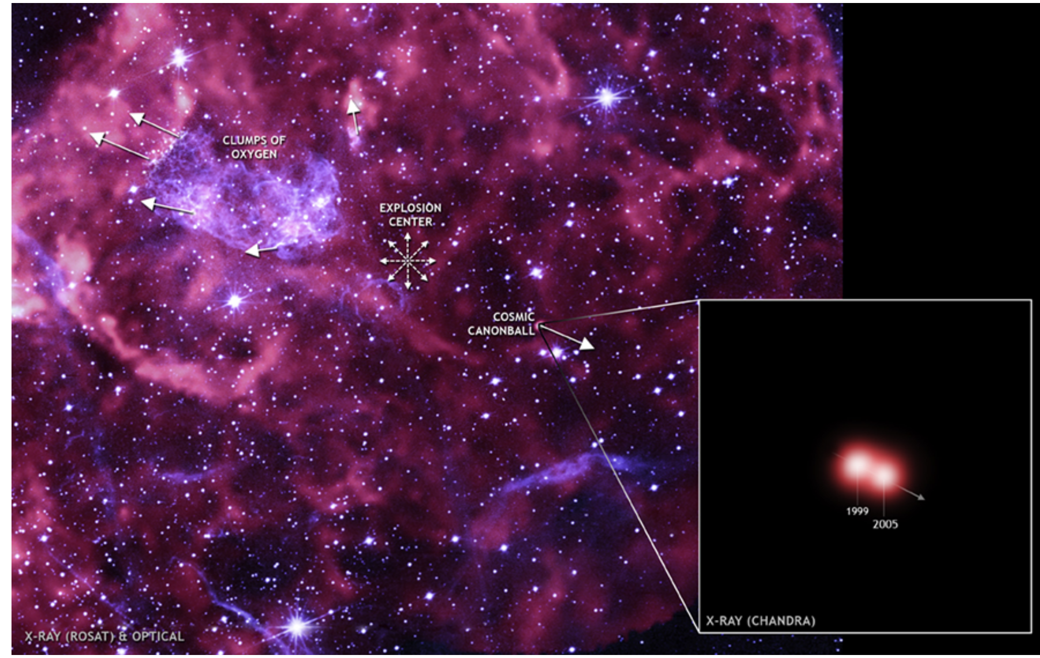
Neutrinos and Gravitational Waves from Core-Collapse Supernovae

B. Müller, MPA Garching

Report on work within the MPA core-collapse group by F. Hanke, H.-Th. Janka, A. Marek, B. Müller, E. Müller & A. Wongwathanarat

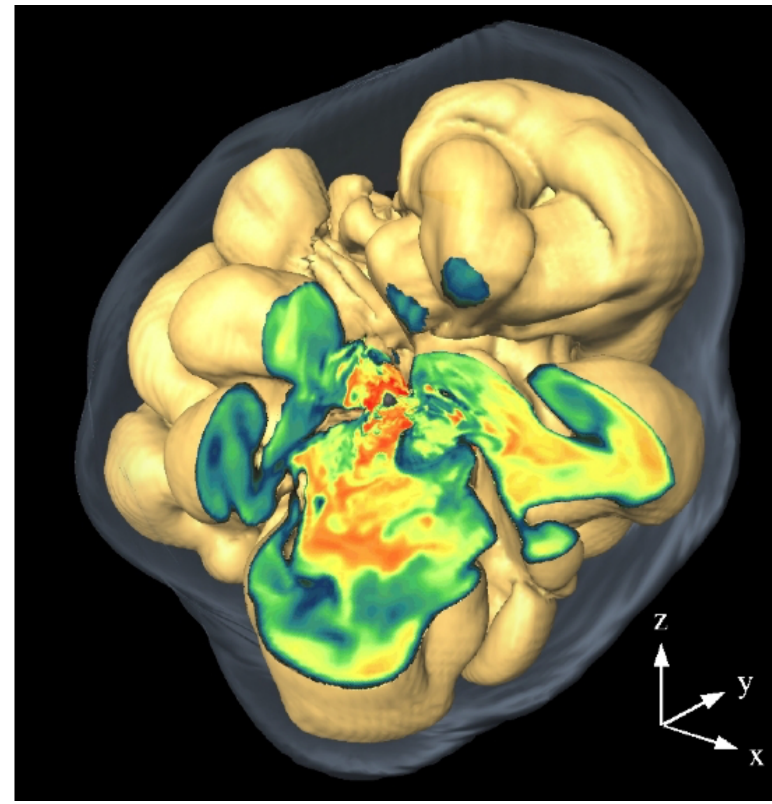
Major Issues in Supernova Physics

- How does the "engine" work?
- What can we observe?
  - **Neutrinos**
  - **Gravitational waves (?)**
  - Ejecta morphology
  - Pulsar kicks
  - Nucleosynthesis yields



Modelling Core-Collapse Supernovae

- Complex interplay of:
  - Neutrino transport
  - Muti-D hydrodynamic
  - Strong-field gravity (general relativity)
  - Nuclear & particle physics
- Various approaches around:
  - “Self-consistent” models, i.e. with energy-dependent transport (Boltzmann/variable Eddington factor/diffusion/IDSA, see also prec. talks)
  - More or less severely parametrized models (e.g. simplified neutrino transport, inner boundary instead of neutron star surface,...)



Hydrodynamic instabilities in core-collapse supernovae: convection & SASI

The Garching Approach to Neutrino Transport in Core-Collapse SNe

- Current status: multi-dimensional (2D) **GR hydro and energy-dependent neutrino transport** for core-collapse supernovae combined for the first time (best so far: modified gravitational potential + transport)
- Hydro and metric: CoCoNuT code (Dimmelmeier et al. 2002)
  - HRSC scheme with PPM reconstruction, HLLC solver
  - Metric in xCFC approximation (Cordero-Carrión et al. 2009, very accurate for core collapse case), but extendible to maximally constrained formulation of the field equations (Bonazzola et al. 2004, Cordero-Carrión 2010)
  - Graviational extraction modified with quadrupole formula at the moment
- Neutrino transport: based on VERTEX code (Rampp et al. 2002)
  - **Energy-dependent** GR transport with variable Eddington factor method and ray-by-ray-plus method for multi-dimensional case
  - **Up-to-date set of interaction rates**

Neutrino moment equations

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

$$
\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(W v_r\frac{\alpha}{\phi^2}-\beta_r\right)\hat{H}\right]- \\
&\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. \\
&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]- \\
&\left.\varepsilon\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_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\}+ \\
&\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]+ \\
&\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}-W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right)+\frac{\partial W}{\partial t}\right]- \\
&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]- \\
&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]+ \\
&\hat{L}\left[\frac{\beta_r W}{r}-\frac{\partial\beta_r W}{\partial r}+W v_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}
$$

K, L needed from model Botzmann eq.

Simplified (model) Boltzmann equation

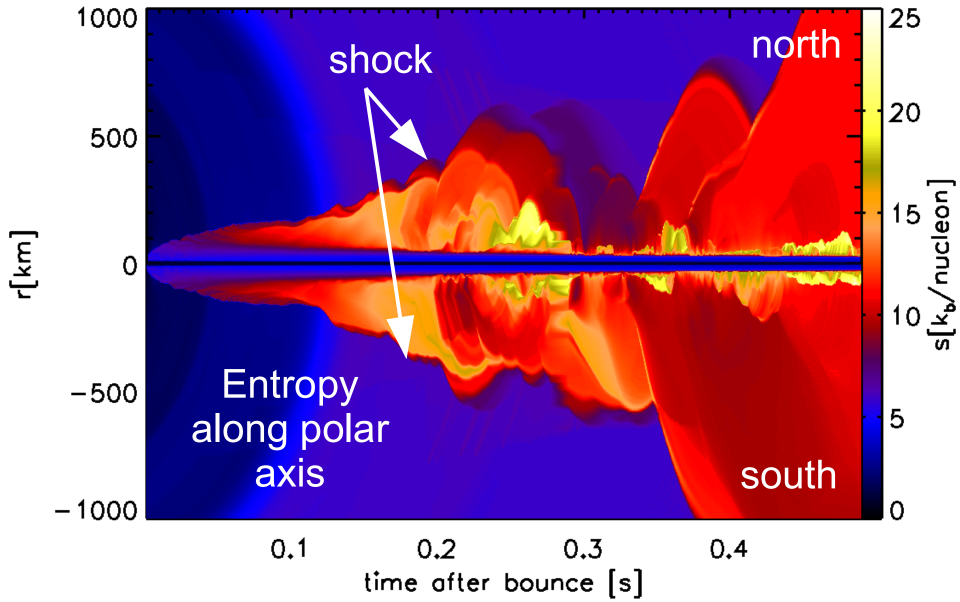
$$
\begin{aligned}
&\frac{\partial\mathcal{I}}{\partial t}+\left(\frac{\alpha v_r}{\phi^2}-\beta^r\right)\frac{\partial f}{\partial r}+\frac{\alpha\mu}{\phi^2}\frac{\partial f}{\partial r}+\mathcal{I}\left[(3-\mu^2)\frac{\alpha v_r}{r\phi^2}\right. \\
&\left.+(1+\mu^2)\alpha\phi^2\frac{\partial v_r}{\partial r}+2\alpha\mu\frac{\partial v_r}{\partial t}\right]-\frac{\partial\mathcal{I}}{\partial\varepsilon}\left\{\varepsilon\left[(1-\mu^2)\frac{\alpha v_r}{r\phi^2}\right.\right. \\
&\left.\left.+\mu^2\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}+\alpha\mu\frac{\partial v_r}{\partial t}\right]\right\}+\frac{\alpha(1-\mu^2)}{r\phi^2}\frac{\partial\mathcal{I}}{\partial\mu}+\frac{\partial}{\partial\mu} \\
&\times\left\{(1-\mu^2)\left[\mu\left(\frac{\alpha v_r}{r\phi^2}-\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r}\right)-\mu\alpha\frac{\partial v_r}{\partial t}\right]\mathcal{I}\right\}=C[\mathcal{I}].
\end{aligned}
\tag{37}
$$

