IV International Summer School 2005
Center for Nuclear Study, University of Tokyo
August 18 – 23, 2005

Nucleosynthesis in Supernovae and the Big-Bang (I)

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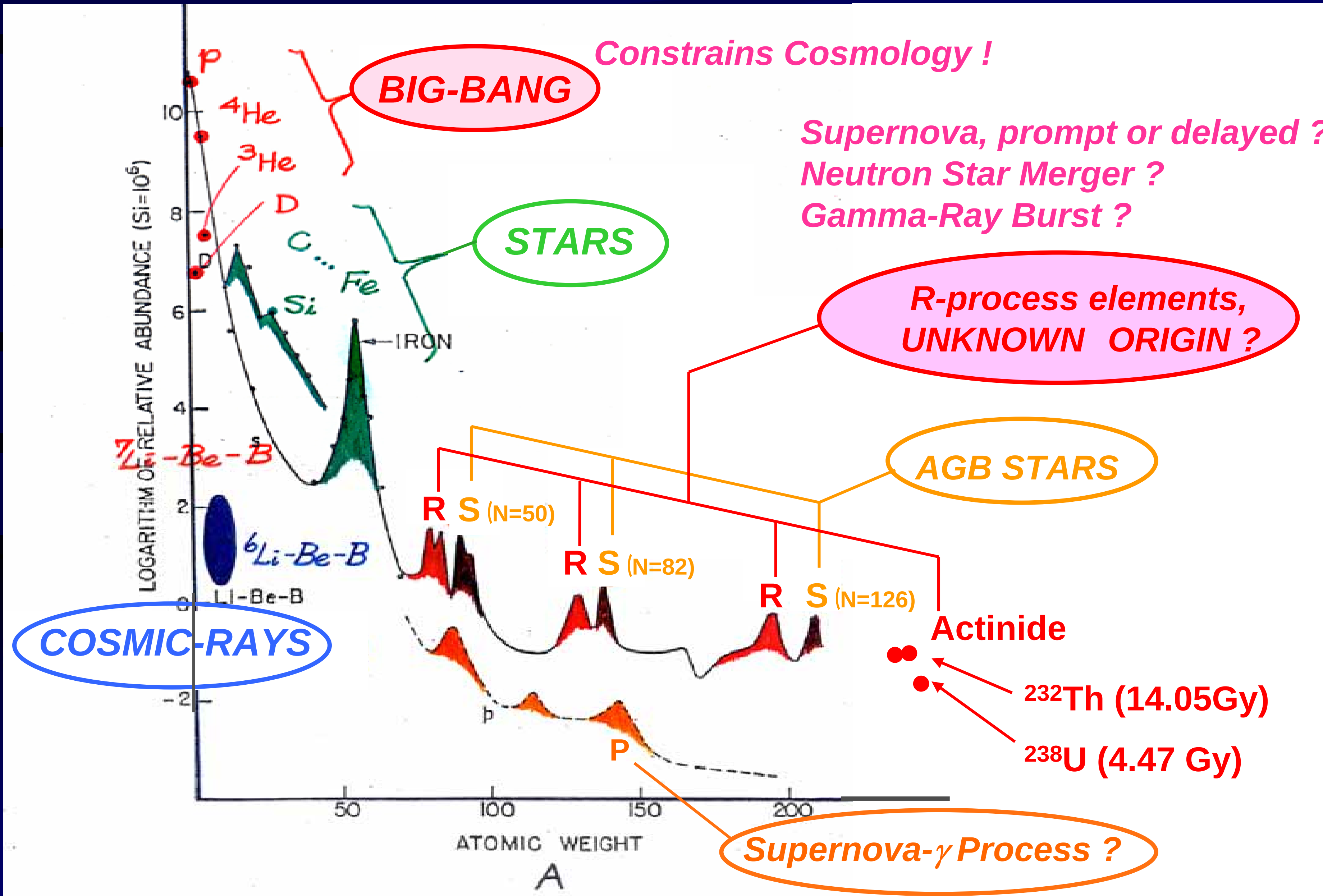
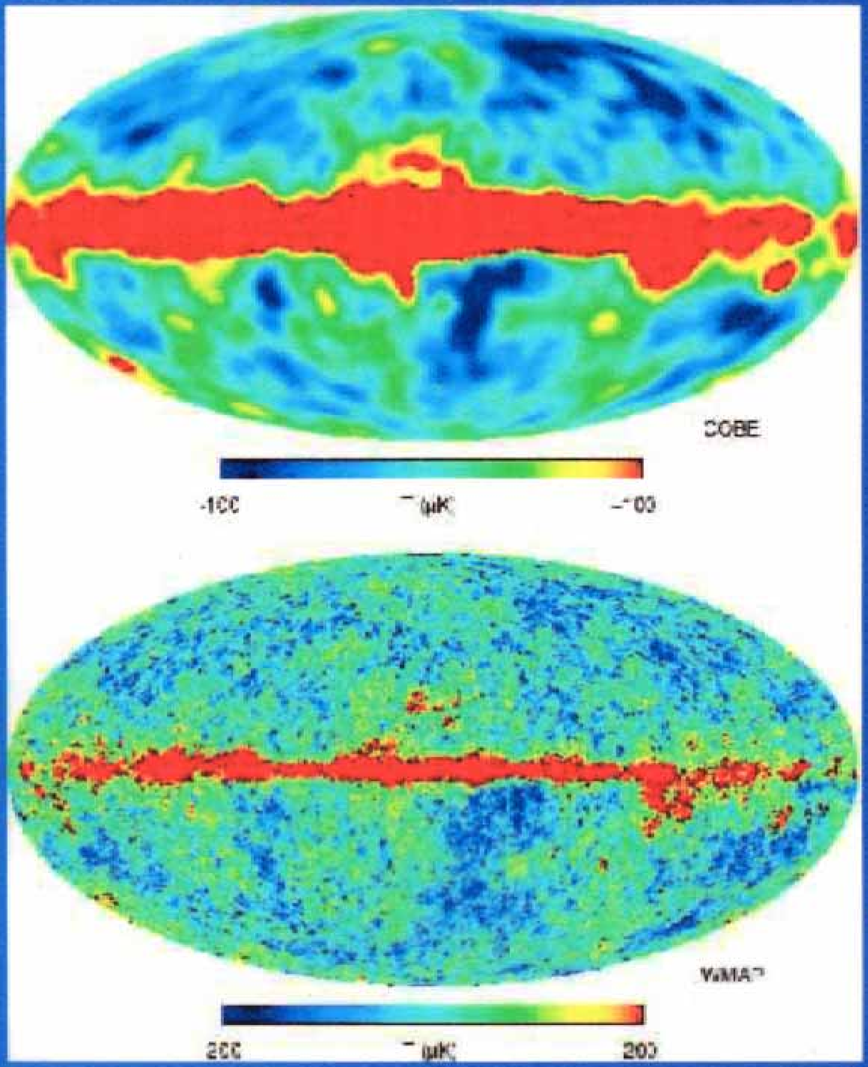
Solar System Abundance



Newest CMB Results

Spergel et al. 2003, ApJS, 148, 175.



WMAP determined all cosmological parameters?

Model dependent !

$$t_0 = 13.7 \pm 0.2 \text{ Gyr}$$

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

$$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_{tot} = 1.02 \pm 0.02$$

$$w_\Lambda < -0.78$$

- **Only 4.4% baryons are known.**
- **What is Ω_m or Ω_Λ ?**

OUTLINE

Universe is likely flat and accelerating!

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

Six (eleven) Parameters !

- **Is BARYON, $\Omega_B = 0.04$, consistent with Big-Bang Cosmology and Nucleosynthesis ?**

CANDLE of dark side of the Universe !!

- **What is the nature of CDM, $\Omega_{CDM} = 0.26$?**

  Disappearing CDM Model in Brane World Cosmology !
  Ichiki, Garnavich, Kajino, Mathews & Yahiro, PRD 68 (2003) 083518

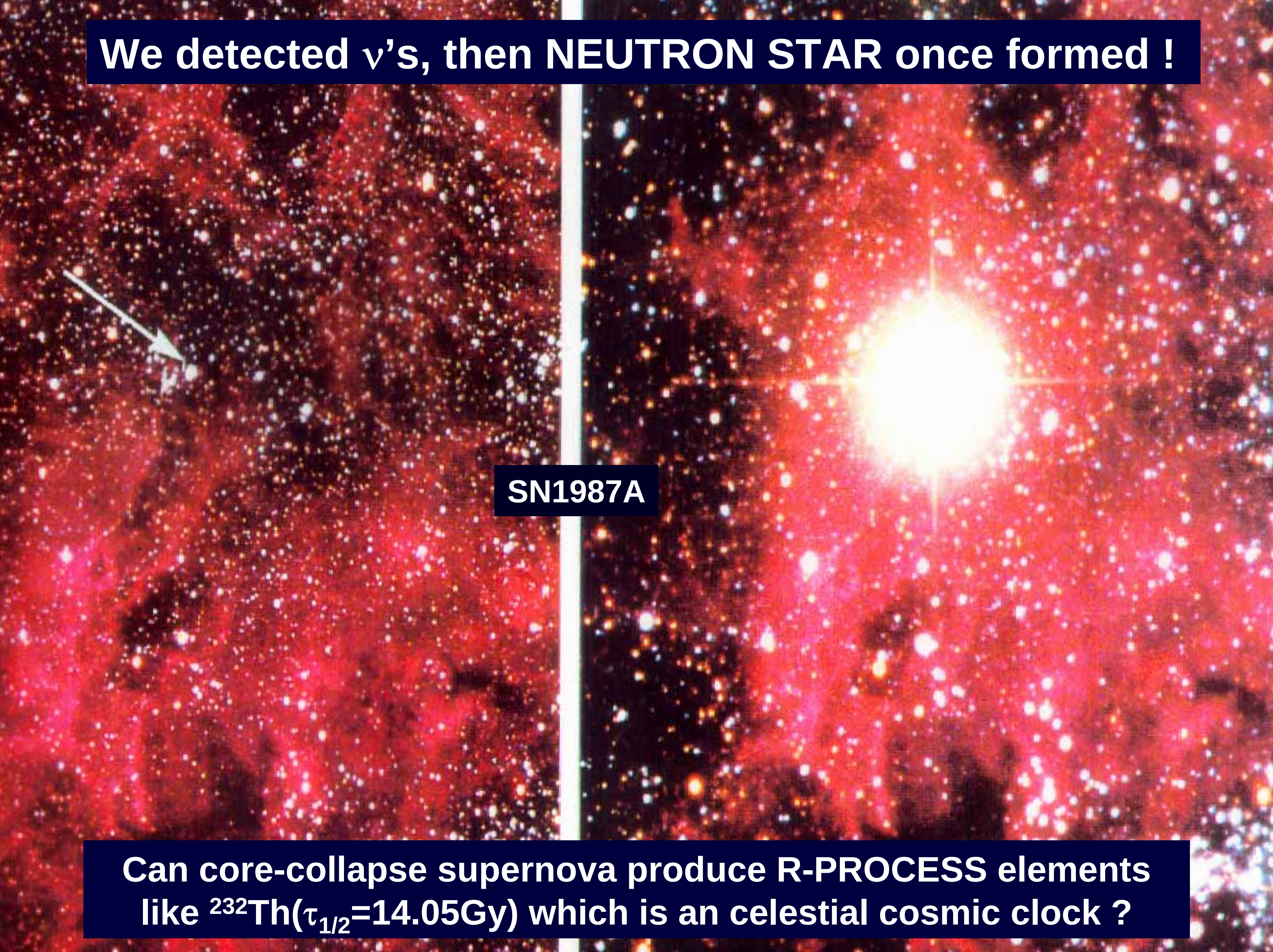
- **What is DARK ENERGY, $\Omega_\Lambda = 0.7$?**

  Growing CDM Model in Brane World Cosmology !
  Umezu, Ichiki, Kajino, Mathews Nakamura & Yahiro,(2005) (astro-ph/0507227)

- **COSMIC AGE (13.7 +- 0.2 Gy), strongly model-dependent ?**

  Supernova R-Process & Origin of ^{232}Th, ^{235,238}U ! --- model-independent !?

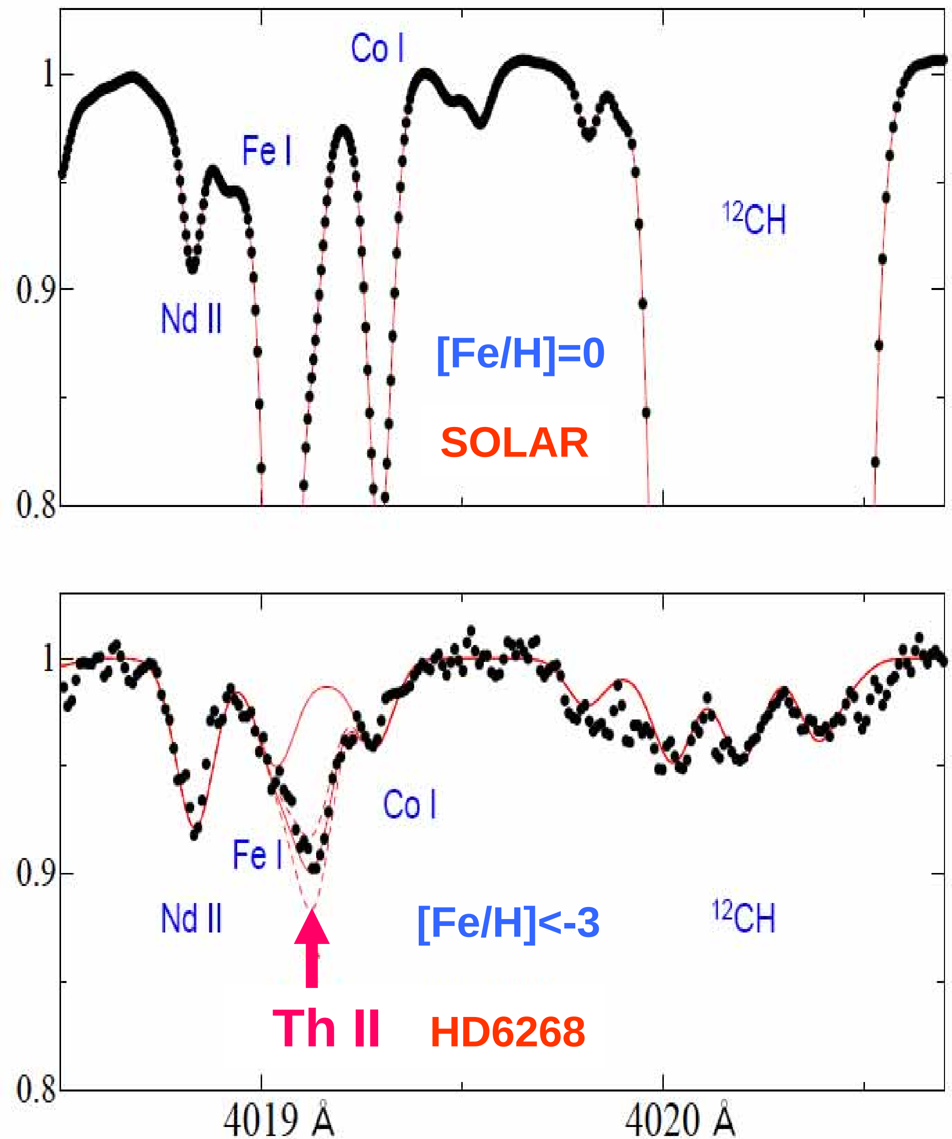
We detected ν's, then NEUTRON STAR once formed !



