Max-Planck-Institut für Astrophysik

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TUM LMU Excellence Cluster Universe

SN 1987A, 30 Years Later
IAUS 331, La Réunion, Feb. 20–24, 2017

3D Supernova Explosion Models
for the Production and Distribution of
^{44}Ti and ^{56}Ni in Cassiopeia A

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Hans-Thomas Janka
for the CCSN Team

COCO2CASA

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COCO2CASA

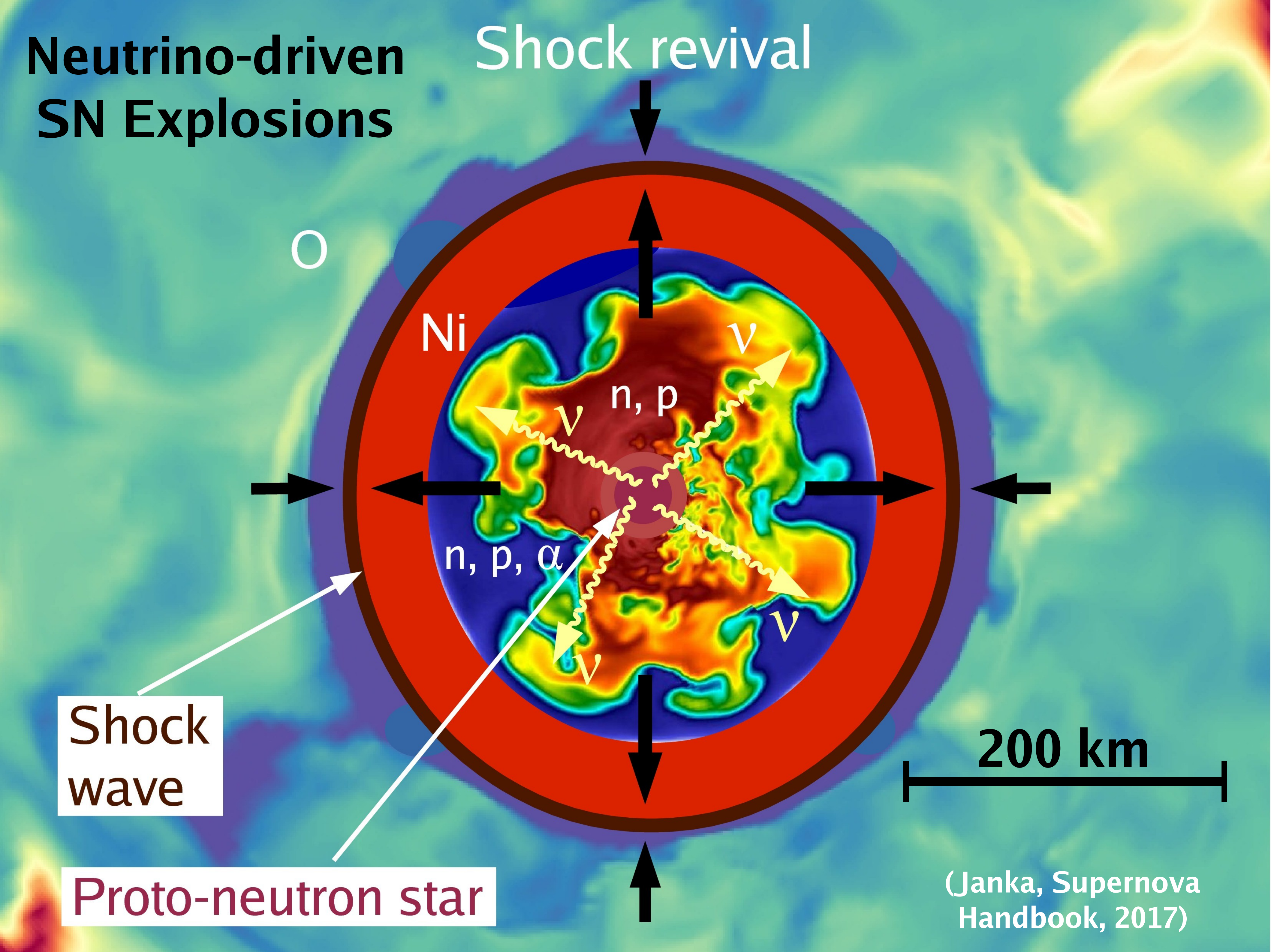
COCO2CASA: Goals

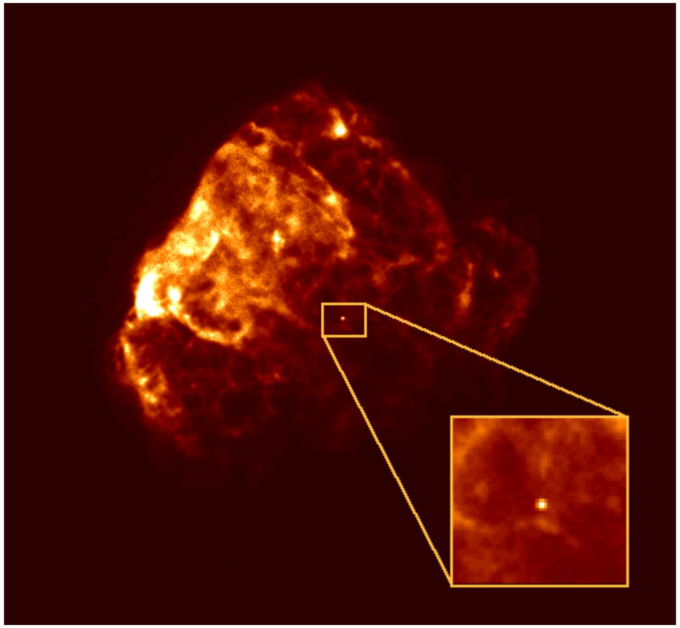
Connecting Supernova Progenitors with Supernova Remnants

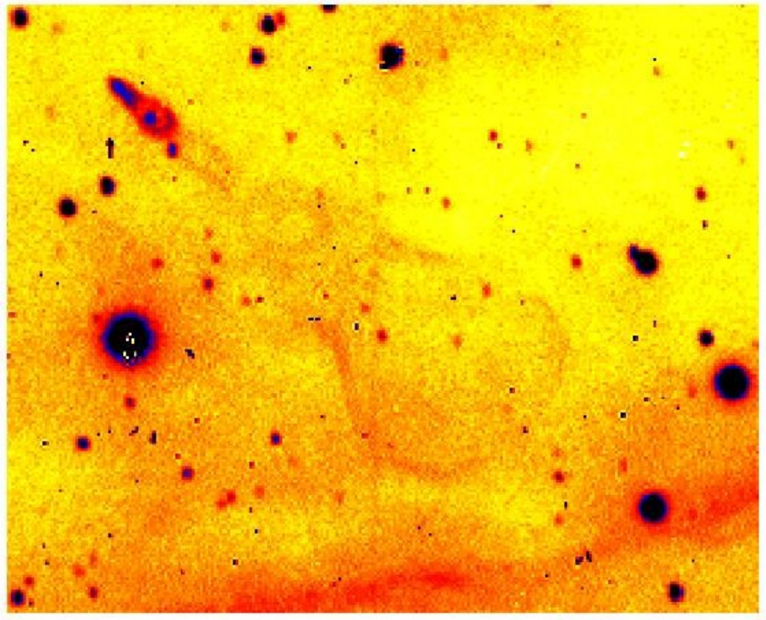
- 3D modeling of latest burning stages of pre-collapse stars
- 3D modeling of SN explosion mechanism
- 3D modeling of evolution from SN explosion to SN-remnant phase

Dedicated targets:

- Explanation of morphological and chemical properties of young, nearby, well studied SN remnants, e.g., Crab, Cas A, SN 1987A.
- Collecting indirect evidence of neutrino-driven explosion mechanism


Neutrino-driven
SN Explosions
Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock
wave
Proto-neutron star
200 km
(Janka, Supernova
Handbook, 2017)



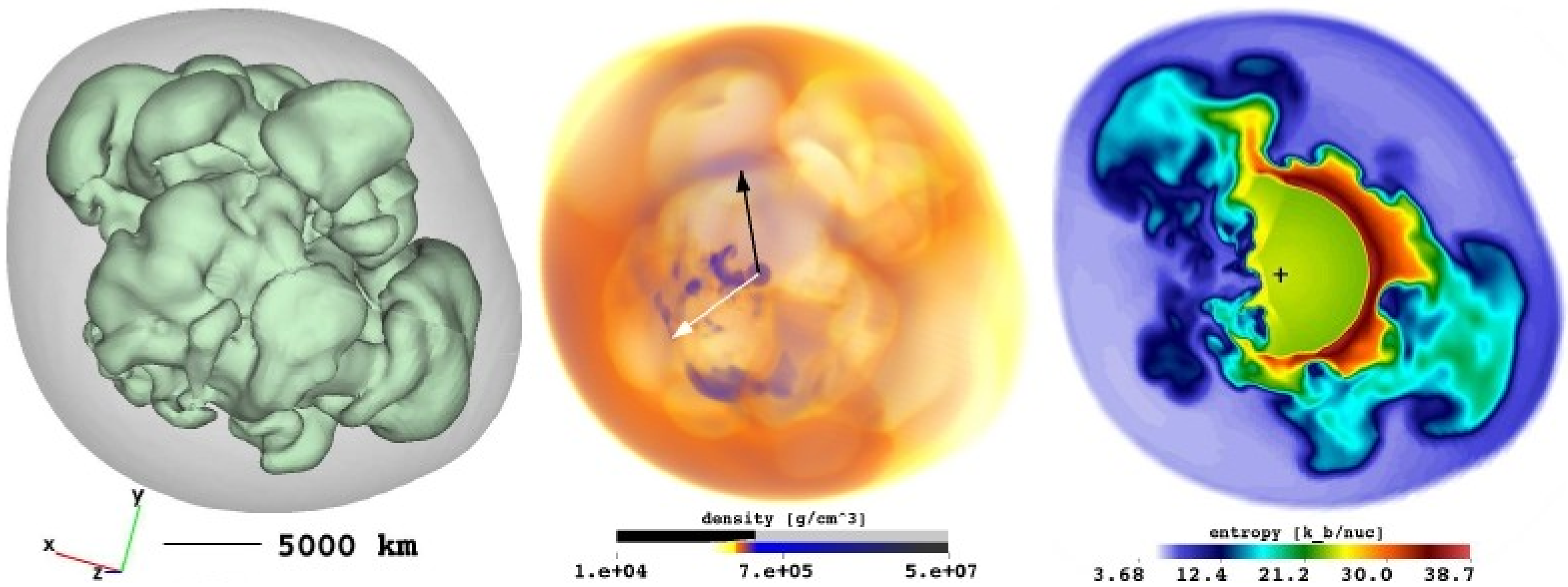


Neutron Star Kicks and Nucleosynthesis Products in 3D SN Explosions

Parametric —not fully self-consistent— explosion simulations:

Neutrino core luminosity of proto-NS chosen;
Accretion luminosity calculated with simple (grey) transport scheme

Neutron Star Recoil in 3D Explosion Models

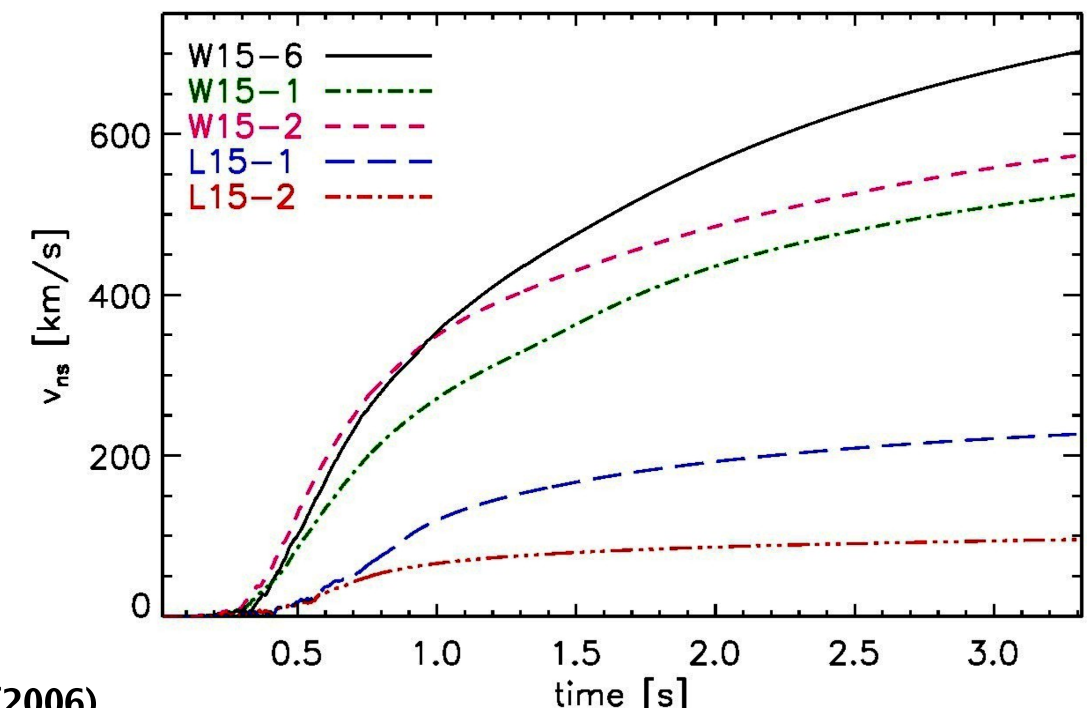


W15-2 @ 1.3 s

Gravitational tug-boat mechanism

$$v_{\mathrm{ns}} \approx \frac{2G\Delta m}{r_{\mathrm{i}} v_{\mathrm{s}}} \approx 540 \left[\frac{\mathrm{km}}{\mathrm{s}}\right] \frac{\Delta m_{-3}}{r_{\mathrm{i},7}\, v_{\mathrm{s},5000}},$$

where Δm is normalized by $10^{-3}\,M_\odot$, r_{i} by 10^7 cm, and v_{s} by $5000\,\mathrm{km\,s^{-1}}$.



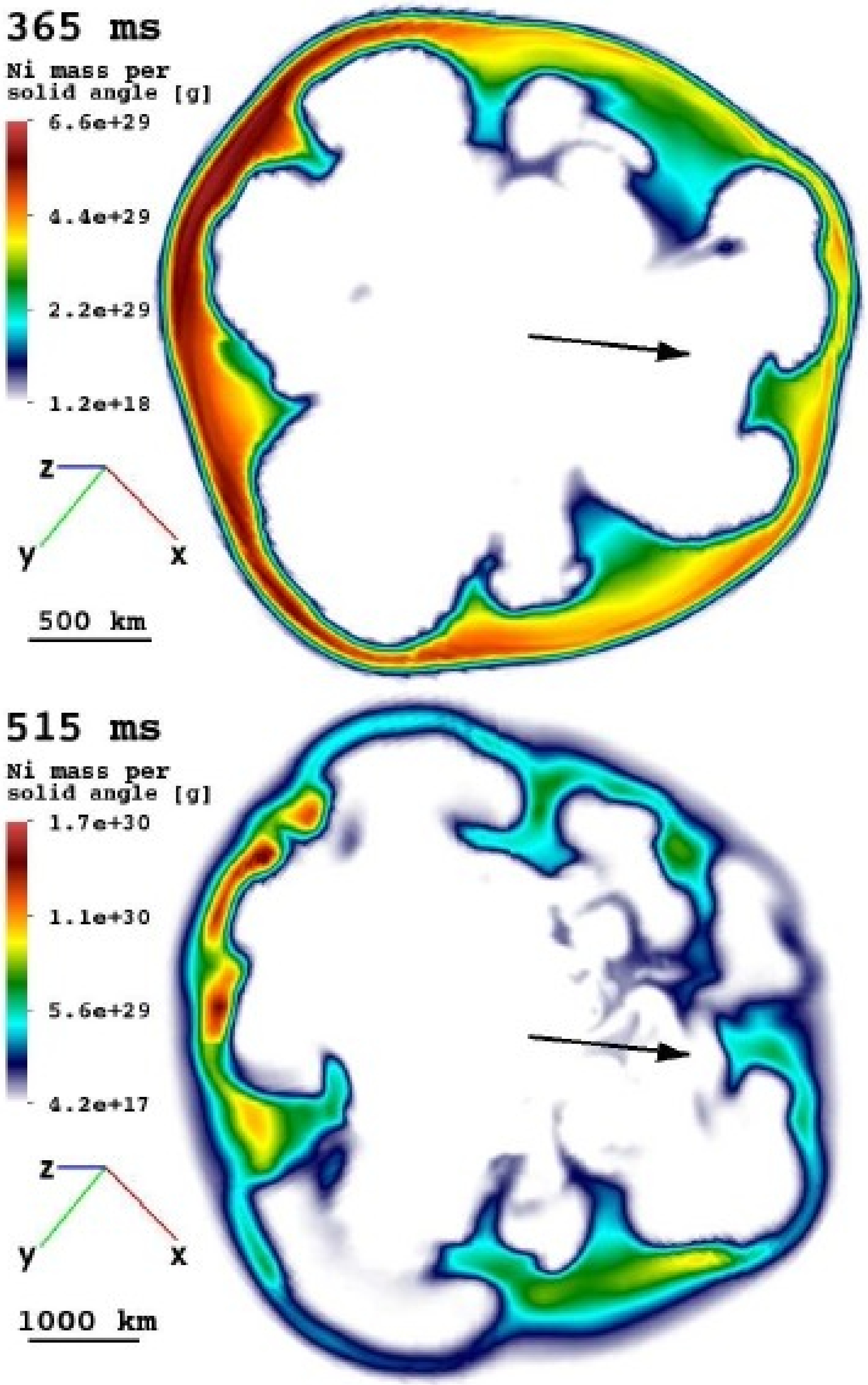
Wongwathanarat, Janka, Müller, ApJL 725, 106 (2010); A&A 552, 126 (2013); Scheck et al., PRL 92, 011103 (2004), A&A 457, 963 (2006)

