Max-Planck-Institut für Astrophysik

TUM LMU ORIGINS Excellence Cluster ESO lrz

SFB 1258 Neutrinos Dark Matter Messengers

Supernova Remnants II

An Odyssey in Space After Stellar Death

3–8 June 2019, Chania, Crete, Greece

3D Core-Collapse Supernova Modeling and Applications to CAS A and other SN Remnants

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Hans-Thomas Janka

MPI for Astrophysics

COCO2CASA

COCO2CASA: Goals

Connecting Supernova Progenitors with Supernova Remnants

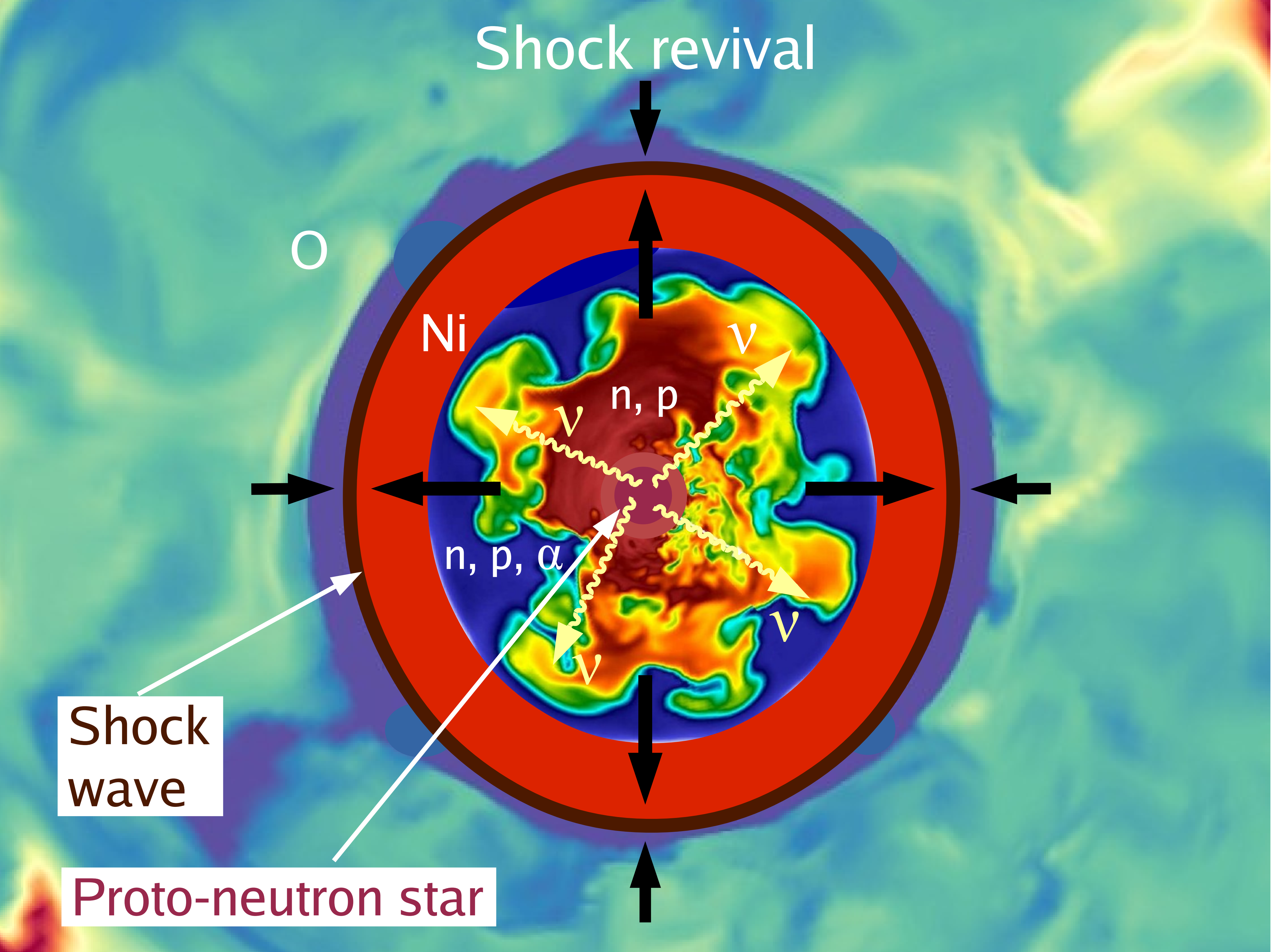
- 3D modeling of latest burning stages of pre-collapse stars
- 3D modeling of SN explosion mechanism
- 3D modeling of evolution from SN explosion to SN-remnant phase

Dedicated targets:

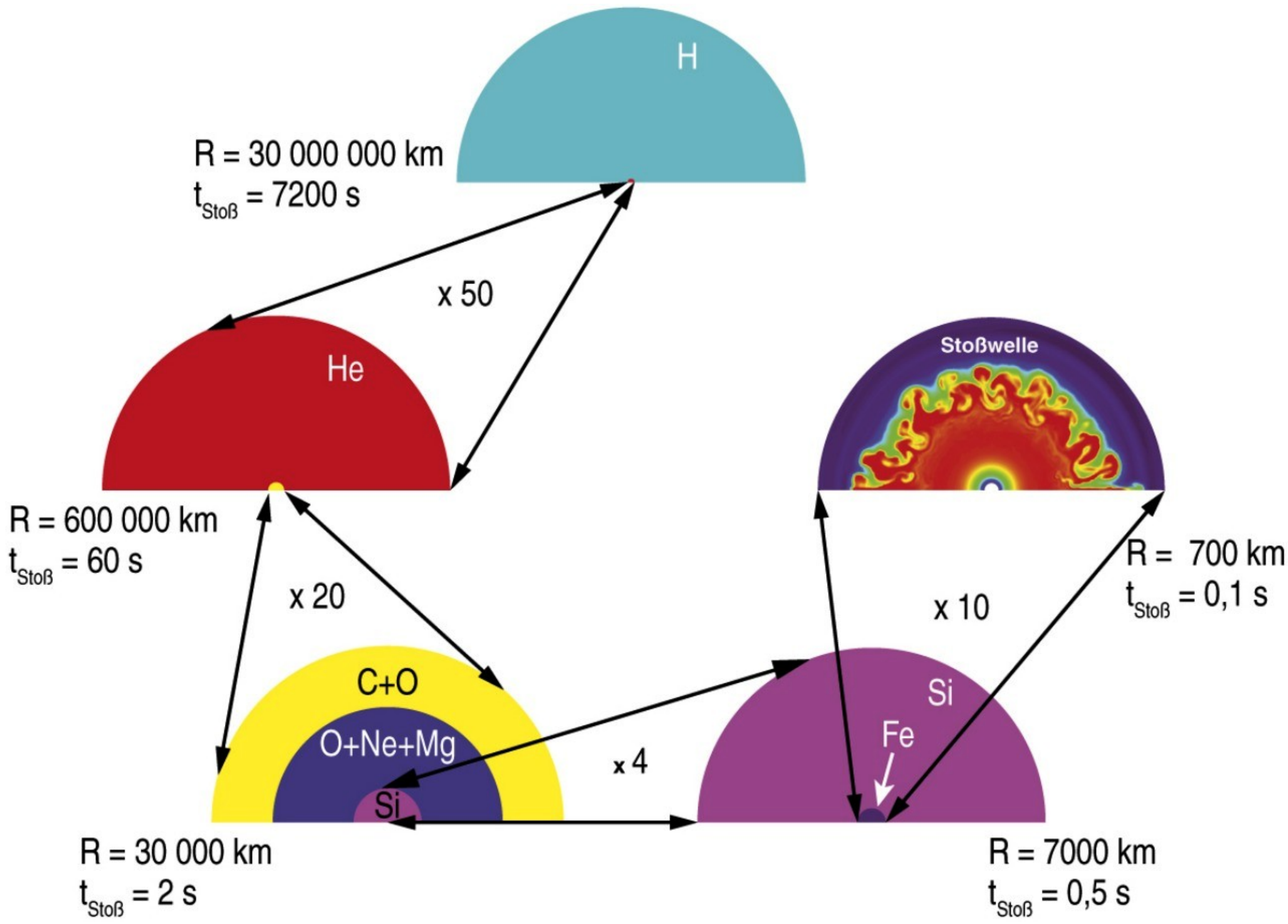
- Explanation of morphological and chemical properties of young, nearby, well studied SN remnants, e.g., Crab, Cas A, SN 1987A
- Collecting indirect evidence for neutrino-driven explosion mechanism

Contents

1. Brief overview: Status of 3D core-collapse SN modeling
2. Pre-collapse progenitor asymmetries:
   Importance for SN explosions in 3D
3. Cas A: Chemical asymmetries and the "jets"
4. SN 1987A: Mixing and 3D morphology
5. Crab: Was SN 1054 an "electron-capture SN" (ECSN) ?


Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock wave
Proto-neutron star

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 !



Status of Neutrino-driven Mechanism in 3D Supernova Models

- 3D modeling has reached mature stage.
  3D differs from 2D in many aspects, explosions more difficult than in 2D.

- M <~ 12–13 M_{sun} stars explode by neutrino-driven mechanism in 3D.
- First neutrino-driven 3D explosions of 15–40 M_{sun} progenitors
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities).
- Explosion energy can take several seconds to saturate !

3D Core-Collapse SN Explosion Models

Oak Ridge (Lentz+ ApJL 2015): **15 M_{sun} nonrotating progenitor** (Woosley & Heger 2007)

Tokyo/Fukuoka (Takiwaki+ ApJ 2014): **11.2 M_{sun} nonrotating progenitor** (Woosley et al. 2002)

Caltech/NCSU/LSU/Perimeter (Roberts+ ApJ 2016; Ott+ ApJL 2018):

27 M_{sun} nonrotating progenitor (Woosley et al. 2002),

15, 20, 40 M_{sun} nonrotating progenitors (Woosley & Heger 2007)

Princeton (Vartanyan+ MNRAS 2019a, Burrows+ MNRAS 2019):

9, 10, 11, 12, 13, 16 M_{sun} nonrot. progenitors (Woosley & Heger 2007, Sukhbold+2016)

3D Core-Collapse SN Explosion Models

Garching/QUB/Monash (Melson+ ApJL 2015a,b; Müller 2016; Janka+ ARNPS 2016, Müller+ MNRAS 2017, Summa+ ApJ 2018):

9.6, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2007)

18 M_{sun} nonrotating progenitor (Heger 2015)

15 M_{sun} rotating progenitor (Heger, Woosley & Spuit 2005, modified rotation)

9.0 M_{sun} nonrotating progenitor (Woosley & Heger 2015)

~19.0 M_{sun} nonrotating progenitor (Sukhbold, Woosley, Heger 2018)

Monash/QUB (Müller+ MNRAS 2018, Müller+MNRAS 2019):

z9.6, s11.8, z12, s12.5 M_{sun} nonrotating progenitors (Heger 2012),

he2,8, he3.0, he3.5 M_{sun} He binary stars, ultrastripped SN progenitors (Tauris 2017)

Status of Neutrino-driven Mechanism in 3D Supernova Models

- **3D modeling has reached mature stage.**
  3D differs from 2D in many aspects, explosions more difficult than in 2D.

- **M <~ 12–13 M_{sun} stars explode by neutrino-driven mechanism in 3D.**
- **First neutrino-driven 3D explosions of 15–40 M_{sun} progenitors**
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities).
- **Explosion energy can take several seconds to saturate !**

- **Progenitors are 1D**, but composition-shell structure and initial progenitor-core asymmetries can affect onset of explosion.
- 3D simulations **still need higher resolution** for convergence.
- **Full multi-D neutrino transport** versus **"ray-by-ray" approximation.**
- **Uncertain/missing physics?**
  Dense-matter nuclear and neutrino physics? Neutrino flavor oscillations?

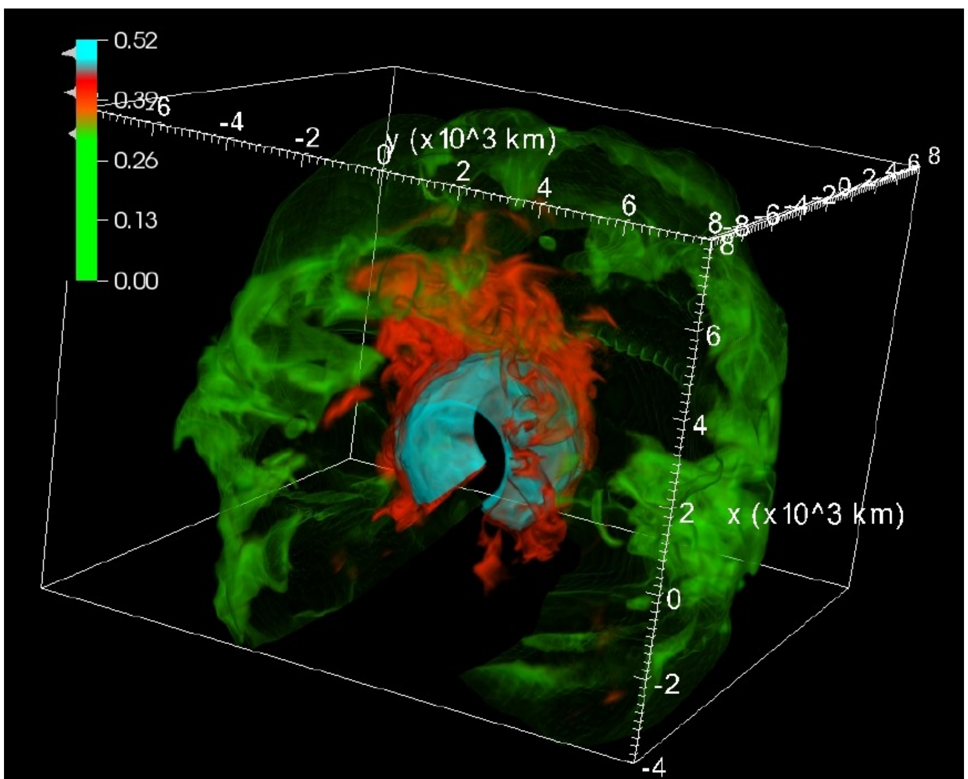
Pre-collapse 3D Asymmetries in Progenitors

With Naveen Yadav (postdoc), Tobias Melson (ex-postdoc) and Bernhard Müller and Alex Heger (Monash University); arXiv:1905.04378

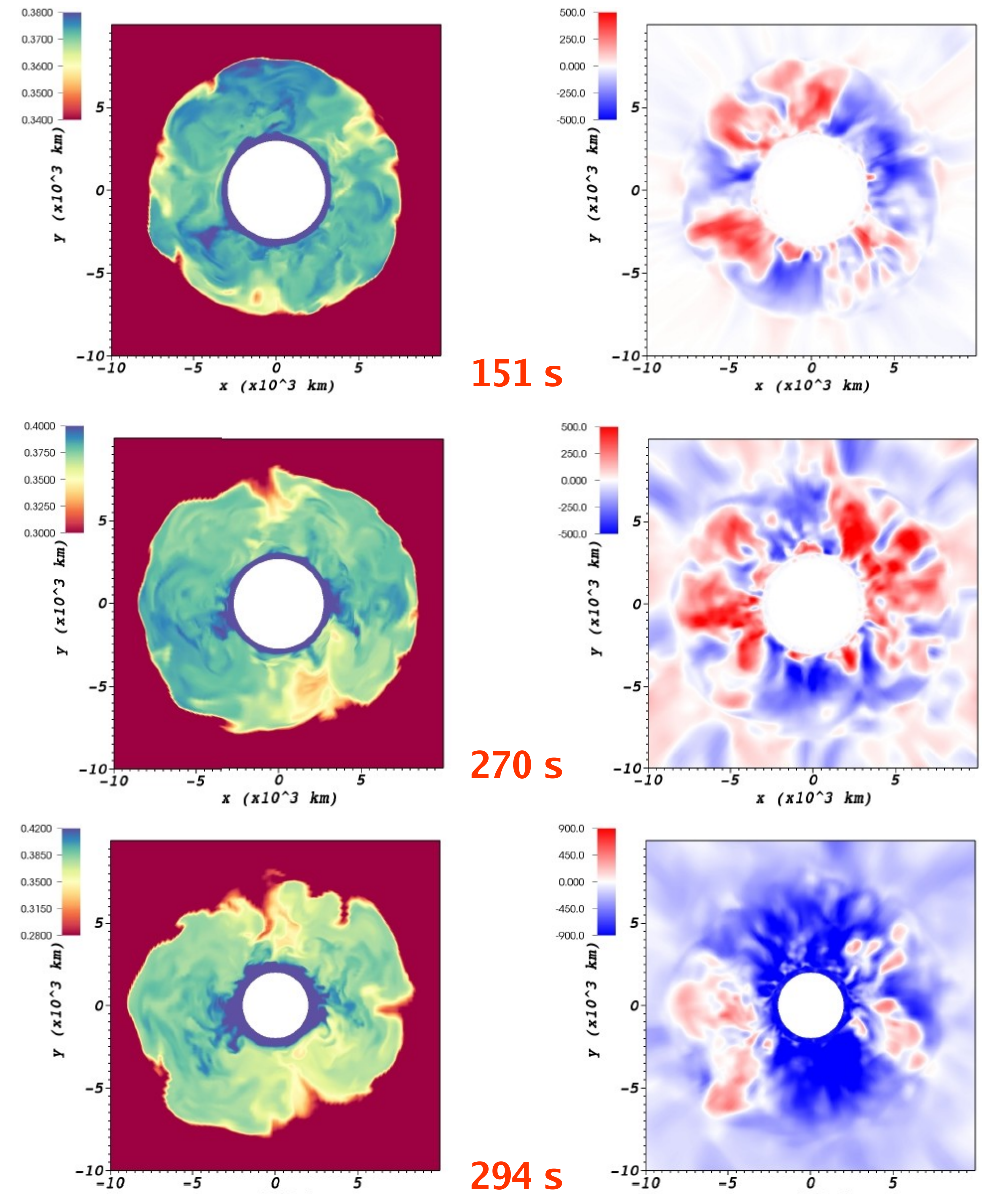
3D Core-Collapse SN Progenitor Model

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.



