（６）超新星爆発での重元素（Rプロセス元素）合成と銀河年齢

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超新星爆発と重元素の起源

重元素＝鉄よりも重い質量を持つトリウムやウランに至る元素

宇宙論との関わり 「宇宙年齢」

宇宙論パラメータによる推定。137 +/- 2 億年。 --- Model dependent!

∵ We don’t know the true nature of DARK MATTER nor DARK ENERGY.

核宇宙年代学 (Nucleo-cosmochronololy)

^{232}Th（半減期140.5億年）、^{238}U（半減期45.7億年）を初期世代天体に検出し、
初期天体の年齢を推定。これにより、銀河・宇宙年齢の下限値を推定する。

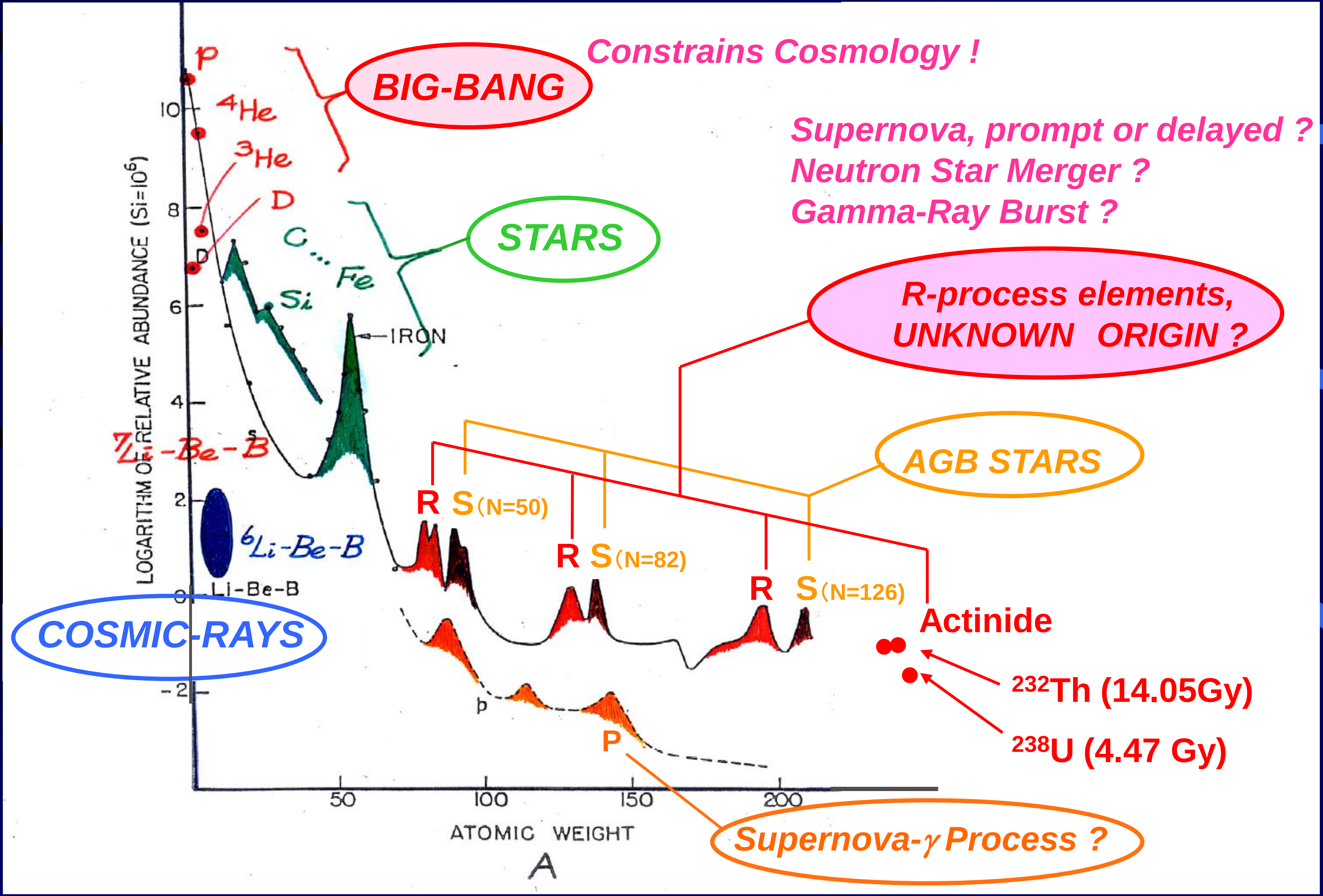
宇宙論パラメータにまったく依存しない。

初期元素量を推定する必要がある。

超新星爆発、重元素合成モデル、ニュートリノ相互作用の精密化。

宇宙の化学進化、重元素の起源論との関わり。

Solar System Abundance



Constrains Cosmology !

BIG-BANG

Supernova, prompt or delayed ?
Neutron Star Merger ?
Gamma-Ray Burst ?

STARS

R-process elements,
UNKNOWN ORIGIN ?

AGB STARS

R S (N=50)

R S (N=82)

R S (N=126)

Actinide

^{232}Th (14.05Gy)

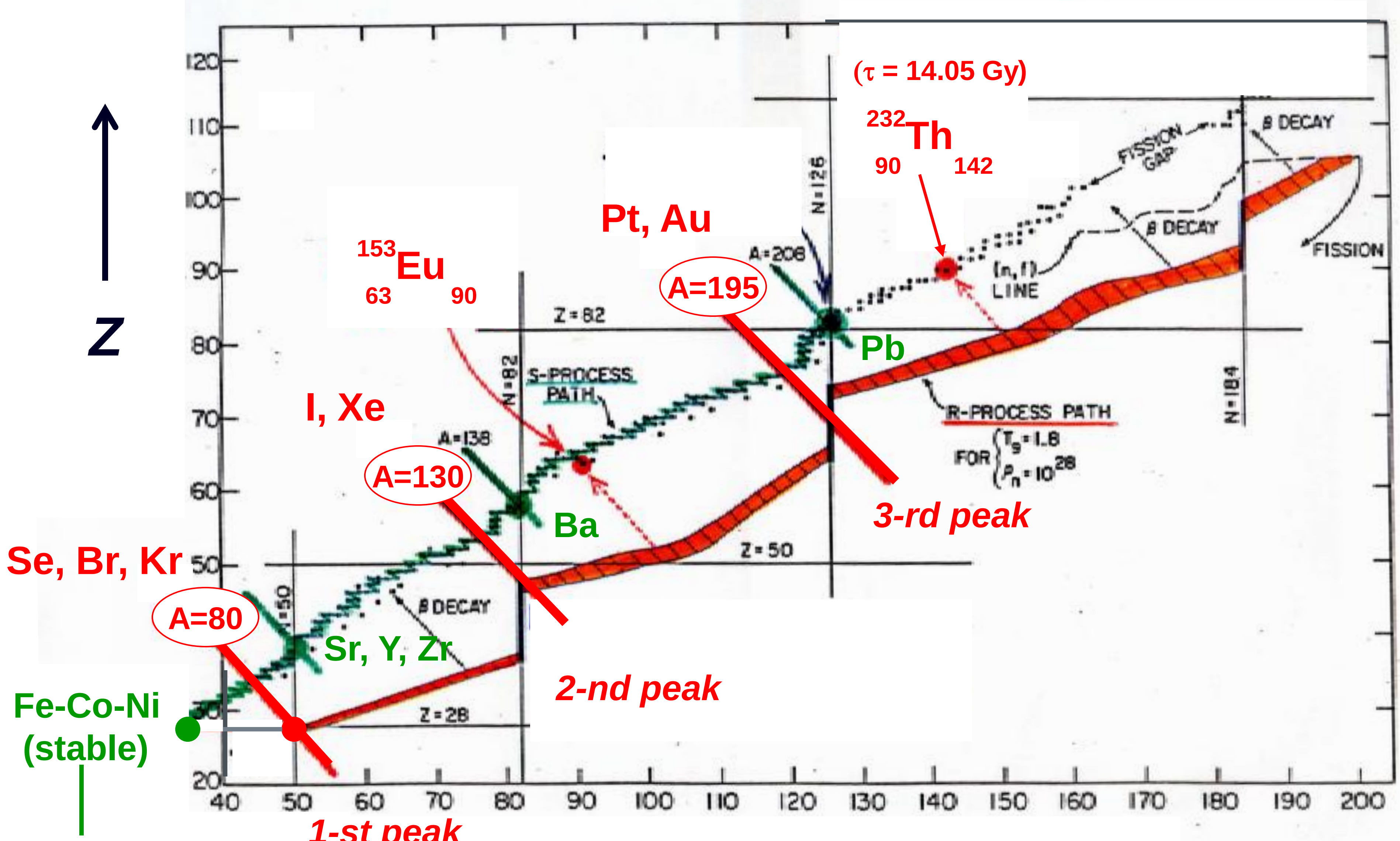
^{238}U (4.47 Gy)

COSMIC-RAYS

P

Supernova-γ Process ?

Very Rapid Neutron-Capture Process



Z

N

(τ = 14.05 Gy)

$^{232}_{90}\mathrm{Th}_{142}$

$^{153}_{63}\mathrm{Eu}_{90}$

Pt, Au

A=195

Pb

I, Xe

A=130

Ba

Se, Br, Kr

A=80

Sr, Y, Zr

Fe-Co-Ni
(stable)

