The 4th DTA Symp. on Compact Stars and GW Astronomy
NAOJ Mitaka, May 13-14, 2016

Neutrinos and Element Genesis as a probe of EOS and Binary Neutron Star Mergers

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Purpose

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

- ■ Relic SN-ν (in SK & HK)

  + EOS of the Neutron Stars

- ■ ν-Nucleosynthesis & Cosmic Clock

  Remarkably Sensitive to MSW Effect

2. How to approach Collective ν-Oscillation

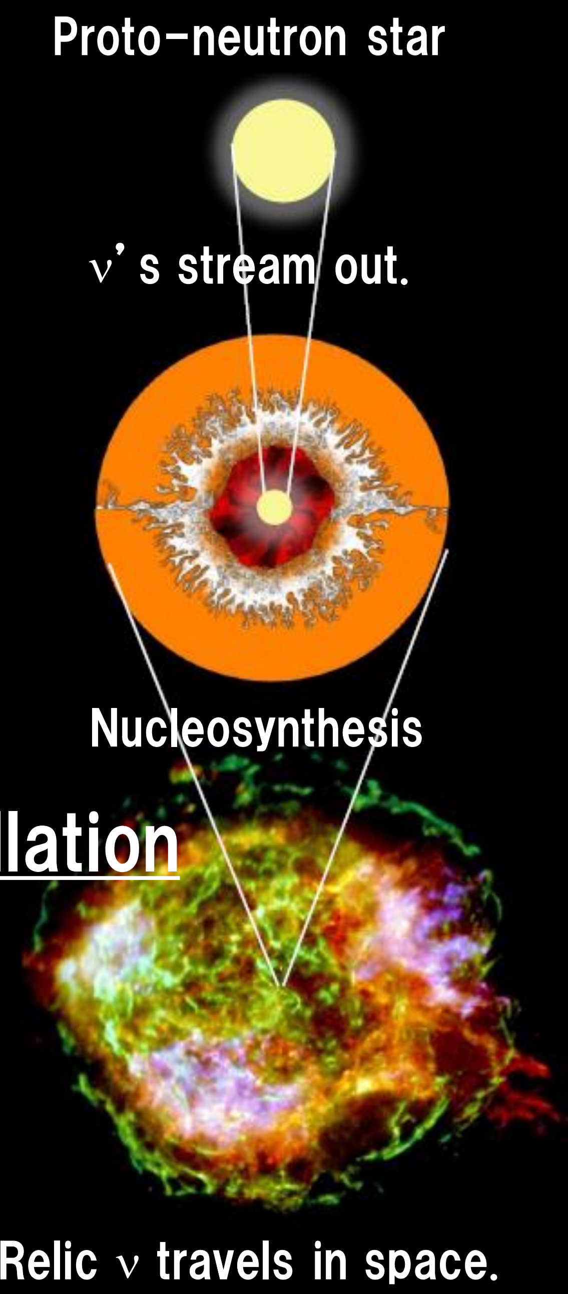
- ■ Origin of r-Process

  Core-Collapse Supernovae

  vs. Binary Neutron Star Mergers ?

- ■ Origin of Life

  Amino Acid on the Earth, all L-handed



Two Astronomical Motivations

G.J. Mathews, J. Hidaka, T. Kajino & J. Suzuki, ApJ 790 (2014) ,115 — SNR problem.
K. Nakazato, E. Mochida, Y, Niino, H. Suzuki, ApJ 804 (2015), 75 — Metallicity Evol.

Supernova Rate Problem

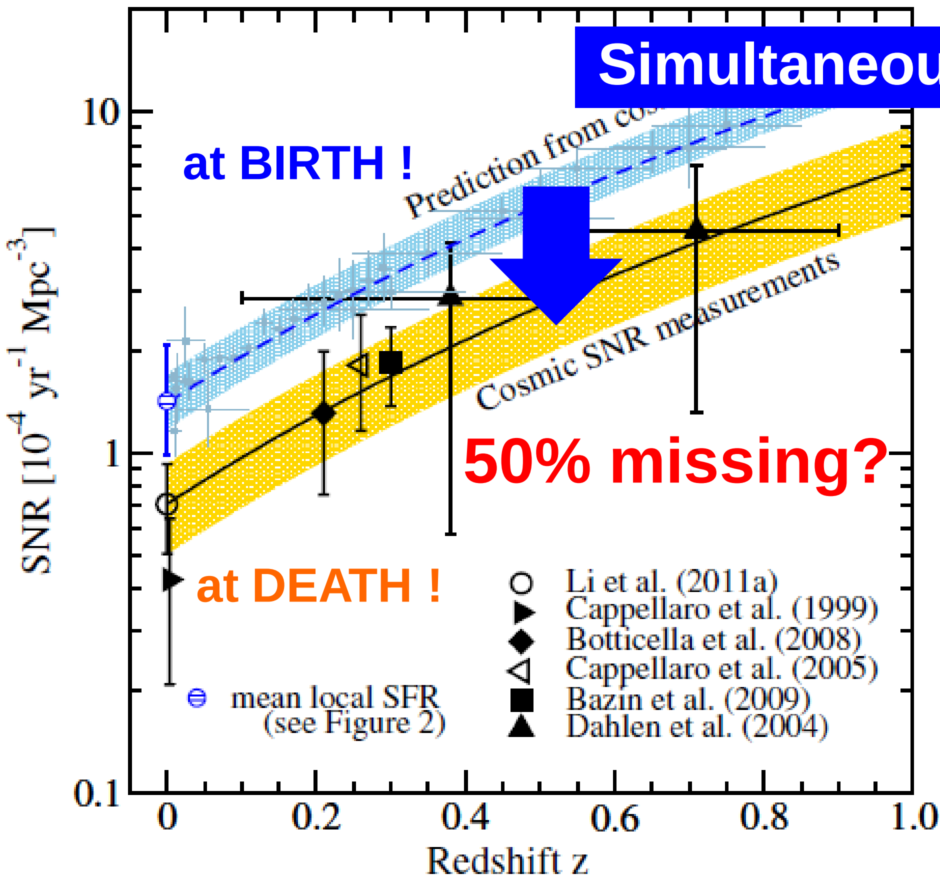
Red Super-Giant Problem

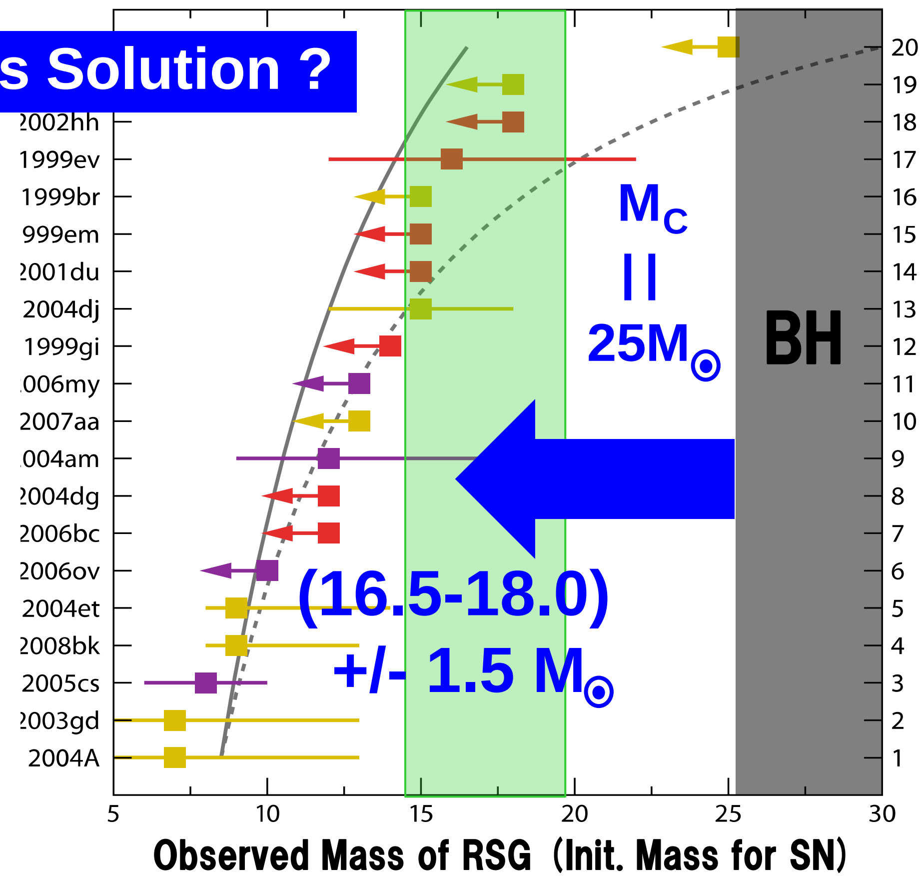
failed-SNe with BH → **Critical mass for failed-SNe ?**

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

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

Simultaneous Solution ?





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

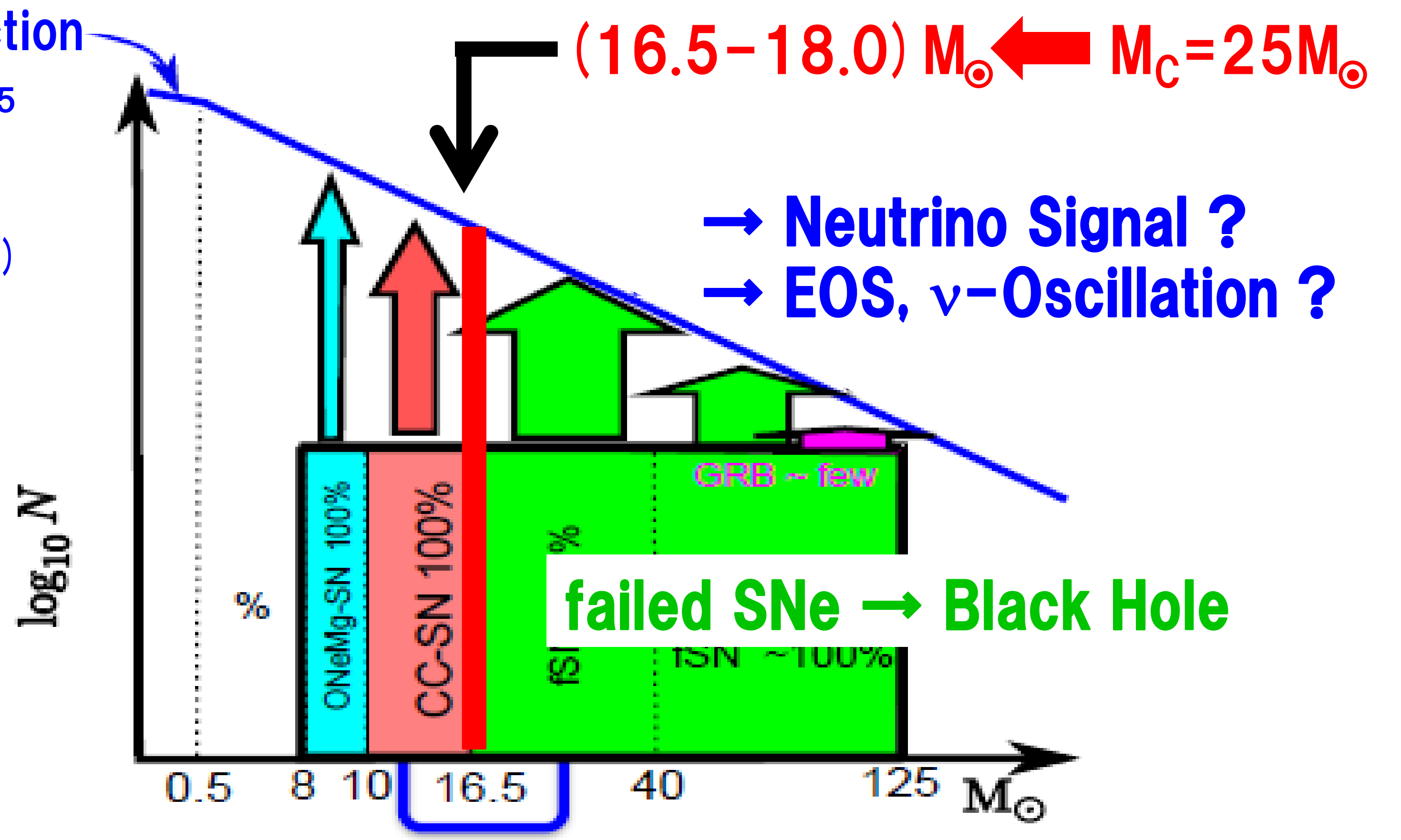
Cosmic Star Formation Rate

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

Initial Mass Function

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

Salpeter (1955)



Survey of Numerical SN-Simulations

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

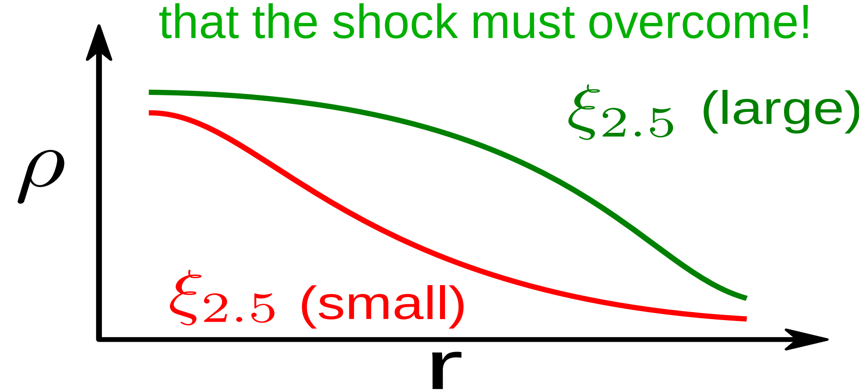
Woosley, Heger, Weaver, RMP 74 (2002), 1015.

