北京大学科維理天文・天体物理研究所 **KIAA**

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Solving the Mystery of the Neutrinos & R-process

Supernova or Neutron-Star Merger ?

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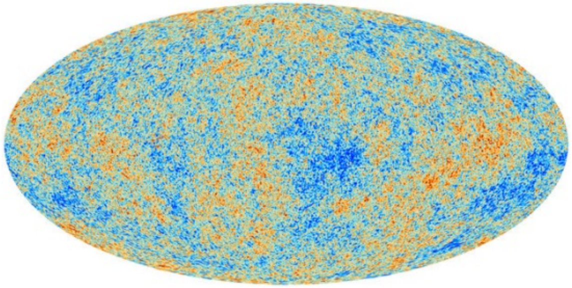
Challenge of the Century

Universal expansion is most likely accelerating and flat ?

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

CMB – Planck 2013

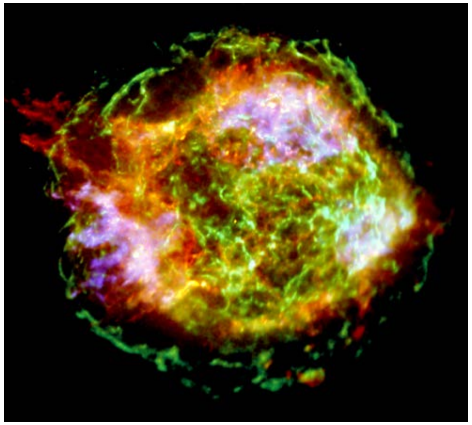


- **What is CDM ($\Omega_{CDM} = 0.27$) and DE ($\Omega_\Lambda = 0.68$) ?**

- **Is BARYON sector ($\Omega_B = 0.05$) well understood ?**

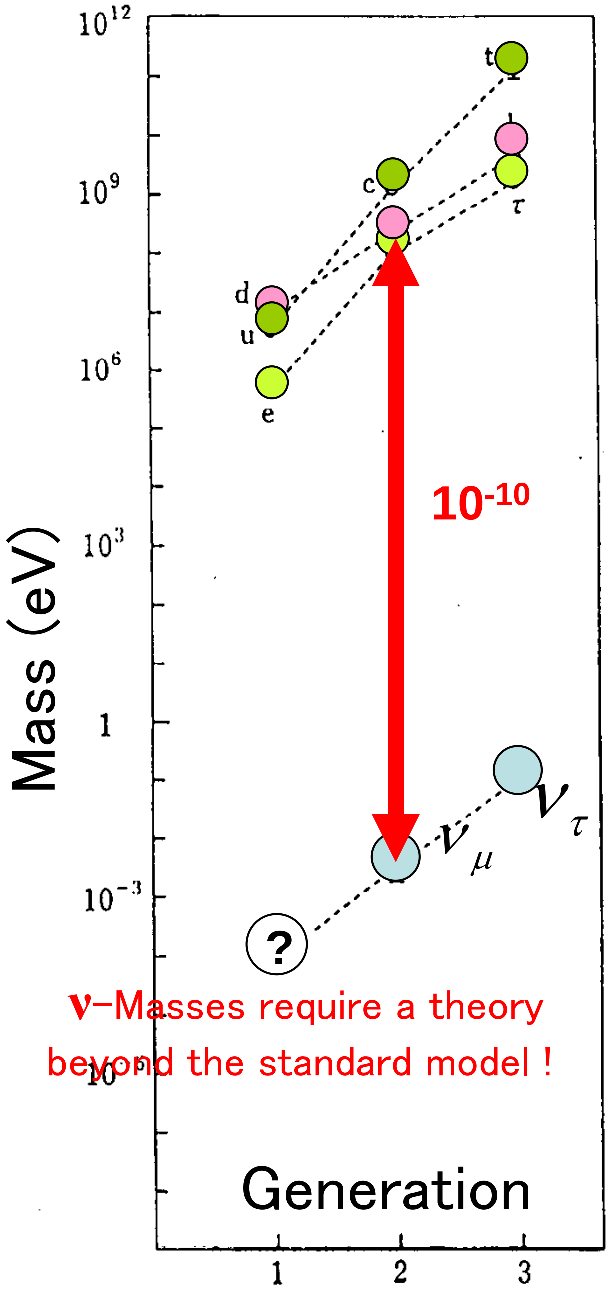
BBN Li problem

Core-collapse Supernova



Standard Model breaks down !

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



ν−Masses require a theory beyond the standard model !

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

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?

Today's Purpose

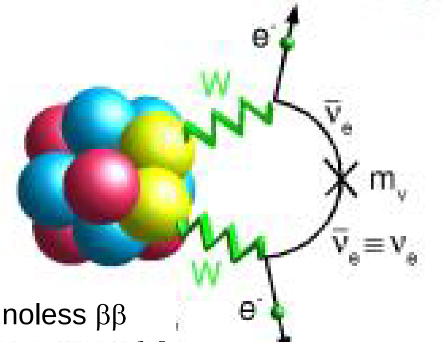
:- is to elucidate the role of Neutrino Physics in the studies of Element Genesis and Cosmic/Galactic Evolution.

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



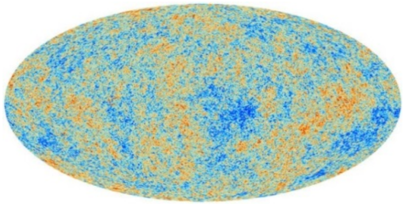
Neutrinoless ββ

- **CMB Anisotropies + LSS**

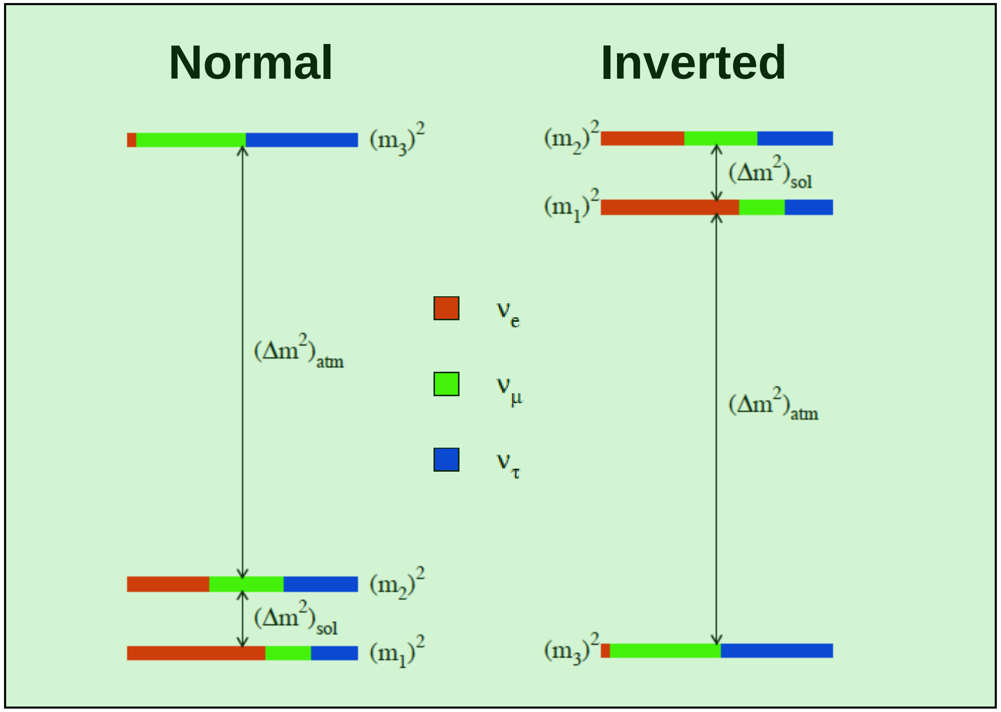
$\sum m_\nu < 0.14 - 0.17$ eV (95%C.L.): WMAP-7yr + Planck + BAO + HST + SZ (2015-16)

< 0.2 eV (2σ, $B_\lambda < 2$nG): + Magnetic Field

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



Planck 2013



ν−Oscillation Physics

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

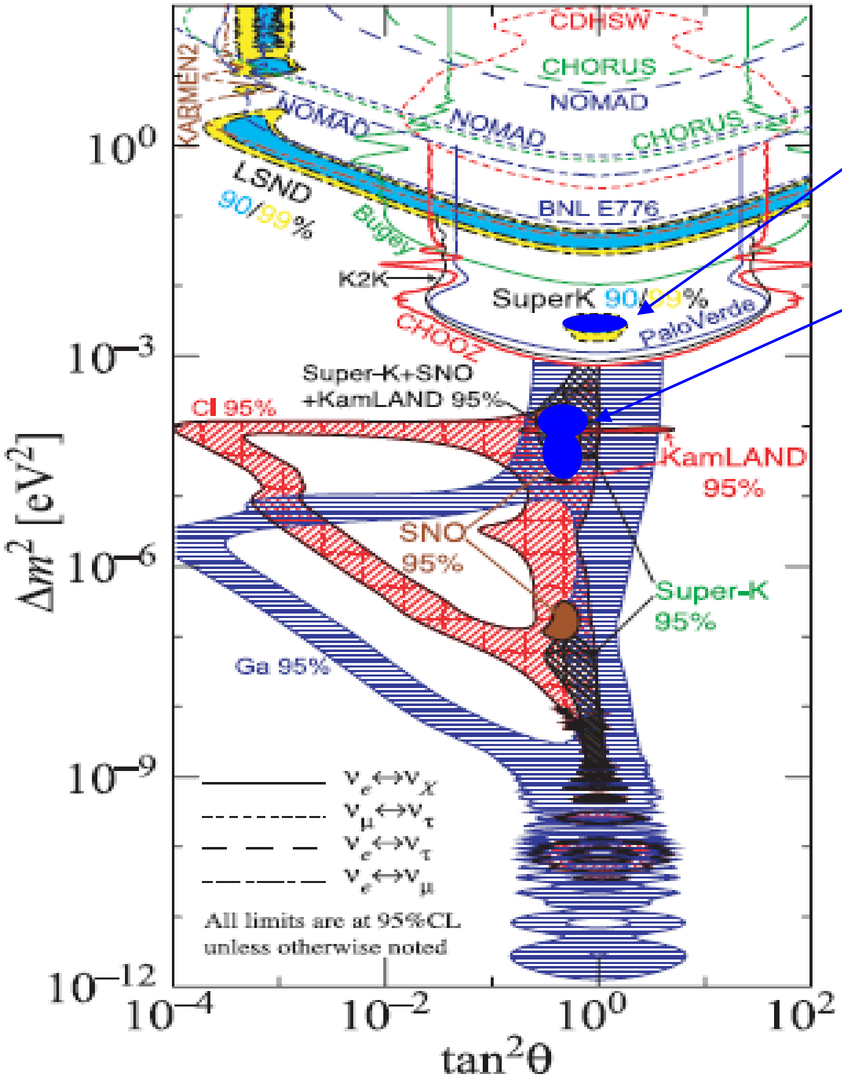
$$|\Delta m^2_{23}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2 = (0.05\ \mathrm{eV})^2$$

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

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

The “KNOWN” in Neutrino Oscillations

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



23－mixing

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

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

12－mixing Cabibbo angle

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

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

“Three 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

● ⊿$m_{13}^2 = \pm 2.4\mathrm{x}10^{-3}\ \mathrm{eV}^2$

● ~~δ　CP violation phase~~

● ~~Absolute Mass~~ 0νββ, cosmology

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

Reactor ν−Oscillation Experiments

RENO, Daya Bay and 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

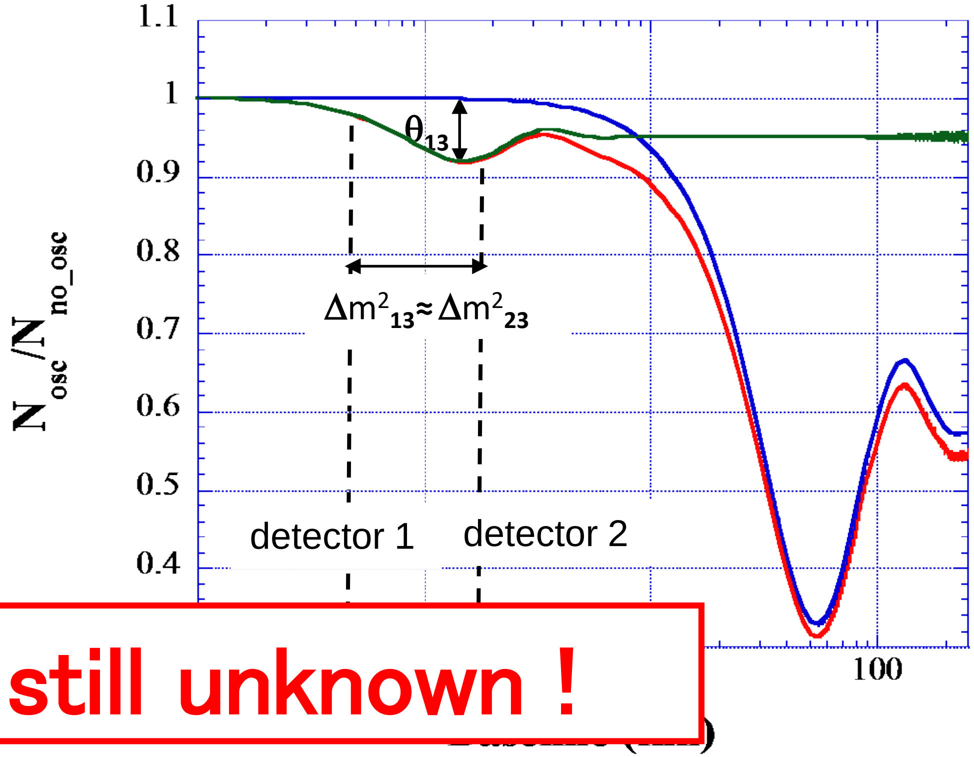
$\sin^2 2\theta_{13} = 0.103 +- 0.013(\mathrm{st})$
$+- 0.011(\mathrm{sys})$

→ $\theta_{13} = 8.88$ deg

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

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



Mass hierarchy is still unknown !

Various Neutrino-Sources in Nature

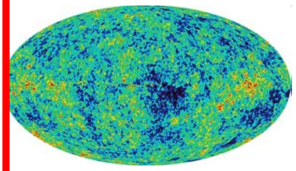
1.9K 0.4 1.0 2.6 8.5 Visible energy [MeV]

neutrino electron elastic scattering $\nu + e^- \rightarrow \nu + e^-$

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

CMB

Cosmic Background



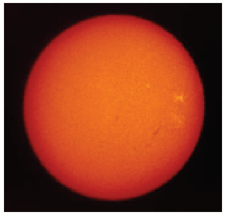
Neutrino Cosmology

verification
of particle model

ν_e, ν_μ, ν_τ

$\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$

^{7}Be solar neutrino



Neutrino Astrophysics

verification of SSM

ν_e

geo-neutrino

Neutrino Geophysics

verification of earth
evolution model

$\overline{\nu}_e$

Atmospheric ν

ν_e, ν_μ

$\overline{\nu}_e, \overline{\nu}_\mu$

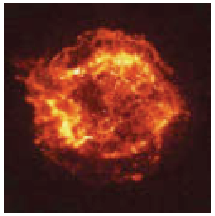
reactor neutrino

Neutrino Physics

Precision measurement
of oscillation parameters

$\overline{\nu}$

supernova relic neutrino
etc.



Neutrino Cosmology

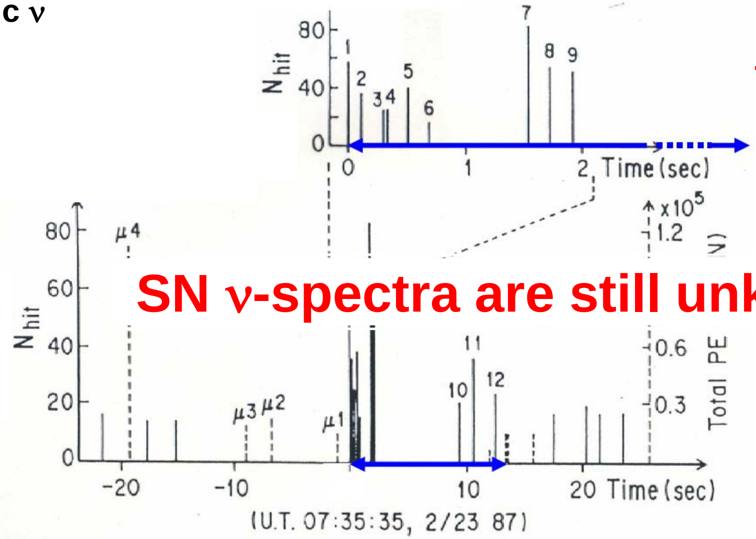
verification of
universe evolution

ν_e, ν_μ, ν_τ

$\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$

Direct signal of
SN neutrinos

Kamiokande (1987)



SN ν-spectra are still unknown !

Courtesy from
K. Inoue

Purpose

1. How to determine ν–Mass Hierarchy through MSW Effect

- ■ ν–Spectrum : Relic SN–ν (in SK & HK)

  + EOS of the Neutron Stars

- ■ ν–Nucleosynthesis

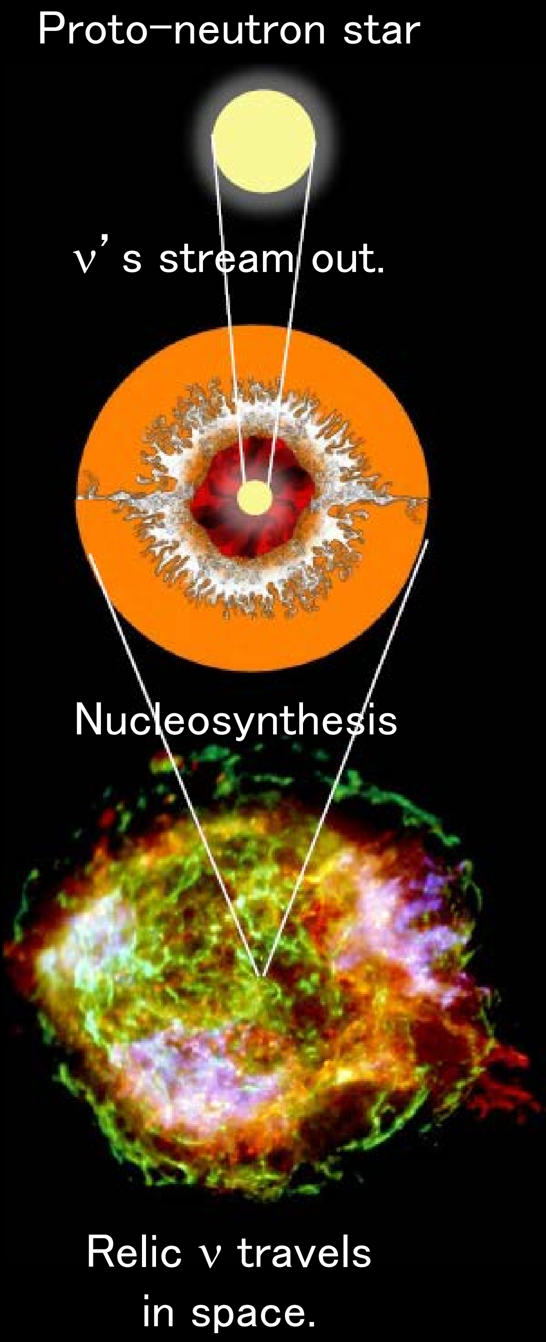
  Sensitive to ν–matter(MSW)effect

2. Solving the Mystery of R–Process

- ■ R–elements, sensitive to ν–interaction

  Core–Collapse Supernovae

  vs. Binary Neutron Star Mergers ?



Two Astronomical Motivations

G.J. Mathews, J. Hidaka, T. Kajino & J. Suzuki, ApJ 790(2014),115 — SNR problem,
J. Hidaka, T. Kajino, and G. J. Mathews, ApJ. 827(2016), 85— RSG problem.

Supernova Rate Problem

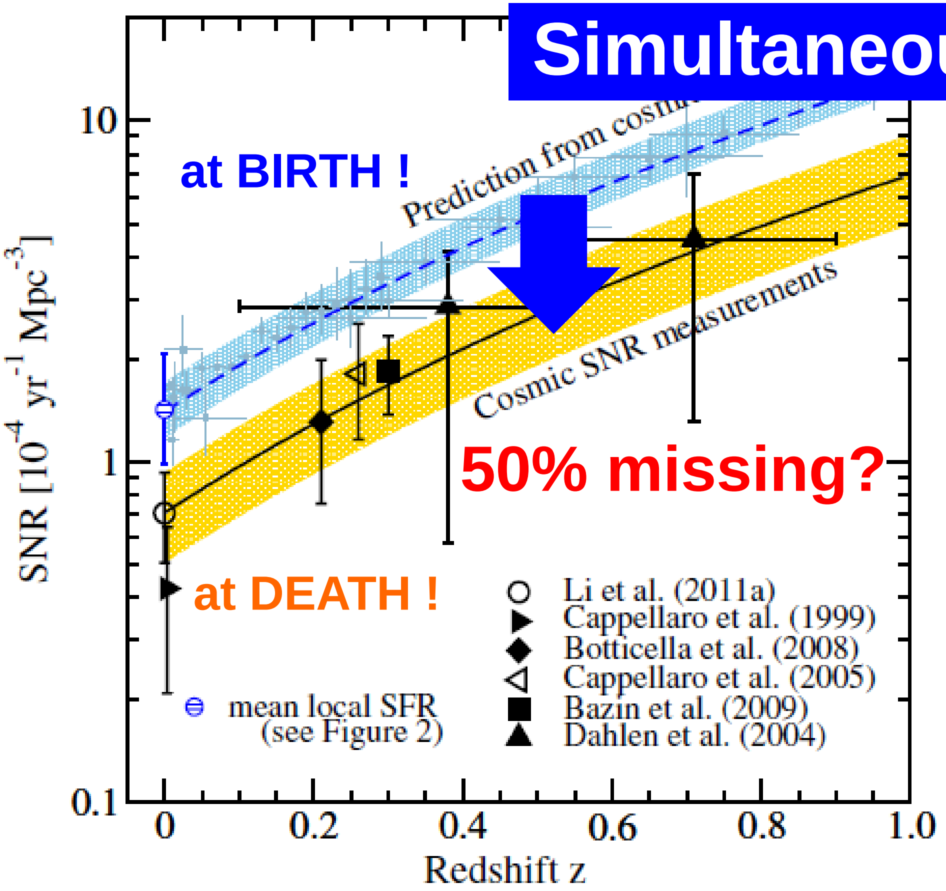
Red Super-Giant Problem

failed-SNe with BH → **Critical mass for failed-SNe ?**

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

Smartt, S.J. 2009, ARA&A 47, 63; 2015, PASA 32, e016

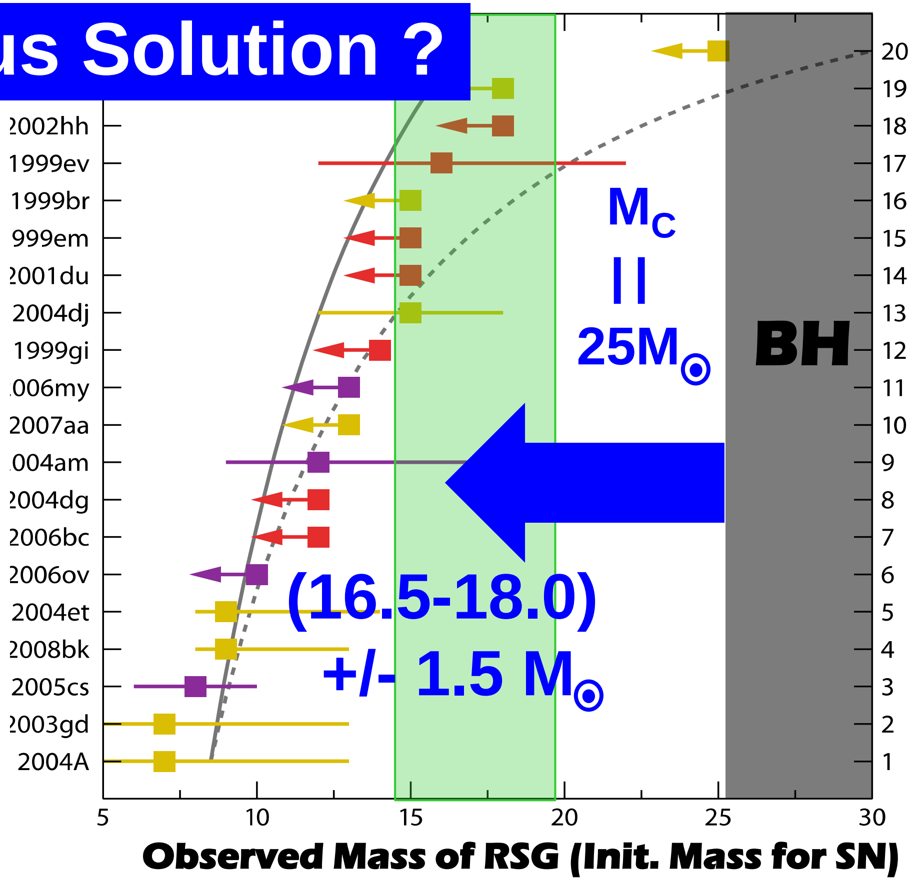
Simultaneous Solution ?



at BIRTH !