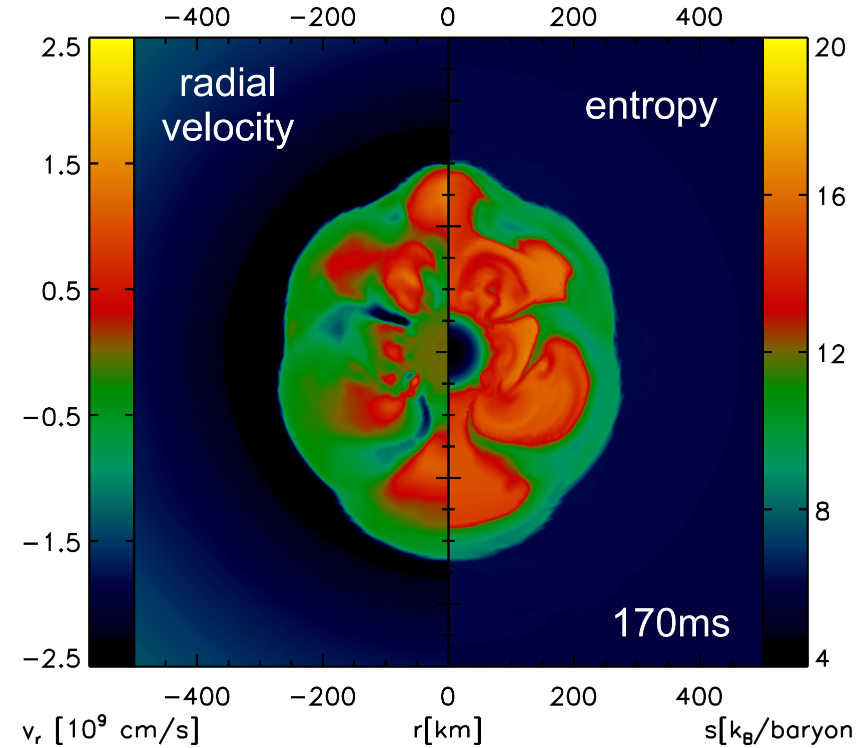
C from solution of moment eqs.

Neutrino microphysics in collision integral
$\nu + A \rightleftharpoons \nu + A$
$\nu\ e^{\pm} \rightleftharpoons \nu\ e^{\pm}$
$\nu\ N \rightleftharpoons \nu\ N$
$\nu_e\ n \rightleftharpoons e^-\ p$
$\bar{\nu}_e\ p \rightleftharpoons e^+\ n$
$\nu_e\ A' \rightleftharpoons e^-\ A$
$\nu + \bar{\nu} \rightleftharpoons e^-\ e^+$
$\nu\bar{\nu}\ NN \rightleftharpoons NN$
$\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau} \rightleftharpoons \nu_e\bar{\nu}_e$
$\overset{(-)}{\nu}_{\mu,\tau}\ \overset{(-)}{\nu}_e \rightleftharpoons \overset{(-)}{\nu}_{\mu,\tau}\ \overset{(-)}{\nu}_e$

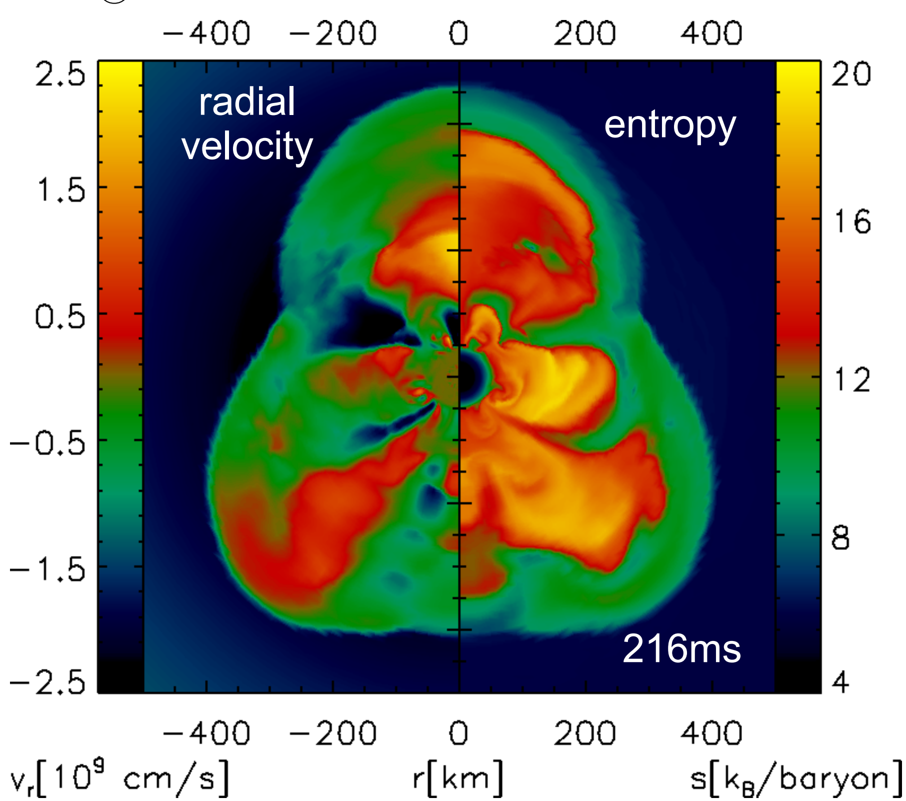
Current Results

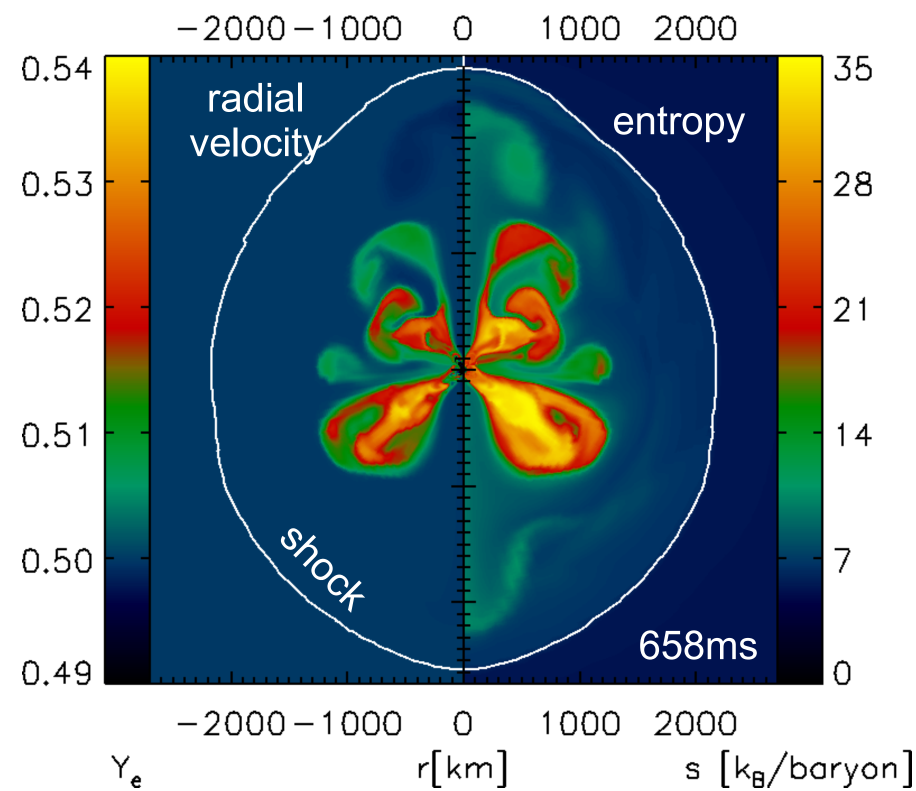
- GR explosion models for 11.2$M_\odot$ and 15$M_\odot$ progenitors, evolved several 100ms into the explosion
- Questions to be addressed:
  - Neutrino & gravitational wave signal for different phases (accretion, explosion)
  - Influence of GR on these observables (e.g. typical frequencies of gravitational waves & neutrino luminosity fluctuations)
  - Heating conditions in GR (may help somewhat for the explosion for more massive progenitors)