Neutron Star Recoil and Explosive Nucleosynthesis

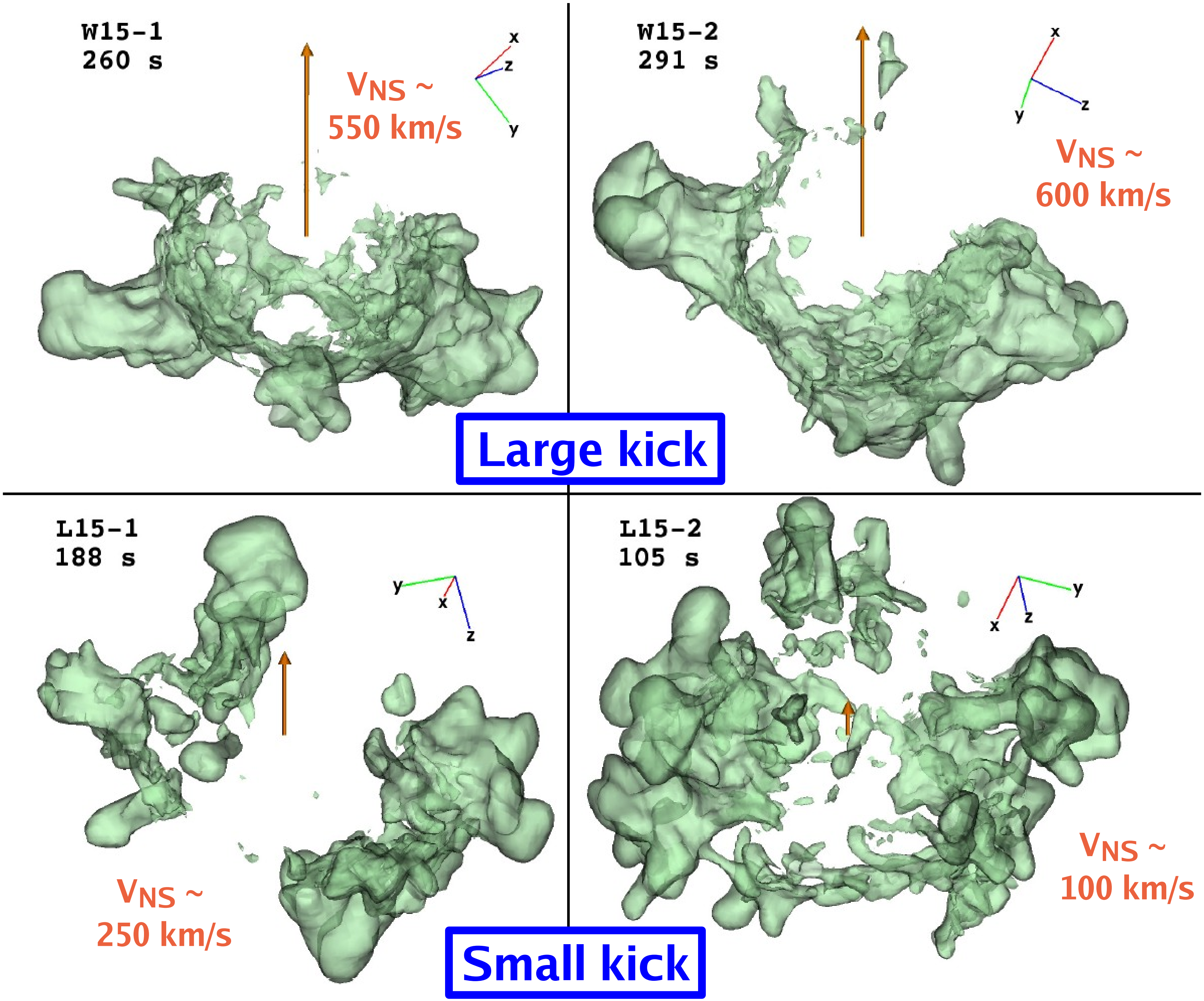
Nickel and all explosively produced elements
(>= ^{28}Si, ^{32}S)
are enhanced in direction of stronger explosion,
i.e. opposite to NS kick

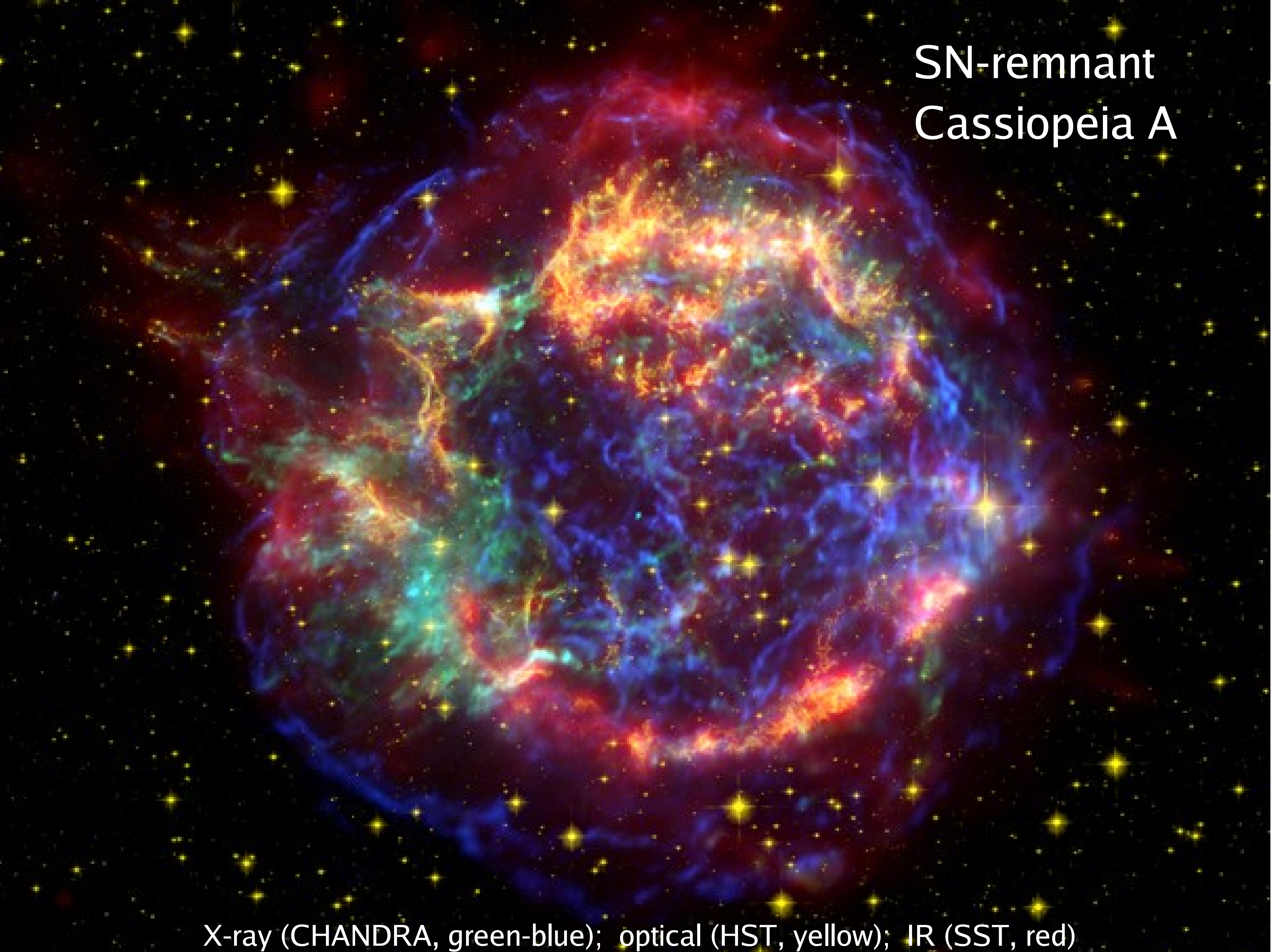
Lighter elements (<= ^{24}Mn) do not carry any pronounced hemispheric asymmetries

(Wongwathanarat, Janka, Müller, A&A (2013)



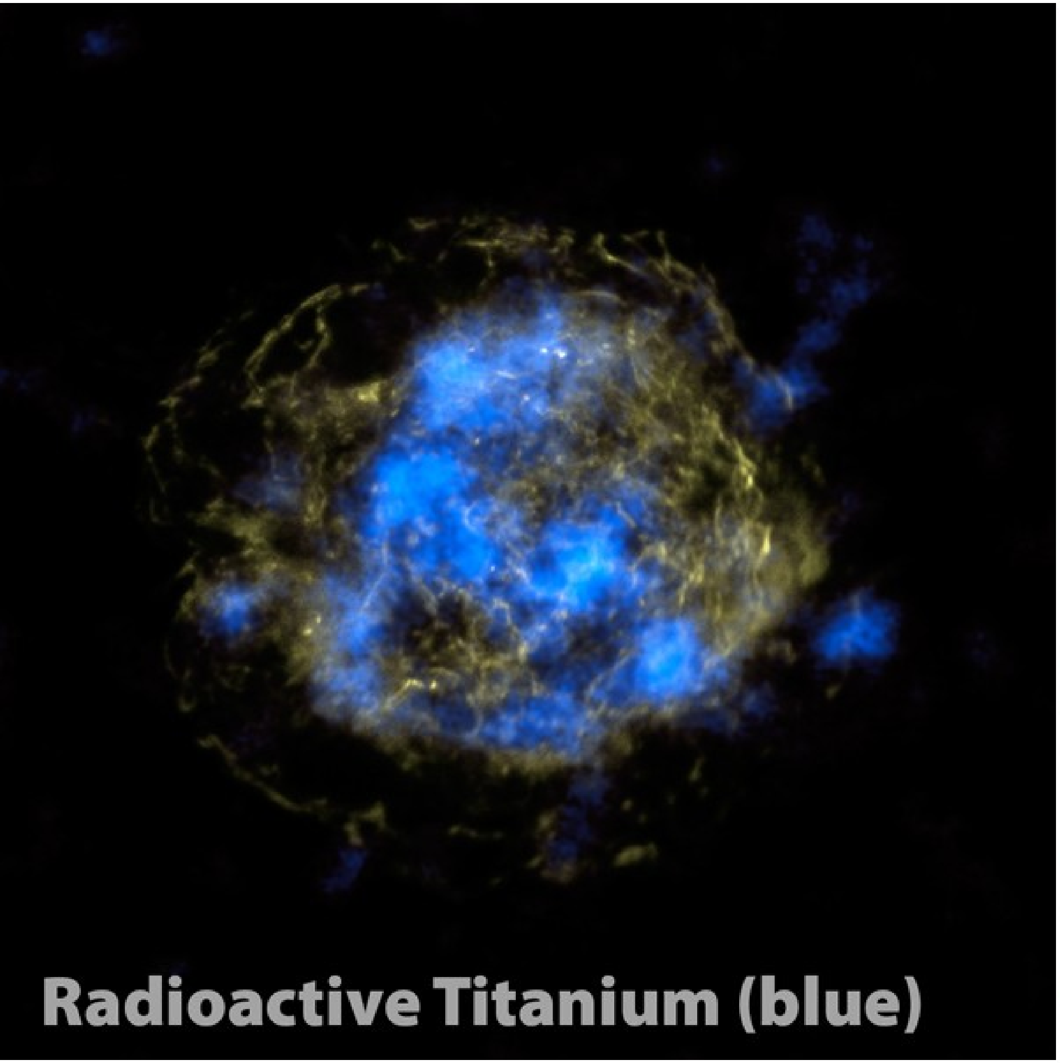
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

