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Neνtrino 2018

XXVIII International Conference on Neutrino Physics and Astrophysics

Heidelberg, 4–9 June, 2018

Neutrino-driven Explosions in 3D Supernova Simulations

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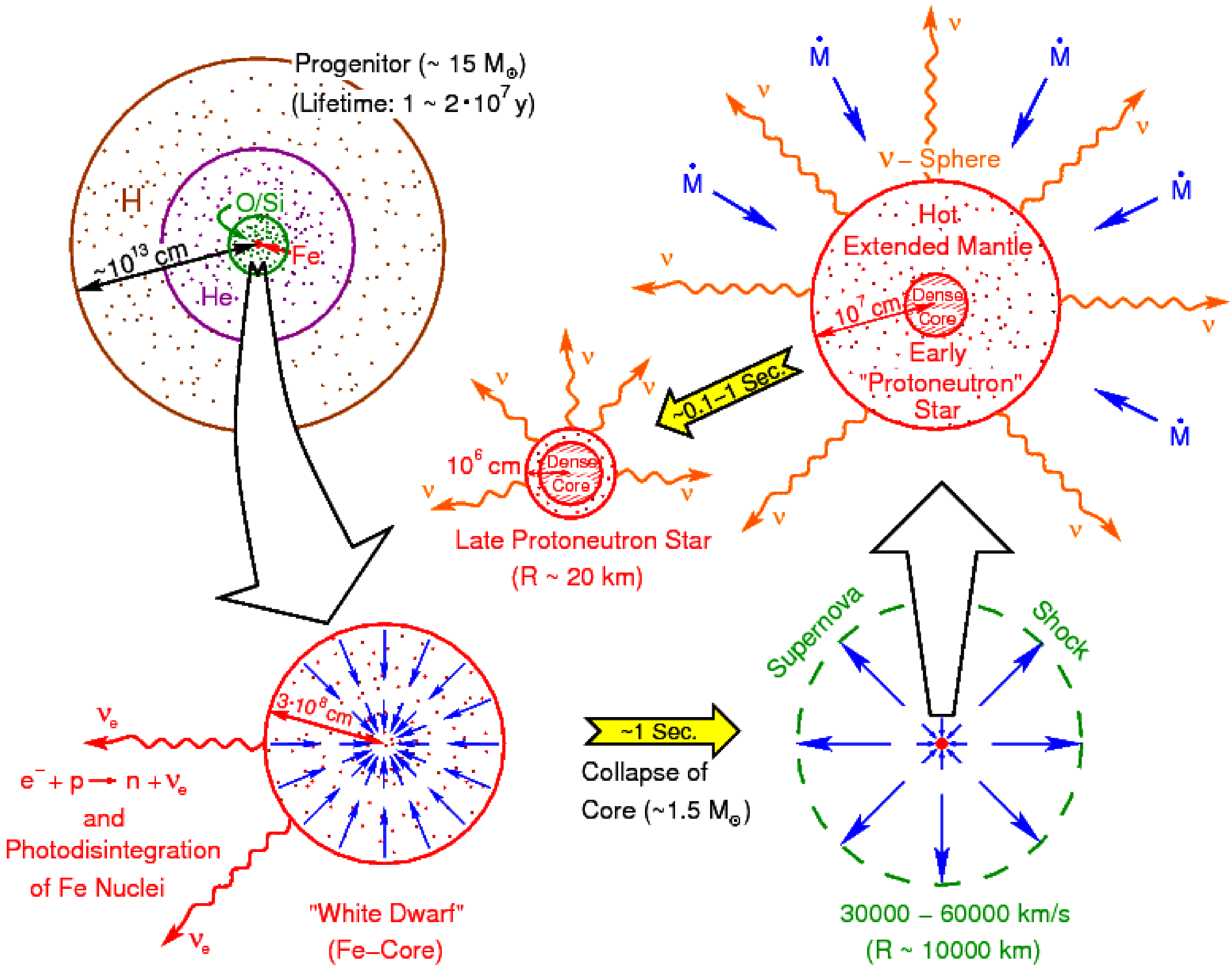
Hans-Thomas Janka
for the Team

COCO2CASA

Stellar Collapse and Supernova Stages

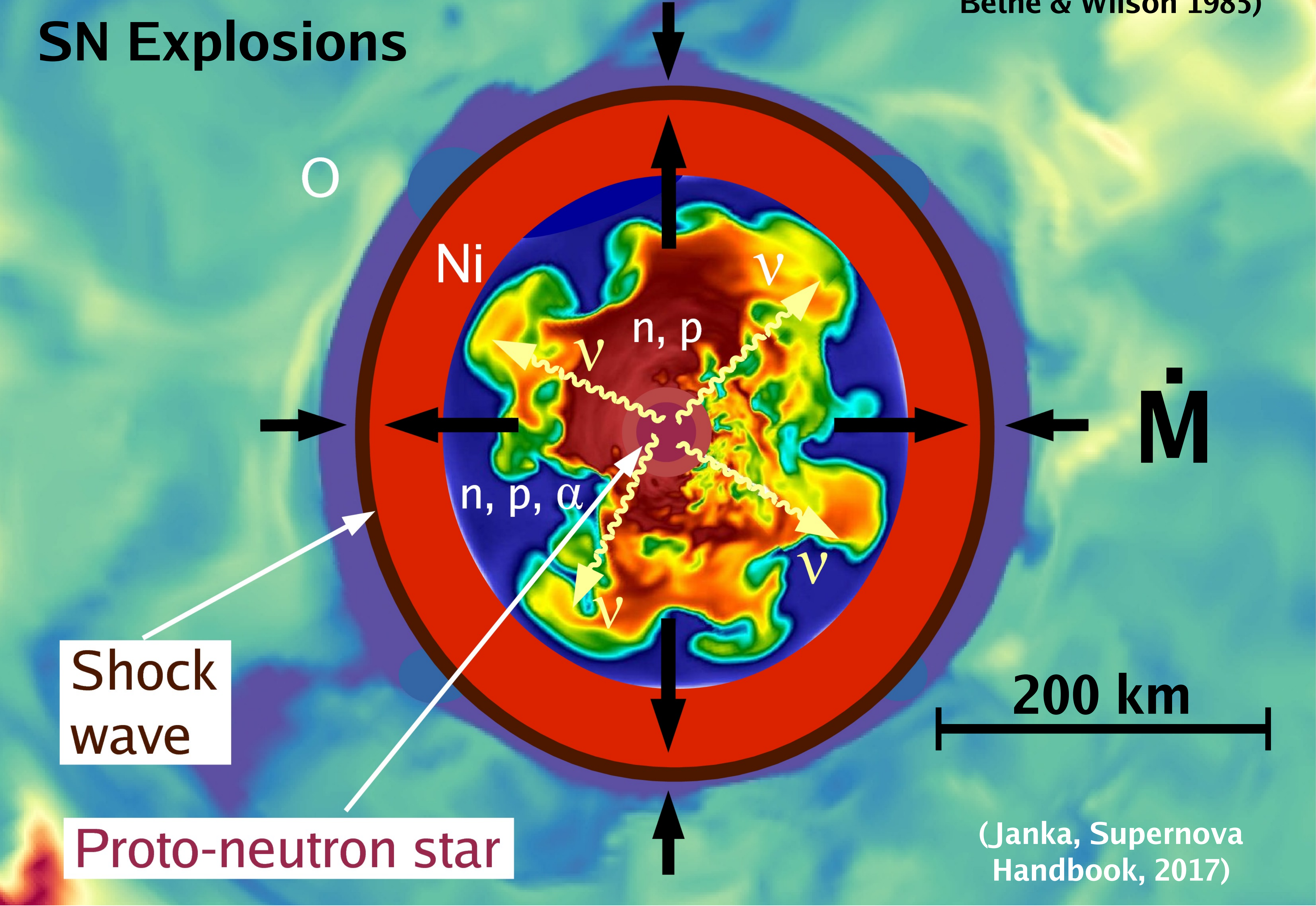


adapted from A. Burrows (1990)

Neutrino-driven SN Explosions

Shock revival

(Colgate & White 1966; Bethe & Wilson 1985)

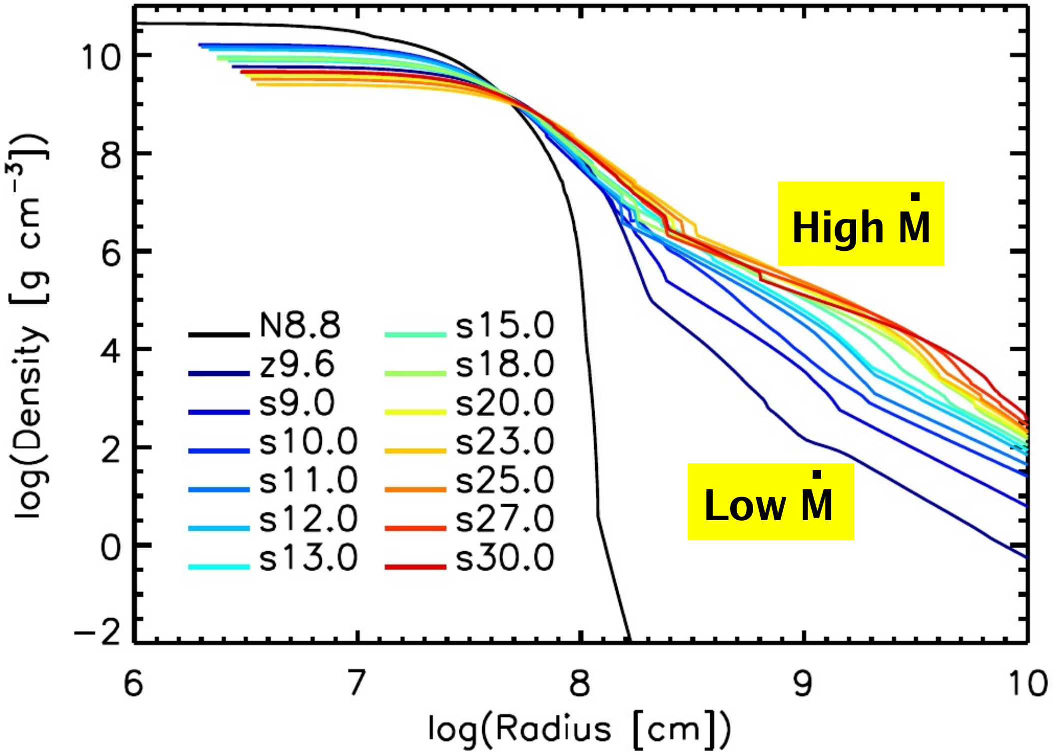


Shock wave

Proto-neutron star

(Janka, Supernova Handbook, 2017)

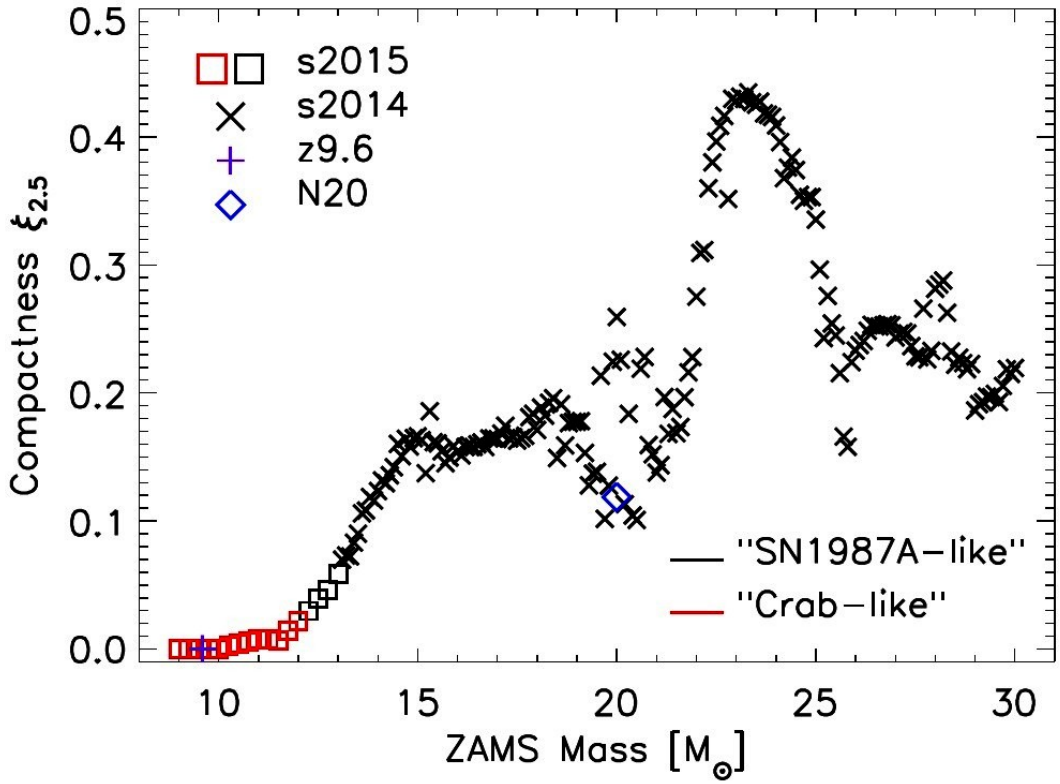
Progenitors: Density Profiles



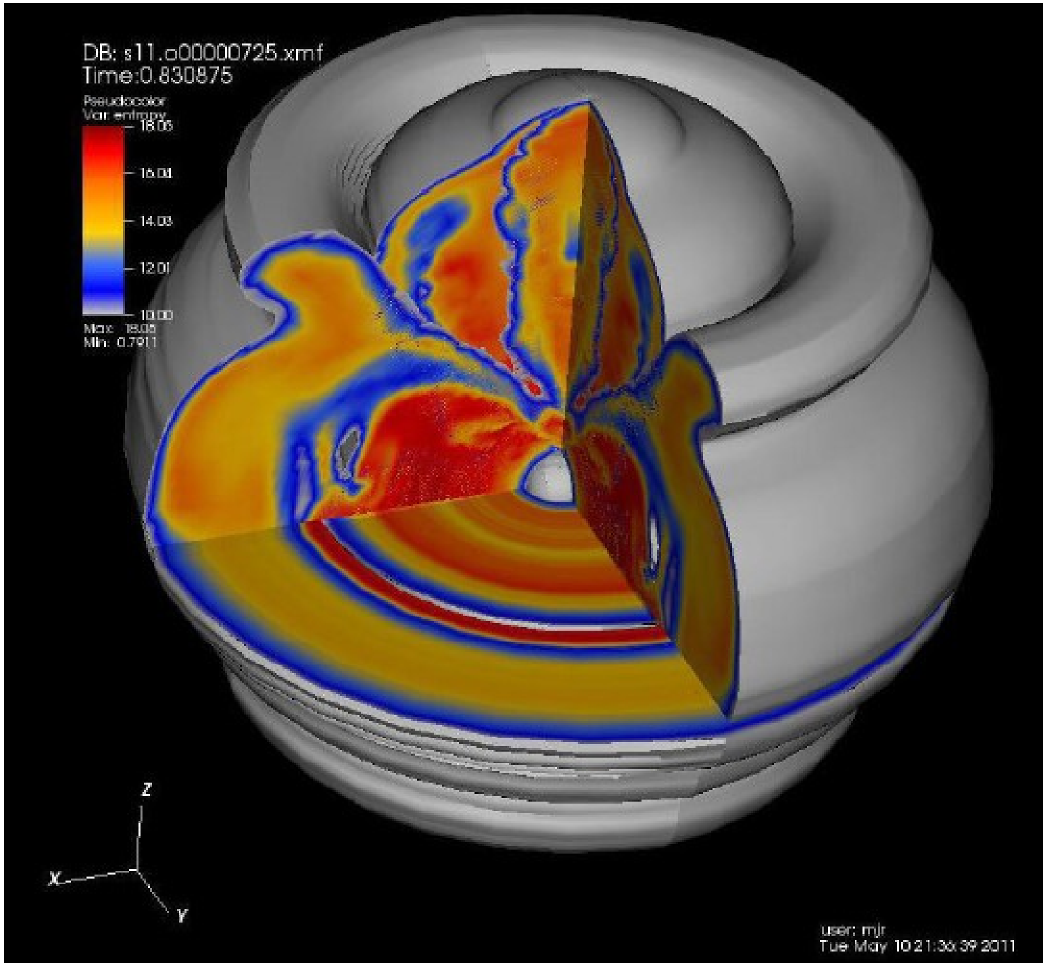
$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}},$$

