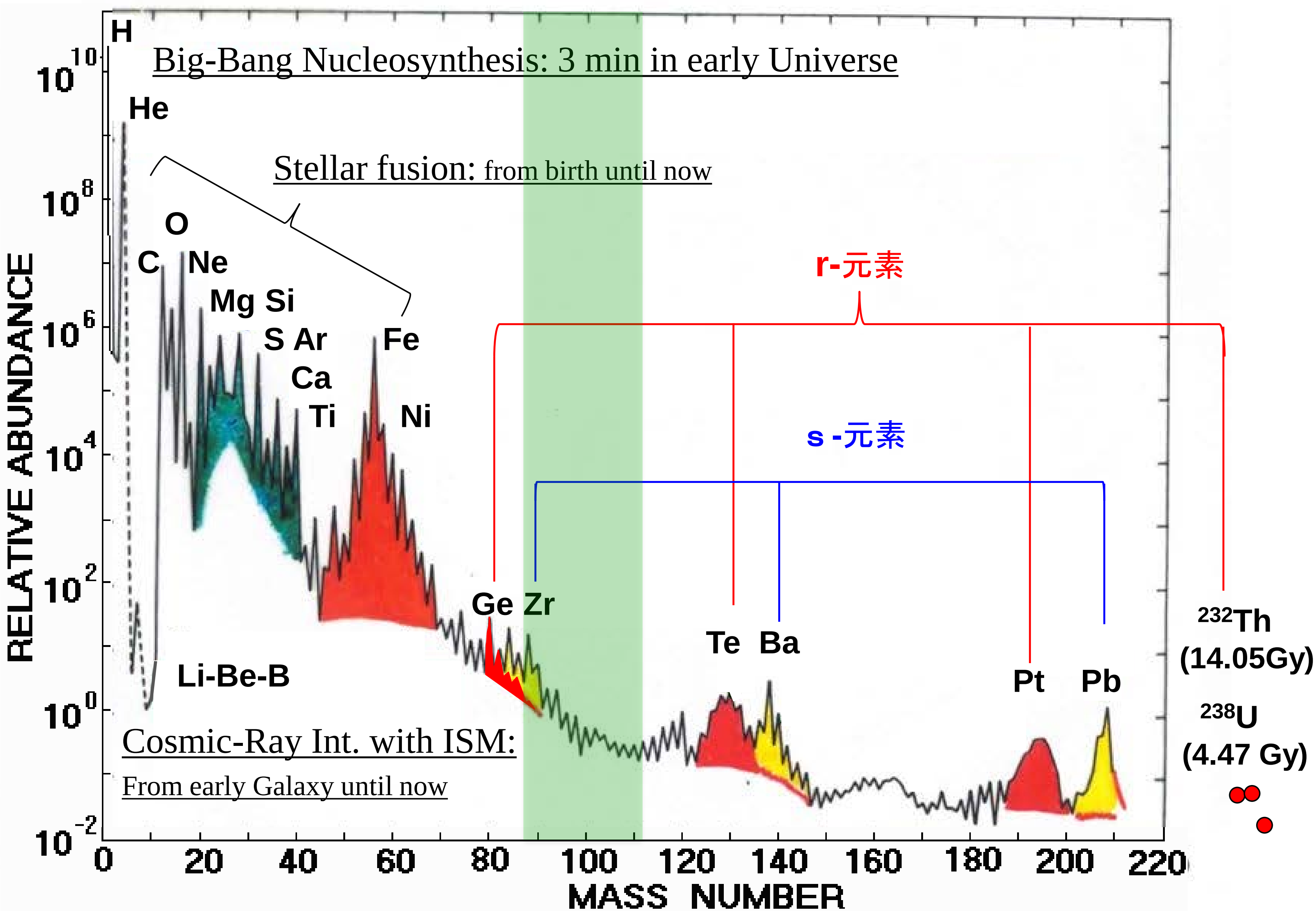
Ian U. Roederer et al., ApJ. 151 (2016), 82;
P. Ji Alexander, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610.

NSM cannot produce A<80 enough !



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

Solar System Abundance

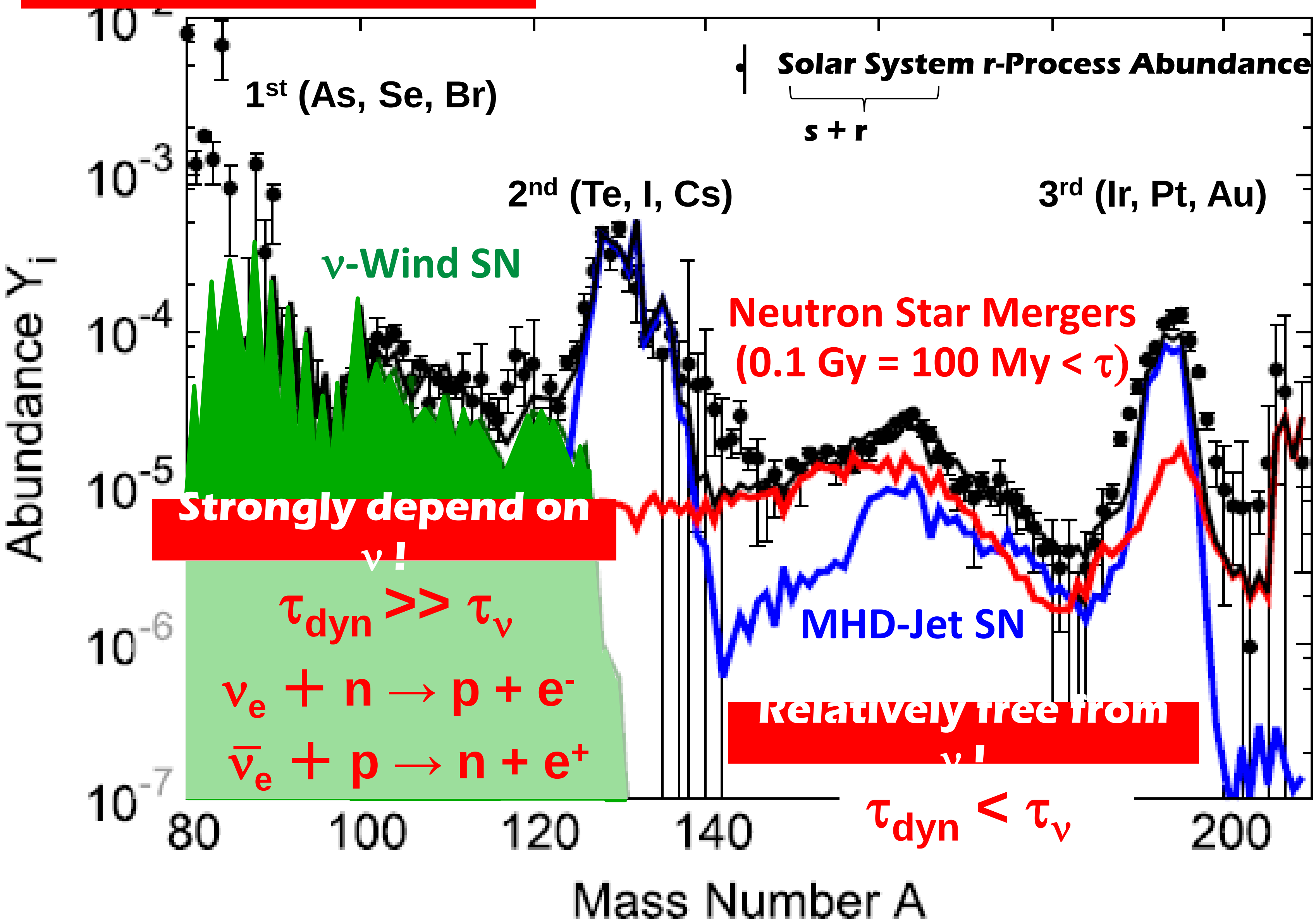


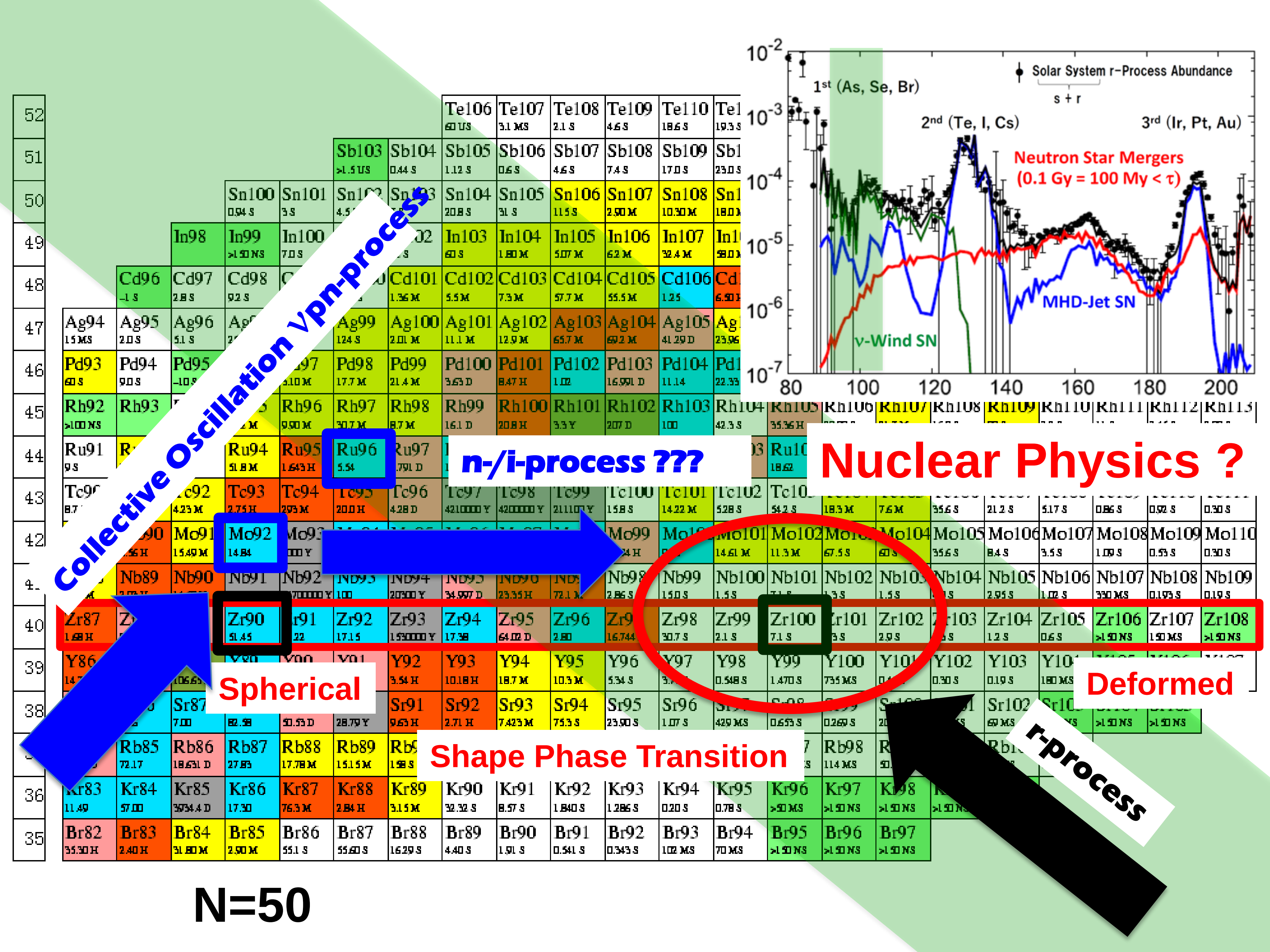
Solar System r-Process Abundance

Present time: t =

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

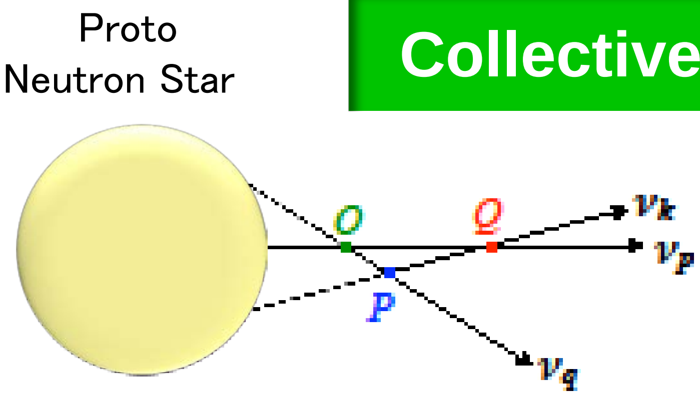
New process, required ?





Collective Oscillation νpn-process
n-/i-process ???
Nuclear Physics ?
Spherical
Deformed
Shape Phase Transition
r-process
N=50
Solar System r-Process Abundance
s + r
1st (As, Se, Br)
2nd (Te, I, Cs)
3rd (Ir, Pt, Au)
Neutron Star Mergers
(0.1 Gy = 100 My < τ)
MHD-Jet SN
ν-Wind SN

Collective ν Oscillation — Many-Body Effect

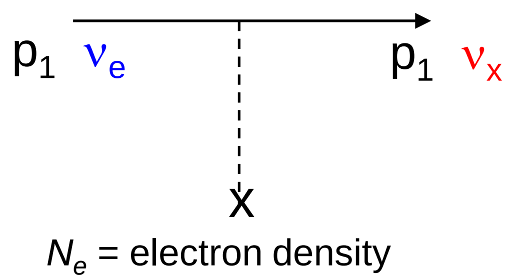


Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101.
Fogli, Lisi, Marrone & Mirizzi, JCAP 12, (2007) 010.
Balantekin, Pehlivan & Kajino, PR D84, (2011), 065008
PR D90, (2014), 065011.

H_ν = Mixing and Int. with Background Electrons

MSW (Matter) Effect

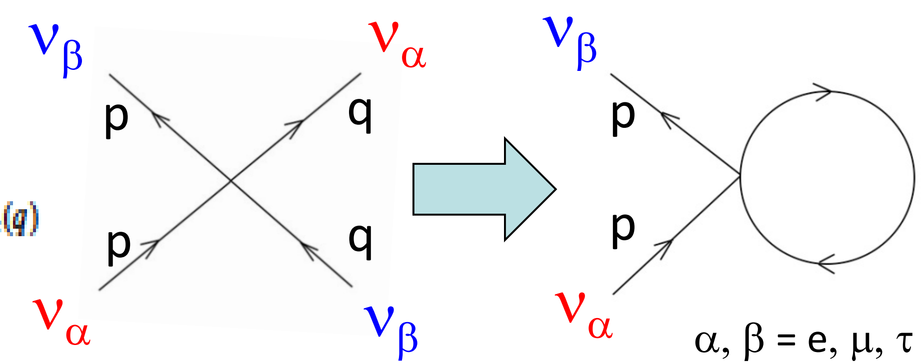
$$H_\nu = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right)$$
$$+\frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$



$H_{\nu\nu}$ = Self-Interactions

Collective Effect for νν-scatt.

$$H_{\nu\nu} = \frac{G_F}{\sqrt{2}V}\int d^3p\, d^3q\, R_{pq}\left[a_e^\dagger(p)a_e(p)a_e^\dagger(q)a_e(q) + a_x^\dagger(p)a_x(p)a_x^\dagger(q)a_x(q)\right.$$
$$\left. + a_x^\dagger(p)a_e(p)a_e^\dagger(q)a_x(q) + a_e^\dagger(p)a_x(p)a_x^\dagger(q)a_e(q)\right].$$



10^{49} ν's with 3-flavors & multi-angles (3 x 3r x 3p /ν) !

➡ 3-Flavor & Multi-Angle Calculations in Mean Field Approx.

Swapped ν Energy Spectra

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

Both Normal & Inverted hierarchy, Observed θ_{13} & Δm^2

r=250km

Energy spectra swap!

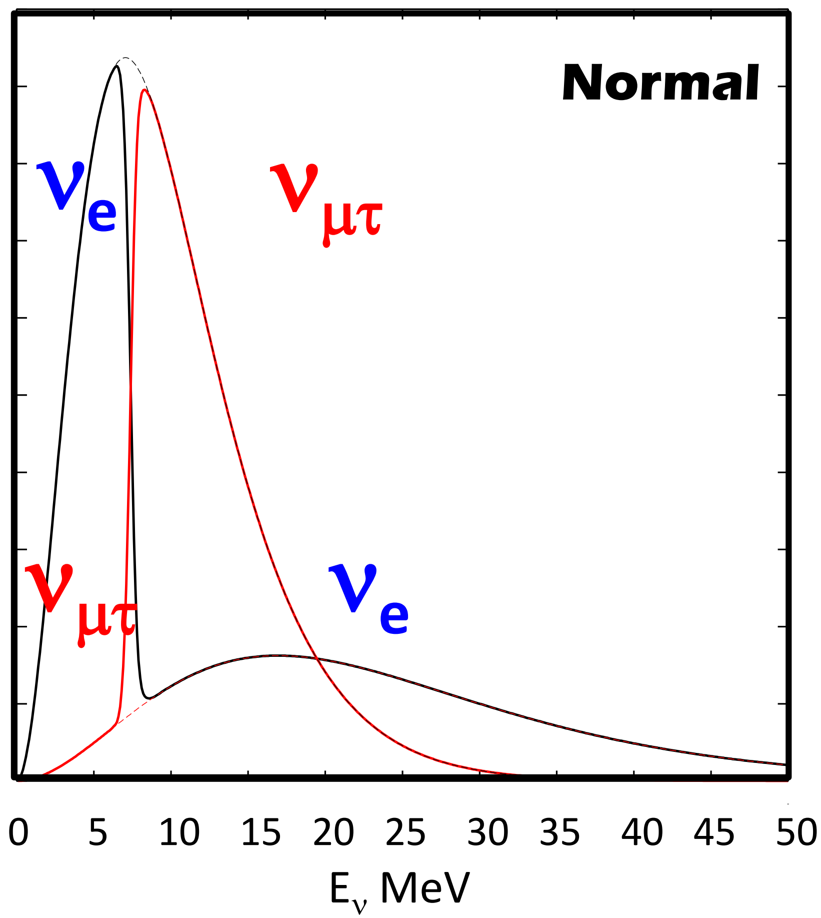
n/p ratio (Y_e<0.5) changes drastically!

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

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

System becomes even proton-rich (0.5<Y_e), and νp- process operates!

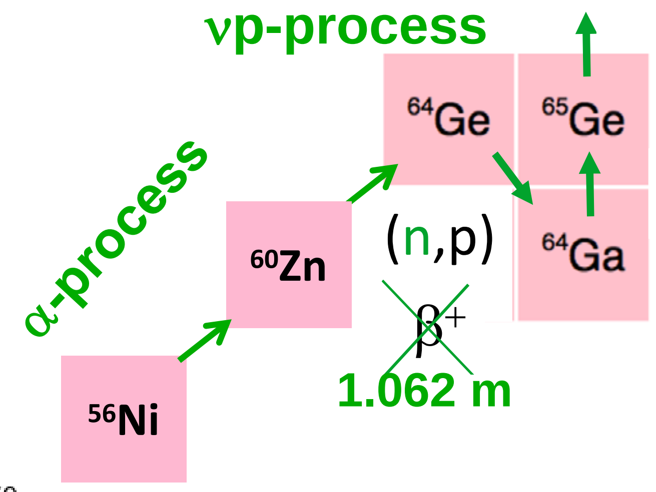
We find extended (n, γ) flow!

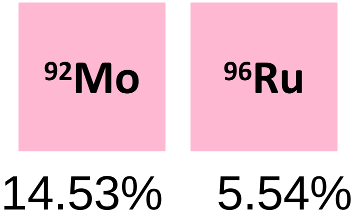


Ordinary νp-process

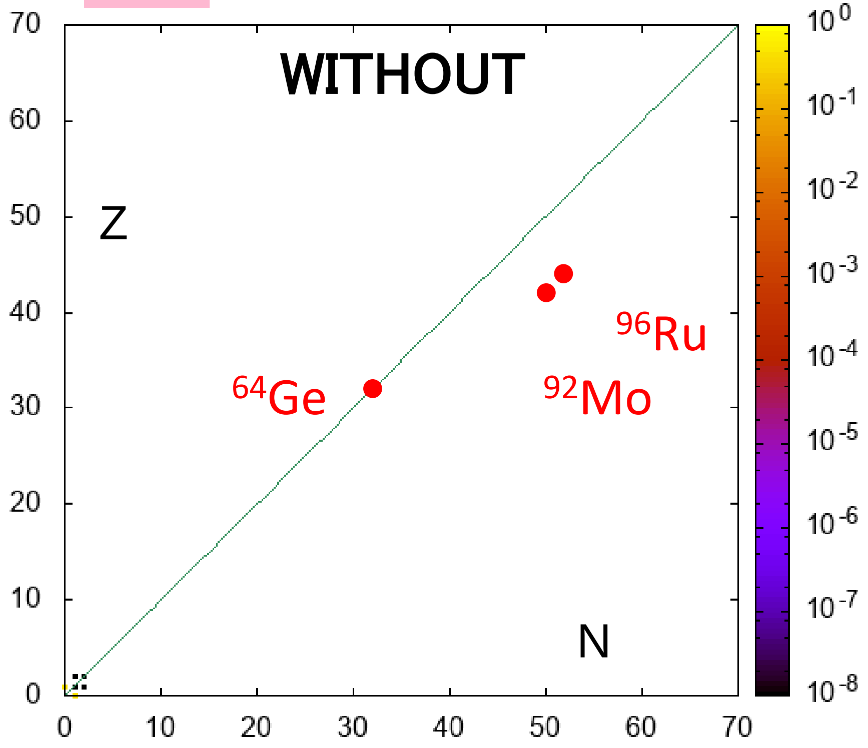
C. Freohlich, et al., PRL 96 (2006), 142502.

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



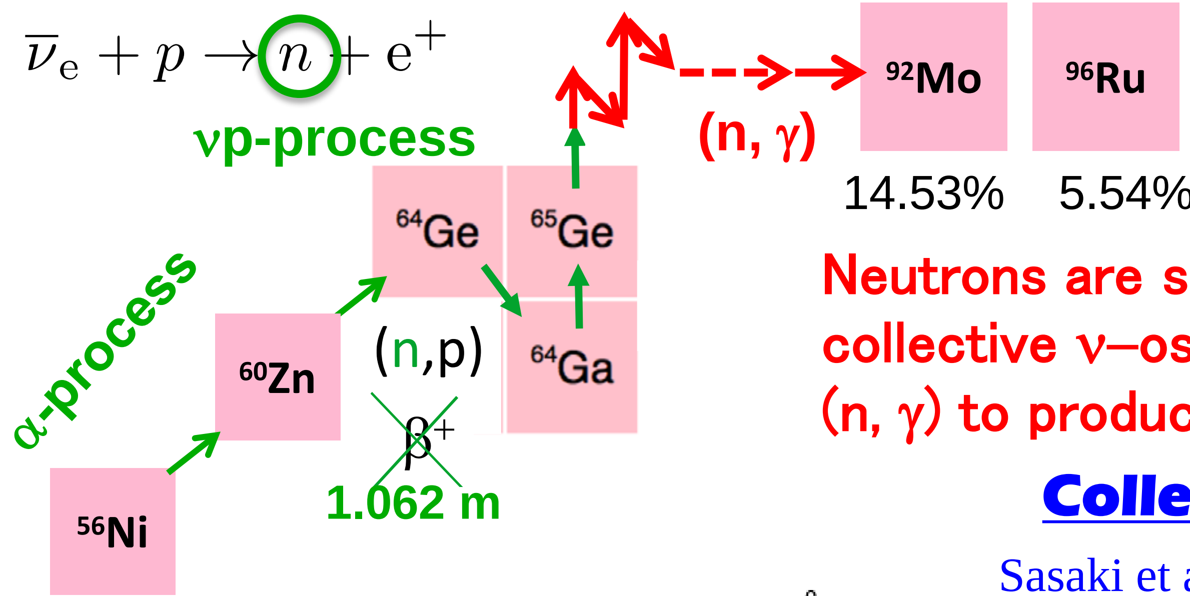


Isotopic ratio of p-nuclei ~ 0.1-1%



Ordinary νp-process

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

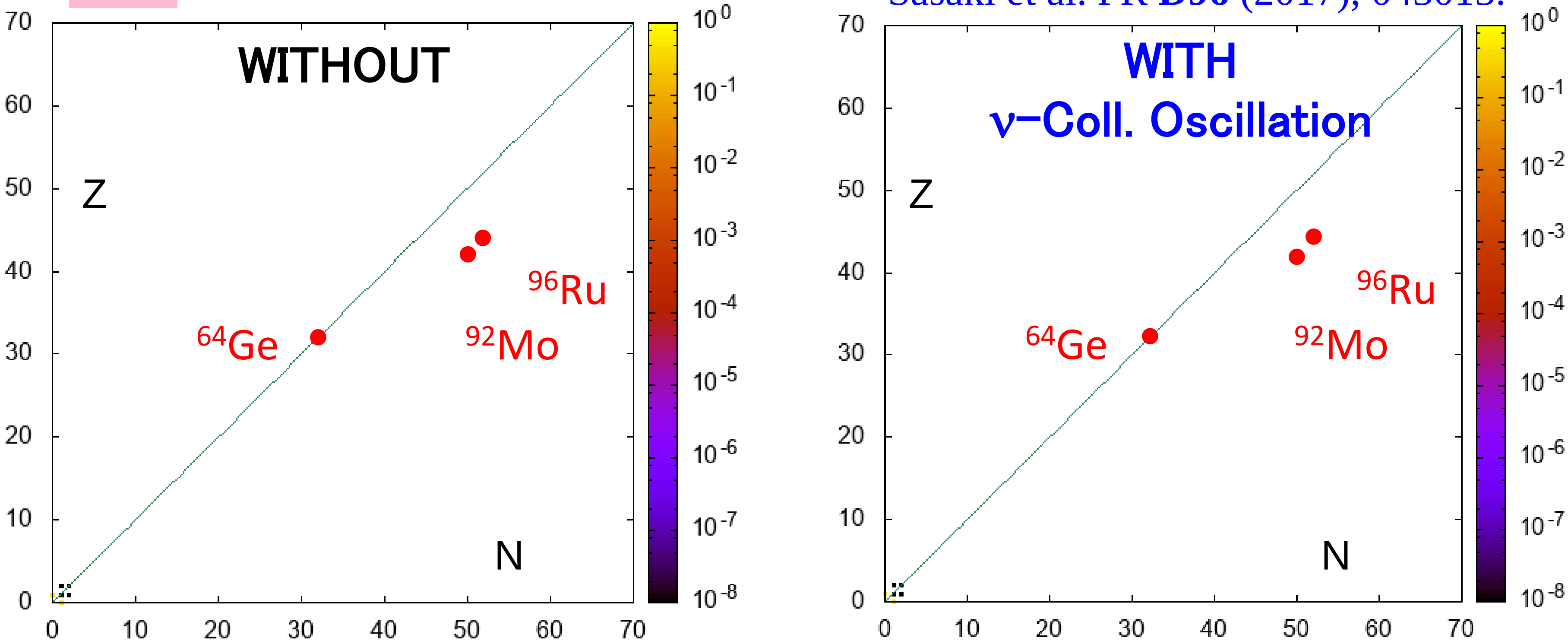


Isotopic ratio of p-nuclei ~ 0.1-1%

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

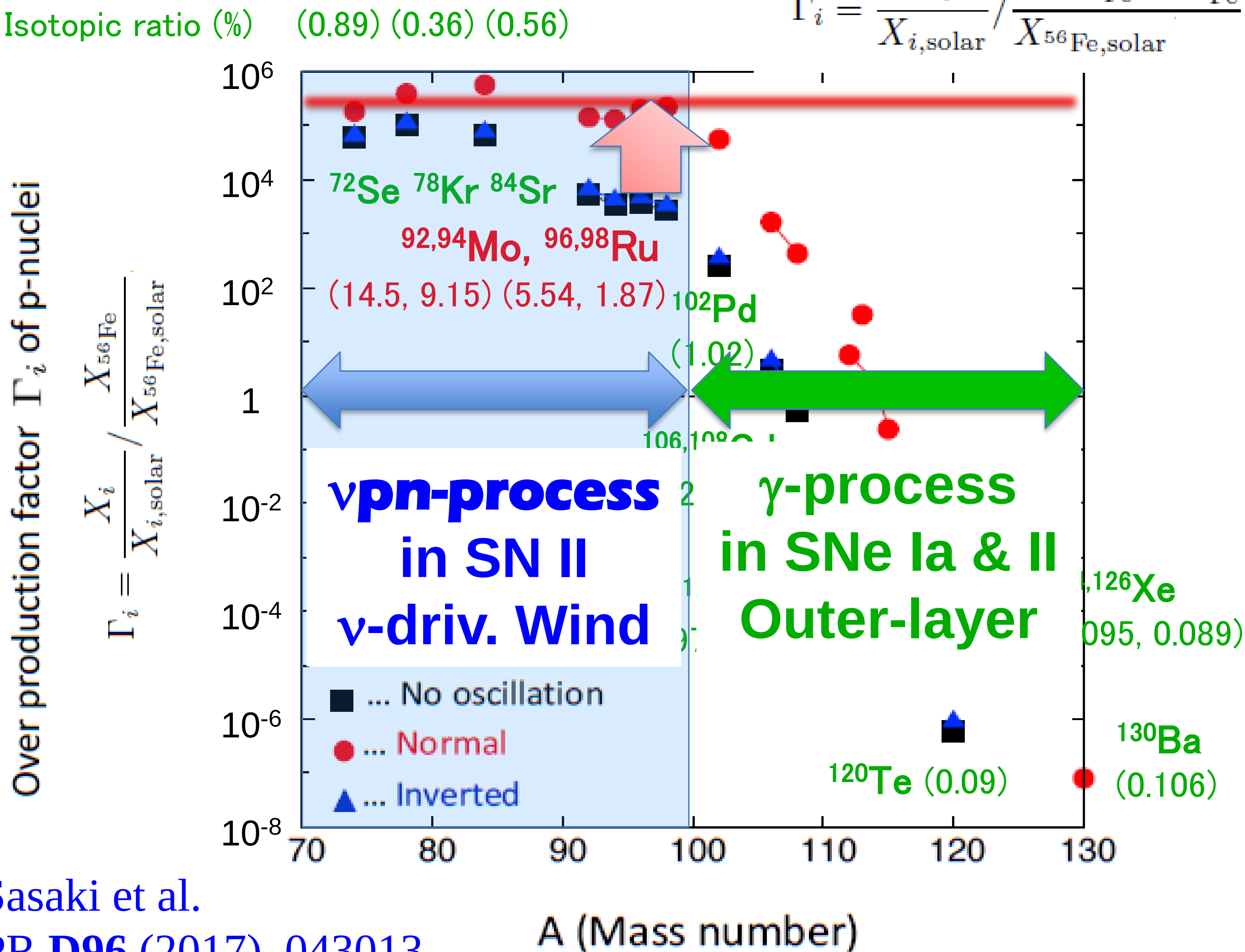
Collective νpn-process

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



P–Nuclei

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



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

ν-Mass, constrained from Cosmology & Nuclear Physics

- **CMB Anisotropies + LSS:** WMAP-7yr + Planck + BAO + HST + SZ (2015-2017)

  $\sum m_\nu < 0.14 – 0.17$ eV (95%C.L.)

  < 0.2 eV (2σ, $B_\lambda < 2$nG)

  Yamazaki, Kajino et al. Phys. Rep. 517 (2012),141; PR D81 (2010), 103519.

- **0νββ decay:** COUORE, NEMO3, EXO, KamLAND Zen (2012-2017) + NνDEX

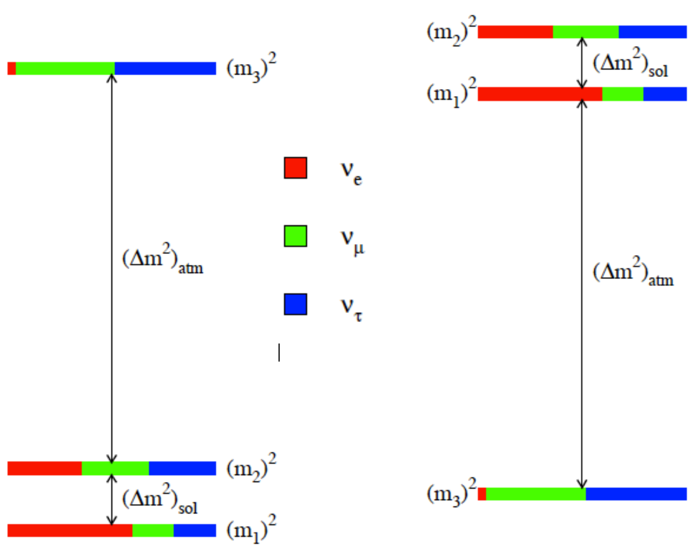
  $|\sum U^2_{e\beta} m_\beta| < 0.3$ eV (—2018)

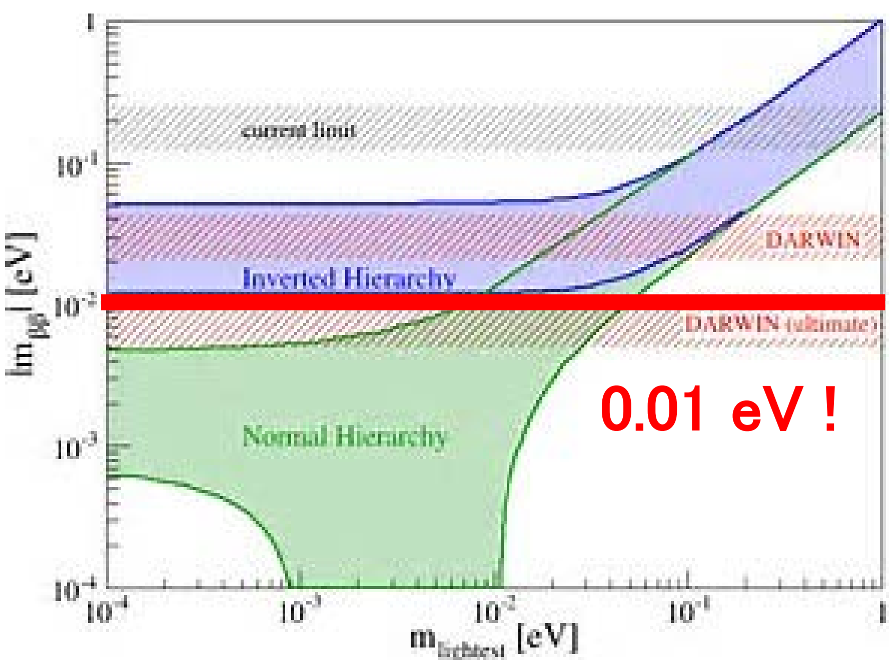
ν−Oscillation Physics

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

Normal: $\Sigma m_\nu \sim 0.05$ eV !

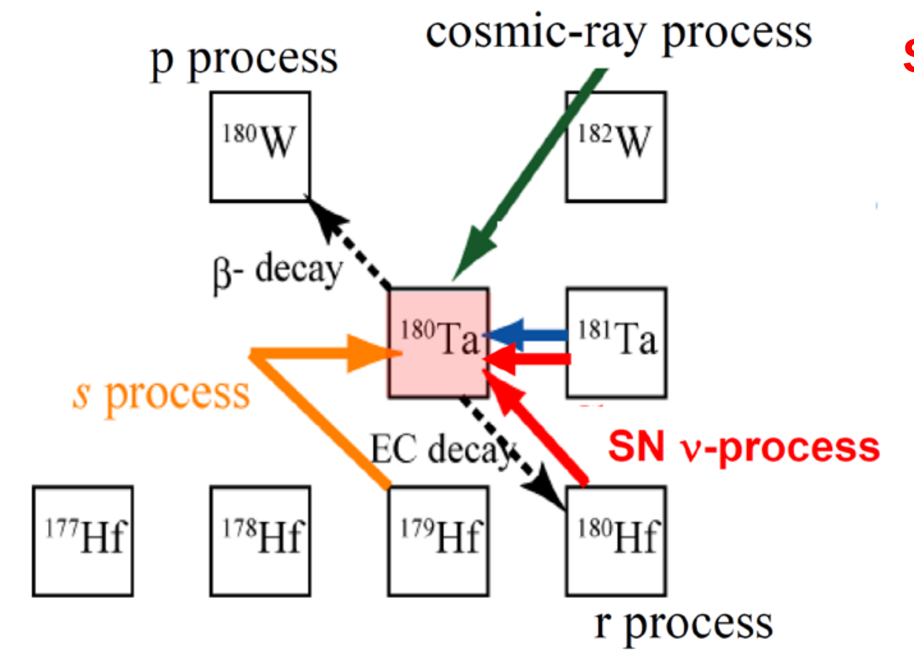
Inverted: $\Sigma m_\nu \sim 0.1$ eV !

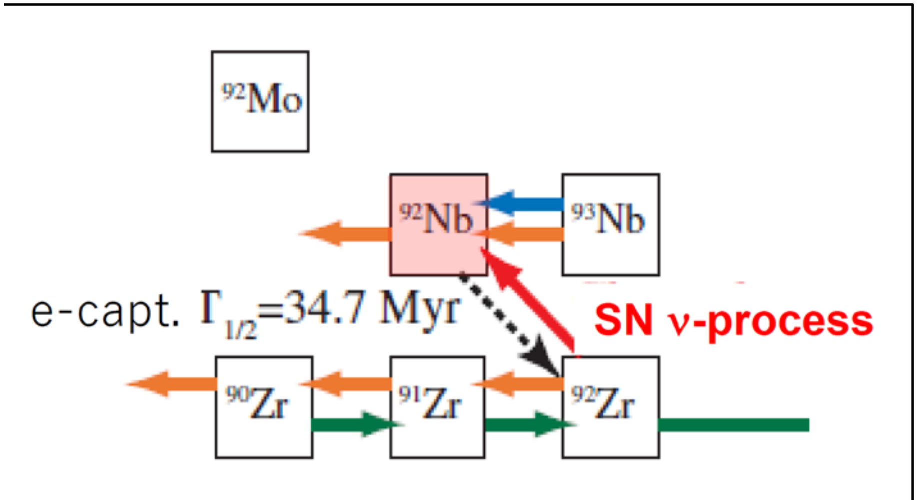




ν-Isotopes: ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

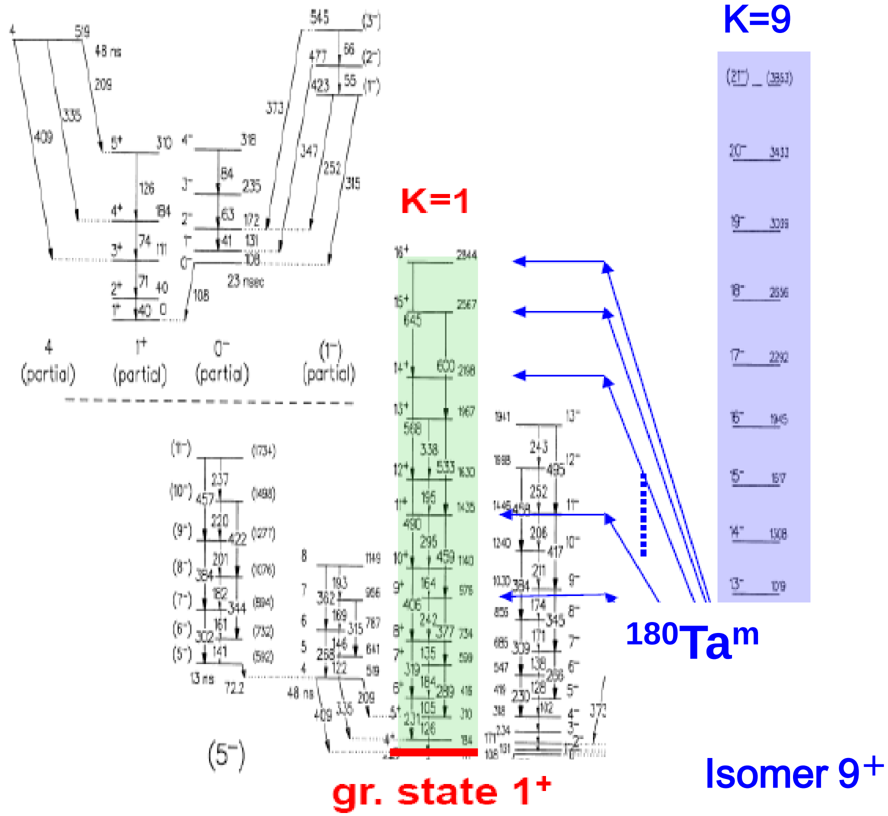
Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®;
PR C82 (2010), 058801; ApJL 779 (2013), L1.





SN ν-process in Einstein AB theory
→ Only 40% survives!

D. Belic et al., PR C65 (2002), 035801.

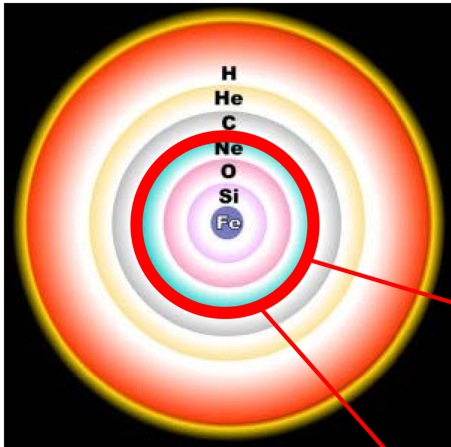


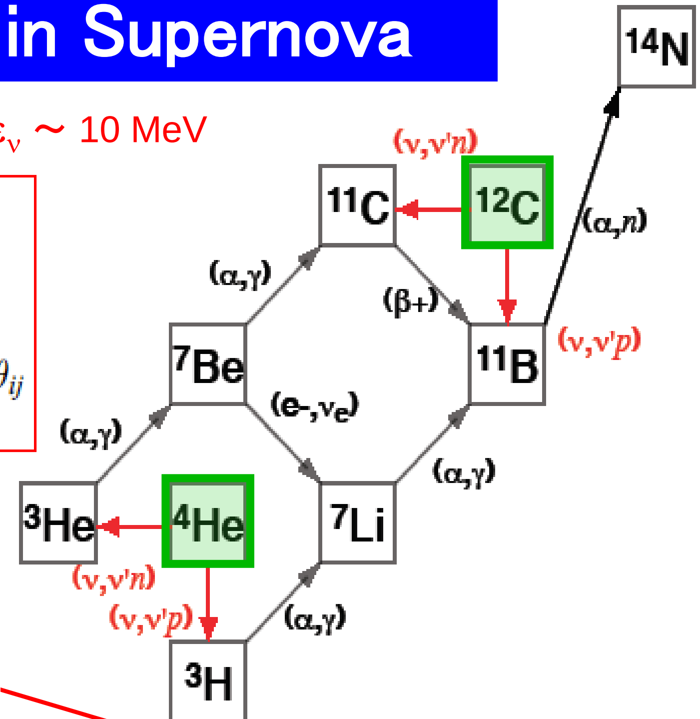
^{180}Ta$_g$($\tau_{1/2}$ = 8h) ^{180}Ta^m($\tau_{1/2}$ > 10^{15}y)

^{6,7}Li–^{9}Be–^{10,11}B : Outer Layer in Supernova

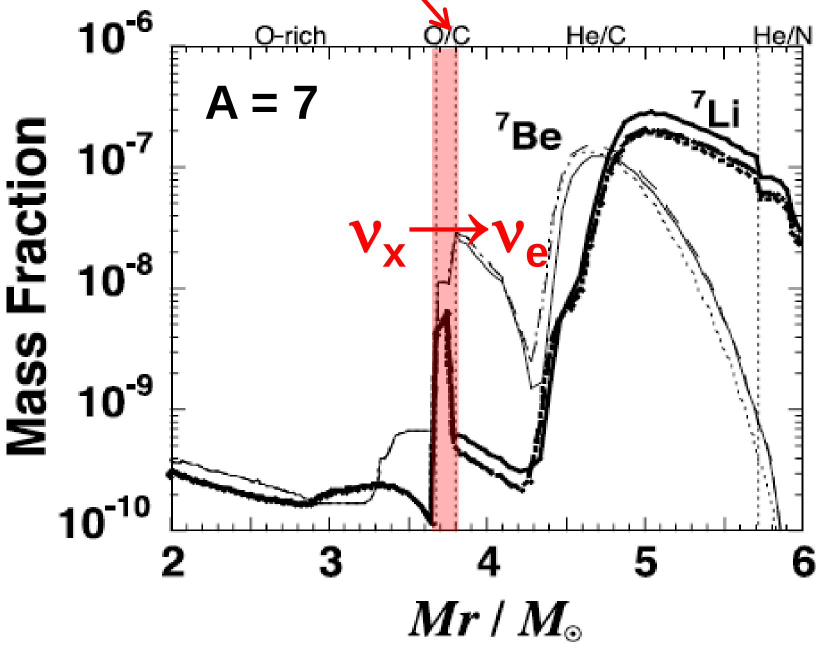
$|\Delta m^2_{13}| = |\Delta m^2_{23}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\varepsilon_\nu \sim 10$ MeV

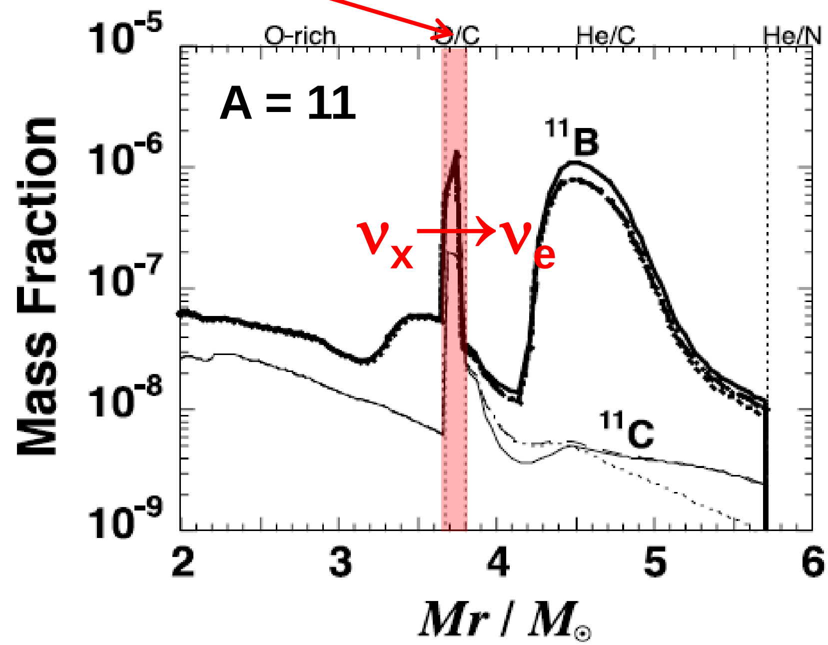
$$\rho_{\rm res} Y_e = \frac{m_u \Delta m^2_{ji} c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu} \quad [\ \mathrm{g\ cm^{-3}}\ ]$$
$$= 6.55 \times 10^6 \left(\frac{\Delta m^2_{ji}}{1\ \mathrm{eV}^2}\right)\left(\frac{1\ \mathrm{MeV}}{\varepsilon_\nu}\right) \cos 2\theta_{ij}$$



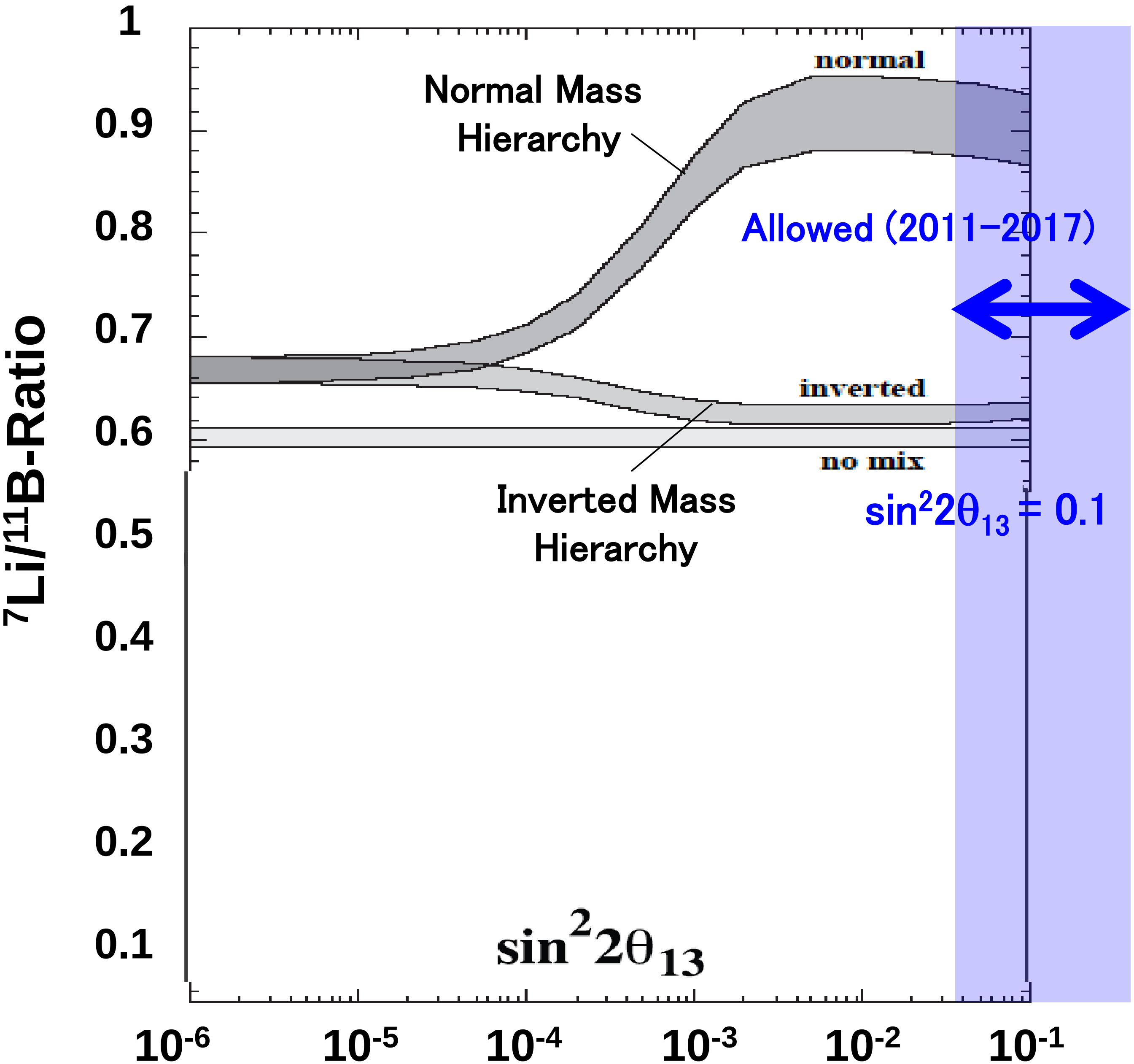


MSW high-density resonance is located at O/C - He/C shell at $\rho \sim 10^3$ g/cm^3.





New Method to constrain Mixing Angle θ_{13} & Mass Hierarchy



Yoshida, Kajino et al. 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.

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

Kajino, Mathews & Hayakawa, J. Phys.G41 (2014), 044007.

Long Baseline Exp. from 2011-2018:

- T2K (Kamioka)
- MINOS

Nuclear Reactor Exp. from2012-2018:

- RENO (KOREA)
- Double CHOOZ
- Daya Bay

Theoretical Calculation for ν-A Cross Secti

New generation SM cal.: ν-^{12}C, ^{4}He

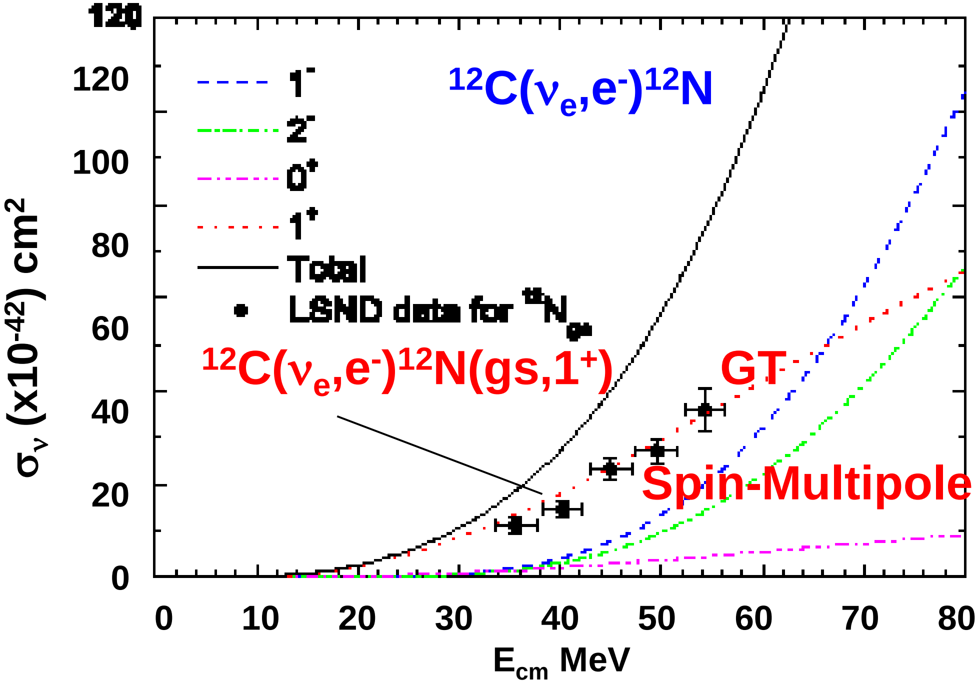
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307;
Suzuki & Kajino, J. Phys. G40 (2013), 083101; ++

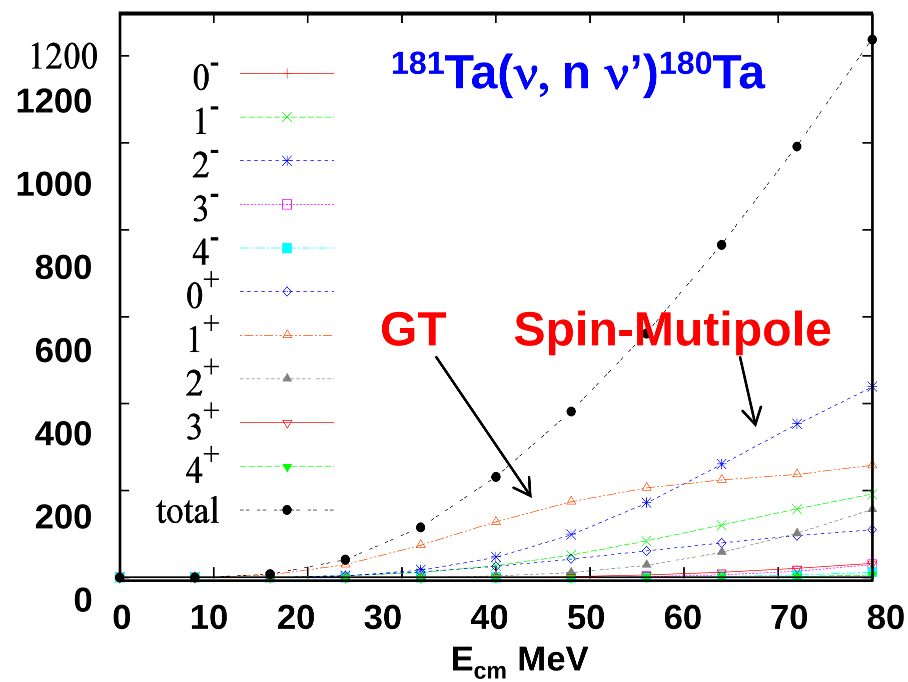
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

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

QRPA cal.: ν-^{12}C, ^{4}He, ^{40}Ar, ^{42}Ca, ^{98}Tc, ^{92}Nb, ^{138}La, ^{180}Ta …

Cheoun, et al., PRC81 (2010), 028501;
PRC82 (2010), 035504: J. Phys. G37 (2010), 055101;
PRC 83 (2011), 028801; PRC 85 (2013), 065807;
PLB 723 (2013), 464; J. Phys. G42 (2015), 045102;
++





★ ν-beam experiment is not available !

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

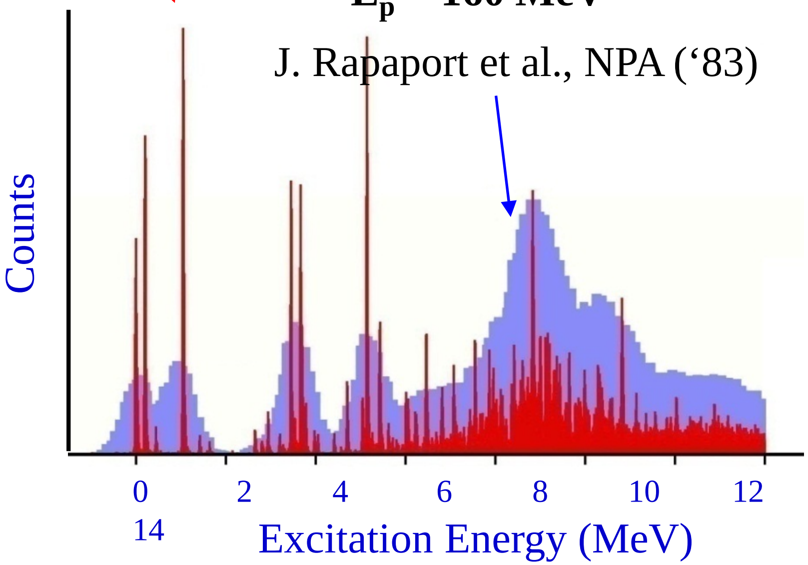
Similarity of Electro-Magnetic & Weak

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

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

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

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



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

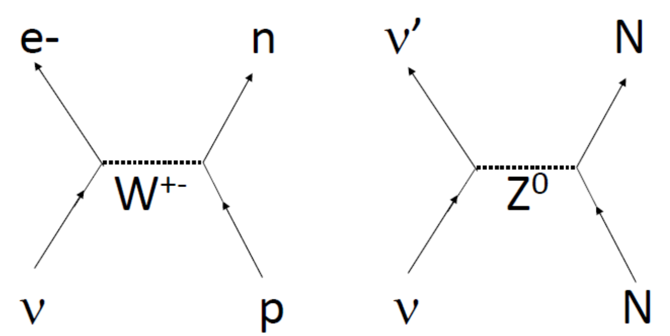
$$\vec{V} \approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m} (\vec{p} + \vec{p}\,')$$

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

Weak operator in non-relativistic limit

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

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



charged-current neutral-current

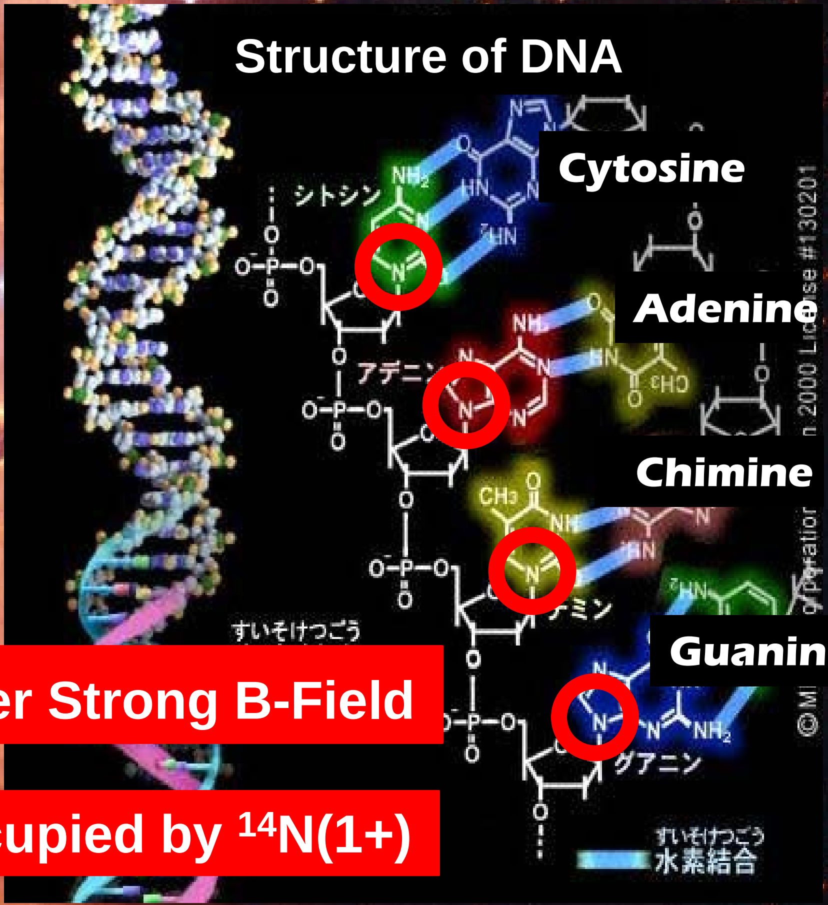
Origin of Life ?

— Key —
All Amino-Acids, Optically Left-Handed ! Why ?

Born in the Universe,
then brought into Earth ?

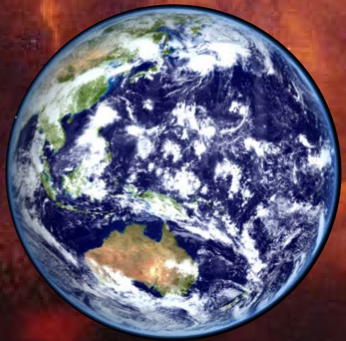
Born on the Earth, then evolved ?

Mann and Primakoff (Origins of Life, 11 (1981), 255) suggested β-decay of ^{14}C.
It is too SLOW!

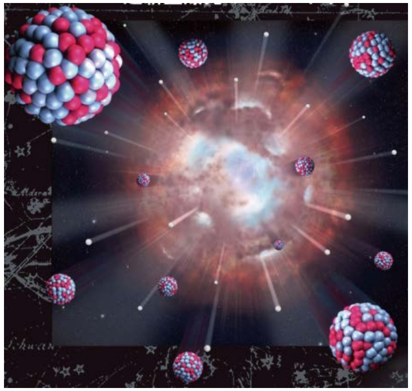


ν-Interaction under Strong B-Field

Connection is occupied by $^{14}N(1+)$



Origin of L-Chirality of Amino Acids



Boyd, Kajino, Onaka & Famiano, et al.

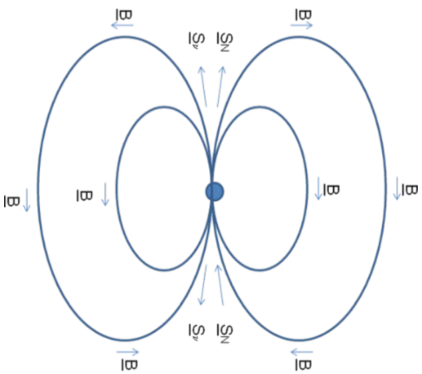
Astrobio. 10(2010),561; Int. J. Mol. Sci. 12 (2011), 3432; Symmetry 6 (2014), 909; Astrophys. J (2018), in press.

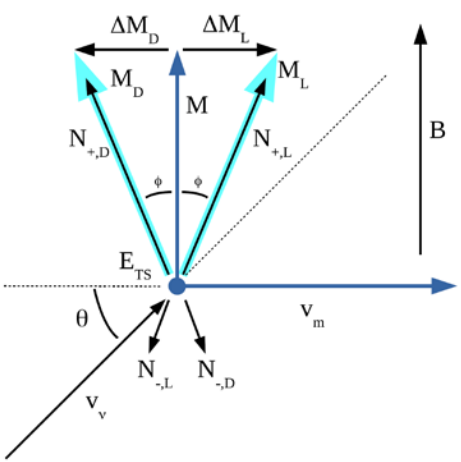
★ **Neutrinos are all left-handed!**

★ **Parity, broken in strongly magnetized NS or BH.**

★ **SN ejecta including ^{14}N form simple amino-acids and interact with neutrinos for ~ 10^{10}y.**

★ **Neutrino-^{14}N coupling is asymmetric & chiral selective. ^{14}N survives in north, but dies in south.**





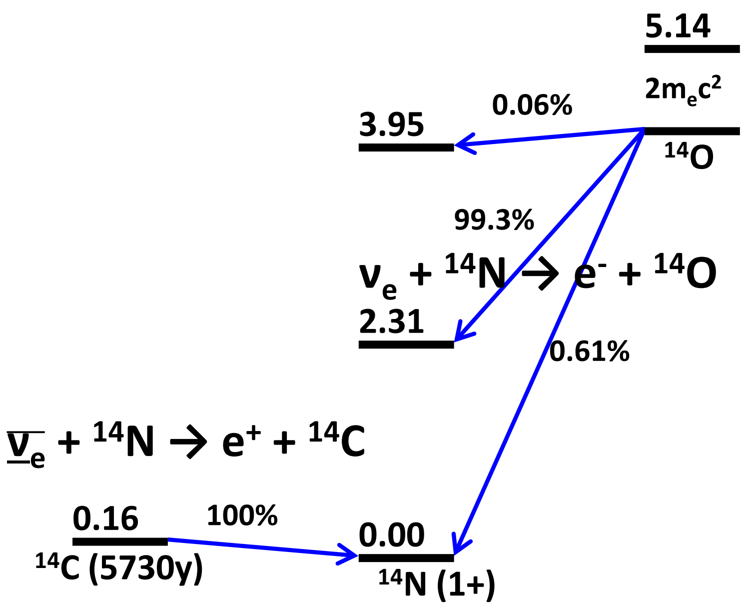


Table 1: Values of the molecular geometry

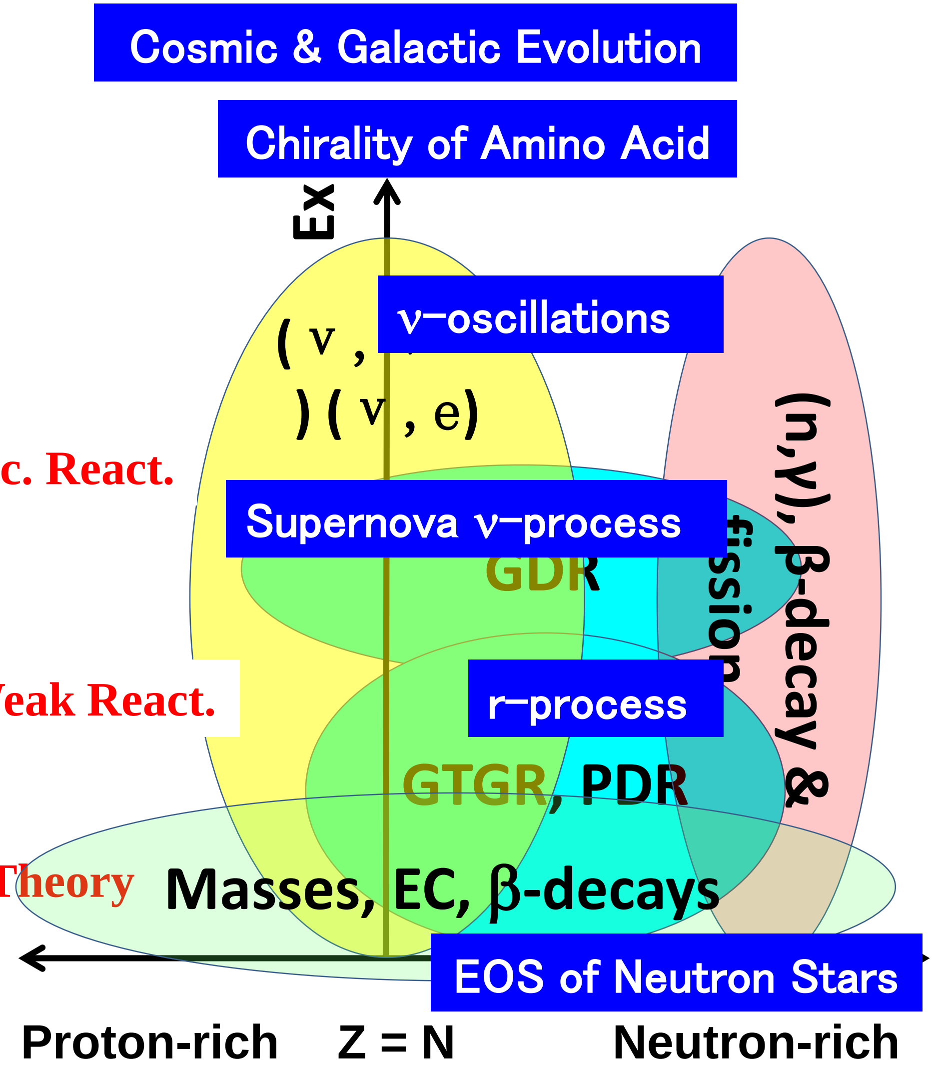
Amino Acid	Ligand	Zwitterion	Optimized
Alanine	-3.87	31.79	39.39 **51.60**
Arginine	7.79	-44.11 **18.57, 47.18**	-160.41
Histidine	-10.55	-44.58 **23.26**	-31.20
Isovaline	-0.63	-1.92	-16.67 **119.94**
Norvaline	5.49	26.24	33.26 **10.50**
Valine	1.01	4.44, 34.52	19.94 **8.47**

Quest for Nuclear Physics in Astrophysics

Developed HI & RIB Technique
+ Intense RI-Beam @ RIFBF
+ High Precision Spectroscopy + …

Probe E* on wide N-Z

Hadronic Charge-Exc. React.



