新学術領域研究第3回研究会
「実験と観測で解き明かす中性子星の核物質」
、Sept. 23-25, 2014, 熱川ハイツ

超新星ニュートリノと原始中性子星の状態方程式

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Outline

1. イントロ ― なぜニュートリノ、状態方程式、元素合成か?
2. 原始中性子星の状態方程式
   ― 超新星背景ニュートリノ（Relic Supernova ν）
3. ニュートリノ振動と超新星元素合成
   ― ニュートリノ元素合成
4. Rプロセス元素（鉄より重い元素）合成
   ― 超新星 vs. 連星中性子星系合体
5. サマリー

Challenge of the Century

The 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) ?**

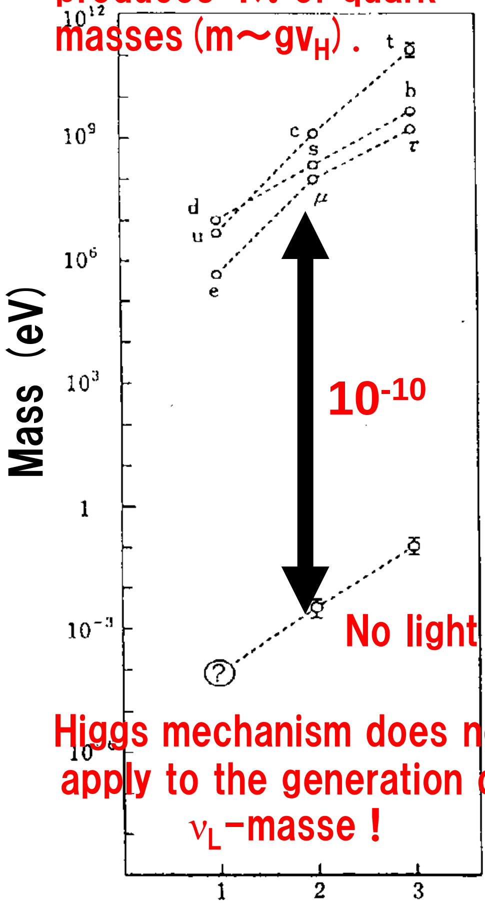
CMB & LSS including absolute mass

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

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

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

Higgs (standard model) produces 1% of quark masses ($m \sim g v_H$) .



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

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 the EoS and Element Genesis for determining the ν-mass and hierarchy from CC-SN Neutrinos.

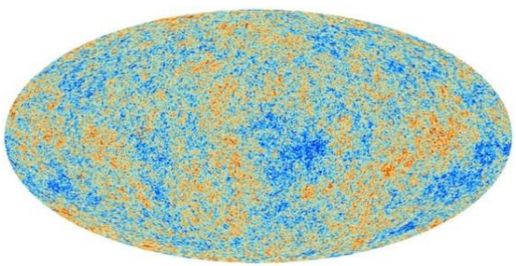
Total absolute ν−Mass, constrained from Cosmology and Nuclear Physics

● CMB Anisotropies + LSS

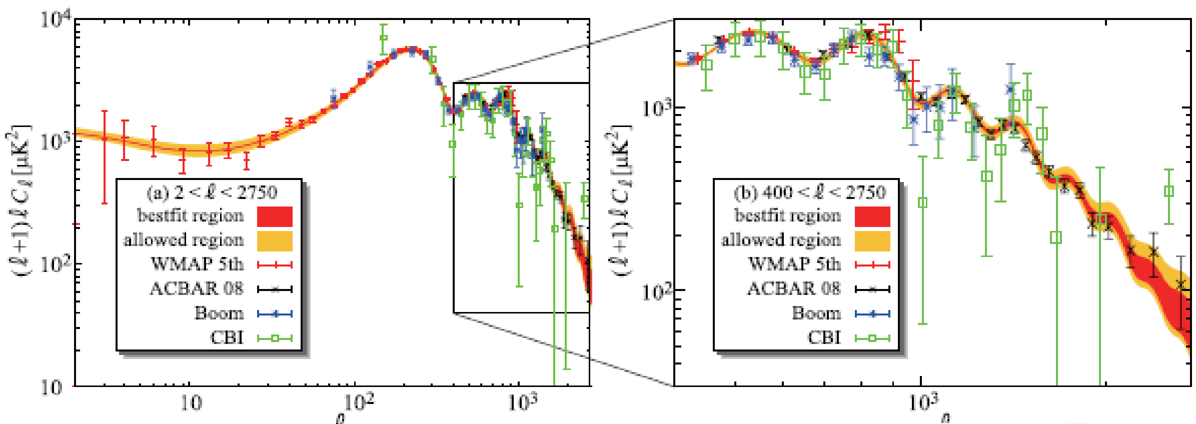
$\sum m_\nu < 0.36$ eV (95%C.L.): **→ 0.1 eV in the future** arXiv:1201.1909)

CMB Anisotropies & Polarization including Cosmic Magnetic Field

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



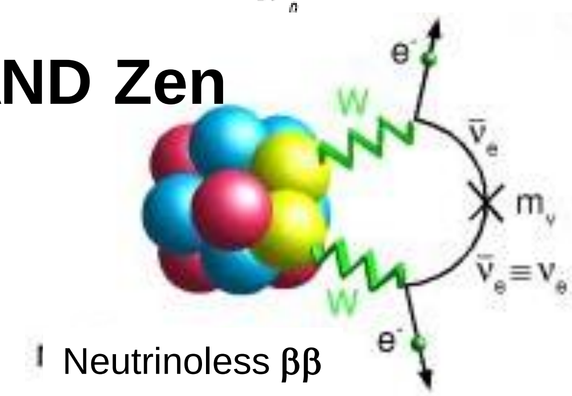
www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe



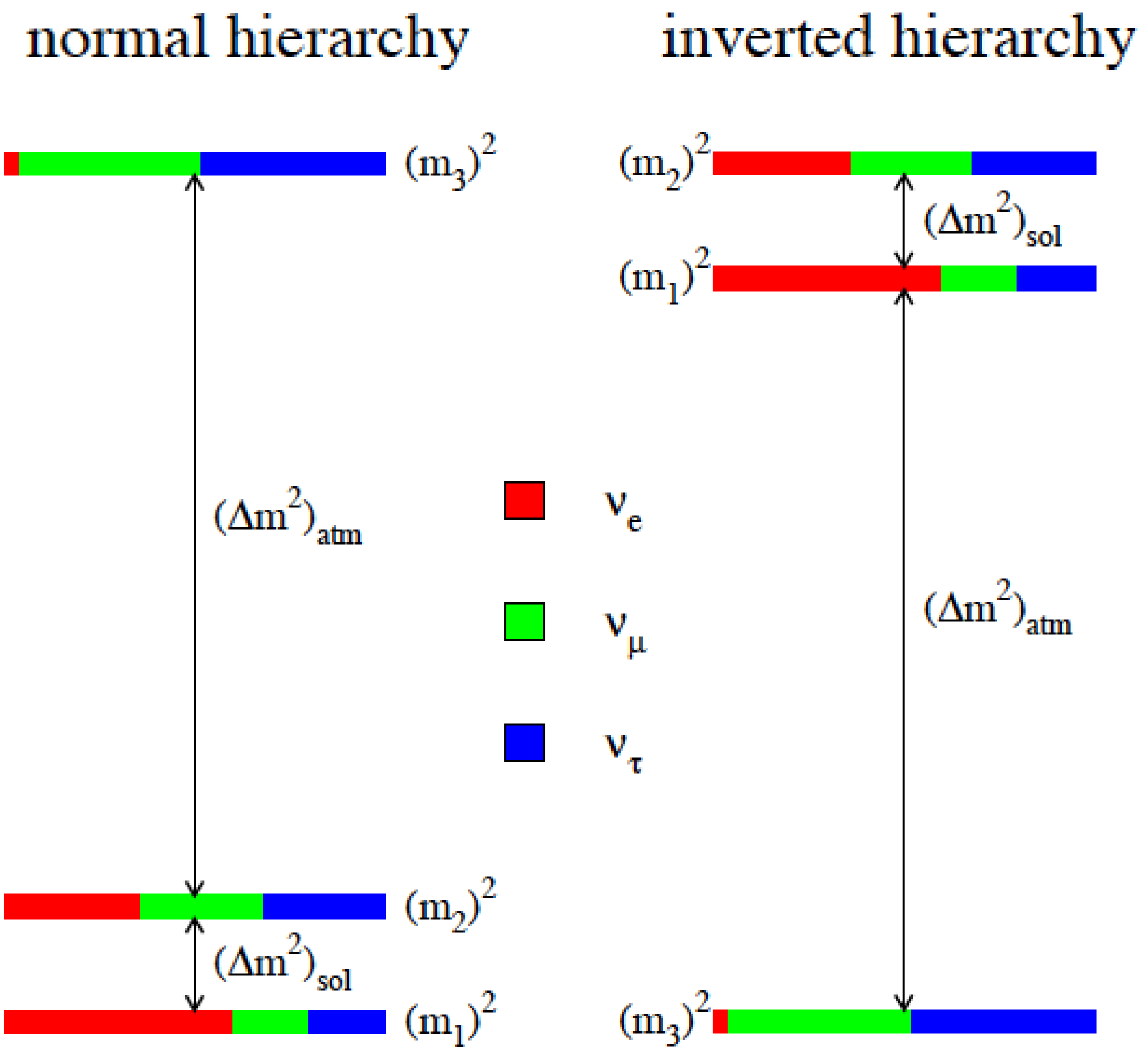
● 0νββ in COUORE, NEMO3, EXO, KamLAND Zen

