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Workshop on
"Probing the Supernova Mechanism by Observations"
Seattle, July 16 – 20, 2012

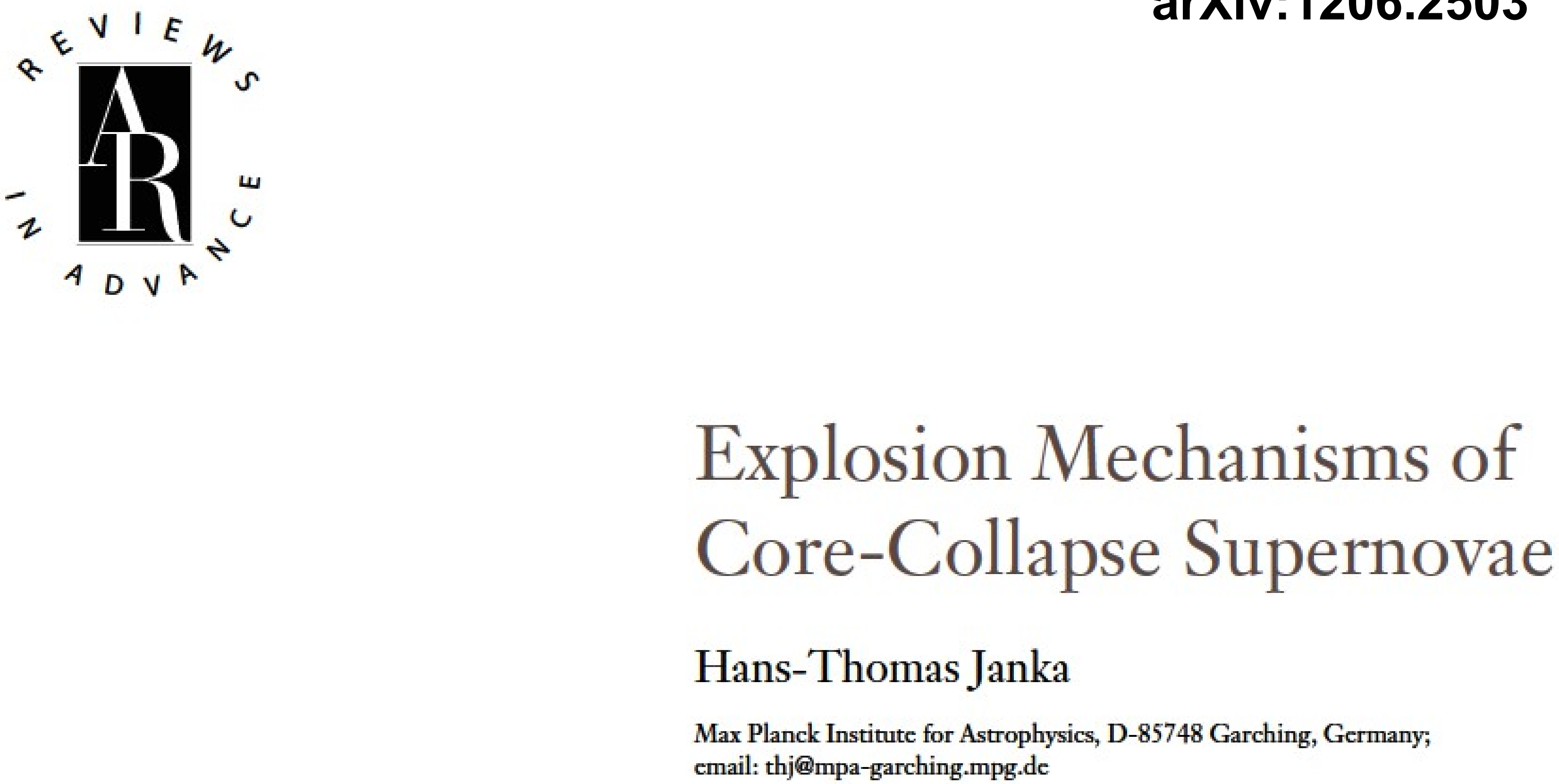
Theoretical Supernova Modeling:

Exploring the Progenitor-Explosion-Remnant Connection by Neutrino-Driven Explosion Models

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching

For a concise review of most of what I will say, see

arXiv:1206.2503



REVIEWS IN ADVANCE

Explosion Mechanisms of Core-Collapse Supernovae

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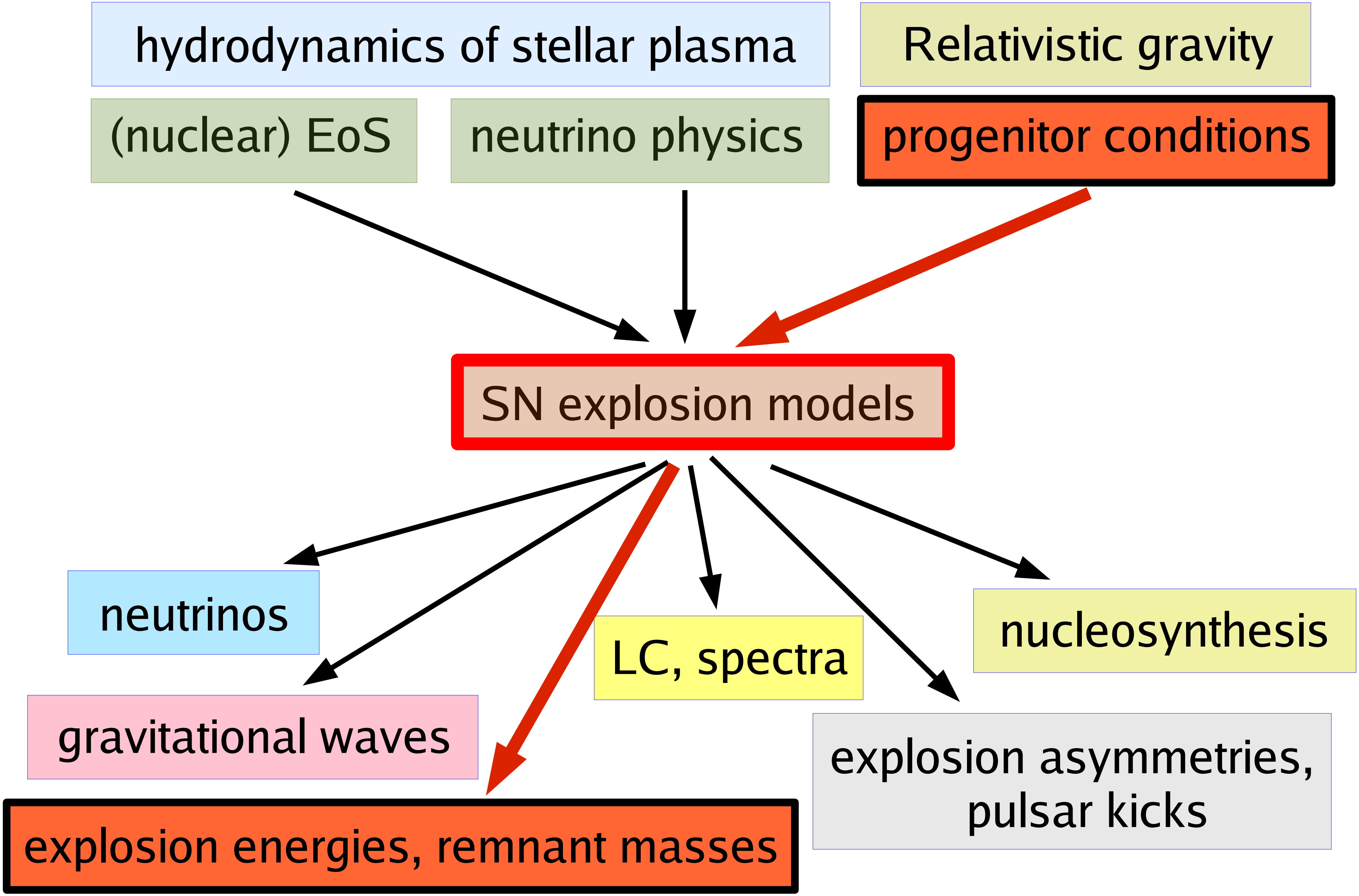
Predictions of Signals from SN Core



hydrodynamics of stellar plasma

Relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

gravitational waves

explosion energies, remnant masses

LC, spectra

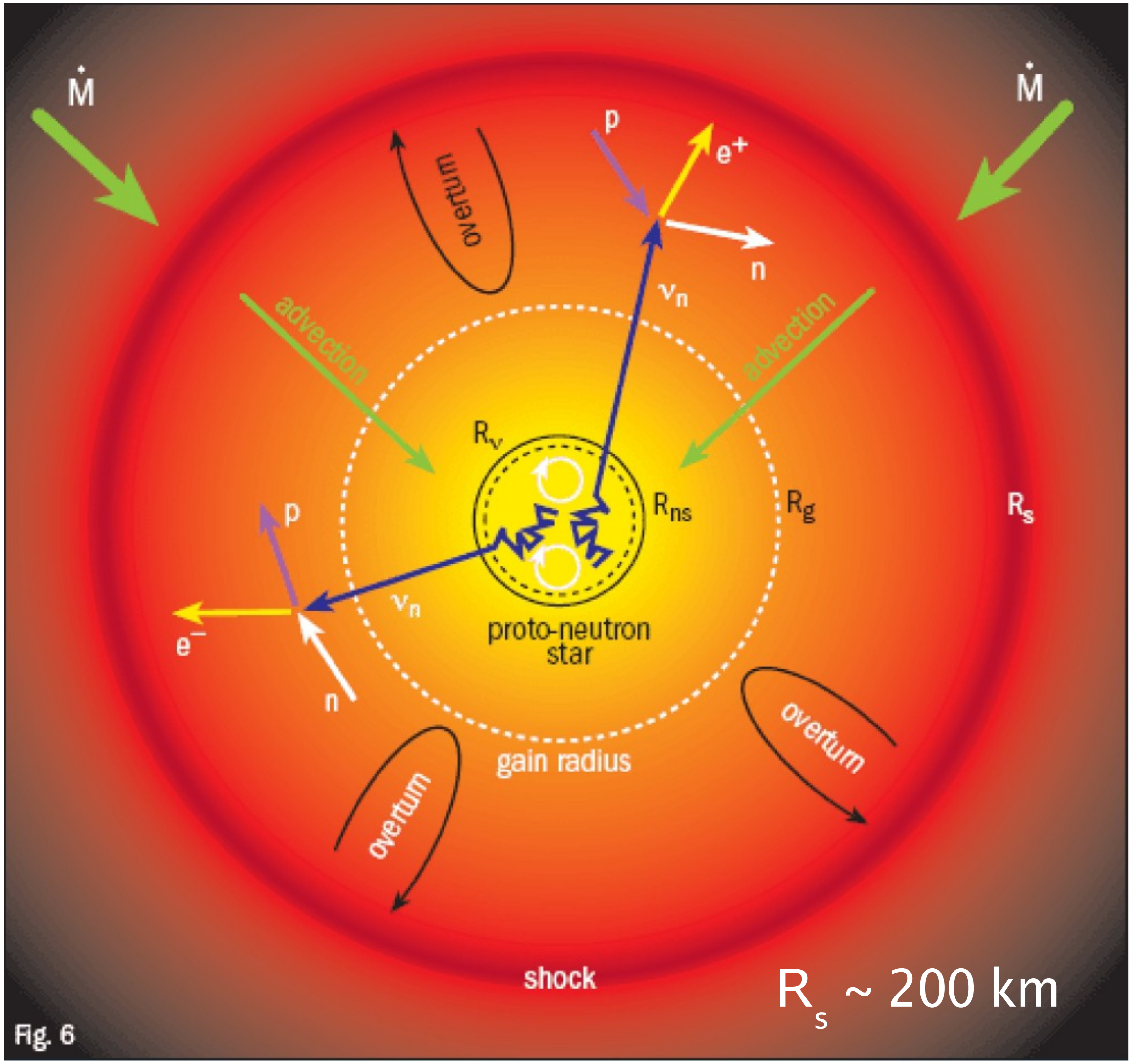
nucleosynthesis

explosion asymmetries, pulsar kicks

Explosion Mechanism
by
Neutrino Heating

Neutrinos & SN Explosion Mechanism

Paradigm: Explosions by the neutrino-heating mechanism, supported by hydrodynamic instabilities in the postshock layer



R_s ~ 200 km

- "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; Scheck et al. 2004,06,08).

Neutrino Heating and Cooling

$$\begin{aligned} \nu_e + n &\rightarrow e^- + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

- Neutrino heating:

$$q_\nu^+ = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{T_{\nu_e}}{4\,\mathrm{MeV}}\right)^2 \times \left(\frac{100\,\mathrm{km}}{r}\right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) \qquad \left[\frac{\mathrm{erg}}{\mathrm{g\,s}}\right]$$

- Neutrino cooling:

$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\,\mathrm{MeV}}\right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) \qquad \left[\frac{\mathrm{erg}}{\mathrm{g\,s}}\right]$$

$$\begin{aligned} Q_\nu^+ &= q_\nu^+ M_\mathrm{g} \\ &\sim 9.4 \times 10^{51} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{k_\mathrm{B} T_\nu}{4\,\mathrm{MeV}}\right)^2 \left(\frac{L_\nu}{3 \cdot 10^{52}\,\mathrm{erg/s}}\right)\left(\frac{M_\mathrm{g}}{0.01\,M_\odot}\right)\left(\frac{R_\mathrm{g}}{100\,\mathrm{km}}\right)^{-2} \end{aligned}$$

$$\begin{aligned} E_N &\sim Q_\nu^+ t_\mathrm{dwell} \\ &\sim 9.4 \times 10^{50}\,\mathrm{erg} \left(\frac{k_\mathrm{B} T_\nu}{4\,\mathrm{MeV}}\right)^2 \left(\frac{L_\nu}{3 \cdot 10^{52}\,\mathrm{erg/s}}\right) \times \\ &\qquad \left(\frac{M_\mathrm{g}}{0.01\,M_\odot}\right)^2 \left(\frac{\dot{M}}{0.1\,M_\odot\,\mathrm{s}^{-1}}\right)^{-1} \left(\frac{R_\mathrm{g}}{100\,\mathrm{km}}\right)^{-2} \end{aligned}$$

$$t_\mathrm{dwell} \approx \frac{M_\mathrm{g}}{\dot{M}}$$

Hydrodynamic instabilities

Explosion Modeling

- Variety of modeling approaches, wide range of sophistication.

- Method of choice depends on questions to be addressed.

- Question of viability of neutrino-driven mechanism requires most detailed and consistent treatment of hydrodynamics, gravity (GR), microphysics, and neutrino transport.

- This also holds for reliable predictions of neutrino and GW signals, nucleosynthesis conditions in neutrino-heated matter.

- Basic understanding of hydrodynamical instabilities, explosion asymmetries, pulsar kicks & spins, progenitor-remnant connection, might be possible with less ambitious modeling approach.

- Keep in mind limitations when conclusions are drawn!

