長滝天体ビッグバン研究室主催「超新星・ガンマ線バースト」研究会2014

2014年8月25日－27日、理研・大河内ホール

超新星・ガンマ線バーストでの元素合成とニュートリノ

Supernova ＆GRB as a Laboratory for Element Genesis and Neutrino Physics

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Dept of Astronomy, University of Tokyo

COSmology and Nuclear AstroPhysics Group

Outline

1. Introduction
   Why element genesis and neutrinos?

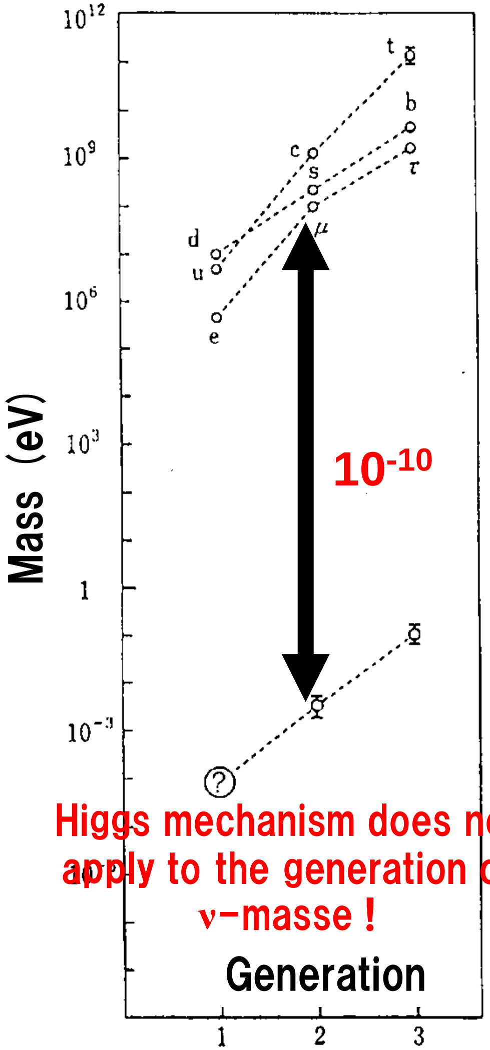
2. MSW & Collective ν-Oscillation
   ν-Process for Mass & Hierarchy

3. Origin of r-Process & Galactic Evolution

4. EoS of Neutron Stars and Relic Supernova ν

5. Summary

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



Higgs mechanism does not apply to the generation of ν-masse !

Challenge of the Century

Universe is flat and expanded acceleratingly.

$$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$$

- **What is CDM (Ω_{CDM} = 0.27) and DE (Ω_Λ = 0.68) ?**

  CMB & LSS including absolute ν-mass

- **Is BARYON sector (Ω_B = 0.05) well understood ?**

  BBN ^{7}Li-Problem with DMs (Axion, SUSY …)

  SUSY-DM ⇒ beyond the Standard Model ⇒ $m_\nu \neq 0$, unique signal

Key Physics with $m_\nu \neq 0$ beyond the Standard Model :

- Unification, CP & L- & B-genesis, Dirac or Majorana ?
- Dark Matter & Big Bang Nucleosynthesis ?
- Explosion Mechanism of CC-SNe & Nucleosynthesis ?

Today's Purpose

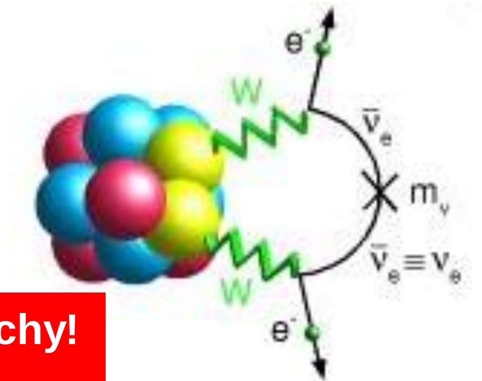
is to elucidate the significance of SUPERNOVA & GRB PHYSICS in the studies of Element Genesis and Neutrino Physics.

Total ν−Mass, constrained from Nuclear Physics and Cosmology

- **0νββ in COUORE, NEMO3, EXO, KamLAI**

→ 0.05∼0.1 eV in the future

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



Neutrinoless ββ

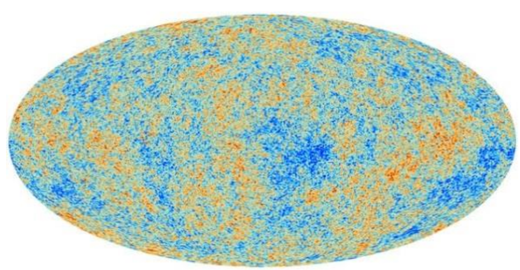
Strongly constrains mass hierarchy!
→ 0.1 eV in the future

- **CMB Anisotropies +**

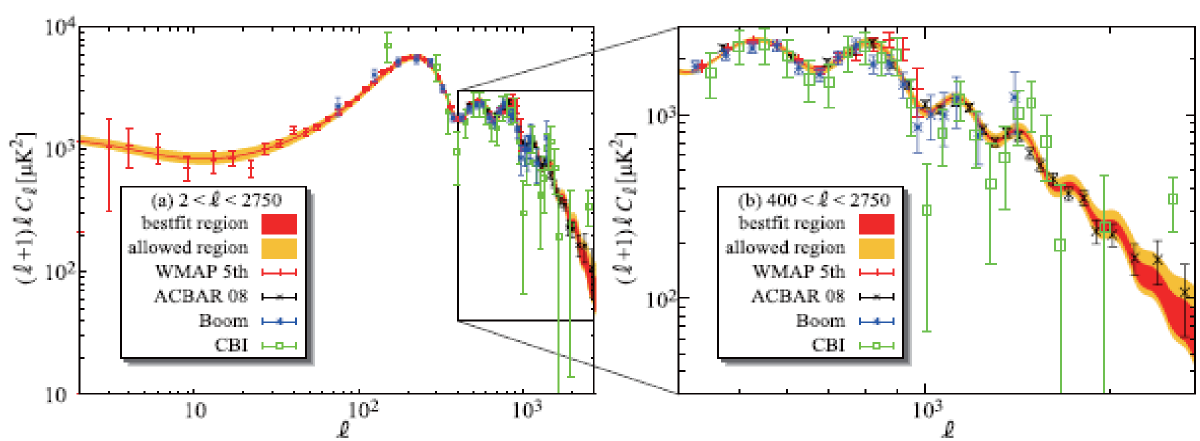
$\sum m_\nu < 0.36$ eV (95%C.L.): WMAP-7yr + HST + CMASS (Putter et al. arXiv:1201.1909)

CMB Anisotropies & Polarization including Cosmic Magnetic Field

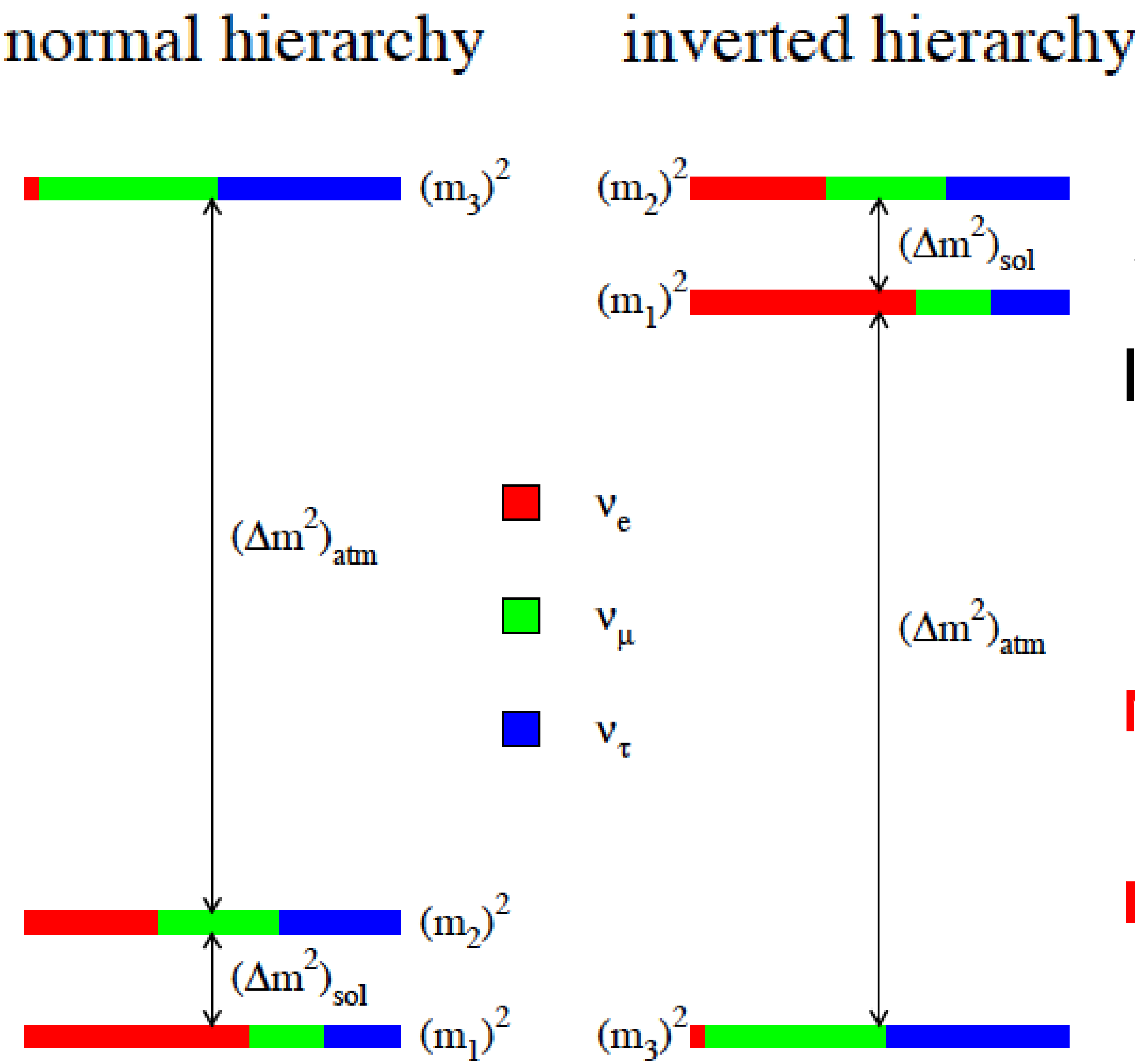
$\sum m_\nu < 0.2$ eV (2σ, B_λ<2nG): with Magnetic Field; Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; Phys. Rev. D81 (2010), 103519.



www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe



Mass Hierarchy ？



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

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

$= (0.05$ eV$)^2$

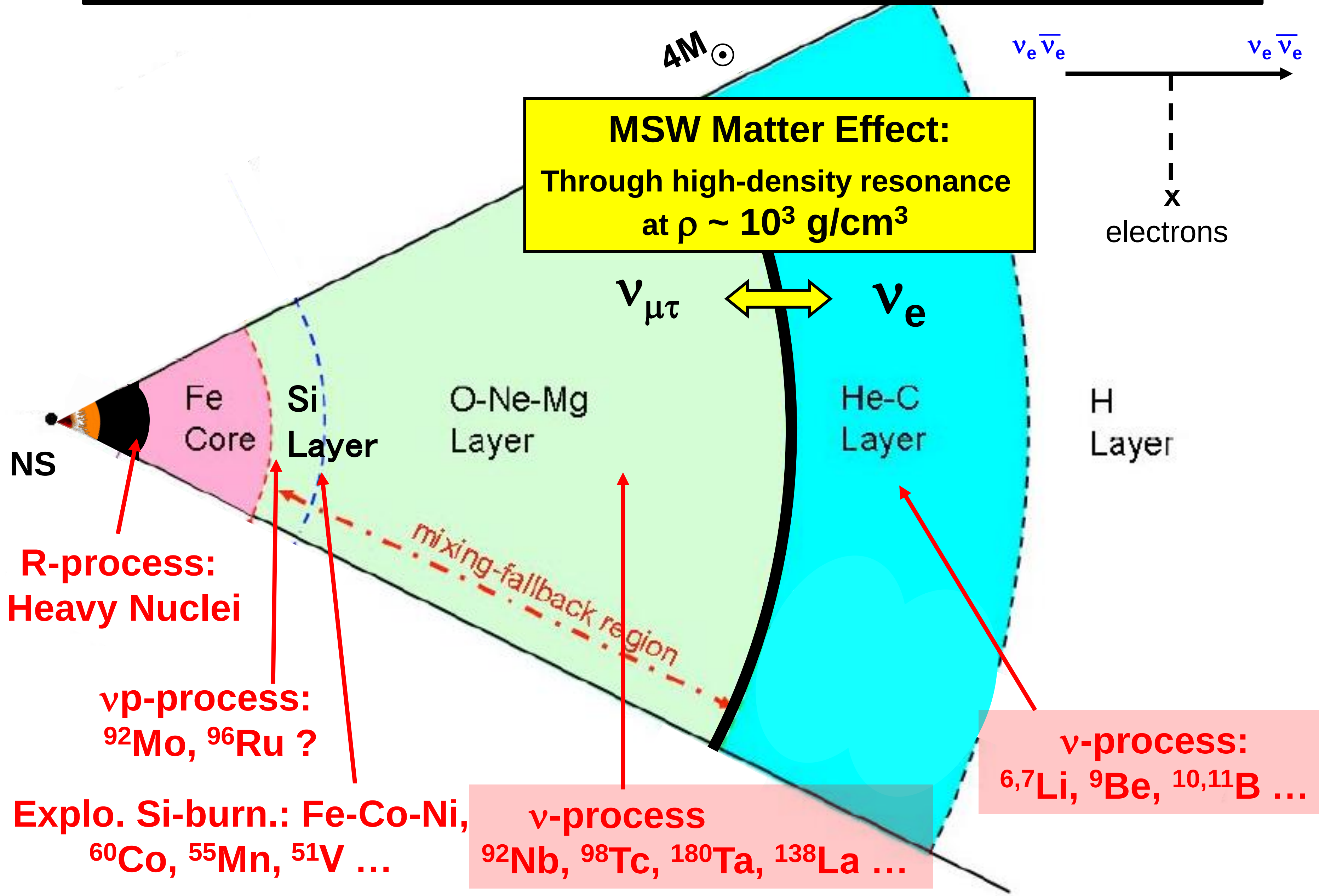
Normal:

$\Sigma\, m_\nu \sim 0.05$ eV !

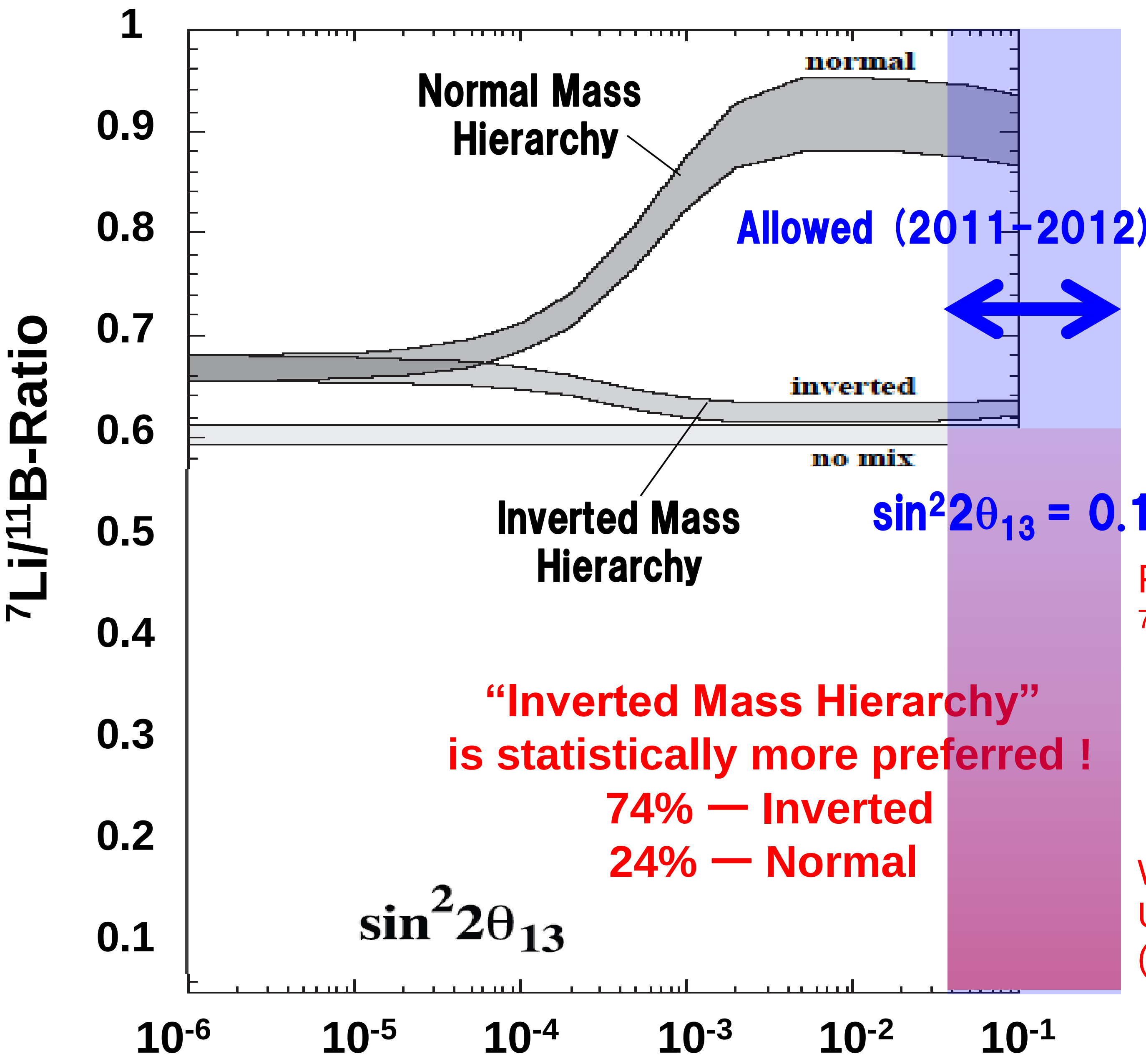
Inverted:

$\Sigma\, m_\nu \sim 0.1$ eV !

Neutrino Oscillation and SN-Nucleosynthesis



New Method for Mixing Angle θ_{13} & Mass Hierarchy

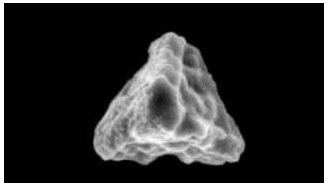


Yoshida, Kajino et al. 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.

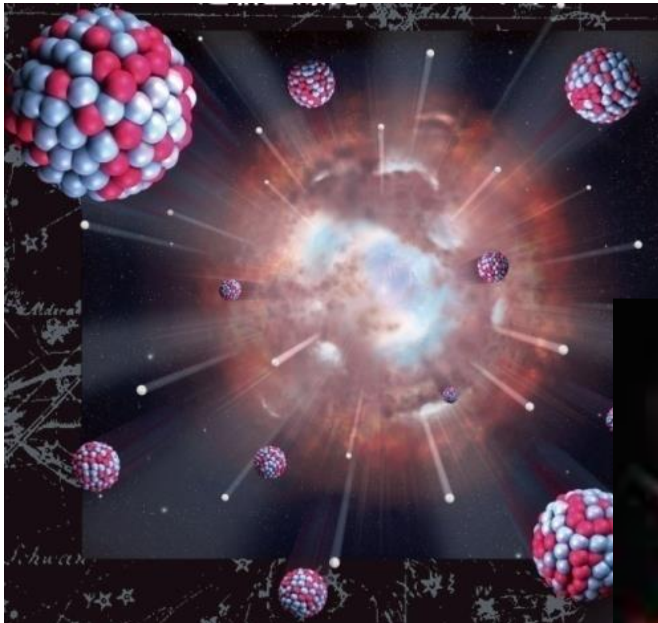
Mathews, Kajino, Aoki & Fujiya, PR D85, 105023 (2012).

Suzuki and Kajino, J. Phys. G40 (2013), 083101.

