International Workshop on Physics of Rare-RI Ring
RIKEN, November 10-12, 2011

R-Process in Gamma-Ray Bursts

★ Supernovae & Gamma-ray Bursts are the most energetic promoters of the Galactic evolution.

★ They explosively create many atomic nuclides.

★ **R-PROCESS ELEMENTS ?**

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PURPOSE

To elucidate the Power of Interdisciplinary Research Collaboration and Synergy among Nuclear Physics-Astronomy-Astrophysics to understand the Galactic Evolution and the the R-process.

OUTLINE

- **Astronomical Observation of R-Process Elements**

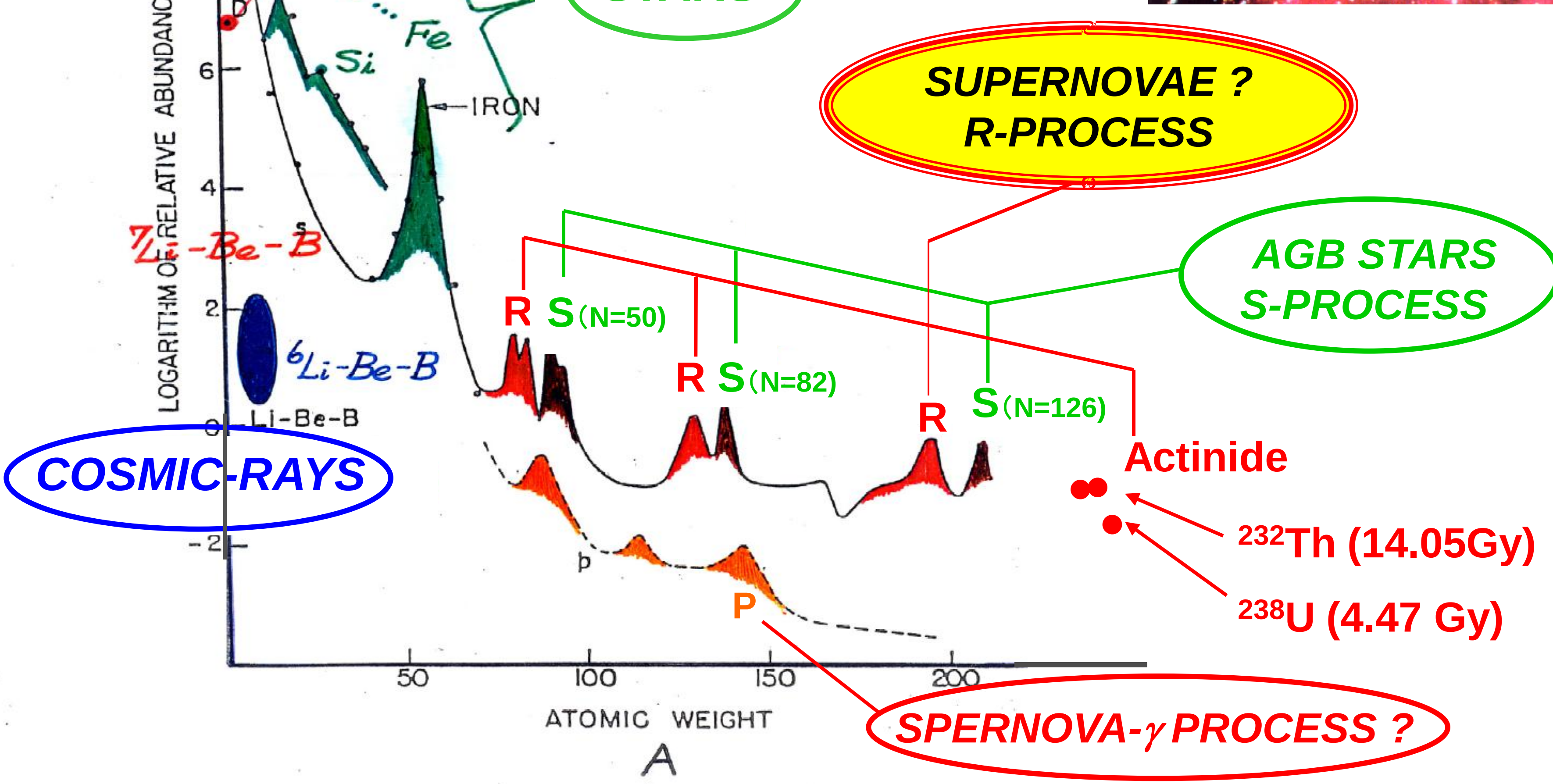
- **Nuclear Physics of the R-Process**

- **Neutrino Pair-heated Collapsar Model for the GRBs for the R-Process**

- **Recent RIKEN Data of β-Half Lives and R-Process**

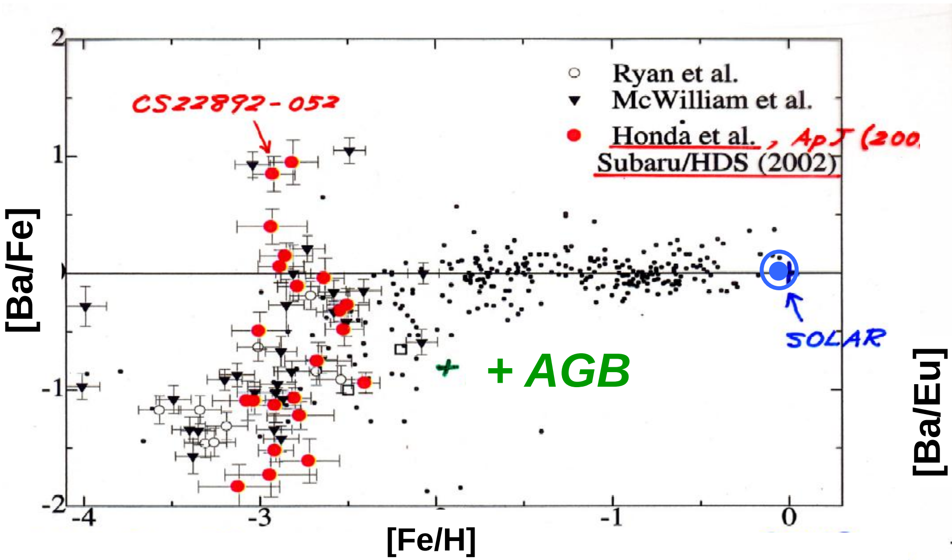
→ **next talk by Shunji Nishimura**

Solar System Abundance

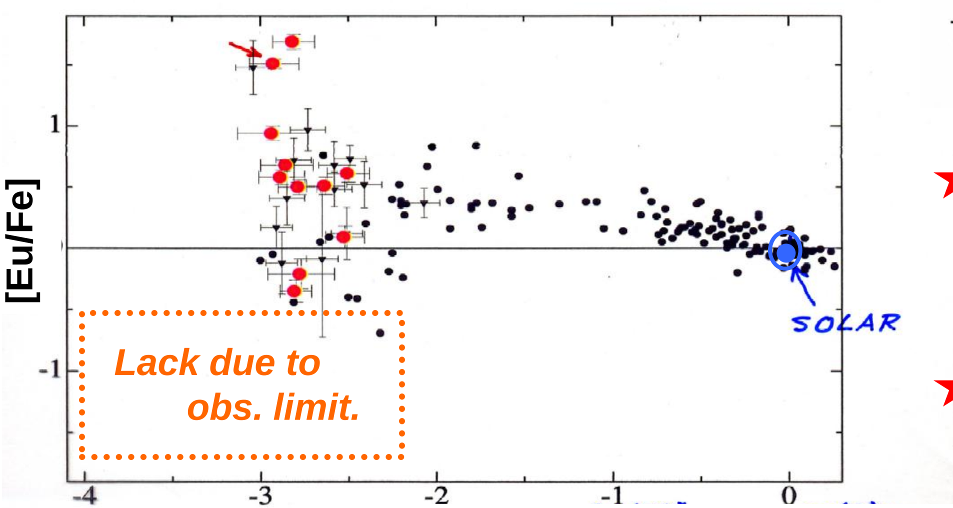


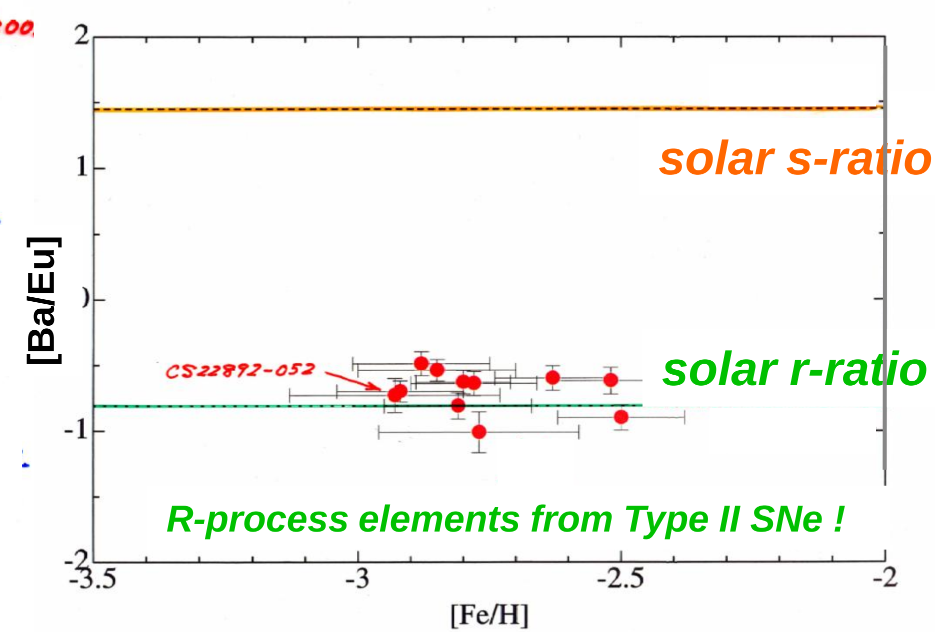
SUBARU Telescope HDS

Honda, Aoki, Kajino et al.
(SUBARU/HDS Collaboration),
2004, ApJS 152, 113; 2004, ApJ 607, 474



SN II → ← SN I + II →





★ Large abundance scatter at [Fe/H]<-2 is an evidence for INDIVIDUAL supernova episode.

★ Only Core-Collapse TYPE II SUPER-NOVAE are the likely astrophysical sites of the R-Process !

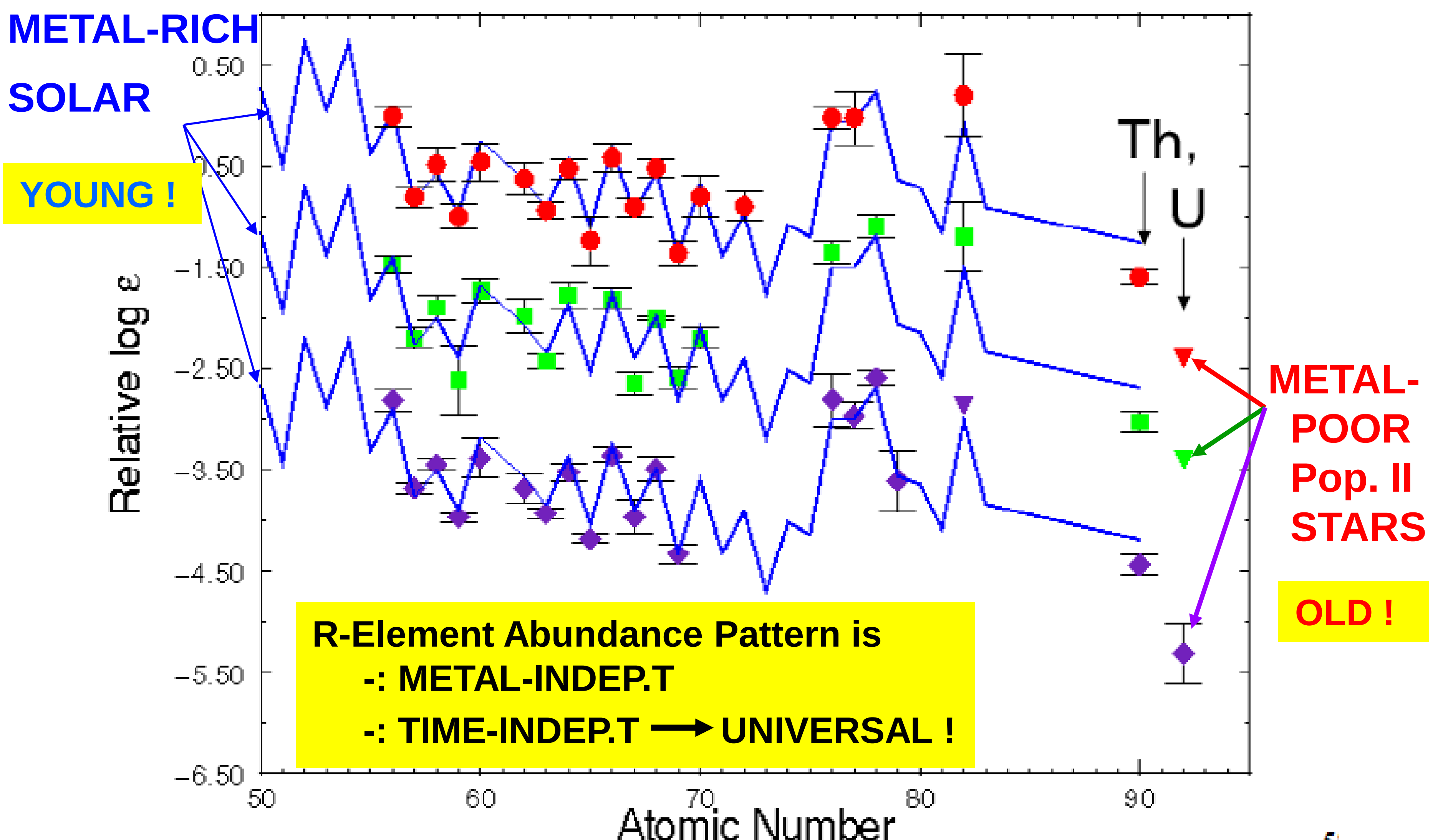
Early Universe ←

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

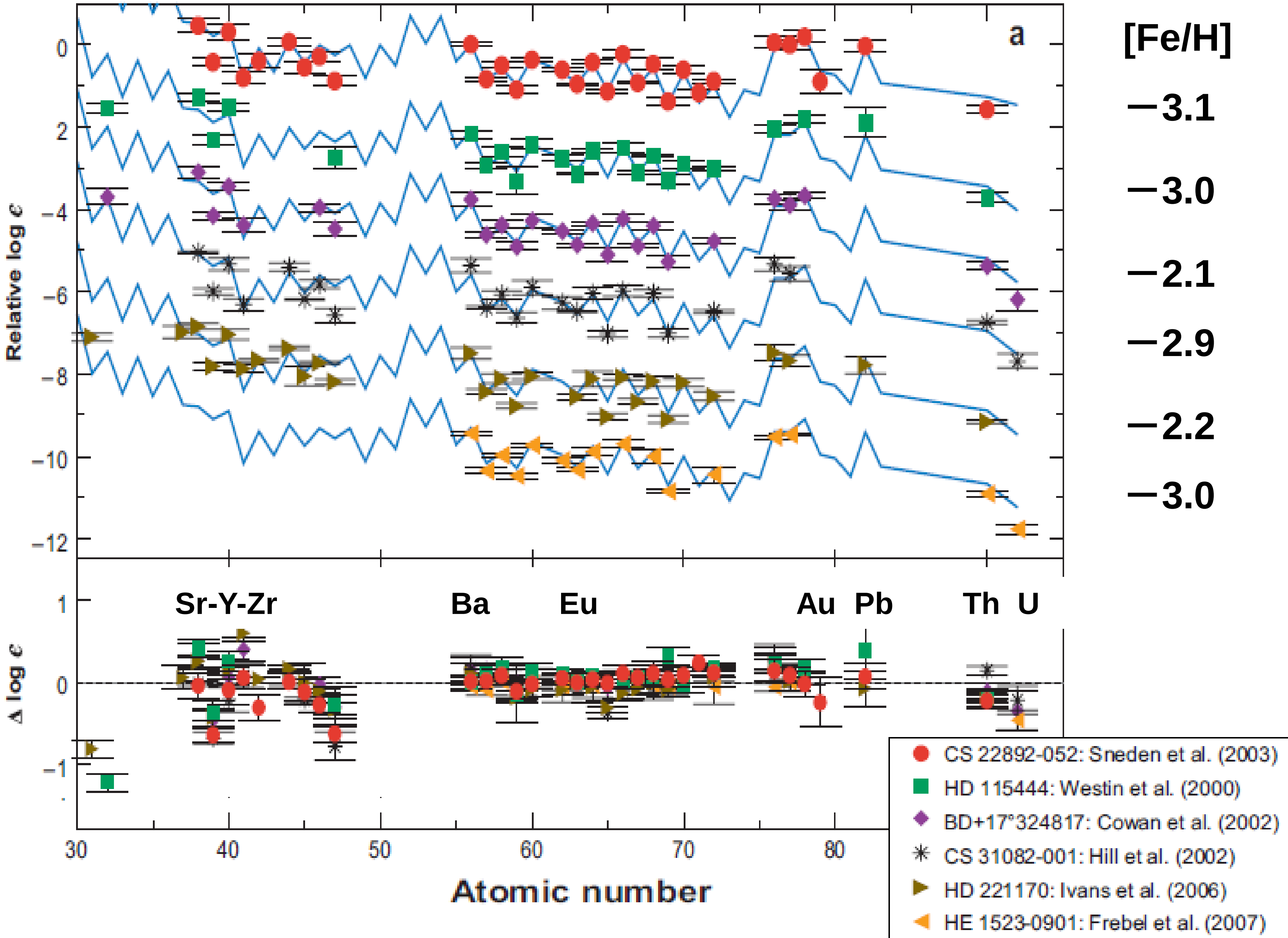
UNIVERSALITY OF R-ELEMENT ABUNDANCES

Sneden et al. (1996 – 2005)

Honda, Aoki, et al.
(SUBARU-HDS), 2004, ApJS 152, 113.