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

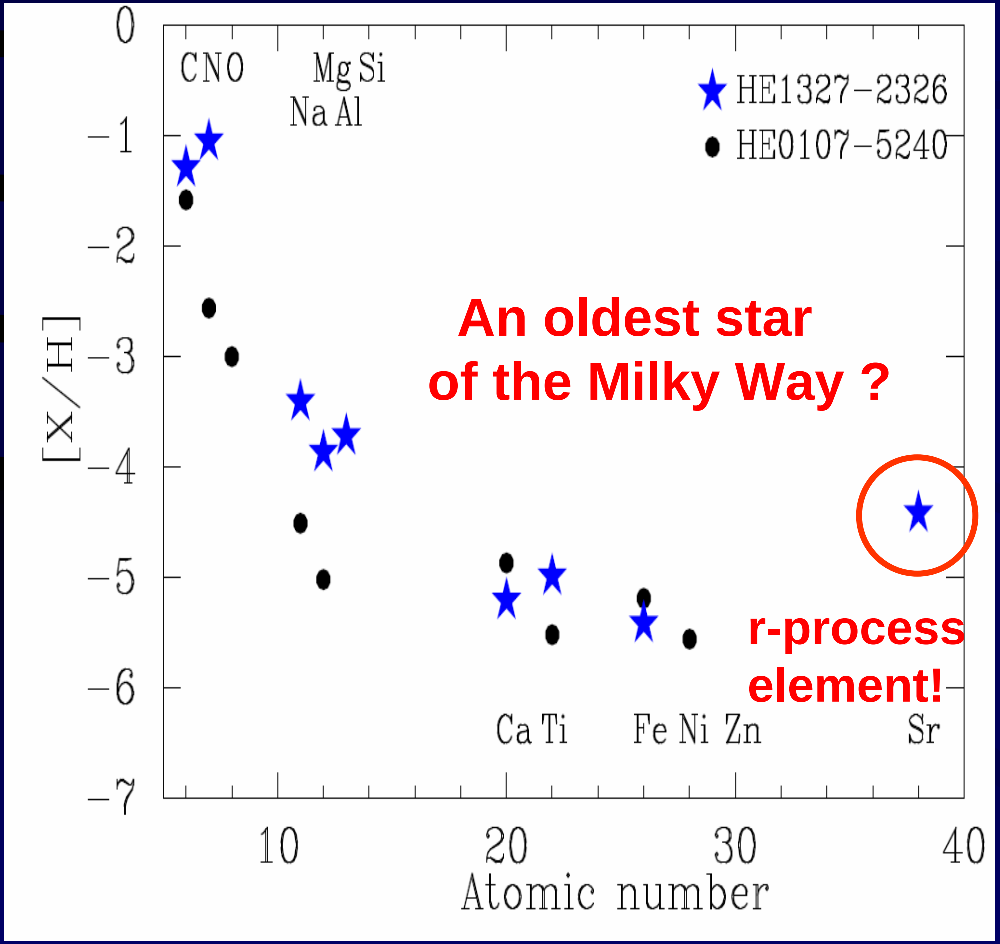
Subaru Telescope

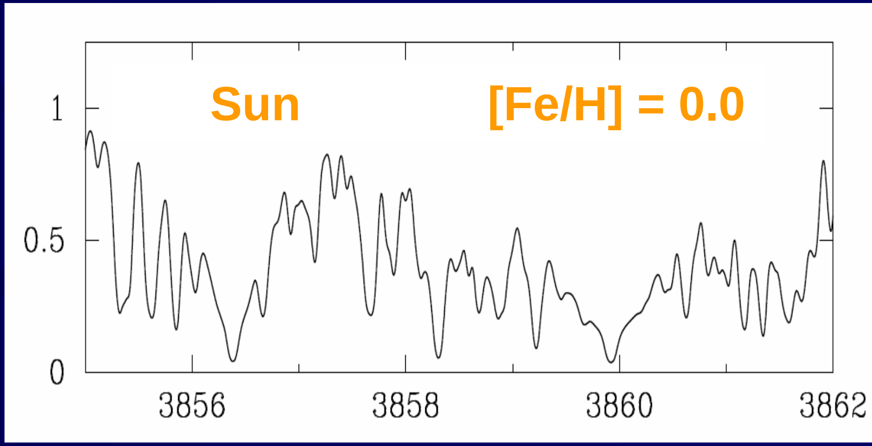
OBSEVES Extremely Metal-Deficient Stars

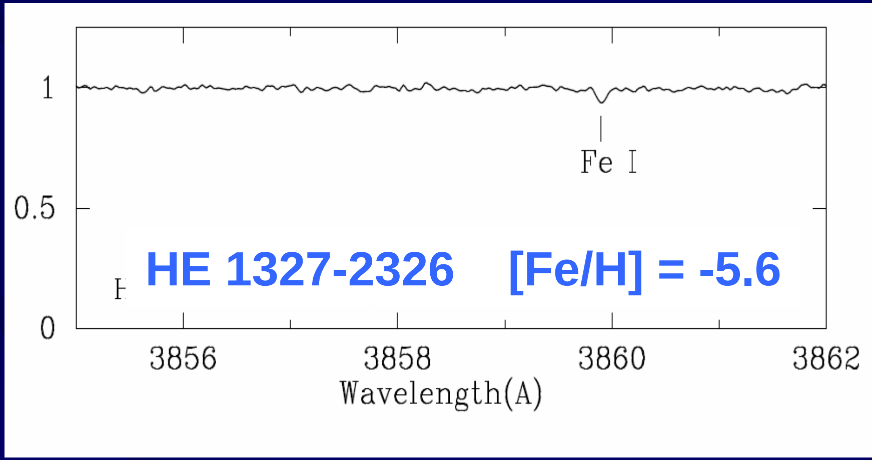


Discovery of Most Metal-Deficient Star HE1327-2326 using SUBARU Telescope

Frebel, Aoki, Kajino ＋SUBARU/HDS Collaboration
NATURE 434 (2005), 871

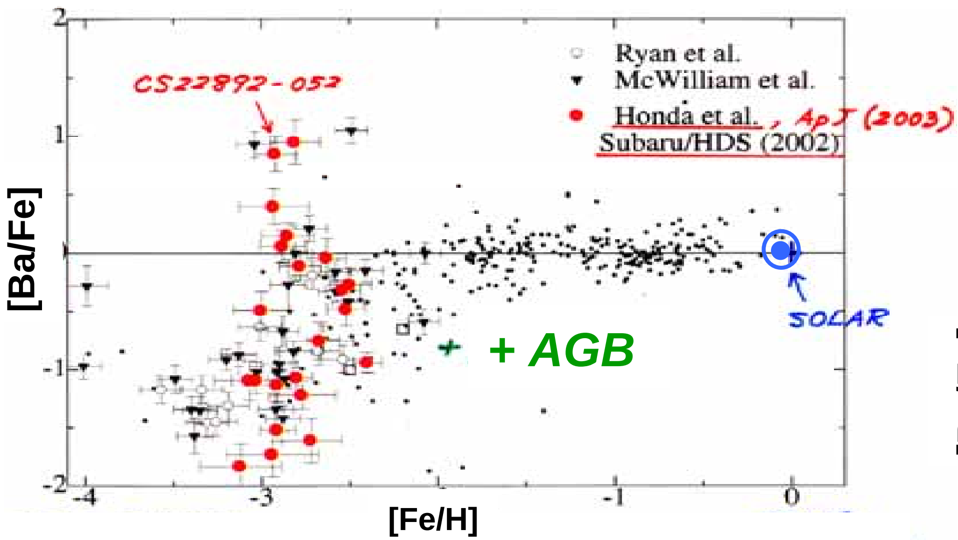




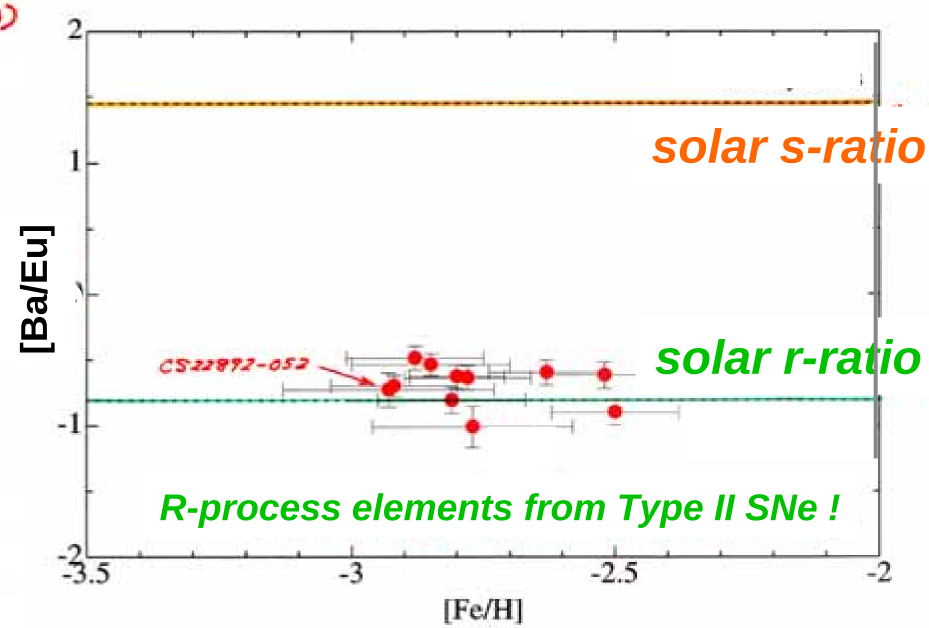


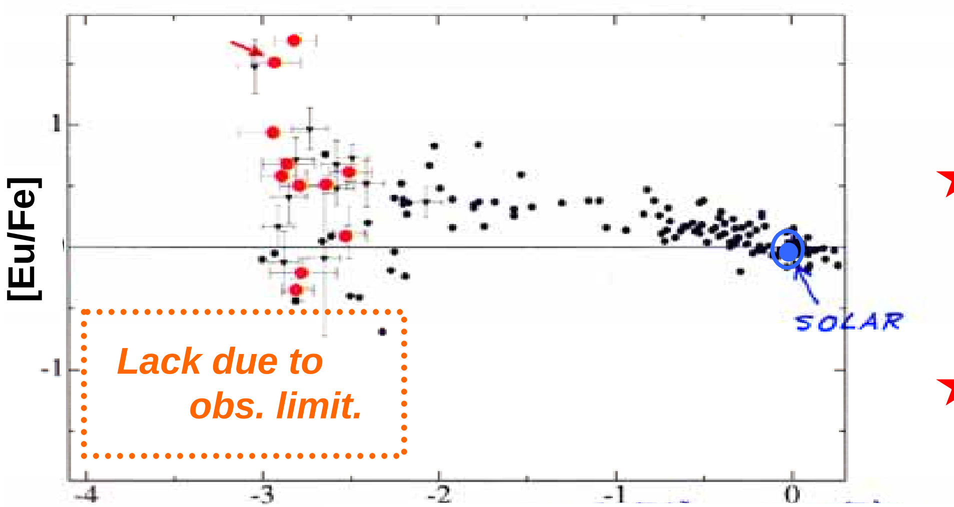
SUBARU Telescope HDS

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



SN II ⟷ SN I + II





Early Galaxy

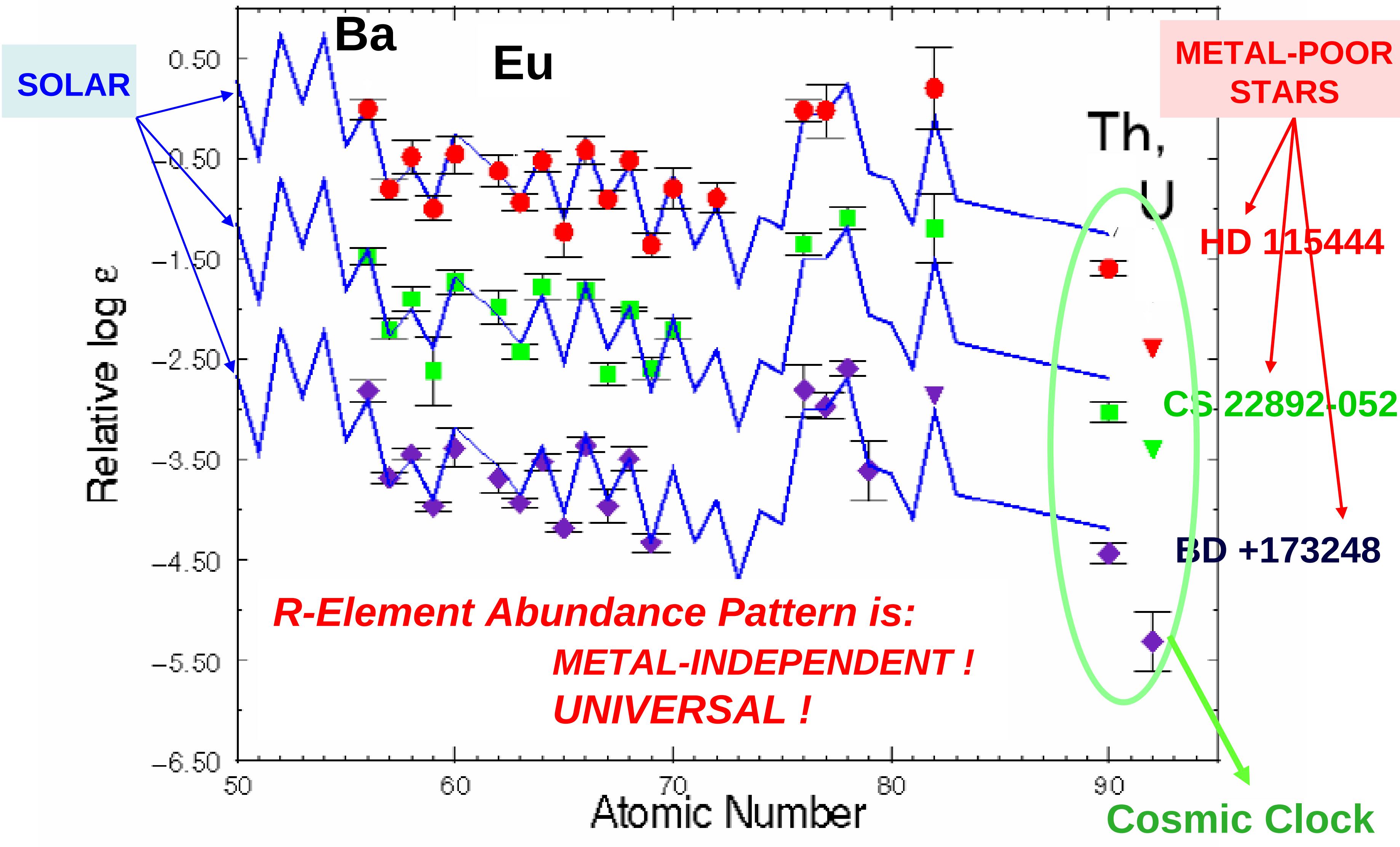
$[Fe/H] = \log(N_{Fe}/N_H)_{\star} - \log(N_{Fe}/N_H)_{\odot}$

★ 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 !

UNIVERSAL SCALING OF R-PROCESS ABUNDANCES

C. Sneden et al. (1996 – 2005)



Modeling Supernova R-Process

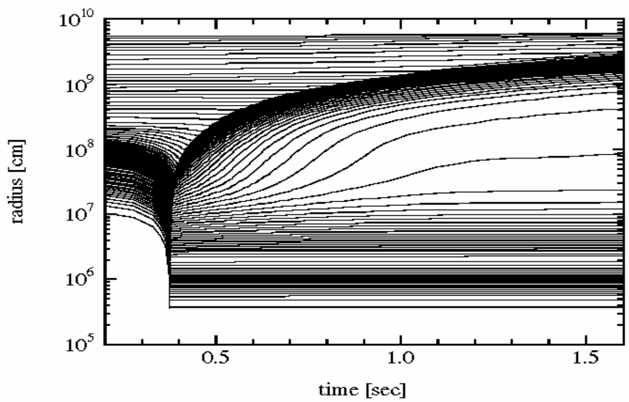
Supernovae are the most spectacular events
since the Big-Bang,
yet they are still poorly understood in their dynamics.

Details are important.

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

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

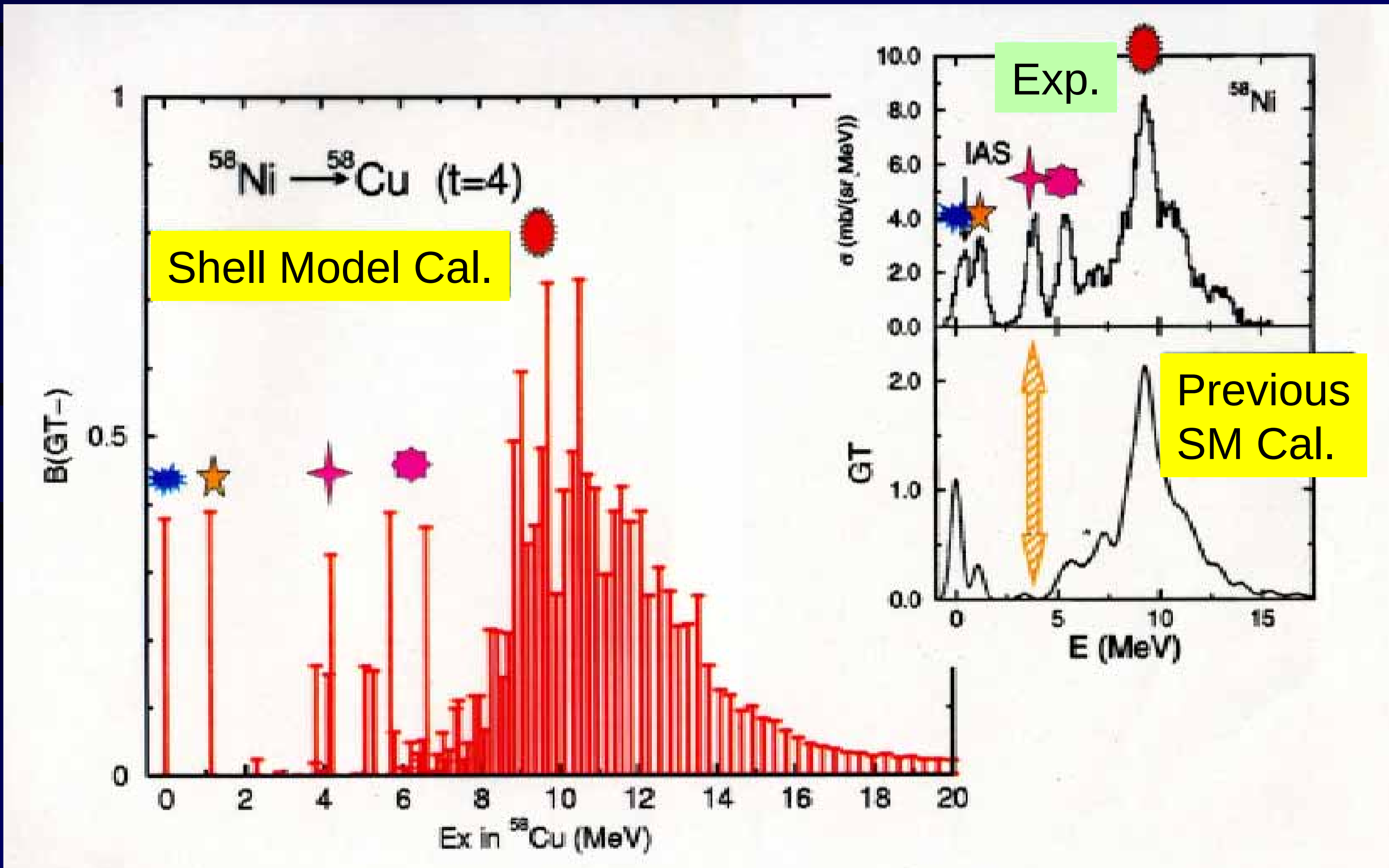
- Stars with $M \sim 10 - 40\ M_{\odot}$ build up an Fe/Ni core.
  Maximum core size $M_{ch} = 5\ Y_e^2\ M_{\odot} \sim 1.3\ M_{\odot}$ (Electron Capture).
- Collapse Separates,
  inner homologous ($v \propto r$) core = $1.1\ M_{\odot}$.
  outer slowly collapsing core = $0.2\ M_{\odot}$.

The central density increases and reaches nuclear matter density,
$\rho_{nucl} \sim 2\text{x}10^{14}$ g cm^{-3} (Nuclear EOS).

Gamow-Teller (β-decay) Strength Distribution of ^{58}Ni

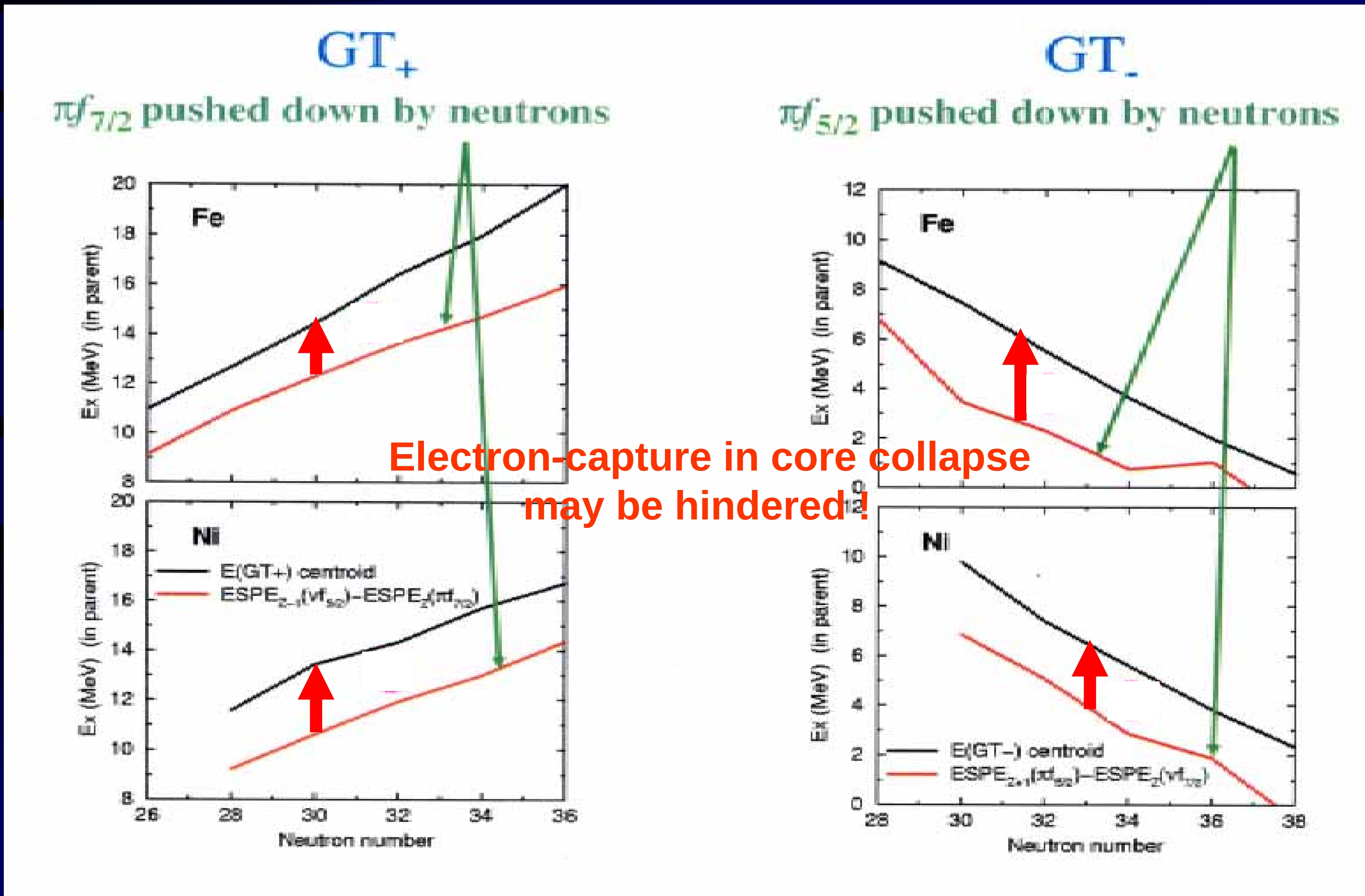
Monte Carlo Shell Model Cal.: Honma-Otsuka (2005)

Experiment: Rapaport (1983), NP A410, 371.



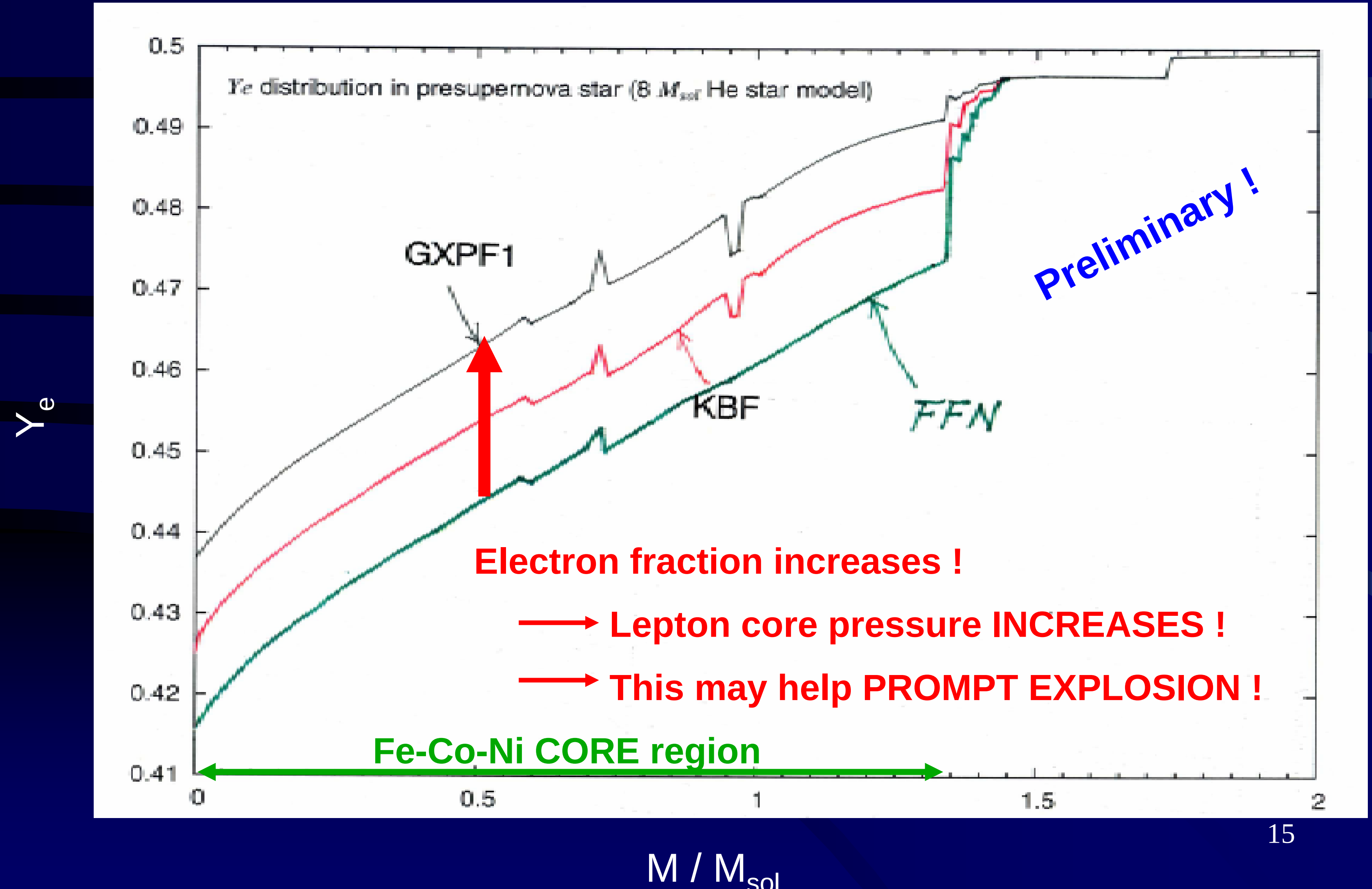
GT centroid energy raised by two-body interaction

Monte Carlo SHELL MODEL calculation: Honma & Otsuka (2005)



