1st RIBF Workshop, RIKEN, May 24, 2012

R-Process: Astro. + Theory Side

Nuclear physics helps understand
the origin of heavy elements
and astrophysics (SNe, GRB …).

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PURPOSE

Eluciate important nuclear properties of the nuclei NOT ONLY between neutron-rich waiting points and the 1st, 2nd, and 3rd abundance peaks BUT ALSO below and beyond the peak nuclei:

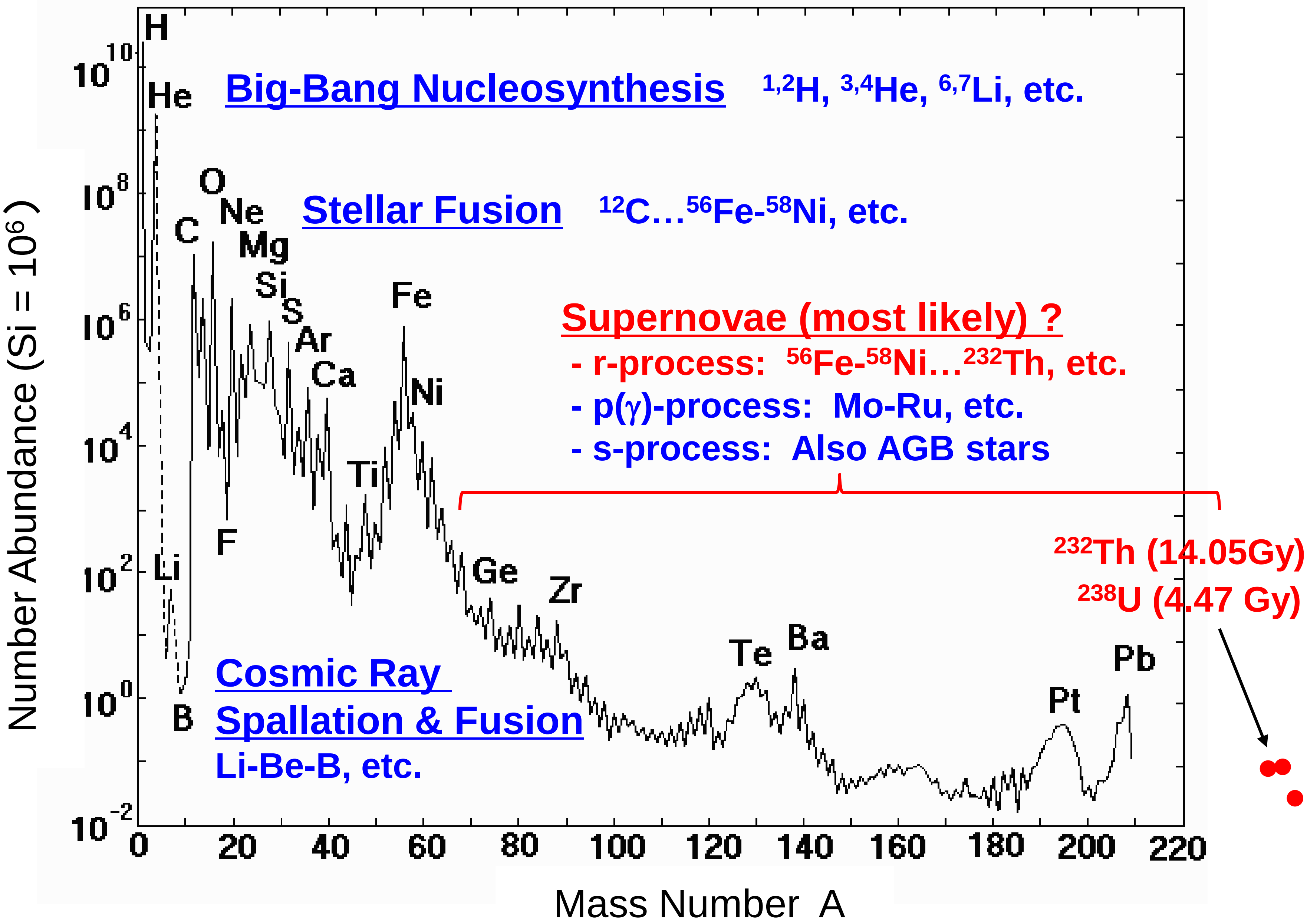
Heavy Nuclei (Fe < A)

- Masses – Q_n – $\sigma(n,\gamma)$: E1-strength
- β-decay half lives: $\tau_{1/2} \propto Q_\beta^5$
- β-delayed nenuton-emission
- Asym. fission, both β-delayed or n-captured

Lighter-to-Intermediate Nuclei (A < Fe)

- p, n, α-induced react., $\sigma(n,\gamma)$ vs. $\sigma(\alpha,n)$
- Roles of ν's in SN-nucleosynthesis

Solar System Abundance



Candidate Astrophysical Sites for R-Process

Supernova Candidate	Physical Conditions: S	Ye	$\dot{M}_r/(SN)$	Expected Event Rate	Evaluation
a. ν-Driven Wind	~ 100	0.45	$10^{-5}M_\odot$	10^{-2}/yr/galaxy*	○ Solar～Metal poor☆ ○ Universality × No explosion model
b. Binary Neutron Star Merger	~ 1	0.1	$10^{-2}M_\odot$	$<10^{-5}$	× Only recently (solar) but NO metal poor☆
c. MHD Jet	~ 10	0.1~0.4	$10^{-3}M_\odot$	$< 10^{-4}$	○ Solar～Metal poor☆ × Universality △ Explosion model, but special condition
Gamma-ray Burst Candidate					
d. Hypernova	1-1000	0.1	$10^{-1}M_\odot$	$< 10^{-6}$	○ Only Metal poor☆ Broken Universality △ Explosion model, but special condition

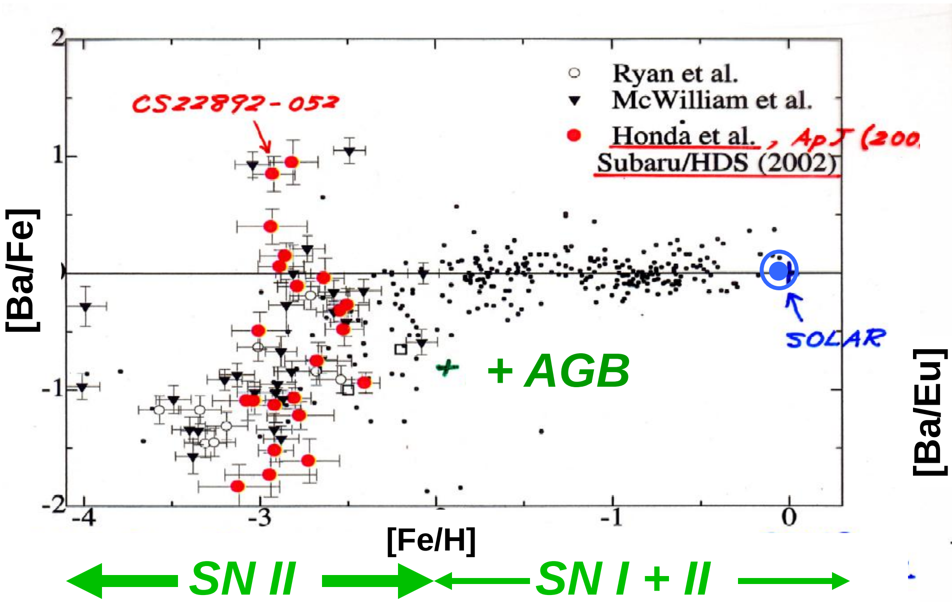
Solar-System r-abundance = $10^3 M_\odot$

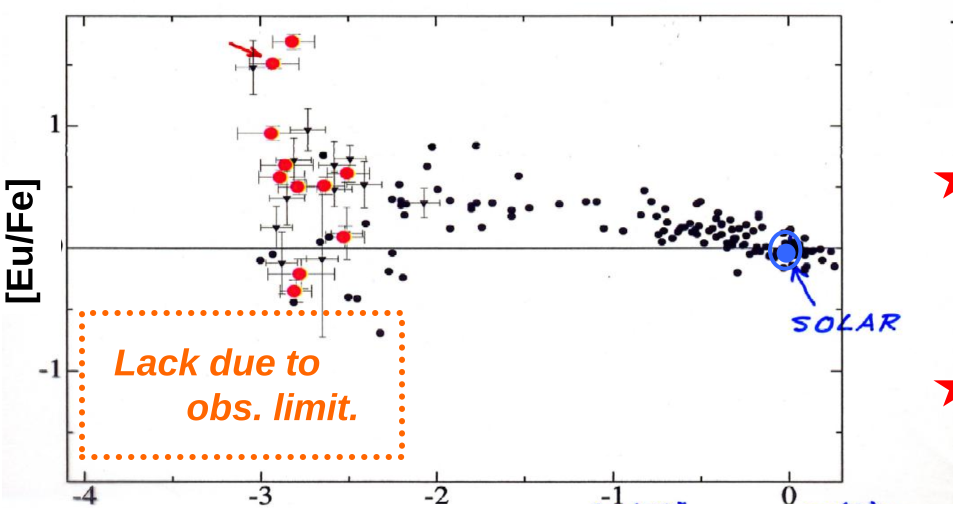
$10^{-5}M_\odot \times 10^{-2} \times 10^{10} = 10^3 M_\odot$

(← 10^{10}: Cosmic age)

* consistent with observed SN frequency

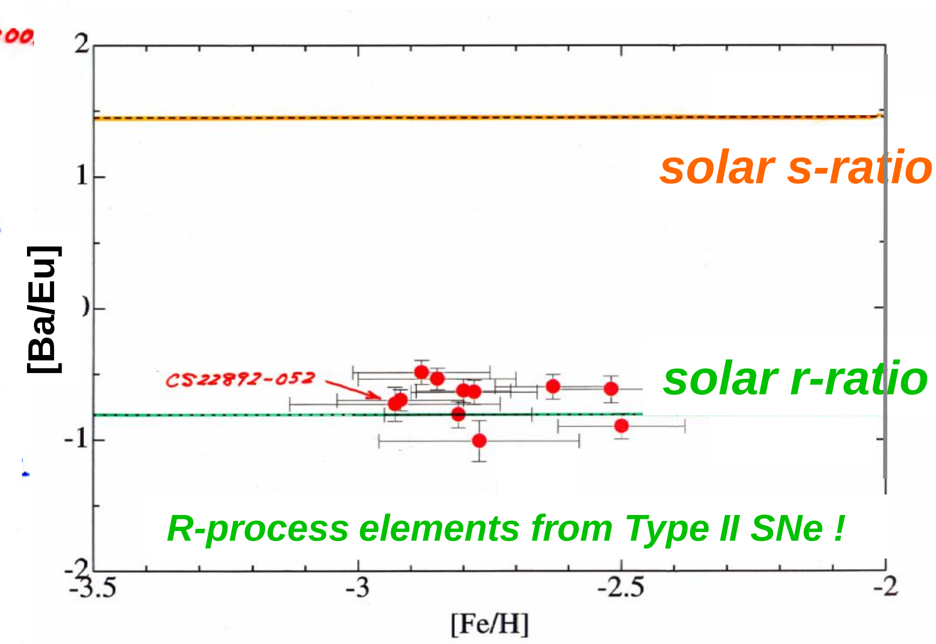
SUBARU Telescope HDS





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

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



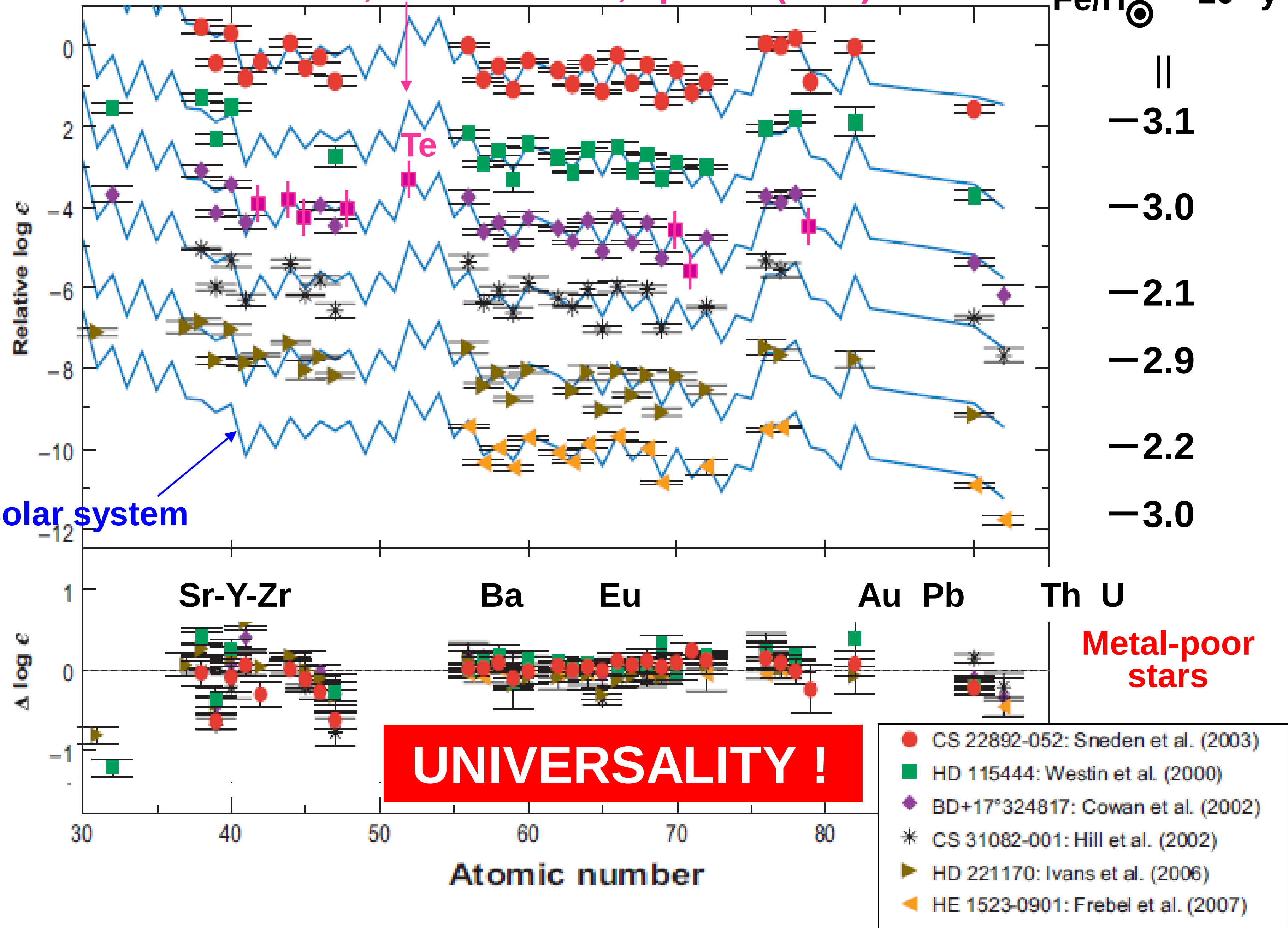
★ Large abundance scatter at [Fe/H]<-2 is an evidence for INDIVIDUAL supernova episode.

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

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

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

$$\log \frac{Fe/H_{\star}}{Fe/H_{\odot}} \propto \frac{t}{10^{10}y}$$

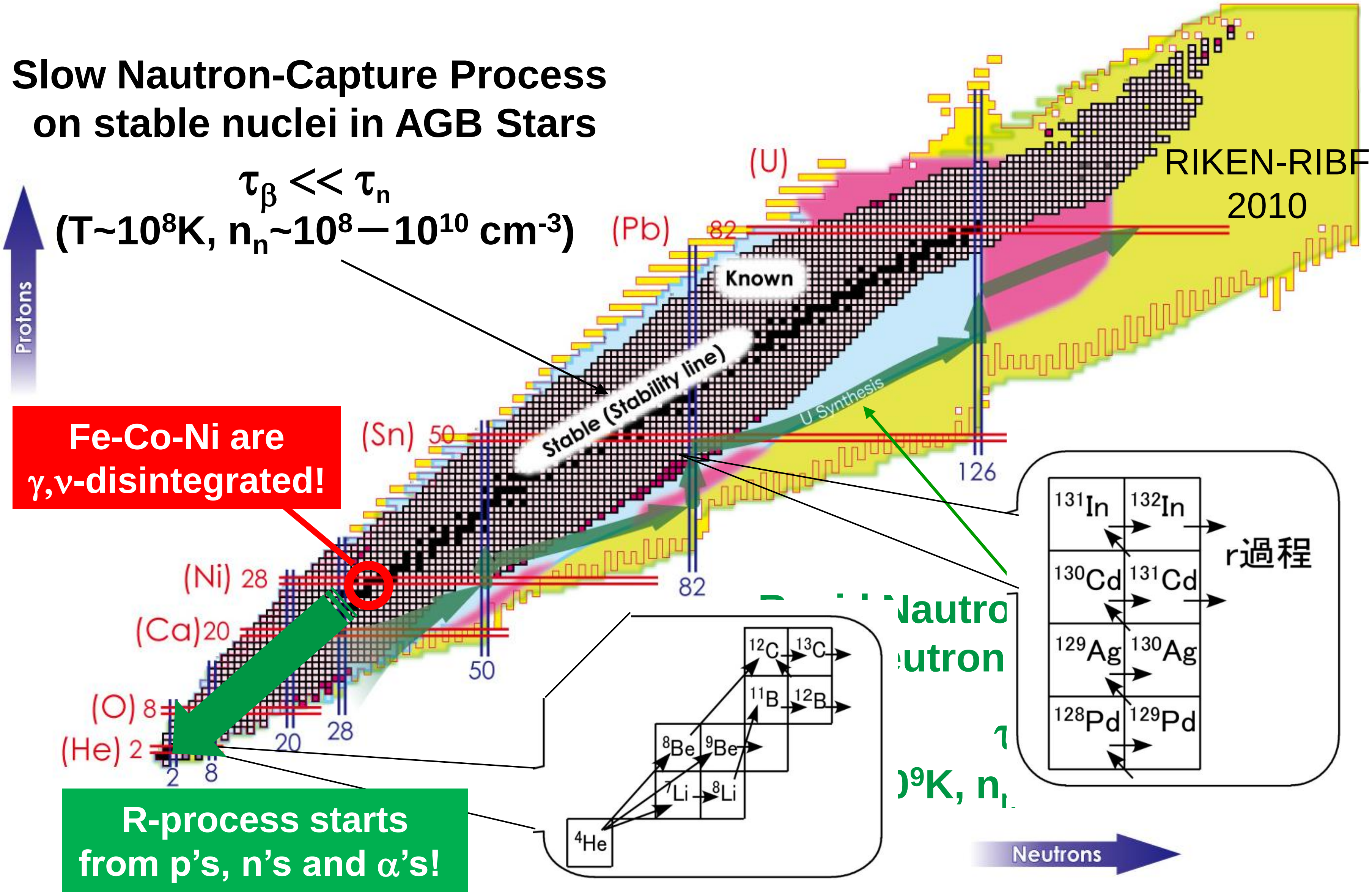


Magic Number and Slow/Rapid Neutron-Capture Processes from Text Book (Kubono & Kajino, 2010)

Slow Nautron-Capture Process on stable nuclei in AGB Stars

$\tau_\beta << \tau_n$

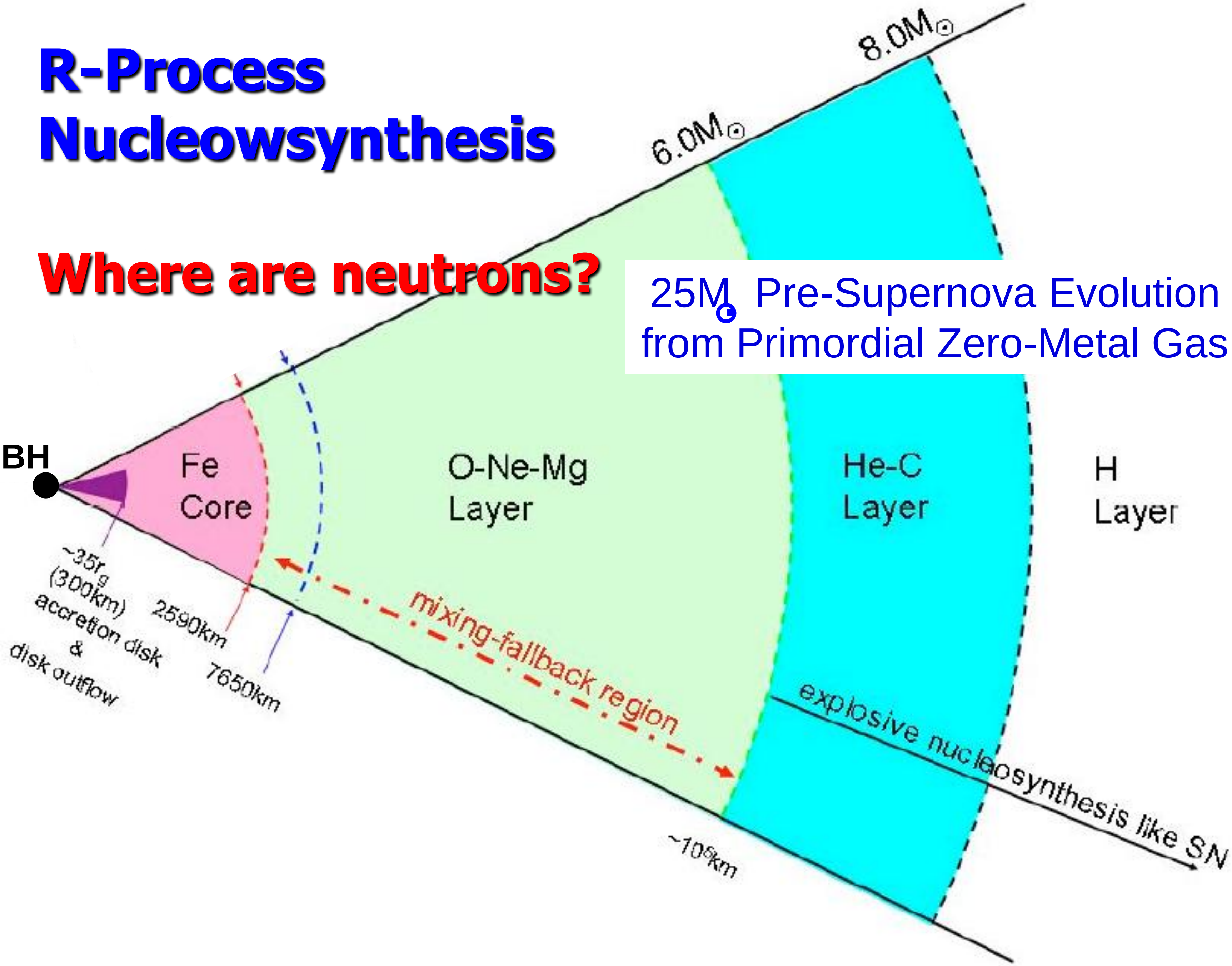
($T \sim 10^8$K, $n_n \sim 10^8 - 10^{10}$ cm^{-3})



R-Process Nucleowsynthesis

Where are neutrons?

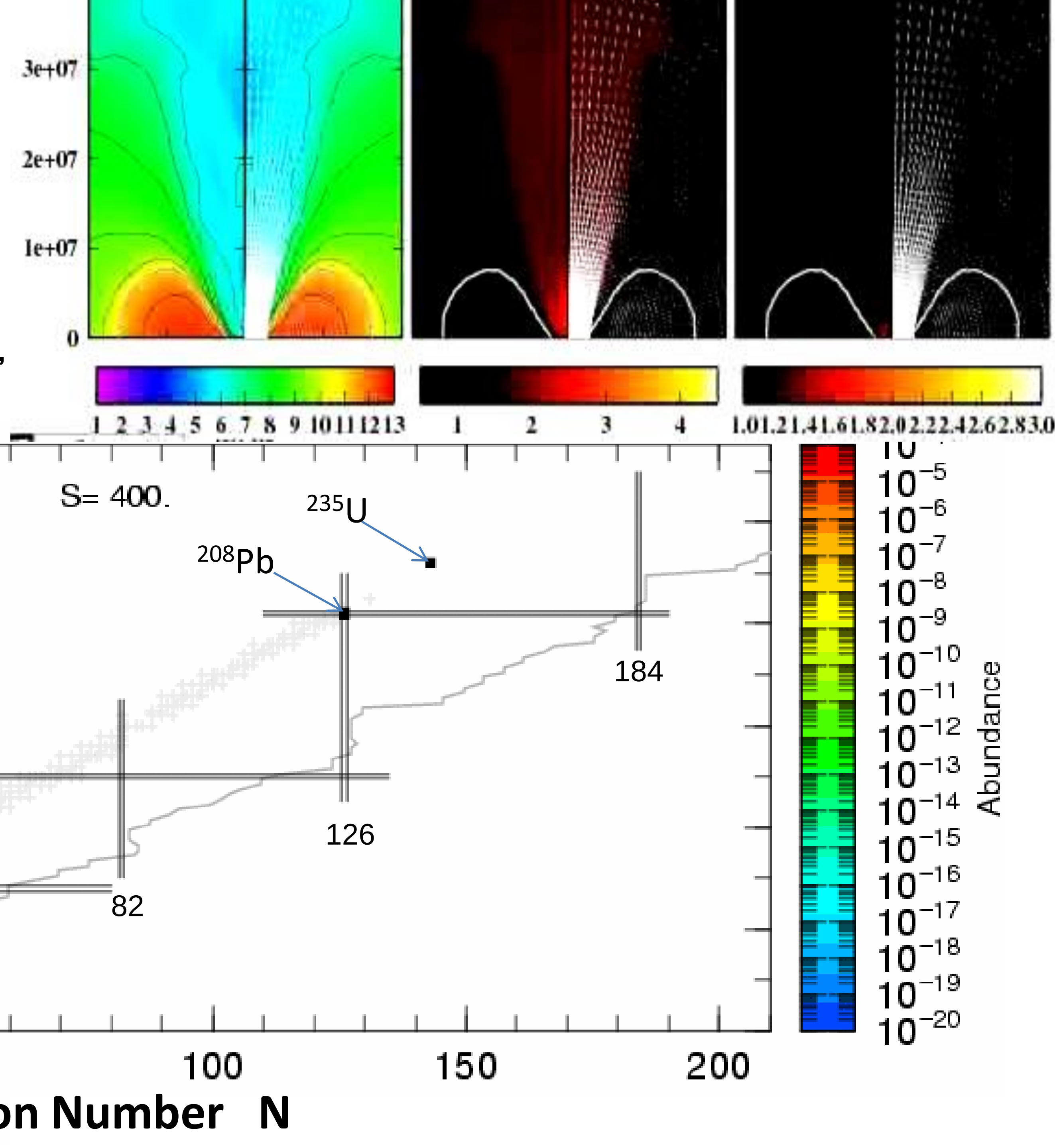
25M⊙ Pre-Supernova Evolution from Primordial Zero-Metal Gas



Supernova Nucleosynthesis Simulation

Movie by S. Chiba & T. Kajino

ν-Pair Heated Collapsar Model
Nakamura, Sato, Harikae, Kajino, & Mathews, ApJ (2012).



Neutrino-driven Wind Model

explains UNIVERSALITY !

