Max-Planck-Institut für Astrophysik

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"Brainstorming and Fun"
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Supernova Simulations
From Progenitors to Remnants

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Hans-Thomas Janka
for the CCSN Team

COCO2CASA

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

- 2D models with relativistic effects (2D GR and approximate GR) and most elaborate microphysics explode for "soft" EoSs, but explosion energies tend to be on the low side.
- 3D modeling has only begun. No final picture of 3D effects yet.

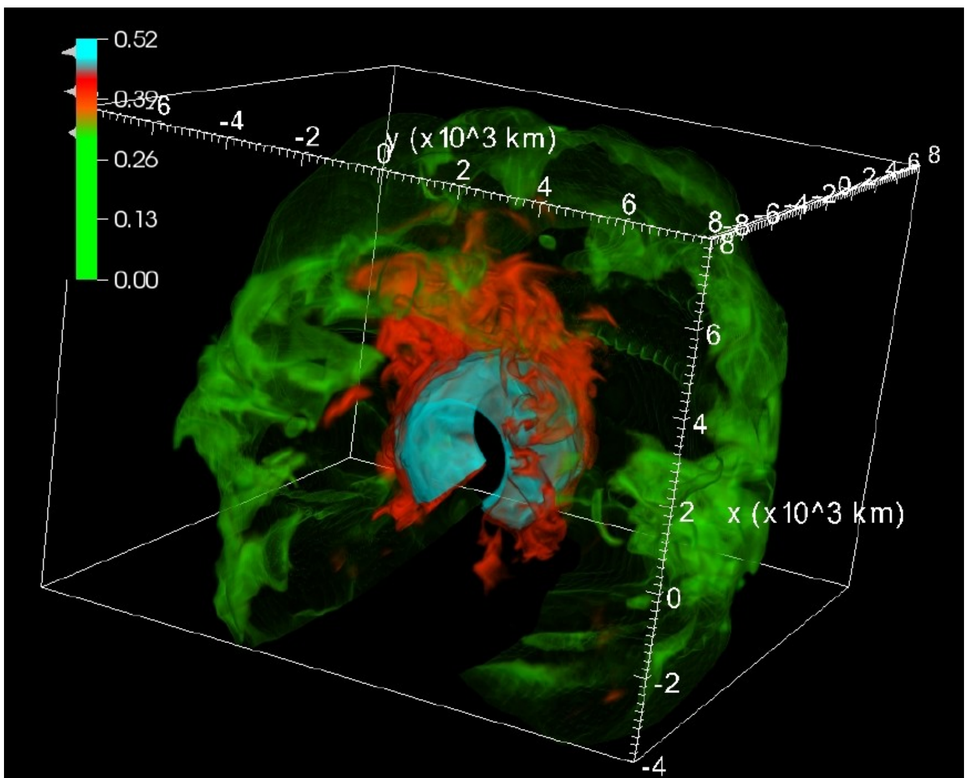
- **$M < 10\ M_{sun}$ explosion in 3D, "Crab-like"** **(Melson+, ApJL 801 (2015), L24).** **First 3D explosions of 15–20 M_{sun} progenitors**
  (Garching 20 Msun model explodes with slightly reduced neutrino-n,p scattering opacities).

- 3D simulations **still need higher resolution** for convergence.
- **Progenitors are 1D**, but shell structure and initial progenitor-core asymmetries can affect onset of explosion.
  (cf. Couch et al. ApJL778:L7 (2013), ApJ (2015); Müller & THJ, MNRAS 448 (2015) 2141, Müller et al. 2016)
- **Uncertain/missing physics ?????**

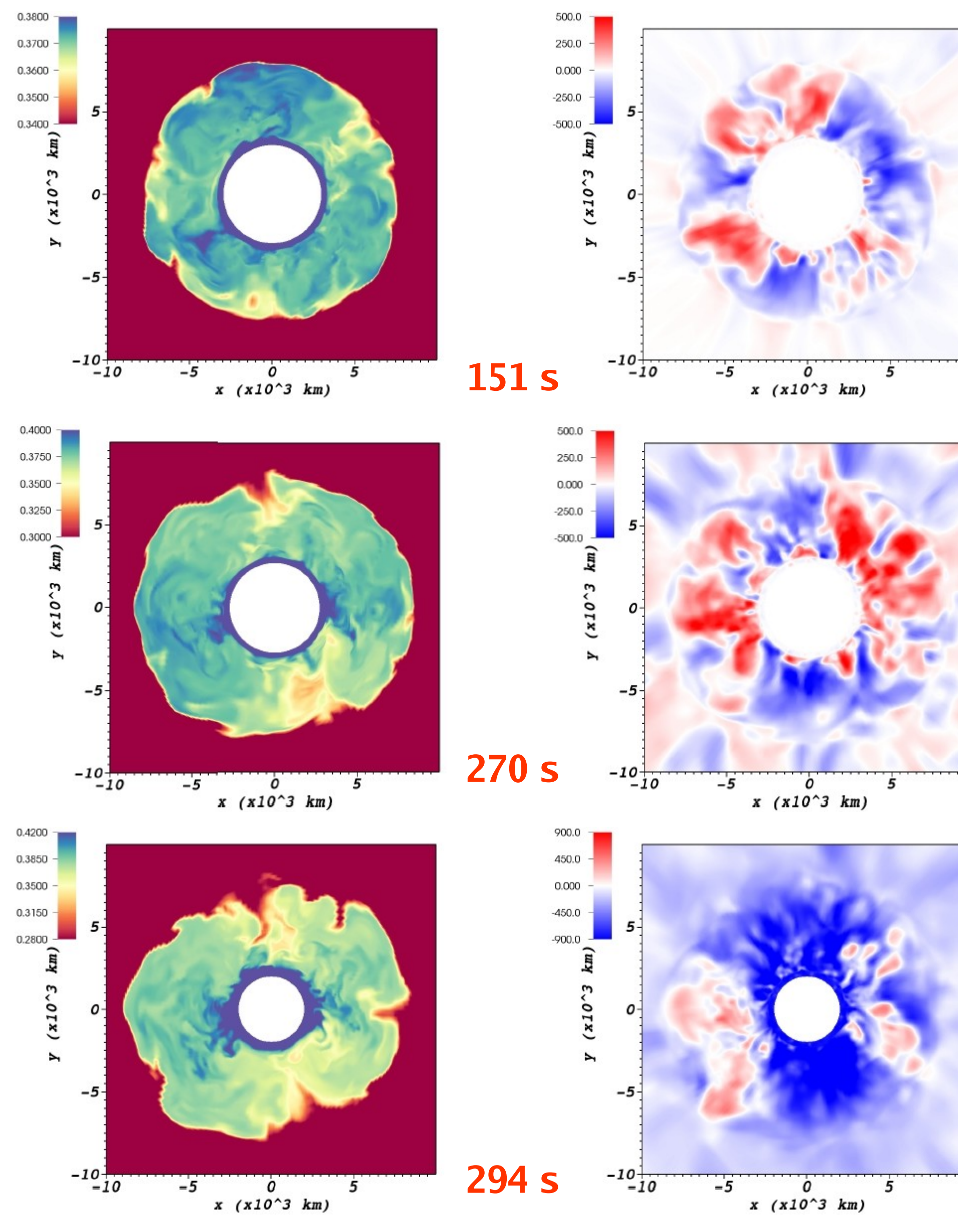
3D Core-Collapse SN Progenitor Model

18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.
This will foster strong postshock convection and could thus reduce the criticial neutrino luminosity for explosion.