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

→ 0.05〜0.1 eV in the future



ν−Mass Hierarchy, constrained from Nuclear Astrophysics



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

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

$$= (0.05\ \mathrm{eV})^2$$

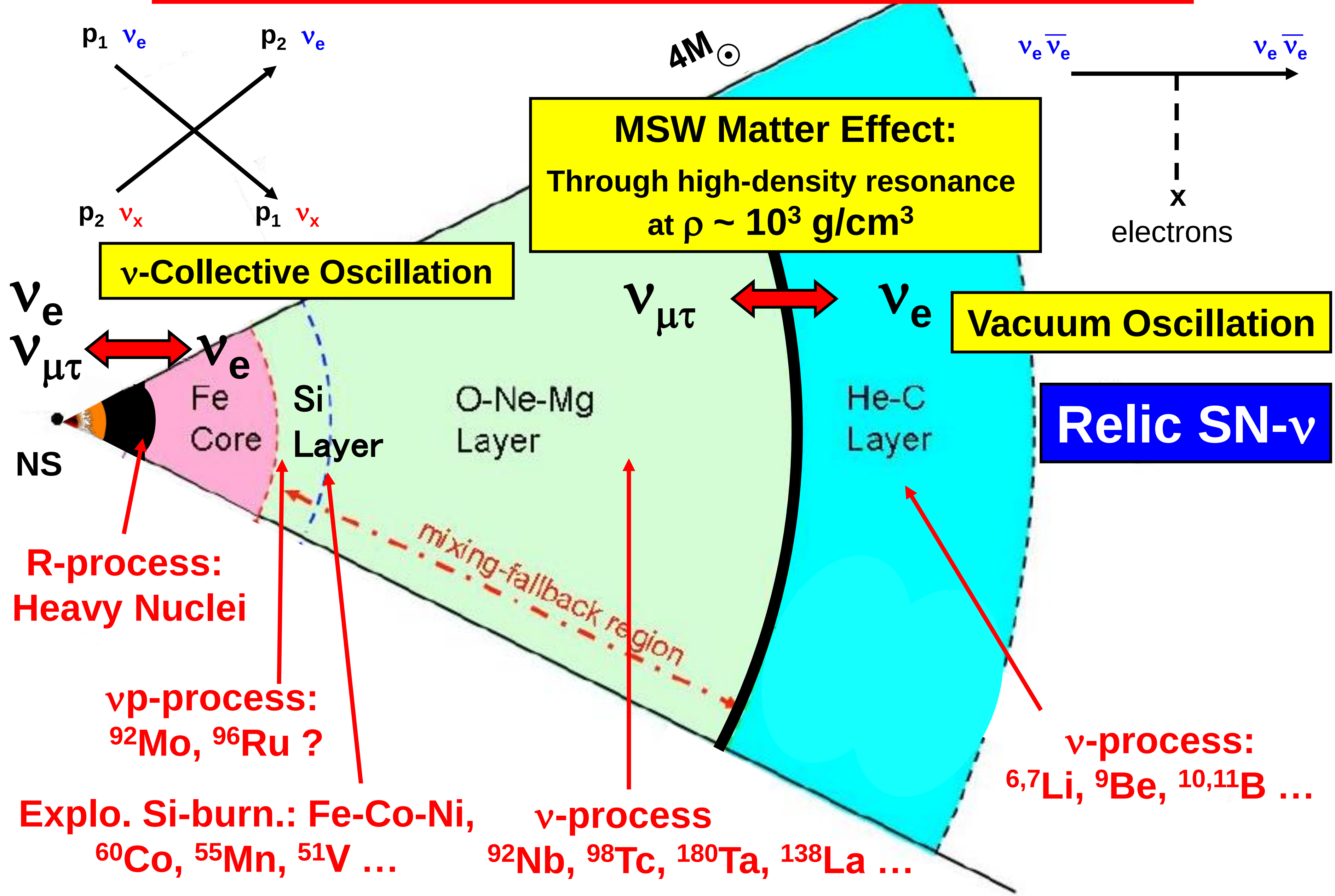
Normal:

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

Inverted:

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

ν-Oscillation, SN-ν and Nucleosynthesis



Relic SN-ν : A New Method to constrain EOS

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

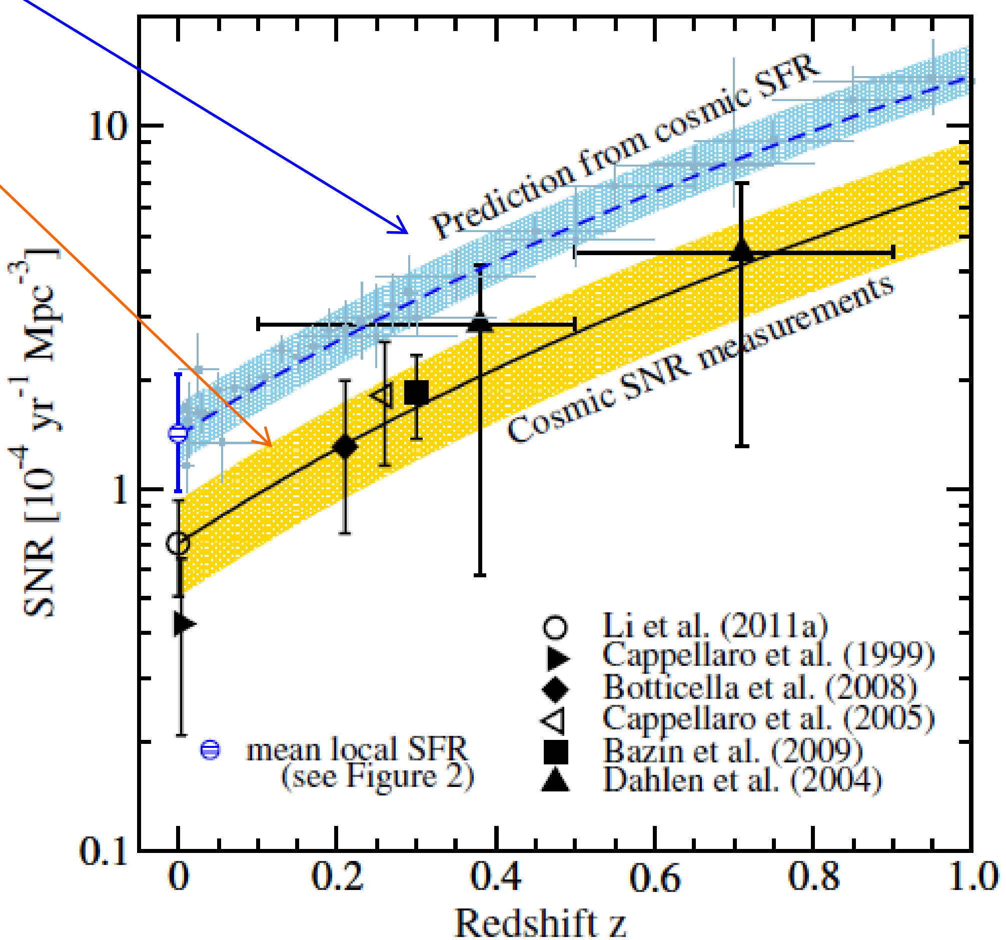
Supernova Rate Problem/Discrepancy

Cosmic ★ Formation Rate (SFR):
Massive Stars at BIRTH !

Supernova Rate (SNR):
Supernova Explosions at DEATH !

50% missing !

Horiuchi, Beacom et al., ApJ 738 (2011) 154.



Expected Reasons:

Half 50% massive stars evolved to **TOO DARK SNe** to detect!

Failed SNe (>25$M_\odot$ BH formation)

