Max-Planck-Institut für Astrophysik

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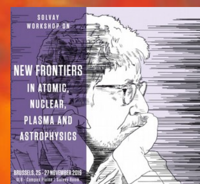
SFB 1258 Neutrinos Dark Matter Messengers



Solvay Workshop on

New Frontiers in Atomic, Nuclear, Plasma and Astrophysics

ULB, Brussels, Belgium, November 25–27, 2019

Stellar Explosions and Nucleosynthesis

erc European Research Council
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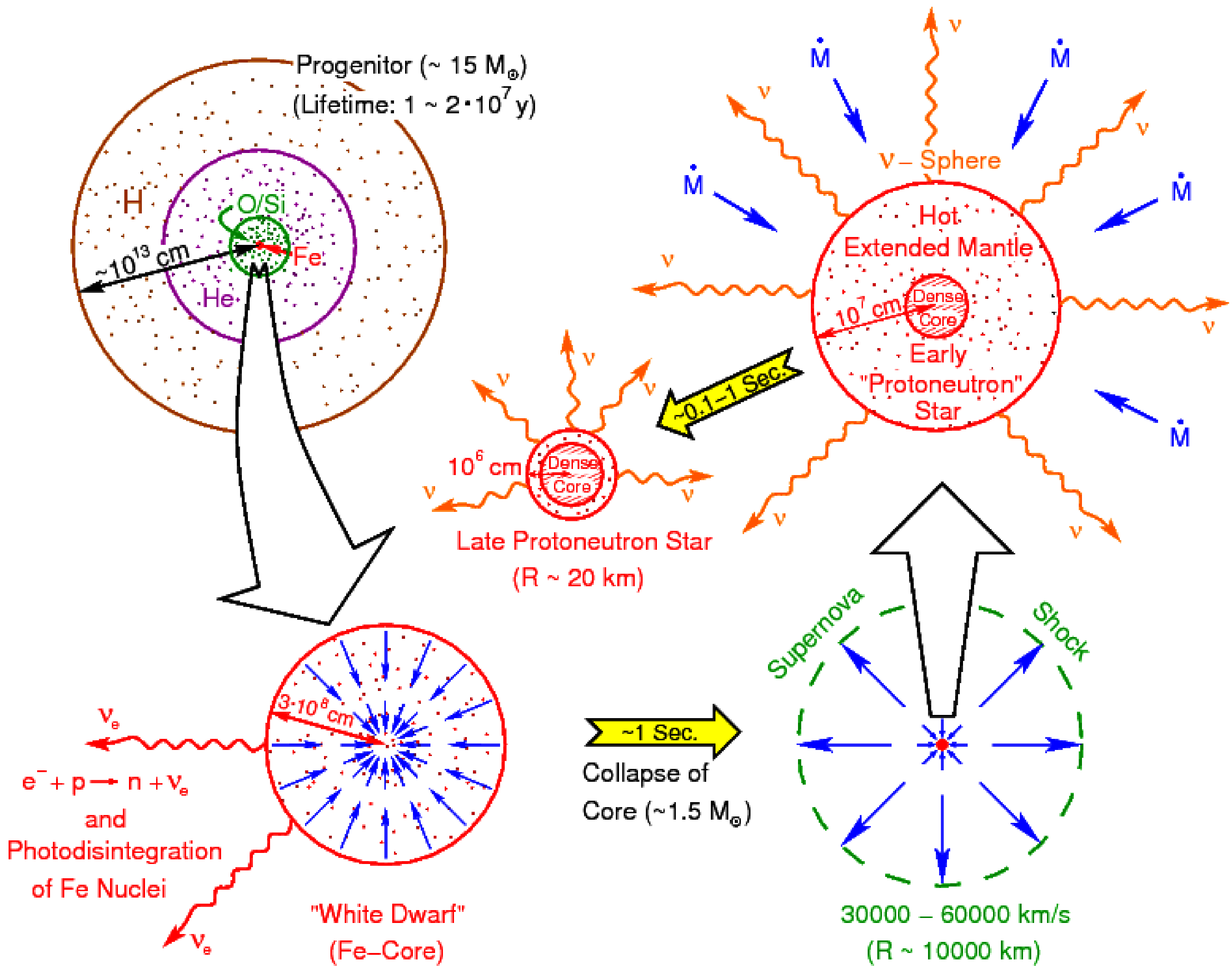
Hans-Thomas Janka
MPI for Astrophysics

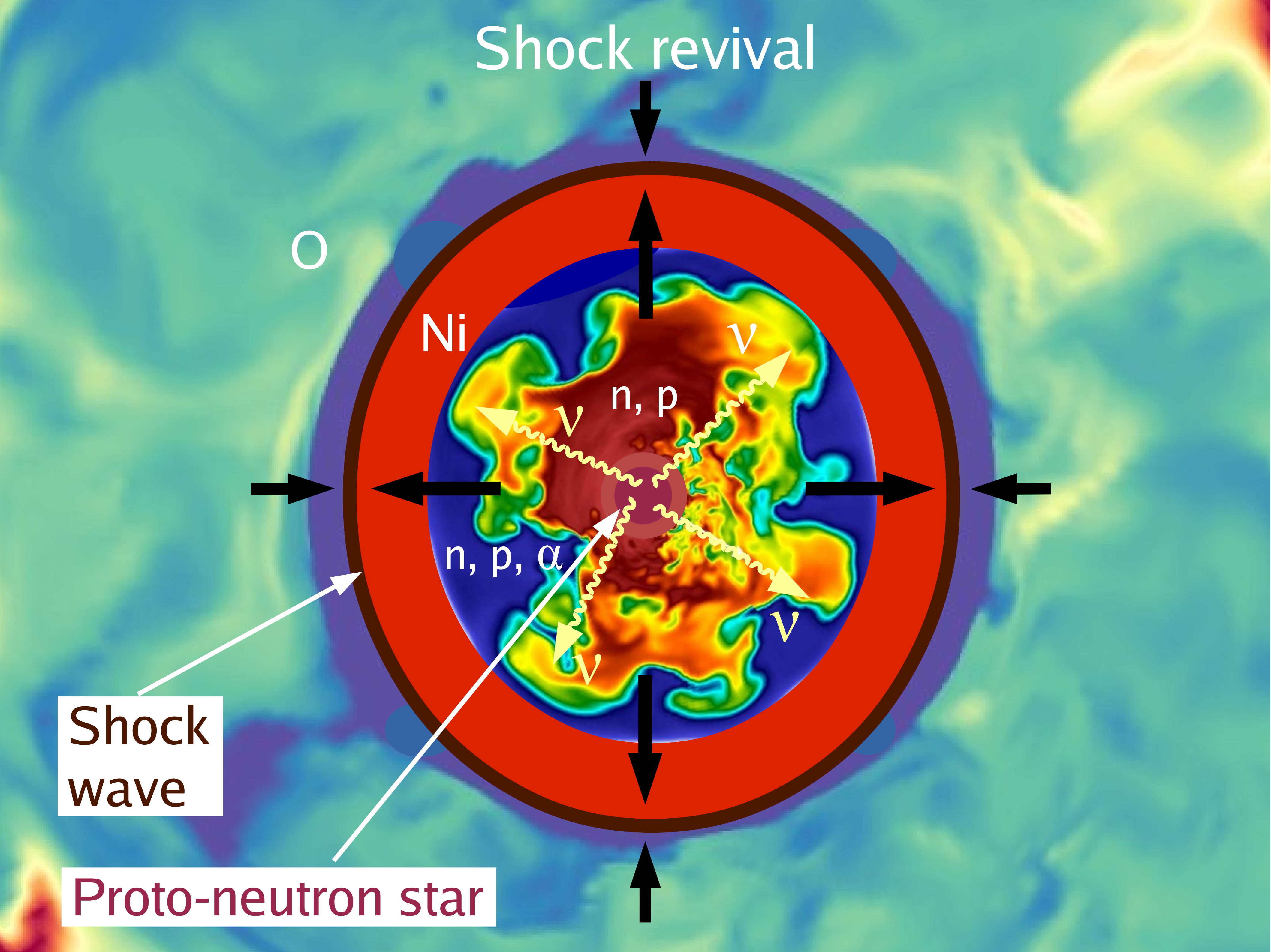
COCO2CASA

Contents

Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)


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

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)

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, Glas+ ApJ 2019):

- 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 many seconds to saturate! 10^{51} erg possible?**

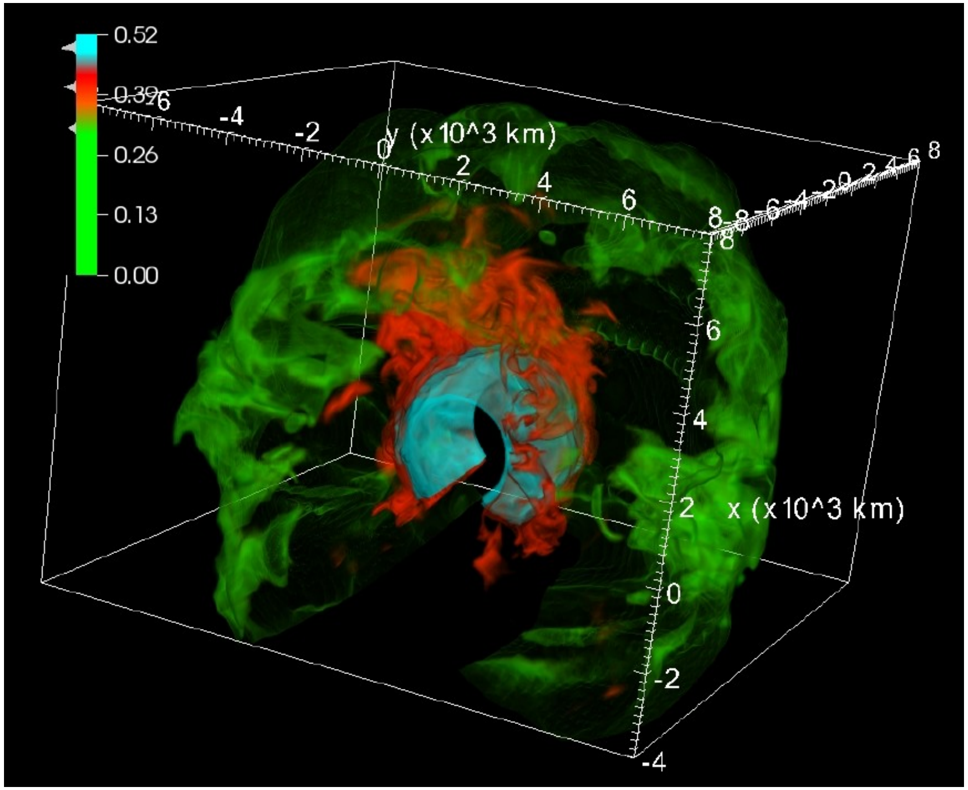
- **Progenitors are 1D**, but composition-shell structure and initial progenitor-core asymmetries can affect onset of explosion.
- 3D simulations may **still need higher resolution** for convergence.
- **Full multi-D neutrino transport** versus **"ray-by-ray" approximation.**
- **Uncertain/missing physics?**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

Pre-collapse
3D Asymmetries
in Progenitors

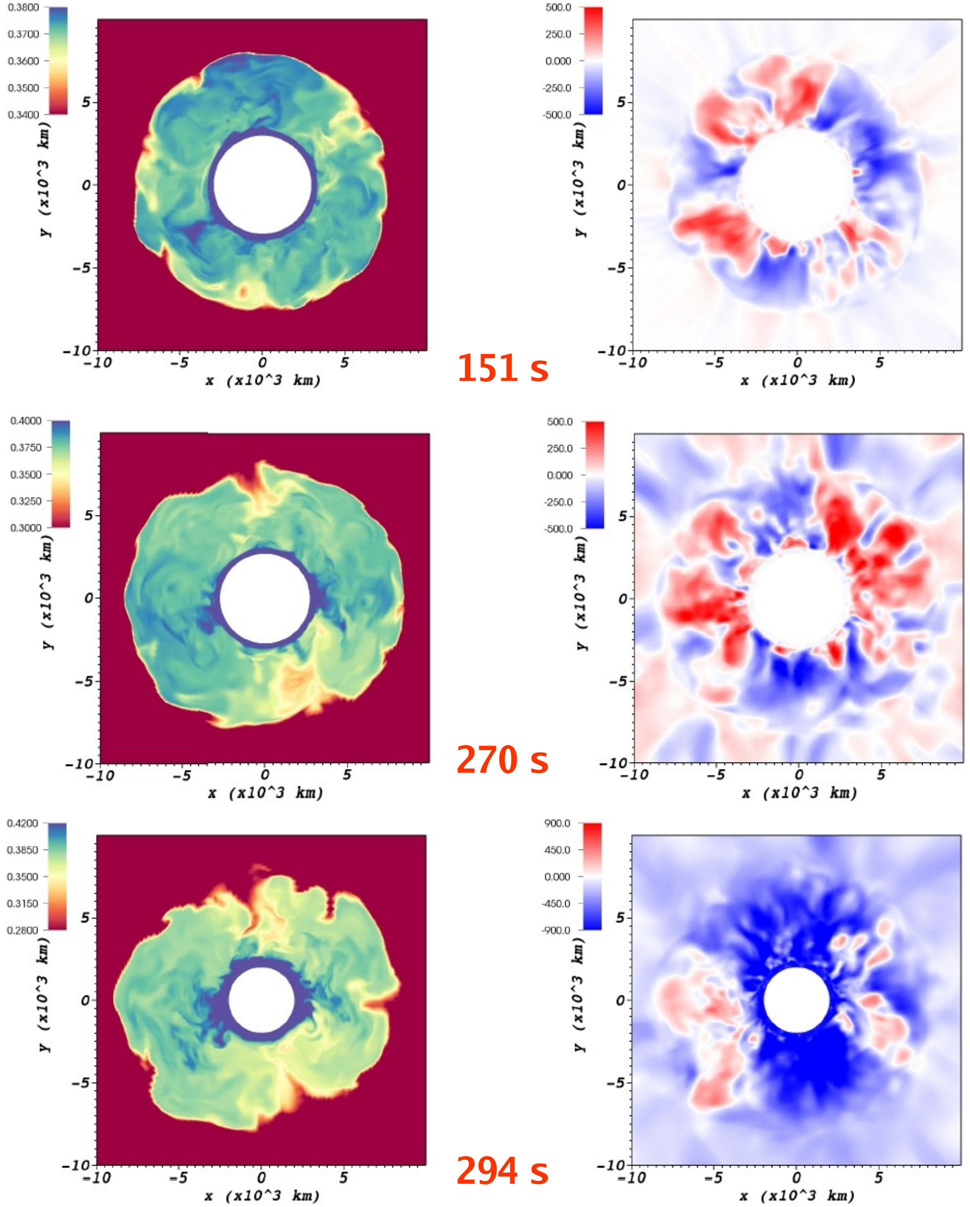
3D Core-Collapse SN Progenitor Model

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)

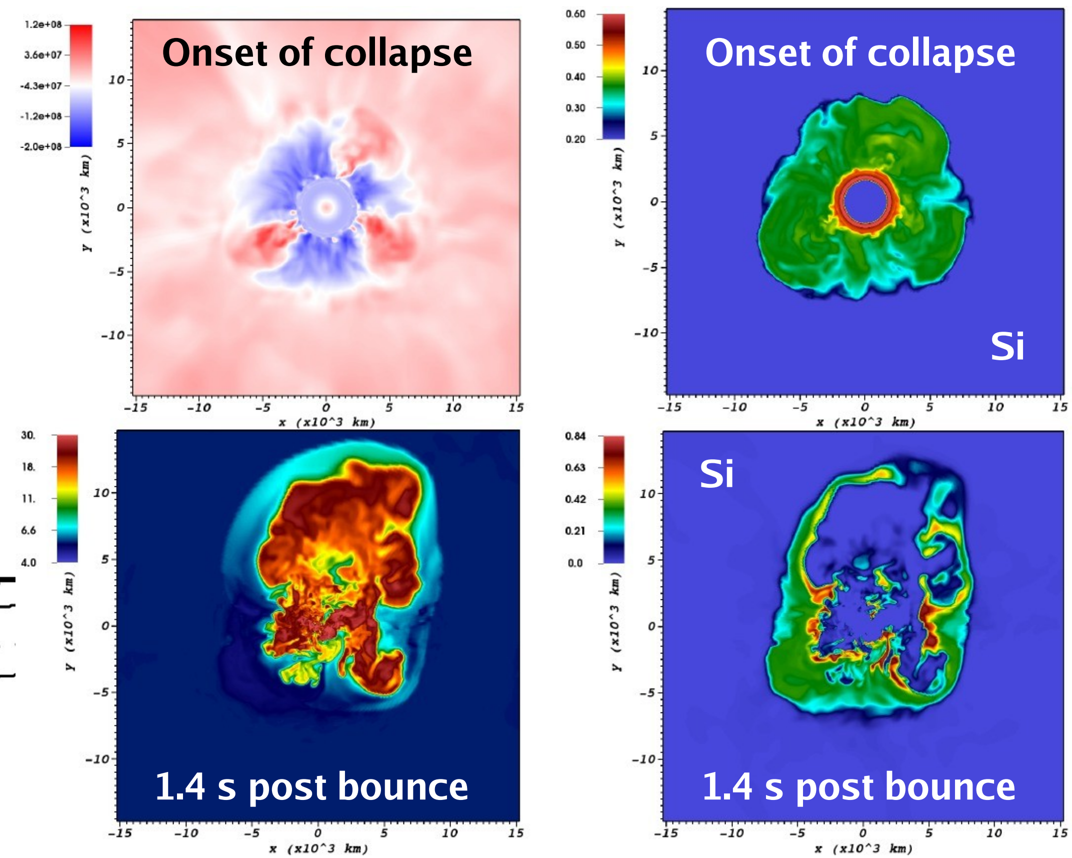


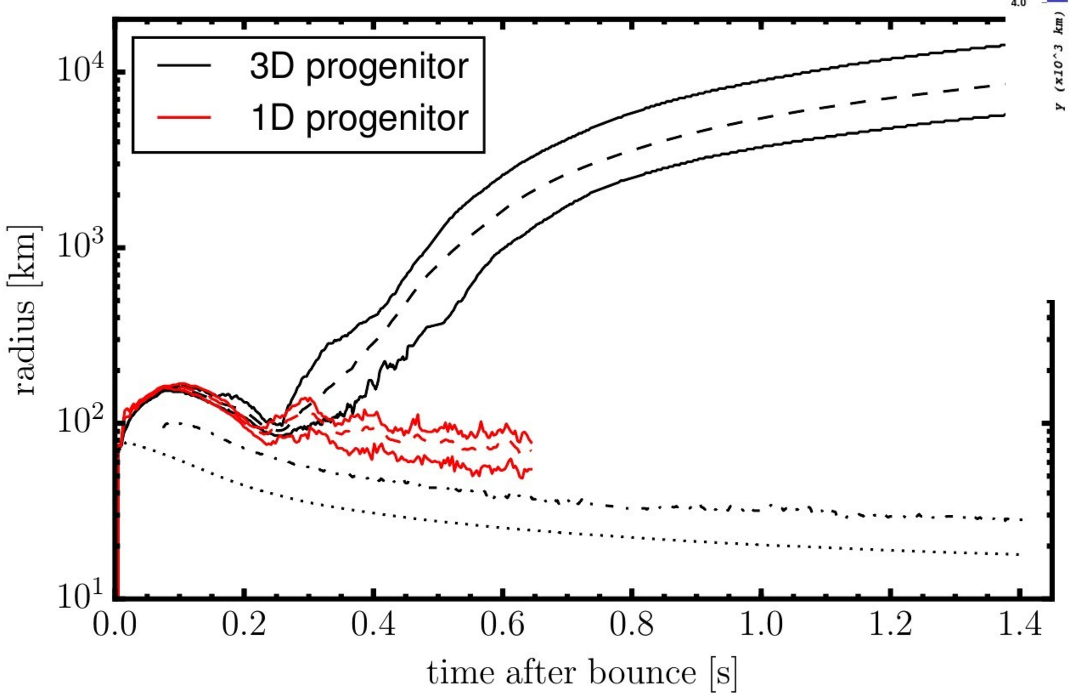
3D Core-Collapse SN Explosion Model

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.





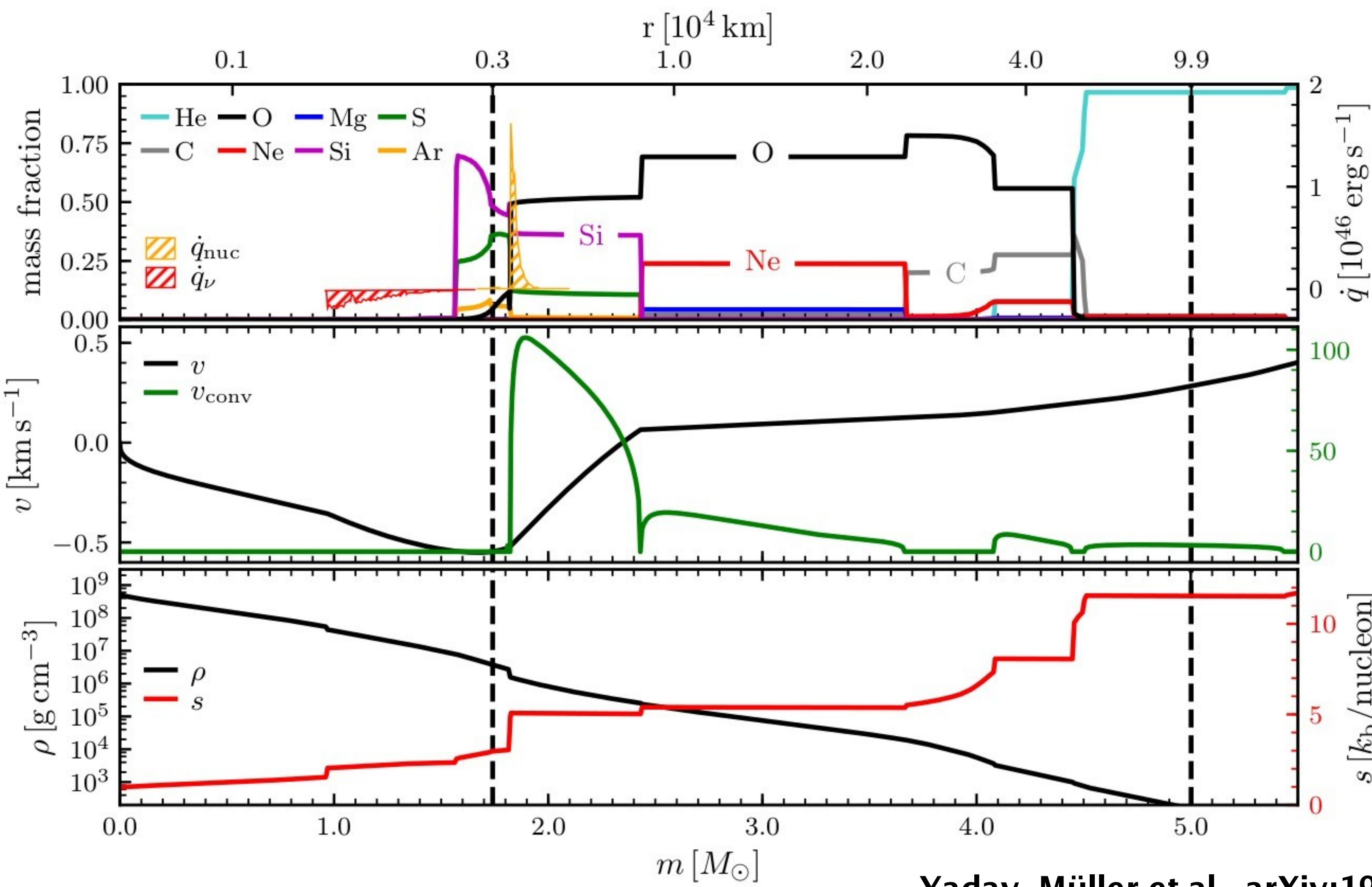
$$\delta\rho/\rho \sim \mathrm{Ma}_{\mathrm{conv}}$$

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

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

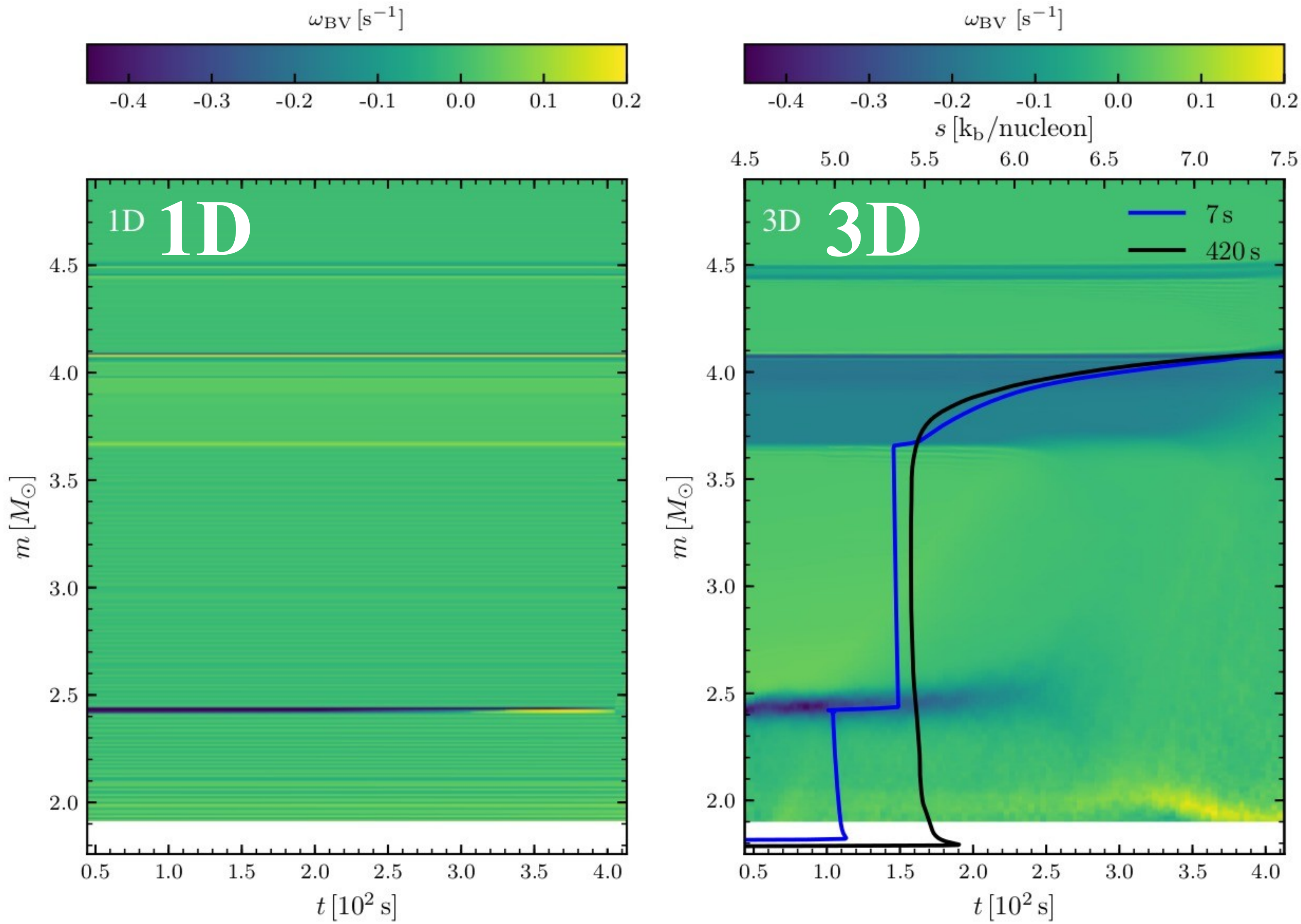
Initial (1D) conditions 7 minutes prior to core collapse.



