Nucleosynthesis in Magnetorotationally Driven Jets and Search for the Evidence of the *r*-process in supernova remnants

Masaomi Ono
YITP, Kyoto Univ.

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Collaborators

S. Nagataki, J. Mao, S.-H. H. Lee, H. Itoh (YITP)

M. Hashimoto (Kyushu Univ.)

S. Fujimoto (Kumamoto Nat. Coll. Tech.)

K. Kotake, W. Aoki (NAOJ)

S. Yamada (Waseda Univ.)

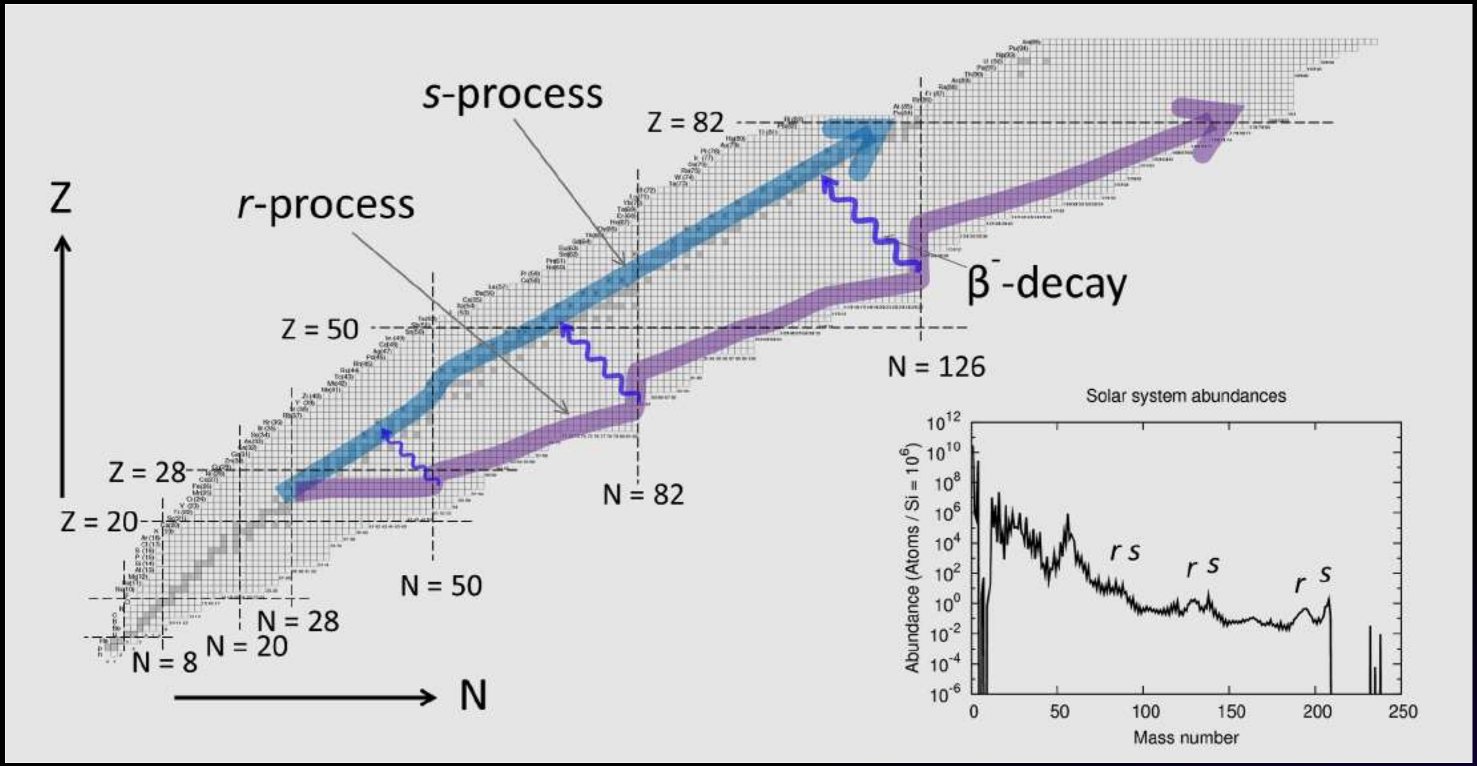
D. C. Ellison (NC state Univ.)

N. Nishimura (Univ. Basel)

Outlines

- The sites of the *r*-process
- Current status of the *r*-process in magnetohydrodynamical (MHD) jets
- Observations of *r*-process elements in supernova remnants
- Multidimensional simulations of matter mixing in supernovae and supernova remnants

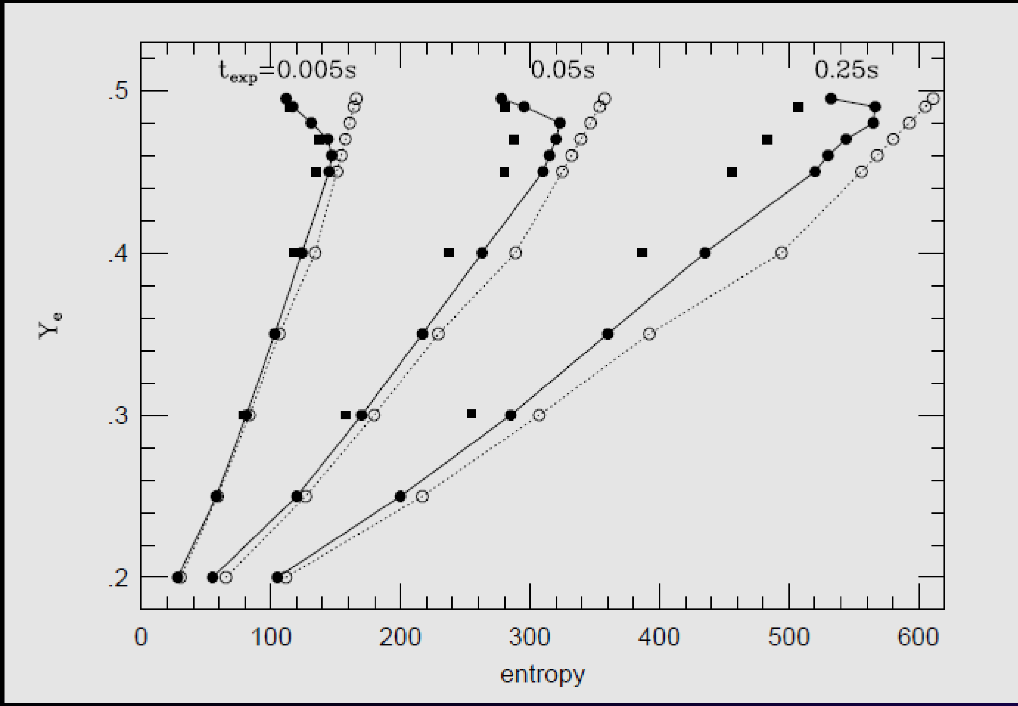
The *r*-process



- Rapid neutron capture (*r*-process) : explosive environment
- Slow neutron capture (*s*-process) : AGB stars, massive star

Key physical parameters for the *r*-process

- Electron fraction Y_e
- Entropy $S \propto T^3/\rho$
- Dynamical (expansion) timescale t_{exp}



