高速回転大質量星の磁気駆動型超新星爆発における r-process元素合成

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連星合体からの重力波・電磁波放射とその周辺領域
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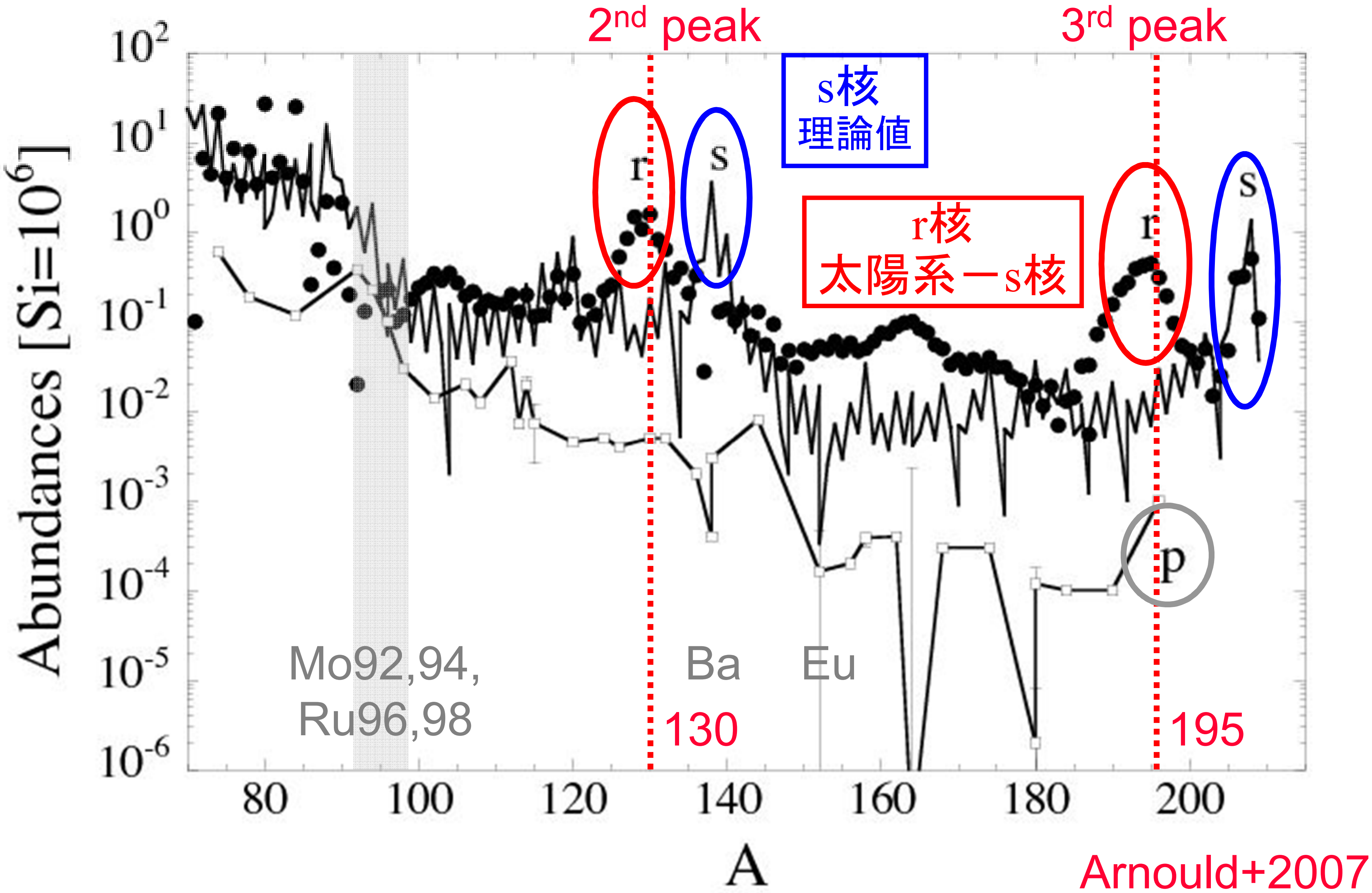
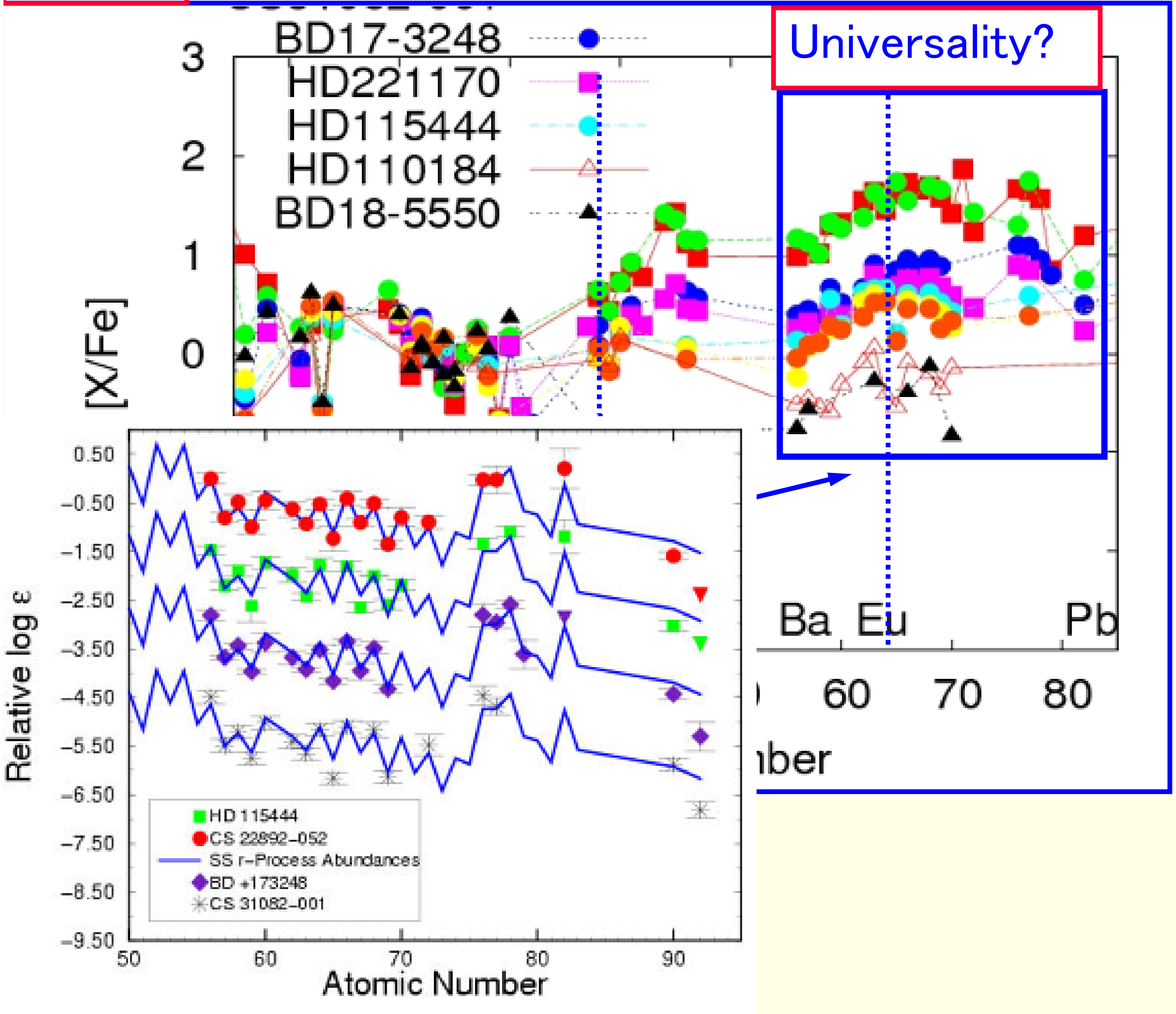
京都大学基礎物理学研究所

