Max–Planck–Institut für Astrophysik

LMU TUM ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers

Multi-dimensional Modeling and Multi-messenger Observations of Core-collapse Supernovae (4M-COCOS)

October 21–24, 2019, Fukuoka University, Fukuoka, Japan

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

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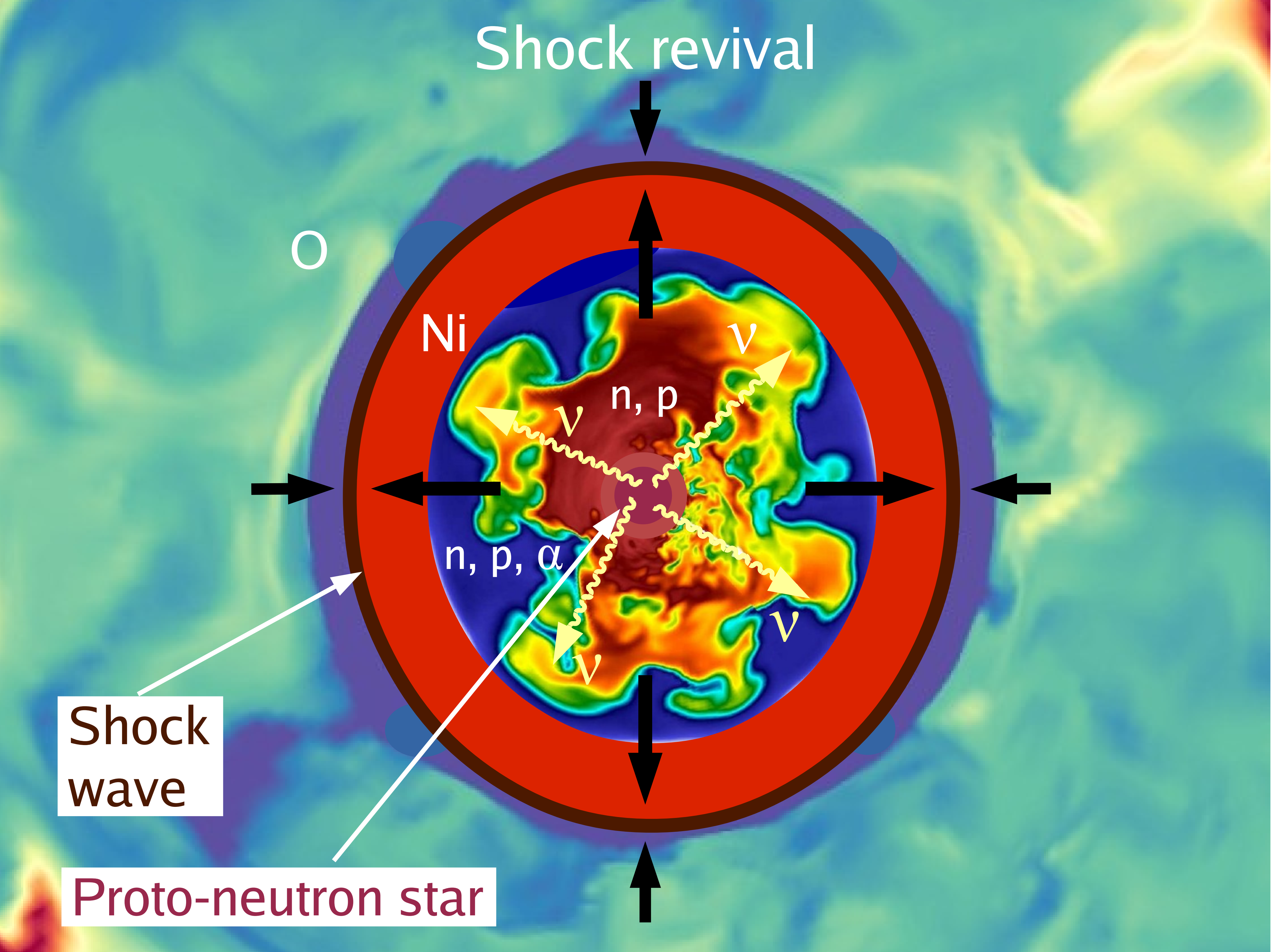
5. Core-collapse or thermonuclear electron-capture SNe? Was SN 1054 (Crab) an "electron-capture SN" (ECSN) ?


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

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):

9–40 M_{sun} suite of 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)

Modeling inputs and results differ in various aspects.
3D code comparison is missing and desirable

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.**

- **Neutrino-driven 3D explosions for progenitors between 9 and 40 M_{sun}**
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities)
- **Explosion energy can take several seconds to saturate !**

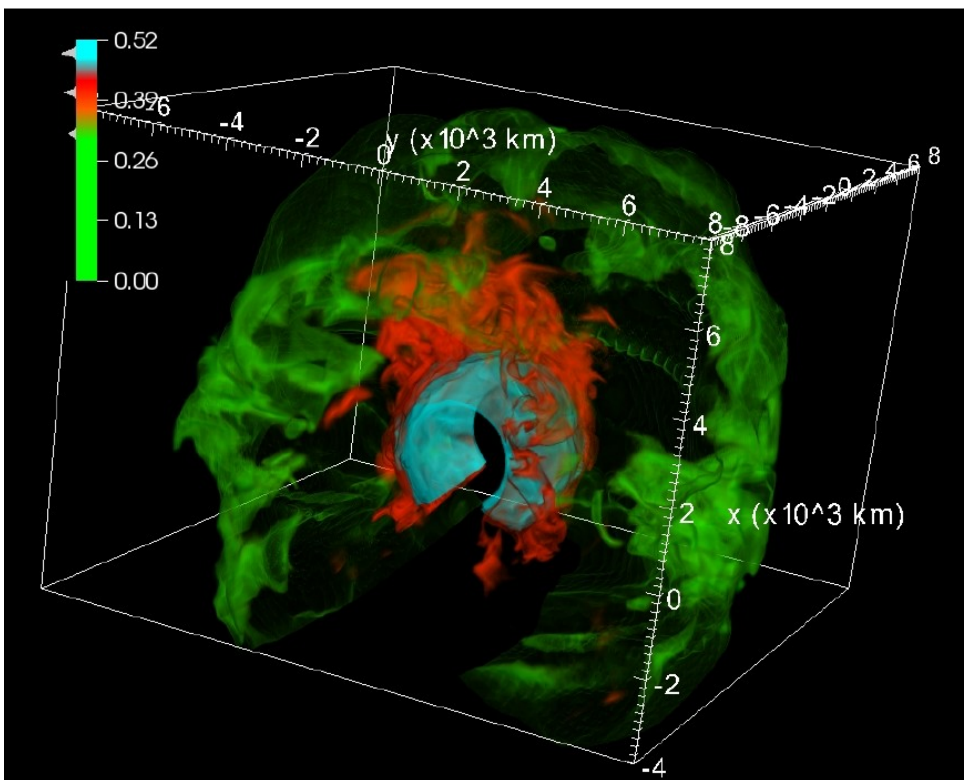
- **Progenitors are 1D**, but composition-shell structure and initial progenitor-core asymmetries can affect onset of explosion.
- 3D simulations may **still need higher resolution** for convergence.
- **Full multi-D neutrino transport** versus **"ray-by-ray" approximation.**
- **Uncertain/missing physics?**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

Pre-collapse 3D Asymmetries in Progenitors

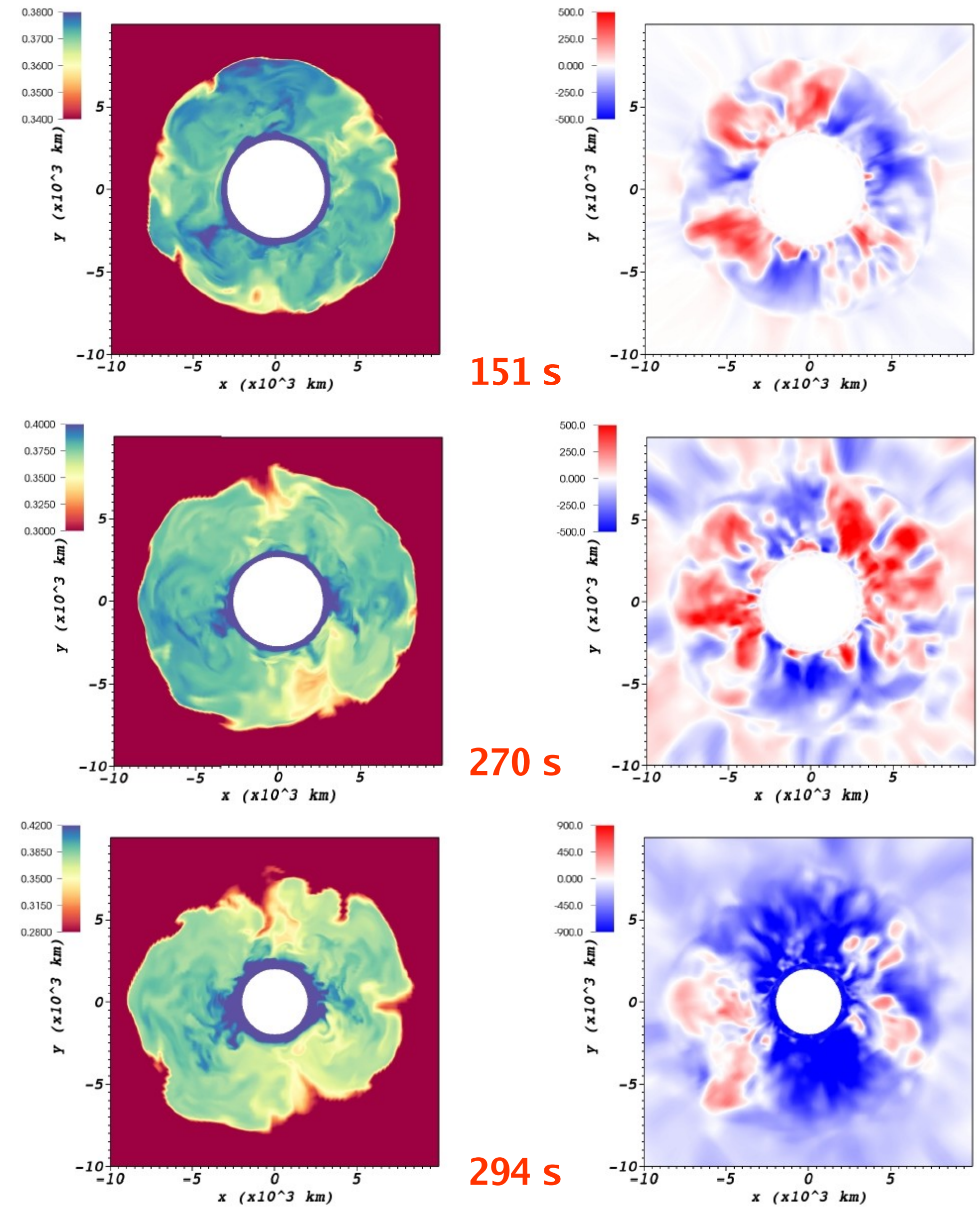
3D Core-Collapse SN Progenitor Model

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)

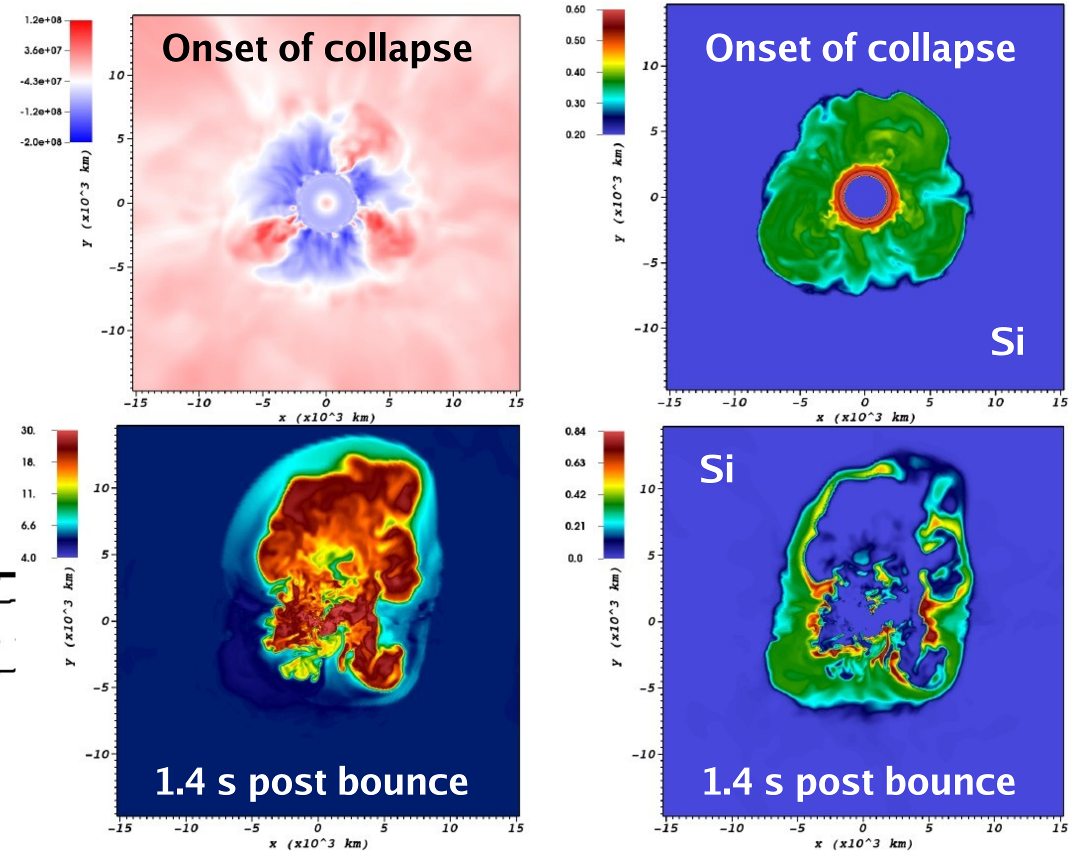


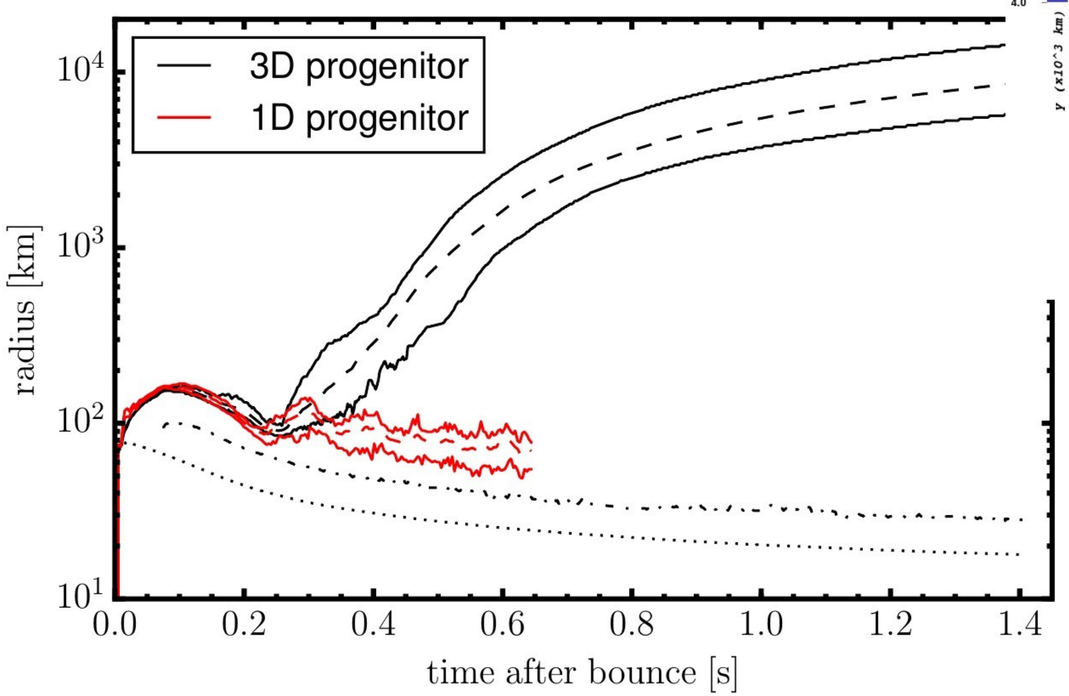
3D Core-Collapse SN Explosion Model

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.





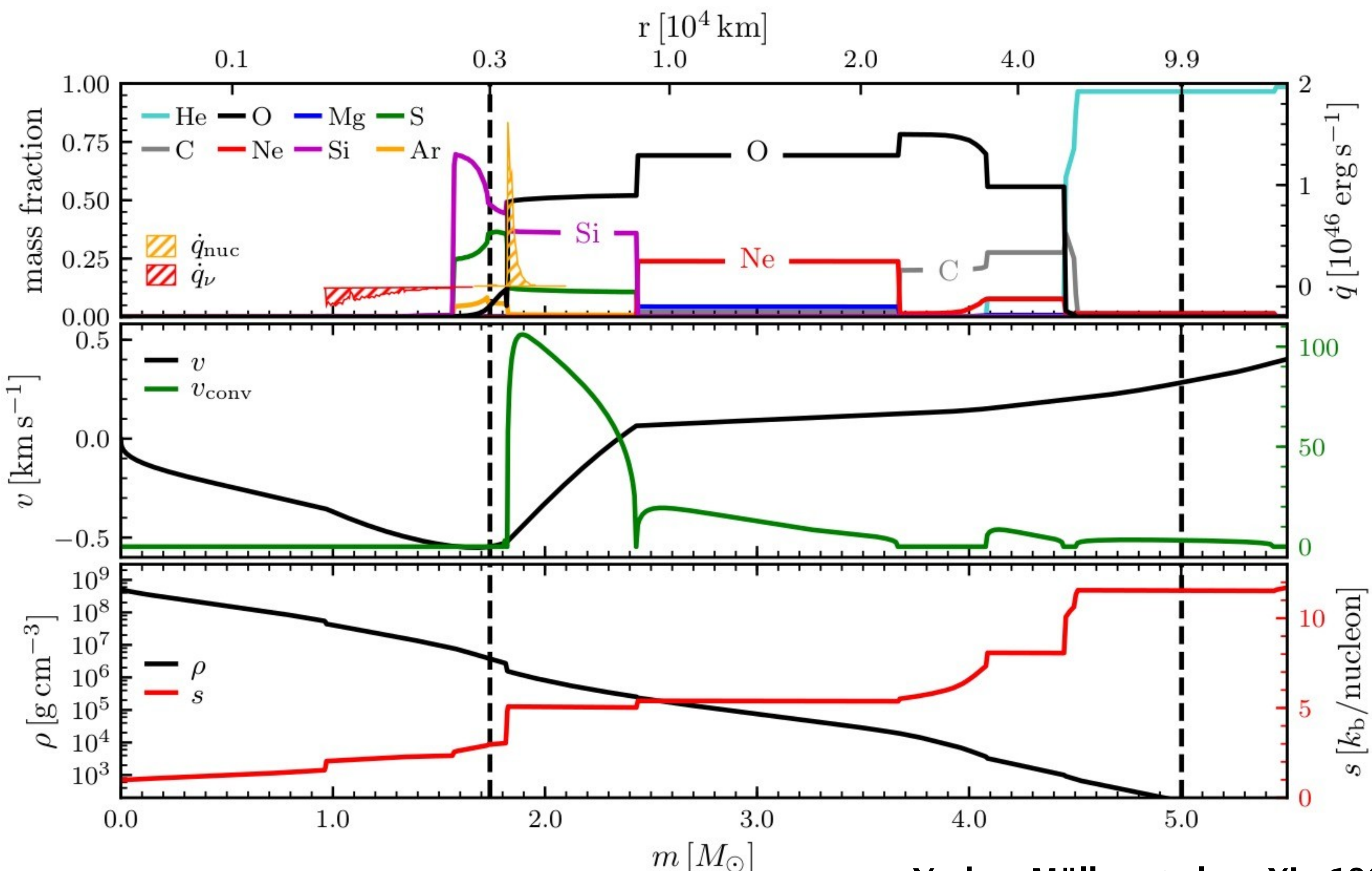
$$\delta\rho/\rho \sim \mathrm{Ma_{conv}}$$

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

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

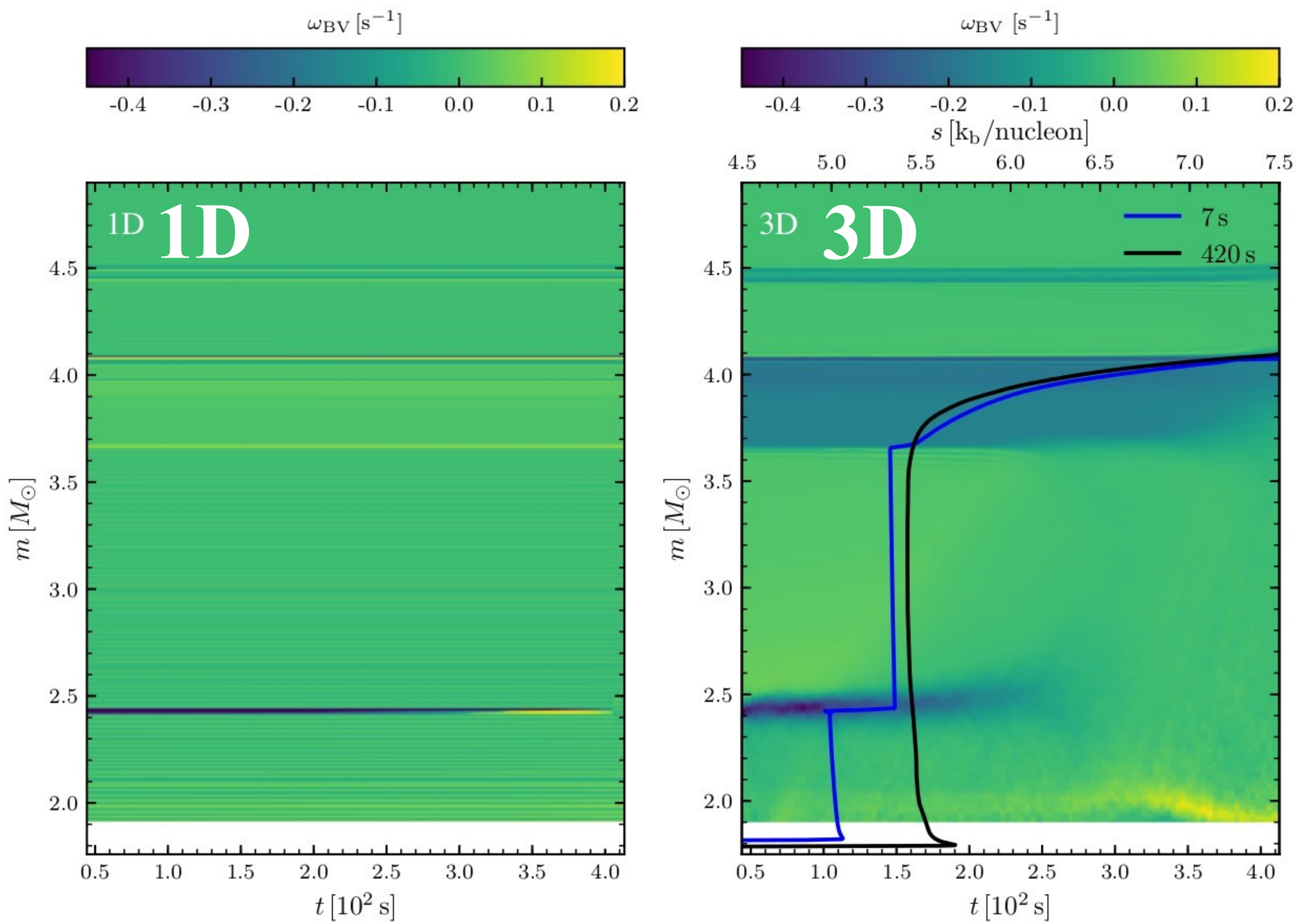
Initial (1D) conditions 7 minutes prior to core collapse.



Yadav, Müller et al., arXiv:1905.04378

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

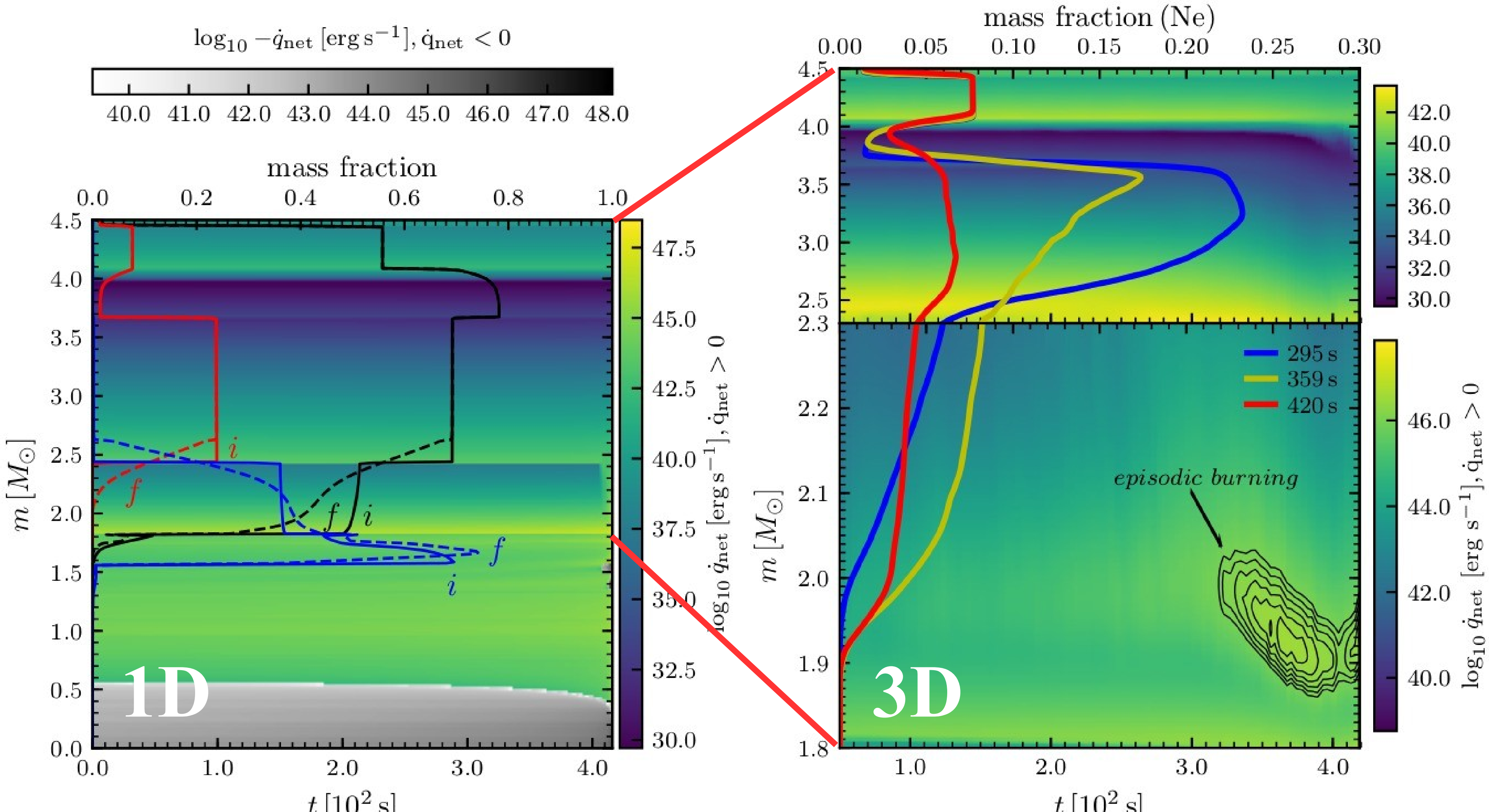
Convectively Ledoux-stable (BV frequency < 0) and Ledoux-unstable regions (BV frequency > 0) regions.