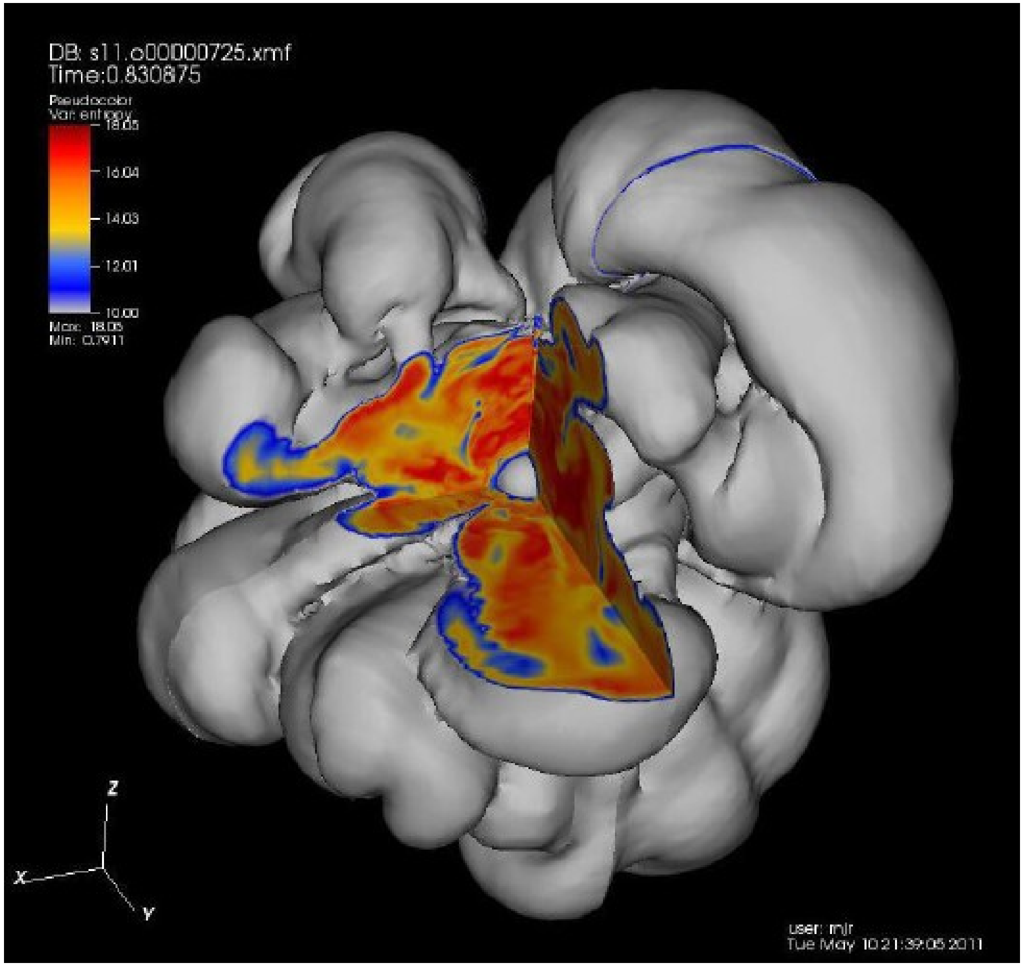
mass $M = 2.5\ M_\odot$

O'Connor & Ott, ApJ 730:70 (2011)



2D and 3D Morphology



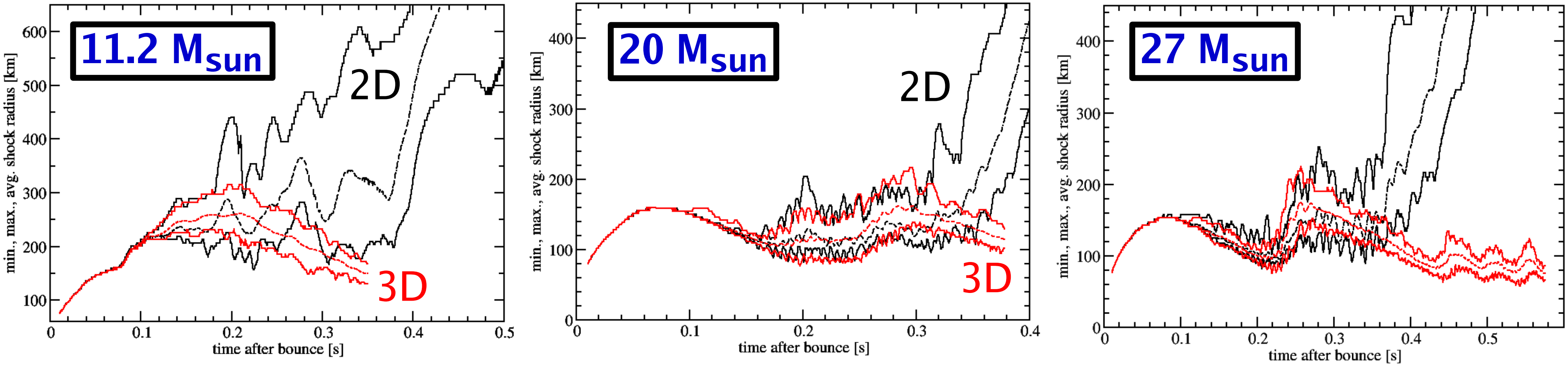


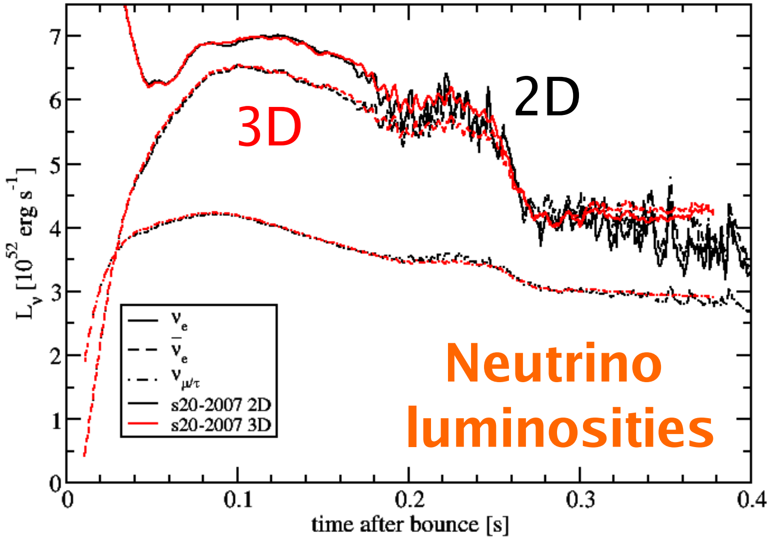
(Images from Markus Rampp, RZG)

2D vs. 3D Core-Collapse SN Explosion Models

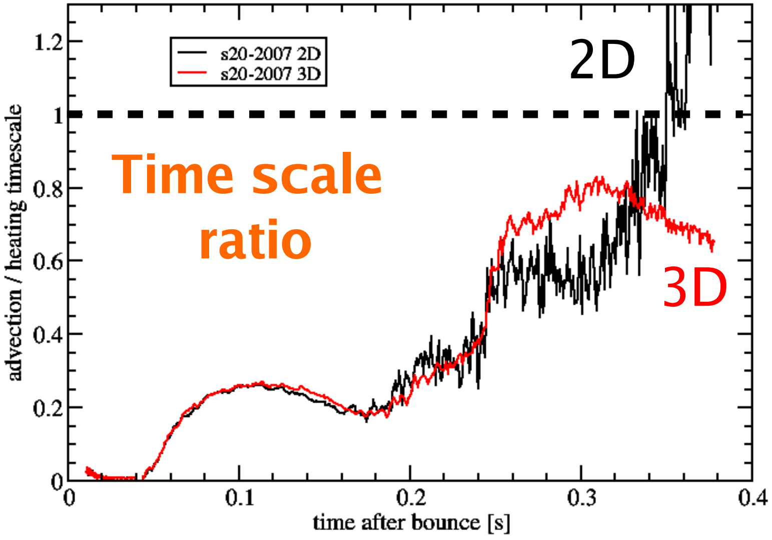
11.2, 20, 27 M_{sun} progenitors (WH 2007)

Shock radii (max., avg., min.) vs. time





Neutrino luminosities



Time scale ratio

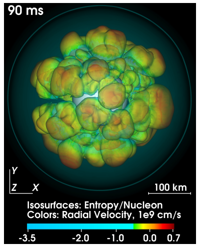
Florian Hanke, PhD project (2014)

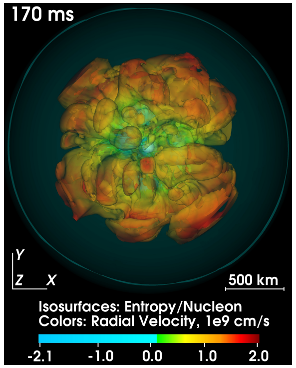
3D Core-Collapse SN Explosion Models

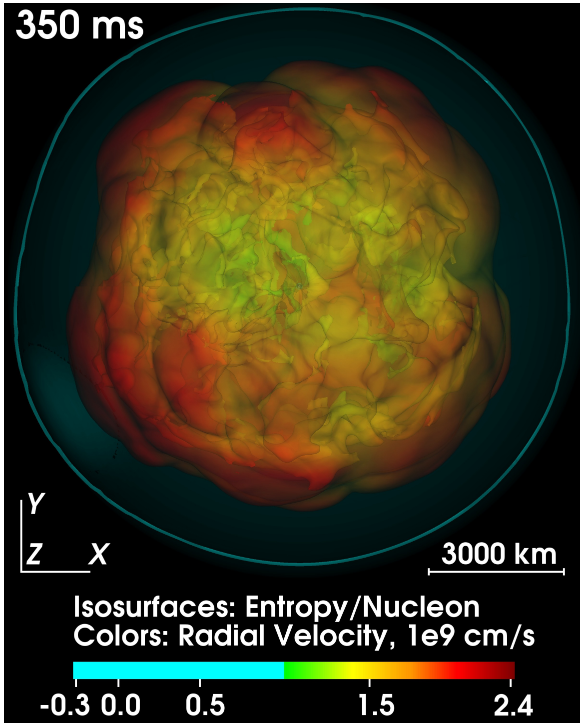
9.6 $M_{\rm sun}$ (zero-metallicity) progenitor (Heger 2010)

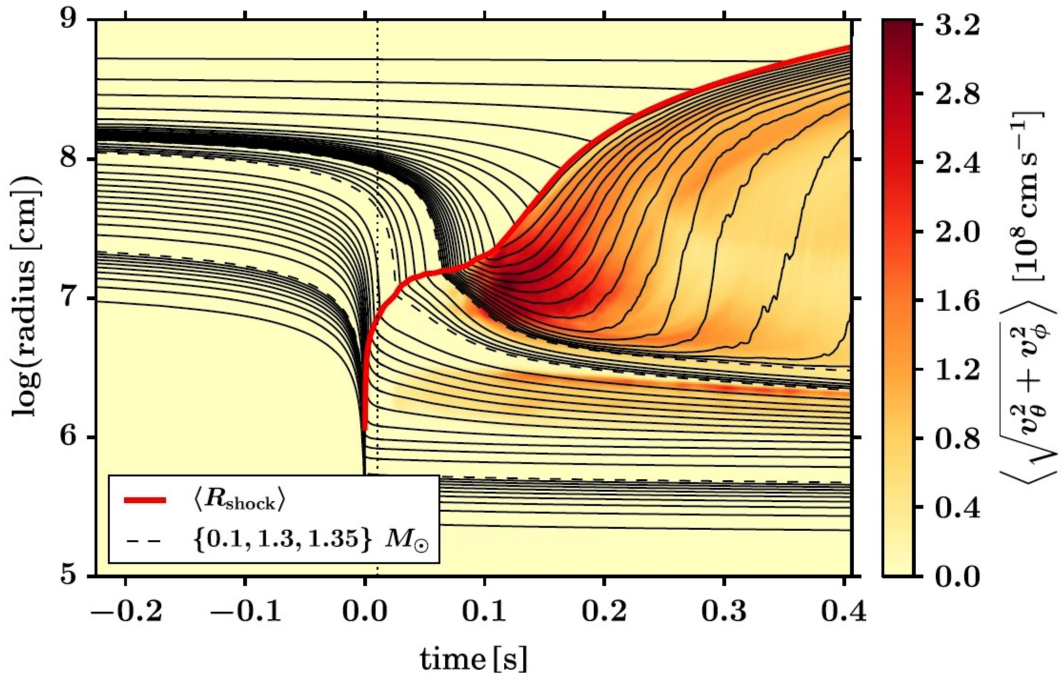
Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.

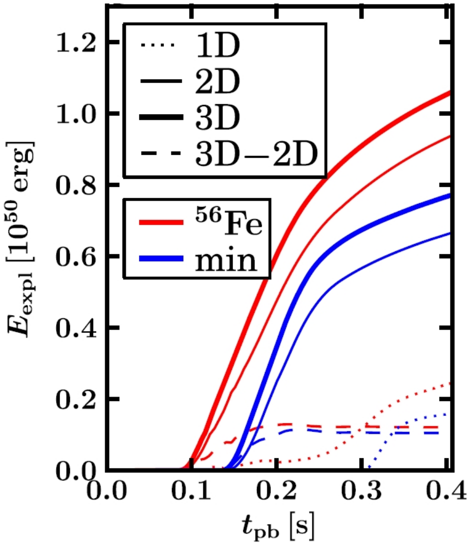
Melson et al.,
ApJL 801 (2015) L24

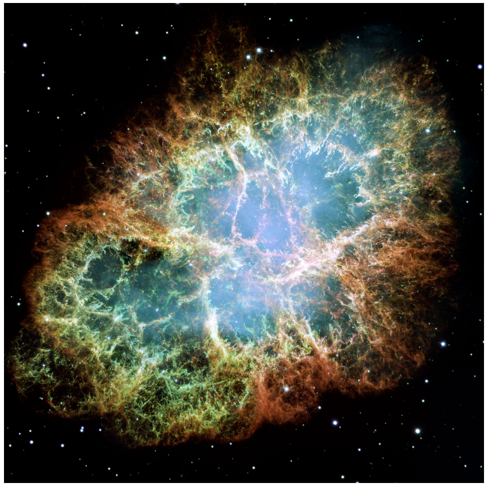












3D Core-Collapse SN Explosion Models

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

Explore uncertain aspects of microphysics in neutrinospheric region.