Expected Effect on Core-Collapse Supernovae

Pre-Supernova Calculation: Yoshida and Kajino (2005)



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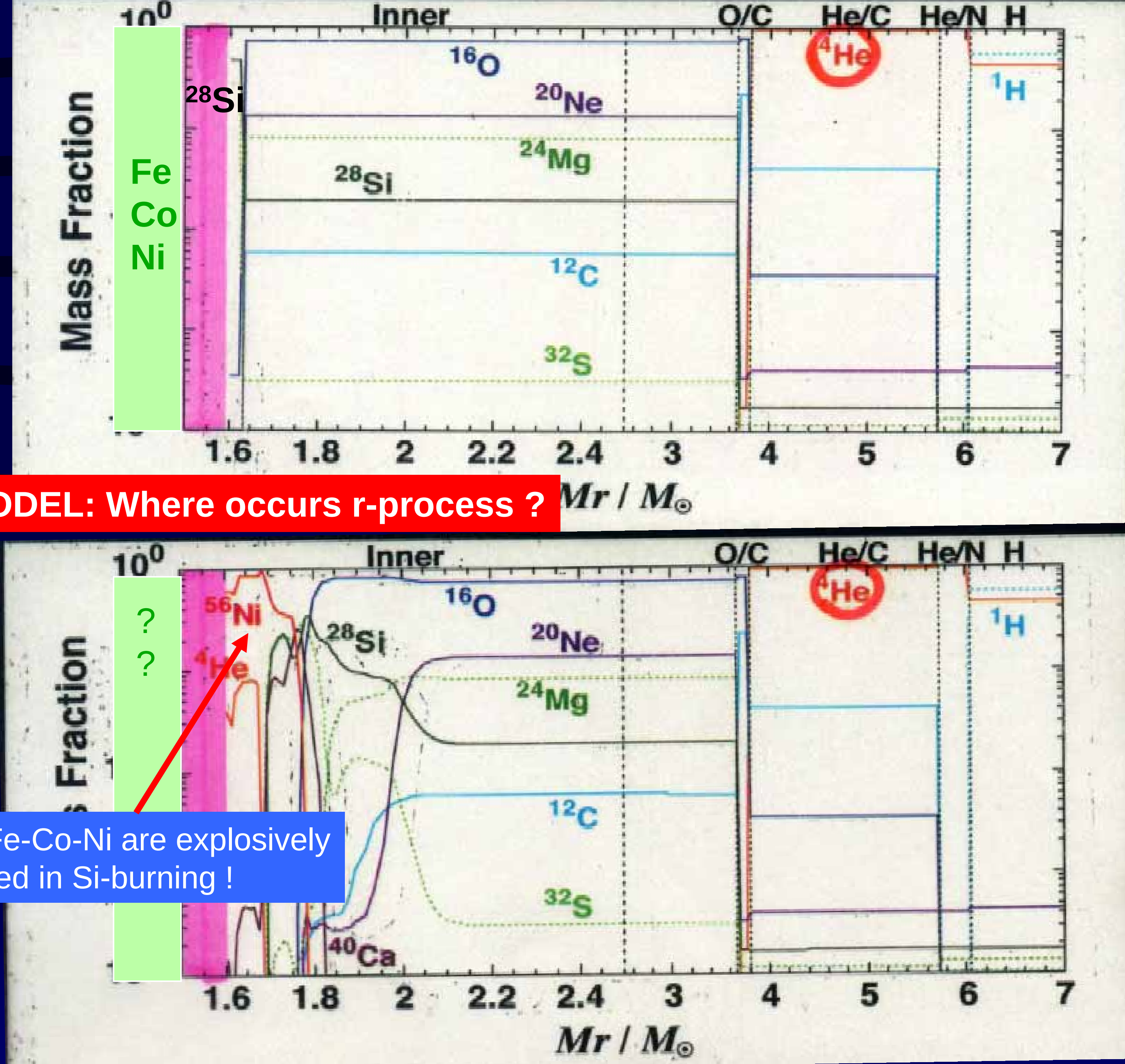
The central density increases and reaches nuclear matter density,
$\rho_{nucl} \sim 2\times10^{14}$ g cm^{-3} (Nuclear EOS).

- 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 deposite 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).

Before Explosion



SN1987A MODEL: Where occurs r-process ?

After Explosion

Ejected Fe-Co-Ni are explosively reproduced in Si-burning !

Core-Collapse and ν-Heating

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

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

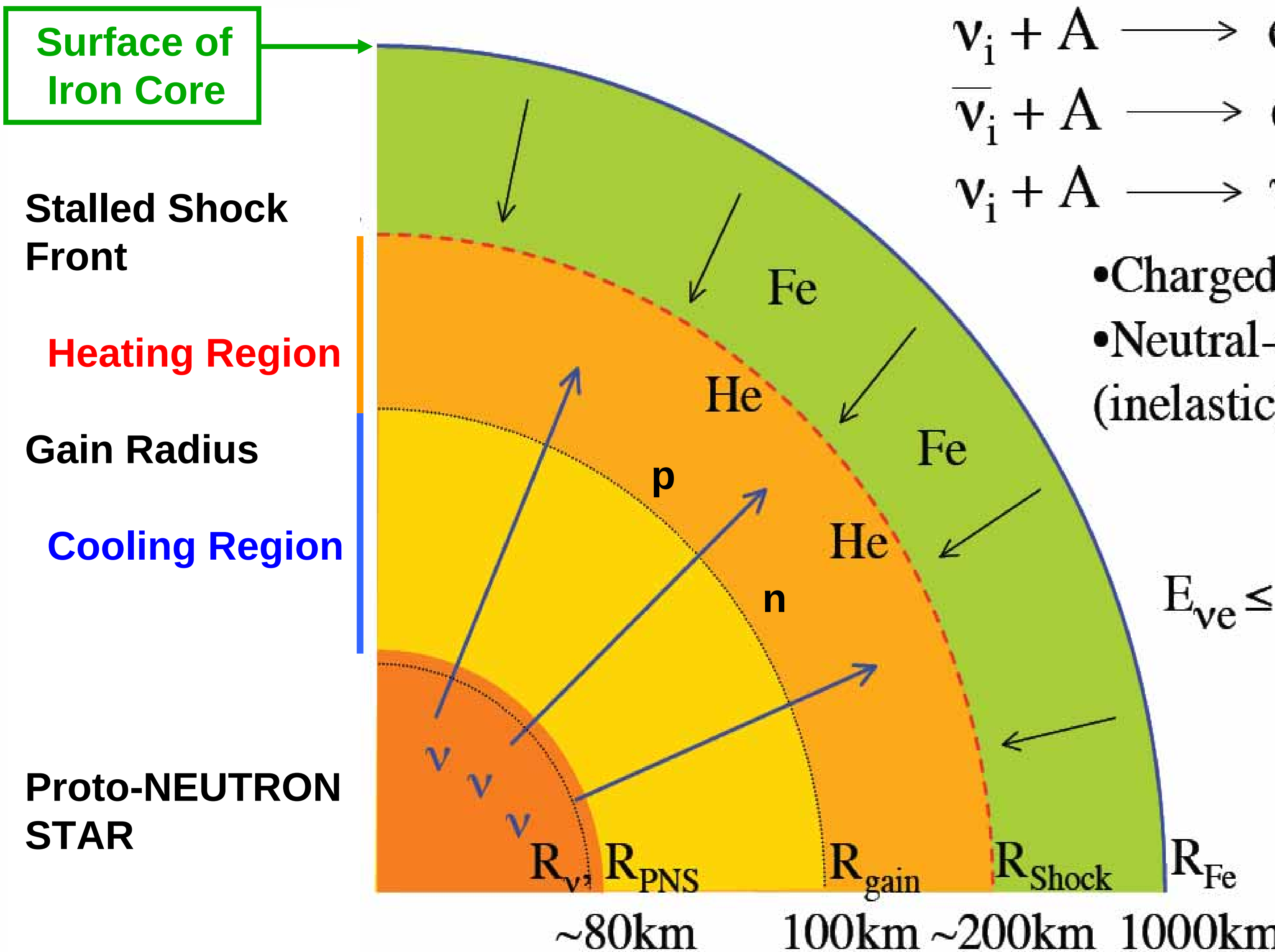
$$\nu_i + A \longrightarrow e^- + A'$$

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

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

- Charged-current
- Neutral-current (inelastic)

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



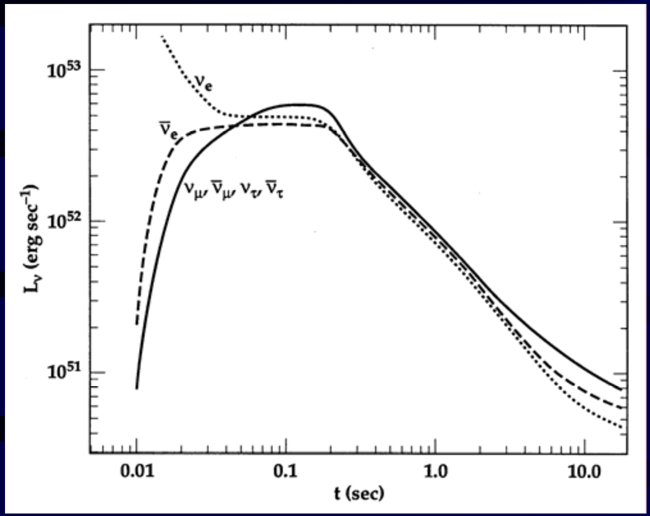
Supernova Simulations First 300 ms: A. Burrows

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

→ 10 km

300 km

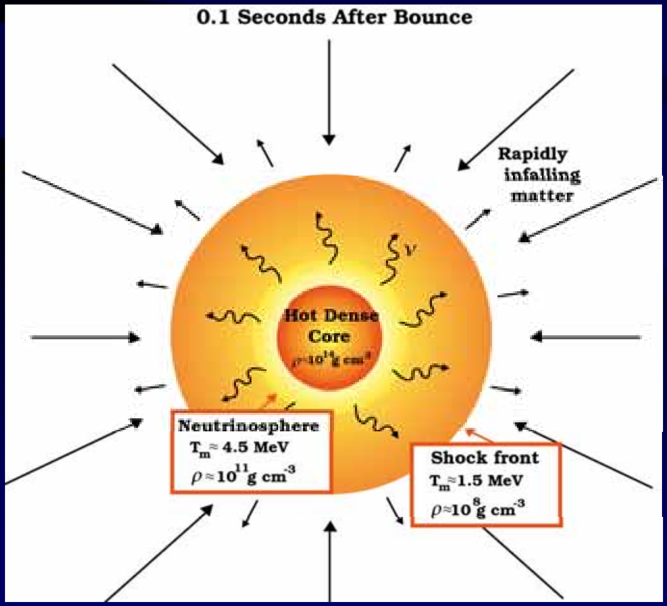
Neutrino Heated Bubble forms

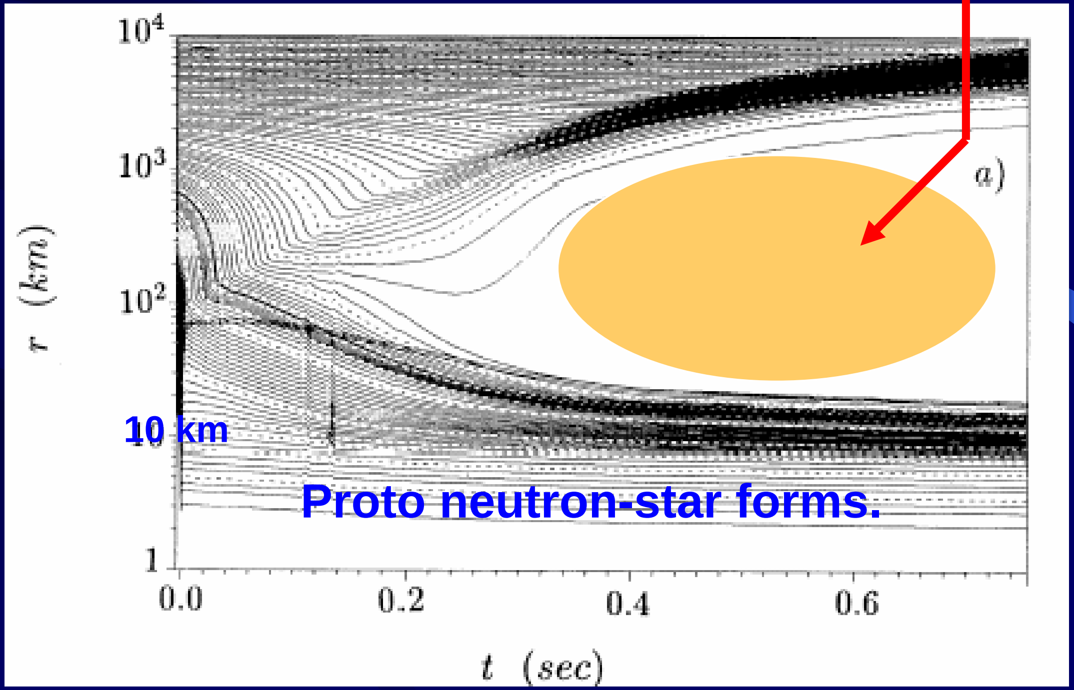


Neutrino Luminosity ~10^{53} erg/s

Neutrino Heating produces a high entropy bubble.

Woosley et al. 1994, ApJ 433, 229





General Relativistic Models of ν-Driven Winds

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

spherically symmetric, steady state winds in Schwarzschild geometry.

$$\dot{M} = 4\pi r^2 \rho_b u = \text{const}$$: mass ejection rate

$$u\frac{du}{dr} = \frac{1}{\rho_{tot} + P}\frac{dP}{dr}\left(1 + u^2 - \frac{2M}{r}\right) - \frac{M}{r^2}$$: equation of motion

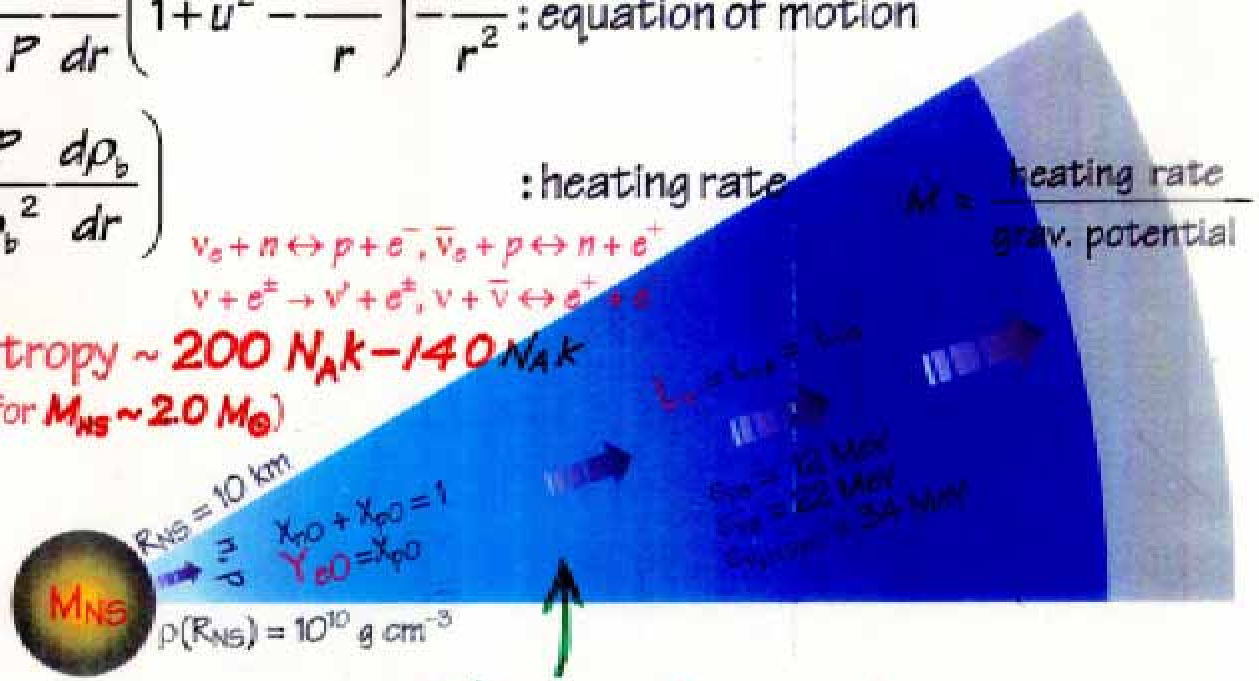
$$\dot{q} = u\left(\frac{d\varepsilon}{dr} - \frac{P}{\rho_b^2}\frac{d\rho_b}{dr}\right)$$: heating rate

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

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

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

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



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

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

Given **T** & ρ :

$$\frac{dn_A}{dt} = -\sum_{jkl} \langle \sigma v \rangle_{Aj \to kl}\, n_A n_j + \sum_{kl} \langle \sigma v \rangle_{kl \to Aj}\, n_k n_l + (\text{THREE BODY \& HIGHER TERMS})$$

Nuclear Reactions

$$- \frac{\ln 2}{T_{1/2}(\beta)}\, n_A$$

β-decays

$$+ (\text{OTHERS})$$

$$+ \vec{\nabla} \cdot D_A \vec{\nabla} n_A$$

Diffusion

Thermonuclear Reaction Rate

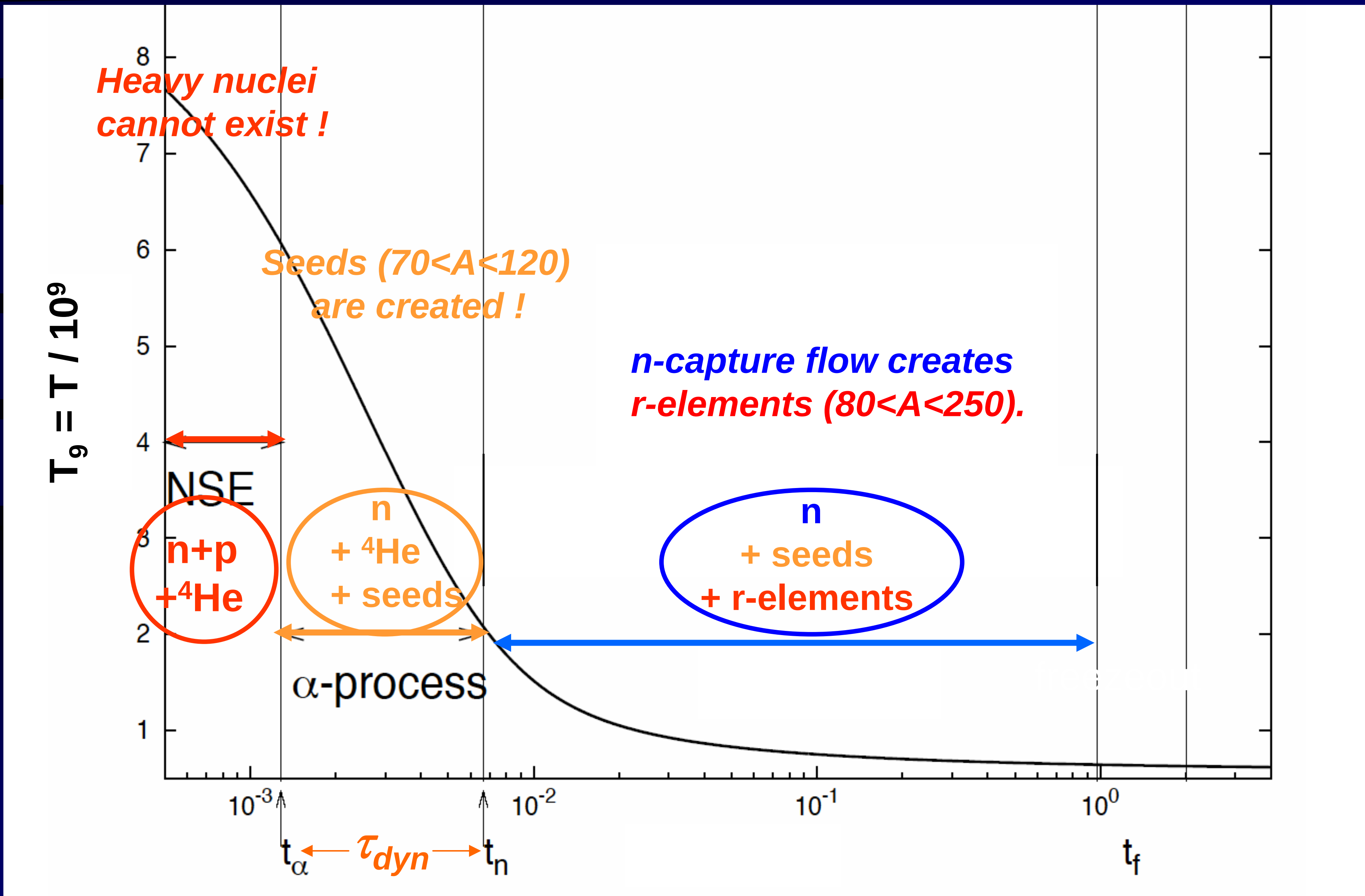
$$\tau_i^{-1} \equiv \rho_B N_A \langle \sigma v \rangle_{ij \to kl}$$

