Max-Planck-Institut für Astrophysik

European Research Council
Established by the European Commission

TUM LMU Excellence Cluster Universe

FOE International Conference on the Physics and Observations of Supernovae and Supernova Remnants
North Carolina State University, Raleigh, NC, USA, June 1–5, 2015

3D Core-Collapse Simulations by the Garching Group

The Route to Explosions

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching

The Team

Students, Postdocs, Collaborators

- Tobias Melson, Robert Bollig, Else Pllumbi, Thomas Ertl, Florian Hanke
- Alexander Summa, Michael Gabler
- Ewald Müller
- Bernhard Müller (Monash)
- Annop Wongwathanarat, Shinya Wanajo (RIKEN)
- Irene Tamborra (GRAPPA)
- Georg Raffelt (MPP)
- Andreas Marek, Lorenz Hüdepohl (RZG)

Outline

Self-consistent ("ab initio") supernova models:

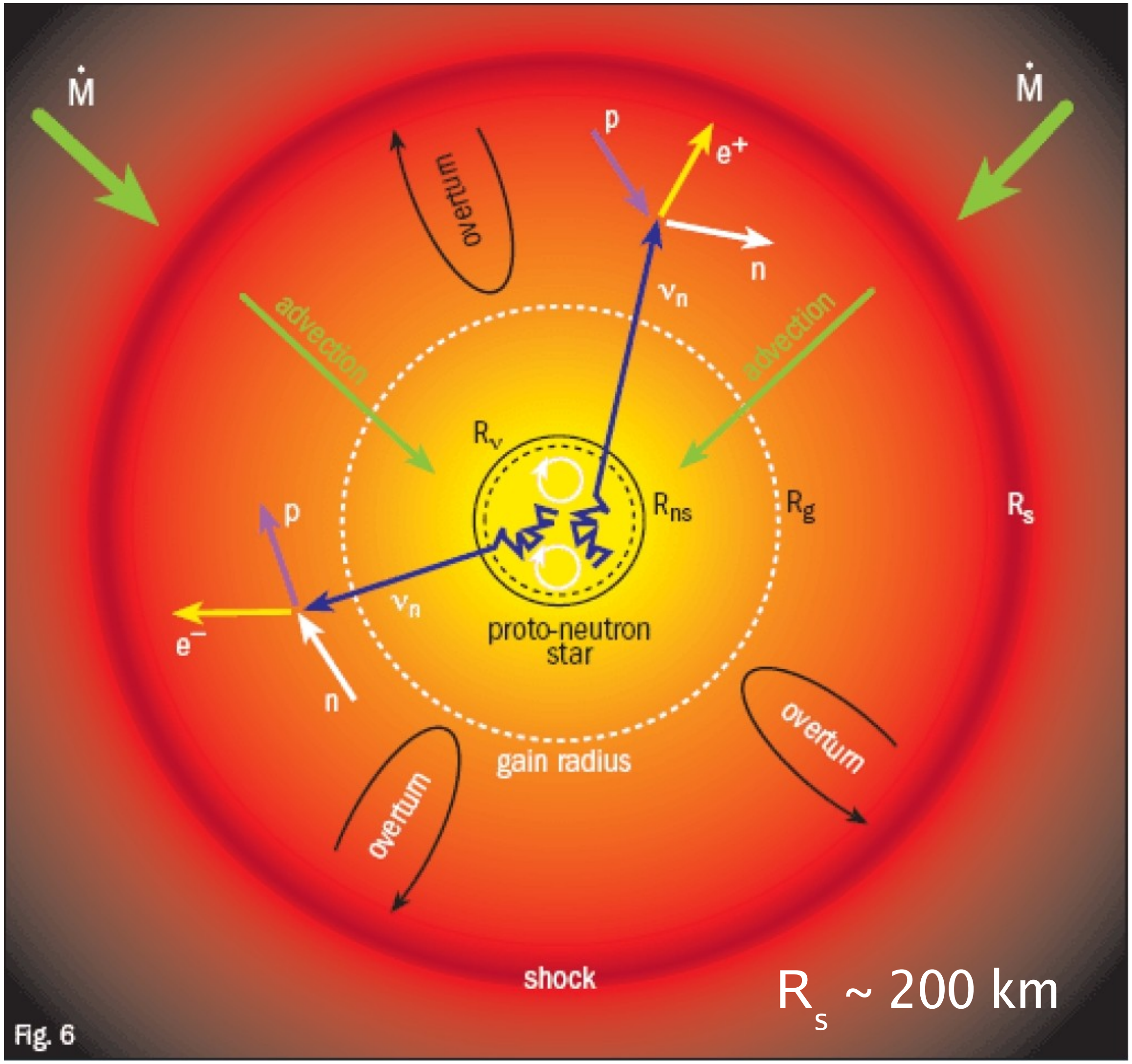
- Successful explosions in 3D
- Non-radial instabilities: new phenomena

Long-time 3D simulations of SNe: the case of CAS A

- 3D explosion asymmetries, NS kicks, and nucleosynthesis
- ^{44}Ti and ^{56}Fe in a CAS A-like model

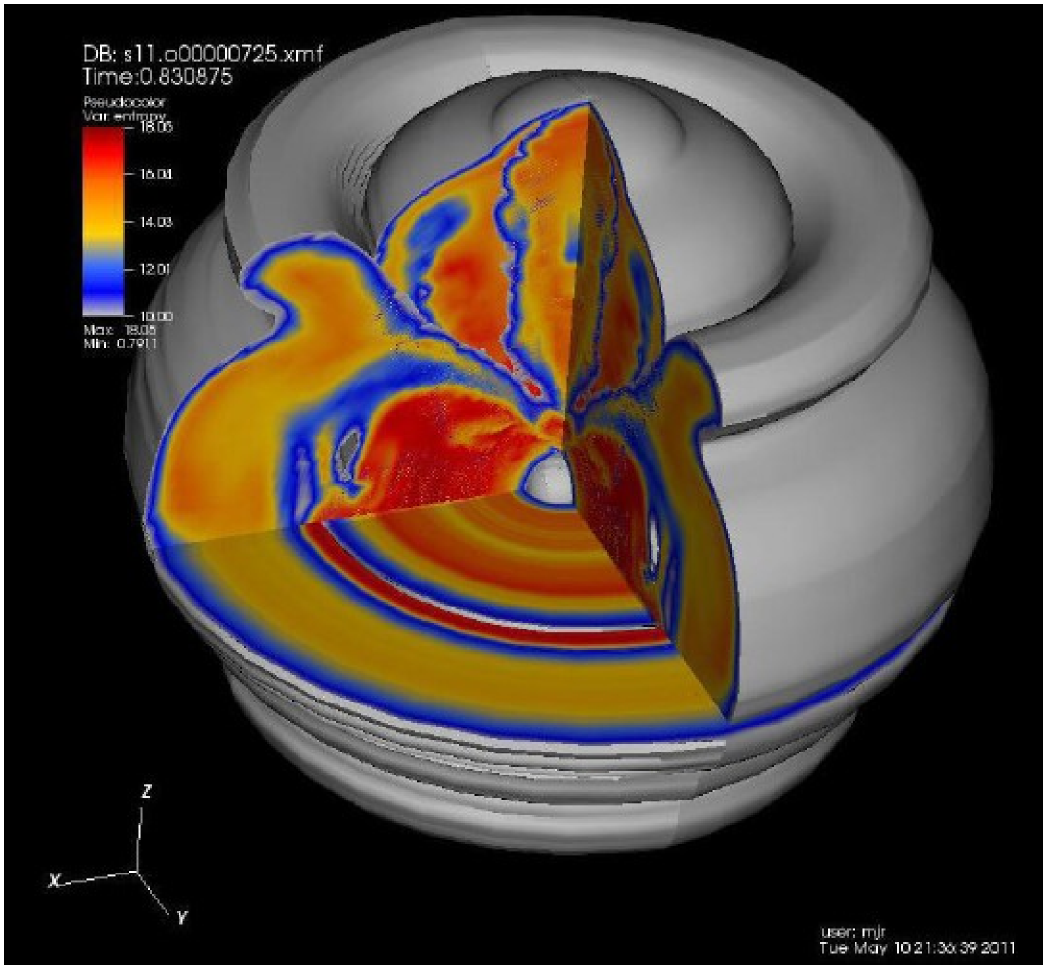
Neutrinos & SN Explosion Mechanism

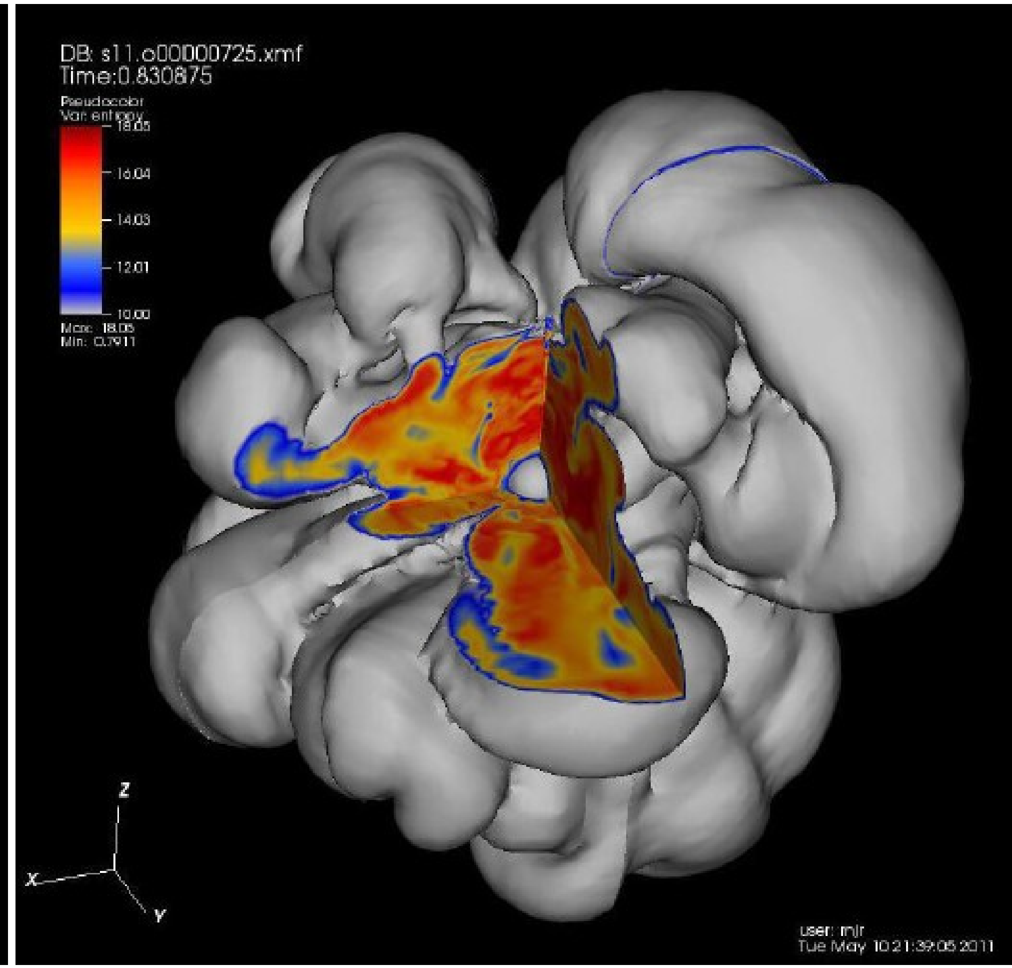
Explosions powered by neutrino heating, supported by violent, large-scale hydrodynamic instabilities in the postshock layer



- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities support the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Blondin & Mezzacappa 2007, Scheck et al. 2004,06,08, Iwakami et al. 2008, 2009, Ohnishi et al. 2006).

2D and 3D Morphology





(Images from Markus Rampp, RZG)

The Simulation Code

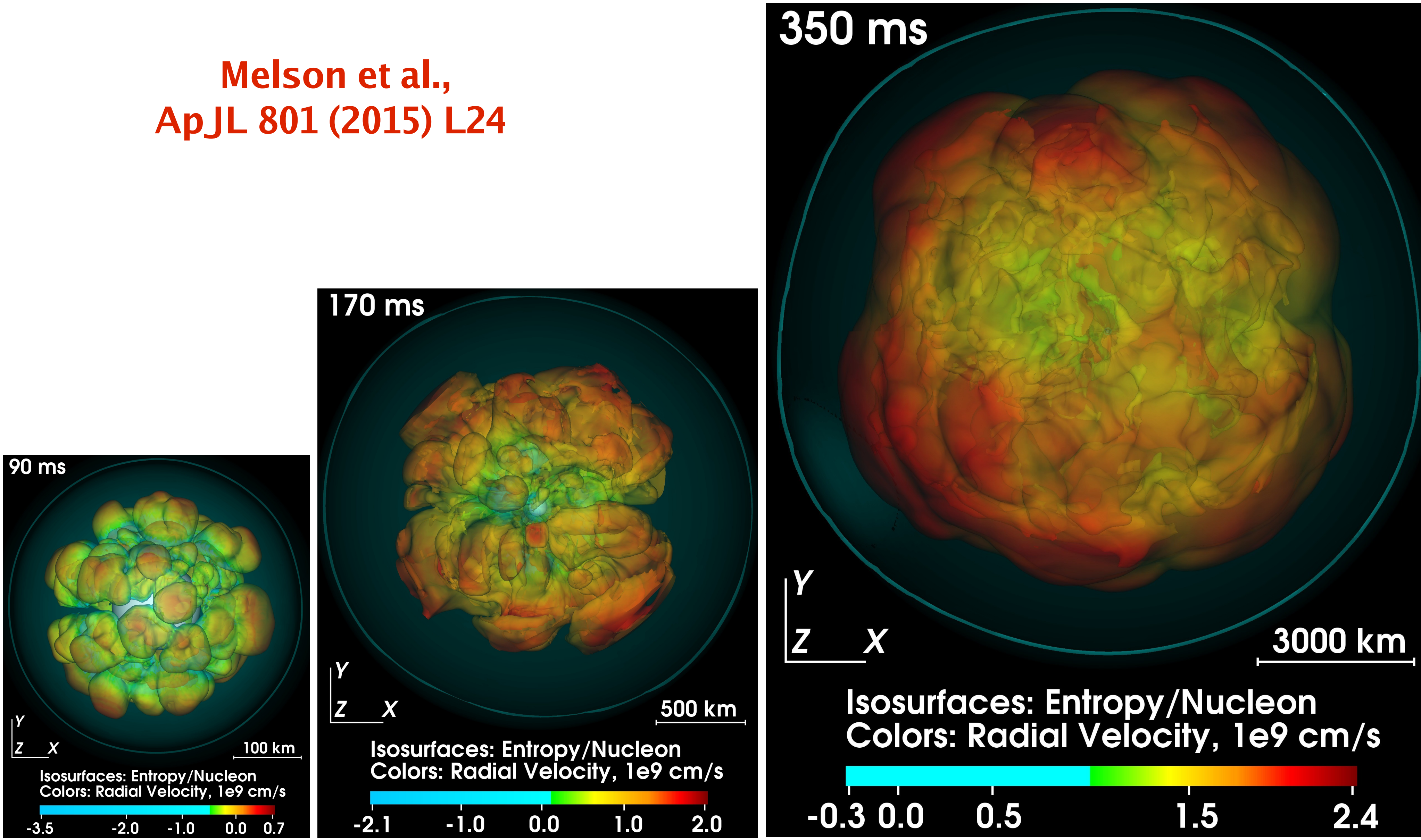
Prometheus/CoCoNuT – VERTEX: 1D, 2D, 3D

- **Hydro modules:**
  Newtonian: *Prometheus* + effective relativistic grav. potential.
  General relativistic: *CoCoNuT*
  Higher-order Godunov solvers, explicit.
- **Neutrino Transport: *VERTEX***
  Two-moment closure scheme with variable Eddington factor based on model Boltzmann equation; fully energy-dependent, O(v/c), implicit, ray-by-ray-plus in 2D and 3D.
- **Most complete set of neutrino interactions applied to date.**
- **Different nuclear equations of state.**
- **Spherical polar grid or axis-free Yin-Yang grid.**

