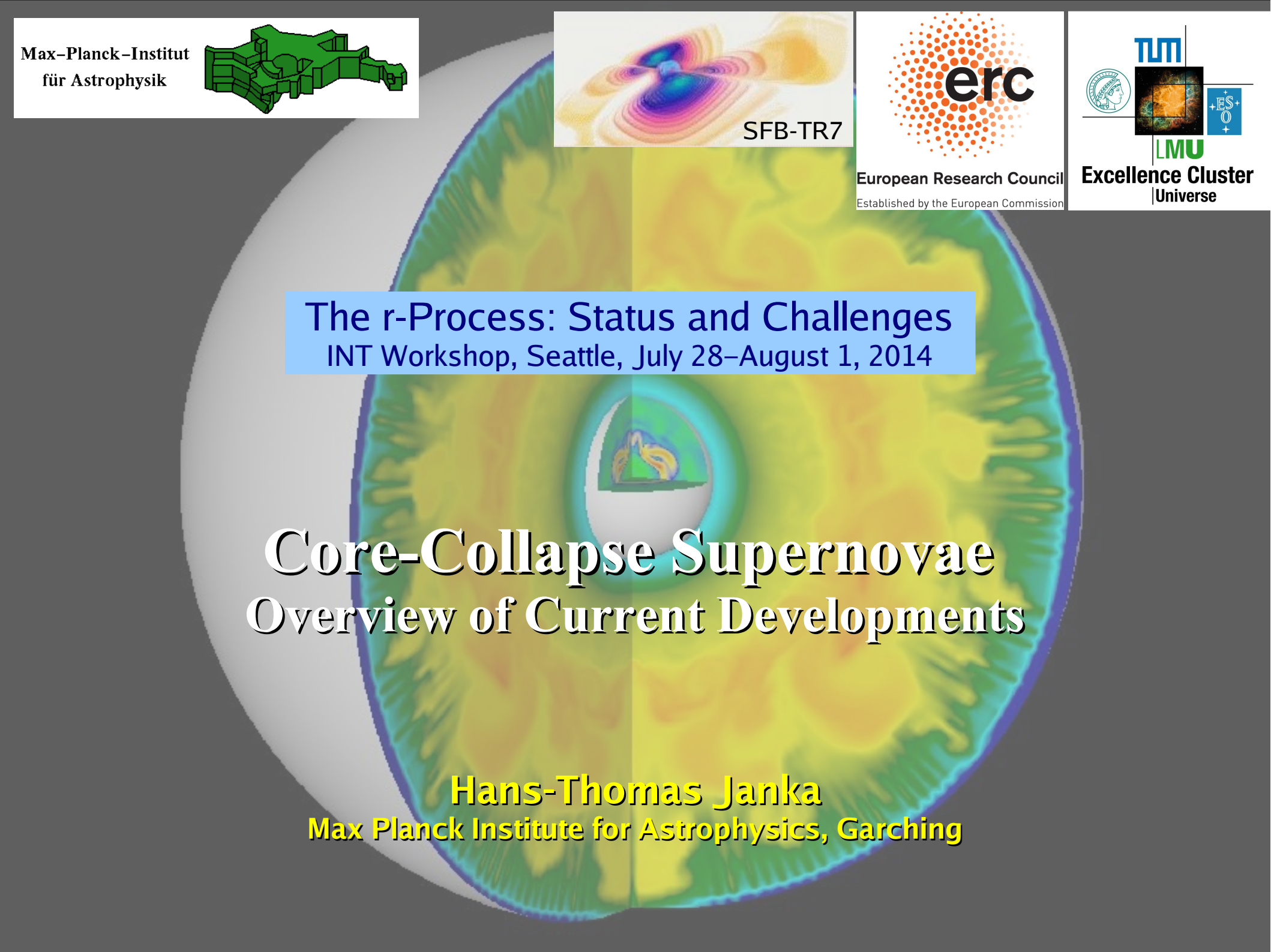


Max-Planck-Institut für Astrophysik

SFB-TR7

European Research Council
Established by the European Commission

Excellence Cluster Universe

The r-Process: Status and Challenges
INT Workshop, Seattle, July 28–August 1, 2014

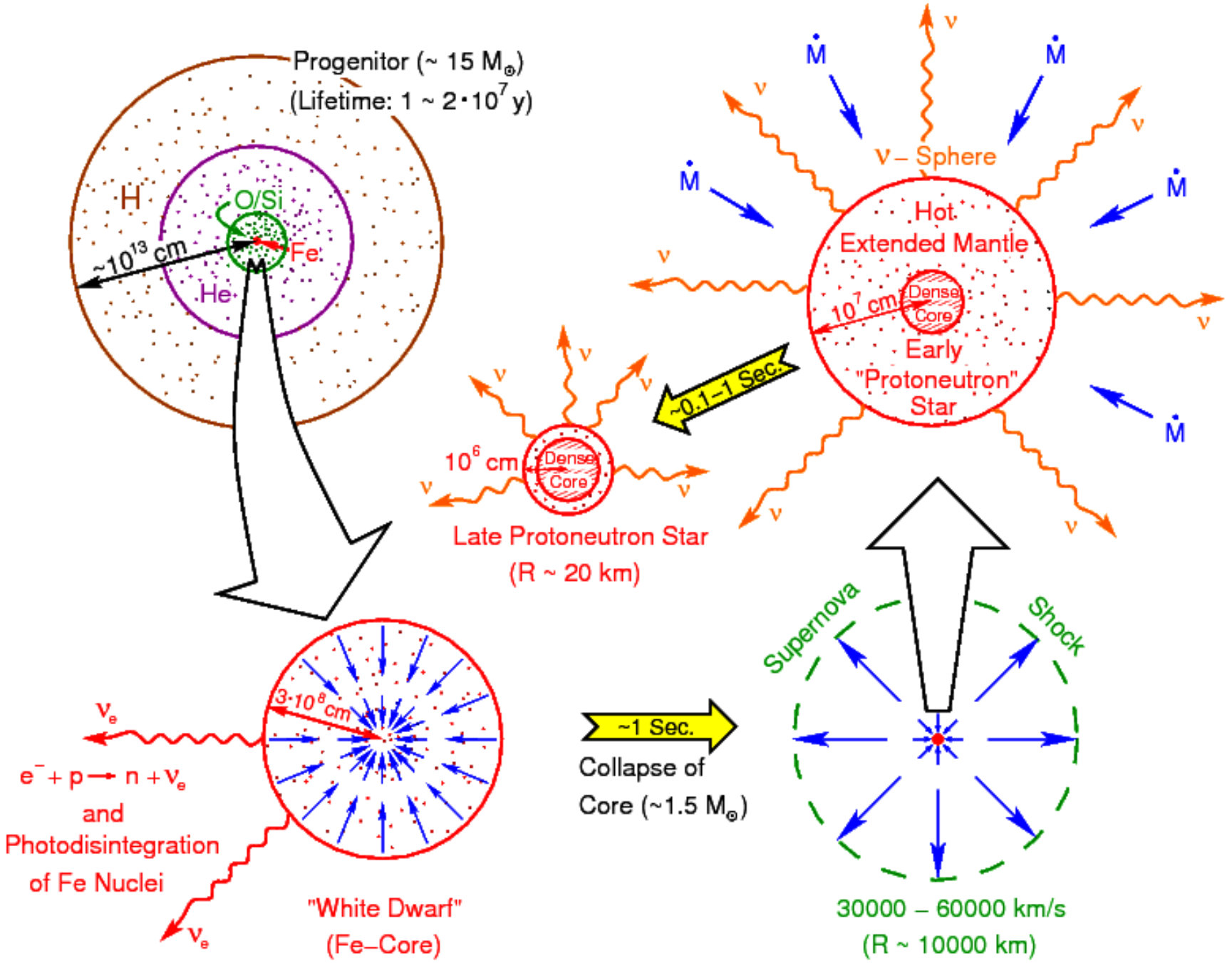
Core-Collapse Supernovae
Overview of Current Developments

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching

Outline

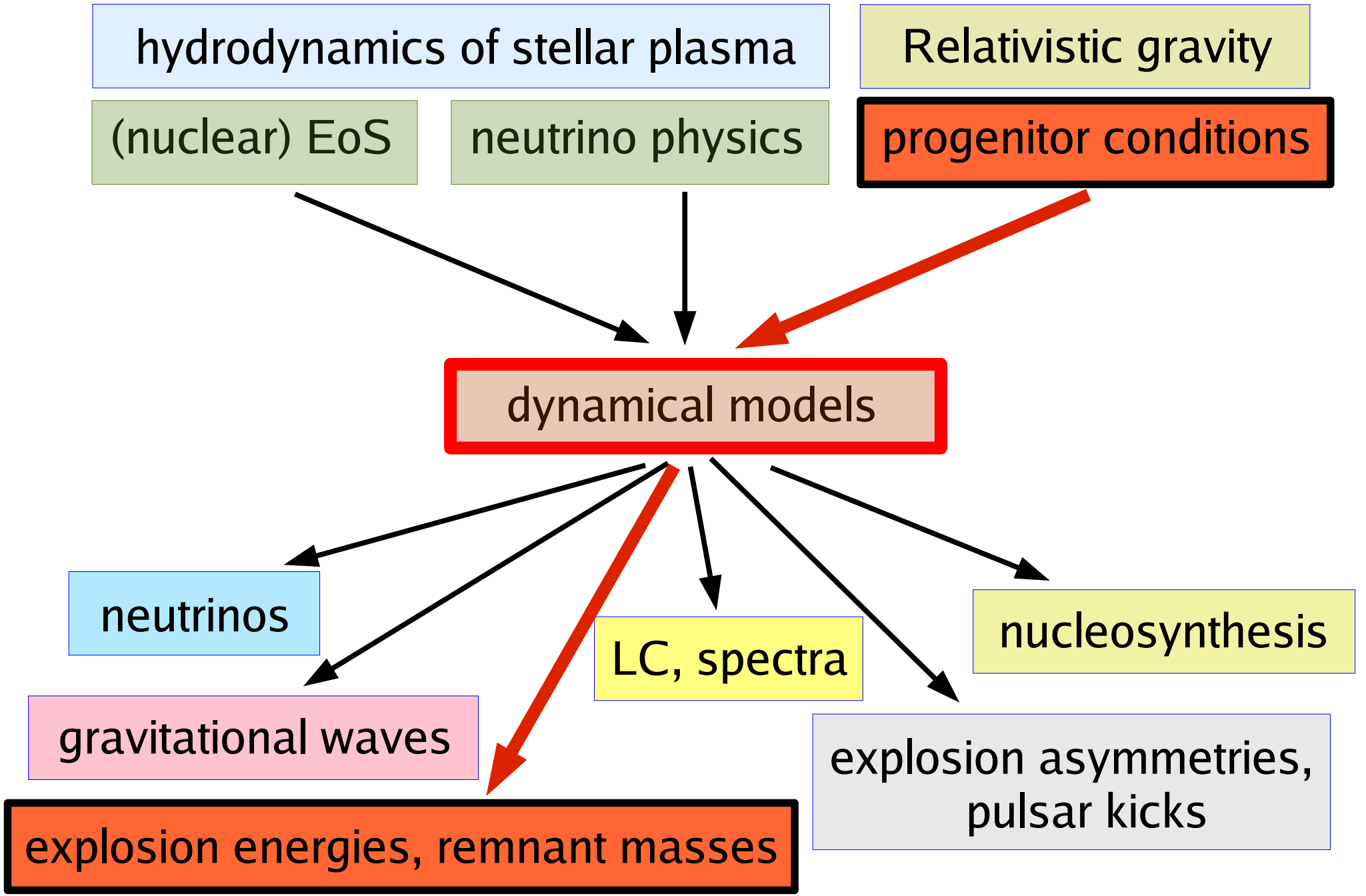
- Status of self-consistent explosion models in two and three dimensions
- 3D models: new puzzles and surprises
- Neutrinos from accretion phase and proto-neutron star cooling: selection of aspects (L. Hüdepohl, R. Bollig)

Stellar Collapse and Supernova Stages

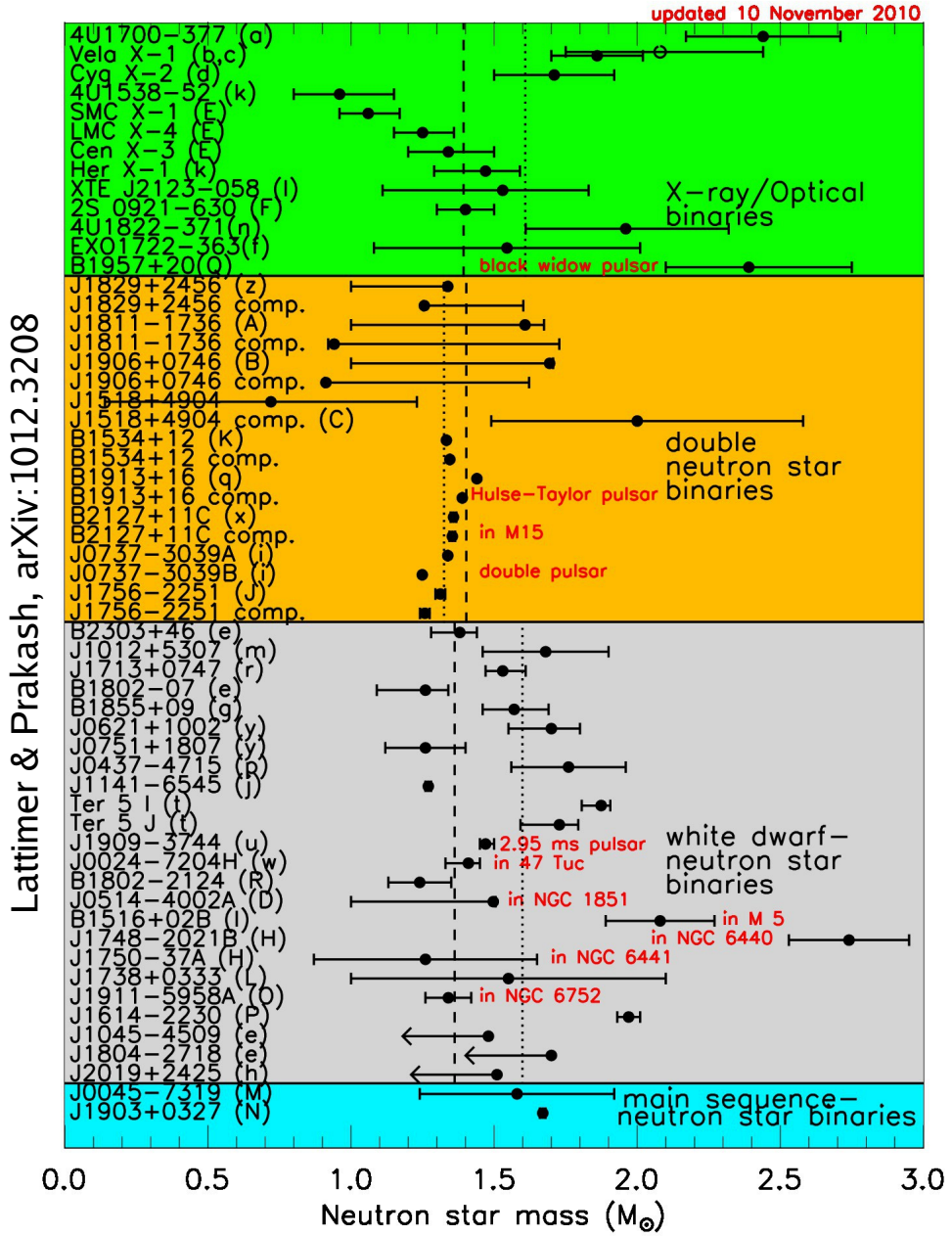


adapted from A. Burrows (1990)

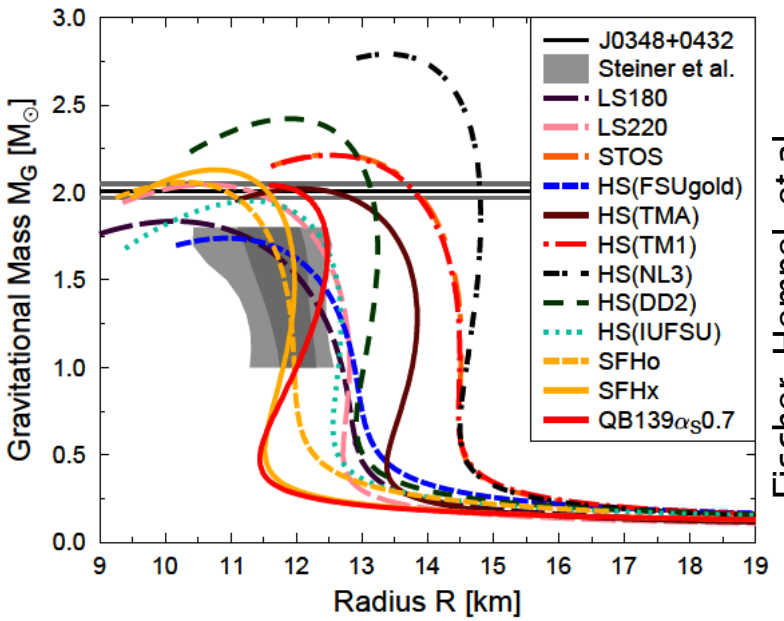
Predictions of Signals from SNe & NSs



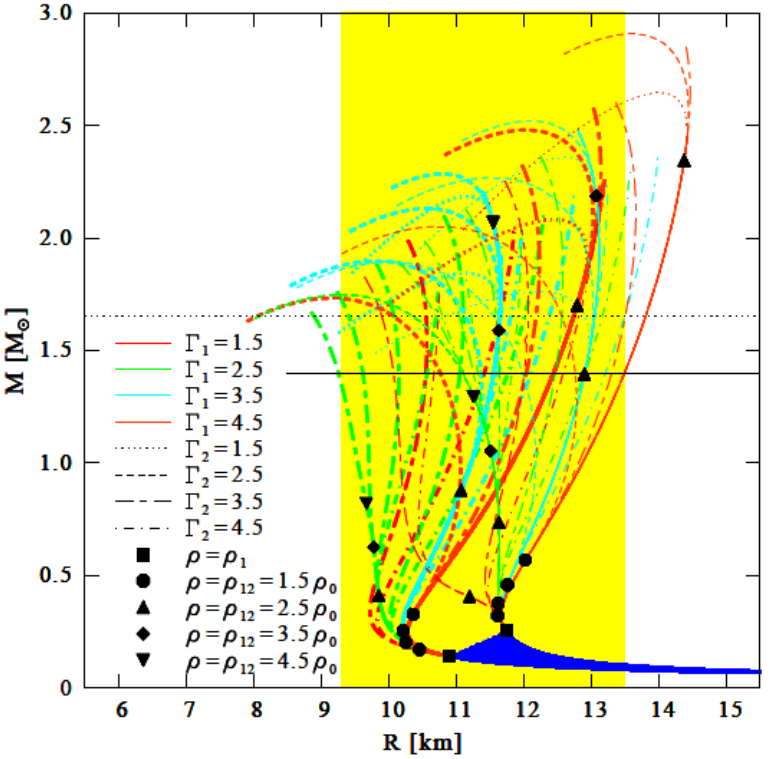
NS Masses and Radii



Lattimer & Prakash, arXiv:1012.3208

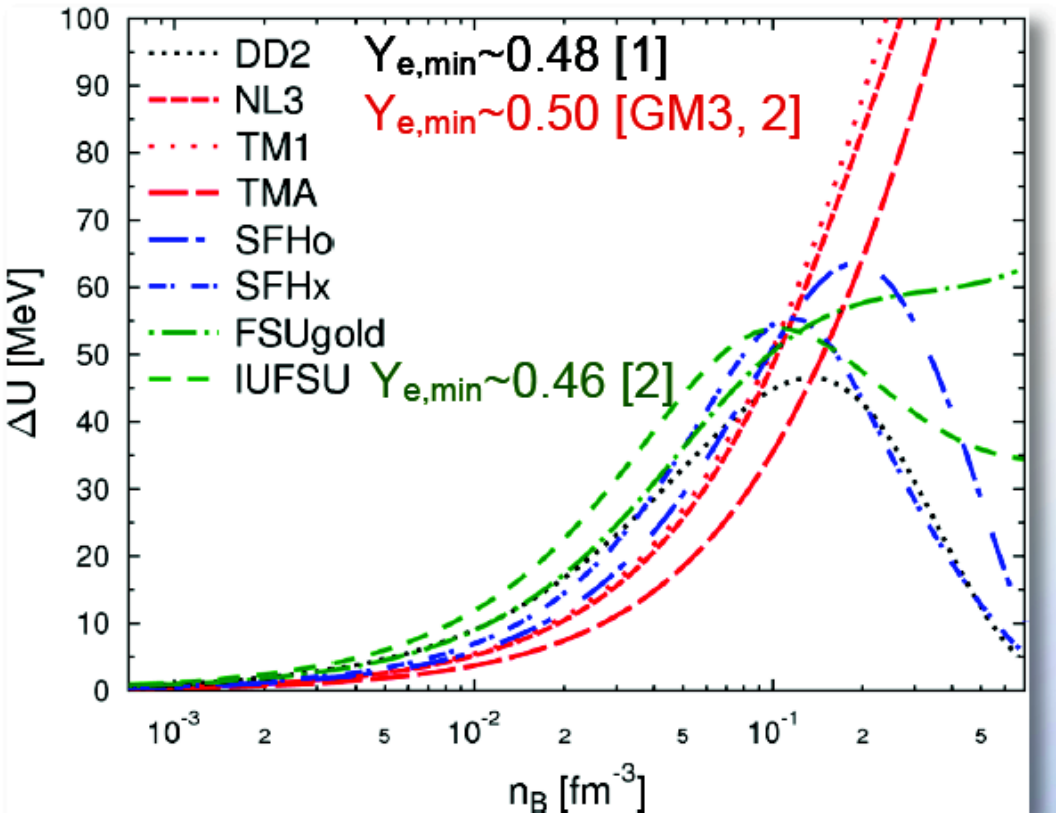


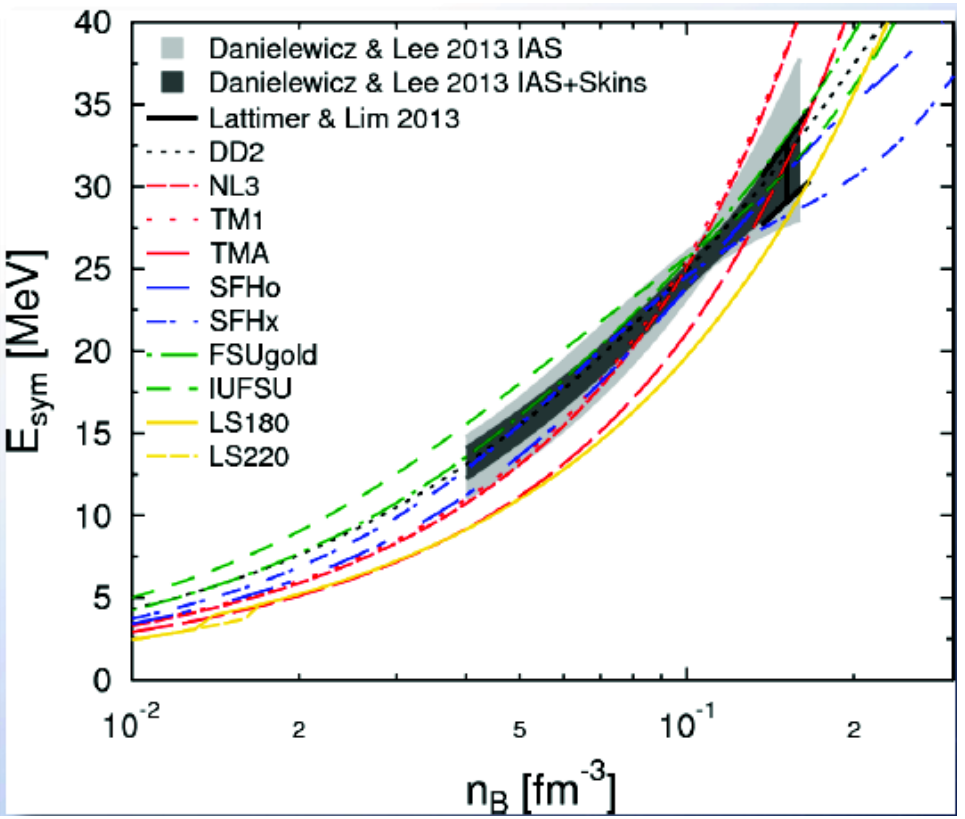
Fischer, Hempel, et al., EPJA (2014) 50: 46



Hebeler et al., arXiv:1007.1746

Neutrino Signal Dependence on EOS: Symmetry Energy





$$\Delta U \simeq 4\,(1-2Y_e)\,E_{\rm sym}^{\rm int}(n_B)$$

M. Hempel, Compstar Conference 2014, Firenze

Neutrino Reactions in Supernovae

Beta processes:

- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$

Neutrino scattering:

- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^{\pm} \rightleftharpoons \nu + e^{\pm}$

Thermal pair processes:

- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$

Neutrino-neutrino reactions:

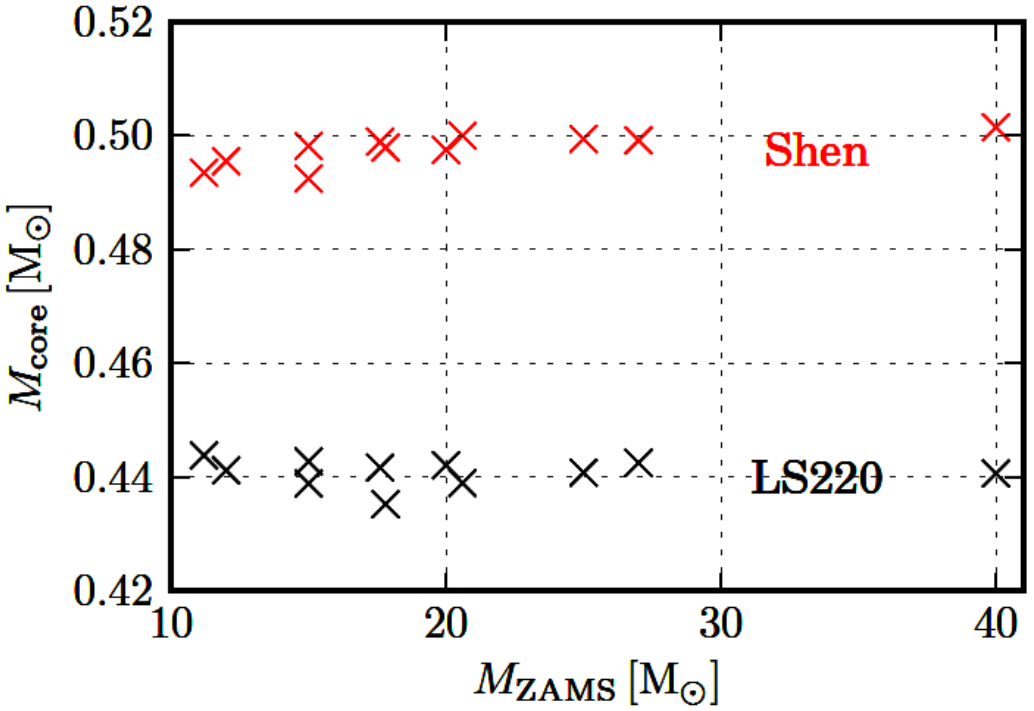
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

The Simulation Code

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

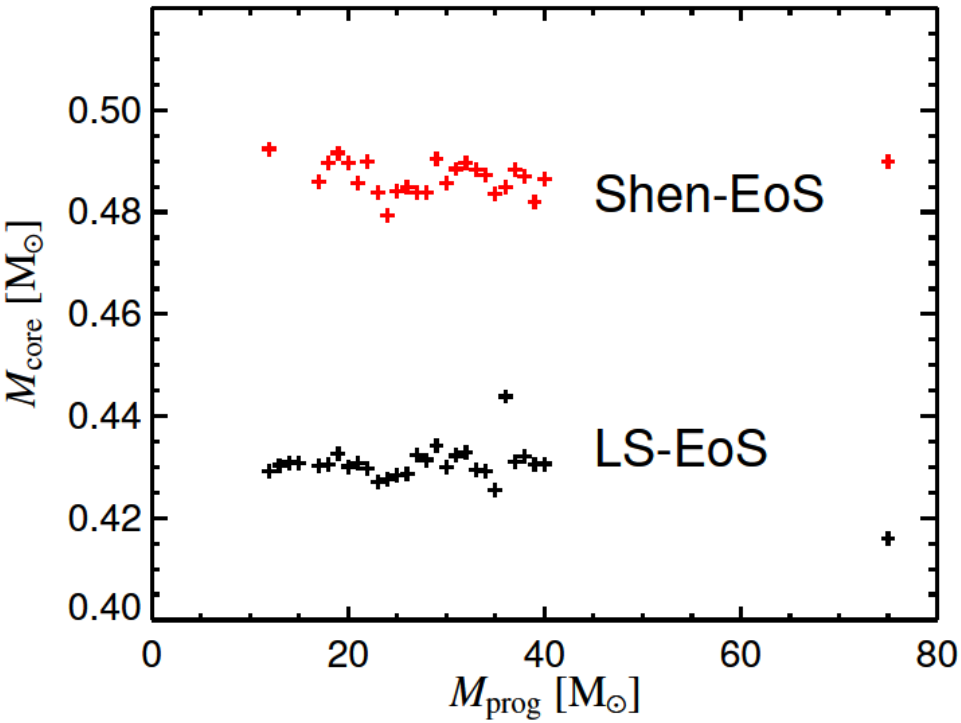
- **Hydro modules:**
  Newtonian: *Prometheus* + effective relativistic grav. potential.
  General relativistic: *CoCoNuT*
  Higher-order Godunov solvers, explicit.
- **Neutrino Transport:** *VERTEX*
  Two-moment closure scheme with variable Eddington factor based on model Boltzmann equation; fully energy-dependent, 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.**