太陽系重元素組成 VS 質量数



低金属星における中性子過剰核

r-rich　[Eu/Ba] > 0　Data from SAGA



太陽系組成:

複数回の超新星爆発

S−processの影響大

同位体比

低金属星:

少ない超新星爆発

s−processの影響小

同位体比は不明

Baより重い核の組成パターンが似ている

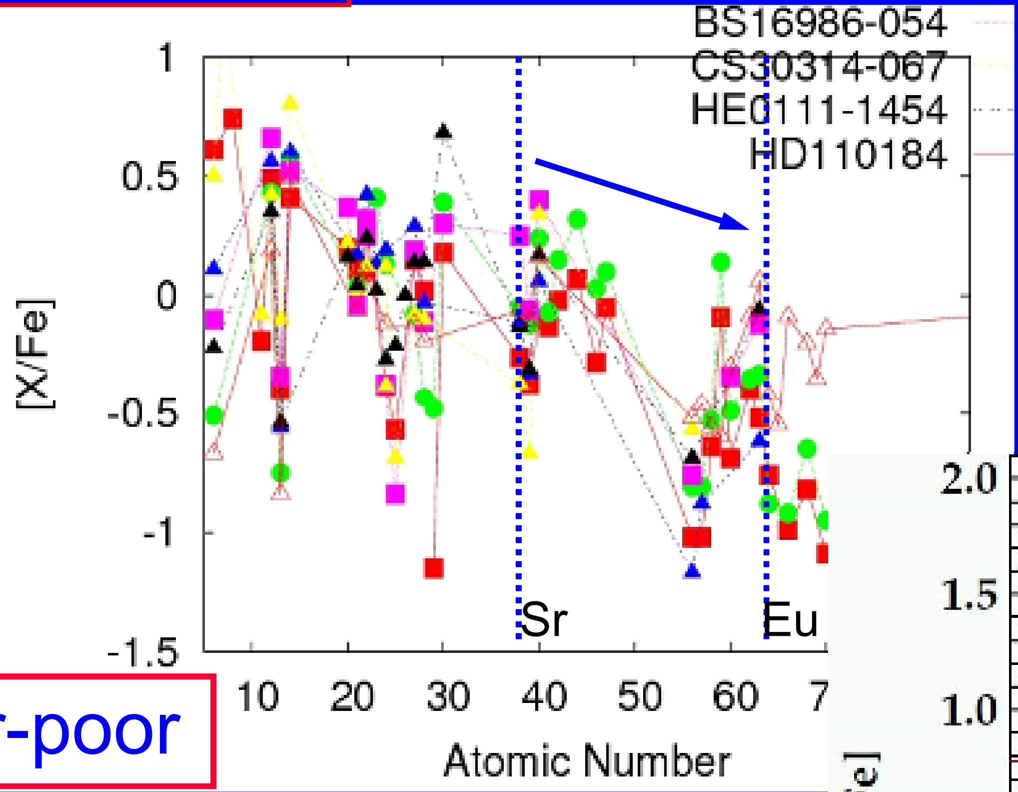
(Main r−process??)