3D Core-Collapse SN Explosion Models

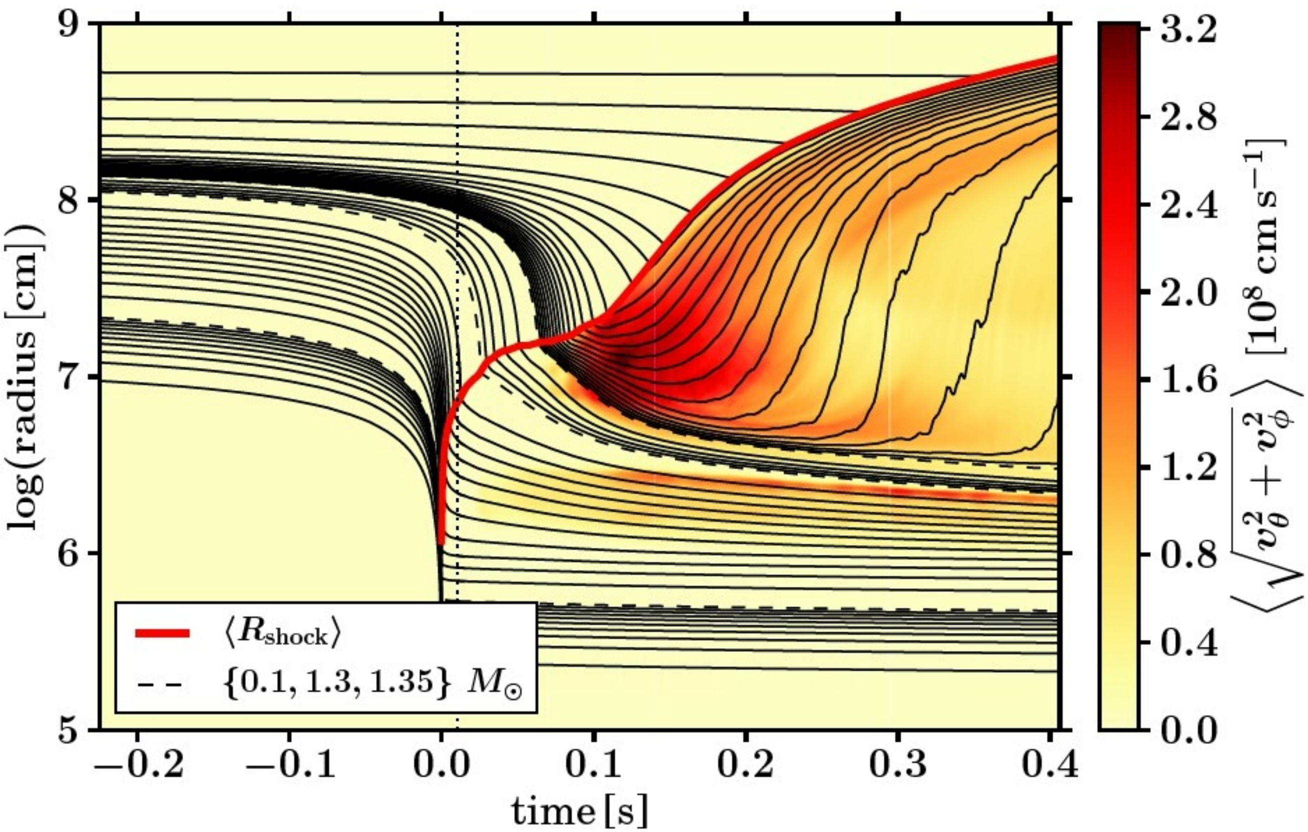
9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

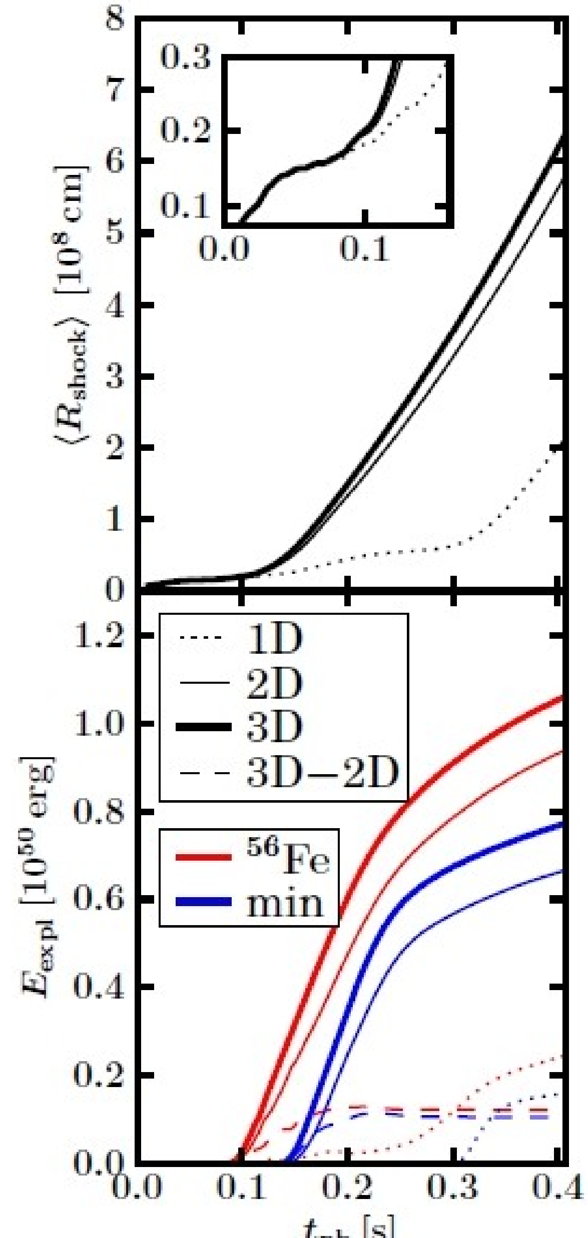
Melson et al.,
ApJL 801 (2015) L24



3D Core-Collapse SN Explosion Models

9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

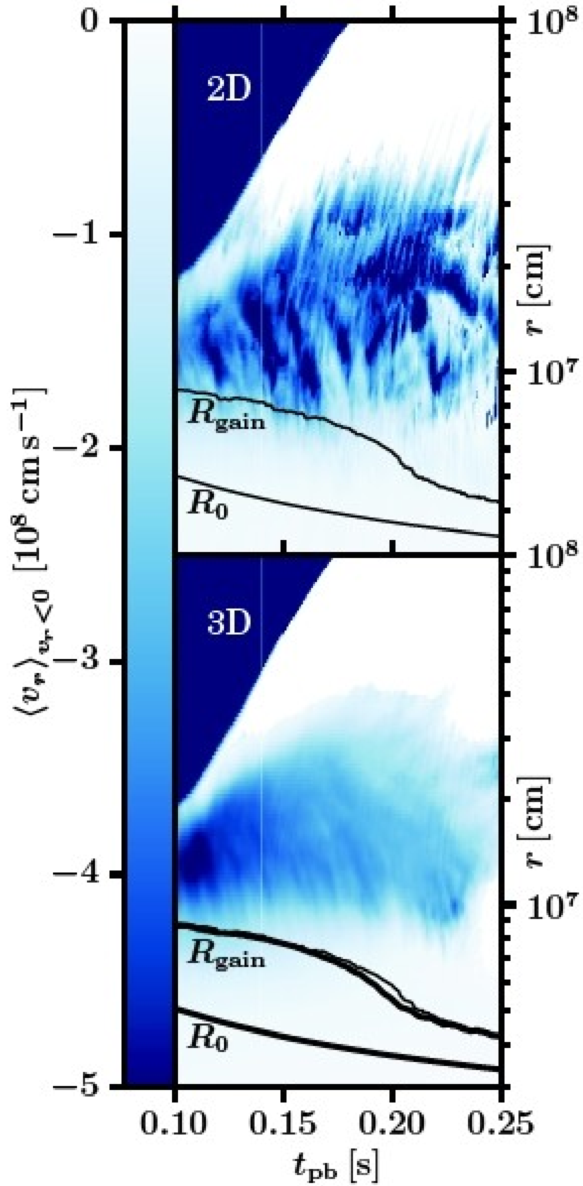


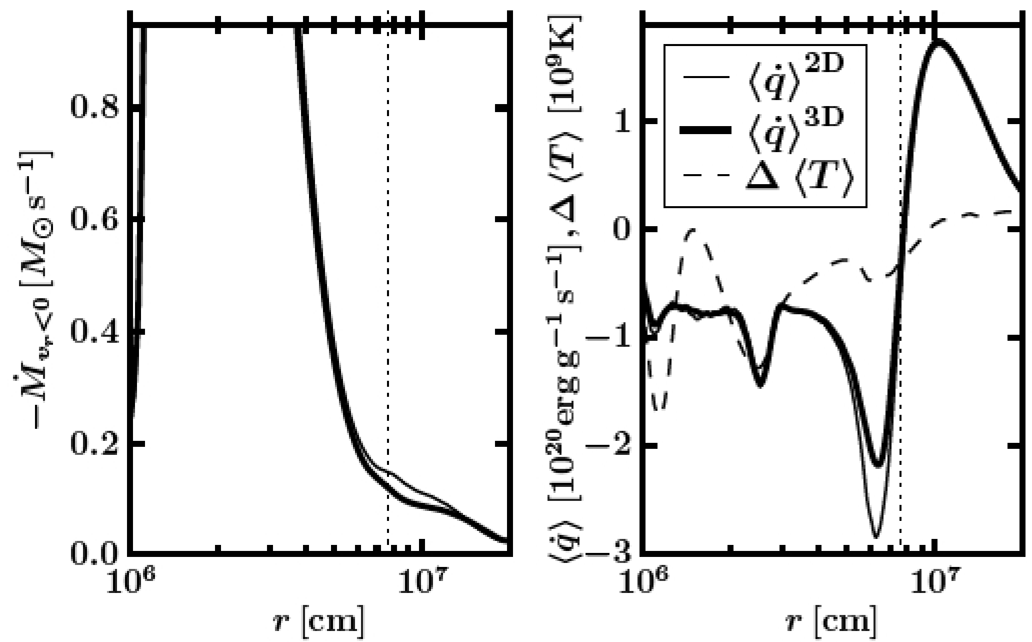


Melson et al., ApJL 801 (2015) L24

3D Core-Collapse SN Explosion Models

9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

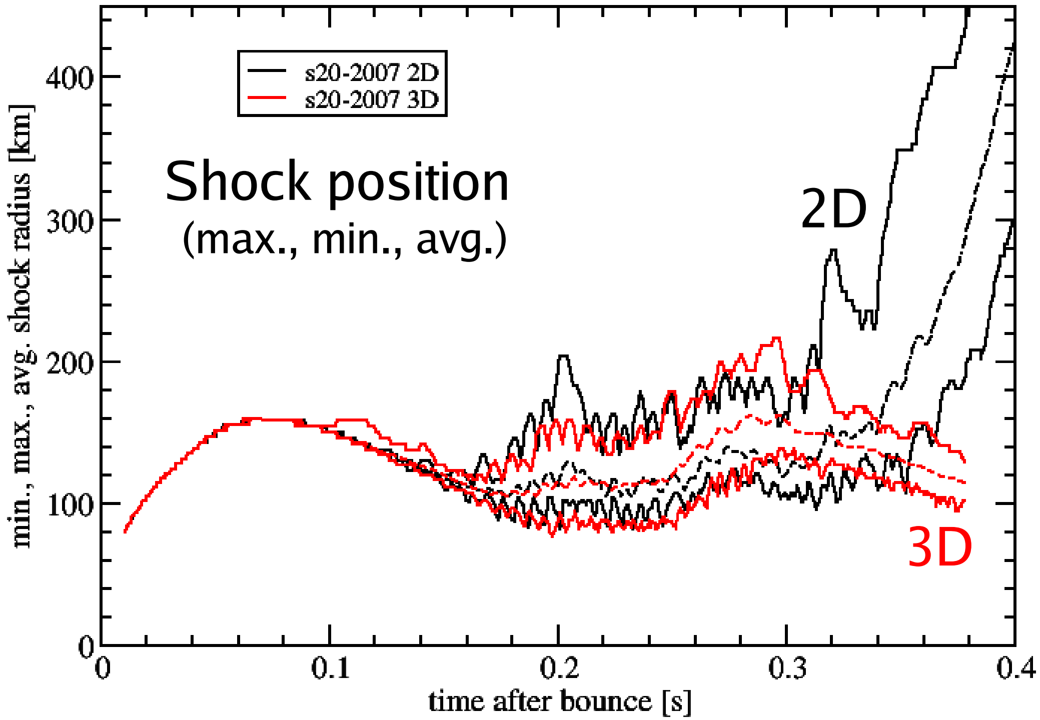


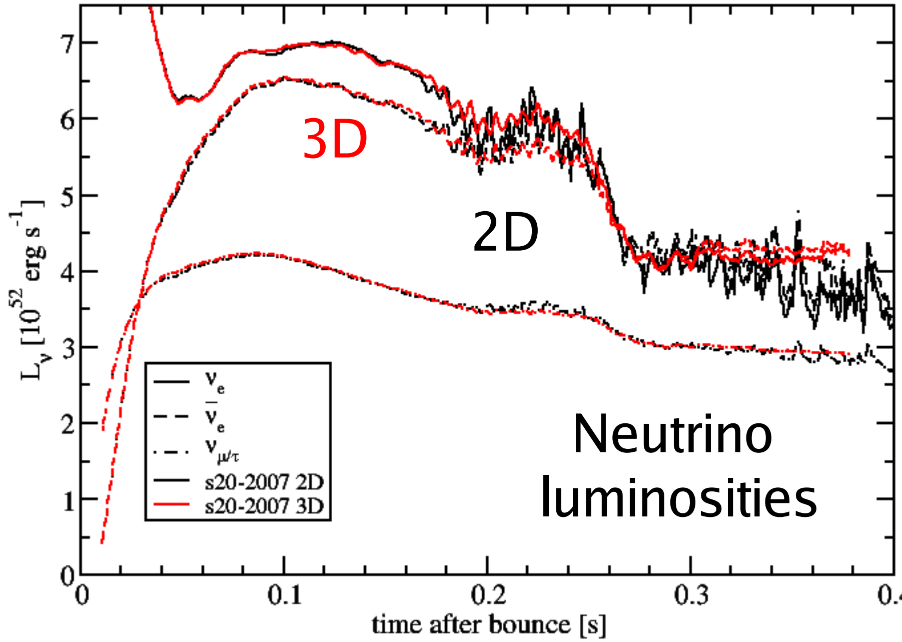


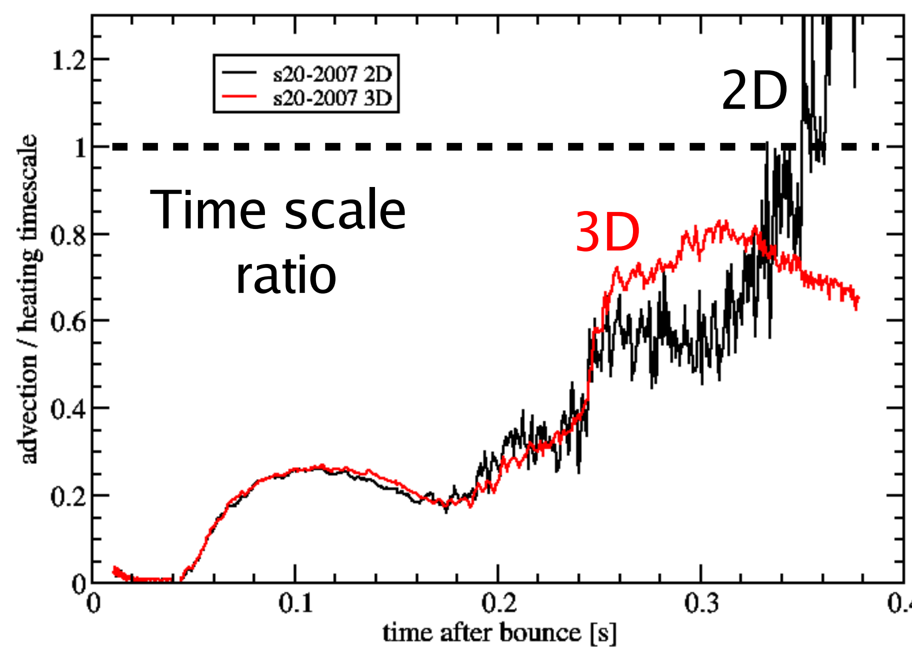
Melson et al., ApJL 801 (2015) L24

3D Core-Collapse SN Explosion Models

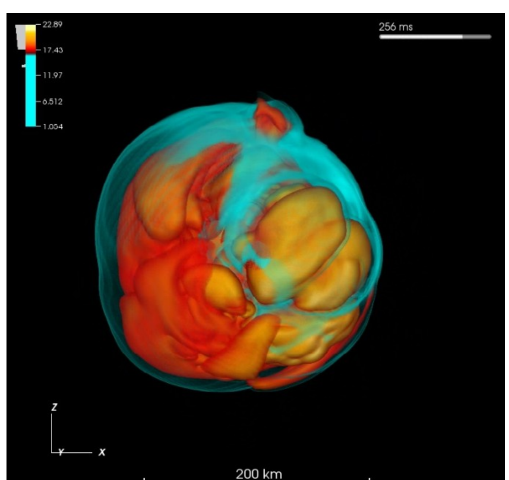
20 M_{sun} progenitor (WH 2007)







Florian Hanke, PhD project



3D Core-Collapse SN Explosion Models

20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)

3. STRANGENESS CONTRIBUTIONS TO NEUTRINO-NUCLEON SCATTERING

The lowest-order differential neutrino-nucleon scattering cross section reads

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 \epsilon^2}{4\pi^2} \left[c_v^2 (1 + \cos\theta) + c_a^2 (3 - \cos\theta) \right] , \quad (1)$$

$$\sigma_0^t = \int_{4\pi} d\Omega \frac{d\sigma_0}{d\Omega} (1 - \cos\theta) = \frac{2G_F^2 \epsilon^2}{3\pi} \left(c_v^2 + 5c_a^2 \right) . \quad (2)$$