B. Müller, Viallet, Heger, & THJ, ApJ 833, 124 (2016)

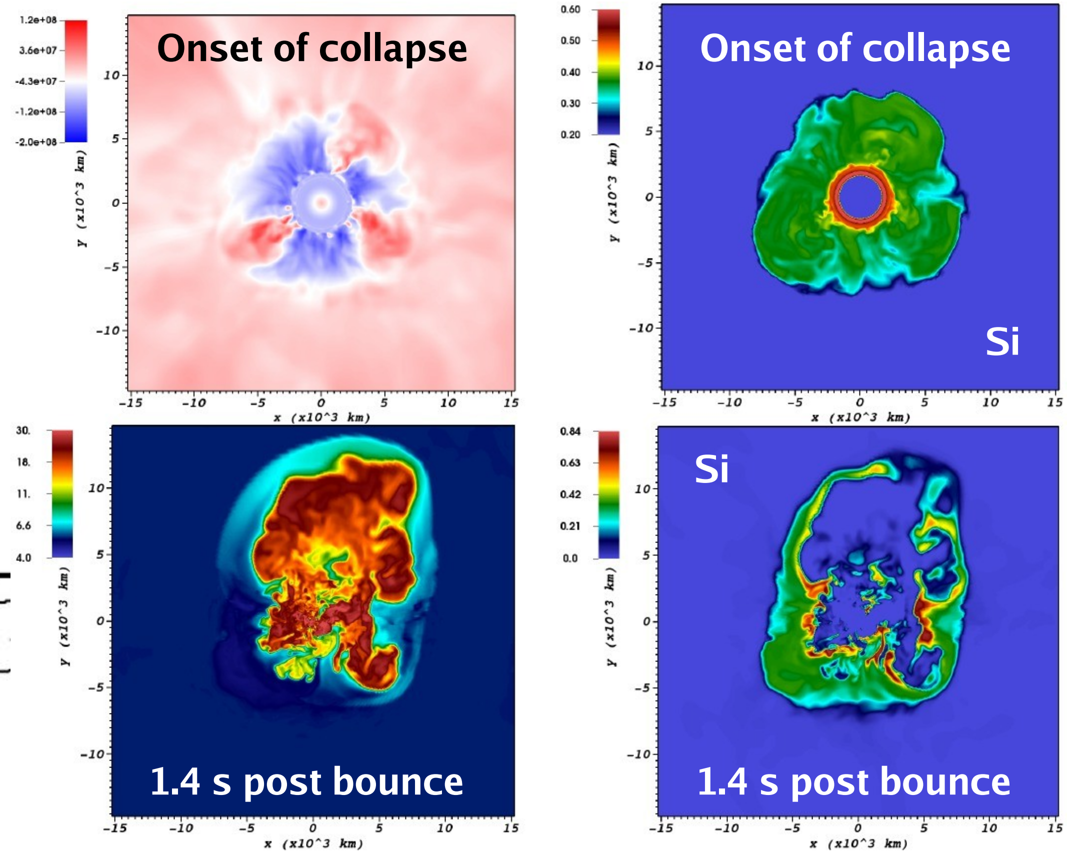


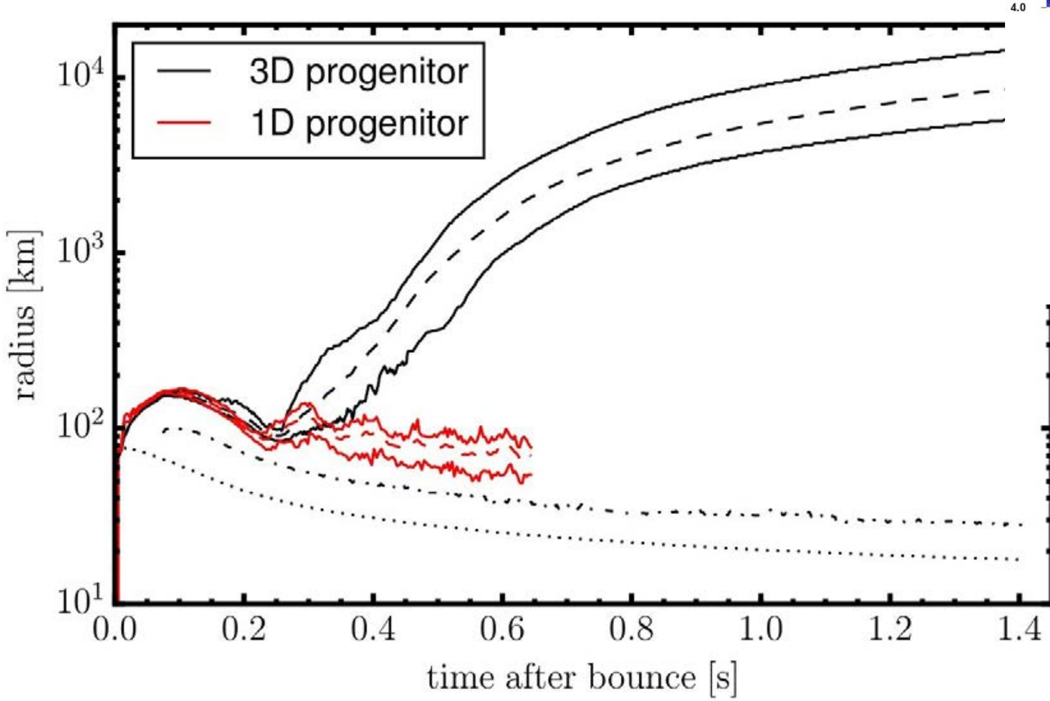
3D Core-Collapse SN Explosion Model

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 fosters strong postshock convection and could thus reduces the criticial neutrino luminosity for explosion.





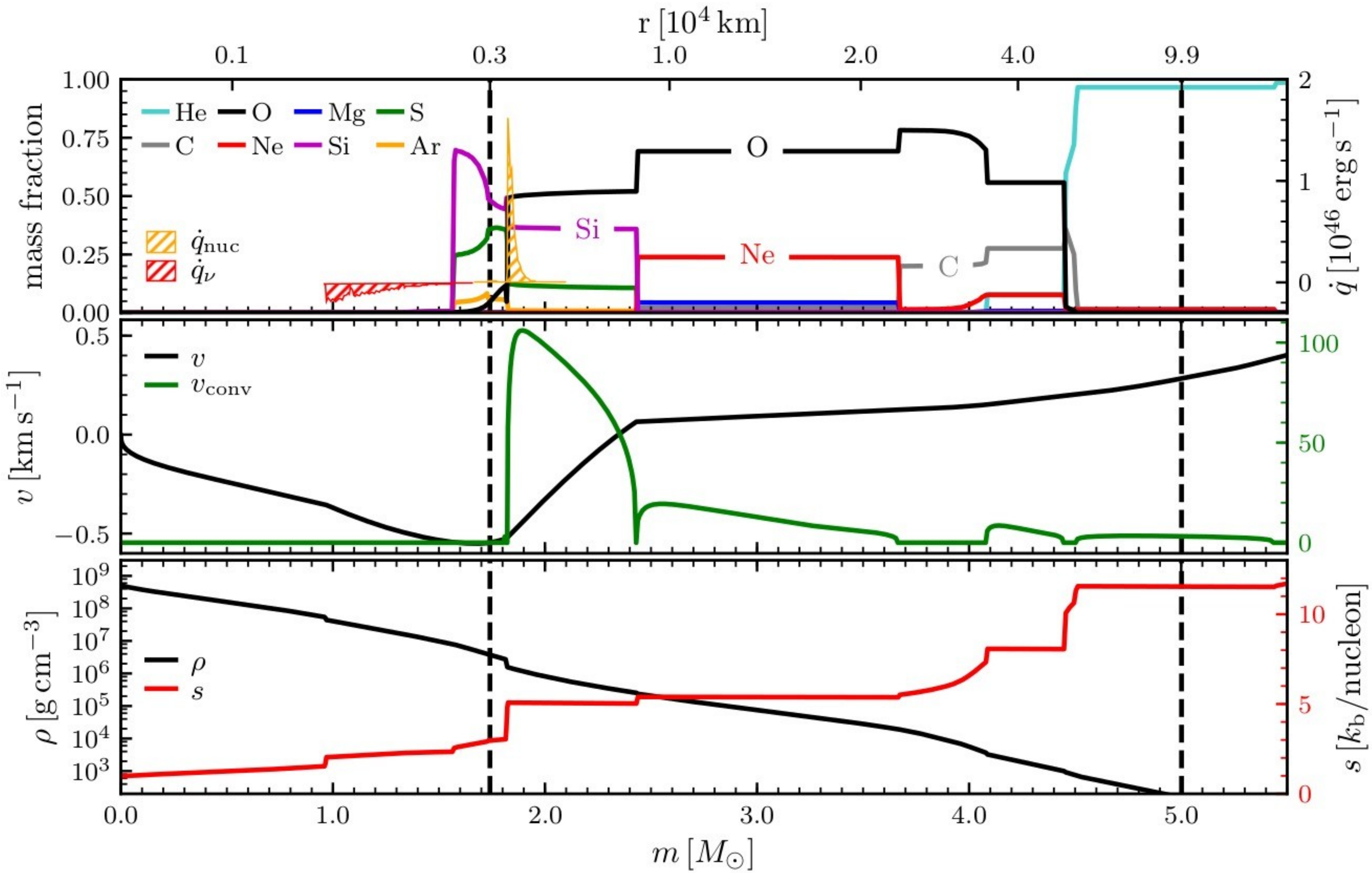
$$\delta\rho/\rho \sim \mathrm{Ma}_{\mathrm{conv}}$$

$$(L_\nu E_\nu^2)_{\mathrm{crit,pert}} \approx (L_\nu E_\nu^2)_{\mathrm{crit,3D}} \left(1 - 0.47 \frac{\mathrm{Ma}_{\mathrm{conv}}}{\ell \eta_{\mathrm{acc}} \eta_{\mathrm{heat}}}\right)$$

B. Müller, PASA 33, 48 (2016);
Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)

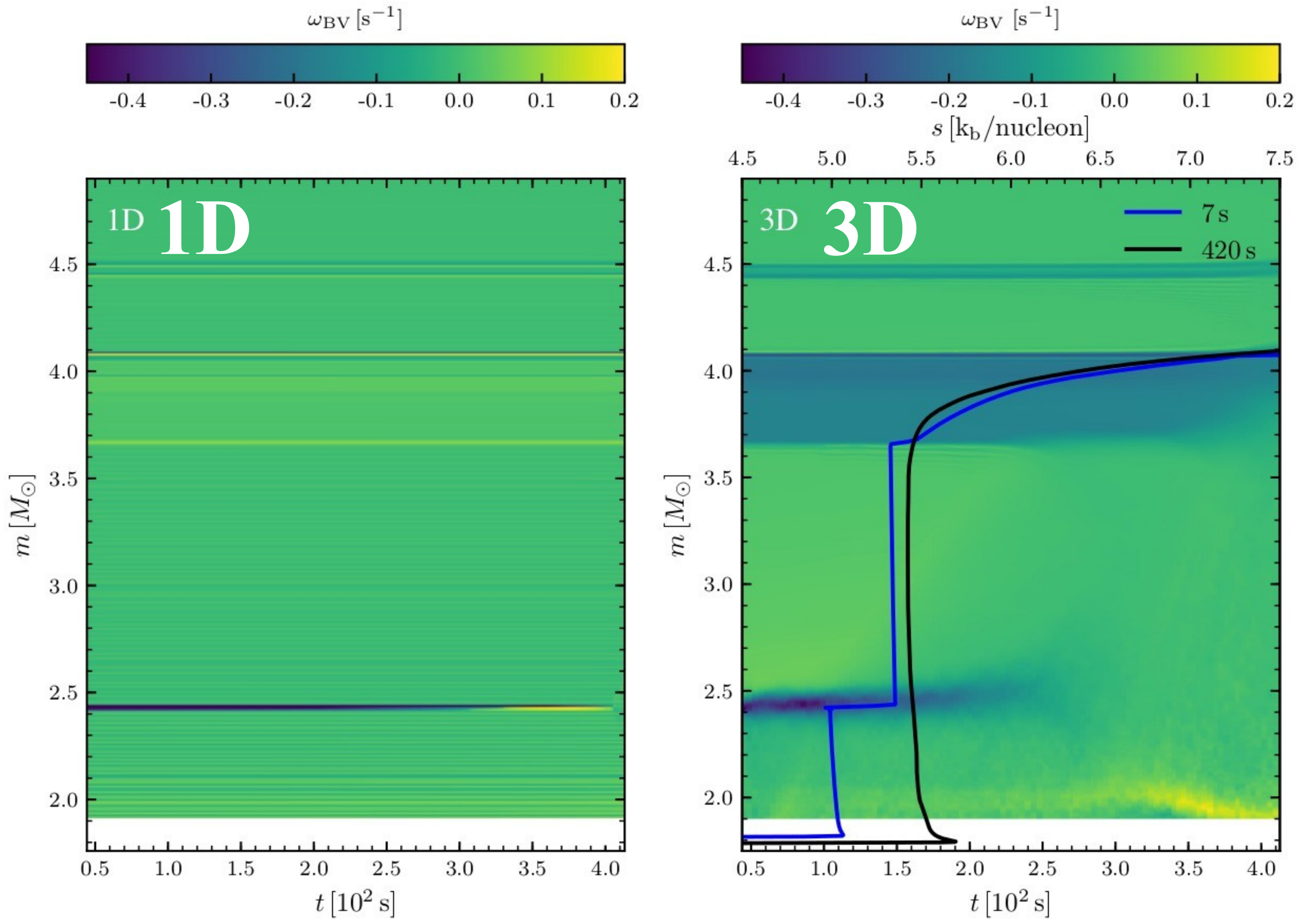
3D Simulations of Convective Oxygen Burning in ~19 M_{sun} Pre-collapse Star

Initial (1D) conditions 7 minutes prior to core collapse.



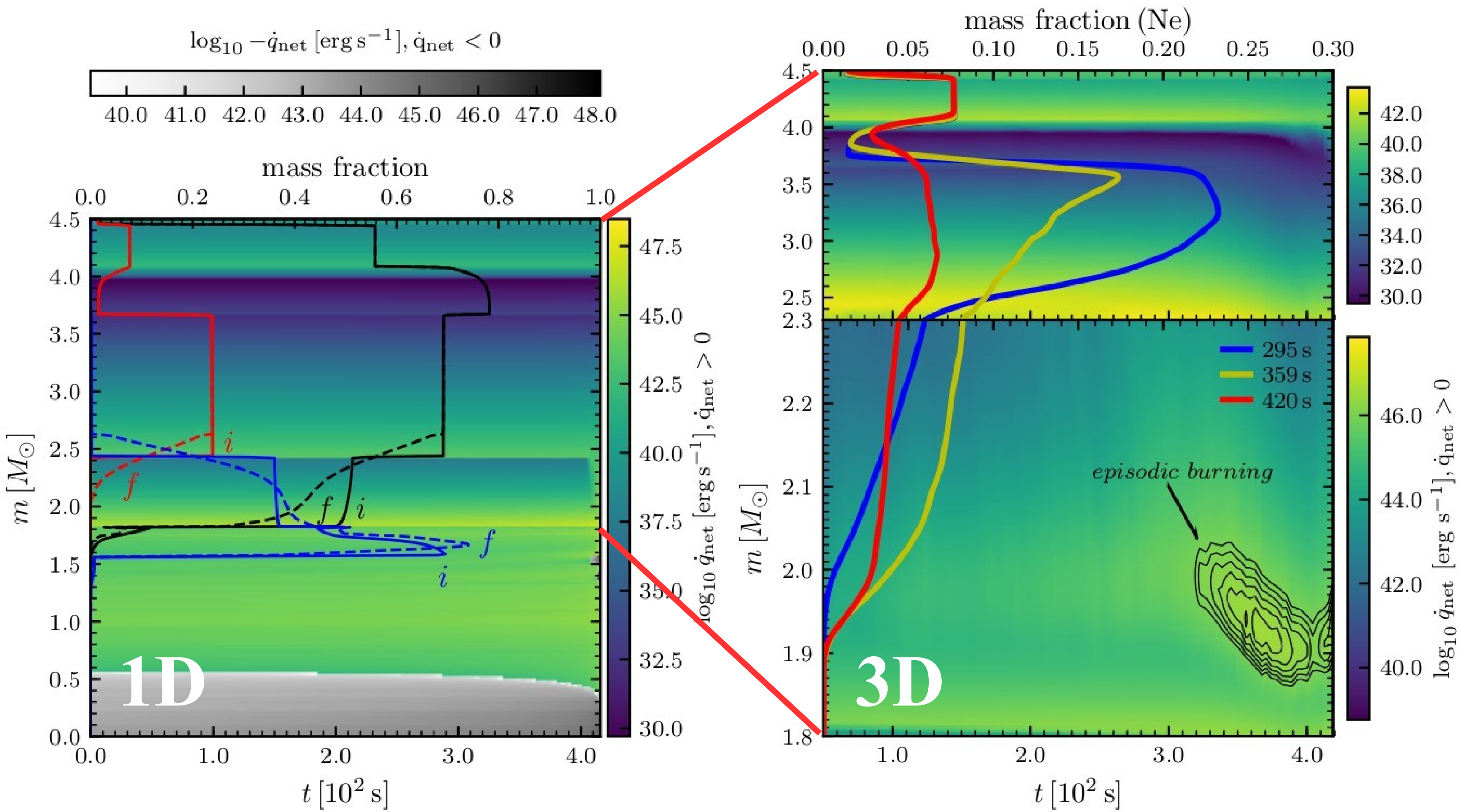
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

Convectively Ledoux-stable (BV frequency < 0) and Ledoux-unstable regions (BV frequency > 0) regions.