太陽系r−elementsのパターンとも似ている

低金属星における中性子過剰核

[Eu/Ba] < 0

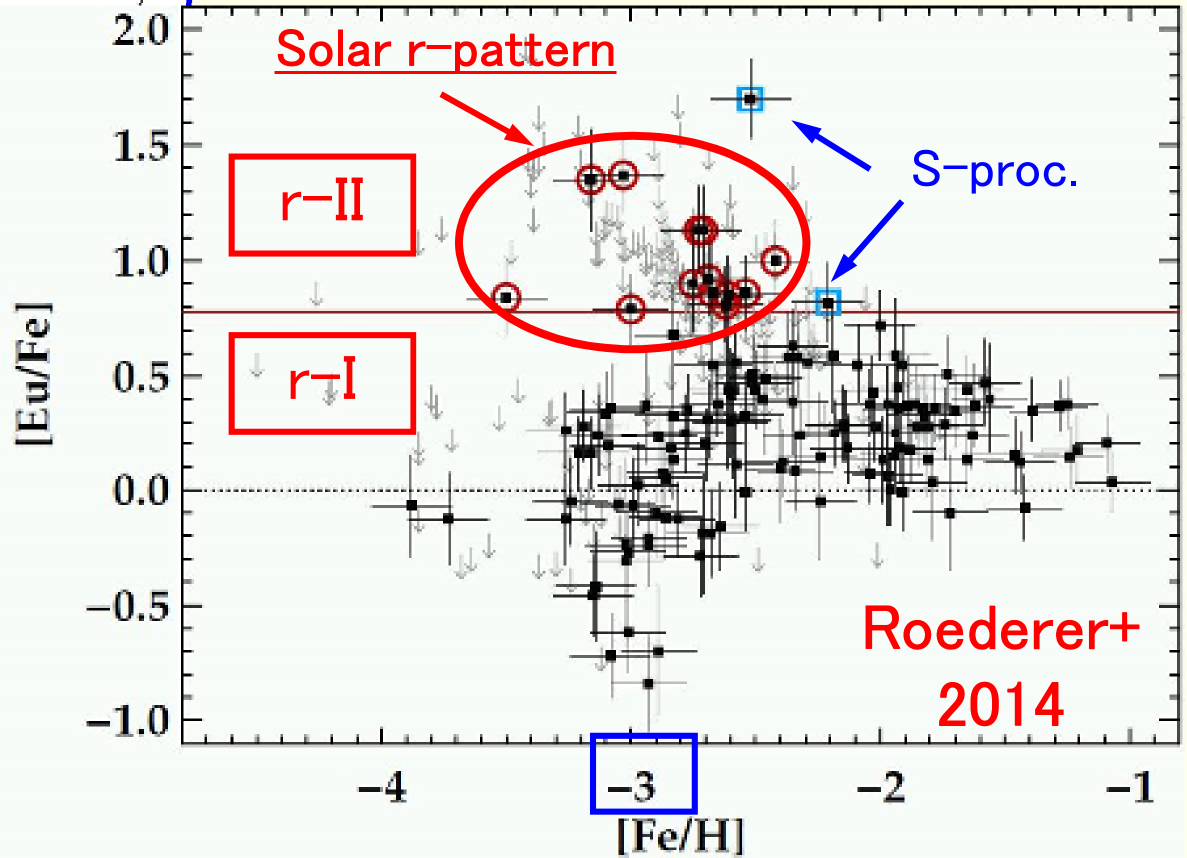
Data from SAGA DB



r-poor

太陽系r-elementパターンと異なる

Weak r-process



[Eu/Fe] > 1 @ [Fe/H] < −3

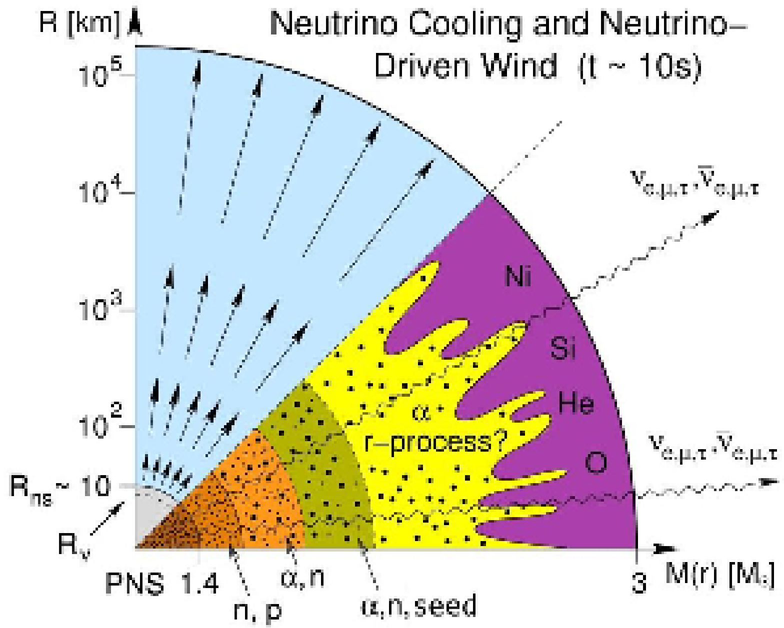
with Solar r-pattern

R-process site candidate

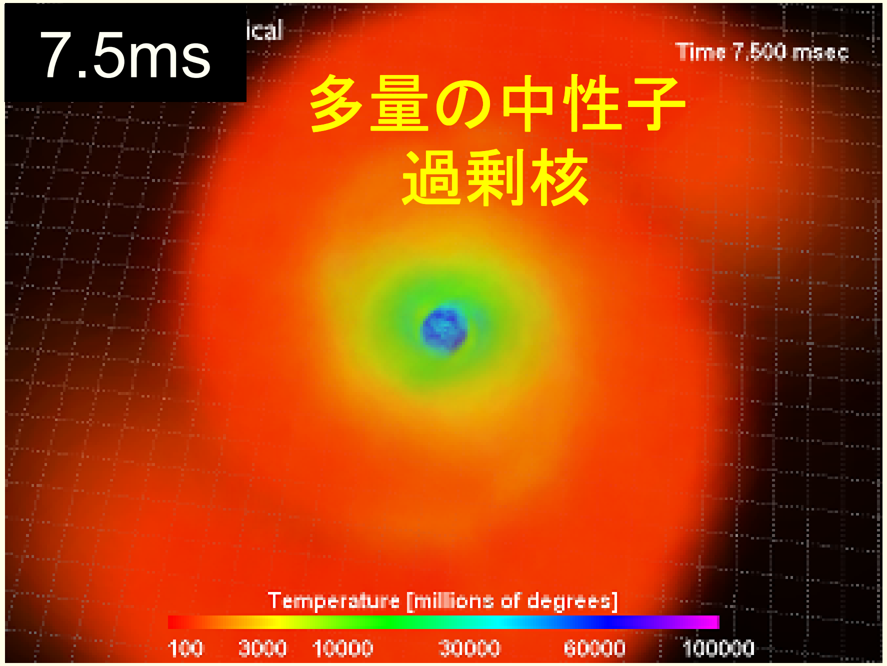
- ニュートリノ駆動風: △
  - 原子中性子星表面のニュートリノ加熱による放出
  - Ye > 0.45？
- 中性子星連星合体: ○
  - 中性子放出
  - 0< Ye < 0.5
  - 銀河進化初期の寄与小（Argast+2004）？
- 重力崩壊型超新星爆発: ？
  - 銀河初期の寄与大
  - ニュートリノ駆動超新星
  - 磁気駆動超新星