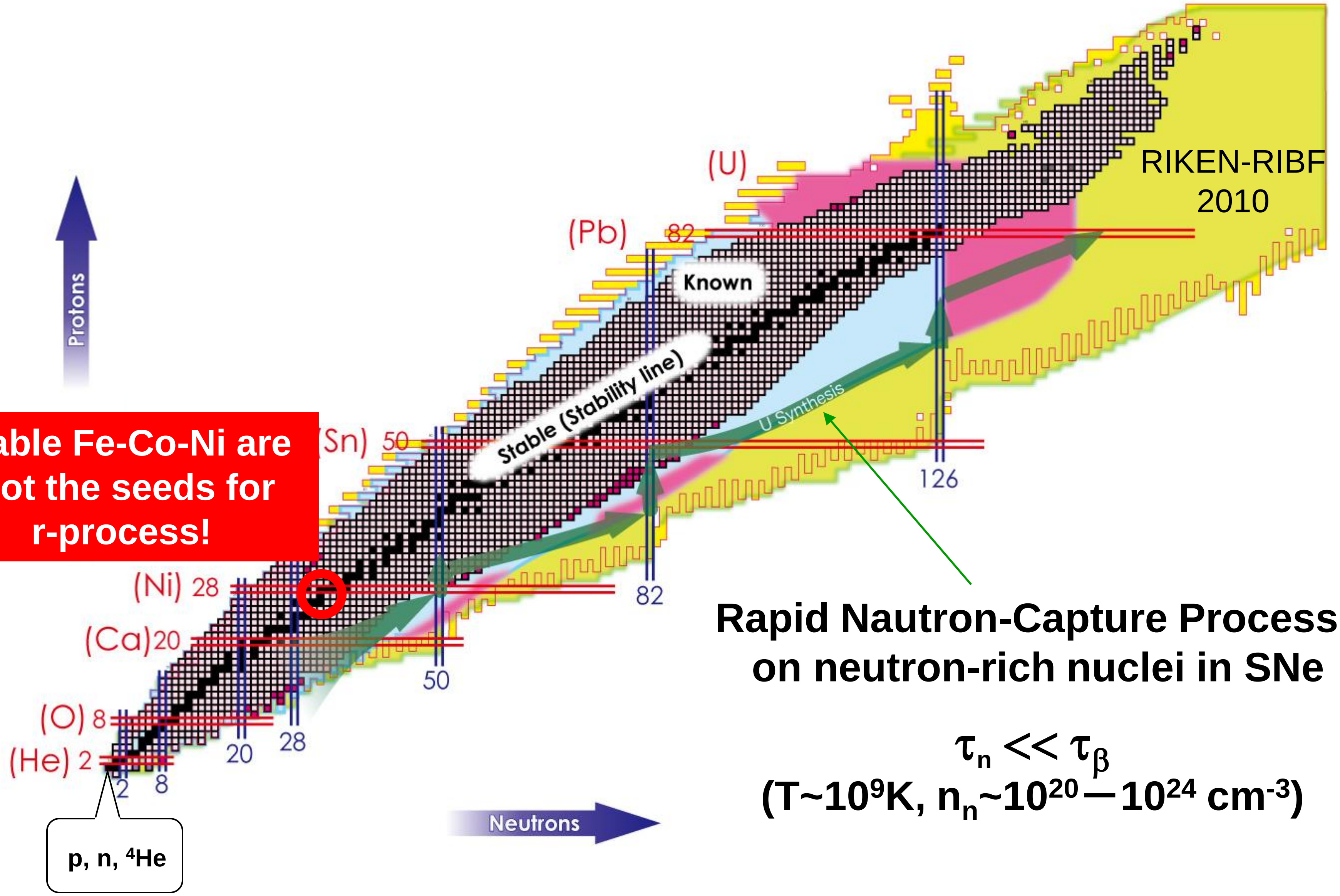


Sneden, Cowan, Gallino, ARAA 46 (2008) 241.



Magic Number and Neutron-Capture Processes

From Text Book (Kubono & Kajino)



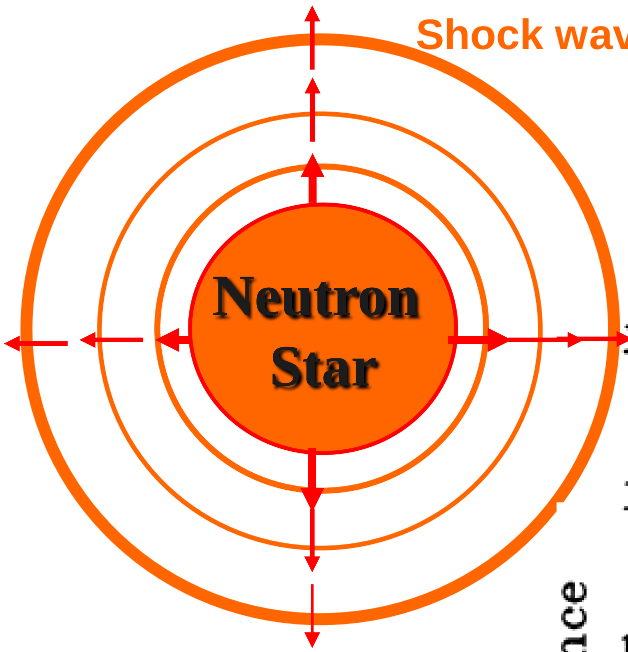
Stable Fe-Co-Ni are not the seeds for r-process!

Rapid Nautron-Capture Process on neutron-rich nuclei in SNe

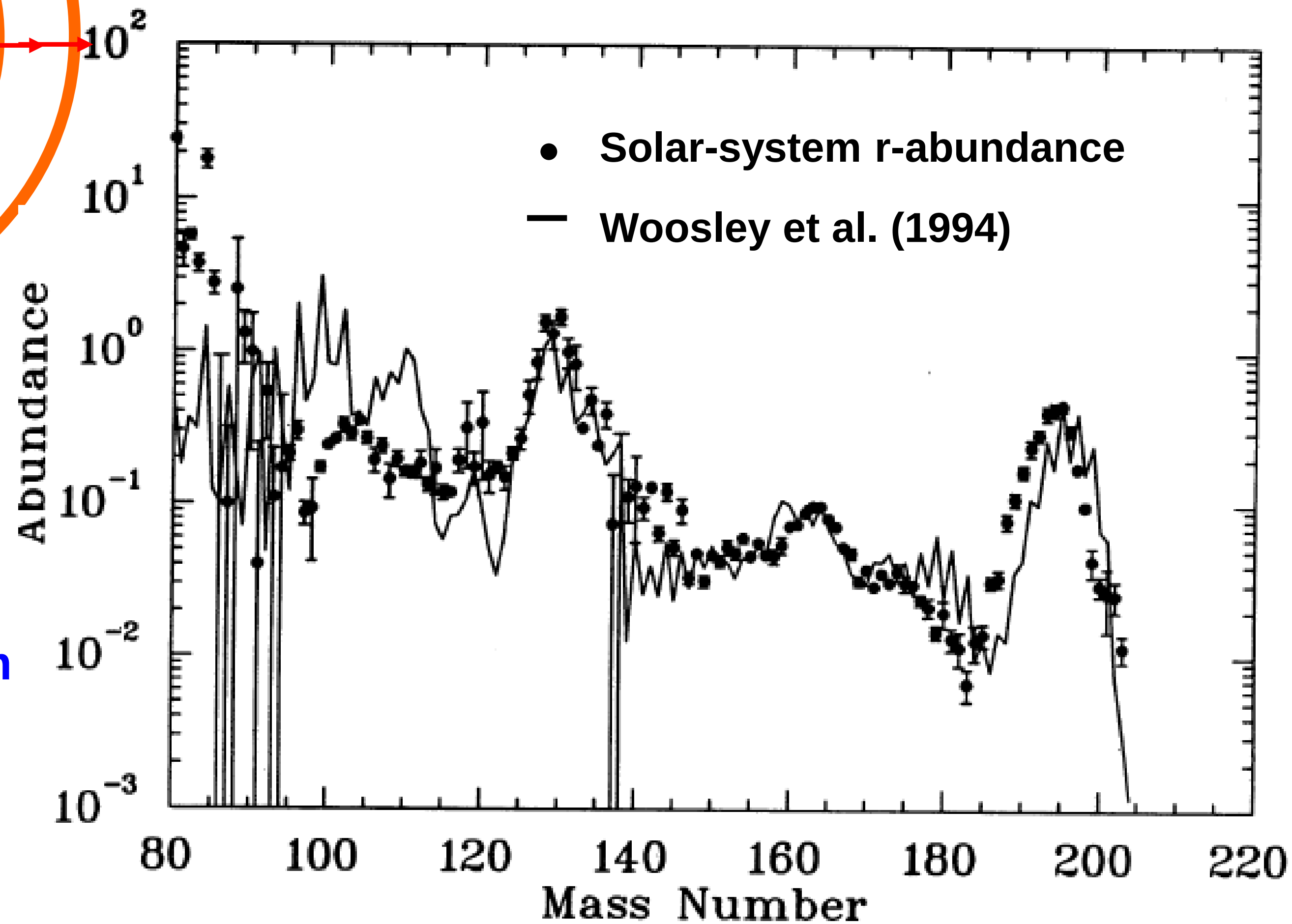
$$\tau_n << \tau_\beta$$

($T \sim 10^9$K, $n_n \sim 10^{20} - 10^{24}$ cm^{-3})

(a) Neutrino-Driven Wind



Woosley, Wilson, Mathews, et al., ApJ 433 (1994), 229.
Meyer, Mathews, Hoffman, Woosley, ApJ 399 (1992), 656.
Otsuki, Tagoshi, Kajino, & Wanajo, ApJ 533 (2000), 424.
Wanajo, Kajino, Mathews, Otsuki, ApJ 554 (2001) 557.
Terasawa, Sumiyoshi, Kajino, et al., ApJ 562 (2001) 470.



- Universality !
- 2nd, REH & 3rd peaks!
- Right total solar-system r-element abundance !

- No explosion model !!

Neutrino-driven Wind Model explains UNIVERSALITY !

Otsuki, Tagoshi, Kajino & Wanajo
2000, ApJ 533, 424
Wanajo, Kajino, Mathews & Otsuki
2001, ApJ 554, 578

t = 0

Neutrino-driven wind forms right after SN core collapse.

n + α + p

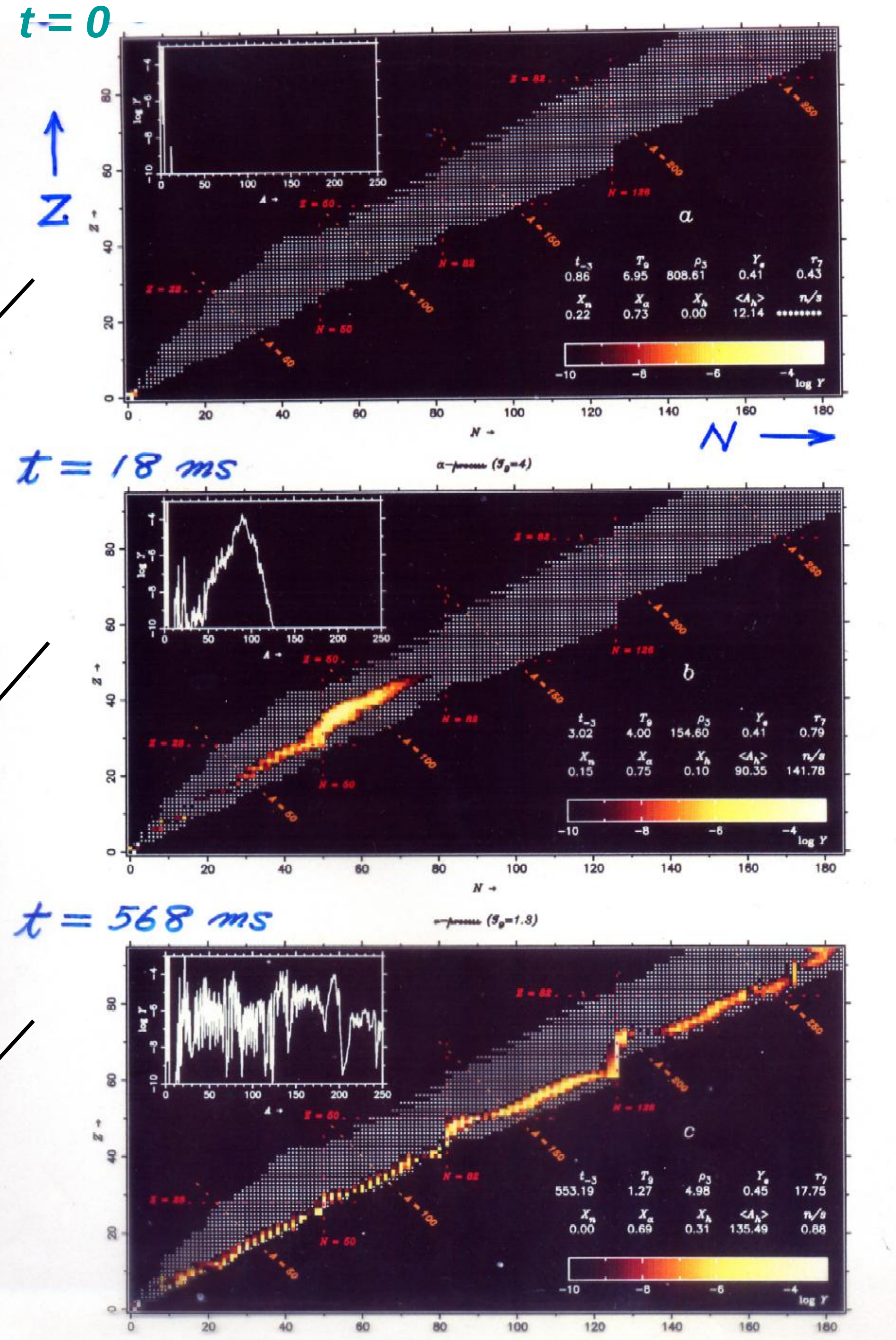
t = 18 ms

Seeds form.

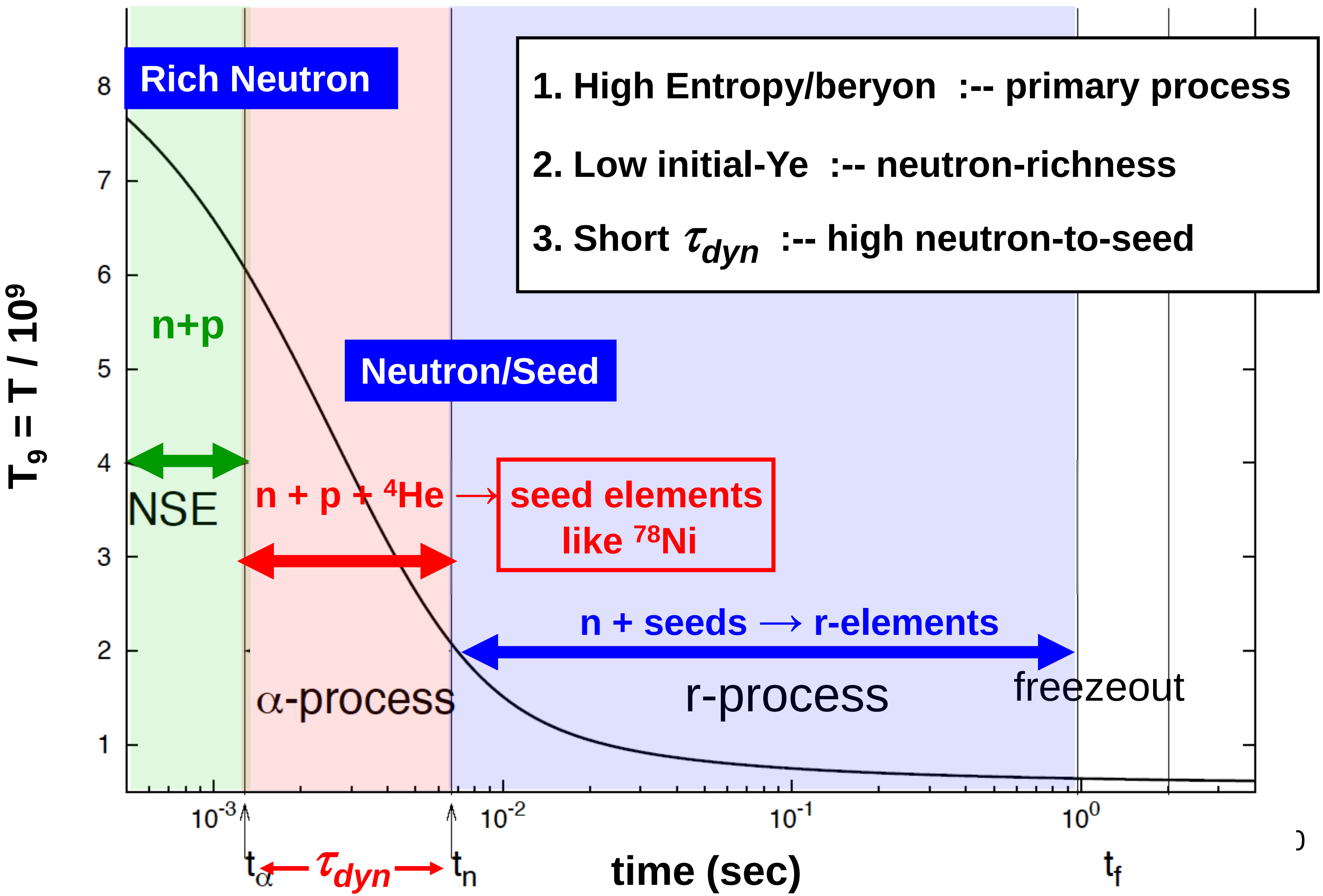
Exotic neutron-rich; ^{78}Ni

t = 568 ms – 1 s

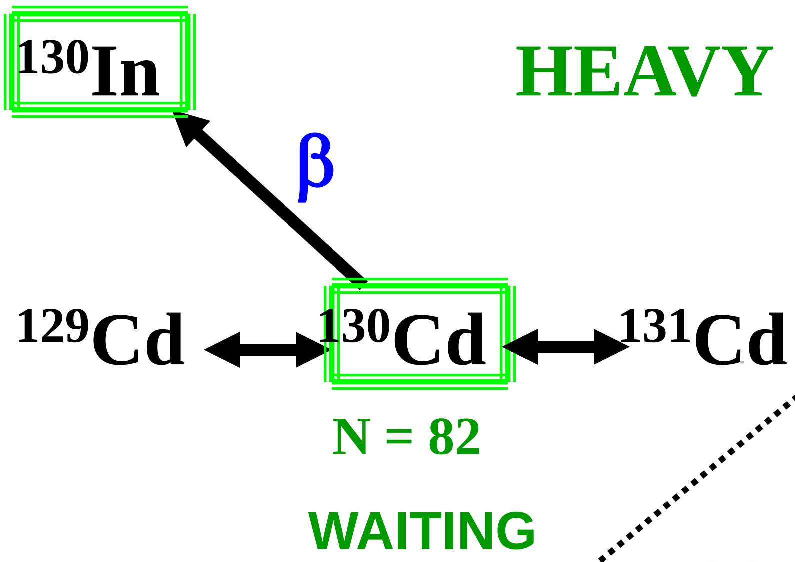
Heavy r-elements form.