Yadav, Müller et al., arXiv:1905.04378

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

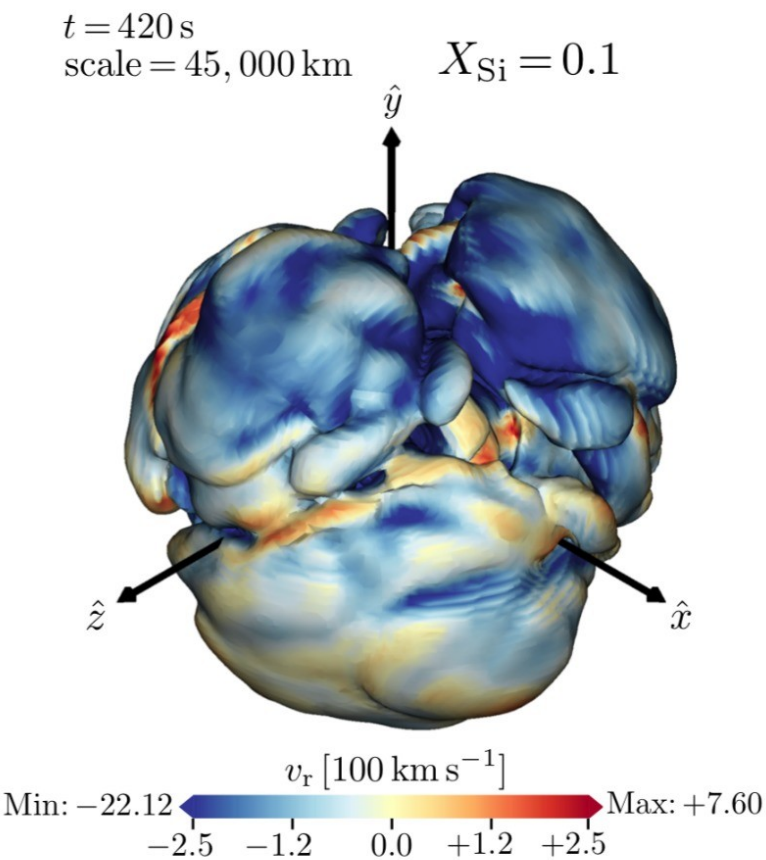
Convectively Ledoux-stable (BV frequency < 0) and Ledoux-unstable regions (BV frequency > 0) regions.

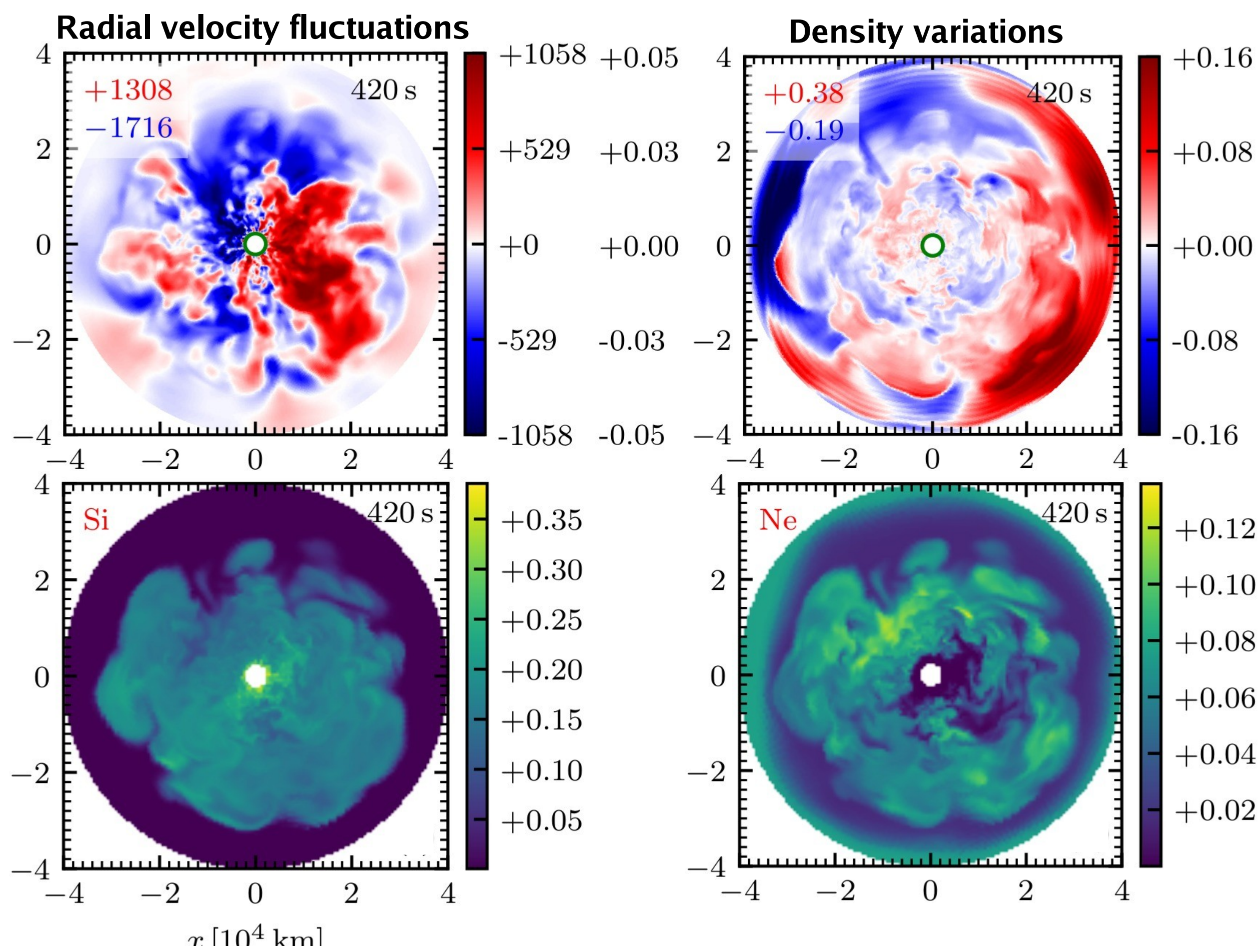


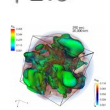
Yadav, Müller et al., arXiv:1905.04378

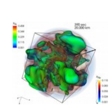
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

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







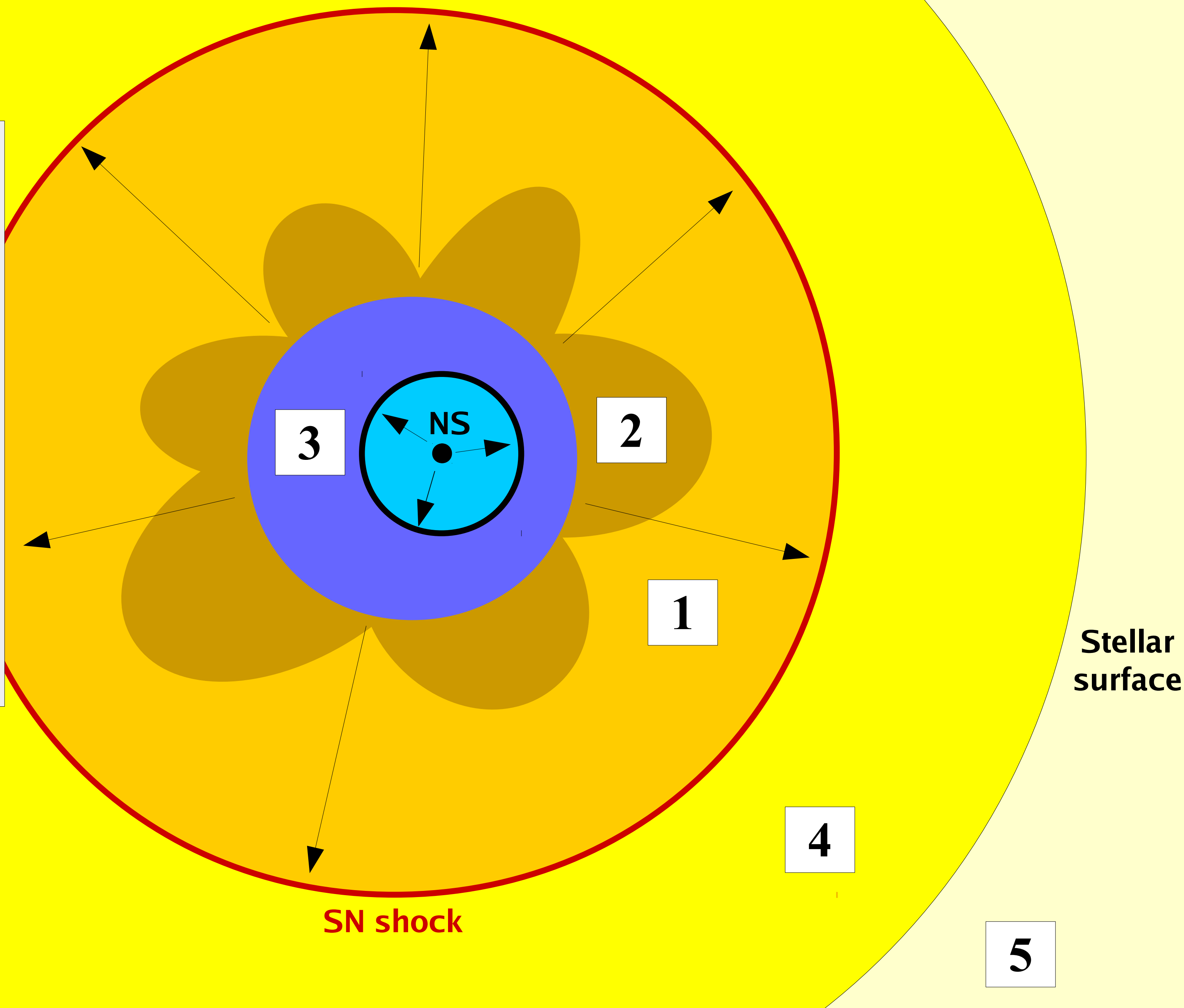


Yadav, Müller et al., arXiv:1905.04378

Nucleosynthesis
&
Supernova Diagnostics

Components of CCSN Nucleosynthesis

1. Shock-heated ejecta: explosive burning
2. Neutrino-heated ejecta: normal freezeout from NSE
3. Neutrino-driven wind: alpha-rich freezeout r-process? νp-process?
4. Neutrino-process in outer shells
5. Stellar wind



Components of CCSN Nucleosynthesis

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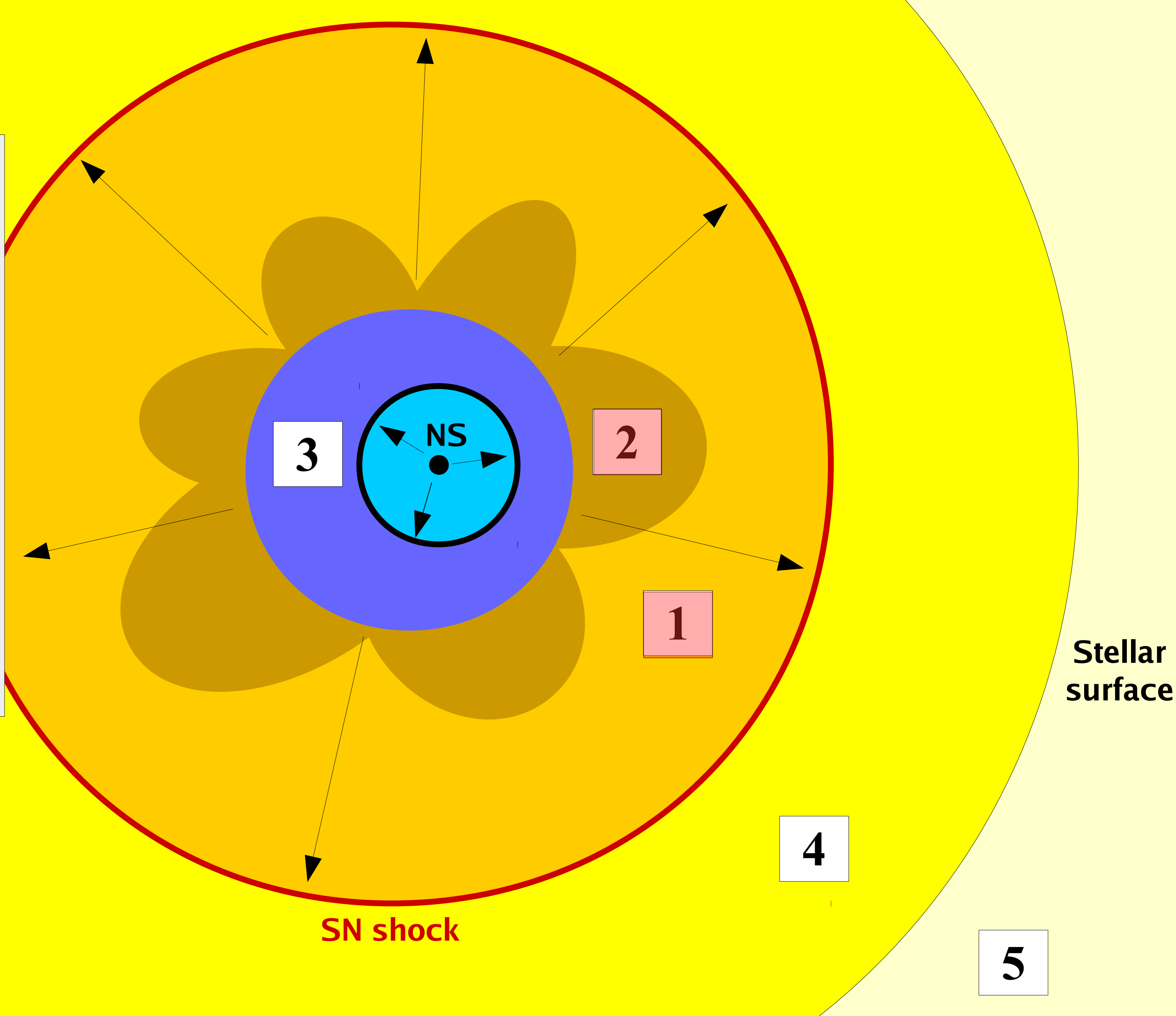
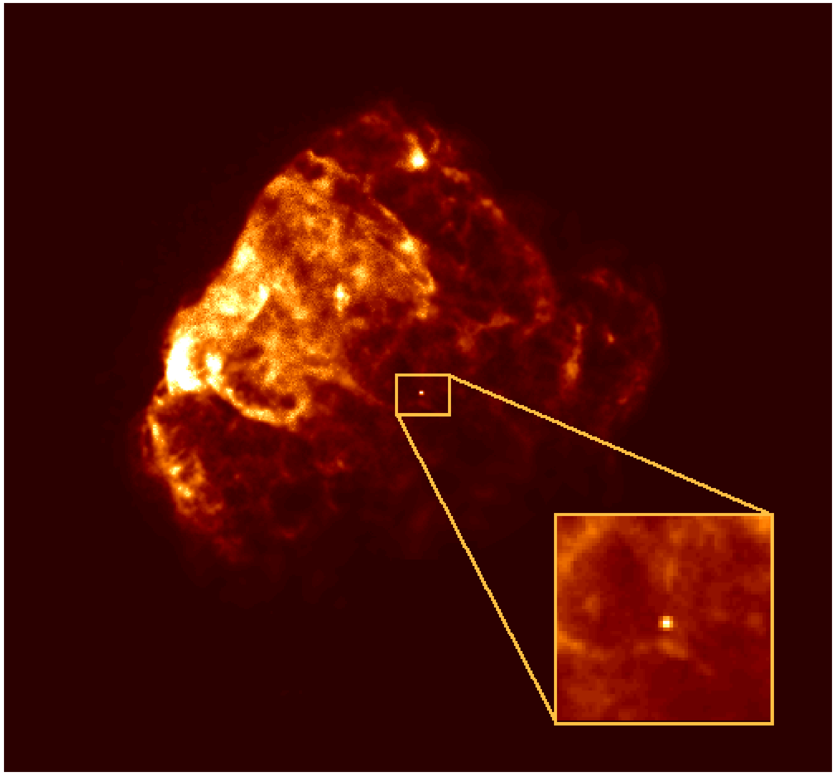
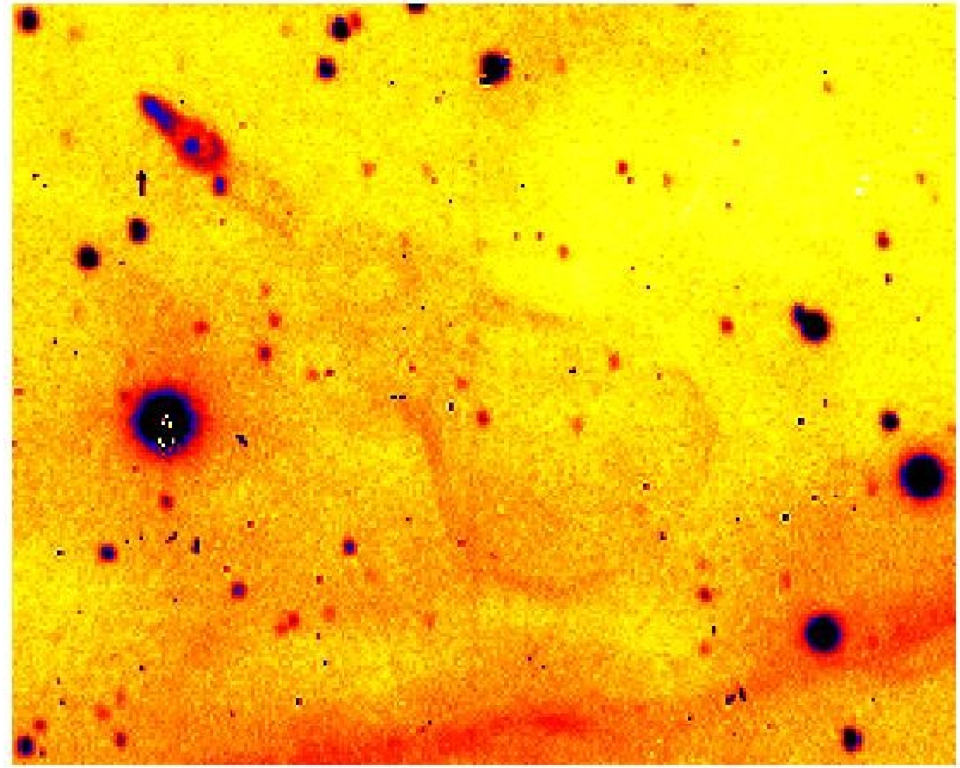
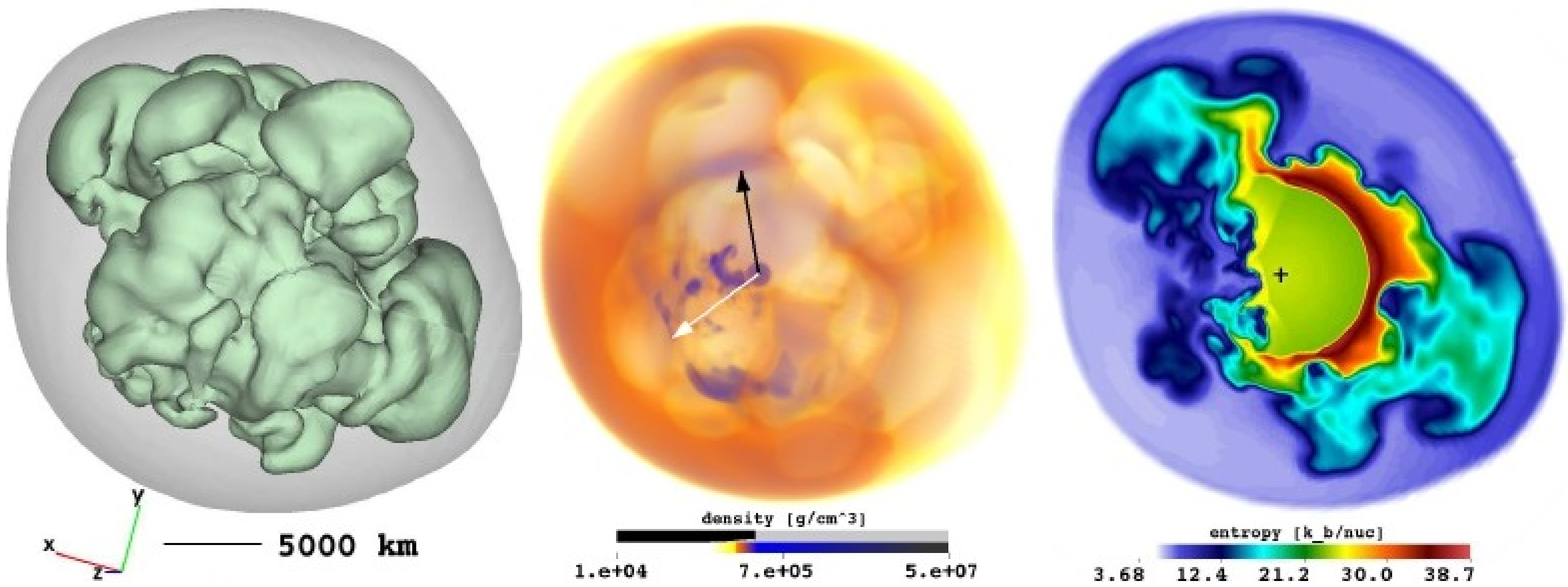


Neutron Star Kicks in 3D SN Explosions

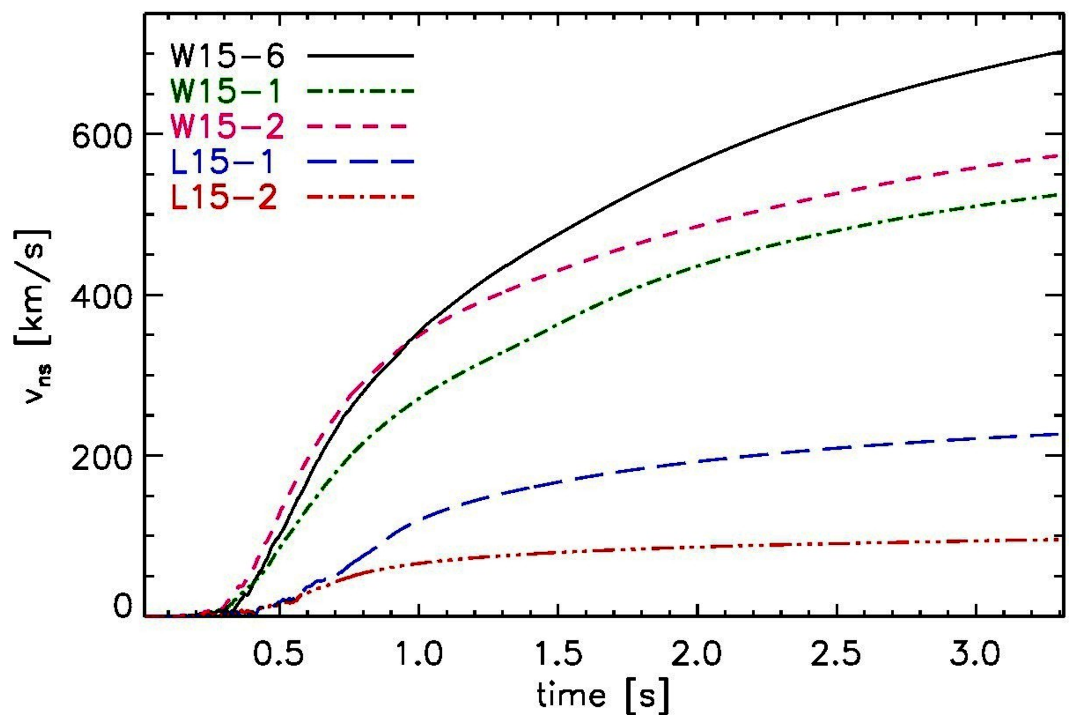
Neutron Star Recoil in 3D Explosion Models



Gravitational tug-boat mechanism

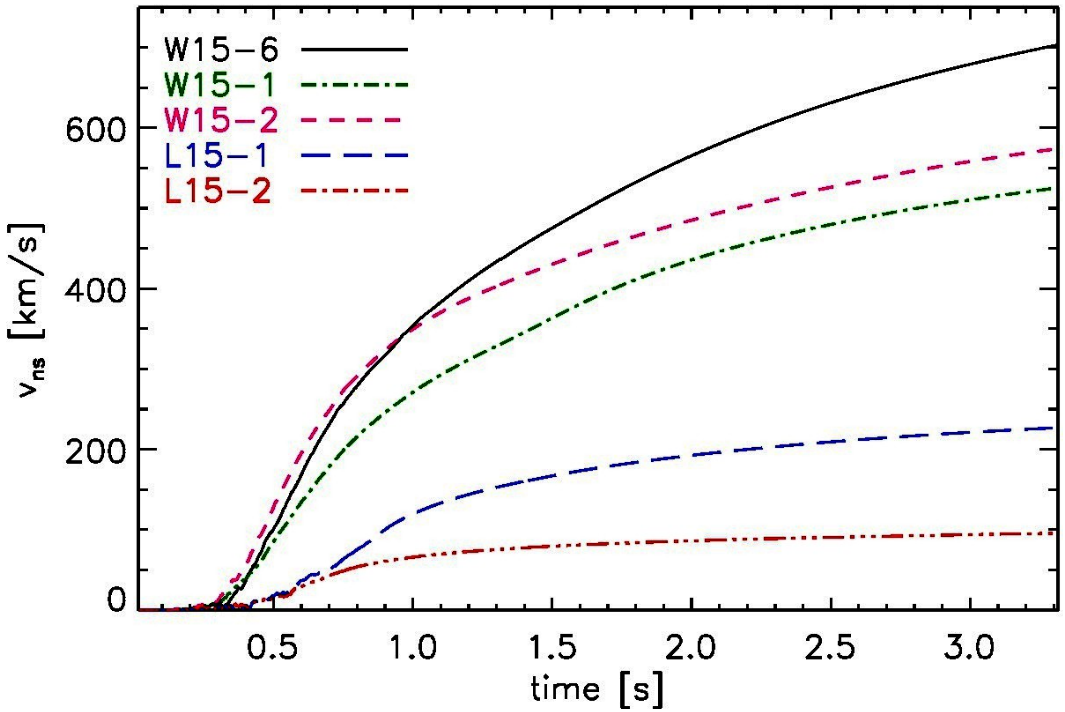
$$v_{\rm ns} \approx \frac{2G\Delta m}{r_{\rm i} v_{\rm s}} \approx 540 \left[\frac{\rm km}{\rm s}\right] \frac{\Delta m_{-3}}{r_{\rm i,7}\, v_{\rm s,5000}},$$