EOS dependence of inner-core mass at bounce

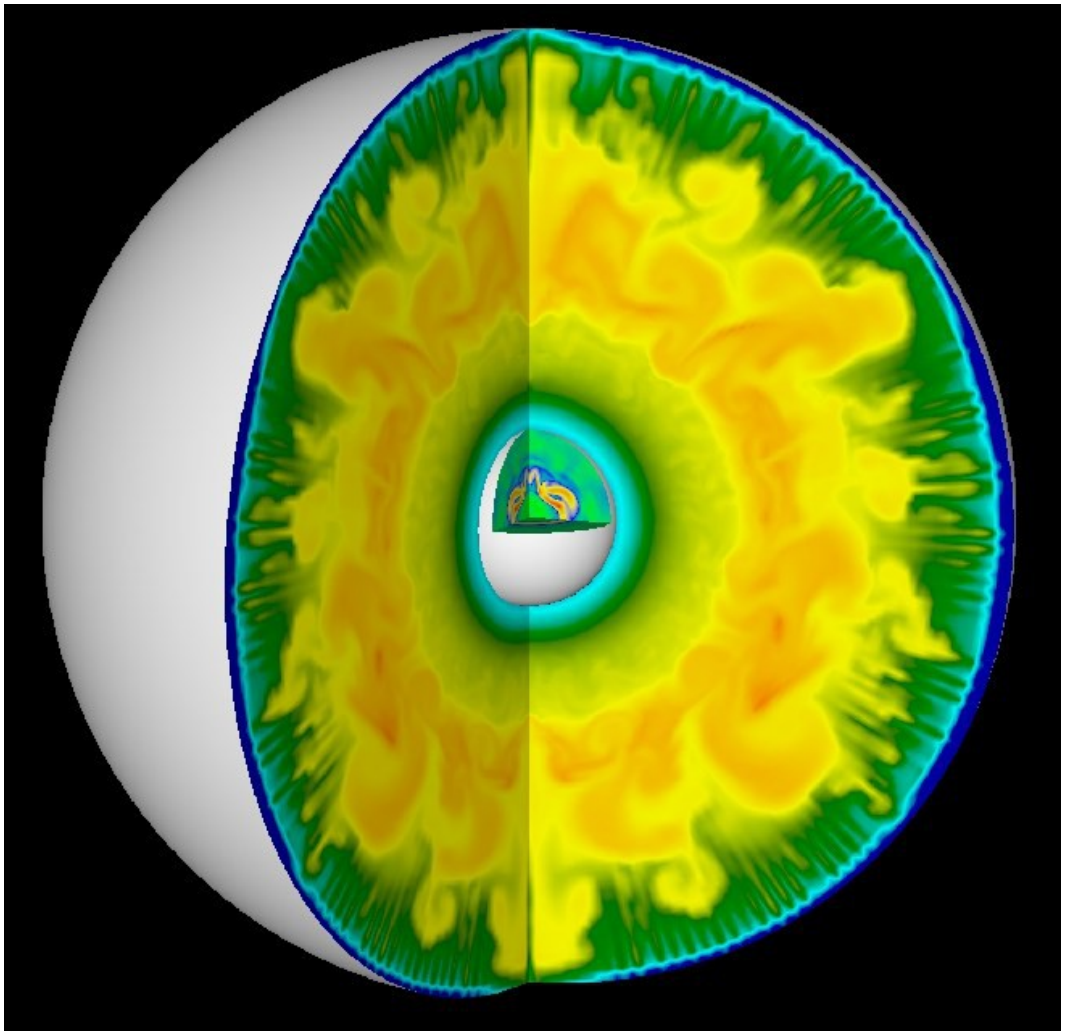


L. Hüdepohl, PhD Thesis (2013)

Janka et al., PTEP (2012)
(from A. Marek, PhD Thesis)



Ledoux Convective Regions in SN Cores



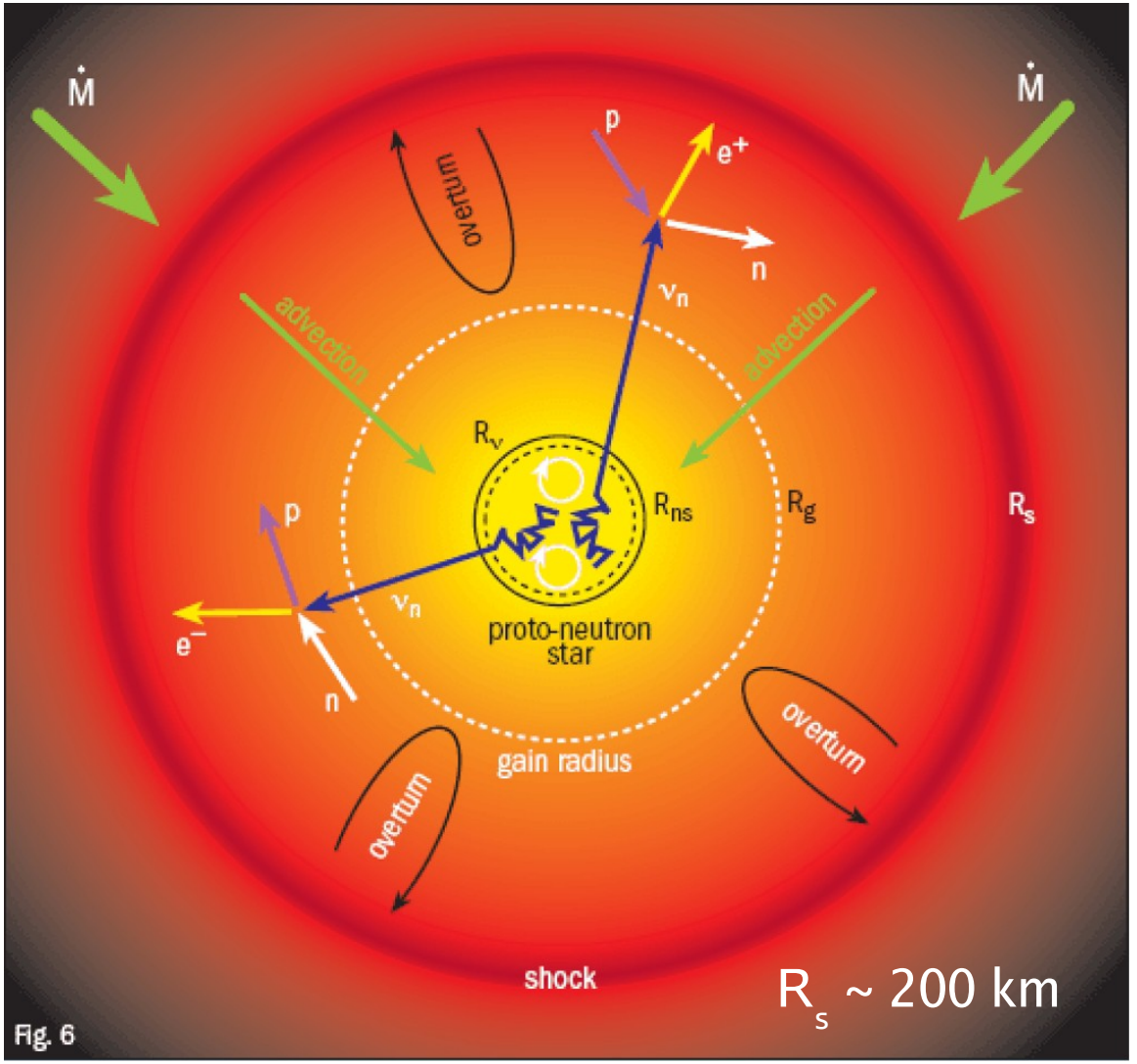
Janka & Müller (A&A, 1995);
Keil, Janka, Müller (ApJL 1996)

Ledoux criterion for convective instability:

$$\mathcal{C}_{\mathrm{L}}(r) \equiv \left(\frac{\partial \rho}{\partial S}\right)_{P,Y_l} \frac{\mathrm{d}S}{\mathrm{d}r} + \left(\frac{\partial \rho}{\partial Y_l}\right)_{P,S} \frac{\mathrm{d}Y_l}{\mathrm{d}r} > 0$$

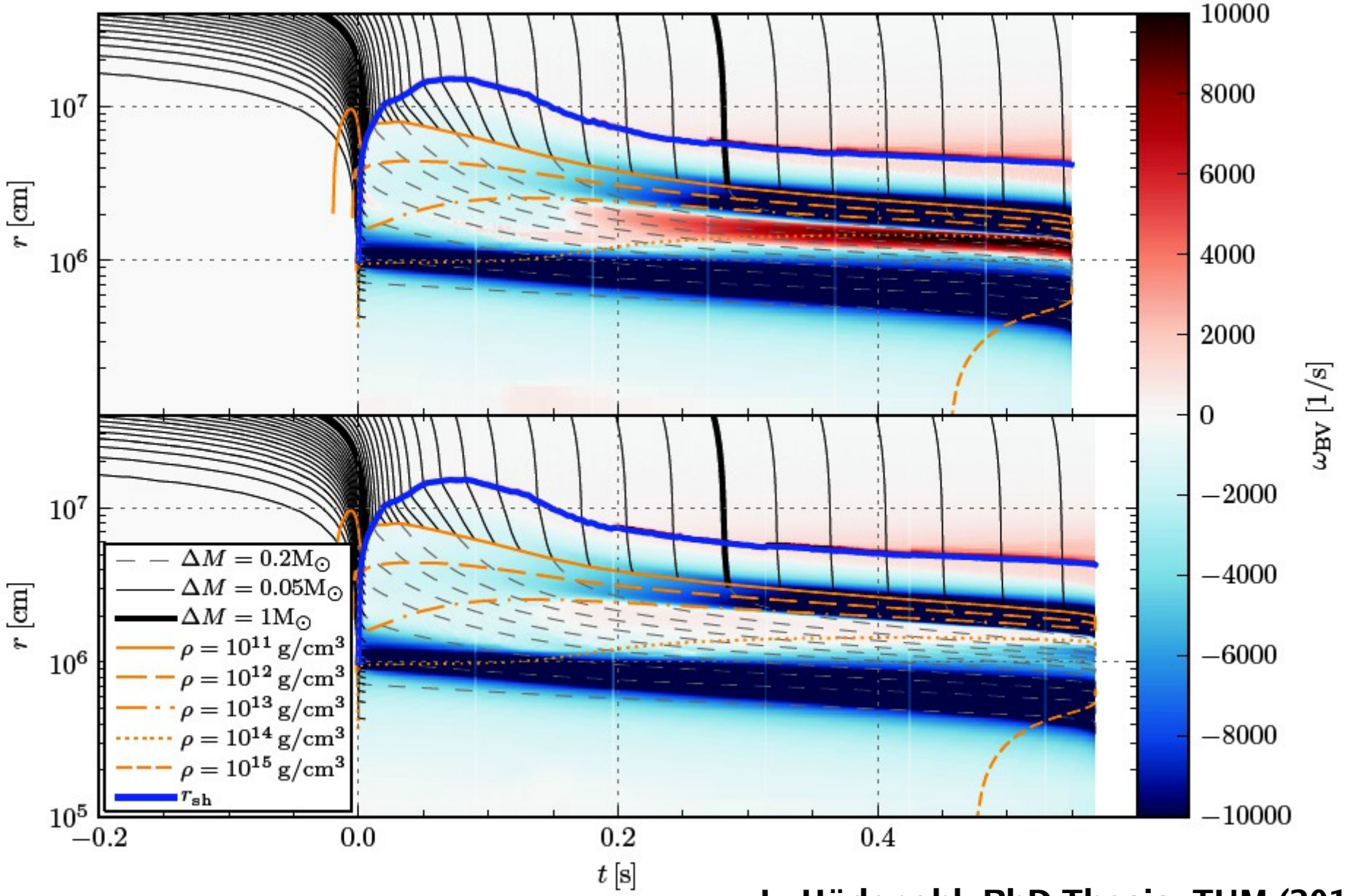
Neutrinos & SN Explosion Mechanism

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).

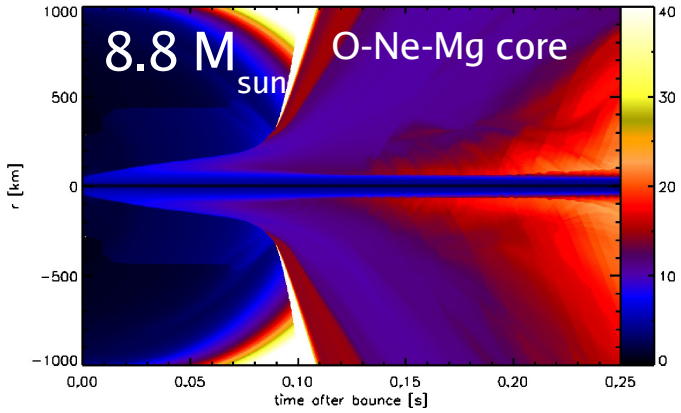
Shock evolution in 1D without and with PNS convection

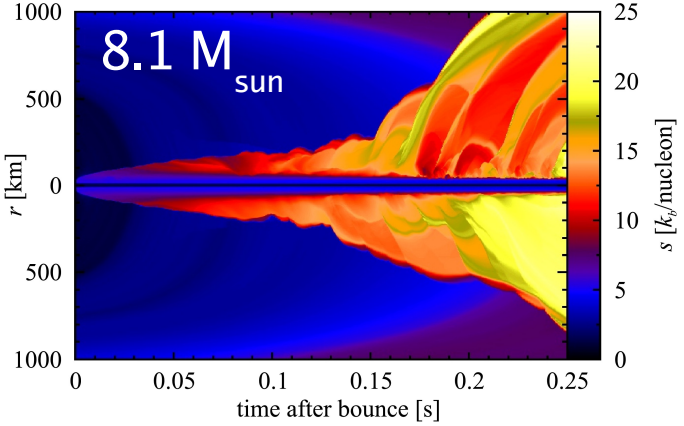


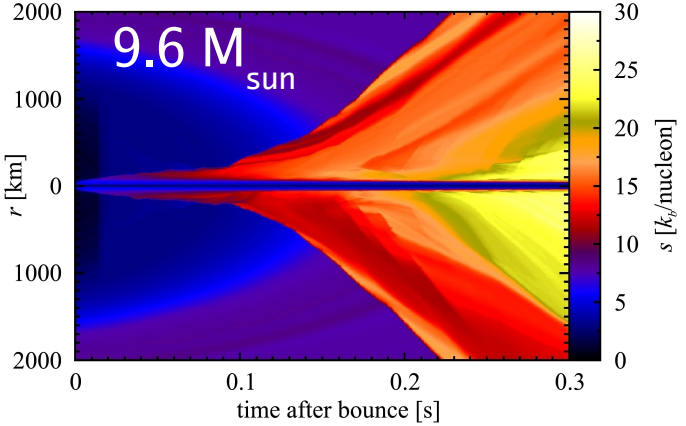
L. Hüdepohl, PhD Thesis, TUM (2013)

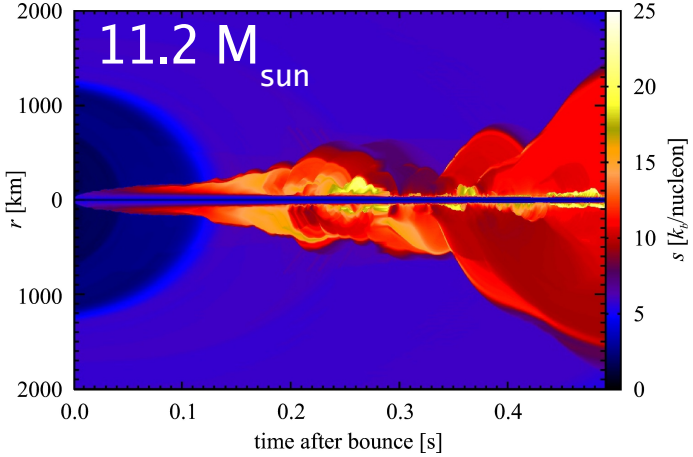
Explosion Mechanism:
Most Sophisticated Current Models

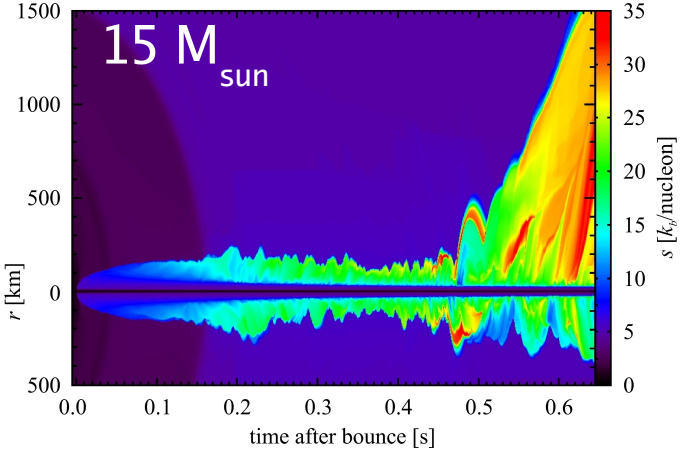
Relativistic 2D CCSN Explosion Models

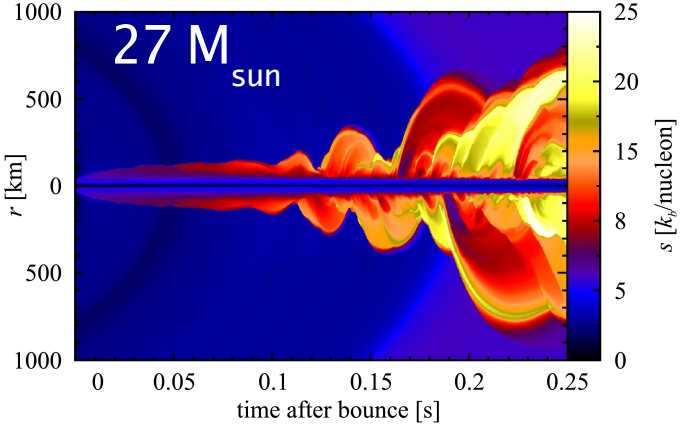


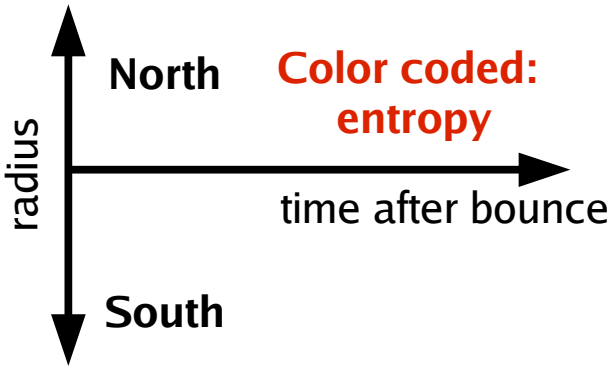


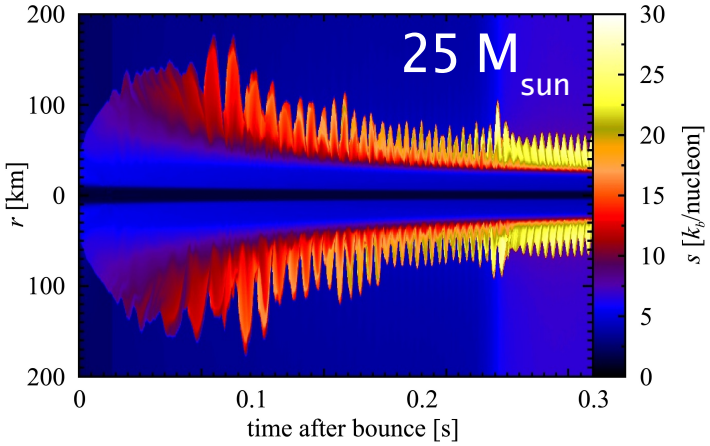








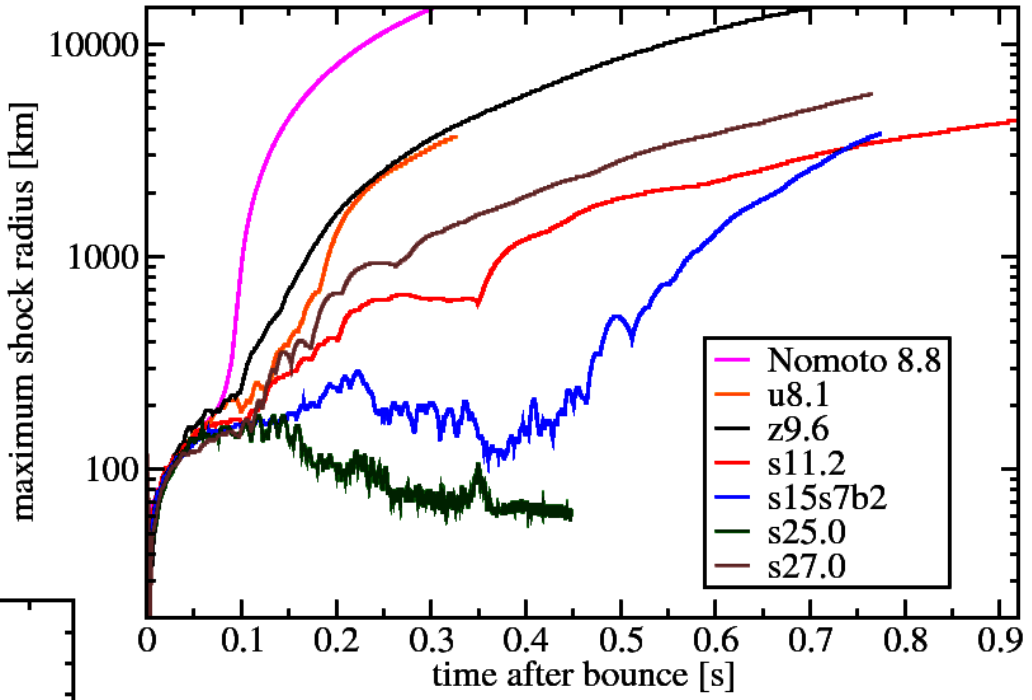




Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, ApJ 766

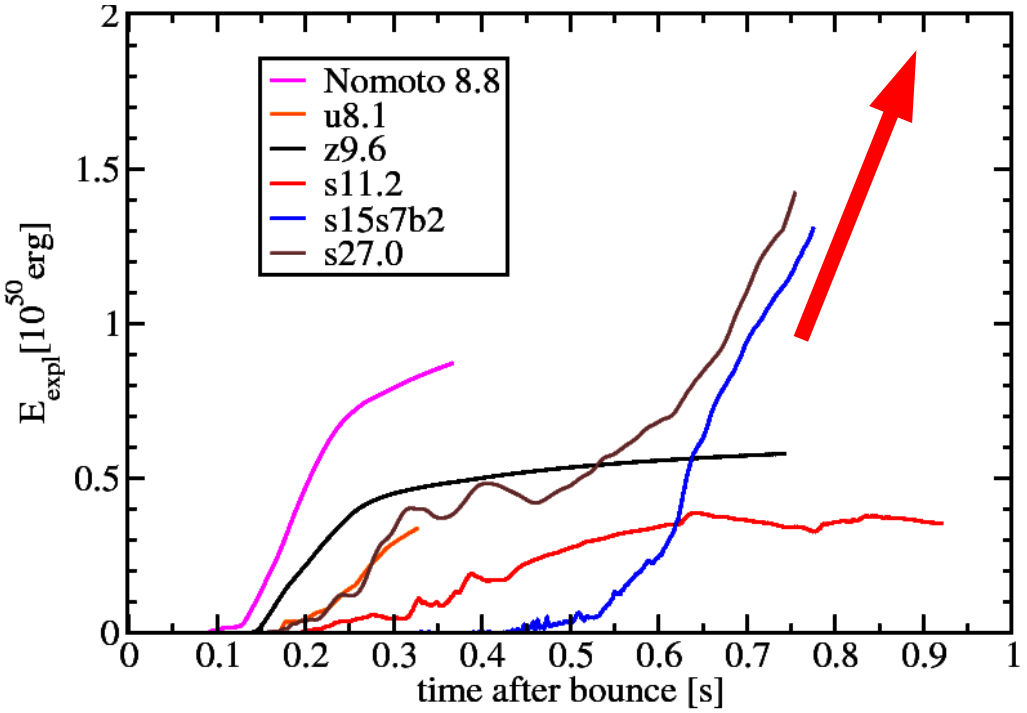
Basic confirmation of previous explosion models for 11.2 and 15 M_{sun} stars by Marek & THJ (2009)

Relativistic 2D CCSN Explosion Models



Maximum shock radius

"Diagnostic energy" of explosion

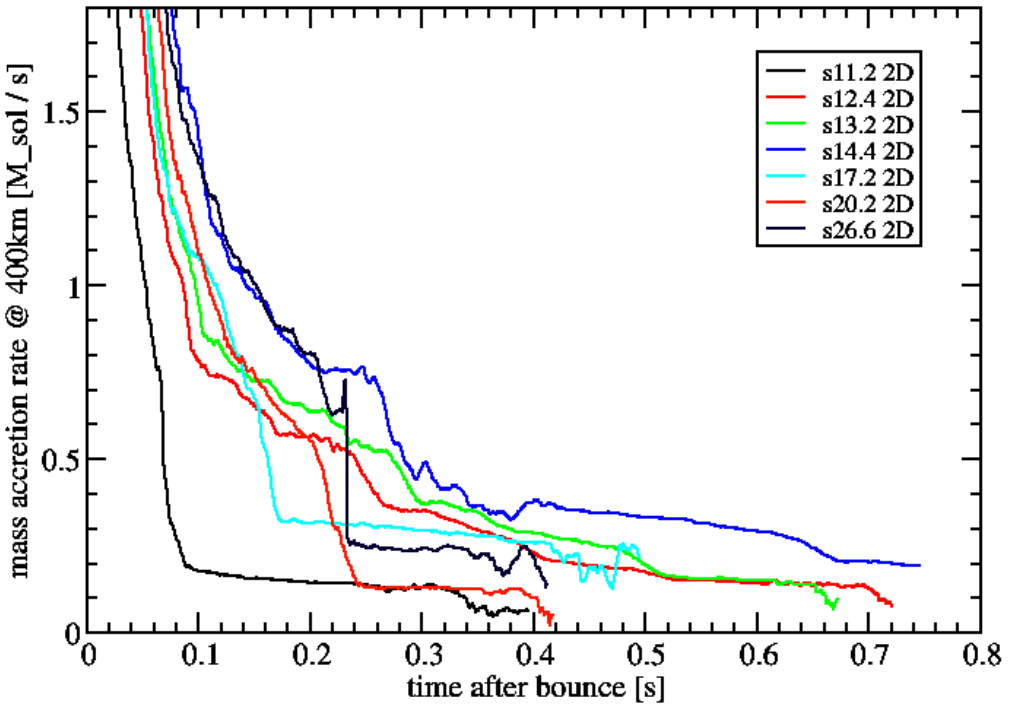


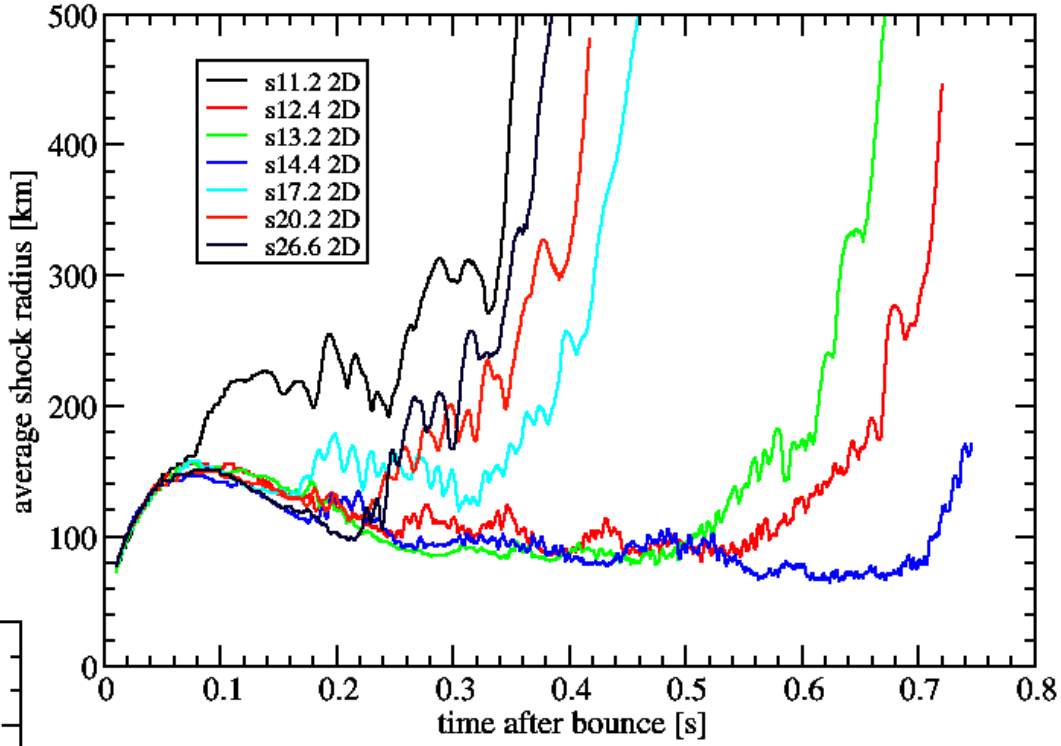
Growing Set of 2D CCSN Explosion Models

Decrease of mass-accretion rate at composition-shell interfaces allows for onset of explosions.