Understanding of EW Response

→ GT + Forbidden Tr.
- SN explosion mechanism
- R-process, Th-U synthesis & cosmochronology

Electro-Weak React.

→ Neutral & Charged currents
- LiBeB synthesis & ν-oscillation
- Fe-Mn synthesis in 1st generations of star
- La, Ta, Nb … synthesis & cosmic clock

Reaction Theory

→ EC/beta-decays
- SN II, SN Ia, X-ray bursts

Structure Theory of Exotic Nuclei, Fission

Sasano @ Uesaka Spin-Isospin Labo., RIKEN

Summary

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

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

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

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

- ◆ Origin of Amino–Acid Chirality:

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

Neutron Star Meregrs, Supernovae → GWs, Lights, Elements & νs

— DAWN of multi-messenger astronomy & nuclear astrophysics
— SYNERGY among astronomy, astro-, particle- & nuclear physics

Purpose

1. How to distinguish r–process in Neutron Star Mergers (NSMs) vs. Core–Collapse Supernovae (CCSNe) ?   Time scale ?

→ **Fission + masses, β-decay, (n, γ)**

→ **GW170817 vs. SiC-X Grains, Sediments**

→ **Actinide Boost Stars …**

CC-SNe = Magneto-Hydrodyn. Jet + ν-Heated Wind

2. How to find the roles of ν–interactions and oscillations ?

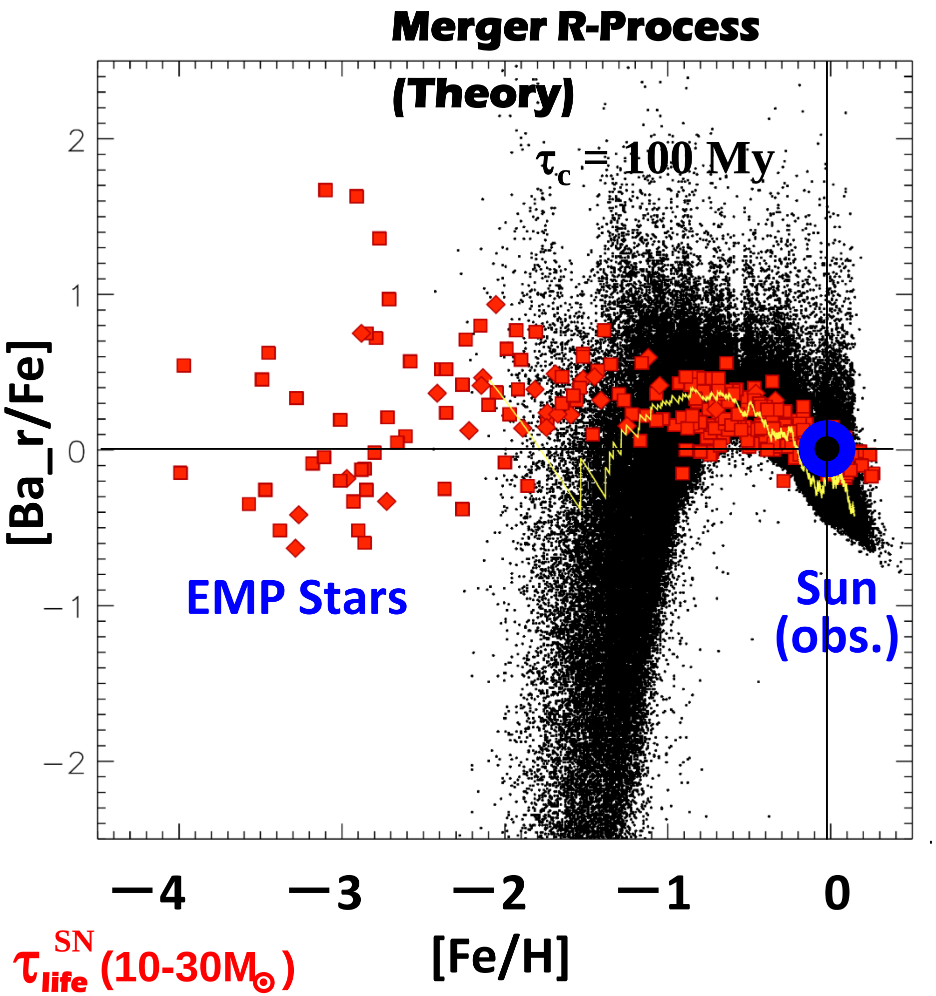
→ **ν-induced Nucleosynthesis**

→ **ν-Oscillations, Hierarchy**

→ **Origin of Amino Acid Chirality**

Time Scale Problem

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



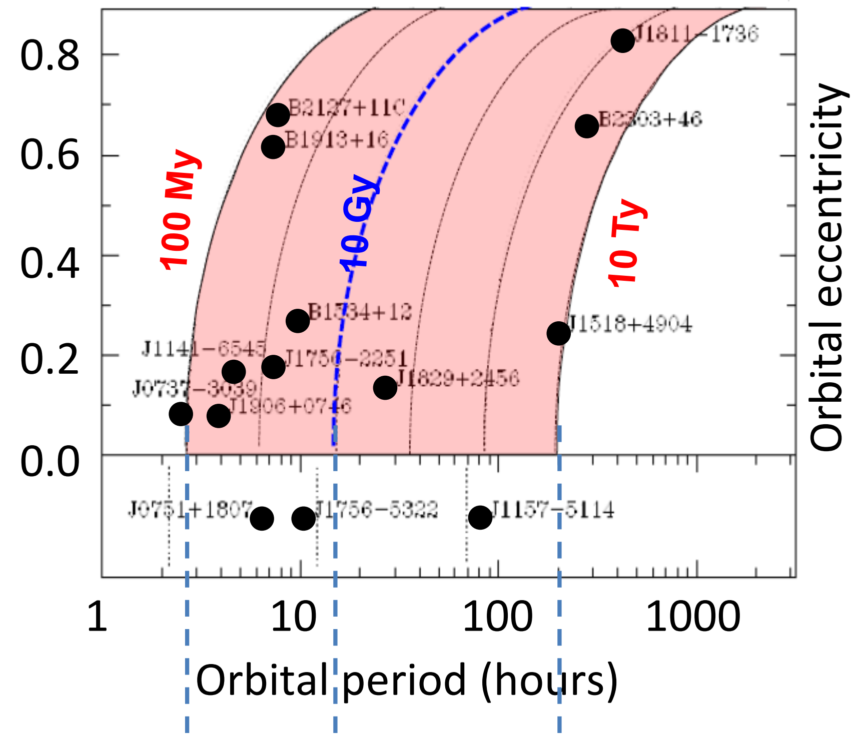
τ_{life}^{SN} (10-30$M_{\odot}$)

1My 10My 100My · · · 10Gy

Binary merger process, too slow for GW radiation: 100My<τ_c

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

Lorimer, Living Rev. Rel. 11(2008), 8.



100My 10Gy 10Ty

Observed Galactic event rates !

Ejected Mass [Msun] x Event Rate [/Galaxy/Century]

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

MHD Jet SNe = 0.6 x 10^{-2} x ((0.03±0.02) x (1.9±1.1)) [b]

Binary NSMs = (2±1) x 10^{-2} x (1-28)x10^{-3} [c]

GW170817 confirmed short-GRB = NSM !

Nature 439, 45 (2006).

b 0.03±0.02 Winteler, et al., ApJ 750, L22 (2012).

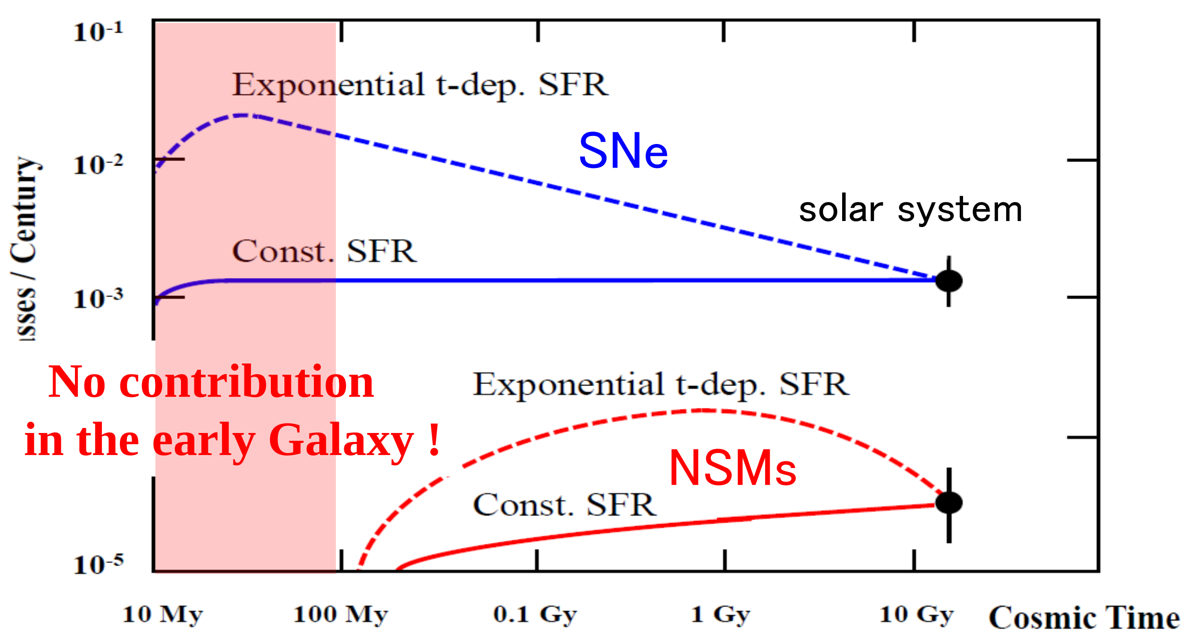
Obs. Estimate c (1-28) x 10^{-3} Kalogera, et al., ApJ 614, L137 (2004).

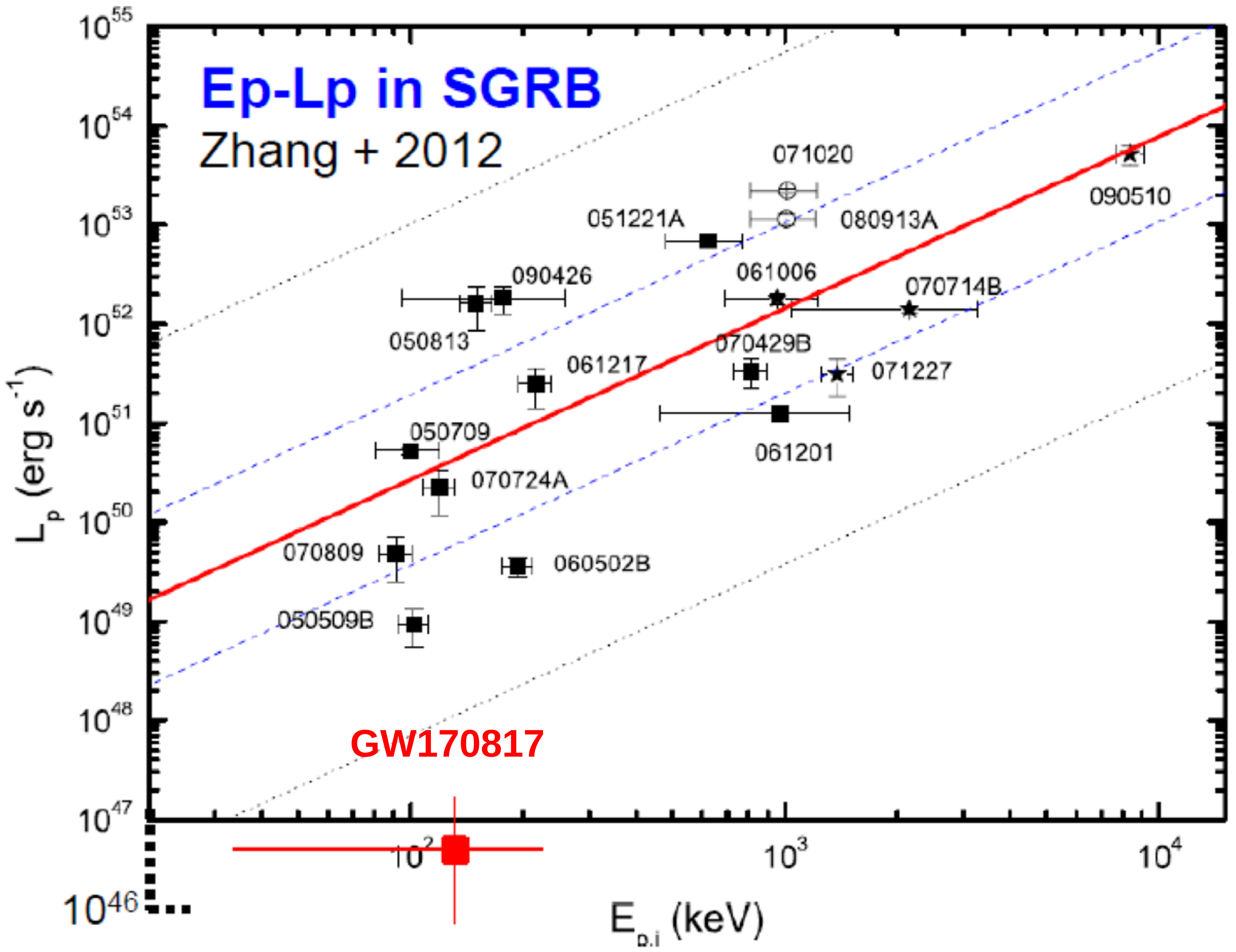
Event rates
including Binary Evolution

Kajino & Mathews, Rep. Prog. Phys. **80** (2017) 08490;
Mathews & Kajino, (2018).

Time Scale Problem in

Neutron Star Mergers



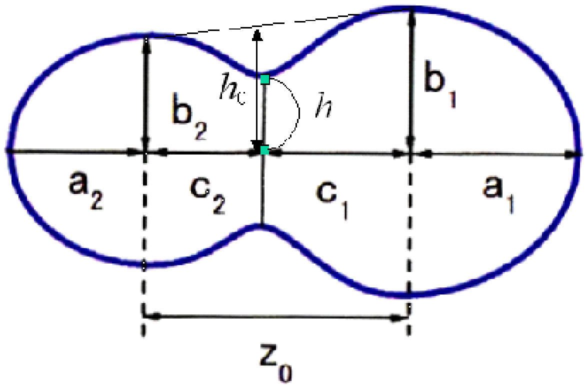

Ep-Lp in SGRB
Zhang + 2012
071020
090510
051221A
080913A
090426
061006
070714B
050813
070429B
061217
071227
050709
061201
070724A
070809
060502B
050509B
GW170817
L_p (erg s^{-1})
$E_{p,i}$ (keV)
10^{55}
10^{54}
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
10^2
10^3
10^4

KTUY Model : Fission Fragment Mass Distribution

M. Ohta et al., Proc. Int. Conf. on NDST, Nice, France, (2007)
S. Chiba et al., AIP Conf. Proc. 1016, 162 (2008).

Liquid Drop Model in Two Center Shell Model

Parameter ⇒ distance z
mass asymmetry α
deformation δ



Fission Fragment Distribution

Potential Energy Surface

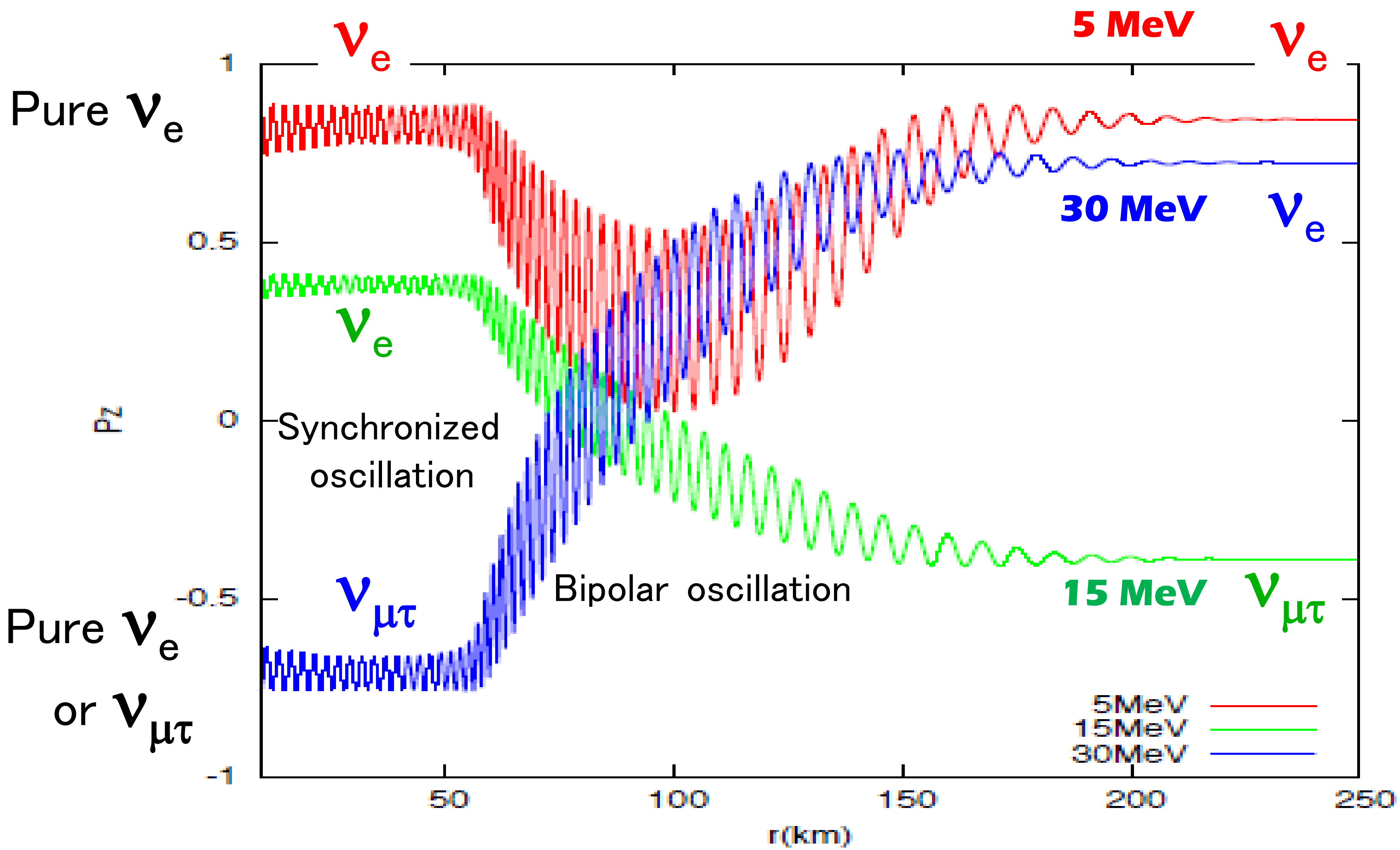
$$f(A) = \frac{1}{\sqrt{2\pi}\sigma}(1-\omega_s)(e^{-(A_H-A)^2/2\sigma^2} + e^{-(A_L-A)^2/2\sigma^2}) + \frac{2\omega_s}{\sqrt{2\pi}\sigma} e^{-((A_H+A_L)/2-A)^2/2\sigma^2}$$

Analysis of Potential Energy near the Scission Point

- Location of the depth of the asymmetric valley at δ=0.2, 0.3
  → mass asymmetry of fission fragment distribution (A_H, A_L)
- Depth of the asymmetric valley & Depth at α=0 and δ~0
  → ratio of the symmetric component and asymmetric component (ω_s)
- σ=7.0

Calculated ν Flavor Oscillation

Energy spectra swap!



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Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®;
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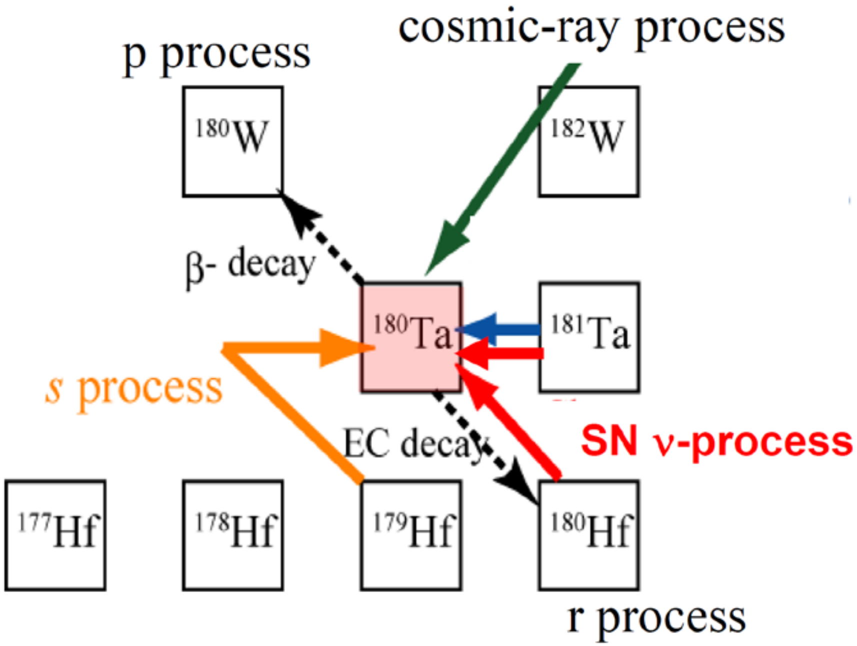
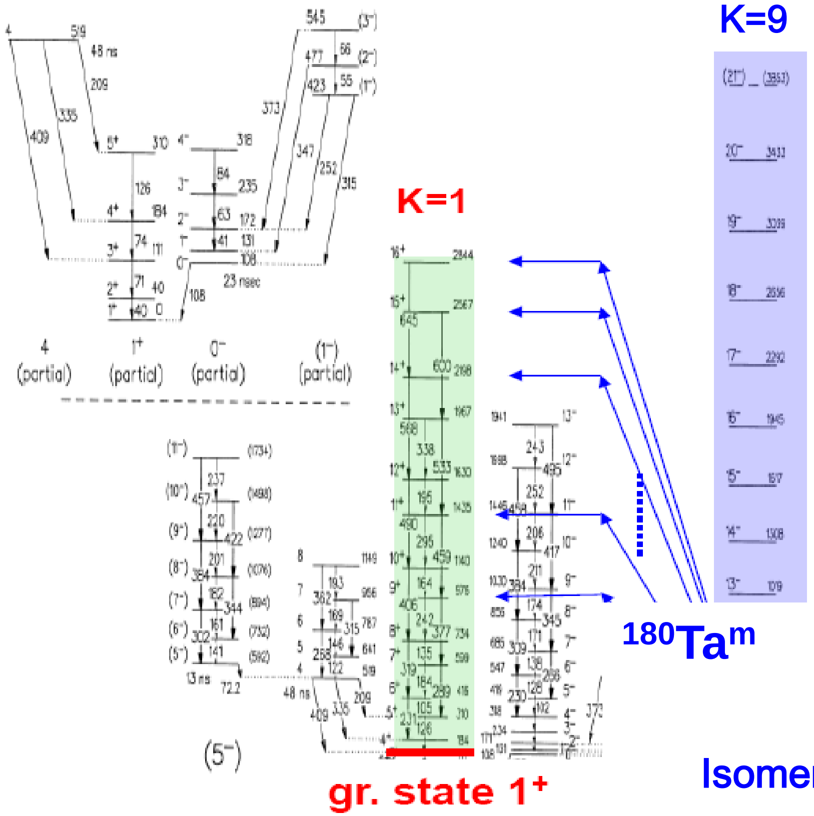
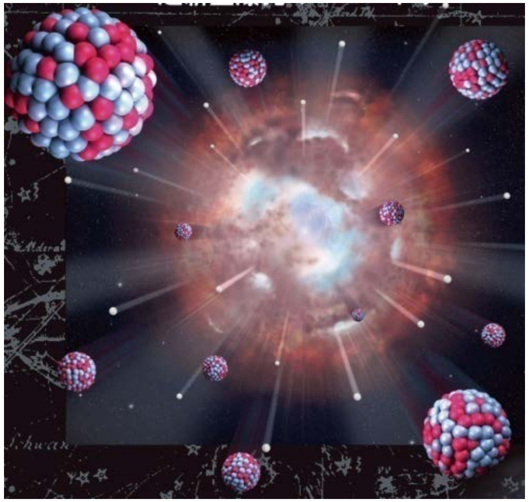


SN ν-process in Einstein AB theory
→ Only 40% survives!

D. Belic et al., PR C65 (2002), 035801.



$^{180}Ta_g(\tau_{1/2} = 8h)$ $^{180}Ta^m(\tau_{1/2} > 10^{15}y)$



The last nearby Supernova

When exploded & formed pre-solar grain?

Primordial Sun formed.

The Sun isolated

4.56 Gy ago !

Present Sun

How long ?

From predicted initial abundance of ^{92}Nb($\tau_{1/2}$=3.47x10^7 y) in GCE + Late Input(SN)model, we conclude;

ΔT = 1～30 My !

Hayakawa, Nakamura, Kajino, Chiba,Iwamoto, Cheoun, Mathews, ApJL **779** (2013), 1.

This is consistent with Standard Solar-System Formation Scenario
which requires ΔT = 1 ~ 10 My (H. Yurimoto, 2016).

Theoretical Calculation for ν-Nucleus Cross Secti

New generation SM cal. with NEW Hamiltonian: ν-^{12}C, ^{4}He

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307;
Suzuki & 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 $^{12}C \to {}^{12}N$, $^{14}C \to {}^{14}N$, etc. (GT)
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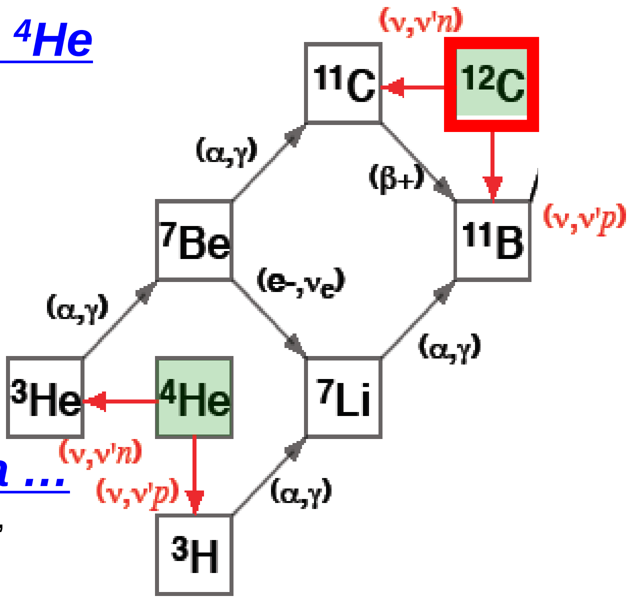

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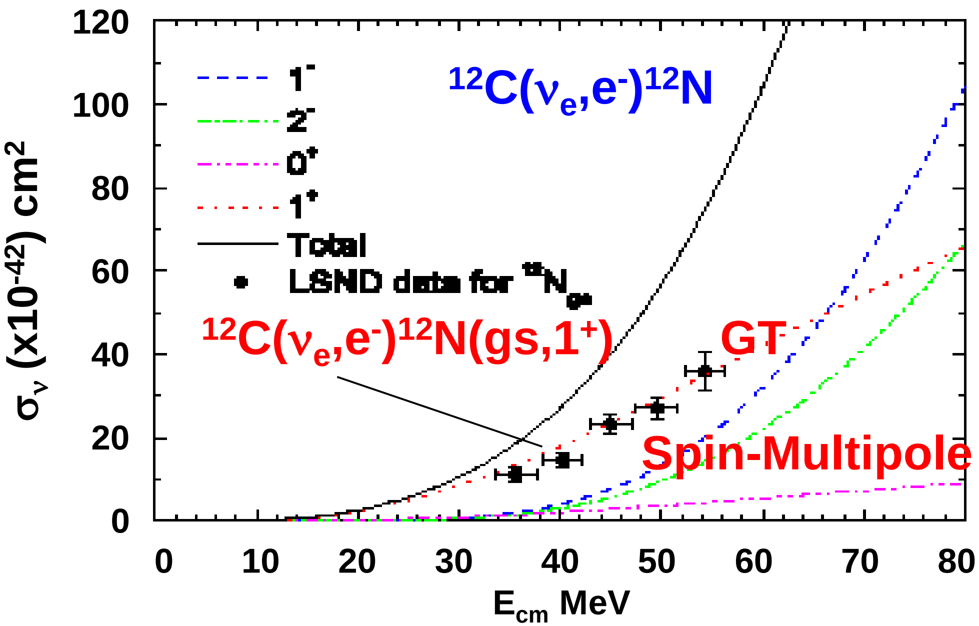
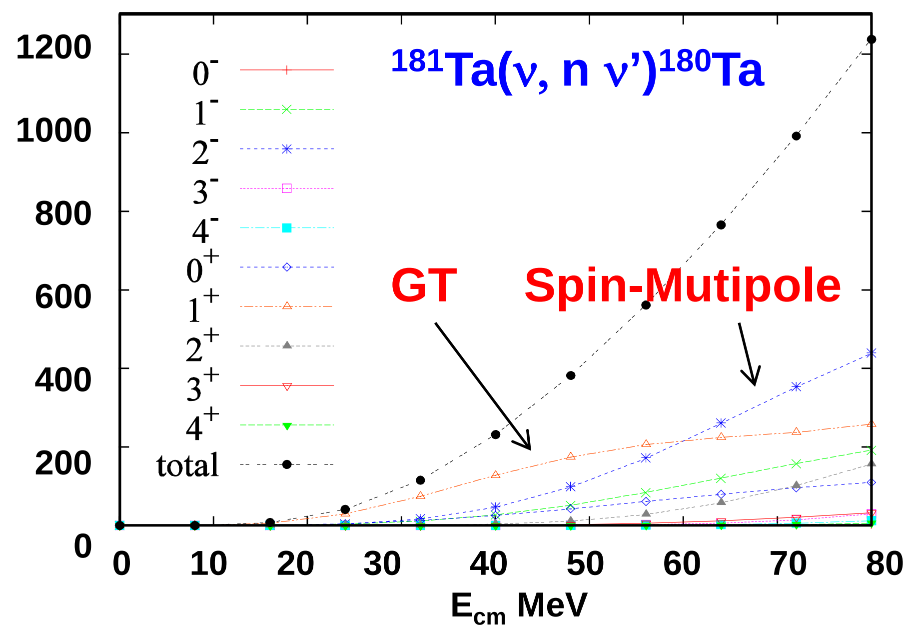
Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801; PRC 85 (2013), 065807; PLB 723 (2013), 464; J. Phys. G42 (2015), 045102; +





Connection among
ν Mass–Double β decay–Astronomy–Cosmology

K. Yako et al., PRL 103 (2009) 012503.

B(GT$^{+/-}$) distribution

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

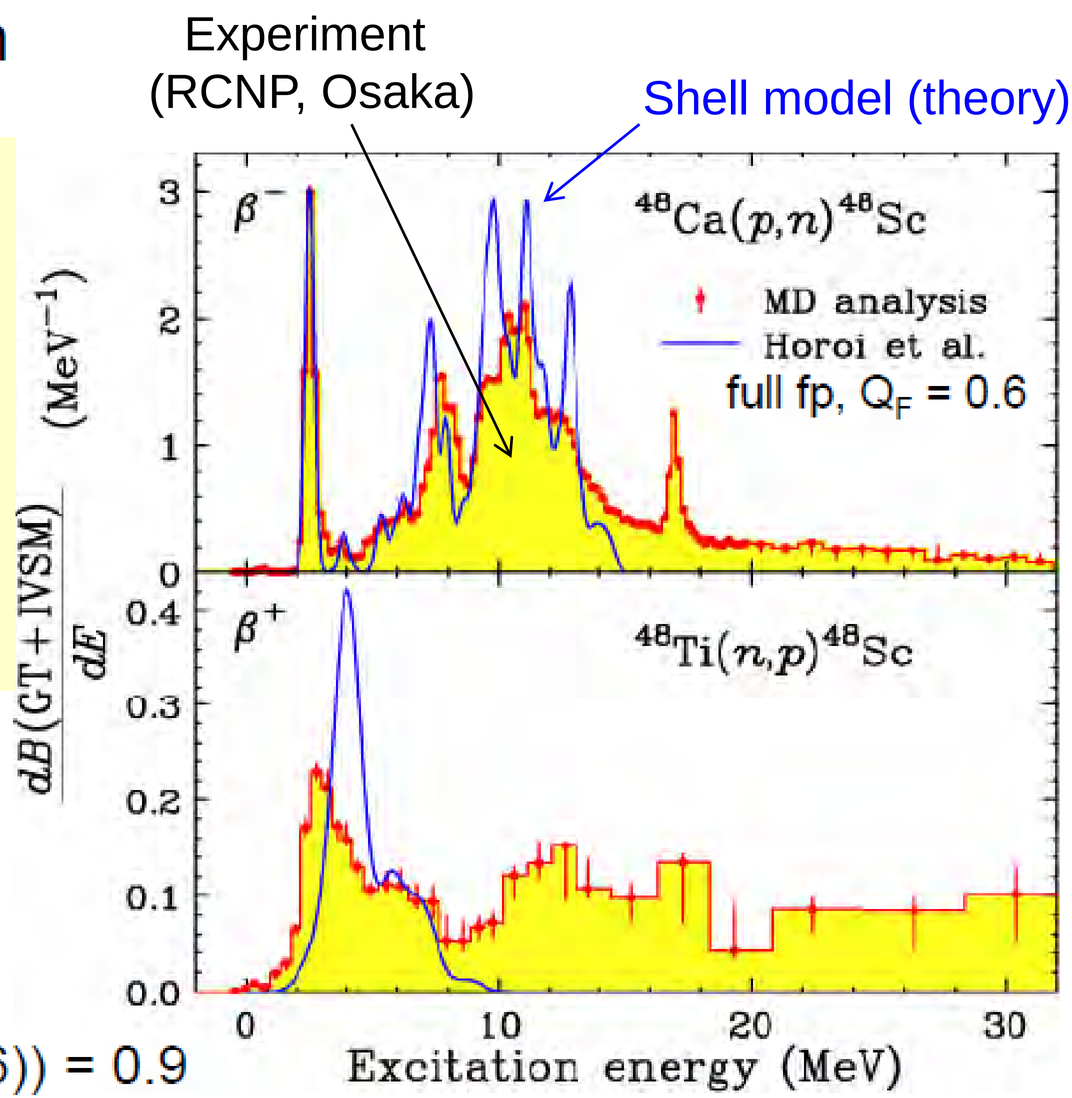
(n,p) channel :

ΣB(GT$^+$;exp) = 1.9±0.3…

(w subtraction of IVSM)

⬍

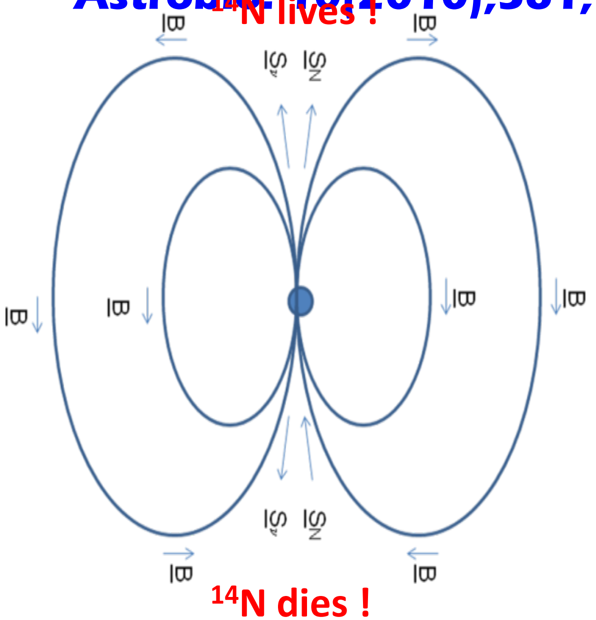
ΣB(GT$^+$;ShellModel(Q_F=0.6)) = 0.9



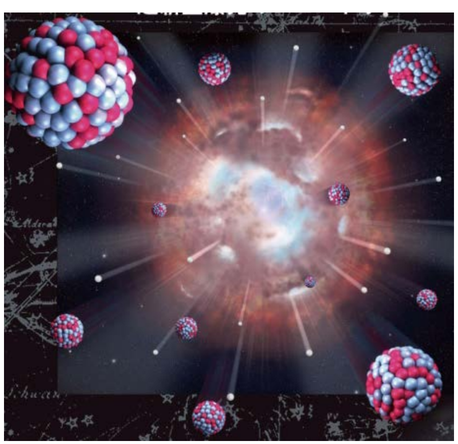
UNIVERSAL Origin of L-handed Chirality of Amino Acids

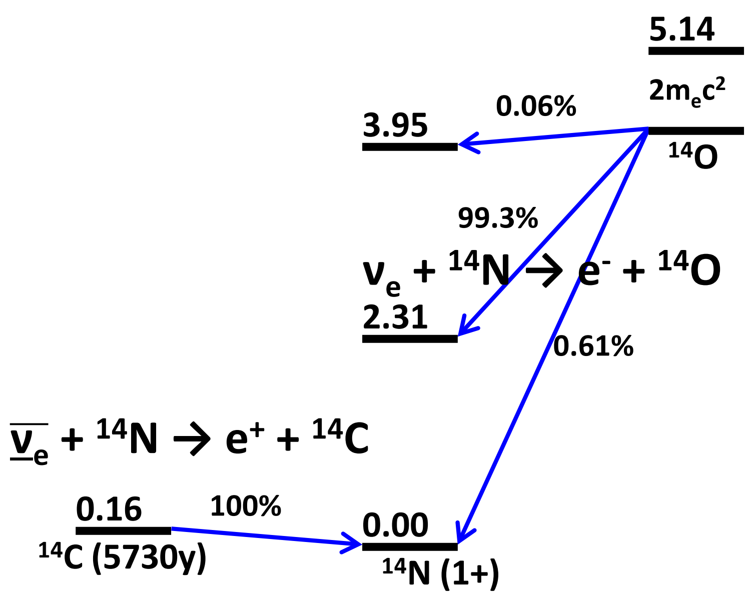
Boyd, Kajino, Onaka & Famiano,

Astrobio. 10(2010),561; Int. J. Mol. Sci. 12 (2011), 3432; Symmetry 6 (2014), 909.



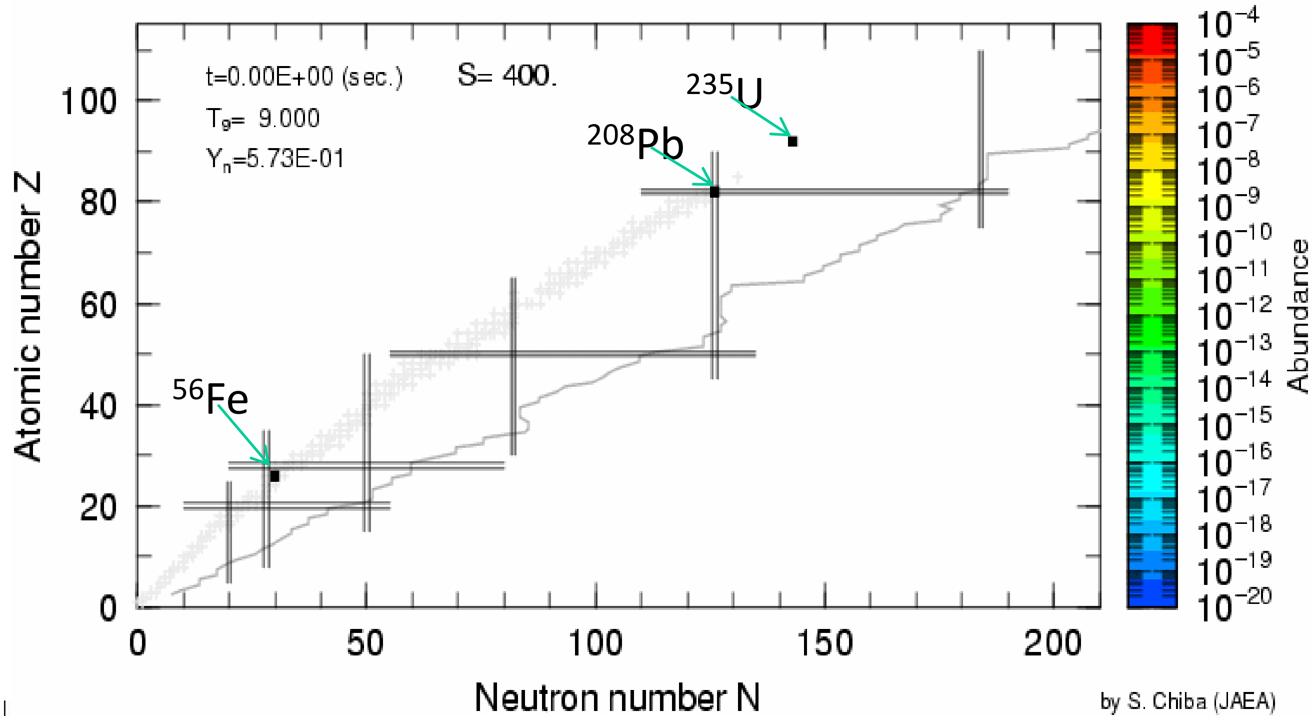
- ★ Neutrinos are all left-handed! (Symmetry is broken.)
- ★ SNe with strongly magnetized NS or BH emit intensive flux of neutrinos 10^8 times over 10^{10} yrs.
- ★ SN ejecta including ^{14}N form simple amino-acids and interact with neutralized e-type neutrino bursts.
- ★ Neutrino-^{14}N coupling is asymmetric & chiral selective. ^{14}N survives in north, but dies in south.



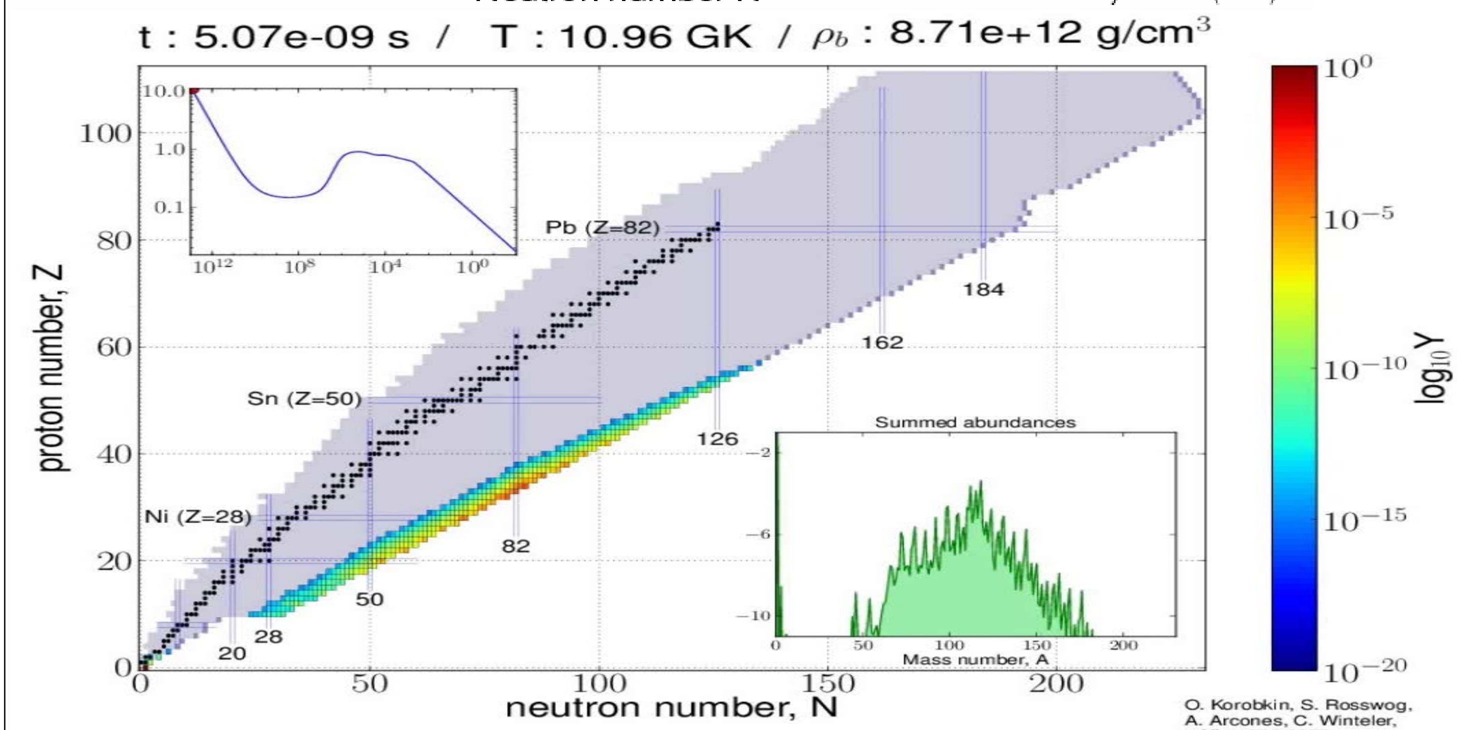


Mann and Primakoff (Origins of Life, 11 (1981), 255) suggested β-decay of 14C, but it's too SLOW!

SN


t=0.00E+00 (sec.)
S= 400.
T9= 9.000
Yn=5.73E-01
235U
208Pb
56Fe
Atomic number Z
Neutron number N
Abundance
by S. Chiba (JAEA)

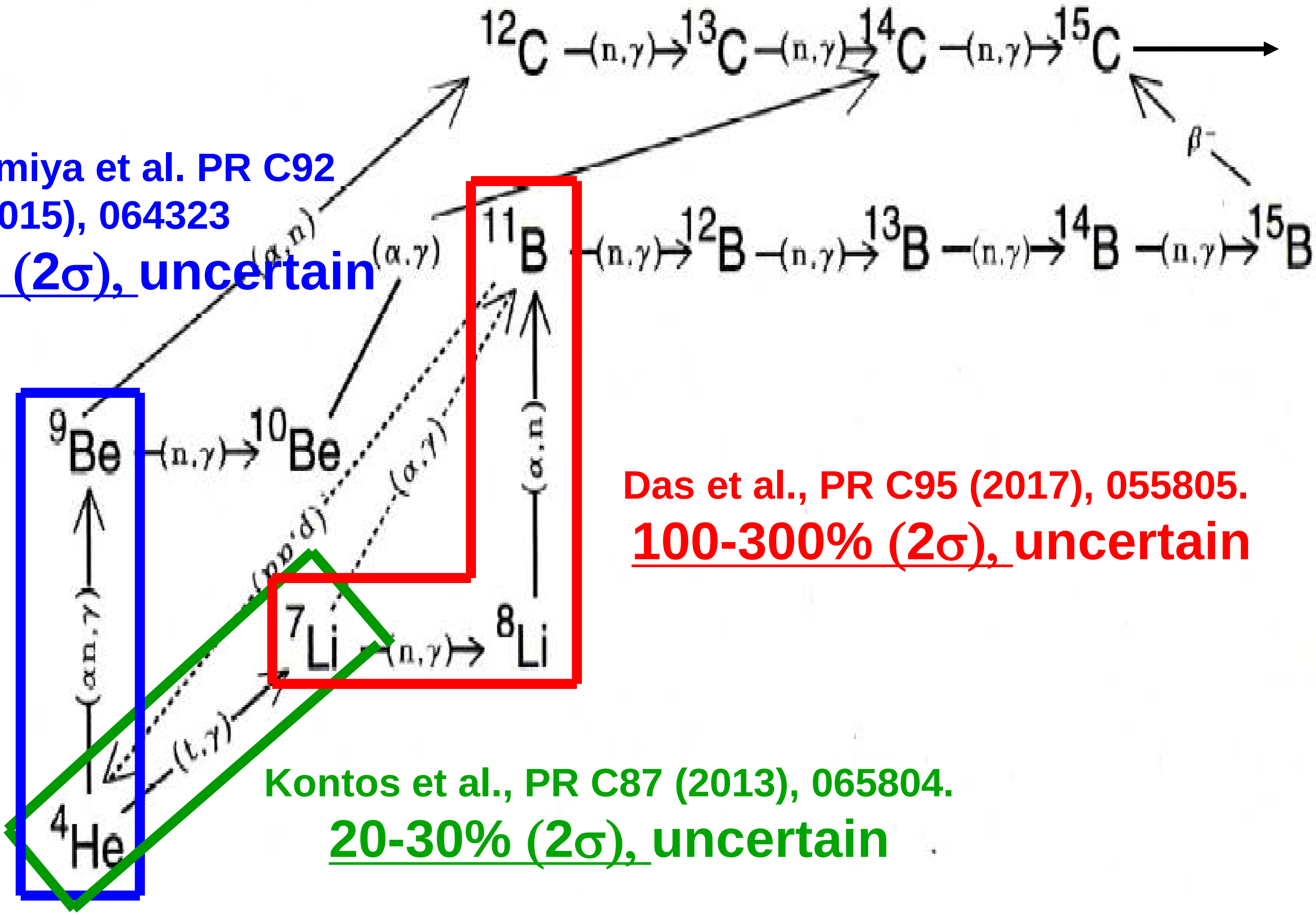
NS Merger


t : 5.07e-09 s / T : 10.96 GK / ρb : 8.71e+12 g/cm3
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
20
28
50
82
126
162
184
Summed abundances
Mass number, A
proton number, Z
neutron number, N
log10Y
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler,

Important Reaction Flows, affecting R-Process

Factor x2 change could lead to $10^{1\text{-}2}$ difference in r-elements !

Kim et al., (2017), on-going project at RAON/RISP/IBS.



Utsunomiya et al. PR C92 (2015), 064323

30-50% (2σ), uncertain

Das et al., PR C95 (2017), 055805.

100-300% (2σ), uncertain

Kontos et al., PR C87 (2013), 065804.

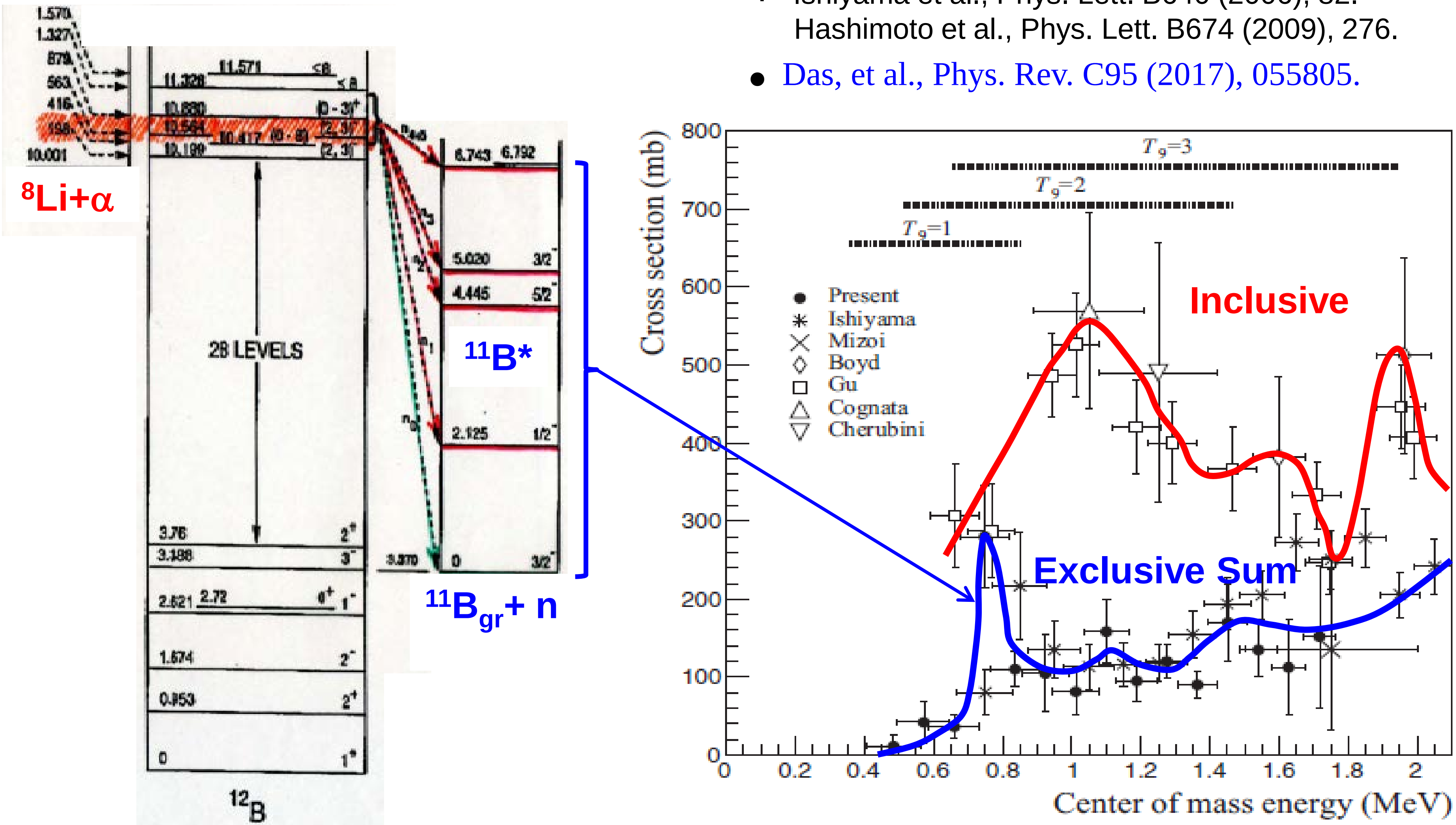
20-30% (2σ), uncertain

$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

Discrepancy
Inclusive > Exclusive Sum ?

100-300% (2σ), uncertain !

- ◇ Boyd et al. Phys. Rev. Lett. 68 (1992), 1283.
- △ LaCognata et al., Phys. Lett. B664 (2008), 157.
- □ Gu et al., Phys. Lett. B343 (1995), 31.
- ✱ Ishiyama et al., Phys. Lett. B640 (2006), 82.
  Hashimoto et al., Phys. Lett. B674 (2009), 276.
- ● Das, et al., Phys. Rev. C95 (2017), 055805.



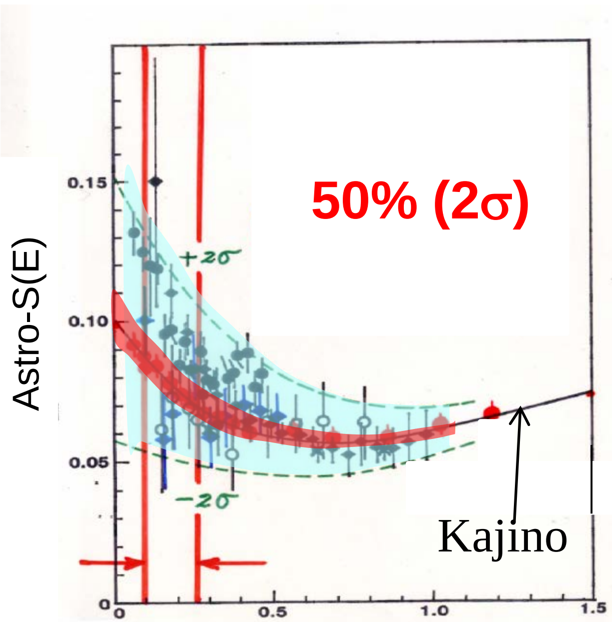
$^4He(^3H,\gamma)^7Li$ Mirror $^4He(^3He,\gamma)^7Be$

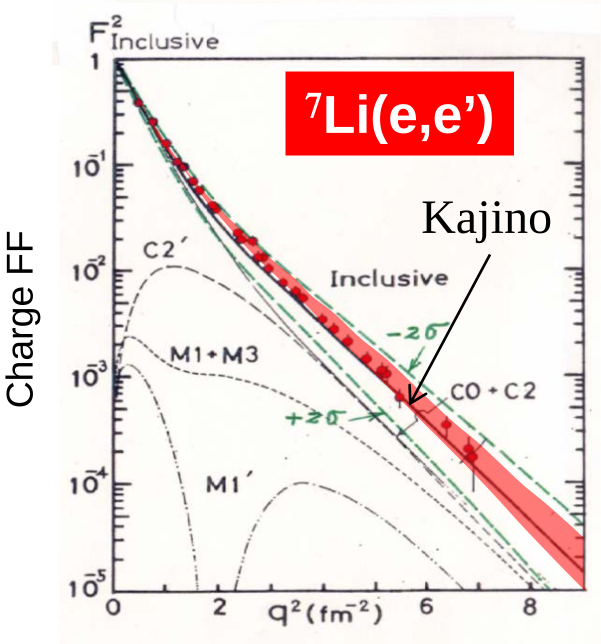
Adelberger, RMP 83 (2011),195.

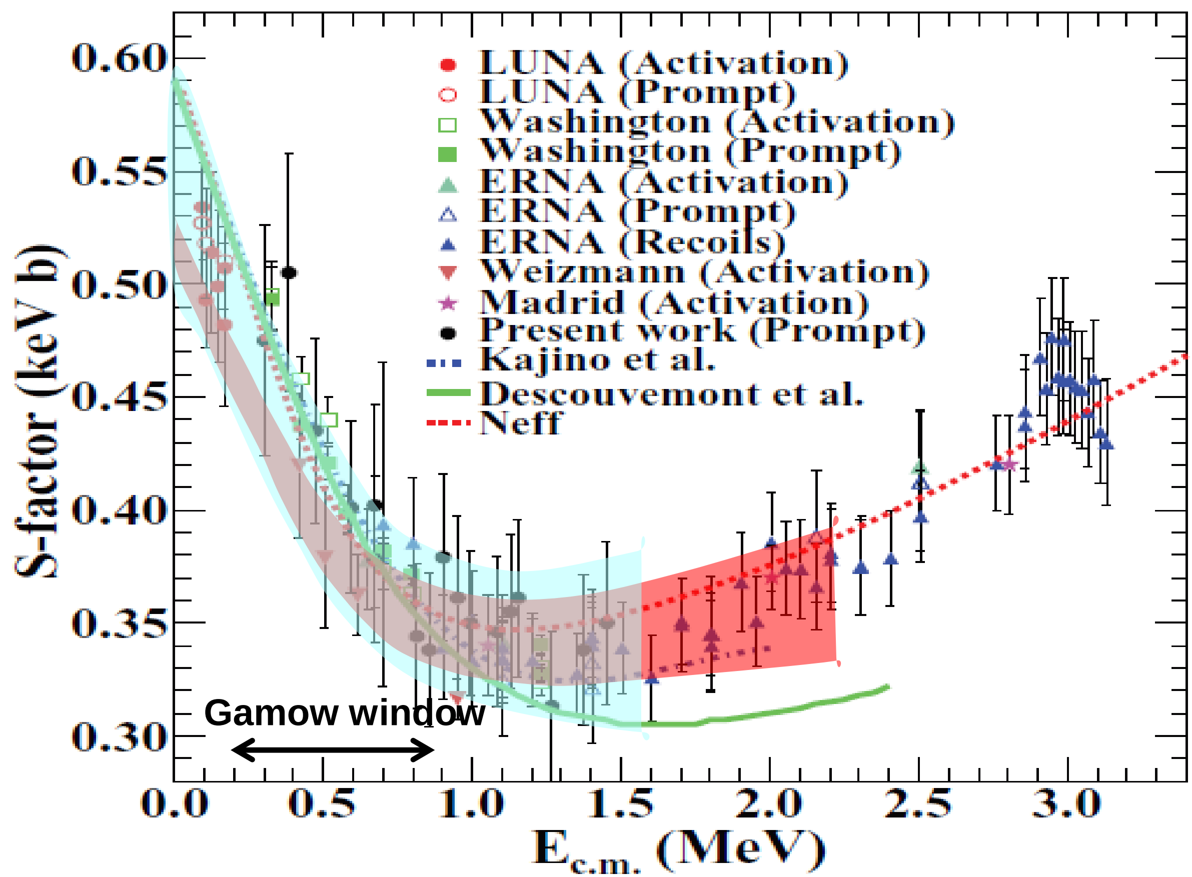
5% (1σ), uncertain !

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

20% (2σ), uncertain !



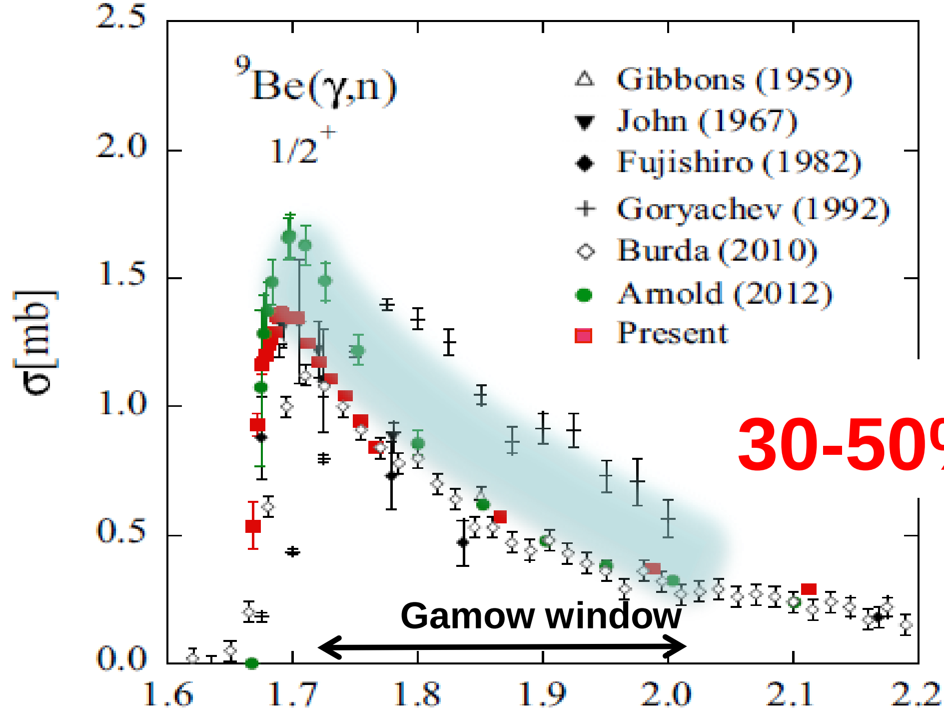




$^9Be(\gamma,n)2\alpha$

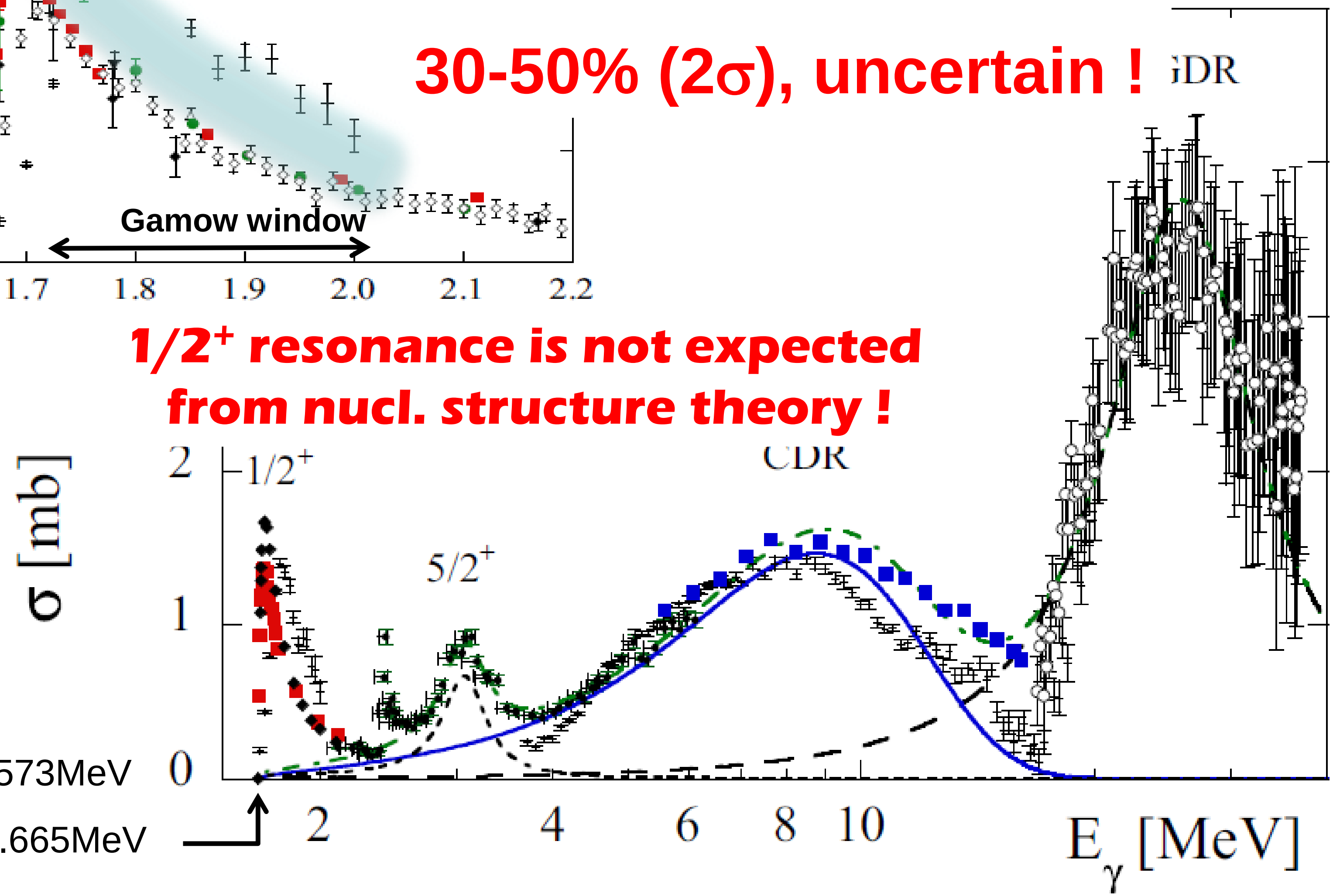
^8Be, ^5He ?