Otsuki, Tagoshi, Kajino & Wanajo
2000, ApJ 533, 424
Wanajo, Kajino, Mathews &

t = 0

Neutrino-driven wind forms right after SN core collapse.

n + α + p

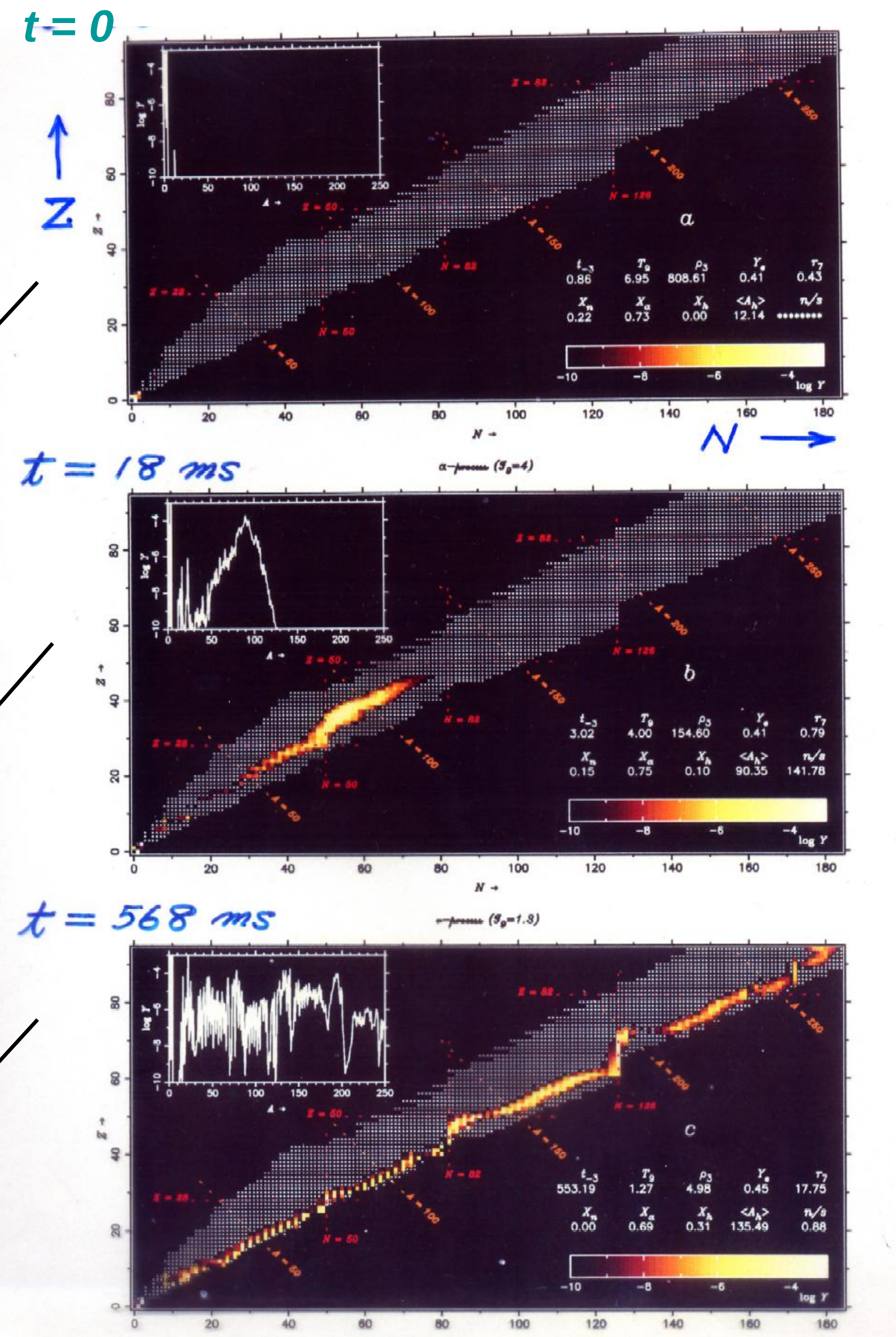
t = 18 ms

Seeds form.

Exotic neutron-rich; ^{78}Ni

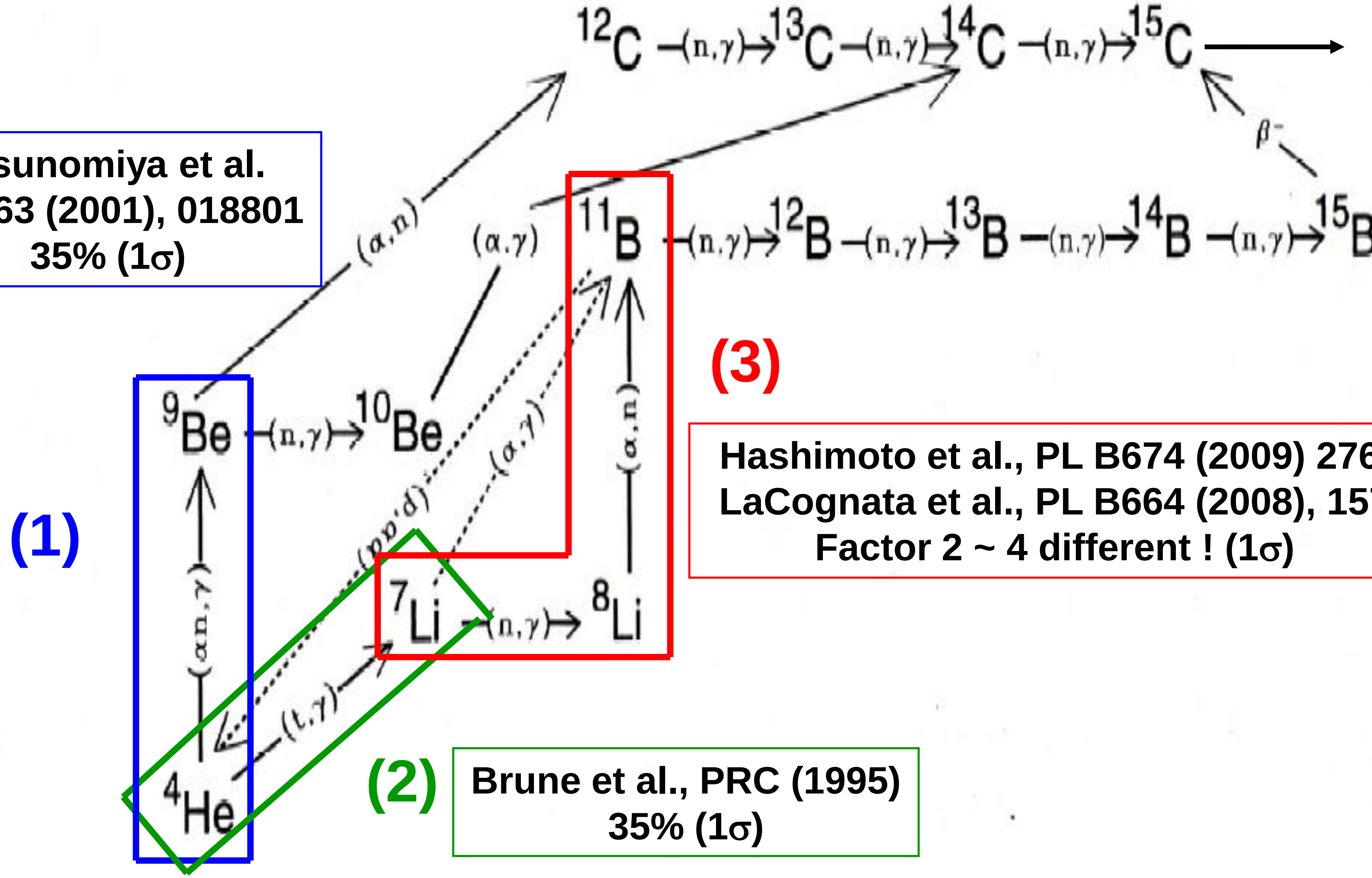
t = 568 ms – 1 s

Heavy r-elements form.



Identified Important Reaction Flow Paths

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

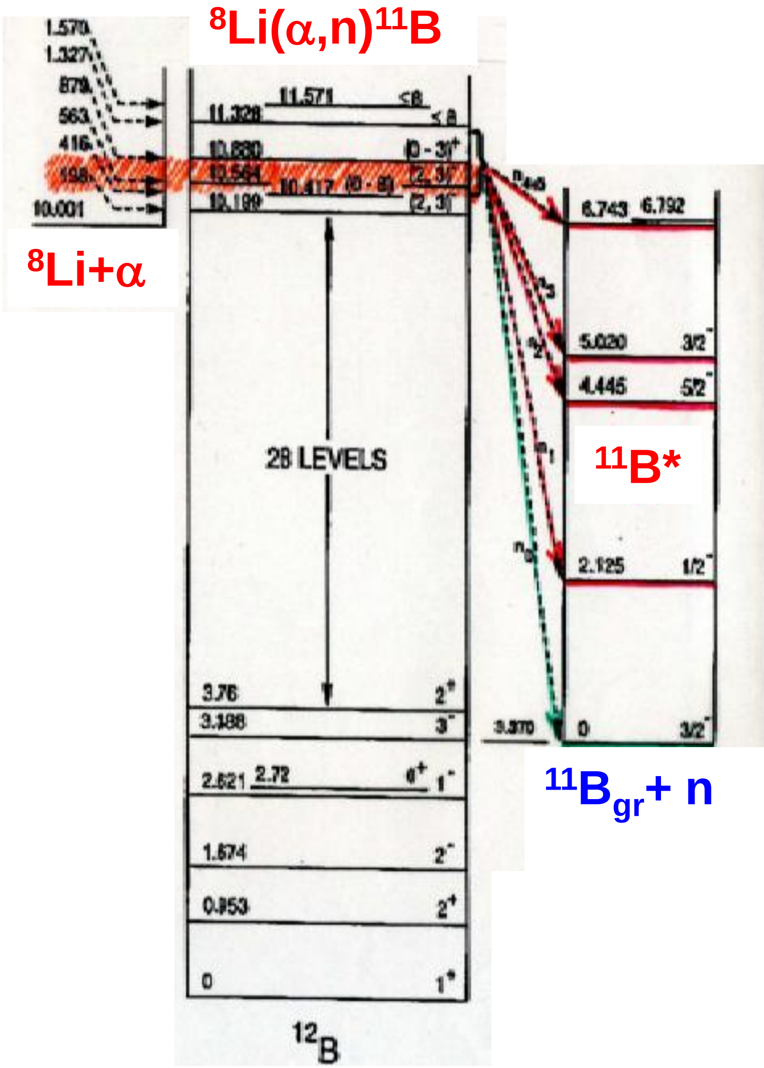


Hashimoto et al., PL B674 (2009) 276.
LaCognata et al., PL B664 (2008), 157.
Factor 2 ~ 4 different ! (1σ)

Brune et al., PRC (1995)
35% (1σ)

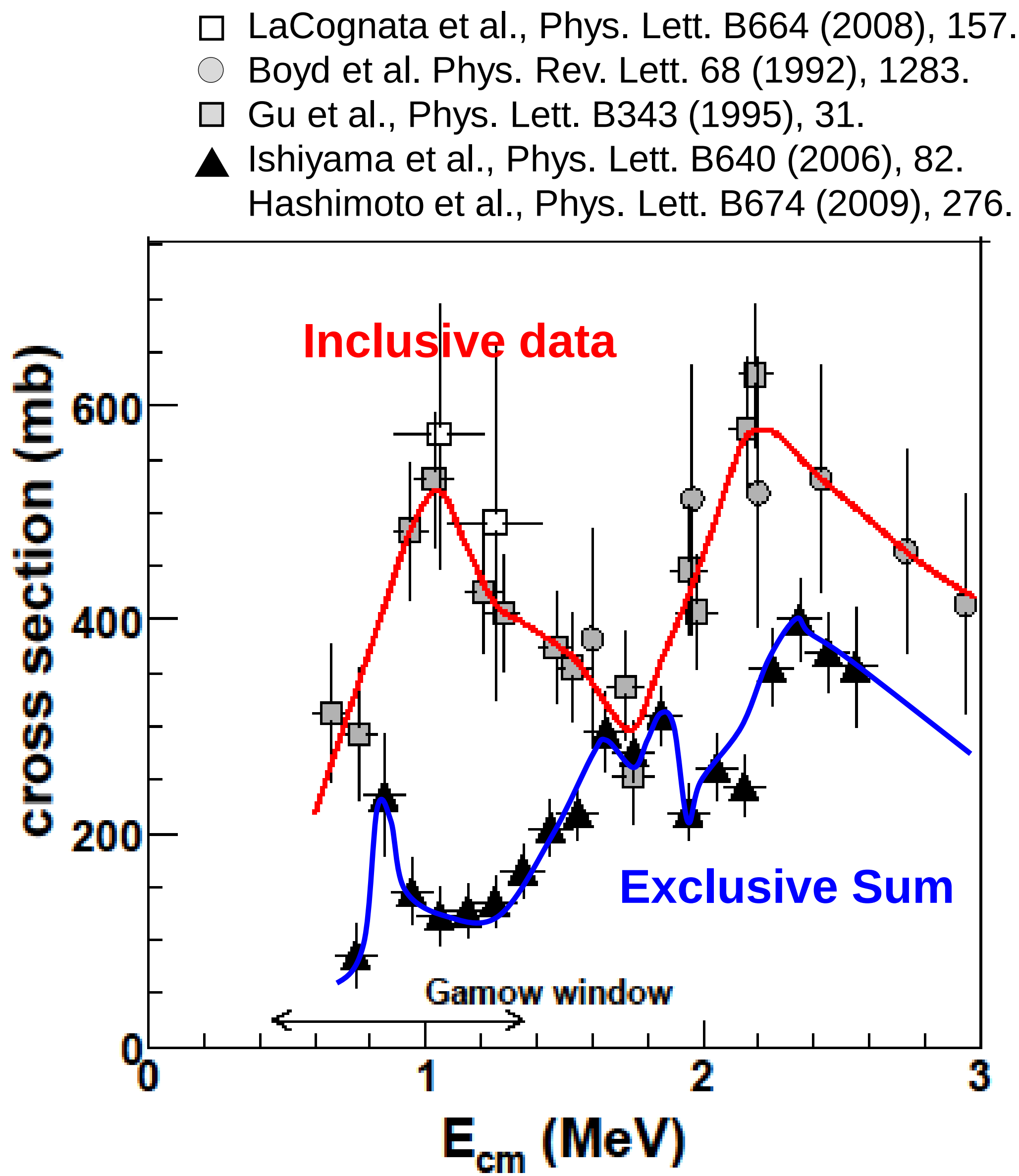
$^7Li(n,\gamma)^8Li(\alpha,n)^{11}B$

LaCognata et al., ApJL (2010).



Discrepancy

Inclusive Data >> Exclusive Sum

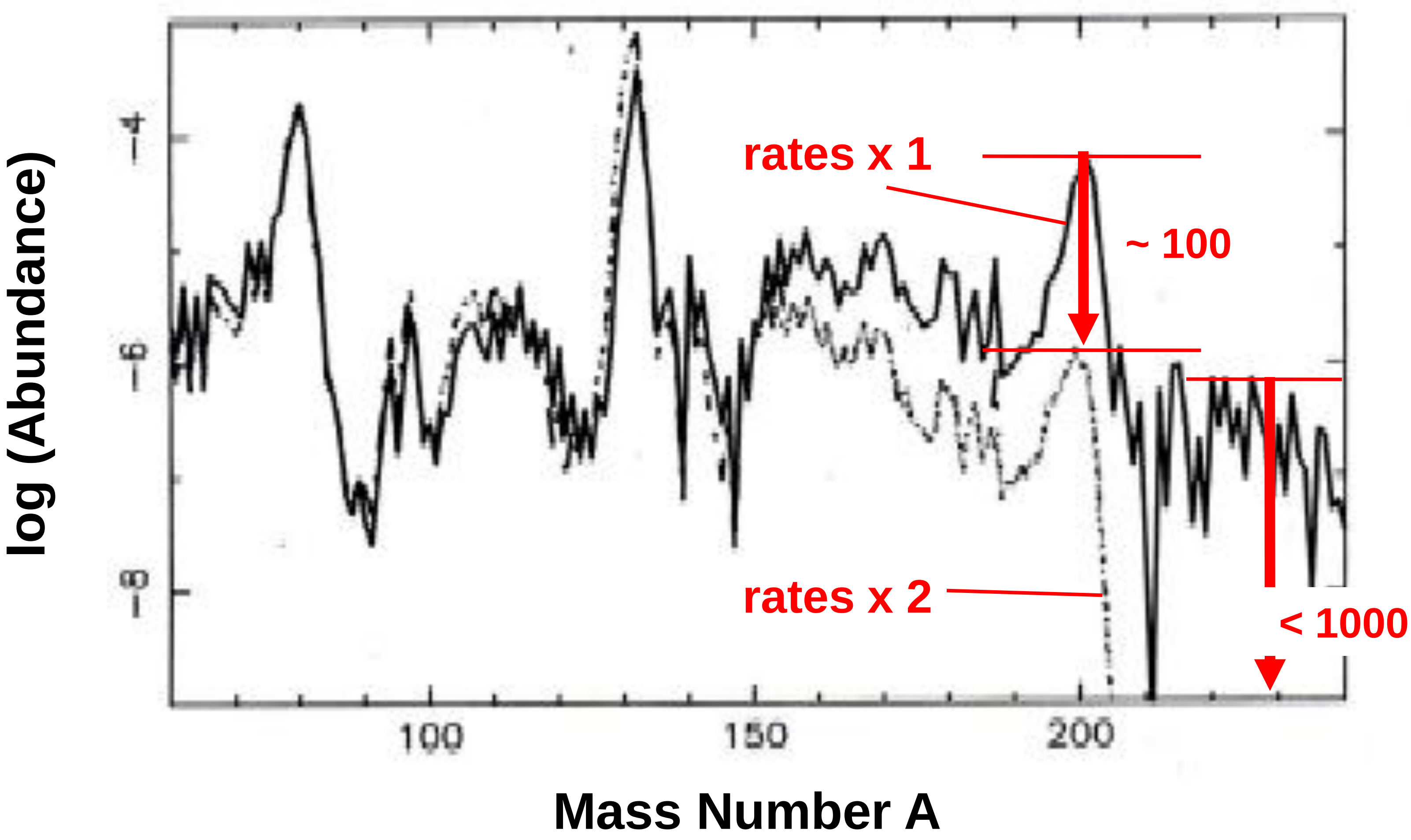


NON-LINEAR Effect of "α-process — r-process"

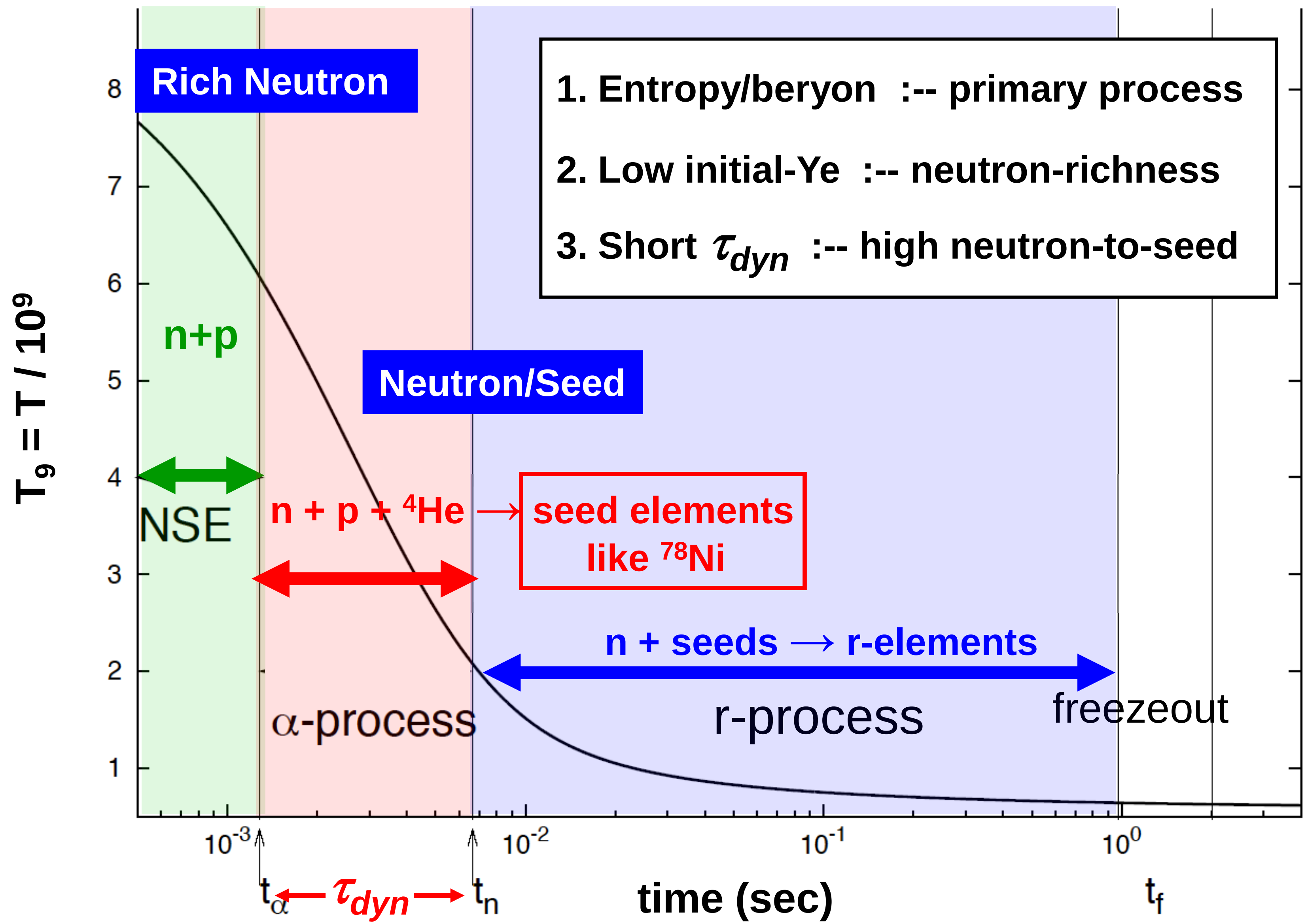
(1) $\alpha(\alpha n, \gamma)^9Be$

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

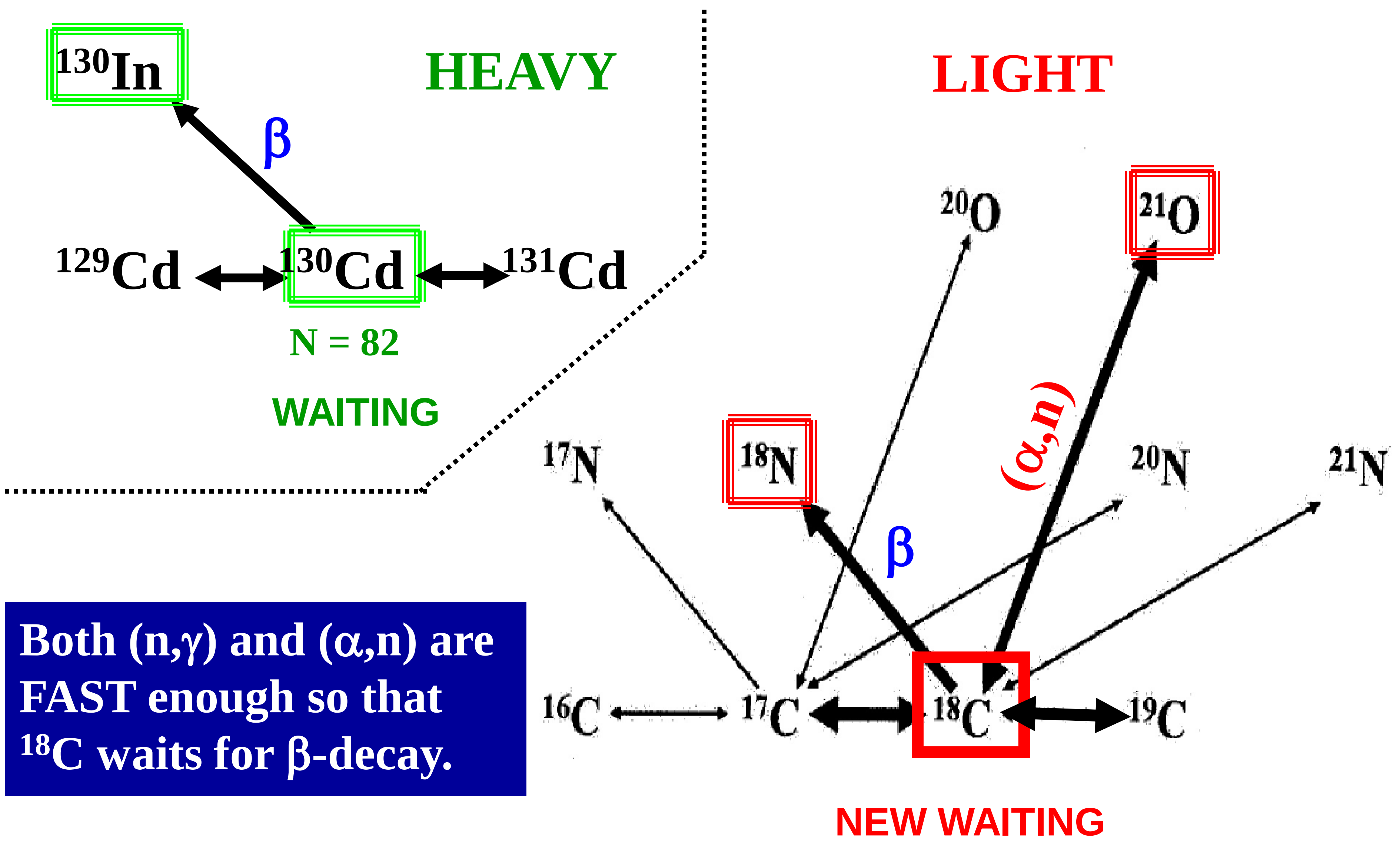
} x 2 artificial change



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

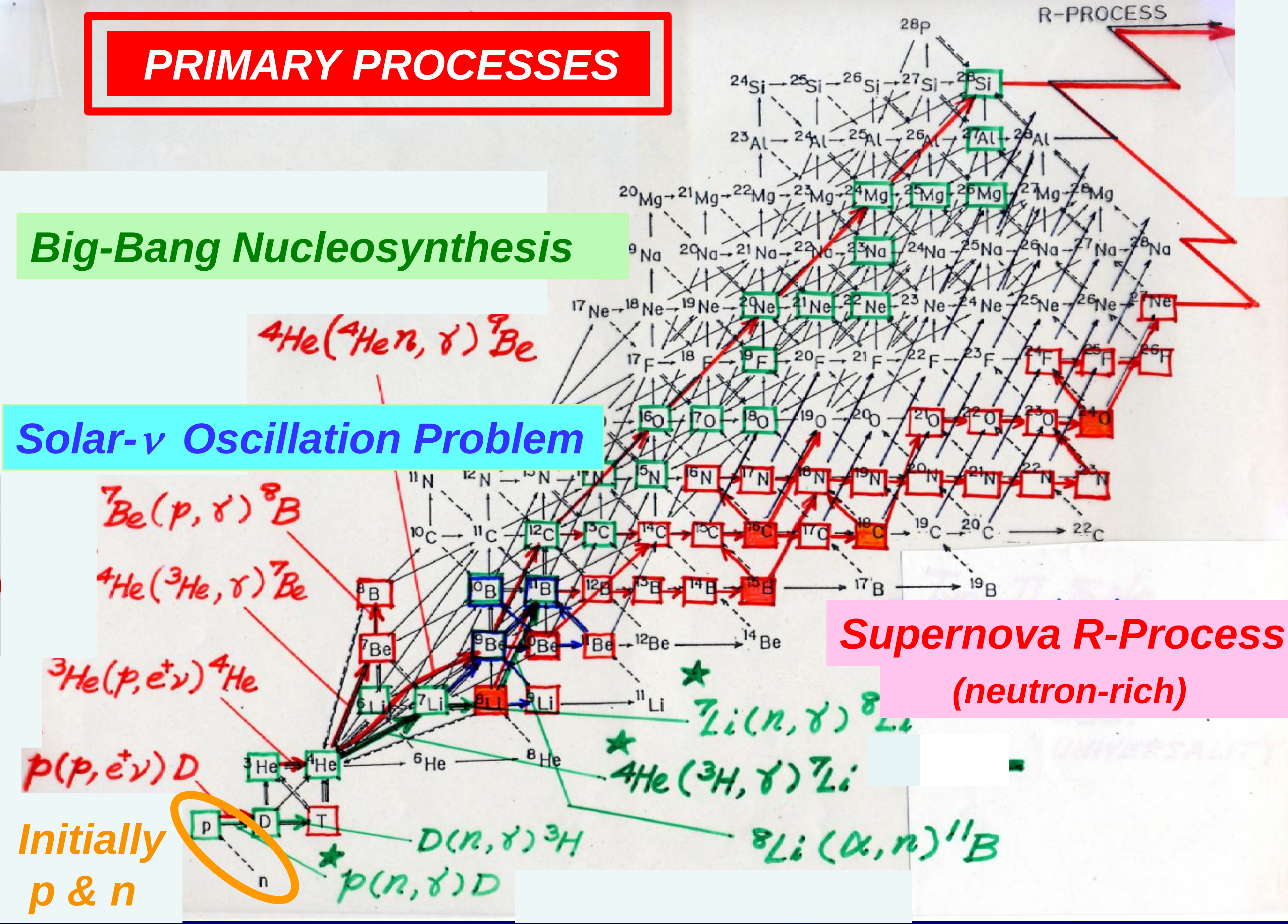


New Waiting Points in Light-Mass Nuclei

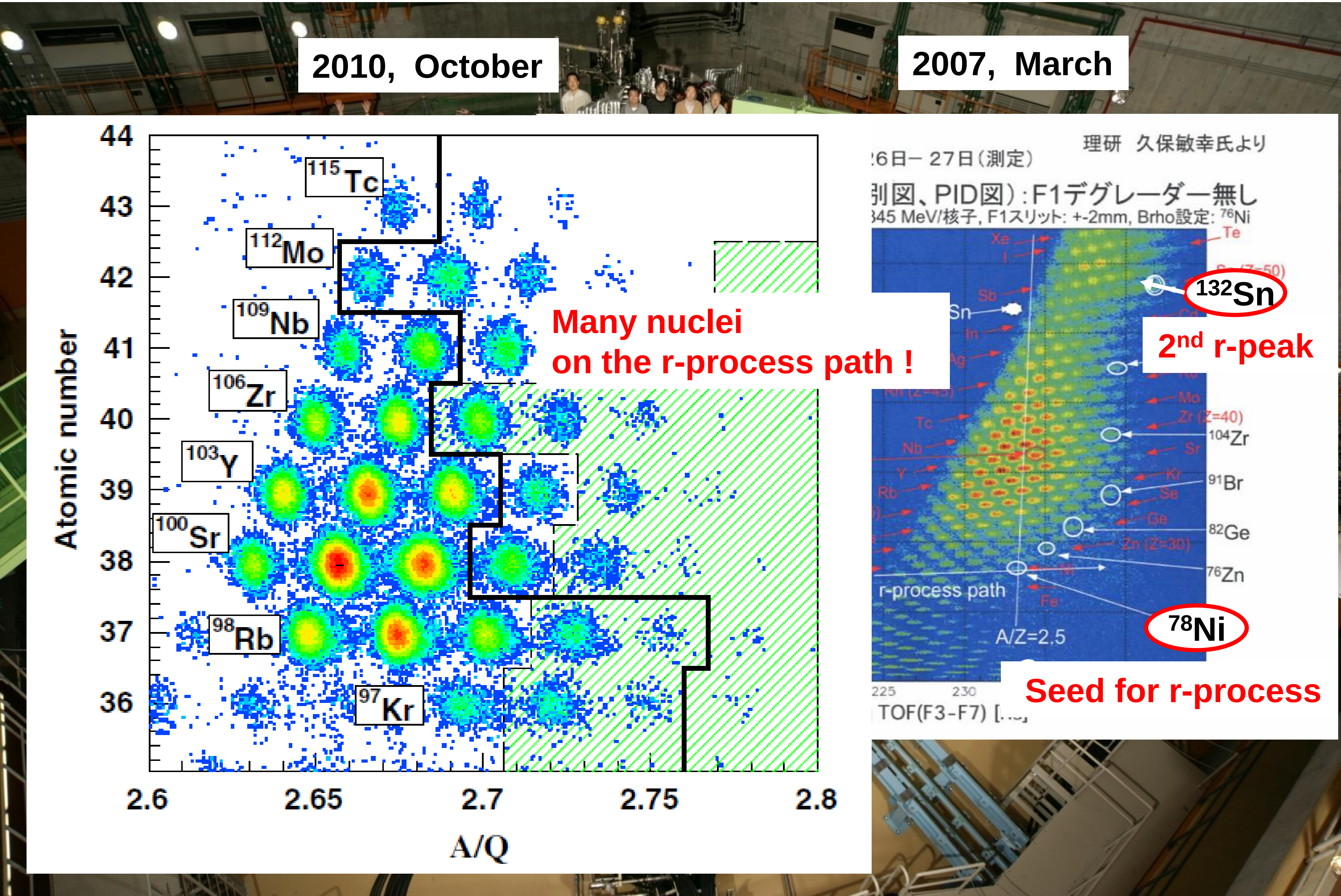


Both (n,γ) and (α,n) are FAST enough so that ^{18}C waits for β-decay.