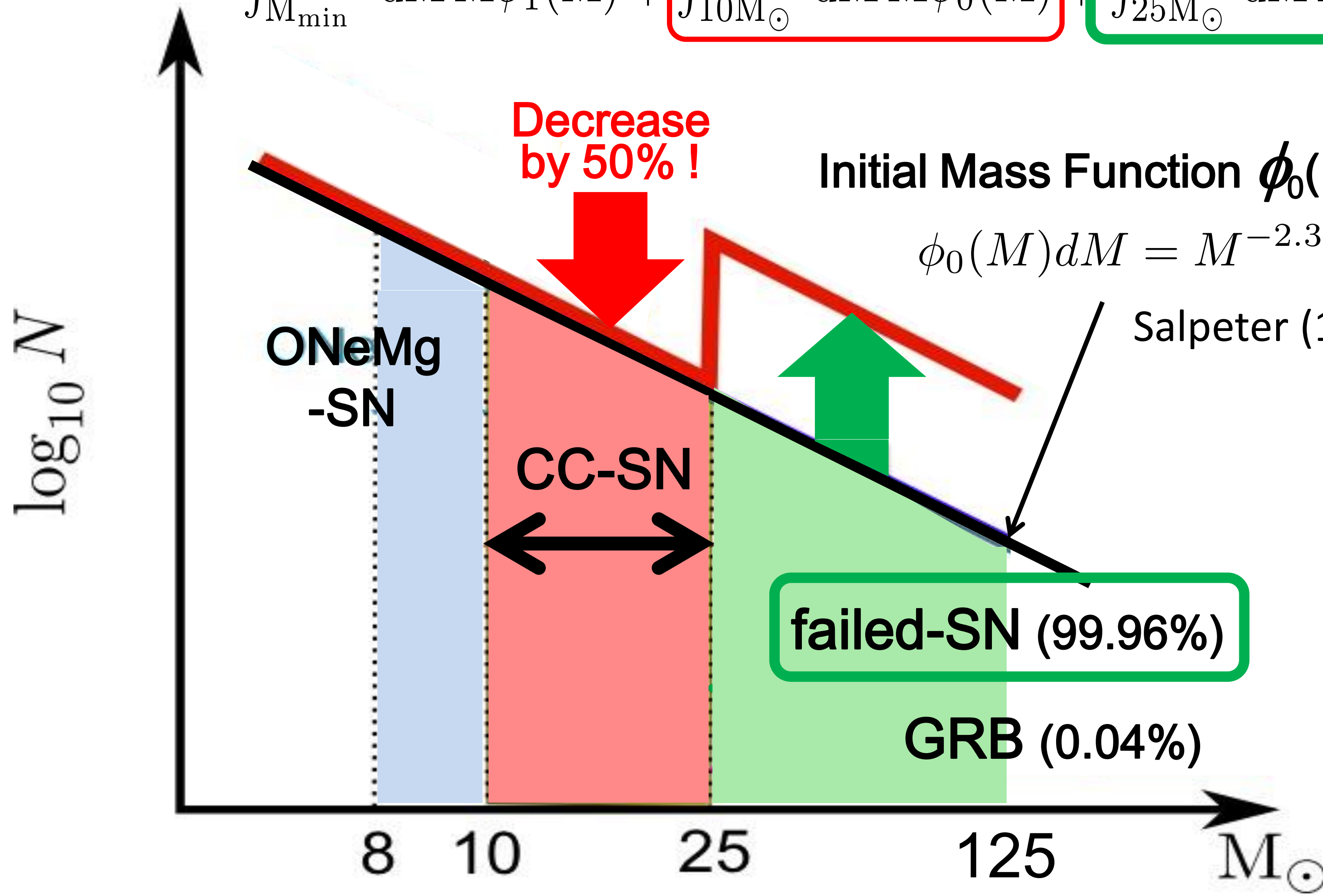
⬇

Different Mass-Function!

Relic SN-ν !

A Possible Solution of SN-Rate Problem

$$R_{SN}(z) = \Psi_*(z) \times \frac{\int_{10M_\odot}^{25M_\odot} dM\,\phi_0(M)}{\int_{M_{min}}^{10M_\odot} dM\,M\phi_1(M) + \int_{10M_\odot}^{25M_\odot} dM\,M\phi_0(M) + \int_{25M_\odot}^{M_{max}} dM\,M\phi_2(M)}$$



Theoretical ν−Spectra for Various Supernovae

Electron−capture SNe (Faint Ne)	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
$E_{\nu_e}^{total}$(erg)	3.3×10^{52}	5.0×10^{52}	5.5×10^{52}	8.4×10^{52}	1.7×10^{53}
$E_{\bar{\nu}_e}^{total}$(erg)	2.7×10^{52}	5.0×10^{52}	4.7×10^{52}	7.5×10^{52}	3.2×10^{53}
$E_{\nu_x}^{total}$(erg)	1.1×10^{52}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	$\sim 0.5s$	$\sim 0.5s$	$\sim 10s$

- **ONeMg SNe:** Hudepohl, et al., PRL 104 (2010).
- **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, K=180):** Lattimer & Swesty, Nucl. Phys. **A535** (1991) 331.
- **GRBs:** Nakamura, Kajino, Mathews, Sato & Harikae, *Int. J. Mod. Phys.* **E22** (2013) 1330022; Kajino, Mathews & Hayakawa, J. Phys. **G41** (2014) 044007.

Spectrum of Relic Supernova Neutrinos (RSNs)

Totani et al. 1996, ApJ 460, 303; Lunadini 2009, PRL 102, 231101.

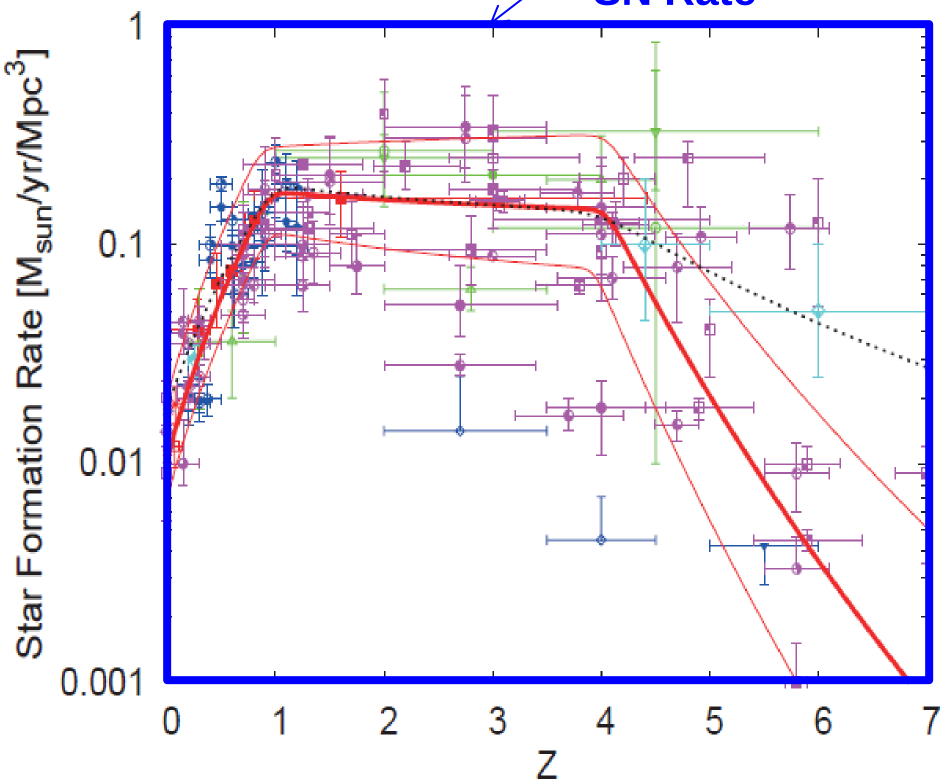
Redshifted $E'_\nu = (1+z)E_\nu$ Expanding Universe ΛCDM

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

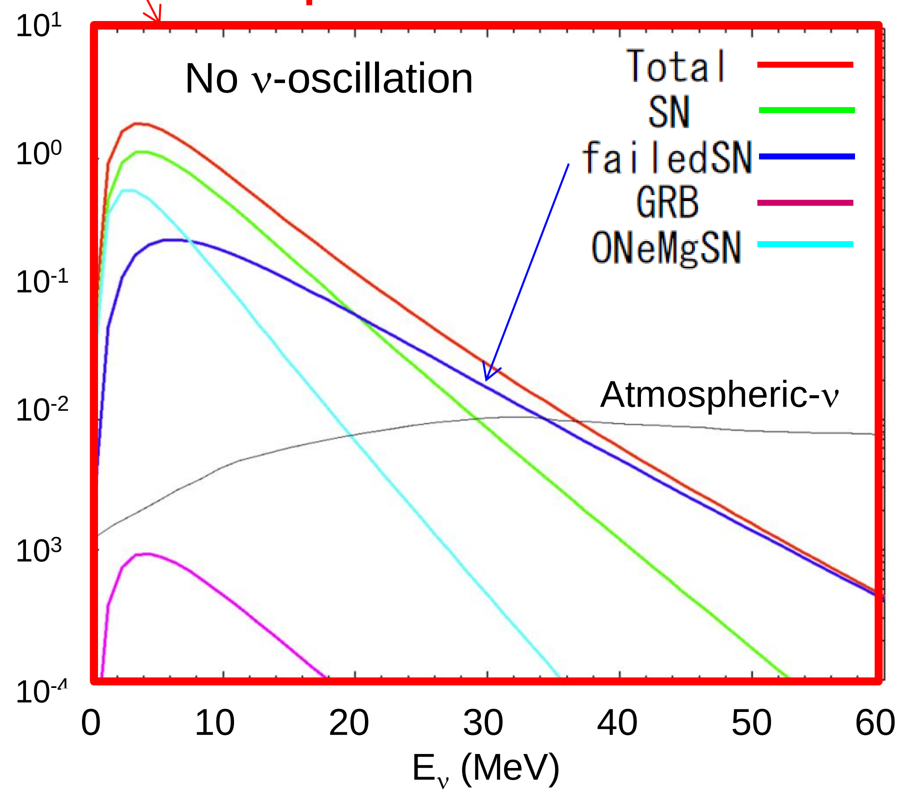
$\Omega_m = 0.3$

$\Omega_\Lambda = 0.7$

SN Rate



ν-Spectra from Various SNe



Relic Supernova Neutrinos (RSNs)