Florian Hanke
(2014, PhD Thesis, TUM)

Mass accretion rate





Average shock radius

Progenitor models:
Woosley et al. RMP (2002)

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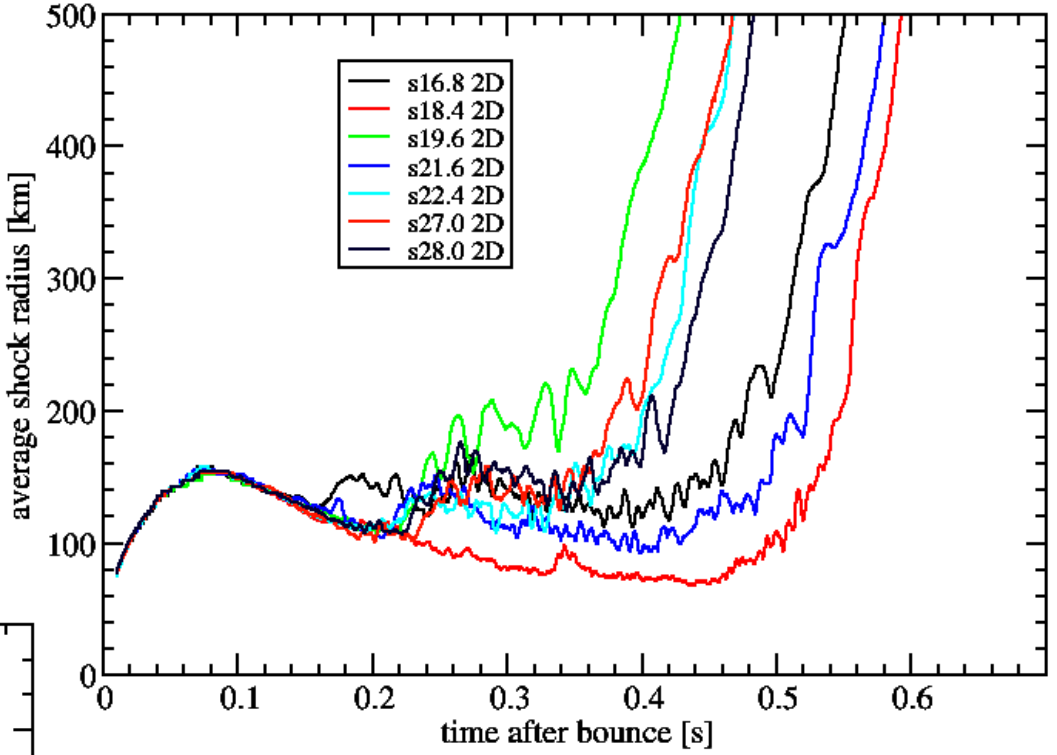
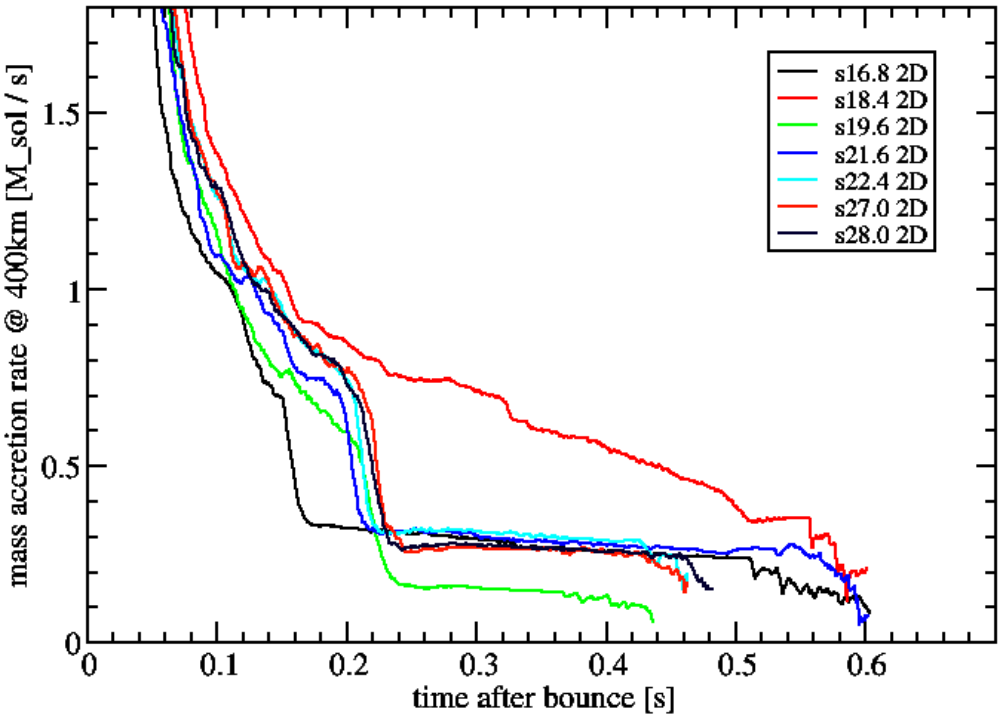


Average shock radius

Mass accretion rate

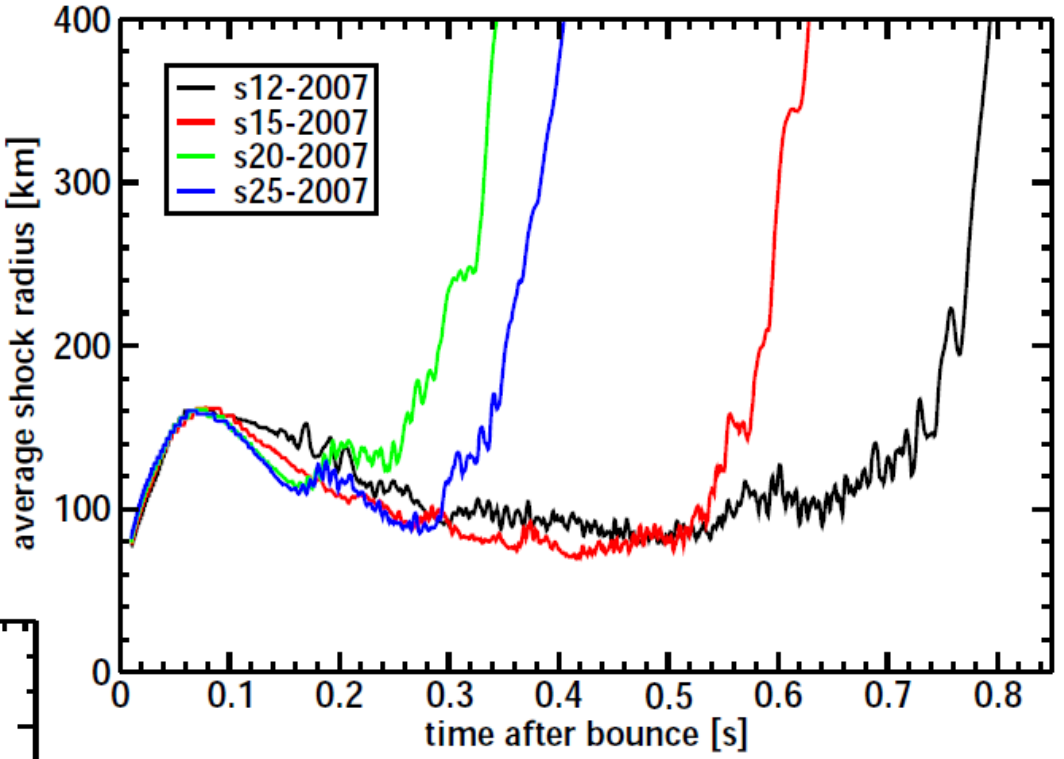


Progenitor models:
Woosley et al. RMP (2002)

Growing Set of 2D CCSN Explosion Models

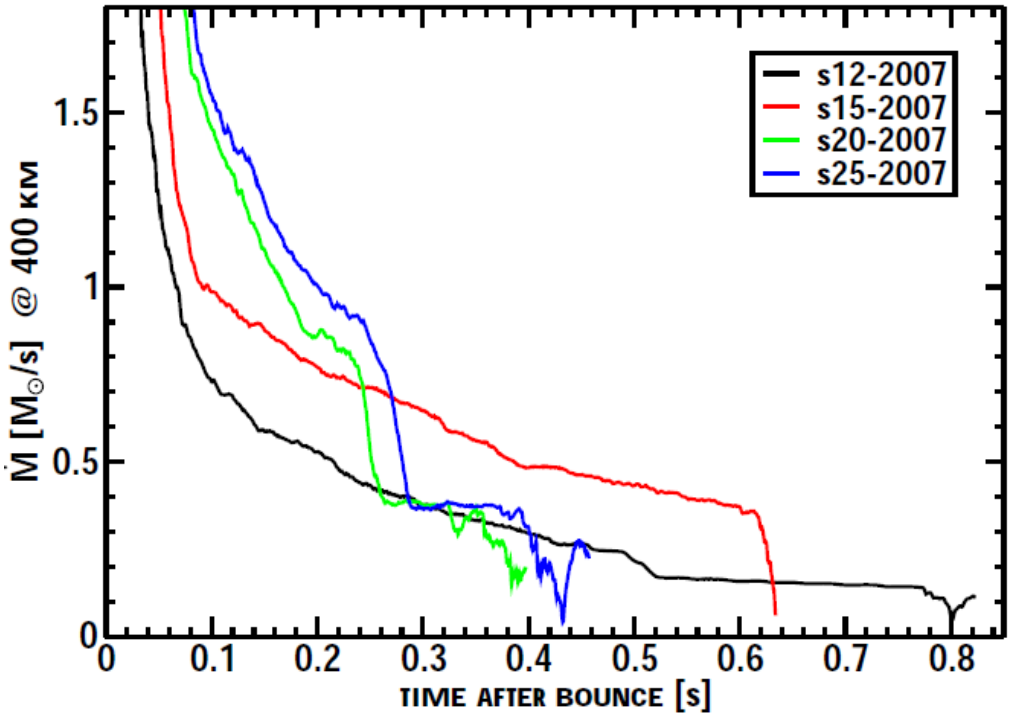
Progenitor models:
12, 15, 20, 25 M_{sun} stars
of Woosley & Heger (2007)

Florian Hanke
(2014, PhD Thesis, TUM)



Average shock radius

Mass accretion rate



F. Hanke (Newtonian with GR gravity corrections) and by B. Müller (GR) agree well with each other.

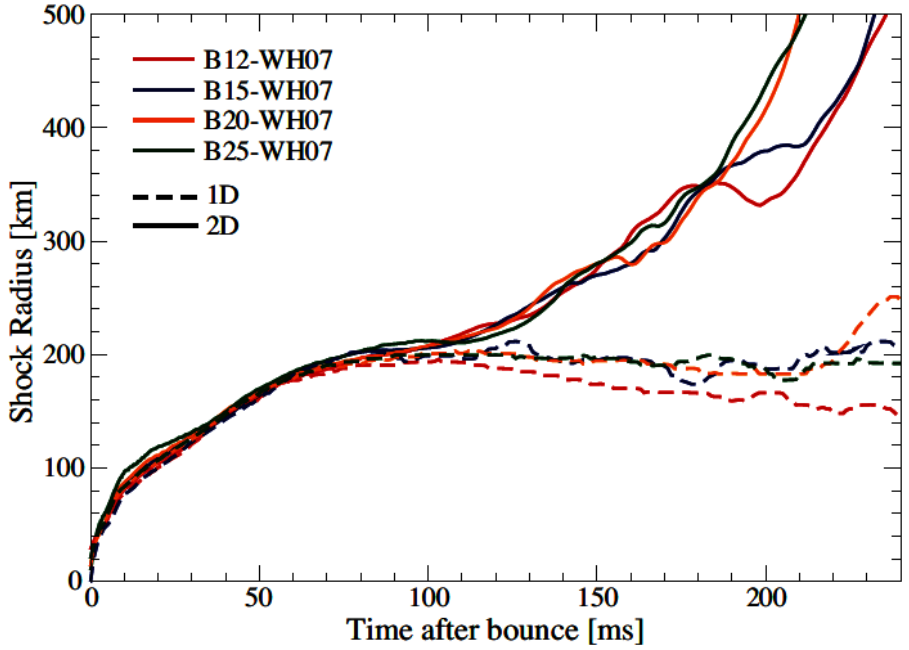
Garching 1D & 2D models show significant differences compared to Bruenn et al. (2012); they are not as close to explosion.

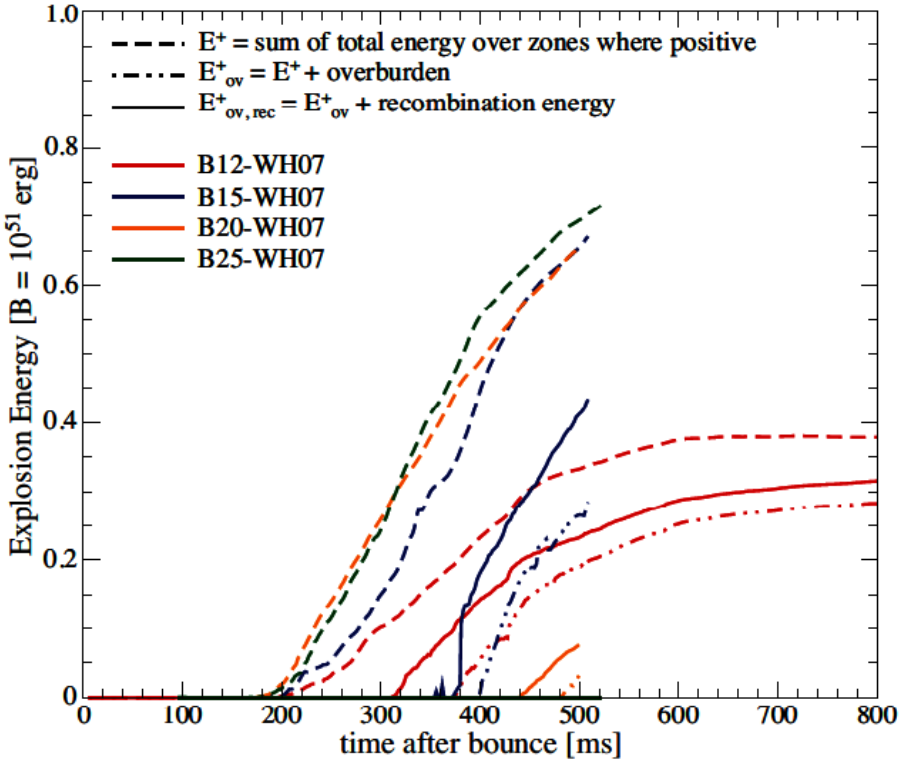
Support for 2D CCSN Explosion Models

AXISYMMETRIC *AB INITIO* CORE-COLLAPSE SUPERNOVA SIMULATIONS OF 12–25 $M_\odot$ STARS

STEPHEN W. BRUENN[1], ANTHONY MEZZACAPPA[2,3,4], W. RAPHAEL HIX[2,3], ERIC J. LENTZ[3,2,5], O. E. BRONSON MESSER[6,3,4], ERIC J. LINGERFELT[2,4], JOHN M. BLONDIN[7], EIRIK ENDEVE[4], PEDRO MARRONETTI[1,8], AND KONSTANTIN N. YAKUNIN[1]

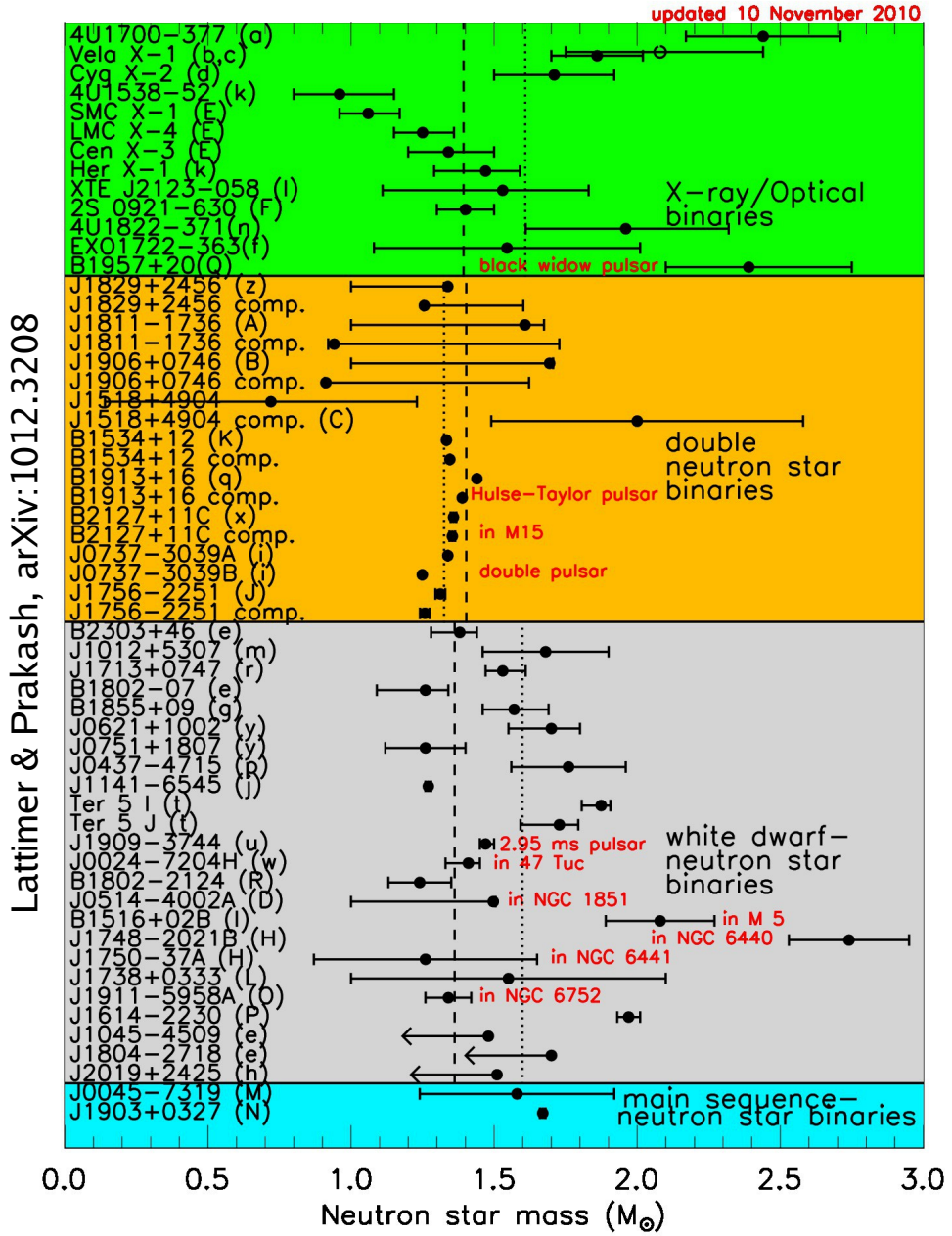
2D explosions for 12, 15, 20, 25 M_{sun} progenitors of Woosley & Heger (2007)



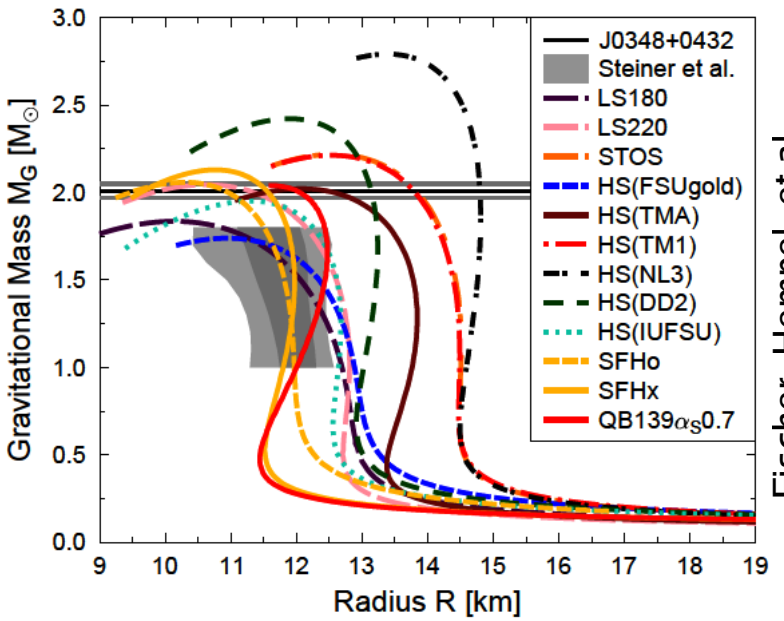


Bruenn et al., ApJL 767, 6 (2013)

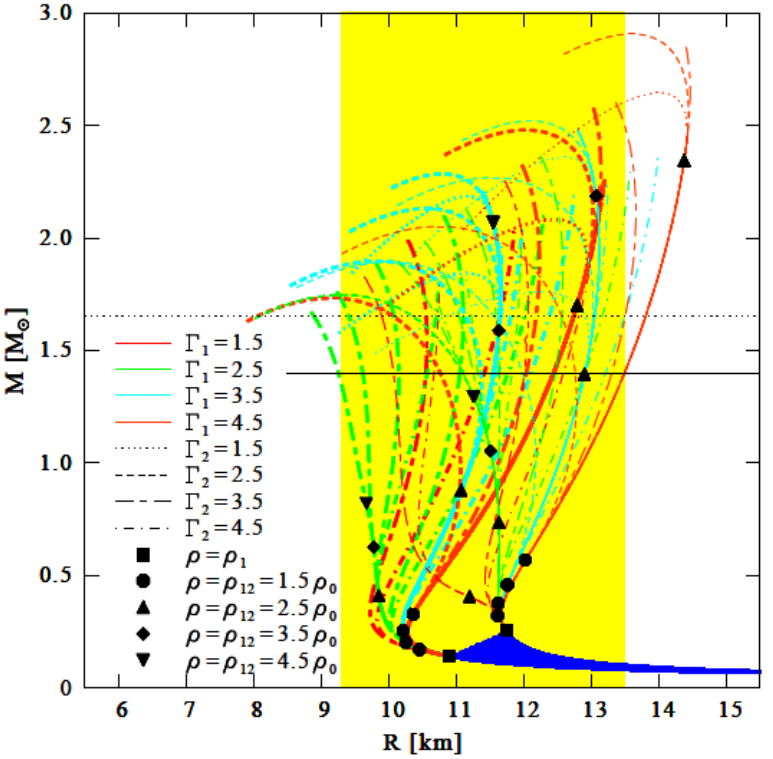
NS Masses and Radii



Lattimer & Prakash, arXiv:1012.3208



Fischer, Hempel, et al., EPJA (2014) 50: 46

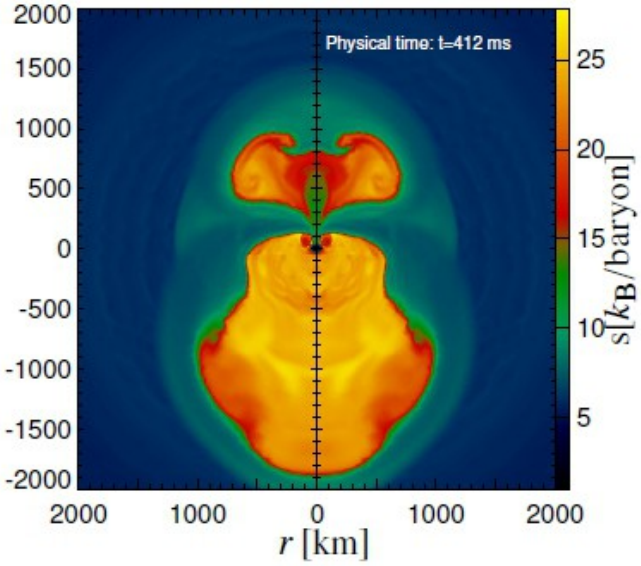


Hebeler et al., arXiv:1007.1746

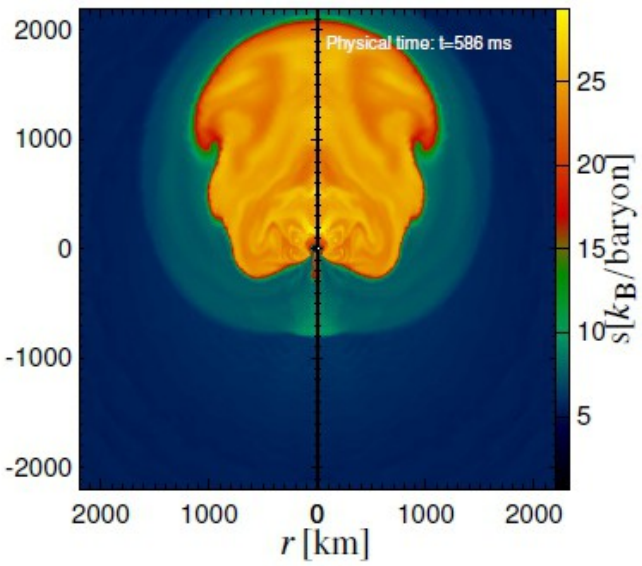
Hadronic EOS and Supernova Explosion

Neutron star contraction has influence on the development of neutrino-driven explosions.