50% missing?

at DEATH !



M_C || $25M_\odot$

BH

(16.5-18.0) +/- 1.5 $M_\odot$

Our Solution to SNR & RSG Problems vs. Init. Mass

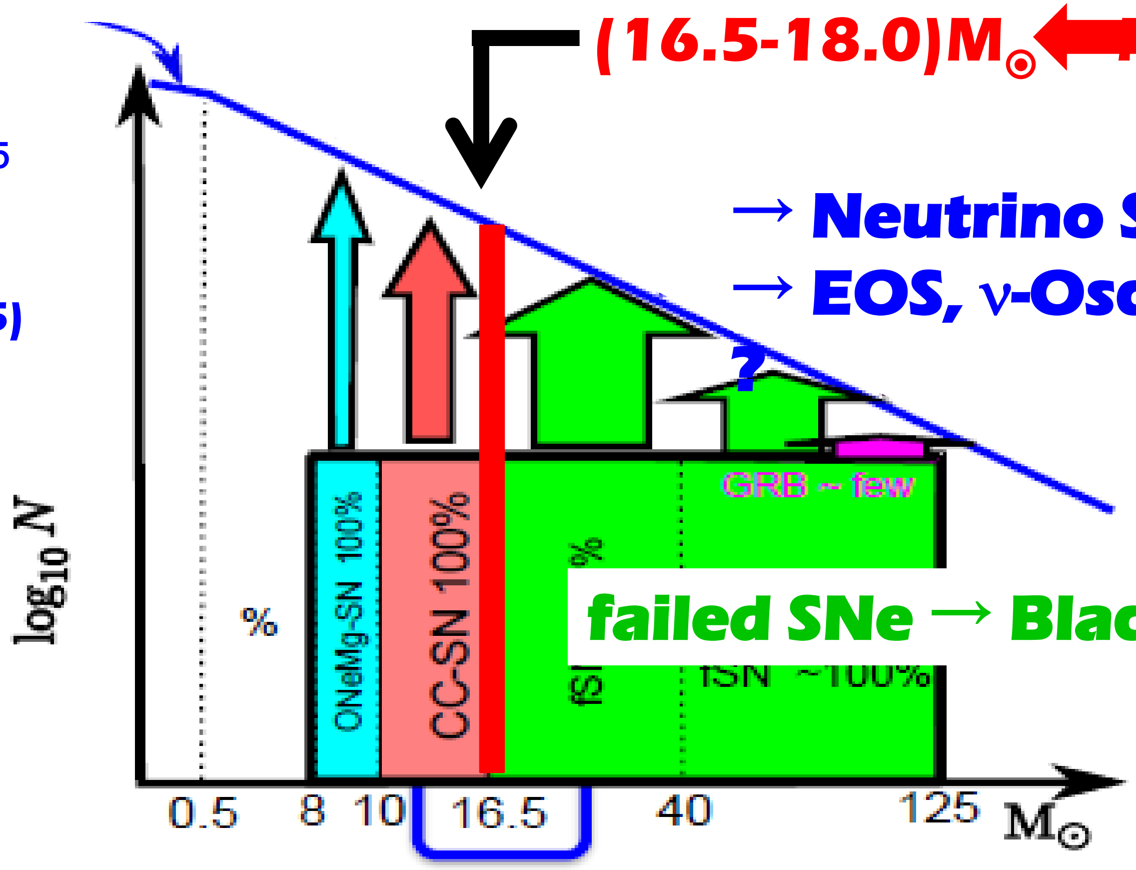
Cosmic Star Formation Rate

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

Initial Mass Function

$\phi_0(M) \propto M^{-2.35}$

Salpeter (1955)



(16.5-18.0)M$_\odot$ ← M$_c$=25M$_\odot$

→ Neutrino Signal ?

→ EOS, ν-Oscillation

failed SNe → Black Hole

Survey of Numerical SN-Simulations

Horiuchi, Nakamura, Takiwaki, Kotake, & Tanaka, MNRAS 445 (2014), L99

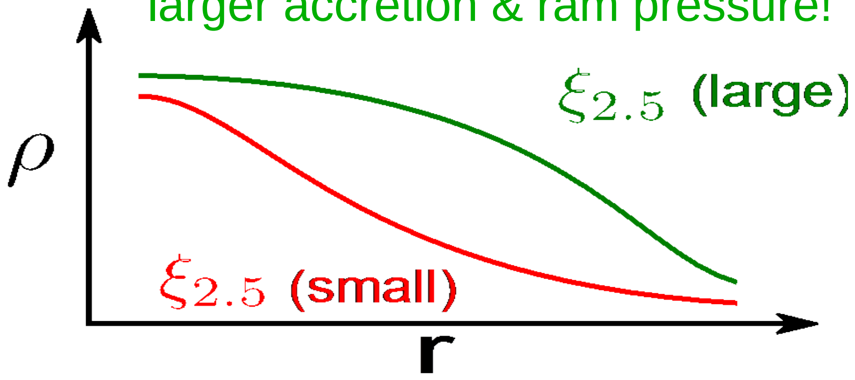
Woosley, Heger, Weaver, RMP 74 (2002), 1015.

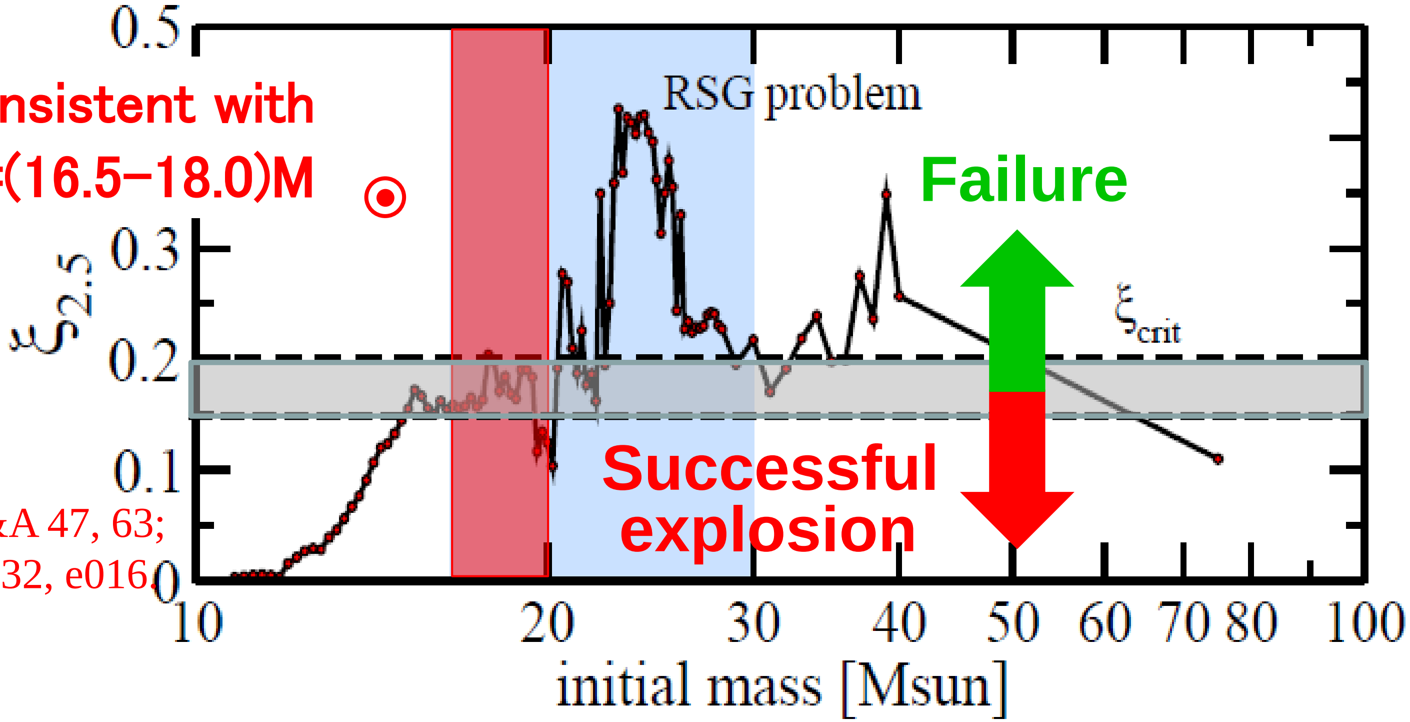
Compactness parameter :

for $M_b = 2.5 M_\odot$ at core-bounce

$$\xi_{2.5} = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}$$

Shock wave must overcome larger accretion & ram pressure!





Consistent with $M_C = (16.5-18.0) M_\odot$

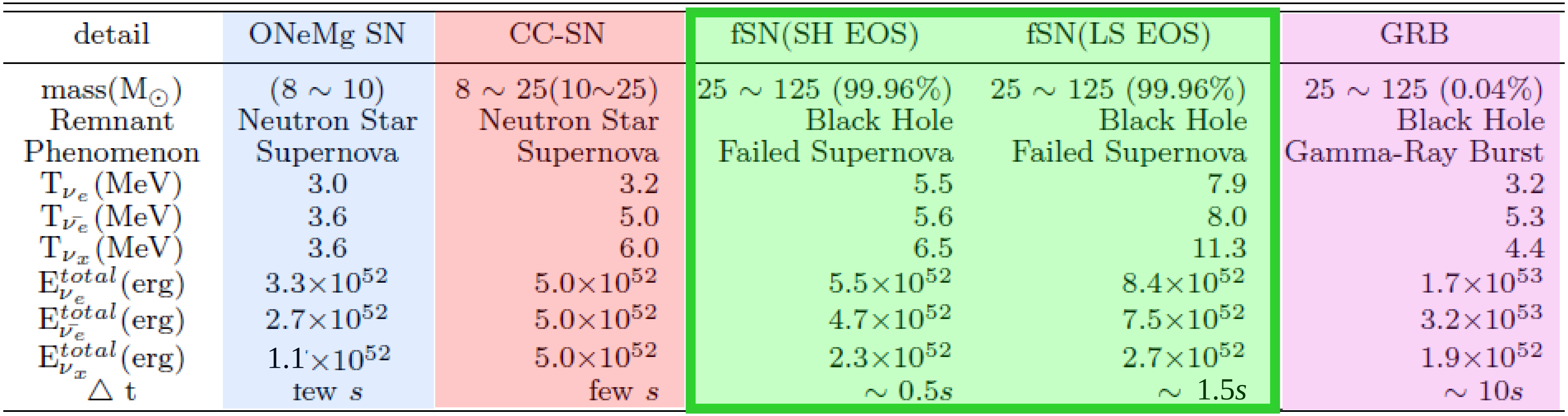
Failure

Successful explosion

Smartt, S.J.
2009, ARA&A 47, 63;
2015, PASA 32, e016.

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)

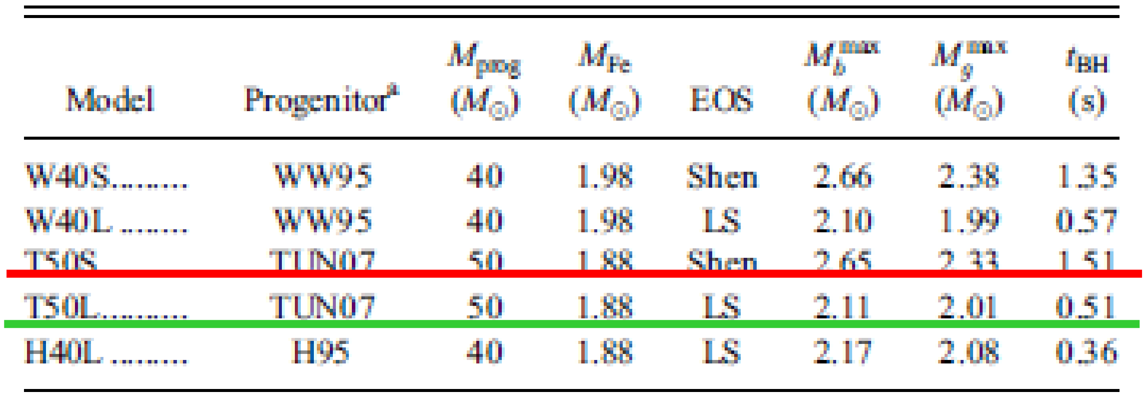


detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e} (MeV)	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
$E^{total}_{\nu_e}$(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^{52}	5.0×10^{52}	2.3×10^{52}	2.7×10^{52}	1.9×10^{52}
△ t	few s	few s	∼ 0.5s	∼ 1.5s	∼ 10s

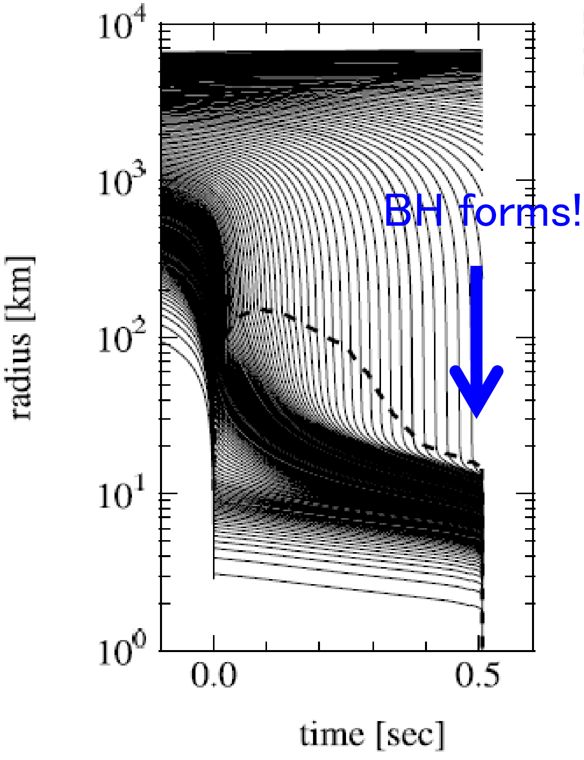
- **ONeMg SNe:** Hudepohl, et al., PRL 104 (2010).
- **CC-SNe:** Yoshida, et al., ApJ **686** (2008), 448;
  Suzuki & Kajino, J. Phys. **G40** (2013) 83101.
- **fSN (failed SNe):** Sumiyoshi, et al., ApJ **688** (2008) 1176.
  - * **Shen-EOS (stiff):** Shen et al. Nucl. Phys. **A637** (1998) 435.
  - * **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.

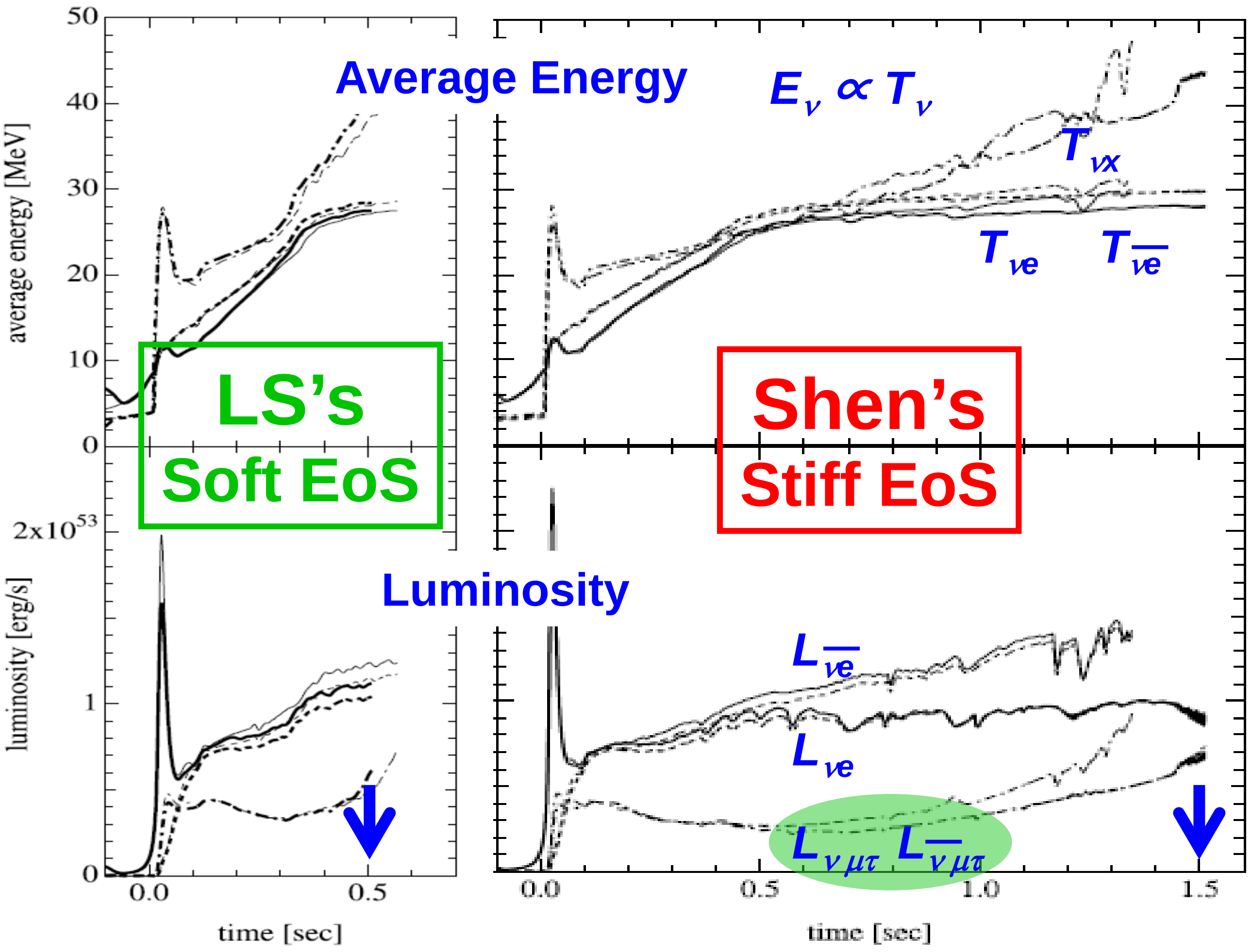
Neutrino Signal from failed SNe

Sumiyoshi, Yamada,
& Suzuki
ApJ **688** (2008)1176.



Model	Progenitor[a]	M_{prog} ($M_\odot$)	M_{Fe} ($M_\odot$)	EOS	M_b^{max} ($M_\odot$)	M_g^{max} ($M_\odot$)	t_{BH} (s)
W40S........	WW95	40	1.98	Shen	2.66	2.38	1.35
W40L	WW95	40	1.98	LS	2.10	1.99	0.57
T50S........	TUN07	50	1.88	Shen	2.65	2.33	1.51
T50L.........	TUN07	50	1.88	LS	2.11	2.01	0.51
H40L	H95	40	1.88	LS	2.17	2.08	0.36





Spectrum of Relic Supernova Neutrinos(RSNs)

Mathews et al. 2014; Totani et al. 1996, ApJ 460, 303; Lunadini 2009, PRL 102, 231101.

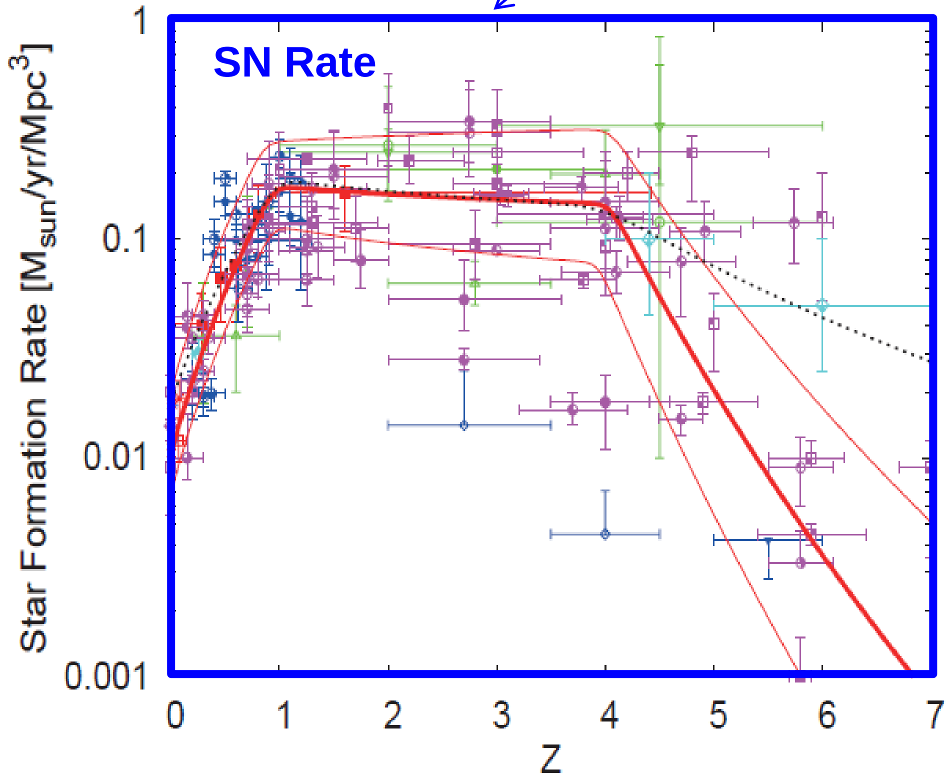
Redshifted $E'_\nu = (1+z)E_\nu$ Expanding Universe $\Lambda\mathrm{CDM}$

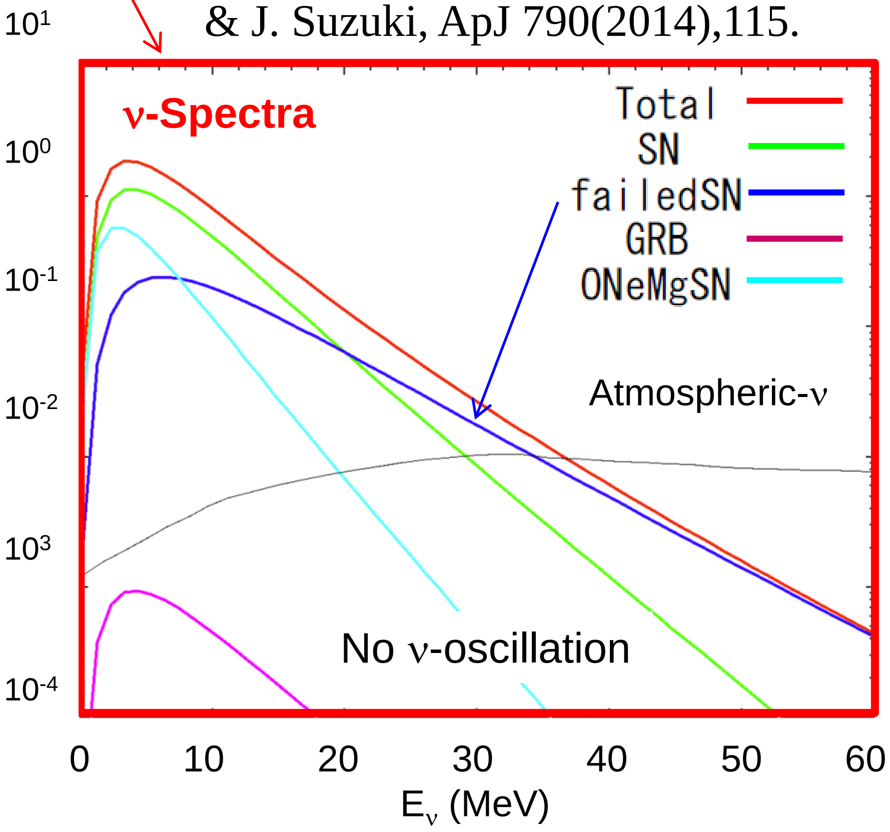
$$\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} \boxed{R_{SN}(z)}\boxed{\frac{dN_\nu(E'_\nu)}{dE'_\nu}} \times \boxed{\frac{dz}{\sqrt{(\Omega_m)(1+z)^3+\Omega_\Lambda}}}$$

$\Omega_m = 0.3$

$\Omega_\Lambda = 0.7$

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

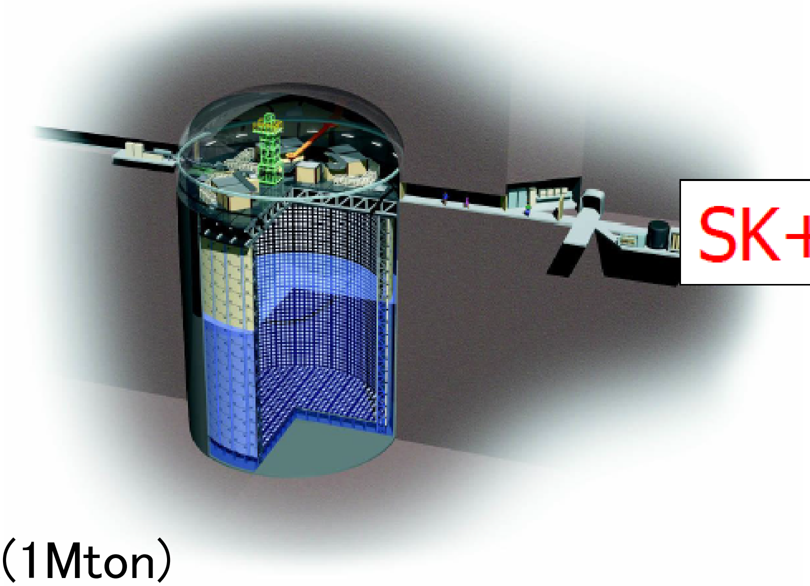




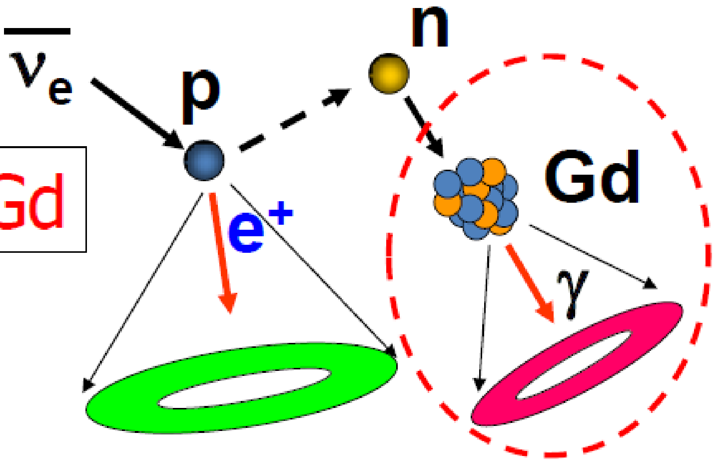
Gd-loaded Water Cherenkov Detector

Vagins and Beacom, PRL 93 (2004), 171101.