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

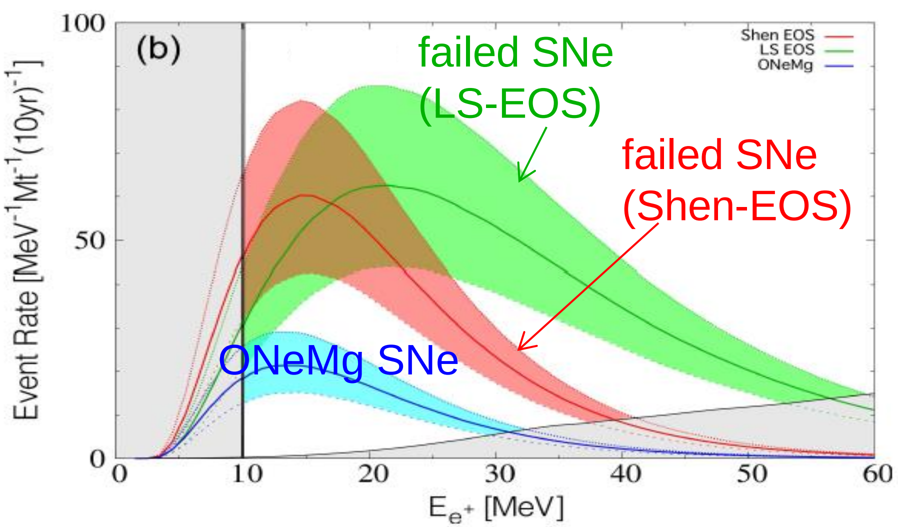
$\bar{\nu}_e + p \rightarrow e^+ + n$

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

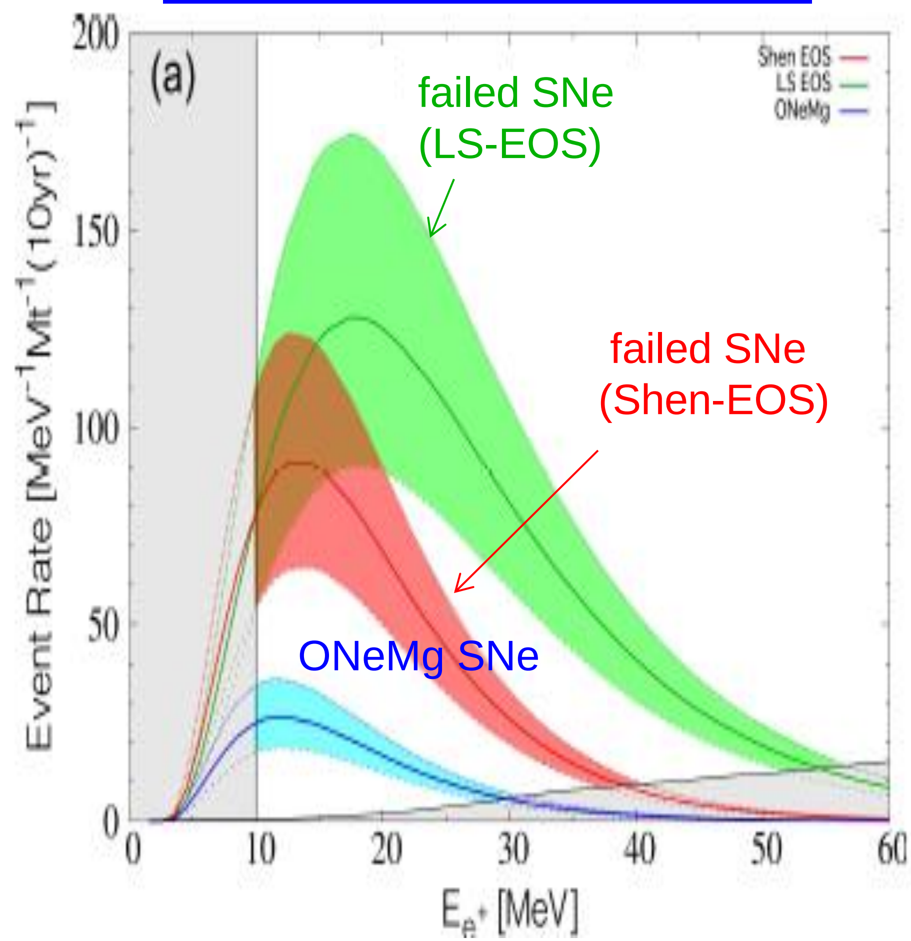
Assuming 2 x failed SNe for BH formation
to solve SN Rate Problem.
Horiuchi, Beacom et al., ApJ 738 (2011), 154.

RSNs could be a good observable to test EOS!

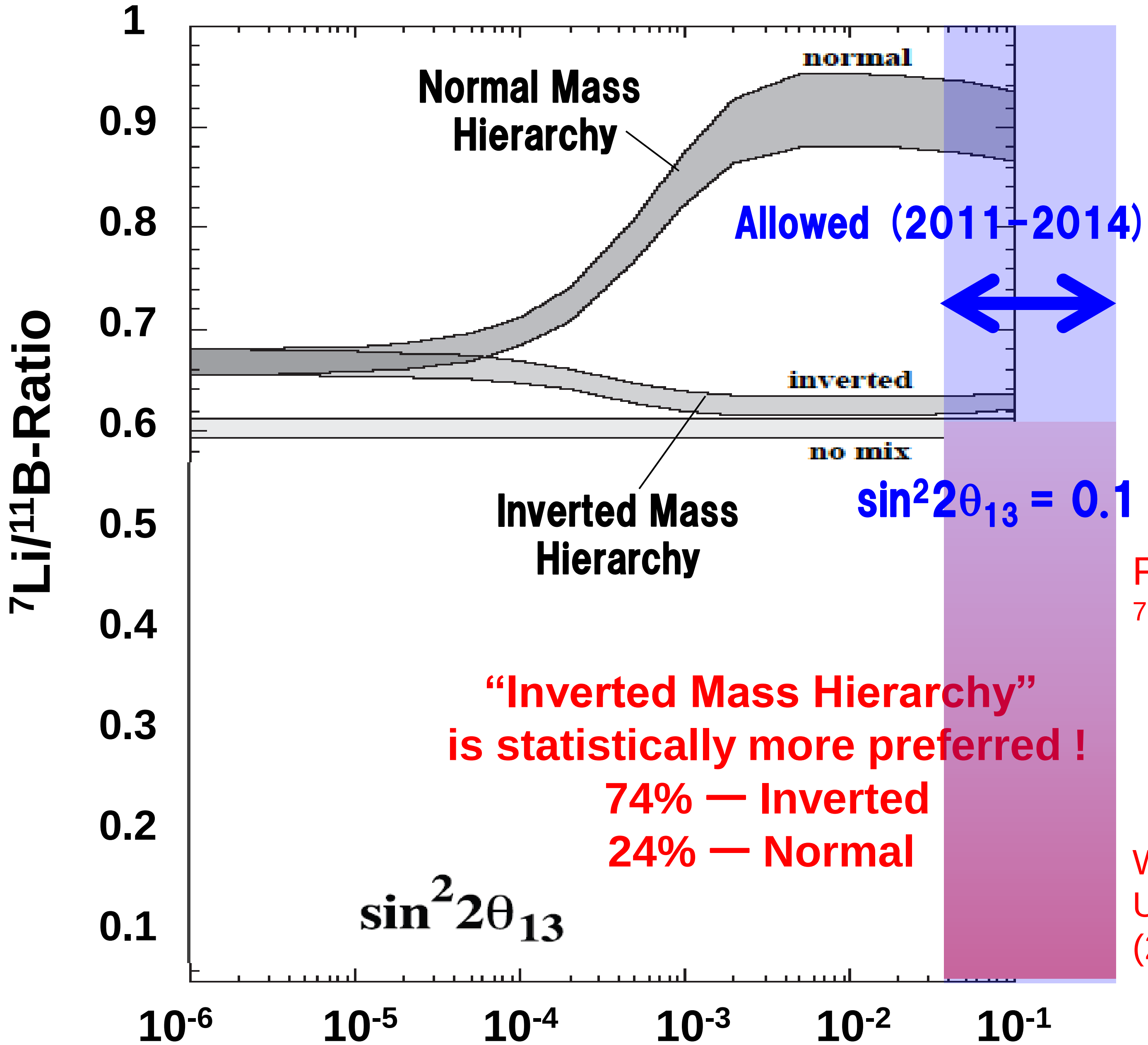
Adiabatic MSW Oscillation



Non-Adiabatic MSW Oscillation



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

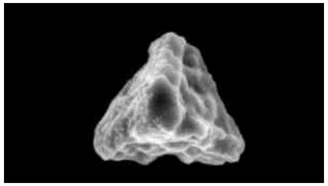


Yoshida, Kajino et al. 2005, PRL94, 231101; 2006, PRL 96, 091101; 2006, ApJ 649, 319; 2008, ApJ 686, 448.

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

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

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



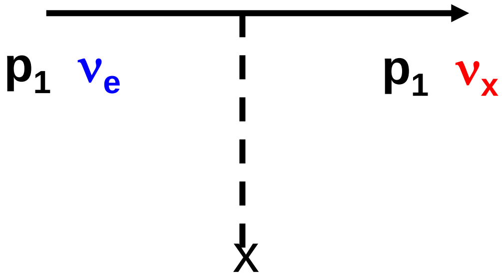
W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).

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)

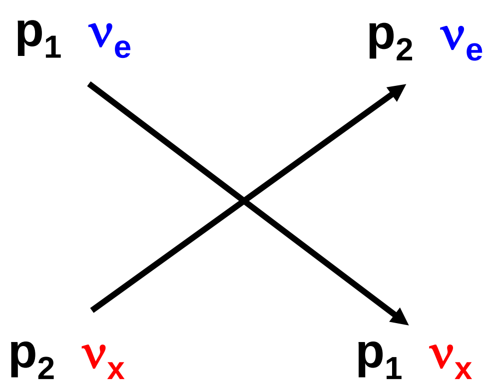
$$H_\nu = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right) + \frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$



N_e = electron density

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

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



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 probe of SN ν-interactions! R-process astrophysical site?