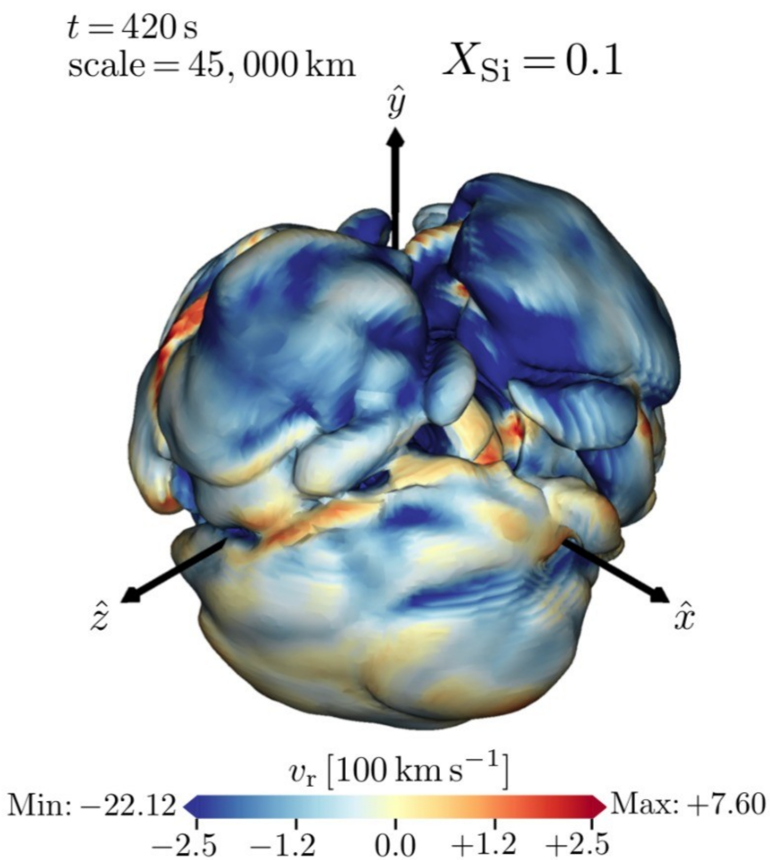
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

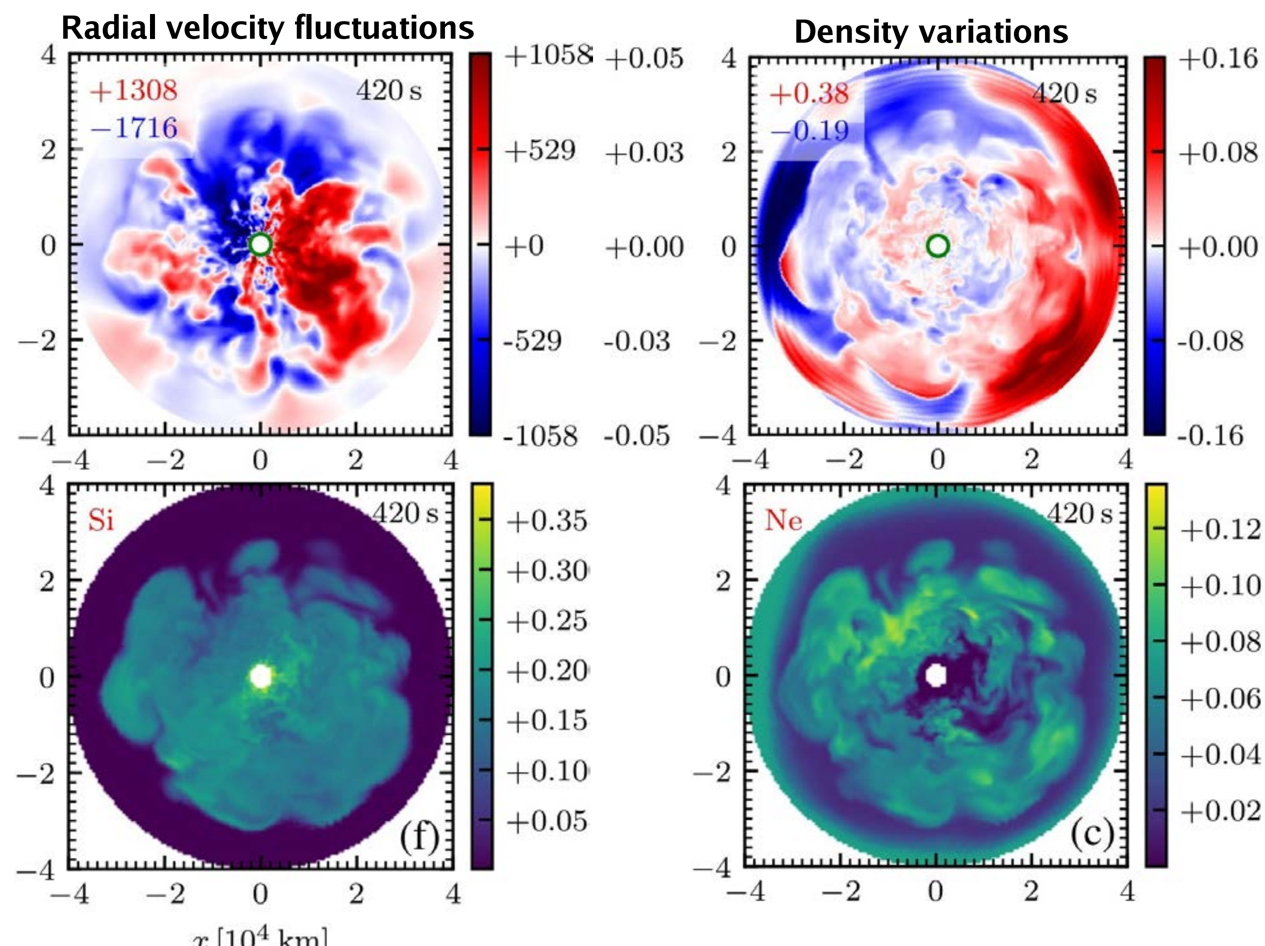
Net energy generation rate (nuclear burning minus neutrino cooling).

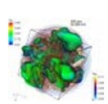


Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

Flash of Ne+O burning creates large-scale asymmetries in density, velocity, Si/Ne composition

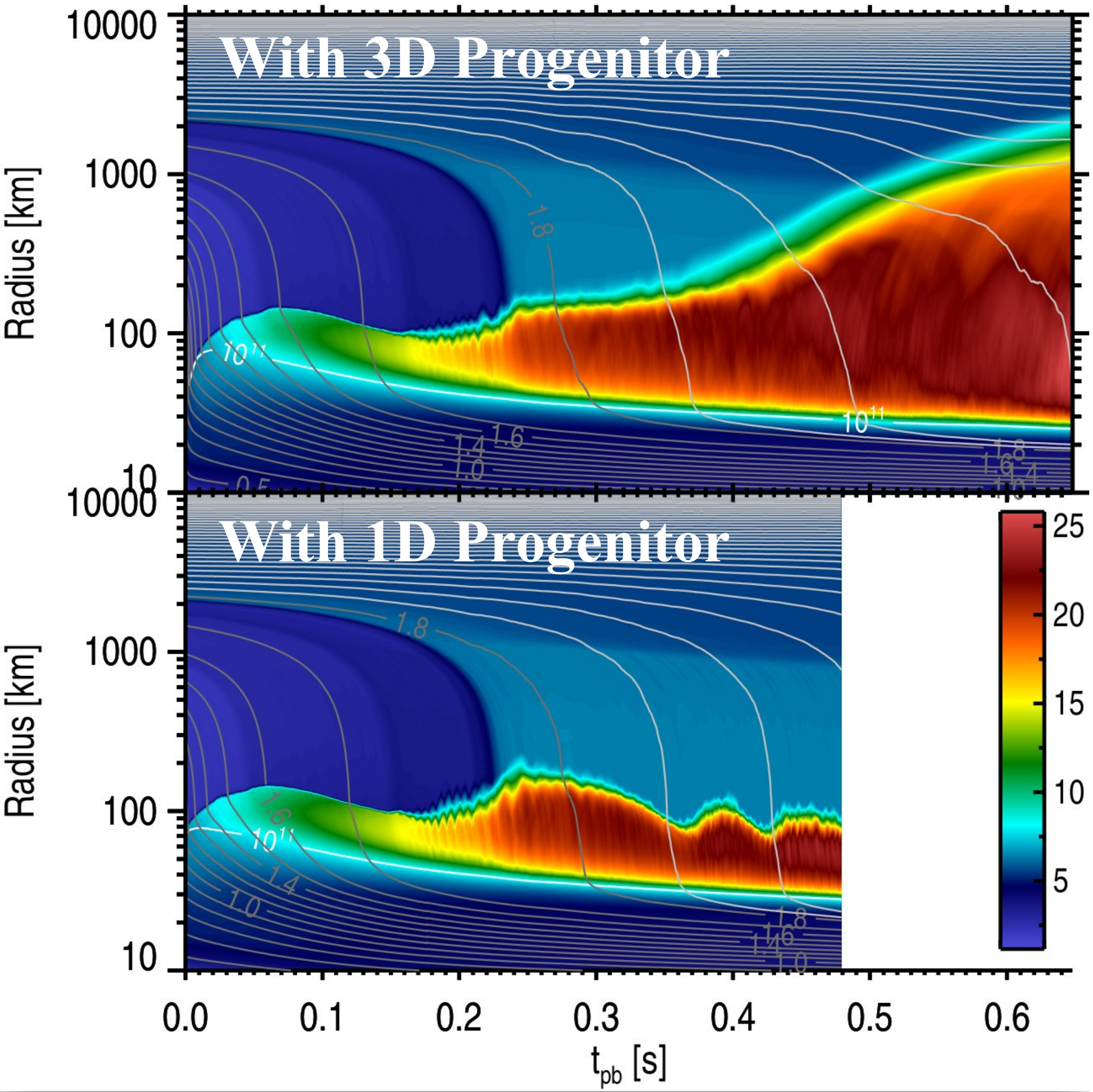


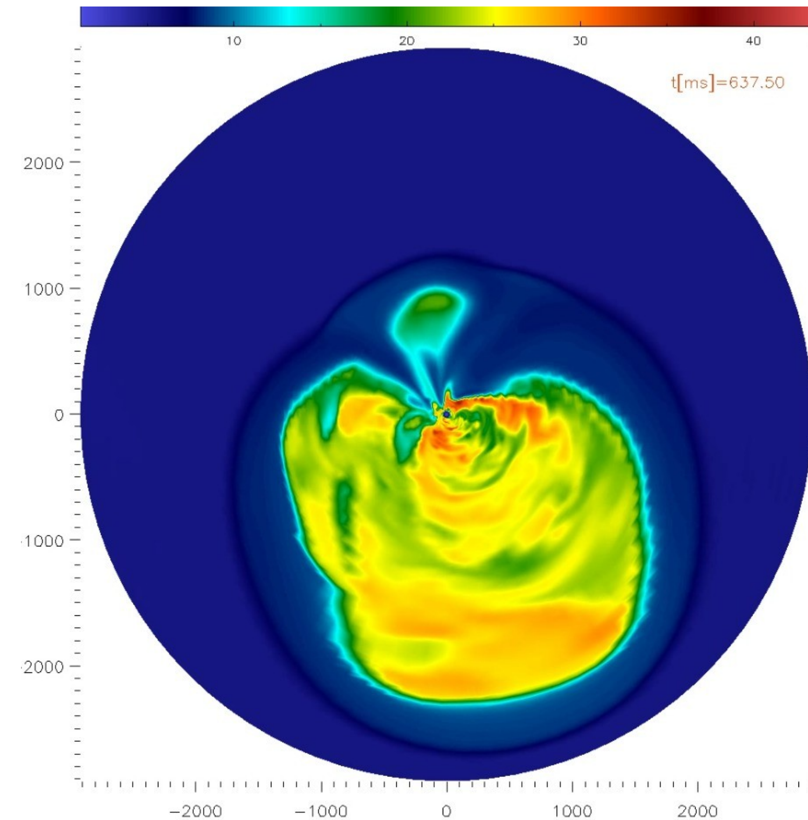




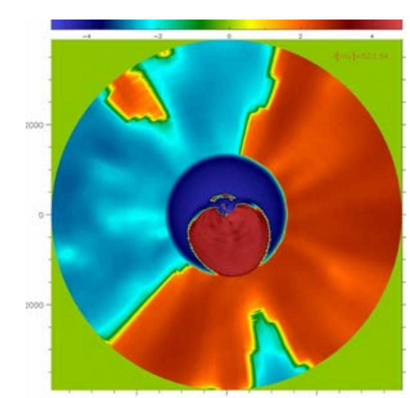
Yadav et al., arXiv:1905.04378

3D Explosion of ~19 M_{sun} Star after Neon-oxygen-shell Merger

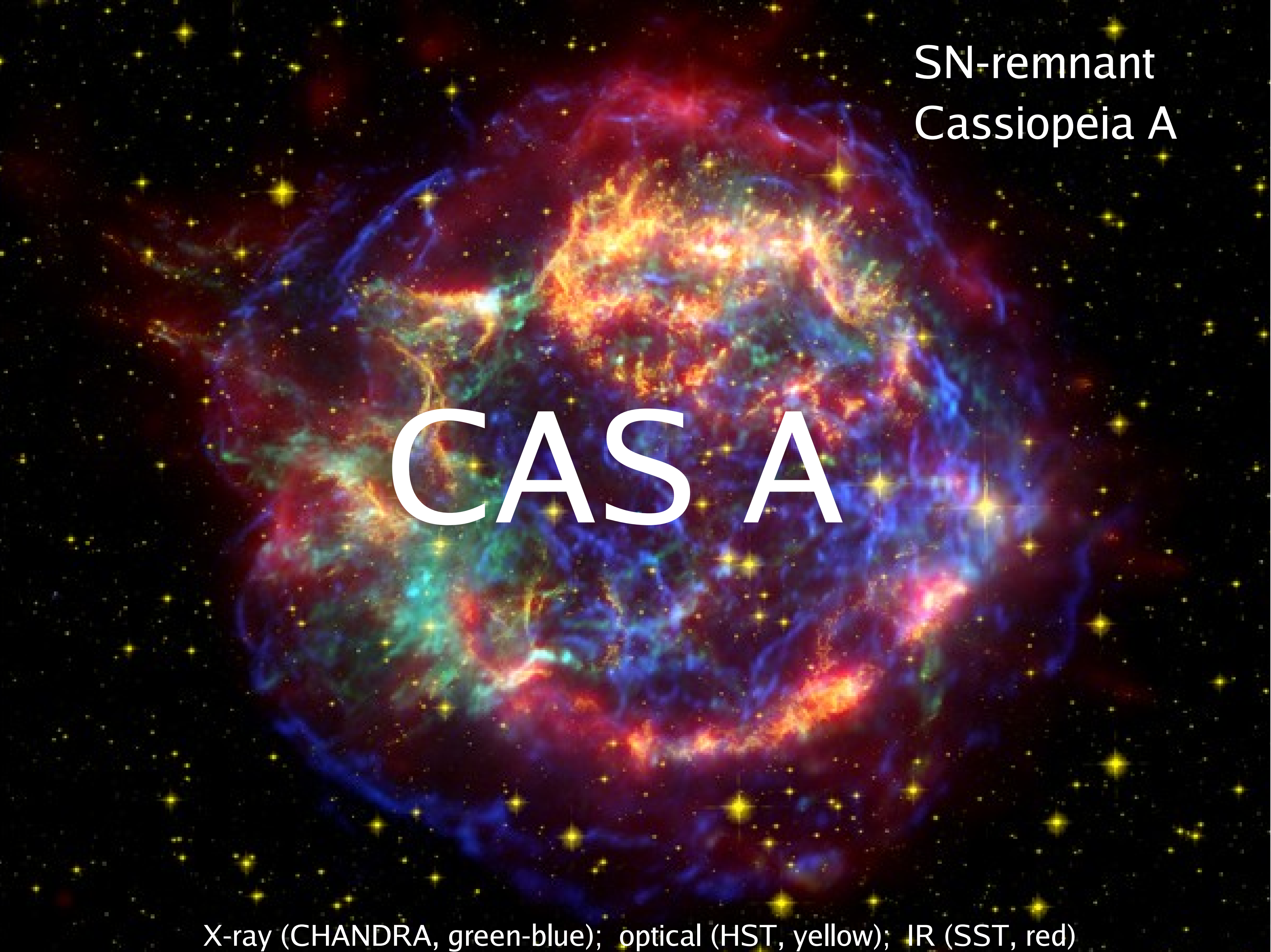




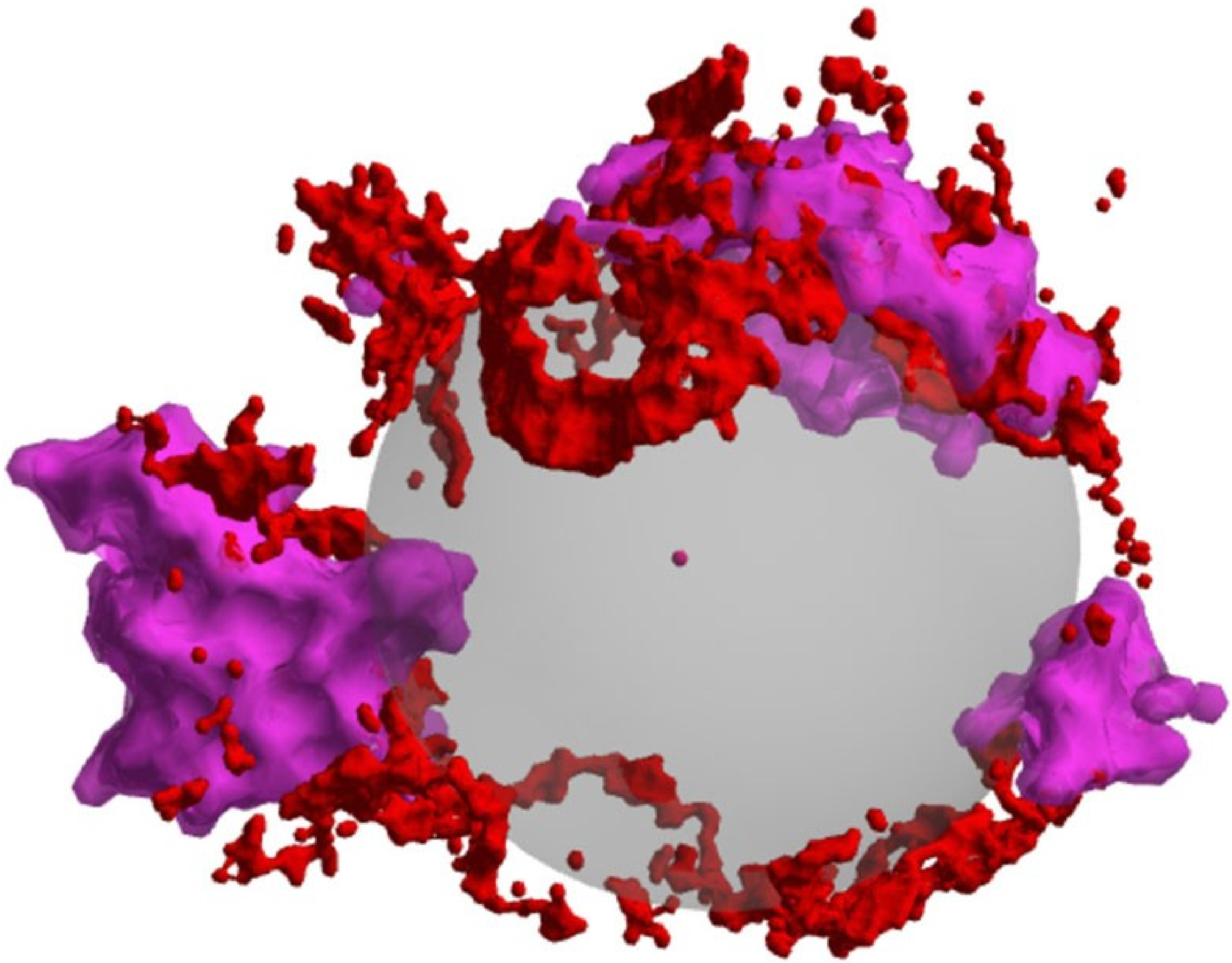
Explosion pushes preferentially in direction of lower infall velocity



R. Bollig et al., in preparation


SN-remnant
Cassiopeia A
CAS A
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