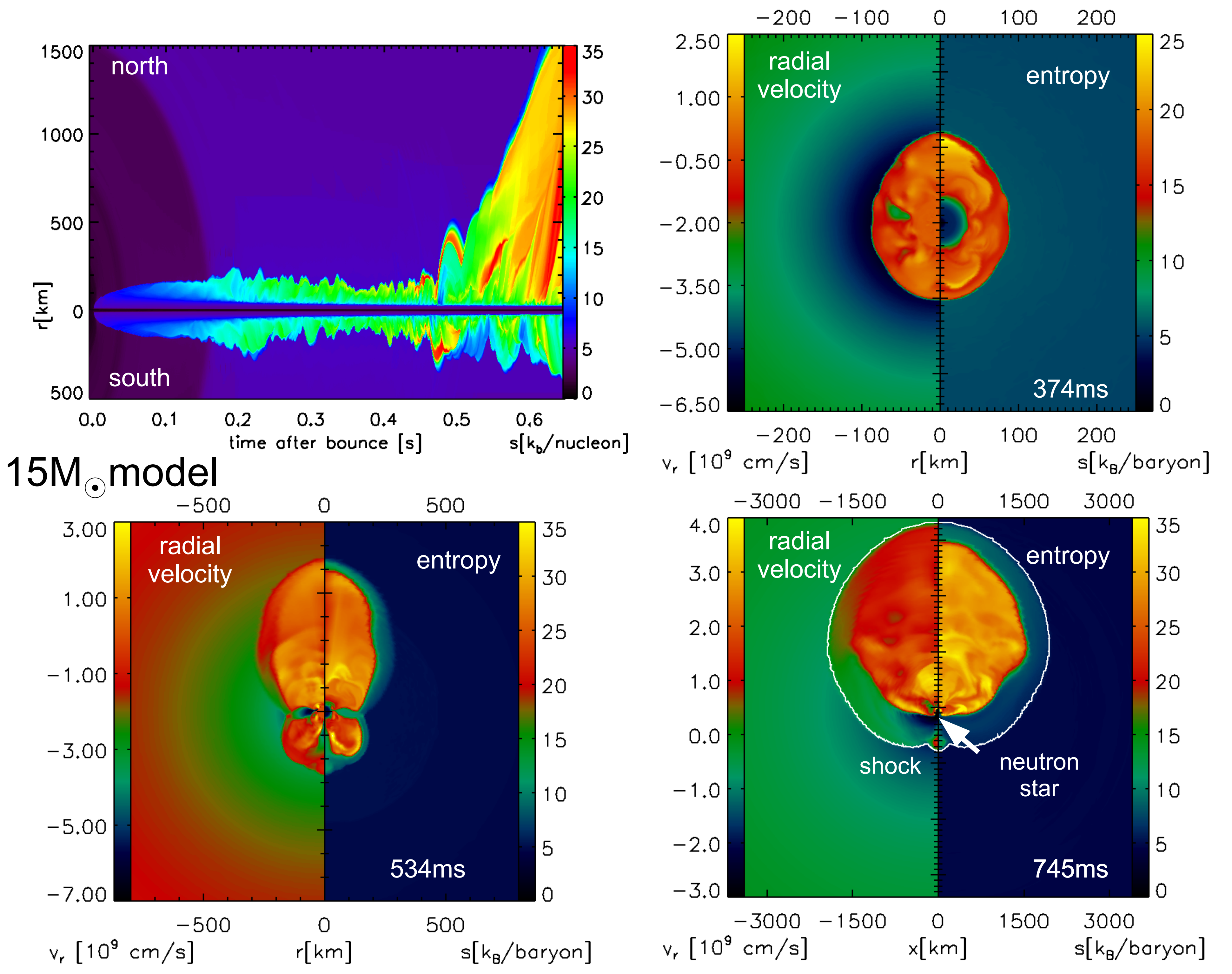




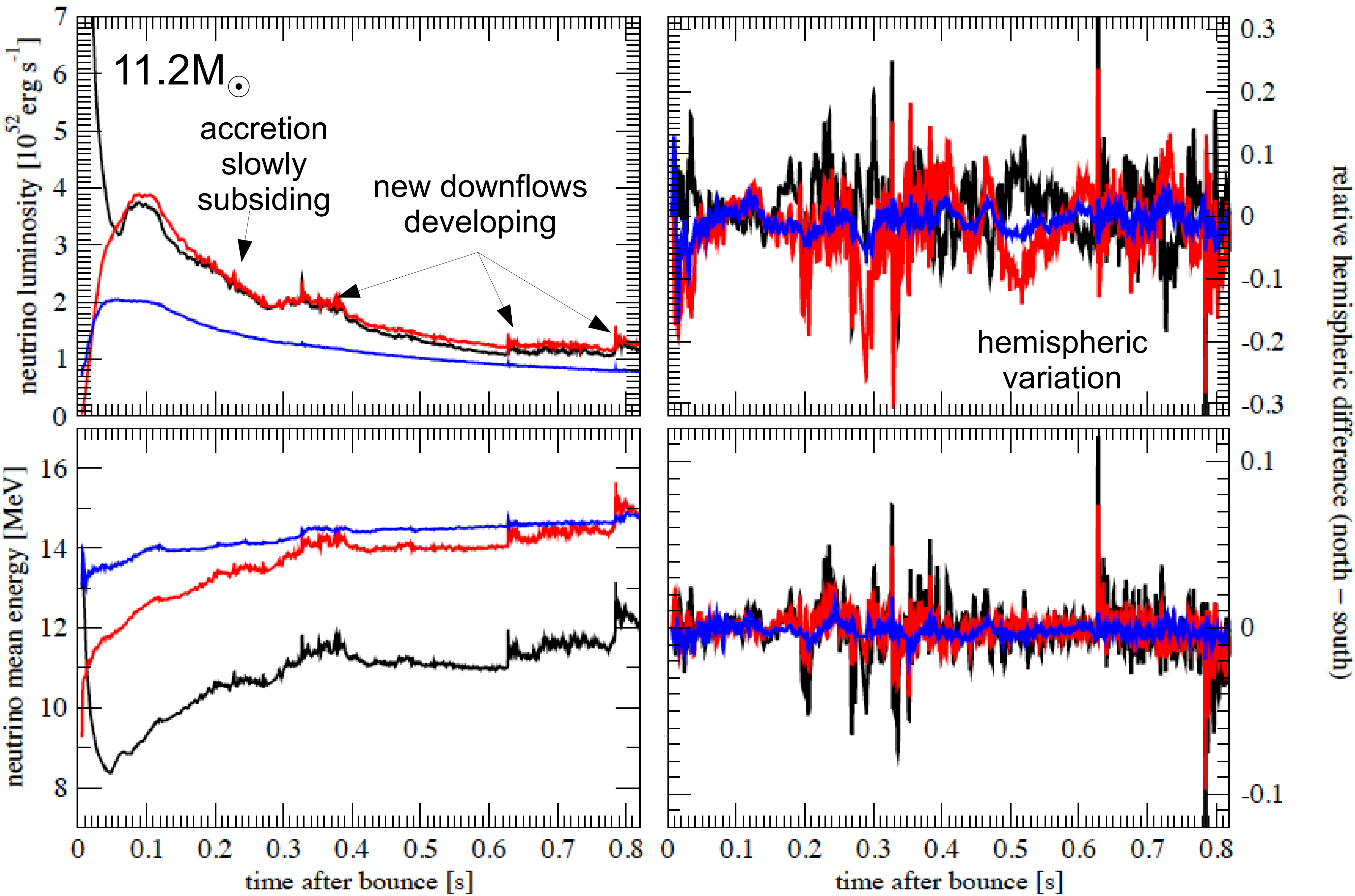
$11.2M_\odot$ model






north
south
r[km]
time after bounce [s]
s[k_b/nucleon]
15M☉model
radial velocity
entropy
374ms
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
radial velocity
entropy
534ms
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
radial velocity
entropy
shock
neutron star
745ms
v_r [10^9 cm/s]
x[km]
s[k_B/baryon]