Hoffman+'97

low Y_e is essential for the *r*-process

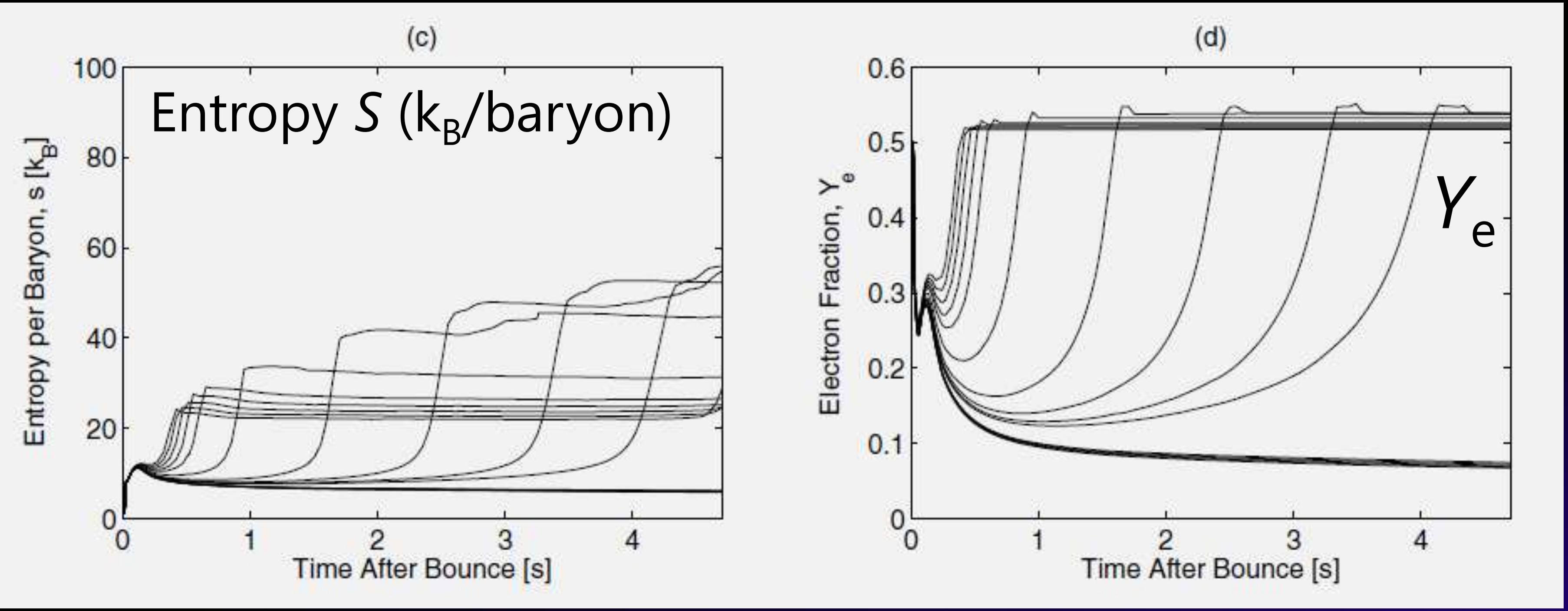
What is the site of the *r*-process ?

Main promising sites

- Neutrino-driven wind (NDW)
- Neutron star mergers (NSM)
- Magnetohydrodynamical (MHD) jets

No *r*-process in neutrino-driven winds?

- Sophisticated 1D core-collapse SN (e.g., Fischer+10)
  - GR, Boltzmann eq. for neutrino transport



Fischer+10

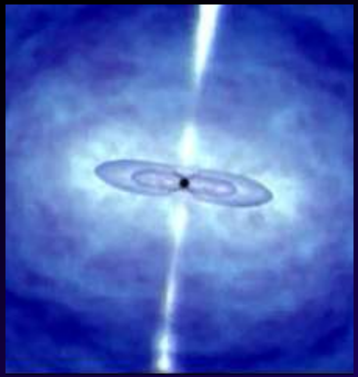
What is the site of the *r*-process ?

- Neutron star mergers (NSM)
  - Difficult to explain the early enrichment of *r*-process elements in galaxies ?
  - But we should carefully investigate (Wanajo-san's talk)
- Magnetohydrodynamical (MHD) jets
- Collapsar jet due to neutrino annihilations (Mathew-san's talk)

r-process in MHD jets

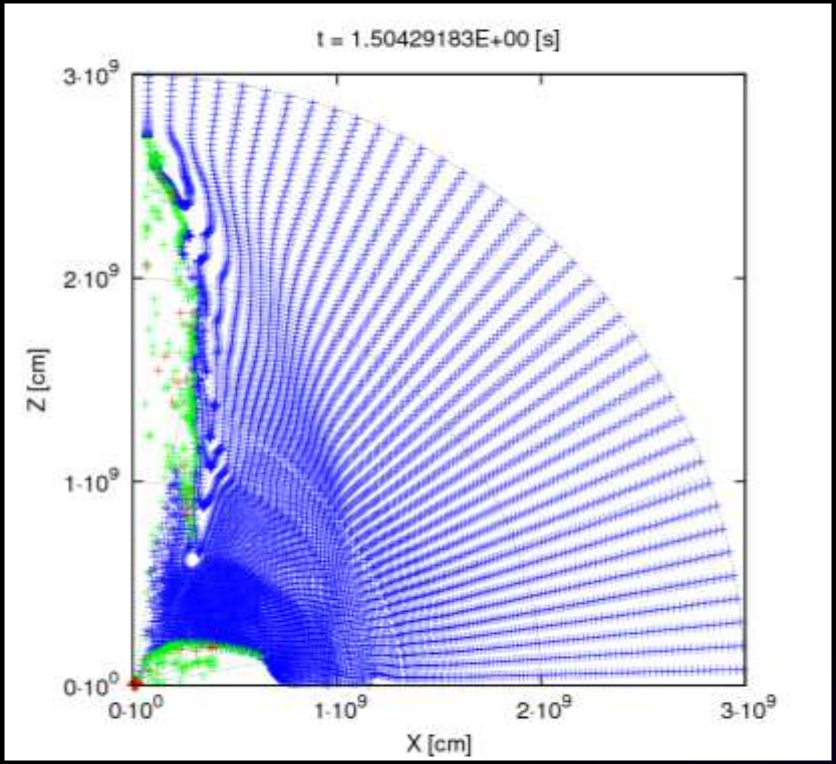
Nucleosynthesis in MHD jets including the *r*-process

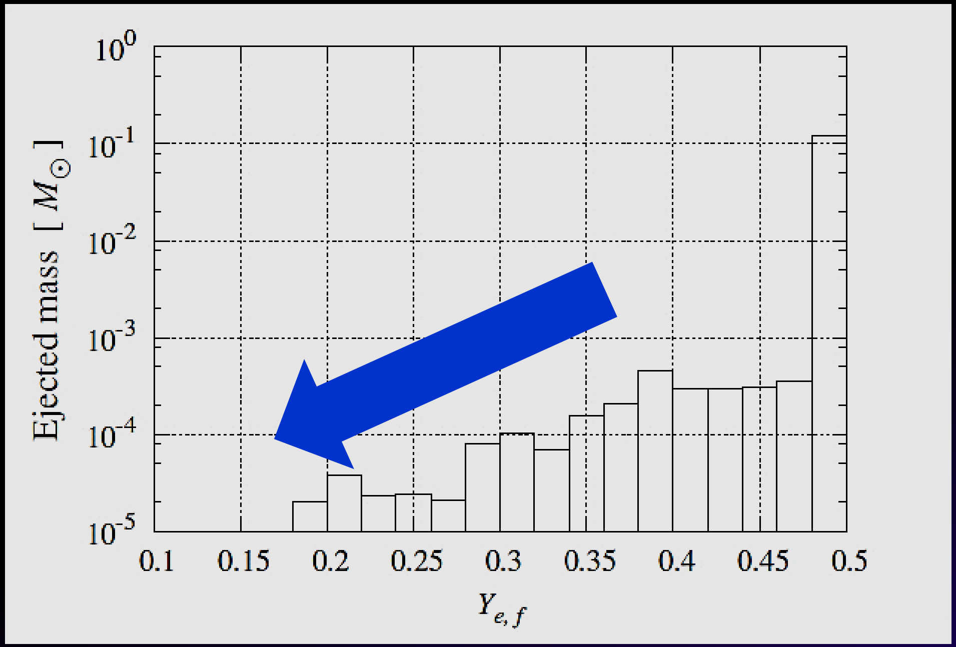
- **Magnetorotationally driven core-collapse supernova** (**MHD-CCSN**)
  - Nishimura +06
  - Winteler +12 (Basel)
  - Nishimura, Takiwaki, & Thielemann (2013 in prep.)
- **Collapar model** (Woosley 1993)
  - Fujimoto +07, 08
  - MO+12 (in press)



Central engine of Gamma-ray bursts ?