SK(22.5kton)



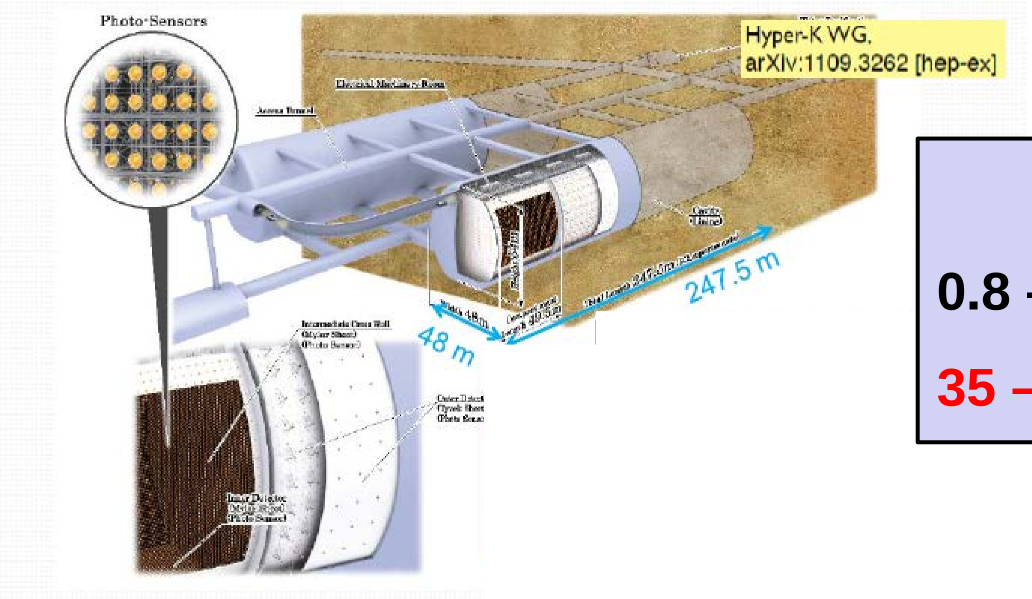
SK+Gd



Present signal **New signal**

COINCIDENCE

HK(1Mton)



Hyper-K WG.
arXiv:1109.3262 [hep-ex]

SRN Event Rate

0.8 – 5 events/year/22.5kton (SK)

35 – 220 events/year/1Mton (HK)

Coutesy of K. Inoue & M. Sakuda

Relic Supernova Neutrino(RSN) Spectrum

SAKUDA, Makoto:Mega−ton, Gd−loaded Water Cherenkov Detector at Super−K

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

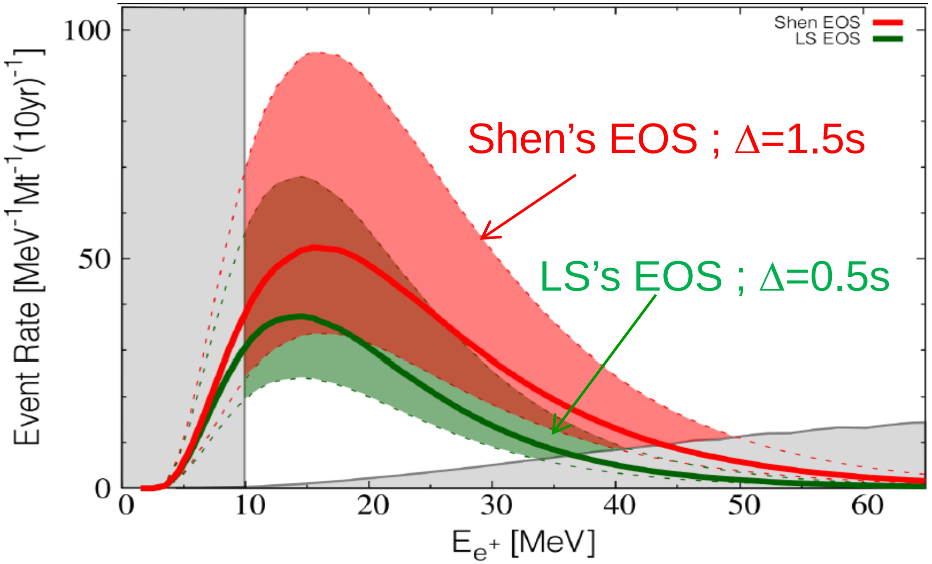
Hidaka, Kajino, & Mathews, ApJ. 827(2016), 85.

Setting M_C=(16.5−18.0) $M_\odot$ to solve SN RATE PROBLEM and RSG PROBLEM simultaneously.

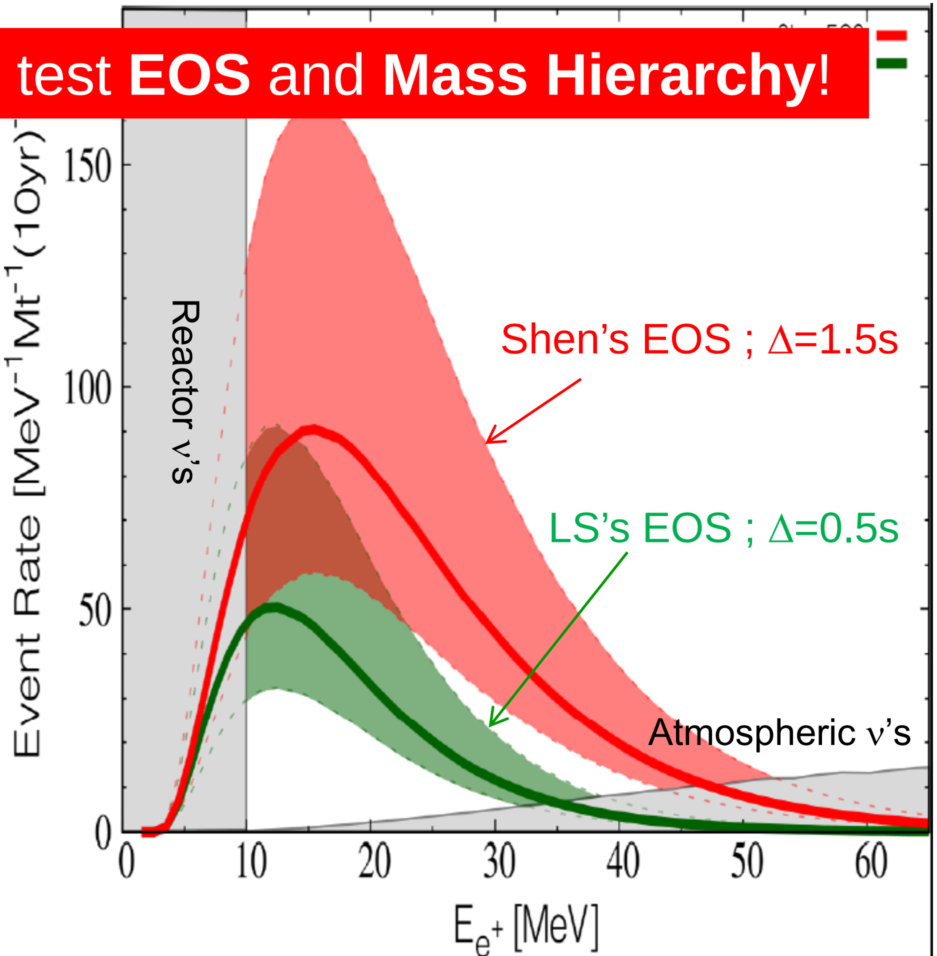
RSNs could be a good probe to test **EOS** and **Mass Hierarchy**!

MSW-HD Res. + ($L_{\nu e} = L_{\bar{\nu} e} \gg L_{\bar{\nu}_{\mu,\tau}}$)

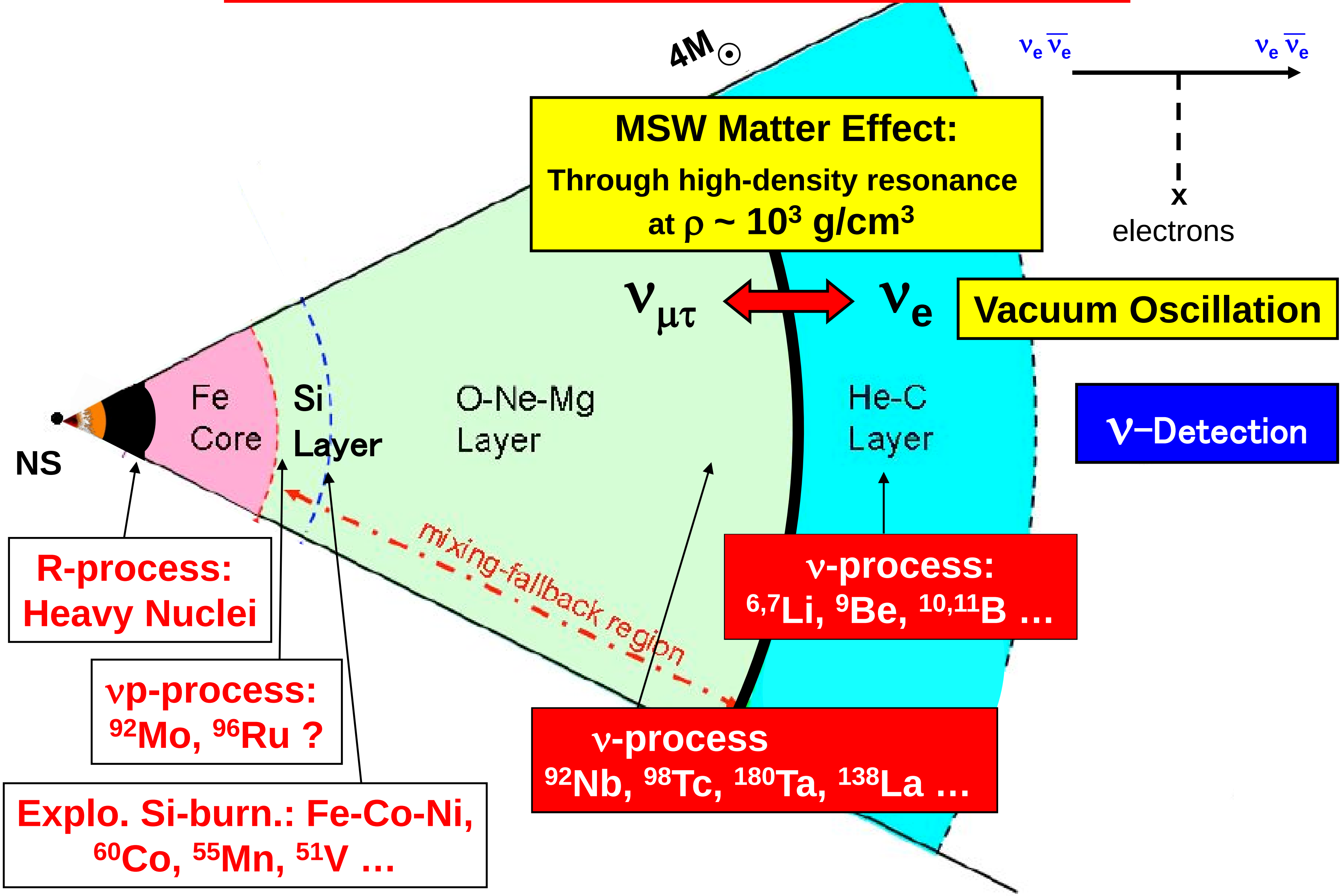
Inverted Hierarchy



Normal Hierarchy



ν-Oscillation and Nucleosynthesis



MSW Matter Effect:

Through high-density resonance at $\rho \sim 10^3$ g/cm^3

Vacuum Oscillation

ν−Detection

R-process: Heavy Nuclei

νp-process: ^{92}Mo, ^{96}Ru ?

Explo. Si-burn.: Fe-Co-Ni, ^{60}Co, ^{55}Mn, ^{51}V …

ν-process: ^{6,7}Li, ^{9}Be, ^{10,11}B …

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

Supernova ν−Process; ^{6,7}Li−^{9}Be−^{10,11}B

^{4}He(ν,ν'*p*)^{3}H, ^{4}He

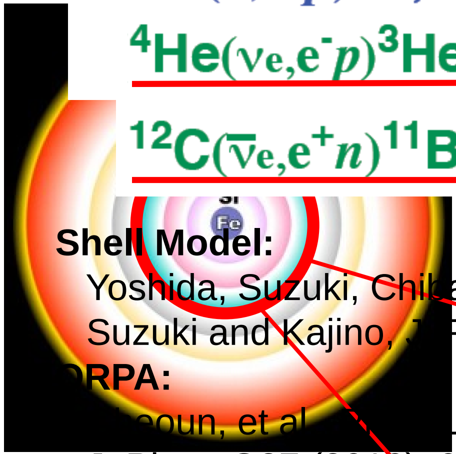
$|\Delta m^2_{13}| = |\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\varepsilon_\nu \sim 10$ MeV

^{4}He(ν$_e$,e$^-$*p*)^{3}He, ^{4}He($\bar{\nu}_e$,e$^+$*n*)^{3}H, ^{12}C(ν$_e$,e$^-$*p*)^{11}C,

^{12}C($\bar{\nu}_e$,e$^+$*n*)^{11}B

$$2\sqrt{2}G_F(\hbar c)^3\varepsilon_\nu$$

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



Shell Model:

Yoshida, Suzuki, Chiba, Kajino, et al., ApJ 686 (2008), 448:

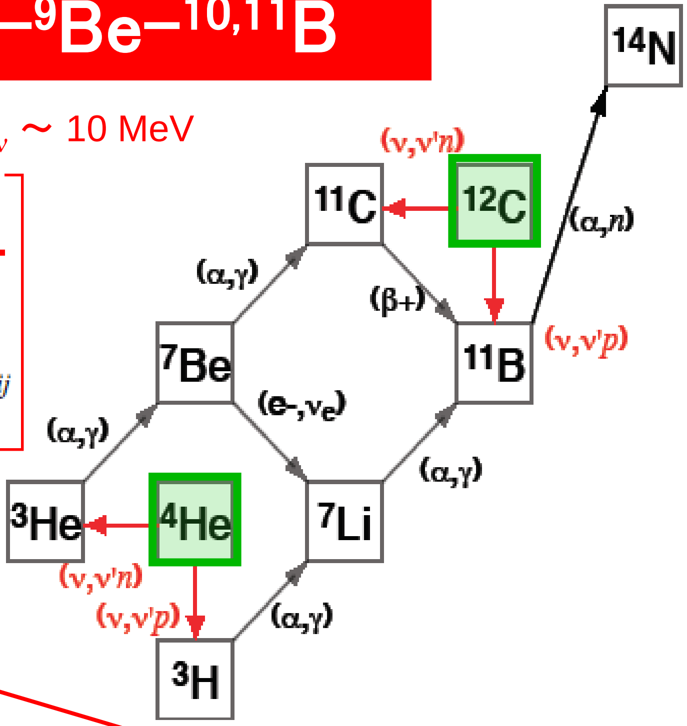
Suzuki and Kajino, J. Phys. G40 (2013), 083101:

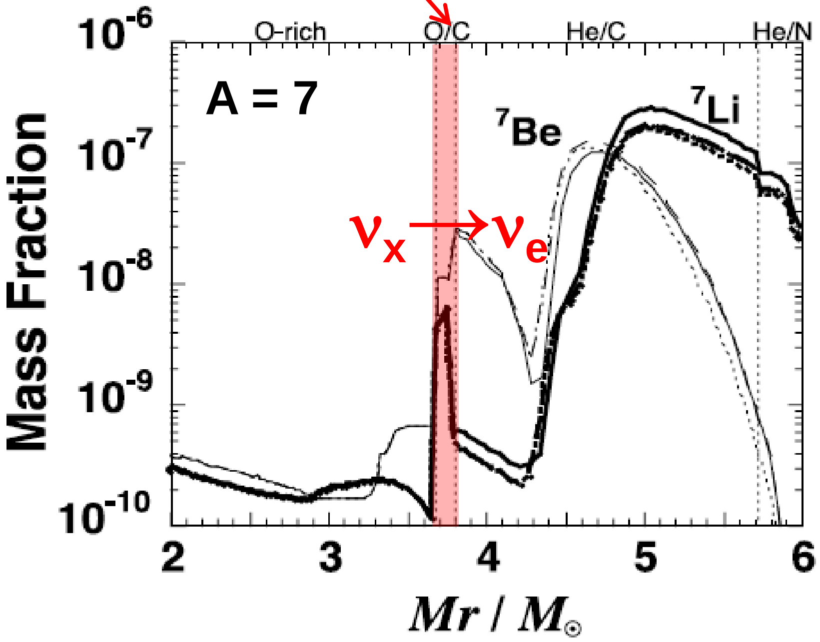
RPA:

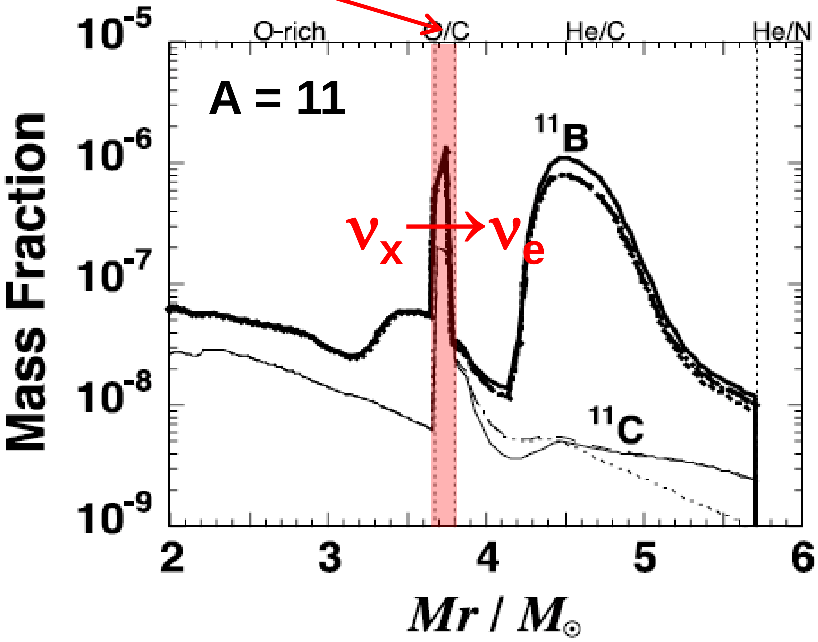
eoun, et al 1 (2010), 028501; PRC82 (2010), 035504;

J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801

MSW high-density resonance is located at O/C - He/C shell at ρ ~ 10^3 g/cm^3.