Utsunomiya et al., PRC92 (2015), 064323.



30-50% (2σ), uncertain !

$1/2^+$ resonance is not expected from nucl. structure theory !

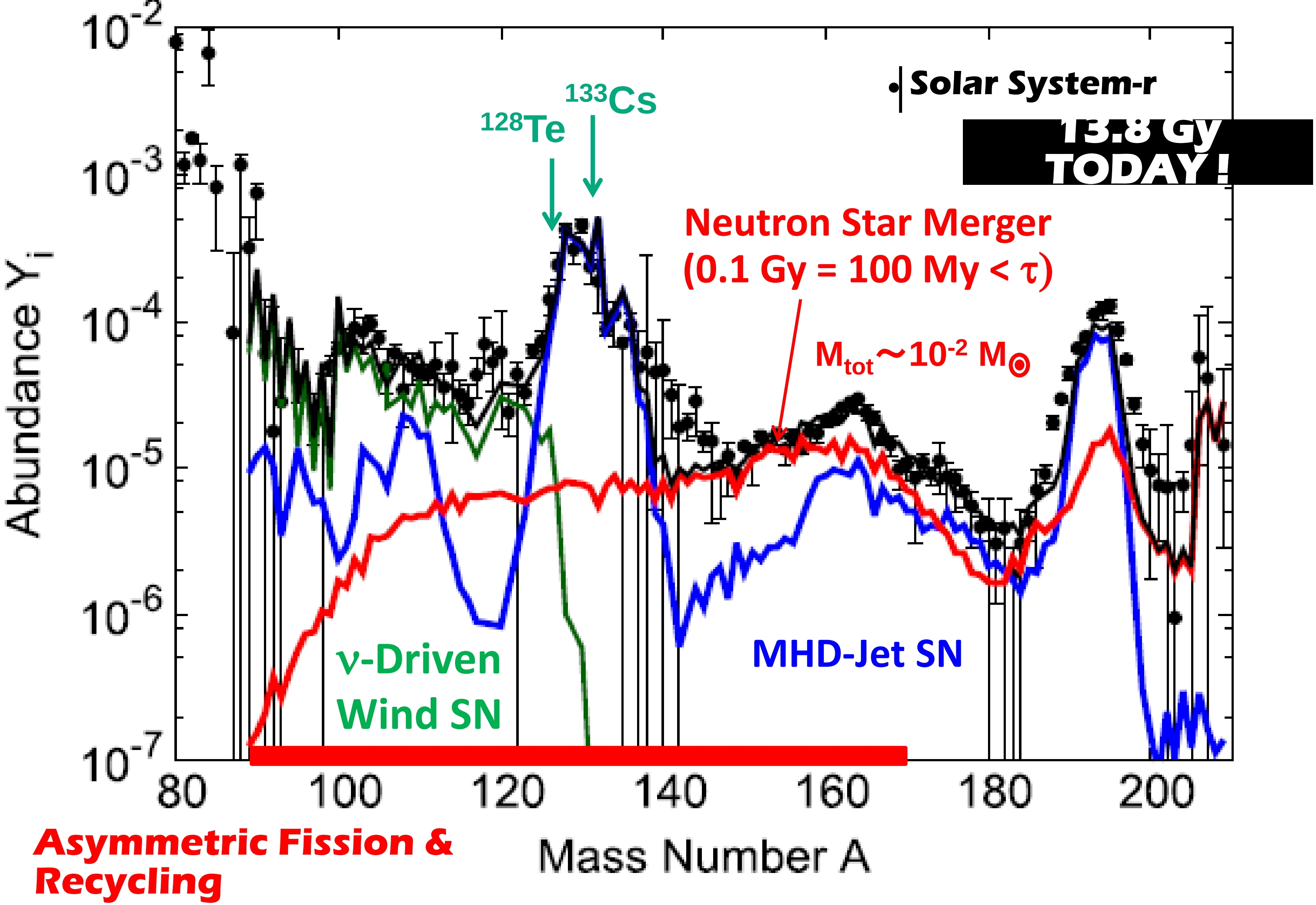


$E_{th}(n+2\alpha)=1.573MeV$

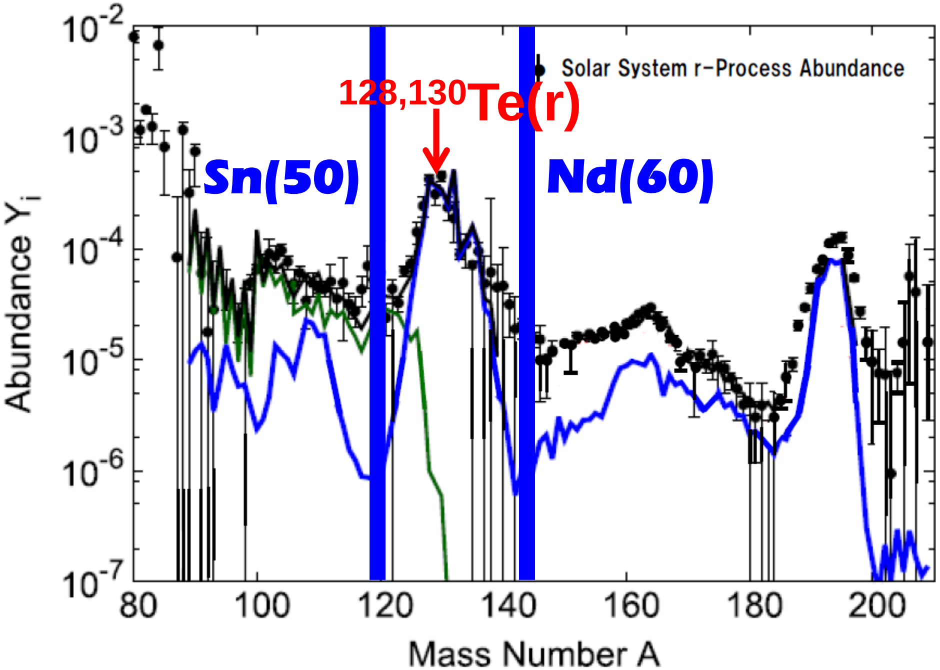
$E_{th}(n+{}^8Be)=1.665MeV$

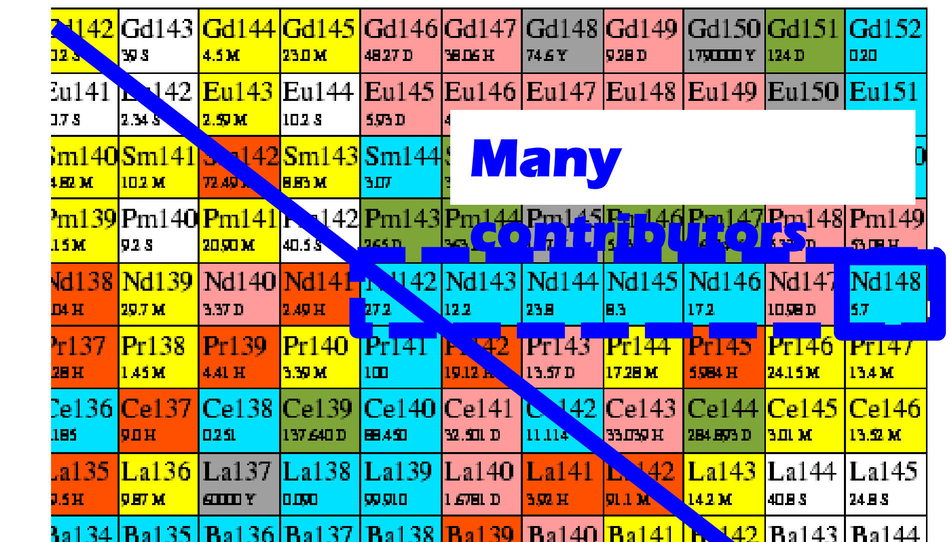
Solar System r-Process Abundance

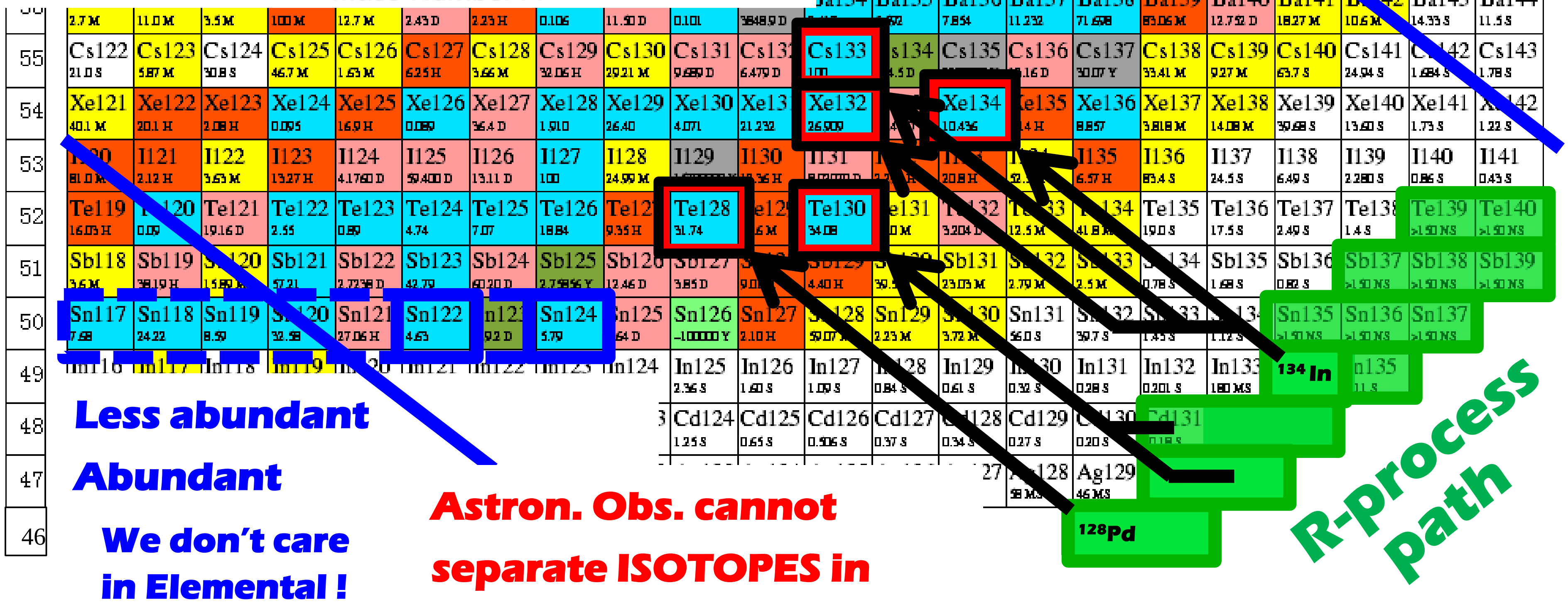
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2018);
Kajino & Mathews (2017), ROPP 80 , 084901.



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







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

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

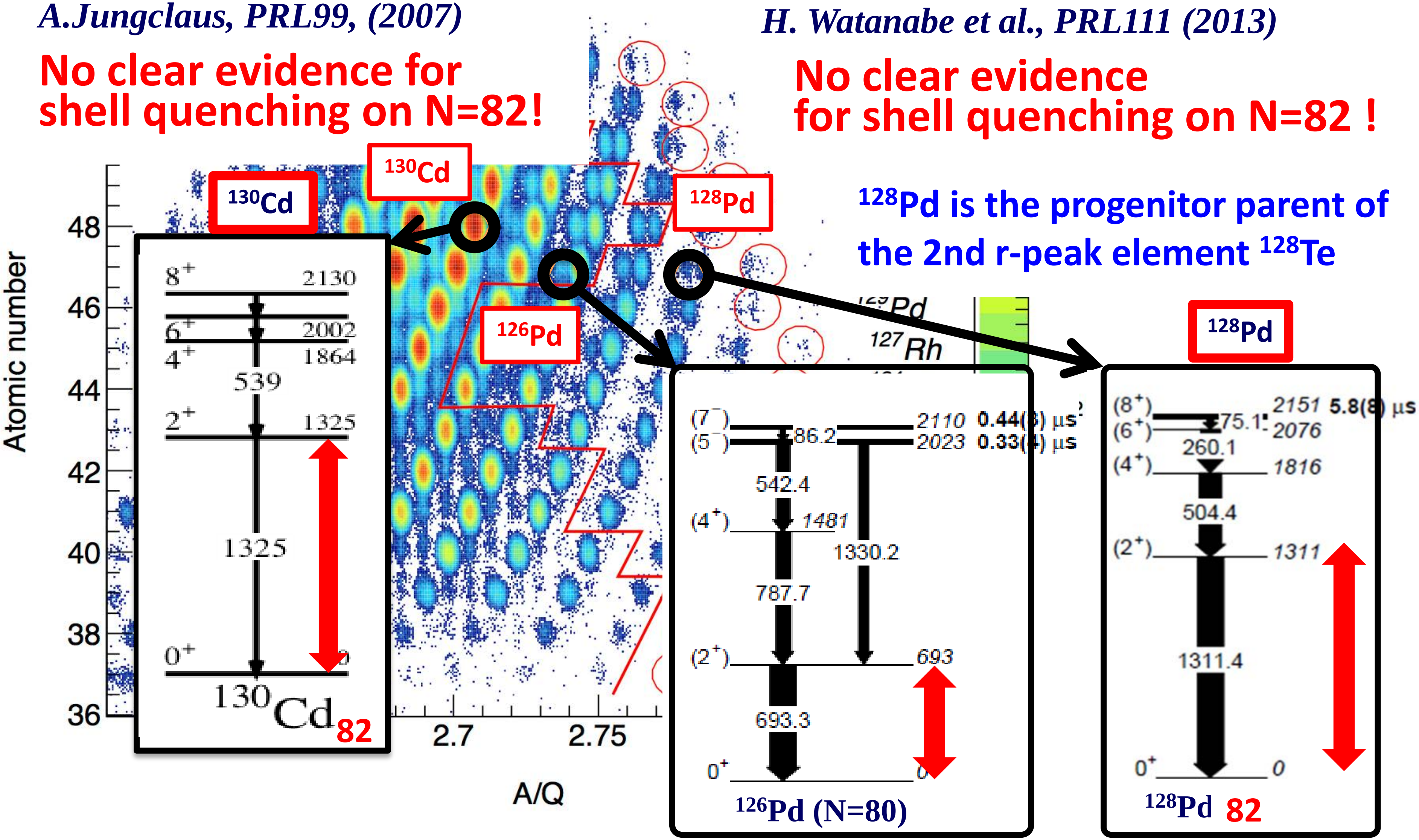
A.Jungclaus, PRL99, (2007)

No clear evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

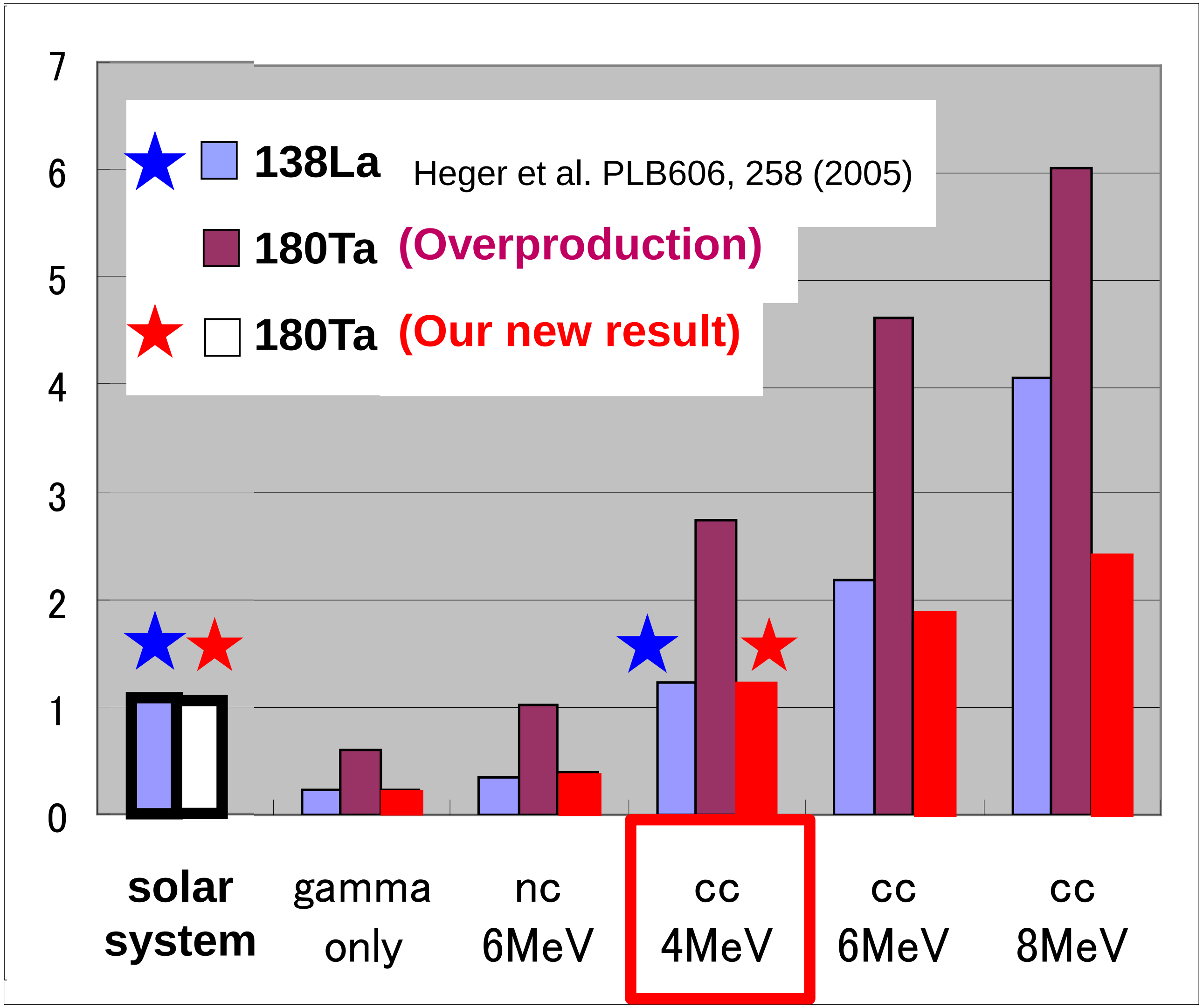
No clear evidence for shell quenching on N=82 !

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



Result from our ν-Nucleosynthesis

T. Hayakawa, P. Mohr, T. Kajino, S. Chiba, and G.J. Mathews, Phys. Rev. C81 (2010), 052801®; Phys. Rev. C82 (2010), 058801.



39% of $^{180}Ta^{m}$ survives in the dynamics of c.c. supernova explosion.

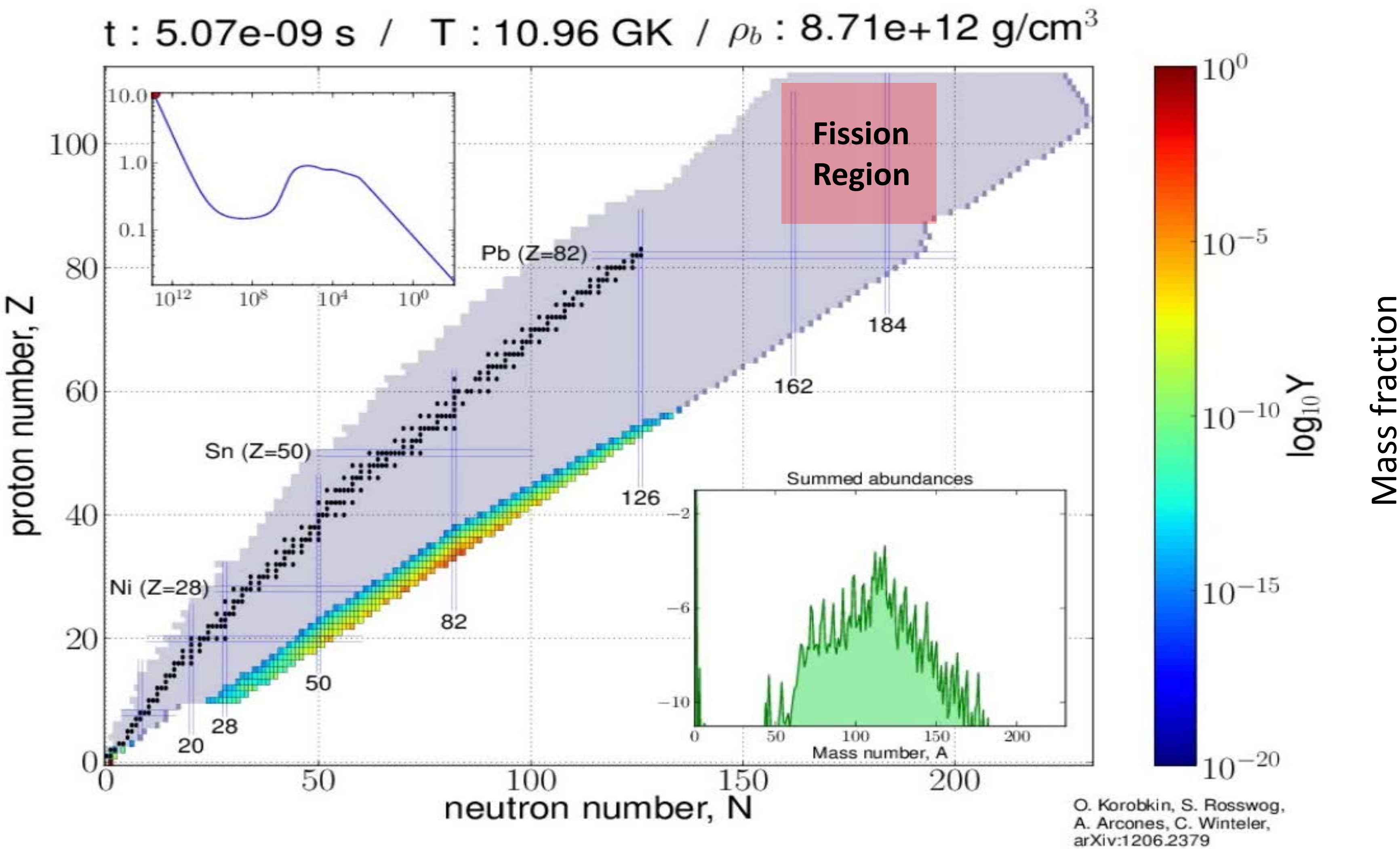
$T_{\nu e} = T_{\overline{\nu e}}$ = 4 MeV.

Consistent with r−process in ν−DW SN !

Dynamical Cal. of r-Process in Neutron Star Merger

Korobkin et al., MNRAS 426 (2012), 1940; Rosswog et al., MNRAS 430 (2013), 2585.
Shibagaki, Kajino, et al. (2016), ApJ 816, 79; Kajino & Mathews (2017), ROPP 80 , 084901.

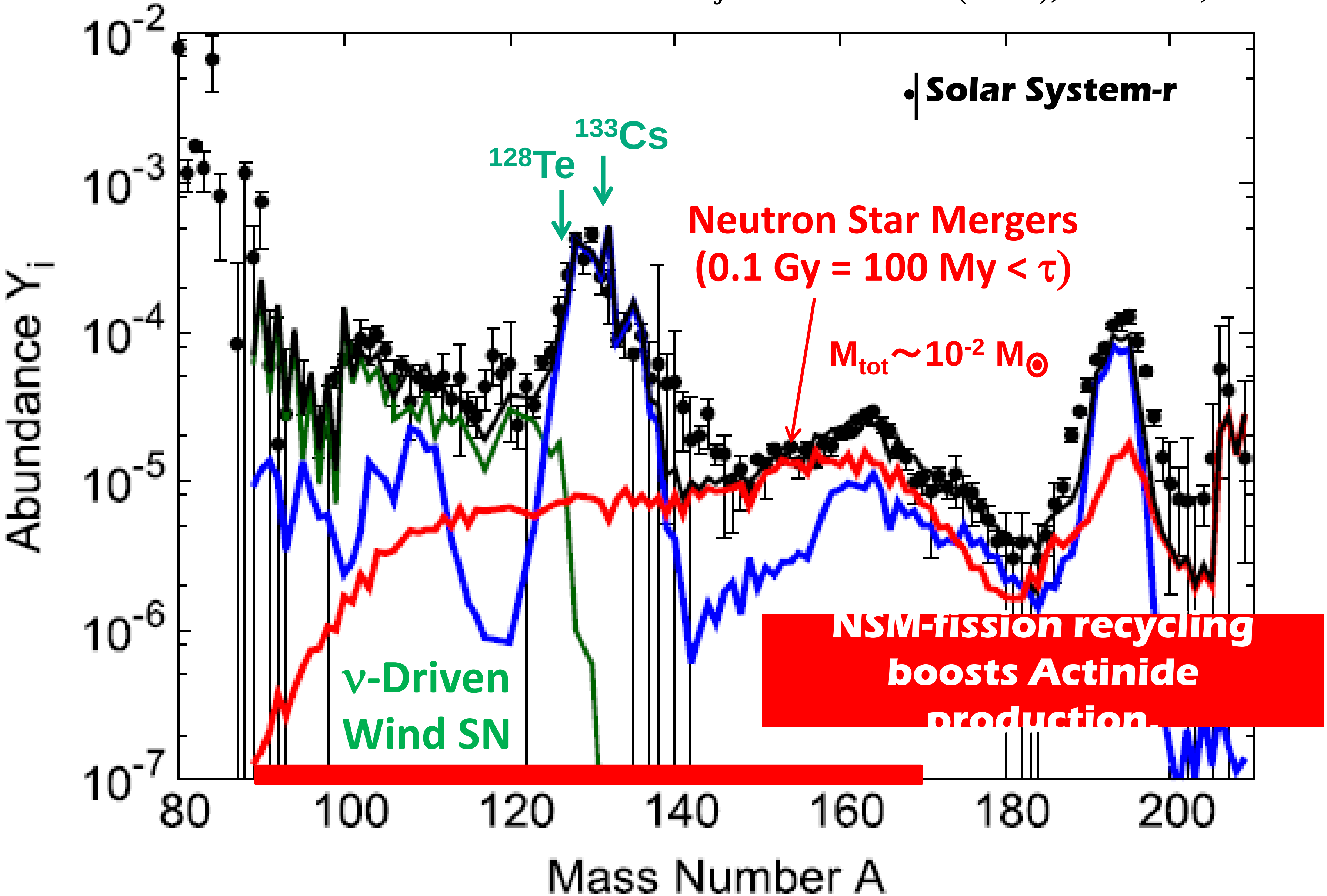
Hundreds of radioactive nuclei contribute!



Solar System r-Process Abundance

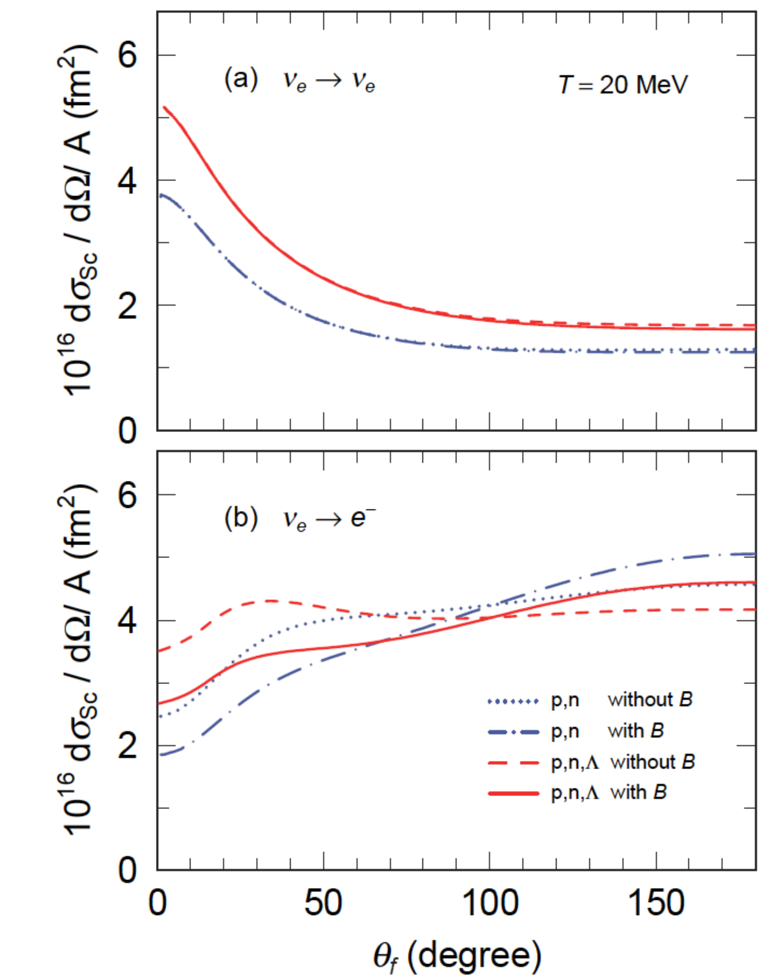
Present time: t =

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



By D.Page

Asymmetric ν-scattering and absorption.



Relativistic Mean Field Theory
+ Numerical Simulation of SNe

T. Maruyama, T. Takiwaki, et al.;

Phys. Rev. ® D83 (2011), 081303
Phys. Rev. D86 (2012), 123003
Phys. Rev. C89 (2014), 035801
Phys. Rev. D90 (2014), 067302

Neutrino scattering and absorption process inside a Strongly Magnetized Neutron Star with B = 10^{15}G is asymmetric.

⇒ **2.2 % asymmetric ν-emission**

⇒ Asymmetry for **Pulsar-Kick !**

V(th) = 300 – 600 km/s

c.f. V(obs) = 400-1600 km/s

強い場の存在下での爆発天体現象が明らかにする 重元素合成, ニュートリノ振動, アミノ酸キラリティーの起源

◎ **強い重力場** ➔ **重力崩壊型新星と中性子星連星系合体で共通。**

◎ **強いニュートリノ場** ➔ **両者で起源は異なる。**

- 重力崩壊型超新星 : neutralized ν_e-burst → ν-sphere → thermalized ν_e, ν_μ, ν_τ
- 中性子星連星系合体 : No neutralized ν_e-burst → No neutrino sphere → disk (heated) ν_e, ν_μ, ν_τ

◎ **強い電磁場** ➔ **超新星(重力崩壊型)爆発機構で異なる。**

- 磁気回転駆動型(MHD Jet SN)
- ニュートリノ加熱型(ν-Wind SN)

➔ 重元素合成, ニュートリノ振動の解明

■ **爆発的元素合成 : r プロセス、ニュートリノ・プロセス**

■ **ニュートリノ振動 : 物質(MSW), 自己相互作用(Collective)**

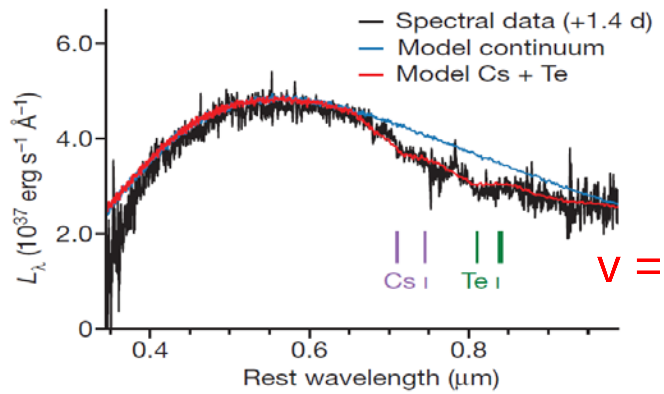
GW170817

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

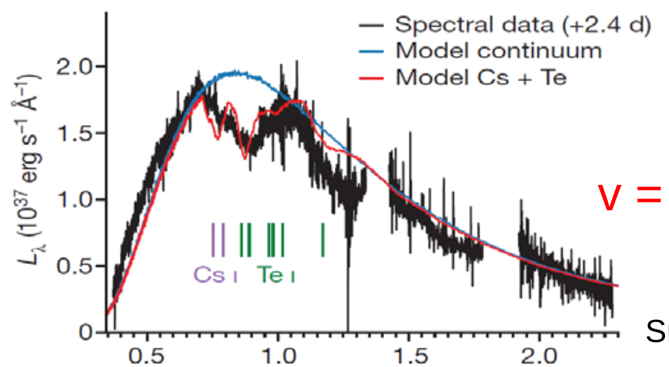
- GW170817 (LIGO-Virgo) : $0.86 < M/M_\odot < 2.26$
- GRB170817A (Fermi-GBM) : 1.7 s
- No ν–Signal: 10^{-6} weaker than SN1987A (1.6×10^5 ly)
- X-rays & Radio waves : Remnant NS or BH, not identified.
- **Optical and Near-infrared : SSS17a (over 70 Telescopes)**

GW170817
SSS17a

◆ **Energy, consistent with r-process!** ◆ **No r-element, identified.**



v = 0.2 c

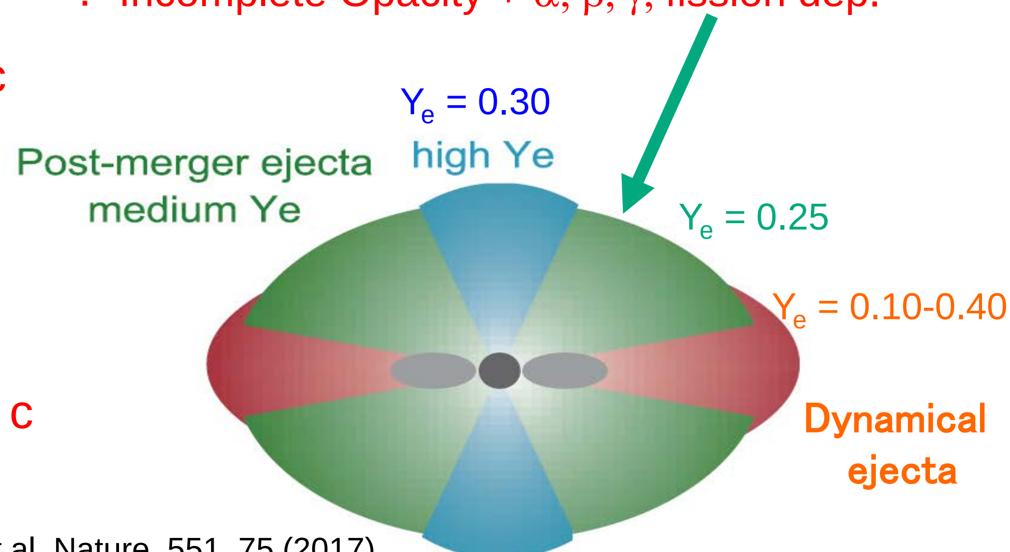


v = 0.13 c

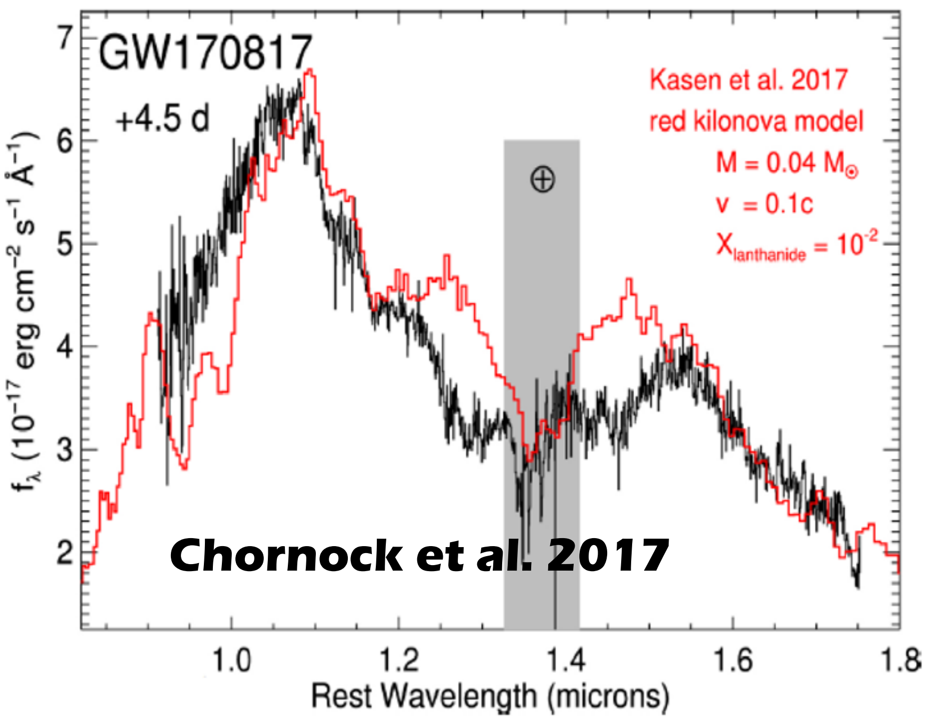
? Line of sight → different Y_e & r-process.

? Ejecta velocities → Blue shifted spectrum.

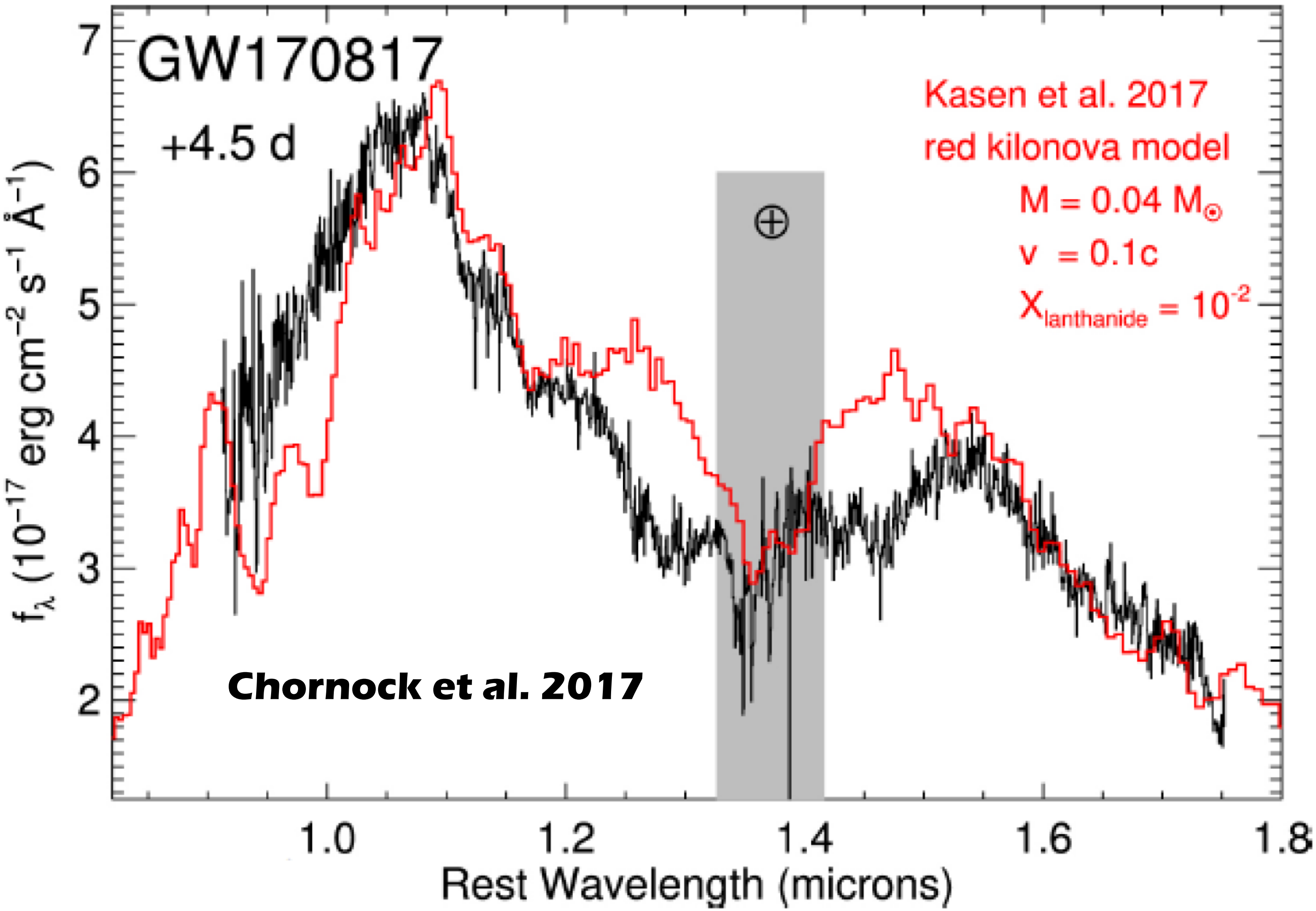
? Incomplete Opacity + α, β, γ, fission dep.



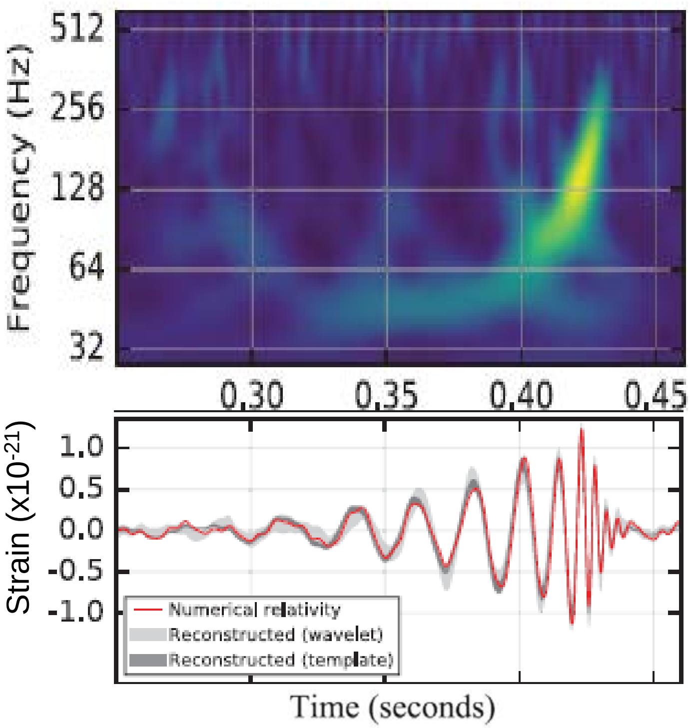
Smartt et al. Nature, 551, 75 (2017).


GW170817
+4.5 d
Kasen et al. 2017
red kilonova model
M = 0.04 M⊙
v = 0.1c
X_lanthanide = 10^-2
⊕
Chornock et al. 2017
f_λ (10^-17 erg cm^-2 s^-1 Å^-1)
Rest Wavelength (microns)
1.0
1.2
1.4
1.6
1.8
2
3
4
5
6
7

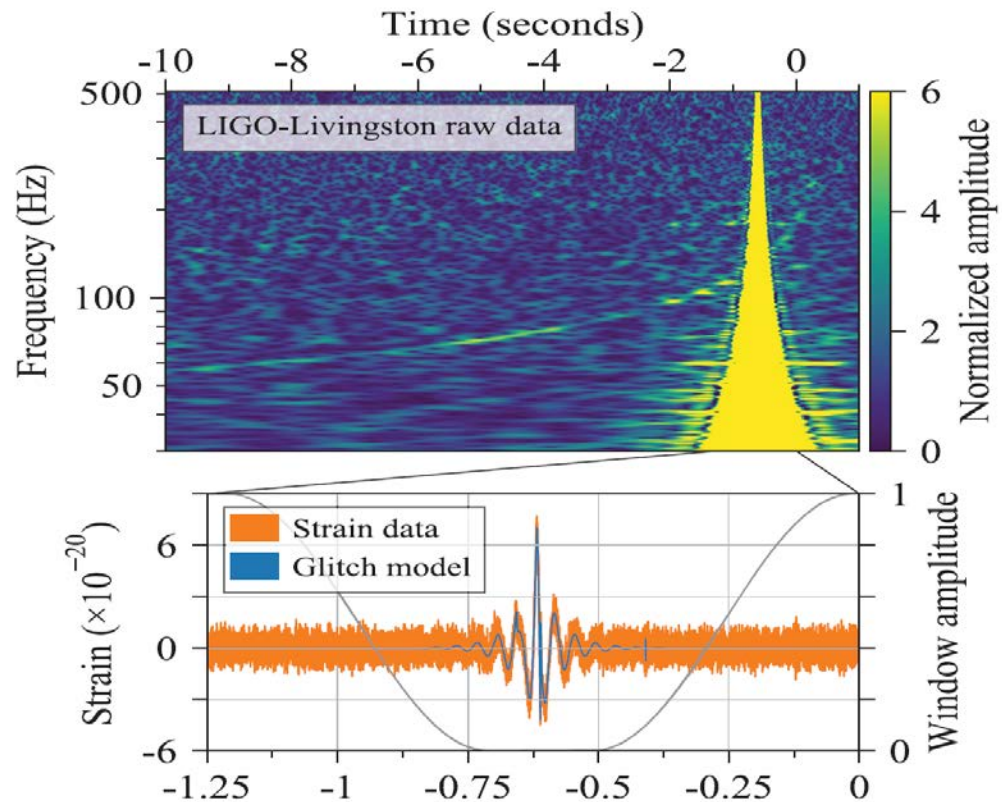
- **Total energy, consistent with radioactive decays of lanth**
- **No r-process element, identified.** **Incomplete OPACITY !**



Binary Black Holes

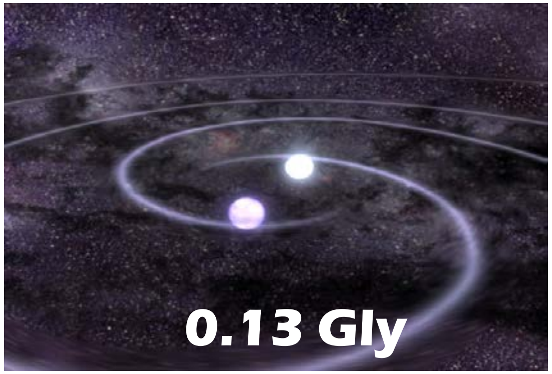


Binary Neutron Stars



GW170817

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



GW170817
SSS17a

- GW170817 (LIGO-Virgo) : $0.86 < M/M_\odot < 2.26$
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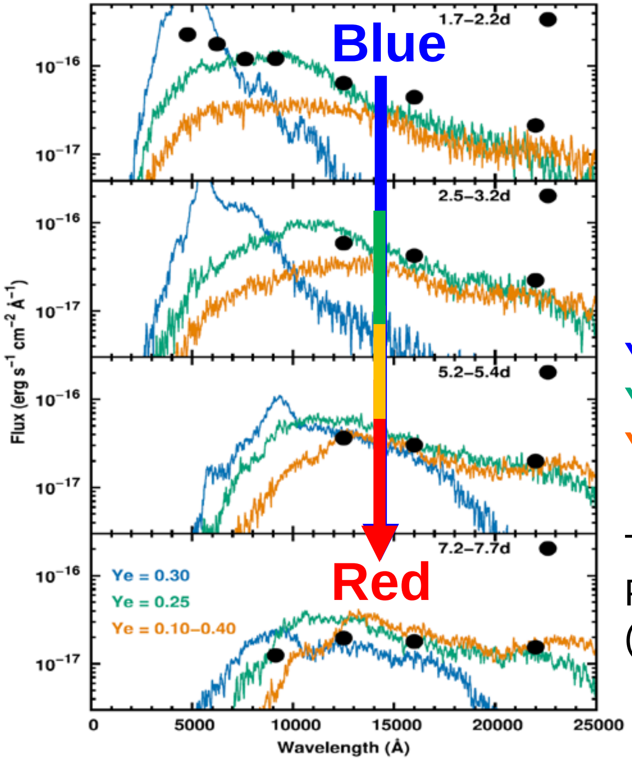
- No ν–Signal: 10^{-6} weaker than SN1987A (1.6×10^{5} ly)
- X-rays & Radio waves :
  Remnant NS or BH, not identified.
- Optical and Near-infrared : SSS17a (by more than 70 Telescopes)
  Consistent with r-process! But no element, identified.

◆ ? Line of sight → different Y_e & r-process ?

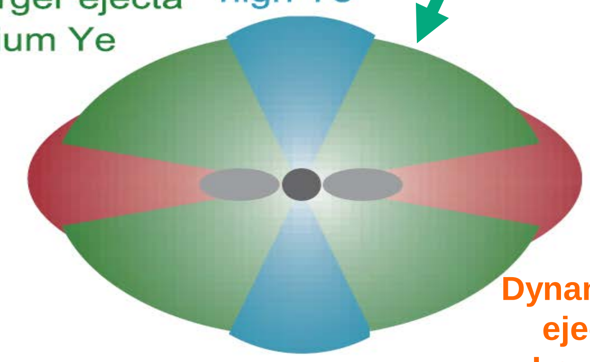


$Y_e = p/(p+n)$

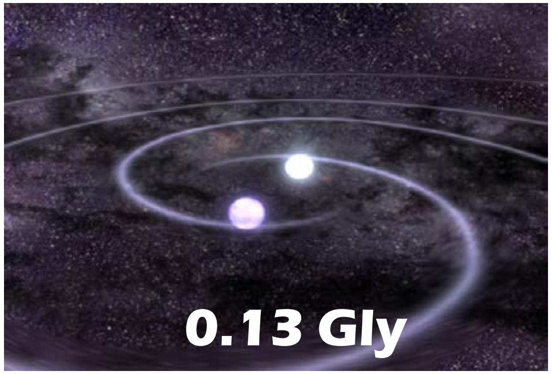
$Y_e = 0.30$
$Y_e = 0.25$
$Y_e = 0.10\text{-}0.40$

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

Line of sight @ 0.13 Gly



Complicated Geometry & Hydro-Dynamics
→ Difficult Element Identification !

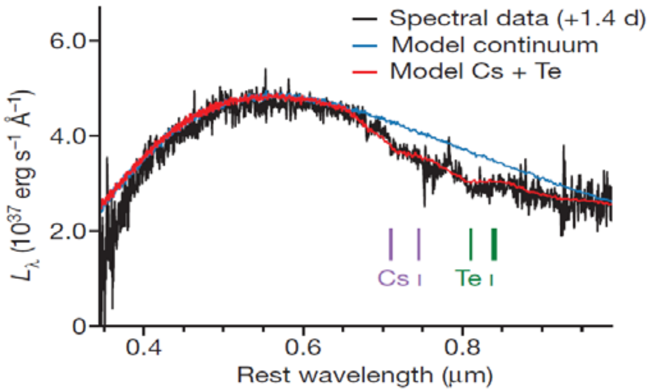


GW170817
SSS17a

◆ ? ? Ejecta velocities → Blue shifted spectrum ?

Why only Cs and Te ?

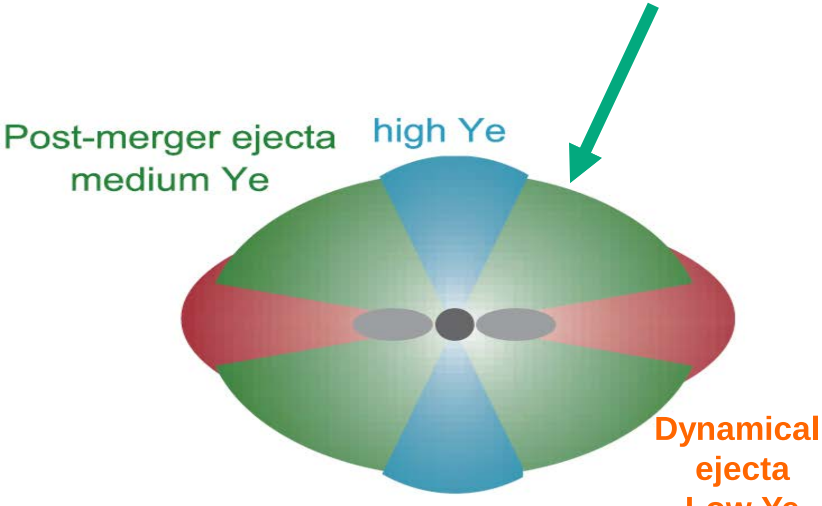
◆ Incomplete & Limited Opacity → Large α, β, γ, fission dependence !

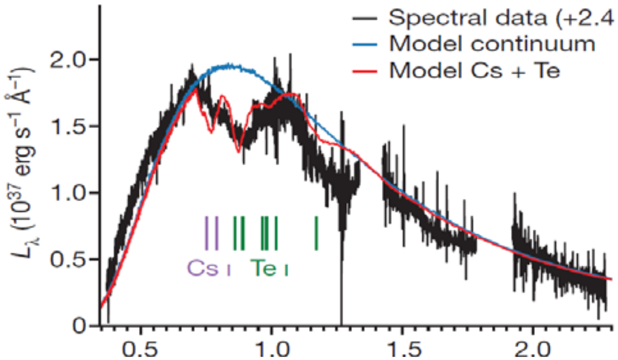


v = 0.2 c

◆ ? Line of sight → different Y_e & r-process ?

Line of sight @ 0.13 Gly





v = 0.13 c

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

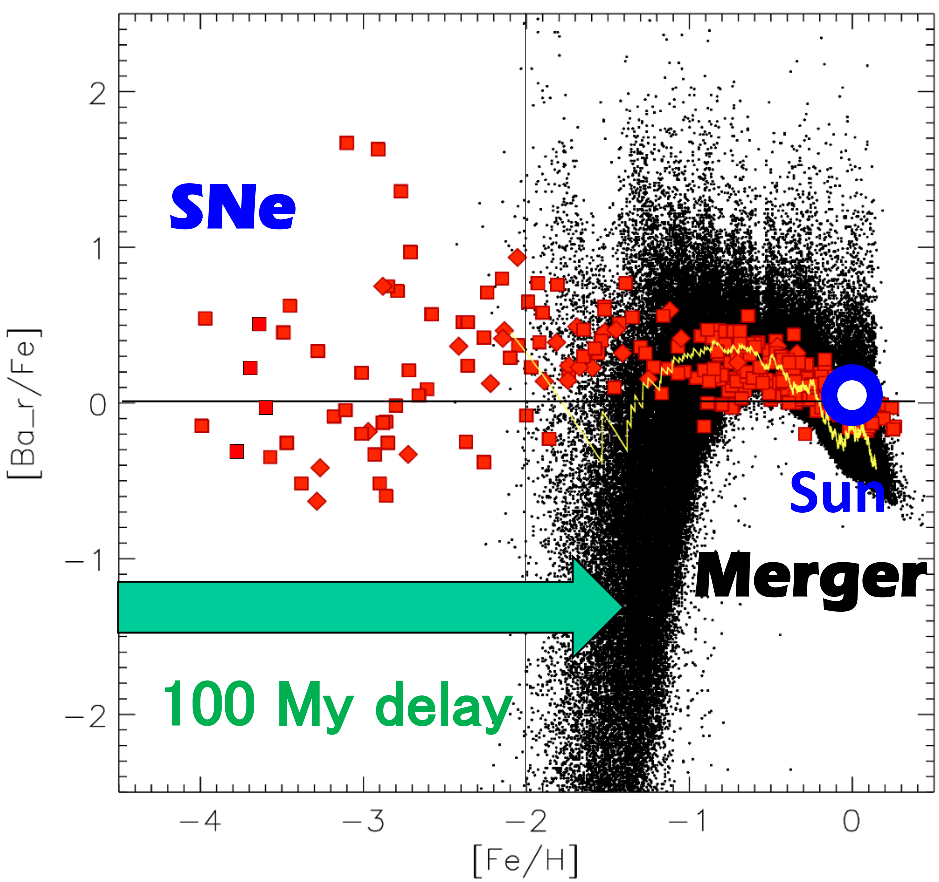
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution
of Dwarf Galaxies → Milky Way (Large Galaxy) ?

SNe→Metals; NSM(τ_c=100My)→r-process elements. Highest resol. n_H>100 cm^{-3} → 10-100pc

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

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

Without Dynamics & GAS MIXING



Summary & Outlook

GW170817

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

◇ **GW ! → EOS ! (Cold NS vs. hot SN core)**

◇ **Neutron star merger → a Central Engine of Short-GRB !**

◇ **Light emissions, not by ^{56}Ni or ^{44}Ti decays like SNe**
→ consistent with radioactive decays of r-process elements !

◆ **No specific element, identified :**
→ Needs another event (once in every 10^4-10^5 yrs in Milky Way) !
→ Needs nuclear mass, α, β, γ, fission studies !
→ Needs complete opacity table for lanthanoids and actinoids !
→ Needs 3D hydrodynamic model & radiative transfer

◆ **No neutrino signal → Micro-physics, yet to be studied !**

Dawn of Nuclear-Particle Astrophysics and Multi-Messenger

Purpose → Difference between Merger and SN r-process !

Purpose and Content

Origin of r-Process: NSMs vs. SNe ?

1. **Neutron Star Mergers** vs. **Supernovae** Nucleosynthesis

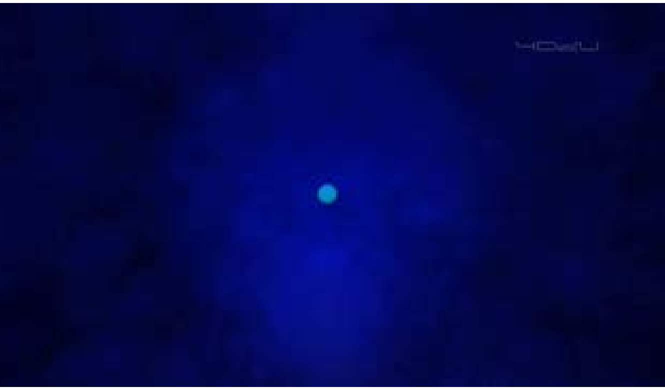
Roles of Nuclear Physics --- FISSION !
Universality !
How to distinguish NSM from SN r-process !

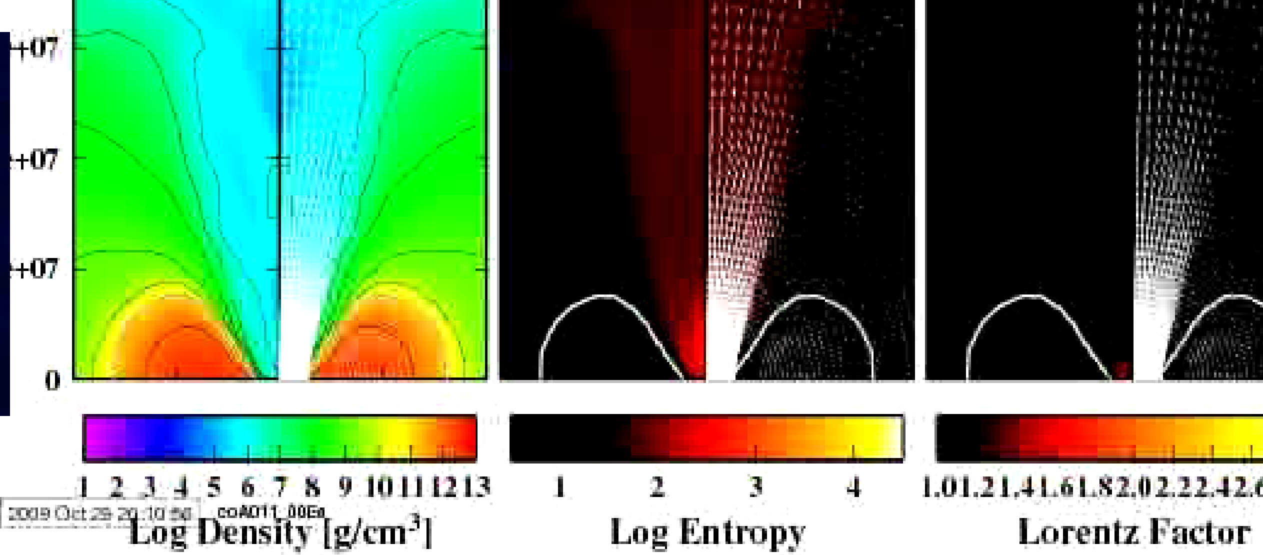
Neutrino Oscillations in SNe ?

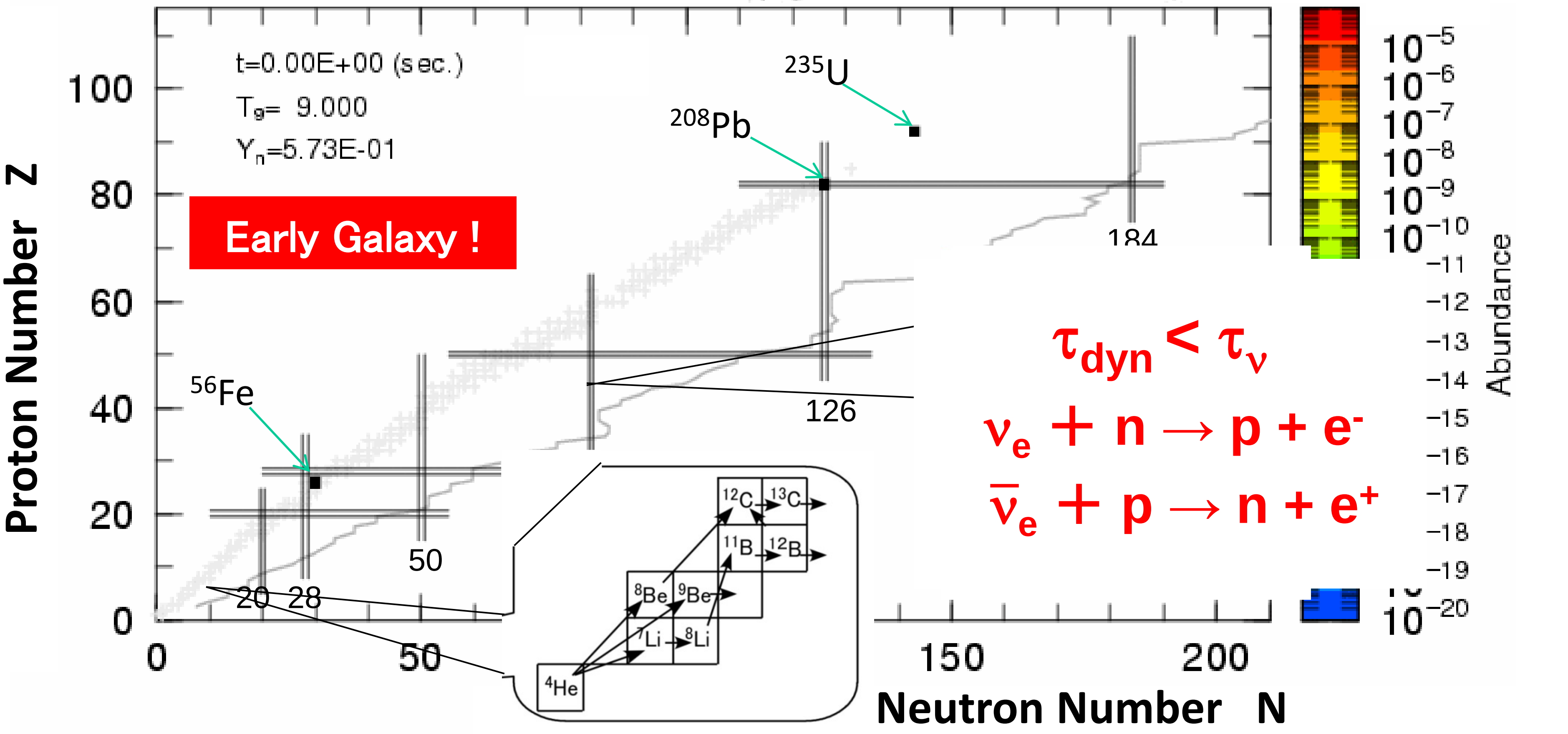
2. **ν-Oscillations** (MSW & Collective) on Nucleosynthesis

Collective (Quantum) Oscillation in $\nu\nu$ Scattering ?