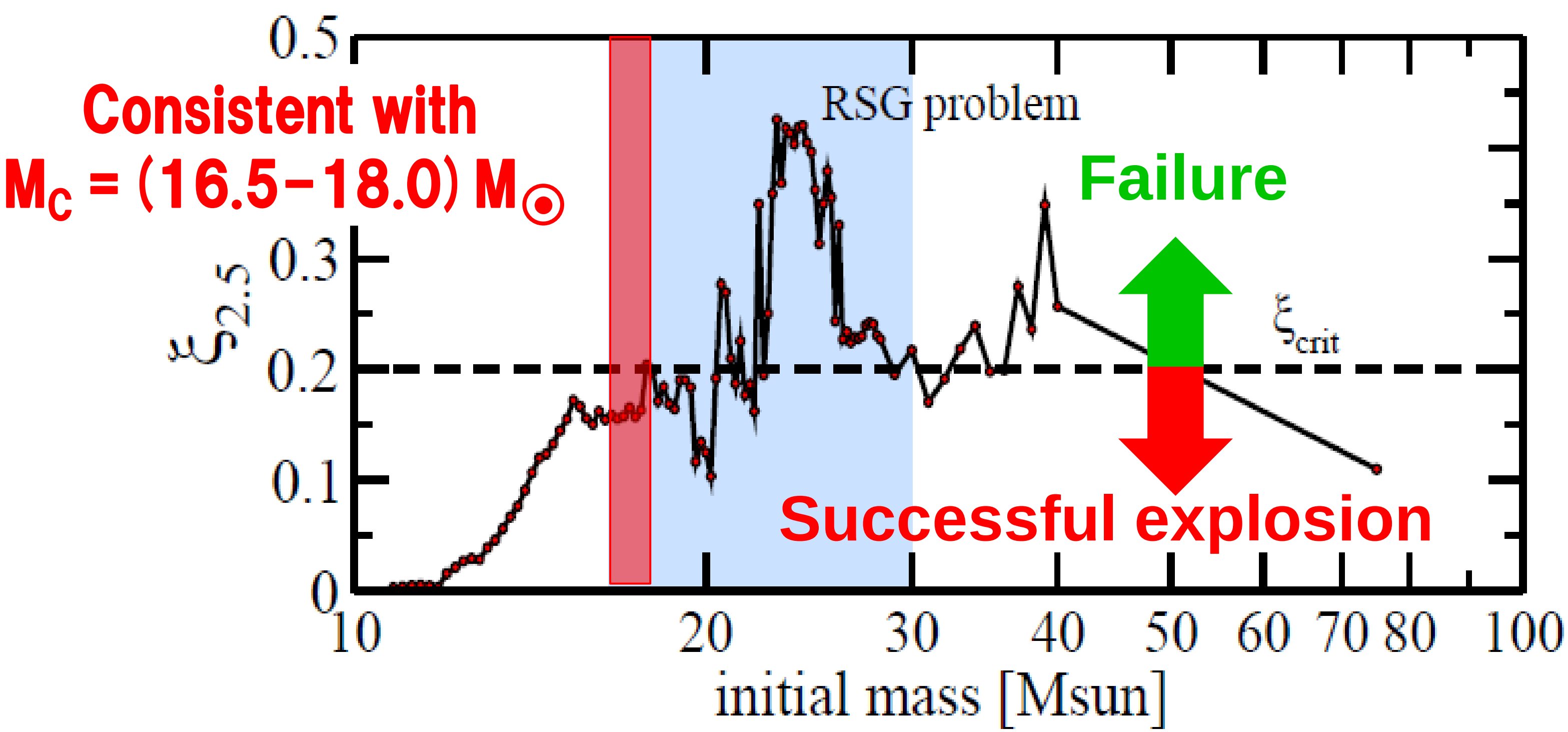
Compactness parameter :

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

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

Larger accretion & ram pressure that the shock must overcome!





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)

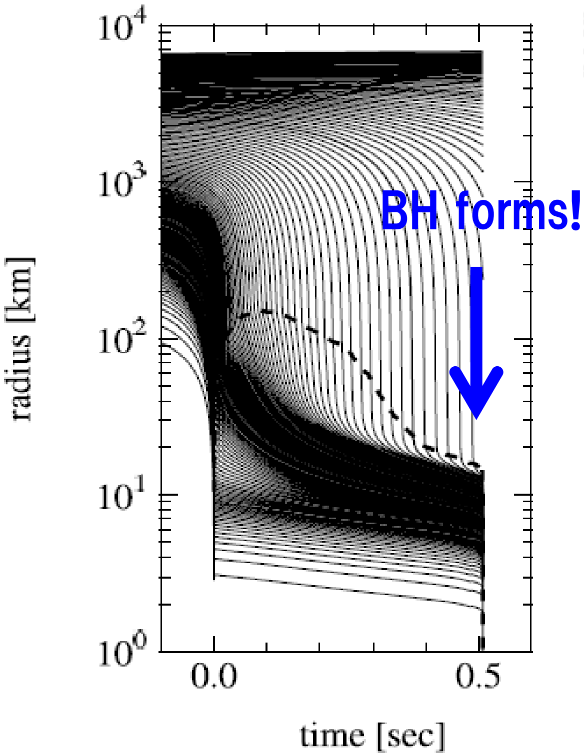
detail	ONeMg SN	CC-SN	fSN(SH EOS)	fSN(LS EOS)	GRB
mass($M_\odot$)	(8 ∼ 10)	8 ∼ 25(10∼25)	25 ∼ 125 (99.96%)	25 ∼ 125 (99.96%)	25 ∼ 125 (0.04%)
Remnant	Neutron Star	Neutron Star	Black Hole	Black Hole	Black Hole
Phenomenon	Supernova	Supernova	Failed Supernova	Failed Supernova	Gamma-Ray Burst
T_{ν_e} (MeV)	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	$\sim 0.5s$	$\sim 1.5s$	$\sim 10s$

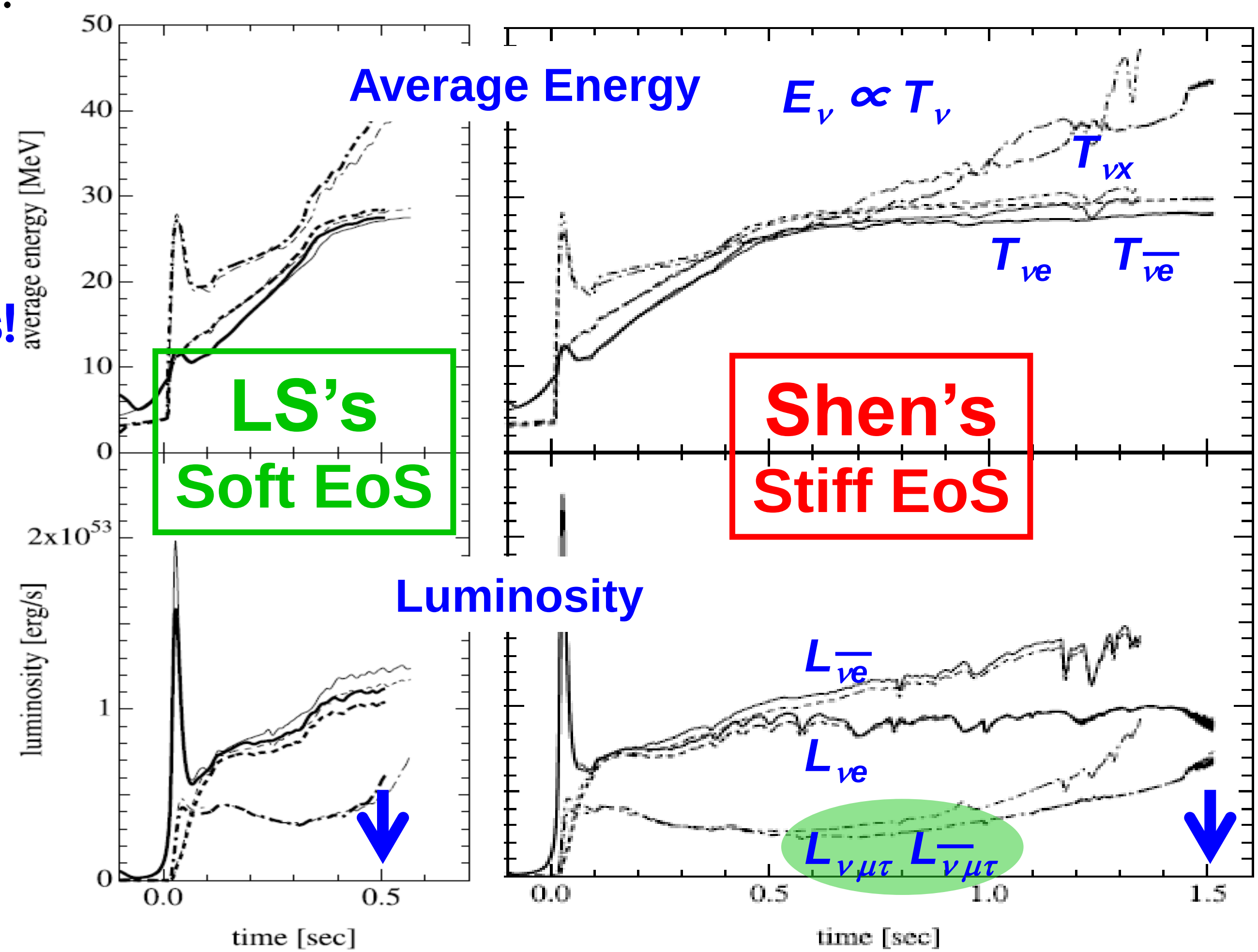
- **ONeMg SNe:** Hudepohl, et al., PRL 104 (2010).
- **CC-SNe:** Yoshida, et al., ApJ **686** (2008), 448;
  Suzuki & Kajino, J. Phys. **G40** (2013) 83101.
- **fSN (failed SNe):** Sumiyoshi, et al., ApJ **688** (2008) 1176.
  - * **Shen-EOS (stiff):** Shen et al. Nucl. Phys. **A637** (1998) 435.
  -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

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)

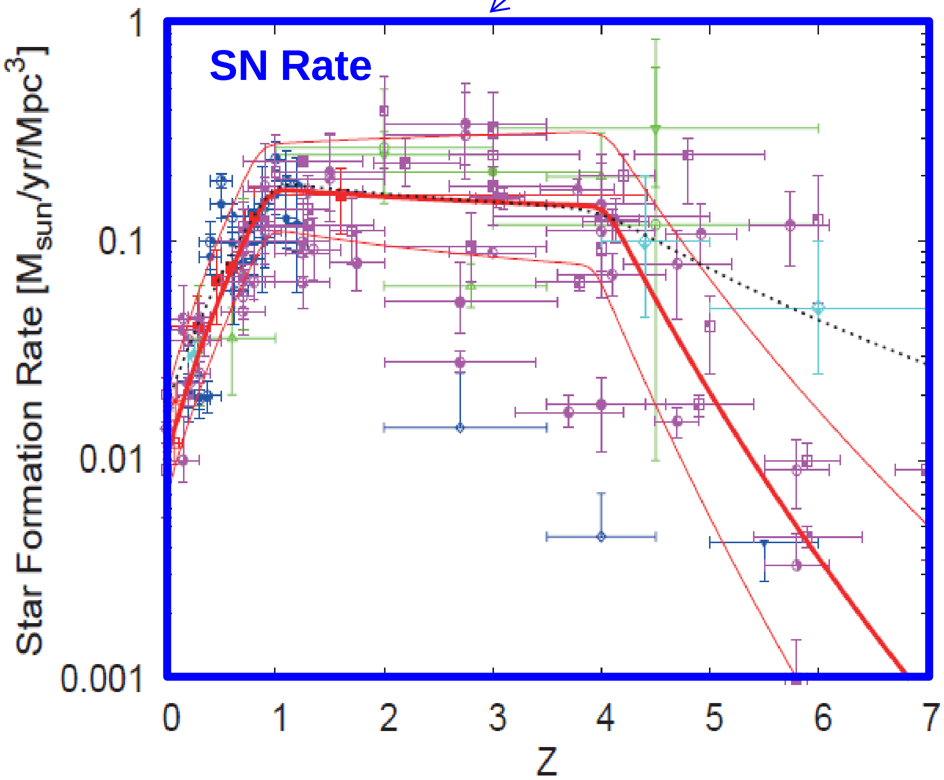
Mathews et al. 2014; Totani et al. 1996, ApJ 460, 303; Lunadini 2009, PRL 102, 231101.

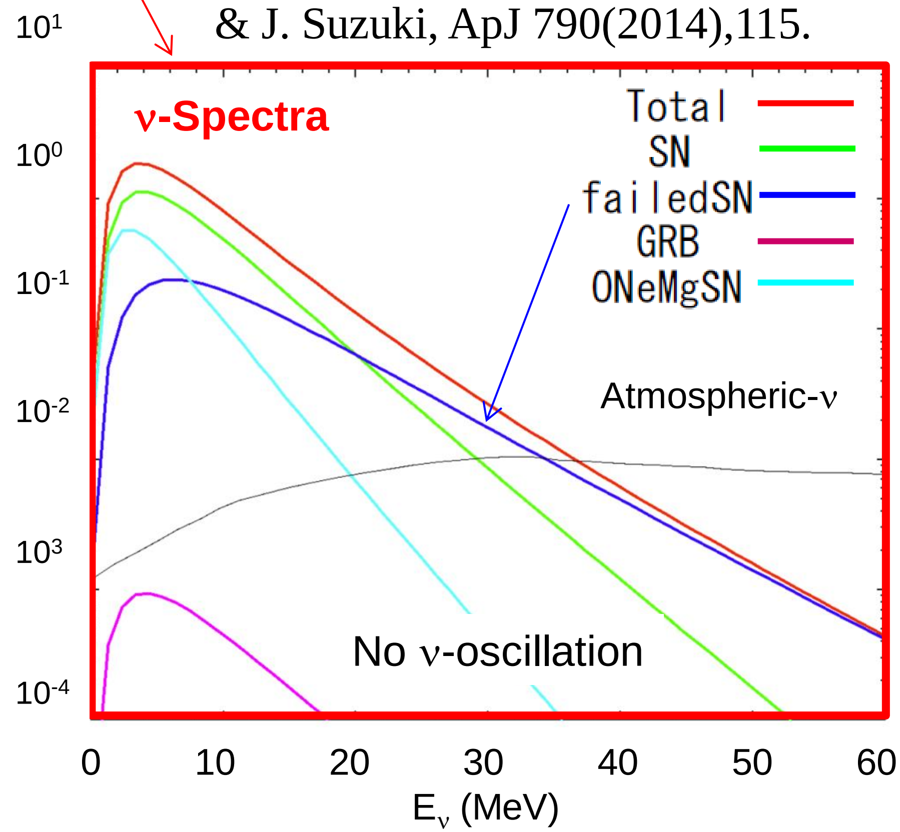
Redshifted $E'_\nu = (1+z)E_\nu$ Expanding Universe ΛCDM

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

$\Omega_m = 0.3$
$\Omega_\Lambda = 0.7$

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

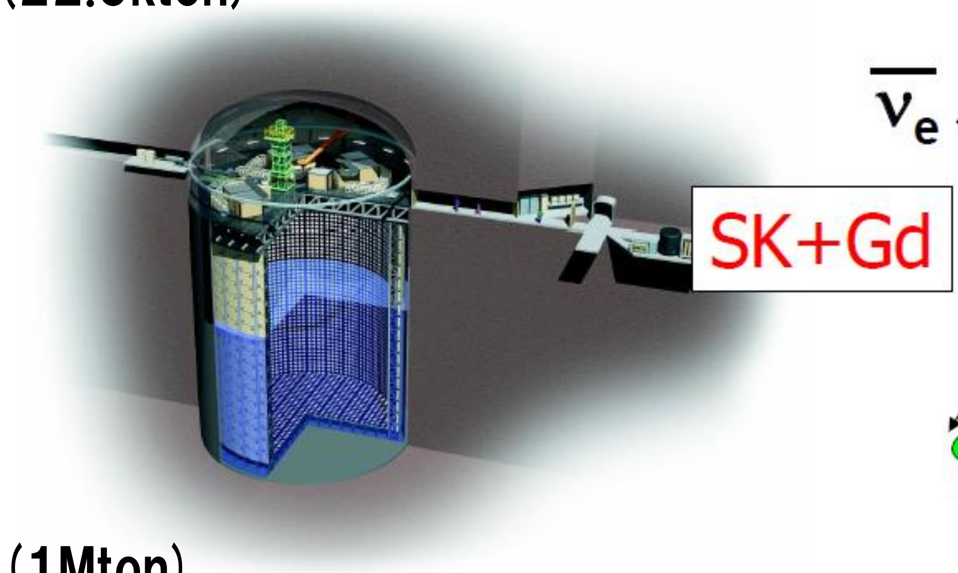


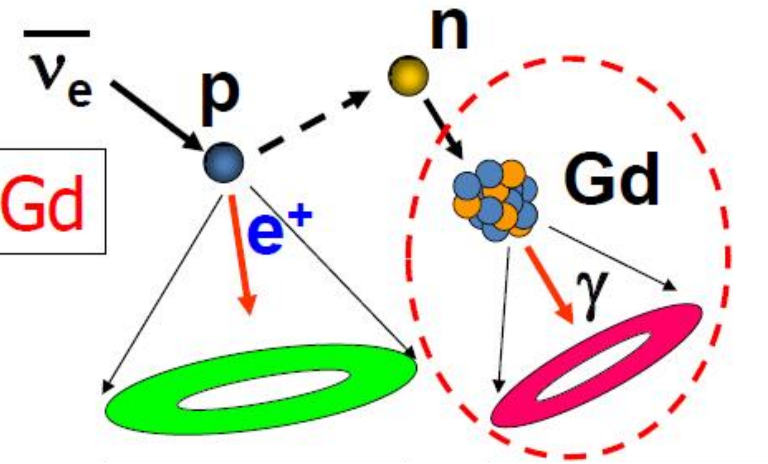


Gd-loaded Water Cherenkov Detector

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

SK (22.5kton)