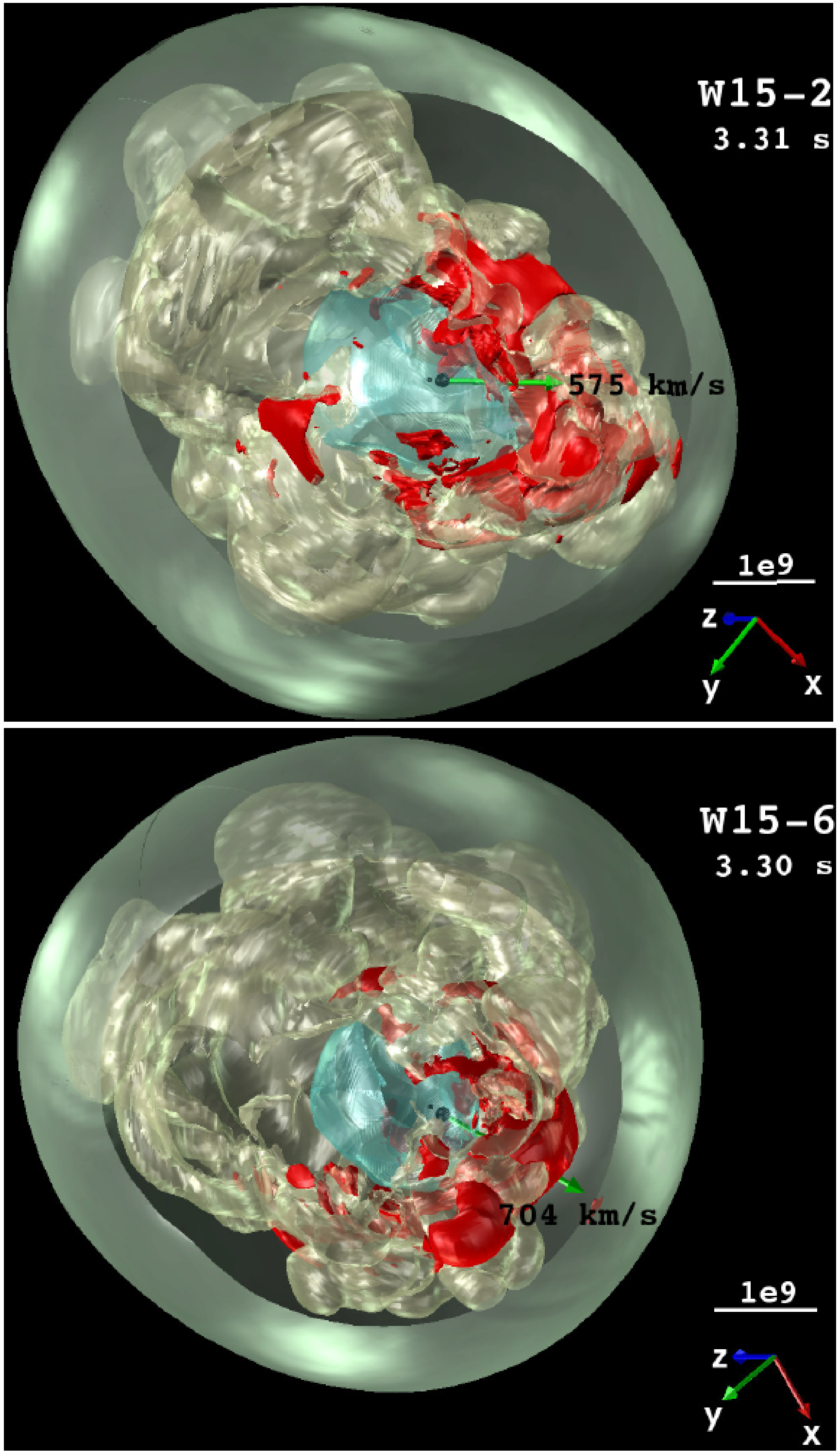
where Δm is normalized by $10^{-3}\,M_{\odot}$, $r_{\rm i}$ by 10^7 cm, and $v_{\rm s}$ by $5000\,{\rm km\,s^{-1}}$.



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

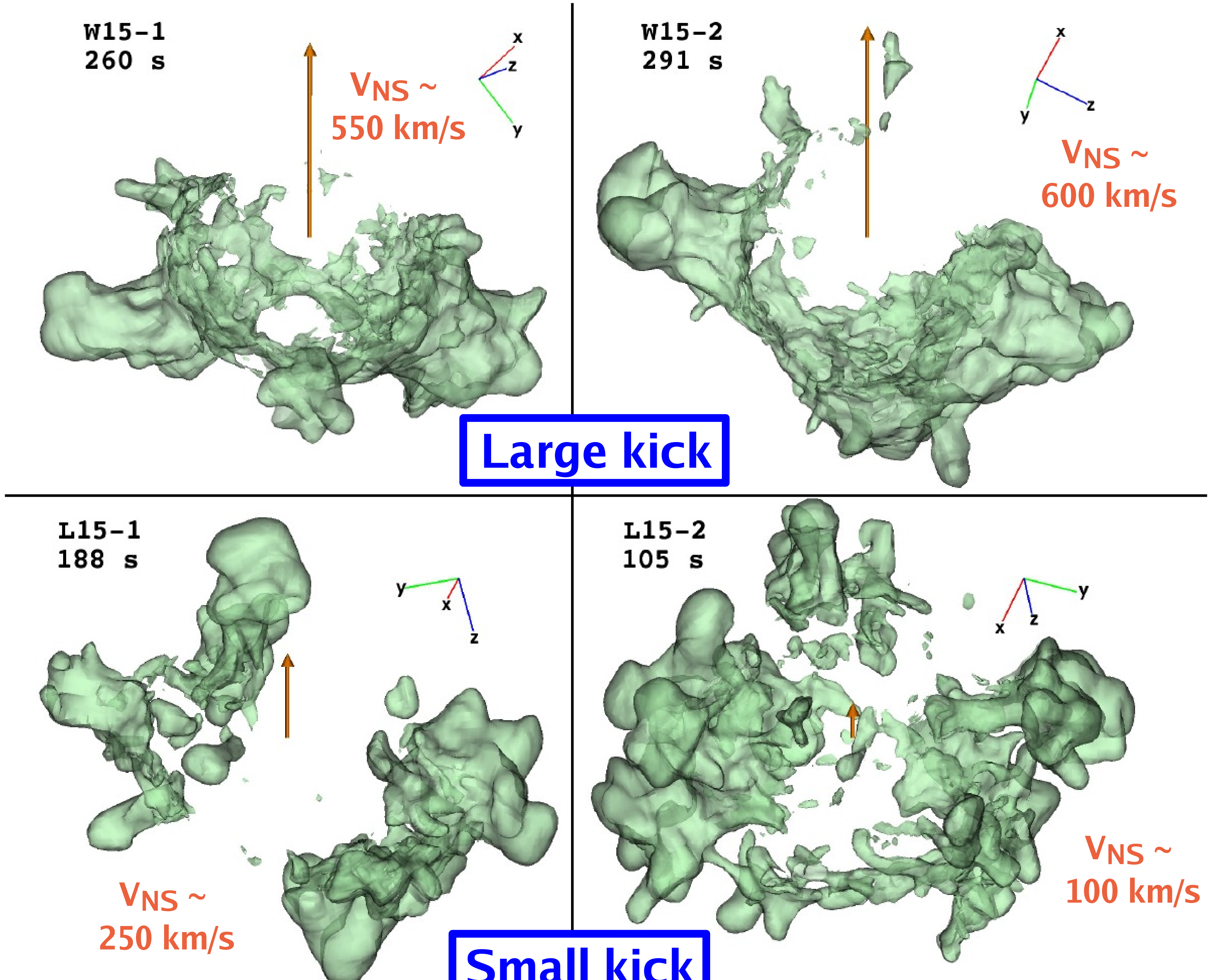
Neutron Star Recoil by "Gravitational Tug-Boat" Mechanism





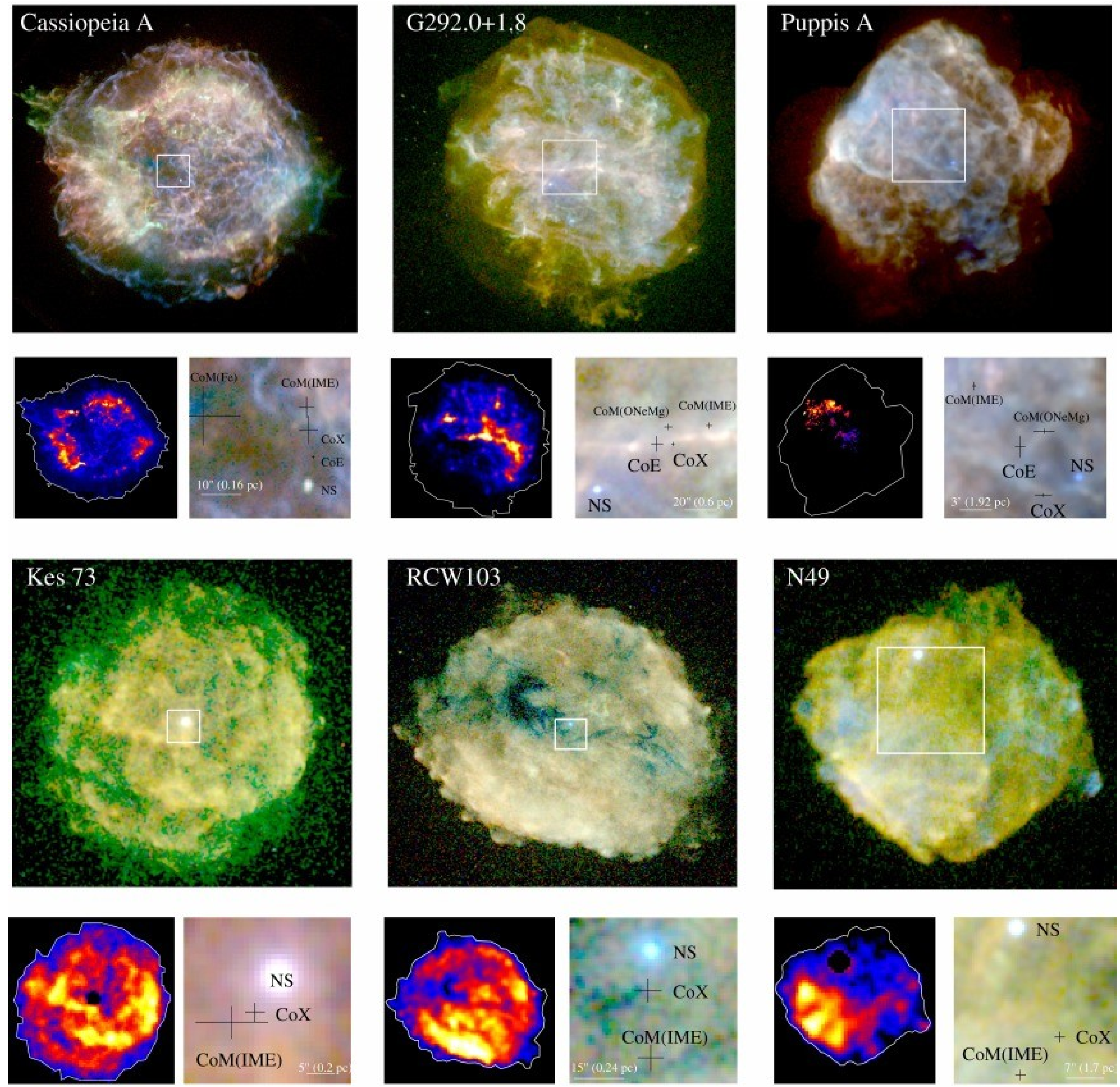
(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A (2013), arXiv:1210.8148)

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



Neutron Star Kicks and Young SN Remnants

Analysis of spatial distribution of IMEs (from Ne to Fe-group) in young, nearby SNRs with known NS kick velocities.



Katsuda, Morii, THJ, et al.
arXiv:1710.10372

see also:
Holland-Ashford, et al., ApJ 844 (2017) 84;
Bear & Soker, arXiv:1710.00819

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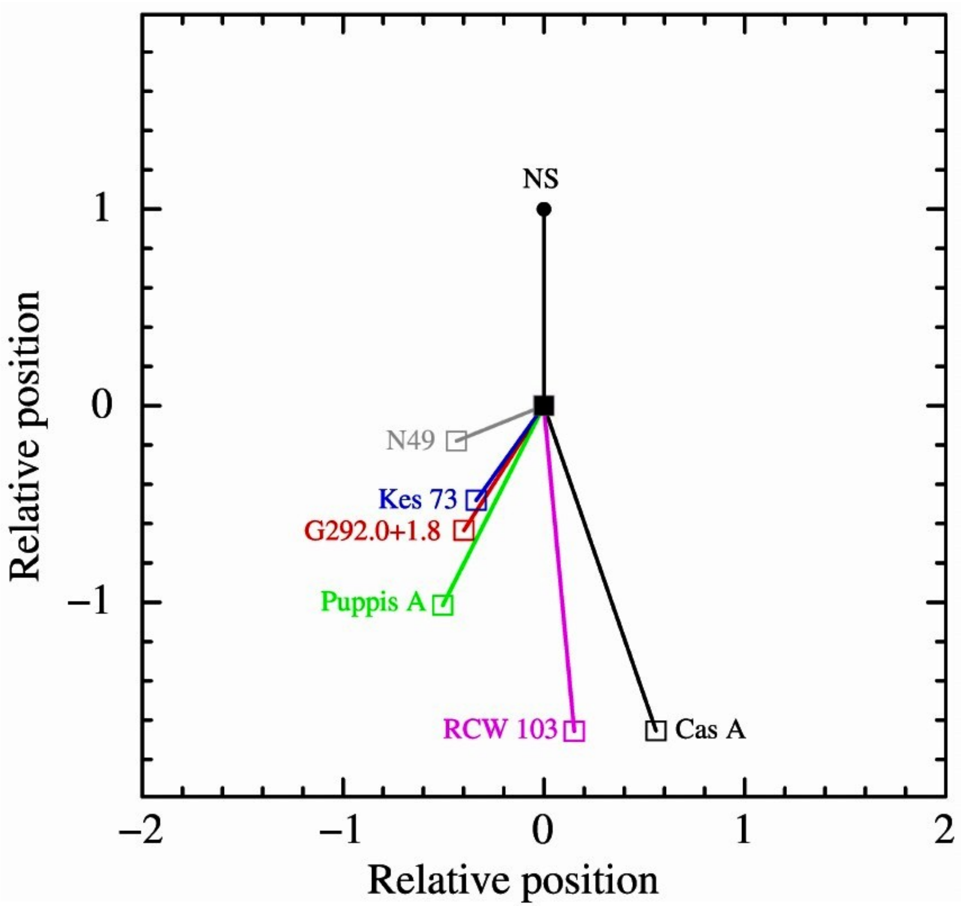
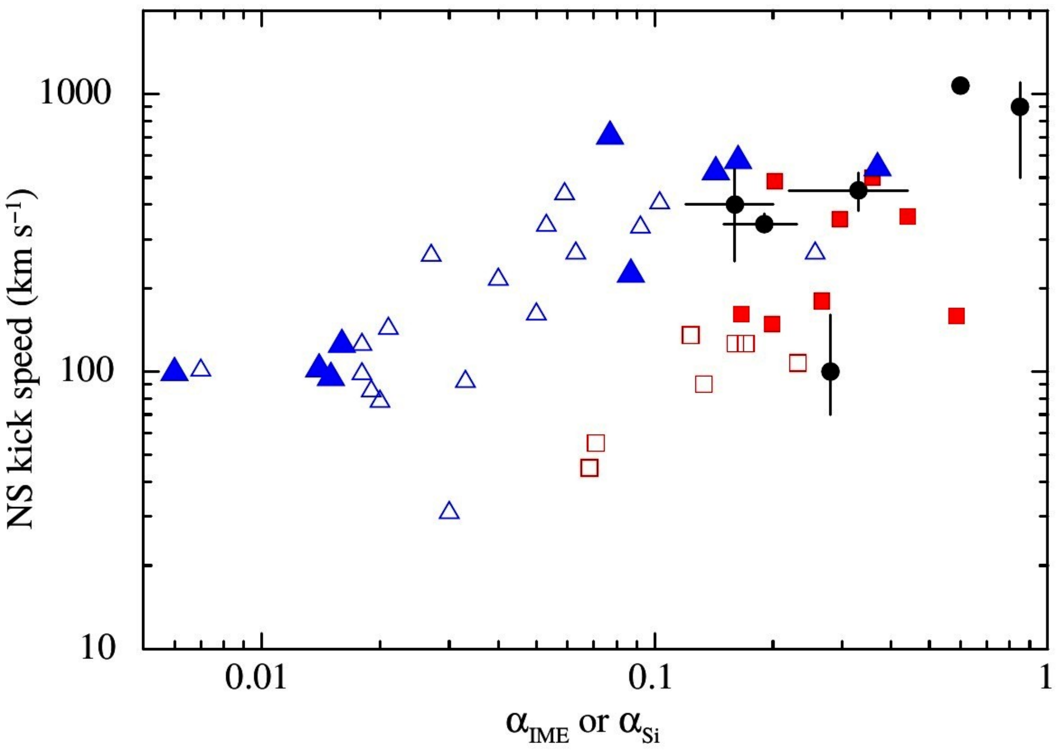
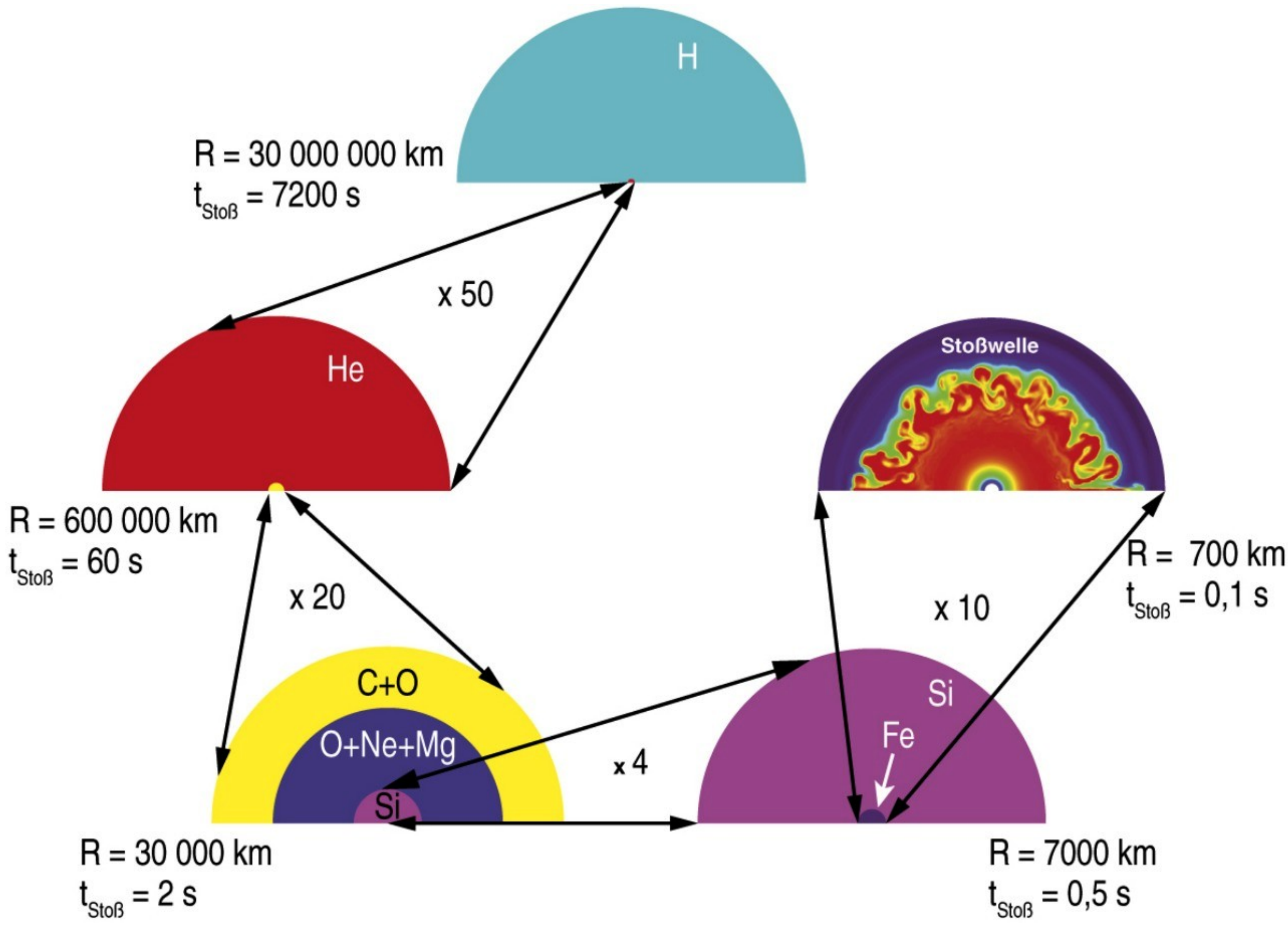
Analysis of spatial distribution of IMEs (from Ne to Fe-group) in young, nearby SNRs with known NS kick velocities.

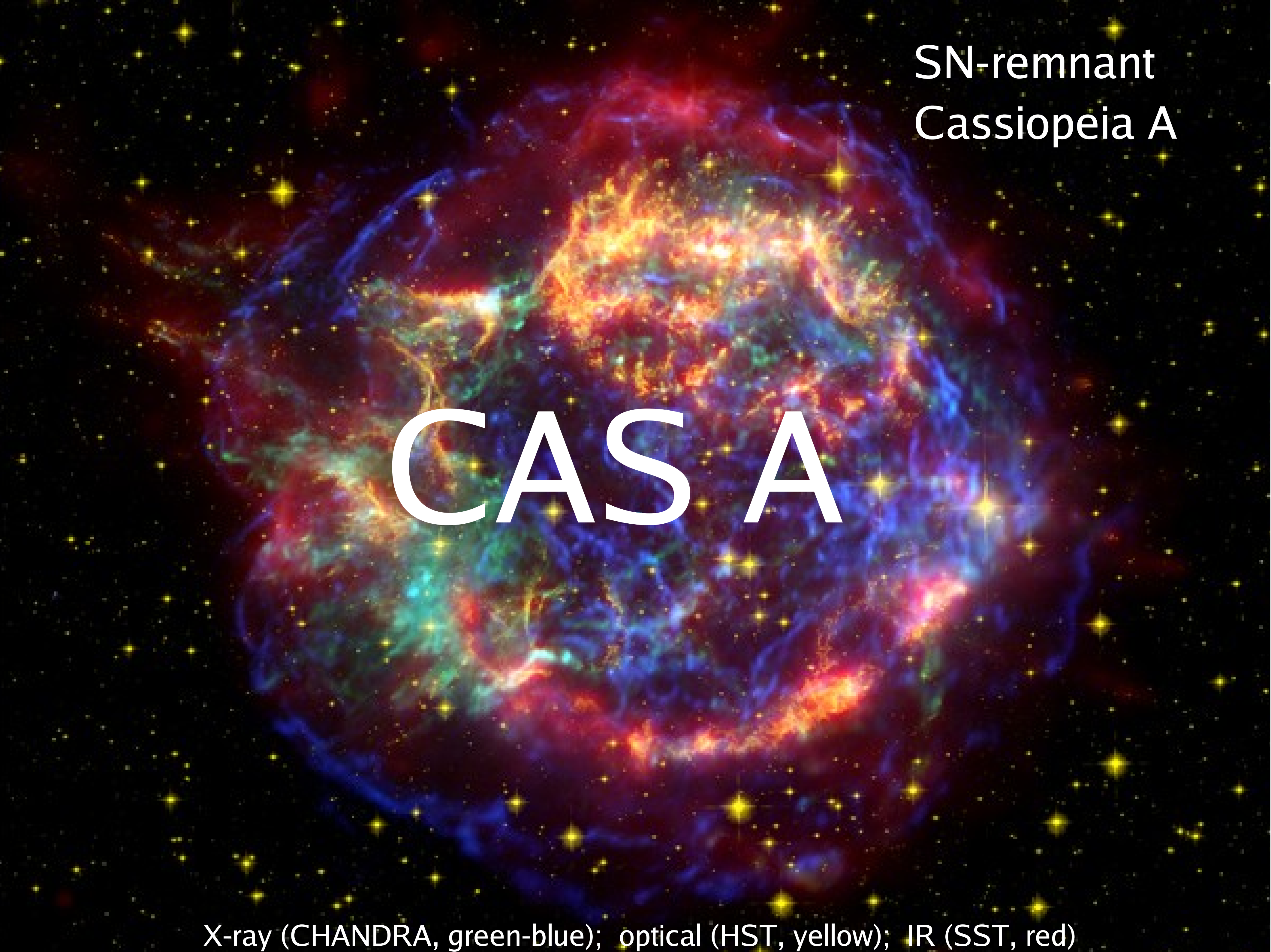


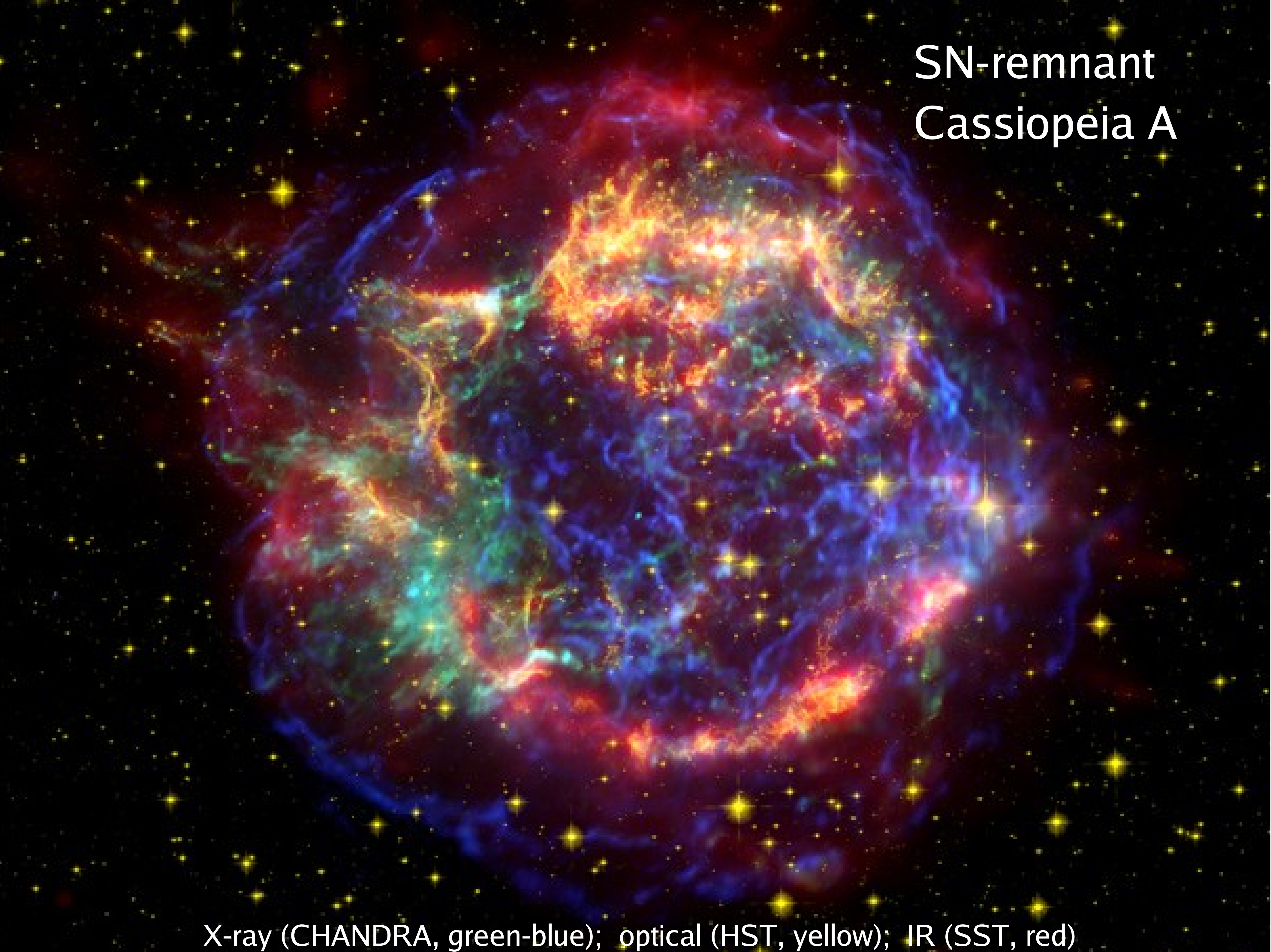


Katsuda, Morii, THJ, et al. arXiv:1710.10372

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 !