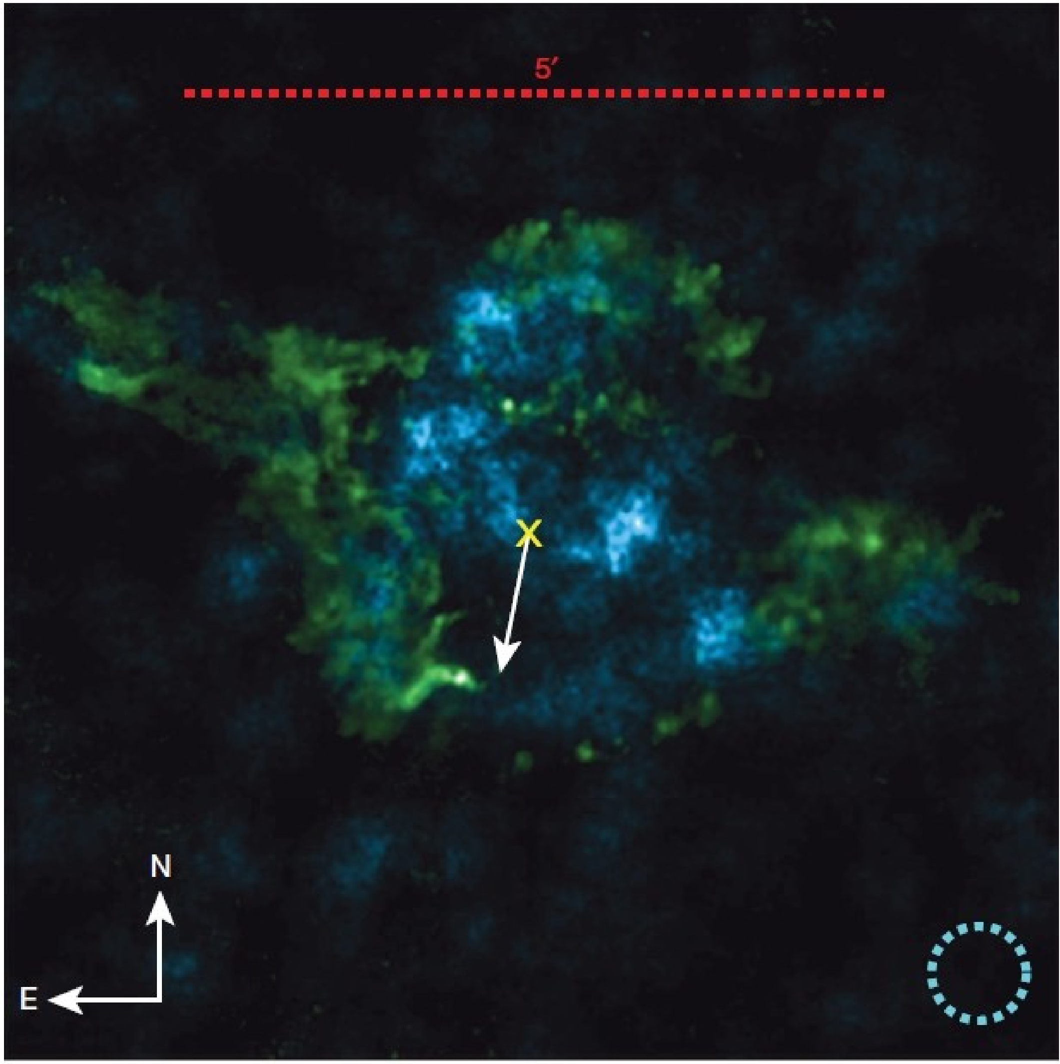




X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

^{44}Ti Asymmetry in the CAS A Remnant





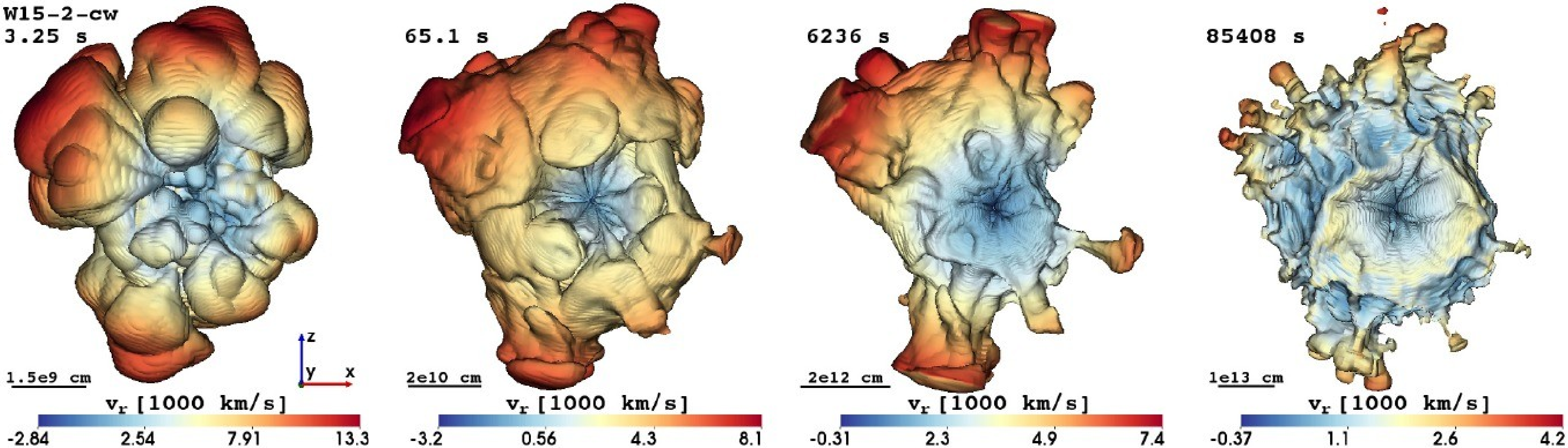
Grefenstette et al., Nature 506 (2014) 340

NuSTAR observations

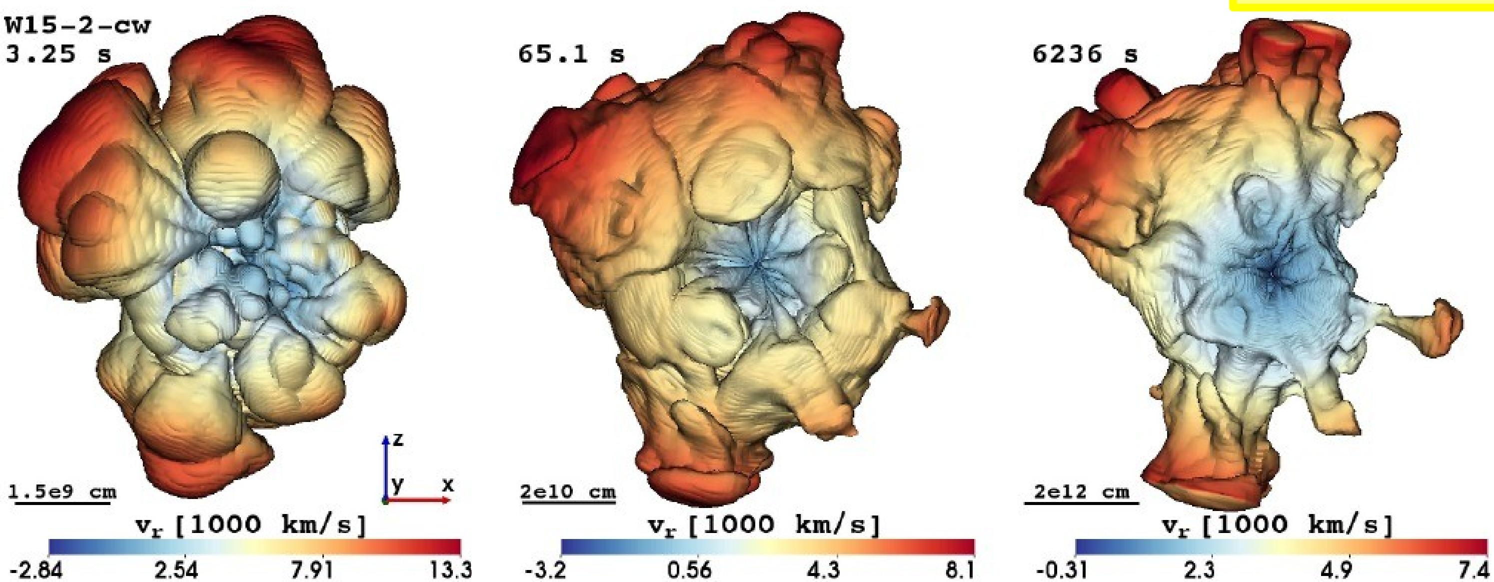
Mixing Instabilities in 3D SN Models

Model W15-2: 15 M_{sun} RSG, SN II-P case:

(Wongwathanarat, E. Müller, THJ, A&A 577 (2015) A48)



Model W15-2-IIb: 15 M_{sun} , H envelope removed, SN IIb case:

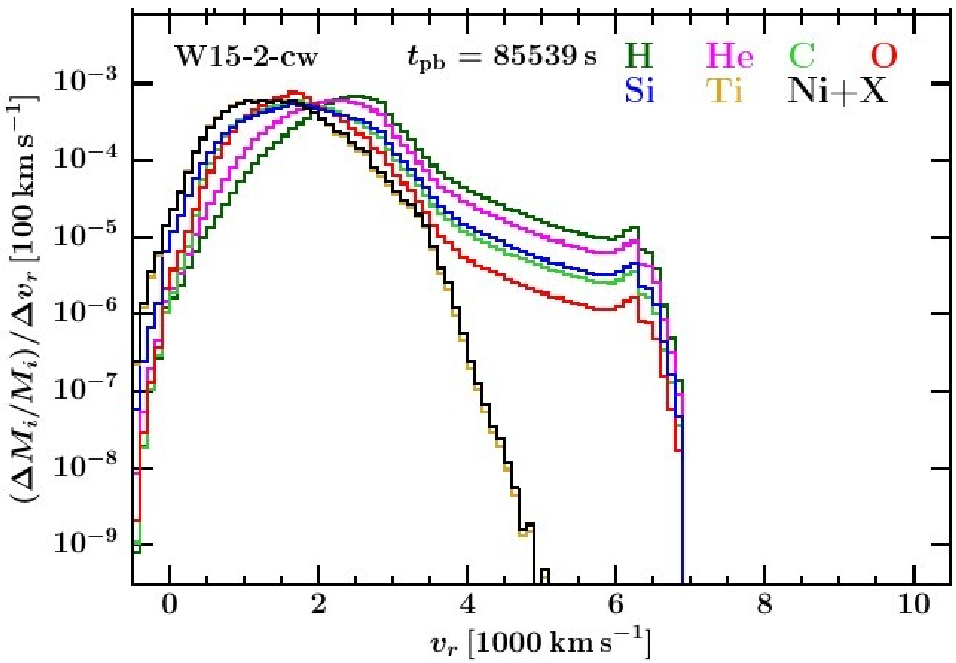


3D asymmetries from the onset of the explosion determine asymmetry of the SN ejecta and SN remnant.