Explosion Mechanism: Most Sophisticated Current Models

General-Relativistic 2D Supernova Models

(Müller B., PhD Thesis (2009);
Müller et al., ApJS, (2010))

$$\frac{\partial\sqrt{\gamma}\rho W}{\partial t}+\frac{\partial\sqrt{-g}\rho W\hat{v}^i}{\partial x^i} = 0, \tag{2.5}$$

$$\frac{\partial\sqrt{\gamma}\rho h W^2 v_j}{\partial t}+\frac{\partial\sqrt{-g}\left(\rho h W^2 v_j\hat{v}^i+\delta^i_j P\right)}{\partial x^i} = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\frac{\partial g_{\mu\nu}}{\partial x^j}+\left(\frac{\partial\sqrt{\gamma}S_j}{\partial t}\right)_C, \tag{2.6}$$

$$\frac{\partial\sqrt{\gamma}\tau}{\partial t}+\frac{\partial\sqrt{-g}\left(\tau\hat{v}^i+Pv^i\right)}{\partial x^i} = \alpha\sqrt{-g}\left(T^{\mu 0}\frac{\partial\ln\alpha}{\partial x^\mu}-T^{\mu\nu}\Gamma^0_{\mu\nu}\right)+\left(\frac{\partial\sqrt{\gamma}\tau}{\partial t}\right)_C. \tag{2.7}$$

$$\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}+\frac{\partial\sqrt{-g}\rho W Y_e\hat{v}^i}{\partial x^i}=\left(\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}\right)_C, \tag{2.8}$$

$$\frac{\partial\sqrt{\gamma}\rho W X_k}{\partial t}+\frac{\partial\sqrt{-g}\rho W X_k\hat{v}^i}{\partial x^i}=0. \tag{2.9}$$

GR hydrodynamics (CoCoNuT)

CFC metric equations

$$\hat{\Delta}\Phi = -2\pi\phi^5\left(E+\frac{K_{ij}K^{ij}}{16\pi}\right), \tag{2.10}$$

$$\hat{\Delta}(\alpha\Phi) = 2\pi\alpha\phi^5\left(E+2S+\frac{7K_{ij}K^{ij}}{16\pi}\right), \tag{2.11}$$

$$\hat{\Delta}\beta^i = 16\pi\alpha\phi^4 S^i+2\phi^{10}K^{ij}\hat{\nabla}_j\left(\frac{\alpha}{\Phi^6}\right)-\frac{1}{3}\hat{\nabla}^i\hat{\nabla}_j\beta^j, \tag{2.12}$$

$$\begin{aligned}
&\frac{\partial W\left(\hat{J}+v_r\hat{H}\right)}{\partial t}+\frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2}-\beta_r v_r\right)\hat{H}+\left(Wv_r\frac{\alpha}{\phi^2}-\beta_r\right)\hat{J}\right]- \\
&\quad\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{J}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]+\right. \\
&\quad W\varepsilon\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]- \\
&\quad\left.\varepsilon\hat{K}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+Wv_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]\right\}- \\
&\quad W\hat{J}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]- \\
&\quad W\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]+ \\
&\quad\hat{K}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+Wv_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]=\alpha\hat{C}^{(0)},
\end{aligned} \tag{2.28}$$

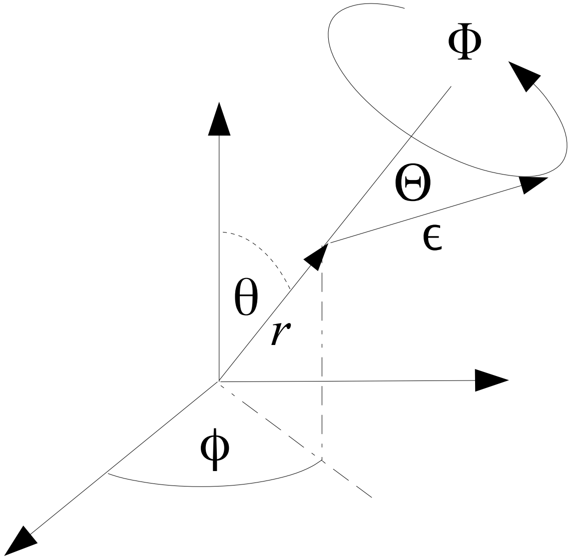
$$\begin{aligned}
&\frac{\partial W\left(\hat{H}+v_r\hat{K}\right)}{\partial t}+\frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2}-\beta_r v_r\right)\hat{K}+\left(Wv_r\frac{\alpha}{\phi^2}-\beta_r\right)\hat{H}\right]- \\
&\quad\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{H}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]+\right. \\
&\quad W\varepsilon\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]- \\
&\quad\left.\varepsilon\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+Wv_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]\right\}+ \\
&\quad\left(\hat{J}-\hat{K}\right)\left[v_r\left(\frac{\beta_r}{r}-\frac{\partial\beta_r}{\partial r}\right)+\frac{\partial}{\partial r}\left(\frac{W\alpha}{\phi^2}\right)-\frac{W\alpha}{r\phi^2}+W^3\left(\frac{\partial v_r}{\partial t}-\beta_r\frac{\partial v_r}{\partial r}\right)\right]+ \\
&\quad\left(\hat{H}-\hat{L}\right)\left[\frac{W^3\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+\frac{\beta W}{r}-\frac{\partial\beta W}{\partial r}-Wv_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+\frac{\partial W}{\partial t}\right]- \\
&\quad W\hat{H}\left[\frac{1}{r}\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)+2\left(\beta_r-\frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right]- \\
&\quad W\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r}-2\frac{\partial\ln\phi}{\partial t}\right)-\frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r}+\alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r}-\frac{\partial v_r}{\partial t}\right)\right]+ \\
&\quad\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+Wv_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+v_r\frac{\partial v_r}{\partial t}\right)\right]=\alpha\hat{C}^{(1)}.
\end{aligned} \tag{2.29}$$

Neutrino transport (VERTEX)

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 Curse and Challenge of the Dimensions



Boltzmann equation determines neutrino distribution function in 6D phase space and time

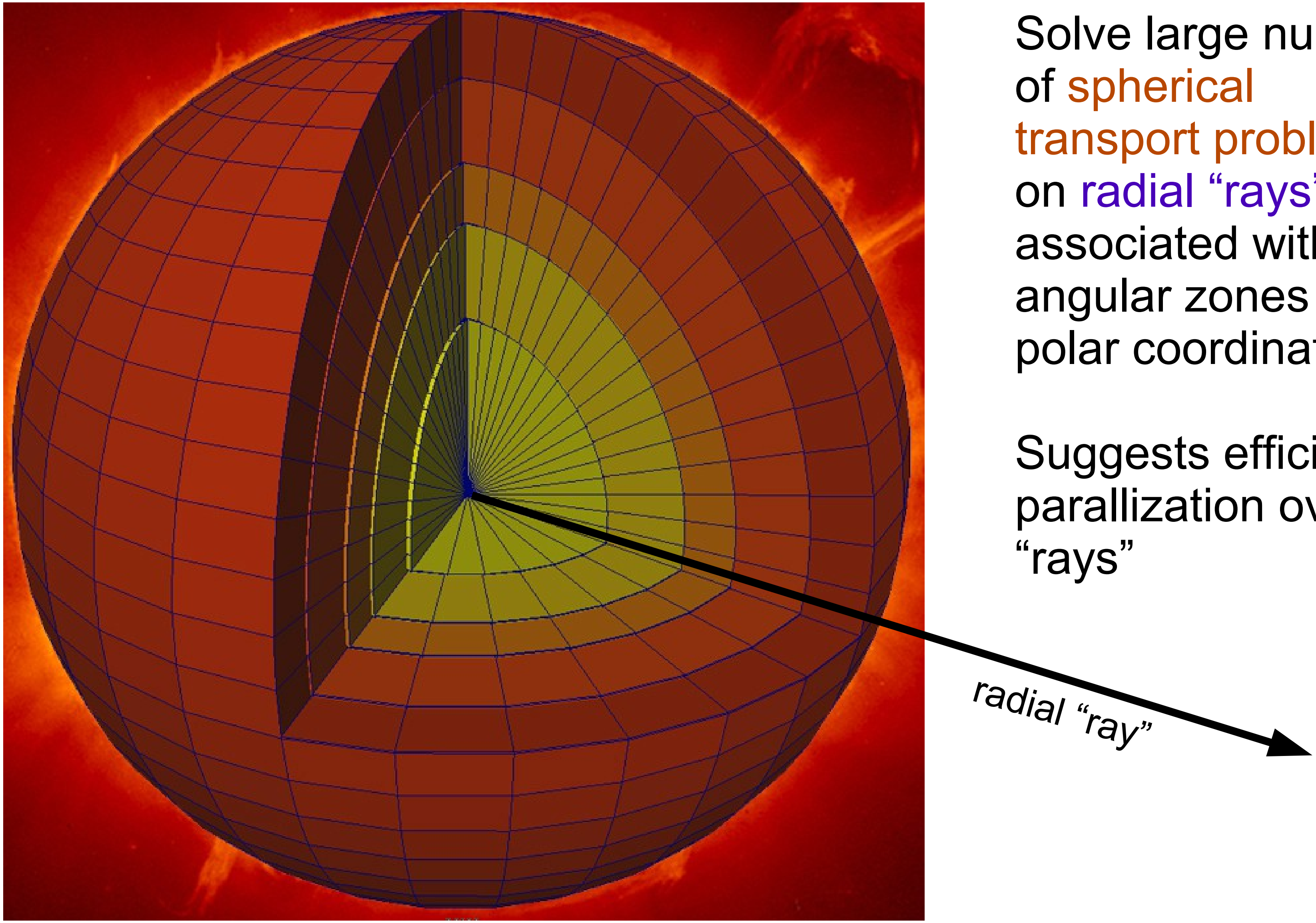
$$f(r, \theta, \phi, \Theta, \Phi, \epsilon, t)$$

Integration over 3D momentum space yields source terms for hydrodynamics

$$Q(r, \theta, \phi, t), \dot{Y}_e(r, \theta, \phi, t)$$

Solution approach	**Required resources**
• **3D** hydro + **6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12)	• ≥ 10–100 PFlops/s (sustained!)
• **3D** hydro + two-moment closure of Boltzmann Eq. (may be next feasible step on way to full 3D)	• ≥ 1–10 Pflops/s, TBytes
• **3D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• ≥ 0.1–1 PFlops/s, Tbytes
• **2D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• ≥ 0.1–1 Tflops/s, < 1 TByte

"Ray-by-Ray" Approximation for Neutrino Transport in 2D and 3D Geometry

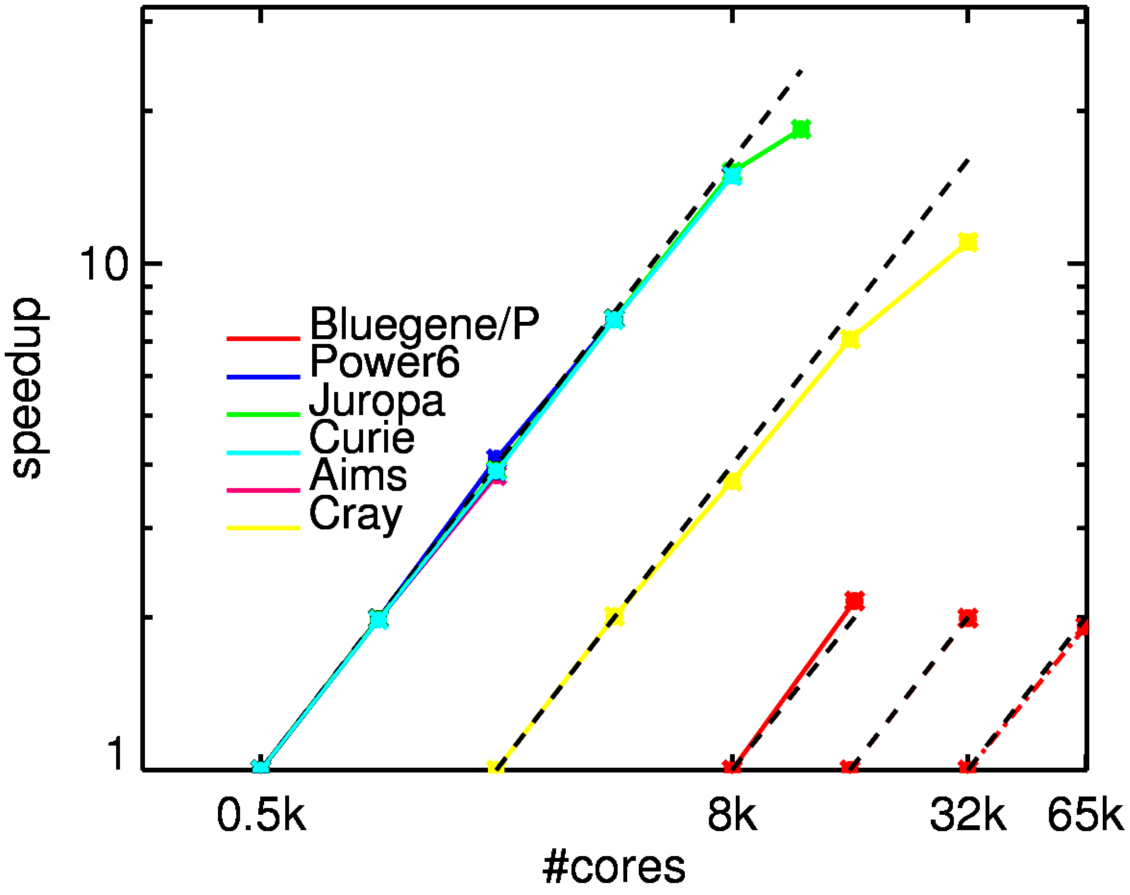


Solve large number of spherical transport problems on radial "rays" associated with angular zones of polar coordinate grid

Suggests efficient parallization over the "rays"

Performance and Portability of our Supernova Code *Prometheus-Vertex*

- Code employs hybrid MPI/OpenMP programming model (collaborative development with **Katharina Benkert, HLRS**).
- Code has been ported to different computer platforms by **Andreas Marek, High Level Application Support, Rechenzentrum Garching (RZG).**
- Code shows excellent parallel efficiency, which will be fully exploited in 3D.



Strong Scaling

Andreas Marek, RZG (2011)

Computing Requirements for 2D & 3D Supernova Modeling

Time-dependent simulations: t ~ 1 second, ~ 10^6 time steps!

CPU-time requirements for one model run:

- **In 2D with 600 radial zones, 1 degree lateral resolution:**

  ~ $3*10^{18}$ Flops, need ~10^6 processor-core hours.

- **In 3D with 600 radial zones, 1.5 degrees angular resolution:**

  ~ $3*10^{20}$ Flops, need ~10^8 processor-core hours.