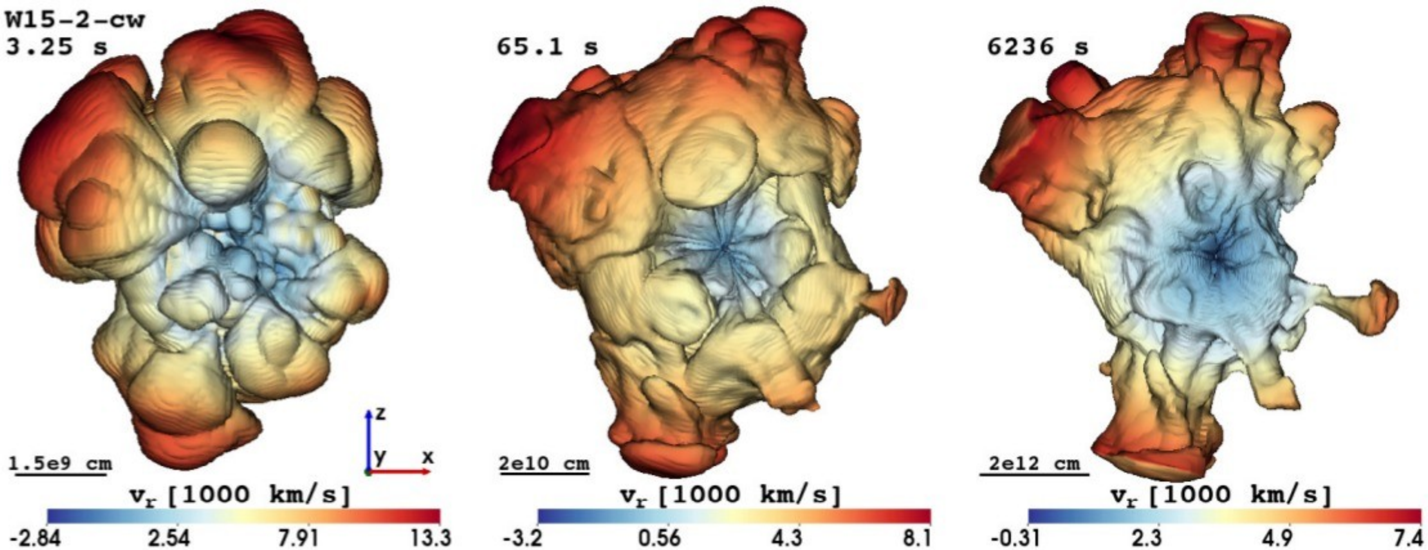

SN-remnant
Cassiopeia A
CAS A
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

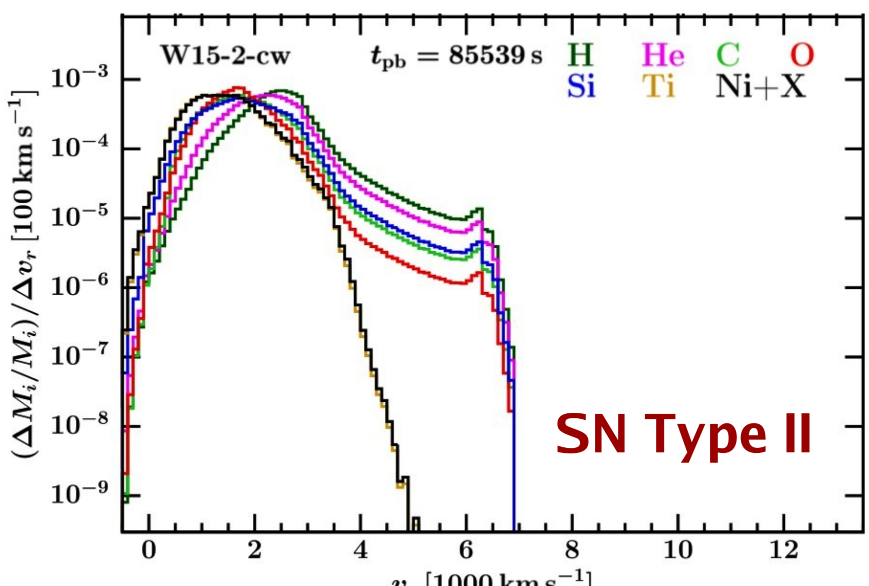


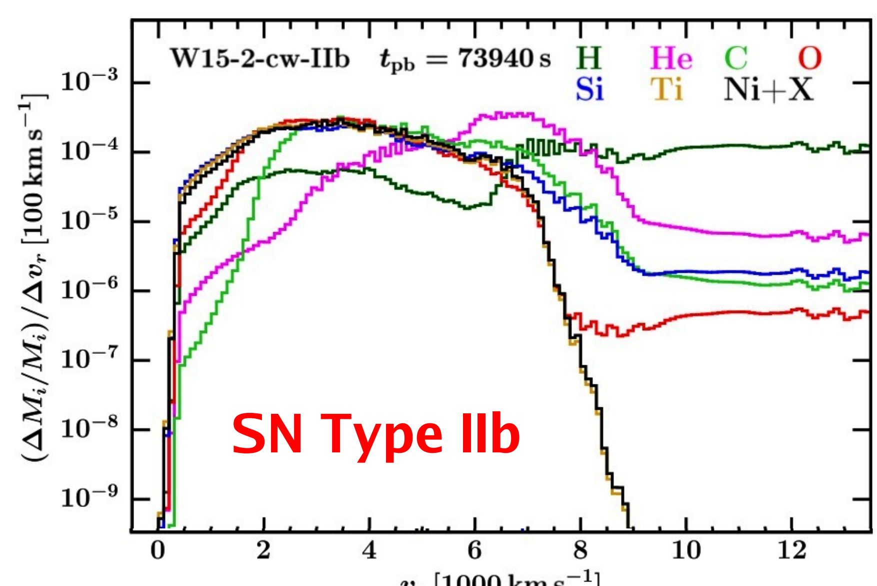
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

Supernovae Type IIb: Very little Hydrogen

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







Total ^{56}Ni (^{56}Fe) and ^{44}Ti Yields

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

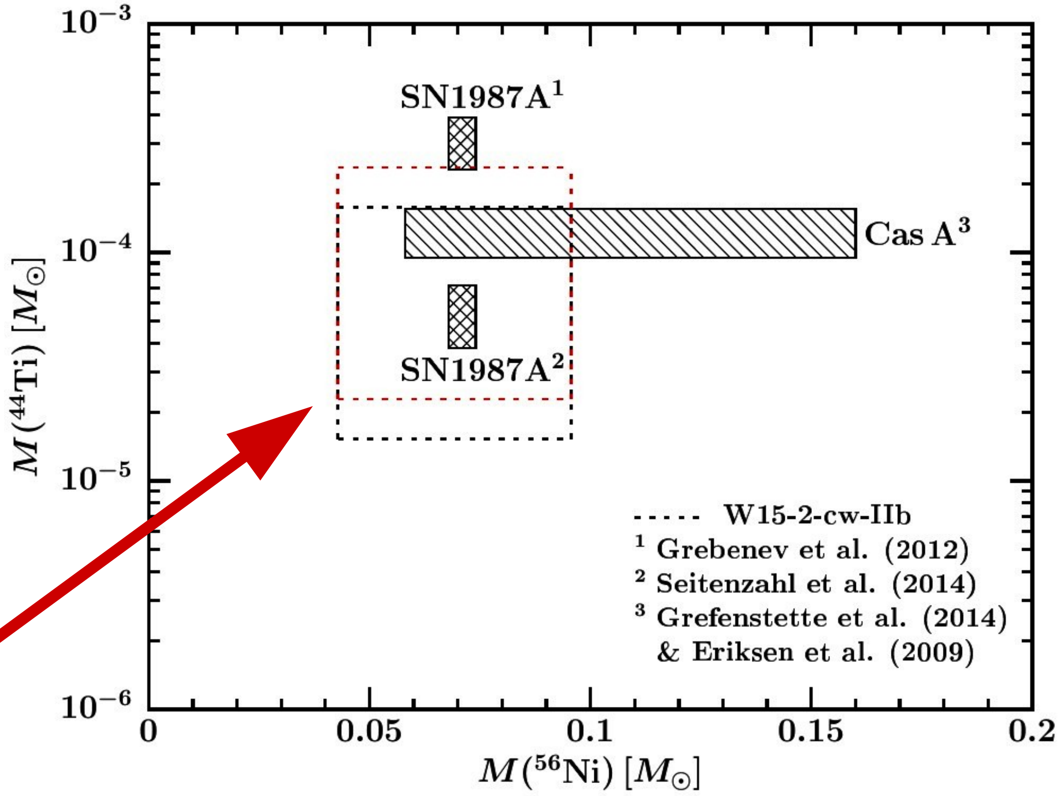
Table 1. Yields from nucleosynthetic post-processing of tracer particles.

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}
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

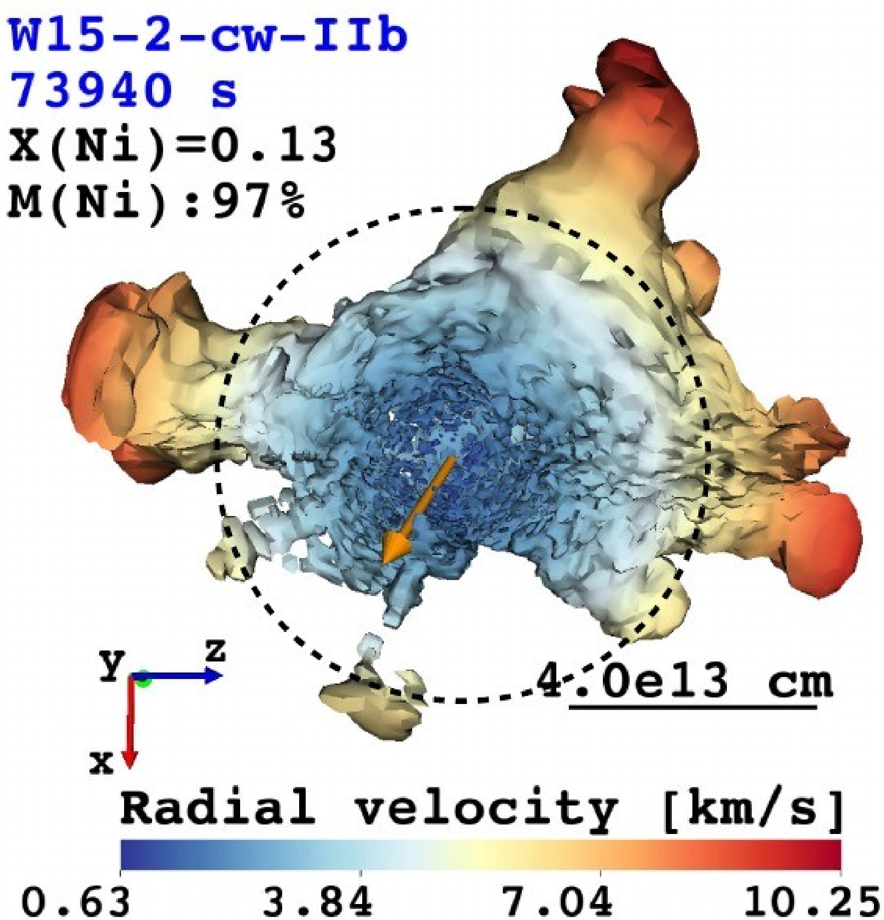
^{44}Ti yield is increased by factor 1.5 when rate of ^{44}Ti(α,p)^{47}V reaction is reduced by factor of 2 as suggested by recent experiments (Margerin et al. 2014).

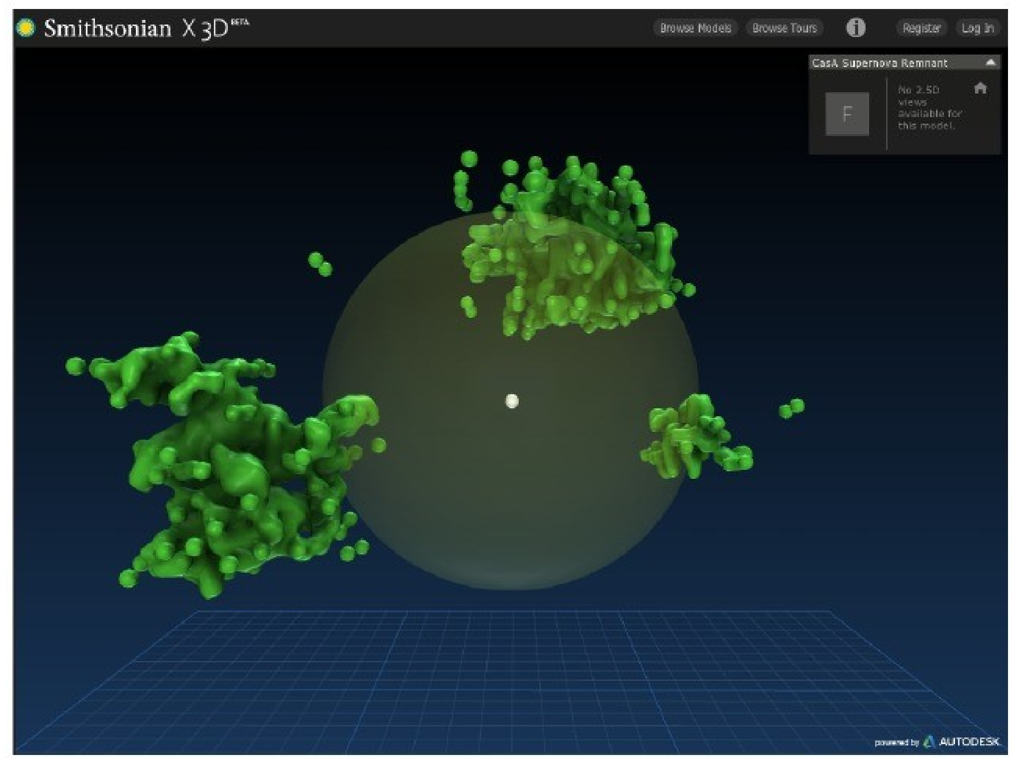


Wongwathanarat et al., ApJ 842 (2017) 13

Chemical Asymmetries in CAS A Remnant

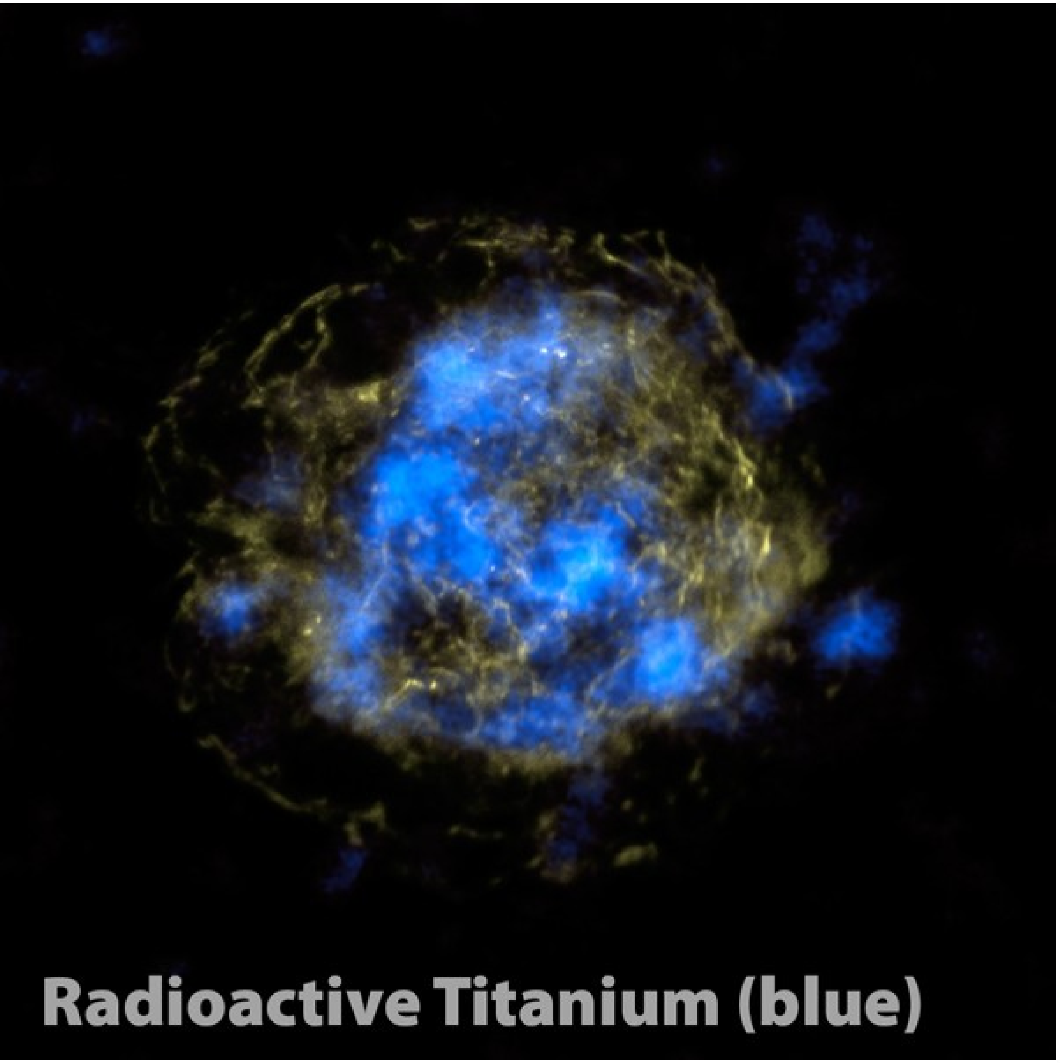
Iron in Cas A is visible in three big "fingers" in the remnant shell that is heated by reverse shock from circumstellar medium interaction.