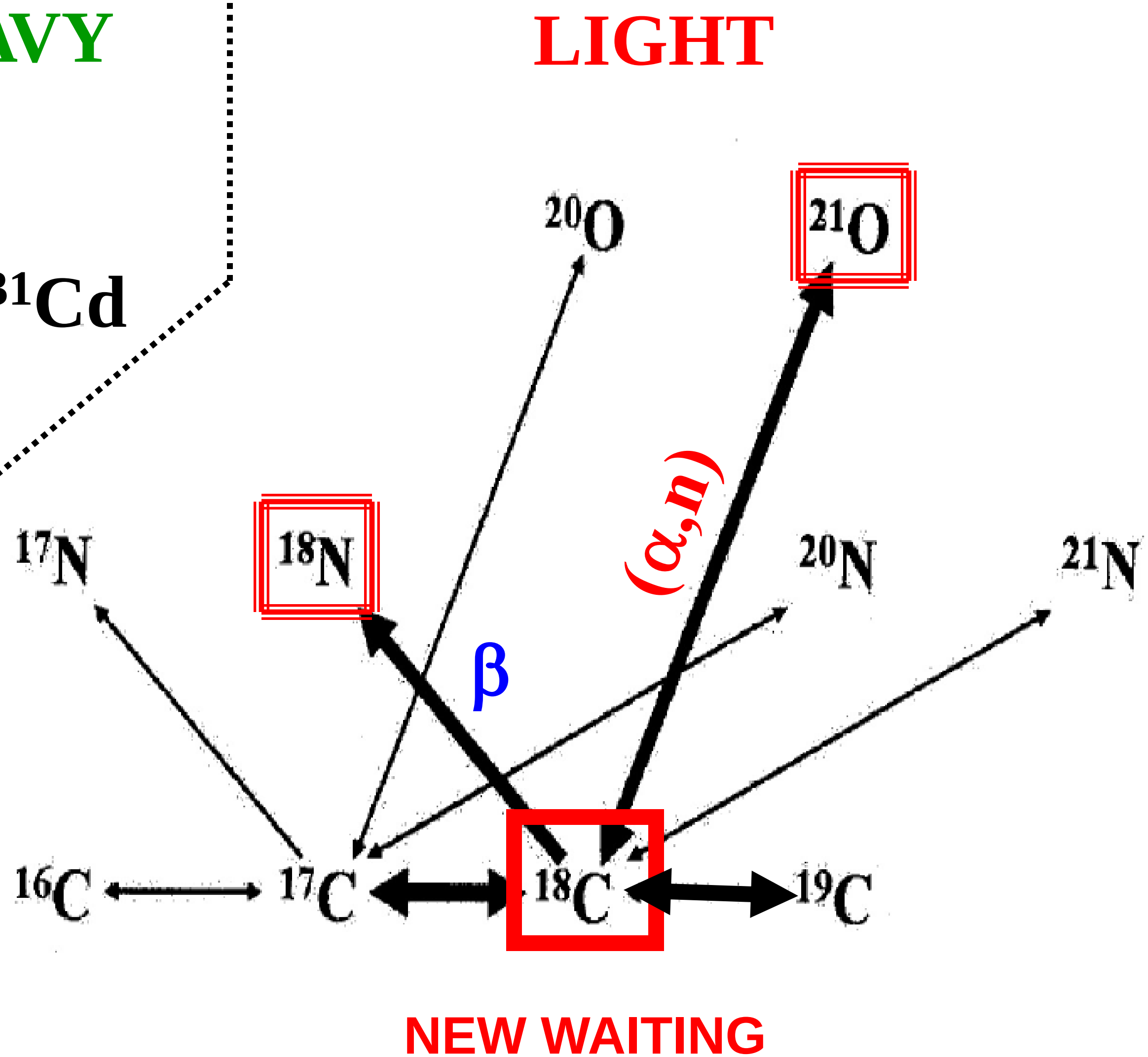


Nucleosynthesis proceeds: NSE → α-process → r-process



New Waiting Points in Light-Mass Nuclei





Both (n,γ) and (α,n) are FAST enough so that ^{18}C waits for β-decay.

Candidate Astrophysical Sites for R-Process

Supernova R-Process

from Ishiyama & Miyatake (2009)

Candidate	Physical Conditions			Expected Event Rate	Evaluation
	S	Ye	$M_r/(SN)$		
(a) ν-Driven Wind	~ 100	0.45	$10^{-5} M_\odot$	10^{-2}/yr/galaxy*	○ Solar-system r ! × No explosion model
(b) Binary Neutron Star Merger	~ 1	0.1	$10^{-2} M_\odot$	$<10^{-5}$	× Metal poor☆ ?
(c) MHD Jet	~ 10	0.1~0.4	$10^{-3} M_\odot$	$< 10^{-6}$	△ Explode, but special condition required?

Solar-System r-abundance = $10^3 M_\odot$

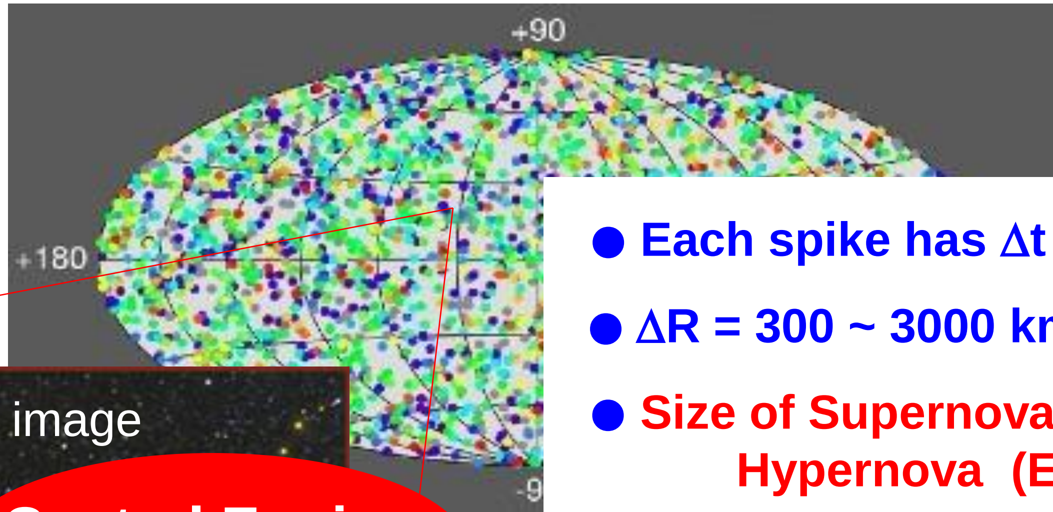
* Observed SN frequency

$10^{-5} M_\odot \times 10^{-2} \times 10^{10} = 10^3 M_\odot$

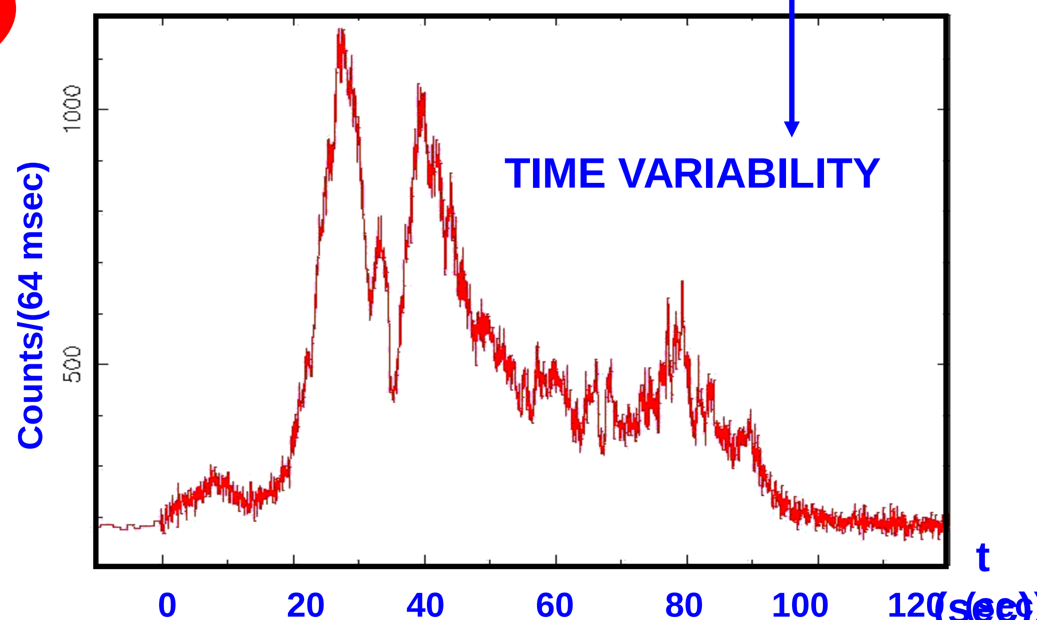
Cosmic age

There is another candidate of Gamma-ray Bursts !

GRBs are cosmological activities at high redshifts (0< z <6.6) in the early Universe.



- **Each spike has Δt = 1 ~ 10 ms.**
- **ΔR = 300 ~ 3000 km**
- **Size of Supernova-Core !**
  Hypernova (E/10^{51}erg ~ 10)



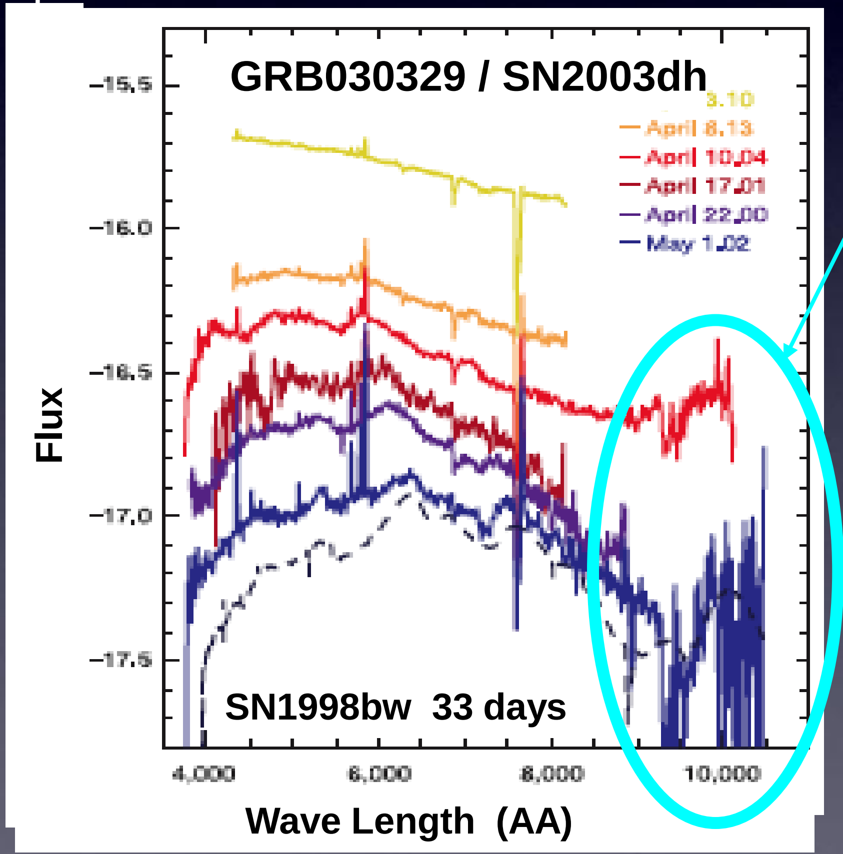
GRB - Hypernova Connection

Gamma-Ray Bursts (GRBs) cf. SNe: $E \sim 10^{51}$erg

➡ Some GRBs, associated with Hypernovae ($E \sim 10^{52}$erg)

➡ We expect completely different nucleosynthesis.

Spectral evolution



"GRB980425 / SN1998bw"
"GRB030329 / SN2003dh"
- H α, β, γ, δ - He α, He I
- N II - O II, III - Ne III - Si II

- GRB is an extra-galactic activity at high redshifts 0 < z < 6.6.

- Our Milky Way (z=0) is not a special Galaxy among many other galaxies.
- GRBs should have occurred in the early epoch of our Milky Way, too.

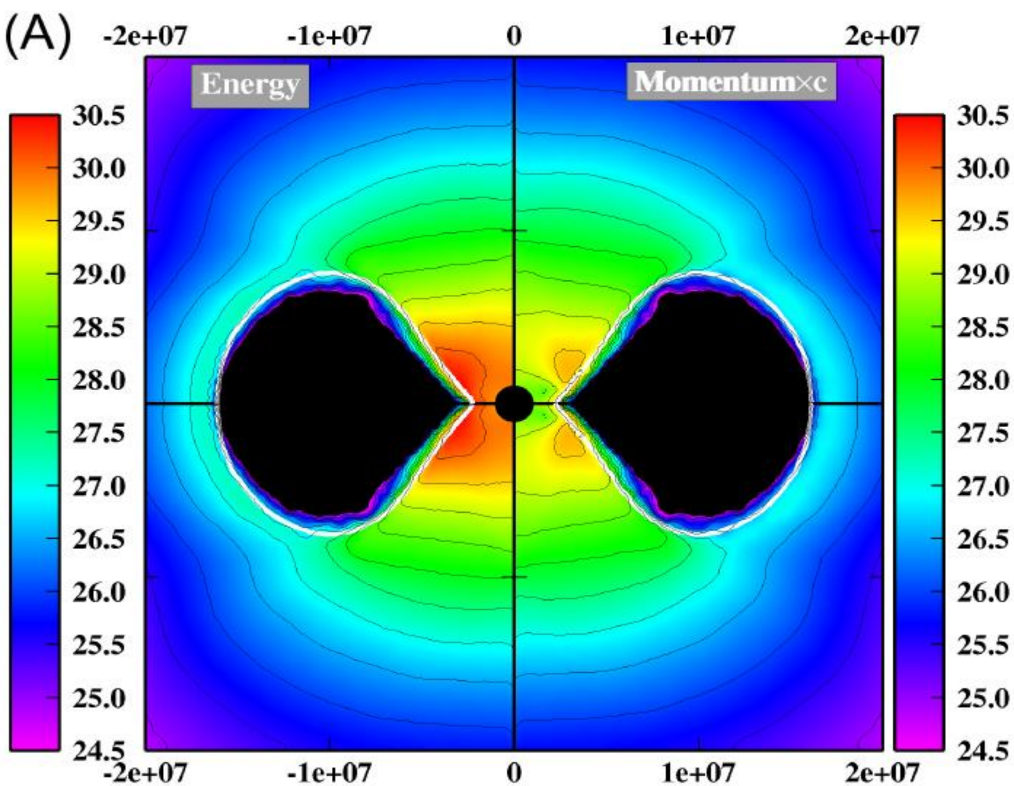
- GRB (1st Hypernova) affected early generation metal-poor Pop. II stars.

Gamma-Ray Bursts : 2D Hydrodynamic Model
Central Engine = Collapsar

Harikae et al., ApJ 704 (2009), 304; ApJ 720 (2010), 614; ApJ 713 (2010), 304.