Yadav, Müller et al., arXiv:1905.04378

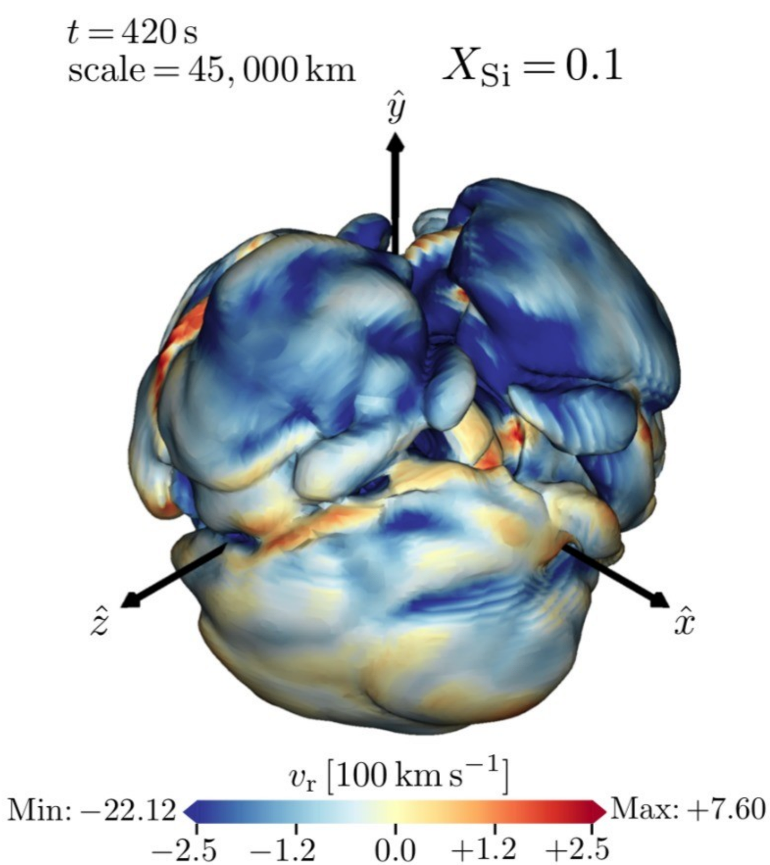
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M$_{sun}$

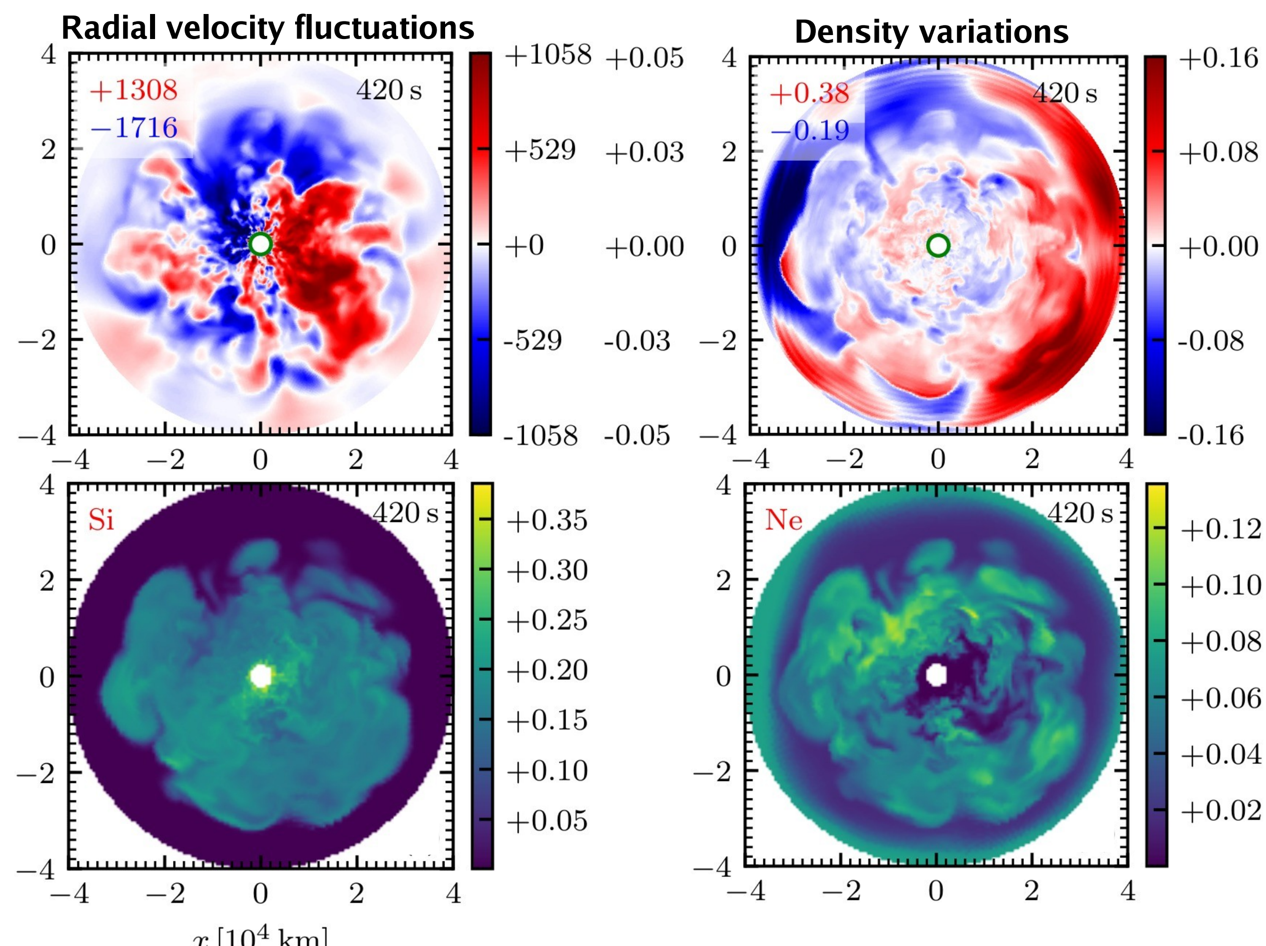
Net energy generation rate (nuclear burning minus neutrino cooling).

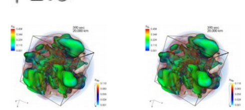


Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

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

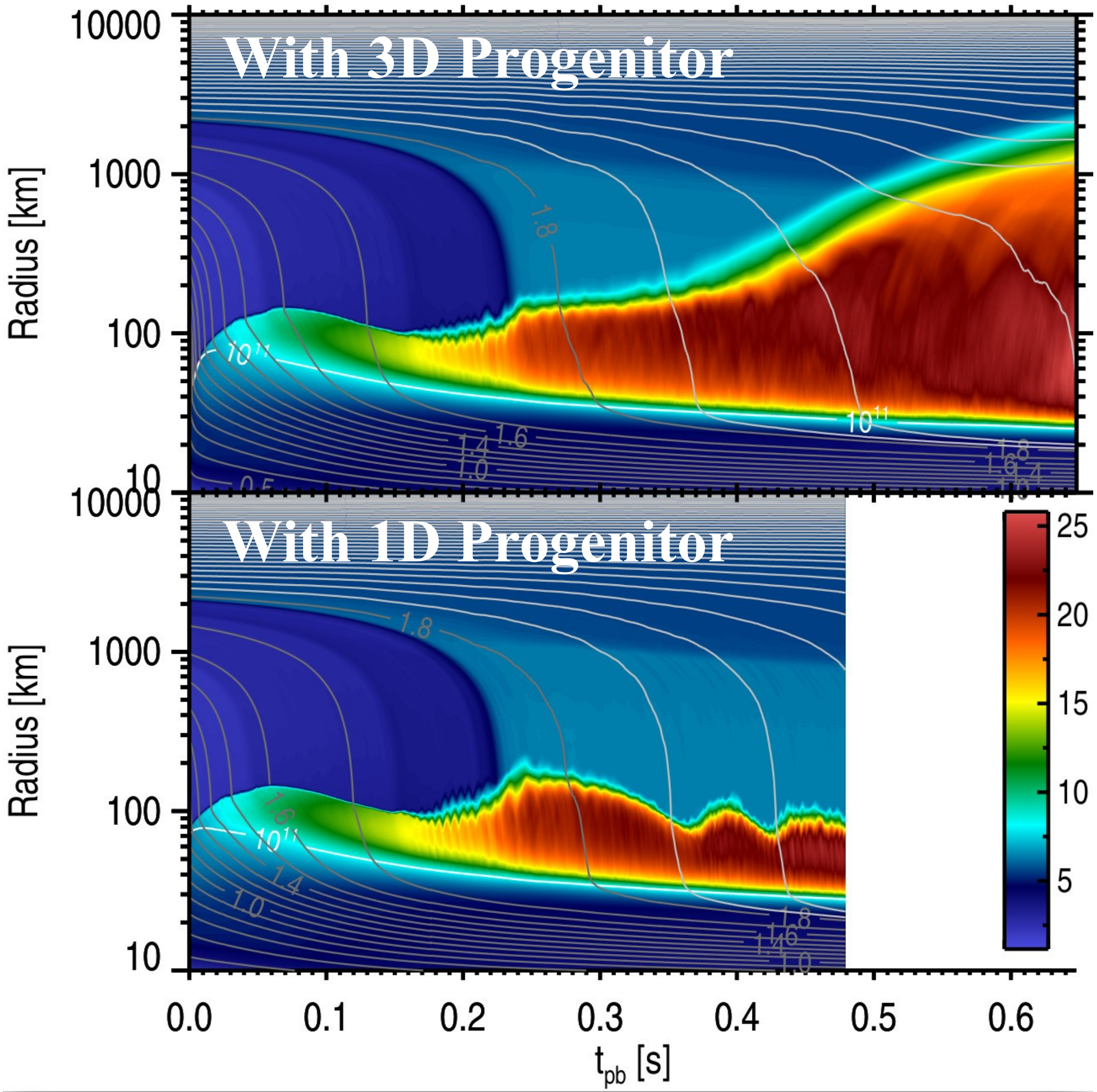


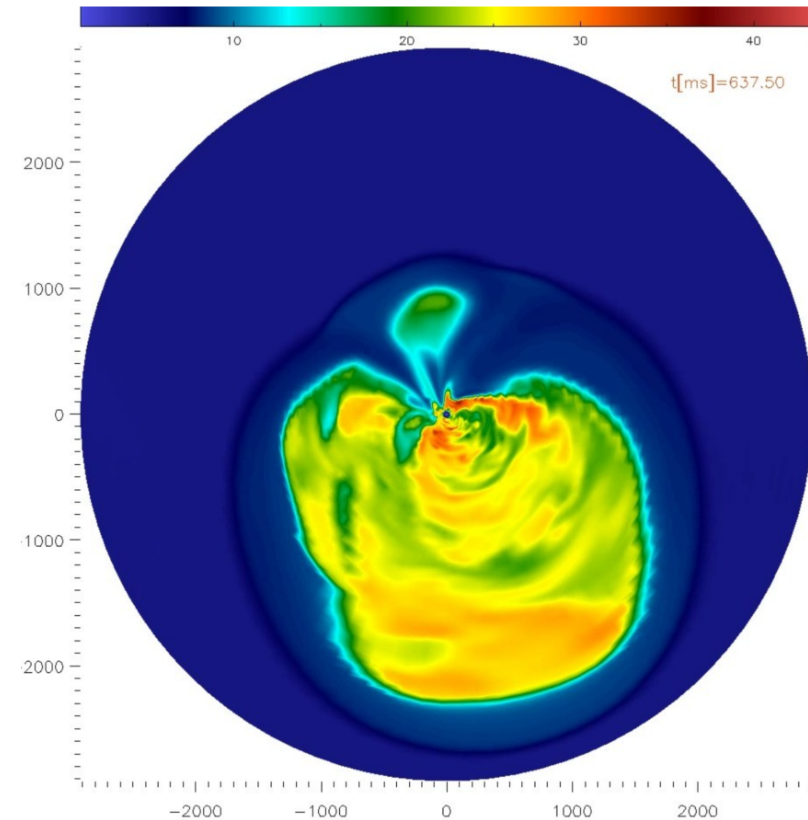




Yadav, Müller et al., arXiv:1905.04378

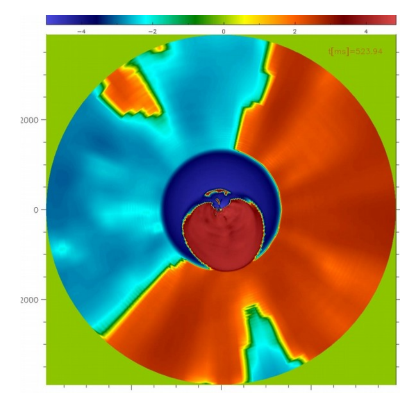
3D Explosion of ~19 M_{sun} Star after Neon-oxygen-shell Merger





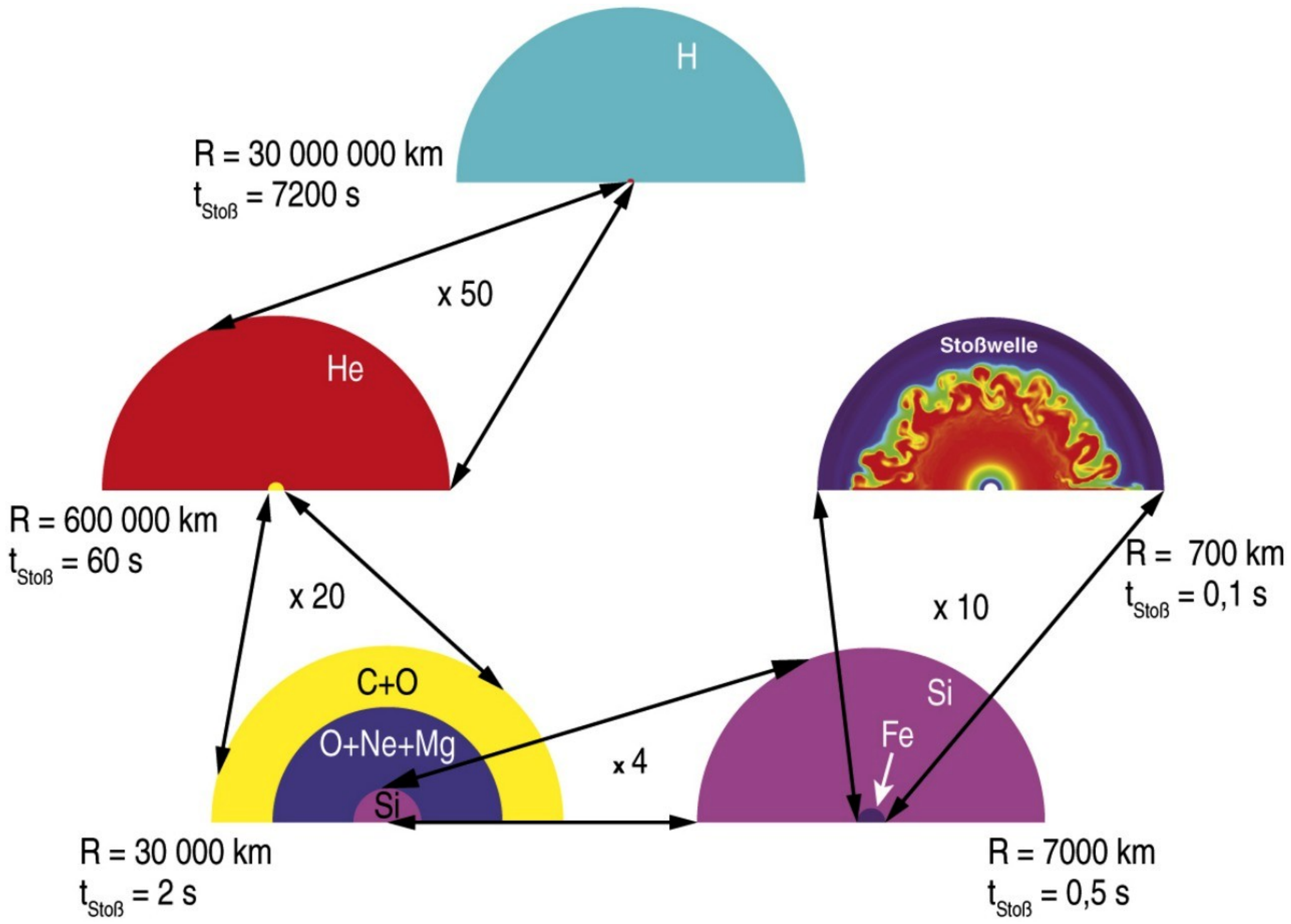
R. Bollig et al., in preparation

Explosion pushes preferentially in direction of lower infall velocity

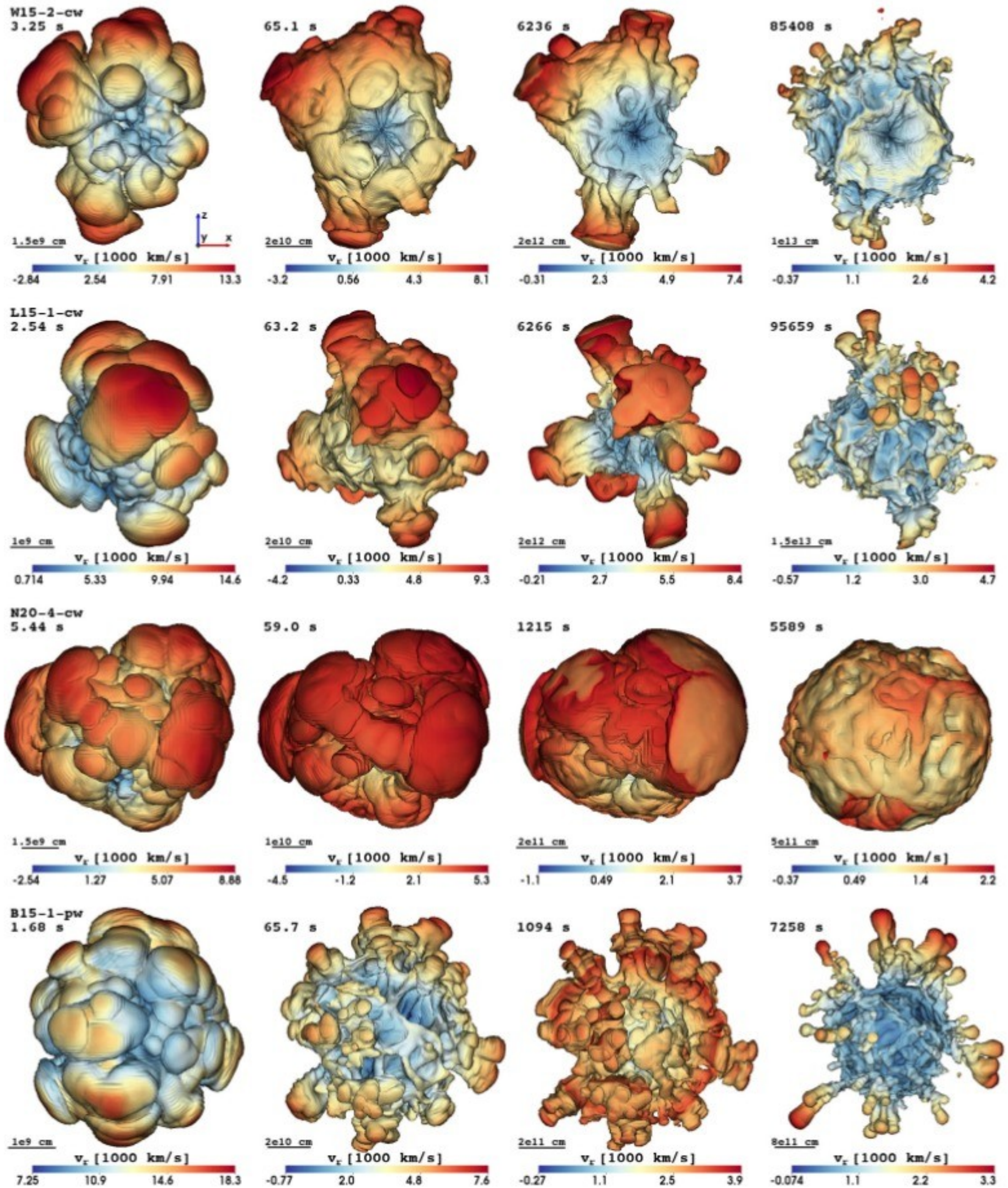


Long-time Explosion Modeling Towards Observations

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 !



SN Evolution From Bounce to Shock Breakout



RSG W15

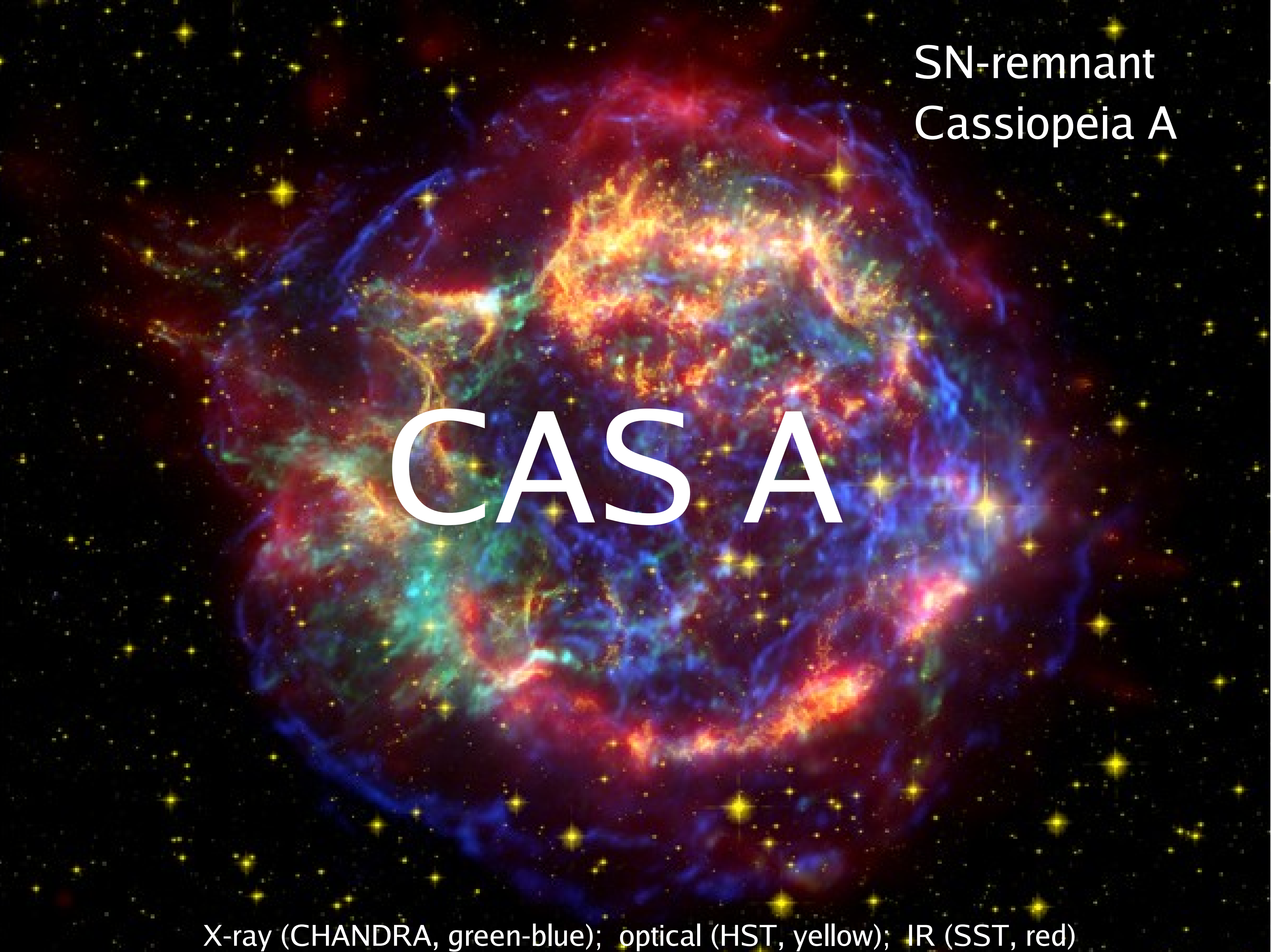
RSG L15

BSG N20

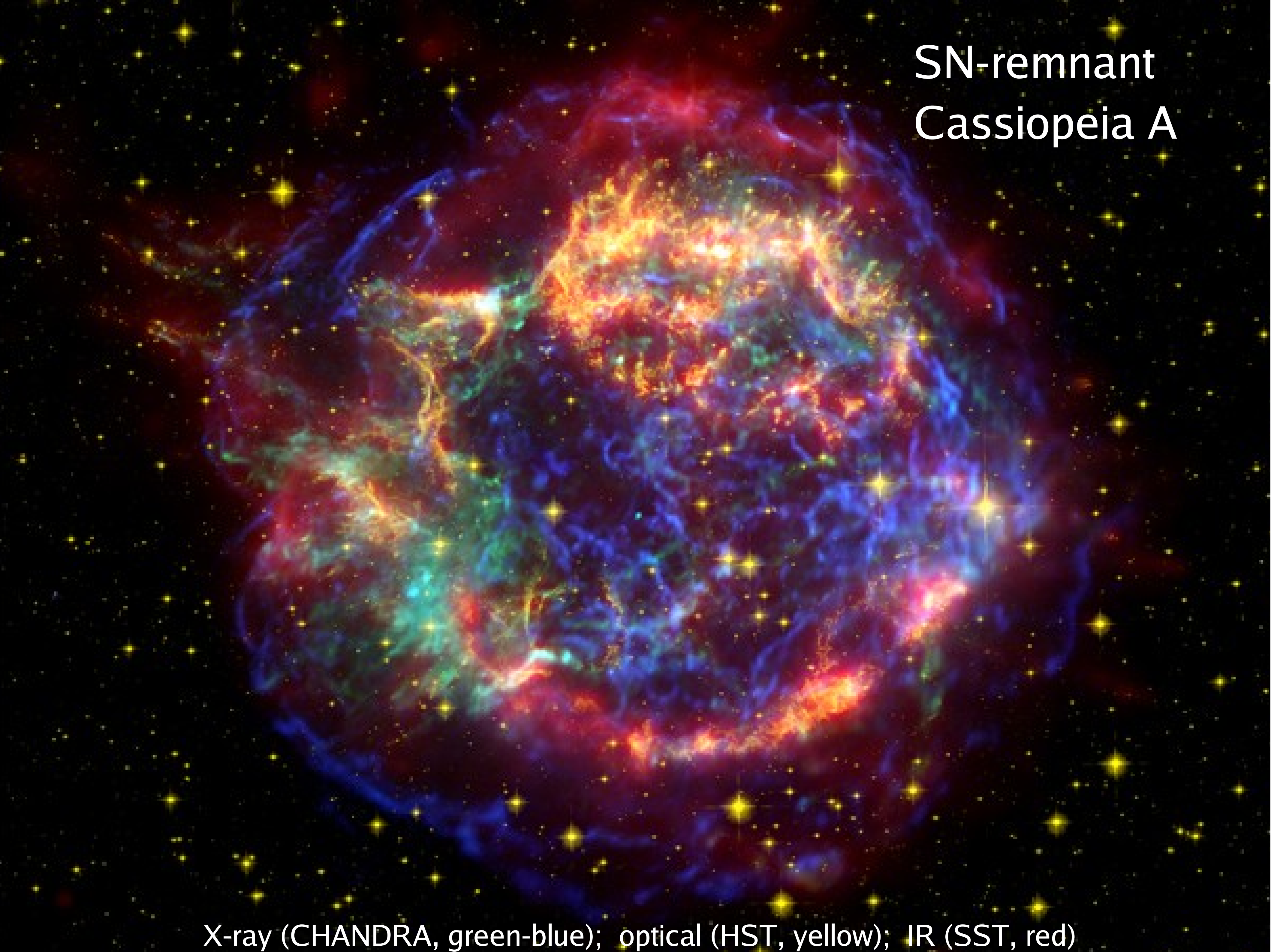
BSG B15

Times: shock at C+O/He, He/H interface, in H envelope, at stellar surface.