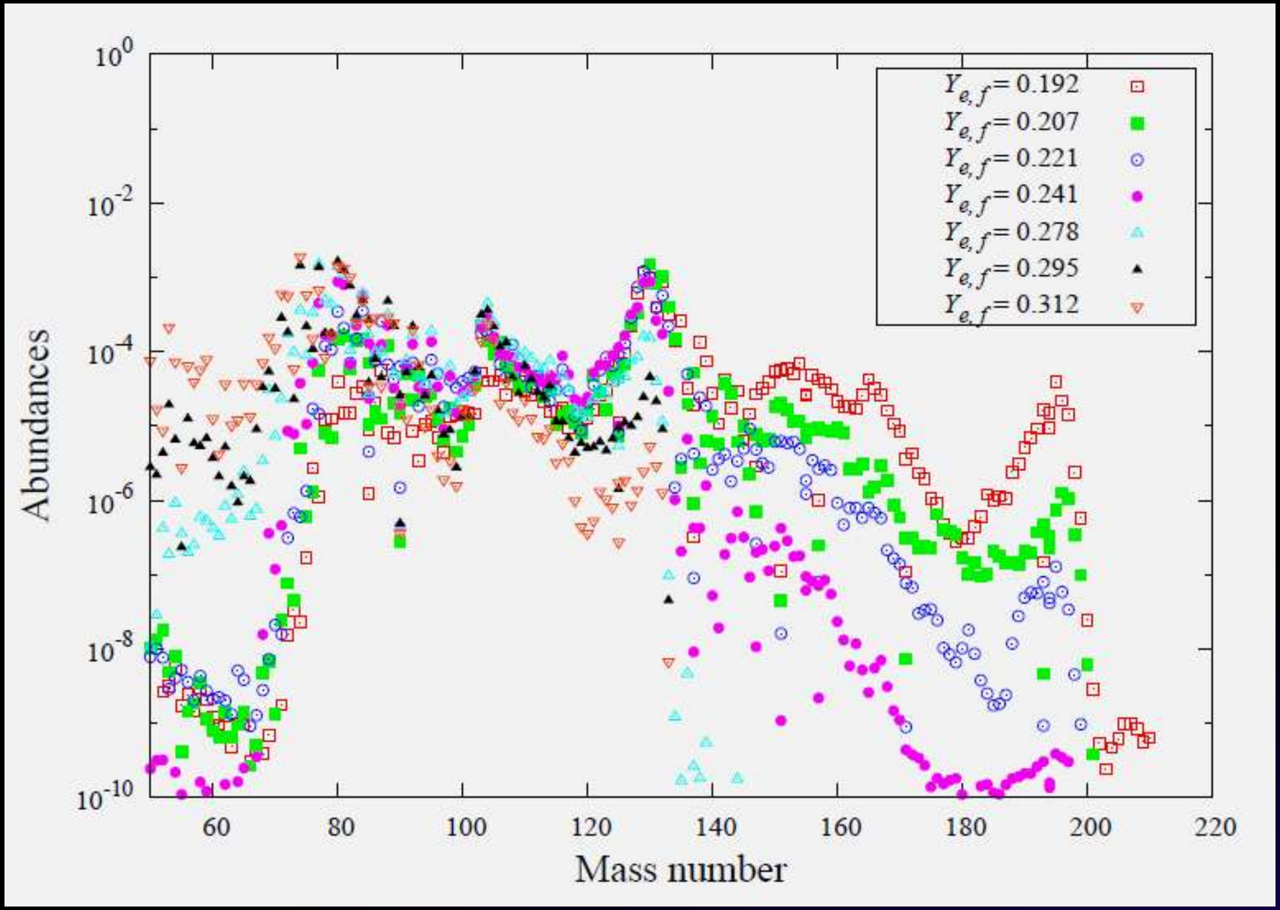
Nucleosynthesis in the MHD jet from a collapsar including weak *s*-, *p*-, and *r*-processes





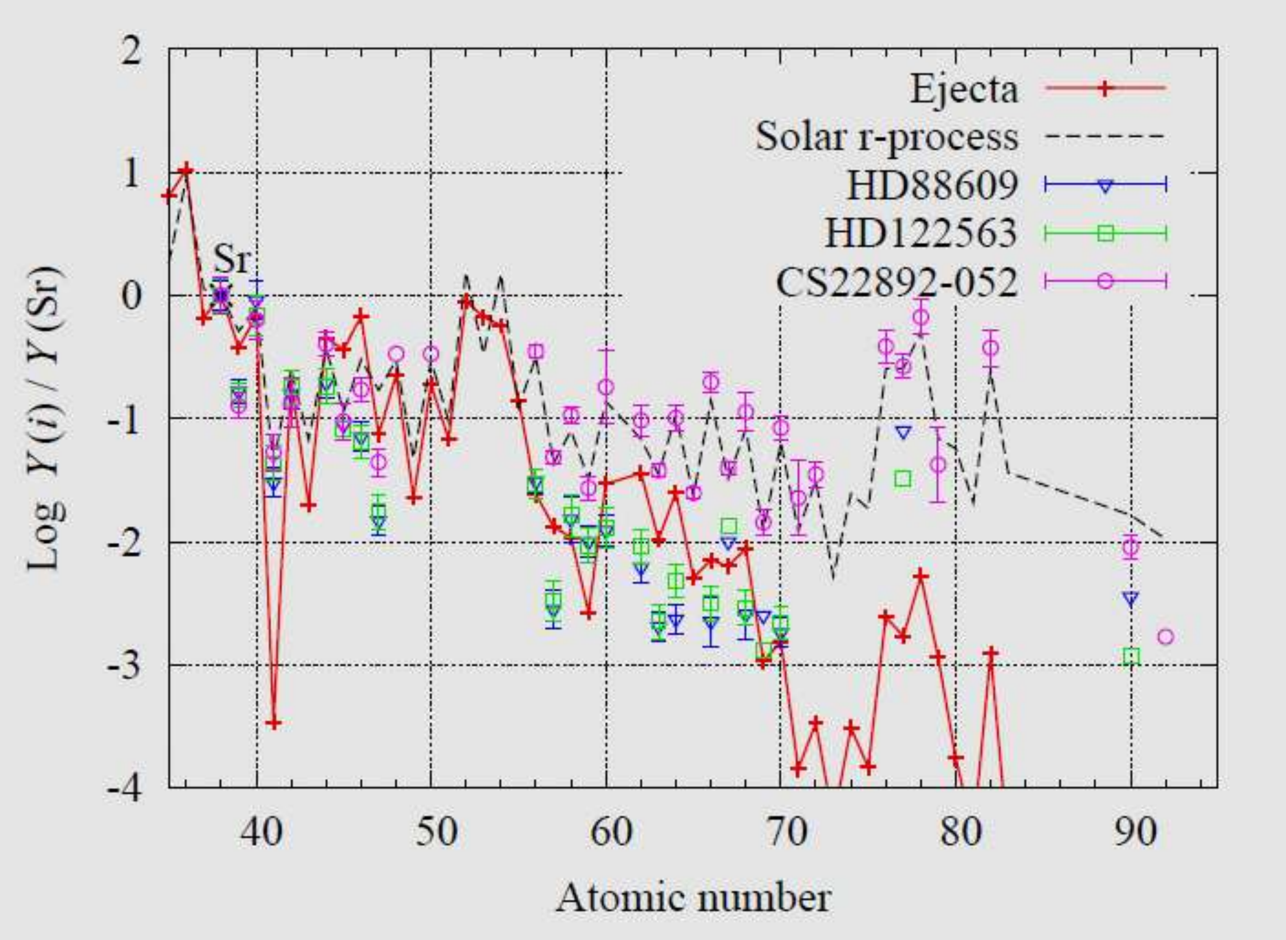
MO+12 (in press)

Abundances in ejected particles that have different Y_e



MO+12 (in press)

Comparison with abundances of the solar and metal-poor stars



- Weak *r*-process ?
- Primary synthesis Sr-Y-Zr
  ↓
  Lighter element primary process (LEPP) ?