B. Müller, Viallet, Heger, & THJ, arXiv:1605.01393



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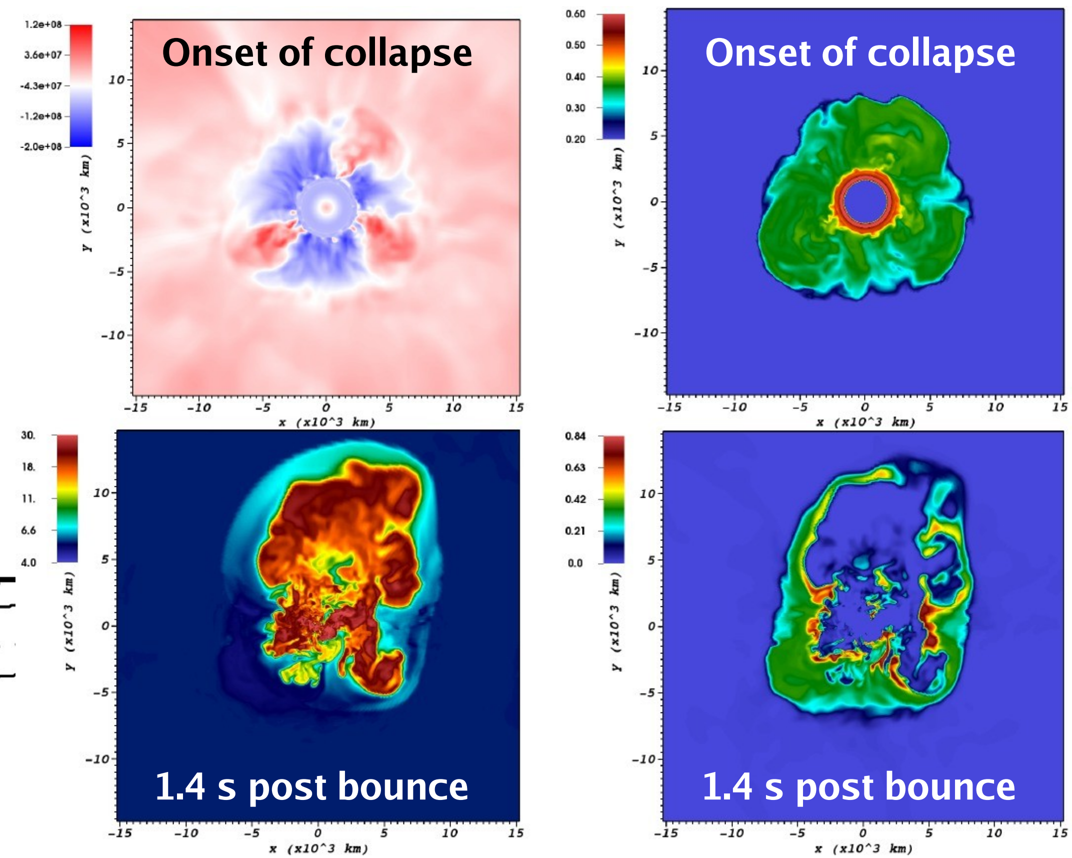
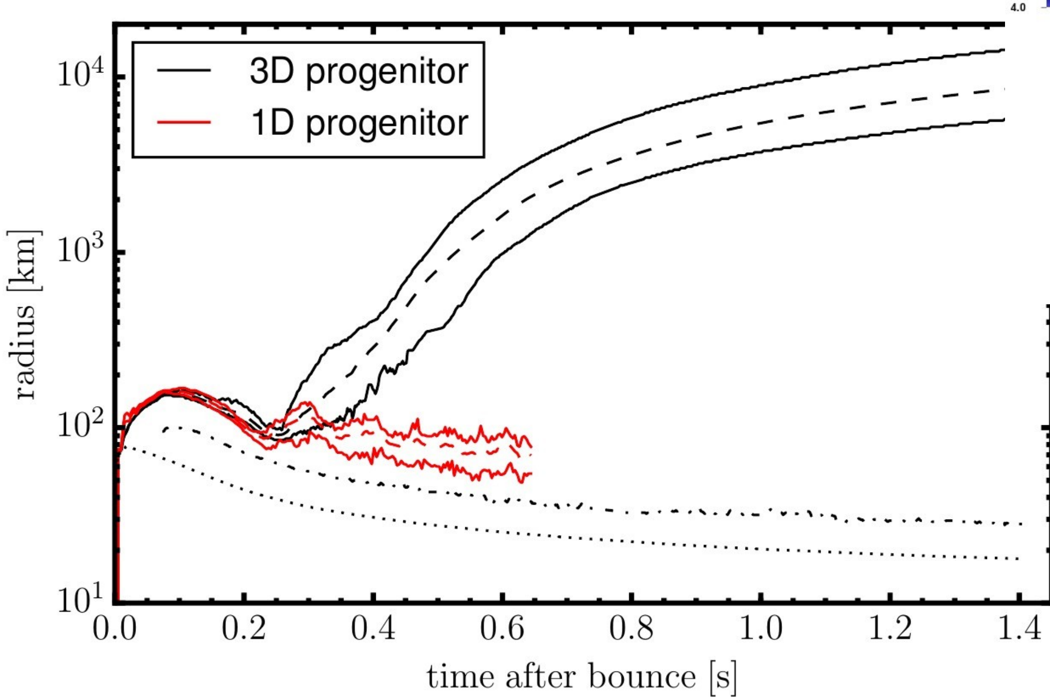