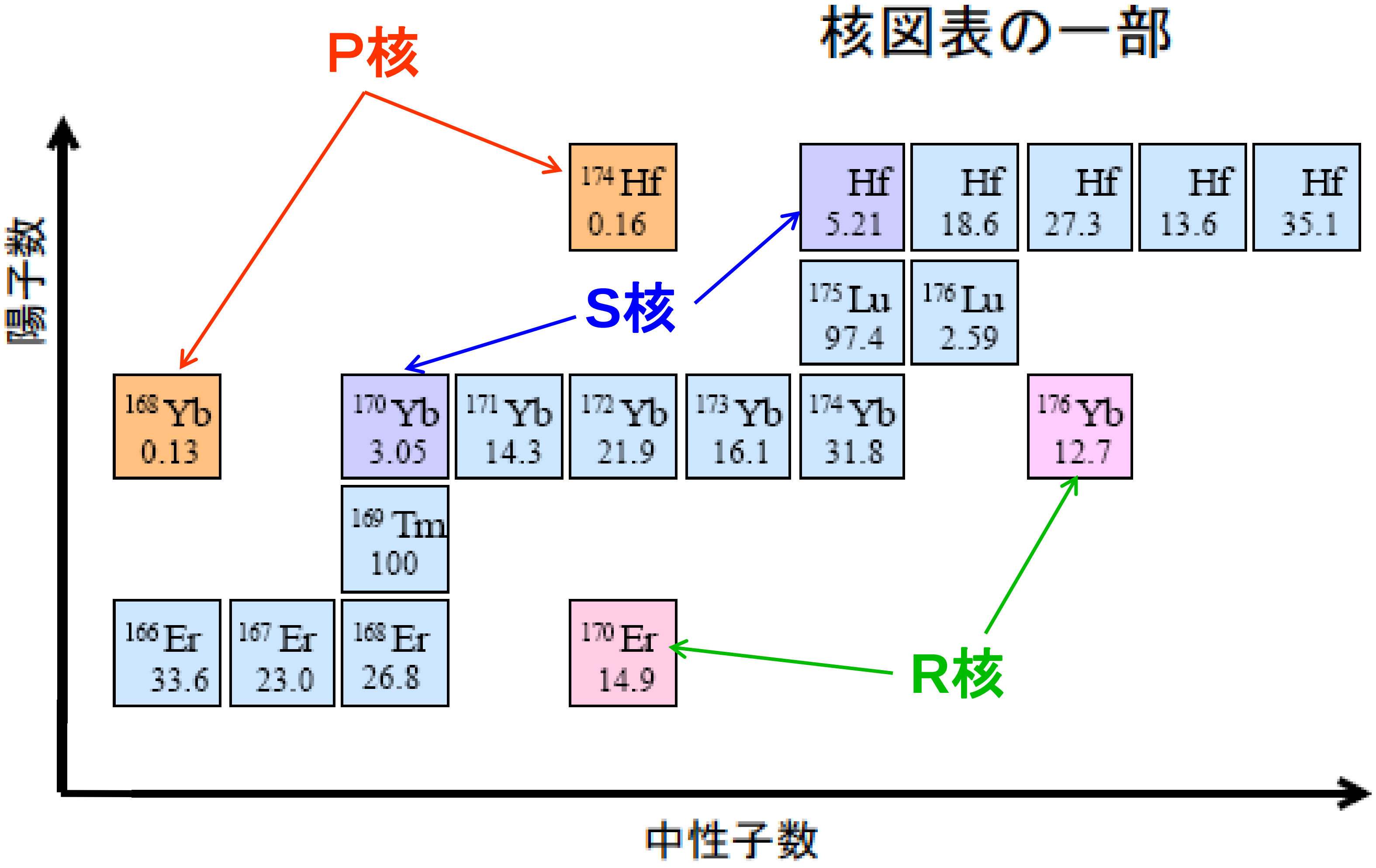
1-st peak

2-nd peak

3-rd peak

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

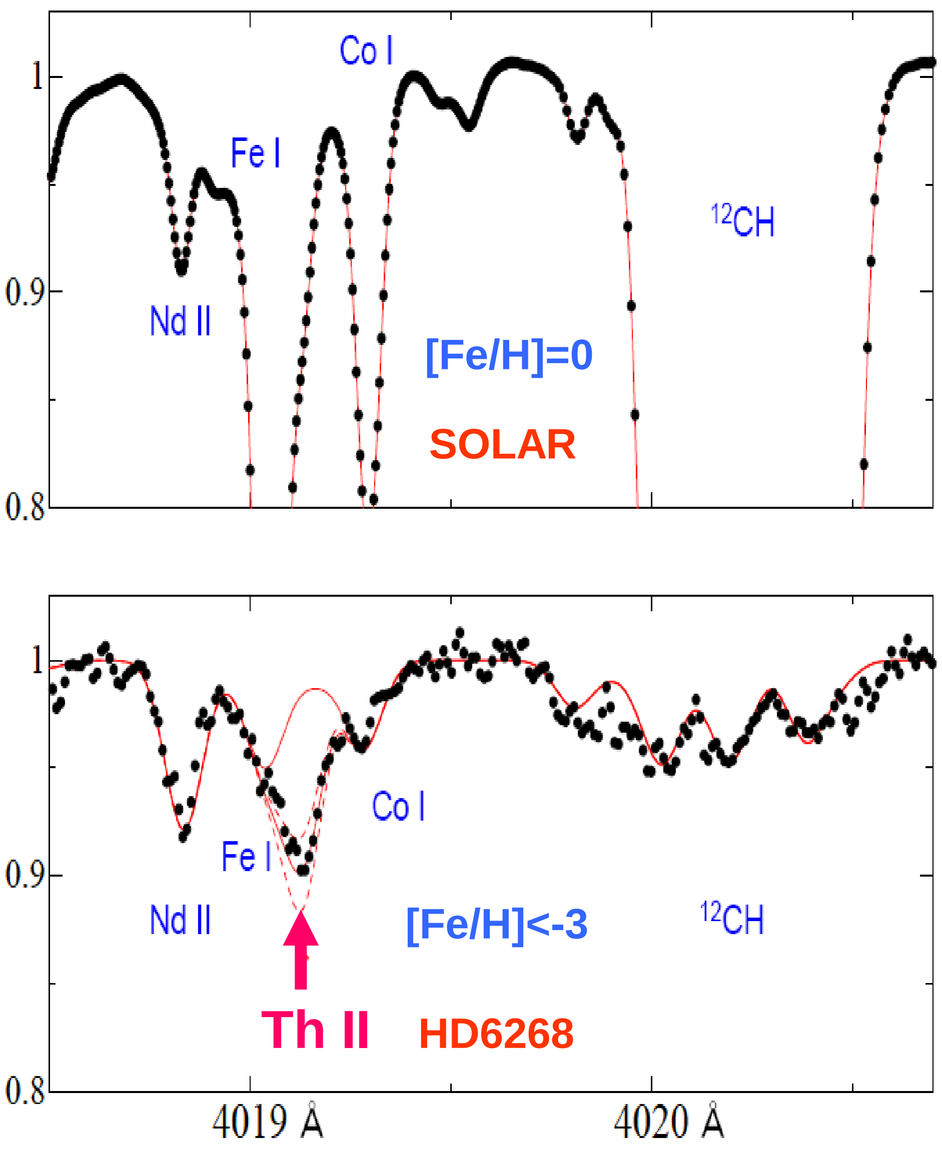
核図表と重元素の起源



- •鉄より重い重元素の約99%は、中性子捕獲反応で生成された。
- •その一方で、p核と呼ばれる同位体の起源は謎であった。

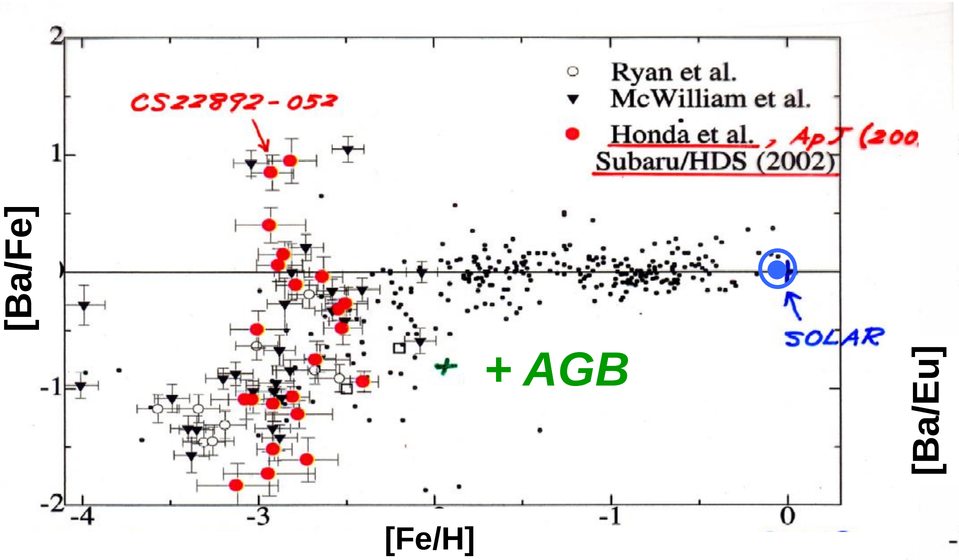
Subaru Telescope

OBSEVES Extremely Metal-Deficient Stars

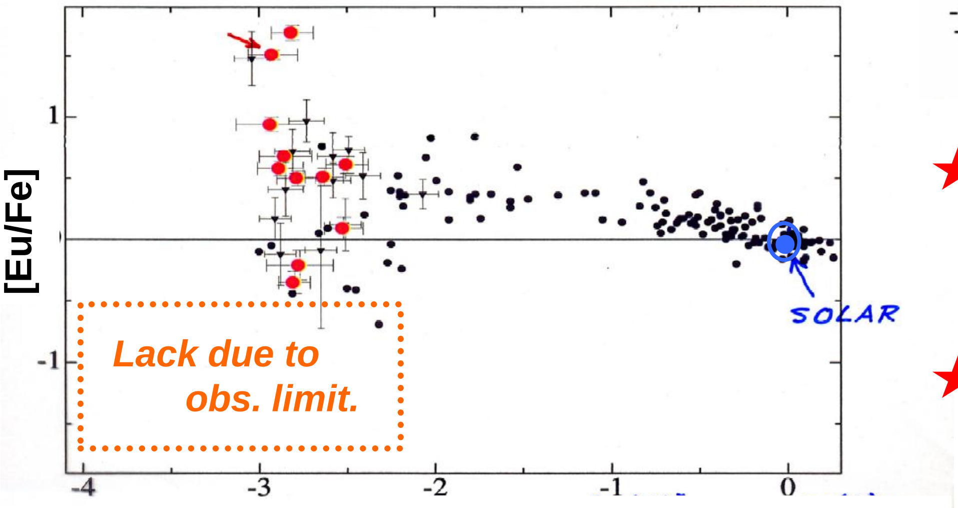


SUBARU Telescope HDS

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

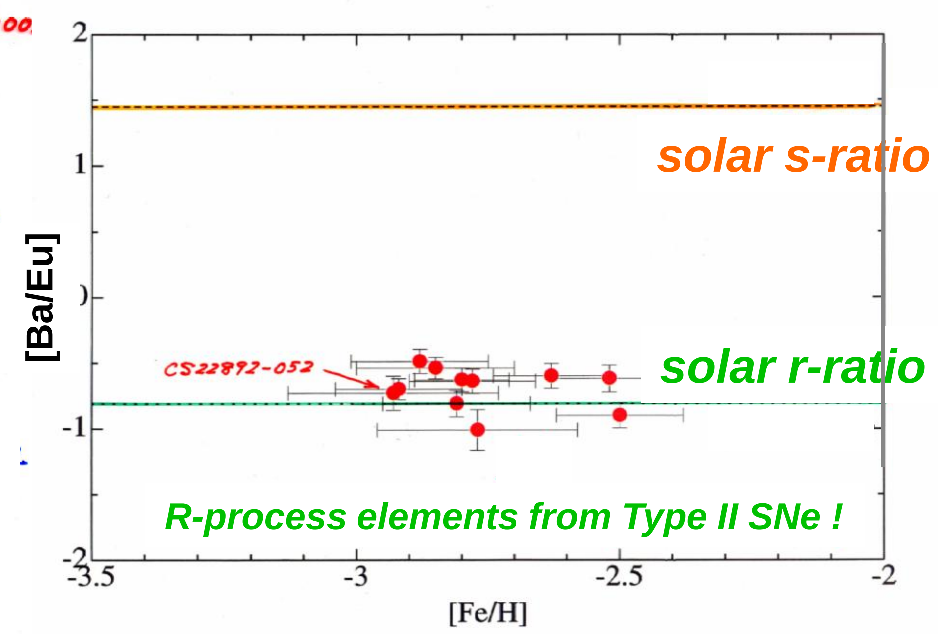


SN II ⟵ ⟶ SN I + II ⟶



Early Galaxy ⟵

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



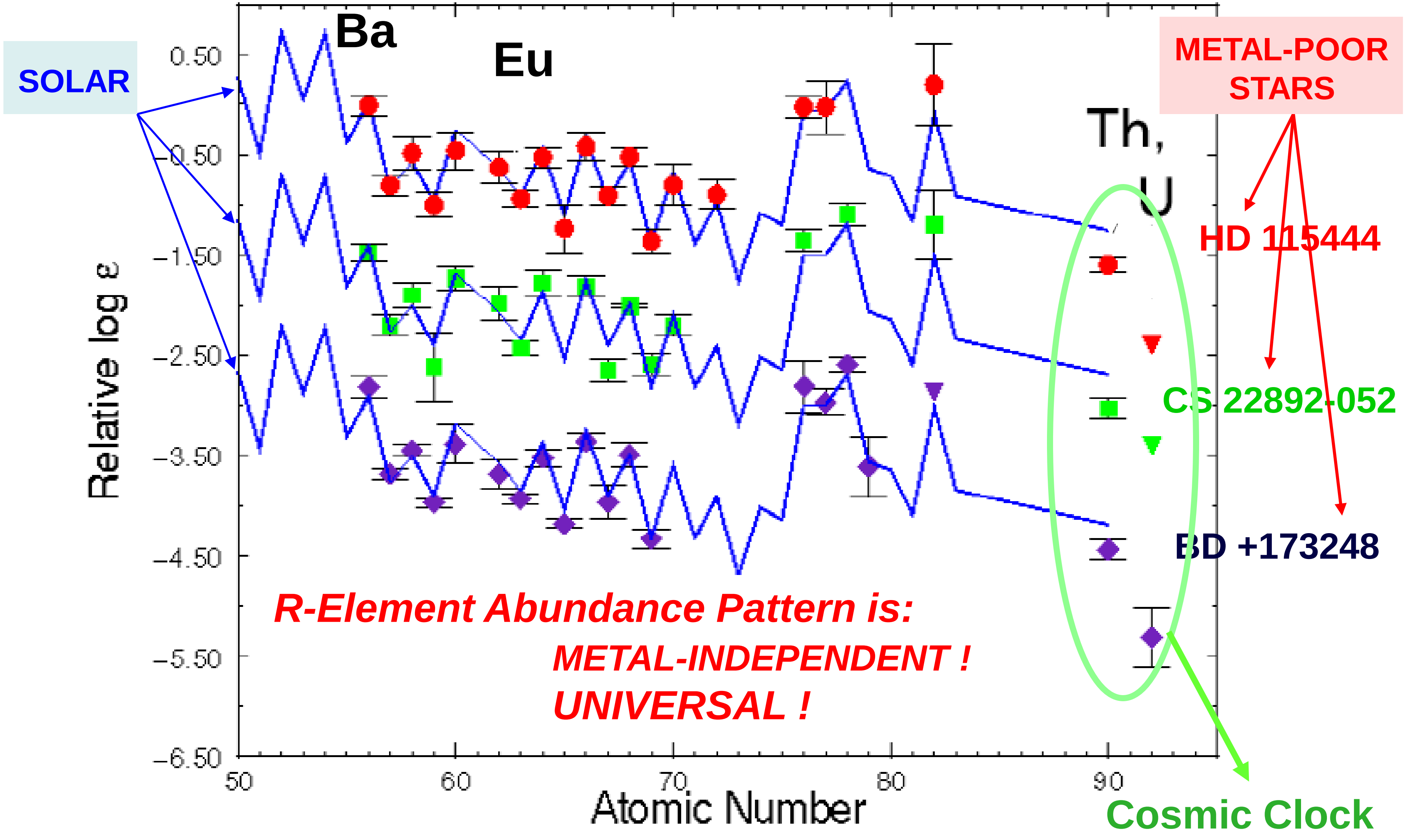
R-process elements from Type II SNe !

★ **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 !**

UNIVERSAL SCALING OF R-PROCESS ABUNDANCES

C. Sneden et al. (1996 – 2005)



SOLAR

METAL-POOR STARS

HD 115444

CS 22892-052

BD +173248

R-Element Abundance Pattern is:

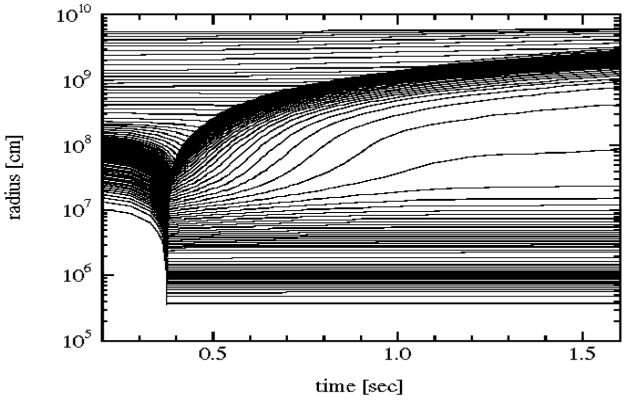
METAL-INDEPENDENT !

UNIVERSAL !

Cosmic Clock

Collapse of the Core

Prompt core bounce



E(iron core) ~ GM^2/r ~ 10^{51} erg

E(neutron star) ~ GM^2/r ~ 10^{53} erg

E(neutron star) - E(iron core) ~ 10^{53} erg

99% is emitted as neutrinos!

E(shock) ~ 10^{51} erg

1% is kinetic energy!

Usually the shock is absorbed by dissociating the iron core.

Neutrino-heated explosion
DELAYED SUPERNOVA

Steps to a Core Collapse Supernova

- Stars with M ~ 10 - 40 $M_\odot$ build up an Fe/Ni core.

  Maximum core size $M_{ch} = 5\ Y_e^2\ M_\odot \sim 1.3\ M_\odot$ (Electron Capture).
- Collapse Separates,

  inner homologous ($v \propto r$) core = 1.1 $M_\odot$.

