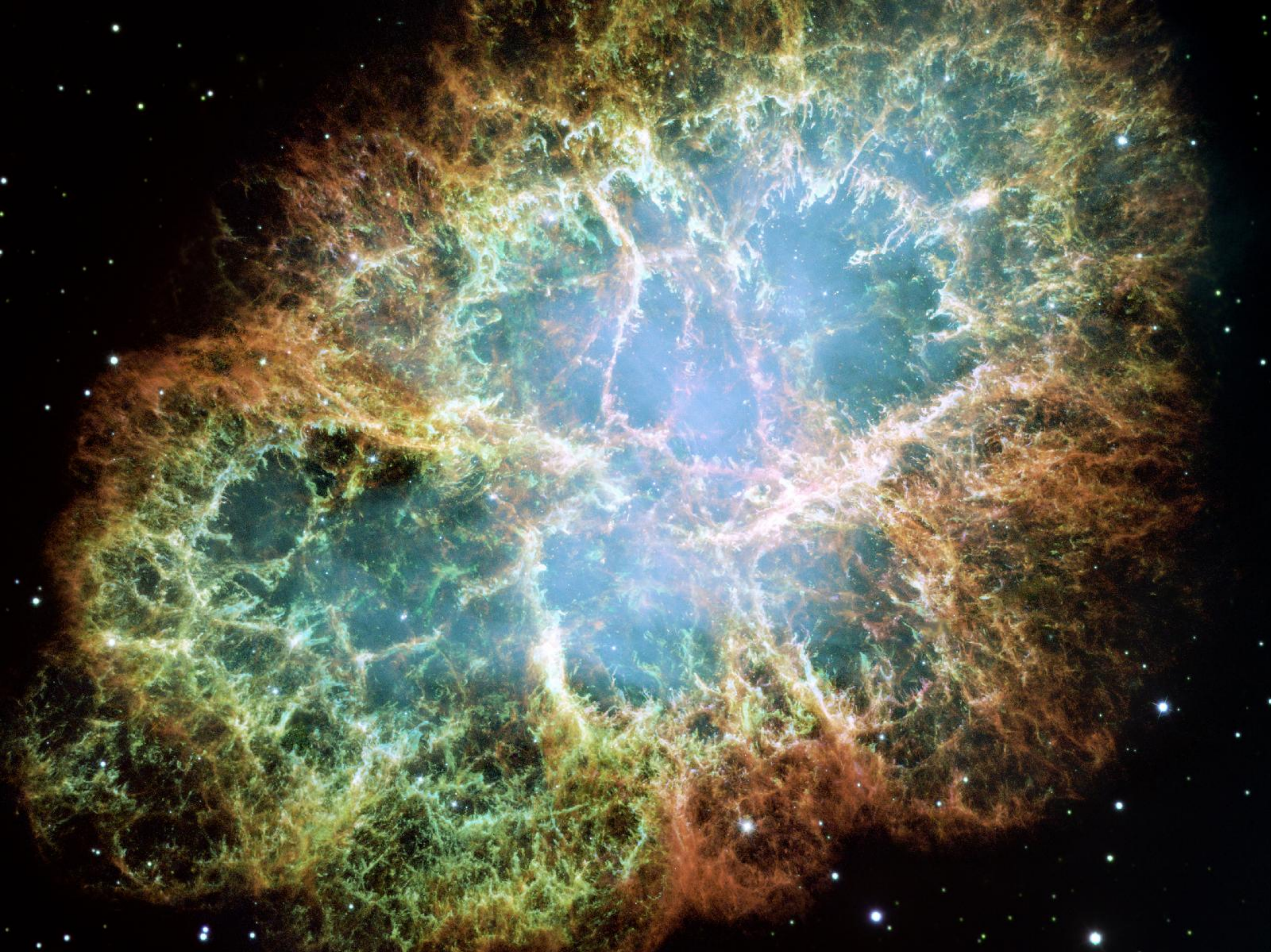

Relativistic Core-Collapse Supernova Models

Identifying the Key Elements for Successful Neutrino-Driven Explosions

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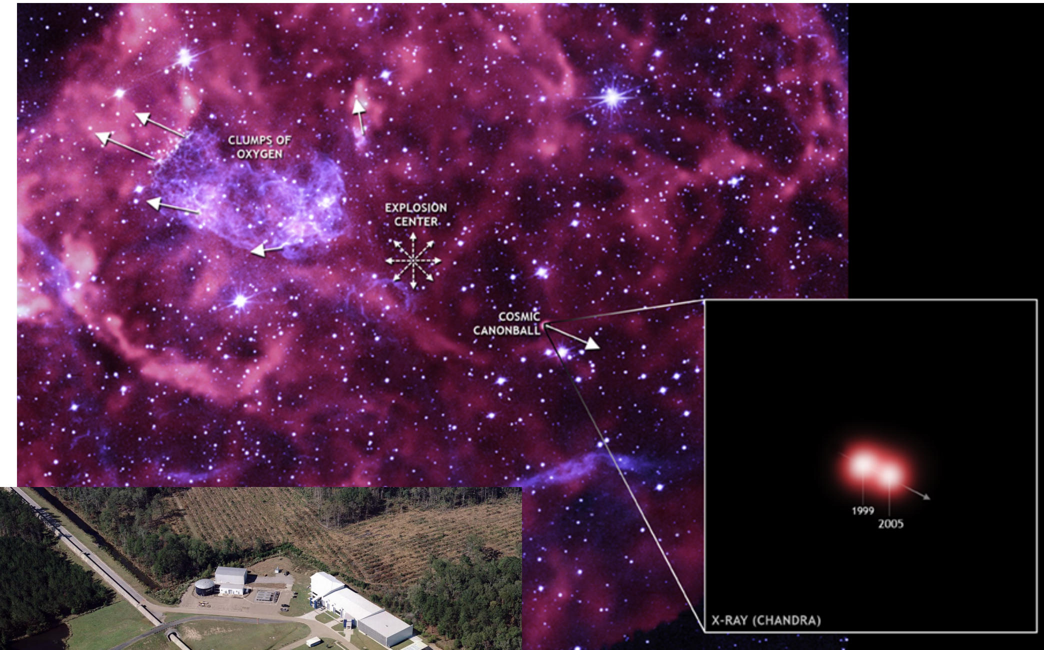
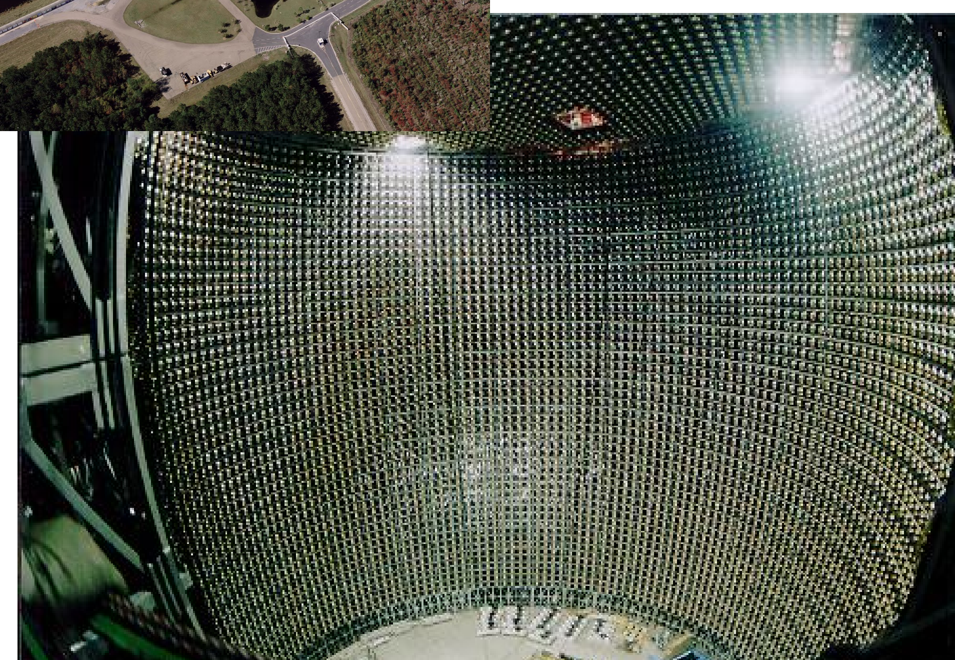
Max-Planck-Institut für Astrophysik, Garching

With H.-Th. Janka, A. Marek, A. Heger

Major Questions

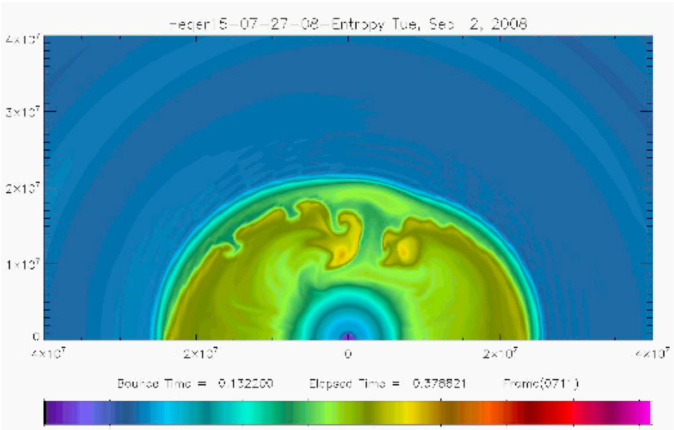
- How does the "engine" work? Do ν-driven explosions work or do we need an alternative?
- What can we observe?