A Core-Collapse Supernova Model

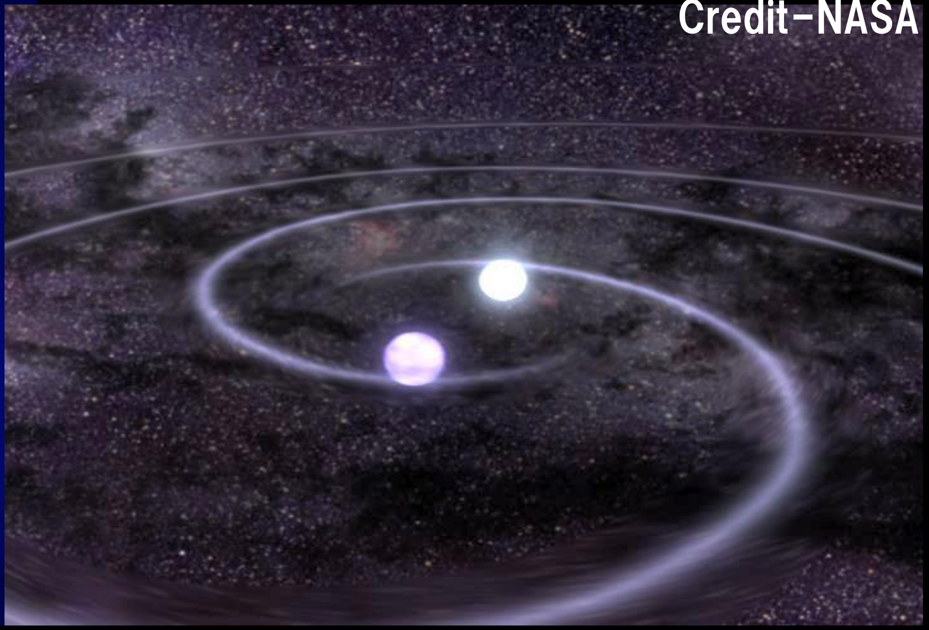
ν-driven Wind, 3D Hydrodynamics, Newtonian gravity, 11.2 M_sun

Takiwaki, Kotake, Suwa, ApJ 786 (2014), 83.

A Binary Neutron-Star Merger

SPH, Newtonian gravity, ν-Leakage scheme

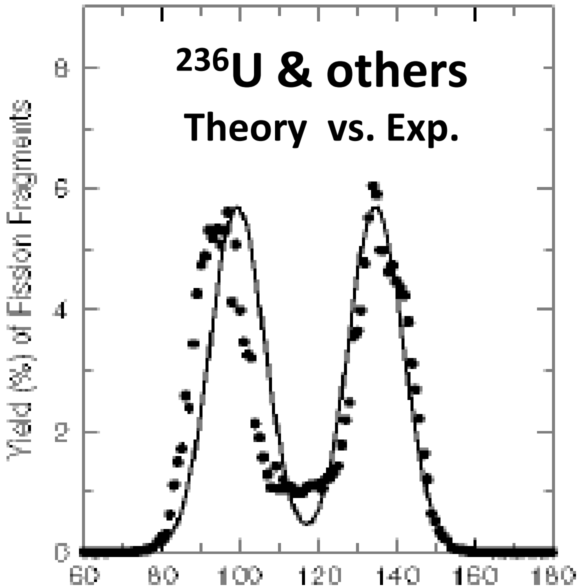
Korobkin et al., MNRAS 426 (2012), 1940.
Piran et al., MNRAS 430 (2013), 2121.
Rosswog et al., MNRAS 430 (2013), 2585.



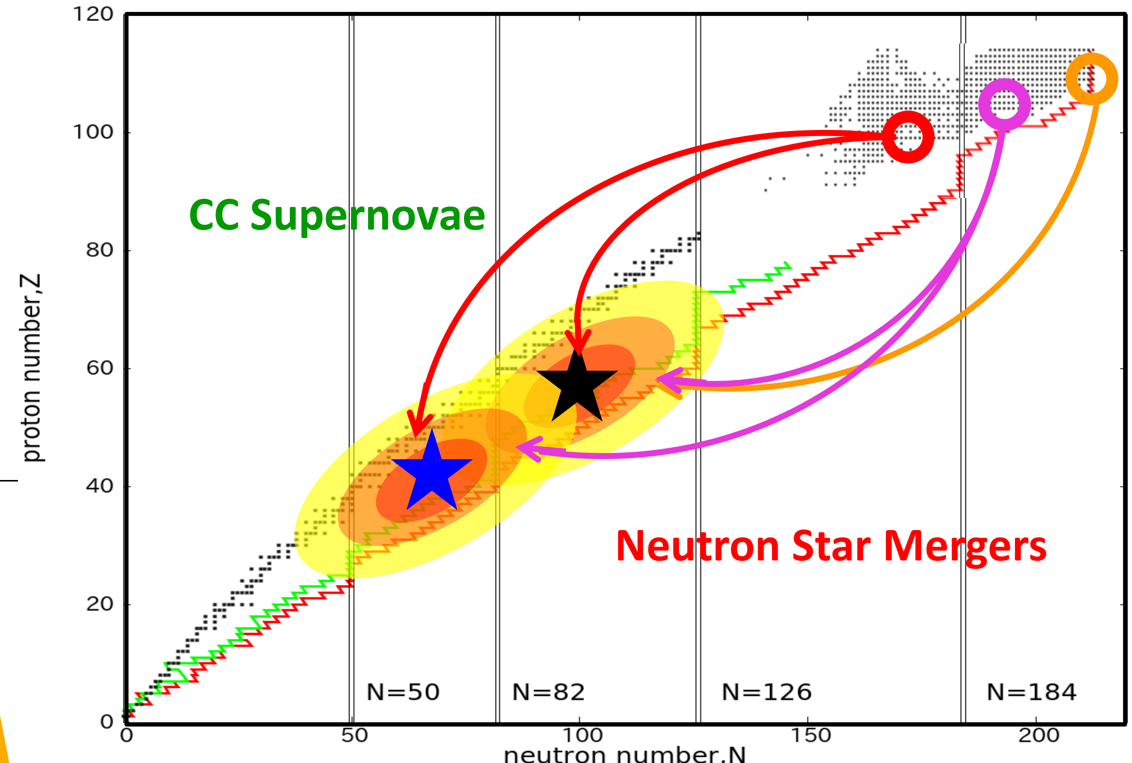
Credit-NASA

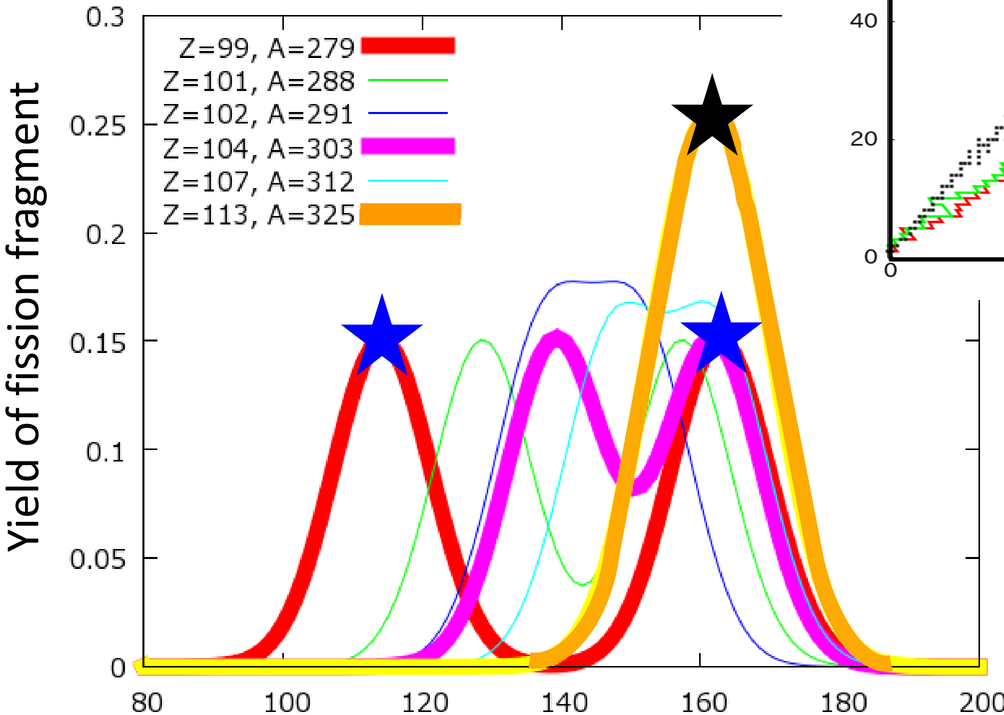
Fission Fragment Mass Distribution

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



Fission fragment mass **A**





Fission Fragment mass **A**

Bimordial or Trimodal FFD:

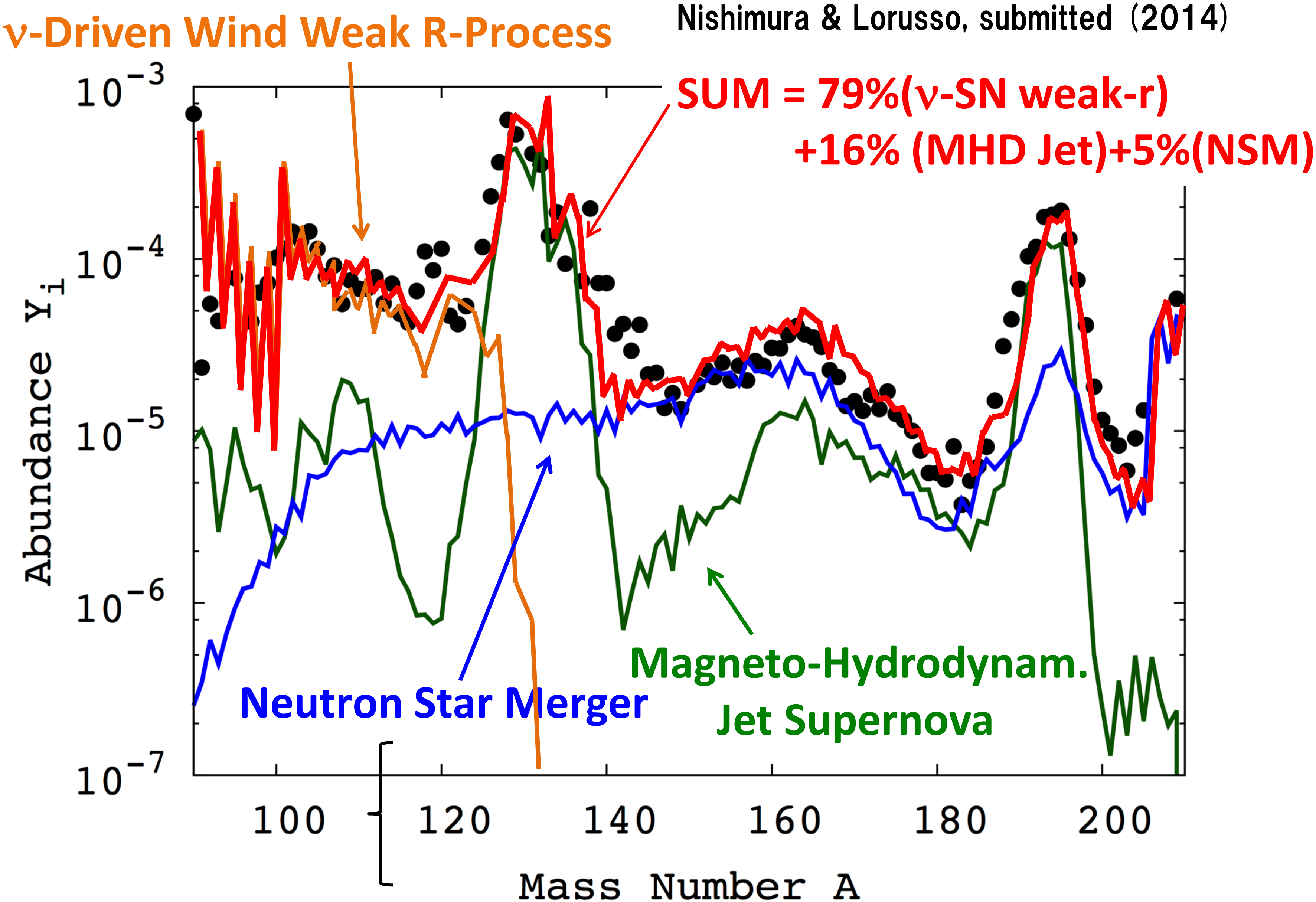
$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi}\sigma} W_i \exp\left(\frac{-(A - A_i)^2}{2\sigma^2}\right)$$

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

Recipe to reproduce solar r-elements

S. Wanajo, ApJL, L22 (2013)

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



Recipe to reproduce solar r-elements

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

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

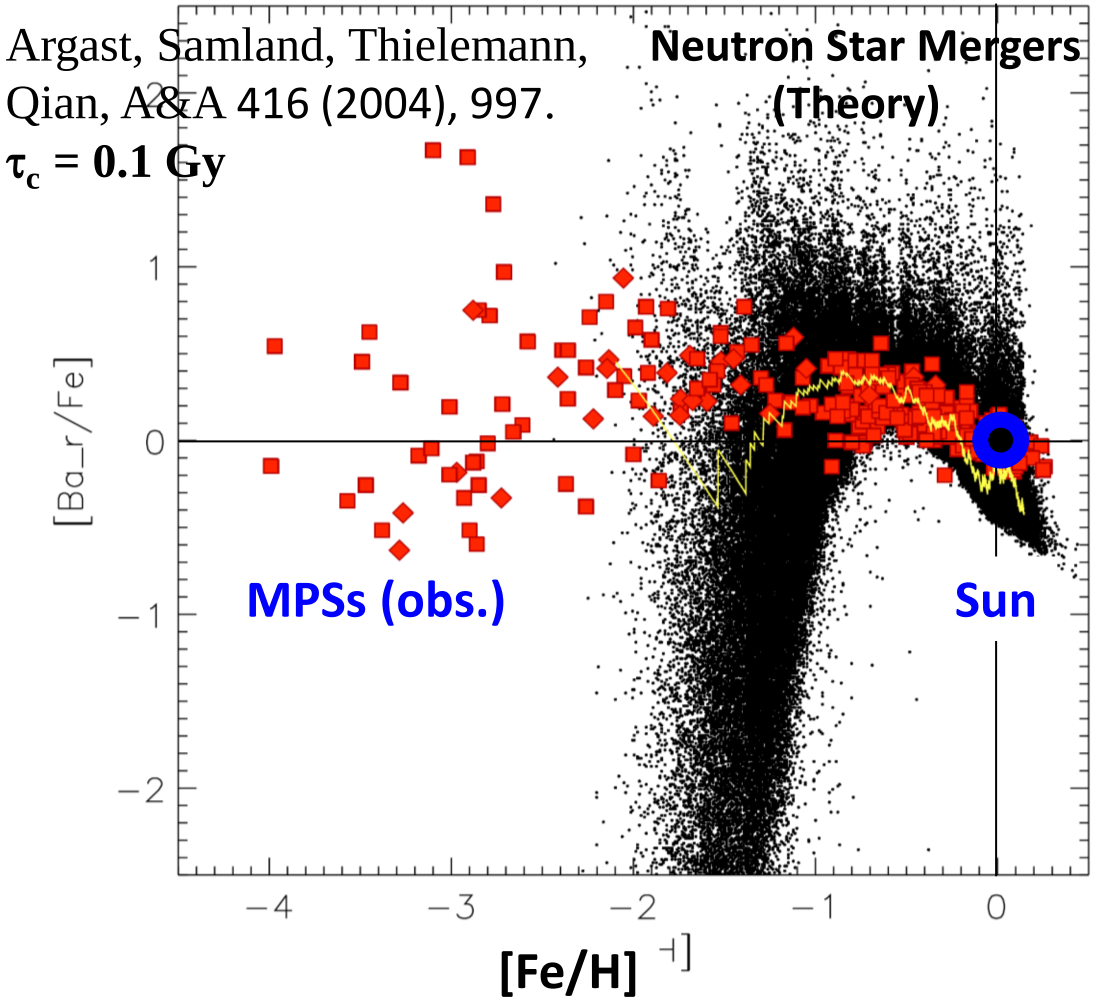
Ejected Mass x Event Rate

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

MHD Jet = 0.6×10^{-2} x ((0.03±0.02) x (1.9±1.1)) [Msun/Galaxy/Century]

NSM = (2±1)x10^{-2} x (1-28)x10^{-3} [Msun/Galaxy/Century]

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



1My 10My 0.1Gy 1Gy 10Gy

Early Universe ← → Present Time

$$[Fe/H] = \log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$$

Binary Neutron Star Mergers

Coalescence time scale is too long;

0.1 Gy < τ_c !

Wanderman and Piran (2014). arXiv: 1405.5878.
τ_c = 1–4 Gy

Origin of Universality ?

Galactic Chemo-Dynamical Evolution !

