（7）ガンマ線バーストでの元素合成

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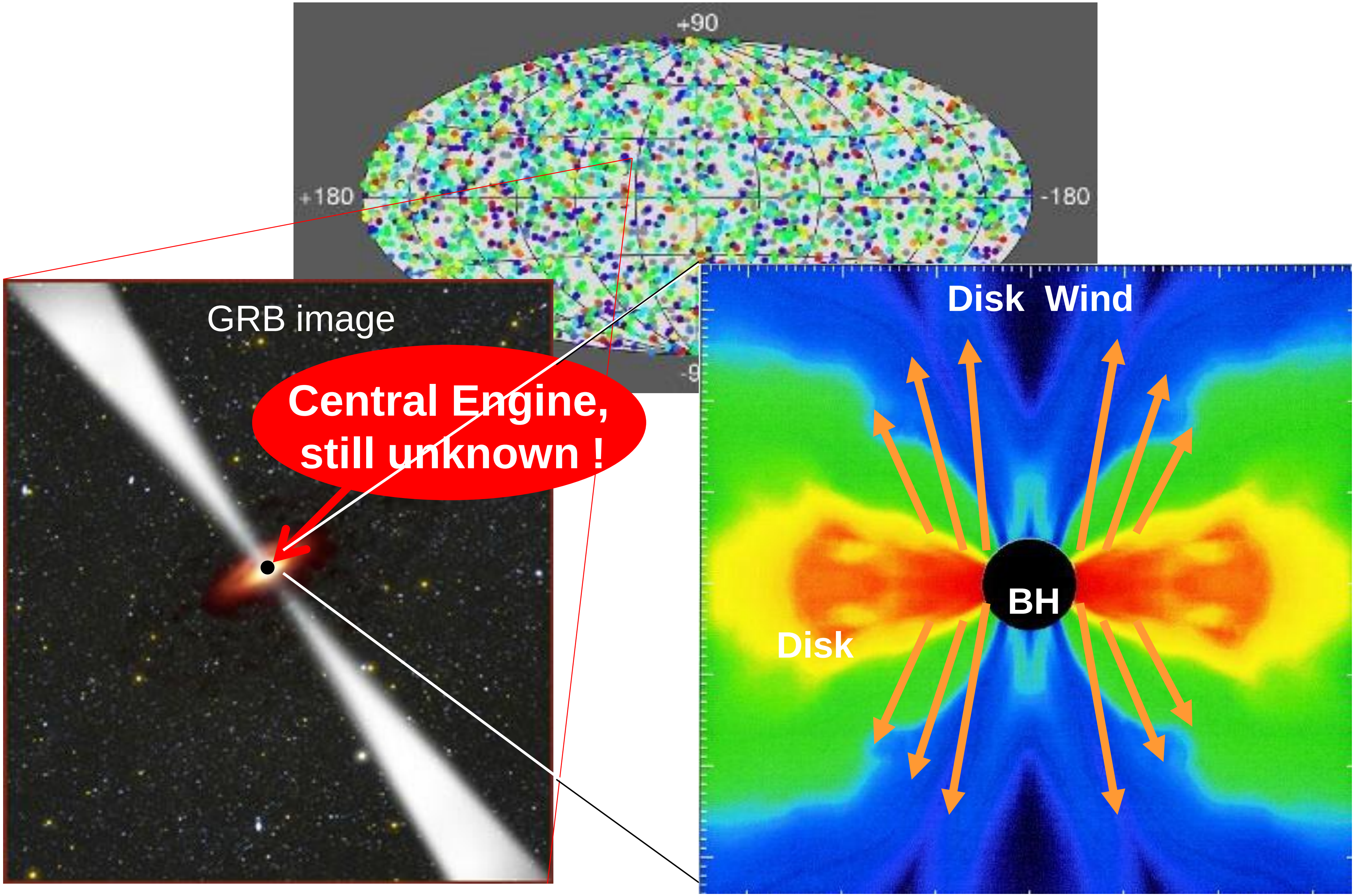
GRBs are cosmological activities at high redshifts (0< z <6.6) in the early Universe.



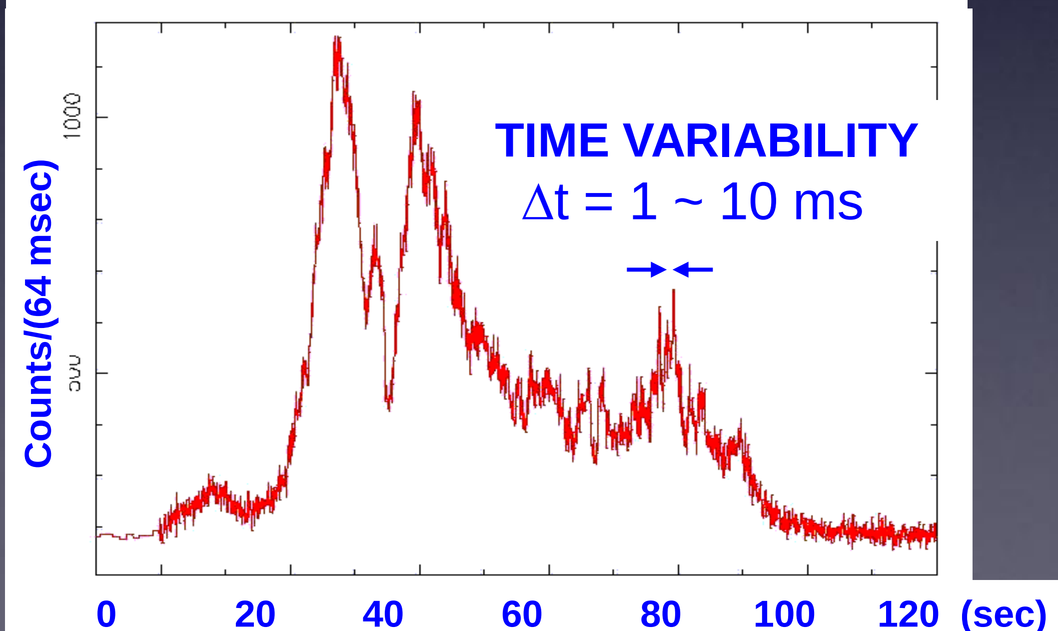
What is the Central Engine of GRB ?

Gamma-Ray Bursts (GRBs) are the highest energy cosmological phenomena at high redshifts (0< z <6.6) in the early Universe.

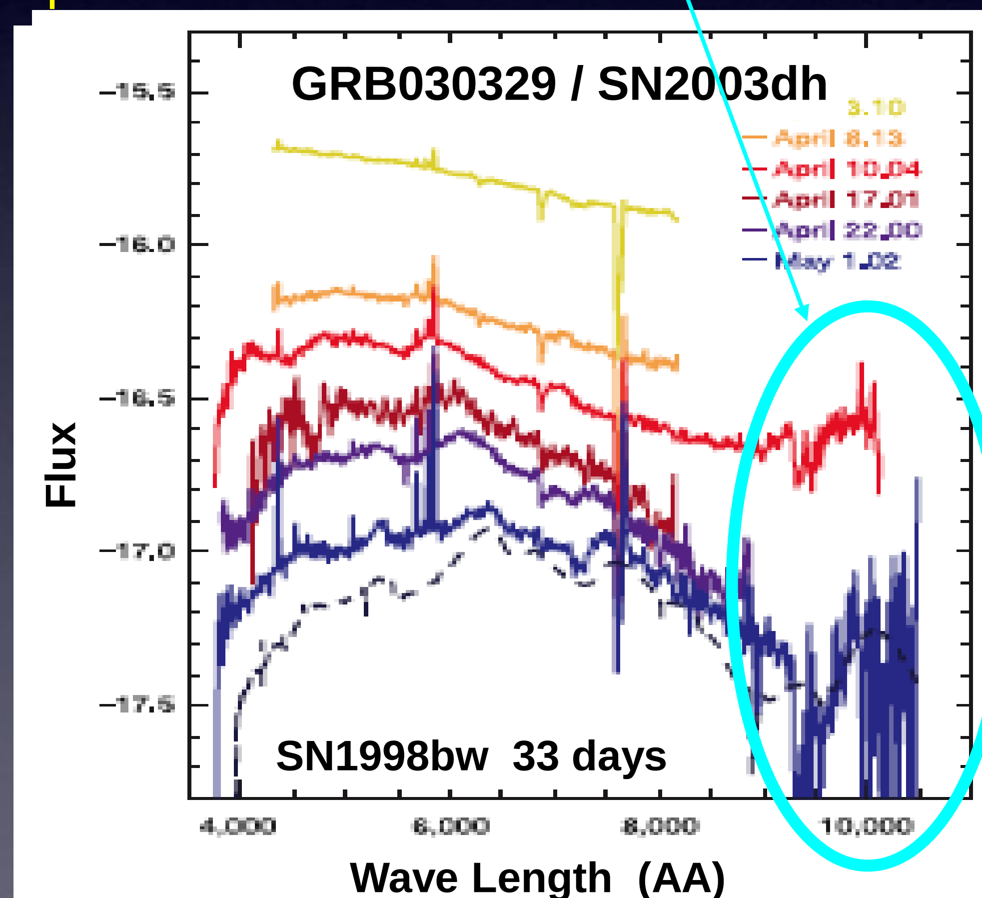
- **Time variability indicates SN-core size.**
- **We expect nucleosynthetic signature.**

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

- **Each spike has Δt = 1 ~ 10 ms.**
- **ΔR = 300 ~ 3000 km**
- **Size of Supernova-Core !**
  Energy might be huge: E ~ 10^{52}erg