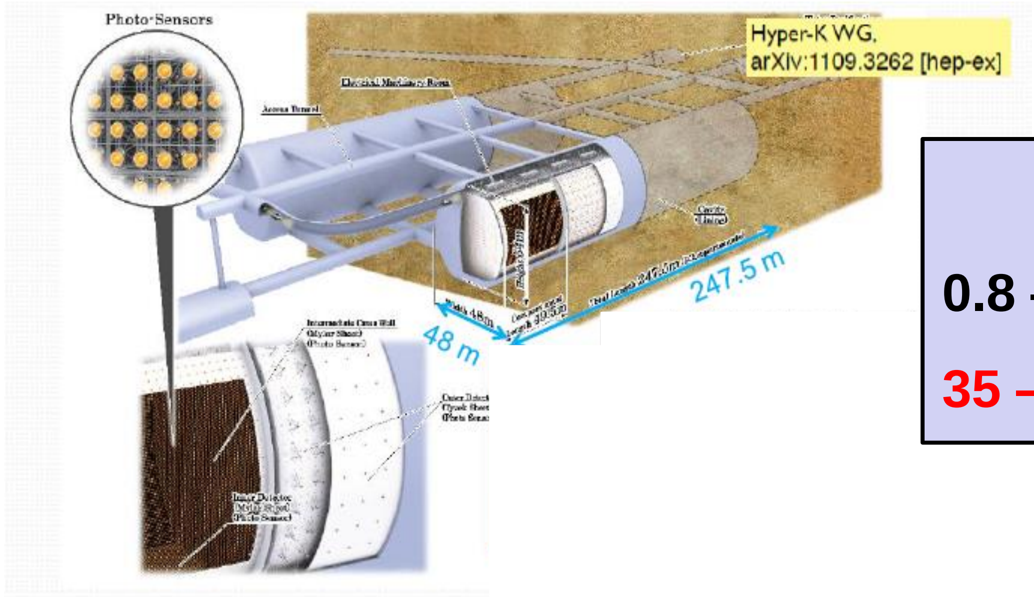




Present signal   New signal

COINCIDENCE

HK (1Mton)



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

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

Hidaka, Kajino, Mathews, ApJ (2016), submitted.

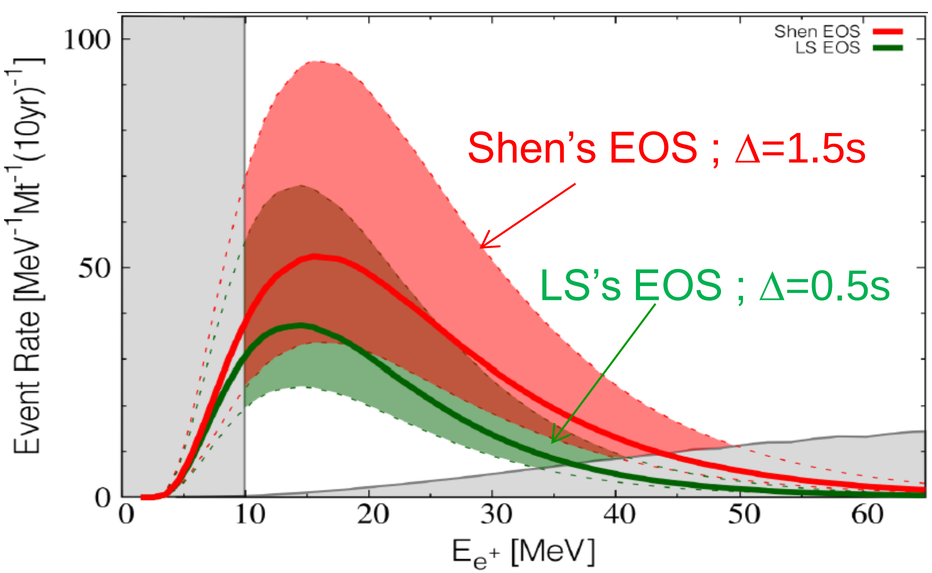
Setting M_C= (16.5-18.0) $M_\odot$ to solve SN RATE PROBLEM and RSG PROBLEM simultaneously.

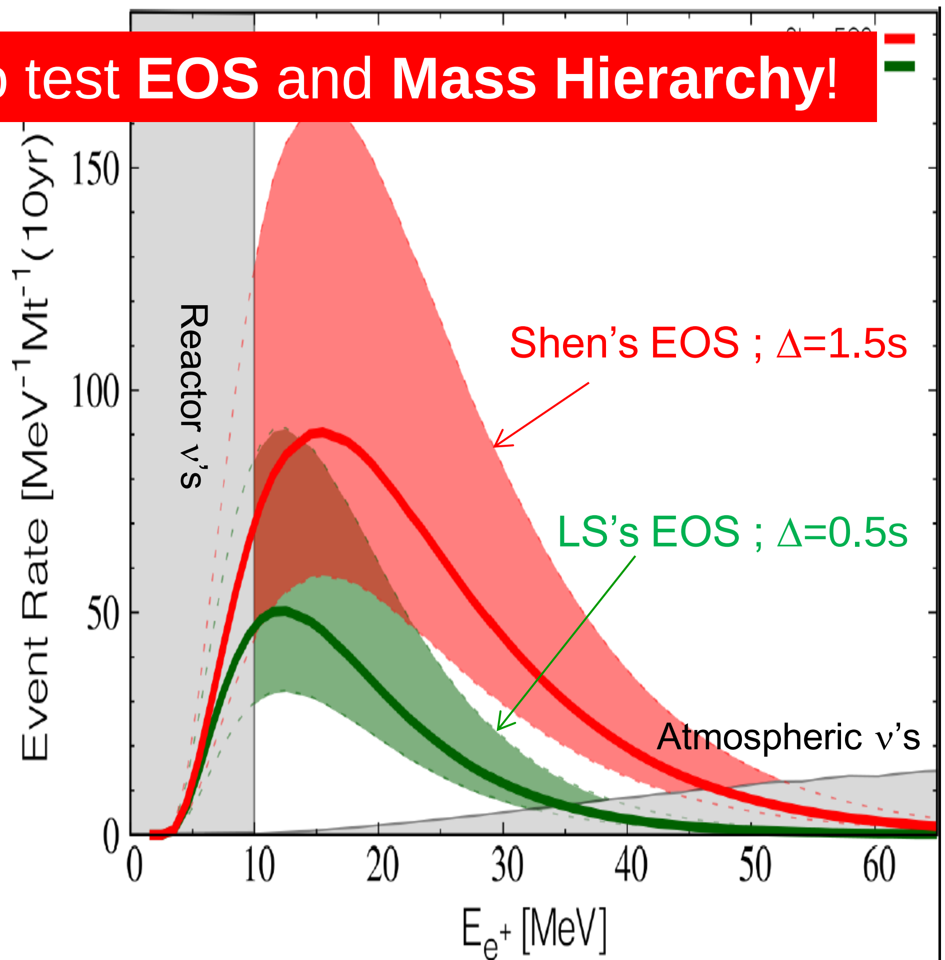
Normal Hierarchy

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

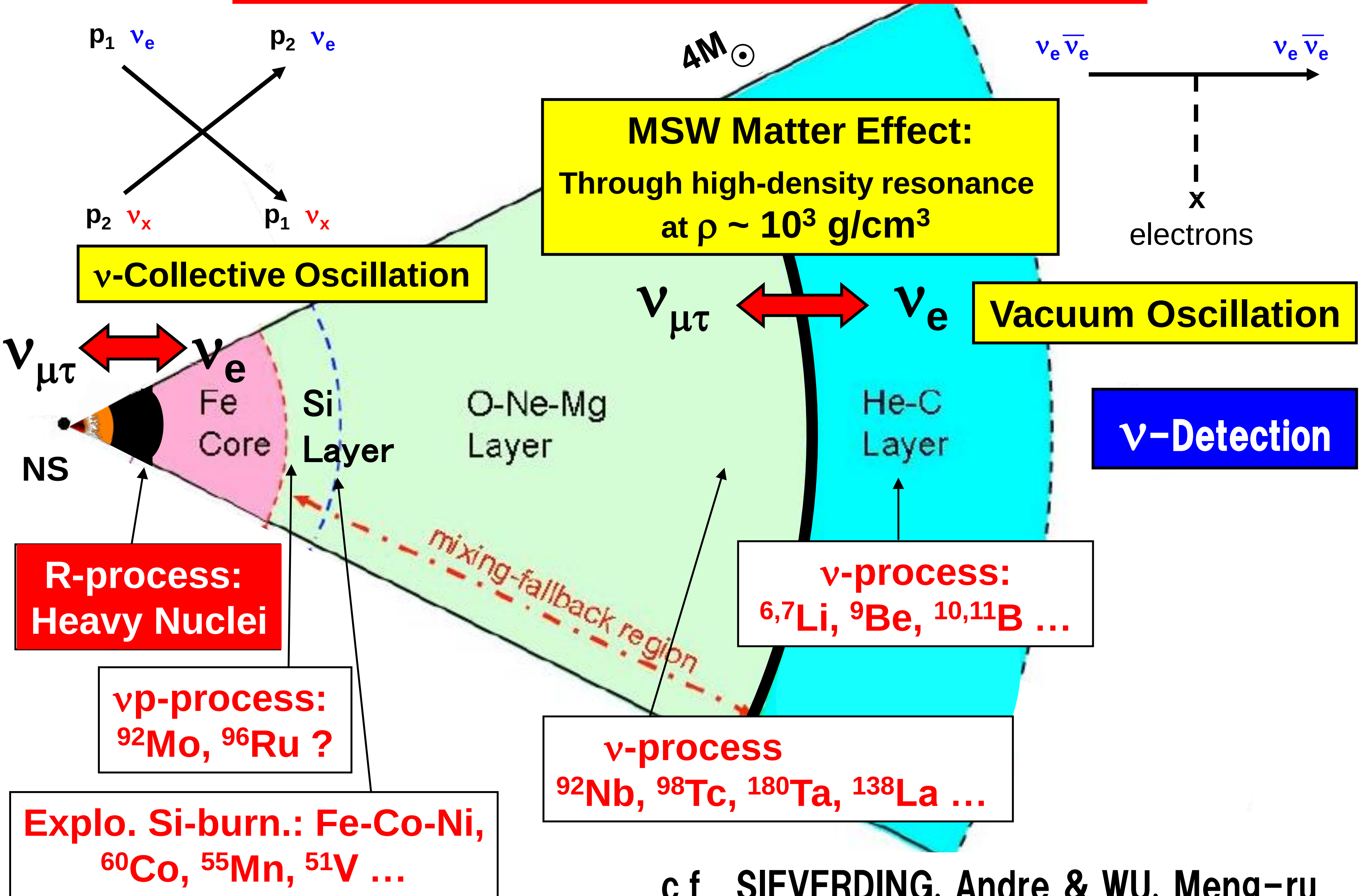
MSW-HD Res. + ($L_{\nu e} = L_{\overline{\nu e}} \gg L_{\overline{\nu \mu,\tau}}$)

Inverted Hierarchy



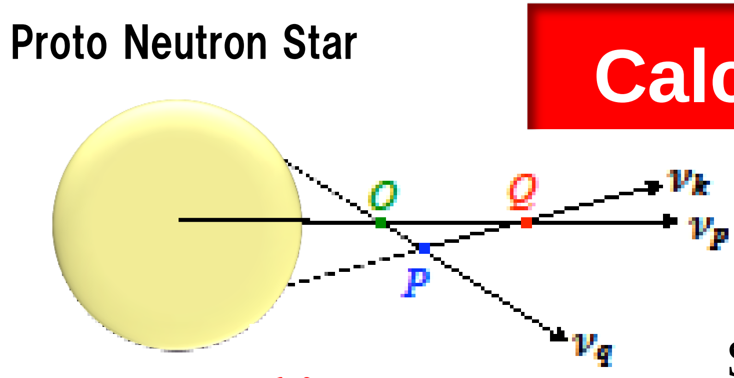


ν-Oscillation and Nucleosynthesis



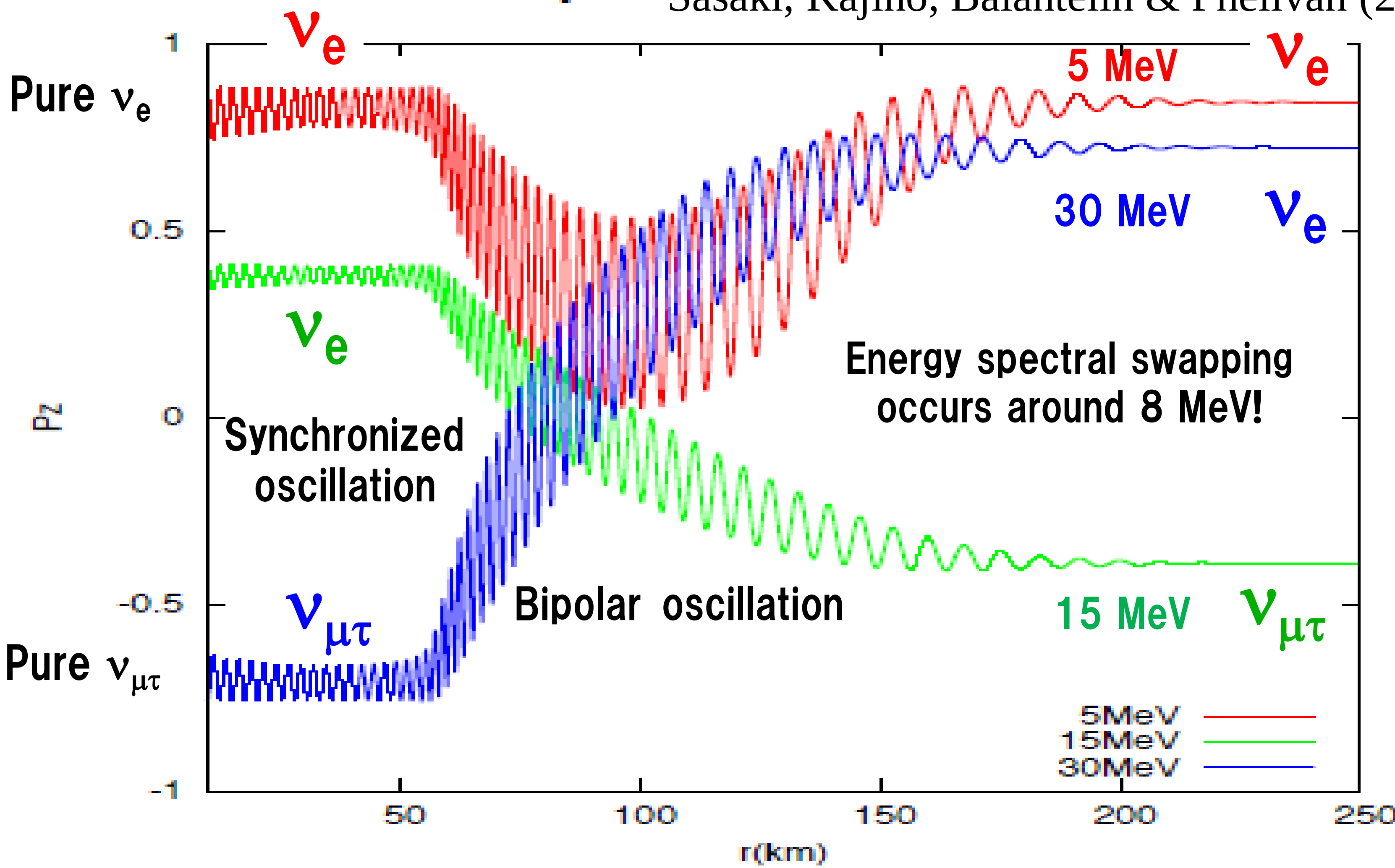
c.f. SIEVERDING, Andre & WU, Meng-ru

Calculated ν Flavor Oscillation



Energy spectra SWAP!