Example: strangeness contribution to nucleon spin, affecting axial-vector neutral-current scattering of neutrinos on nucleons.

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

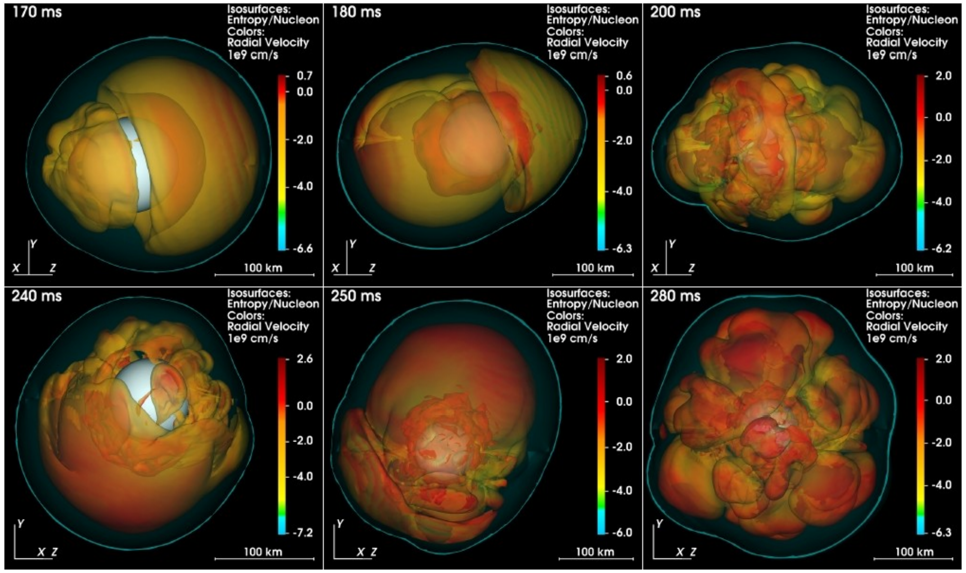
$$\sigma_0^t = \int_{4\pi} d\Omega \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2 + 5c_a^2\right). \qquad (2)$$

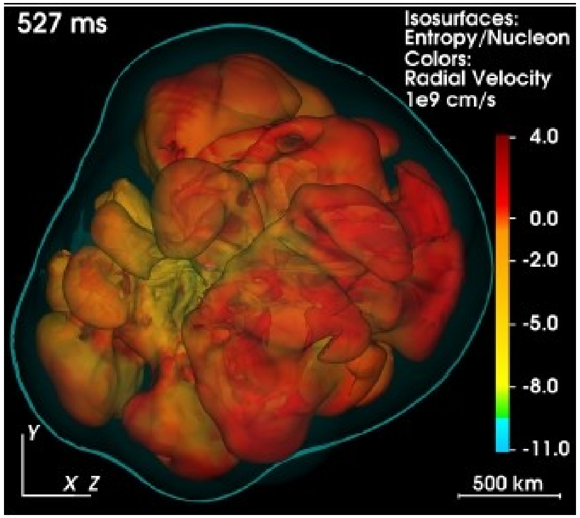
$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right), \qquad (3)$$

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

Currently favored theoretical & experimental (HERMES, COMPASS) value:
$g_a^s \sim -0.1$

Effective reduction of neutral-current neutrino-nucleon scattering by ~15%.



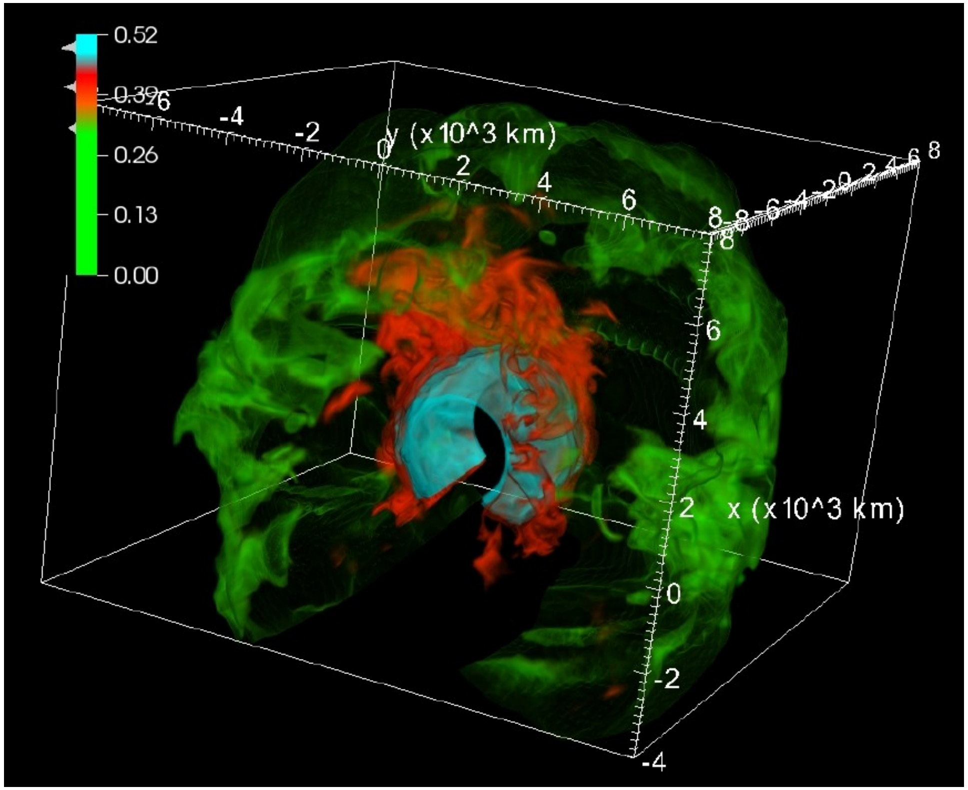


Melson et al., ApJL 808 (2015) L42

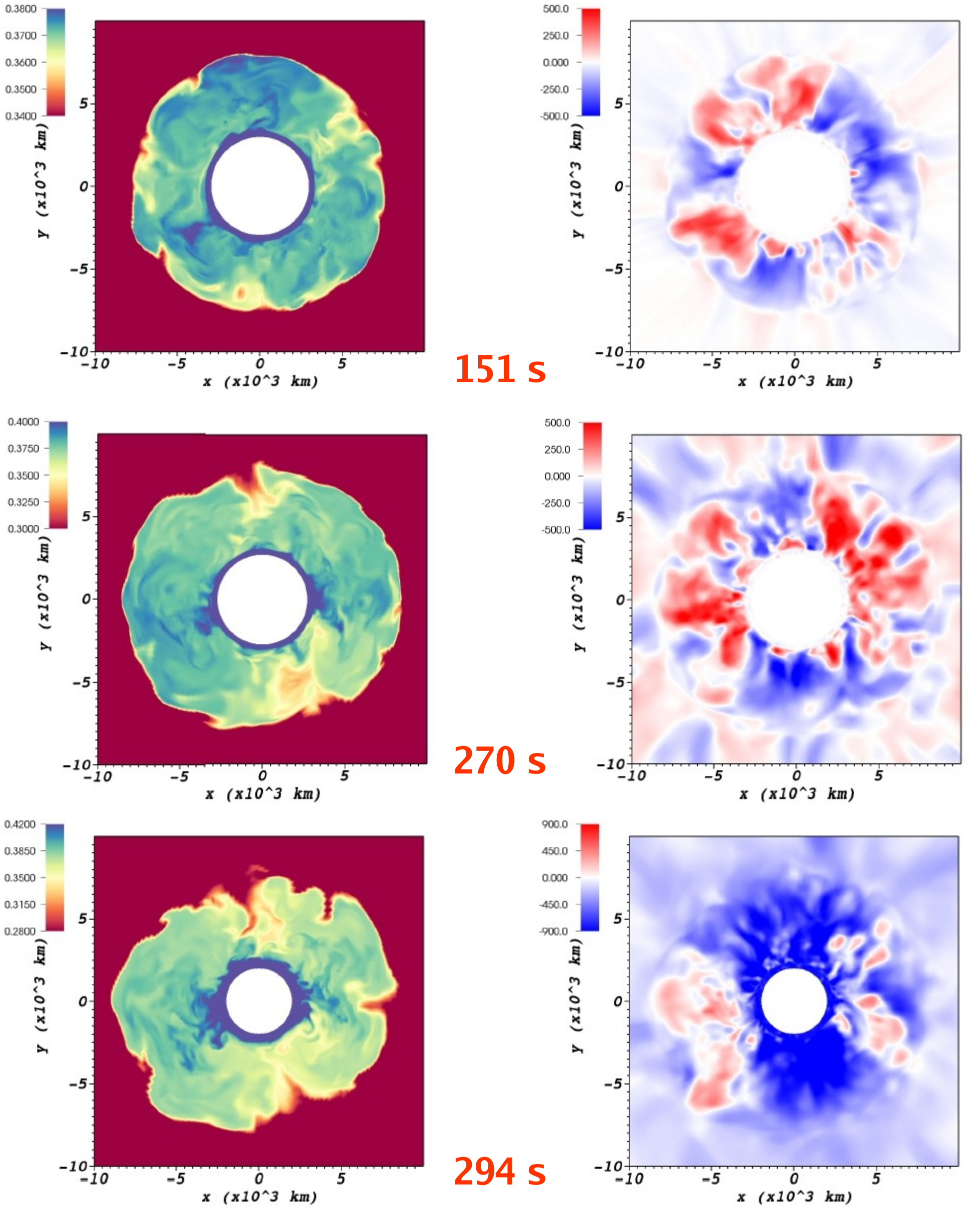
3D Core-Collapse SN Progenitor Model

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)

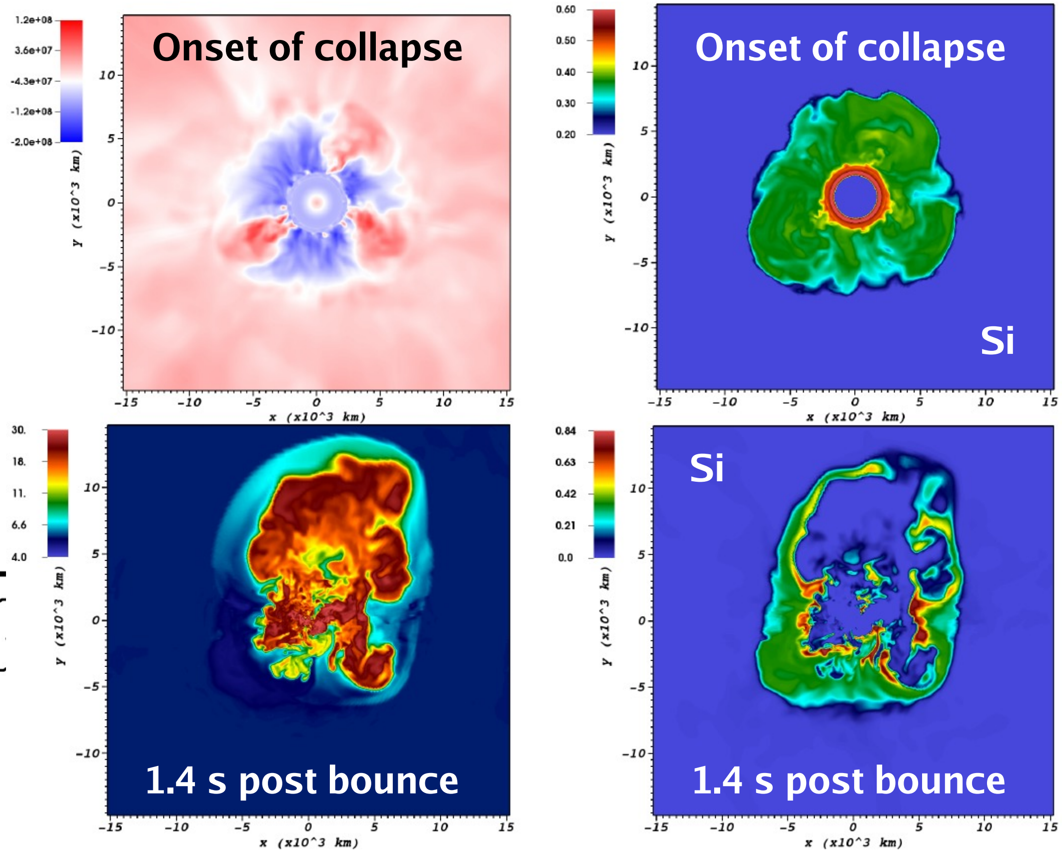


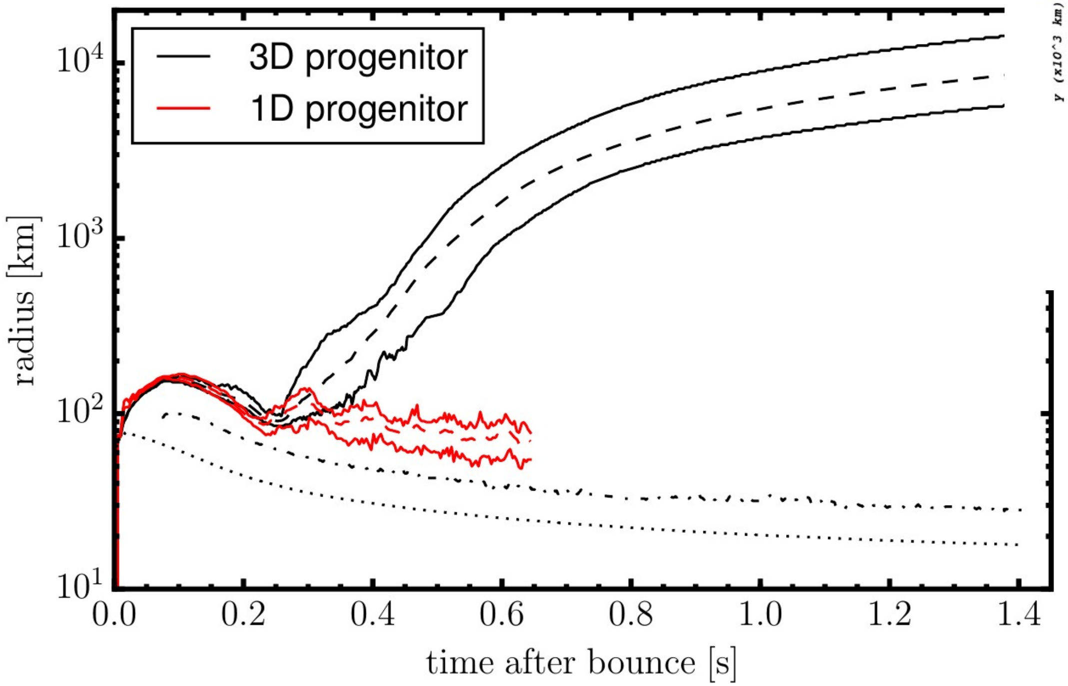
3D Core-Collapse SN Explosion Model

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 thus reduces the critical 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 CCSN Explosion Model with Rotation