Translating the dynamics into the ν-signal



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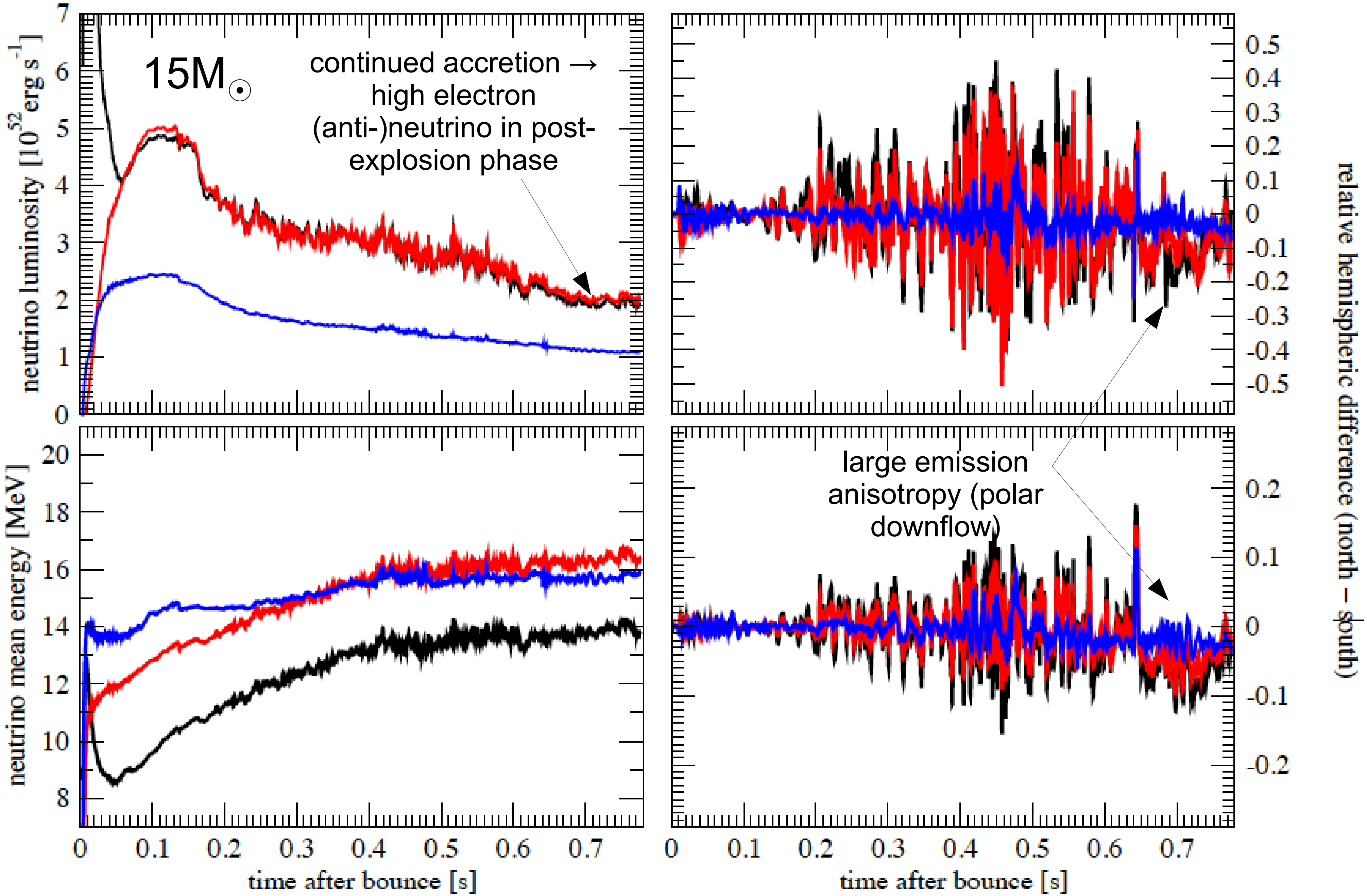
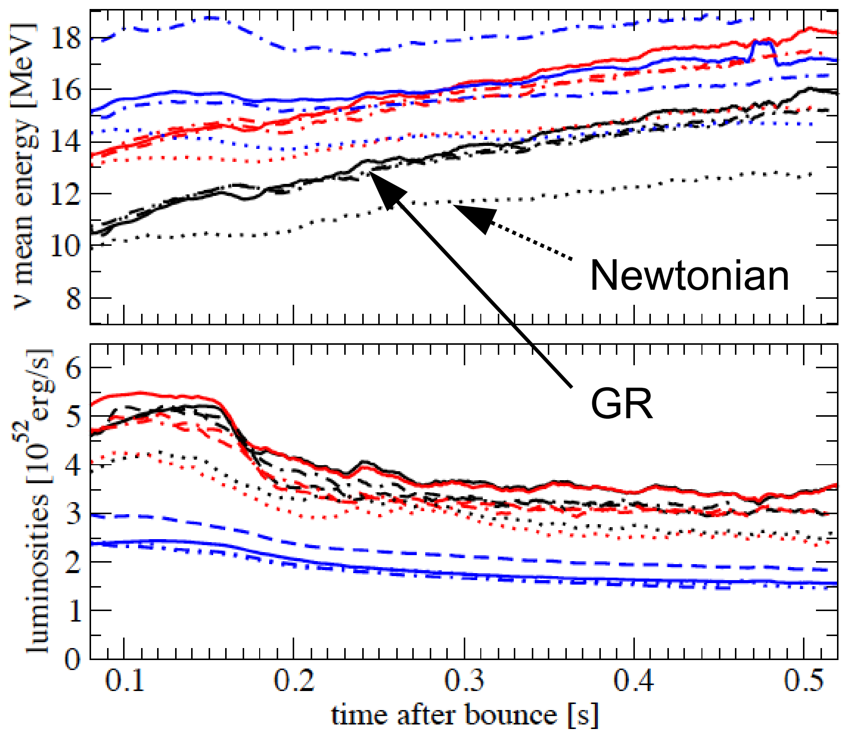


Neutrinos from 2D Explosion Models

- Summary of conspicuous features
  - SASI-induced oscillatory anisotropies as in Newtonian case (frequency 50...100Hz → SASI frequencies), cp. Ott et al. (2008), Marek et al. (2009), Lund et al. (2010), Brandt et al. (2011) for fluctuations
  - High ν_e and anti-ν_e luminosities after the onset of the explosion for more massive progenitor → nucleosynthesis
  - Large (10..20%) emission anisotropy for strongly asymmetric explosion
- Perspectives for non-linear flavour oscillation? Viability for early phase doubtful according to recent studies (Dasgupta et al. 2011, Chakraborty et al. 2011)



Neutrino mean energy & luminosity at gain radius: GR vs. Newtonian approximation (cp. Bruenn et al. 2001)