PRIMARY PROCESSES

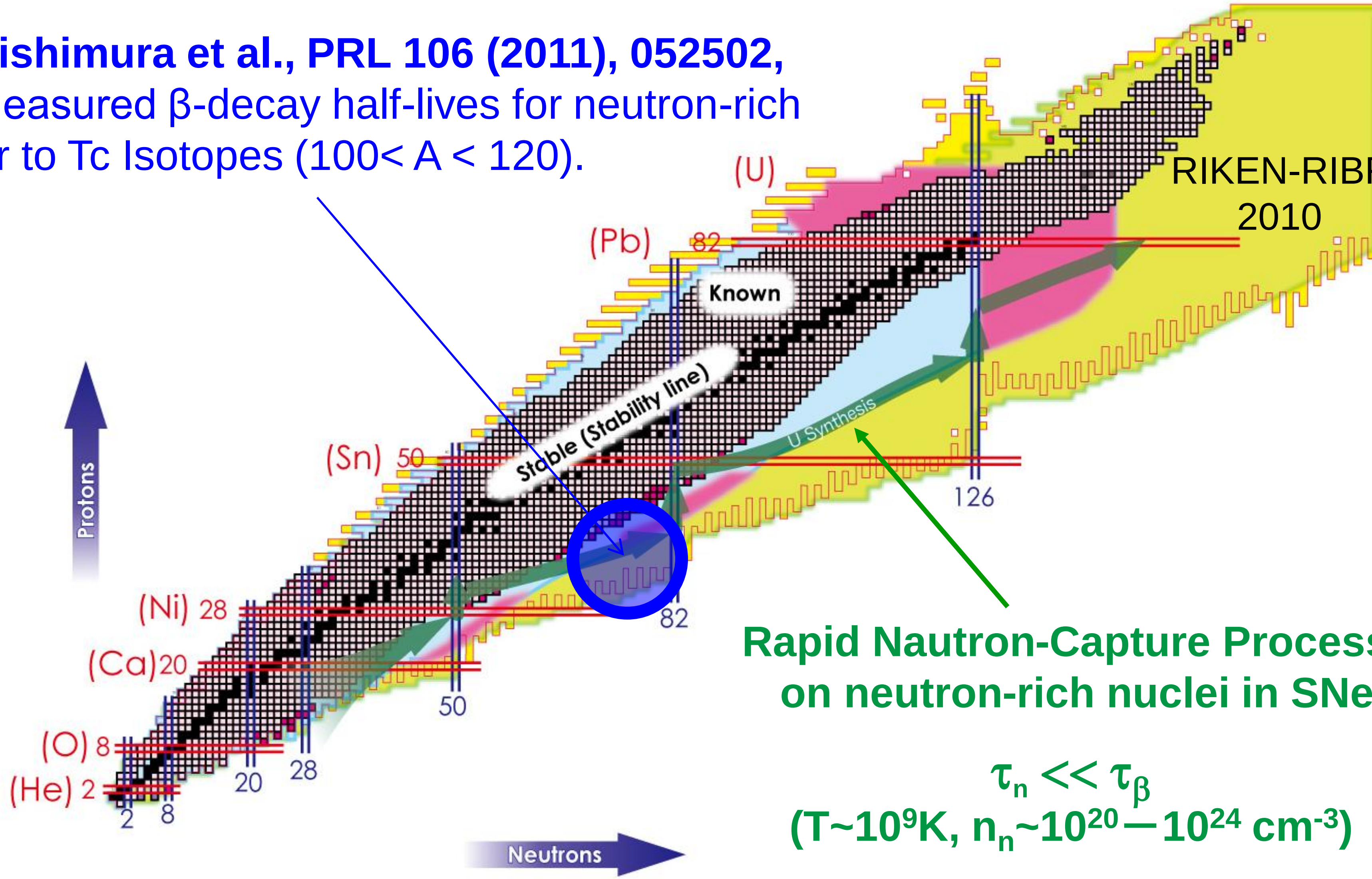


RIKEN-RIBF New Ring Cyclotron (since 2007)



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

Nishimura et al., PRL 106 (2011), 052502,
measured β-decay half-lives for neutron-rich Kr to Tc Isotopes (100< A < 120).



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

$\tau_n << \tau_\beta$

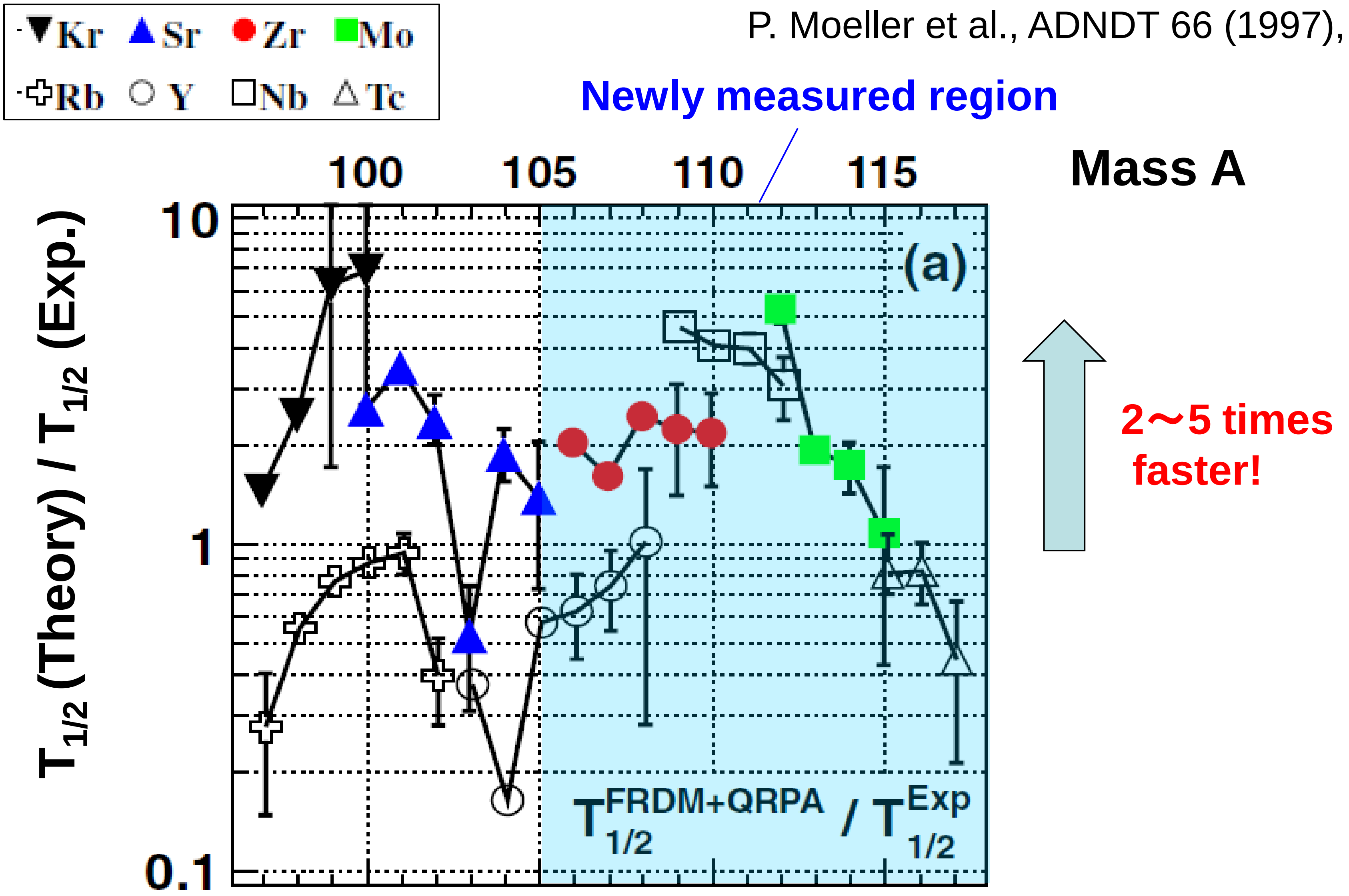
($T \sim 10^9$K, $n_n \sim 10^{20} — 10^{24}$ cm^{-3})

β-decays are FASTER than FRDM+QRPA theory !

Nishimura et al., PRL 106 (2011) 052502

FRDM = Finite Range Droplet Mass model

P. Moeller et al., ADNDT 66 (1997), 131

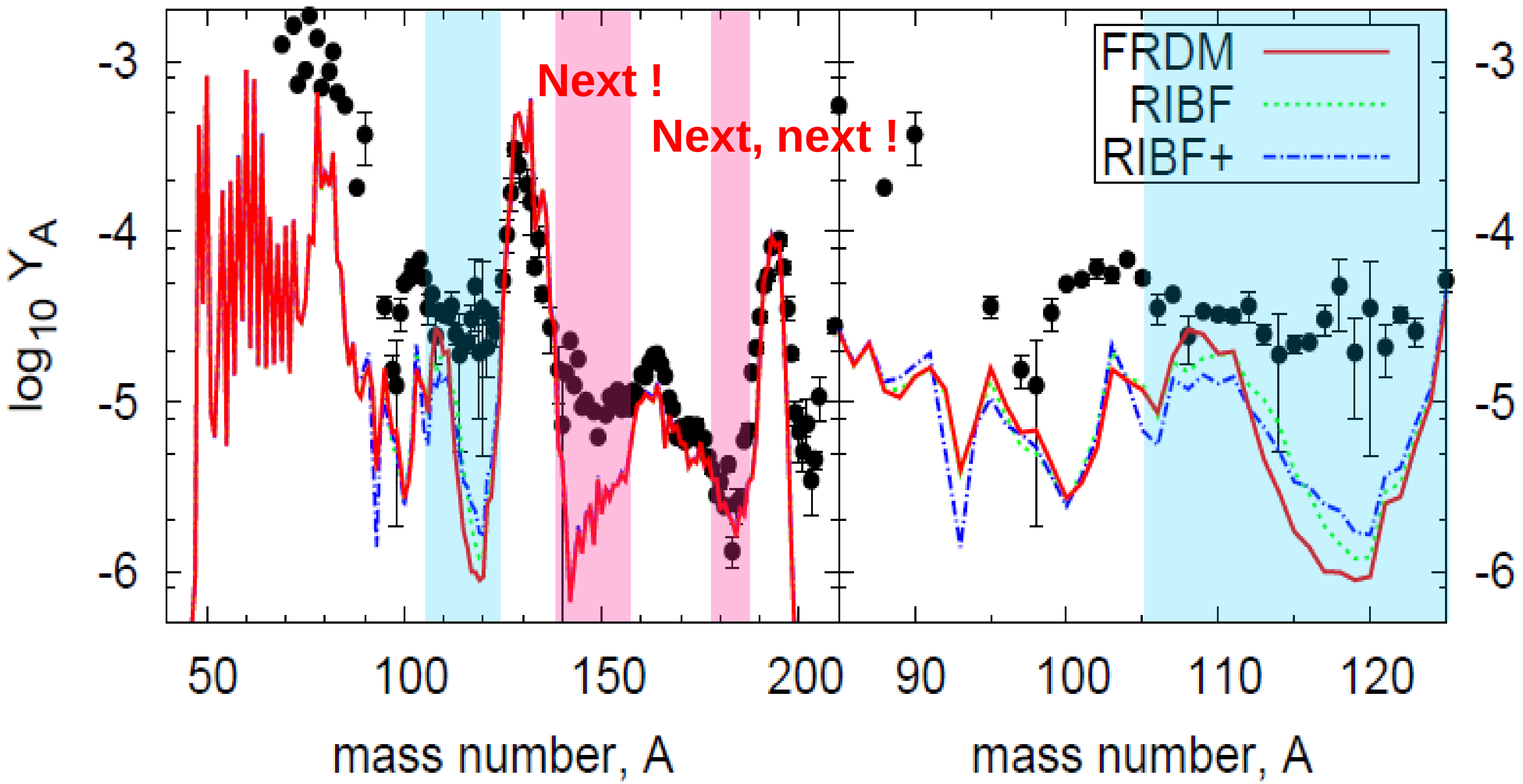


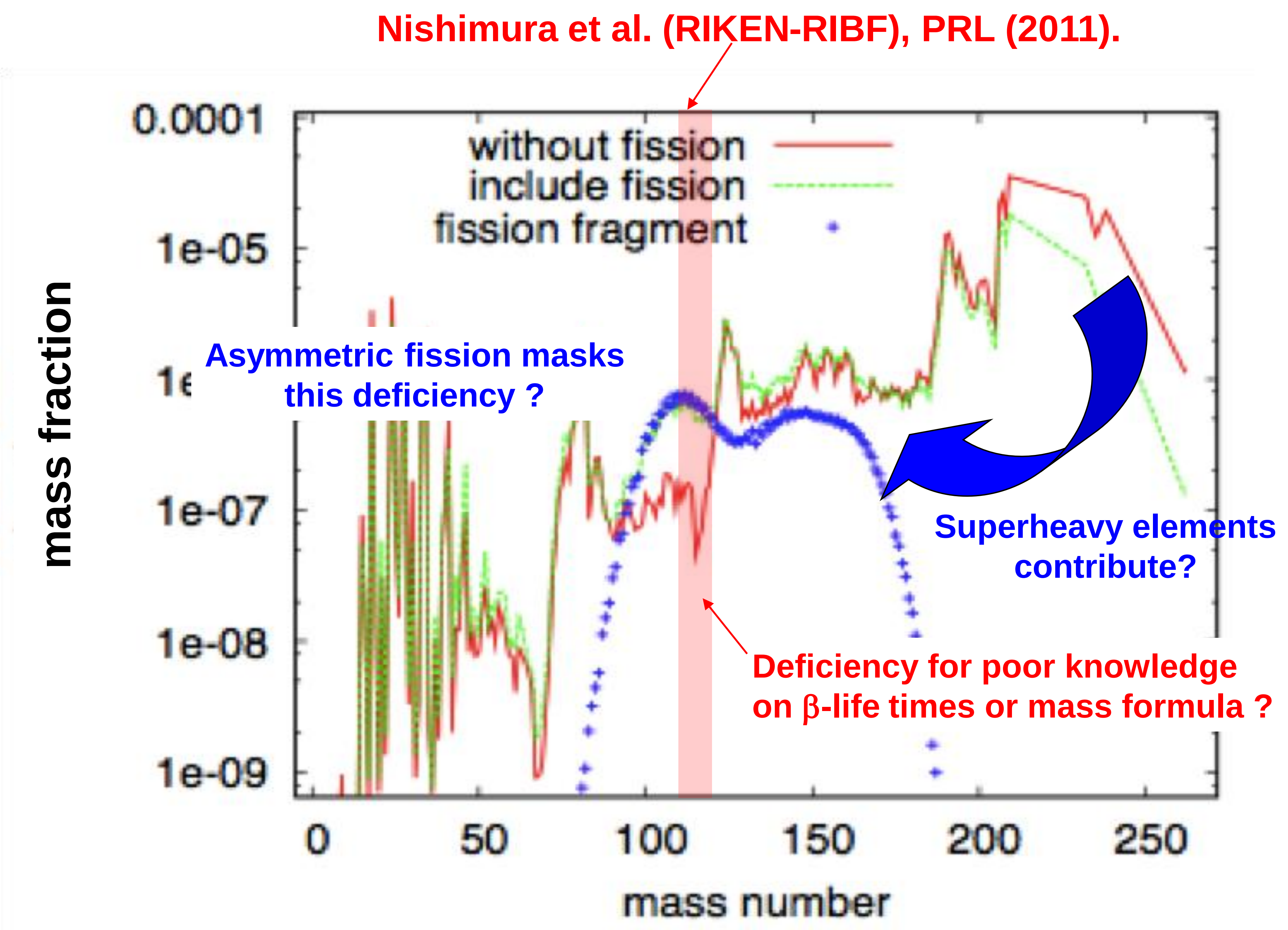
DEFICIENCY problem at A = 105-120

Is this caused by "~~Nuclear Physics~~" or "Astrophysics"?

MHD-Jet SN Model
Nishimura, Kajino, Mathews,
Nishimura & Suzuki (2012),
PR C85, 048801

New RIKEN data of β-lives (& Q-values) only slightly improve this deficiency, but not enough !





Nishimura et al. (RIKEN-RIBF), PRL (2011).
0.0001
1e-05
1e-07
1e-08
1e-09
0
50
100
150
200
250
mass fraction
mass number
without fission
include fission
fission fragment
Asymmetric fission masks
this deficiency ?
Superheavy elements
contribute?
Deficiency for poor knowledge
on β-life times or mass formula ?

Candidate Astrophysical Sites for R-Process

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Gamma-ray Burst Candidate					○ Only Metal poor☆ Broken Universality △ Explosion model, but special condition
d. Hypernova	1-1000	0.1	$10^{-1}M_\odot$	< 10^{-6}	

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

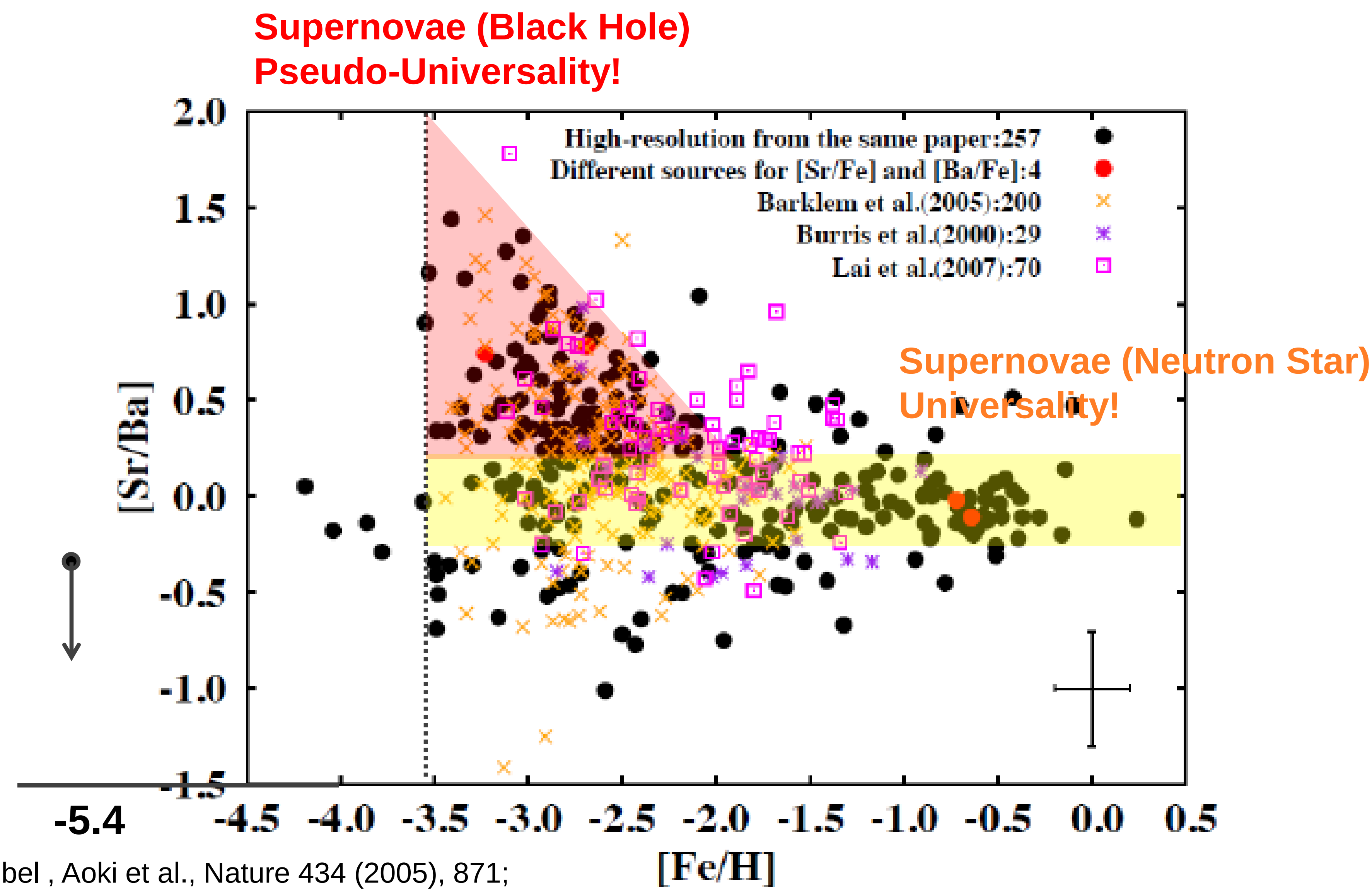
$10^{-5}M_\odot \times 10^{-2} \times 10^{10} = 10^3 M_\odot$

Cosmic age (→ 10^{10})

* consistent with observed SN frequency

New Insights into the Astrophjysical r-Process

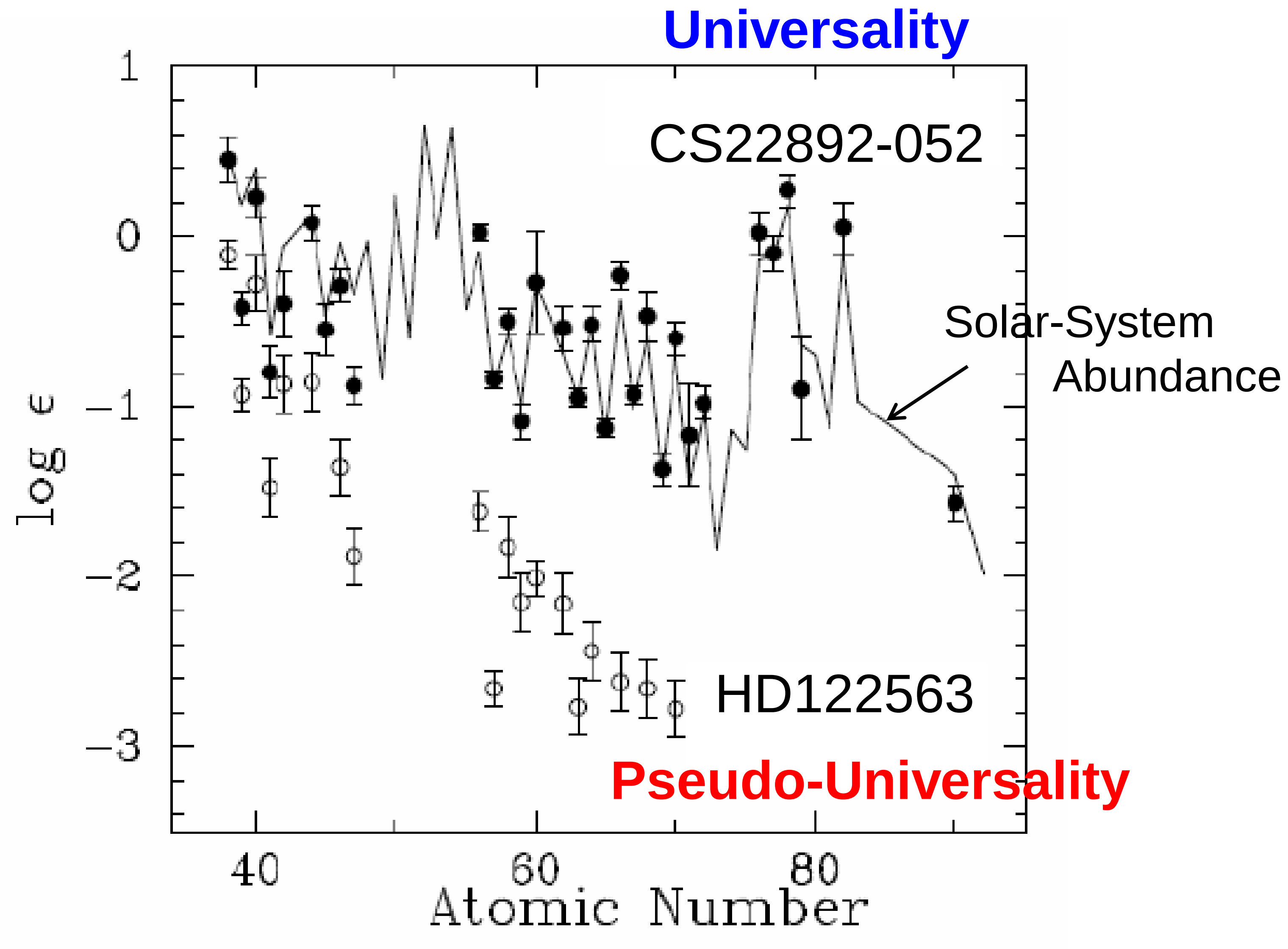
W. Aoki, R.N. Boyd, M. Famiano, T. Suda, and T. Kajino



Frebel , Aoki et al., Nature 434 (2005), 871;
Aoki et al., ApJ 639 (2006), 897.