Wongwathanarat et al.,
A&A 577 (2015) A48



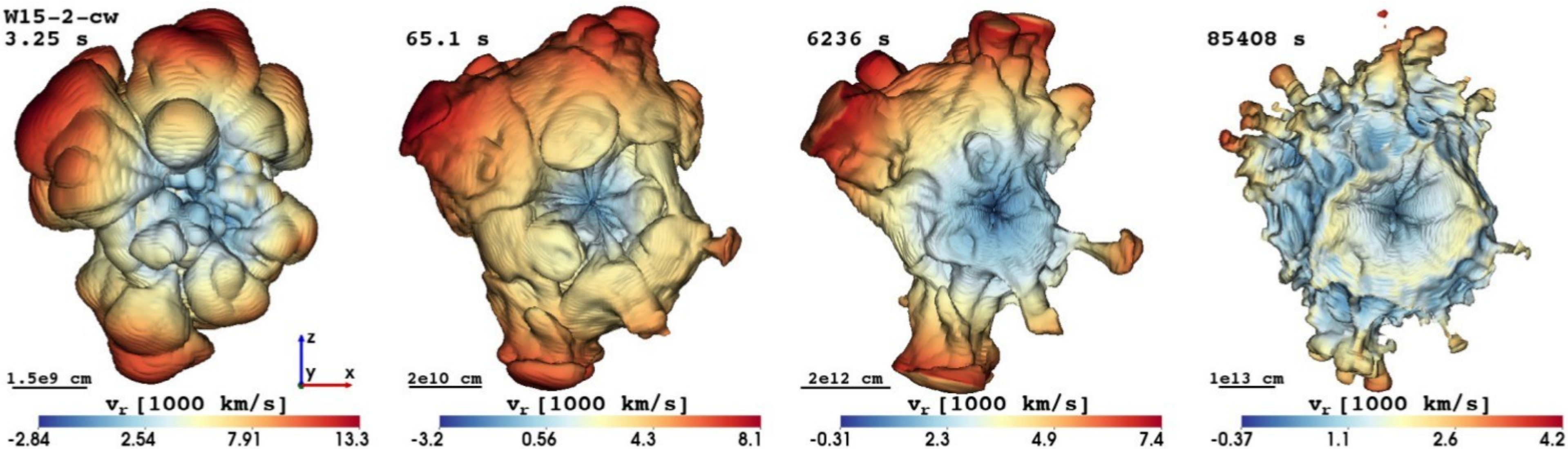
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

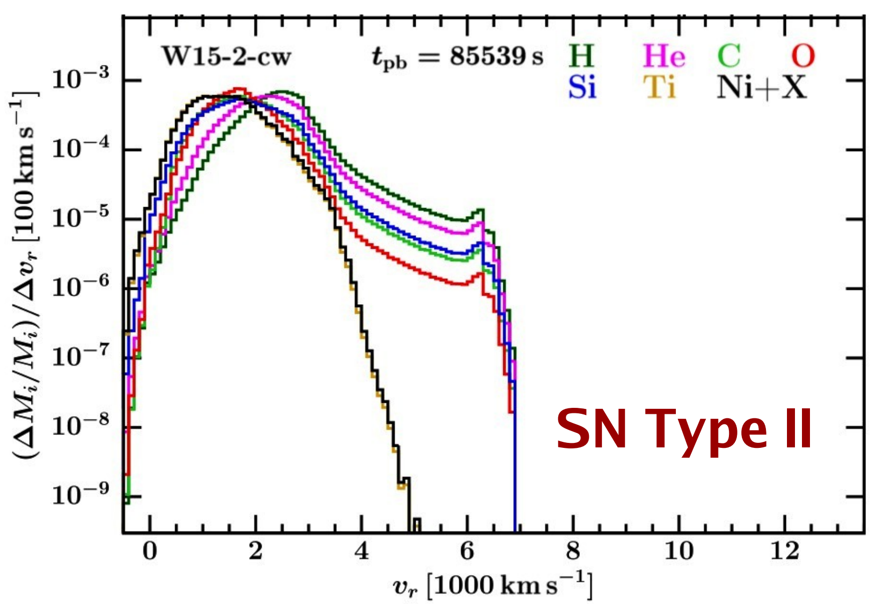


X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

Supernovae Type II: With Massive H-envelope

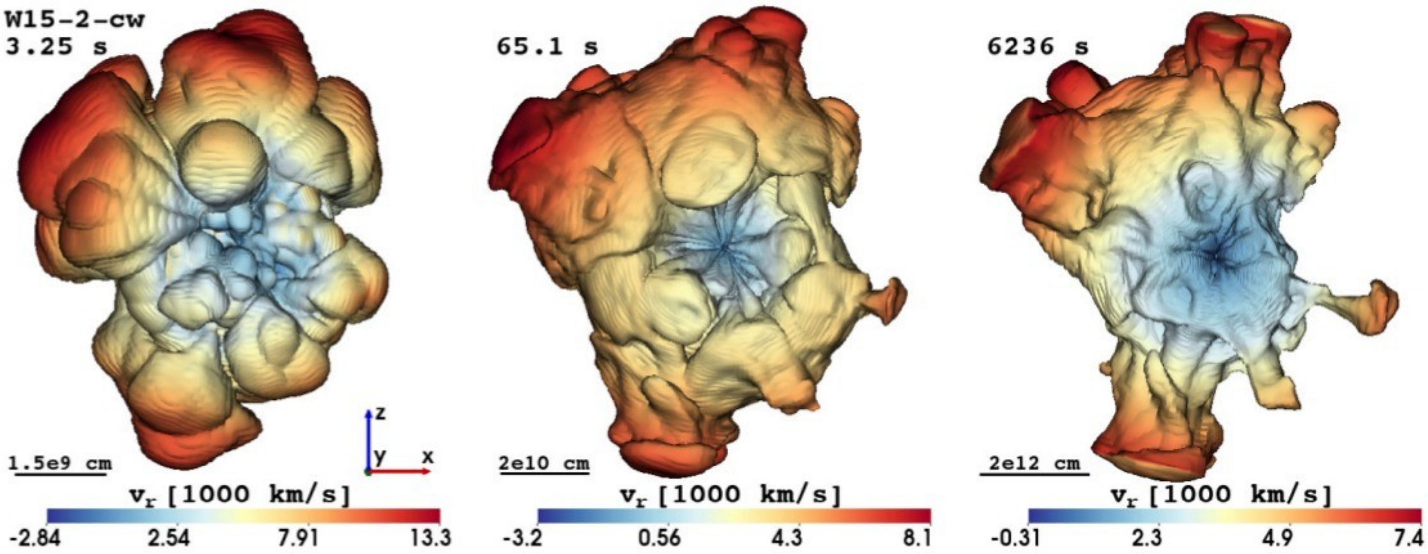
Reverse shocks from C+O/He and He/H interface lead to Rayleigh-Taylor instabilities and "fragmentation" of initial explosion asymmetries

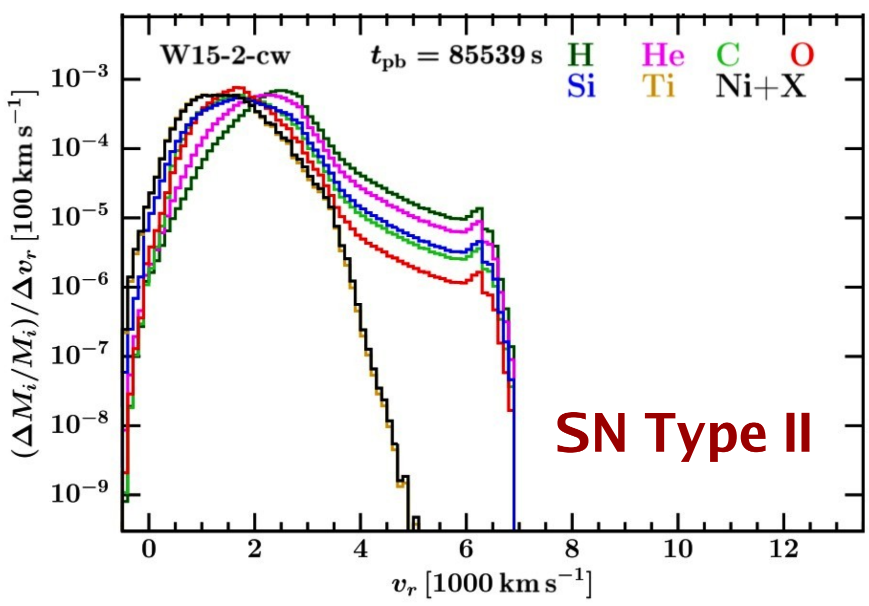


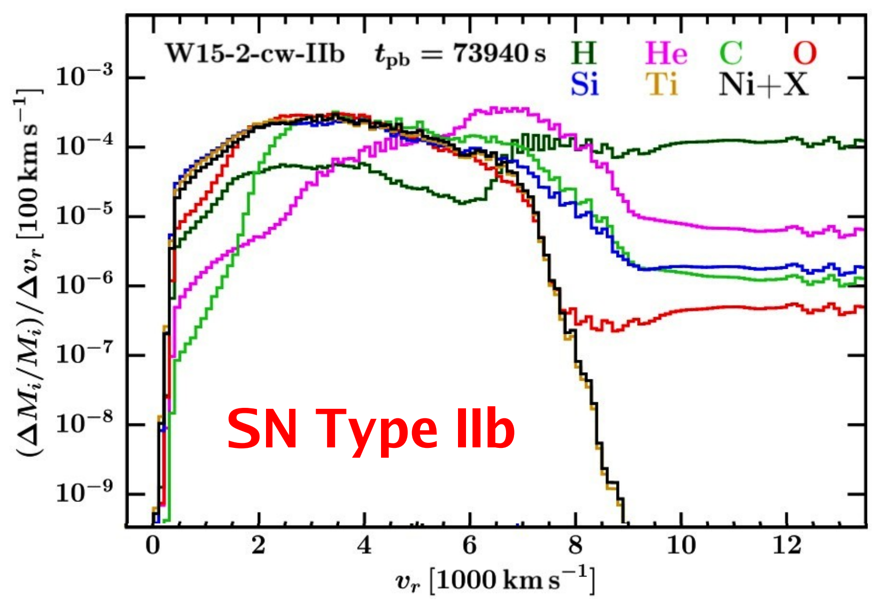


Supernovae Type IIb: Very little Hydrogen

No reverse shock from He/H interface, no further fragmentation

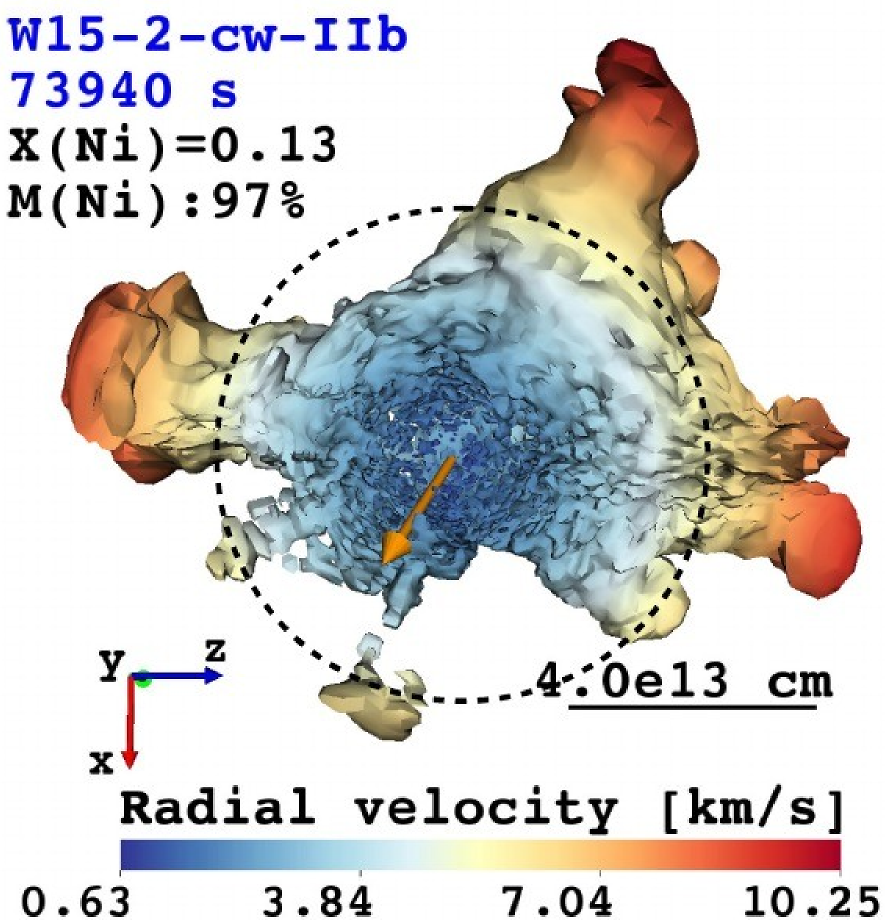


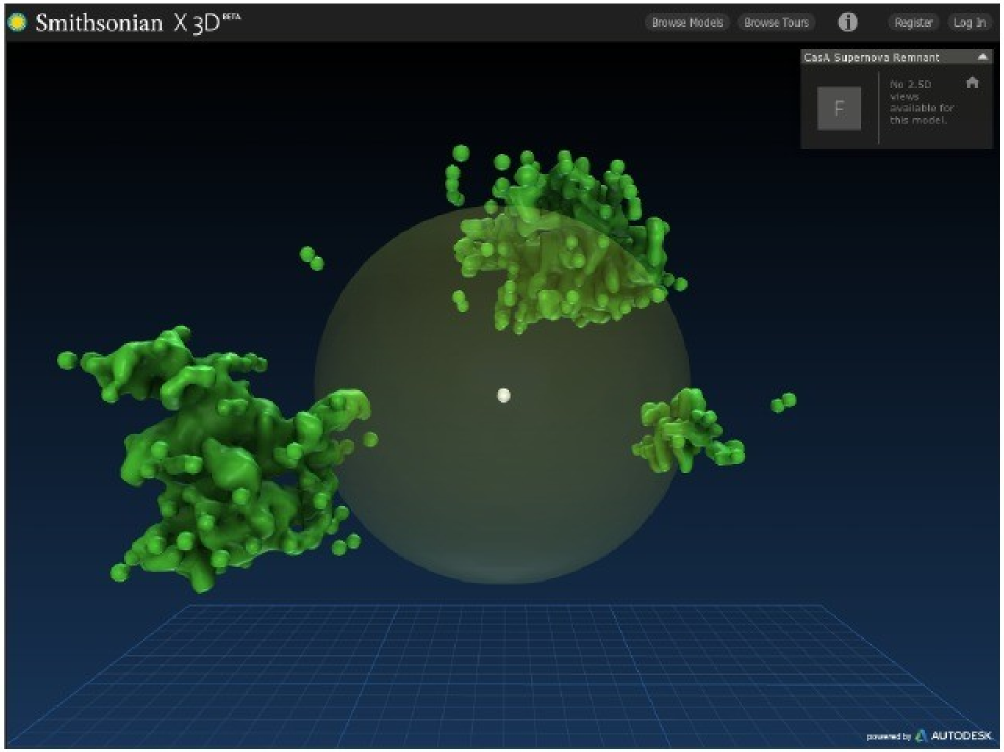




Chemical Asymmetries in CAS A Remnant

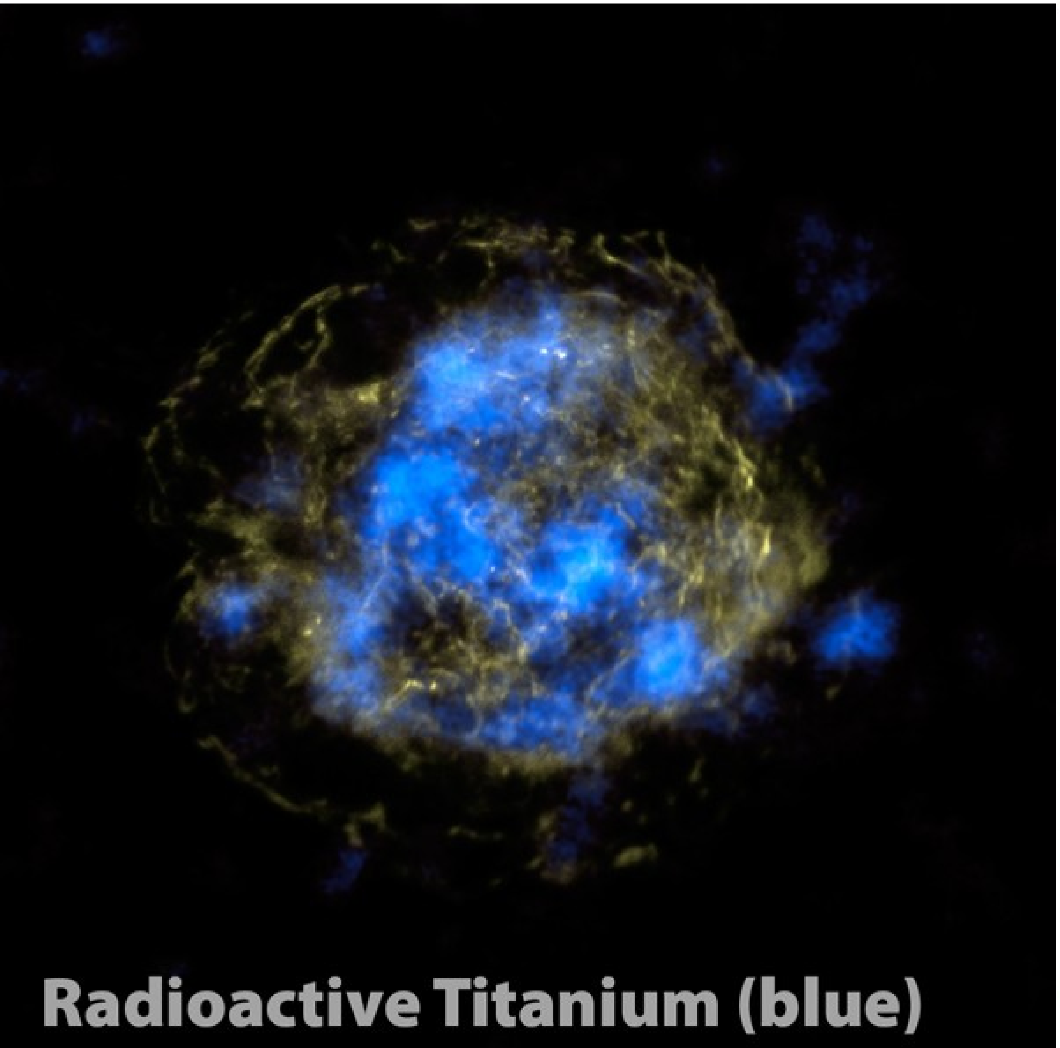
Iron in Cas A is visible in three big "fingers" in the remnant shell that is heated by reverse shock from circumstellar medium interaction.

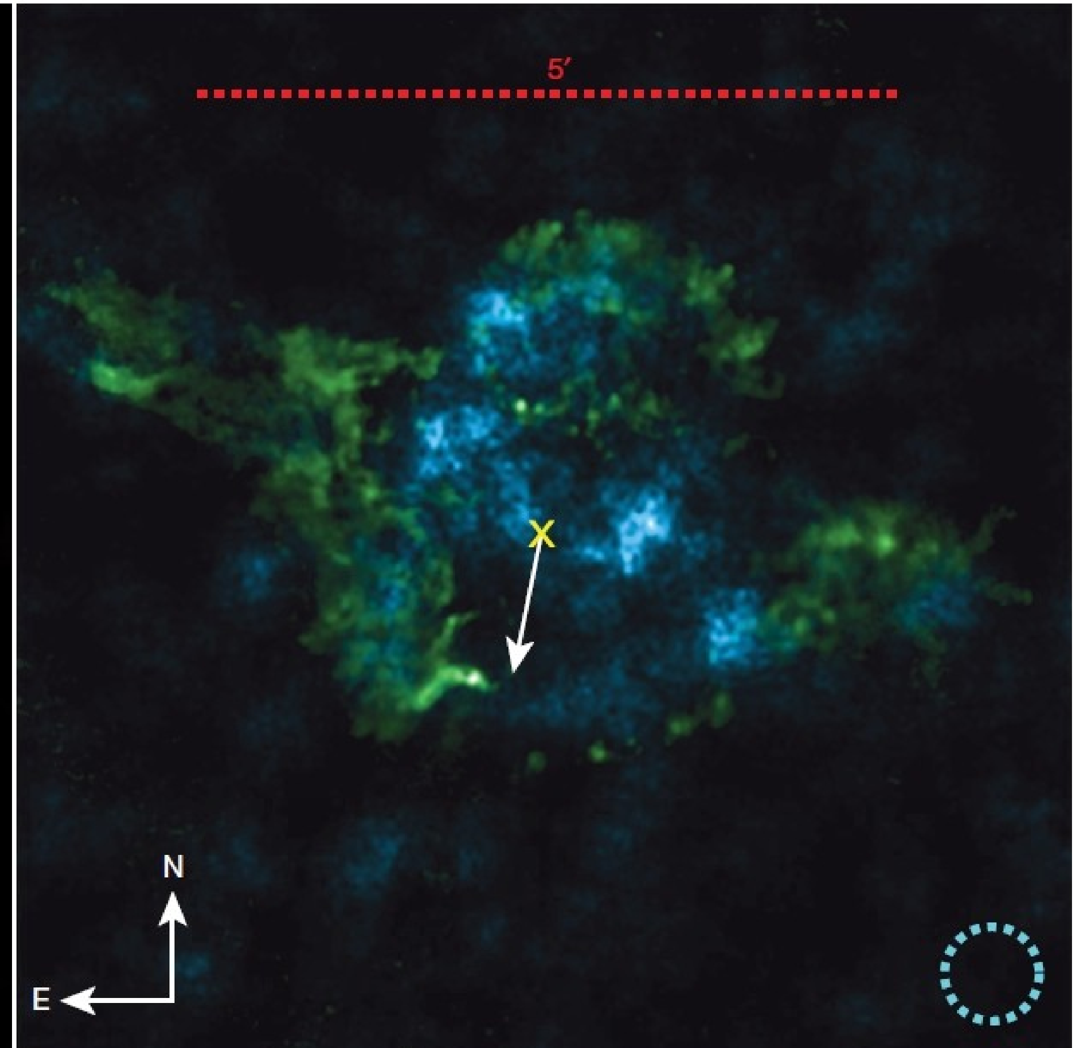




Wongwathanarat et al., ApJ 842 (2017) 13

^{44}Ti Asymmetry in the CAS A Remnant

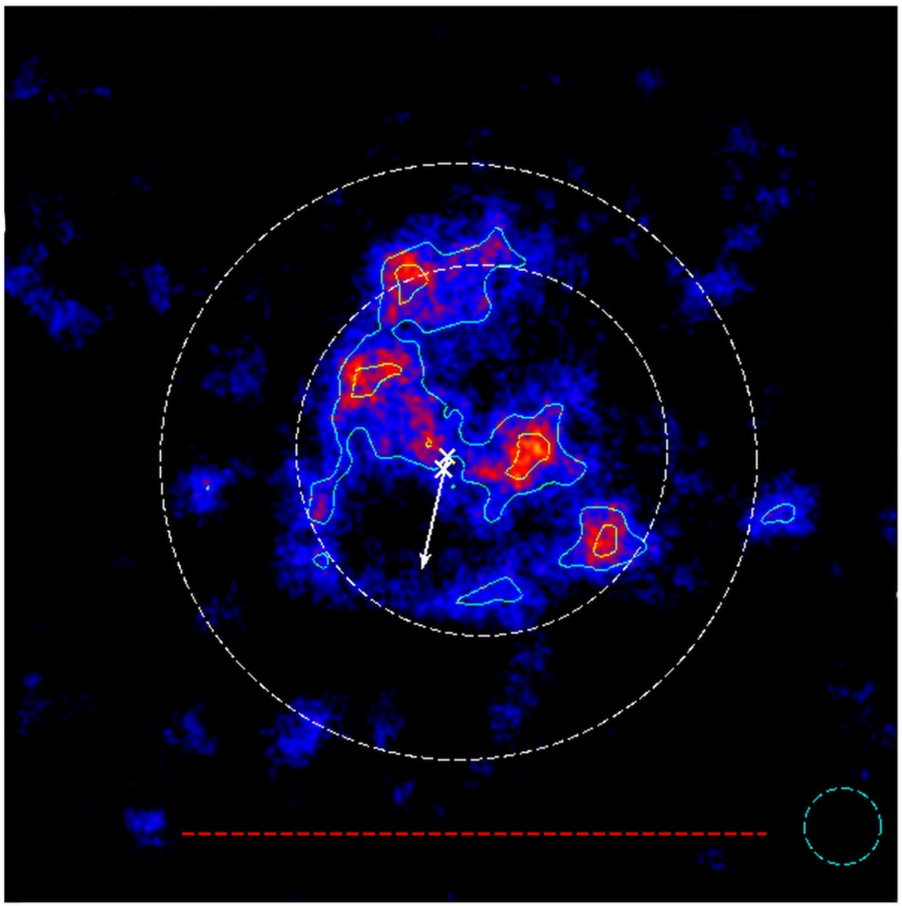




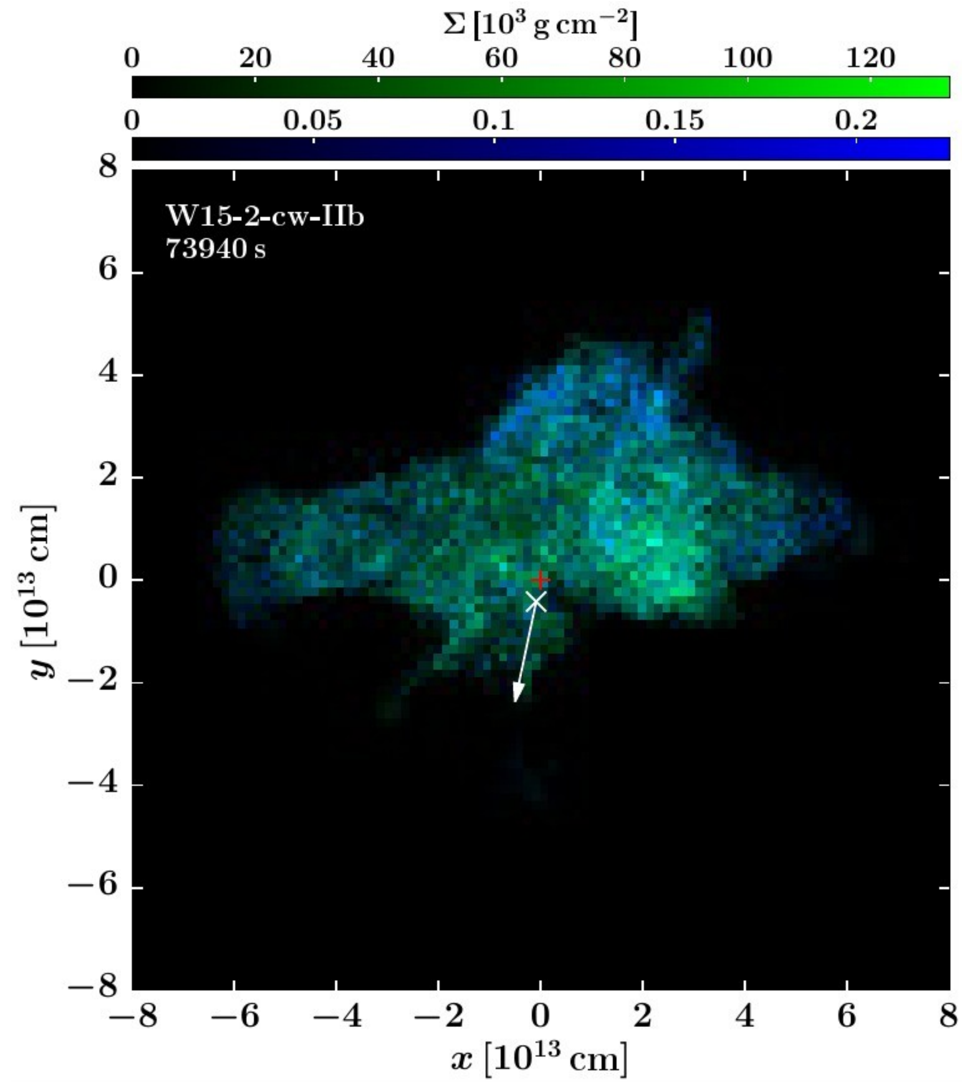
Grefenstette et al., Nature 506 (2014) 340