  - Neutrinos – from bounce to cooling
  - Gravitational waves (?)
  - Ejecta morphology
  - Pulsar kicks
  - Nucleosynthesis yields



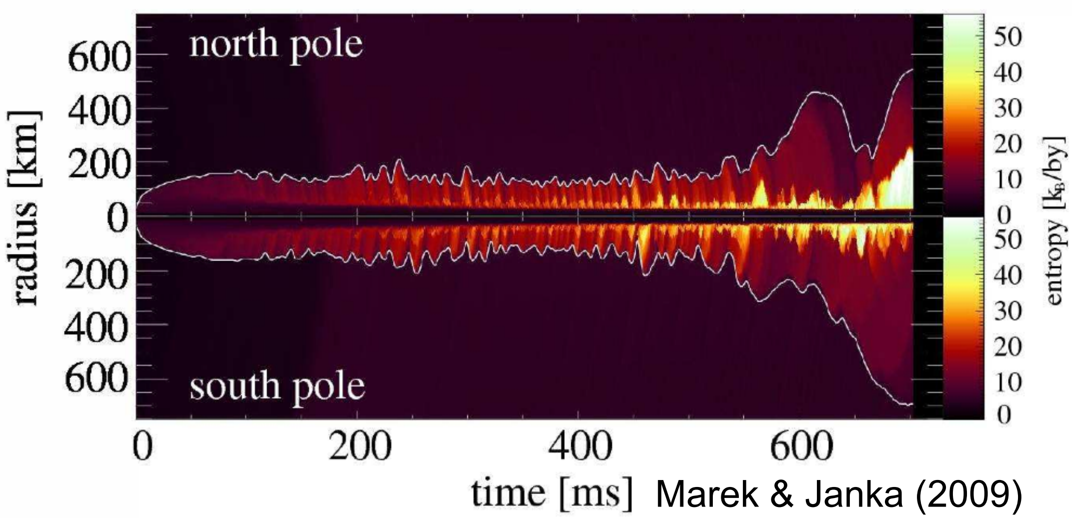


Status of Neutrino-Driven Explosions

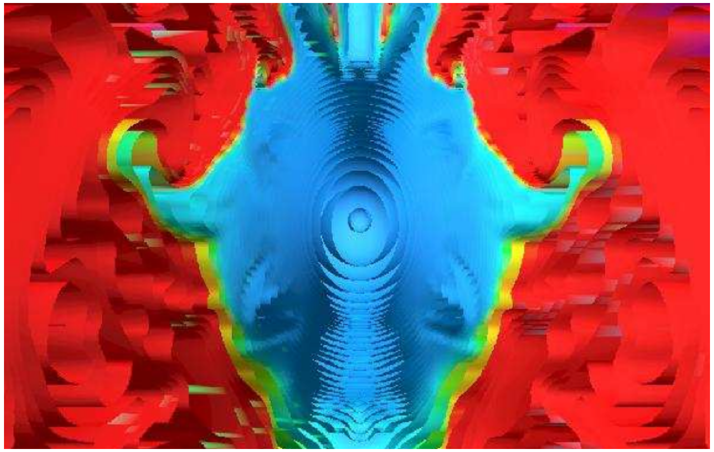
- Axisymmetric multi-group simulations by different groups not yet in agreement
- Concerns: only few weak & late explosions, limited range of progenitors
- Potential ingredients for neutrino-driven explosions to be investigated in more detail:
  - General relativity
  - Neutrino physics
  - 3D effects
  - Equation of state