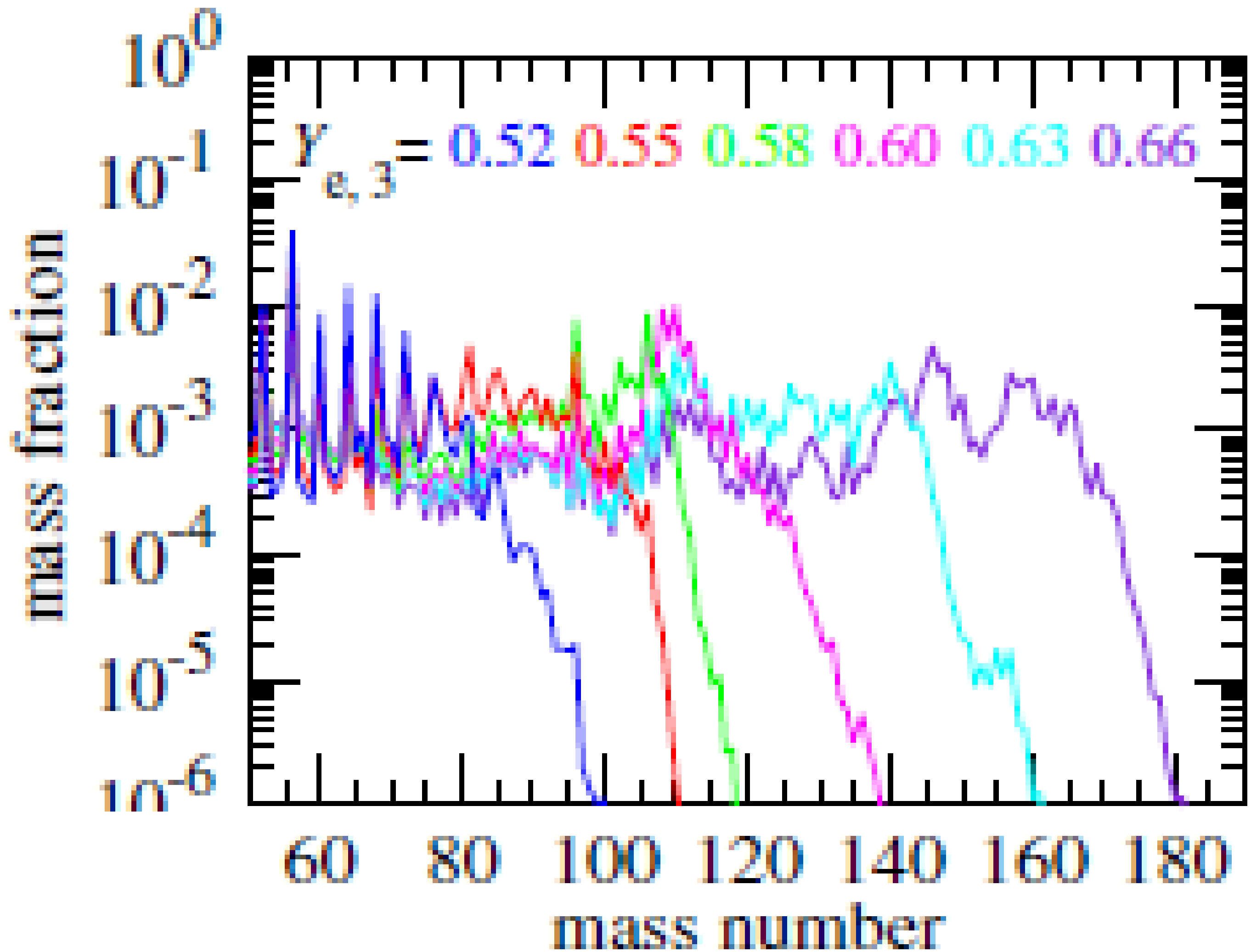
UNIVERSALITYの亜種の発見

（Honda, Aoki, + すばる望遠鏡HDSチーム）



UNCERTAINTIES IN THE νp-PROCESS: SUPERNOVA DYNAMICS VERSUS NUCLEAR PHYSICS

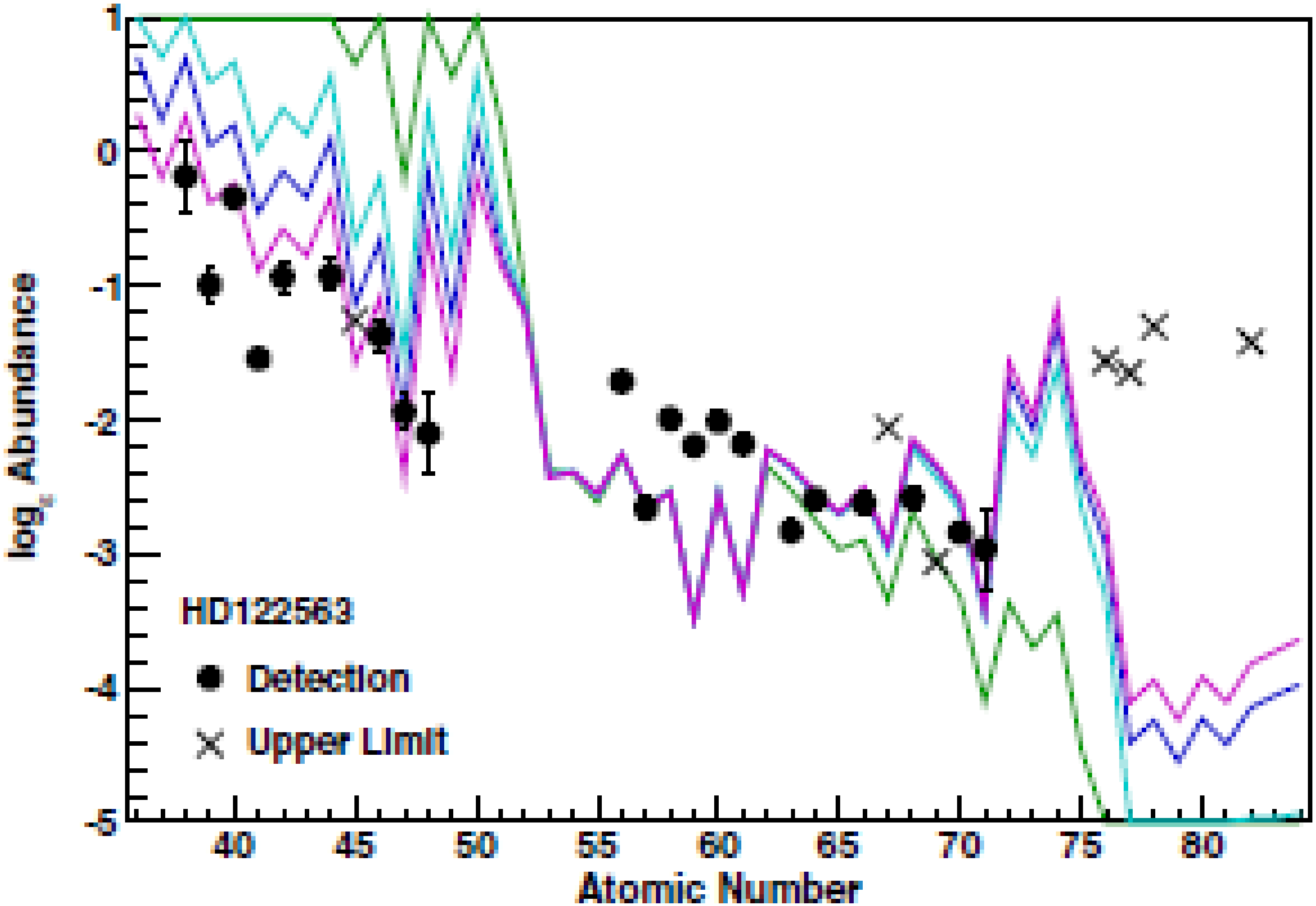
Shinya Wanajo[1,2], Hans-Thomas Janka[2], and Shigeru Kubono[3]



The Astrophysical Journal Letters, 744:L14 (4pp), 2012 January 1

THE r-PROCESS IN METAL-POOR STARS AND BLACK HOLE FORMATION

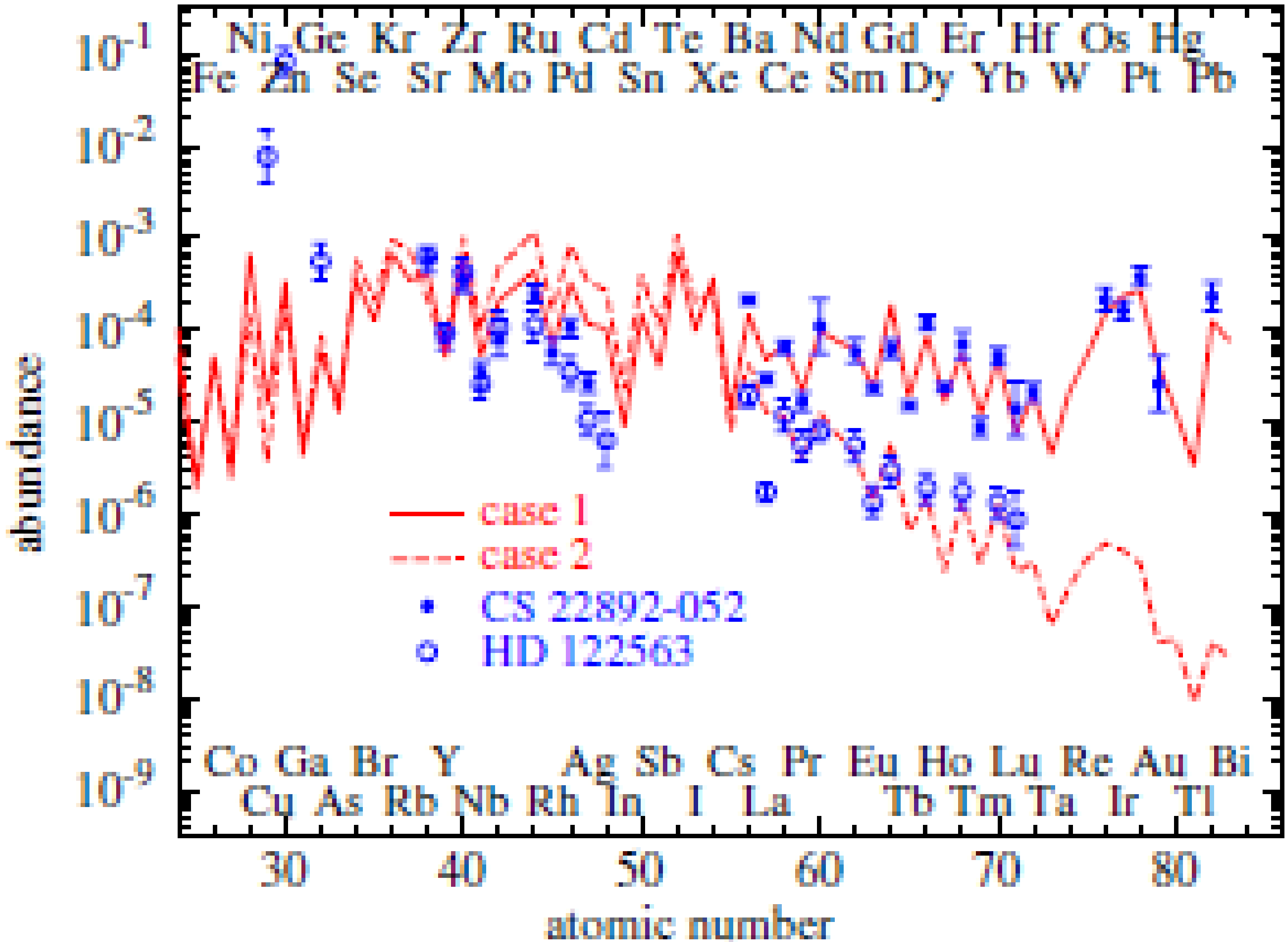
R. N. Boyd[1], M. A. Famiano[2], B. S. Meyer[3], Y. Motizuki[4], T. Kajino[5,7], and I. U. Roederer[6]



The Astrophysical Journal, 746:180 (15pp), 2012 February 20

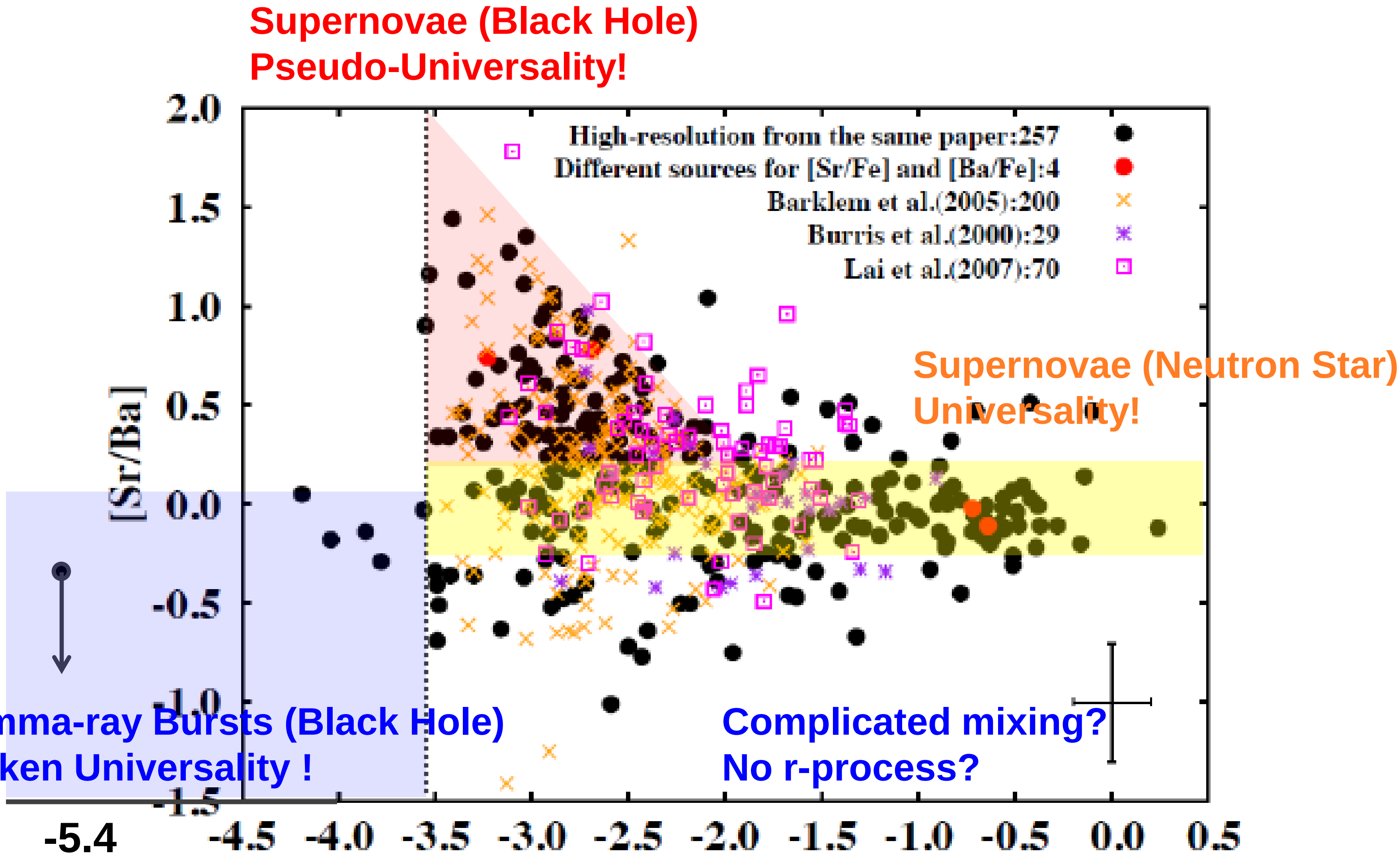
The r-PROCESS IN THE NEUTRINO-DRIVEN WIND FROM A BLACK-HOLE TORUS

Shinya Wanajo[1,2] and Hans-Thomas Janka[2]



New Insights into the Astrophjysical r-Process

W. Aoki, R.N. Boyd, M. Famiano, T. Suda, and T. Kajino



Frebel , Aoki et al., Nature 434 (2005), 871;
Aoki et al., ApJ 639 (2006), 897.

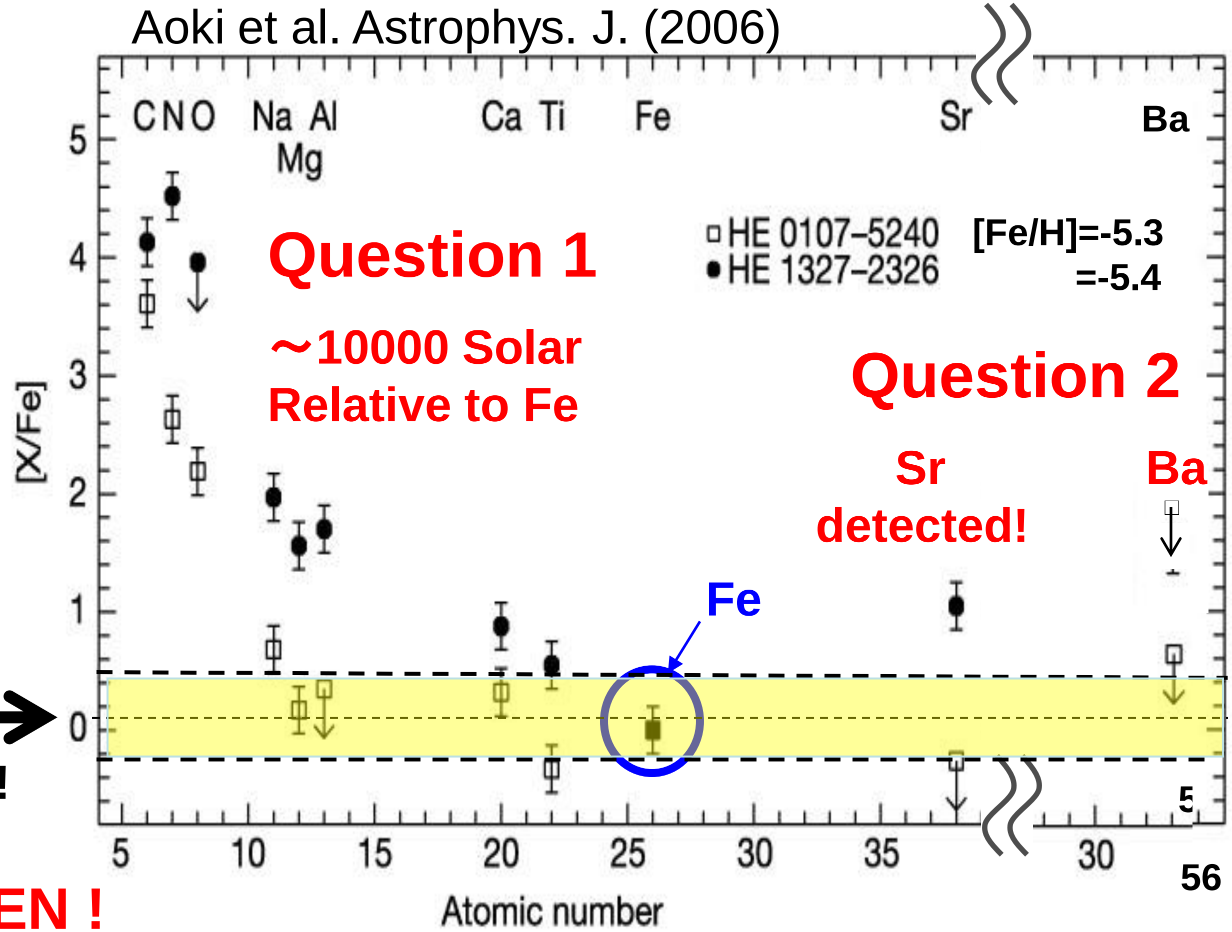
Our SUBARU-HDS group discovered an oldest Pop. II Halo Star in the Milky Way !

[Fe/H] = -5.4 ! → 1/250,000 x Solar-Fe

SUBARU Telescope

Mauna Kea, Hawaii

Frebel, Aoki, et al. Nature 434 (2005), 871,
Aoki et al. Astrophys. J. (2006)

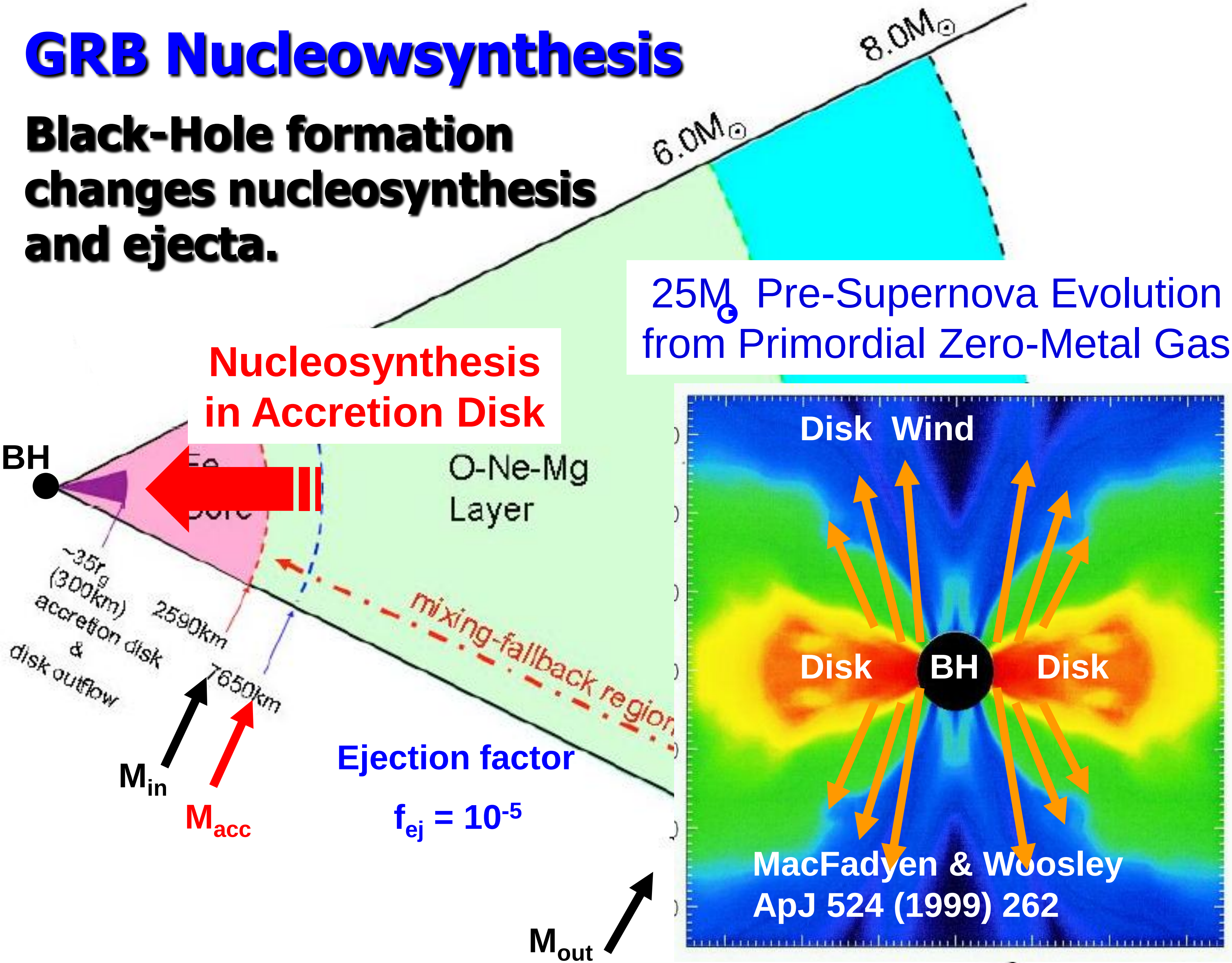


Standard SN model Prediction = Universality! →

Universality is BROKEN !

GRB Nucleowsynthesis

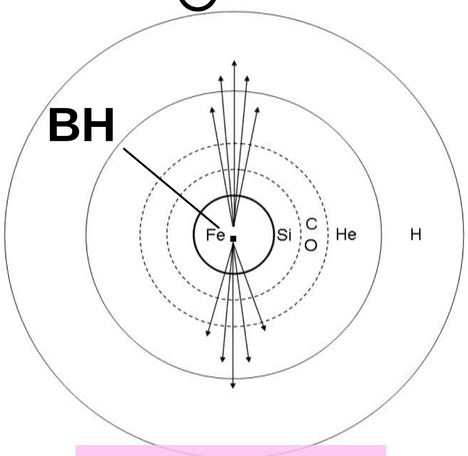
Black-Hole formation changes nucleosynthesis and ejecta.



GRB Nucleosynthesis Model Prediction

Heavy nuclei are produced in r-process in the disk-wind.

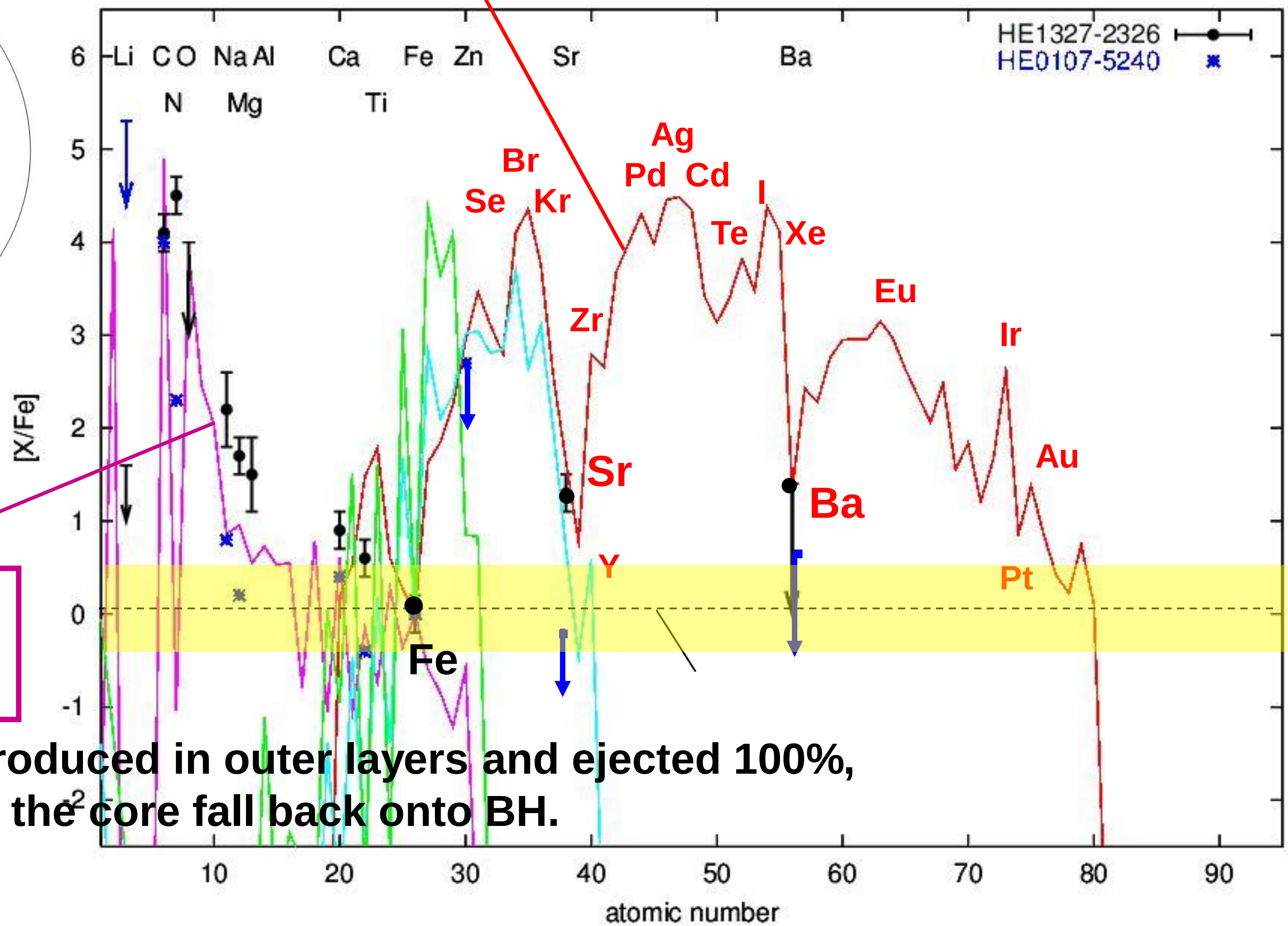
Pre-Collapsar
25M$_\odot$



Outer Layer

R-Process from Disk-Wind Outflow

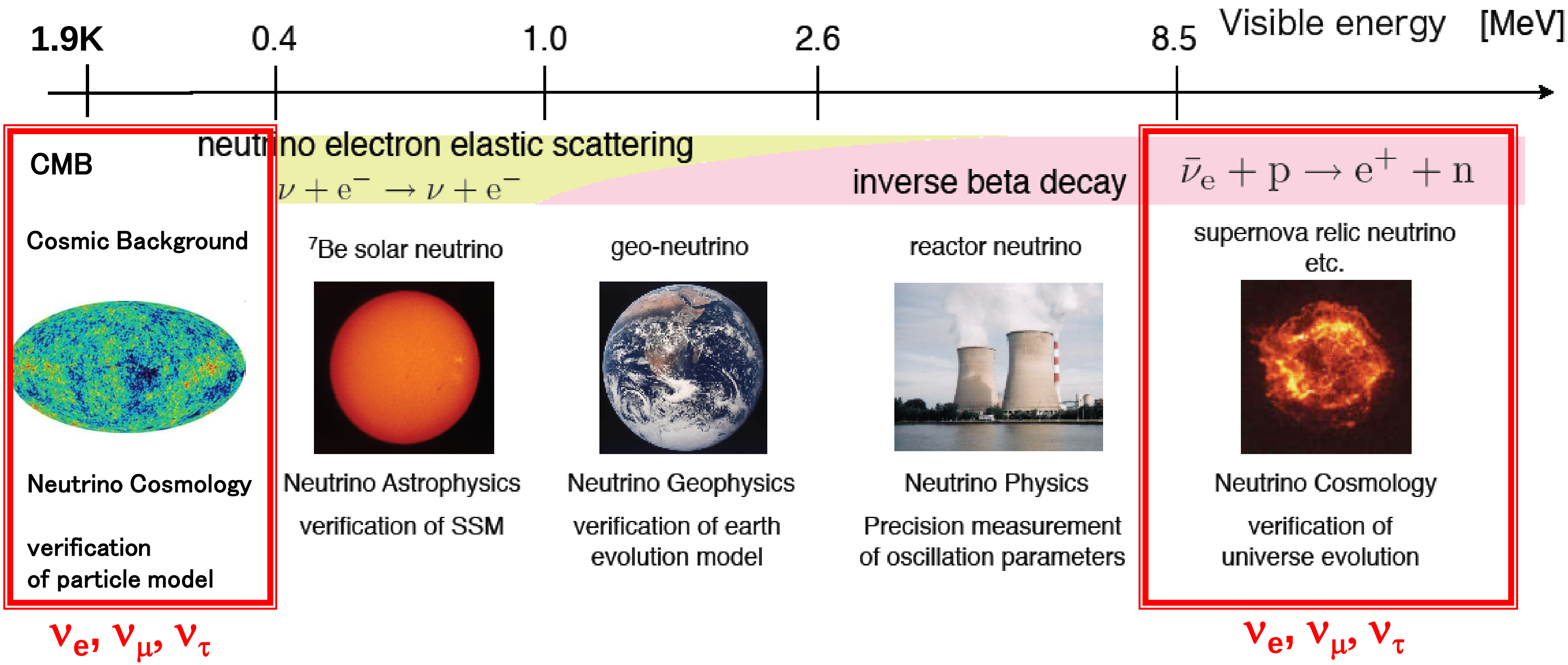
Kajino, Shaku, Sasaqui, Yoshida, Aoki & Mathews (2010): Kajino, Sato, Nakamura, Nishmura & Mathews (2010)



Mixing Fallback onto BH

Light nuclei are produced in outer layers and ejected 100%, but products near the core fall back onto BH.