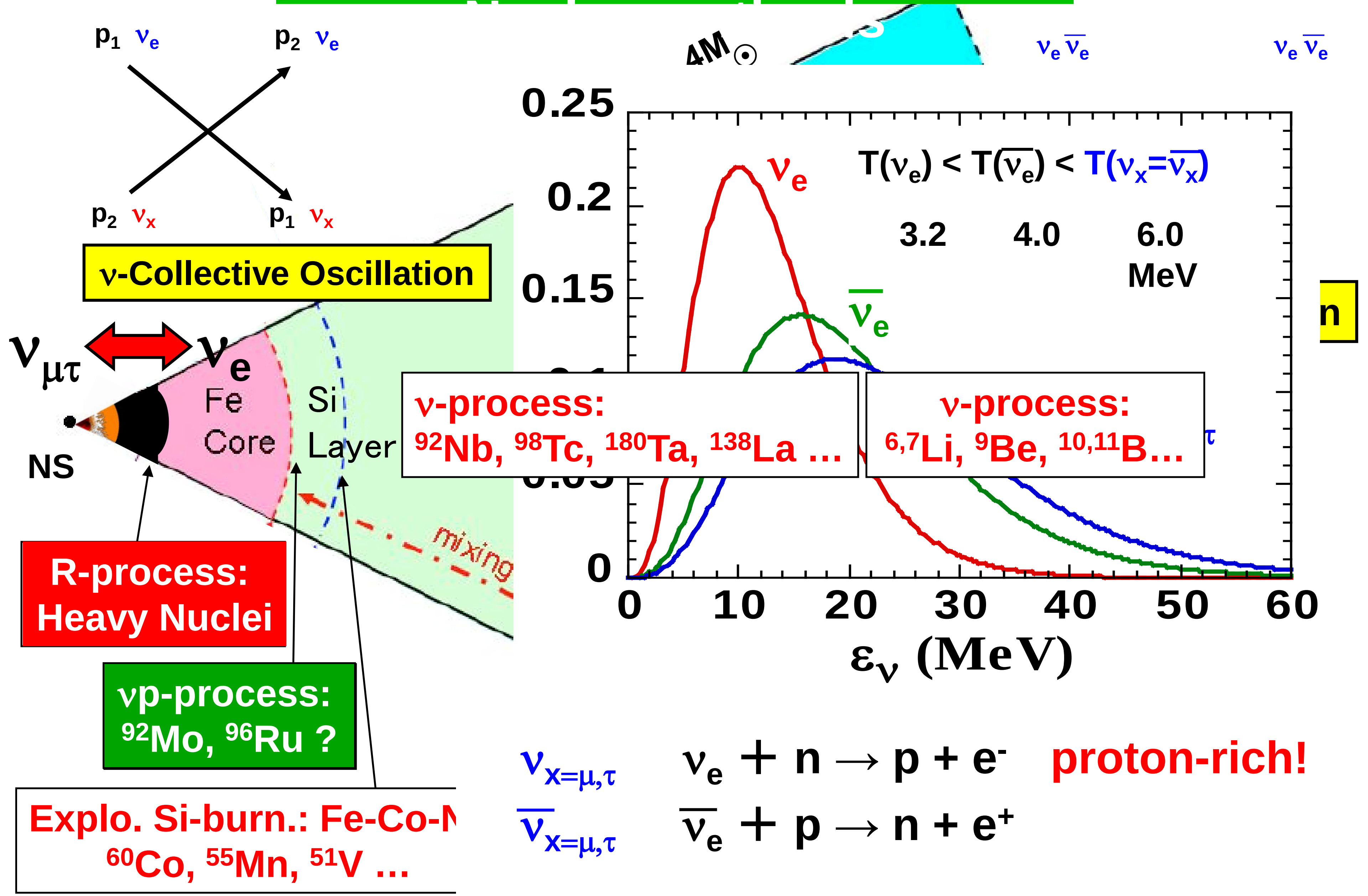
MHD-Jet Supernova







ν-Oscillation and



Theoretical Method

3 x 3 density matrices

$\rho(t,\mathbf{p})$ for ν, $\bar{\rho}(t,\mathbf{p})$ for $\overline{\nu}$.

$$\bar{\rho}(t,\mathbf{p}) = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{e\mu} & \bar{\rho}_{e\tau} \\ \bar{\rho}_{\mu e} & \bar{\rho}_{\mu\mu} & \bar{\rho}_{\mu\tau} \\ \bar{\rho}_{\tau e} & \bar{\rho}_{\tau\mu} & \bar{\rho}_{\tau\tau} \end{pmatrix}$$

$$\langle a^\dagger_\alpha(\mathbf{p}) a_\beta(\mathbf{q})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{q}) f(t,\mathbf{p})\rho(t,\mathbf{p})_{\beta\alpha}$$

$$\langle b^\dagger_\alpha(\mathbf{p}) b_\beta(\mathbf{q})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{q}) g(t,\mathbf{p})\bar{\rho}(t,\mathbf{p})_{\alpha\beta}$$

$$\mathrm{Tr}\rho(t,\mathbf{p}) = \mathrm{Tr}\bar{\rho}(t,\mathbf{p}) = 1$$

G. Sigl and G. Rafflet,Nucl. Phys. B 406, 423, 1993

Diagonal components $\rho_{\alpha\alpha}$ represents the probability of finding ν_α.

Solving dynamical eqs.

$$\frac{d}{dt}\rho_{\alpha\beta}(t,\mathbf{p}) = -i\left[\rho(t,\mathbf{p}), \Omega(\mathbf{p}) + V(t,\mathbf{p})\right]_{\alpha\beta}$$

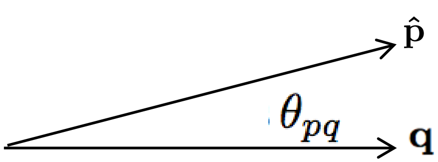
$$\frac{d}{dt}\bar{\rho}_{\alpha\beta}(t,\mathbf{p}) = -i\left[\bar{\rho}(t,\mathbf{p}), -\Omega(\mathbf{p}) + V(t,\mathbf{p})\right]_{\alpha\beta}$$

$\Omega(\mathbf{p})$ ......Vacuum Hamiltonian

$V(t,\mathbf{p}) = V_{\mathrm{MSW}} + V_{\mathrm{self}}$ ...... Potential in flavor space

Mean field ν-ν coherent scattering term

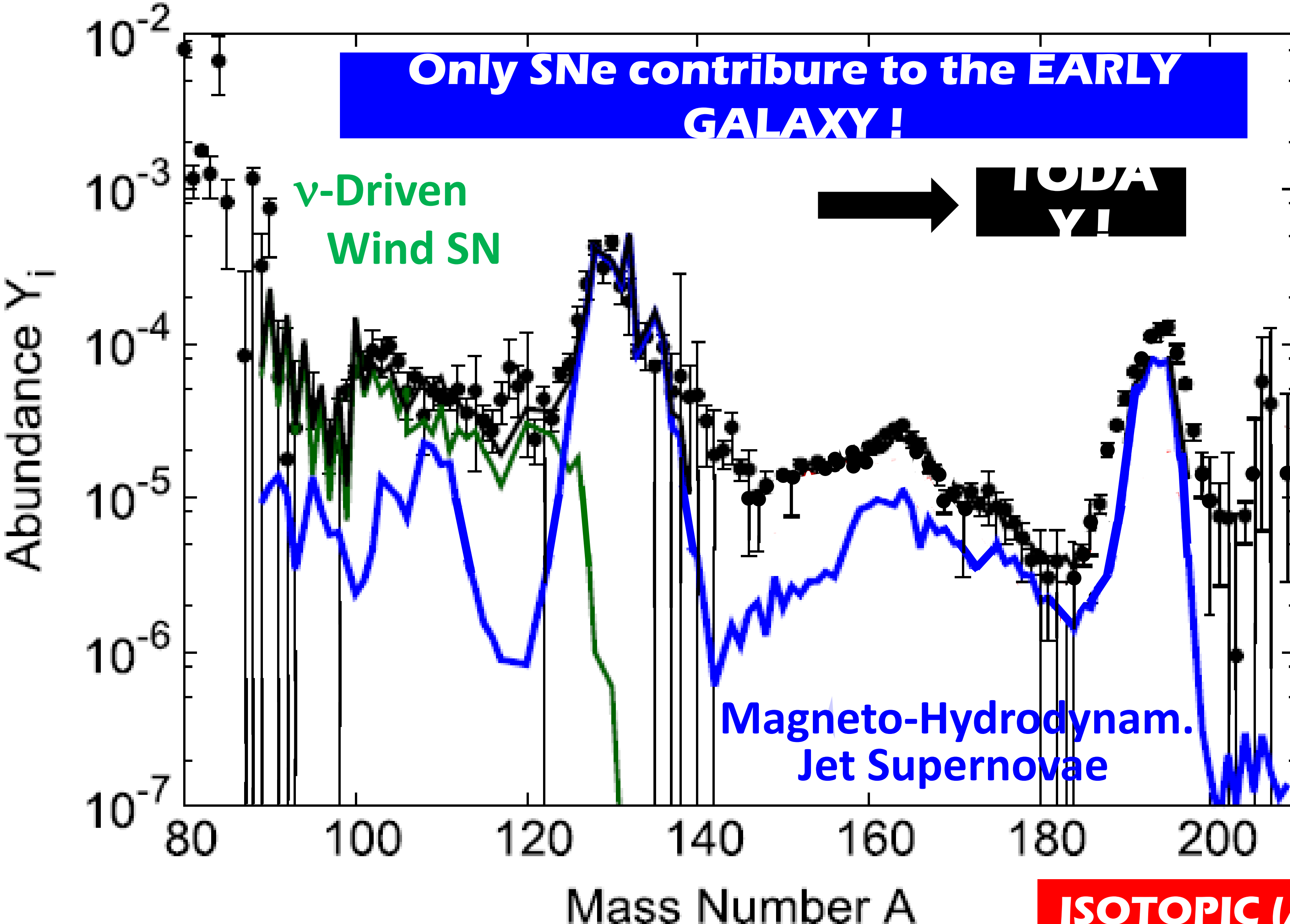
$$V_{\mathrm{self}\,\alpha\beta} = \sqrt{2}G_F \int \frac{\mathrm{d}^3q}{(2\pi)^3}(1-\cos\theta_{pq})\{f(t,\mathbf{q})\rho_{\alpha\beta}(t,\mathbf{q}) - g(t,\mathbf{q})\bar{\rho}_{\alpha\beta}(t,\mathbf{q})\}$$



$$\int \frac{\mathrm{d}^3p}{(2\pi)^3} f(p) = n_\nu \qquad \int \frac{\mathrm{d}^3p}{(2\pi)^3} g(p) = \bar{n}_\nu$$

EVOLUTION of the r-Process Abundance

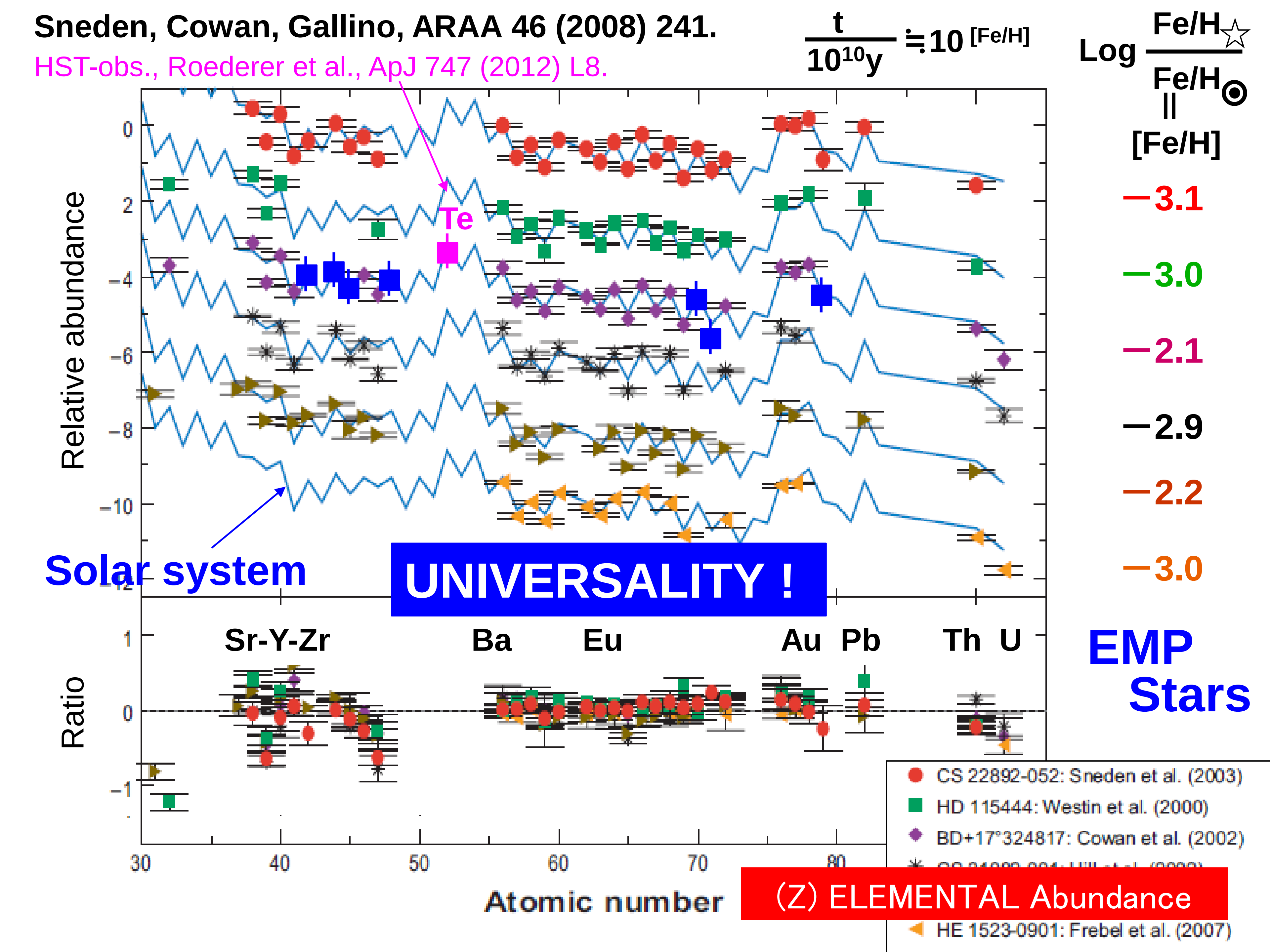
Kajino & Mathews (2017), ROPP 80 , 084901.



ISOTOPIC (A) !

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

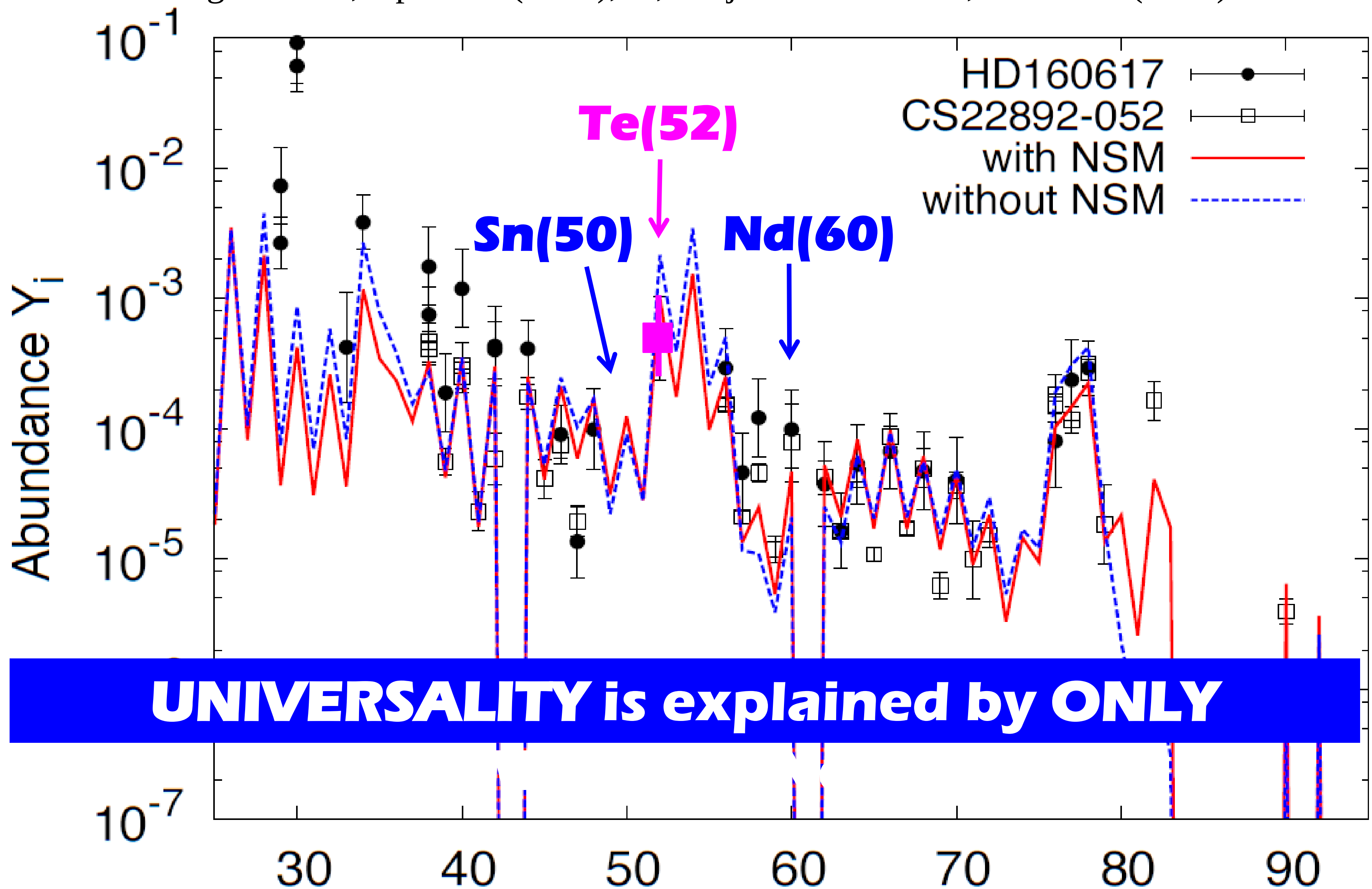
HST-obs., Roederer et al., ApJ 747 (2012) L8.



UNIVERSALITY !

Early Galaxy !

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

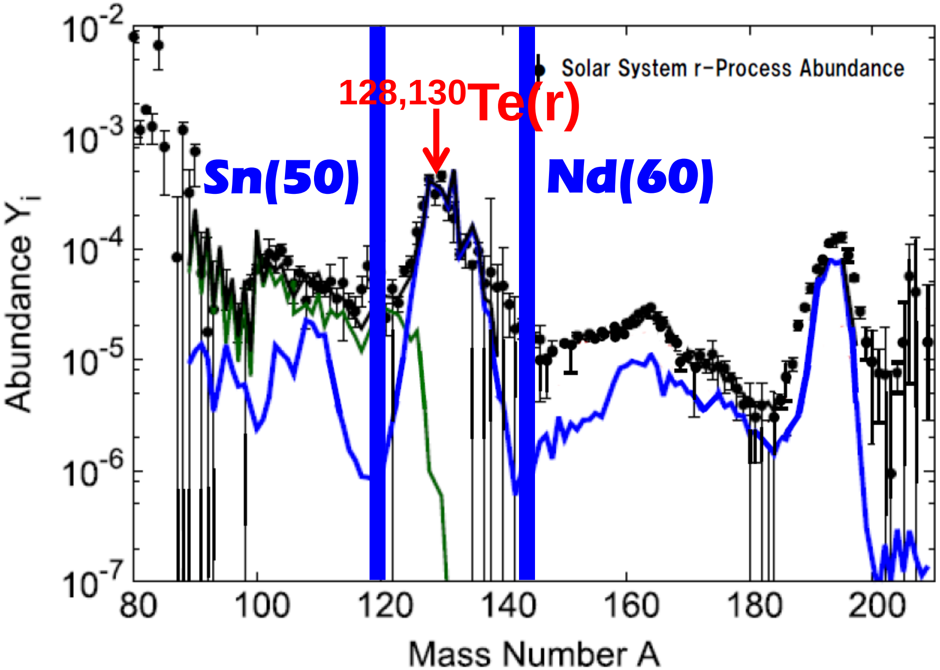


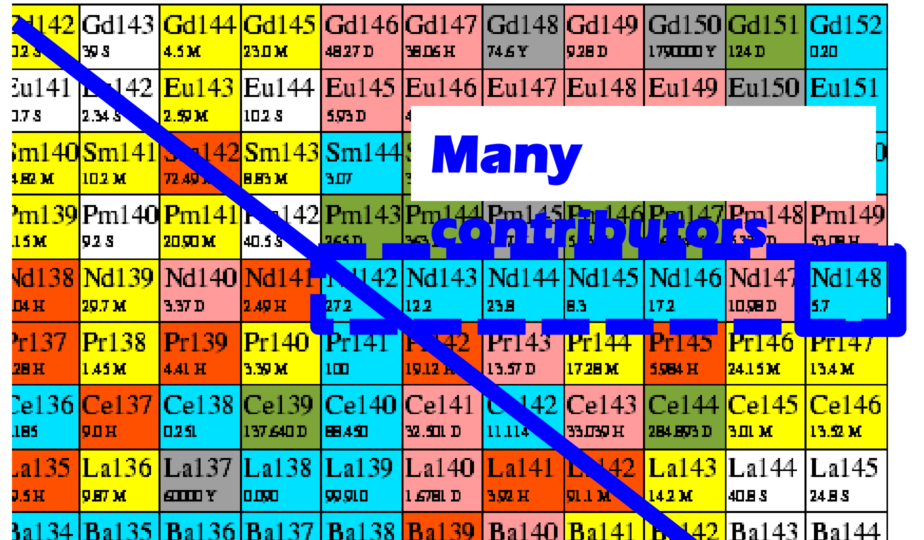
UNIVERSALITY is explained by ONLY

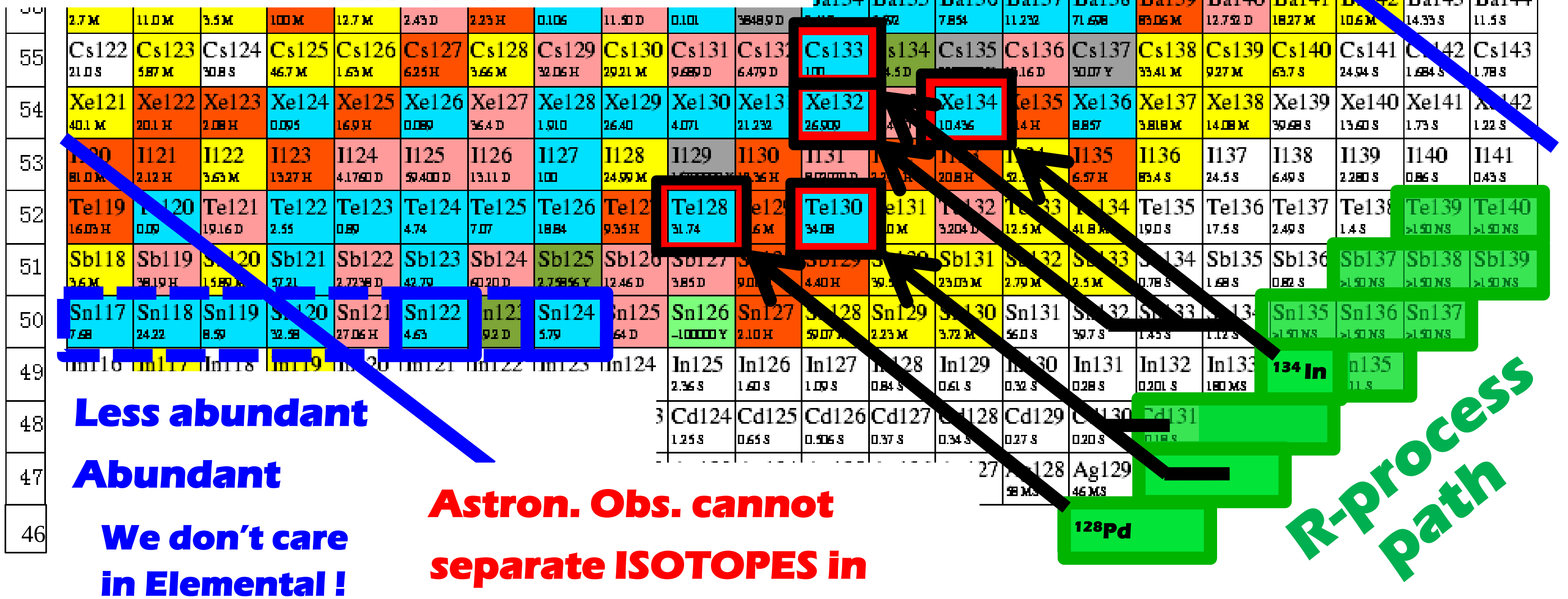
Astron. Obs. cannot separate ISOTOPES !

ELEMENTAL (Z)

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



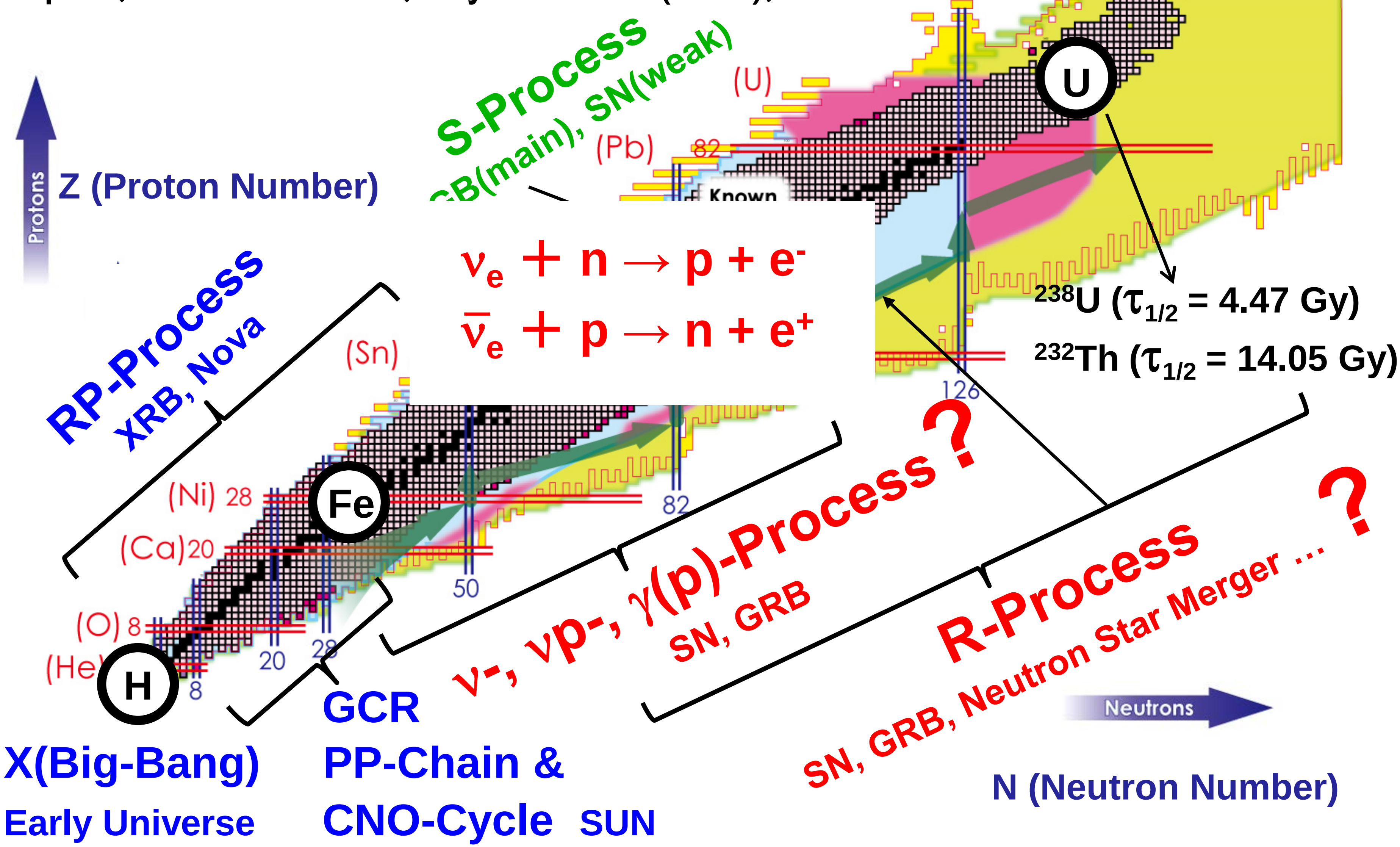




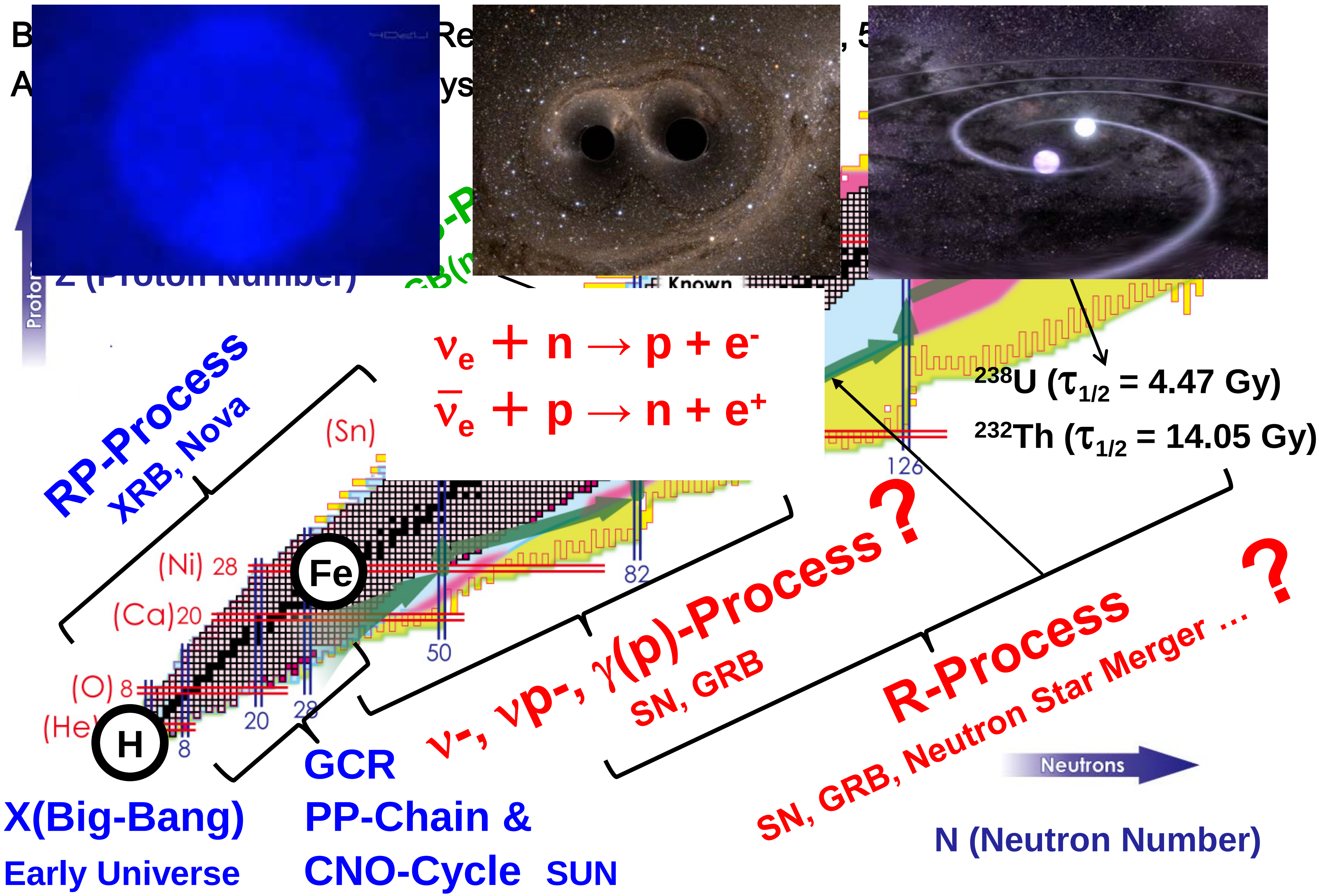
Element Genesis from Nuclear Processes in Cosmos

Burbidge², Fowler & Hoyle, Rev. Mod. Phys. 29 (1957), 547-650.

Alpher, Bethe & Gamow, Phys. Rev. 73 (1958), 803.



Element Genesis from Nuclear Processes in Cosmos



Hierarchical Galaxy Formation Scenario

SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution

Komiya & Shigeyama, ApJ 830, 10 (2016).

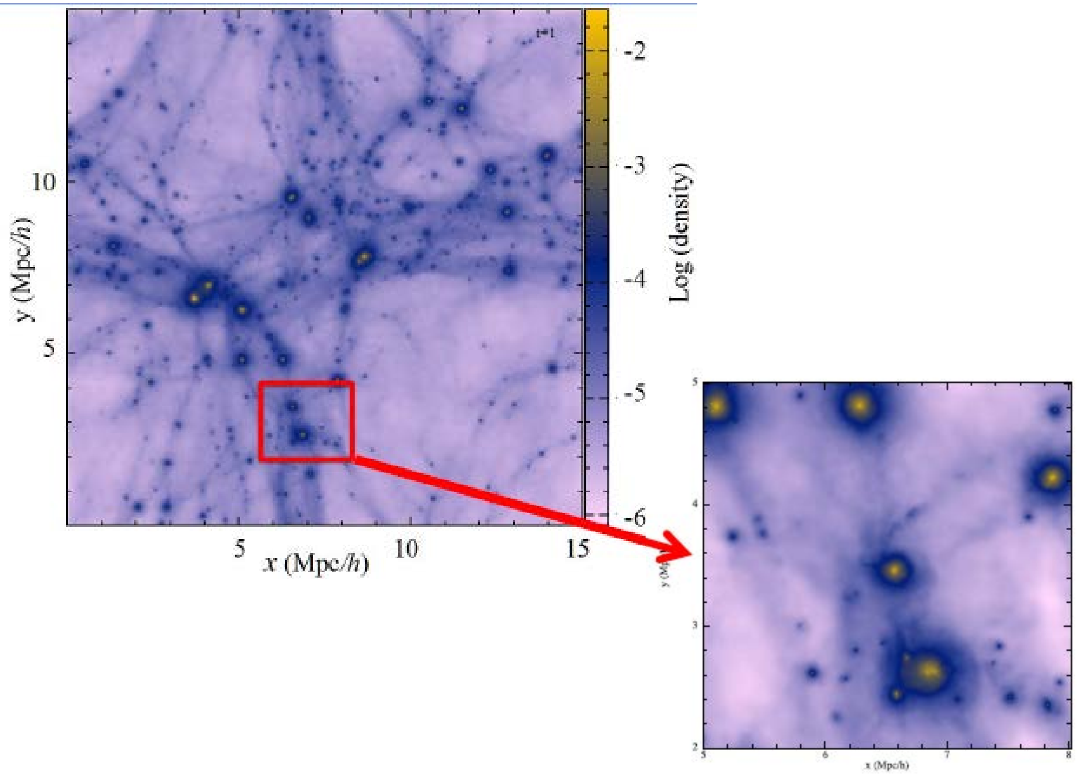
Mixing of r-elements between neighboring Dwarf Galaxies is small 0.001-0.1% for[Fe/H]<-3.5.

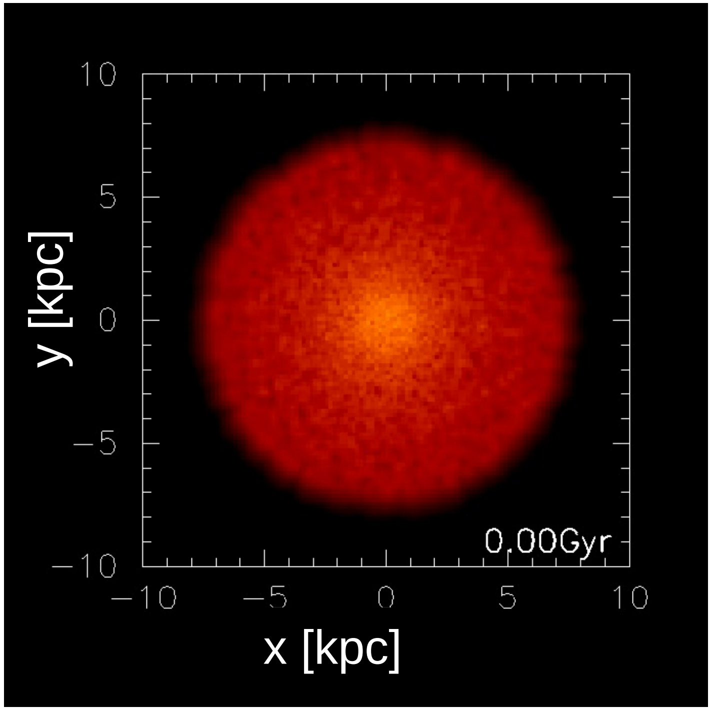
Mathews et al., MPL A29 (2014), 1430012-118.

N-Body/SPH Simulation DM + GAS + Star Particles with GAS-MIXING in the star forming region.

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

M_{tot} = 7x10^{8}M_{sun}, N_i = 5x10^{5} particles, $M_{\bigstar}$ = 100M_{sun}





Fluid-Dynamical Model for Neutron Star Merger

Binary Neutron Star Merger ~ more than 100 flows

Korobkin et al., MNRAS 426 (2012), 1940; Rosswog et al., MNRAS 430 (2013), 2585.

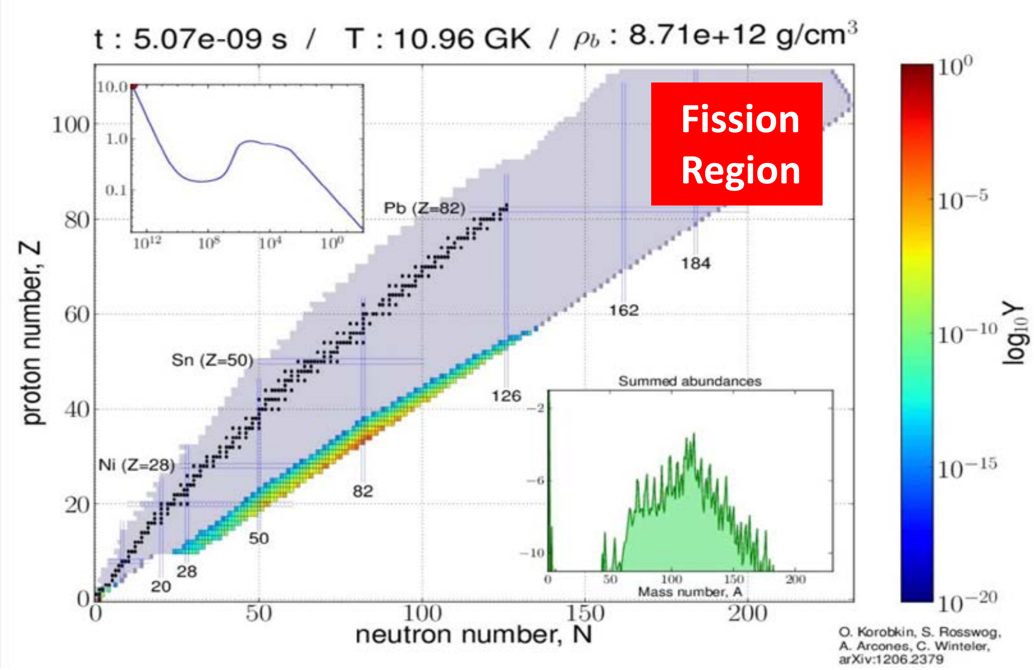
SPH Simulation: (Adiabatic Expansion)

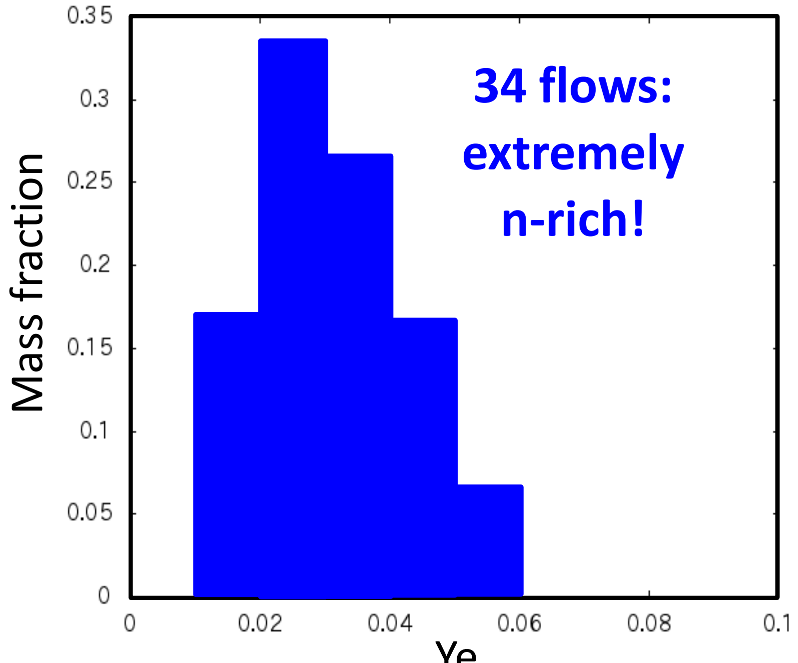
Newtonian gravity, Neutrino Leakage scheme

Entropy, Ye, T, ρ Evolution: (Fission is a strong heat-source: $S \sim \dot{q}/T$)

We solved thermodynamic evolution of each trajectory from the initial conditions.

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

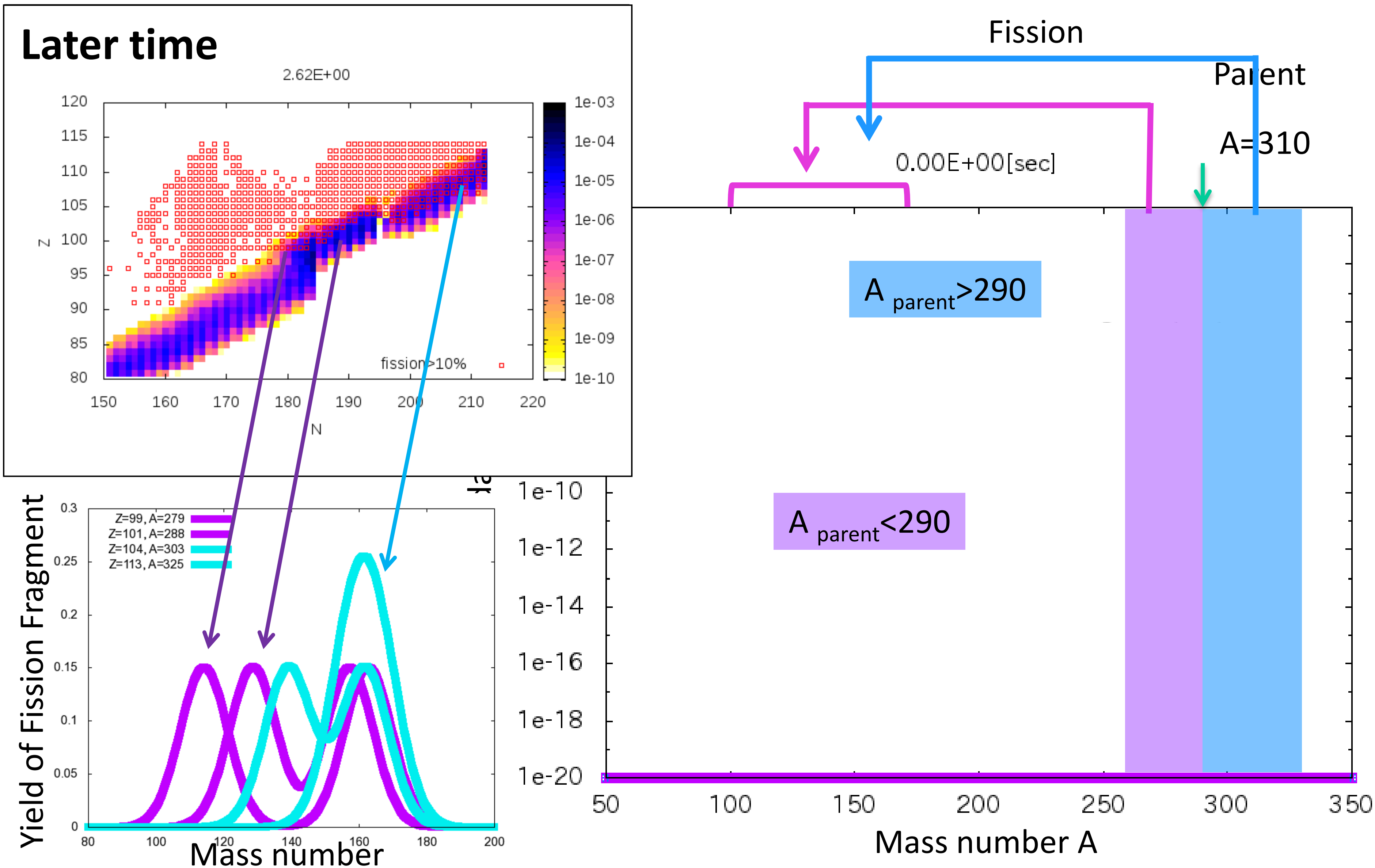




Abundance Evolution of Fission Recycling

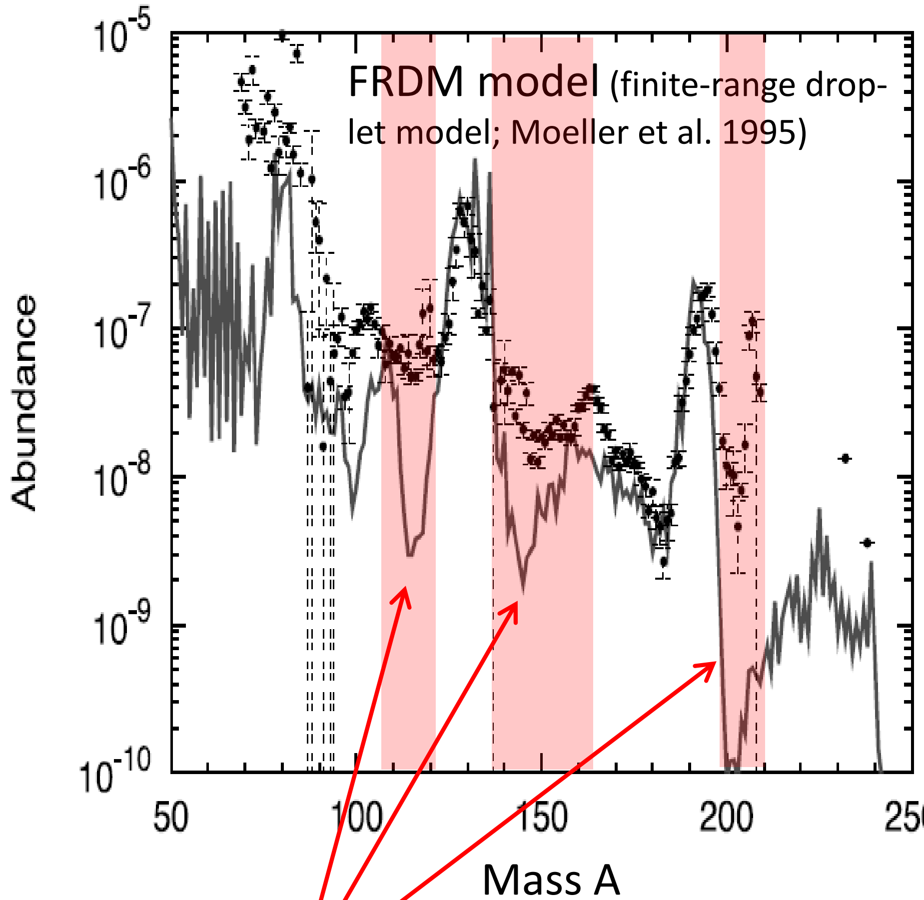
Binary Neutron Star Merger Model : SPH simulation – Newtonian gravity, Neutrino Leakage scheme

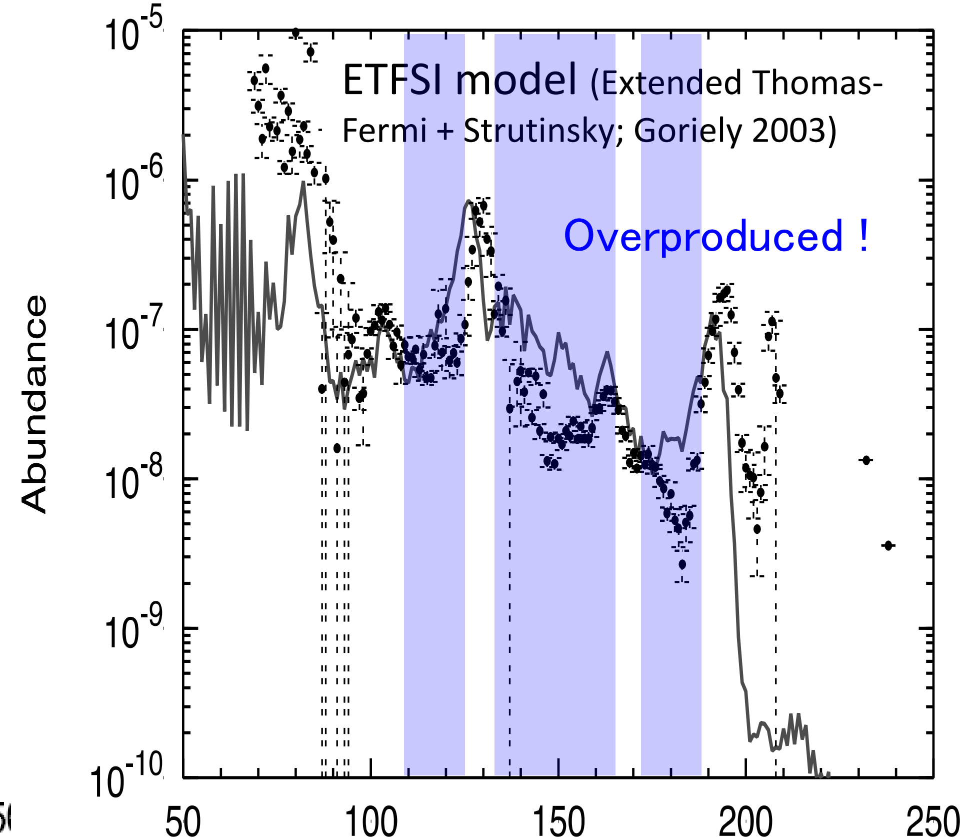
Korobkin et al., MNRAS 426 (2012), 1940.



CCSN: Magneto–Hydrodynamic Jets

S. Nishimura, et al., ApJ , 642, 410 (2006) ; T. Takiwaki, K.Kotake and K. Sato, ApJ 691, 1360 (2009); C. Winteler, et al., ApJ 750, L22 (2012).



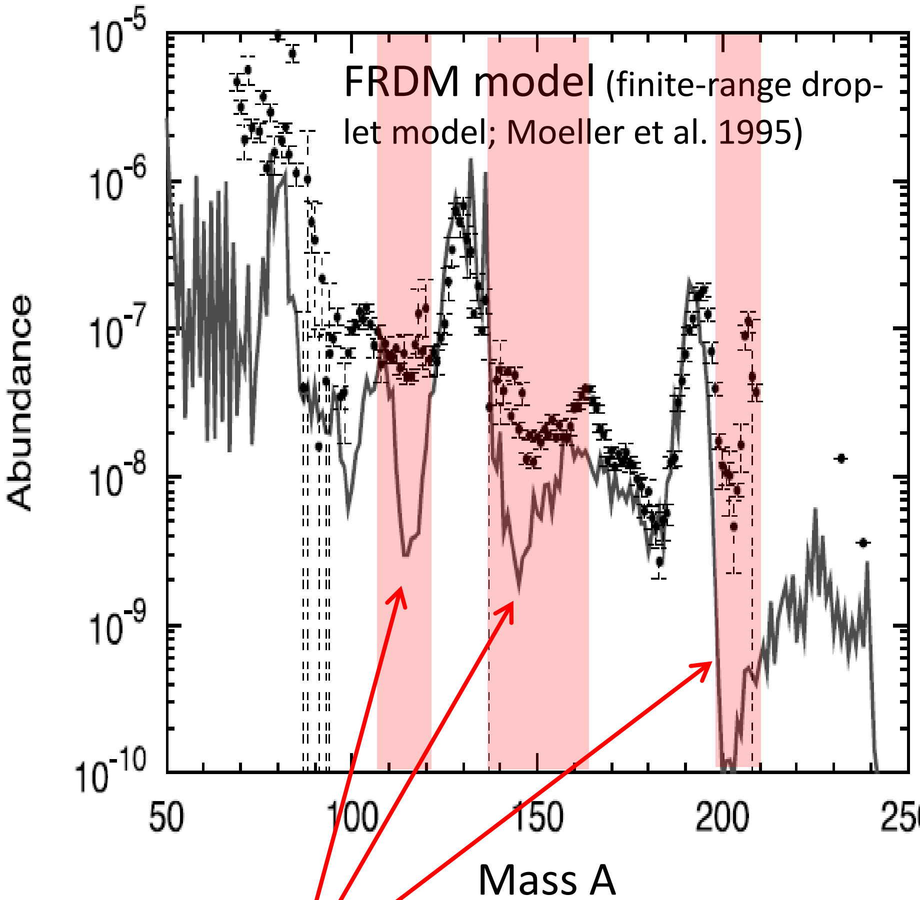


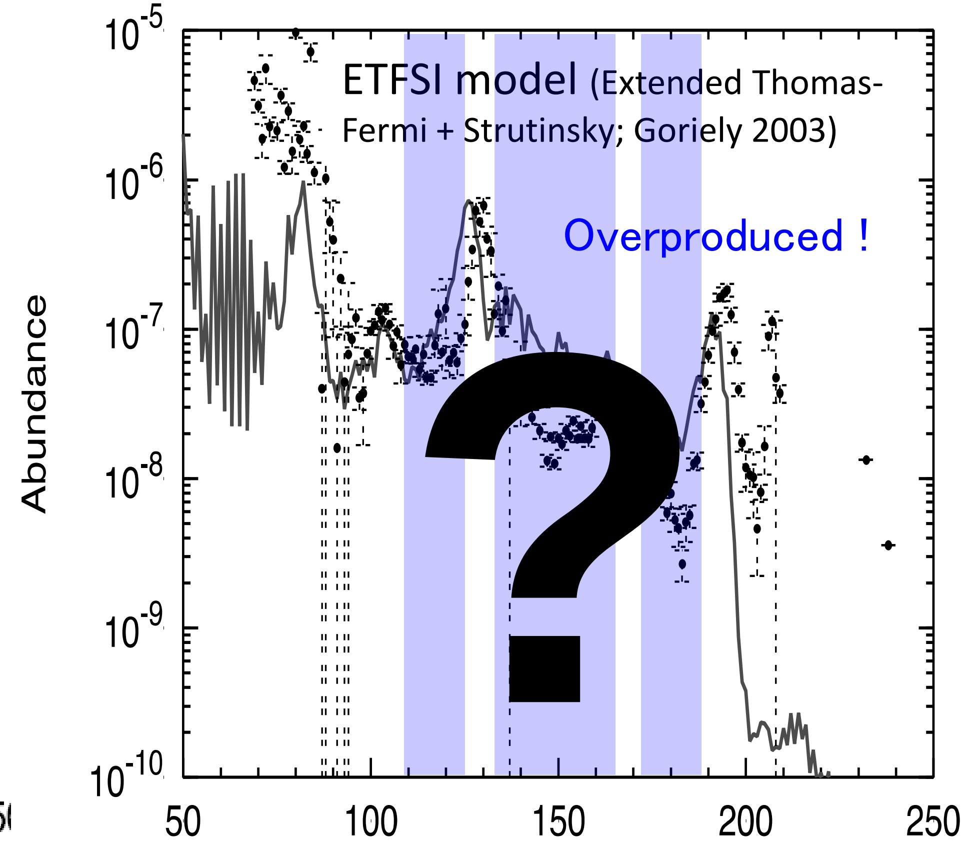
Underproduction PROBLEM ! —— **Possible Solutions**

- Nucl. Phys. – Shell quenching?

CCSN: Magneto-Hydrodynamic Jets

S. Nishimura, et al., ApJ , 642, 410 (2006) ; T. Takiwaki, K.Kotake and K. Sato, ApJ 691, 1360 (2009); C. Winteler, et al., ApJ 750, L22 (2012).





Underproduction PROBLEM ! — **Possible Solutions**

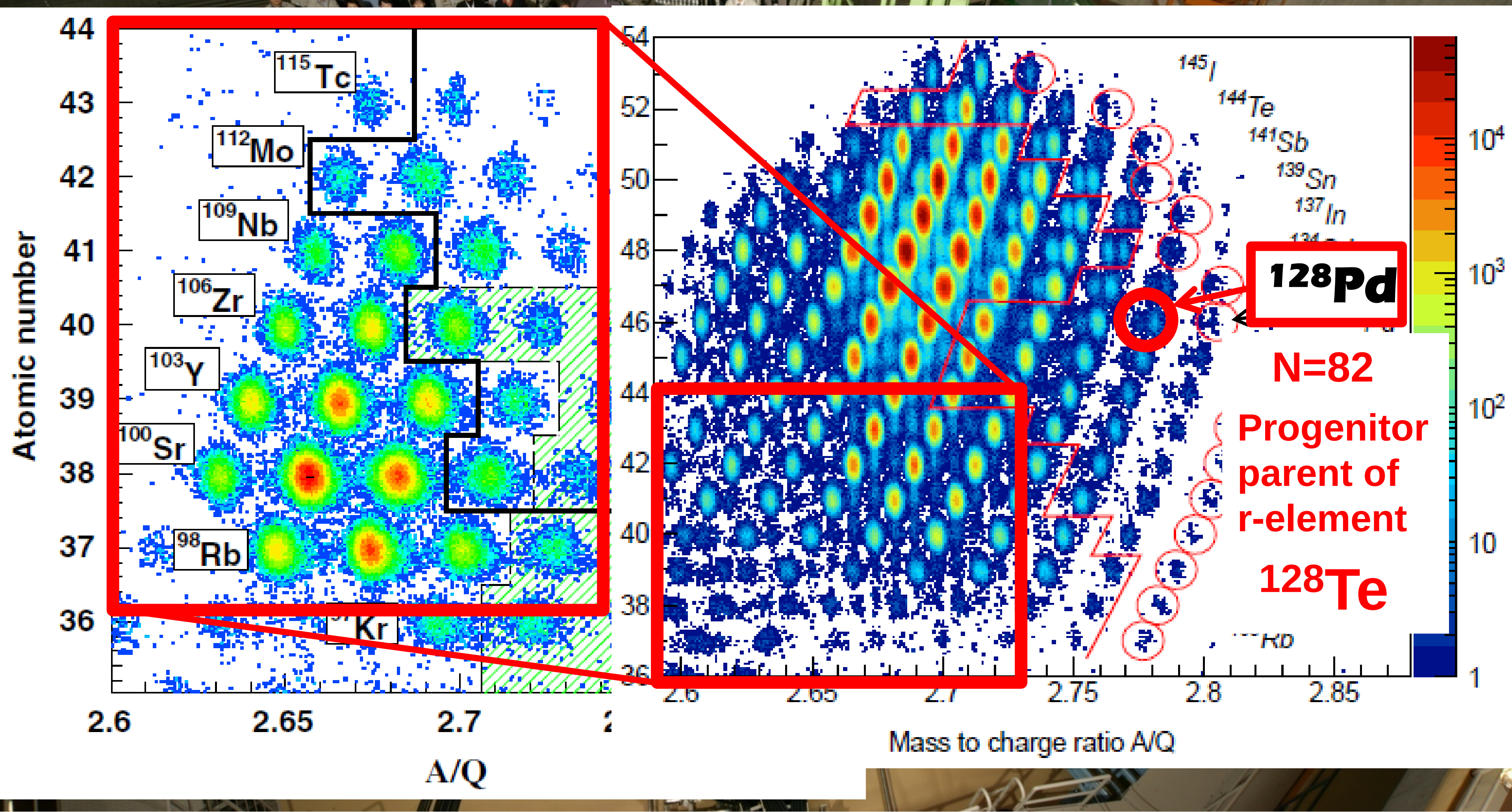
- Nucl. Phys. – ~~Shell quenching?~~
- Another Astro. Site – NSM

RIKEN-RIBF New Ring Cyclotron (since 2007)

Many nuclei on the r-process flow path !

2010, October

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



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

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

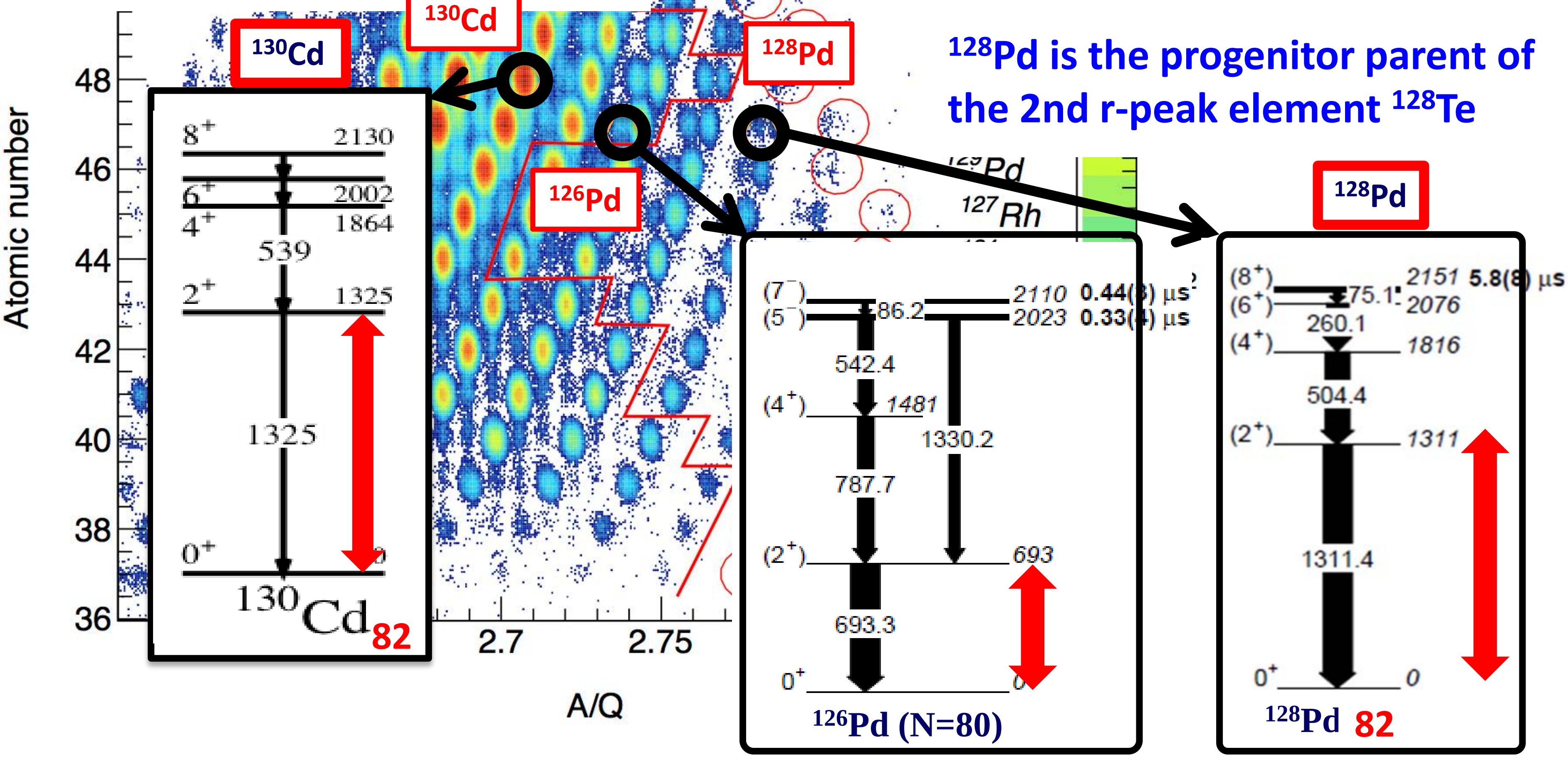
A.Jungclaus, PRL99, (2007)

No clear evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)

No clear evidence for shell quenching on N=82 !

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



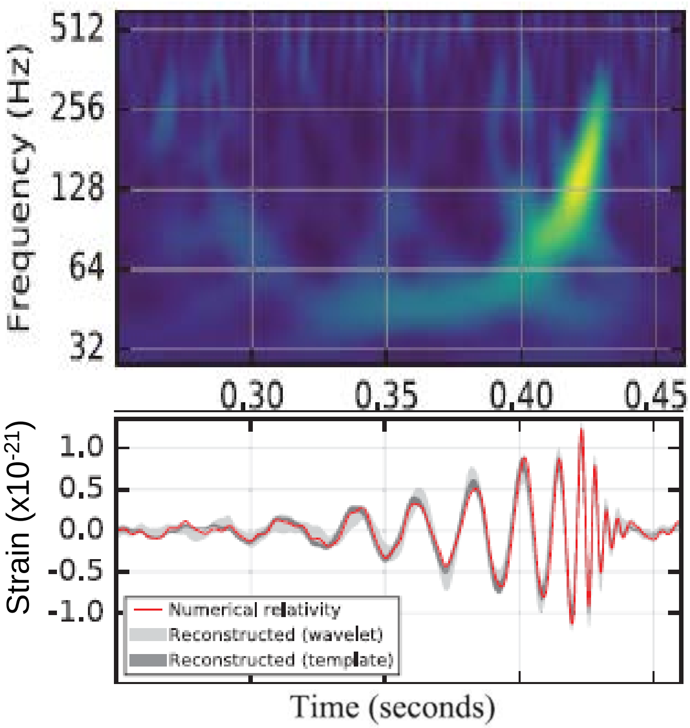
Binary Black Hole Merger (simulation)

Gravitational Wave

from Black Hole Merger GW150914 was detected !

Abbott et al. (LIGO-Virgo Coll.)
PRL 116, 061102 (2016)

A. Einstein predicted in 1915:
Distortion of space-time due to asymmetric, catastrophic phenomena could propagate as a gravitational wave.



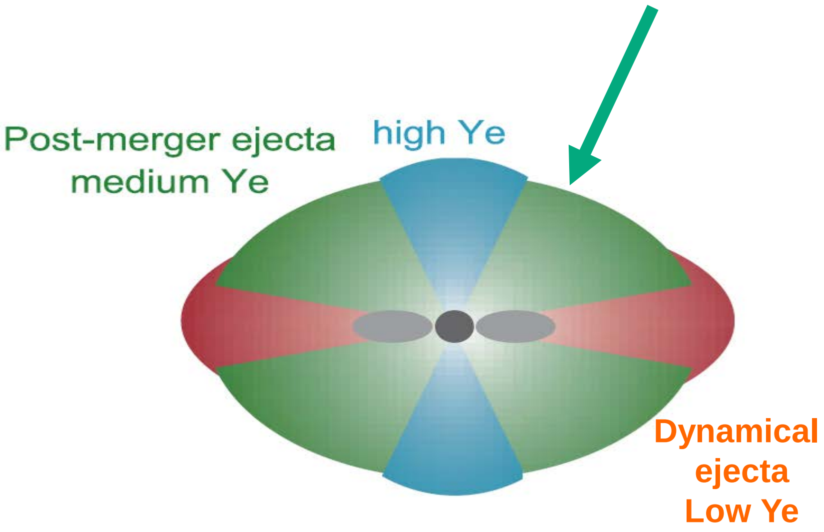
Optical & Near-Infrared Emission

Total emission, consistent with decay of r-process elements.
No specific element, identified.