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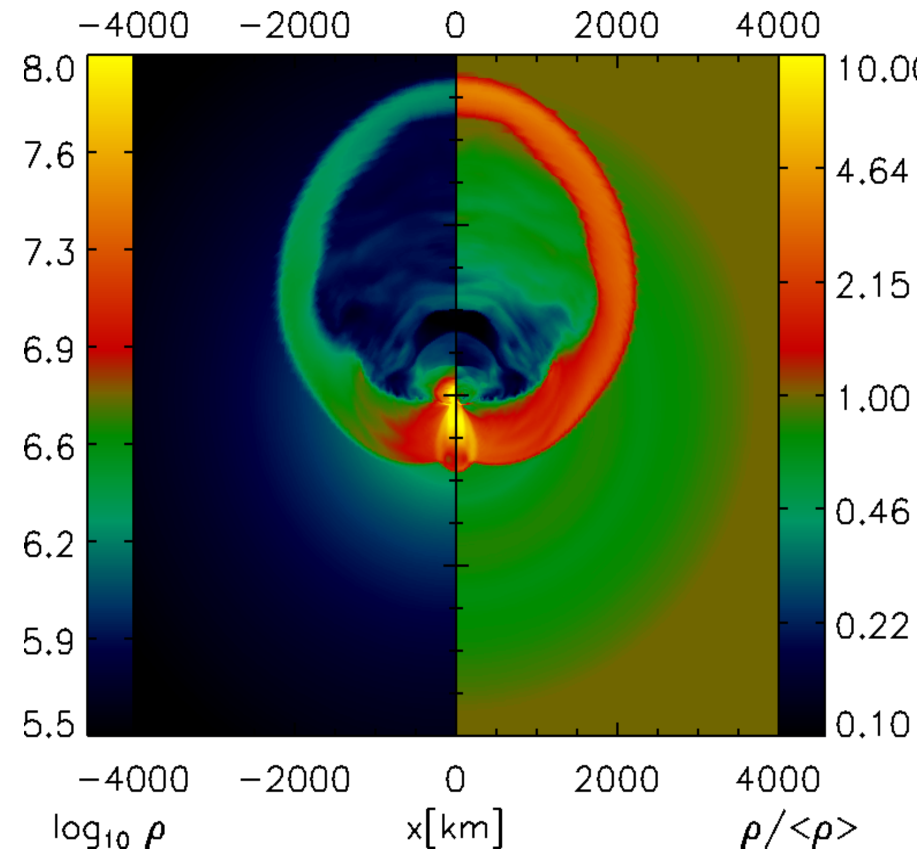
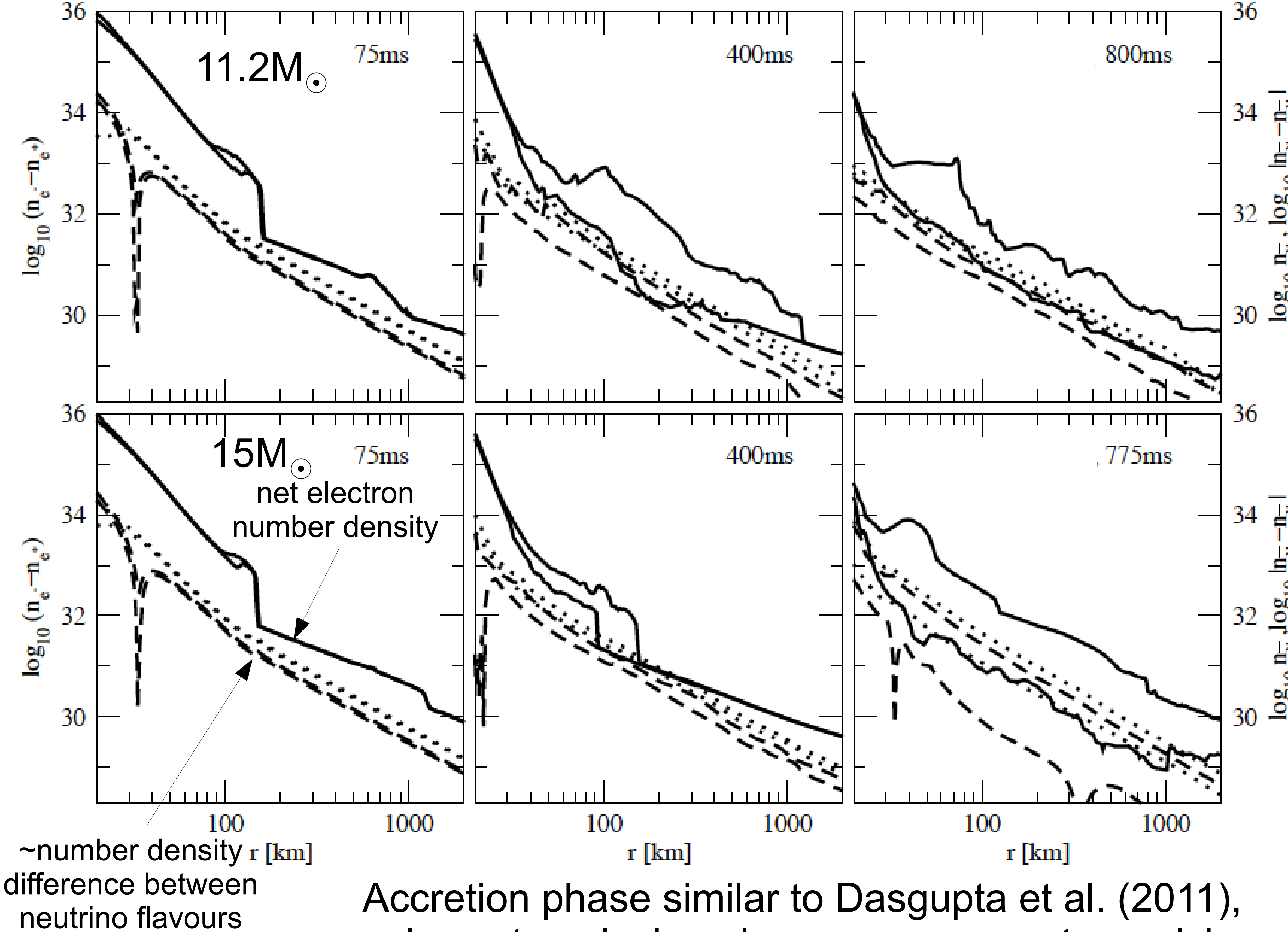


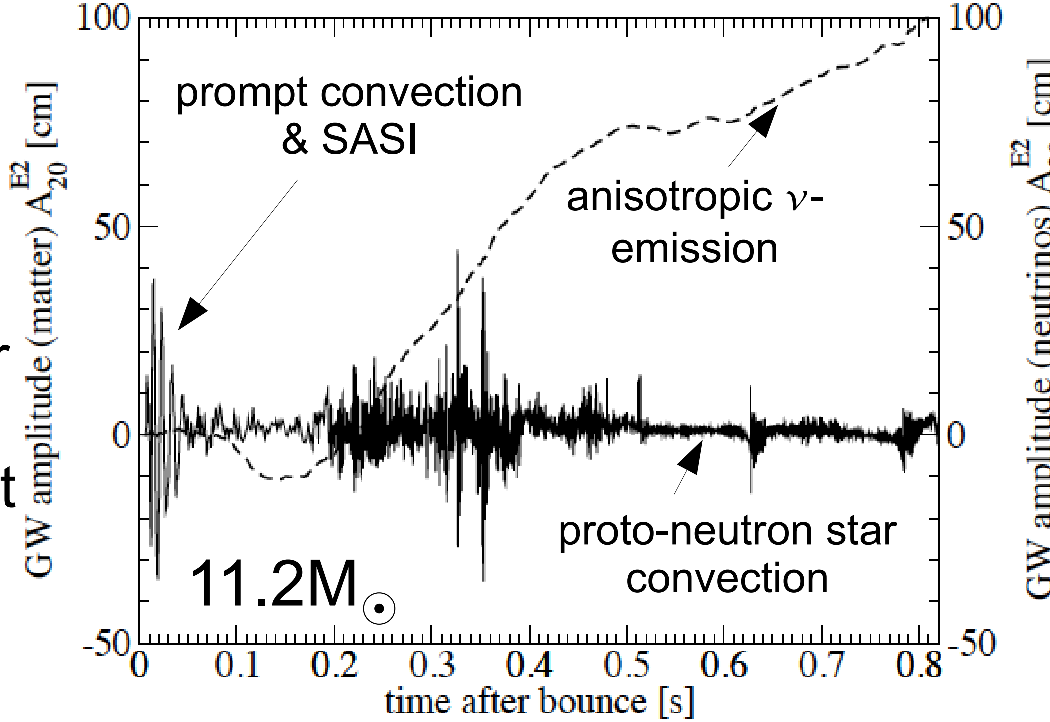
Density anisotropy for $15M_{\odot}$ model, 775ms after bounce

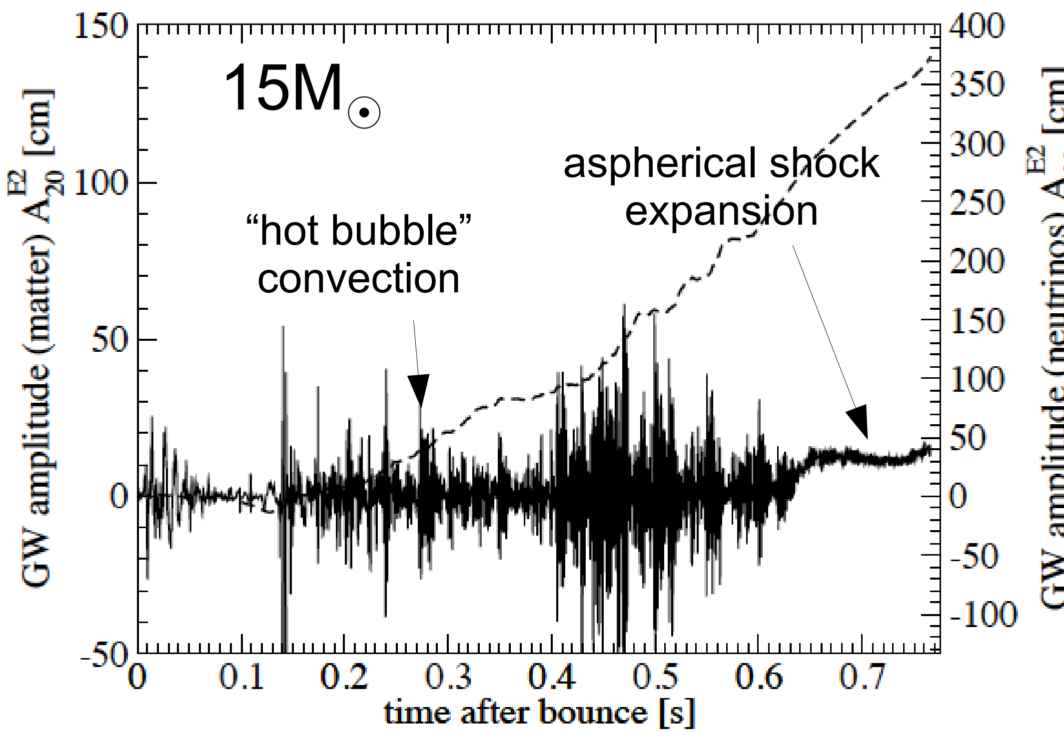


Accretion phase similar to Dasgupta et al. (2011), early post-explosion phase appears post promising

Gravitational Wave Signal

- Signal exhibits features familiar from simulations with Newtonian hydro (e.g. Marek et al. 2009, Murphy et al. 2009, Yakunin et al. 2010):
  - Prompt convection signal
  - Stochastic hot-bubble signal with shifting frequency peak
  - “tail” during explosion
- Amplitudes also similar
- What about the typical frequencies?