Spectral evolution



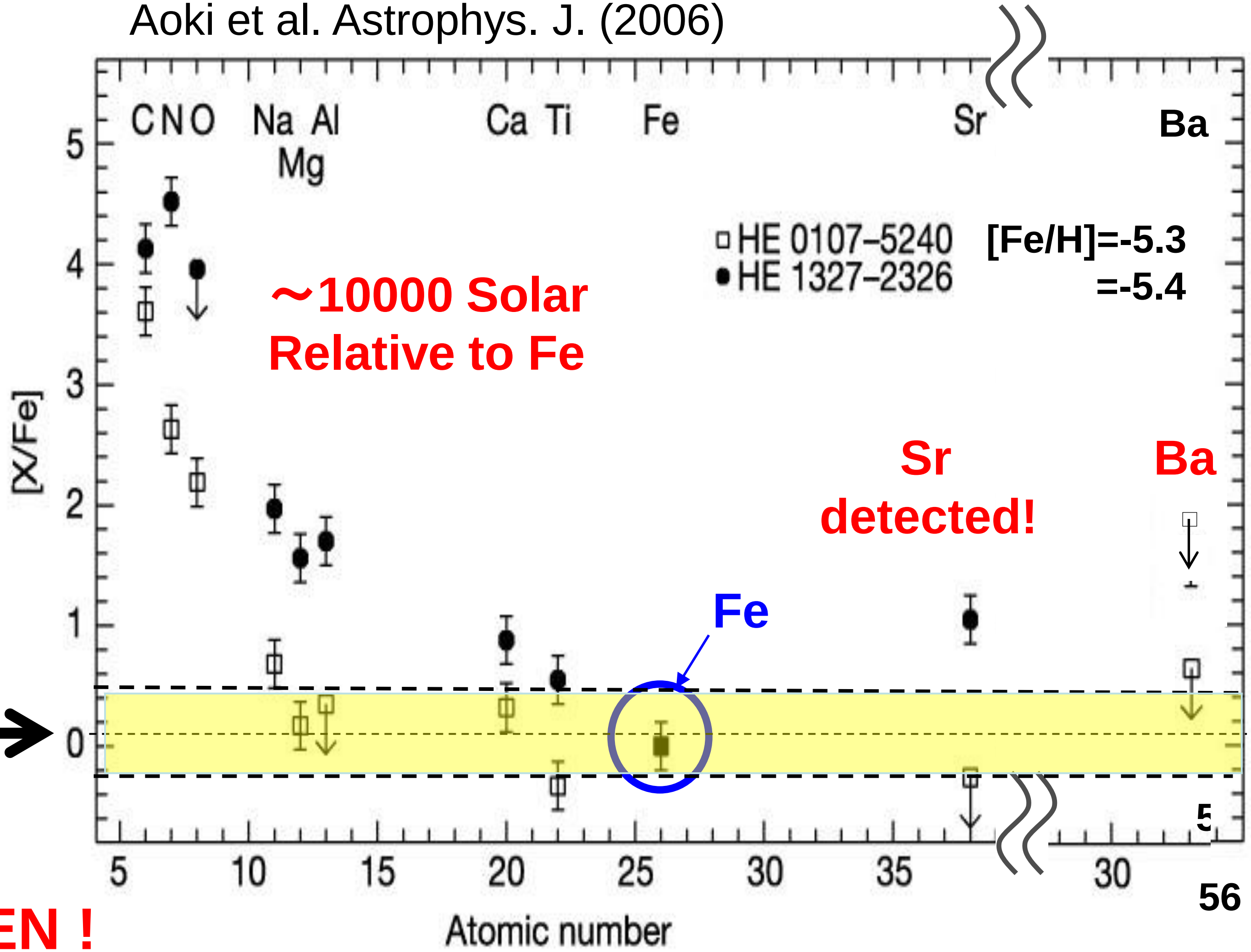
Our SUBARU-HDS group discovered an oldest Pop. II Halo Star in the Milky Way !

[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 fails !

Universality is BROKEN !

目的

すばる望遠鏡観測で、天の川に最も金属量の少ない初期世代星HE1327-2326 を発見。 異常な元素組成を示す！

- ☆ 鉄: 太陽系組成の25万分の一！
- ☆ 炭素、酸素: 超新星モデルの予言値の一万倍！
- ☆ 重いr過程元素: Sr, Baが鉄の十倍！

元素量のアノマリーの原因はなにか？
起源天体は何か？

元素組成の異常性を説明できる極新星(ハイパーノヴァ)-コラプサーモデルを構築し、「ガンマ線バーストの中心起源天体は、ブラックホールと降着円盤を形成して重力崩壊し非球対象な爆発を起こすコラプサーである。」という理論仮説を実証したい！

OUTLINE

Astrophysical Sites for “R-PROCESS”

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Supernova Model (remnant = Neutron Star)

(a) Neutrino-Driven Wind (ν-heated SN)

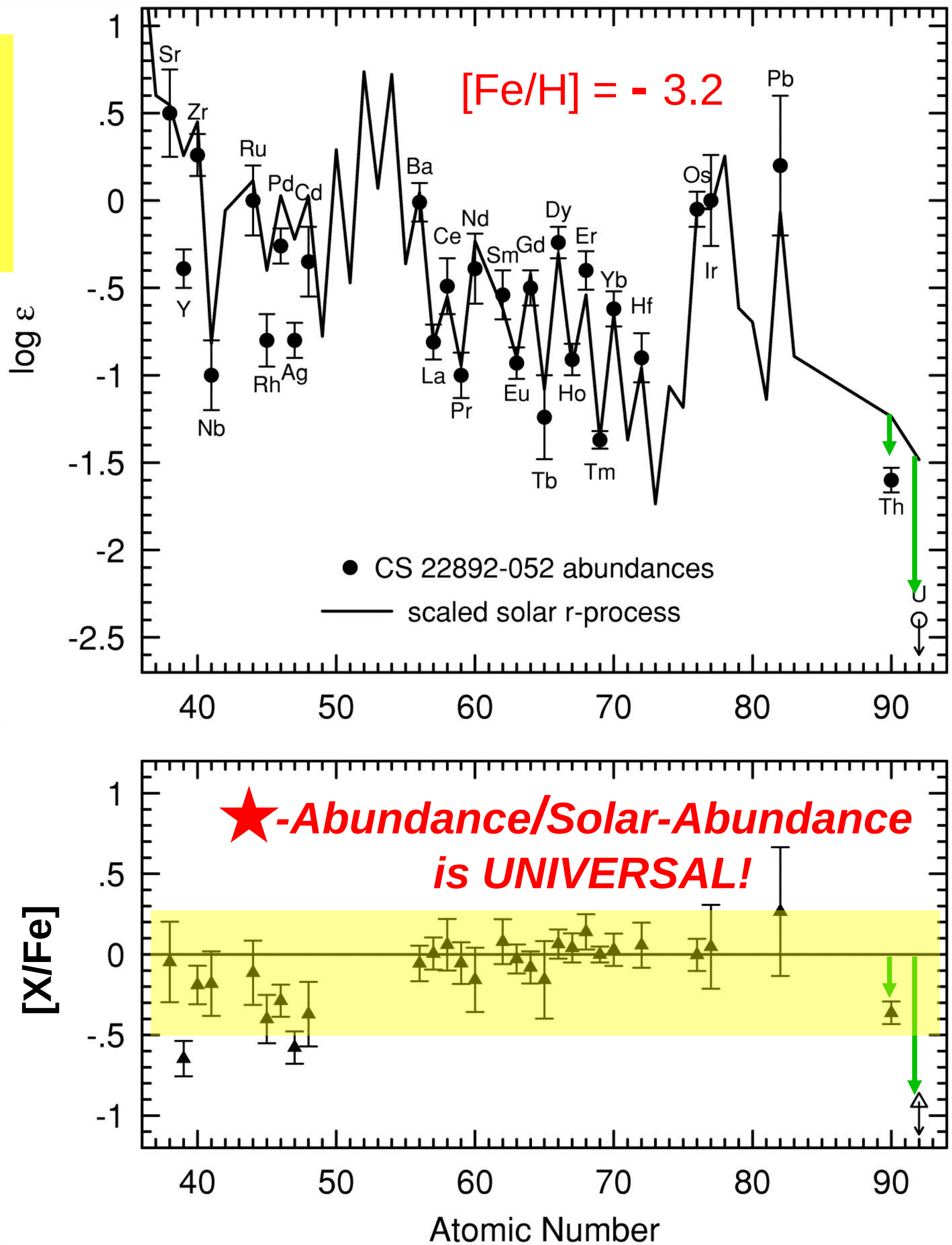
(b) Binary Neutron-Star Merger

(c) MHD JET (Rotational Magneto-HydroDynamic Jet)

Gamma-Ray Burst Model (remnant = Black Hole)

(d) Collapsars

Universality between the Sun and old Metal-Poor Stars



Neutrino-driven Wind Model explains UNIVERSALITY !

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

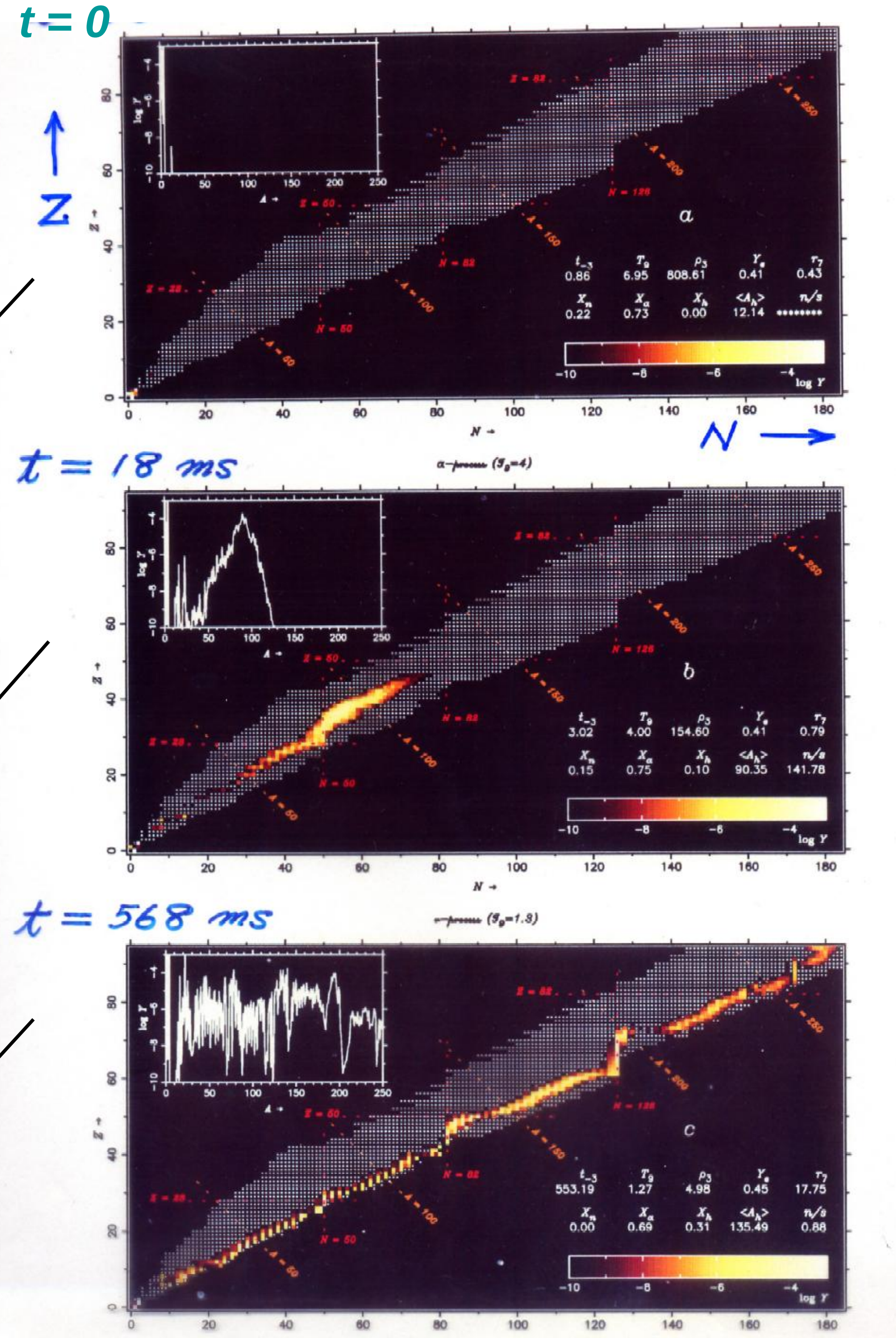
t = 0
Neutrino-driven wind forms
right after SN core collapse.
n + α + p