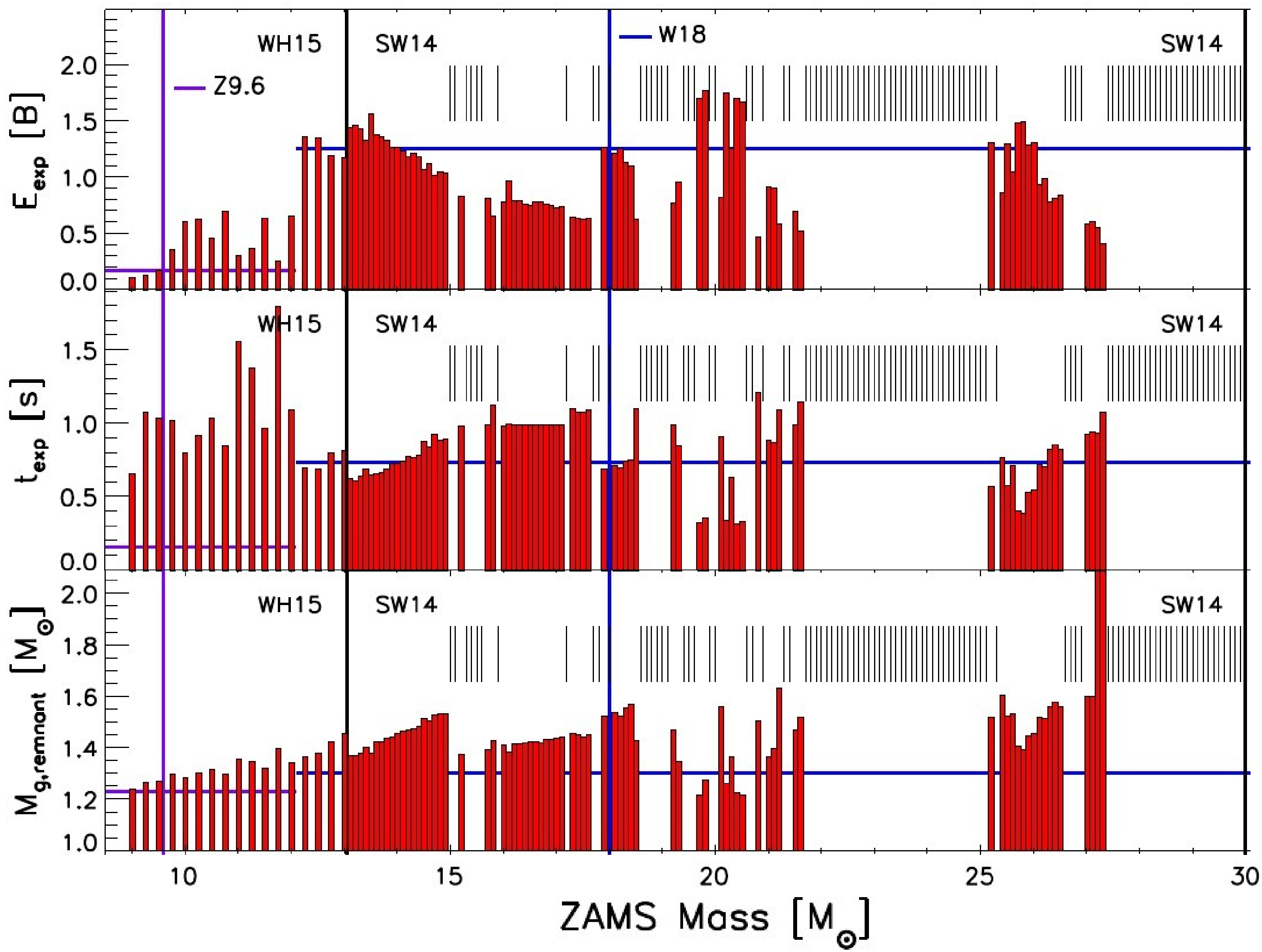


B. Müller, PASA review, arXiv:1608.03274

Consequences of (Asymmetric) Supernova Explosions —

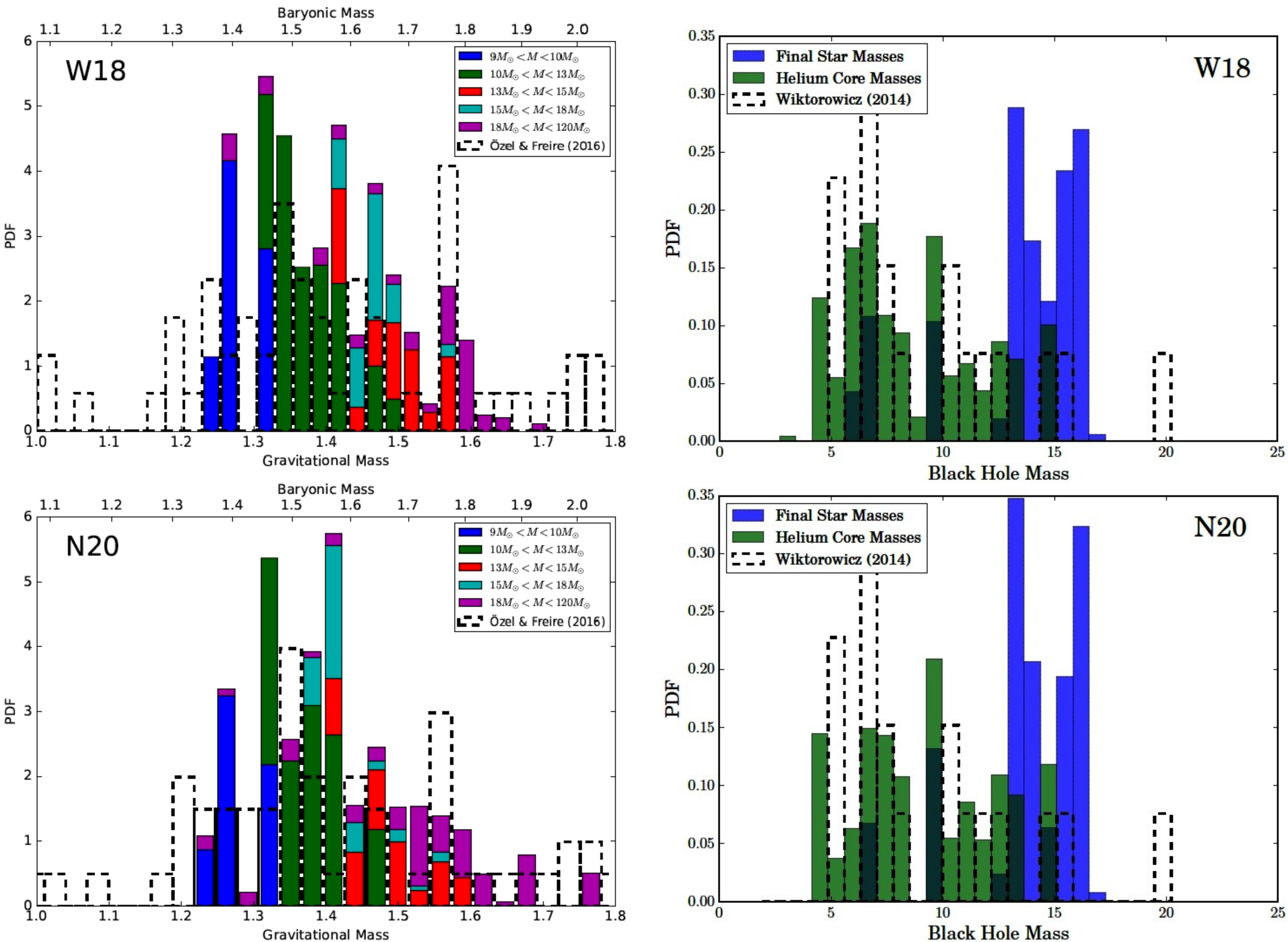
Probing the Mechanism by Observational Constraints

Progenitor-Explosion Systematics: "Supernova Landscape"



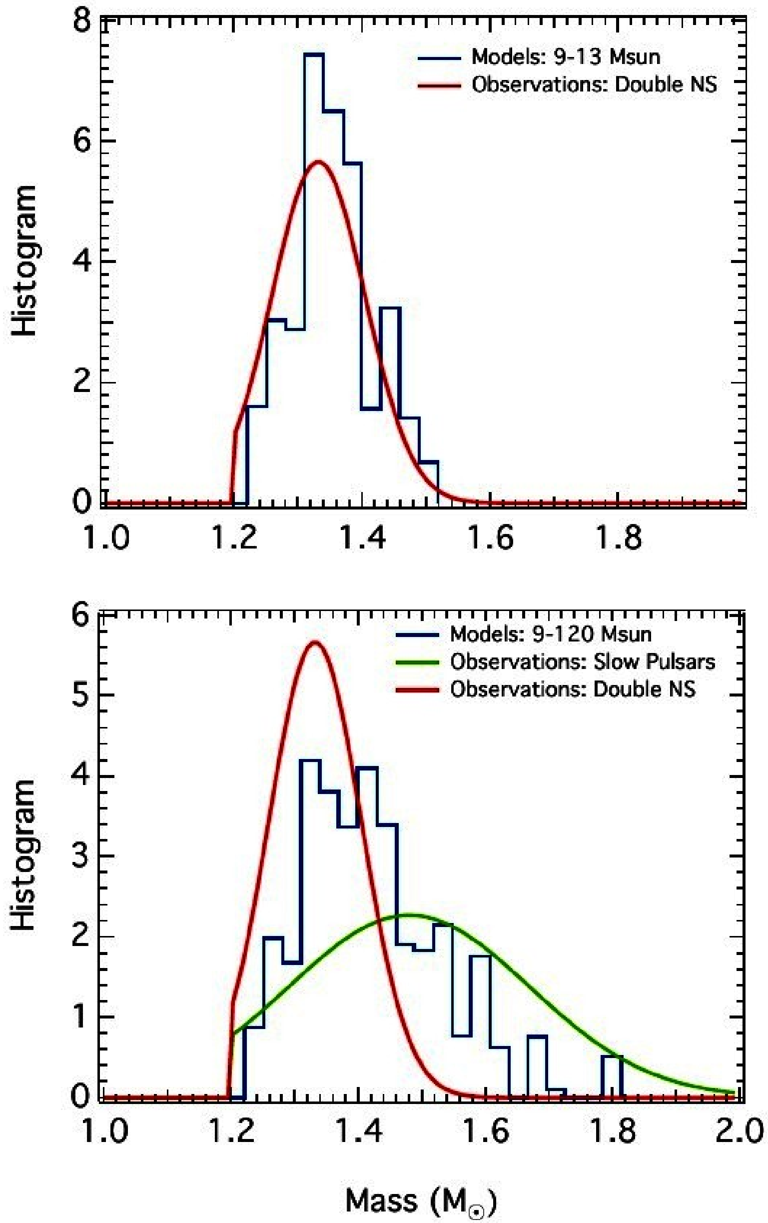
O'Connor & Ott (2011), Ugliano et al. (2012), Pejcha & Thompson (2015), Ertl et al. (2016), Sukhbold et al. (2016), Müller et al. (2016)

Birth-Mass Distributions of NSs and BHs



(Sukhbold, Ertl et al., ApJ 821 (2016) 38)