Sasaki, Kajino, Balantelin & Phelivan (2016)

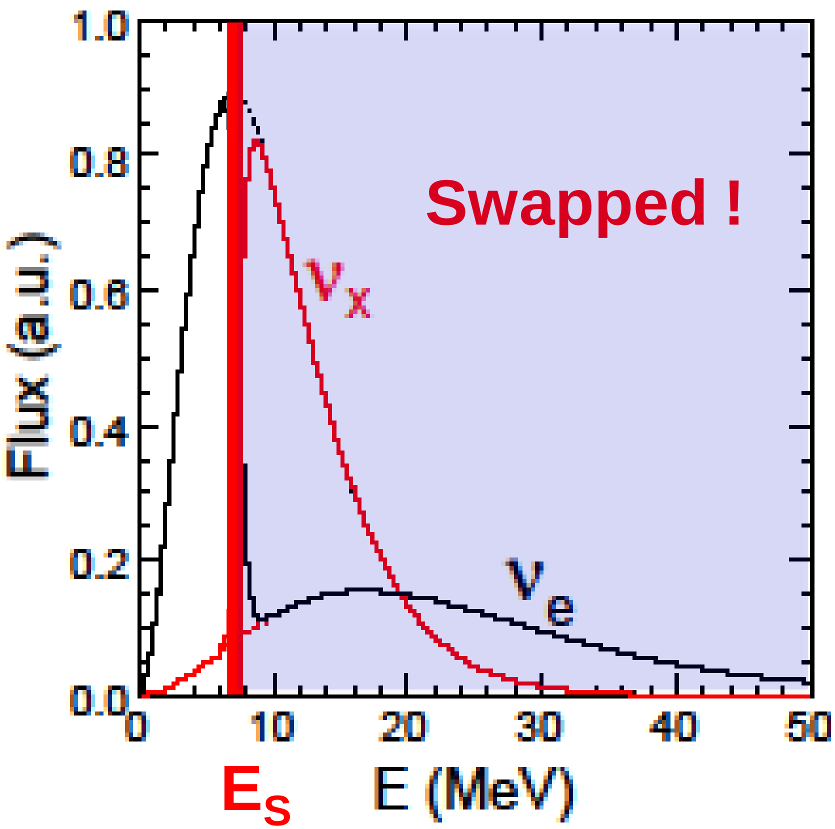


Mean Field Approx. (single angle, 2 flavor) loses many symmetries!

★ Quest for solving many-body Hamiltonian EXACTLY !

Y. Pehlivan, A.B. Balantekin, T. Yoshida & T. Kajino, Phys. Rev. D84 (2011), 065008,
Y. Pehlivan, A.B. Balantekin & T. Kajino, Phys. Rev. D90 (2014), 065011.

Single angle approx. (Inverted)



How to predict Split Energy E_S ?

"INVARIANCE"

$H_{\nu\nu}$ = Many-body Hamiltonian

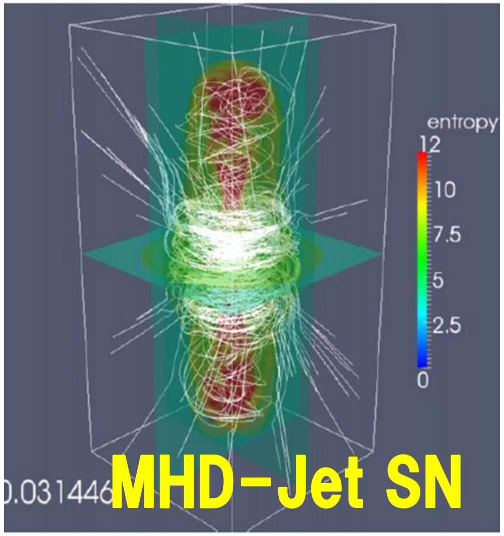
: similar to BCS or Spin-Lattice

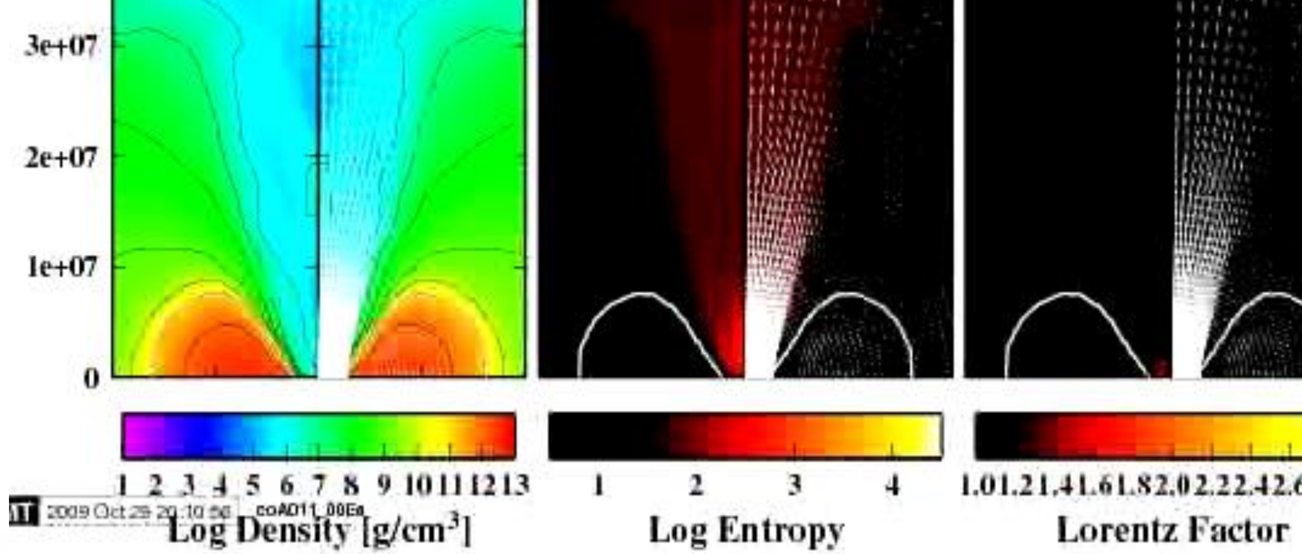
: holds the same "Symmetries"

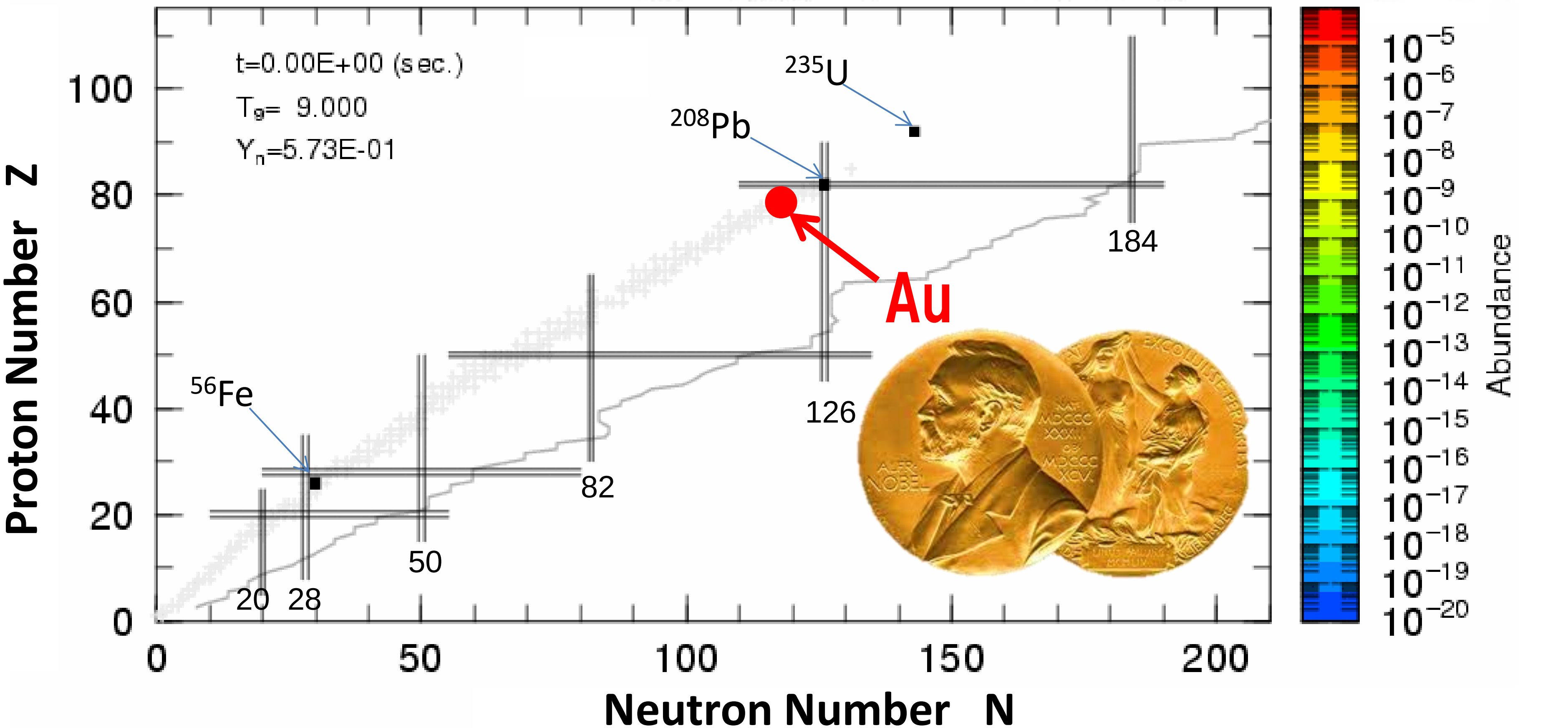
Bethe ansatz (Homogenous matter)

$$I_p = I \sum_{i=1}^{3} \frac{1}{T^4_{\alpha_i}} \frac{p^2}{1+e^{p/T_{\alpha_i}}} \int dq \left(\frac{\frac{1}{T^4_{\alpha_i}} \frac{q^2}{1+e^{q/T_{\alpha_i}}}}{\frac{1}{2p} - \frac{1}{2q}} - \frac{\frac{1}{T^4_{\bar{\alpha}_i}} \frac{q^2}{1+e^{q/T_{\bar{\alpha}_i}}}}{\frac{1}{2p} + \frac{1}{2q}} \right)$$

$$I_{-p} = I \sum_{i=1}^{3} \frac{1}{T^4_{\bar{\alpha}_i}} \frac{p^2}{1+e^{p/T_{\bar{\alpha}_i}}} \int dq \left(\frac{\frac{1}{T^4_{\bar{\alpha}_i}} \frac{q^2}{1+e^{q/T_{\bar{\alpha}_i}}}}{\frac{1}{2p} - \frac{1}{2q}} - \frac{\frac{1}{T^4_{\alpha_i}} \frac{q^2 q}{1+e^{q/T_{\alpha_i}}}}{\frac{1}{2p} + \frac{1}{2q}} \right)$$


entropy
12
10
7.5
5
2.5
0
0.031446
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 20:10:56
coA011_00Ea


t=0.00E+00 (sec.)
T9= 9.000
Yn=5.73E-01
235U
208Pb
56Fe
Au
20
28
50
82
126
184
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

Astrophysical site for the r-process ?

Core-Collapse Supernovae?

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

R-process cond. of high S/k & low Y_e?

τ =1-10My

Explosion Mechanism ?

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).

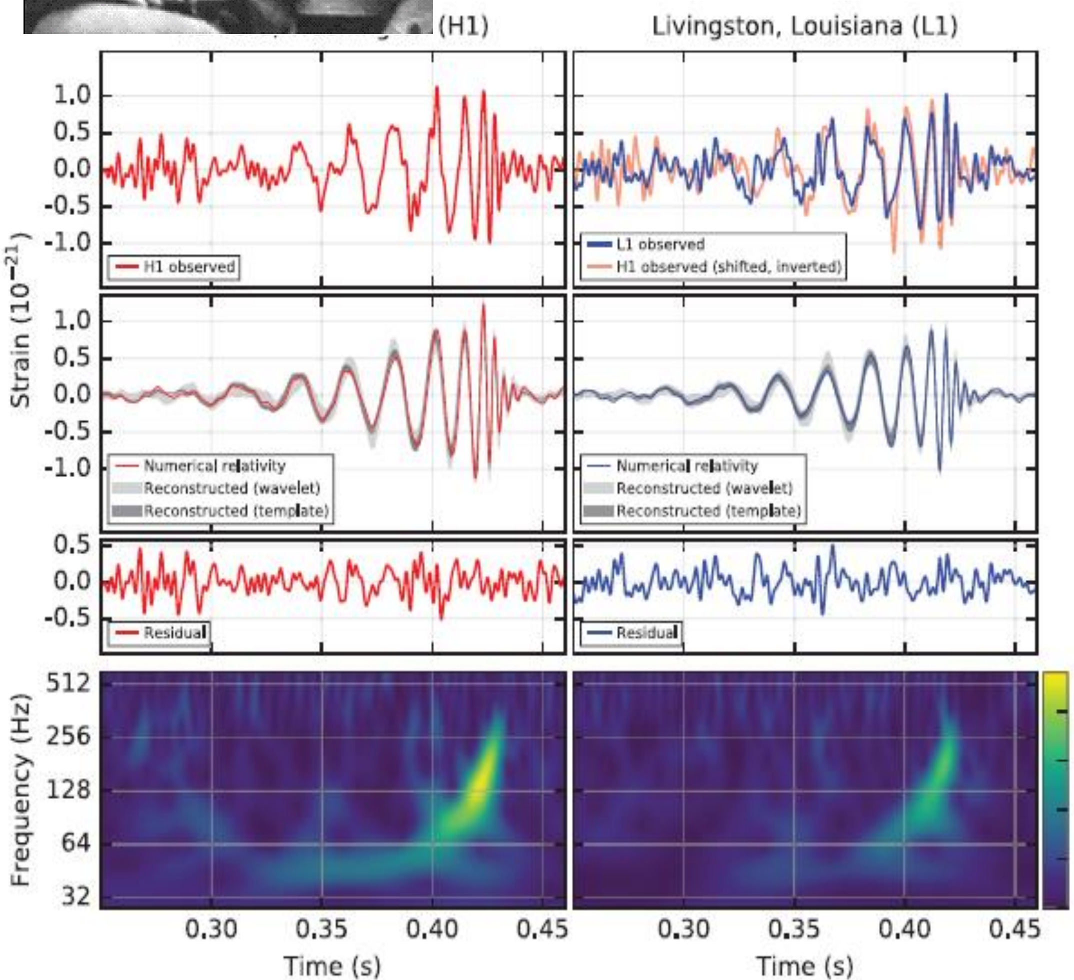
Binary NSs arrive too late ?