Chemical Asymmetries in CAS A Remnant

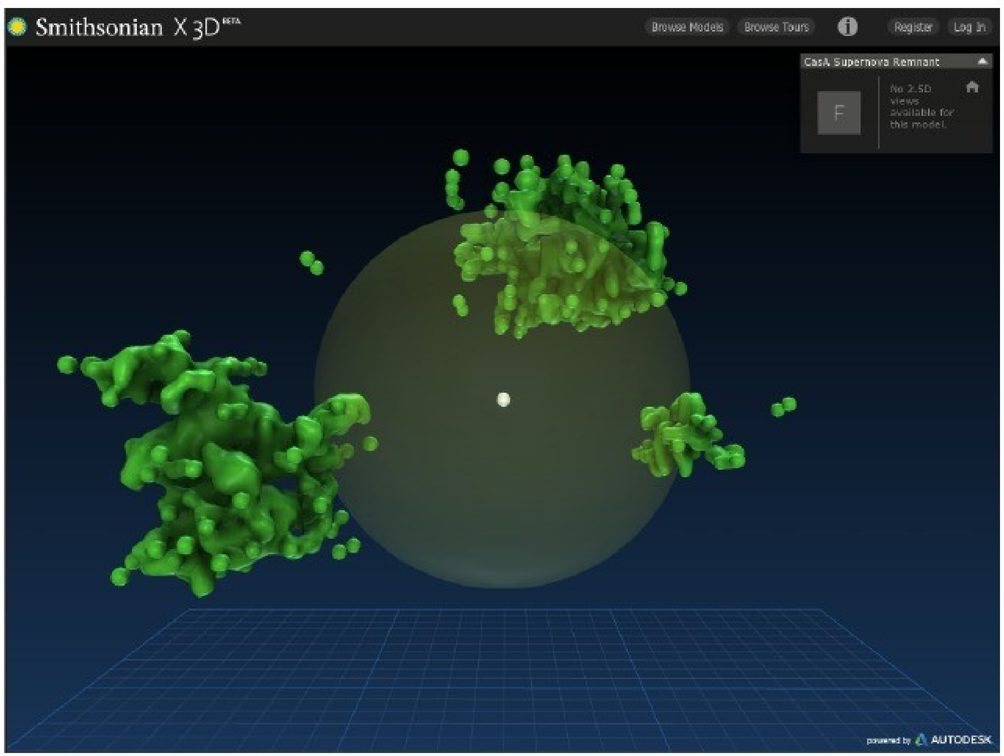


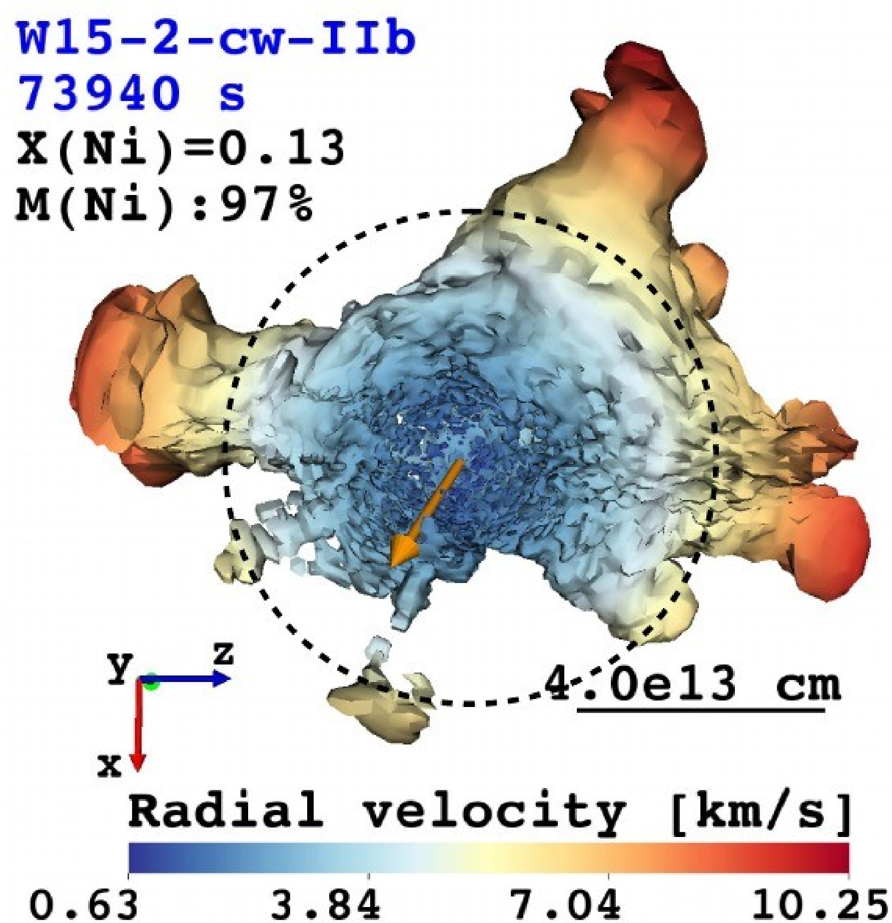
Red: Ar, Ne, and O (optical)
Purple: Iron (X-ray)

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

Chemical Asymmetries in CAS A Remnant

Reverse-shock heated iron is visible in three big "fingers"