Complicated Config. & Geometry and Hydro-Dynamics
→ Element identification, generically difficult !

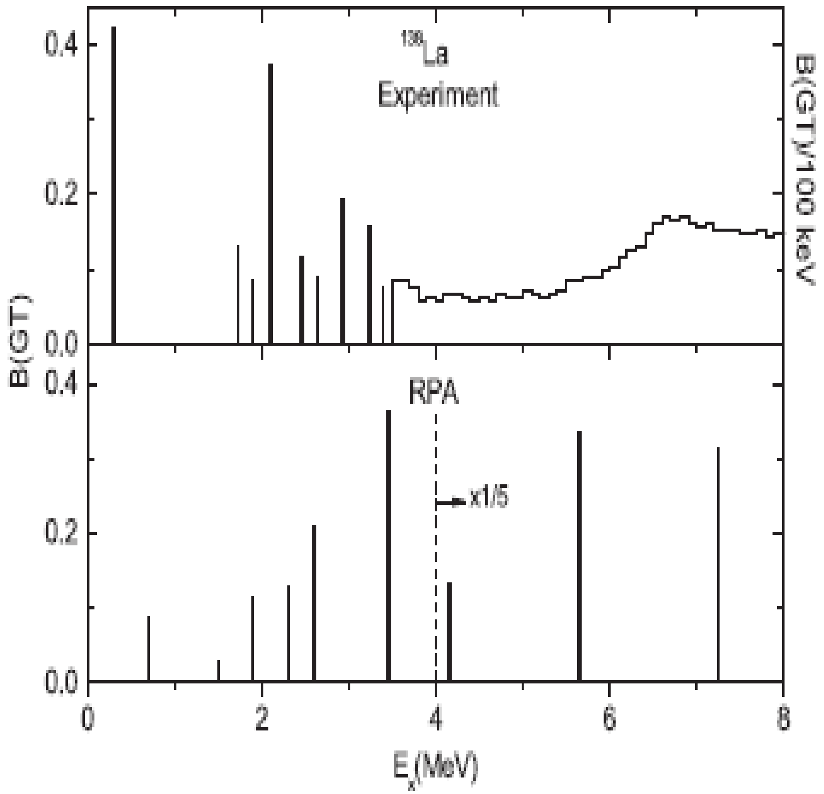
- Line of sight → different Y_e, different r-process !
- Ejecta velocity → Blue shifted spectrum ?
- Incomplete & Limited Opacity → Large α, β, γ, fission dependence !

Line of sight @ 0.13 Gly

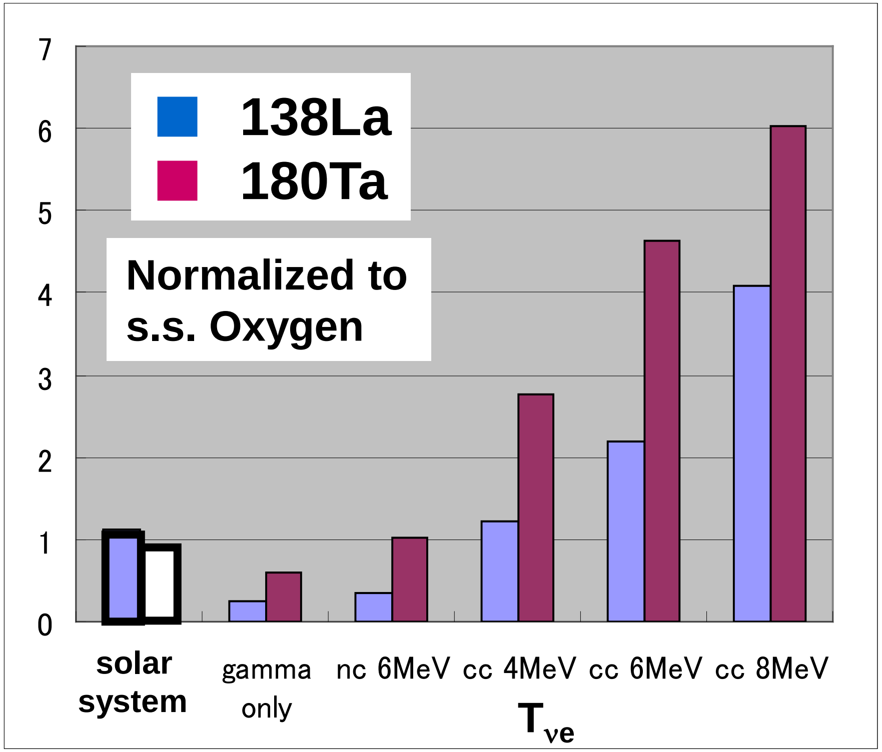


Impact of CEX Reaction on ν-Process

Byelikov + Fujita et al., PRL (2007), RCNP measurement of GT strength.



A. Heger, Phys. Lett. B 606, 258 (2005)



(1) Forbidden transitions + as well as GT contribute!

Eν = 0 ~ 80 MeV

(2) Overproduction of ^{180}Ta relative to ^{138}La!

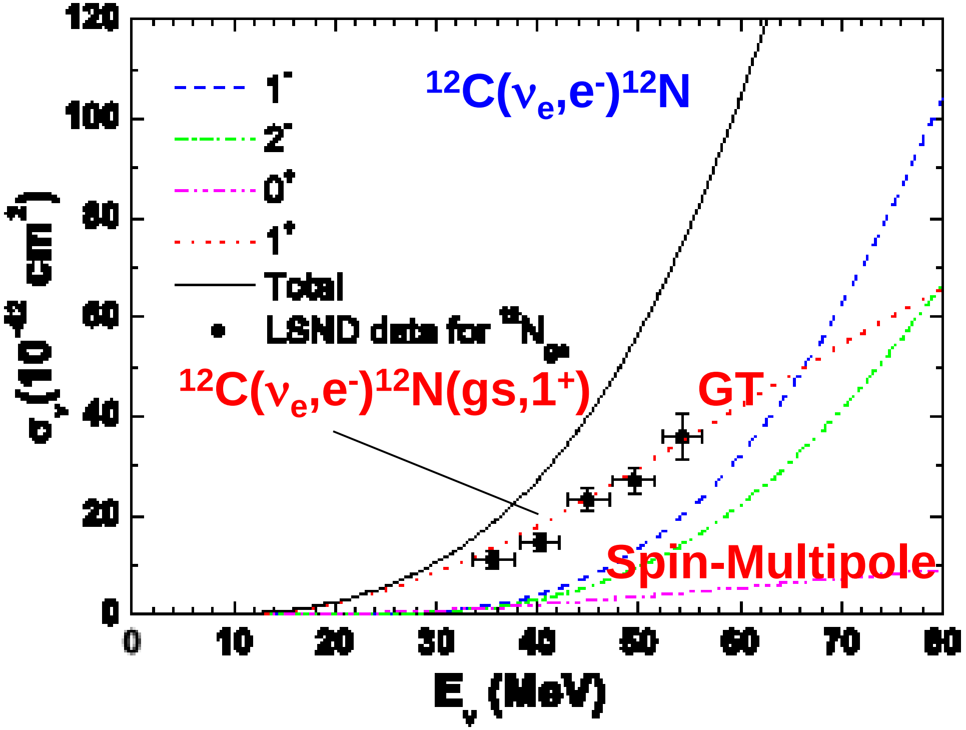
(1) Neutrino-^{138}La, ^{180}Ta cross section calculations in Quasi-particle Random Phase Approximation

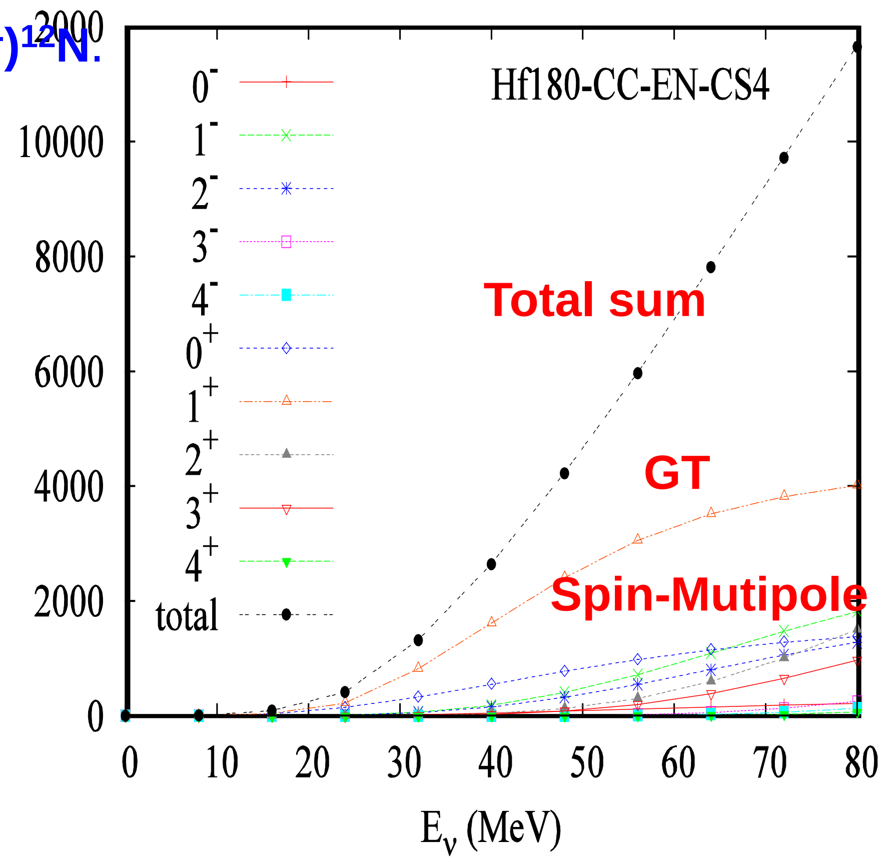
Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801: Suzuki, et al., PR C74 (2006), 034307; PR C67, 044302 (2003).

GT and Forbidden Transitions, equally importa

^{180}Hf + $\nu \rightarrow$ ^{180}Ta + e^- (CC)

Calibrated by unique data on $^{12}C(\nu_e,e^-)^{12}N$.

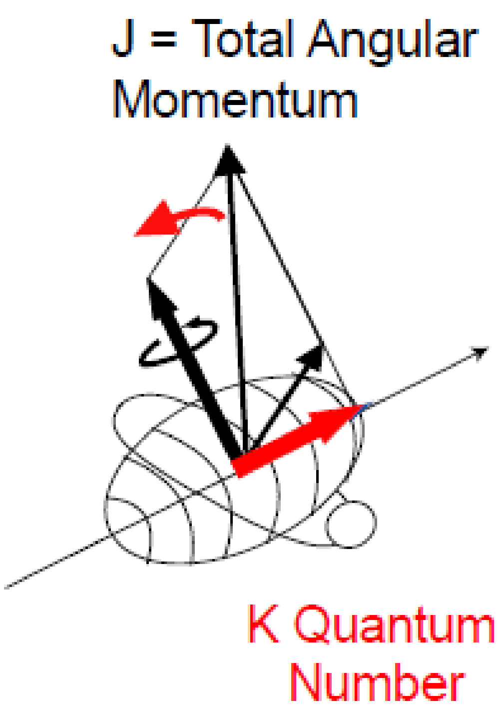


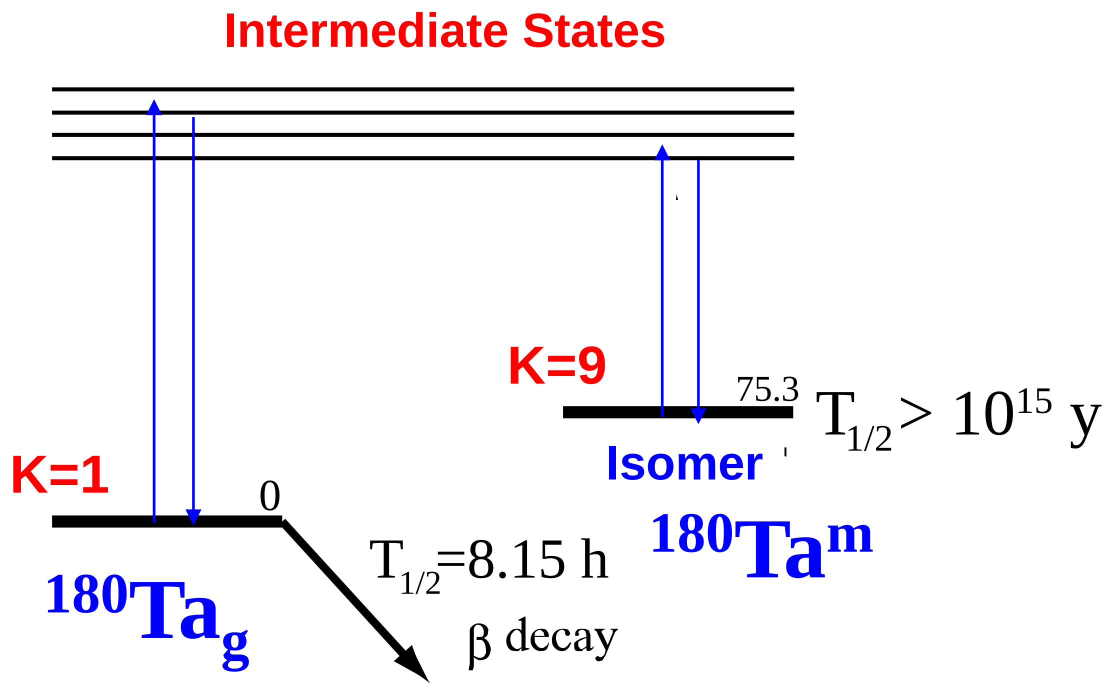


(2) OVEREPRODUCTION of Isomer state ^{180}Ta

How robust is $^{180}Ta^{m}$ ($T_{1/2} > 10^{15}$ y) in SN explosion dynamics at very high temperature?

★ $^{180}Ta_{g}$ and $^{180}Ta^{m}$ can couple with each other through intermediate linking transitions in hot SN explosions.



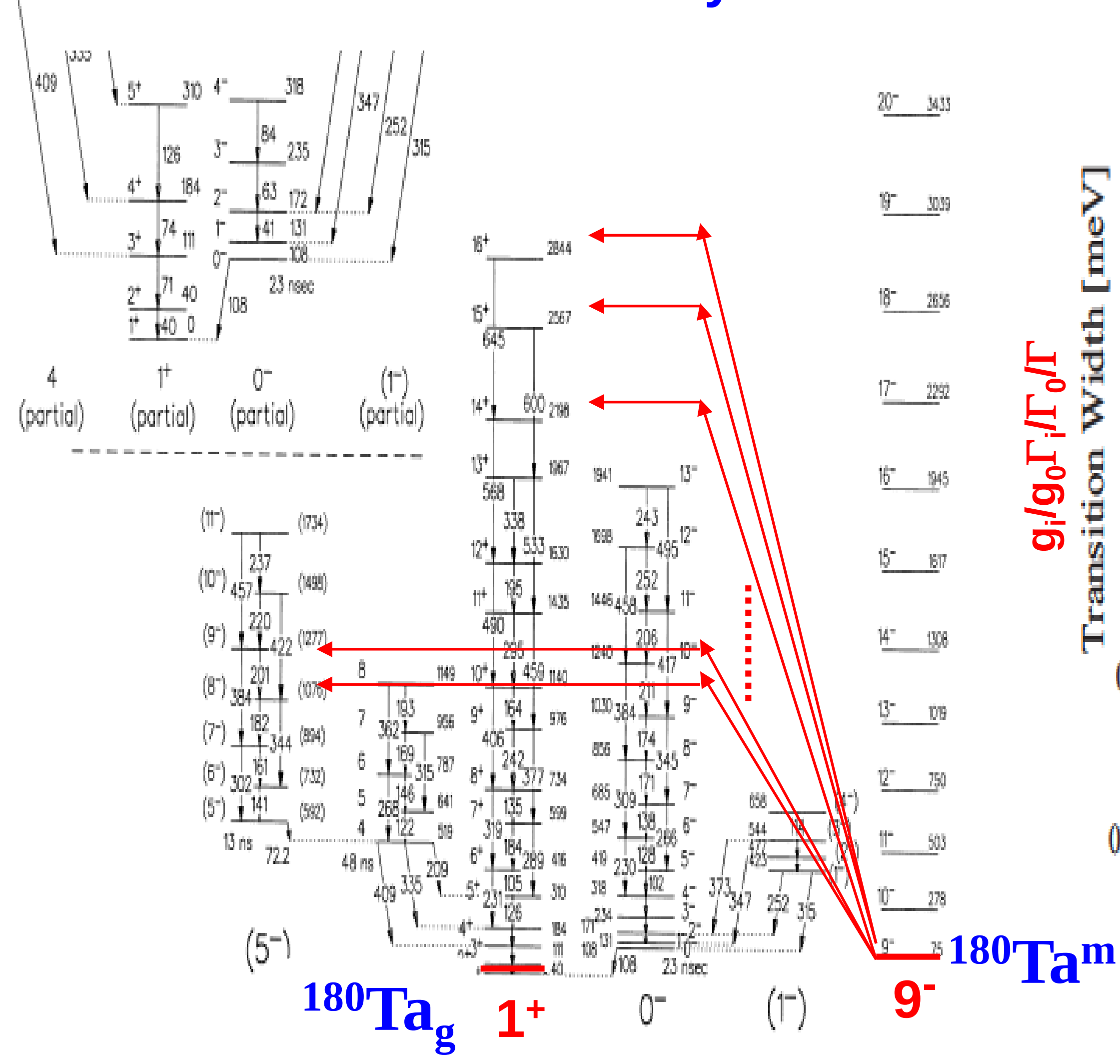


Measurement of Gamma-Decay Widths of Excited States

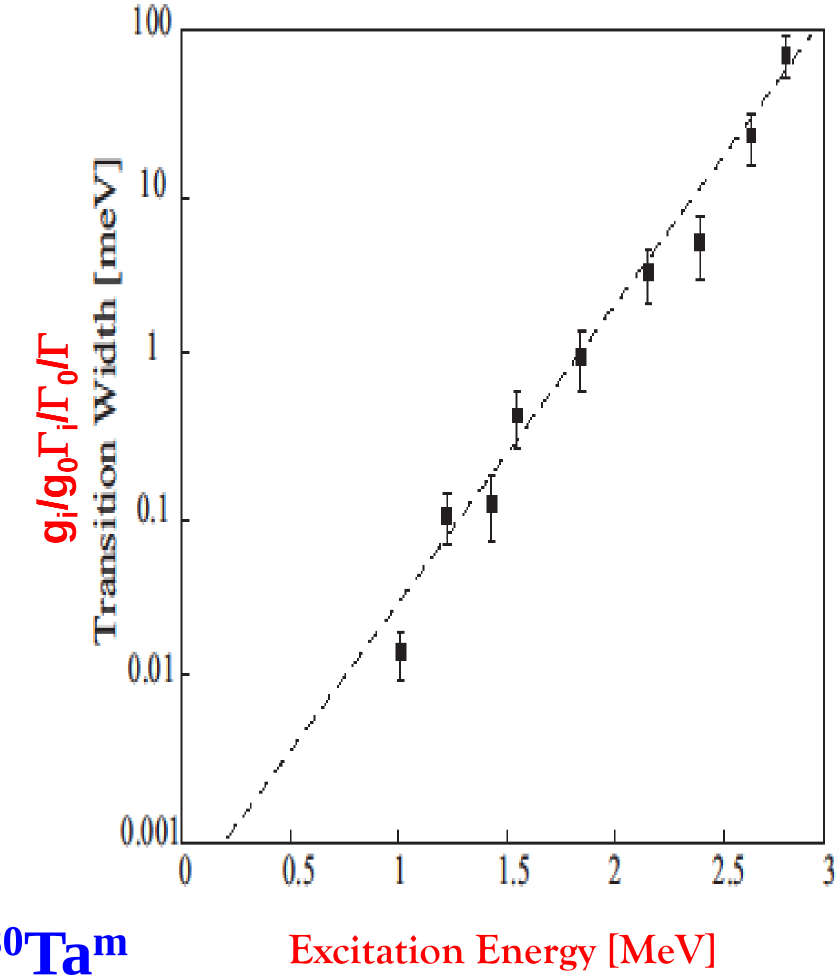
Saitoh et al. (NBI group), NPA 1999 +
Dracoulis et al. (ANU group), PRC 1998 +

Very small total decay width

Linking transitions between K = 1 and 9 bands are extremely weak.

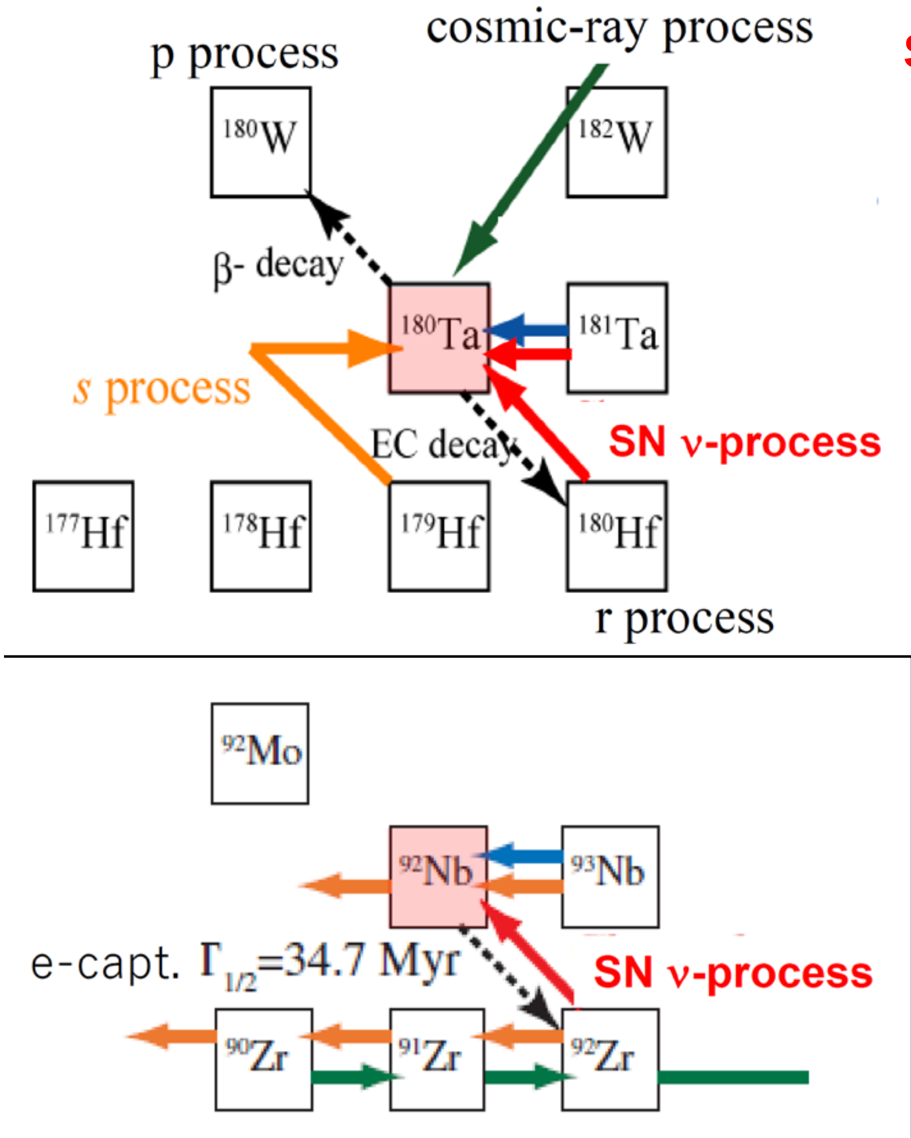


D. Belic et al., PR C65 (2002), 035801.



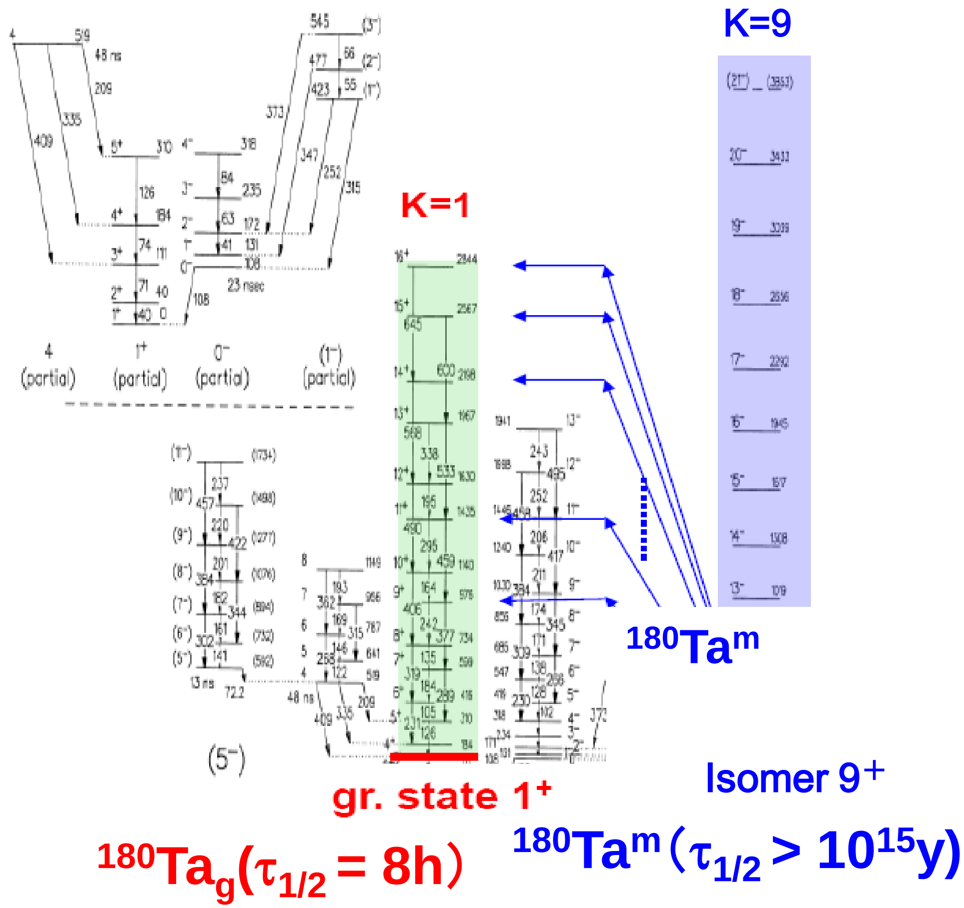
ν-Isotopes: ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

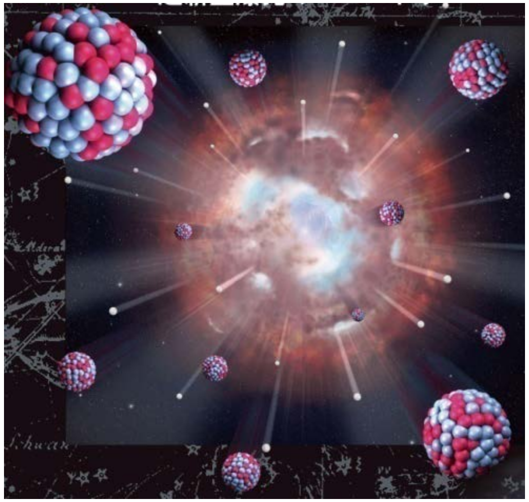
Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®;
PR C82 (2010), 058801; ApJL 779 (2013), L1.



SN ν-process in Einstein AB theory
→ Only 40% survives!

D. Belic et al., PR C65 (2002), 035801.





The last nearby Supernova

When exploded & formed pre-solar grain?

Primordial Sun formed.

The Sun isolated

4.56 Gy ago !

Present Sun

How long ?

From predicted initial abundance of $^{92}Nb(\tau_{1/2}=3.47\times10^{7}$ y) in GCE + Late Input(SN)model, we conclude;

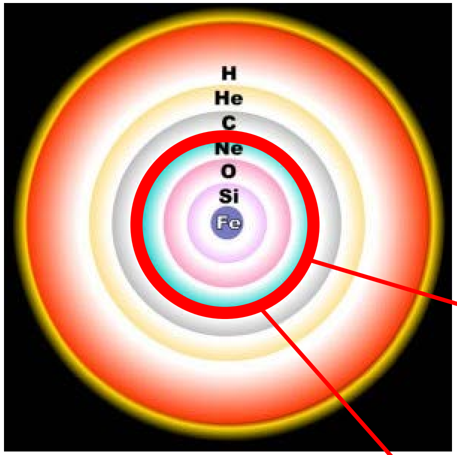
$\Delta T = 1 \sim 30$ My !

Hayakawa, Nakamura, Kajino, Chiba,Iwamoto, Cheoun, Mathews, ApJL **779** (2013), 1.

This is consistent with Standard Solar-System Formation Scenario
which requires $\Delta T = 1 \sim 10$ My (H. Yurimoto, 2016).

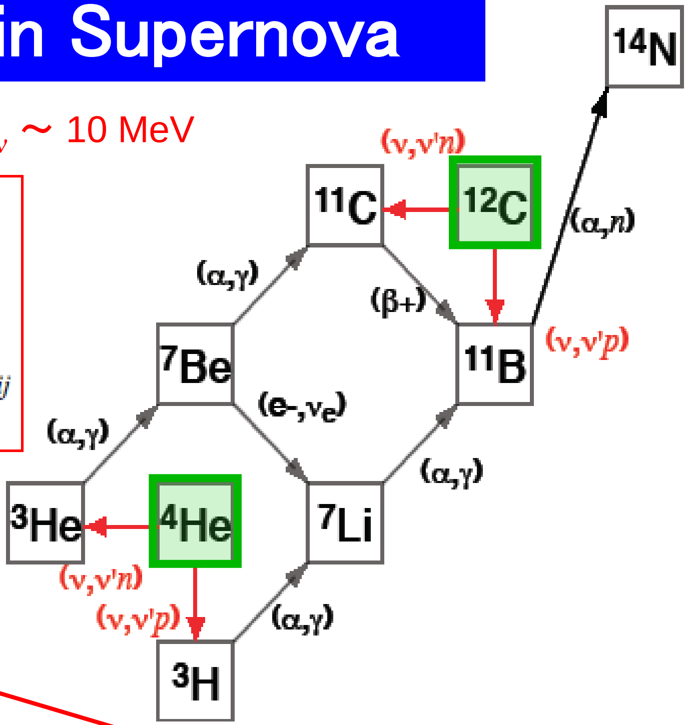
^{6,7}Li–^{9}Be–^{10,11}B : Outer Layer in Supernova

$|\Delta m^2_{13}| = |\Delta m^2_{23}| = 2.4\times 10^{-3}$ eV^2, $\varepsilon_\nu \sim 10$ MeV

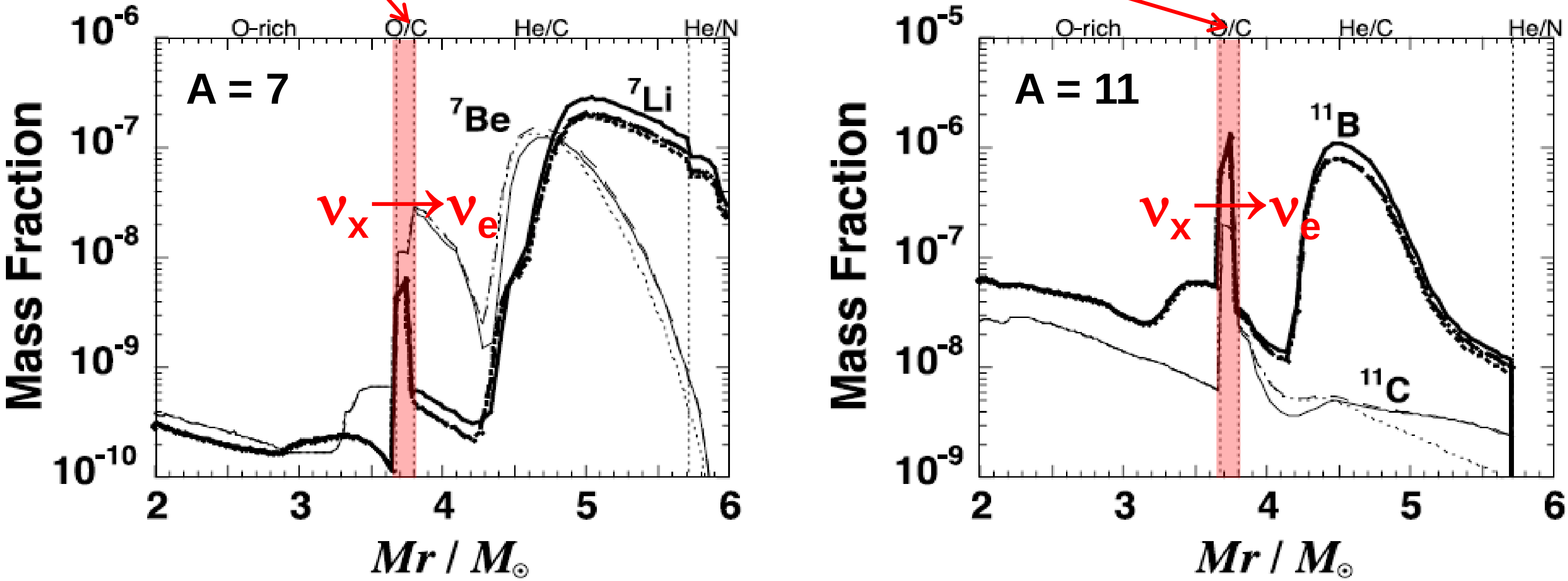


$$\rho_{\rm res} Y_e = \frac{m_u \Delta m^2_{ji} c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu} \quad [\text{ g cm}^{-3}]$$

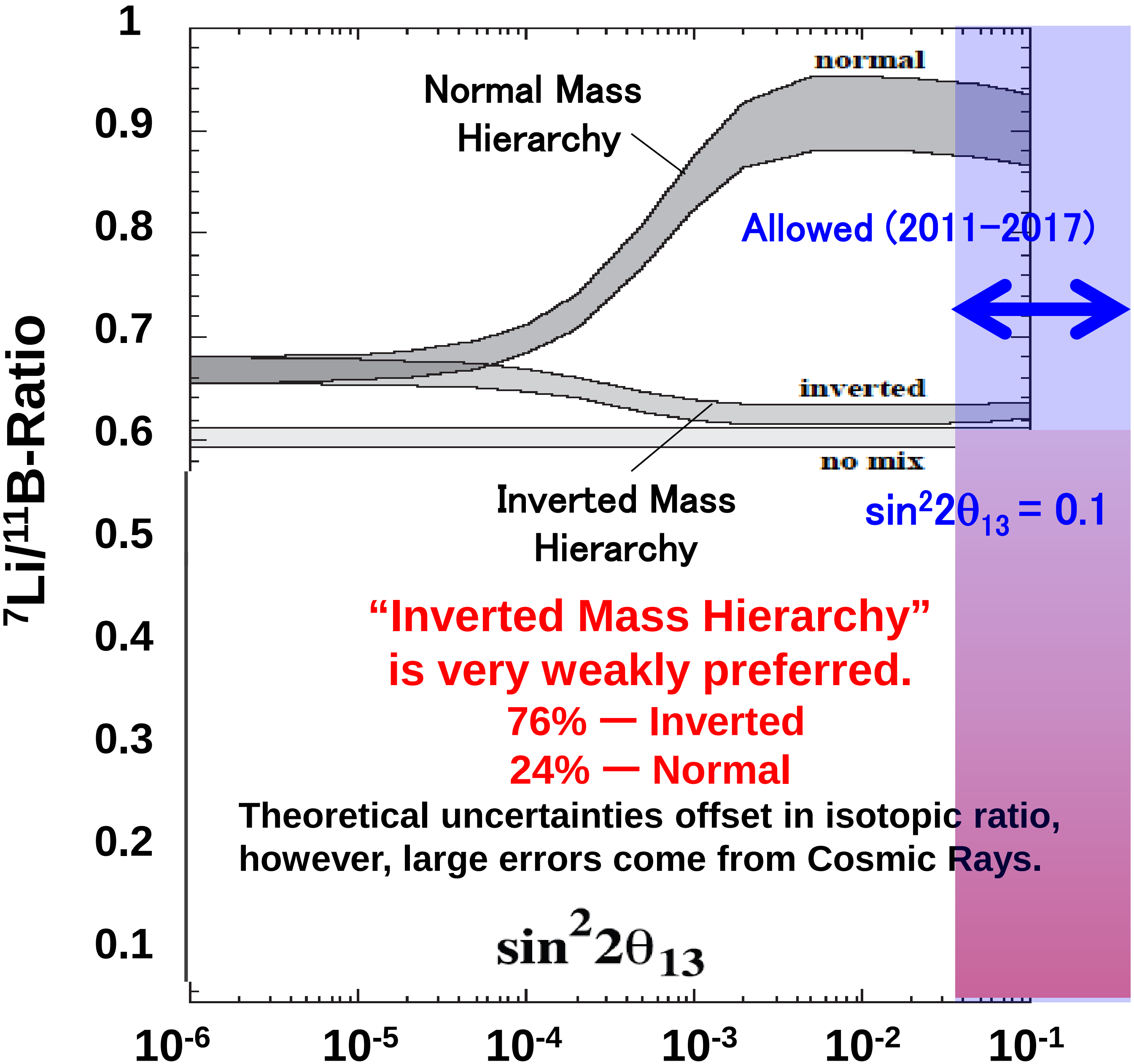
$$= 6.55\times 10^6 \left(\frac{\Delta m^2_{ji}}{1\text{ eV}^2}\right)\left(\frac{1\text{ MeV}}{\varepsilon_\nu}\right)\cos 2\theta_{ij}$$



MSW high-density resonance is located at O/C - He/C shell at $\rho \sim 10^3$ g/cm^3.



New Method to constrain Mixing Angle θ_{13} & Mass Hierarchy

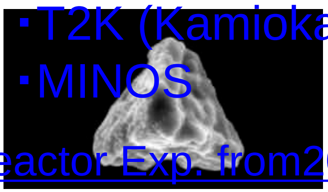


Yoshida, Kajino et al. 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.

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

Kajino, Mathews & Hayakawa, J. Phys.G41 (2014), 044007.

First Detection of $^7Li/^{11}B$ in SN-grains



Fujiya, Hoppe, & Ott, ApJ 730, L7 (2011).

Kajino, Mathews & Hayakawa, J. Phys. G41, 044007 (2014).

Long BaselineExp. from 2011-:

- T2K (Kamioka)
- MINOS

Reactor Exp. from2012-:

- RENO (KOREA)
- Double CHOOZ
- Daya Bay

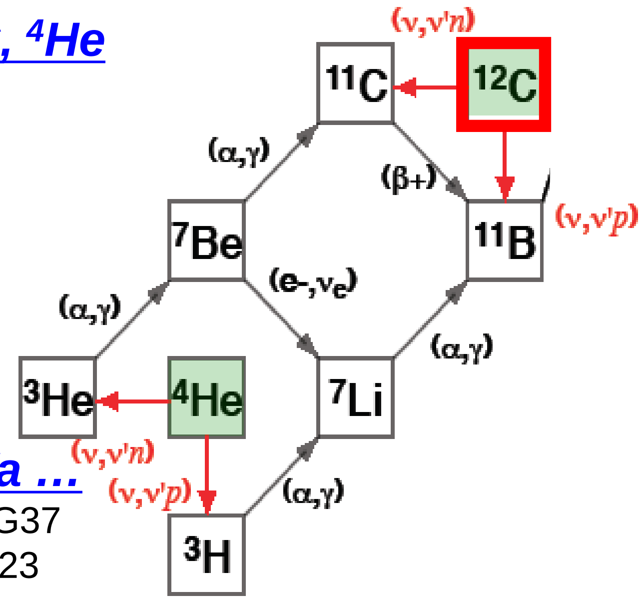
Theoretical Calculation for ν-Nucleus Cross Secti

New generation SM cal. with NEW Hamiltonian: ν-^{12}C, ^{4}He

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307;
Suzuki & Kajino, J. Phys. G40 (2013), 083101; +

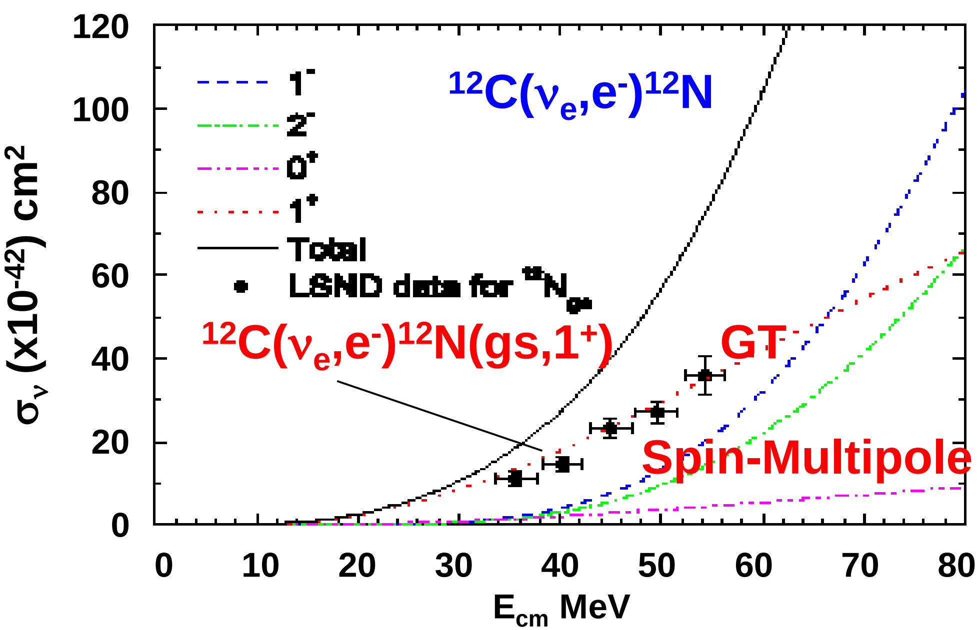
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

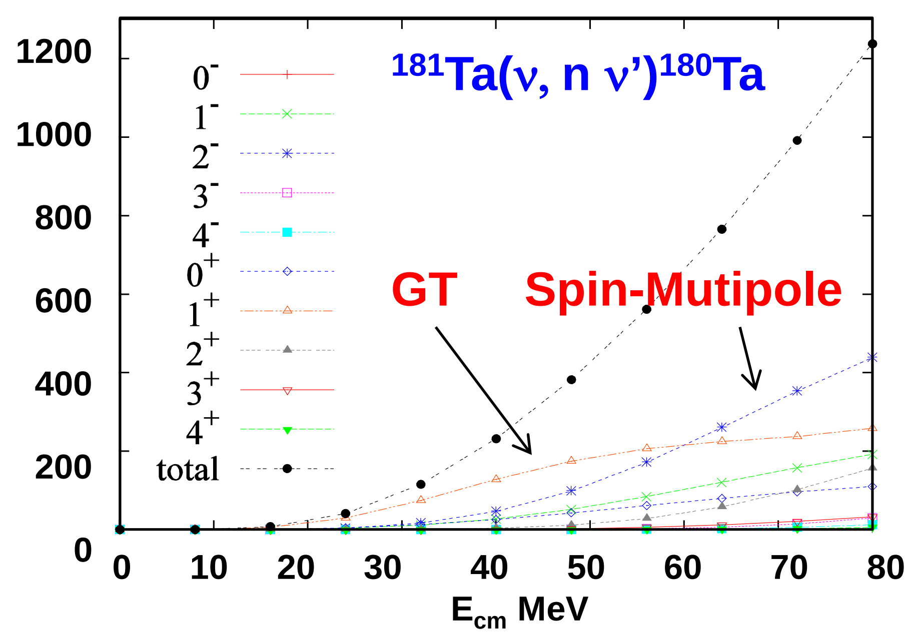
- μ-moments of p-shell nuclei
- GT strength for $^{12}C \rightarrow ^{12}N$, $^{14}C \rightarrow ^{14}N$, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections



QRPA cal.: ν-^{4}He, ^{12}C, ^{40}Ar, ^{42}Ca, ^{98}Tc, ^{92}Nb, ^{138}La, ^{180}Ta …

Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801; PRC 85 (2013), 065807; PLB 723 (2013), 464; J. Phys. G42 (2015), 045102; +





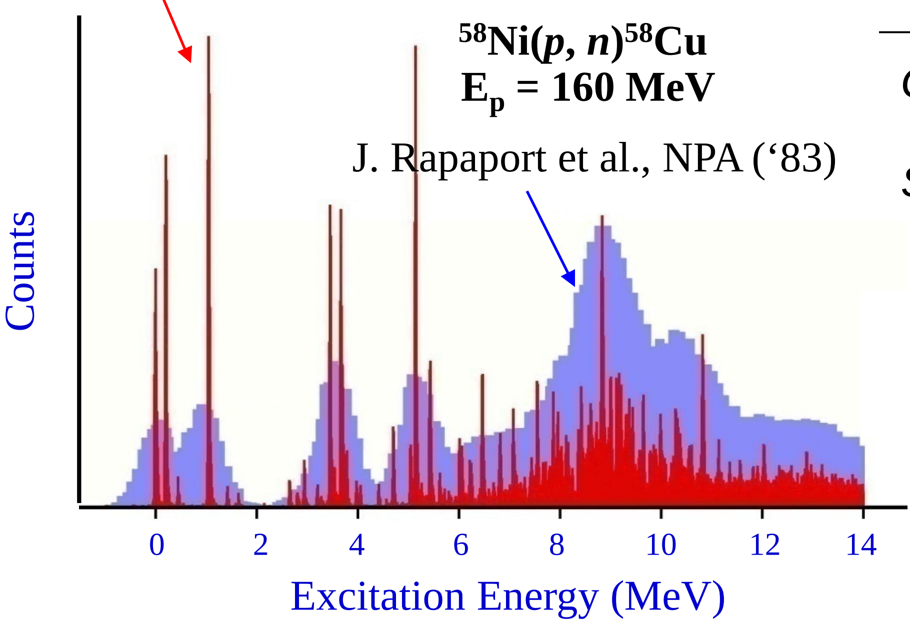
ν−BEAM spectro. Exp., still difficult at E<100 MeV.

→ **Hadronic CEX, charg. lepton (e μ), photon (γ) !**

Similarity between Electro-Magnetic & Weak Interactions

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

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



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-Teller operator = $\vec{\sigma}\tau_{\pm}$

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

Cosmology − ν mass − 0νββ
− ν mass hierarchy
− Astro Connection

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

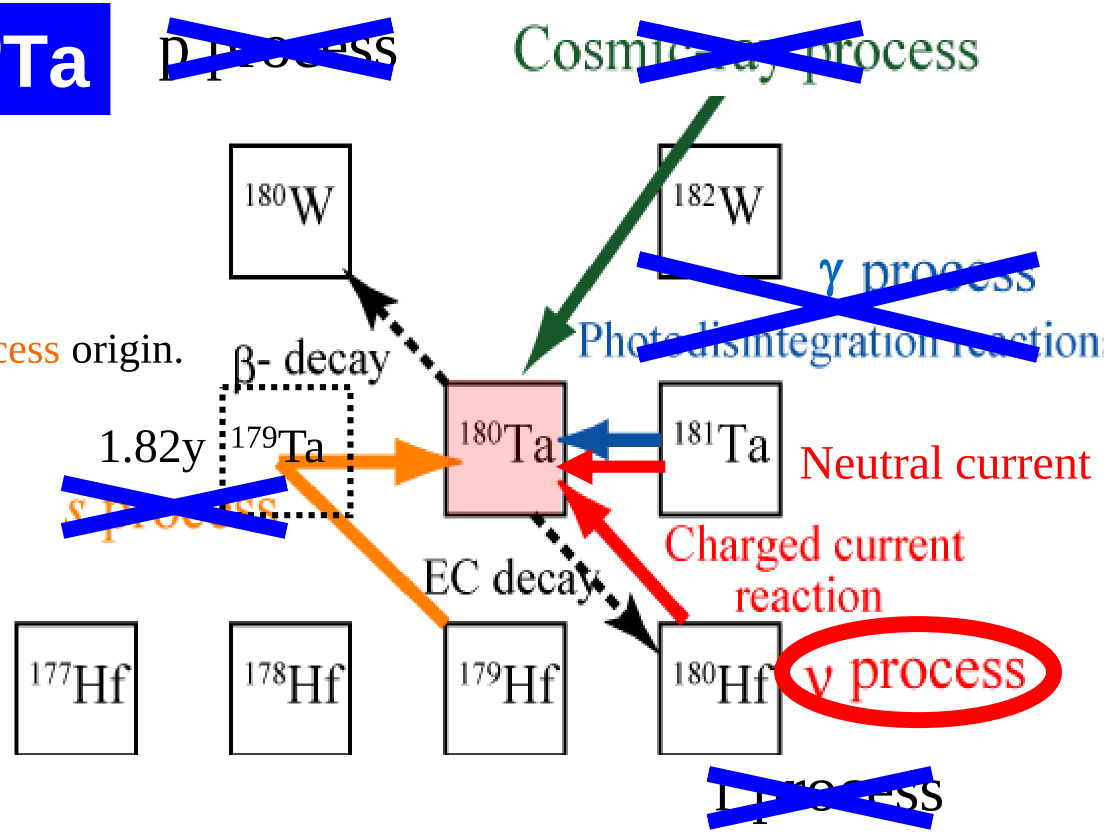
Missing Origin of ^{180}Ta

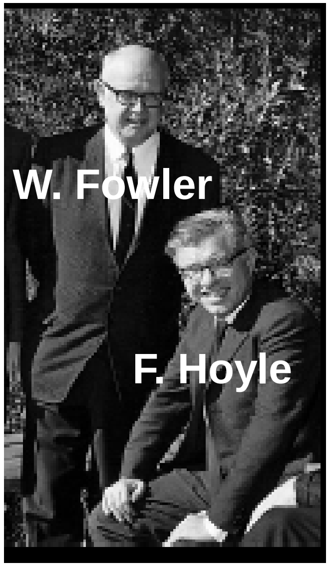
^{138}La = spherical
^{180}Ta = deformed

K.Yokoi, Nature (1983) proposal of s-process origin.

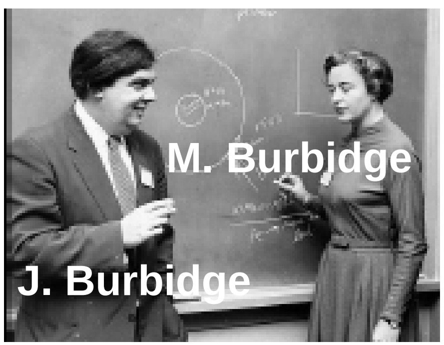
Belic et al., Phys. Rev. Lett. (1999)
Wisshak, Phys. Rev. Lett. (2001)

S-process can NOT produce both ^{138}La & ^{180}Ta consystently with s.s. abundance.





B^{2}FH,
RMP. 29 (1957), 547-650.
"Element Genesis in Stars"



Supernova neutrino-process:

Nucleosynthesis Theory
Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272.
Heger et al., Phys. Lett. B 606, 258 (2005)

Nucleo-Cosmochronology:
Hayakawa, Shimizu, Kajino, Ogawa, & Nakada, PRC 77 (2008), 065802; 79 (2009) 059802.

Tantalum ^{180}Ta

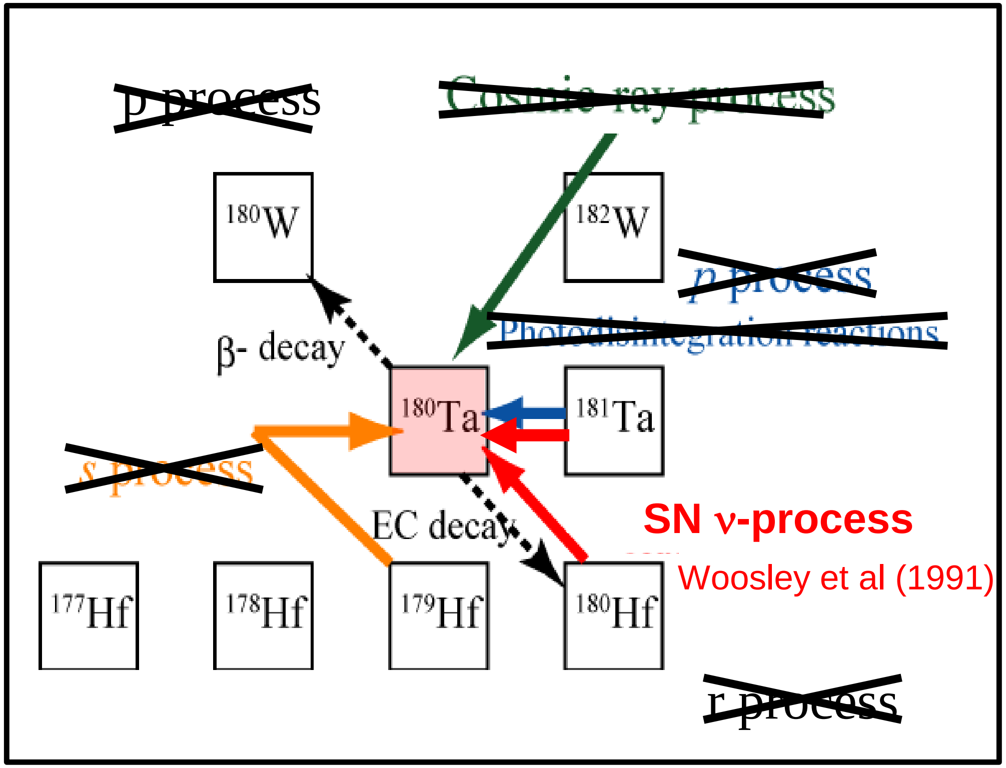
Explosive SN nucleosynthesis coupled with quantum transitions can reproduce both ^{180}Ta and ^{138}La simultaneously.

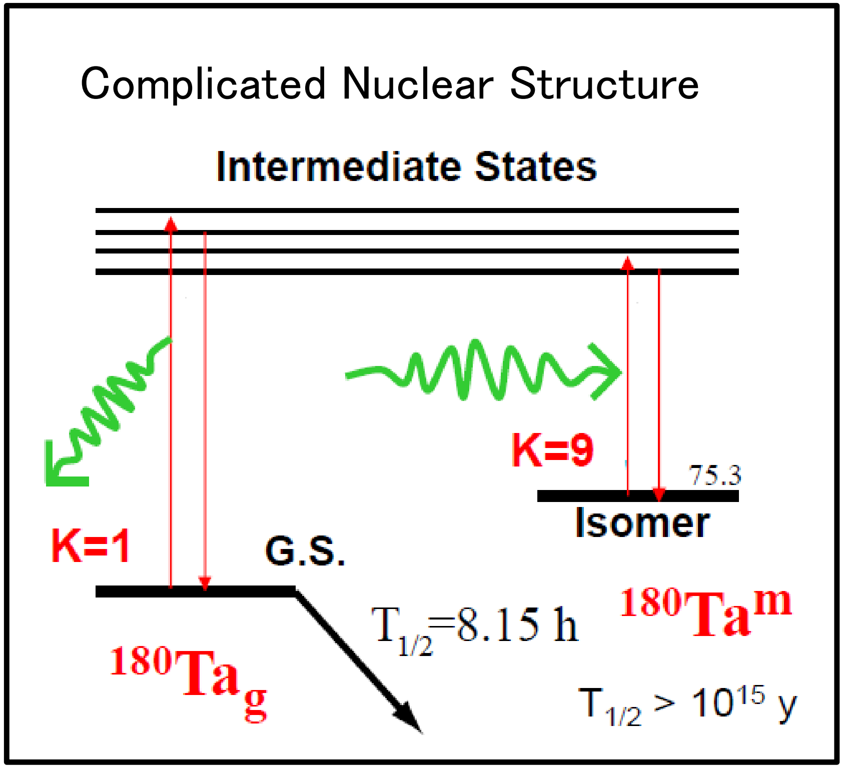
Hayakawa et al. (2010) PRC81, 052801®; (2010) PR C82, 058801.

Overproduction problem, solved!

$(^{180}\text{Ta}/^{138}\text{La})_{theory} = 1$

→ ***Only when*** $T_{\nu e}$ **= 3.2MeV,** $T_{\overline{\nu e}}$ **= 4-5MeV !**





SN ν–Process : Origin of ^{92}Nb !

Hayakawa, Nakamura, Kajino, Chiba, Iwamoto, Cheoun, Mathews,
Astrophys. J. Lett. **779** (2013), L1.

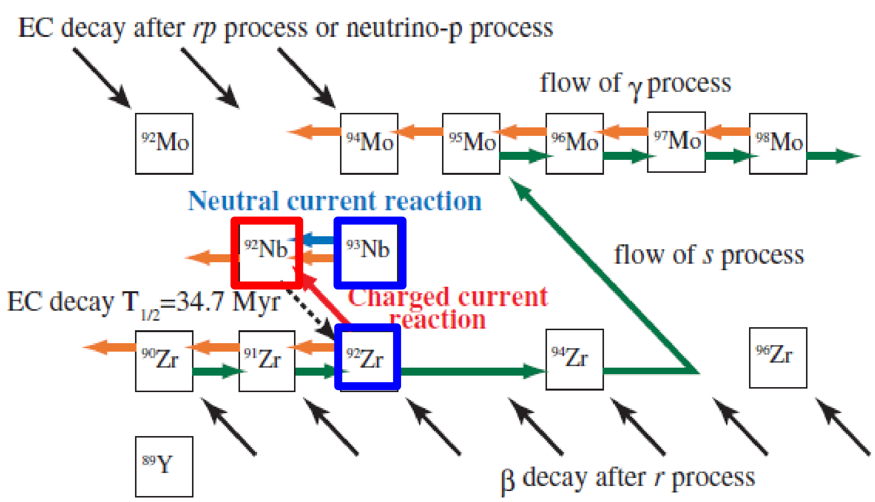
★ ^{92}Nb($\tau_{1/2}$=3.47x10^{7} y) existed at the s.s. formation (4.56 Gy ago)!

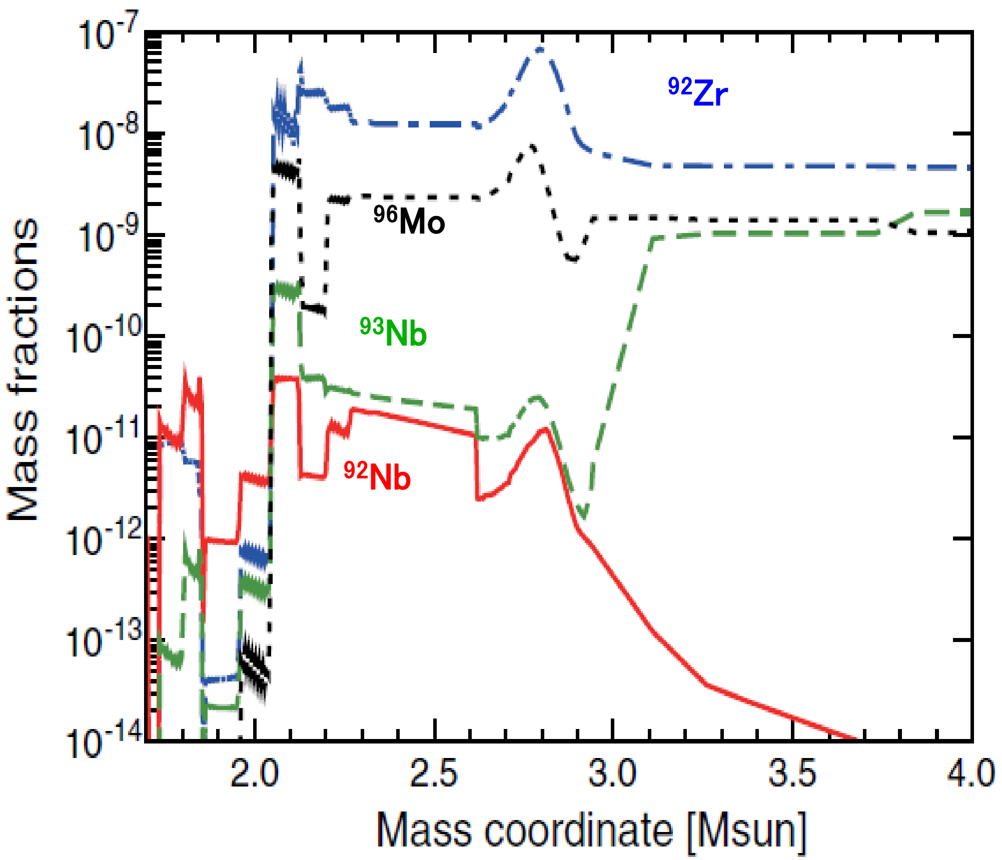
★ Isotopic anomaly in meteoritic, found;

^{92}Zr/^{93}Nb ∼ 10^{-3}

When did the last nearby SN exploded before the solar sytem formation ?

$T_{\nu e}$ = 3.2 MeV, $T_{\overline{\nu e}}$ = 4.0 MeV, $T_{\nu x}$ = 6.0 MeV





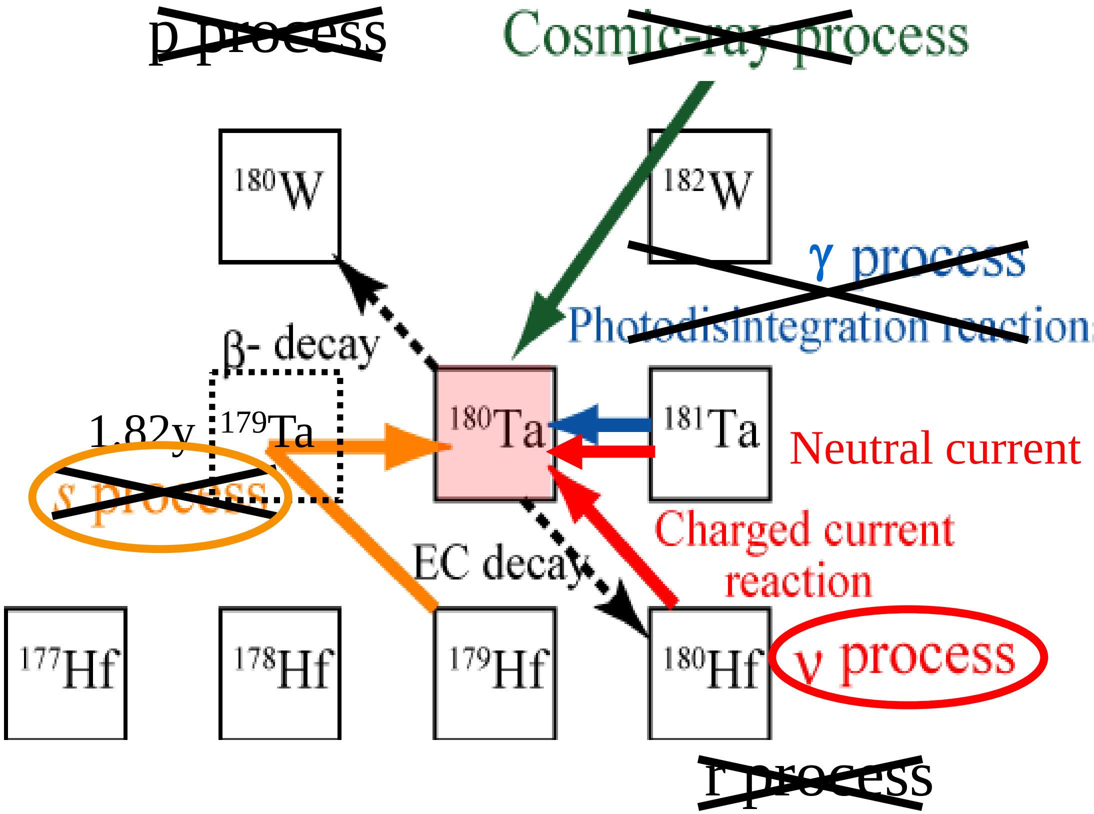
Origin of ^{180}Ta

^{138}La = spherical
^{180}Ta = deformed

K.Yokoi, Nature (1983)
proposal of s-process origin.

Belic et al., Phys. Rev. Lett. (1999)
Wisshak, Phys. Rev. Lett. (2001)

S-process cannot produce both ^{138}La & ^{180}Ta.



Supernova neutrino-process:

Nuclear Experiment & Theory

Goko, Phys. Rev. Lett. (2007)
Byelilov , Phys. Rev. Lett. (2007)
Cheoun et al., (2010), in preparation.

Nucleosynthesis Theory

Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272.
Heger et al., Phys. Lett. B 606, 258 (2005)

Nucleo-Cosmochronology:

Hayakawa, Shimizu, Kajino, Ogawa, & Nakada, PRC 77 (2008), 065802; 79 (2009) 059802.

Origin of HEAVY Atomic Nuclei (r-elements)?

CC-Supernovae?

ν-DW ? Woosley, et al., ApJ 433, 229 (1994). +
Nishimura, et al., ApJ 642, 410 (2006).
Fujimoto, et al., ApJ 680, 1350 (2008).
MHD-Jet Winteler, et al., ApJ 750, L22 (2012).
Nishimura et al., ApJ, 810, 109 (2015)
Long-GRB Nakamura, et al, A&Ap 582 A34 (2015)

τ =1My

Explosion Condition(Ω, B) !

1st, 2nd, 3rd peaks ?

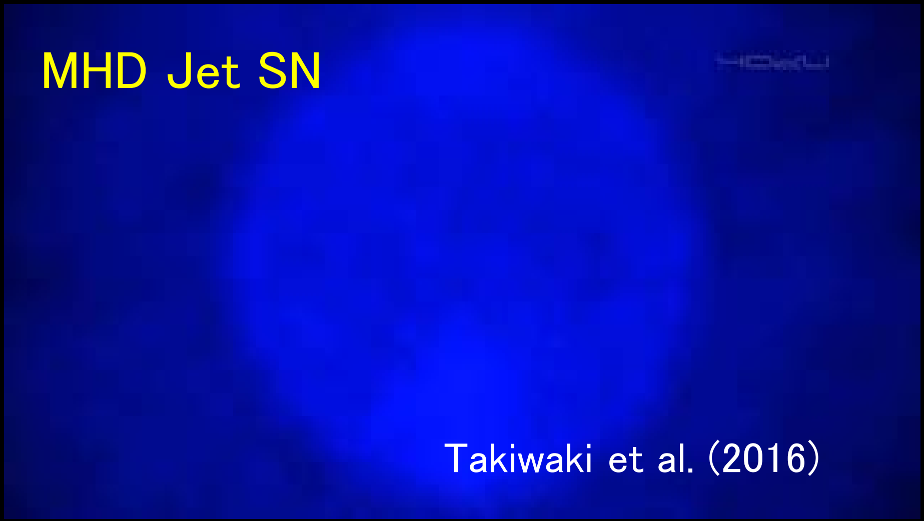
Binary Neutron-Star Mergers?