$100My \leq \tau_c \leq 10Ty$

Time Scale Problem ?

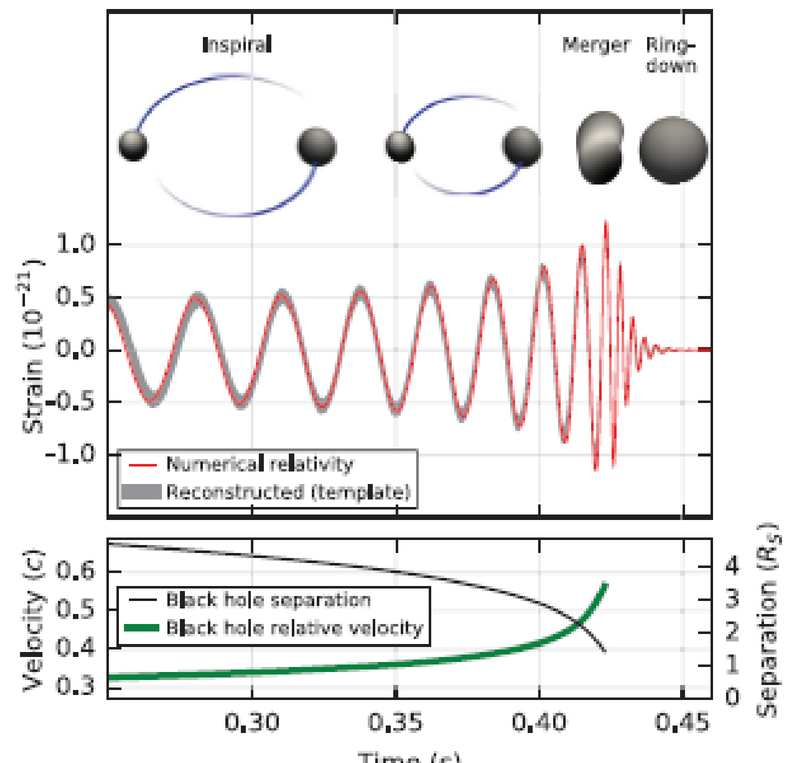
GW from Binary BH Merger is most likely detected in 2015-16！

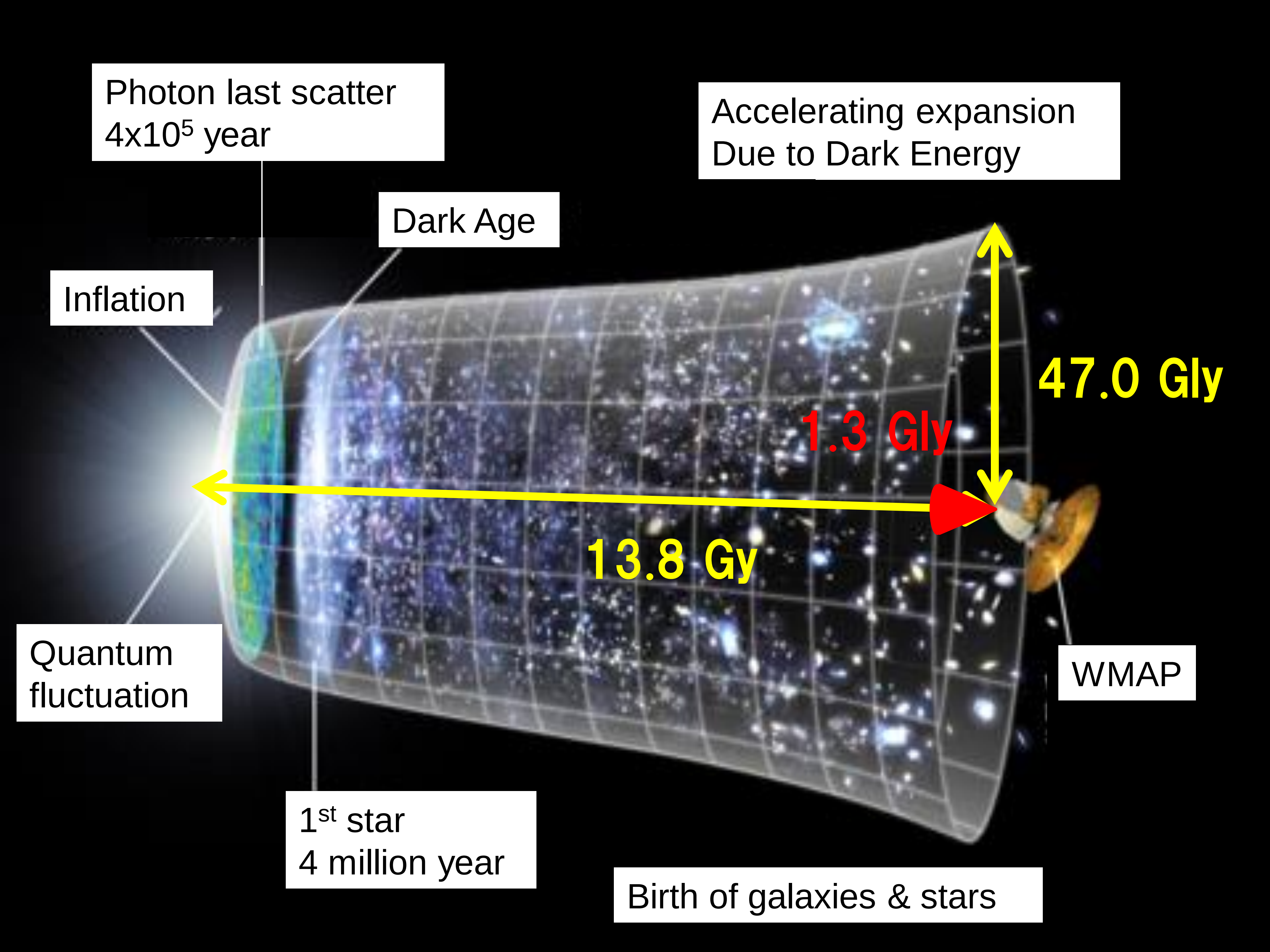
A. Einstein predicted 100 yrs ago.



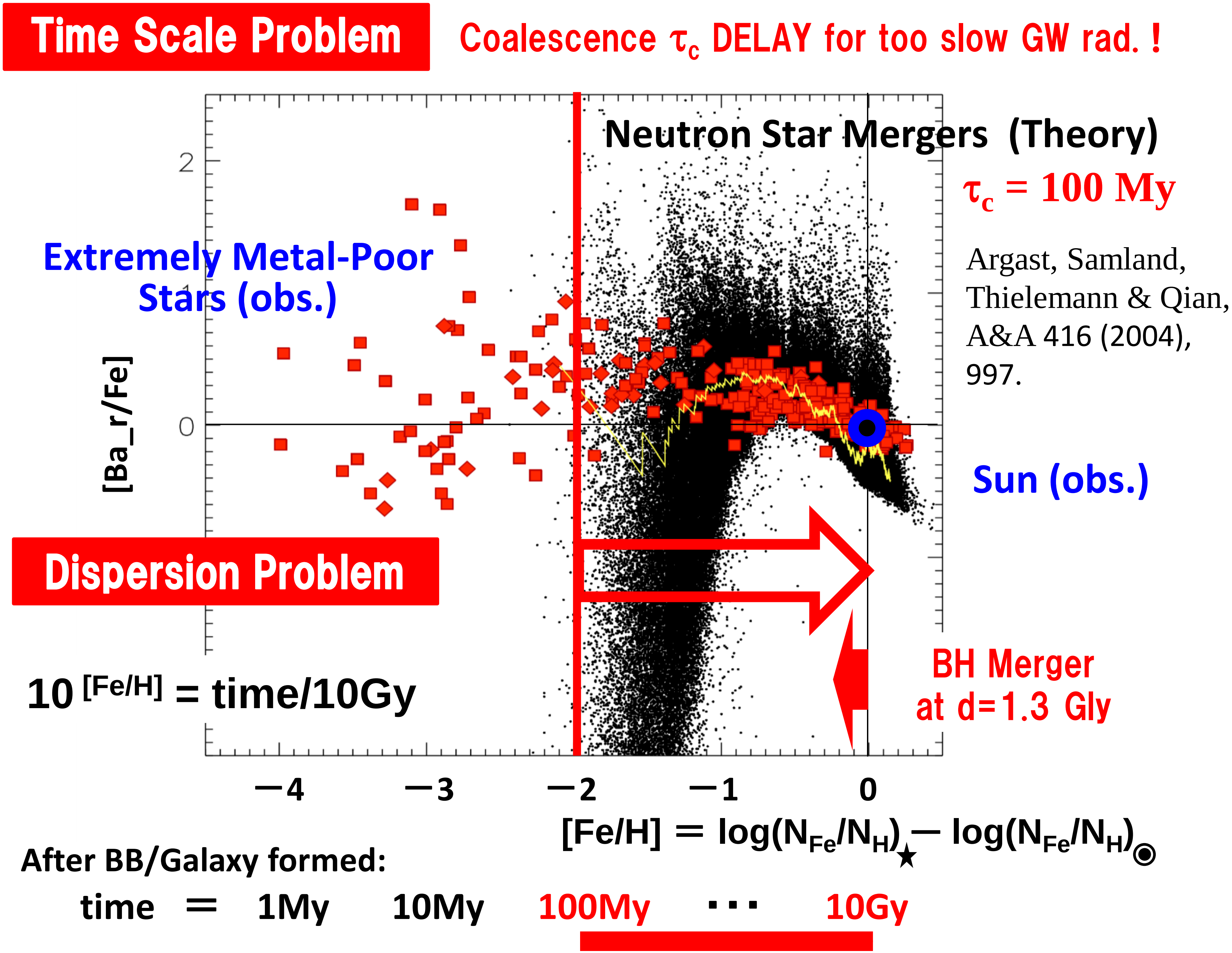
Black Hole Binary at d=1.3 Gly

(Horizon～47.0 Gly)





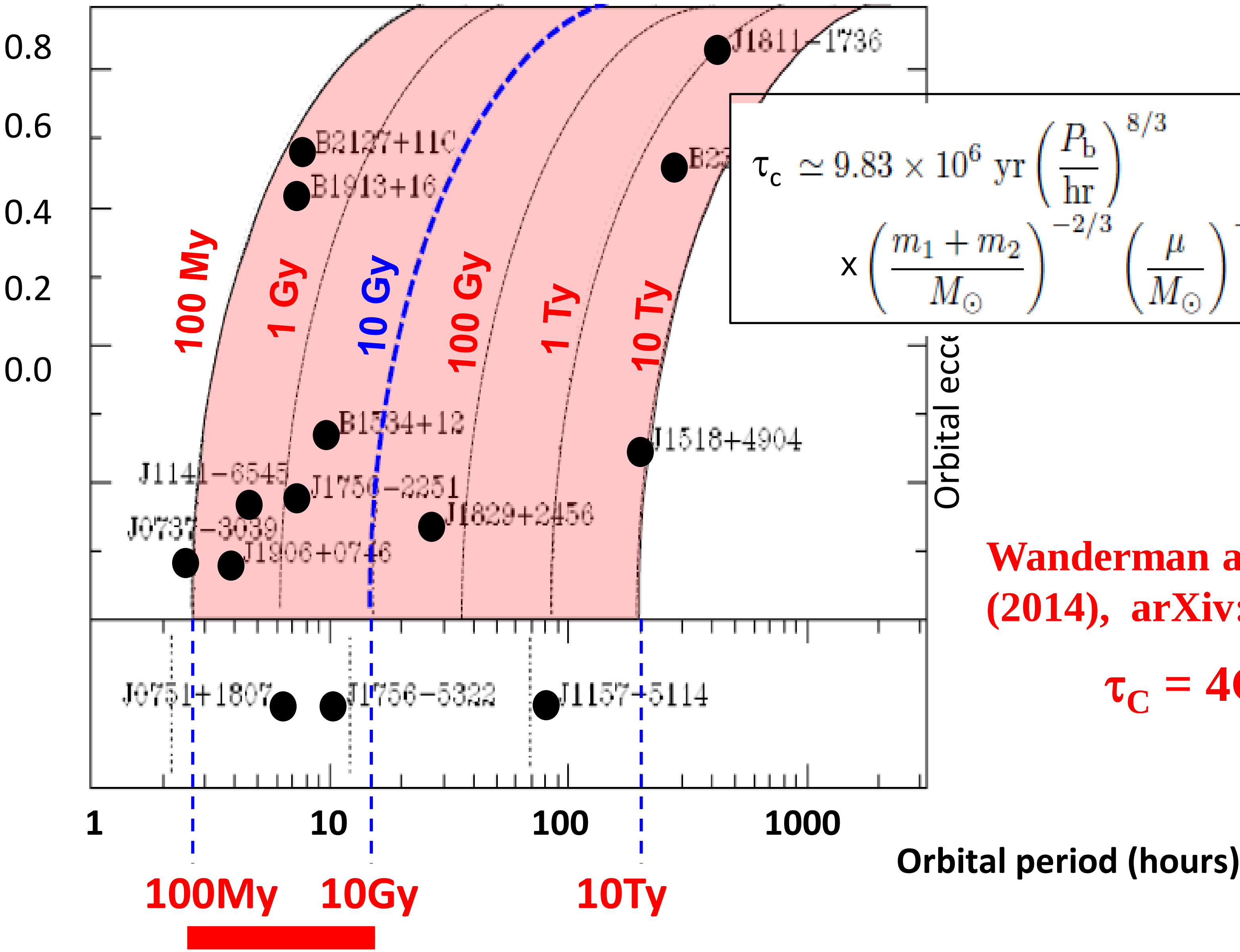
Photon last scatter
4x10^5 year
Accelerating expansion
Due to Dark Energy
Dark Age
Inflation
47.0 Gly
1.3 Gly
13.8 Gy
Quantum
fluctuation
WMAP
1st star
4 million year
Birth of galaxies & stars


Time Scale Problem
Coalescence τc DELAY for too slow GW rad. !
Neutron Star Mergers (Theory)
τc = 100 My
Argast, Samland, Thielemann & Qian, A&A 416 (2004), 997.
Extremely Metal-Poor Stars (obs.)
Sun (obs.)
[Ba_r/Fe]
2
0
Dispersion Problem
BH Merger at d=1.3 Gly
10 [Fe/H] = time/10Gy
−4
−3
−2
−1
0
[Fe/H] = log(NFe/NH)★ − log(NFe/NH)⊙
After BB/Galaxy formed:
time = 1My 10My 100My ··· 10Gy

Time Scale Problem

Coalescence τ_c DELAY for too slow GW rad. !