While in our SN simulations corrections due to nucleon thermal motions and recoil, weak magnetism, and nucleon correlations at high densities are taken into account (Rampp & Janka 2002; Buras et al. 2006), Eqs. (1,2) provide good estimates. Strange quark contributions to the nucleon spin modify c_a according to

$$c_a = \frac{1}{2} (\pm g_a - g_a^s) , \quad (3)$$

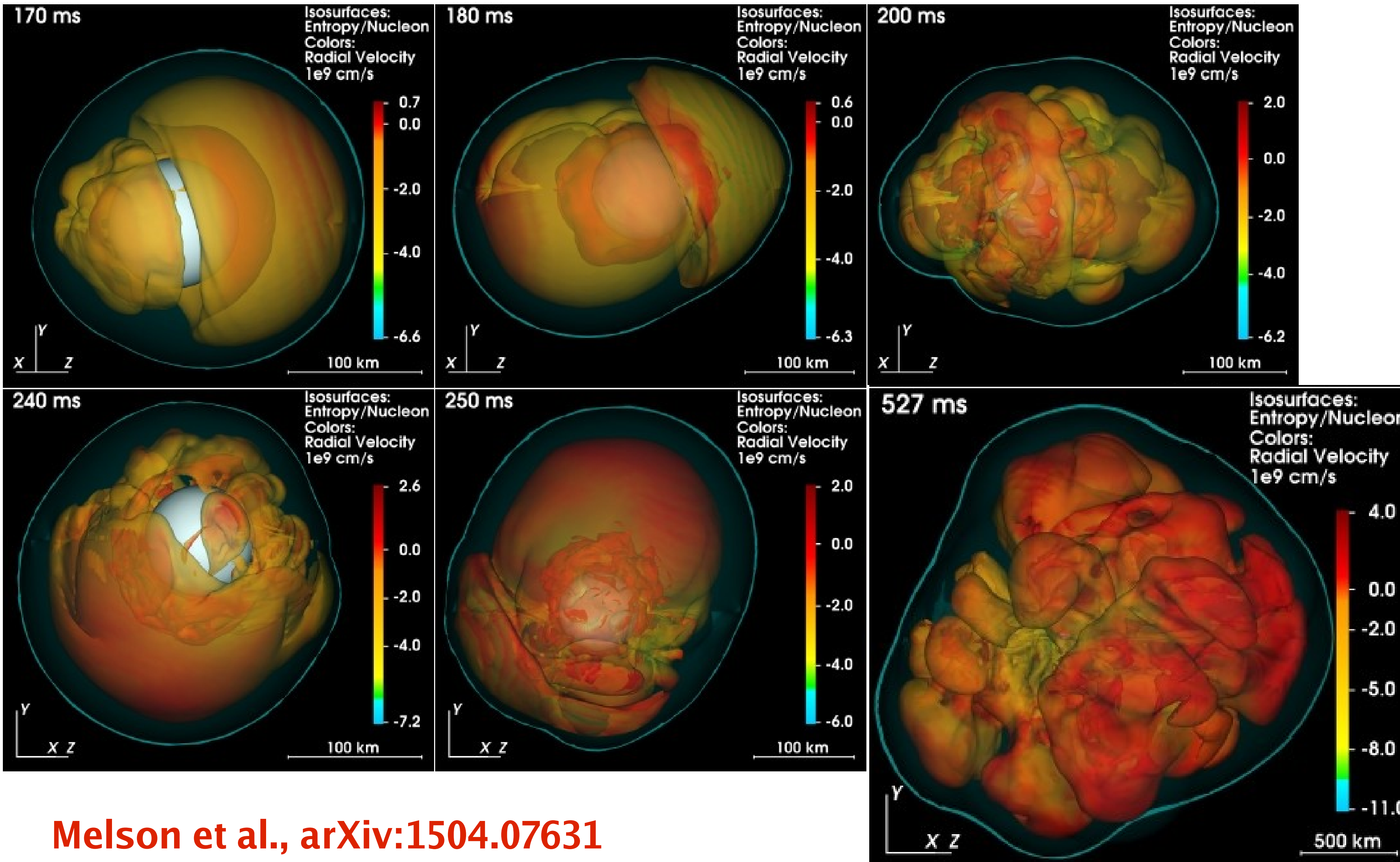
where the plus sign is for νp and the minus sign for νn scattering (see, e.g., Horowitz 2002; Langanke & Martínez-Pinedo 2003). Since $g_a^s \leq 0$, the cross section for νp-scattering is increased and for νn-scattering decreased.

We use:
$g_a = 1.26$
$g_a^s = -0.2$

Melson et al., arXiv:1504.07631

3D Core-Collapse SN Explosion Models

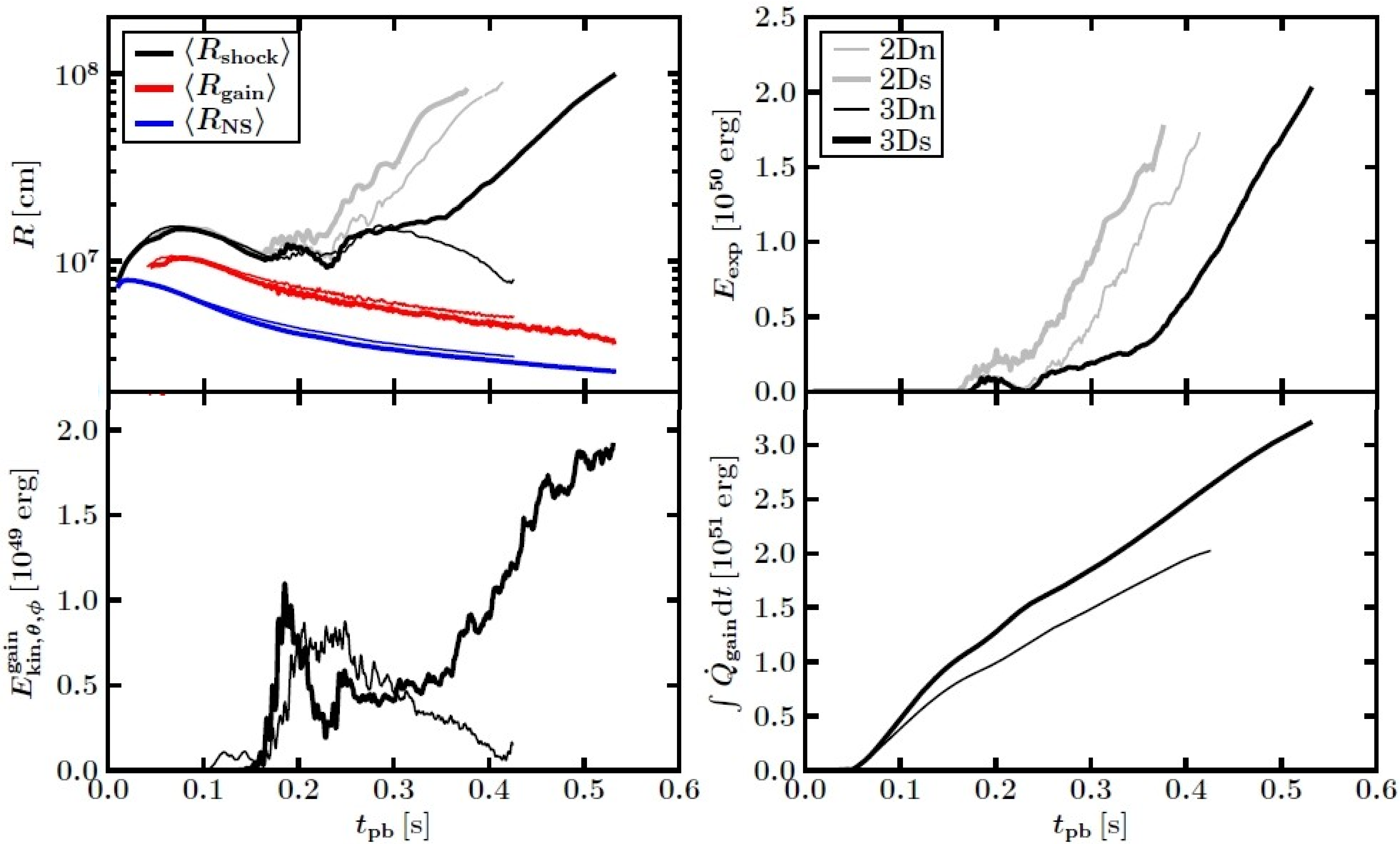
20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)



Melson et al., arXiv:1504.07631

3D Core-Collapse SN Explosion Models

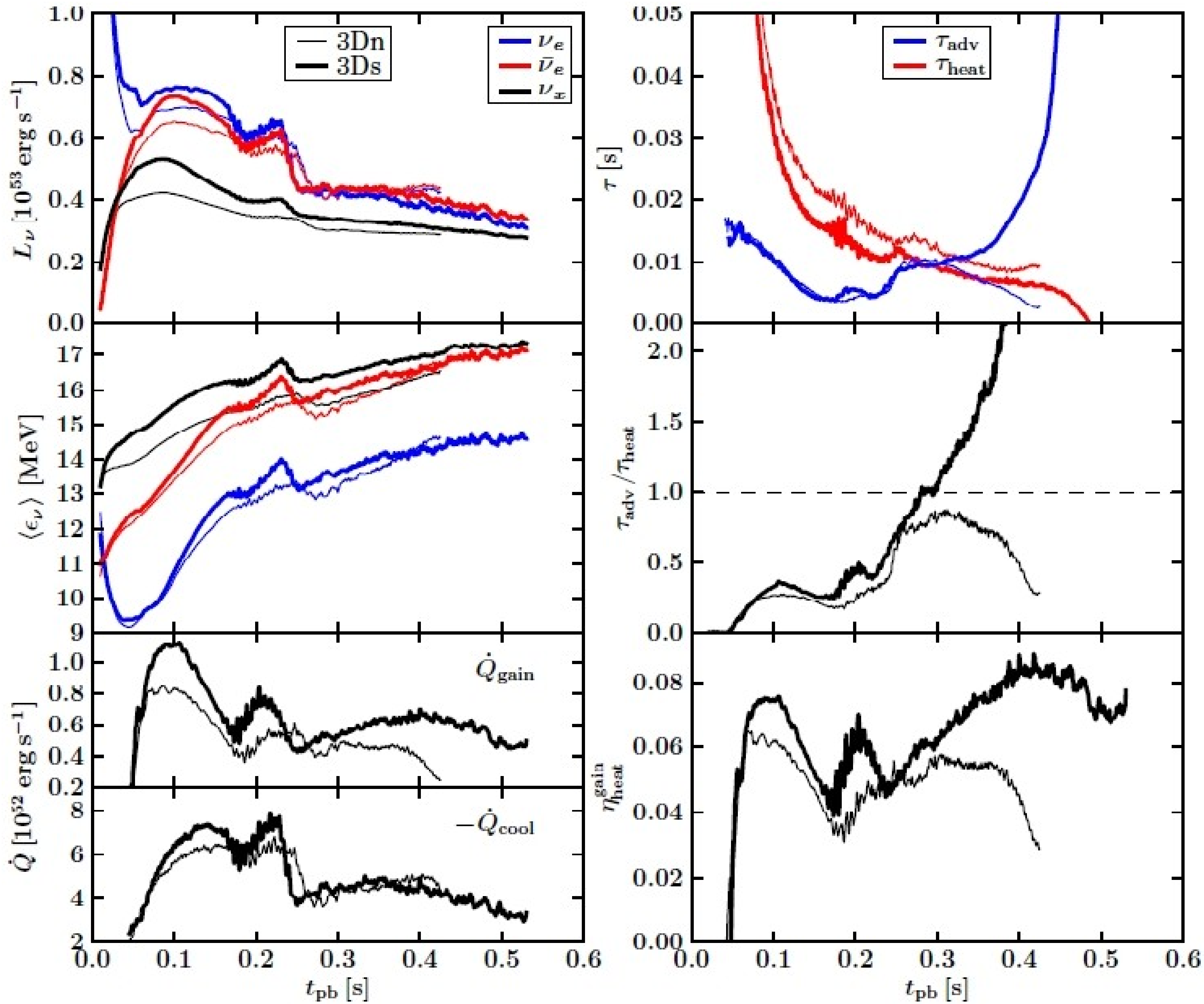
20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)



Melson et al., arXiv:1504.07631

3D Core-Collapse SN Explosion Models

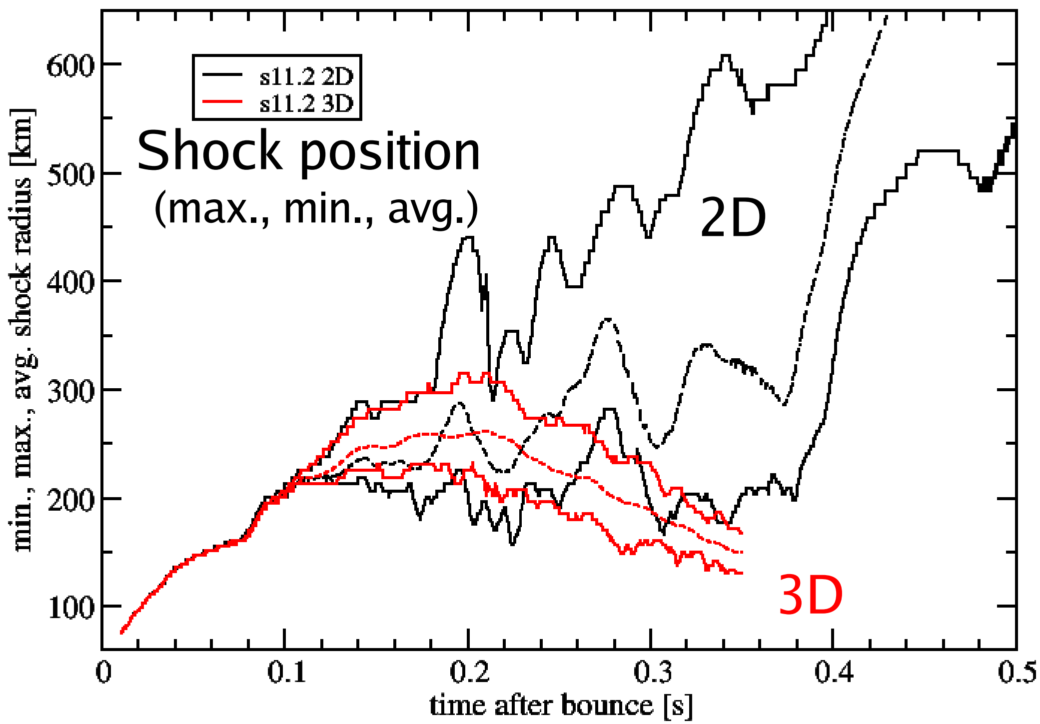
20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)

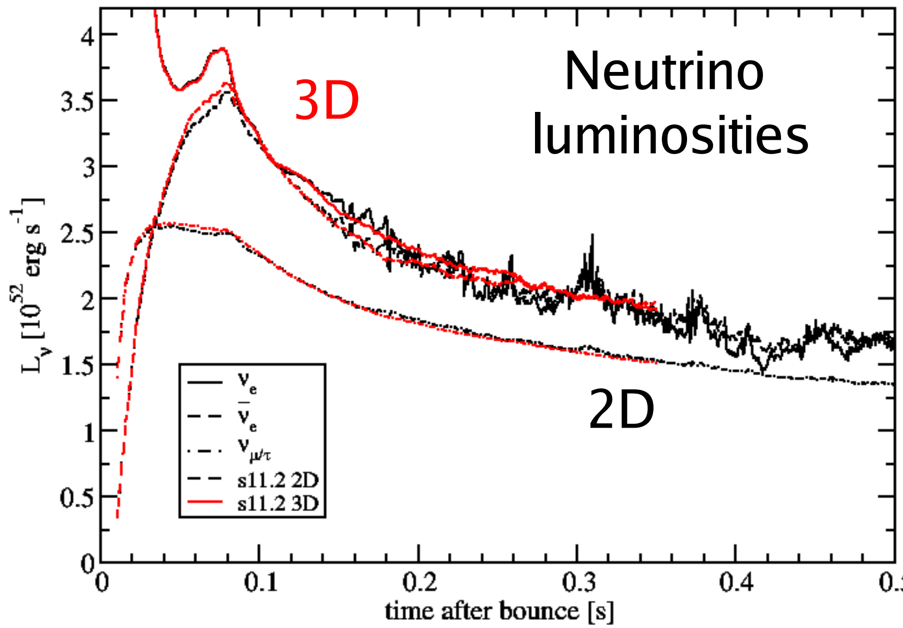


Melson et al., arXiv:1504.07631

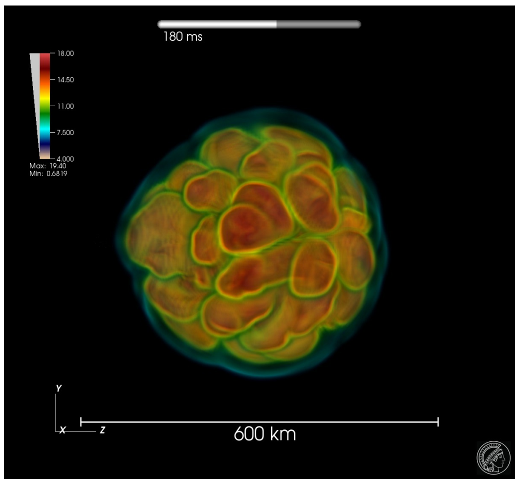
3D SNCC Models with Neutrino Transport

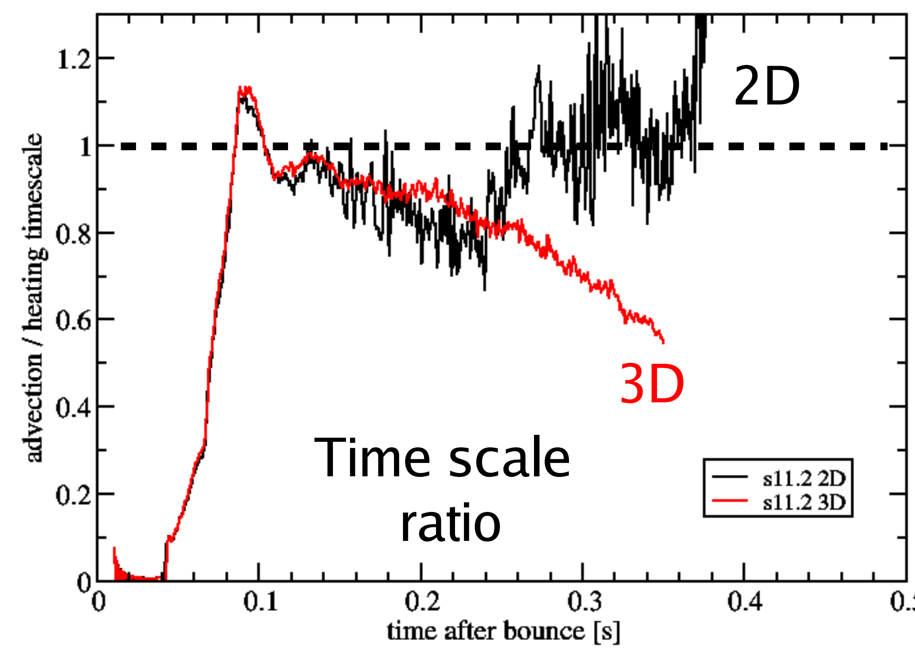
11.2 M_{sun} progenitor (WHW 2002)