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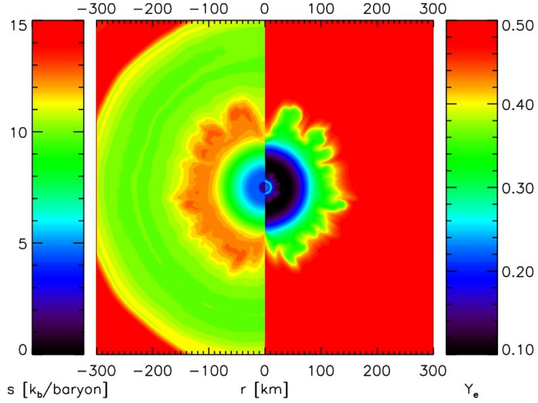
Supernova Explosion Models in 2D

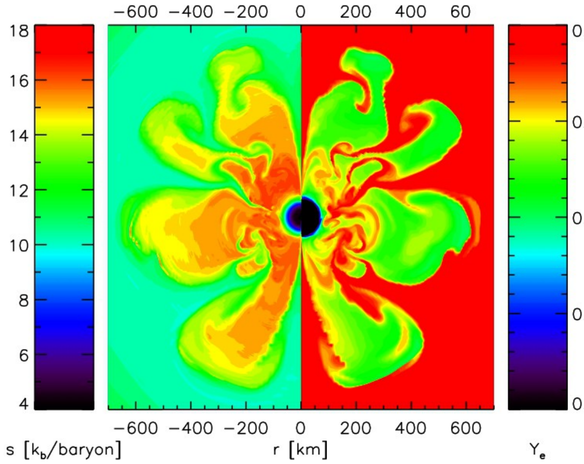
SN Models of 8.8 M_{sun} Star with O-Ne-Mg Core

Convection leads to slight increase of explosion energy, causes explosion asymmetries, and ejects n-rich matter!

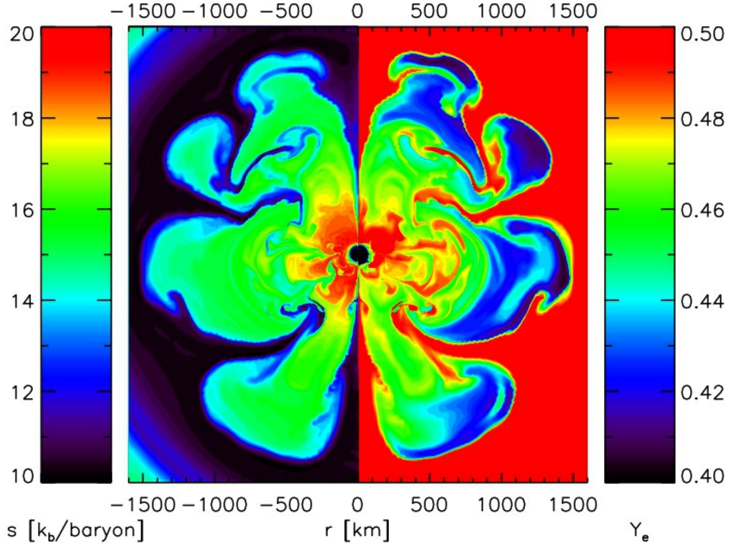
Entropy Y_e



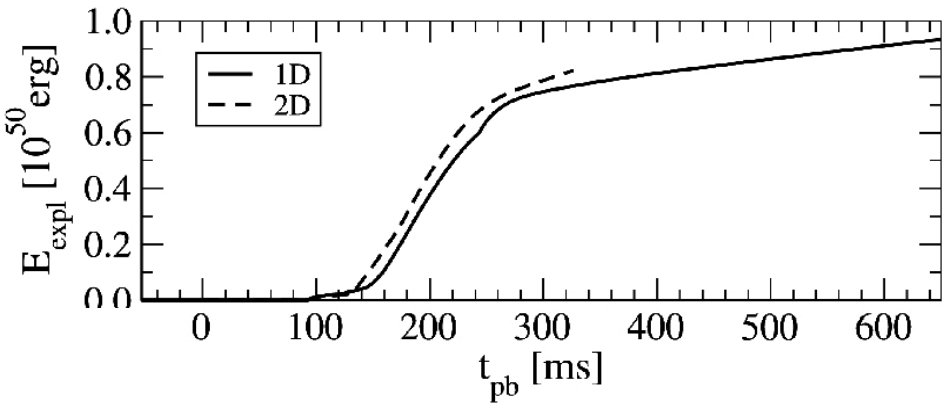
t = 0.097 s after core bounce

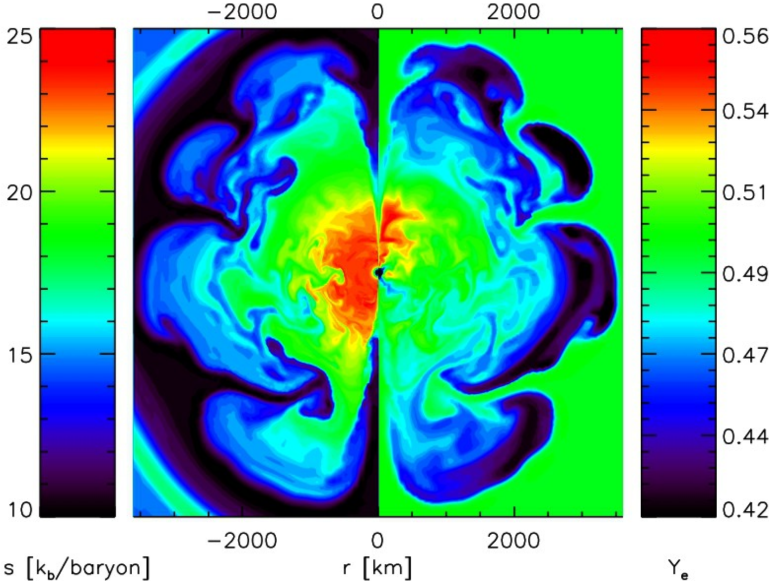


t = 0.144 s after core bounce



t = 0.185 s after core bounce

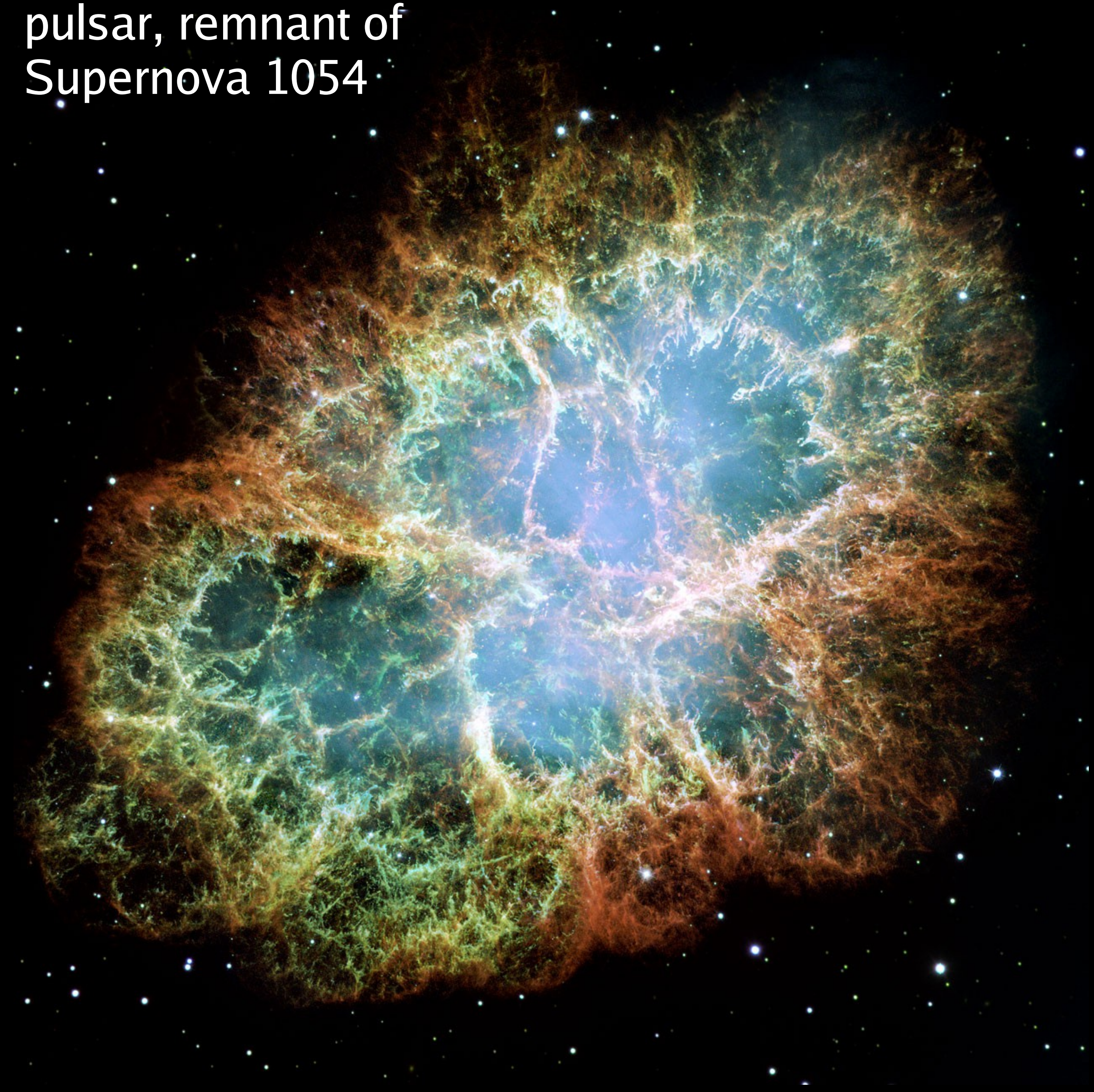




t = 0.262 s after core bounce

Janka et al. (2008), Wanajo et al. (2011)

CRAB Nebula with pulsar, remnant of Supernova 1054



Explosion properties:

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

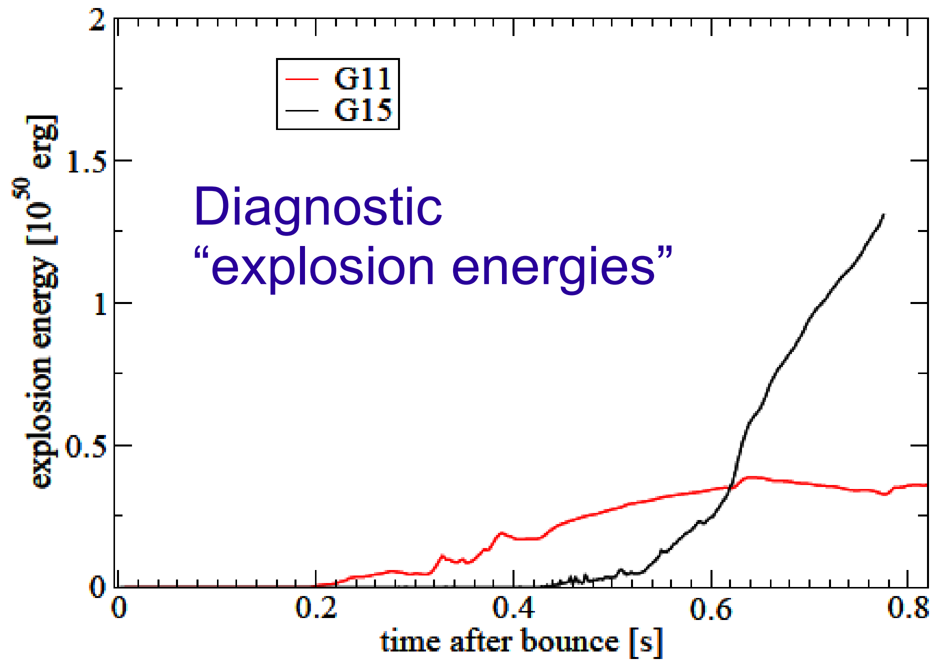
Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

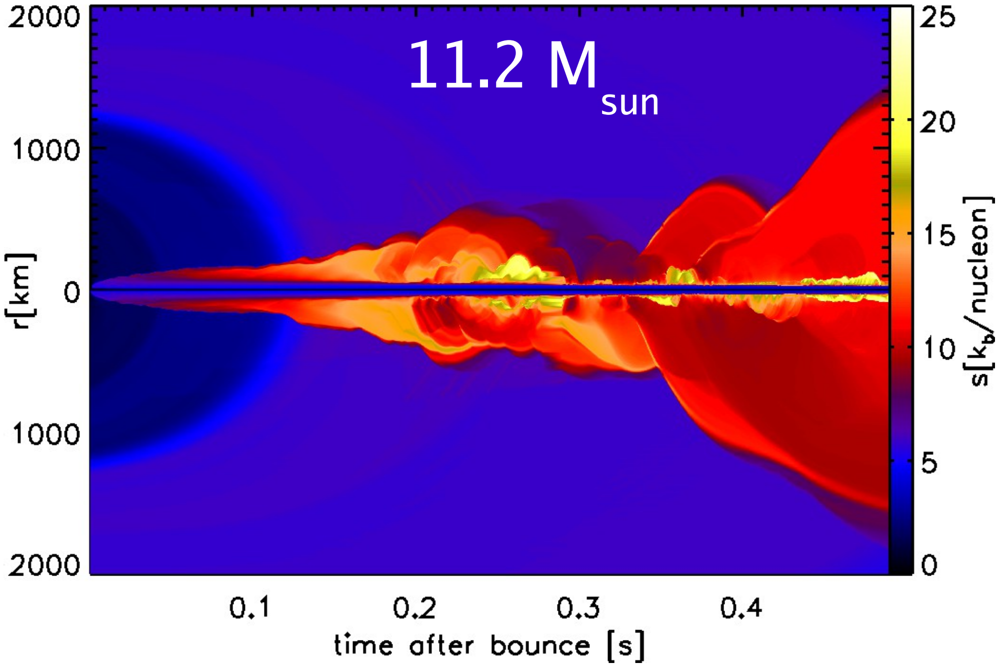
Might also explain other low-luminosity supernovae (e.g. SN1997D, 1999br, 2008bk)

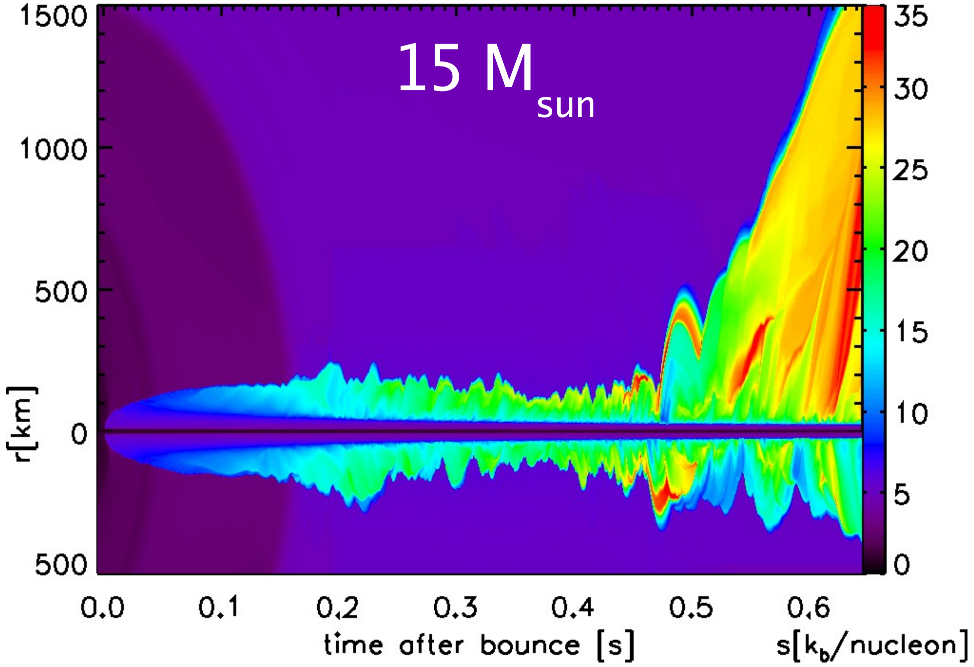
Relativistic 2D SN Models Fe-Core Stars

- Relativistic (GR) 2D calculations basically confirm our explosions with “effective relativistc gravity potential”.
- Explosions in GR can develop faster and earlier. GR effects help!
- 2D explosions are seemingly “marginal”, i.e., tend to set in relatively late and tend to be weak and highly deformed.