NuSTAR observations

Neutron Star Recoil and Nickel & 44Ti Distribution

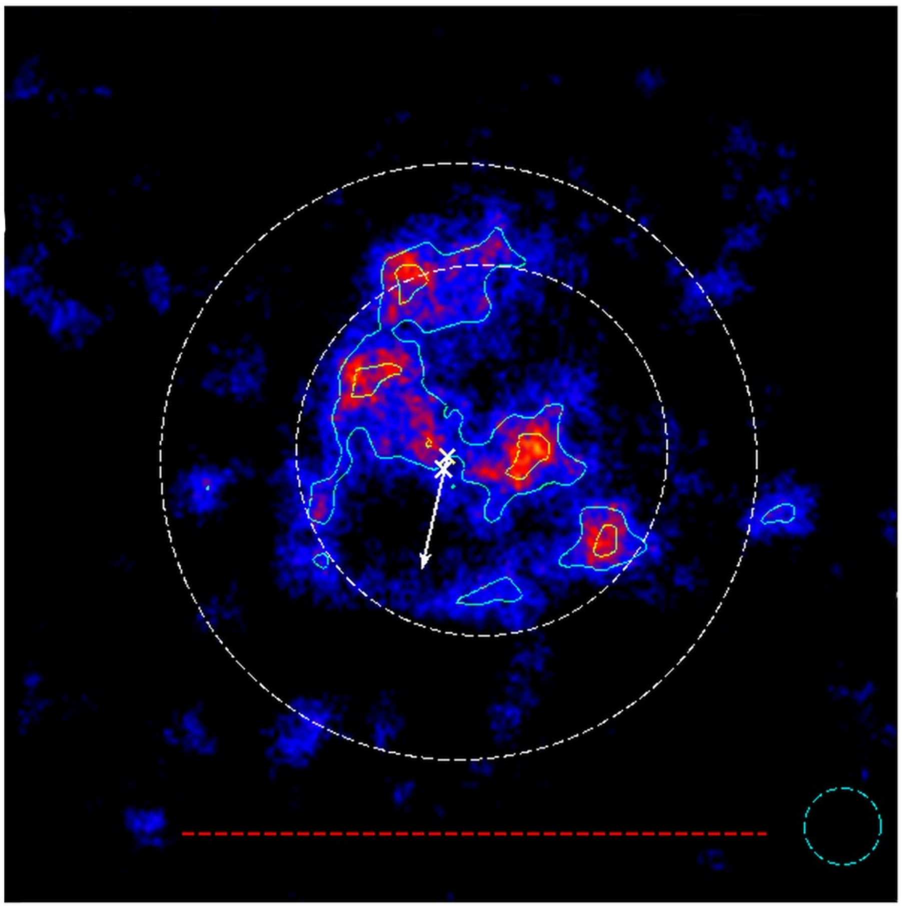


Grefenstette et al., Nature 506 (2014) 340

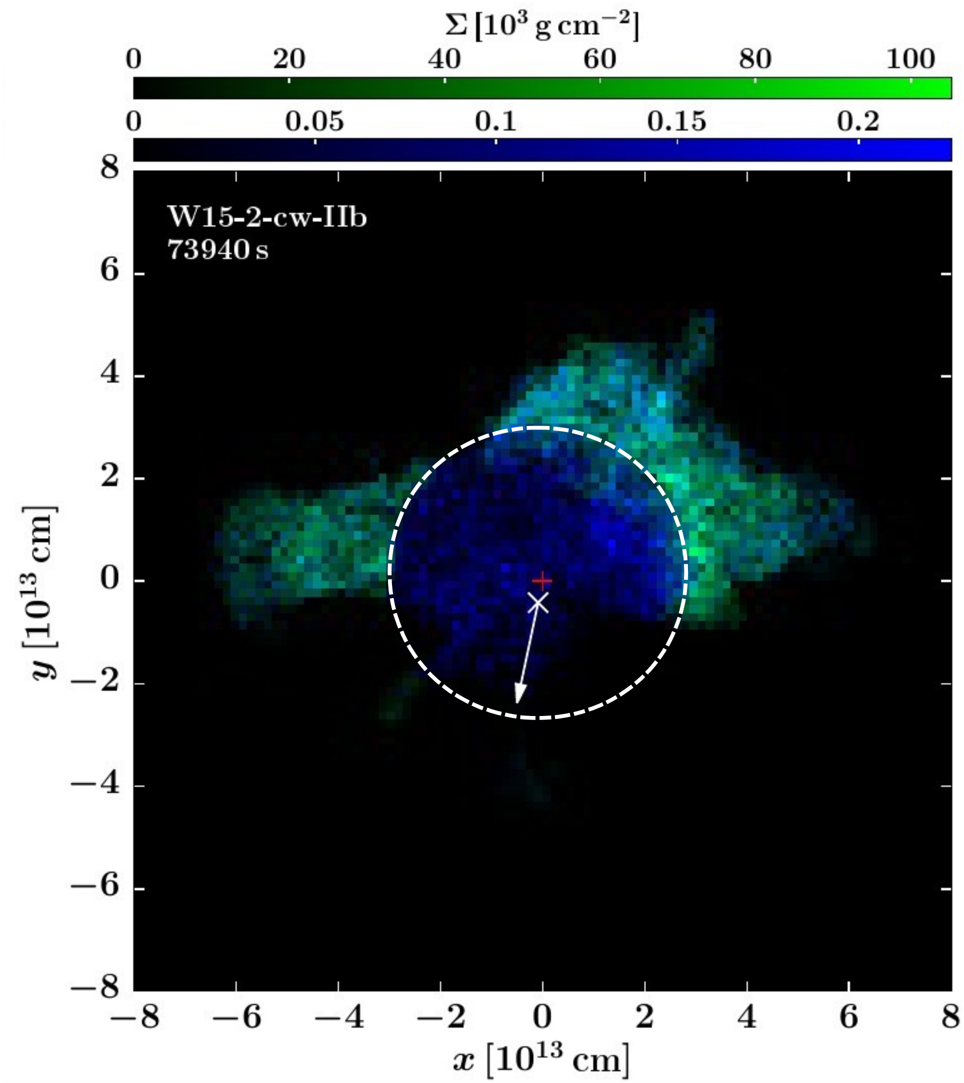


Wongwathanarat et al., ApJ 842 (2017) 13

Neutron Star Recoil and Nickel & 44Ti Distribution



Grefenstette et al., Nature 506 (2014) 340



Wongwathanarat et al., ApJ 842 (2017) 13

Observed ^{44}Ti 3D Distribution in CAS A

CAS A "Thick Disk"

Grefenstette et al., ApJ 834 (2017) 19

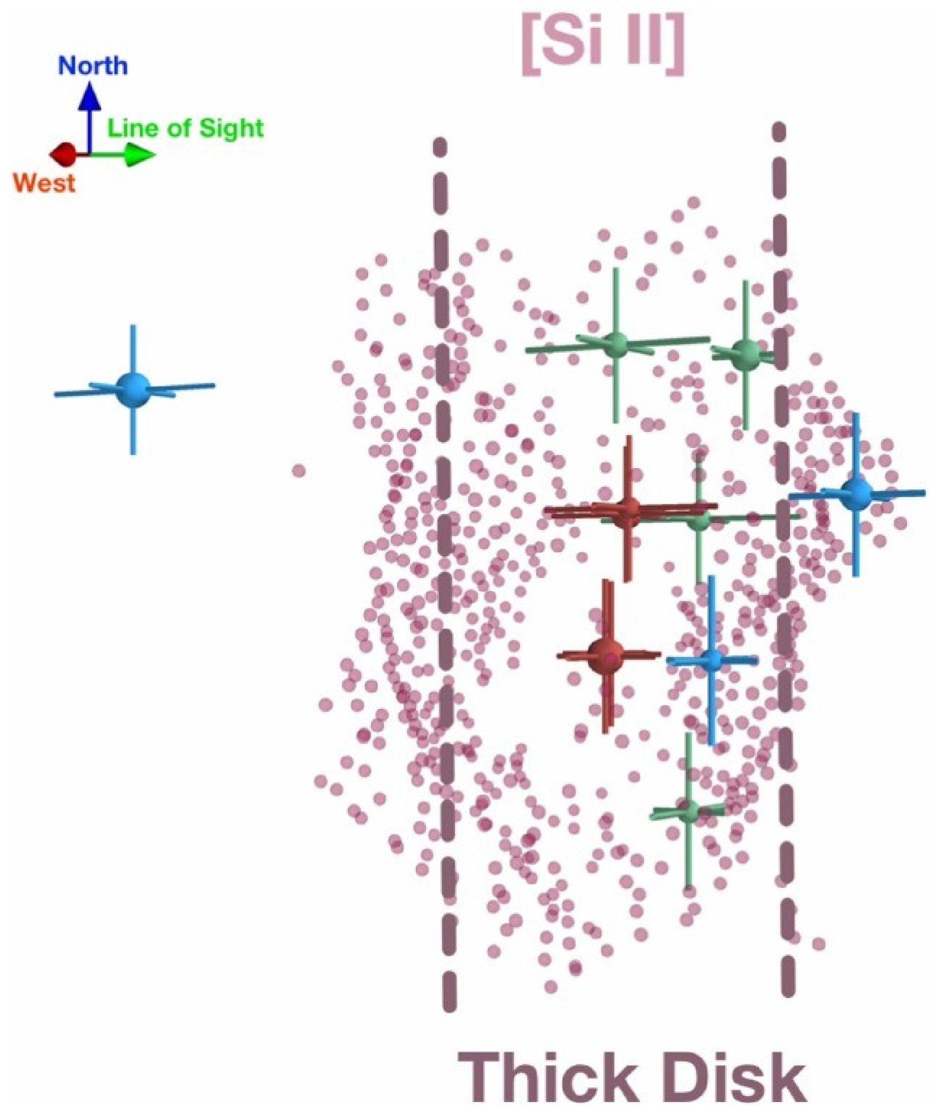
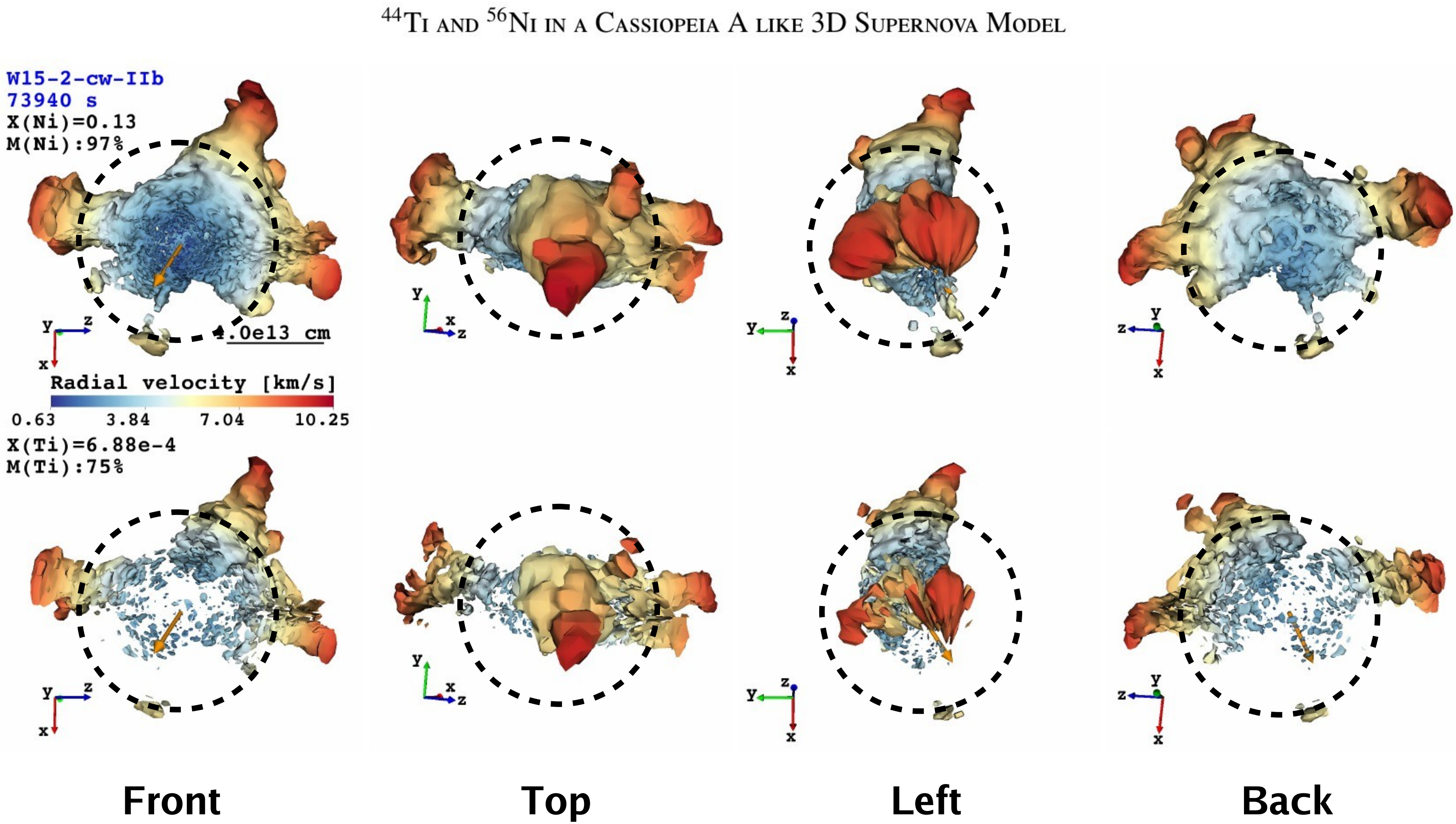


Figure 12. The 3D distribution of the observed ^{44}Ti ejecta compared with the IR [Si II] emission observed by *Spitzer* (DeLaney et al. 2010). The ^{44}Ti ejecta

Thick Disk Structure of CAS A Model



Wongwathanarat et al., ApJ 842 (2017) 13

Thick Disk of CAS A Remnant and NS Kick

CAS A "Thick Disk"

Grefenstette et al., ApJ 834 (2017) 19

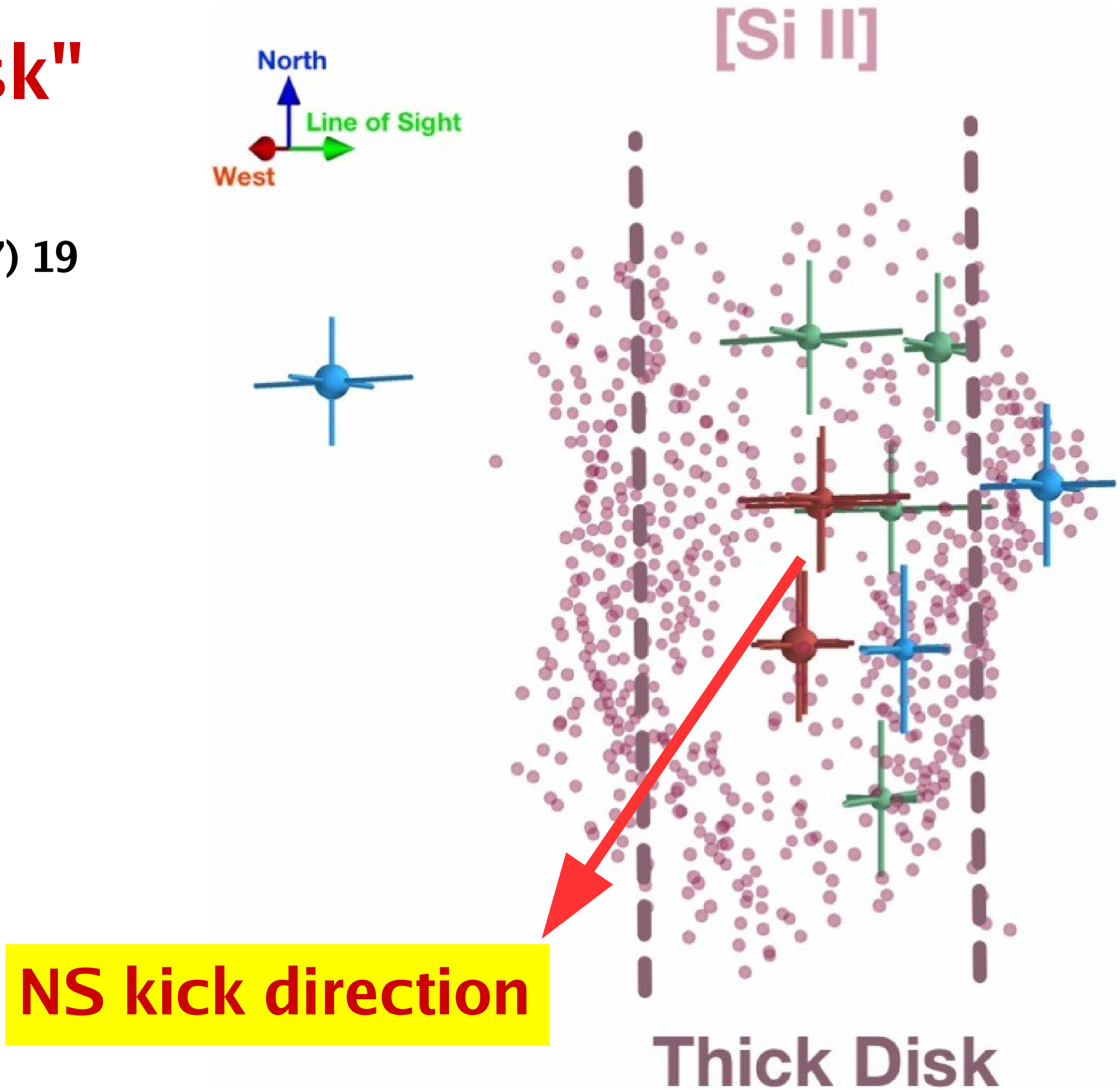
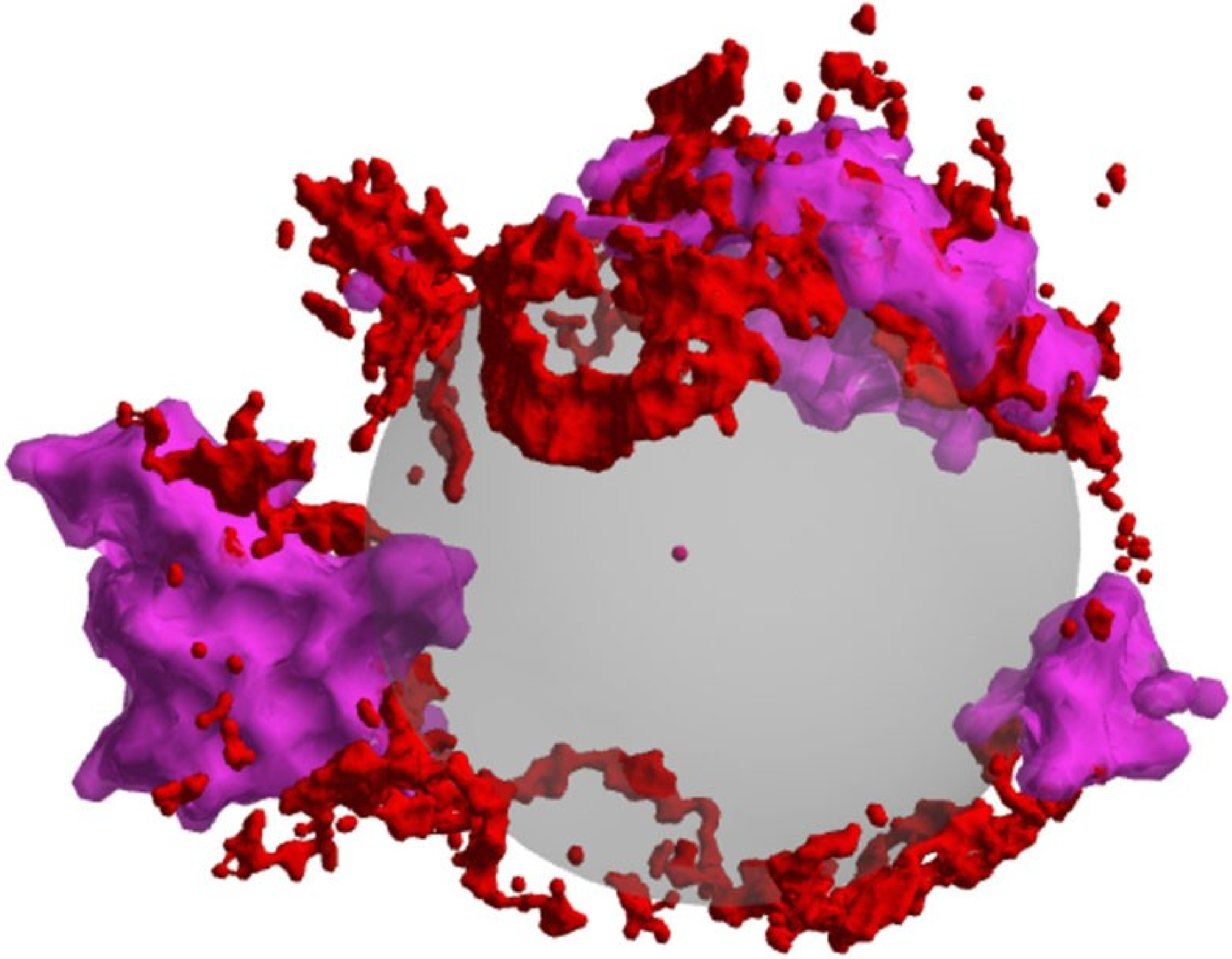


Figure 12. The 3D distribution of the observed ^{44}Ti ejecta compared with the IR [Si II] emission observed by *Spitzer* (DeLaney et al. 2010). The ^{44}Ti ejecta

Intermediate Mass Element Asymmetries in CAS A Remnant

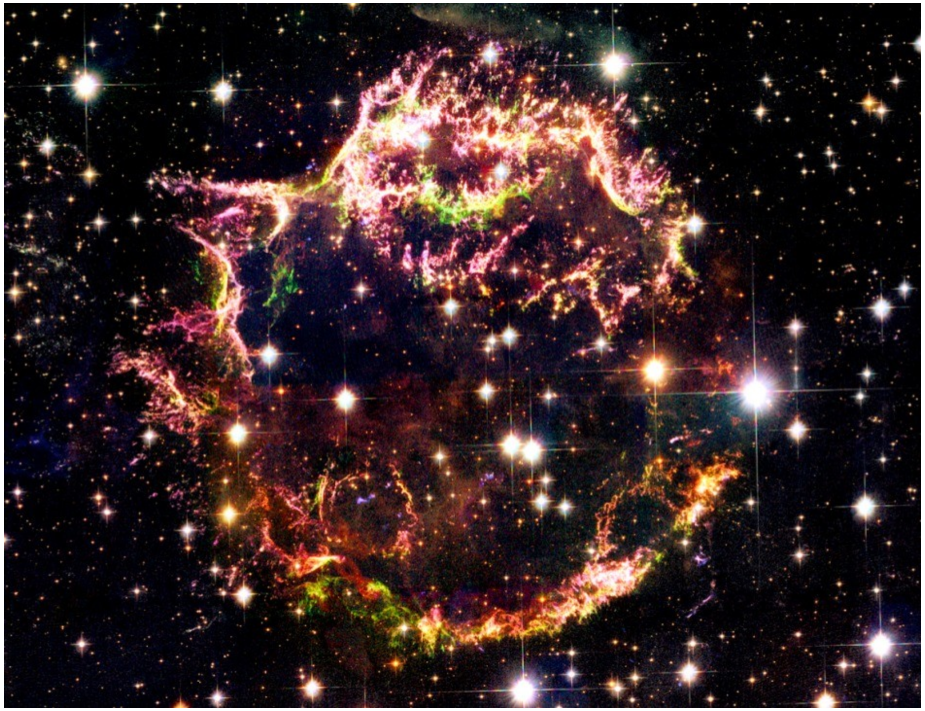


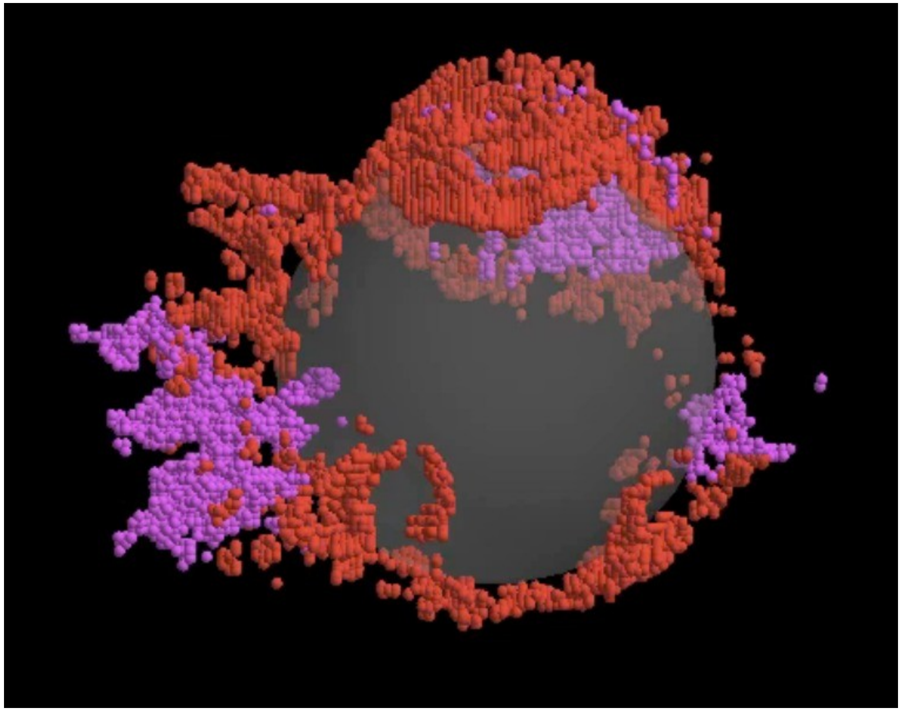
Red: Ar, Ne, and O (optical)
Purple: Iron (X-ray)

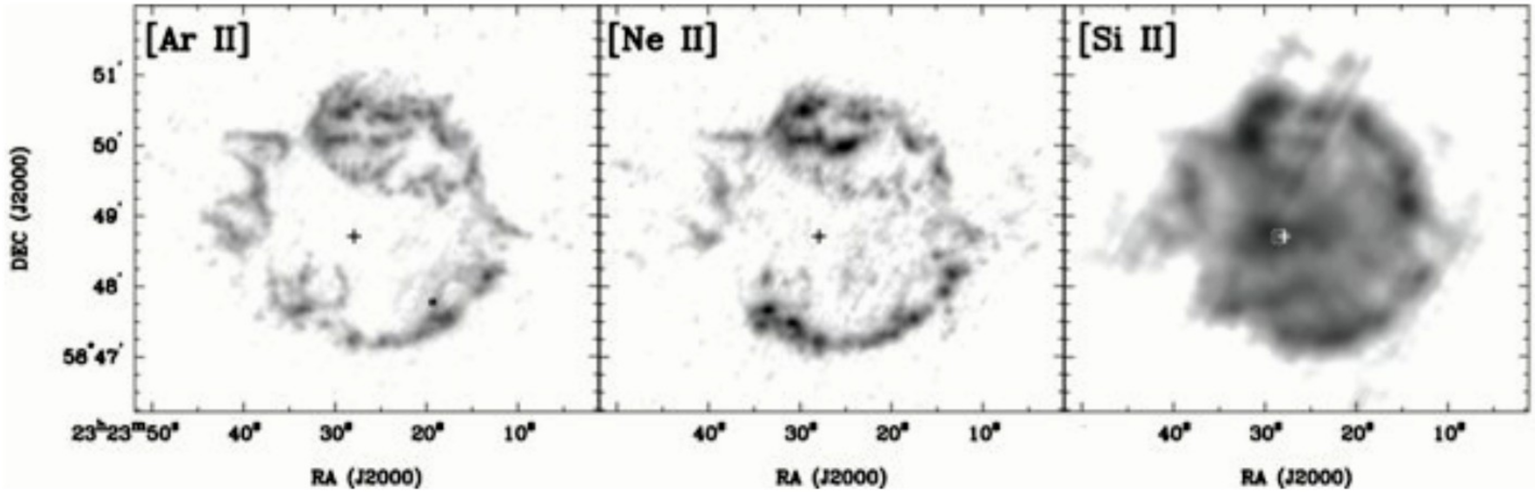
Image: Robert Fesen and Dan Milisavljevic, using iron data from DeLaney et al. (2010)

Intermediate Mass Element Asymmetries in CAS A Remnant

Reed et al (1995) and Lawrence et al. (1995) determined optical emission structure



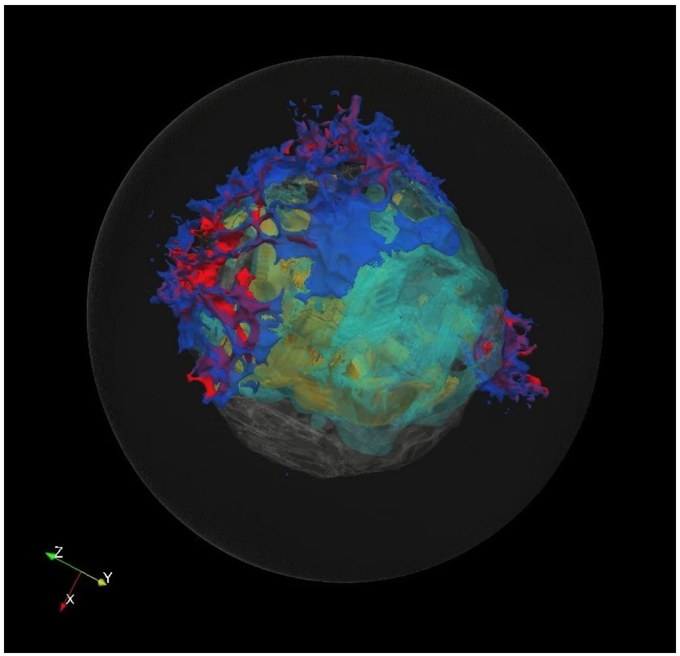




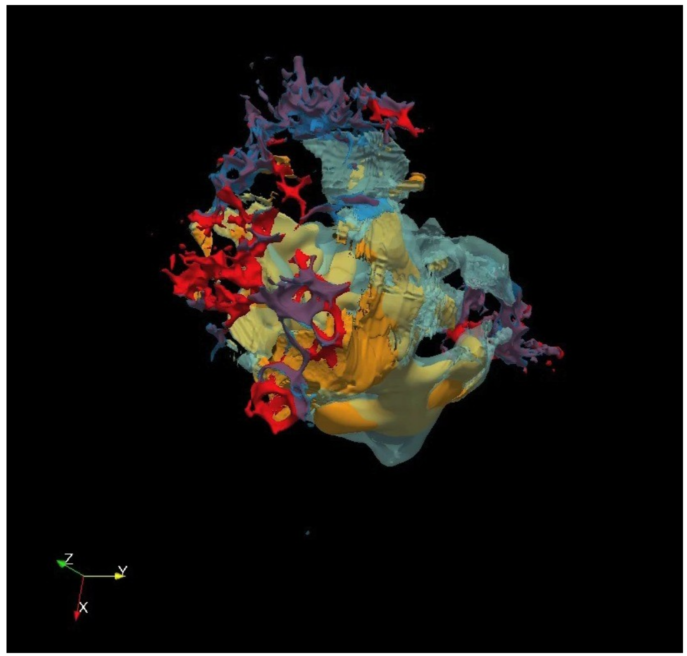
Evolution of 3D Supernova Model of CAS A into the Remant Stage