Bruenn et al. (2009)



Marek & Janka (2009)



Burrows et al. 2006: explosion **not** by ν-heating, but by “acoustic mechanism”

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- Concerns: only few weak & late explosions, limited range of progenitors
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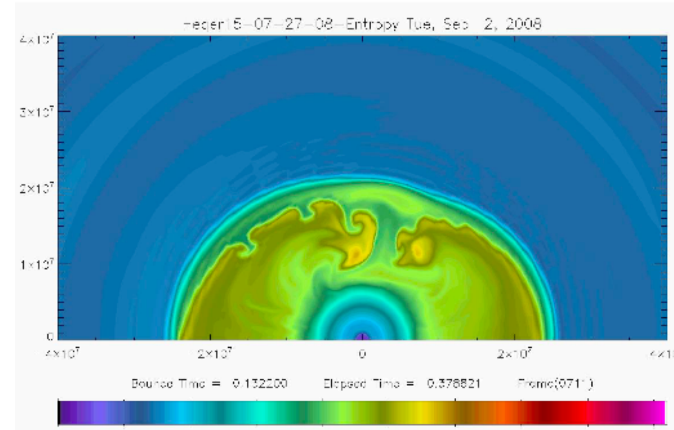
    - General relativity
    - Neutrino physics
    - 3D effects → still controversial, see for example Florian Hanke's talk this afternoon
    - Equation of state



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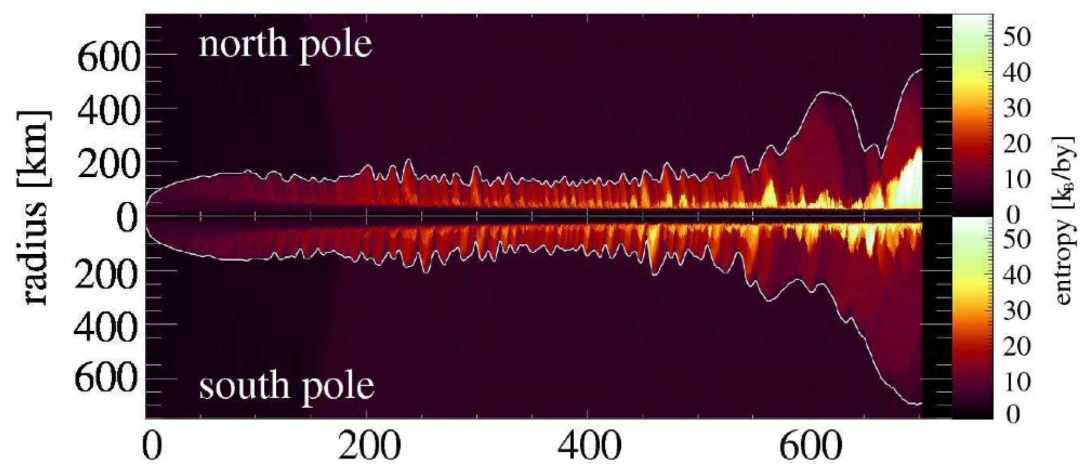