Diagnostic “explosion energies”

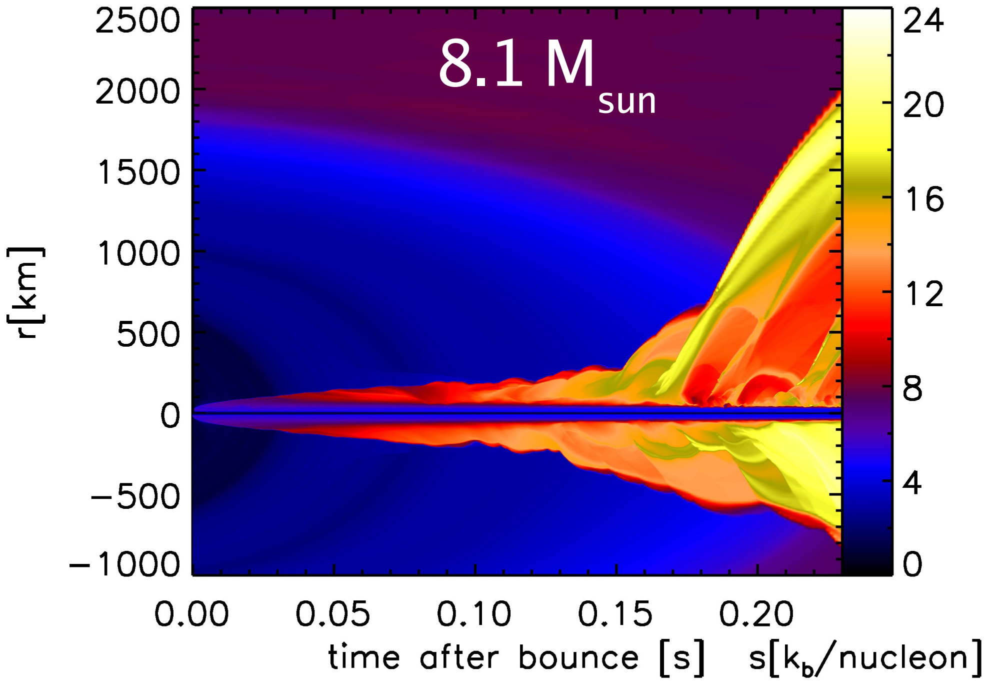
(Müller, THJ, Marek, arXiv:1202.0815)

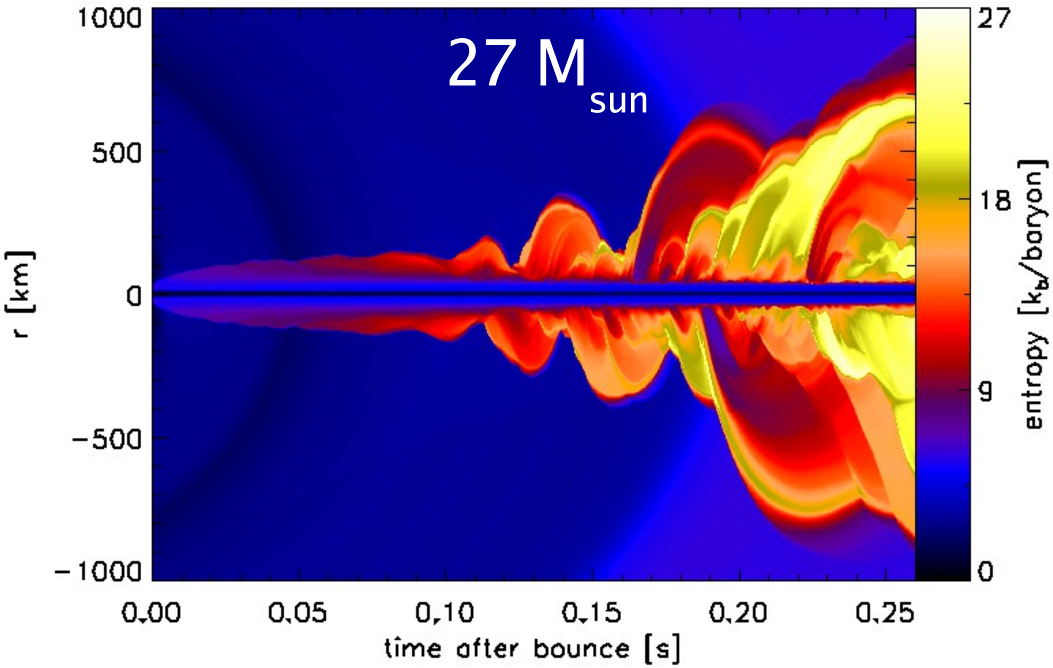

11.2 M_{sun}


15 M_{sun}

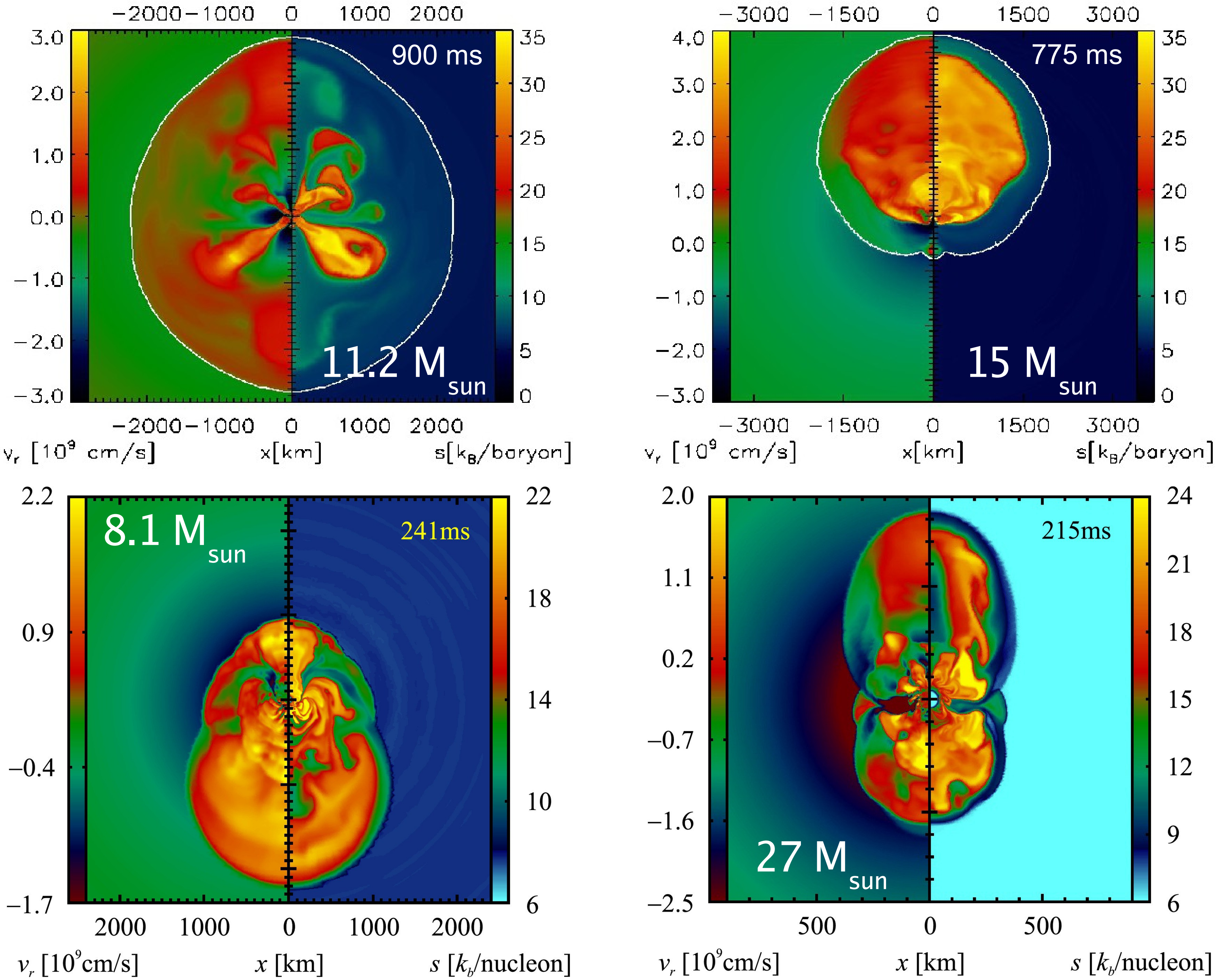
Relativistic 2D SN Simulations

- Convection or SASI (= “standing accretion shock instability”) ?
- Violent, long lasting shock oscillations support onset of explosion and produce quasi-periodic variations of neutrino emission and gravitational-wave signal.



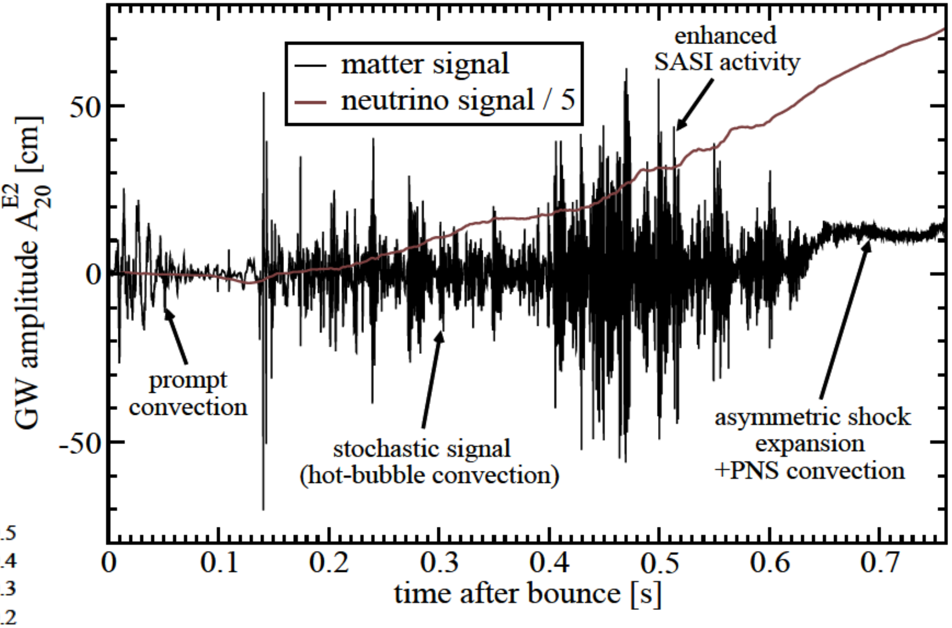


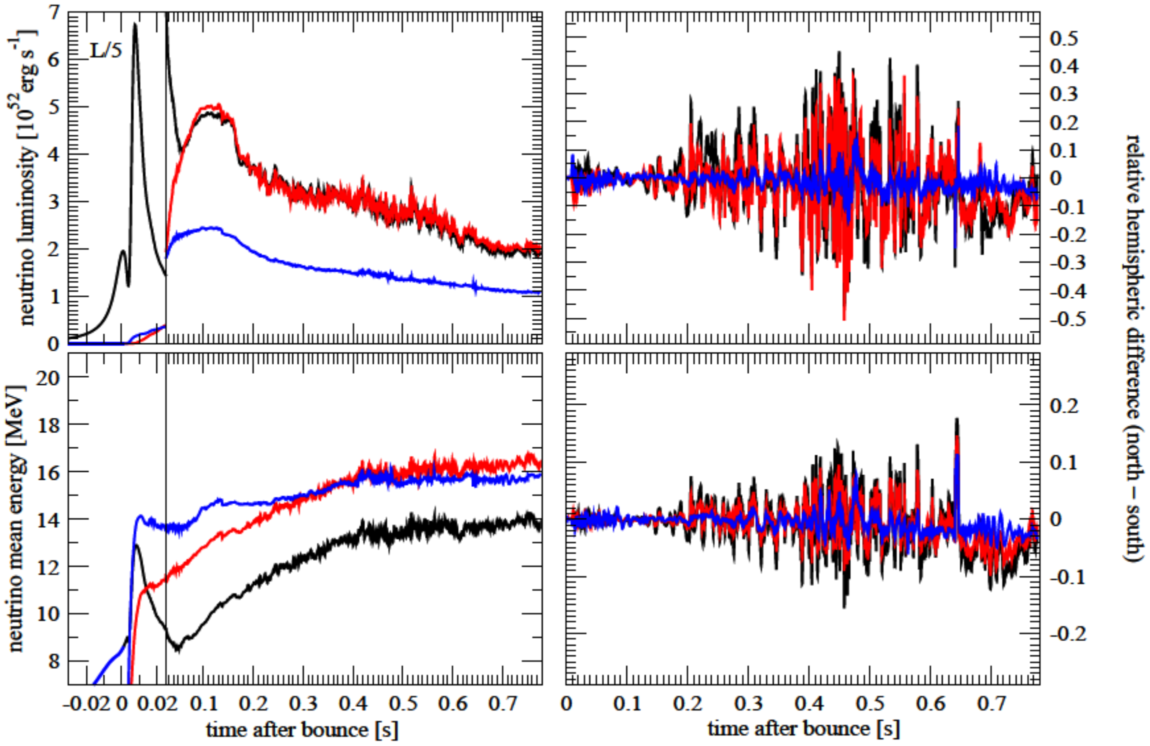
(Müller, THJ, Heger, arXiv:1205.7078)