Modeling of the explosion has to be performed in 3D consistently from pre-collapse stage to SNR phase !

Velocity Distributions of Chemical Elements

Model W15-2: 15 M_{sun} RSG,
SN II-P:



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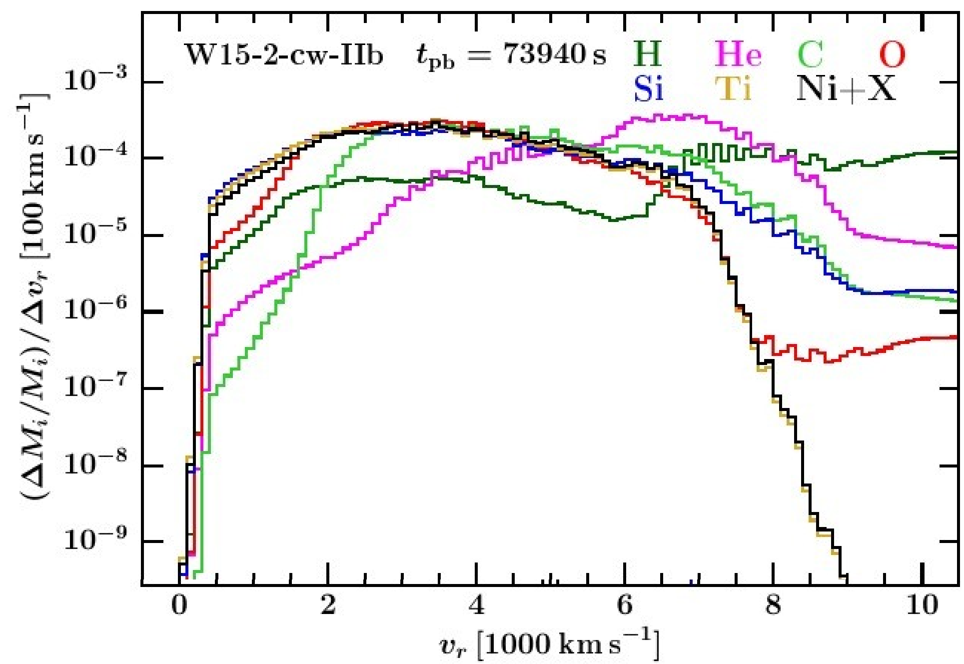


E_{exp} = 1.5 x 10^{51} erg

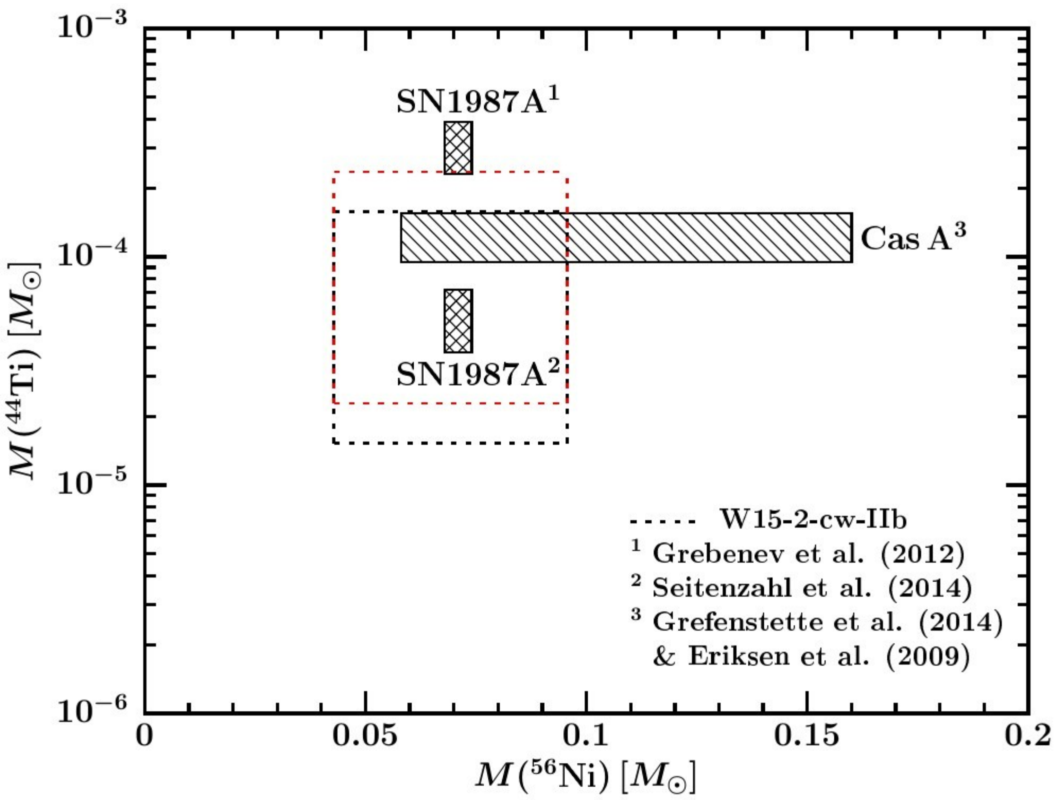
Wongwathanarat et al., arXiv:1610.05643

Total $^{56}Ni/^{56}Fe$ and ^{44}Ti Yields

$E_{exp} = 1.5 \times 10^{51}$ erg

Table 1. Yields from nucleosynthetic post-processing of tracer particles.

Model	M(^{44}Ti) [$M_\odot$]	M(^{56}Ni) [$M_\odot$]
W15-2-cw-IIb	1.57×10^{-4}	9.57×10^{-2}
W15-2-cw-IIb-shock	8.66×10^{-6}	4.20×10^{-2}
W15-2-cw-IIb-νproc	1.49×10^{-4}	5.38×10^{-2}



Y_e (nu-heated ejecta) = 0.5

Wongwathanarat et al., arXiv:1610.05643

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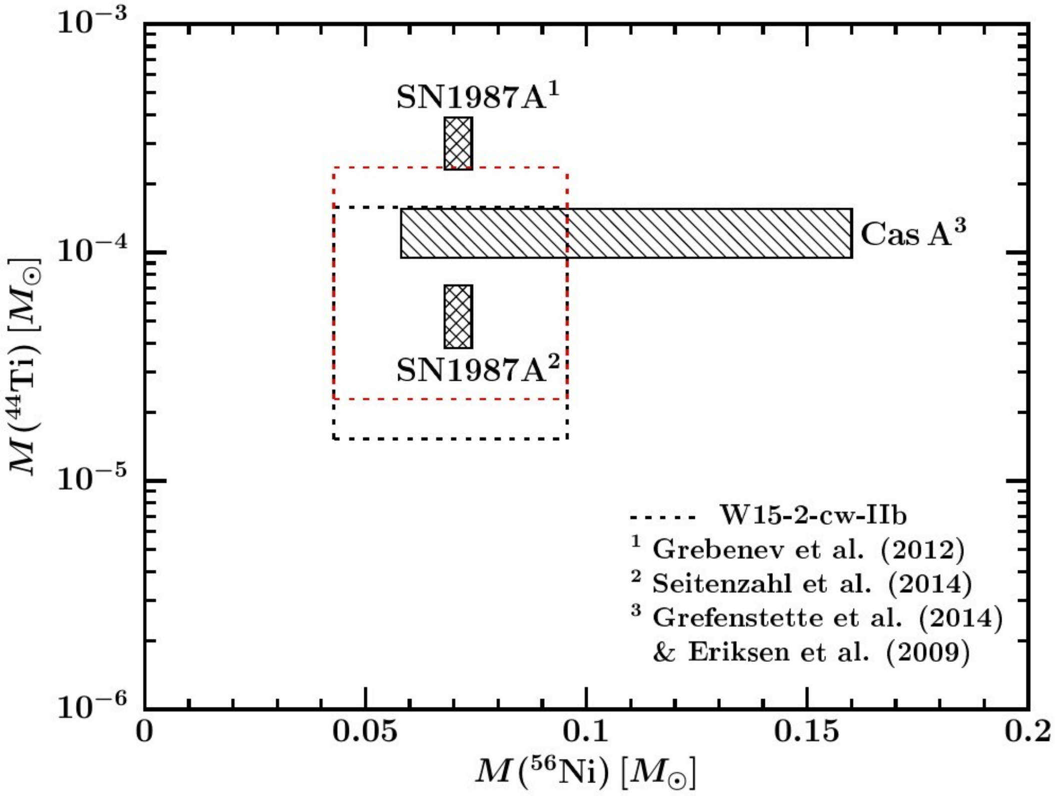
W15-2-cw-IIb-Ye$_{sim}$	1.58×10^{-5}	4.29×10^{-2}
W15-2-cw-IIb-shock	8.66×10^{-6}	4.20×10^{-2}
W15-2-cw-IIb-νproc-Ye$_{sim}$	7.16×10^{-6}	0.10×10^{-2}