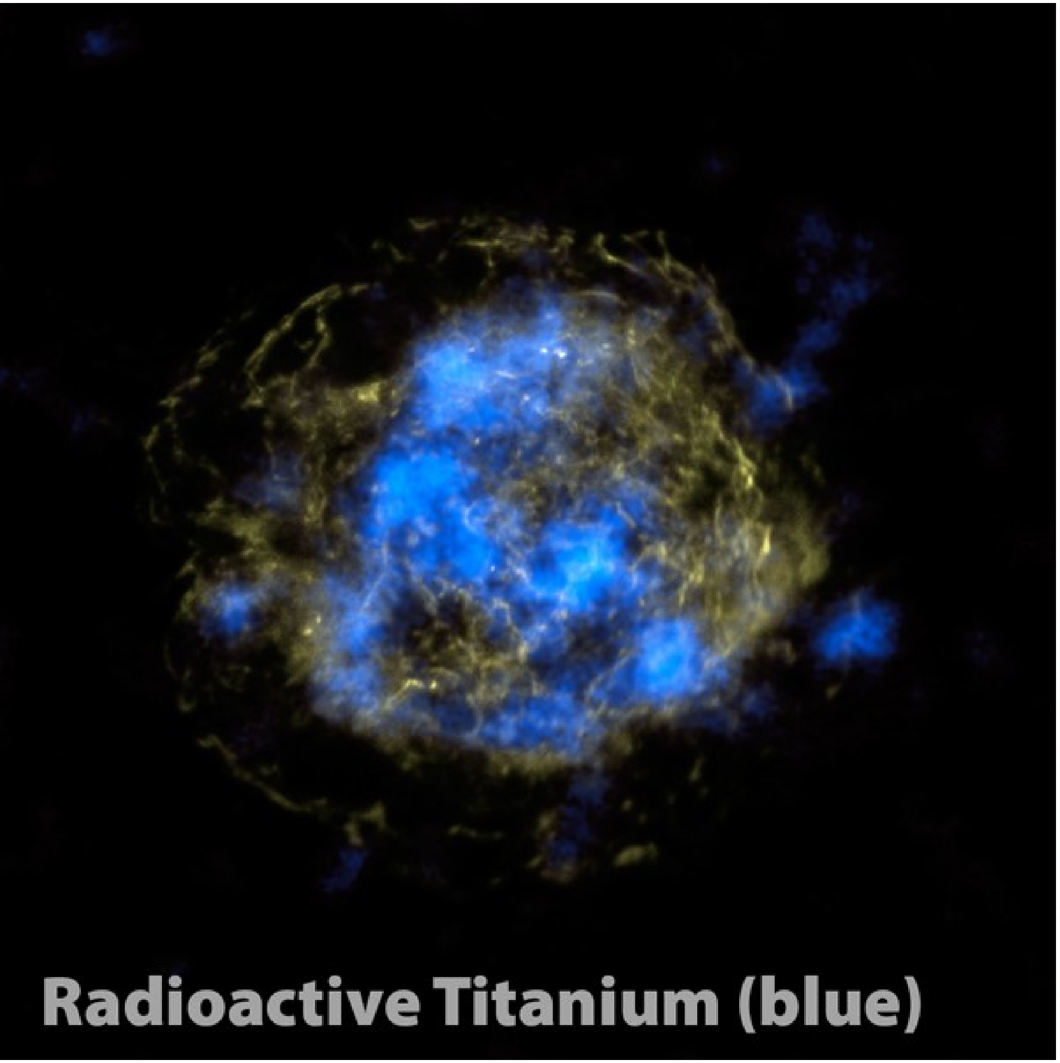


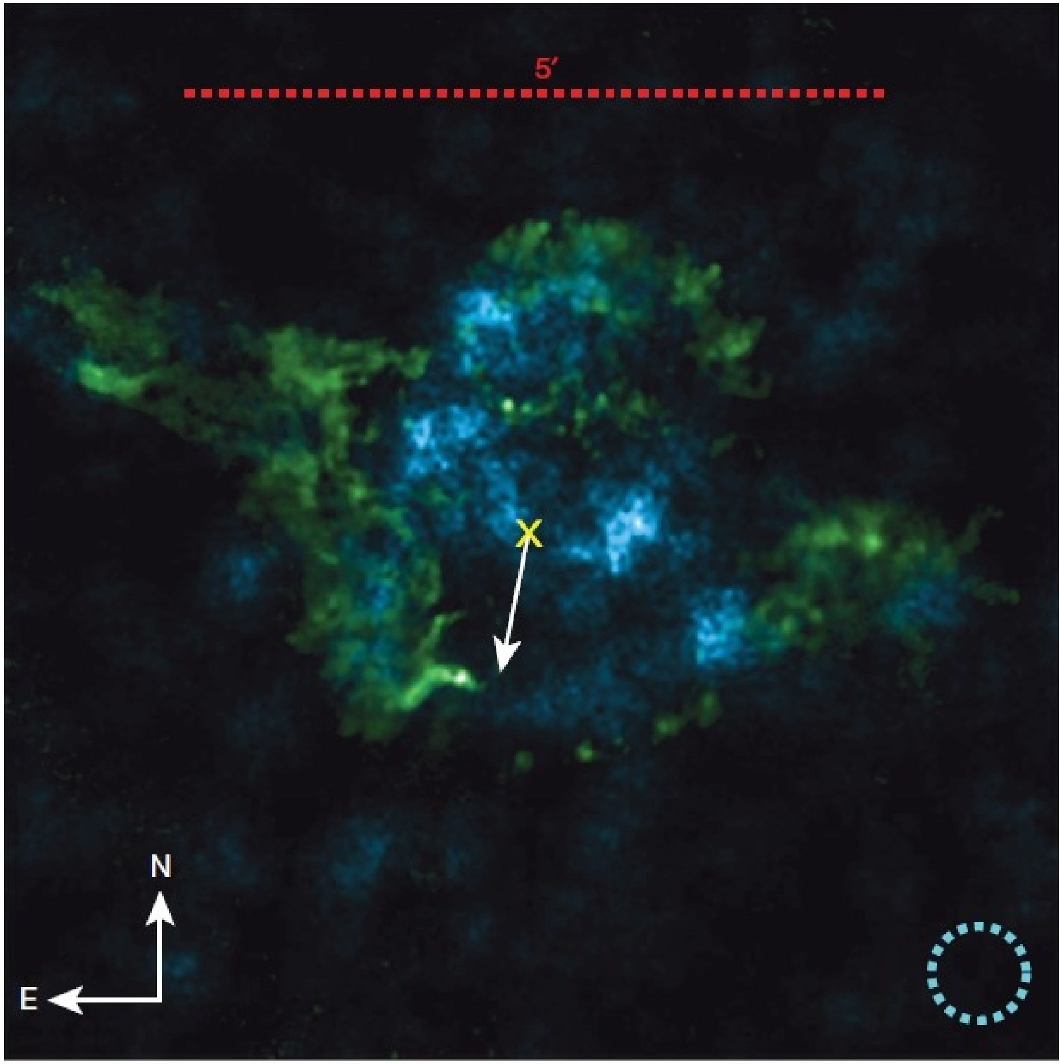


—> More: see talk by Annop Wongwathanarat on Wednesday

Wongwathanarat et al., ApJ 842 (2017) 13

^{44}Ti Asymmetry in the CAS A Remnant

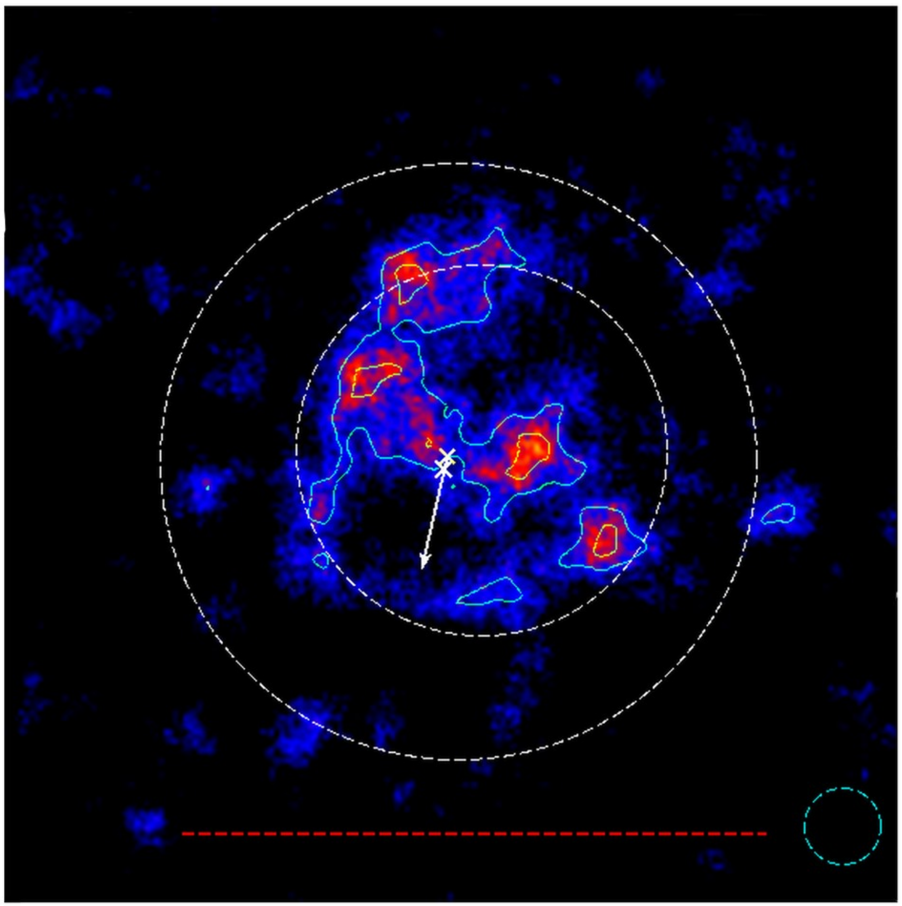




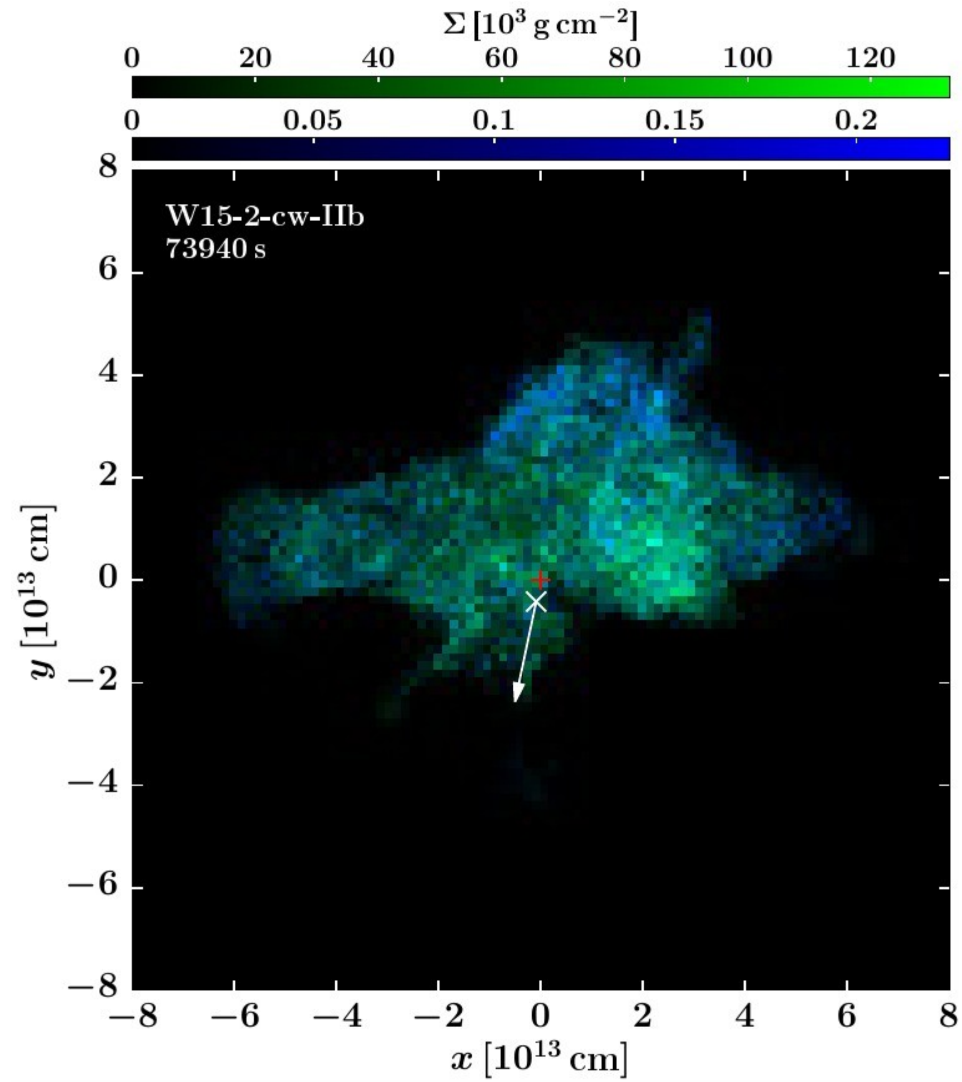
NuSTAR observations

Grefenstette et al., Nature 506 (2014) 340

Neutron Star Recoil and Nickel & 44Ti Distribution

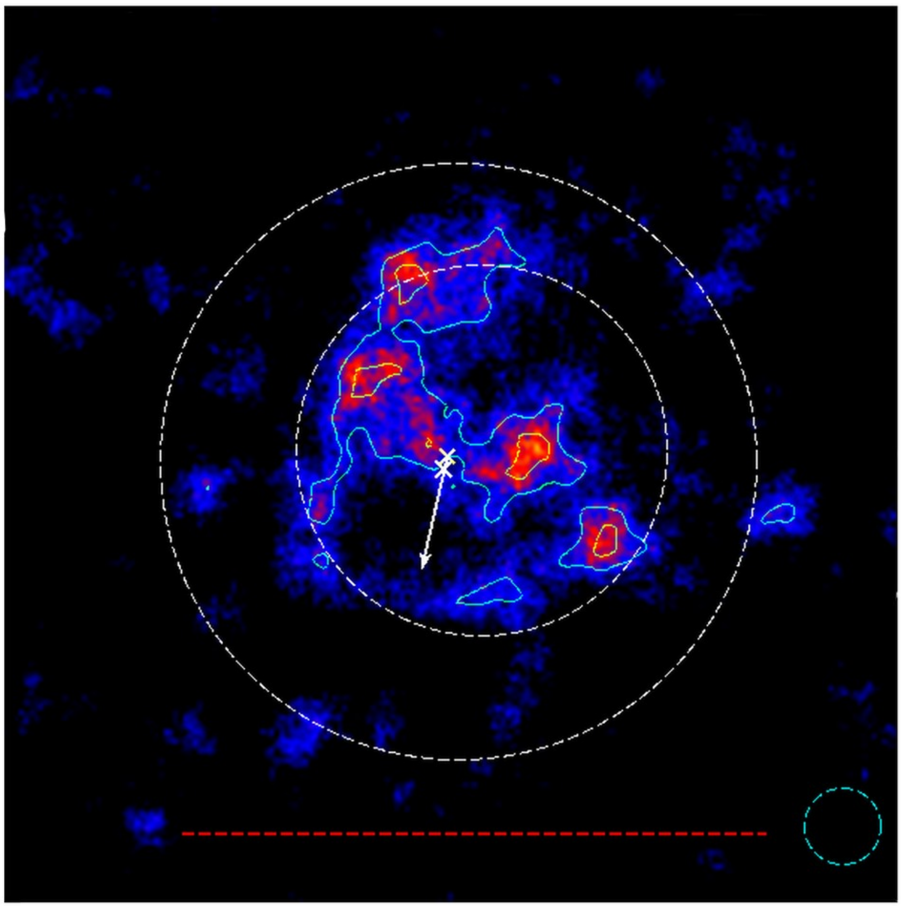


Grefenstette et al., Nature 506 (2014) 340

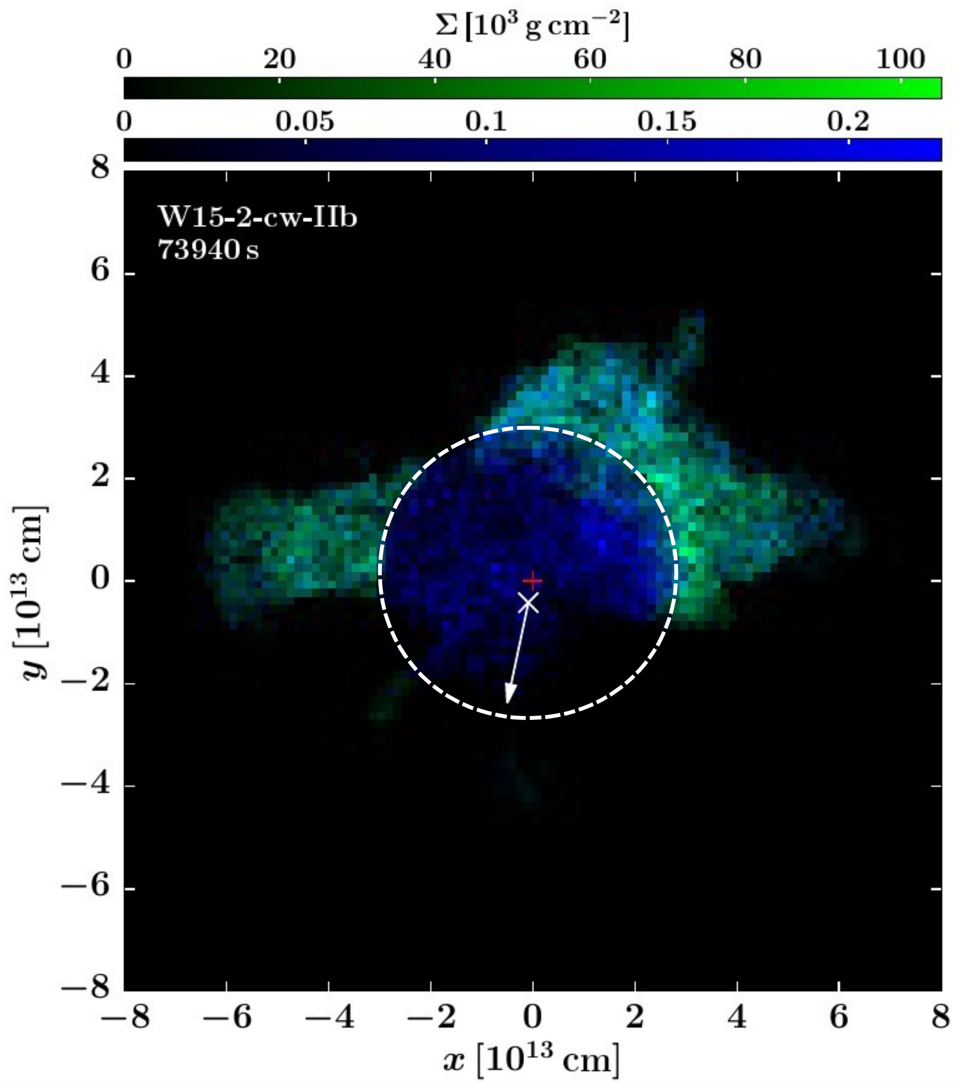


Wongwathanarat et al., ApJ 842 (2017) 13

Neutron Star Recoil and Nickel & 44Ti Distribution

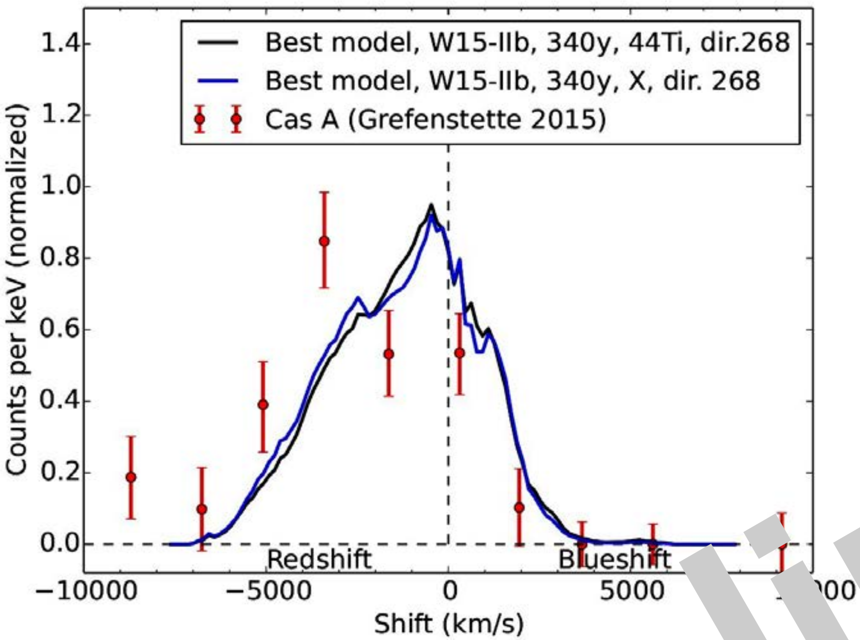


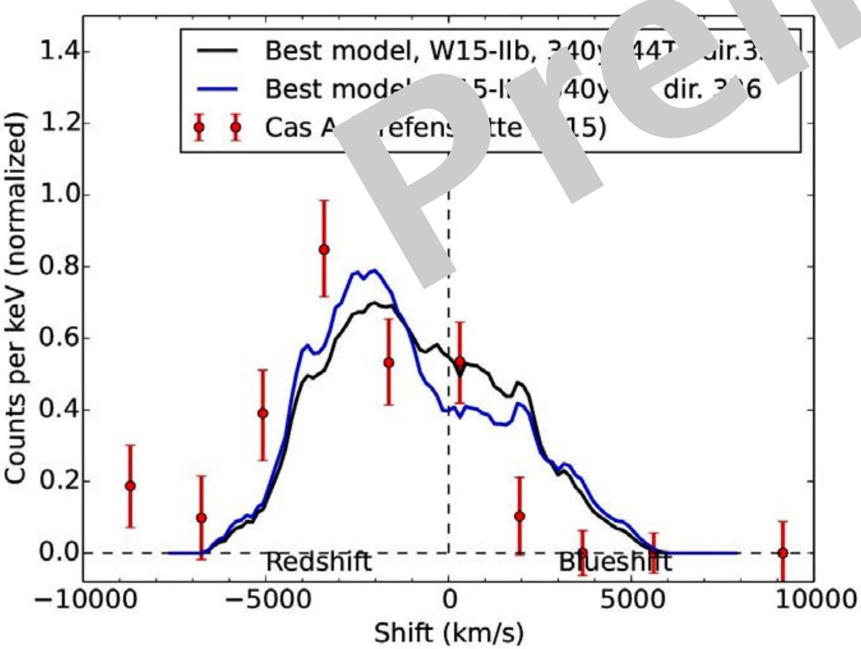
Grefenstette et al., Nature 506 (2014) 340

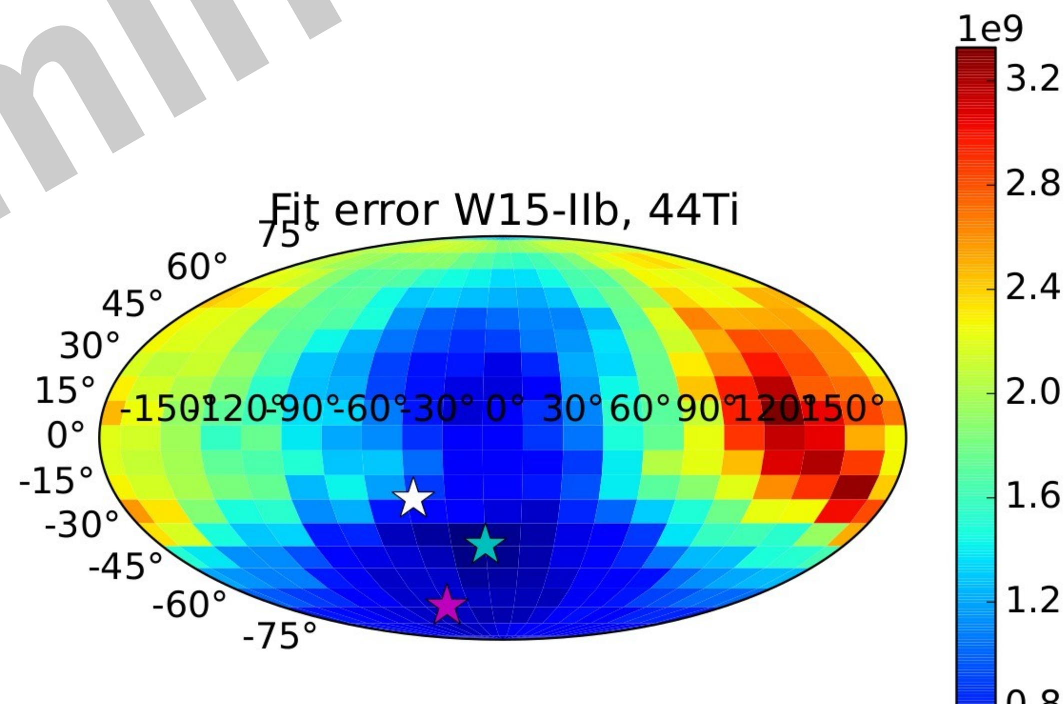


Wongwathanarat et al., ApJ 842 (2017) 13

Cas A: Gamma-Ray Line Profiles of ^{44}Ti







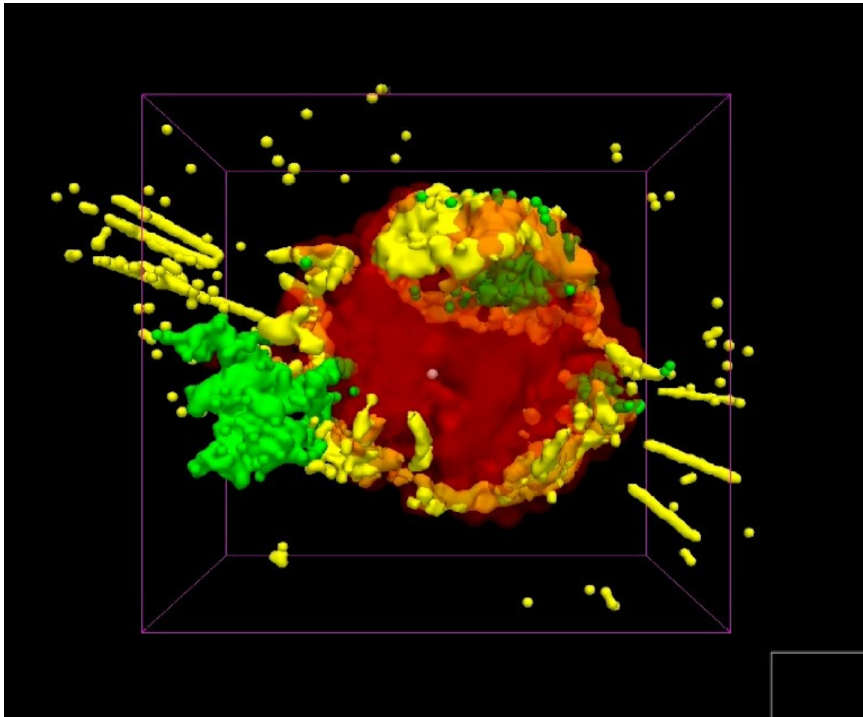
Preliminary

NS in Cas A has high kick with inclination angle of ~30–70 degrees to line of sight.

Consistent with analysis of 44Ti 3D distribution by Grefenstette et al. (2016).

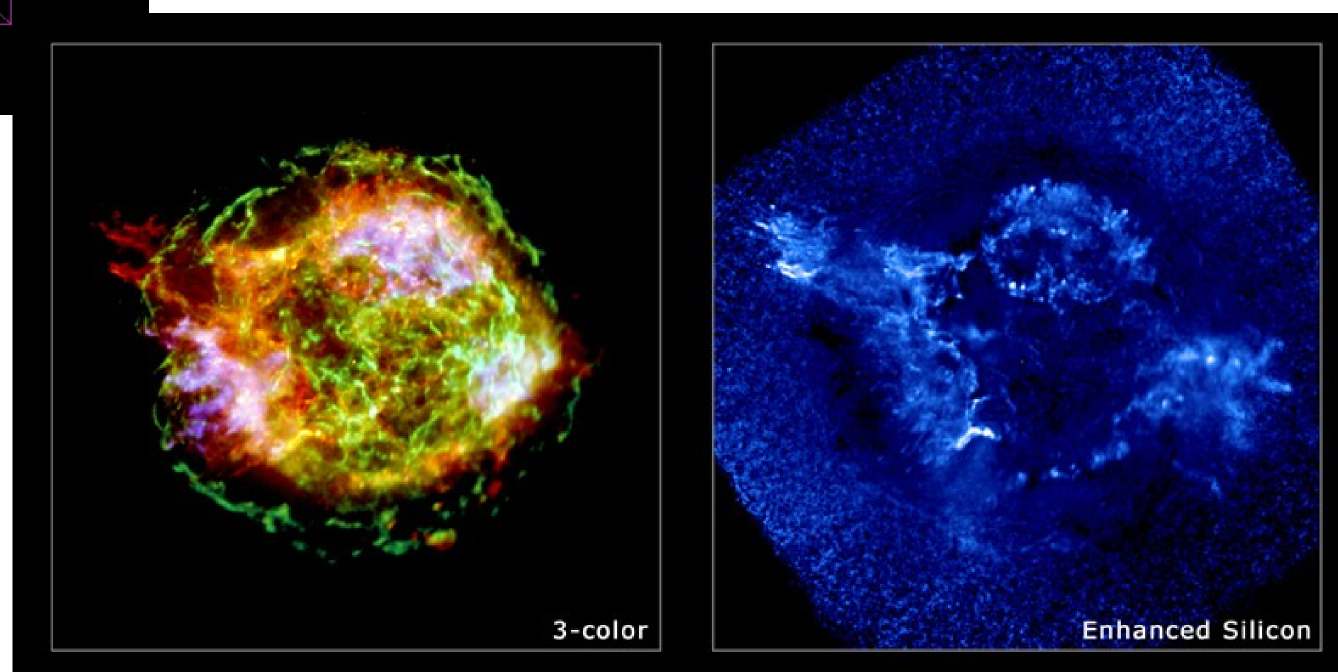
Jerkstrand et al., in preparation

CAS A Si-Ne-rich Wide-angle "Jets"



- Wide-angle features in NE and SW directions with up to 15,000 km/s expansion velocity.

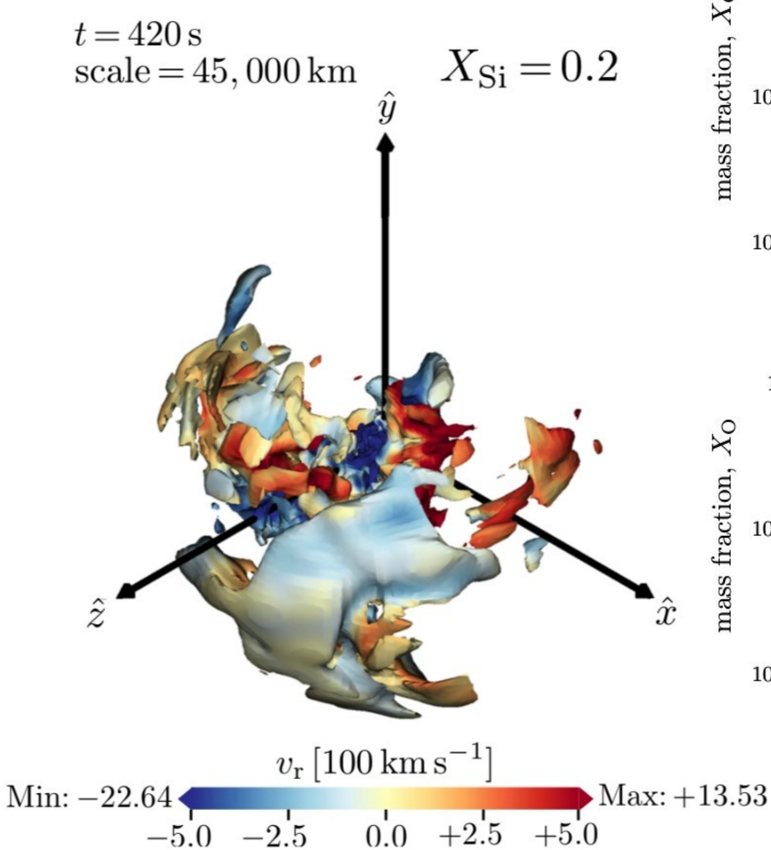
- Rich in Si and Ne, but poor in iron.