Boltzmann average

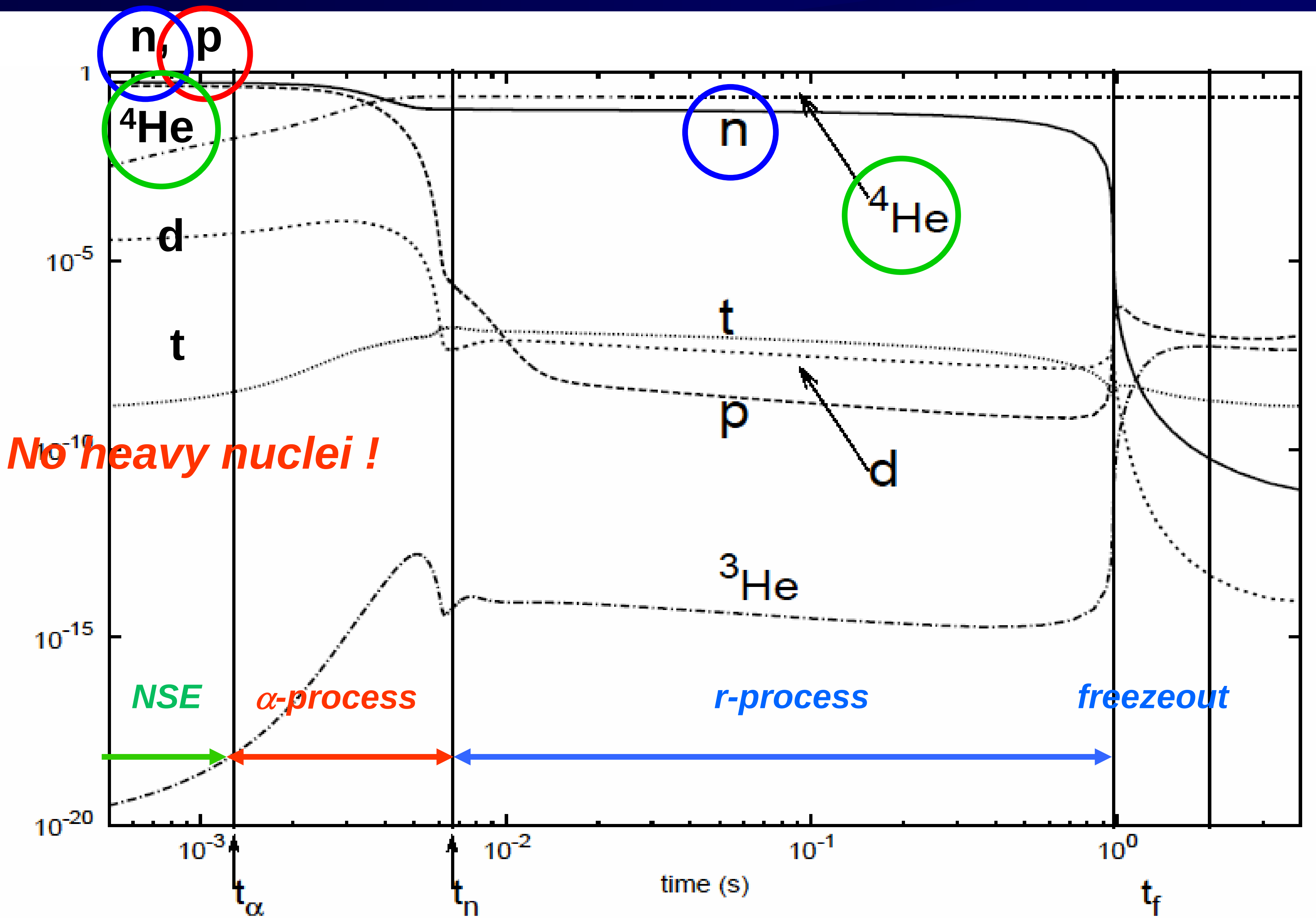
$$= \rho_B N_A \sqrt{\frac{8}{\mu \pi}}\, \frac{1}{(kT)^{3/2}} \int_0^{\infty} E\, \sigma_{ij \to kl}(E)\, \exp(-E/kT)\, dE$$

Cross Section

Neutrino-Driven Wind Model: 1D-Hydro. Steady-Flow



Nucleosynthesis in SN ν - Driven Wind



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

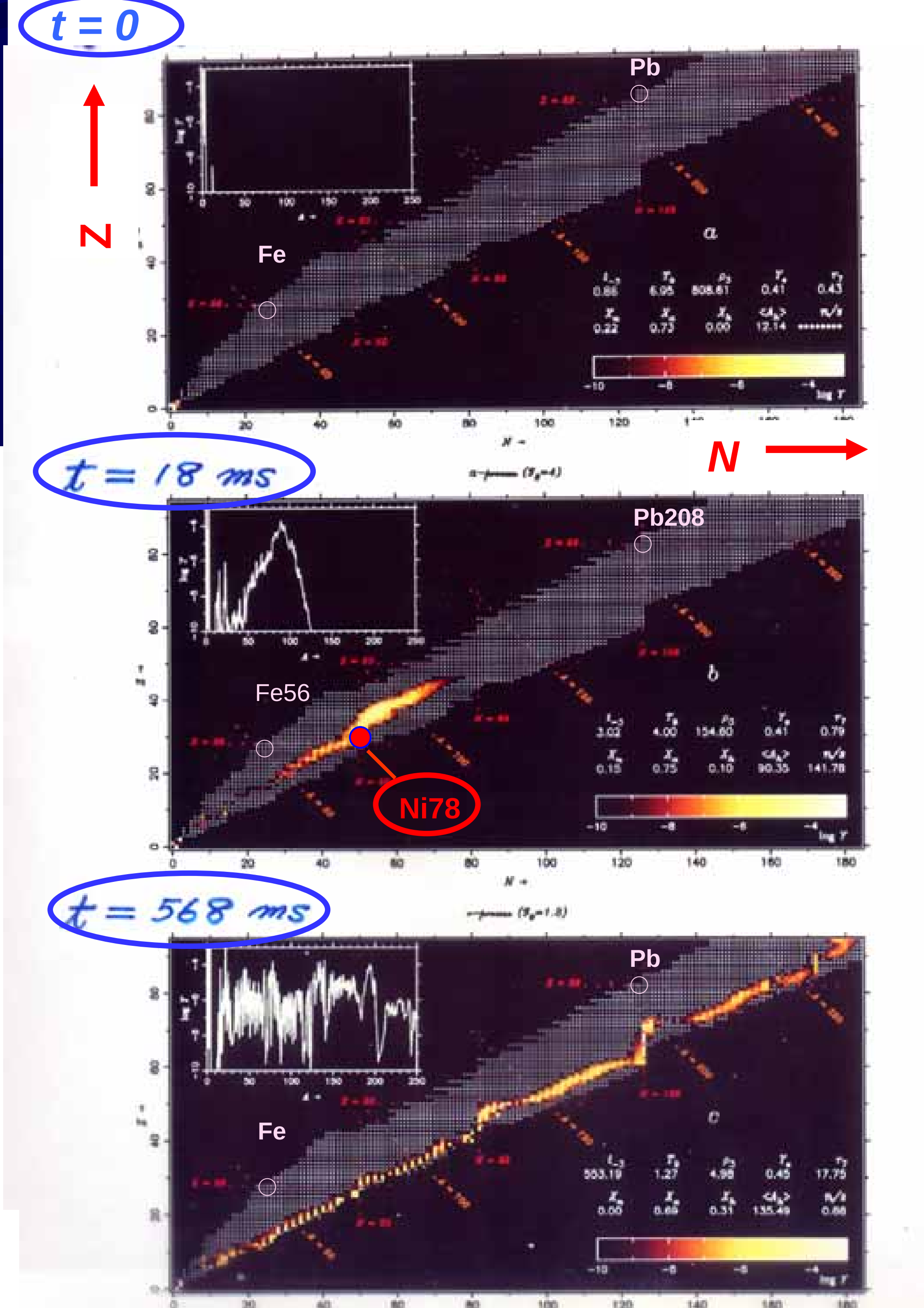
Seeds form.

Exotic neutron-rich ^{78}Ni

↓

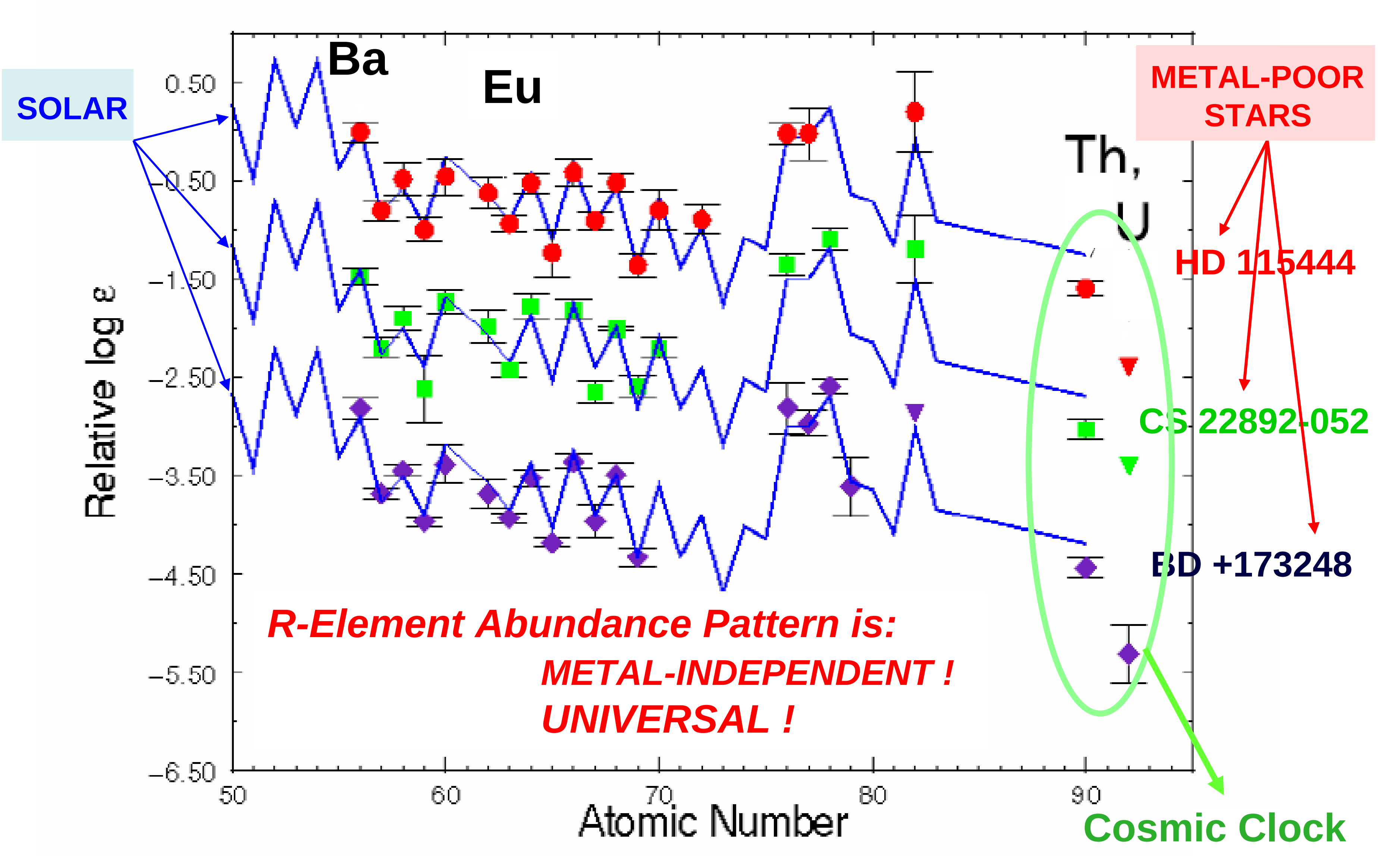
t = 568 ms – 1 s

Heavy r-elements synthesize.



UNIVERSAL SCALING OF R-PROCESS ABUNDANCES

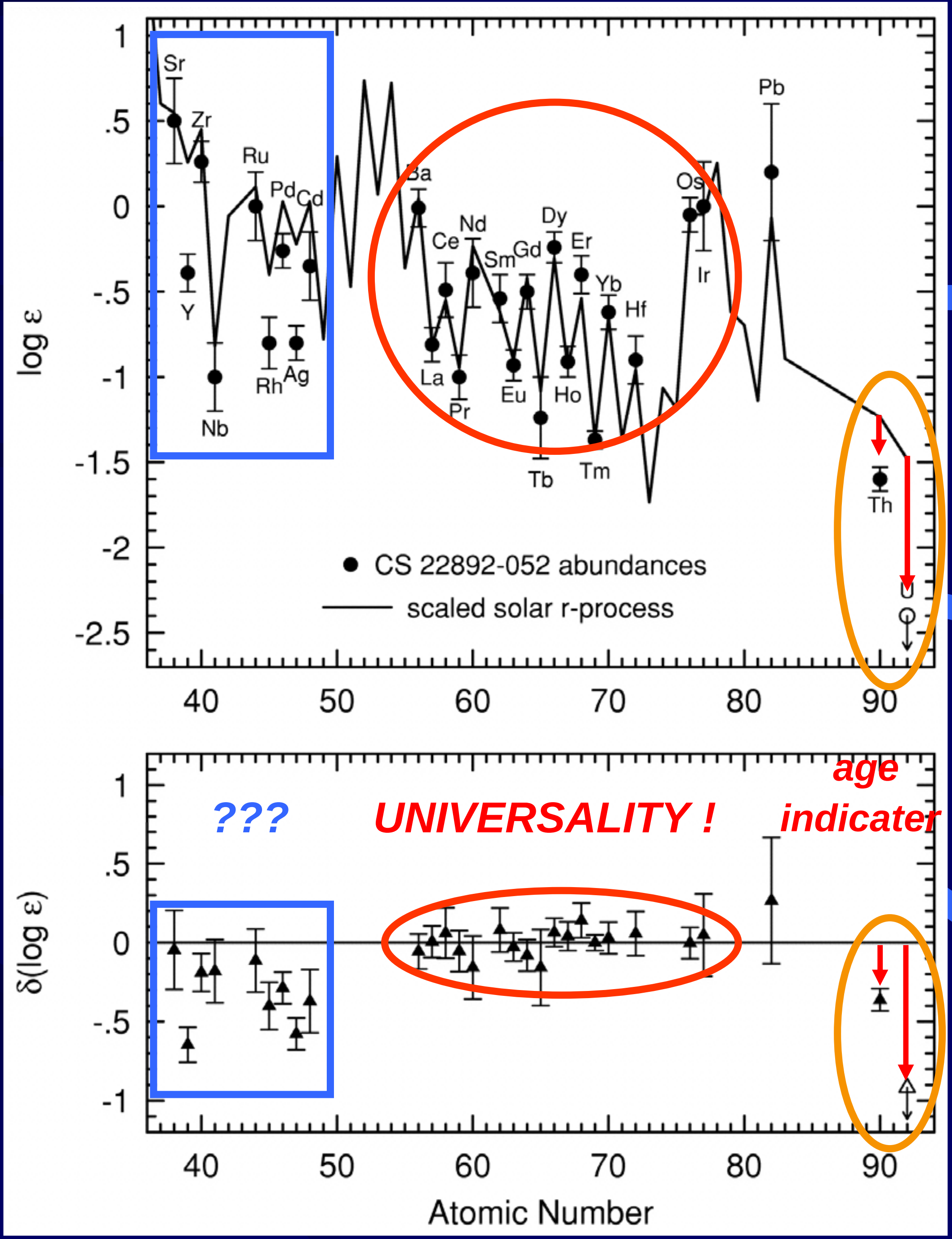
C. Sneden et al. (1996 – 2005)



Universal Abundances

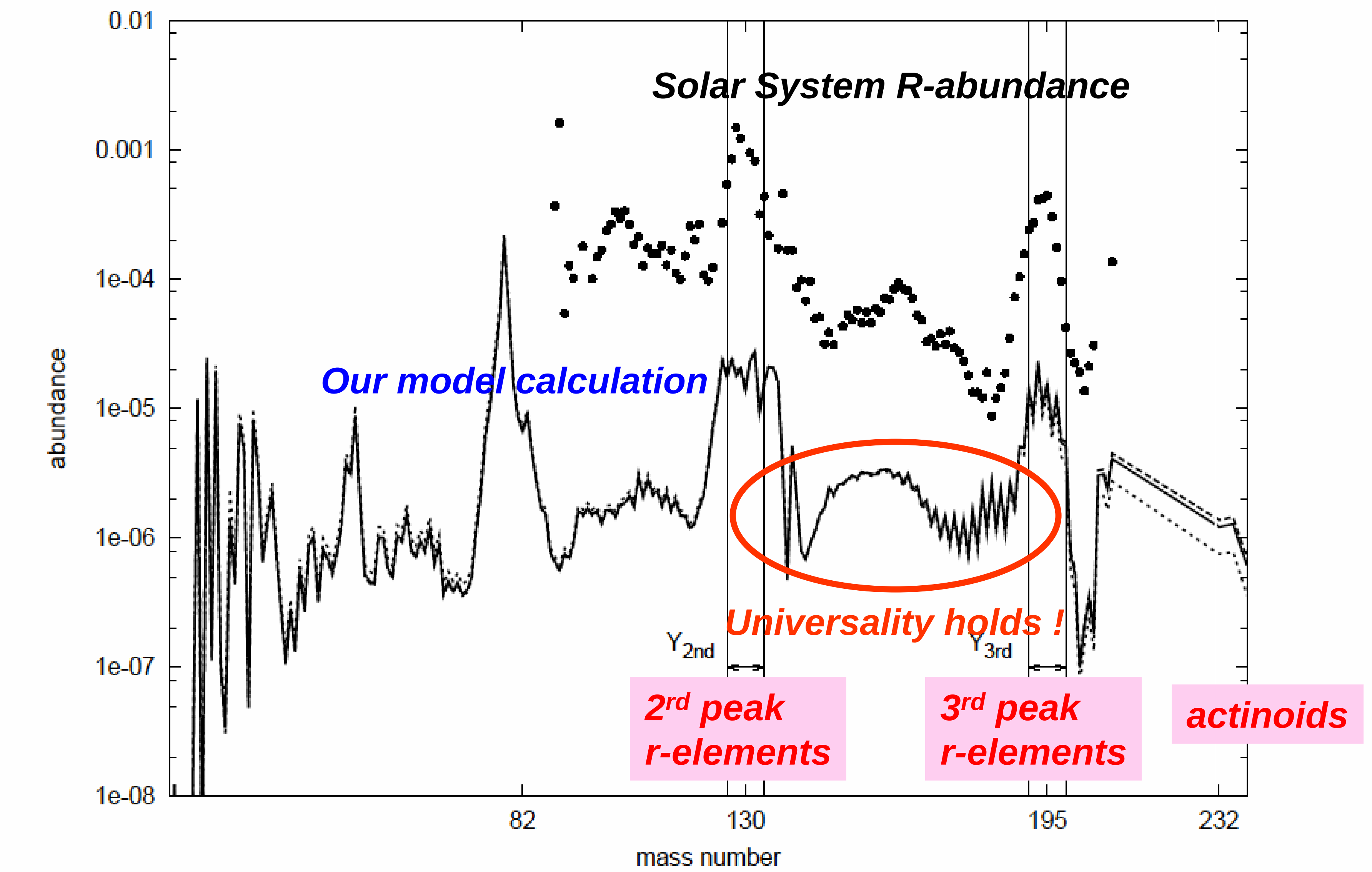
C. Sneden et al. (1996 – 2005)

- Universality applies
  only for 56 < Z < 75 !
- Z < 56 : Large Dispersion
  - Two r-processes?
  - Different Conditions at early times?
  - Another process?
- Z > 75 uncertain?
  Nuclear Physics?
  BH vs. NS formation?

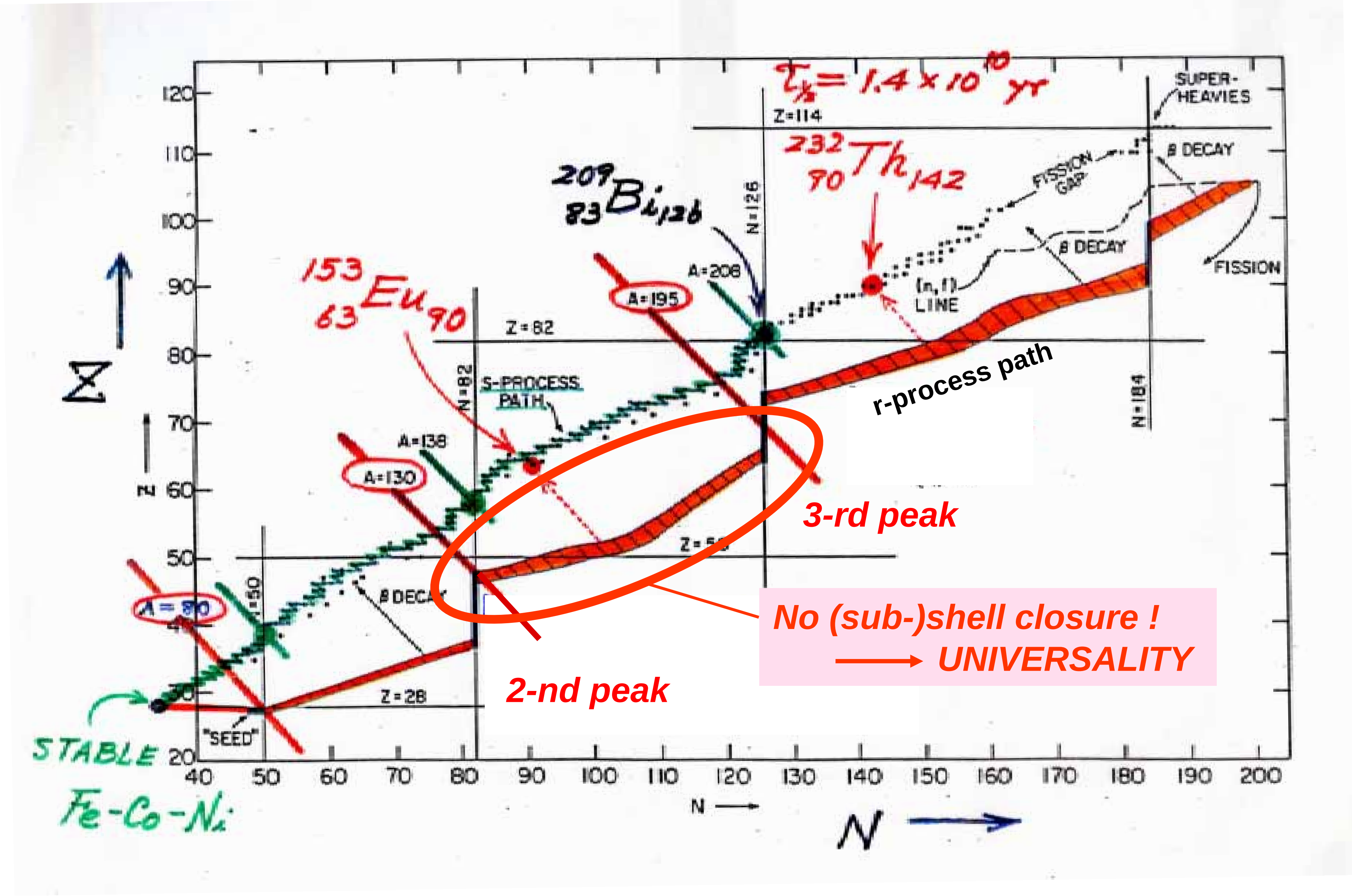


R-Process Yields in Type-II SN ν-Driven Wind Model

Sasaqui, Kajino, Mathews, Otsuki, & Nakamura 2005, ApJ, in press.