15 M_{sun} rotating progenitor (Heger, Woosley & Spruit 2005)

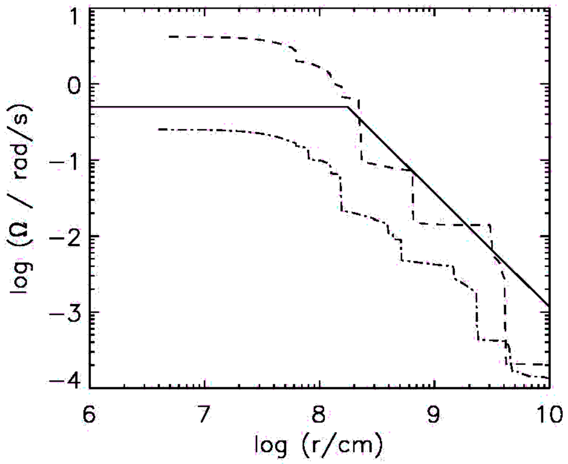
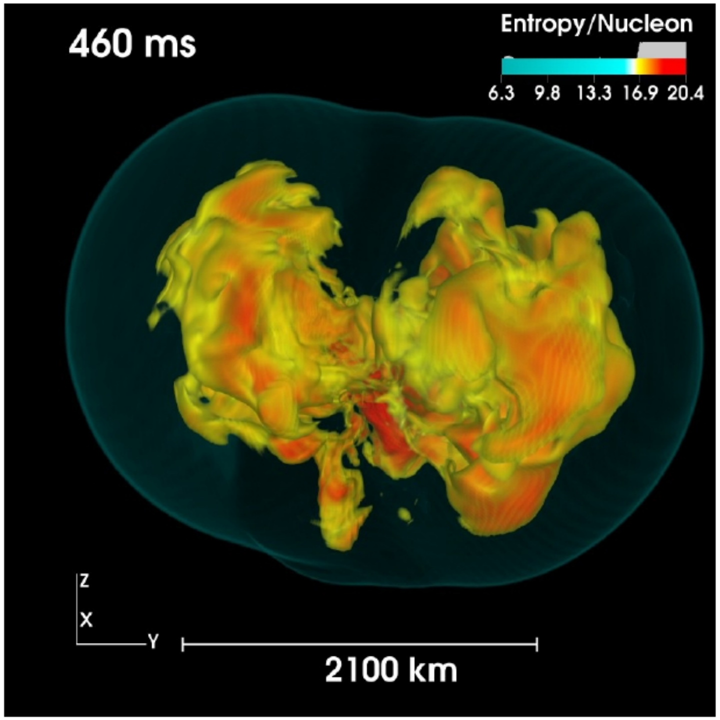
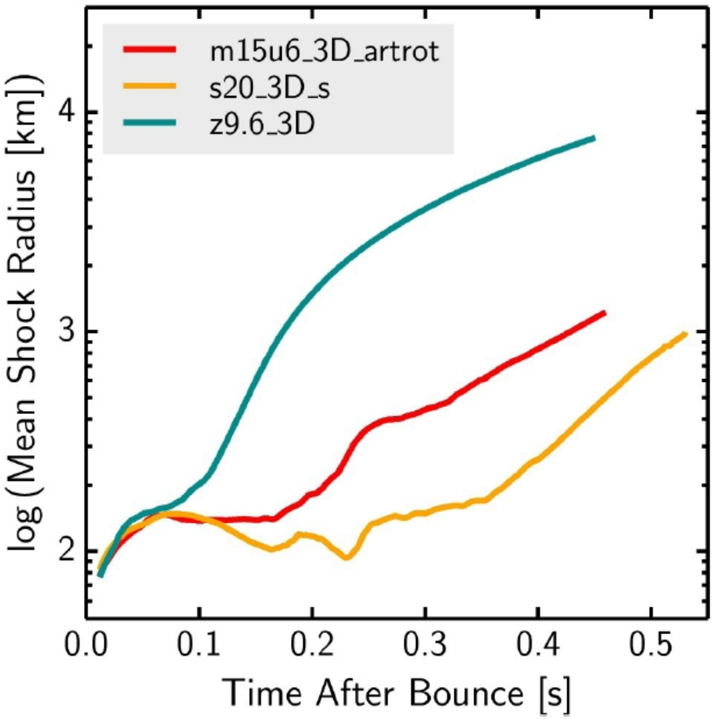


Fig. 1.—Angular velocity Ω as a function of radius *r* for the rotating 15 $M_\odot$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_\odot$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid curve*).

Explosion occurs for angular velocity of Fe-core of 0.5 rad/s, rotation period of ~12 seconds (several times faster than predicted for magnetized progenitor by Heger et al. 2005). Produces a neutron star with spin period of ~1–2 ms.

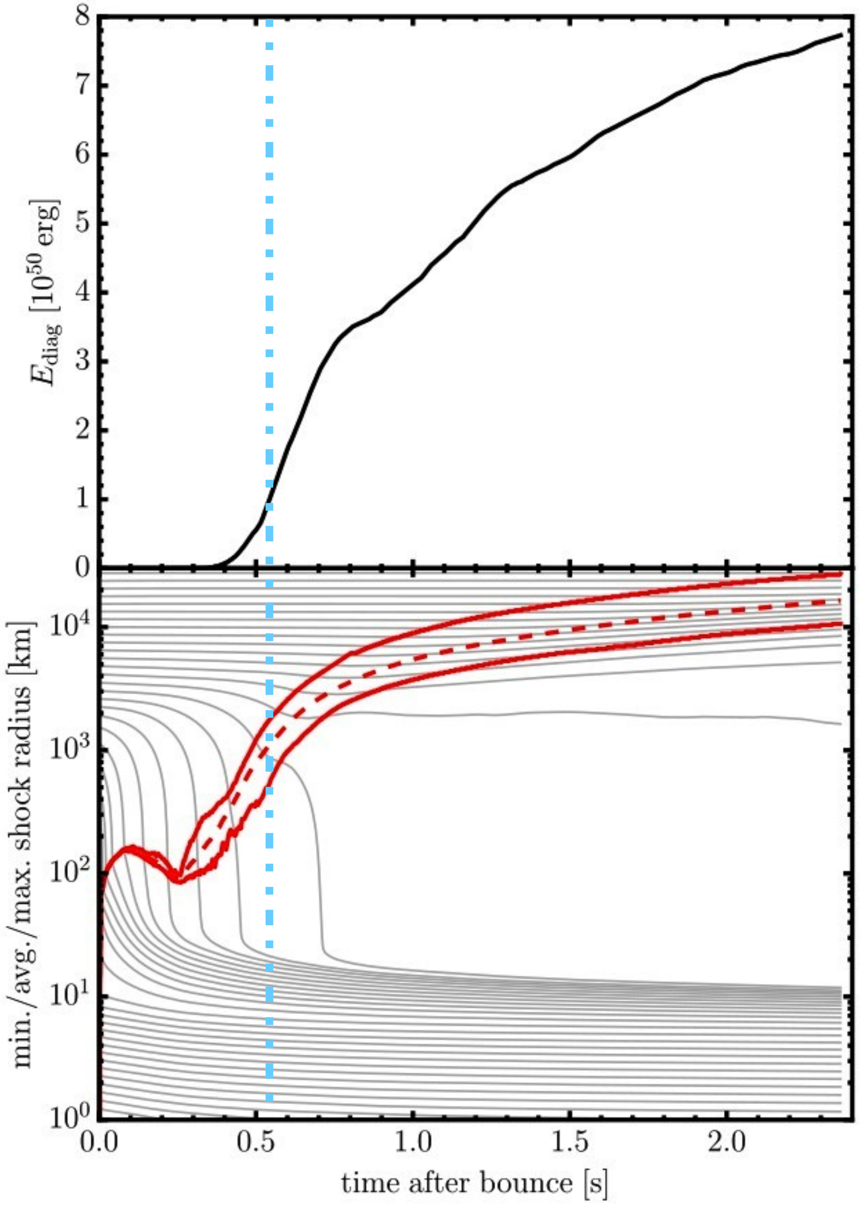




Janka, Melson & Summa, ARNPS 66 (2016);
Summa et al., ApJ 852 (2018) 28

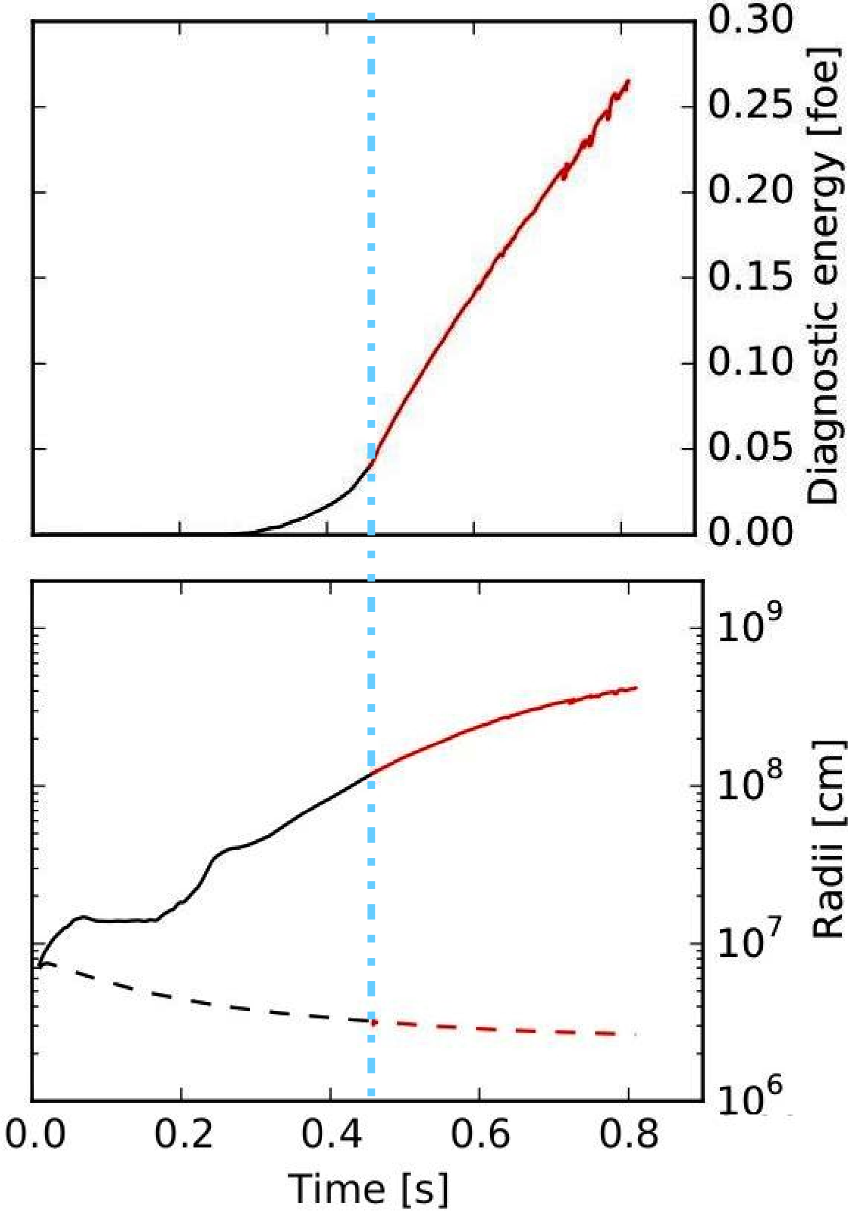
Explosion Energies for Neutrino-Driven Explosions in 3D

18 Msun explosion



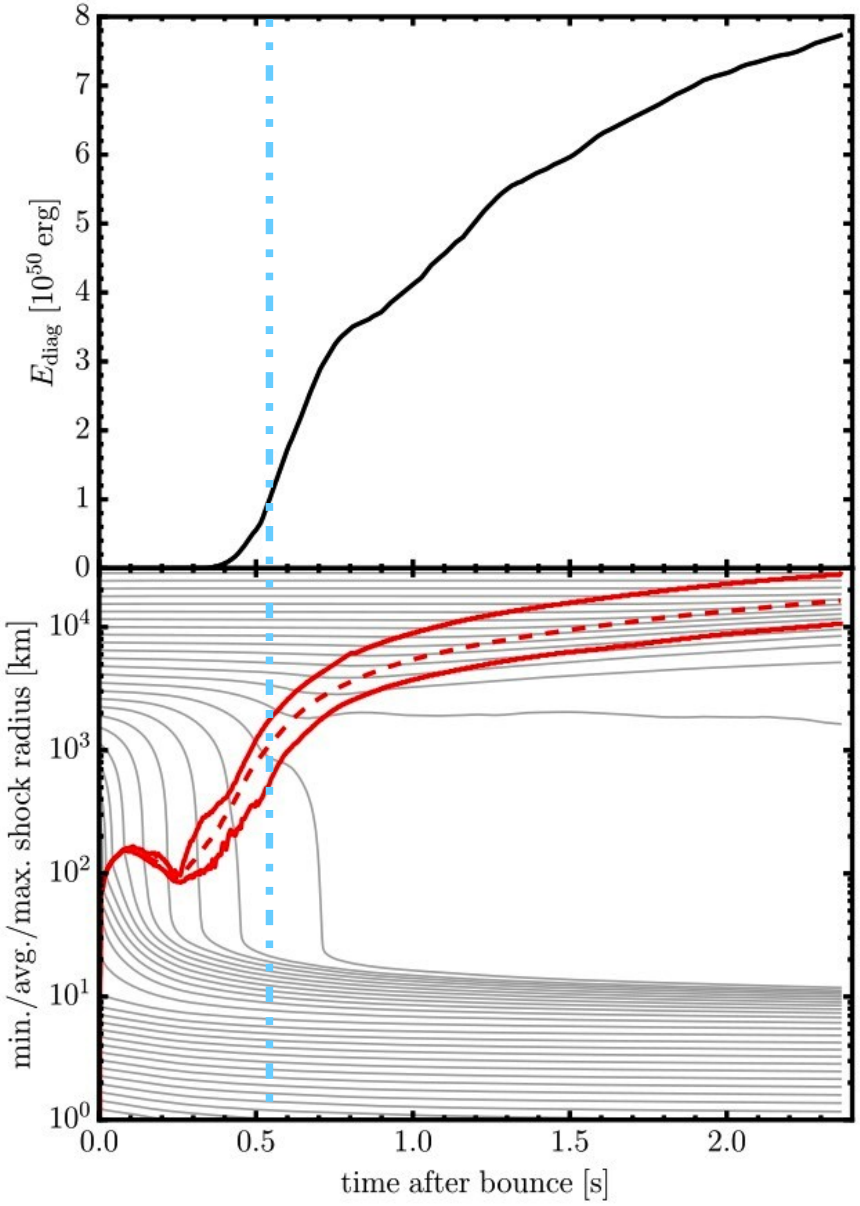
Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)