$$Y_e = \frac{p}{n+p},\ n/p = \frac{1-Y_e}{Y_e}$$

ニュートリノ駆動風 Janka2006



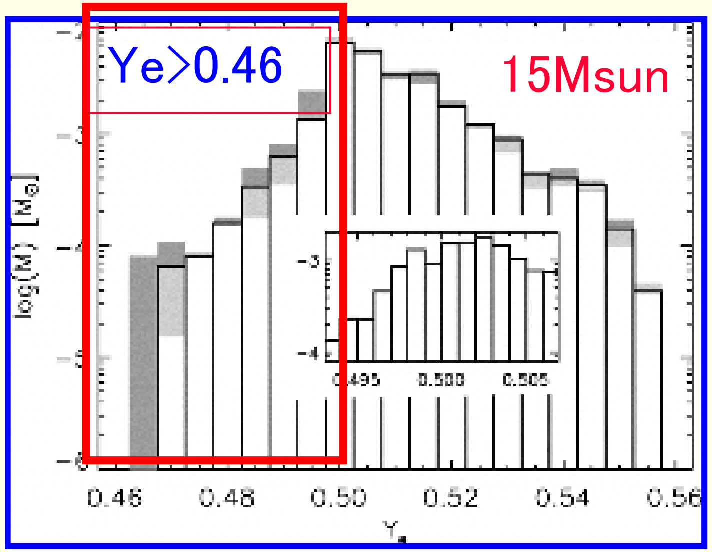
中性子星連星合体 Rosswog+2003



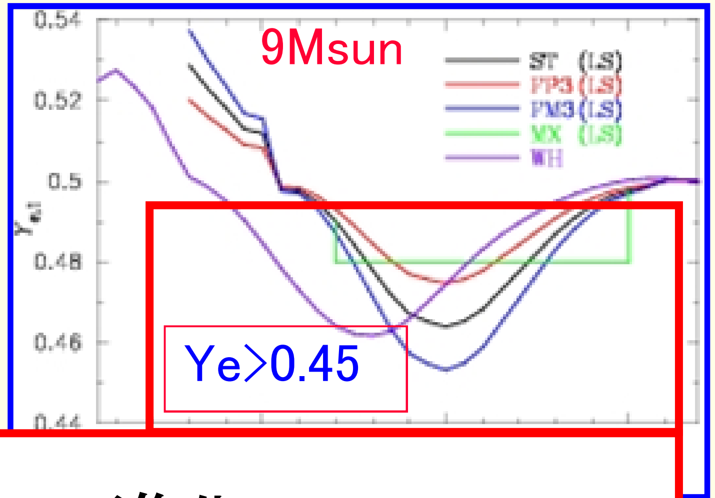
neutron-rich ejecta from SNe

- ニュートリノ駆動超新星爆発
  - 中性子のニュートリノ吸収による加熱
  - Ye ＞ 0.45？
- 磁気駆動超新星爆発
  - ニュートリノ吸収は爆発に非本質的
  - 高いn/p比が期待
  - 13Msun: 2D MHD、Ye進化なし 中性子星(S.Nishimura,SF+06)
  - 15Msun: 3D MHD+Ye進化 中性子星(Wintler+12)
  - 25Msun: 2D MHD+Ye進化 中性子星(N.Nishimura+15)
  - 40&70Msun: 2D MHD、Ye進化なし BH(SF+07,08, Ono,SF+10,11)

Ejecta from nu−driven SN、Pruet05



Ejecta from nu−driven SN、Wanajo07



本研究: 40Msun 2D MHD+Ye進化
→ R-process nucleosynthesis+ニュートリノ吸収

MHD Code

- ZEUS 2D Code: 2.5D Axisymmetric, Newtonian
- Realistic equation of state: Shen EOS (Kotake+03)
- Neutrino transport : Leakage Scheme (Ruffert+96)
  - three flavors
  - Cooling: e- e+ capture, pair annihilation, plasmon decay
  - **Ye evolution**: neutrino interactions in an optically thick region, in addition to e- e+ capture
- Self gravity with approximate GR effects (Marek+05)

Code test: reasonable agreement between our results and those of more elaborate simulations (Sumiyoshi+05,07) for the spherical collapse of 15Msun and 40 Msun stars

Initial setup for MHD simulations

Progenitor models = 40Msun

massive stars before the core collapse (Hashimoto 1995)

Angular velocity

$$\Omega(r) = \Omega_0 \frac{r^2}{r^2 + R_0^2}$$

Slow core

$$\Omega_0 = 1\ \mathrm{s}^{-1}$$
$$R_0 = 3200\ \mathrm{km}$$

Moderate core

$$\Omega_0 = 2.5\ \mathrm{s}^{-1}$$
$$R_0 = 2000\ \mathrm{km}$$

Rapid core

$$\Omega_0 = 5\ \mathrm{s}^{-1}$$
$$R_0 = 1400\ \mathrm{km}$$

Initial magnetic fields

Vertical and uniform

(B0/G=10^{10})

3 models

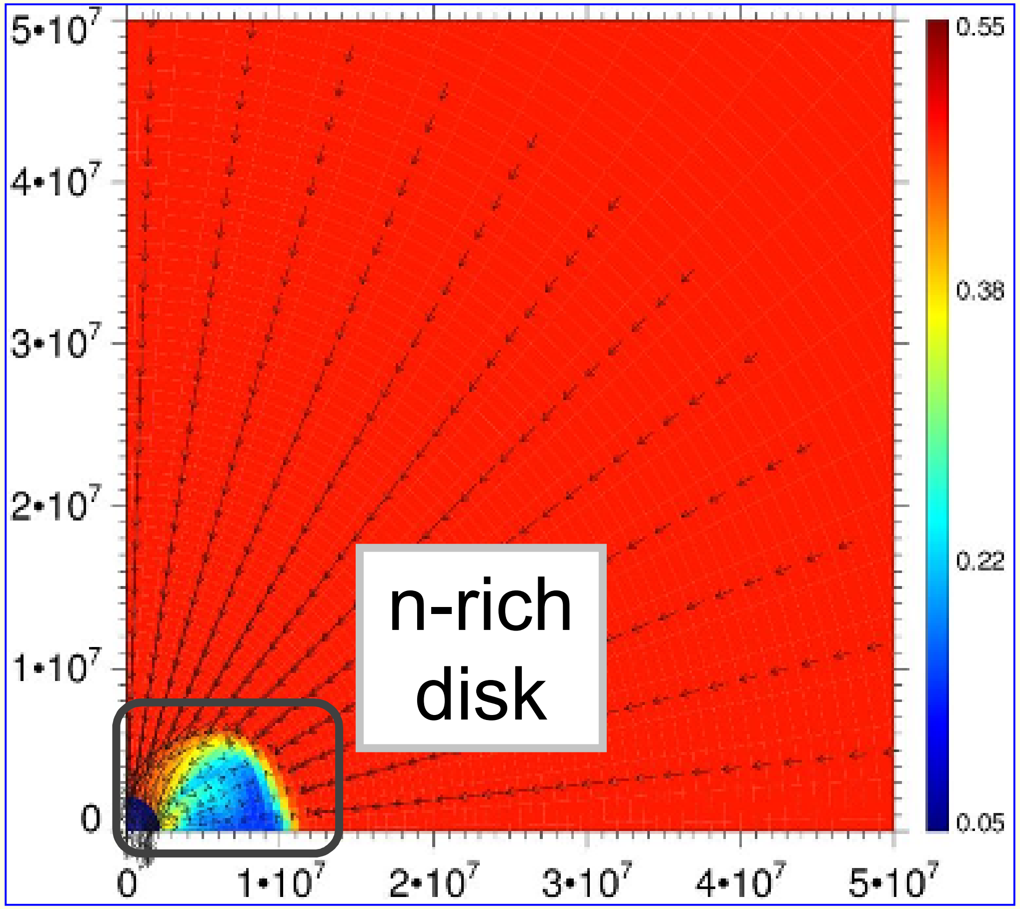
	40Msun		
Model	O1.0	O2.5	O5.0
$\frac{\Omega_0}{s^{-1}}$	1.0	2.5	5.0