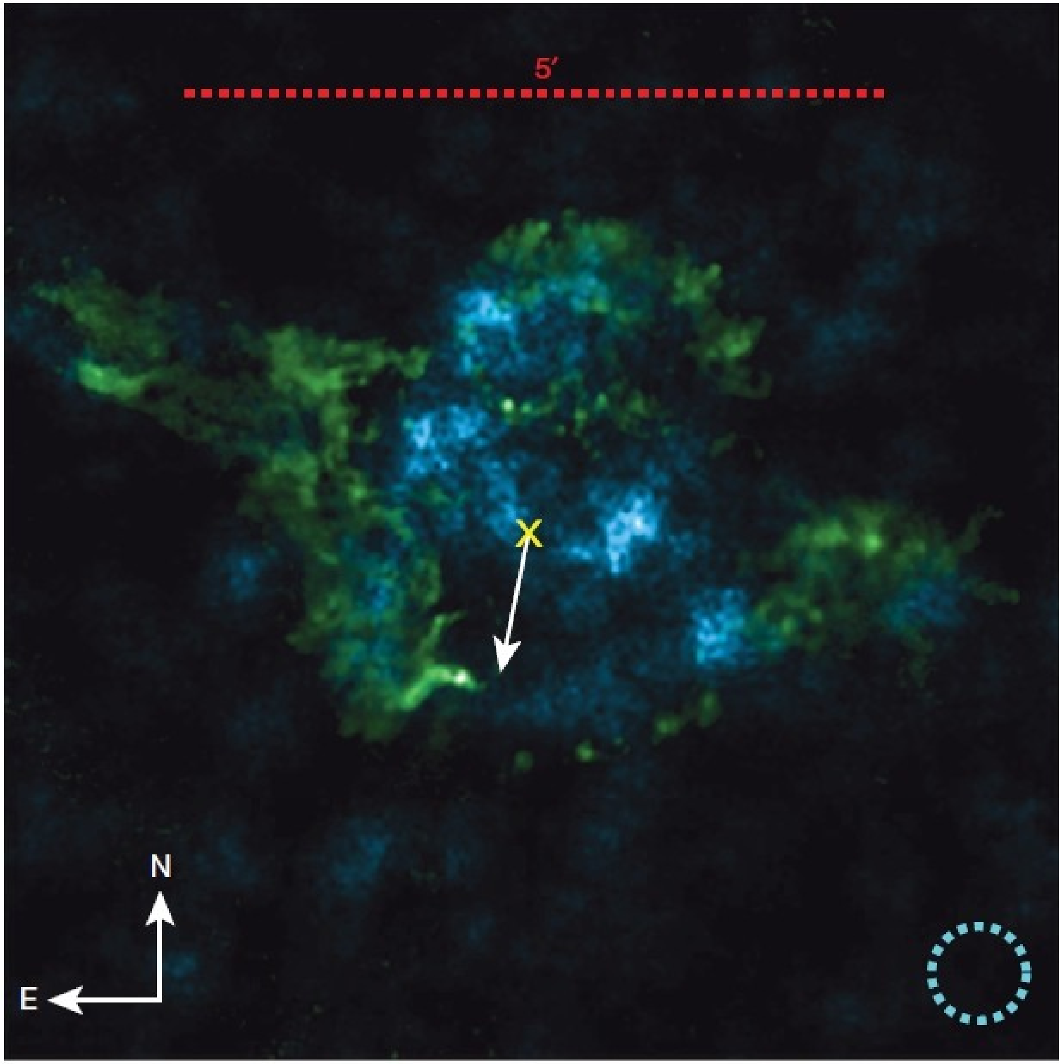




Wongwathanarat et al., ApJ 842 (2017) 13

^{44}Ti Asymmetry in the CAS A Remnant

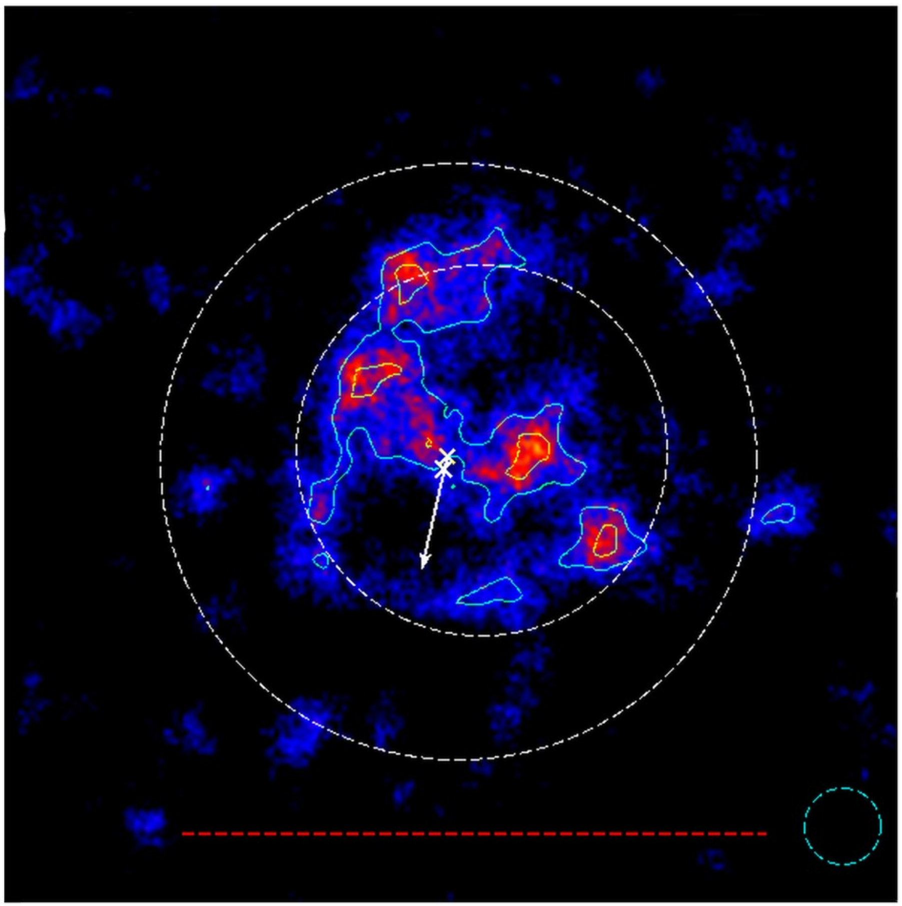


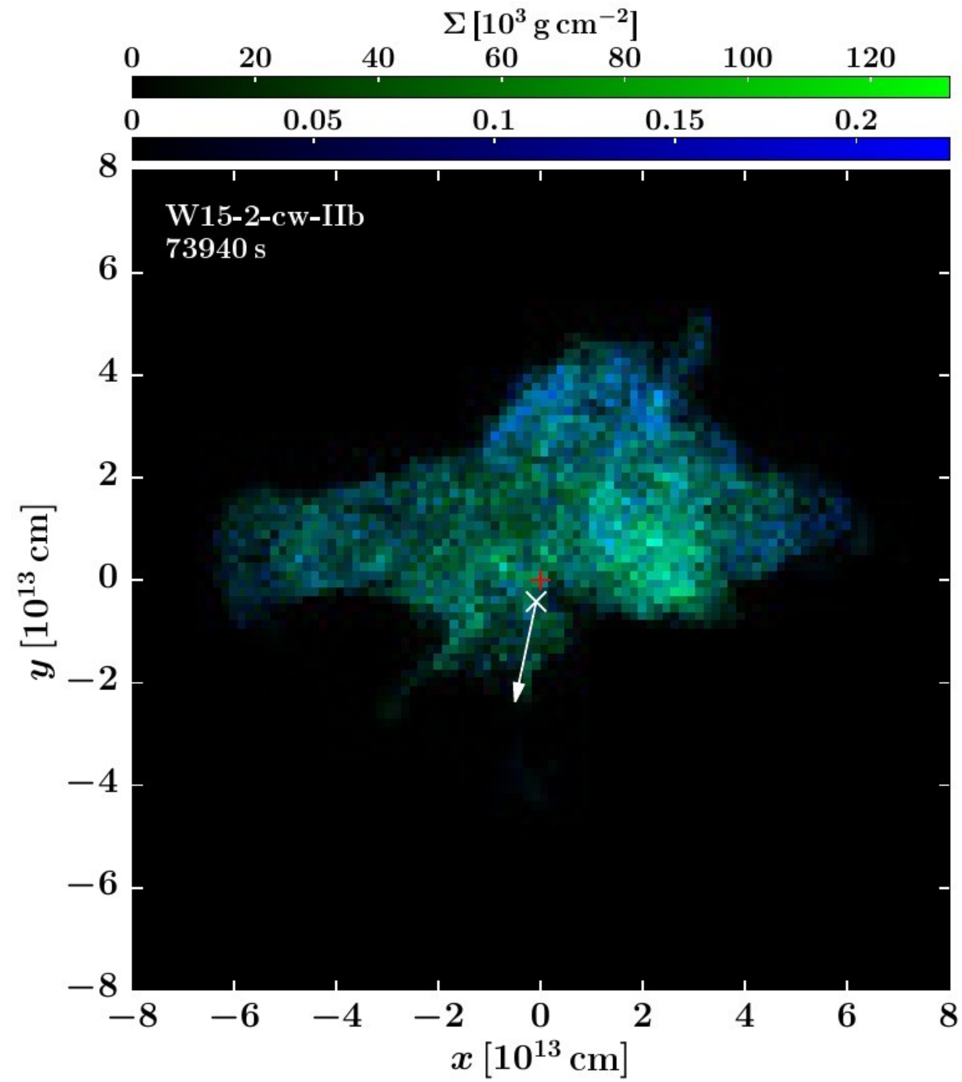


NuSTAR observations

Grefenstette et al., Nature 506 (2014) 340

Neutron Star Recoil and Nickel & 44Ti Distribution

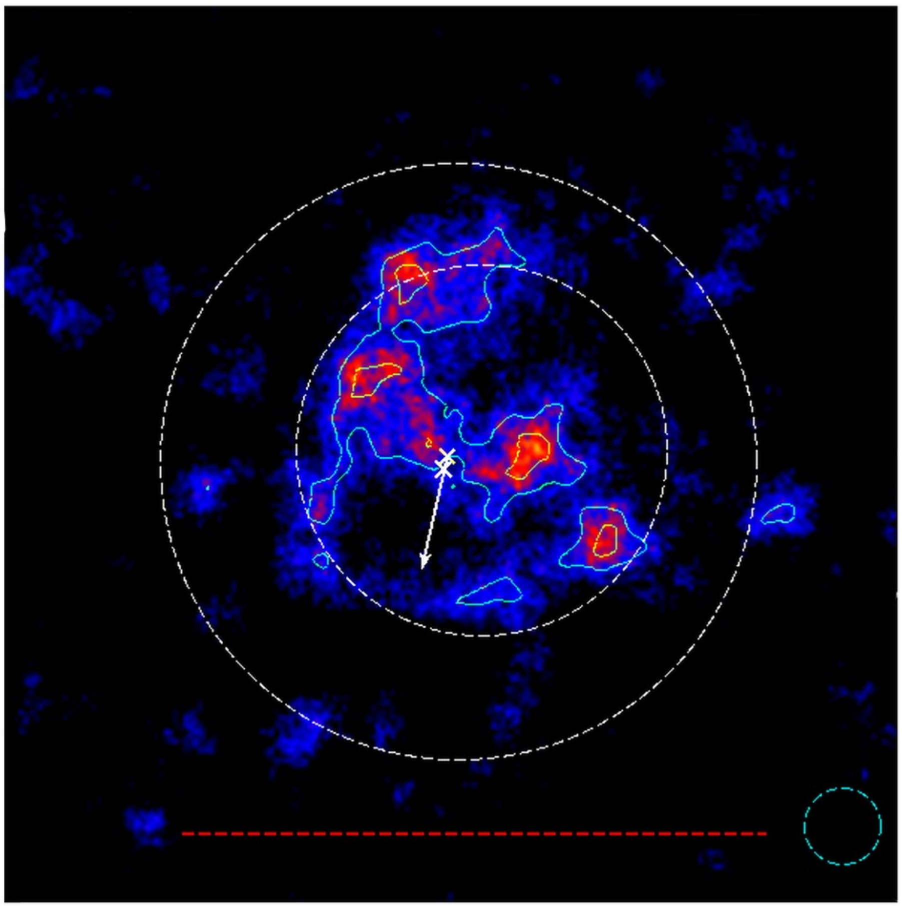




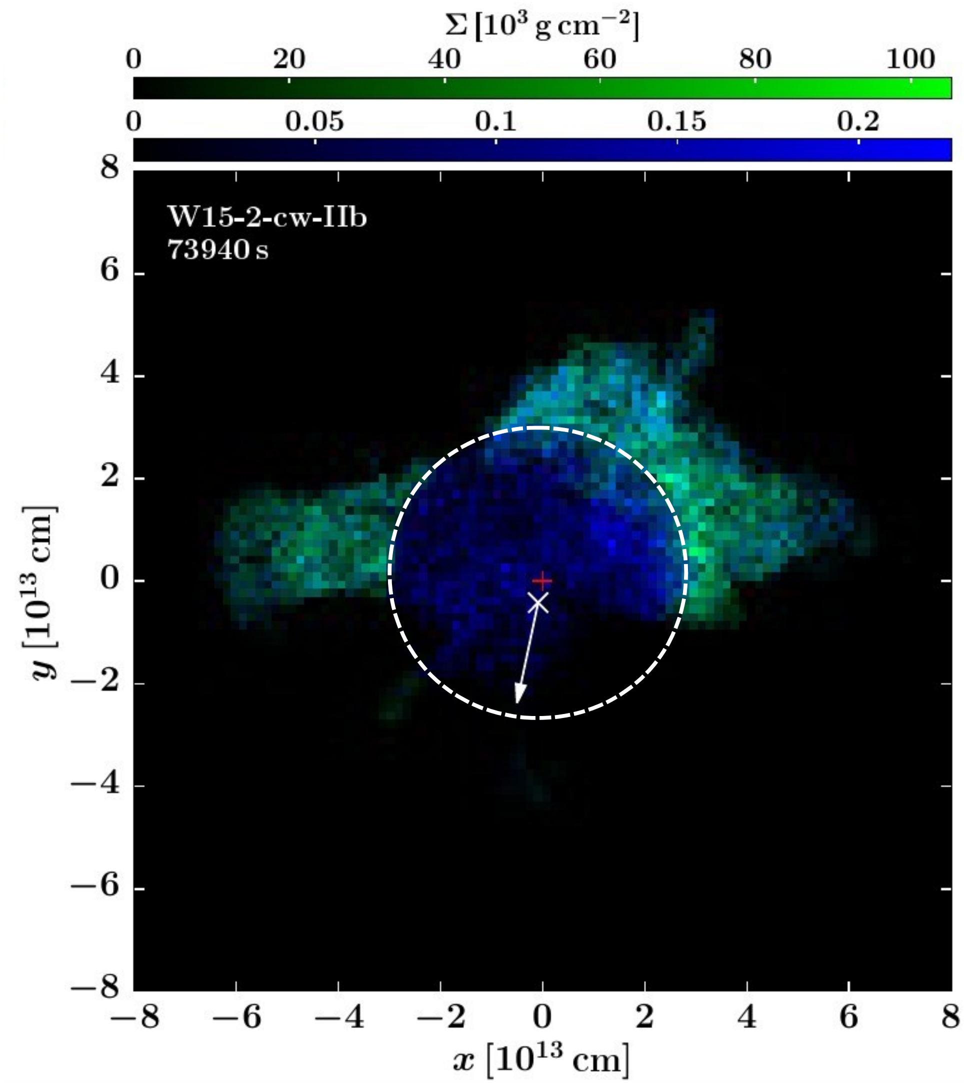
Grefenstette et al., Nature 506 (2014) 340

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

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

CAS A "Thick Disk"

Grefenstette et al., ApJ 834 (2017) 19

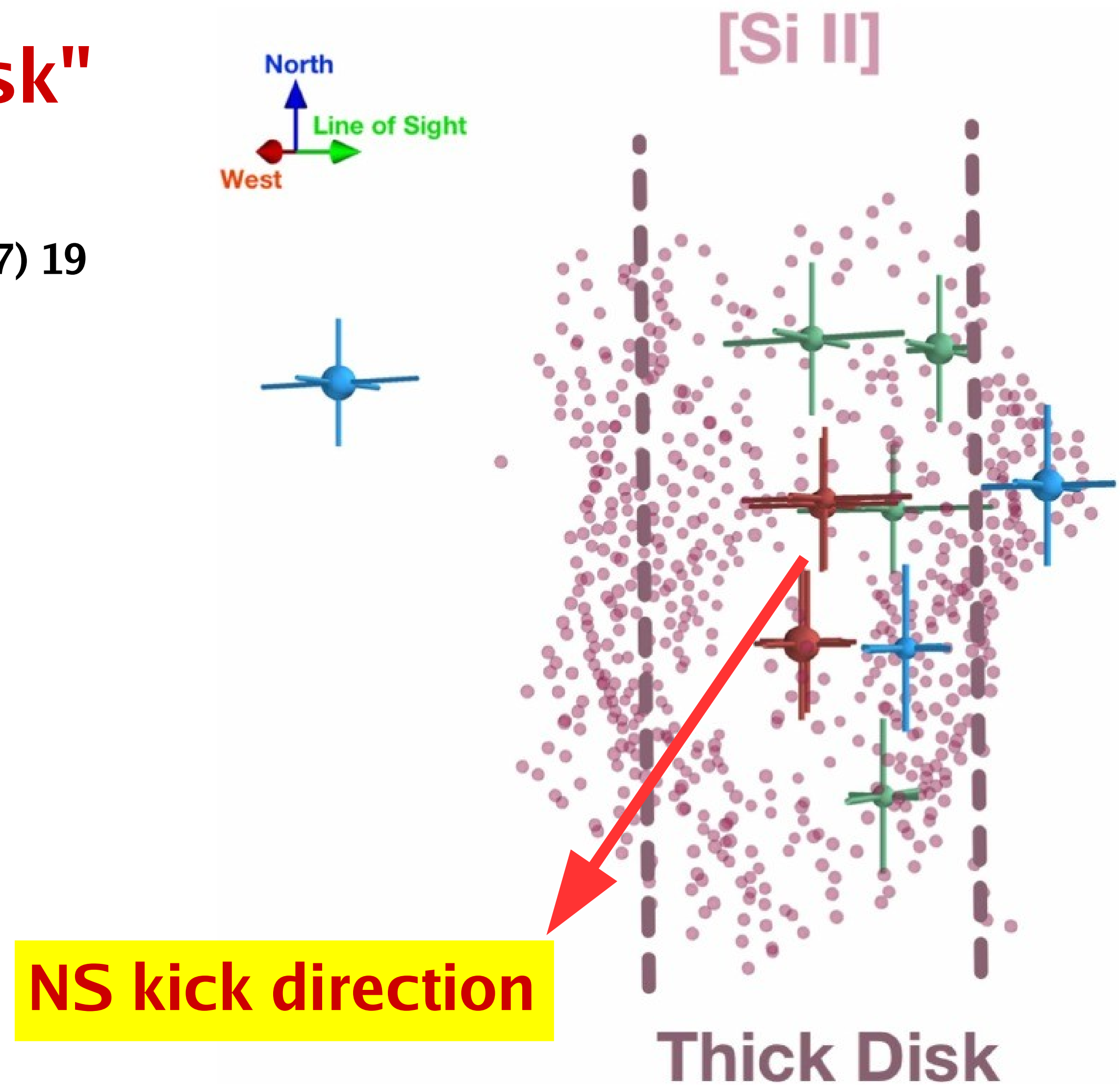
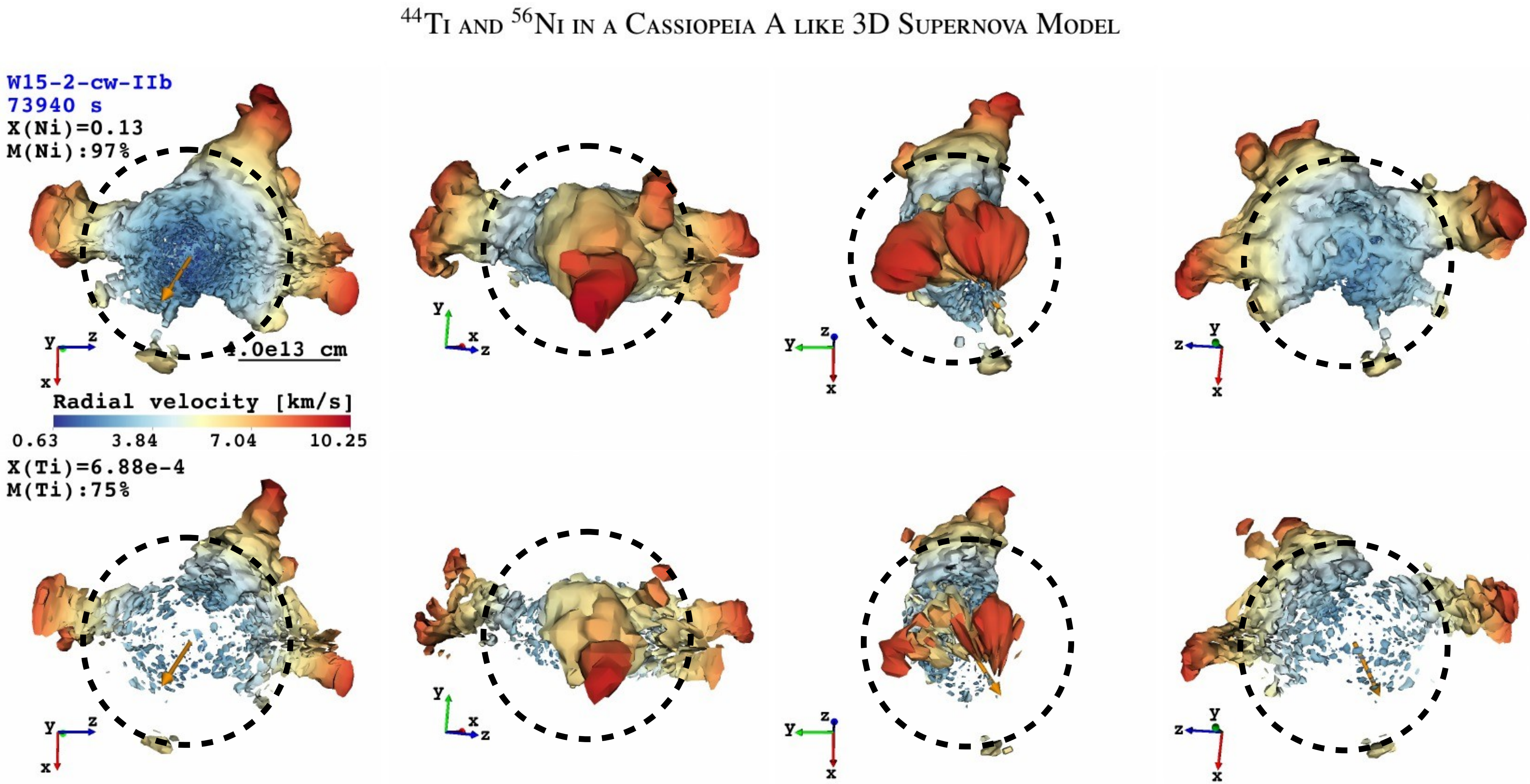


Figure 12. The 3D distribution of the observed ^{44}Ti ejecta compared with the IR [Si II] emission observed by *Spitzer* (DeLaney et al. 2010). The ^{44}Ti ejecta

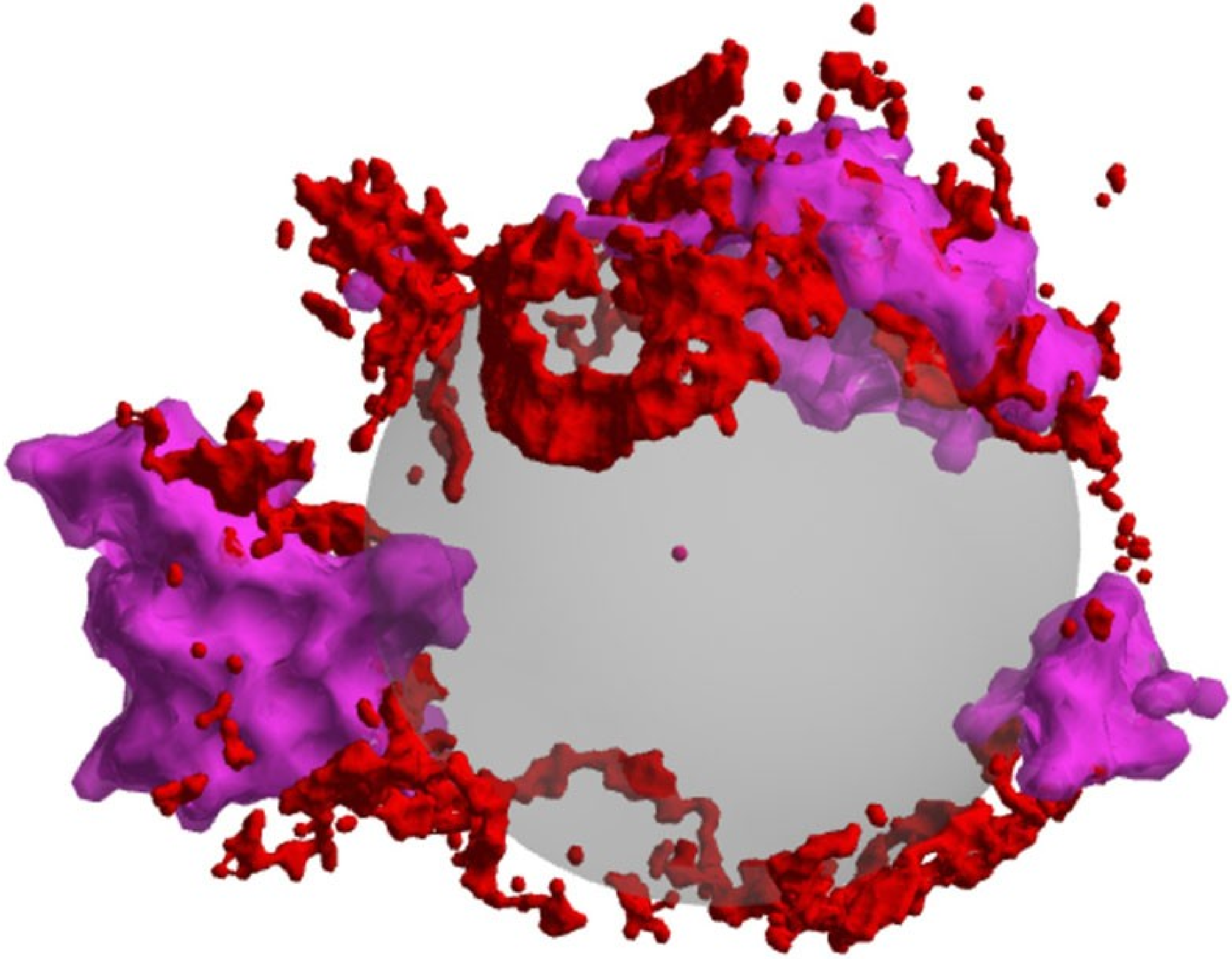
Thick Disk Structure of CAS A Model



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

Wongwathanarat et al., ApJ 842 (2017) 13

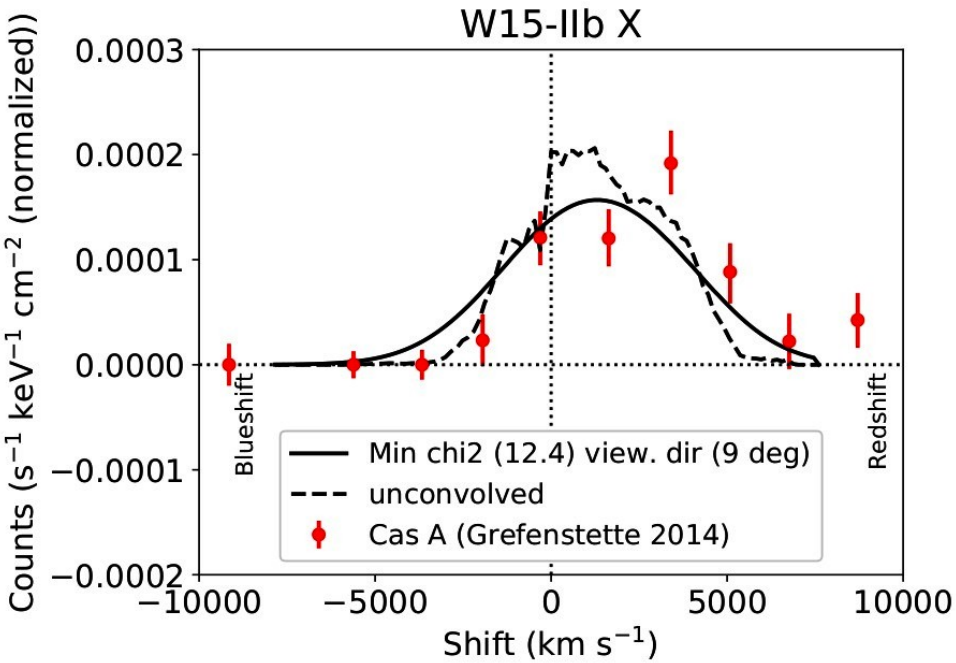
Intermediate Mass Element Asymmetries inCAS A Remnant



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

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

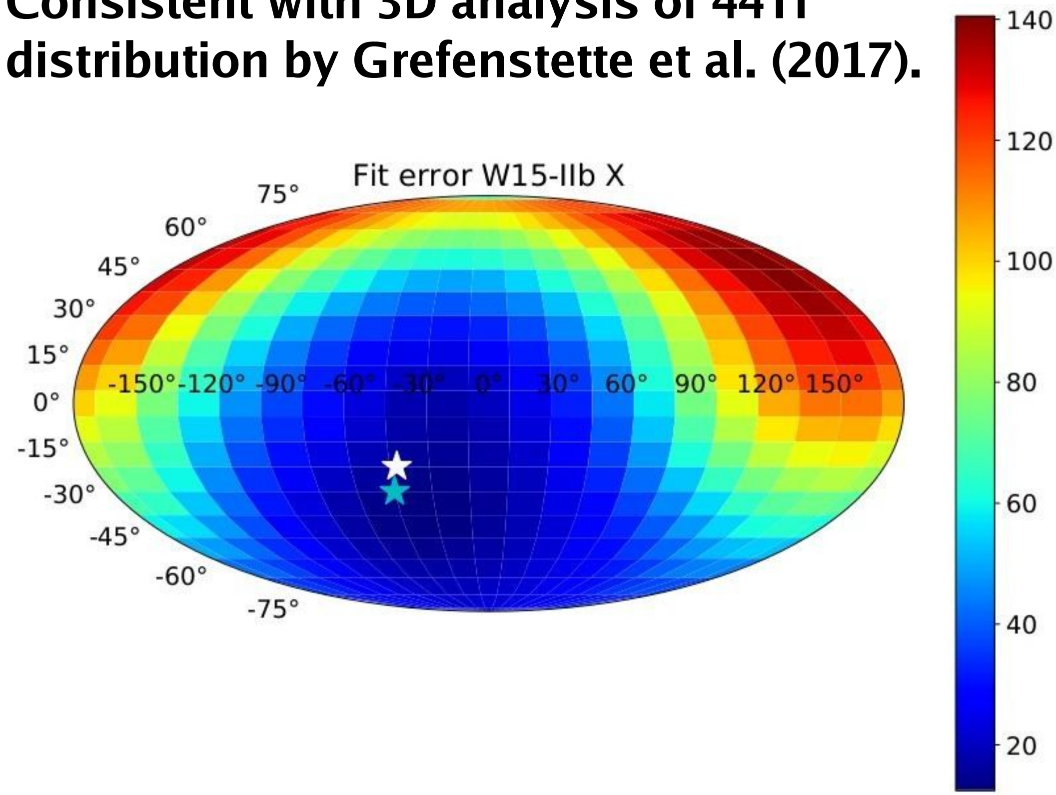
Cas A: Gamma-Ray Line Profiles of ^{44}Ti



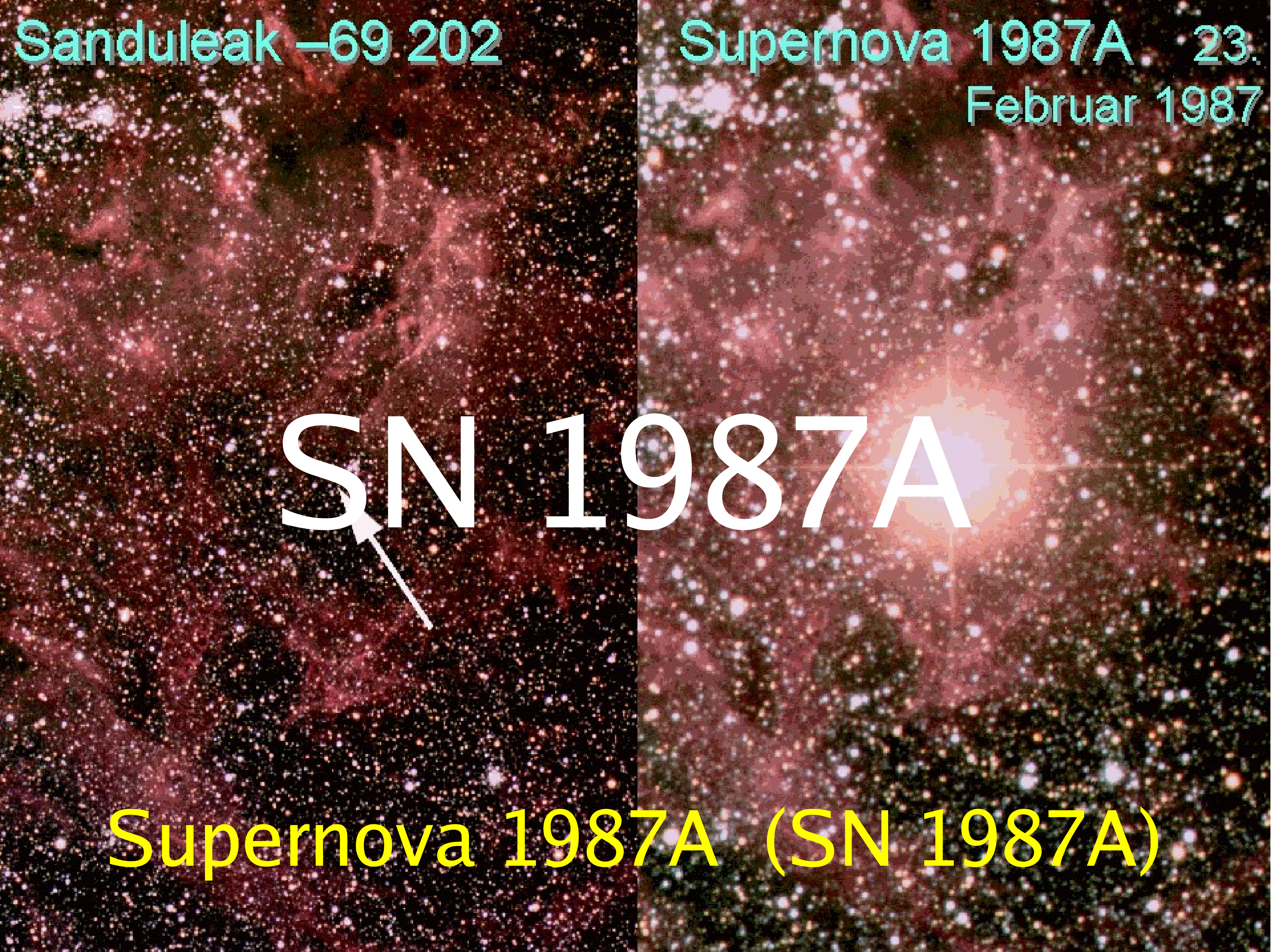
NS in Cas A has high kick (~500–700 km/s) with small inclination angle (within <40–5 0 degrees) to line of sight.