15 Msun explosion



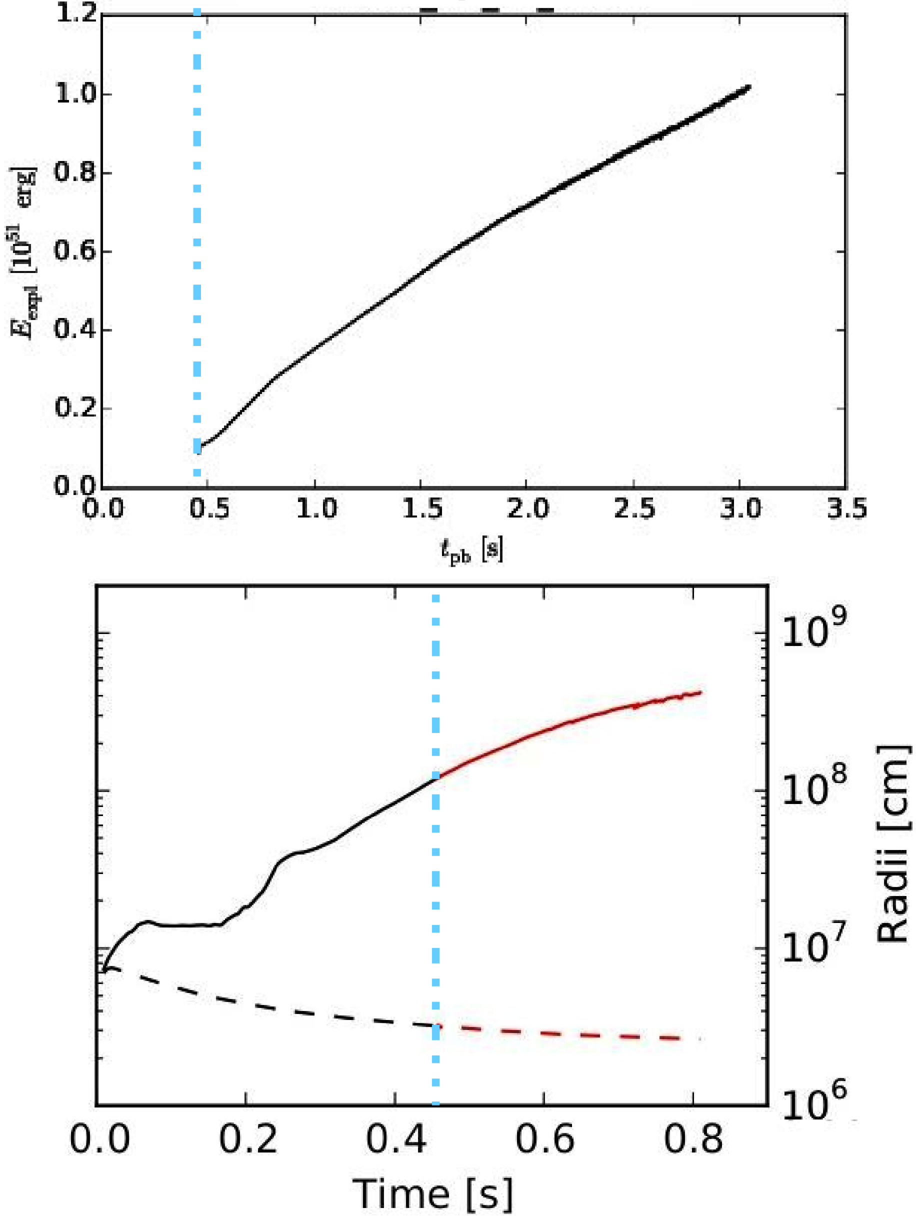
Explosion Energies for Neutrino-Driven Explosions in 3D

18 Msun explosion



Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)

15 Msun explosion



Universal Critical Neutrino Luminosity for Explosion

$$\left(L_\nu \langle E_\nu^2 \rangle\right)_{\rm crit} \propto \left(\dot{M} M\right)^{3/5} \xi_{\rm g}$$

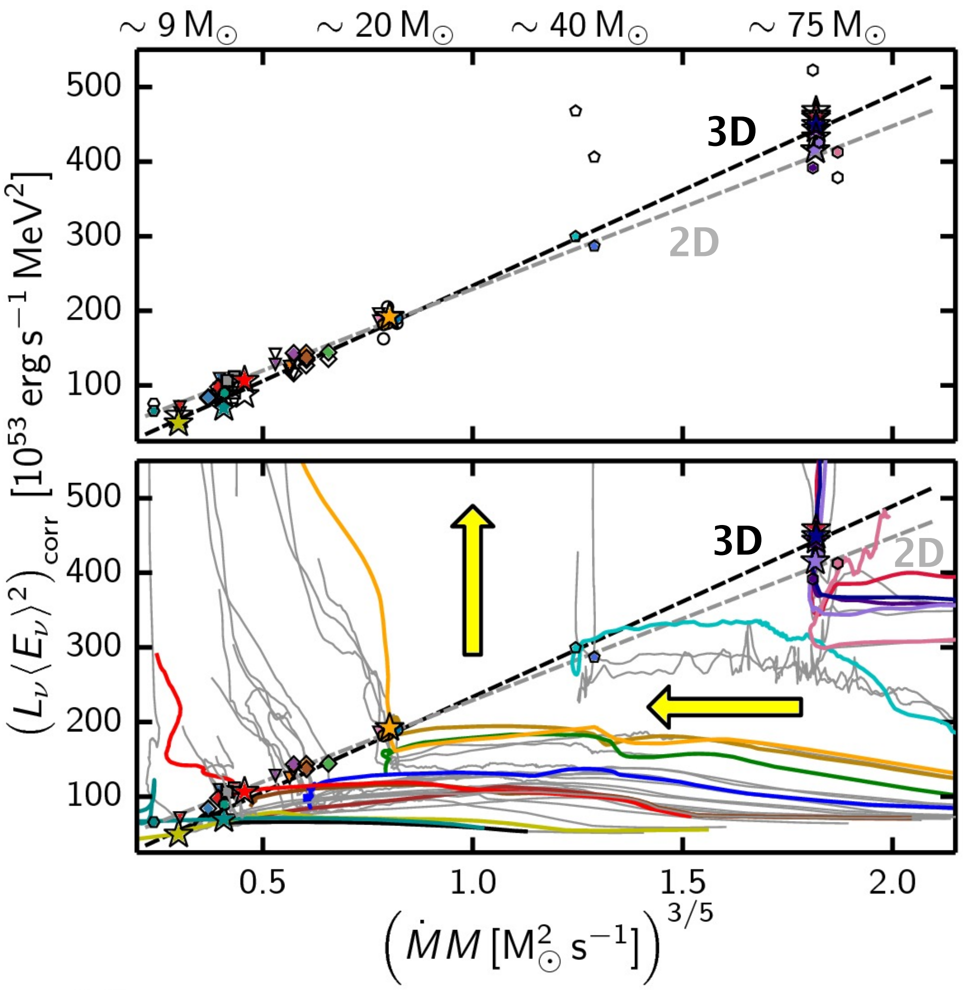
$$\xi_{\rm g} \equiv \left|\bar{e}_{\rm tot,g}\right|^{3/5} R_{\rm g}^{-2/5}\, \xi_{\rm turb}^{-3/5}\, \xi_{\rm rot}^{6/5}$$

$$\xi_{\rm turb} = 1 + \frac{4}{3}\langle {\rm Ma}^2 \rangle \geq 1$$

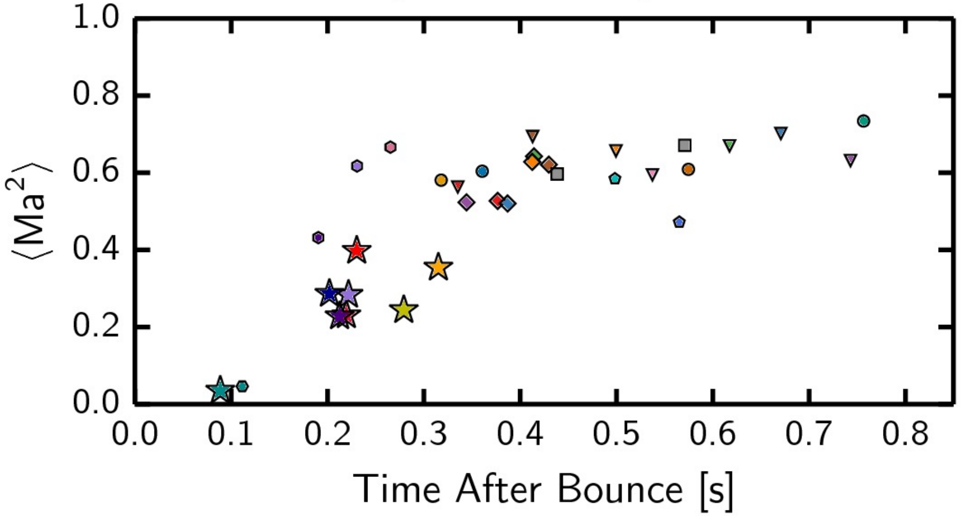
$$\bar{e}_{\rm tot,g} = \frac{E_{\rm tot,g}}{M_{\rm g}}$$

$$\xi_{\rm rot} = \sqrt{1 - \frac{j_0^2}{2GMR_{\rm s}}} \leq 1$$

$$\left(L_\nu \langle E_\nu^2 \rangle\right)_{\rm crit,corr} \equiv \frac{1}{\xi_{\rm g}/\xi_{\rm g}^*} \left(L_\nu \langle E_\nu^2 \rangle\right)_{\rm crit} \propto \left(\dot{M} M\right)^{3/5}$$



Summa et al., ApJ 852 (2018) 28



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)

Garching/QUB/Monash

(Melson+ ApJL 2015a,b; Müller 2015; Janka+ ARNPS 2016, Müller+ MNRAS 2017):

9.6, 11.2, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2002, 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)

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

- 2D models **with relativistic effects** (2D GR and approximate GR) **explode for “soft” EoSs**.
- 3D modeling has begun. **3D differs from 2D in many aspects, explosions are more difficult than in 2D.**

- **M < 10 M_{sun} stars explode in 3D.**
- **First 3D explosions of 11–27 M_{sun} progenitors**
  (with rotation, 3D progenitor perturbations or slightly modified neutrino opacities).
- **Explosion energy can take several seconds to saturate !**

- 3D simulations **still need higher resolution** for convergence.
- “Ray-by-ray” approximation agrees well with **full multi-D transport in 3D.**
- **Progenitors are 1D**, but shell structure and initial asymmetries in progenitor core can affect onset of explosion.
- **Uncertain/missing physics ? (Fast) neutrino flavor oscillations ?**

Muons in Hot Neutron-Star Medium

R. Bollig, THJ, G. Martinez-Pinedo, A. Lohs, C. Horowitz, & T. Melson

PRL 119, 242702 (2017); arXiv:1706.04630

- **Muon rest mass** much larger than electron rest mass:

$$m_\mu c^2 \approx 105.66\,\mathrm{MeV}$$

- **Therefore muons have traditionally been ignored in SN and NS-merger modeling.**
- **But: Temperatures T > 30 MeV and electron chemical potentials μ_e > 100 MeV can be reached easily.**

- **Consequence: muon abundance is not negligibly small.**

$$e^- + e^+ \longrightarrow \mu^- + \mu^+ \,, \quad \gamma + \gamma \longrightarrow \mu^- + \mu^+ ,$$

$$\nu_\ell + n \longleftrightarrow p + \ell^-$$

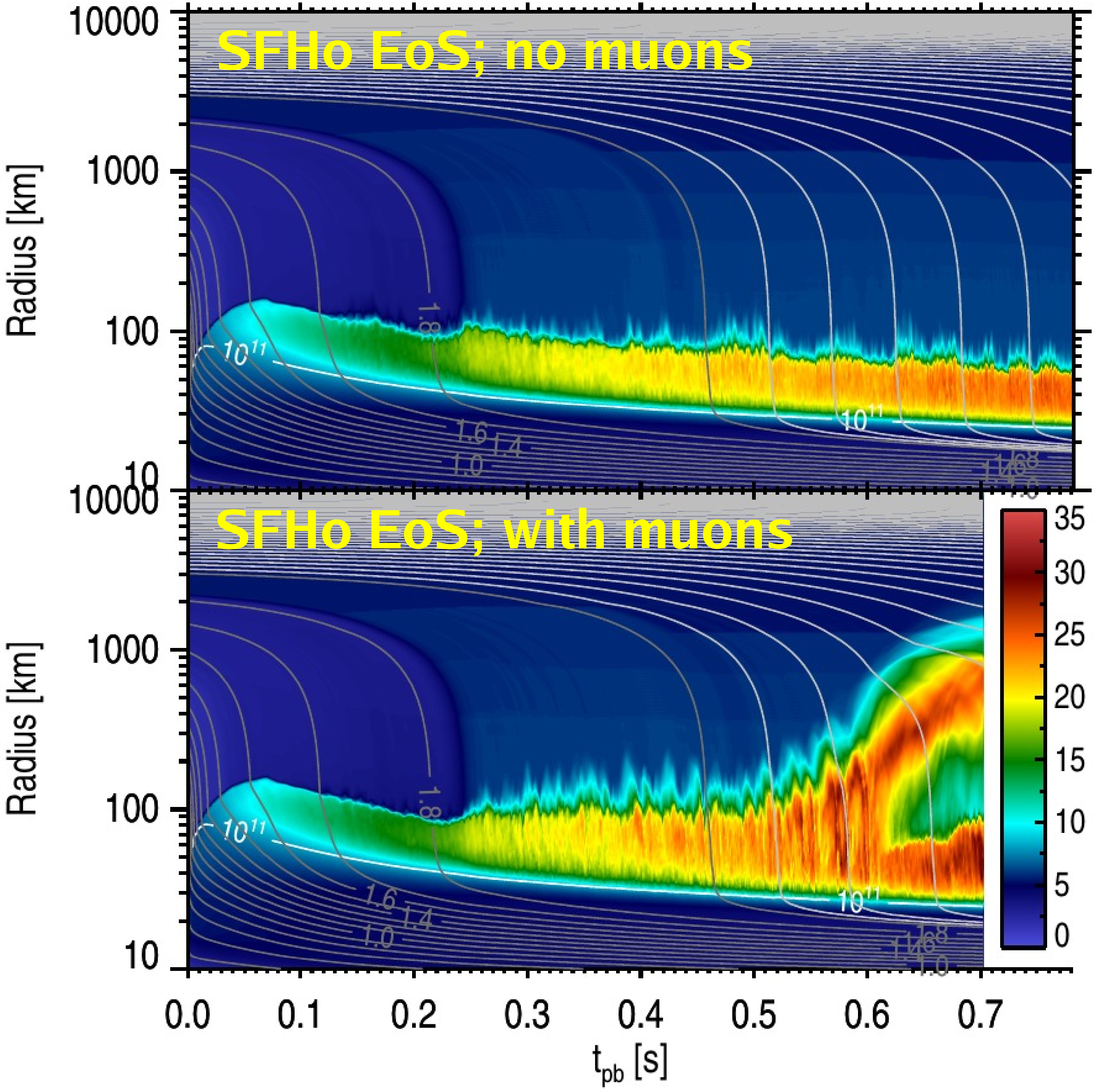
$$\bar{\nu}_\ell + p \longleftrightarrow n + \ell^+$$