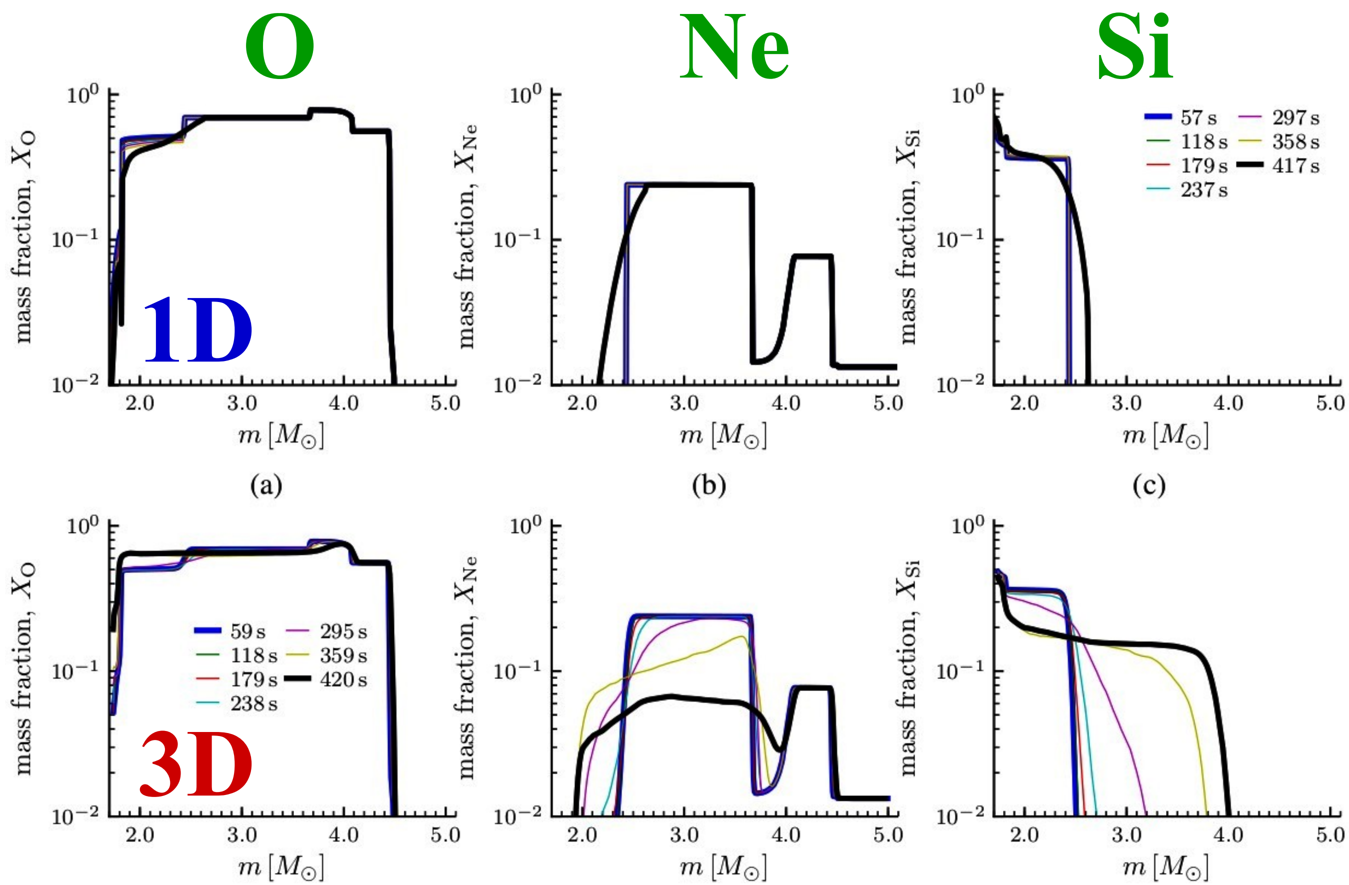


Credit: NASA/CXC/GSFC/U.Hwang et al.

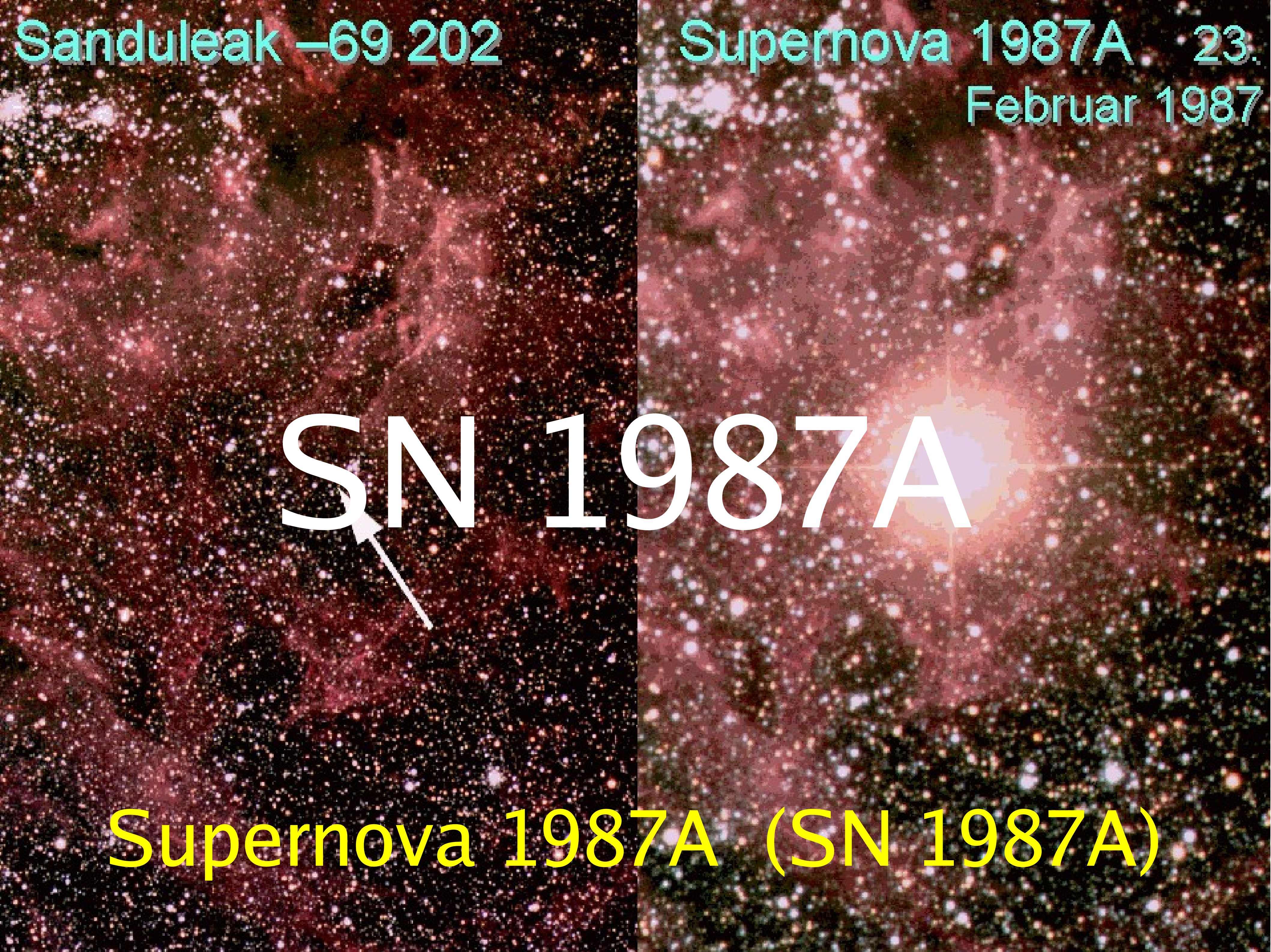
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

Flash of Ne+O burning mixes Si and Ne; distribution highly asymmetric in mass and velocity space

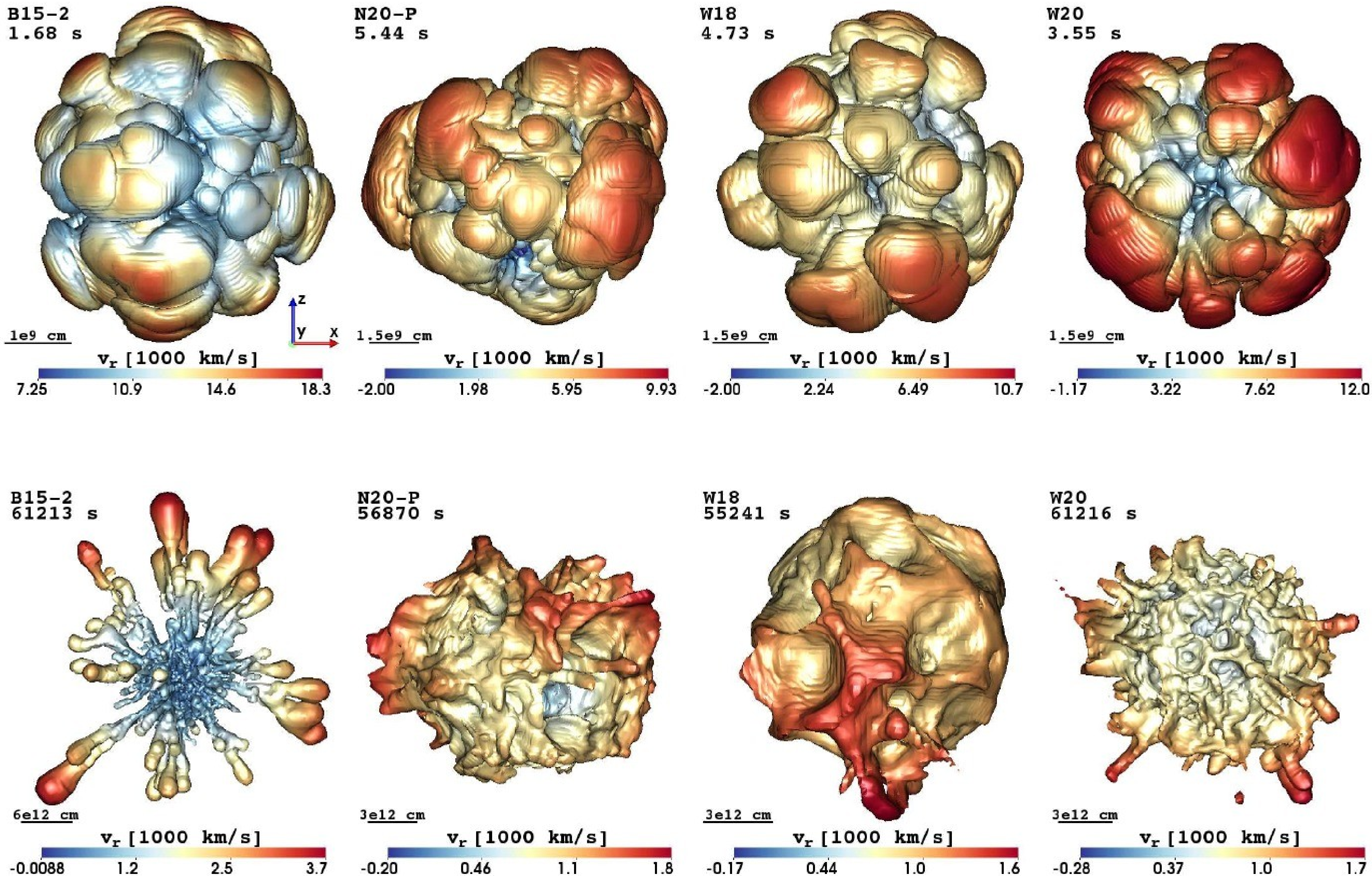




Yadav et al., arXiv:1905.04378


Sanduleak –69 202
Supernova 1987A 23. Februar 1987
SN 1987A
Supernova 1987A (SN 1987A)

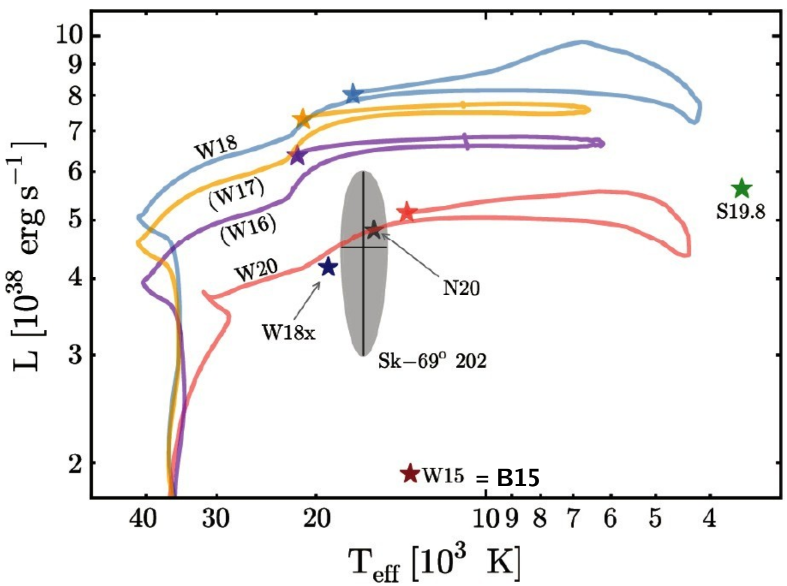
SN1987A Models: 3D Morphology



Wongwathanarat et al., A&A 577 (2015) A48 ; Utrobin et al., A&A 581 (2015) A40

New Single-star Models for SN1987A: Bolometric Light Curves from 3D Explosions

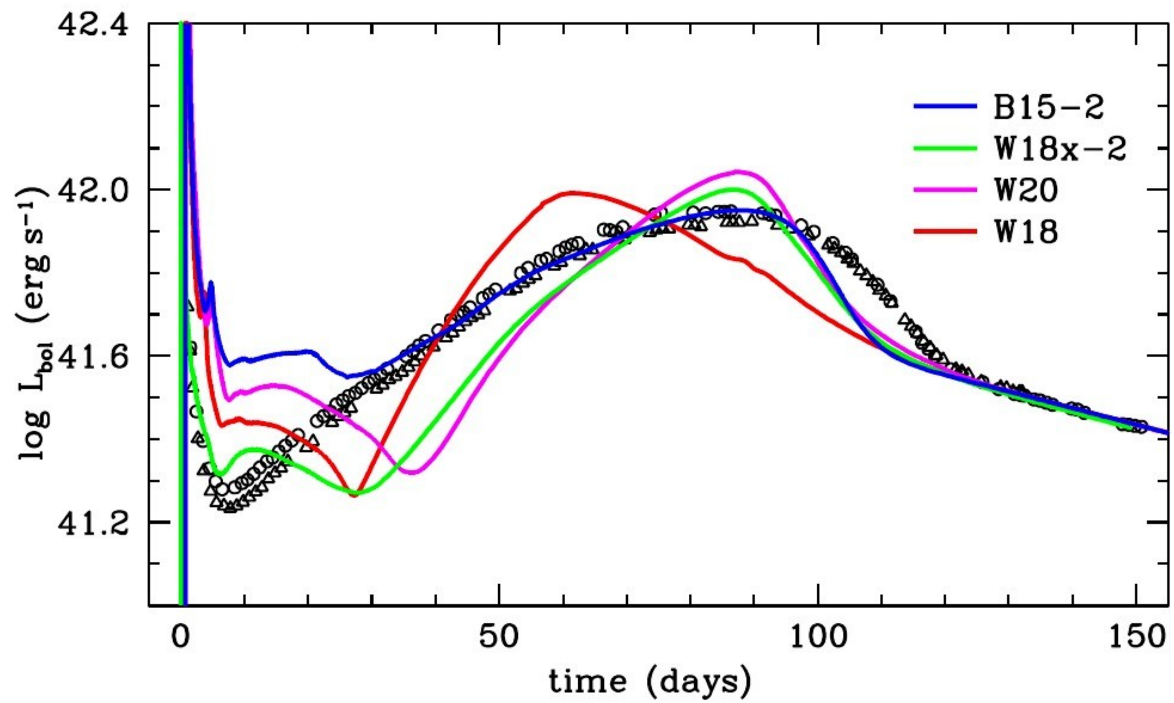
Hertzsprung-Russell Diagram for SN 1987A Progenitors.
Single Star Scenario



Sukhbold et al. (2016)

Utrobin et al., A&A 624 (2019) A116

Bolometric Light Curves



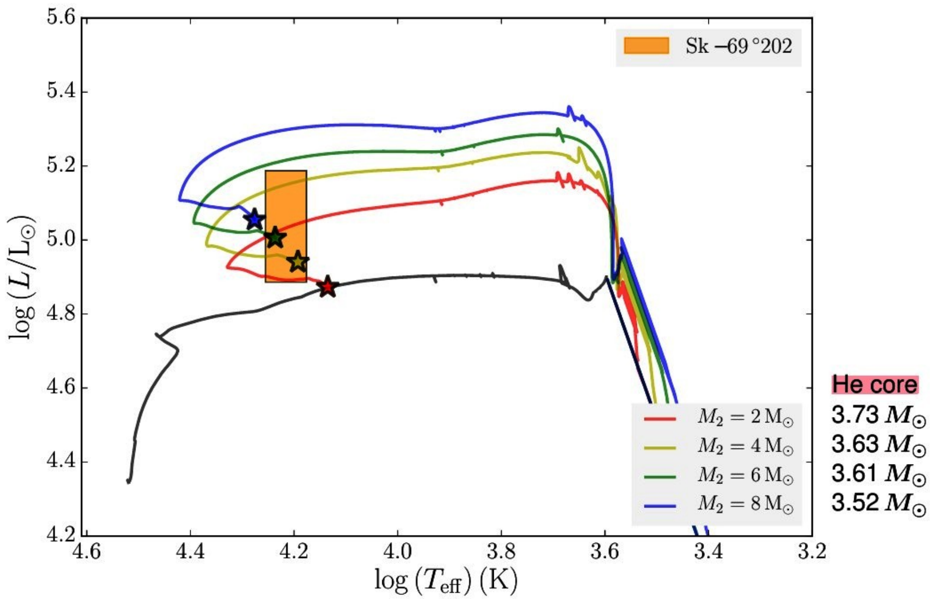
The total ^{56}Ni mass is scaled to fit the observed luminosity in the radioactive tail.

Not enough radial mixing of Ni outward and H inward in the 3D simulations of neutrino-driven explosions.