↓

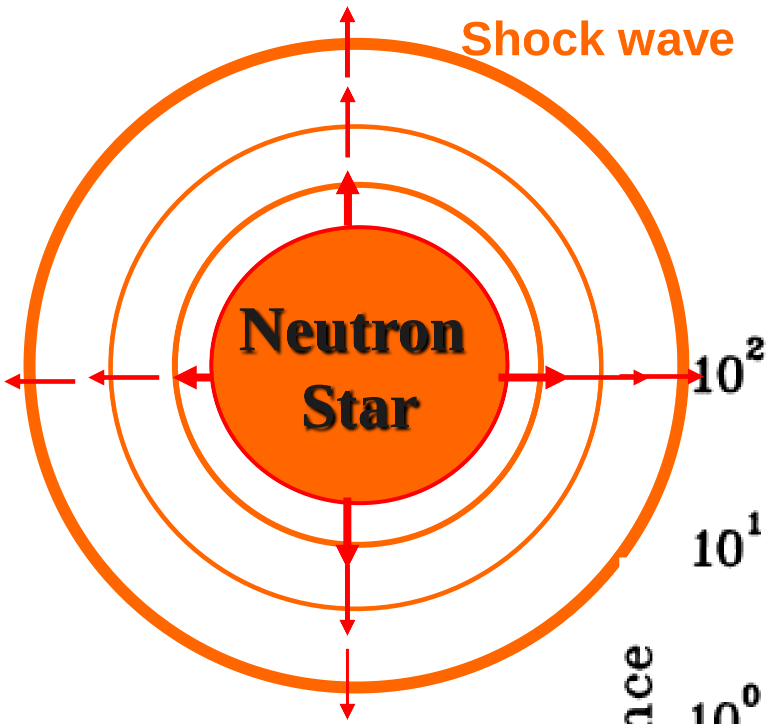
t = 18 ms
Seeds form.
Exotic neutron-rich; ^{78}Ni

↓

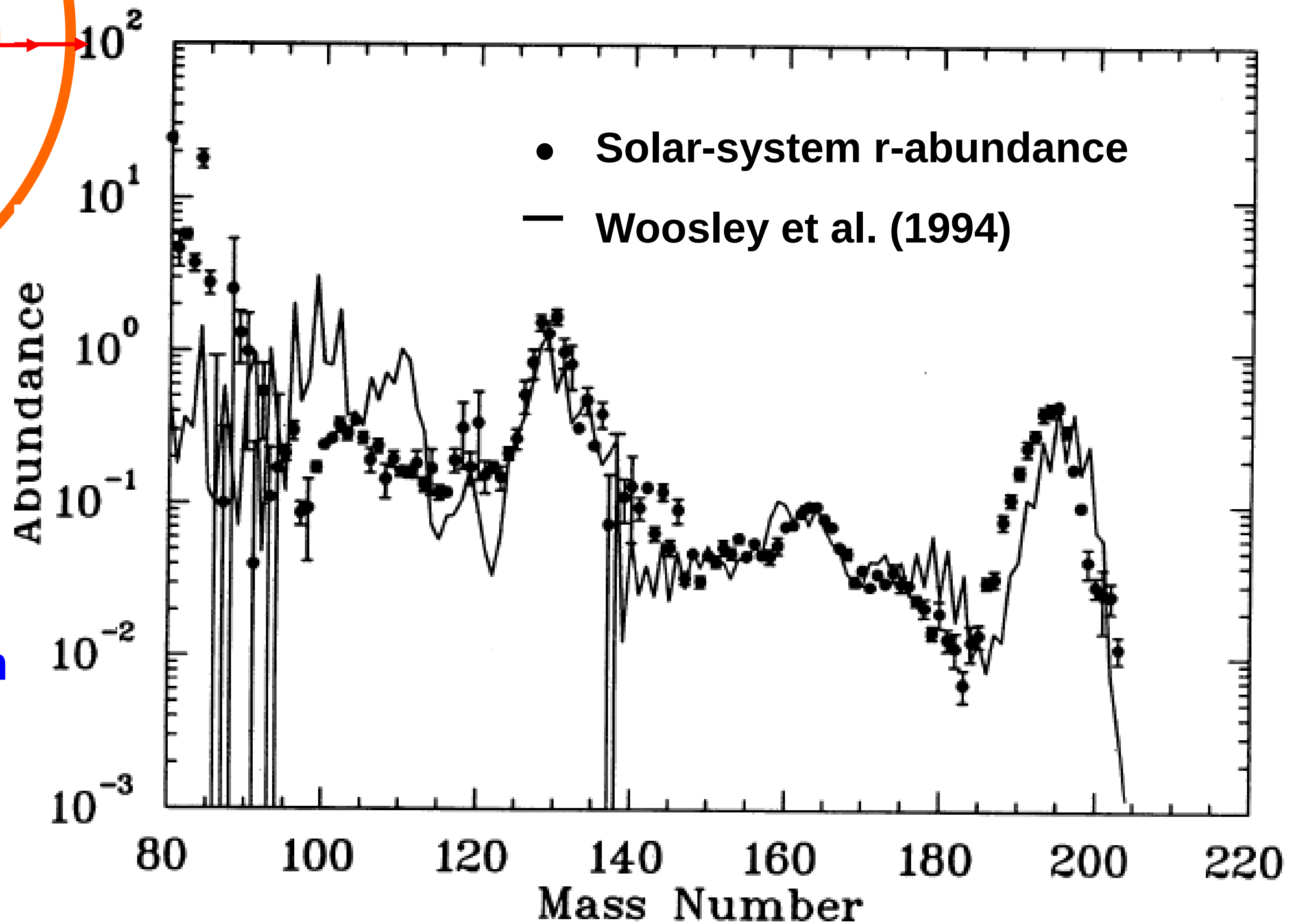
t = 568 ms – 1 s
Heavy r-elements form.



(a) Neutrino-Driven Wind



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

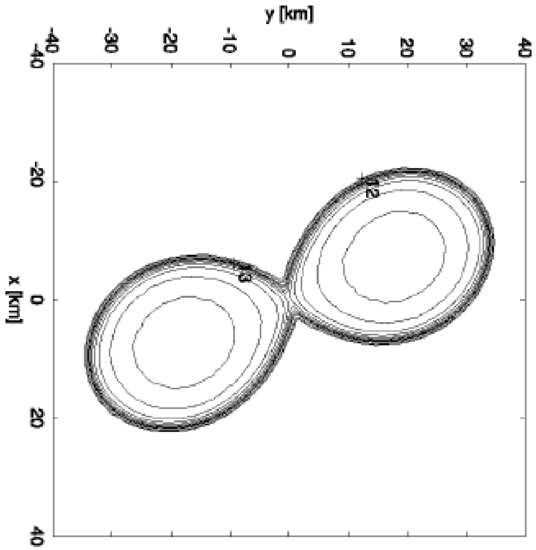


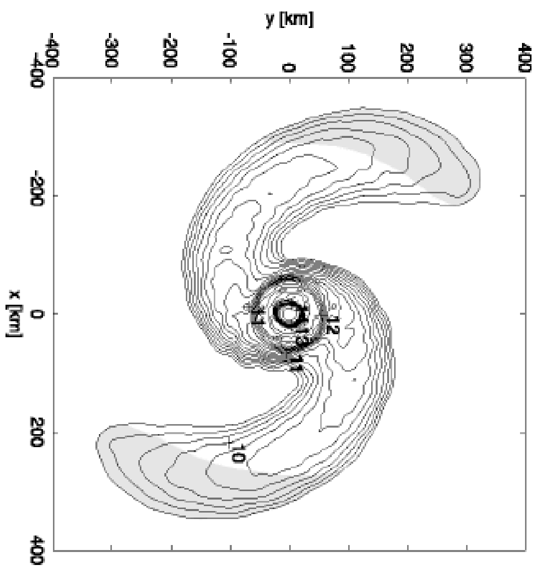
- Universality !
- 2nd, REH & 3rd peaks!
- Right total solar-system r-element abundance !

- No explosion model !!

(b) Binary Neutron-Star Merger

Freiburghaus, Rossbog, a& Thielemasnn, ApJL 525 (1999), 121.