Muons in Hot Neutron-Star Medium

- **Neutrino-driven supernova explosions are favored by appearance of muons!**

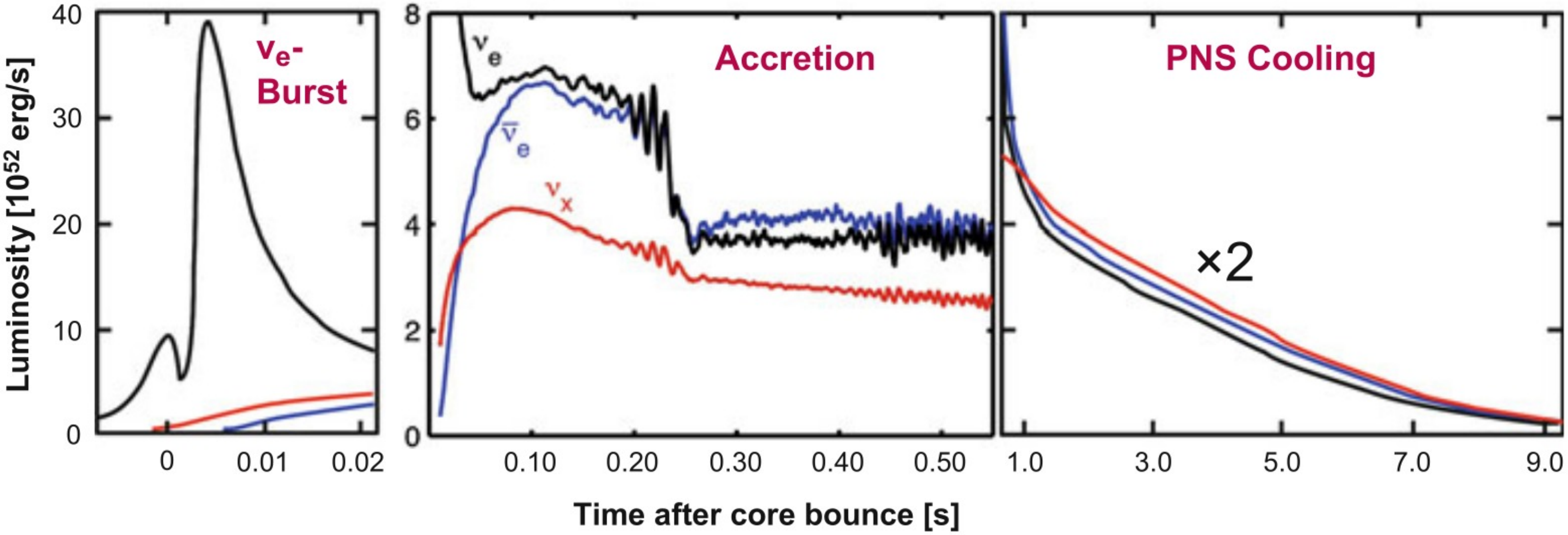
- **Here:**

  2D simulations of 20 M_{sun} non-rotating progenitor



Bollig et al., PRL 119, 242702 (2017)

Neutrino-Signal Features During (Pre-)explosion Phase

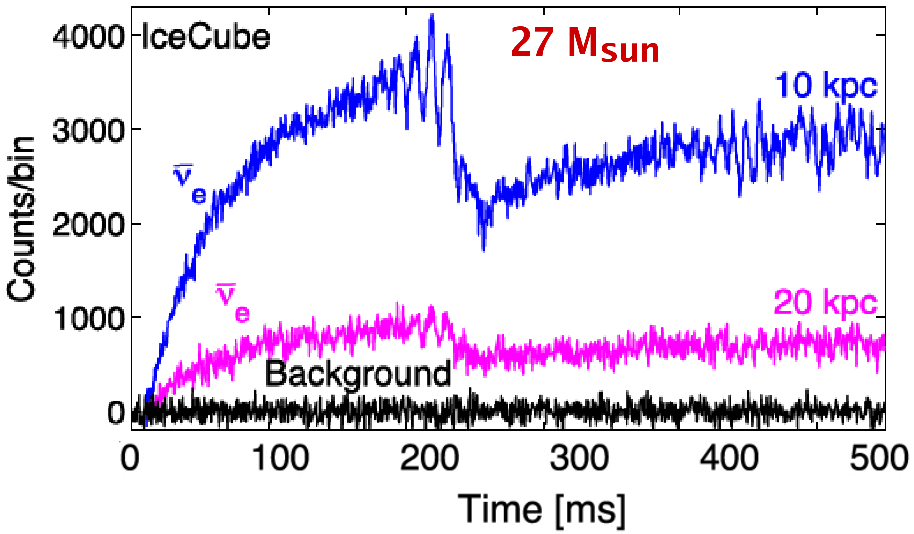


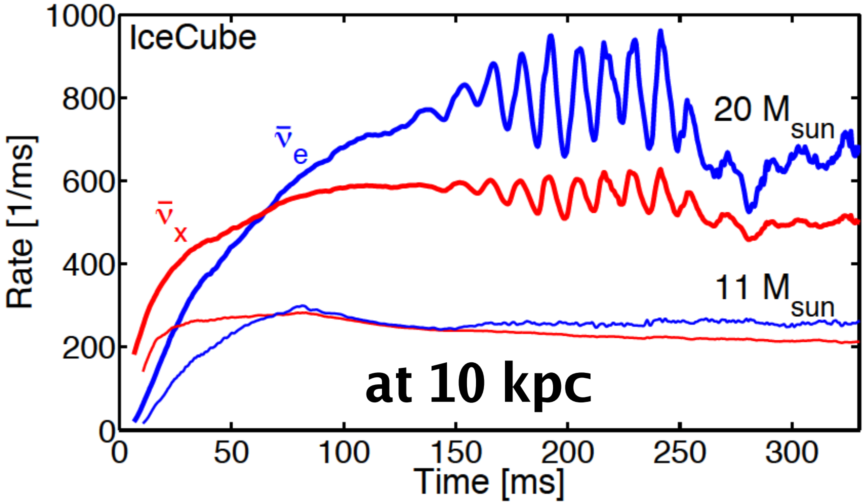
Janka H.-T., in: *Handbook of Supernovae* (2016); arXiv:1702.08825

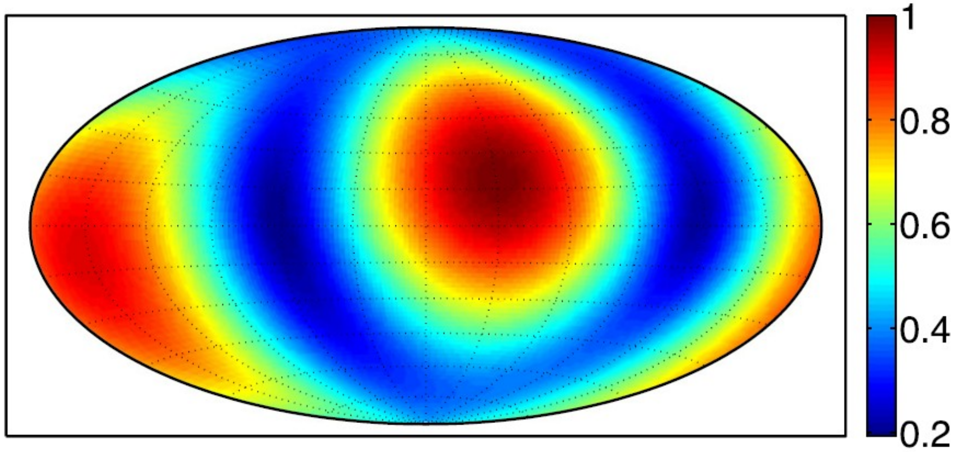
3D Core-Collapse Models: Neutrino Signals

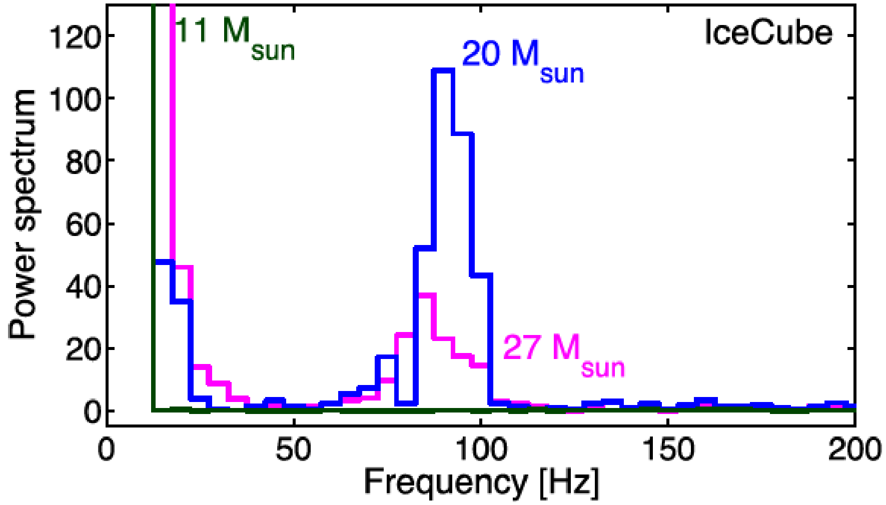
11.2, 20, 27 M_{sun} progenitors (WHW 2002)

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





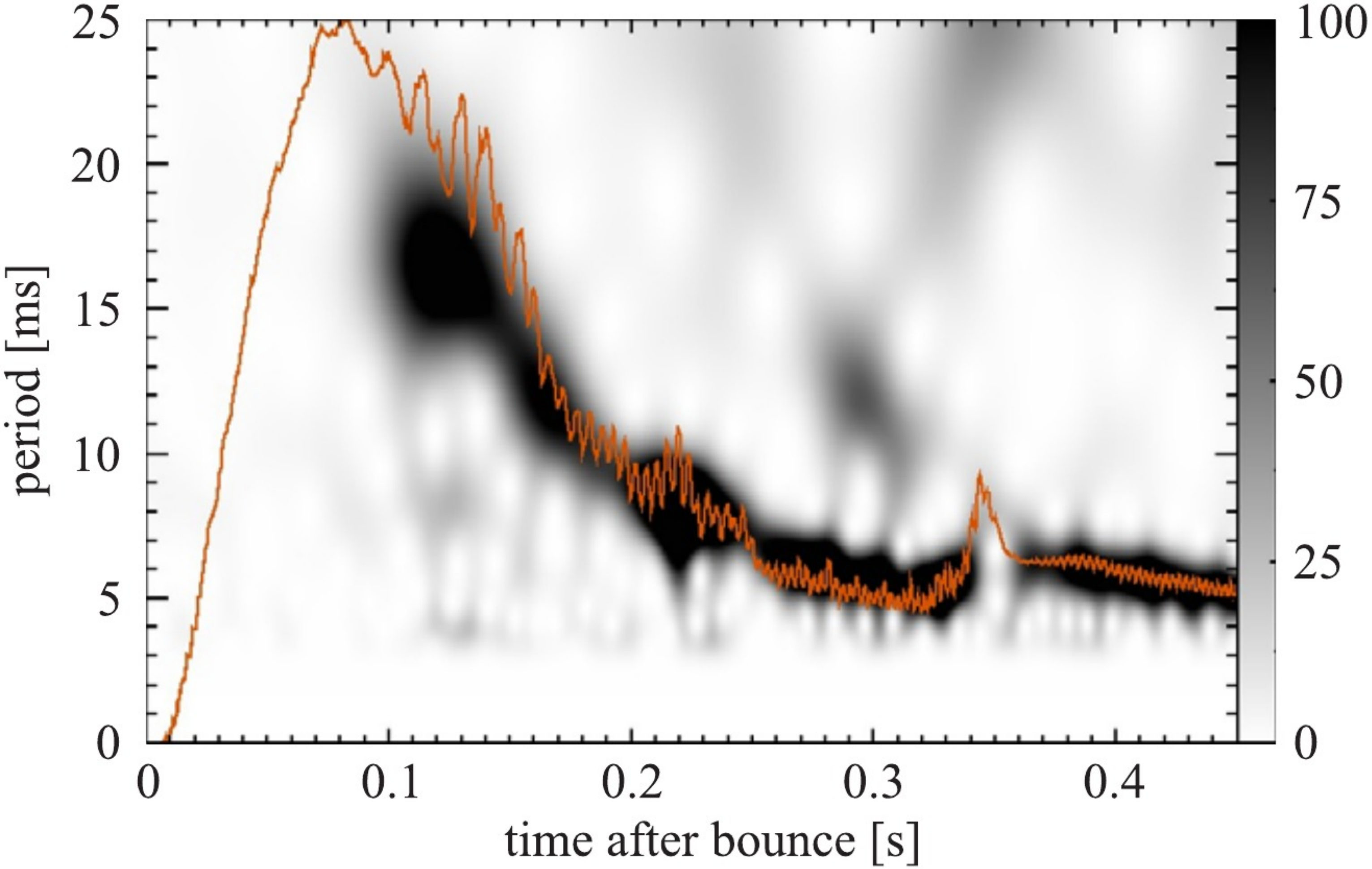




Tamborra et al., PRL 111, 121104 (2013); PRD 90, 045032 (2014)

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

SASI Period Measures Shock Radius Evolution



Müller & THJ, ApJ 788 (2014) 82

$$T_{\mathrm{SASI}} = 19\,\mathrm{ms}\left(\frac{r_{\mathrm{sh}}}{100\,\mathrm{km}}\right)^{3/2}\ln\left(\frac{r_{\mathrm{sh}}}{r_{\mathrm{PNS}}}\right)$$