Various Neutrino-Sources in Nature

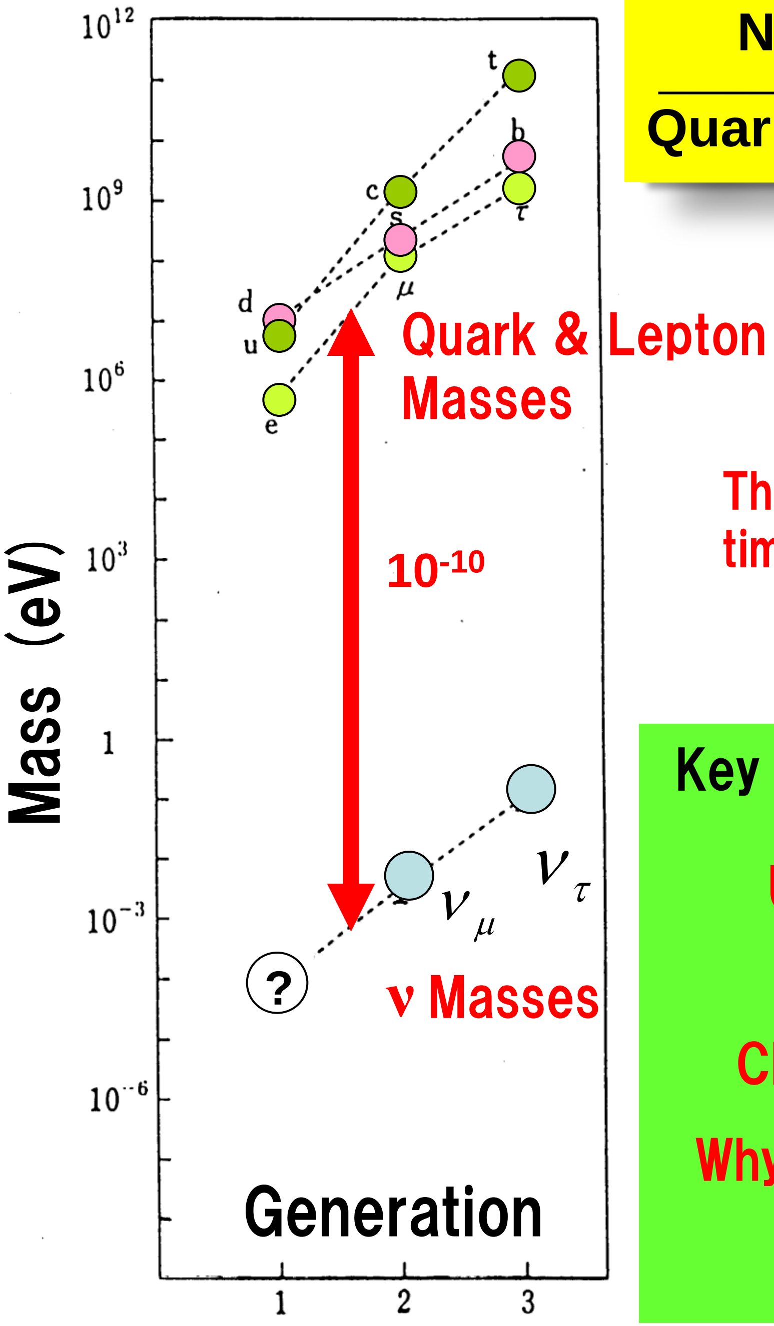


PURPOSE

1. To study supernova nucleosynthesis and ν-oscillation.

1st, SN-temperature, 2nd, ν-oscillation physics.

2. To constrain the total ν–mass from cosmology.



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

⇓

$E = mc^2$

Why 10^{-10} ?

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 mass neutrinos:

Unification of elementary forces BEYOND the standard model ?

CP violation and Lepto- & Baryo-genesis ?

Why left-handed neutrinos, Majorana or Dirac ?

Explosion Mechanism of Supernovae ?

Challenge of the Century

Universal expansion is most likely accelerating and flat !

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

- **What is the CDM, $\Omega_{CDM} = 0.23$, and Dark Energy, $\Omega_\Lambda = 0.73$?**

  CMB including ν-mass: Yamazaki, Kajino, Mathews & Ichiki, Phys. Rep. (2012), in press.

- **Is BARYON, $\Omega_B = 0.04$, well understood ?**

  BBN with Axions + **SUSY** to solve **Dark Matter Problem & Li Problem**:

  Kusakabe, Balantekin, Kajino & Pehlivan, (2012) arXiv:1202.560.

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

➡ **Total ν mass, Hierarchy, details of mixing nature ?**

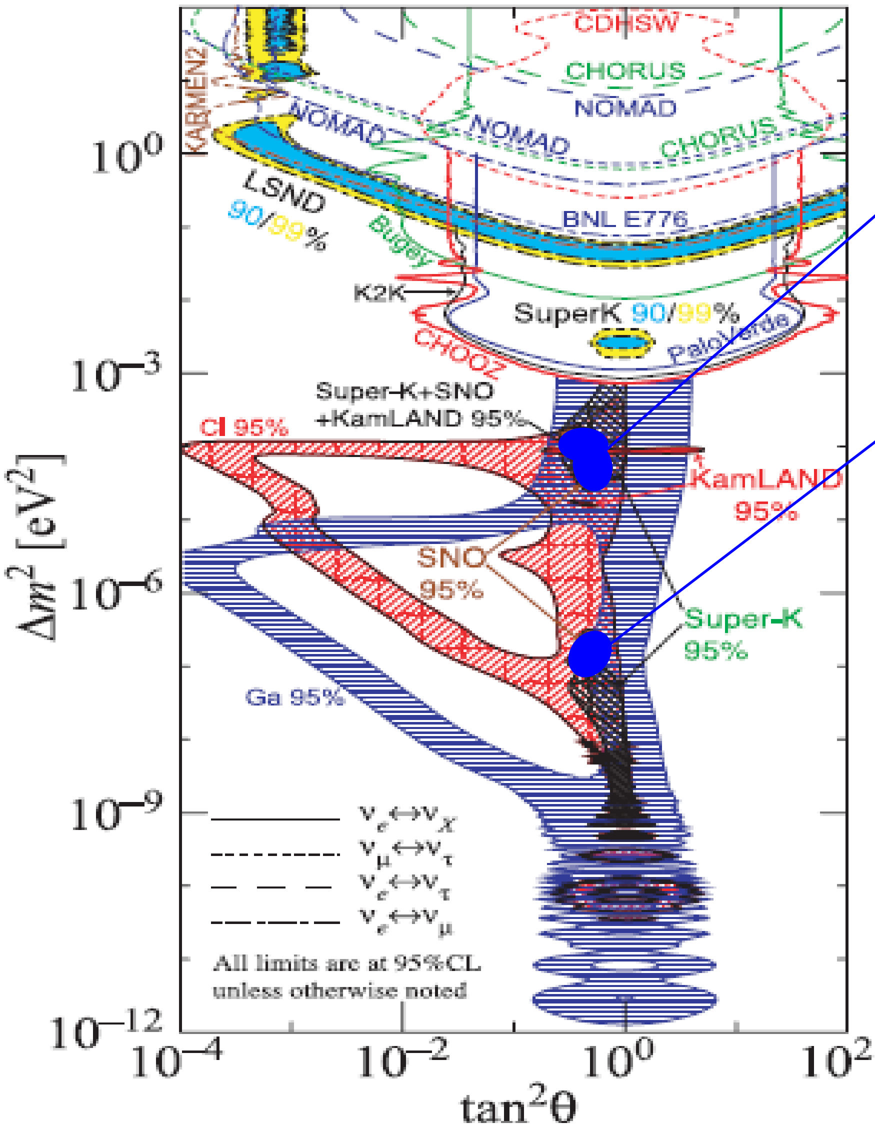
Purpose

.

"Supernova ν-Process Nucleosynthesis"
to determine the MASS HIERARCHY of Active Neurinos.

"KNOWN" of Neutrino Oscillations

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



23－mixing

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

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

12－mixing Cabibbo angle

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

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

"UNKNOWN"

13－mixing

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

E(νμ)=E(ντ): Yokomakura et al., PL B544, 286.

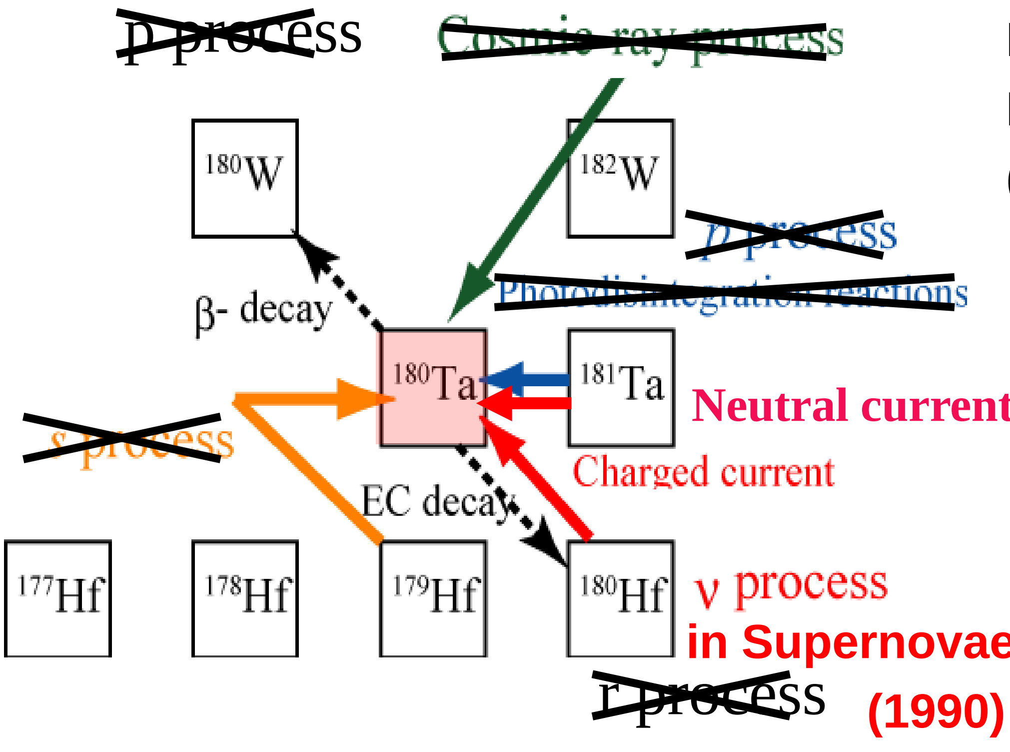
Tantalum (^{180,181}Ta)

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

The rarest isotope in the Universe!

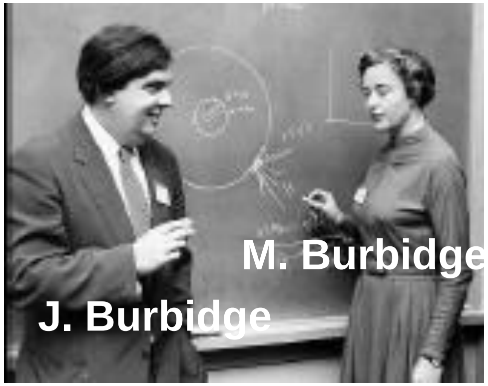
Origin of ^{180}Ta was unknown.

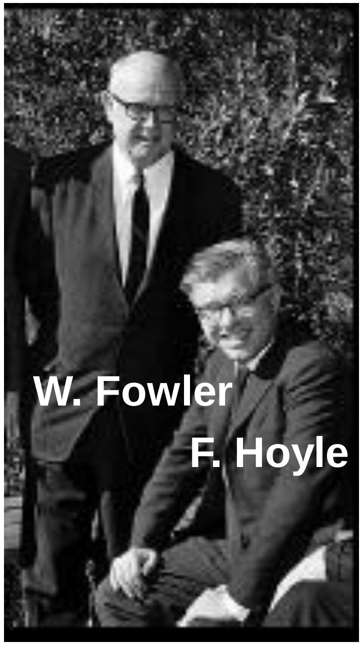
"SN ν-process", overproduces ^{180}Ta !



Burbidge^2-Fowler-Hoyle, Rev. Mod. Phys. 29 (1957), 547-650.

"Element Genesis"



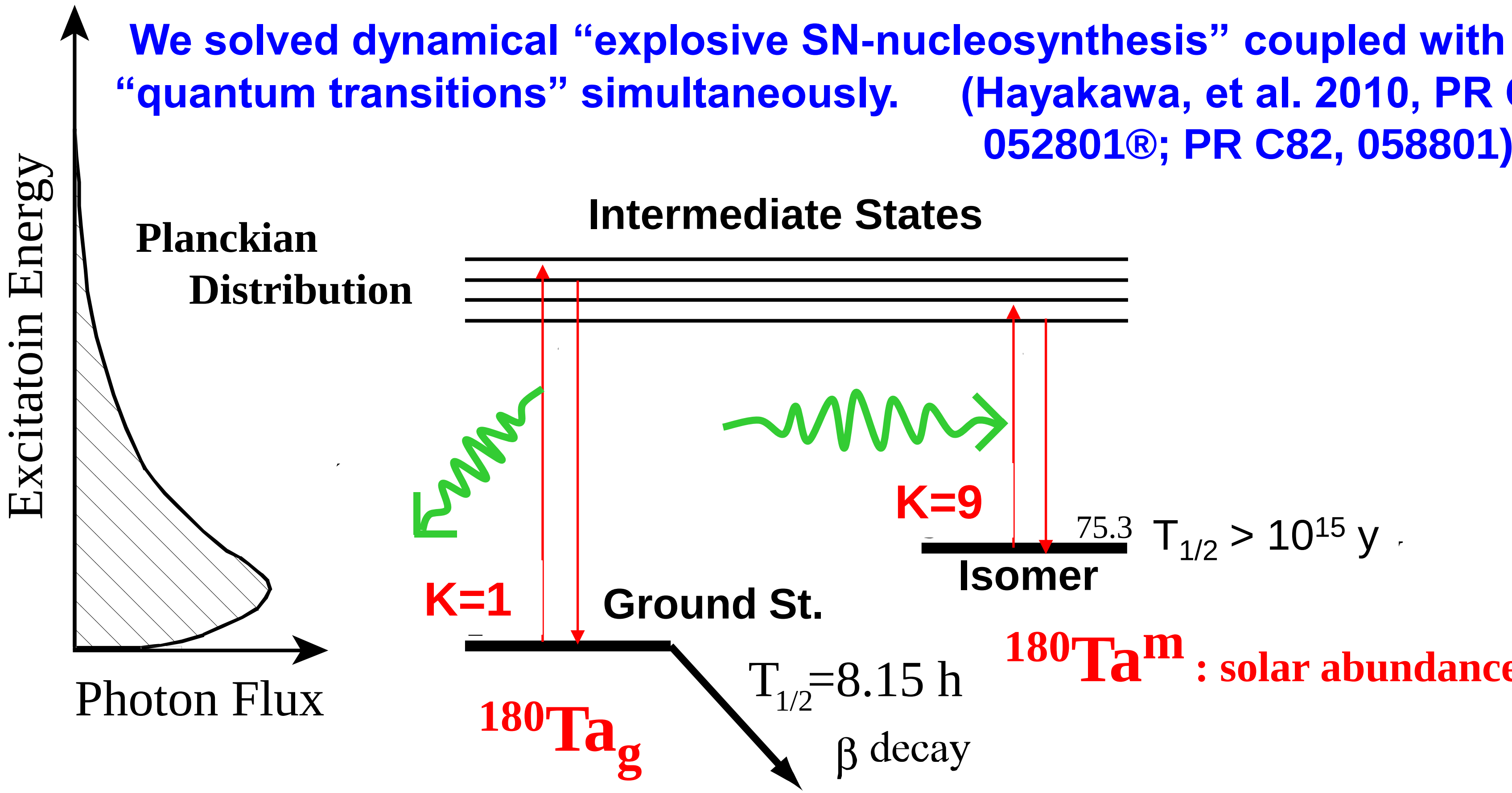


^{180}Ta-genesis needs Quantum Phys. + SN Hydro-dyn.

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

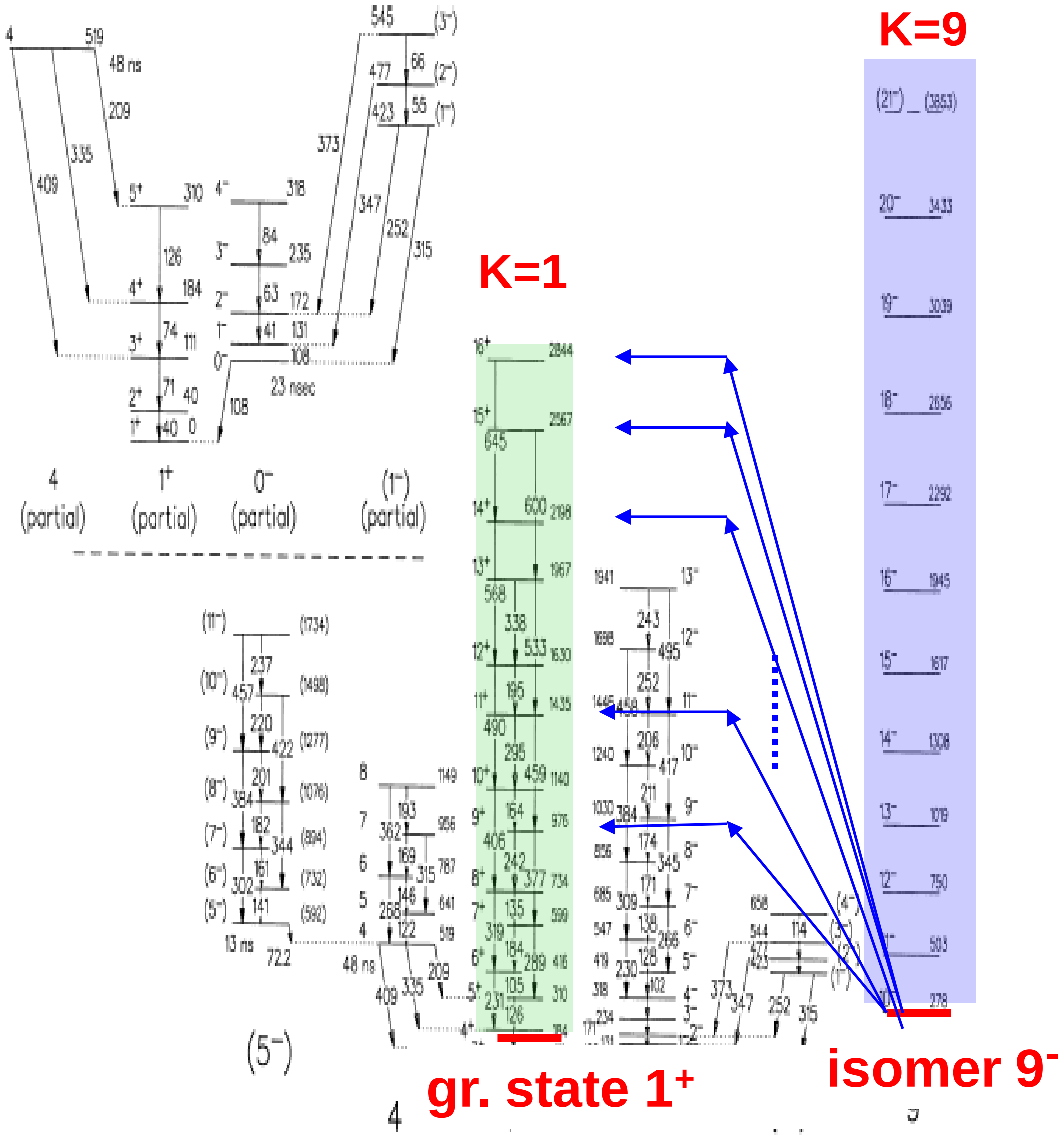
- **Long lived ^{180}Ta^{m} is excited in hot SN-photon bath.**
- **Intermediate states are depopulated to the ground state, which decays in 8 hours.**

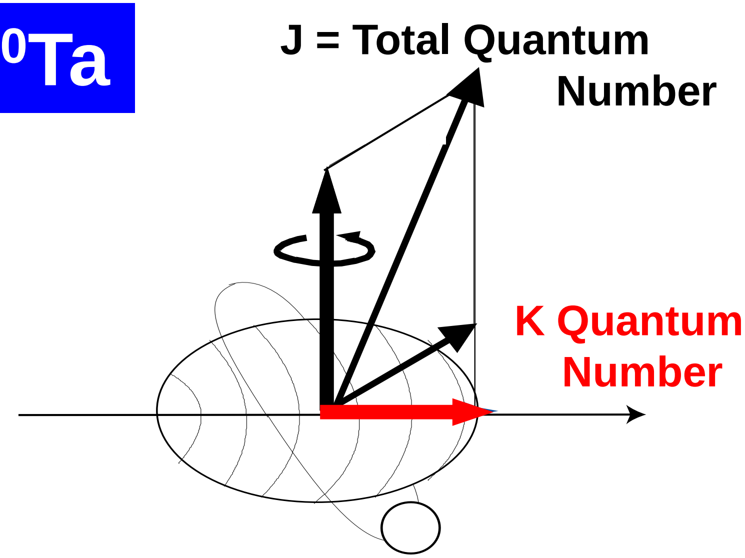
We solved dynamical "explosive SN-nucleosynthesis" coupled with "quantum transitions" simultaneously. (Hayakawa, et al. 2010, PR C81, 052801®; PR C82, 058801)



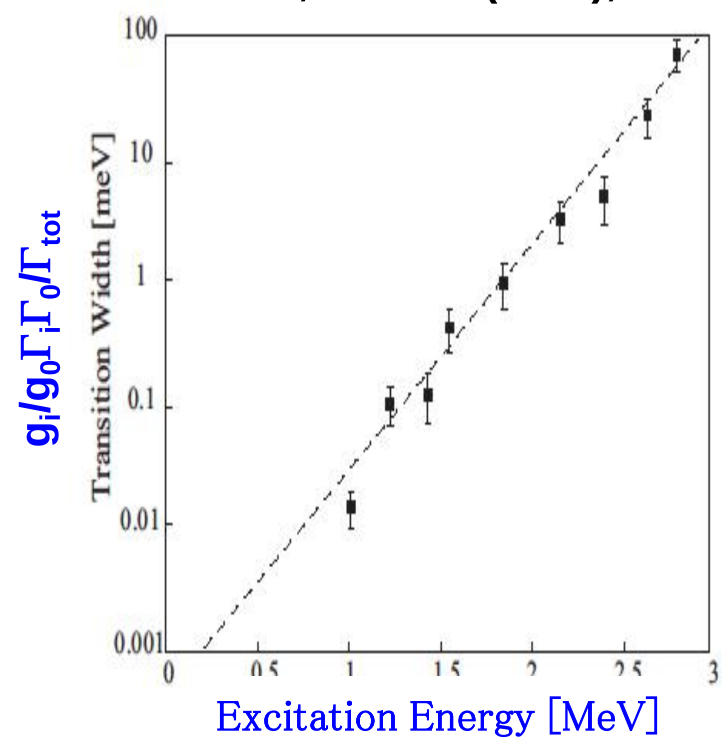
ν-Process and Structure of ^{180}Ta

Saitoh et al. (NBI group), NPA 1999, +
Dracoulis et al. (ANU group), PRC 1998, +



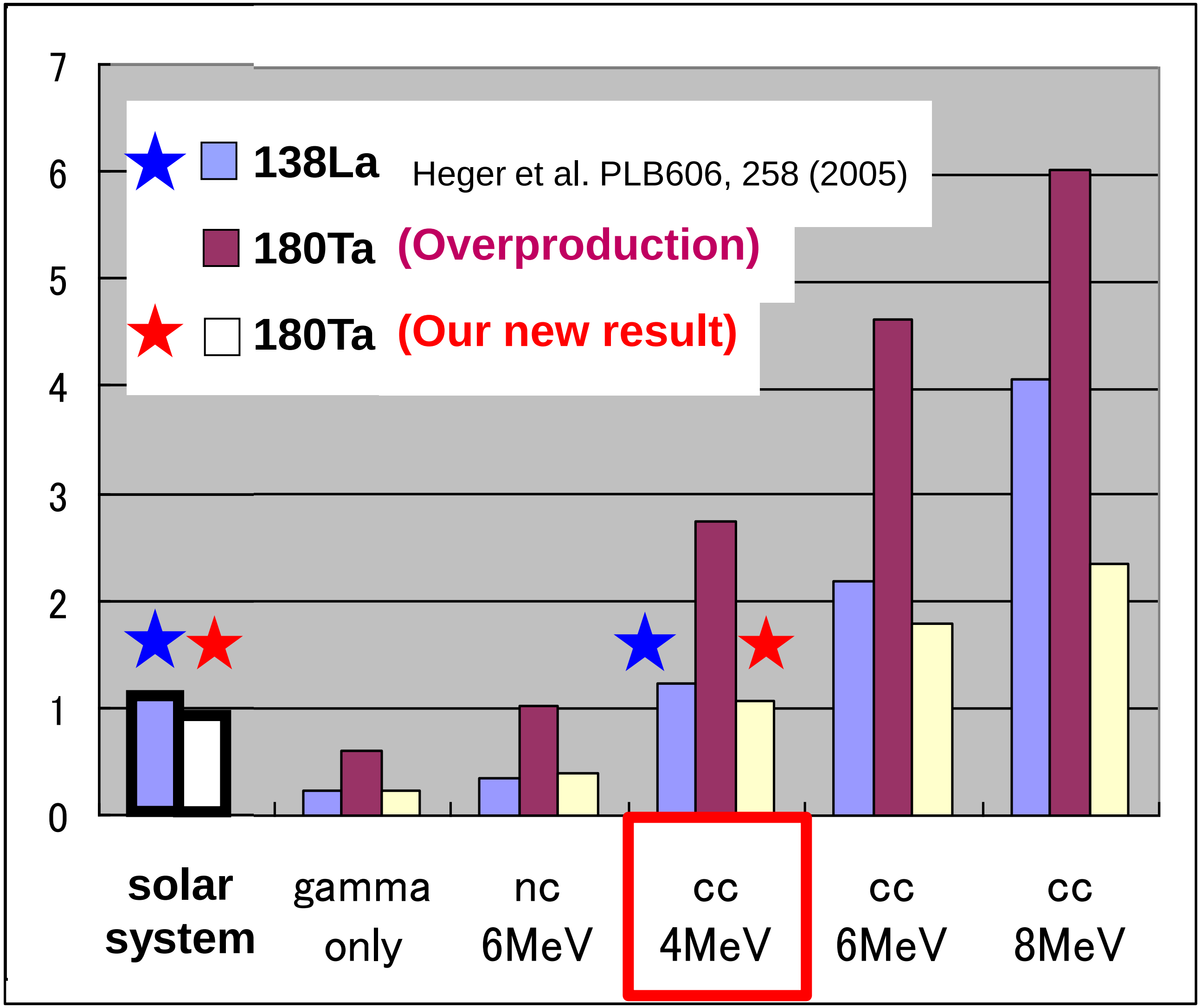


D. Belic et al., PR C65 (2002), 035801.



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

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

⇕

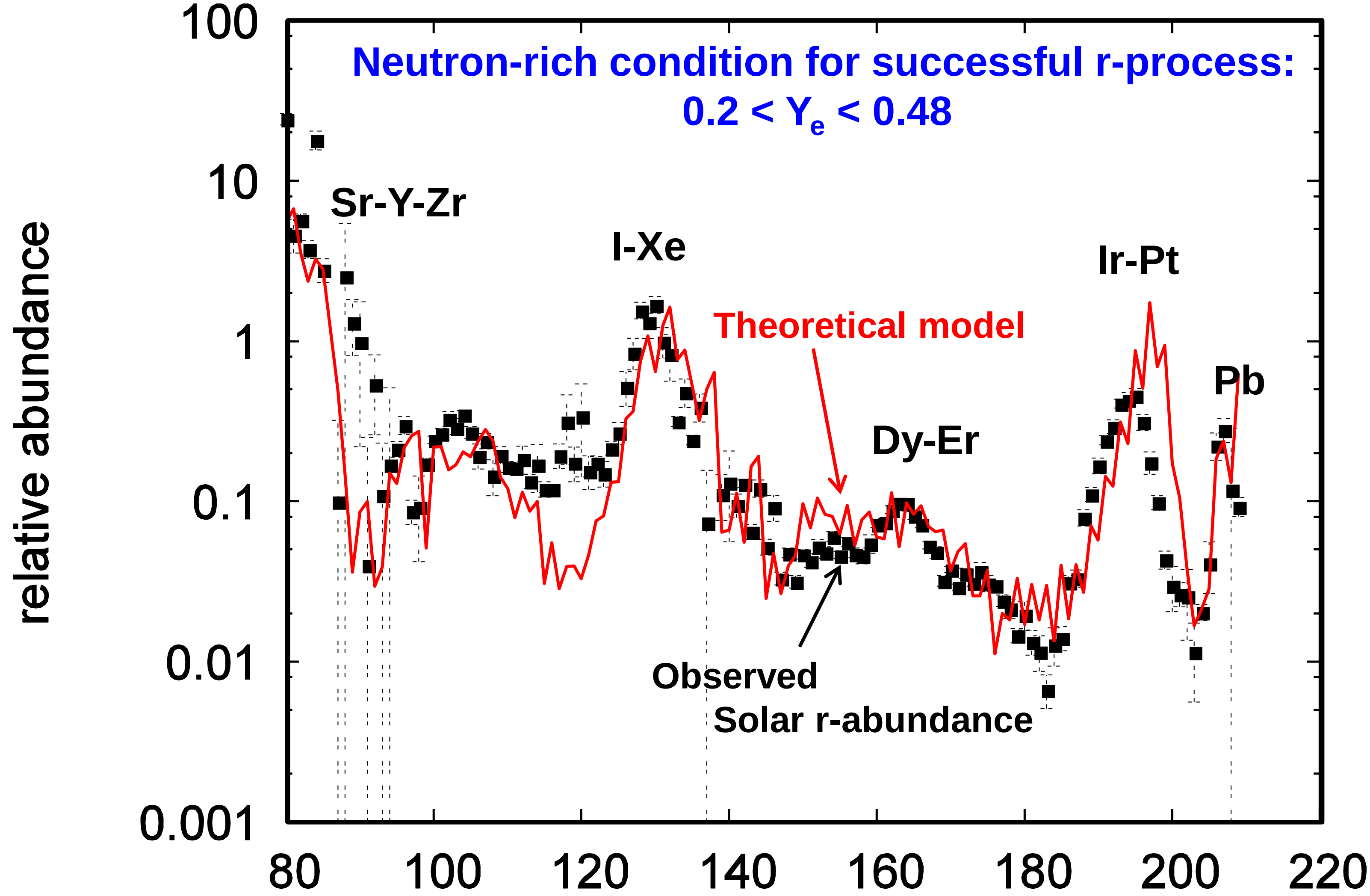
Consistent with the r-process !