Birth-Mass Distributions of NSs and BHs



NS birth-mass distributions deduced from observations: bimodality:

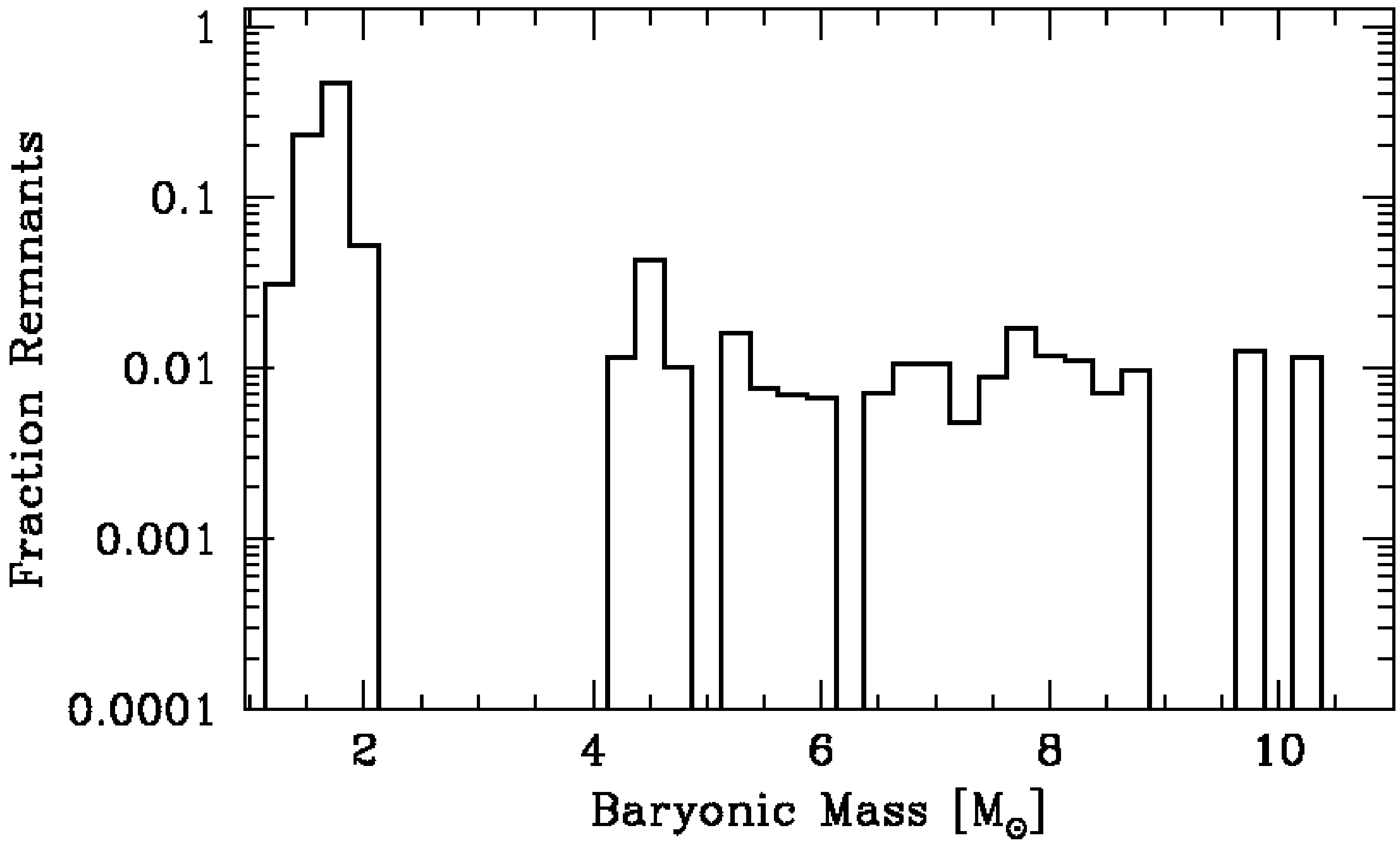
Antoniadis, Tauris, Özel, et al., ApJ, 2016

Comparison of Ertl et al. model results with observations

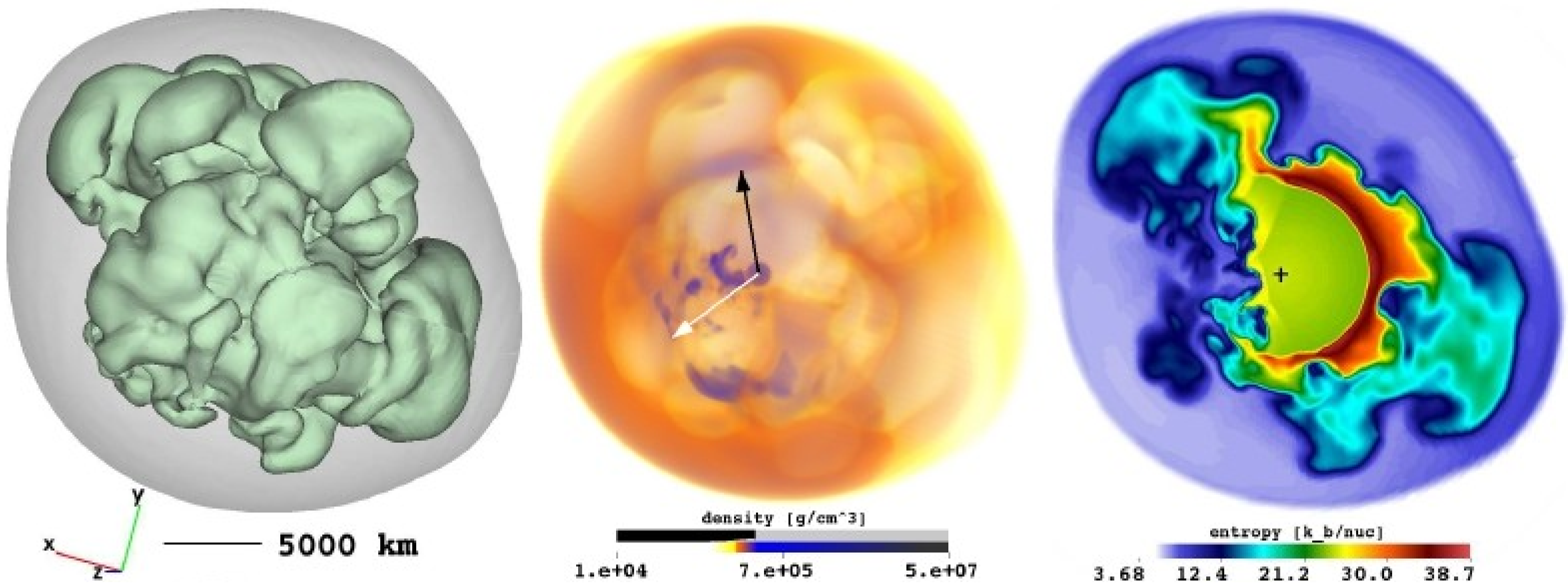
F. Özel, private communication, 2015

Theoretical Remnant Mass Distribution

Our model results reproduce possible gap
in the observed distribution of NS and BH masses if
H-shell stripping for BH formation without SN is included.