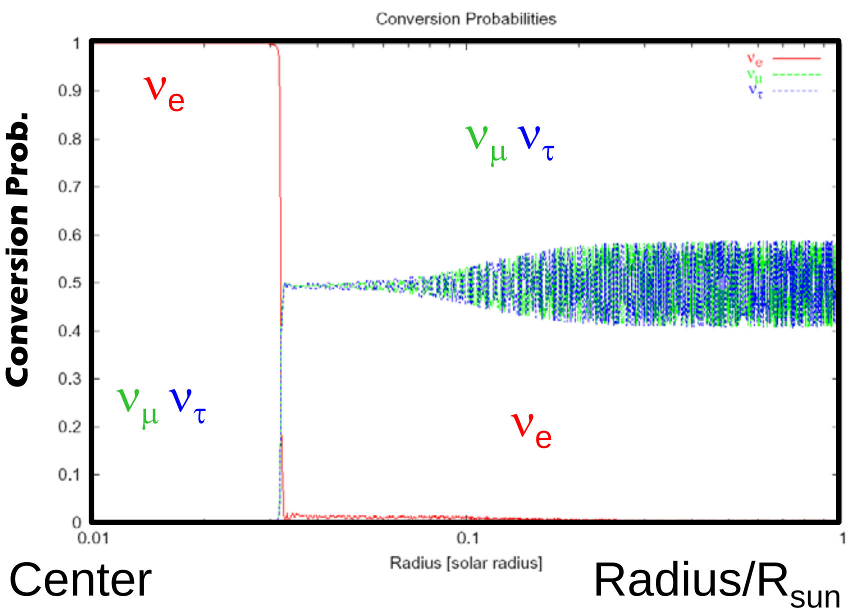




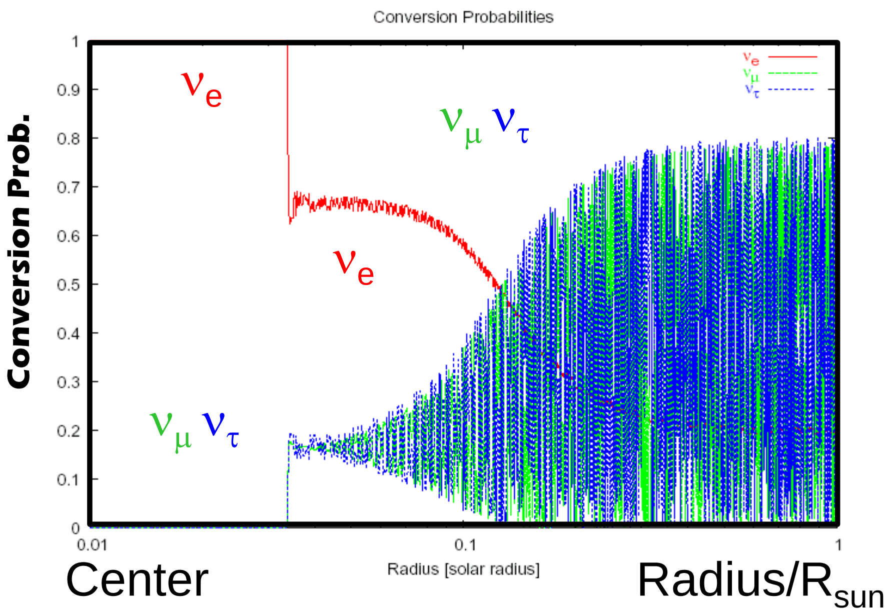


SN-Neutrino Oscillation (MSW) Effect on ν-Process

Adiabatic



Non-Adiabatic



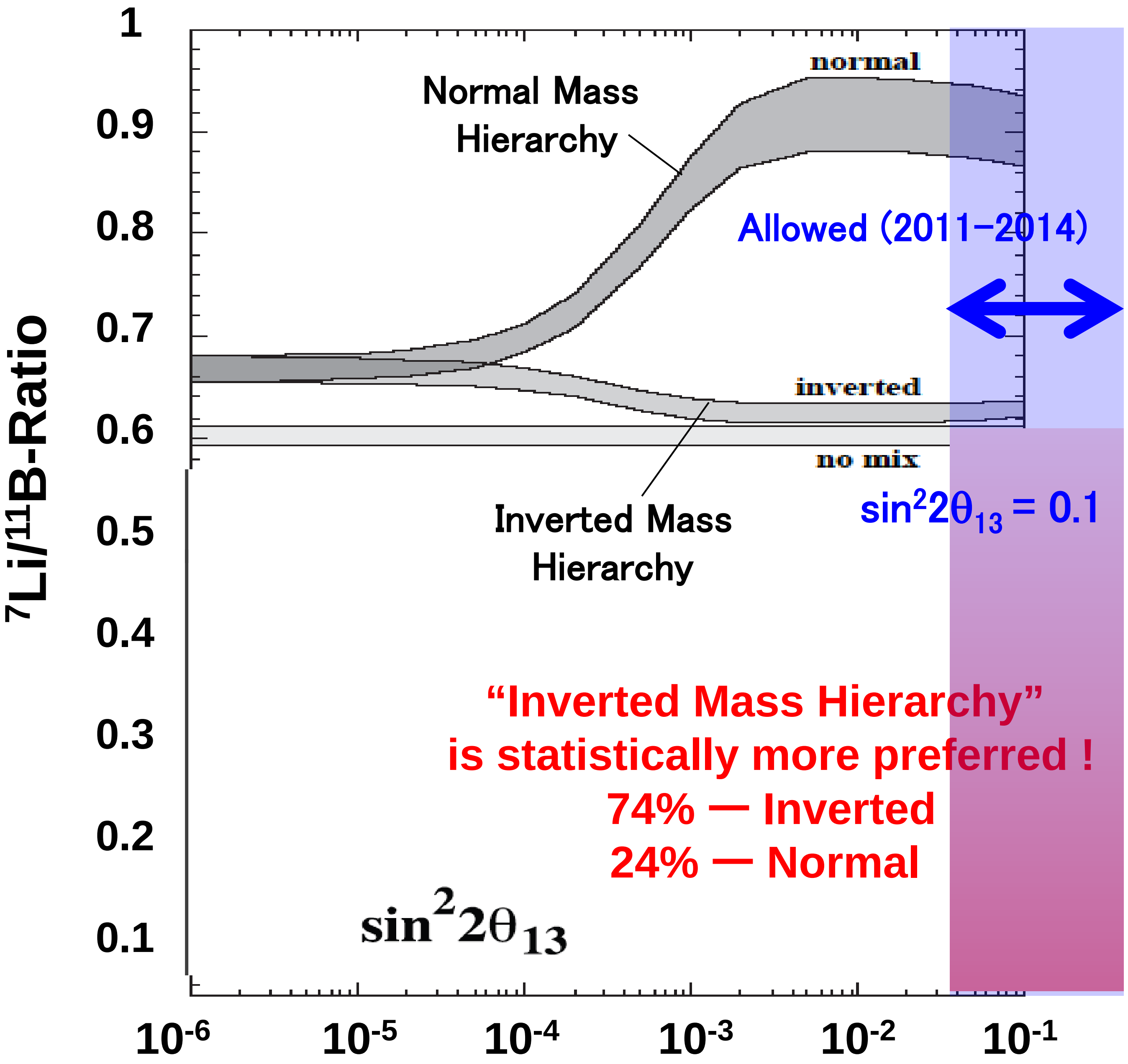
Parameters:

$25M_{solar}$ SN model (Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV^2
- $L_\nu = 3\times10^{53}$ erg, τ_ν = 3 sec
- $E_{\nu e}$=12MeV, $E_{\overline{\nu e}}$=15MeV, $E_{\nu\mu\tau}$=24MeV

Fermi-Dirac distr. of ν-spectrum, so that the observed ^{11}B abundance in Supernova Nucleosynthesis is reproduced.

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



"Inverted Mass Hierarchy" is statistically more preferred !

74% — Inverted

24% — Normal

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)

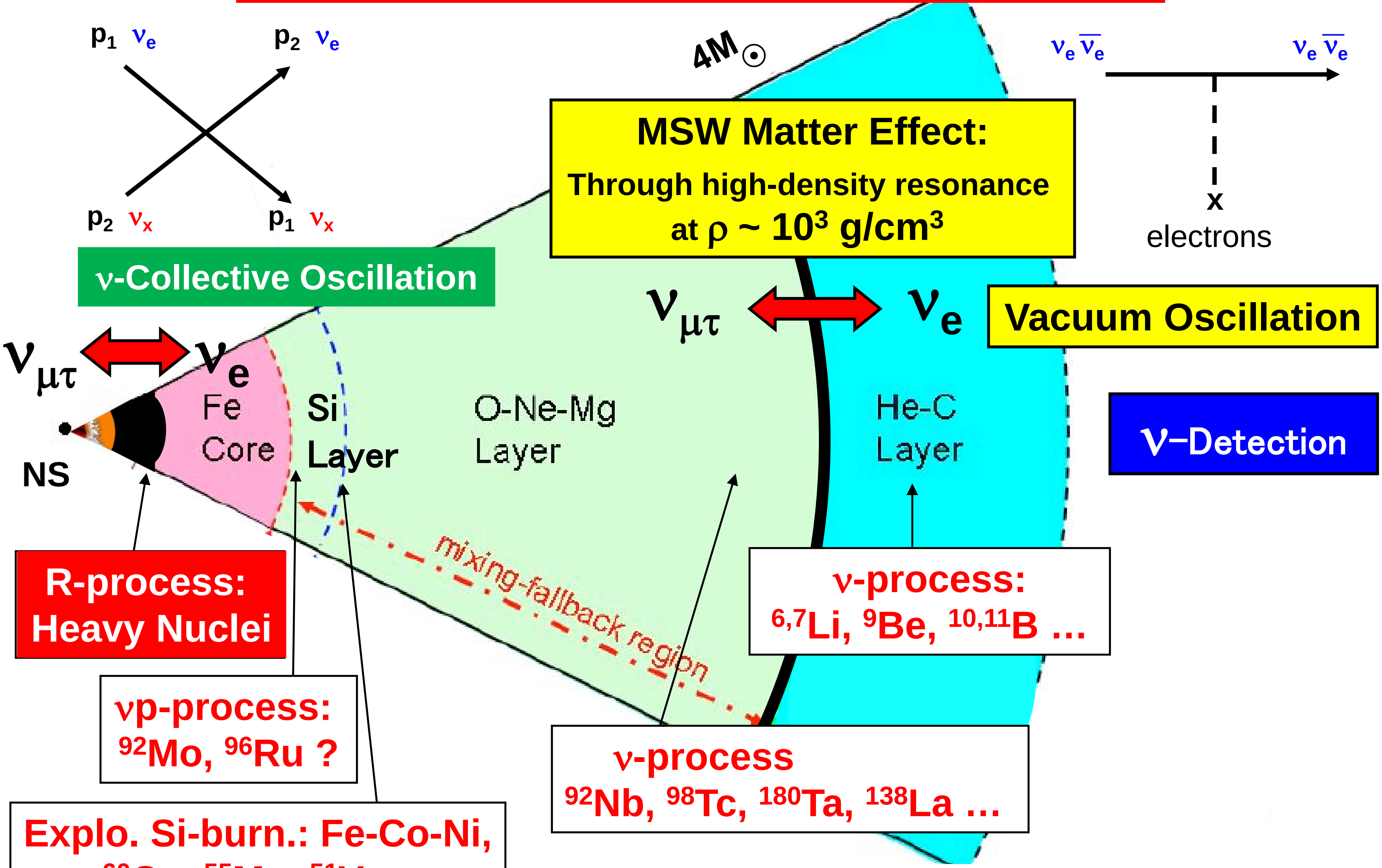
Long BaselineExp. in 2011:

- T2K (Kamioka)
- MINOS

Reactor Exp. in2012:

- RENO (KOREA)
- Double CHOOZ
- Daya Bay

ν-Oscillation and Nucleosynthesis



MSW Matter Effect:
Through high-density resonance at $\rho \sim 10^3$ g/cm^3

ν-Collective Oscillation

Vacuum Oscillation

ν−Detection

R-process:
Heavy Nuclei

νp-process:
^{92}Mo, ^{96}Ru ?

Explo. Si-burn.: Fe-Co-Ni,
^{60}Co, ^{55}Mn, ^{51}V …

ν-process:
^{6,7}Li, ^{9}Be, ^{10,11}B …

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

c.f. *SIEVERDING, Andre & WU, Meng*

Astrophysical sites for the r–process ?

Core–Collapse Supernovae?

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

τ =1–10My

Underproduction, off peaks ?

Explosion Condition(Ω, B)?

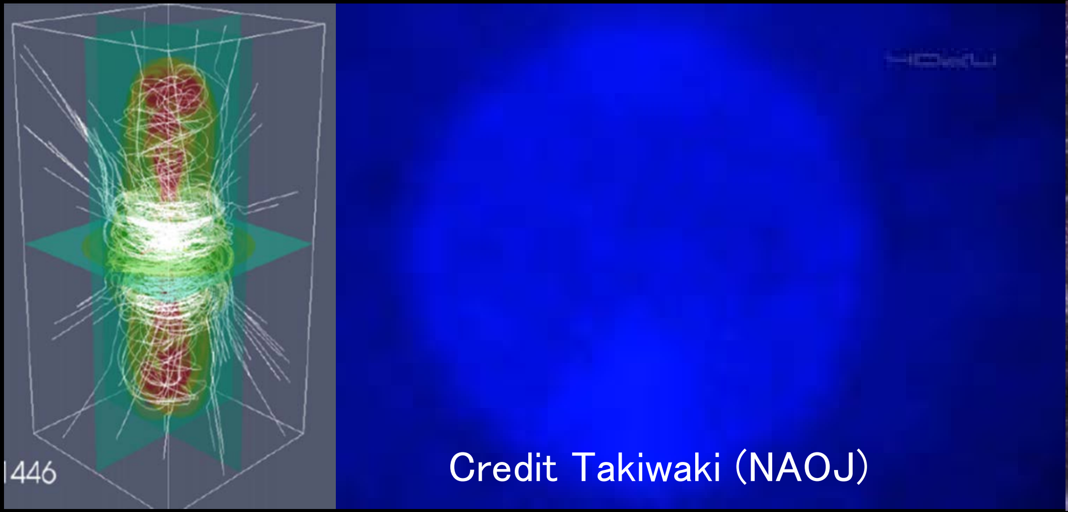
Binary Neutron–Star Mergers?

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 $\lesssim \tau_c \lesssim$ 10Ty

Binary NSs arrive too late ?

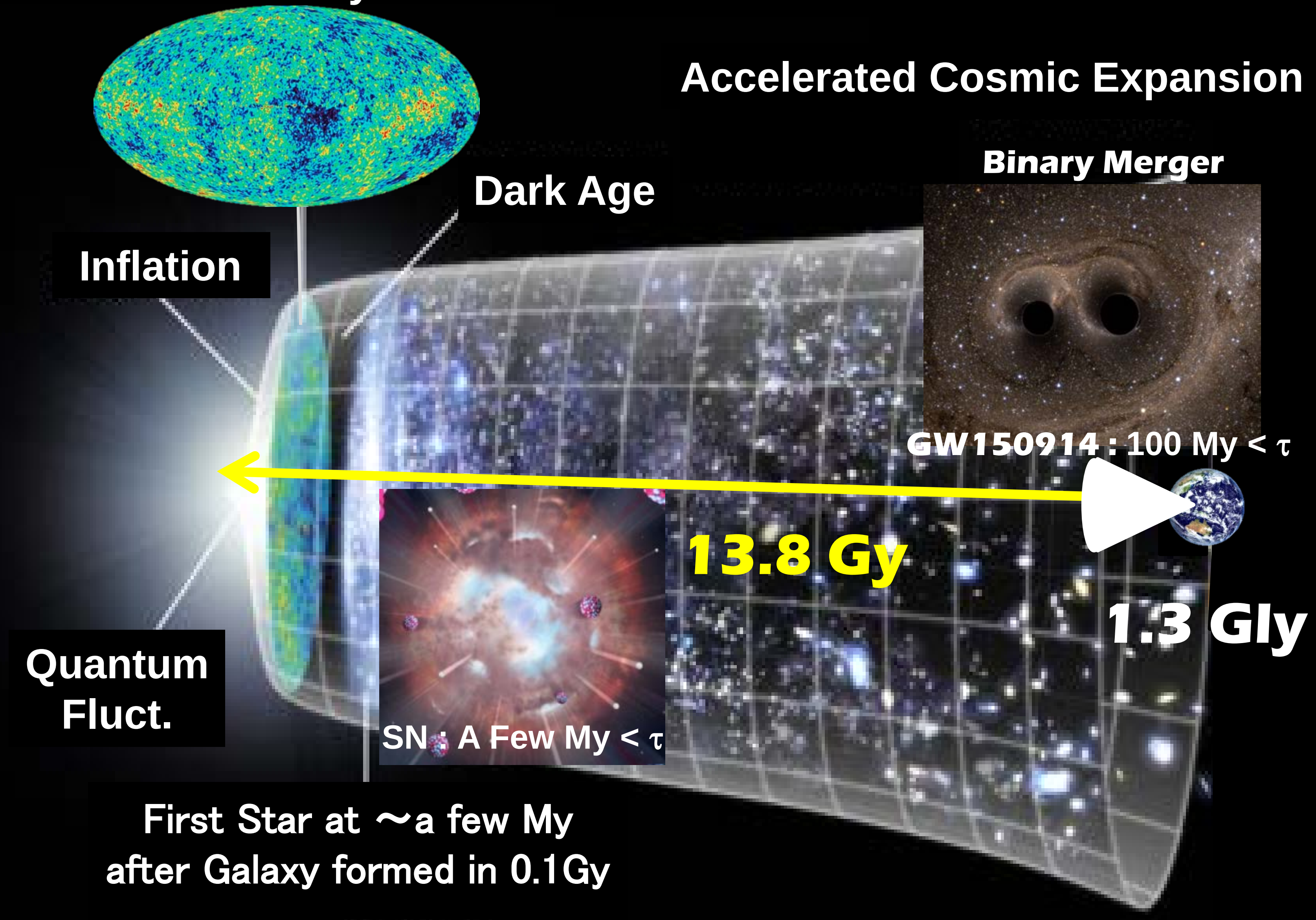
Time Scale Problem ?



Credit Takiwaki (NAOJ)

Credit NASA

Cosmic Evolution



Photon Last Scatt.
3.8×10^5 y

Accelerated Cosmic Expansion

Dark Age

Binary Merger

Inflation

GW150914 : 100 My < τ

13.8 Gy

1.3 Gly

Quantum Fluct.

SN : A Few My < τ

First Star at ～a few My
after Galaxy formed in 0.1Gy

Galactic Chemo-Dynamical Evolution

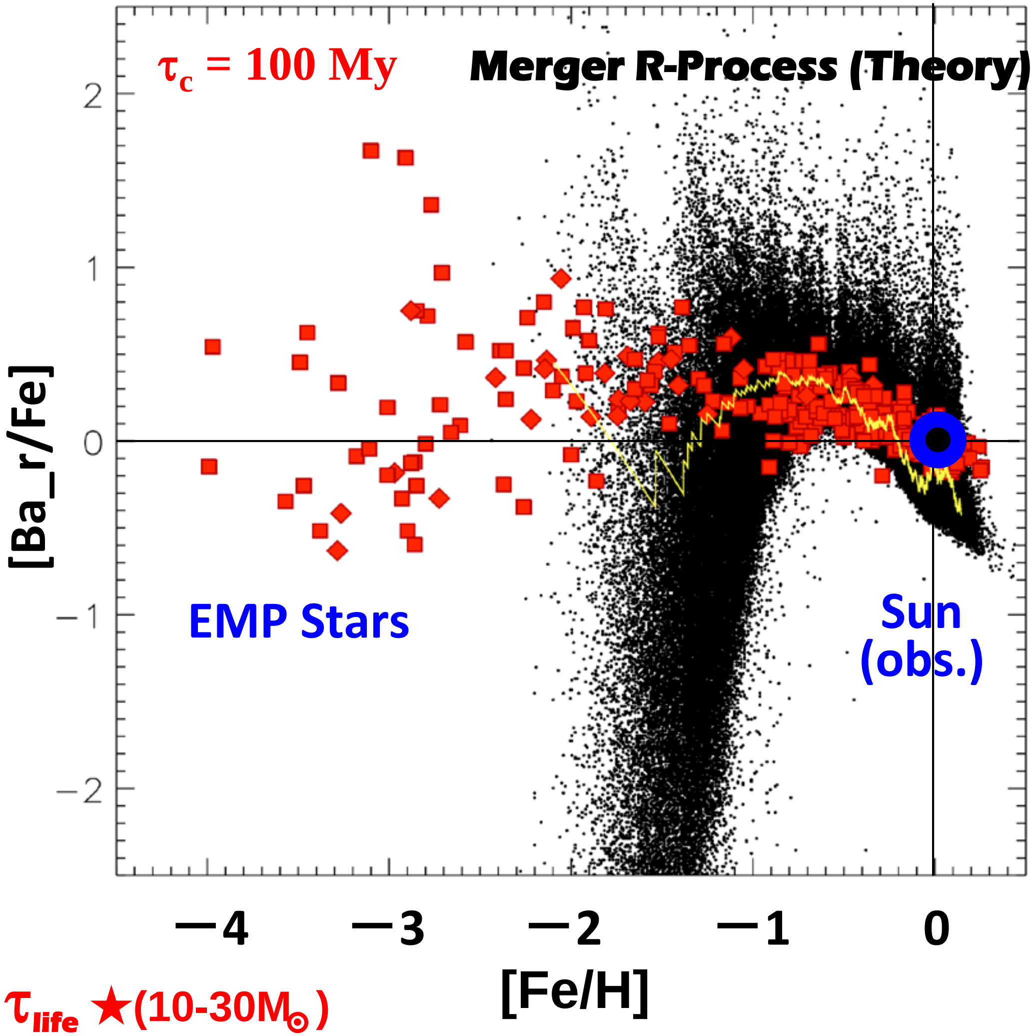
Gal. Chem. Evolution (not Dynamical)

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

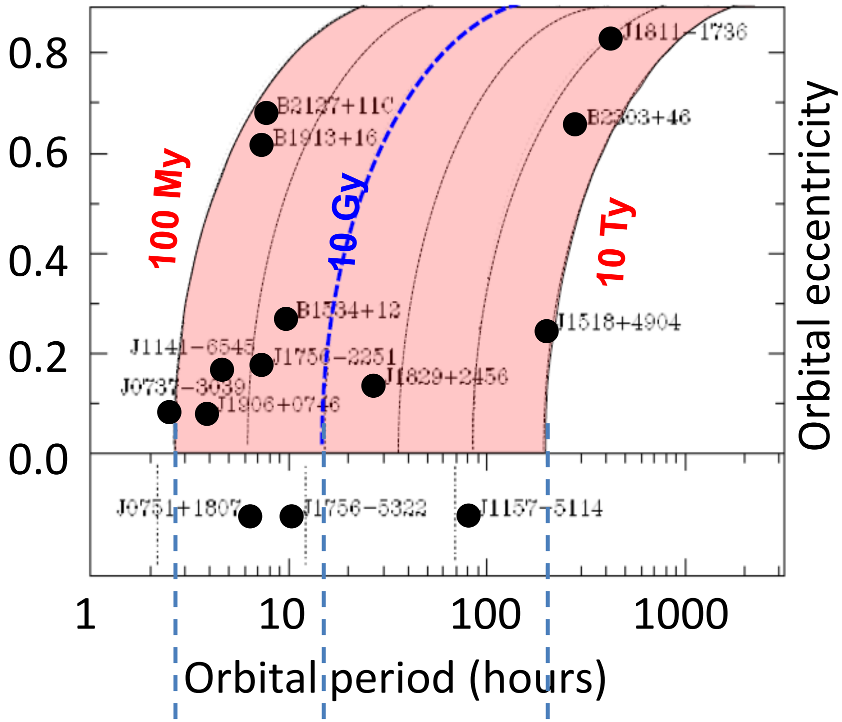
Time Scale Problem

Merging, too slow for GW rad.:
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



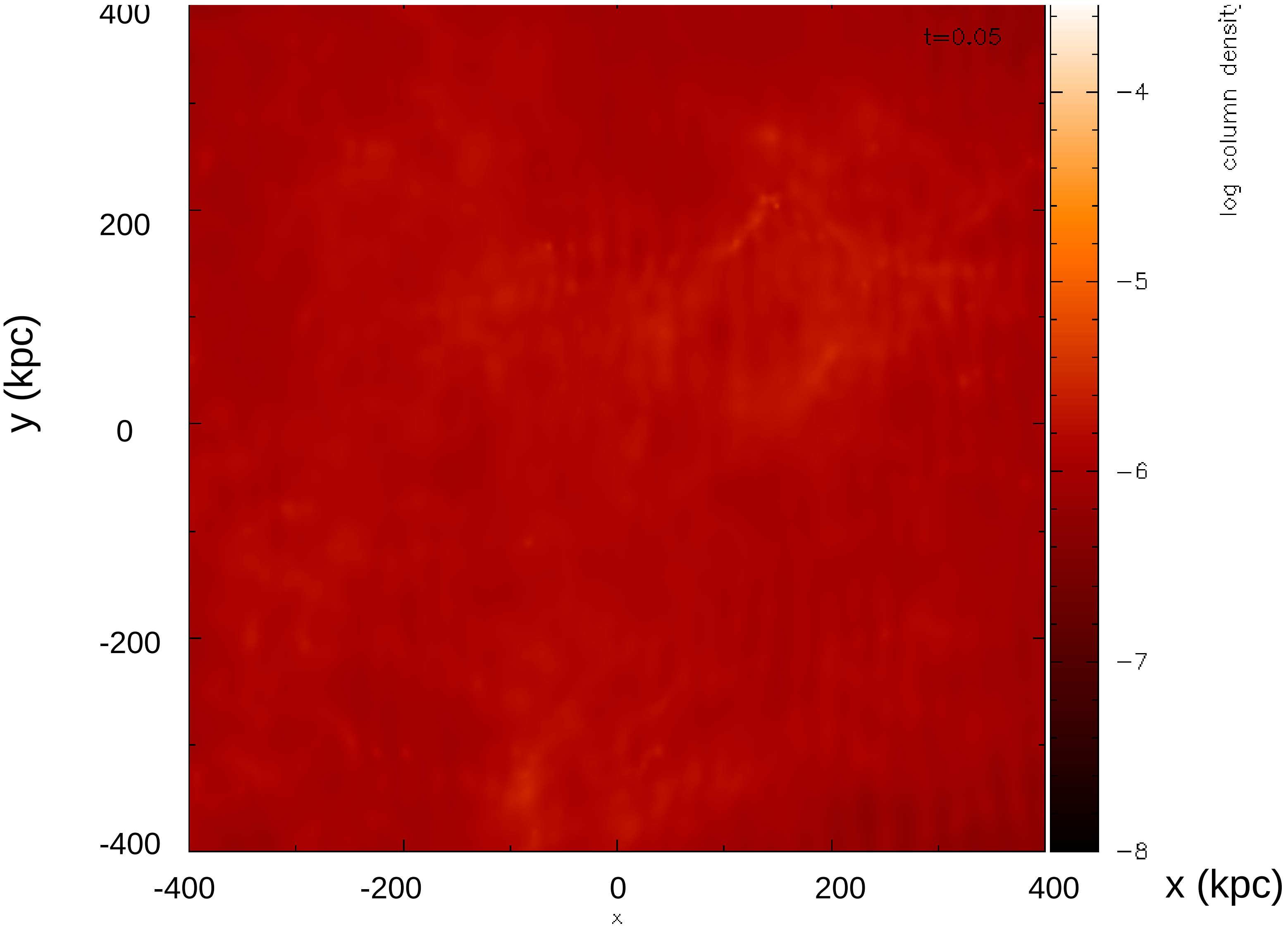
τ_{life} ★(10-30$M_\odot$)

1My 10My 100My ・・・ 10Gy

100My 10Gy 10Ty

Mixing of r-elements between Neighboring UFDGs is limited to [Fe/H] < -3.5 and only fractional 0.001-0.1%.