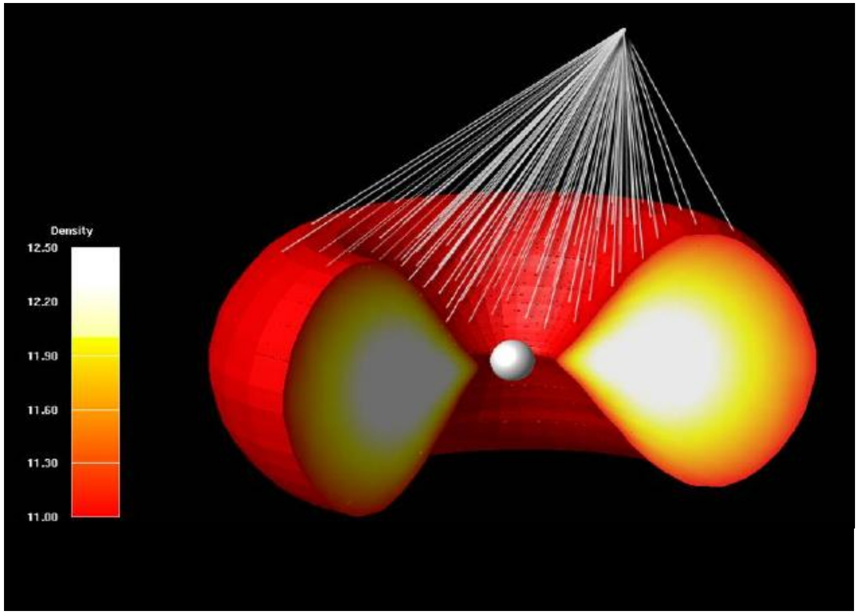
$$\frac{dq^{+}_{\nu\bar{\nu}}(r)}{dtdV} = \iint f_{\nu}(p_{\nu}, r) f_{\bar{\nu}}(p_{\bar{\nu}}, r)\sigma|v_{\nu} - v_{\bar{\nu}}|(\epsilon_{\nu} + \epsilon_{\bar{\nu}})d^3p_{\nu}d^3p_{\bar{\nu}}$$

Energy production **Momentum transfer**



200 km 0 200 km

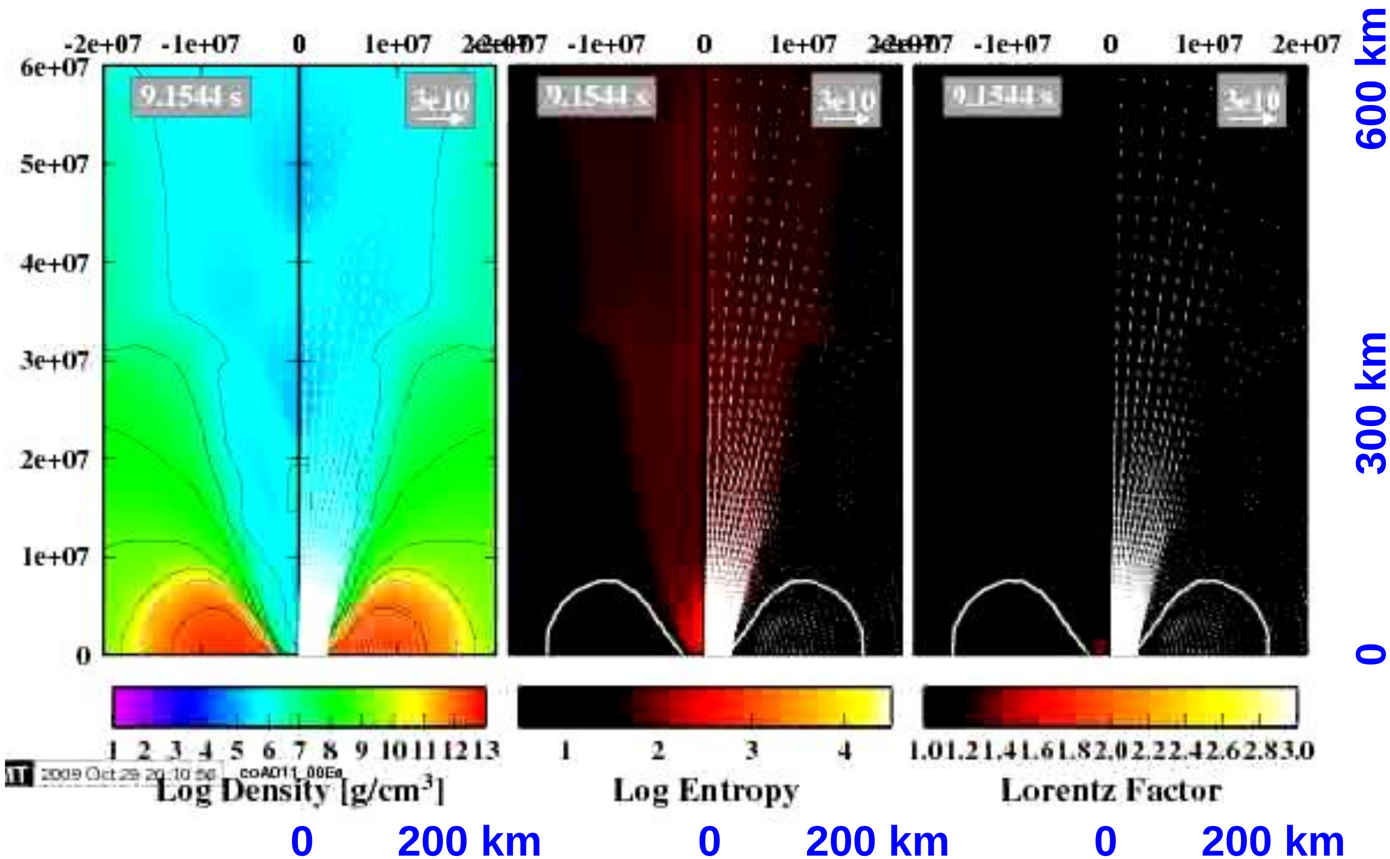
Neutrino Pair-Annihilation



Ray-tracing neutrino pair-annihilation when time scale of neutrino heating is shorter than dynamical (free-fall) time.

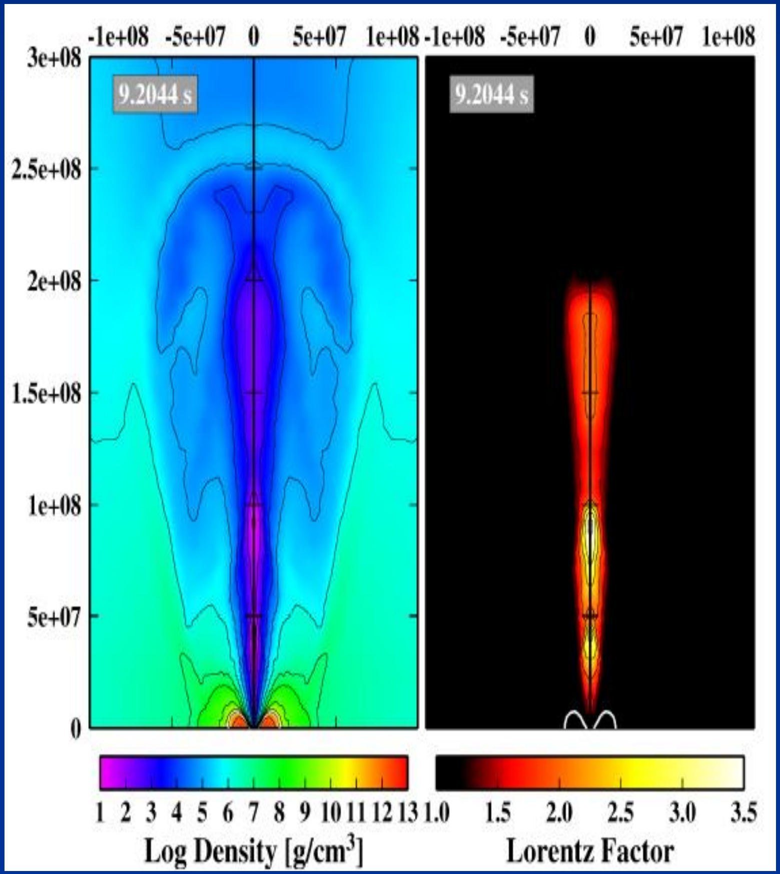
Neutrino Pair-Heating Wind → High Entropy

Density **Entropy/Baryon** **Lorentz Factor (in linear scale)**



Properties of Wind Outflow

Harikae et al., ApJ 704 (2009), 304; ApJ 720 (2010), 614; ApJ 713 (2010), 304,
Nakamura Sato, Kajino and Mathews (2011), ApJ, submitted.



At the edge of Iron-Core ~3000km

- $\rho \sim 10^3$ g/cm^3 (High density)
- $S/k \sim$ 100-1000 (High entropy)
- $Y_e < 0.5$ (Neutron rich)
- $\Gamma > 2.0$ (Relativistic flow)

Kinetic Energy Production

$dE/dt > 4 \times 10^{49}$ erg/s

⬇

Possible GRB candidate !

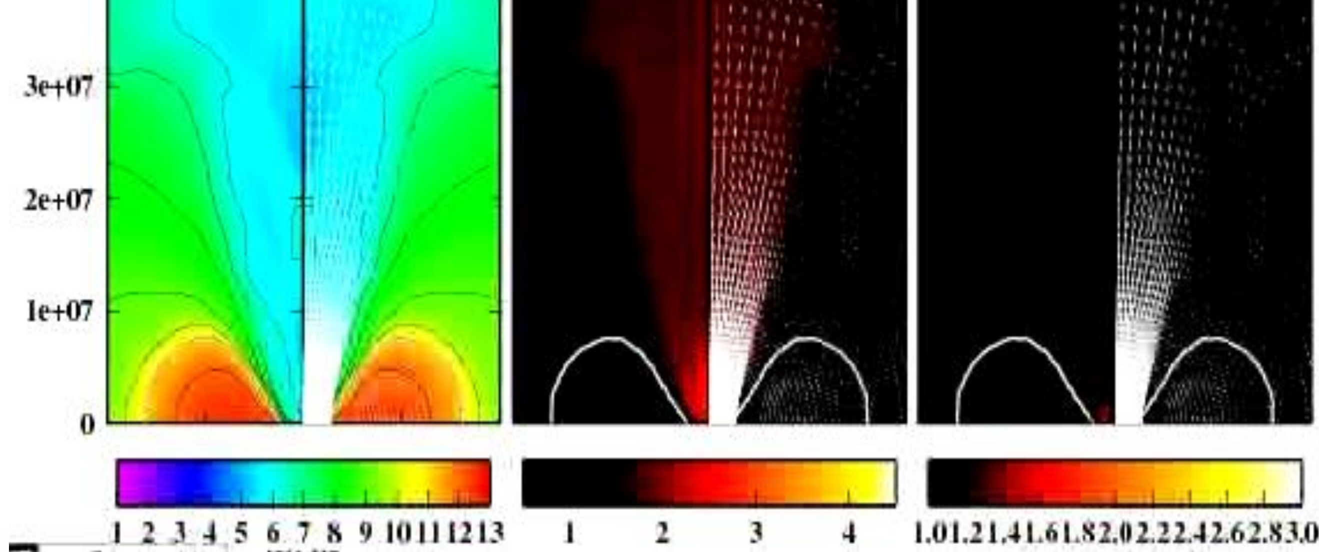
R-Process !?

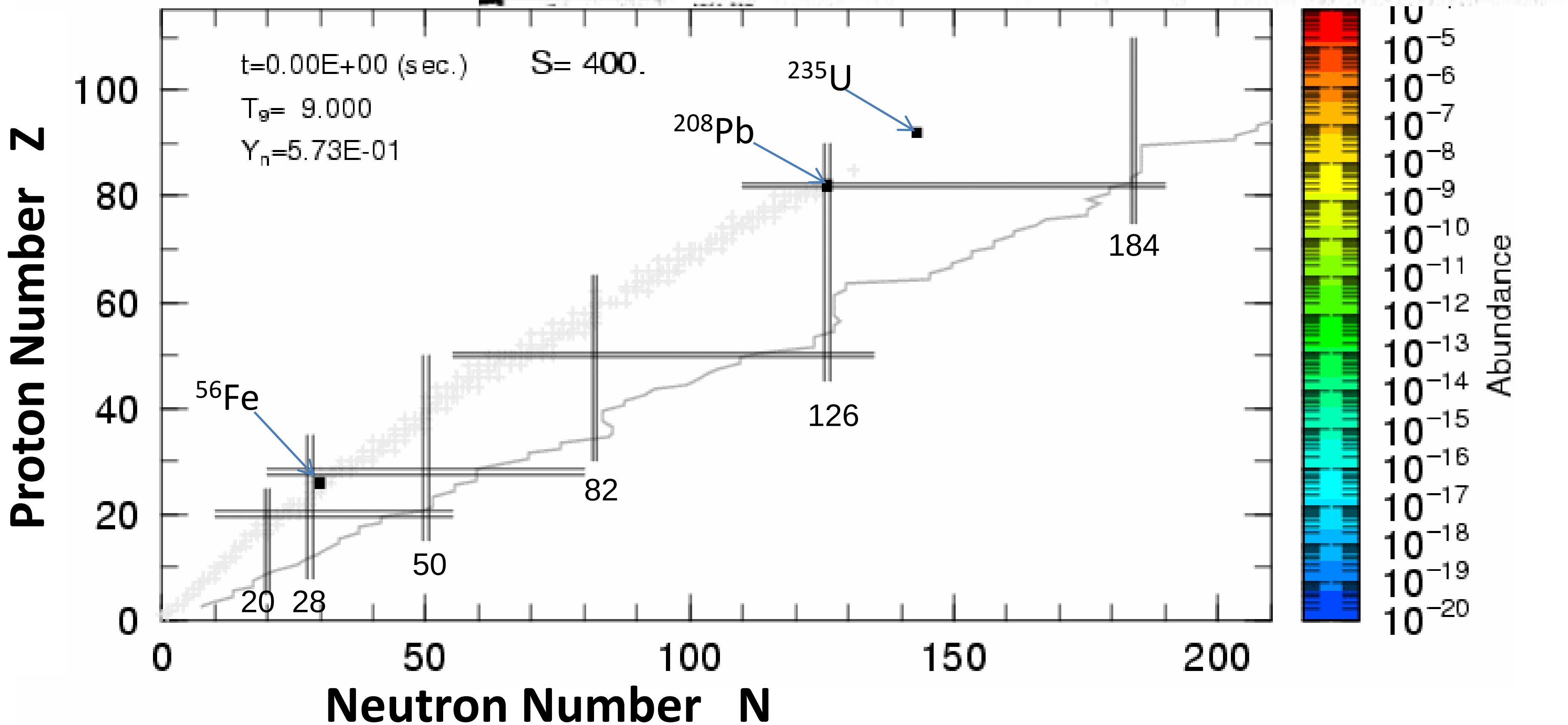
1,215 trajectories out of ~ 4,000 are the ejected outflows!

Supernova Nucleosynthesis Simulation

T. Kajino & S. Chiba

ν-Pair Heated Collapsar Model
K. Nakamura, et al. ApJ (2011).

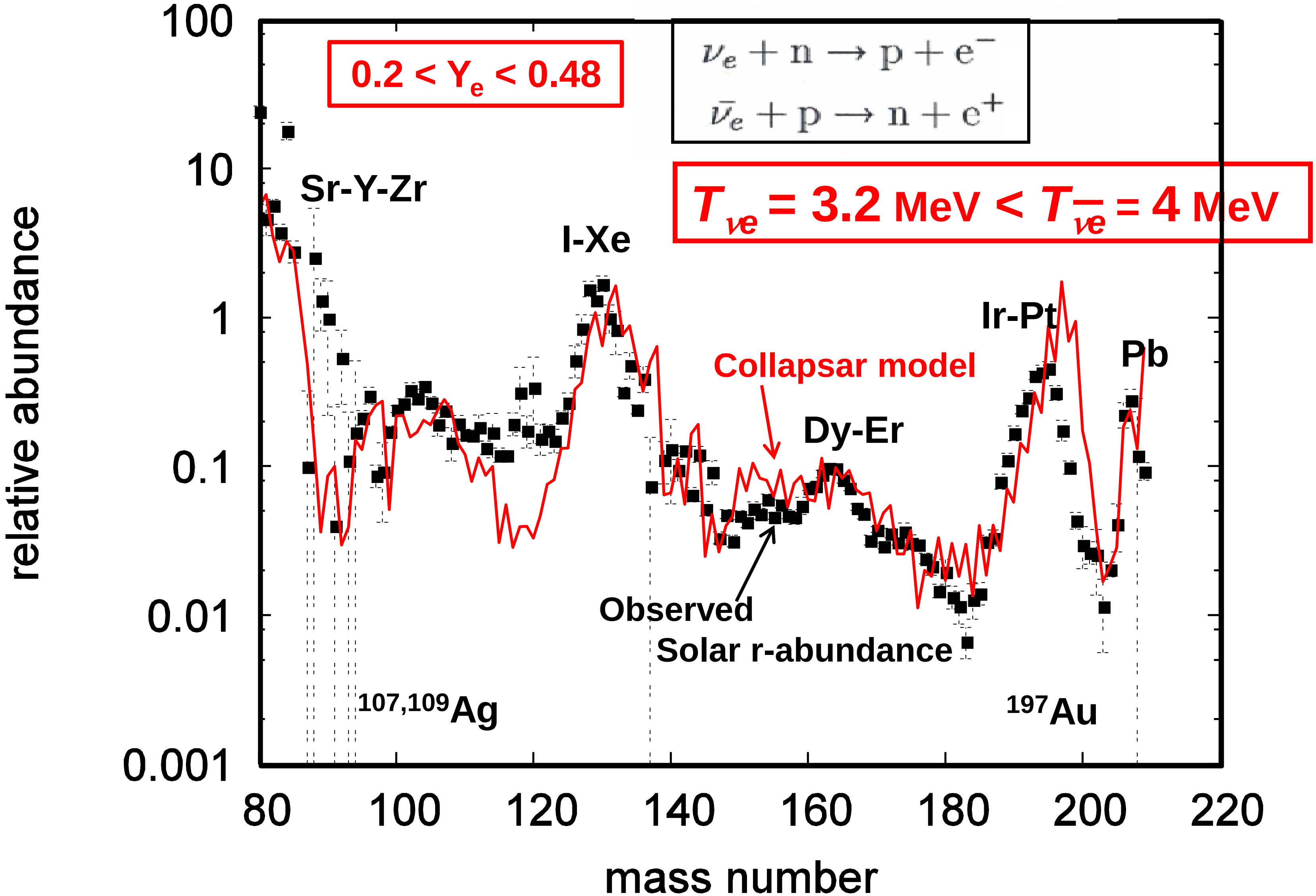




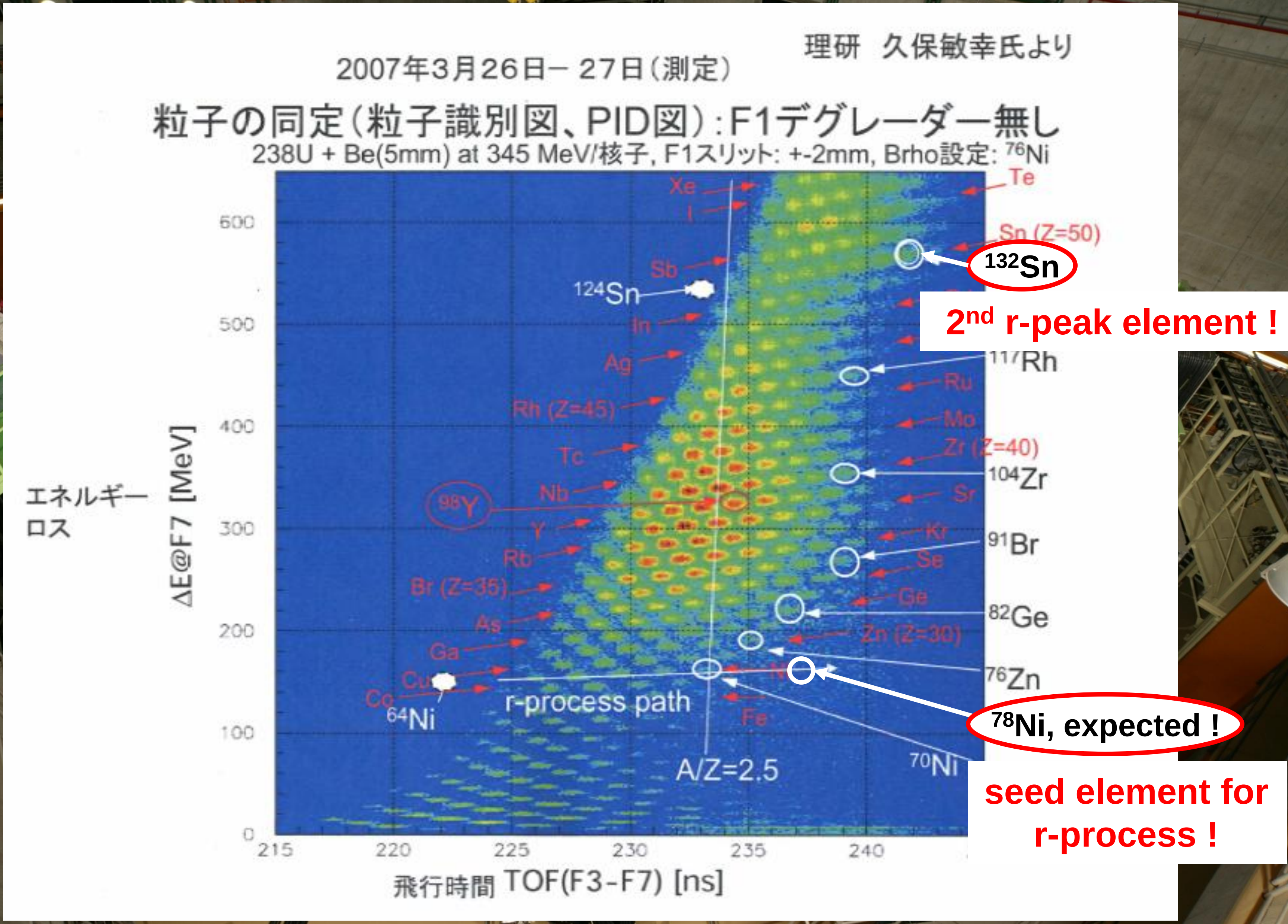
R-process in Pair ν-Heated Collapsar Model for GRB