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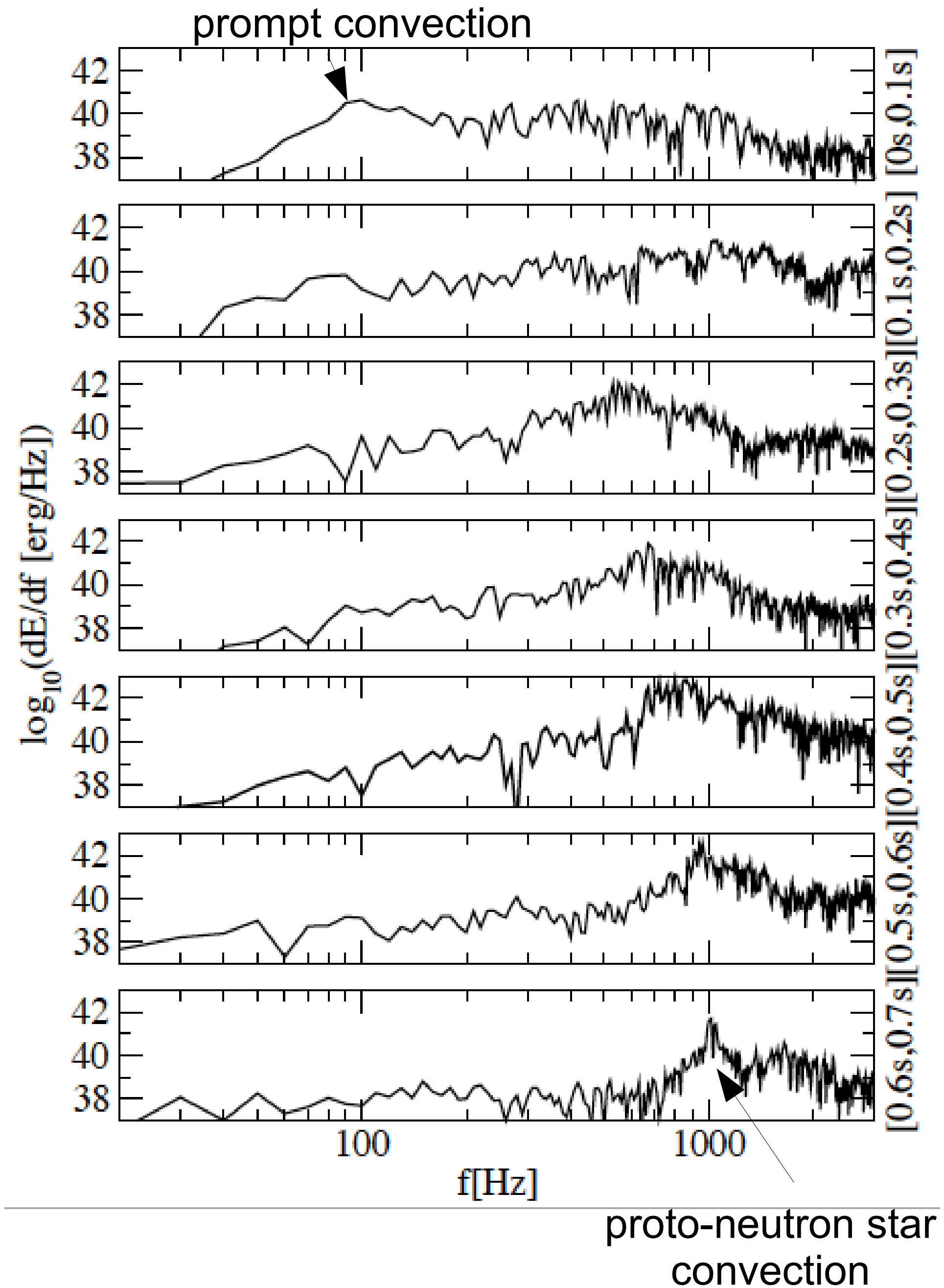
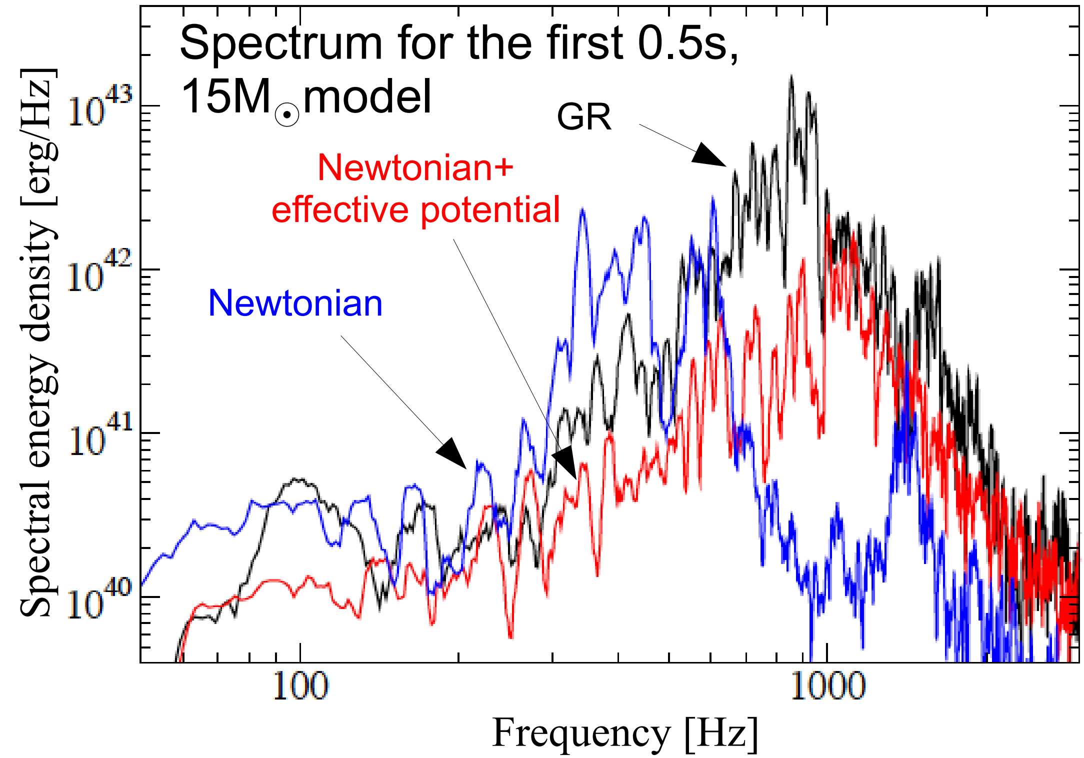
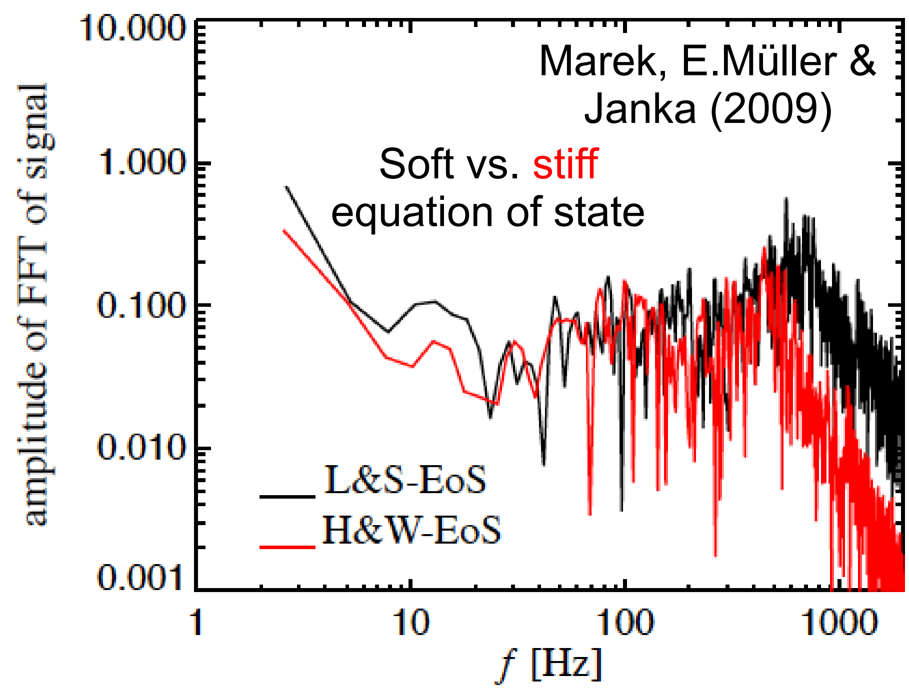