MO+12 (in press)

r-process in a MHD-CCSN including effects of neutrino absorptions on Y_e

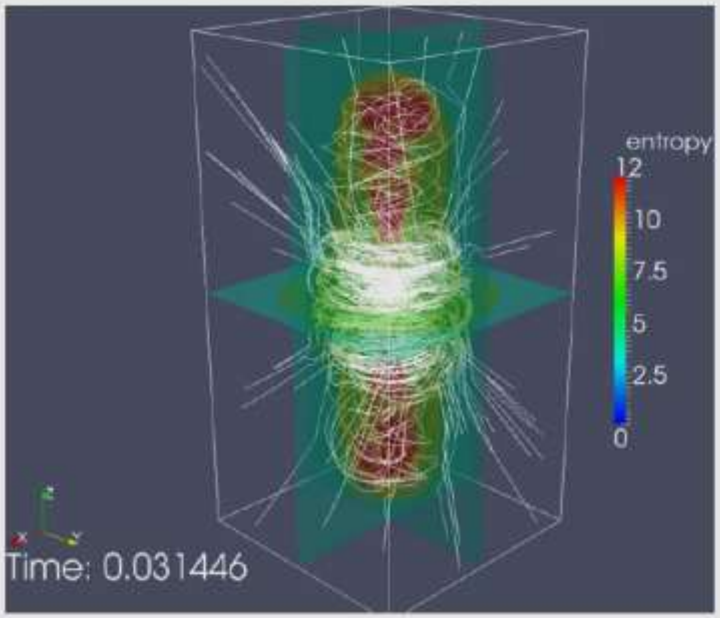
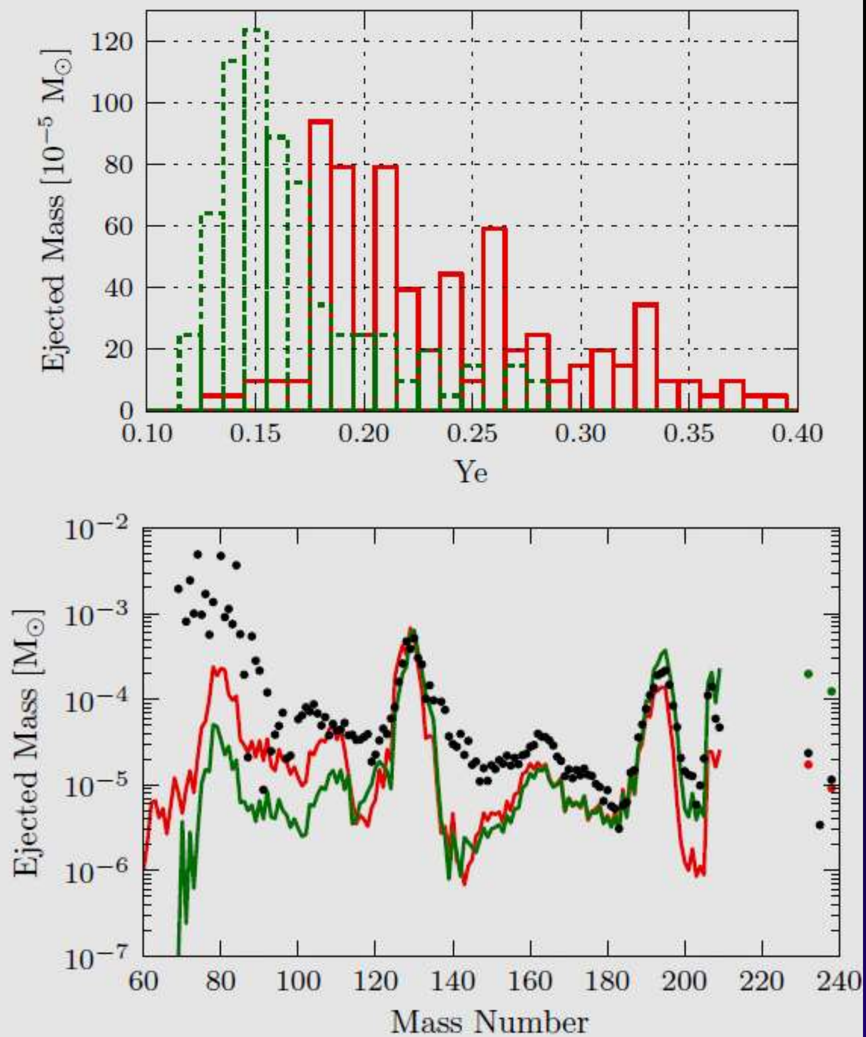


Figure 1. 3D entropy contours spanning the coordinates planes with magnetic field lines (white lines) of the MHD-CCSN simulation ~31 ms after bounce. The 3D domain size is 700 × 700 × 1400 km.



Winteler+12 (Basel)

r-process in MHD-CCSN models

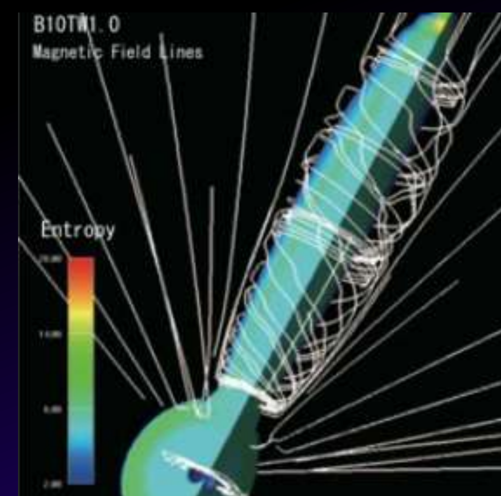
Nishimura, Takiwaki, and Thielemann (2013 in prep.)

SR-MHD-CCSN (Takiwaki+09, 11)

explosion energy 10^{51} erg

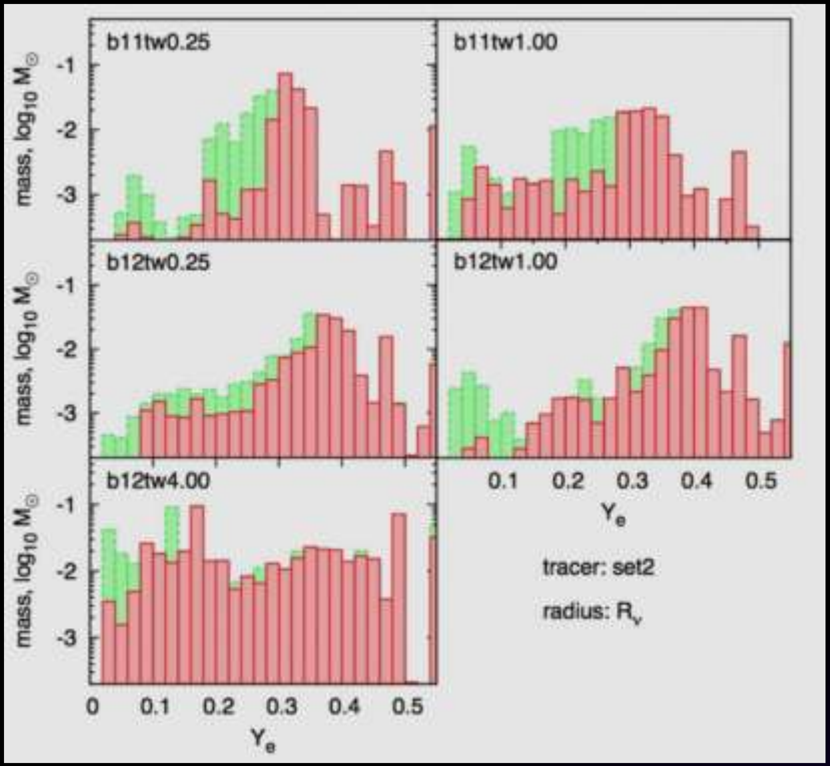
		$T/\|W\|(\%)$			
		0.25%	1.0%	4.0%	
	10^{10}G	0.02	0.094	0.006	"delayed"
B_0(Gauss)	10^{11}G	0.05	0.23	0.010	"prompt"
	10^{12}G	1.3	1.4	1.0	

