阪大核物理センター（RCNP）研究会
「超新星爆発とニュートリノ・原子核反応」
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超新星、ガンマ線バースト天体でのニュートリノ反応

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SN1987AからのニュートリノをKAMIOKANDE & IMBで検出

⟶ ニュートリノ·原子核相互作用の重要性

超新星ν＋MSW効果を使ってニュートリノ振動の精密決定は可能か？

超新星ニュートリノの温度（スペクトル）は決定可能か？

ニュートリノ·原子核反応は重力崩壊型超新星爆発を助けるか？

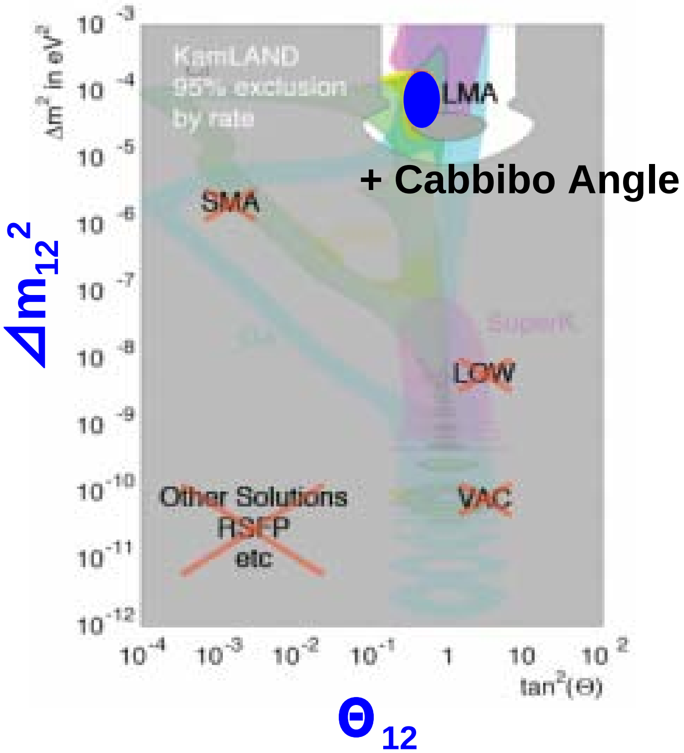
ニュートリノ·原子核反応の重要性と重元素（R過程元素）の起源？

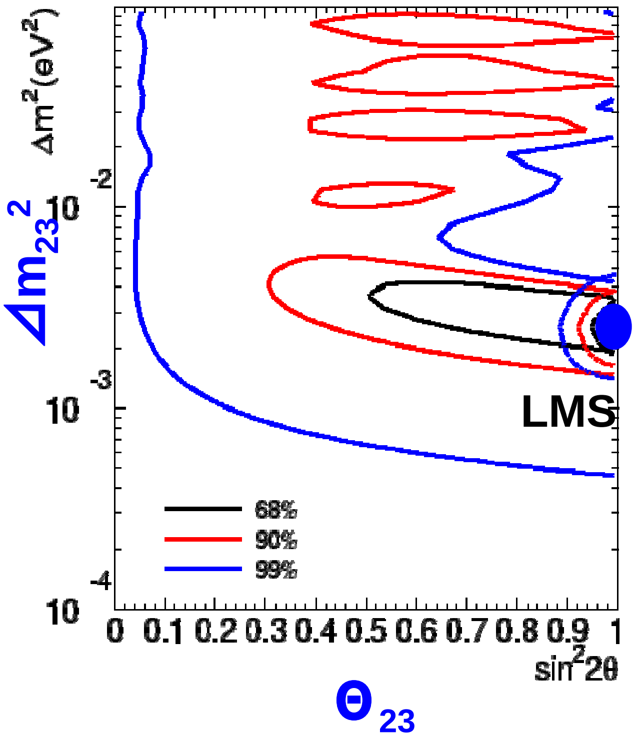
ガンマ線バーストの起源中心天体（コラプサー）と元素合成の異常性？

“KNOWN” Neutrino Oscillation Parameters

Super-K, SNO, KamLand (reactor ν)
determined Δm_{12}^2 and θ_{12} uniquely.

Super Kamiokande (atmospheric ν)
determined Δm_{23}^2 and θ_{23} uniquely.



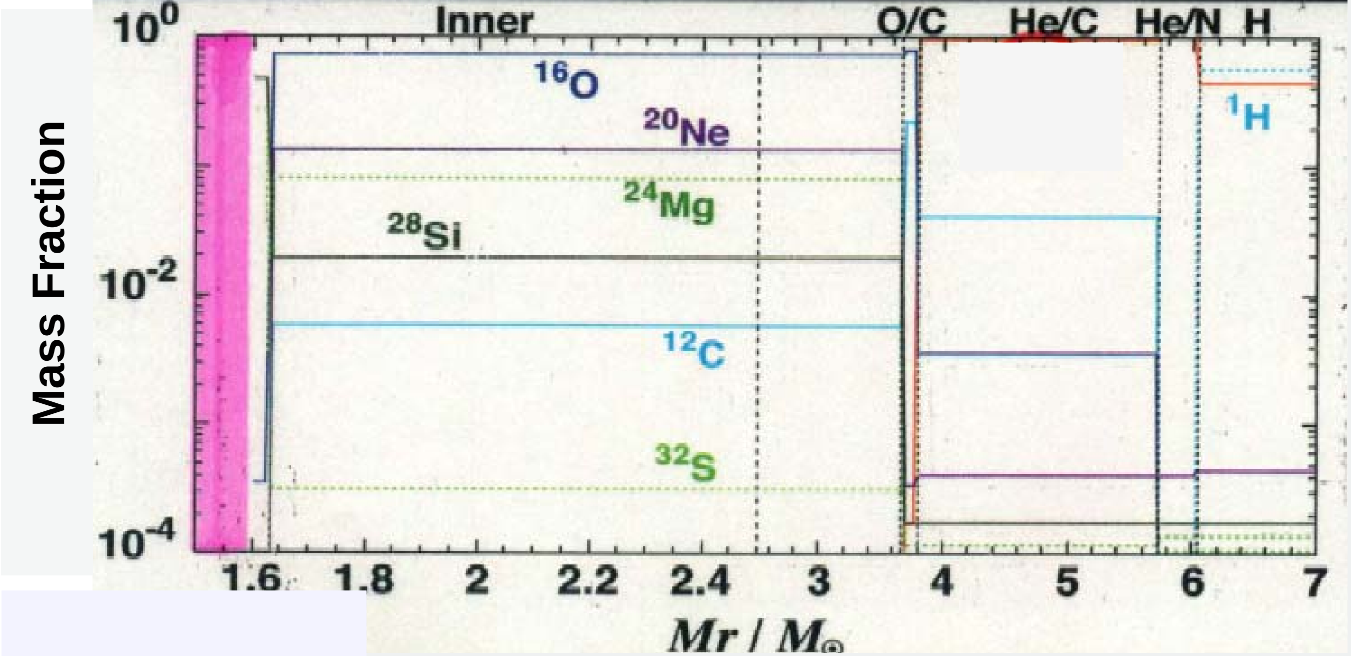


“UNKNOWN”

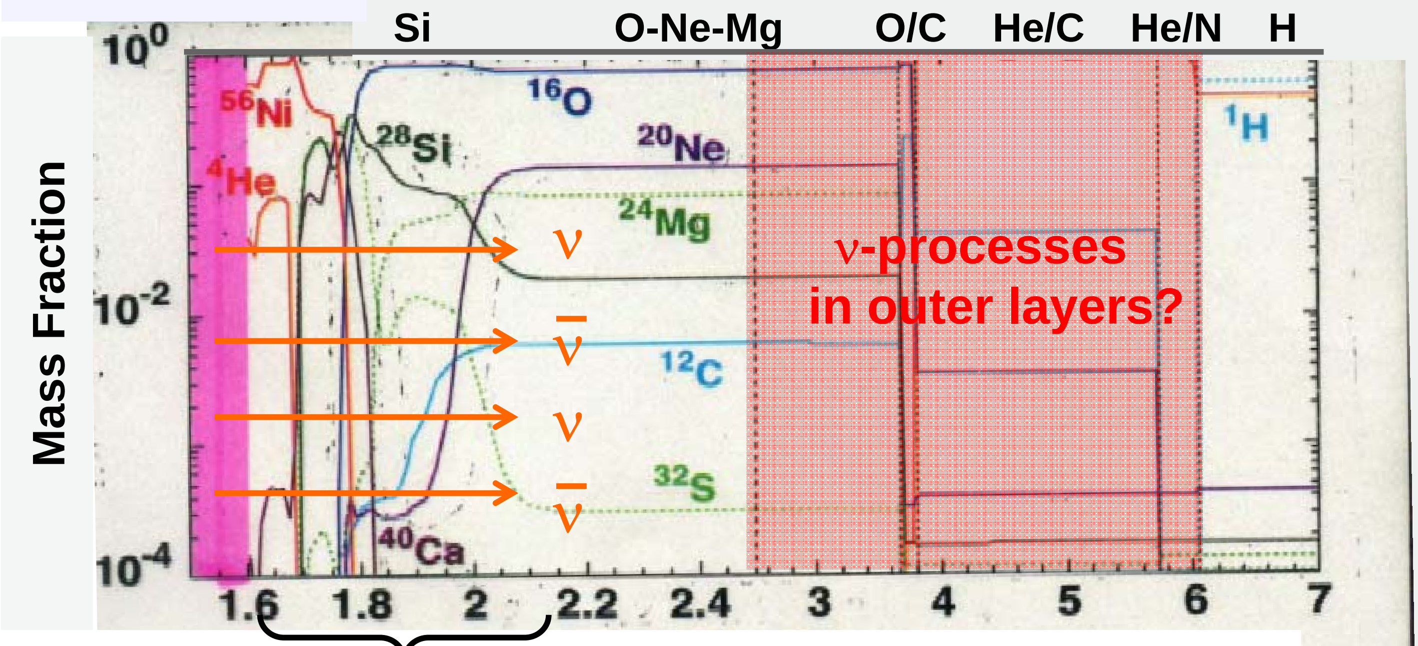
$\sin^2 2\theta_{13} < 0.1$, $|\Delta m_{13}^2| = 2.4\times10^{-3}$ eV^2 ?

We propose a new method to determine θ_{13} and mass hierarchy using the MSW-effect on the ”SN ν-process nucleosynthesis” !

Before Explosion



After Explosion (∼10 s)



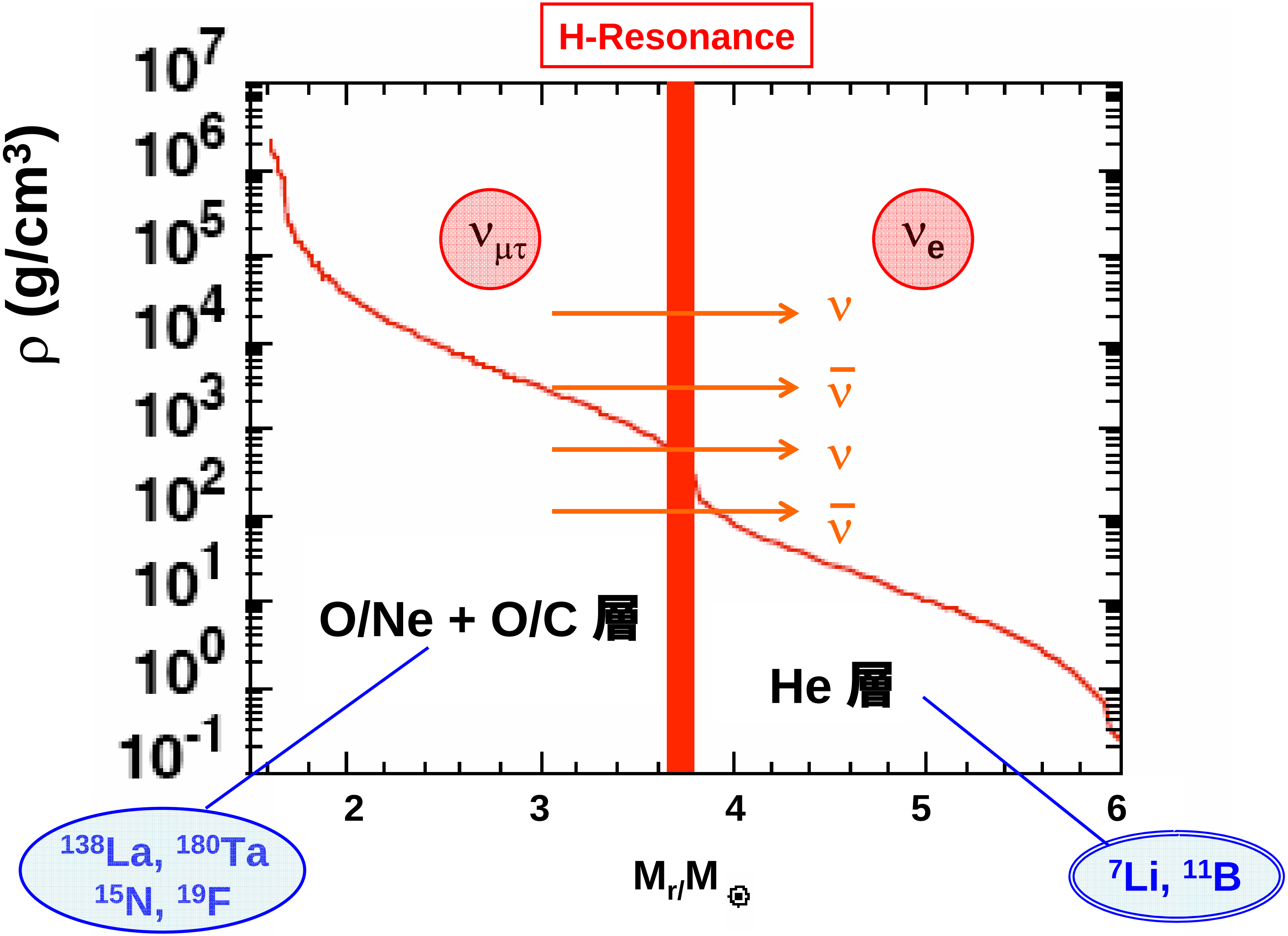
ν-processes in outer layers?

Neutral current (Umeda's talk)

Yoshida's talk

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

Supernova Density Profile & Resonance



Core-Collapse, ν-Heating, Nucleosynthesis

Energy Hierarchy due to neutron-rich matter !

$$E_{\nu e} \le E_{\bar{\nu} e} \le E_{\nu\mu\tau}$$

$$\nu_e + n \longrightarrow e^- + p$$
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$
$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$

Surface of Iron Core

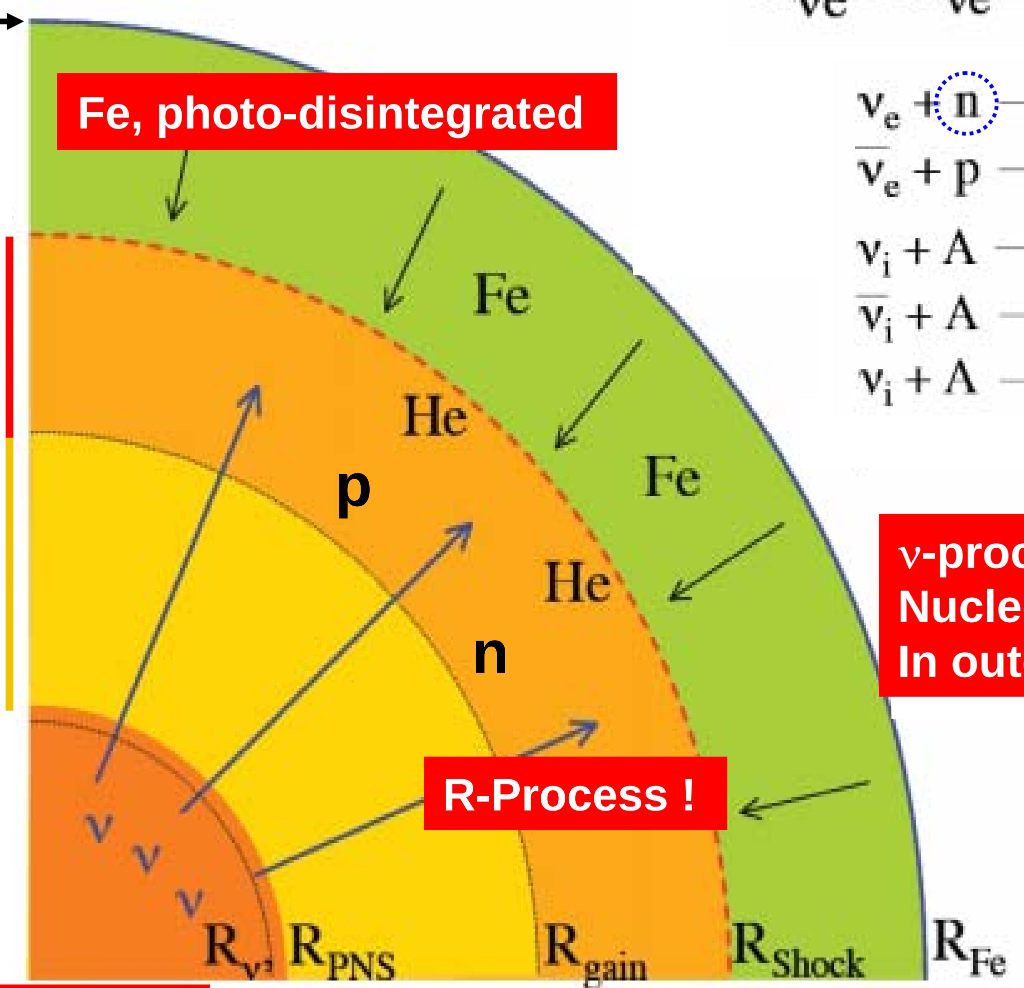
Stalled Shock

Heating Region
→ Hot Bubble

Gain Radius

Cooling Region

Proto-NEUTRON STAR



Fe, photo-disintegrated

R-Process !

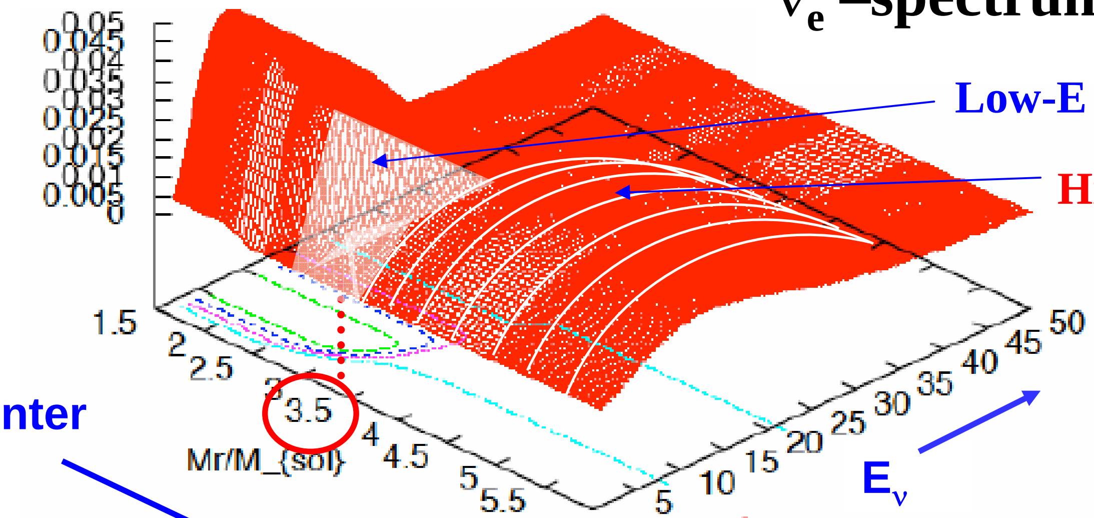
ν-process Nucleosynthesis In outer layers !

~ 10km **~20━100km** **~1000km**

ν–A int. help explosion ?
ν–ν int. & ν–oscillation ?

Neutrino Oscillation (MSW Effect) through propagation

ν_e –spectrum



Low-E comp., cut off

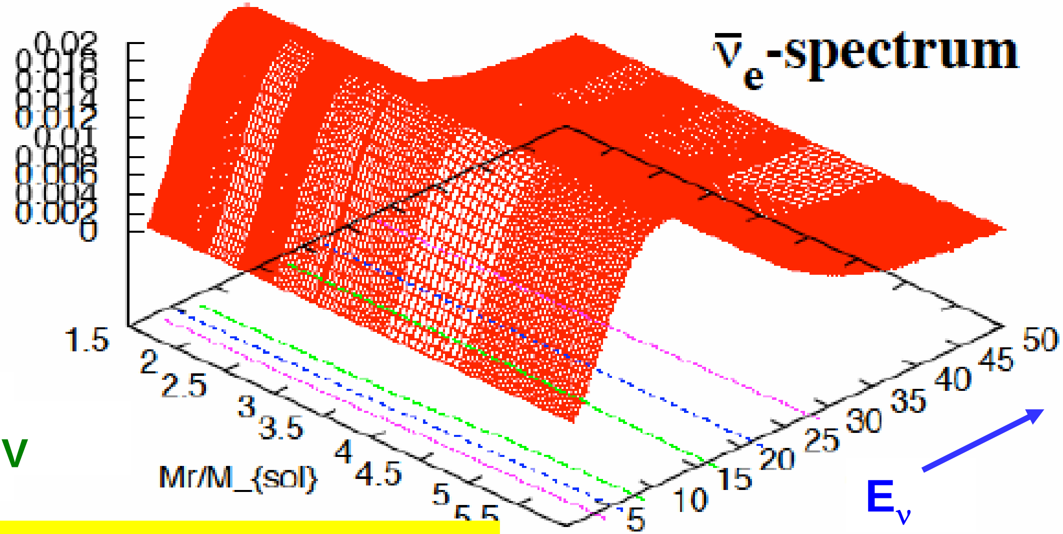
High-E comp. appears !