R-process Nucleosynthesis

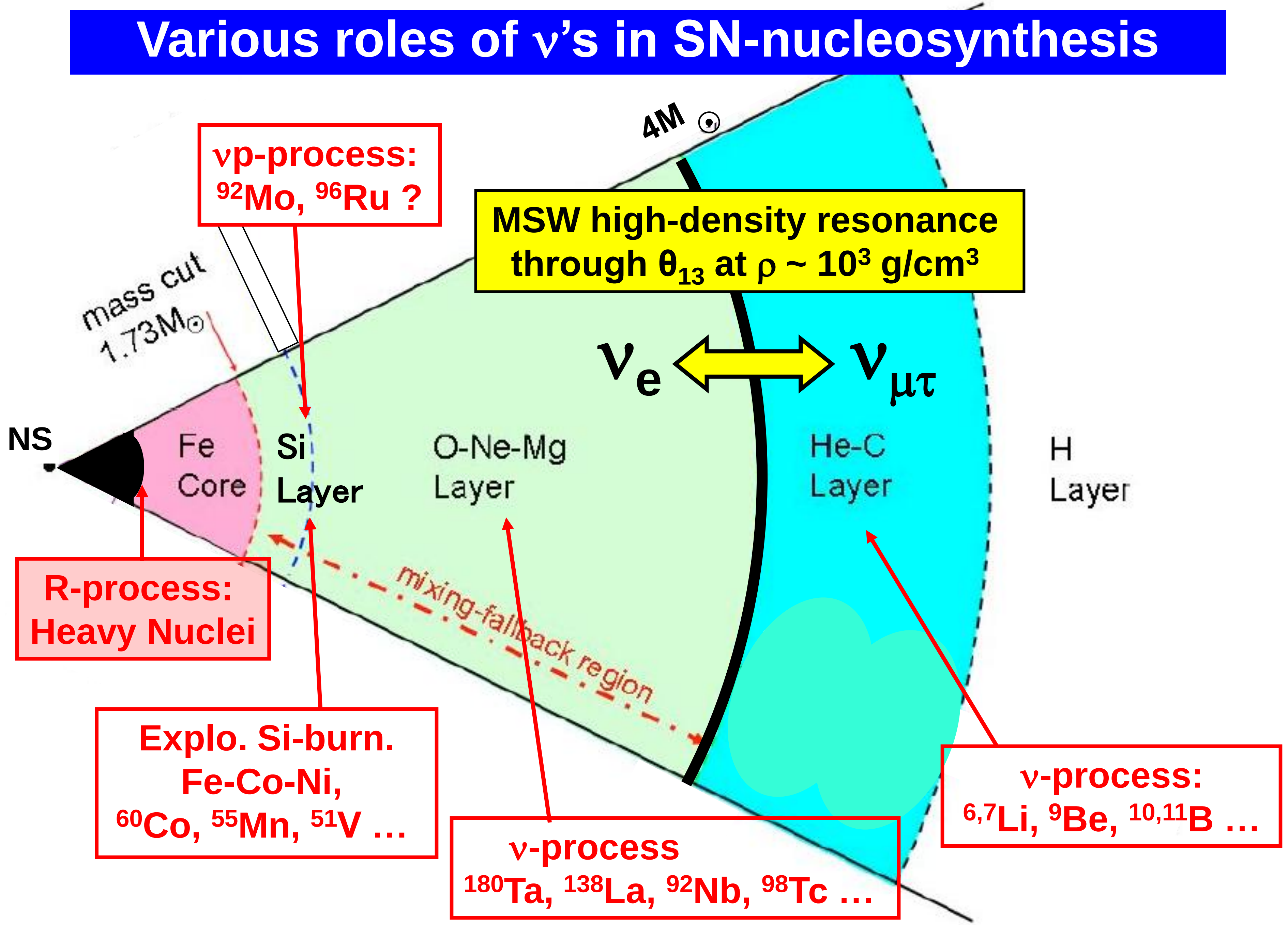
K. Nakamura. S. Sato. S. Harikae. T. Kajino and G.J. Mathews (2012), submitted to ApJ.

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

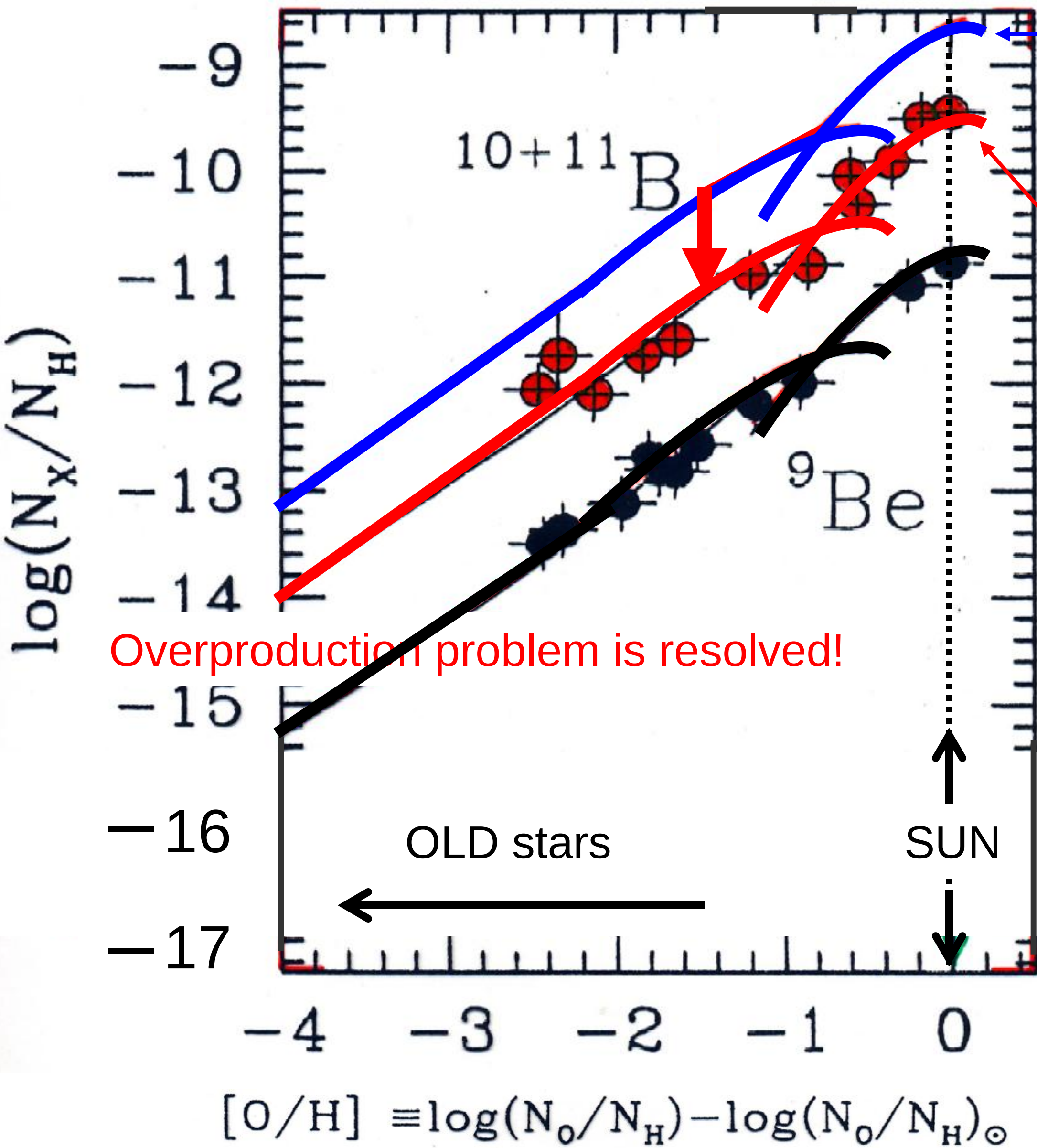
$T_{\nu e}$ = 3.2 MeV < $T_{\bar{\nu} e}$ = 4 MeV



Various roles of ν's in SN-nucleosynthesis



Galactic Chemical Evolution of ^{9}Be & ^{10,11}B



Livermore Model

$T_{\nu_{\mu,\tau}}$ = **8 MeV**

Woosley -Weaver 1995, ApJS 101, 181.

$\sigma \propto E_\nu^2$

^{9}Be:

— Galactic Cosmic Rays

$^{10+11}$B + ^{11}B:

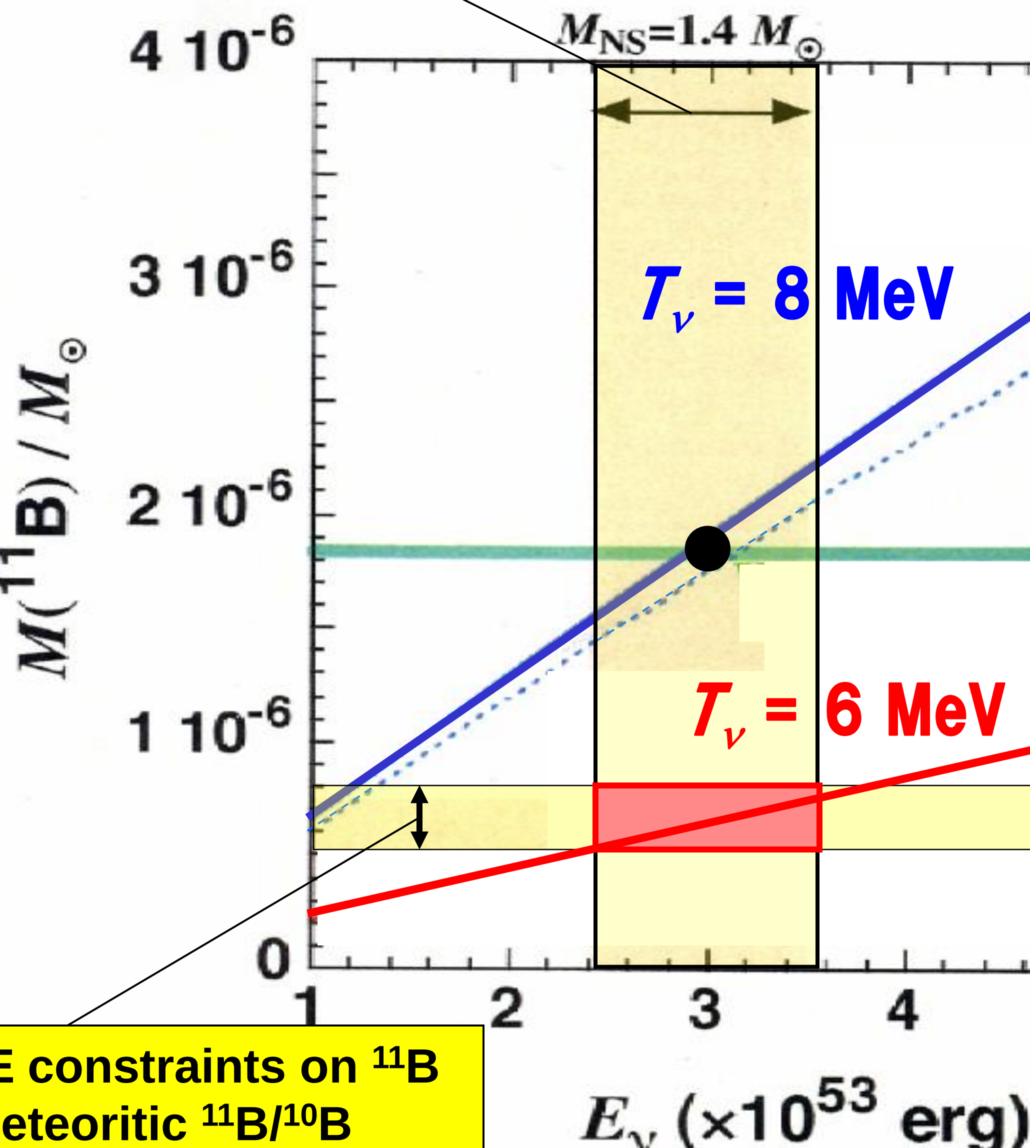
— Galactic Cosmic Rays

— Supernova ν−process

Yoshii, Kajino, Ryan, 1997, ApJ 486, 605.
Ryan, Kajino, Suzuki, 2001, ApJ549, 55.

SN-Boron calculations and constraints on SN- ν

SN1987A constraint on $E_{\nu,tot}$ & Grav. Energy



Woosley & Weaver
ApJS 101 (1995), 181.

Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.

Consistent with recent numerical simulation by Thomas-Janka et al. (MPA group) 2004-2011.

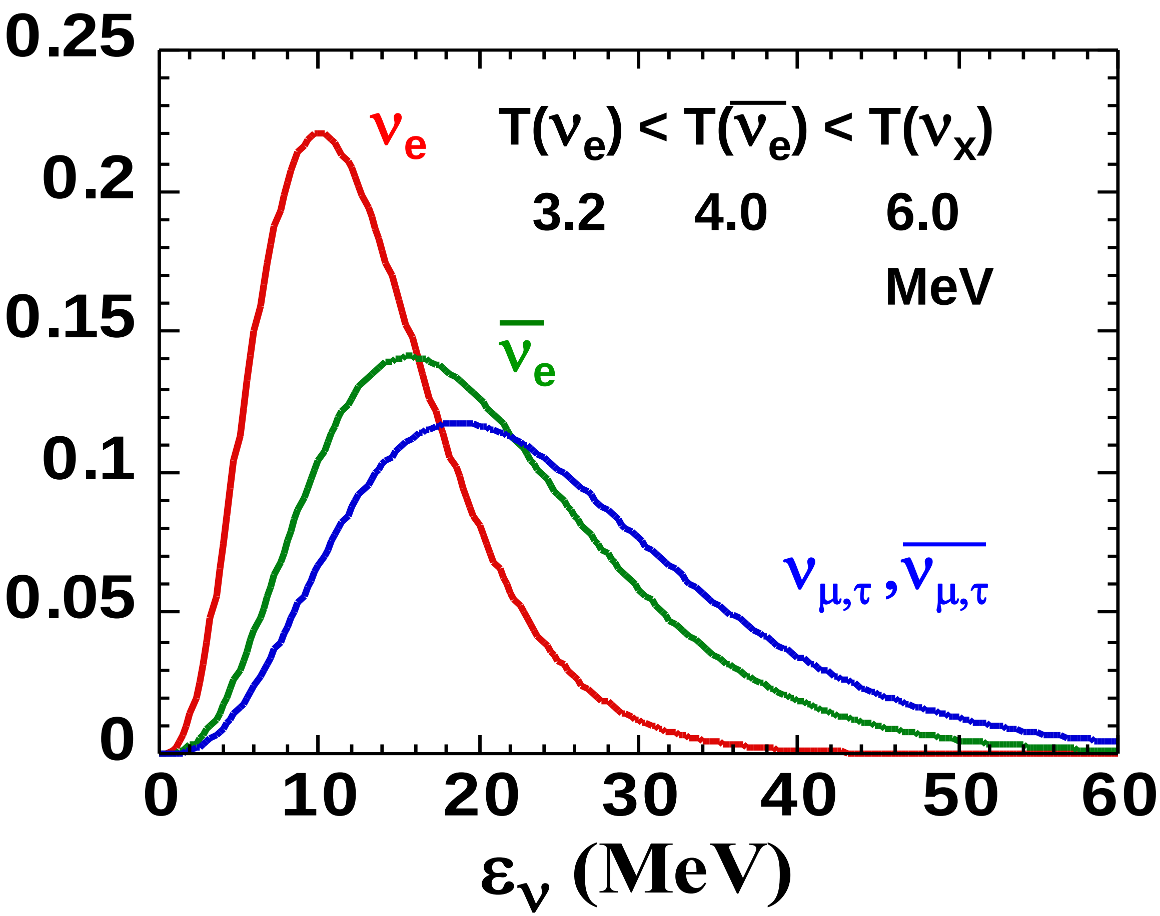
GCE constraints on ^{11}B & meteoritic $^{11}B/^{10}B$

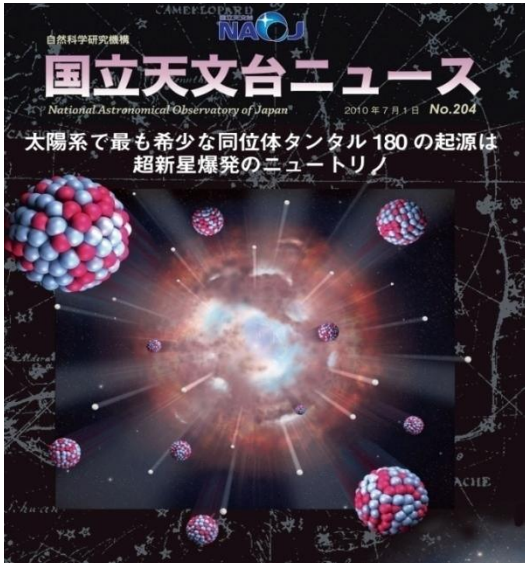
Supernova ν-Process to estimate $T\nu_{\mu}$, and $T\nu_{\tau}$

R-process, ^{180}Ta/^{138}La ⇨ $T\nu_e = 3.2$ MeV, $T\bar{\nu}_e = 4$ MeV

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

ν-temperatures are known!





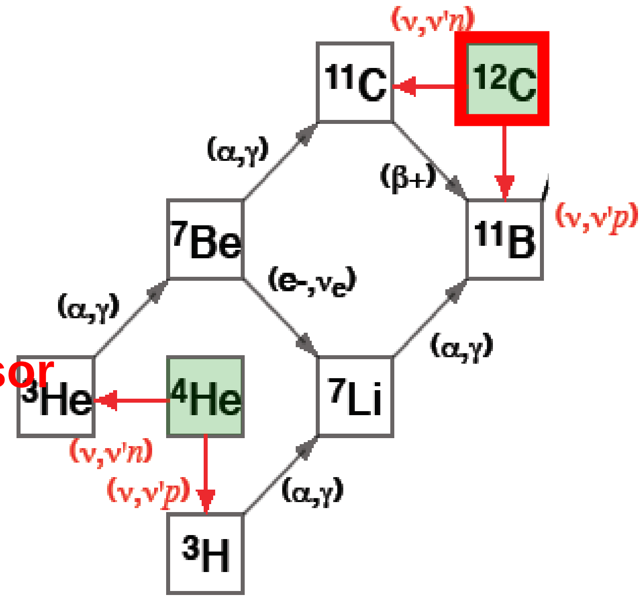
ν-A reaction cross sections?

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.

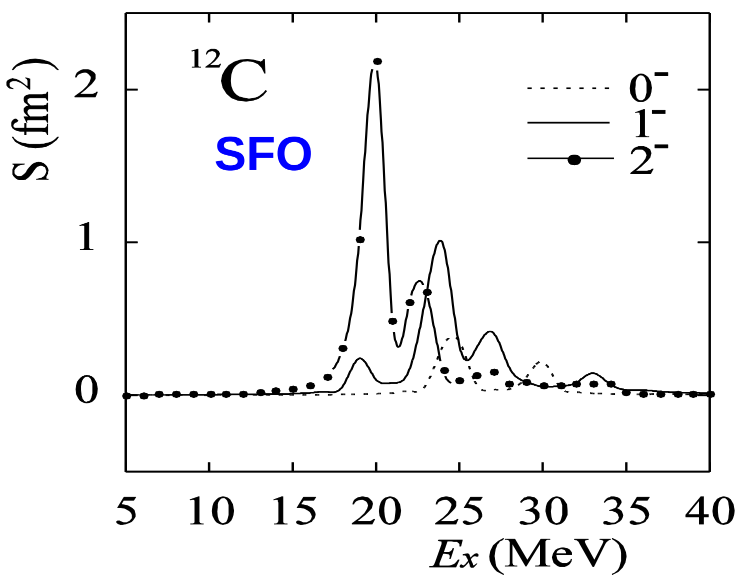
Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003) → **SFO**

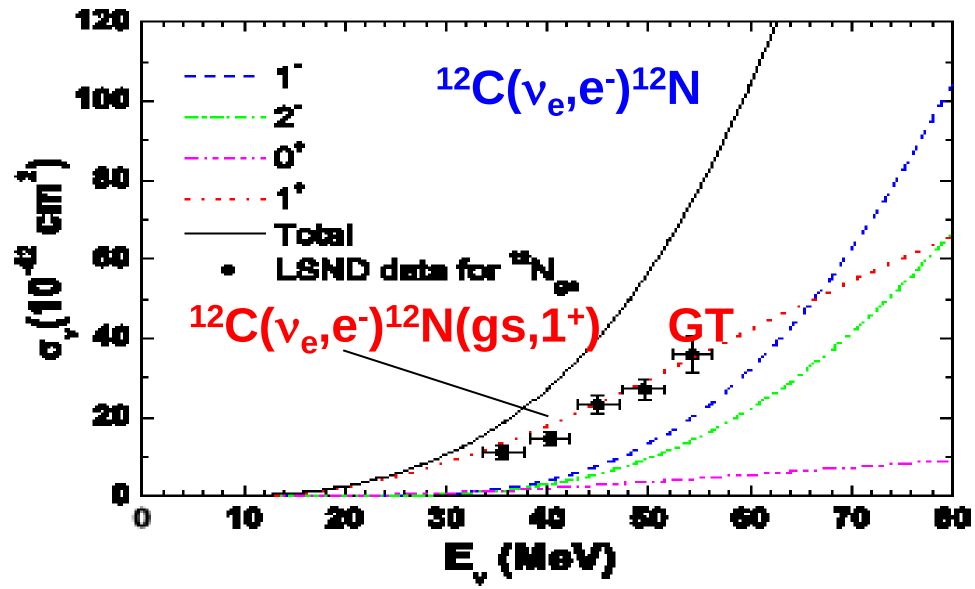


^{12}C: SFO Hamiltonian = Spin-isospin flip int. with tensor force to explain neutron-rich exotic nuclei.

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

Cheoun et al., PRC81 (2010), 028501; J. Phys. G37 (2010) 055101: QRPA Cal.



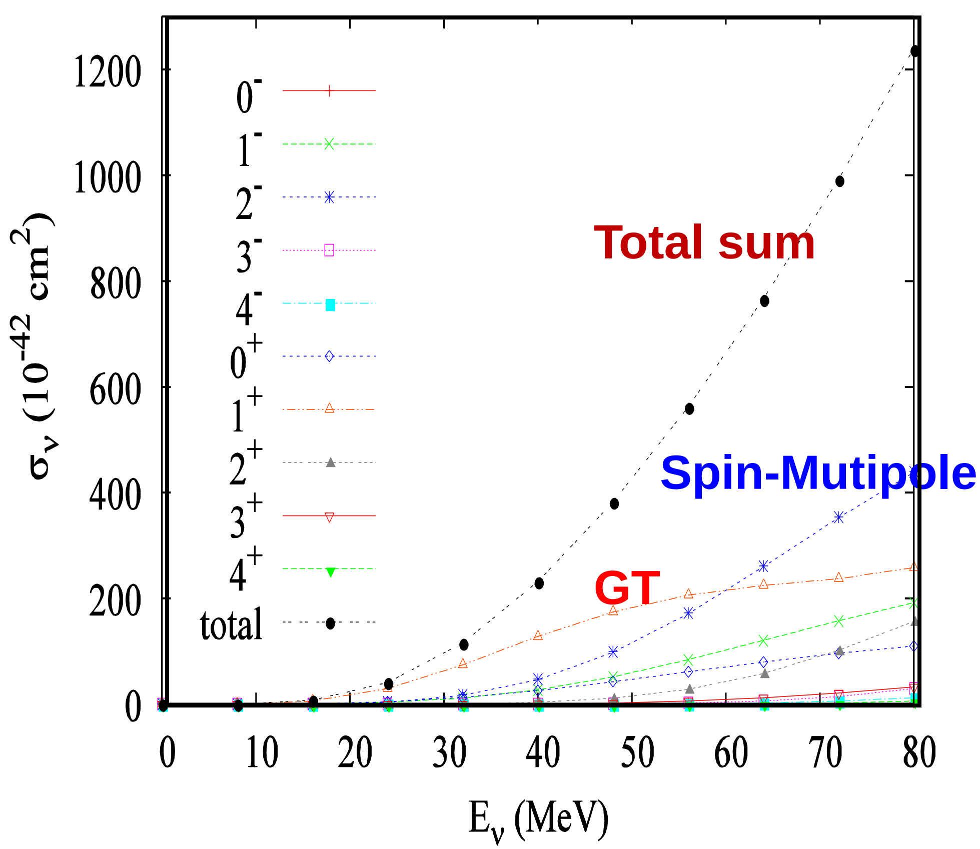


ν-^{180}Ta, ^{138}La, ^{92}Nb, ^{42}Ca, ^{12}C, ^{4}He… cross sections calculated in Quasi-particle Random Phase Approximation

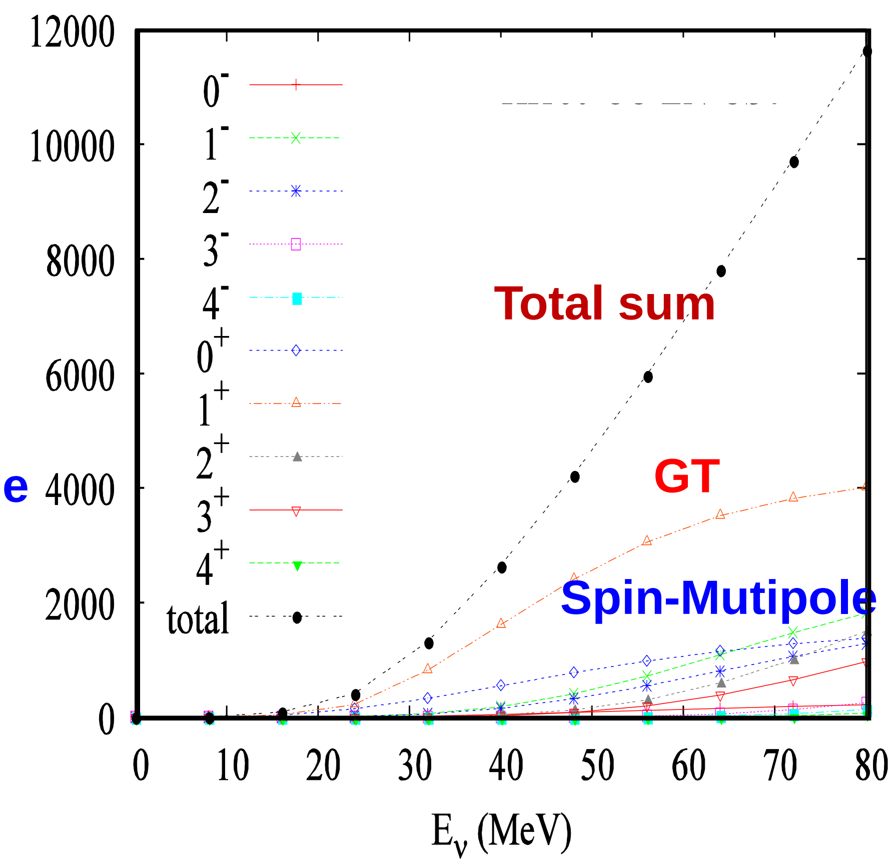
Cheoun, Ha, Hayakawa, Kajino & Chiba, PRC82 (2010), 035504; Cheoun, Ha, Kim, & Kajino, J. Phys. G37 (2010) 055101; Cheoun, Ha & Kajino, PRC 83 (2011), 028801

GT + Spin-Multipole transitions !