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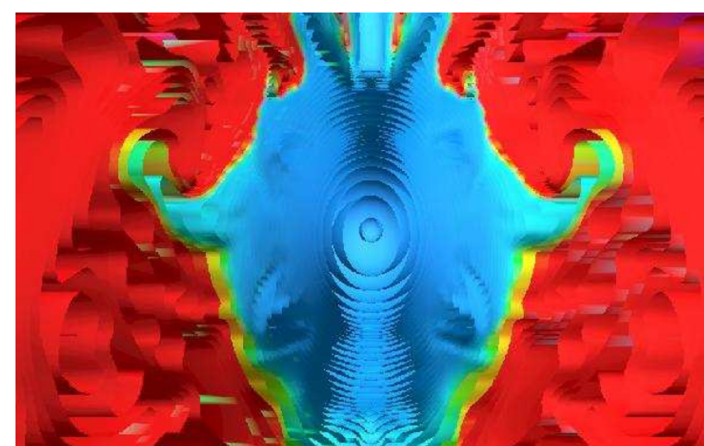
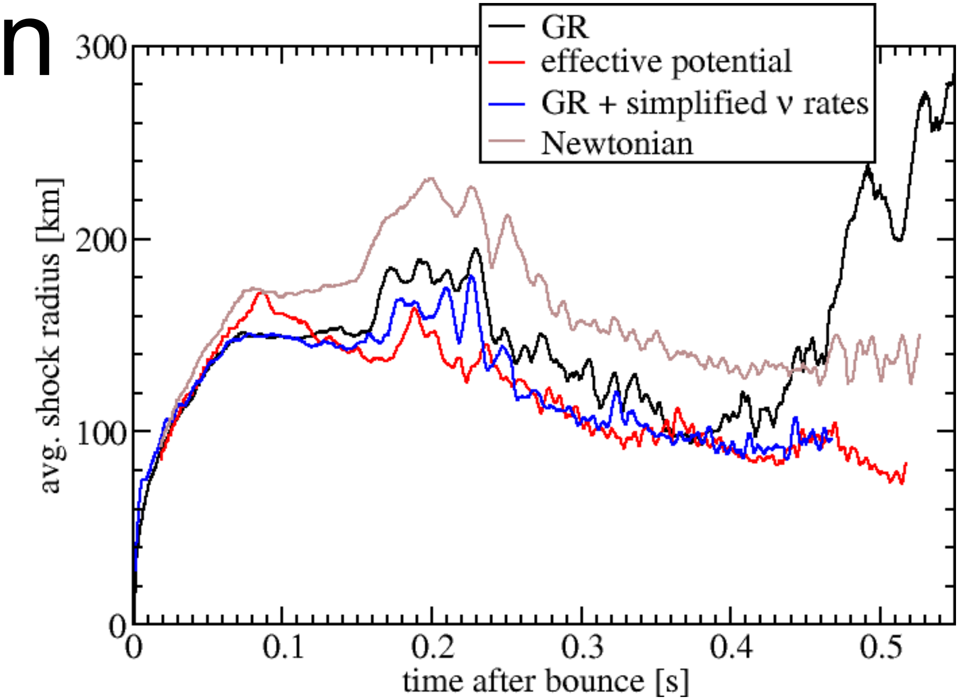
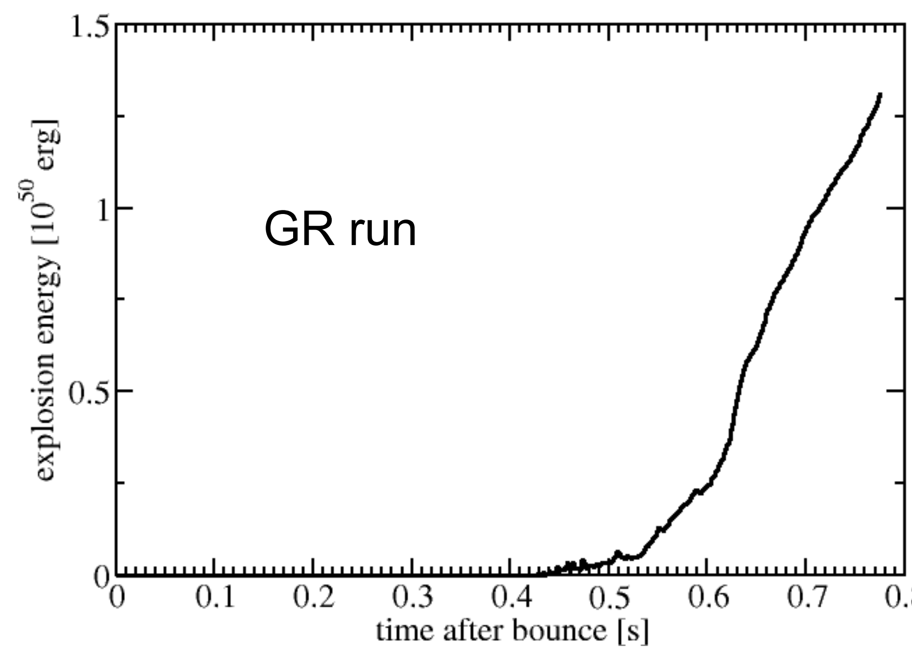


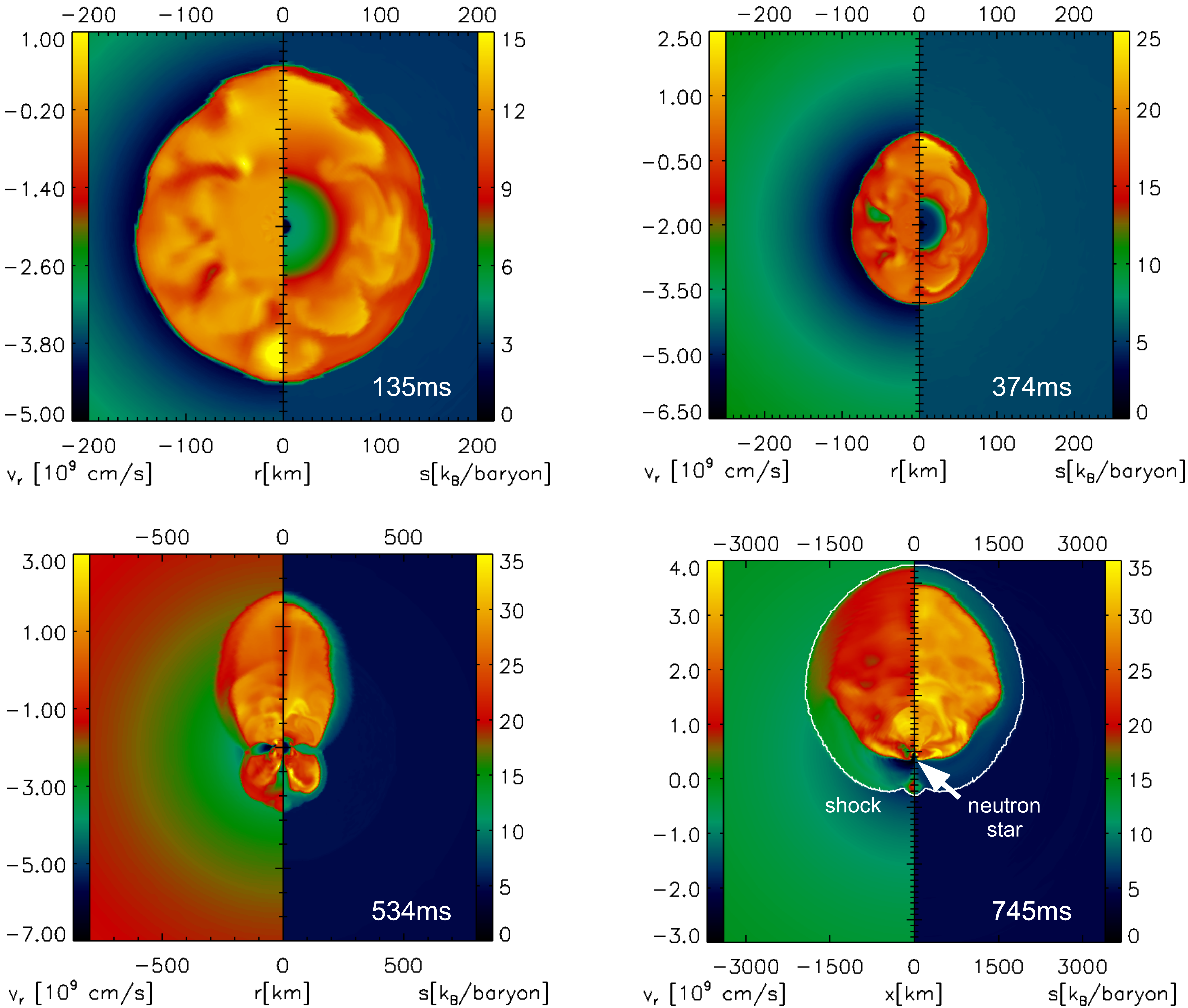
Burrows et al. 2006: explosion **not** by ν-heating, but by “acoustic mechanism”