Morphology of the remnant and distribution of chemical elements is affected by Rayleigh-Taylor instabilities growing between forward shock and reverse shock

CAS A at 350 years

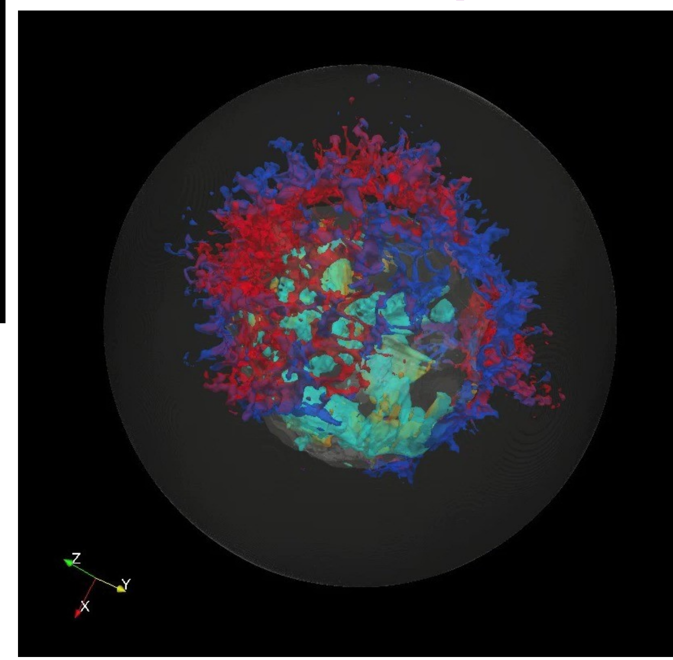


red: shocked Fe; orange: unshocked Fe
blue: shocked Si; light blue: unshocked Si



red: shocked Fe; orange: unshocked Fe
blue: shocked Ti; light blue: unshocked Ti

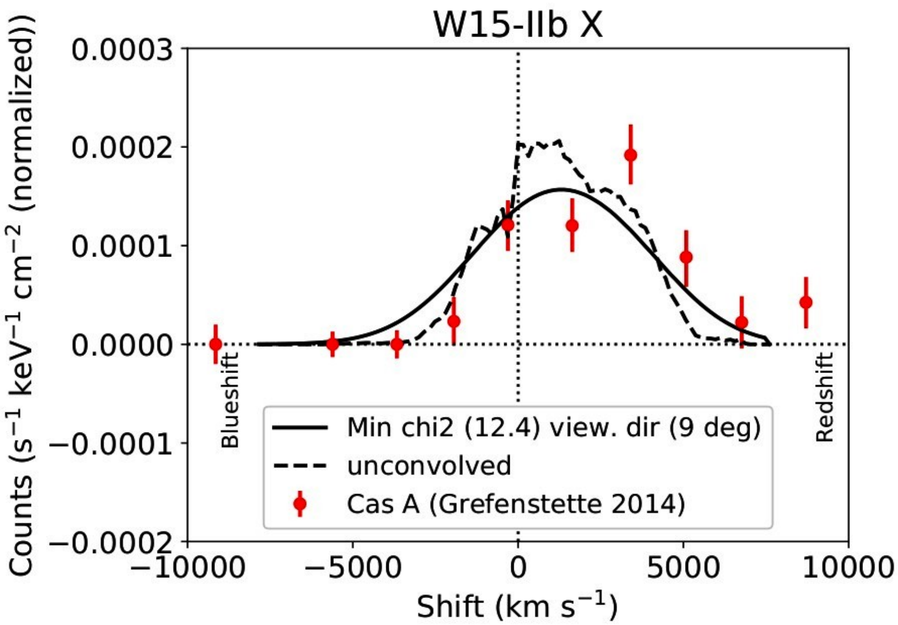
CAS A at 1500 years



red: shocked Fe; orange: unshocked Fe
blue: shocked Si; light blue: unshocked Si

Ongoing project: Salvatore Orlando, Marco Miceli, Shigehiro Nagataki, Masaomi Ono, Annop Wongwathanarat, HTJ

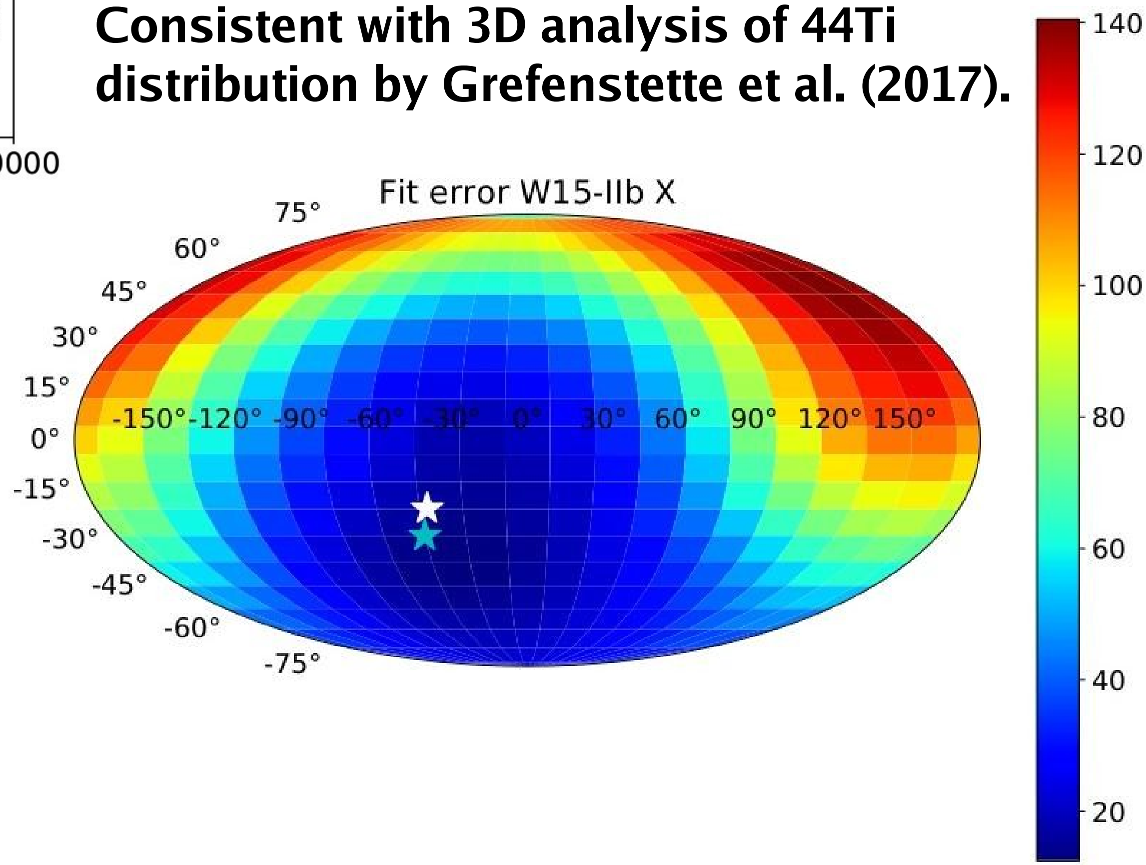
Cas A: Gamma-Ray Line Profiles of ^{44}Ti



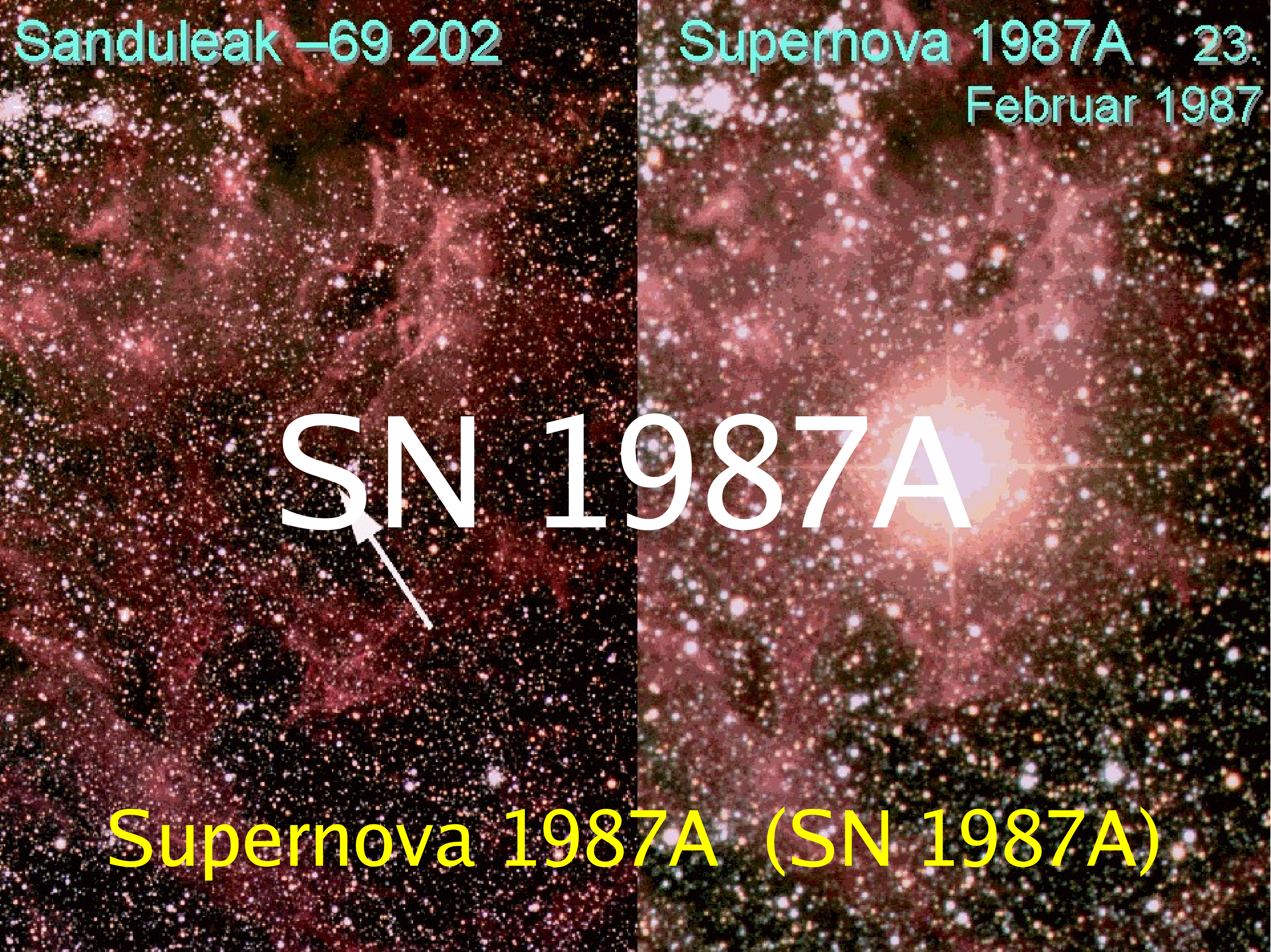
NS in Cas A has high kick with small inclination angle (within <40–5 0 degrees) to line of sight.

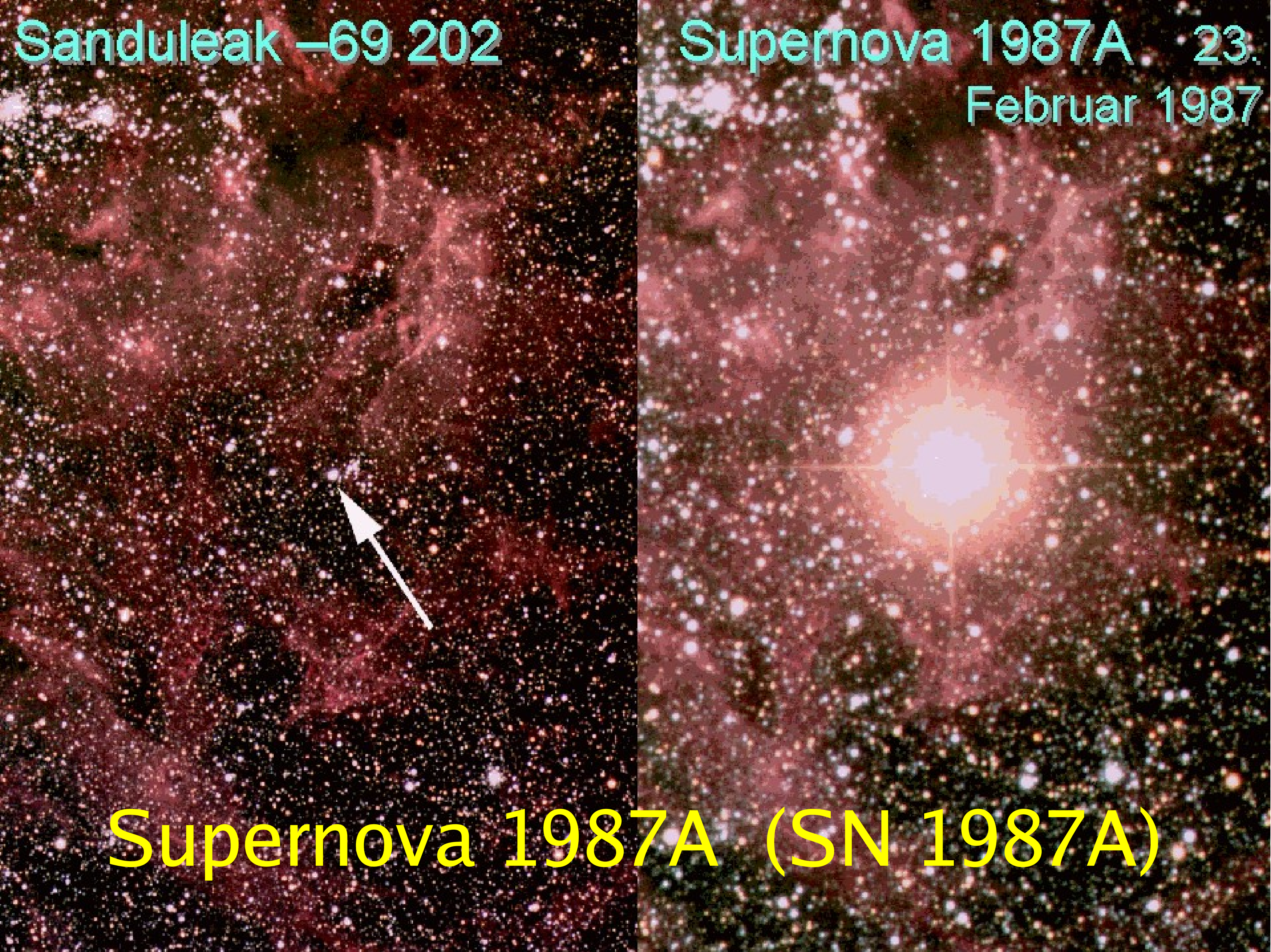
Consistent with 3D analysis of 44Ti distribution by Grefenstette et al. (2017).

Line centroid of 44Ti decay line strongly redshifted.

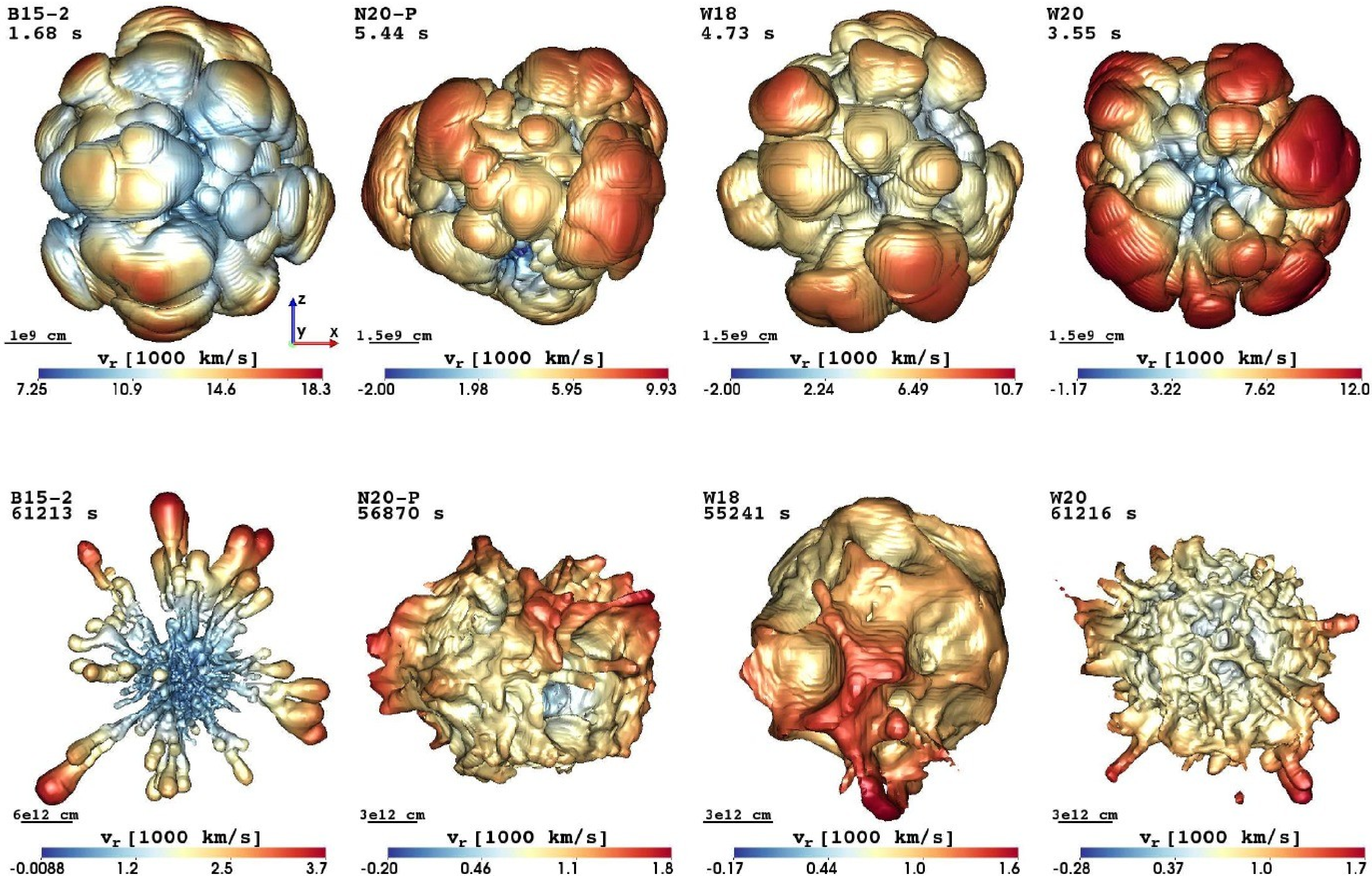


Jerkstrand et al., in preparation


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

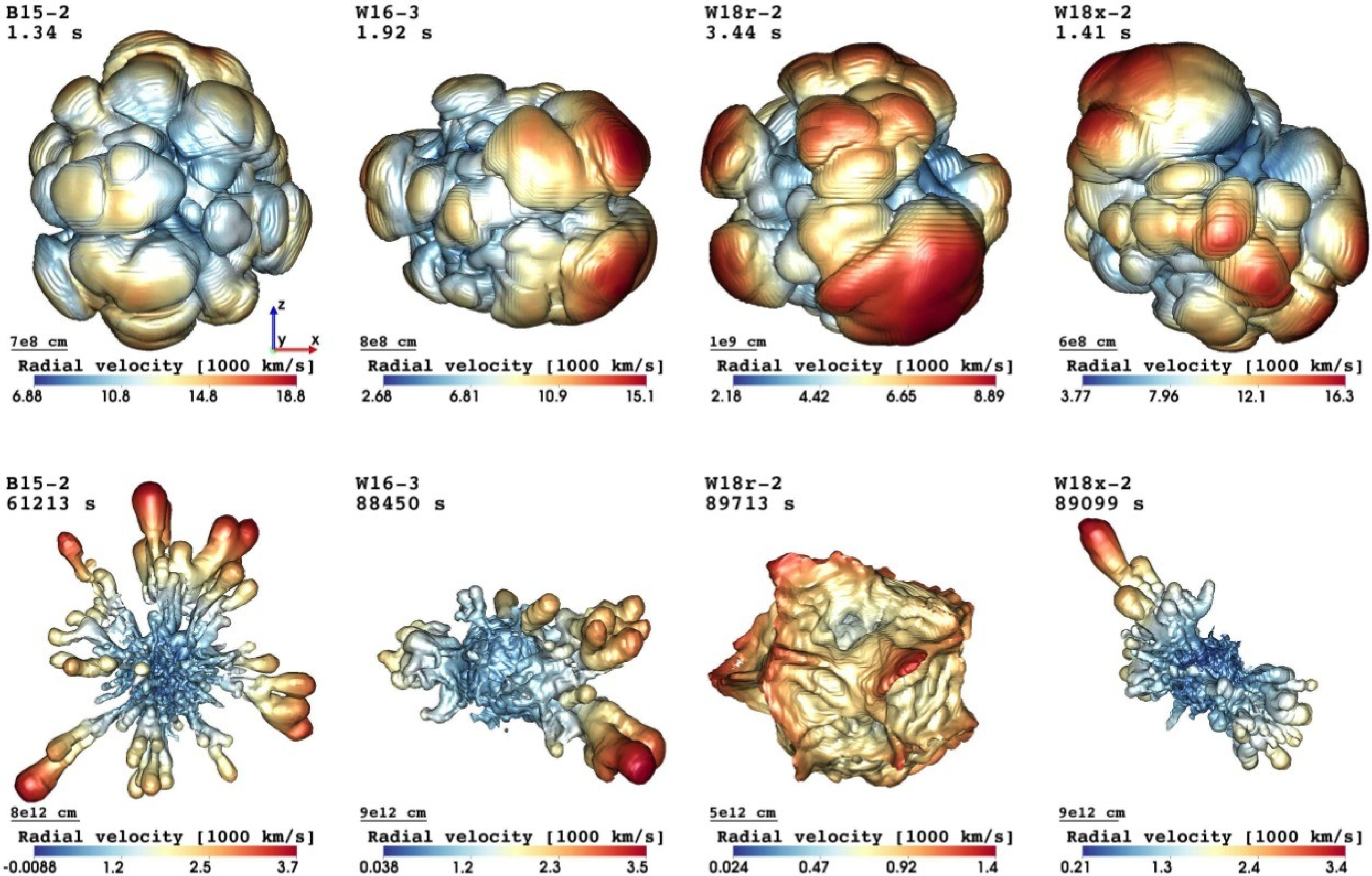

Sanduleak –69 202
Supernova 1987A 23. Februar 1987
Supernova 1987A (SN 1987A)

SN1987A Models: 3D Morphologies



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

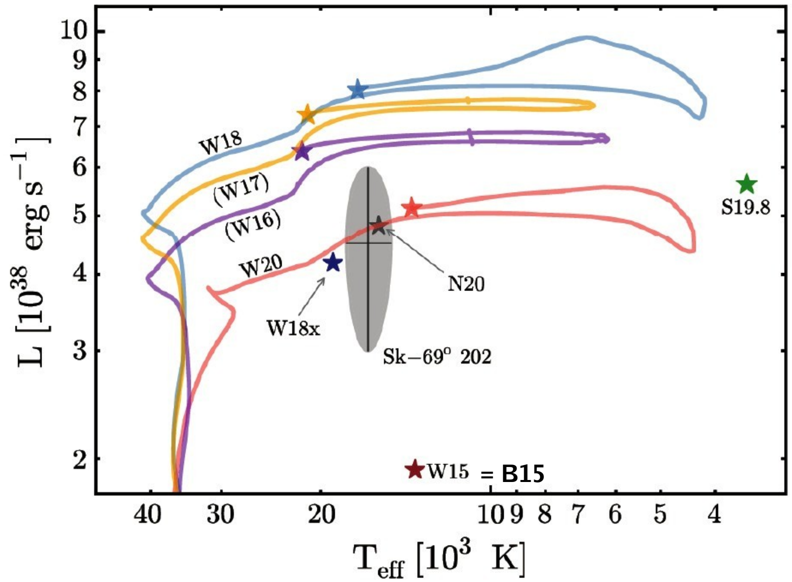
SN1987A Models: 3D Morphologies



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

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

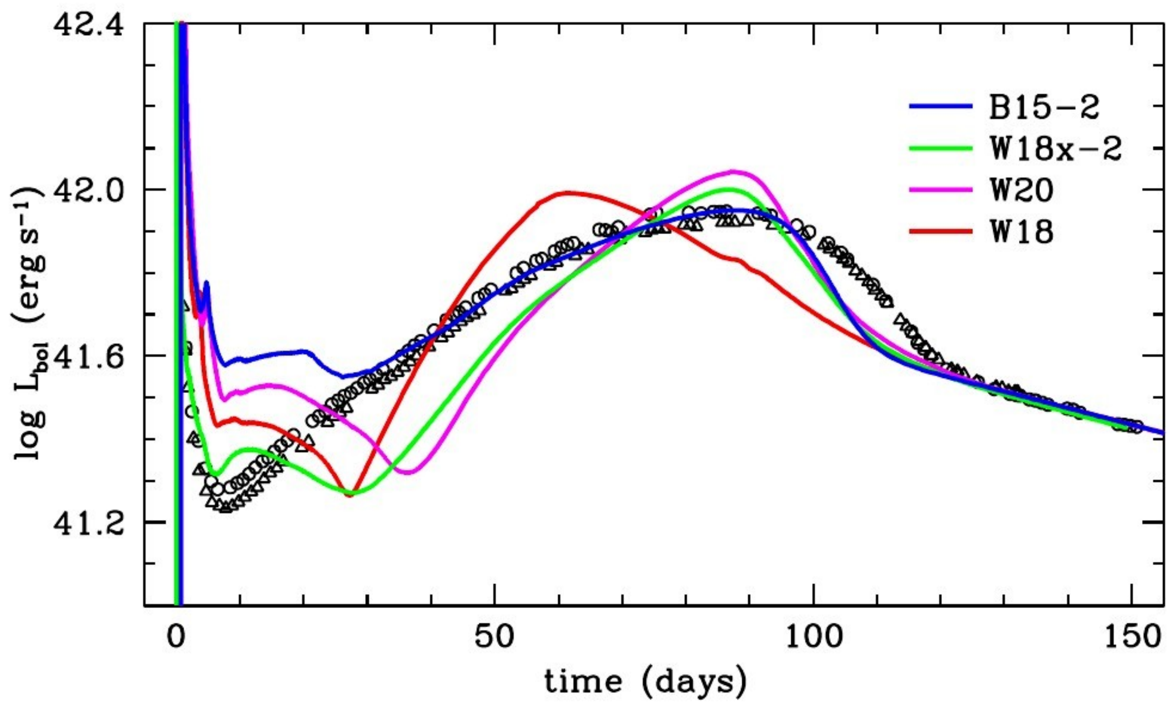
Hertzsprung-Russell Diagram for SN 1987A Progenitors.
Single Star Scenario



Sukhbold et al. (2016)