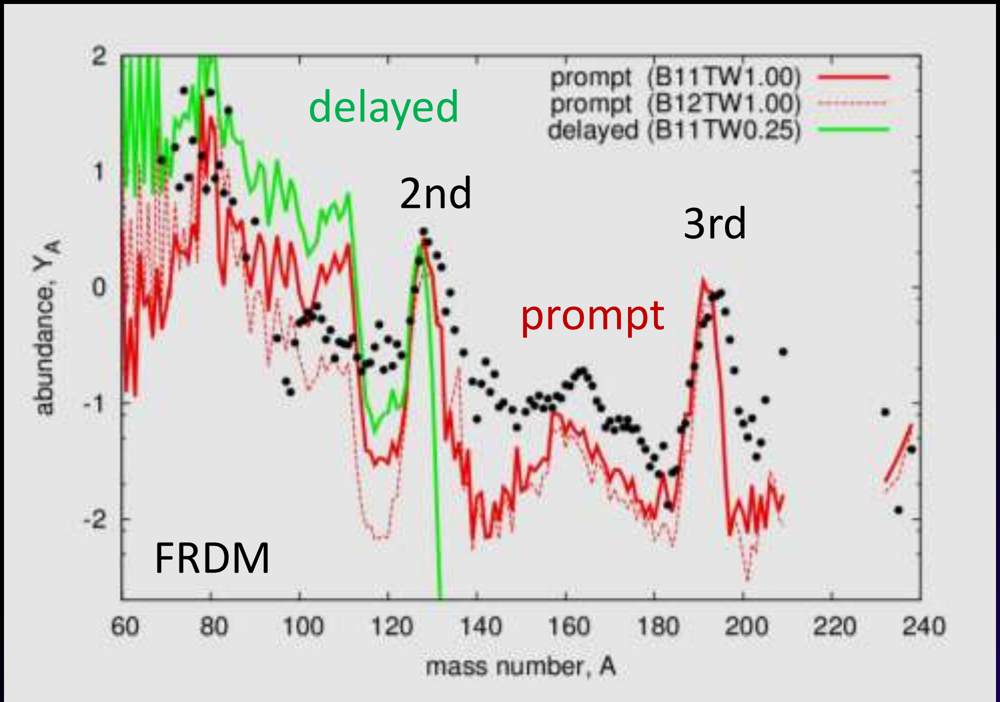
extreme case



Successful *r*-process in strong explosion models

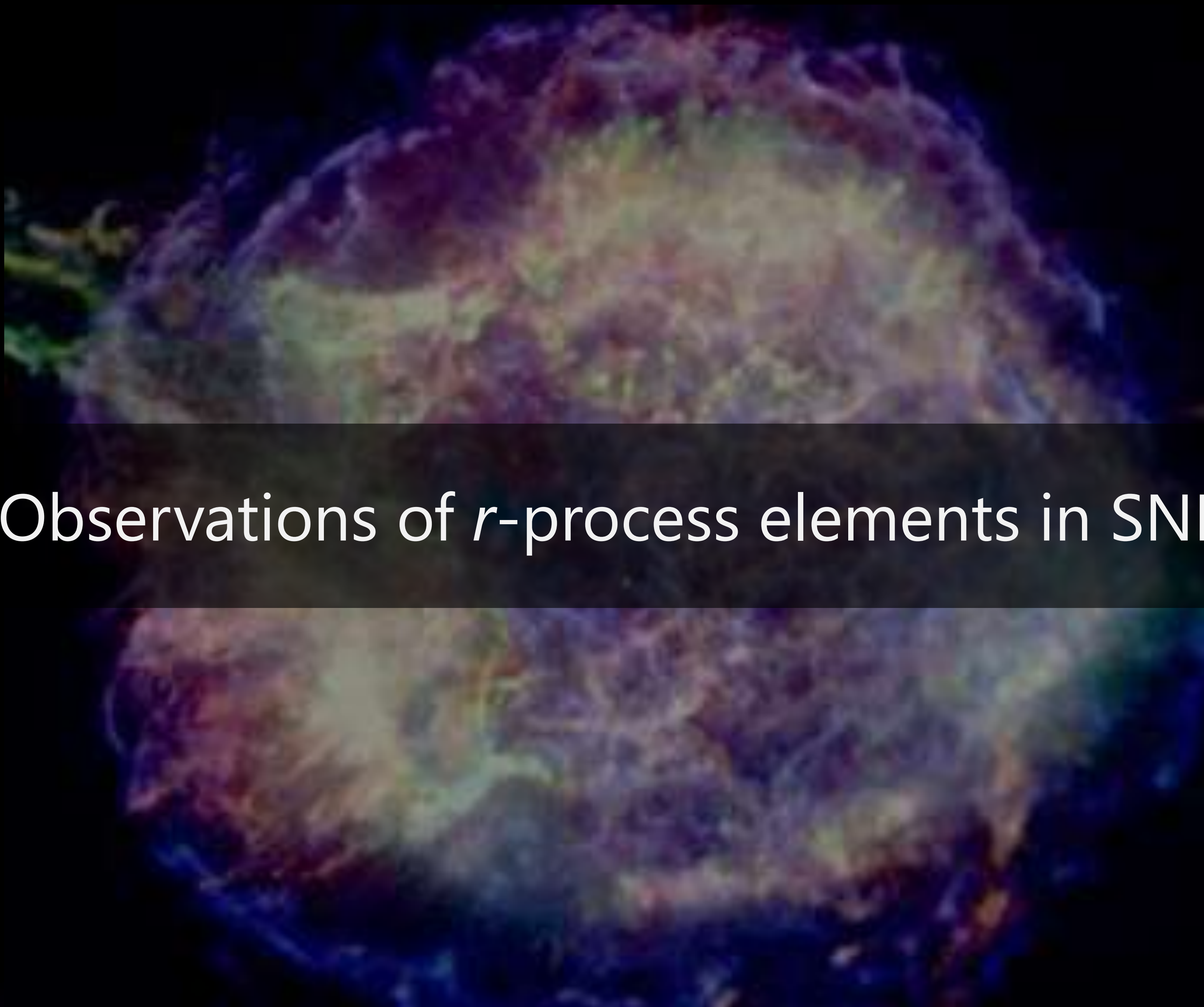
Nishimura, Takiwaki, and Thielemann (2013 in prep.)





MHD jets can be the source of the *r*-elements … ?

- Successful *r*-process in MHD jets
  - **Strong magnetic field** & **rapid rotation**
  - Ejected mass of *r*-elements $\mathbf{10^{-2}}$ **-** $\mathbf{10^{-3}}$ $\boldsymbol{M_\odot}$ > mean $\mathbf{10^{-4}}$ $\boldsymbol{M_\odot}$
  - **1% of canonical CCSNe**
  - Such **rapidly rotating** stars are **1 % of all stars** above 10 $M_\odot$ (Woosley & Heger 2006)
- Uncertainties
  - Magnetic field and rotation at the pre-collapse phase
  - Amplification of magnetic field (Magnetorotational Instability:MRI)
  - Input nuclear physics (Mass models, treatments fissions, ..)



Observations of *r*-process elements in SNRs

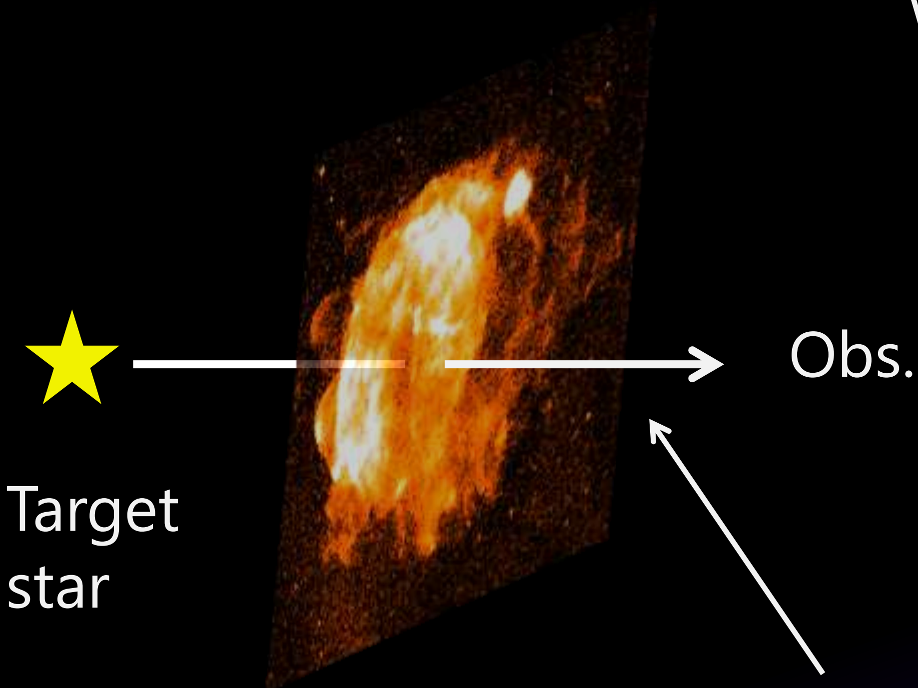
Direct evidence for the *r*-process ?