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

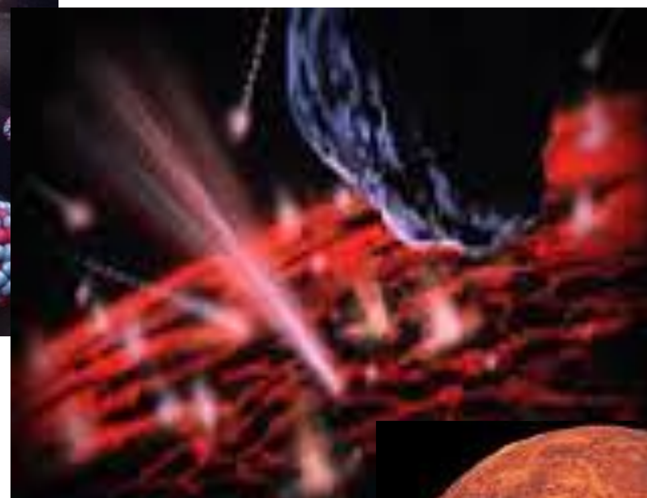


W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).



The last Supernova nearby

Formation of Primordial Sun



Primordial Sun

4.56 Gy ago

Present Sun

How long ?

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

^{92}Nb ($\tau_{1/2}$=3.47x10^7 y) : ΔT = 1∼30 My !

SN ν–Process Origin of ^{92}Nb !

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

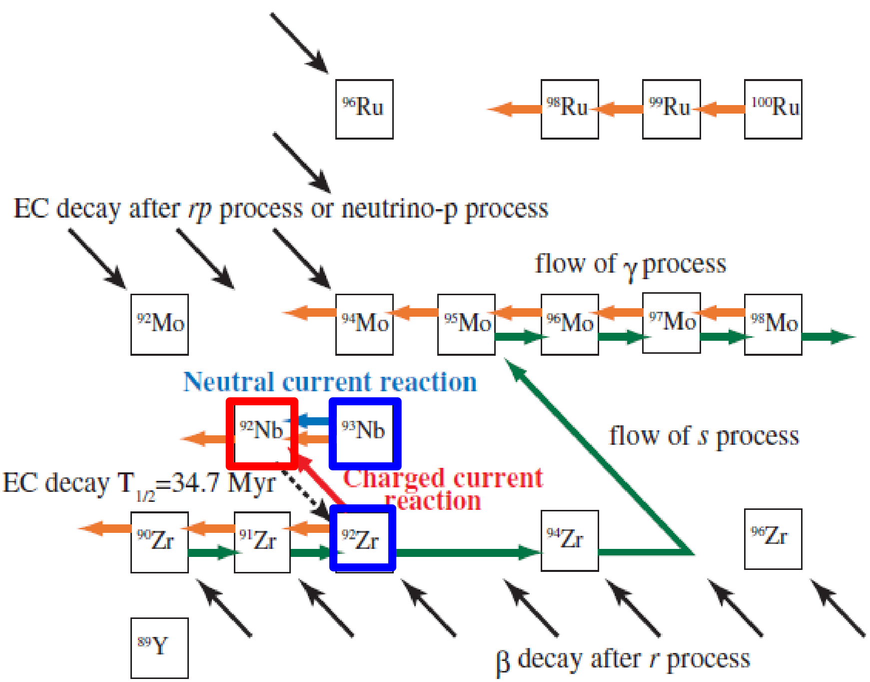
^{92}Nb ($\tau_{1/2}$=3.47x10^7 y) : Unique Chronometer of SN ν–Process

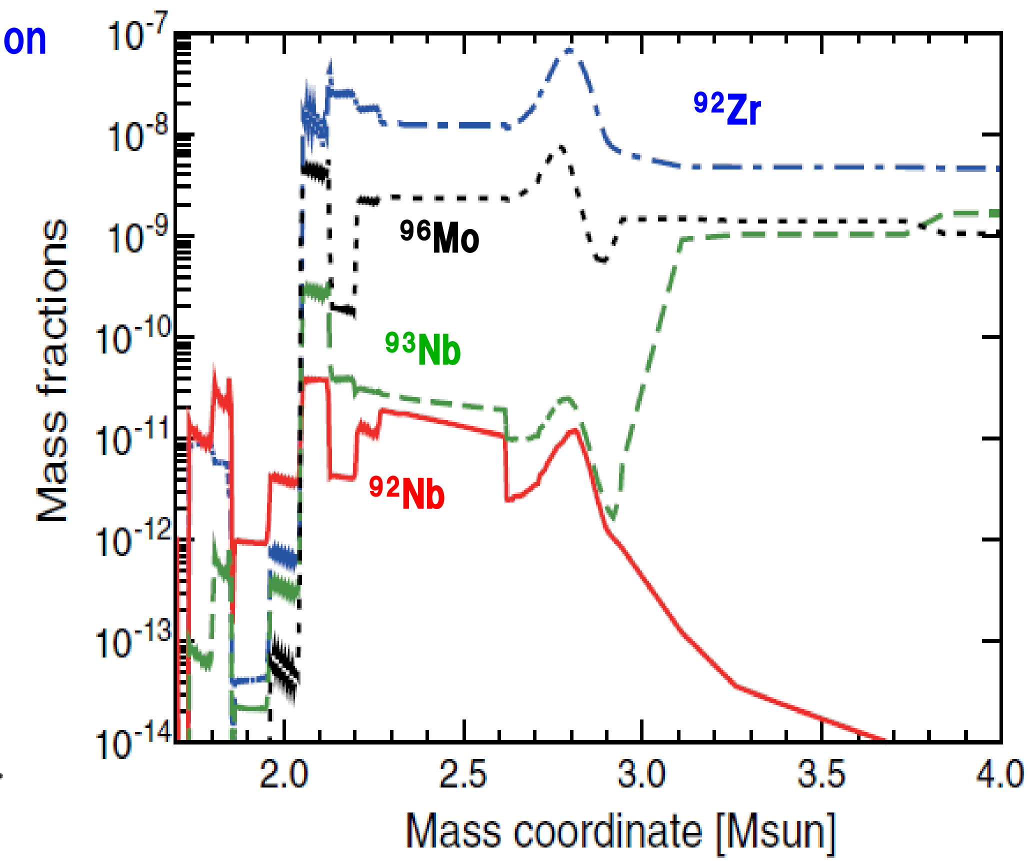
★ Isotopic anomaly in meteoritic ^{92}Zr/^{93}Nb

★ Time duration after the last nearby Supernova to the Solar-System formation

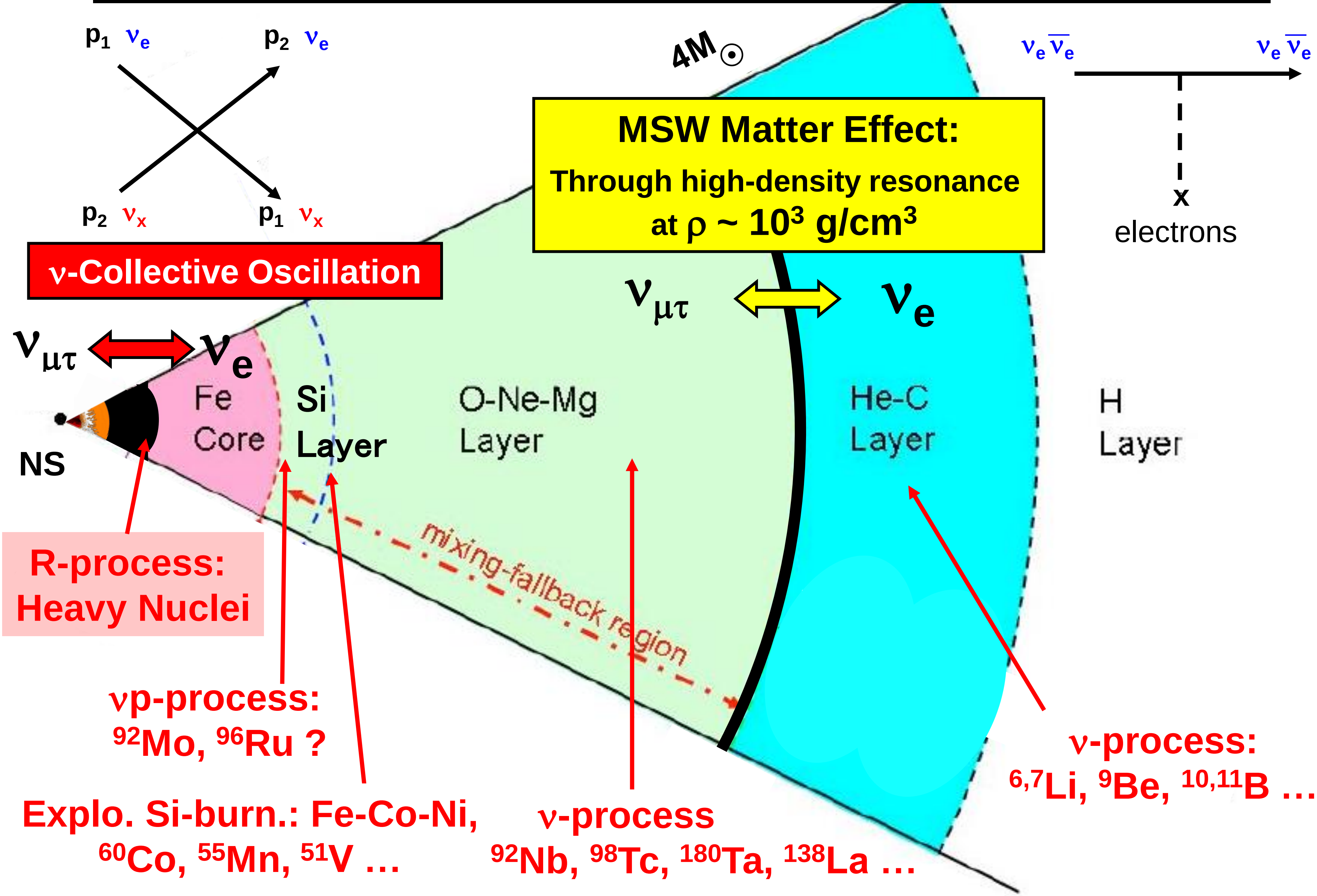
Δ = 1x10^6—3x10^7 y

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



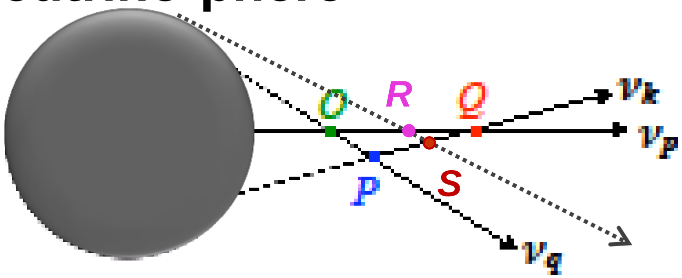


Neutrino Oscillation and SN-Nucleosynthesis



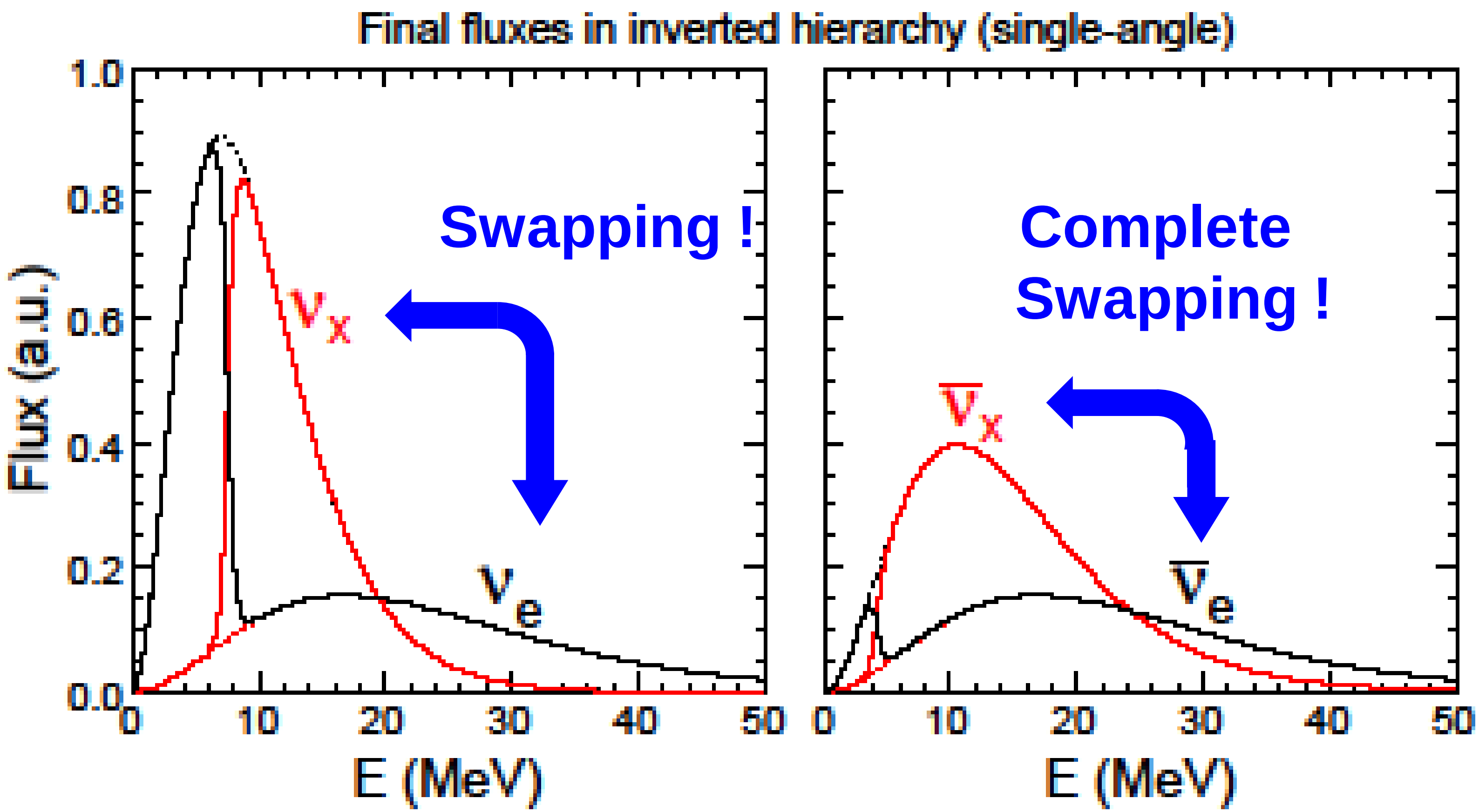
ν self-interaction = Collective Oscill.

neutrino-phere



H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, PRL 97 (2006), 241101.
G. Fogli, E. Lisi, A. Marrone, & A. Mirizzi, JCAP 12, (2007) 010.
A. B. Balantekin, Y. Pehlivan, J. Phys.G34, (2007) 47.

r = 200km

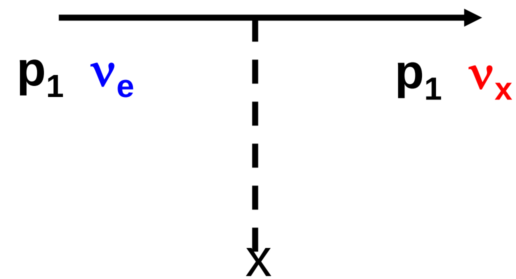


Neutrino Hamiltonian: $H_{tot} = H_\nu + H_{\nu\nu}$

H_ν = *Mixing and Interactions with Background Electrons*

MSW (Matter) Effect: Mikeheev-Smirnov-Wolfebstein (1978, 1985)

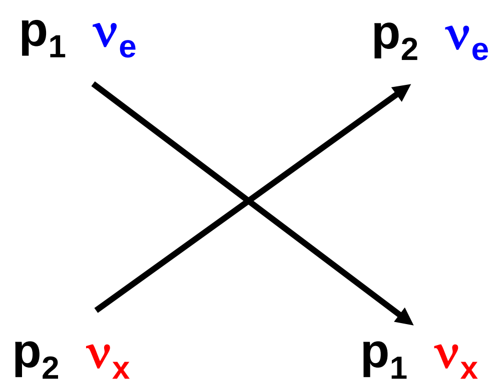
$$H_\nu = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right)$$
$$+\frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$



N_e = electron density

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

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



Quest for BETTER (hopefully BEST) Approximation to many-body SOLUTION !

"Invariants of collective neutrino oscillations"

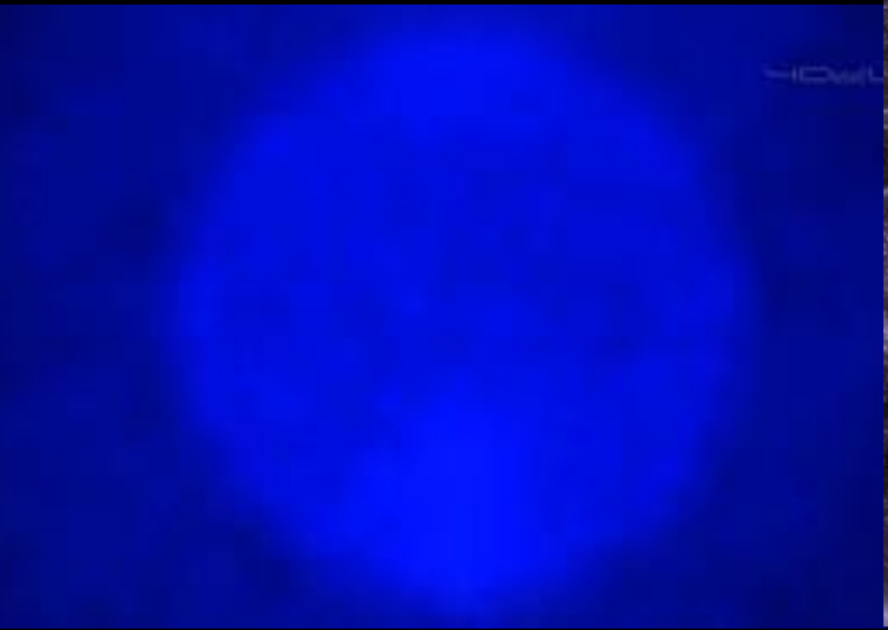
Y. Pehlivan, A.B. Balantekin, T. Kajino & T. Yoshida, Phys. Rev. D84, 065008 (2011),
Y. Pehlivan, A.B. Balantekin, & T. Kajino, Phys. Rev. D (2014), in press.

R-process is a clear probe of ν-interactions!

Where is the r-process astrophysical site?

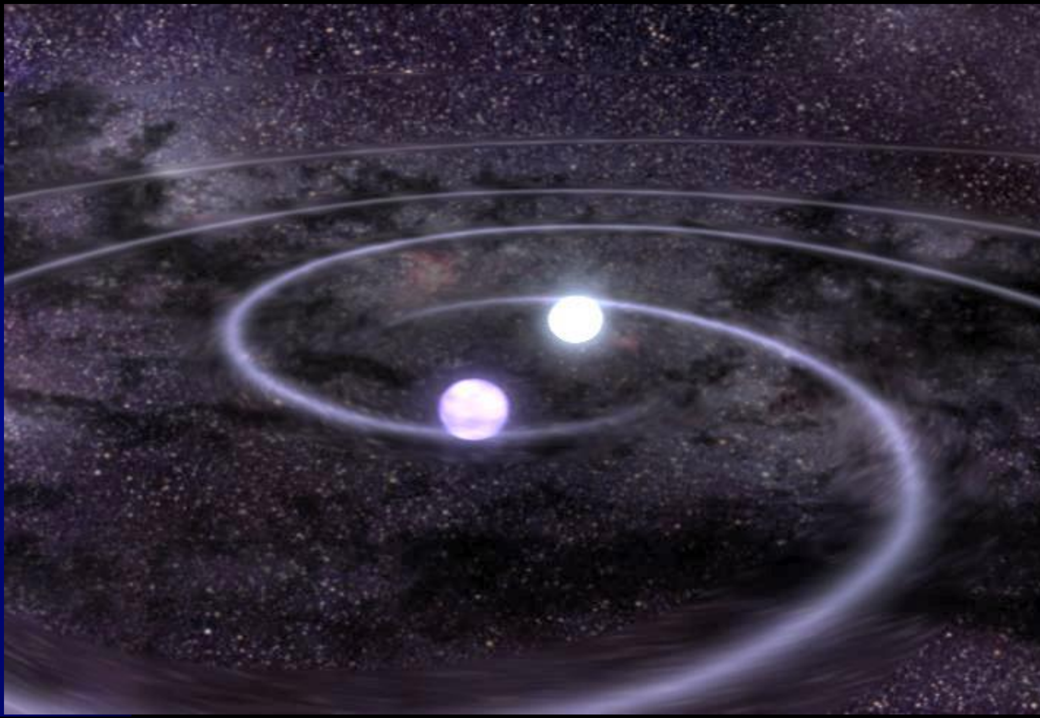
A Core-Collapse Supernova

3D ν-driven Wind Supernova
(11.2 Msun)
Takiwaki, Kotake, Suwa, ApJ 786 (2014), 83.