Spectral energy distribution for different time intervals, 15M$_\odot$ model

Gravitational Wave Signal

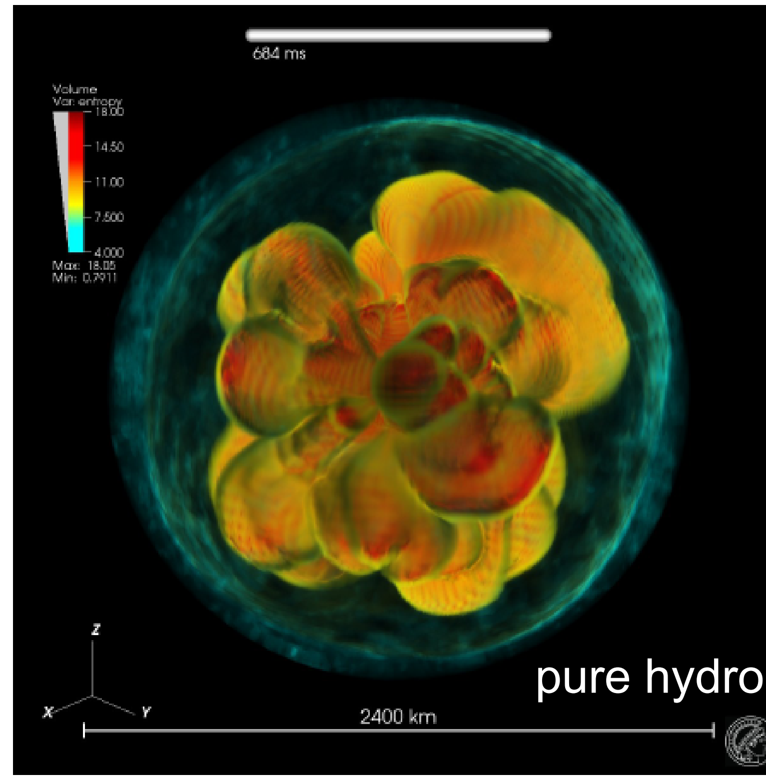
- Frequency most sensitive to GR effects
- **Huge** differences compared to Newtonian case:
  - PNS convection: +60...70%
  - Hot bubble convection: +20...50%
- Simulations with effective gravitational potential closer to GR, but no perfect match
- Influence of GR comparable to or larger than that of the EoS
- Strong sensitivity to the transport treatment (cooling region!), cp. frequencies of Murphy et al. (2009)





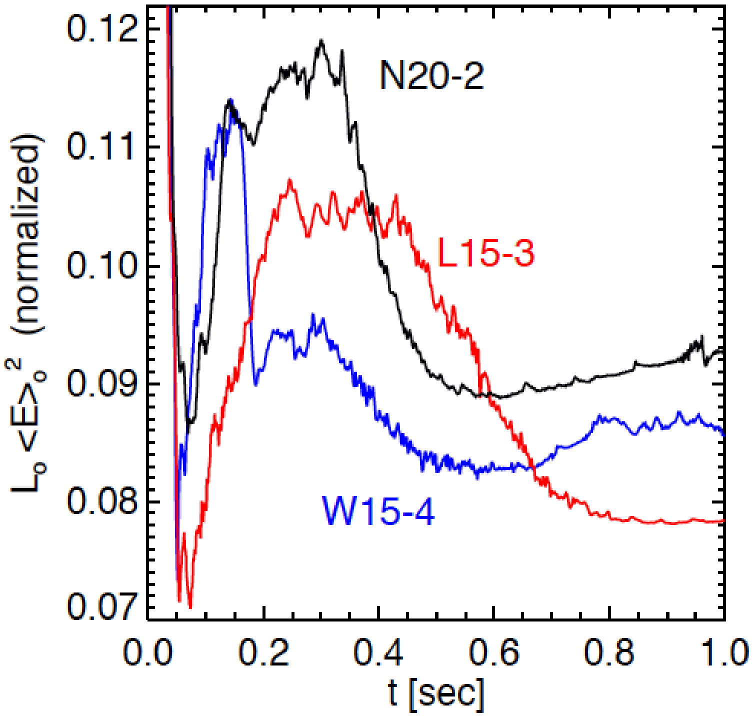
What About 3D Effects?

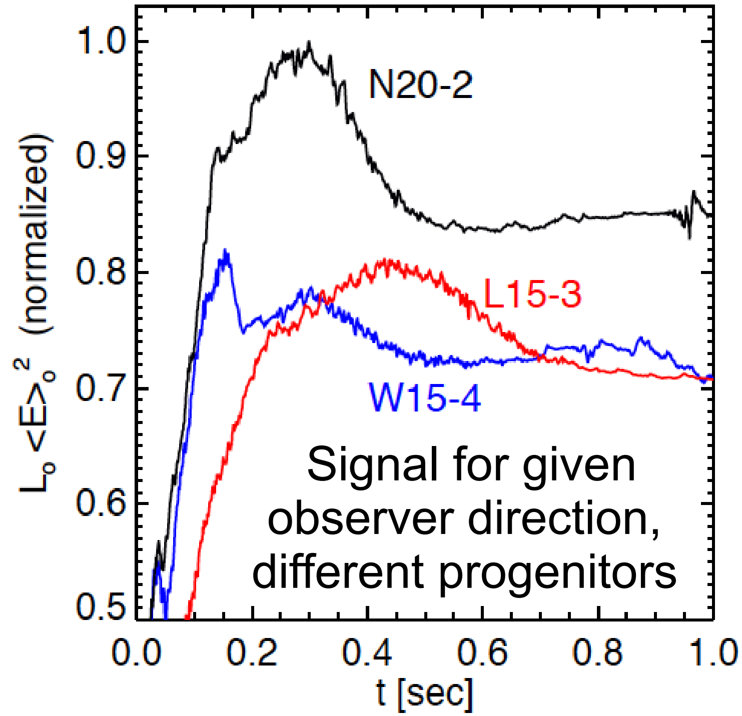
- Explosion geometry & strength of anisotropies dependent on dimensionality
- 3D modelling indispensable, but simulation to $\approx$1s with full transport not available yet
- Simpler, parametrized schemes as an avenues towards exploratory studies (observables, explosion mechanism)

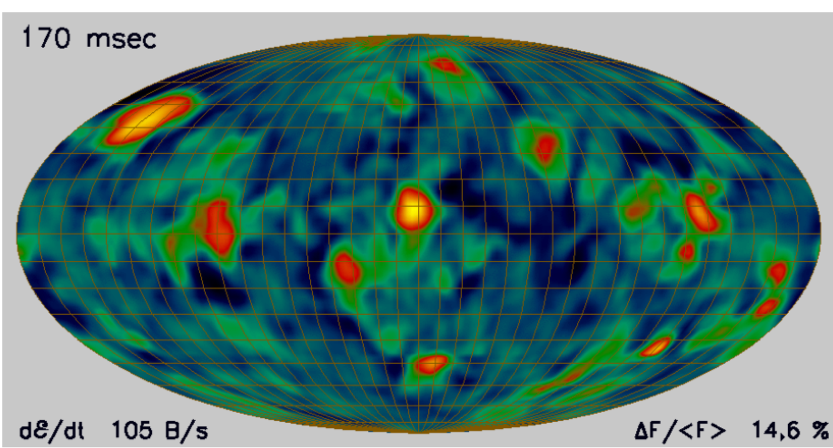


Simulations: Florian Hanke;
Visualization: Elena Erastova, Markus Rampp (RZG)