$\tau_\mu, \tau_\tau \longrightarrow \tau_e$

Center

outside

$\bar{\nu}_e$-spectrum



Parameters:

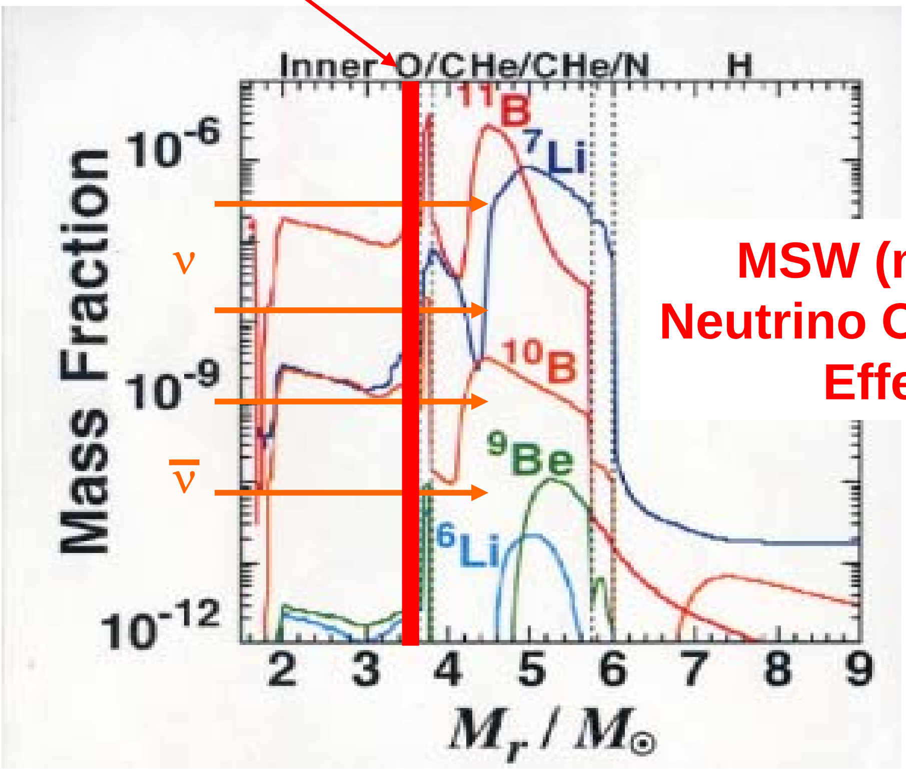
$25M_{solar}$ SN model
(Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\Delta m_{13}^2 = 2.4\text{x}10^{-3}$ eV^2
- $L_\nu = 3\text{x}10^{53}$ erg, $\tau_\nu = 3$ sec
- $E_{\nu e}$=12MeV, $E_{\nu e}$=20MeV, $E_{\nu\mu\tau}$ =24MeV

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

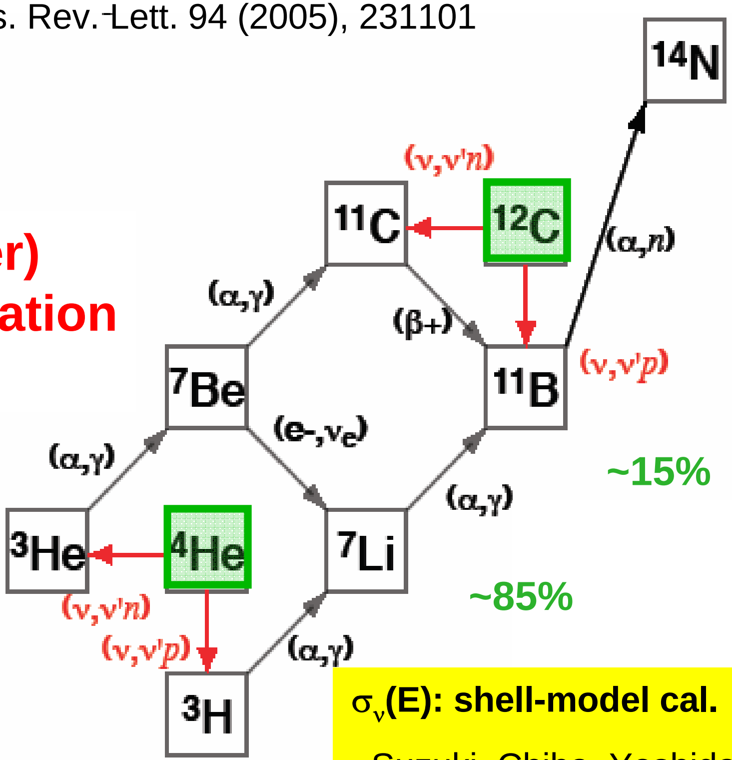
Supernova ν-Process & Key Reactions

H-Resonance



MSW (matter) Neutrino Oscillation Effect

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



σ_ν(E): shell-model cal.

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

$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}$, $^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}$, $^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$

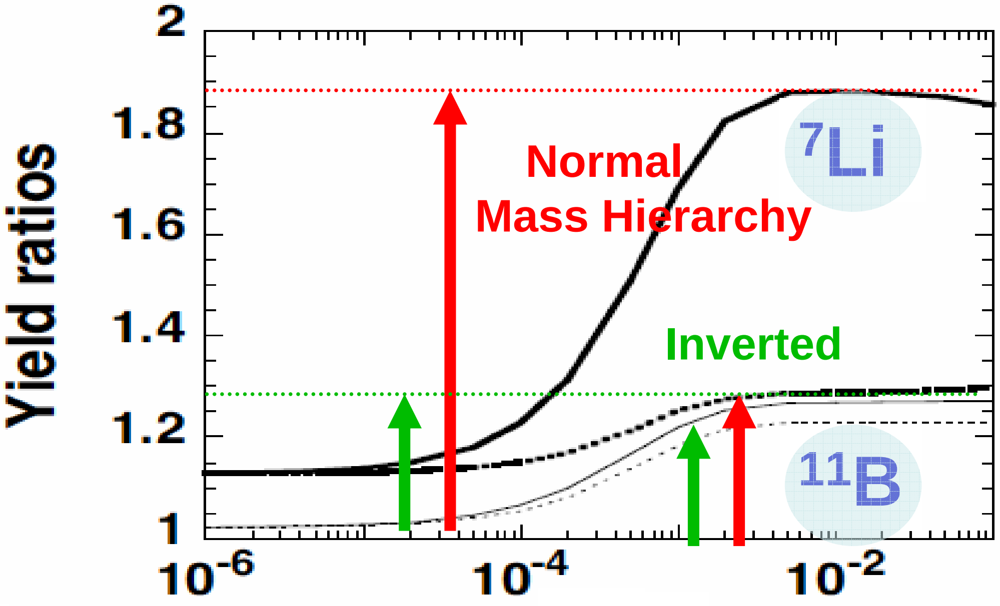
$^{4}\mathrm{He}(\nu_e,e^- p)^{3}\mathrm{He}$, $^{4}\mathrm{He}(\bar{\nu}_e,e^+ n)^{3}\mathrm{H}$, $^{12}\mathrm{C}(\nu_e,e^- p)^{11}\mathrm{C}$, $^{12}\mathrm{C}(\bar{\nu}_e,e^+ n)^{11}\mathrm{B}$

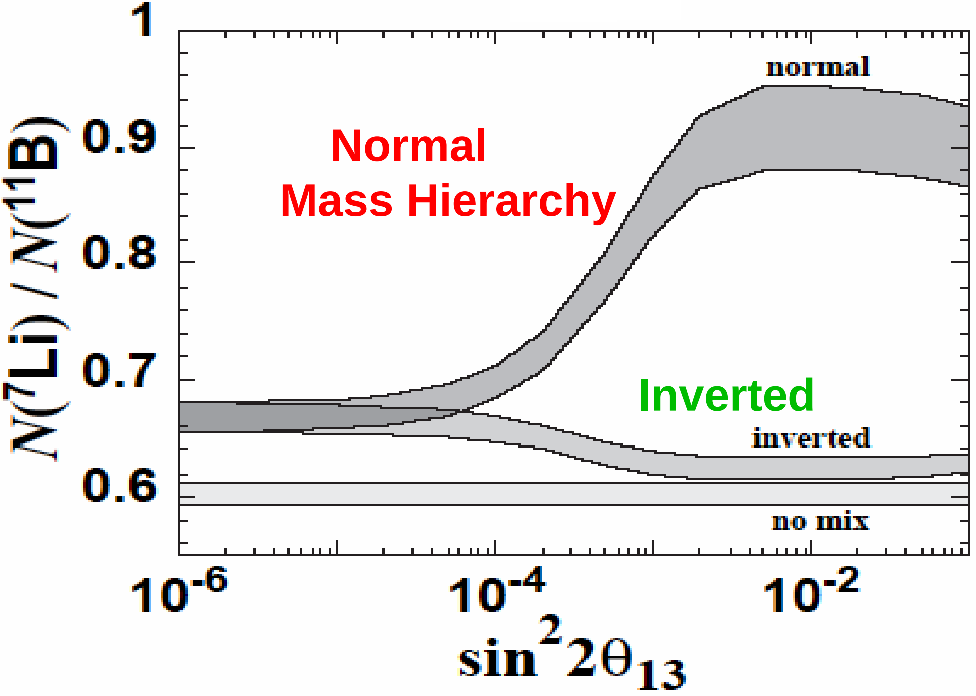
Additional Charged Current Int.

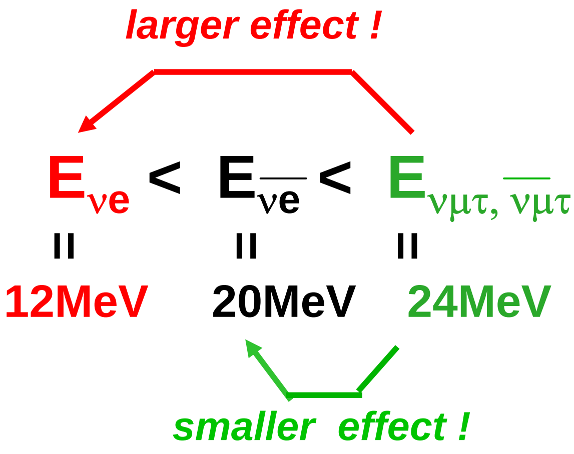
$\nu_{\mu\tau}(\bar{\nu}_{\mu\tau}) \longrightarrow \nu_e\ (\bar{\nu}_e)$

$^{4}\mathrm{He}(\nu_e,e^- p)^{3}\mathrm{He}$ & $^{4}\mathrm{He}(\bar{\nu}_e,e^+ n)^{3}\mathrm{H}$

energetic energetic






larger effect !

$$E_{\nu e} < E_{\bar{\nu} e} < E_{\nu\mu\tau,\ \bar{\nu}\mu\tau}$$

$$\| \qquad \| \qquad \|$$

12MeV 20MeV 24MeV

smaller effect !

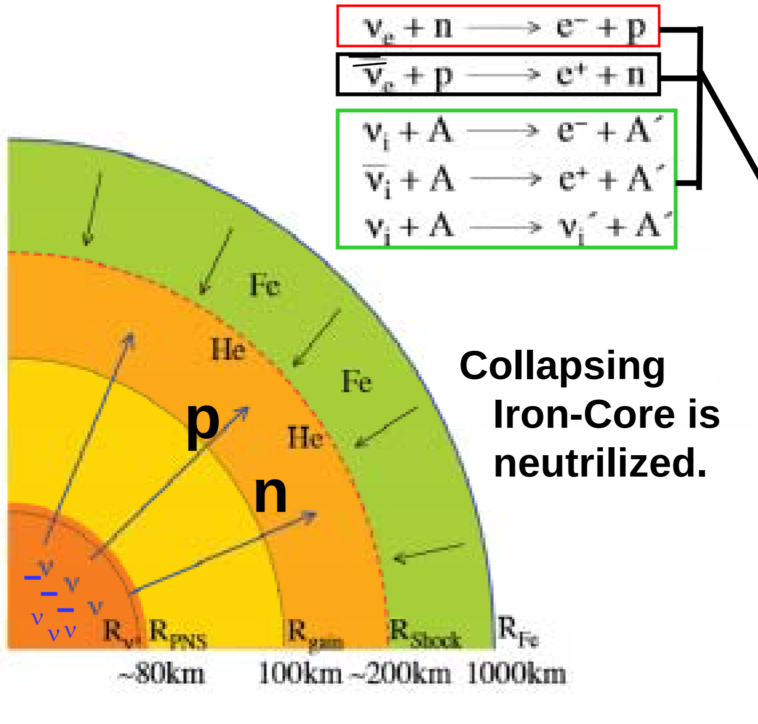
Yoshida, Kajino, Yokomakura, Kimura, Takamura & Hartmann,
PRL 96 (2006) 09110; ApJ 649 (2006), 349.

^{7}Li/^{11}B ratios from Supernova nucleosynthesis help determine

- **Mass Hierarchy, Δm_{13}^2**
- **13-Mixing Angle, θ_{13}**

Laboratory Experiments:

T2K, Double CHOOZ, Daya Bay



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

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

$\nu_i + A \longrightarrow e^- + A'$

$\bar{\nu}_i + A \longrightarrow e^+ + A'$

$\nu_i + A \longrightarrow \nu_i' + A'$

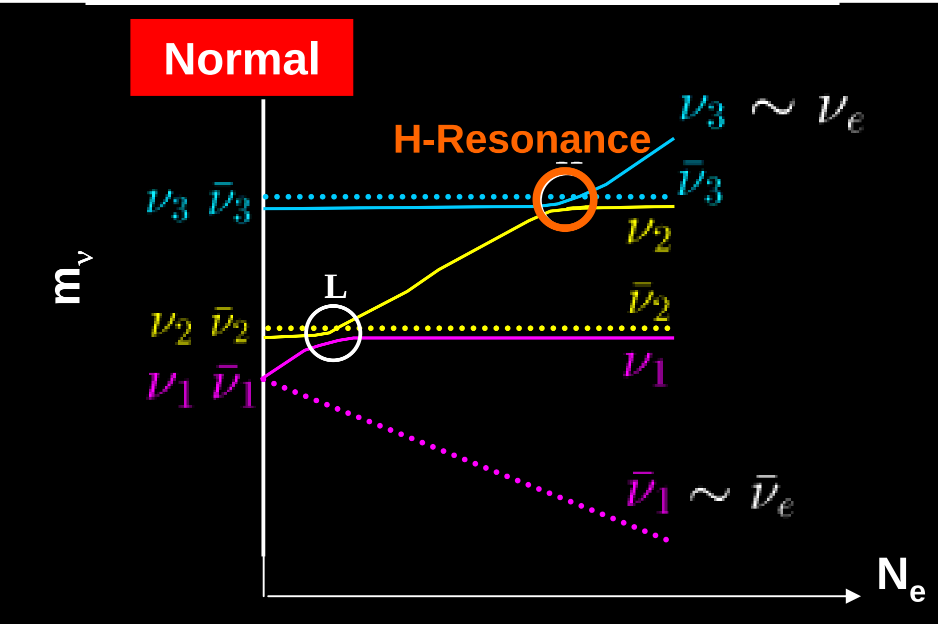
Collapsing Iron-Core is neutrilized.

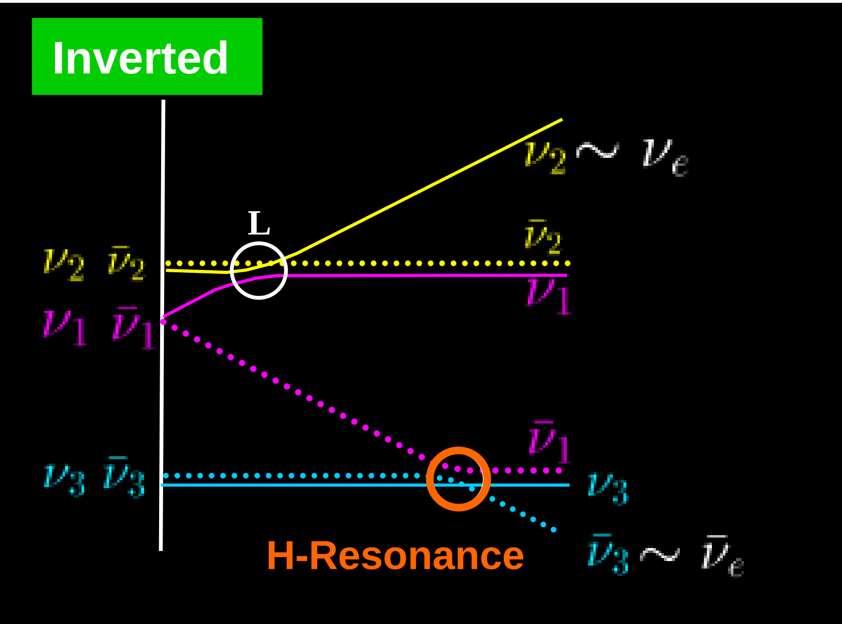
The KEY
of our "NUCLEOSYNTHESIS PROPOSAL"
is the ENERGY HIERARCHY of SN- ν's.

ENERGY HIERARCHY

$$E_{\nu e} < E_{\bar{\nu} e} < E_{\nu\mu\tau,\, \bar{\nu}\mu\tau}$$

$$\begin{array}{ccc} \| & \| & \| \\ 12\text{MeV} & 20\text{MeV} & 24\text{MeV} \end{array}$$





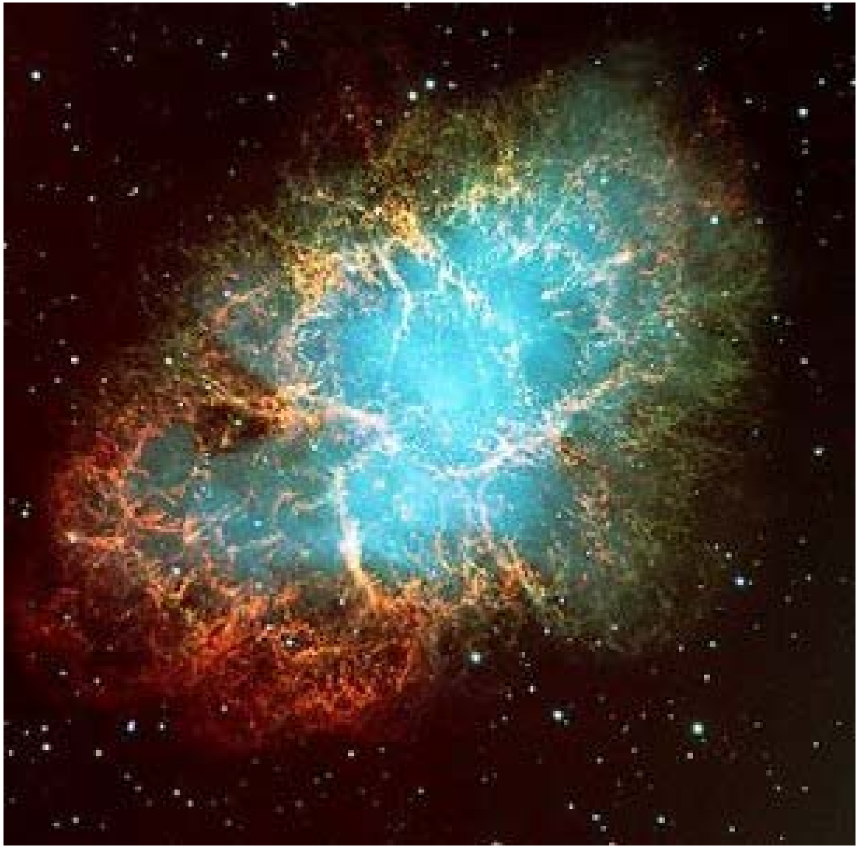
How to get observational signature of the $^{7}\mathrm{Li}/^{11}\mathrm{B}$ ratio from almost pure SN-nucleosynthesis?

- **Optical spectroscopic observation of SN-remnants !**

2. **Analysis of chemical composition of presolar grains originating from SN-nucleosynthesis !**

SN1987A Remnant
Too hot → Emission lines ?

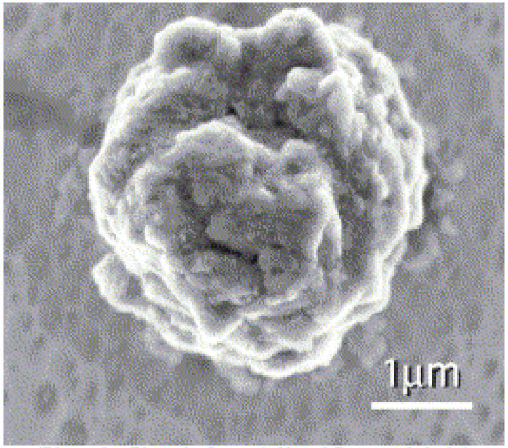
Crab Nebula
Too low density → Too weak absorption lines



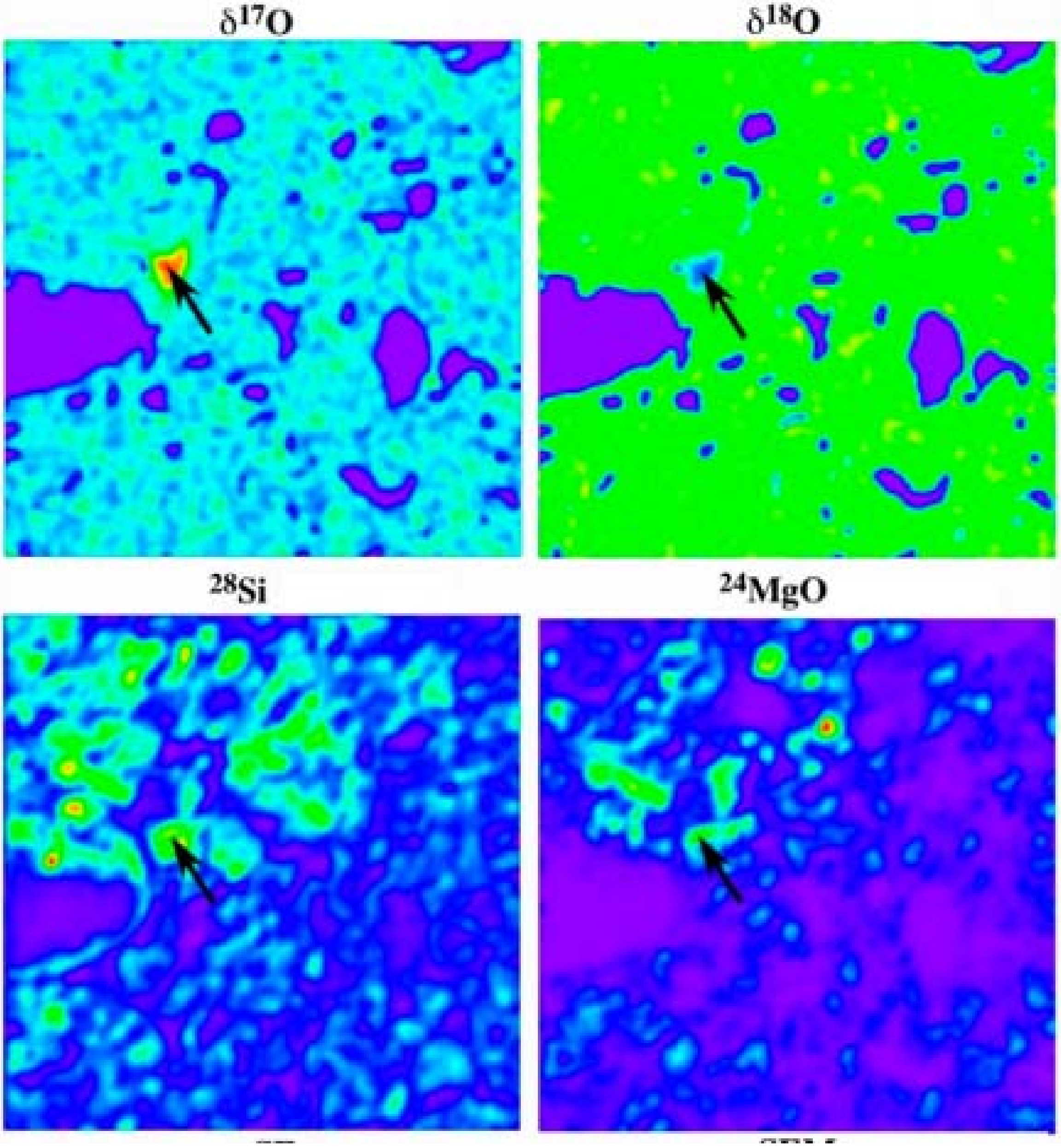
^{7}Li absorption line ～ 6708 A
Ground Base Telescope
like SUBARU

^{11}B absorption line ～ 2719 A
Space Telescope like HST

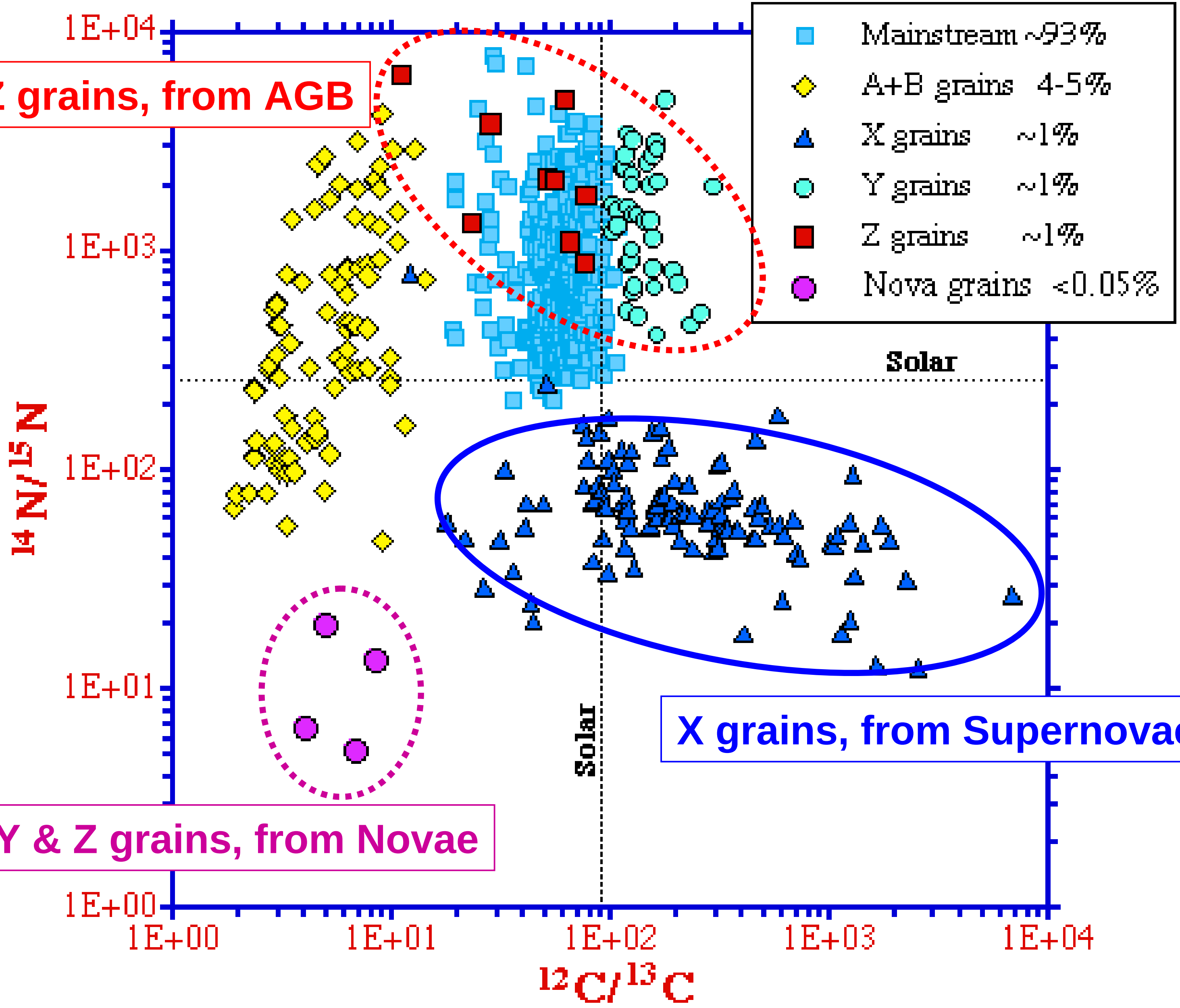
Presolar SiC Grain



(Photo by Rhonda Stroud, Naval Research Lab.)