A Binary Neutron-Star Merger

Binary Neutron Star Merger
Credit-NASA



Candidate Astrophysical Sites for R-Process in Metal-Poor Stars

	Physical Conditions: S/k	Ye	$\dot{M}_r/(SN)$	Expected Event Rate	Evaluation
Supernovae					
ν-Driven Wind	100	0.45	$10^{-5}M_\odot$	10^{-2}/yr/gal*	○ Solar∼Metal poor stars ○ Universality → Weak-r ? △ Explosion model Too high Y_e ?
MHD Jet	10	0.1-0.4	$10^{-3}M_\odot$	10^{-4}	○ Solar∼Metal poor stars X Universality, broken △ Explosion model Special cond. ?
Gamma-ray Burst					
(S) Binary Neutron Star Merger	1	0.1	$10^{-2}M_\odot$	10^{-5}	X Universality, broken ? τ>1Gy, too late for [Fe/H]<-3? △ Explosion model Special cond. ?
(L) Collapsar	1-10^4	0.1	$10^{-1}M_\odot$	10^{-5}	○ Solar∼Metal poor stars X Universality, broken △ Explosion model Mechanism ?

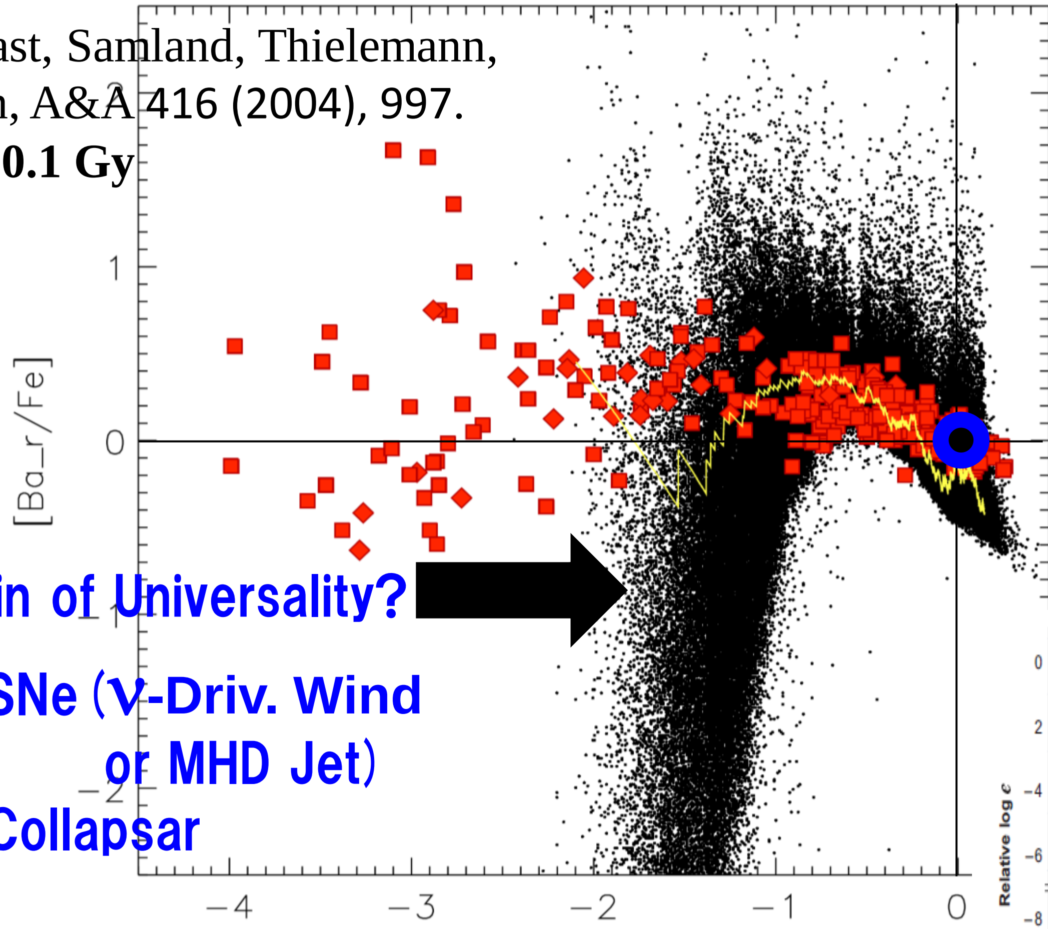
*Solar-System r-abundance = $10^3 M_\odot$ ← $10^{-5}M_\odot \times 10^{-2} \times 10^{10} = 10^3M_\odot$

Consistent with observed SN frequency

Cosmic age

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

τ_c = **0.1 Gy**



[Fe/H] ⟶ Galactic Time

Binary Neutron Star Mergers: Merging time scale, too long;

➡ **τ=3-4 Gy !**,

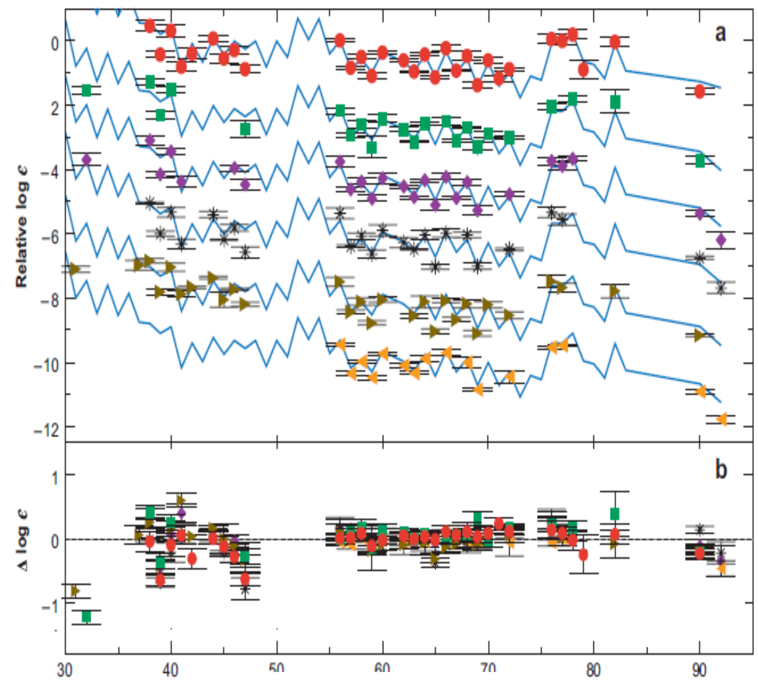
Wanderman and Piran (2014). arXiv: 1405.5878.

Serious Difficulty of Binary Neutron Star Mergers!

Origin of Universality?

- SNe (ν-Driv. Wind or MHD Jet)
- Collapsar
- Binary Neutron Star Merger could not be the Origin of Universality !

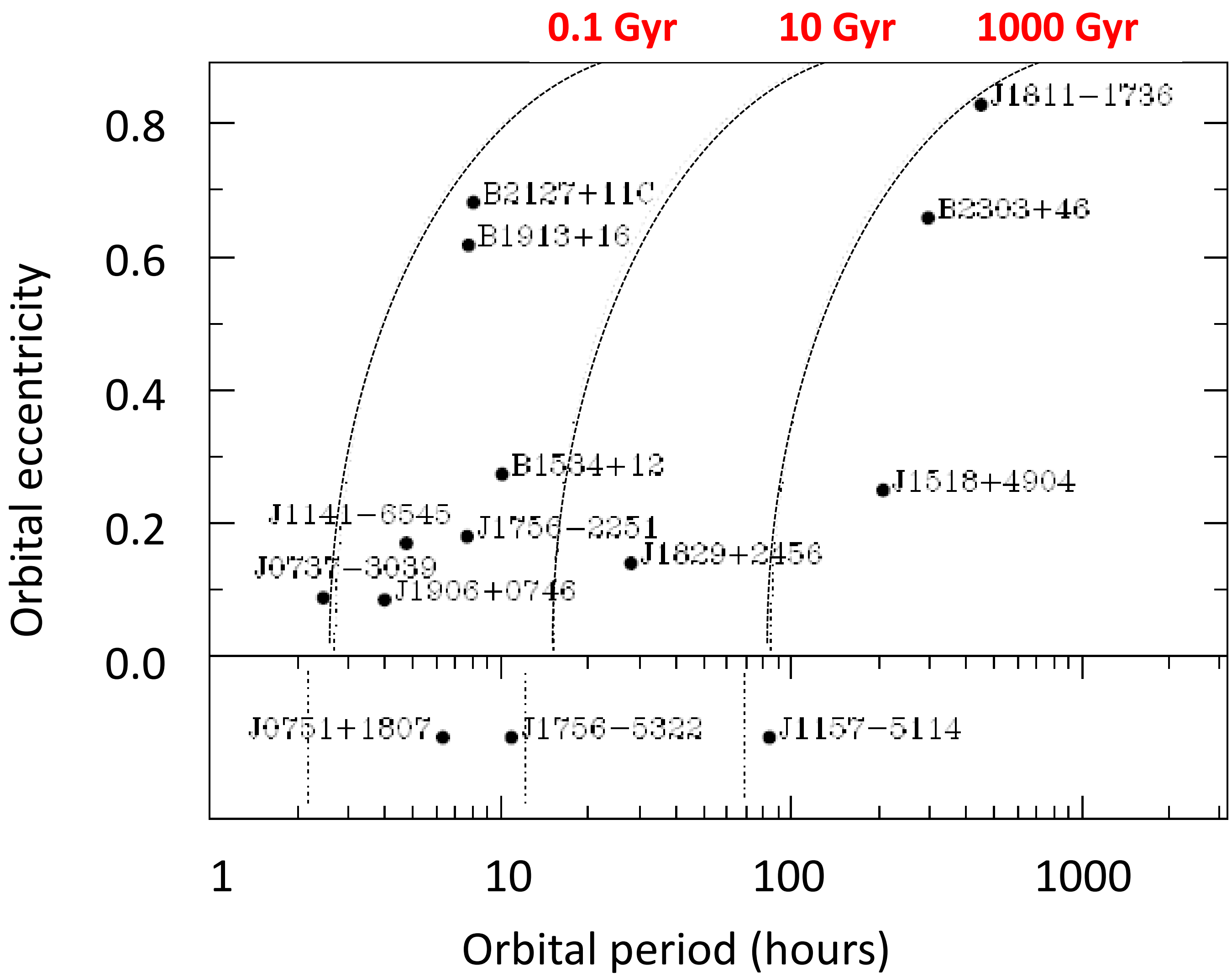
More Theoretical Studies of Galactic Chemo-Dynamical Evolution, REQIRED !



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

Time delay for coalescence = τ_c

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

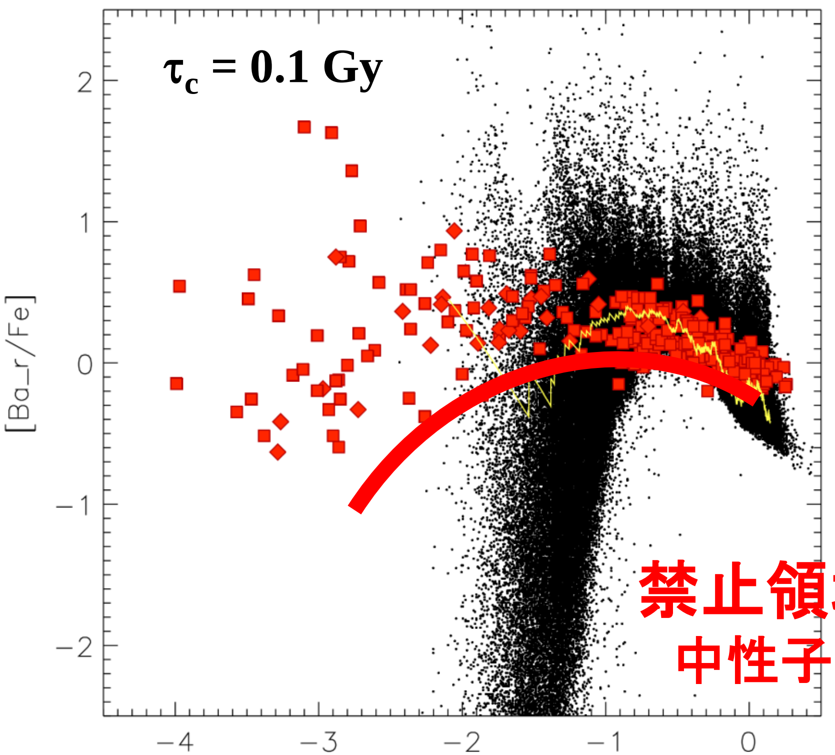


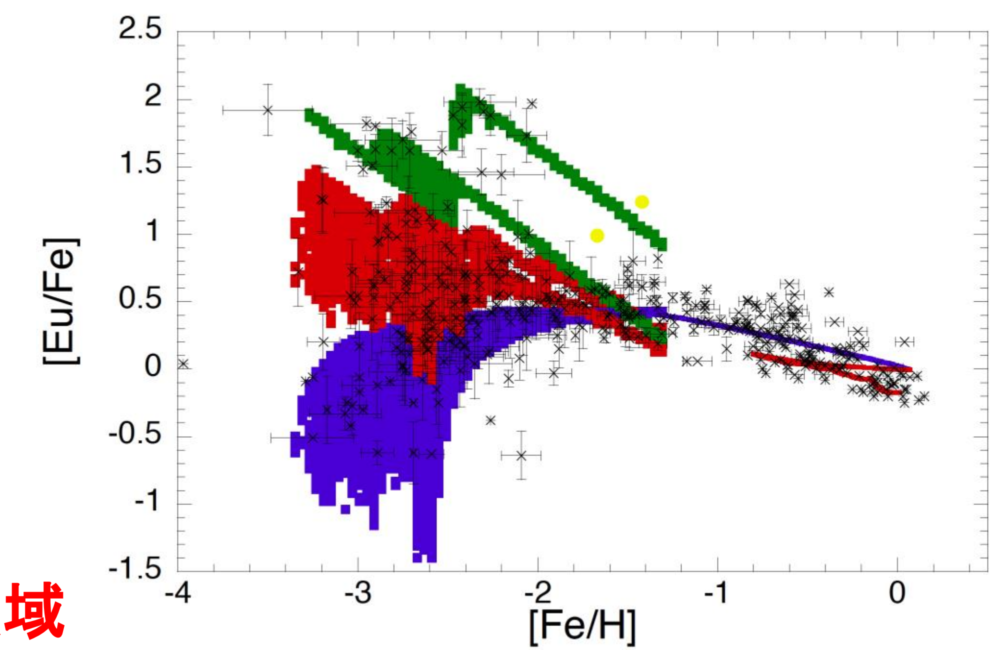
化学進化計算からの示唆

中性子星合体で元素は速度0.2cで放出されることを考慮し、
サブハローの集積モデルを用いることで解決？

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

Tsujimoto & Shigeyama, A&A 565 (2014), L5, Ishimaru et al. (2014)





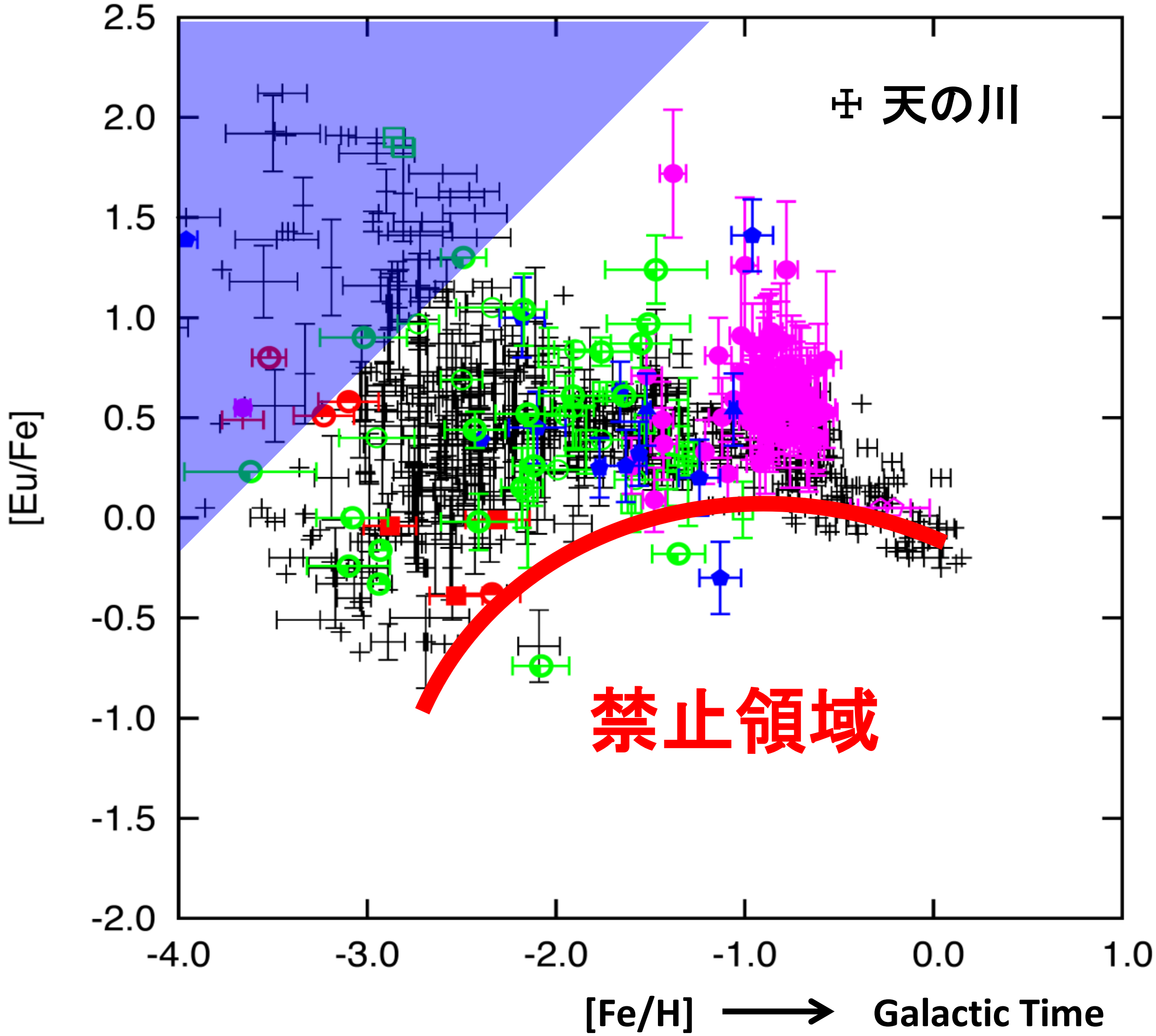
禁止領域

中性子星連星系合体の本質的困難！

[Fe/H] ⟶ Galactic Time

矮小銀河の r プロセス元素の観測

SAGA database (Suda et al. 2008)



- 禁止領域がある。τ_c（delay time for coalescence）を強く制限。
- rプロセス元素が卓越した extremely metal–poor stars が極めて少ない。
- [Fe/H]～−1付近にrプロセス元素量の異常がある。