900 ms
11.2 M sun
−2000 −1000 0 1000 2000
3.0 2.0 1.0 0.0 −1.0 −2.0 −3.0
35 30 25 20 15 10 5 0
v_r [10^9 cm/s]
x[km]
s[k_B/baryon]
775 ms
15 M sun
−3000 −1500 0 1500 3000
4.0 3.0 2.0 1.0 0.0 −1.0 −2.0 −3.0
35 30 25 20 15 10 5 0
v_r [10^9 cm/s]
x[km]
s[k_B/baryon]
8.1 M sun
241ms
2.2 0.9 −0.4 −1.7
22 18 14 10 6
2000 1000 0 1000 2000
v_r [10^9cm/s]
x [km]
s [k_b/nucleon]
215ms
27 M sun
2.0 1.1 0.2 −0.7 −1.6 −2.5
24 21 18 15 12 9 6
500 0 500
v_r [10^9cm/s]
x [km]
s [k_b/nucleon]

2D GR Explosions of 15 M_{sun} Star: Neutrinos and Gravitational Waves

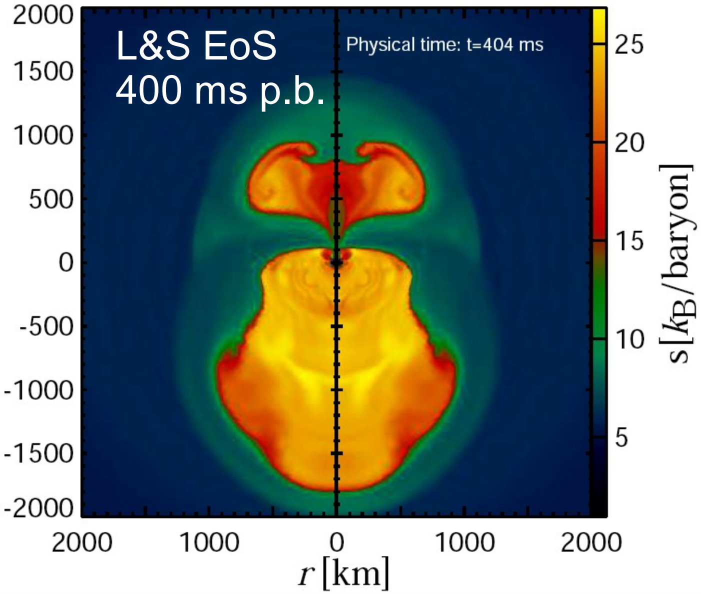
(Müller et al. 2011; Müller, THJ, Marek 2012)

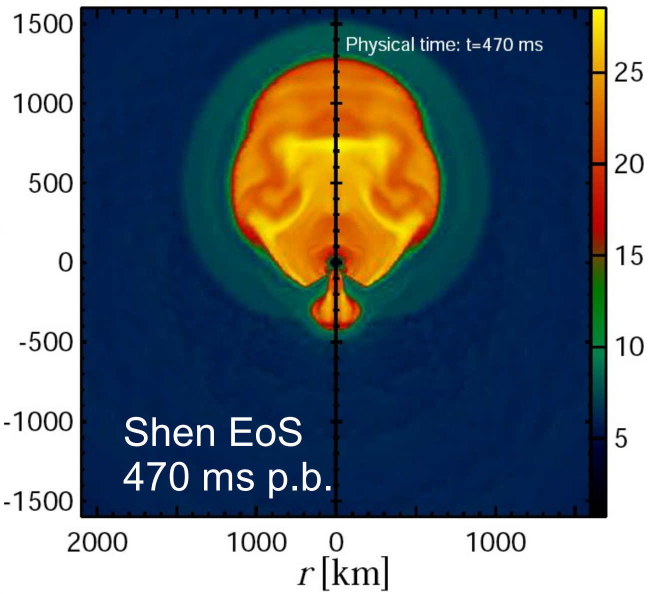


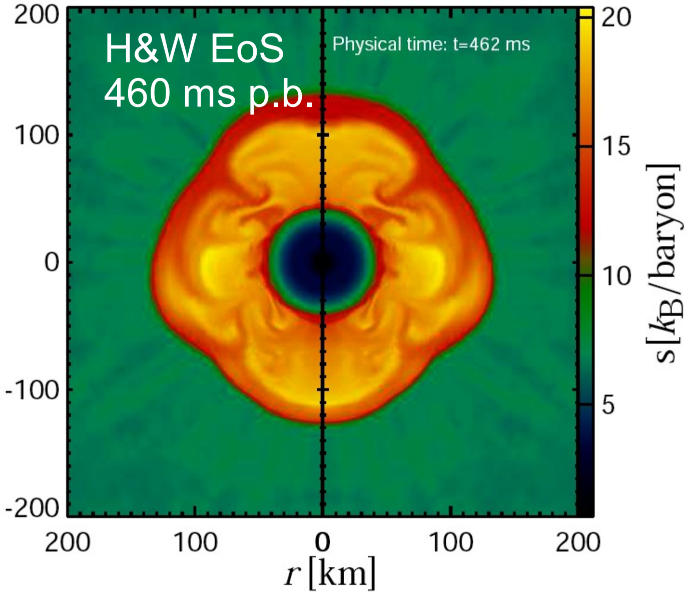


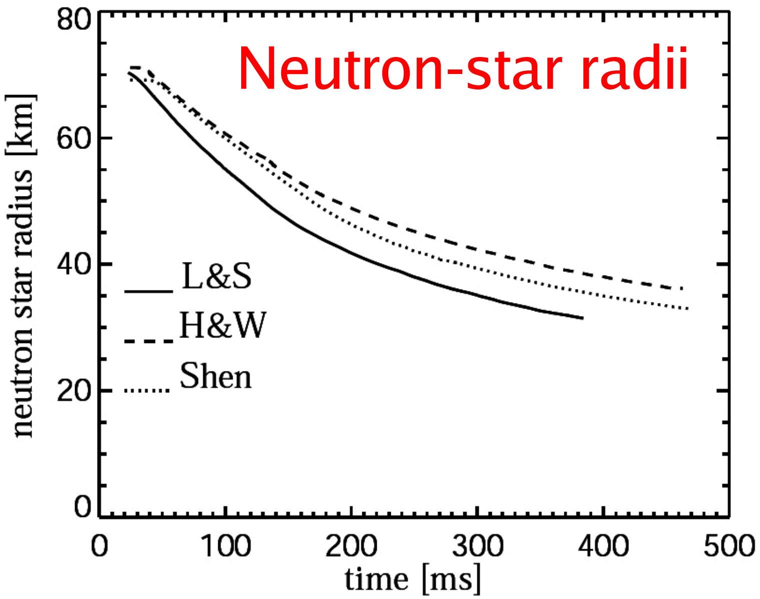
Influence of NS EoS

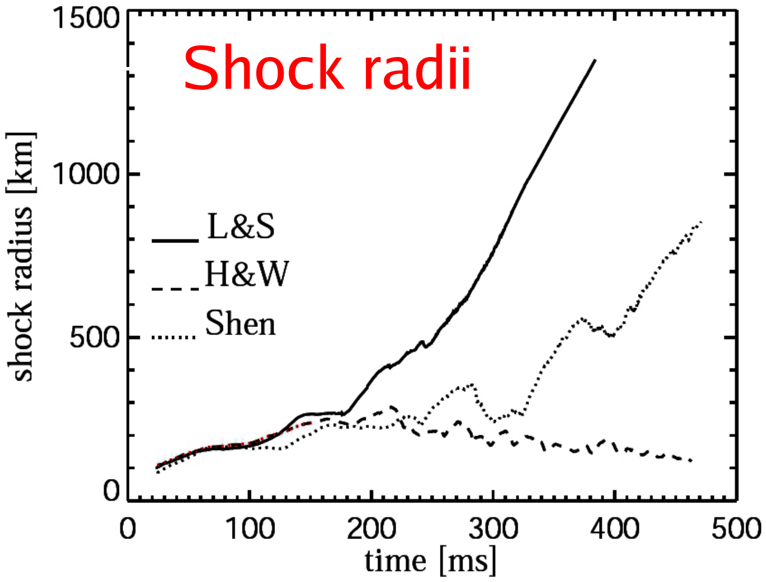
2D Explosions of 11.2 M_{sun} Star: Test of EoS Influence











(Andreas Marek 2010, unpublished; THJ, arXiv:1206.2503)

Test of EoS Influence

Connection between 1D shock stagnation radius and NS radius:

$$R_{\rm s} \propto \frac{(L_\nu \langle \epsilon_\nu^2 \rangle)^{4/9} R_{\rm ns}^{16/9}}{\dot{M}^{2/3} M_{\rm ns}^{1/3}} \propto \frac{R_{\rm ns}^{8/3} (k_{\rm B} T_\nu)^{8/3}}{\dot{M}^{2/3} M_{\rm ns}^{1/3}} \propto \frac{L_\nu^{4/3}}{\dot{M}^{2/3} M_{\rm ns}^{1/3} (k_{\rm B} T_\nu)^{8/3}}$$

$R_{\rm g} \propto R_{\rm ns}$

$L_\nu \propto R_{\rm ns}^2 T_\nu^4$, and $\langle \epsilon_\nu^2 \rangle \propto (k_{\rm B} T_\nu)^2$ for neutrino $(\nu \in \{\nu_e, \bar{\nu}_e\})$

(THJ; arXiv:1206.2503)

For study of influence of EoS without accretion feedback and PNS evolution, see S.M. Couch (arXiv:1206.4724)

Progenitor-Explosion and SN-Remnant Connections

Questions for SN Modeling in Astrophysical Context

- Astrophysical consequences of neutrino-driven SN explosions
- Compact-remnant masses of stellar core collapse
- Variation of explosion properties (explosion energy, nickel yield) in dependence of progenitors
- Comparison of neutrino-driven to piston-driven/artificial explosions
- What are the limits/constraints of neutrino-driven explosions?

Explosion Trigger

So far:

- Piston-driven explosions with chosen mass cut and explosion energy (e.g., Weaver & Woosley 1995, Zhang et al. 2010)
- "Thermal bombs" with predefined explosion energy (e.g., Aufderheide et al. 1998)
- Application of simple, parametric explosion criterion based on progenitor/bounce compactness (O'Connor & Ott 2011)
- Application of simple analytic theory of explosion energetics and fallback (Fryer 2006, Belczynski et al. 2011, Fryer et al. 2011)
- 2D explosions for ~0.5 seconds for few (3) progenitors (Fryer 1999, Fryer & Kalogera 2001)

Explosion Trigger

Now: (Ugliano, THJ, Marek, Arcones, arXiv:1205.3657)

- Self-consistent, parametrized neutrino-driven explosions in 1D: After onset of explosion follow neutron-star cooling for 15−20 s, continue to track SN explosion with fallback for days to weeks

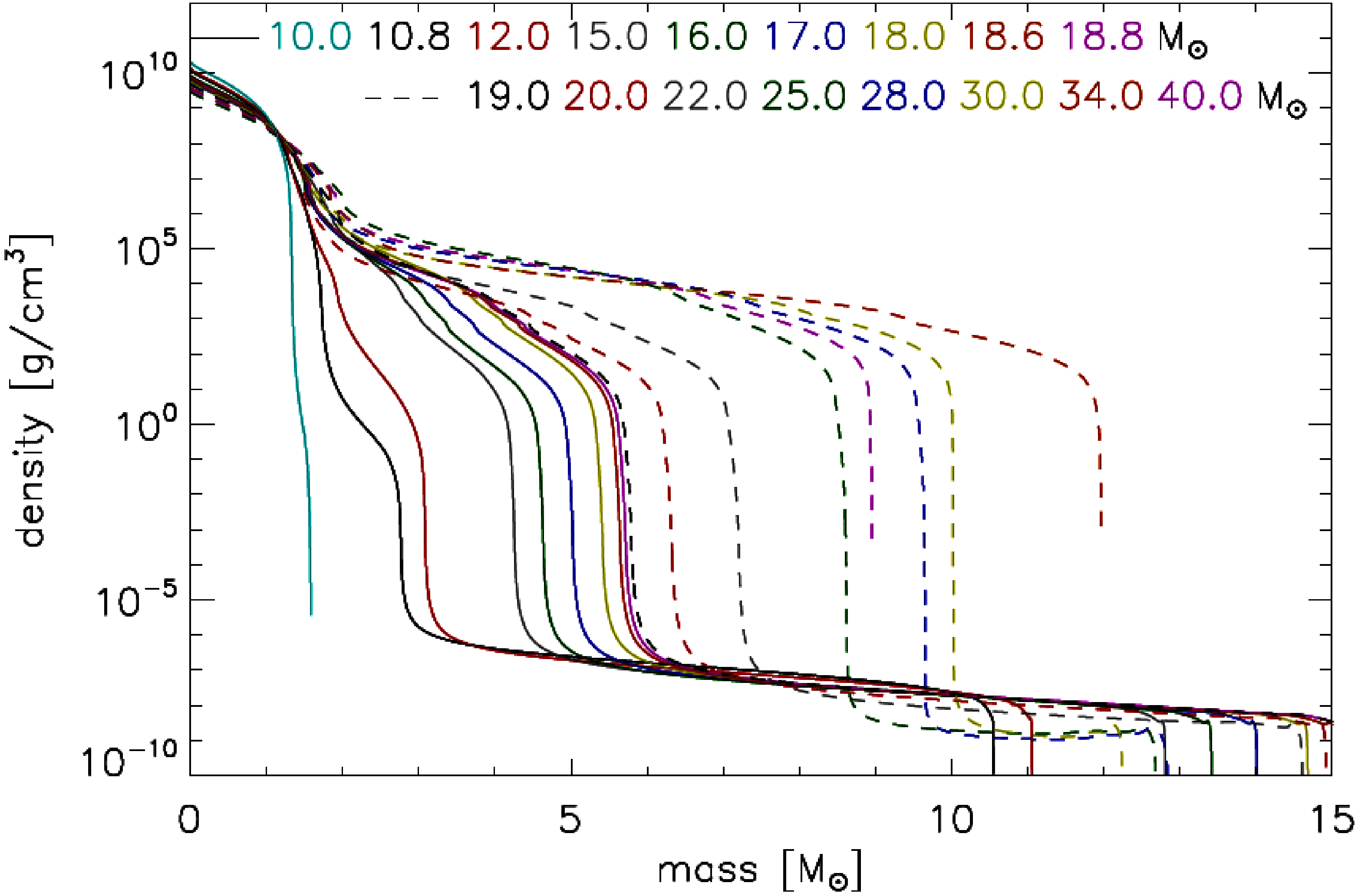
- Analytic, parametrized neutron-star core-cooling model, including self-consistent simulation of accretion luminosity

- Parameters of NS core-cooling calibrated for reproducing explosion energy, nickel mass, and (roughly) remnant mass/neutrino-energy loss observed for SN 1987A