K. Nakamura, S. Sato, S. Harikae, T. Kajino and G.J. Mathews (2011), submitted to ApJ.

Neutron-rich condition for successful r-process:

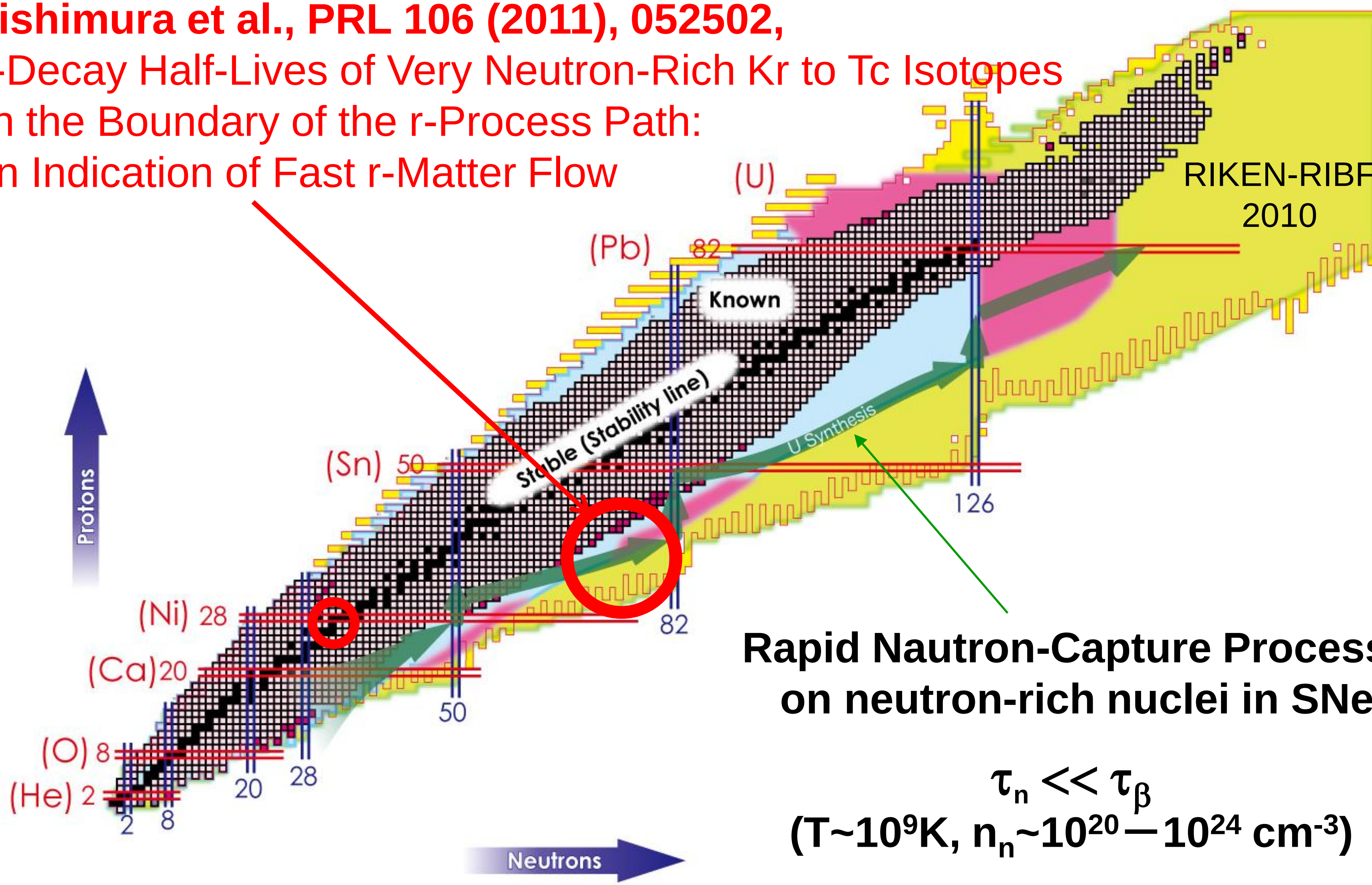


RIKEN-RIBF New Ring Cyclotron (2007)



Magic Number and Neutron-Capture Processes
From Text Book (Kubono & Kajino)

Nishimura et al., PRL 106 (2011), 052502,
β-Decay Half-Lives of Very Neutron-Rich Kr to Tc Isotopes
on the Boundary of the r-Process Path:
An Indication of Fast r-Matter Flow



Rapid Nautron-Capture Process on neutron-rich nuclei in SNe

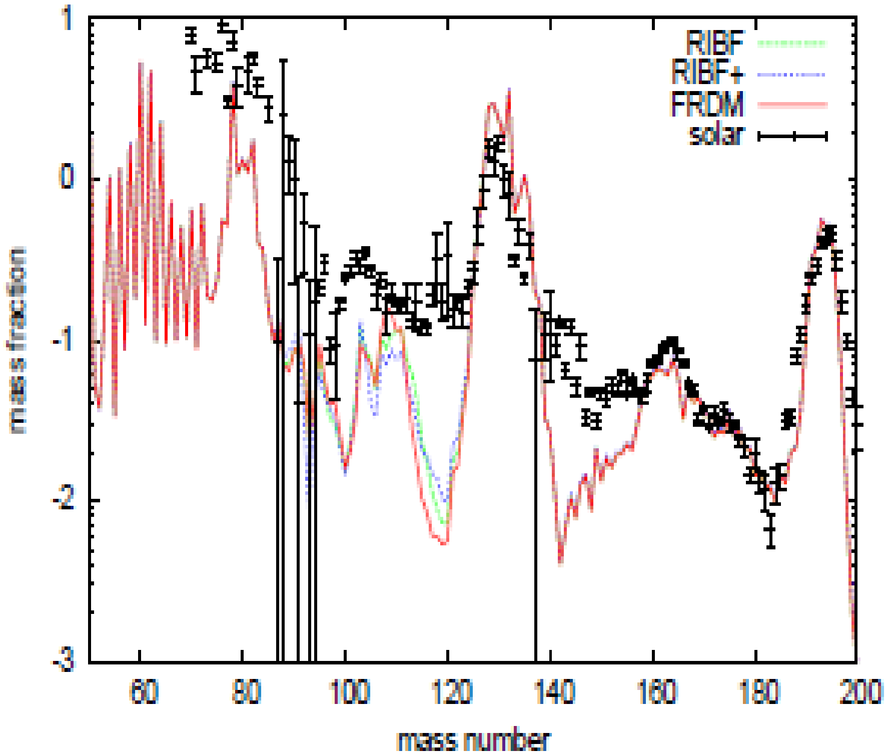
$$\tau_n << \tau_\beta$$

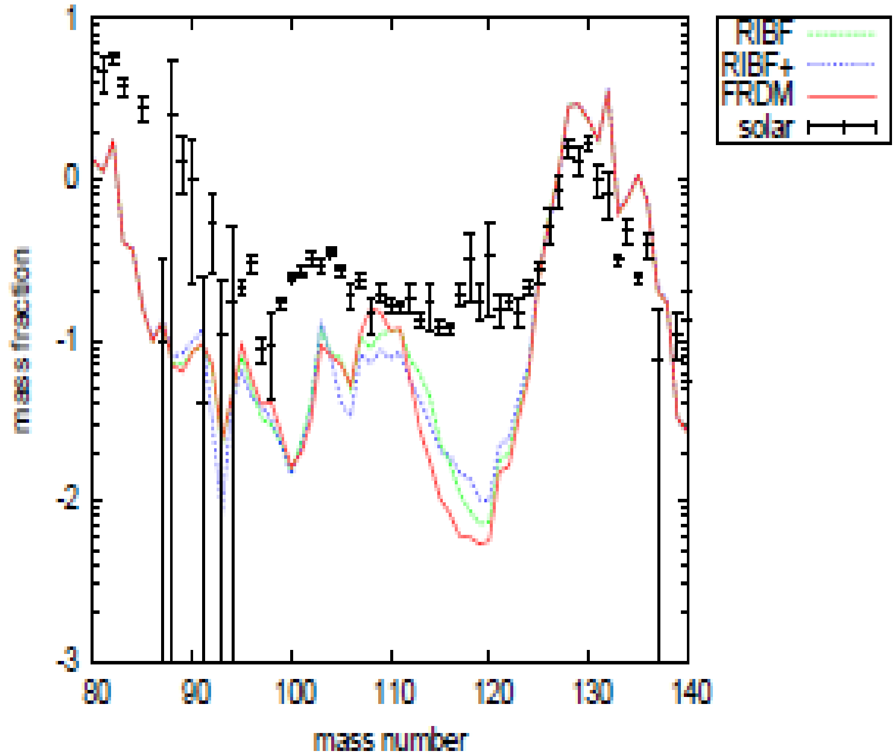
(T~10^{9}K, n_n~10^{20}—10^{24} cm^{-3})

Measured β-half lives @ RIKEN slightly improves the DEFICIENCY around A = 110-120.

Q-values (masses)?
Astrophys. conditions ?

Nishimura, Nishimura, Kajino, Suzuki & Mathews (2011), in preparation.
MHD-Jet Model

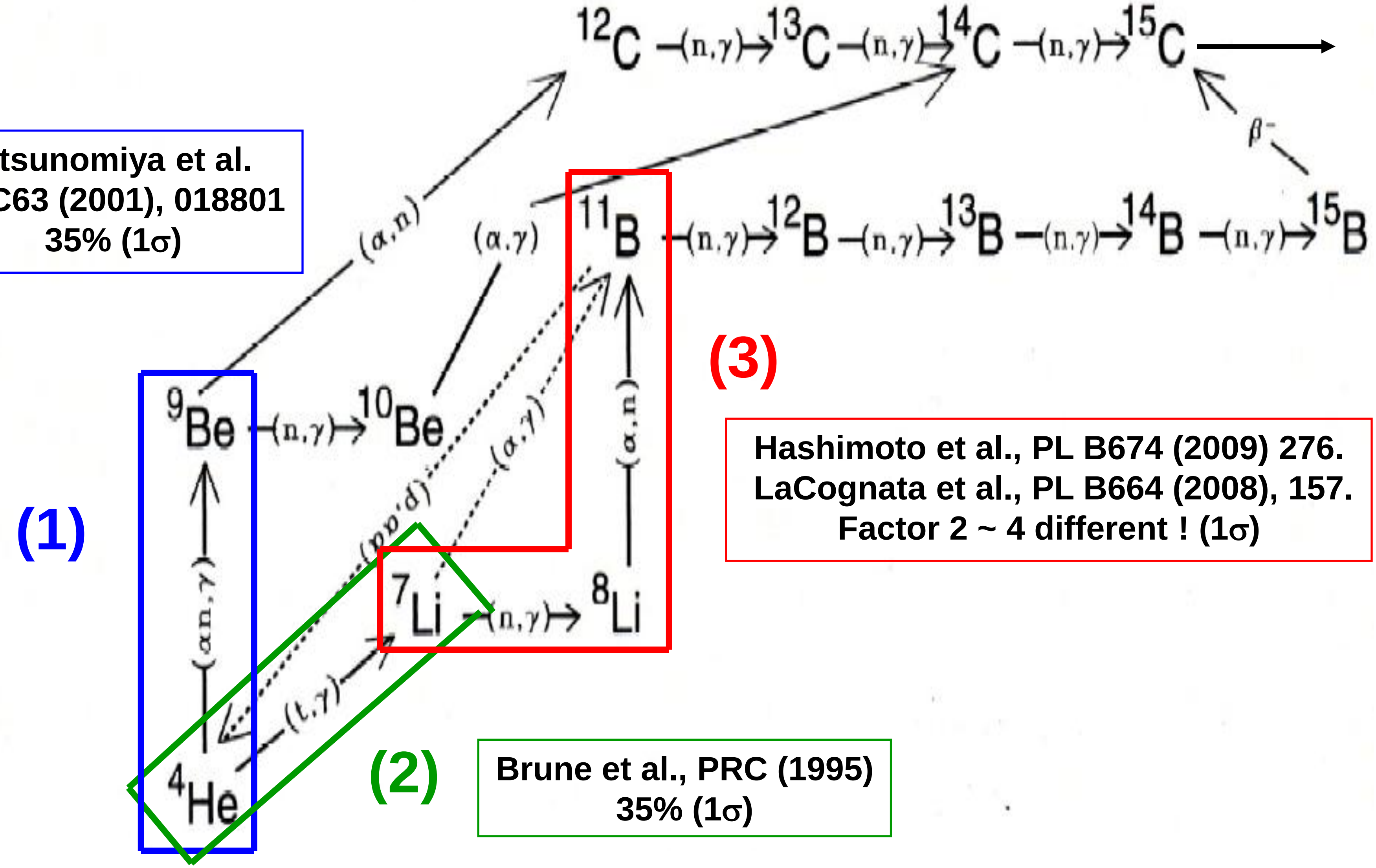




Identified Important Reaction Flow Paths

Liu's talk

Utsunomiya et al.
PRC63 (2001), 018801
35% (1σ)



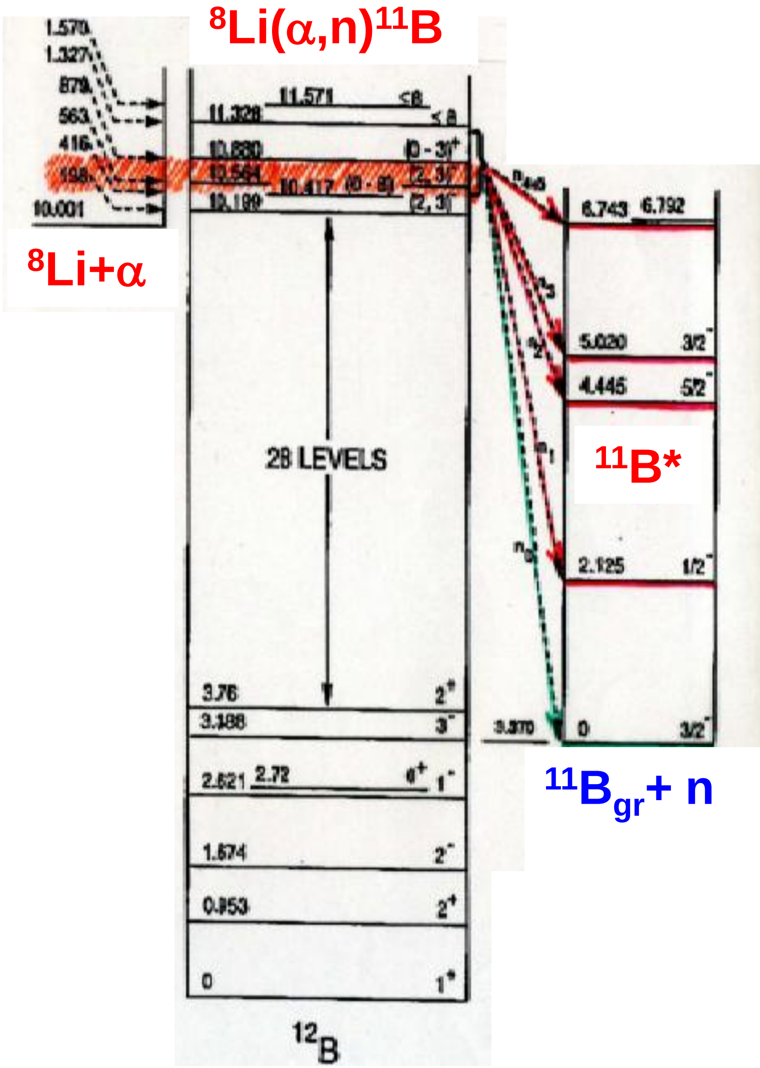
Hashimoto et al., PL B674 (2009) 276.
LaCognata et al., PL B664 (2008), 157.
Factor 2 ~ 4 different ! (1σ)

Brune et al., PRC (1995)
35% (1σ)

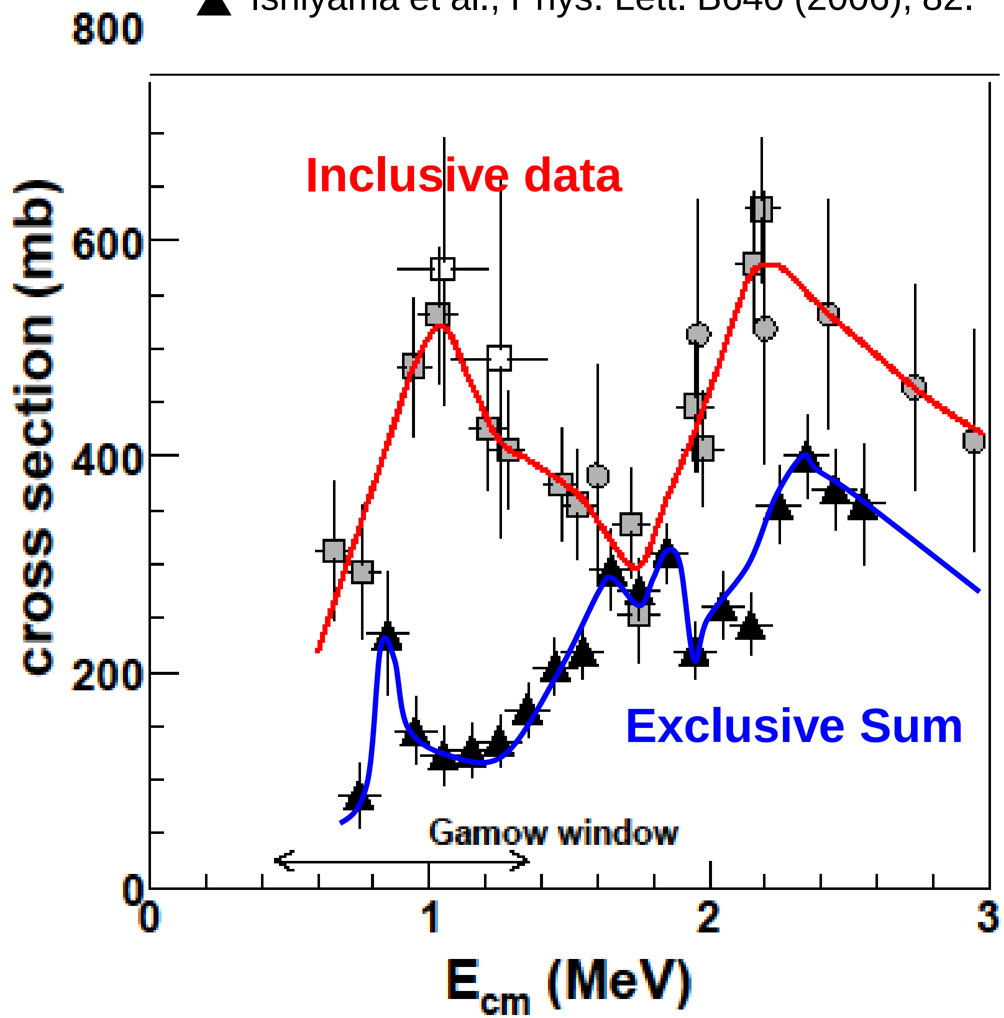
$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

Discrepancy
Inclusive Data >> Exclusive Sum

LaCognata et al., ApJL (2009), in press.