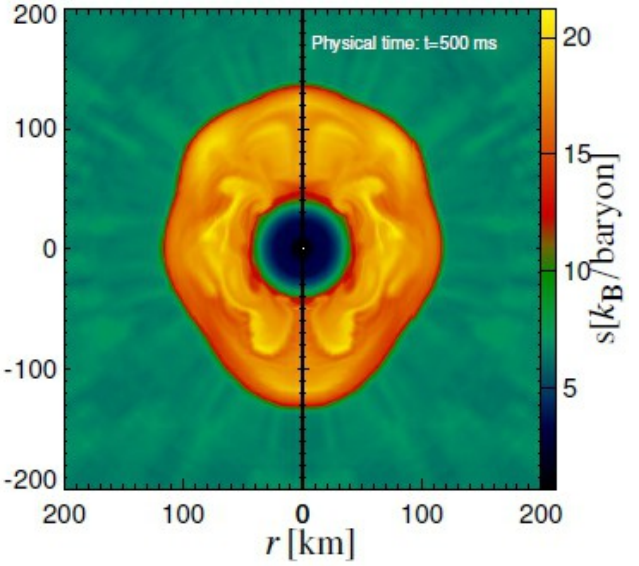
L&S

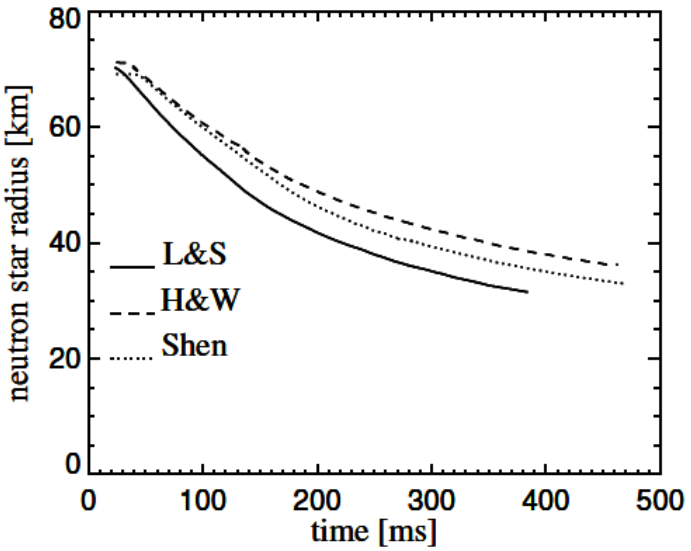


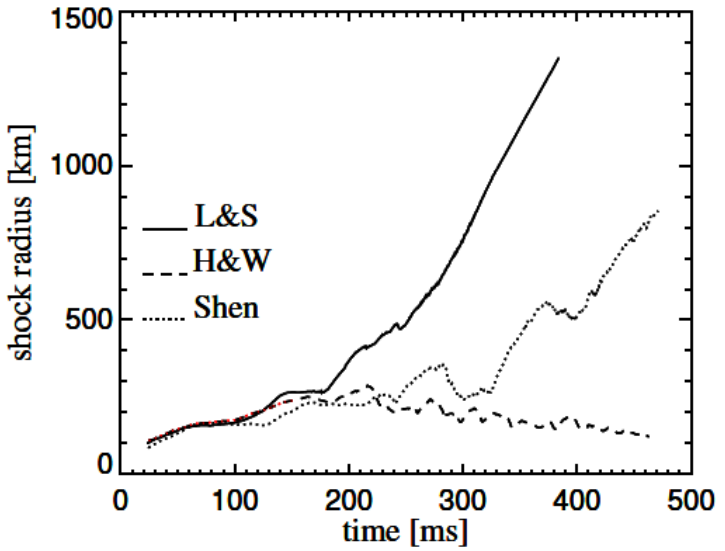
Shen



H&W







Hadronic EOS and Supernova Explosion

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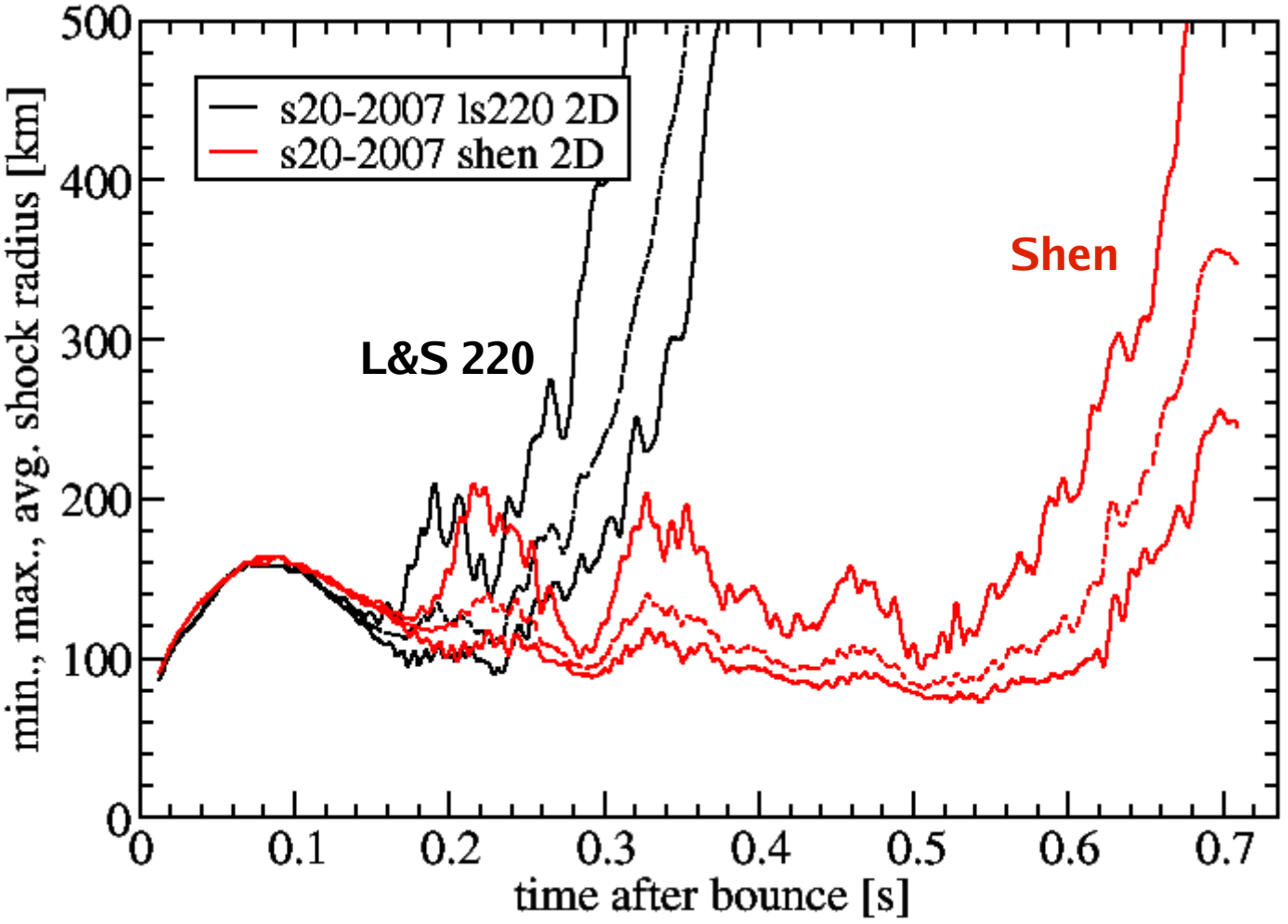
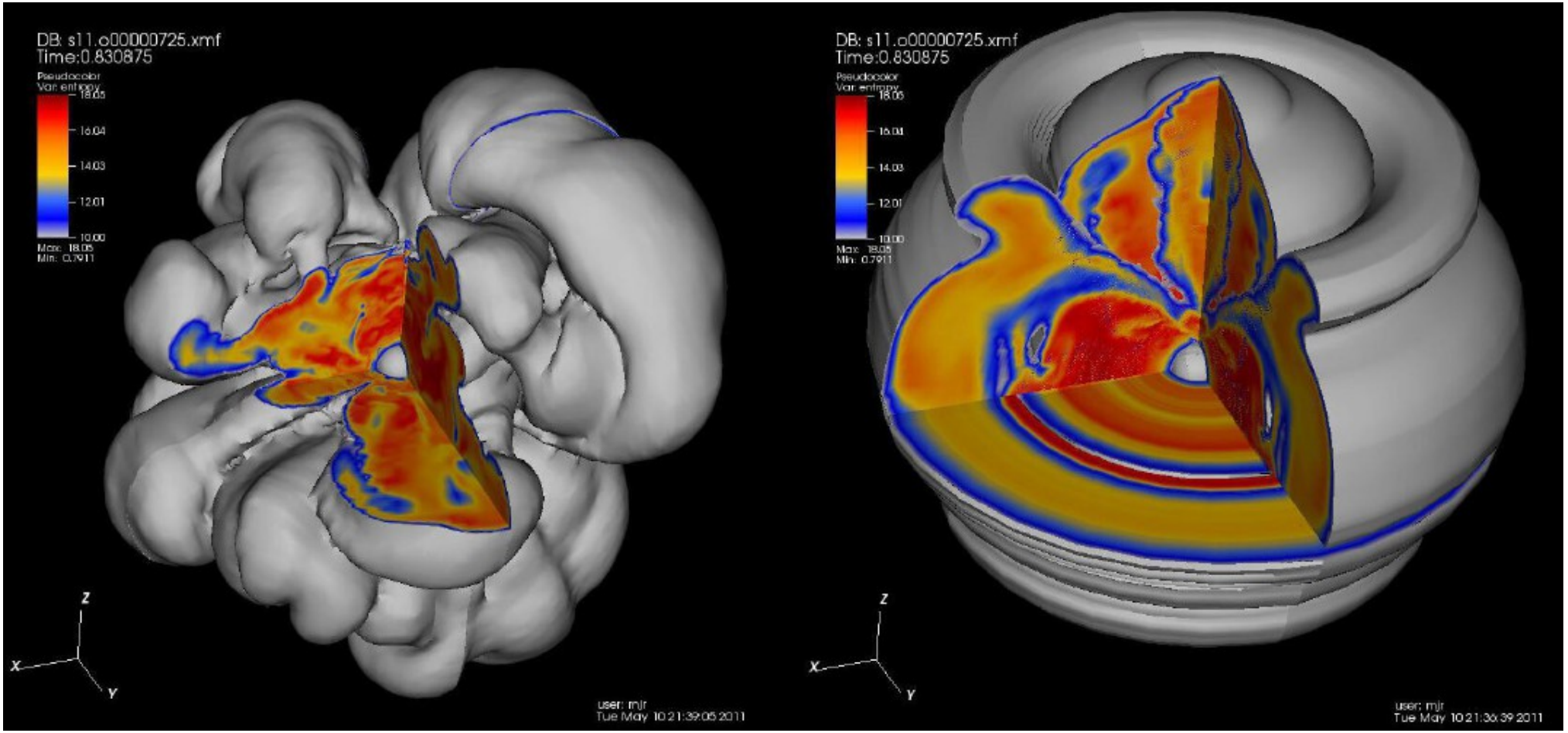
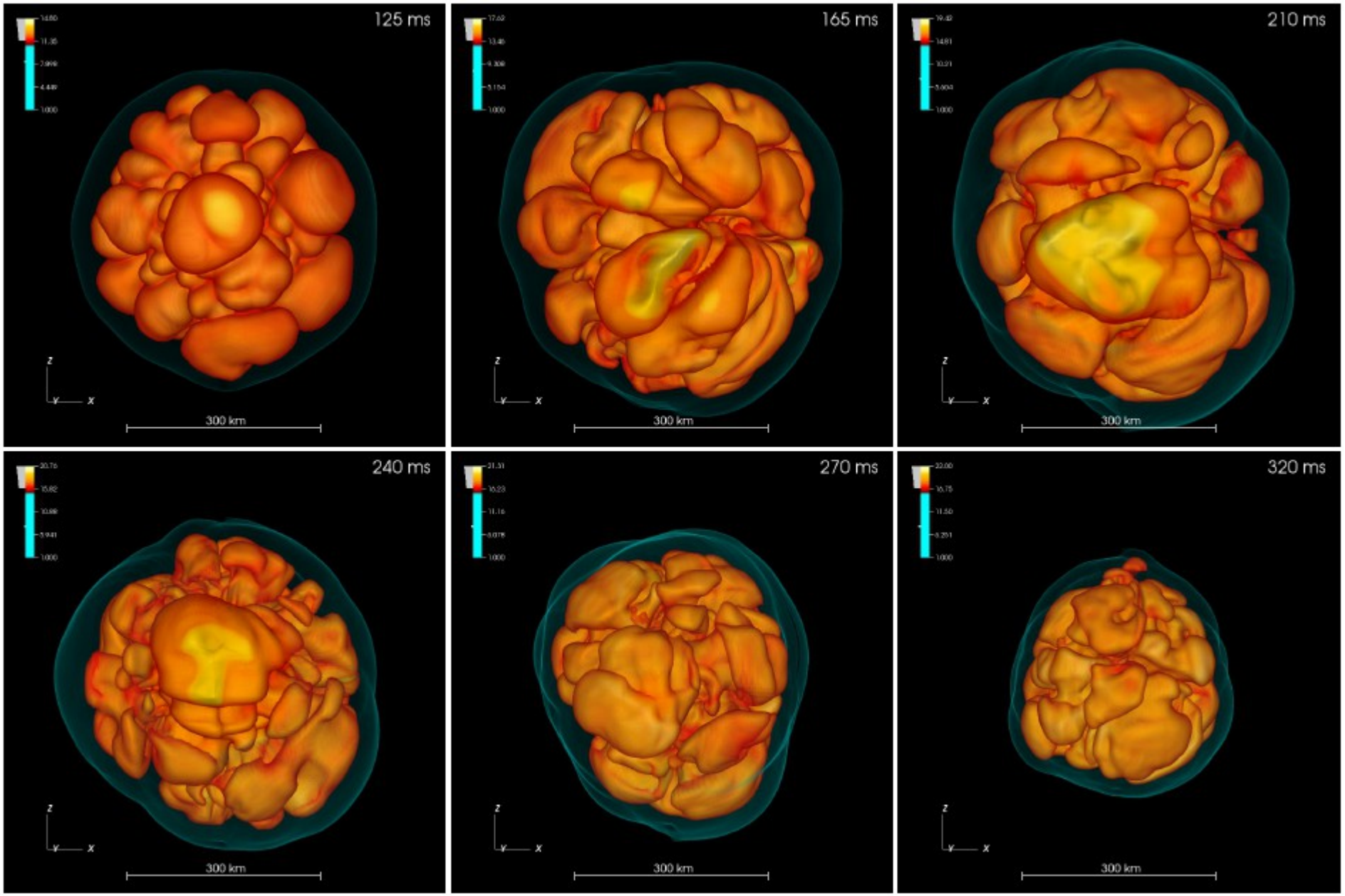


2D vs. 3D Morphology



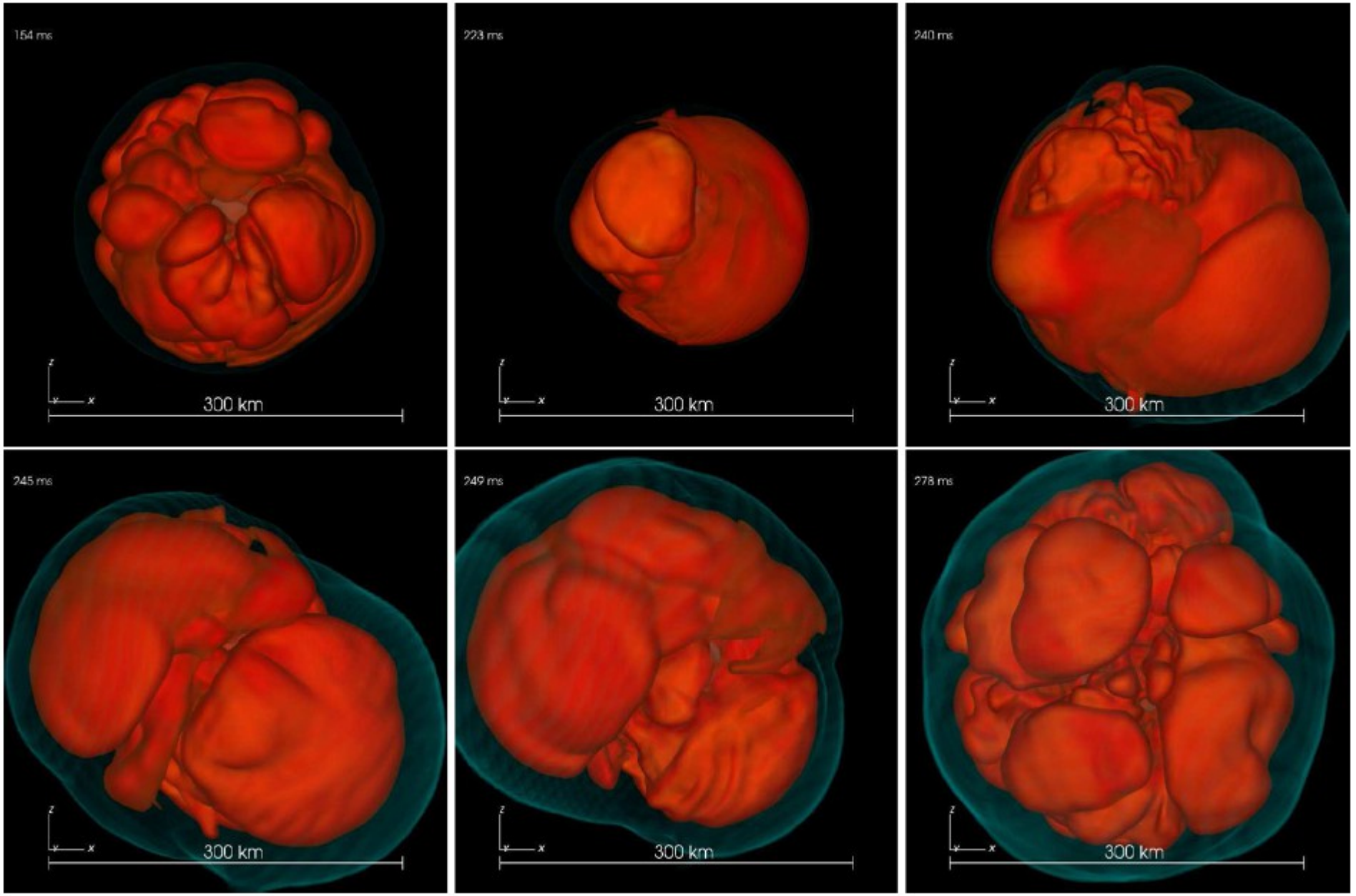
(Images from Markus Rampp, RZG)

Convective Overturn in Neutrino-Heating Layer



11.2 M_{sun} progenitor (WHW 2002) Tamborra, Hanke et al., arXiv:1402.5418

SASI in the Postshock Accretion Layer



27 M_{sun} progenitor (WHW 2002)

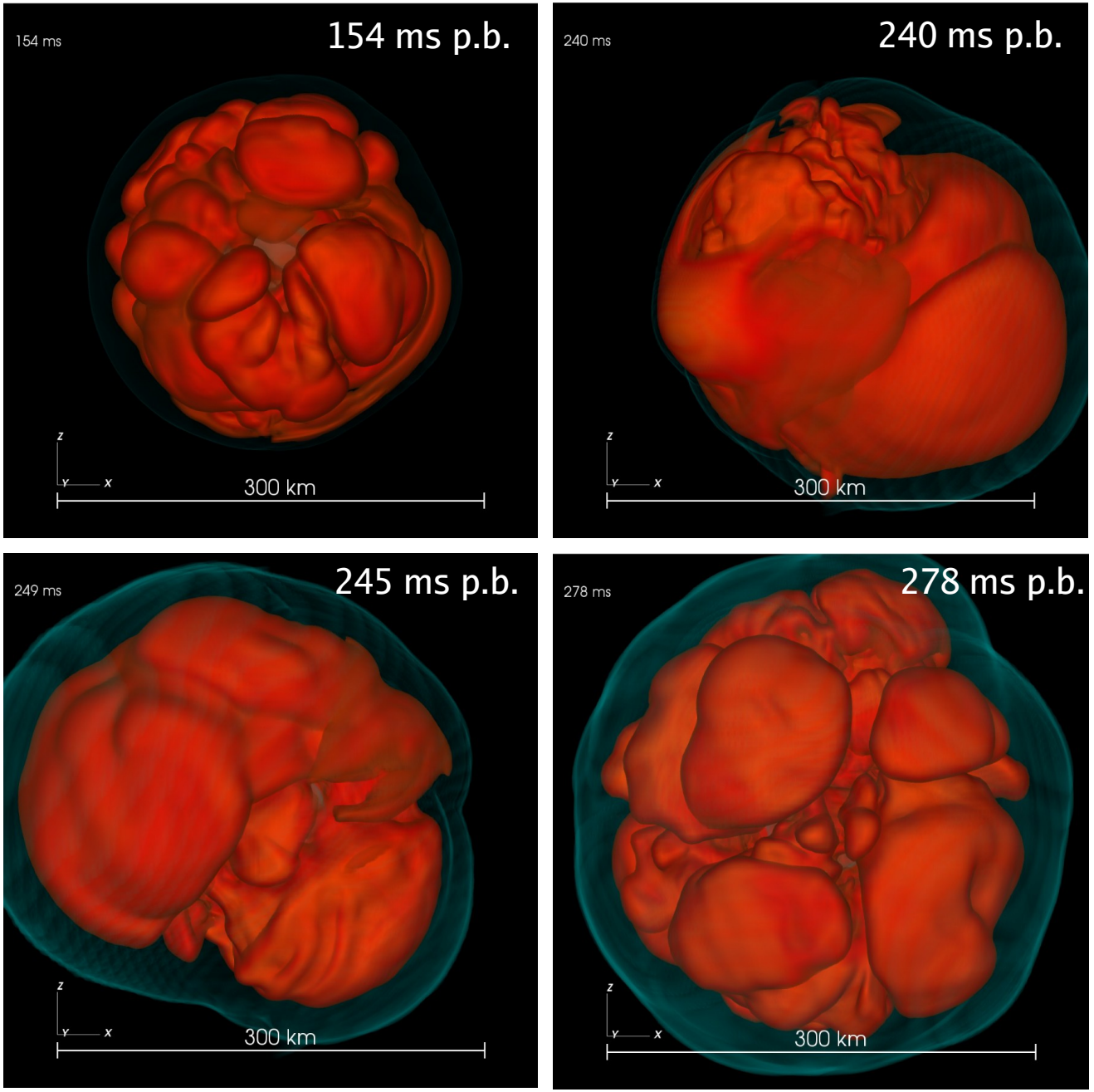
F. Hanke et al., ApJ 770 (2013) 66

3D Core-Collapse Models

27 M_{sun} progenitor (WHW 2002)

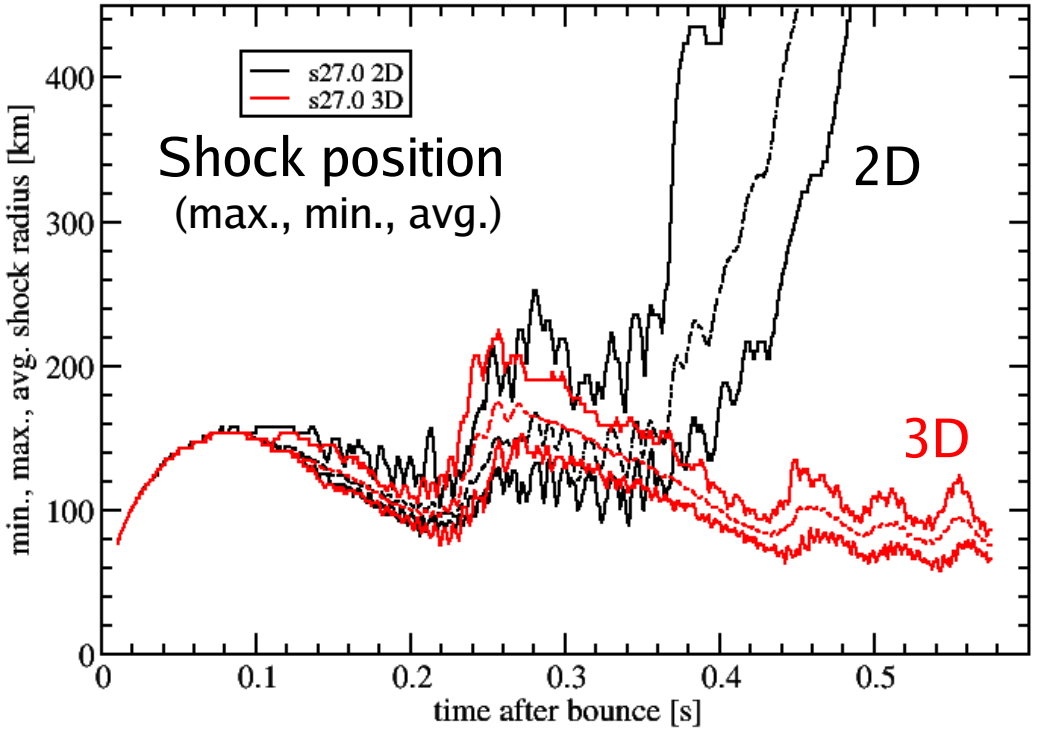
27 M_{sun} SN model with neutrino transport develops spiral SASI as seen in idealized, adiabatic simulations by Blondin & Mezzacappa (Nature 2007)

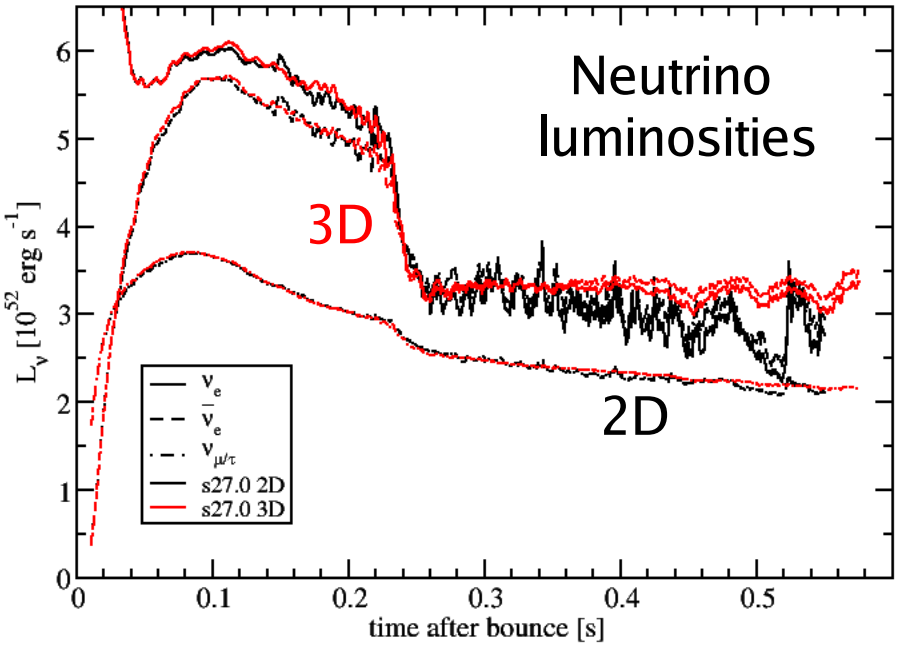
F. Hanke et al., ApJ 770 (2013) 66



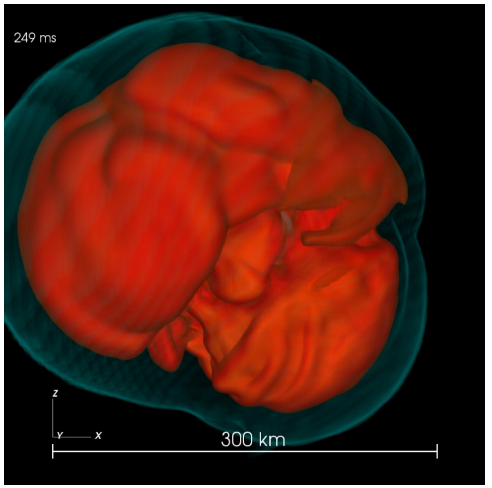
3D SNCC Models with Neutrino Transport

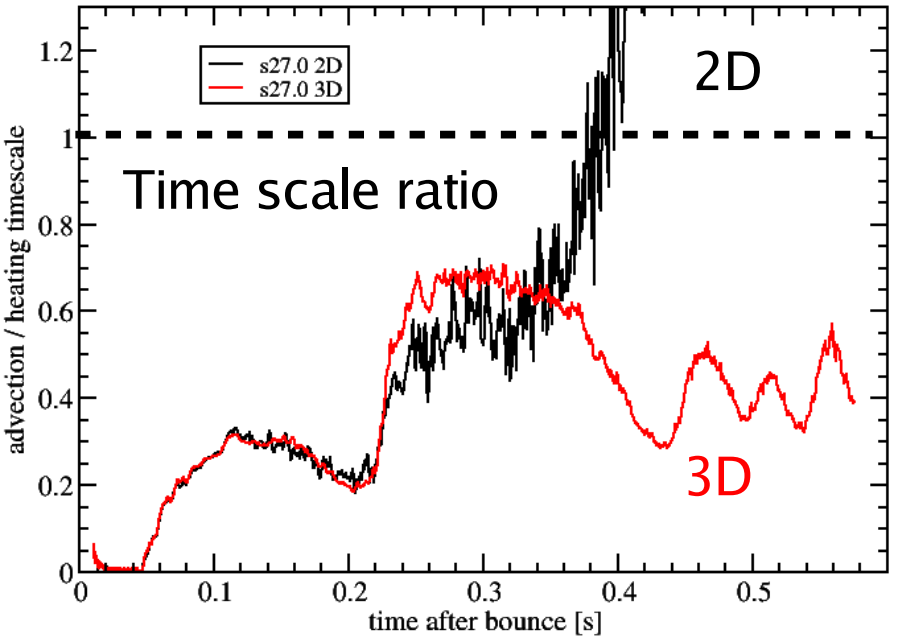
27 M_{sun} progenitor (WHW 2002)