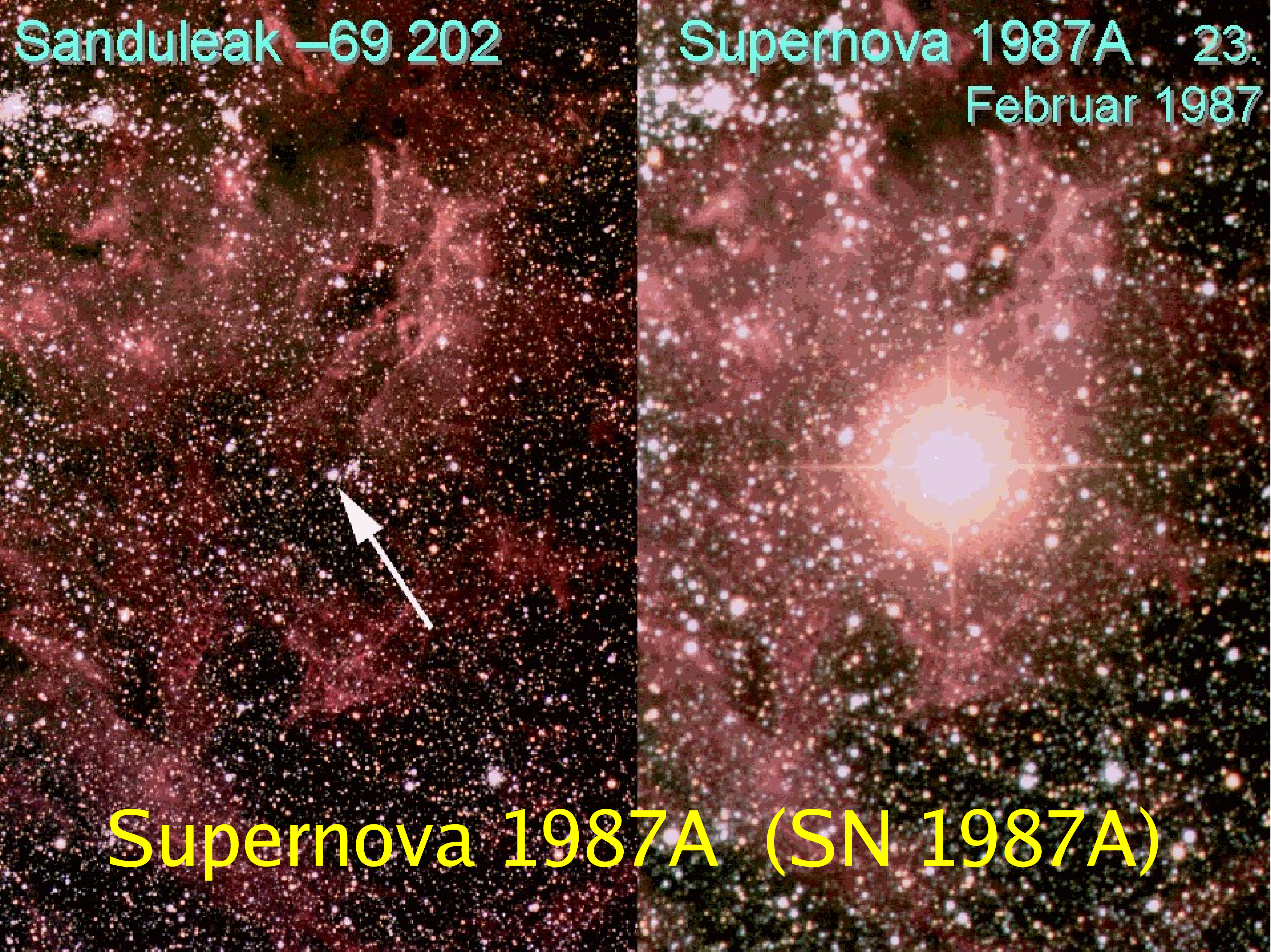
Consistent with 3D analysis of 44Ti distribution by Grefenstette et al. (2017).

Line centroid of ^{44}Ti decay line strongly redshifted

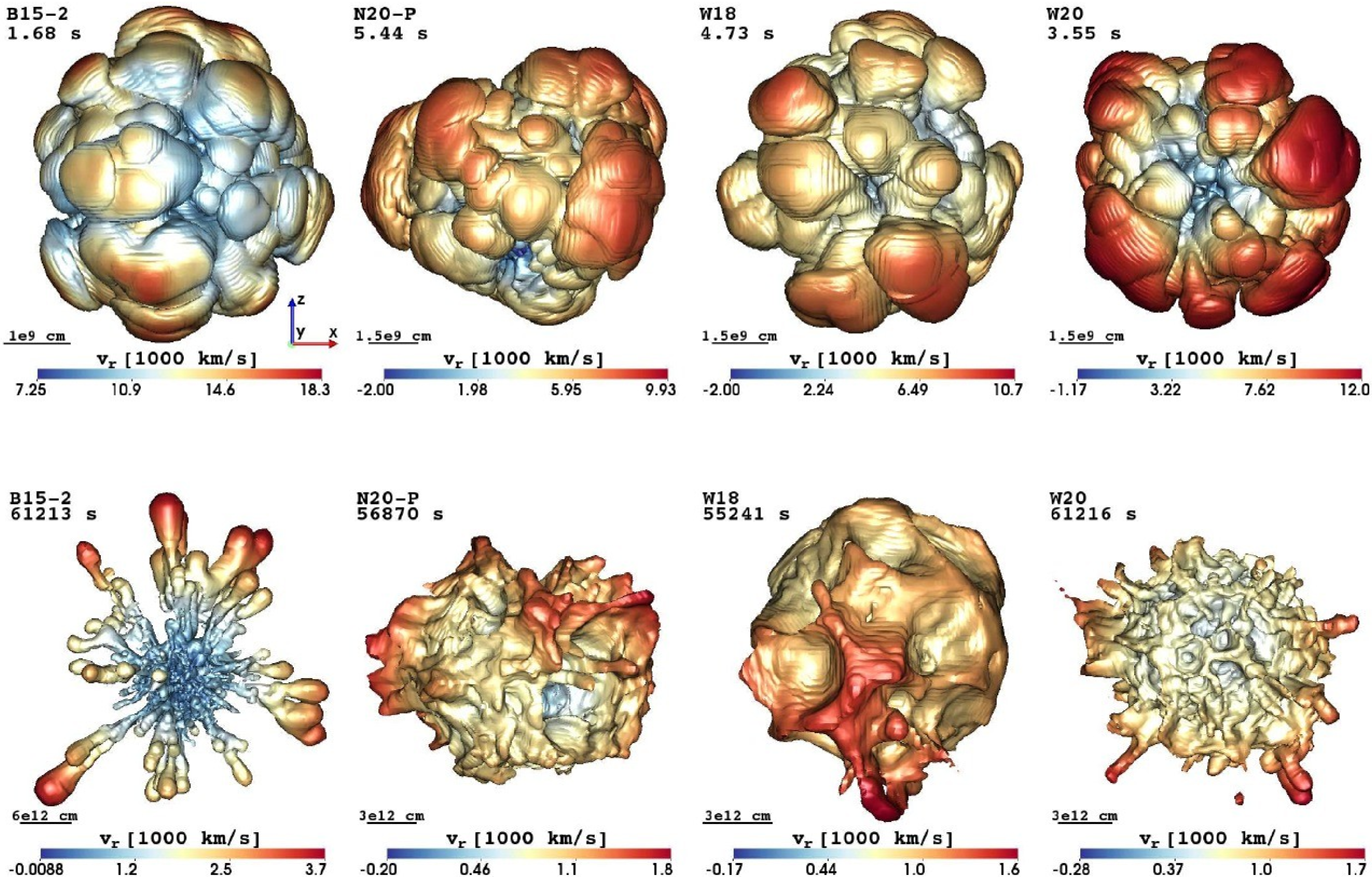


Jerkstrand et al., in preparation


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)

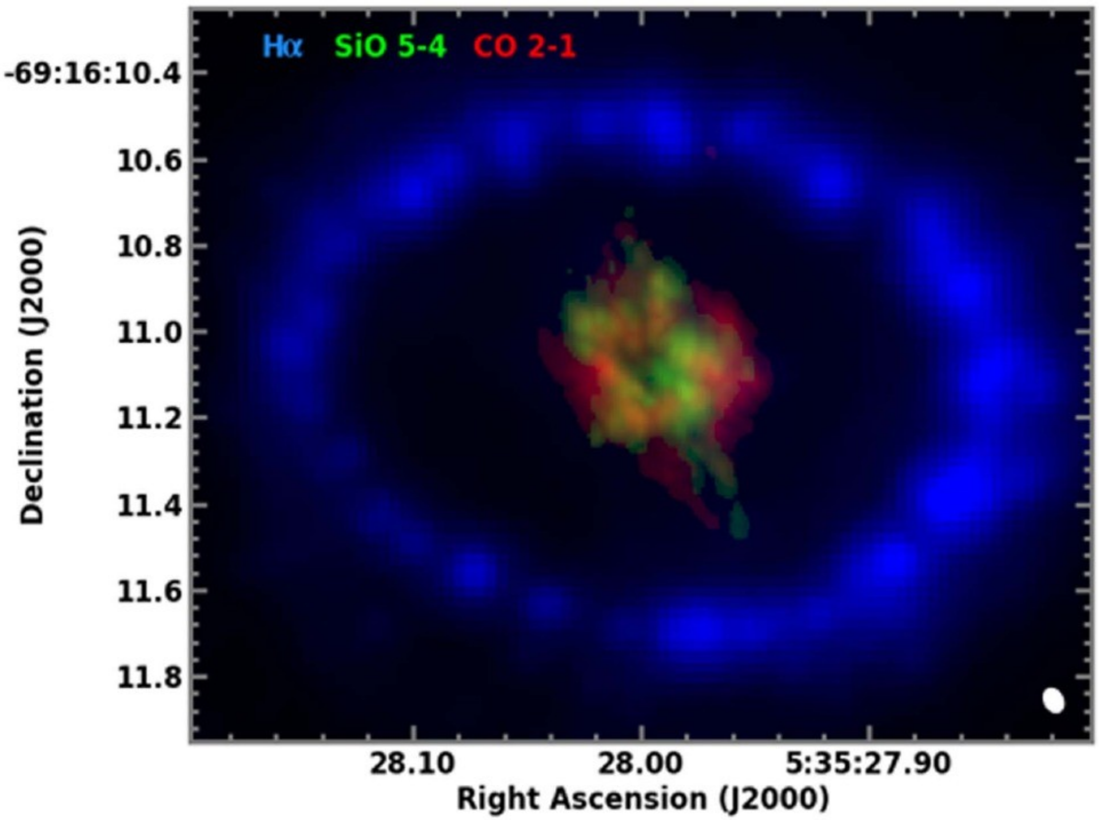
SN1987A Models: 3D Morphologies



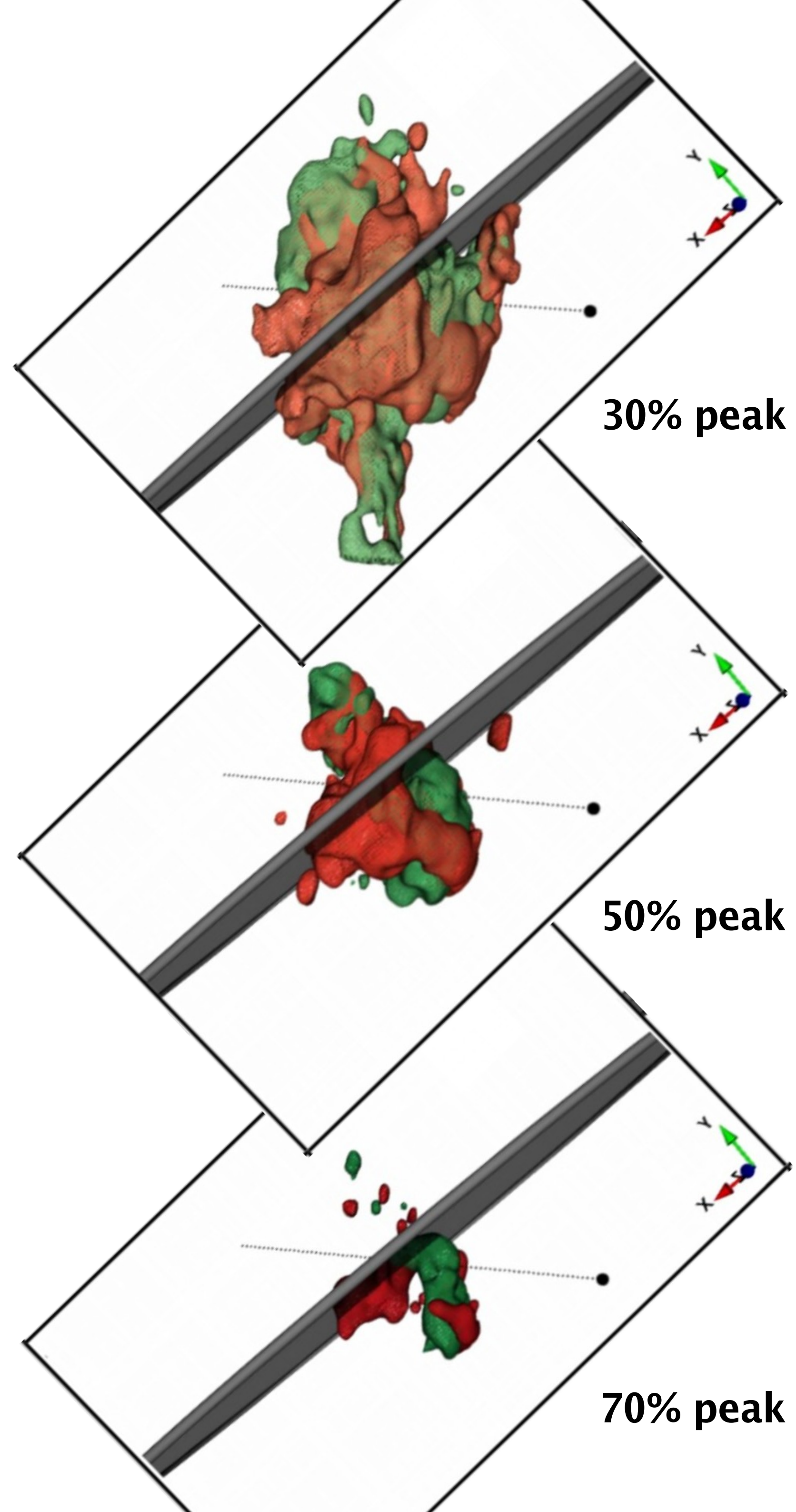
Wongwathanarat et al., A&A 577 (2015) A48 ; Utrobin et al., A&A 581 (2015) A40

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



3D Geometry of SN1987A: Observations vs. Models

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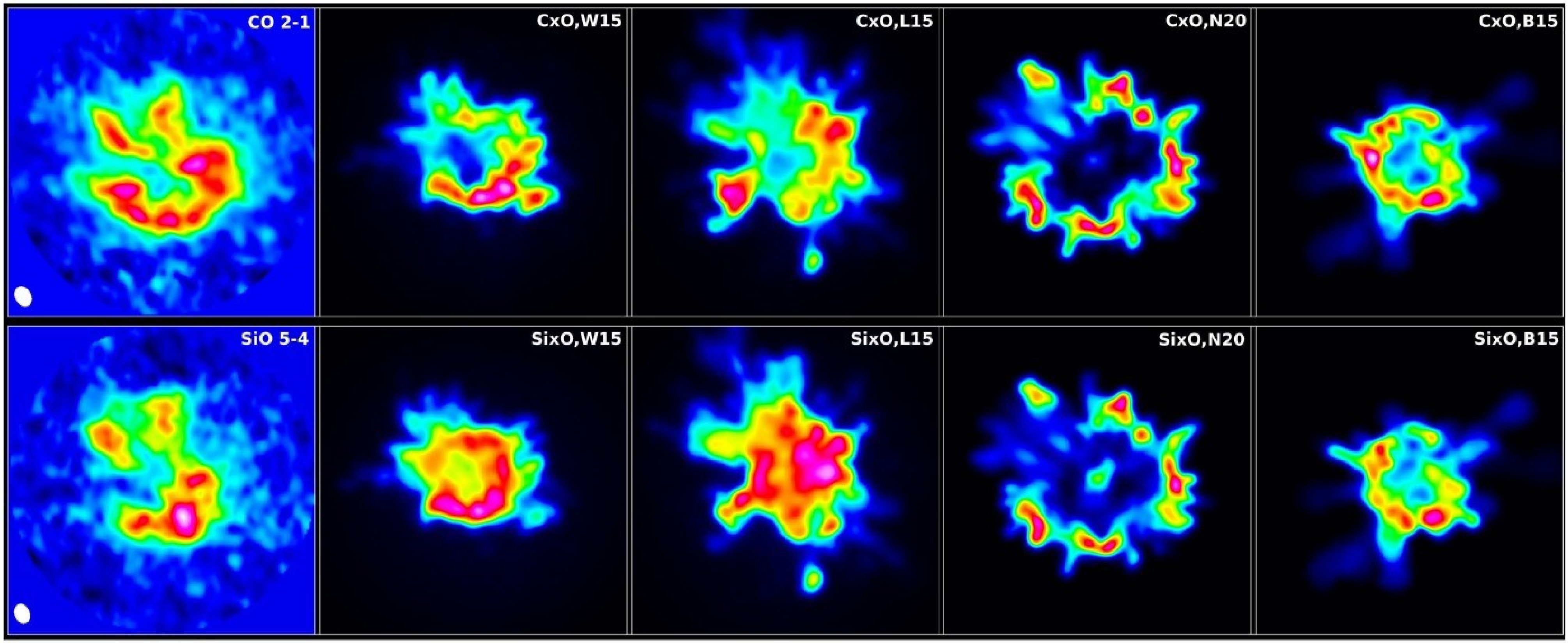
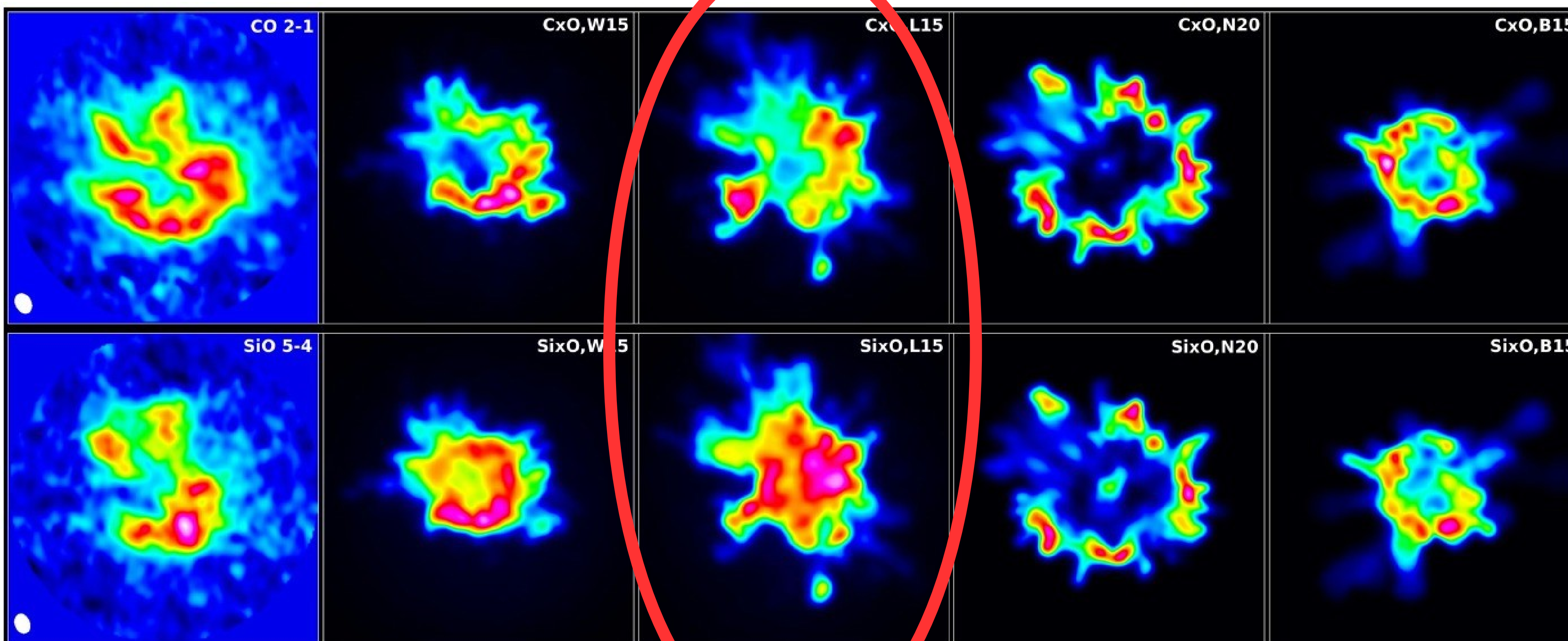


W15 L15 N20 B15

3D Geometry of SN1987A: Observations vs. Models

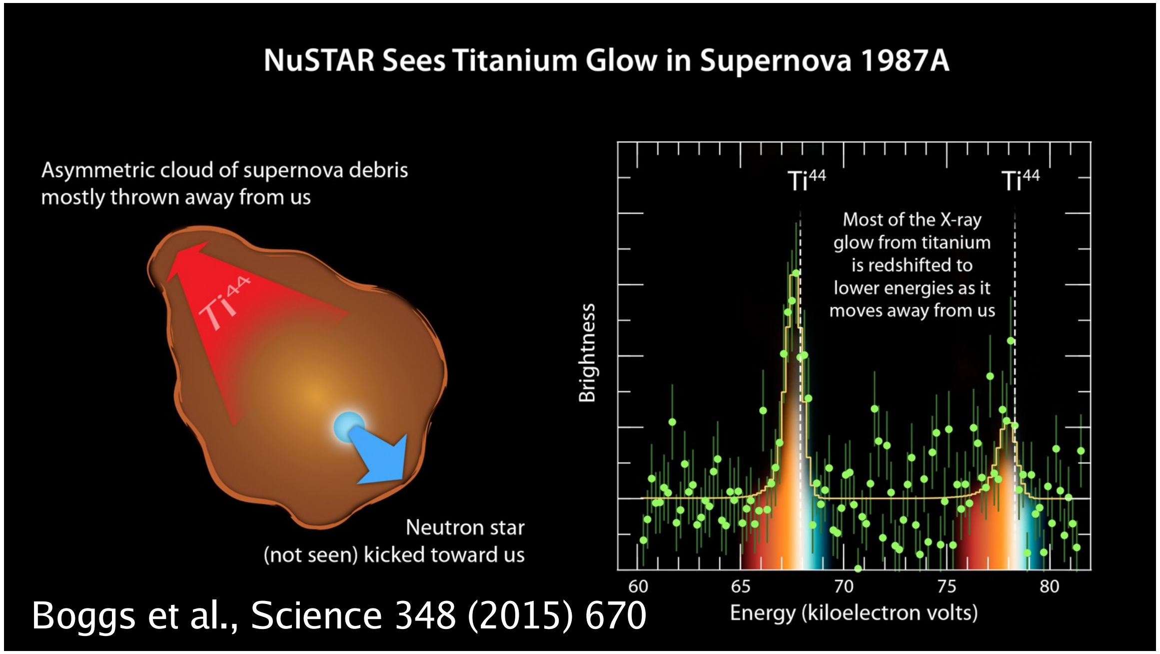
Molecular CO 2-1 and SiO 5-4 emission observed by ALMA