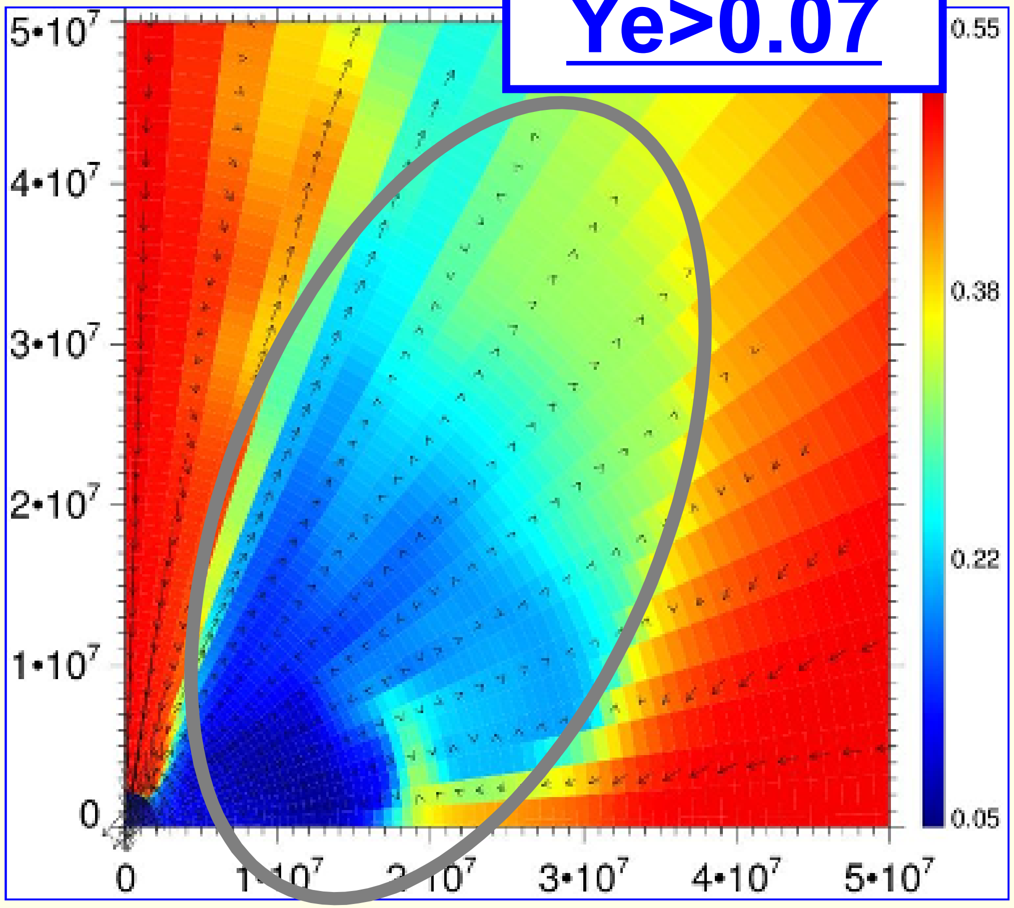
Formation of n-cirh disk & jets

O2.5

Ye=electron fraction

n-rich jets:
Ye>0.07





500km x
500km

Production of 3rd-peak
elements in jets expect

Nuclear reaction network

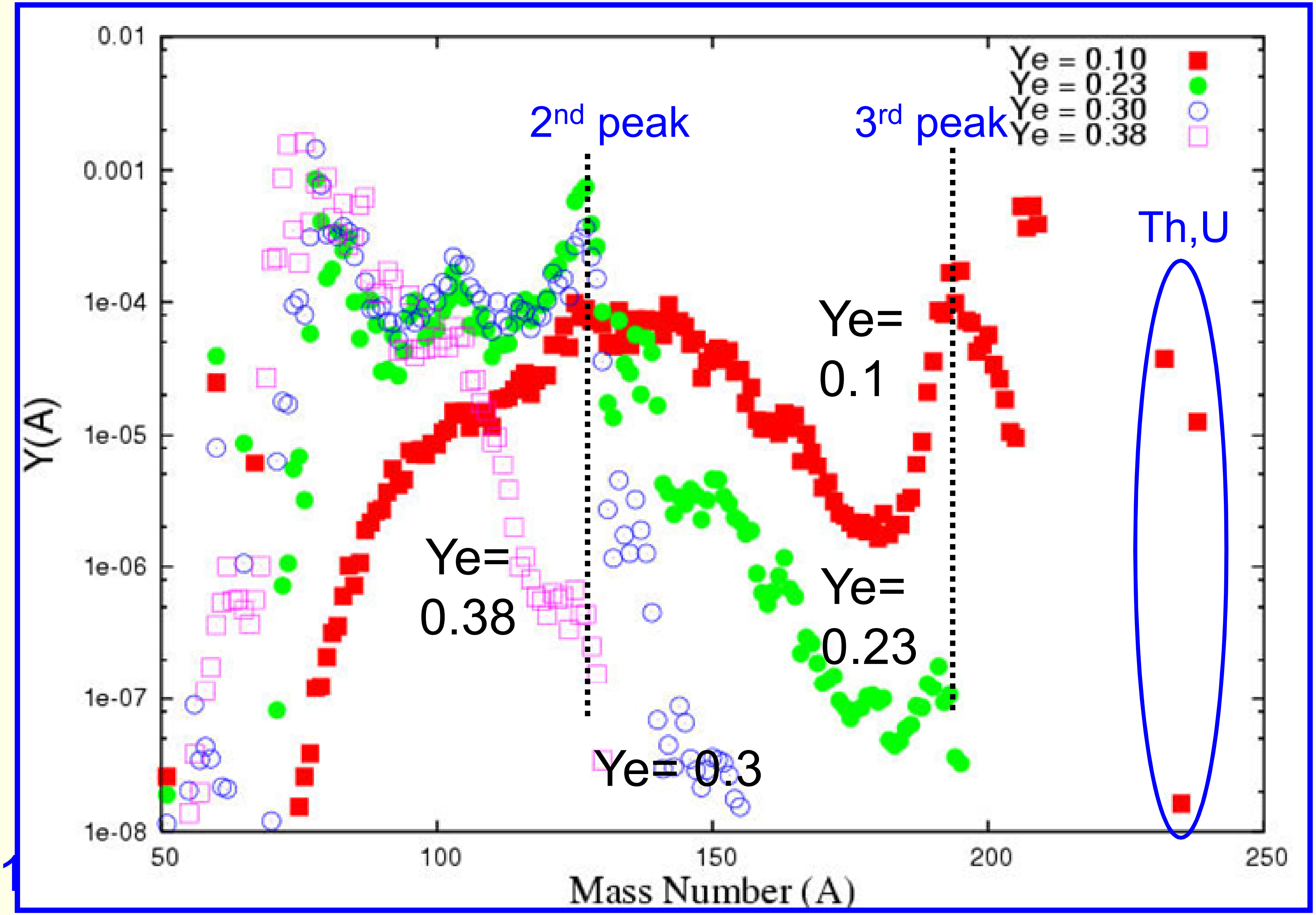
- about 4000 nuclides with atomic number, Z <=100 (Fm)
- two and three body reactions with screening effects
- beta-decay, alpha-decay, and beta-delayed neutron emission
- spontaneous and beta-delayed fission (asymmetric fission yields)
- electron and positron captures
- nuclear masses: (experimental or theoretical masses)

Experimental rates and masses if available,
otherwise theoretical values are adopted

two networks with theoretical rates and masses based on different mass model

1. extended Thomas-Fermi plus Strutinsky integral (ETFSI)
2. finite range droplet model (FRDM)