Neutron Star Recoil in 3D Explosion Models

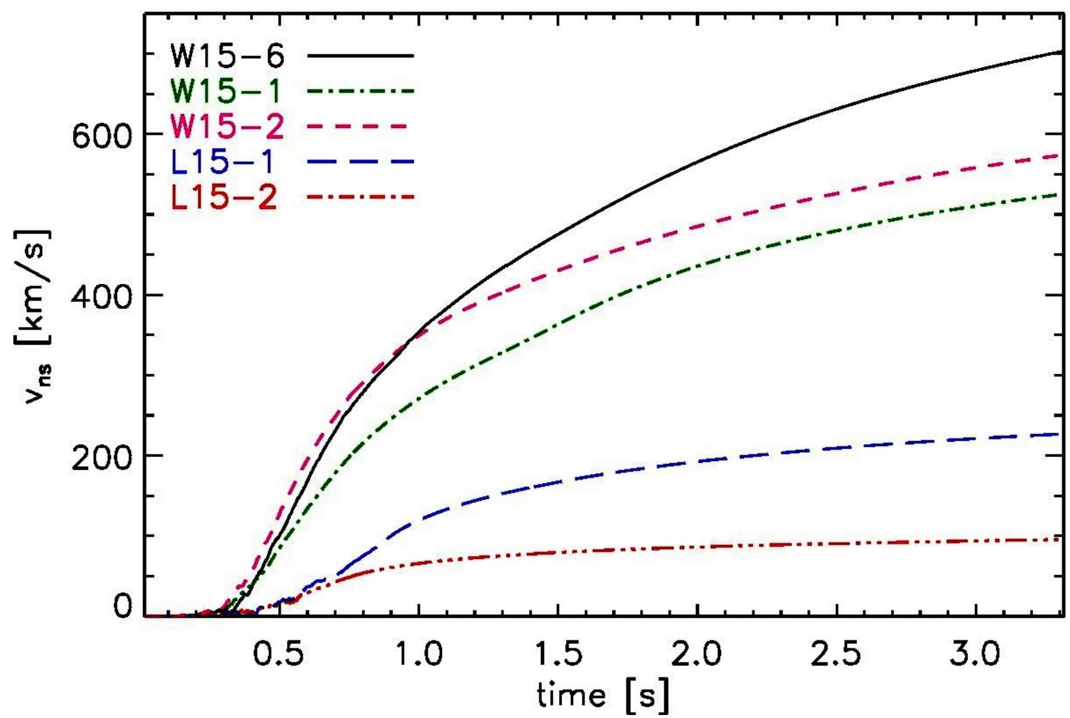


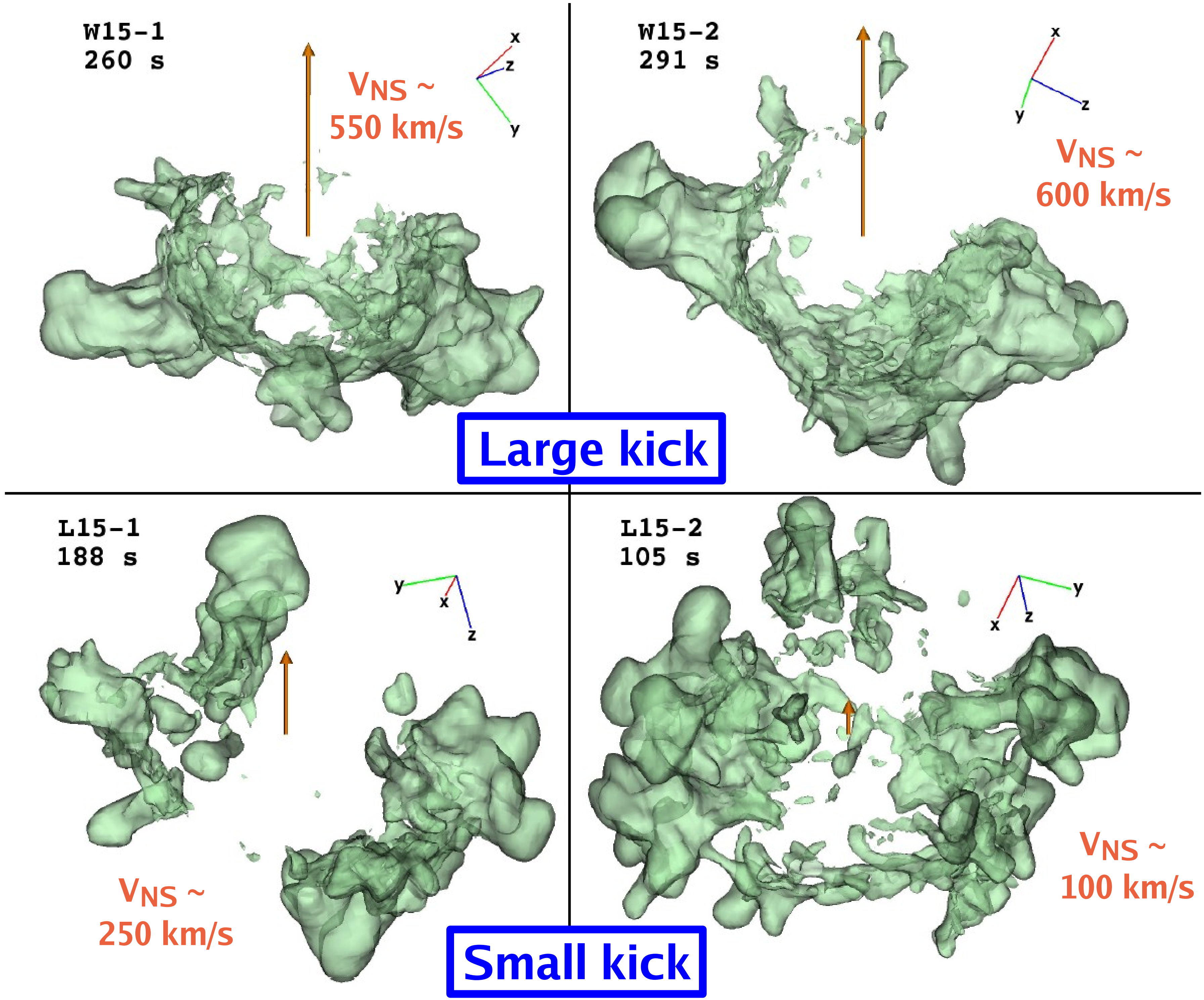
Gravitational tug-boat mechanism

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

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

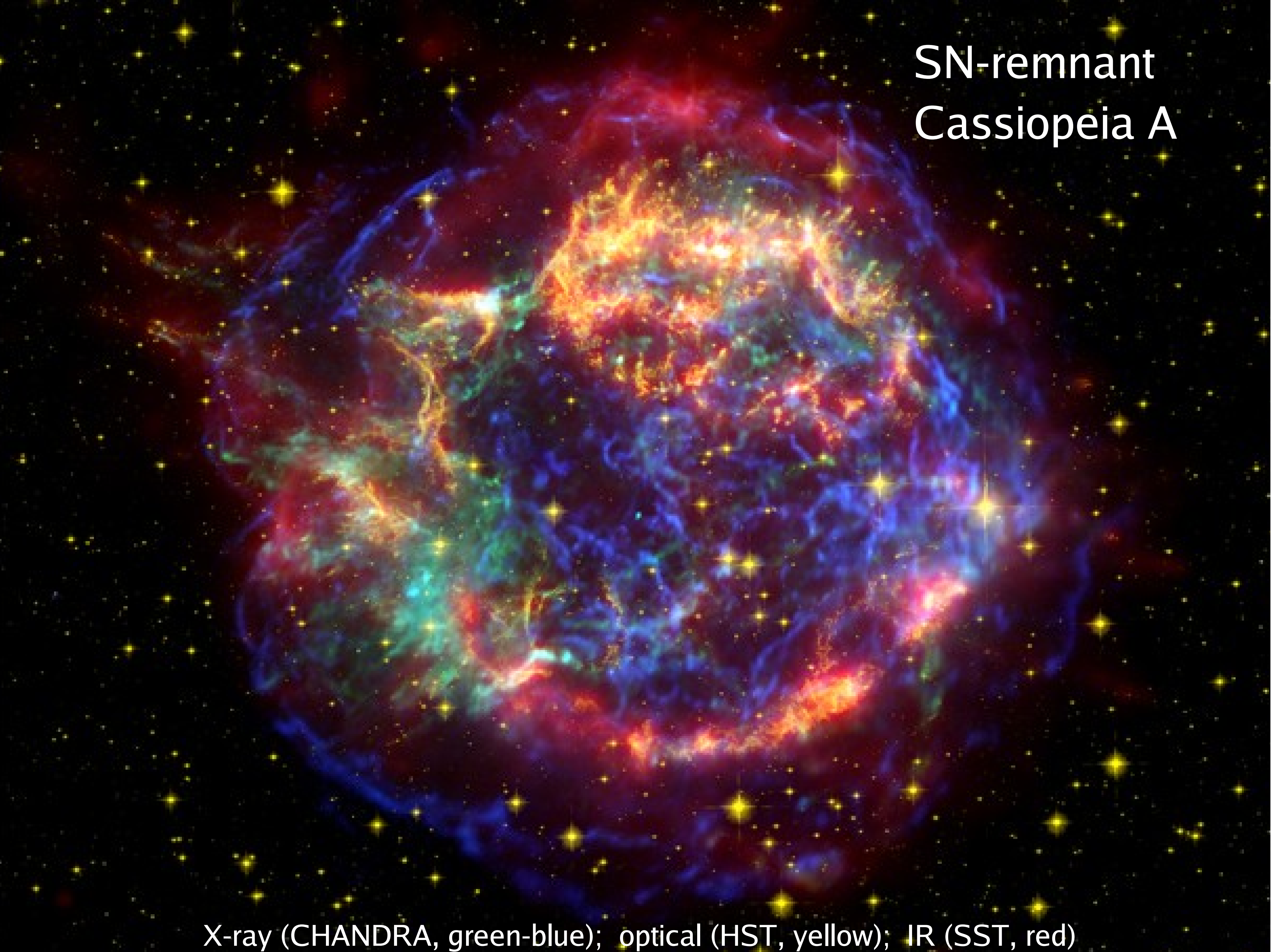
Wongwathanarat, Janka, Müller,
ApJL 725, 106 (2010); A&A 552, 126 (2013)