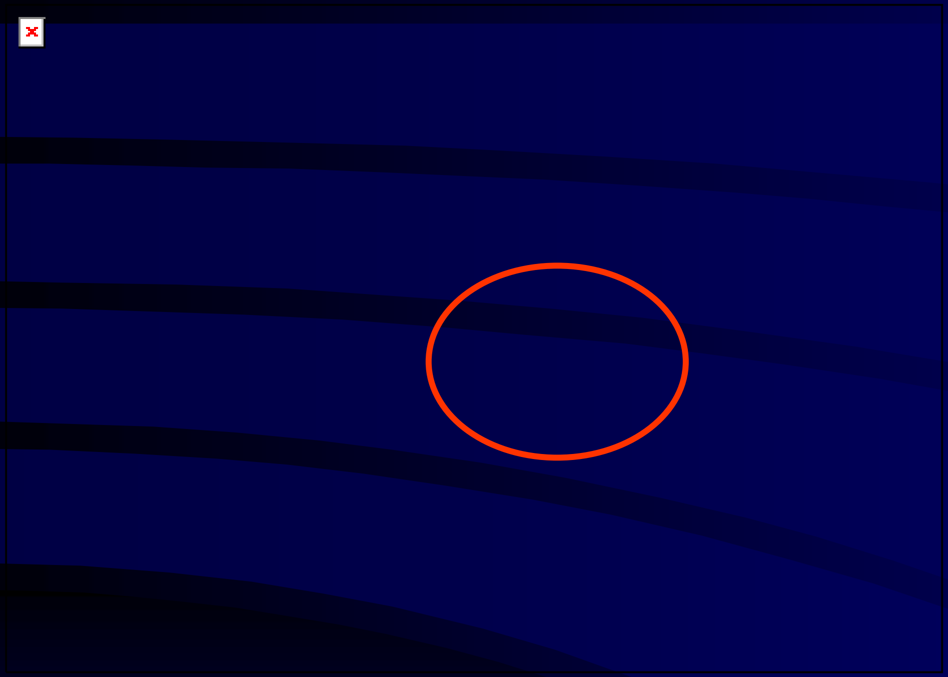


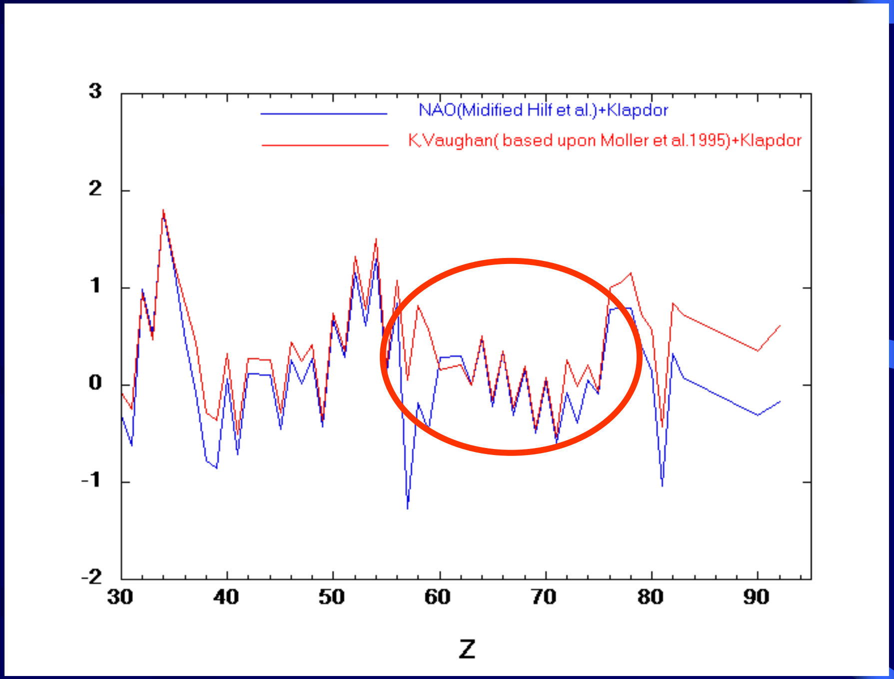
Nuclear Physics Origin of Universality



Dependence upon Nuclear Input

Otsuki, Mathews & Kajino 2003, NewA 8, 767





Different beta-decay rates

Different Mass Formulae

Abundance pattern is most sensitive to the beta-decay rate.

PRIMARY PROCESSES

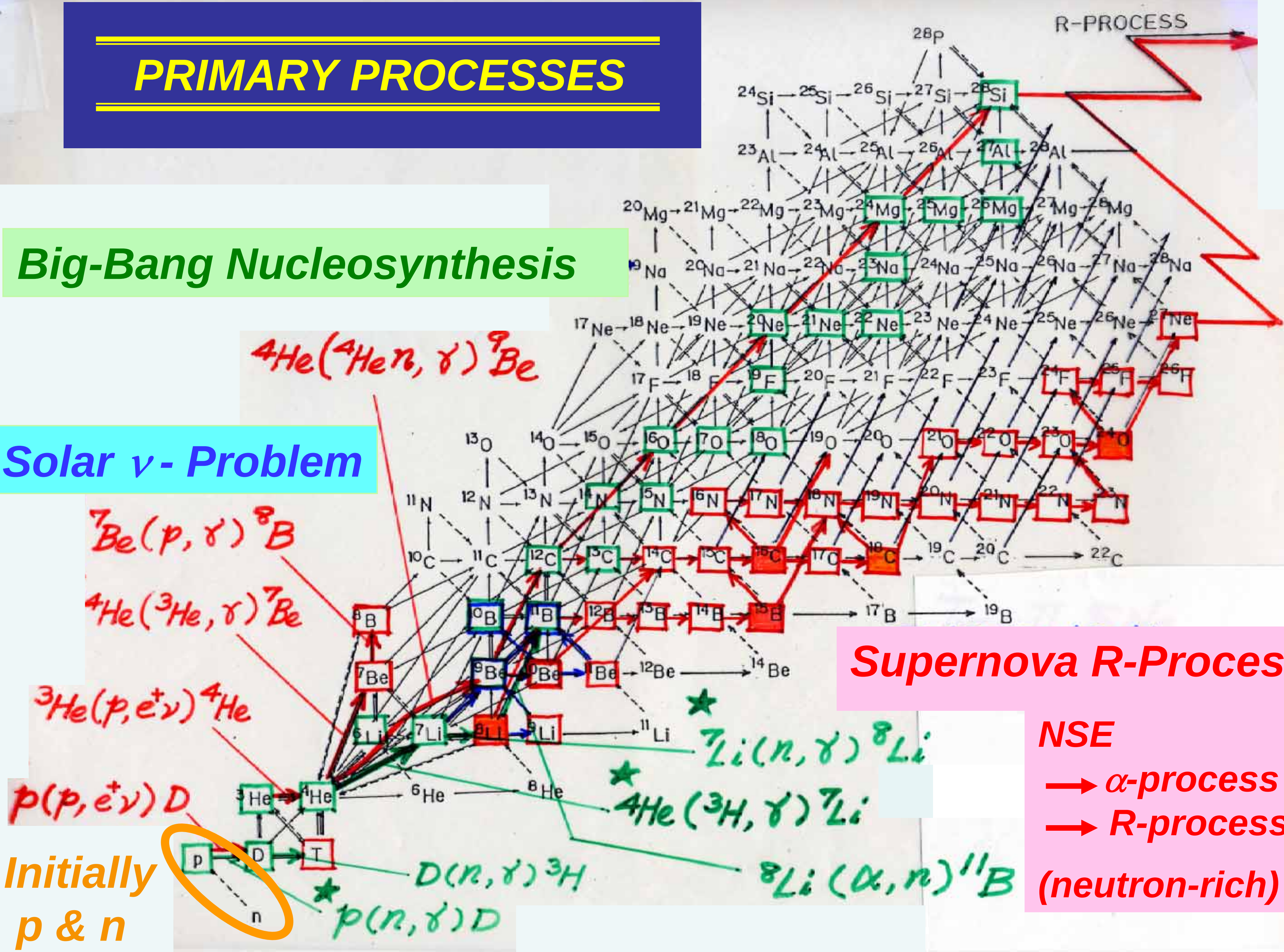
Big-Bang Nucleosynthesis

Solar ν - Problem

Supernova R-Process

NSE
→ α-process
→ R-process
(neutron-rich)

Initially p & n



Reaction Sensitivity

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

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

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

Power Index
Sensitivity Parameter

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

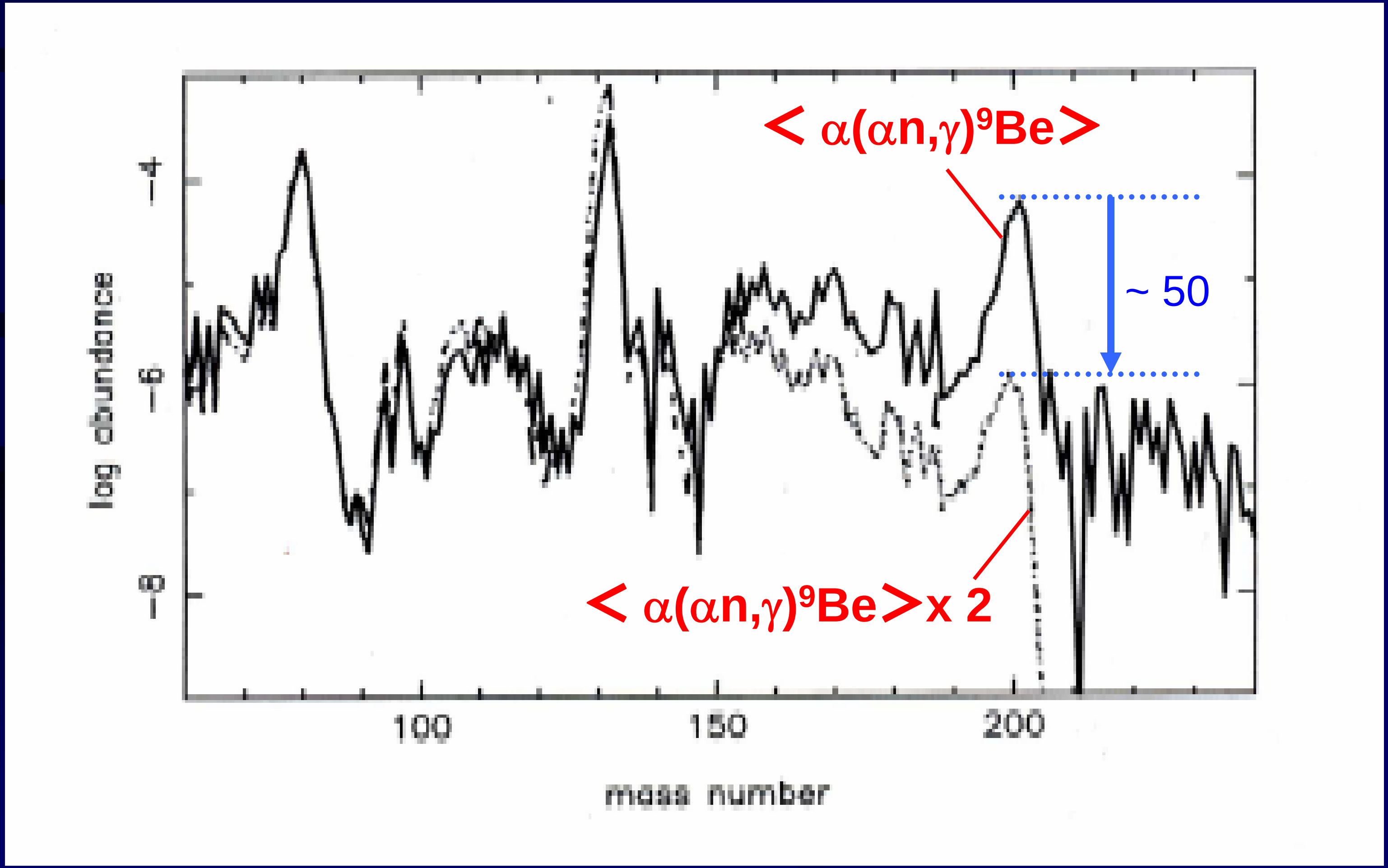
$$R = 1.35\mathrm{SNU} \times \left(\frac{S_{11}}{S_{11}(0)}\right)^{-2.5} \left(\frac{S_{33}}{S_{33}(0)}\right)^{-0.37} \left(\frac{S_{34}}{S_{34}(0)}\right)^{+0.8}$$
$$\times \left[1 + 3.47 \left(\frac{S_{17}}{S_{17}(0)}\right)^{+1.0} \left(\frac{\lambda_{e7}}{\lambda_{e7}(0)}\right)^{-1.0}\right]$$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

R-Process Sensitivity to Individual Reaction

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

→ About factor 50 change in r-element yields !

(slowly expanding ν-wind model)

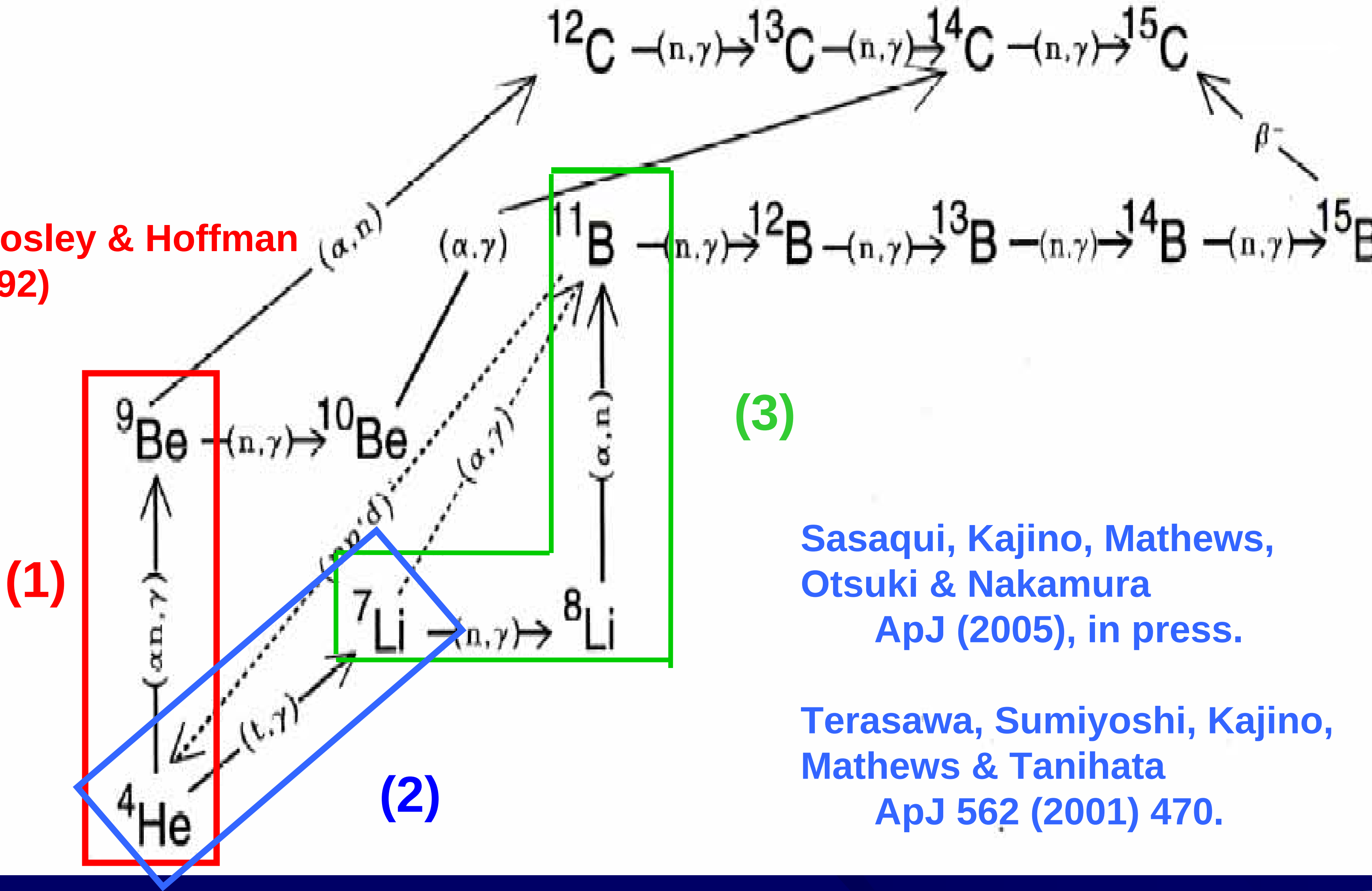


Relevant Reactions in R-Process & SENSITIVITY

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

No.	reaction	sensitivity(α_i)					current importance	
		2nd peak	3rd peak	^{232}Th	^{235}U	^{238}U		
(1)	$\alpha(\alpha n,\gamma)^{9}$Be	0.1823	-0.6546	-1.9423	-1.9819	-2.1006	0.3445	11.2222
(2)	$\alpha(t,\gamma)^{7}$Li	0.2874	-0.7474	-2.7125	-2.7857	-2.9583	0.2658	13.2353
(3)	^{7}Li$(n,\gamma)^{8}$Li	0.0465	-0.0917	-0.4296	-0.4436	-0.4729	0.7881	1.7163
(4)	^{8}Li$(\alpha,n)^{11}$B	0.0017	-0.0032	-0.0164	-0.0170	-0.0181	0.9882	1.0120
(5)	^{9}Be$(n,\gamma)^{10}$Be	0.0042	-0.0105	-0.0337	-0.0346	-0.0365	0.9761	1.0245
(6)	^{11}B$(n,\gamma)^{12}$B	-0.0100	0.0096	0.1119	0.1166	0.1256	1.0853	0.9214
(7)	^{12}B$(n,\gamma)^{13}$B	0.0015	-0.0079	-0.0114	-0.0115	-0.0012	0.9944	1.0056
(8)	^{13}B$(n,\gamma)^{14}$B	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(9)	^{14}B$(n,\gamma)^{15}$B	0.00010	-0.0002	-0.0032	-0.0034	-0.0035	0.9977	1.0024
(10)	^{12}C$(n,\gamma)^{13}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(11)	^{13}C$(n,\gamma)^{14}$C	0.0005	-0.0045	-0.0214	-0.0227	-0.0232	0.9846	1.0157
(12)	^{14}C$(n,\gamma)^{15}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(13)	^{15}C$(n,\gamma)^{16}$C	0.0040	-0.0194	-0.0899	-0.0878	-0.0867	0.8163	1.2250
(14)	^{16}C$(n,\gamma)^{17}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(15)	^{17}C$(n,\gamma)^{18}$C	0.0274	-0.0209	-0.1624	-0.1735	-0.1767	0.6747	1.4821
(16)	^{18}C$(n,\gamma)^{19}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(17)	^{19}C$(n,\gamma)^{20}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(18)	^{18}C$(\alpha,n)^{21}$O	0.0233	-0.0017	-0.0285	-0.0288	-0.0298	0.9354	1.0691

Identified Important Reaction Flow Paths



Woosley & Hoffman (1992)

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

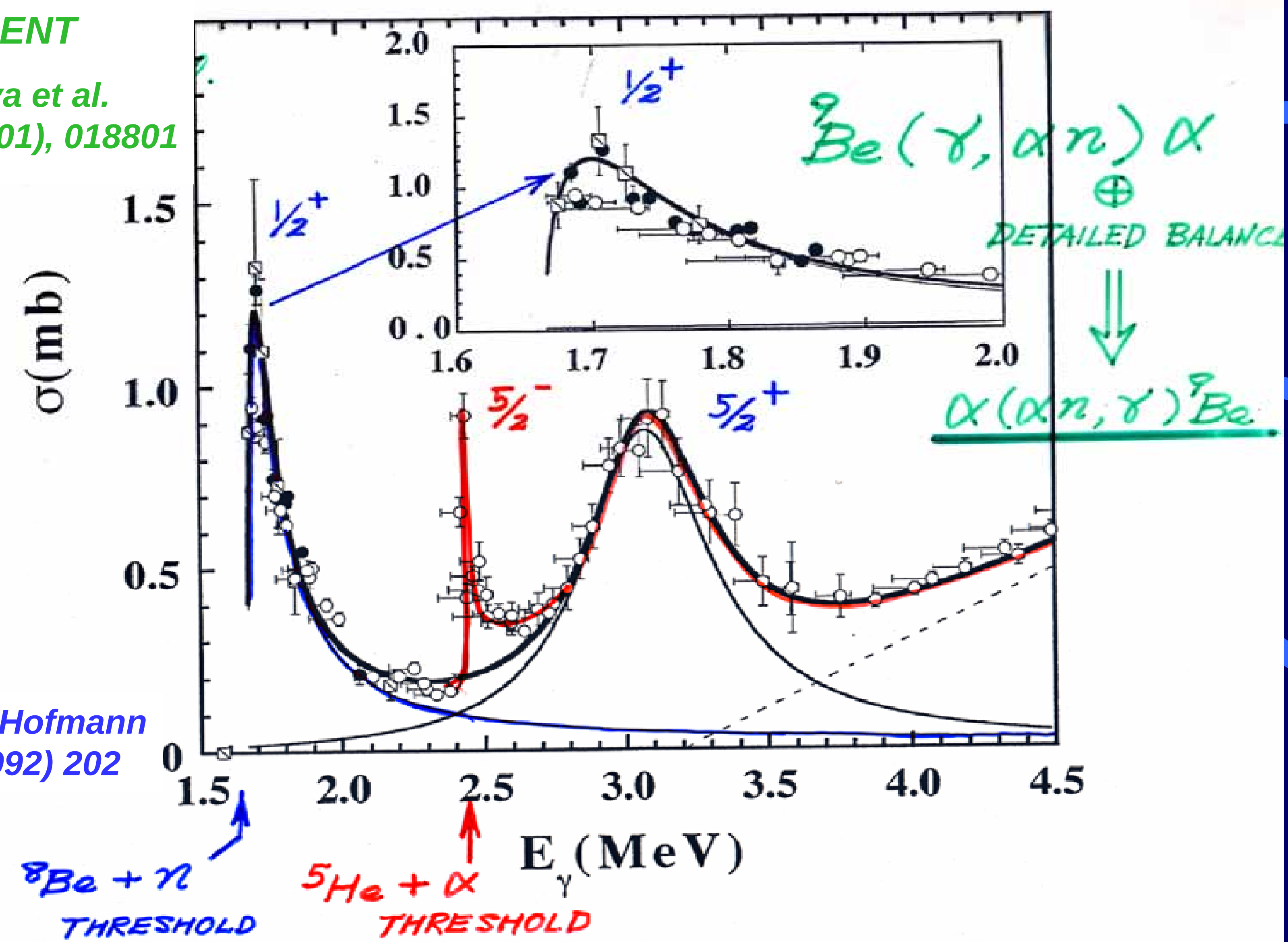
Terasawa, Sumiyoshi, Kajino, Mathews & Tanihata
ApJ 562 (2001) 470.