Abellán et al., ApJL 842 (2017) L24



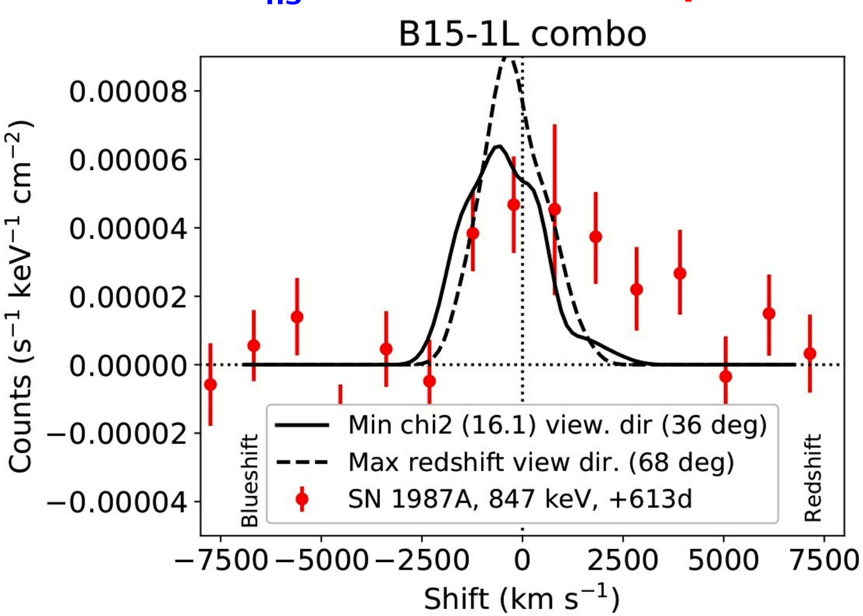
W15 L15 N20 B15

SN 1987A: Gamma Lines of ^{44}Ti & ^{56}Co

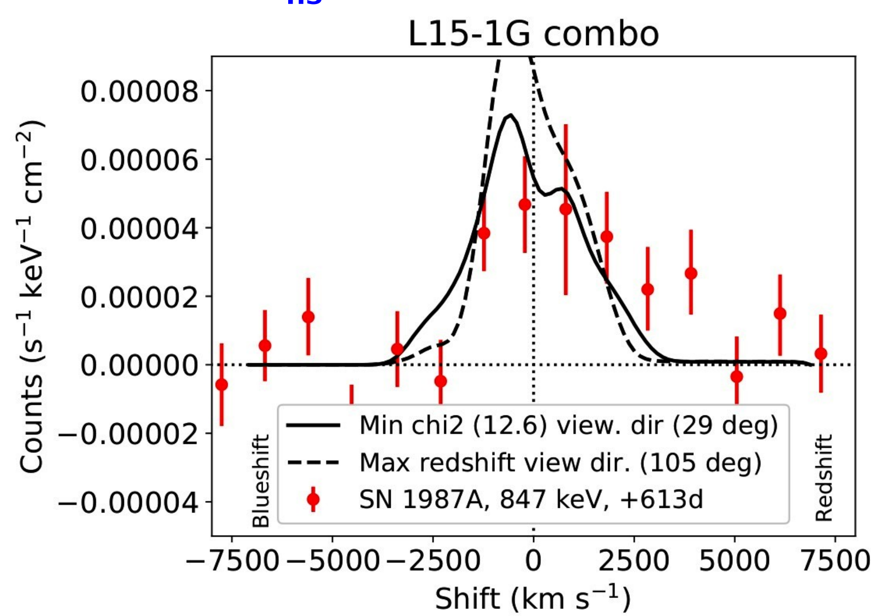


Boggs et al. (2015):
Redshifted ^{44}Ti lines suggest that NS in SN 1987A is likely to have fairly high kick towards us.

v_{ns} ~100 km/s: Incompatible

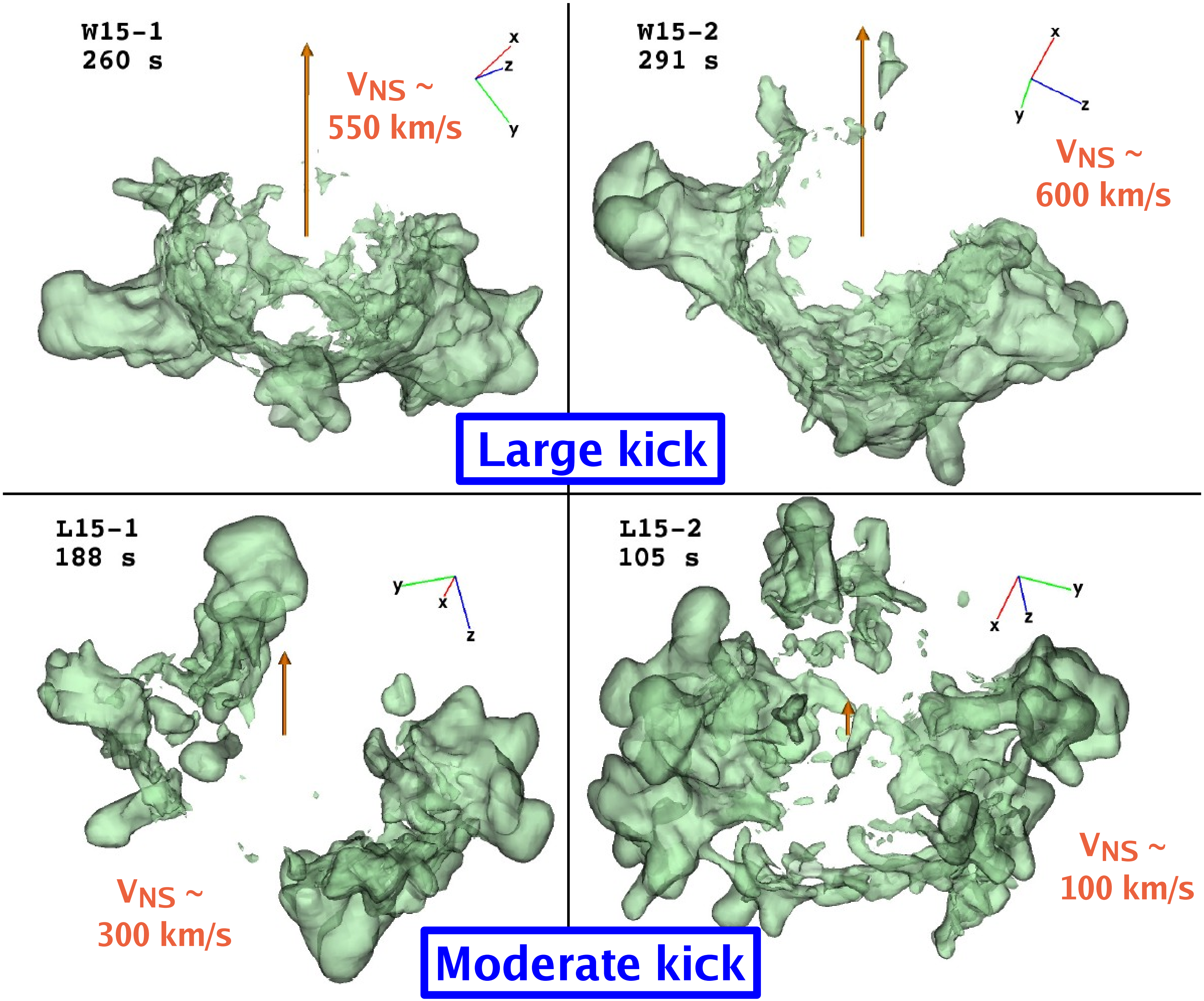


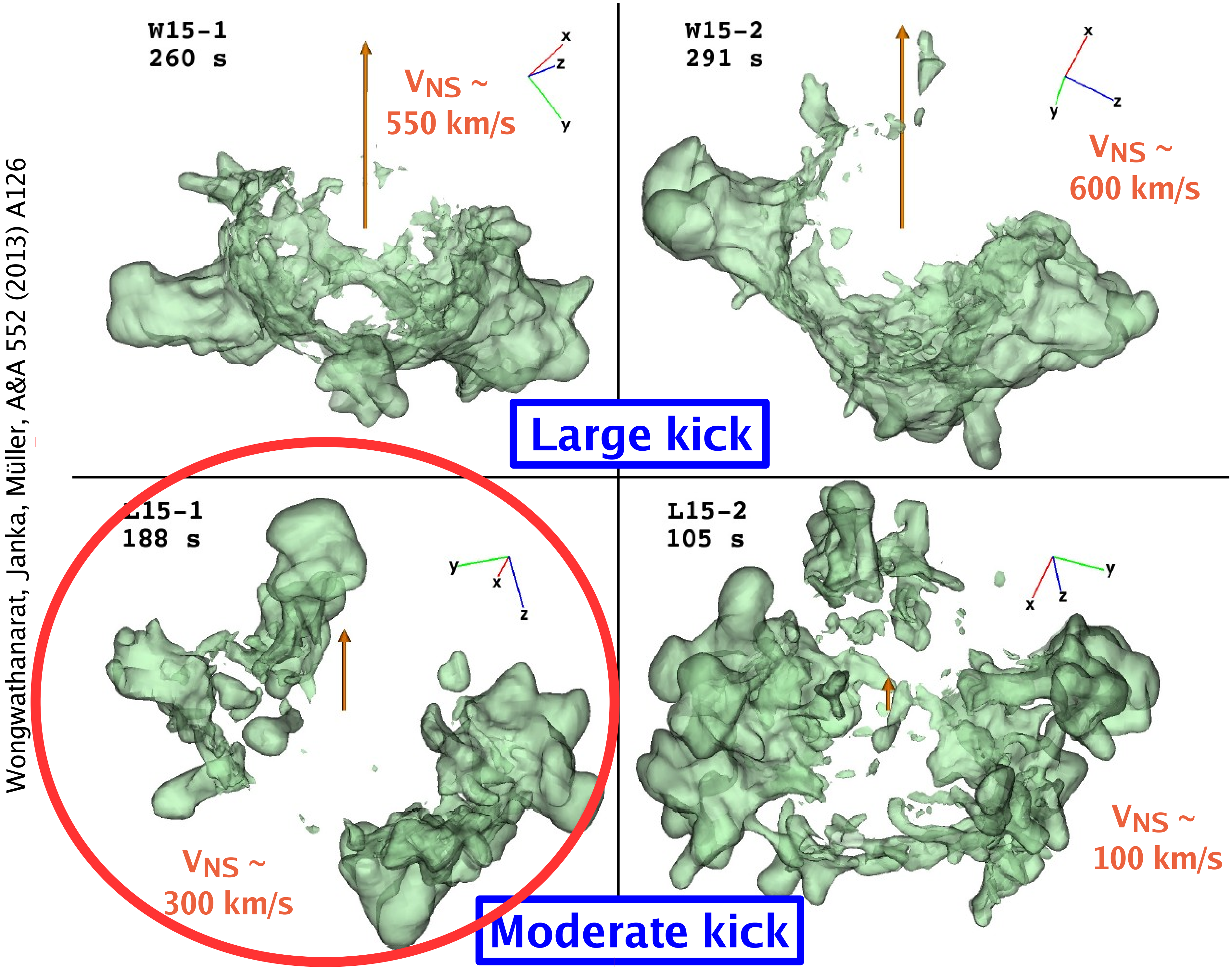
v_{ns} ~300 km/s: Better fit!



Jerkstrand et al., in preparation

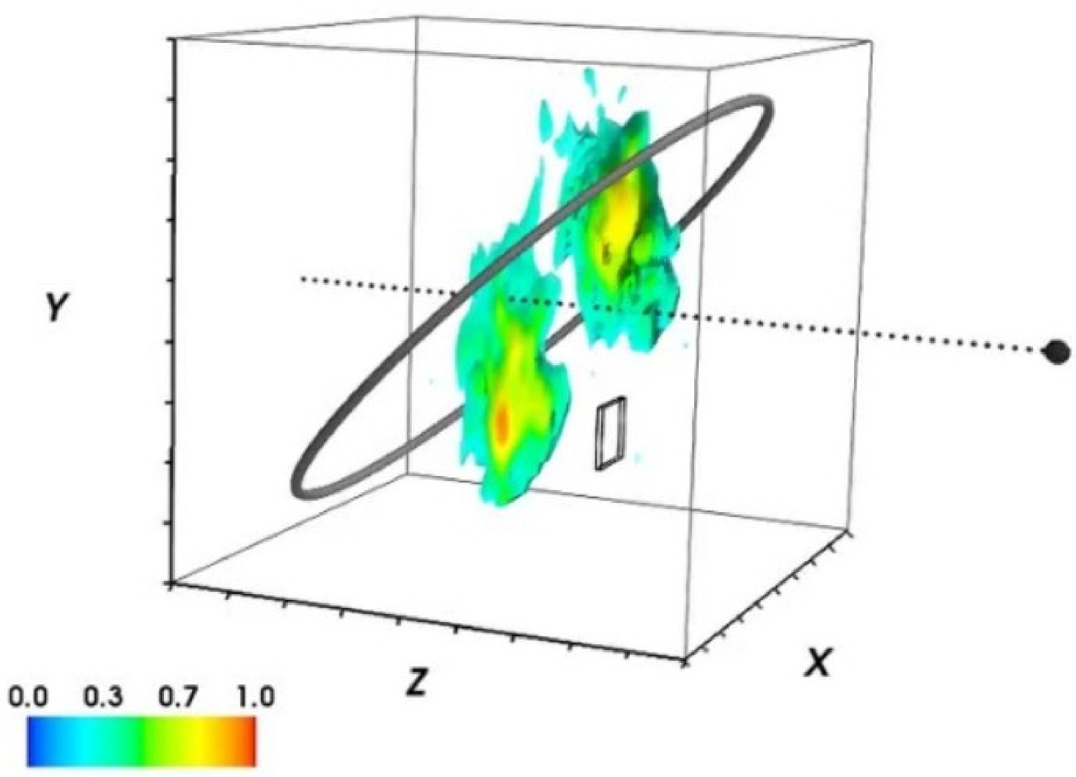
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

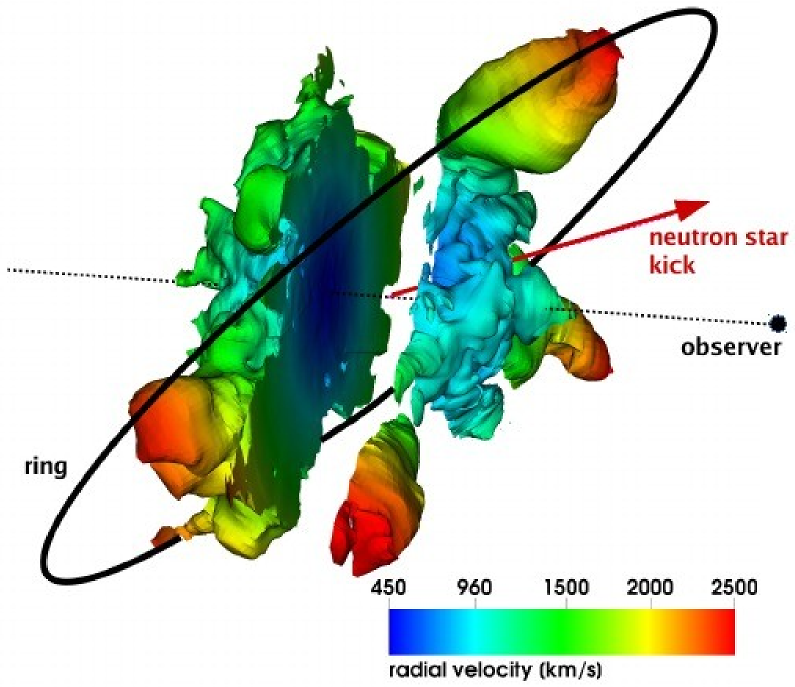



W15-1
260 s
VNS ~
550 km/s
W15-2
291 s
VNS ~
600 km/s
Large kick
L15-1
188 s
VNS ~
300 km/s
L15-2
105 s
VNS ~
100 km/s
Moderate kick
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

3D Geometry of SN1987A: Observations vs. Models

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



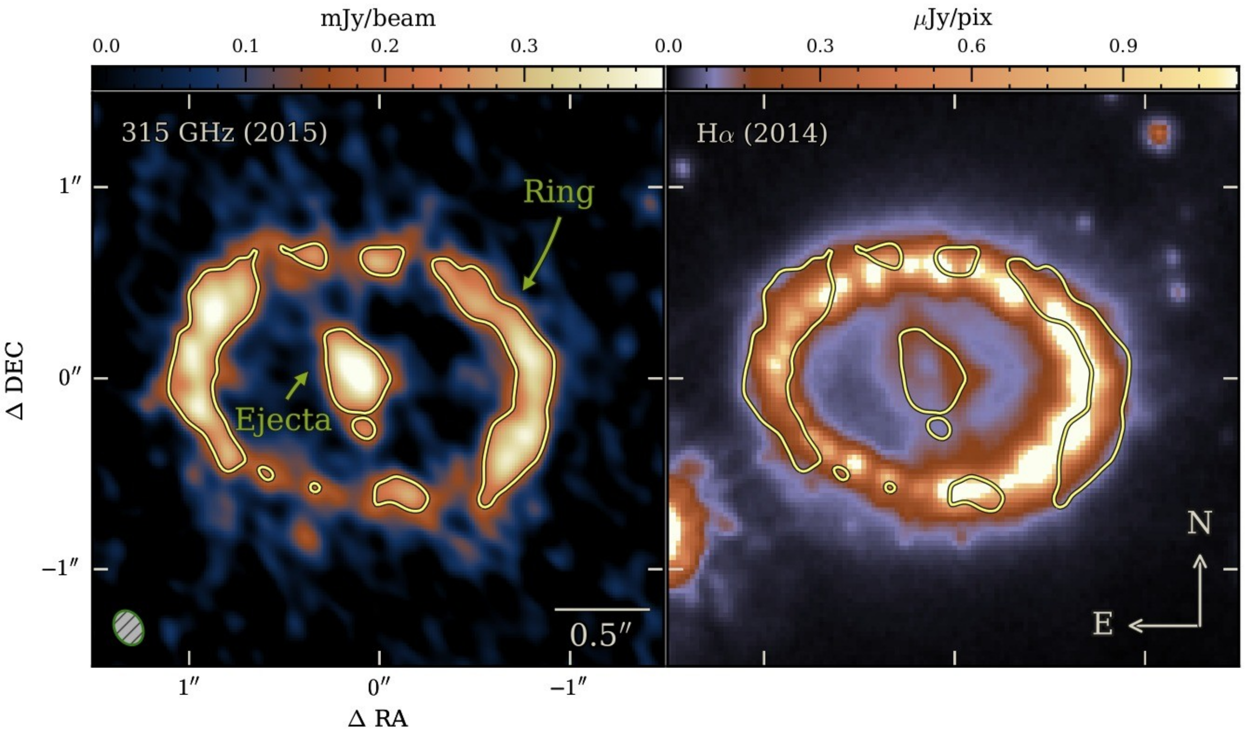


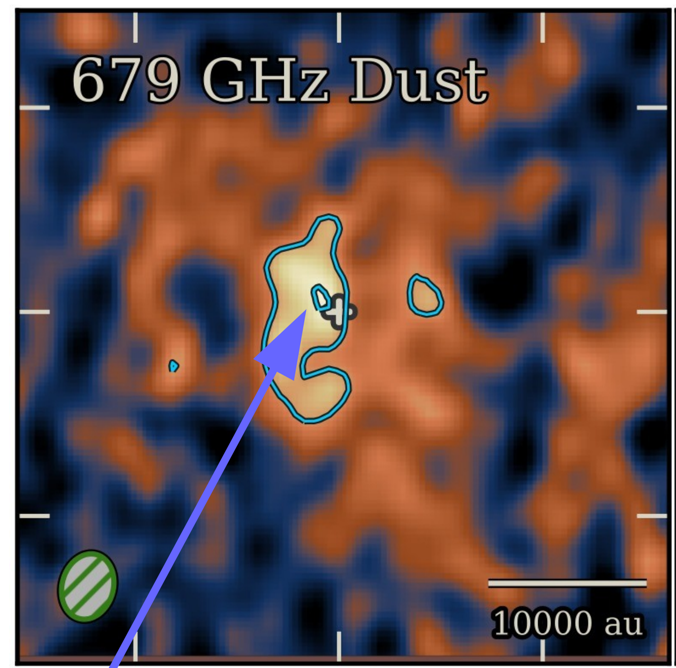
HST & VLT obs. (Larsson et al., ApJ 833 (2016) 147)

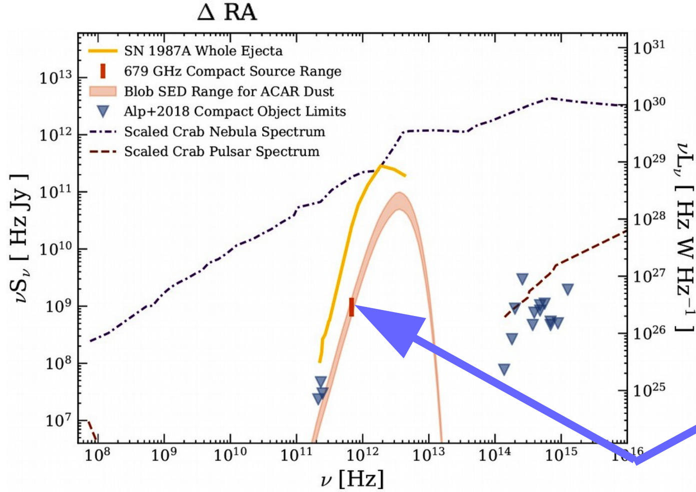
3D model L15 (Janka et al., arXiv:1705.01159)

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)

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

Cassiopeia A (SN IIb):

$M_{prog} \sim 17–20\ M_{sun}$, $M_{ej} \sim 4\ M_{sun}$, $M_{He\text{-}core} \sim 6\ M_{sun}$,
$E_{exp} \sim 2.3 \times 10^{51}$ erg , $v_{ns} \sim 400$ km/s

M (^{56}Ni) ~ 0.1~0.2 M_{sun}

M (^{44}Ti) = (1.25±0.3) $10^{-4}\ M_{sun}$ (NuSTAR; Grefenstette et al. 2014)

M (^{44}Ti) = (1.37±0.19) $10^{-4}\ M_{sun}$ (INTEGRAL; Siegert et al. 2015)

M (^{44}Ti) = (1.3±0.4) $10^{-4}\ M_{sun}$ (INTEGRAL; Wang & Li 2016)

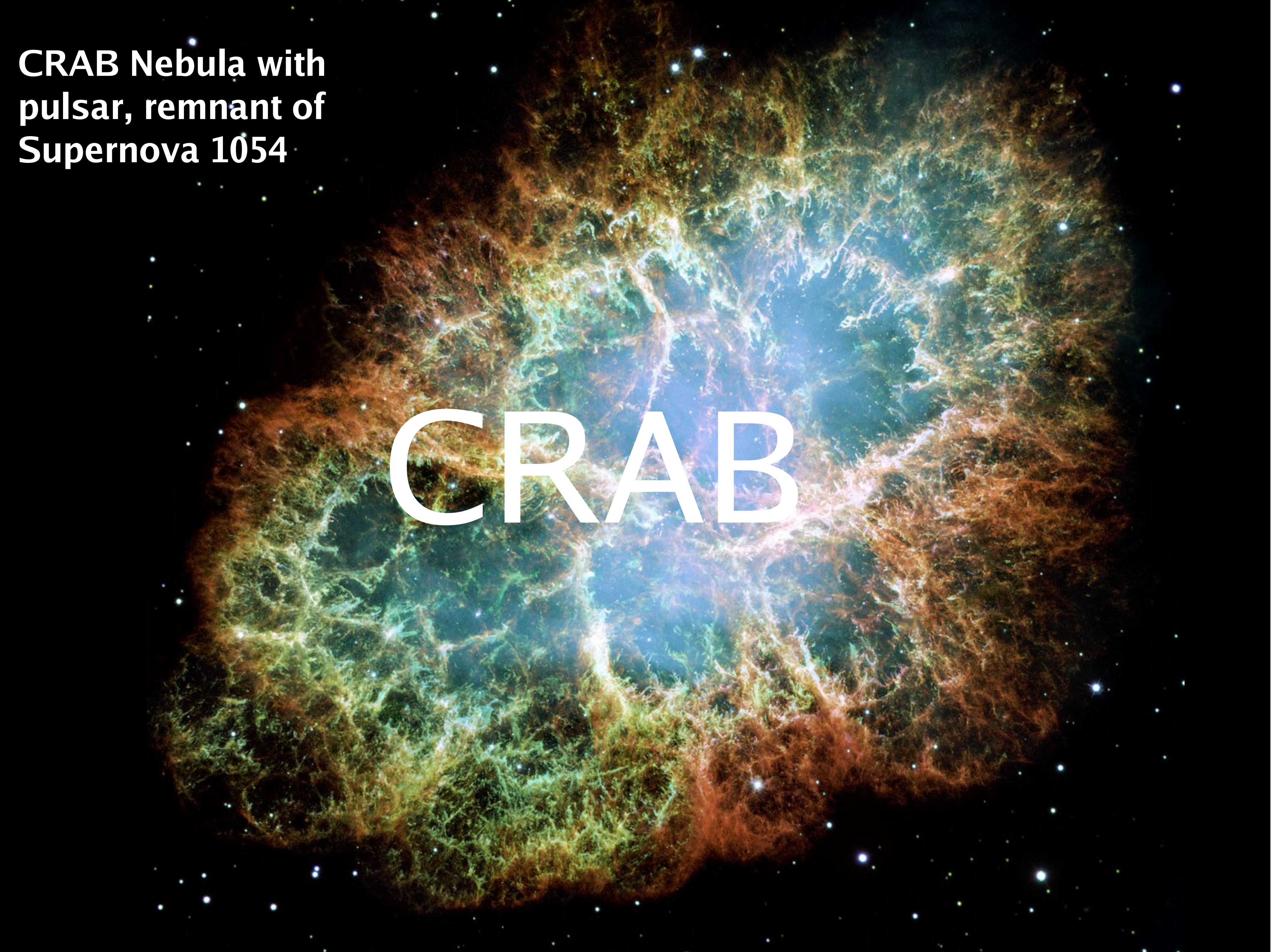
SN1987A (SN IIP–pec):