Binary-star Models for SN1987A: Bolometric Light Curves from 3D Explosions

Hertzsprung-Russell Diagram for SN 1987A Progenitors

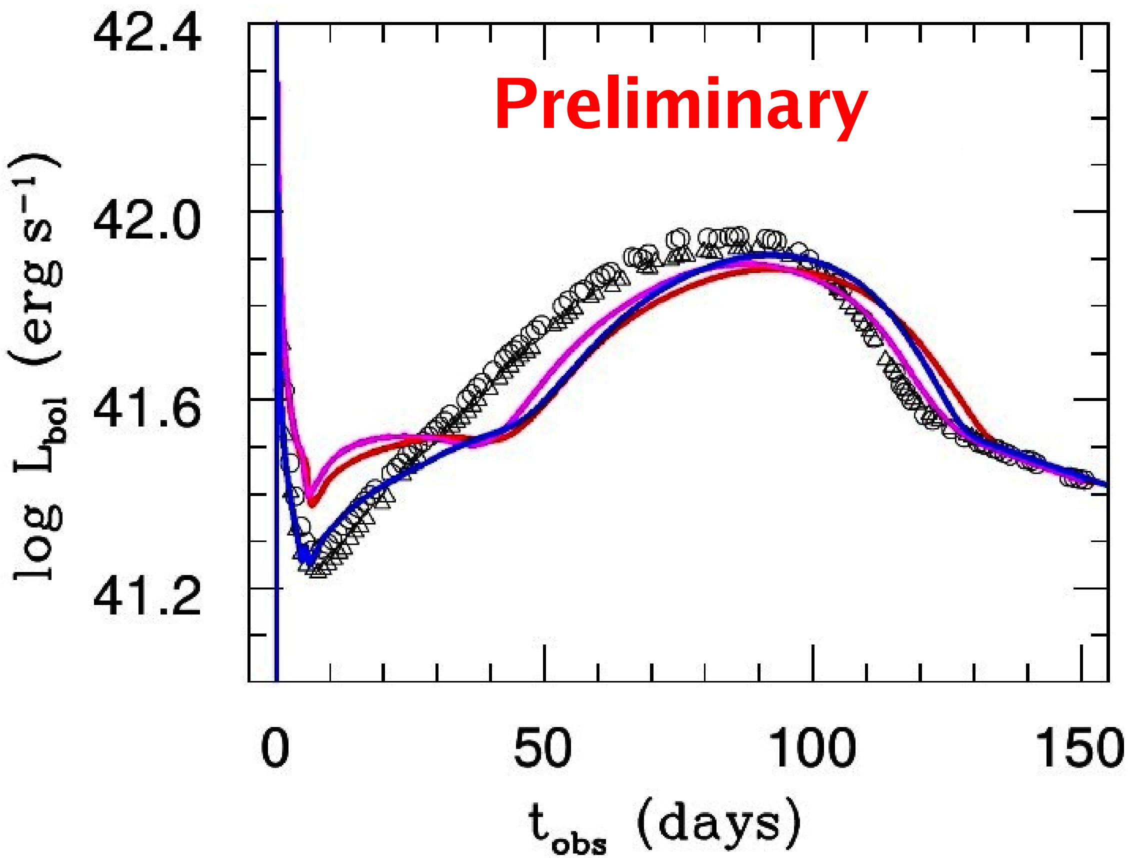
Binary Merger Scenario



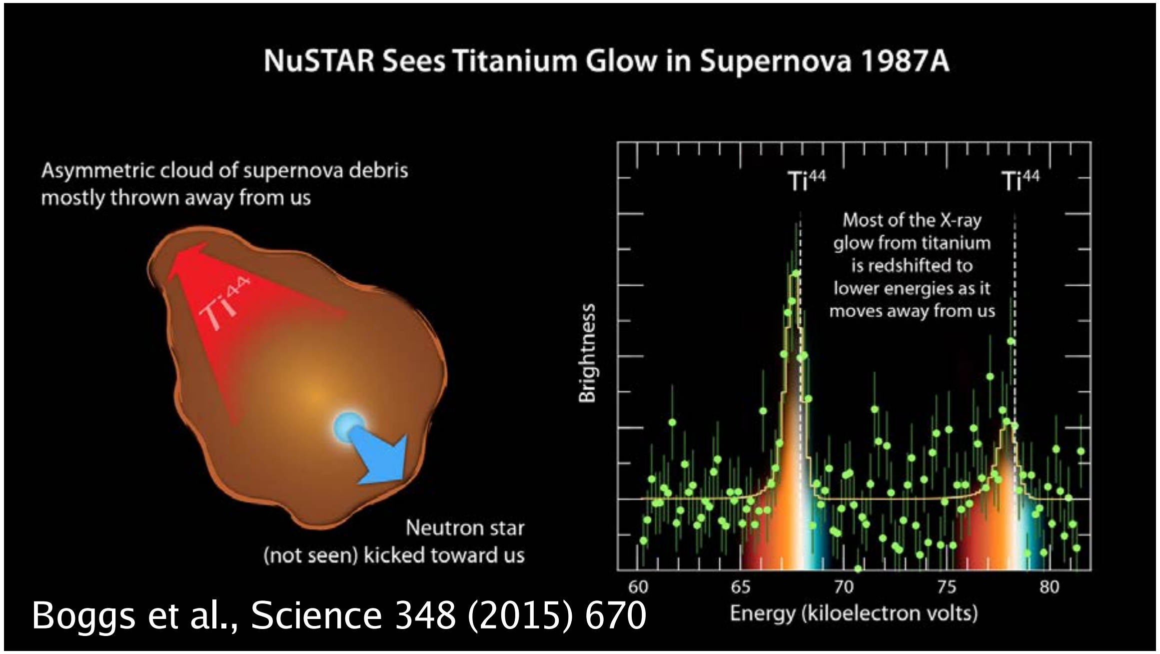
$M_1 = 16\,M_\odot$

Menon & Heger (2017);
based on original suggestion by
Podsiadlowski and coworkers (1990ff)

Utrobin et al., in preparation



SN 1987A: Gamma-Ray Line Profiles of ^{56}Co

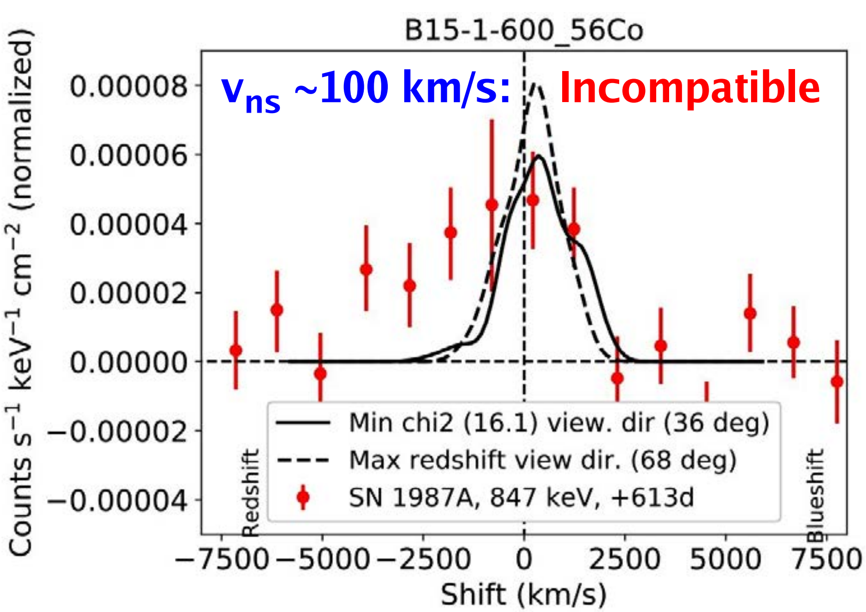


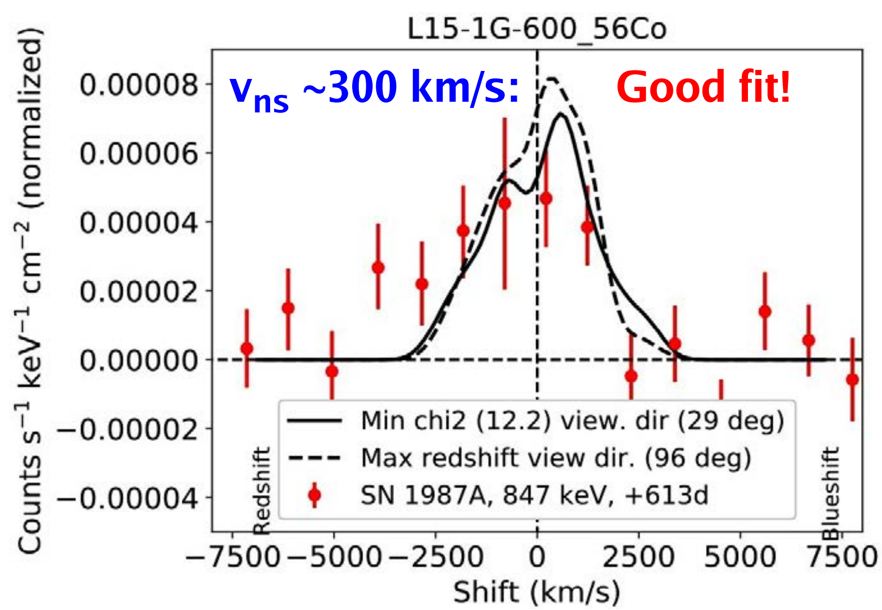
Boggs et al., Science 348 (2015) 670

NS in SN 1987A is likely to have fairly high kick towards us.

—> See also Poster 3.1 by Dennis Alp for X-ray and gamma-ray emission from 3D SN models compared to SN1987A

Jerkstrand et al., in preparation

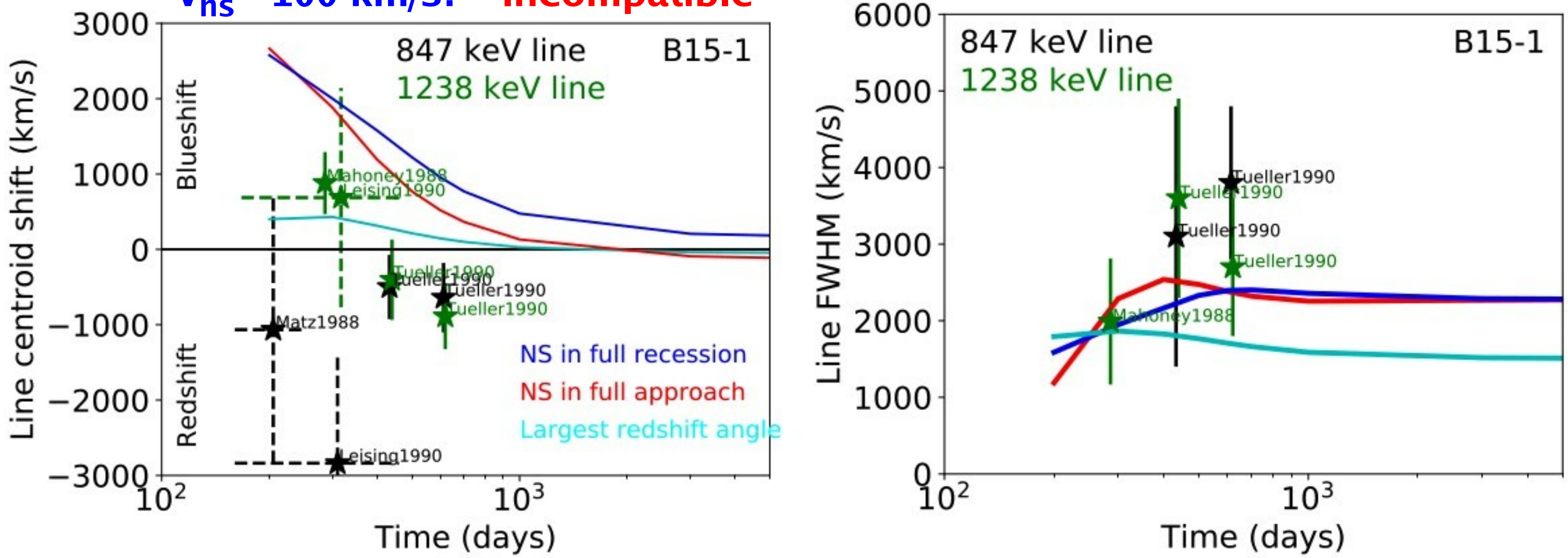




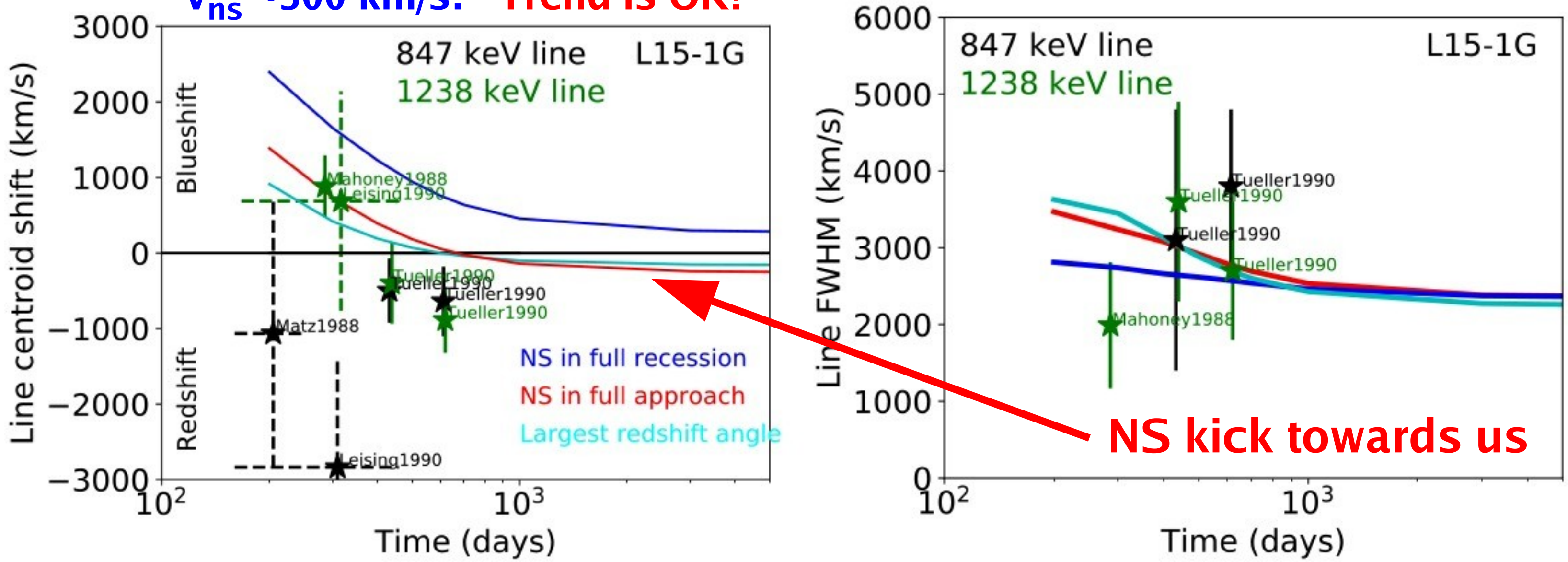
SN 1987A: Gamma-Ray Line Profiles of ^{56}Co

NS in SN 1987A is likely to have fairly high kick towards us.

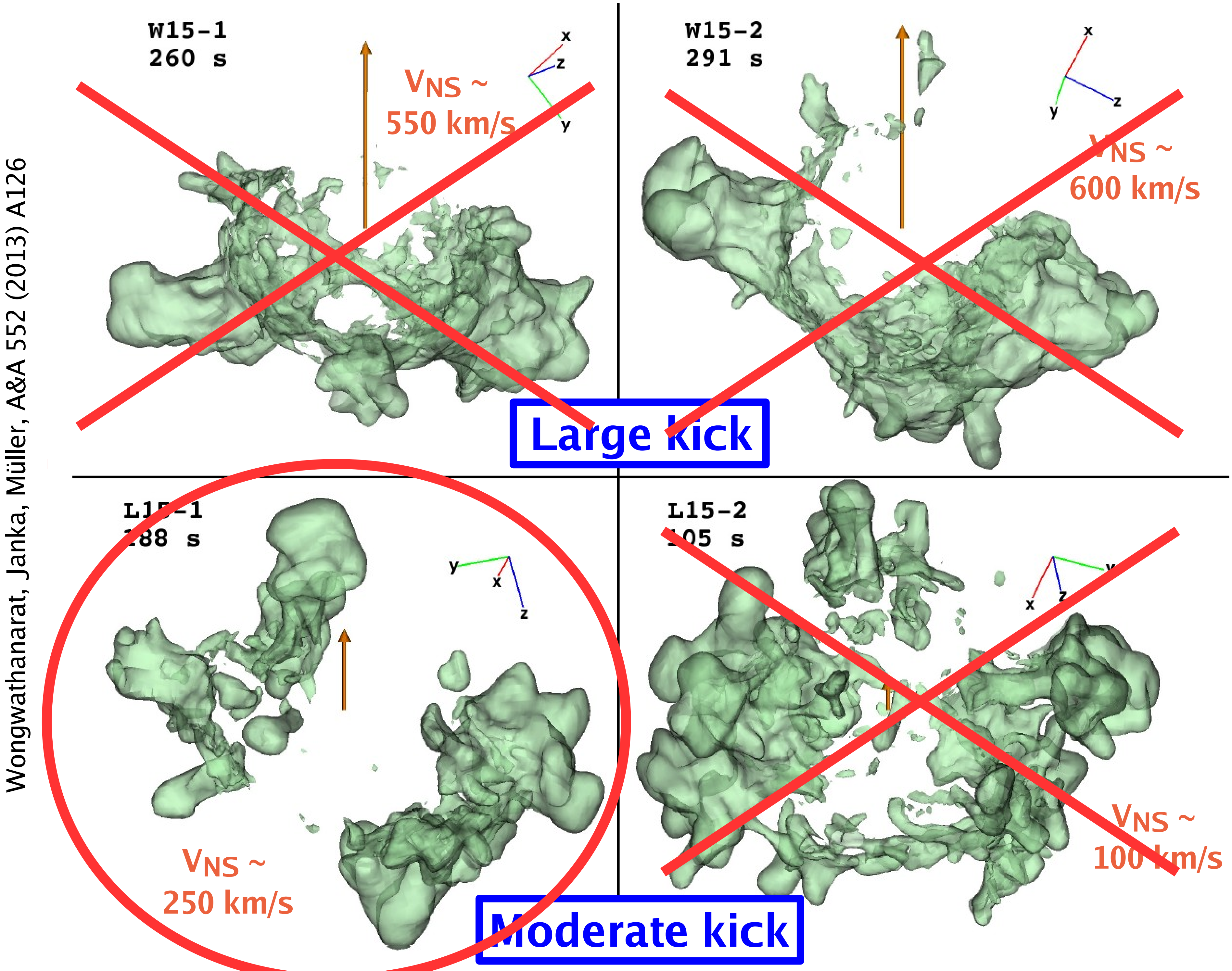
v_{ns} ~100 km/s: Incompatible



v_{ns} ~300 km/s: Trend is OK!