□ LaCognata et al., Phys. Lett. B664 (2008), 157.
○ Boyd et al. Phys. Rev. Lett. 68 (1992), 1283.
■ Gu et al., Phys. Lett. B343 (1995), 31.
▲ Ishiyama et al., Phys. Lett. B640 (2006), 82.

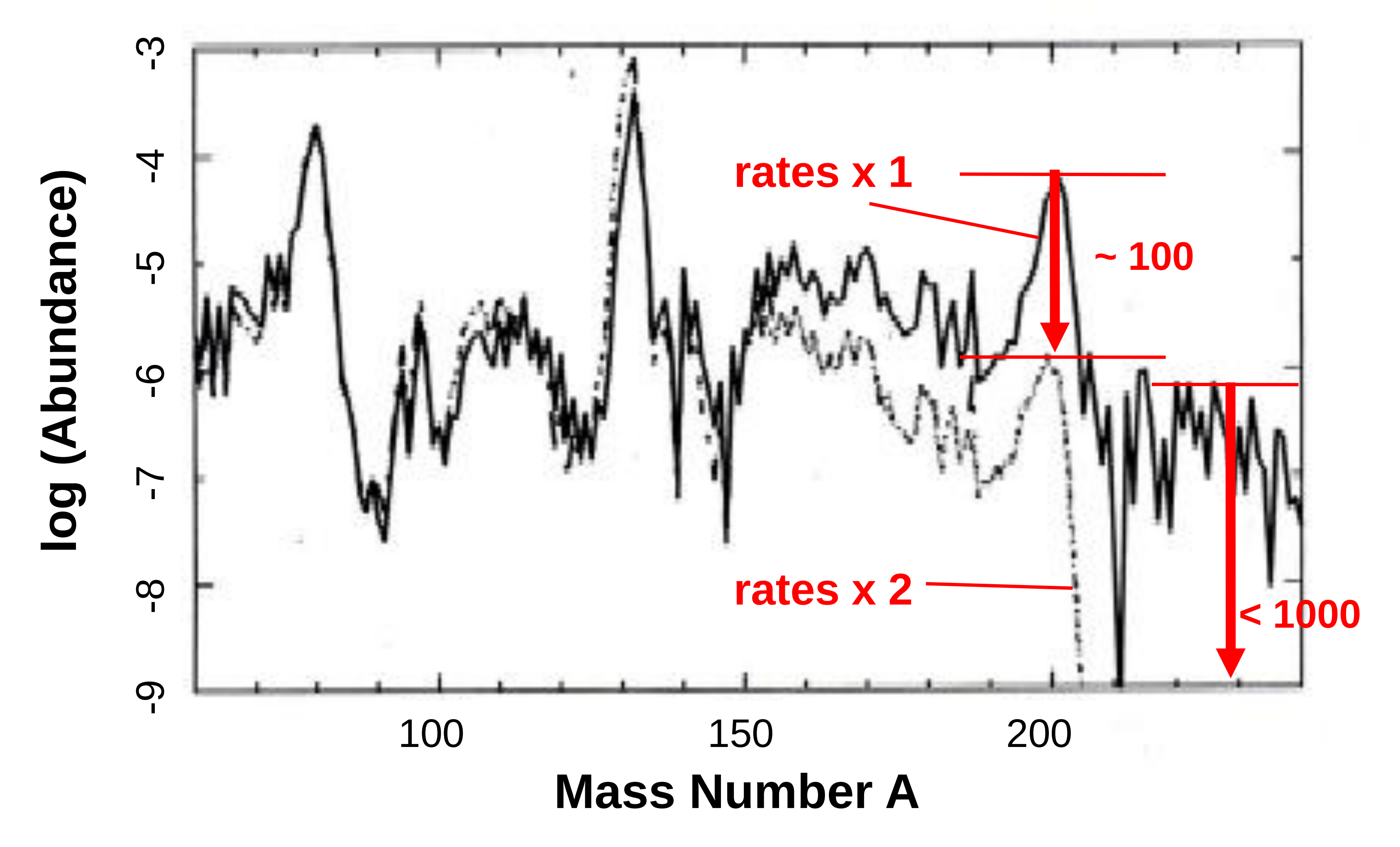


NON-LINEAR Effect of "α-process — r-process" Seque

(1) $\alpha(\alpha n, \gamma)^{9}Be$

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

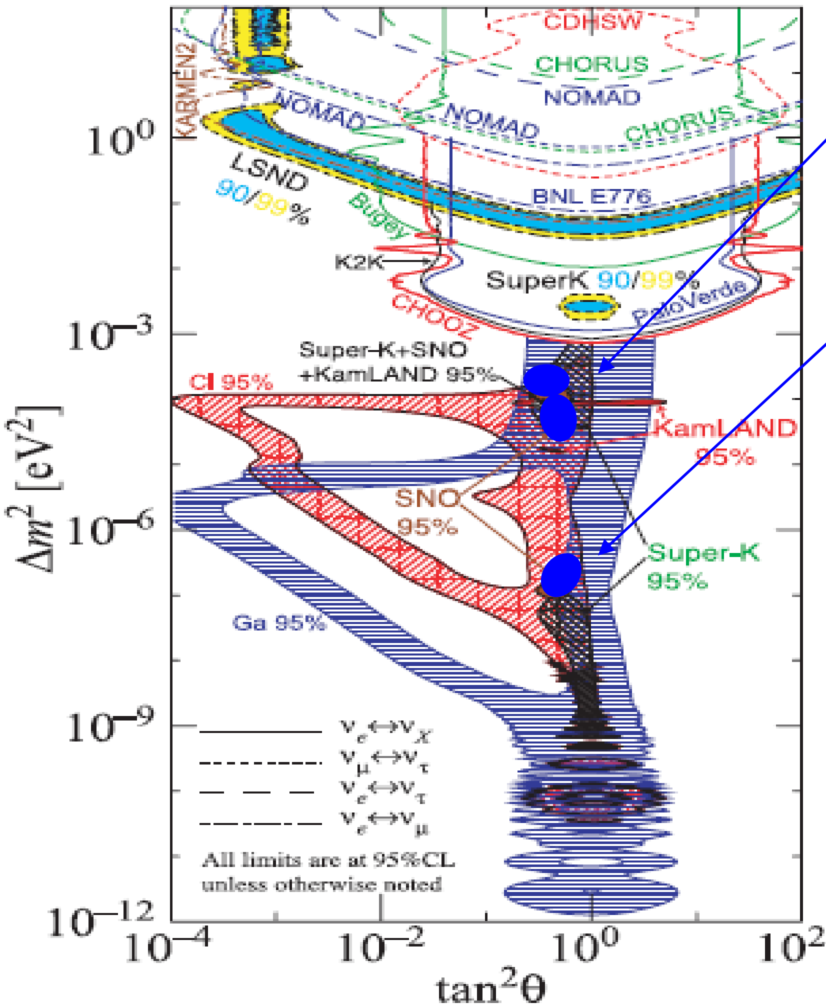
} x 2 artificial change



Neutrino Oscillations

$|\Delta m_{23}^2|$ and θ_{23} —— SK (atmospheric ν)
Δm_{12}^2 and θ_{12} —— KAMIOKANDE, SK, KamLand (reactor ν), SNO

"KNOWN"



<u>23－mixing</u>

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

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

<u>12－mixing</u> Cabibbo angle

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

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

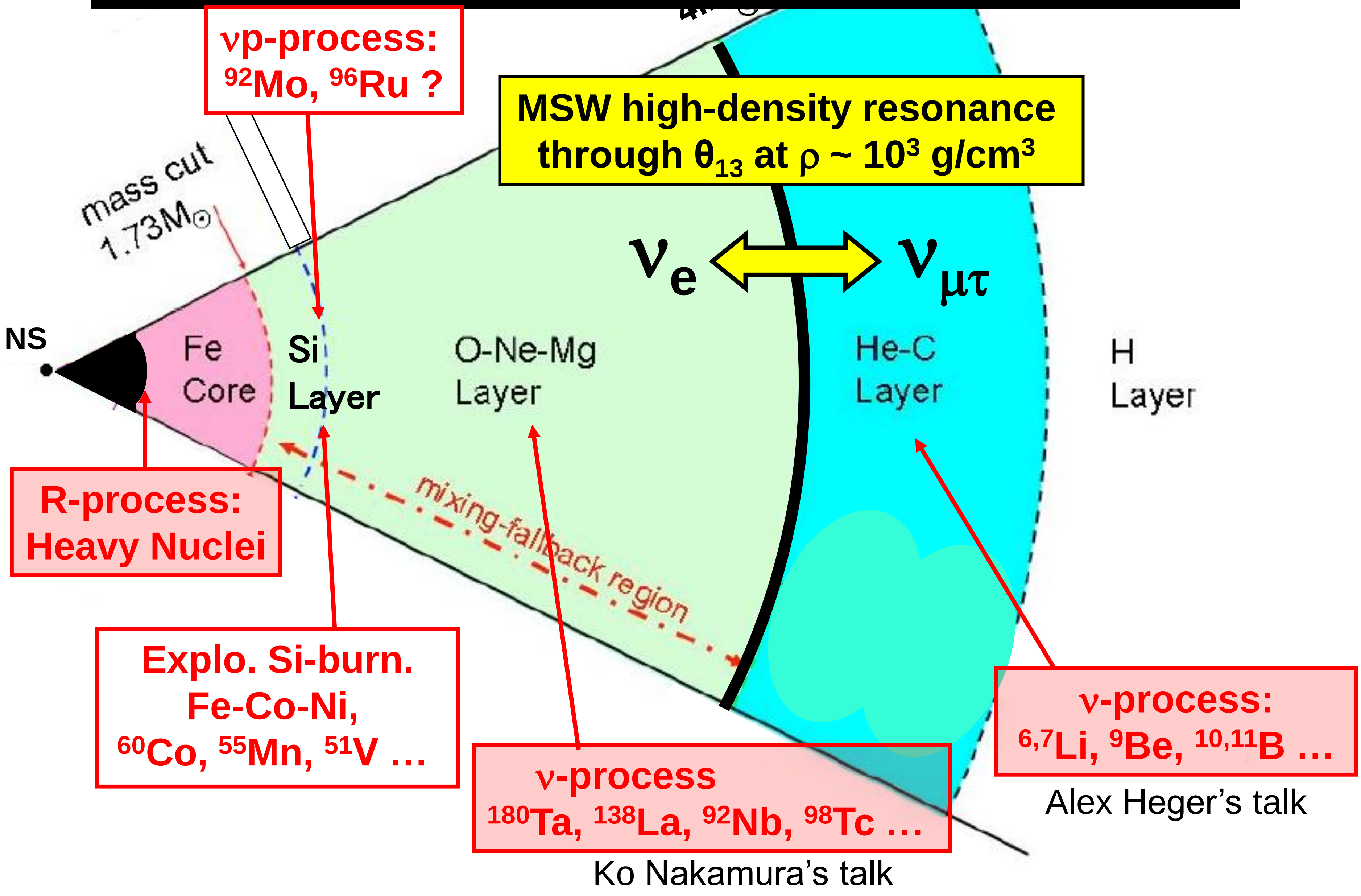
"UNKNOWN"

<u>13－mixing</u>

- $\sin^2 2\theta_{13}$ (< 0.1)
  T2K, June 14, 2011
- $\Delta m_{13}^2 = \pm 2.4 \times 10^{-3}$ eV^2
- ~~δ＝CP-phase~~
- ~~Absolute Mass~~

E(νμ)=E(ντ): Kobayashi-Masukawa, PTP (1973)
Yokomakura et al., PL B (1986)

Various roles of ν's in SN-nucleosynthesis

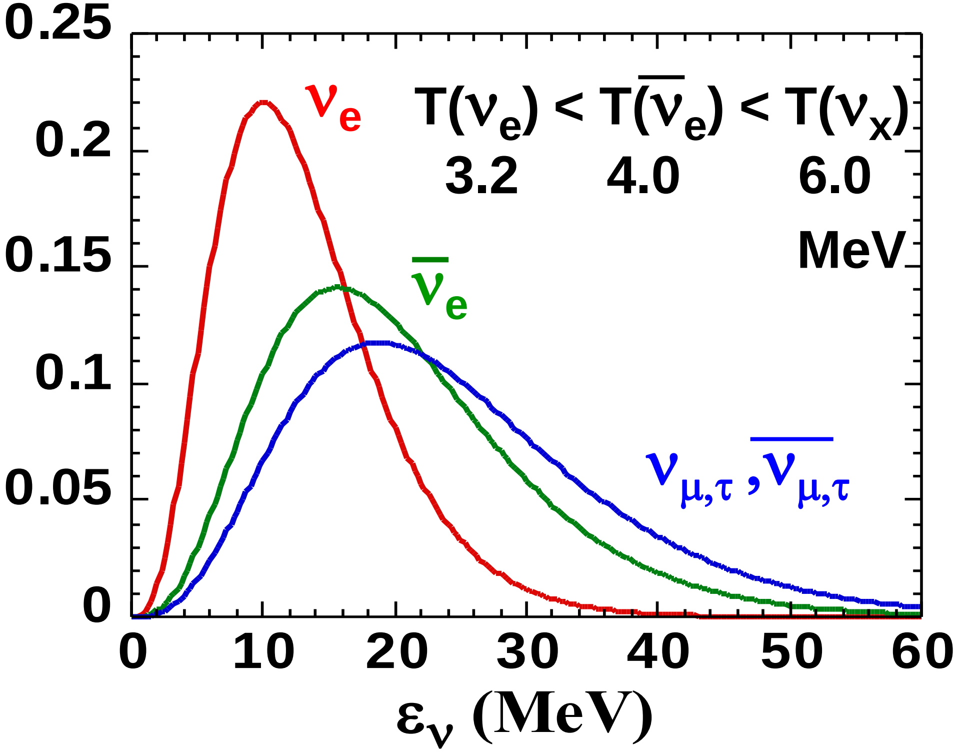


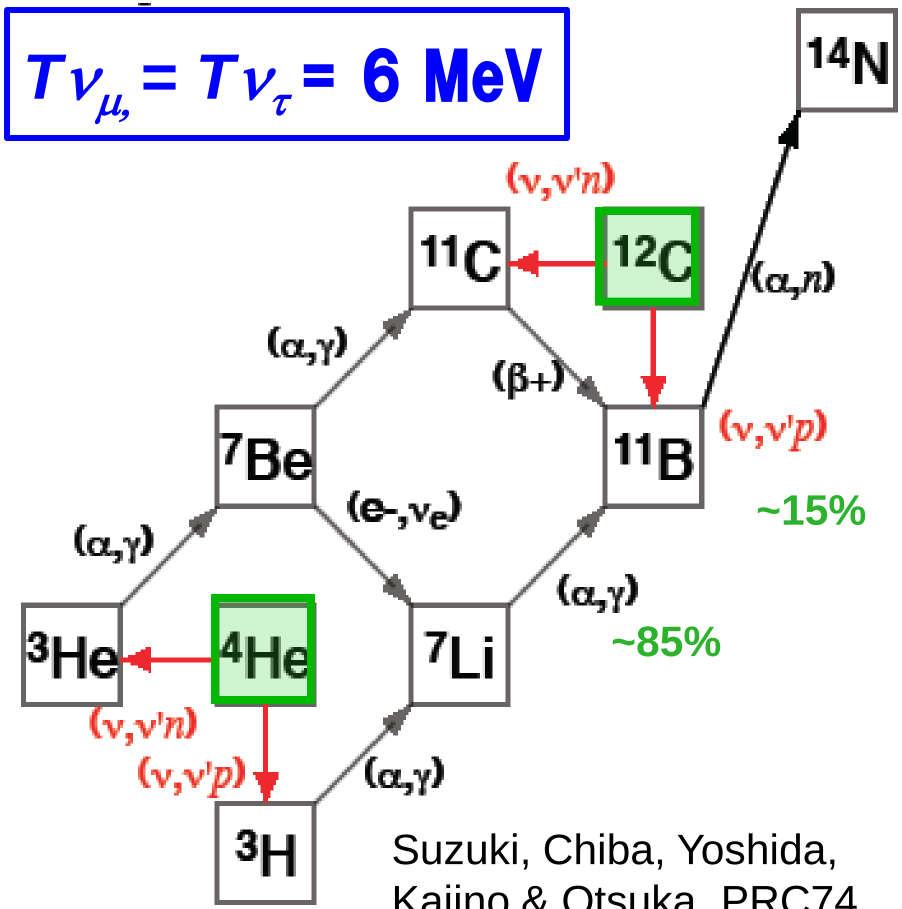
Oscillation (MSW) Effect on Supernova ν-Process

SN II: Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.
SNIc + II: Nakamura, Yoshida, Shigeyama, Kajino, ApJL 718 (2010), L137.