Presolar SiC grains



Y & Z grains, from AGB

X grains, from Supernovae

Y & Z grains, from Novae

Uncertainties ?

1. Neutrino Energy Spectrum, well known?

Fermi-Dirac distr. of T_ν

How to determine T_ν ? ← from “SN1987A obs.” & “GCE”

Yoshida, T., Kajino, T., & Hartmann, D. H., PRL 94 (2005), 231101

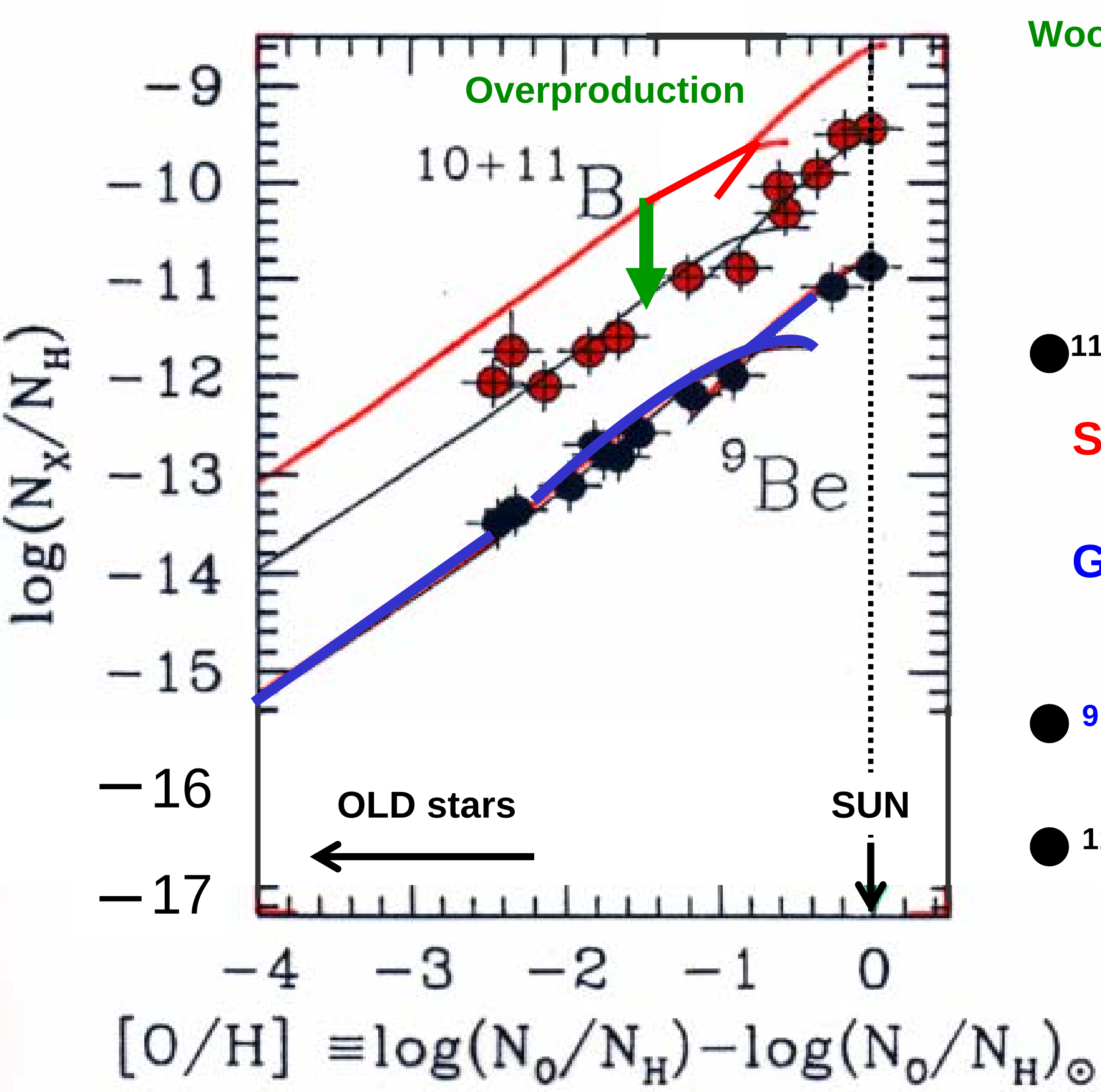
2. Neutrino-Nucleus Cross Section σ_ν(E), well known?

Previous SM cal. by W. Haxton (1990)

Precise SM cal. using better interactions, done (2006) !

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

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



Woosley and Weaver, ApJ (1995)

$T\nu_{\mu,\tau} = 8$ MeV

- ● **^{11}B has two origins:**

Supernova ν−process

+

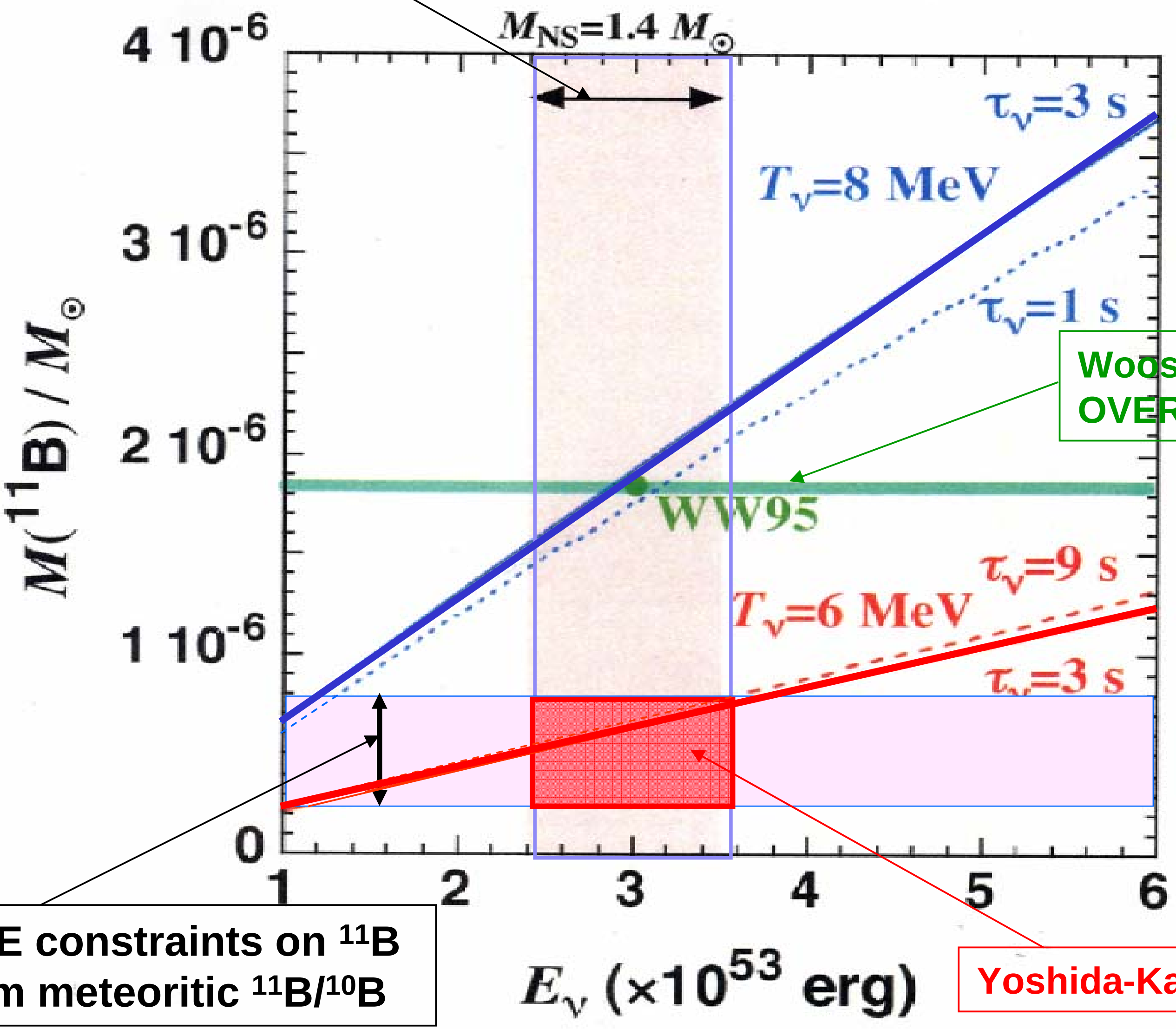
Galactic Cosmic Rays (GCR)

- ● **^{9}Be has pure GCR origin.**
- ● **^{11}B >> ^{10}B**

How to know SN $\nu_{\mu\tau}$-Spectrum ?

Yoshida, T., Kajino, T., and Hartmann, D., PRL 94 (2005), 231101.

Grav. Potential constraint



Woosley & Weaver (1995) OVERPRODUCTION

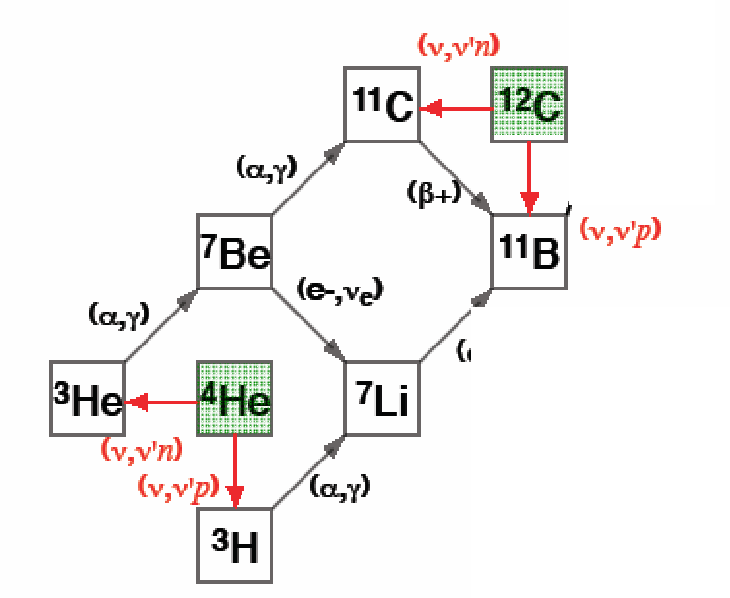
Consistent with the recent theoretical ν-transfer calculation (Thomas-Janka et al. 2004)

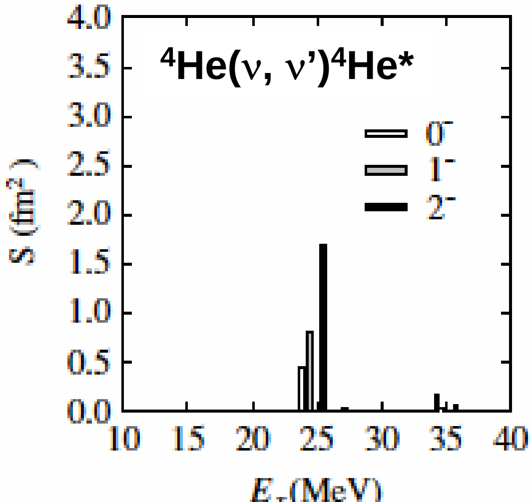
GCE constraints on ^{11}B from meteoritic $^{11}B/^{10}B$

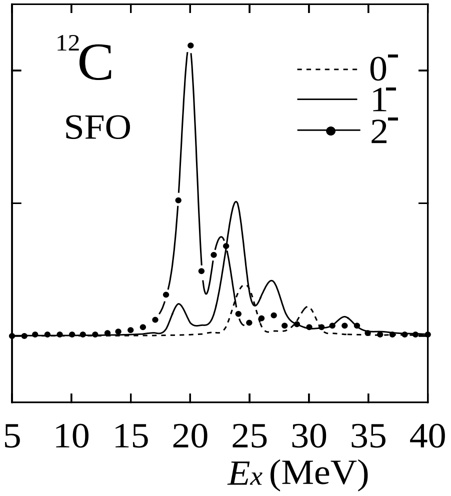
Yoshida-Kajino-Hartmann (2005)

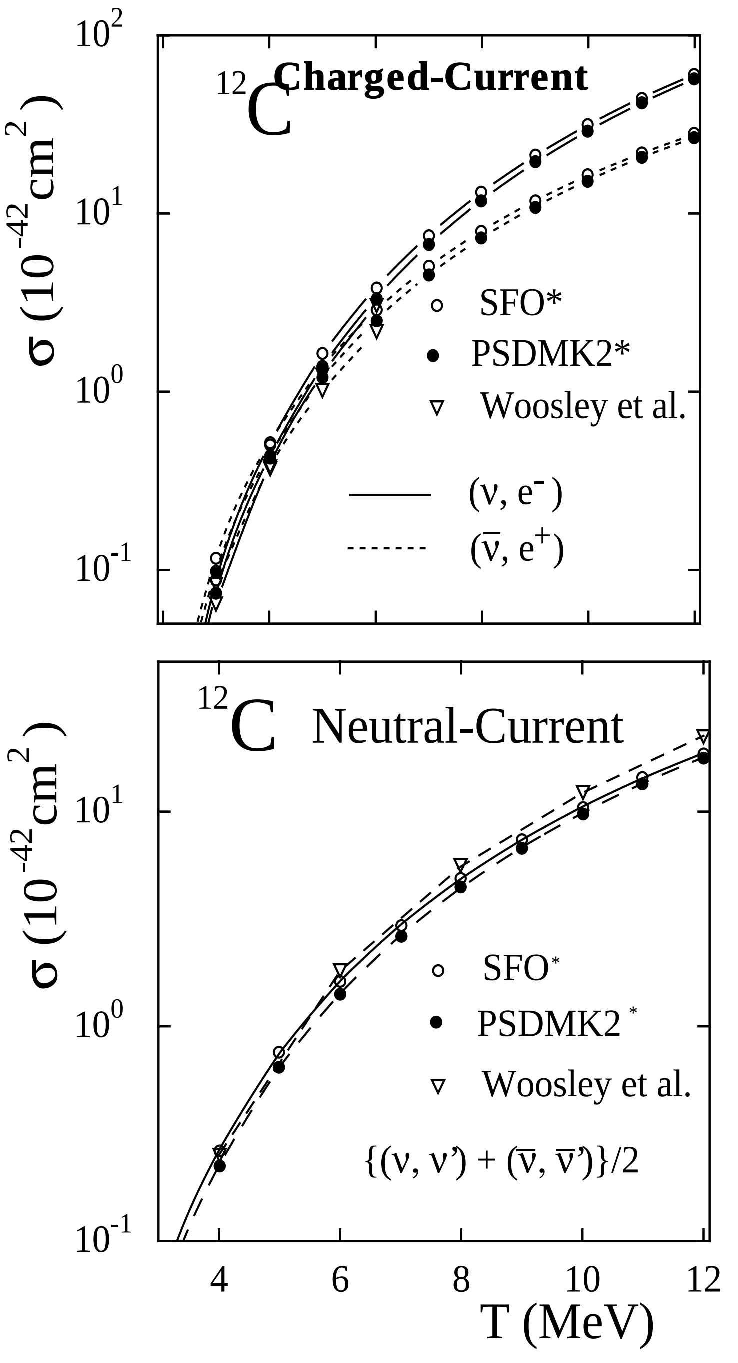
Shell Model Cal. with new Hamiltonian

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



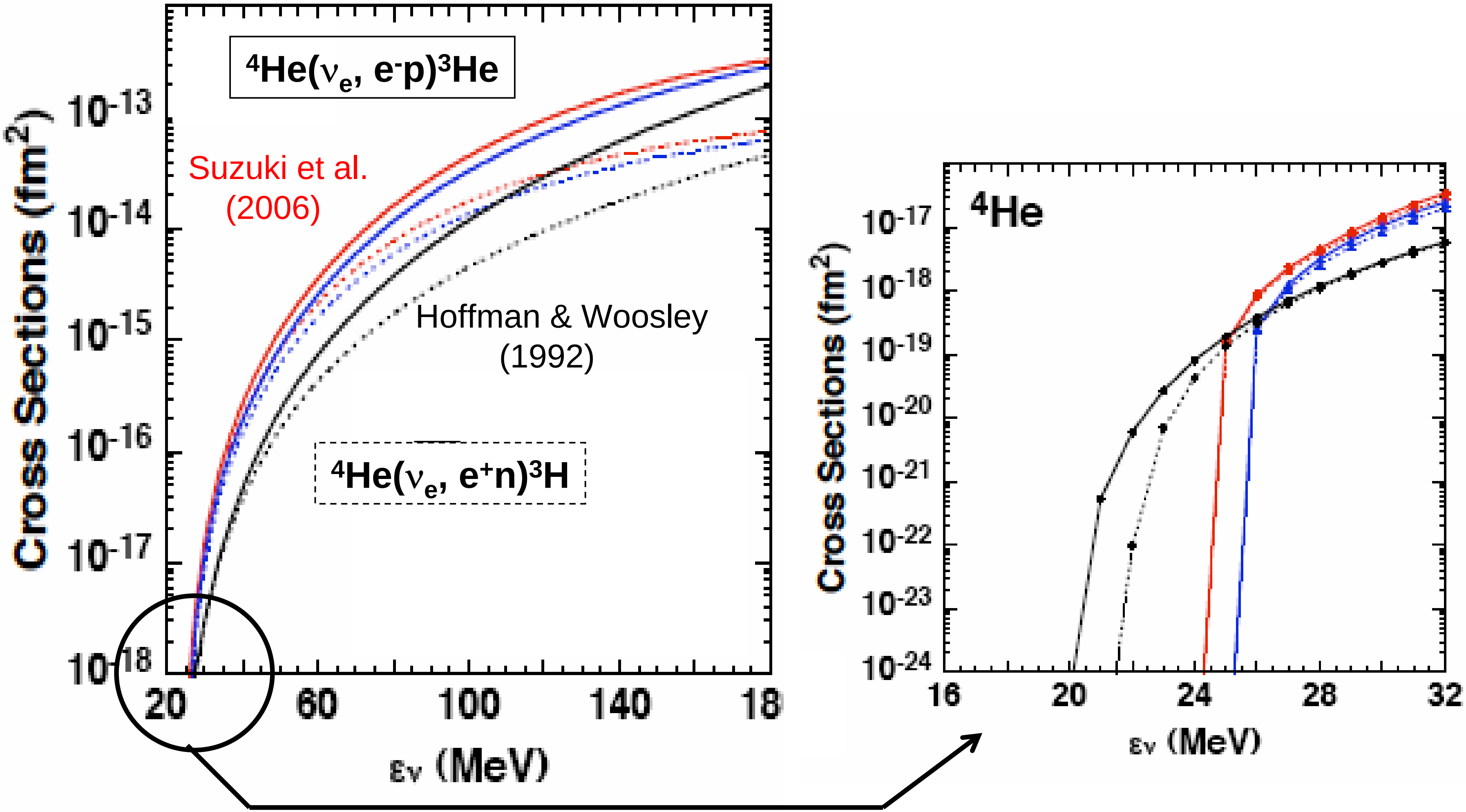






Comparison of $\sigma_\nu(E)$ from two Shell Model Calculations

Suzuki, Chiba, Yoshida, Kajino & Otsuka, Phys. Review C74 (2006), 034307.