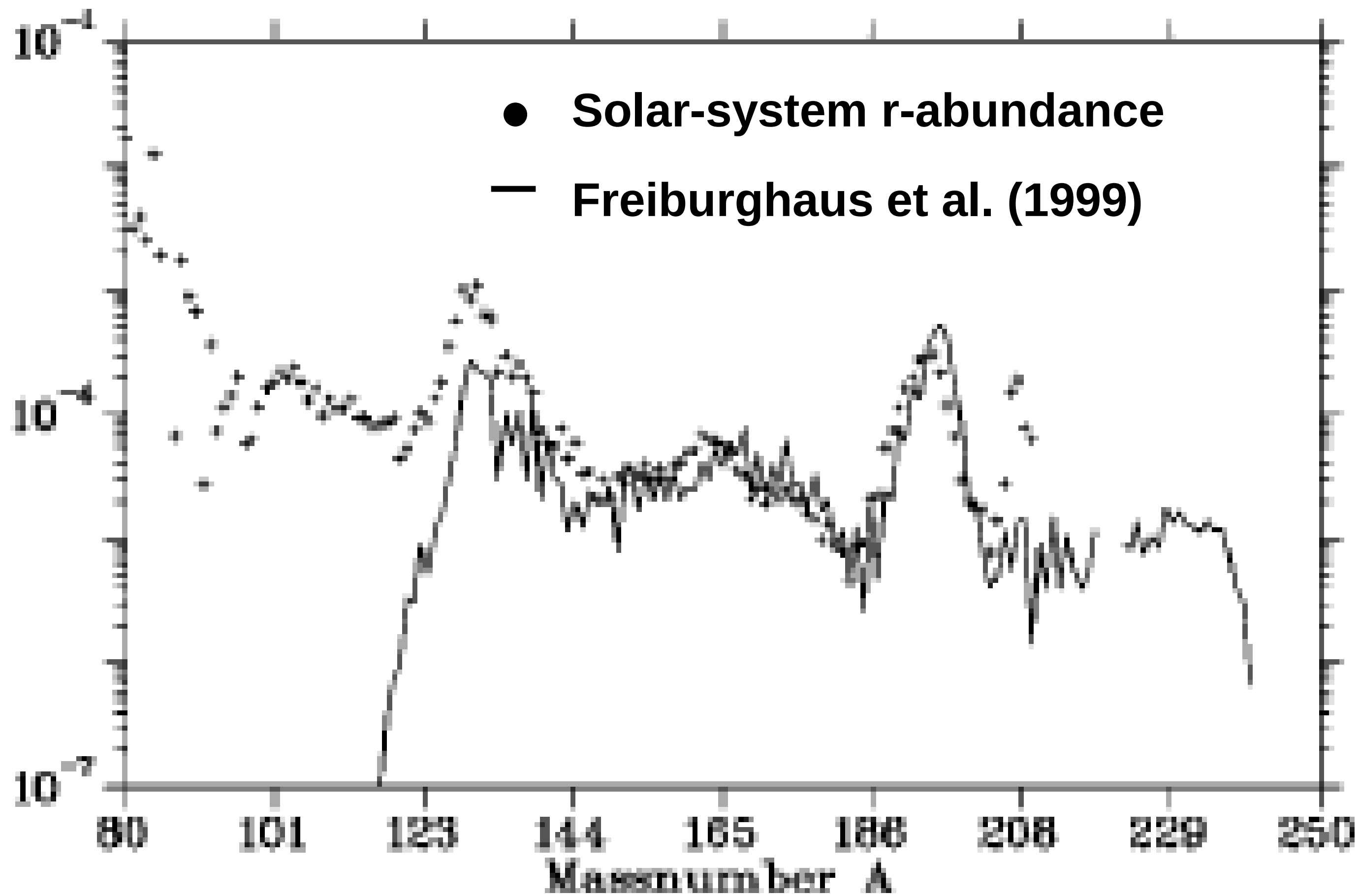


- REH & 3rd peaks!

- Universality breaks down (No 1st peak) !

- Too rare event (takes cosmological time scale) !

Not Solar-system abundamce.



(c) MHD JET

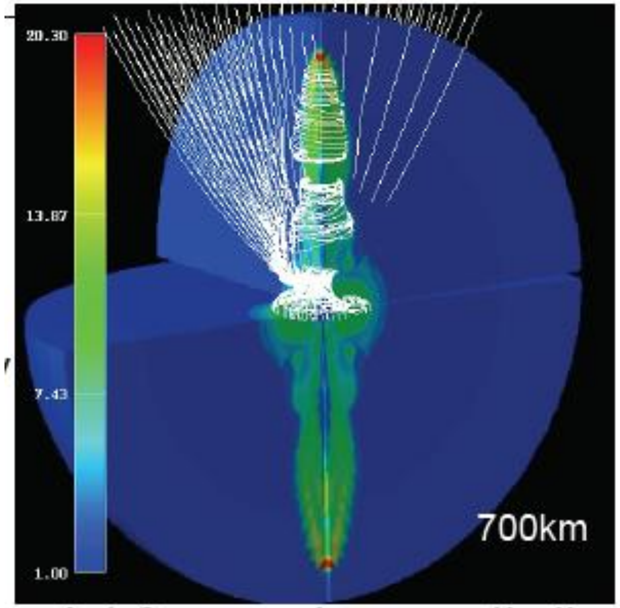
Nishimura, Hashimoto, Fujimoto, Kotake, & Yamada, Proc. Nuclei in Cosmos (2006), 151.1.

Nishjimimura, Kotake, et al. (2009), in preparation.

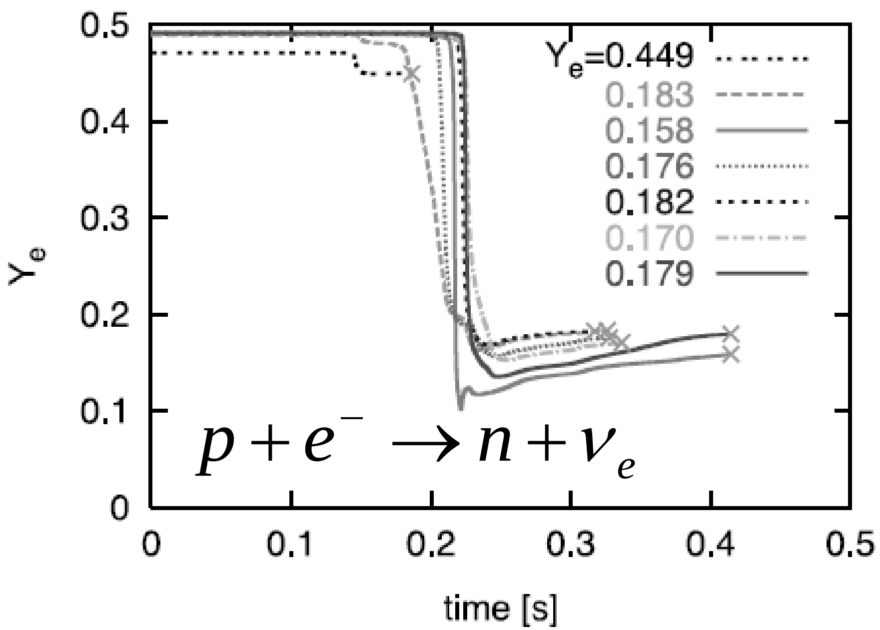
- **EXPLOSION succeeds, when strong magnetic field and fast rotation are fine tuned.**

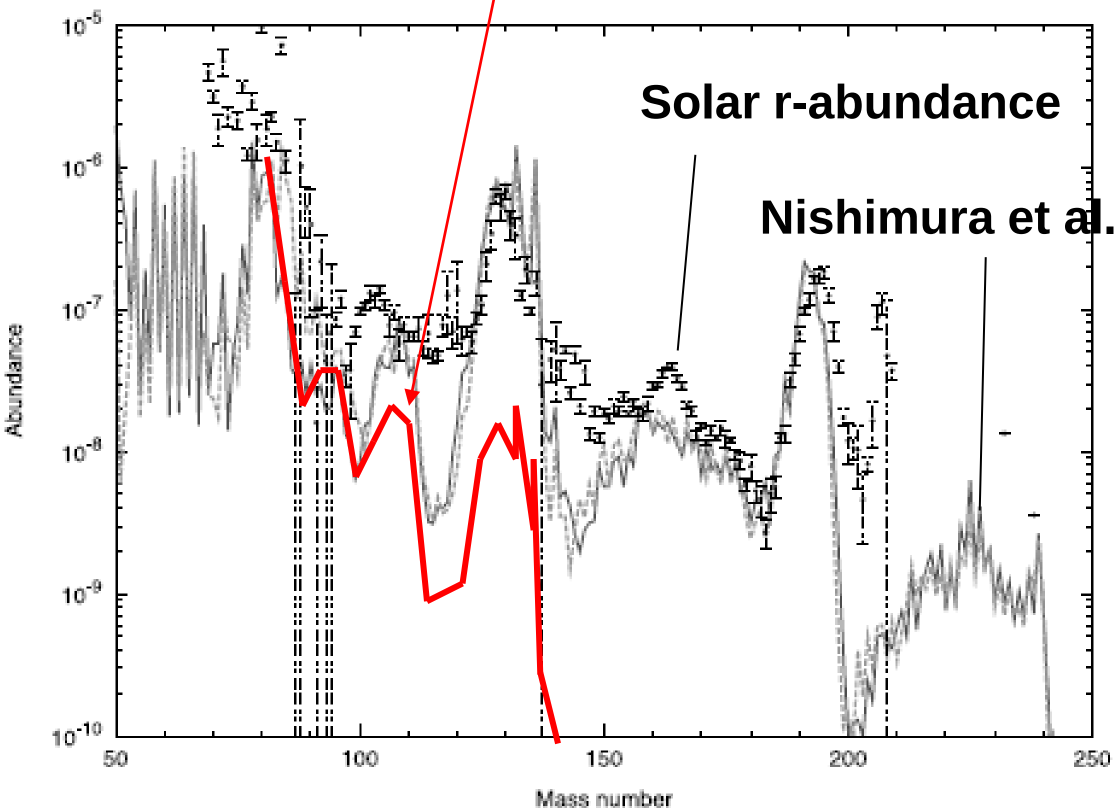
  Ω_0=42.9 (s^{-1}), B_0=5.2 × 10^{13} (G)

- **Universality, not good ! No s.-s. abundance!**
- **R-process breaks down when turning on ν-interactions.** $n+\nu_e \to p+e^-$ $p+\overline{\nu}_e \to n+e^+$



Jet & wound magnetic line (entropy contour)





Candidate Astrophysical Sites for R-Process

Supernova R-Process

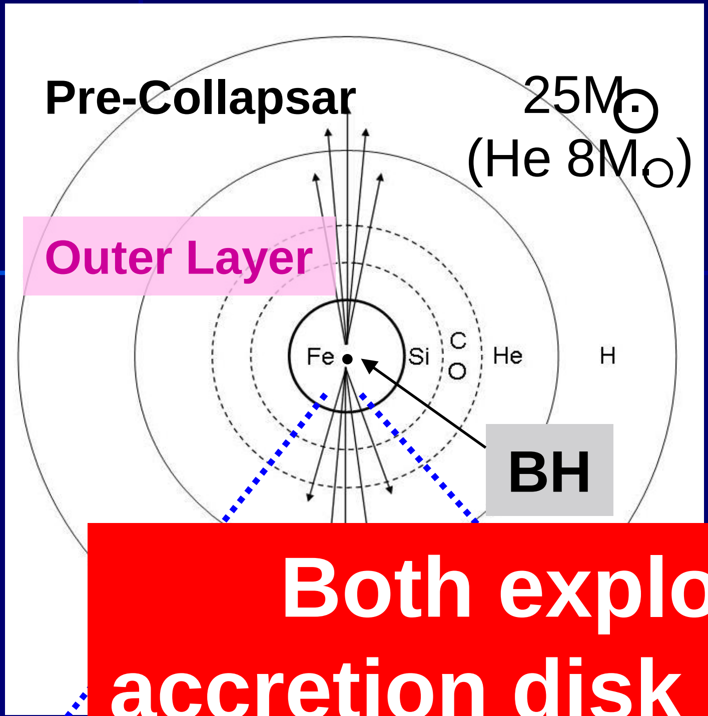
from Ishiyama & Miyatake (2009)