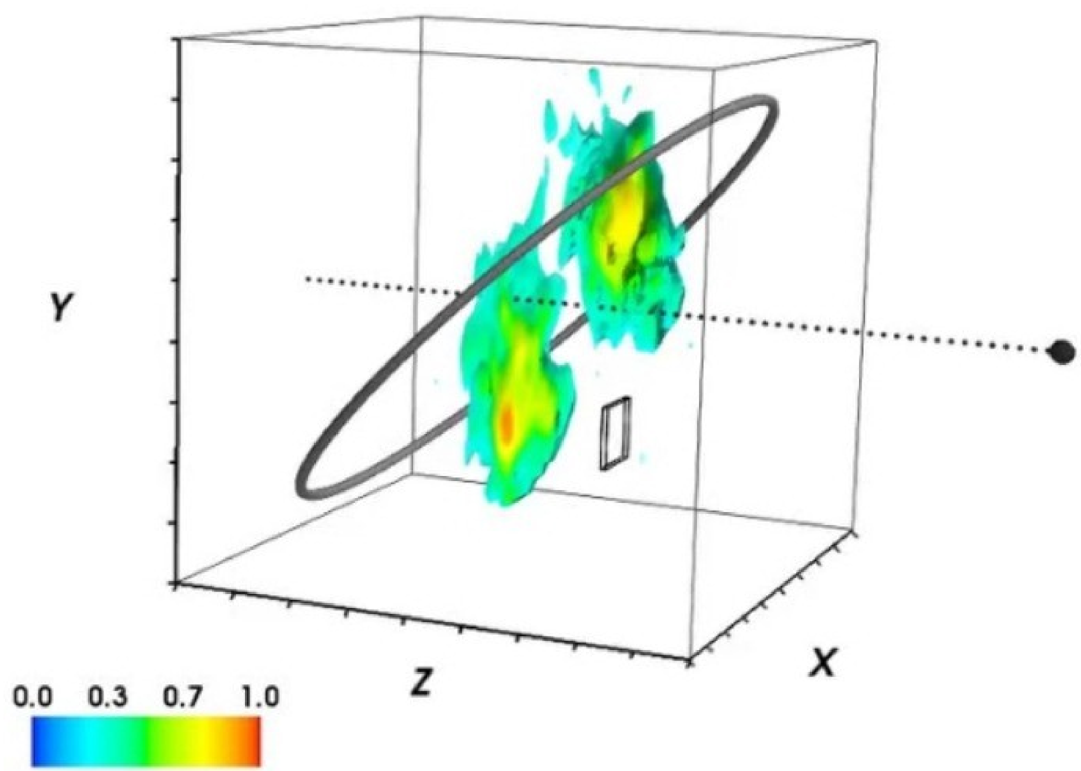
Jerkstrand et al., in preparation

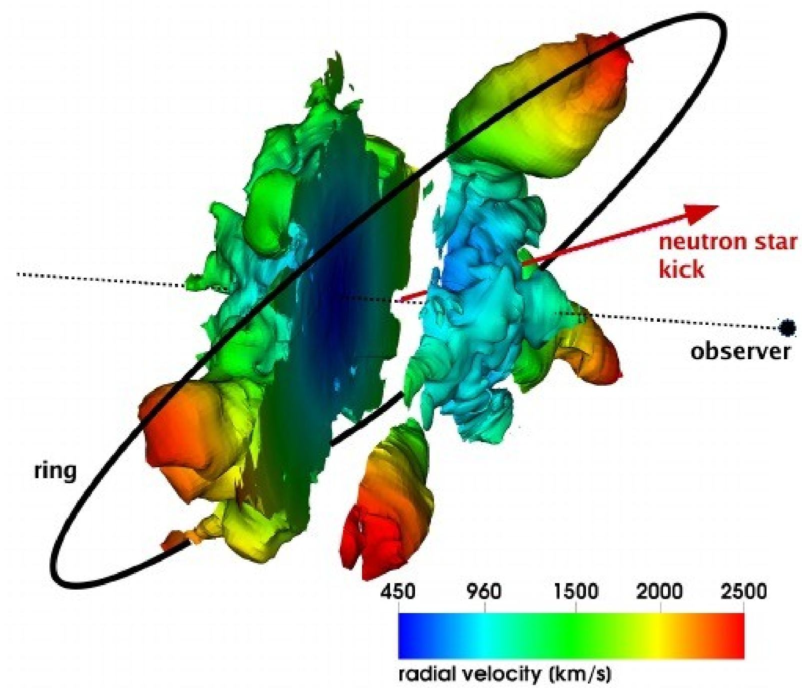


Wongwathanarat, Janka, Müller, A&A 552 (2013) A126
W15-1
260 s
V_{NS} ~
550 km/s
W15-2
291 s
V_{NS} ~
600 km/s
Large kick
L15-1
188 s
V_{NS} ~
250 km/s
L15-2
105 s
V_{NS} ~
100 km/s
Moderate kick

3D Geometry of SN1987A: Observations vs. Models

3D isosurfaces of iron and silicon ([FeII]+[SiI])





HST & VLT obs.: Larsson et al., ApJ 833 (2016) 147

3D model: Janka et al., arXiv:1705.01159

^{44}Ti and ^{56}Ni in SN Remnants

Cassiopeia A:

$M_{prog} \sim 17\text{–}20\ M_{sun}$, $M_{ej} \sim 4\ M_{sun}$,
$E_{exp} \sim 2.3 \times 10^{51}$ erg, $v_{ns} \sim 500$ km/s

$M(^{56}Ni) \sim 0.1\text{~}0.2\ M_{sun}$

$M(^{44}Ti) = (1.25\pm0.3)\ 10^{-4}\ M_{sun}$ (NuSTAR; Grefenstette et al. 2014)

$M(^{44}Ti) = (1.37\pm0.19)\ 10^{-4}\ M_{sun}$ (INTEGRAL; Siegert et al. 2015)

$M(^{44}Ti) = (1.3\pm0.4)\ 10^{-4}\ M_{sun}$ (INTEGRAL; Wang & Li 2016)

SN1987A:

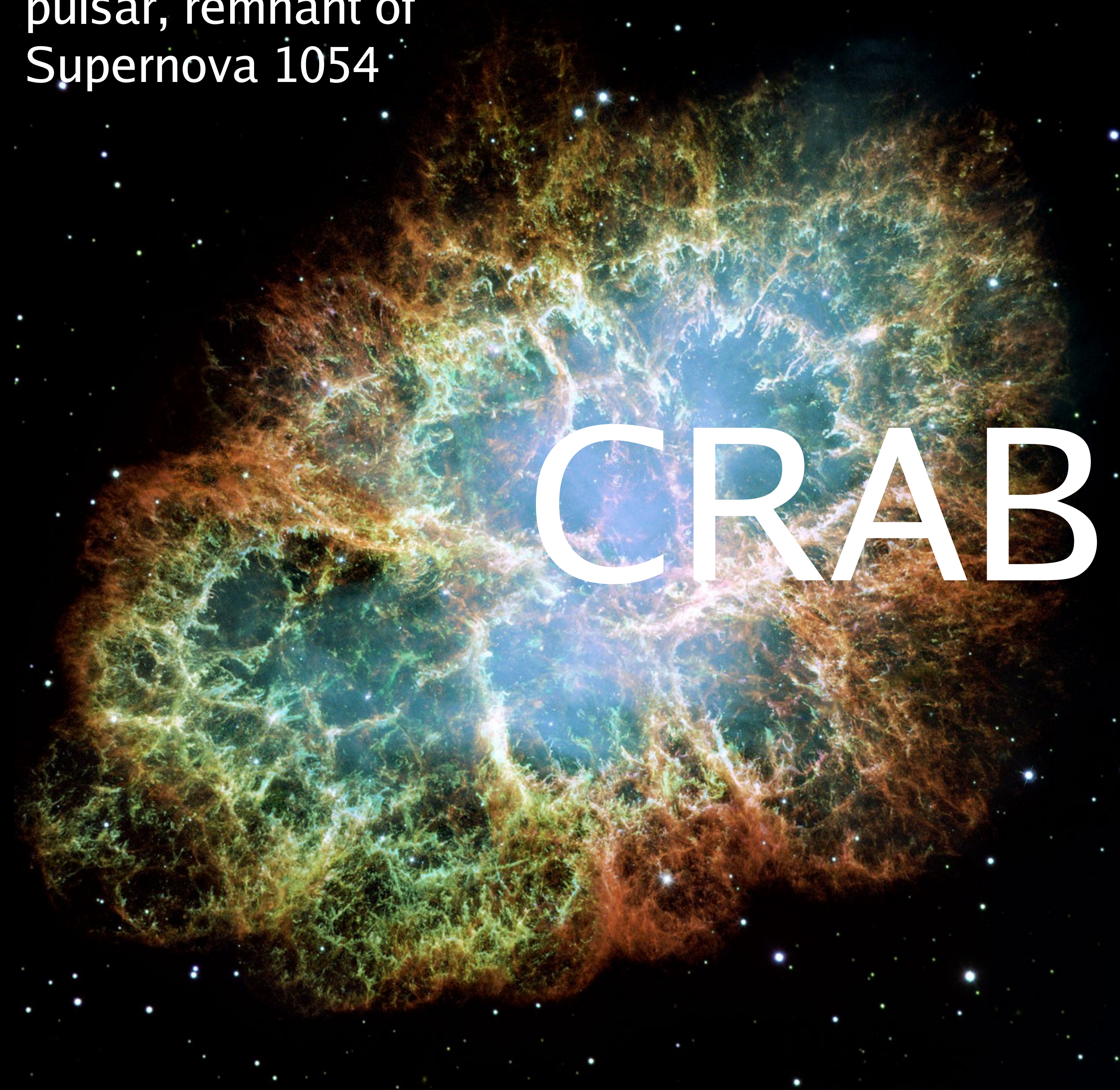
$M_{prog} \sim 15\text{–}20\ M_{sun}$, $M_{ej} \sim 15\ M_{sun}$,
$E_{exp} \sim 1.5 \times 10^{51}$ erg, $v_{ns} \sim 300$ km/s

$M(^{56}Ni) = 0.071\ M_{sun}$

$M(^{44}Ti) = (1.5\pm0.3)\ 10^{-4}\ M_{sun}$ (NuSTAR; Boggs et al. 2015)

$M(^{44}Ti) = (1.5\pm0.5)\ 10^{-4}\ M_{sun}$ (Jerkstrand et al. 2011)

CRAB Nebula with pulsar, remnant of Supernova 1054



CRAB (SN1054):

Low explosion energy and ejecta composition (He richness, low O, Fe abundances) are compatible with ONeMg core explosion

(Nomoto et al., Nature, 1982; Hillebrandt, A&A, 1982)

ECSN properties:

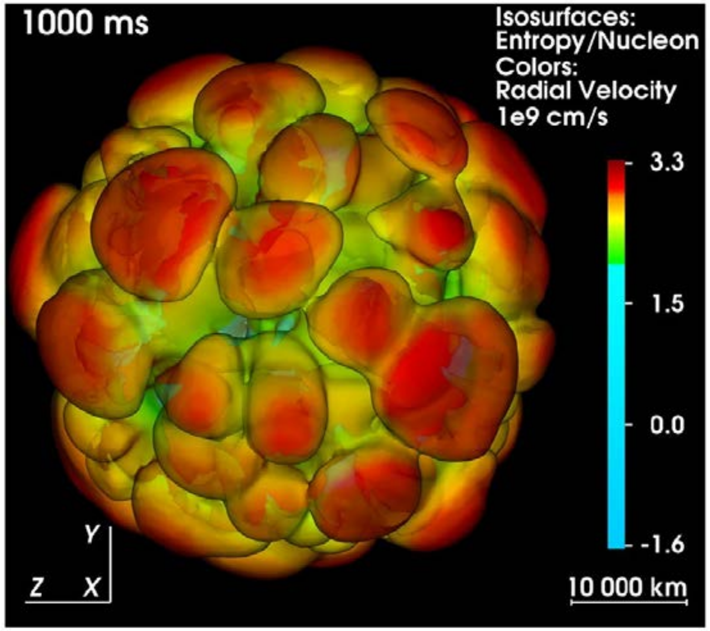
E_{exp} ~ 10^{50} erg = 0.1 bethe

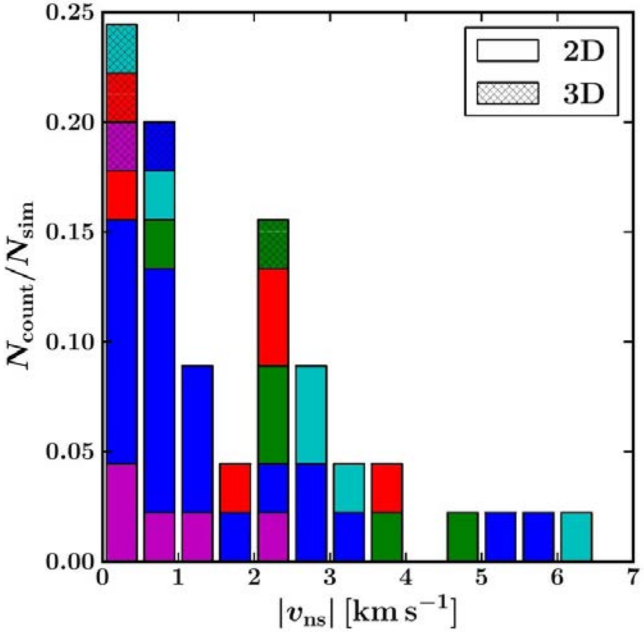
M_{Ni} ~ 0.003 M_{sun}

Neutron Star Recoil in 2D and 3D ECSN Models

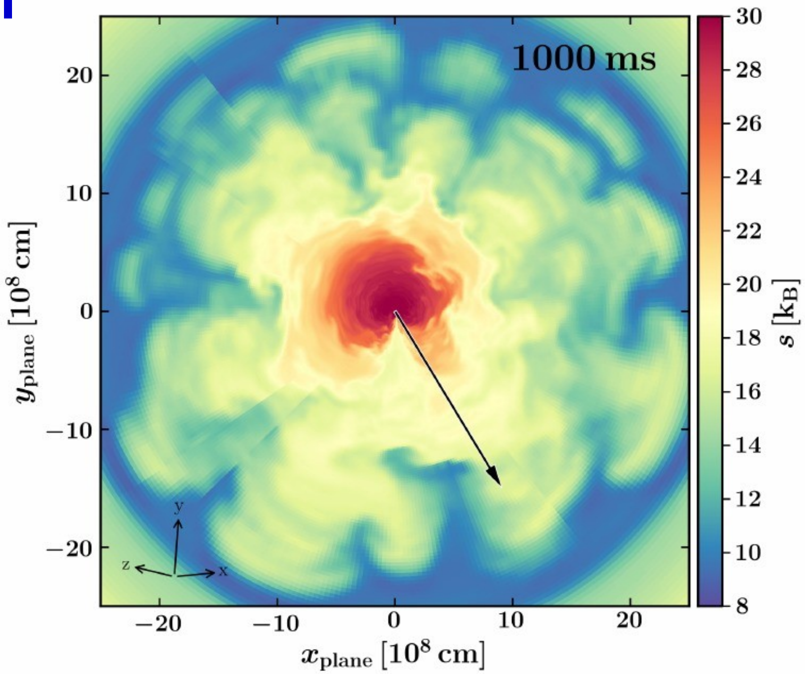
ECSN models:
40 2D runs
5 3D runs

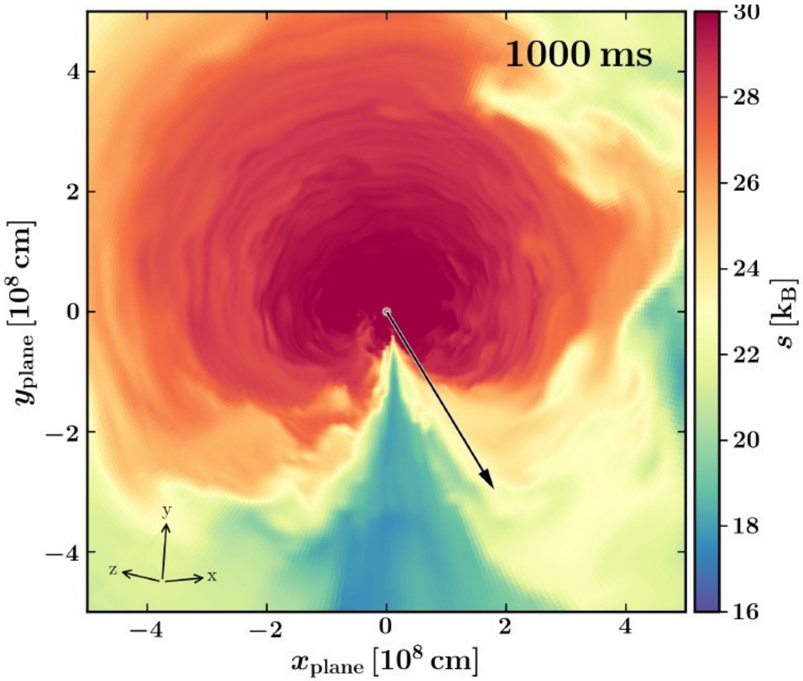
with energies in
[0.3, 1.6] x 10^{50} erg





Hydrodynamical NS kicks only a few km/s;
in 3D: < 3 km/s





Gessner & Janka,
arXiv:1802.05274

Implications for CRAB SN Remnant

- CRAB pulsar: Proper motion of ~160 km/s

- This is NOT compatible with SN birth in ECSN explosion

Therefore:

- Either: CRAB was SN explosion of (low-mass) Fe-core progenitor and not an ECSN of ONeMg core progenitor
- Or: Pulsar kick by anisotropic neutrino emission instead of hydrodynamic mechanism!

- Also possible (?): Binary break-up in SN explosion
- Not possible: Electromagnetic recoil (Harrison-Tademaru)

Implications of Neutrino-driven Explosions in 3D Supernova Models

- Delayed neutrino-driven explosions work in 2D and 3D!
- "Details" of the physics in the core still need further studies. Can dense-matter effects be settled in near future?
- Multi-D models of neutrino-driven explosions are sufficiently mature to test them against observations.
- 3D geometry of neutrino-driven explosions seems to explain morphology of SNRs such as Cas A and SN 1987A.
  What are the Cas A "jets"? How much Fe is unshocked in Cas A?
- Pulsar kick in CRAB is hardly compatible with origin in ECSN !
  Do ECSNe exist?