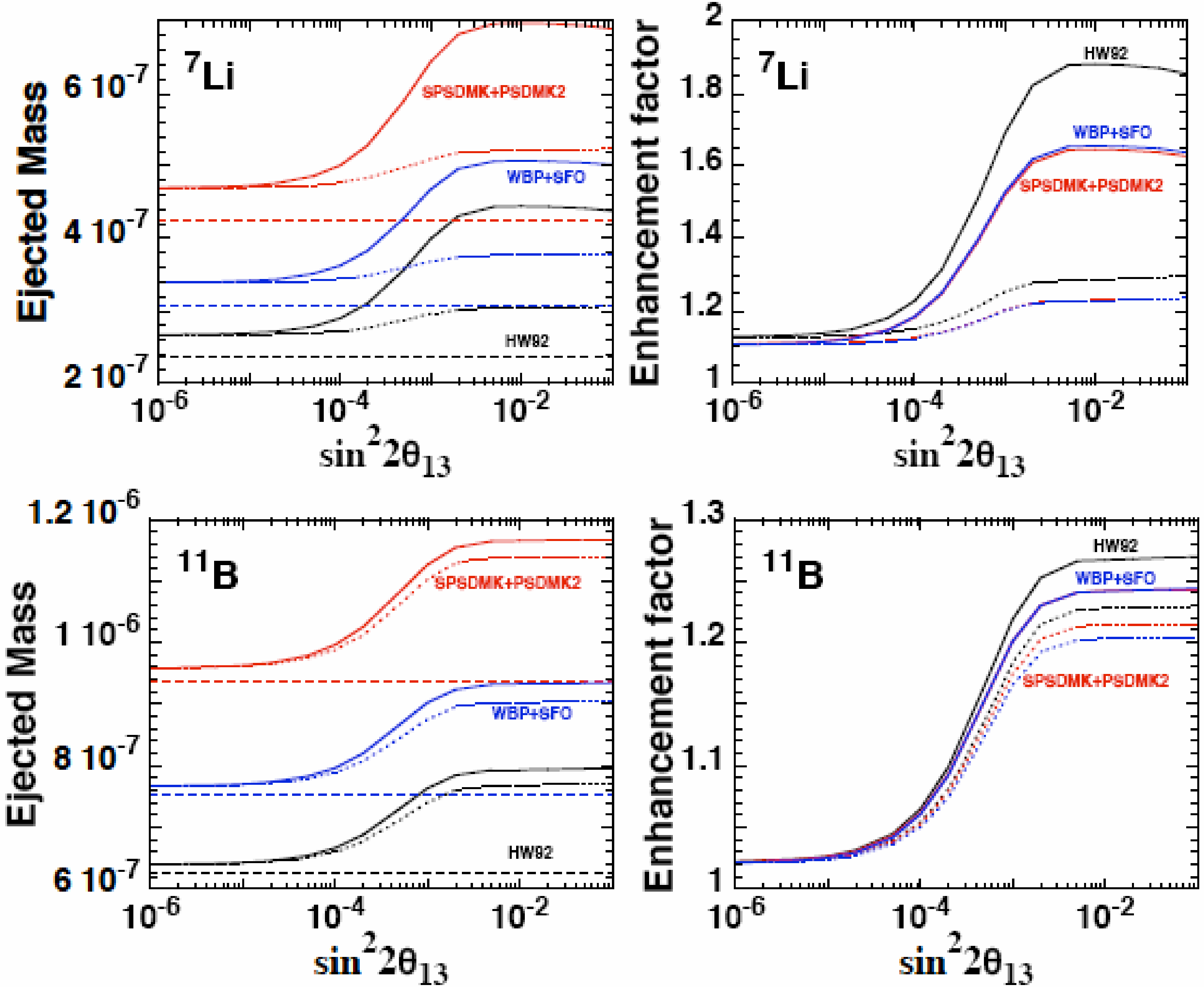
$^4He(\nu_e, e^-p)^3He$

Suzuki et al.
(2006)

Hoffman & Woosley
(1992)

$^4He(\nu_e, e^+n)^3H$

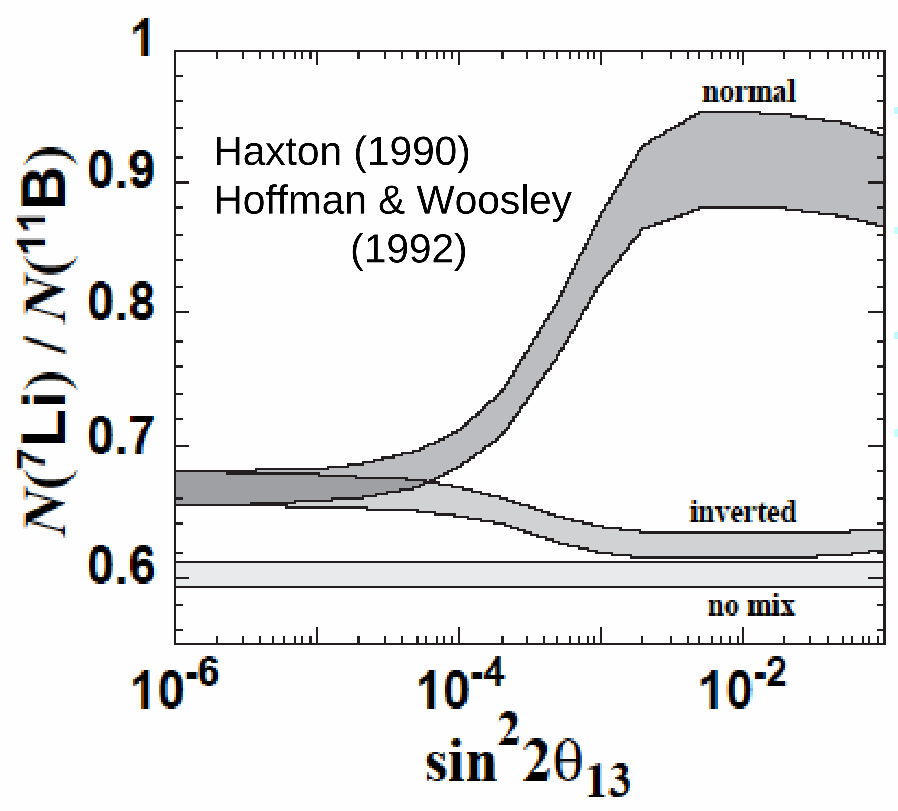
Neutrino Oscillation Effect



Neutrino Oscillation Effect on ^{7}Li/^{11}B-ratio

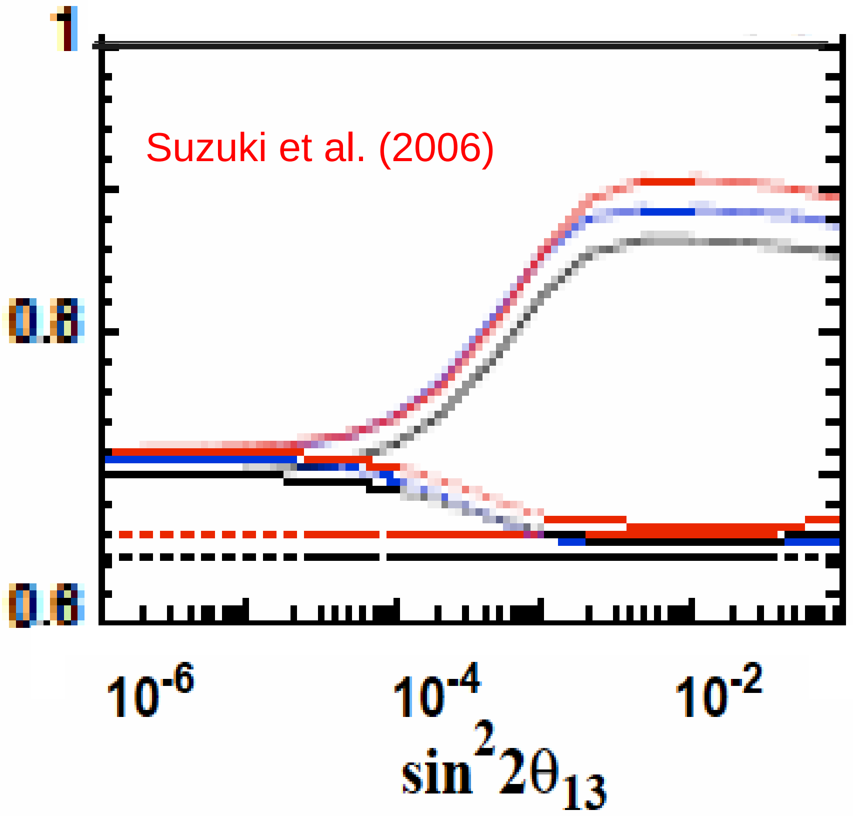
Previous SM-σ_{ν}(E) of Haxton

Woosley, Haxton, Hoffmann, Wilson, ApJ. (1990
Hoffmann & Woosley, ApJ. (1992).



New SM-σ_{ν}(E) using WBP(^{4}He) & SFO(^{12}C) interactions

Suzuki, Chiba, Yoshida, Kajino & Otsuka,
Phys. Review C74 (2006), 034307.



Almost the same result ! → ^{7}Li/^{11}B-ratio is SM independent !

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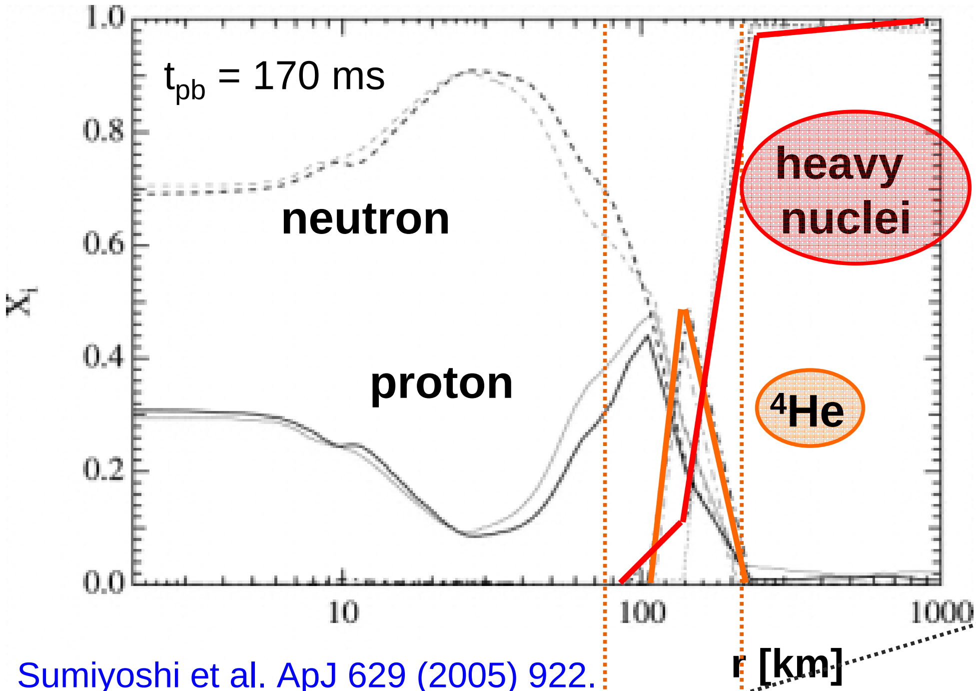
ν-Heating Machanism

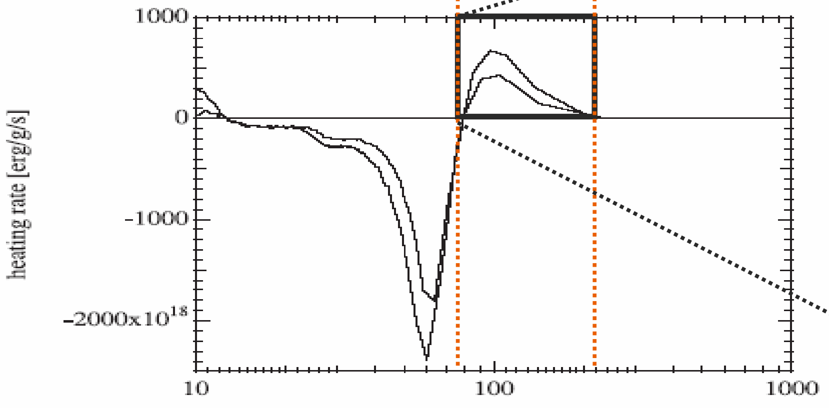
Importance of ν(ν̄) + A interaction ?!

$$\dot{q} = \dot{q}_1 - \dot{q}_2 + \dot{q}_3 - \dot{q}_4 + \dot{q}_5$$

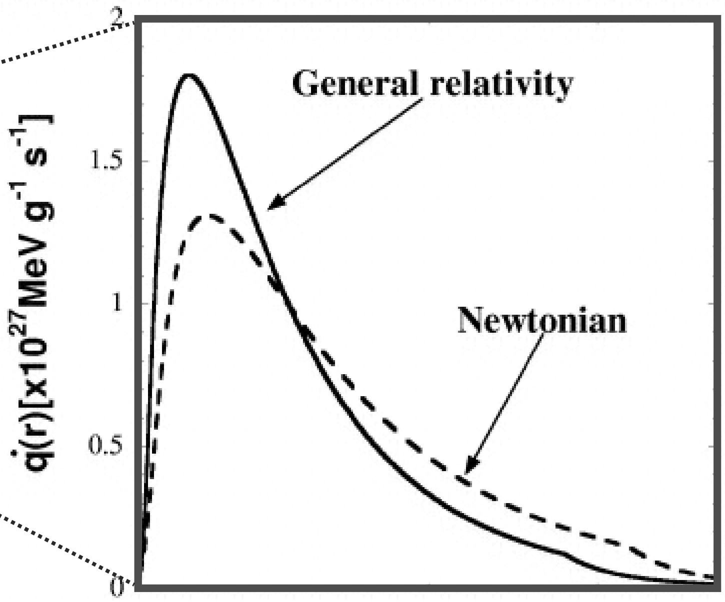
$$\begin{cases} \dot{q}_1 = & \nu_e + n \rightarrow p + e^- \\ & \bar{\nu}_e + p \rightarrow n + e^+ \\ \dot{q}_2 = & \text{reverse of “1”} \\ \dot{q}_3 = & \nu_e + e^{+/-} \rightarrow \nu_e + e^{+/-} \\ & \bar{\nu}_e + e^{+/-} \rightarrow \bar{\nu}_e + e^{+/-} \\ \dot{q}_4 = & \text{reverse of “3”} \\ \dot{q}_5 = & \nu_e + \bar{\nu}_e \rightarrow e^- + e^+ \end{cases}$$



Sumiyoshi et al. ApJ 629 (2005) 922.



Otsuki et al. ApJ 533 (2000) 424.



Similarity between ElectroMagnetic & Weak Interactions.

Suzuki et al. Phys. Rev. C74 (2006) 034307.

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

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

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

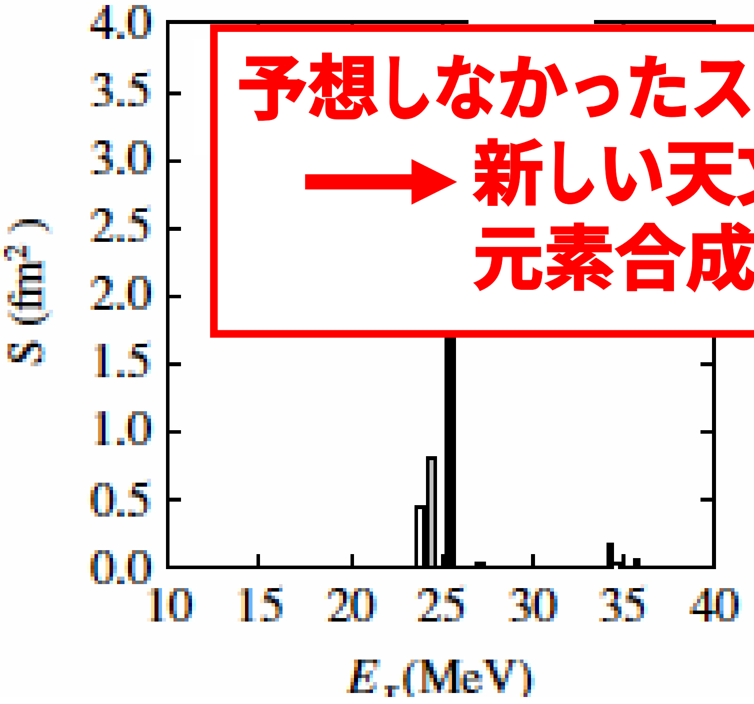
GT = $\vec{\sigma}\,\tau_{\pm}$

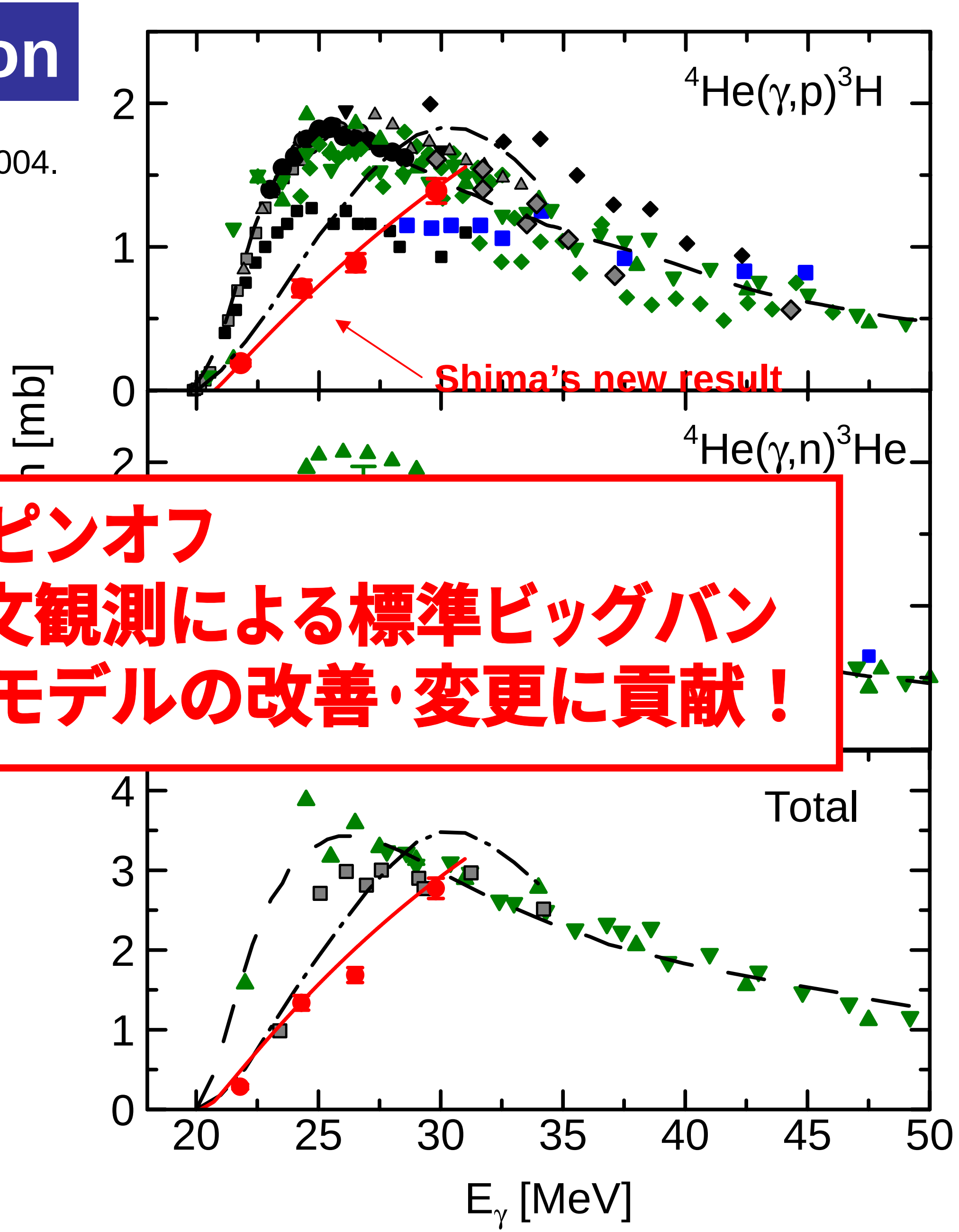
Spin-Dipole **=** $[\vec{\sigma} \times \vec{r}\,]^J \tau_{\pm}$

Photo-induced Reaction

Shima et al. Phys. Rev. C72 (2005) 044004.

^{4}He(^{7}Li,^{7}Be)： 中山信太郎



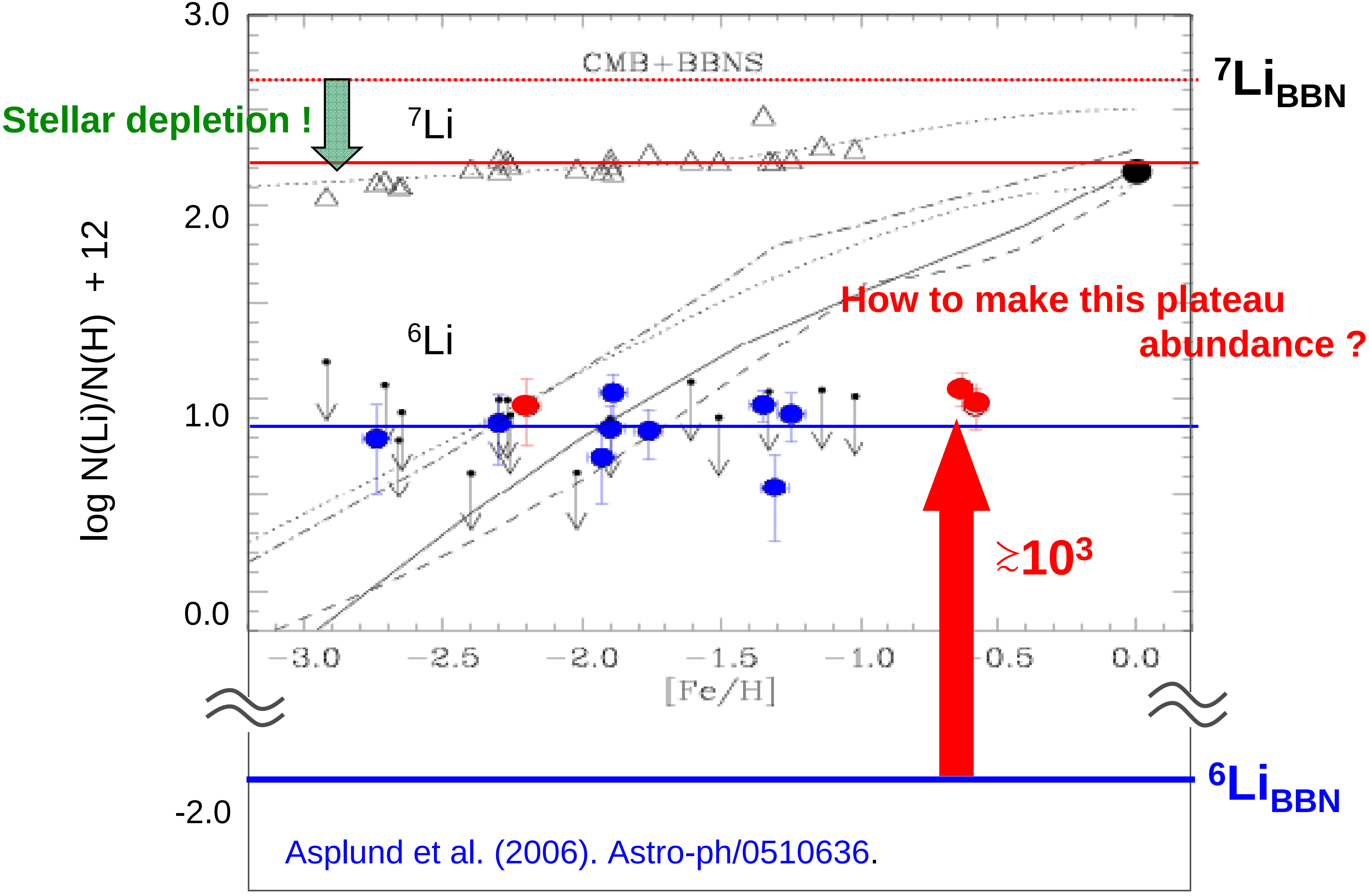


予想しなかったスピンオフ

⟶ 新しい天文観測による標準ビッグバン
元素合成モデルの改善･変更に貢献！

Suzuki et al. Phys. Rev. C74 (2006) 034307.

Astronomers found ^{6}Li plateau abundance as well as ^{7}Li plateau !



$^7\mathrm{Li}_{\mathrm{BBN}}$

Stellar depletion !

How to make this plateau abundance ?

$\gtrsim 10^3$

$^6\mathrm{Li}_{\mathrm{BBN}}$

Asplund et al. (2006). Astro-ph/0510636.

What could make ^{6}Li ?