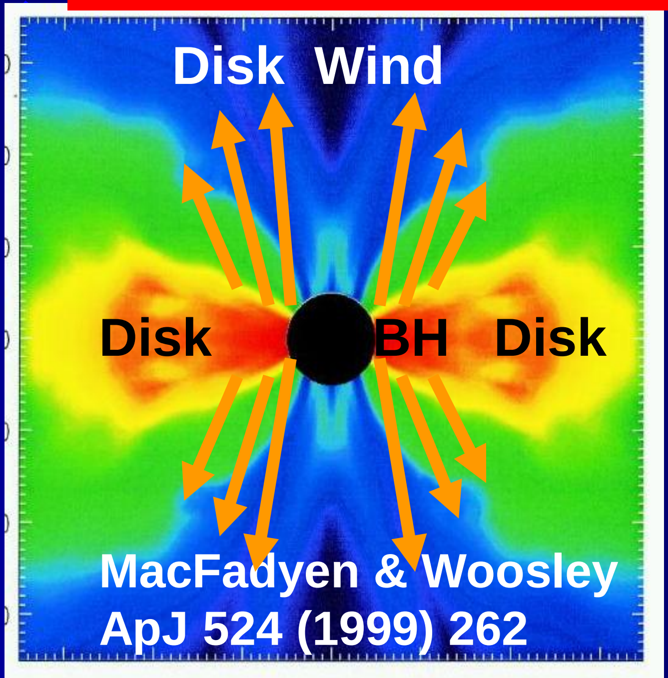
Candidate	Physical Conditions: S	Ye	$M_r/(SN)$	Expected Event Rate	Evaluation
(a) ν-Driven Wind	~ 100	0.45	$10^{-5} M_\odot$	10^{-2}/yr/galaxy*	
(b) Binary Neutron Star Merger	~ 1	0.1	$10^{-2} M_\odot$	$(<10^{-5})$	
(c) MHD Jet	~ 10	0.1~0.4	$10^{-3} M_\odot$	$(< 10^{-6})$	

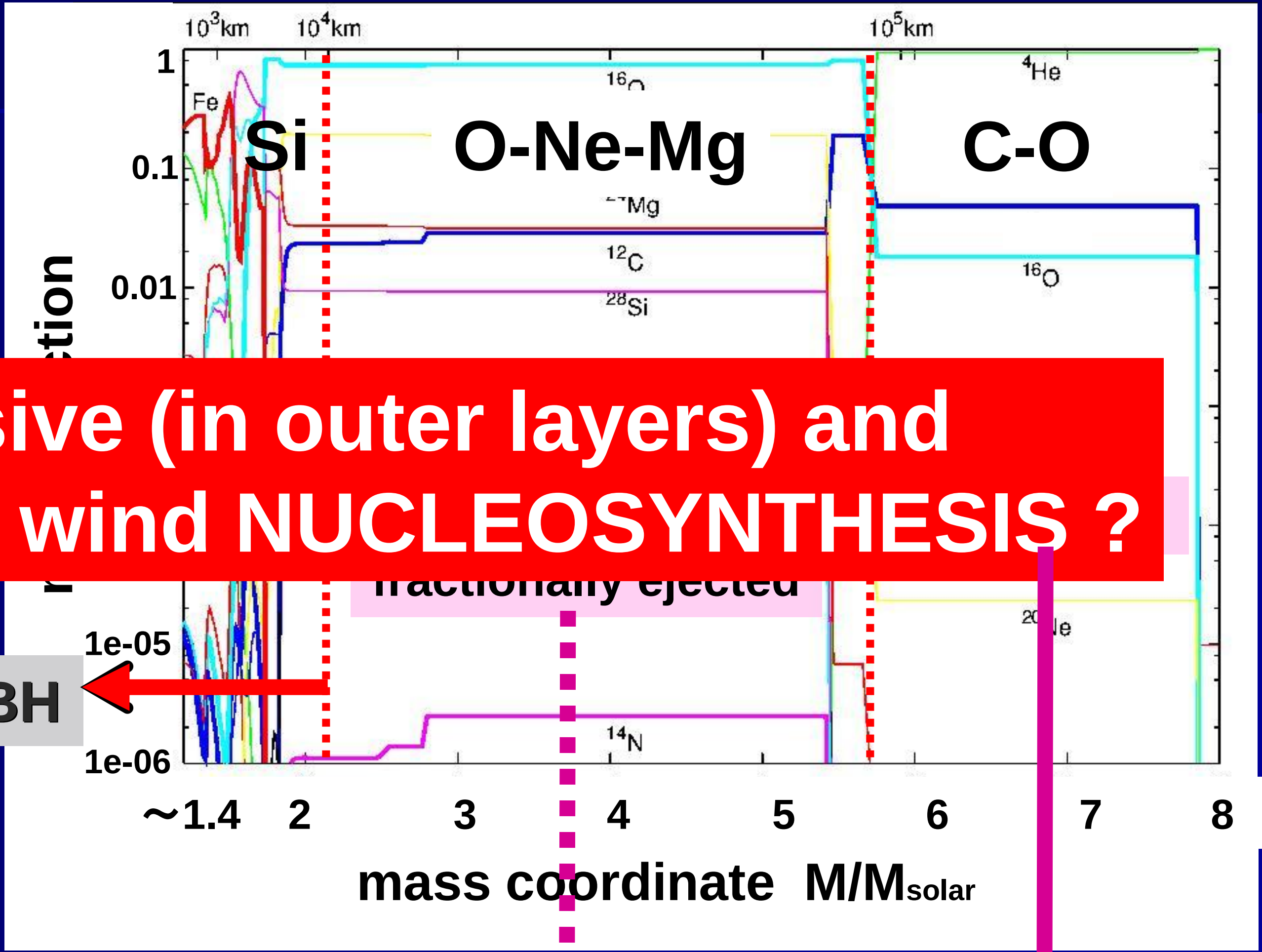
Abundance anomaly found in a most metal-deficient star HE 1327-2326 [Fe/H] = -5.4 cannot be explained!

Expected nucleosynthesis in GRB

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







Both explosive (in outer layers) and accretion disk + wind NUCLEOSYNTHESIS ?

$f_{ej} = 10^{-5}$

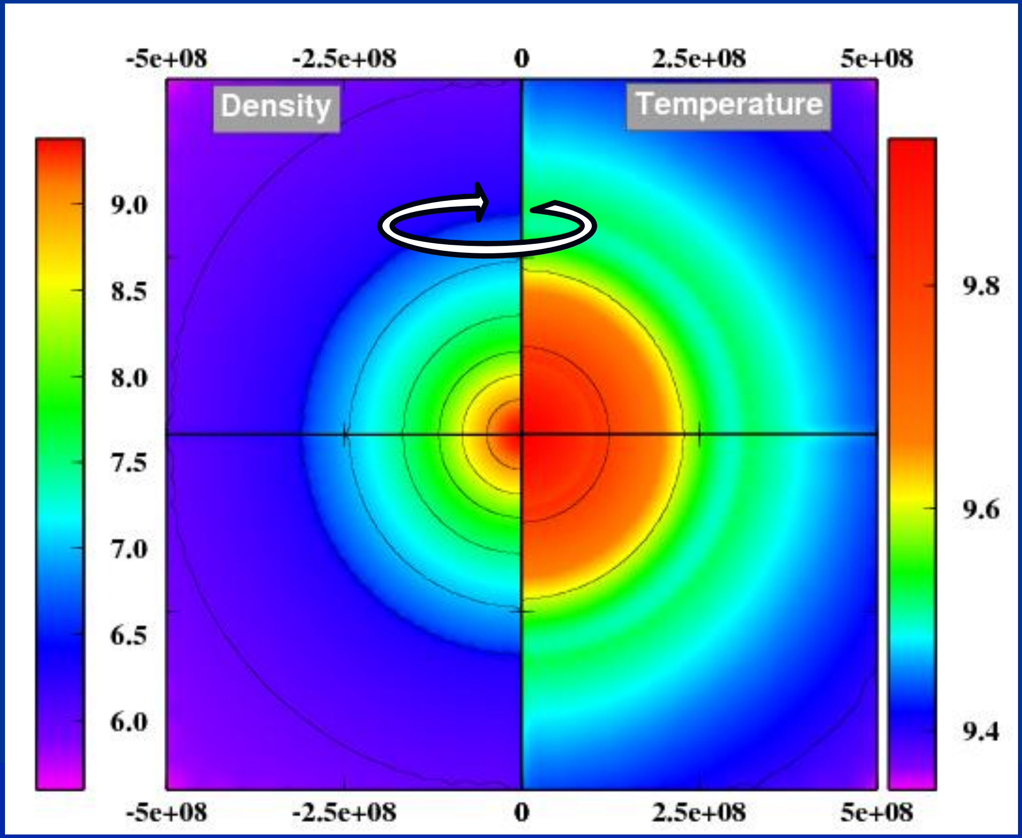
CNO elements enhanced !

1. 2D Hydrodynamic Disk Formation

Harikae et al. 2009, submitted to ApJ.

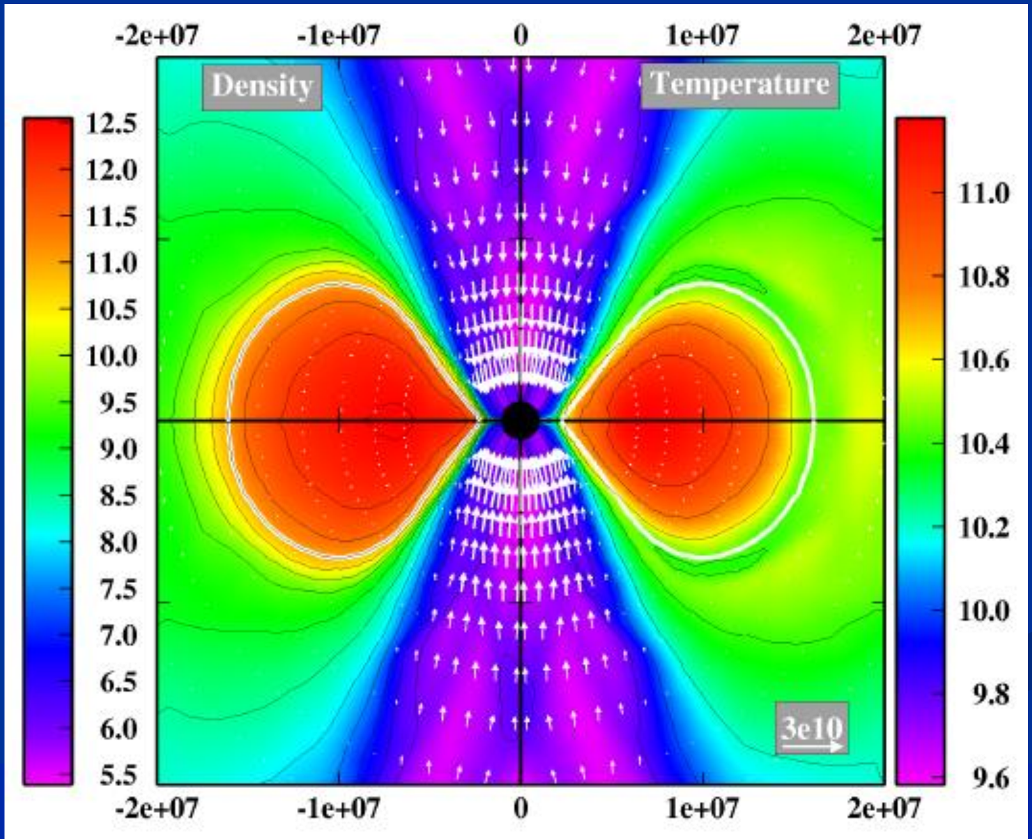
Core collapse onto BH → Formation of BH disk