^{181}Ta + ν → ^{180}Ta + n + ν' (NC)



^{180}Hf + ν → ^{180}Ta + e$^-$ (CC)

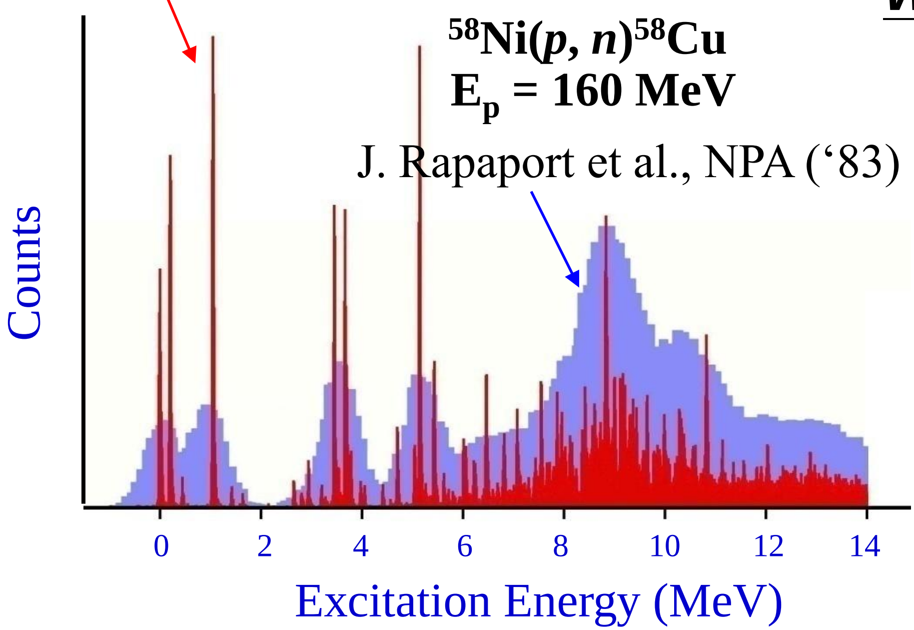


- **ν-beam is not yet available for ν-A X-section studies!**
- **We can use Electro-Magnetic PROBE !**

Similarity between Electro-Magnetic & Weak Interactions

^{58}Ni(^{3}He, *t*)^{58}Cu
E = 140 MeV/u

Y. Fujita et al., EPJ A 13 ('02) 411.
Y. Fujita et al., PRC 75 ('07)



EM-current = $\vec{V}$, Weak-current = $\vec{V}$ - $\vec{A}$

$$\vec{V} \approx g_V^{IV} \frac{i}{2m} \vec{\sigma} \times \vec{q} + \frac{g_V}{2m}(\vec{p} + \vec{p}\,')$$

$$\vec{A} \approx g_A \vec{\sigma}$$

Weak operator in non-relativistic limit

Gamow-Tellar operator = $\vec{\sigma}\tau_{\pm}$

Spin-Multipole operator $[\vec{\sigma} \times Y(L)]^J \tau_{\pm}$

★ Charge-Exchange Reaction

★ Photo-induced Reaction

Astrophysical Applications of Charge-Exchange Reactions at RIKEN

Masaki Sasano
Uesaka Spin-Isospin Labo., RIKEN

The developed technique
+ RIKEN RIBF (intense RI beam)
+ SAMURAI spectrometer (efficient PID)
+ Neutron wall (WINDS)

Probe any Ex on any A/Z
(beam intensity 10^{4-5} pps)

Better understanding of weak response in astro-processes →

- **EC/beta-decays**
- **Neutral weak currents**

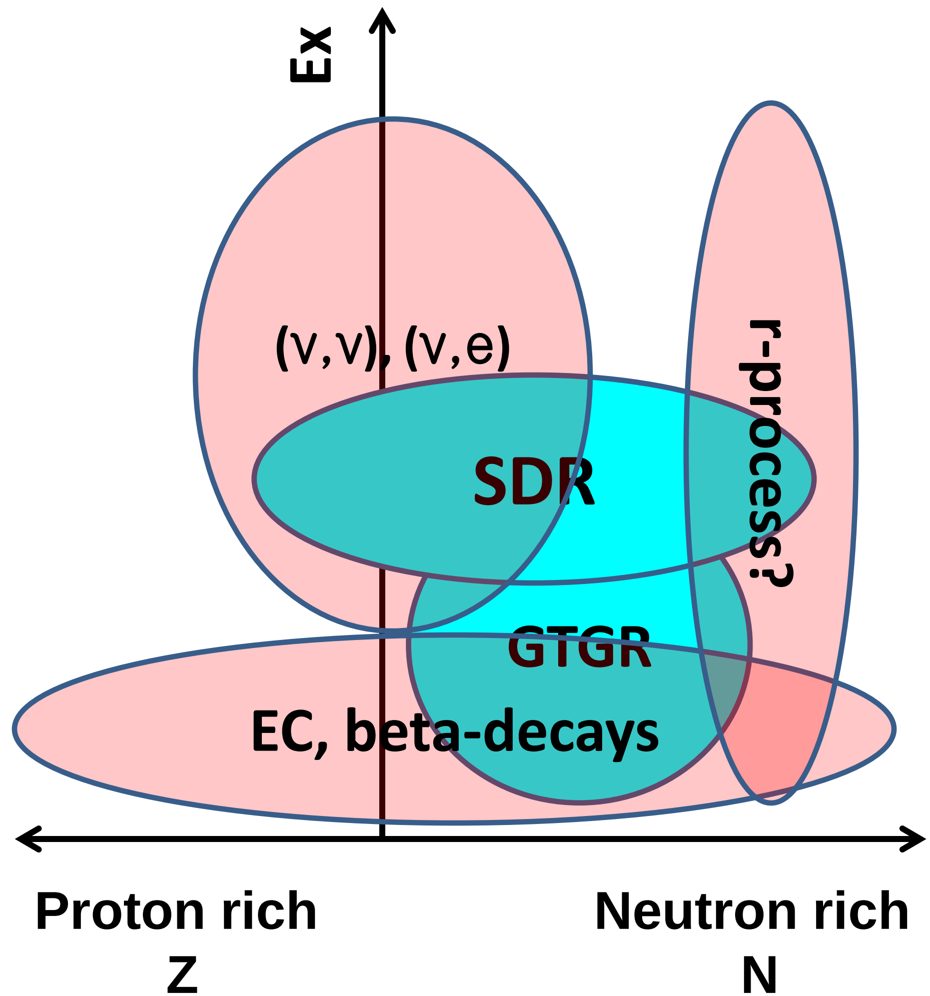
e.g., Synthesis of Mn

$^{56}Ni(\nu,\nu p)^{55}Co \rightarrow {}^{55}Fe \rightarrow {}^{55}Mn$

T. Suzuki et al., PR C79, 061603(R) (2009).

- **R-process (GT + first forbidden)**

T. Suzuki et al., arXiv:1110.3886



Double β decay – ν mass – Astro-Cosmology Connection

K. Yako et al., PRL 103 (2009) 012503.

B(GT$^{+/-}$) distribution

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

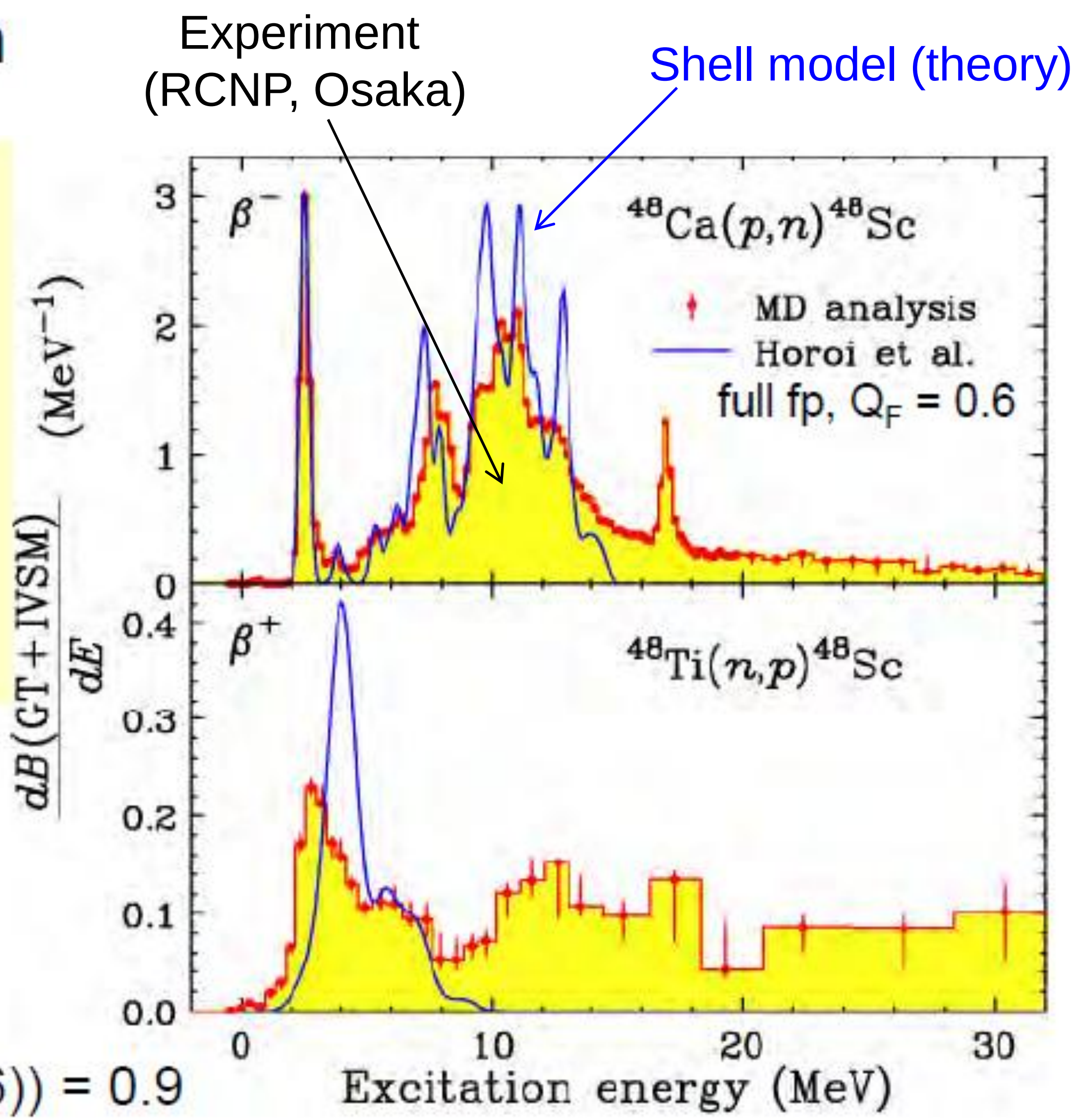
(n,p) channel :

$\Sigma B(GT^+;exp) = 1.9 \pm 0.3$…

(w subtraction of IVSM)

⬍

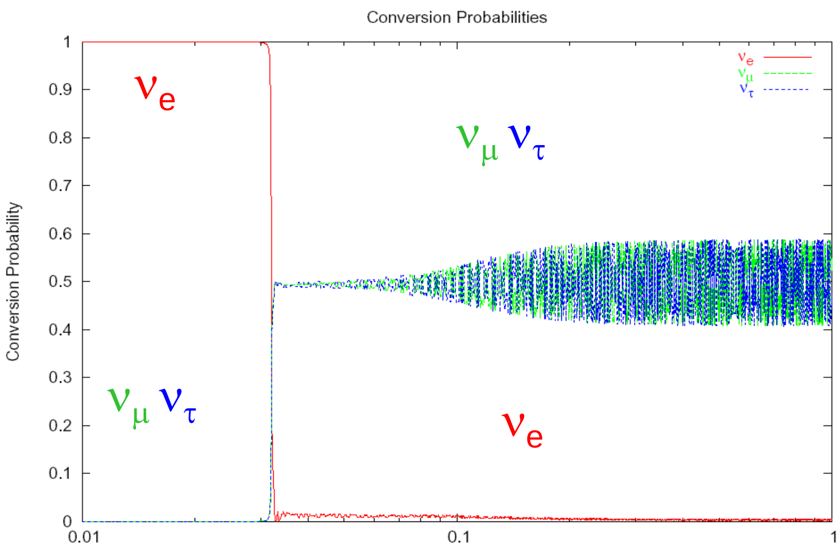
$\Sigma B(GT^+;ShellModel(Q_F=0.6)) = 0.9$



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

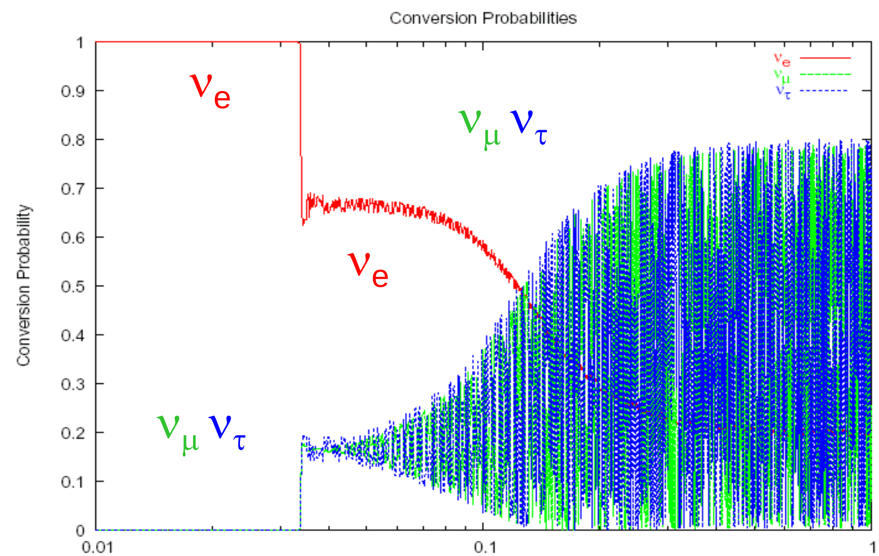
Conversion Probability

Adiabatic



Center Radius/R_{sun} →

Non-Adiabatic



Center Radius$_{sun}$ →

Parameters:

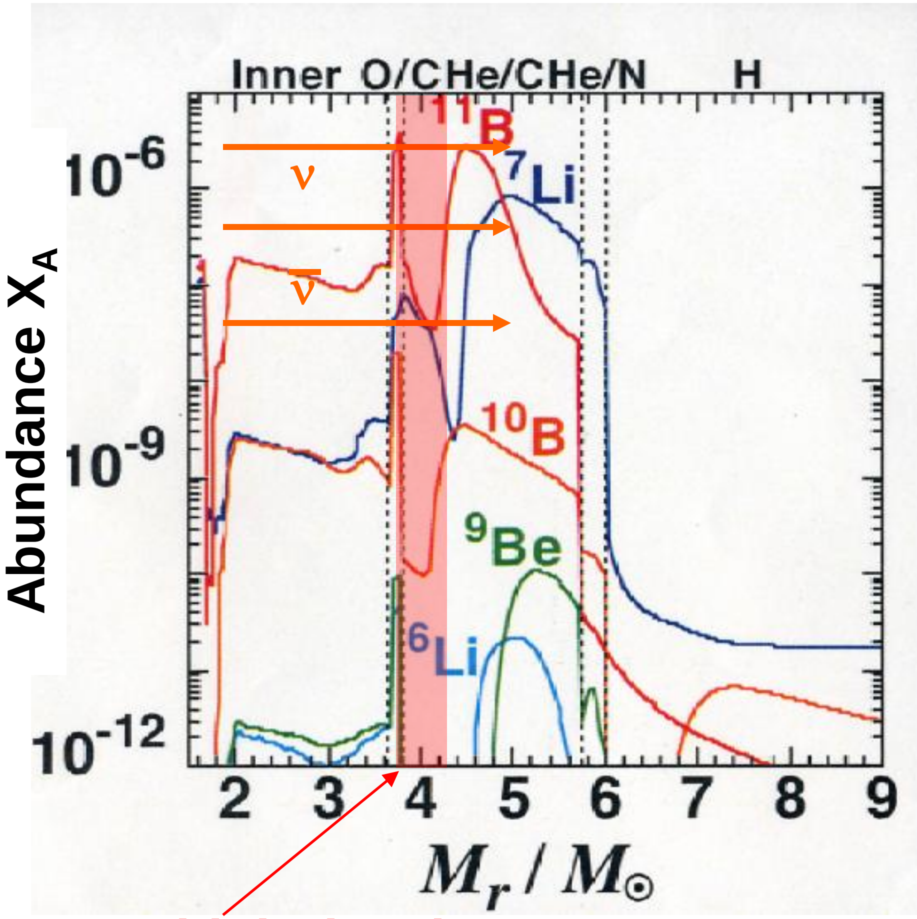
$25M_{solar}$ SN model (Hashimoto & Nomoto 1999)

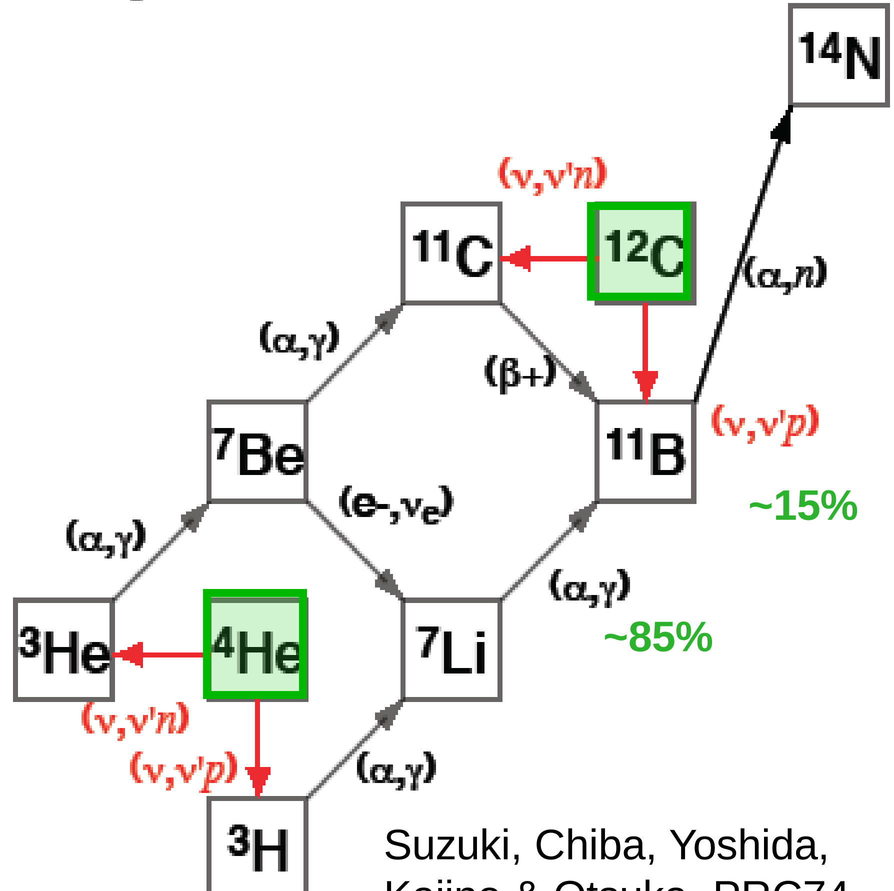
- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV^2
- $L_\nu = 3\times10^{53}$ erg, $\tau_\nu = 3$ sec
- $E_{\nu e}$=12MeV, $E_{\bar{\nu} e}$=20MeV, $E_{\nu\mu\tau}$=24MeV

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

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.





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

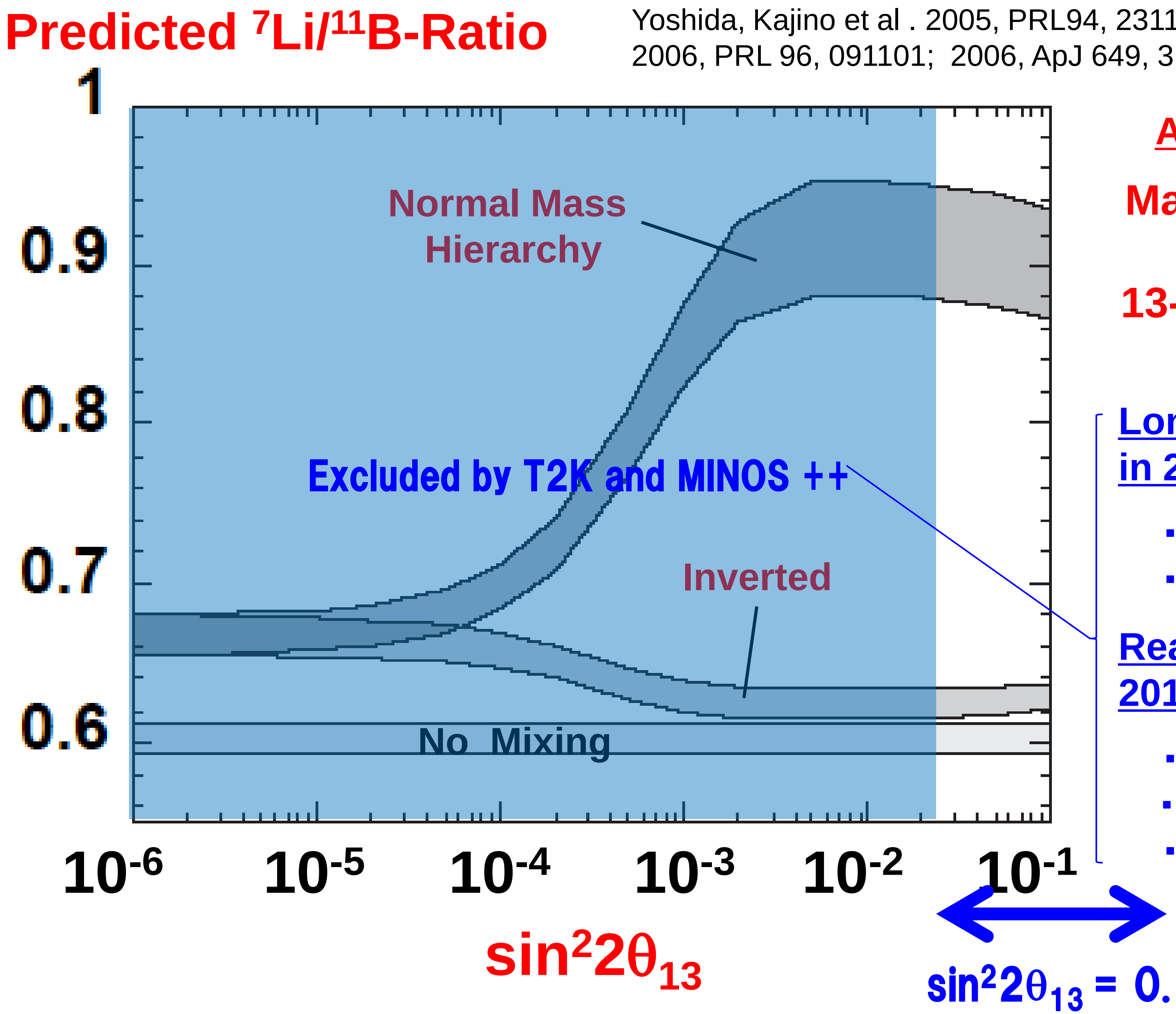
MSW high-density resonance

^{4}He(ν,ν'p)^{3}H, ^{4}He(ν,ν'n)^{3}He, ^{12}C(ν,ν'p)^{11}B

$\nu_x \rightarrow \nu_e$ ^{4}He(ν_e,e$^-$$p$)^{3}He, ^{4}He($\bar{\nu}_e$,e$^+$$n$)^{3}H, ^{12}C($\nu_e$,e$^-$$p$)^{11}C, ^{12}C($\bar{\nu}_e$,e$^+$$n$)^{11}B

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 BaselineExp. in 2011:

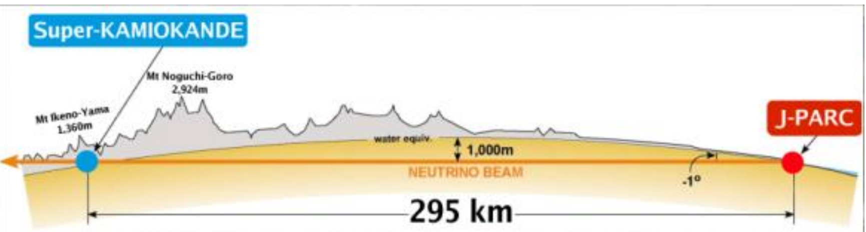
- T2K (Kamioka)
- MINOS

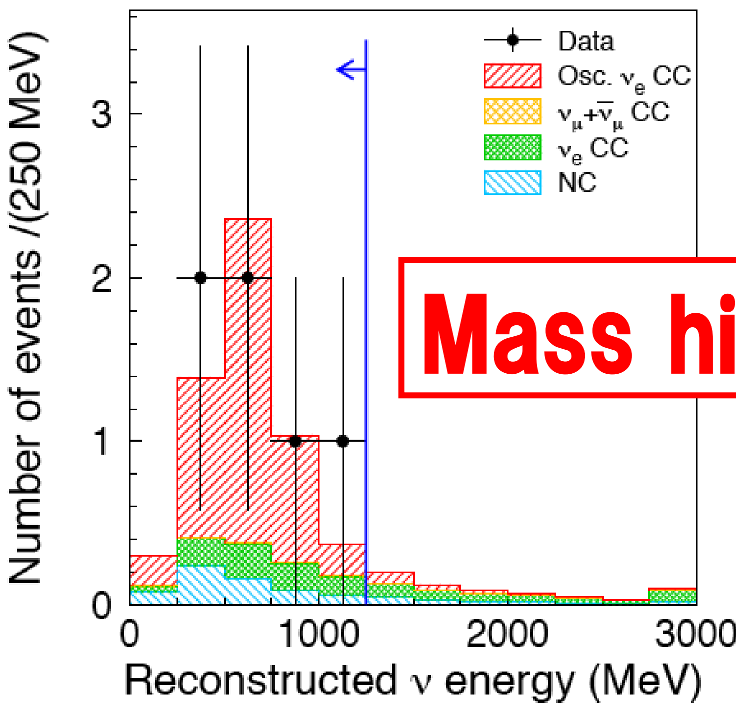
Reactor Exp. in 2012:

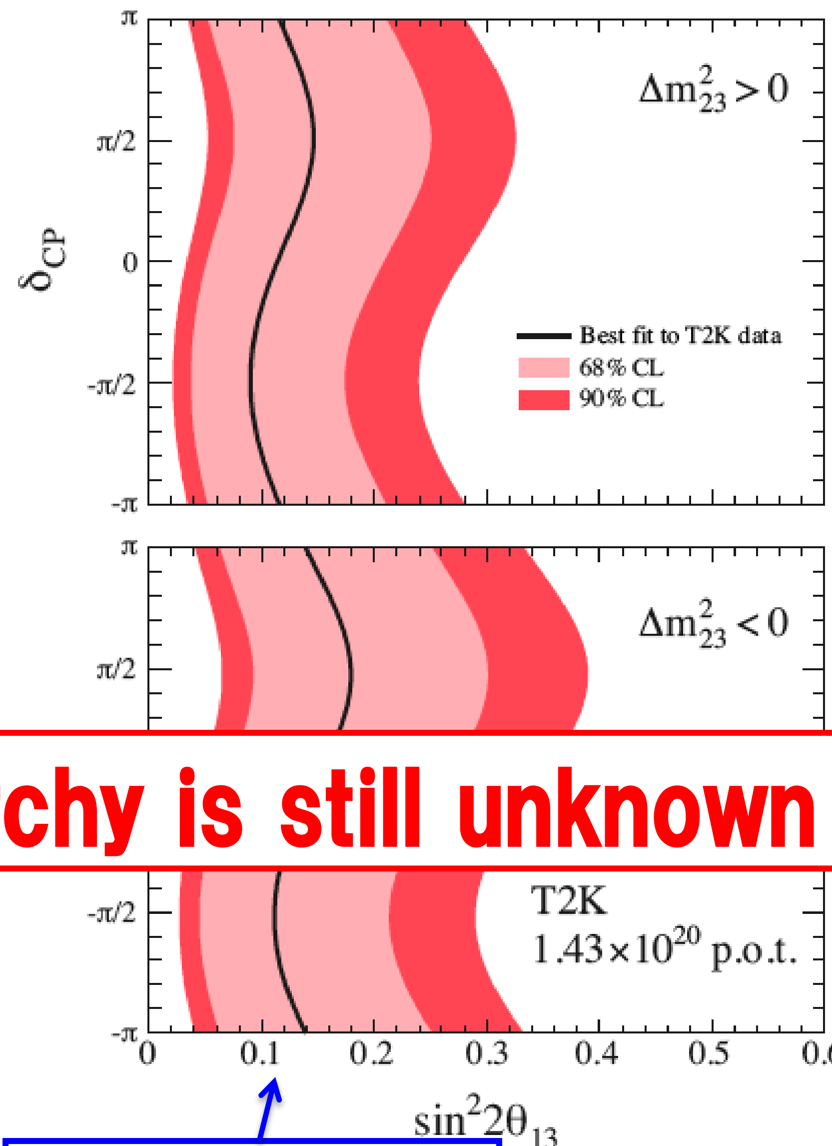
- Double CHOOZ
- Daya Bay
- RENO (KOREA)

T2K & MINOS results (2011)

$\sin^2 2\theta_{23}=1$







Mass hierarchy is still unknown !