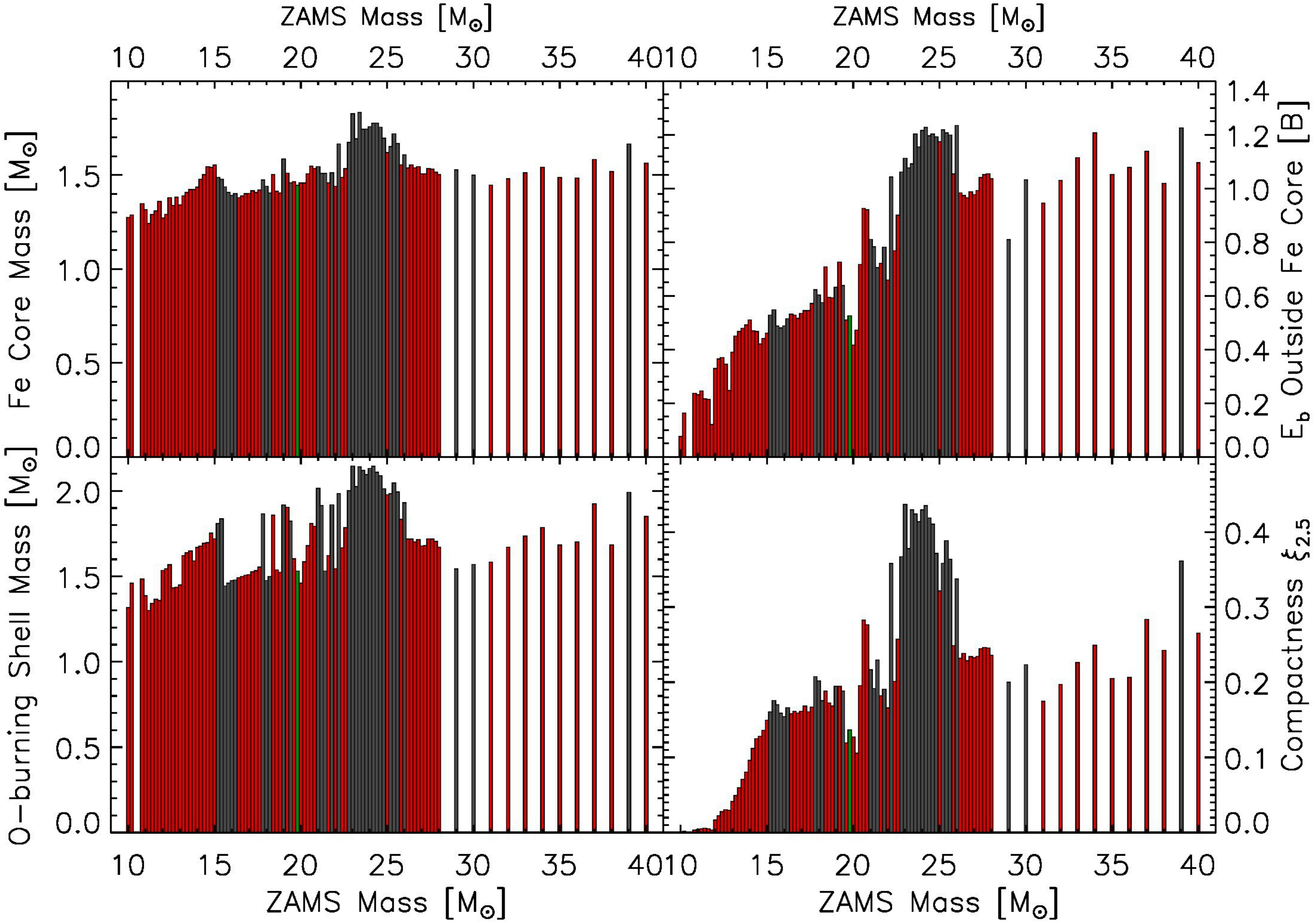
- Core-collapse simulations for 101 solar-metallicity progenitors (from Woosley, Heger, & Weaver 2002)

Progenitor Variations

Progenitor models from Woosley, Heger, & Weaver (2002)



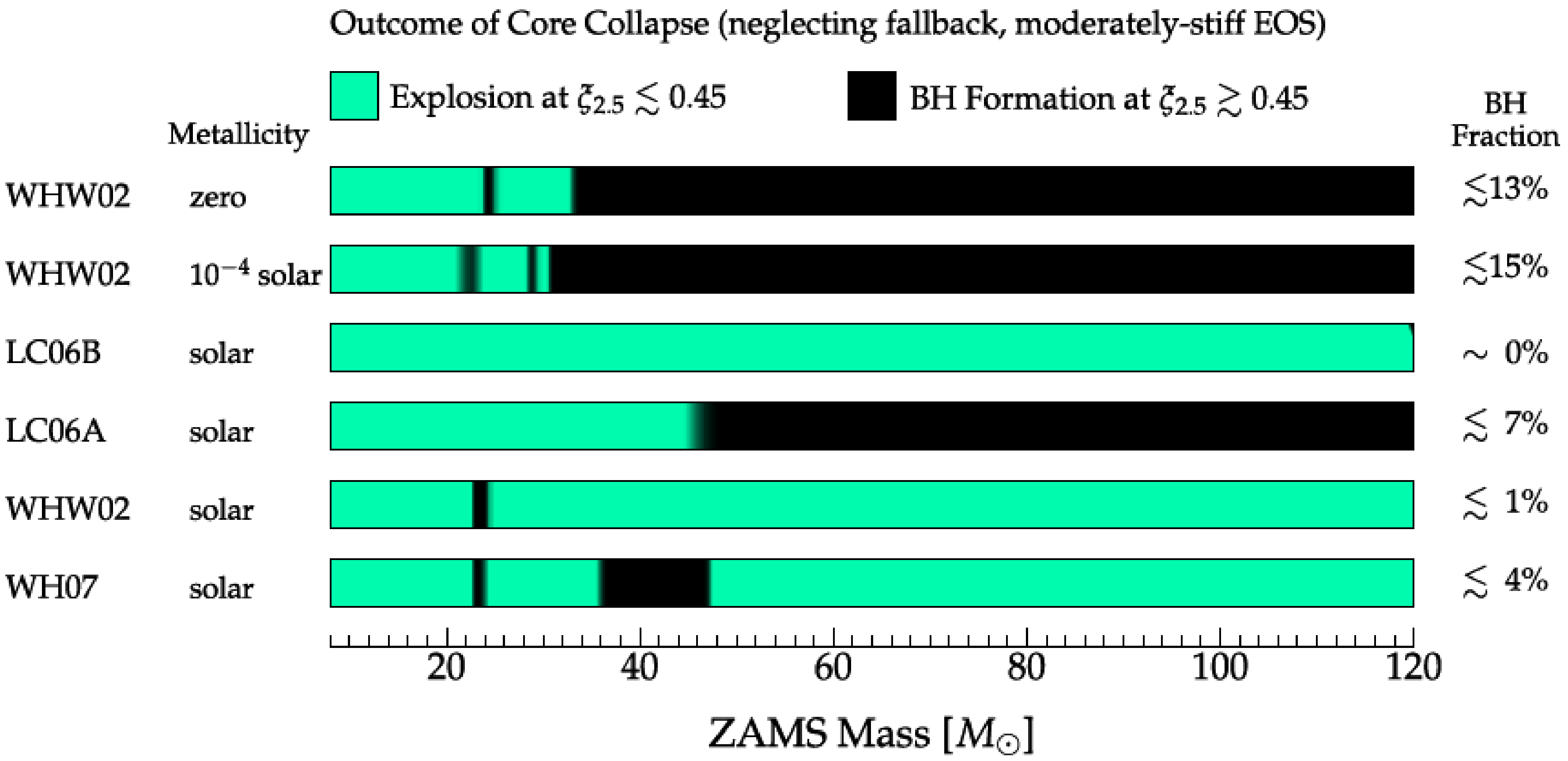
Progenitor Properties



Grey = BH formation cases

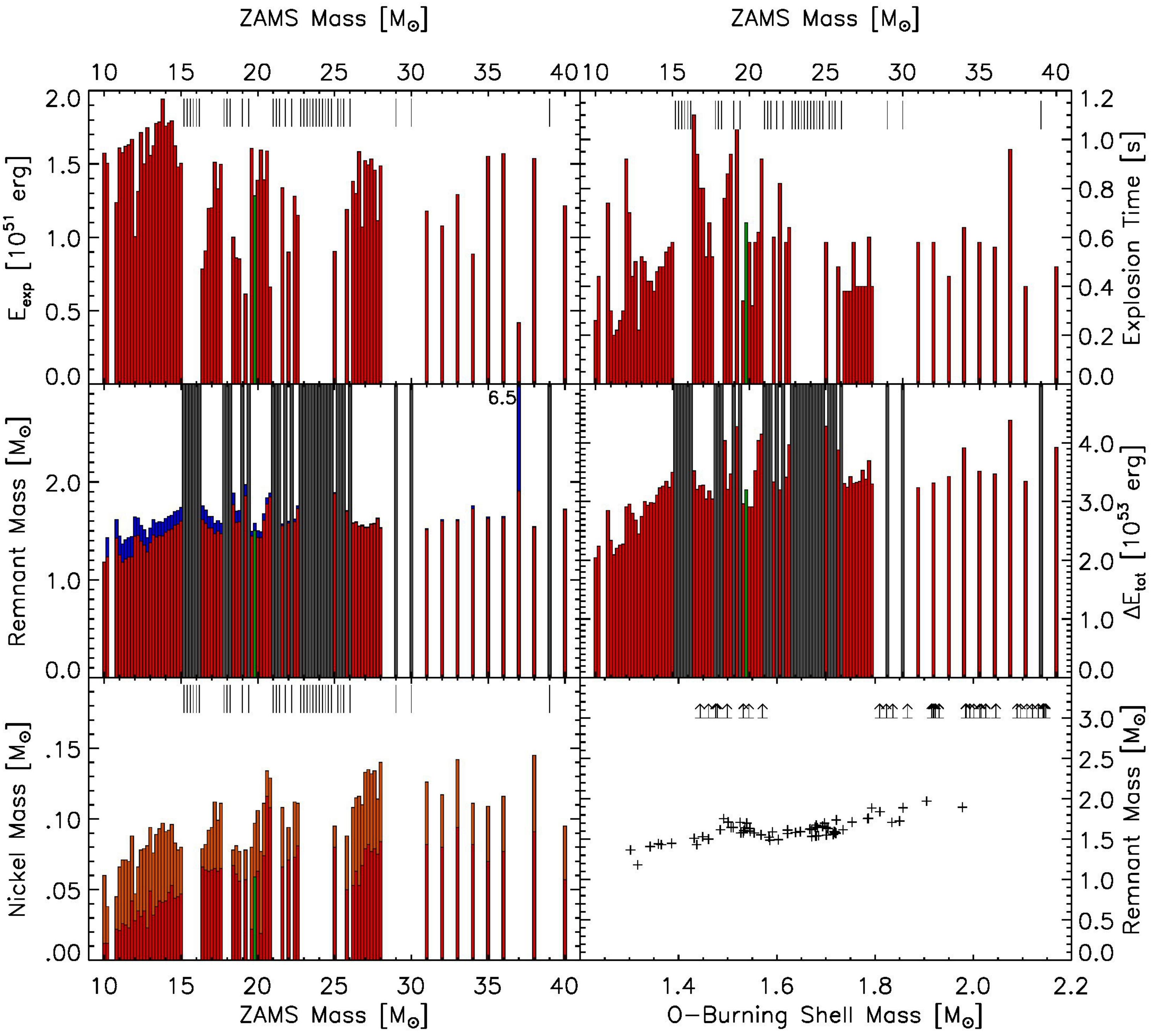
Ugliano, THJ, Marek, & Arcones
(arXiv:1205.3657)

NS and BH Regimes

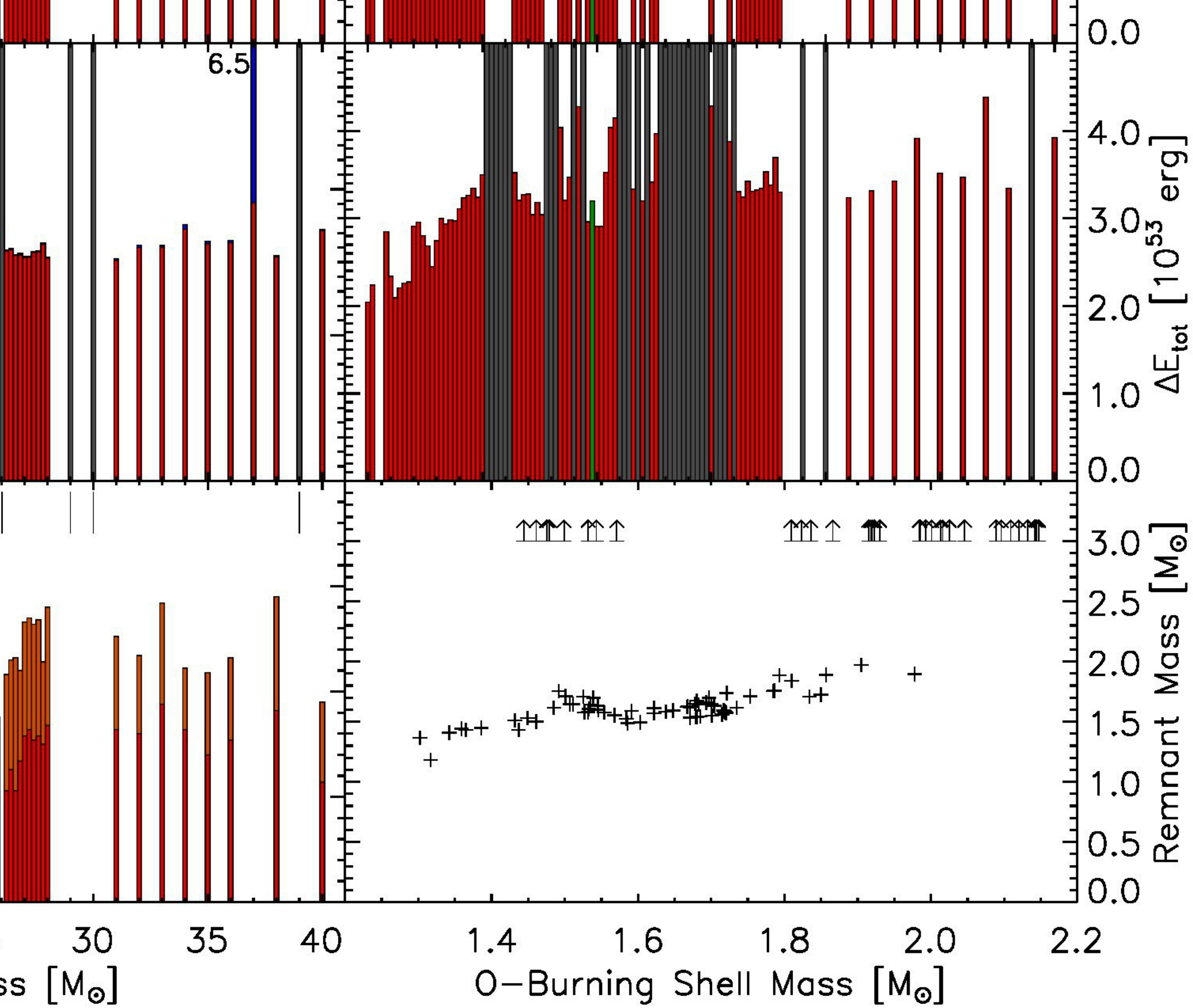


O'Connor & Ott, ApJ 730:70 (2011)