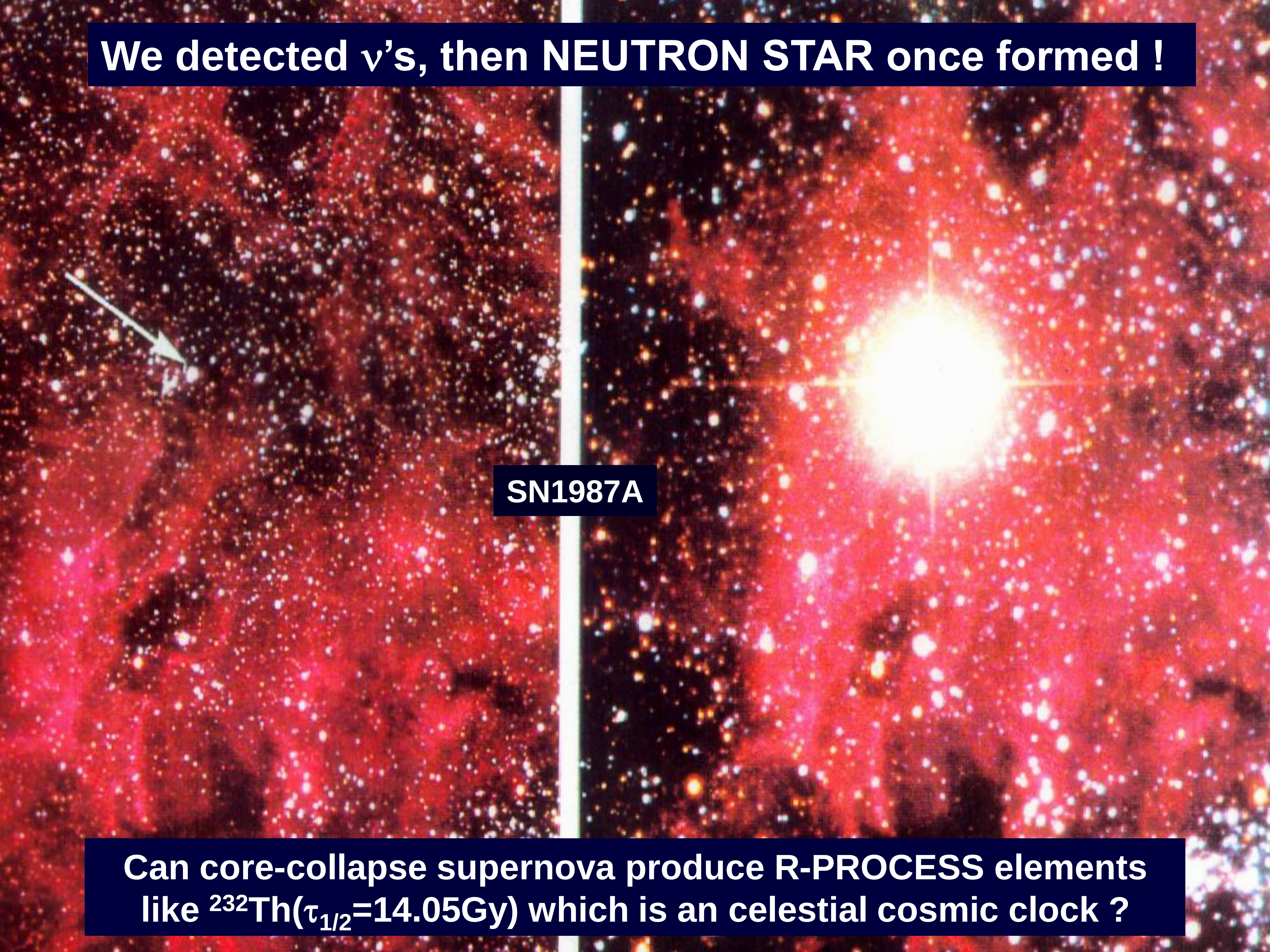
  outer slowly collapsing core = 0.2 $M_\odot$.

The central density increases and reaches nuclear matter density,

$\rho_{nucl} \sim 2 \mathrm{x} 10^{14}$ g cm^{-3} (Nuclear EOS).

- An outward moving shock develops due to nuclear saturation.
- The shock dissociates the outer iron core into free nucleons.
- Neutrinos scatter off the heated material behind the shock and deposit energy into p, n, and e^+e^-.
- A high entropy heated region forms and begins to lift the outer layers of the star (neutrino-driven wind).

We detected ν's, then NEUTRON STAR once formed !



SN1987A

Can core-collapse supernova produce R-PROCESS elements like ^{232}Th($\tau_{1/2}$=14.05Gy) which is an celestial cosmic clock ?

超新星爆発の数値計算機シミュレーション

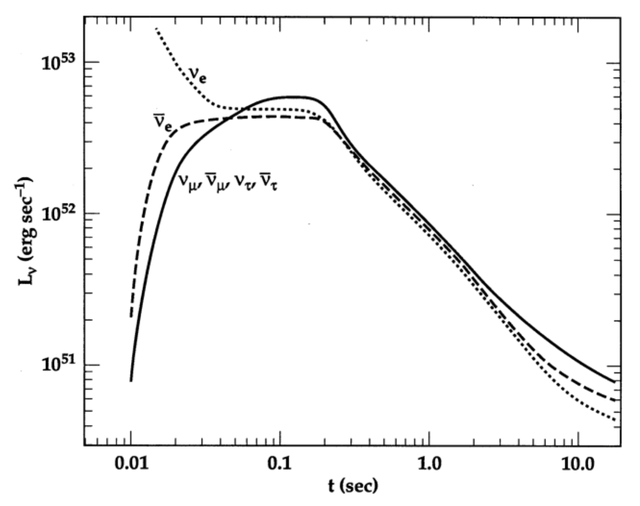
バロウズ（アリゾナ大）

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

→ 10 km

300 km

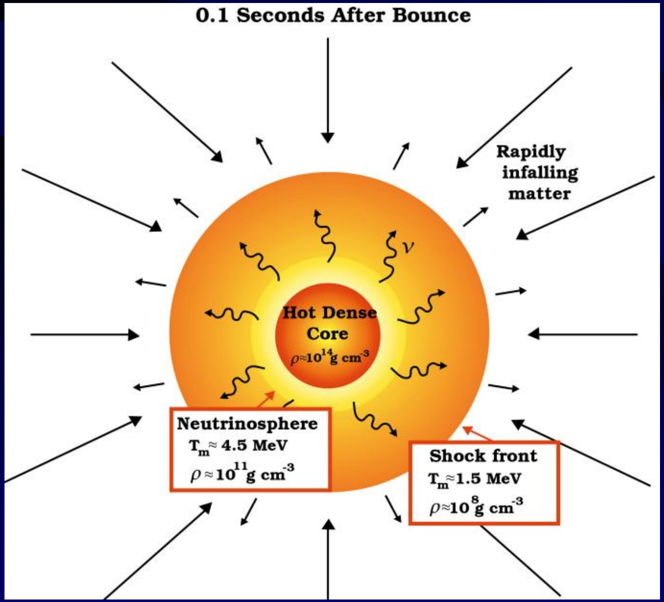
Neutrino Heated Bubble forms

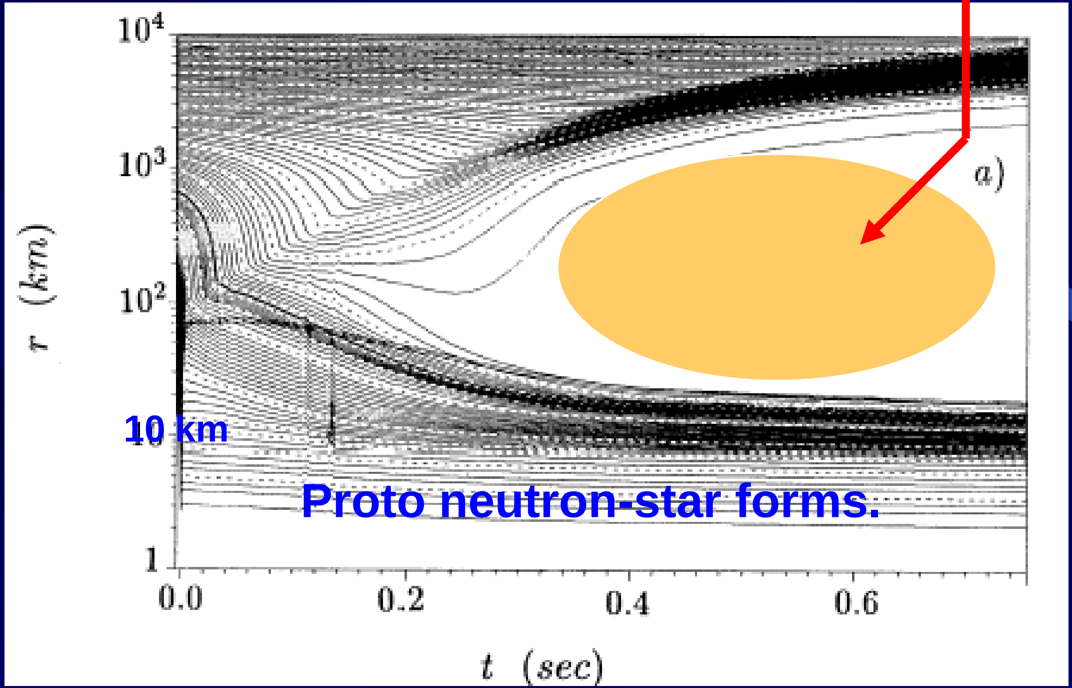


Neutrino
Luminosity
~10^{53} erg/s

Neutrino Heating
produces
a high entropy bubble.

Woosley et al. 1994, ApJ 433, 229

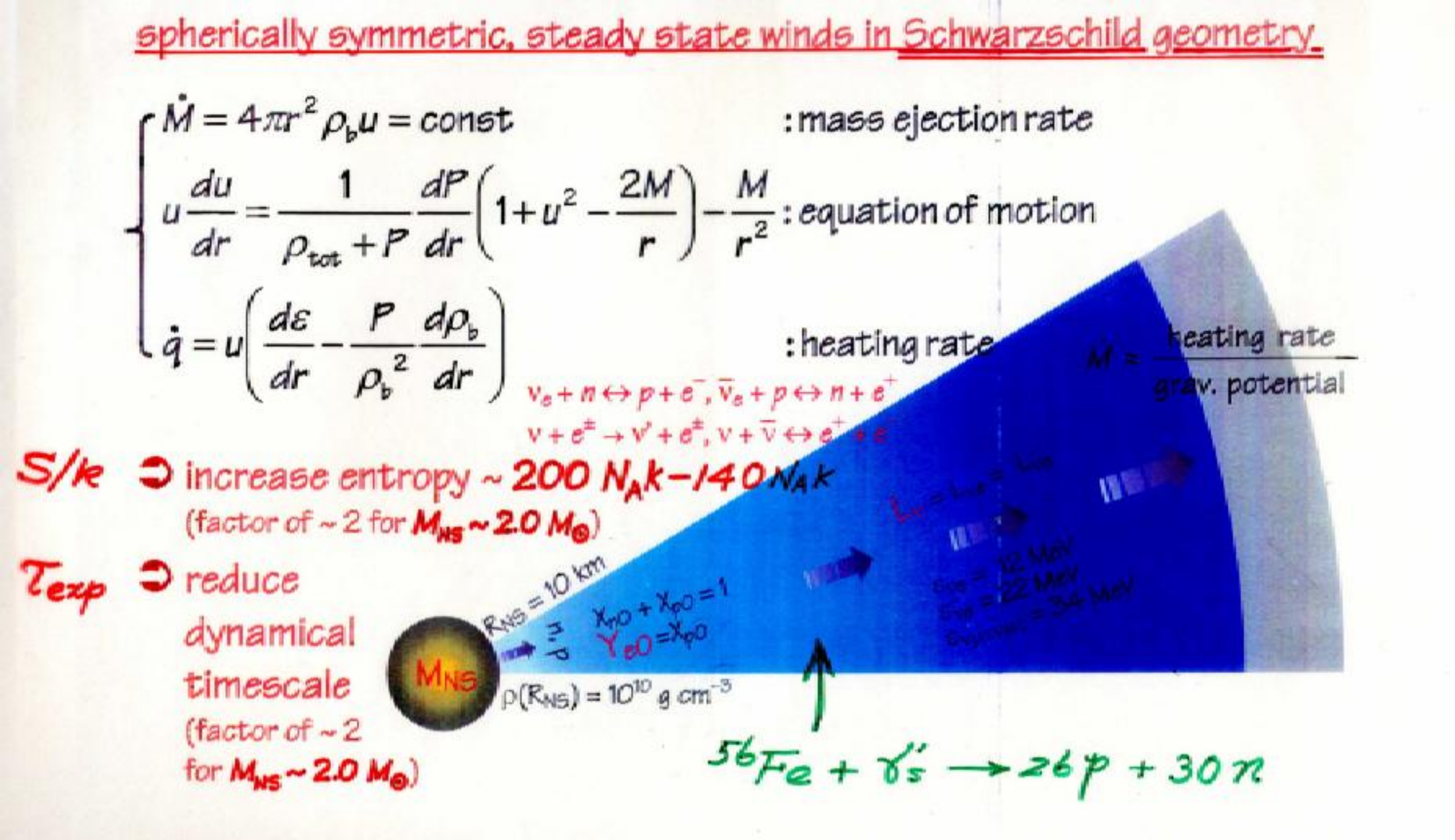




Proto neutron-star forms.

General Relativistic Models of ν-Driven Winds

Otsuki, Tagoshi, Kajino and Wanajo 2000, ApJ 533, 424



spherically symmetric, steady state winds in Schwarzschild geometry

$$\begin{cases} \dot{M} = 4\pi r^2 \rho_b u = \text{const} & \text{: mass ejection rate} \\ u\dfrac{du}{dr} = \dfrac{1}{\rho_{tot} + P}\dfrac{dP}{dr}\left(1 + u^2 - \dfrac{2M}{r}\right) - \dfrac{M}{r^2} & \text{: equation of motion} \\ \dot{q} = u\left(\dfrac{d\varepsilon}{dr} - \dfrac{P}{\rho_b{}^2}\dfrac{d\rho_b}{dr}\right) & \text{: heating rate} \end{cases}$$

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

$\nu + e^\pm \rightarrow \nu' + e^\pm, \nu + \bar{\nu} \leftrightarrow e^+ + e^-$

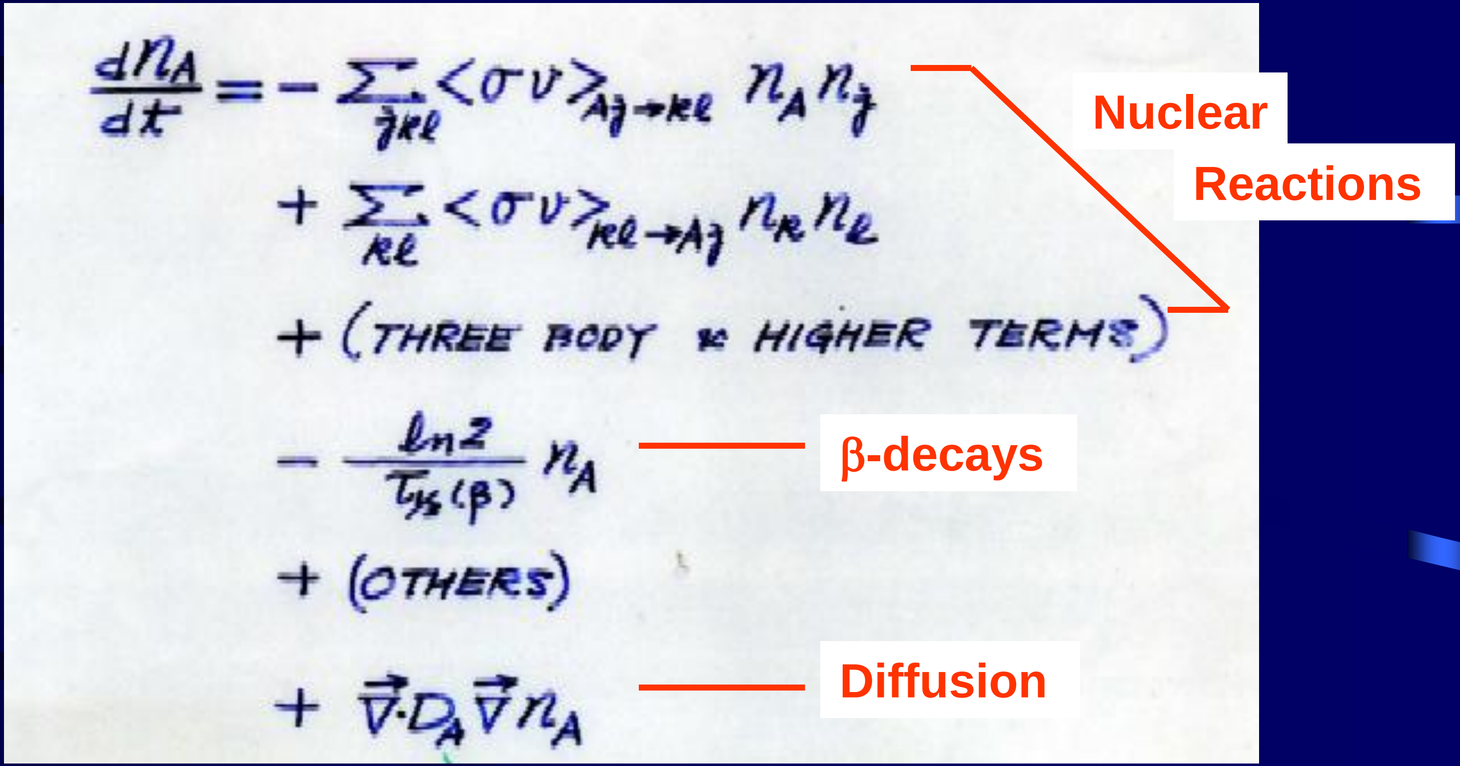
S/k ➲ increase entropy ~ $200\, N_A k - 140\, N_A k$
(factor of ~ 2 for $M_{NS} \sim 2.0\, M_\odot$)