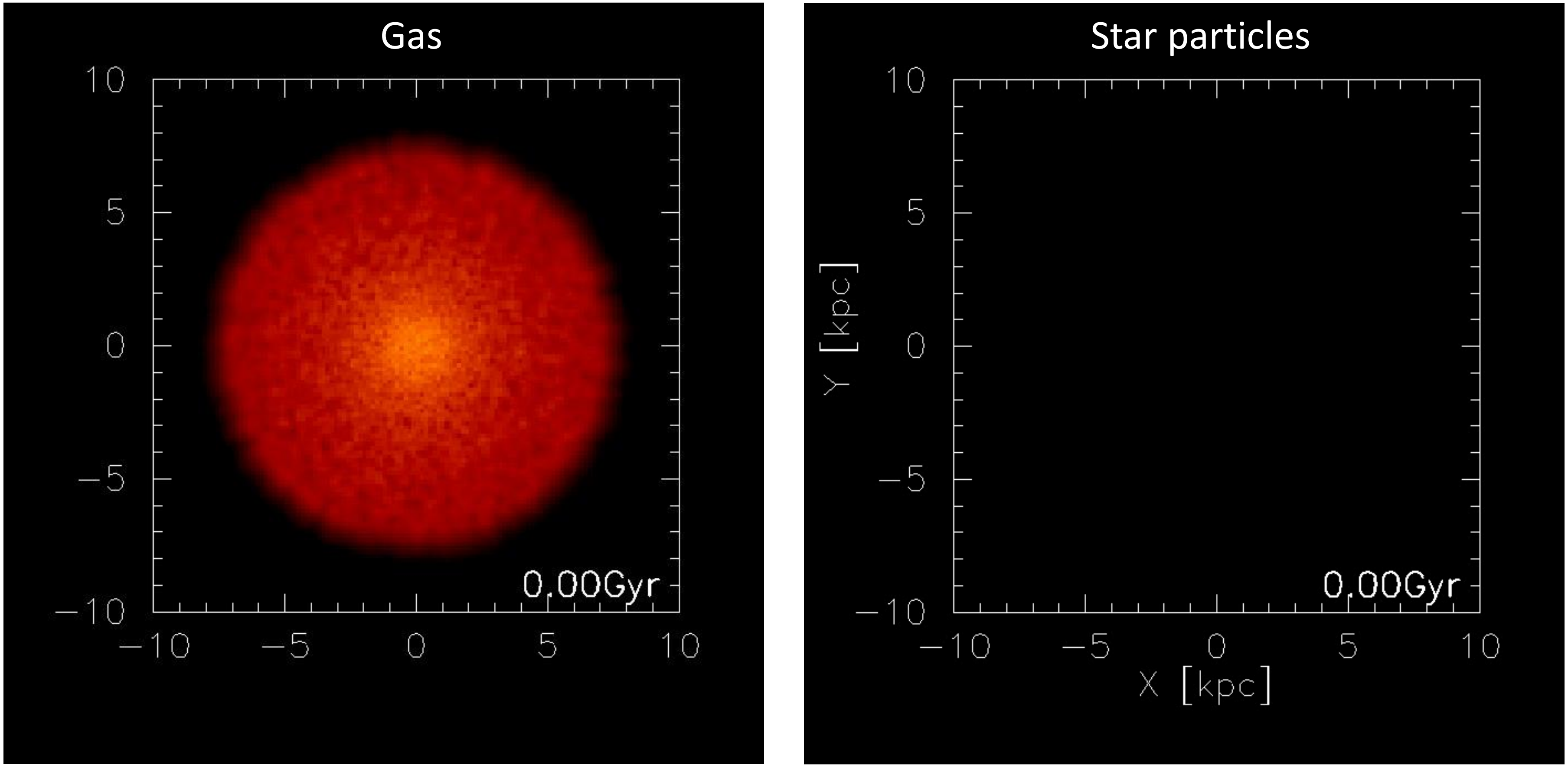
化学動力学進化計算 by ASURA（スパコン大規模計算）

ASURA (Saitoh et al., PASJ 60 (2008), 667; PASJ 61 (2009), 481)

SPH Simulation of Chemo–Dynamical Evolution of Dwarf Spheroidal:
SNe + NSM (τ_c=0.1Gy), Gas mixing & dilution for accretion & outflow in SF & SNe

Hirai, Kajino, et al., (COSNAP group) (2014)
$M_{tot} = 7x10^8 M_{sun}$, $N_i = 5x10^5$ particles, $M_\star = 100 M_{sun}$

Priliminary



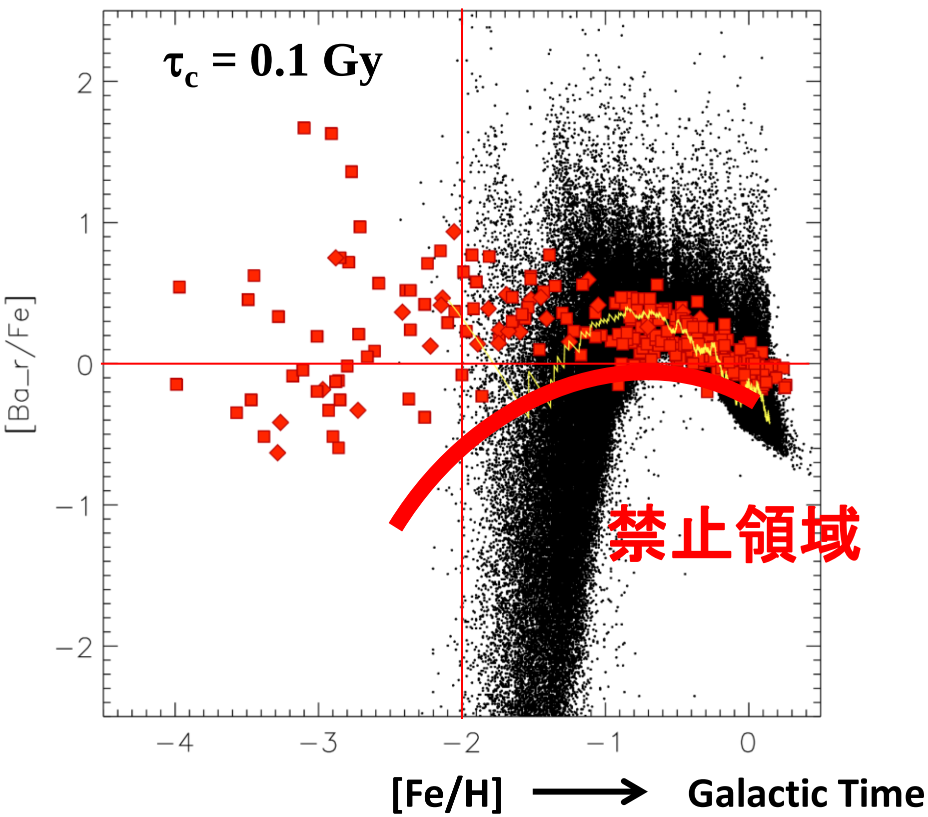
化学動力学進化計算：ASURA

Yesterday → Priliminary

SPH Simulation of Chemo–Dynamical Evolution of Dwarf Spheroidal:
SNe + NSM (τ_c=0.1Gy), Gas mixing & dilution for accretion & outflow in SF & SNe

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

Hirai, et al. (2014) (COSNAP group)



中性子星連成系合体までの時間（τ_c）が銀河進化に及ぼす効果

τ_c= 0.1 Gy (1億年)：観測的最小値

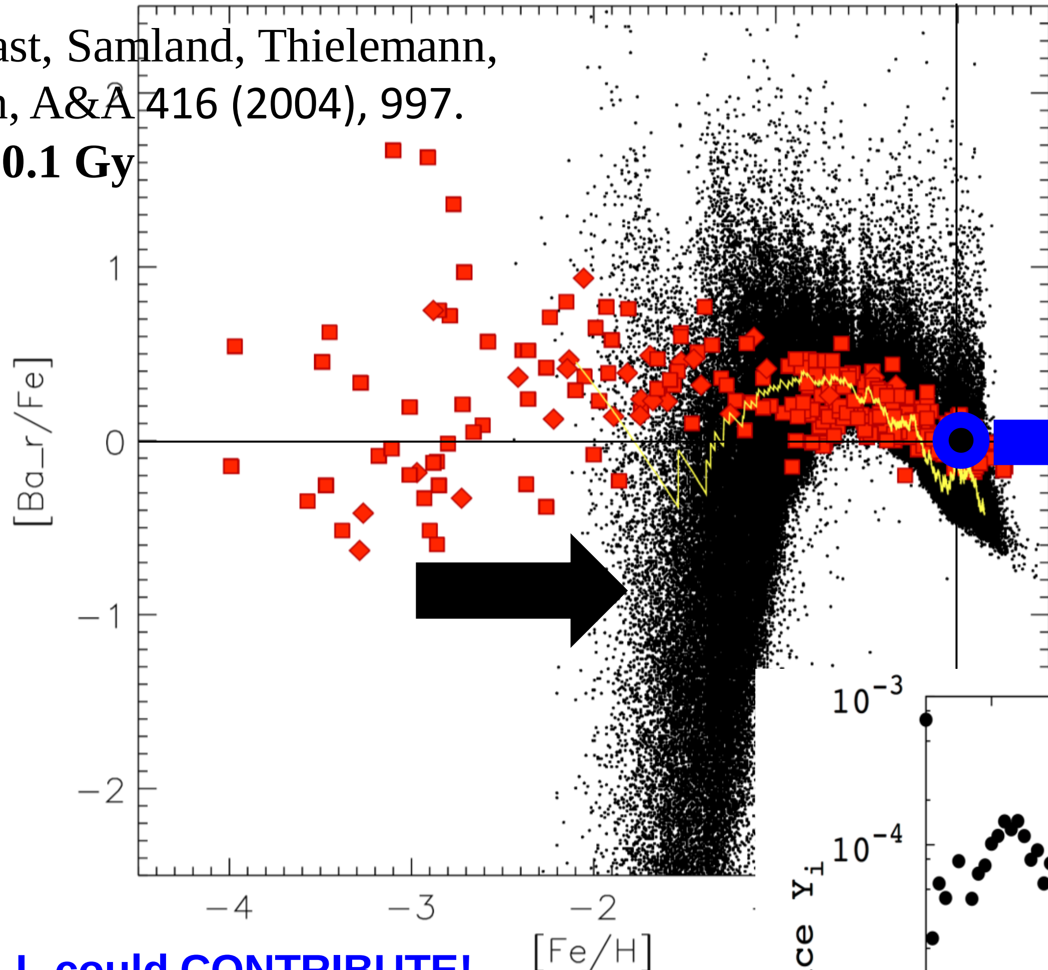
観測的禁止領域を再現できる可能性あり。

τ_c> 1 Gy (10億年):多数の観測例

現在、計算中。

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

τ_c = 0.1 Gy

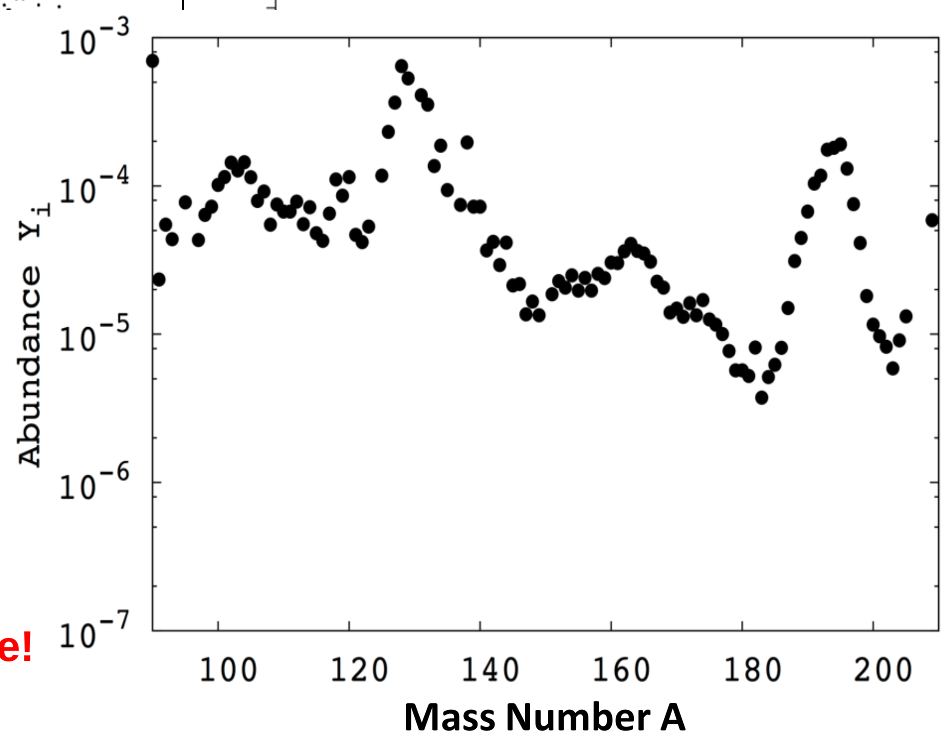


Binary Neutron Star Mergers: Merging time scale, too long;

→ **τ=3-4 Gy !**,

Wanderman and Piran (2014). arXiv: 1405.5878.

Solar System Abund.



ALL could CONTRIBUTE!

1) **ν-Driven Wind SNe**
2) **MHD Jet SNe**
3) **Neutron Star Mergers (τ > 1Gy)**
4) **Collapsars**

Problem of Merging time scale has gone!

PURPOSE

1. Solar-system R-process:
   Clarify thecontributions from MHD-Jet & Neutron Star Merger！

2. Relic Neutrinos:
   Constrain the EOS from SN & GRB ν's！

Fluid-Dynamical Data for Neutron Star Merger

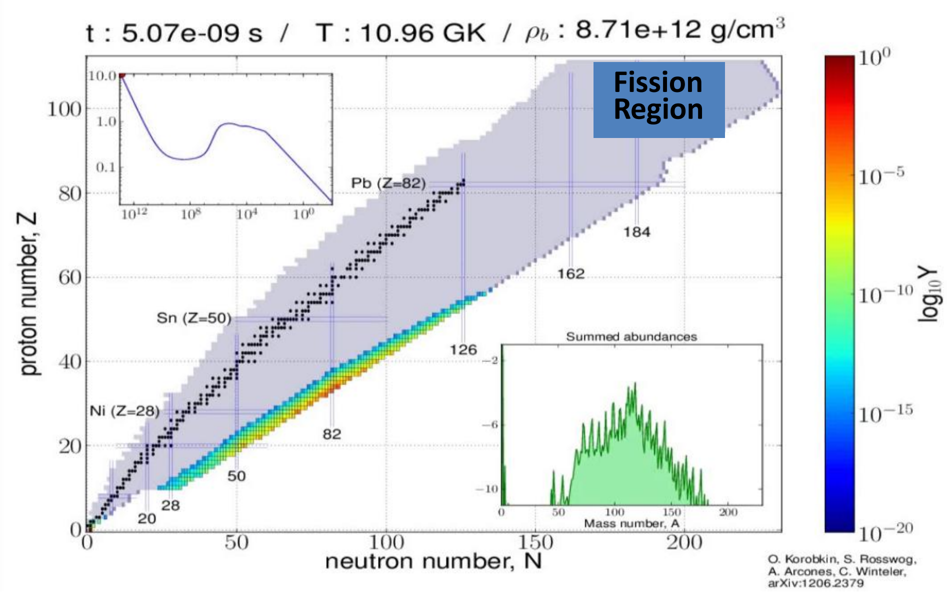
Binary Neutron Star Merger:

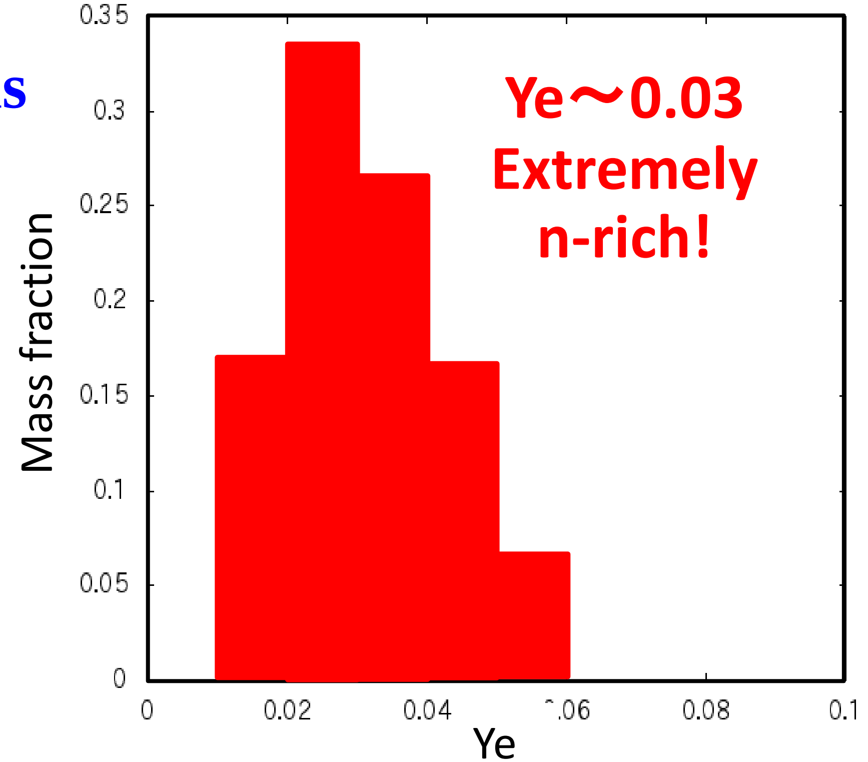
-Korobkin et al., MNRAS 426 (2012), 1940.
-Piran et al., MNRAS 430 (2013), 2121.
-Rosswog et al., MNRAS 430 (2013), 2585.
-Hotokezaka, K., Kiuchi, K., Kyutoku, K., et al., PR D87 (2013), 024001.
-Sekiguchi et al., (2014), in preparation.
-Wanajo, Sekiguchi, Nishimura, Kiuchi, Kyutoku, Shibata, ApJ 789 (2014), L39.

SPH simulation:

-Newtonian gravity
-Neutrino Leakage scheme

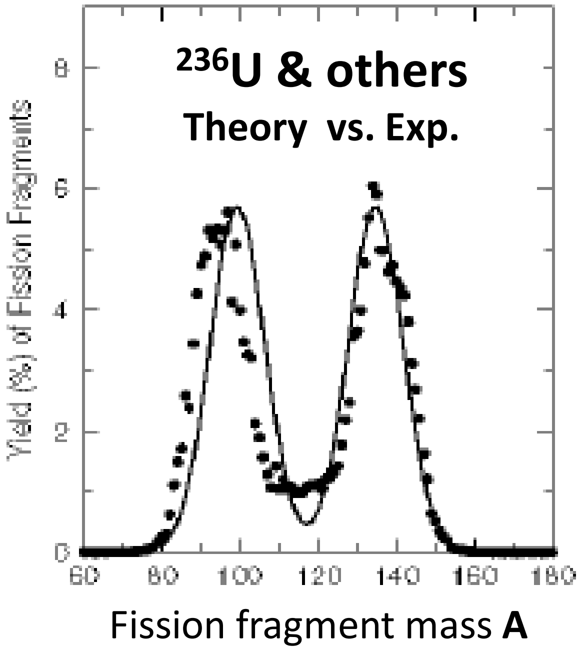
Apply to R-Process Nucleosynthesis

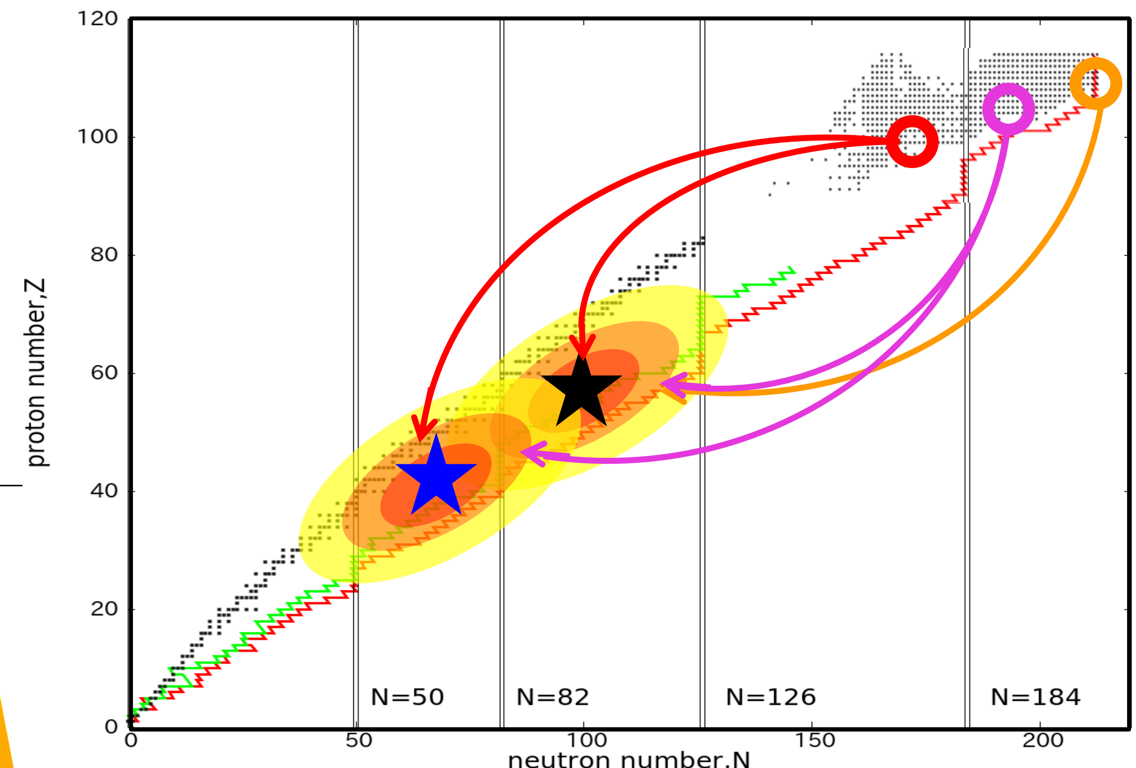


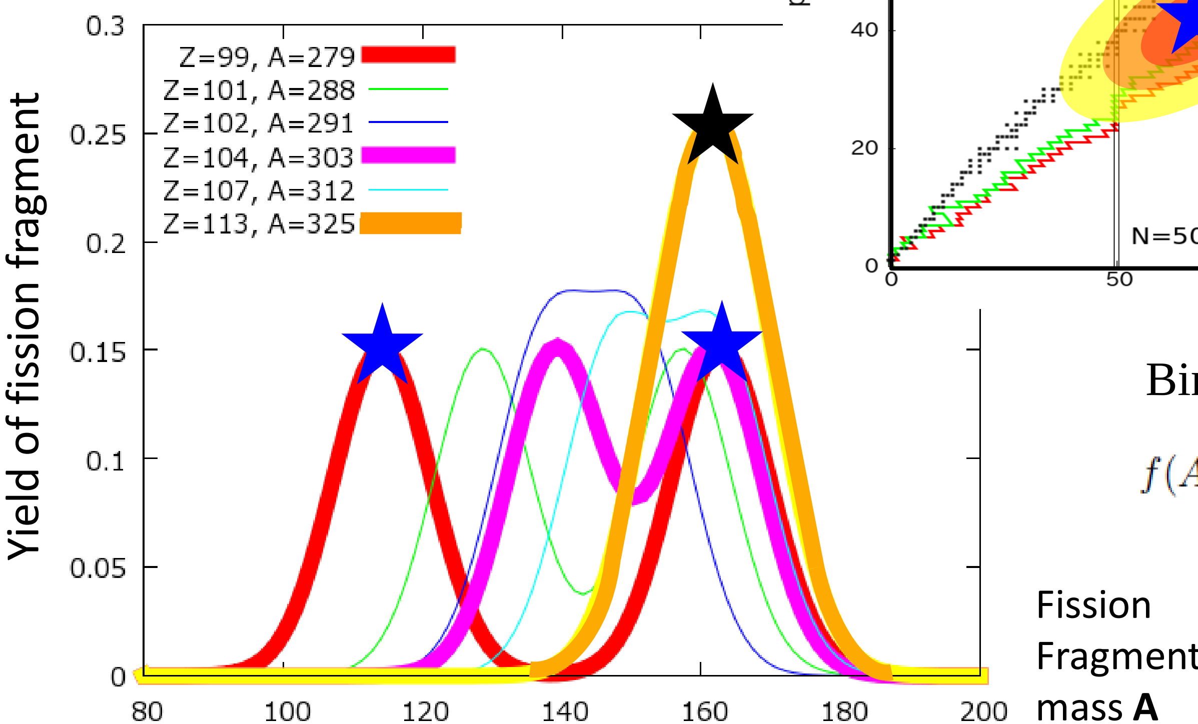


Fission Fragment Mass Distribution

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





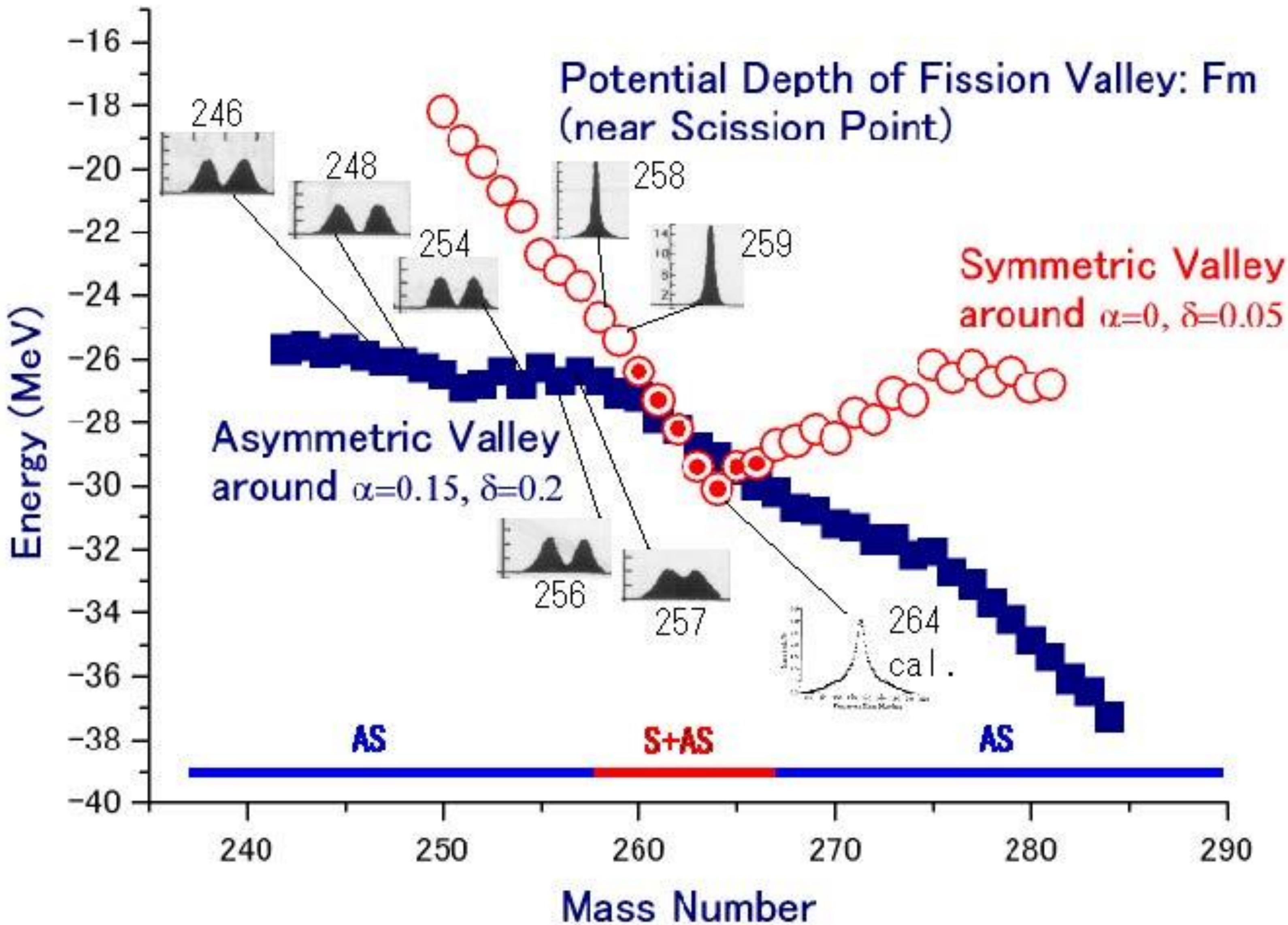


Bimordial or Trimodal FFD:

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

$$\begin{aligned} A_H &= (1+\alpha)(A_p - N_{loss})/2 \\ A_L &= (1-\alpha)(A_p - N_{loss})/2 \\ A_M &= (A_H + A_L)/2. \end{aligned}$$

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



Nuclear Models
— sensitive to Fission —

One of the Best Models !

Nuclear Mass Model :

KTUY Model

Fission Barrier, Q_β, (n,γ)

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

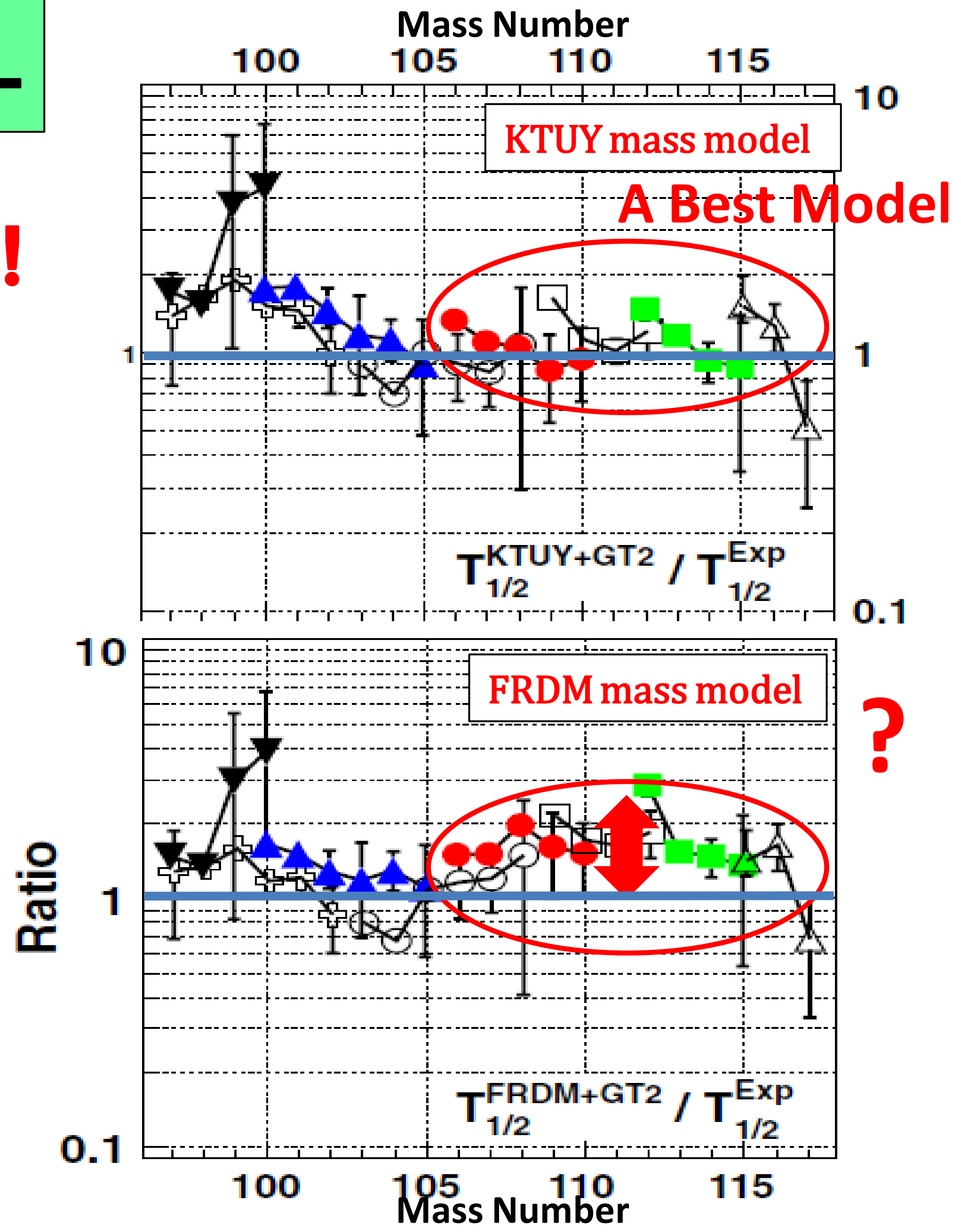
Reaction Rates:

α-decay, β-decay, fission

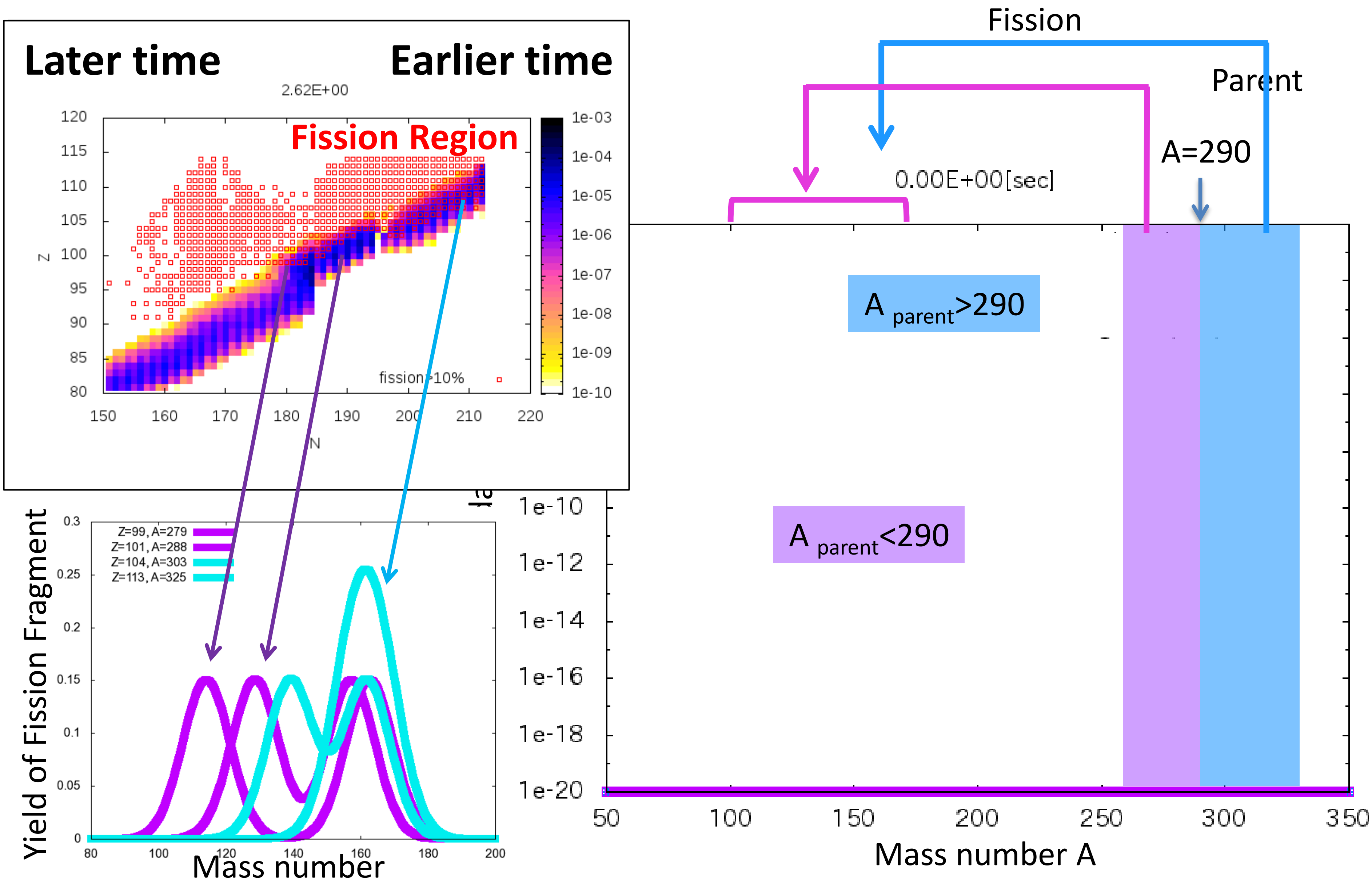
H. Koura, AIP Conf. Proc. 704, 60, (2004).

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

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



Abundance Evolution of Neutron Star Merger (MOVIE)

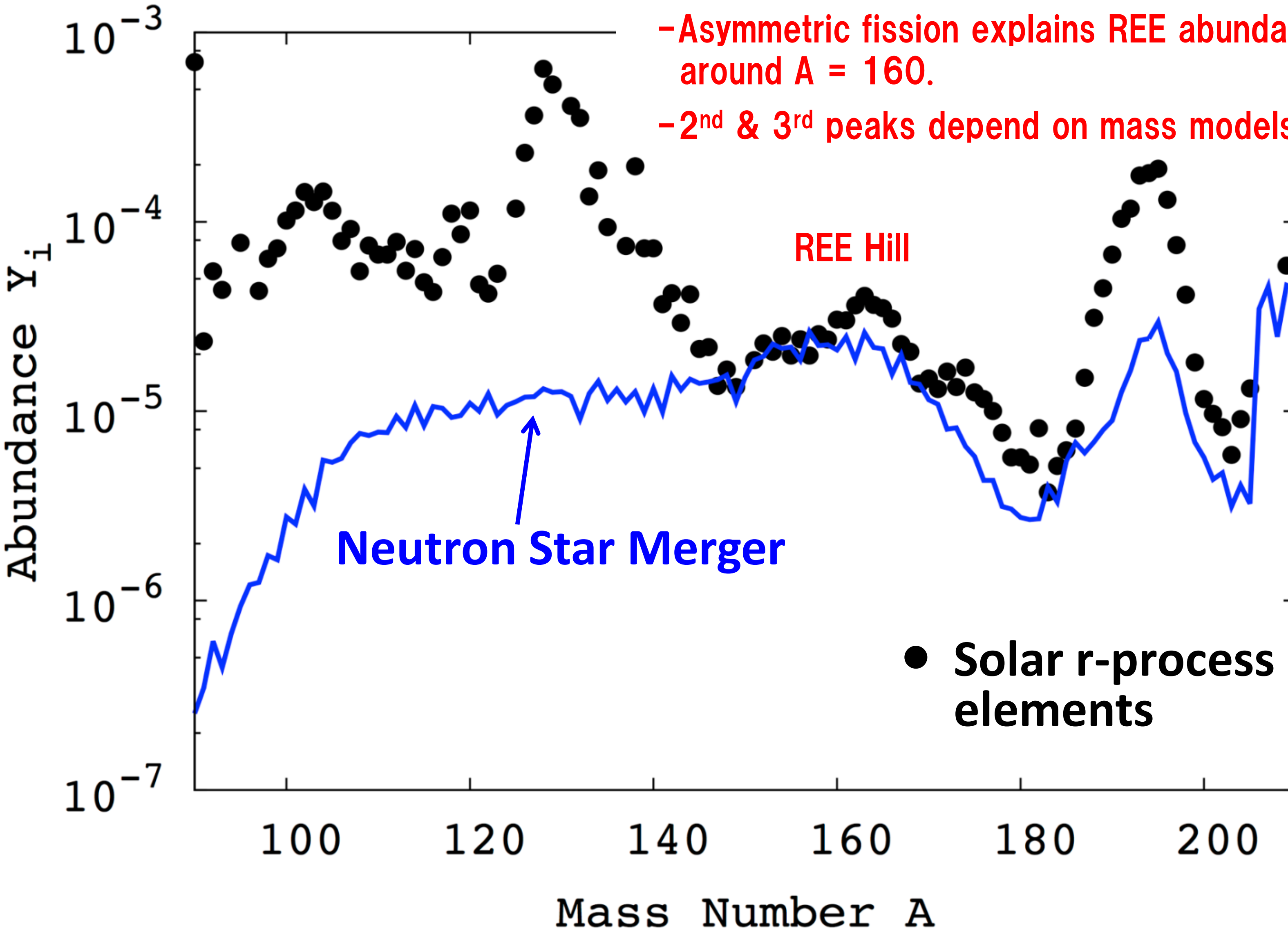


Contribution from Neutron Star Merger

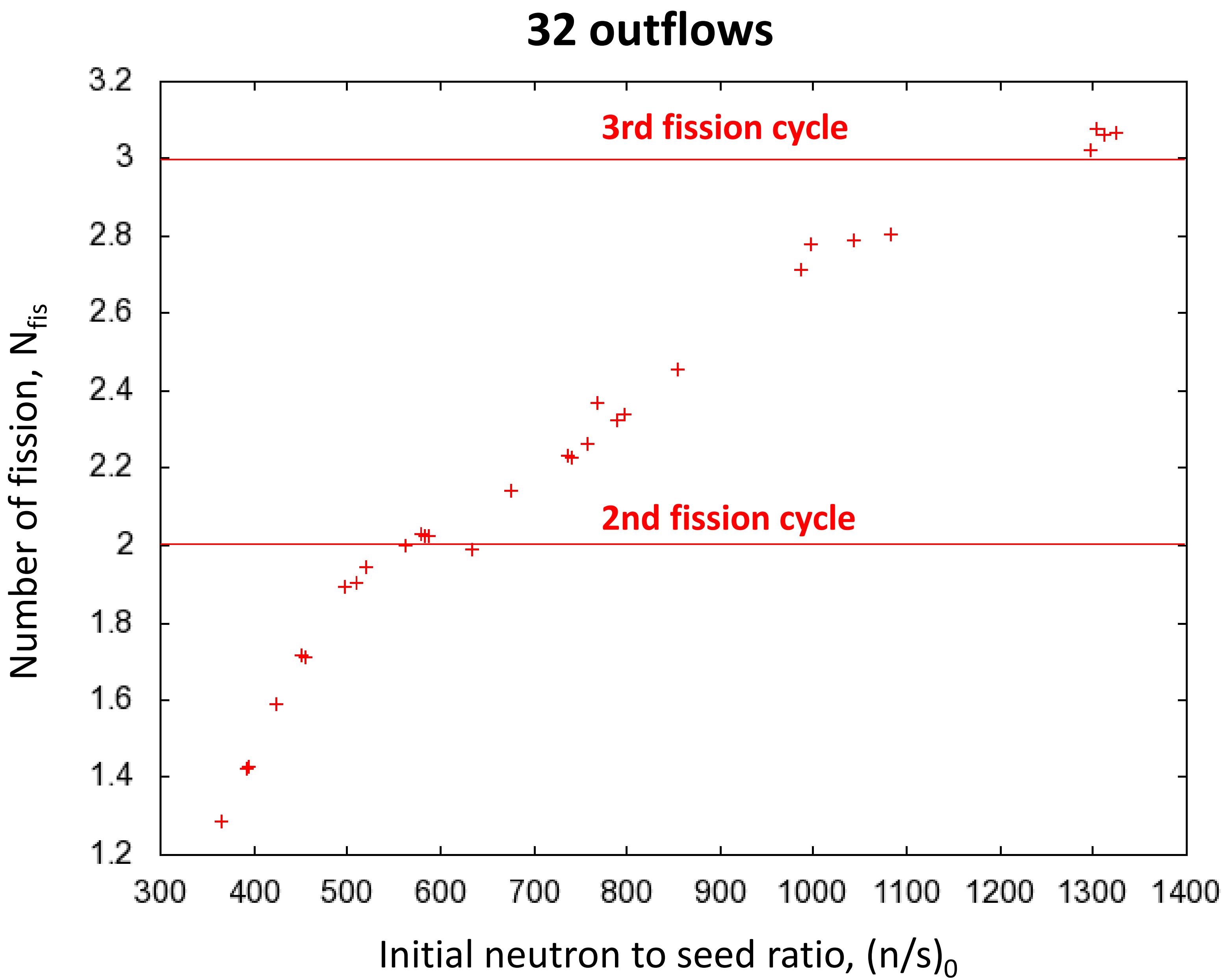
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso, submitted (2014)

S. Goriely et al., PRL 111, 242502 (2013)
M. Eichler, talk in this Conf. (7/11/2014)

- Asymmetric fission explains REE abundance hill around A = 160.
- 2nd & 3rd peaks depend on mass models & FFD.