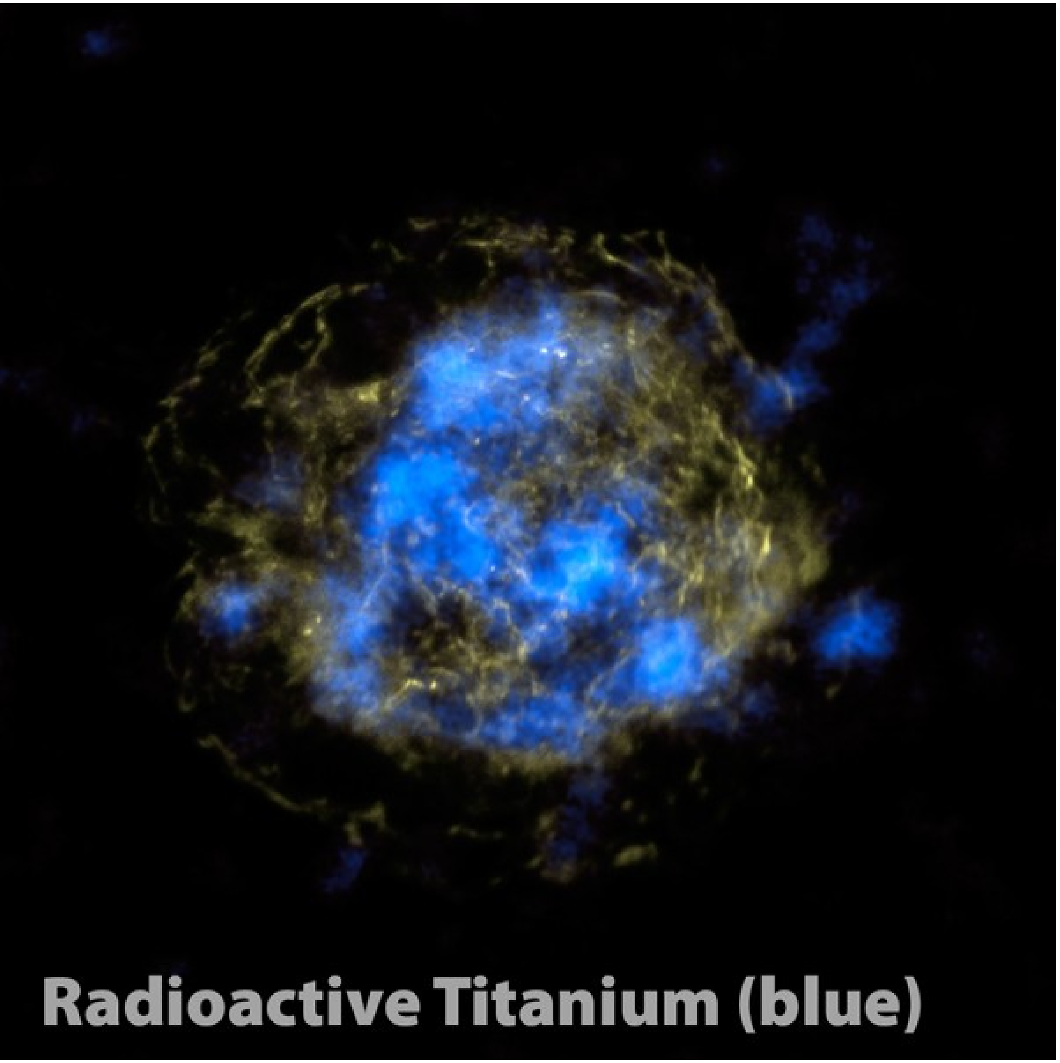
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