Ingredients for ν-driven Explosions

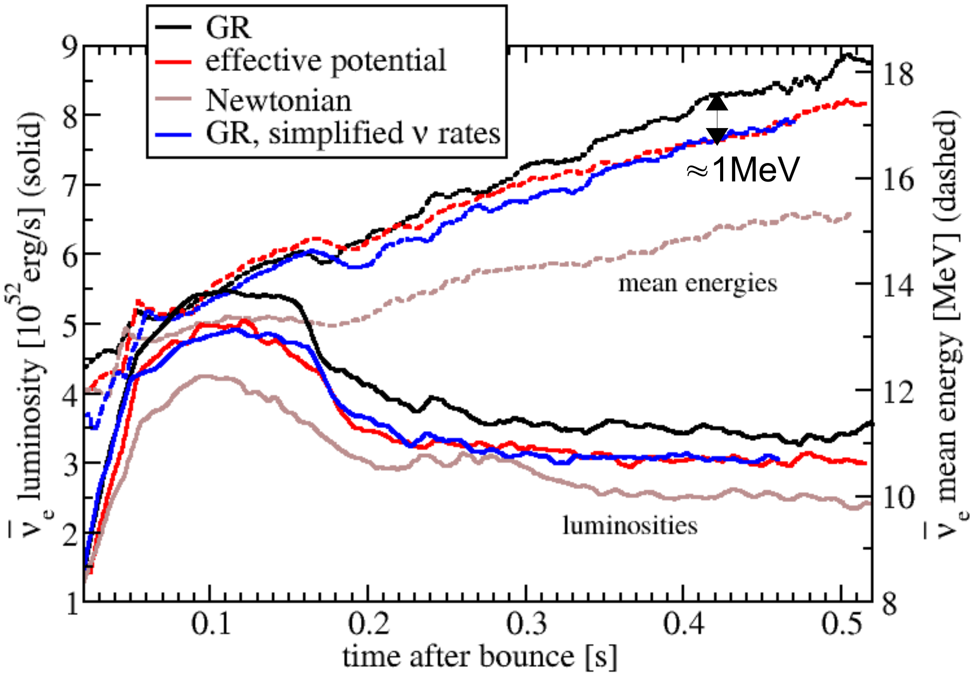
- Detailed neutrino physics & general relativity sometimes dismissed as unimportant, but tests in multi-D required!
- Müller et al. (2012): Detailed comparison of four models using the $15M_\odot$ progenitor of Woosley & Weaver (1995)
    - Newtonian vs. GR
    - Newtonian + "effective" pseudo-GR potential vs. GR
    - Up-to-date neutrino reaction rates vs. simplified rates (e.g. no recoil energy transfer in ν-nucleon reactions)
- Only GR model with up-to-date rates explodes → GR and ν rates can make a difference!