τ_{exp} ➲ reduce dynamical timescale
(factor of ~ 2 for $M_{NS} \sim 2.0\, M_\odot$)

$^{56}Fe + \gamma's \longrightarrow 26p + 30n$

Nucleosynthesis + Diffusion Equation for Z < 100 (~3000 species)

Given **T** & ρ :



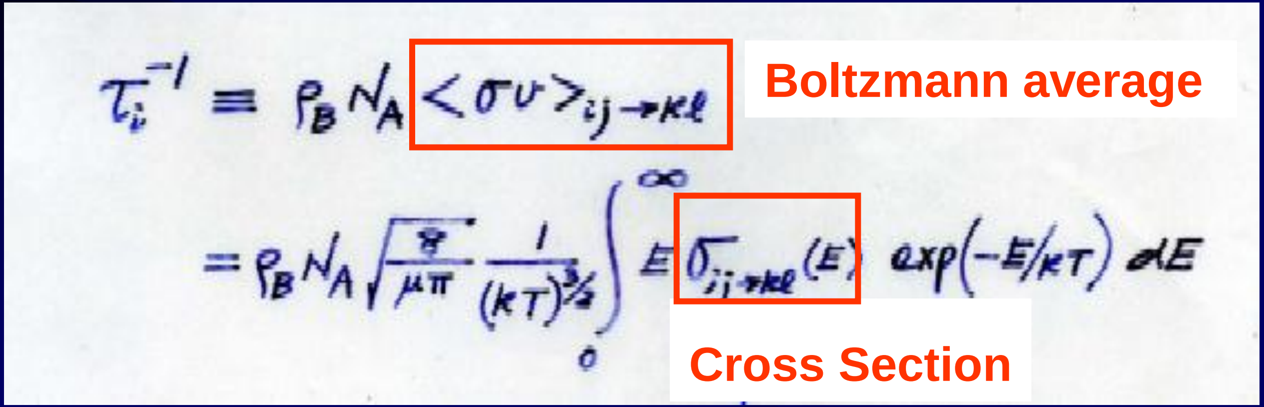
$$\begin{aligned}\frac{dn_A}{dt} = & -\sum_{jkl}\langle\sigma v\rangle_{Aj\to kl}\, n_A n_j \\ & + \sum_{kl}\langle\sigma v\rangle_{kl\to Aj}\, n_k n_l \\ & + (\text{THREE BODY \& HIGHER TERMS}) \\ & - \frac{\ln 2}{\tau_{1/2}(\beta)}\, n_A \\ & + (\text{OTHERS}) \\ & + \vec{\nabla}\cdot D_A \vec{\nabla} n_A\end{aligned}$$

Nuclear Reactions

β-decays

Diffusion

Thermonuclear Reaction Rate



$$\tau_i^{-1} = \rho_B N_A \boxed{\langle\sigma v\rangle_{ij\to kl}}$$

$$= \rho_B N_A \sqrt{\frac{8}{\mu\pi}}\,\frac{1}{(kT)^{3/2}}\int_0^\infty E\,\boxed{\sigma_{ij\to kl}(E)}\,\exp(-E/kT)\,dE$$

Boltzmann average

Cross Section

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.

n + p + α

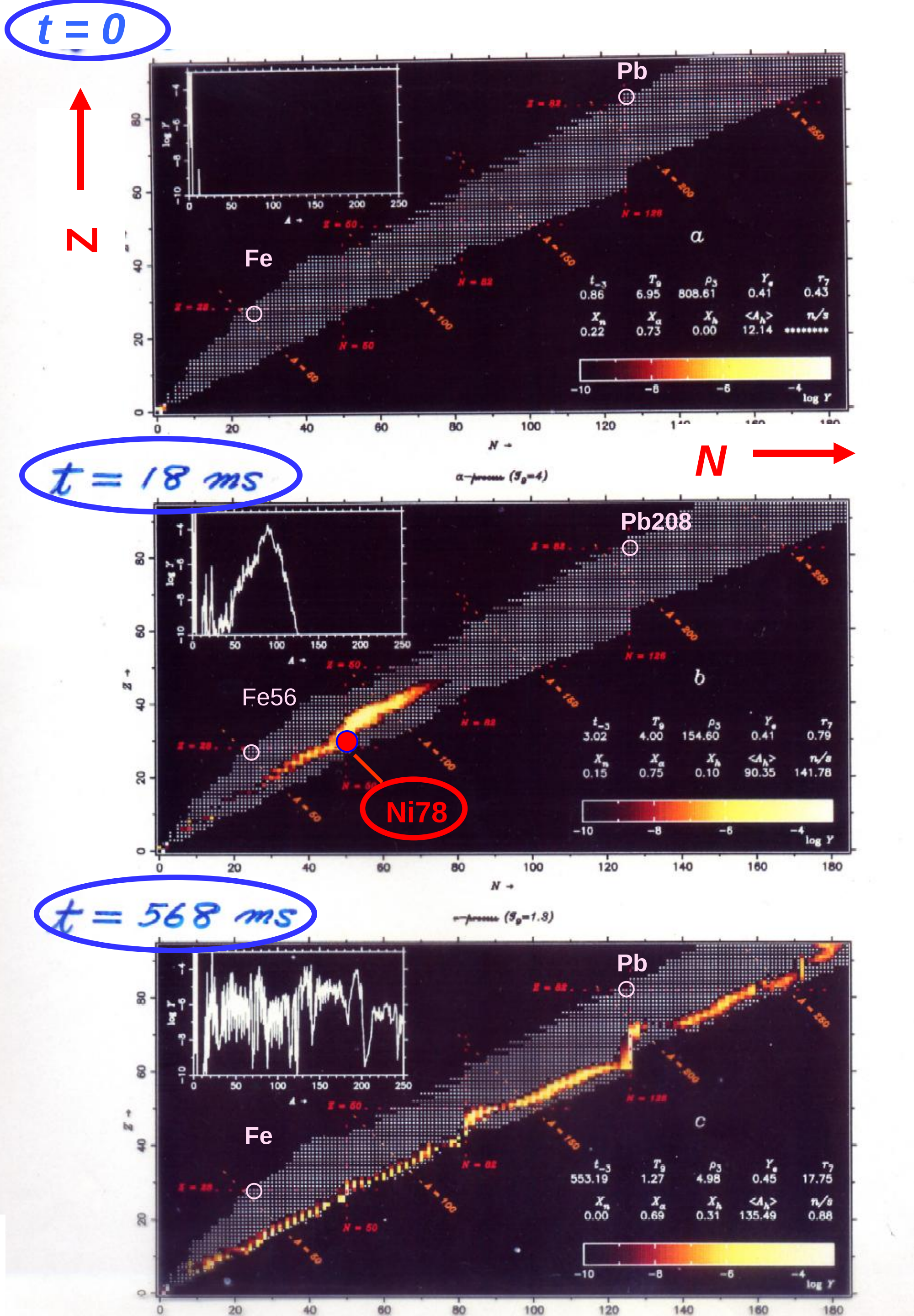
t = 18 ms

Seeds form.

Exotic neutron-rich ^{78}Ni

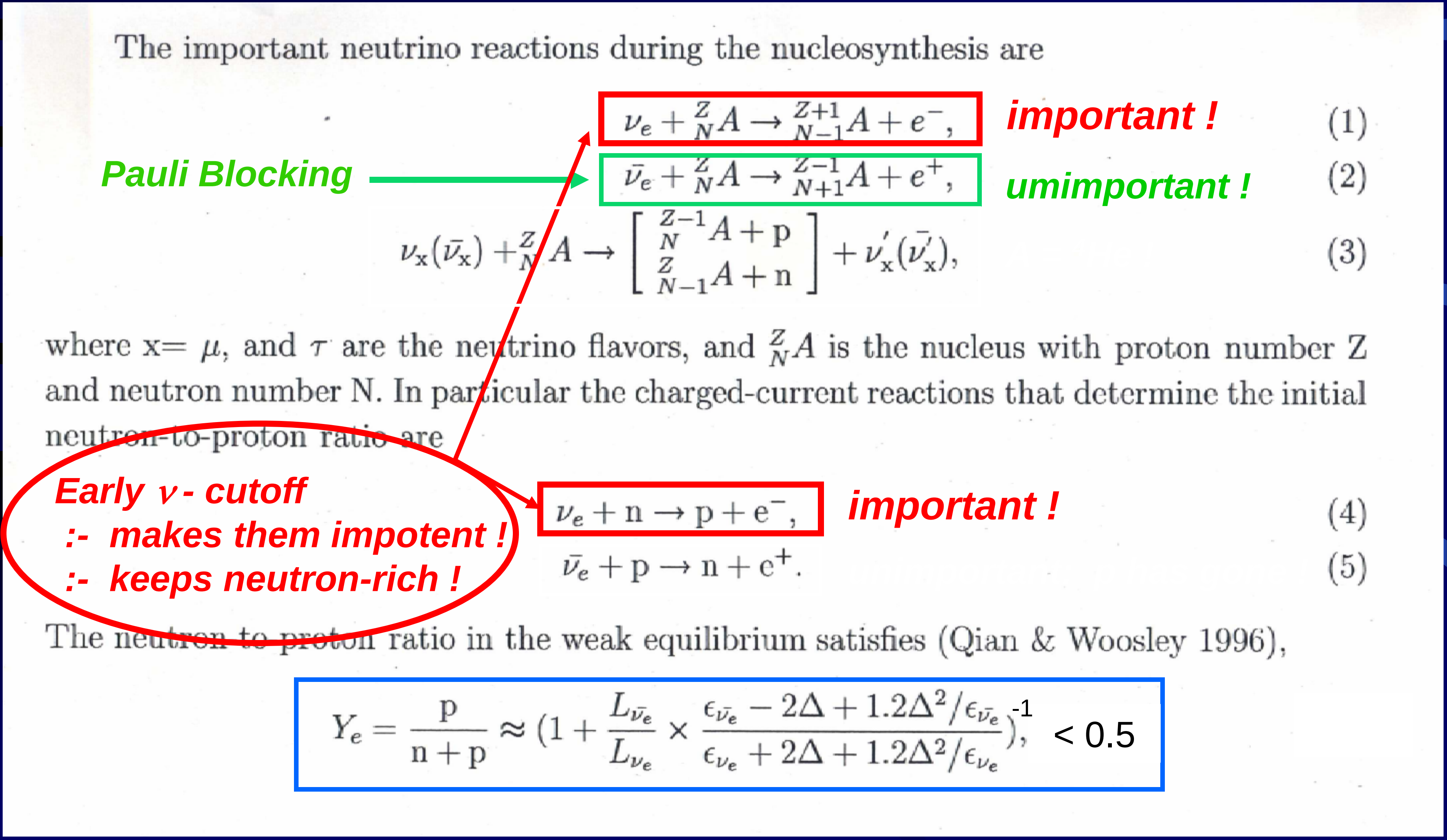
t = 568 ms – 1 s

Heavy r-elements synthesize.



Neutrino Effects on Black Hole vs. Neutron Star Formation

Sasaqui, Kajino & Balantekin 2005, ApJ, in press. (astro-ph/0506100)



The important neutrino reactions during the nucleosynthesis are

$$\boxed{\nu_e + {}^{Z}_{N}A \rightarrow {}^{Z+1}_{N-1}A + e^-,} \quad \text{important !} \tag{1}$$

Pauli Blocking

$$\boxed{\bar{\nu}_e + {}^{Z}_{N}A \rightarrow {}^{Z-1}_{N+1}A + e^+,} \quad \text{umimportant !} \tag{2}$$

$$\nu_x(\bar{\nu}_x) + {}^{Z}_{N}A \rightarrow \begin{bmatrix} {}^{Z-1}_{N}A + \mathrm{p} \\ {}^{Z}_{N-1}A + \mathrm{n} \end{bmatrix} + \nu'_x(\bar{\nu}'_x), \tag{3}$$

where x= μ, and τ are the neutrino flavors, and ${}^{Z}_{N}A$ is the nucleus with proton number Z and neutron number N. In particular the charged-current reactions that determine the initial neutron-to-proton ratio are

Early ν - cutoff
:- makes them impotent !
:- keeps neutron-rich !