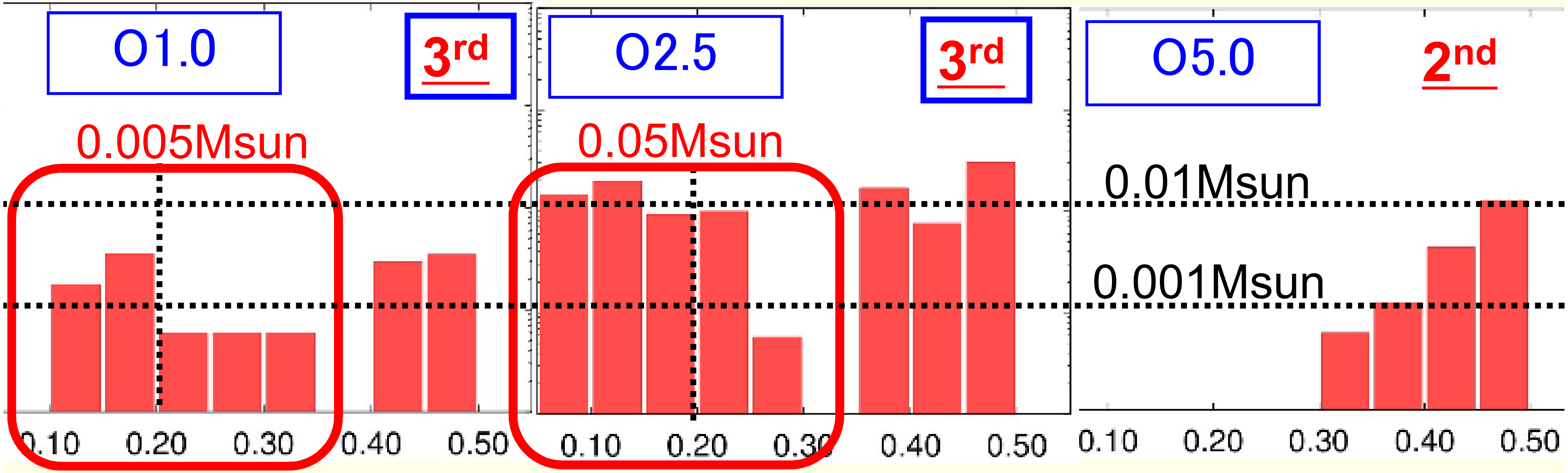
Ye VS Abundances



Ye distribution of the jets

M(Ye) VS Ye

ニュートリノ吸収無視

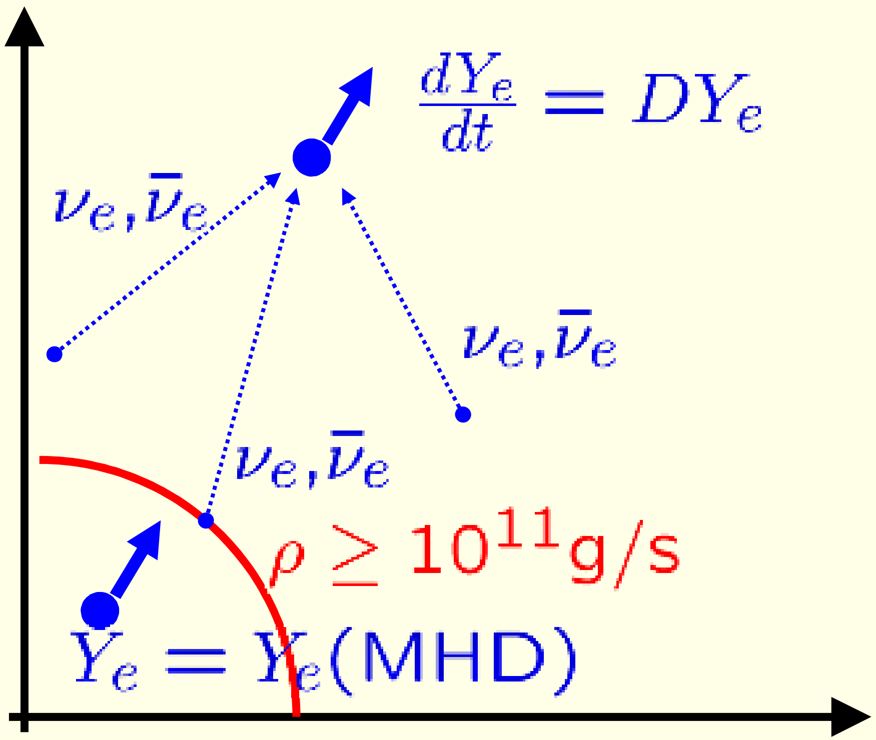