$M_{prog} \sim 15–20\ M_{sun}$, $M_{ej} \sim 15\ M_{sun}$, $M_{He\text{-}core} \sim 3–7\ M_{sun}$,
$E_{exp} \sim 1.5 \times 10^{51}$ erg , v_{ns} >~ 500 km/s

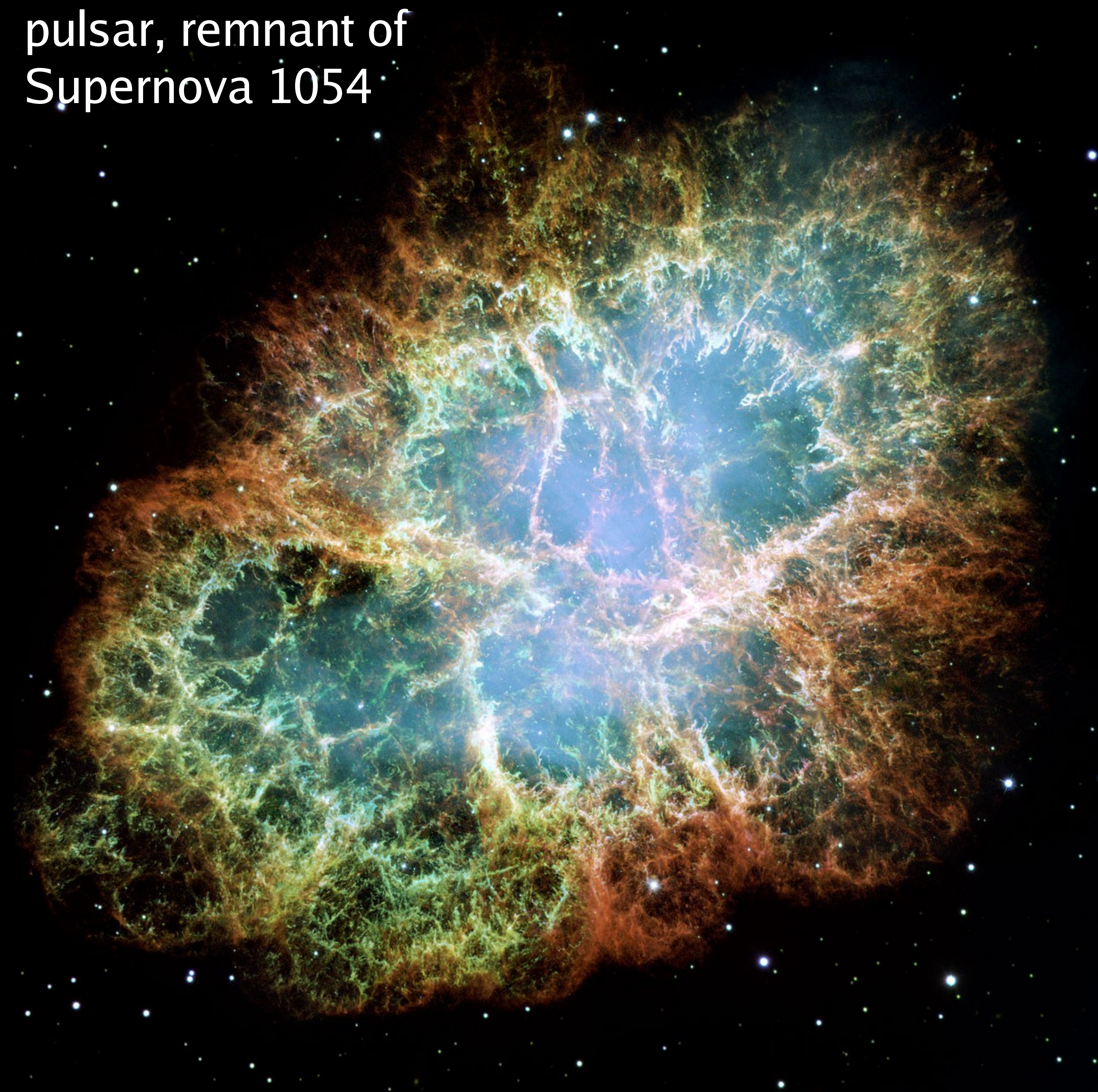
M (^{56}Ni) = 0.071 M_{sun}

M (^{44}Ti) = (1.5±0.3) $10^{-4}\ M_{sun}$ (NuSTAR; Boggs et al. 2015)

M (^{44}Ti) = (1.5±0.5) $10^{-4}\ M_{sun}$ (Jerkstrand et al. 2011)


CRAB Nebula with pulsar, remnant of Supernova 1054
CRAB

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)

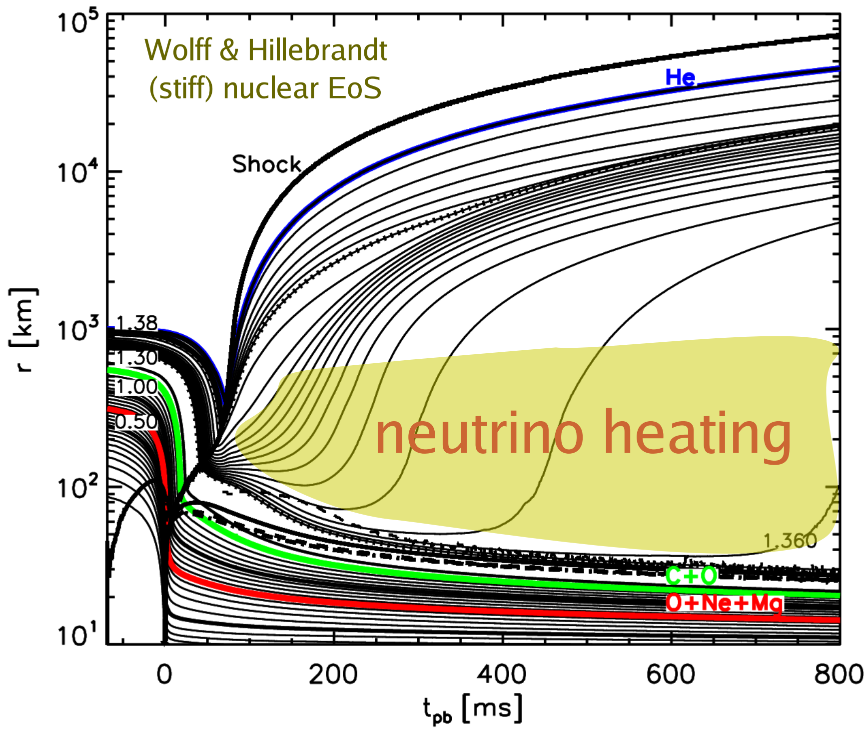
ECSN properties:

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

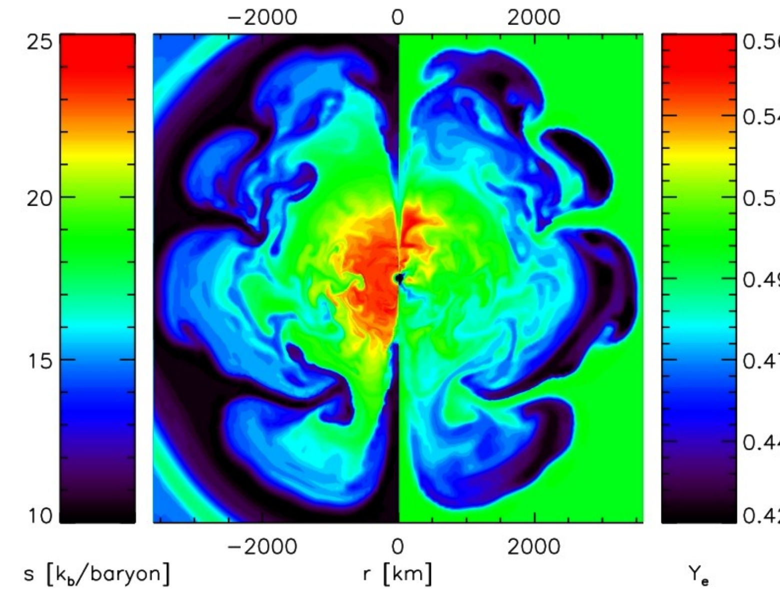
M_{Ni} ~ 0.003 M_{sun}

2D and 3D ECSN Models

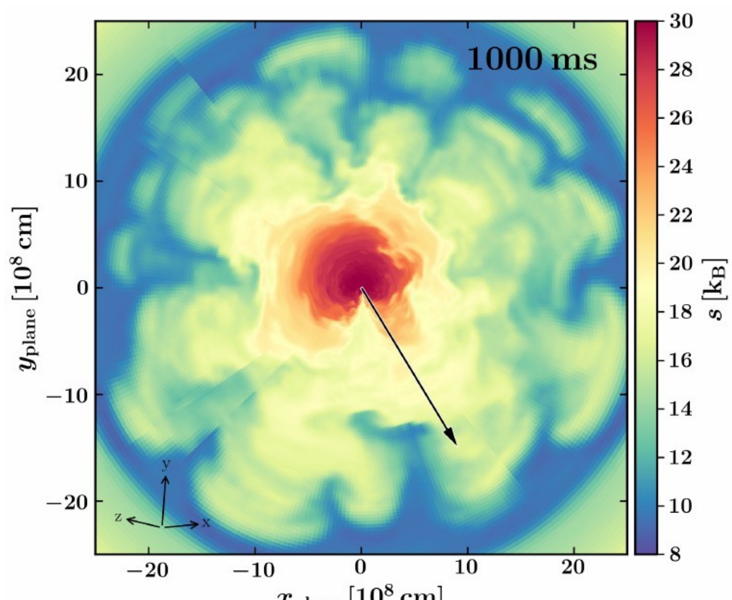
ECSNe:
Explosions of low-mass stars (~9 M_{sun}) with O-Ne-Mg cores

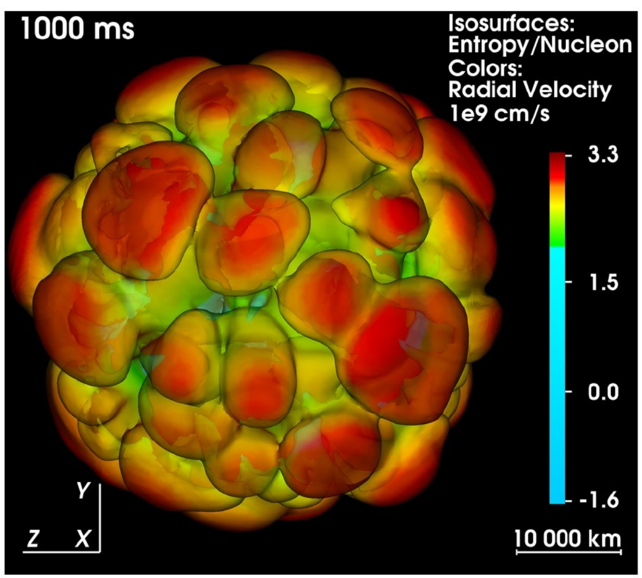


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199



$E_{exp} \sim 10^{50}$ erg
$= 0.1$ bethe
$M_{Ni} \sim 0.003\ M_{sun}$



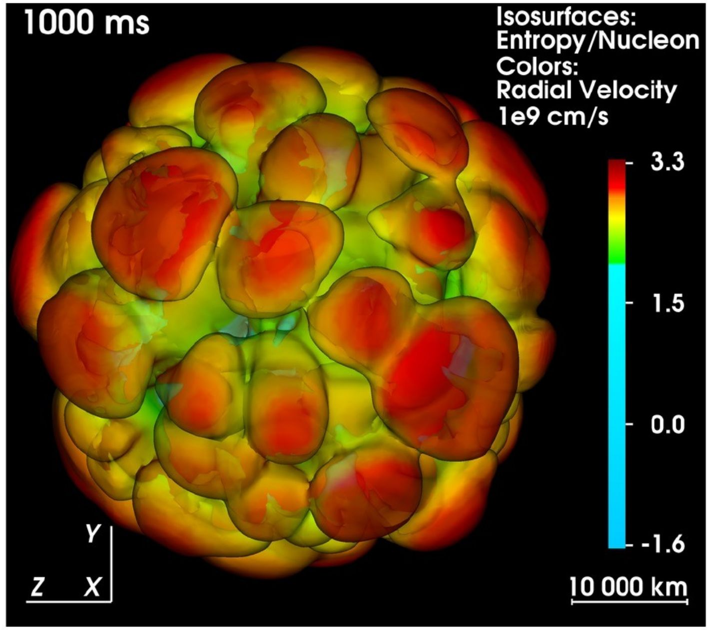


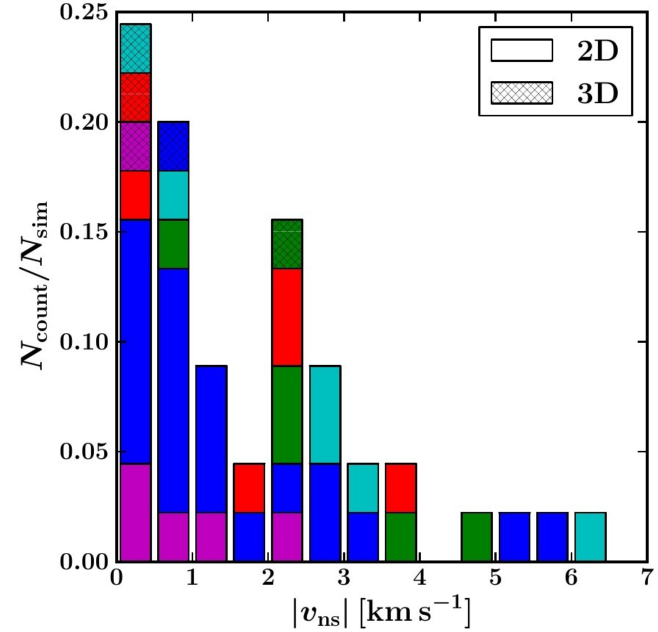
Gessner & Janka, ApJ 865 (2018) 61

Neutron Star Recoil in 2D and 3D ECSN Models

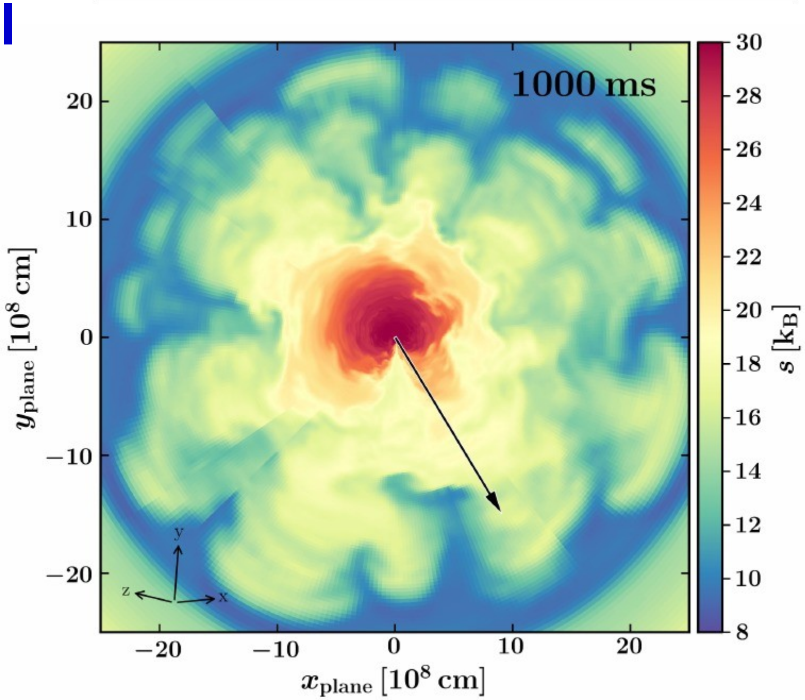
ECSN models:
40 2D runs
5 3D runs

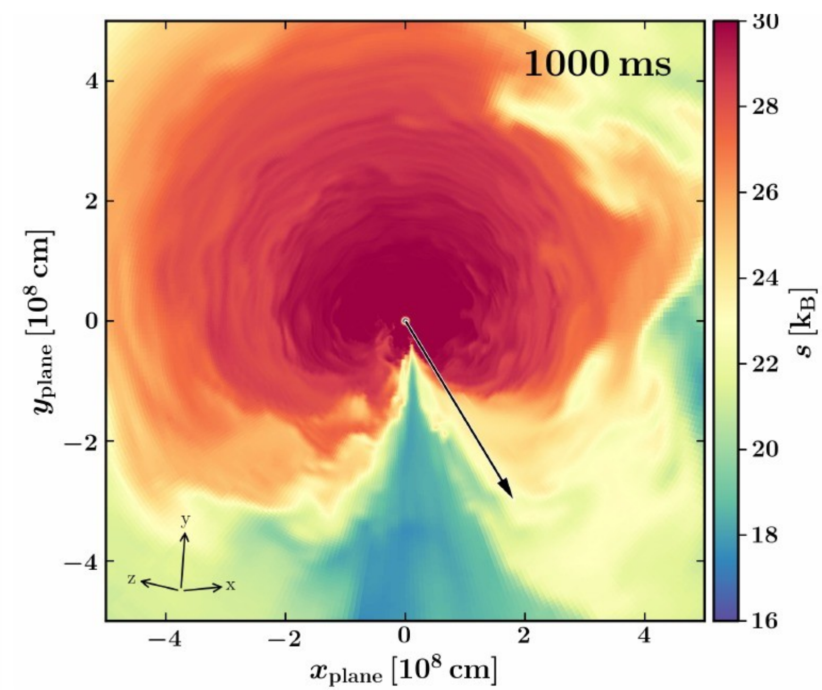
with energies in $[0.3, 1.6] \times 10^{50}$ erg





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

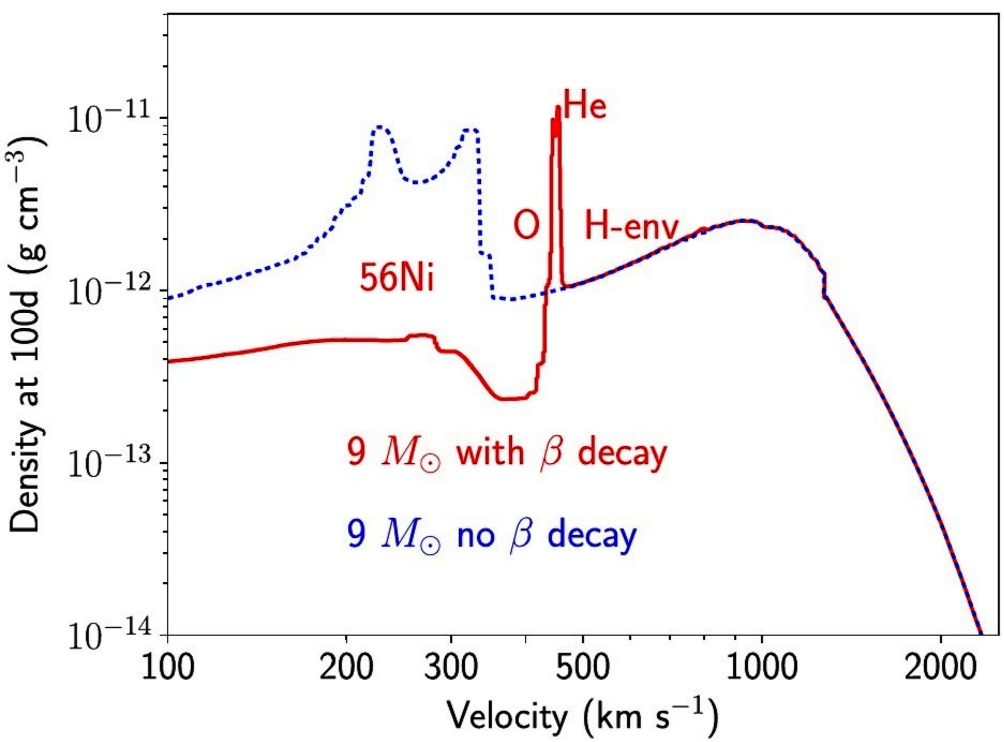
Compare low-luminosity supernovae SN 1997D, 2005cs, 2008bk

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

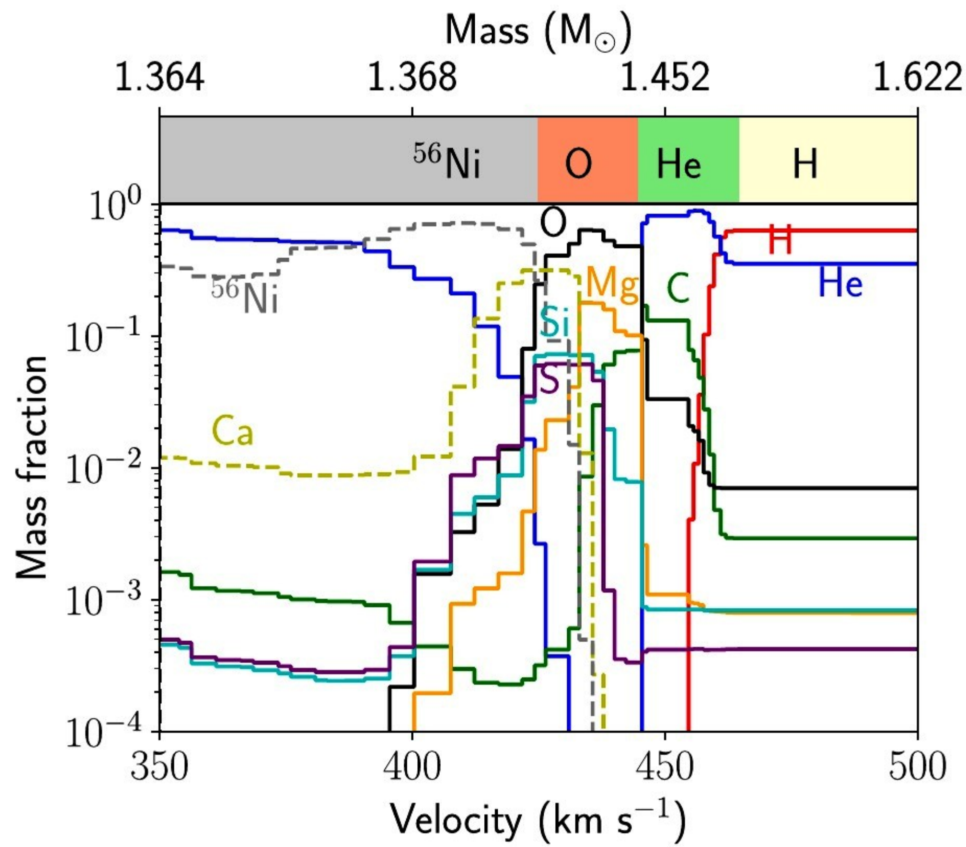
spectral analysis during nebular phase (> 100 days after onst of explosion)

(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

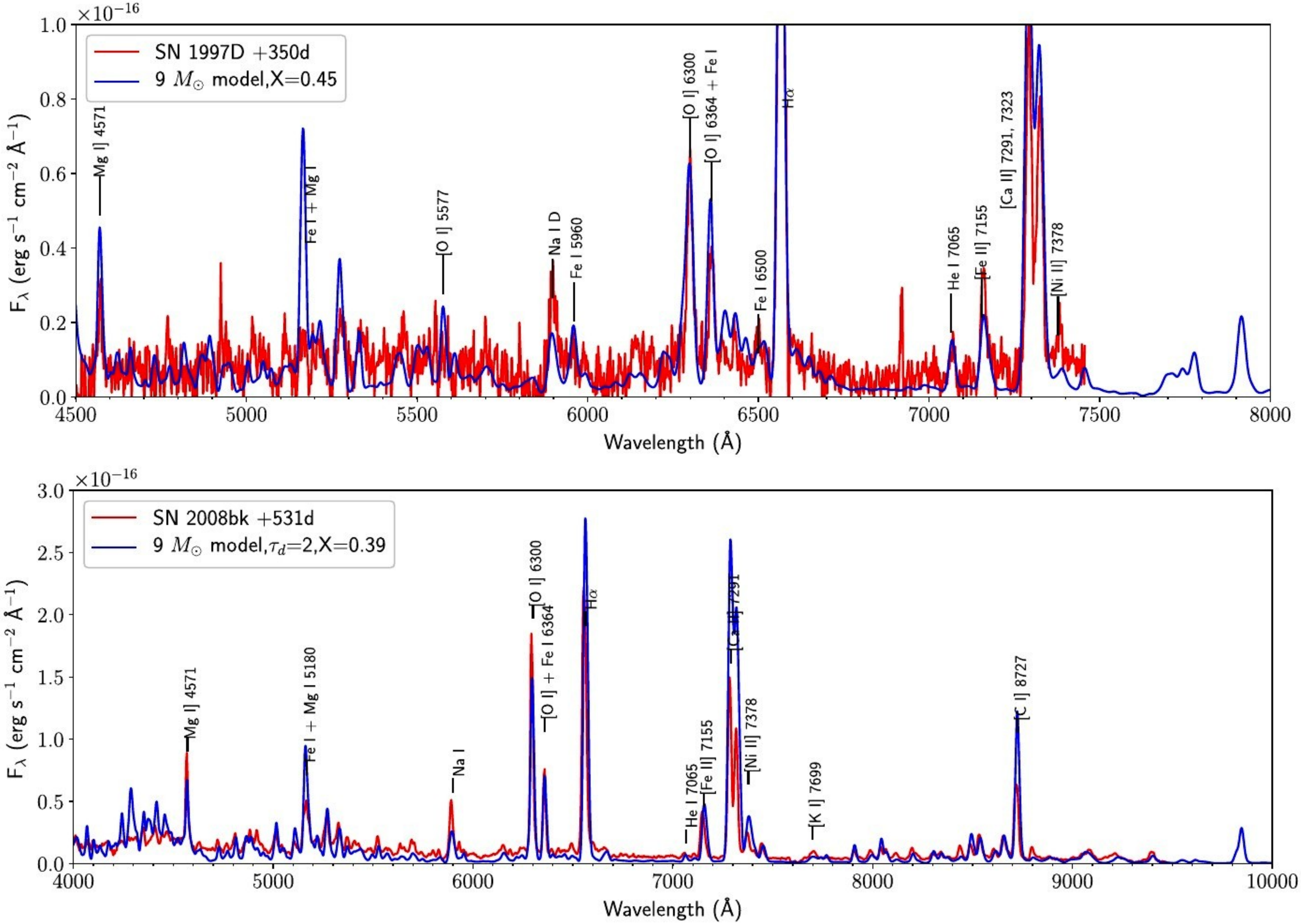
Jerkstrand et al., MNRAS 475 (2018) 277

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



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?