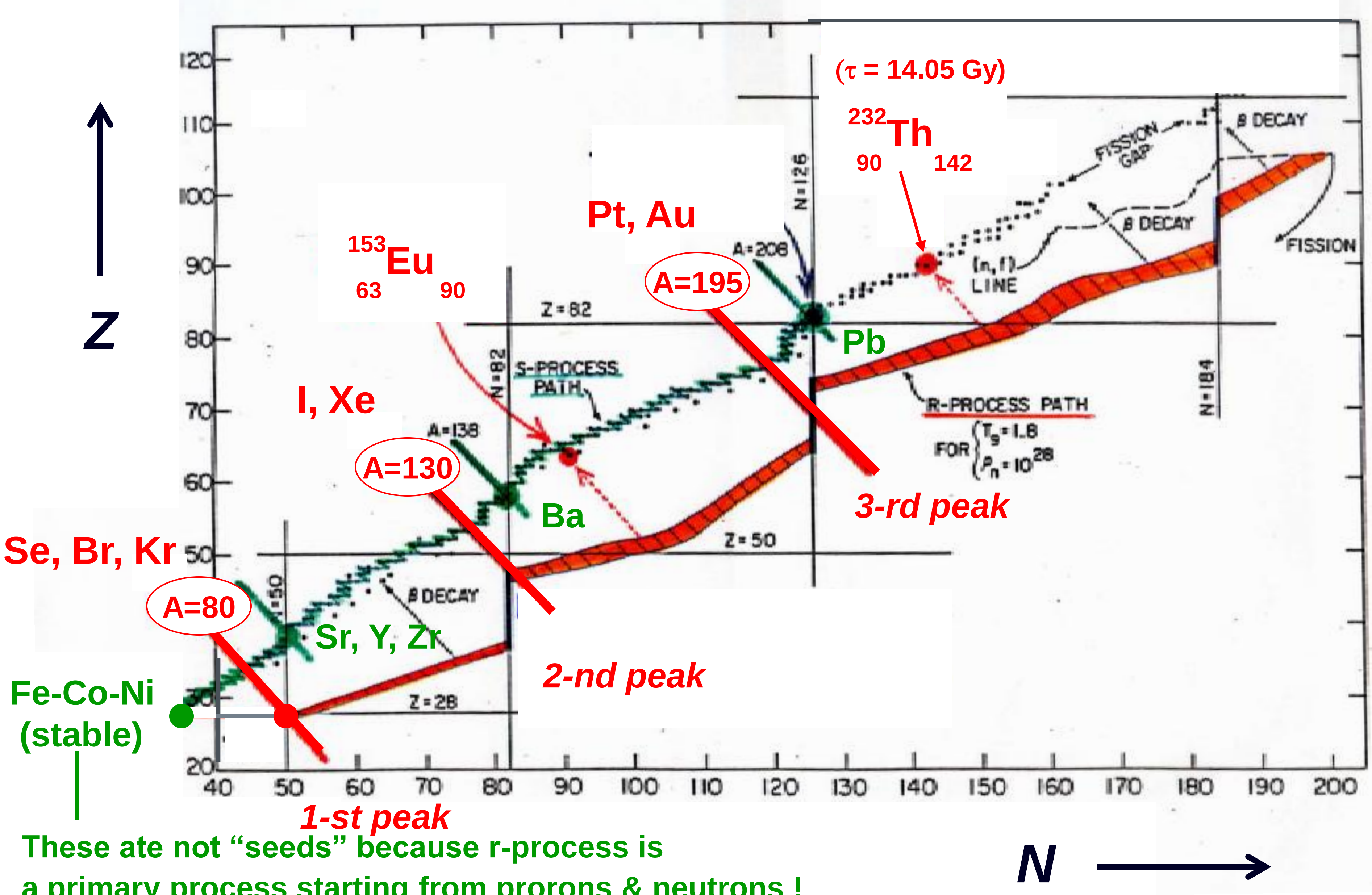
$$\boxed{\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-,} \quad \text{important !} \tag{4}$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+. \tag{5}$$

The neutron to proton ratio in the weak equilibrium satisfies (Qian & Woosley 1996),

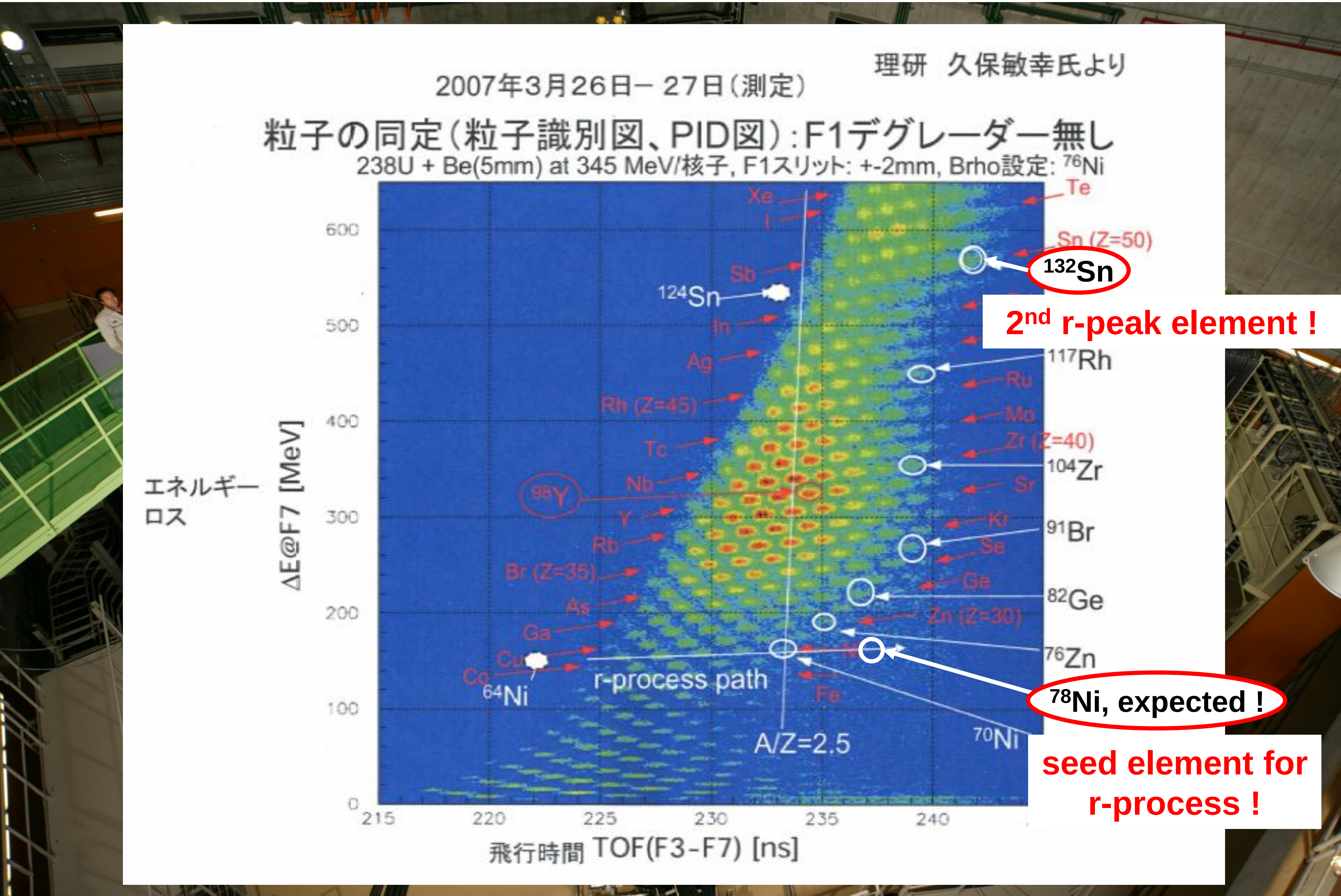
$$\boxed{Y_e = \frac{\mathrm{p}}{\mathrm{n}+\mathrm{p}} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \times \frac{\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}}\right)^{-1}, \quad < 0.5}$$

Very Rapid Neutron-Capture Process



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

RIKEN-RIBF New Ring Cyclotron (2007)



理研 久保敏幸氏より

2007年3月26日－27日（測定）

粒子の同定（粒子識別図、PID図）：F1デグレーダー無し

238U + Be(5mm) at 345 MeV/核子, F1スリット: +-2mm, Brho設定: ^{76}Ni

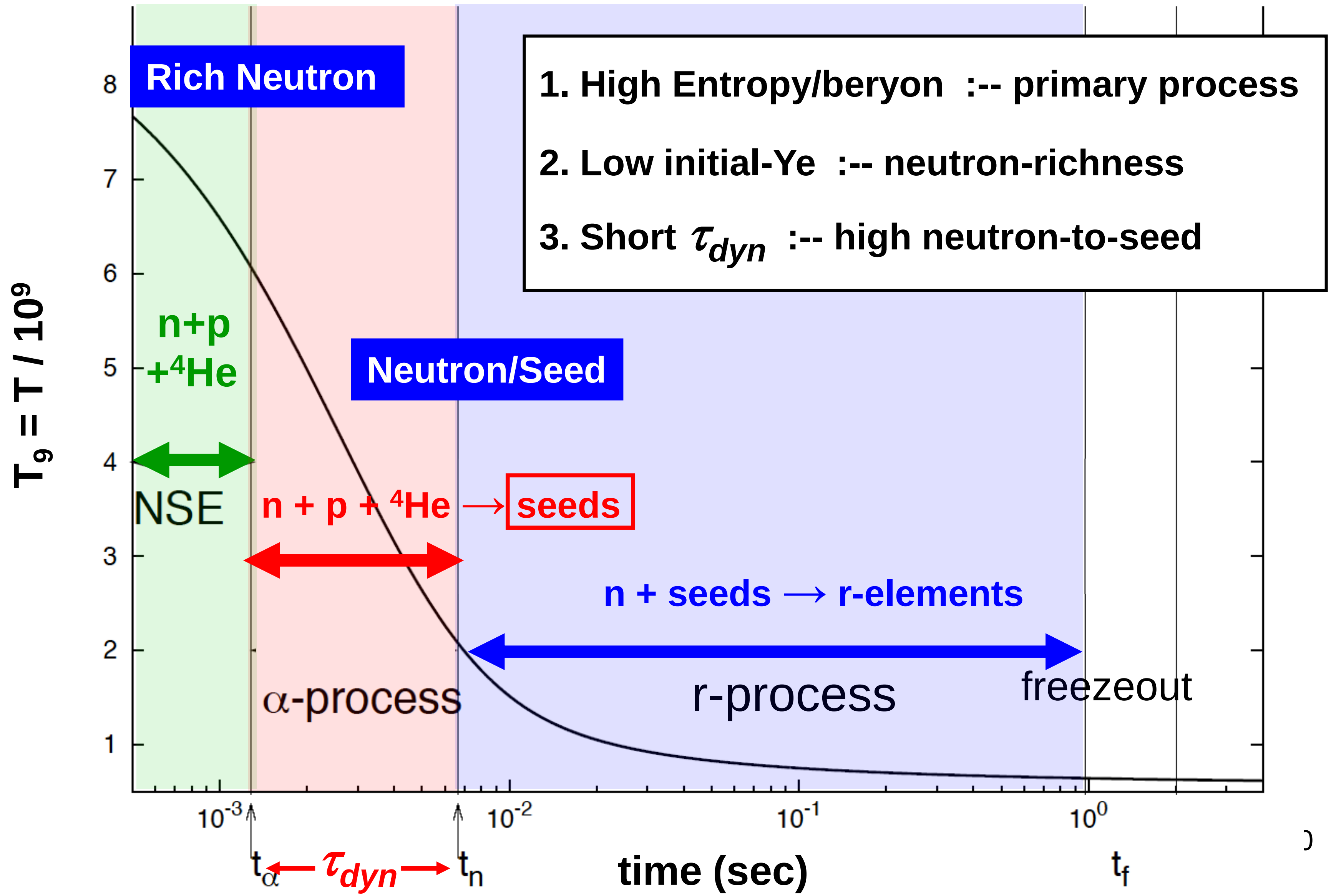
^{132}Sn

2nd r-peak element !

^{78}Ni, expected !

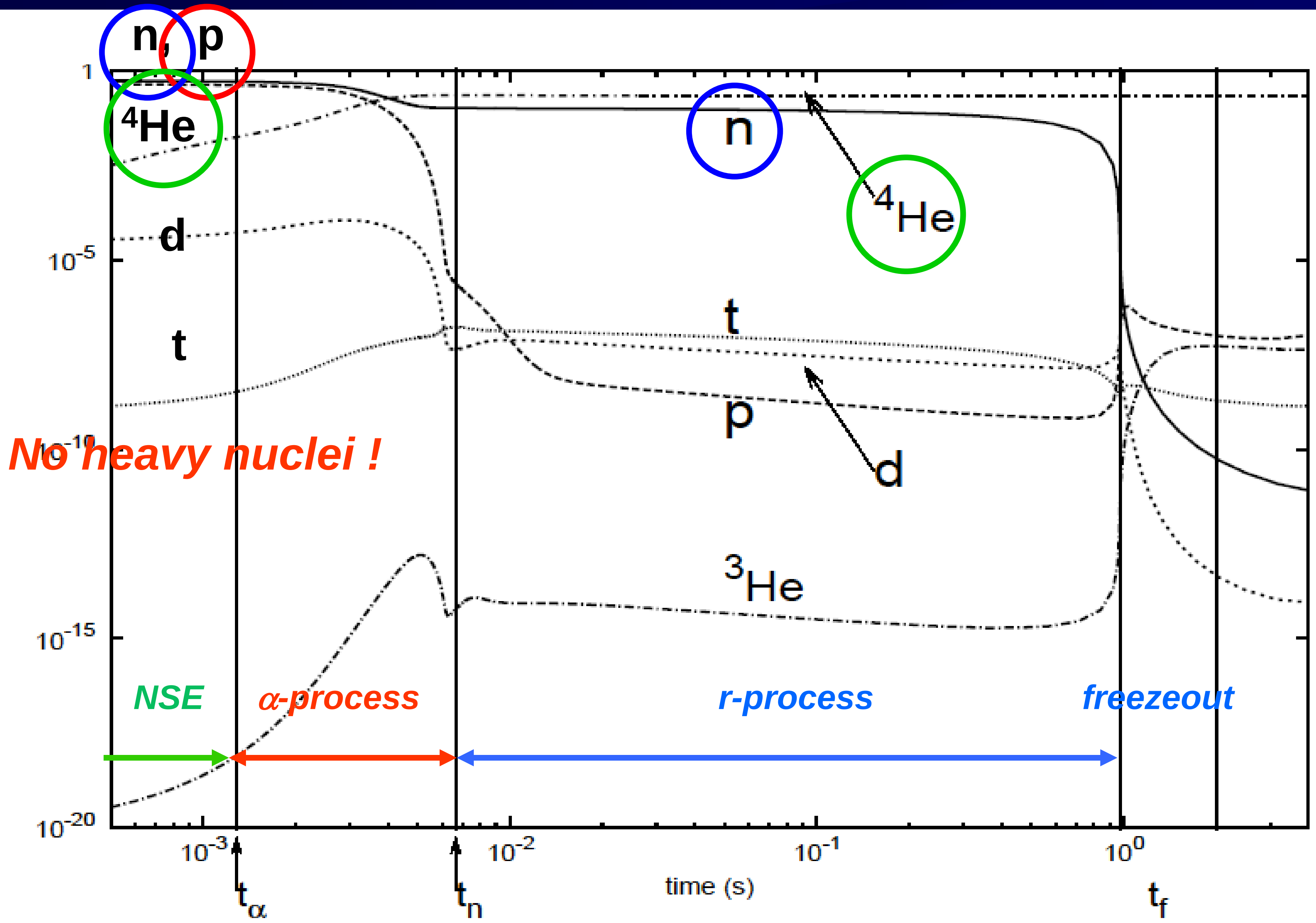
seed element for r-process !