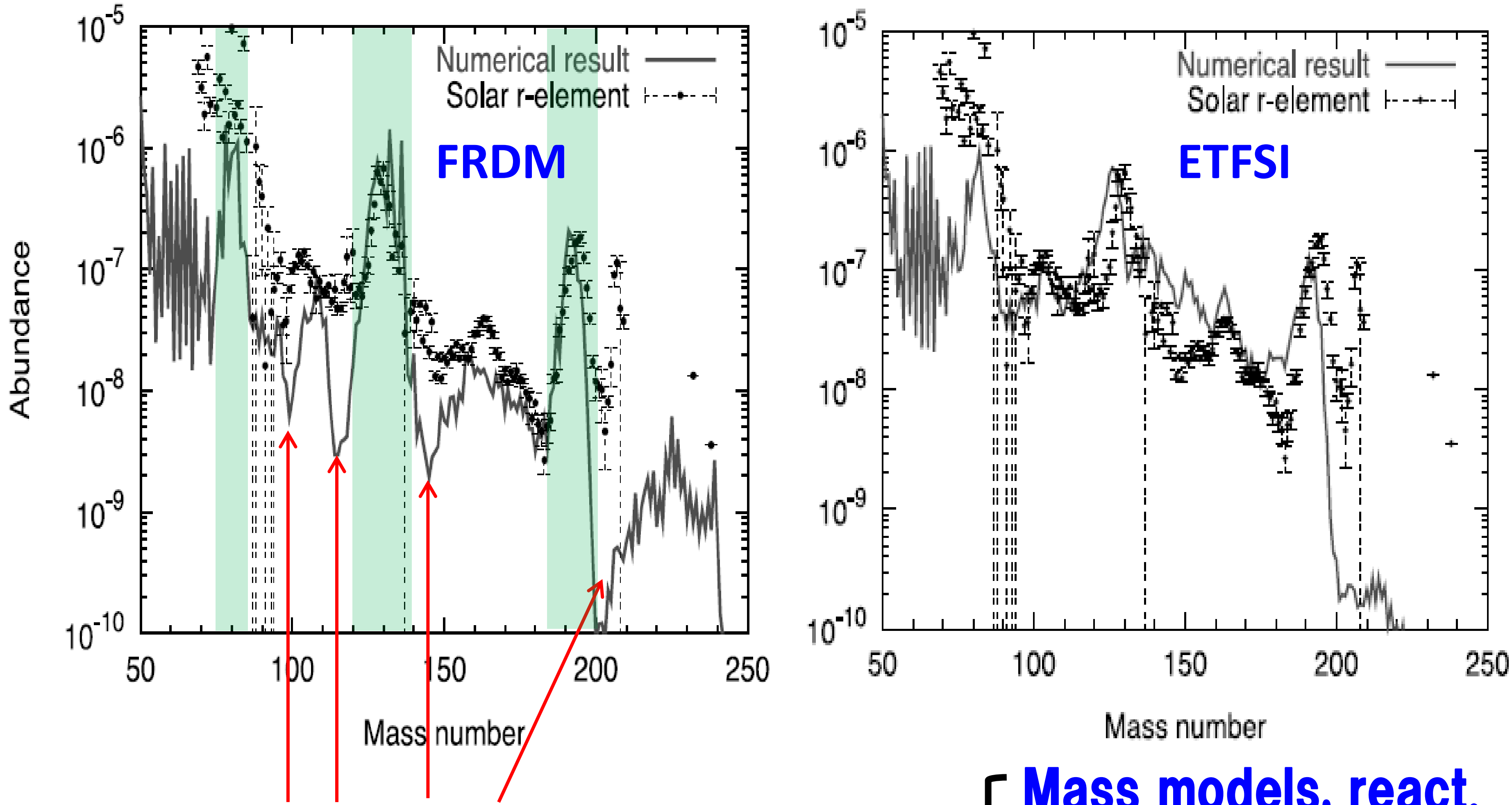


Estimated Number of Fission Cycles



Magneto-hydrodynam. (MHD) Jet Supernova

S. Nishimura, et al., ApJ , 642, 410 (2006)); T. Takiwaki, K.Katake and K. Sato, ApJ 691, 1360 (2009); Winteler, Kaeppeli, Perego, A., ApJ 750, L22 (2012); Takiwaki + (2014～) → Various conditions.

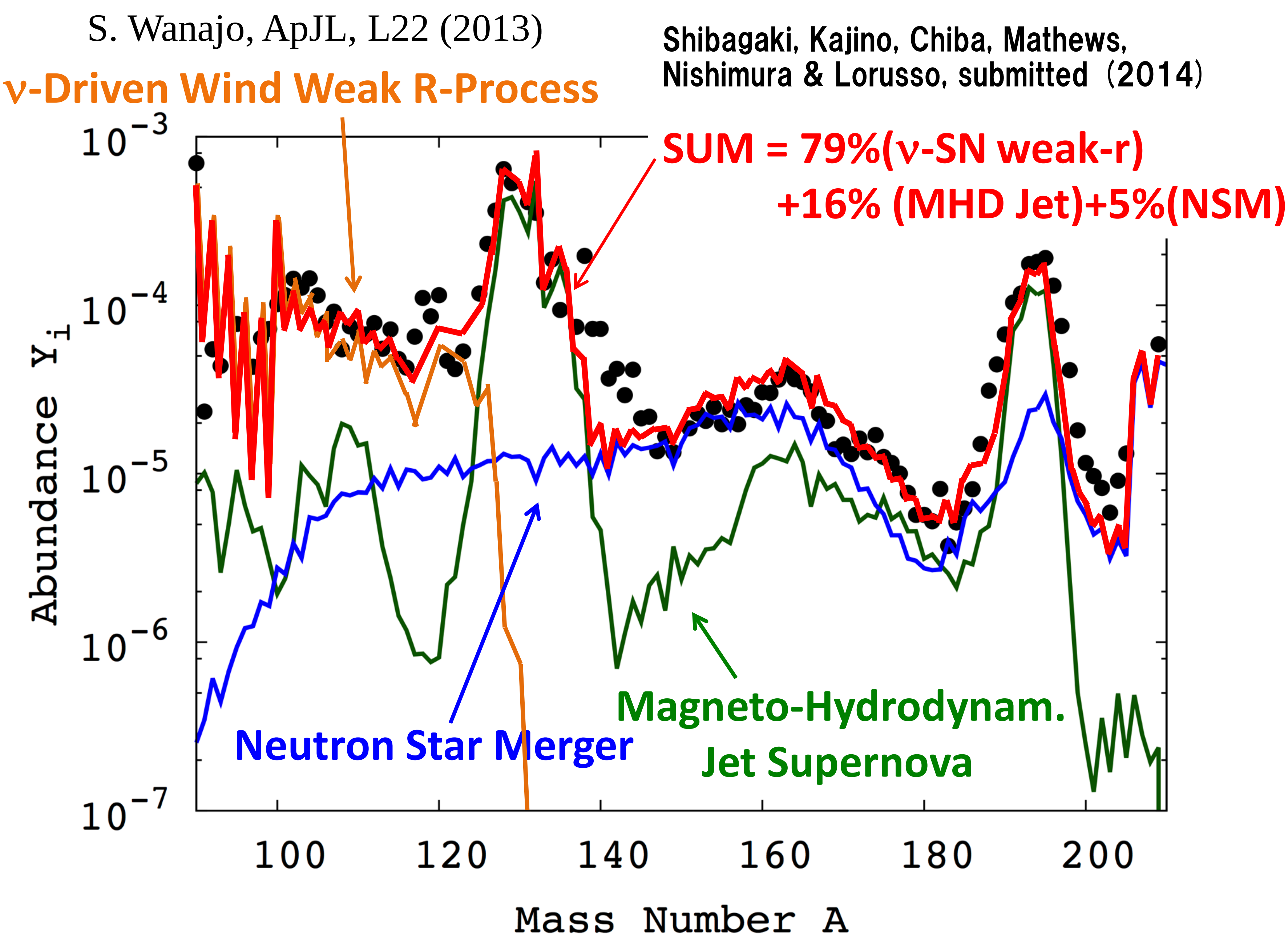


Underproduction PROBLEM !

Possible Solutions

- **Mass models, react. rates & partition fnct.**
- **Neutron Star Merger**

Recipe to reproduce solar r-elements



79% : 16% : 5% consistent with Observations !

Ejected Mass x Event Rate

Weak r = 7.4×10^{-4} x (1.9 ± 1.1) [M_{sun}/Galaxy/Century]

MHD Jet = 0.6×10^{-2} x $((0.03 \pm 0.02) \times (1.9 \pm 1.1))$ [M_{sun}/Galaxy/Century]

NSM = $(2 \pm 1) \times 10^{-2}$ x $(1\text{-}28) \times 10^{-3}$ [M_{sun}/Galaxy/Century]

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

A New Method to constrain EOS from Relic SN-ν

G.J. Mathews, J. Hidaka, T. Kajino & J. Suzuki, ApJ 790 (2014) ,115.

The Astrophysical Journal, 738:154 (16pp), 2011 September 10

THE COSMIC CORE-COLLAPSE SUPERNOVA RATE DOES NOT MATCH THE MASSIVE-STAR FORMATION RATE

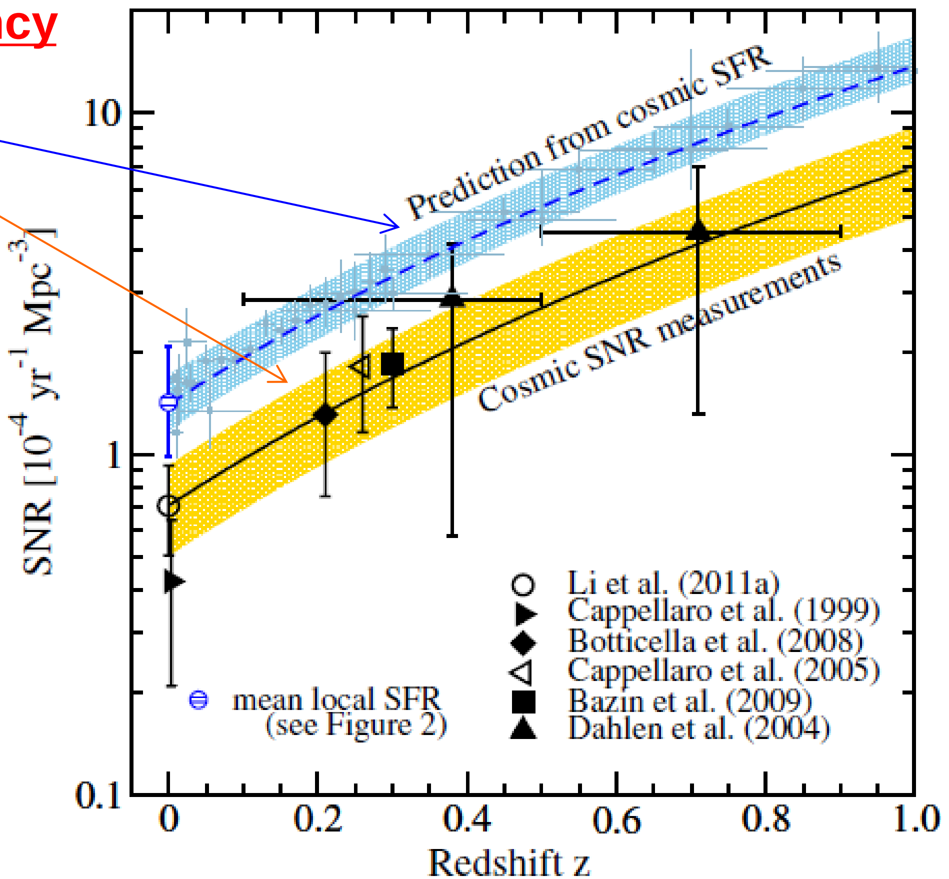
Shunsaku Horiuchi[1,2], John F. Beacom[1,2,3], Christopher S. Kochanek[2,3], Jose L. Prieto[4,5], K. Z. Stanek[2,3], and Todd A. Thompson[2,3,6]

Supernova Rate Problem/Discrepancy

SFR of Massive Stars at birth

SNR: Supernova Explosions at death !

50% Massive Stars, missing !



Expected Reasons:

Half was evolved into too dark SNe to detect!

1. Failed SNe (<25M⊙ BH formation)
2. Faint ONeMg-SNe (8-10 M⊙)

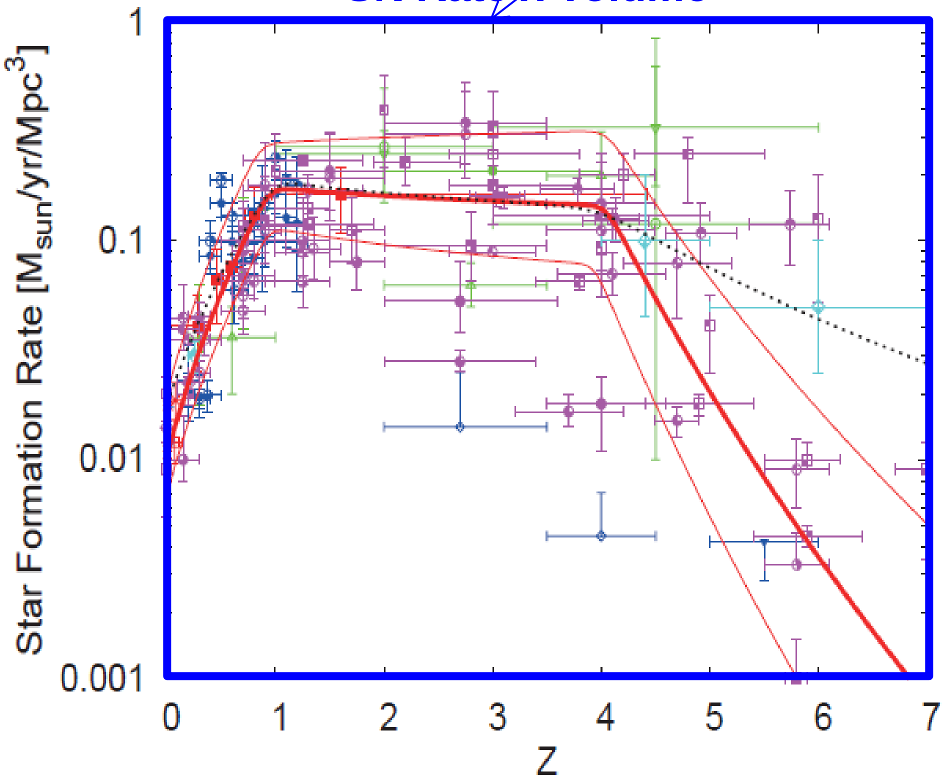
or the mass function changed!

Spectrum of Relic Supernova Neutrinos (RSNs)

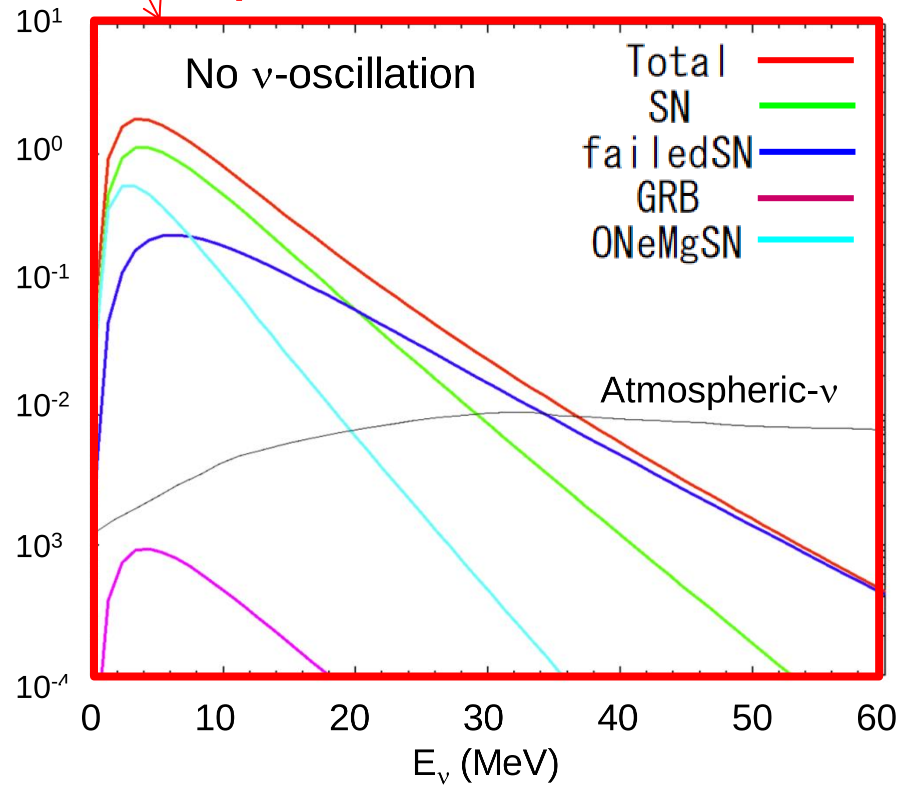
Totani, T., Sato, K. & Yoshida, Y. 1996, ApJ, 460, 303
Totani, T., et al., 1998, ApJ, 496, 216

$$\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\times\frac{dz}{\sqrt{(\Omega_m)(1+z)^3+\Omega_\Lambda}}$$

SN Rate x Volume



ν-spectrum at Various SNe & GRB

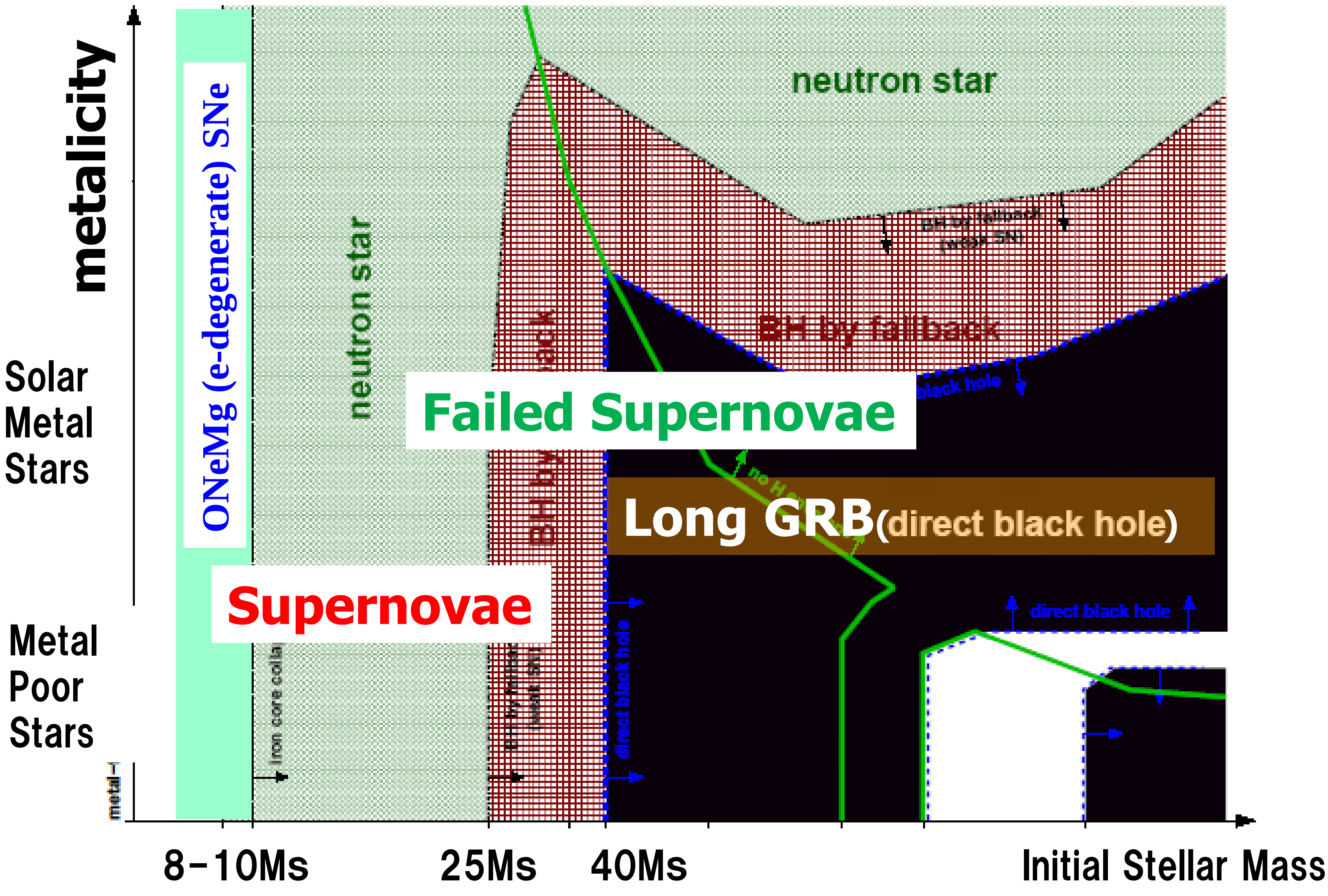


SNe & GRBs are the Multi-Messengers

Relic Neutrinos → Constrain EOS !