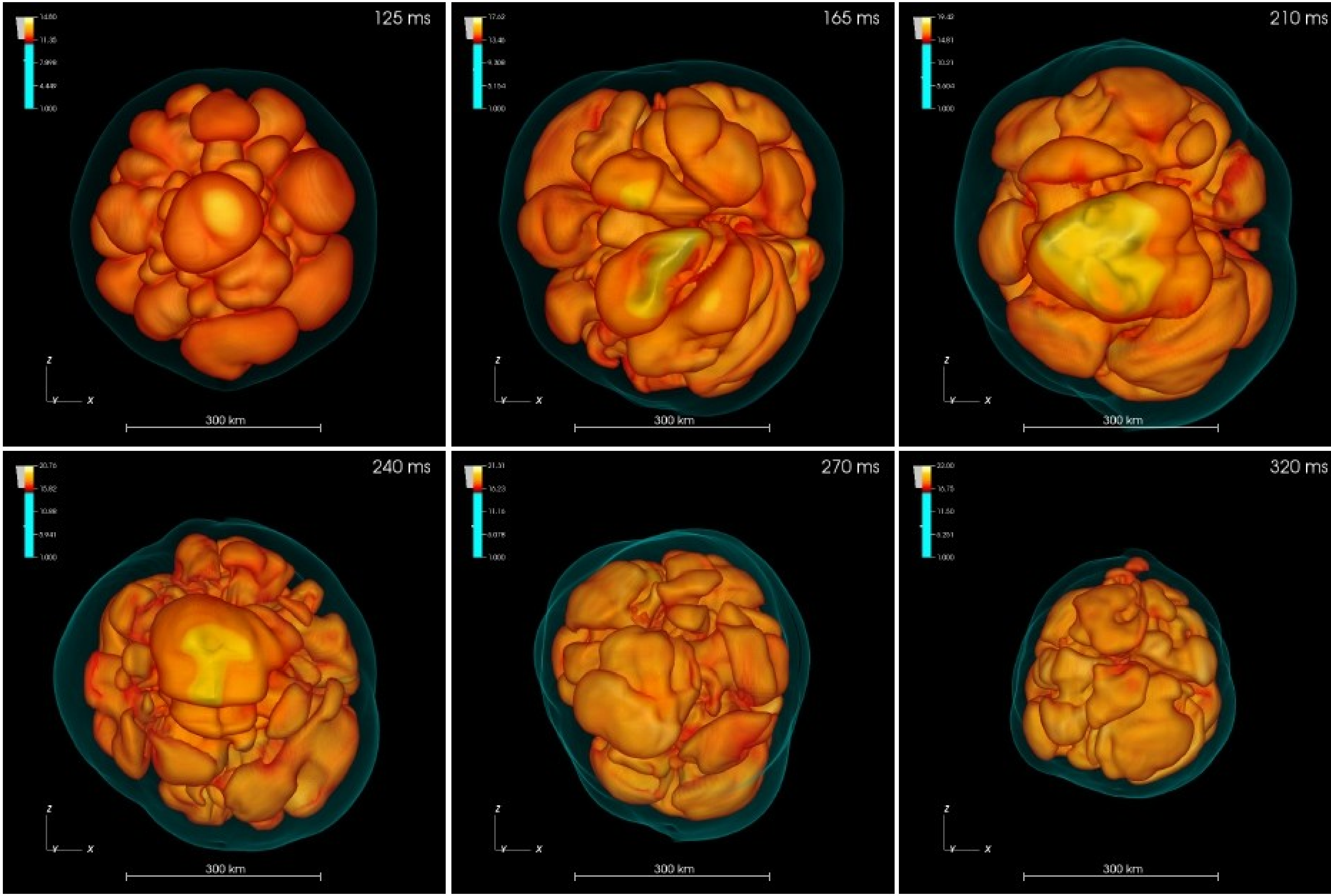


Florian Hanke, PhD thesis (2014)





Convective Overturn in Neutrino-Heating Layer



11.2 M_{sun} progenitor (WHW 2002)

Tamborra, Hanke et al., ApJ (2014)

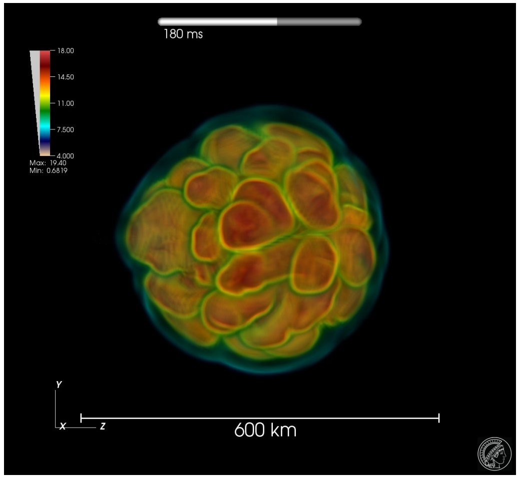
A New Nonradial, Neutrino-Hydrodynamical Instability

LESA:
Lepton-Emission Self-sustained Asymmetry

Tamborra, Hanke, Janka, et al., ApJ 792, 96 (2014)

→ see also talk by Irene Tamborra

A New Nonradial 3D Instability

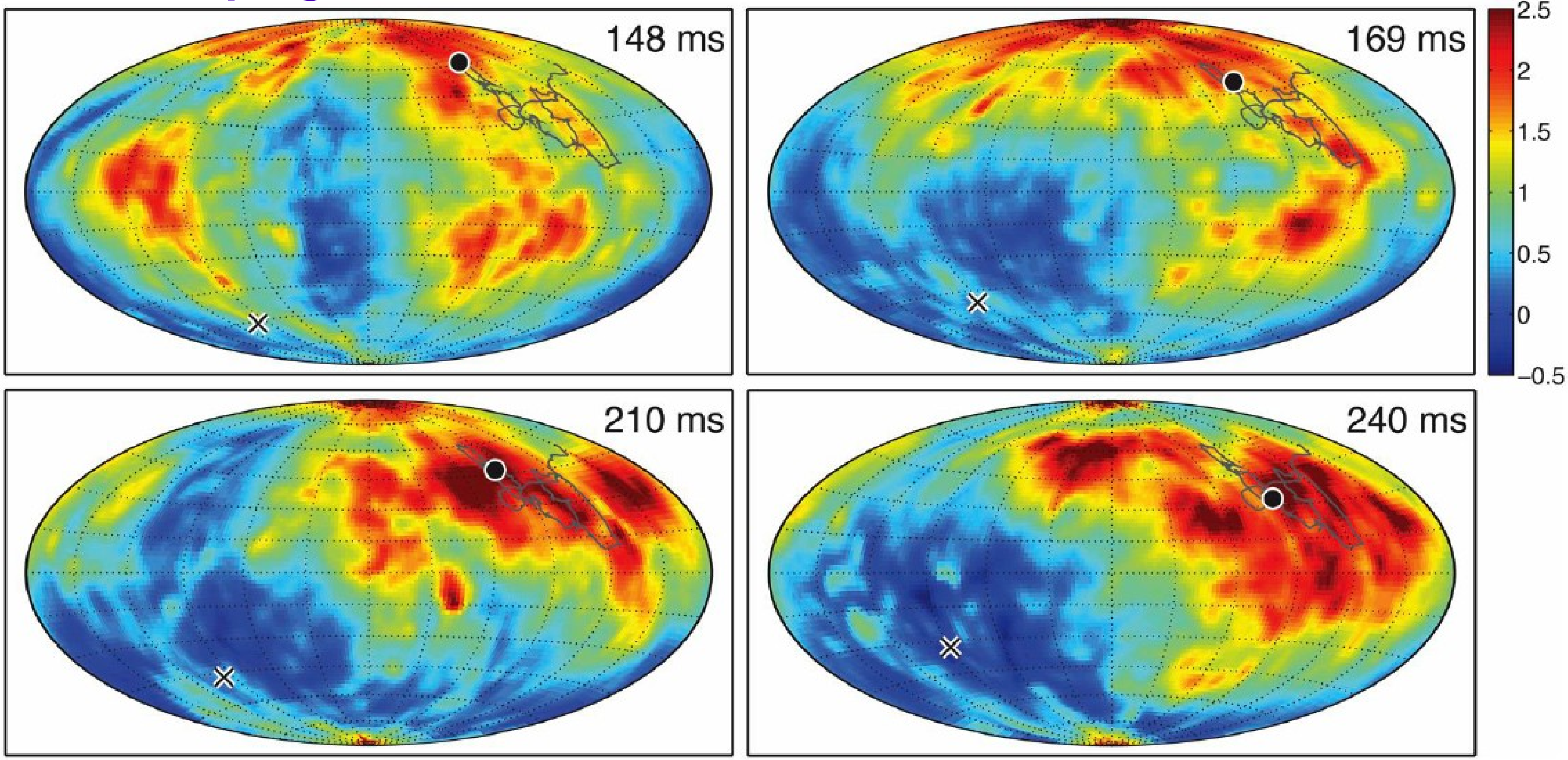


Dipole asymmetry of lepton number emission (LESA)

Lepton number flux: ν_e minus anti-ν_e

$$(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e} \rangle$$

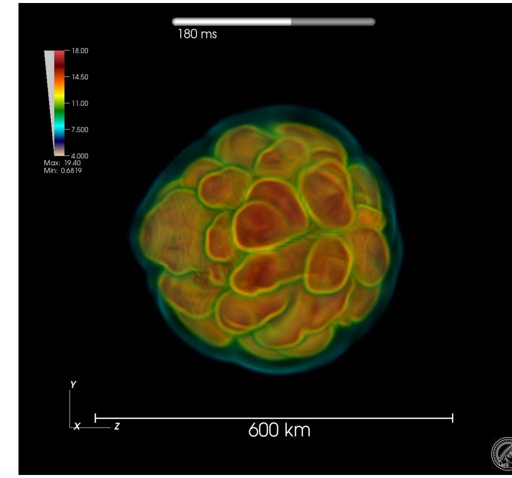
11.2 M_{sun} progenitor (WHW 2002)



Tamborra, Hanke, Janka, et al., ApJ 792, 96 (2014)

A New Nonradial 3D Instability

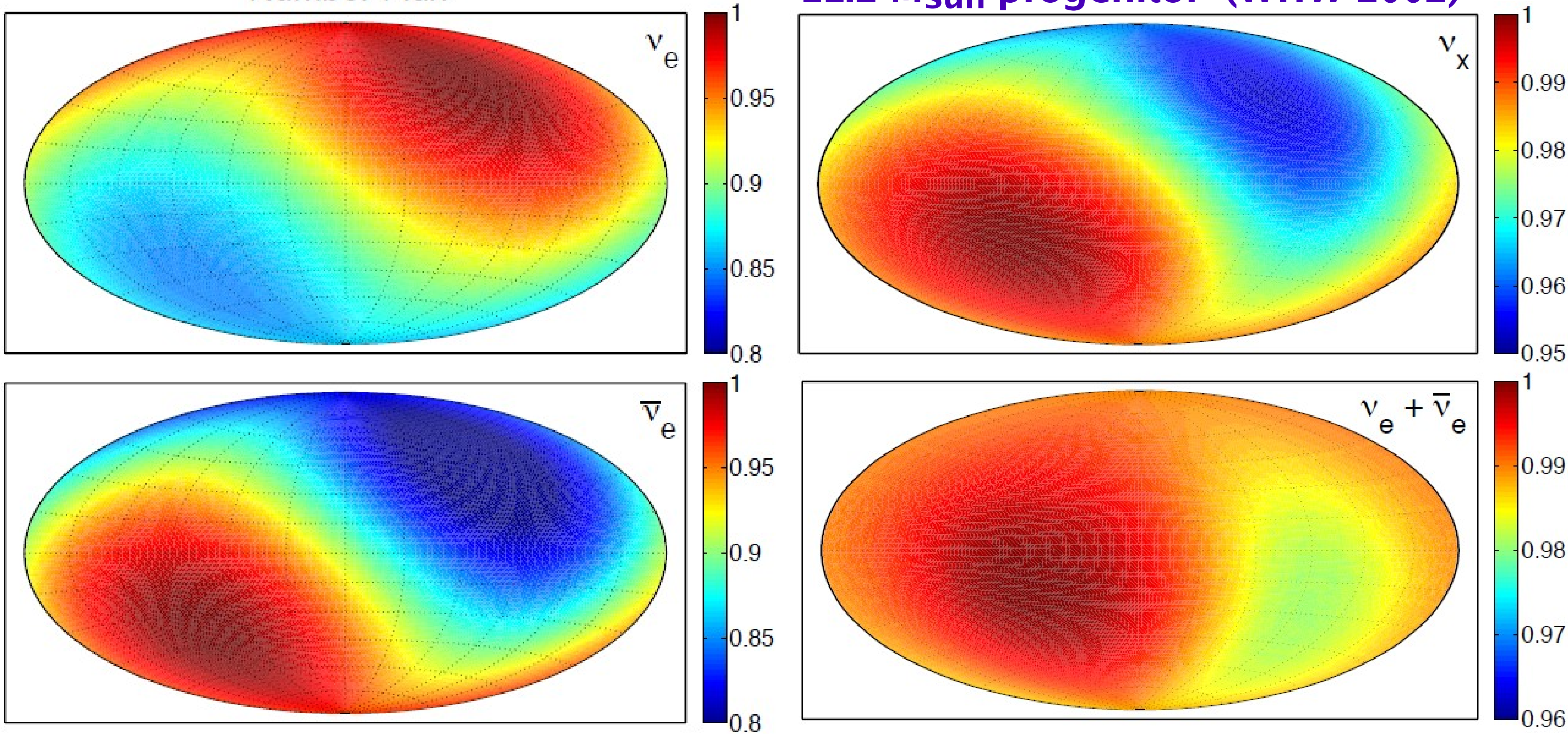
Dipole asymmetry of lepton number emission (LESA)



Tamborra, Hanke, Janka, et al.,
ApJ 792, 96 (2014)