$\sin^2 2\theta_{13} = 0.1$

RENO, Daya Bay and Double Chooz results (2012)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Measuring θ_{13} with Reactor Anti-neutrinos

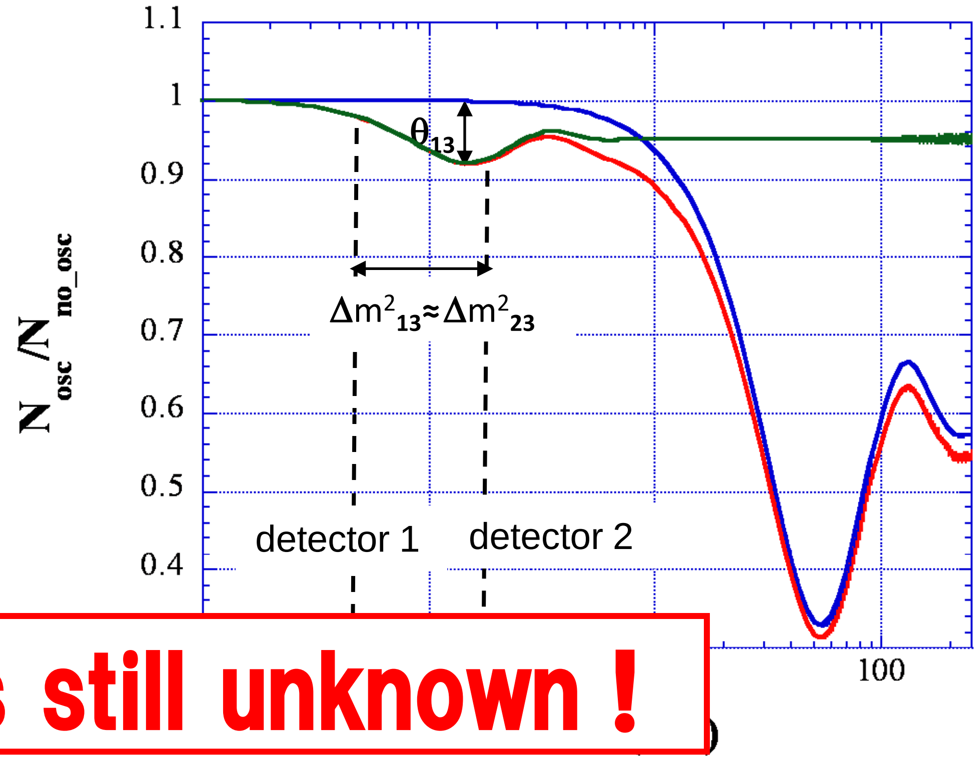
$\sin^2 2\theta_{13} = 0.103 \pm 0.013$ (st) ± 0.011 (sys)

$\rightarrow \theta_{13} = 8.88$ 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}

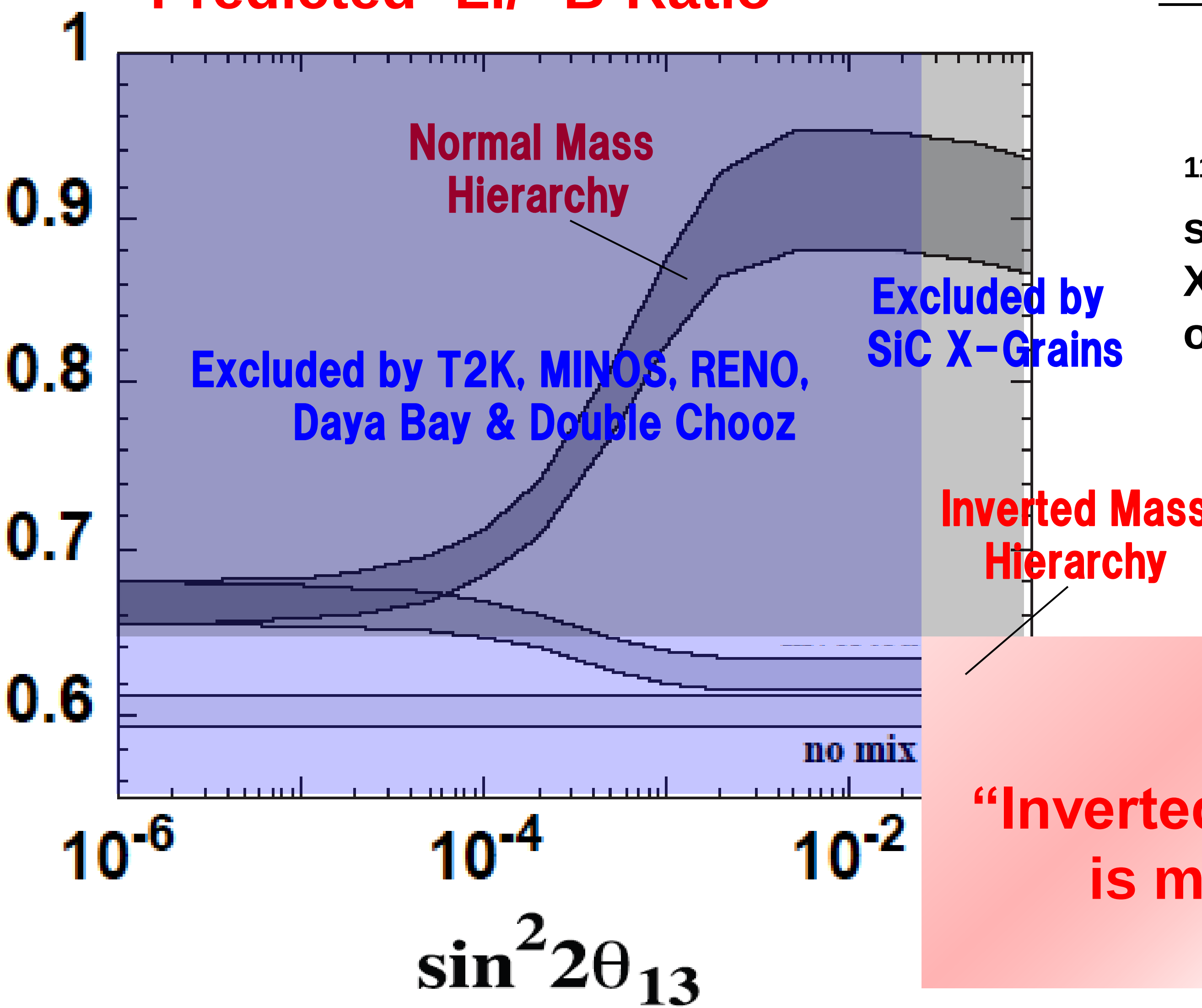


Mass hierarchy is still unknown !

Mass Hierarchy, Normal or Inverted ?

Mathews, Kajino, Aoki and Fujiya, Phys. Rev. D85,105023 (2012).

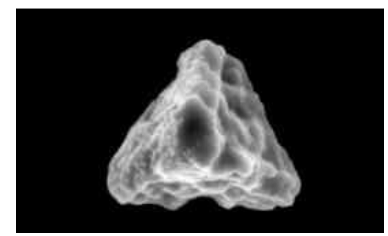
Predicted $^{7}Li/^{11}B$-Ratio



First Detection of $^{7}Li/^{11}B$

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

^{11}B and ^{7}Li were measured in SiC presolar X-grains which are made of Supernova dusts.



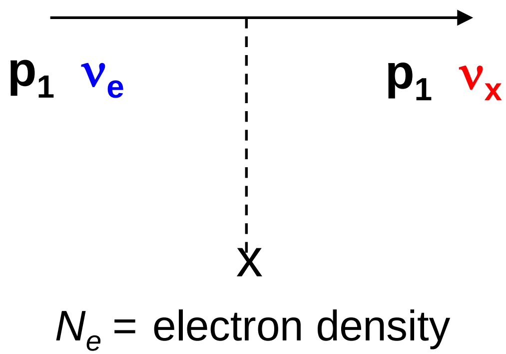
"Inverted Mass Hierarchy" is more preferred !

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

H_{ν} = Mixing and Interaction with Background Electrons

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

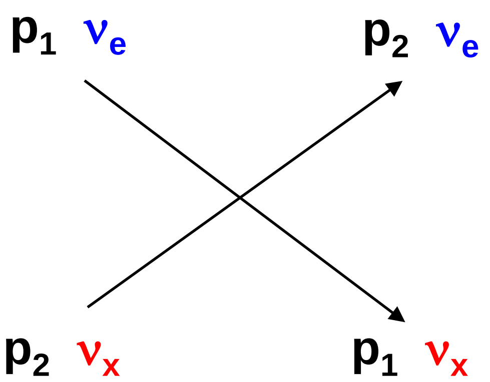
$$H_{\nu} = \frac{1}{2}\int d^3p \left(\frac{\delta m^2}{2p}\cos 2\theta - \sqrt{2}G_F N_e\right)\left(a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)\right) + \frac{1}{2}\int d^3p \frac{\delta m^2}{2p}\sin 2\theta\left(a_x^\dagger(p)a_e(p) + a_e^\dagger(p)a_x(p)\right).$$



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

Self-Interaction

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



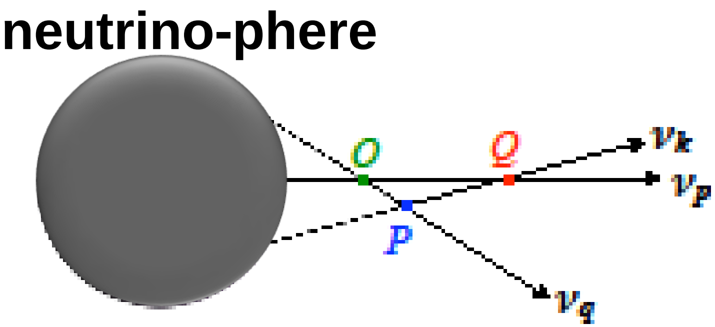
Quest for EXACT Many-Body SOLUTION !

"Invariants of collective neutrino oscillations"

Y. Pehlivan, A.B. Balantekin, T. Kajino & T. Yoshida

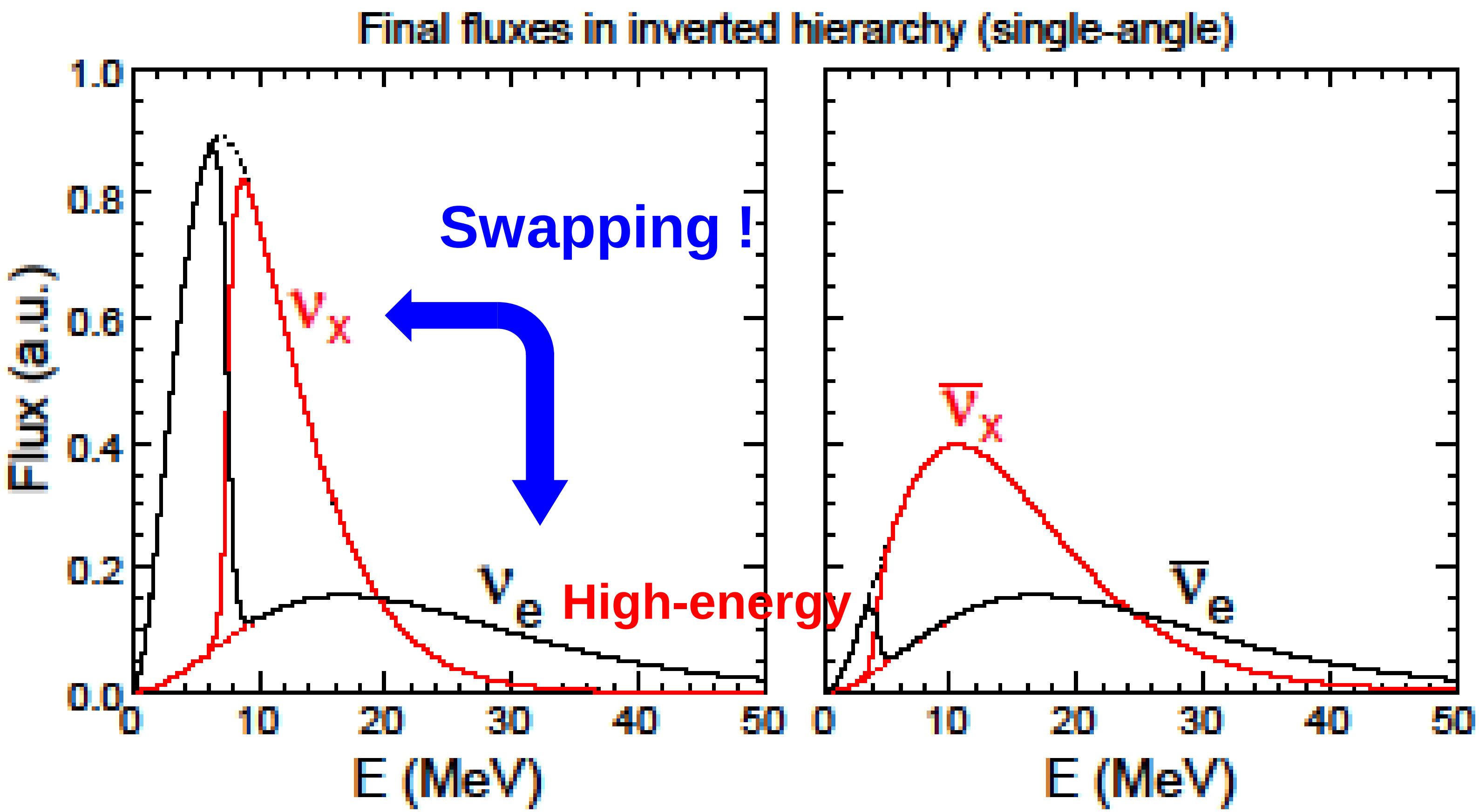
Phys. Rev. D84, 065008 (2011)

ν self-interaction (Quantum Effect)



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

r = 200km



Neutrino Mass in Physics & Cosmology

$0\nu\beta\beta$ COUORE, NEMO3, EXO, KamLAND Zen:

$|\sum U^2_{e\beta} m_\beta| < 0.3$ eV ➡ 0.01 ~ 0.05 eV ! (future)

CMB Anisotropies + LSS

$\Sigma m_\nu < 0.28$ eV (95% C.L.): WMAP-7yr +SPT (Benson et al. arXiv:1112.5435)

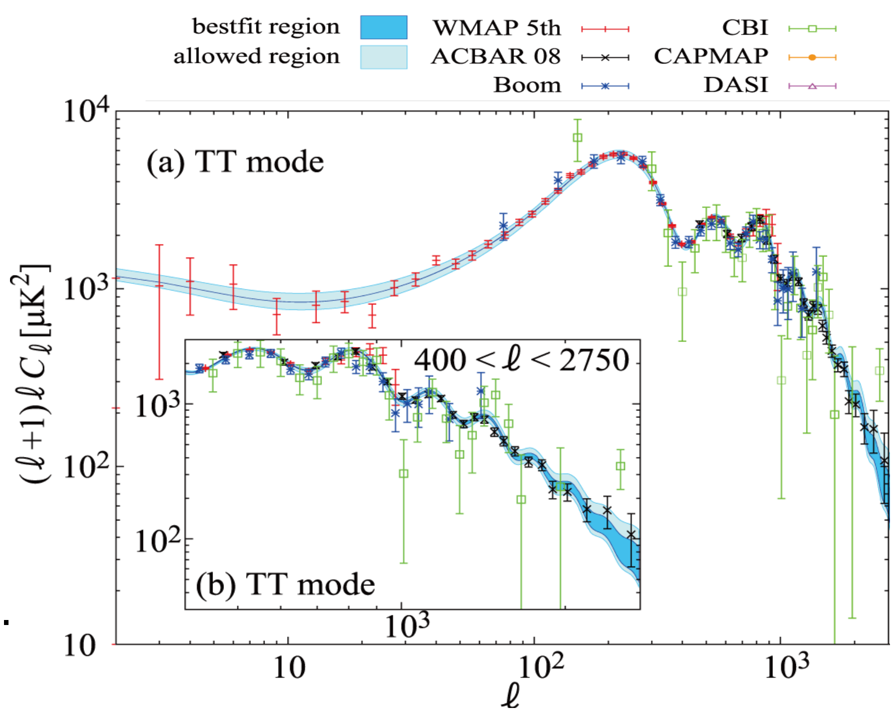
< 0.36 eV (95%C.L.): WMAP-7yr + HST + CMASS (Putter et al. arXiv:1201.1909)

Recent more complete analysis:

Cosamic Magnetic Field + Neutrino Mass
(+ SZ effect + integrated SW effect
+ Neutrino free streaming)

$\sum m_\nu < 0.2$ eV (2σ, B<2nG)

Yamazaki, Kajino, Mathews & Ichiki,
Phys. Rep. (2012), in press;
PR D81 (2010), 103519; D77, (2009) 043005.

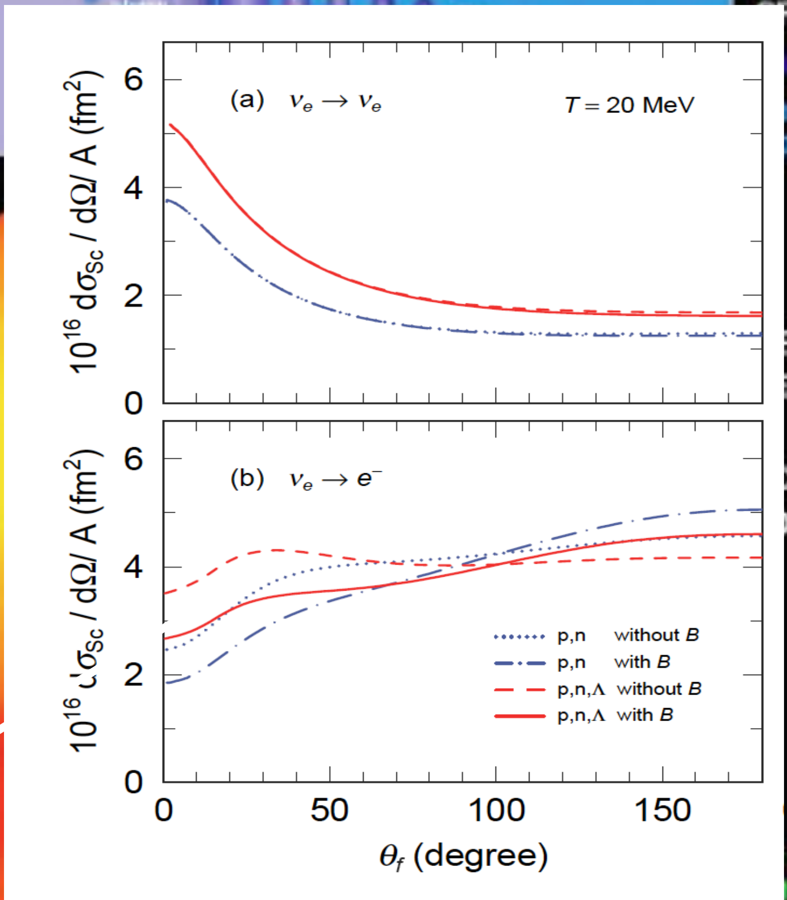


By D.Page

Hadronic Structure of compact stars

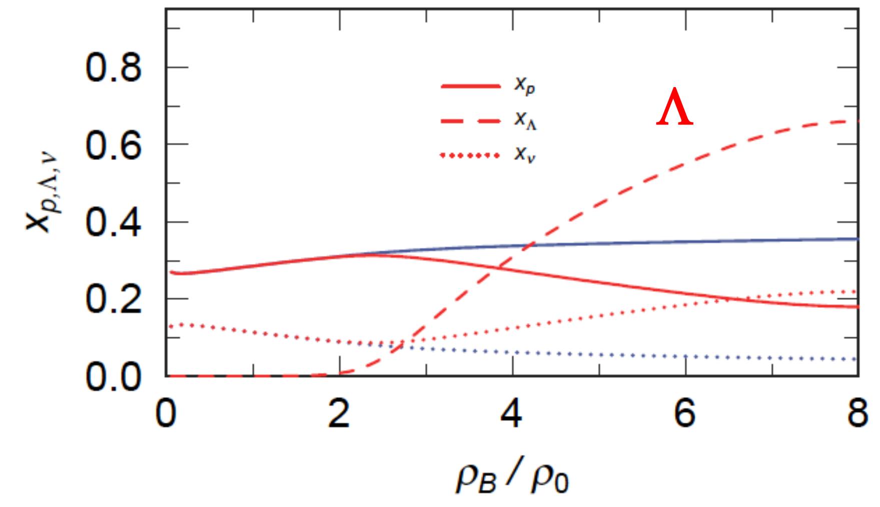
Interactions between Hadrons (p, n, Λ, Σ …) and Lepton (e,ν…) at High-ρ and High-T in QCD and Relativistic Field Theory

ν-scattering and absorption.



Maruyama, Kajino, Yasutake, Cheoun, Ryu, PRD83 (2011), 081303.

RMF theory leads to appearance of Λ in magnetized neutron star.



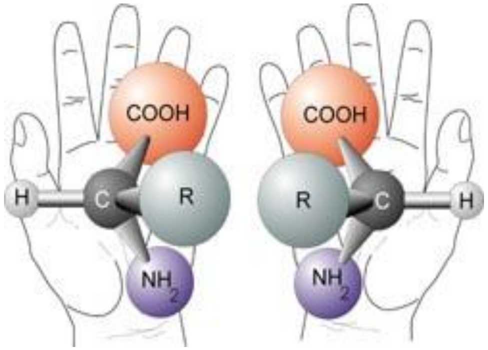
Neutrino scattering and absorption process inside the magnetized neutron star (10^{15}G) is asymmetric.

⇒ ~ 2 % asymmetric ν-emission !

⇒ Enough Asymmetry for Pulsar-Kick !

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

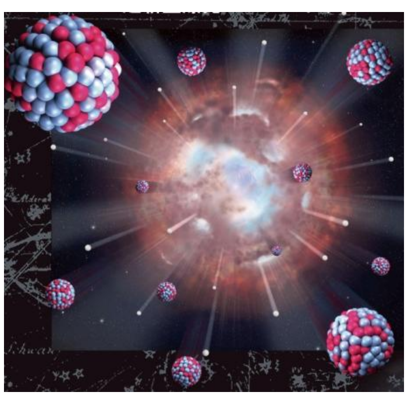
Chitrality, earth/solar origin or universal in cosmos?

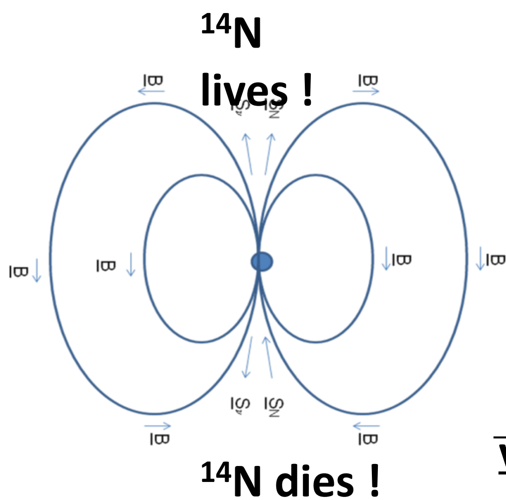


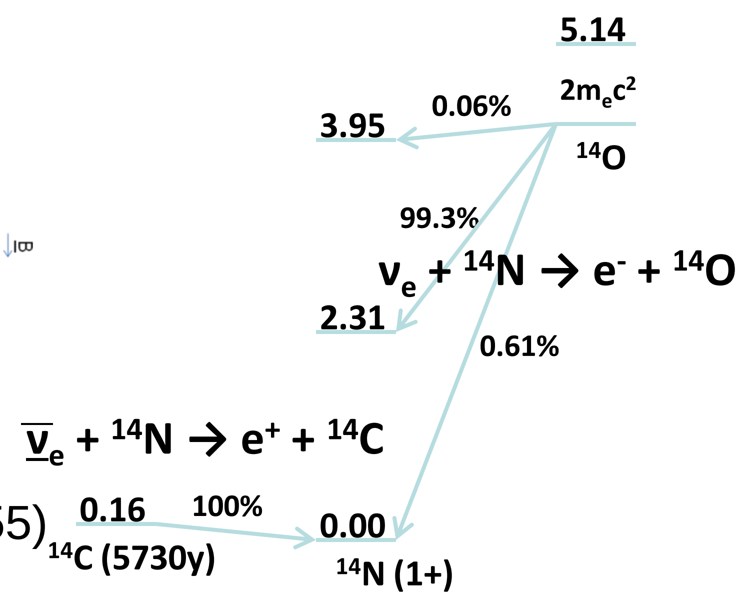
- ★ **Neutrinos are all left-handed!**
- ★ **Supernovae with strongly magnetized neutron star or BH emit intensive flux of neutrinos over 10^{10} yrs!**
- ★ **SN ejecta including ^{14}N interact with neutrino under strong magnetic field!**
- ★ **Neutrino-^{14}N coupling is asymmetric & chiral selective!**

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!

SUMMARY-1

Eluciate important nuclear properties of the nuclei NOT ONLY between neutron-rich waiting points and the 1st, 2nd, and 3rd abundance peaks BUT ALSO below and beyond the peak nuclei:

Heavy Nuclei (Fe < A)

- Masses – Q_n – $\sigma(n,\gamma)$: E1-strength
- β-decay half lives: $\tau_{1/2} \propto Q_\beta{}^5$
- β-delayed nenuton-emission
- Asym. fission, both β-delayed or n-captured

Lighter-to-Intermediate Nuclei (A < Fe)

- p, n, α-induced react., $\sigma(n,\gamma)$ vs. $\sigma(\alpha,n)$
- Roles of ν's in SN-nucleosynthesis

SUMMARY-2

Unknown ν-oscillation parameters, mass hierarchy Δm_{13}^2 (and mixing angle θ_{13}), could be determined simultaneously by supernova ν-process for ^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc, ^{7}Li, ^{11}B, etc.

Recent results on θ_{13} (T2K+MINOS for long baseline ν and RENO + Daya+Bay+Double Chooz for reactor ν) and ^{7}Li/^{11}B ratio in SN grains $\Rightarrow$ **"inverted mass hierarchy" more preferred**.

Theoretical and experimental studies of nuclear weak interactions using spin-isospin response and photon-induced reactions should play the critical roles in neutrino astrophysics in the studies of element genesis in the universe.