Fate of Massive Star

A. Heger et al. (2003)

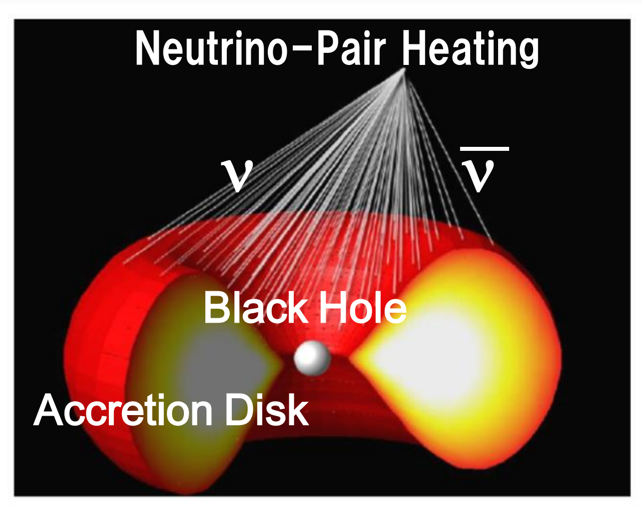


ν-driven wind weak-r	MHD-Jet SNe	faint !	Long GRB

Electron-capture SNe (Faint SnNe)	Normal CC-SNe (Neutron Star fromation)	Failed SNe (Black Hole formation)	Pair-ν heated SNe (BH + Acc. Disk)

detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e} (MeV)	3.0	3.2	5.5	7.9	3.2
$T_{\bar{\nu}_e}$ (MeV)	3.6	5.0	5.6	8.0	5.3
T_{ν_x} (MeV)	3.6	6.0	6.5	11.3	4.4
$E^{total}_{\nu_e}$ (erg)	3.3×10^{52}	5.0×10^{52}	5.5×10^{52}	8.4×10^{52}	1.7×10^{53}
$E^{total}_{\bar{\nu}_e}$ (erg)	2.7×10^{52}	5.0×10^{52}	4.7×10^{52}	7.5×10^{52}	3.2×10^{53}
$E^{total}_{\nu_x}$ (erg)	1.1×10^{53}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	$\sim 0.5s$	$\sim 0.5s$	$\sim 10s$

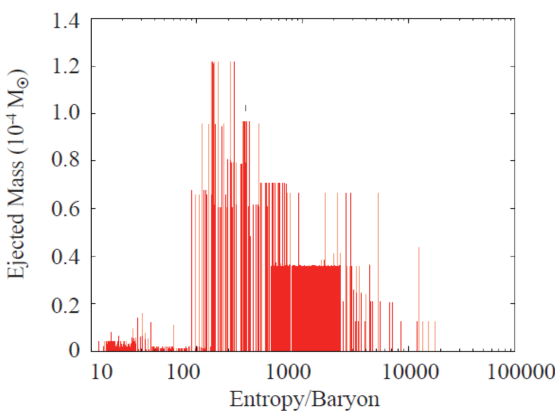
- **CC-SNe:** Yoshida, et al., ApJ **686** (2008), 448; Suzuki & Kajino, J. Phys. **G40** (2013) 83101.
- **fSN (failed SNe):** Sumiyoshi, et al., ApJ **688** (2008) 1176.
  - * **Shen-EOS (stiff):** Shen et al. Nucl. Phys. **A637** (1998) 435.
  - * **LS-EOS (soft):** Lattimer & Swesty, Nucl. Phys. **A535** (1991) 331.
- **ONeMg SNe:** Hudepohl, et al., PRL 104 (2010).
- **GRBs:** Nakamura, Kajino, Mathews, Sato & Harikae, *Int. J. Mod. Phys.* **E22** (2013) 1330022; Kajino, Mathews & Hayakawa, J. Phys. **G41** (2014) 044007.

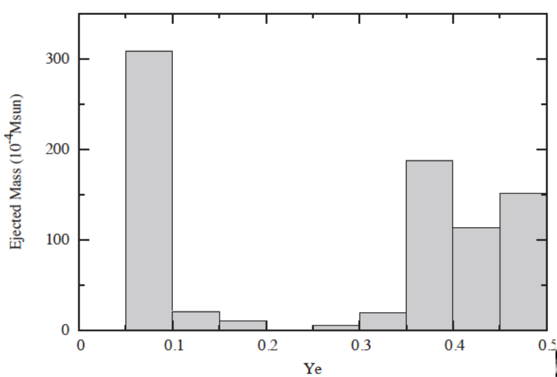


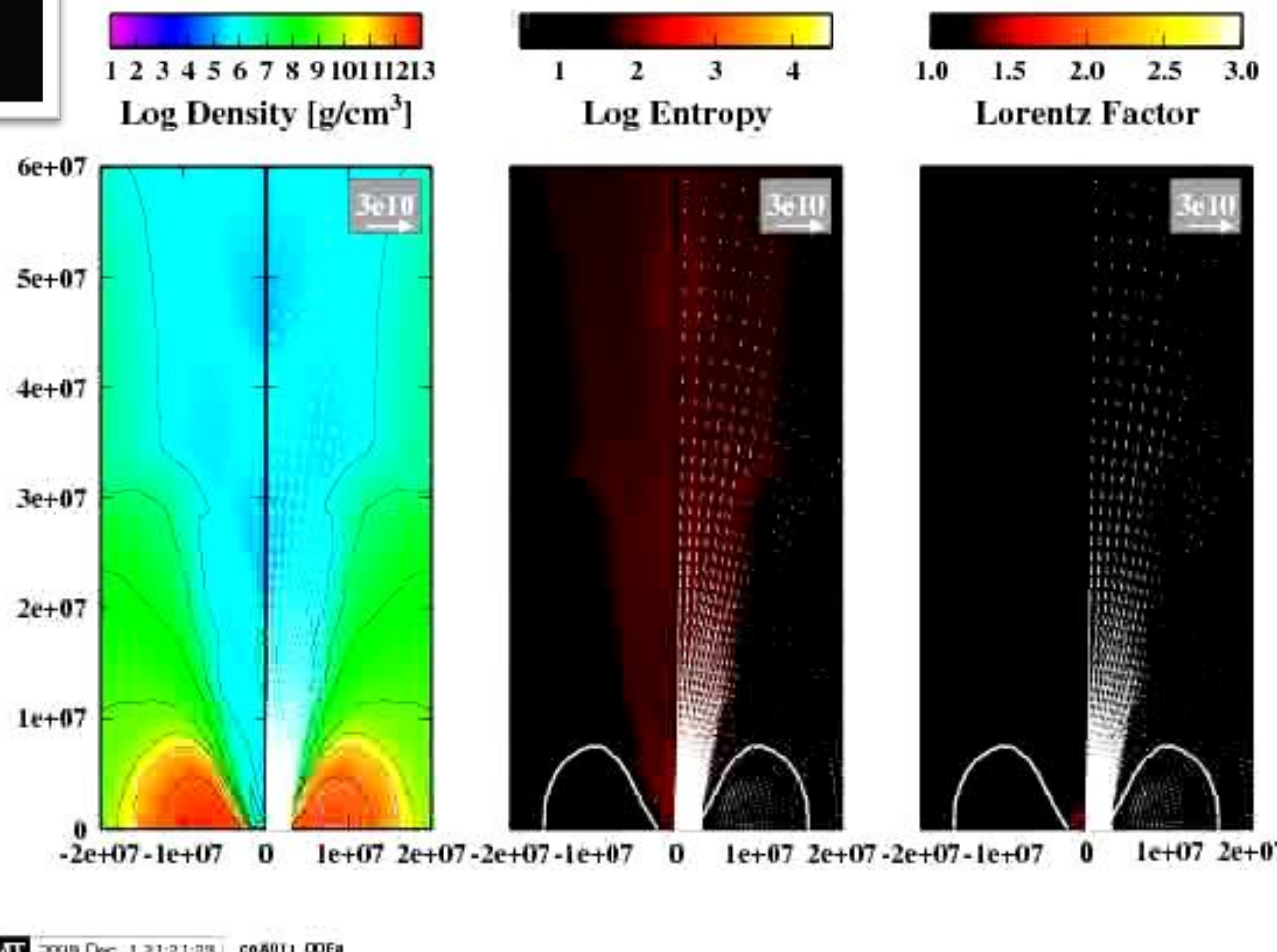
Collapsars for Long GRBs

MacFayden & Woosley (1999), Nagataki (1996):

Harikae, Takiwaki & Kotake, ApJ 704 (2009), 354; 713 (2010) 304.
Nakamura, Kajino, Mathews, Sato & Harikae, IJMP 22(2013), 1330022.

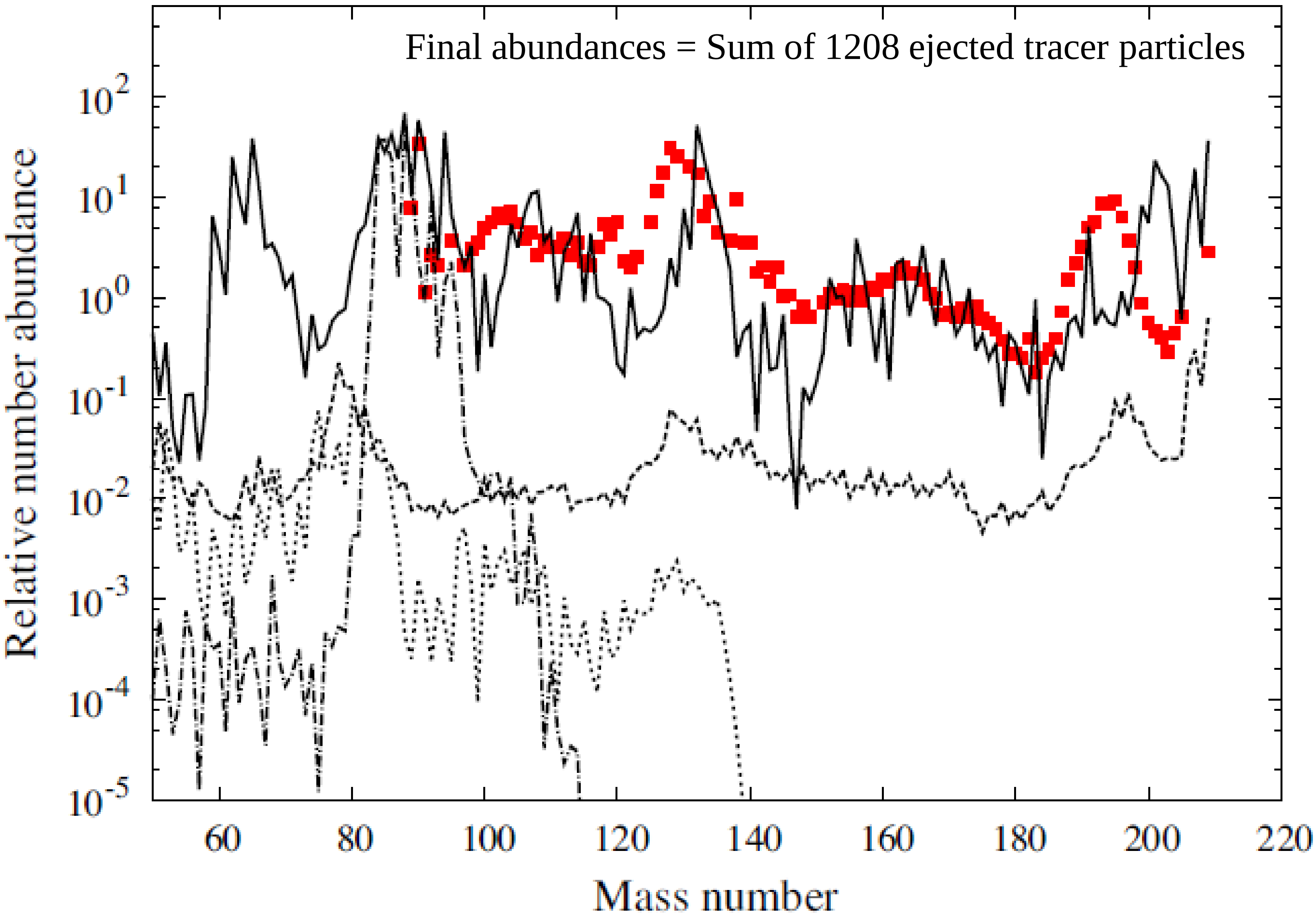






R-Process Nucleosynthesis in Gamma-Ray Bursts

Nakamura, Kajino, Mathews, Sato & Harikae, IJMP 22(2013), 1330022.



Relic Supernova Neutrinos (RSNs)

Hyper-Kamiokande (Mega-ton, 10y), Gd-loaded Water Cherenkov Detector

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

G. J. Mathews, J. Hidaka, T. Kajino, and J. Suzuki, A... (2014),115.

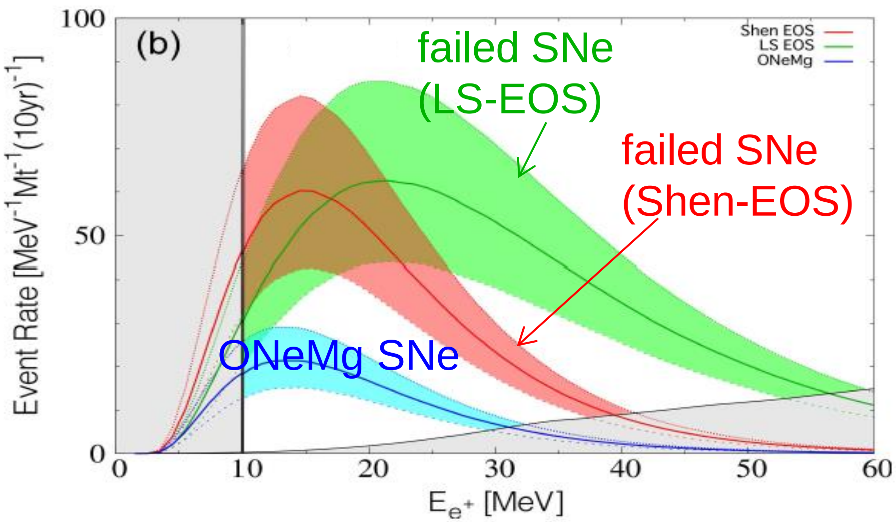
Assuming 2 x failed SNe for BH formation!

SN rate problem is resolved!

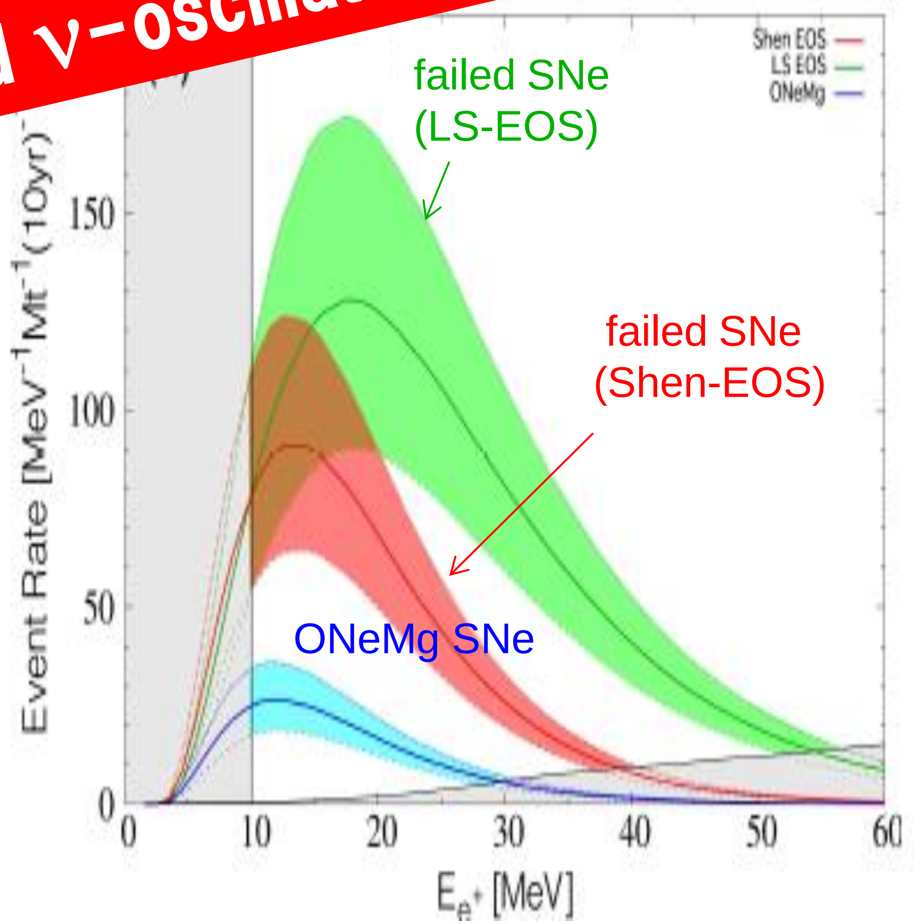
Same assumpti...

RSN-ν is a sensitive probe of the EoS of the Proto-Neutron Star and ν-oscillation pattern !