GCE of ^{11}B & $^{11}B/^{10}B$ ⇨ $T\nu_{\mu} = T\nu_{\tau} = 6$ MeV

ν-temperatures are known!

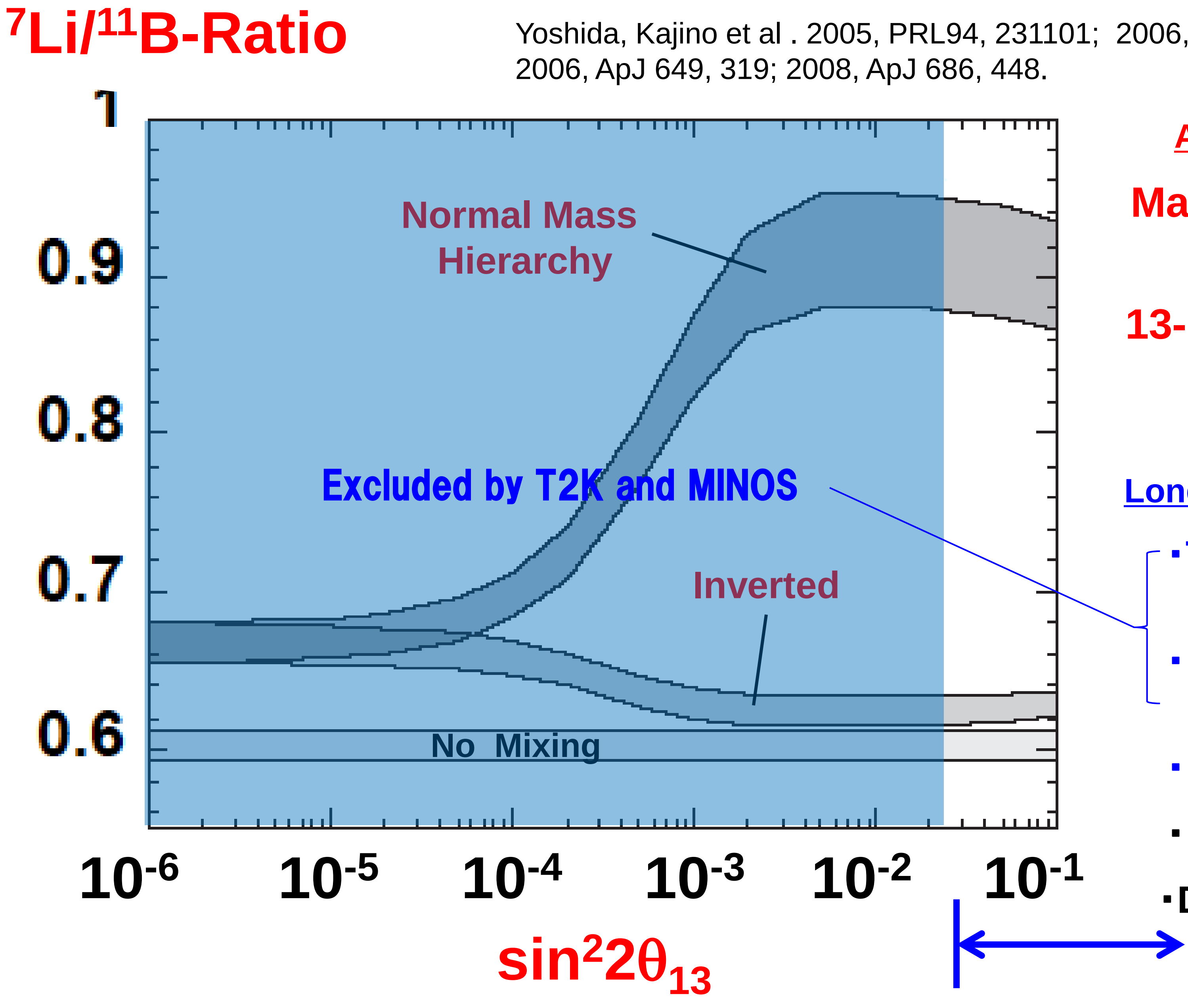




Suzuki, Chiba, Yoshida, Kajino & Otsuka, PRC74 (2006), 034307

Our Theoretical Prediction

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



Astrophysics:

Mass Hierarchy
Δm_{13}^2

13-Mixing Angle
θ_{13}

Long Baseline Exp:

- T2K (Kamioka) June 14, 2011
- MINOS July 29, 2011
- RENO (KOREA)
- Double CHOOZ
- Daya Bay

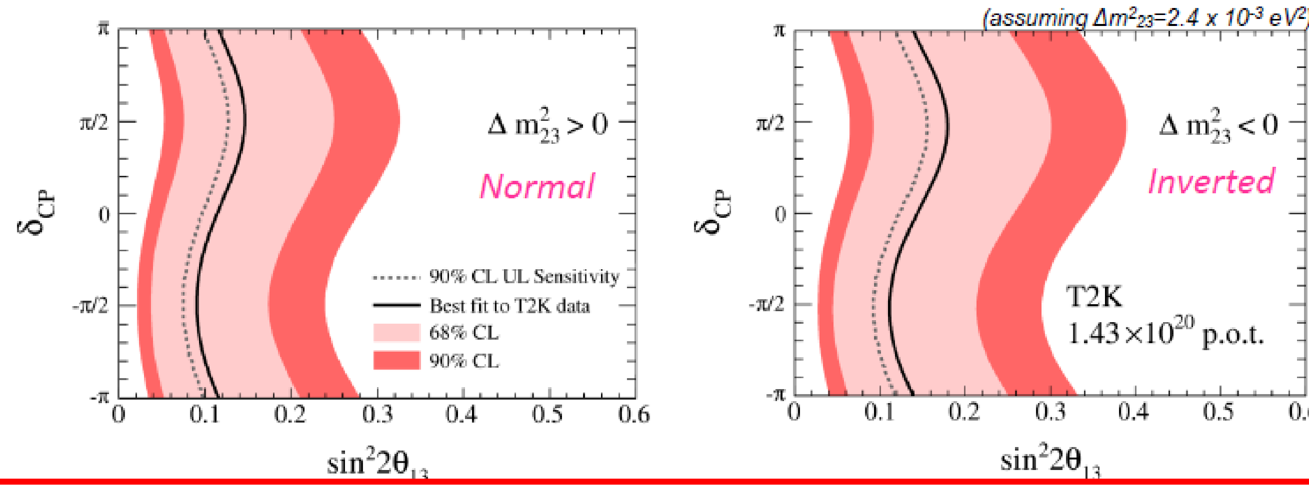
Allowed region of $\sin^2 2\theta_{13}$ for δ_{CP}

T2K

S. Abe, et al., PRL 107, 041801 (2011)

Confidence level intervals for $\sin^2 2\vartheta_{13}$ vs δ_{CP}

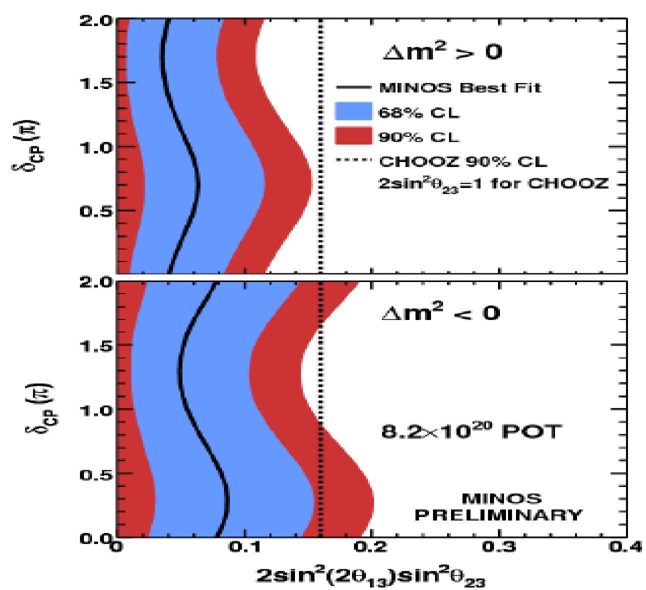
Feldman-Cousins method was used for constructing confidence interval



Mass hierarchy is still unknown !

MINOS

P. Adamson, et al. arXiv:1108.0015



Assuming:
δ=0, $\theta_{23} = \pi/4$
normal (inverted) hierarchy

$\sin^2(2\theta_{13})<0.12(0.19)$ 90% CL

$\sin^2(2\theta_{13})=0.04(0.08)$ Best Fit

We exclude $\sin^2 2\theta_{13}$=0 at 89% CL

Feldman-Cousins contours

Uncertainties in the other oscillation parameters are included

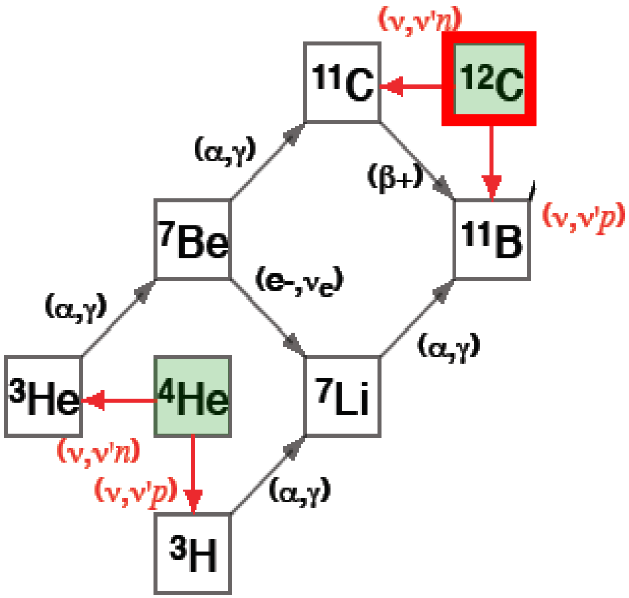
ν-Nucleus interaction cross section?

Haxton's SM cal. (Woosley et al. ApJ. 356 (1990), 272)

Suzuki's new SM cal. with NEW Hamiltonian

Suzuki, Chiba, Yoshida, Kajino & Otsuka, PR C74 (2006), 034307, ++

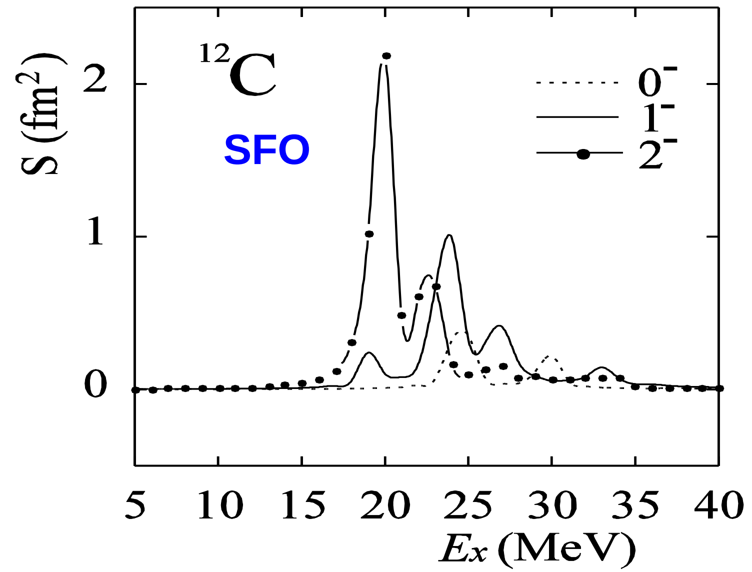
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003) → SFO

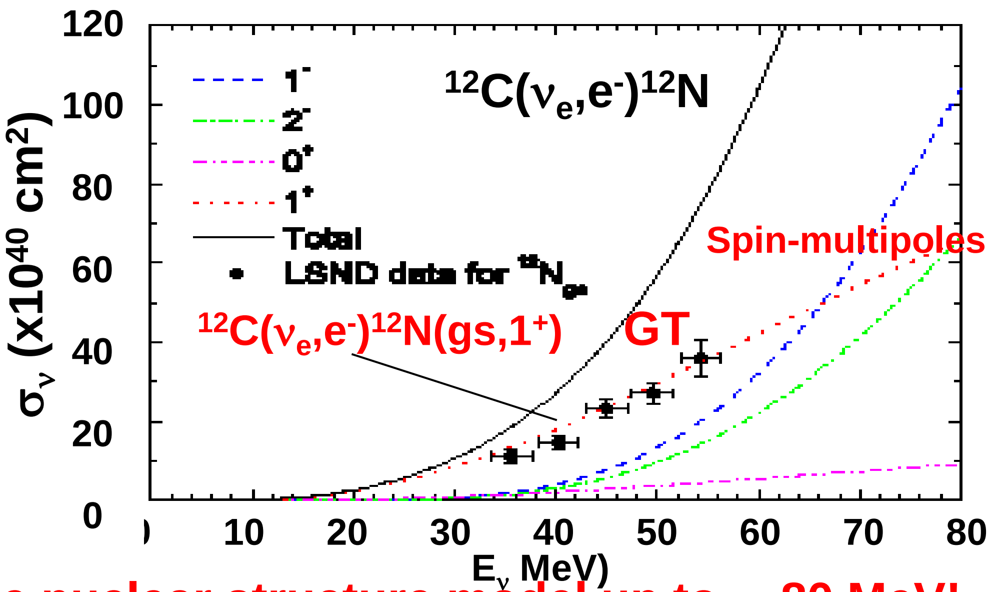


^{12}C: SFO Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

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

QRPA: Cheoun, Ha, Lee, Kim, So & Kajino, PRC81 (2010), 028501





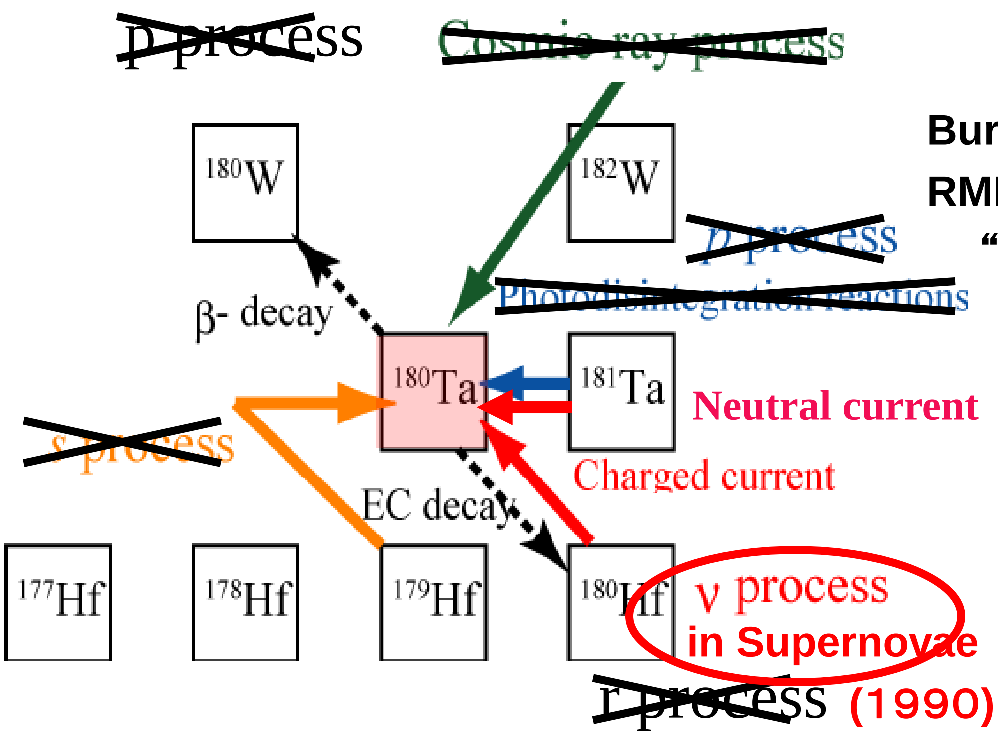
We need precise nuclear structure model up to ~80 MeV!

Tantalum (^{180,181}Ta)

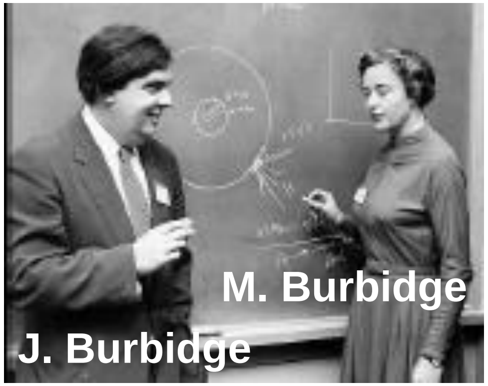
$^{181}Ta_g$ (stable), $^{180}Ta_g$(unstable, $\tau_{1/2}$ = 8h), $^{180}Ta^m$ (isomer, $\tau_{1/2} > 10^{15}$y)

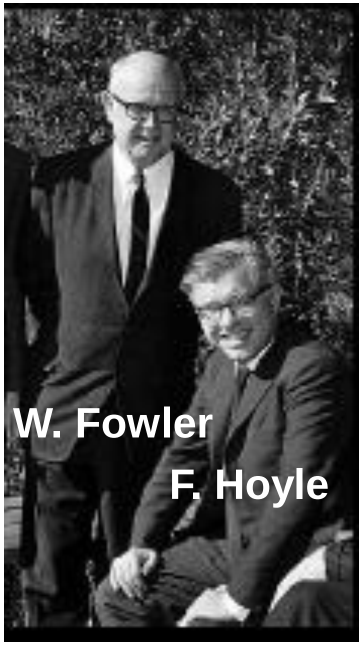
^{180}Ta is the rarest isotope in the Solar-Systerm and even in the Universe!

Where was ^{180}Ta synthesized ?