(1) $\alpha(\alpha n,\gamma)^9Be(\alpha,n)^{12}C$ 35%(1σ)

Sumiyoshi, Utsunomiya, Goko, and Kajino, Nucl. Phys. A709 (2002), 467

EXPERIMENT

Utsunomiya et al.
PRC63 (2001), 018801



Woosley & Hofmann
ApJ 395 (1992) 202

Principle of the Detailed Balance

$CPT = 1$, T: Time Reversality

P: Parity Conservation

$$\begin{matrix} 1 & & 2 & & \gamma & & c \\ A & + & p & \longrightarrow & \gamma & + & C^* \end{matrix}$$

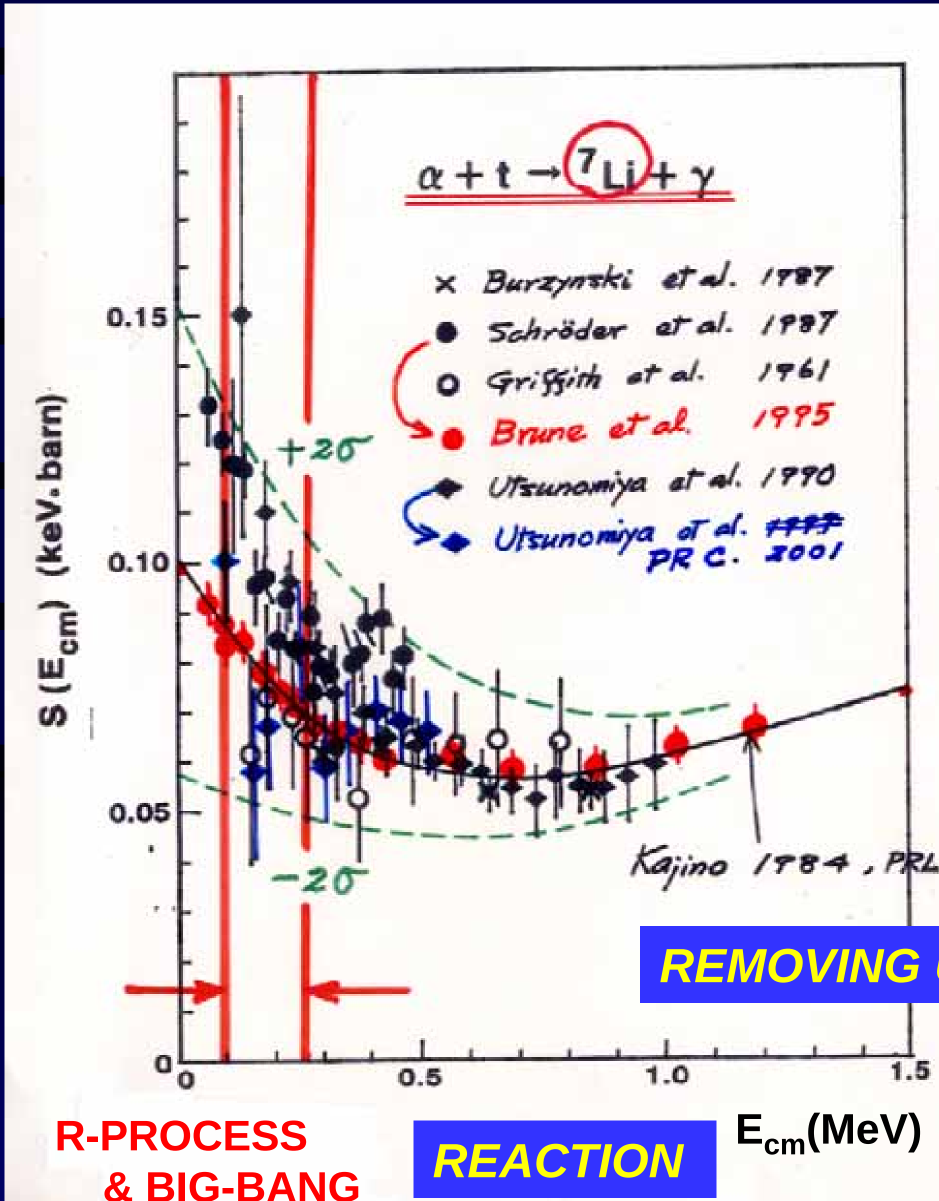
Radiative-Capture Reaction

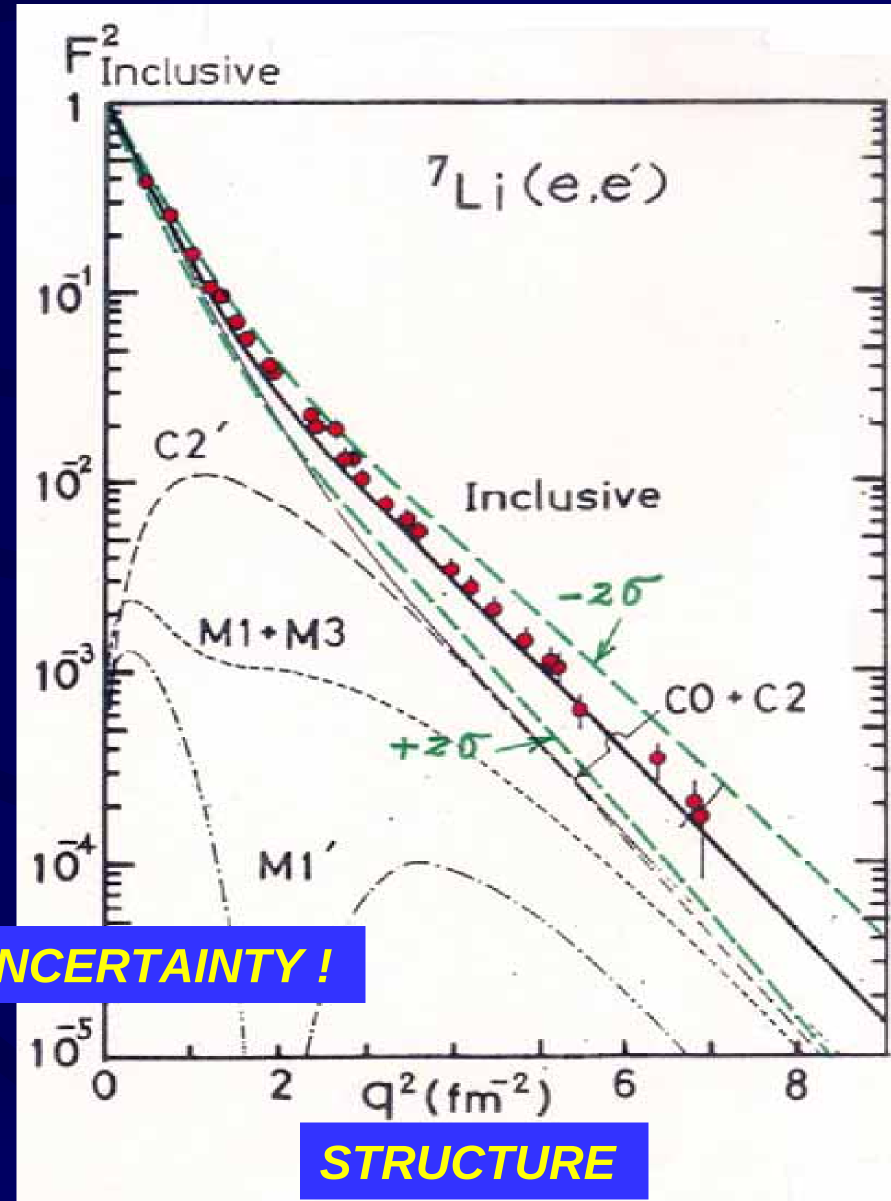
Photo-Disintegration Reaction

$$\sigma^{DC}_{(p,\gamma)}(E) = \frac{1}{E}\exp\left(\frac{-2\pi Z_1 Z_2 e^2}{\hbar v}\right) S^{DC}_{(p,\gamma)}$$

$$= \left[\frac{2(2J_c+1)}{(2J_1+1)(2J_2+1)}\right]\left(\frac{\kappa_\gamma}{k}\right)^2 \sigma_{(\gamma,p)}(E_\gamma),$$

(2)$\alpha(t,\gamma)^7Li$ 30%(1σ)

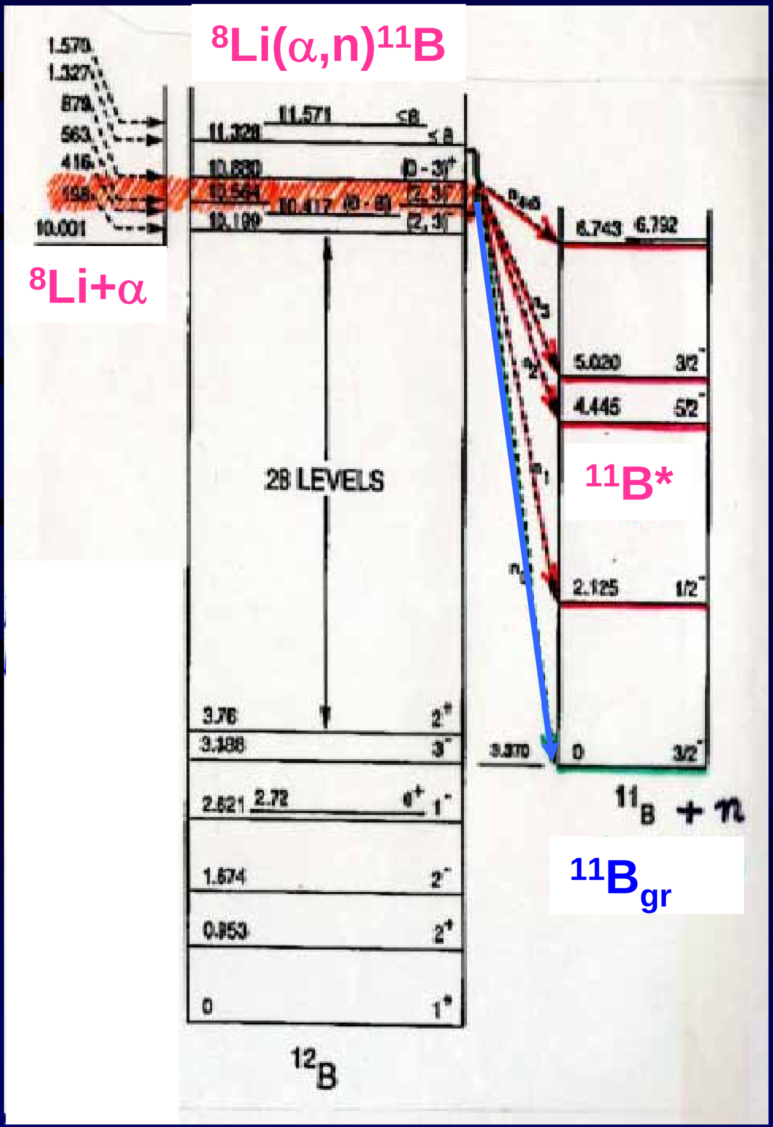


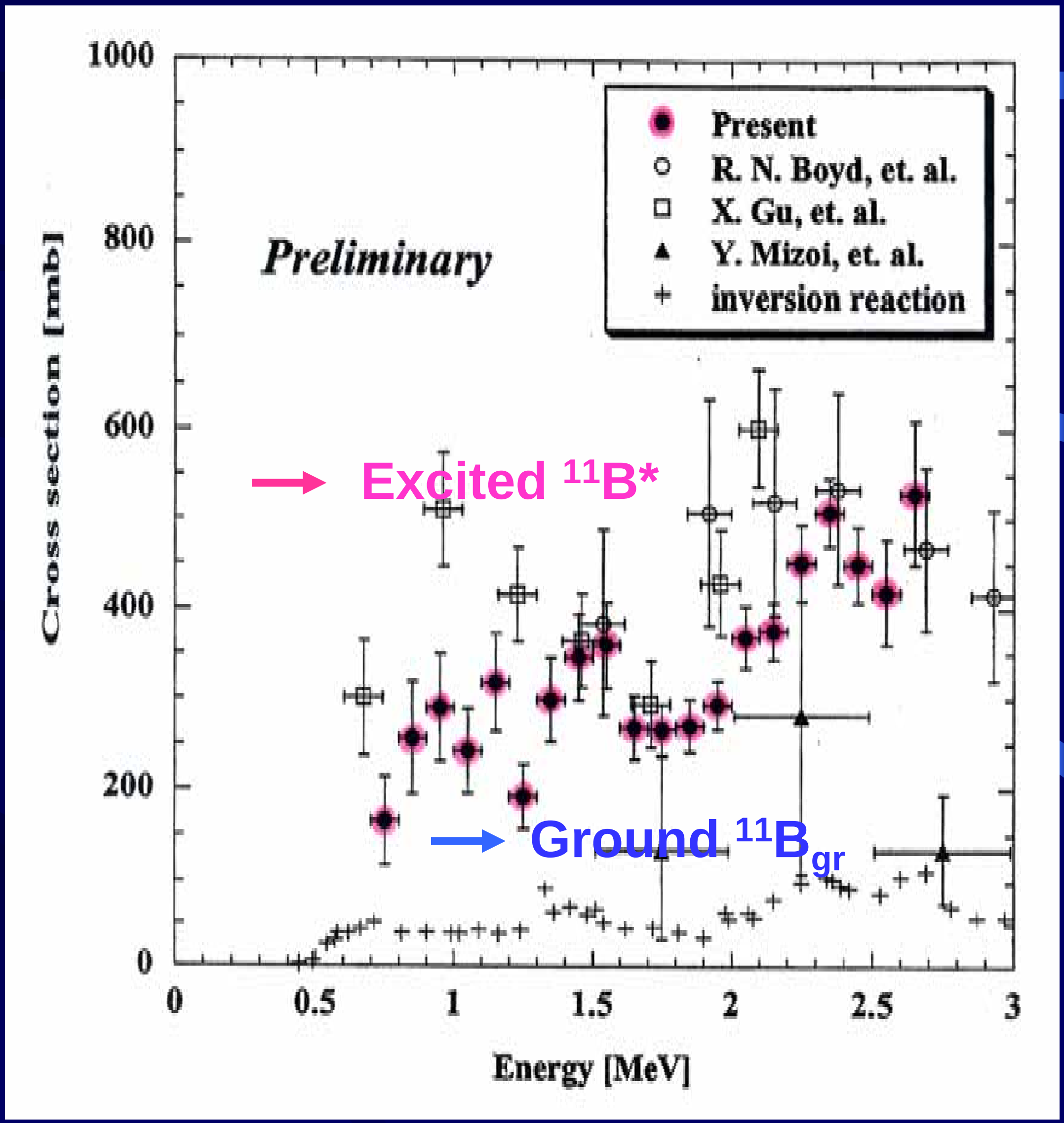


REMOVING UNCERTAINTY !

(3) $^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$ Factor 2 (1σ)

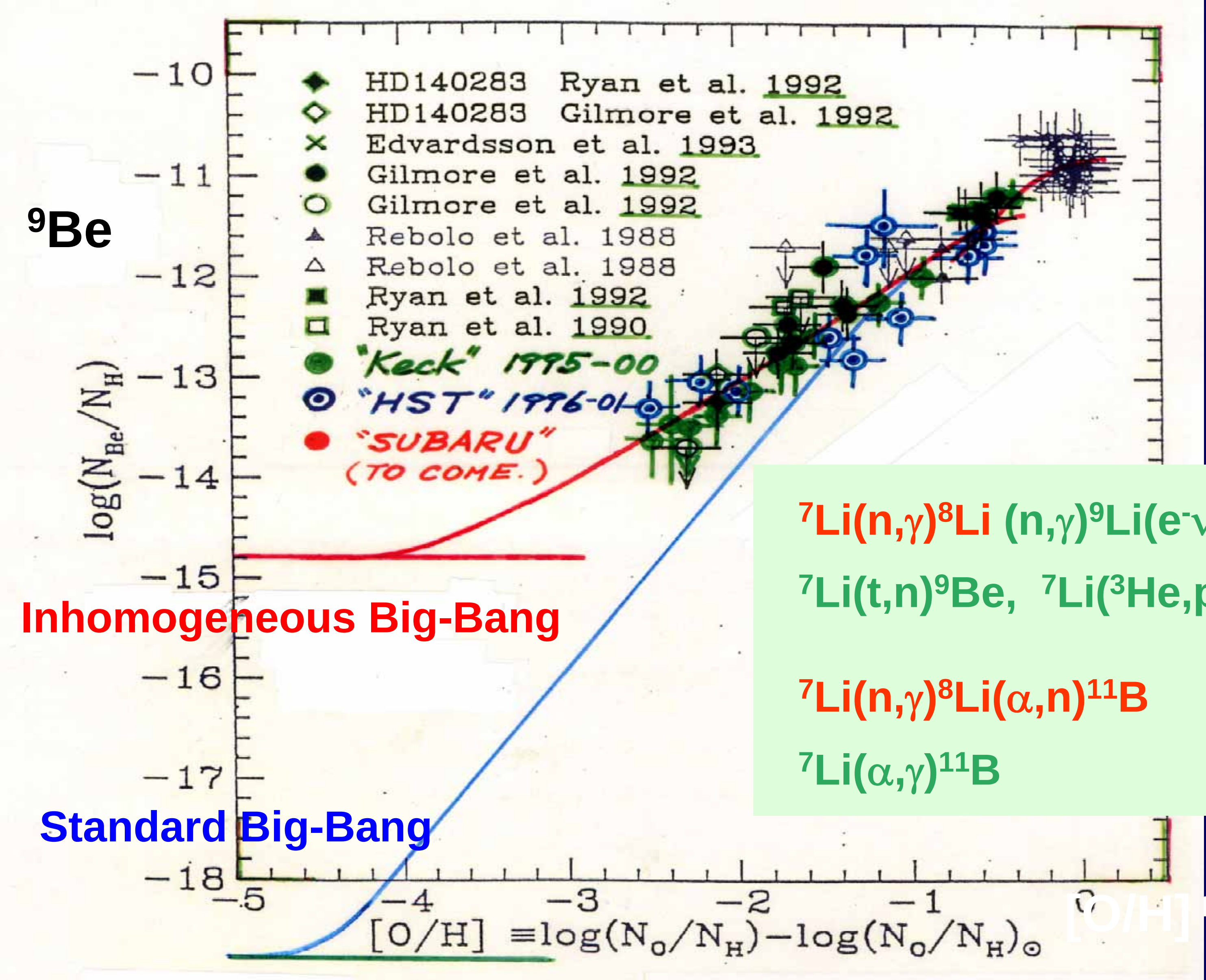
H. Ishiyama et al. AIP Conf. Proc. 704 (2004) 453.





INHOMOGENEOUS BIG-BANG NUCLEOSYNTHESIS

Kajino and Boyd, ApJ 359 (1990) 267; Orito, Kajino, Boyd & Mathews, ApJ 488 (1997) 515.



^{7}Li(n,γ)^{8}Li (n,γ)^{9}Li(e$^-\nu$)^{9}Be,

^{7}Li(t,n)^{9}Be, ^{7}Li(^{3}He,p)^{9}Be

^{7}Li(n,γ)^{8}Li(α,n)^{11}B

^{7}Li(α,γ)^{11}B

SENSITIVITY of Relevant Reactions to R-Process

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

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

(1) $\alpha(\alpha n,\gamma)^9$Be 1σ = 35% ⟶ $(Y_0+\delta Y)/Y_0$ = 0.35 ~ 11.2

(2) $\alpha(t,\gamma)^7$Li 1σ = 30% ⟶ 0.27 ~ 13.2

(3)(4) ^{7}Li $(n,\gamma)^8$Li$(\alpha,n)^{11}$B 1σ = 35%, x2 ⟶ 0.79 ~ 1.7

Δ(Th/Eu)=0.7 ⟶ ΔT_G = 7.2 Gy !