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



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

Wanderman and Piran (2014), arXiv:1405.5878

τ_C = 4Gy

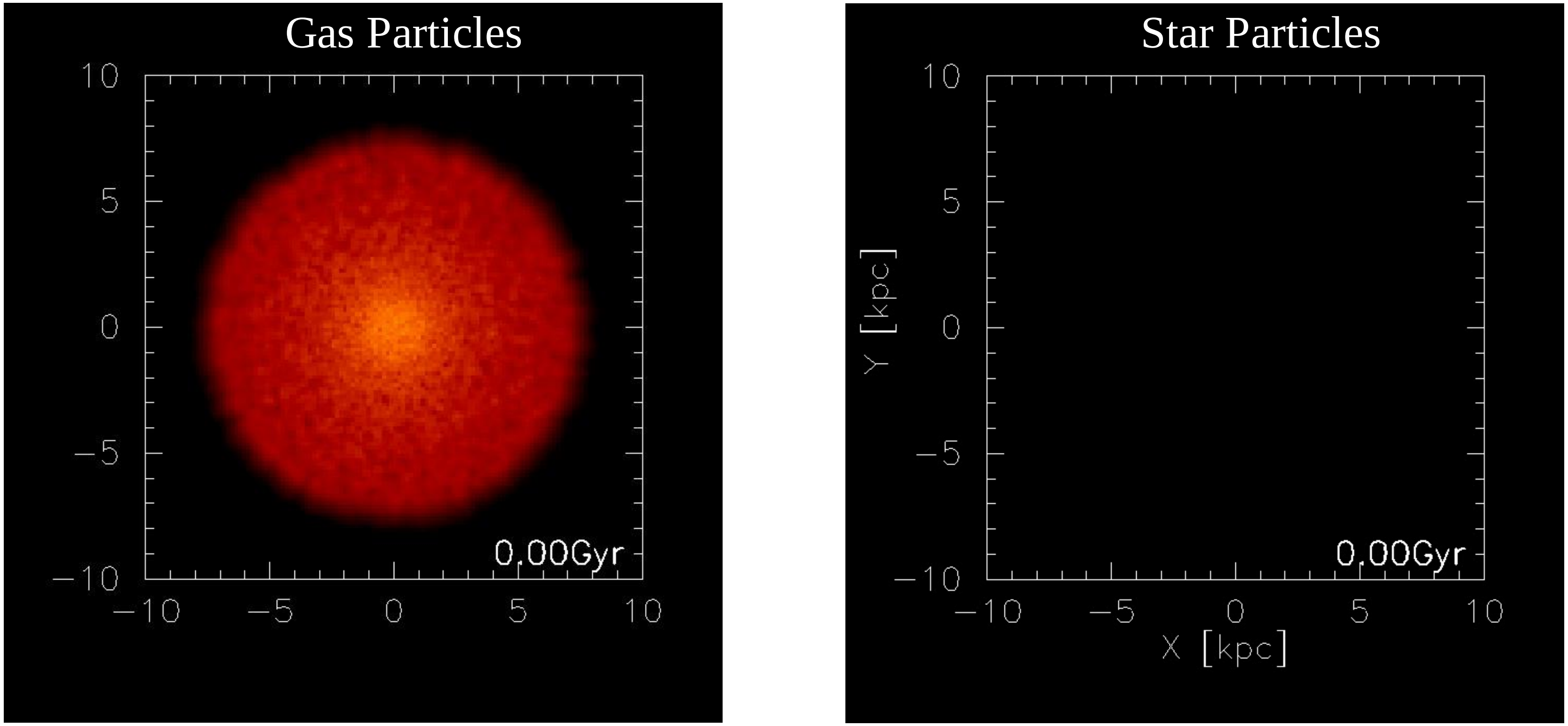
SUPERCOMPUTING of Galactic Chemo−Dynamical Evolution of Dwarf Spheroidal

N−Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.
SNe = Metals ; NSM (τ_c=100My) = r−process elements.

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

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

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



SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Spheroidal

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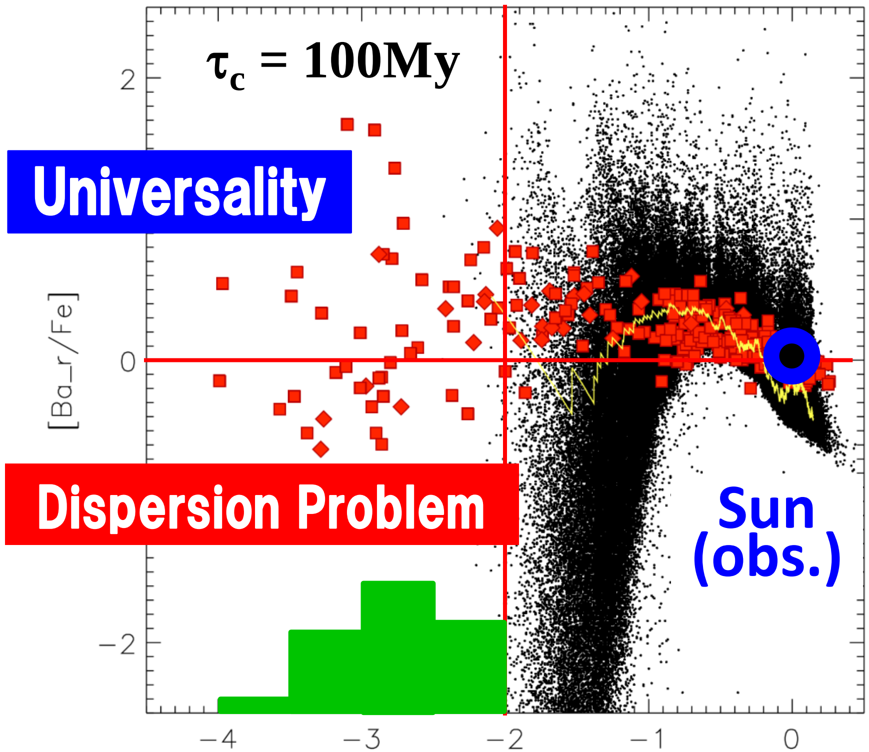
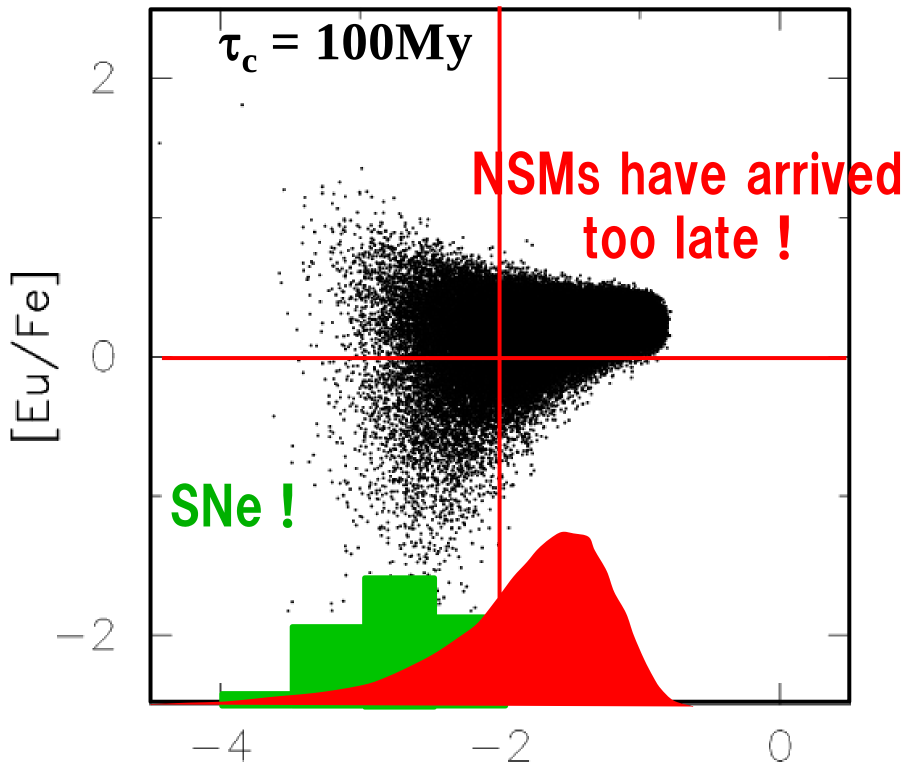
Argast, Samland, Thielemann, Qian, A&A 416 (2004), 997.

Hirai, Ishimaru, Saitoh, Fujii, Hidaka and Kajino, ApJ 814 (2015), 41.

Without GAS MIXING



With GAS MIXING



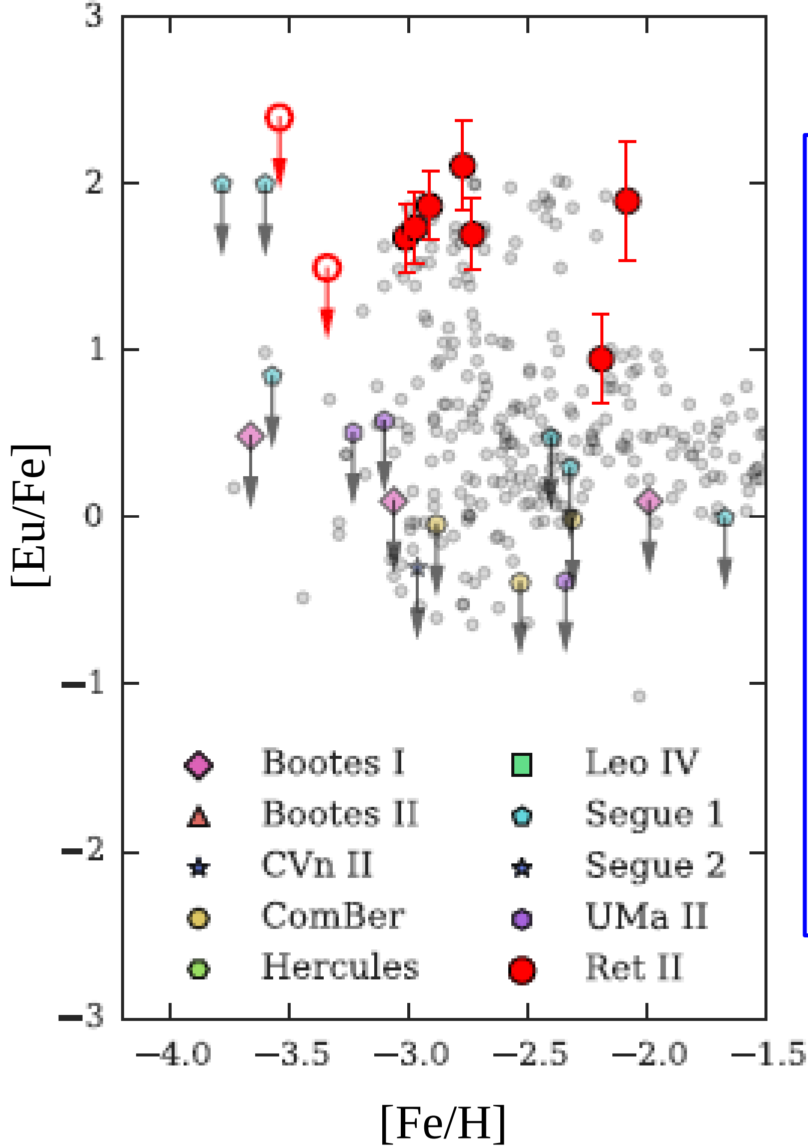
[Fe/H] ⟶ Galactic Time

[Fe/H] ⟶ Galactic Time

Universality in Ultra-Faint Dwarf Galaxy, Ret. II

Alexander P. Ji, Anna Frebel, Anirudh Chiti, Joshua D. Simon, Nature 531 (2016), 610

UFDG Ret II



R-Process site: SN (MHD-Jet) or NS-Merger ?

1. **Event Rate ?**

   (2.6 +/- 0.2)x10^3 $M_\odot$

   → ~10 SNe

   → less than 0.01~0.28 NSM !

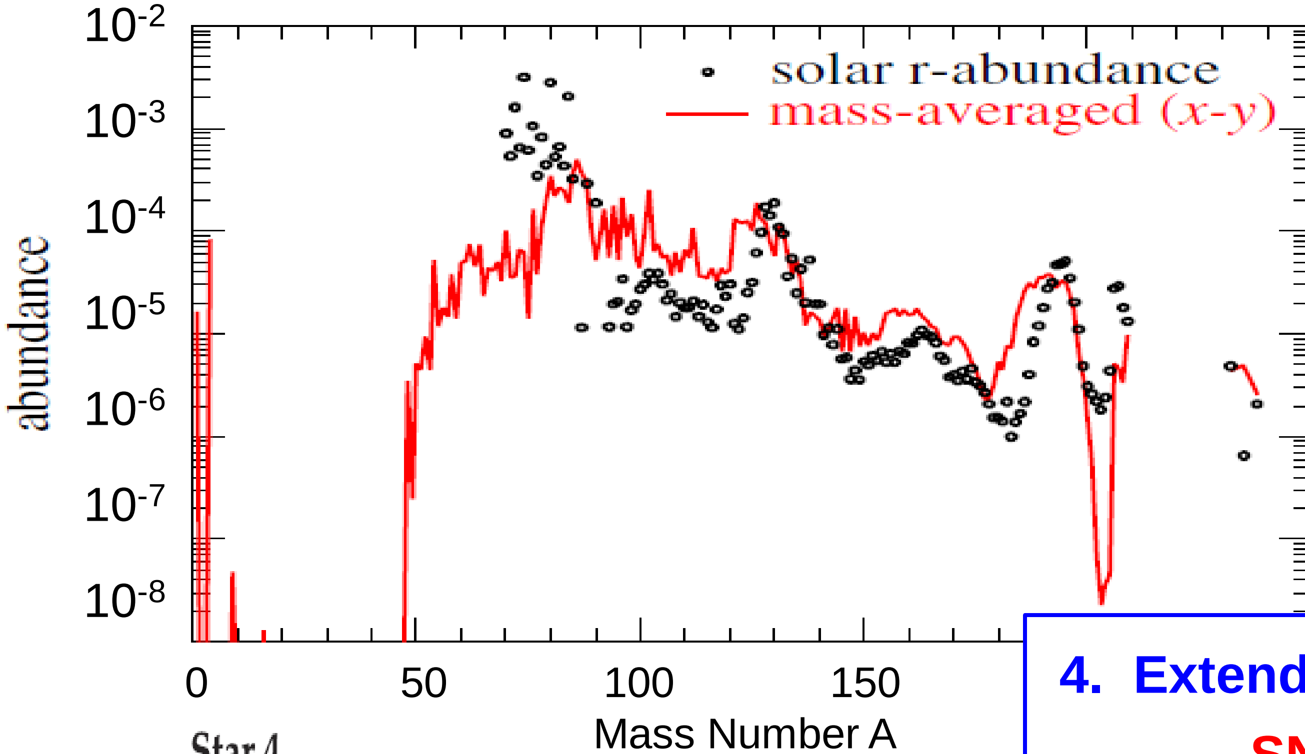
   SN ? NSM ?

2. **UFDG, very old with [Fe/H] = -3 ?**

   SN ! NSM ?

3. **Ejecta stops in shallow grav. pot ?**

   SN ! NSM ?