Burbidge^2–Fowler-Hoyle,
RMP 29 (1957), 547-650.
"Element Genesis"



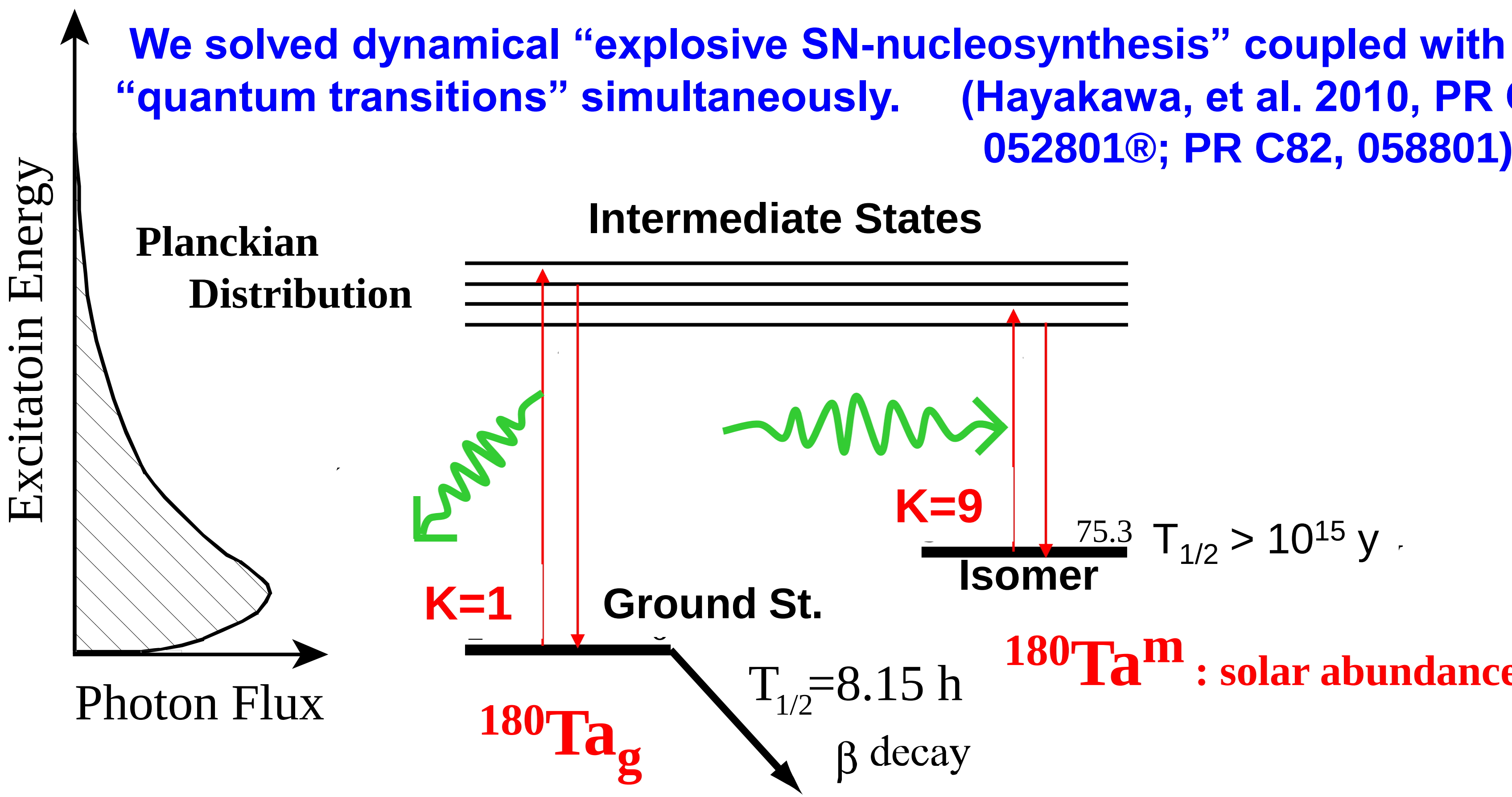


^{180}Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

Solar-^{180}Ta is all “ISOMER” with $T_{1/2} > 10^{15}$ y!

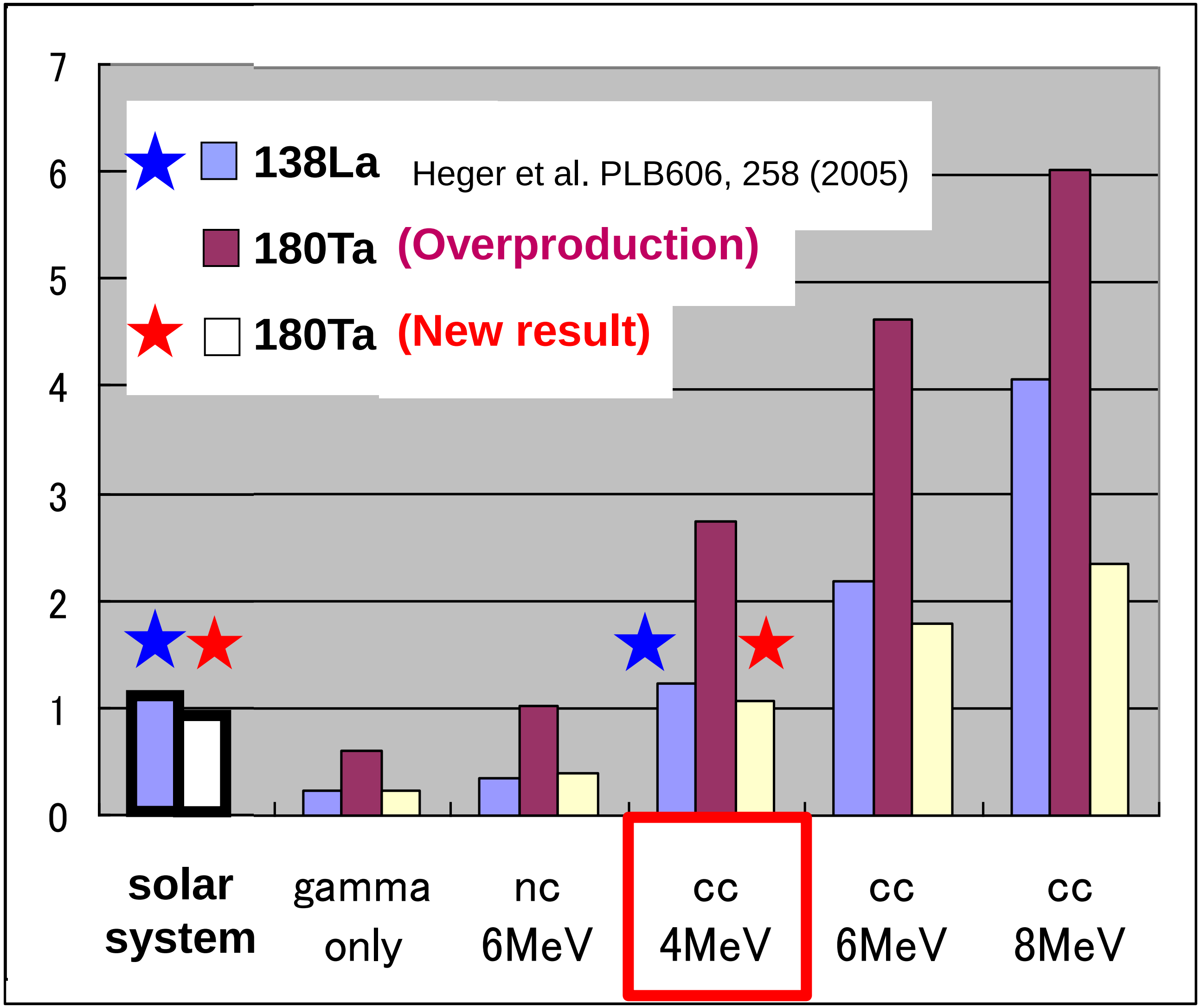
- **Long lived $^{180}Ta^m$ is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

We solved dynamical “explosive SN-nucleosynthesis” coupled with “quantum transitions” simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)



Result from ν-Nucleosynthesis

T. Hayakawa, T. Kajino, S. Chiba, and G.J. Mathews, Phys. Rev. C81 (2010), 052801®



About 40% $^{180}Ta^{m}$ survives in supernova explosion.

Then, both ^{138}La and ^{180}Ta abundances can be consistently reproduced by the CC-int. of ν_e and $\overline{\nu}_e$ of

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

⇕

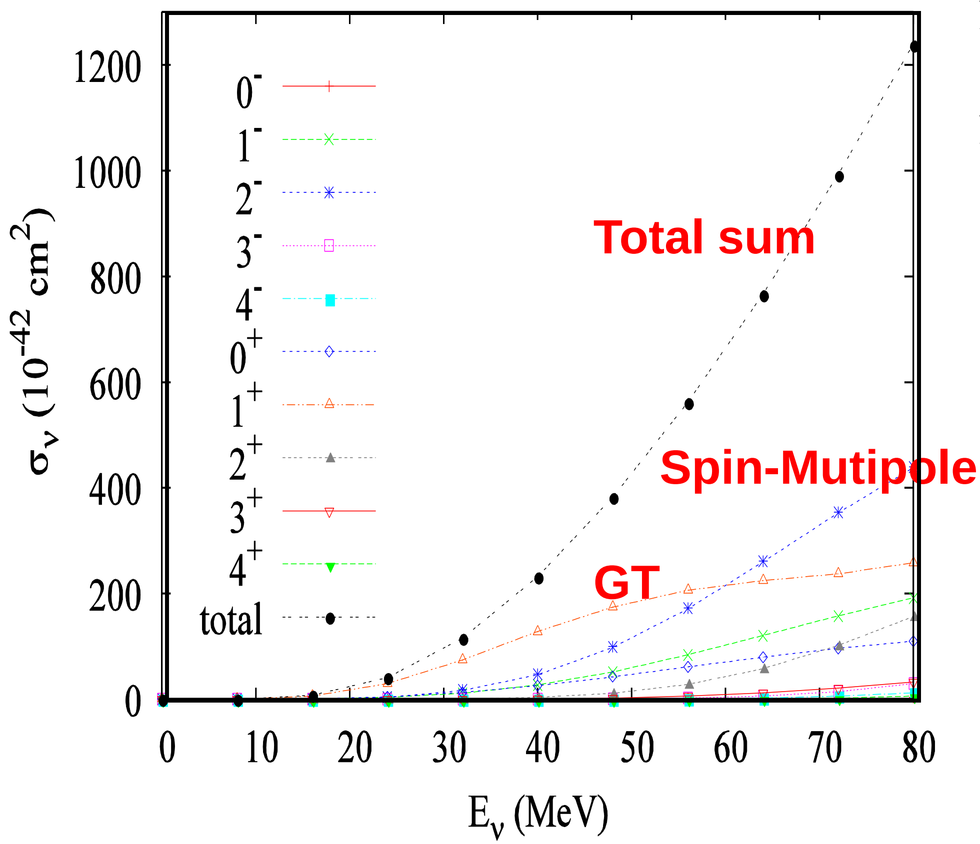
Consistent with the r-process !

ν-^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc, ^{12}C, ^{4}He… X-sections calculated in Quasi-particle Random Phase Approximation

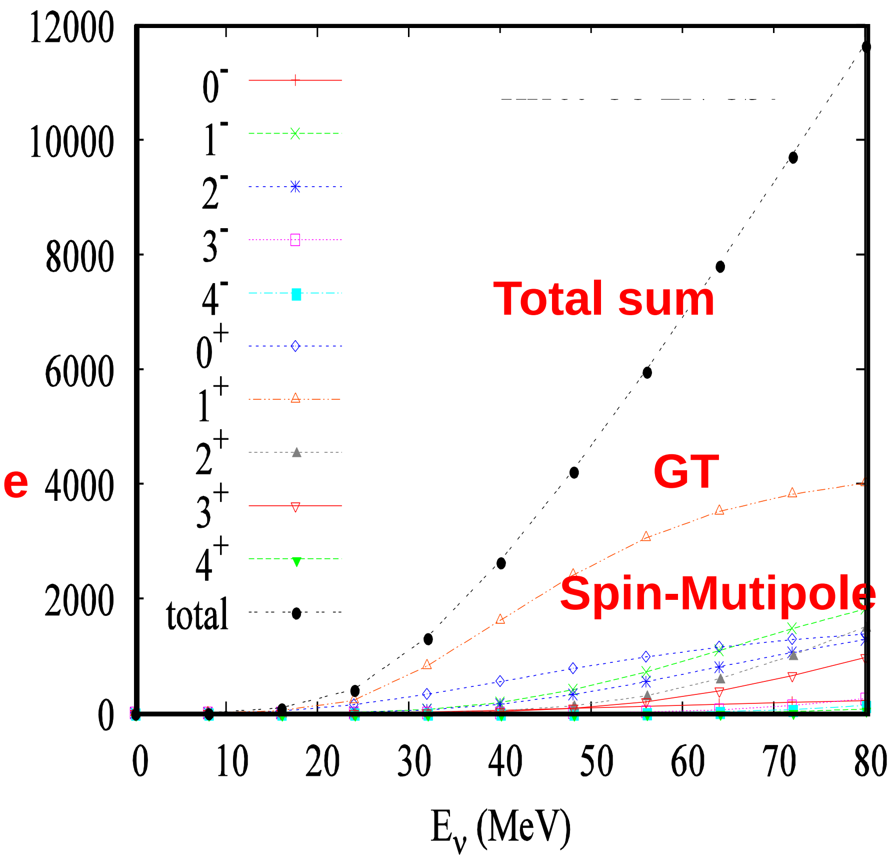
Cheoun, Ha, Hayakawa, Kajino & Chiba, PRC82 (2010), 035504;
Cheoun, Ha, Kim, & Kajino, J. Phys. 37 (2010) 055101; Cheoun, Ha & Kajino, PRC 83 (2011), 028801

GT and Spin-Multipole transitions !

^{181}Ta + ν → ^{180}Ta + n + ν' (NC)

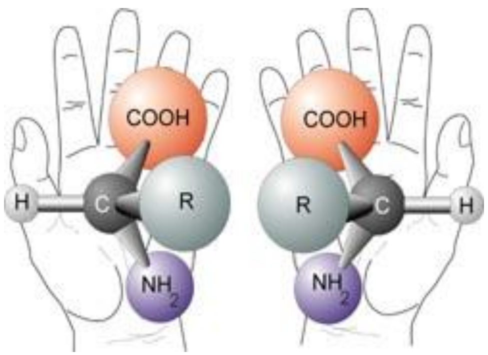


^{180}Hf + ν → ^{180}Ta + e$^-$ (CC)



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

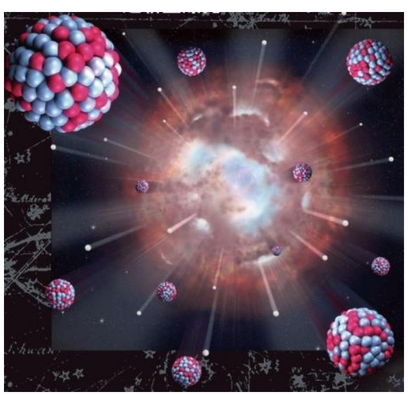
Chitrality, earth/solar origin or universal in cosmos?

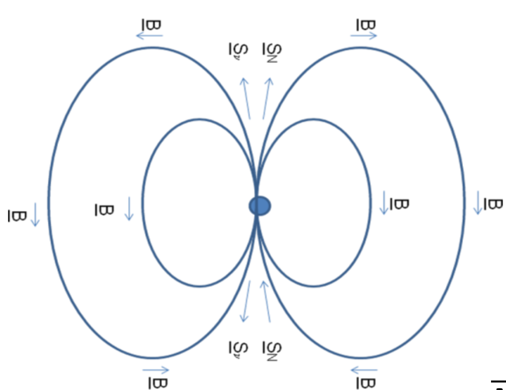


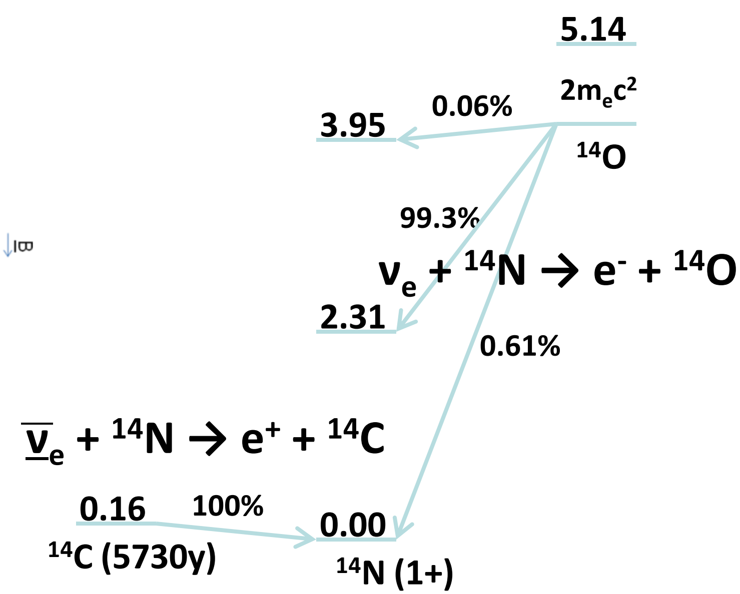
- ★ **Neutrinos are all left-handed!**
- ★ **Supernovae with strongly magnetized neutron star or BH emit intensive flux of neutrinos over 10^{10} yrs!**
- ★ **SN ejecta including ^{14}N interact with neutrino under strong magnetic field!**
- ★ **Neutrino-^{14}N coupling is asymmetric & chiral selective!**

Boyd, Kajino, & Onaka (Astrobiology 10 (2010), 561-568)
suggest L-handed chirality of amino acids is UNIVERSAL !

Magnetized supernova







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

SUMMARTY

- We constructed a COLLAPSAR Model for the central engines of the GAMMA-RAY BURSTS (GRBs), and applied to nucleosynthesis.
- We succeeded in reproducing observed abundances of the R-PROCESS ELEMENTS that satisfy the UNIVERSALITY.
- Much effort should launch in both NUCLEAR PHYSICS and ASTROPHJYSICS in order to understand the origin of the r-process elements.
  - ★ Nuclear Masses (Q-values), β-decay lives, (n, γ) & (α, n) rates on intermediate-to-heavy nuclei, p,n,α-induced reactions on light nuclei
  - ★ Models for Astrophysical sites