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

Relevant Reactions in R-Process & SENSITIVITY

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

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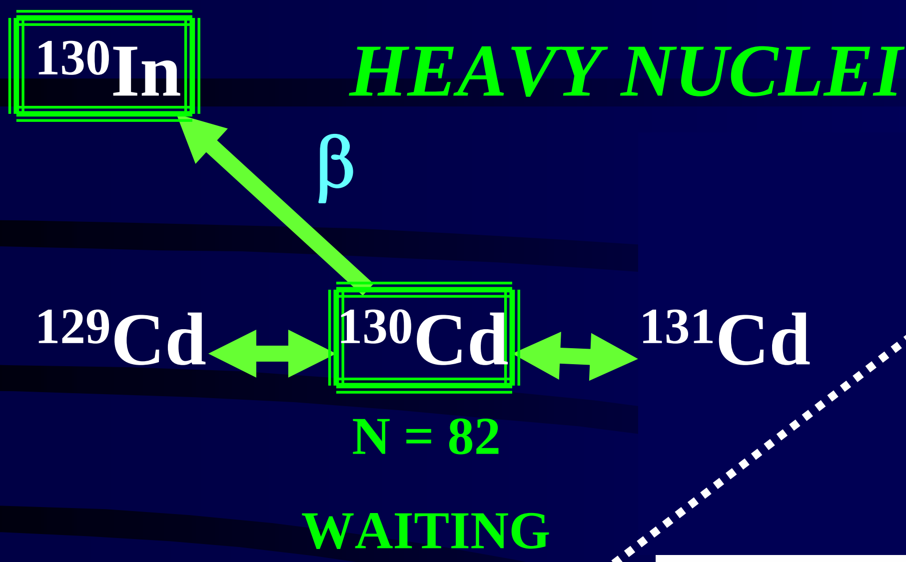
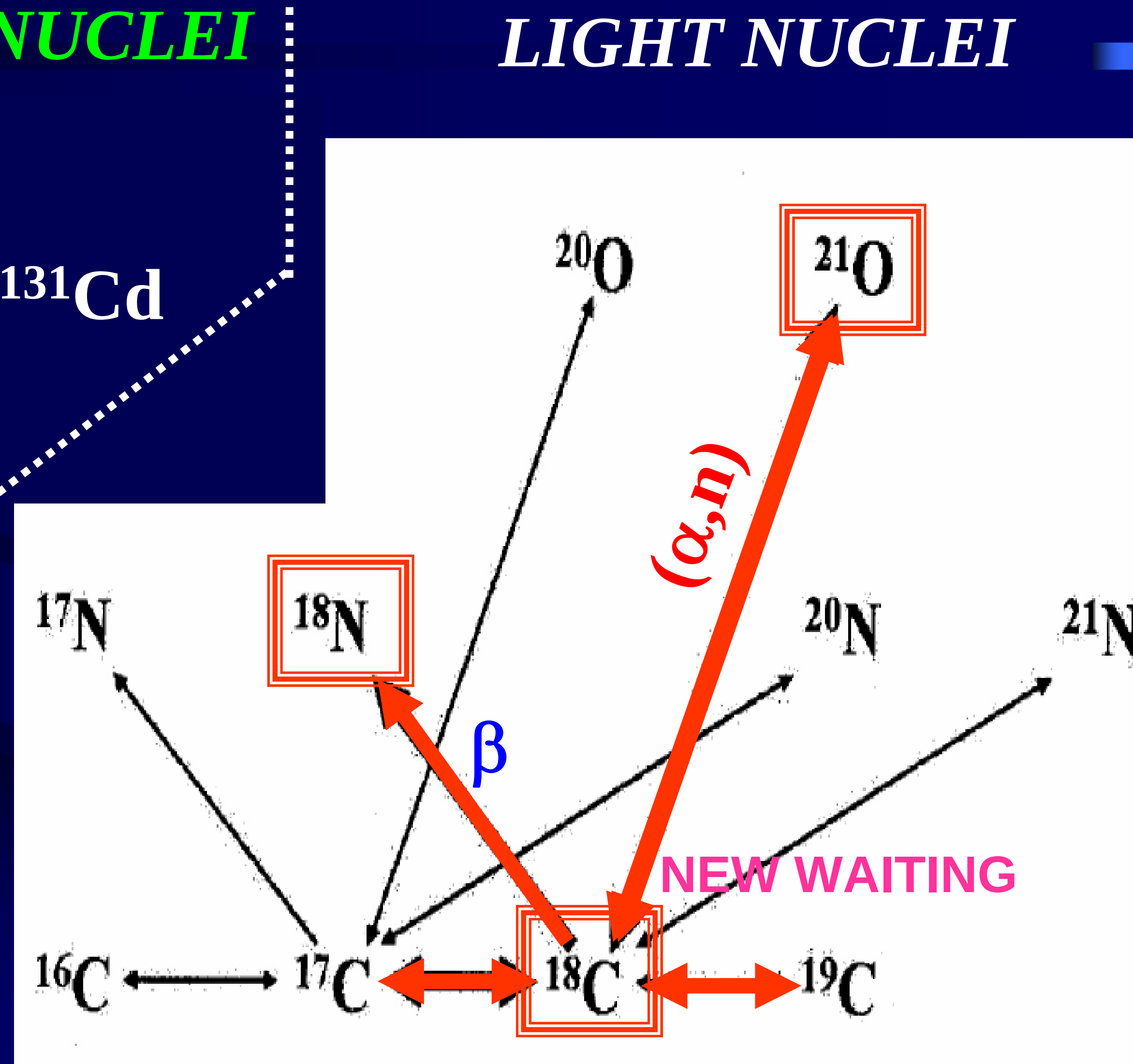
(5)	^{9}Be$(n,\gamma)^{10}$Be	0.0042	-0.0105	-0.0337	-0.0346	-0.0365	0.9761	1.0245
(6)	^{11}B$(n,\gamma)^{12}$B	-0.0100	0.0096	0.1119	0.1166	0.1256	1.0853	0.9214
(7)	^{12}B$(n,\gamma)^{13}$B	0.0015	-0.0079	-0.0114	-0.0115	-0.0012	0.9944	1.0056
(8)	^{13}B$(n,\gamma)^{14}$B	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(9)	^{14}B$(n,\gamma)^{15}$B	0.00010	-0.0002	-0.0032	-0.0034	-0.0035	0.9977	1.0024
(10)	^{12}C$(n,\gamma)^{13}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(11)	^{13}C$(n,\gamma)^{14}$C	0.0005	-0.0045	-0.0214	-0.0227	-0.0232	0.9846	1.0157
(12)	^{14}C$(n,\gamma)^{15}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(13)	^{15}C$(n,\gamma)^{16}$C	0.0040	-0.0194	-0.0899	-0.0878	-0.0867	0.8163	1.2250
(14)	^{16}C$(n,\gamma)^{17}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(15)	^{17}C$(n,\gamma)^{18}$C	0.0274	-0.0209	-0.1624	-0.1735	-0.1767	0.6747	1.4821
(16)	^{18}C$(n,\gamma)^{19}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(17)	^{19}C$(n,\gamma)^{20}$C	0.0	0.0	0.0	0.0	0.0	1.0	1.0
(18)	^{18}C$(\alpha,n)^{21}$O	0.0233	-0.0017	-0.0285	-0.0288	-0.0298	0.9354	1.0691

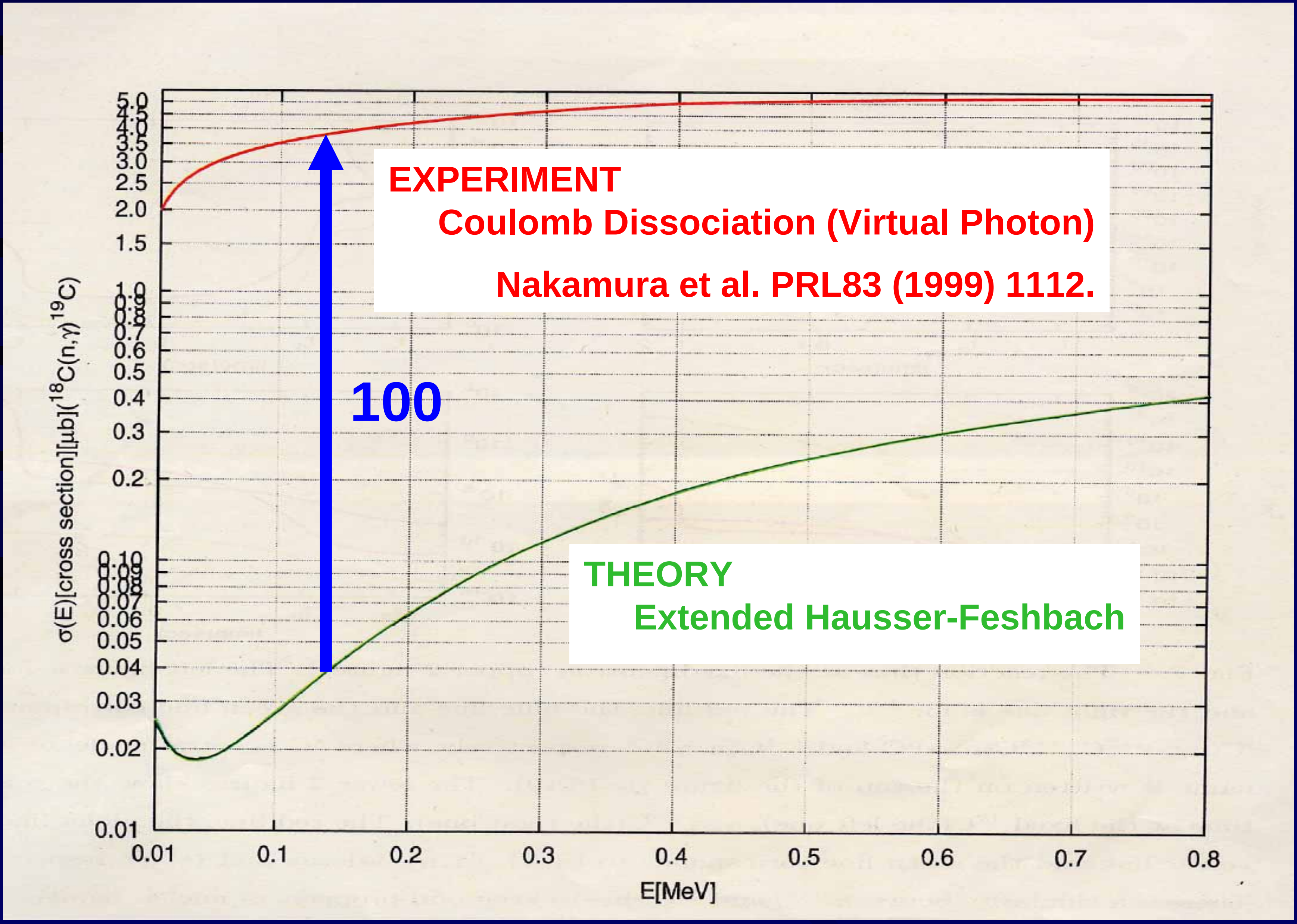
New Waiting Points in Light-Mass Nuclei





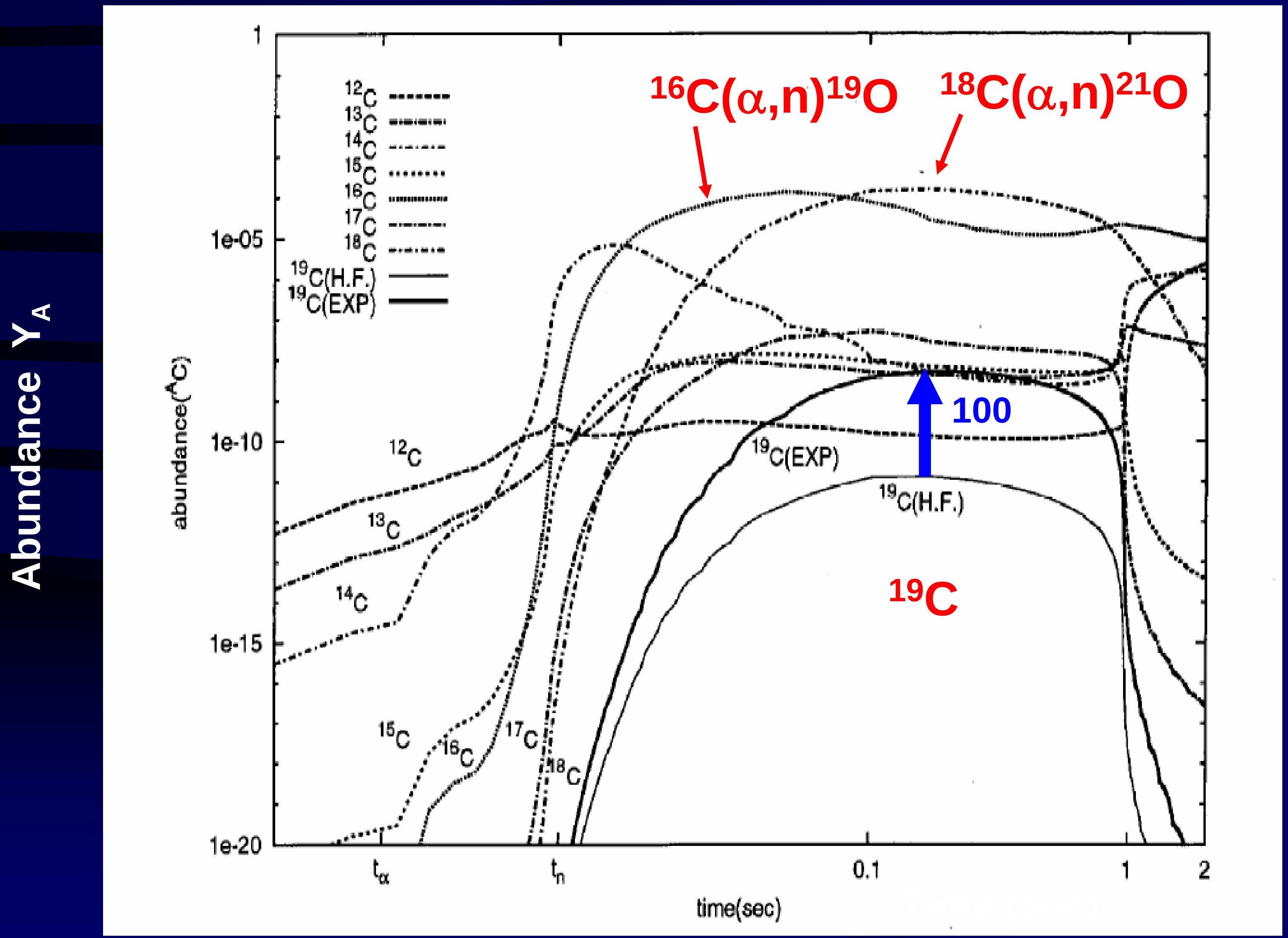
Both (n,γ) and (α,n) are FAST enough so that ^{18}C waits for β-decay.

Neutron-Capture Cross Section $\sigma(^{18}C(n,\gamma)^{19}C)$ [μb]



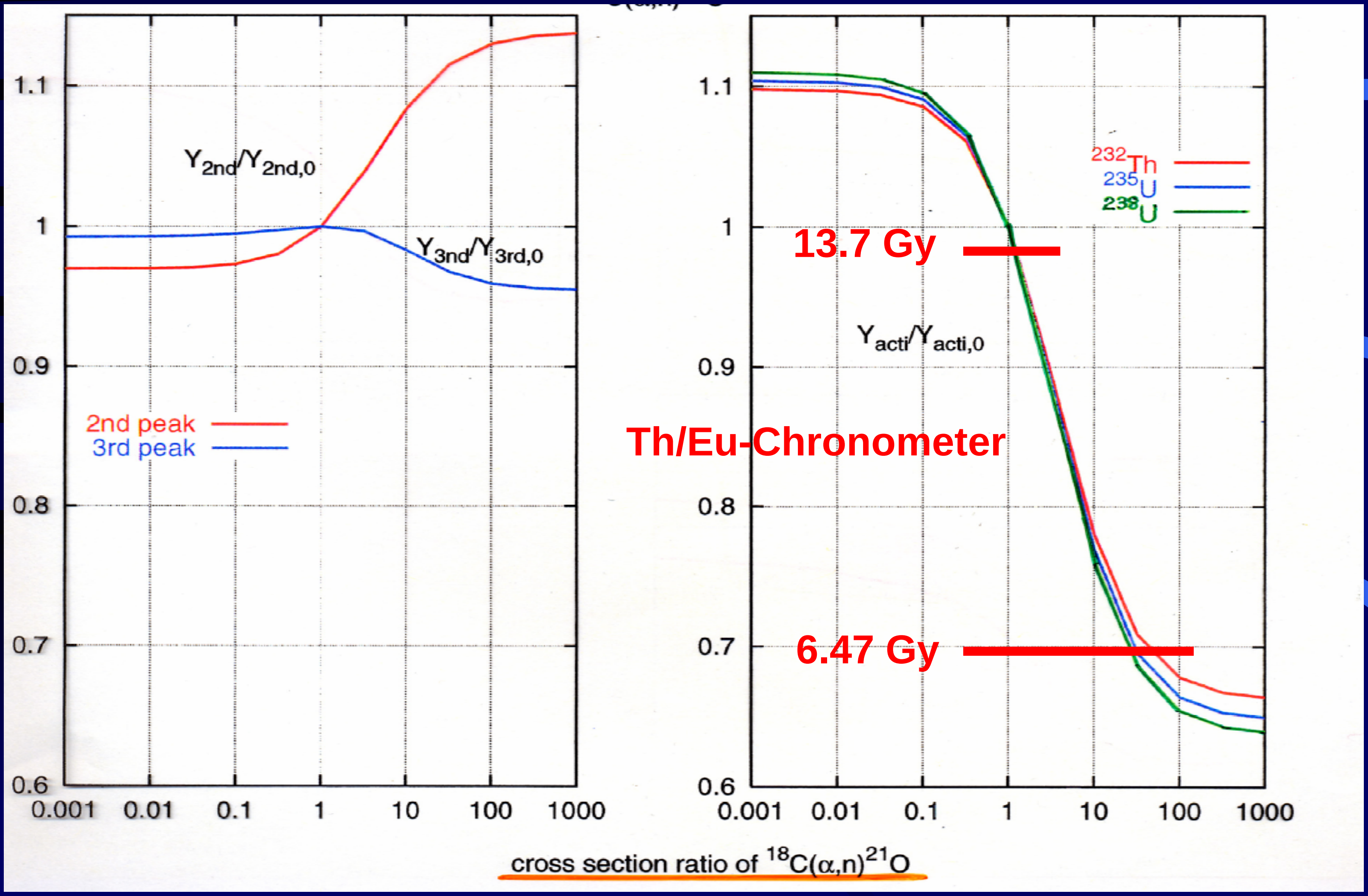
Abundance Evolution of Carbon Isotopes

Sasaqui et al. (2005)



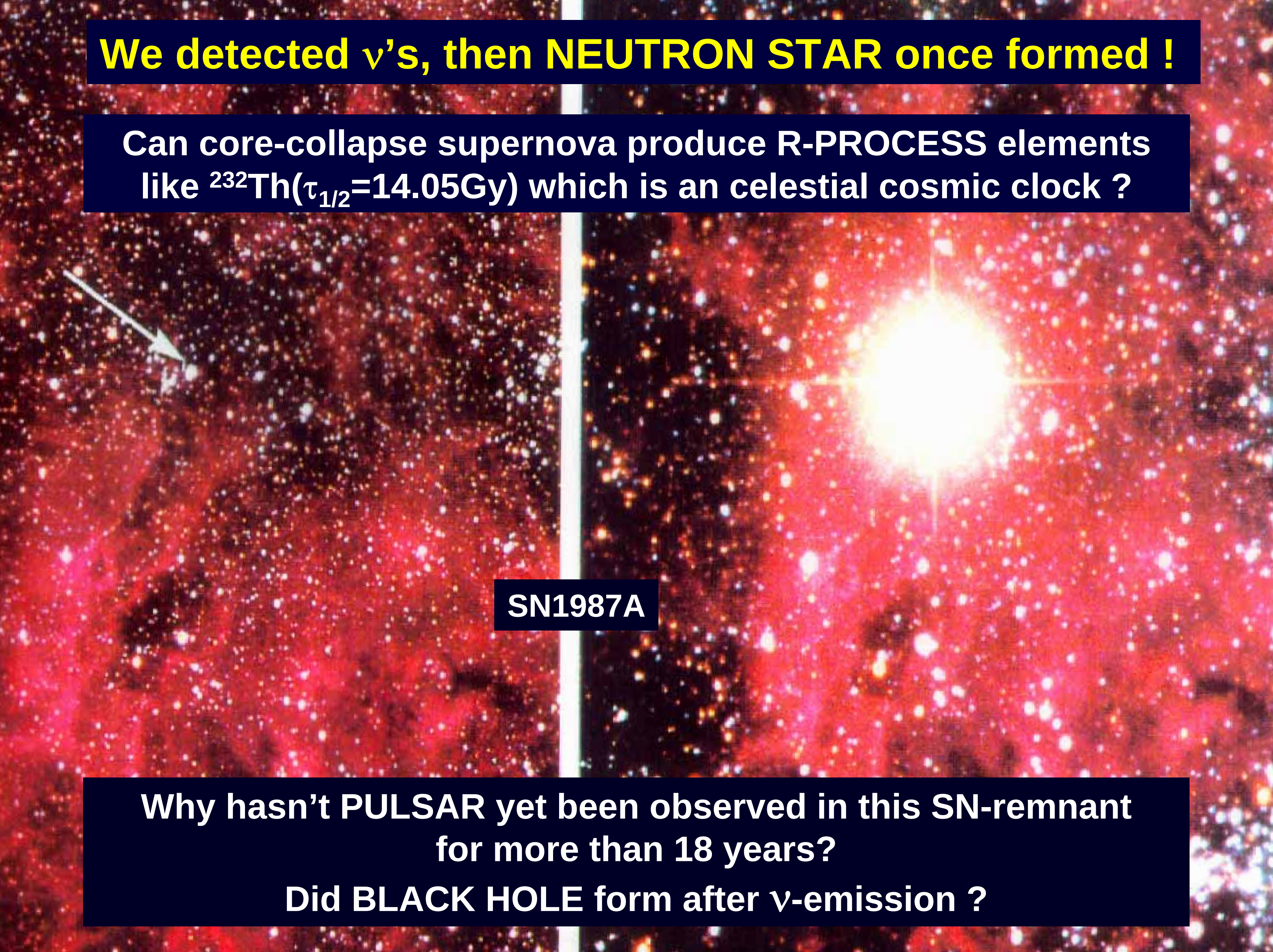
SENSITIVITY of ^{232}Th & ^{235,238}U to ^{18}C(α,n)^{21}O