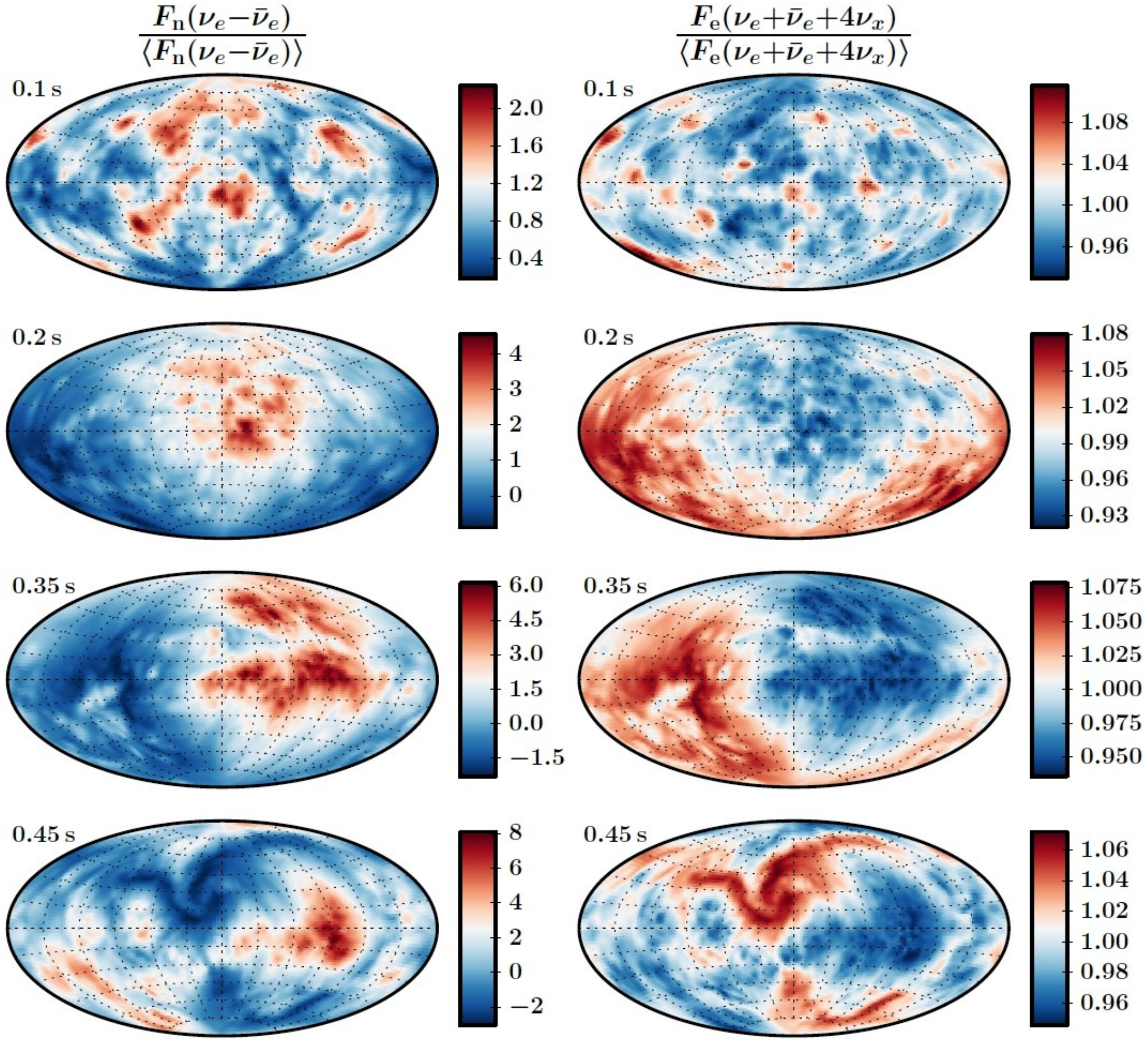
LESA: A New Nonradial 3D Instability

Dipole asymmetry of lepton-number emission (LESA)

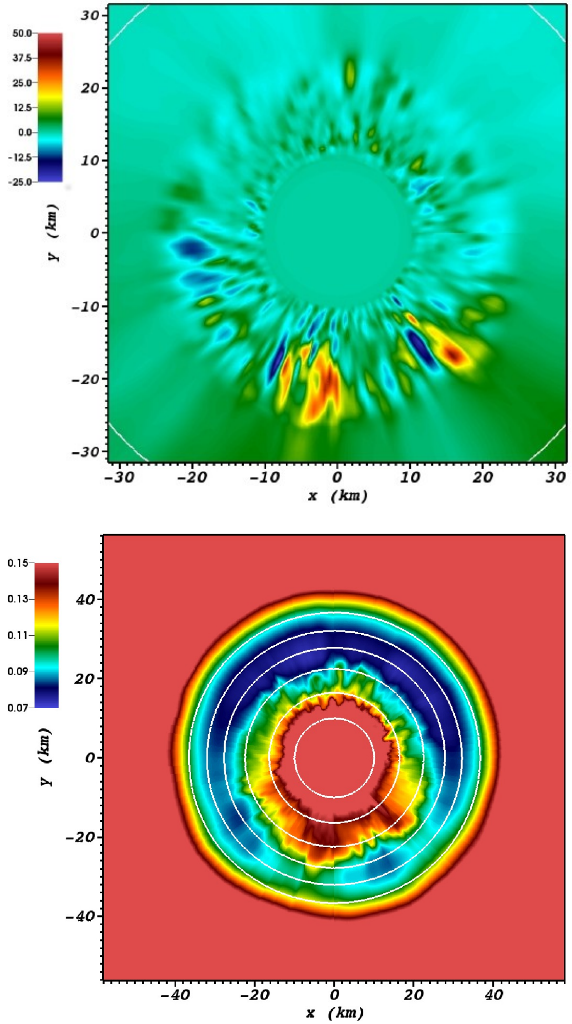
Lepton number flux:
ν_e minus anti-ν_e

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

Total energy flux:
ν_e plus anti-ν_e plus
heavy-lepton neutrinos

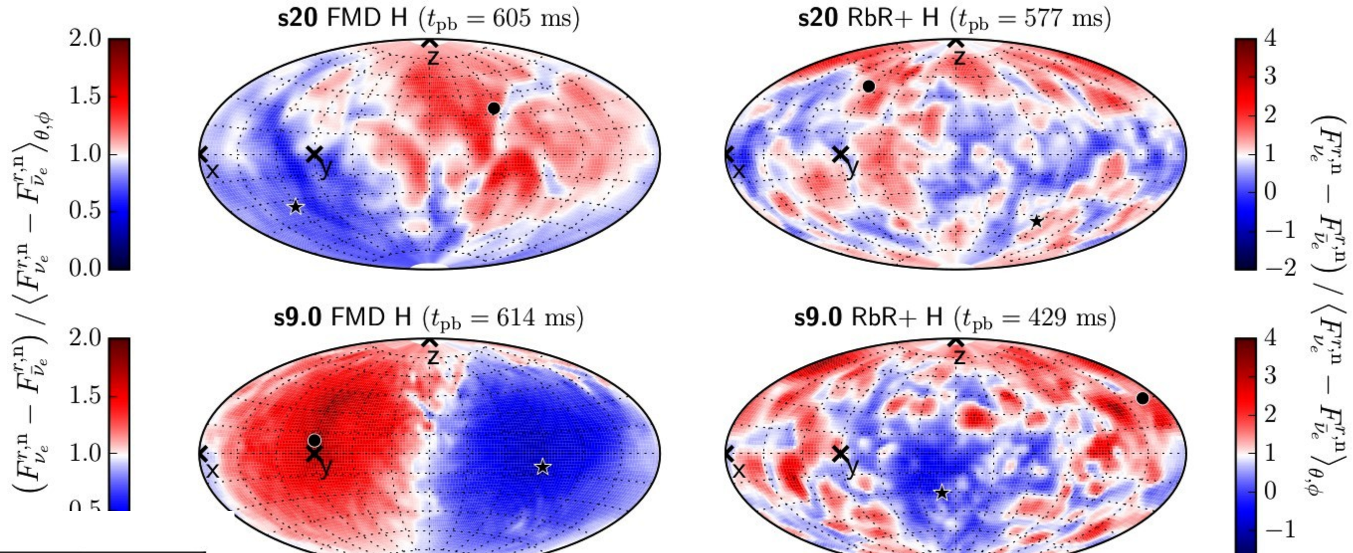


Anisotropic convection inside the proto-neutron star

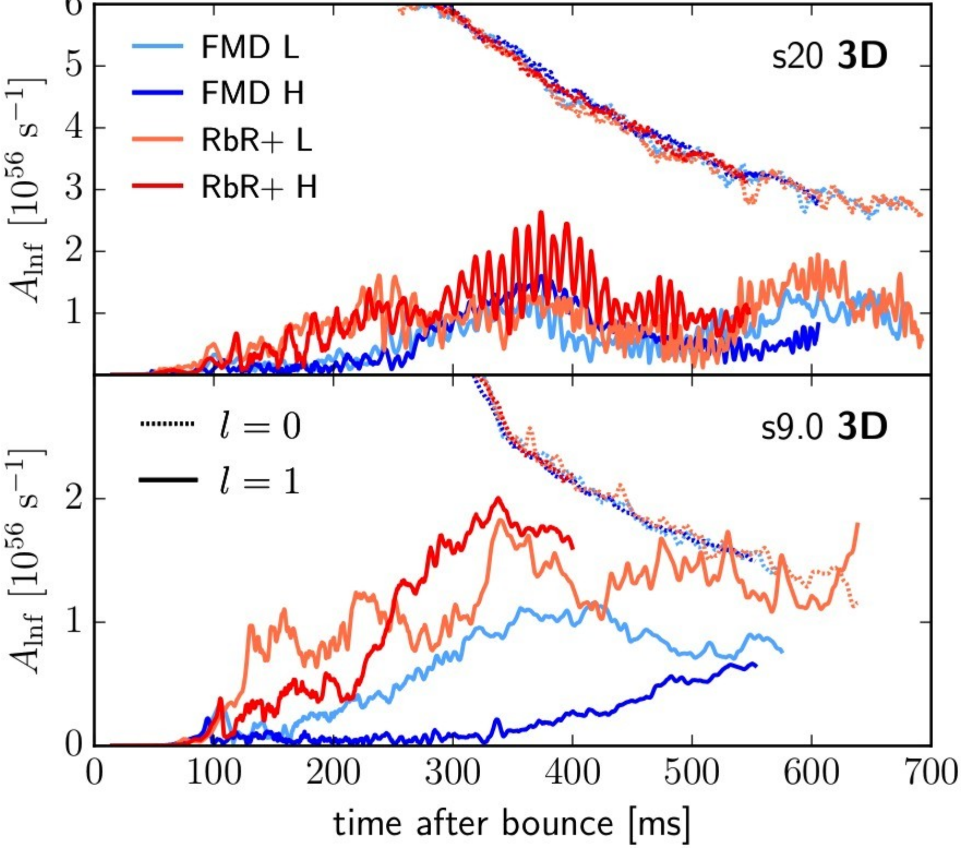


Tamborra, Hanke, THJ, et al., ApJ 792, 96 (2014);
THJ et al., ARNPS 66 (2016)

LESA with RbR+ and M1 Neutrino Transport



Robert Glas, PhD Thesis;
Glas, Just, THJ, Obergaulinger,
to be submitted



Consequences of LESA:

- Neutron-star kicks (~10–100 km/s?)
- Supernova nucleosynthesis in ν-heated ejecta is direction dependent
- Viewing-angle dependent lepton flux
- Neutrino-flavor oscillations are direction dependent

Implications of Neutrino-driven Explosions in 3D Supernova Models

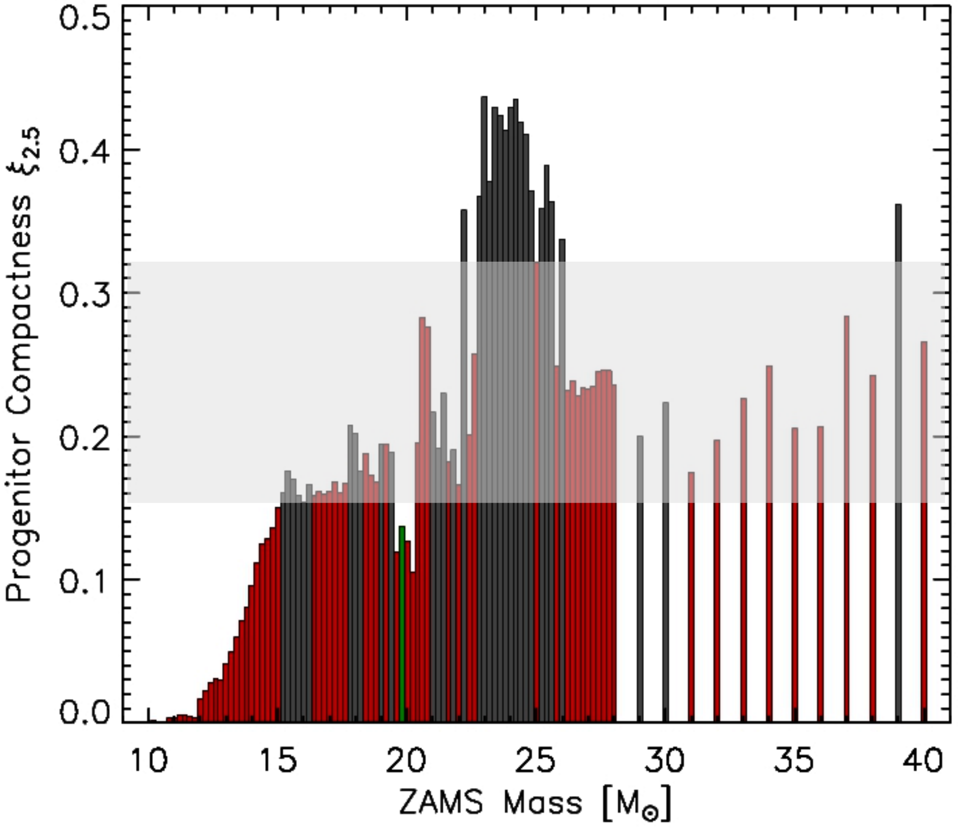
- Delayed neutrino-driven explosions work in 2D and 3D.
- “Details” of the physics in the core still need further studies. Can dense-matter effects be settled in near future?
- Multi-D models of neutrino-driven explosions are sufficiently mature to test them against observations (SN explosion energies, NS & BH masses, NS kicks and spins, morphology of SN remnants, etc).
- Neutrino signal from supernovae carries information of hydrodynamical mass motions and evolution of shock radius.
- Strong variations of explosion properties and neutrino emission with mass of progenitor star.