Y_e (nu-heated ejecta) = 0.5

Y_e (nu-heated ejecta) = 0.47–0.49



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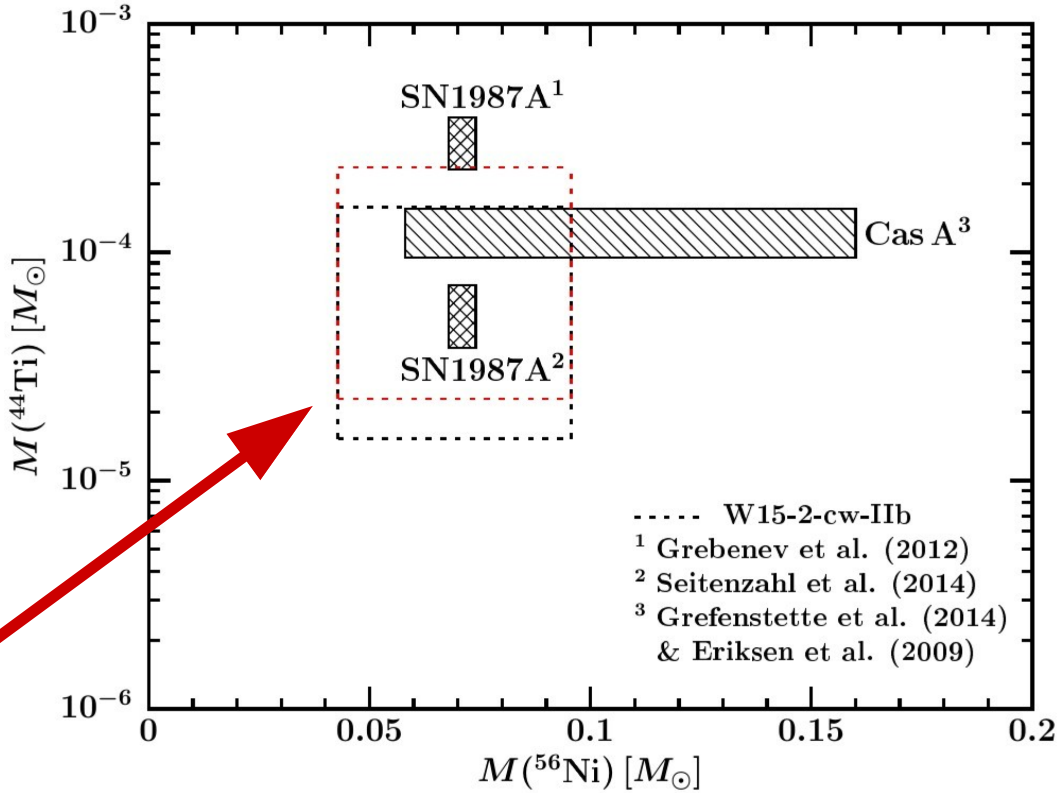
Y_e (nu-heated ejecta) = 0.5

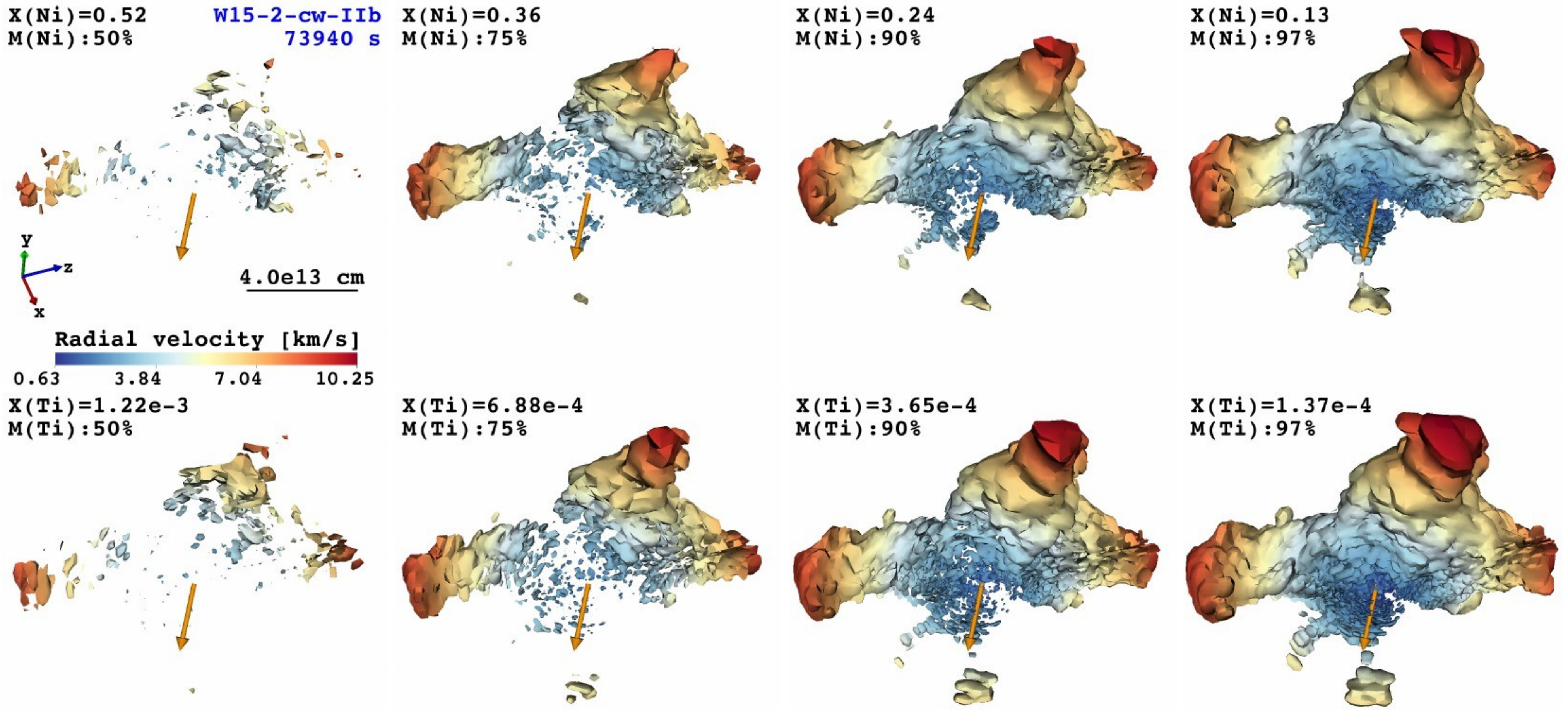
Y_e (nu-heated ejecta) = 0.47–0.49

^{44}Ti yield is increased by factor 1.5 when rate of ^{44}Ti(α,p)^{44}V reaction is reduced by factor of 2 as suggested by recent experiments (Margerin et al. 2014).



Wongwathanarat et al., arXiv:1610.05643

Neutron Star Recoil and Nickel & 44Ti Distribution



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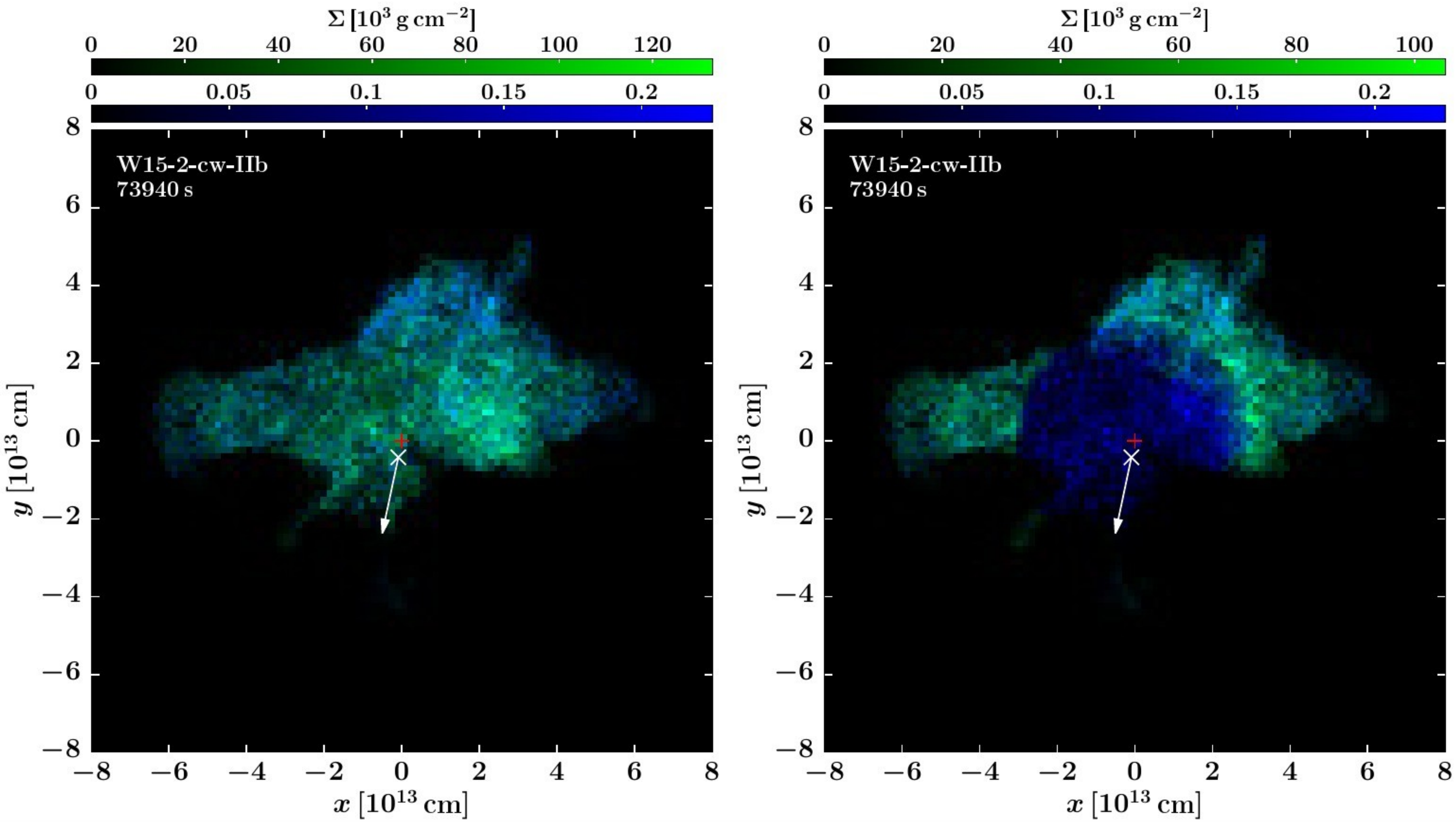