Explosion Properties

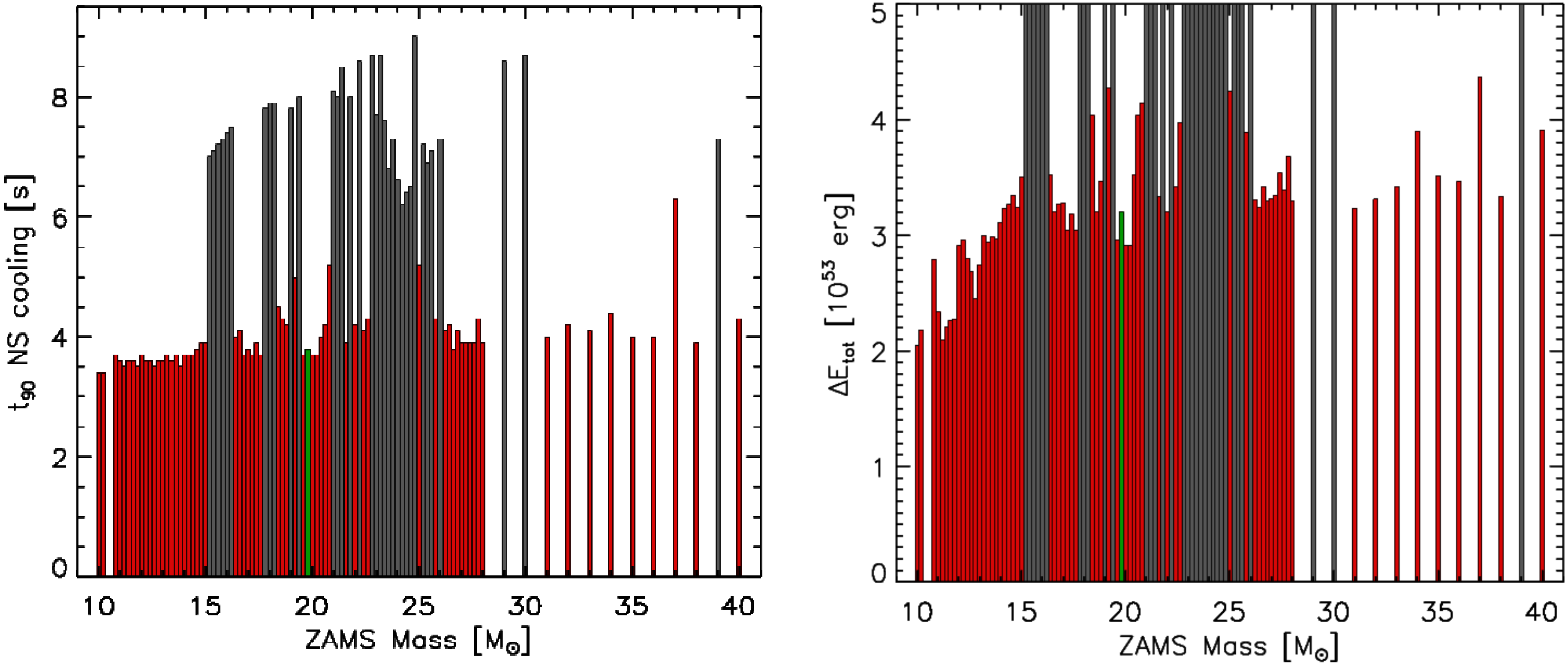


Ugliano, THJ, Marek, & Arcones (arXiv:1205.3657)

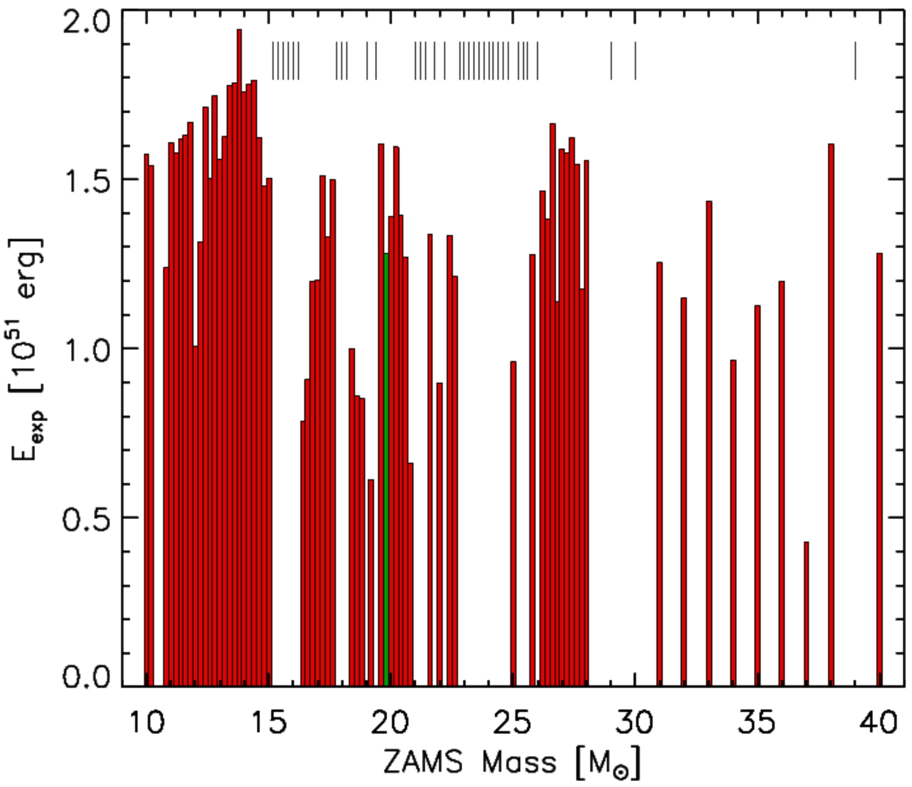


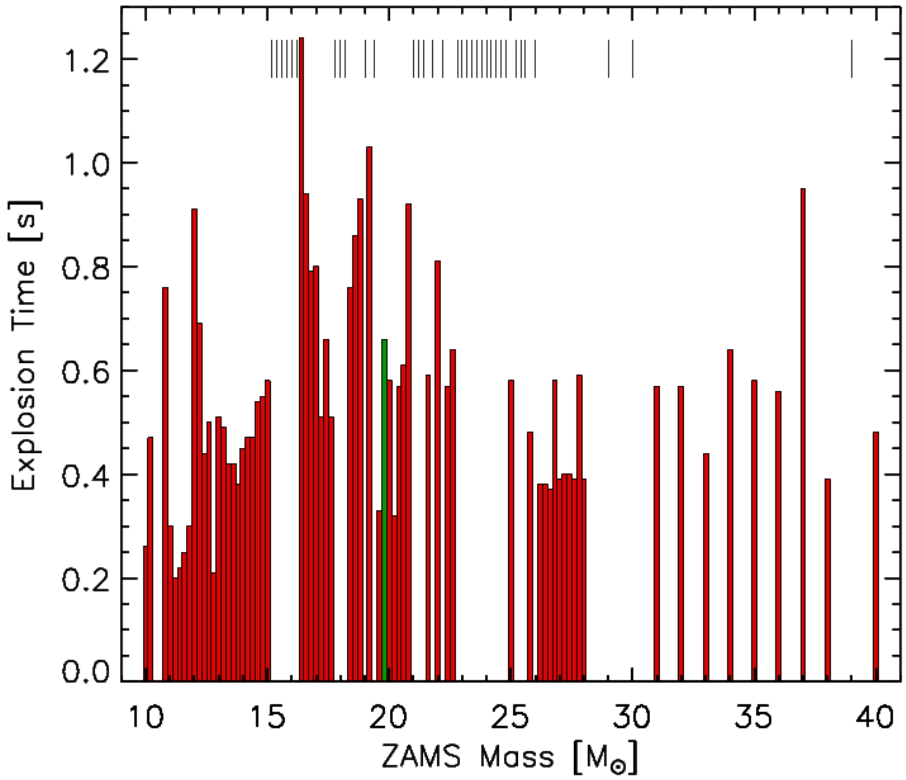
Ugliano, THJ, Marek, & Arcones (arXiv:1205.3657)

Neutrino Emission Timescale and Energy

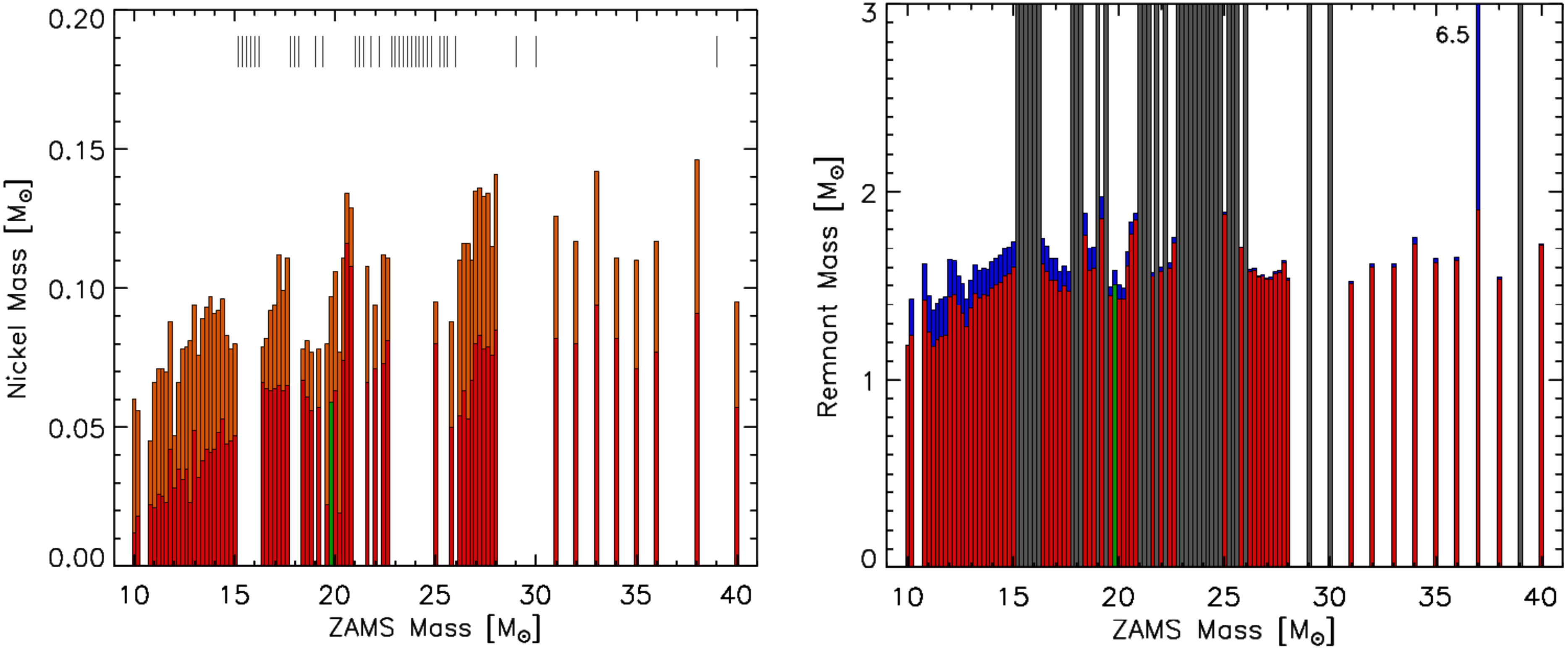


Explosion Time and Energy



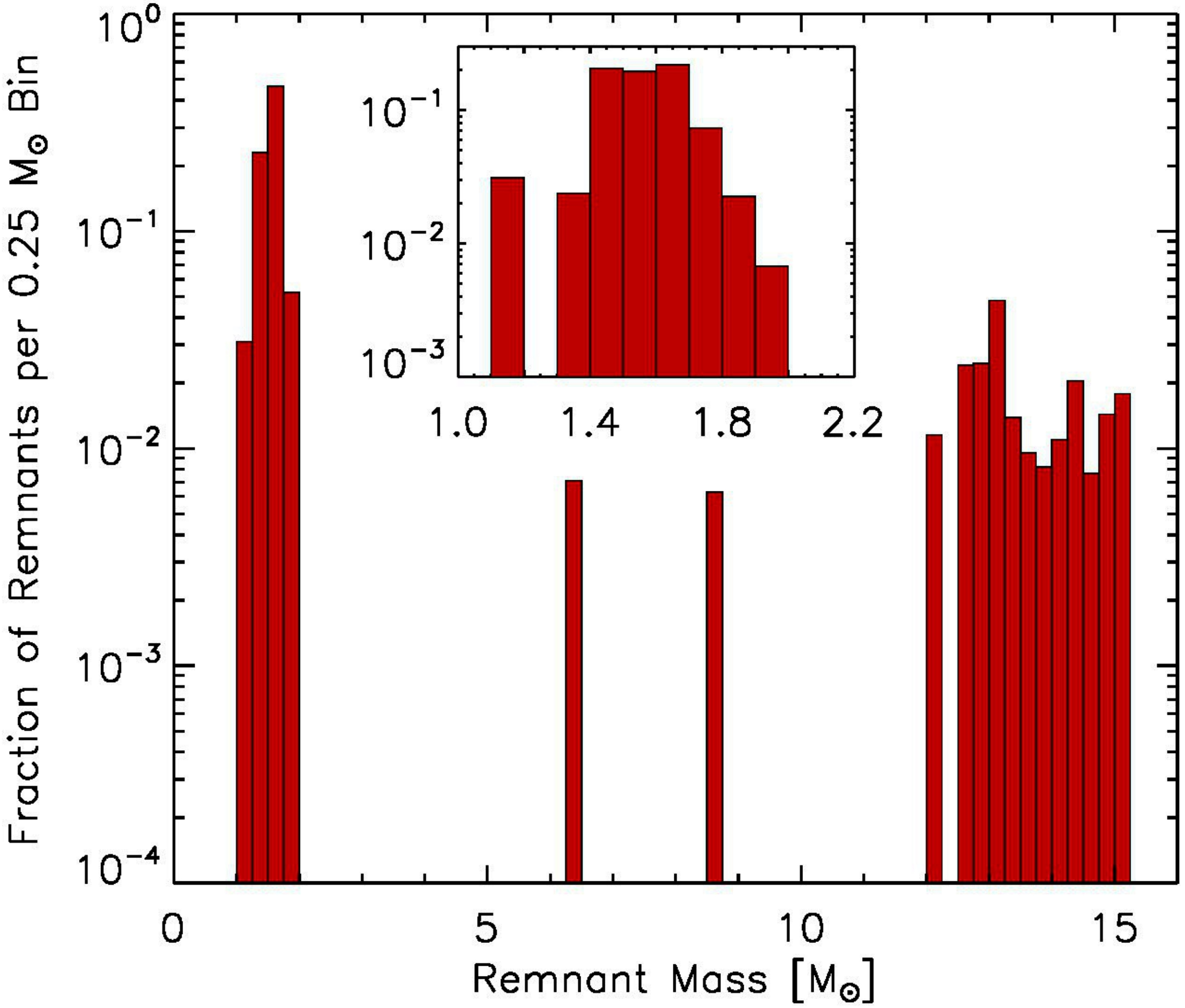


Ejected Ni Mass and Compact Remnant Mass



Remnant Mass Distribution

Model results folded with Salpeter IMF:
23% of all stellar core collapses produce BHs