- Post-star formation
  - Production by flare-accelerated ^{3}He through ^{4}He(^{3}He,p)^{6}Li

    Tatischeff &Thibaud (2006)

- Pre-star formation
  - Hierarchical structure formation shock induced $\alpha+\alpha$ fusion

    Suzuki & Inoue (2002)

  - Cosmological CR burst induced pregalactic $\alpha+\alpha$ fusion

    (Pop III stars may be related) Rollinde et al. (2005, 2006)

  - Non-standard BBN (z>>1000)

    Jedamzik (2000-04), Kawasaki et al. (2005)

    Decay/annihilation of exotic CDM (SUSY, etc.) particles

    Radiative decay at ~10^3s after Bigbang Kusakabe, Kajino & Mathews (2006)

    → photons, ~~partons~~

    ~~very complicated & many parameters !~~

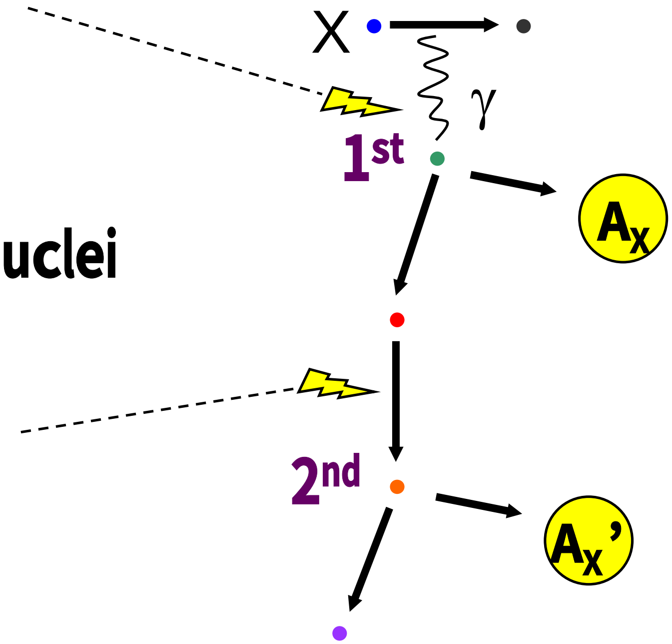
Model

- Assume : exotic particle (X) decays life time τ_X

→γ emerges with energy **$E_{\gamma 0}$**

abundance parameter

$$\boxed{\zeta_X = \frac{n_X^0}{n_\gamma^0} E_{\gamma 0}}$$



Interactions with background γ and e±
(Kawasaki & Moroi 1995)

1. Primary (1st) process

- **Nonthermal γ reacts with background nuclei**

(Cyburt et al. 2003)

Interactions with background γ and e±
(Kawasaki et al. 2005)

2. Secondary (2nd) process

- **Reactions between primary product with background nuclei**

(Cyburt et al. 2003, Kusakabe et al. 2006)

3. Tertiary process

e.g. ^{6}Li(p.α)^{3}He

Theoretical Method

Spectrum of nonthermal photons

$$p_\gamma(E_\gamma)$$

- **Primary γ interacts with CBRs to realize an equilibrium spectrum**
  - **pair creation ($\gamma\gamma_{bg} \to e^+e^-$)**
  - **inverse Compton ($e^\pm + \gamma_{bg} \to e^\pm + \gamma$)**
- **Then it degrades its energy by**
  - **Compton scattering ($\gamma + e^\pm_{bg} \to \gamma + e^\pm$)**
  - **Bethe-Heitler process (γ+nuclus$_{bg} \to e^+ + e^-$+nucleus)**
  - **photon-photon scattering ($\gamma\gamma_{bg} \to \gamma\gamma$)**
- **Reaction rates are high and quasi static equilibrium spectrum is obtained**

$$N_\gamma^{QSE}(E_\gamma) = \frac{n_X\, p_\gamma(E_\gamma)}{\Gamma_\gamma(E_\gamma)\tau_X}$$

Reaction process

Rate equation

Particle # related

Mole fraction $Y_j = \frac{X_j}{A_j} = \frac{N_j}{\rho N_A}$

$$\frac{dY_A}{dt} = \sum_P N_A(P)\left(-\frac{Y_A}{N_A(P)!}[A\gamma]_P + \frac{Y_P}{N_P(P)!}[P\gamma]_A\right)$$

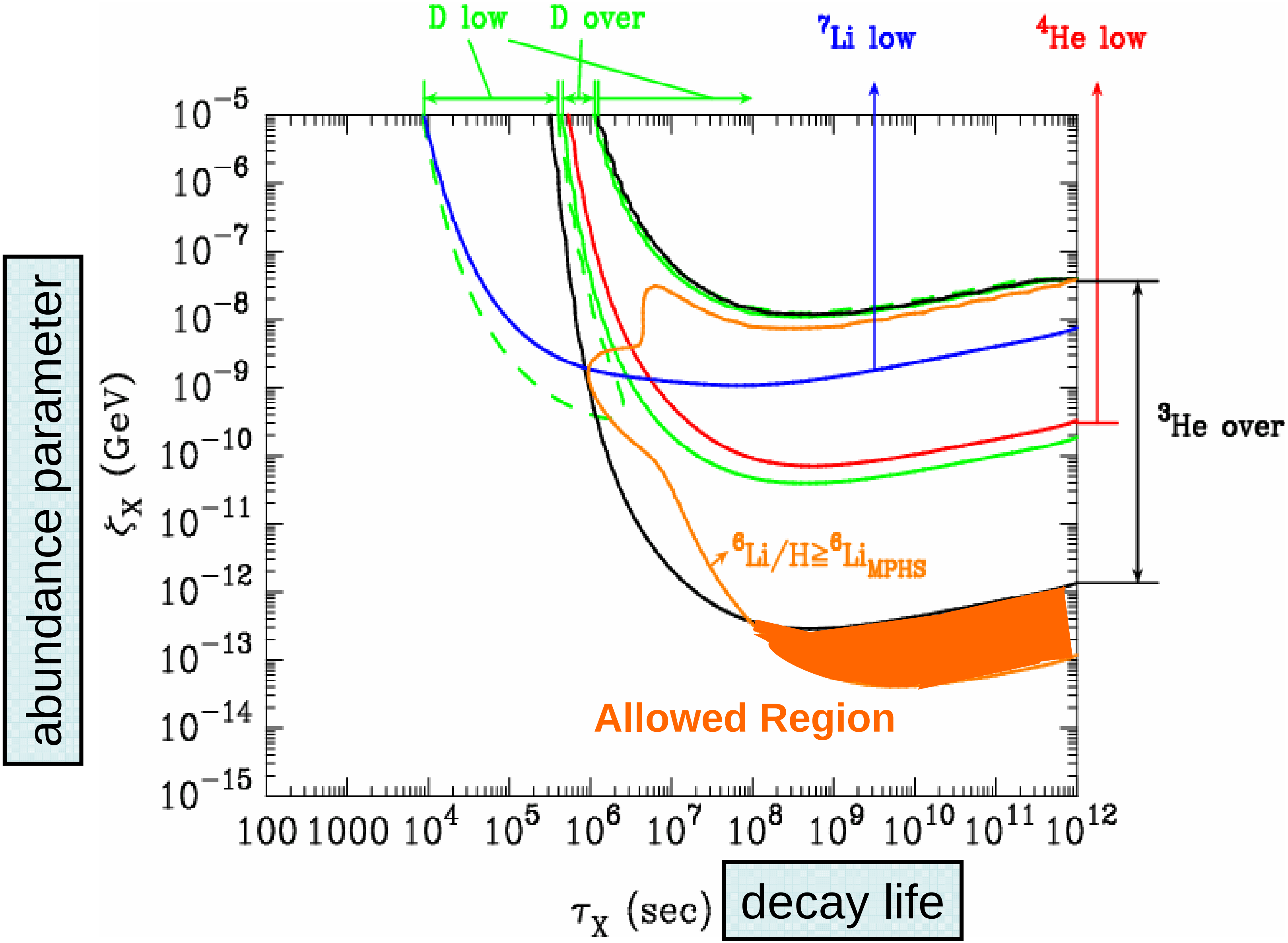
Present photon # density

$$\zeta_X = \frac{n_X^0}{n_\gamma^0} E_{\gamma 0}$$

$$H_r = \sqrt{\frac{8\pi G \rho_{rad}^0}{3}}$$

$$[A\gamma]_P \equiv \frac{n_\gamma^0 \zeta_X}{\tau_X}\left(\frac{1}{2H_r t}\right)^{3/2} \exp(-t/\tau_X) \int_0^\infty \left(\frac{\tau_X}{E_{\gamma 0} n_X} N_\gamma^{QSE}(E_\gamma)\right) \sigma_{\gamma + A \to P}(E_\gamma)$$

BBN Light Elemental Abundance Constraints on X particle properties



^{6}Li Production from Rdiative Decay of Relic X particles

Relic DM particles (SUSY, etc.) X's decay to non-thermal photons:

γ_{NT}

Non-thermal photons spalt ^{4}He into:

^{3}He, ^{3}H

New class of BBN occurs to make:

$^4\mathrm{He}(\gamma_{NT},n)^3\mathrm{He}(^4\mathrm{He},p)^6\mathrm{Li}$

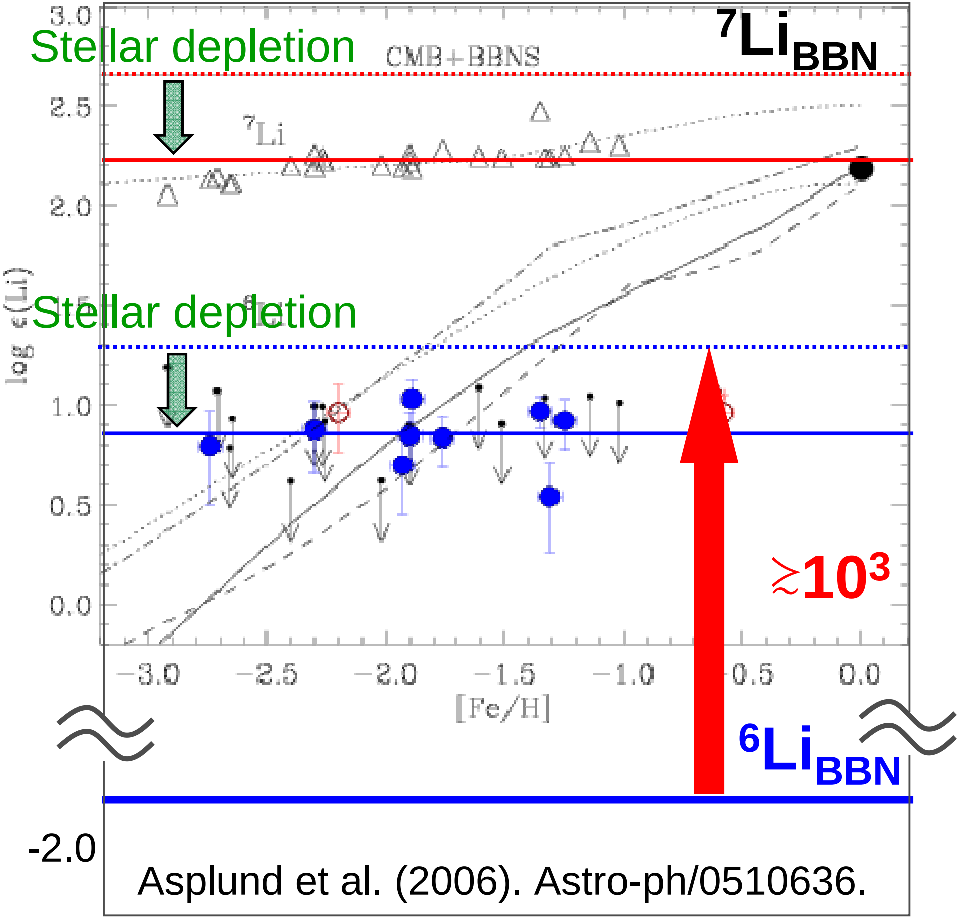
$^4\mathrm{He}(\gamma_{NT},p)^3\mathrm{H}(^4\mathrm{He},n)^6\mathrm{Li}$

Cosmological radiative decay of relic partciles and stellar depletion could explain both

^{6}Li and ^{7}Li

plateau abundances in metal-pdeficient population II stars !

Kusakabe, Kajino & Mathews, Phys. Rev. D74 (2006), 023526.



Asplund et al. (2006). Astro-ph/0510636.

SN1987Aからのニュートリノを KAMIOKANDE & IMB で検出
→ ニュートリノ・原子核相互作用の重要性

超新星ν＋MSW効果を使ってニュートリノ振動の精密決定は可能か？

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Core-Collapse, ν-Heating, Nucleosynthesis

Energy Hierarchy due to neutron-rich matter !

$$E_{\nu e} \leq E_{\bar{\nu} e} \leq E_{\nu \mu \tau}$$

Surface of Iron Core

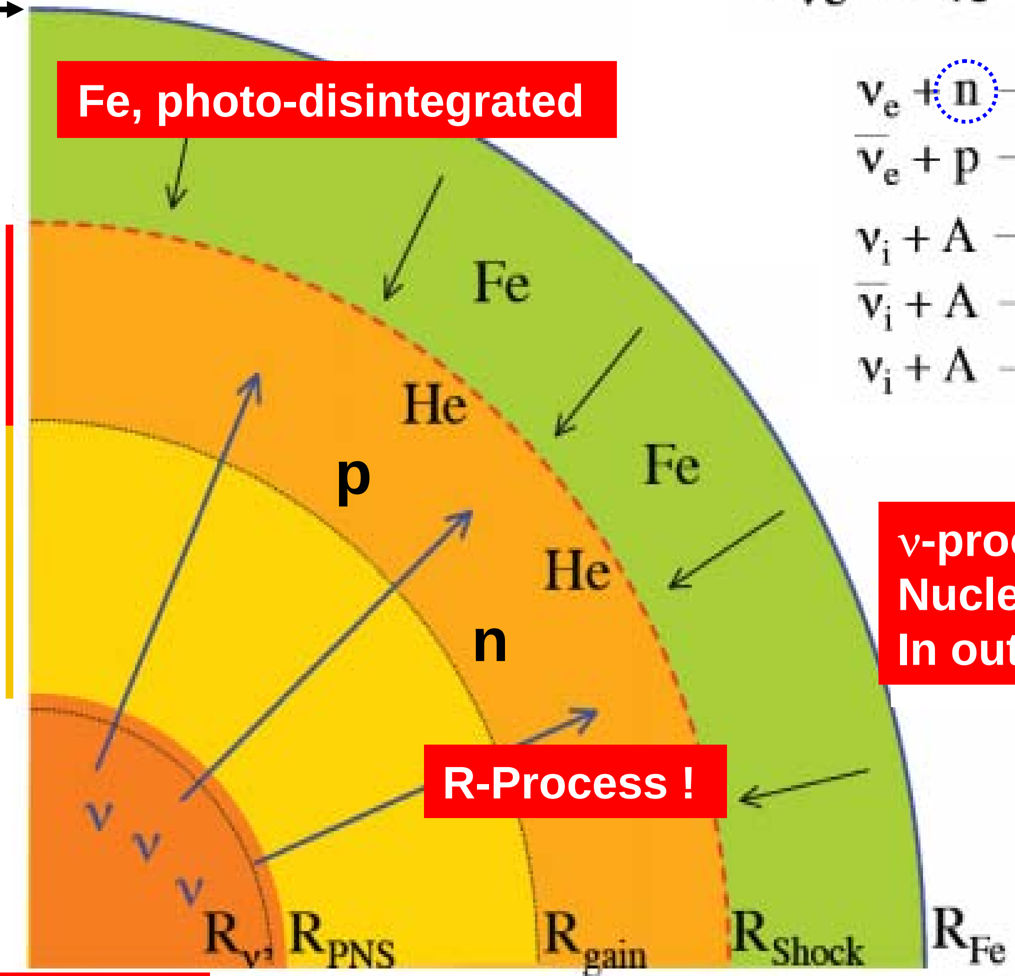
Stalled Shock

Heating Region → Hot Bubble

Gain Radius

Cooling Region

Proto-NEUTRON STAR



Fe, photo-disintegrated

R-Process !

$$\nu_e + n \longrightarrow e^- + p$$
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$
$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$

ν-process Nucleosynthesis In outer layers !

ν−A int. help explosion ?
ν−ν int. & ν−oscillation ?

~ 10km **~20−100km** **~1000km**

SUPERNOVA R-PROCESS

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.

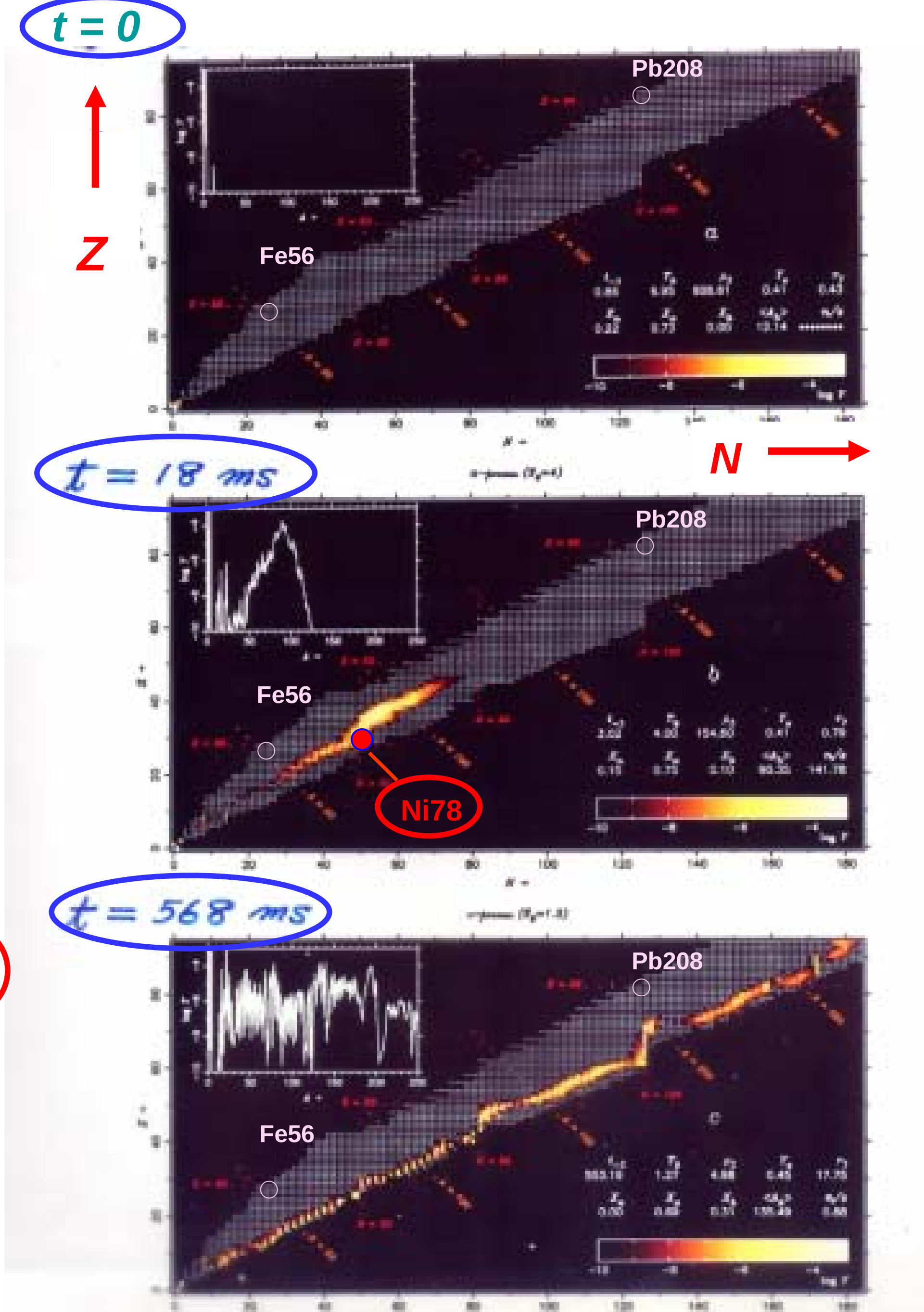
t = 18 ms

Seeds form.

Extremely neutron-rich ^{78}Ni

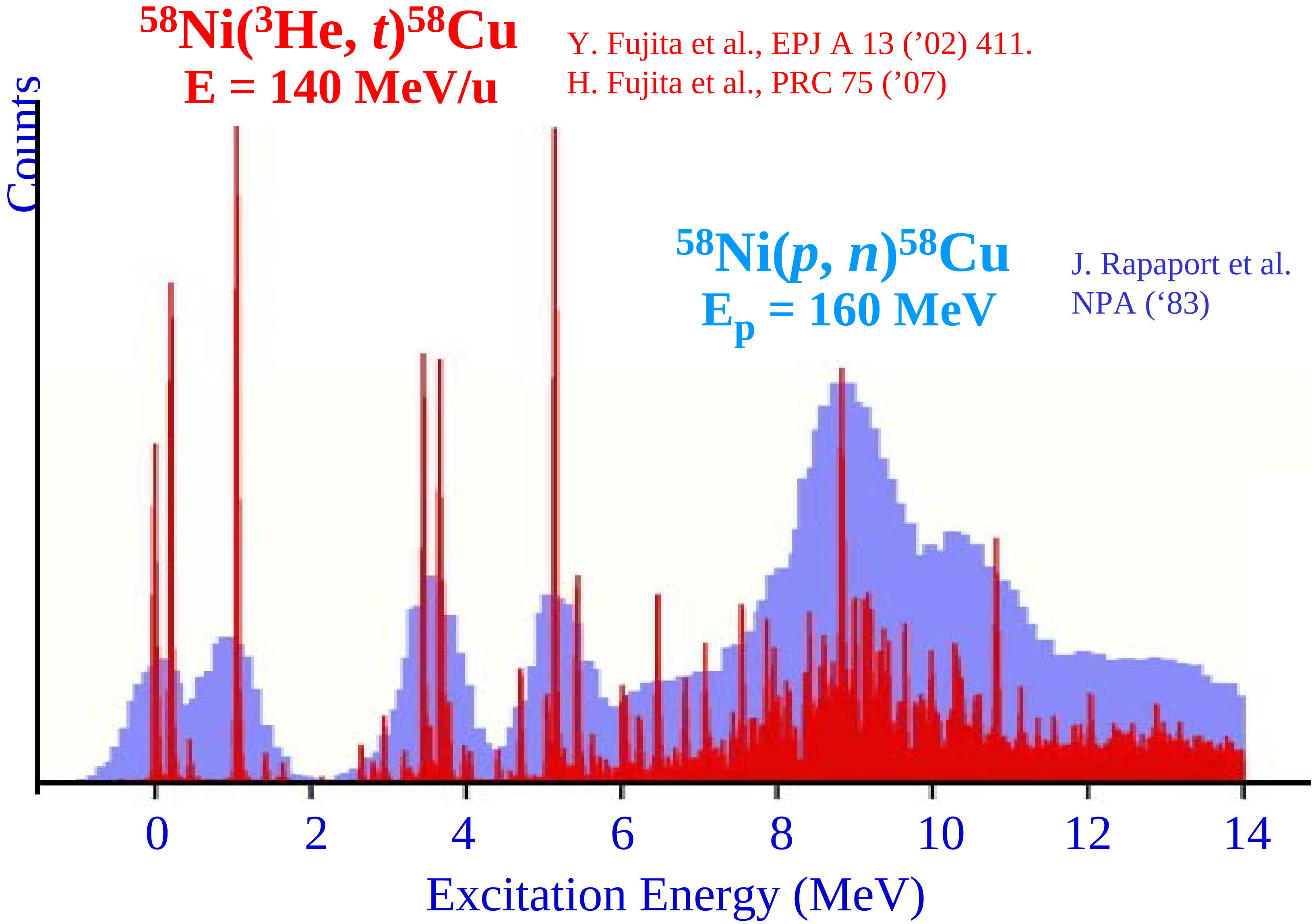
t = 568 ms – 1 s

R-elements synthesize.