Density Temperature



5000 km 0 5000 km

Density Temperature



200 km 0 200 km

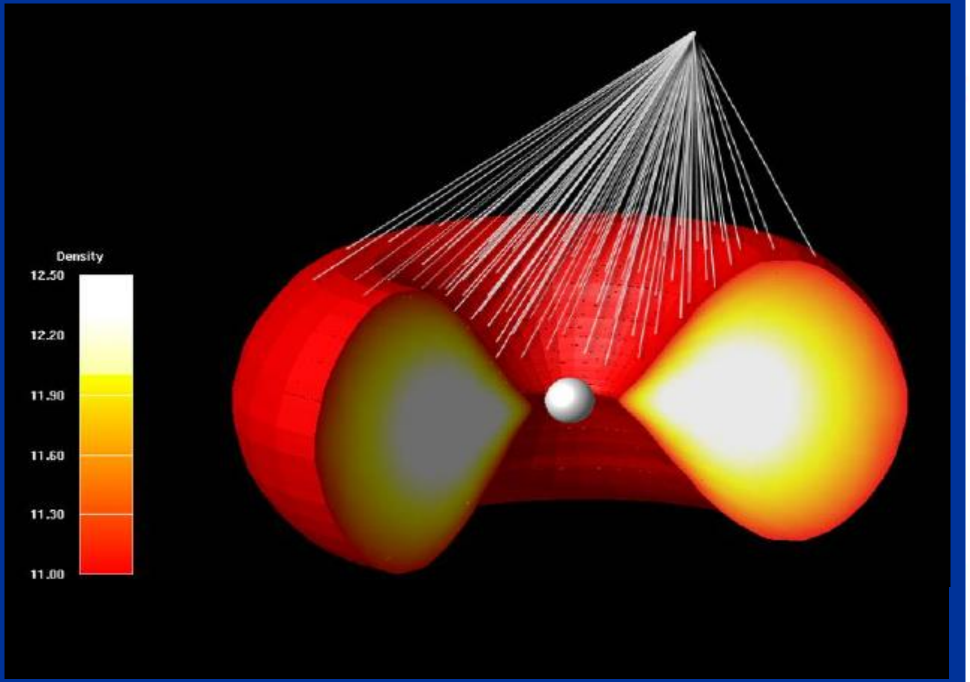
Neutrino Pair-Annihilation

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

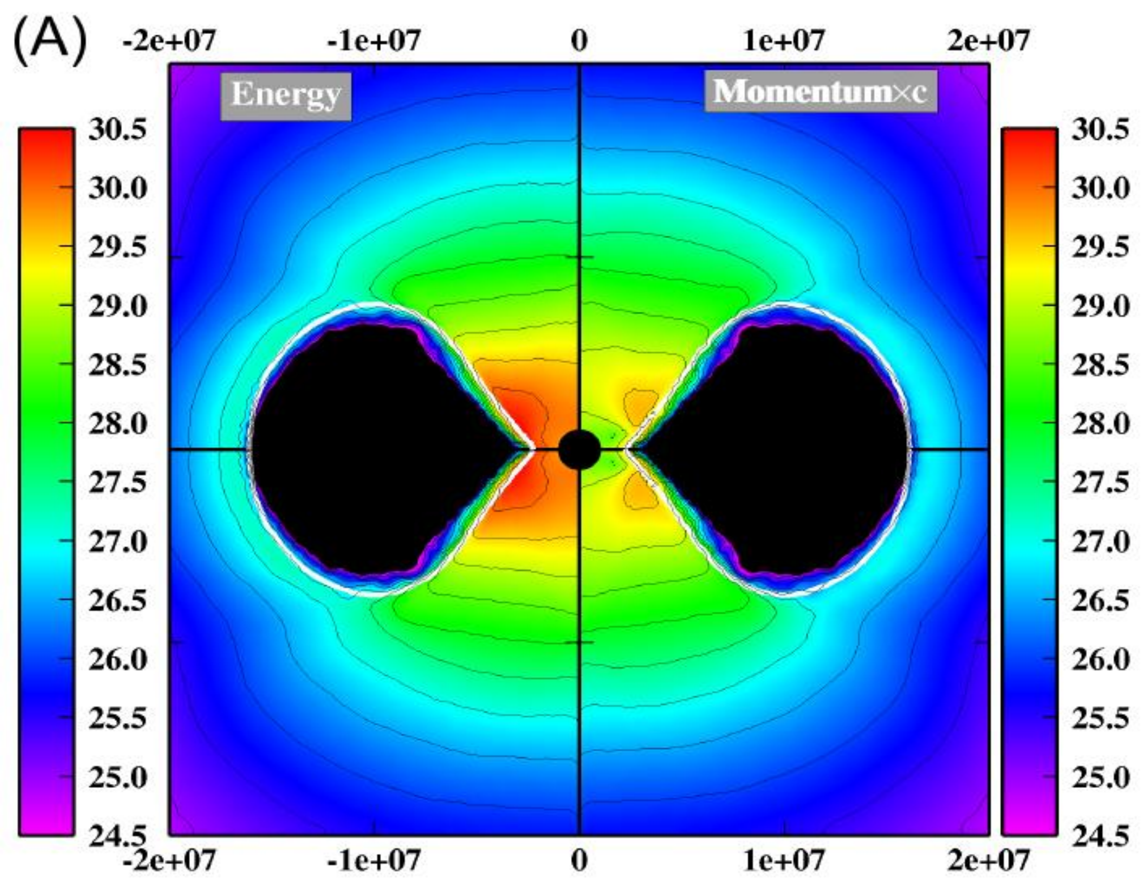
We ray-trace neutrino pair-annihilation when the time scale of neutrino heating is shorter than dynamical (free-fall) time scale.