- There is no successful observation of *r*-elements in SNRs

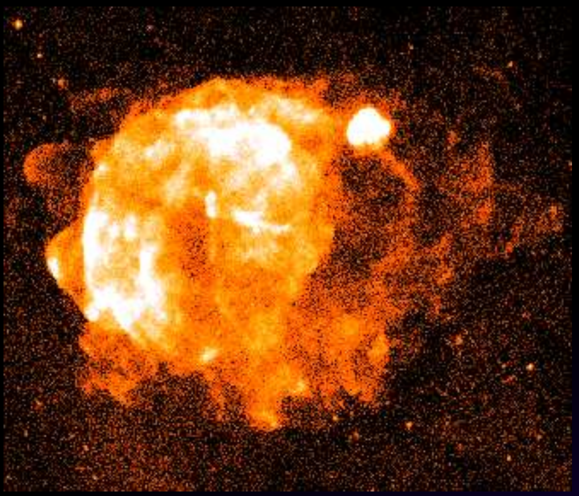
- The detection of newly synthesized *r*-elements in SNRs can be the direct evidence of the site of the *r*-process

Search for *r*-process elements in a SNR

Wallerstein et al. 1992; 1995

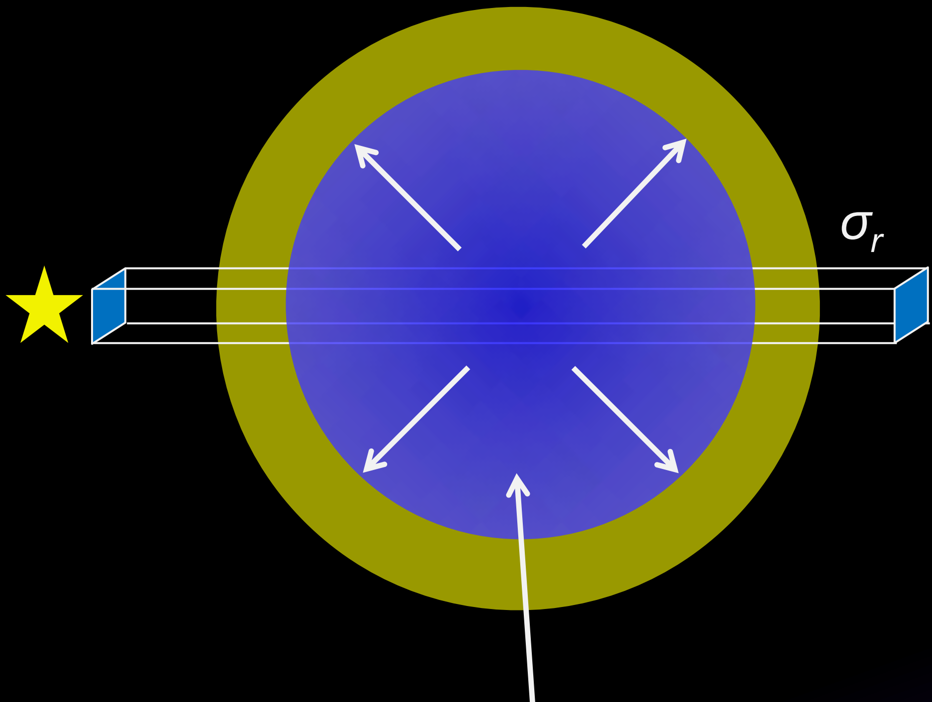


Absorption features of *r*-elements ?



Vela SNR

Detectability of newly synthesized *r*-process elements



cooled
(Ejecta + swept out ISM)

- Criterions of the detection
  - Enough column density of *r*-process elements
  - Enhancement of *r*-elements relative to the ambient component

$$\sigma_{r,\ \mathrm{ejecta}} > \sigma_{r,\ \mathrm{ambient}}$$

Wallerstein et al. 1995

Observations of *r*-elements in Vela SNR

- Eu II, Gd II, Ra II, and Th II (Wallerstein et al. 1992)
- Yb II, Os II, Hg I (Wallerstein et al. 1995)

Column Densities of Interstellar Lines in the Vela Remnant

Species	log Column Density (cm^{-2}) HD 72127A	HD 72127B	HD 72350	HD 72798	HD 74455	Mean of Three Stars[a] Outside Vela	ζ Oph[b]
Mg II......	14.95	14.9	15.1	14.85	...	...	14.45
S II	15.45	15.45	15.6	...	15.6	15.5[c]	15.5[c]
Ge II	11.55	<11.3	11.75	...	11.5	11.4	11.35
Kr I	<11.9	<12.0	<11.9	...	<11.3	<11.2	11.5
Yb II	<11.9	...	<12.35	<11.95			
Os II	<10.2	...	<10.65	<10.25			
Hg I	<10.65	...	<11.1	<10.7			

[a] From Hobbs et al. 1993.
[b] From Cardelli, Savage, & Ebbets 1991 and Savage, Cardelli, & Sofia 1992.
[c] Set arbitrarily to be equal to the mean of the S II column density of the Vela stars.

No excess of *r*-process elements

Wallerstein et al. 1995

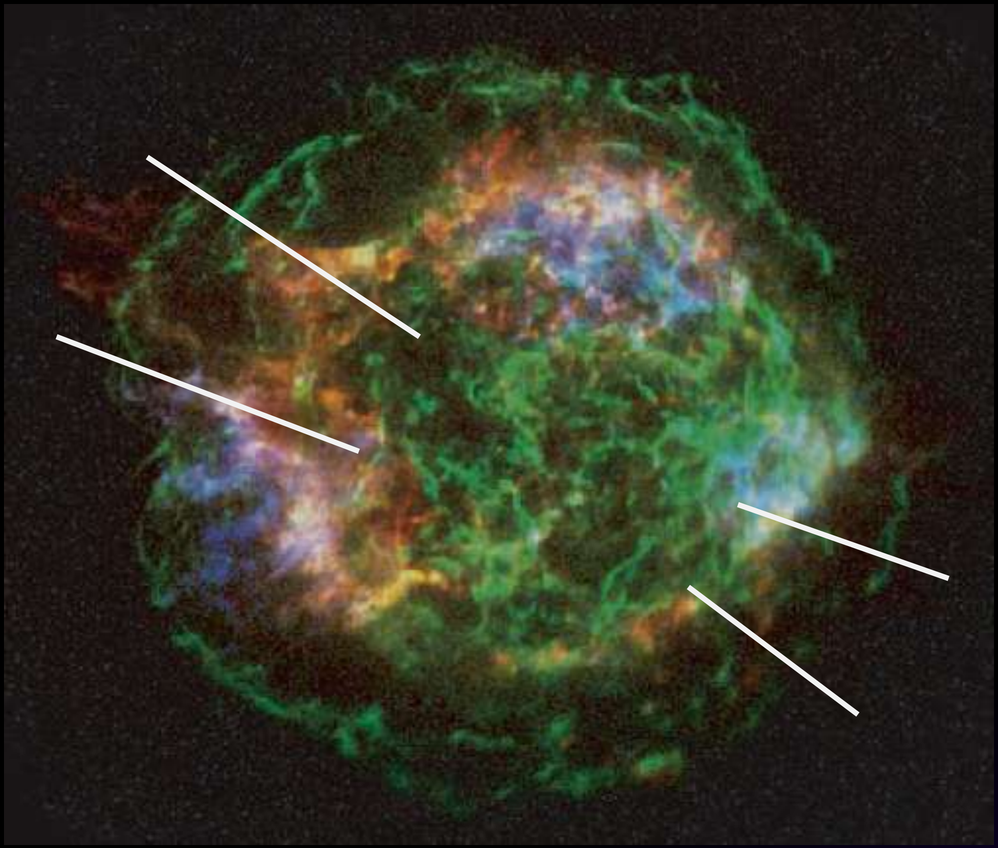
Our plan

- Service program of Subaru Telescope
  - HDS (High Dispersion Spectrograph)
  - Eu II, Th II (Gd II, Ra II) (3,500 – 4,500 Å)
- Target SNR
  - Cassiopeia A (Cas A)
  - *Prominent jet structure*
  - Age : ～ 330 yr (< Vela : 10^4 yr)
  - Distance : 3.4 kpc (> Vela : 0.25 kpc)