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



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution **Dwarf Galaxies = Building Blocks of Milky Way Galaxy**

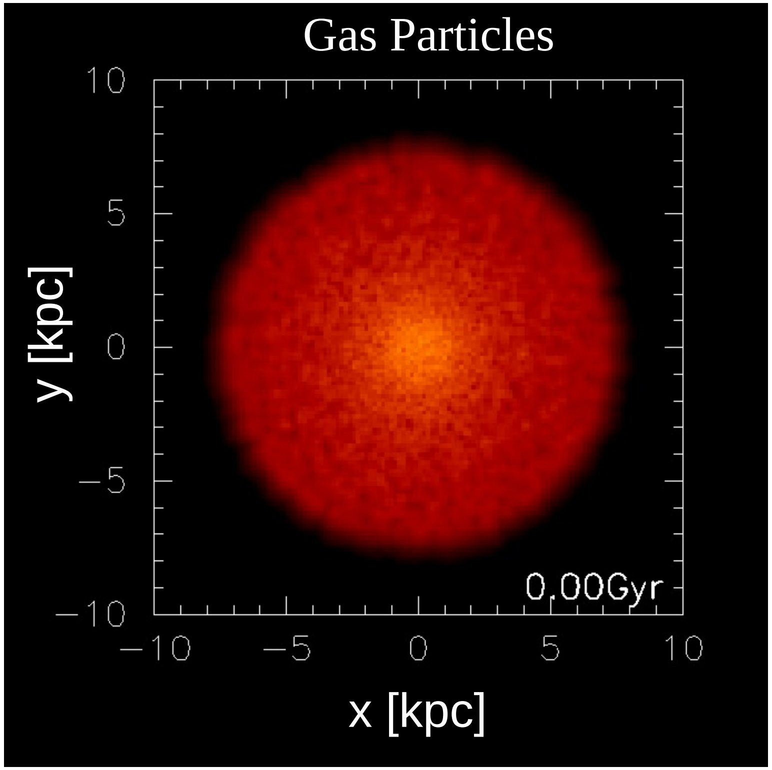
N-Body/SPH Simulation of DM+GAS+Star Particles with SN Feedback & GAS MIXING in SFR.

SNe→metals ; NSM(τ_C=100My)→ r-process elements. **(n_H >100 cm^{-3} → ~ 10-100pc)**

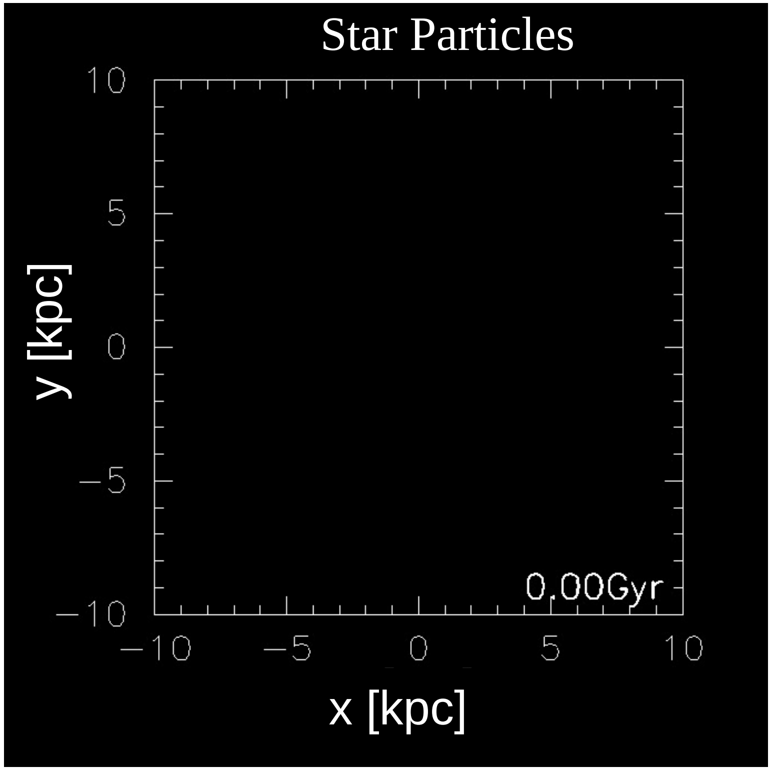
SPH code = ASURA (Saitoh et al., PASJ 60 (2008), 667; PASJ 61 (2009), 481)

Yutaka Hirai et al., ApJ 814 (2015), 41 & MNRAS 466 (2017), 2472.

$M_{tot} = 7\mathrm{x}10^8 M_{sun}$, $N_i = 5\mathrm{x}10^5$ particles, $M_\star = 100M_{sun}$



Gas Particles



Star Particles

SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution Dwarf Galaxies = Building Blocks of Milky Way Galaxy

N-Body/SPH Simulation of DM+GAS+Star Particles with SN Feedback & GAS MIXING in SFR.

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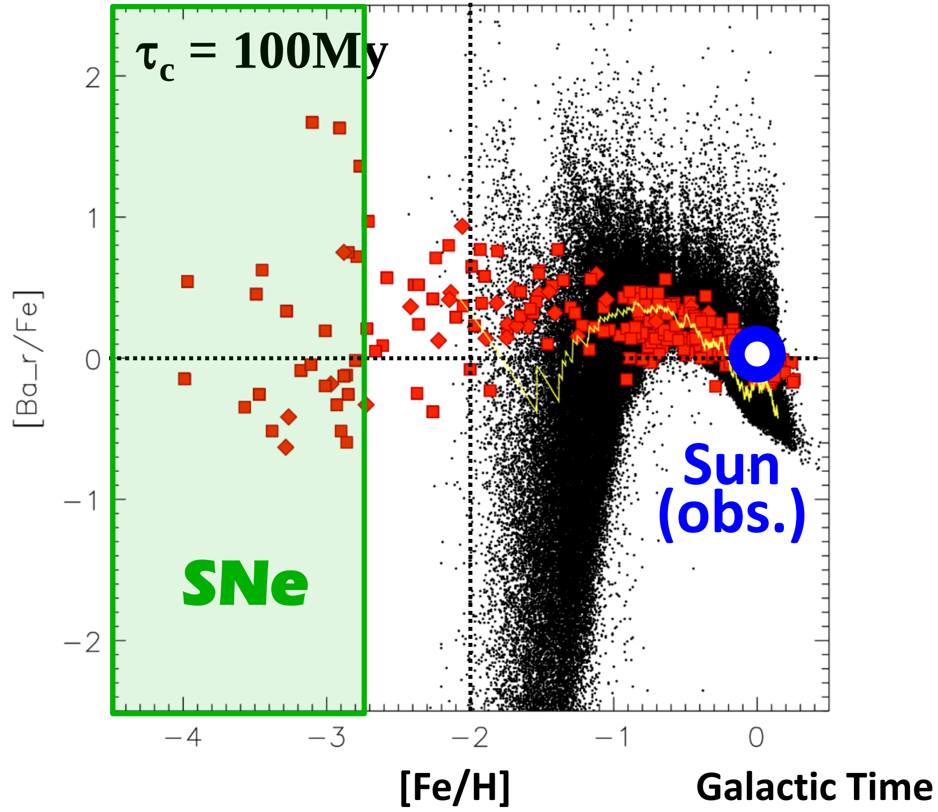
Argast, Samland, Thielemann,
Qian, A&A 416 (2004), 997.

Chemical Evolution



Galactic Chemo-Dynamical (N-Body/SPH) Simulation

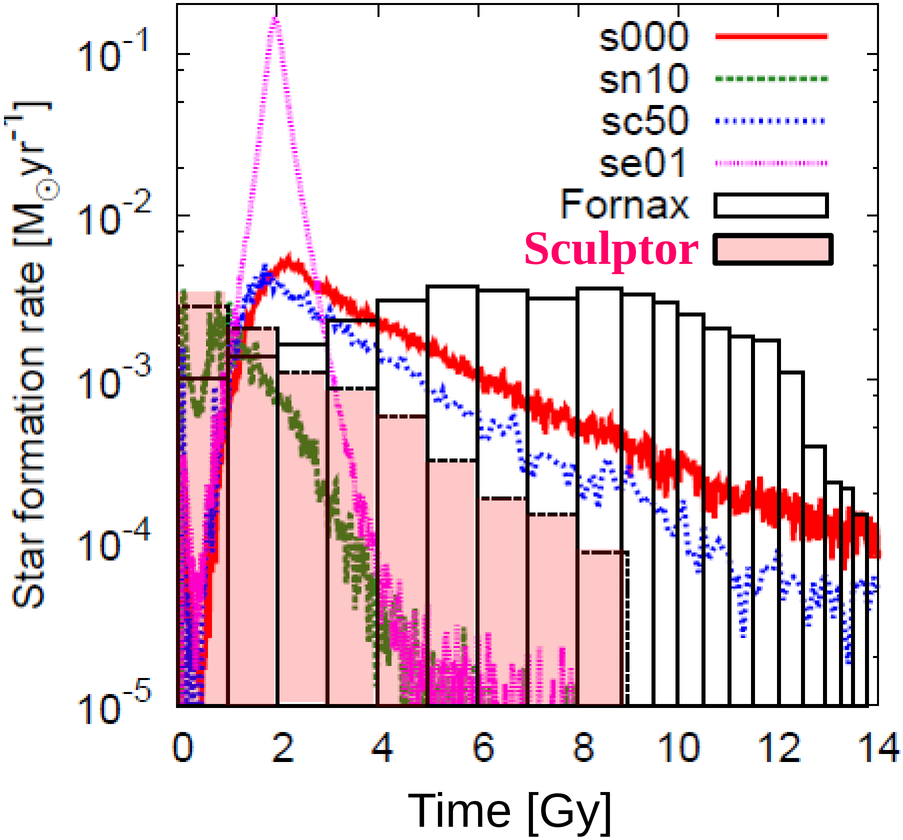
No need of introducing artificial parameters!

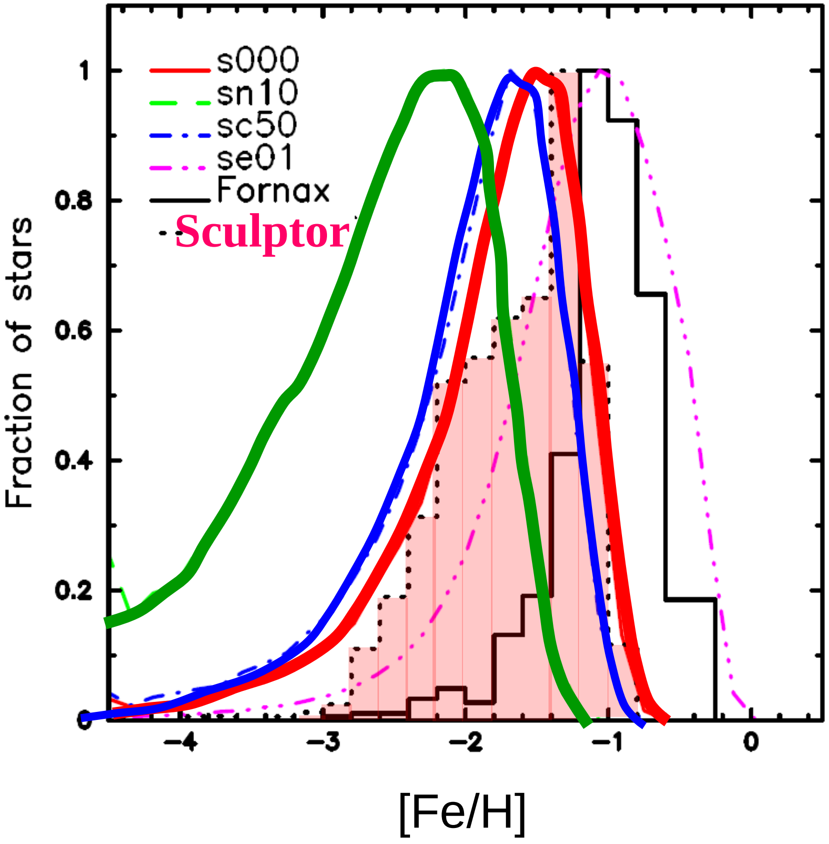
Hirai, Ishimaru, Saitoh, Fujii, Hidaka & Kajino, ApJ 814 (2016), 41; MNRAS (2017), in press.

Time-scale for STAR FORMATION ~ 1-2Gy(1000My)

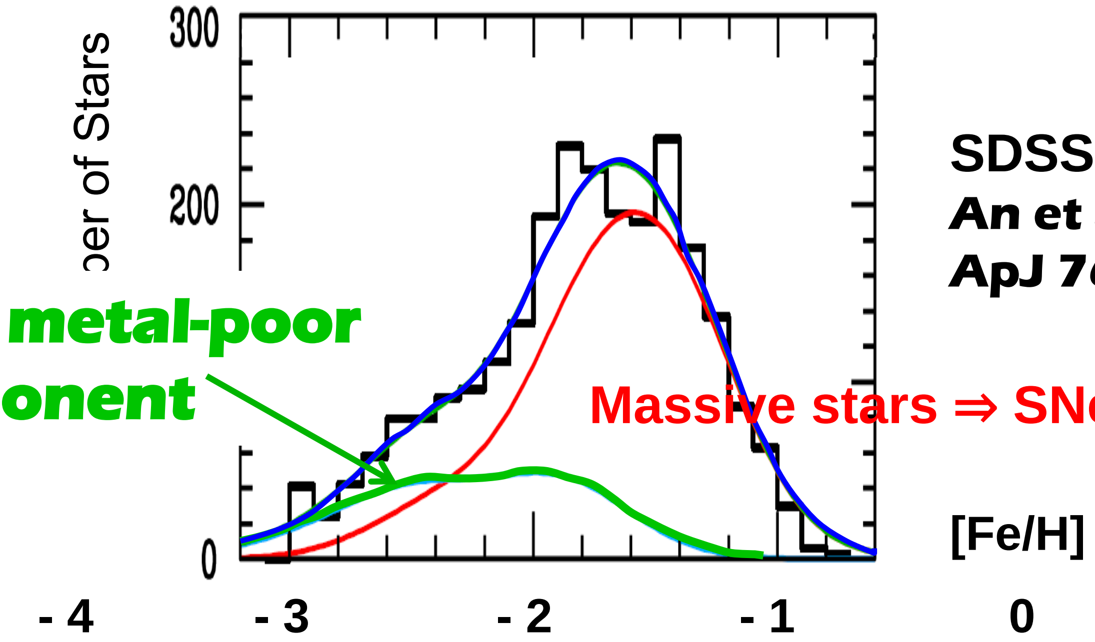
Binary NSMs (100My<τ_c)can contribute from the epoch of INHOMOGENEOUS

Star Formation History





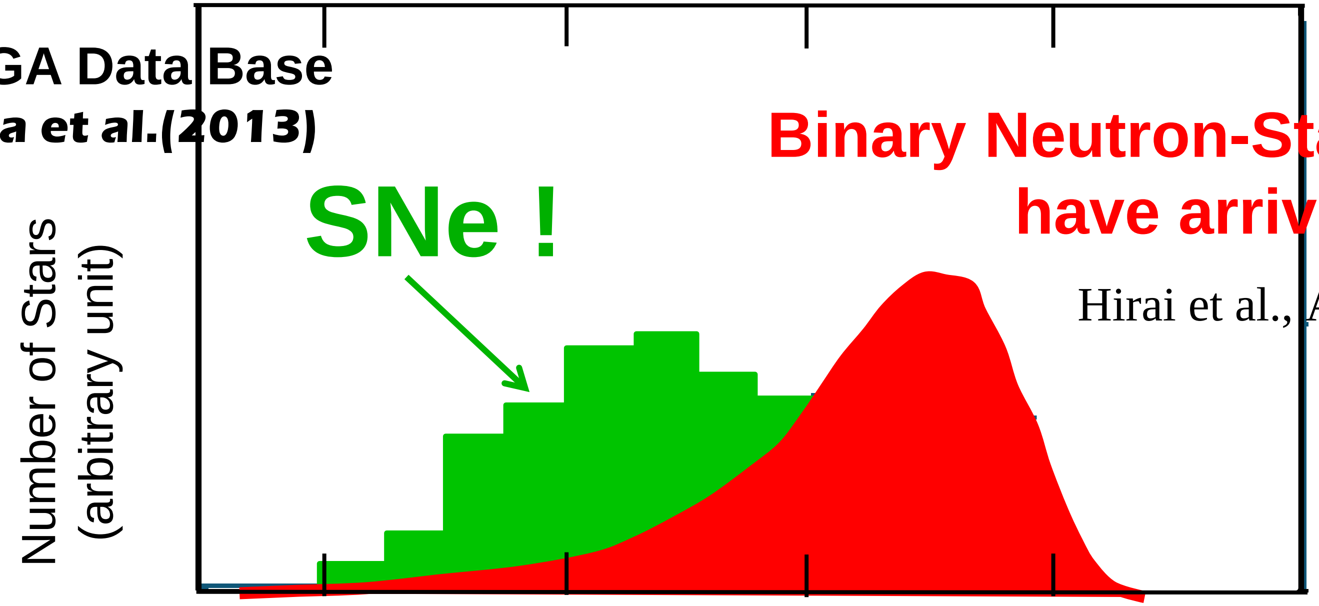
Observational Data of Milky Way HALO



SDSS Survey
An et al.
ApJ 763 (2013), 65

Extremely metal-poor component

Massive stars ⇒ SNe & NSMs



SAGA Data Base
Suda et al.(2013)

SNe !

Binary Neutron-Star Mergers have arrived too late.

Hirai et al., ApJ 814 (2015), 41.

Astrophysical sites for the r–process ?

Core–Collapse Supernovae?

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ν–DW	Woosley, et al., ApJ 433, 229 (1994). +
Long–GRB	Nakamura, et al, A&Ap 582 A34 (2015)

τ =1–10My

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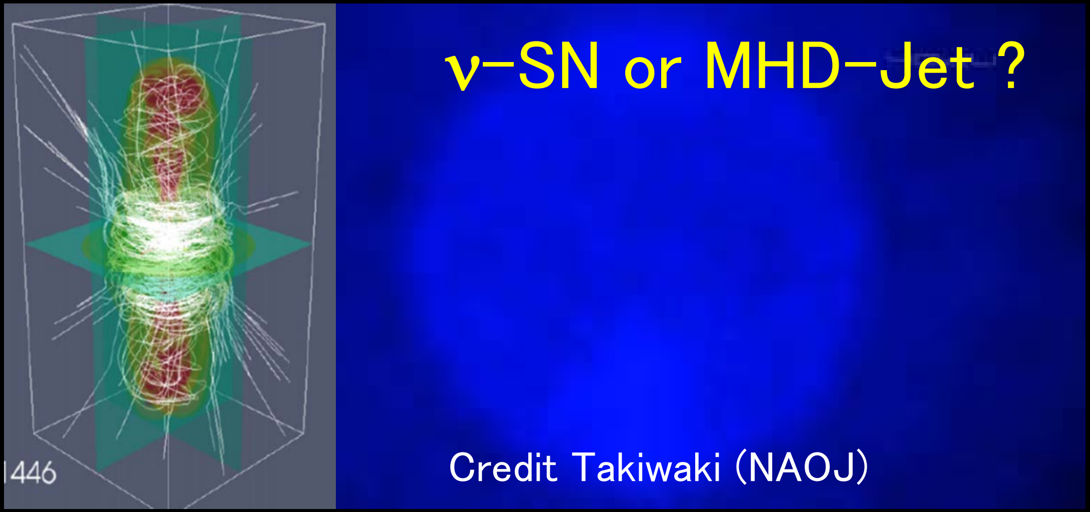


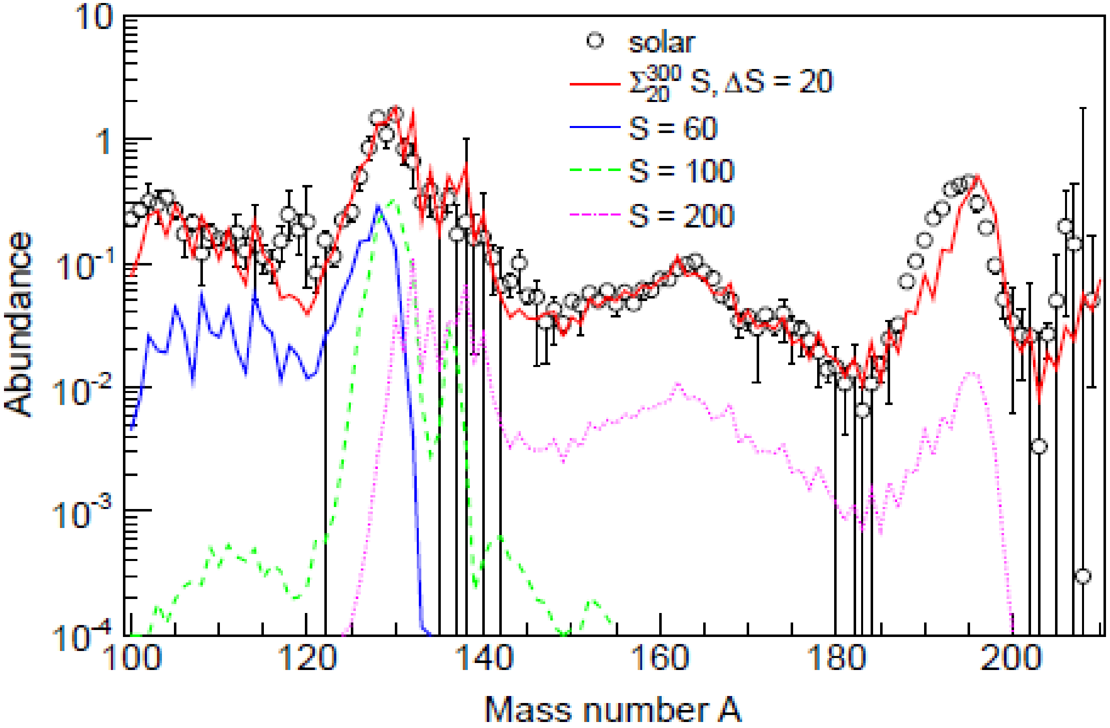
ν–SN or MHD–Jet ?

Credit Takiwaki (NAOJ)

ν's plays CRITICAL ROLES in CCSNe

in Nucleosynthesis & Explosion Dynamics

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



Several numerical supernova simulations suggest;

$Y_e > 0.5$.

Roberts, Reddy and Shen(PRC86, 065803, 2012)pointed out

$Y_e < 0.5$ (neutron-rich)!

in ν-transport cal's by taking account of nucleonic potential plus Pauli-blocking effects.

Otsuki, Tagoshi, Kajino and Wanajo, ApJ 533(2000),424; Wanajo, Kajino, Mathews and Otsuki, ApJ 554(2001),578.