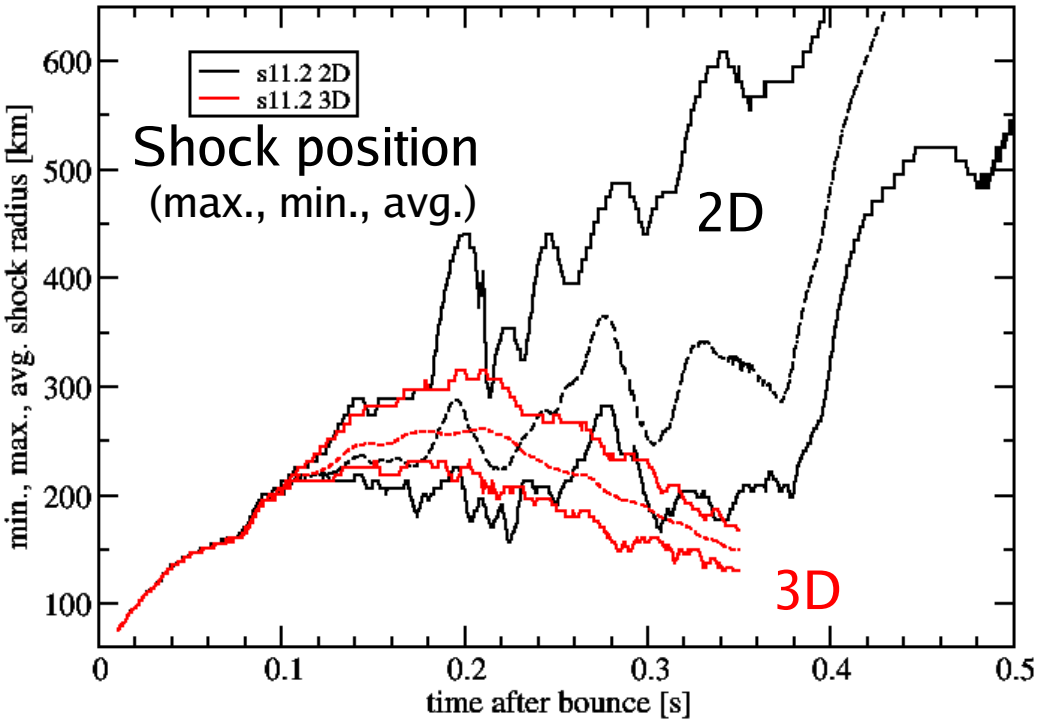
F. Hanke et al.,
ApJ 770 (2013) 66

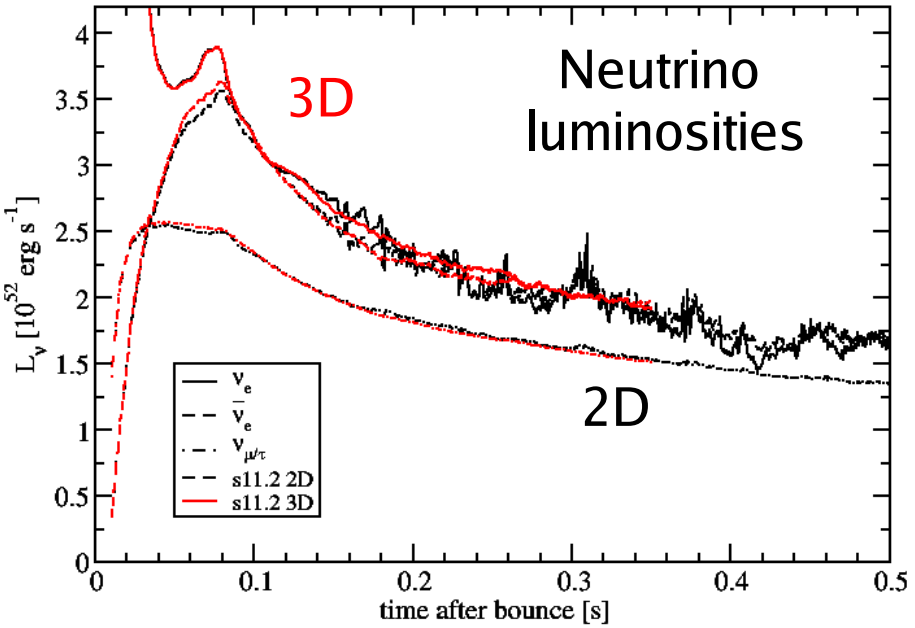


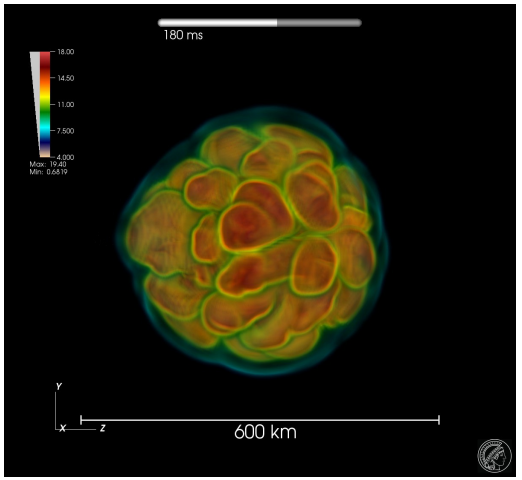


3D SNCC Models with Neutrino Transport

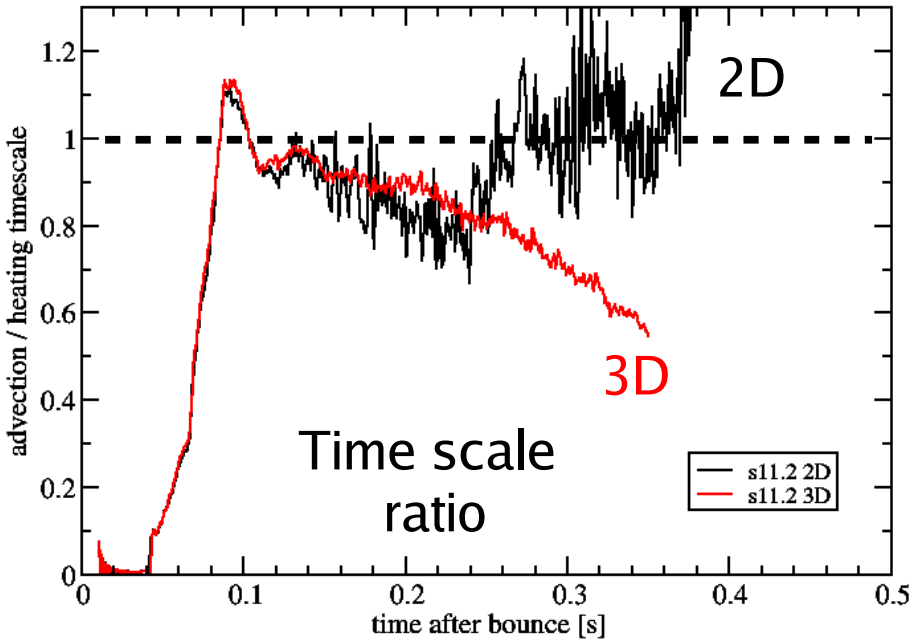
11.2 M_{sun} progenitor (WHW 2002)





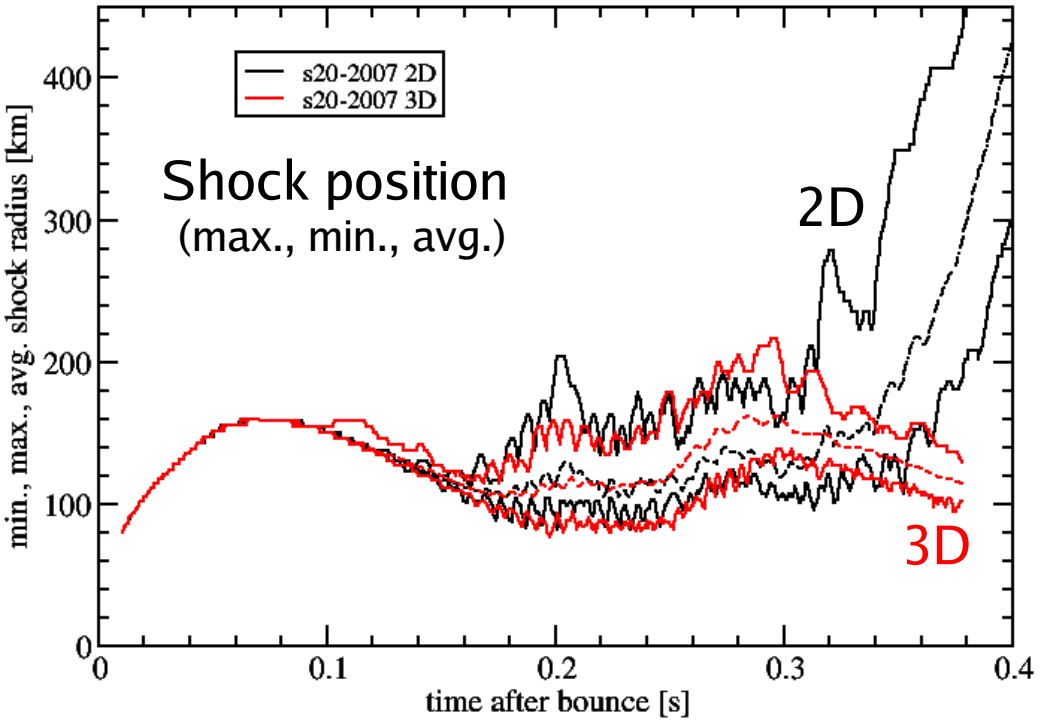


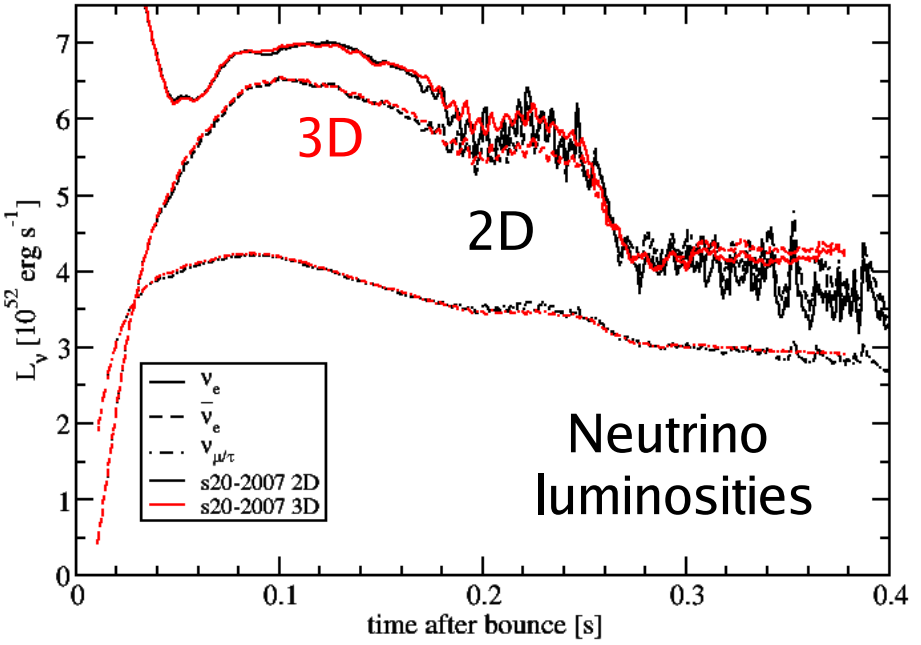
Florian Hanke,
PhD project

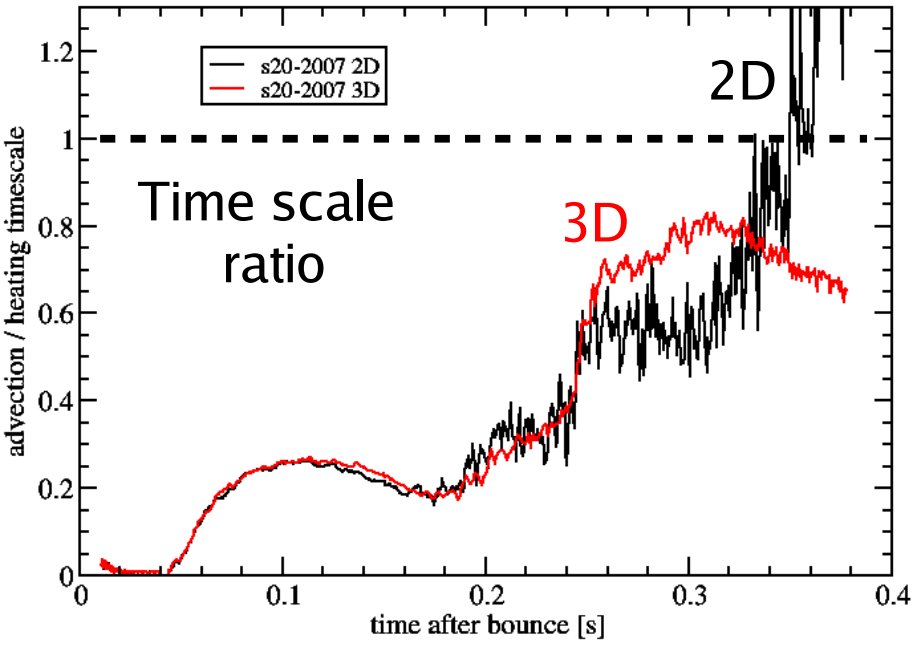


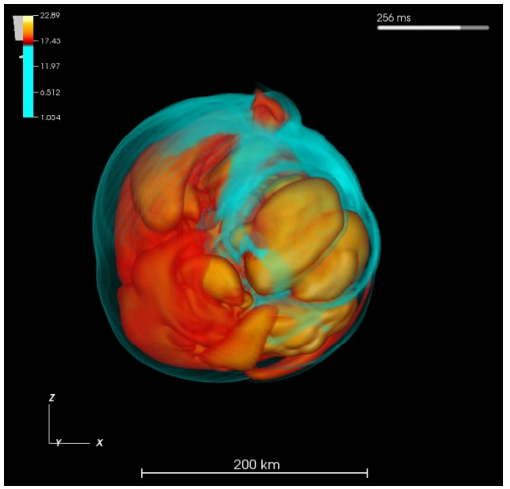
3D SNCC Models with Neutrino Transport

20 M_{sun} progenitor (WH 2007)









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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 finally clear picture of 3D effects yet. **SASI can dominate (certain phases) also in 3D models!**
- **Intriguing new phenomena in 3D!**

- 3D models do not yet show explosions, but **still need higher resolution** for convergence.
- **Uncertain/missing physics ?????**
- **Progenitors are 1D**, but shell structure and initial progenitor-core asymmetries can affect onset of explosion (cf. Couch & Ott, ApJL778:L7 (2013))! How important is slow rotation for SASI growth?

Numerical Convergence?

Hanke et al., ApJ 755 (2012) 138; arXiv:1108.4355

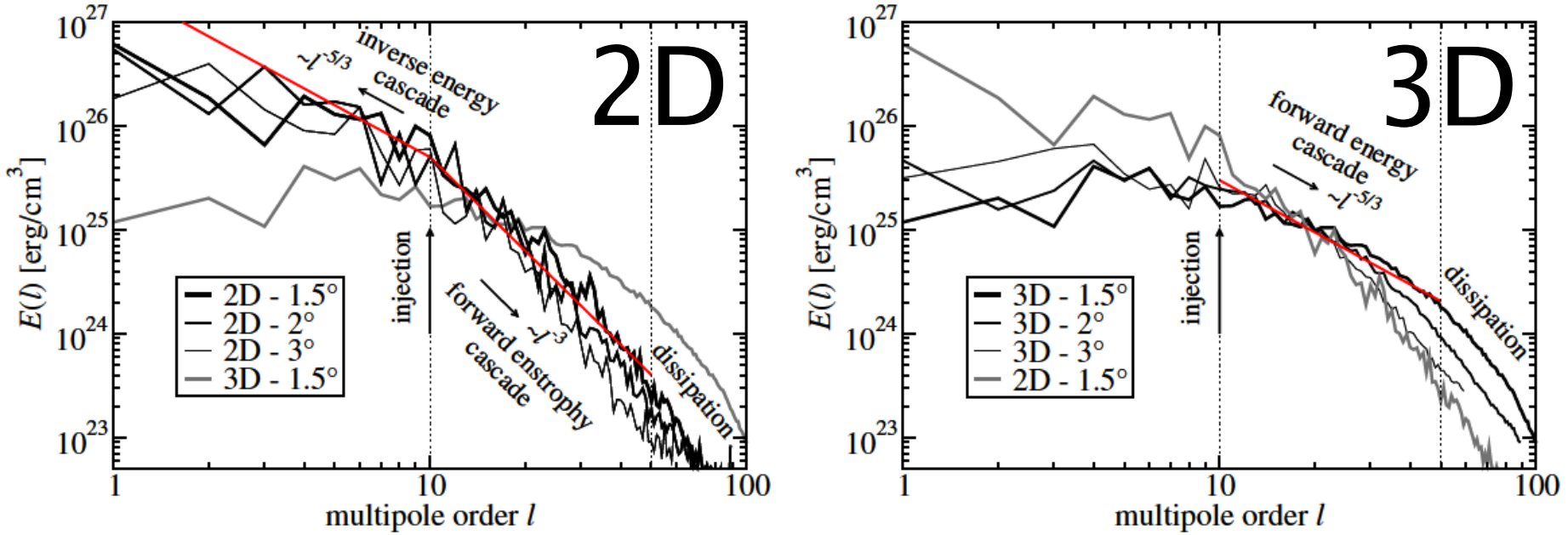
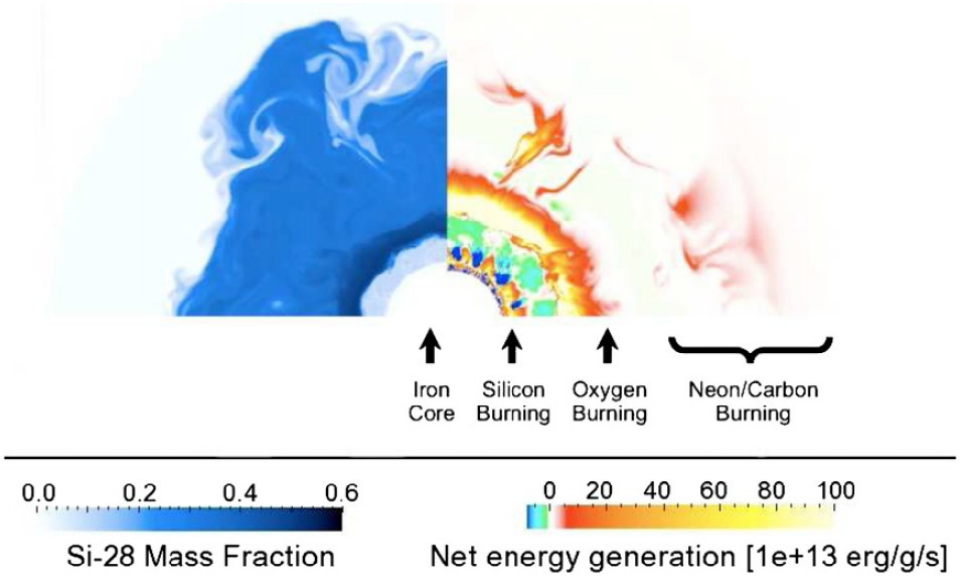


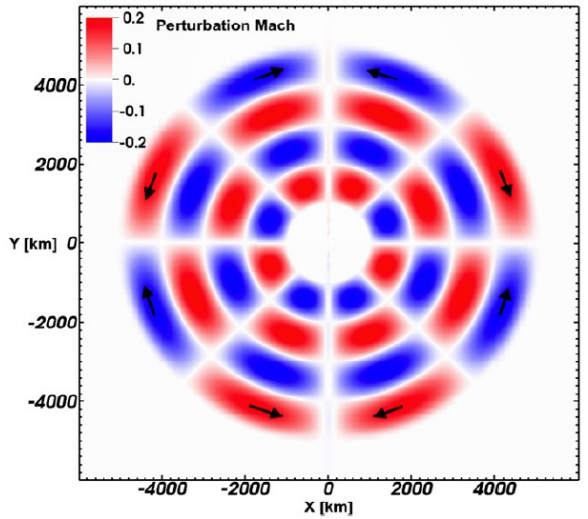
Figure 16. Turbulent energy spectra $E(l)$ as functions of the multipole order l for different angular resolution. The spectra are based on a decomposition of the azimuthal velocity v_θ into spherical harmonics at radius $r = 150$ km and 400 ms post-bounce time for 15 $M_\odot$ runs with an electron–neutrino luminosity of $L_{\nu_e} = 2.2 \times 10^{52}$ erg s^{-1}. Left: 2D models with different angular resolution (black, different thickness) and, for comparison, the 3D model with the highest employed angular resolution (gray). Right: 3D models with different angular resolution and, for comparison, the 2D model with the highest employed angular resolution (gray). The power-law dependence and direction of the energy and enstrophy cascades (see the text) are indicated by red lines and labels for 2D models in the left panel and 3D models in the right panel. The left vertical, dotted line roughly marks the energy-injection scale, and the right vertical, dotted line denotes the onset of dissipation at high l for the best-displayed resolution.

Turbulent energy cascade in 2D from small to large scales, in 3D from large to small scales! =====> **More than 2 degree resolution needed in 3D!**

Large-scale Progenitor-Core Asymmetries?

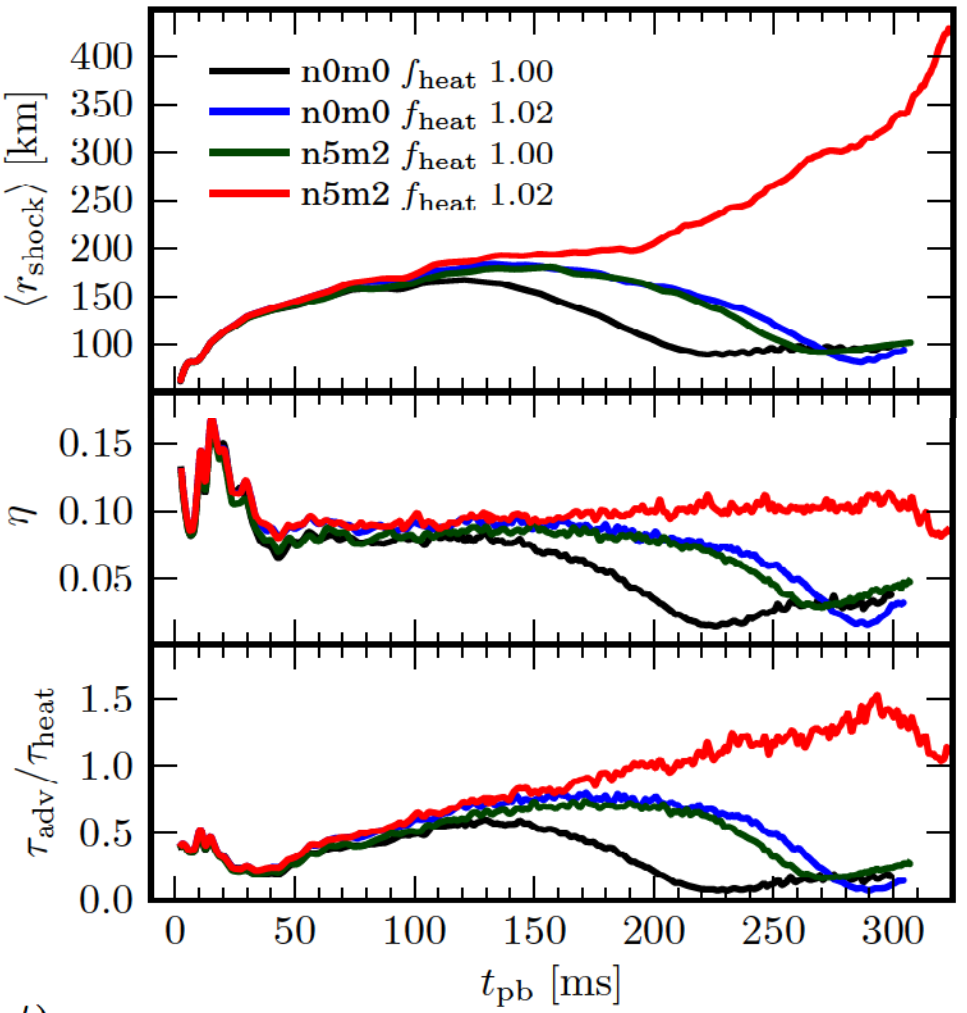


Arnett & Meakin, ApJL 733:78 (2011)



Couch & Ott, ApJL 778:L7 (2013)

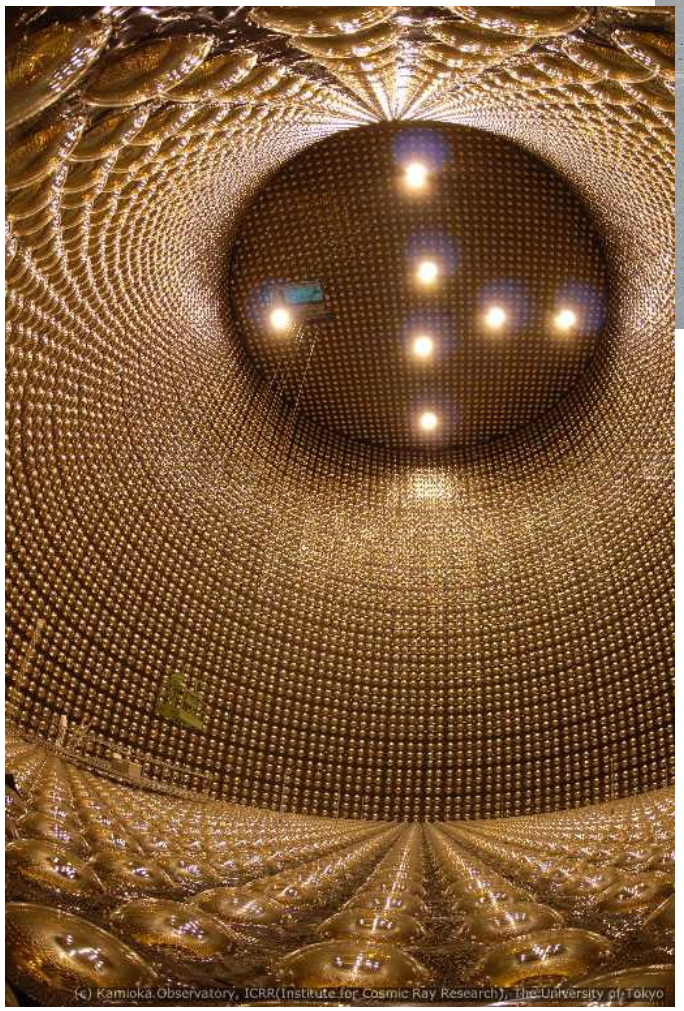
Couch & Ott, ApJL 778:L7 (2013)

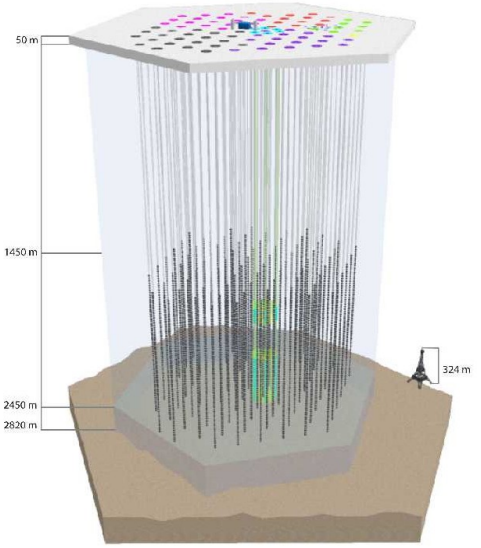


$$\delta v_\theta = M_{\rm pert} c_S \sin[(n-1)\theta] \sin[(n-1)\zeta] \cos(n\phi)$$

Detecting Core-Collapse SN Signals

Superkamiokande





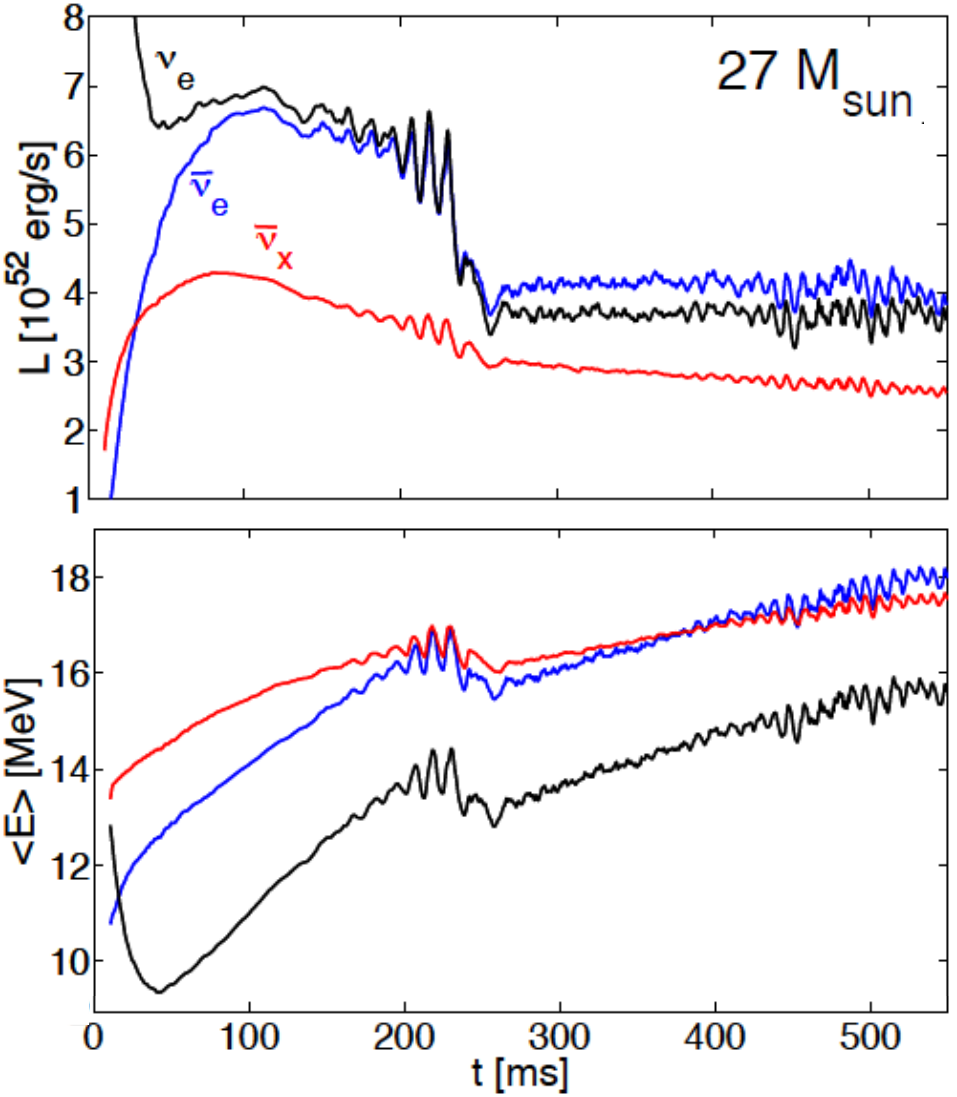
IceCube

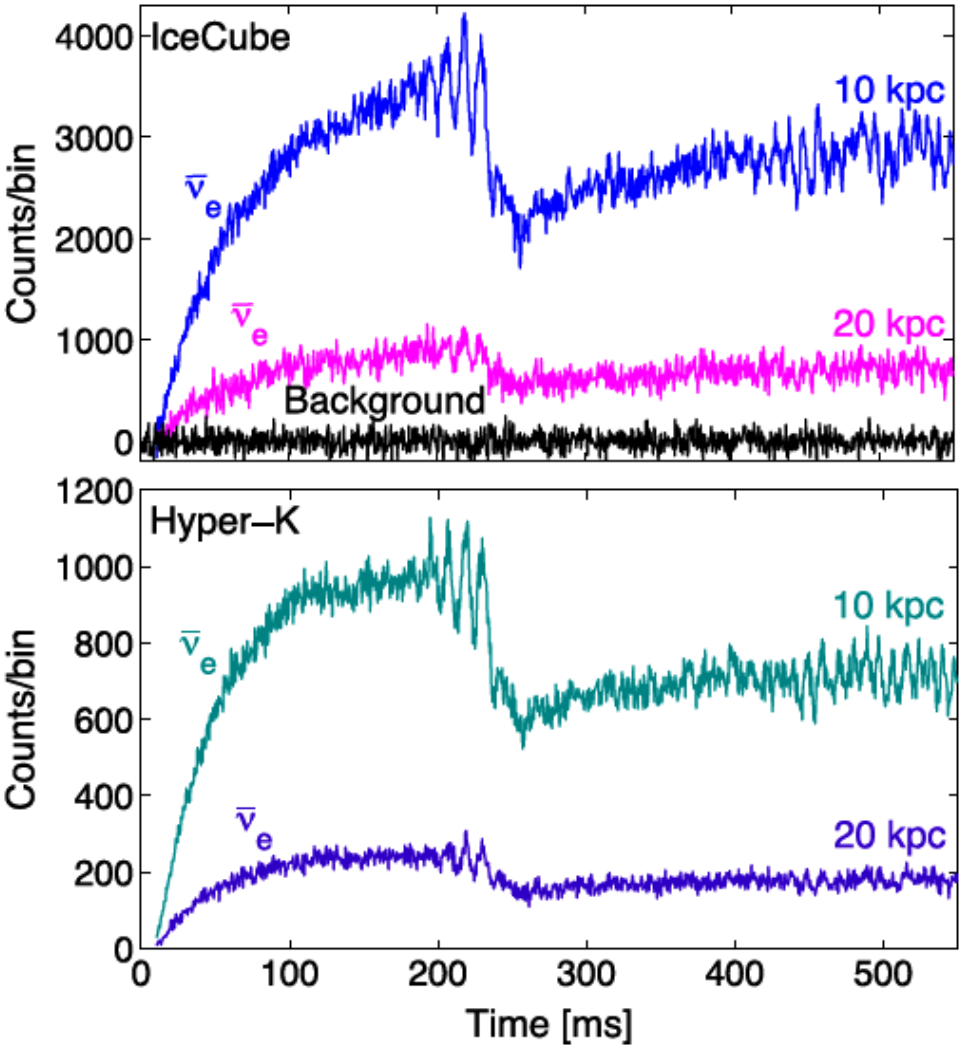
VIRGO

3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 M_{sun} progenitors (WHW 2002)

SASI produces modulations of neutrino emission and gravitational-wave signal.