銀河の化学動力学進化

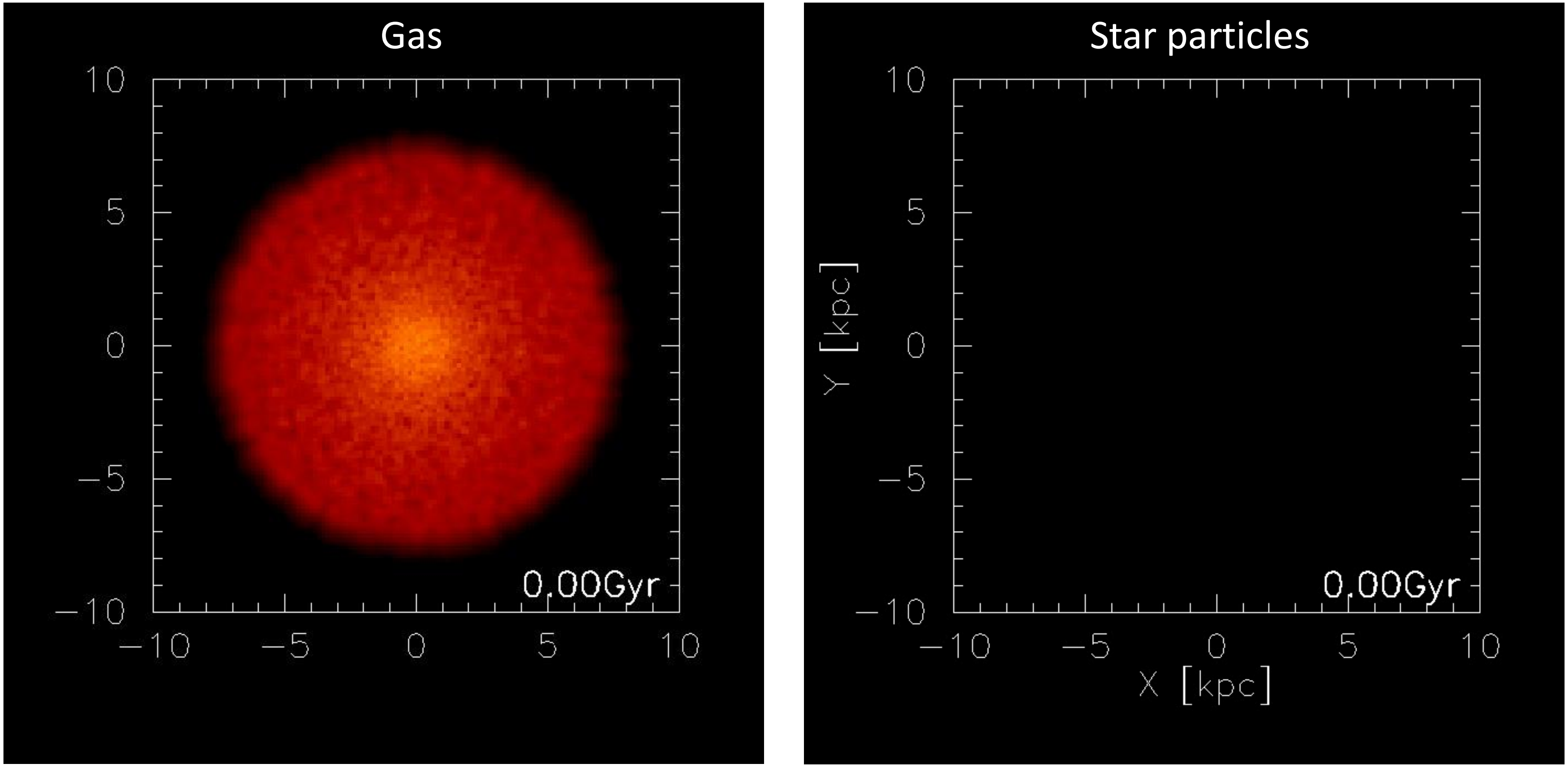
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Spheroidals

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

N-Body/SPH Simulation of Chemo-Dynamical Evolution of Dwarf Spheroidal: SNe + NSM (τ_c=0.1Gy), Gas mixing in star forming region is included.

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

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



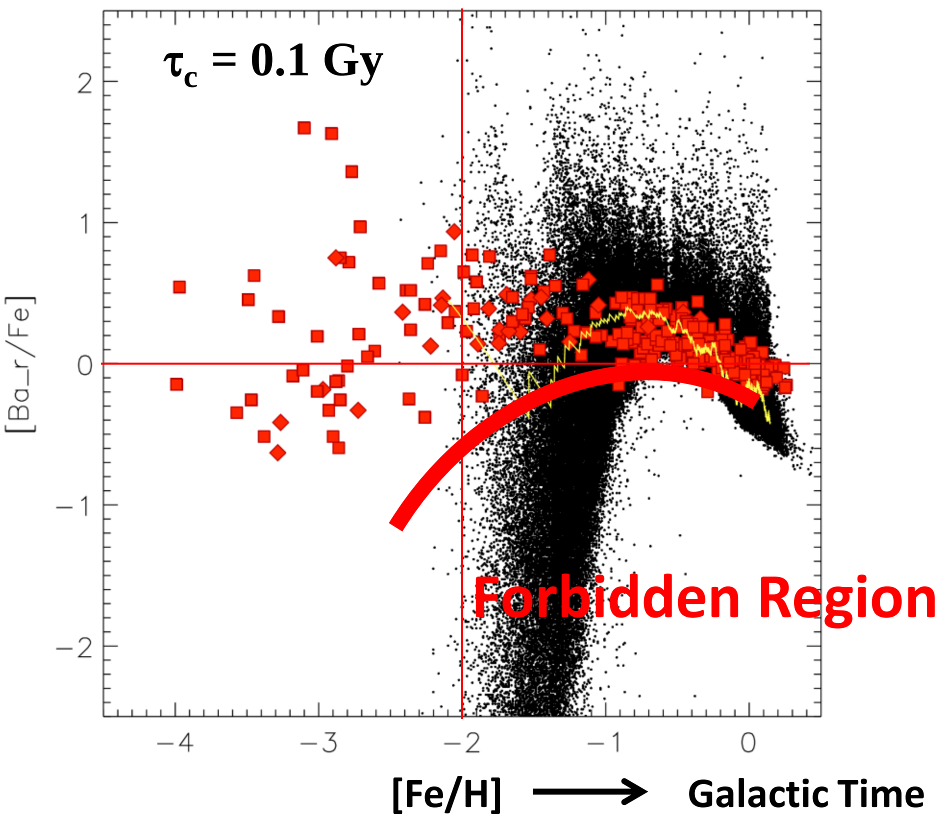
GCDE: Calculated Result (Preliminary)

Universality of r-elements is recovered !

N-Body/SPH Simulation of Chemo-Dynamical Evolution of Dwarf Spheroidal:
SNe + NSM (τ_c=0.1Gy), Gas mixing in star forming region is included.

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

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

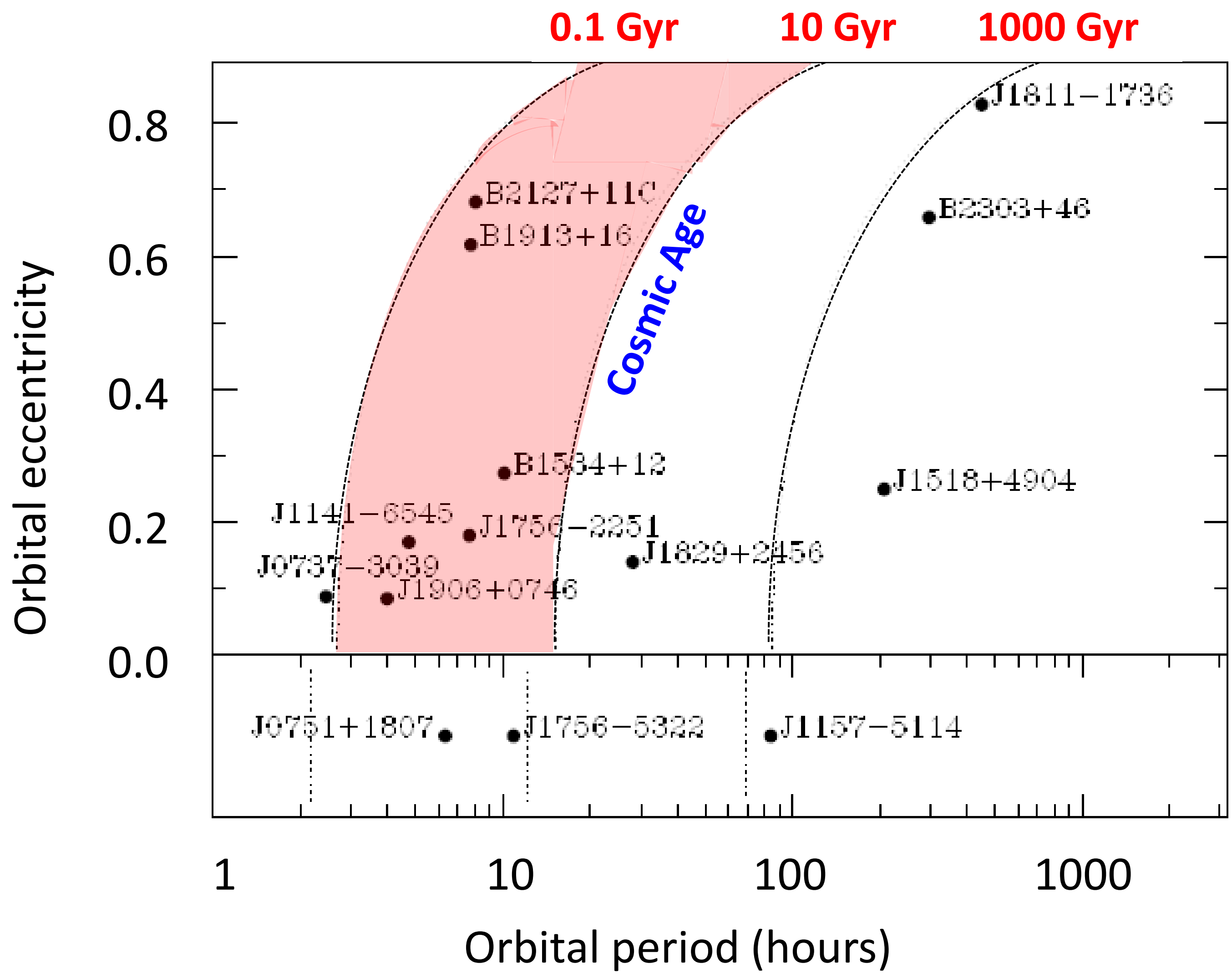


Forbidden Region may disappear for τ_c = 0.1 Gy (min. Allowed Time-Delay) .

Difficulty may come back again for τ_c >1 Gy.