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



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

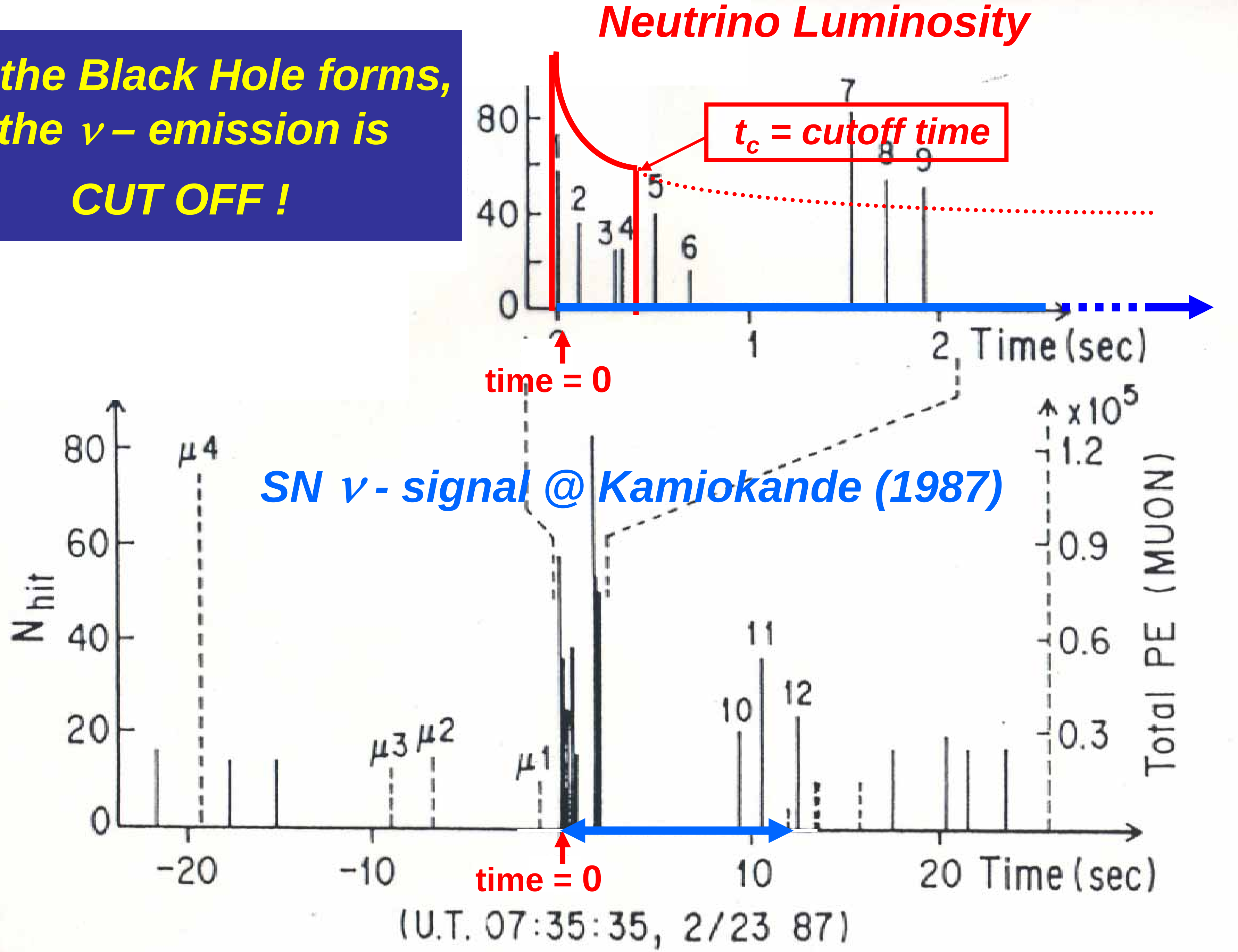
Can core-collapse supernova produce R-PROCESS elements like ^{232}Th($\tau_{1/2}$=14.05Gy) which is an celestial cosmic clock ?



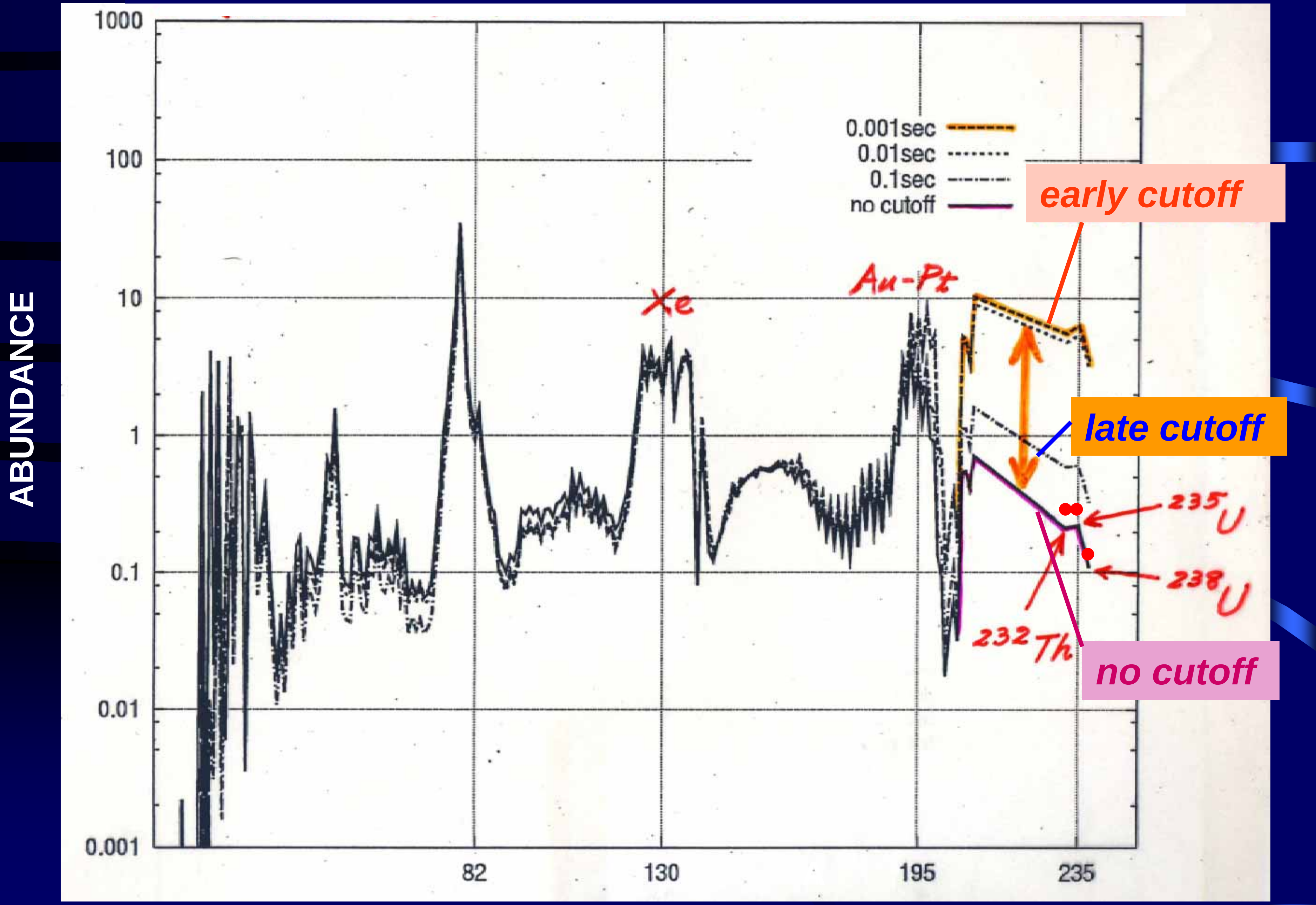
Why hasn't PULSAR yet been observed in this SN-remnant for more than 18 years?

Did BLACK HOLE form after ν-emission ?

If the Black Hole forms, the ν – emission is CUT OFF !



ν-CUTOFF EFFECT ON ACTINOID



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

$$\nu_e + {}^{Z}_{N}A \rightarrow {}^{Z+1}_{N-1}A + e^-, \quad (1)$$

important !

Pauli Blocking →

$$\bar{\nu}_e + {}^{Z}_{N}A \rightarrow {}^{Z-1}_{N+1}A + e^+, \quad (2)$$

umimportant !

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

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 !

$$\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-, \quad (4)$$

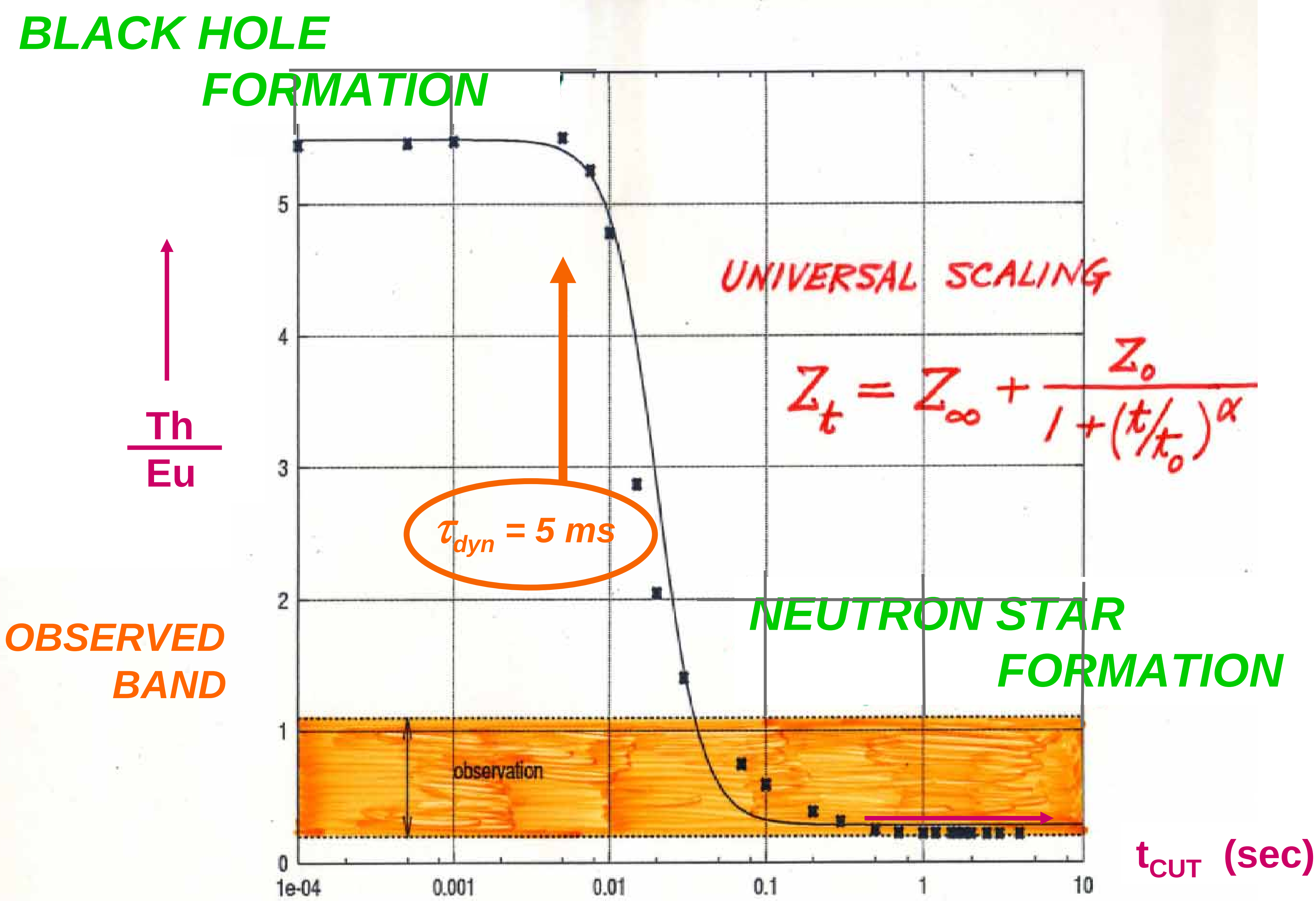
important !

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

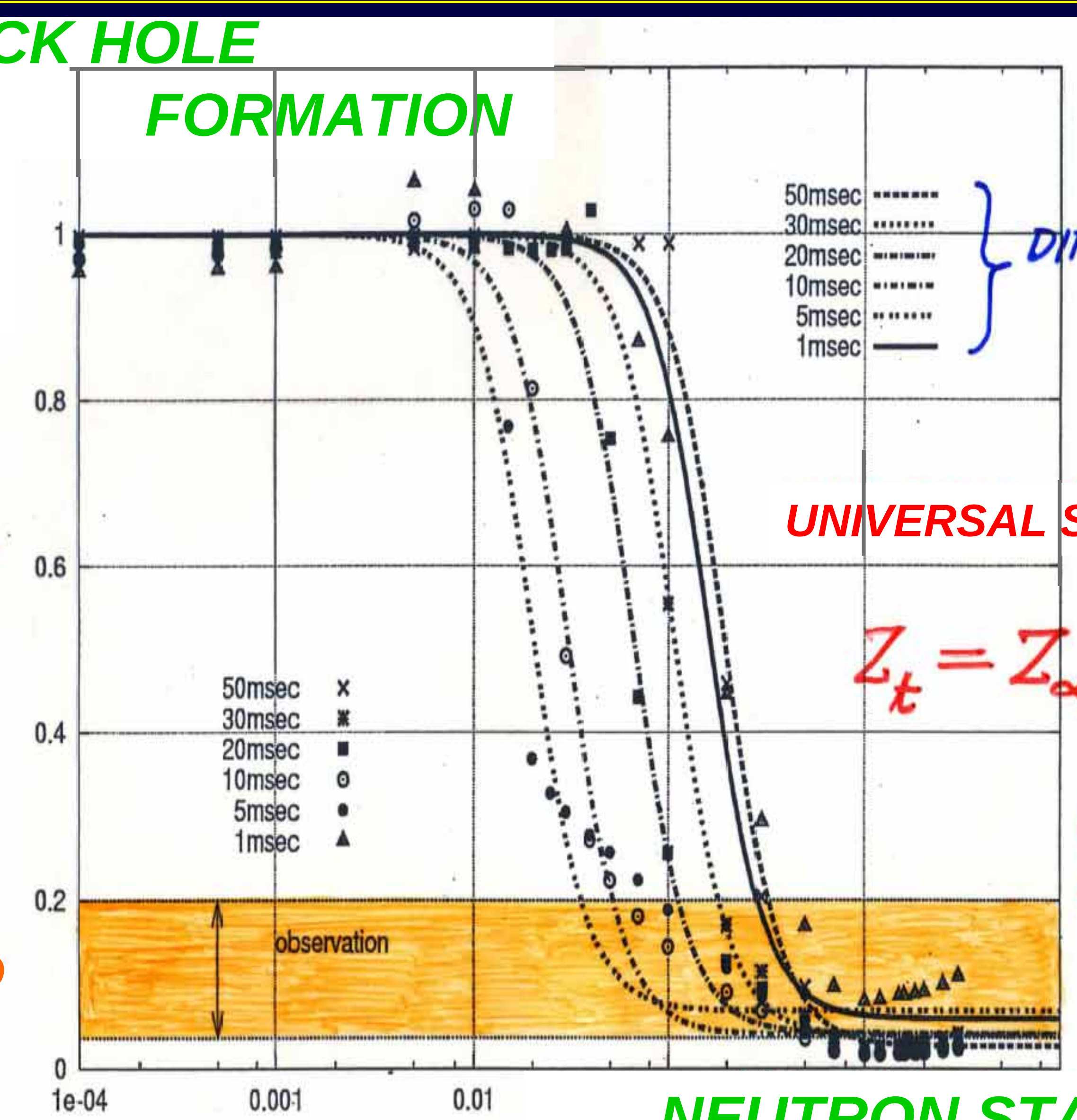
The neutron to proton ratio in the weak equilibrium satisfies (Qian & Woosley 1996),

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

R-elements in Black-Hole vs. Neutron Star Formation



Different Supernova-Flow (τ_{dyn}) Models



$$\frac{Z_t - Z_\infty}{Z_0} = \frac{1}{1+(t/t_0)^\alpha}$$

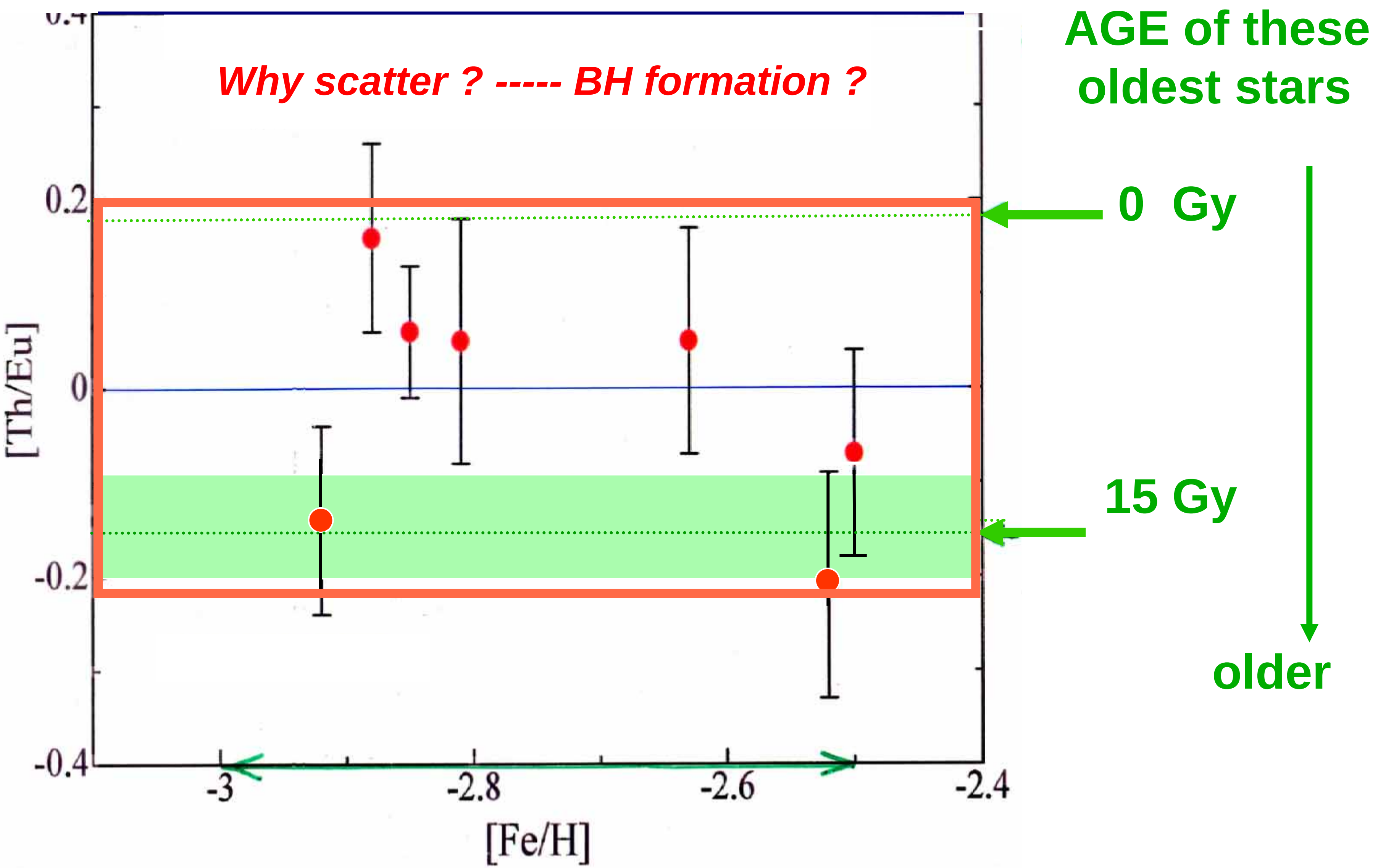
$$Z_t = Z_\infty + \frac{Z_0}{1+(t/t_0)^\alpha}$$

$\alpha \approx 3.0$

$t_0 = 0.02 - 0.16\,s$

SUBARU Telescope HDS

Honda et al. 2004, ApJ 607, 474



Conclusions

Core-collapse supernovae are the viable astrophysical sites for the r-process nucleosynthesis.

We still needs more precise nuclear physics data for light-to-Intermediate as well as heavy mass neutron-rich nuclei:

- Some new key reactions: $\alpha(\alpha n,\gamma)^{9}Be$, $\alpha(t,\gamma)^{7}Li$, $^{7}Li(n,\gamma)^{8}Li$, $^{8}Li(\alpha,n)^{11}B$
- Key data: S_n, β-lives, ν-induced n-emission and fission rates.
- New concept of SEMI-WAITING: (n, γ) and (α, n) reactions are fast enough to wait for β-decay on ^{8}Li, ^{15}B, $^{16, 18}C$, ^{24}O, …

We studied the neutrino cutoff effect due to the Black-Hole formation in core-collapse supernovae.

- **The r-process drastically changes if $\tau_{dyn} < t_{CUT}$, making maximal effect on the ^{232}Th and $^{235,238}U$.**
- **Detection of this effect in SN1987A ejecta is highly desirable to find a signature for the Black Hole formation.**