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

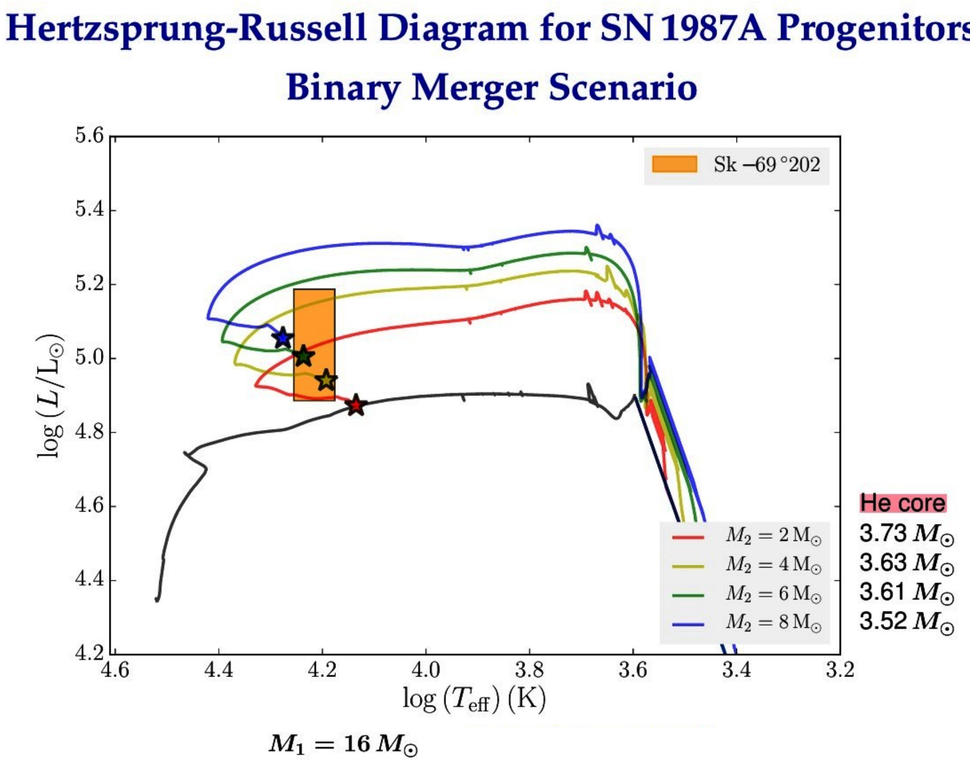
Bolometric Light Curves



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

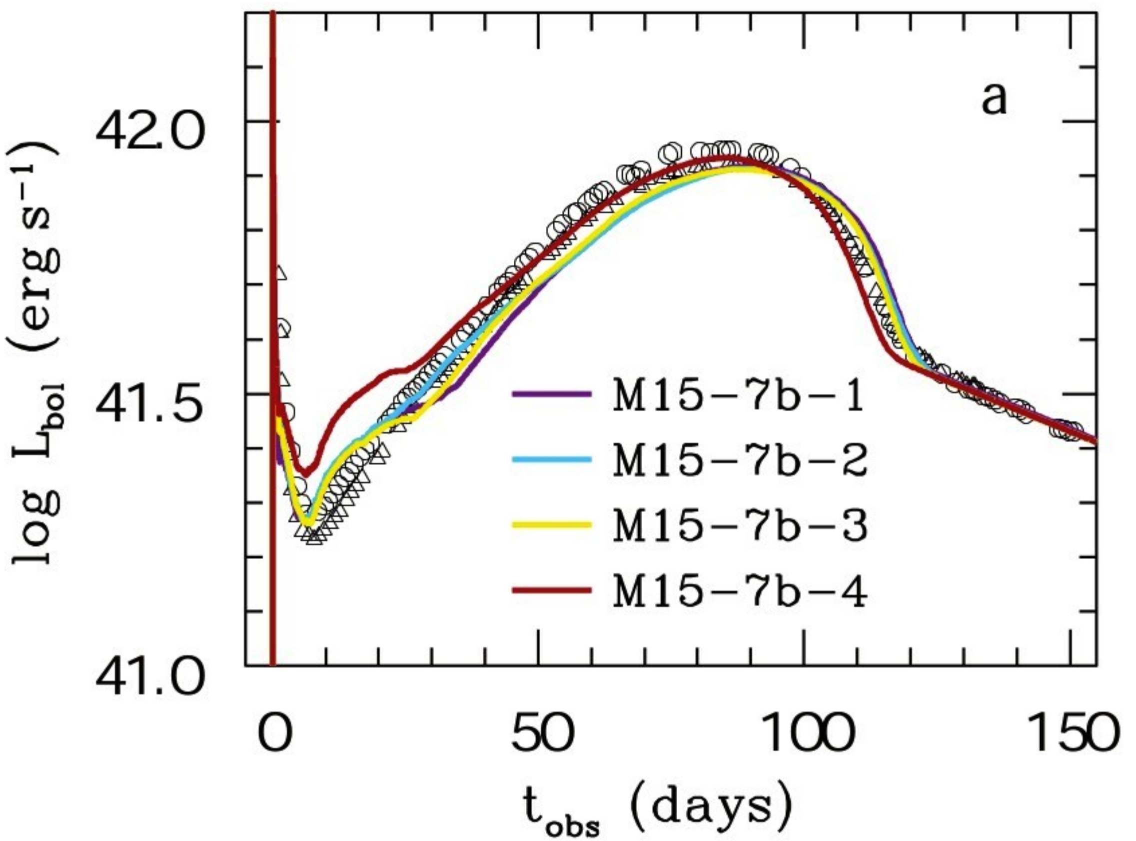
Self-consistent 3D simulations of explosions by neutrino heating do not produce sufficient outward mixing of Ni and inward mixing of H in most progenitors.

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



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

Utrobin et al., in preparation



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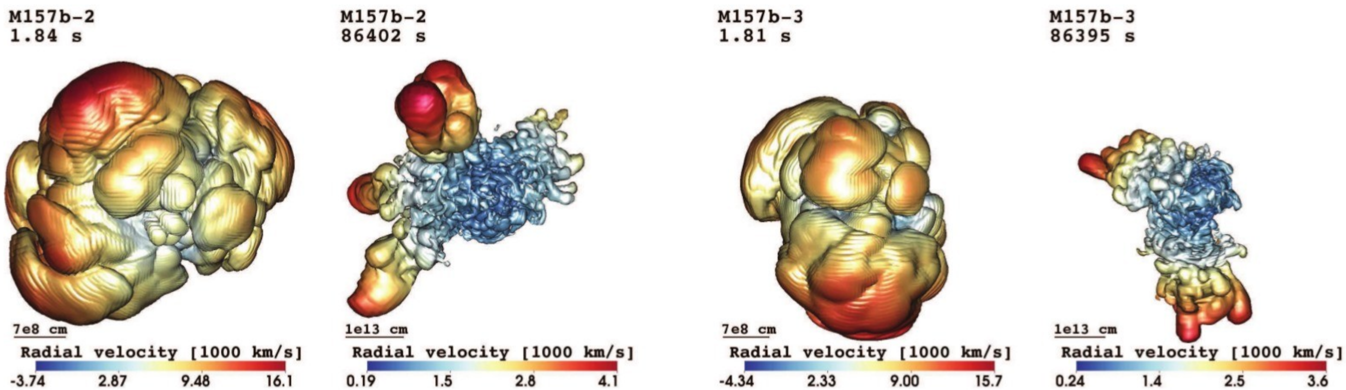
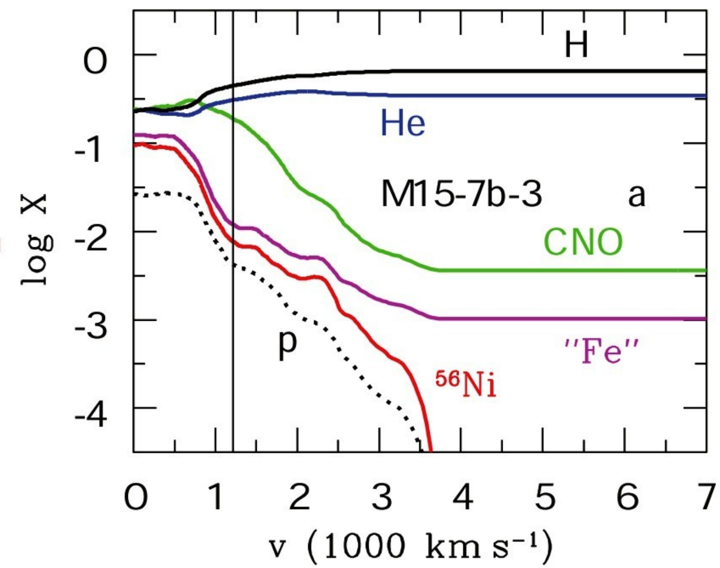
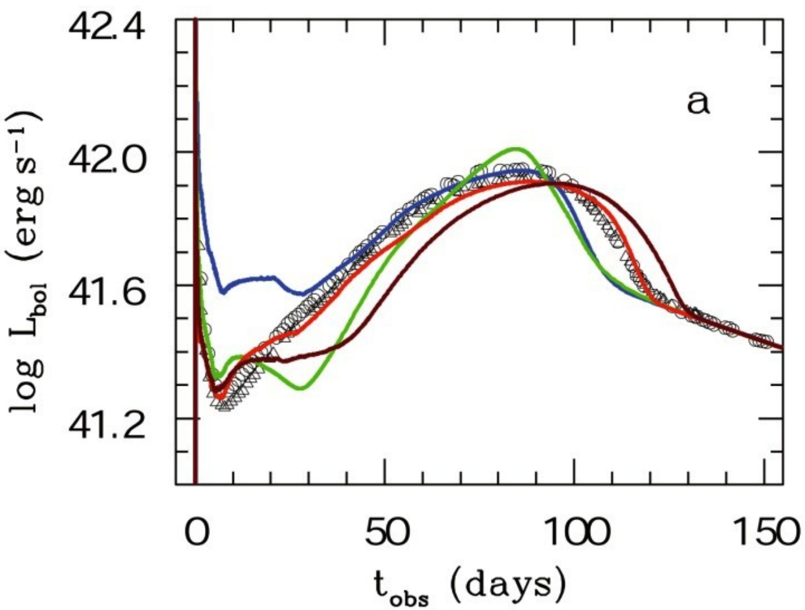
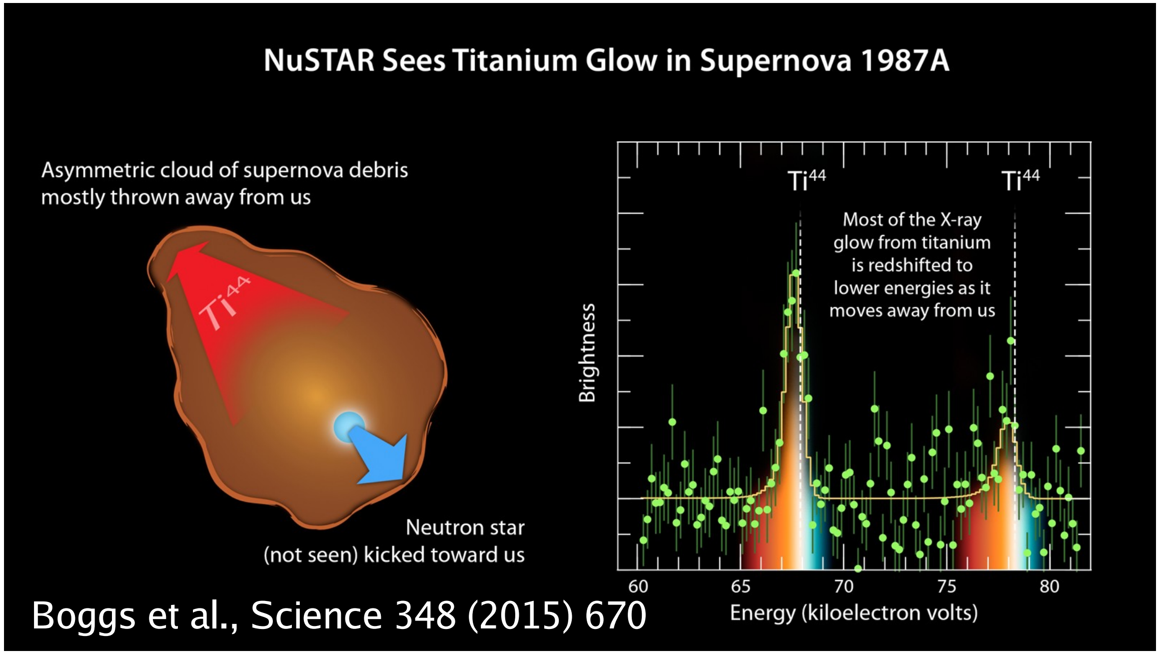






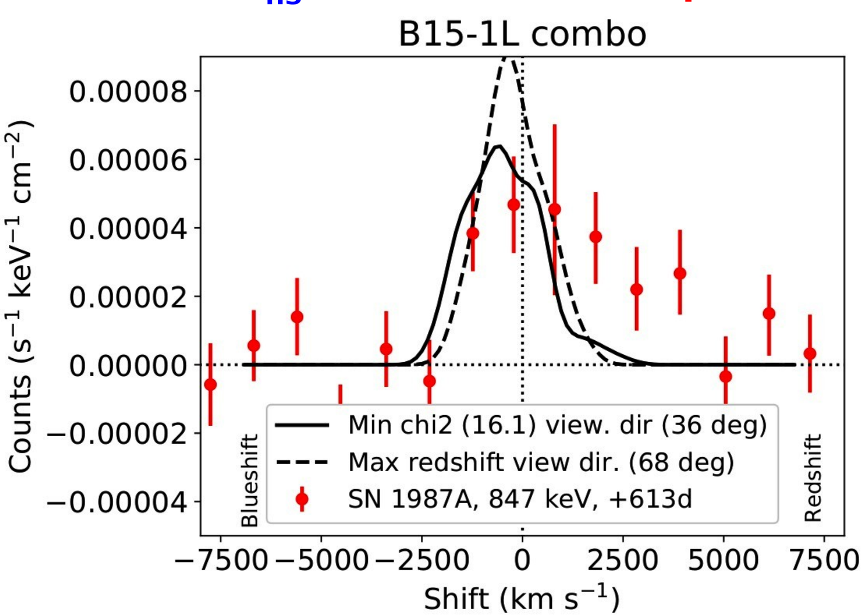
Model	M_{NS}	M_{CO}^{core}	M_{He}^{core}	M_{ej}	E_{exp}	M_{Ni}^{f}	v_{Ni}^{bulk}	v_{H}^{min}	ΔM_{H}^{2000}	ΔM_{O}	Remark
		($M_\odot$)			(B)	(10^{-2} $M_\odot$)	(km s^{-1})		($M_\odot$)		
B15-2	1.25	1.64	4.05	14.20	1.40	7.25	3370	28	0.922	0.16	single-star
W18x-2	1.52	2.12	5.13	16.03	1.45	7.55	2460	147	0.847	0.36	single-star
M15-7b-3	1.58	2.48	2.90	19.46	1.48	7.29	3024	29	2.93	0.83	binary-merger
M15-8b-1	1.32	2.50	2.95	20.73	1.62	7.41	1863	27	2.93	0.96	binary-merger
Constraint						≈7.5	∼3000	≤700	∼2.2	0.7–2.0	

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

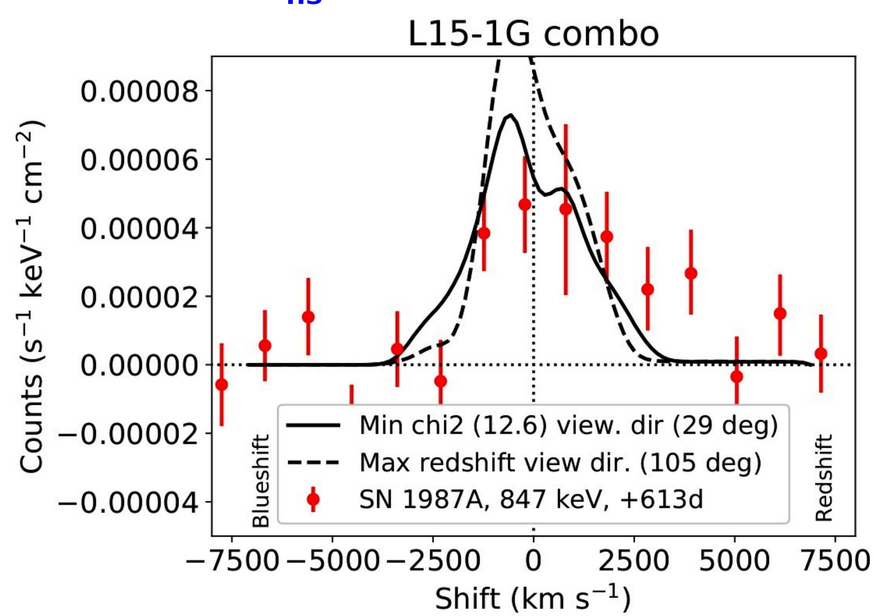


Boggs et al. (2015): Redshifted ^{44}Ti lines suggest that NS in SN 1987A is likely to have fairly high kick towards us.

v_{ns} ~100 km/s: Incompatible



v_{ns} ~300 km/s: Better fit!

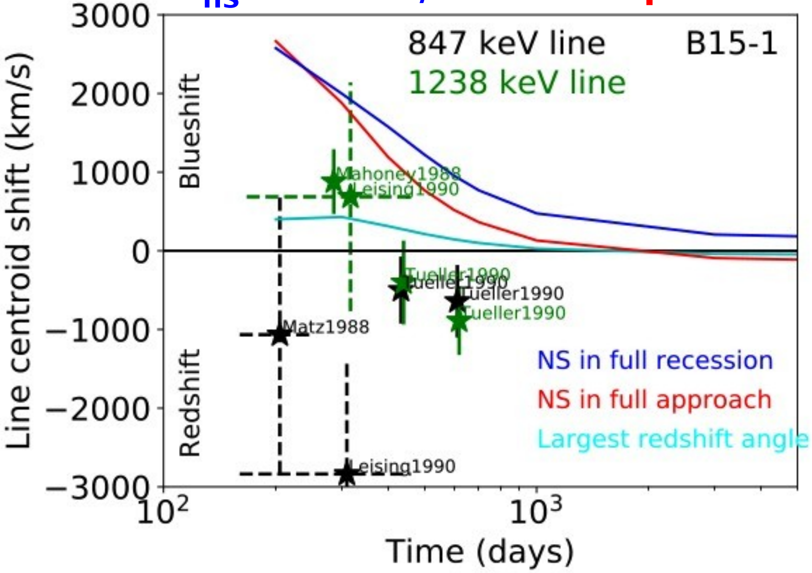


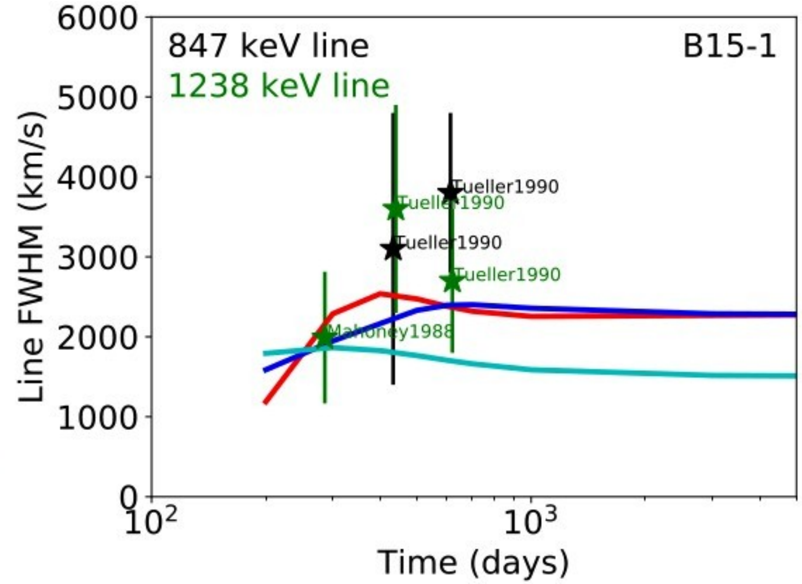
Jerkstrand et al., in preparation

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

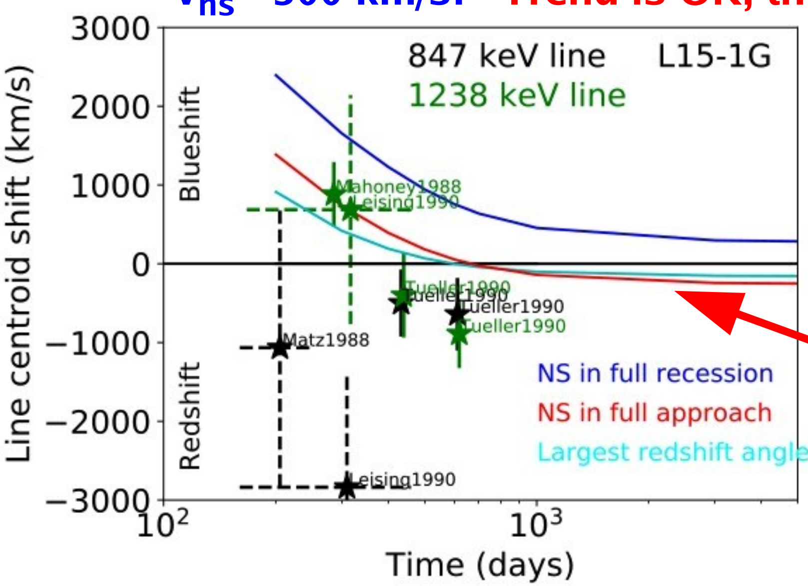
NS in SN 1987A is likely to have fairly high kick velocity towards us.

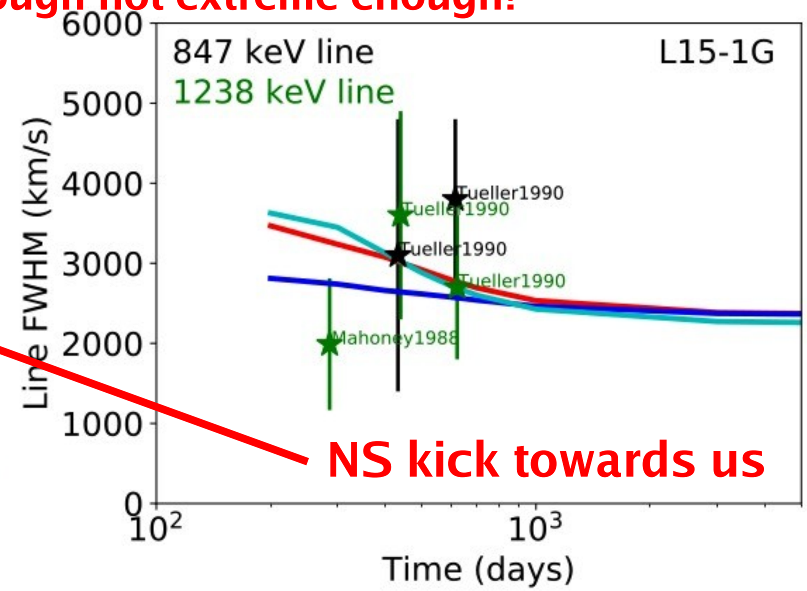
v_{ns} ~100 km/s: Incompatible





v_{ns} ~300 km/s: Trend is OK, though not extreme enough!