Time delay for coalescence = τ_c

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



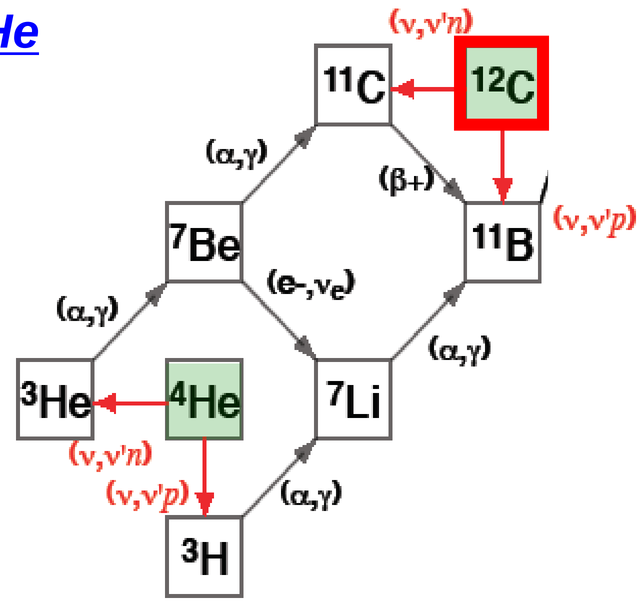
Theoretical Calculation for ν−Nucleus Cross Sections

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)

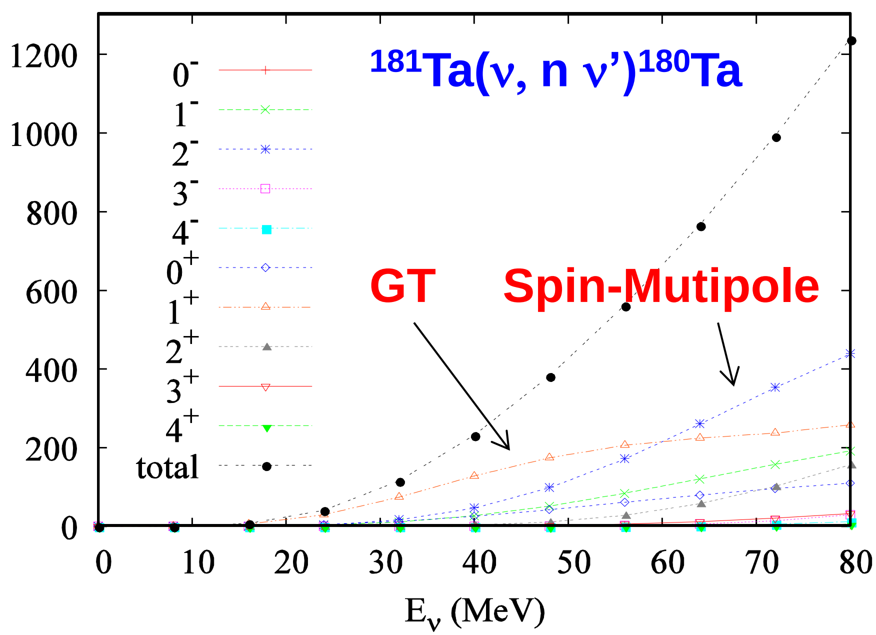
^{12}C: New Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

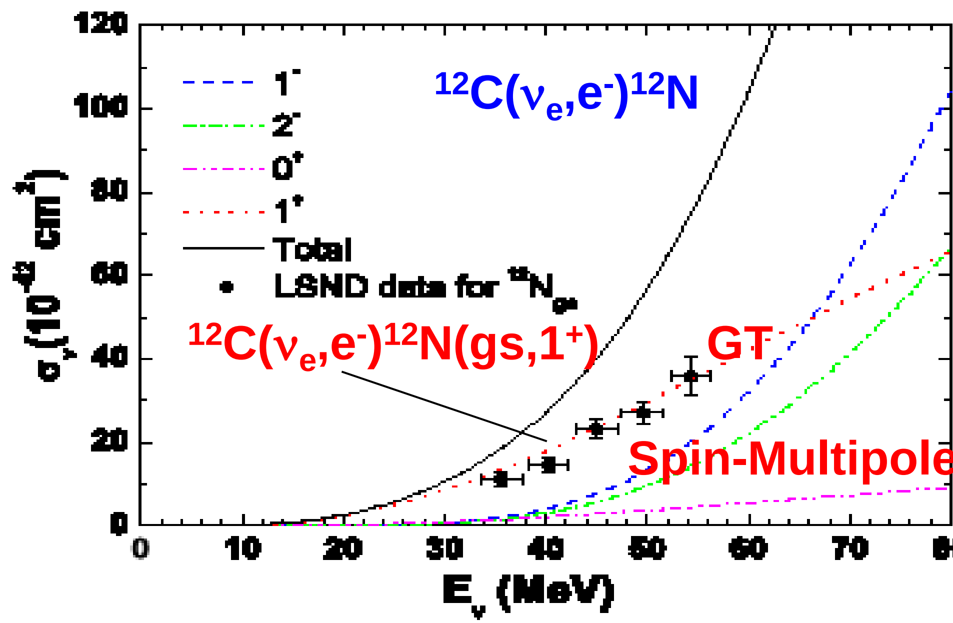
- μ-moments of p-shell nuclei
- GT strength for ^{12}C→^{12}N, ^{14}C→^{14}N, etc. (GT)
- DAR (ν,ν'), (ν,e-) cross sections



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





Roles of Nuclear Astrophysics in the Studies of Cosmic Evolution and Element Genesis

The developed HI & RIB technique
+ Intense RI-Beam at World RIFactories
+ High Precision Spectroscopy +

Probe any Energy on wide N-Z (Isospin)

HI & 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

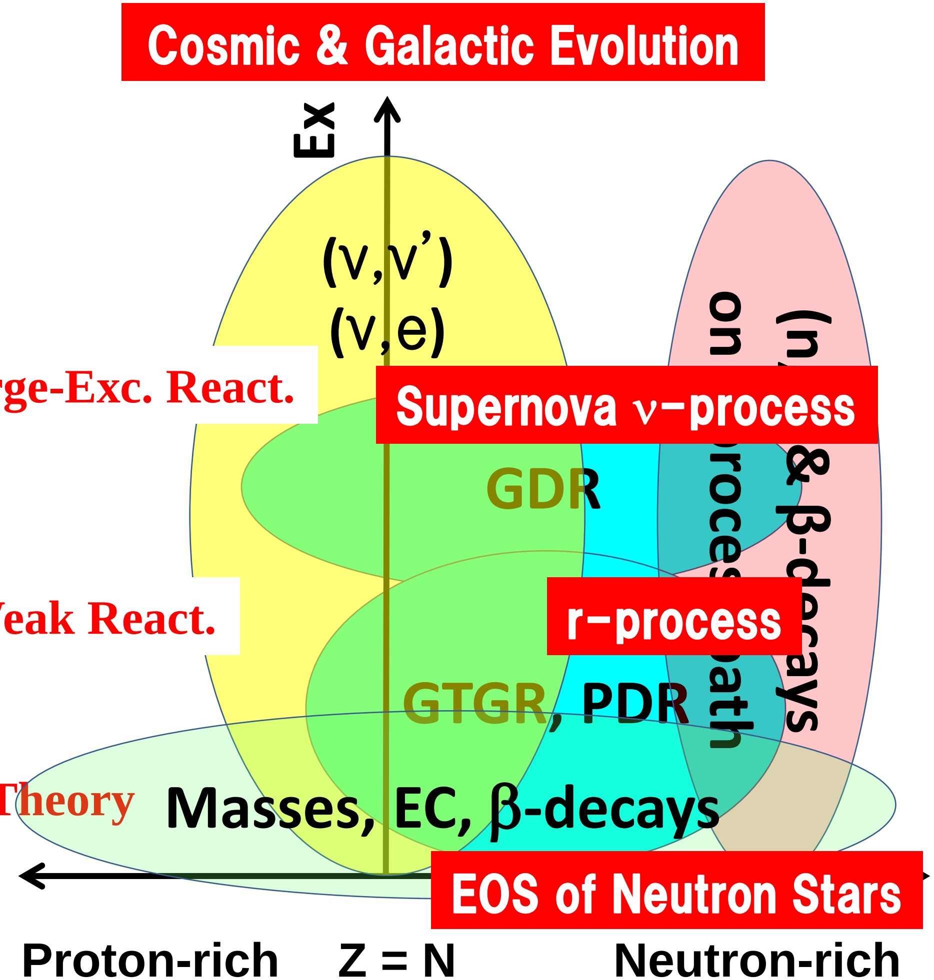
Electro-Weak React.

→ **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

宇宙は基礎物理学の実験場である。
Our Universe is a laboratory for fundamental science!

[1] Detection of Relic SN νs could test the EoS of proto-neutron stars and neutrino flavor-oscillation pattern.

➡ Gd roaded SK or mega-ton HK water Cherenkov detectors !

[2] Supernova ν-process could test the mass hierarchy.

➡ Study both MSW & collective ν-flavor oscillation !

[3] R-process in supernovae (ν-wind and MHD-Jet) and binary neutron star mergers (NSMs) could explain the universality if binary coalescence time-delay is τ_c = 0.1 Gy or less.

➡ ν-wind SN : MHD-Jet SN : NSM = 79% : 16% : 5% ➡ Study GCDE !

➡ Study of fission fragment distribution, mass and beta-lives !

★ Electroweak & hadronic CEX plus heavy-ion reactions play the critical roles for knowing ν-nucleus & e-capture rates and EoS.