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



1. **High Entropy/beryon :-- primary process**
2. **Low initial-Ye :-- neutron-richness**
3. **Short τ_{dyn} :-- high neutron-to-seed**

Nucleosynthesis in SN ν - Driven Wind

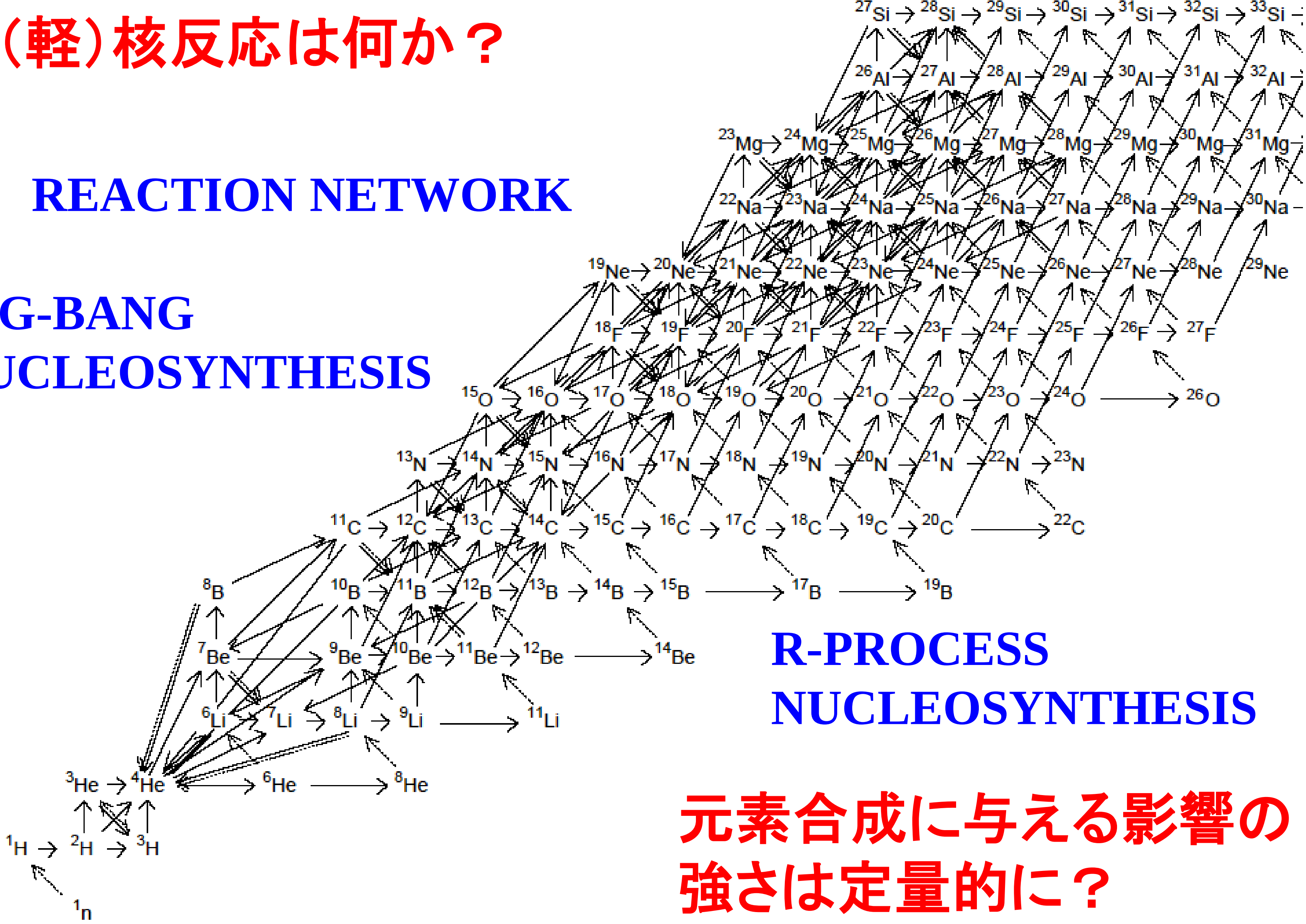


No heavy nuclei !

R過程（プライマリー）で重要な（軽）核反応は何か？

REACTION NETWORK

BIG-BANG NUCLEOSYNTHESIS



R-PROCESS NUCLEOSYNTHESIS

元素合成に与える影響の強さは定量的に？

Reaction Sensitivity

Sasaqui, Kajino, Mathews, Otsuki & Nakamura
Astrophys. J. (2005), submitted.

$$Y_{\mathrm{2nd}} = Y_{\mathrm{2nd}}(0) \prod_i \left(\frac{S_i}{S_i(0)} \right)^{\boxed{\sigma_i}}$$

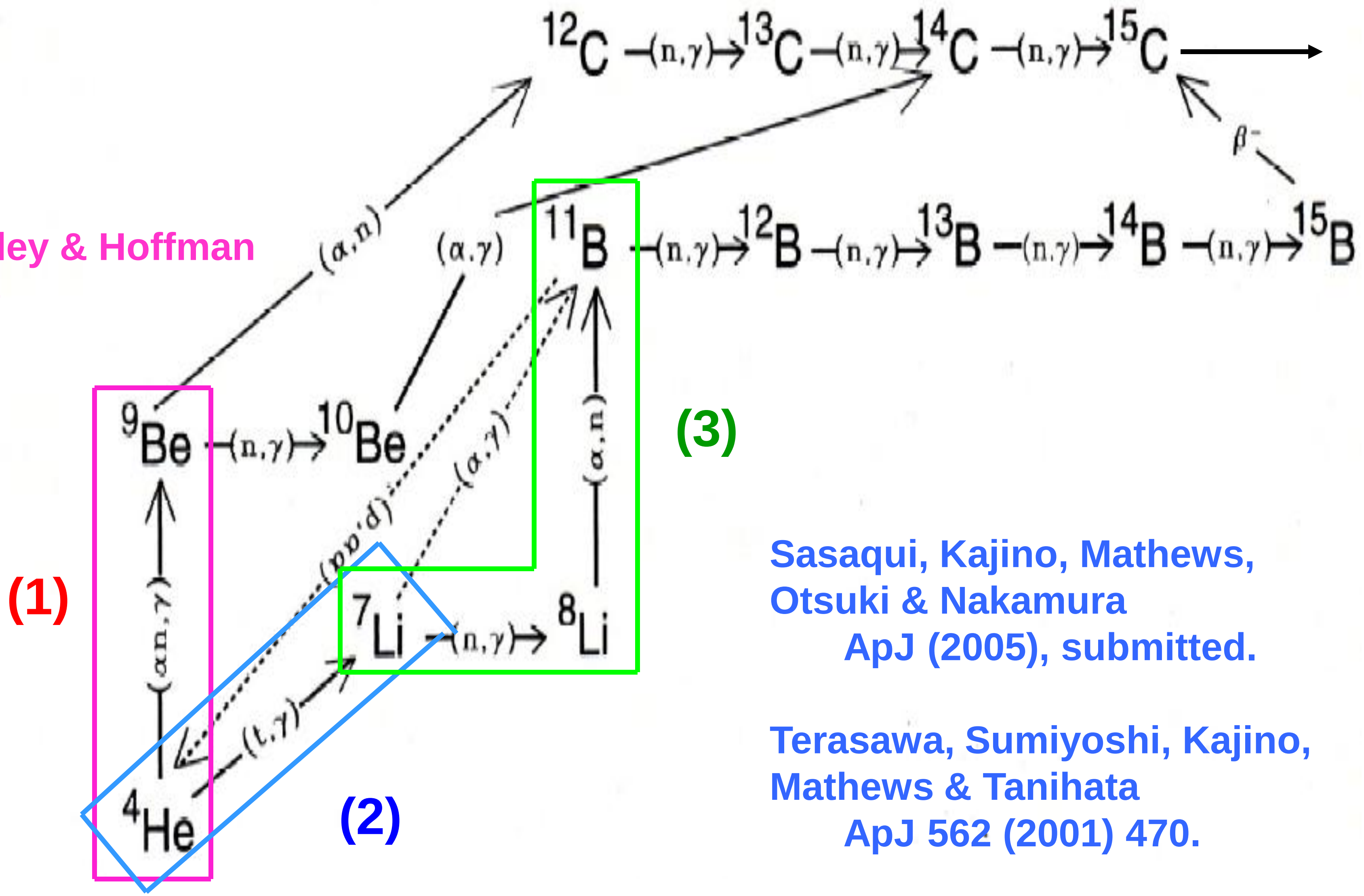
$$Y_{\mathrm{3rd}} = Y_{\mathrm{3rd}}(0) \prod_i \left(\frac{S_i}{S_i(0)} \right)^{\boxed{\sigma_i}}$$

$$\boxed{\sigma_i = \frac{\partial \left(\log \frac{Y_j}{Y_j(0)} \right)}{\partial \left(\log \frac{S_i}{S_i(0)} \right)} .}$$

Solar Neutrino Flux (J. Bahcall, Rev. Mod. Phys. 1982)

$$\begin{aligned} R &= 1.35\mathrm{SNU} \times \left(\frac{S_{11}}{S_{11}(0)} \right)^{-2.5} \left(\frac{S_{33}}{S_{33}(0)} \right)^{-0.37} \left(\frac{S_{34}}{S_{34}(0)} \right)^{+0.8} \\ &\times \left[1 + 3.47 \left(\frac{S_{17}}{S_{17}(0)} \right)^{+1.0} \left(\frac{\lambda_{e7}}{\lambda_{e7}(0)} \right)^{-1.0} \right] \\ &\times \left(\frac{t_{age}}{4.7 \times 10^9 \mathrm{yr}} \right)^{+1.4} \left(\frac{Z}{0.015} \right)^{+1.1} \end{aligned}$$

Identified Important Reaction Flow Paths



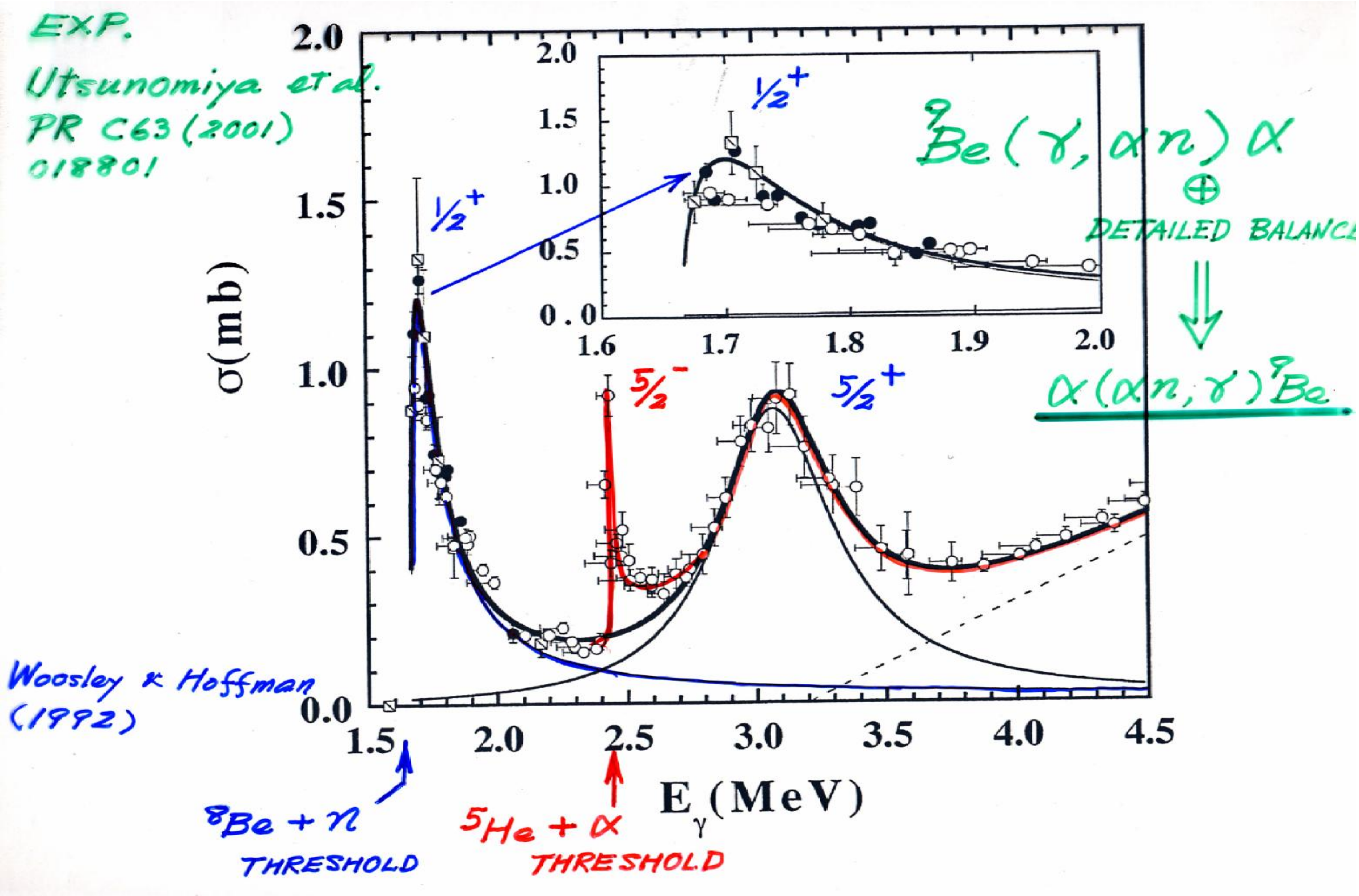
Woosley & Hoffman (1992)

Sasaqui, Kajino, Mathews, Otsuki & Nakamura
ApJ (2005), submitted.

Terasawa, Sumiyoshi, Kajino, Mathews & Tanihata
ApJ 562 (2001) 470.