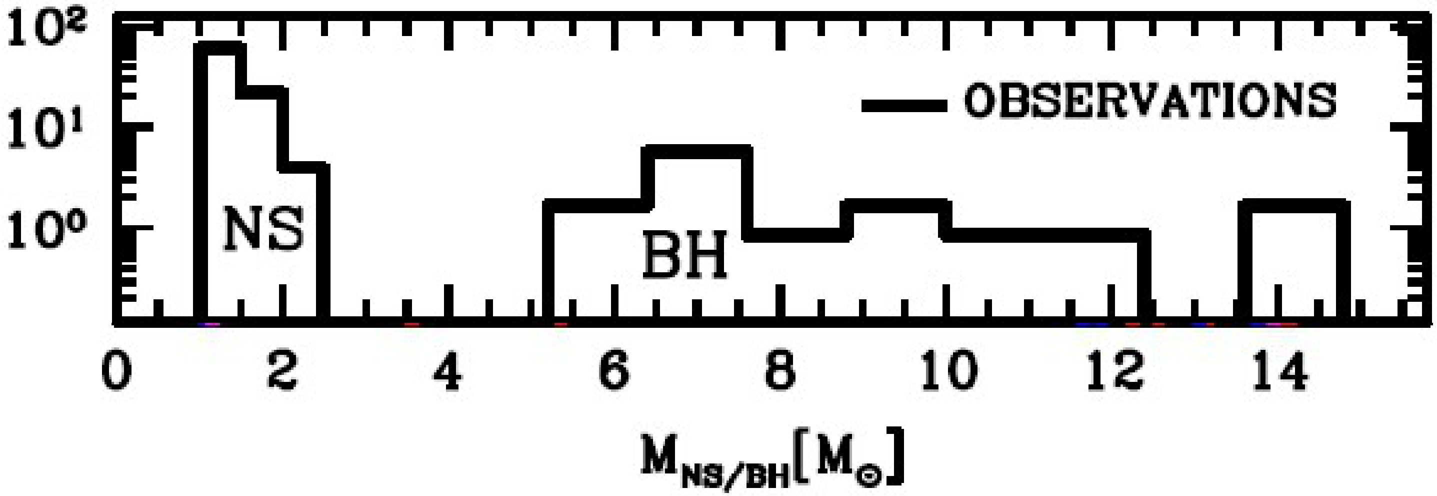


Baryonic Remnant Mass

Ugliano, THJ, Marek, & Arcones (arXiv:1205.3657)

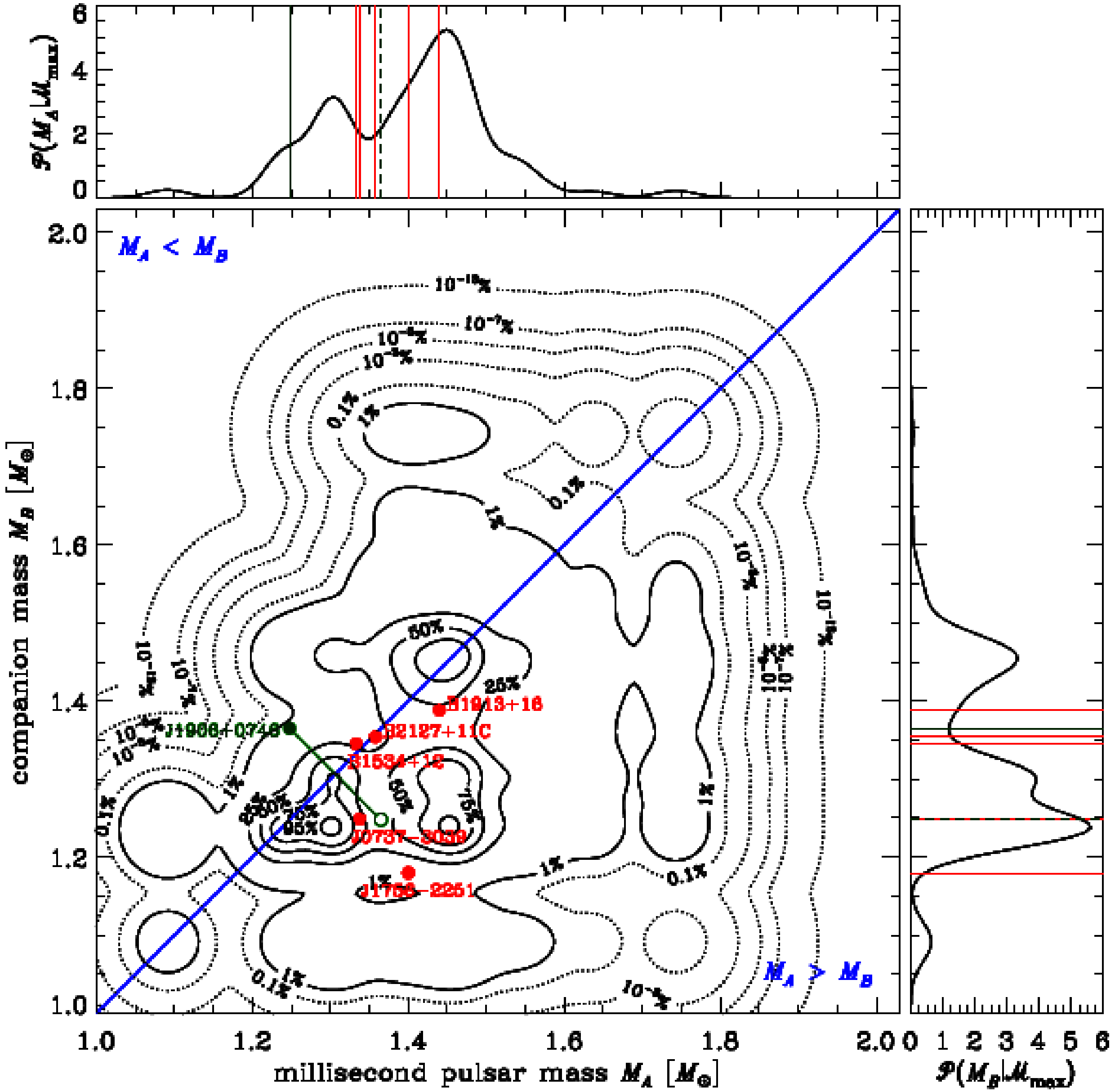
Remnant Mass Distribution

Model results reproduce possible gap in the observed distribution of NS and BH masses



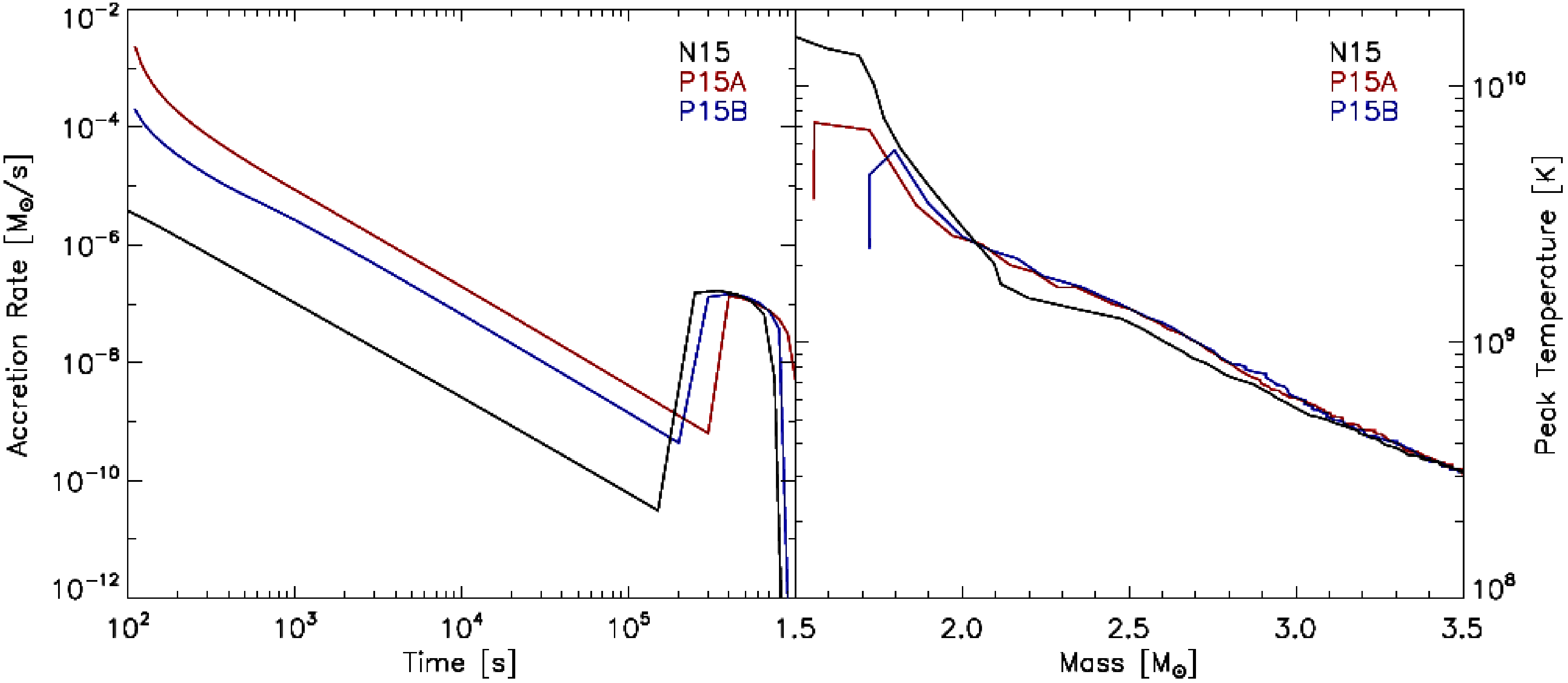
Belczynski et al. (2011)

Bayesian analysis: Observed double NS systems vs. theoretical mass distribution

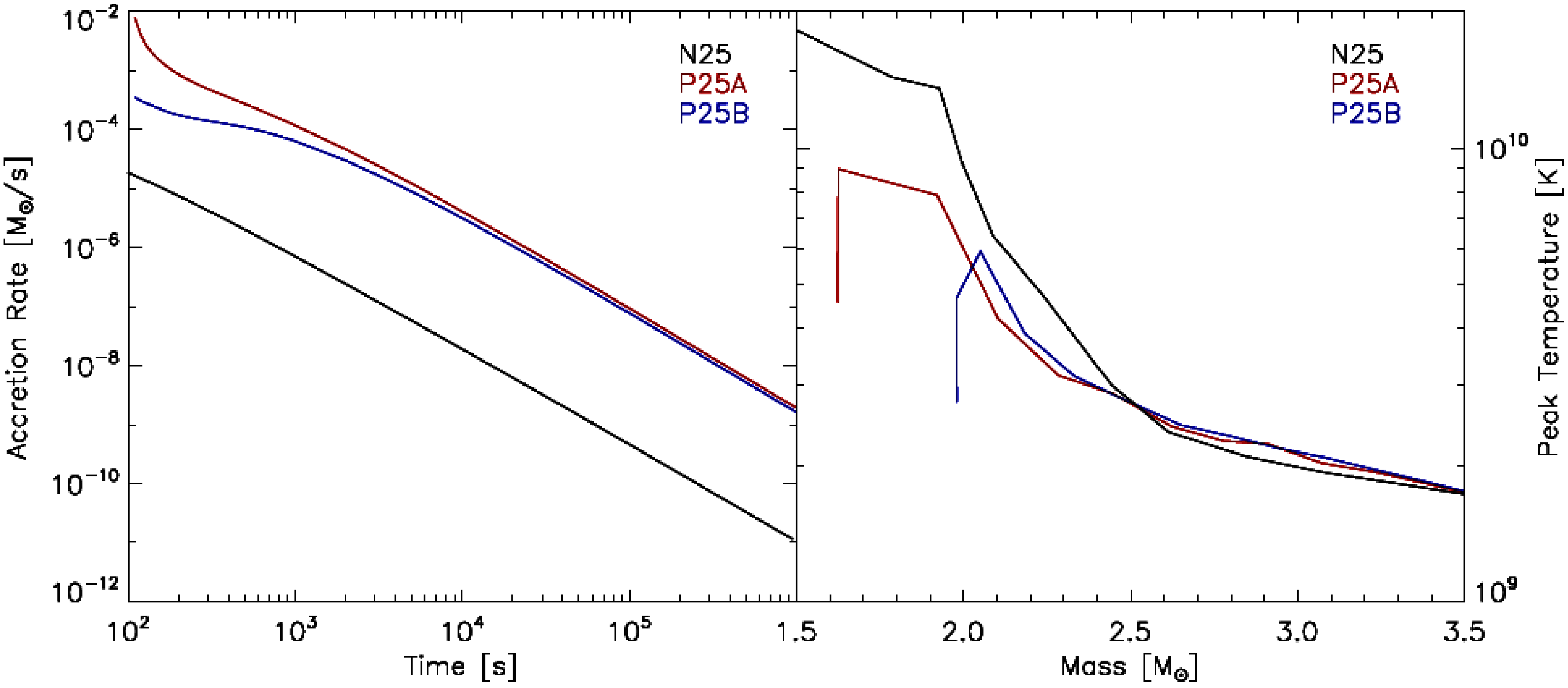


Pejcha, Thompson &
Kochanek, MNRAS (2012)

Piston vs. Neutrinos: Fallback



Piston vs. Neutrinos: Fallback



Results

- BH formation seems possible for progenitors with $M < 15\ M_{sun}$ (ZAMS mass).
- Neutrino-driven explosions can explain SN energies $< 2*10^{51}$ erg and nickel masses $< 0.2\ M_{sun}$.
- Hypernovae with higher energies and more Ni ejection seem to require a different mechanism.
- Gap of remnant distribution between NS and BH masses naturally occurs.
- Results of supernova and remnant systematics depend on set (e.g., metallicity) of progenitor models, of course.

Summary

- Understanding of SN explosion mechanism has made big progress.
- 2-dimensional relativistic models yield explosions for “soft” EoS. Explosion energy tends to be on low side.
- 3D modeling is needed.
- 3D models can explain observed pulsar kicks as well as mixing processes and global explosion asymmetries seen in SN 1987A and other supernovae.
- Neutrino-driven mechanism is likely to revise some of the existing paradigms for progenitor-supernova-remnant connection.