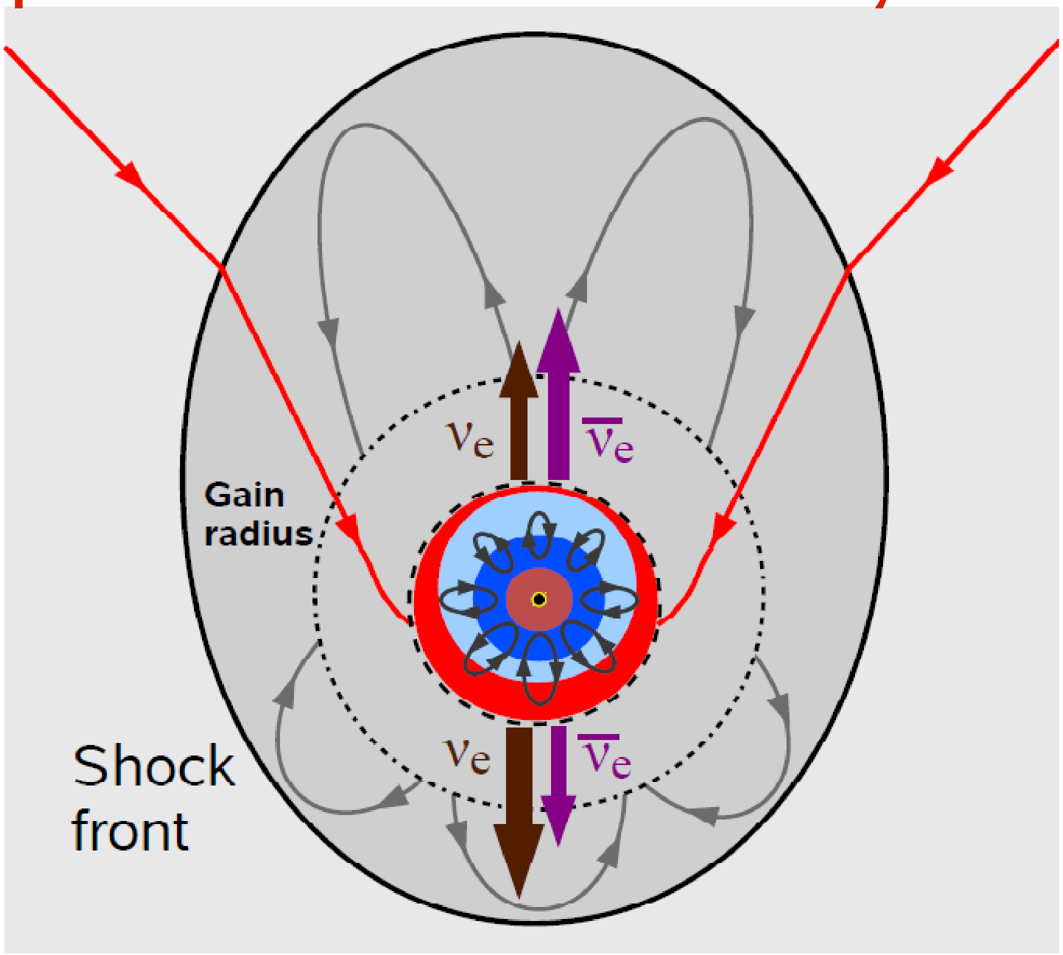
Number Flux

11.2 M_{sun} progenitor (WHW 2002)

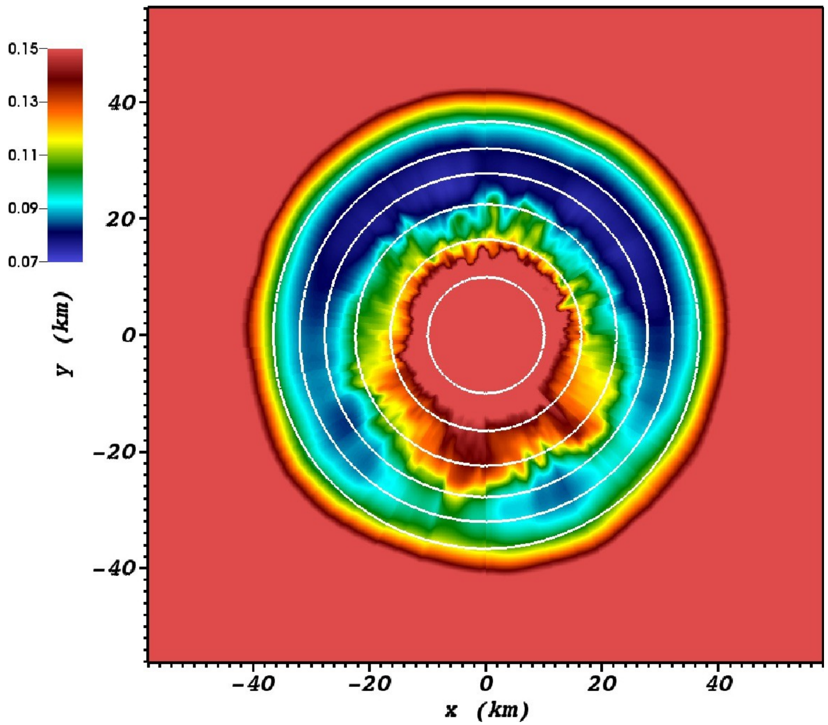


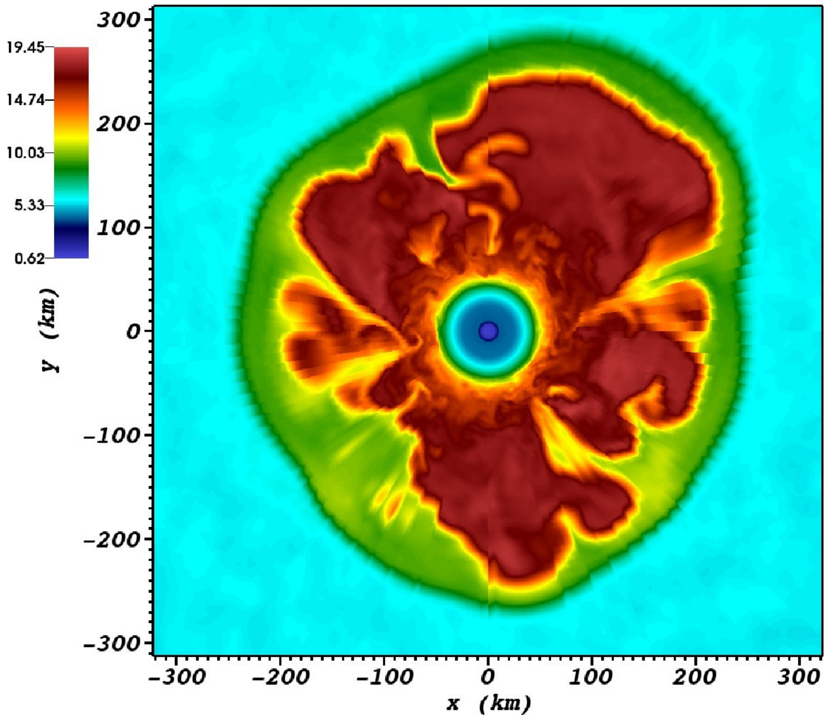
A New Nonradial 3D Instability: "LESA"

Lepton Emission Self-sustained Asymmetry
caused by
dipolar convection and accretion asymmetry



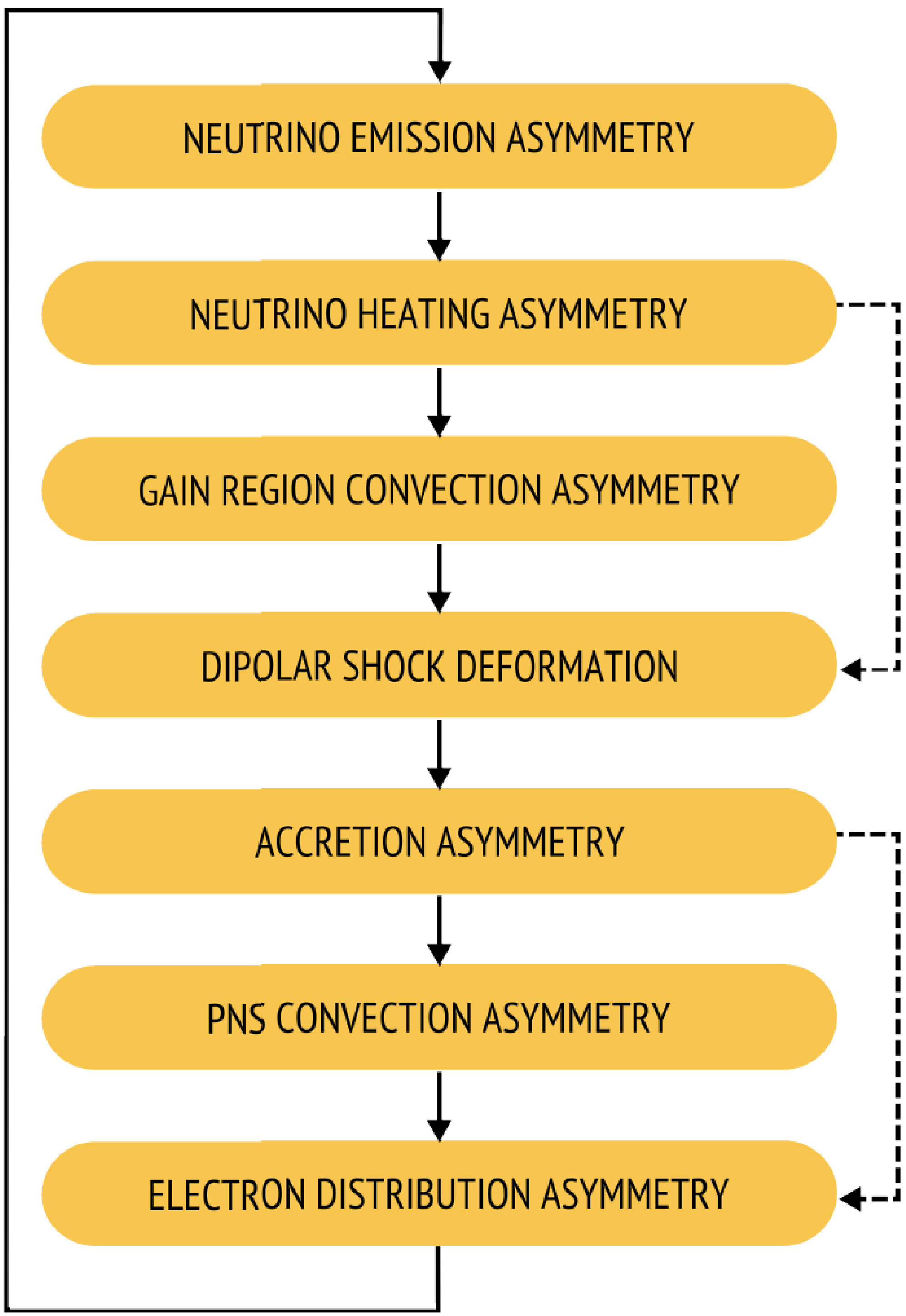
$$\dot{q} \propto \frac{\sigma_0}{r^2} \left(L_{\nu_e} \left\langle \epsilon_{\nu_e}^2 \right\rangle Y_n + L_{\bar{\nu}_e} \left\langle \epsilon_{\bar{\nu}_e}^2 \right\rangle Y_p \right)$$





LESA

"Flow Chart"



Dimitri Chuard, Project Thesis, MPA/Paris (2014)

Consequences of the New Instability

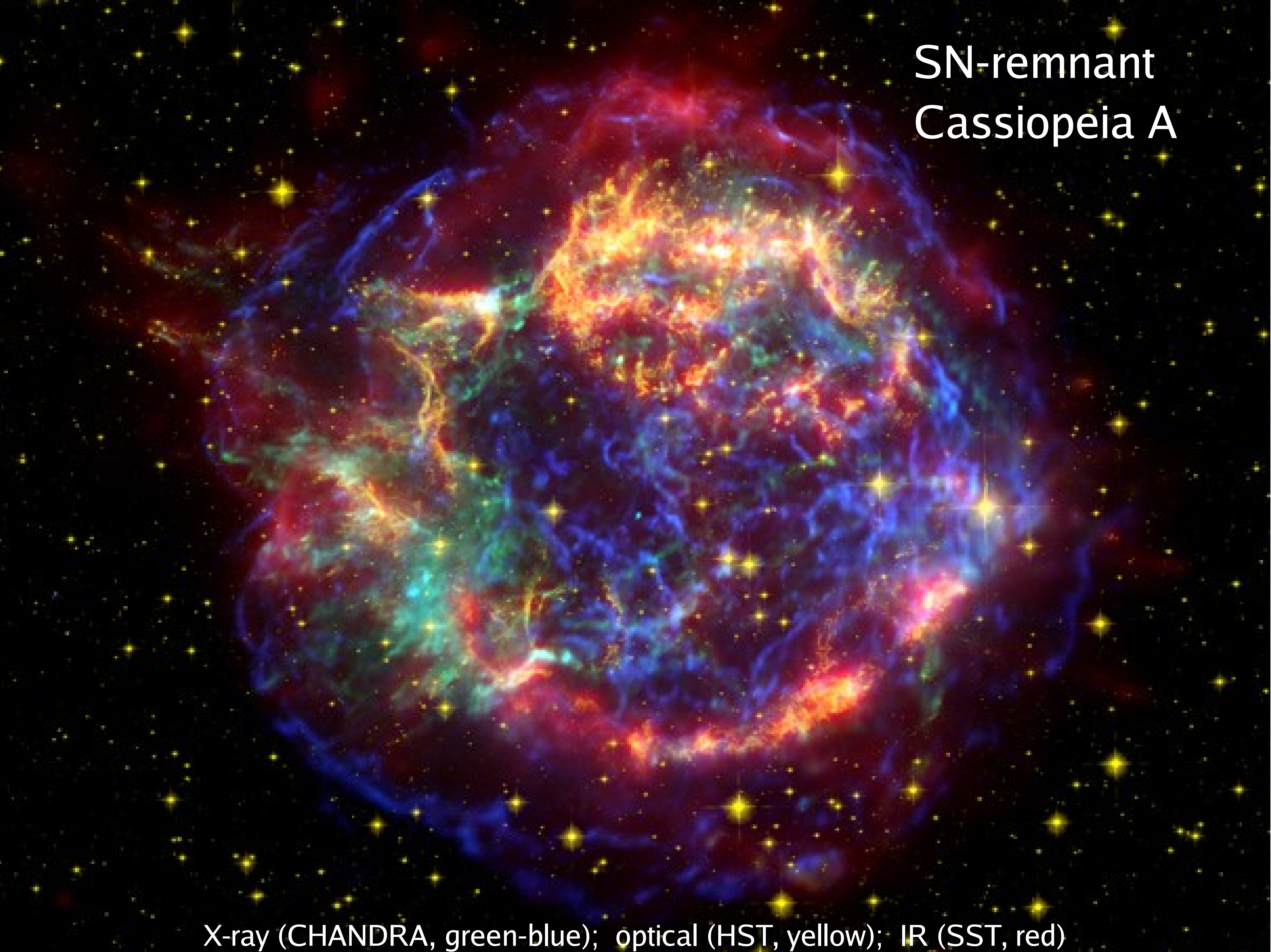
- Observable neutrino signal varies with viewing angle
- Anisotropic nucleosynthesis conditions
- Anisotropic neutrino-flavor oscillations
- NS kicks; some 10 km/s, potentially ~100 km/s

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

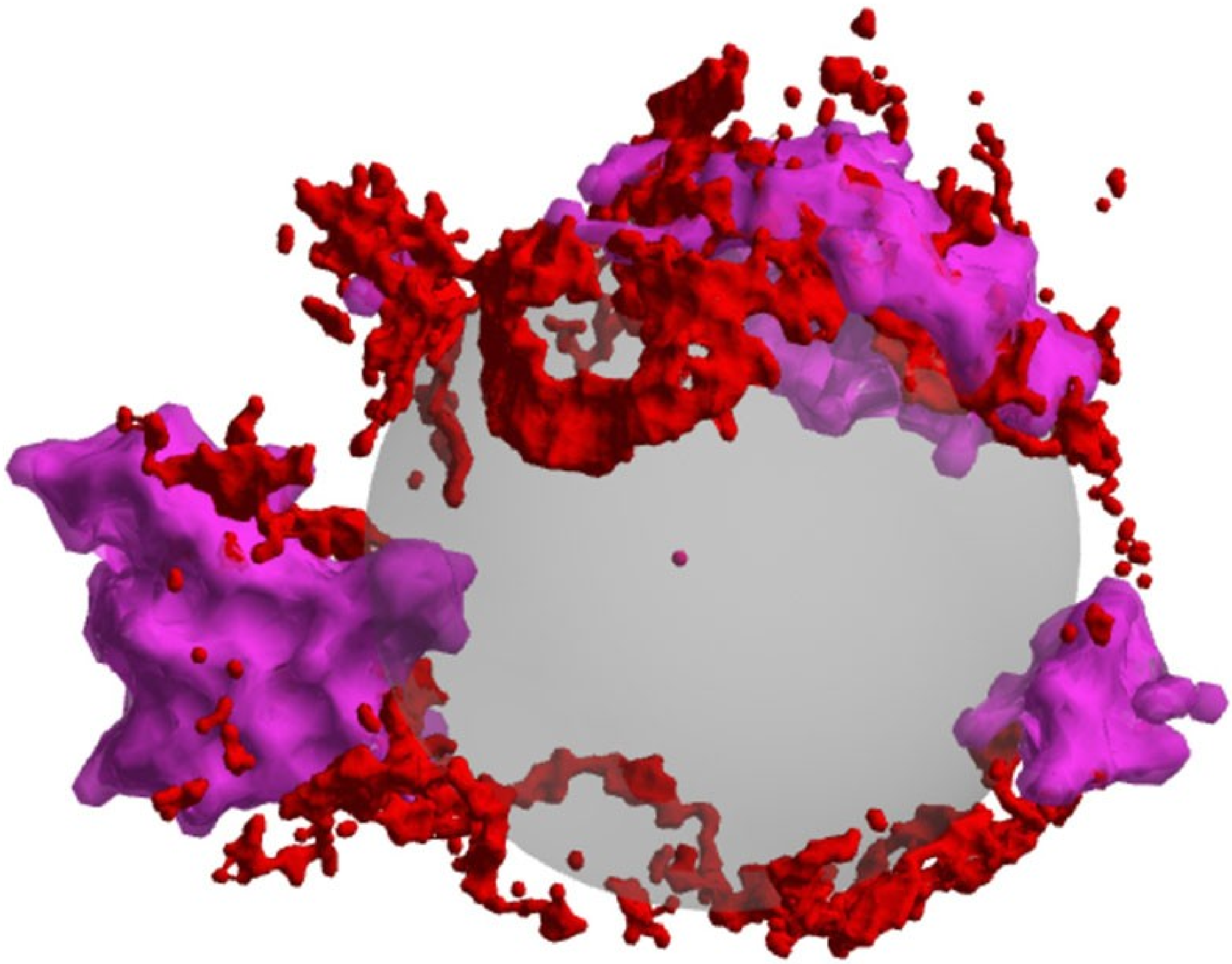
- 2D models with relativistic effects (2D GR and approximate GR) yield explosions for "soft" EoSs, but explosion energies tend to be low.
- 3D modeling has only begun. No final picture of 3D effects yet.
- **SASI can dominate (certain phases) also in 3D models!**
- **Intriguing new phenomena (LESA) in 3D!**
- $M < 10\ M_{sun}$ stars explode in 3D;
  first 3D explosion of $20\ M_{sun}$ progenitor (due to strangeness effects)
- 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 & Ott, ApJL778:L7 (2013); Couch et al., arXiv:1503.02199; Muller & THJ, MNRAS 448 (2015) 2141)
- **Uncertain/missing physics ?????**

Asymmetries in Nucleosynthesis and Ejecta

Using 3D simulations with parametric neutrino transport to trigger neutrino-driven explosions