Energy Production

Momentum Transfer



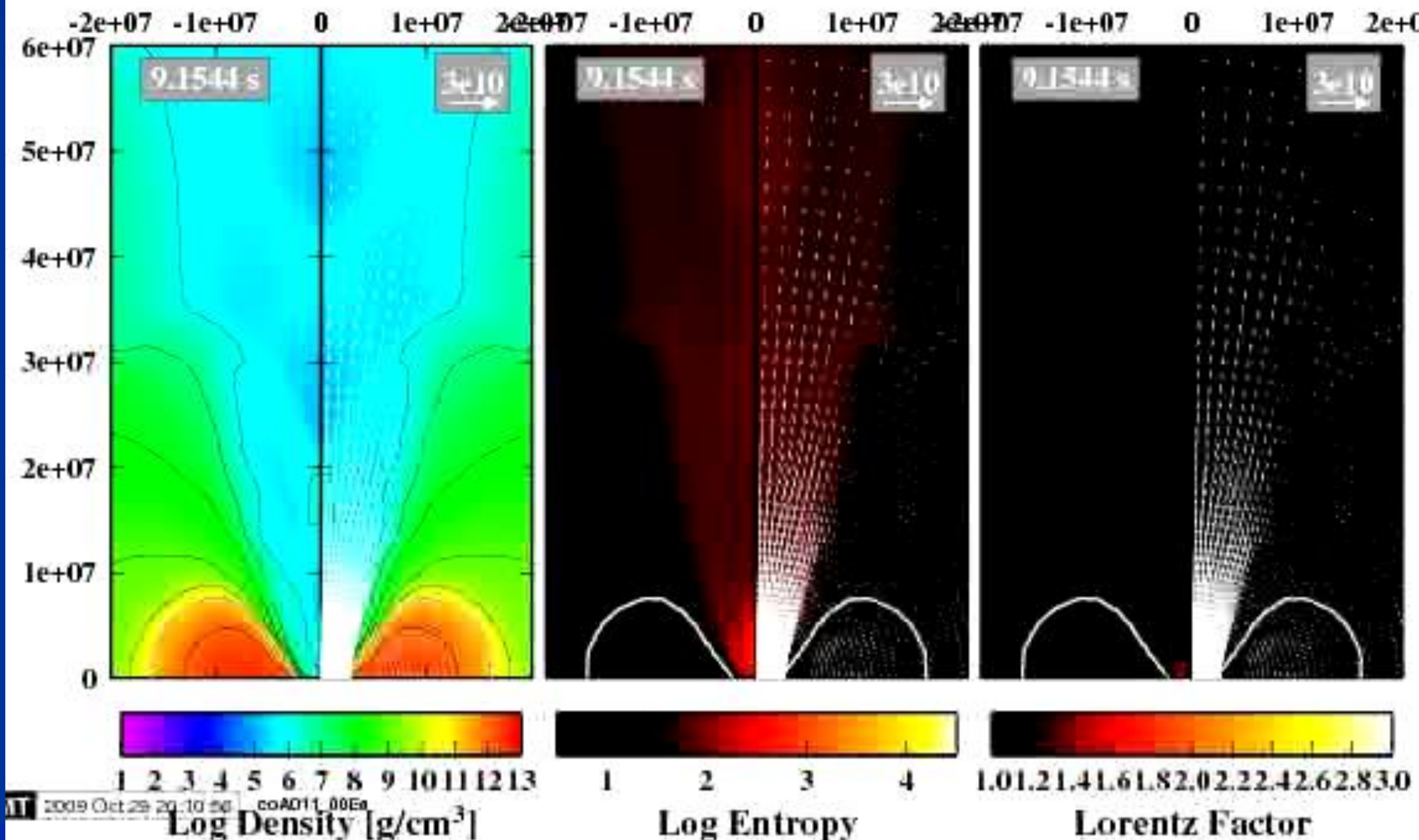
Newtonian



200 km   0   200 km

Neutrino-Heating of Polar Wind

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



600 km

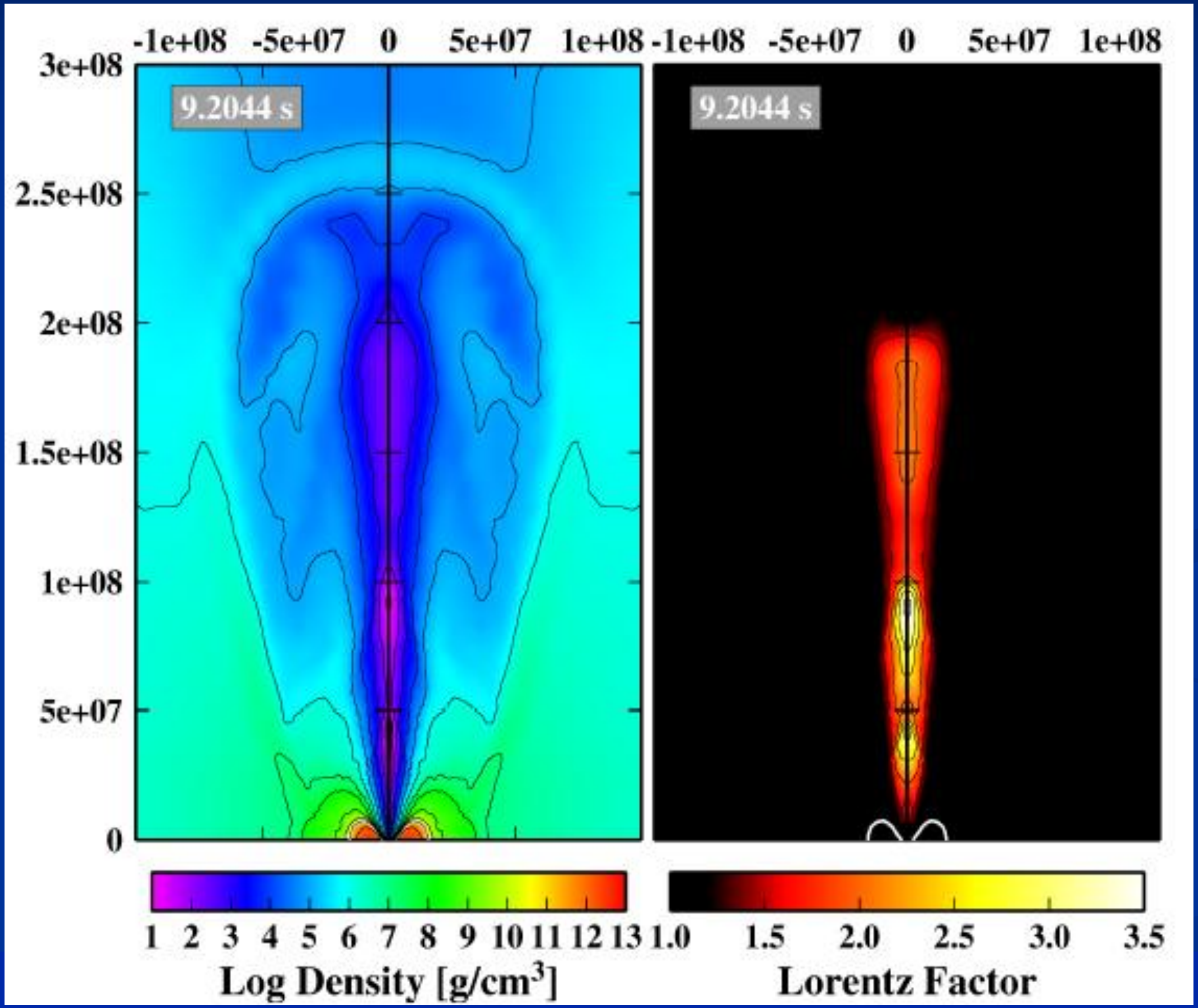
300 km

0

0 200 km 0 200 km 0 200 km

Properties of Wind Outflow

Harikae et al. 2009, submitted to ApJ.



At the edge of Iron-Core (～3000km)

$\rho \sim 10^3$ g/cm^3

S/k ～ a few hundreds

$Y_e < 0.5$

$\Gamma > 3.0$

Energy Production

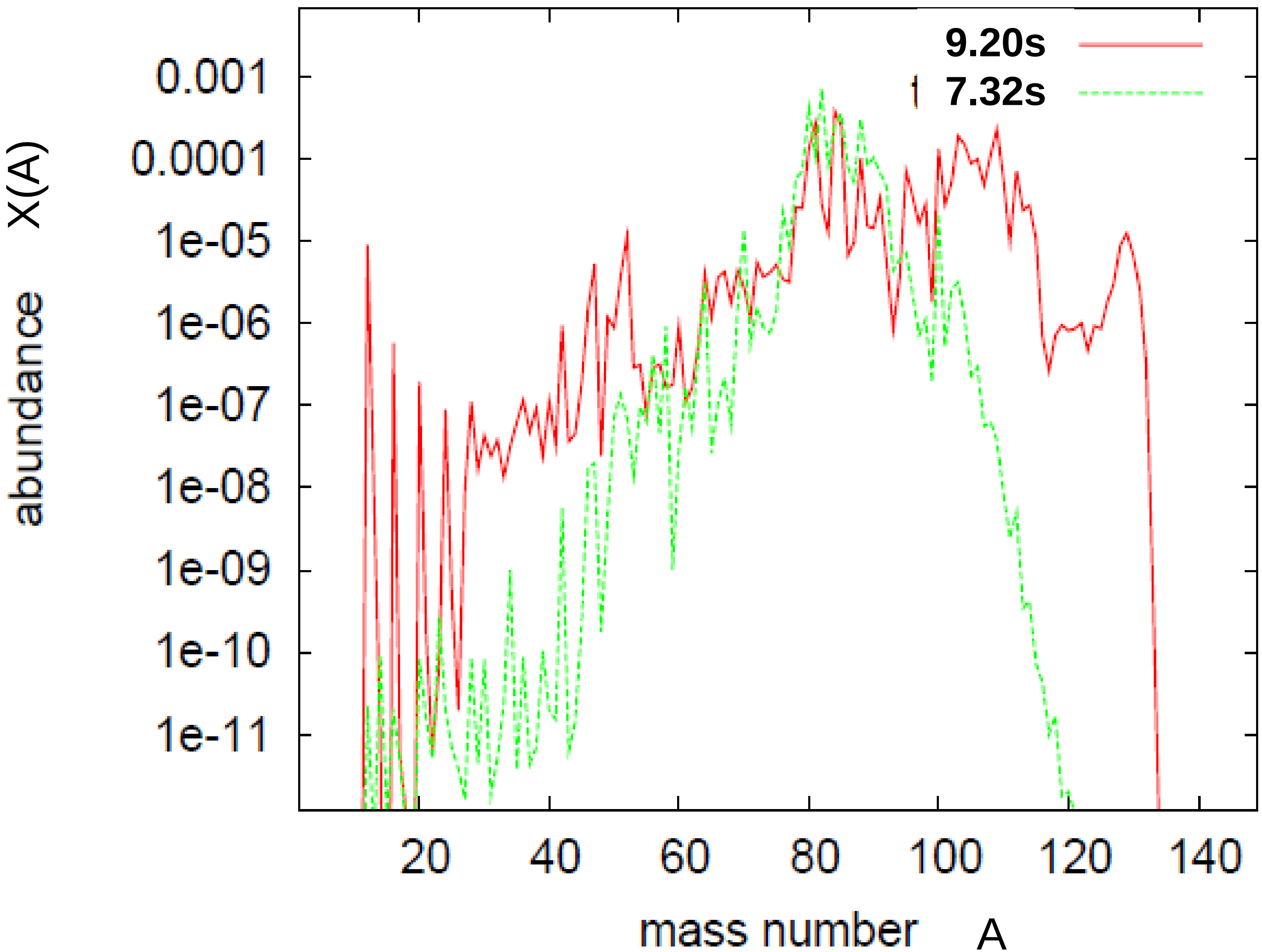
dE/dt ～4×10^{49} erg/s

⬇

GRB candidate !

2-1. Nucleosynthesis in the 2D-Wind Outflow

Single trajectory **Kajino, Sato, Nakamura, Nishimura & Mathews (2010)**



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

理論モデル

- **定常Accretion disk**
  - z-方向は1 zone
  - 移流優勢
  - Pseudo-Newtonian重力場
  - 質量降着率$\dot{M}$：パラメータ
- **円盤風(outflow)**
  - 速度一定　f_v：パラメータ
  - 断熱膨張
  - Outflow範囲

    $5\, r_g < r_0 < 100\, r_g$
- **元素合成計算**
  - 約5,000核種
  - 初期組成 ➡ $8M_\odot$ He星モデルの酸素層の組成

Basic Equations for Semi-Analytic Static Accretion Disk and Winds

Kajino, Shaku, Sasaqui, Yoshida, Aoki & Mathews (2010)

Mass Cons. : $\dot{M} = 2\pi r v_r \Sigma,$ $\Sigma = 2\rho H$

Ang. Momt. Cons. : $4\pi\alpha_{vis} PH = \Omega_K \dot{M}\left(1 - \sqrt{\frac{r_0}{r}}\right)\frac{3(r-r_g)}{3r-r_g}$

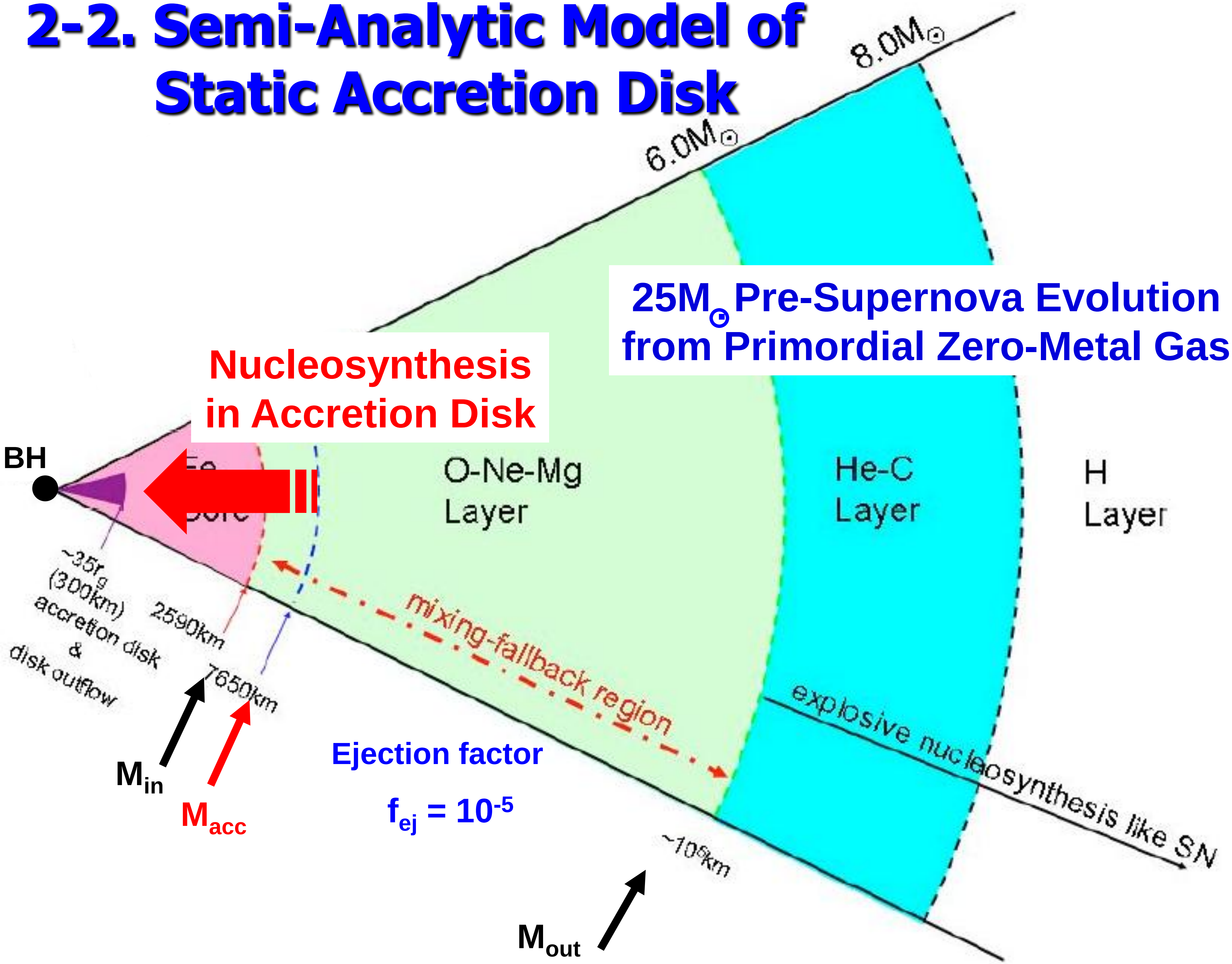
Z- Pressure Equilib. : $\frac{P}{H} = -\rho\frac{GM}{(r-r_g)^2}\frac{H}{r}$ $(P = \rho H^2 \Omega_K^2)$