(1) $\alpha(\alpha n,\gamma)^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$

35%(1σ)

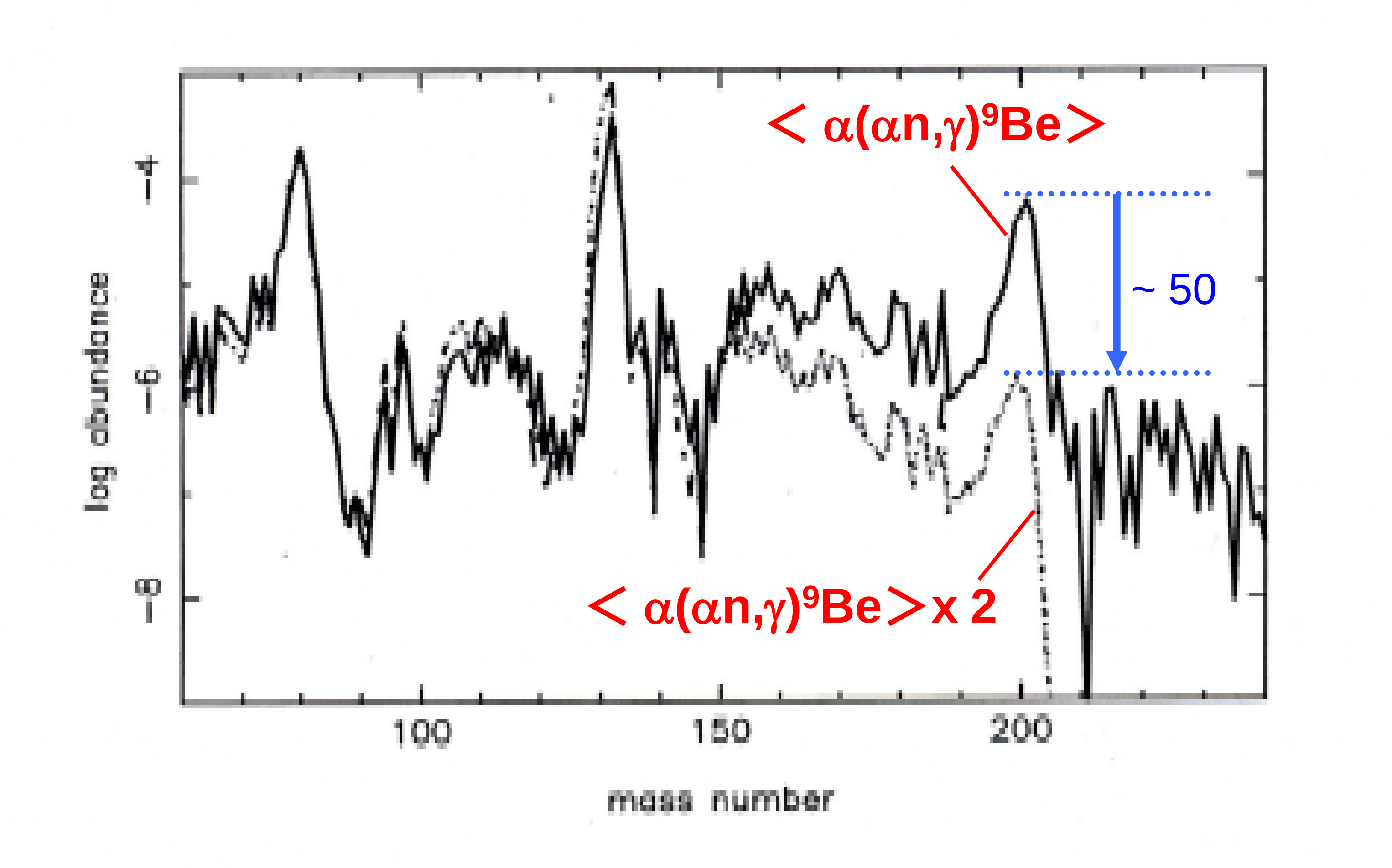


R-Process Sensitivity to Individual Reaction

Factor of 2 change of $\alpha(\alpha n,\gamma)^{9}\mathrm{Be}$ reaction rate

→ About factor 50 change in r-element yields !

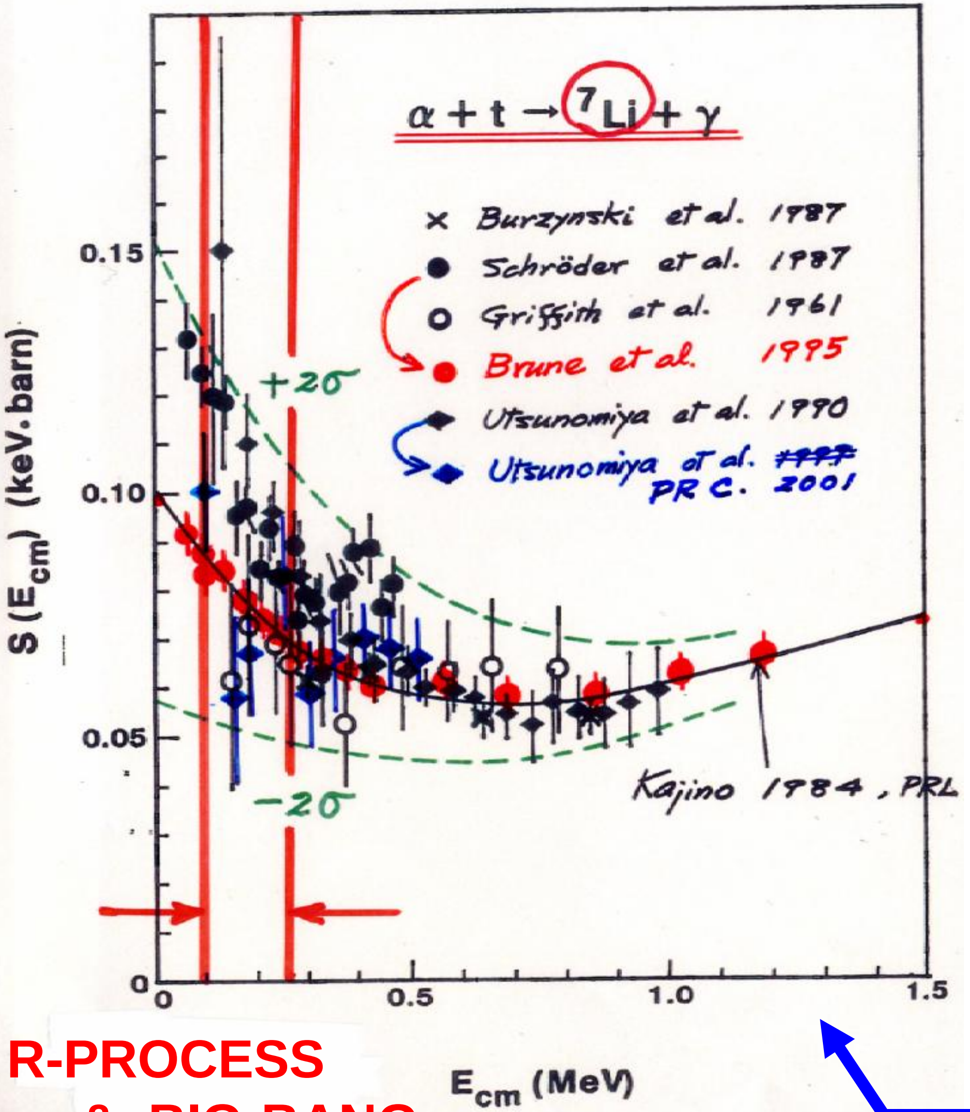
(slowly expanding ν-wind model)

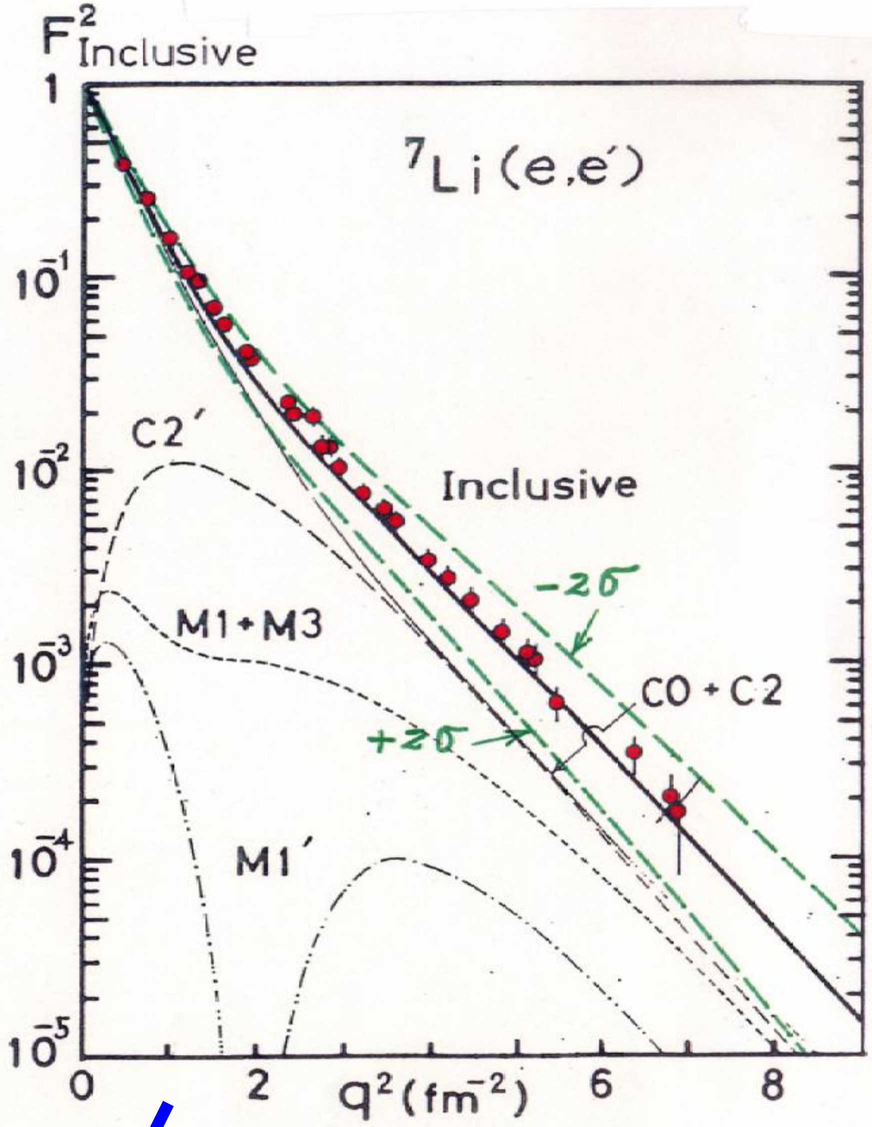


(2) $\alpha(t,\gamma)^7$Li

30%(1σ)

Kajino et al. (2005)





R-PROCESS
& BIG-BANG

REMOVING UNCERTAINTY !

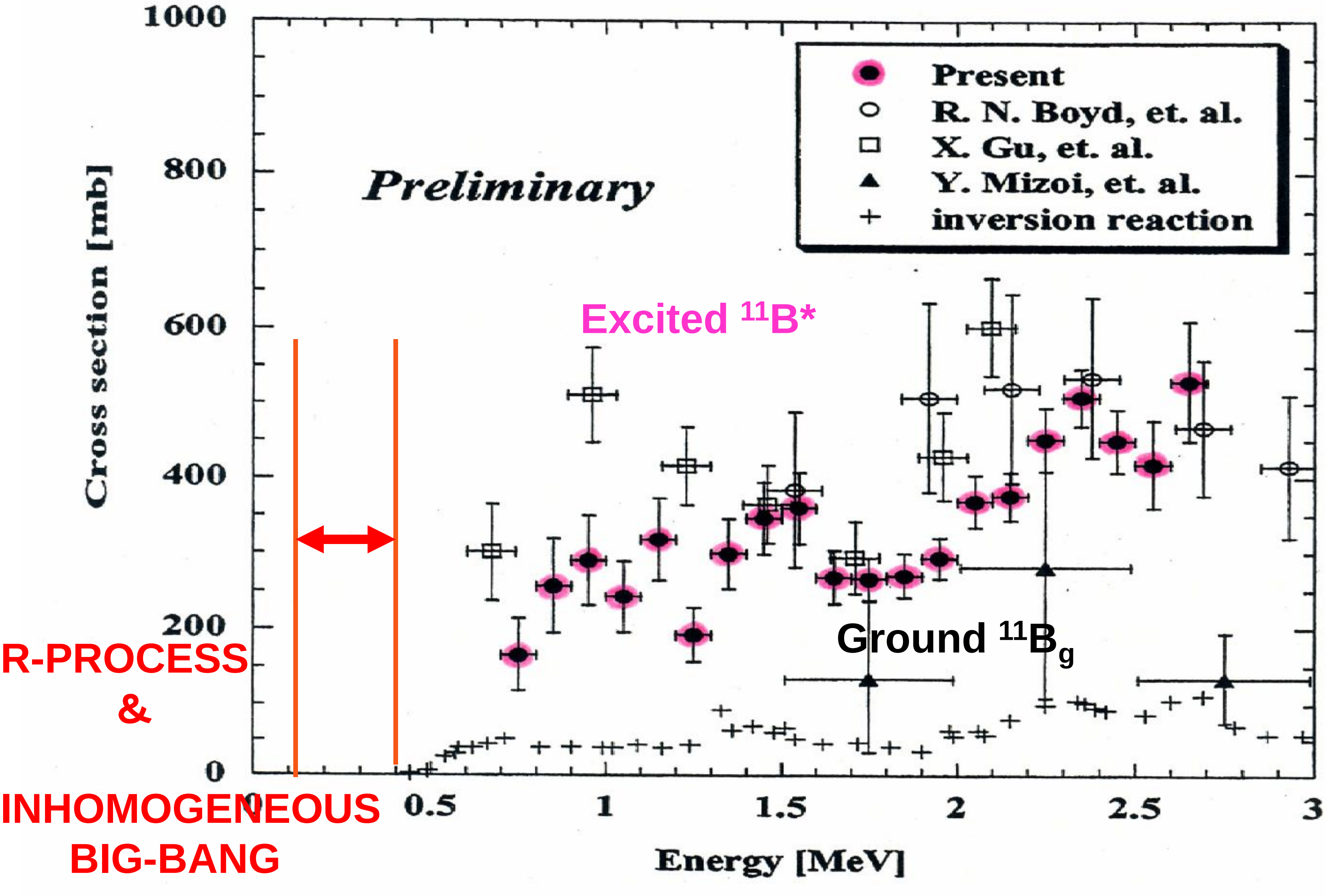
(3) $^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

Factor 2 (1σ)

THEORY, unfinished.
Yamamoto, Kubo, Ogawa & Kajino

H. Ishiyama et al. AIP Conf. Proc. 704 (2004) 453.

$^{11}B_g$ + several $^{11}B^*$ (EXCLUSIVE EXP.)



R-PROCESS
&
INHOMOGENEOUS
BIG-BANG

SENSITIVITY of Relevant Reactions to R-Process

Sasaqui, Kajino, Mathews, Otsuki & Nakamura, ApJ (2005) submitted.
Otsuki, Tagoshi, Kajino & Wanajo, ApJ 533 (2000), 424.