(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 M_{sun} progenitors (WHW 2002)

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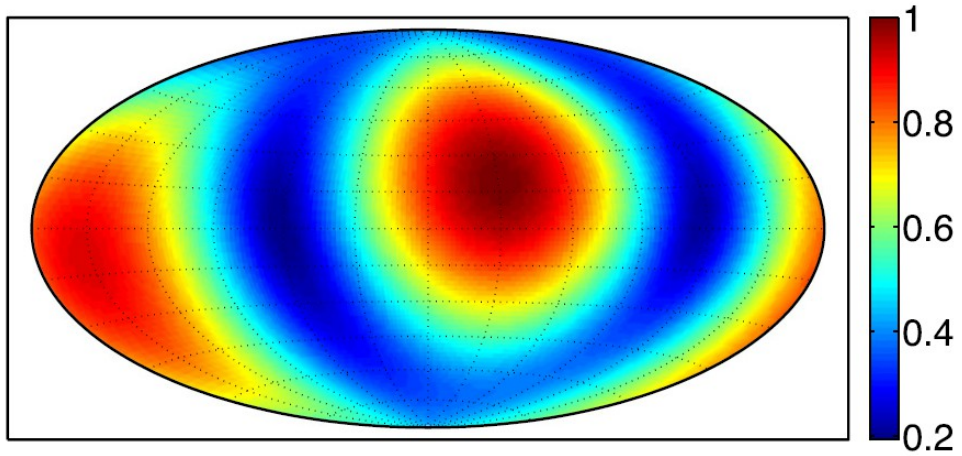
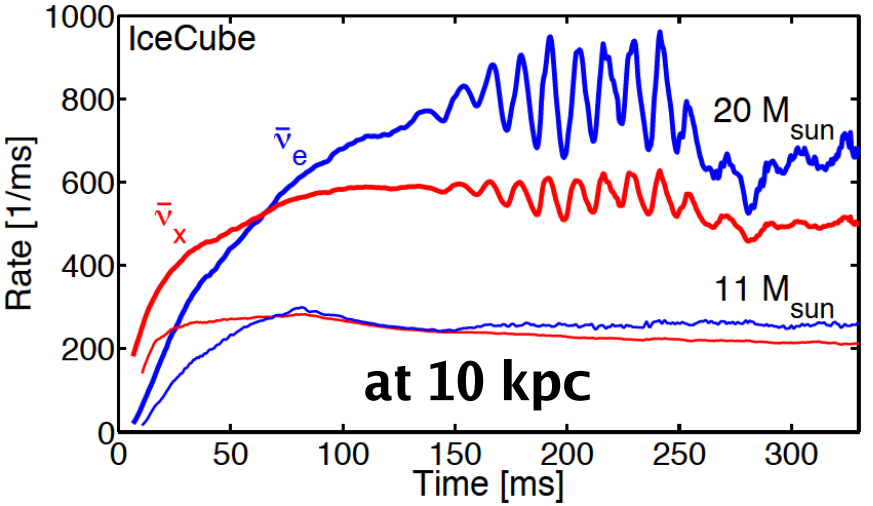
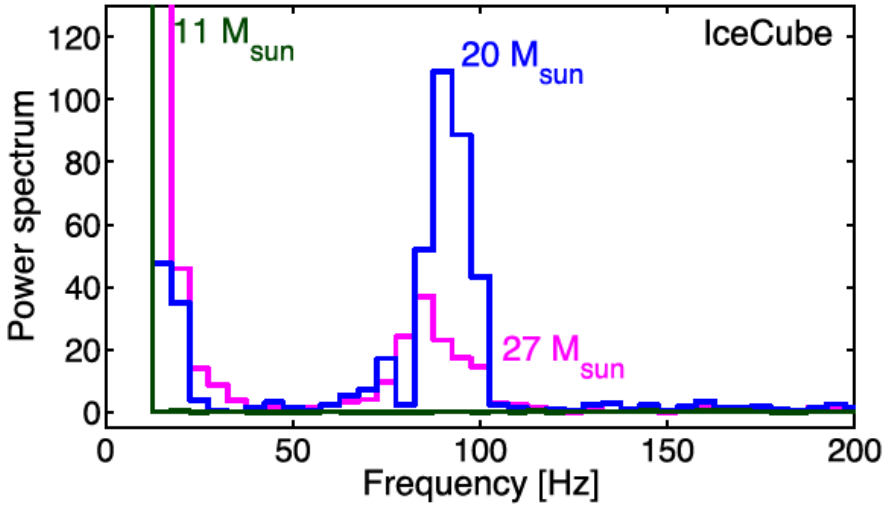


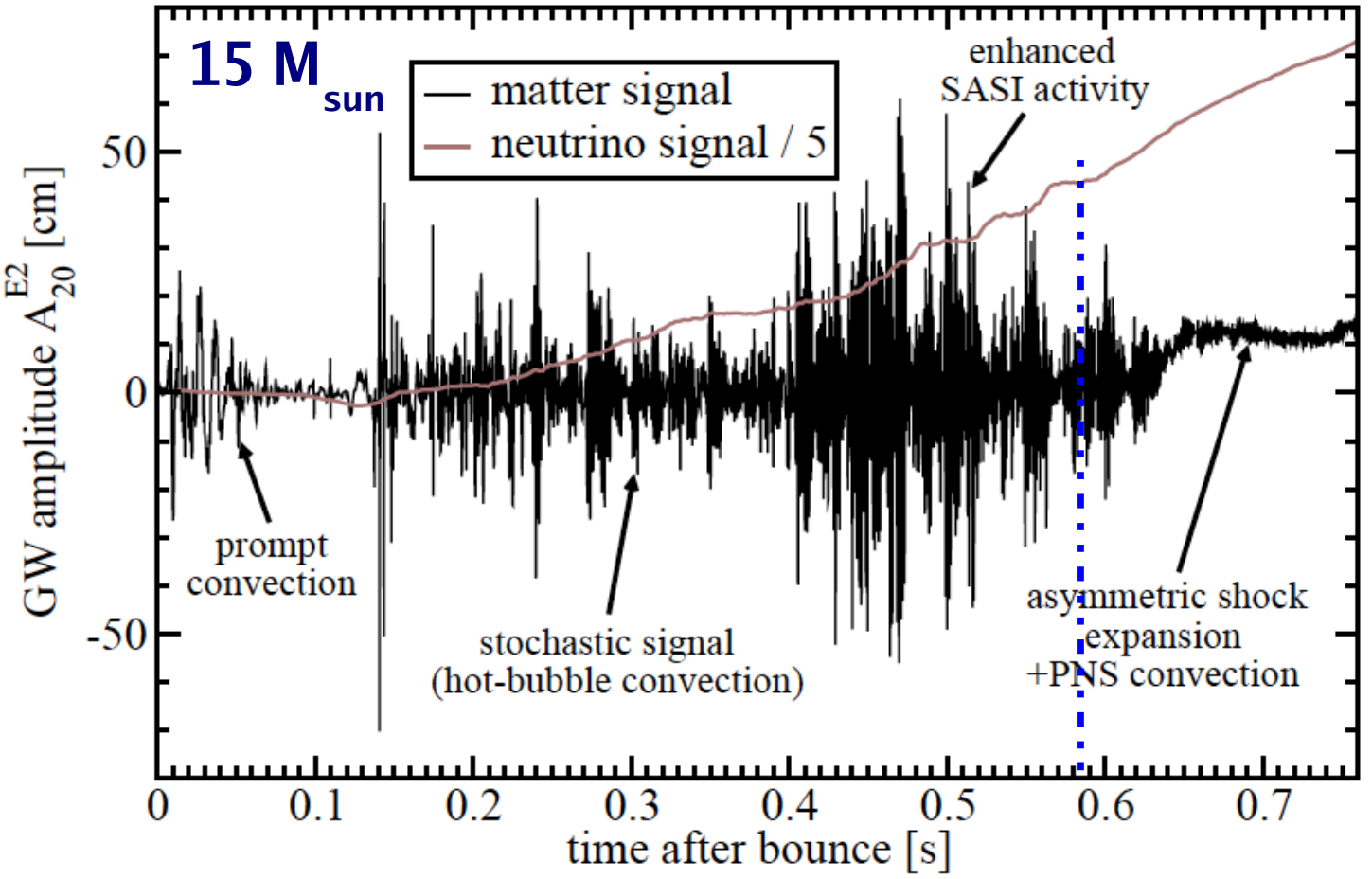


$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$



(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

Gravitational Waves for 2D SN Explosions



(Müller, THJ, & Marek, ApJ 766 (2013) 43)

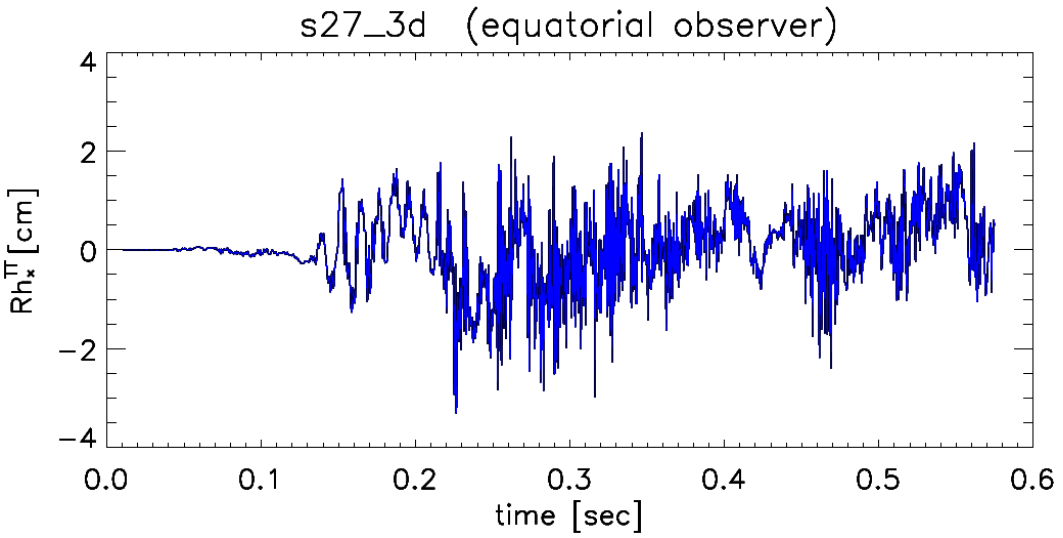
$$h = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\Theta\frac{A_{20}^{E2}}{R}$$

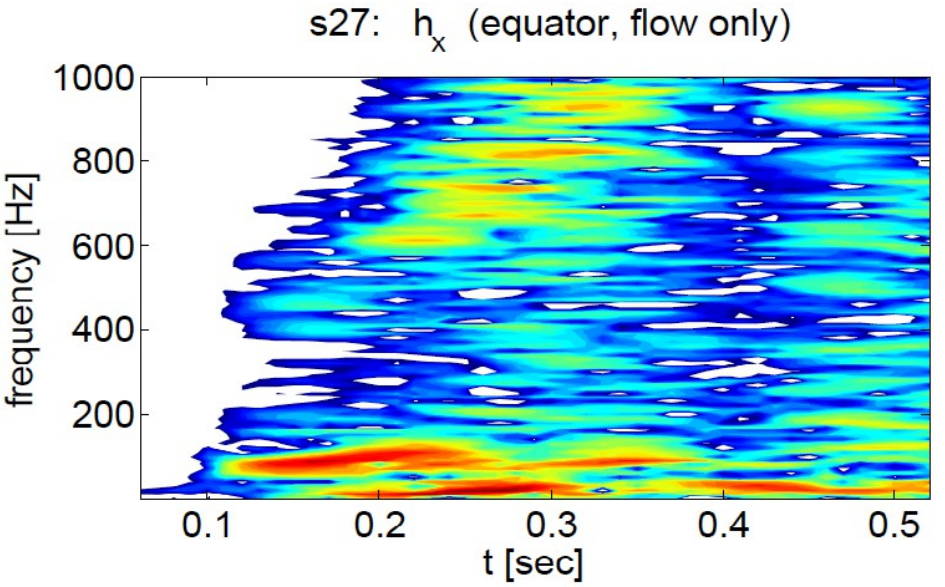
$$h_\nu = \frac{2G}{c^4 R}\int_0^t L_\nu(t')\alpha_\nu(t')\,dt'$$

$$\alpha_\nu = \frac{1}{L_\nu}\int \pi \sin\theta\,(2|\cos\theta| - 1)\frac{dL_\nu}{d\Omega}d\Omega$$

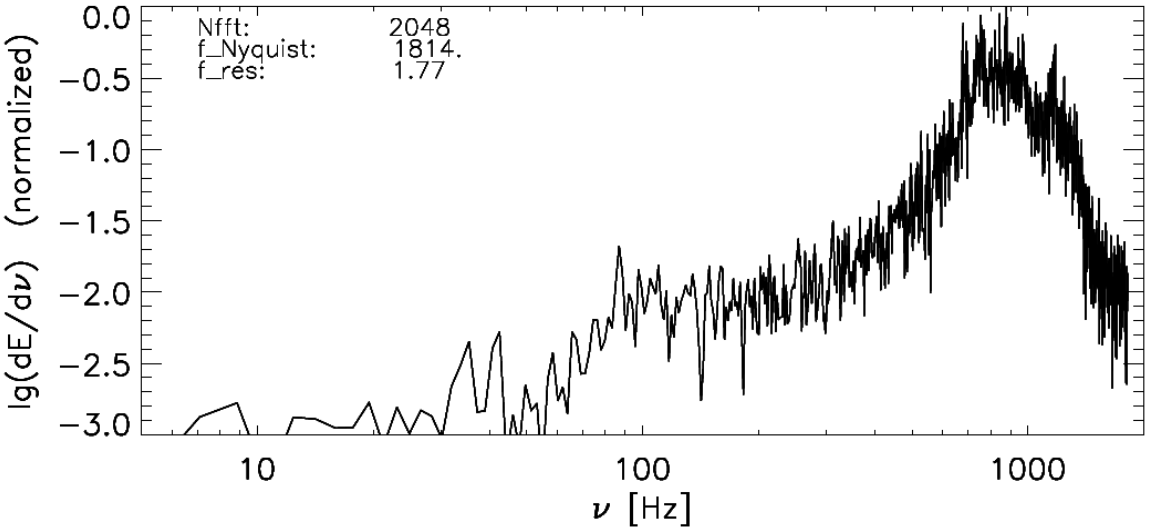
3D Core-Collapse Models: Gravitational Waves

27 M_{sun} progenitor (WHW 2002)

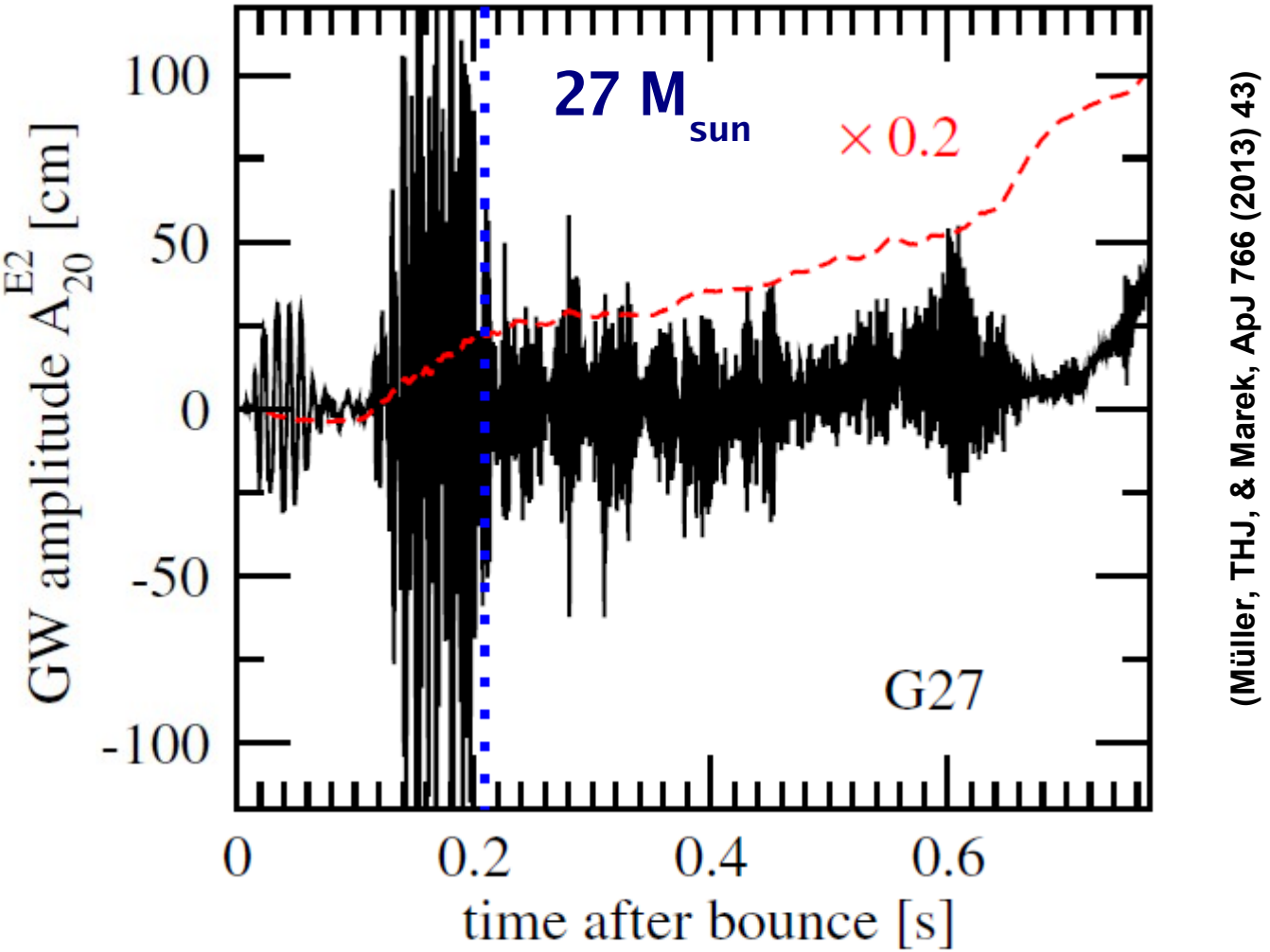




Preliminary analysis
by E. Müller of
model from
F. Hanke et al.,
ApJ 770 (2013) 66



Gravitational Waves for 2D SN Explosions



(Müller, THJ, & Marek, ApJ 766 (2013) 43)

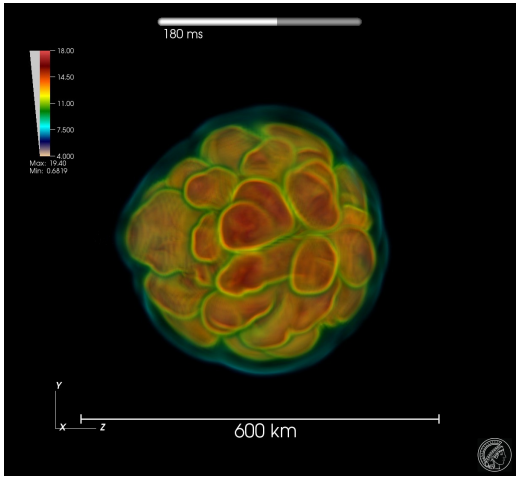
GW amplitudes in 2D are considerably larger than in 3D.
No template character, in 3D strongly direction dependent.

A New Nonradial, Neutrino-Hydrodynamical Instability

LESA:
Lepton-Emission Self-sustained Asymmetry

Tamborra, Hanke, Janka, Müller B., Raffelt & Marek,
arXiv:1402.5418 (astro-ph)

A New Nonradial 3D Instability

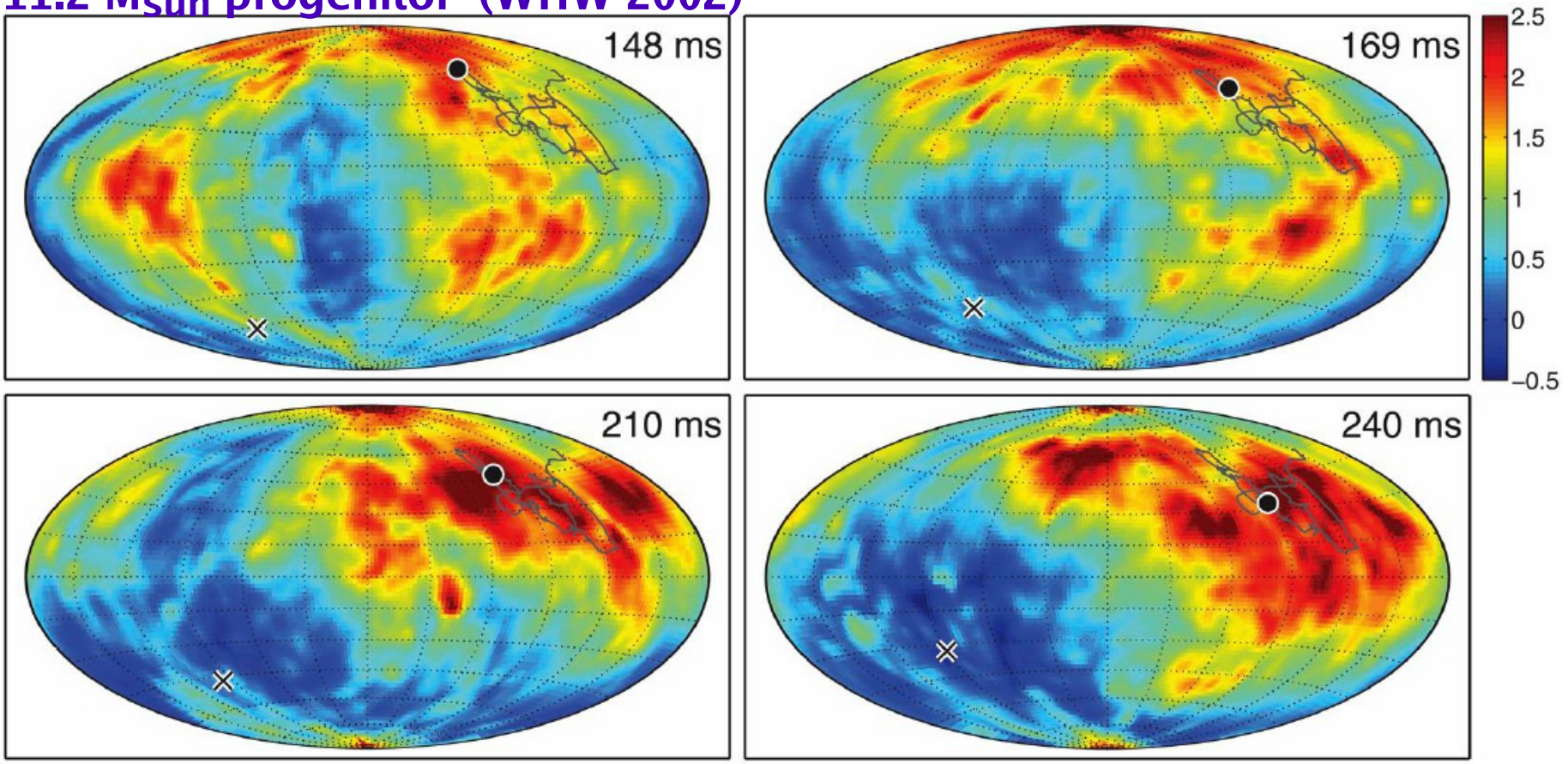


Dipole asymmetry of lepton number emission

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)

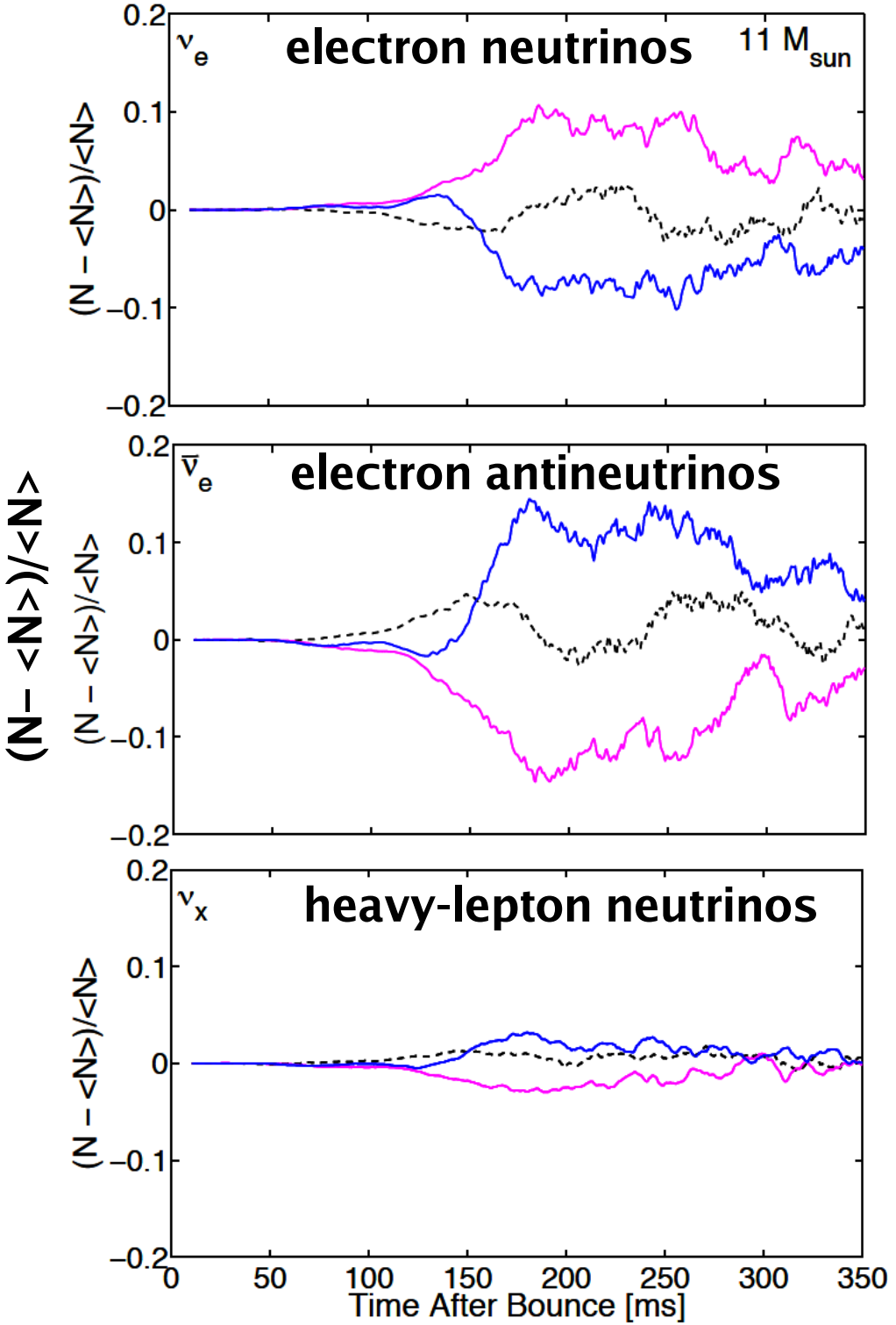


Tamborra, Hanke, Janka, et al., arXiv:1402.5418

A New Nonradial 3D Instability

Dipole asymmetry of lepton-number emission

11.2 M_{sun} progenitor (WHW 2002)

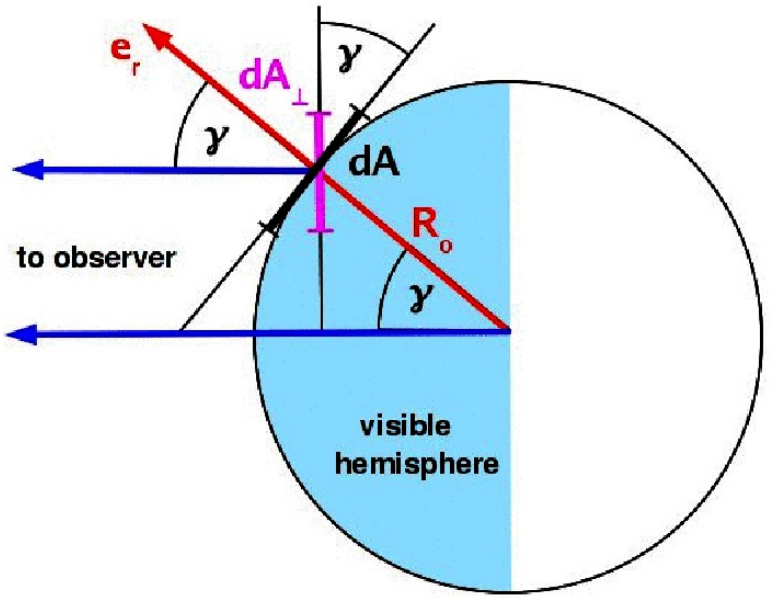


Tamborra, Hanke, Janka, et al., arXiv:1402.5418

Observable number and energy luminosities from ray-by-ray fluxes, accounting for projection and limb-darkening effects:

$$N(t) = 2 \int_{\text{vis.hem.}} \mathrm{d}A \, \cos\vartheta \, F_{\mathrm{n}}(\boldsymbol{R}, t) \left(1 + \frac{3}{2}\cos\vartheta\right)$$