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

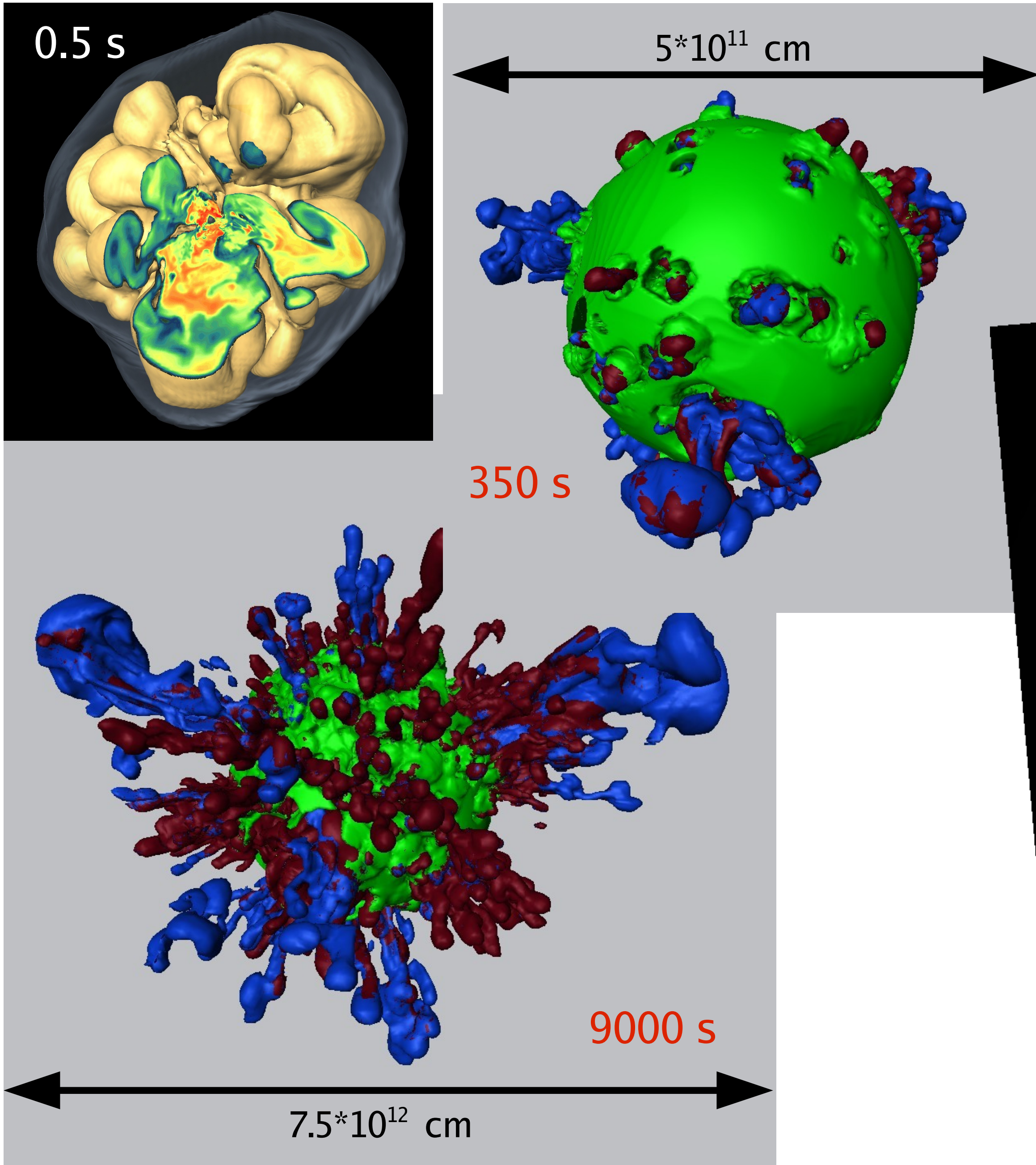
Chemical Asymmetries in CAS A Remnant



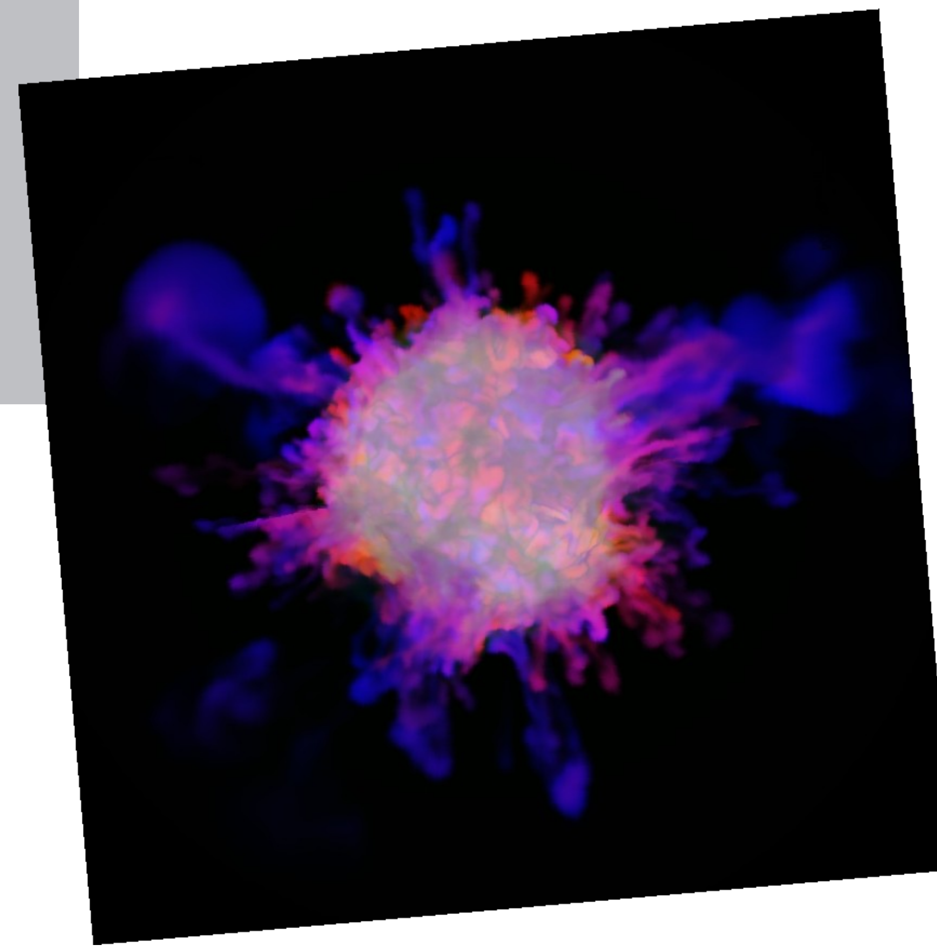
Red: sulfur and oxygen (optical)
Purple: Iron (X-ray)

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

Mixing Instabilities in 3D SN Models

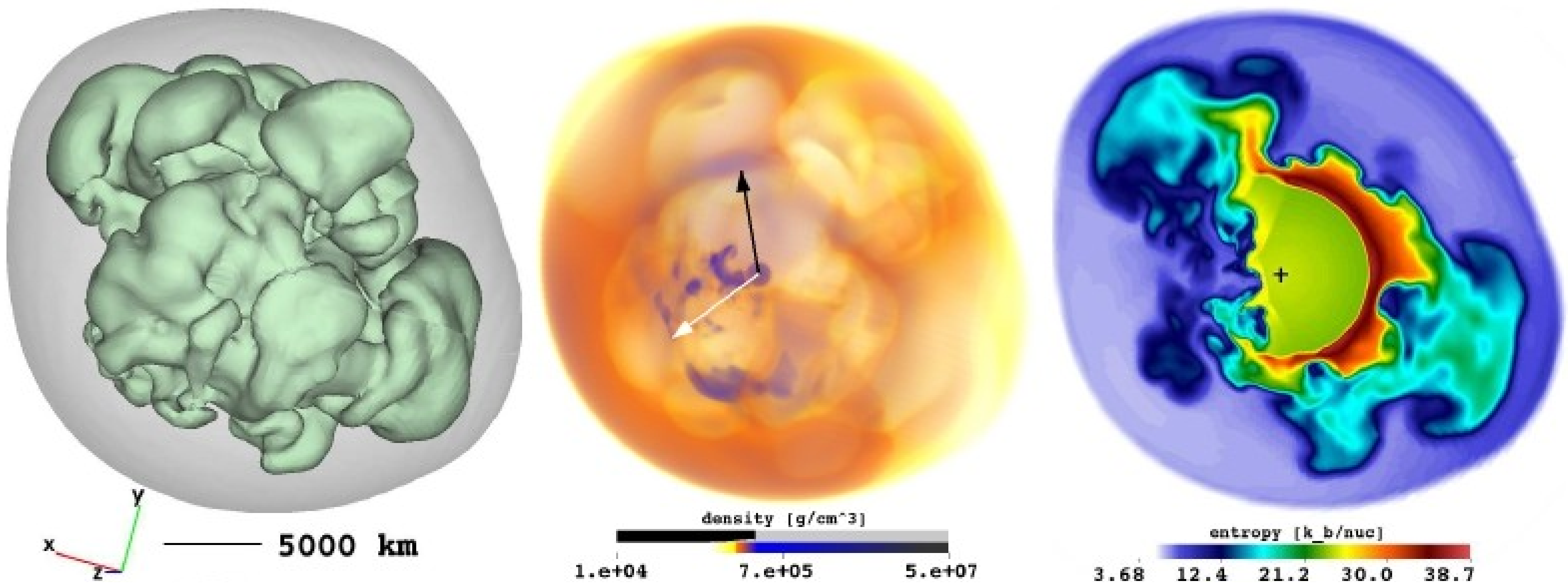


green: carbon
red: oxygen
blue: nickel



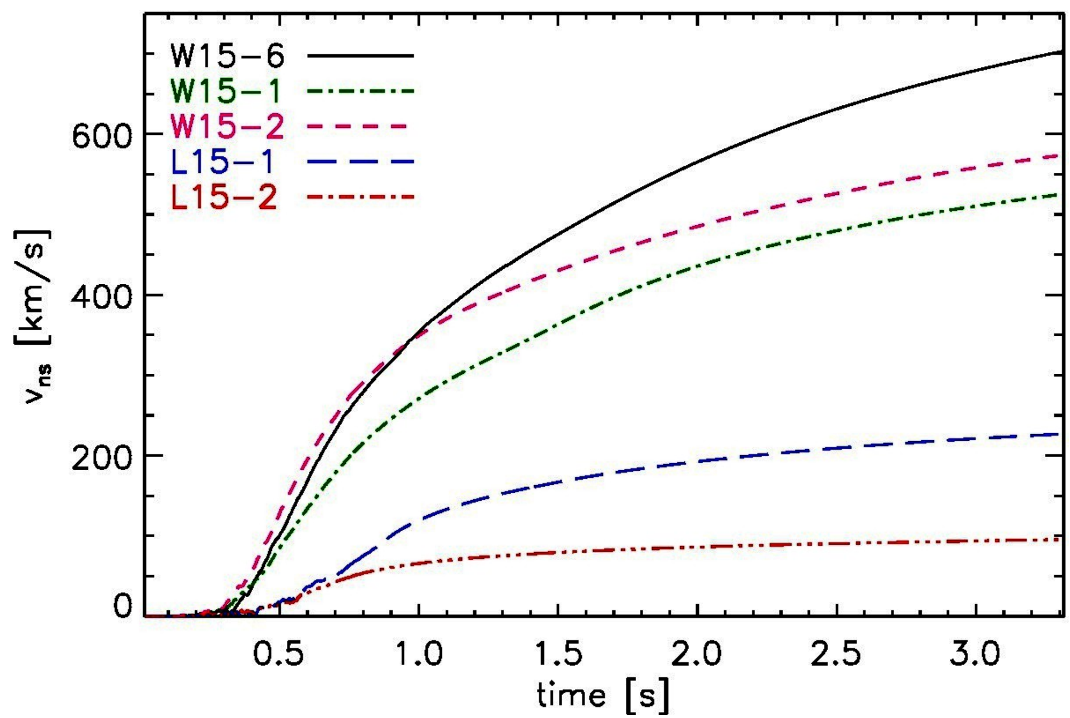
(Hammer, Janka, Müller, ApJ 2010)

Neutron Star Recoil in 3D Explosion Models



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

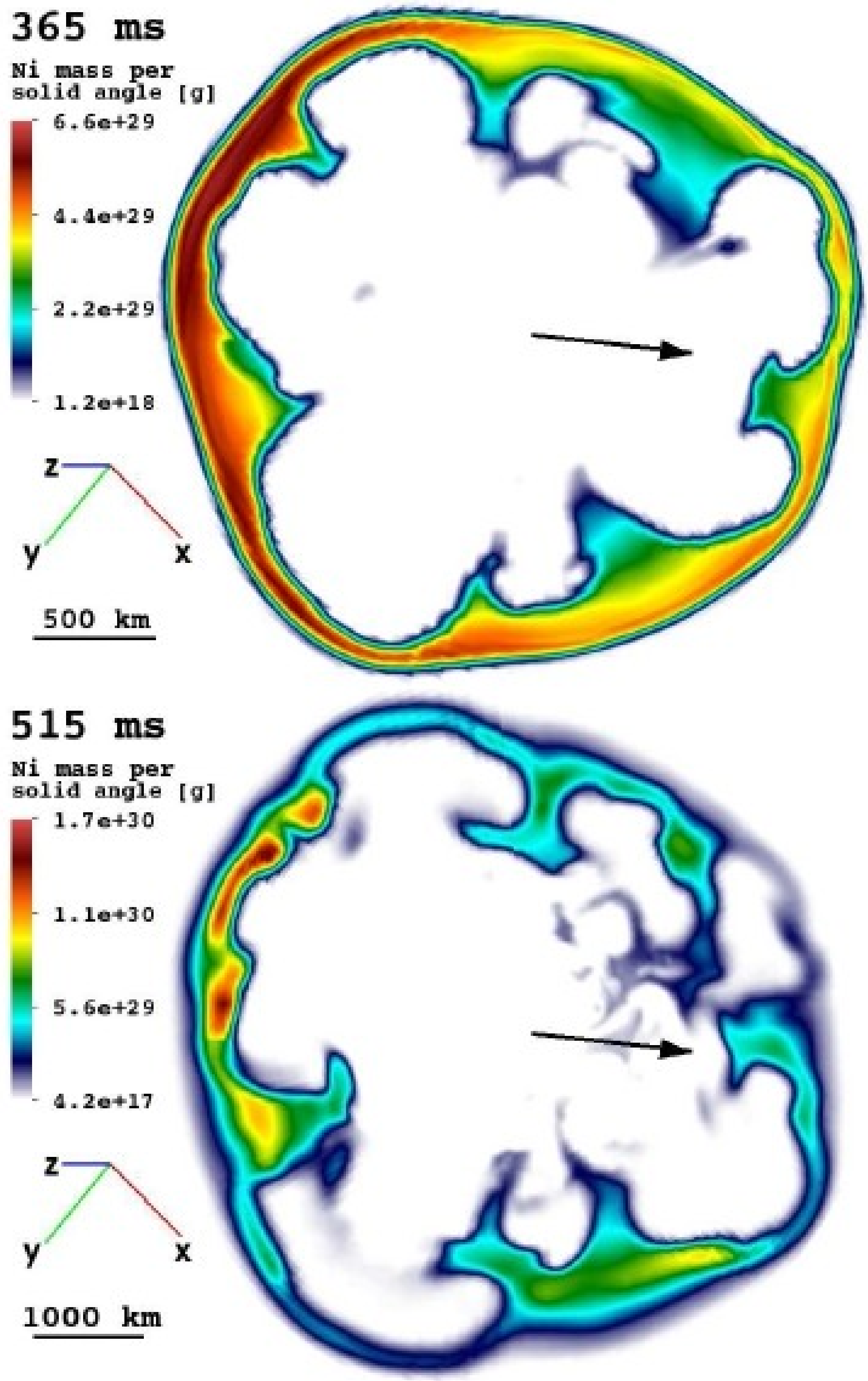
where Δm is normalized by $10^{-3}\, M_\odot$, r_i by 10^7 cm, and v_s by $5000\,\mathrm{km\,s^{-1}}$.



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

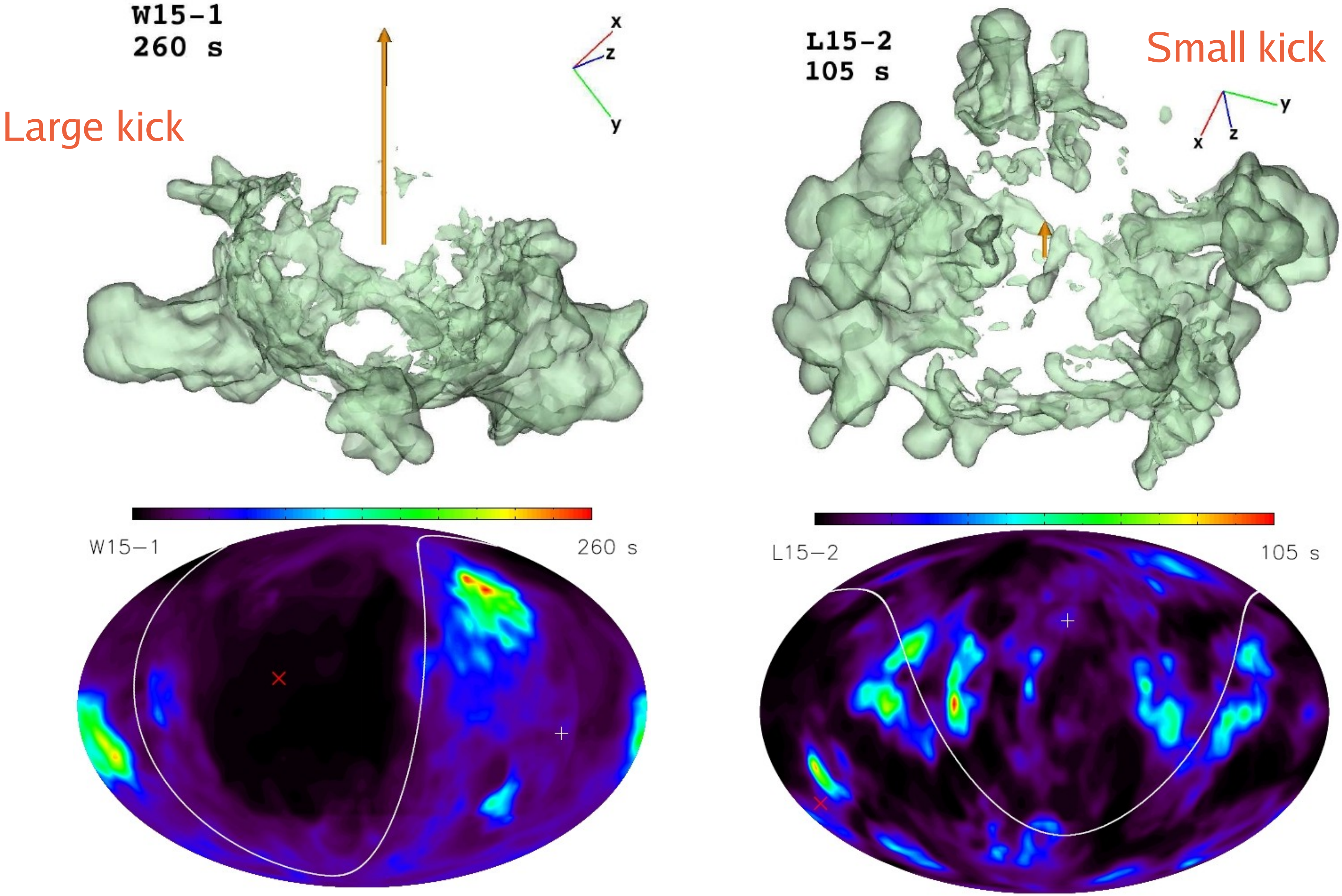
Neutron Star Recoil and Nickel Production