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

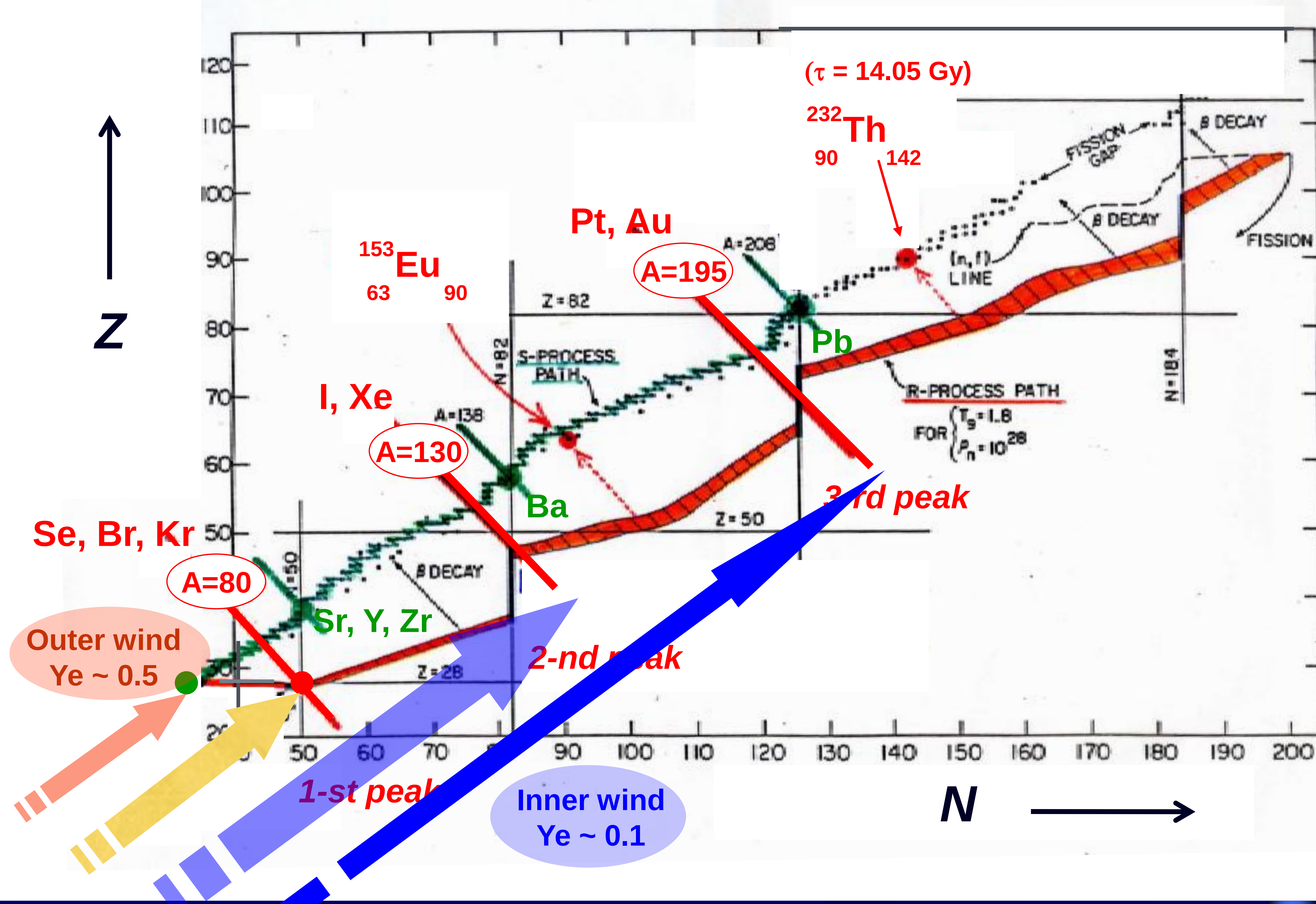
Equation of Motion γ & e± : $P = \frac{11}{12} a T^4$

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

2-2. Semi-Analytic Model of Static Accretion Disk



GRB-Wind: Very Rapid Neutron-Capture Process



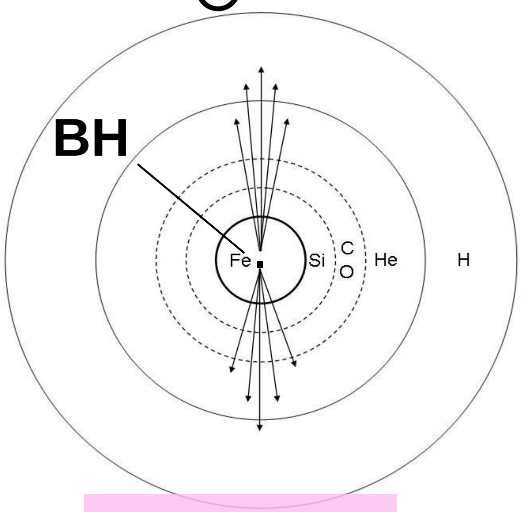
GRB Nucleosynthesis Model Prediction

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

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

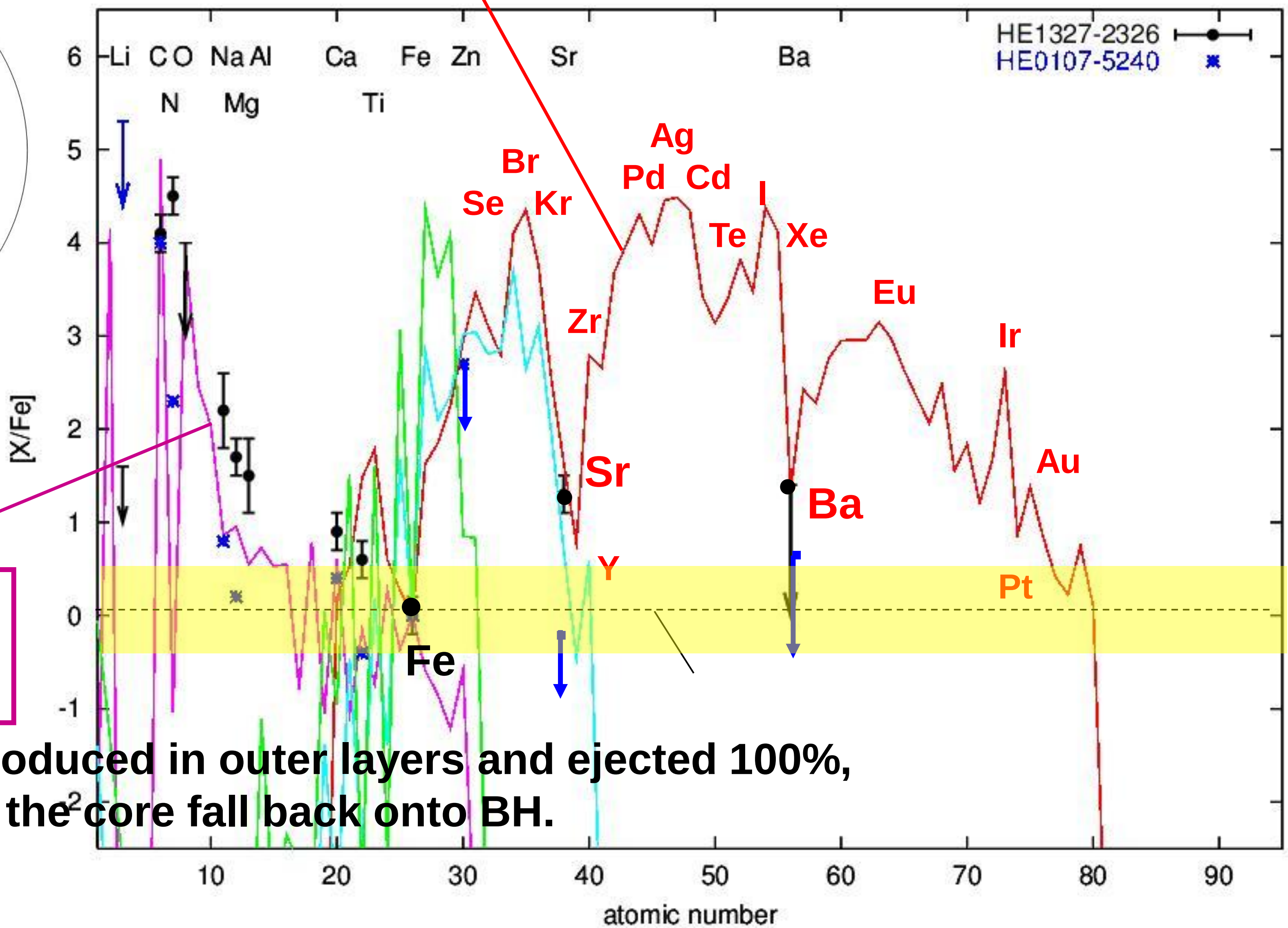
Pre-Collapsar

$25M_\odot$



Outer Layer

R-Process from Disk-Wind Outflow



Mixing Fallback onto BH

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

SUMMARTY

（1） We constructed a 2D hydrodynamic (heated by neutrino pair-annihilation) and semi-analytic models of collapsar which is the central engine of gamma-ray bursts, which consists of Black Hole and Accretion Disk.

（2） Explosive nucleosynthesis in COLLAPSAR models (2D hydro and Semi-Analytic) for the GRB central engines can explain newly discovered elemental abundances of the most metal-deficient ([Fe/H] = -5.4) halo star HE 1327 2326.

- Enhanced CNO could be a signature for BH.
- Heavy elements (Sr, Ba …) could be a signature for the R-PROCESS in accretion-disk wind outflow.

⇒ Neutrino interaction & oscillation effects