Charge Exchange Reactions ⟶ B(GT)

Y. Fujita
足立竜也

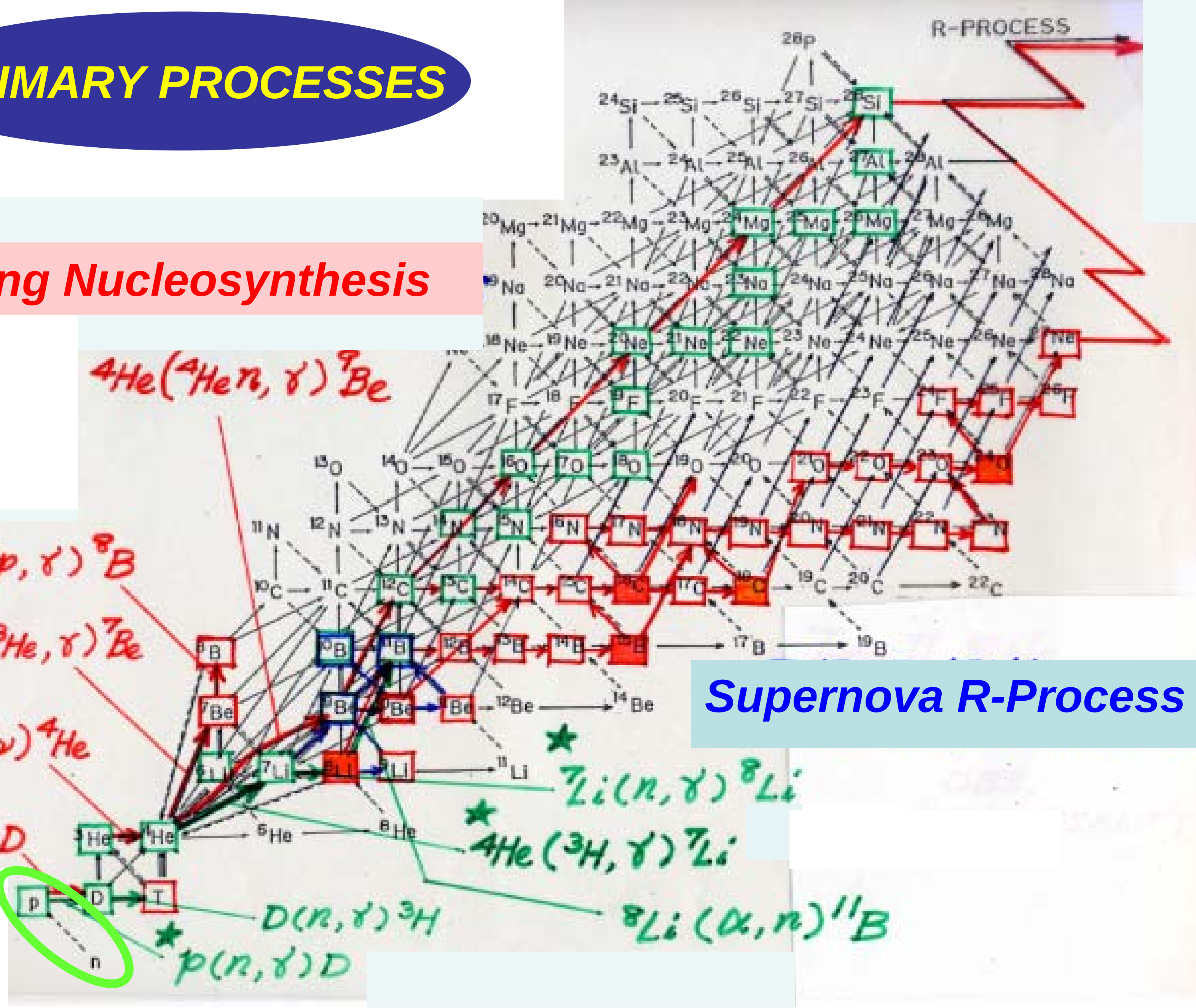


Y. Fujita et al., EPJ A 13 ('02) 411.
H. Fujita et al., PRC 75 ('07)

J. Rapaport et al.
NPA ('83)

PRIMARY PROCESSES

Big-Bang Nucleosynthesis

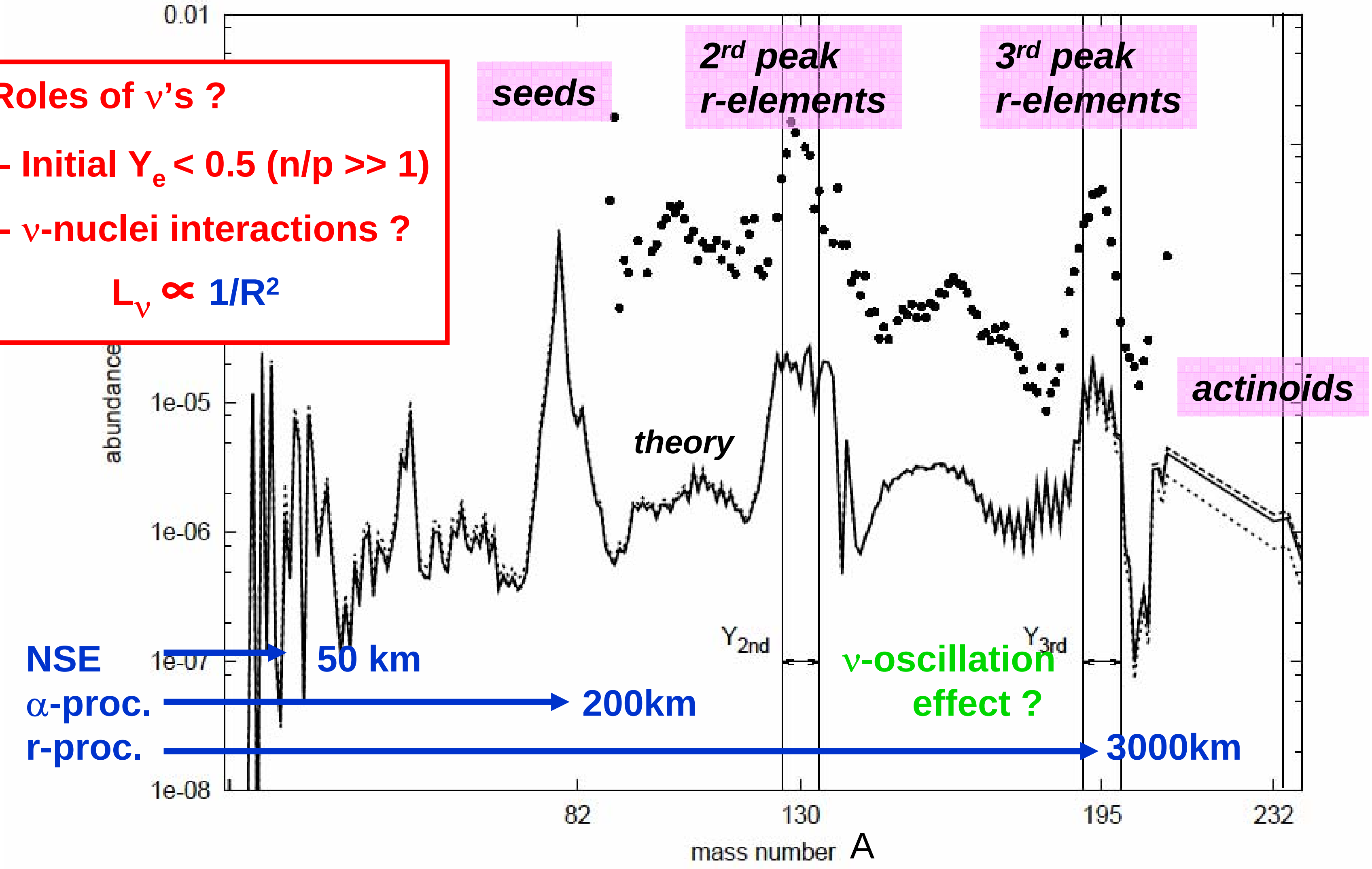


Supernova R-Process

Initially p & n

R-Process is a Primary Process in Neutrino-Driven Winds

Meyer, et al., ApJ. 399 (1992), 656: Woosley et al. ApJ. 433 (1994), 229: Otsuki et al., ApJ. 533 (2000), 424: Terasawa et al., ApJ. 562 (2001), 470: Sasaqui et al., ApJ. 643 (2005), 1173.



Roles of ν's ?

- **Initial $Y_e < 0.5$ (n/p >> 1)**
- **ν-nuclei interactions ?**

$L_\nu \propto 1/R^2$

seeds

2^{rd} peak r-elements

3^{rd} peak r-elements

actinoids

theory

ν-oscillation effect ?

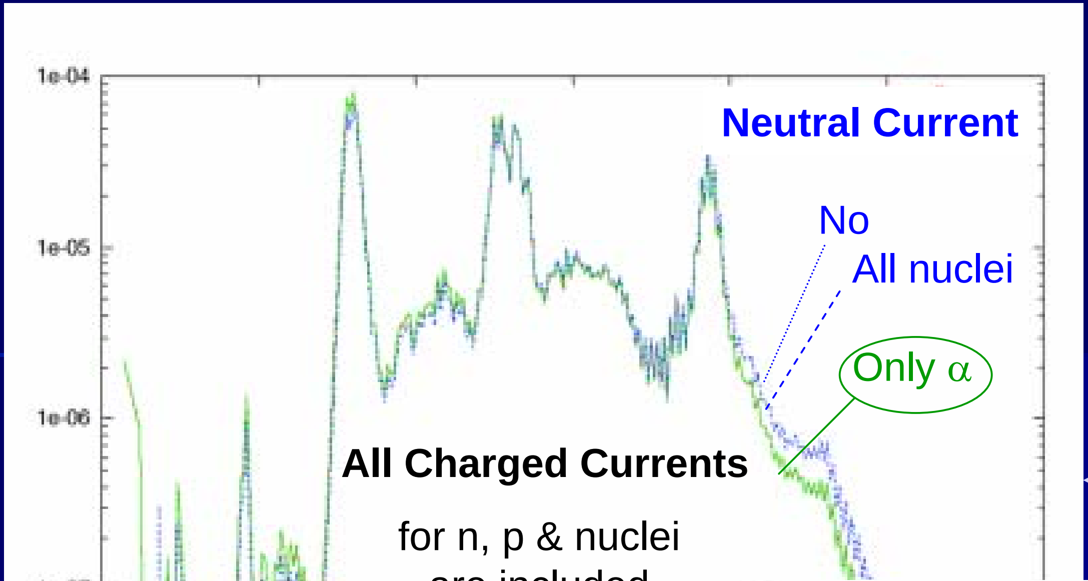
NSE → **50 km**

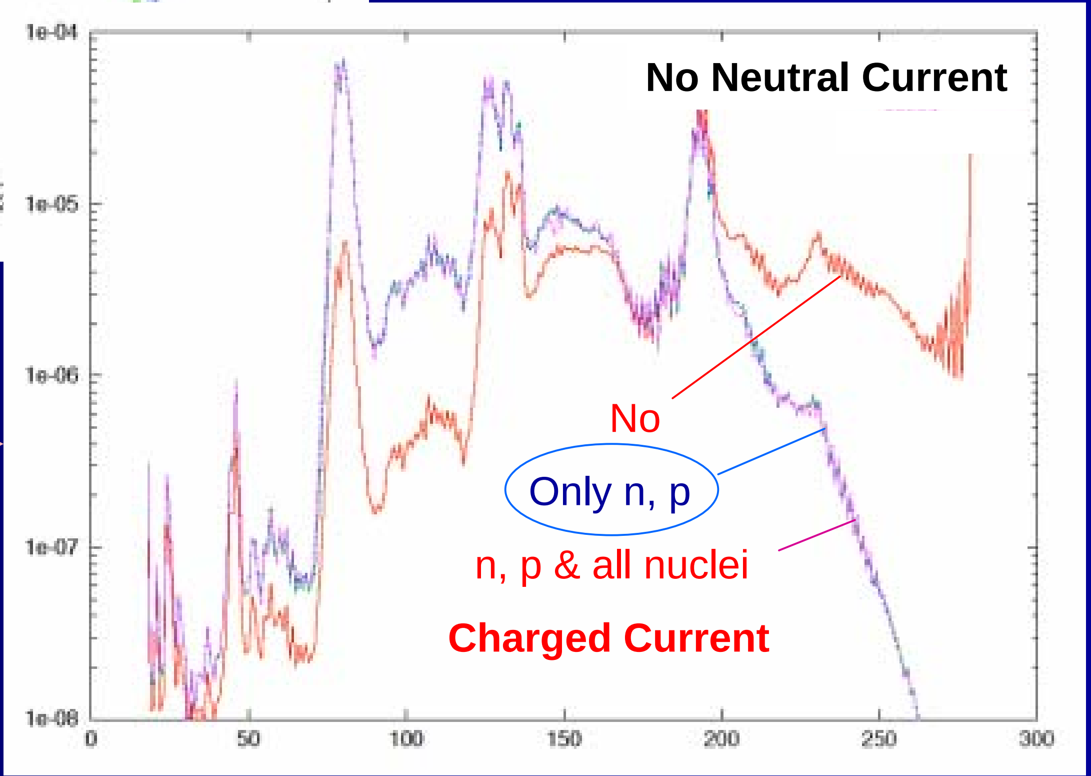
α-proc. → **200km**

r-proc. → **3000km**

Terasawa, Langanke, Kajino, Mathews & Kolbe, ApJ. 608 (2004), 470.

Neutral current interaction on alpha particles is significant !
Meyer, ApJ (1994).



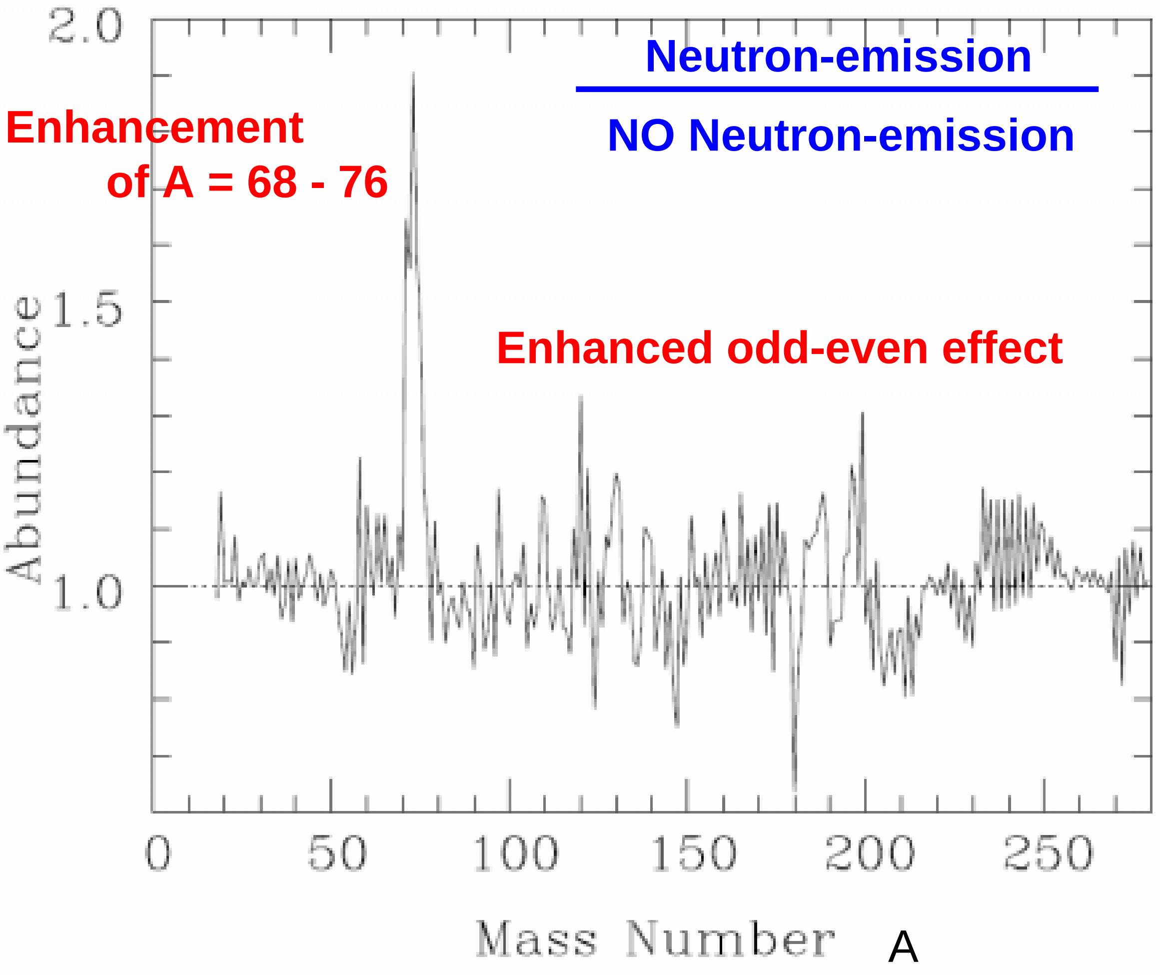


Charged current interaction on neutrons and protons is significant !

Significance of ν-induced (CC) Neutron-Emission

$$\nu_e + (Z,A) \longrightarrow (Z+1,A) + e^- + n\text{'s}$$
$$\bar{\nu}_e + (Z,A) \longrightarrow (Z-1,A) + e^+ + n\text{'s}$$

Terasawa, Langanke, Kajino, Mathews & Kolbe, ApJ. 608 (2004), 470.



Neutron-emission

NO Neutron-emission

Enhancement of A = 68 - 76

Enhanced odd-even effect

Charged Current Recation Rates:

Langanke & Kolbe
ADNDA 79 (2001) 293,
82 (2002) 191.

Kolbe, Langanke,
Martinez-Pinedo & Vogel
J. Phys. G29 (2003), 2569

Neutral Current Recation Rates:

Woosley, Hartmann, Hoffman,
& Haxton, ApJ. 356 (1990),
272

Qian, Haxton, Langanke &
Vogel, phys. Rev. C55
(1997), 1532.

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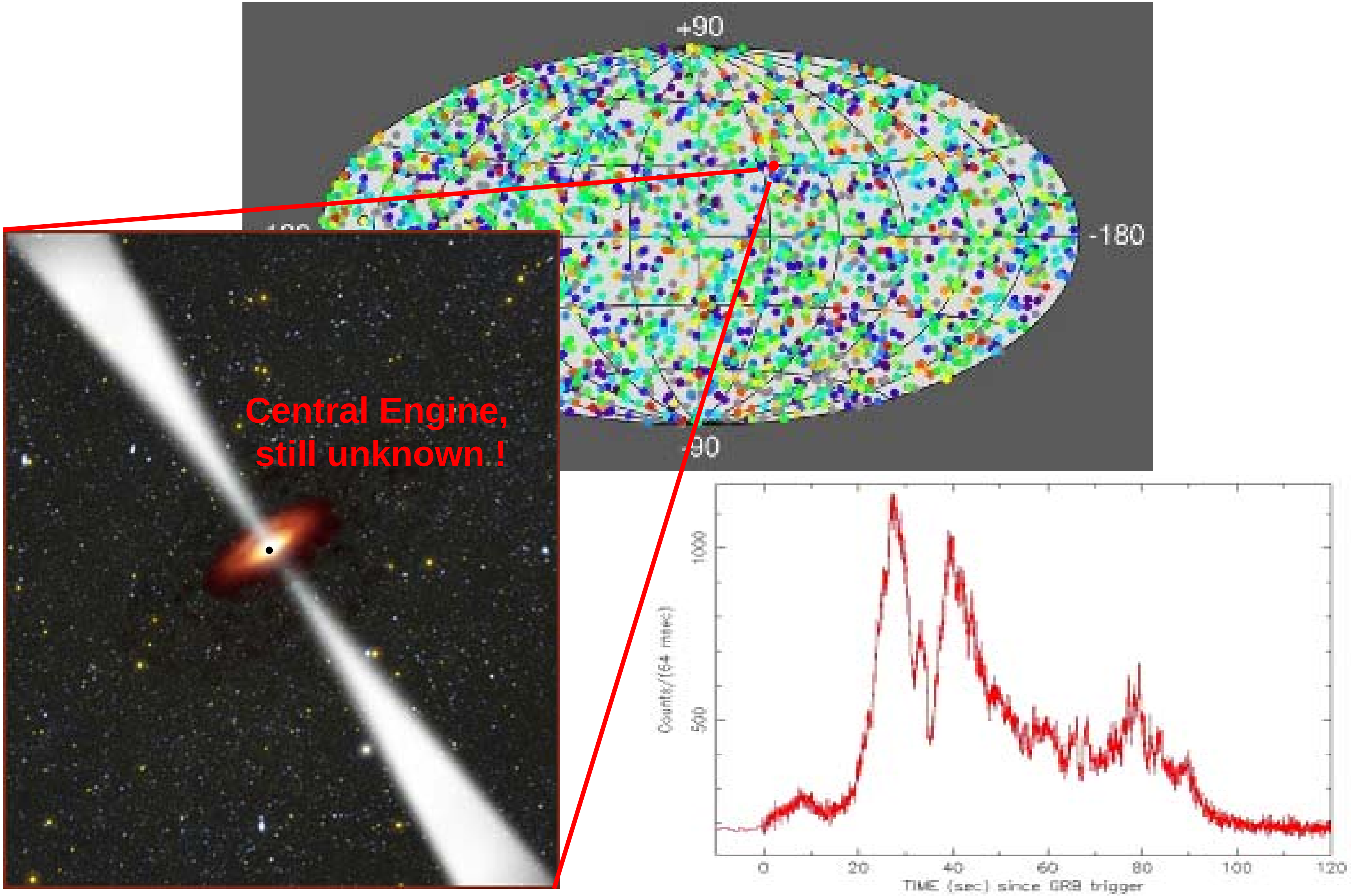
GRBs are cosmological activities at high redshifts in the early Universe.



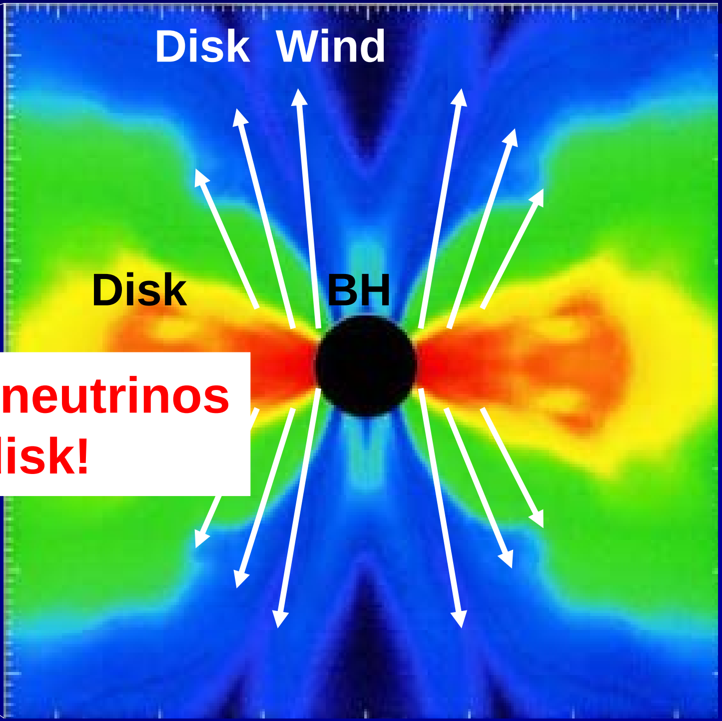
Central Engine, still unknown !

Collapsar is a viable candidate for the Central Engine of GRBs

GRB (image)

Collapsar Model

McFadyen & Woosley, ApJ 524 (1999), 252



Effect of pair-neutrinos from the disk!

Collapsar is a core-collapse supernova of the first-generation massive star formed from primeval gas in the early Universe.

Undoubtedly, our Milky Way also had the similar GRB activity in the early epoch.

Unfortunately, we cannot directly look back! →

Observational Evidence for GRB-Collapsar connection?

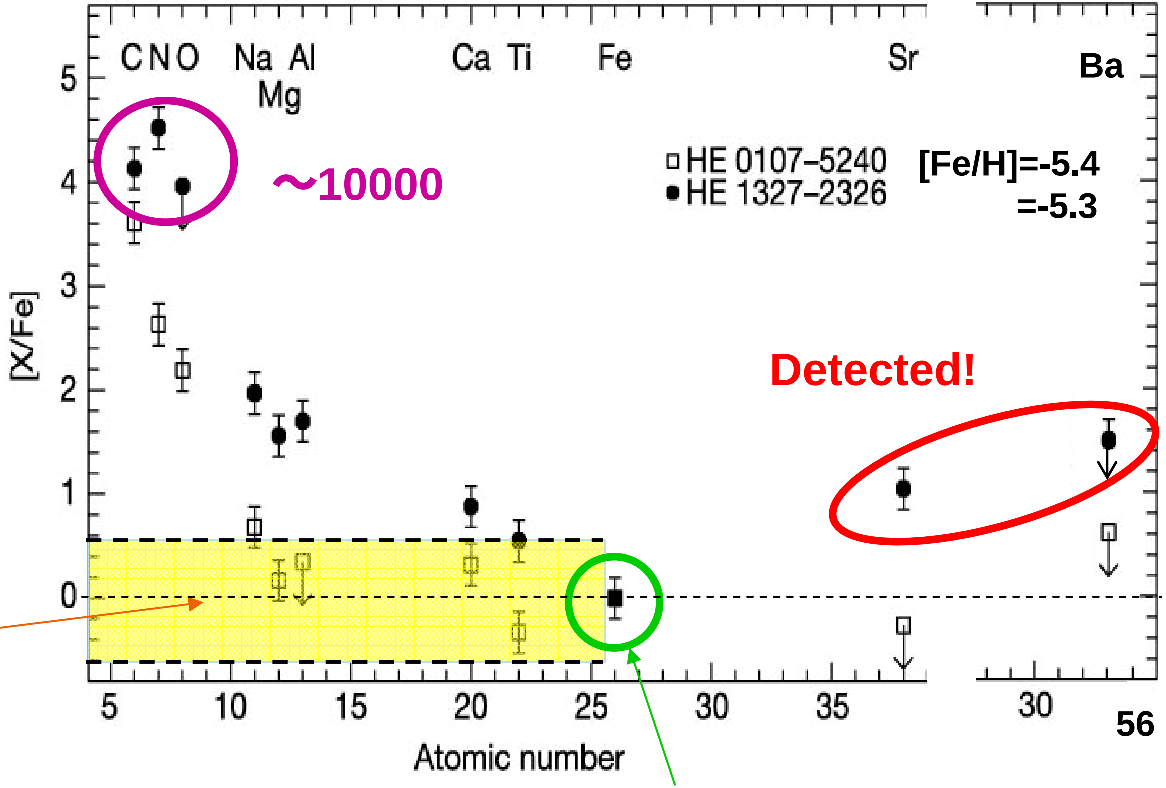
Nucleosynthetic Signature !