Neutron-rich condition for successful r-process: $Y_e << 0.4$

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

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

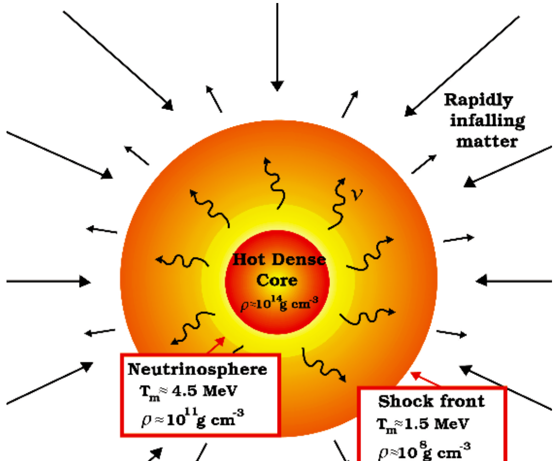
$$Y_e = \frac{p}{n+p} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \times \frac{\boxed{\epsilon_{\bar{\nu}_e}} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\boxed{\epsilon_{\nu_e}} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}$$

$\varepsilon_\nu = 3.15\, T_\nu$

$T_{\nu e} = 3.2$ MeV, $T_{\overline{\nu e}} = 4$ MeV

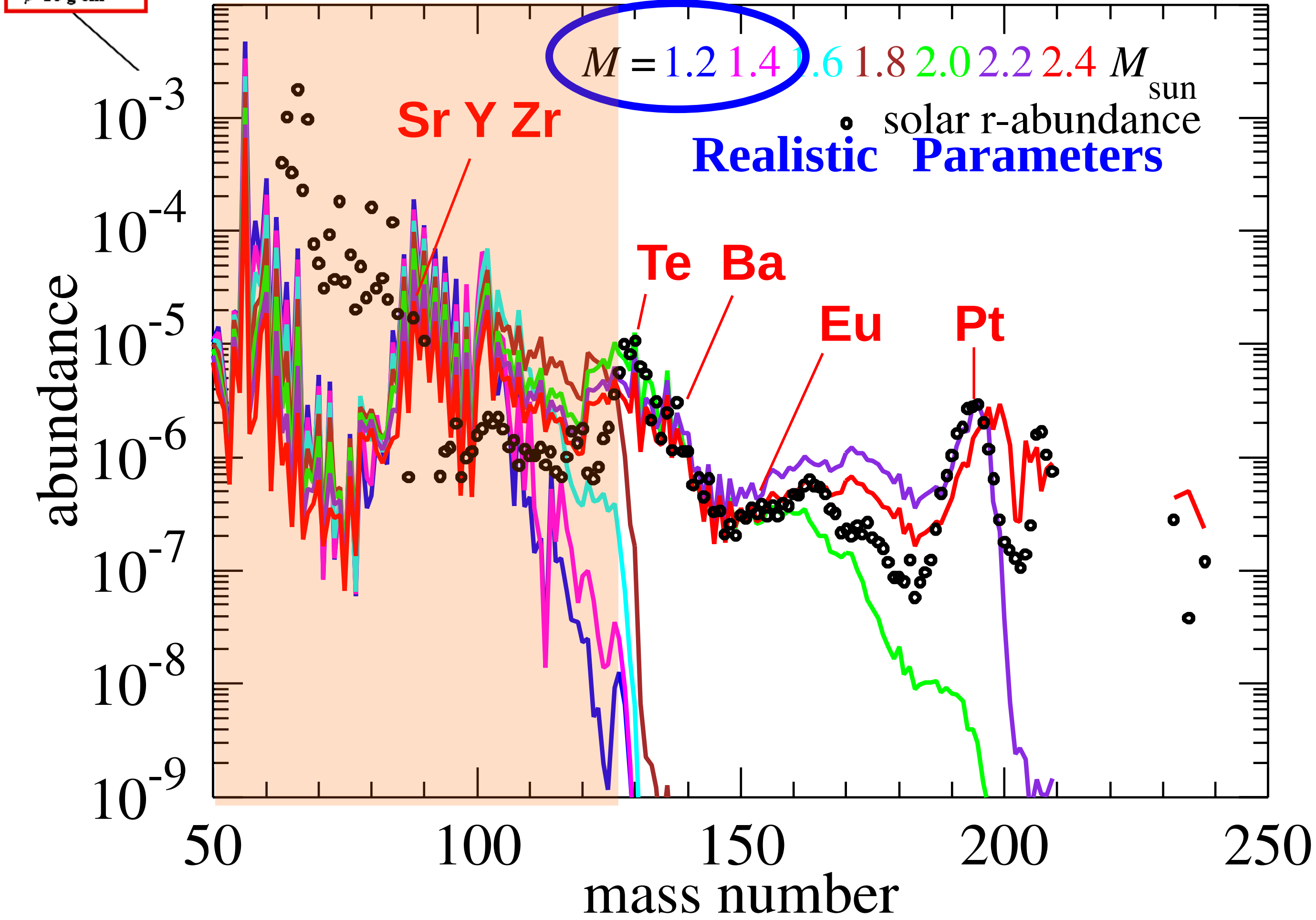
ν-Driven Wind SN for 10-13 $M_\odot$

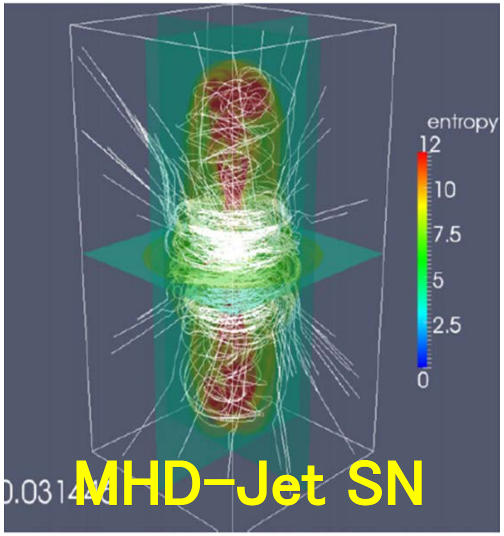
More careful simulions

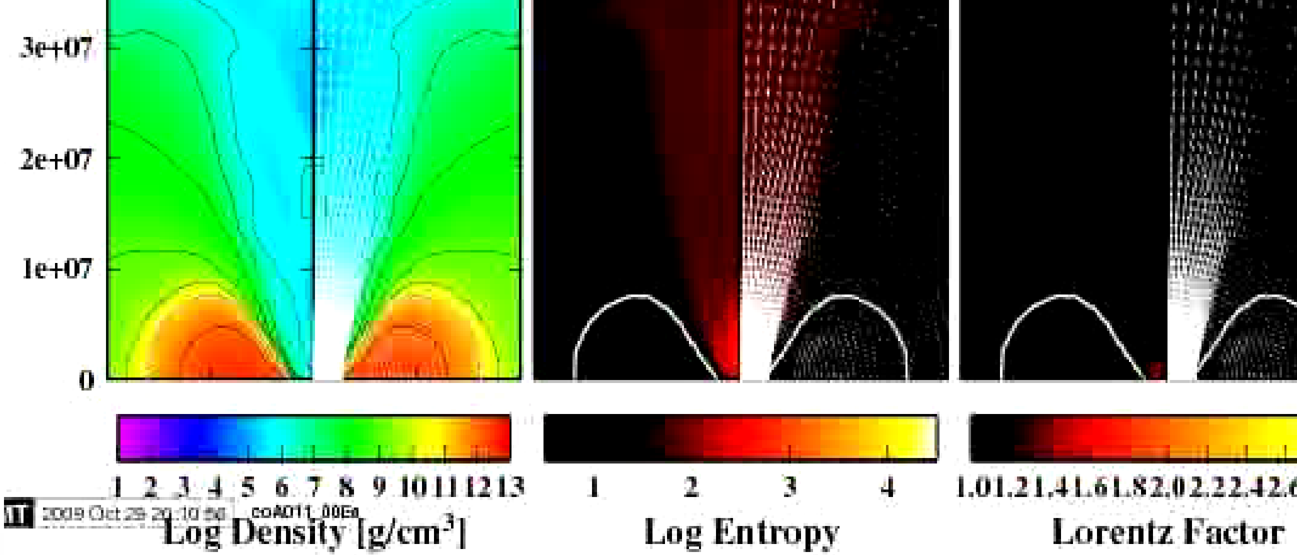


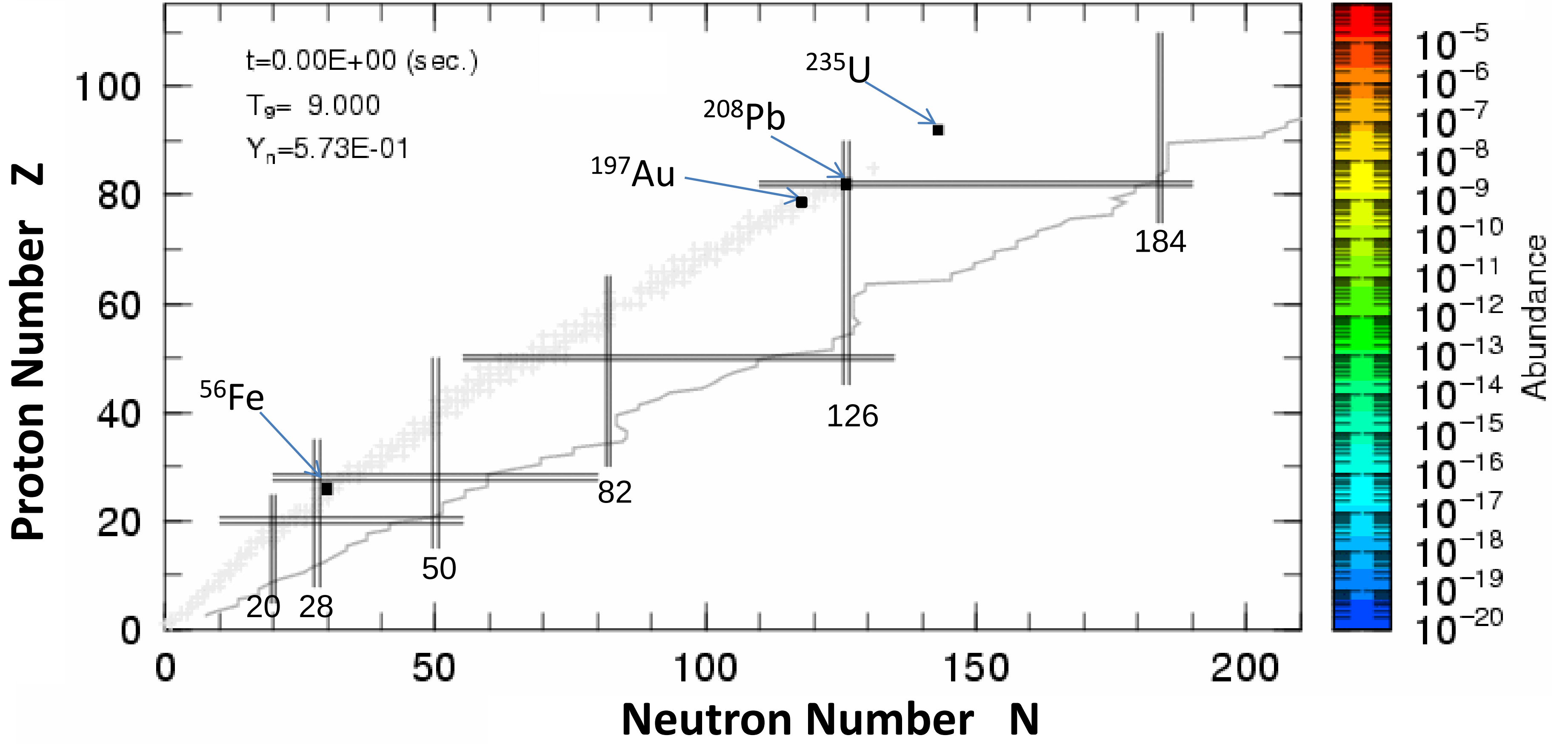
S. Wanajo, ApJL, L22 (2013)

Only up to 1st Peak r-Elements!

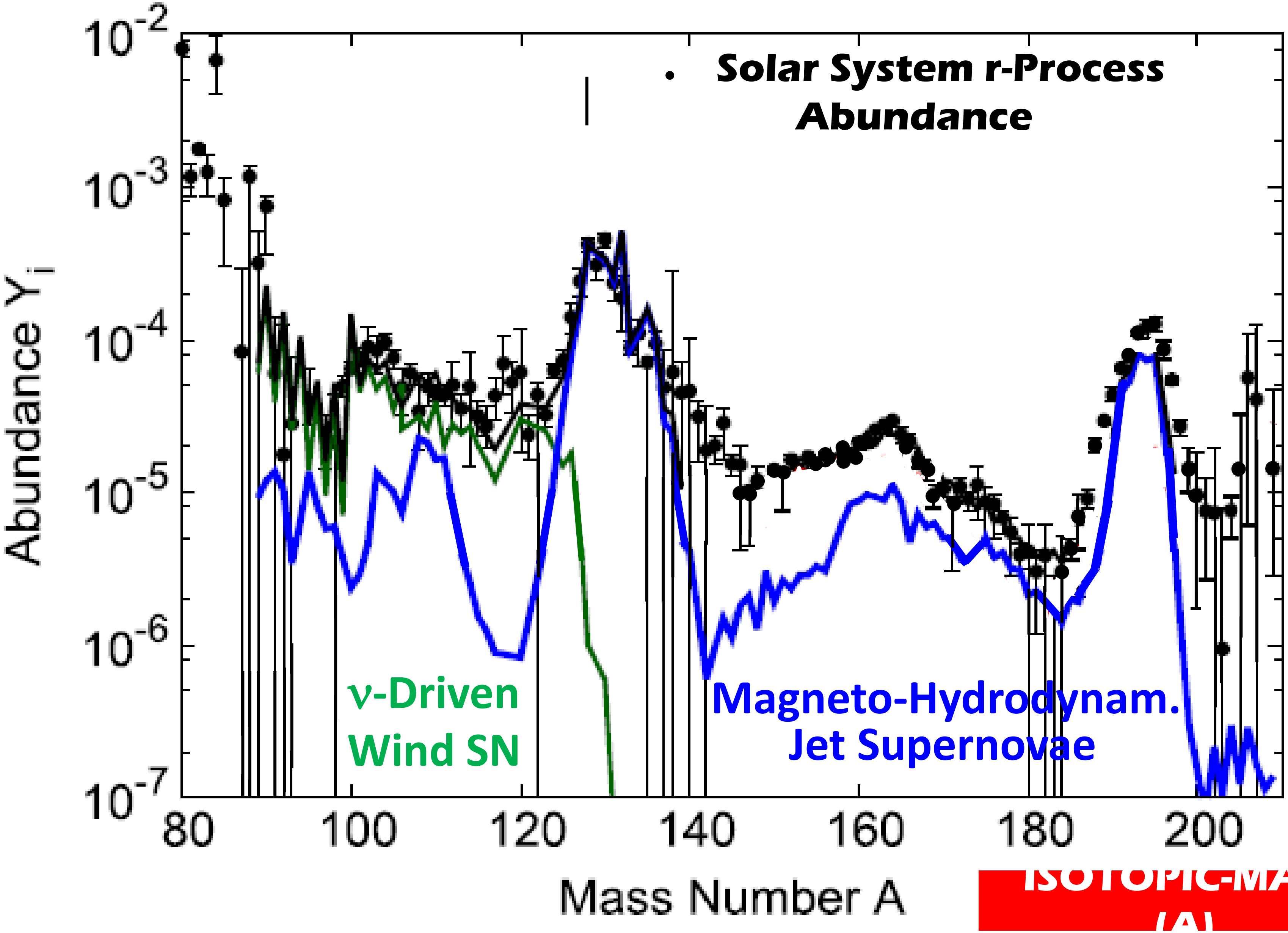



entropy
12
10
7.5
5
2.5
0
0.0314
MHD–Jet SN


3e+07
2e+07
1e+07
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Log Density [g/cm³]
1 2 3 4
Log Entropy
1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
Lorentz Factor
2009 Oct 29 20:10:50 coA011_00Ea


t=0.00E+00 (sec.)
T₉= 9.000
Yₙ=5.73E-01
²³⁵U
²⁰⁸Pb
¹⁹⁷Au
⁵⁶Fe
184
126
82
50
20
28
Proton Number Z
Neutron Number N
0
20
40
60
80
100
0
50
100
150
200
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
Abundance

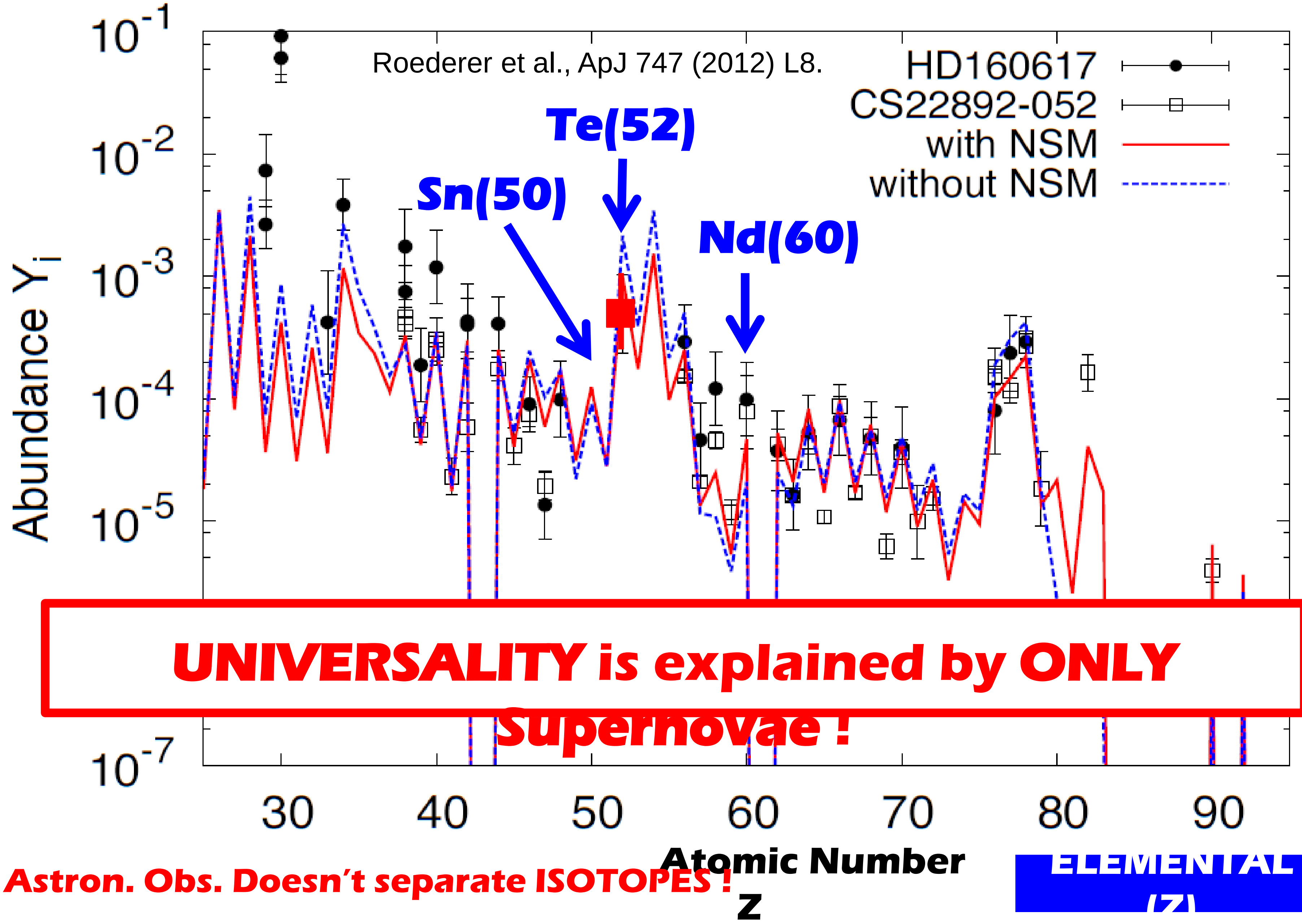
Early Galaxy !



ISOTOPIC-MASS (A)

UNIVERSALITY !

Early Galaxy !



UNIVERSALITY is explained by ONLY Supernovae !

Astron. Obs. Doesn't separate ISOTOPES !

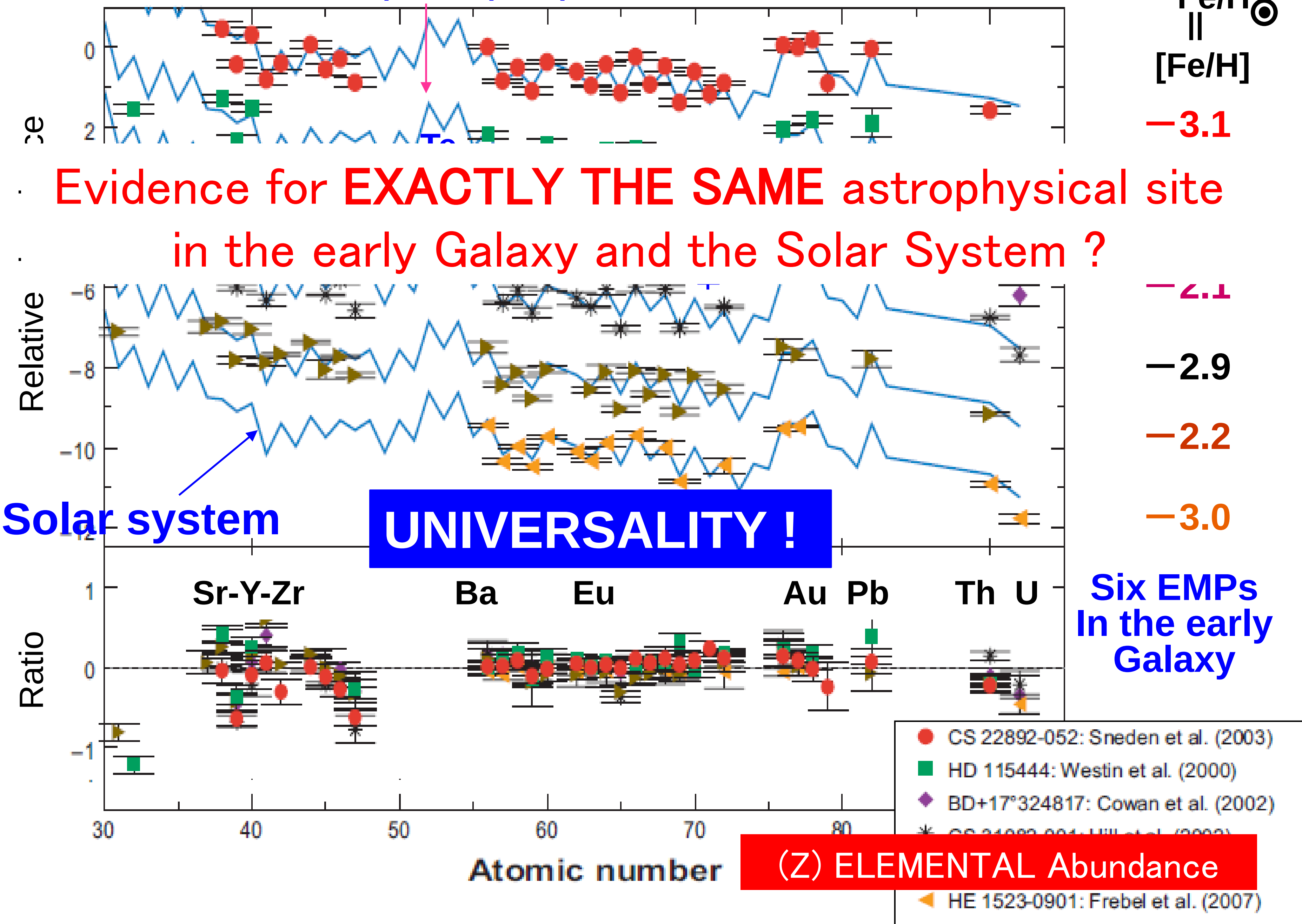
ELEMENTAL (Z)

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

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

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

$$\mathrm{Log}\,\frac{Fe/H_{☆}}{Fe/H_{\odot}} = [Fe/H]$$



−3.1

−2.1

−2.9

−2.2

−3.0

Evidence for **EXACTLY THE SAME** astrophysical site in the early Galaxy and the Solar System ?