HDS

http://www.subarutelescope.org/Introduction/instrument/j_HDS.html

Cas A SNR



X-ray image : Chandra

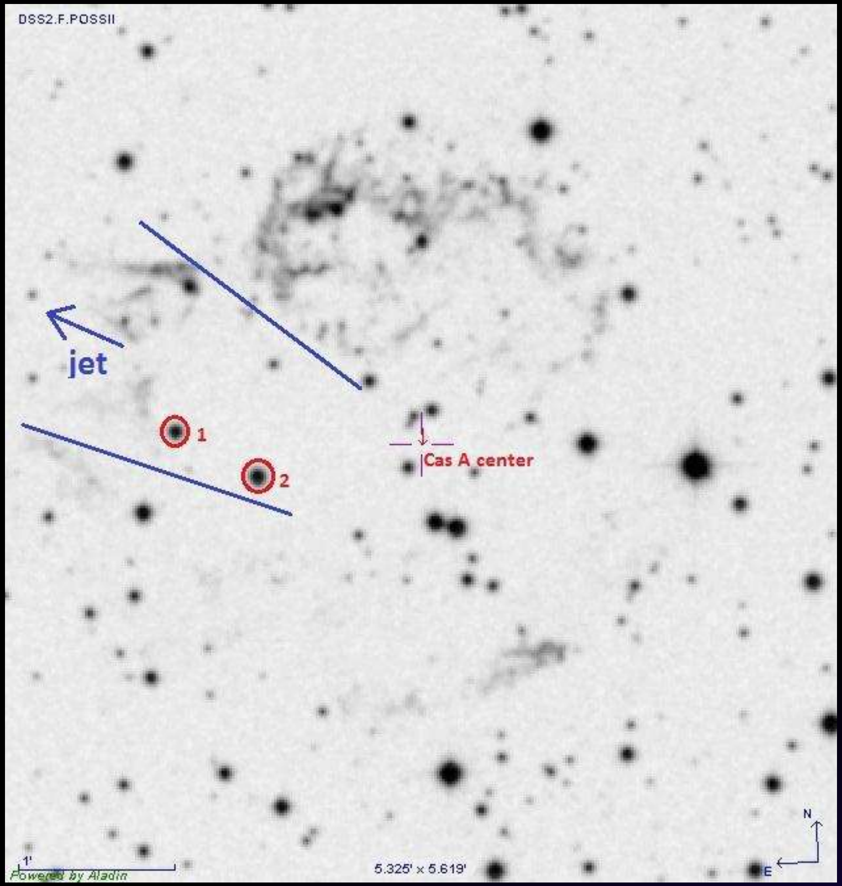
Red : Si, Hα (1.78-2.0 keV)

Blue : Fe, K (6.52-6.95 keV)

Green : 4.2-6.4 keV continuum

Hwang et al. 2004

Target stars



- Target stars 1, 2
  - Jet region
  - Clean region

Prospects

- Excess of *r*-elements could be higher than Vela SNR
  - *r*-process in jets should be 2 orders of magnitude effective
  - Cas A is younger than Vela

  But …

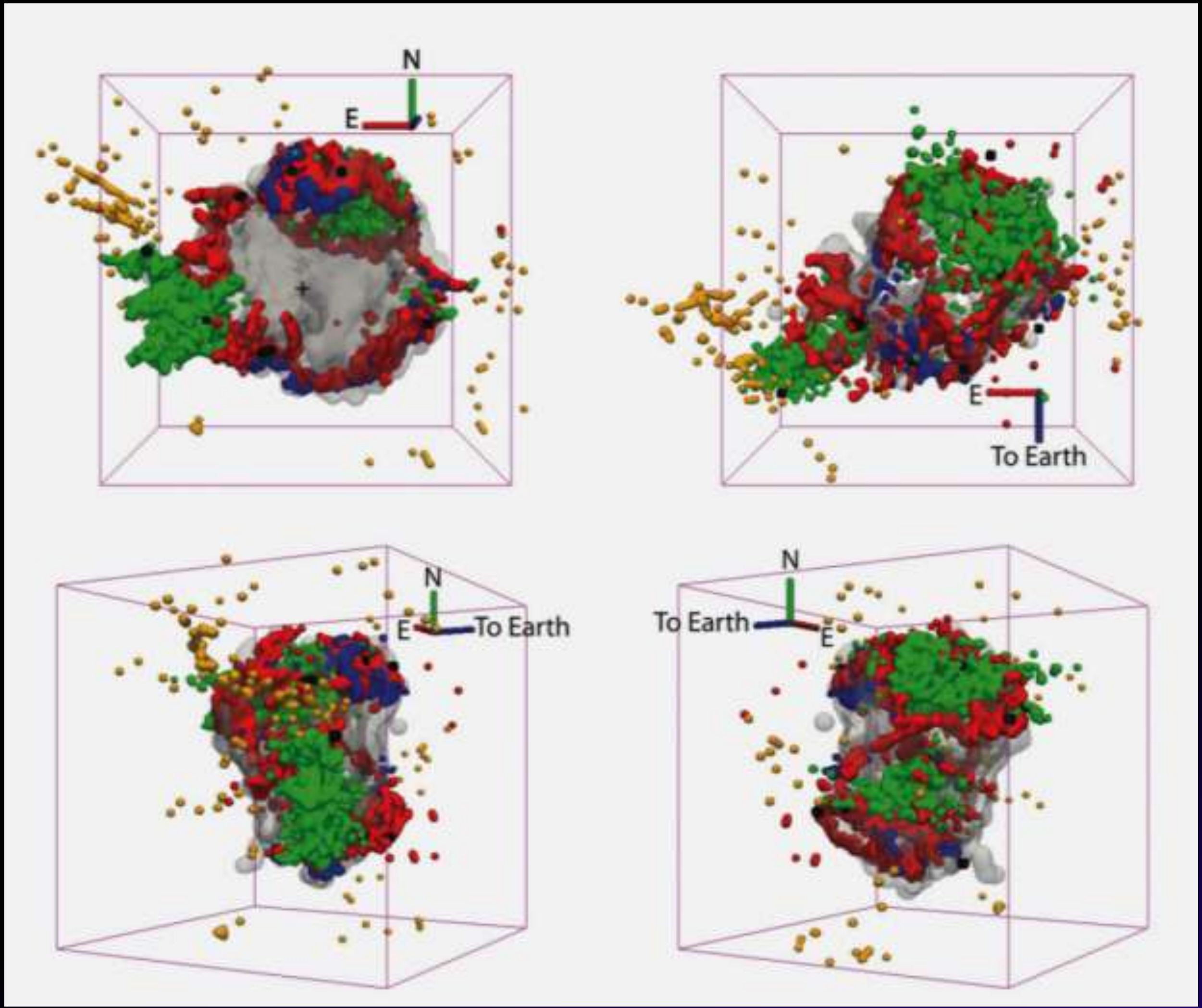
- We don't know weather the target stars are in the background or foreground of Cas A
- We don't know the ionization stucture of the ejecta well

If we detect any excess of *r*-elements, which is the first observation of newly synthesized *r*-elements in a SNR

How synthesized elements are ejected?