Collapsar (1st generation ★) affected metal-poor Pop. II stars.

We SUBARU-HDS team discovered an oldest Pop. II star in the Milky Way:
[Fe/H] = -5.4 ! ⟷ 1/500,000 x Solar-Fe

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

SUBARU Telescope



~10000

Detected!

Standard SN model prediction

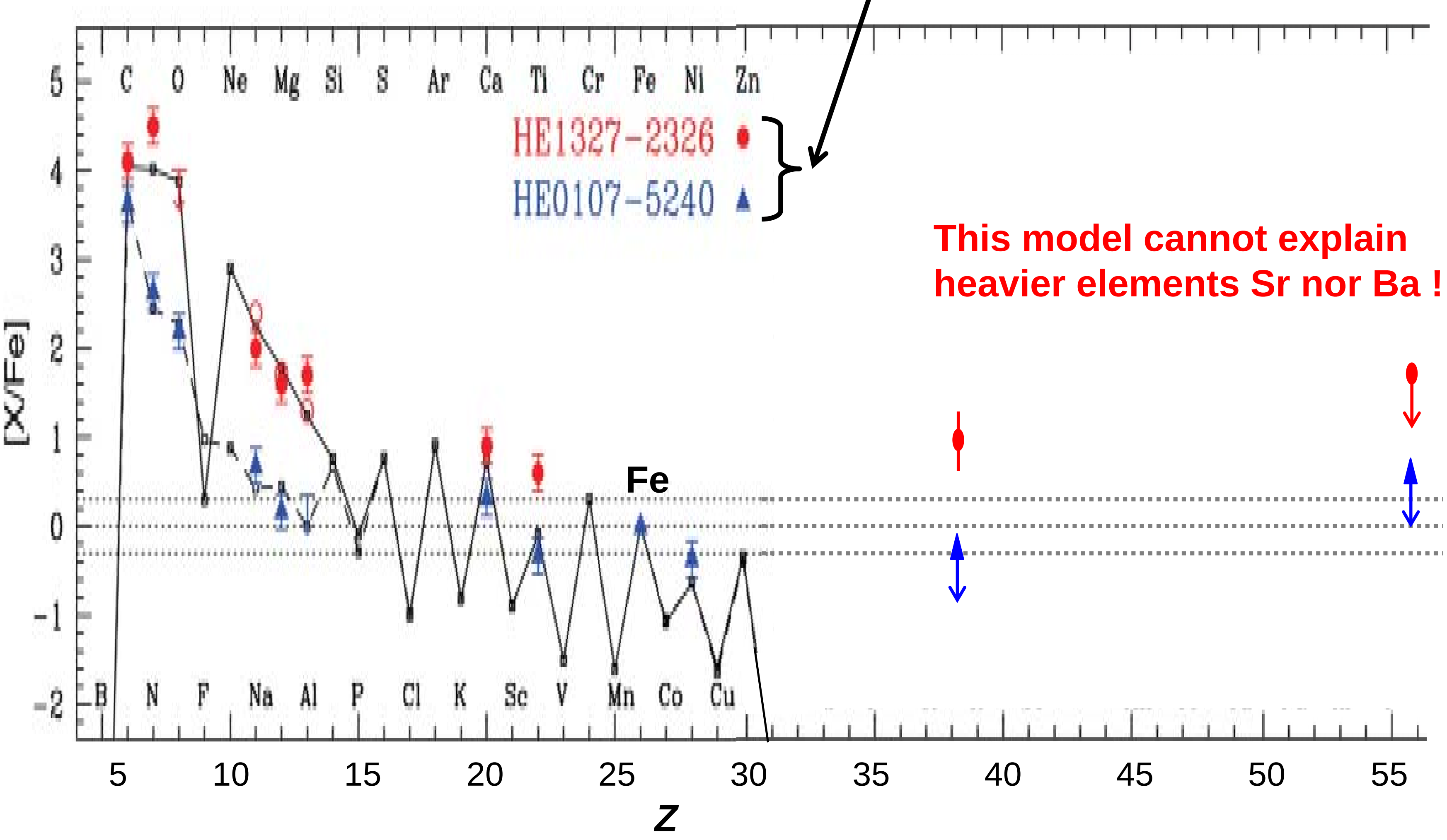
Fe

HYPERNOVA MODEL

Umeda & Nomoto, Nature 422 (2003), 871.
Iwamoto et al., Science 309 (2005), 451.

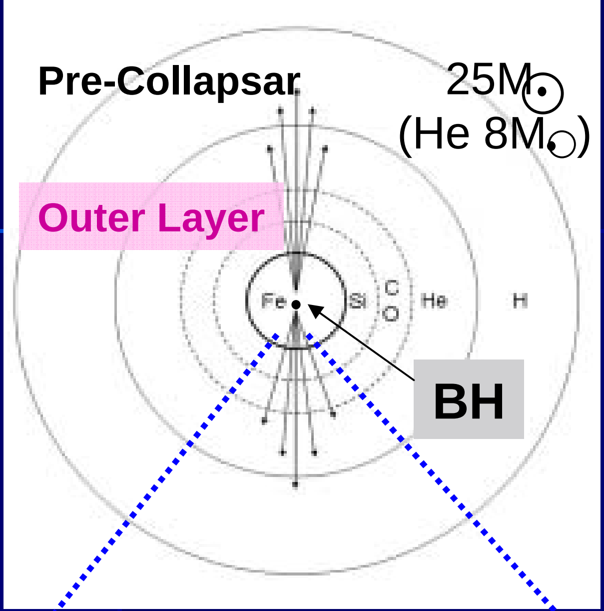
1st generation

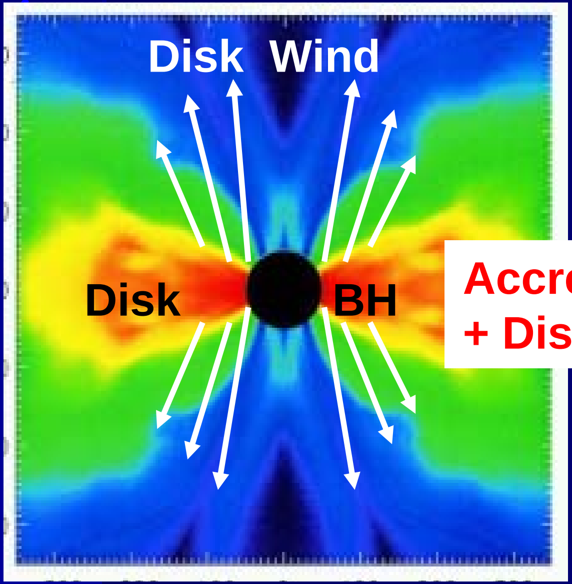
2nd generation stars !



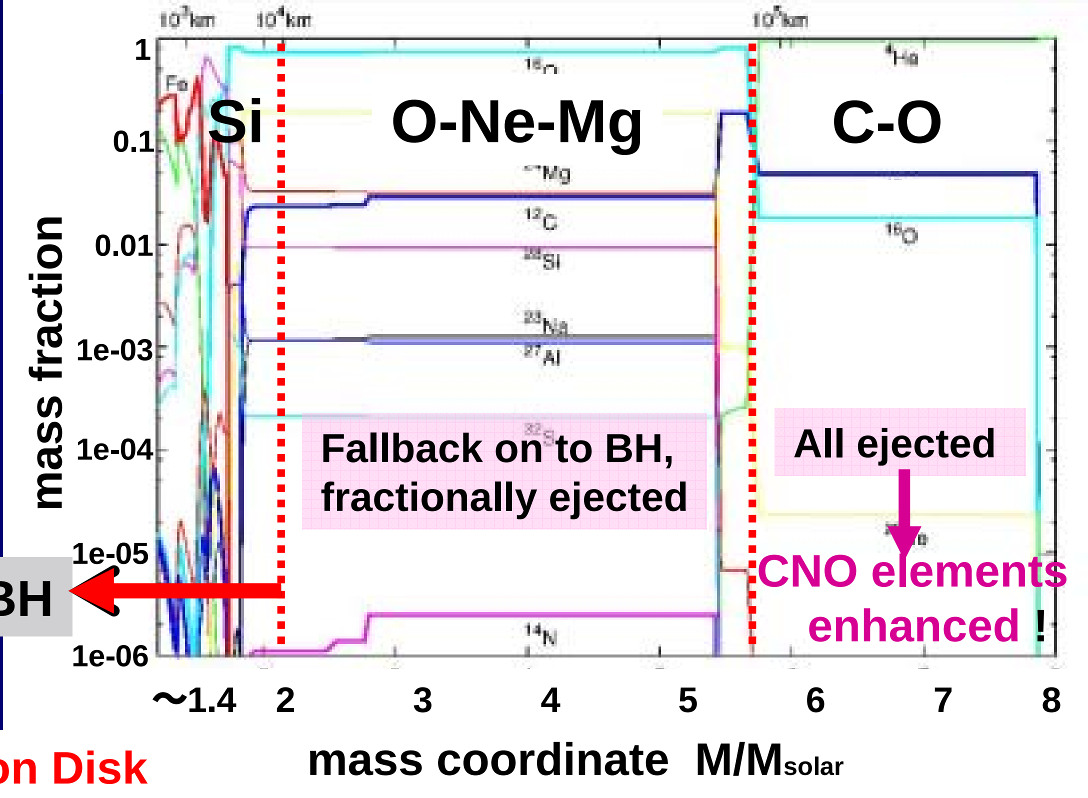
This model cannot explain heavier elements Sr nor Ba !

1st & 2nd Modes of Nucleosynthesis in Collapsar





Accretion Disk + Disk Wind Flow

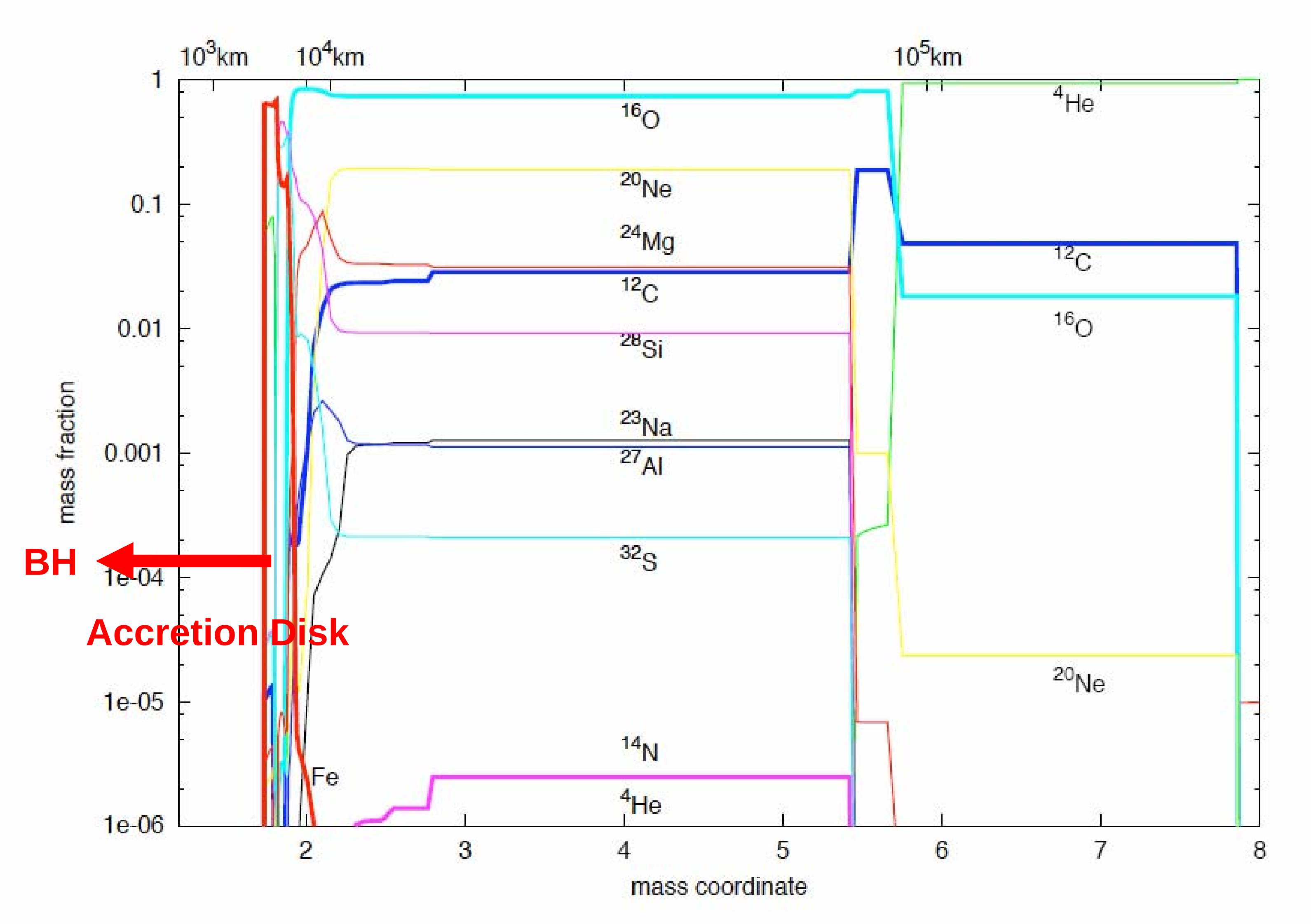


2nd nucleosynthesis
R-Process ?

1st nucleosynthesis:
Umeda & Nomoto, Nature 422 (2003), 871.
Iwamoto et al., Science 309 (2005), 451.

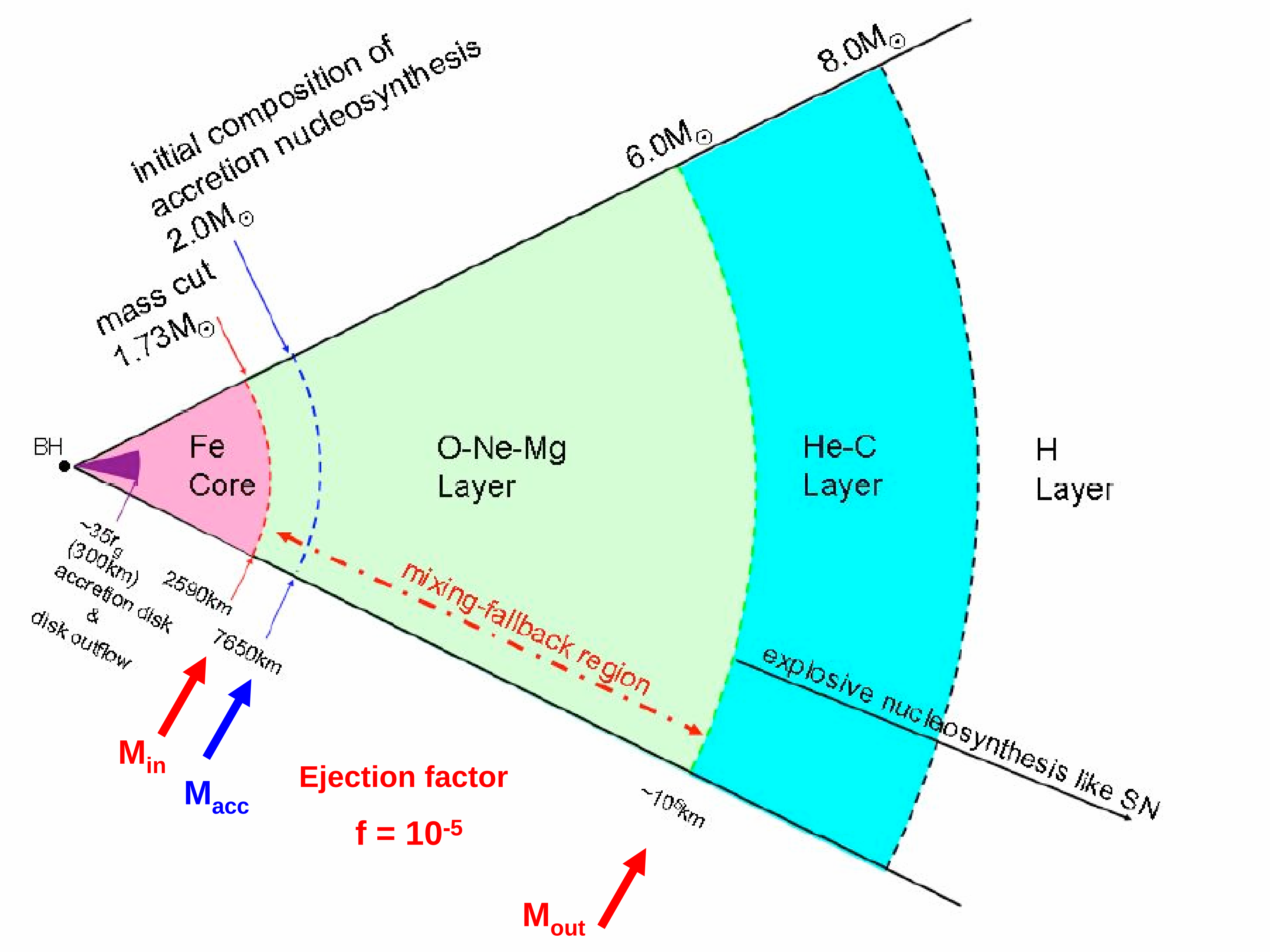
Progenitor Star = 25 $M_\odot$, evolved from primeval zero-metal gas

Yoshida, Kajino & Sasaqui (2006)



BH

Accretion Disk



Ejection factor

$f = 10^{-5}$

Basic Equations for Semi-Analytic Static Accretion Disk and Winds

Fujimoto, S., et al. ApJ 585 (2003), 418; 614 (2004), 847.
Sasaqui, Kajino, Otsuki, Yoshida & Aoki, (2007) to be published.

Mass Cons. :

$$\dot{M} = 2\pi r v_r \Sigma, \qquad \Sigma = 2\rho H$$

Ang. Momt. Cons. :

$$4\pi \alpha_{vis} P H = \Omega_K \dot{M} \left(1 - \sqrt{\frac{r_0}{r}}\right) \frac{3(r-r_g)}{3r-r_g}$$

Z- Pressure Equilib. :

$$\frac{P}{H} = -\rho \frac{GM}{(r-r_g)^2} \frac{H}{r} \qquad (P = \rho H^2 \Omega_K^2)$$

Energy Cons. :

$$\frac{2}{3} \alpha_{vis} P H \Omega_K = v_r \frac{H}{r} \frac{11}{3} a T^4$$

Equation of Motion :
γ, $e^{\pm}$

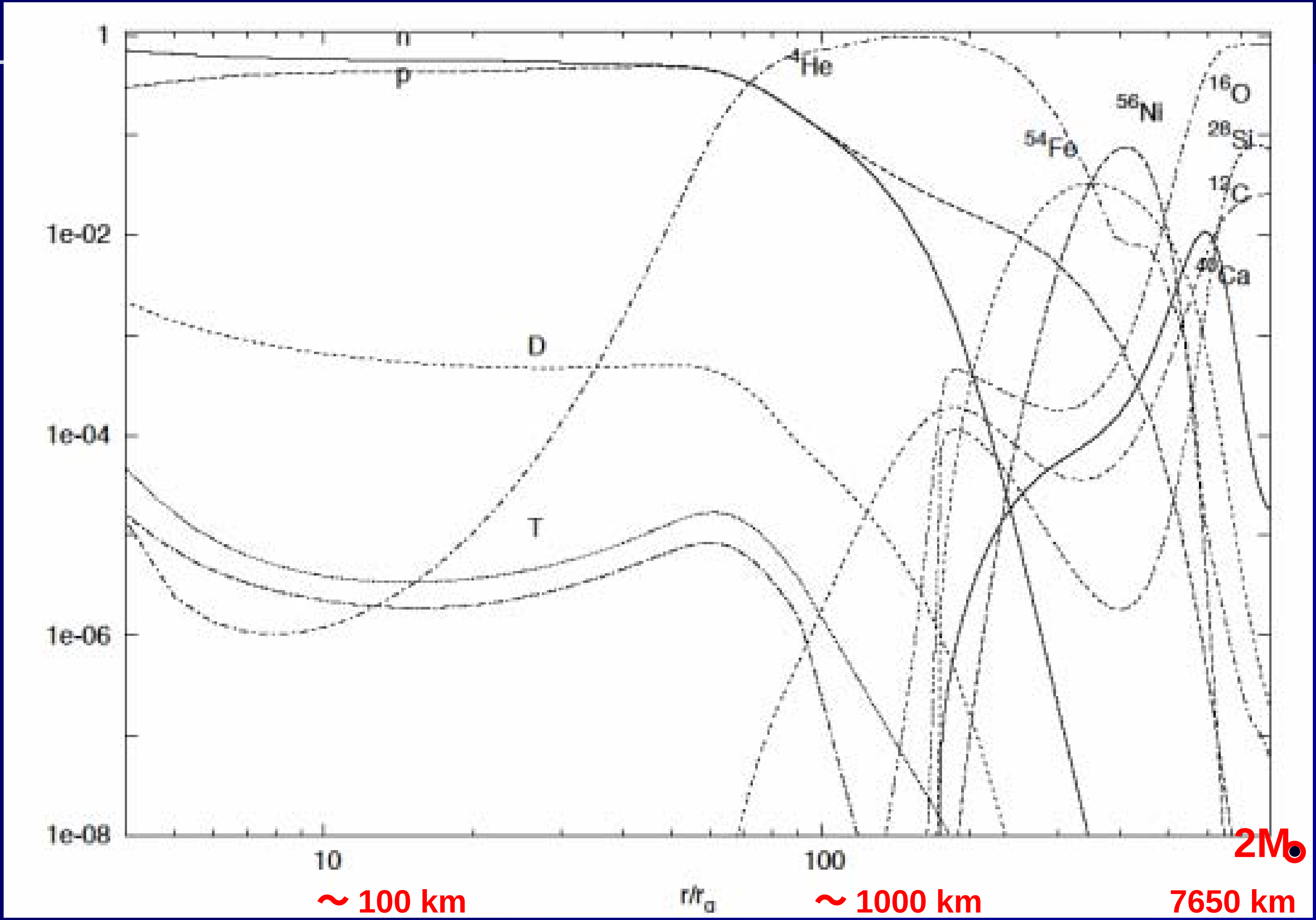
$$P = \frac{11}{12} aT^4$$

Charge Cons. :

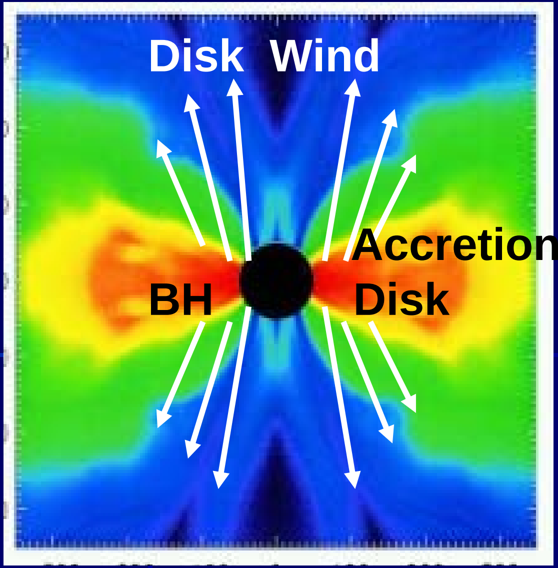
$$v_r \left(\frac{dY_e}{dr}\right) = \sum_i \lambda_{e^-,i} Y(Z_i, N_i) + \sum_i \lambda_{e^+,i} Y(Z_i, N_i) + \lambda_{\nu_e n} Y_n - \lambda_{\bar{\nu}_e p} Y_p$$

Nucleosynthesis in BH Accretion Disk

Nuclear Statistical Equilibrium ← Helium Burning Process



Why does accretion disk become very neutron-rich ?