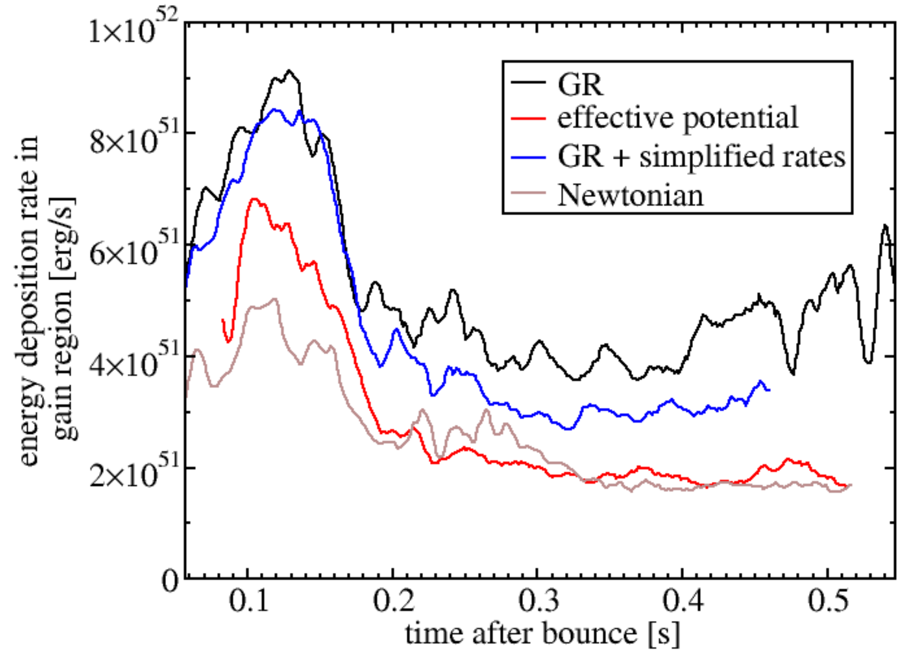




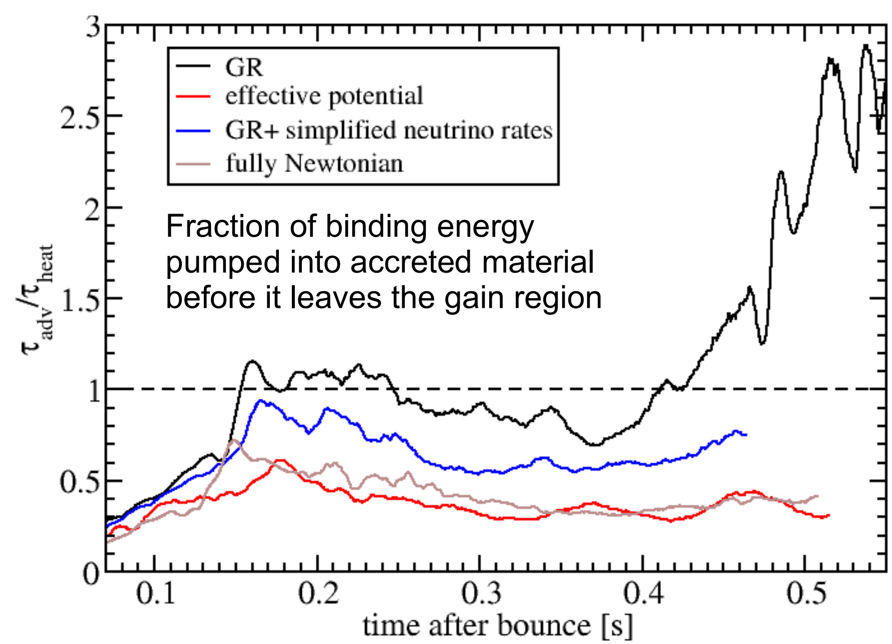

135ms
374ms
534ms
745ms
shock
neutron star
v_r [10^9 cm/s]
r[km]
x[km]
s[k_B/baryon]

Systematic Differences in the Heating Conditions

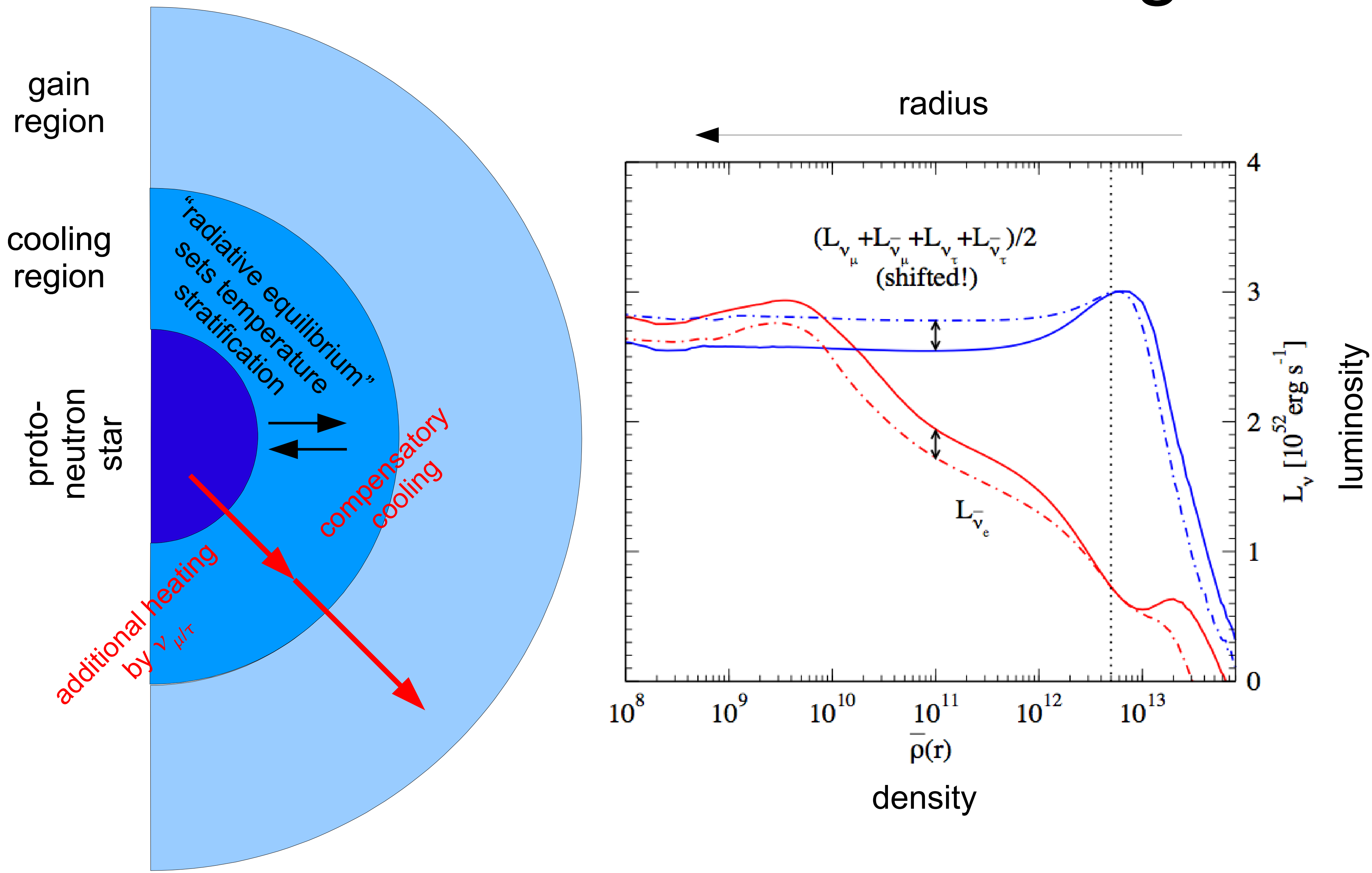




- Increased electron (anti-)neutrino luminosity L and mean energies $\langle E_\nu \rangle$ in GR (hotter neutron star surface)
- Local heating rate ~L$\langle E_\nu \rangle^2$, but feedback effects (stronger convection, larger shock radius) further increase the integrated heating rates (up to ~100%)
- Improved microphysics: energy transfer from $\nu_{\mu/\tau}$ to the medium allows stronger (anti-)ν_e emission in cooling region → similar increase in heating in gain region