Rotation of progenitor core　slow ⟷ rapid

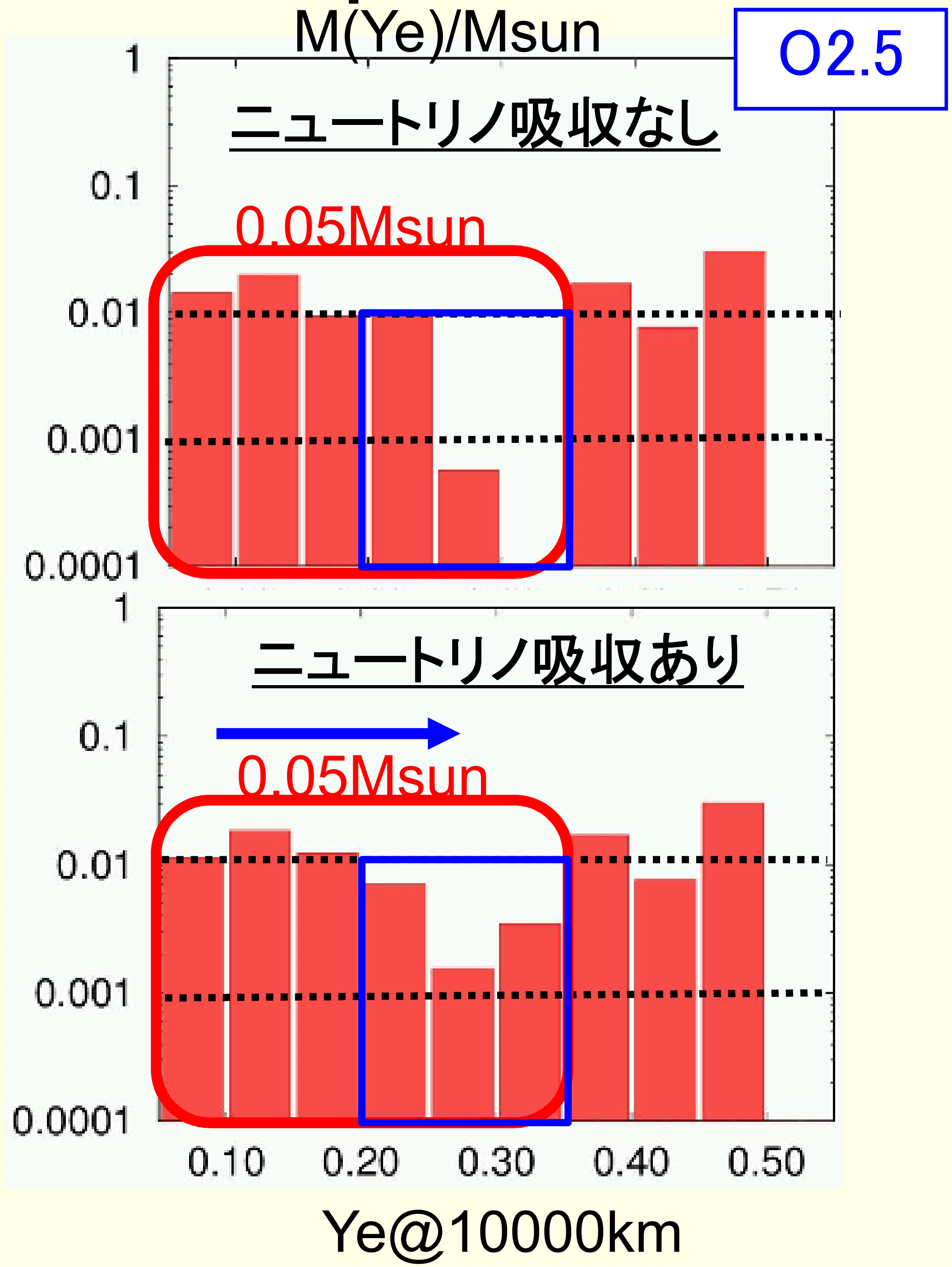
ニュートリノ光度=1e52erg/s

ニュートリノ吸収無視?