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

100My $\lesssim \tau \lesssim$ 10Ty

Merging time, too long !

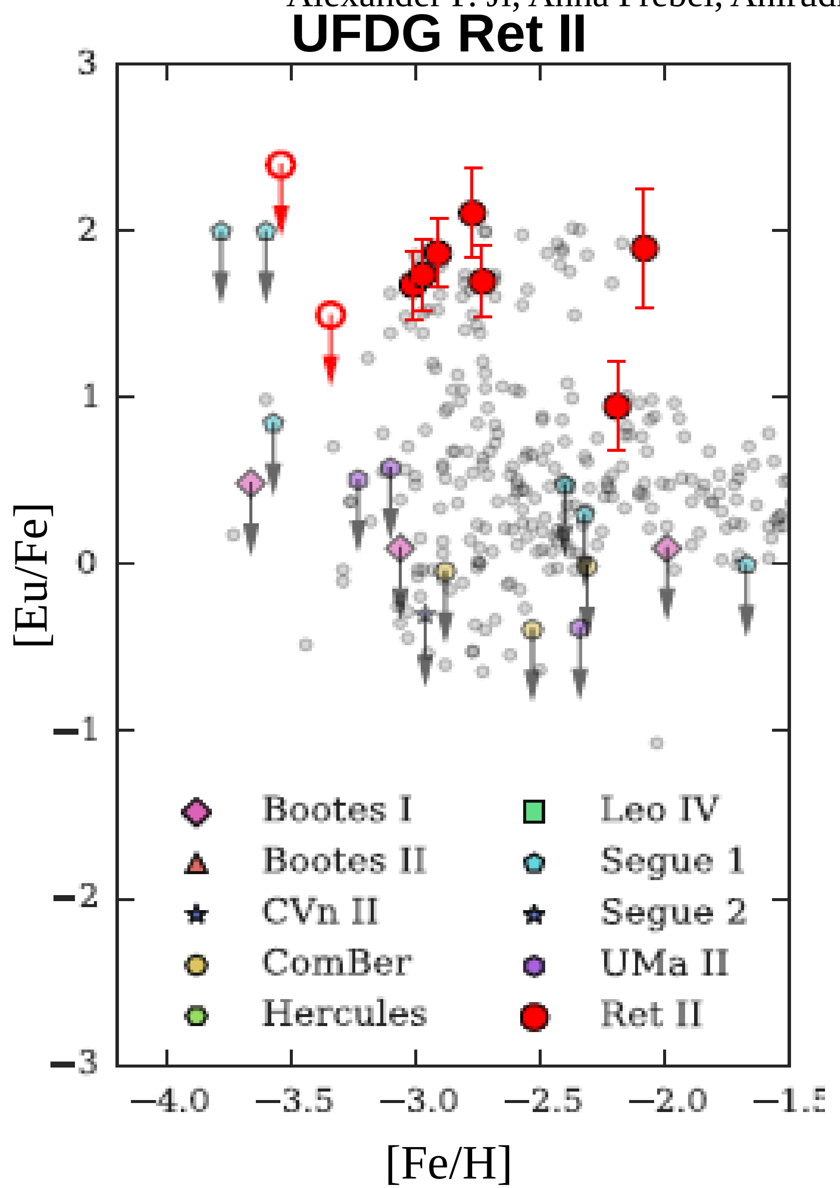
Time Scale Problem ?



Strong Universality in Ultra-Faint Dwarf Ret. II

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

Alexander P. Ji, Anna Frebel, Anirudh C...



Which is likely r-process site, MHD-Jet SN or Binary NSM?

Product. Yield ~ 10^{-2} $M_\odot$ /event

1. **Rare Event Rate ?**

   (2.6 +/- 0.2)x$10^3 M_\odot$ Ret. II baryon mass

   ⟶ ~10 SNe IMF

   ⟶ ~(0.01-0.3)x10 NSM/SN (0.1%) MHDJ/SN (1-3%)

   SN !? NSM !?

2. **Very old ?**

   SN ! NSM !

3. **Extended Universality ? Dust forms ?**

   SN ! NSM ?

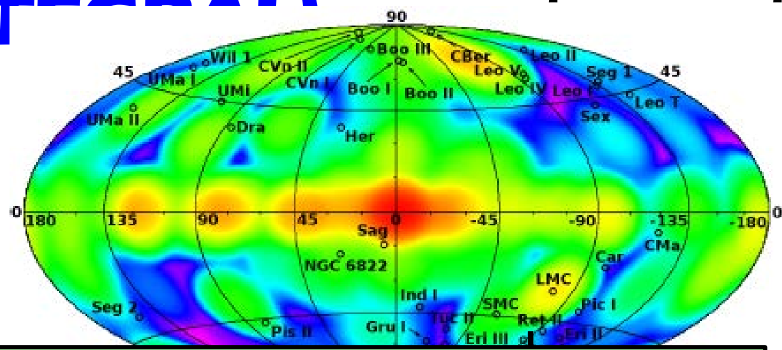
4. **Ejecta escape from shallow pot. ?**

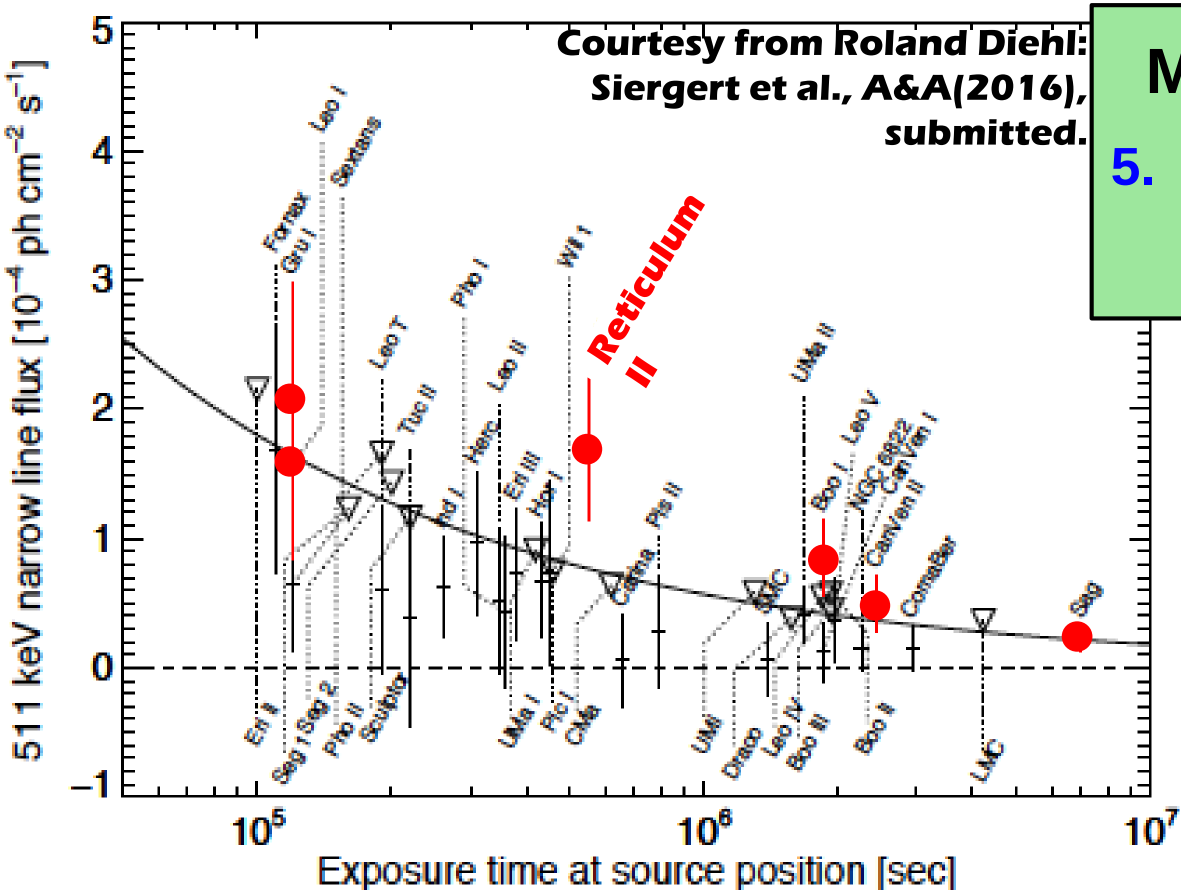
   SN ! NSM ?

Search for 511 keV emission from e+e- annihilation in nearby dSph galaxies (INTEGRAL)

- Dark Matter or Stellar e^+ ?
- No significant detection except for **Reticulum II** ⇒ **Stellar e^+**

Exposure map

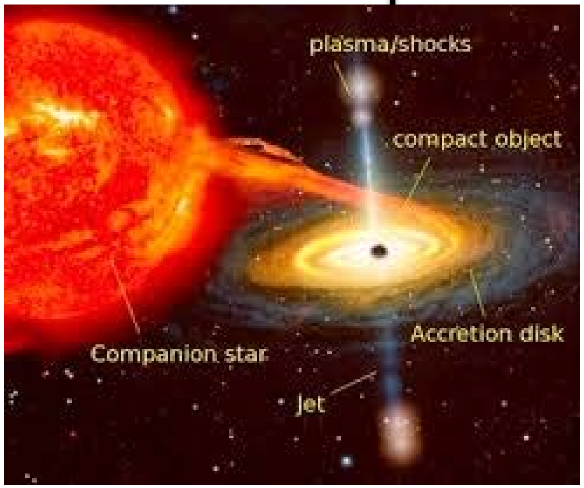




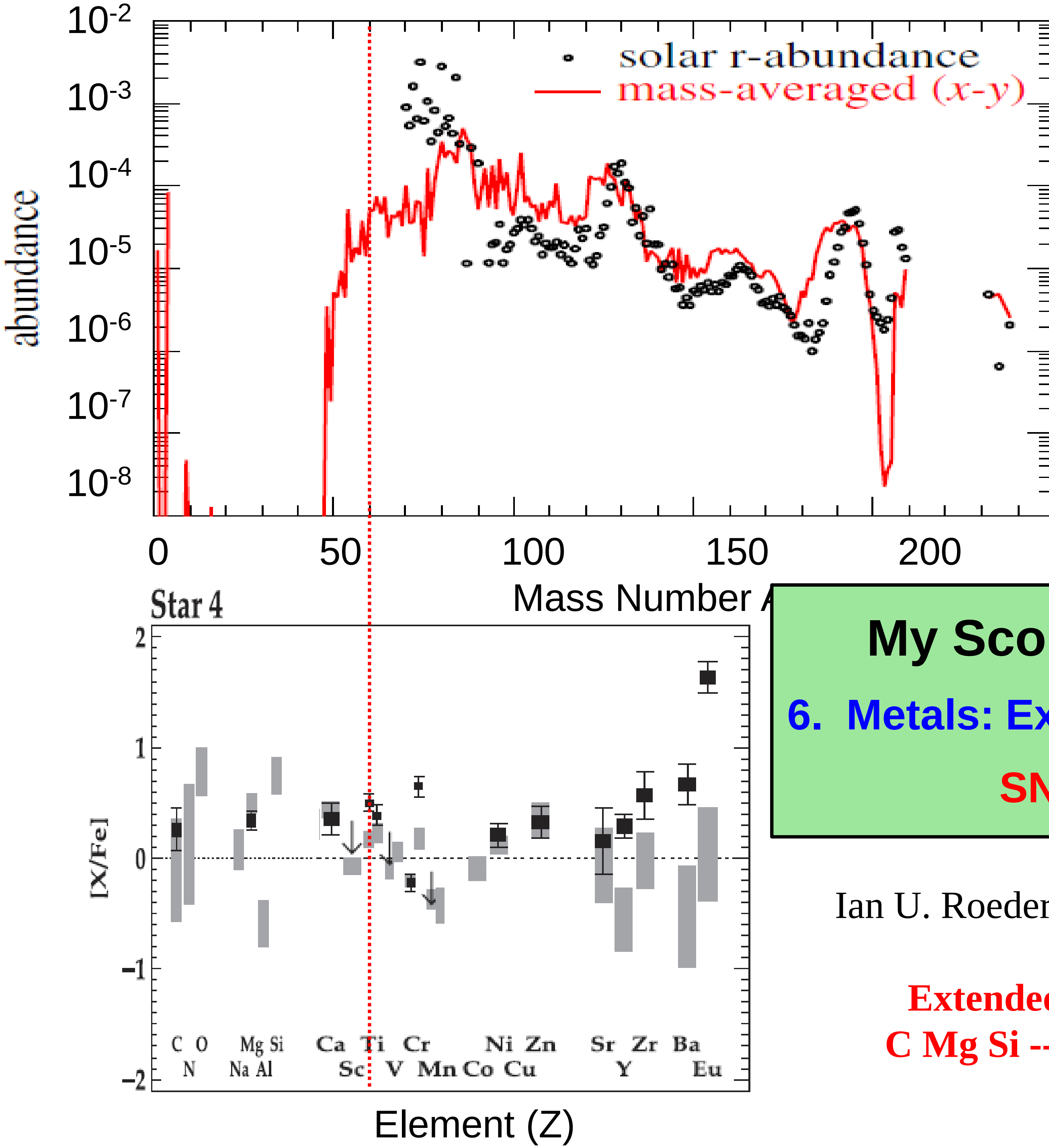
My Score Sheet (cont')

5. Stellar e+ 511 keV ?

SN ! NSM ?



Micro-quasar ?



Almost No Production of Light Elements A < 50!

NSM R-Process cal.

S. Wanajo et al., ApJ. 789 (2014), L39.

S. Shibagaki et al., ApJ. 816 (2016), 79.

Ian Roederer

My Score Sheet (cont')

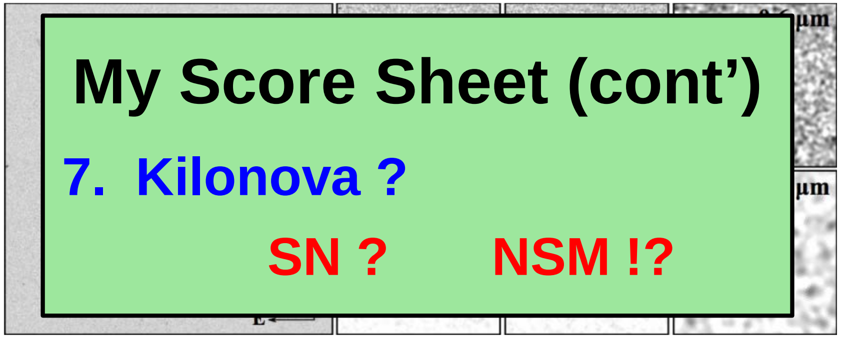
6. Metals: Extended Universality ?

SN ! NSM ?

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

Extended Universality, found in C Mg Si ---Fe Ni Zn --- R-elements

Evidence for r-Process in Neutron Star Mergers?



My Score Sheet (cont')

7. Kilonova ?

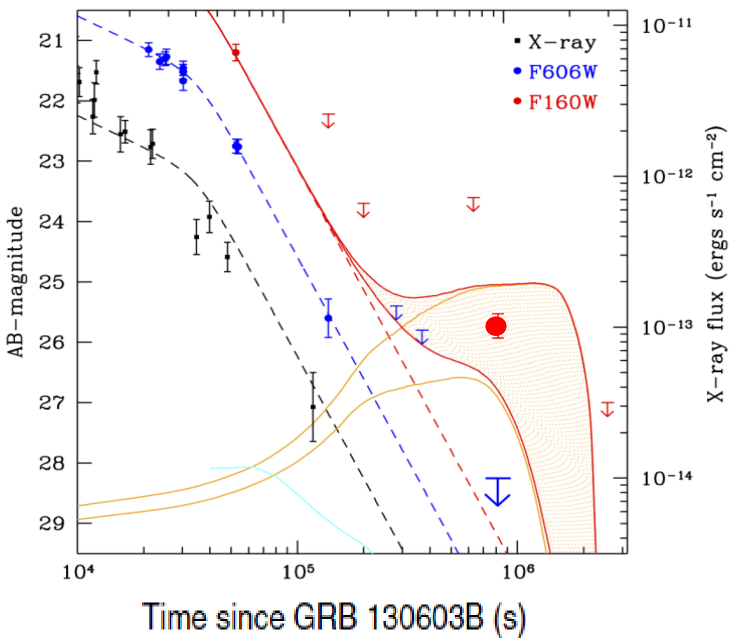
SN ?   NSM !?

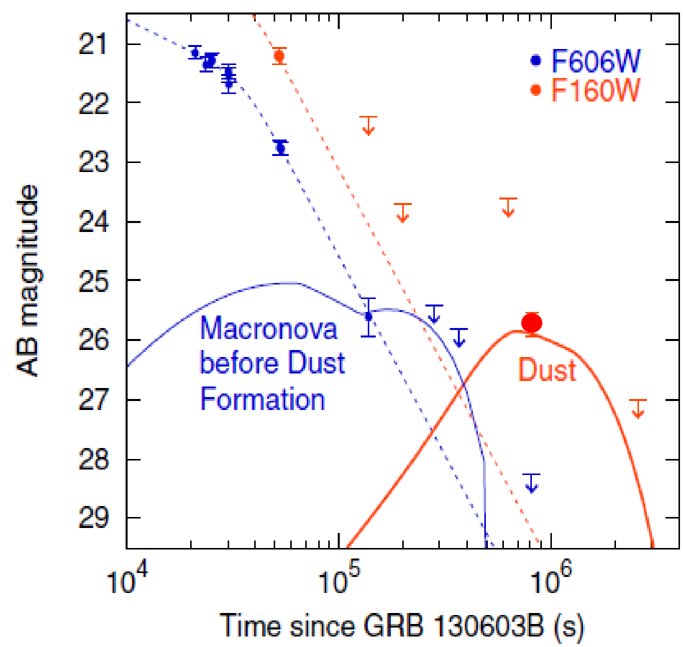
Macronova (Kilonova)

Tanvir, Levan, Fruchter, et al., Nature 500, 547 (2013)

Dust is hard to form for deficient Carbon and other lighter elements.

Takami, Nozawa & Ioka, ApJ 786, L5 (2014).





Dust formation becomes even more difficult when one includes more complete opacity table for heavy actinide elements.

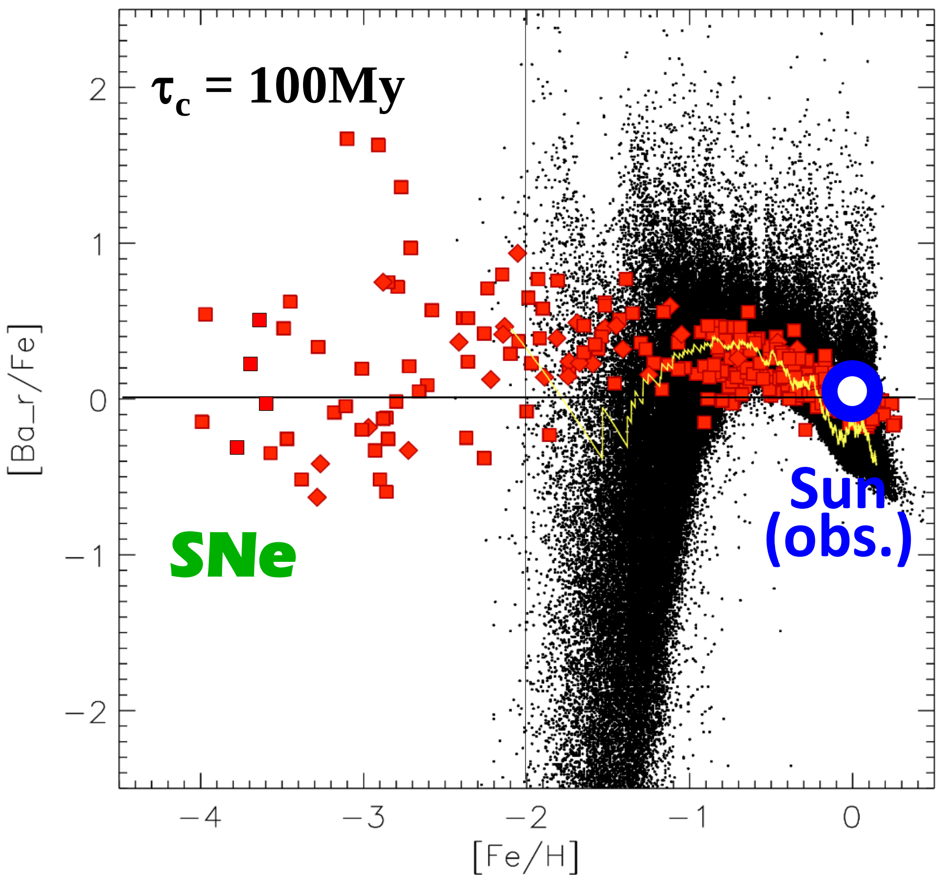
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

SNe = Metals ; NSM(τ_c=100My)= r-process elements.
Star forming condition, n_H >100 cm^{-3} → ~ 10-100pc)

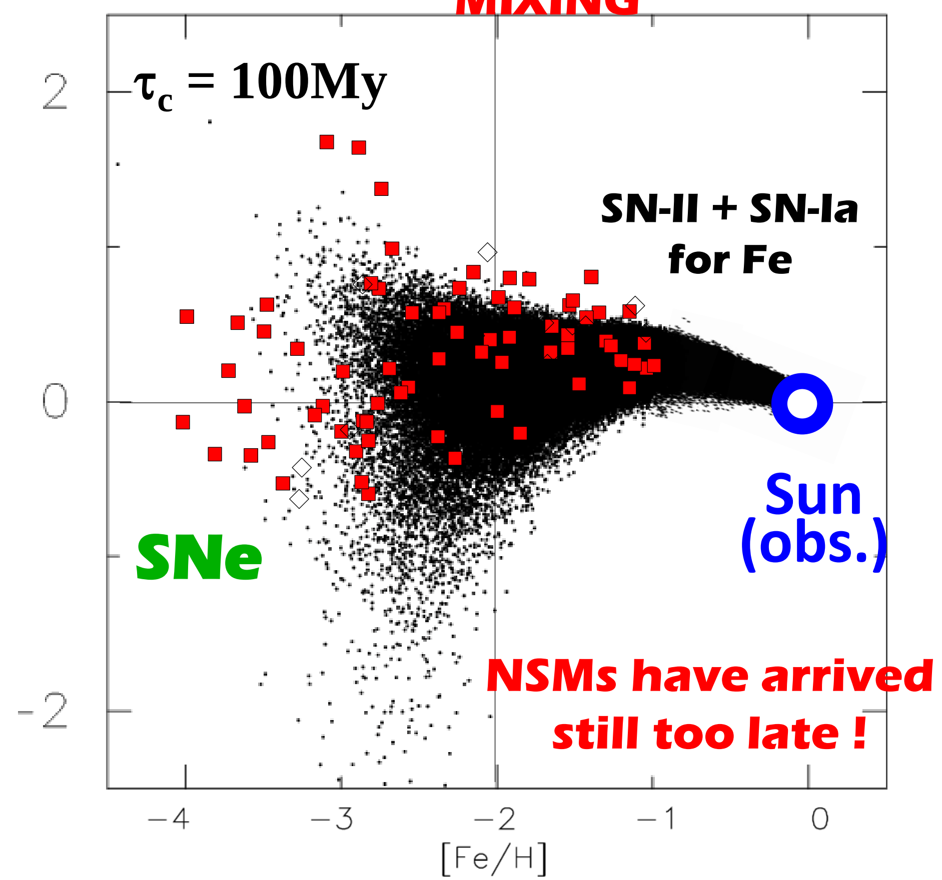
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

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

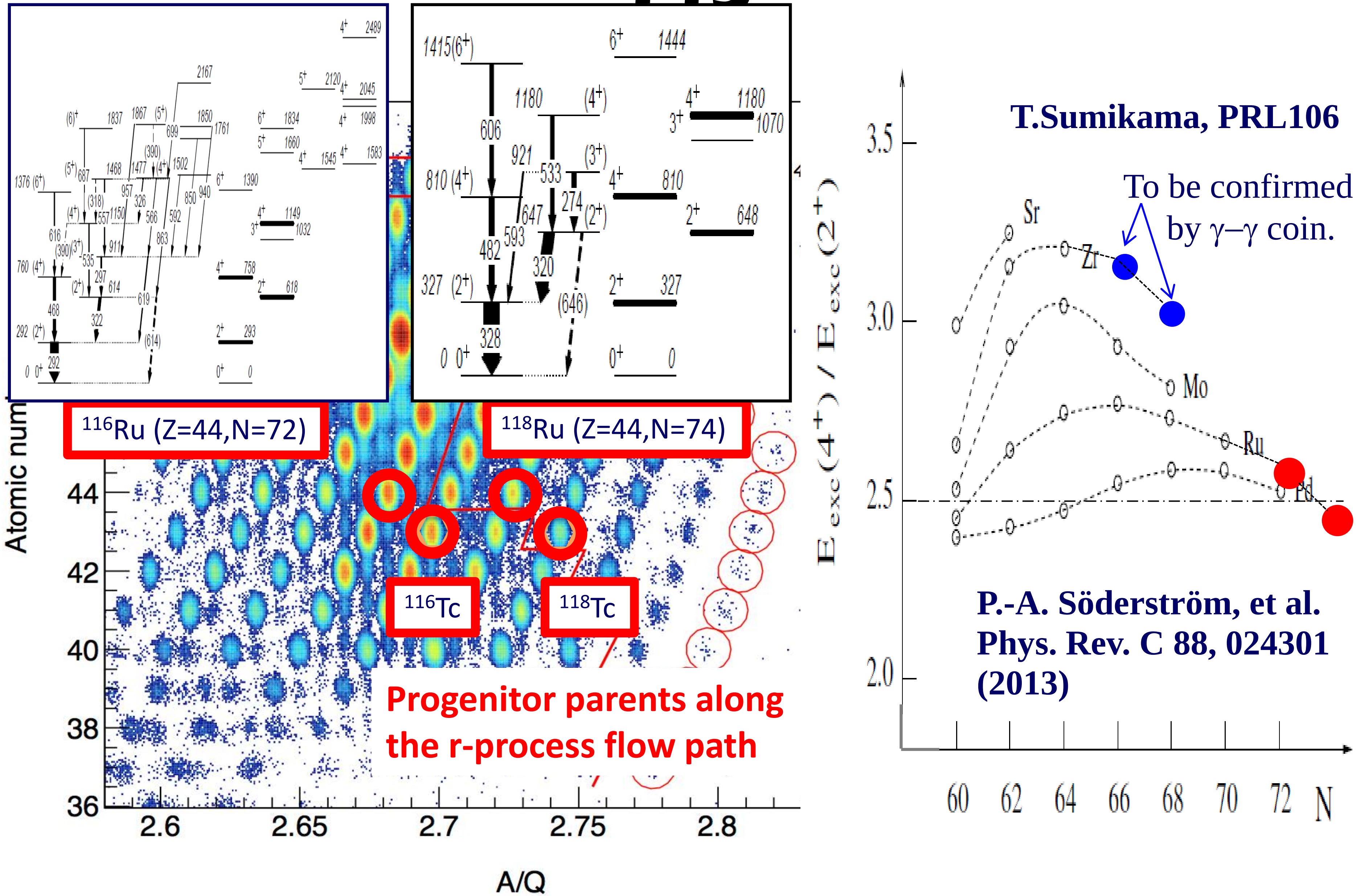
Without Dynamics & GAS MIXING

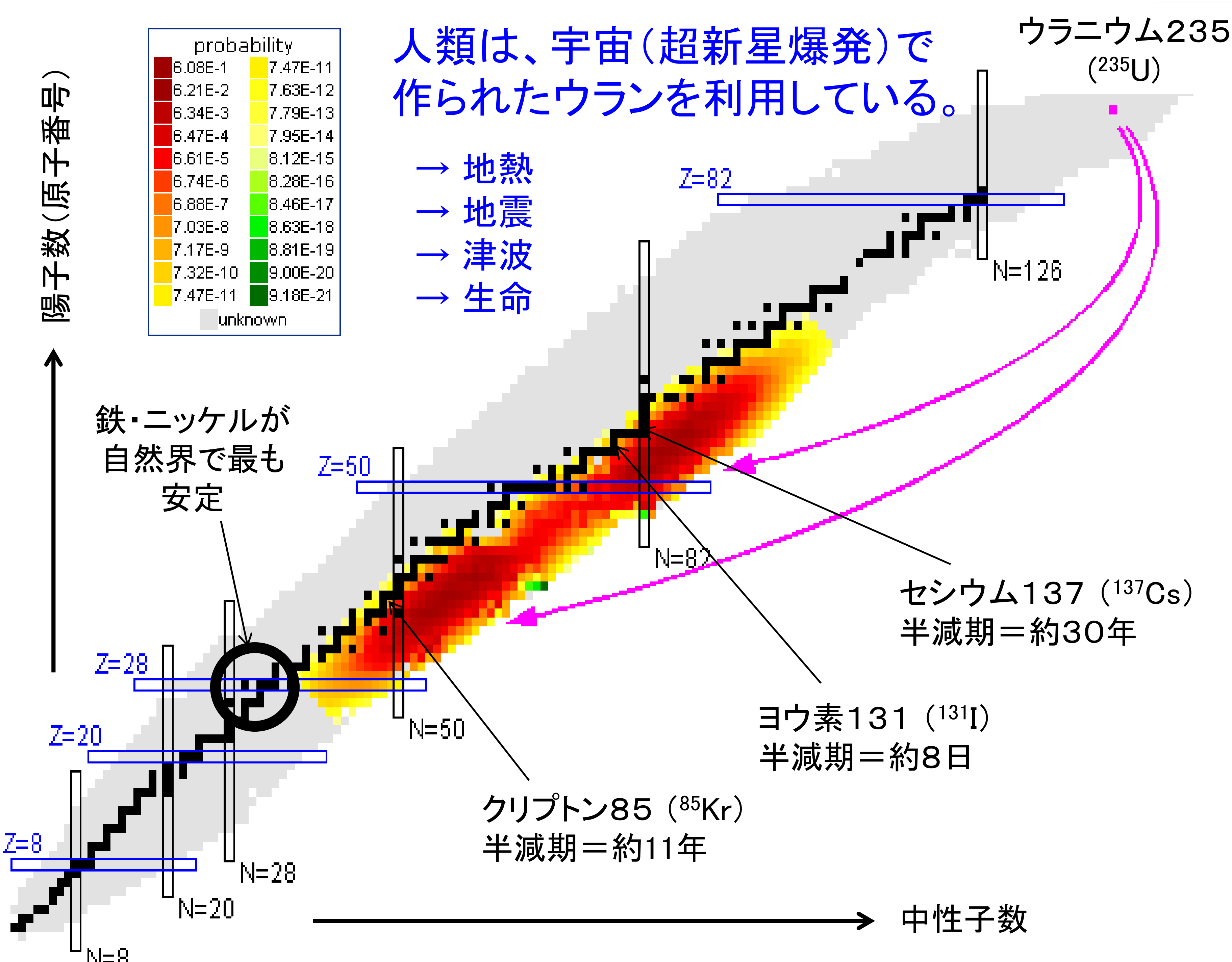


With Dynamics & GAS MIXING



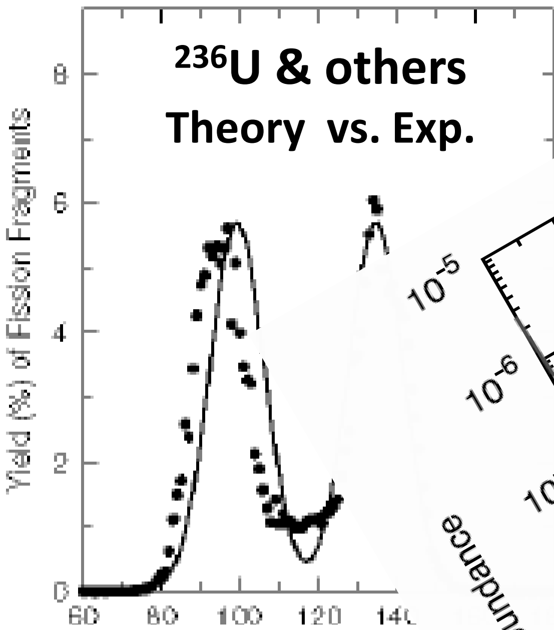
Decay Spectroscopy around A = 100-145

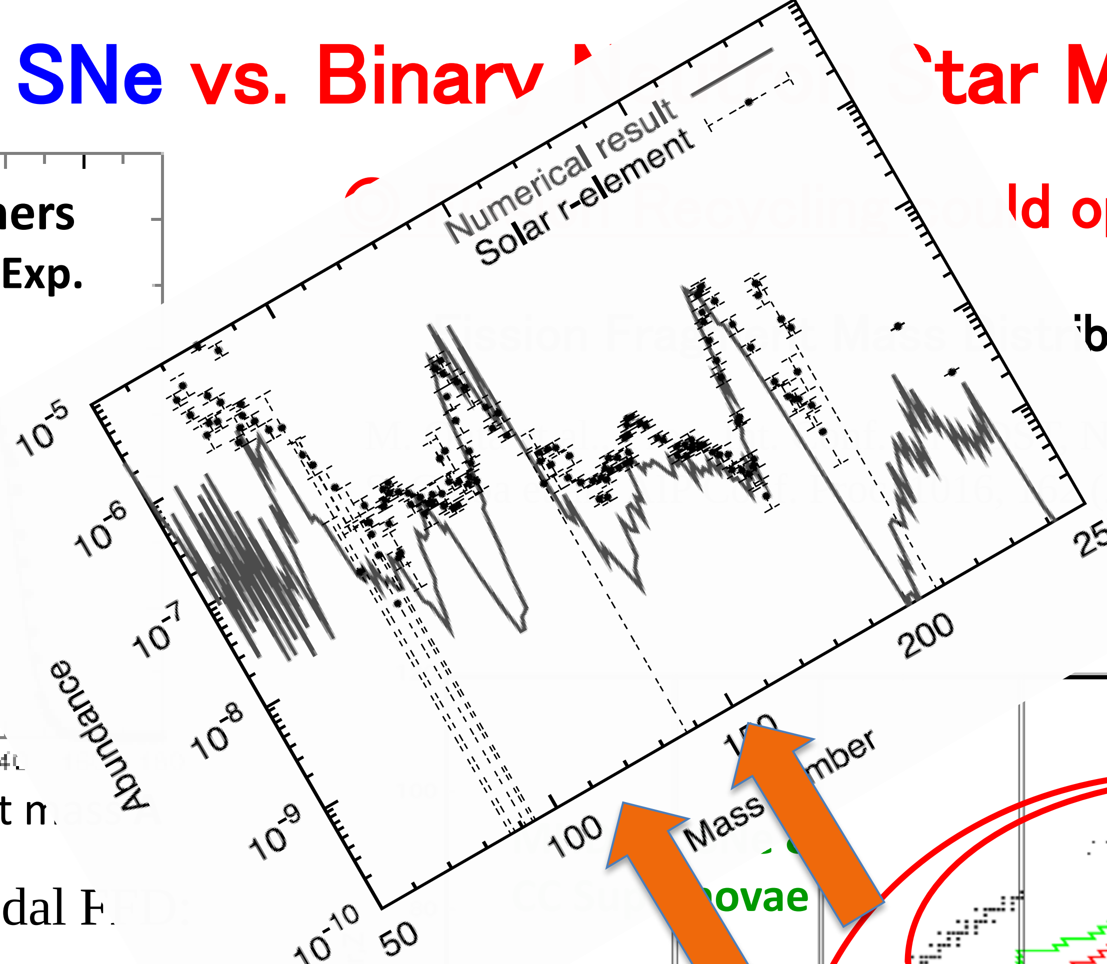




人類は、宇宙(超新星爆発)で
作られたウランを利用している。
→ 地熱
→ 地震
→ 津波
→ 生命
ウラニウム235
(235U)
probability
6.08E-1
6.21E-2
6.34E-3
6.47E-4
6.61E-5
6.74E-6
6.88E-7
7.03E-8
7.17E-9
7.32E-10
7.47E-11
7.47E-11
7.63E-12
7.79E-13
7.95E-14
8.12E-15
8.28E-16
8.46E-17
8.63E-18
8.81E-19
9.00E-20
9.18E-21
unknown
陽子数(原子番号)
中性子数
鉄・ニッケルが
自然界で最も
安定
Z=82
Z=50
Z=28
Z=20
Z=8
N=126
N=82
N=50
N=28
N=20
N=8
セシウム137 (137Cs)
半減期＝約30年
ヨウ素131 (131I)
半減期＝約8日
クリプトン85 (85Kr)
半減期＝約11年

MHD-Jet SNe vs. Binary … tar Mergers



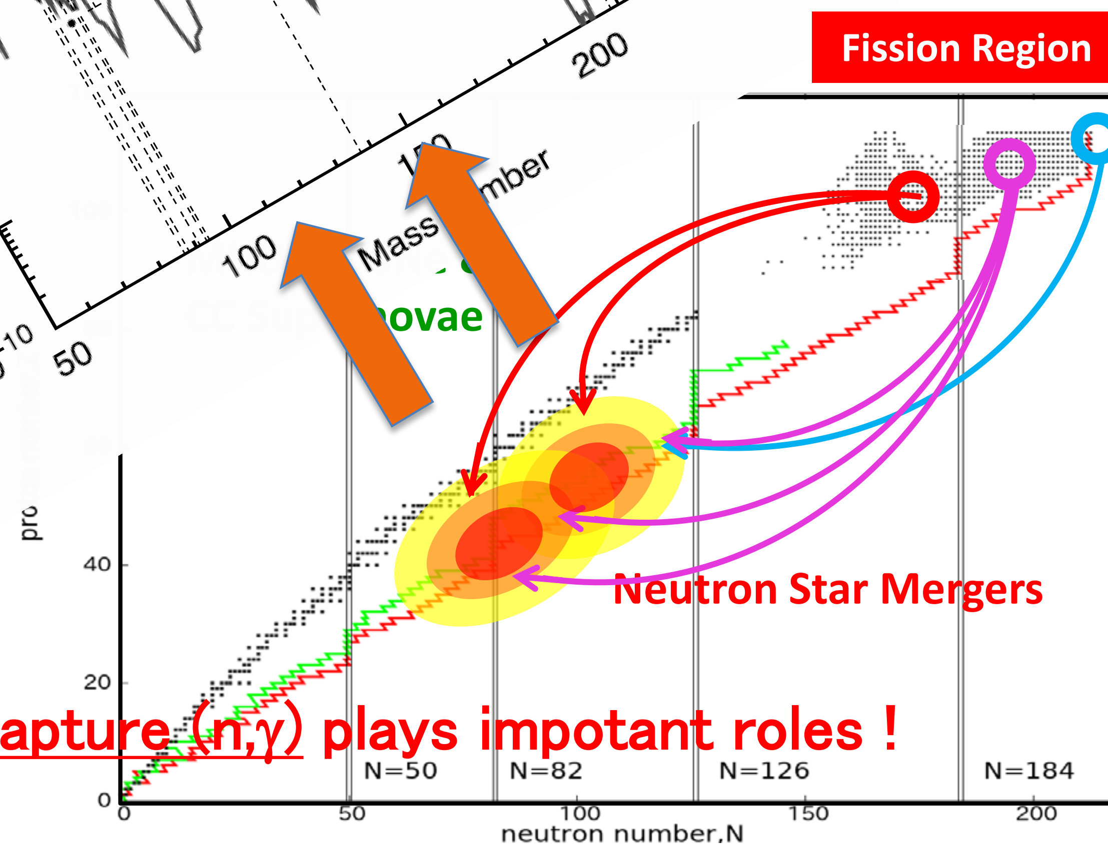


…ld operate!

…ibution

…e, France, (2007)

…8).



Bimordial or Trimodal F…

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

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

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

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

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

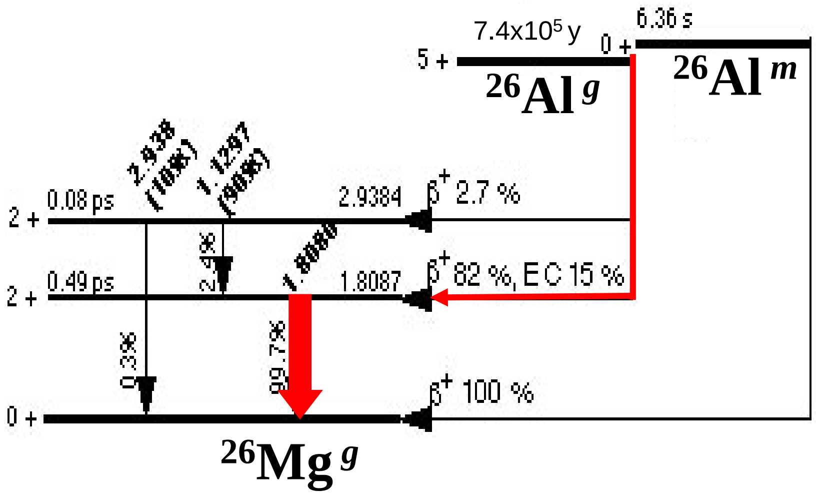
Skymap of γ-ray line Satellites (COMPTEL & INTEGRAL)

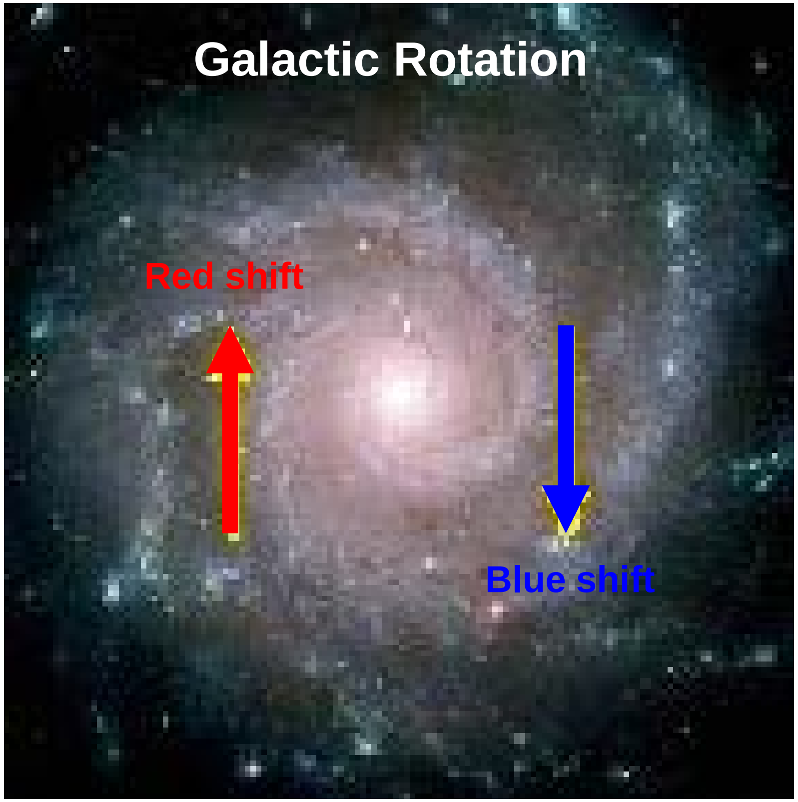
R. Diehl et al., Nature 439 (2006), 45.

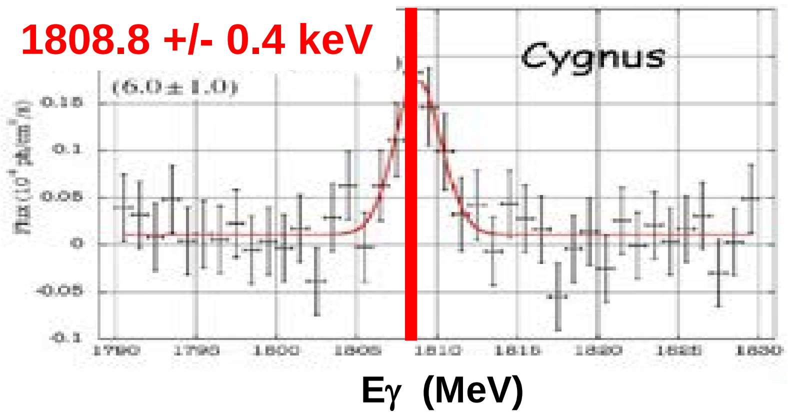
^{26}Al (5$^+$,0.72MeV; 7.4x10^5 y)

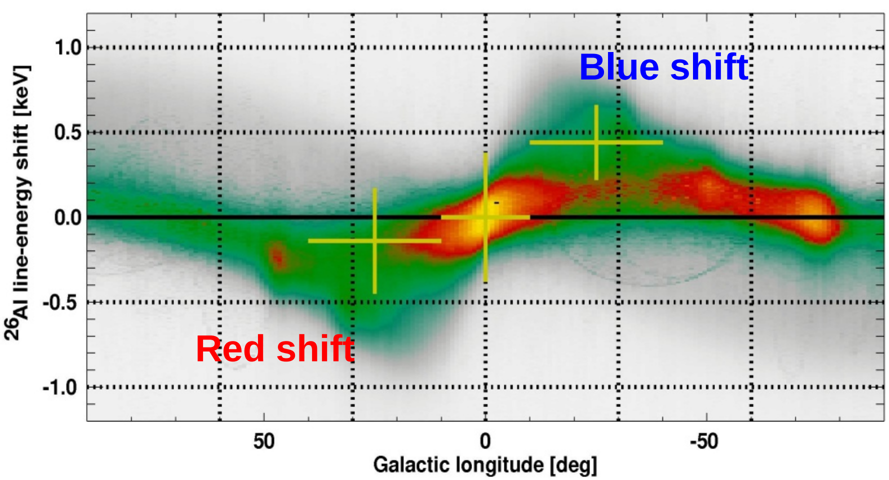
→ ^{26}Mg (2$^+$)

→ ^{26}Mg(0$^+$) + 1.809MeV









Astrophysical Implication

The total "OBSERVED" ^{26}Al gamma-ray flux in model 3D spatial distribution turns out to be 3.3(±0.4) × 10^{-4} ph $cm^{-2}s^{-1}$.

➡ **Equilibrium ^{26}Al mass = 2.8 ±0.8 Msun**

"THEORETICAL" nucleosynthesis yields in core-collapse supernovae and the preceding Wolf-Rayet phase stars:

Rauscher, T., Heger, A., Hoffman, R.D., Woosley S.E., ApJ, 576, 323 (2002)
Limongi, M., & Chieffi, A., Nucl.Phys.A, 758, 11c (2005)
Palacios, A., Meynet, G., Vuissoz, C., et al., A&A., 429, 613 (2005)
Woosley, S. E., Heger, A., Hoffman, R. D., ApJ. (2005)

➡ **Average ejected ^{26}Al/massive star = 1.4 × 10^{-4} Msun**

"SN Event Rate": Stellar yields + IMF -> independent estimate of the Galactic SFR. IMF; Scalo IMF ($\xi \sim m^{-2.7}$, m=10-120Msun)

Galactic CCSN Rate

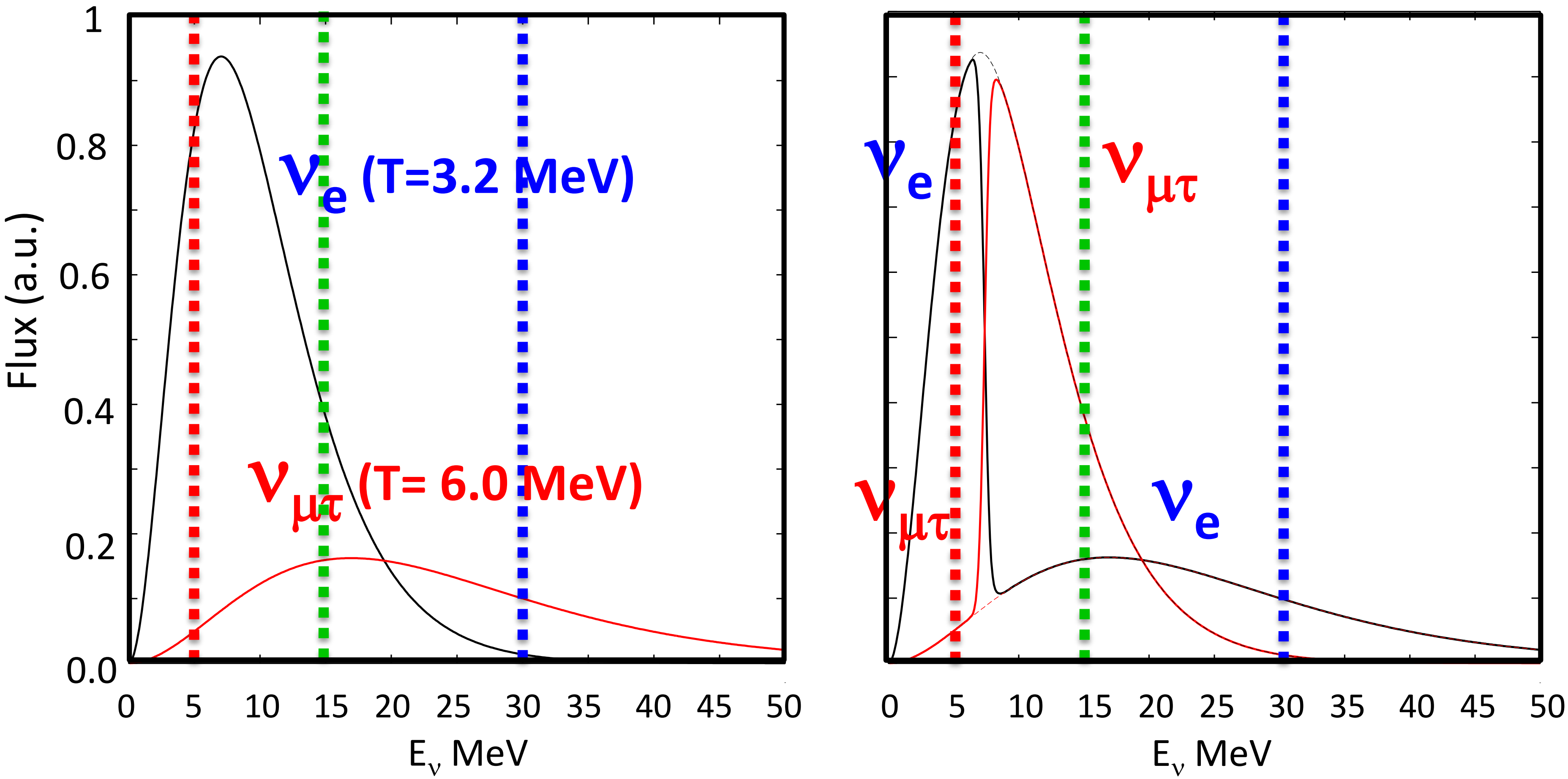
1.9 ± 1.1 /century/Milky Way

Swapped ν Energy Spectra

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

Inverted hierarchy($m_1>m_3$), Observed θ_{13} & Δm^2

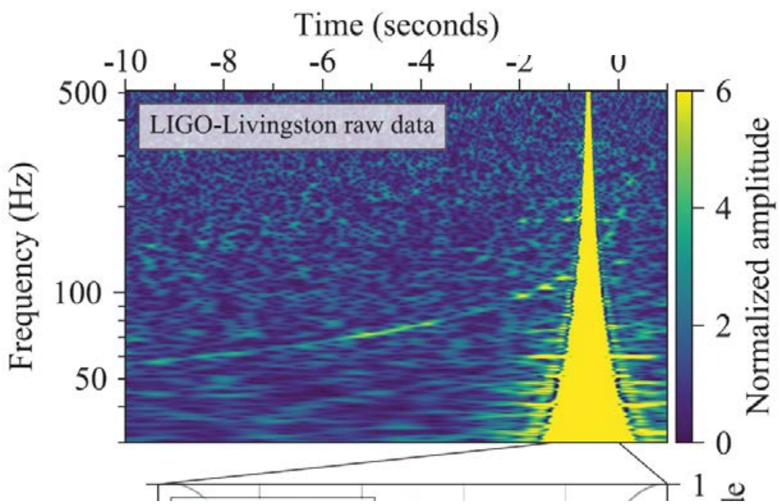
r = 10km (ν-sphere) → r=250km

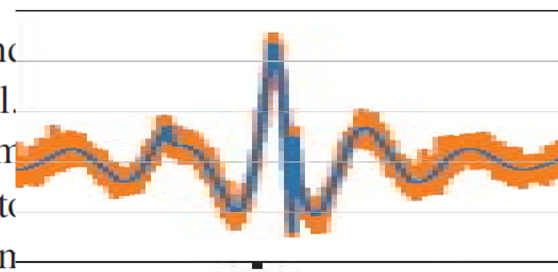


Selected for a Viewpoint in Physics
PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

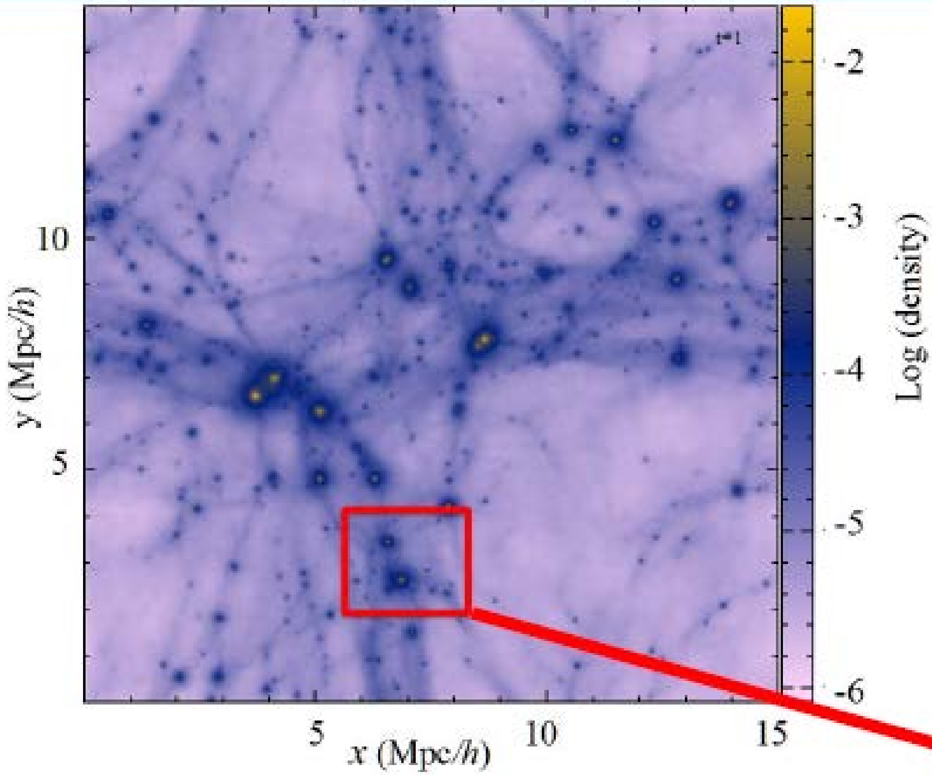
B. P. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)



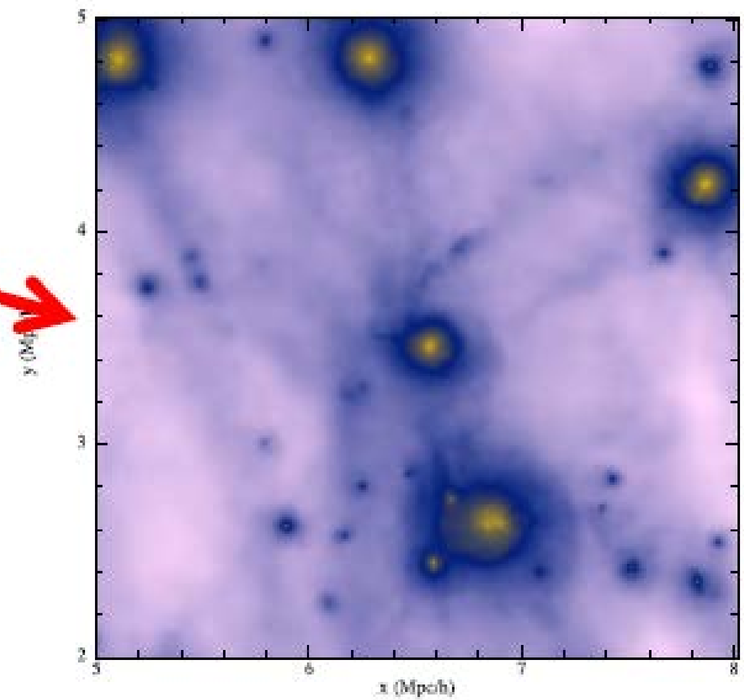


On August 17, 2017 at 12:41:04 UTC the Advanced LIGO anc ave
etectors made their first observation of a binary neutron star inspiral. tec
ith a combined signal-to-noise ratio of 32.4 and a false-alarm pe
.0 × 10^4 years. We infer the component masses of the binary t , i
greement with masses of known neutron stars. Restricting the con l i
inary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass o
e system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and
ad a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal
et. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the
oalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a
nk between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts
cross the electromagnetic spectrum in the same location further supports the interpretation of this event as
neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides
sight into astrophysics, dense matter, gravitation, and cosmology.

Hierarchical Galaxy Formation Scenario



Arrival of r-process material in Milky Way halo requires Chemo-Dynamical Evolution



X. Zhao & G. Mathews (2014)

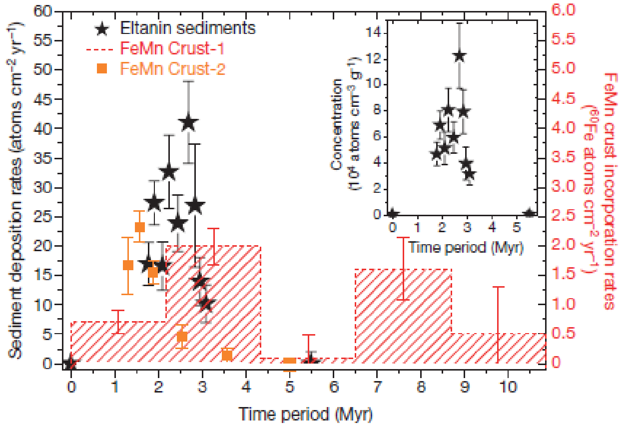
Deep Sea Sediments & EMPS points DUALITY of SN & NSM

^{244}Pu/^{60}Fe in Earth's Deep Sea Sediments → NSM/MHDJ : SNe = 1 : 100

NSM, ~~MHDJ~~ — **^{244}Pu(80.8 My)**: Wallner et al., Nature Comm. 6 (2015), 1-9; NPA8 (2017)

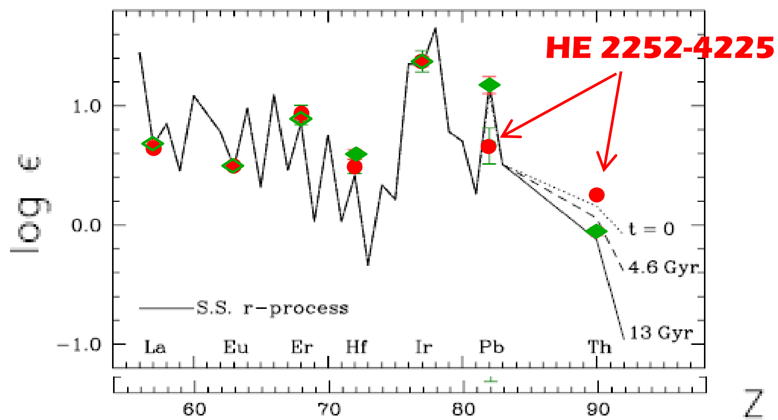
ν-DW — **^{60}Fe(2.62 My)**: Wallner et al. N

Over 25 My

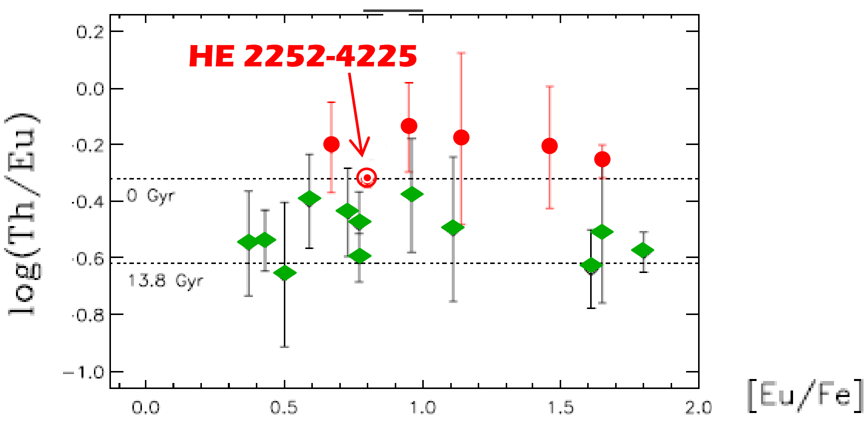


Actinide Boost EMP Stars needs "Fission-Recycling R-process in NSMs".

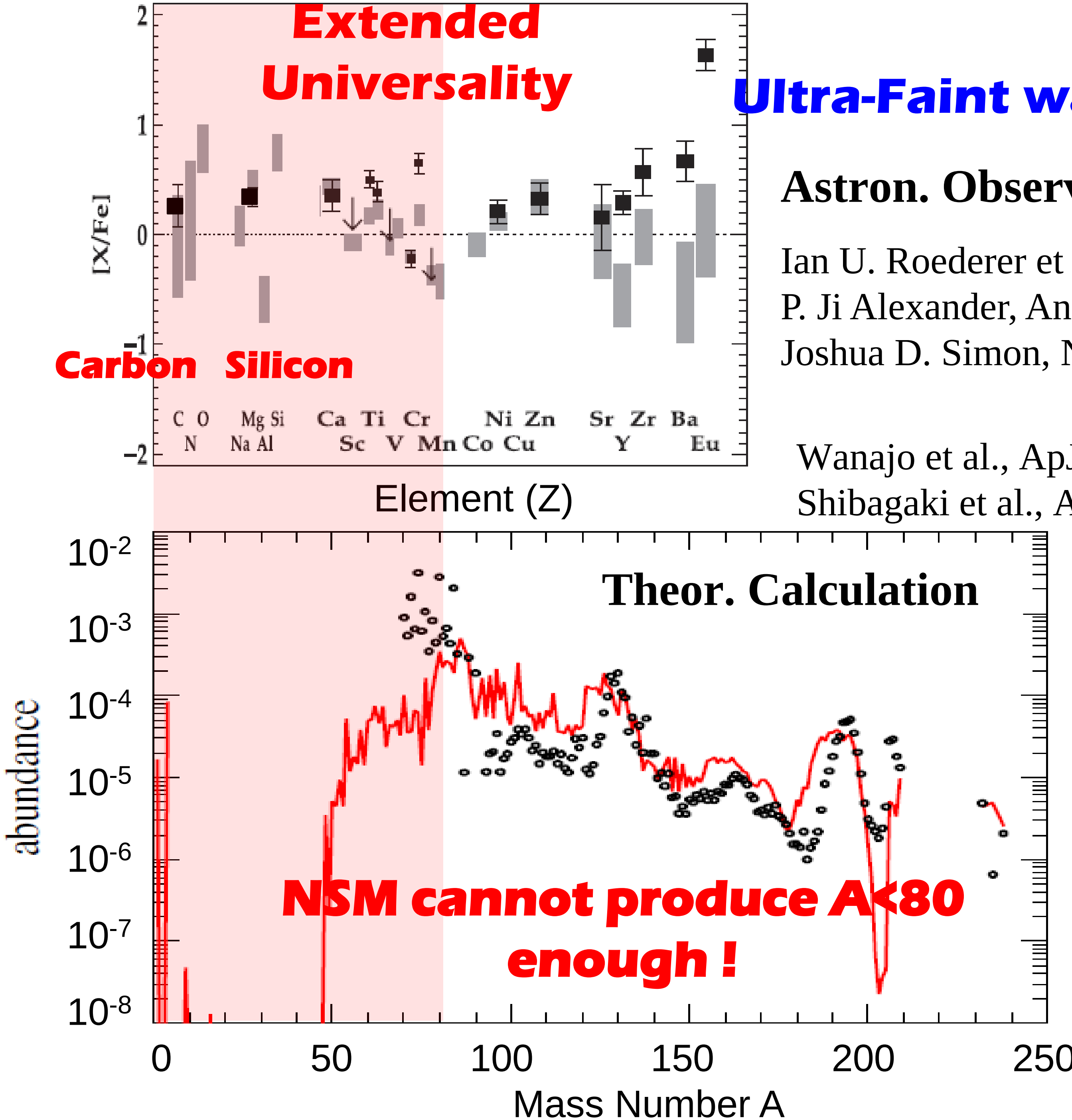
Mashonkina et al. A&A 569, A43 (2014)



Roederer et al. ApJ 698, 1963 (2009)
Hill et al., arXiv:1608.07463v1



Ultra-Faint warf Galaxy: Ret. II



Astron. Observation

Ian U. Roederer et al., ApJ. 151 (2016), 82;
P. Ji Alexander, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610.