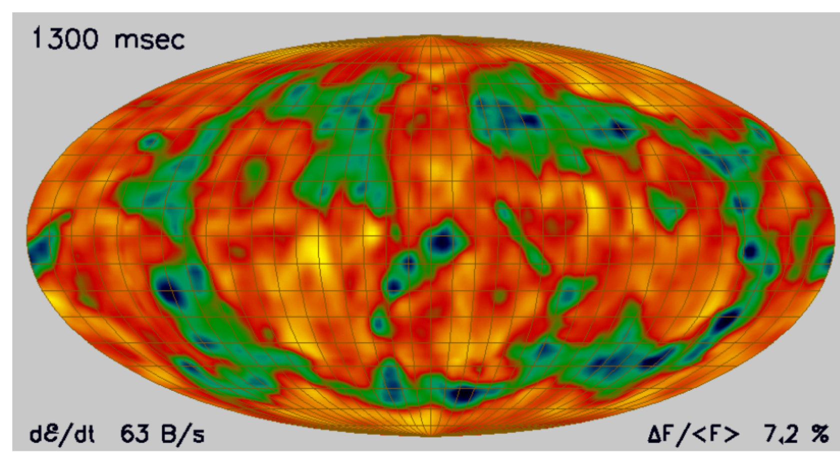
Neutrino & Matter Anisotropies in 3D





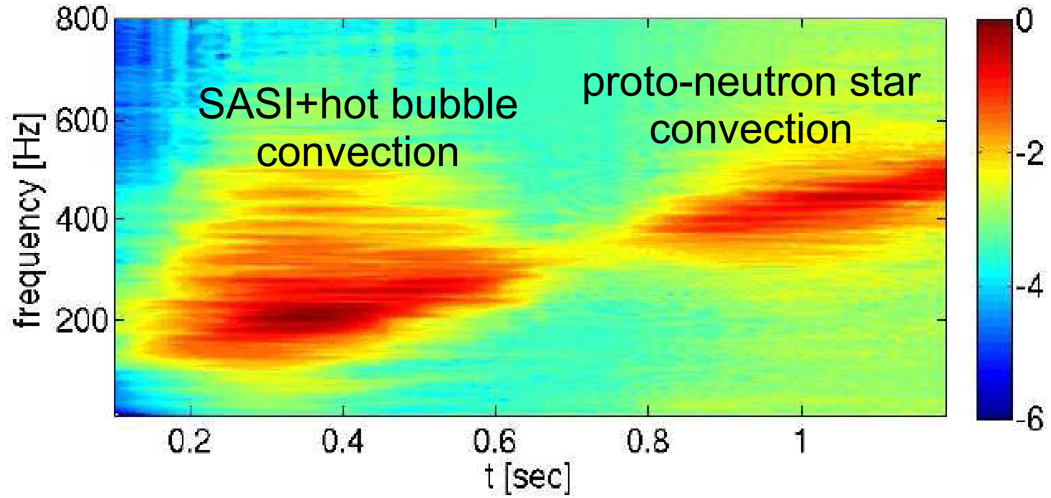


Neutrino flux asymmetry



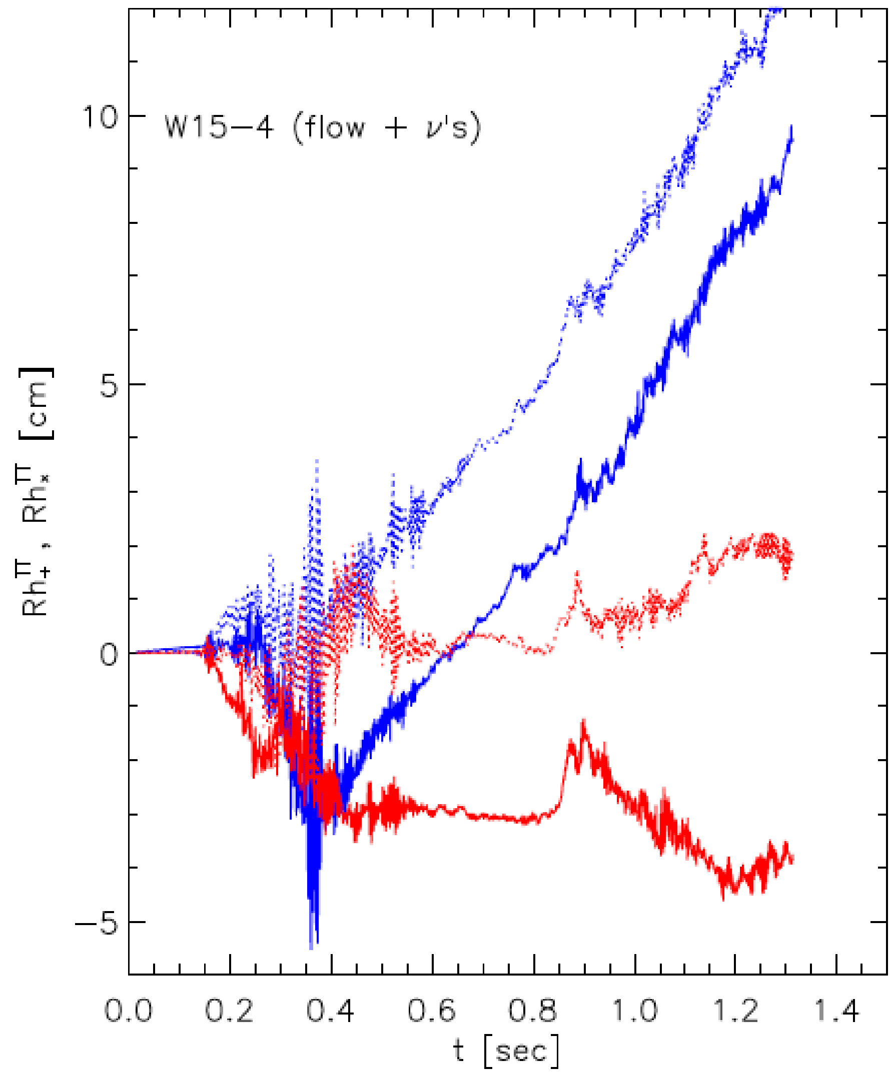
E.Müller, Janka & Wongwathanarat (submitted)

Gravitational Wave Signal



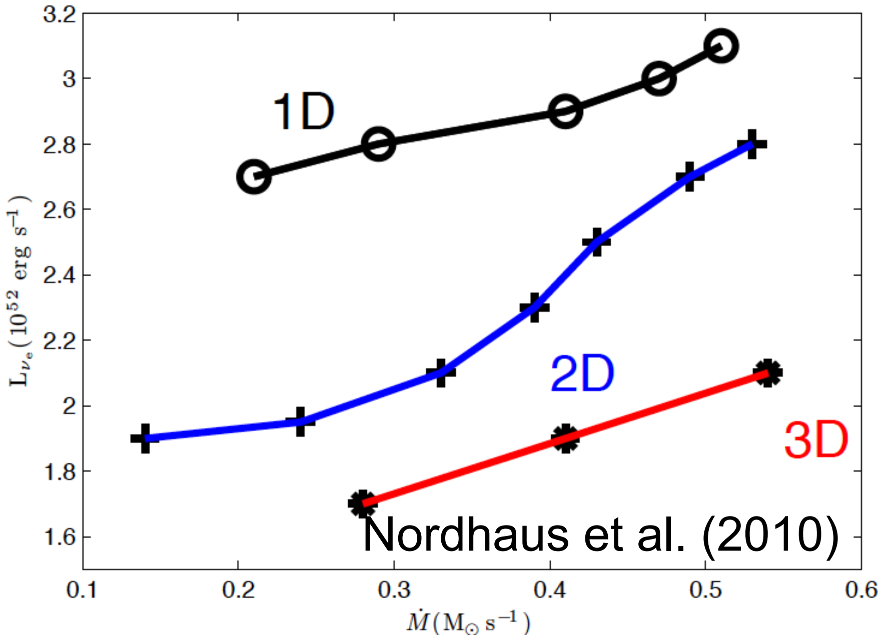
Normalized spectrogram, 15$M_{\odot}$ model

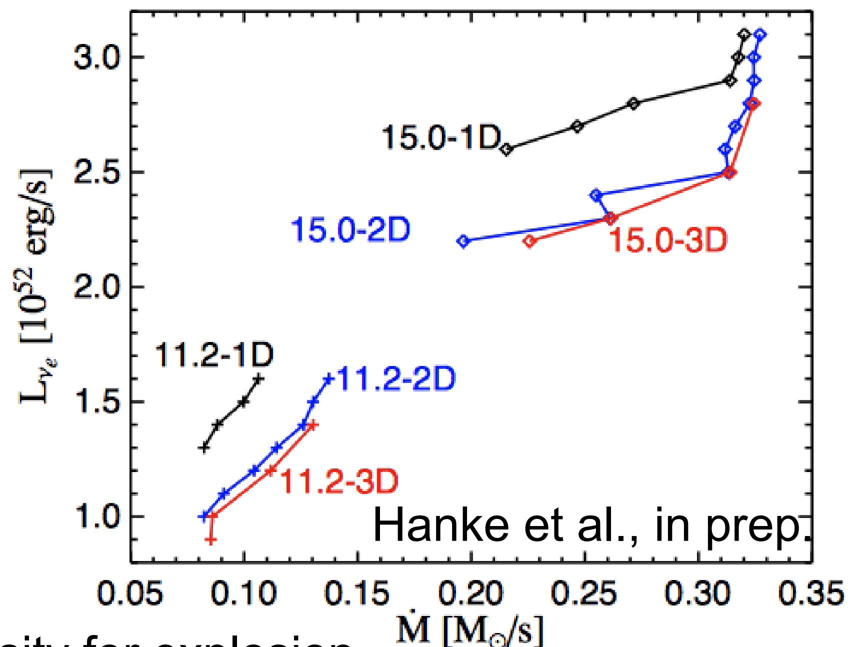
- Luminosity fluctuations less pronounced than in 2D
- Gravitational wave strain also somewhat smaller
- Not a final answer (model limitations)



Gravitational wave amplitude, 15$M_{\odot}$ model

Outlook





"Critical" luminosity for explosion

- Non-spherical motion of matter & anisotropic neutrino emission intimately tied to model dynamics (time of explosion, strength of SASI & convection)
- SASI (presence of sloshing or spiral mode) & convection in turn possibly strongly dependent on heating conditions, neutron star compactness, etc.
- Impact of dimensionality (3D vs. 2D) not yet well understood
- Self-consistent 3D simulations required!