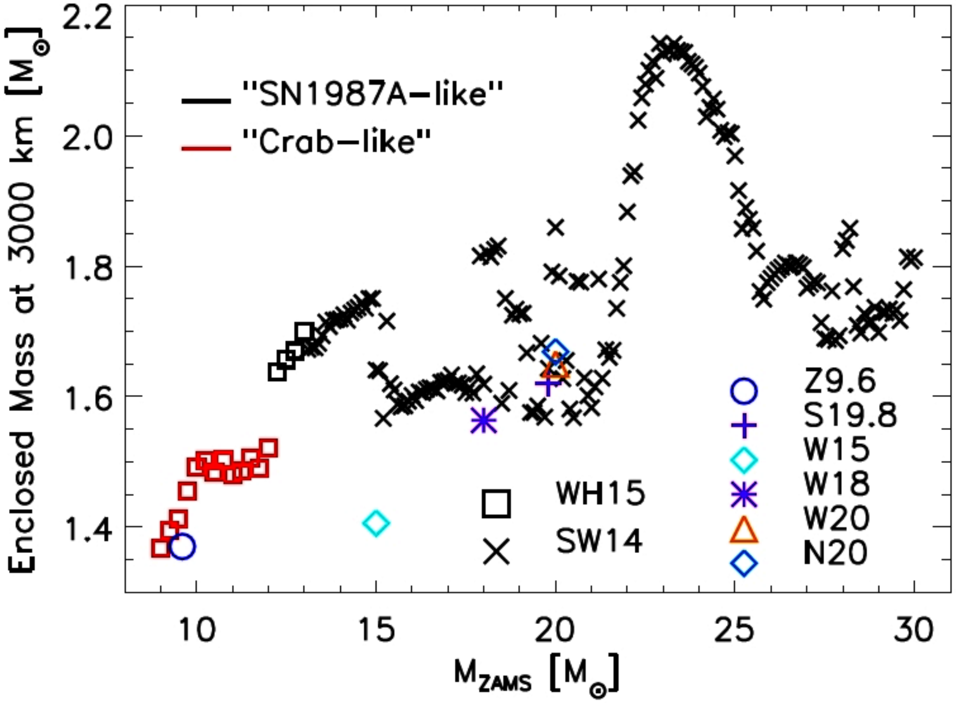
Progenitor-star dependences of neutrino-driven explosions

Stellar Compactness and Explosion

Core compactness can be non-monotonic function of ZAMS mass

Progenitor models:
Woosley et al. (RMP 2002), Sukhbold & Woosley (2014), Woosley & Heger (2015)





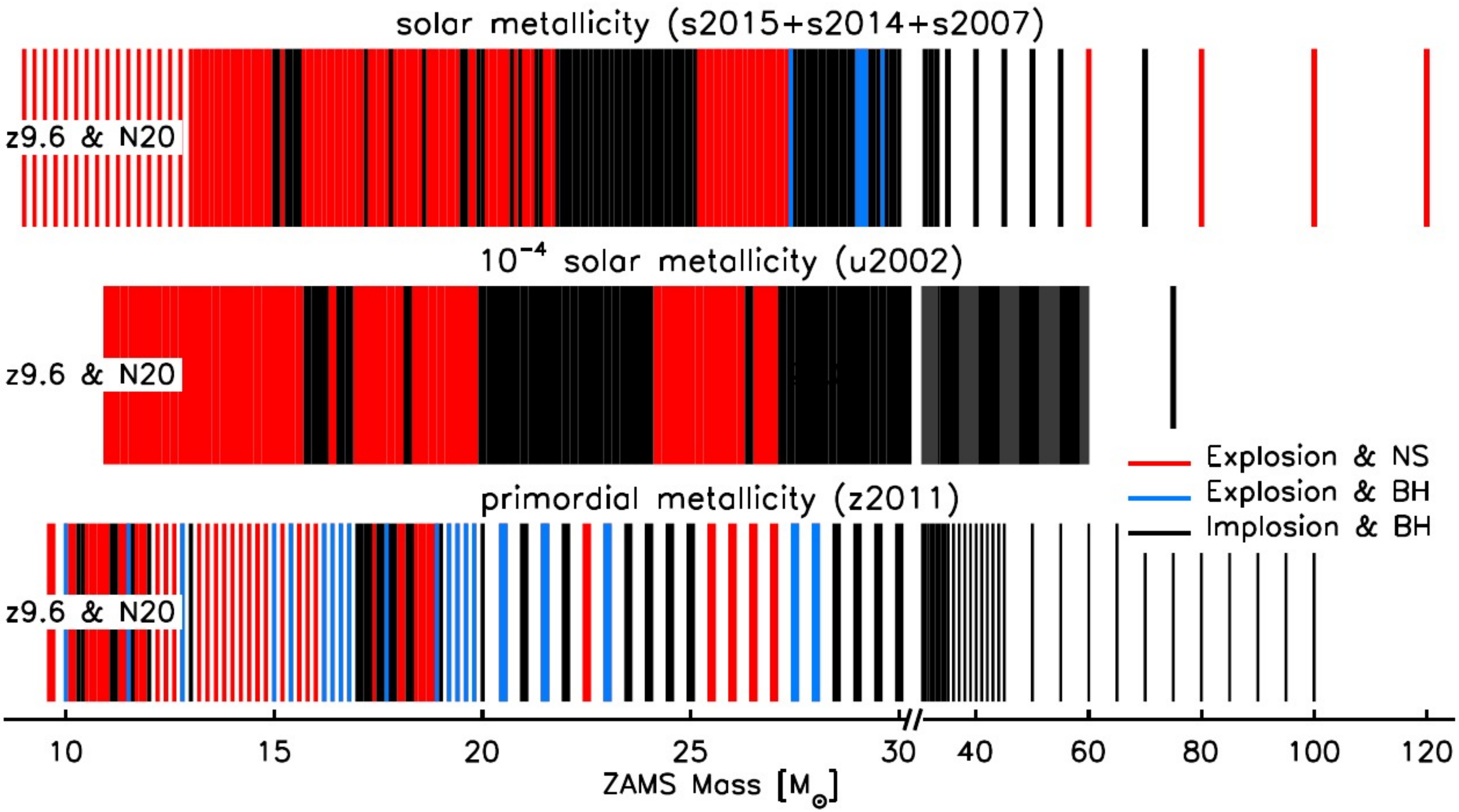
$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\,, \qquad \text{mass } M = 2.5\ M_\odot$$

O'Connor & Ott, ApJ 730:70 (2011)

(Ugliano et al., ApJ 757 (2012) 69;
Ertl et al., ApJ 818 (2016) 124;
Sukhbold, Ertl et al., ApJ 821 (2016) 38)

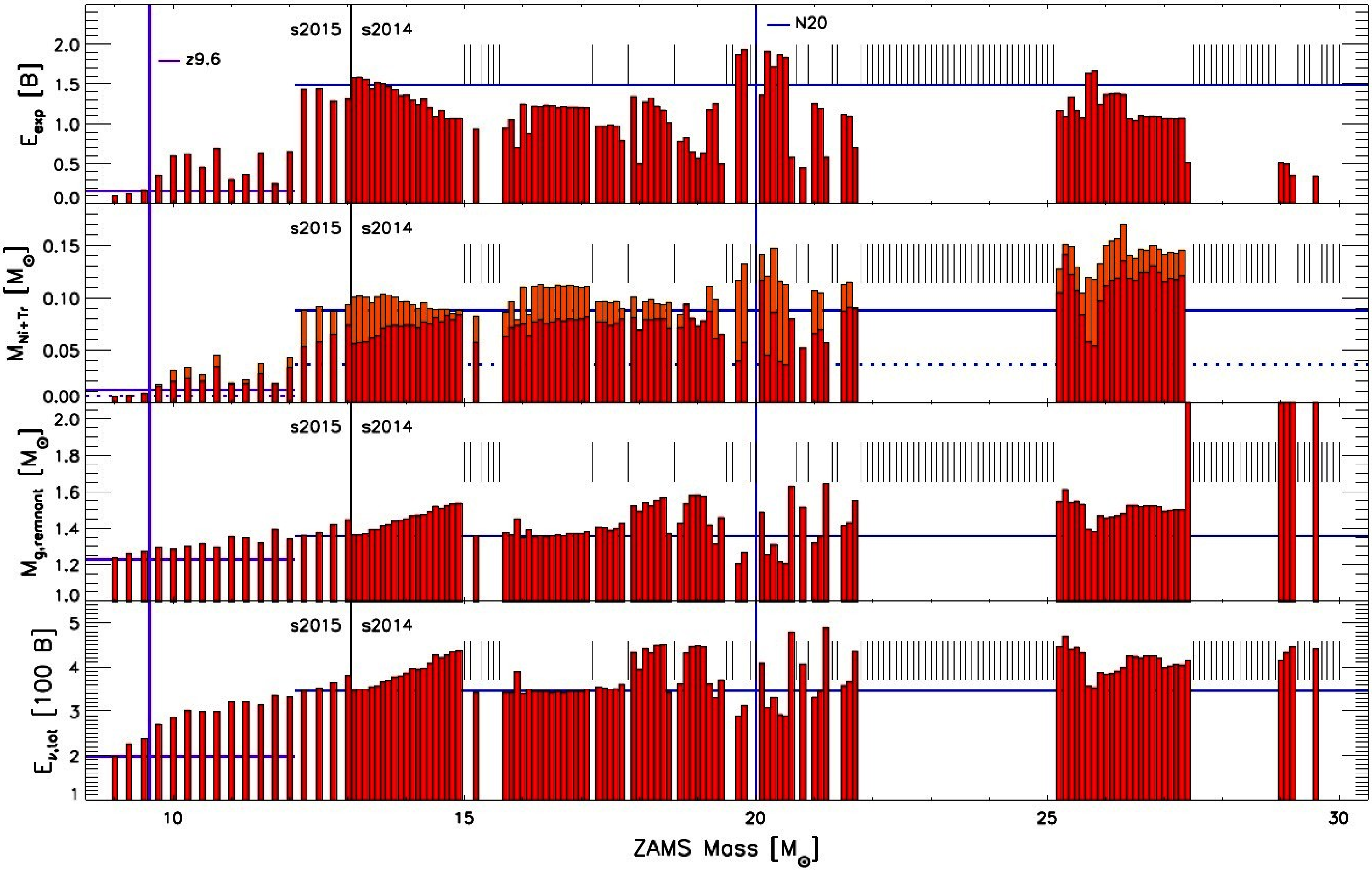
Neutrino-driven Explosions vs. Metallicity and ZAMS mass

Exploration of progenitor landscape with 1D simulations using a parametrized and calibrated "neutrino engine".



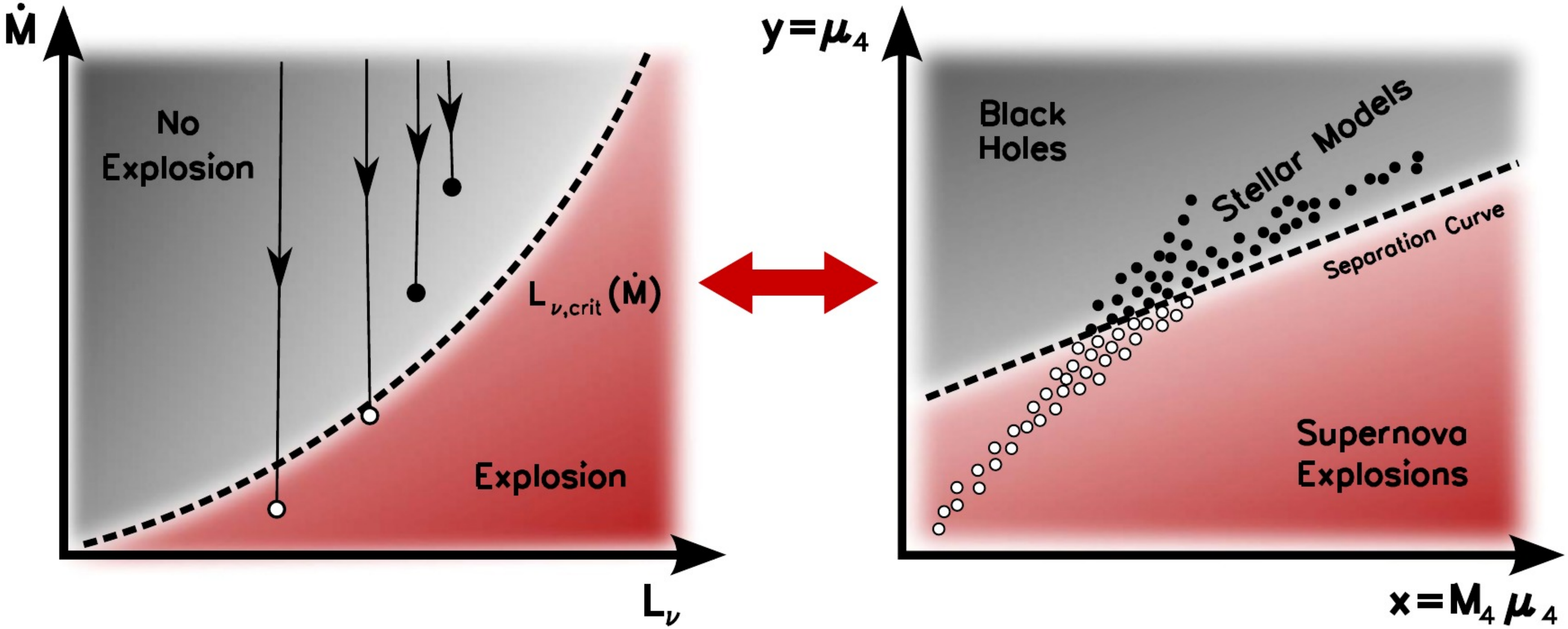
(Ertl, PhD Thesis 2016; Janka, Handbook of Supernovae, arXiv:1702.08825)

Neutrino-driven Explosions vs. ZAMS mass

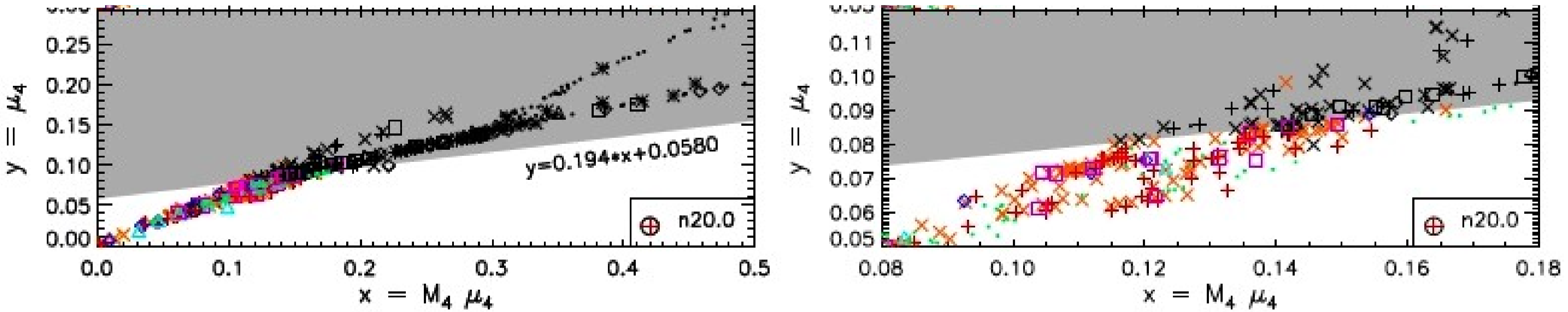


(Ertl, Janka, et al., ApJ 818, 124 (2016); arXiv:1503.07522)

Two-Parameter Criterion for "Explodability"



$$M_4 \equiv m(s=4)/M_\odot \sim \mathbf{M_{NS}} \quad ; \quad \mu_4 \equiv \left.\frac{dm/M_\odot}{dr/1000\ \mathrm{km}}\right|_{s=4} \sim \mathbf{dM_{NS}/dt}$$



(Ertl, Janka, et al., ApJ 818, 124 (2016); arXiv:1503.07522)