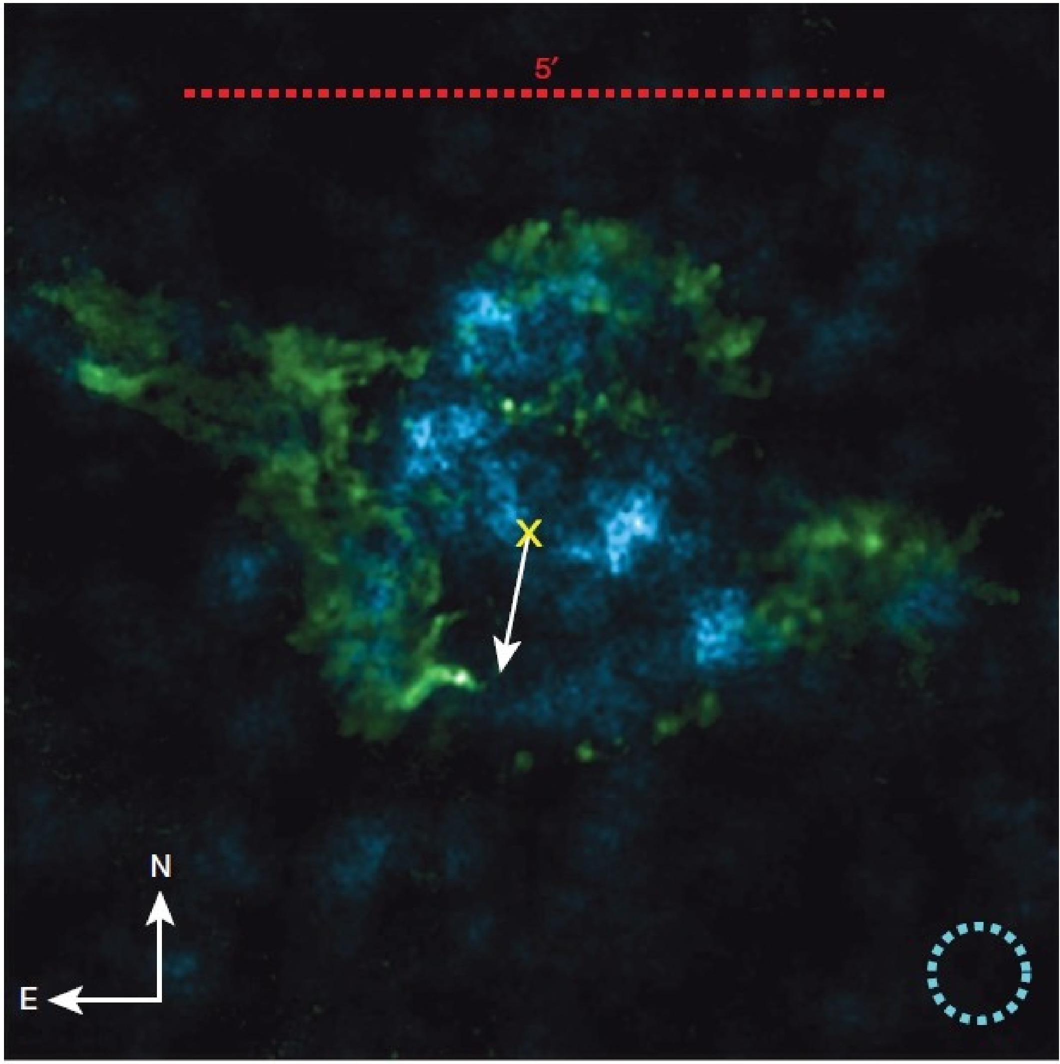
SN-remnant Cassiopeia A



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

^{44}Ti Asymmetry in the CAS A Remnant

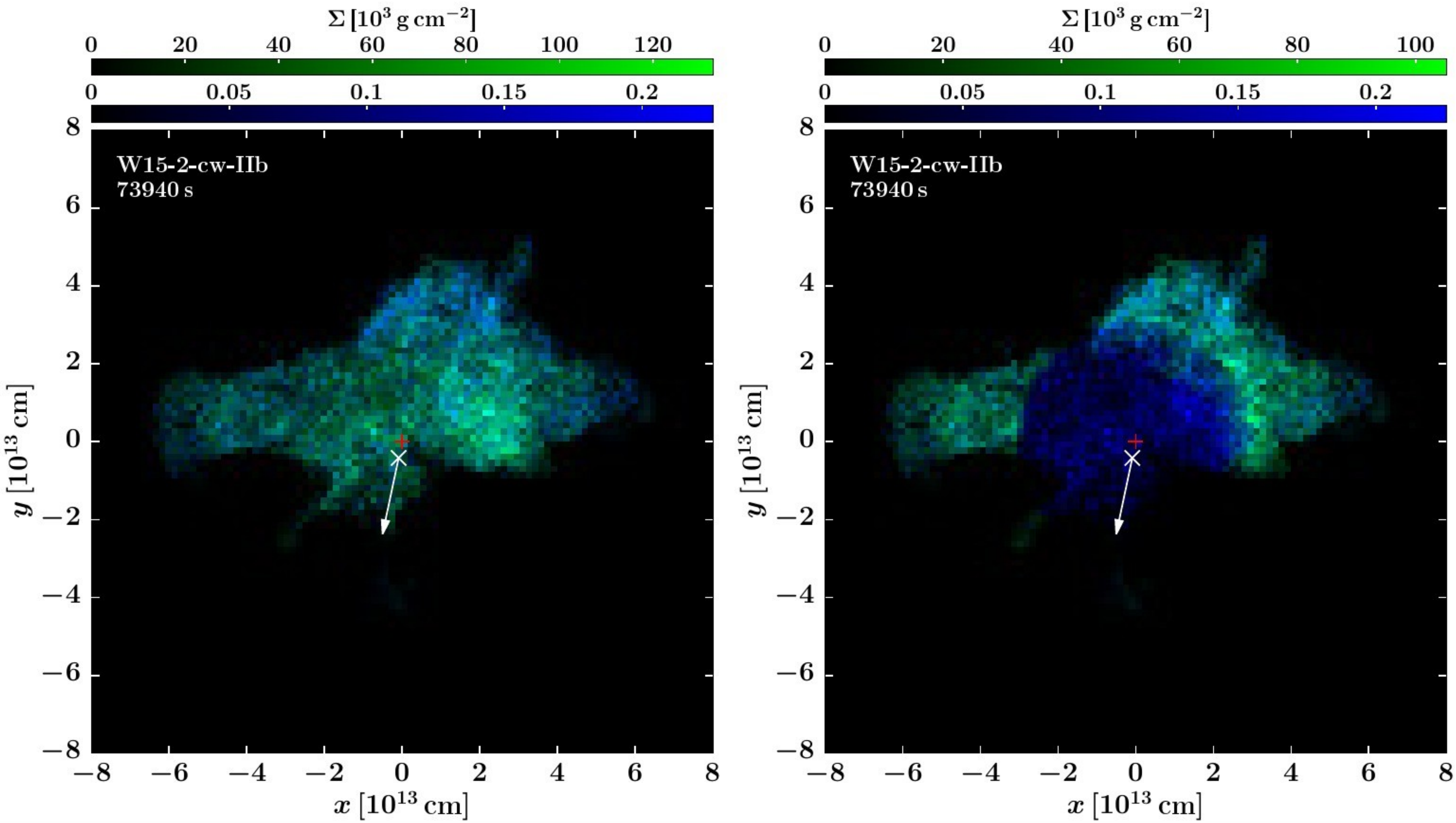




Grefenstette et al., Nature 506 (2014) 340

NuSTAR observations

Neutron Star Recoil and Nickel & 44Ti Distribution



Wongwathanarat et al., in preparation

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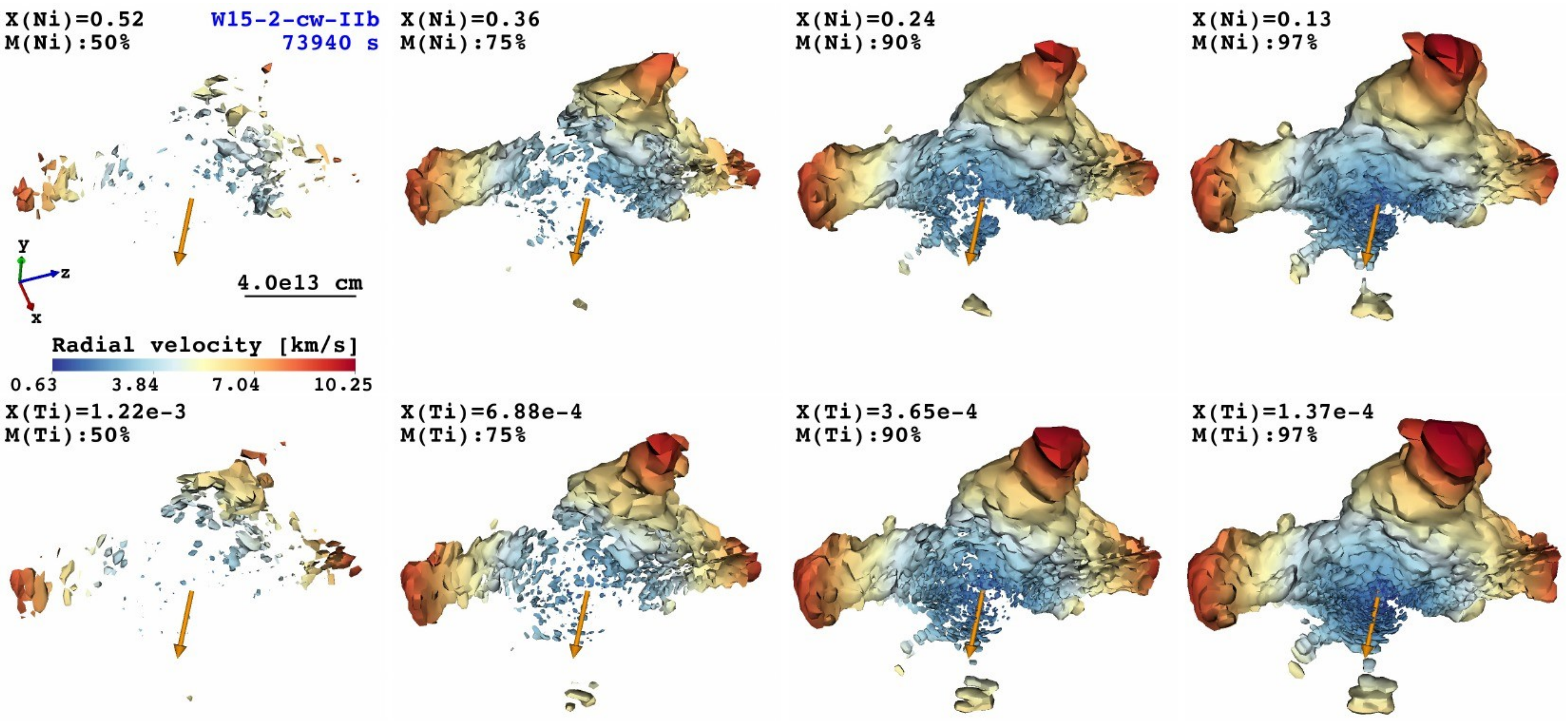