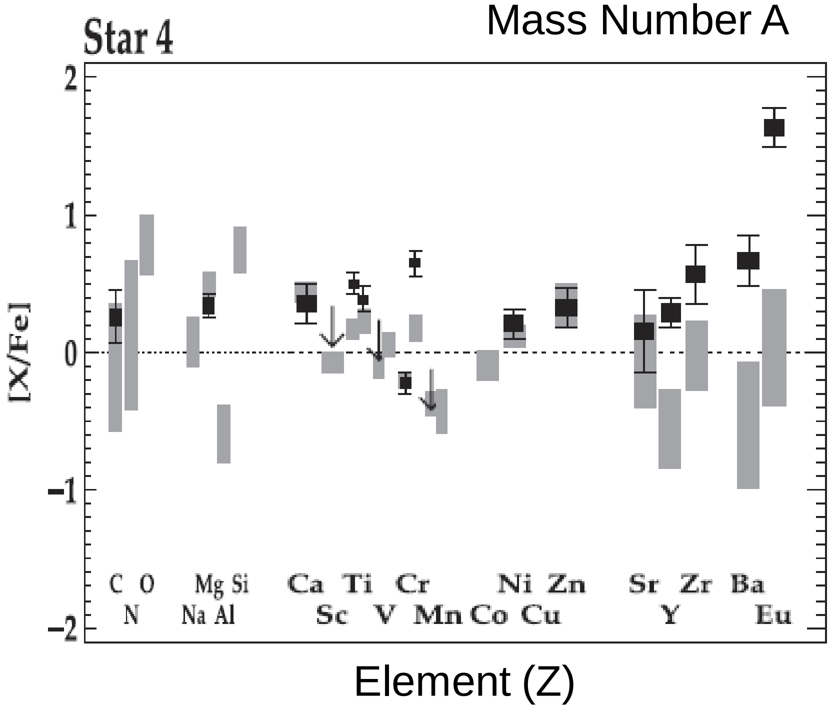


NSM R-Process cal.:
S. Wanajo et al.,
ApJ. 789 (2014), L39.

No Production of
Light Elements A < 50!

4. Extended Universality ?

SN ! NSM ?



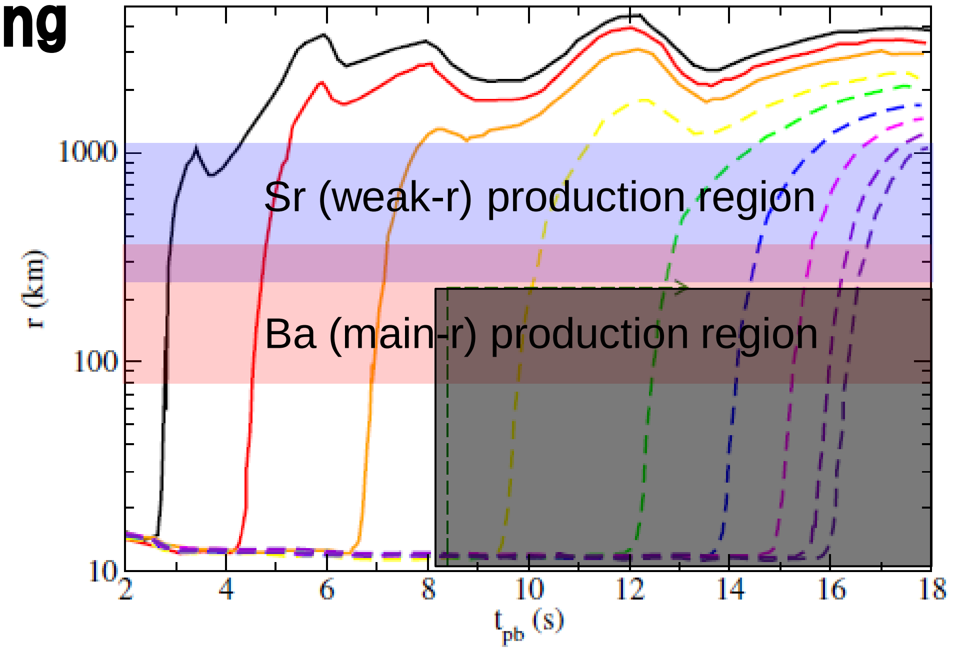
Ian U. Roederer et al., ApJ. 151 (2016), 82.

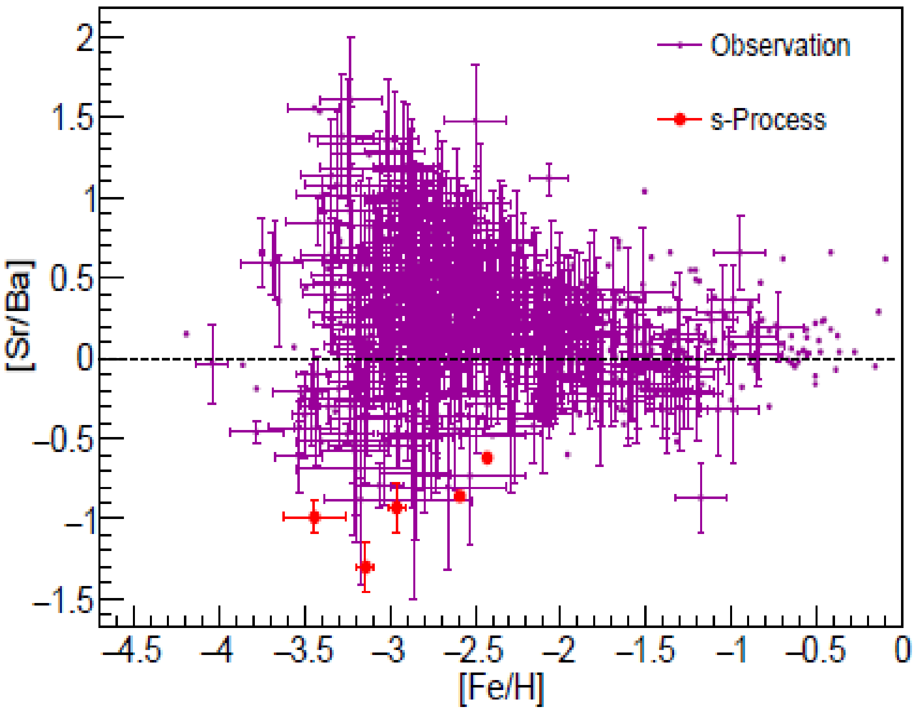
Extended Universality, found in
C Mg Ca ---Fe Ni Zn --- R-elements

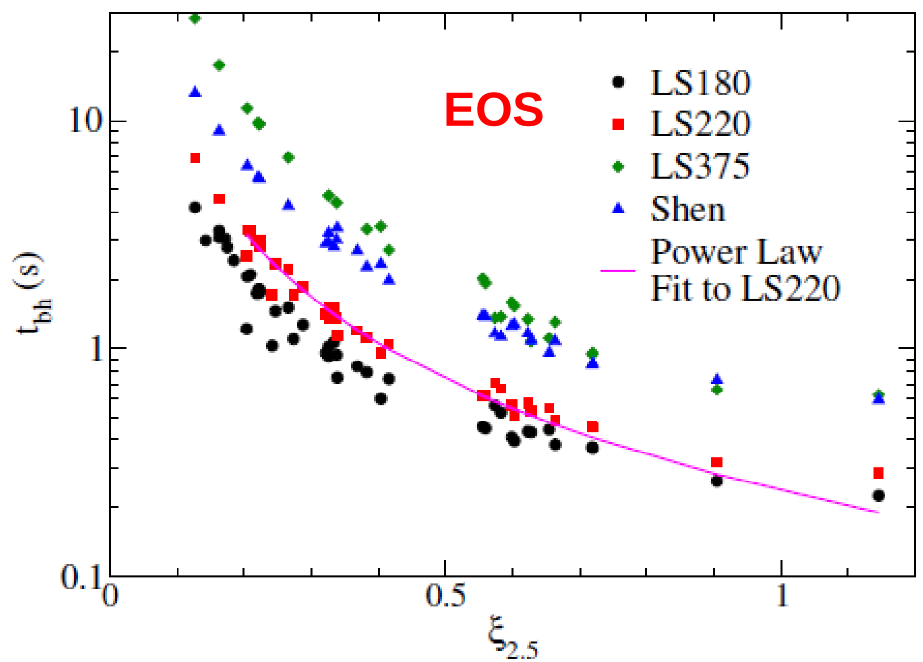
Dispersion due to Turbulent Mixing in individual SN Ejecta

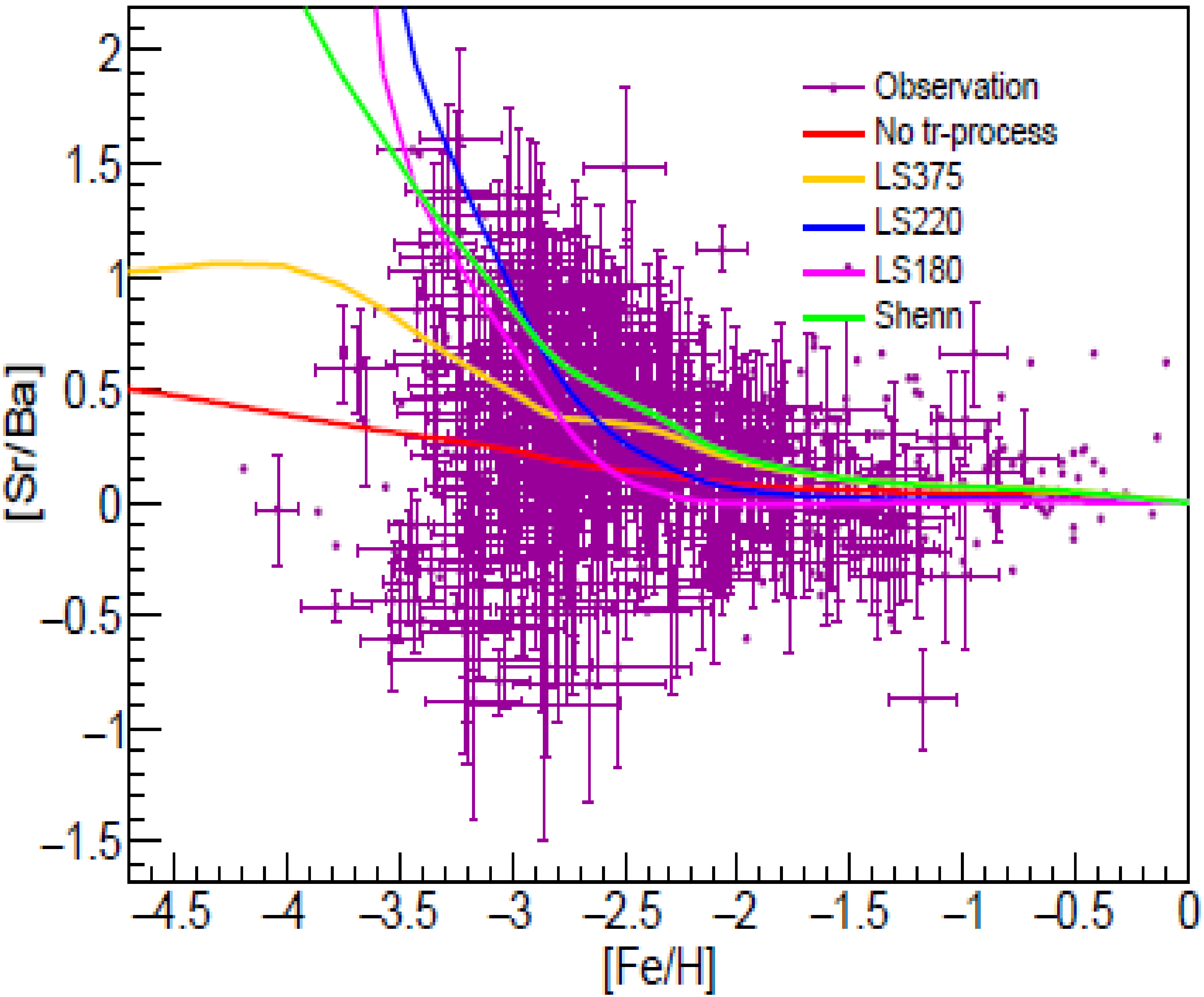
Dependence of the r-element dispersion on **EOS** in Metal-Poor Halo Stars

Famaiano, Kajino, Aoki and Suda, ApJ (2016), submitted.

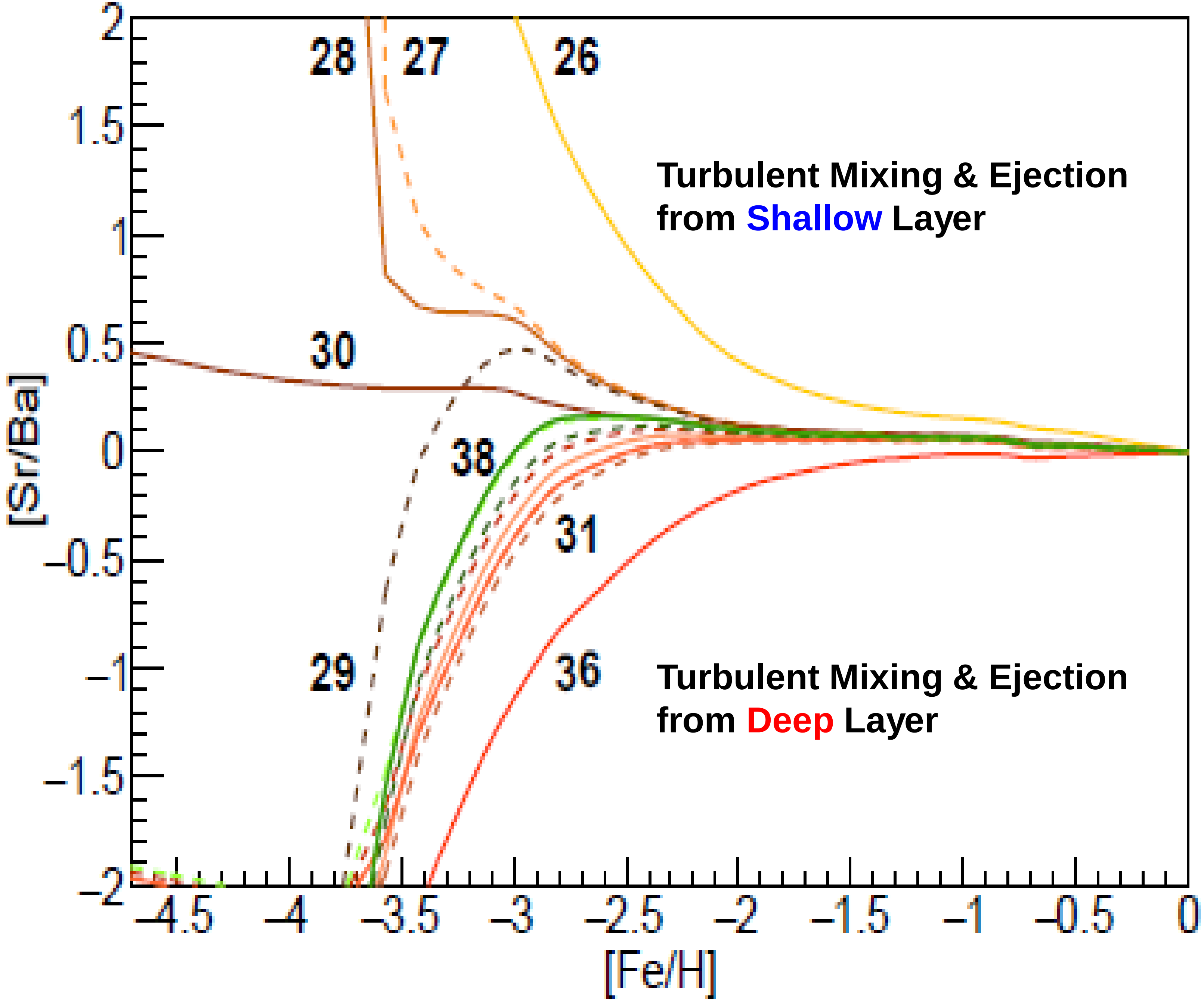








Observation
No tr-process
LS375
LS220
LS180
Shenn
[Sr/Ba]
[Fe/H]
2
1.5
1
0.5
0
−0.5
−1
−1.5
−4.5
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0