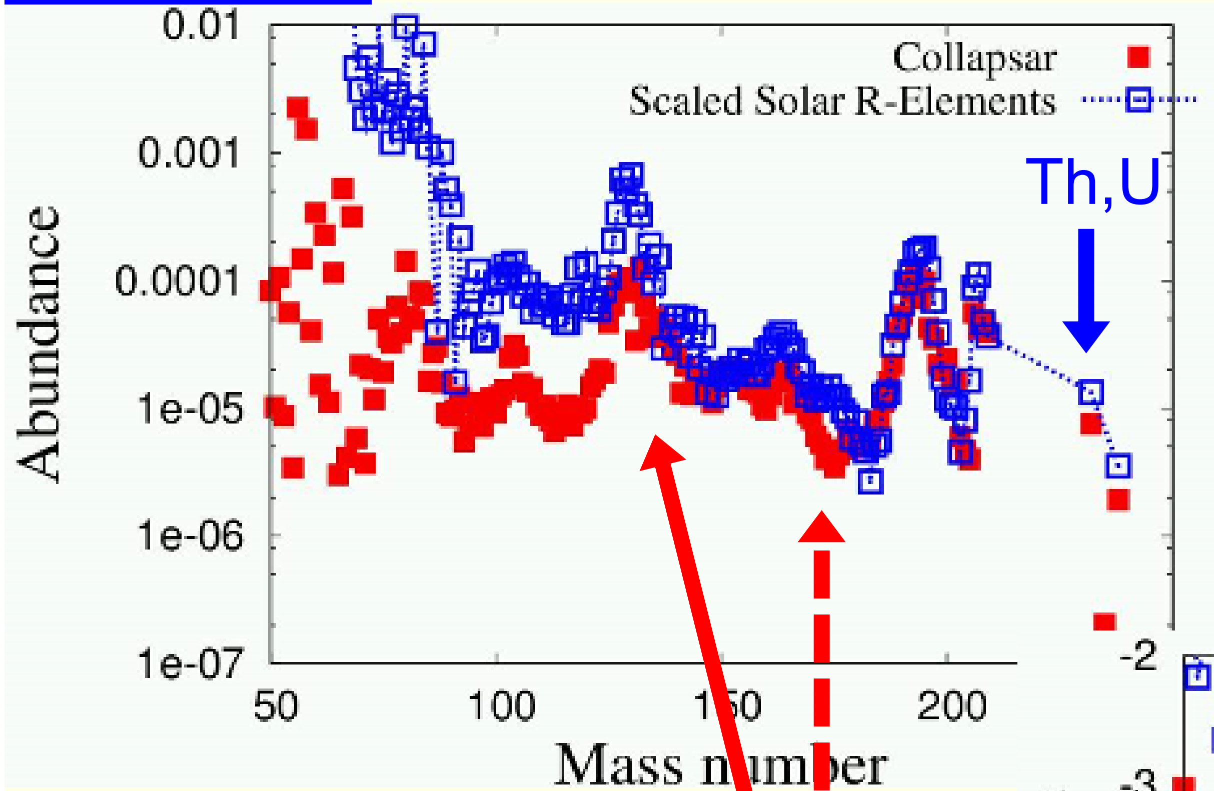
Effects of neutrino-absorption on Ye



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



O2.5 磁気駆動超新星 & Solar system

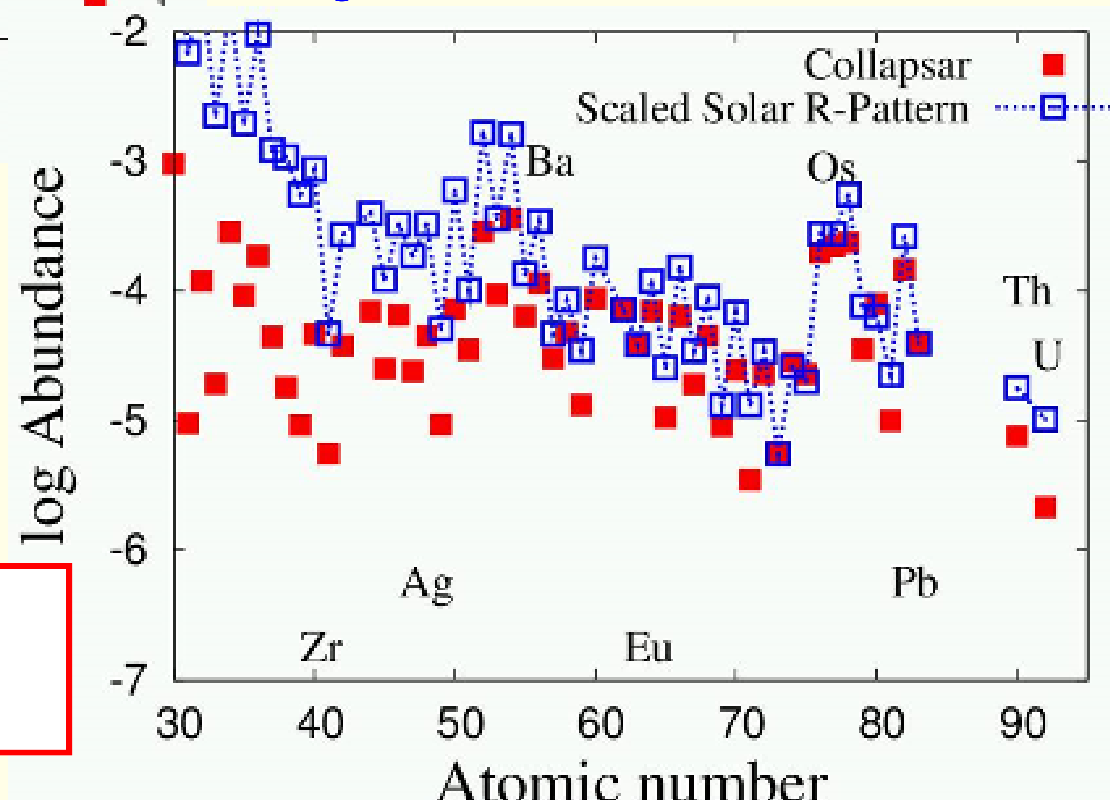


Th,U

ニュートリノ吸収考慮

similar to the abundance profile of solar r-elements

Log Abundances vs Z



Abundances vs A

underproduction
2^{nd} peak & A < 130

underproduction
Z < 50

Ejected masses

- M(Ye<0.4)～0.05Msun
- M(Eu)～3e-4Msun, M(Fe)～0.01Msun
- For an ejection fraction = 0.2-0.3
  - M(C)～0.1Msun
  - M(O)～2Msun
  - M(Si)～0.01Msun
- Event rate=Long GRB rate1e-5/yrと仮定
  - M(r核)=0.05Msun X 1e10yr X 1e-5/yr = 5e3Msun
- 銀河系全ての星が太陽系組成を持つと仮定
  - M(r核)～1e4Msun

Summary

We have investigated r-process 元素合成
in baryon-rich jets from 40Msun磁気駆動超新星,
based on 2D MHD simulations

- 組成
  - ニュートリノ吸収の影響を考慮しても 3rd peak核
  - U and Th
  - O1.0 & O2.5: 太陽系r核に似た組成パターン
  - O5.0: Weak r−process ?
- 質量
  - 多量のr核(0.001Msun−0.05Msun)
  - Small M(Fe) <0.01Msun but large M(O)～2Msun