Nickel production is enhanced in direction of stronger explosion, i.e. opposite to NS kick



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

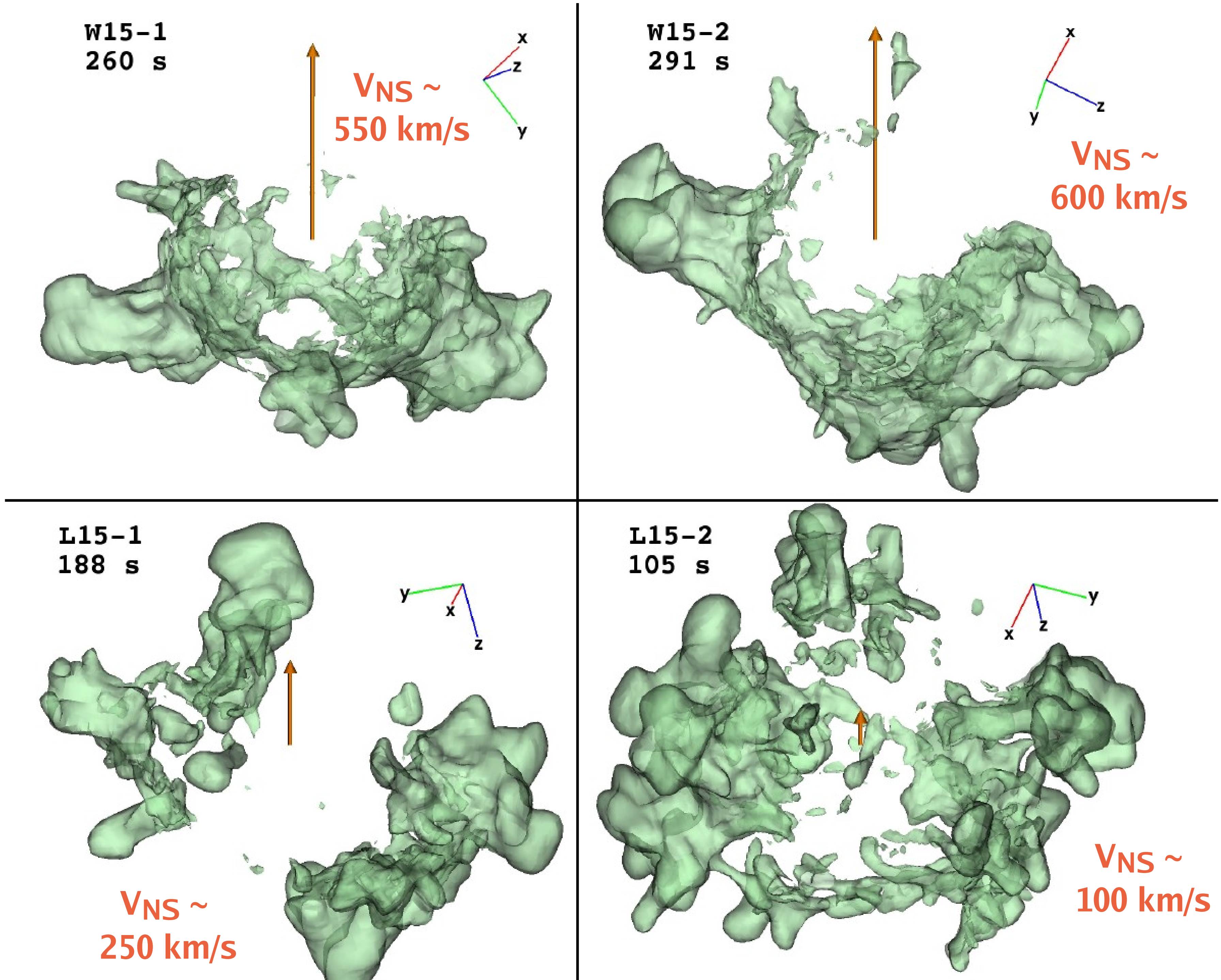
Neutron Star Recoil and Nickel Production



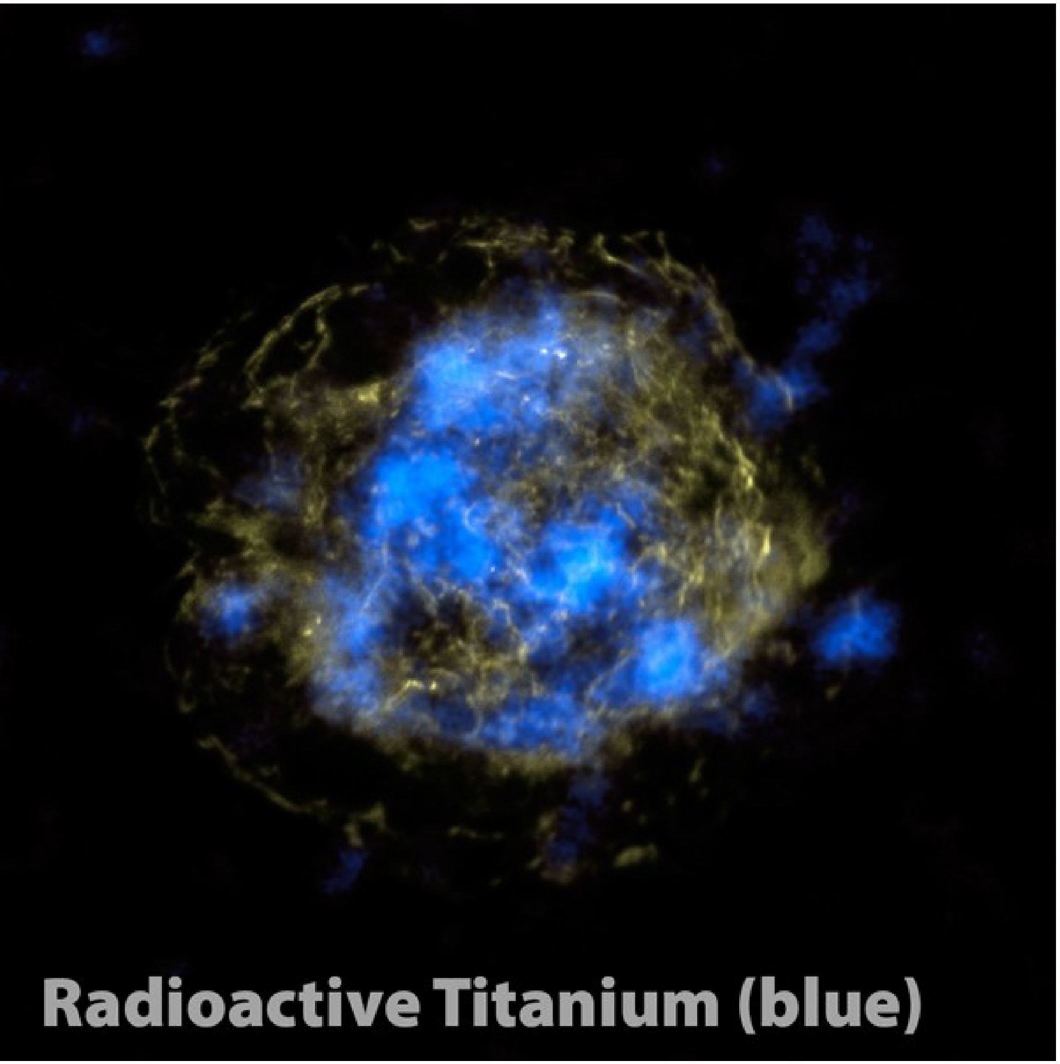
Wongwathanarat, Janka, Müller, A&A 552 (2013) A126

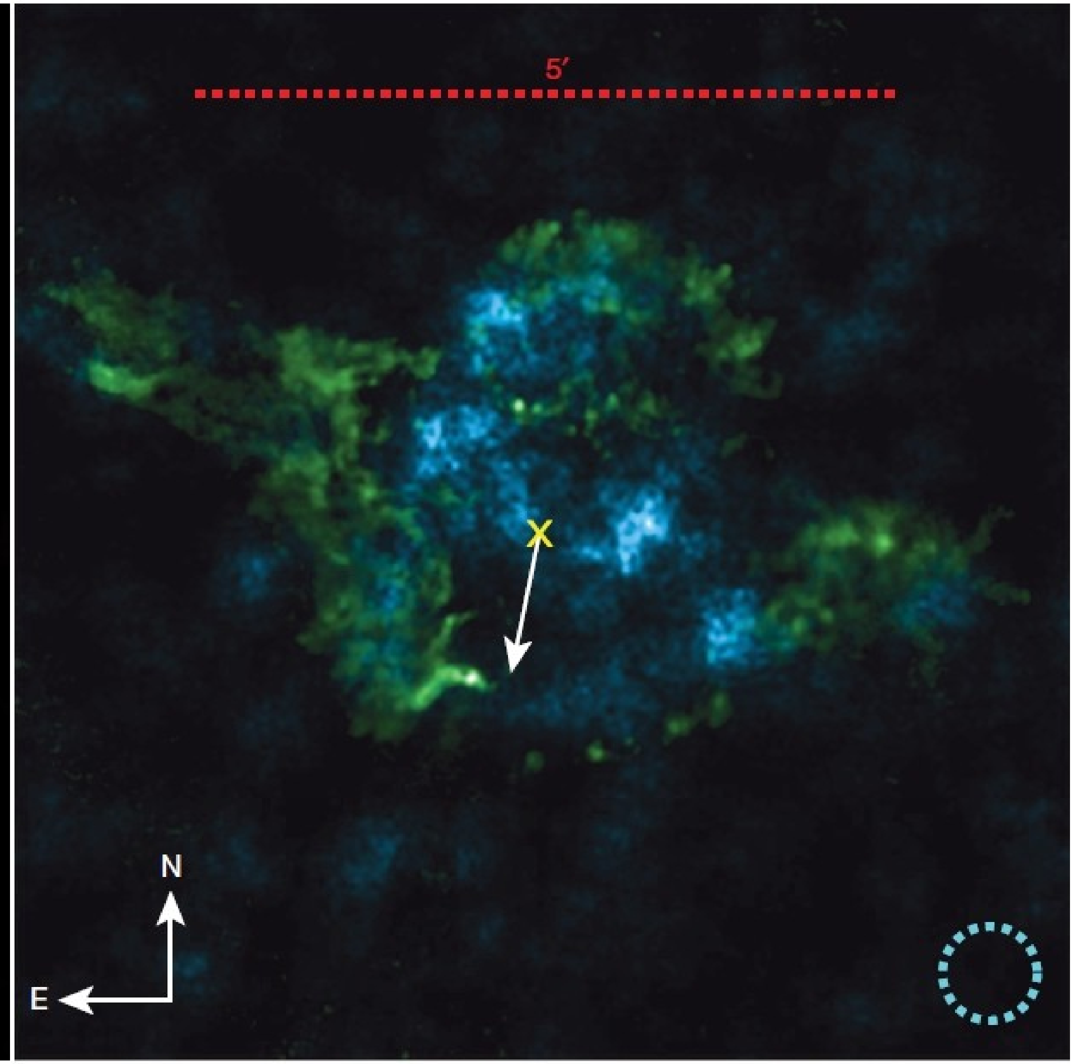
Enhanced concentration of iron in supernova remnants opposite to direction of large pulsar kick can be observable consequence of hydrodynamical kick mechanism.