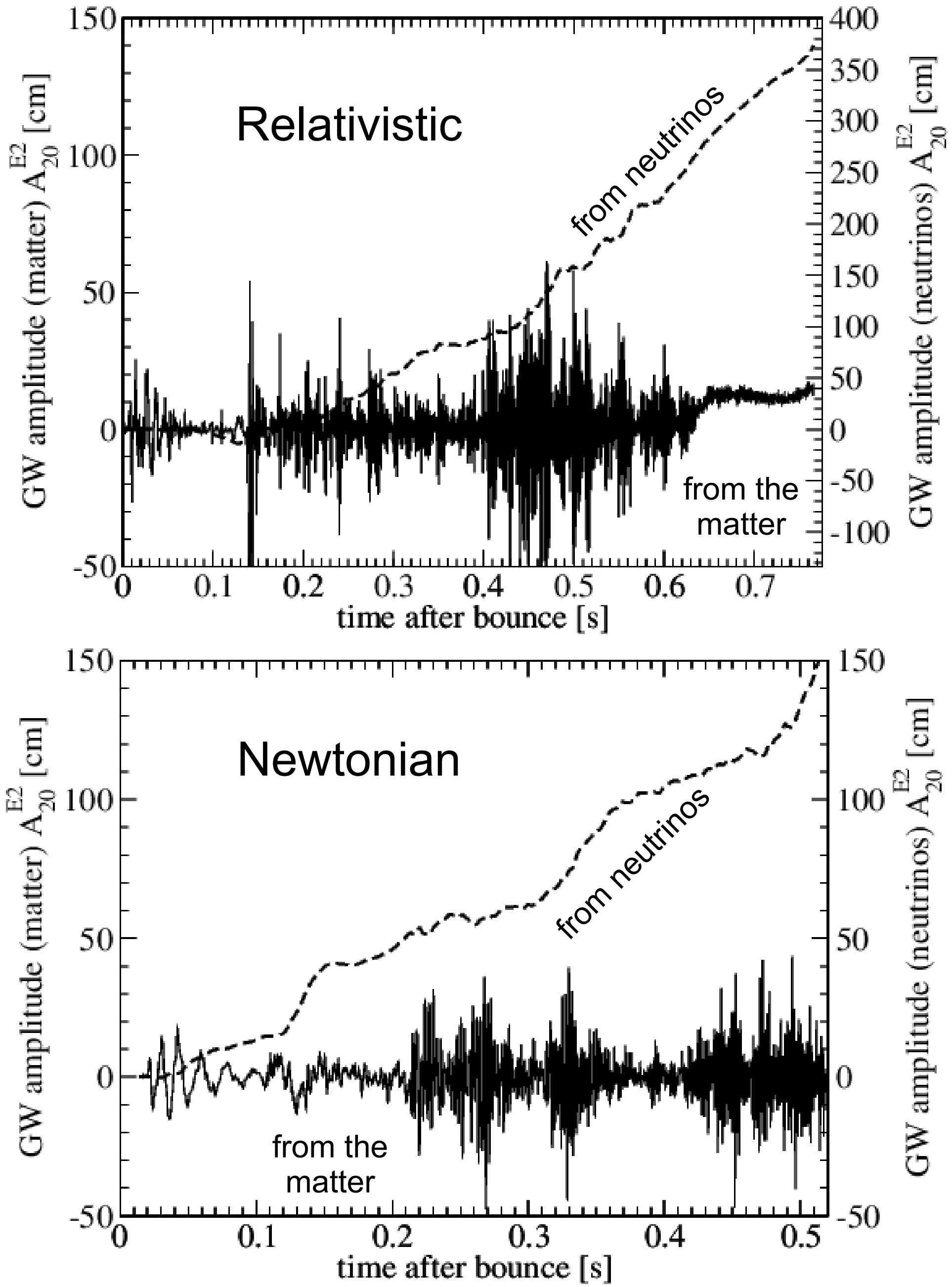


The Role of Non-Isoenergetic Neutrino-Nucleon Scattering

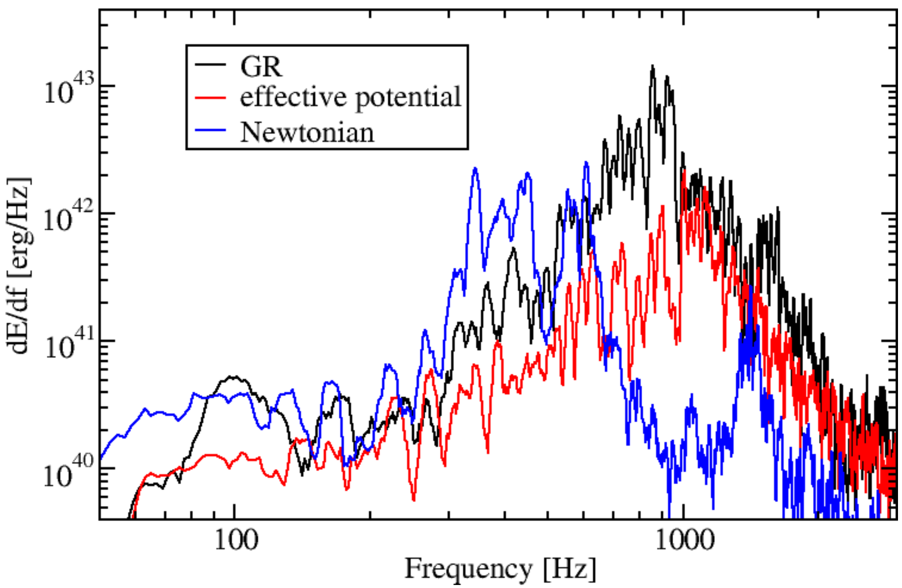


GR and the Gravitational Wave Signals

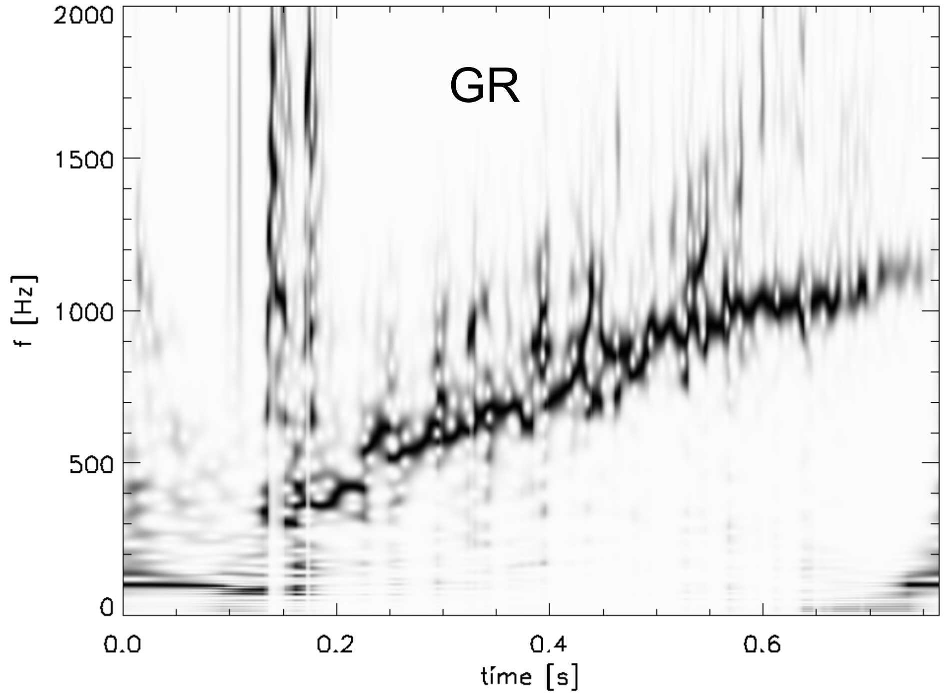
- GR is important for the dynamics, so what about the gravitational wave signal?
- Overall signal structure and amplitudes similar in GR & in the Newtonian approximation
- Signal from convection shows stochastic amplitude variations → model properties better reflected in the spectra
- Reference scale: typical frequencies vary by ~30% for different equations of state (Marek et al. 2008)