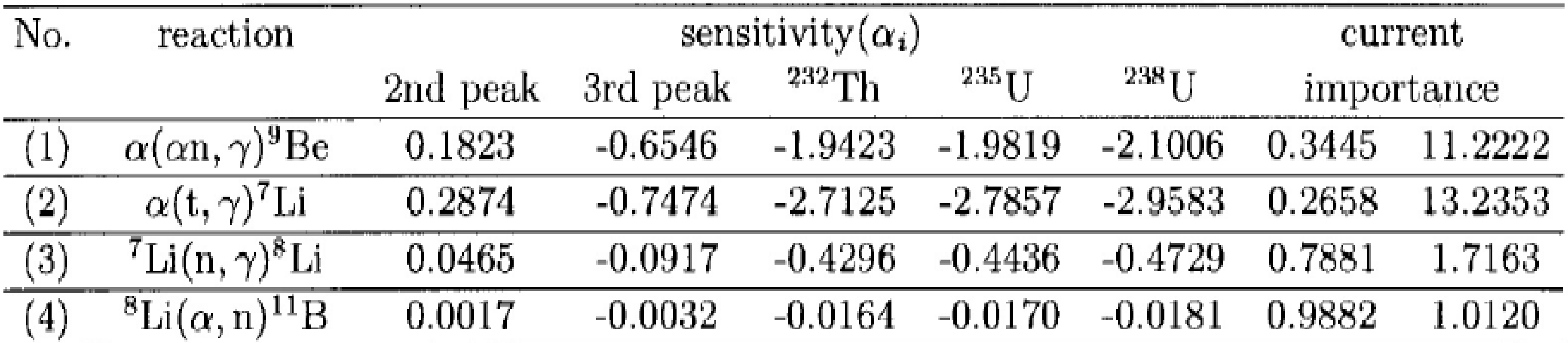
$$Y_{0,r}+\delta Y_r = Y_{0,r}\ \{1+2\sigma\}^{\alpha}$$

(1) $\alpha(\alpha n,\gamma)^{9}\mathrm{Be}$ $1\sigma = 35\% \longrightarrow (Y_0+\delta Y)/Y_0 = 0.35 \sim 11.2$

(2) $\alpha(t,\gamma)^{7}\mathrm{Li}$ $1\sigma = 30\% \longrightarrow 0.27 \sim 13.2$

(3)(4) $^{7}\mathrm{Li}\,(n,\gamma)^{8}\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ $1\sigma = 35\%, \times 2 \longrightarrow 0.79 \sim 1.7$

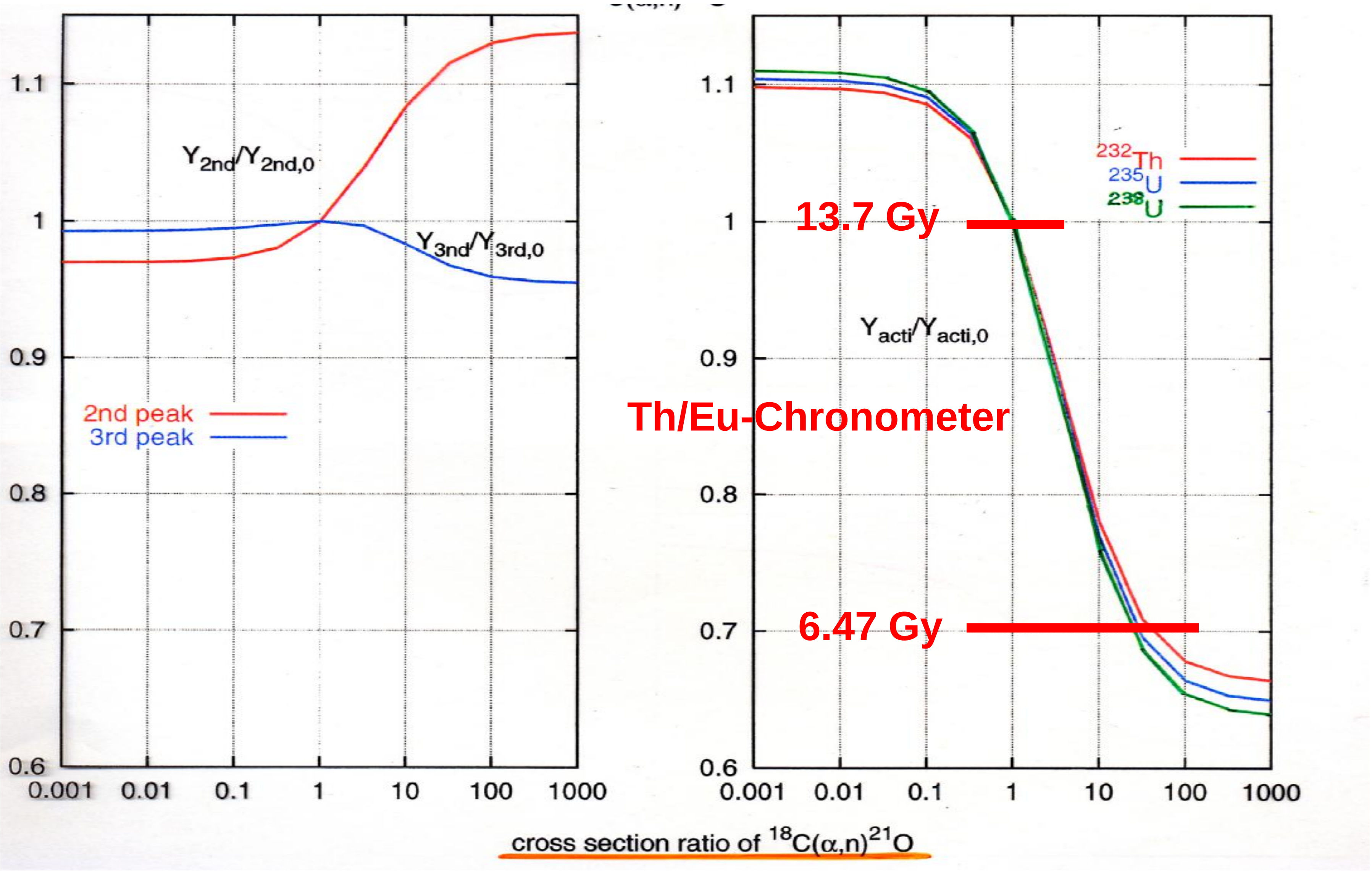
(Th/U)=0.56-0.79



No.	reaction	sensitivity(α_i)					current importance	
		2nd peak	3rd peak	^{232}Th	^{235}U	^{238}U		
(1)	$\alpha(\alpha n,\gamma)^{9}\mathrm{Be}$	0.1823	-0.6546	-1.9423	-1.9819	-2.1006	0.3445	11.2222
(2)	$\alpha(t,\gamma)^{7}\mathrm{Li}$	0.2874	-0.7474	-2.7125	-2.7857	-2.9583	0.2658	13.2353
(3)	$^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}$	0.0465	-0.0917	-0.4296	-0.4436	-0.4729	0.7881	1.7163
(4)	$^{8}\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$	0.0017	-0.0032	-0.0164	-0.0170	-0.0181	0.9882	1.0120

SENSITIVITY of ^{232}Th & ^{235,238}U to ^{18}C(α,n)^{21}O

Sasaqui, Kajino, Mathews, Otsuki & Nakamura, ApJ (2005) submitted.



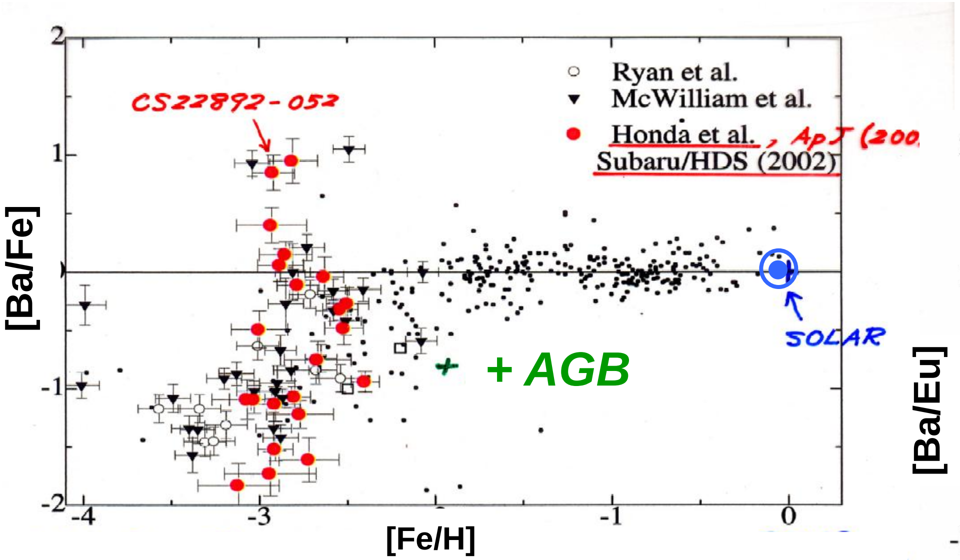
13.7 Gy

Th/Eu-Chronometer

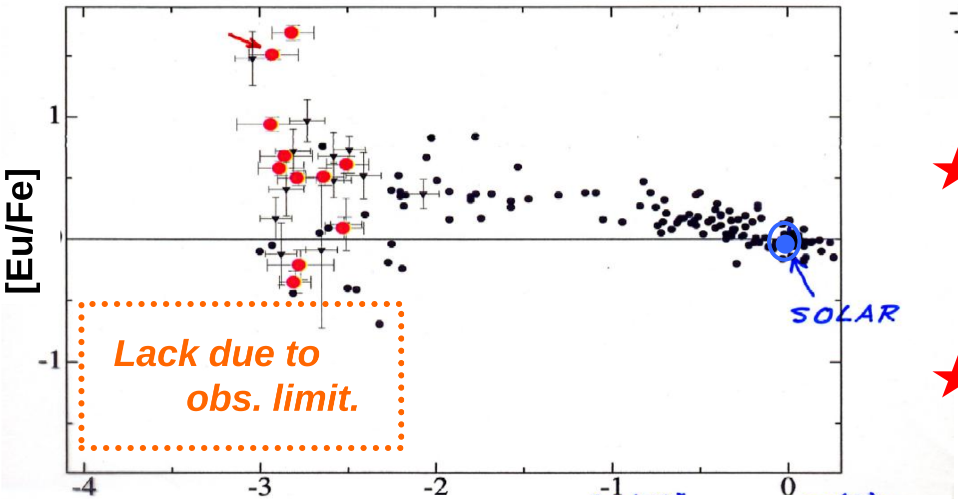
6.47 Gy

SUBARU Telescope HDS

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

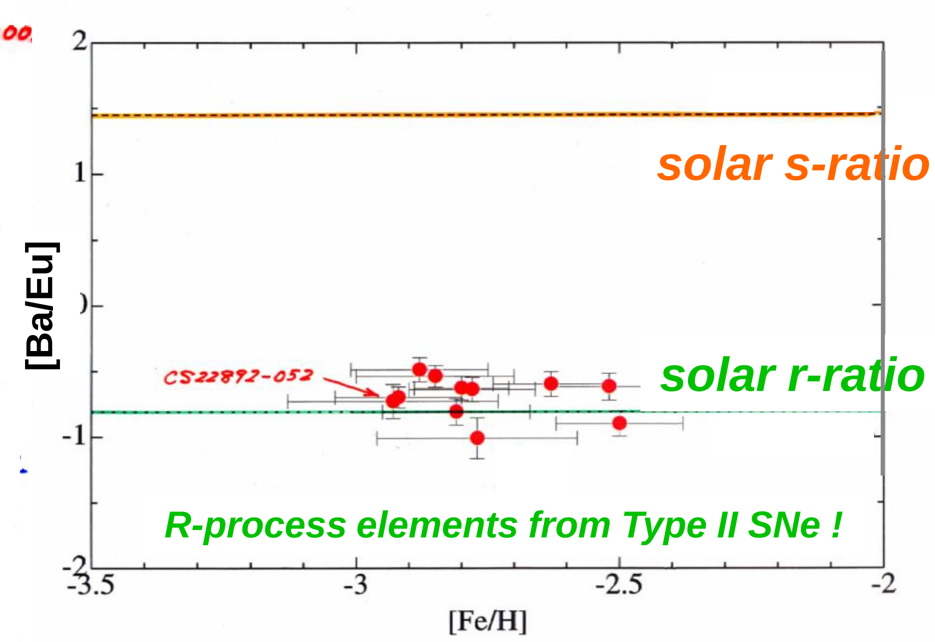


← **SN II** → ← **SN I + II** →



Early Galaxy ←

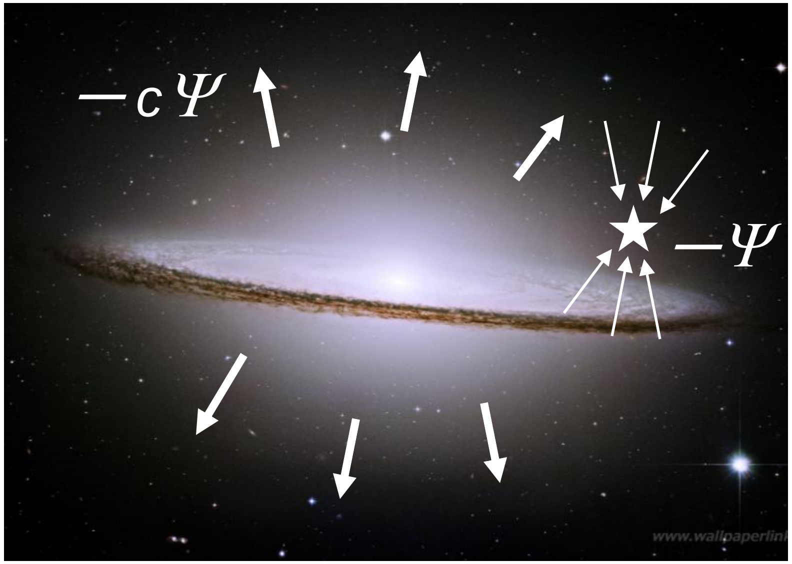
[Fe/H] = $\log(N_{Fe}/N_H)_{\star} - \log(N_{Fe}/N_H)_{\odot}$



- ★ **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 !**

Simple Galactic Chemical Evolution (GCE) Model

http://www.kabegamilink.com/act/0704/03242.html



Halo-Gas (M_G) and **Stars** (M_{tot} -M_G)

- Z_i = Mass Fraction of Nucleus-*i*
- y_i = Stellar Production Yield
- Ψ = Star Formation Rate
- ϕ = Galactic Cosmic Ray
- $c\Psi$ = Galactic Wind
- R = Returned Fraction $R = \sum R_i Z_i$

$$\left\{\begin{aligned}
&\frac{dM_{tot}}{dt} = -c\psi &&\text{—— (1)}\\
&\frac{dM_G}{dt} = -(1-R+c)\psi &&\text{—— (2)}\\
&\frac{d(M_G Z_i)}{dt} = y_i\psi - (1-R_i+c)\psi Z_i &&\text{—— (3)}\\
&\frac{d(M_G Z_L)}{dt} = y_L\psi + \sum_j Z_j\left(\frac{A_L}{A_j}\right)\langle\sigma_{jL}\phi\rangle - (1-R_L+c)\psi Z_L &&\text{—— (4)}
\end{aligned}\right.$$

Stellar Production

GCR production

結論

☆超新星Rプロセスはプライマリー過程。金属量に依らない。

- 超金属欠乏星のすばる天文観測と合致。
- 教科書き換え→
「Rプロセスは高温・高密度状態で数秒間に進行する爆発的元素合成過程であり、ばらばらの中性子と陽子から始まる。安定な鉄族元素を必要としない。」

☆重い原子核の性質　S_n、τ_β、$\sigma(n,\gamma)$、$\sigma(\nu+A)$ ばかりでなく、軽い中性子過剰核の $\sigma(n,\gamma)$、$\sigma(\alpha,n)$が重要。

- Th/U、Th/Eu など核宇宙時計の精度を保つために、原子核反応率をさらに5%程度の精度で決定する必要がある。

☆ビッグバン元素合成（プライマリー過程）と共通点多く、宇宙論モデルを強く制限する。