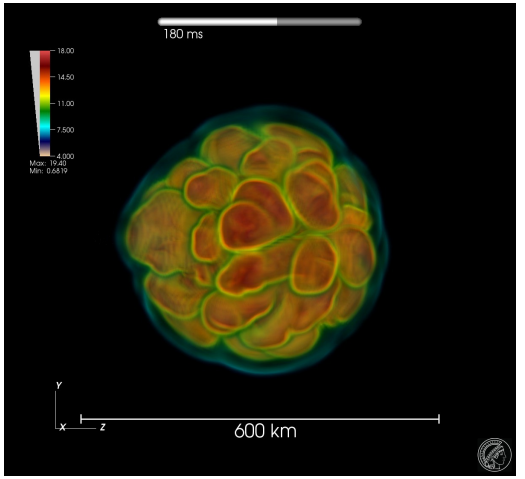
$$L(t) = 2 \int_{\text{vis.hem.}} \mathrm{d}A \, \cos\vartheta \, F_{\mathrm{e}}(\boldsymbol{R}, t) \left(1 + \frac{3}{2}\cos\vartheta\right)$$



Müller, Janka, Wongwathanarat,
A&A 537 (2012) A63

A New Nonradial 3D Instability

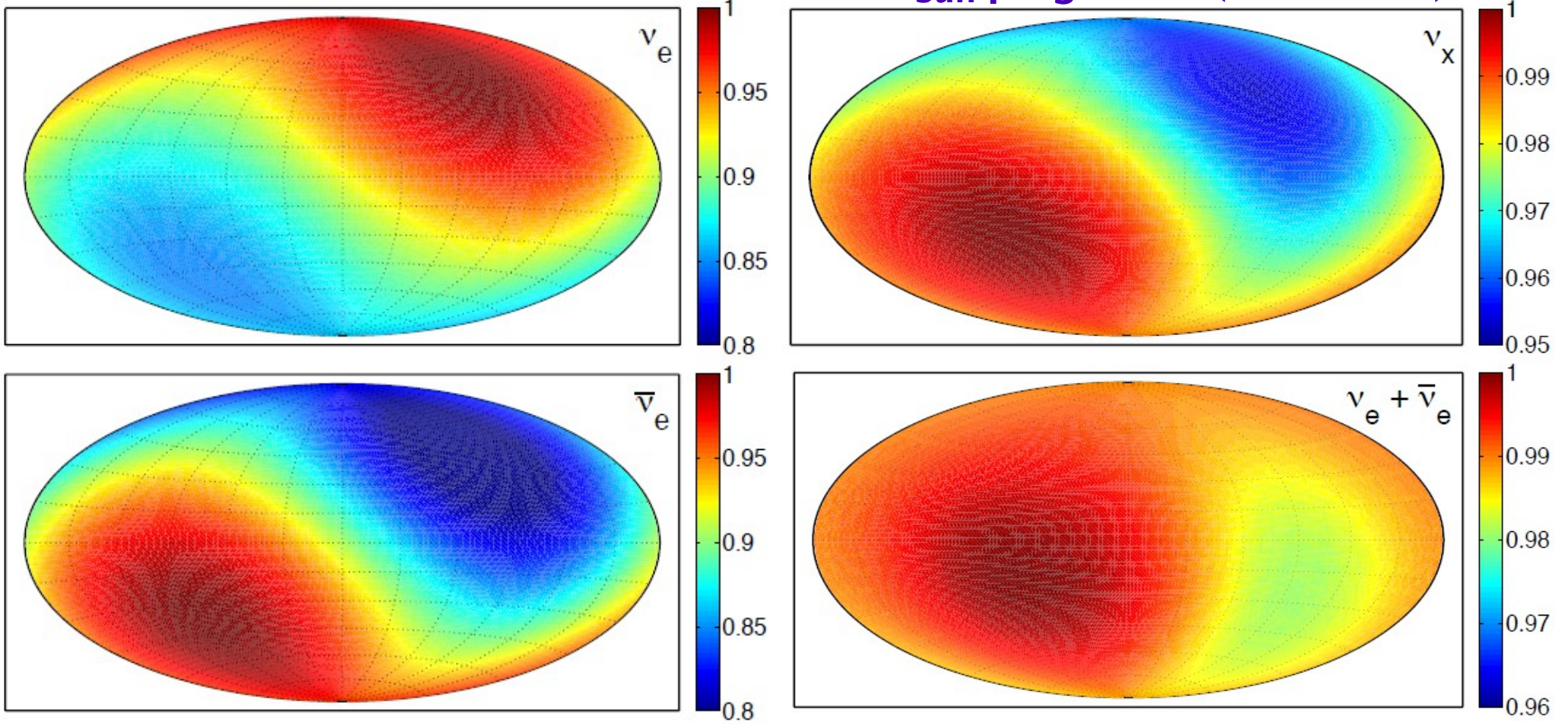
Dipole asymmetry of lepton-number emission



Tamborra, Hanke, Janka, et al.,
arXiv:1402.5418

Number Flux

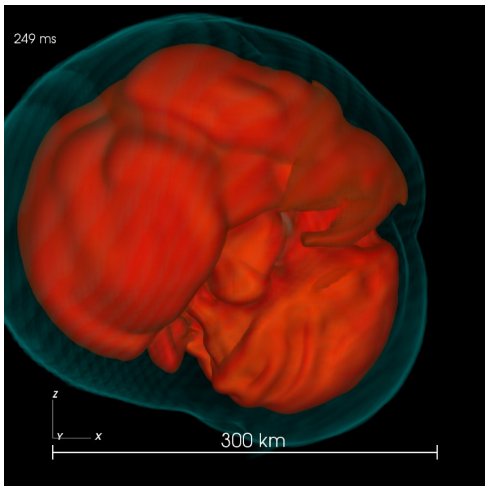
11.2 M_{sun} progenitor (WHW 2002)



A New Nonradial 3D Instability

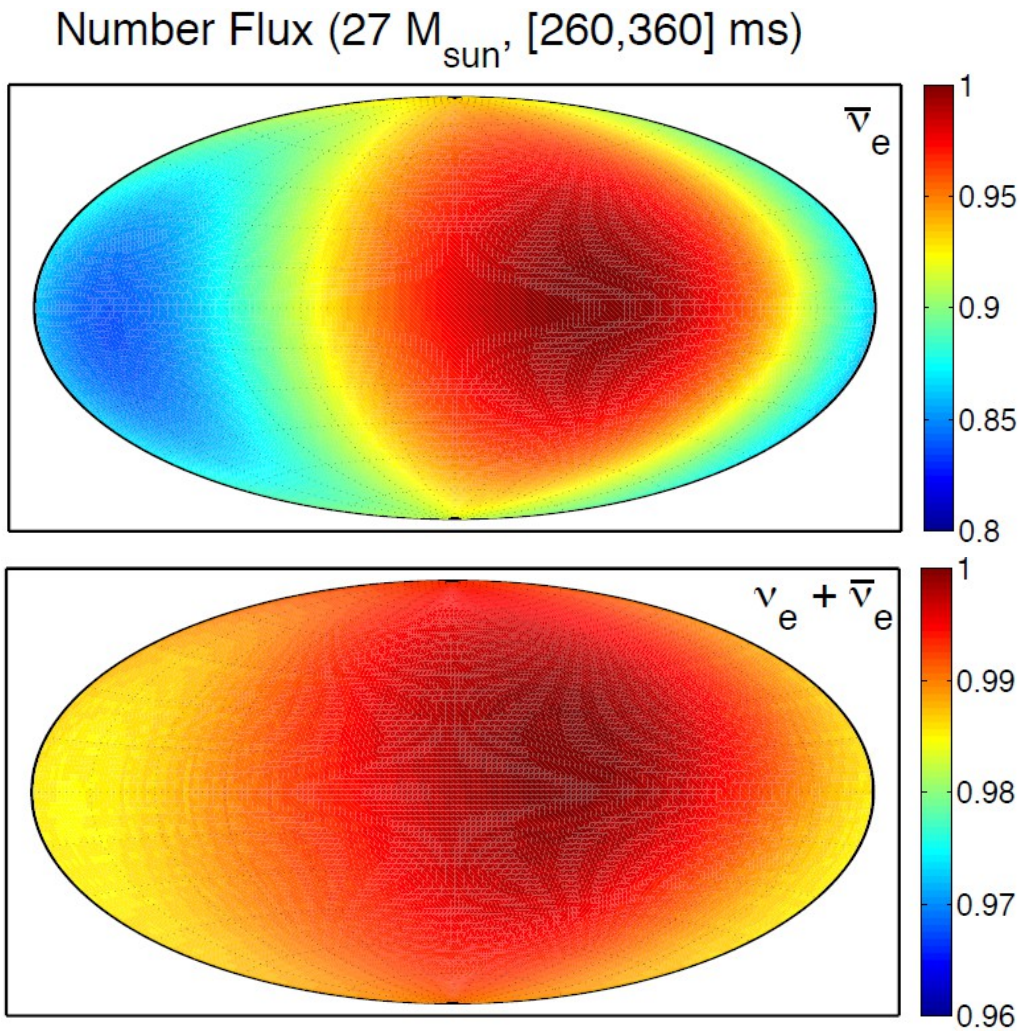
Dipole asymmetry of lepton-number emission

Tamborra, Hanke, Janka, et al., arXiv:1402.5418



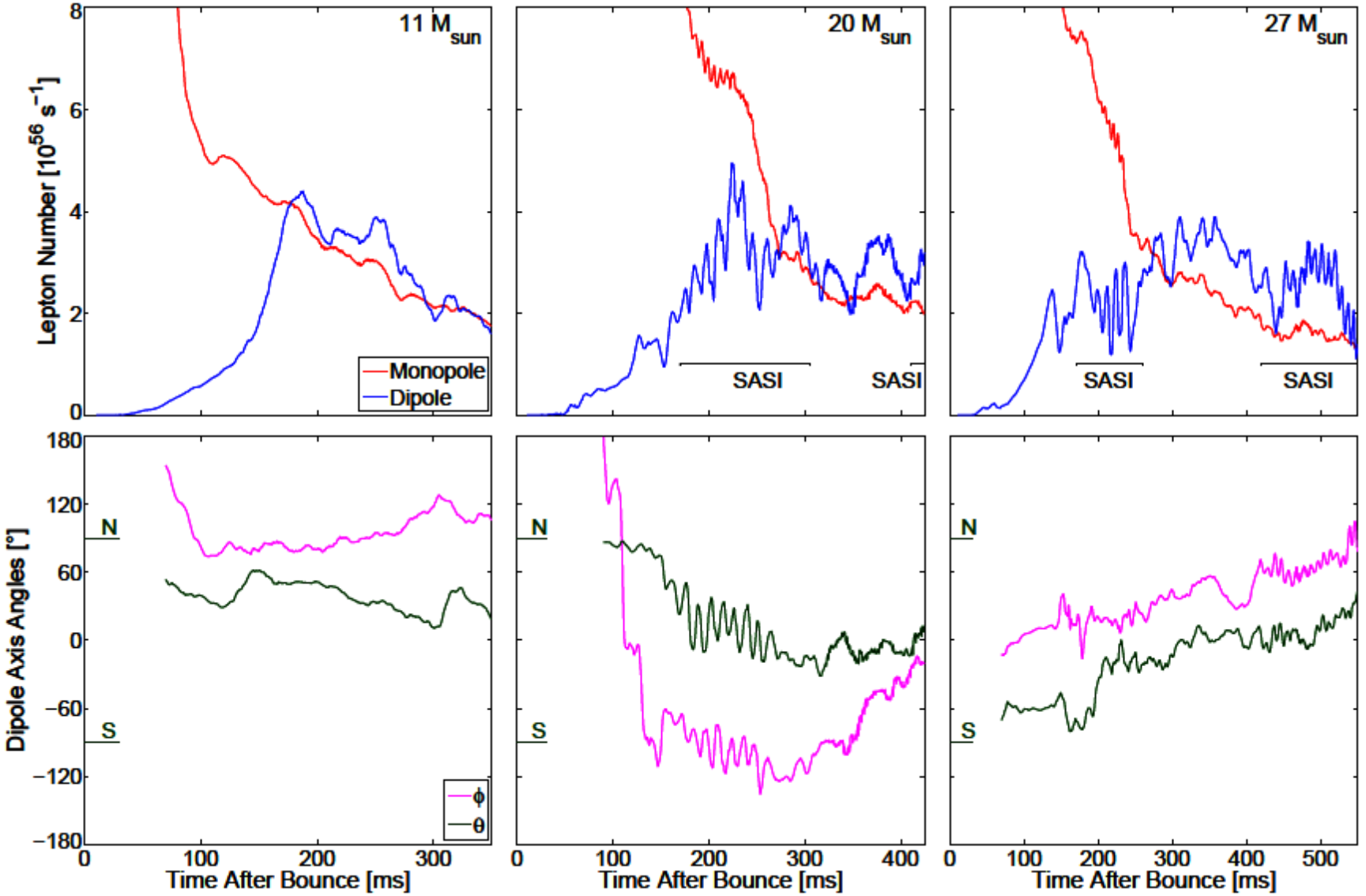
F. Hanke et al., ApJ 770 (2013) 66

27 M_{sun} progenitor (WHW 2002)

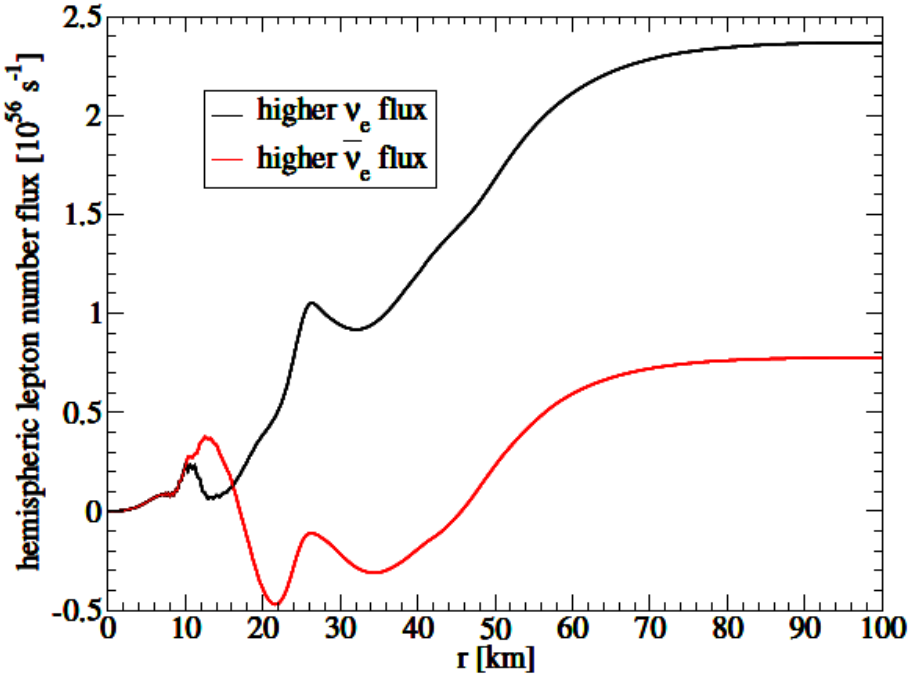


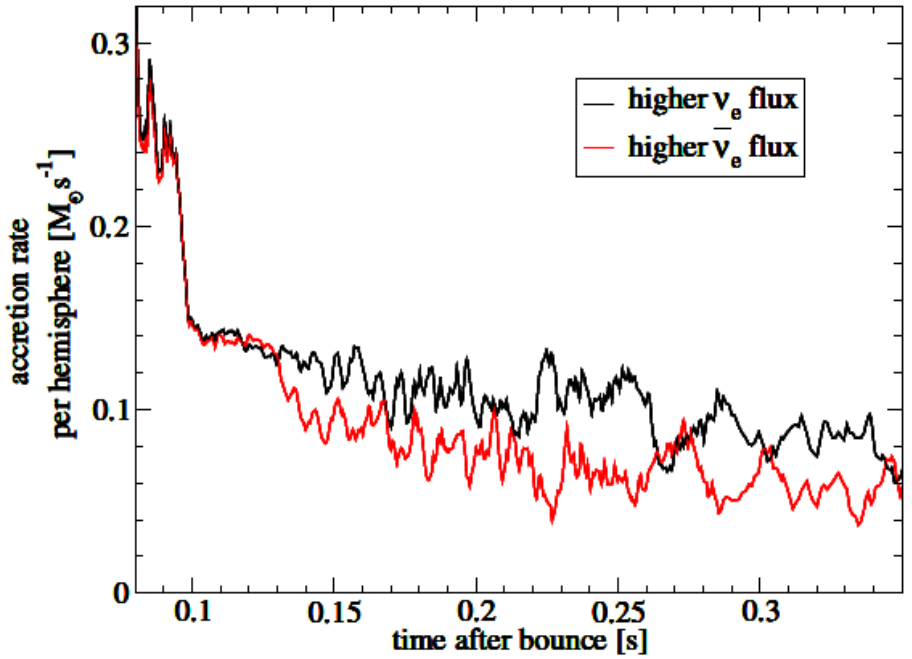
Evolution of Dipole Stength and Direction

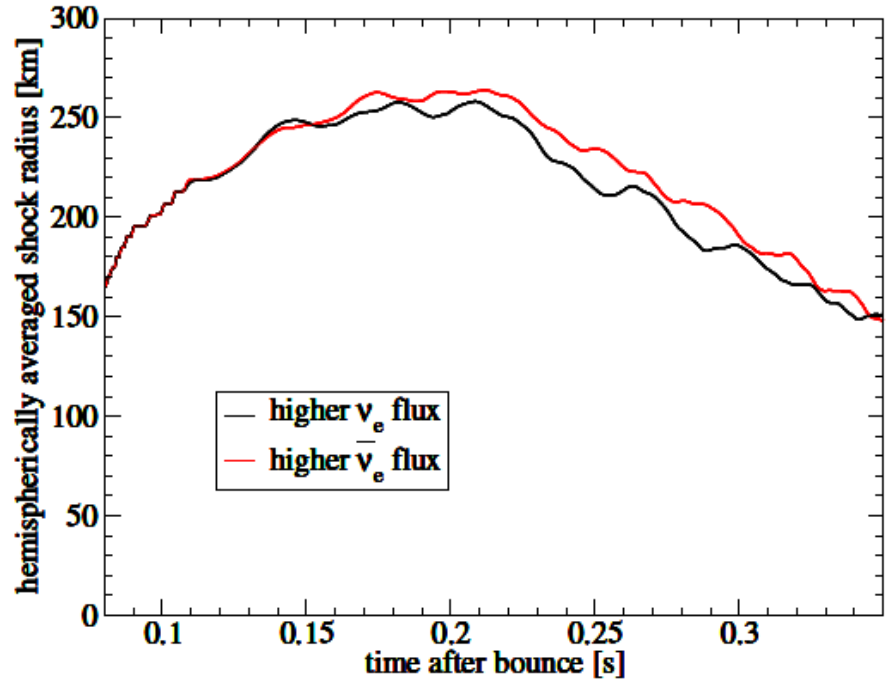
$$A_{\text{Monopole}} + A_{\text{Dipole}} \cos\vartheta$$

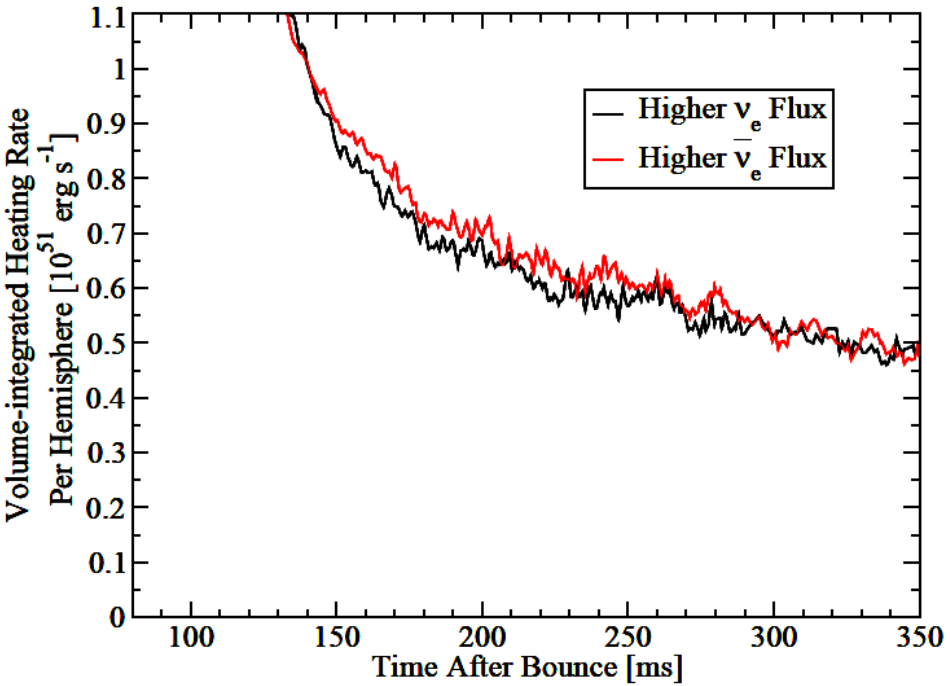


Tamborra, Hanke, Janka, et al., arXiv:1402.5418



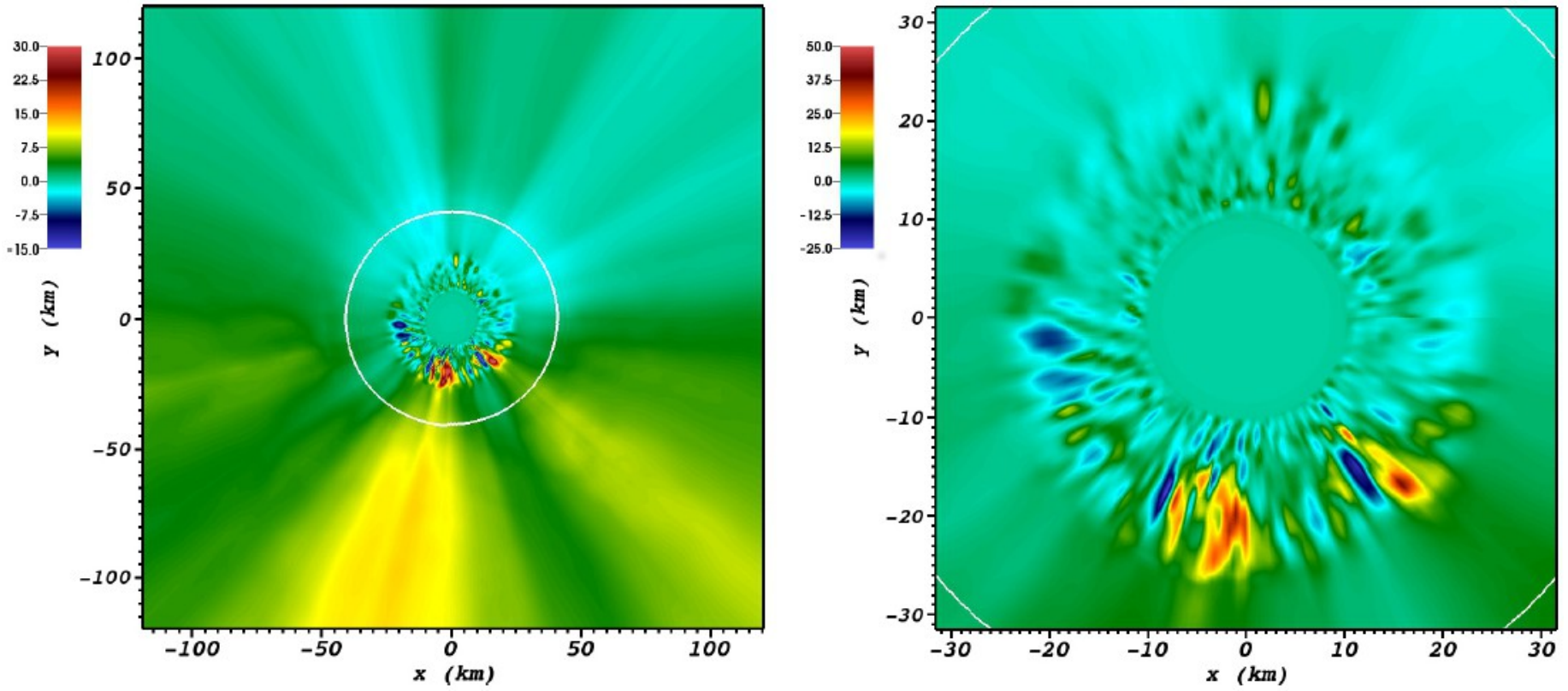




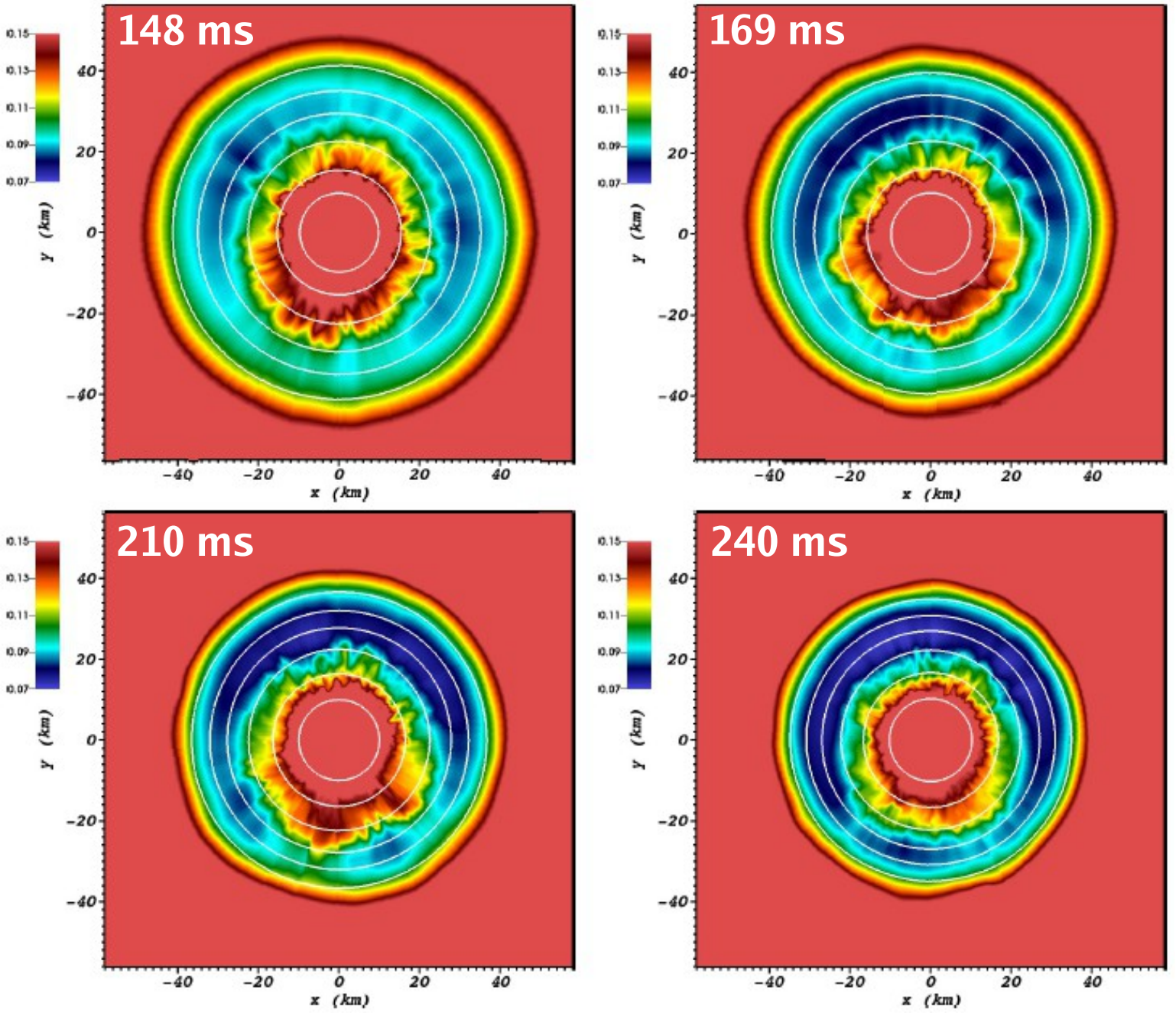


$$\dot{q} \propto \frac{\sigma_0}{r^2}\left(L_{\nu_e}\left\langle\epsilon_{\nu_e}^2\right\rangle Y_n + L_{\bar{\nu}_e}\left\langle\epsilon_{\bar{\nu}_e}^2\right\rangle Y_p\right)$$