3D structure of Cas A

Delaney et al. 2010



Chandra 's X-rays

Spitzer 's infrared

Green: X-ray Fe-K

Black: X-ray Si XIII

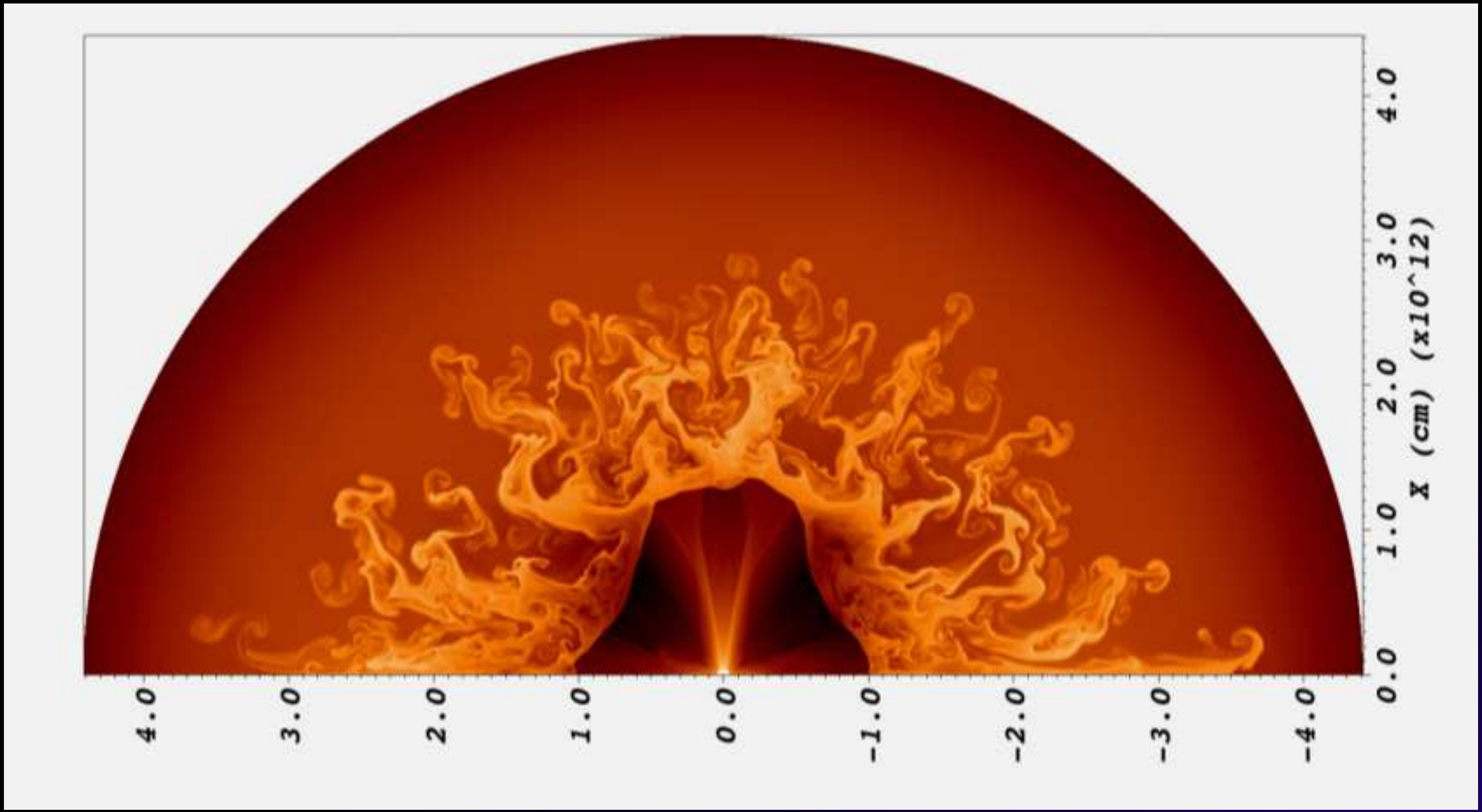
Red: IR [Ar II]

Blue: high [Ne II]/[Ar II] ratio

Grey: IR [Si II]

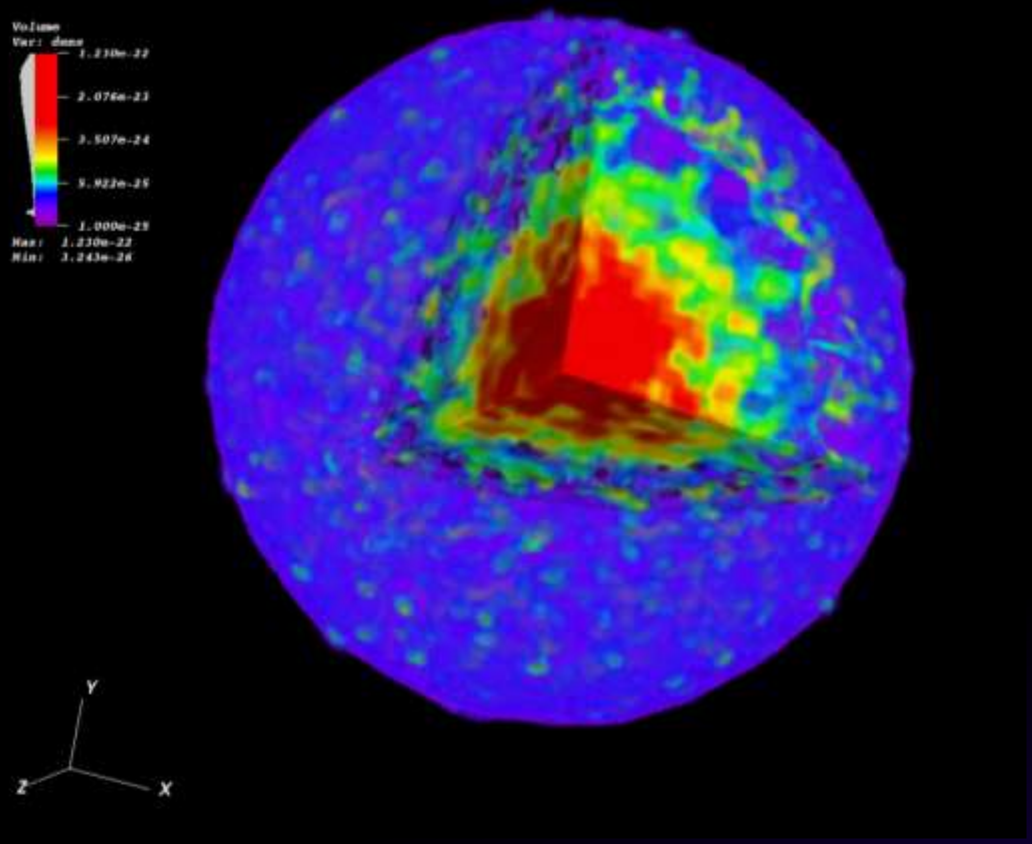
Yellow: optical outer ejecta

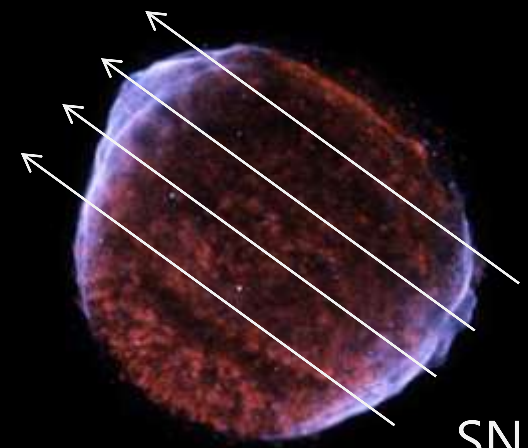
Matter mixing in core-collapse supernova



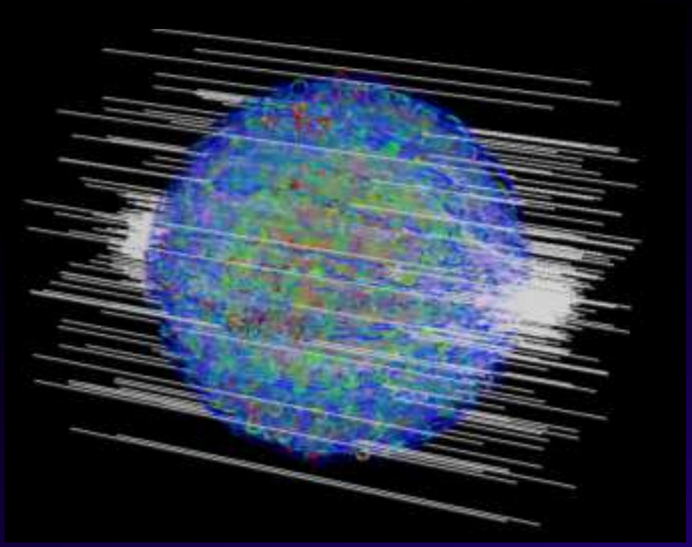
M.O. et al. (2013 prep.)

3d MHD simulation of a Type Ia SNR





SN1006



MO (2013 prep.)

Summary

- MHD jets can be one of the sites of the *r*-process, although there are still many uncertainties
- Detection of *r*-elements in a SNR has a great impact on determining the sites of the *r*-process
- It is very unobvious how synthesized elements are ejected

Workshop on Supernovae and Gamma-ray busts, in Kyoto, 2013

http://www2.yukawa.kyoto-u.ac.jp/ws/2013/sngrb/SN-GRB2013.html

- Long-term workshop (5 weeks in total)
- Two – one week conferences on SNe and GRBs, respectively
- Remaining three weeks are for workshops on
  Nuclear physics in SNe and GRBs, CC-SNe , and GRBs

Thank you for your attention