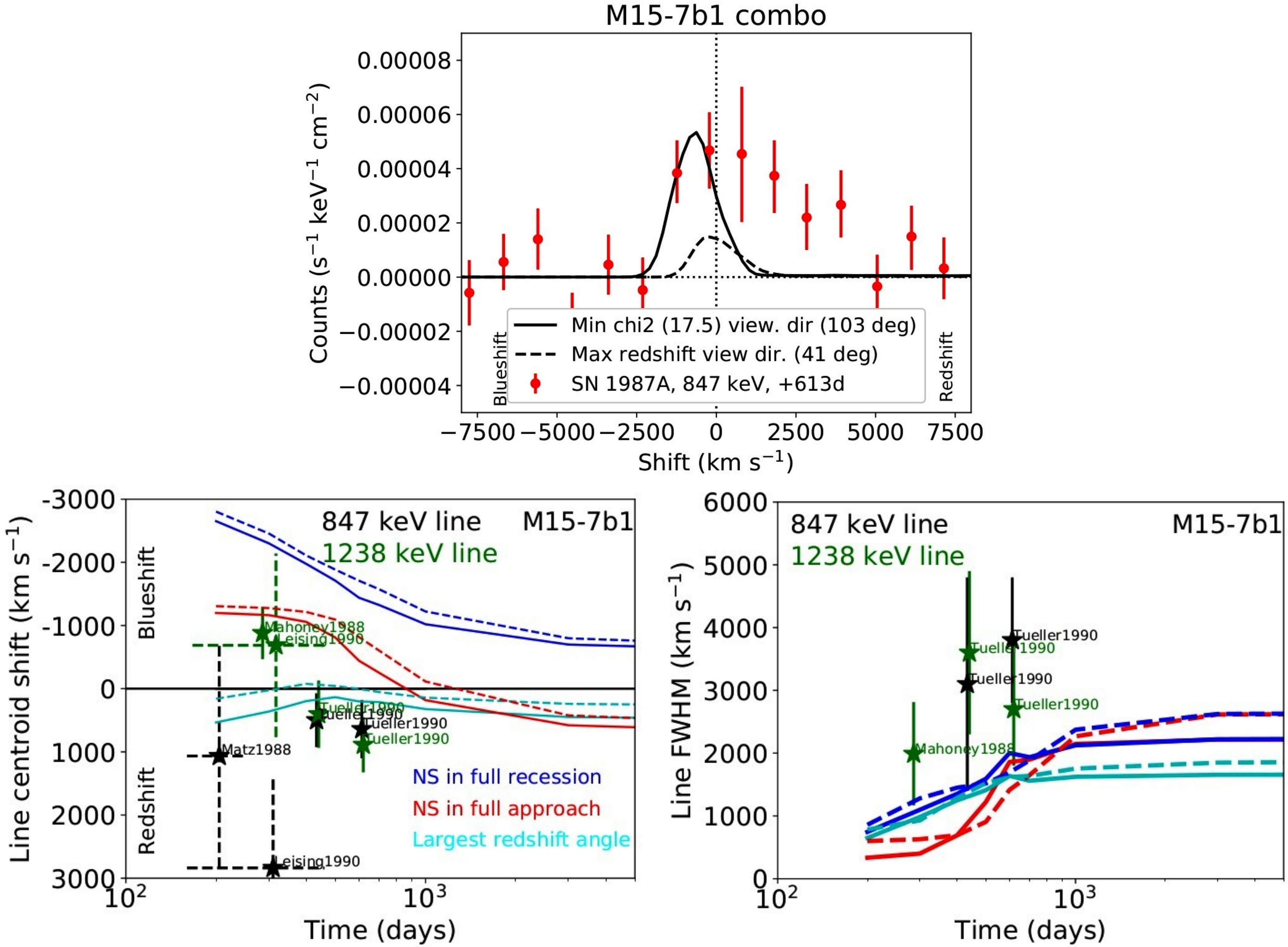


NS kick towards us

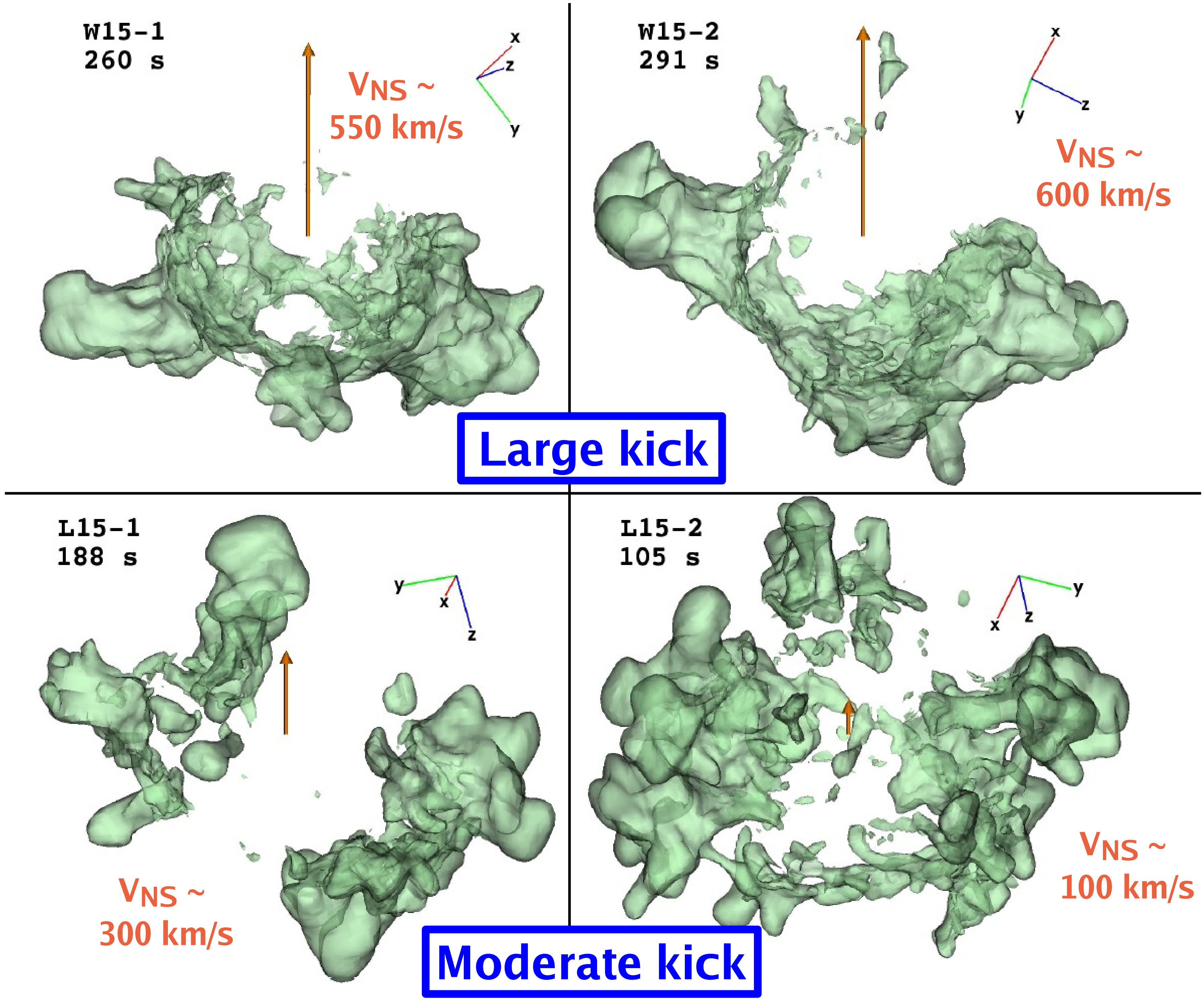
Jerkstrand et al., in preparation

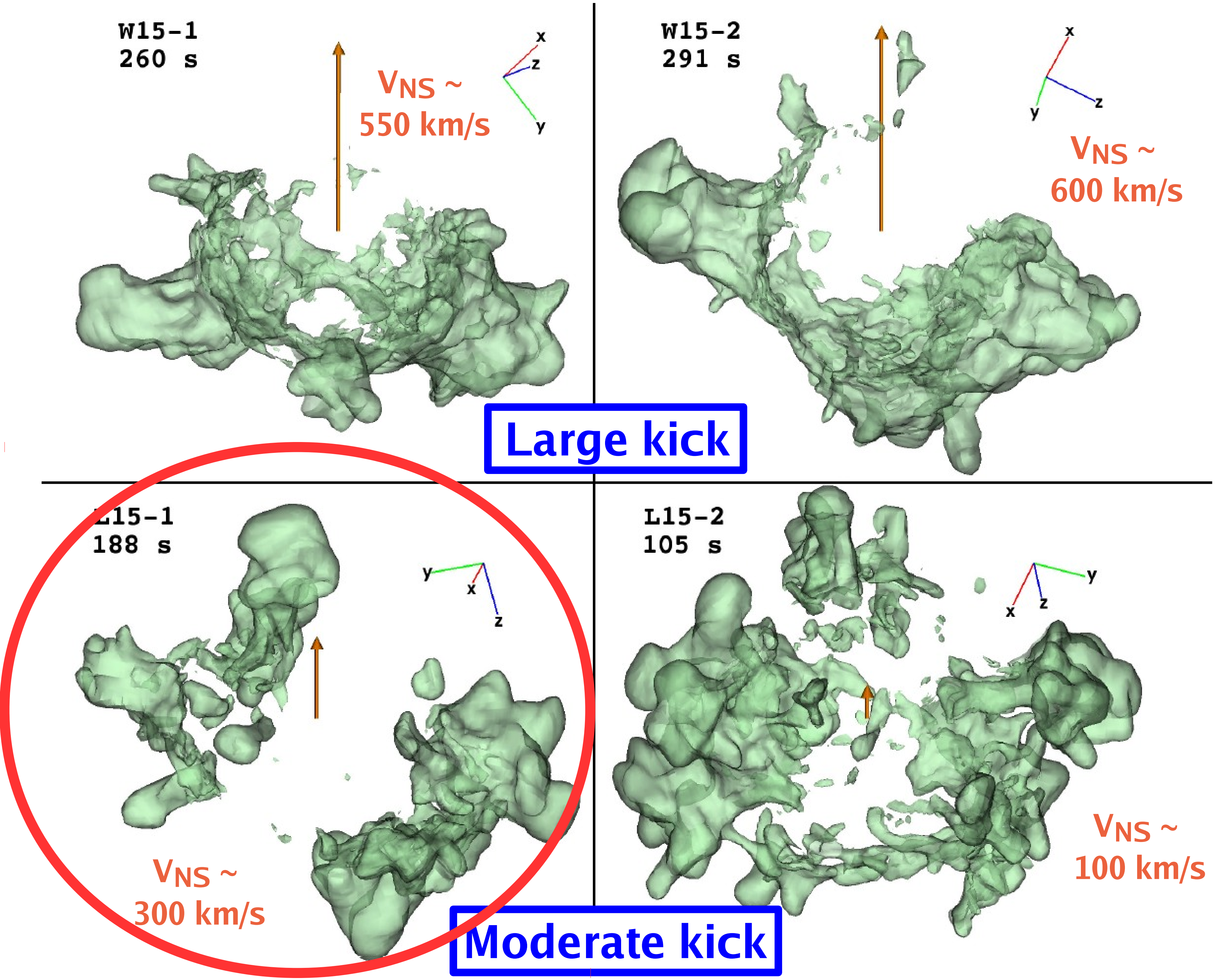
SN 1987A: Gamma-Ray Line Profiles of ^{56}Co

^{56}Co lines of M15-7b are too blueshifted, despite high NS kick of ~650 km/s. Reason is too large an ejecta mass (19 M_{sun} instead of ~14 M_{sun}).



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

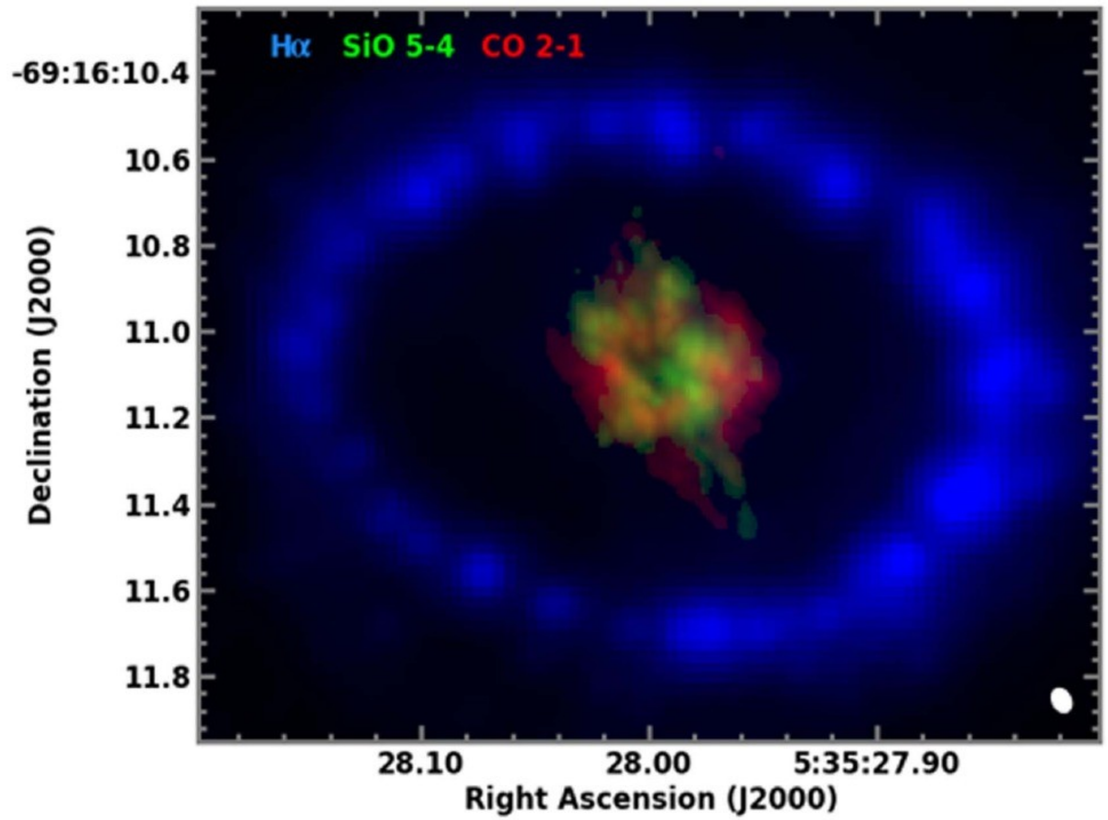




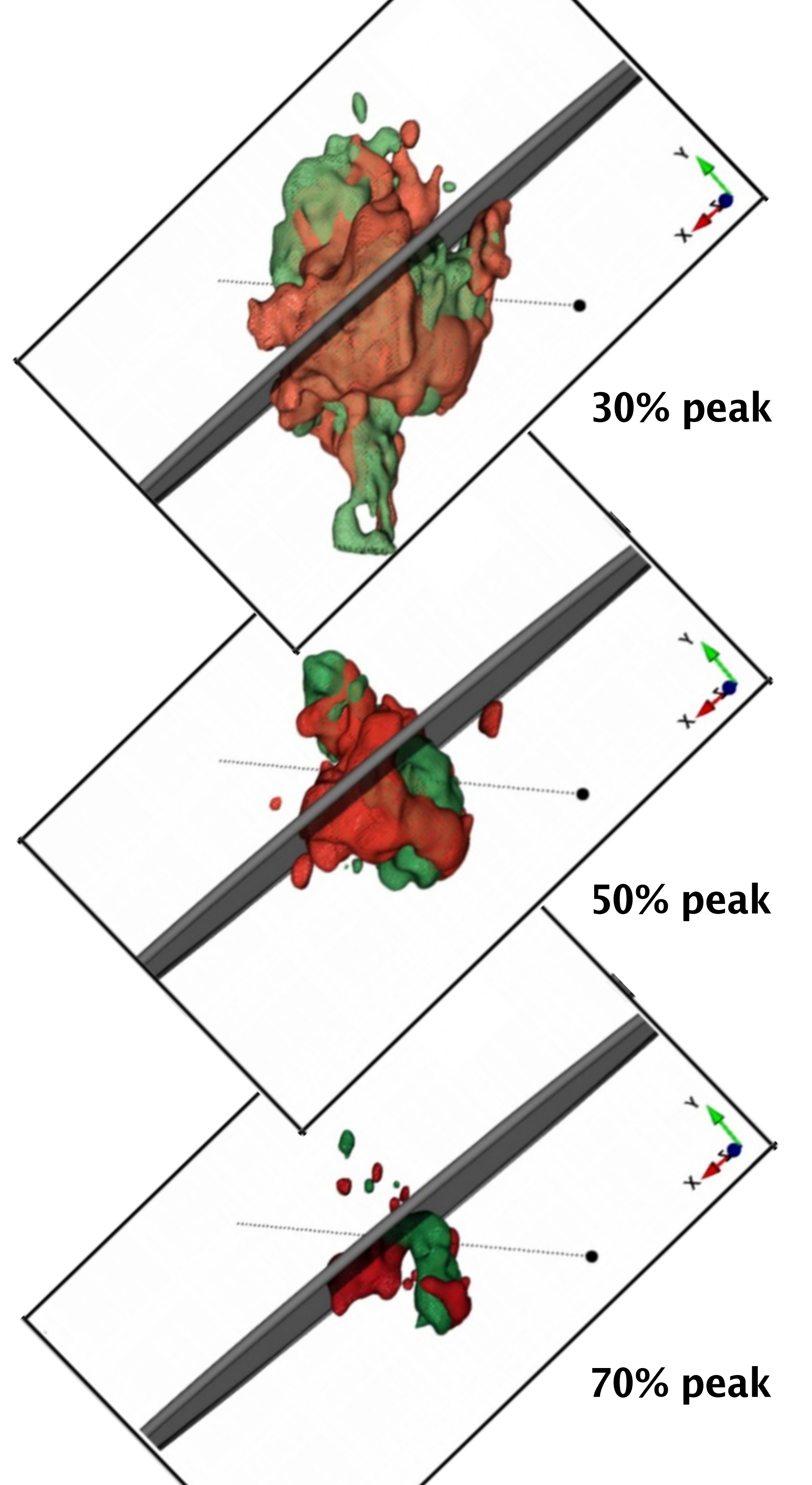
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

3D Geometry of SN1987A: Observations vs. Models

Molecular CO 2-1 and SiO 5-4 emission observed by ALMA



Abellán et al., ApJL 842 (2017) L24



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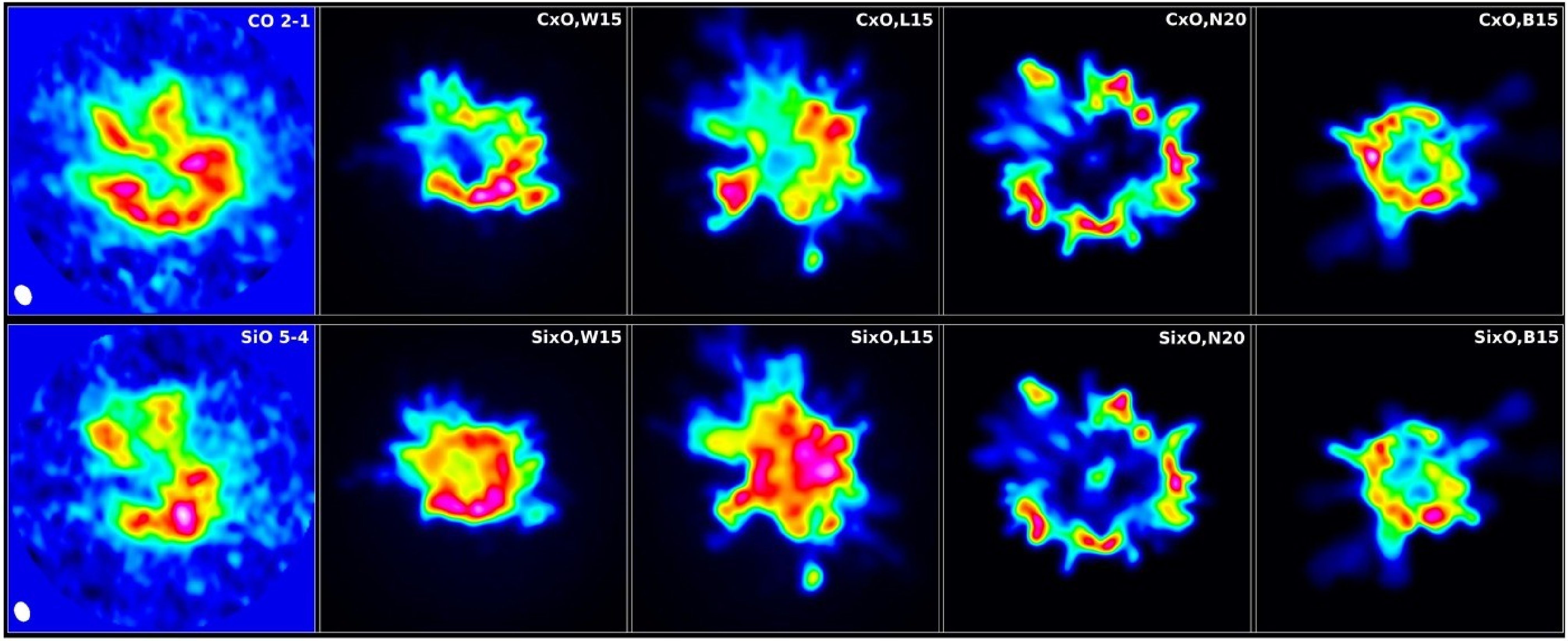

W15 L15 N20 B15

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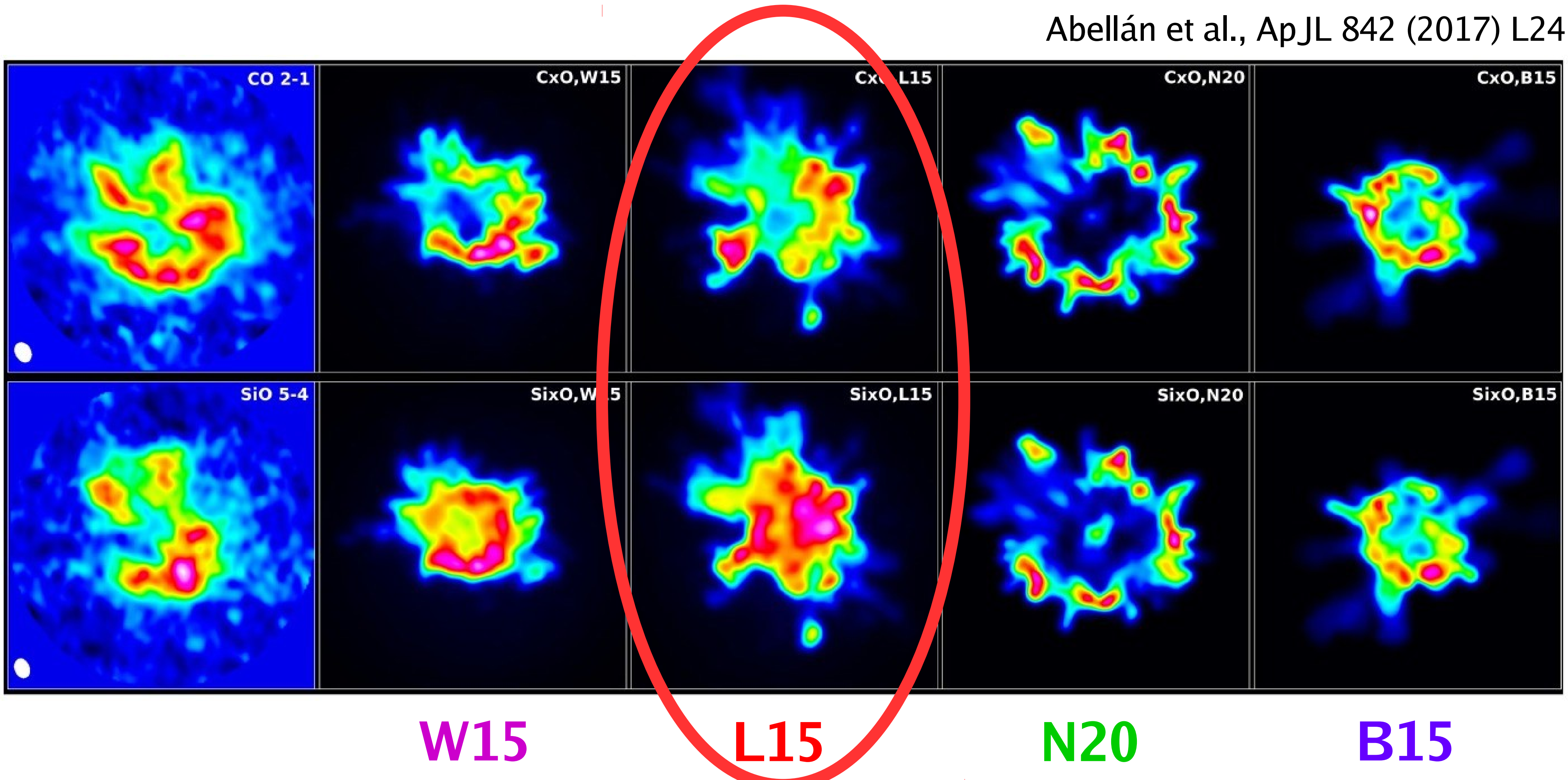
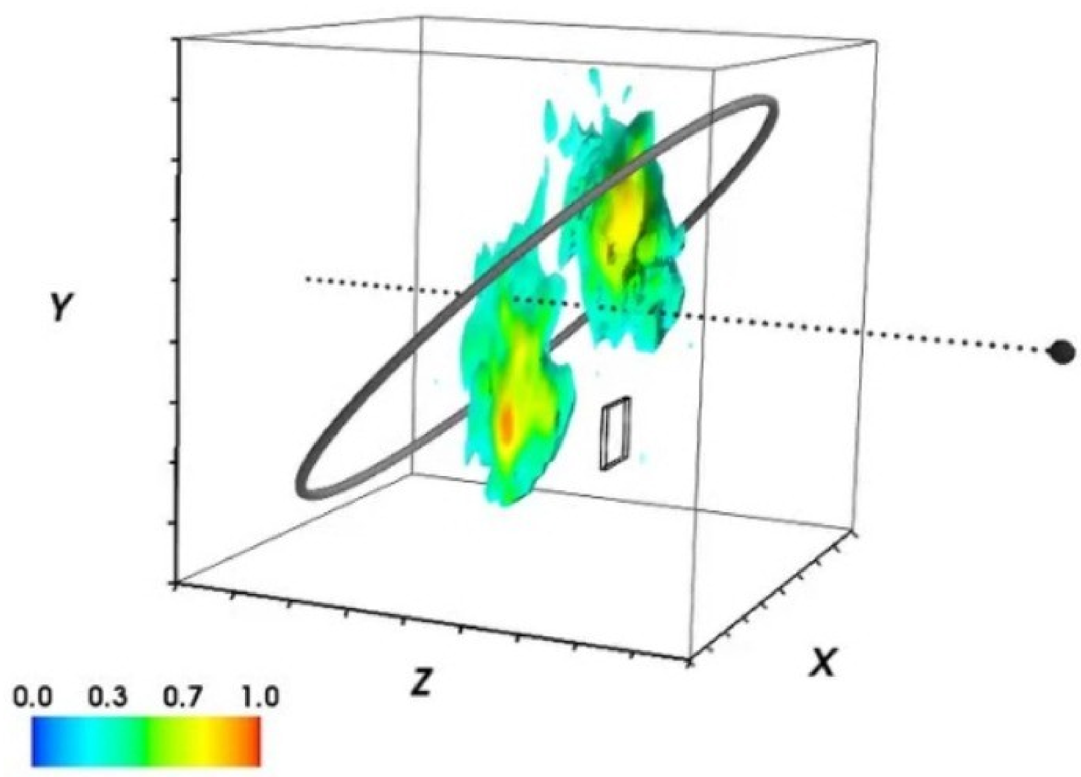
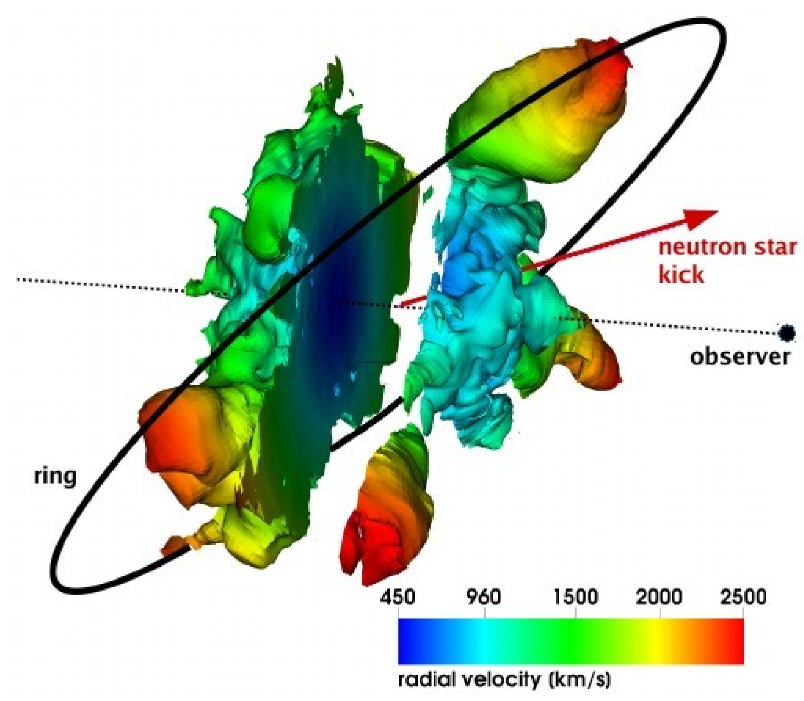


3D Geometry of SN1987A: Observations vs. Models

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

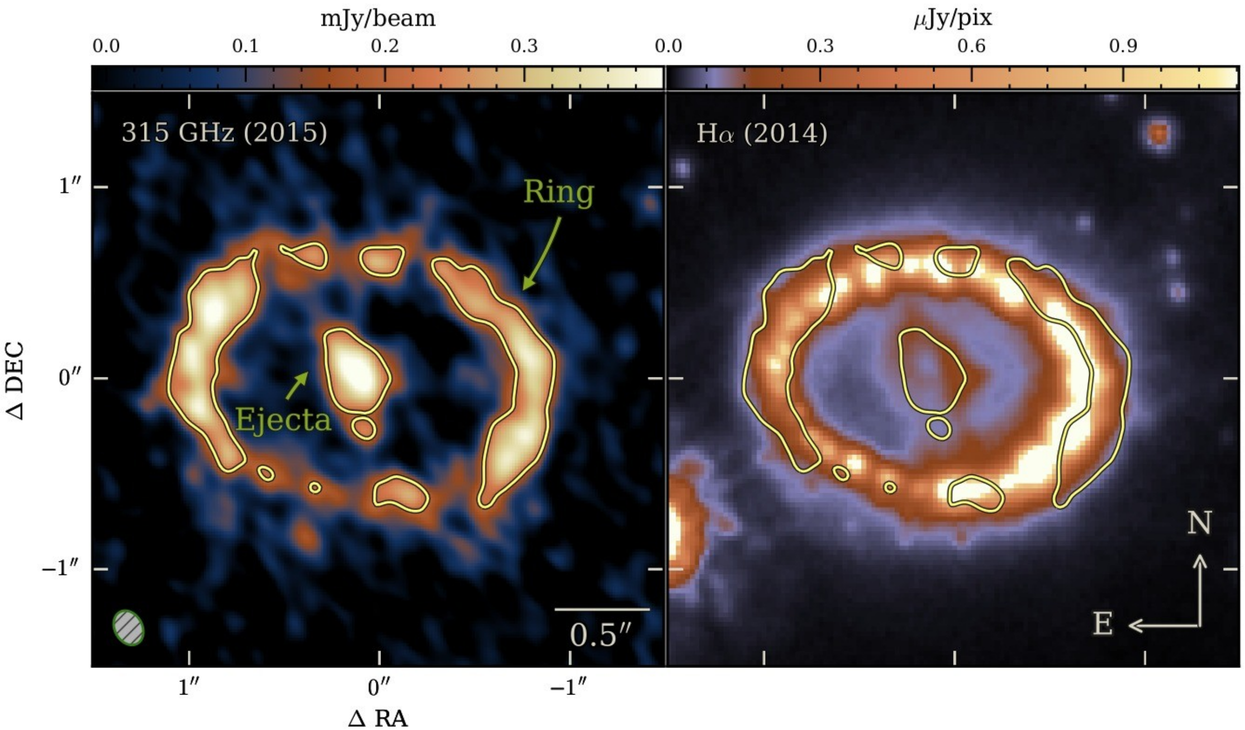


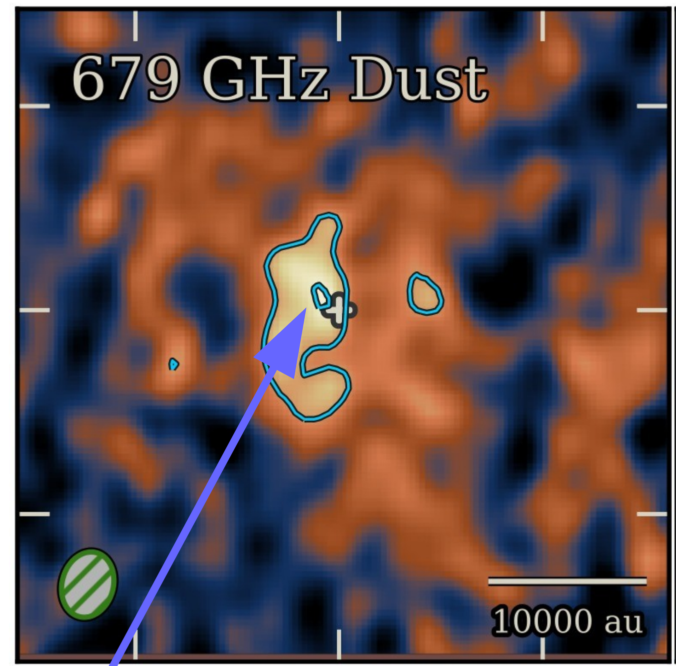


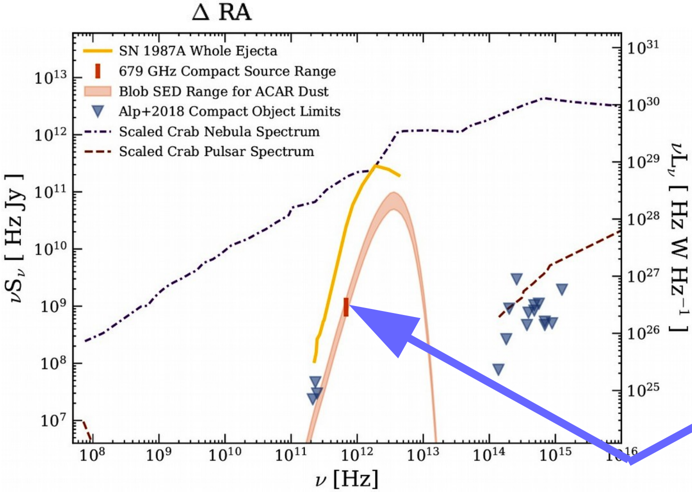
HST & VLT obs. (Larsson et al., ApJ 833 (2016) 147) 3D model L15 (Janka et al., arXiv:1705.01159)

A Compact Object in SN1987A?