Lepton-Number Flux 2D Cuts

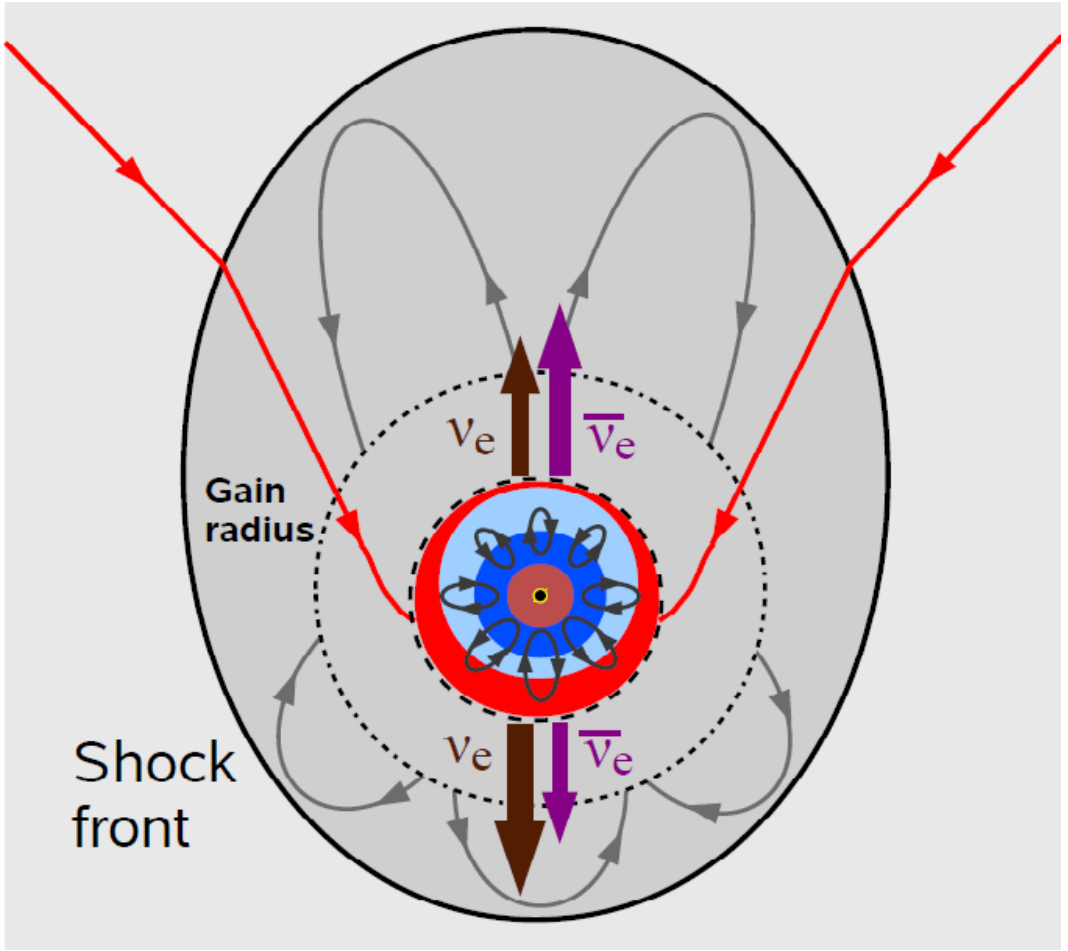


Electron Fraction 2D Cuts

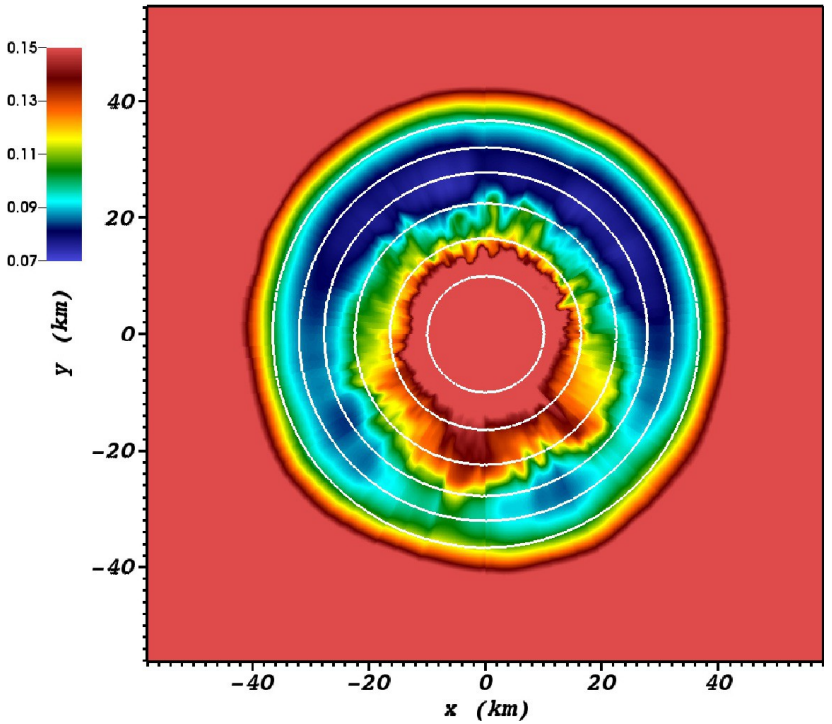


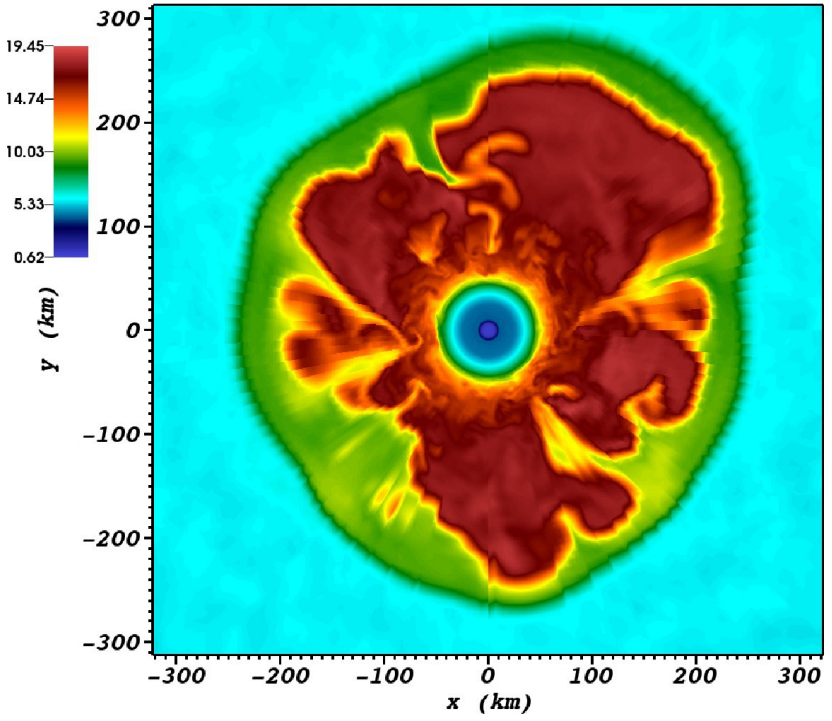
A New Nonradial 3D Instability: "LESA"

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



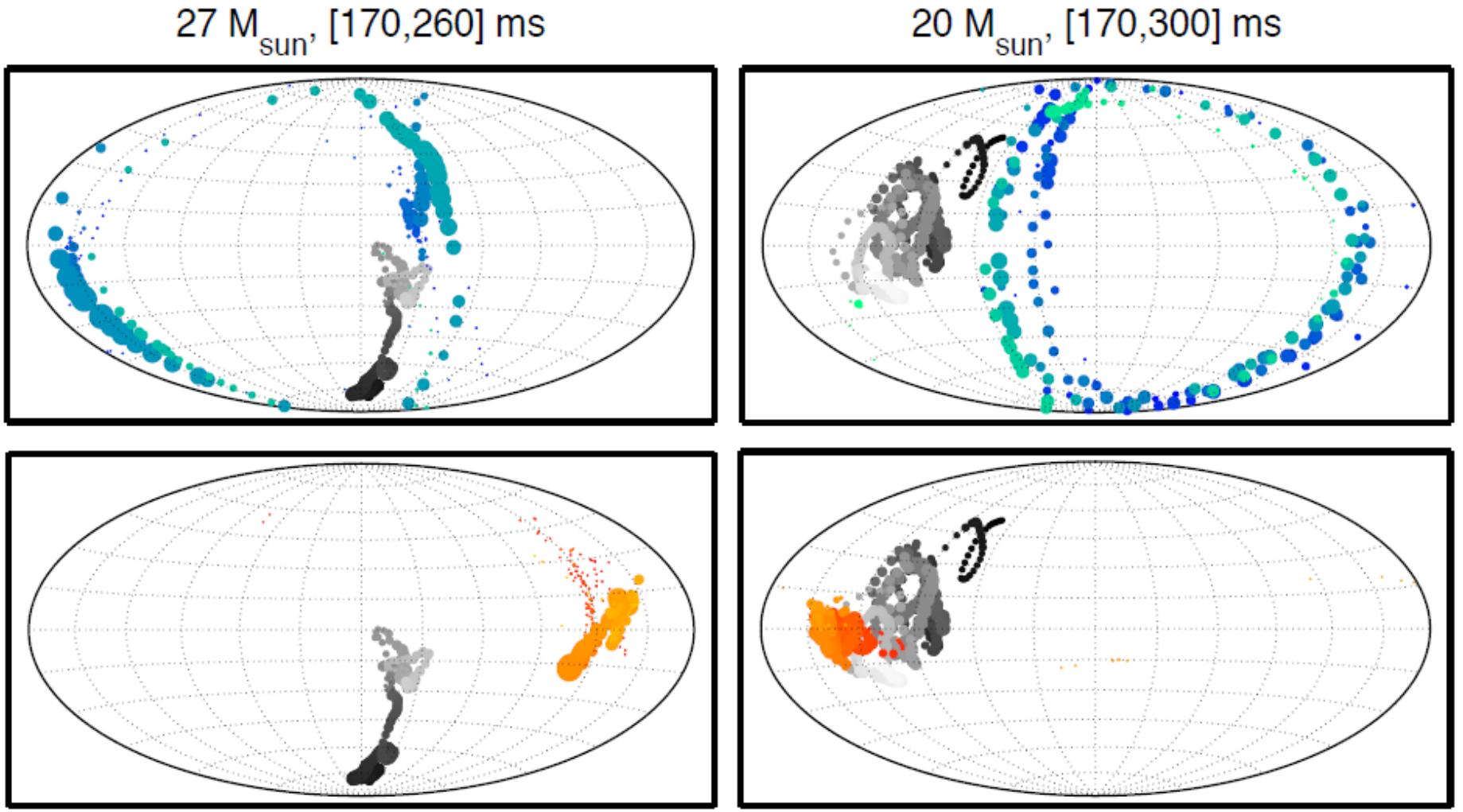
$$\dot{q} \propto \frac{\sigma_0}{r^2}\left(L_{\nu_e}\left\langle\epsilon_{\nu_e}^2\right\rangle Y_n + L_{\bar{\nu}_e}\left\langle\epsilon_{\bar{\nu}_e}^2\right\rangle Y_p\right)$$





LESA-SASI-Interference

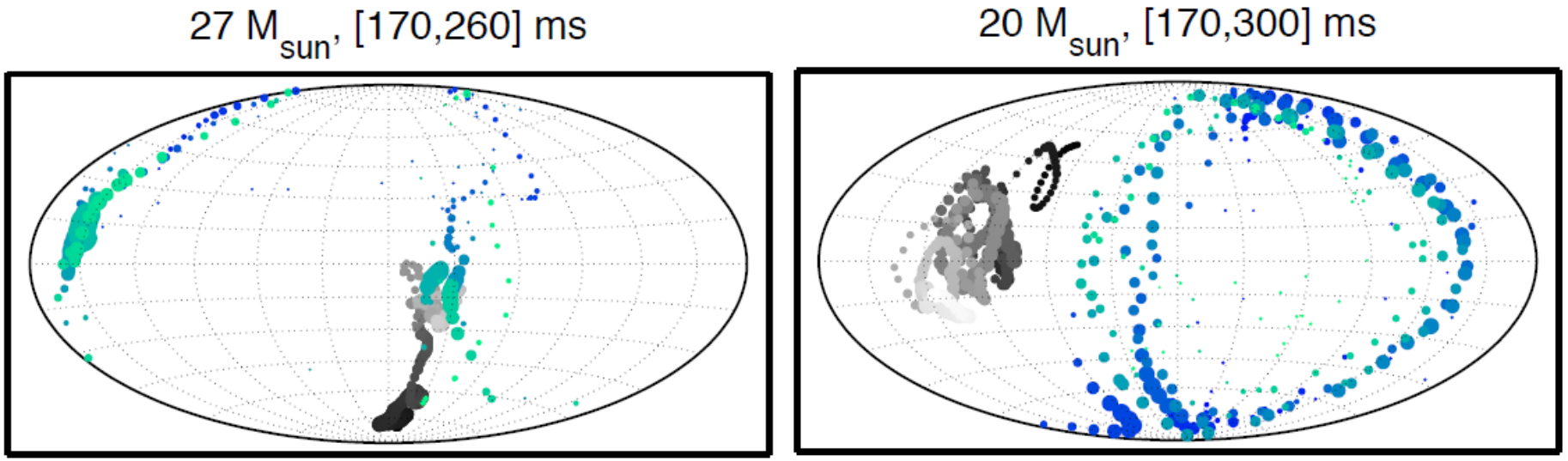
Drifting of LESA direction during first SASI episode



Tamborra, Hanke, Janka, et al., arXiv:1402.5418

LESA and SASI Effects in Neutrino Emission

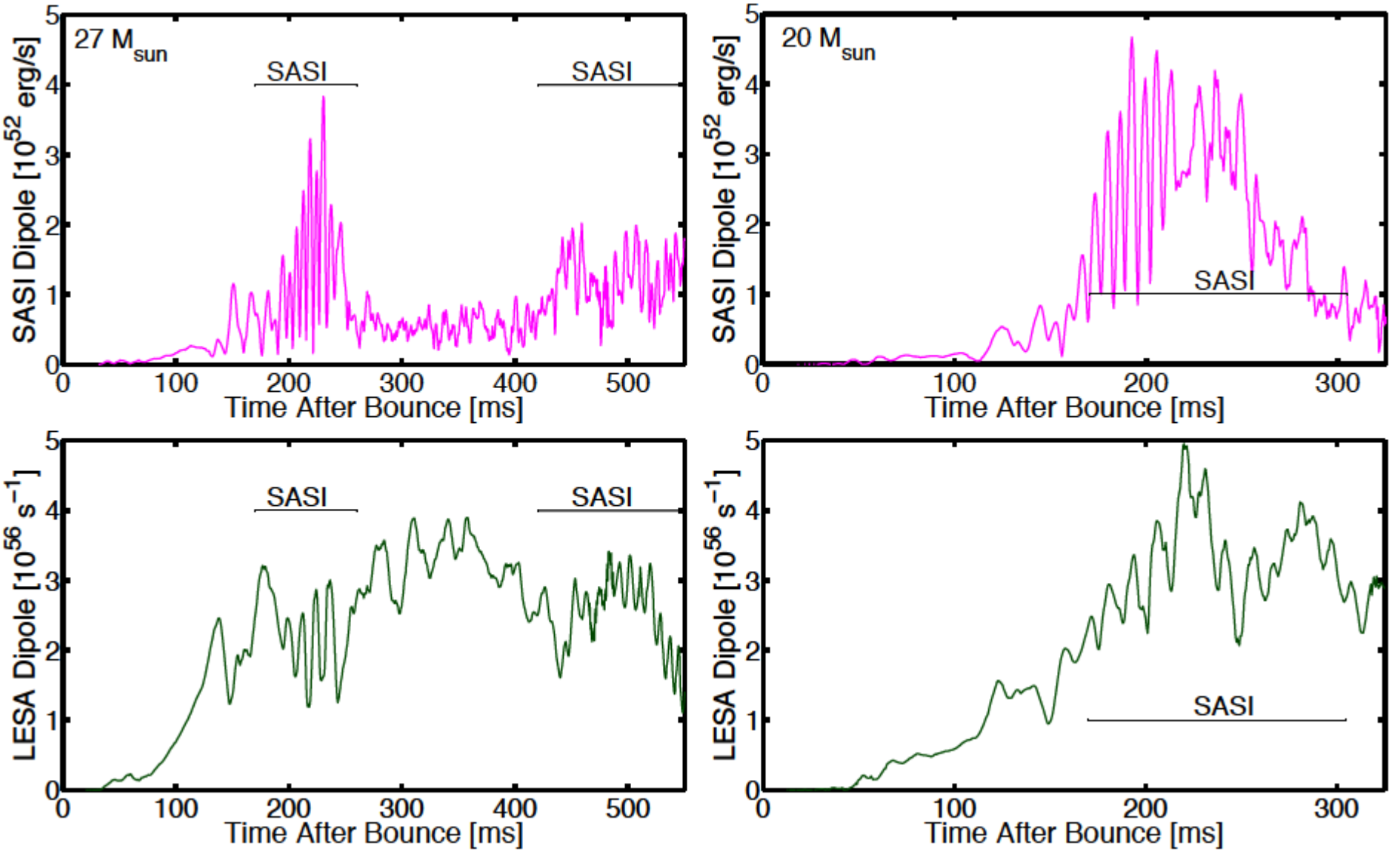
Drifting of LESA direction during first SASI episode



Tamborra et al., arXiv:1406.0006

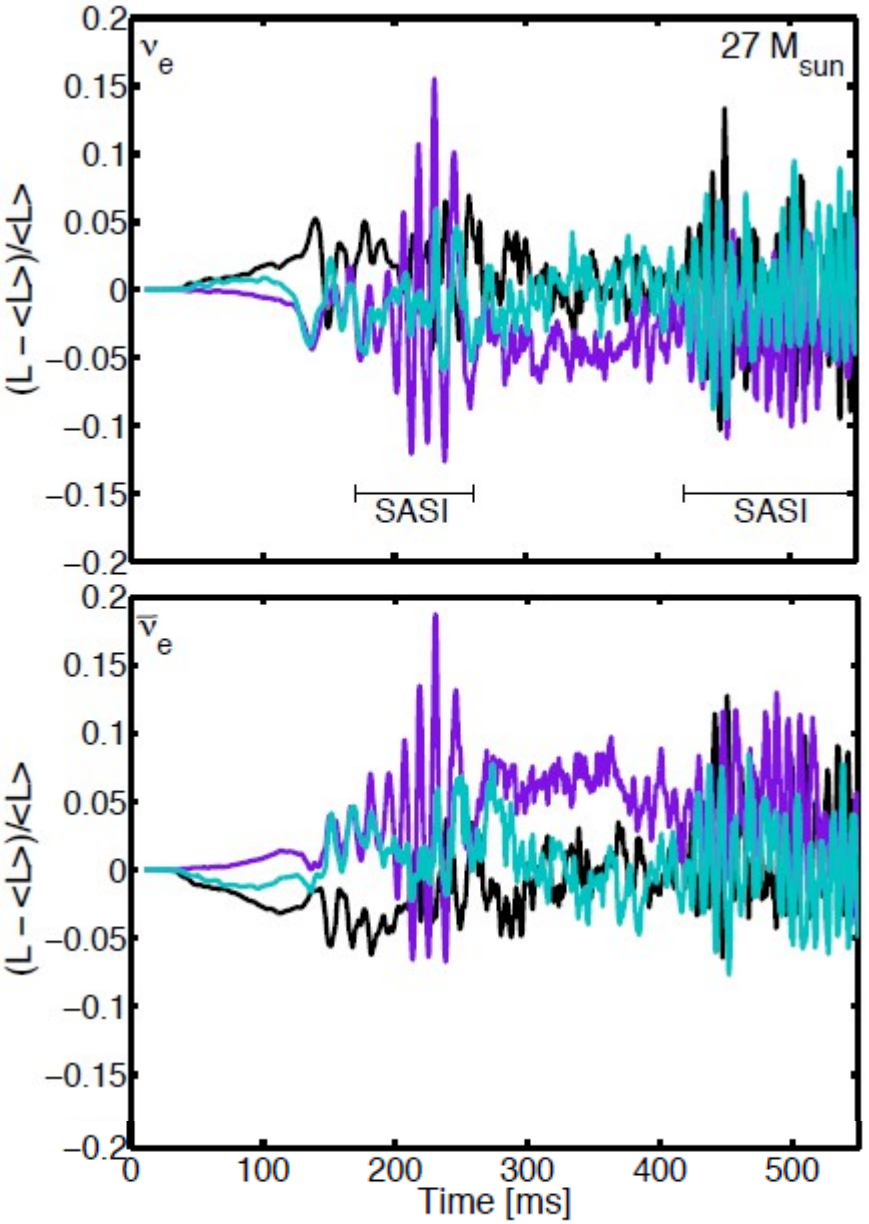
LESA and SASI Effects in Neutrino Emission

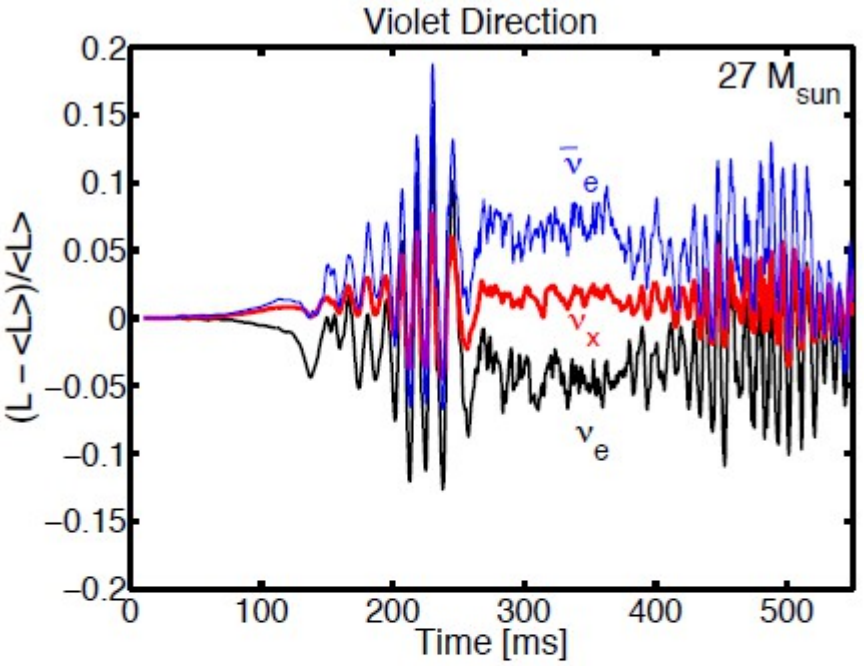
Time evolution of dipole amplitudes of total neutrino luminosity and of lepton-number emission



Tamborra et al., arXiv:1406.0006

LESA and SASI Effects in Neutrino Emission

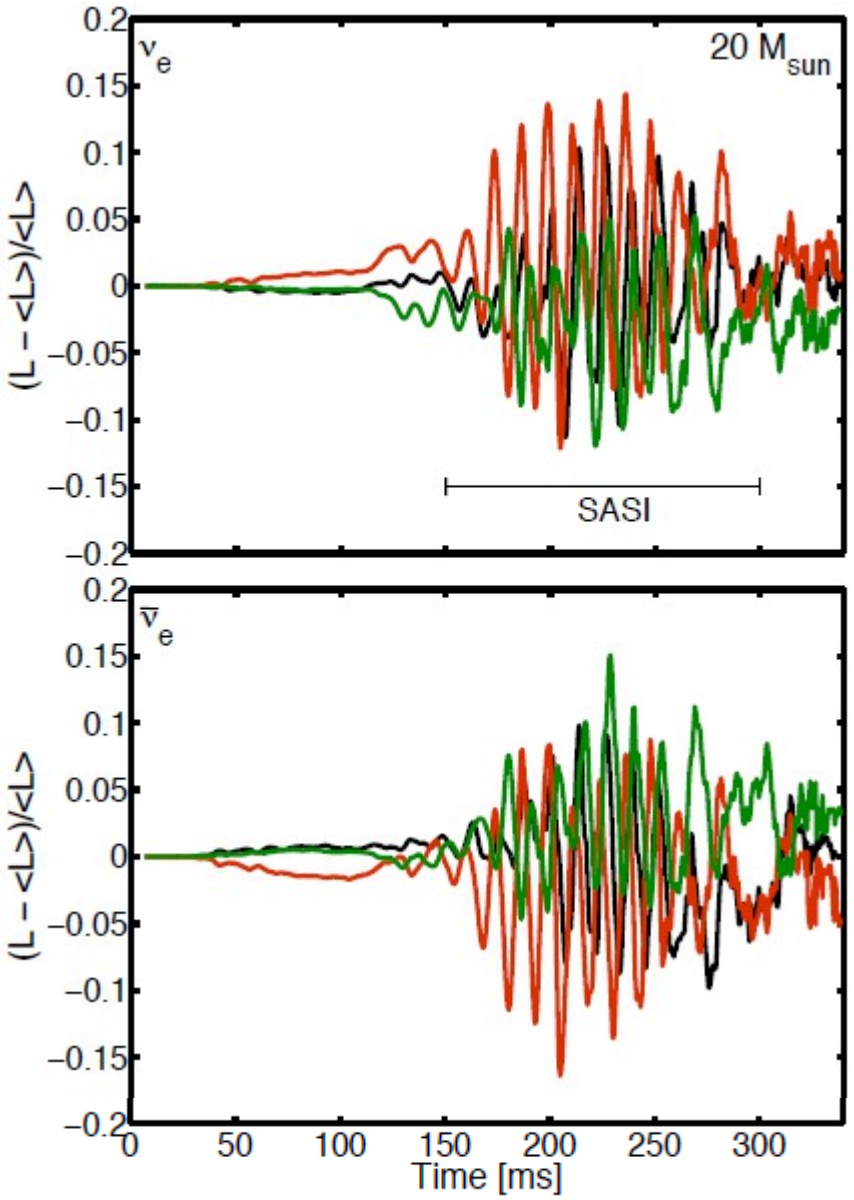


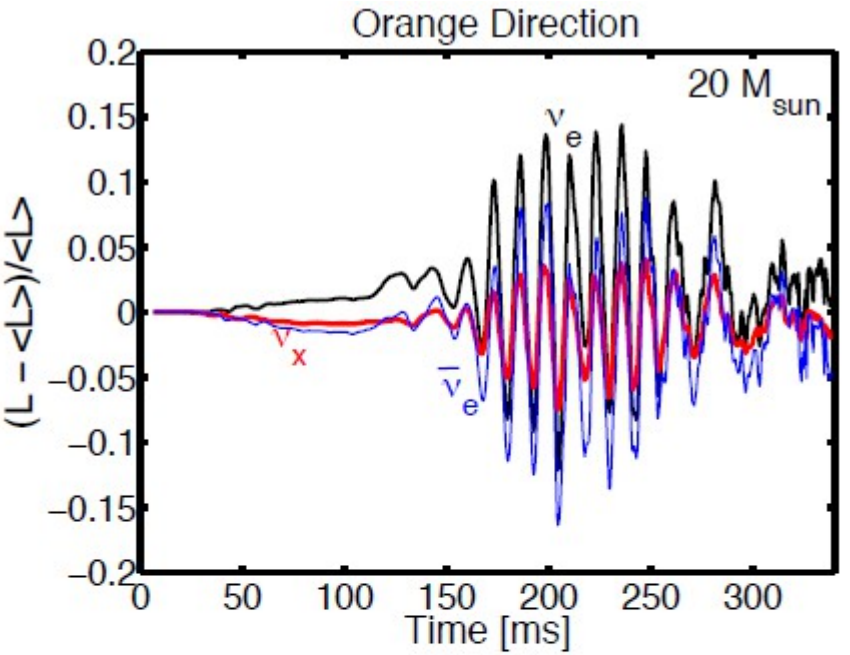


Modulation of neutrino signal of 27 Msun model in plane of SASI sloshing and spiralling

Tamborra et al., arXiv:1406.0006

LESA and SASI Effects in Neutrino Emission





Modulation of neutrino signal of 20 Msun model in plane of SASI sloshing and spiralling

Tamborra et al., arXiv:1406.0006

Consequences of the New Instability

- Anisotropic nucleosynthesis conditions
- Anisotropic neutrino-flavor oscillations
- NS kicks; some 10 km/s, potentially 100–200 km/s