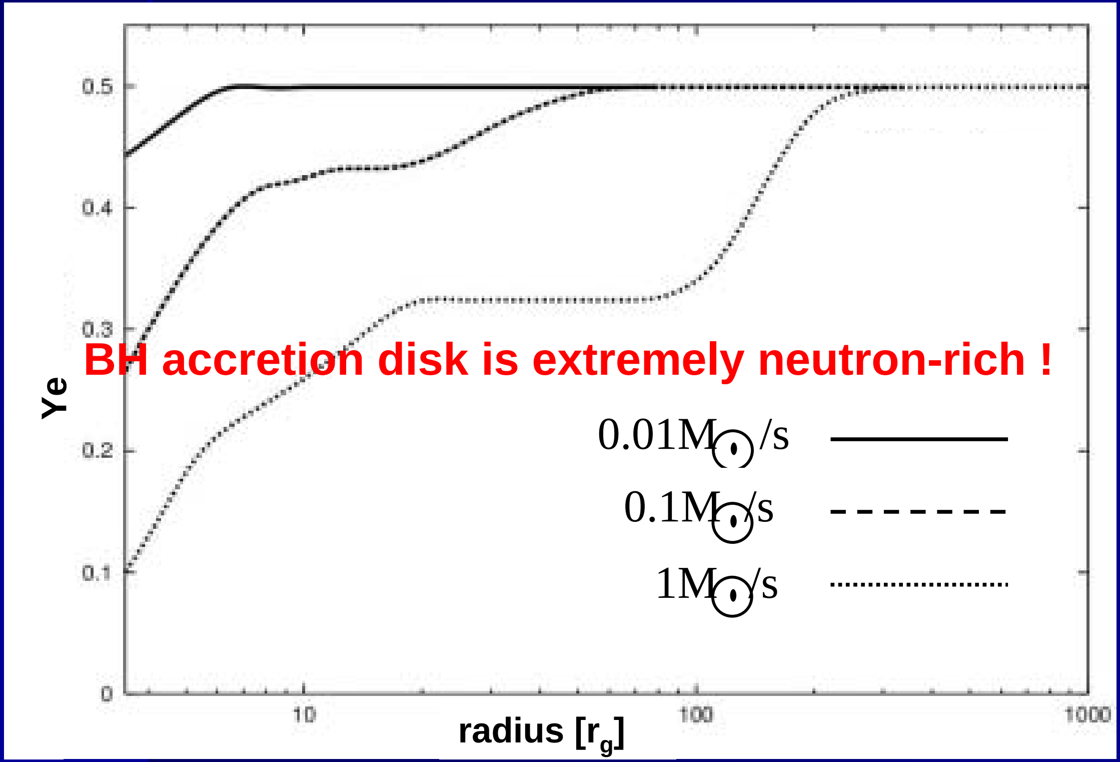


$$v_r\left(\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right) = \sum_i \lambda_{e^-,i} Y(Z_i,N_i) + \sum_i \lambda_{e^+,i} Y(Z_i,N_i) + \lambda_{\nu_e n} Y_n - \lambda_{\bar{\nu}_e p} Y_p$$

$$Y(Z,A) = \frac{G(Z,A)A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3(A-1)/2}\left(\frac{\rho}{m_u}\right)^{A-1} Y_n^{A-Z} Y_p^{Z} \exp\left[\frac{B(Z,A)}{kT}\right]$$

$$Y_e = Y_p + \sum_{(Z,A)} Z Y(Z,A)$$

$$1 = Y_n + Y_p + \sum_{(Z,A)} A Y(Z,A)$$



BH accretion disk is extremely neutron-rich !

$\dot{M}$ ↗

T、ρ ↗

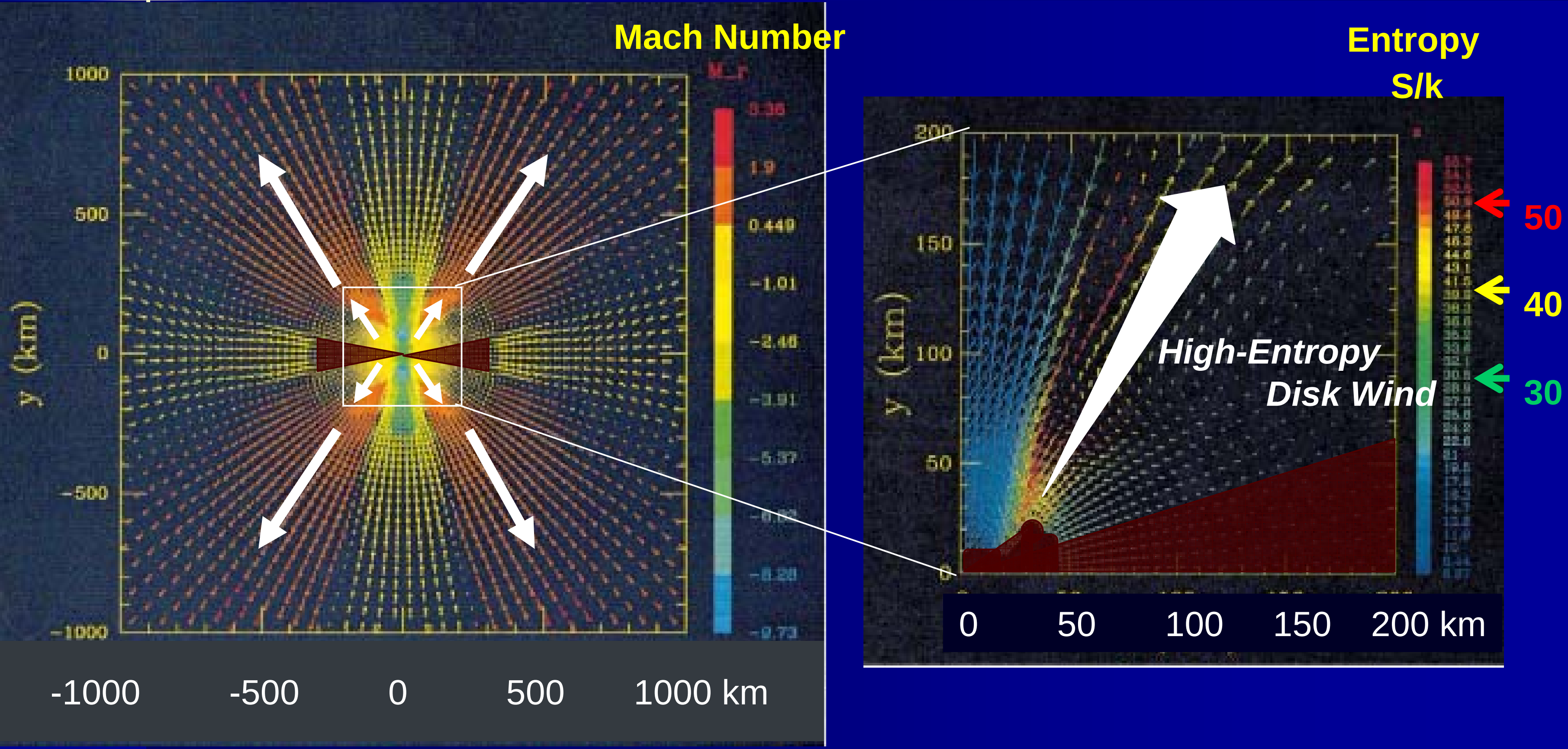
λ_{e^-} ↗

} Y_e ↘

Collapsar Model

McFadyen & Woosley, ApJ 524 (1999), 252

High-entropy disk-winds blow off accretion disk.

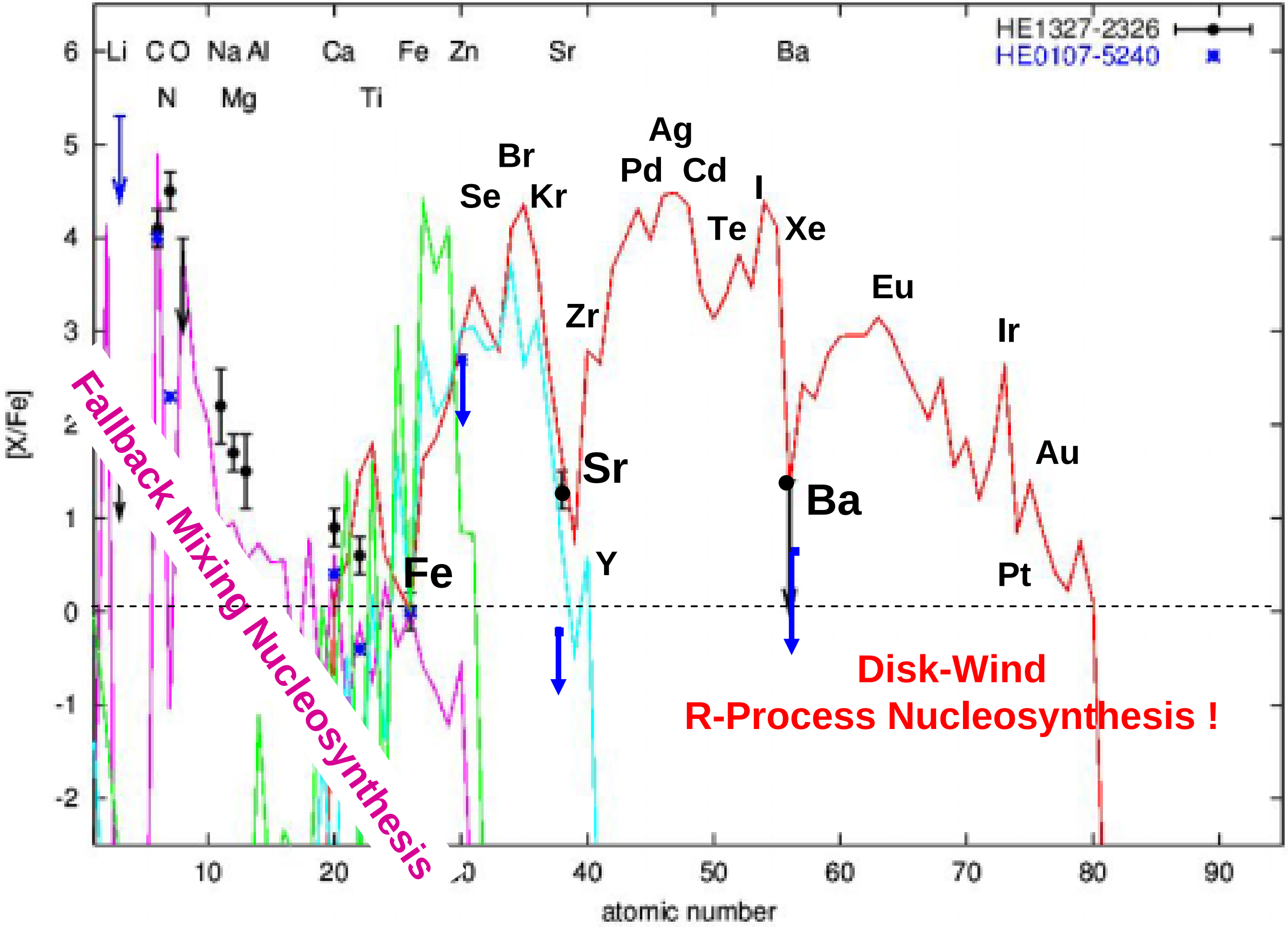


Collapsar (1st generation ★) affected metal-poor Pop. II stars.

Sasaqui, Kajino, Otsuki, Yoshida & Aoki, (2007),
to be published.

SUBARU
Telescope

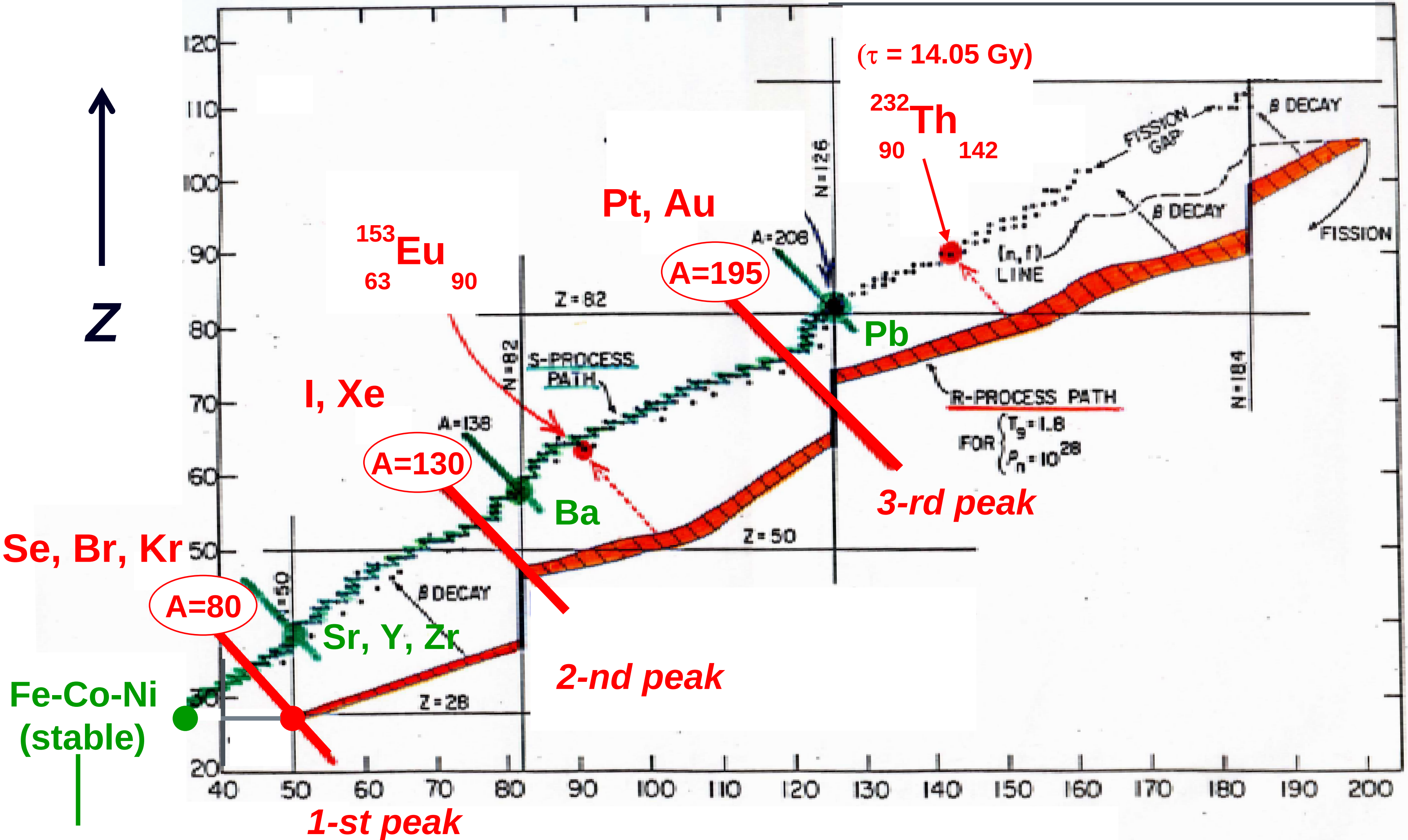
Frebel, Aoki, et al.
(SUBARU-HDS
international team)
Nature 434 (2005), 871



Fallback Mixing Nucleosynthesis

Disk-Wind
R-Process Nucleosynthesis !

Very Rapid Neutron-Capture Process



These ate not “seeds” because r-process is
a primary process starting from prorons & neutrons !

SUMMARY

1. 超新星ニュートリノ元素合成過程で作られる ^{7}Li/^{11}B-組成比に及ぼすMSW効果から、ニュートリノ振動の混合角 θ_{13} と質量階層 Δm_{13}^2 を同時に決定できる可能性がある。

2. 超新星ニュートリノの温度 $T\nu_{\mu\tau}$ は、^{10,11}B 元素の銀河内化学進化および隕石の ^{11}B/^{10}B-組成比から、また、温度 $T\nu_e$ はR元素合成量から、ニュートリノ振動パラメータによらずに決定できる可能性がある。

3. ニュートリノ・原子核反応は、重力崩壊型超新星爆発を助ける可能性がある。

4. 重元素（R過程元素）の起源天体を解明する上で、ニュートリノ・原子核反応は重要である。中性子過剰の軽～重元素とニュートリノとの反応断面積の測定実験が待たれる。更に、ニュートリノ振動（MSW）効果の解明が重要。

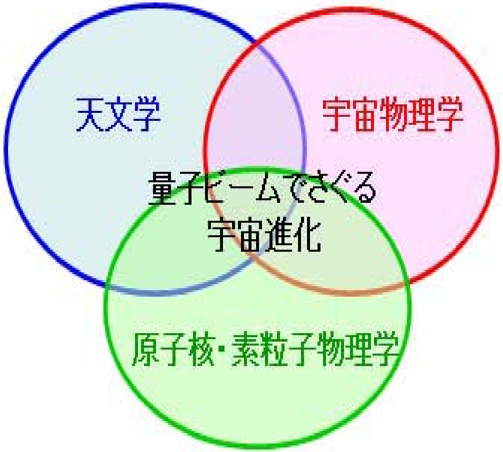
5. ブラックホール形成、強磁場、回転をともなうコラプサーでの元素合成が、ガンマ線バーストの起源中心天体である可能性を解明する鍵を握っている。（Collapsar→GRB connection）。さらに、ディスクからのニュートリノが元素合成に及ぼす影響およびニュートリノ振動効果の解明が重要。

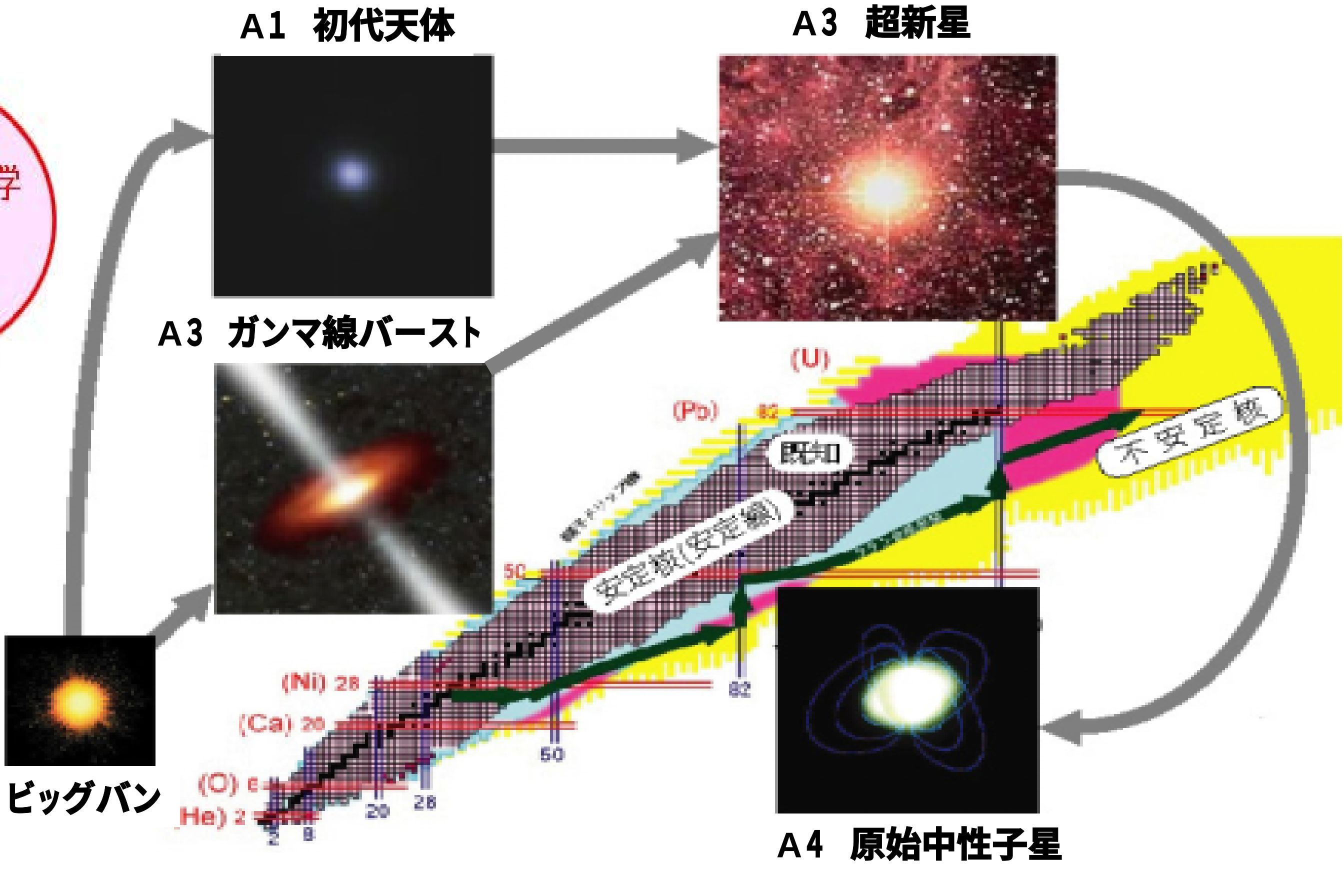
特定領域　量子ビームでさぐる宇宙進化　project (2007〜)

目的： 極限状態での不安定核の性質を解明し　(原子核・素粒子物理学)
初代天体から太陽系に至るまでの元素にみる宇宙進化像を構築し　(宇宙物理学)
理論予測と理解の正しさを天文観測によって検証する。　(天文学)

意義： 物質と宇宙」に関する人類の知見を、未知の領域にまで押し広げる。

方法： 基幹研究分野「原子核・素粒子物理学」、「宇宙物理学」、「天文学」を統合。
新たな発想と活力の下に、学際領域「宇宙核物理学」を拓く。





特定領域（２００７～）project
量子ビームでさぐる宇宙進化

A01「初代天体と鉄族に至る元素合成」

A01-ア「第一世代星の炭素，酸素，ストロンチウム合成過程」（代表 久保野　茂、分担4名）
A01-イ「未知核種の質量･半減期の網羅的測定」（代表 和田道治、分担5名）
A01-ウ「初代天体の重元素合成」（代表 野本憲一、分担4名）

A02「ガンマ線バースト天体と中性子過剰核」

A02-エ「核反応･崩壊様式でさぐる極限的重元素合成」（代表 宮武宇也、分担１０名）
A02-オ「変形･光応答測定でさぐる重元素合成過程」（代表 本林　透、分担4名）
A02-カ「中性子捕獲元素でみる宇宙の化学進化」（代表 青木和光、分担3名）
A02-キ「元素合成でさぐるガンマ線バースト」（代表 梶野敏貴、分担4名）

A03「超新星と光-核、ニュートリノ-核相互作用」

A03-ク「光量子ビームでさぐる重元素合成」（代表 宇都宮弘章、分担4名）
A03-ケ「強弱電磁プローブでさぐるニュートリノ核反応」（代表 藤田佳孝、分担2名）
A03-コ「r過程領域核の反応と励起」（代表 大塚孝治、分担3名）

A04「原始中性子星と極限核物質」

A04-サ「不安定核ビームではかる極限核物質の圧縮率」（代表 中村隆司、分担5名）
A04-シ「反応断面積からさぐる中性子過剰核物質の状態方程式」（代表 小沢　顕、分担2名）
A04-ス「核データによる状態方程式と原始中性子星誕生･進化」（代表住吉光介,分担3名）