Wanajo et al., ApJ. 789 (2014), L39.
Shibagaki et al., ApJ. 816 (2016), 79; (2017)

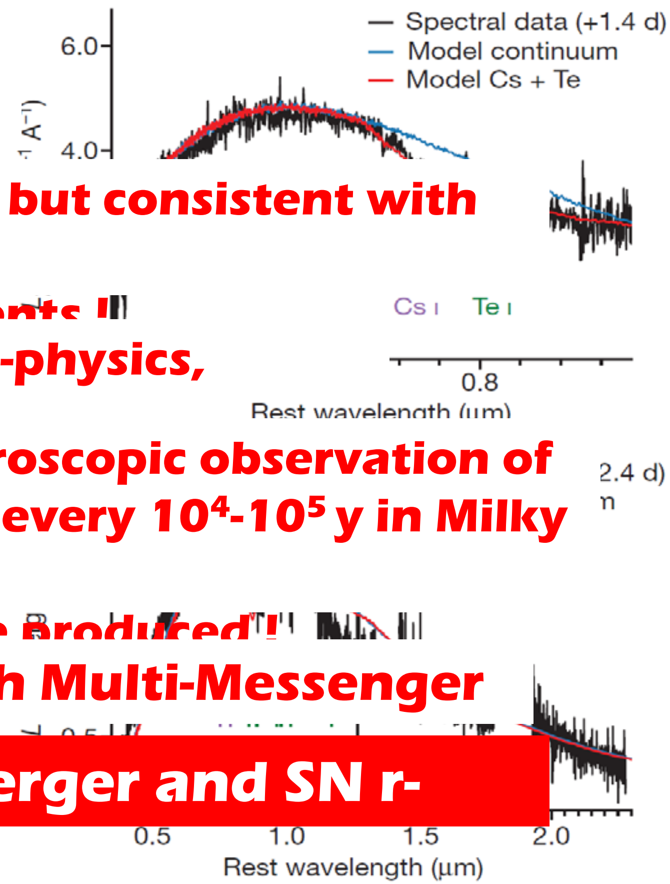
Goriely, et al., ApJ 738, L32 (2011); Korobkin, et al., MNRAS 426, 1940 (2012); Bauswein, et al., ApJ 773, 78 (2013); Rosswog, et al., MNRAS 430, 2585 (2013); Goriely, et al., PRL 111, 242502 (2013), (2015): Piran, et al., MNRAS 430, 2121 (2013).

GW170817

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

- GW170817 (LIGO-Virgo) : $0.86 < M/M_{\odot} < 2.26$
- GRB170817A (Fermi-GBM) : 1.7 s
- Optical and Near-infrared : SSS17a
  r-process elements! Non of the elements, identified.
- X-rays & Radio waves
  Remnant NS or BH, not identified.
- No ν–Signal: 10^{-6} weaker than SN1987A
  (1.6×10^5 ly)

GW170817 – SSS17a
Smartt et al. Nature, 551, 75 (2017)



- **GW ! Ring down → EOS to be clarified !**
- **Photon emissions, not by ^{56}Ni or ^{44}Ti, but consistent with probably radioactive decays of r-process elements !**
- **Neutrino signals, wanted ! No micro-physics, clarified !**
- **No element, identified → Need spectroscopic observation of nearby neutron star merger (once in every 10^4-10^5 y in Milky Way) to identify which heavy-elements are produced !**

Dawn of Nucl.-Particle Astrophys. with Multi-Messenger Astronomy !

Purpose → Difference between Merger and SN r-

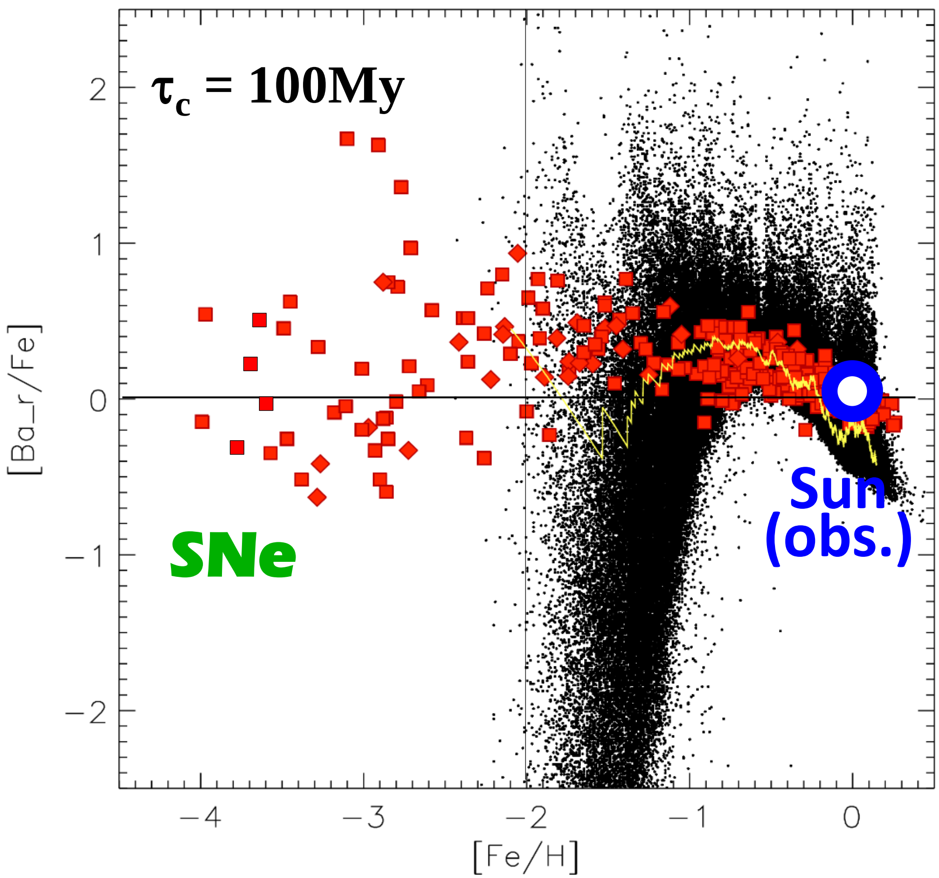
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

SNe = Metals ; NSM(τ_c=100My)= r-process elements.
Star forming condition, n_H >100 cm^{-3} → ~ 10-100pc)

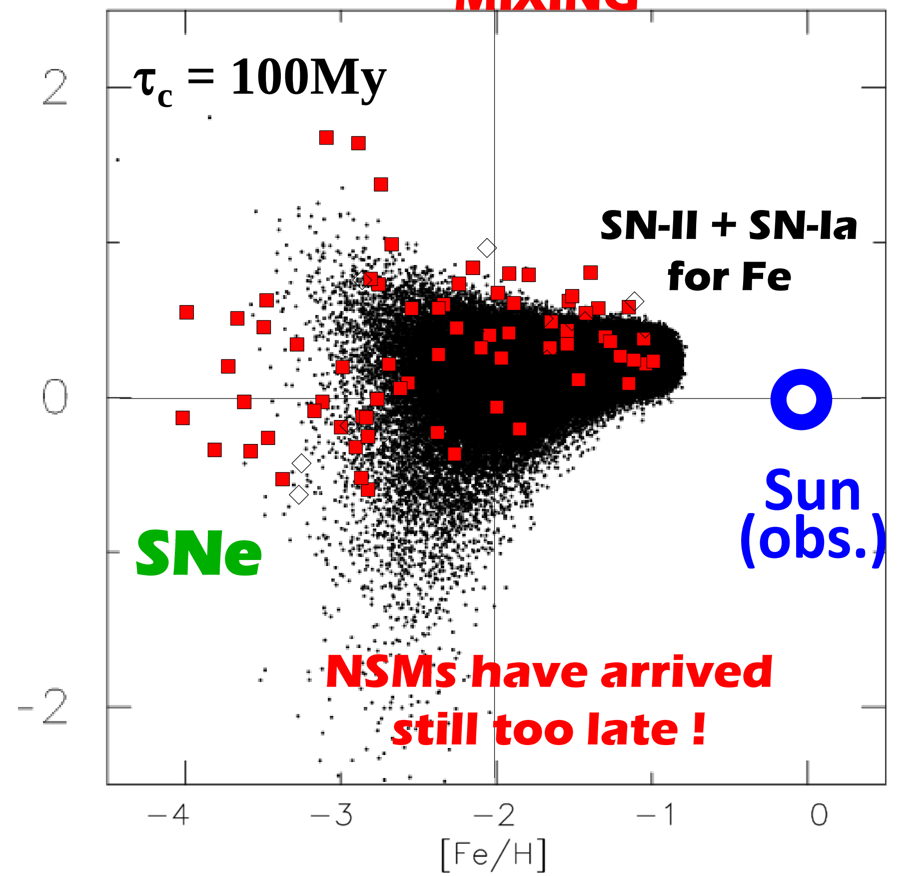
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

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

Without Dynamics & GAS MIXING



With Dynamics & GAS MIXING



Colloquium at T. D. Lee Institute, SJTU, Dec. 12, 2017

Impact of Neutron Star Merger vs. Supernova Nucleosynthesis and Neutrino Physics

Taka KAJINO 梶野敏貴

北京航空航天大学
大爆炸宇宙学与元素起源国**际交叉**研究中心

東京大学大学院天文学専攻
日本国立天文台

My Spirits

Legacy Spirits from William A. Fowler (1983, Nobel Laureate)

Seek for truth, Work hard, play hard, and help people !

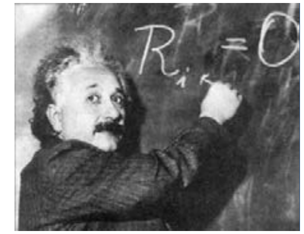
宇宙の始まりと宇宙背景放射

1914年　一般相対性理論、宇宙方程式 の提唱

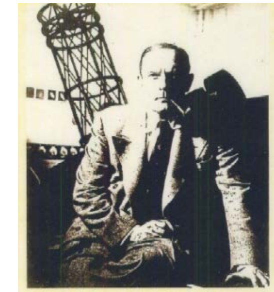
1917年　定常宇宙実現のため宇宙項を導入

1929年　互いに遠ざかる銀河を発見

宇宙項を撤回：生涯最大の過ち！(A. アインシュタイン)



A. アインシュタイン



E. ハッブル

1948年　火の玉宇宙の名残・宇宙背景放射、
17年前　ビッグバン元素合成の予言

1965年　火の玉宇宙の名残・宇宙背景放射を発見

1992年　宇宙背景放射の温度揺らぎを発見

1998年　加速膨張する宇宙を発見

G. ガモフ

A.　ペンジャス
B.　R. ウィルソン

G. スムート

J. マザー

S. パールマター

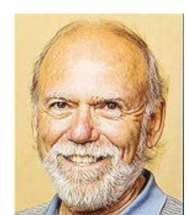
B. シュミット

A. リース

2015年　ブラックホール合体からの
重力波を検出

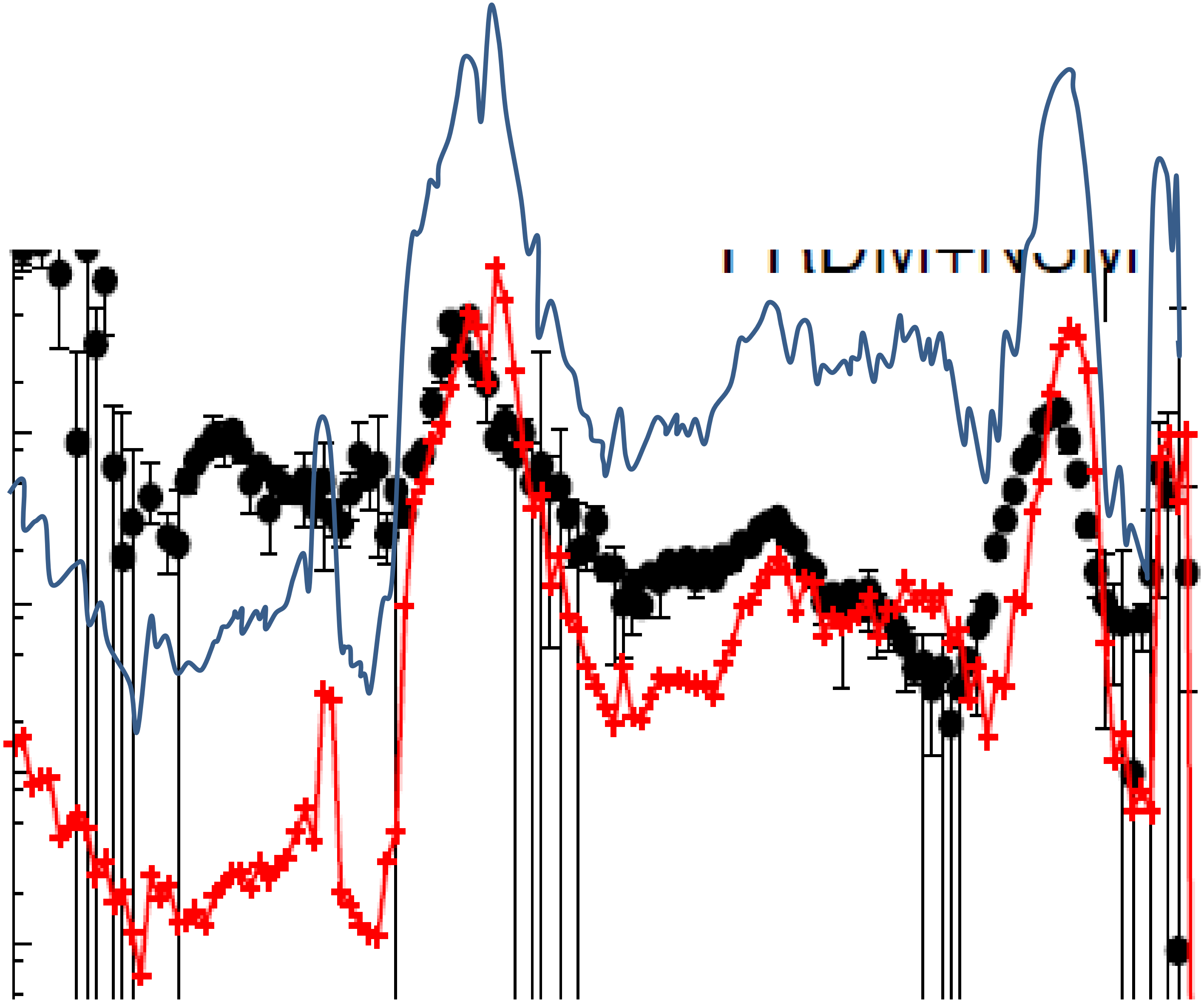
1915年の理論予言！(A. アインシュタイン)

R. ワイス



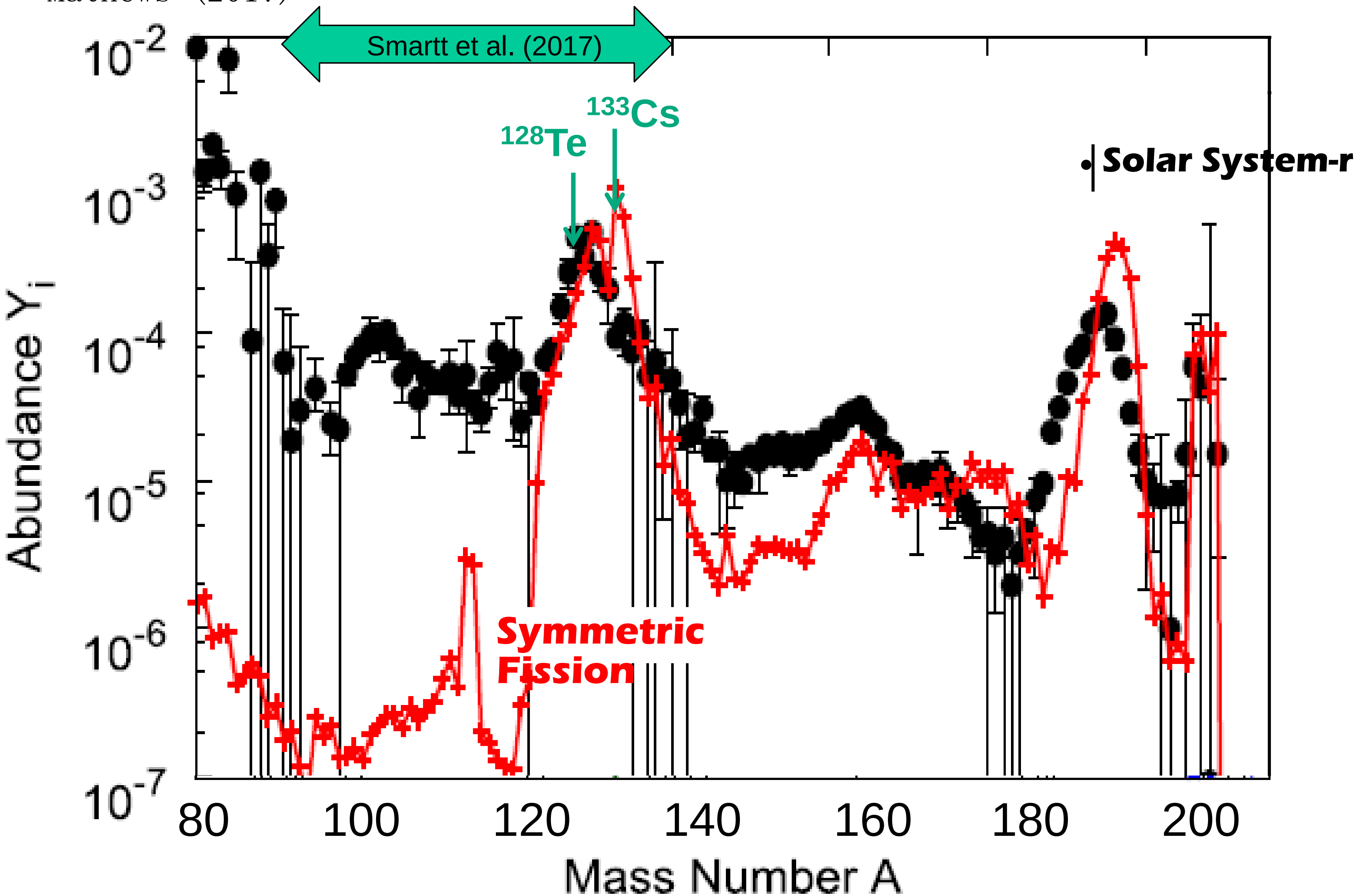
B. C. バリッシュ

K. S. ソーン



Challenge of Nucear Physics — Fission & Mass Formula

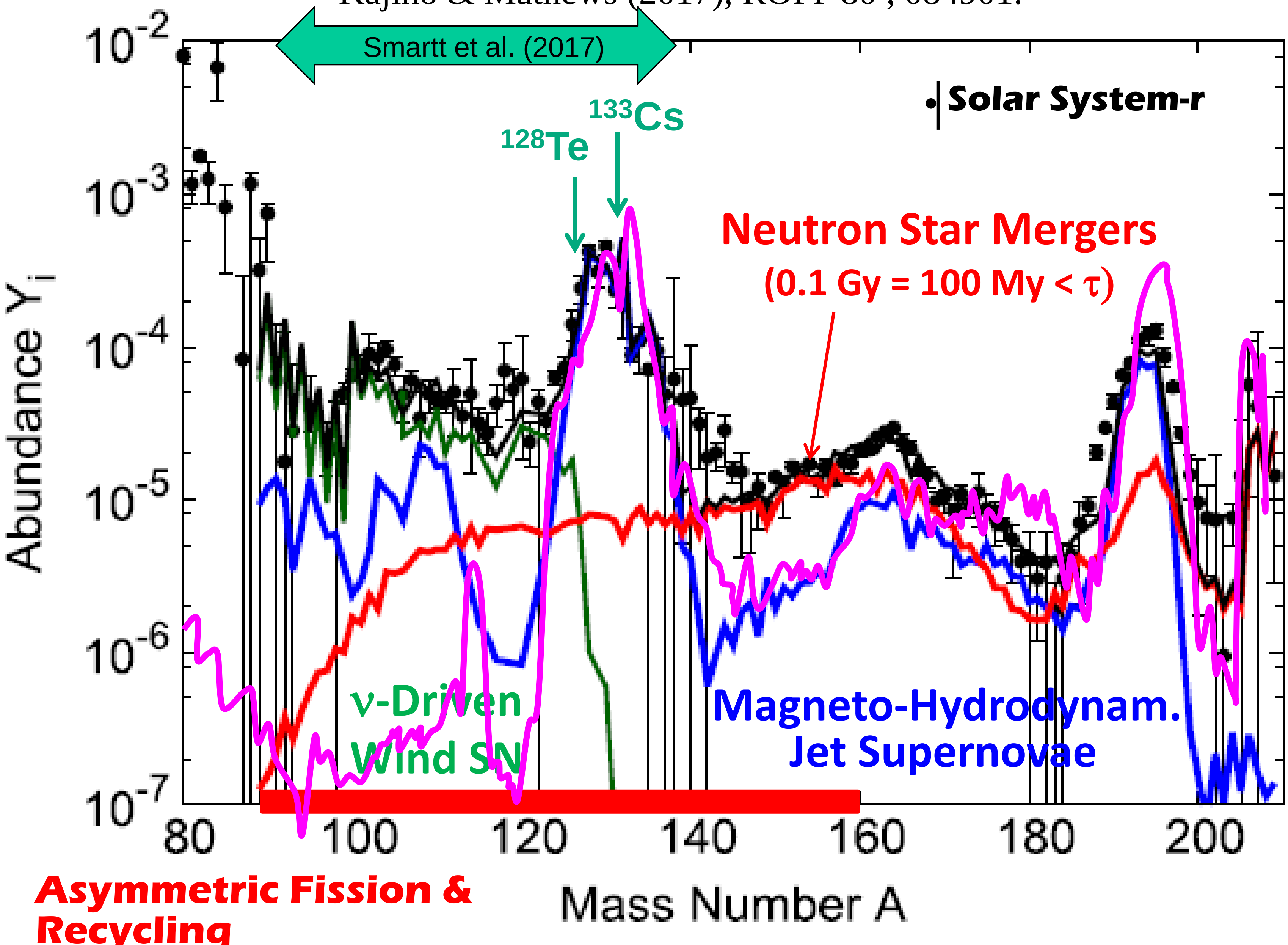
Mass Formula: FRDM (Moeller & Kratz)　　Shibagaki, Kajino, Mathews (2017)



Solar System r-Process Abundance

Present time: t =

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



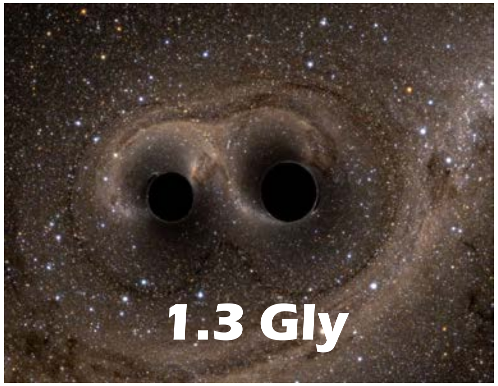
GW150914
Abbott et al. (LIGO-Virgo Coll.)
PRL 116, 061102 (2016)

GW170817
Abbott et al. (LIGO-Virgo Coll.)
PRL 119, 16101 (2017)

A. Einstein predicted in 1915:
Distortion of space-time due to asymmetric, catastrophic phenomena could propagate as a gravitational wave.

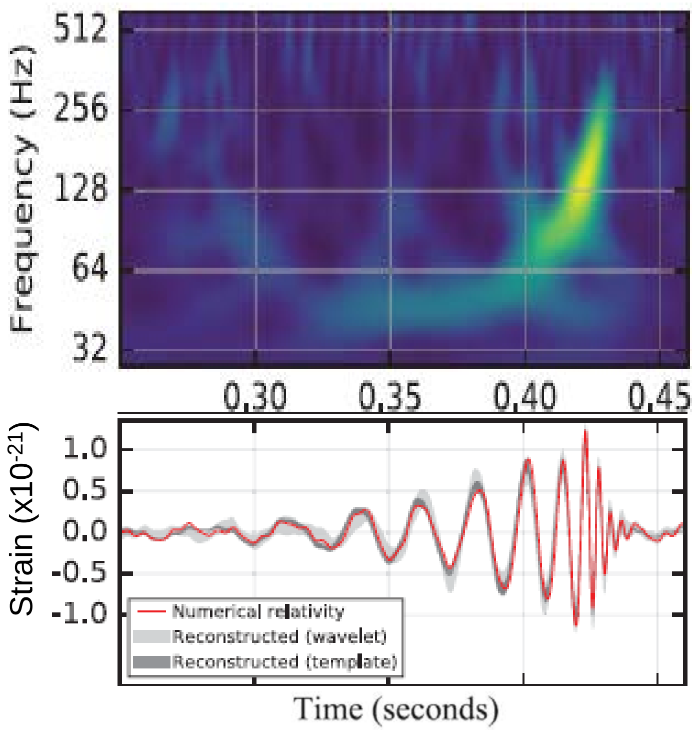
Abbott et al. (LIGO-Virgo Collaboration)
Phys. Rev. Lett. 116 (2016), 061102.

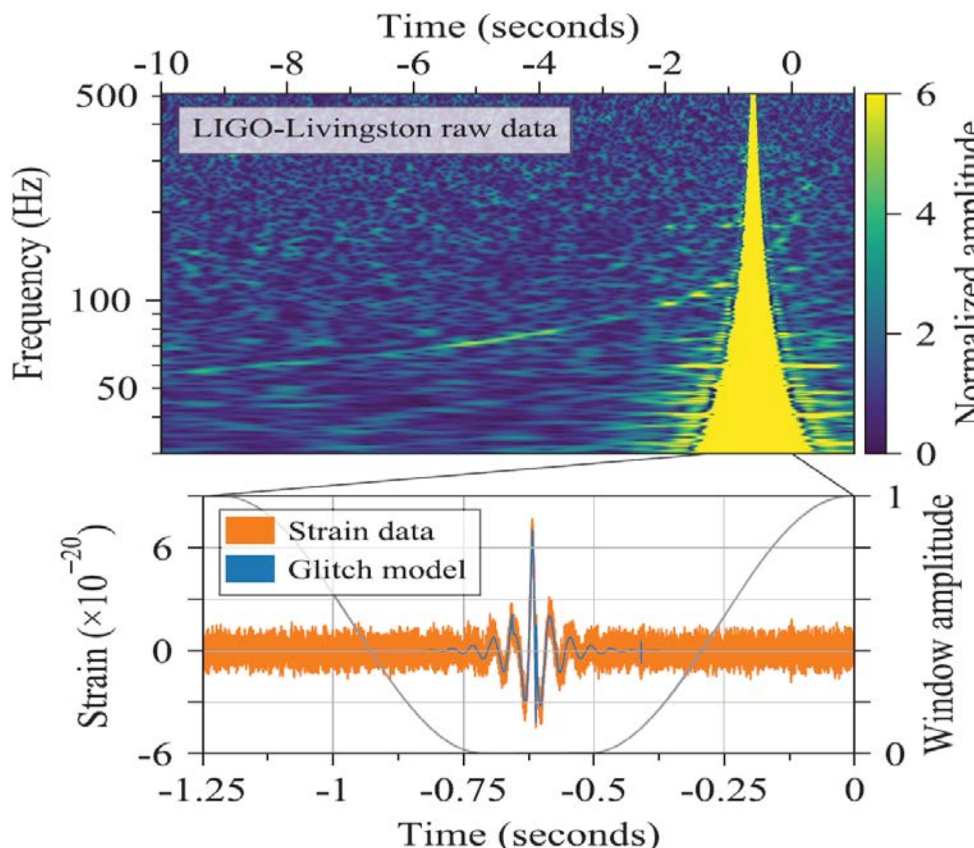
Black Hole Merger
GW150914 @1.3 Gly

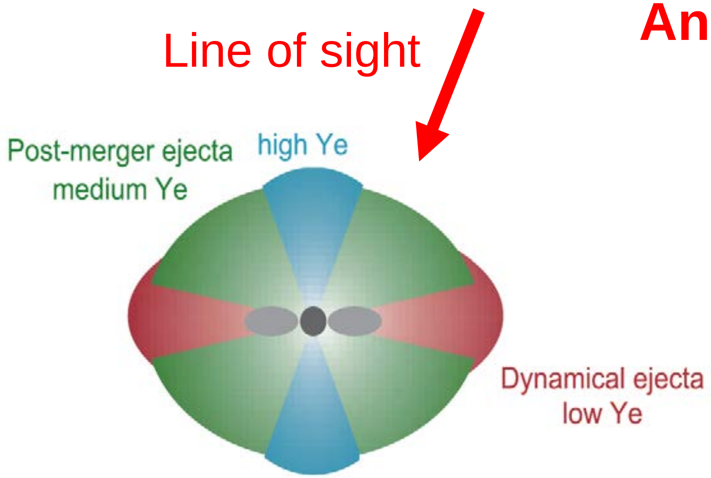


GW150914
Abbott et al. (LIGO-Virgo Coll.)
PRL 116, 061102 (2016)

GW170817
Abbott et al. (LIGO-Virgo Coll.)
PRL 119, 16101 (2017)





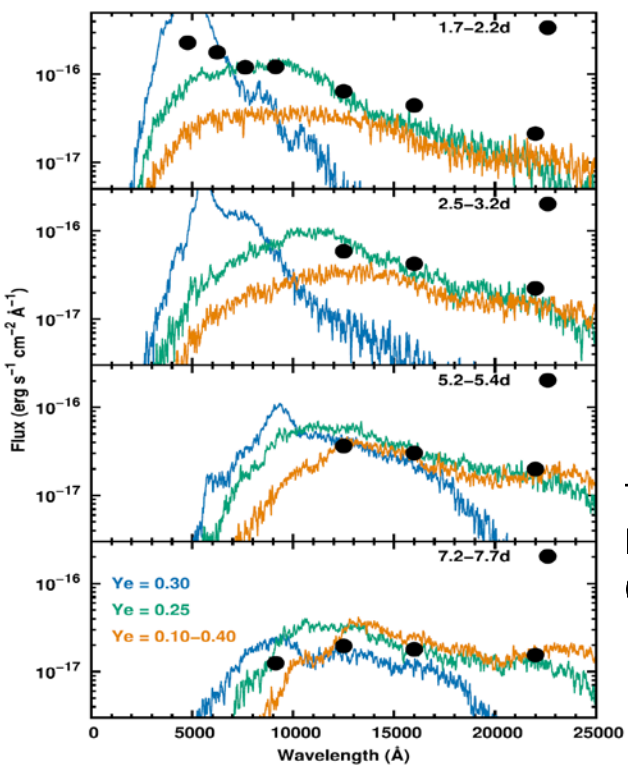


Analysis, based on Too Complicated Geometry, Hydro-Dynamics & Configurations

→ Results are quite Uncertain.

- ◆ Line of sight → Y_e, r-process ?
- ◆ Ejecta velocity → Blue shifted spectrum ?
- ◆ Incomplete & Limited Opacity → α, β, γ, fission ?

→ Element Identification, extremely Difficult.

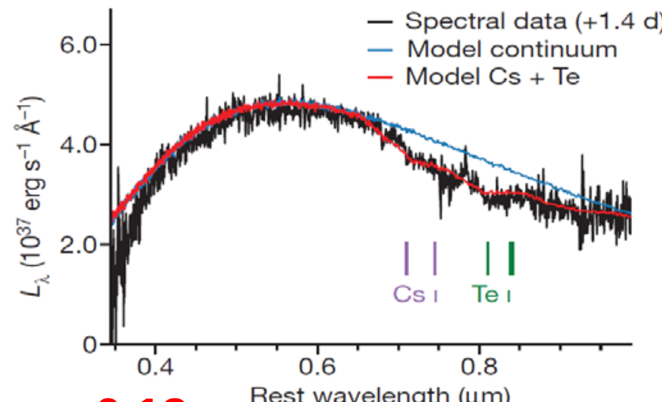


Tanaka et al.
PASJ 00, 1-7
(2017)

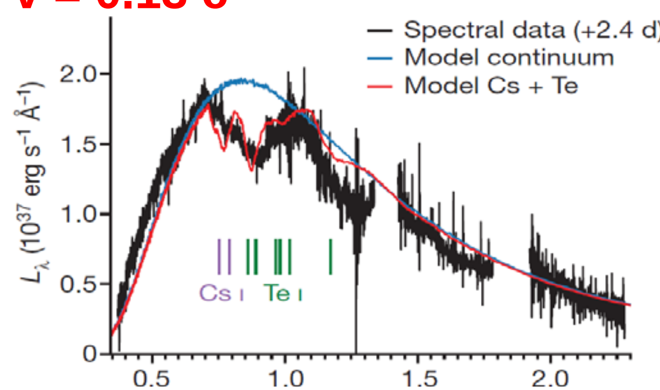
SSS17a

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

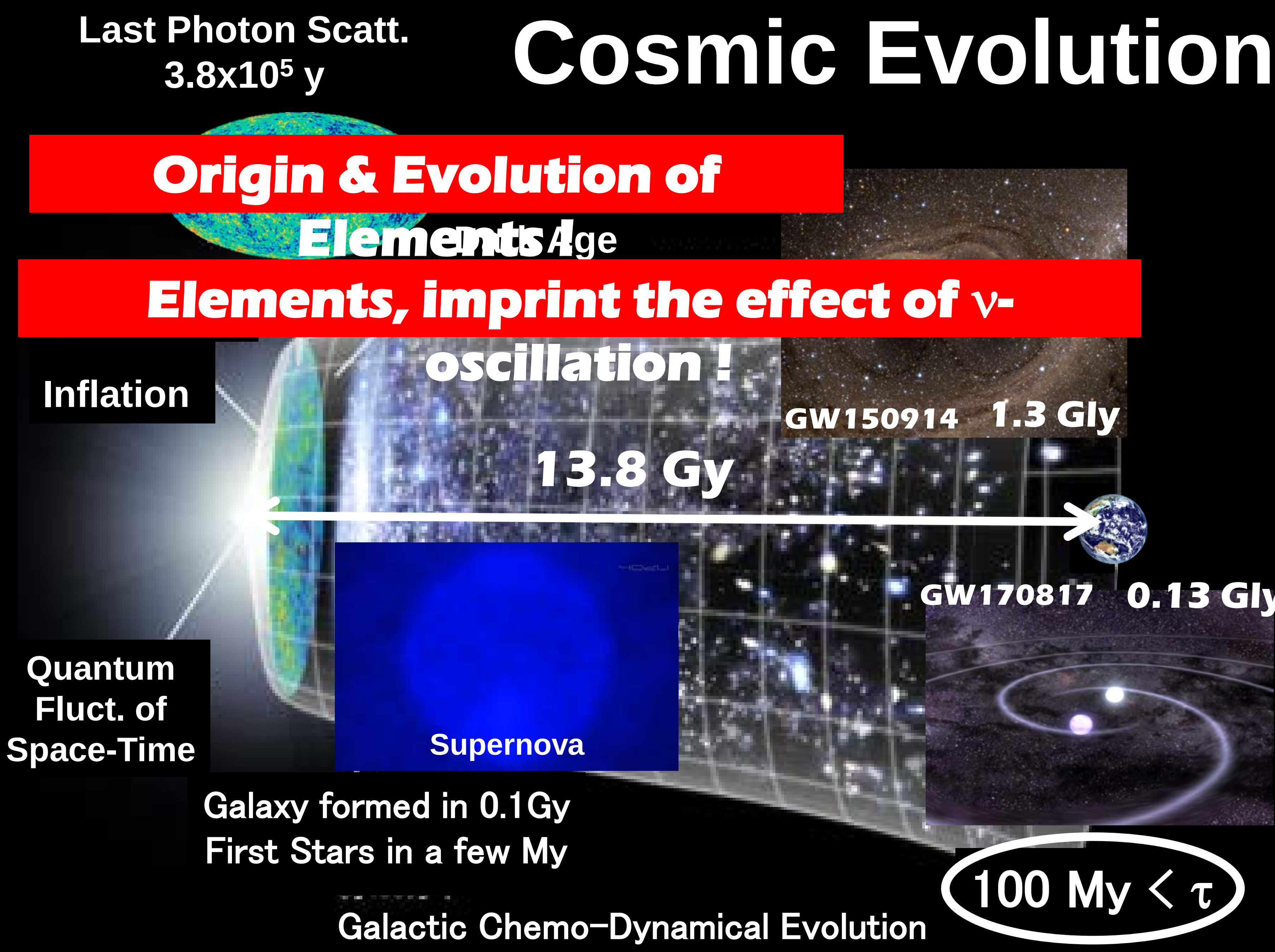
v = 0.2 c

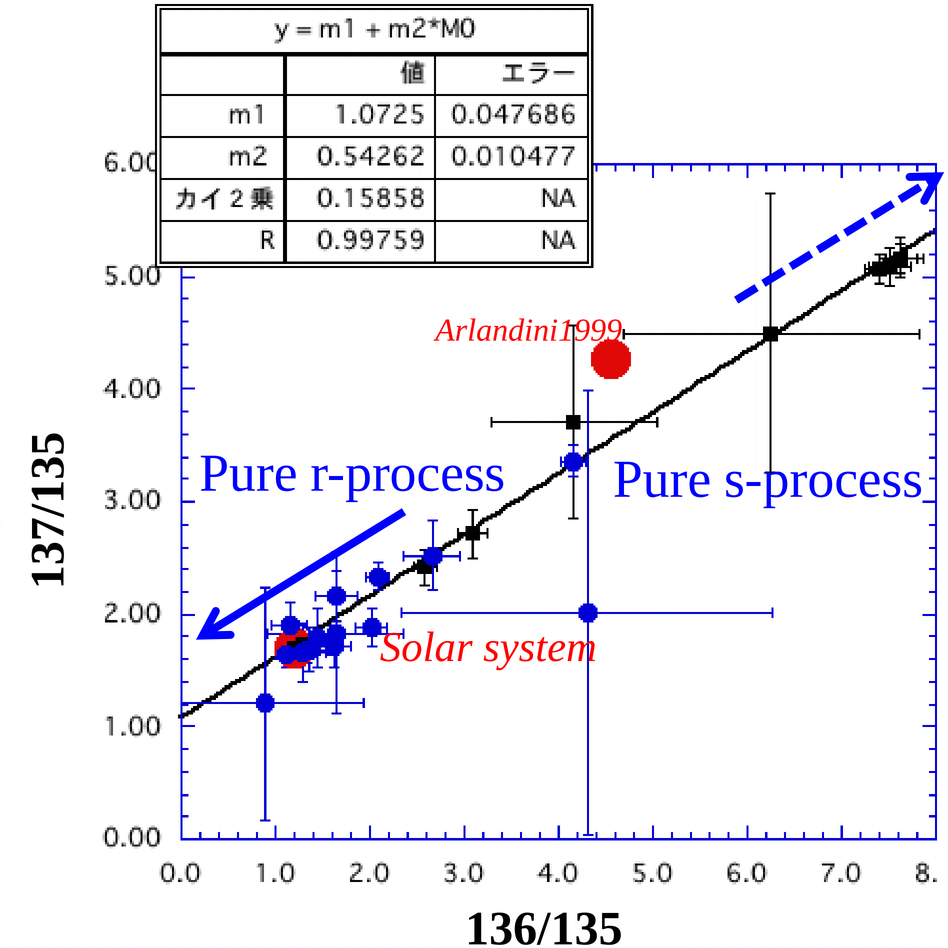


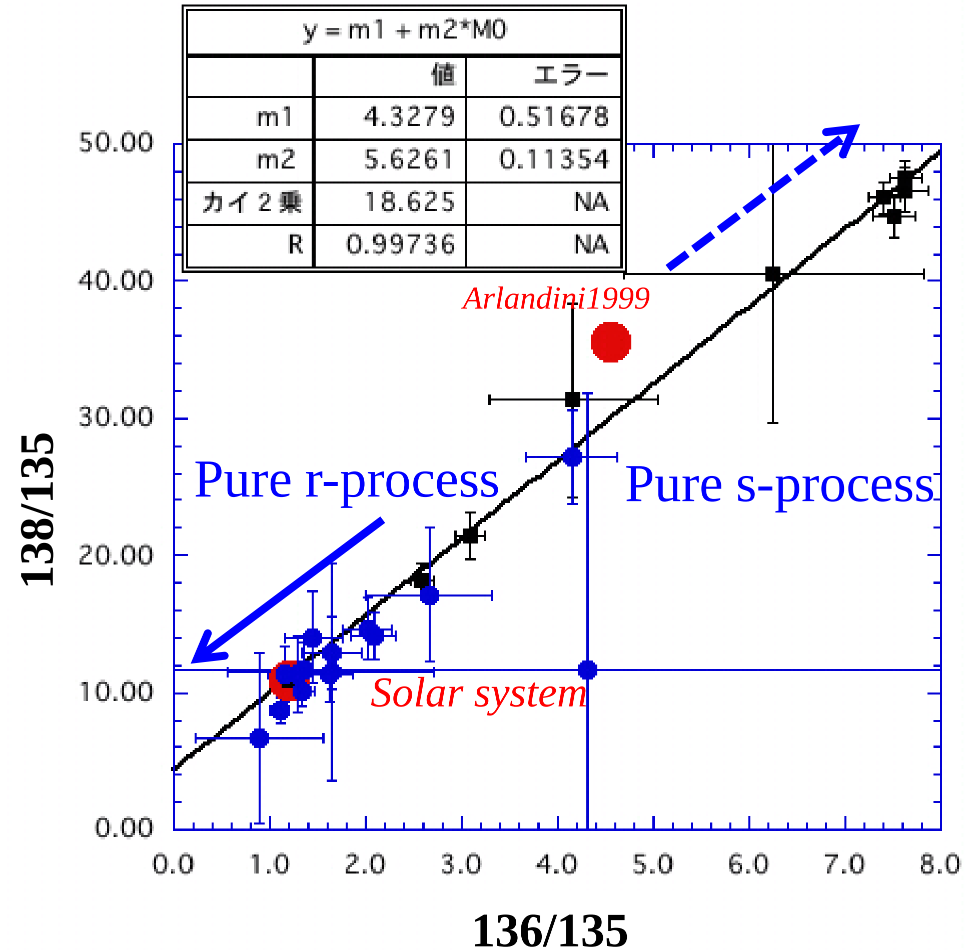
v = 0.13 c



Cosmic Evolution







Meteorite (Terada et al. 2017)

^{136}Ba=s-only: In the limit of ^{136}Ba→0, pure r-component is extracted.

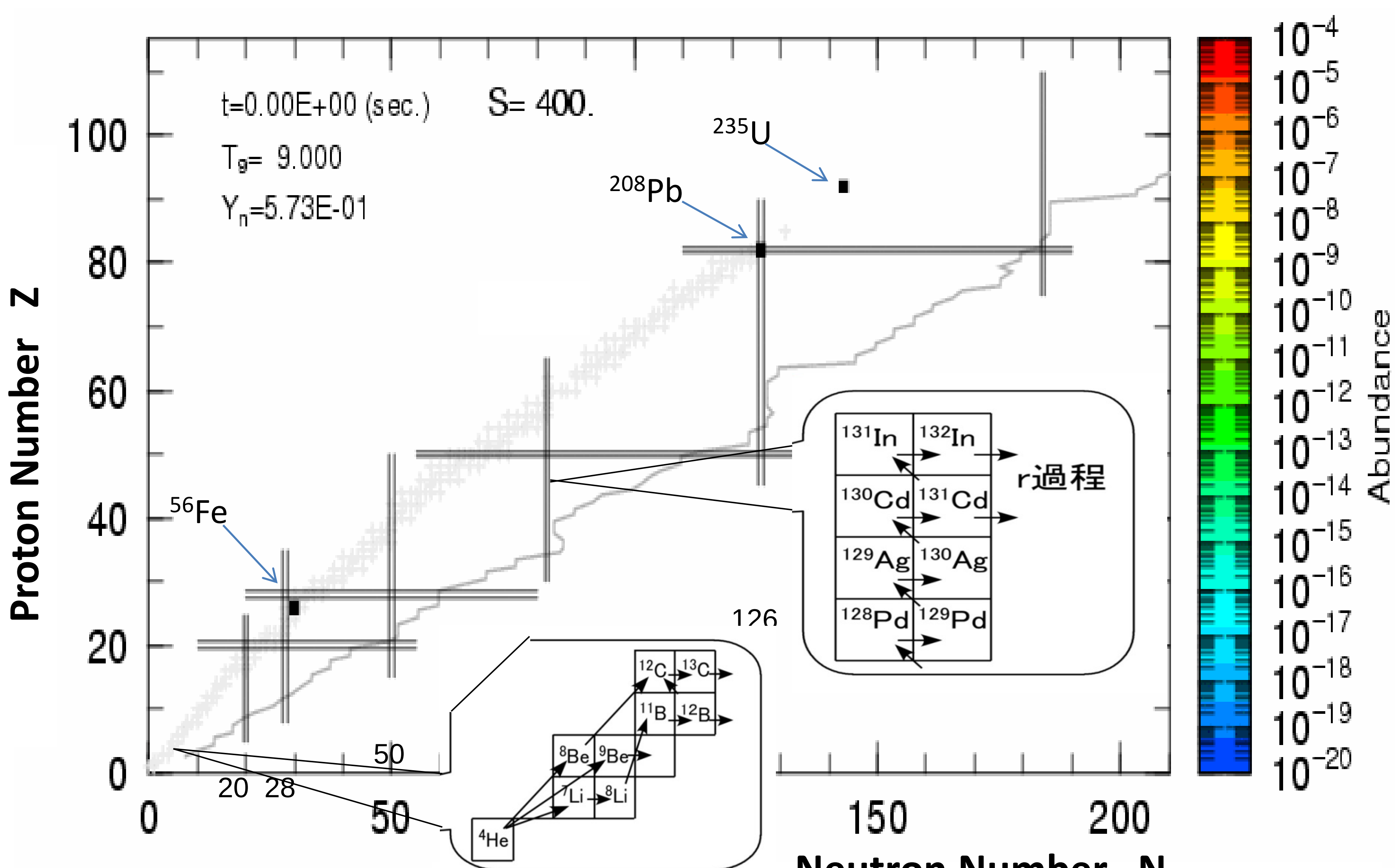
Isotopic ratios	Wanajo et al et al. (2014) **NSM**	Giuseppe et al. (2015) **ν–DW**	Shibagaki et al. (2016) **NSM**	**MHD-jet**
137/135=1.07 ± 0.05	**0.218**	**2.23**	**1.0**	**0.2**
138/135=4.33 ± 0.52	**0.294**	**3.46**	**1.1**	**0.18**

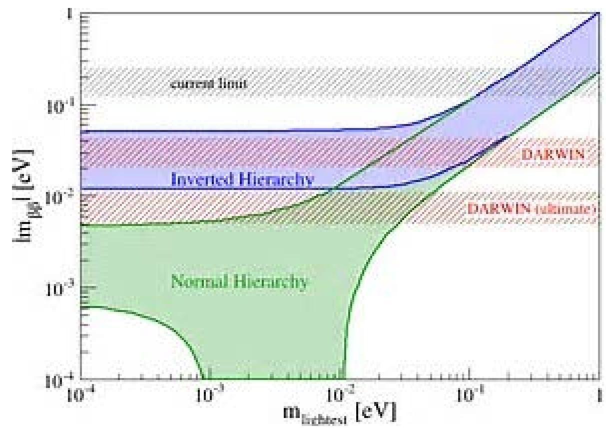
ν−Wind Supernova

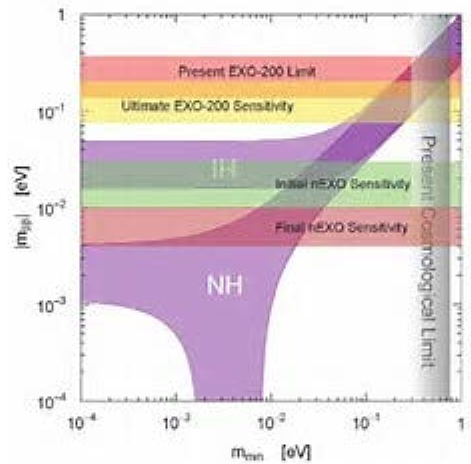
$\tau_\nu < \tau_{dyn}$

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

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




current limit
Inverted Hierarchy
DARWIN
DARWIN (ultimate)
Normal Hierarchy
$|m_{\beta\beta}|$ [eV]
$m_{lightest}$ [eV]

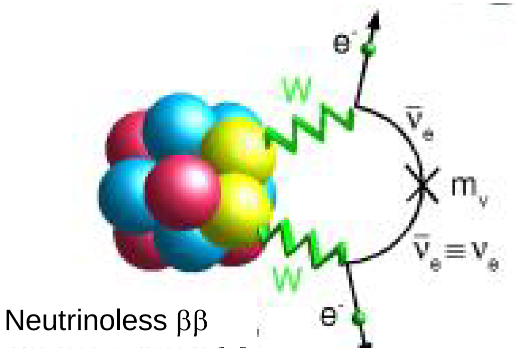

Present EXO-200 Limit
Ultimate EXO-200 Sensitivity
IH
Initial nEXO Sensitivity
Final nEXO Sensitivity
NH
Present Cosmological Limit
$|m_{\beta\beta}|$ [eV]
m_{min} [eV]

ν-Mass, constrained from Nuclear Physics and Cosmology

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

  $|\sum U^2_{e\beta} m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen (2012)

  ⟶ 0.05〜0.1 eV in the future

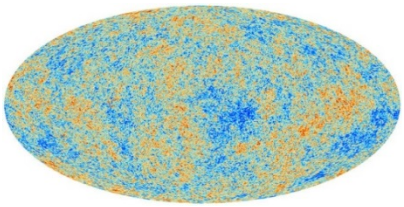


- **CMB Anisotropies + LSS**

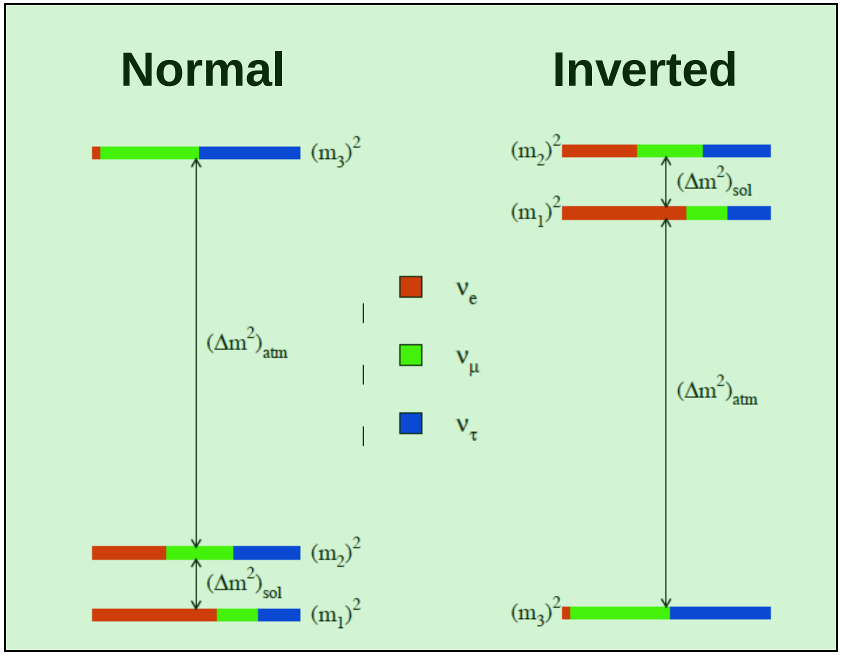
  $\sum m_\nu < 0.14 – 0.17$ eV (95%C.L.): WMAP-7yr + Planck + BAO + HST + SZ (2015-16)

  < 0.2 eV (2σ, B_λ<2nG): + Magnetic Field

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



Planck 2013



ν−Oscillation Physics

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

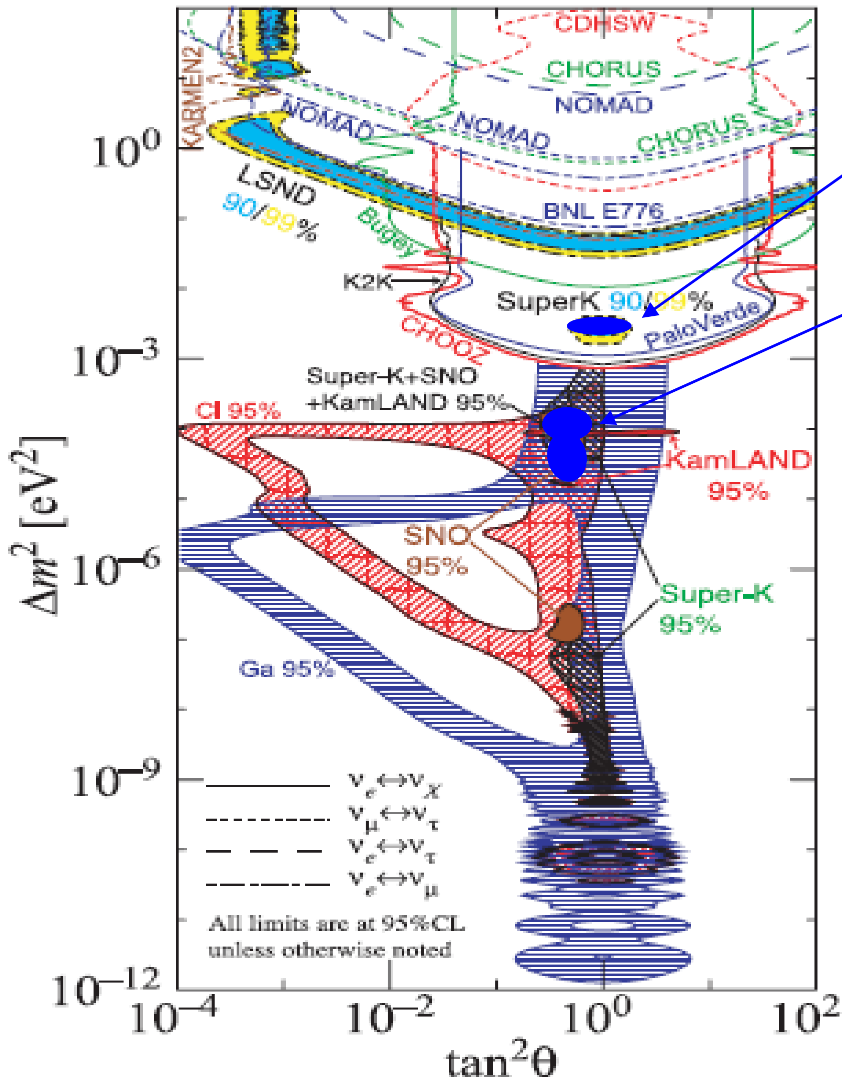
$$|\Delta m^2_{23}| = 2.4 \times 10^{-3}\ \text{eV}^2 = (0.05\ \text{eV})^2$$

Normal: $\Sigma m_\nu \sim 0.05$ eV !

Inverted: $\Sigma m_\nu \sim 0.1$ eV !

The “KNOWN” in Neutrino Oscillations

KAMIOKANDE, SK, KamLand (reactor ν), SNO determined
Δm_{12}^2 and θ_{12} uniquely: SK (atmospheric ν) determined
Δm_{23}^2 and θ_{23} uniquely.



23－mixing

$\sin^2 2\theta_{23} = 1.0$

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

12－mixing Cabibbo angle

$\sin^2 2\theta_{12} = 0.816$ $(\theta_{12}+\theta_C=\pi/2)$

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

“3 UNKNOWN”

1 2 3 4

13-mixing, hierarchy, ~~δ_{CP}, mass~~

- $\sin^2 2\theta_{13} = 0.1 \pm 0.02$
  T2K, MINOS, RENO, Daya Bay, Double Chooz
- $\Delta m_{13}^2 = \pm 2.4 \times 10^{-3}$ eV^2
- ~~δ CP violation phase~~
- ~~Absolute Mass~~ 0νββ, cosmology

E(ν_μ)=E(ν_τ): Yokomakura et al., PLB544, 286.

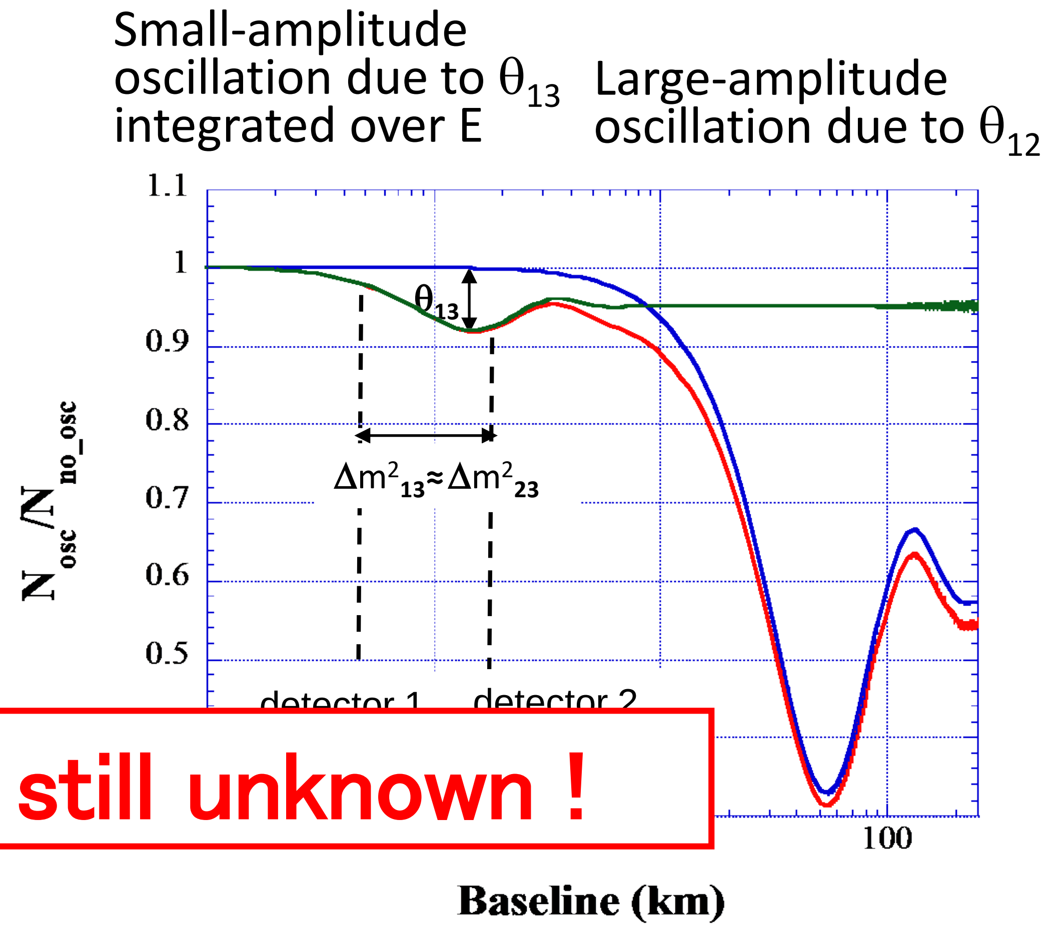
Reactor ν–Oscillation Experiments
Daya Bay, RENO, Double Chooz(2012–2017)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Measuring θ_{13} with Reactor Anti–neutrinos

$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\mathrm{st}) \pm 0.011(\mathrm{sys})$

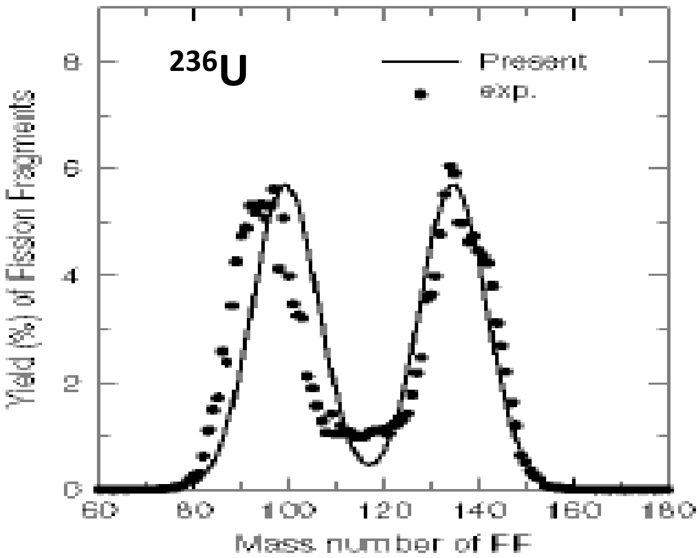
→ θ_{13} = 8.88 deg



Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).

Mass hierarchy is still unknown !

Important Nucl. Phys. in NS Mergers



◎(n, γ)reaction cross section !

◎ Fission fragment distribution !

M. Ohta et al., Proc. Int. Conf. on NDST, Nice, France, (2007)
S. Chiba et al., AIP Conf. Proc. 1016, 162 (2008).

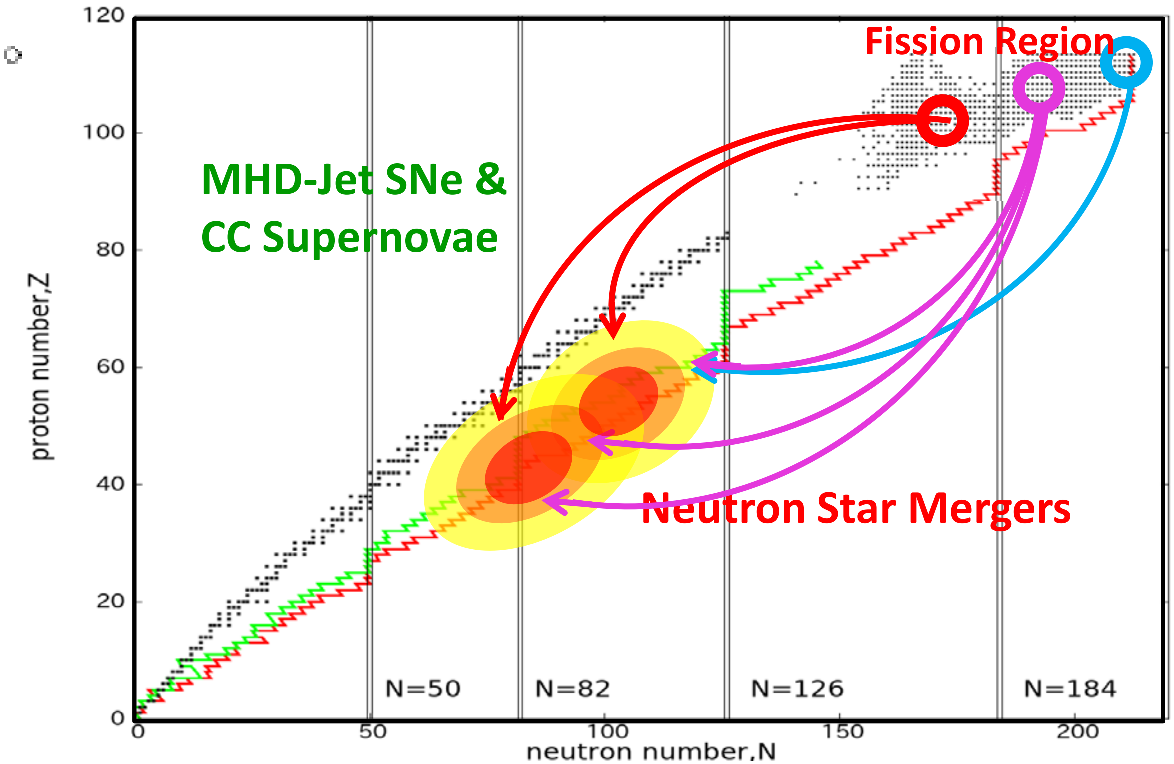
Bimordial or Trimodal FFD:

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

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

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

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



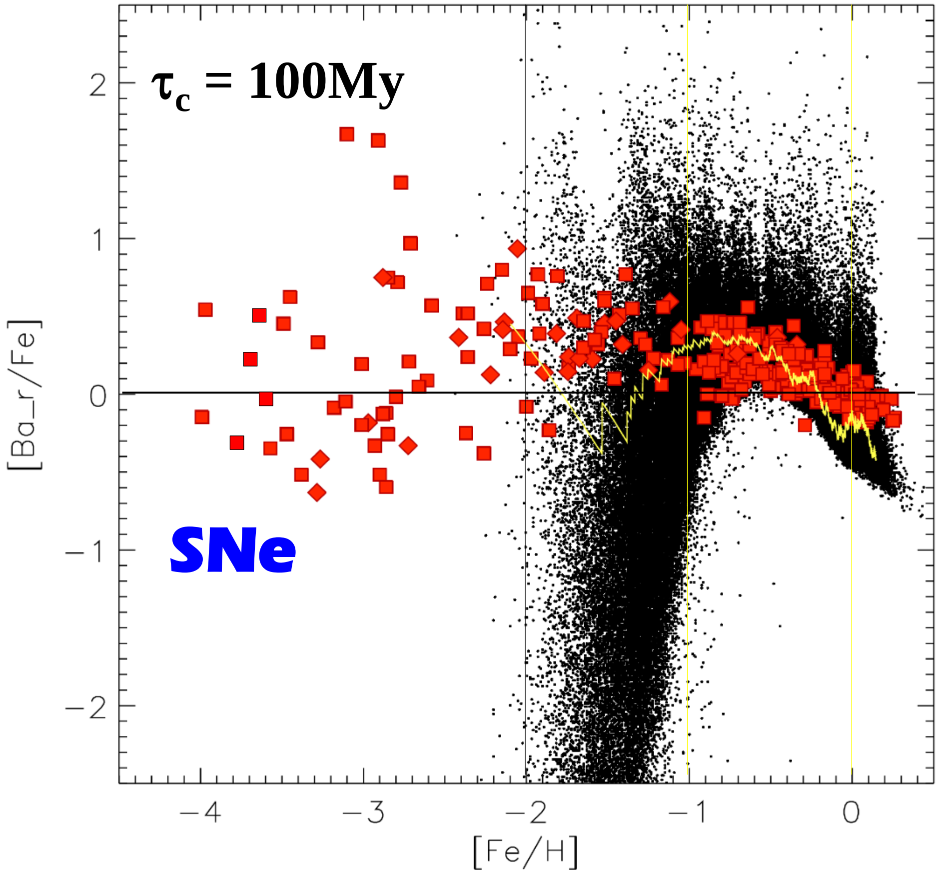
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies → Milky Way (Large Galaxy) ?