Wongwathanarat et al., in preparation

Chemical Asymmetries in CAS A Remnant

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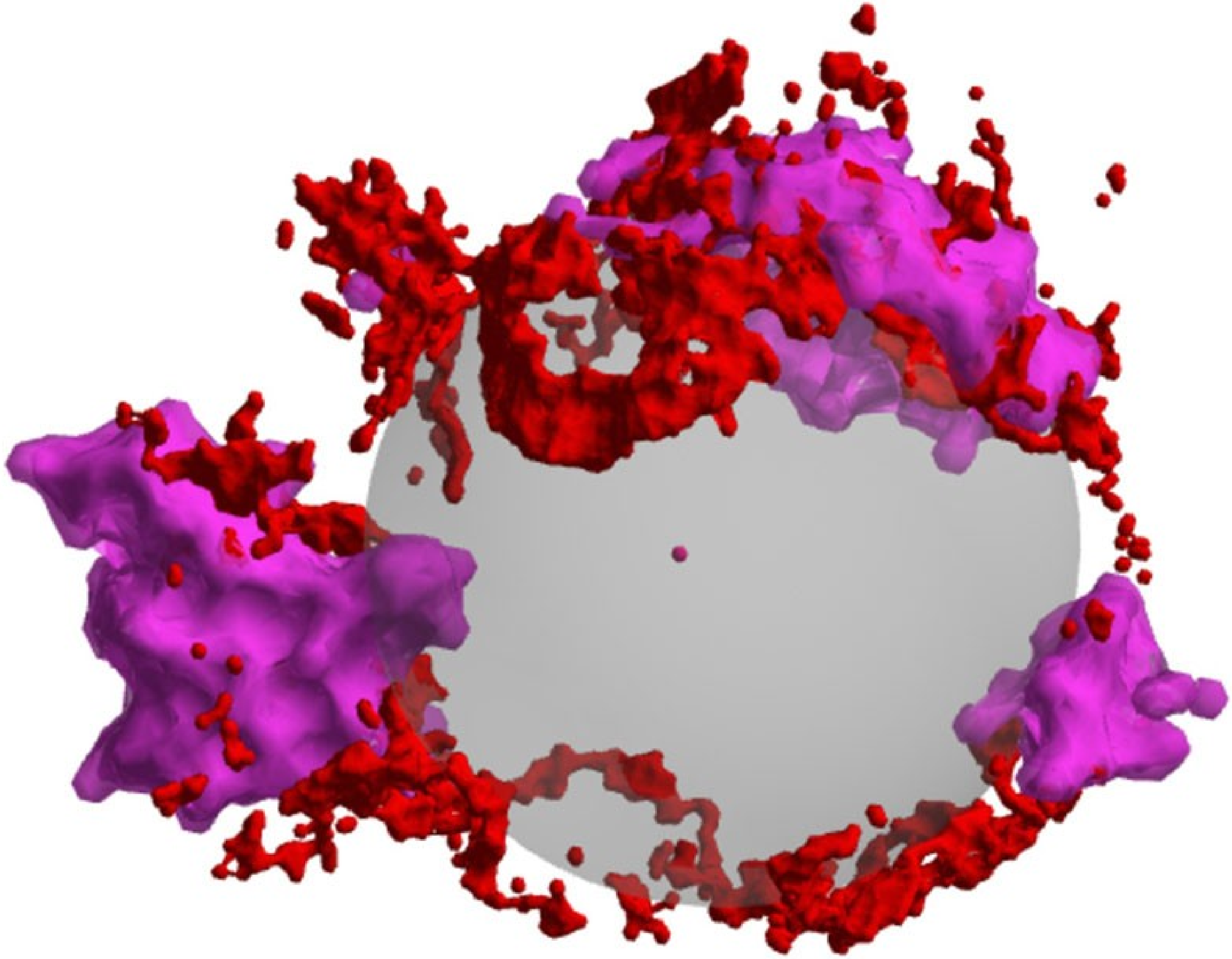
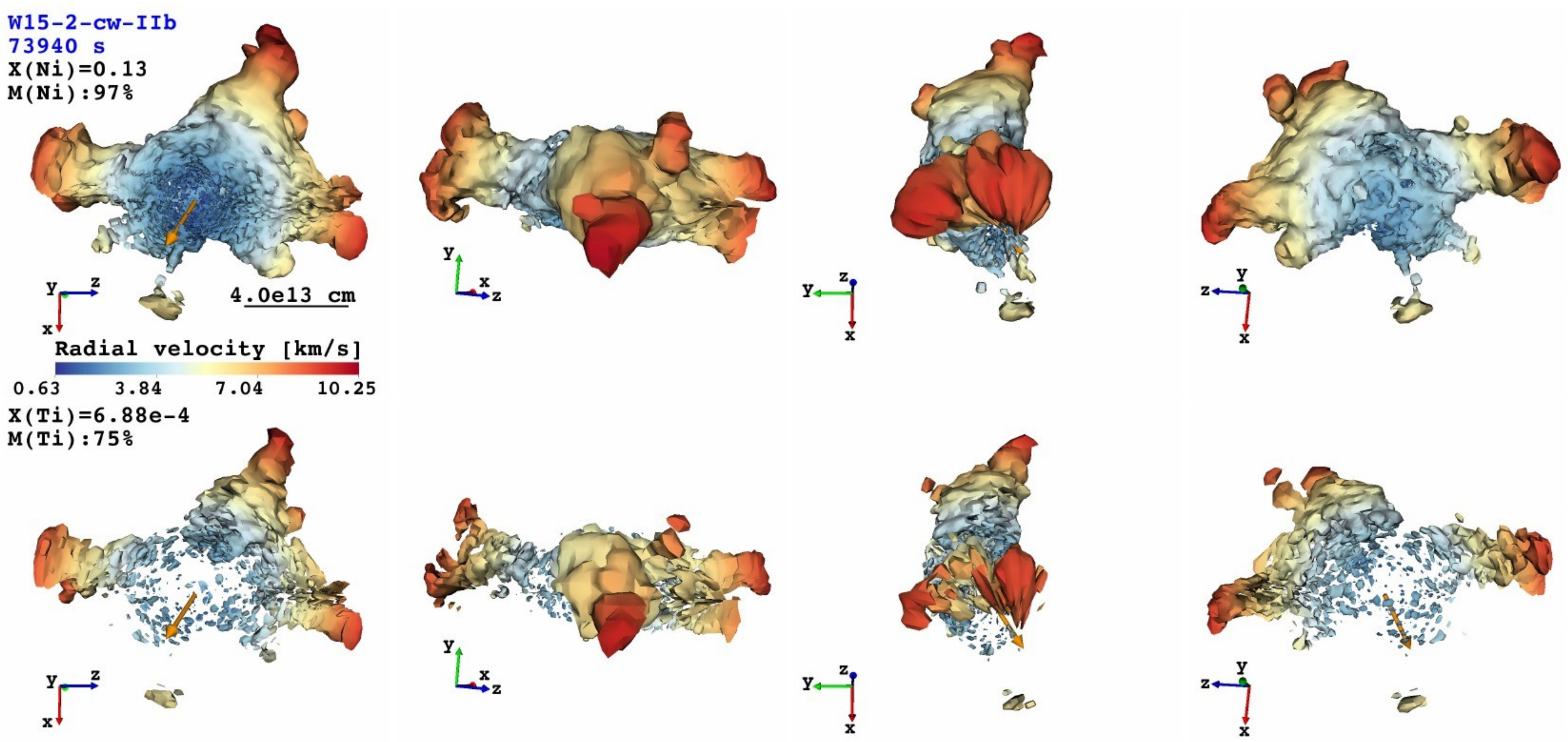


Red: Ar, Ne, and O (optical)
Purple: Iron (X-ray)

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

Chemical Asymmetries in CAS A Remnant

^{44}Ti and ^{56}Ni in a Cassiopeia A like 3D Supernova Model



Wongwathanarat et al., in preparation

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.**