High angular resolution ALMA images of dust and molecules in the ejecta of SN 1987A







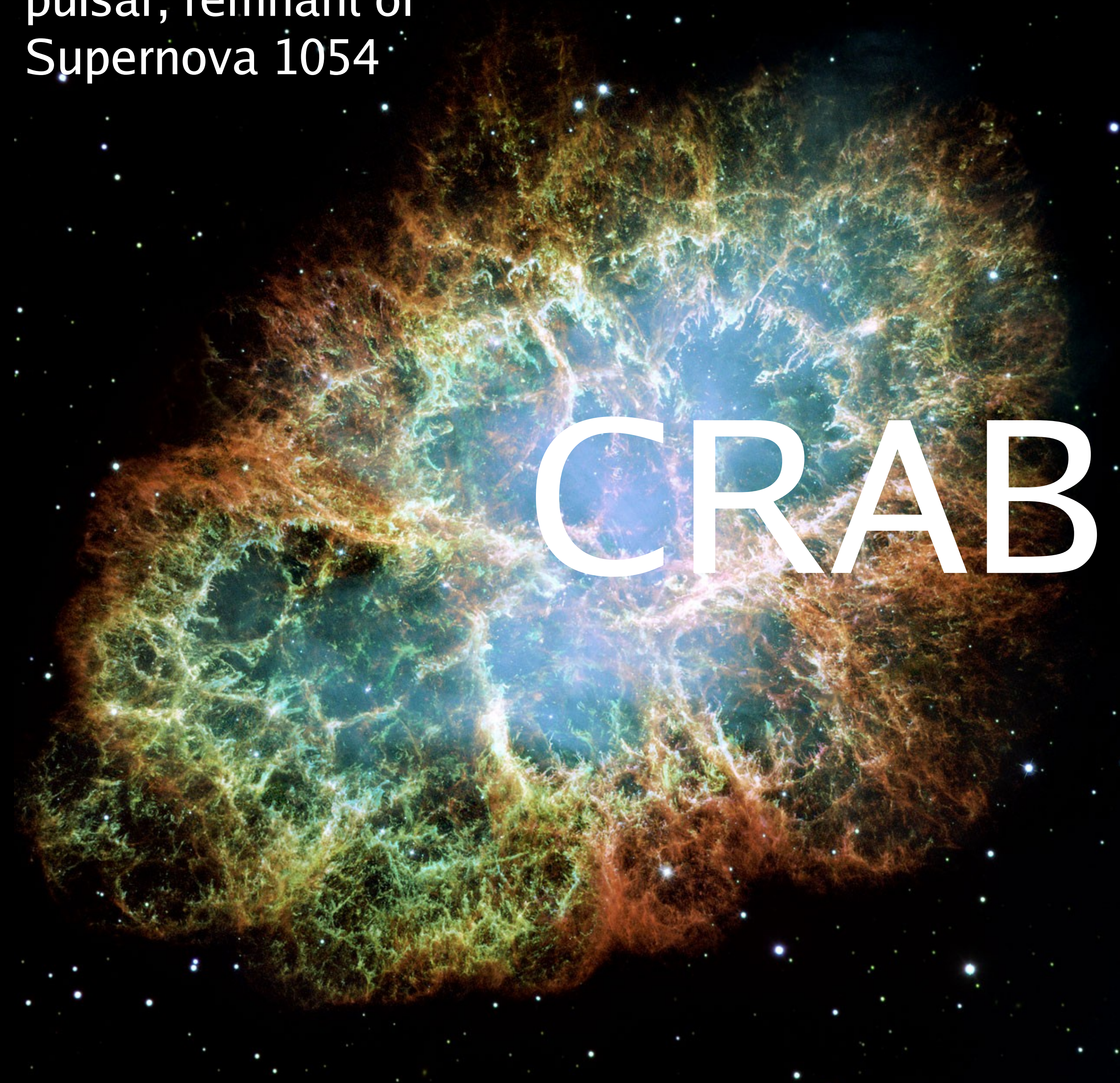
5-sigma hot "blob" north-east of ejecta center: Energy input by a hot NS (or, less likely, accretion by BH)?

[Compatible with recent limits by Alp et al. (ApJ 864 (2018) 174)].

(Cigan, Matsuura, et al., ApJ, accepted, arXiv:1910.02960)

Core-collapse or Thermonuclear ECSNe?

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}

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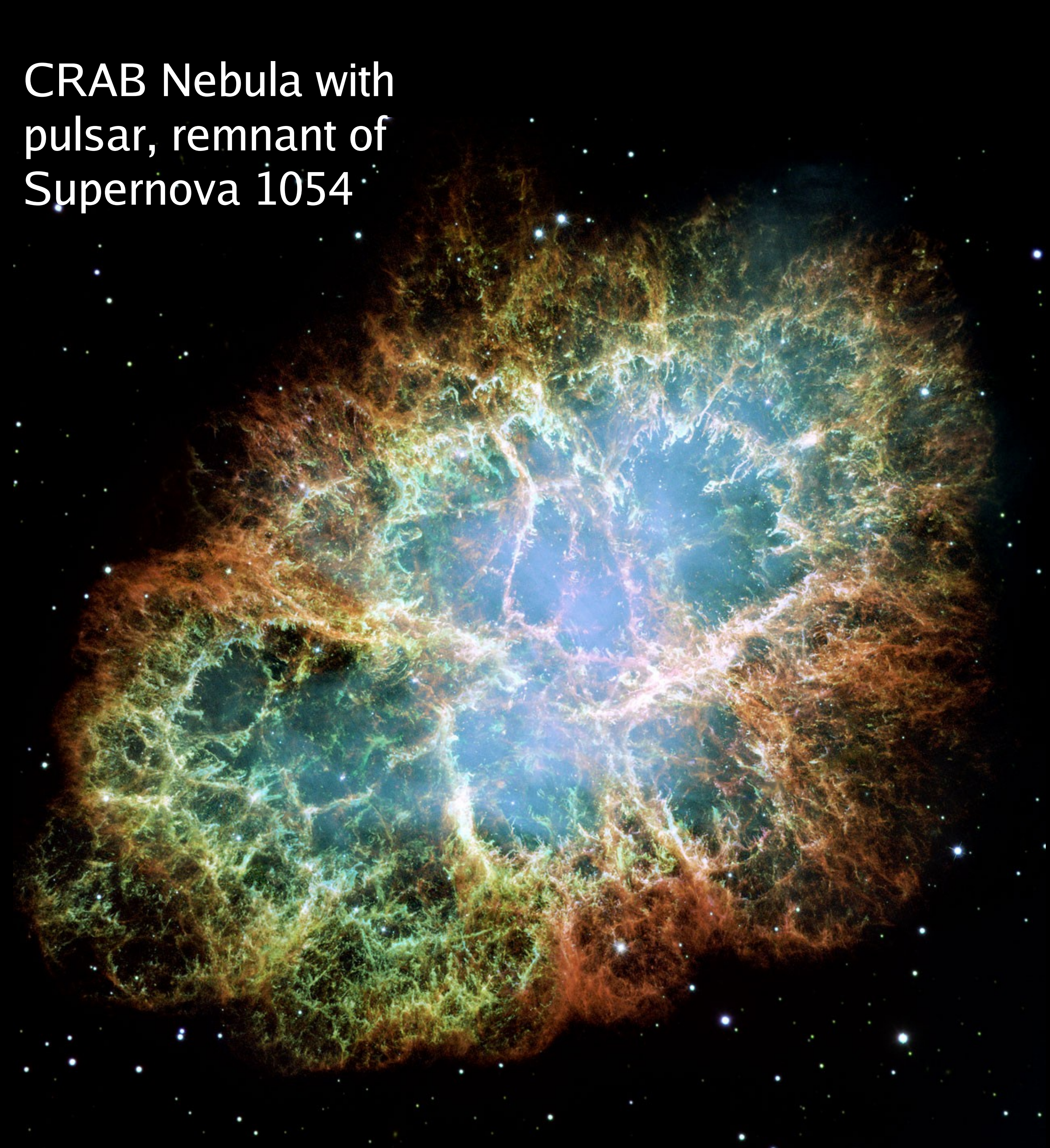

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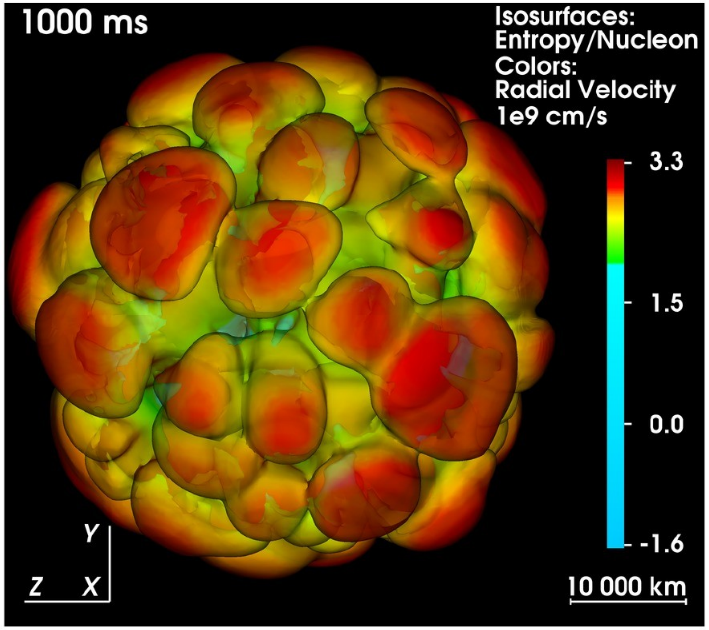
Neutron Star Recoil in 2D and 3D ECSN Models

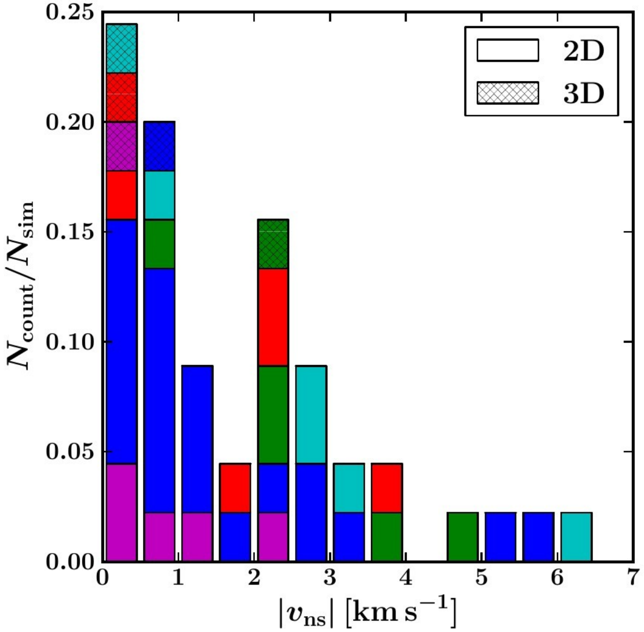
ECSN models:

40 2D runs

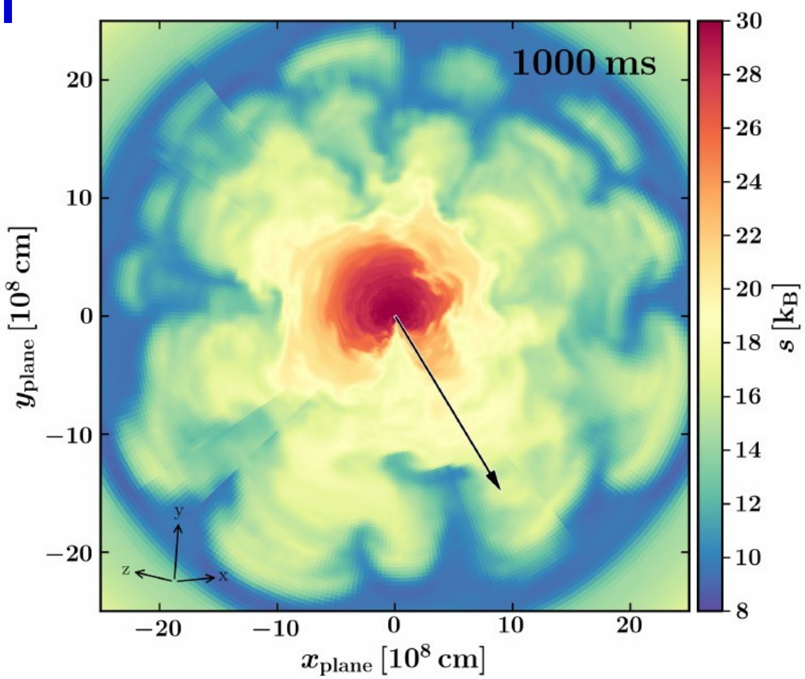
5 3D runs

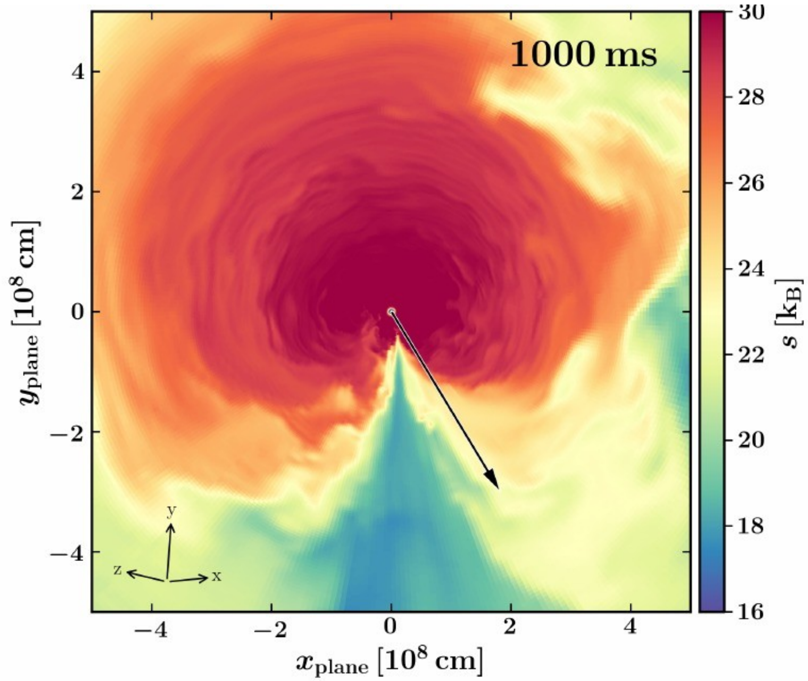
with energies in [0.3, 1.6] x 10^{50} erg





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)

Nebular Spectra of Neutrino-driven Explosions

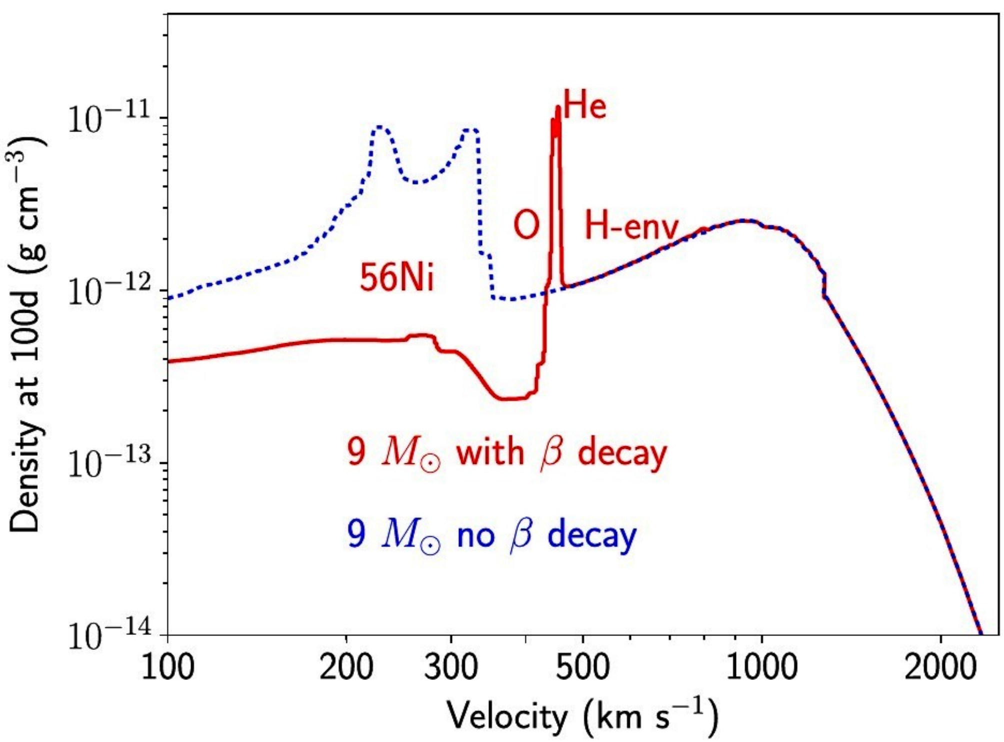
Compare low-luminosity supernovae SN 1997D, 2005cs, 2008bk

with low-energy neutrino-driven explosion of 9.0 M_{sun} iron-core progenitor;

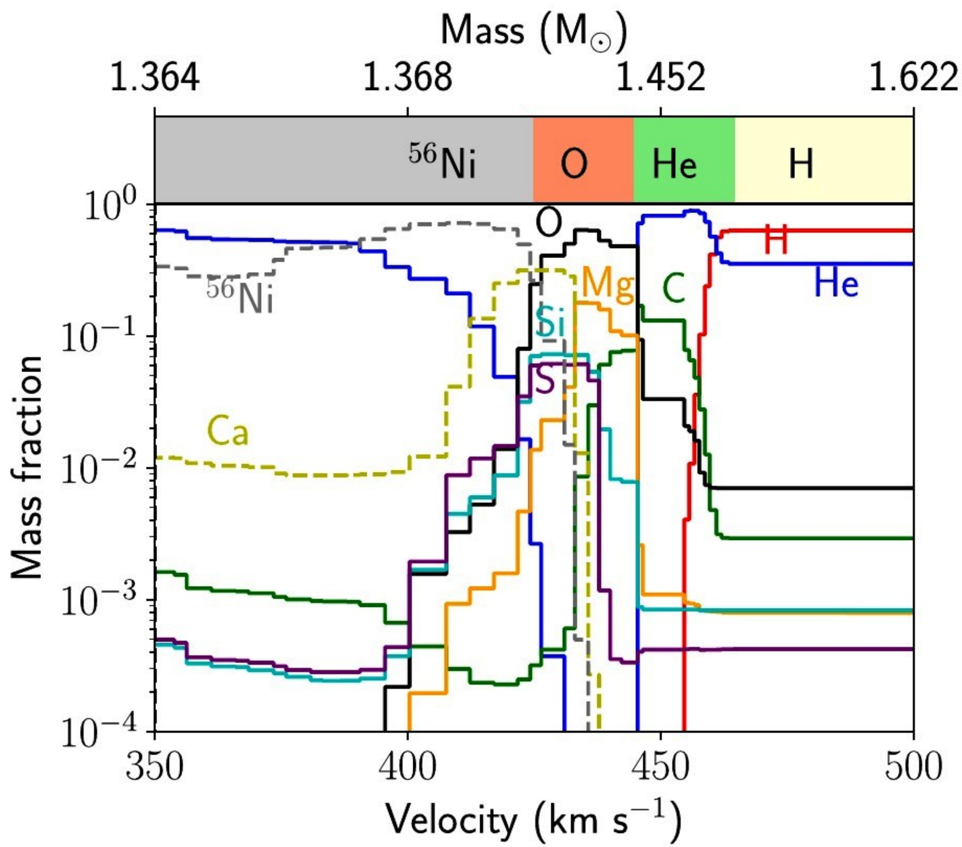
spectral analysis during nebular phase (> 100 days after onst of explosion)

(Jerkstrand et al., MNRAS 475 (2018) 277)

Density profile



Composition profile



Progenitor model: Woosley & Heger (2015)

Nebular Spectra of Neutrino-driven Explosion of 9.0 M_{sun} Fe-core Progenitor

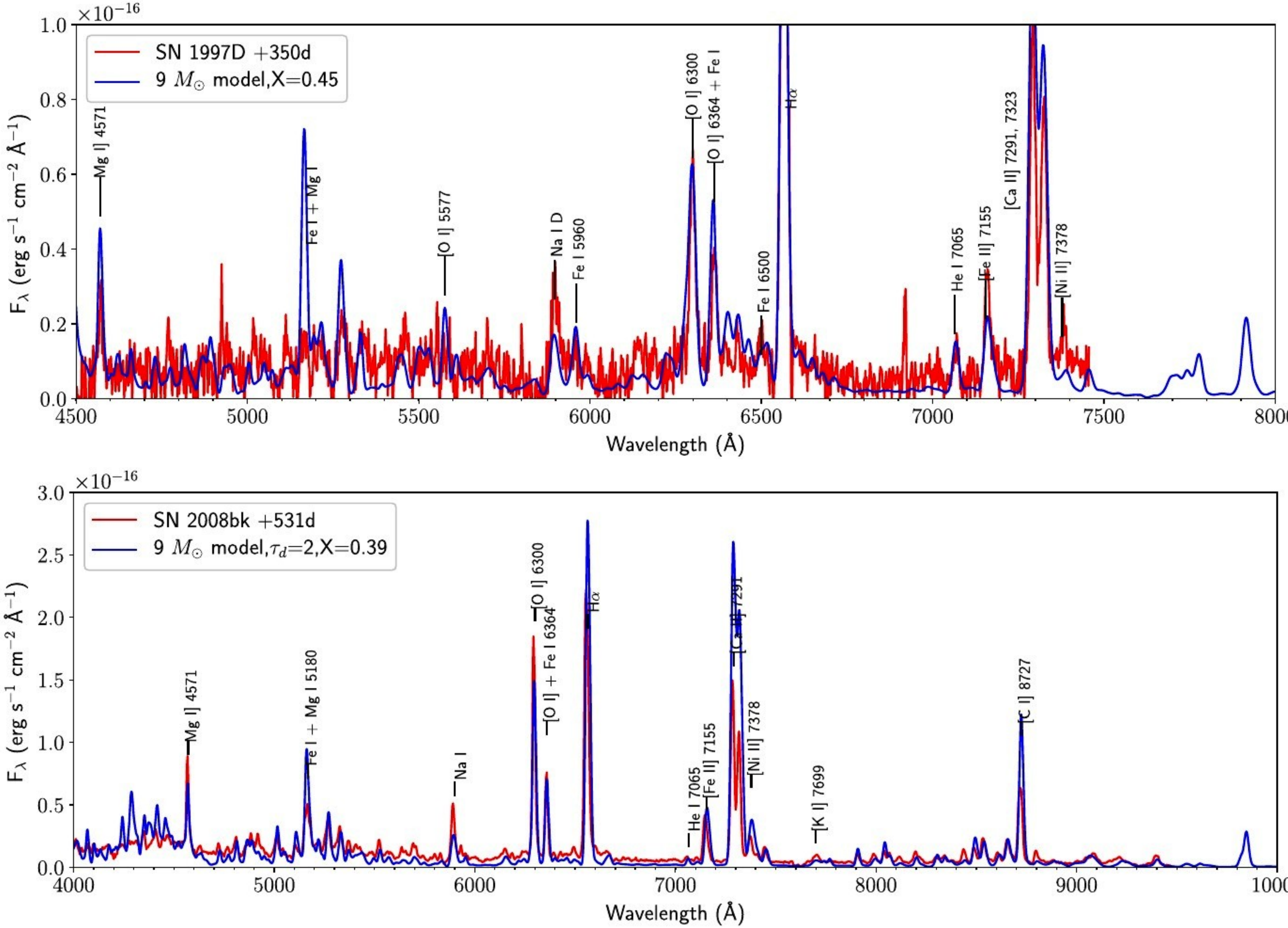
Spectra and line profiles of 1D explosion model:

Good agreement with SN 1997D and SN 2008bk; SN 2005cs unclear

All cases show clear O and He lines and no high $^{58}Ni/^{56}Ni$ ratio

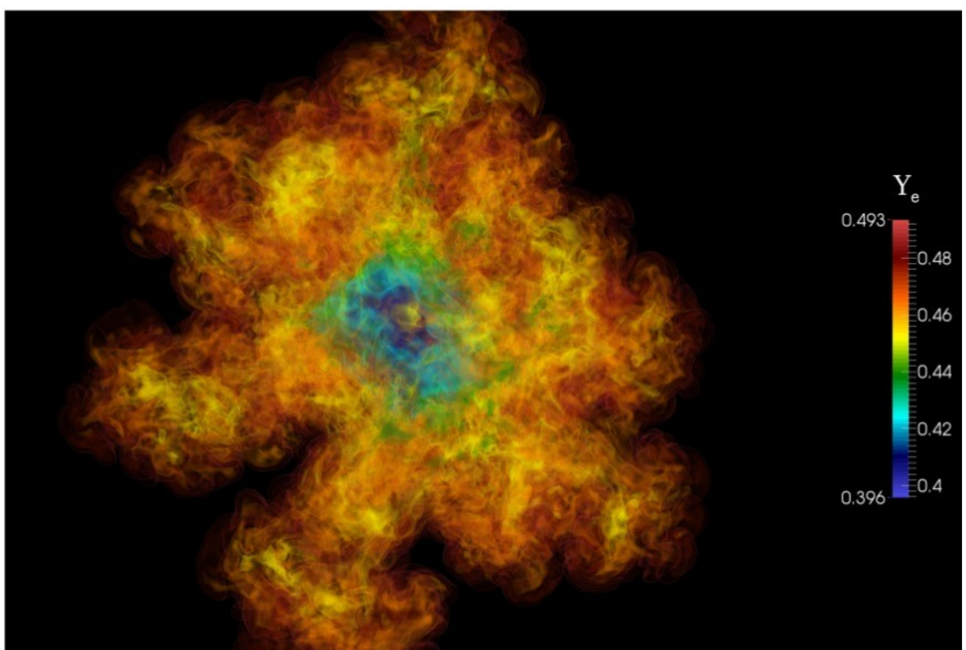
ECSNe disfavored; explosions of low-mass Fe-core progenitors more likely

Jerkstrand et al., MNRAS 475 (2018) 277

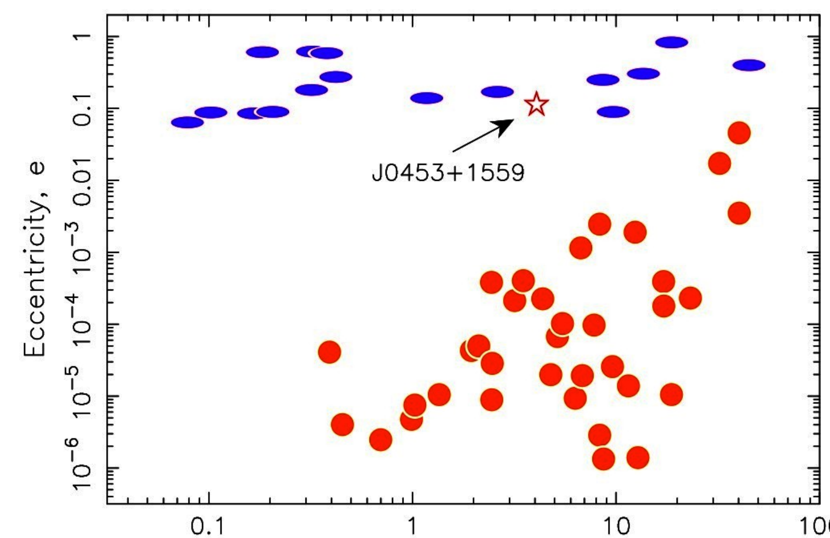


Is J0453+1559 a NS-WD Binary Born in a Thermonuclear ECSN?

- Compact binary radio pulsar system J0453+1559 consists of recycled pulsar (1.559(5) Msun) and unseen companion (1.174(4) Msun).
- The companion was argued to be a NS because of high orbital eccentricity of e = 0.1125.
- This makes the companion the lowest-mass NS known.
- However, also a thermonuclear ECSN could explain the system properties.
- In this case the pulsar companion would be an ONeMg WD.



Tauris & Janka, arXiv:1909.12318



tECSN: Jones et al. (A&A 593 (2016) A72); Jones et al. (A&A 622 (2019) A74)

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 core-collapse ECSNe exist?

Thank You!