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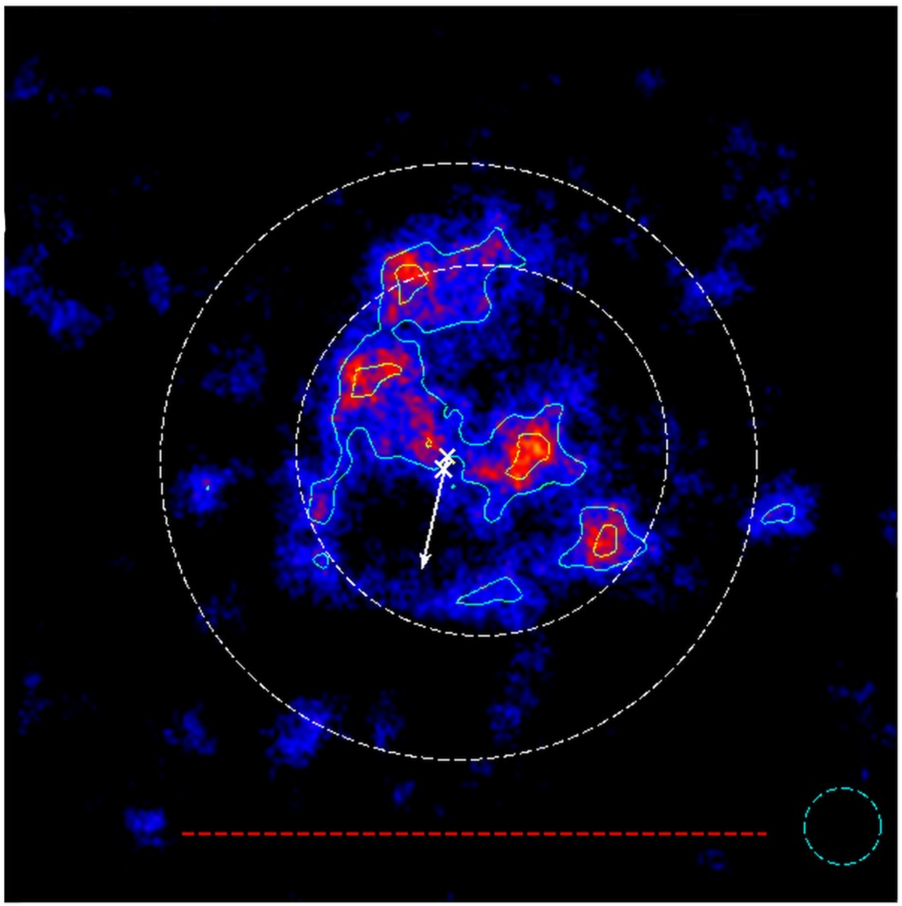
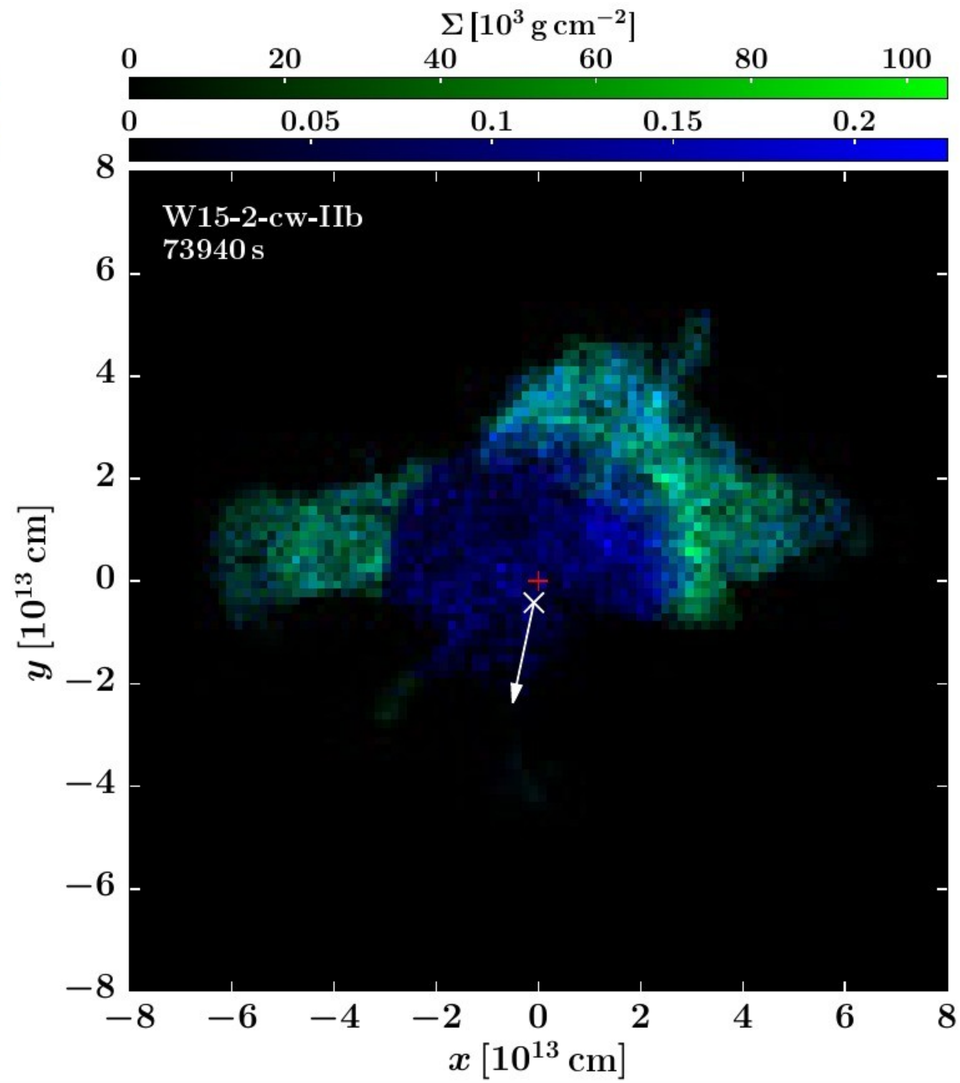


Grefenstette et al., Nature 506 (2014) 340



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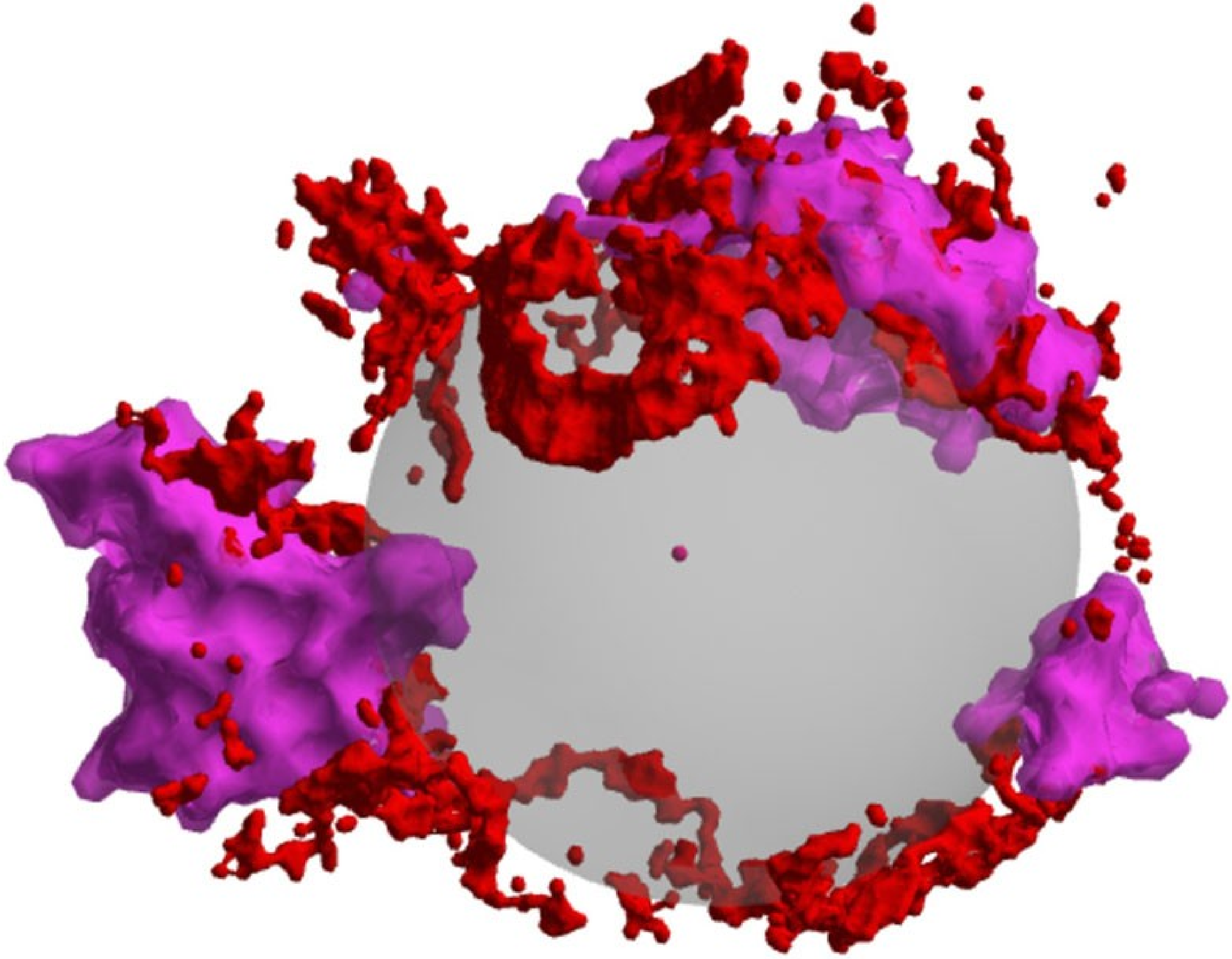
Chemical Asymmetries in CAS A Remnant