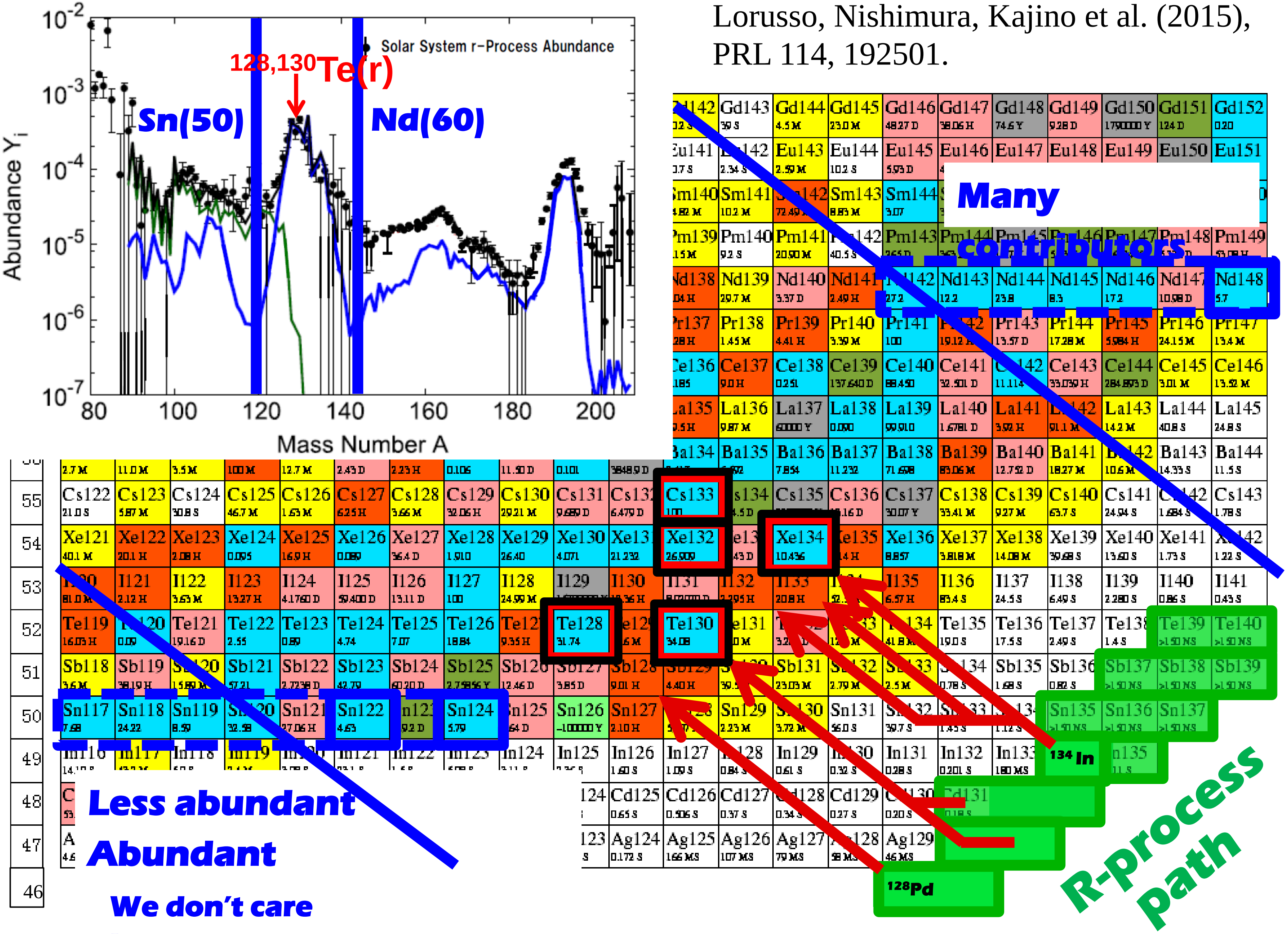
Solar system

UNIVERSALITY !

Six EMPs In the early Galaxy

(Z) ELEMENTAL Abundance

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



												Gd142 [illegible]	Gd143 39 S	Gd144 4.5 M	Gd145 23.0 M	Gd146 48.27 D	Gd147 38.06 H	Gd148 74.6 Y	Gd149 9.28 D	Gd150 1790000 Y	Gd151 124 D	Gd152 0.20
												Eu141 [illegible]	Eu142 2.34 S	Eu143 2.59 M	Eu144 10.2 S	Eu145 5.93 D	Eu146 [illegible]	Eu147 [illegible]	Eu148 [illegible]	Eu149 [illegible]	Eu150 [illegible]	Eu151 [illegible]
												Sm140 4.82 M	Sm141 10.2 M	Sm142 72.49 [illegible]	Sm143 8.83 M	Sm144 3.07	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
												Pm139 [illegible]	Pm140 9.2 S	Pm141 20.90 M	Pm142 40.5 S	Pm143 265 D	Pm144 [illegible]	Pm145 [illegible]	Pm146 [illegible]	Pm147 [illegible]	Pm148 [illegible]	Pm149 53.08 H
												Nd138 [illegible]	Nd139 29.7 M	Nd140 3.37 D	Nd141 2.49 H	Nd142 27.2	Nd143 12.2	Nd144 23.8	Nd145 8.3	Nd146 17.2	Nd147 10.98 D	Nd148 5.7
												Pr137 [illegible]	Pr138 1.45 M	Pr139 4.41 H	Pr140 3.39 M	Pr141 100	Pr142 19.12 H	Pr143 13.57 D	Pr144 17.28 M	Pr145 5.984 H	Pr146 24.15 M	Pr147 13.4 M
												Ce136 [illegible]	Ce137 9.0 H	Ce138 0.251	Ce139 137.640 D	Ce140 88.450	Ce141 32.501 D	Ce142 11.114	Ce143 33.039 H	Ce144 284.893 D	Ce145 3.01 M	Ce146 13.52 M
												La135 [illegible]	La136 9.87 M	La137 60000 Y	La138 0.090	La139 99.910	La140 1.6781 D	La141 3.92 H	La142 91.1 M	La143 14.2 M	La144 40.8 S	La145 24.8 S
[illegible]		2.7 M	11.0 M	3.5 M	100 M	12.7 M	2.43 D	2.23 H	0.106	11.50 D	0.101	3848.9 D	Ba134 [illegible]	Ba135 [illegible]	Ba136 7.854	Ba137 11.232	Ba138 71.698	Ba139 83.06 M	Ba140 12.752 D	Ba141 18.27 M	Ba142 10.6 M	Ba143 14.33 S	Ba144 11.5 S
55		Cs122 21.0 S	Cs123 5.87 M	Cs124 30.8 S	Cs125 46.7 M	Cs126 1.63 M	Cs127 6.25 H	Cs128 3.66 M	Cs129 32.06 H	Cs130 29.21 M	Cs131 9.689 D	Cs132 6.479 D	Cs133 100	Cs134 [illegible]	Cs135 [illegible]	Cs136 [illegible]	Cs137 30.07 Y	Cs138 33.41 M	Cs139 9.27 M	Cs140 63.7 S	Cs141 24.94 S	Cs142 1.684 S	Cs143 1.78 S
54		Xe121 40.1 M	Xe122 20.1 H	Xe123 2.08 H	Xe124 0.095	Xe125 16.9 H	Xe126 0.089	Xe127 36.4 D	Xe128 1.910	Xe129 26.40	Xe130 4.071	Xe131 21.232	Xe132 26.909	Xe133 [illegible]	Xe134 10.436	Xe135 [illegible]	Xe136 8.857	Xe137 3.818 M	Xe138 14.08 M	Xe139 39.68 S	Xe140 13.60 S	Xe141 1.73 S	Xe142 1.22 S
53		I120 81.0 M	I121 2.12 H	I122 3.63 M	I123 13.27 H	I124 4.1760 D	I125 59.400 D	I126 13.11 D	I127 100	I128 24.99 M	I129 [illegible]	I130 [illegible]	I131 [illegible]	I132 2.295 H	I133 20.8 H	I134 [illegible]	I135 6.57 H	I136 83.4 S	I137 24.5 S	I138 6.49 S	I139 2.280 S	I140 0.86 S	I141 0.43 S
52		Te119 16.03 H	Te120 0.09	Te121 19.16 D	Te122 2.55	Te123 0.89	Te124 4.74	Te125 7.07	Te126 18.84	Te127 9.35 H	Te128 31.74	Te129 [illegible]	Te130 34.08	Te131 [illegible]	Te132 [illegible]	Te133 [illegible]	Te134 [illegible]	Te135 19.0 S	Te136 17.5 S	Te137 2.49 S	Te138 1.4 S	Te139 >150 NS	Te140 >150 NS
51		Sb118 3.6 M	Sb119 38.19 H	Sb120 15.89 M	Sb121 57.21	Sb122 2.7238 D	Sb123 42.79	Sb124 60.20 D	Sb125 2.75856 Y	Sb126 12.46 D	Sb127 3.85 D	Sb128 9.01 H	Sb129 4.40 H	Sb130 [illegible]	Sb131 23.03 M	Sb132 2.79 M	Sb133 2.5 M	Sb134 0.78 S	Sb135 1.68 S	Sb136 0.82 S	Sb137 >150 NS	Sb138 >150 NS	Sb139 >150 NS
50		Sn117 7.68	Sn118 24.22	Sn119 8.59	Sn120 32.58	Sn121 27.06 H	Sn122 4.63	Sn123 [illegible]	Sn124 5.79	Sn125 [illegible]	Sn126 ~100000 Y	Sn127 2.10 H	Sn128 [illegible]	Sn129 2.23 M	Sn130 3.72 M	Sn131 56.0 S	Sn132 39.7 S	Sn133 1.45 S	Sn134 1.12 S	Sn135 >150 NS	Sn136 >150 NS	Sn137 >150 NS
49		In116 [illegible]	In117 [illegible]	In118 [illegible]	In119 [illegible]	In120 [illegible]	In121 [illegible]	In122 [illegible]	In123 [illegible]	In124 [illegible]	In125 [illegible]	In126 1.60 S	In127 1.09 S	In128 0.84 S	In129 0.61 S	In130 0.32 S	In131 0.28 S	In132 0.201 S	In133 180 MS	^{134}In	In135 [illegible]		
48		[illegible]									[illegible]	Cd125 0.65 S	Cd126 0.506 S	Cd127 0.37 S	Cd128 0.34 S	Cd129 0.27 S	Cd130 0.20 S	Cd131 [illegible]					
47		[illegible]									[illegible]	Ag124 0.172 S	Ag125 166 MS	Ag126 107 MS	Ag127 79 MS	Ag128 58 MS	Ag129 46 MS						
46																	^{128}Pd						

Many contributors

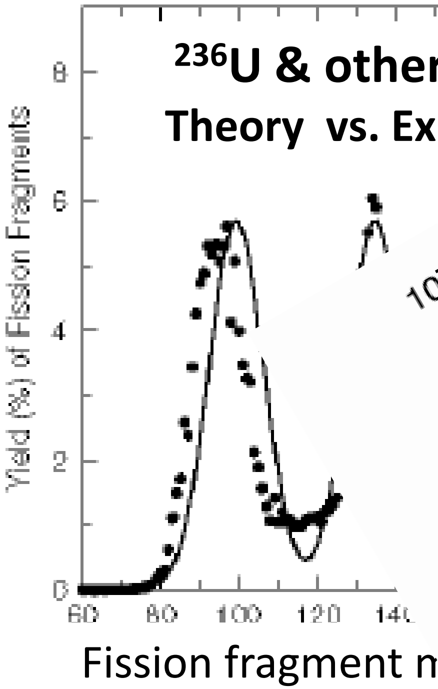
Less abundant

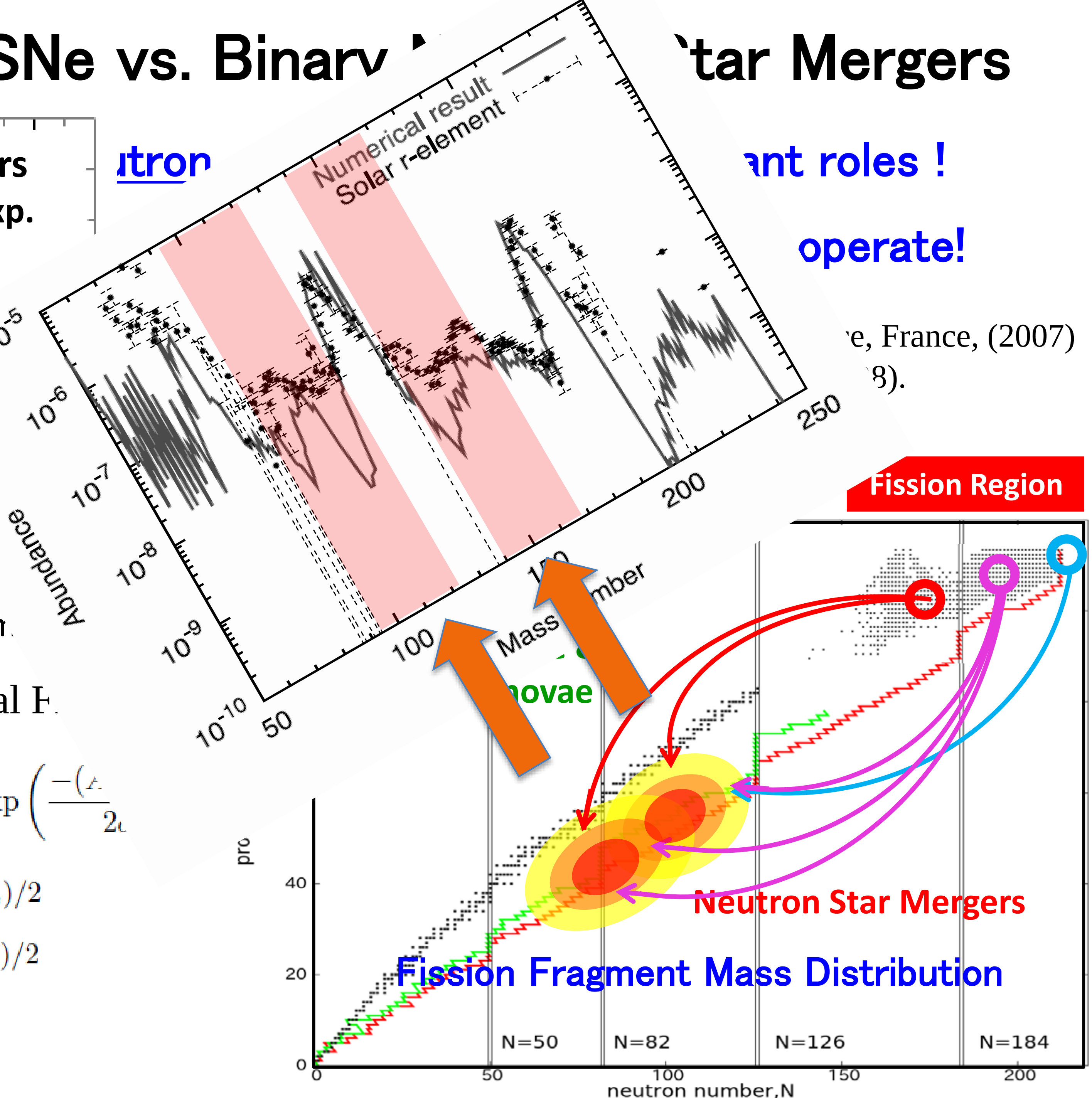
Abundant

We don't care in Elemental !

R-process path

MHD−Jet SNe vs. Binary … tar Mergers





tron

ant roles !

operate!

e, France, (2007)

8).

Bimordial or Trimodal F

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

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

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

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

Fluid-Dynamical Model for Neutron Star Merger

Binary Neutron Star Merger

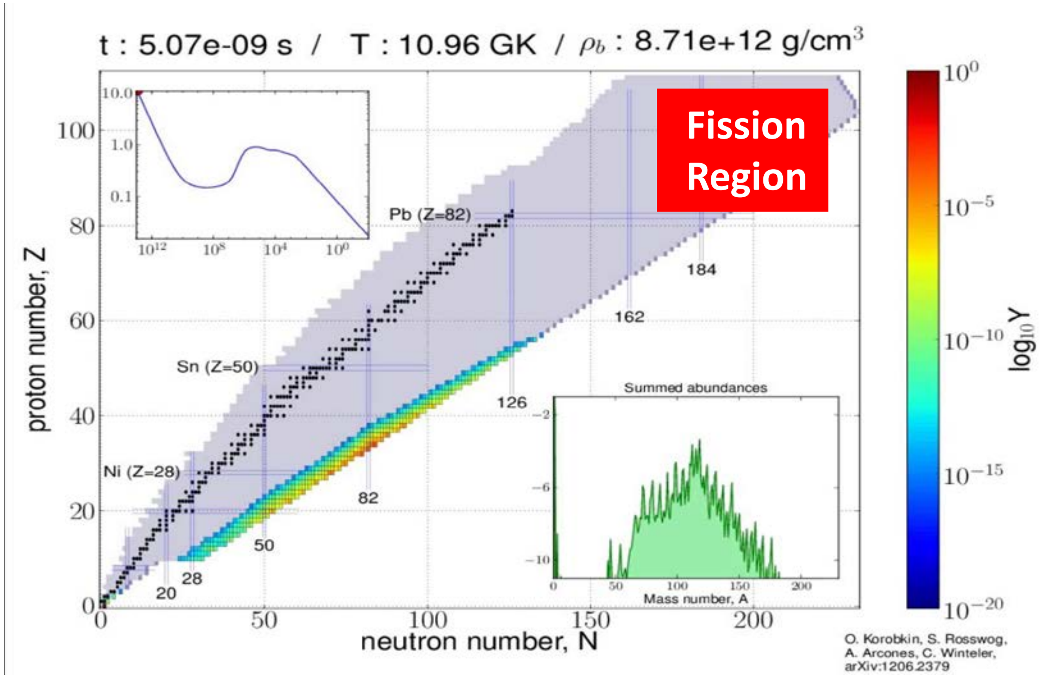
Korobkin et al., MNRAS 426 (2012), 1940; Rosswog et al., MNRAS 430 (2013), 2585.

SPH Simulation: (Adiabatic Expansion)

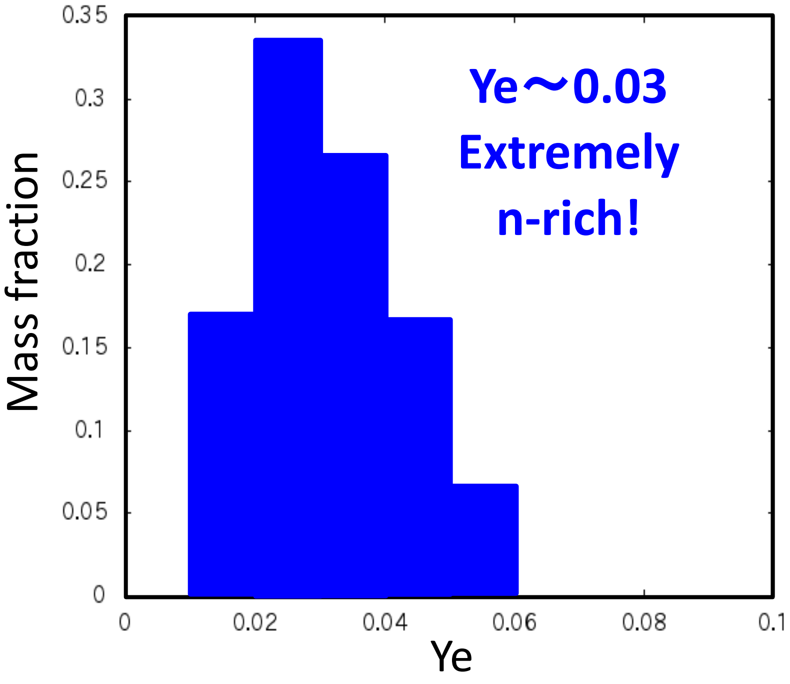
Newtonian gravity, Neutrino Leakage scheme

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.



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

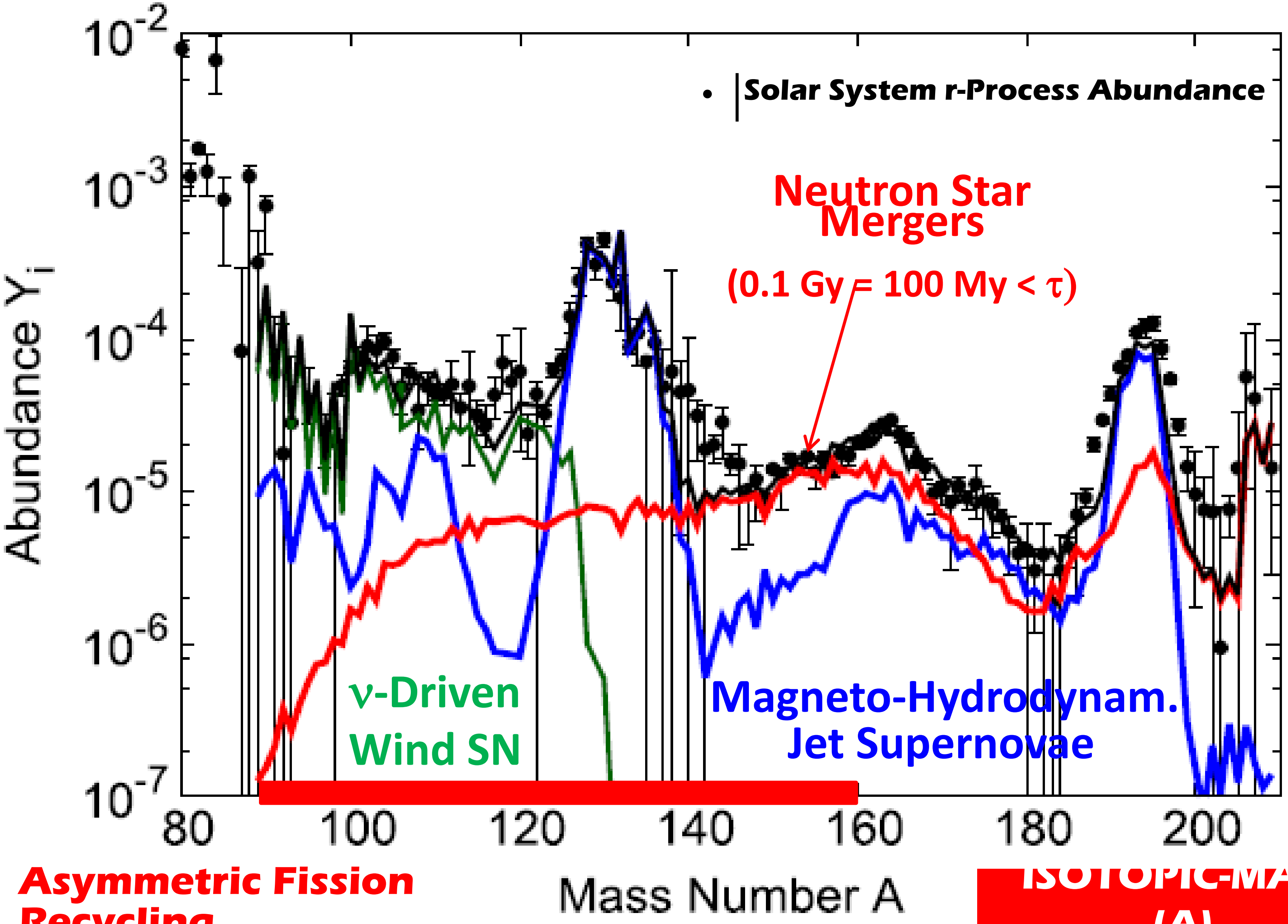


Ye～0.03
Extremely
n-rich!

Solar System r-Process Abundance

Solar Sys. at

Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79.



Neutron Star Mergers

(0.1 Gy = 100 My < τ)

ν-Driven Wind SN

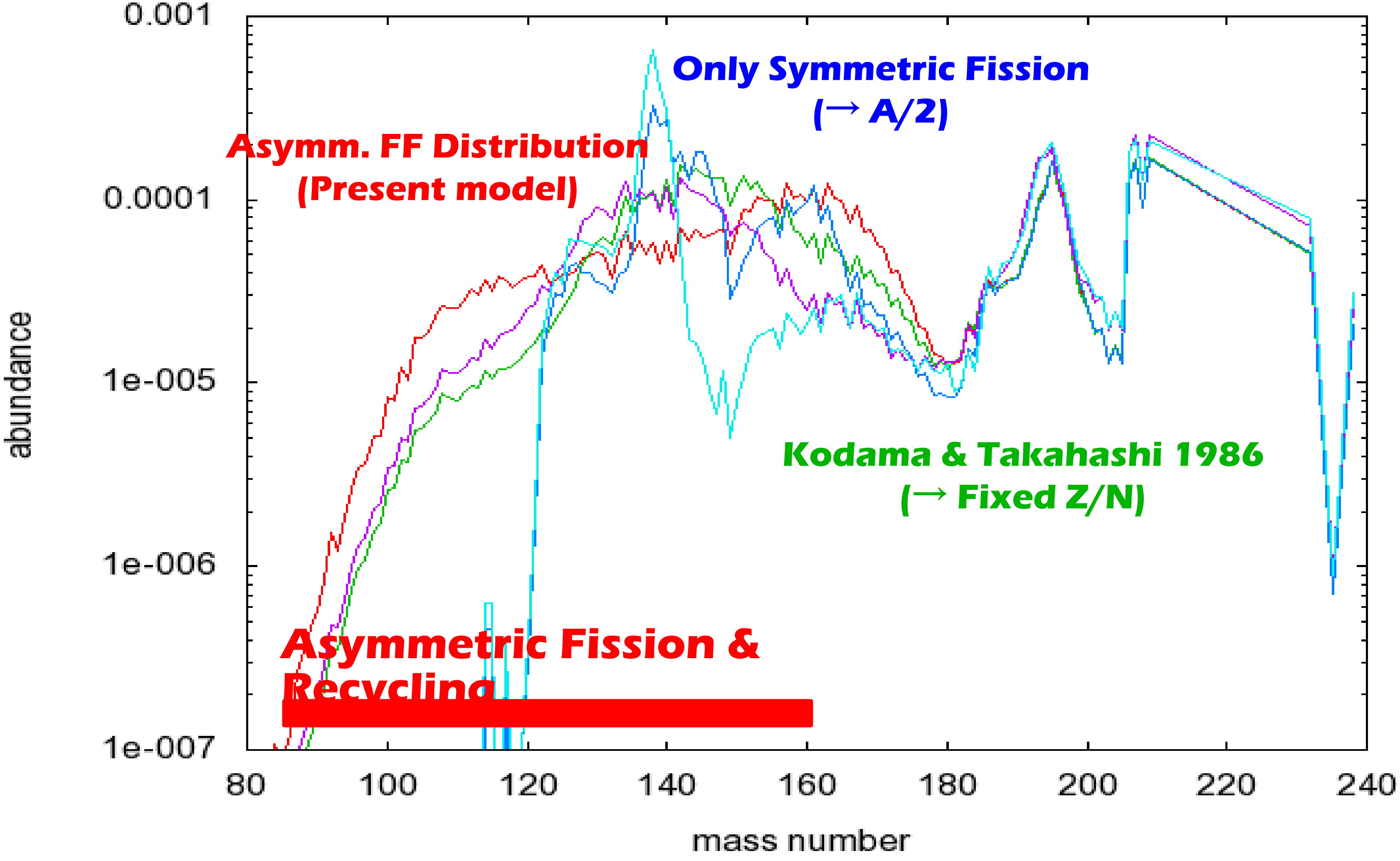
Magneto-Hydrodynam. Jet Supernovae

Asymmetric Fission Recycling

ISOTOPIC-MASS (A)

Symmetric fission makes sharp 2nd & 3rd peaks.