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



^{44}Ti Asymmetry in the CAS A Remnant

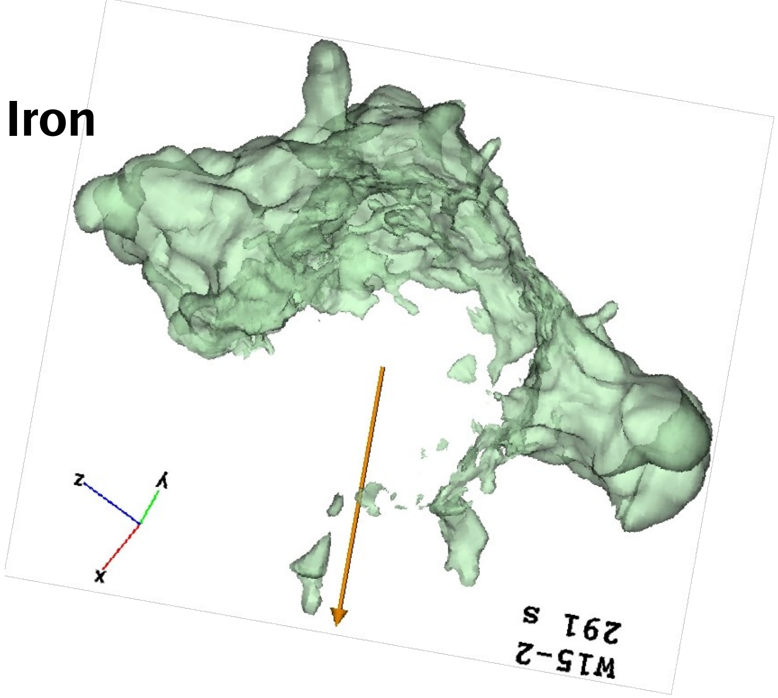


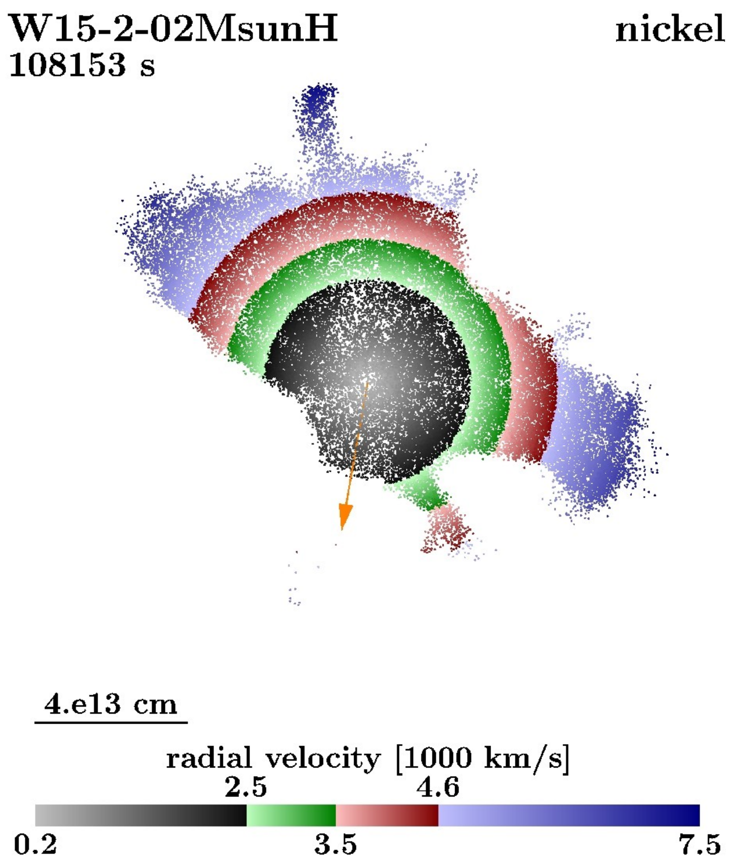


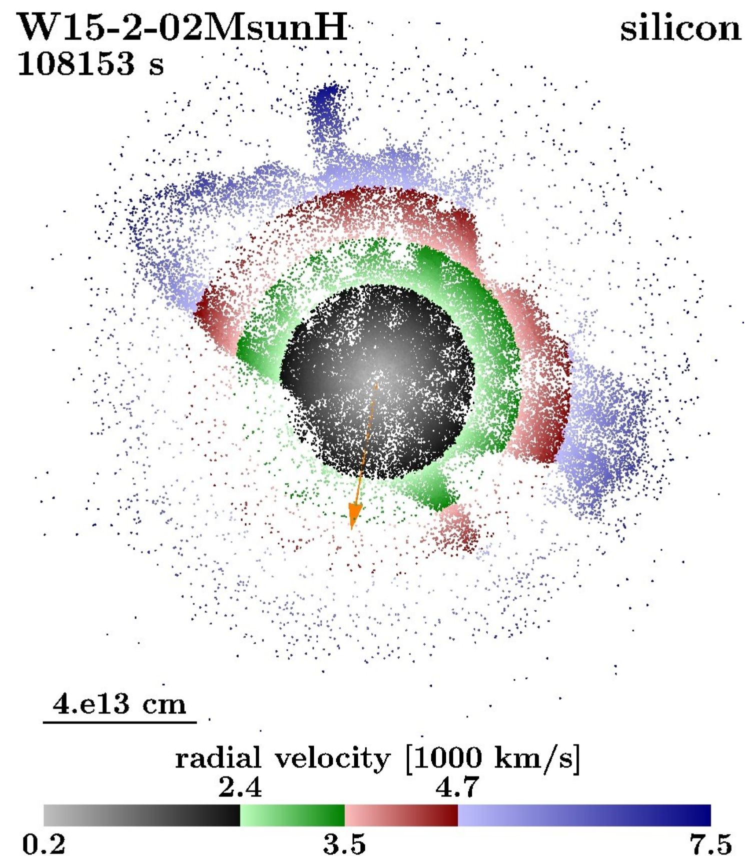
NuSTAR observations

Grefenstette et al., Nature 506 (2014) 340

Doppler Velocities of Iron, Titanium, Silicon

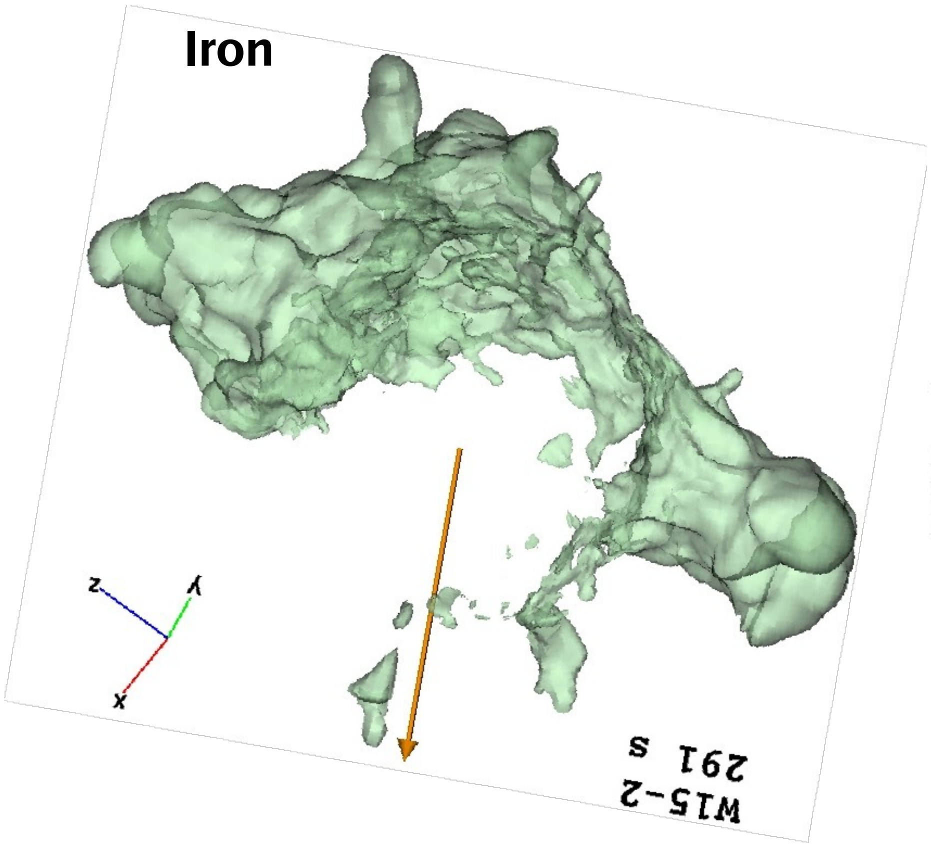


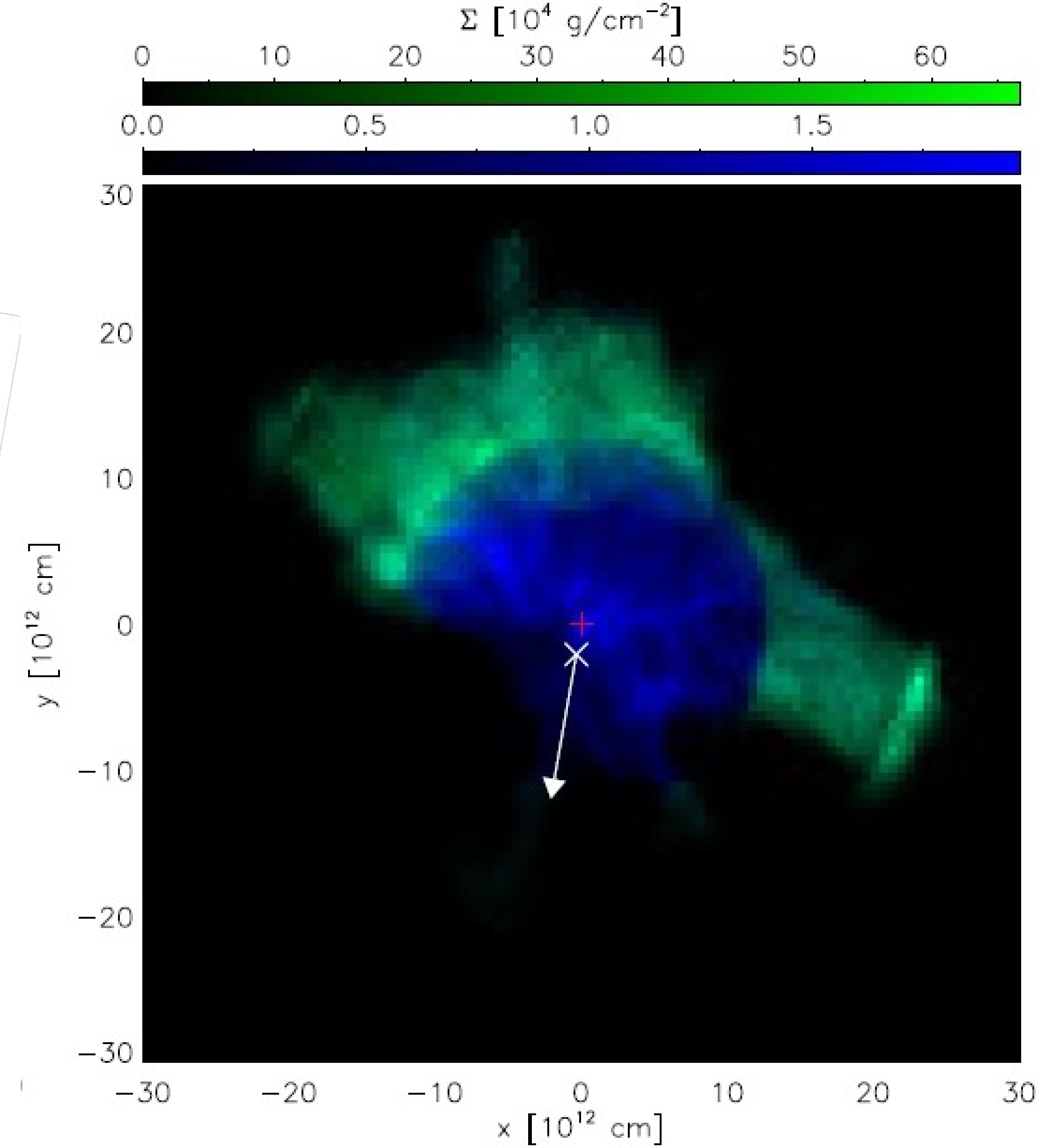




Annop Wongwathanarat

Neutron Star Recoil and Iron & ^{44}Ti Distribution

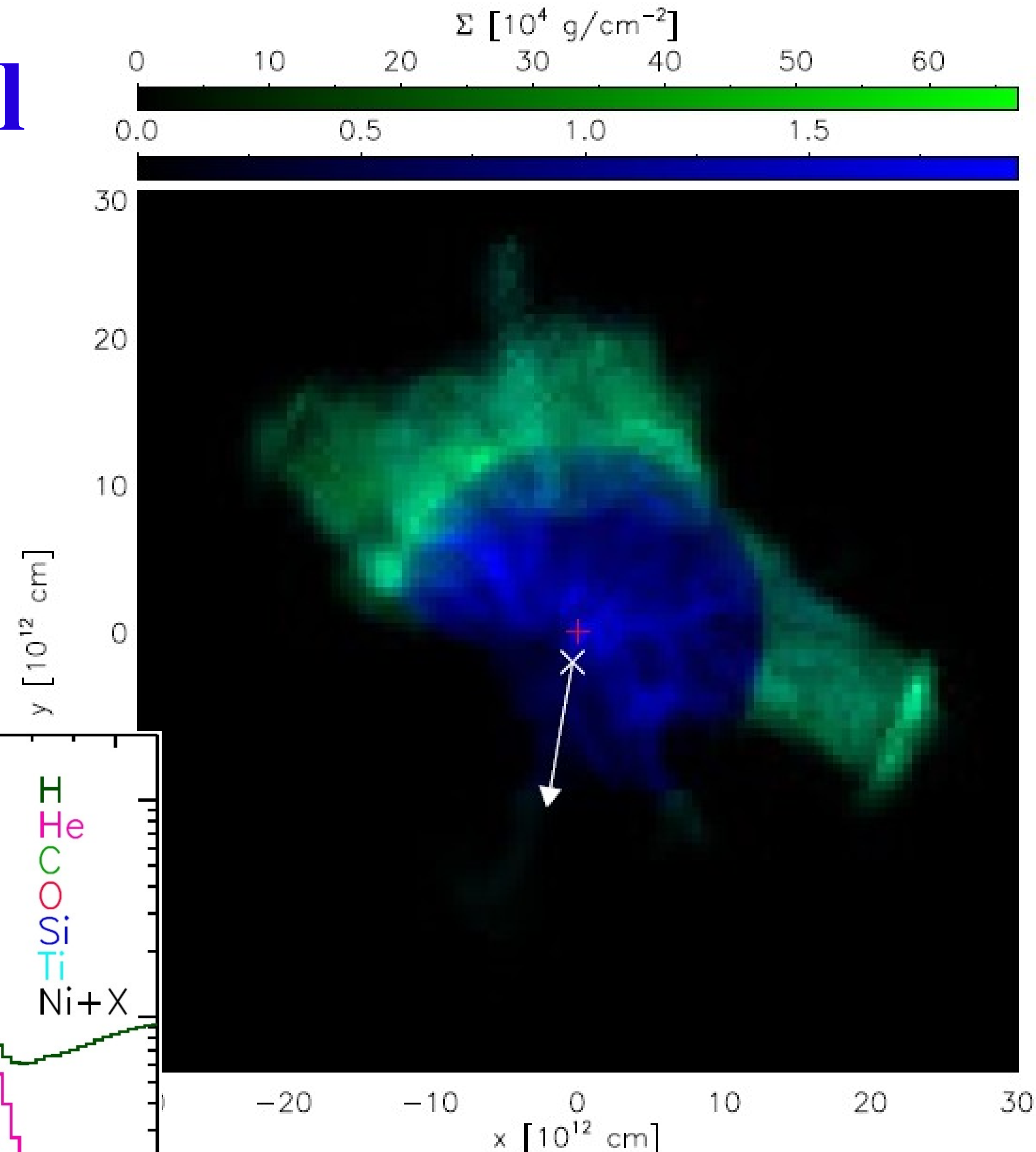


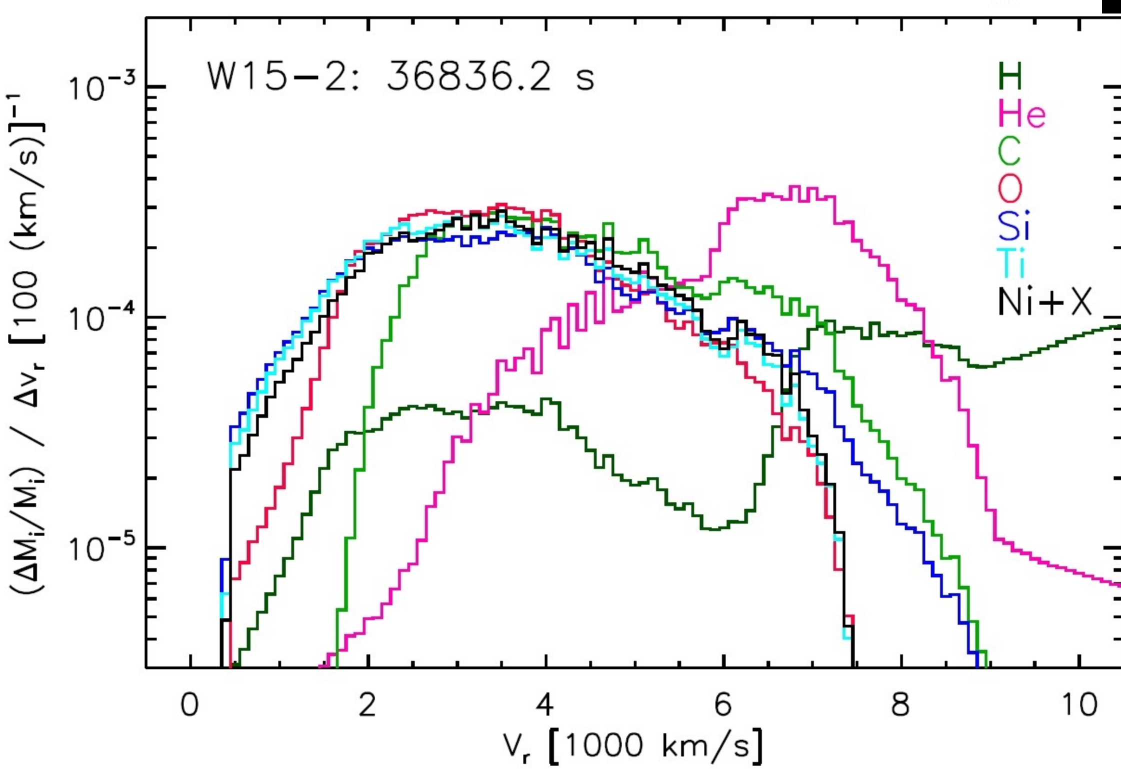


Annop Wongwathanarat

Neutron Star Recoil and Iron & ^{44}Ti Distribution

3D simulation for Type IIb-like progenitor by Annop Wongwathanarat





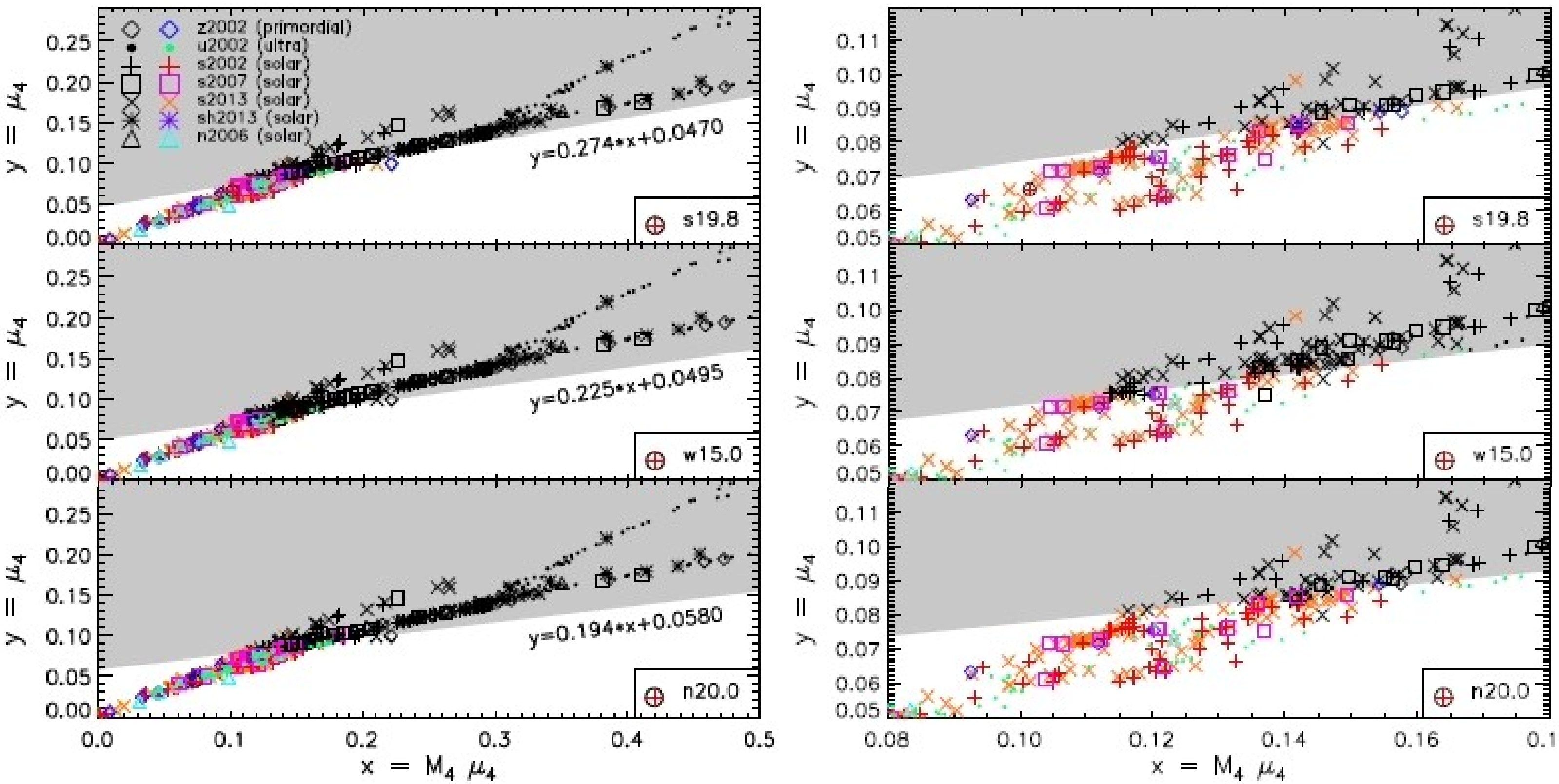
Velocities based on E_{exp} ~ 1.3 B, will increase roughly with square root of E_{exp}.

Progenitor-Explosion and SN-Remnant Connections

A TWO-PARAMETER CRITERION FOR CLASSIFYING THE EXPLODABILITY OF MASSIVE STARS BY THE NEUTRINO-DRIVEN MECHANISM

T. Ertl[1,2], H.-Th. Janka[1], S. E. Woosley[3], T. Sukhbold[3], and M. Ugliano[4]

Draft version March 25, 2015



→ **see poster by Thomas Ertl and talk by Tug Sukhbold**