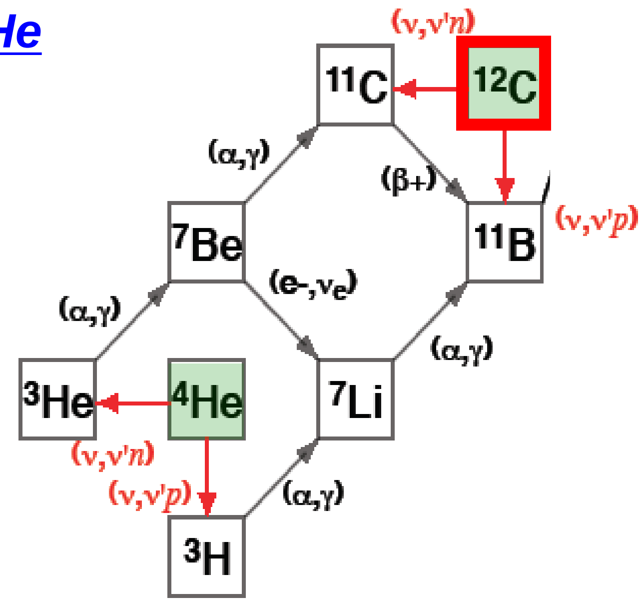
Adiabatic MSW Oscillation



...lation



Theoretical Calculation for ν–Nucleus Cross Sections



New Shell Model cal. with NEW Hamiltonian: *ν-^{12}C, ^{4}He*

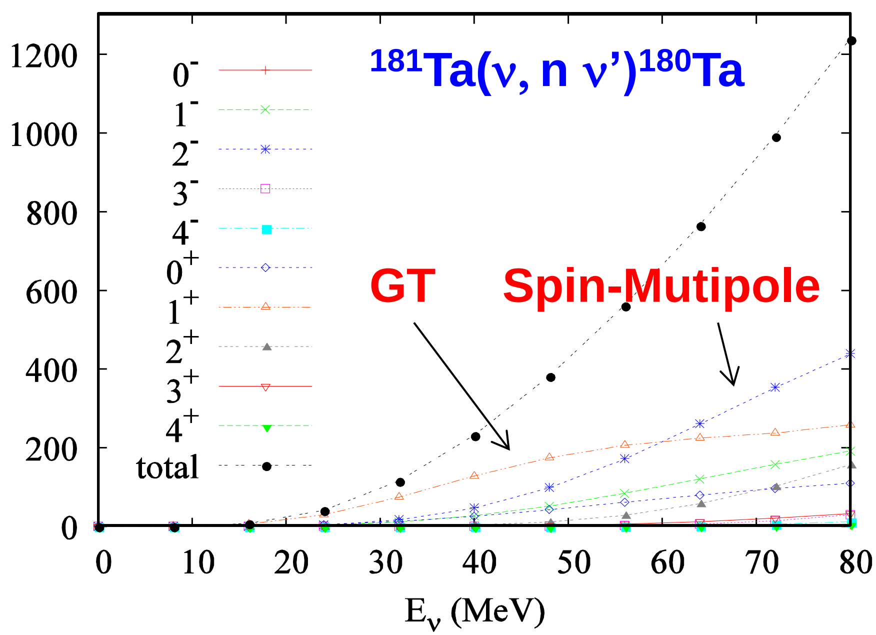
Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307.
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

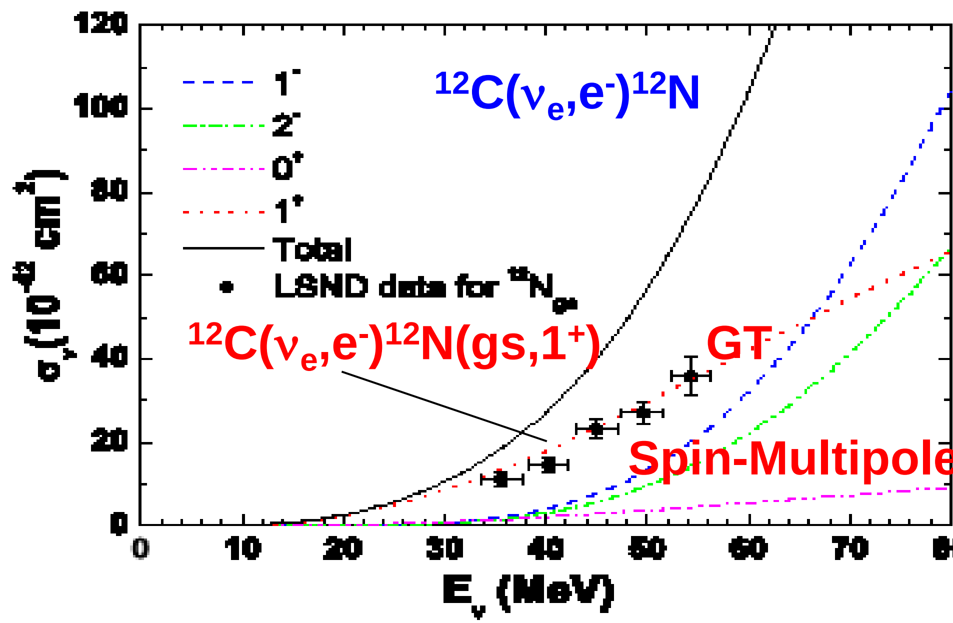
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

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

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

Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504:
J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801





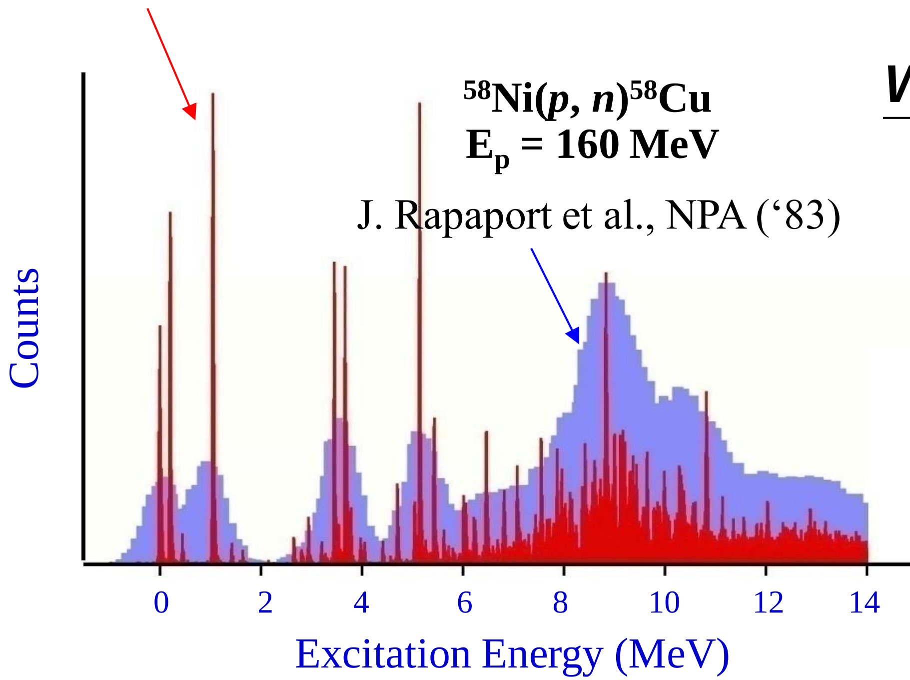
Far to reach ν-BEAM Experiment at E<100 MeV

We can use e-, μ-, γ- & hadronic PROBE !

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

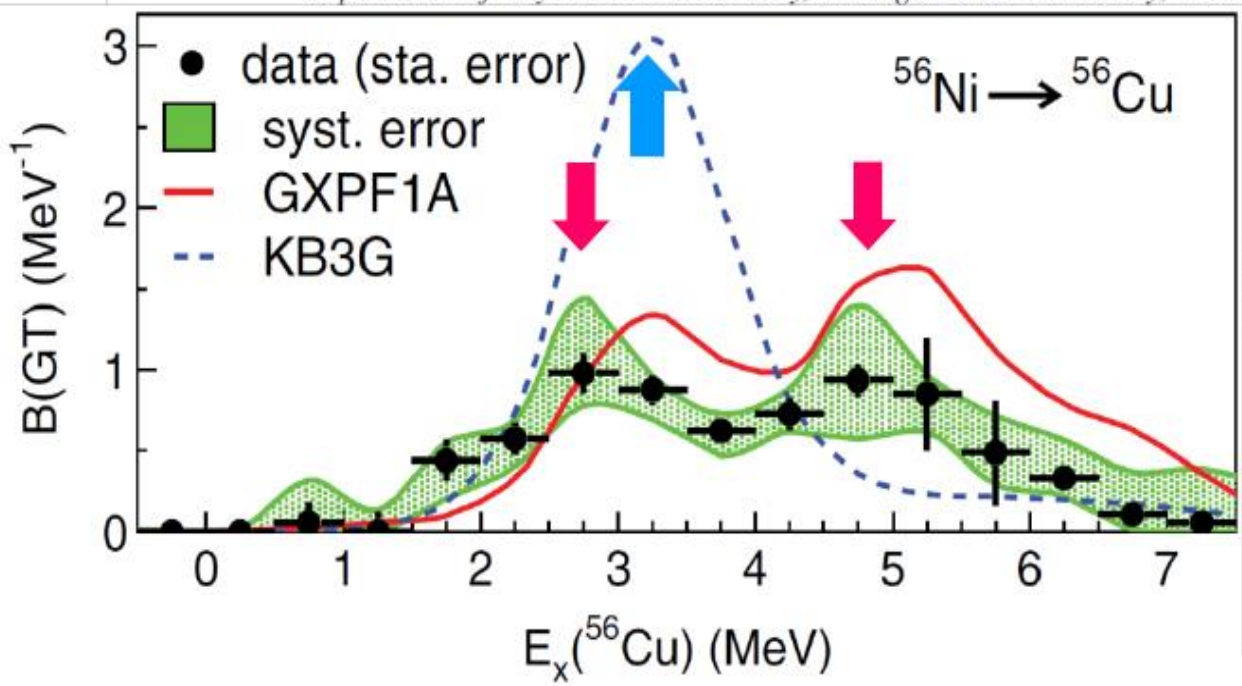
e-captures and Type-Ia SN Nucleosynthesis

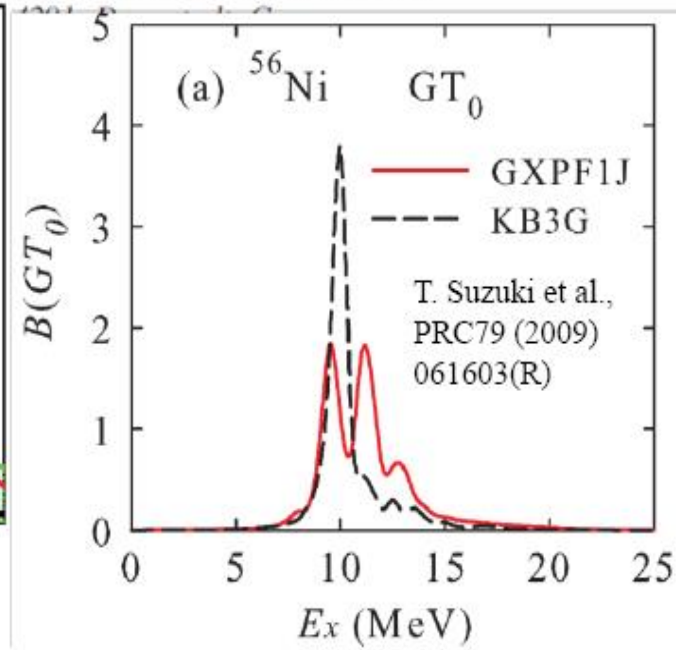
Selected for a Viewpoint in *Physics*
PRL **107**, 202501 (2011) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2011

Gamow-Teller Transition Strengths from ^{56}Ni

M. Sasano,[1,2] G. Perdikakis,[1,2] R. G. T. Zegers,[1,2,3] Sam M. Austin,[1,2] D. Bazin,[1] B. A. Brown,[1,2,3] C. Caesar,[4] A. L. Cole,[5] J. M. Deaven,[1,2,3] N. Ferrante,[6] C. J. Guess,[7,2] G. W. Hitt,[8] R. Meharchand,[1,2,3] F. Montes,[1,2] J. Palardy,[6] A. Prinke,[1,2,3] L. A. Riley,[6] H. Sakai,[9] M. Scott,[1,2,3] A. Stolz,[1] L. Valdez,[1,2,3] and K. Yako[10]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[2]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*



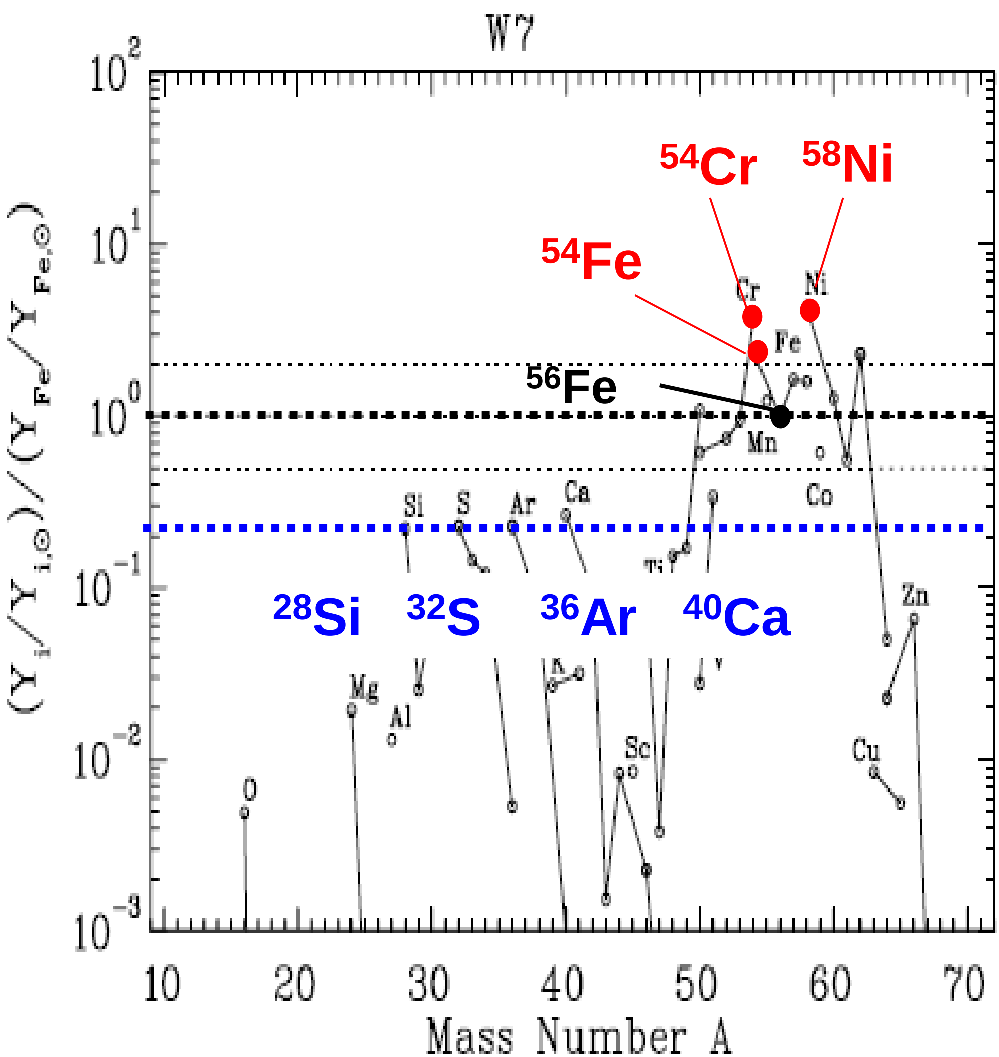


Quenching factor = 0.74

The Astrophysical Journal Supplement Series, 125:439–462, (1999)

NUCLEOSYNTHESIS IN CHANDRASEKHAR MASS MODELS FOR TYPE Ia SUPERNOVAE AND CONSTRAINTS ON PROGENITOR SYSTEMS AND BURNING-FRONT PROPAGATION

Koichi Iwamoto,[1,2,3] Franziska Brachwitz,[4] Ken'ichi Nomoto,[1,2,3] Nobuhiro Kishimoto,[1]
Hideyuki Umeda,[2,3] W. Raphael Hix,[3,5] and Friedrich-Karl Thielemann[3,4,5]



Type Ia SN Nucleosynthesis

^{54}Cr, ^{54}Fe, ^{58}Ni / ^{56}Fe

（N-excess Isotopes）

Overproduction-Problem!

- **Detonation vs. Defragration ?**
  → NOT a solution !
- **n-Excess, known correctly?**
  → e-capture takes a KEY !

Suzuki, Otsuka, Kajino, Hidaka et al. (2014)

Roles of Astro-Nuclear Physics in the Studies of Cosmic Evolution and Element Genesis

The developed HI & RIB technique
+ Intense RI-Beam at RIKEN, RAON
+ High Precision Spectroscopy at RCNP

↓

Probe any Energy on wide N-Z (Isospin)

↓ Hadronic Charge-Exc. React.

Understanding of nuclear electro-weak response in astrophysical processes

→ **GT + first forbidden**
- SN explosion mechanism
- R-process, Th-U synthesis & cosmochronology

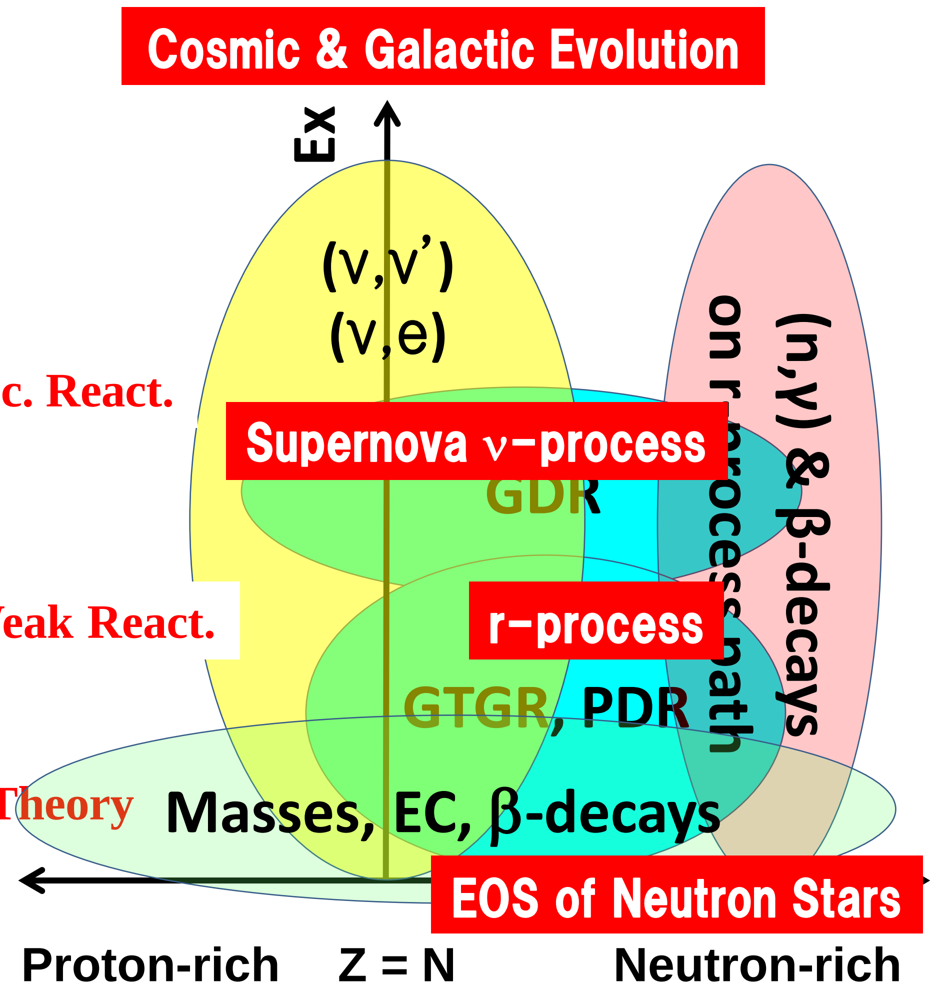
Electro-Weak React.

→ **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



Sasano @ Uesaka Spin-Isospin Labo., RIKEN

Summary

[1] Supernova ν-process nucleosynthesis could be a viable observable to determine the mass hierarchy and $\sin^2\theta_{13} \sim 0.1$ simultaneously. Inverted hierarchy is statistically more preferred.

→ ν-collective oscillation as well as MSW !

→ r-process & ν-process take the key !

[2] ν-driven and MHD-Jet SN models could predict successful s.s. 1st, 2nd and 3rd r-process abundance peaks, while binary NSMs resolve the underproduction just below and above the abundance peaks.

→ ν-driven SN : MHD-Jet SN : NSM = 79% : 16% : 5%

→ Galactic Chemo-Dynamical Simulations

[3] On-going observation of relic supernova νs (RSNs) in SK or megaton HK water-Cherenkov detectors could identify the missing SN rate (cosmological SFR), and also neutrino oscillation pattern and the EOS of proto-neutron stars.