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



Observed Galactic event rates !

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

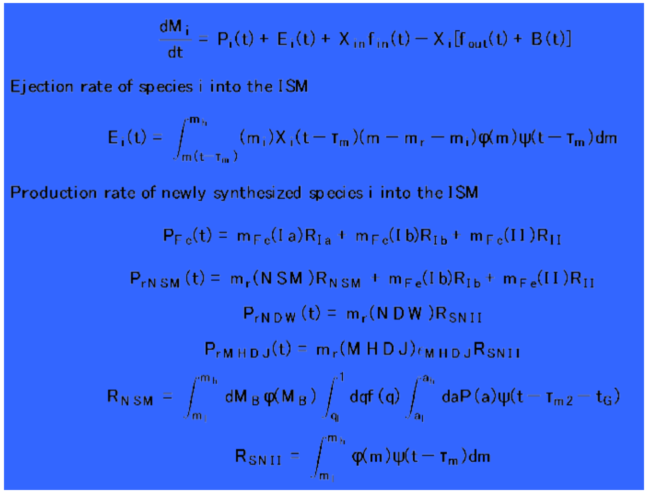
νSN (Weak r) = 7.4×10^{-4} x (1.9 ± 1.1) [a]

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).

Galactic Evolution including Binary Evolution
Kajino, Mathews et al. (2017)



$$\frac{dM_i}{dt} = P_i(t) + E_i(t) + X_{in} f_{in}(t) - X_i[f_{out}(t) + B(t)]$$

Ejection rate of species i into the ISM

$$E_i(t) = \int_{m(t-\tau_m)}^{m_h} (m_i) X_i(t-\tau_m)(m - m_r - m_i)\varphi(m)\psi(t-\tau_m)dm$$

Production rate of newly synthesized species i into the ISM

$$P_{Fe}(t) = m_{Fe}(Ia)R_{Ia} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

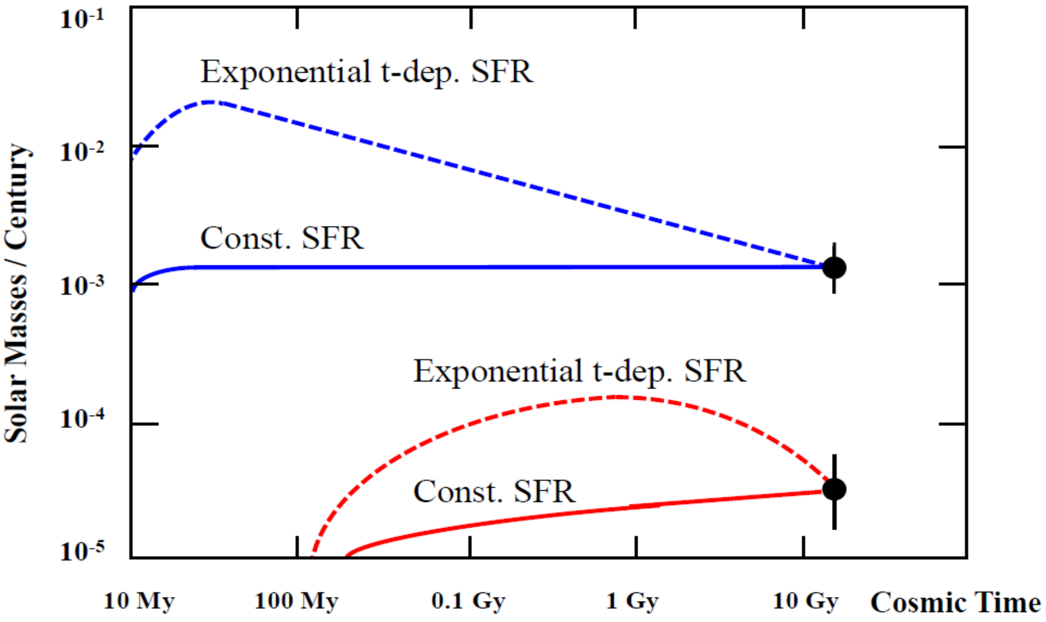
$$P_{rNSM}(t) = m_r(NSM)R_{NSM} + m_{Fe}(Ib)R_{Ib} + m_{Fe}(II)R_{II}$$

$$P_{rNDW}(t) = m_r(NDW)R_{SNII}$$

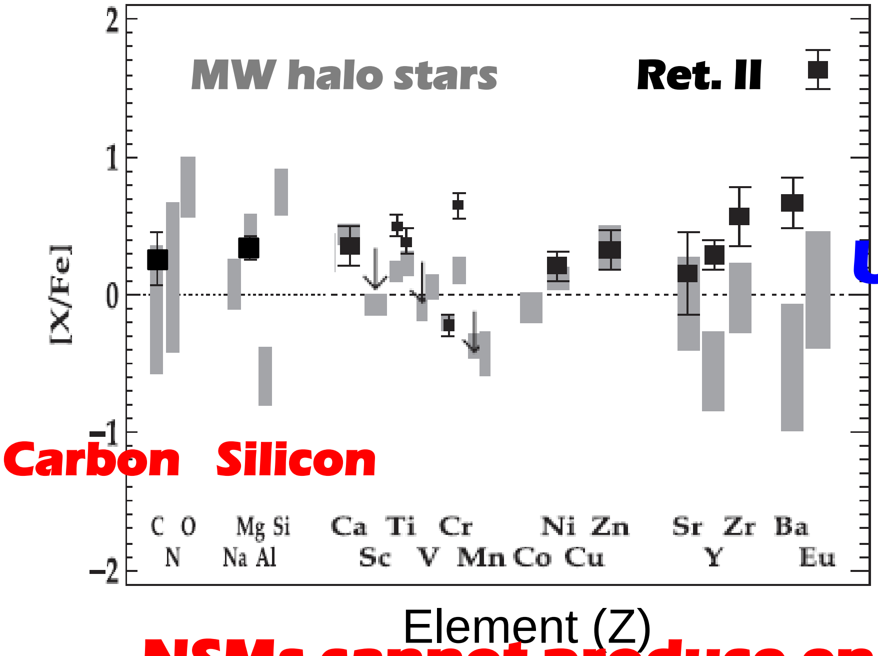
$$P_{rMHDJ}(t) = m_r(MHDJ)\epsilon_{MHDJ}R_{SNII}$$

$$R_{NSM} = \int_{m_l}^{m_h} dM_B\,\varphi(M_B) \int_{q_l}^{1} dq f(q) \int_{a_l}^{a_h} da P(a)\psi(t - \tau_{m2} - t_G)$$

$$R_{SNII} = \int_{m_l}^{m_h} \varphi(m)\psi(t-\tau_m)dm$$



Extended Universality



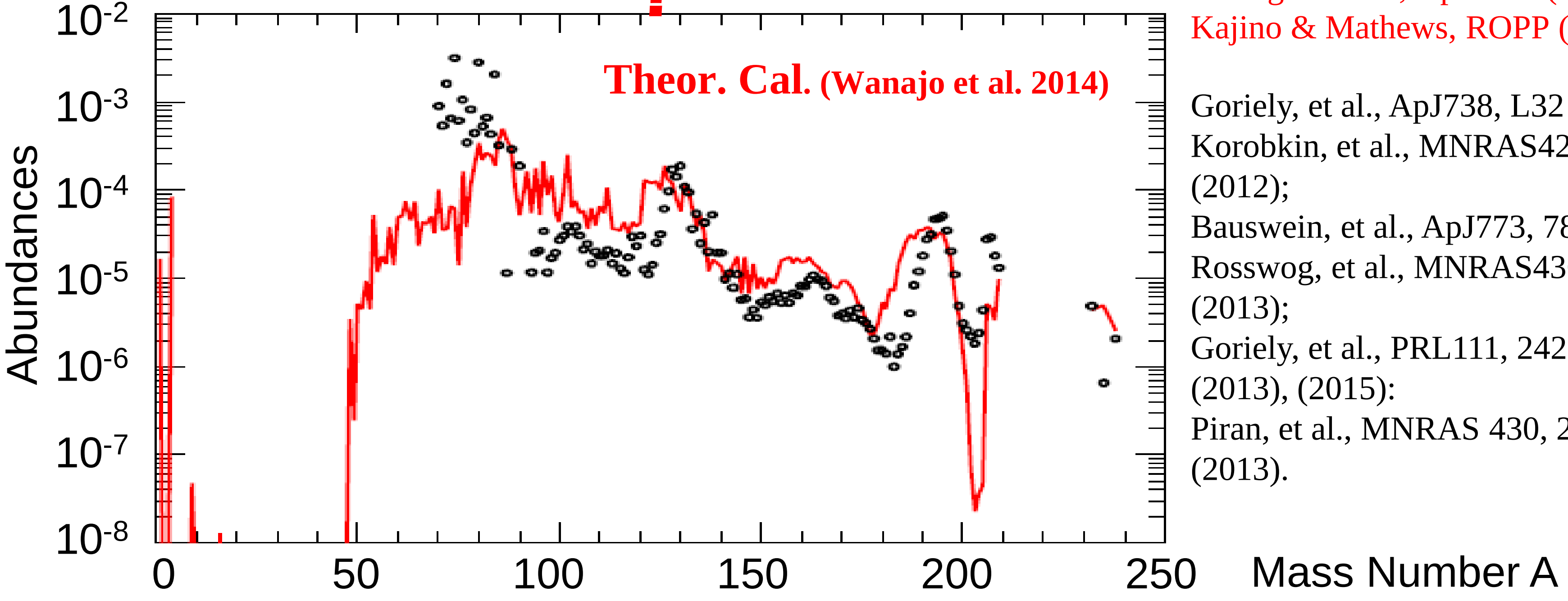
Carbon Silicon

Ultra-Faint warf Galaxy: Ret. II

Astron. Observation

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

NSMs cannot produce enough A < 80 !



Theor. Cal. (Wanajo et al. 2014)

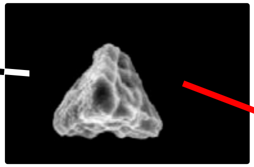
Wanajo et al., ApJ. 789 (2014), L39;
Shibagaki et al., ApJ. 816 (2016), 79;
Kajino & Mathews, ROPP (2017).

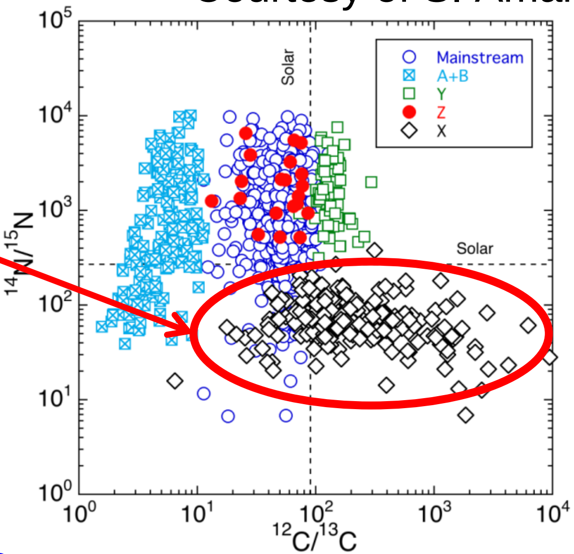
Goriely, et al., ApJ738, L32 (2011);
Korobkin, et al., MNRAS426, 1940 (2012);
Bauswein, et al., ApJ773, 78 (2013);
Rosswog, et al., MNRAS430, 2585 (2013);
Goriely, et al., PRL111, 242502 (2013), (2015):
Piran, et al., MNRAS 430, 2121 (2013).

QUEST for Cosmo-Chemistry and Astronomy:
to find/confirm "EXTENDED UNIVERSALITY"

◎ Supernova Grains e.g. Murchison Meteorite

SiC X-grains




Courtesy of S. Amari

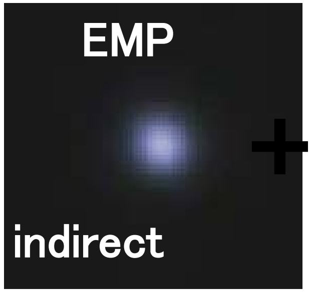
- Enhanced ^{28}Si and ^{12}C ($^{12}C/^{13}C$ > Solar)
- Deficient ^{14}N ($^{14}N/^{15}N$ < Solar)
- Decay of ^{26}Al ($t_{1/2}=7\times10^5$yr), ^{44}Ti ($t_{1/2}=60$yr)$\rightarrow^{44}Ca$

Pre-solar SiC X-grains condense in SN/NSM ejecta.

- If SiC X-grain including r-elements → NSM ? SN !
- If extended Universality manifests in [r/C-Si-Fe]=0 → SN !

◎ Spectr. Astron. Obs.

Direct detection of C, Si & r-elements simultaneously !



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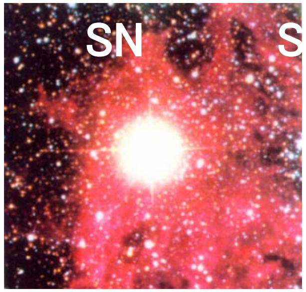
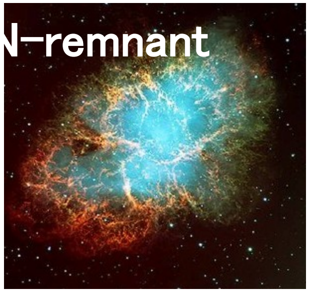
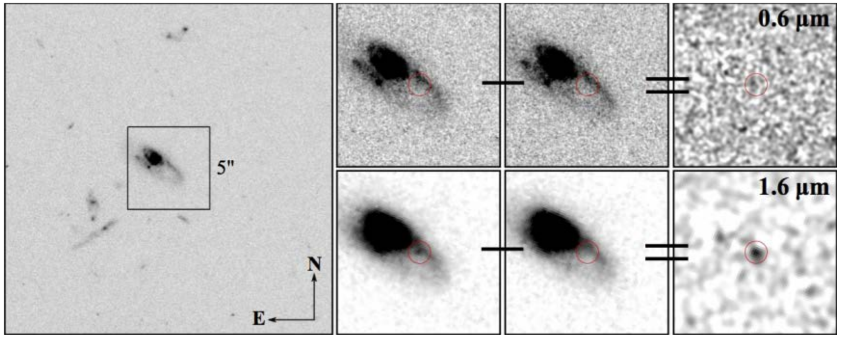




R-Process in Binary NSMs ?

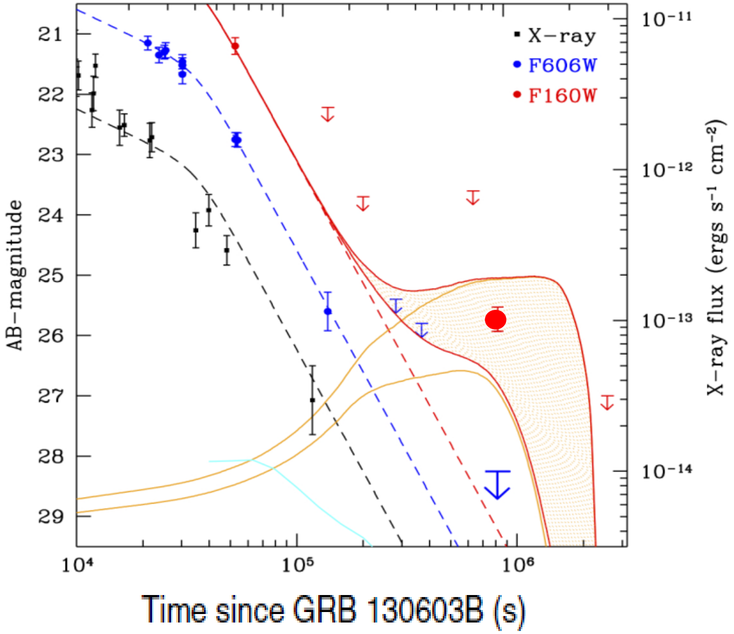


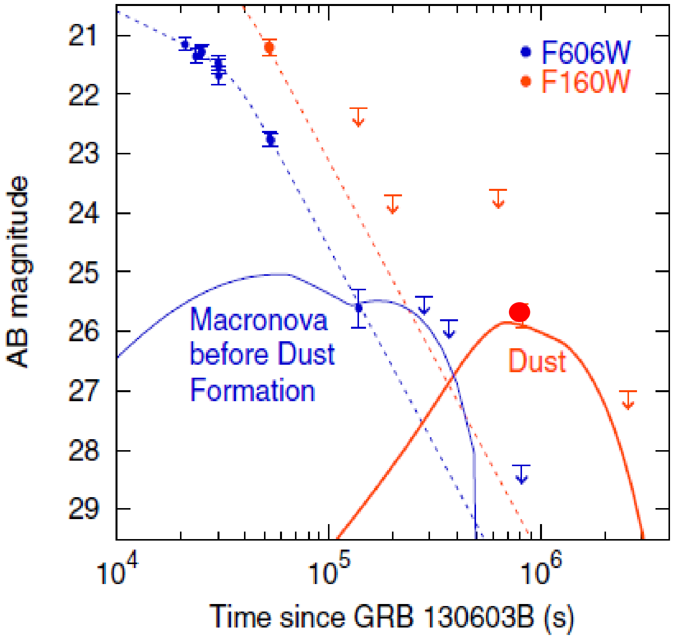
Macronova (Kilonova)

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

Dust is hard to form for deficient C & Si and other lighter elements.

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





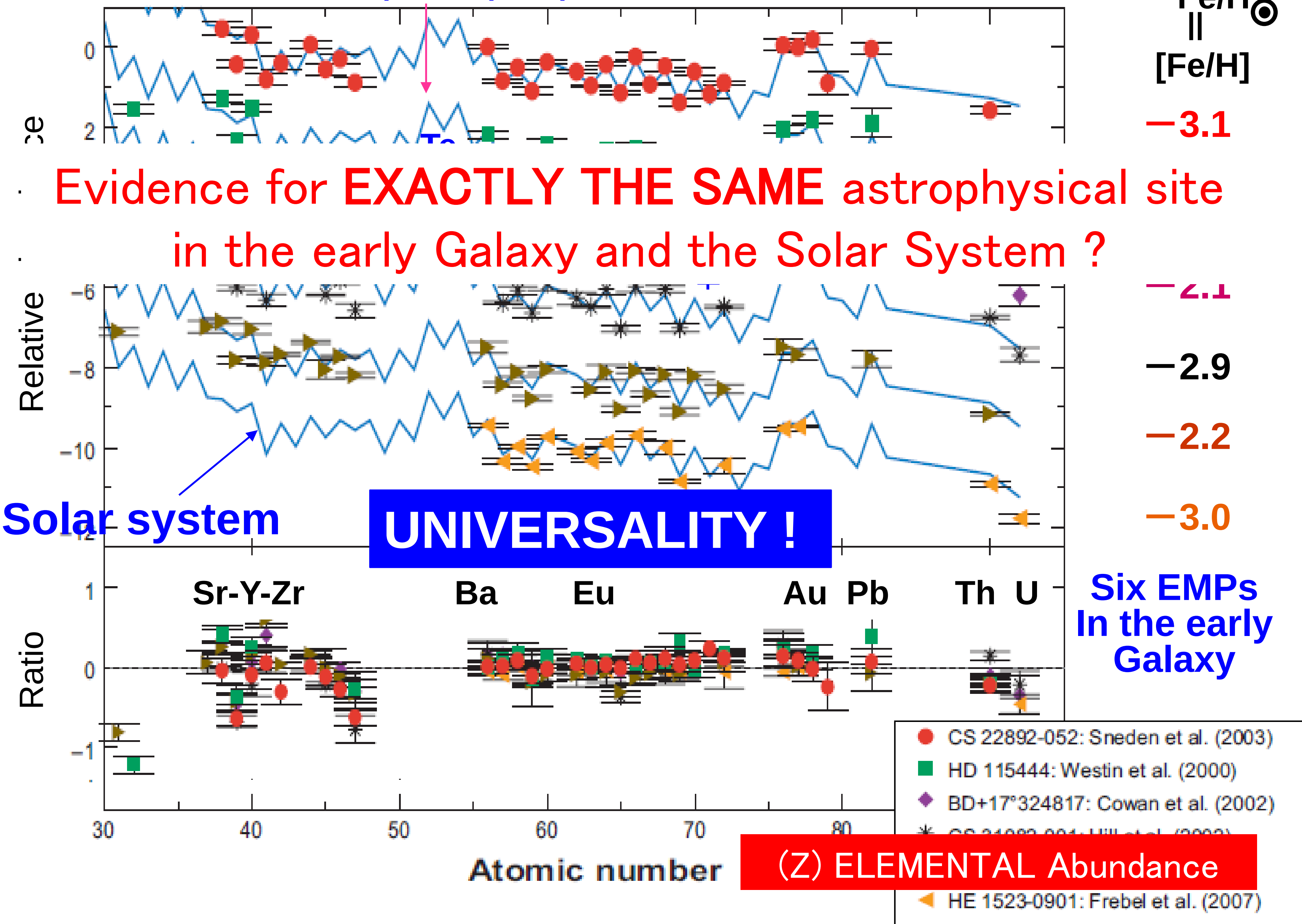
Dust formation becomes even more difficult when one includes more complete opacity table for heavy actinide elements.

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

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

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

$$\log \frac{Fe/H_{☆}}{Fe/H_{\odot}} = [Fe/H]$$



−3.1

−2.1

−2.9

−2.2

−3.0

Evidence for **EXACTLY THE SAME** astrophysical site in the early Galaxy and the Solar System ?

Solar system

UNIVERSALITY !

Six EMPs In the early Galaxy

(Z) ELEMENTAL Abundance

SUMMARY

募集

Solar system ν–process and r–process elements consist of both SN and NSM r–elements.

- Solar system ν–process elements suggest that inverted ν–mass hierarchy is statistically preferred.
- R–elements in the early Universe is dominated by SNe, and NSMs have arrived later.

⇒ Quest for Astronomy: is to look for more ν–elements, and for r–elements time variation of not only elemental(Z) but also isotopic (A) abundances.

⇒ Quest for Nuclear Astrophysics: is to measure/predict nuclear masses, FFD, β half–lives, ν–induced &(n, γ)rates on extremely neutron–rich nuclei.

➡ **Need SYNERGY among Astrophysics, Astronomy and Nuclear & Particle Physics !**

Call for Post Doctoral Fellows

nt. Research Center for Big-Bang Cosmology and Element Genesis(IRCBB
Beihang University

IRCBBC is asking for applications for Post Doctoral Fellows. The term is for two years and the salary per year is 300,000 RMB(~ US$43,400, ~ €40,700, ~ 4,980,000 JP Yen).

The deadline for application: May 20, 2017

IRCBBC is directed by T. Kajino and promotes theoretical studies on Big Bang cosmology and element genesis. We seek for a few postdoctoral research associates in the field of theoretical nuclear astrophysics and cosmology who are interested in explosive nucleosynthesis and neutrino physics of the early Universe and supernovae.

Please send your statement of interest by April 30, 2017. Any questions related to the fellowship are welcome at any time.

Toshitaka Kajino, Director of ICRBBC

University of Tokyo, NAOJ

kajino@nao.ac.jp