SNe = Metals ; NSM(τ_c=100My)= r-process elements.
Star forming condition, n_H >100 cm^{-3} → ~ 10-100pc)

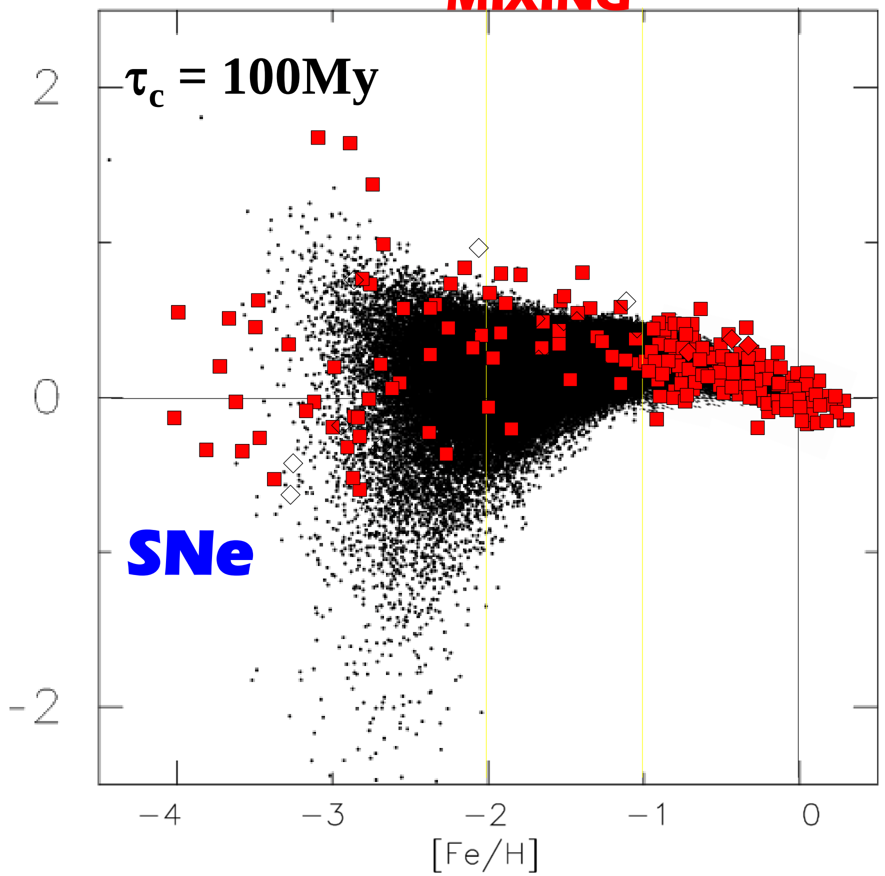
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

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

Without Dynamics & GAS MIXING

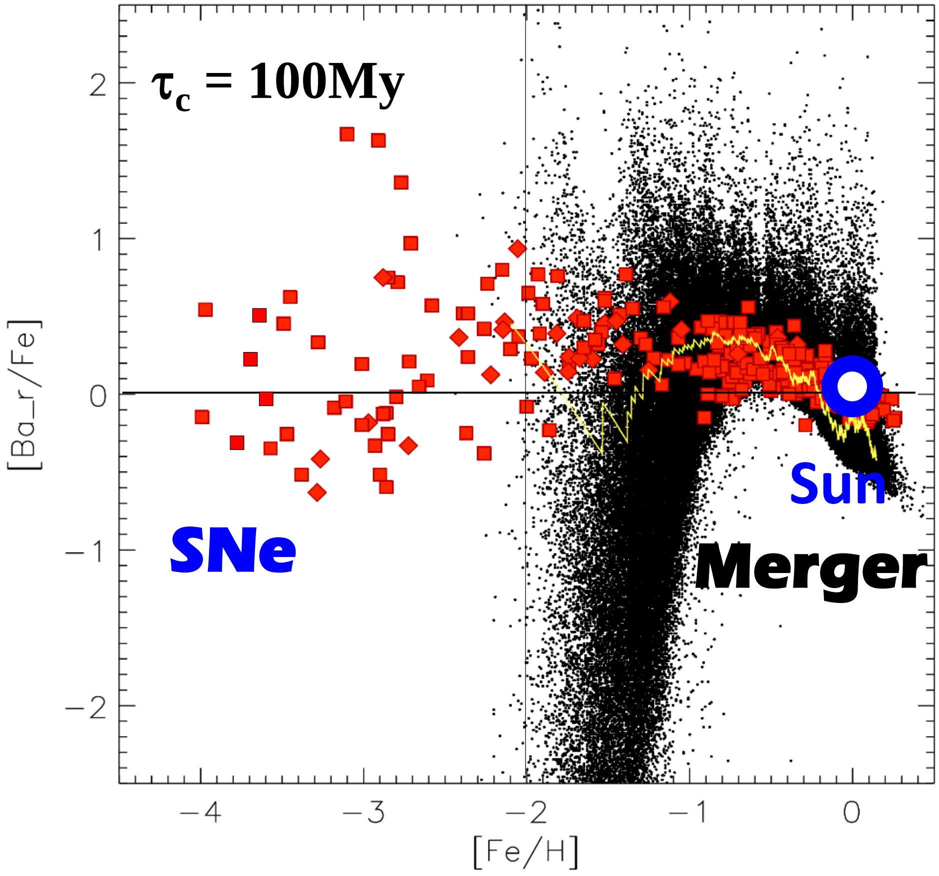


With Dynamics & GAS MIXING



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

Without Dynamics & GAS MIXING



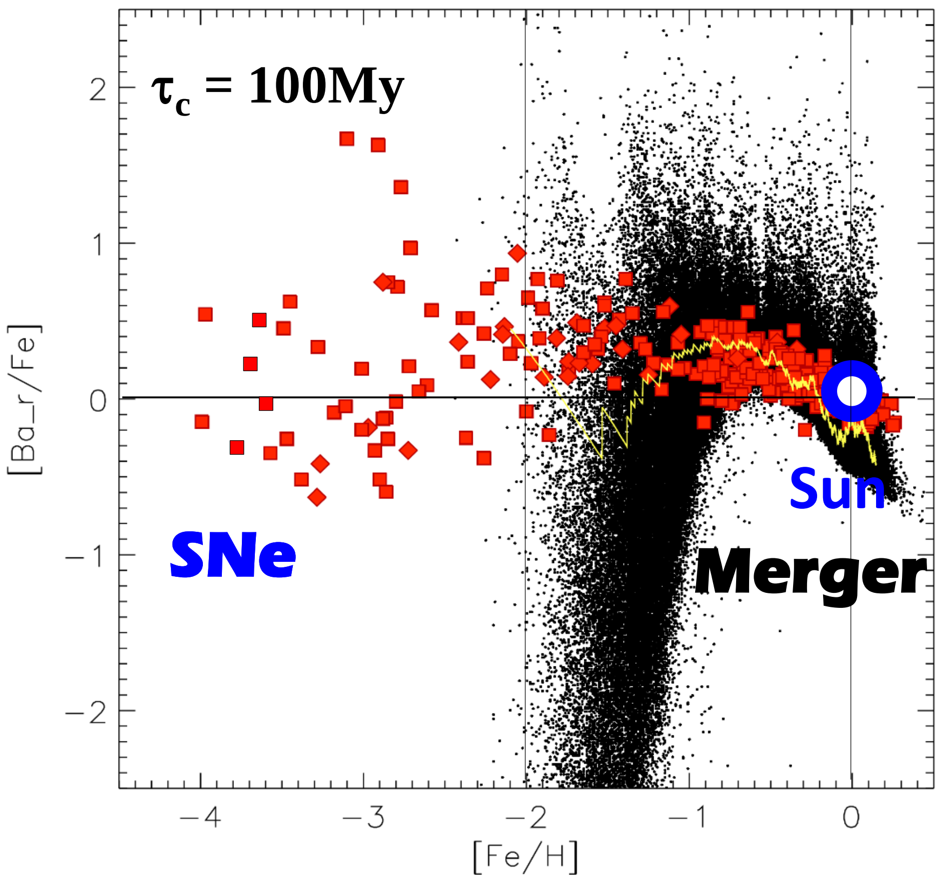
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies →Milky Way (Large Galaxy) ?

SNe→Metals; NSM(τ_c=100My)→r-process elements. Star form. Cond. n_H>100 cm^{-3} → 10-100pc)

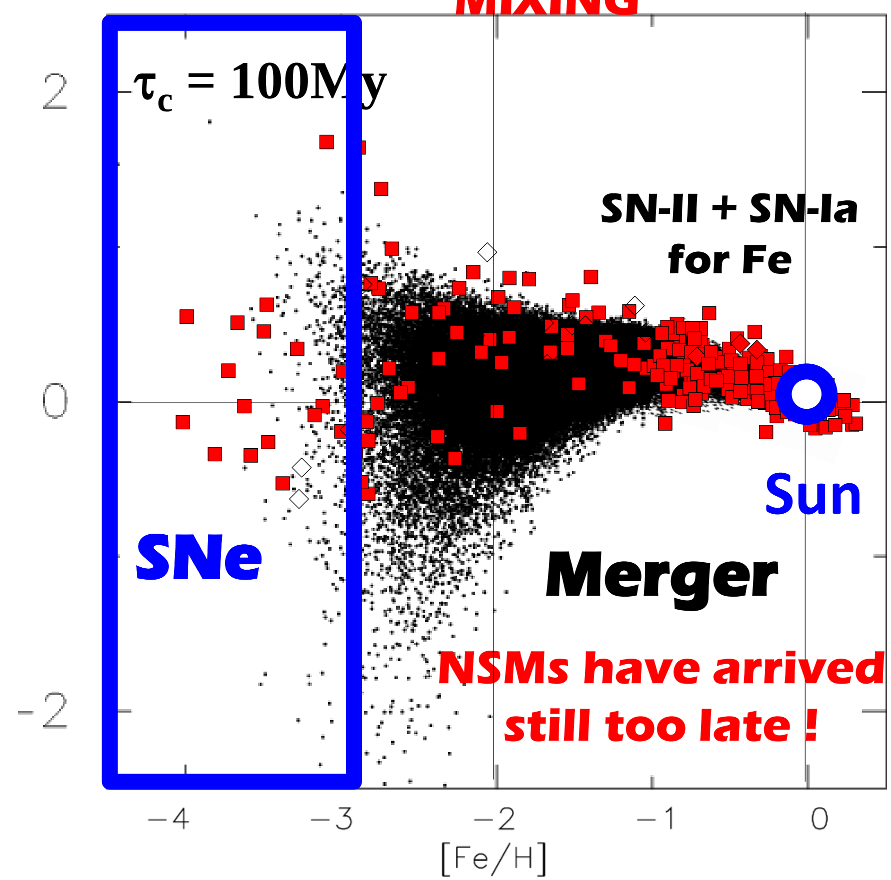
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

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

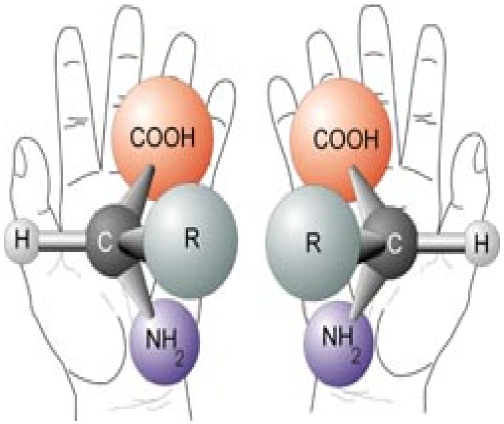
Without Dynamics & GAS MIXING



With Dynamics & GAS MIXING



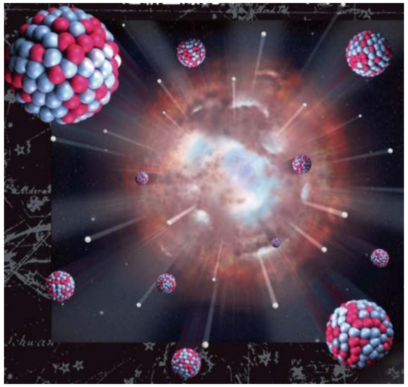
Why are all amino acids on the Earth left-handed?

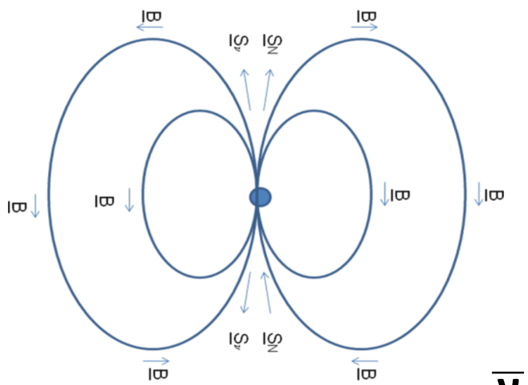


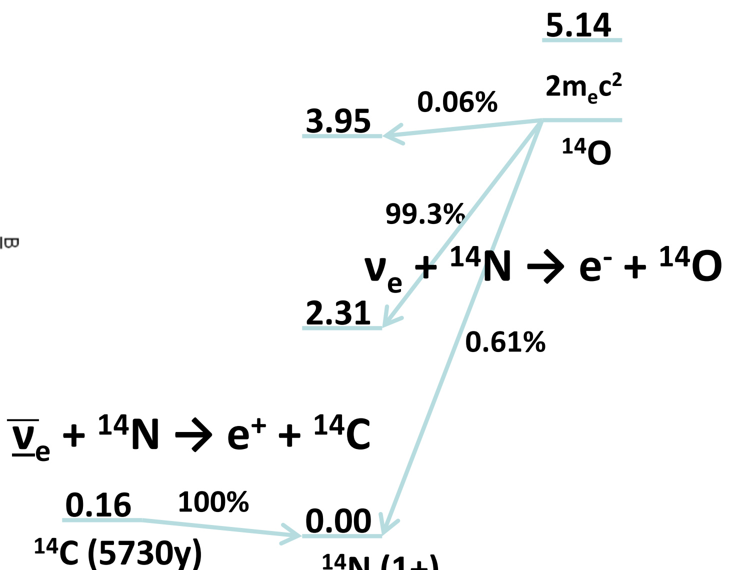
- ★ ν's (anti-ν's) are all left (right)-handed!
- ★ Supernovae with strongly magnetized neutron star or BH emit intensive flux of neutrinos over 10^{10} yrs!
- ★ SN ejecta including ^{14}N interact with neutrino under strong magnetic field!
- ★ Neutrino-^{14}N coupling is asymmetric & chiral selective!

Boyd, Famiano, Kajino, & Onaka, et al.;
Astrobiology 10 (2010), 561-568; Int. J. Mol. Sci. 12 (2011), 3432-3444;
Symmetry 6 (2014), 909-925; Astrobiology (2017), Astrophys. J. (2018).

Magnetized supernova







Mann and Primakoff (Origins of Life, 11 (1981), 255) suggested β-decay of 14C, but it's too SLOW!

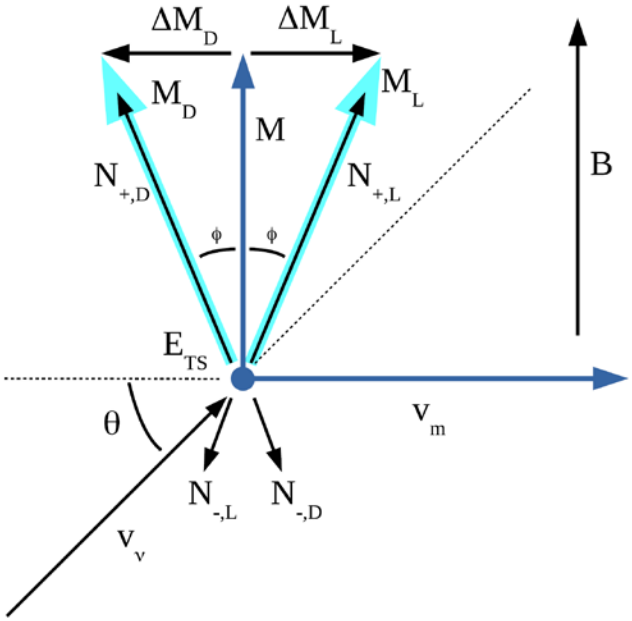
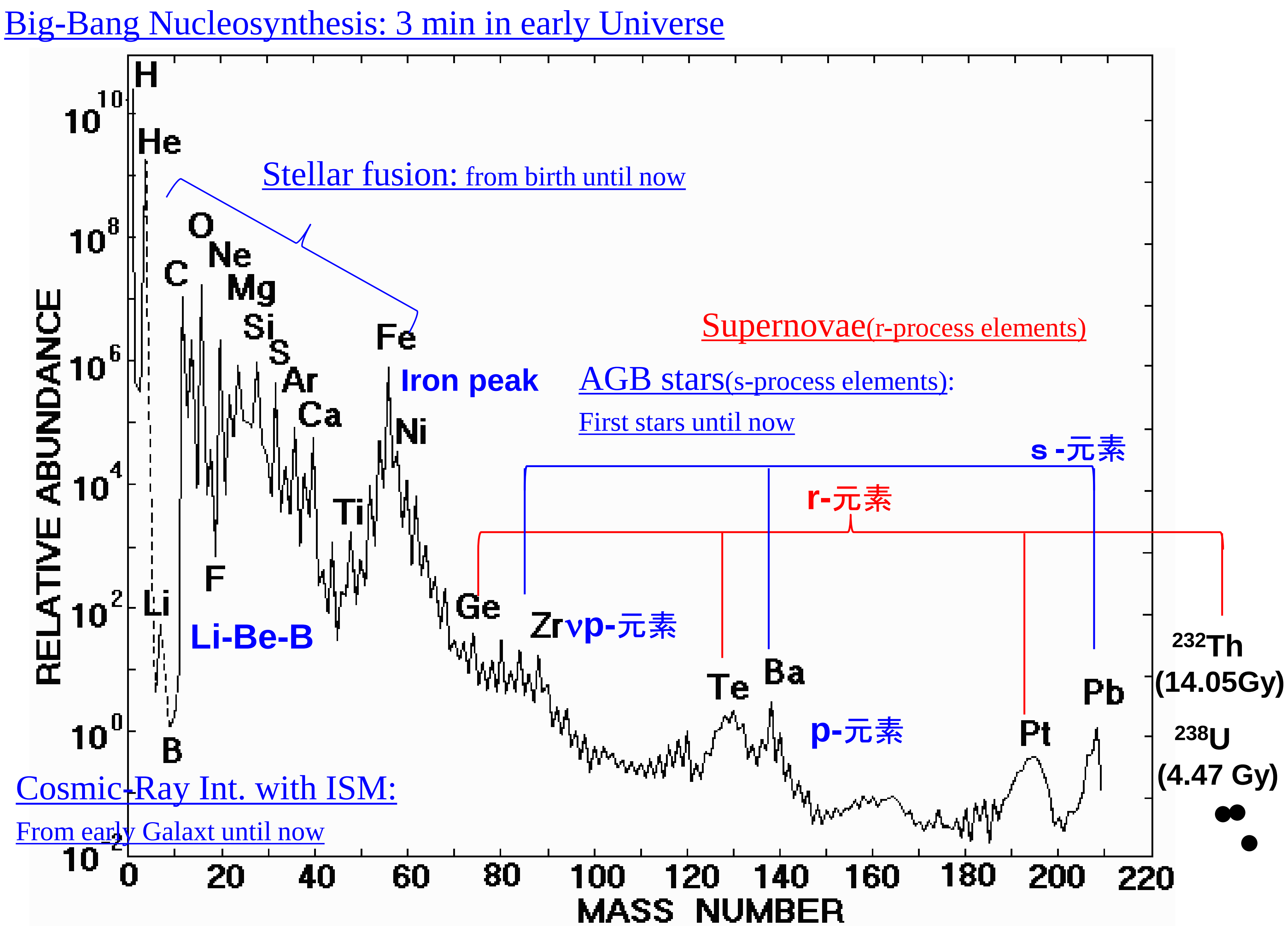


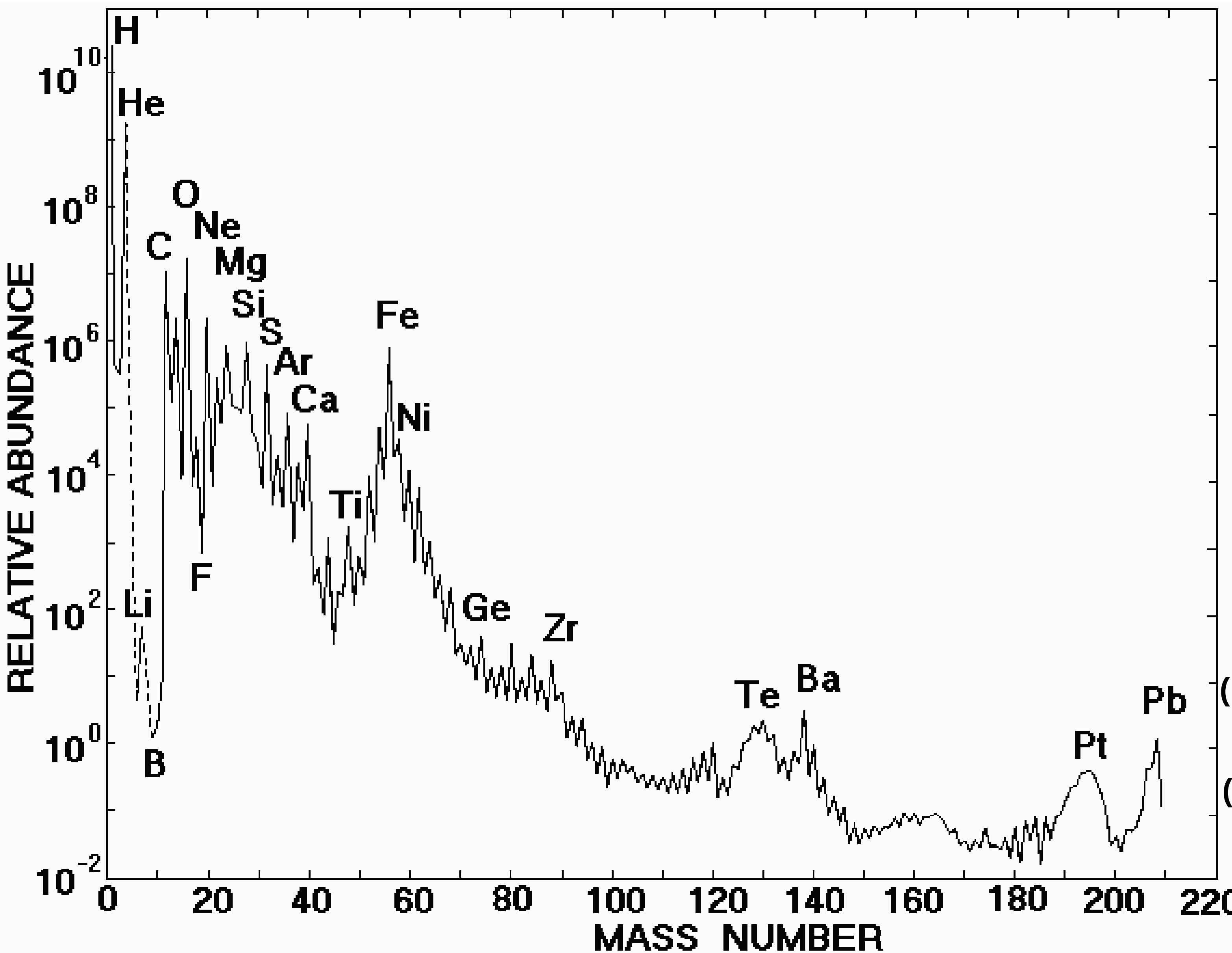
Table 1: **Values of the molecular geometry parameter η_M.**

Amino Acid	Ligand	Zwitterion	Optimized
Alanine	-3.87	31.79	39.39 **51.60**
Arginine	7.79	-44.11 **18.57, 47.18**	-160.41
Histidine	-10.55	-44.58 **23.26**	-31.20
Isovaline	-0.63	-1.92	-16.67 **119.94**
Norvaline	5.49	26.24	33.26 **10.50**
Valine	1.01	4.44, 34.52	19.94 **8.47**

Solar System Abundance



Solar System Abundance

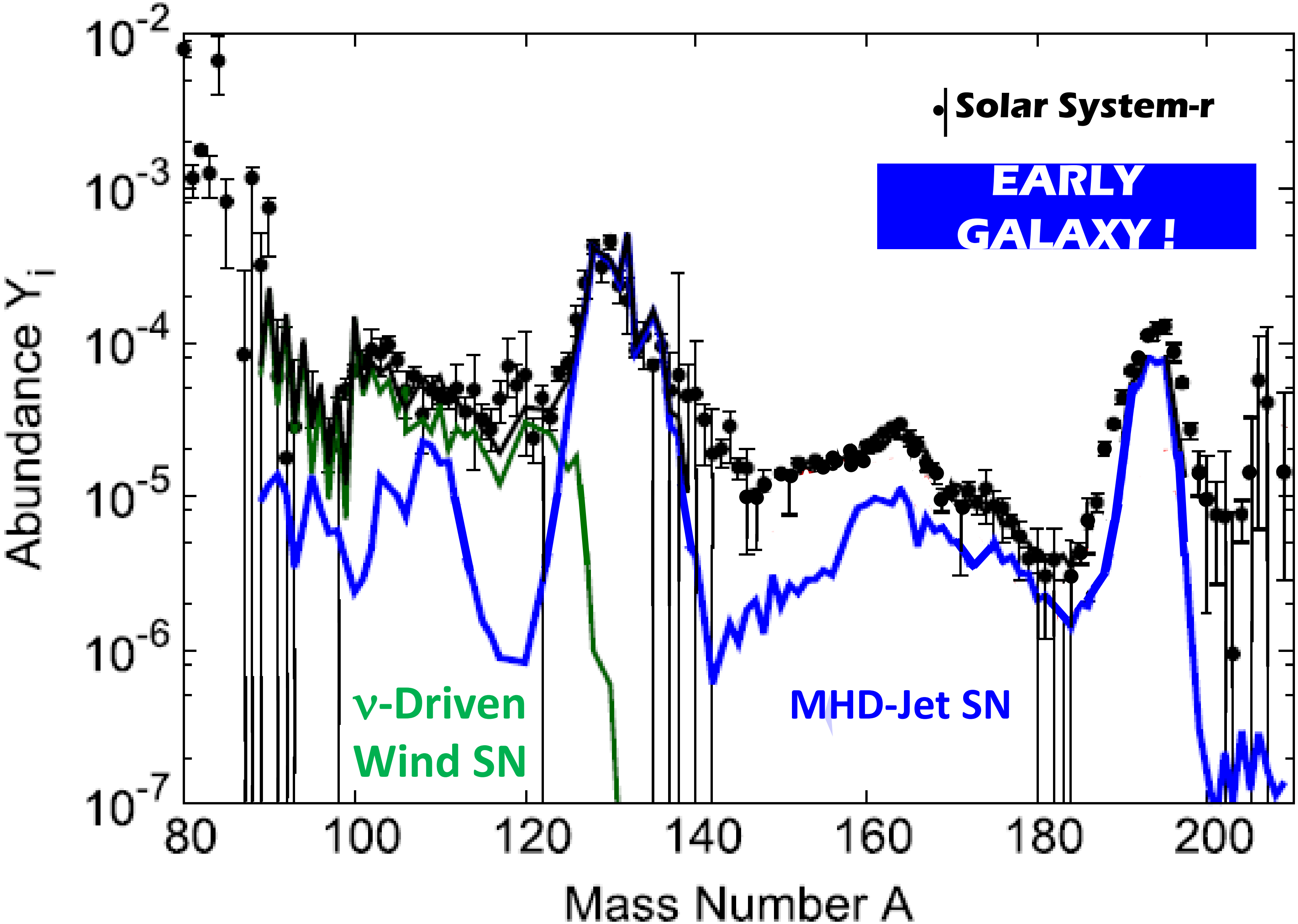


^{232}Th (14.05Gy)

^{238}U (4.47 Gy)

EVOLUTION of the r-Process Abundance

Kajino & Mathews (2017), ROPP 80 , 084901.



Summary & Outlook: GW170817

◇ GW ! → EOS ! (Cold NS vs. hot SN core)

◇ Neutron star merger → a Central Engine of Short-GRB !

◇ Light emissions, not by ^{56}Ni or ^{44}Ti decays like SNe

→ consistent with radioactive decays of r-process elements !

◆ No specific element, identified :

→ Needs another event (once in every 10^4-10^5 yrs in Milky Way) !

→ Needs nuclear mass, α, β, γ, fission studies !

→ Needs complete opacity table for lanthanoids and actinoids !

→ Needs 3D hydrodynamic model & radiative transfer

◆ No neutrino signal → Micro-physics, yet to be studied !

Dawn of Nuclear-Particle Astrophysics and Multi-Messenger

Purpose → Difference between Merger and SN r-process !

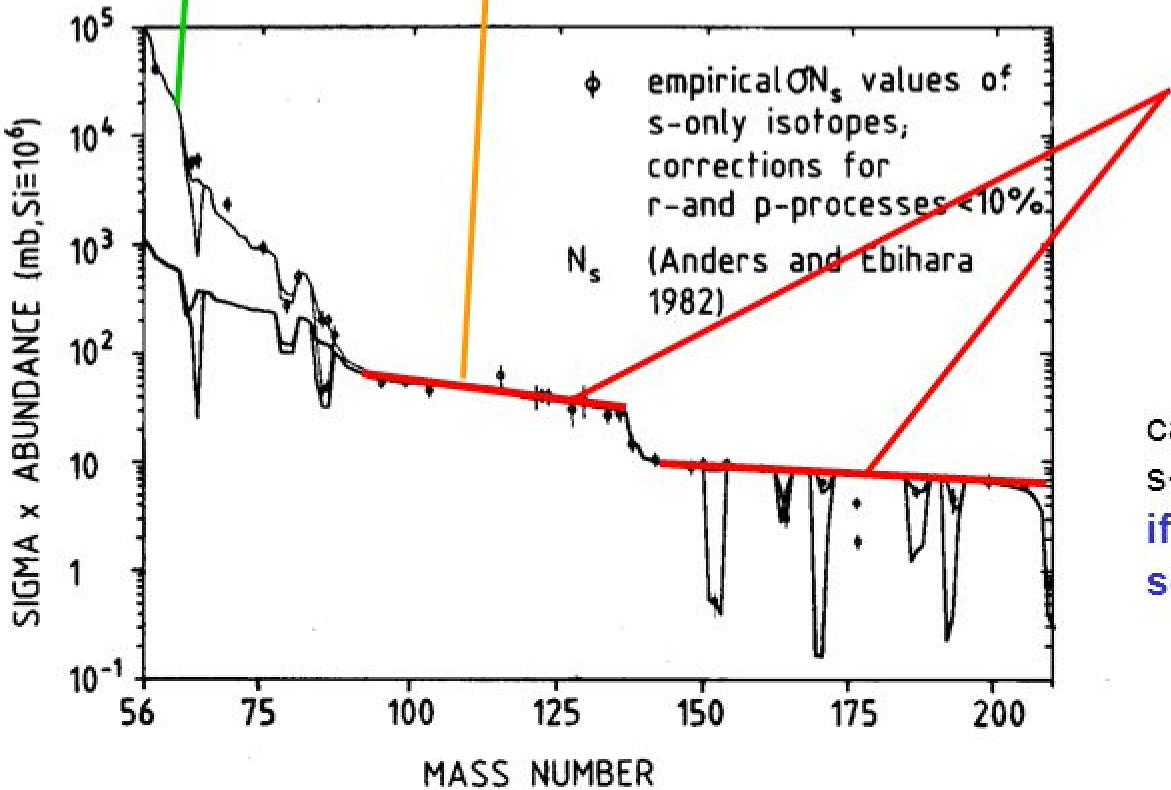
The sites of the s-process

AGB stars(s-process elements):

First stars until now

weak s-process: core He/ shell C burning in massive stars

main s-process: He shell flashes in low mass TP-AGB stars



approx. steady flow

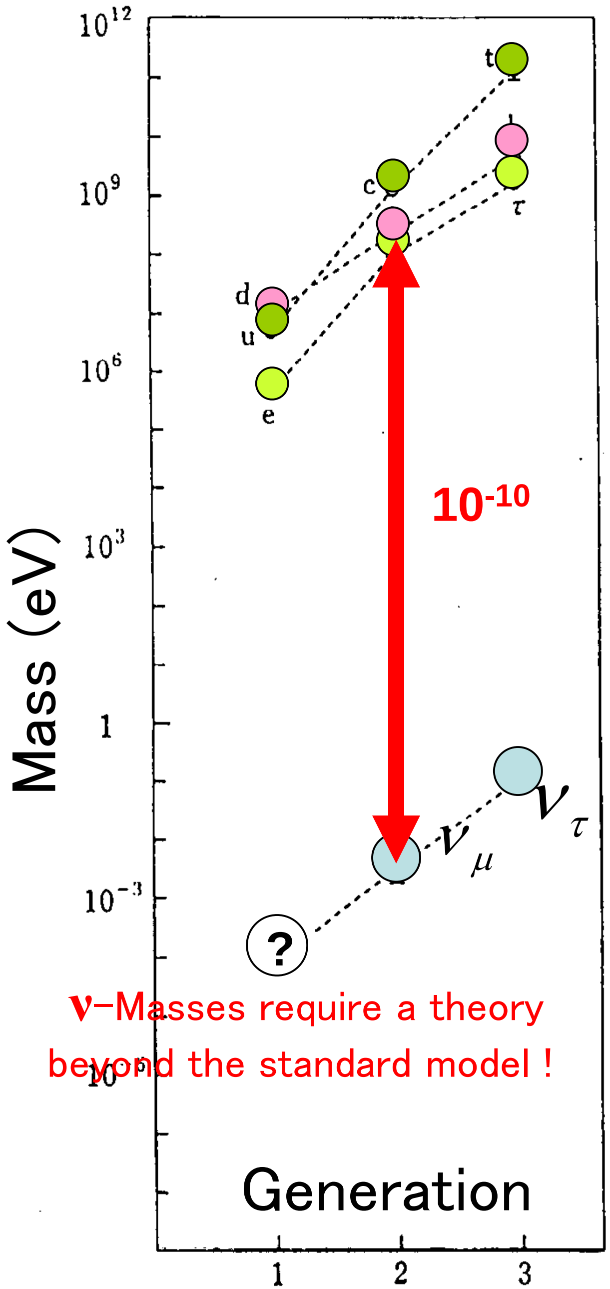
$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

↓

can easily interpolate s-contribution for s+r-nuclei **if neutron capture cross sections are known**

Higgs(standard model) produces 1% of Quark Masses.

Standard Model breaks down !



$$\frac{\textbf{Neutrino Masses}}{\textbf{Quark \& Lepton Masses}} = \frac{1}{10{,}000{,}000{,}000}$$

Why 10^{-10} ?

$E = mc^2$

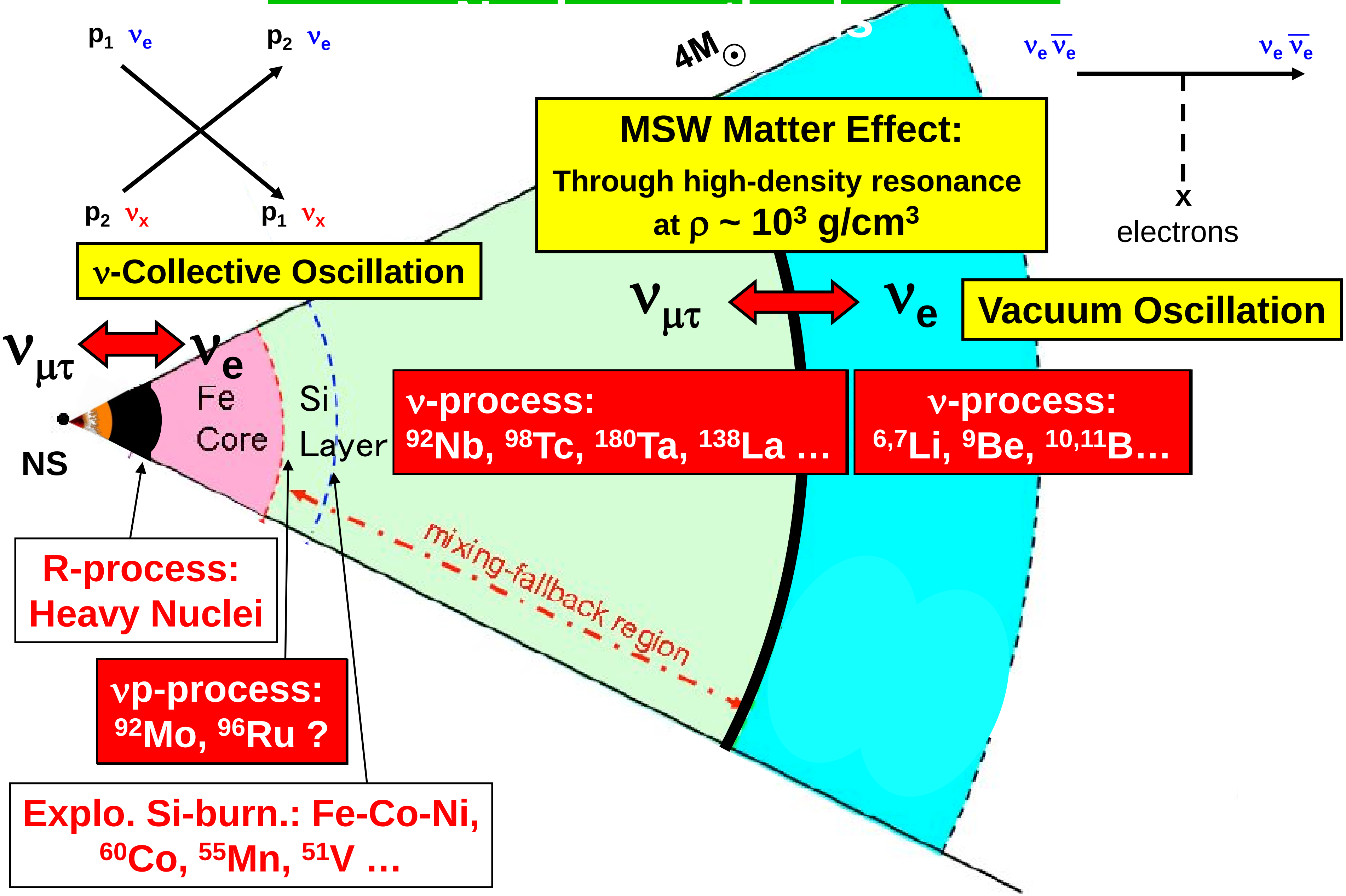
This could be a signature of new physics at 10^{10} times higher energy scale than the ordinary scale.

$$\nu_i + \overline{\nu_i} \rightleftarrows e^+ + e^- \rightleftarrows 2\gamma\ (T)$$

Key Physics suggested by FINITE ν−mass:

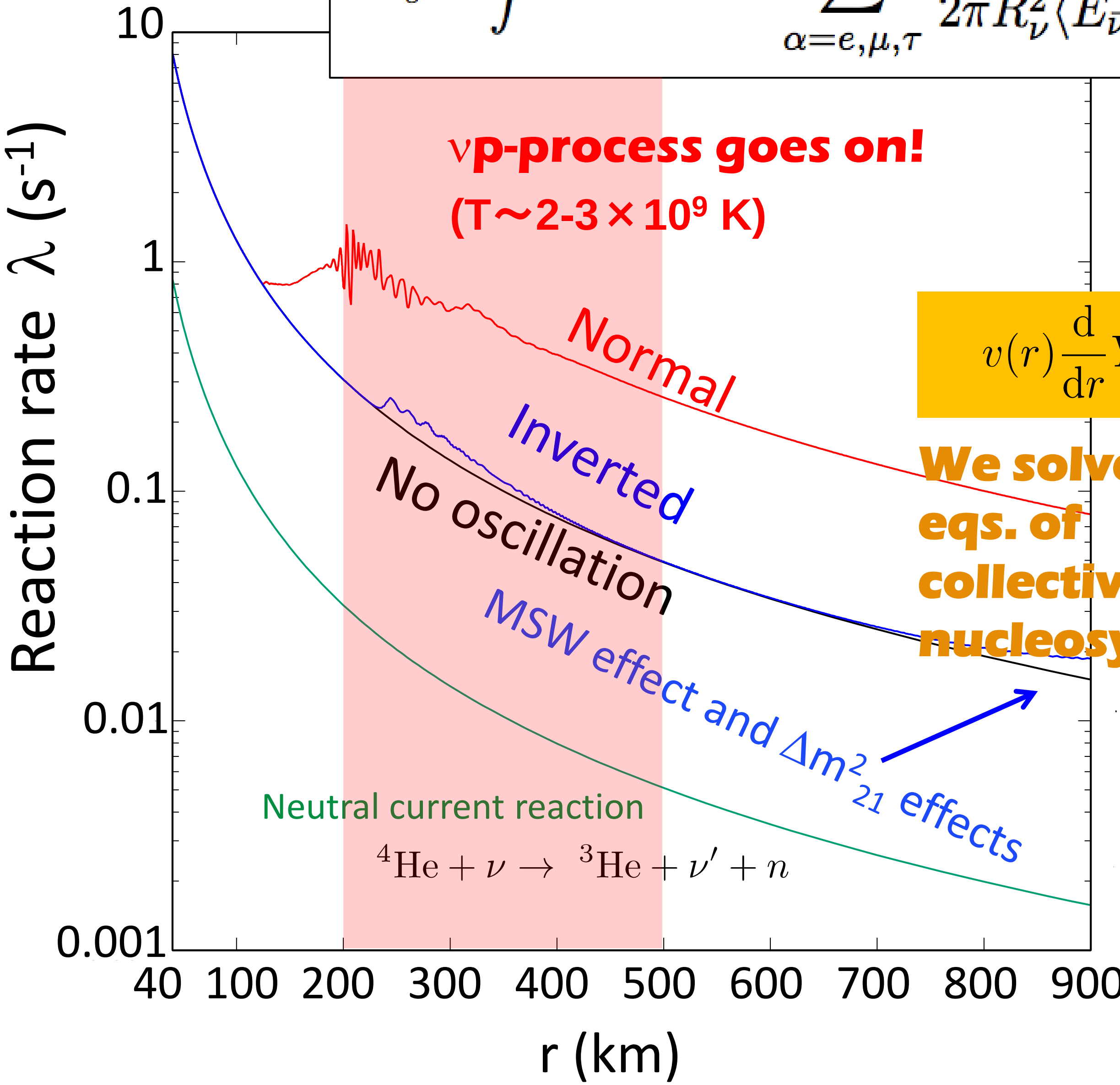
- Unification of elementary forces ?
- CP violation for Lepto− & Baryo−genesis ?
- What are dark matter or dark energy ?
- Why left−handed neutrinos ?
- Majorana or Dirac ?
- Explosion Mechanism of Supernovae ?
- Explosive SN nucleosynthesis ?

ν-Oscillation and



Continuous Collective ν-Oscillation Effect at 200 km < r

$$\lambda_{\bar{\nu}_e} = \int \mathrm{d}E\,\mathrm{d}\cos\theta \sum_{\alpha=e,\mu,\tau} \frac{L_{\bar{\nu}_\alpha}}{2\pi R_\nu^2 \langle E_{\bar{\nu}_\alpha}\rangle} f_{\bar{\nu}_\alpha}(E)\bar{\rho}_{ee}(E,\theta_R)\sigma_{\bar{\nu}_e}(E)$$



Charged current reaction

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

$$v(r)\frac{\mathrm{d}}{\mathrm{d}r}Y_n = \lambda_{\bar{\nu}_e}Y_p + \lambda_{\nu\nu'}Y_{^4\mathrm{He}} + \mathrm{Other}$$

We solved coupled evolution eqs. of collective ν-oscillation, Ye, and nucleosynthesis.

Y_n ... neutron abundance

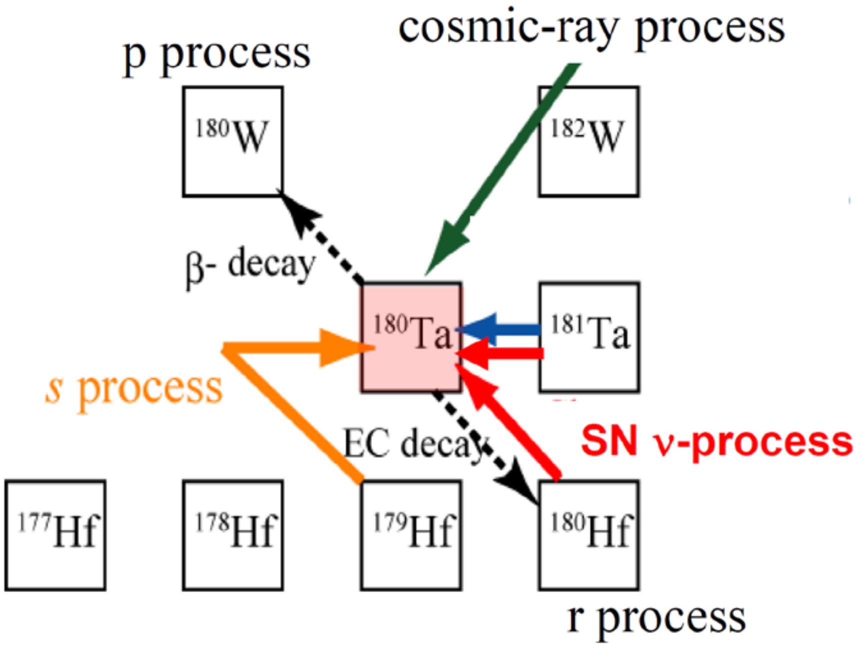
Y_p ... proton abundance

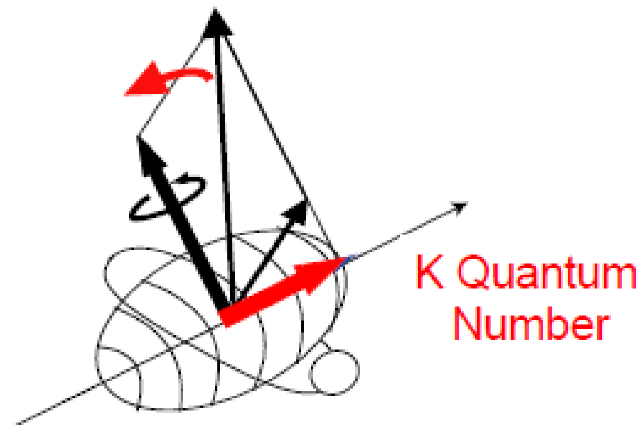
$Y_{^4\mathrm{He}}$ ... helium4 abundance

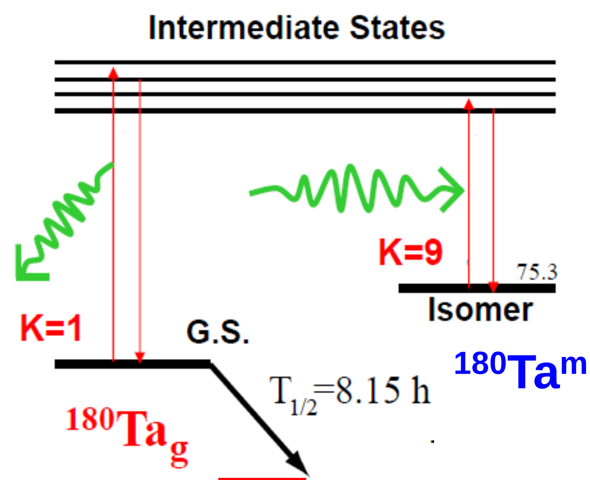
$v(r)$ ... gas velocity

ν-Isotopes: ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®;
PR C82 (2010), 058801; ApJL 779 (2013), L1.







^{180}Ta$_g$($\tau_{1/2}$ = 8h) ^{180}Ta^m($\tau_{1/2}$ > 10^{15}y)

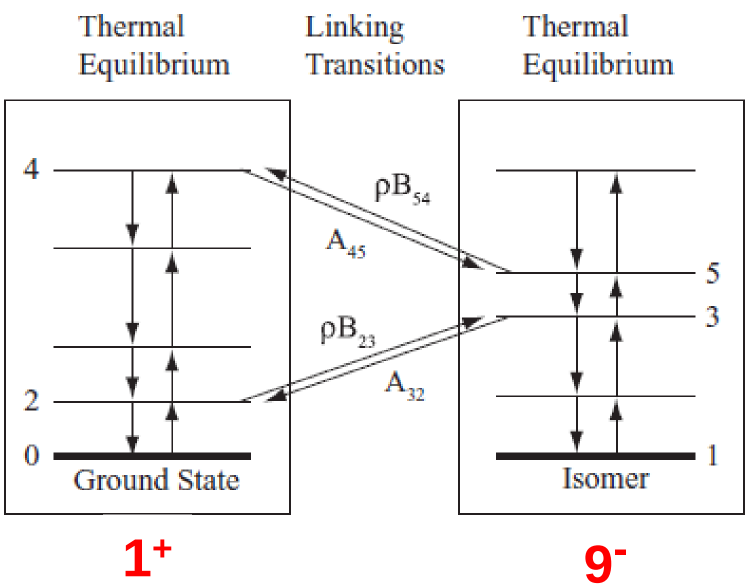
Formula to calculate time-dept linking transitions

Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®; PR C82 (2010), 058801

★ General formula (Einstein AB theory) for *kT << ΔE*

$$\frac{dN_0}{dt} = -\sum_{iP} P_i^g A_{ip} N_0 + \sum_{ip} P_i^m \rho B_{pi}(1-N_0), -\sum_{jq} P_j^g \rho B_{qj} N_0 + \sum_{jq} P_j^m A_{jq}(1-N_0)$$

$$= -\sum_{i\,p} P_0^g \frac{g_i}{g_0} exp(-(E_i - E_0)/kT) A_{ip} N_0 + \sum_{ip} P_1^m \frac{g_i}{g_1} exp(-(E_i - E_1)/kT) A_{ip}(1-N_0),$$



$$m_i/m_j = (2J_i+1)/(2J_j+1) exp(-(E_i - E_j)/kT),$$

$$P_i \equiv m_i/m_{total} = \frac{m_i/m_0}{\sum(m_i/m_0)}.$$

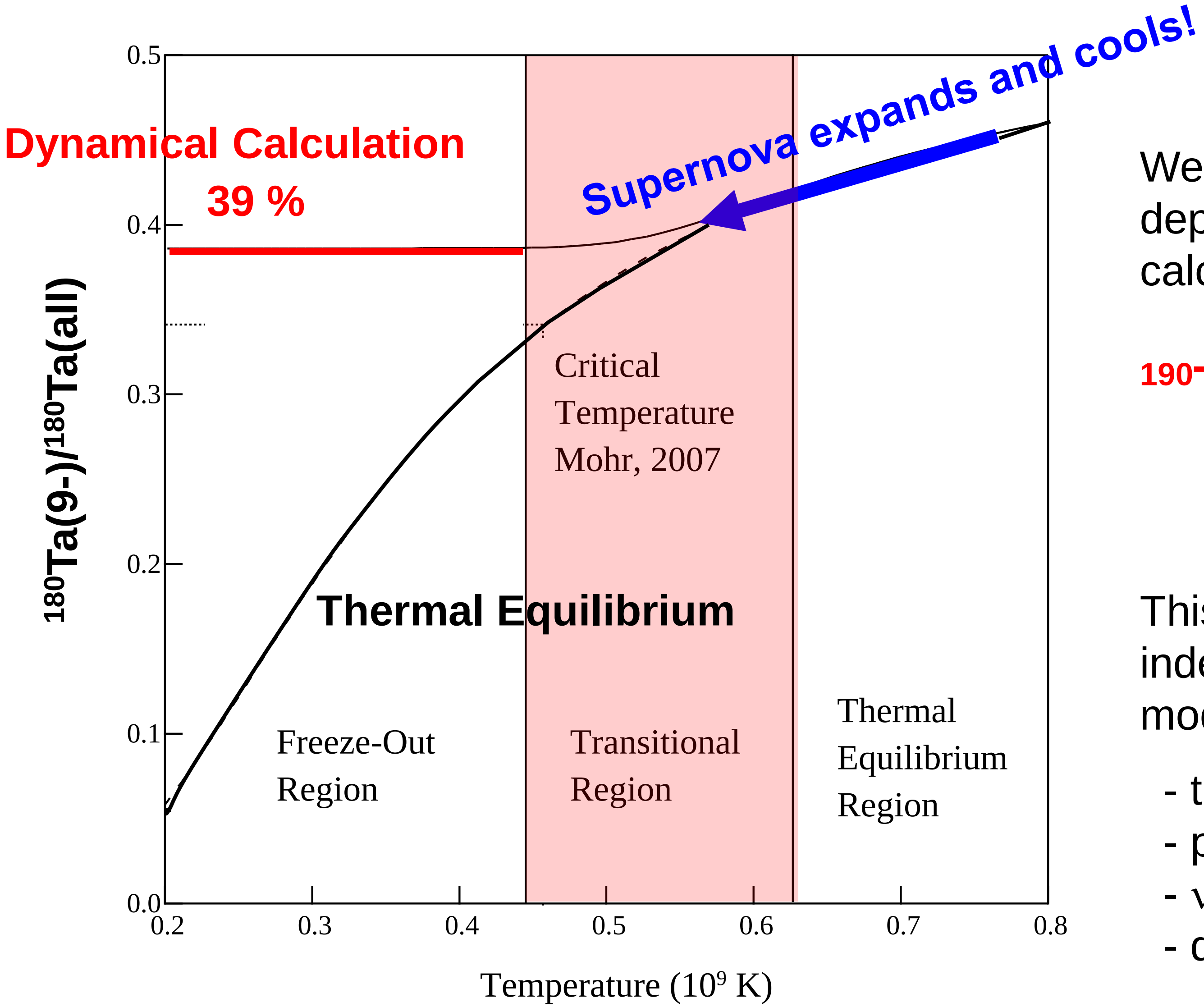
★ In the SPECIFIC case of ^{180}Ta:

Transition prob. $\Sigma_p A_{ip} = \Gamma_i / \hbar$ ⟵ Exp.

$$\frac{dN_0}{dt} = -\sum_i P_0^g \frac{g_1}{g_0} exp(-(E_i - E_0)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar} N_0 + \sum_i P_1^m exp(-(E_i - E_1)/kT) \frac{g_i}{g_1}\frac{\Gamma_i}{\hbar}(1-N_0).$$

Calculated Result

Hayakawa, Mohr, Kajino, Chiba & Mathews, PR **C81** (2010), 052801®; **C82** (2010), 058801.



We carried out time-dependent dynamical calculations:

$^{190}Ta(9^-)/^{190}Ta(all)$ ~ 0.39 survives!

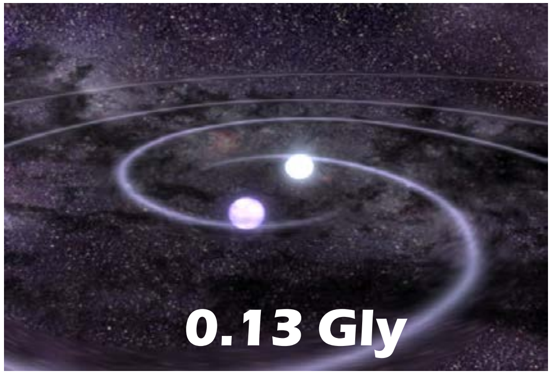
This result is almost independent of SN model parameters, i.e.

- total explosion E,
- progenitor mass,
- ν-luminosity, and
- decay time scale.

GW170817

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

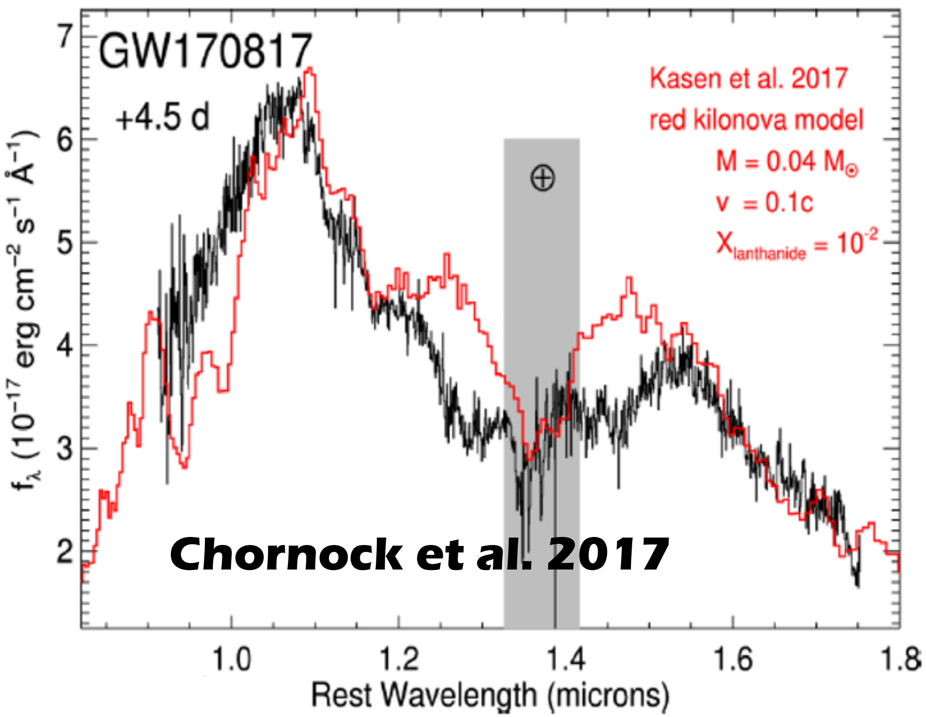
- GW170817 (LIGO-Virgo) : $0.86 < M/M_\odot < 2.26$
- GRB170817A (Fermi-GBM) : 1.7 s
- No ν–Signal: 10^{-6} weaker than SN1987A (1.6×10^5 ly)
- X-rays & Radio waves : Remnant NS or BH, not identified.



GW170817
SSS17a

- **Optical and Near-infrared : SSS17a (over 70 Telescopes)**

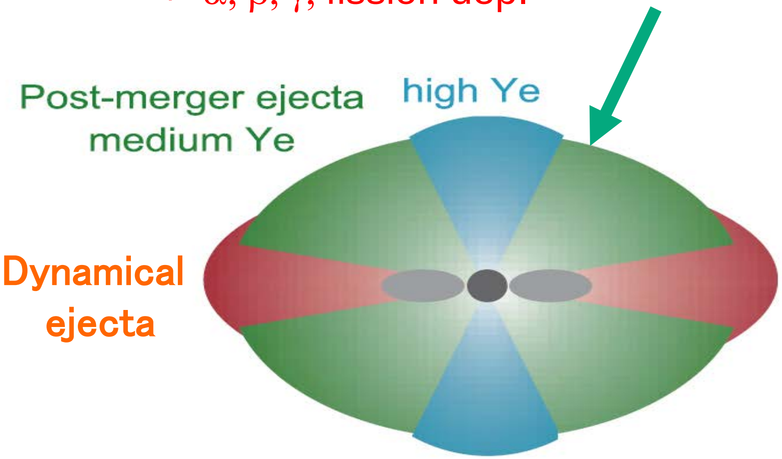
◆ **No r-element, identified.** ◆ **Energy, consistent with r-process!**



? Line of sight → Different Y_e
→ Complicated hydrodyn.

? Ejecta → Different velocities, blue shifts
→ Hundreds of r-elements

? Incomplete Opacity + too many r-elements
+ α, β, γ, fission dep.



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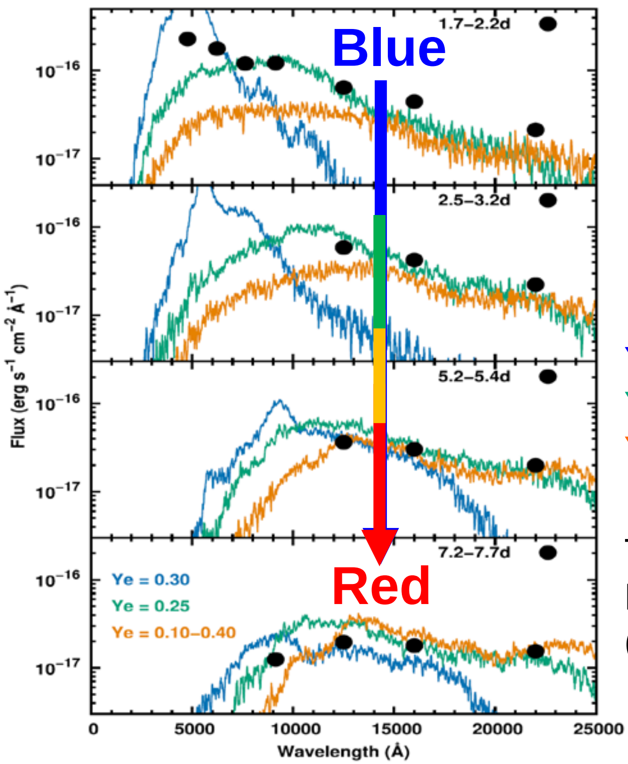
- X-rays & Radio waves :
  Remnant NS or BH, not identified.
- Optical and Near-infrared : SSS17a (by more than 70 Telescopes)
  Consistent with r-process!   But no element, identified.



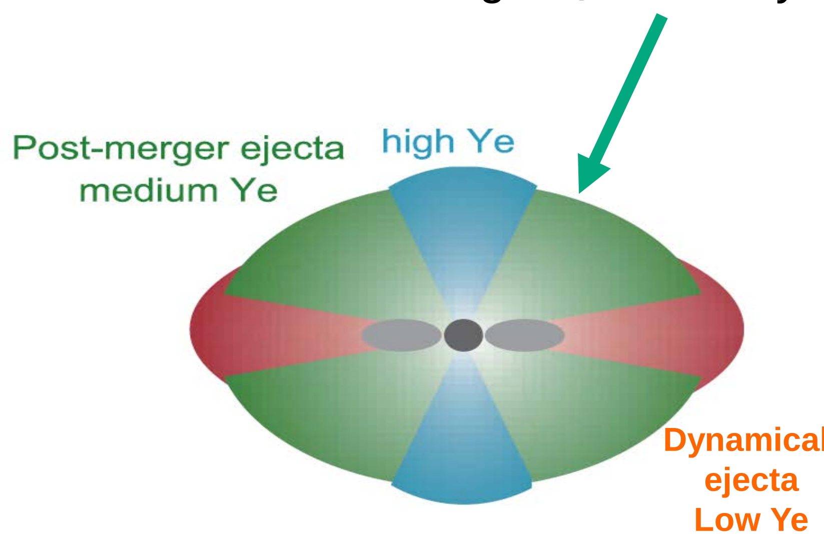
$Y_e = p/(p+n)$

$Y_e = 0.30$
$Y_e = 0.25$
$Y_e = 0.10\text{-}0.40$

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

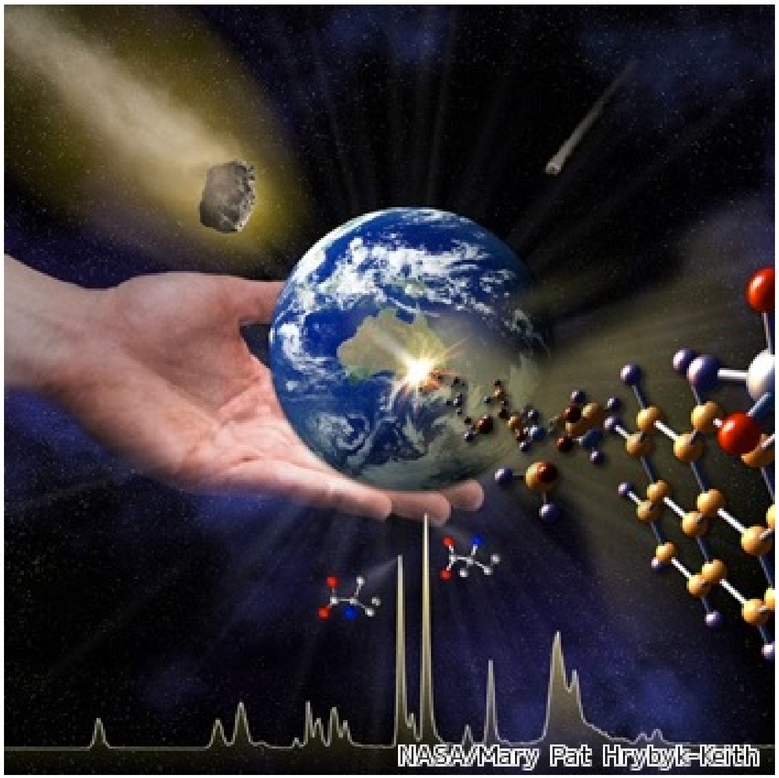
◆ ? Line of sight → different Y_e & r-process ?

Line of sight @ 0.13 Gly

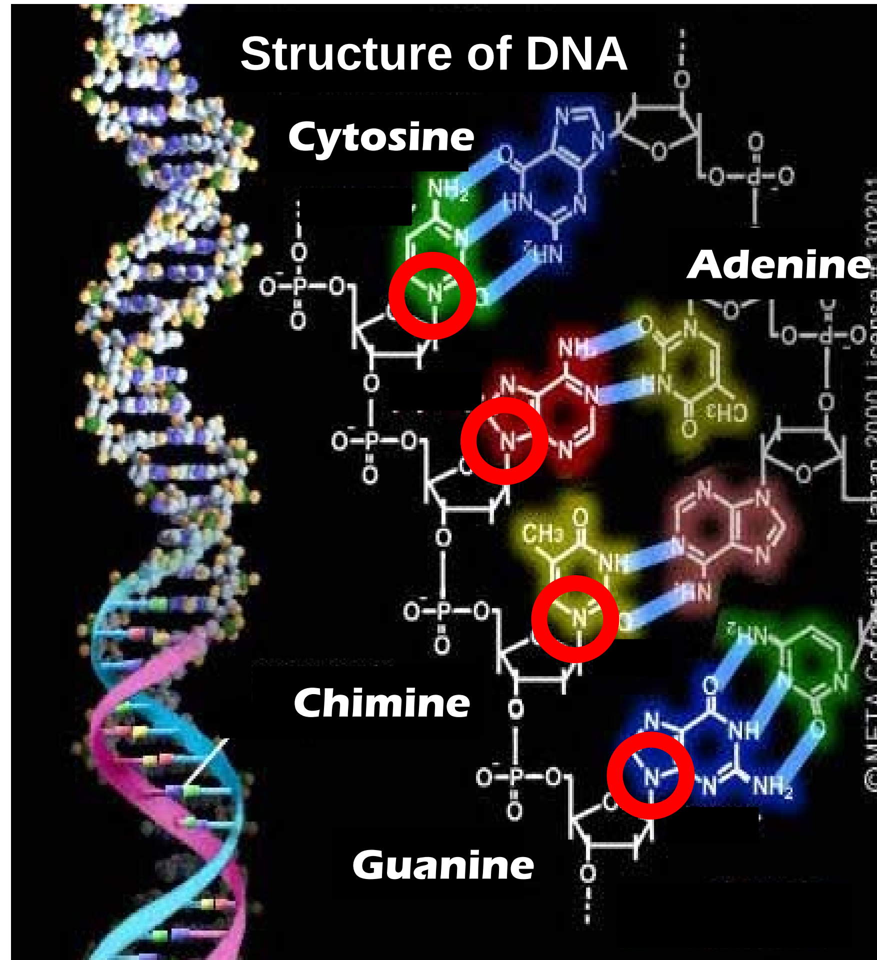


Murchison Meteorite exhibits EXCESS of L-handed Amino Acids! NASA (2009, March 16)

http://tokyo.secret.jp/80s/come/amino-acid.html



アミノ酸のように、構成要素が同じでも鏡に映したような2つの立体構造を取り得る物質を鏡像体(光学異性体)という。同じアミノ酸でも右型と左型では性質が大きく変わり、右型アミノ酸は体に害をなすことも多い。なぜ生命は左型アミノ酸を選んだのか、その理由は宇宙にある…とするのがGlavin氏らの考え。今後のさらなる研究が期待される



Connection is occupied by $^{14}N(1+)$