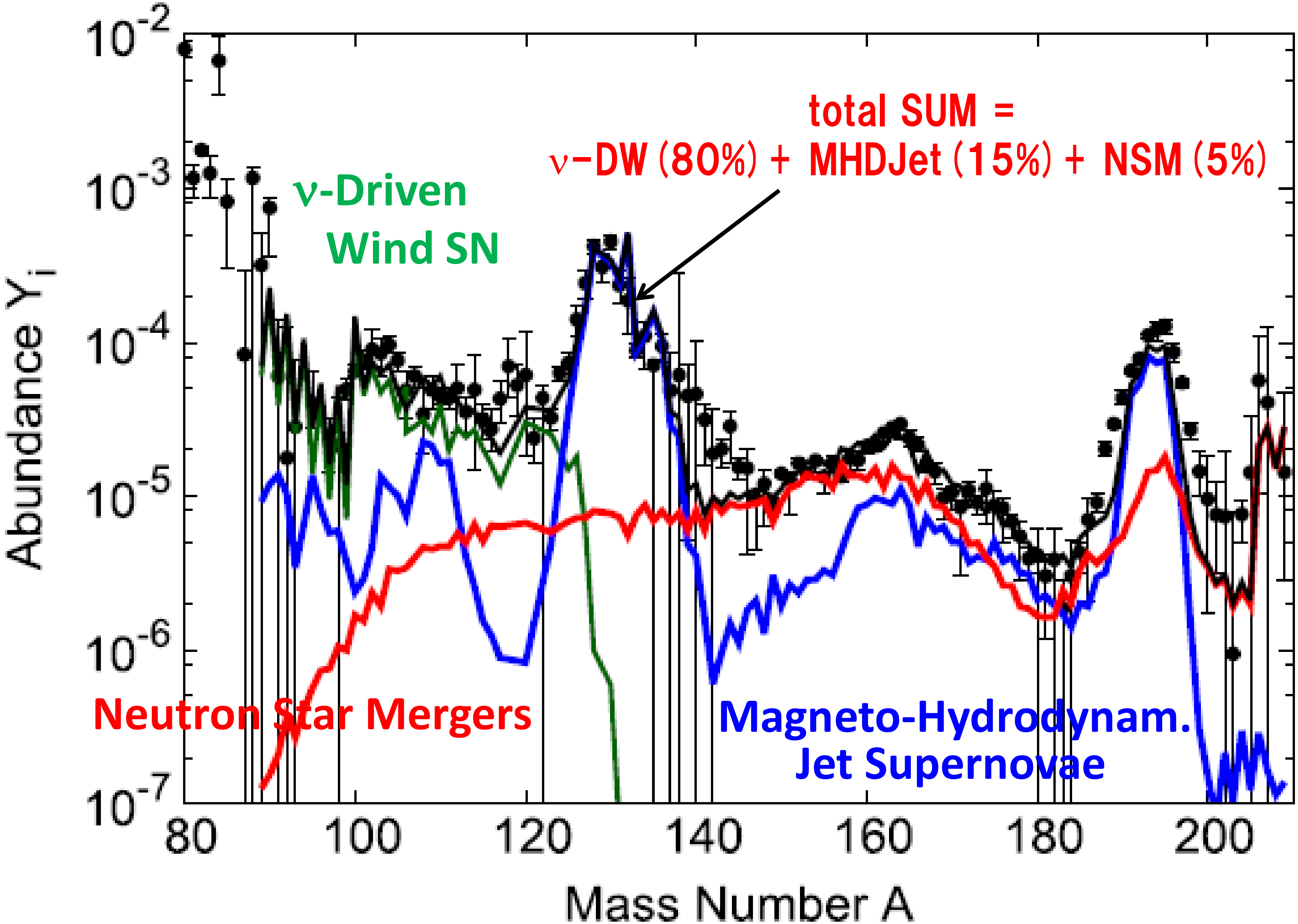


28
27
26
30
38
31
29
36
Turbulent Mixing & Ejection
from Shallow Layer
Turbulent Mixing & Ejection
from Deep Layer
[Sr/Ba]
[Fe/H]
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−4.5
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0

Solar System r-Process Abundance

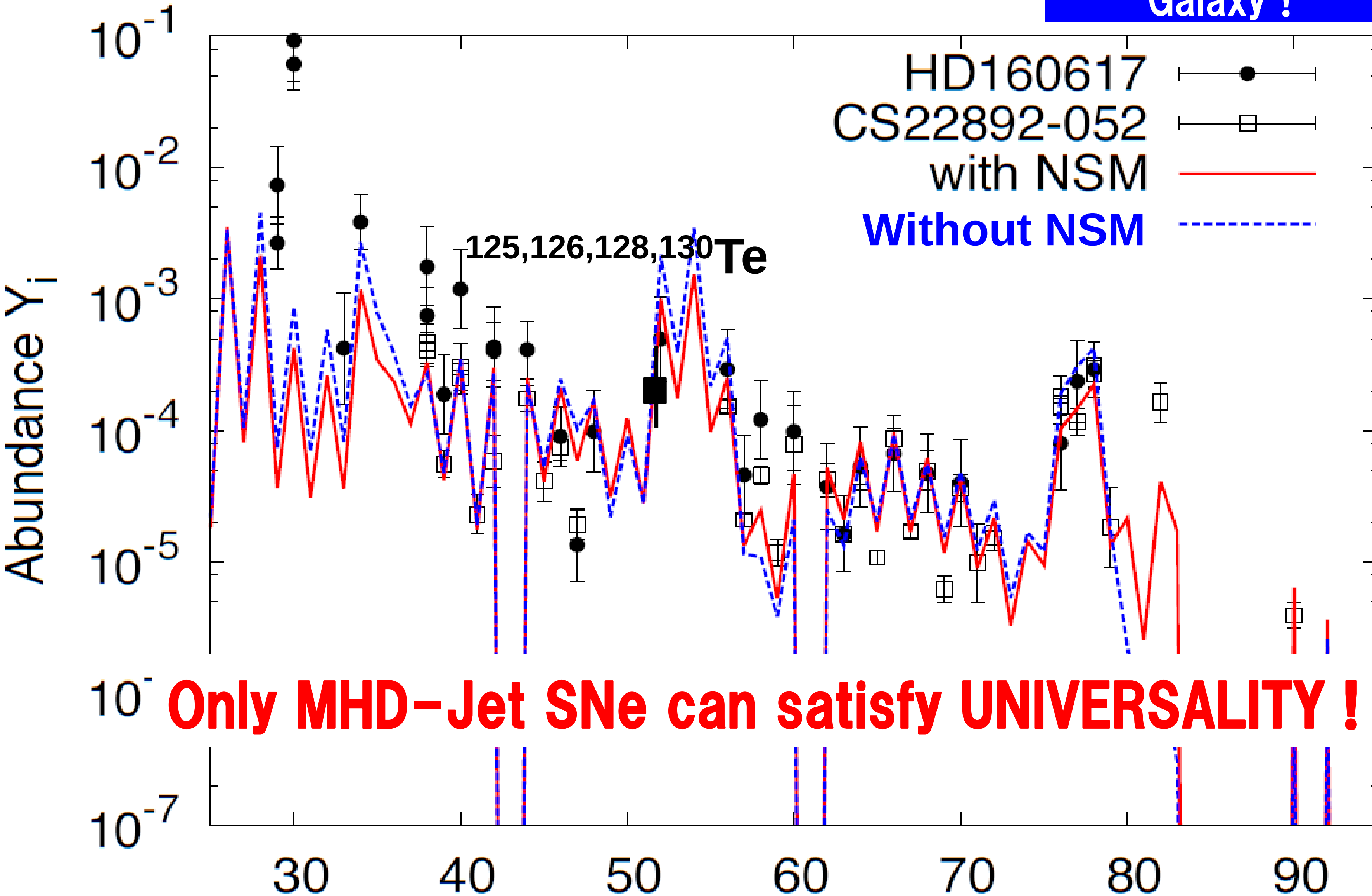
Today !

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



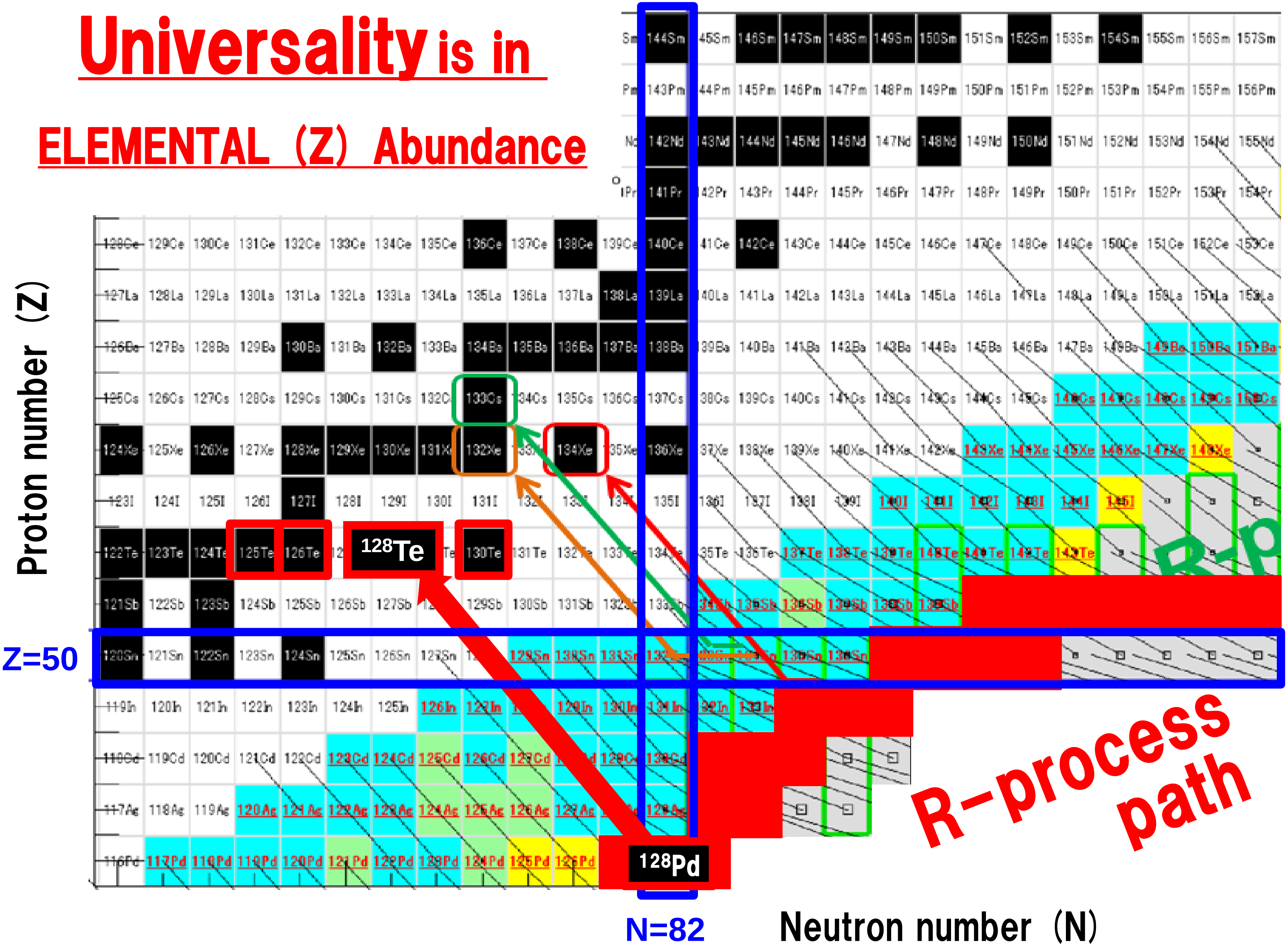
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2015),), ApJ 816, 79. COSNAP + RIKEN Collab.

EMPs in the Early Galaxy !



Astron. obs. cannot separate isotopes ! **Atomic Number Z** **ELEMENTAL !**

Universality is in ELEMENTAL (Z) Abundance



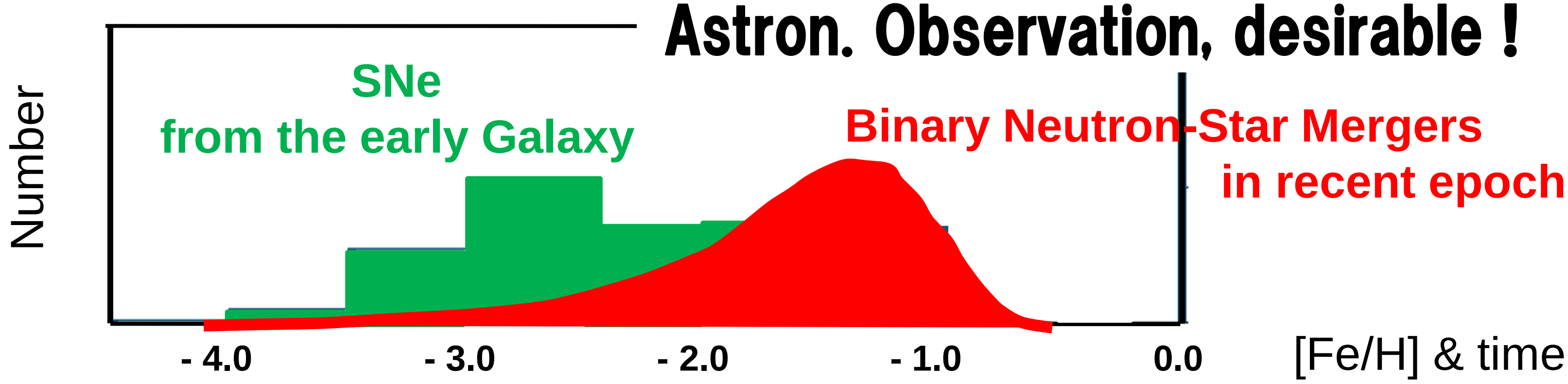
Relative Contributions (ν-SNe : MHD Jets : NSMs) from Observed Galactic event rates !

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	$((0.03\pm0.02) \times (1.9\pm1.1))$ [b]
Binary NSMs	=	$(2\pm1) \times 10^{-2}$	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).

Astron. Observation, desirable !



SUMMARY

Relic Supernova Neutrinos

- Failed-SNe can solve both SN RATE & RSG PROBLEMS simultaneously.
- RSN-ν detection would indicate EOS of neutron stars ν-MASS HIERARCHY.

Origin of R-Process Elements

- Core-collapse (MHD Jet) SNe satisfy UNIVERSALITY from the early Galaxy.
- Time-Scale Problem:
  Binary NSMs have arrived later at $100\mathrm{My} < \tau_c$ and the solar-system abundance consists of both SN & NSM r-process elements.
- Dispersion Problem:
  Abundance Scatter/Dispersion arises from 1) Galactic stellar inhomogeneity for both SNe and NSMs and 2) Turbulent Mixing in SN Ejecta.