Red: Ar, Ne, and O (optical)
Purple: Iron (X-ray)

Image: Robert Fesen and Dan Milisavljevic, using iron data from DeLaney et al. (2010)

Chemical Asymmetries in CAS A Remnant

CAS A "Thick Disk"

Grefenstette et al., ApJ 834 (2017) 19

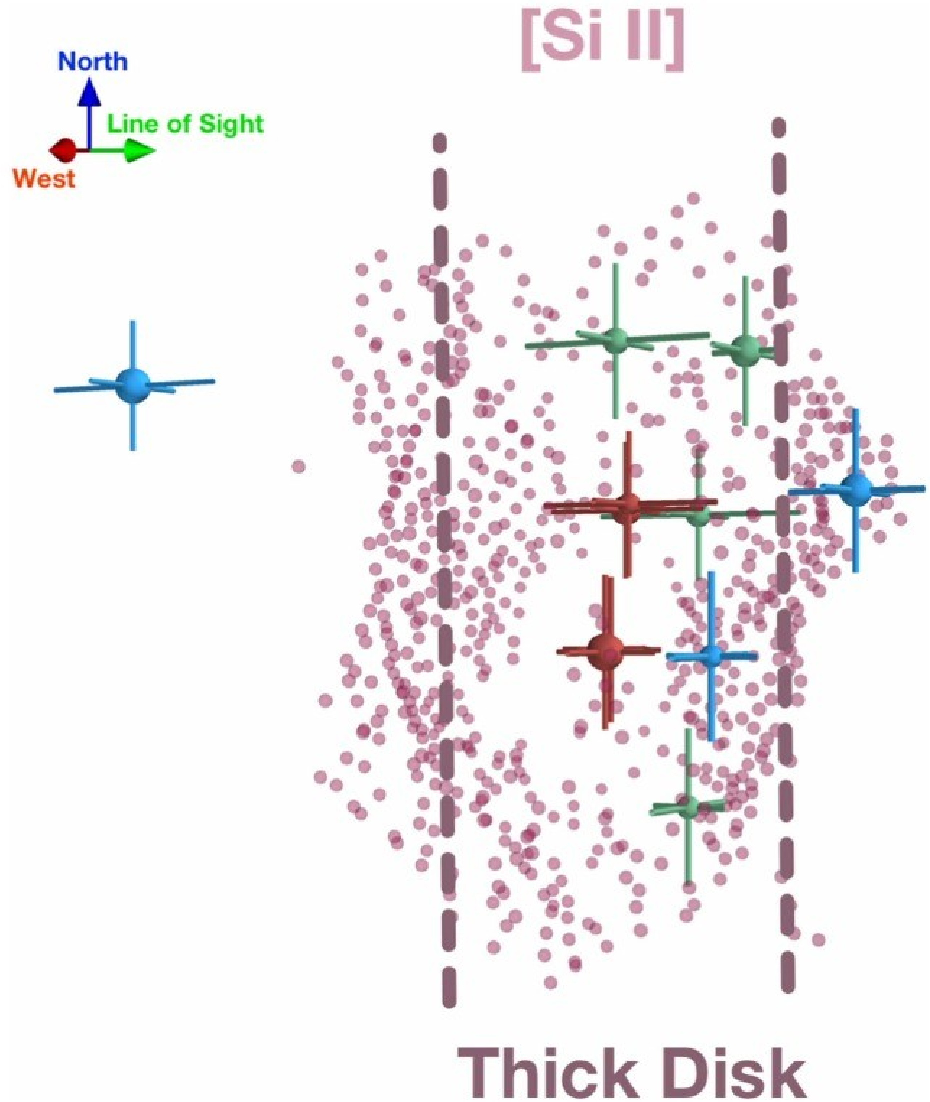
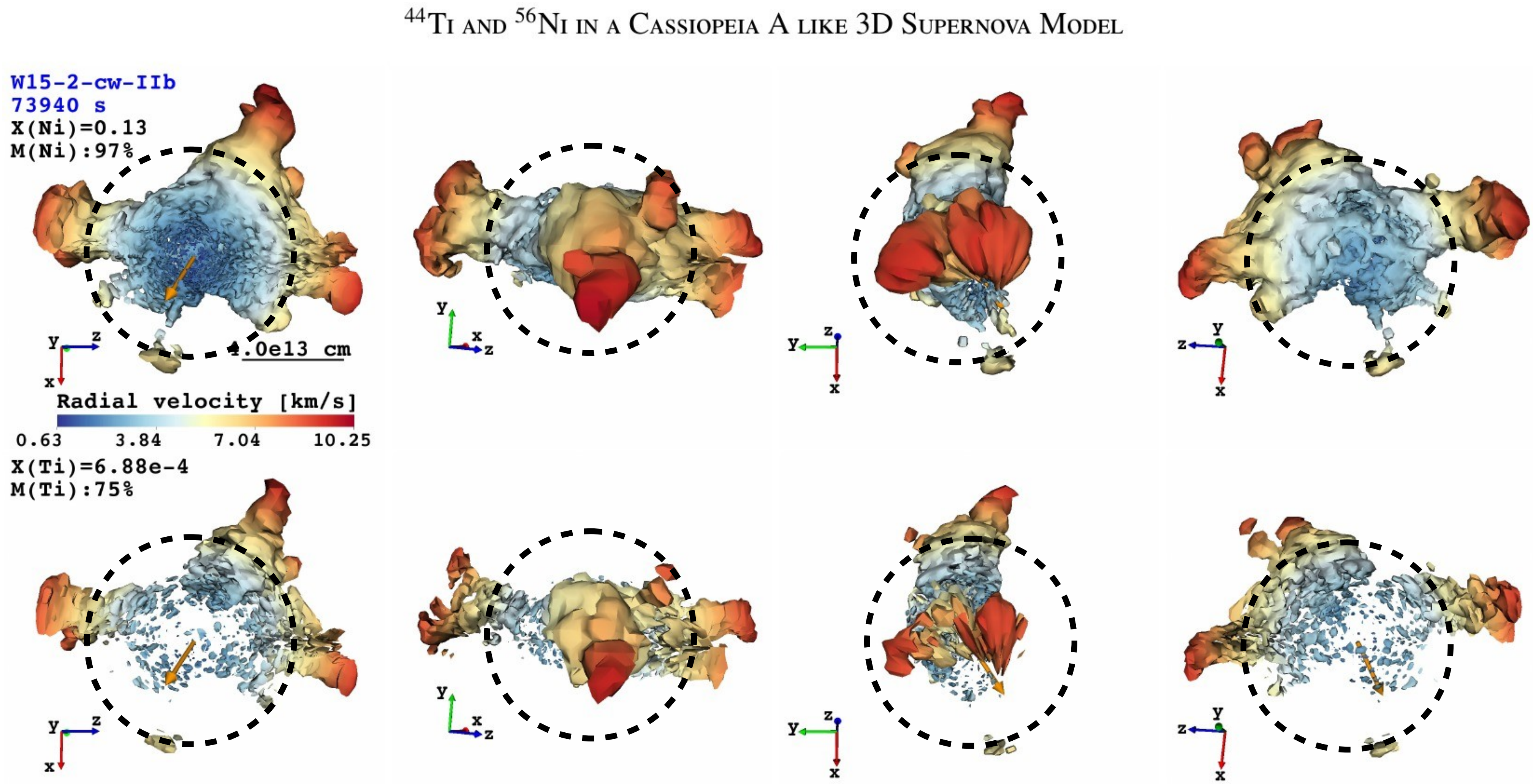


Figure 12. The 3D distribution of the observed ^{44}Ti ejecta compared with the IR [Si II] emission observed by *Spitzer* (DeLaney et al. 2010). The ^{44}Ti ejecta

Chemical Asymmetries in CAS A Remnant



Front **Top** **Left** **Back**

Wongwathanarat et al., arXiv:1610.05643

Cas A: Where We Are

What models can explain

- ✔ **High ^{44}Ti mass** can be accounted for by 3D models if Y_e is close to 0.5. Presently impossible to compute accuractly.
- ✔ **Observed ^{44}Ti velocities** easily compatible with SN IIb explosion for nonrotating Cas A progenitor with explosion energy of ~$2x10^{51}$ erg.
- ✔ **Cas A morphology with iron and titanium distributions** can be accounted for by neutrino-driven explosion of SN IIb.
- ✔ **NS kick, kick velocity and ejecta distribution** agree with theoretical expections based on neutrino-driven explosion models.

Open questions

- Why did Cas A and SN 1987A produce atypically much ^{44}Ti ?
  Is this characteristic of progenitor masses around 15–20 M_{sun} ?
- Why is hardly any ^{44}Ti seen in iron-rich regions?
  Is ^{44}Ti decay prevented by ionization in shocked region?
- What causes the fiducial "jet" and "counter-jet"?
  Is this connected to progenitor asymmetries (e.g. in the convective O-burning shell) or magnetic, bipolar activity of the new-born neutron star ?

Status of Neutrino-driven Mechanism in 2D & 3D Supernova Models

- **Young SN remnants** like CAS A, SN 1987A and Crab provide wealth of observational information that can be used to **probe explosion mechanism**.
- NS kick, Ti and Ni masses, velocities, and spatial distribution of **CAS A can be explained by** nonradial hydrodynamic instabilities associated with **neutrino-driven explosion mechanism.**

Ringberg Workshop on
Progenitor – Supernova – Remnant Connection
Ringberg Castle, Tegernsee
July 24-28, 2017
http://www.mpa-garching.mpg.de/conf/psrc/