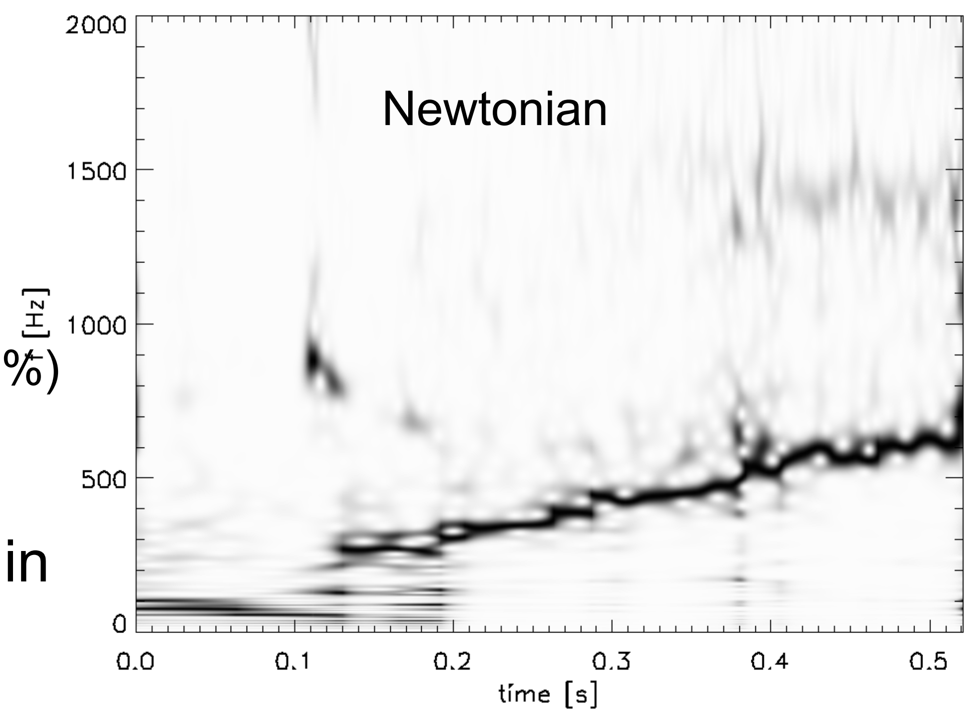
Note: GW extraction with modified quadrupole formula for strong-field background metric



Gravitational wave energy spectrum
for the first 500ms.

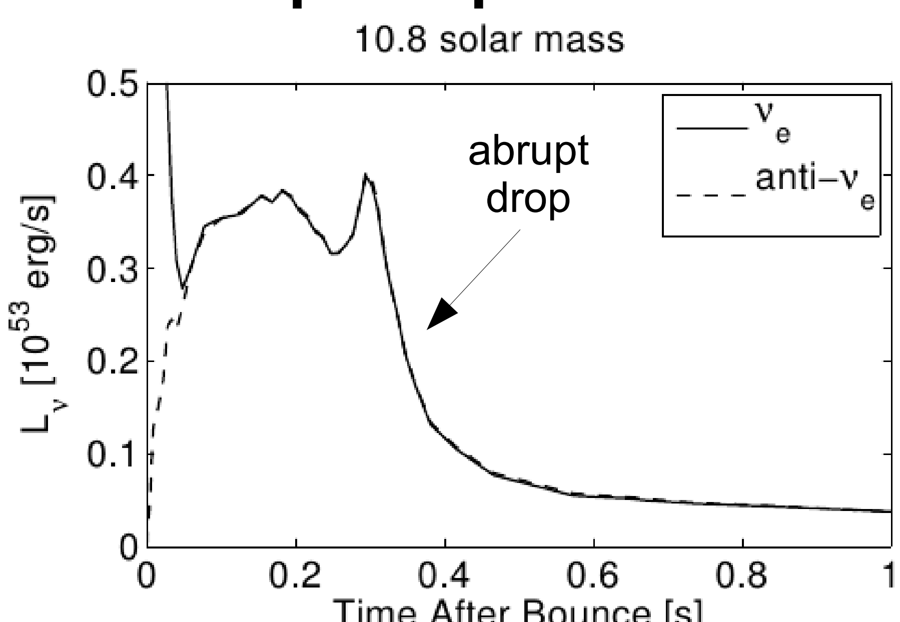


- Frequency shift in the GW energy spectra depending on the GR treatment (measured by the median)
  - GR: 900Hz
  - Newtonian: 500 Hz (woefully low...)
  - effective potential: 1100Hz (accurate to ~20%)
- Comparable to EoS effects!
- Result of different buoyancy frequency in neutron star surface region: This is a systematic effect!

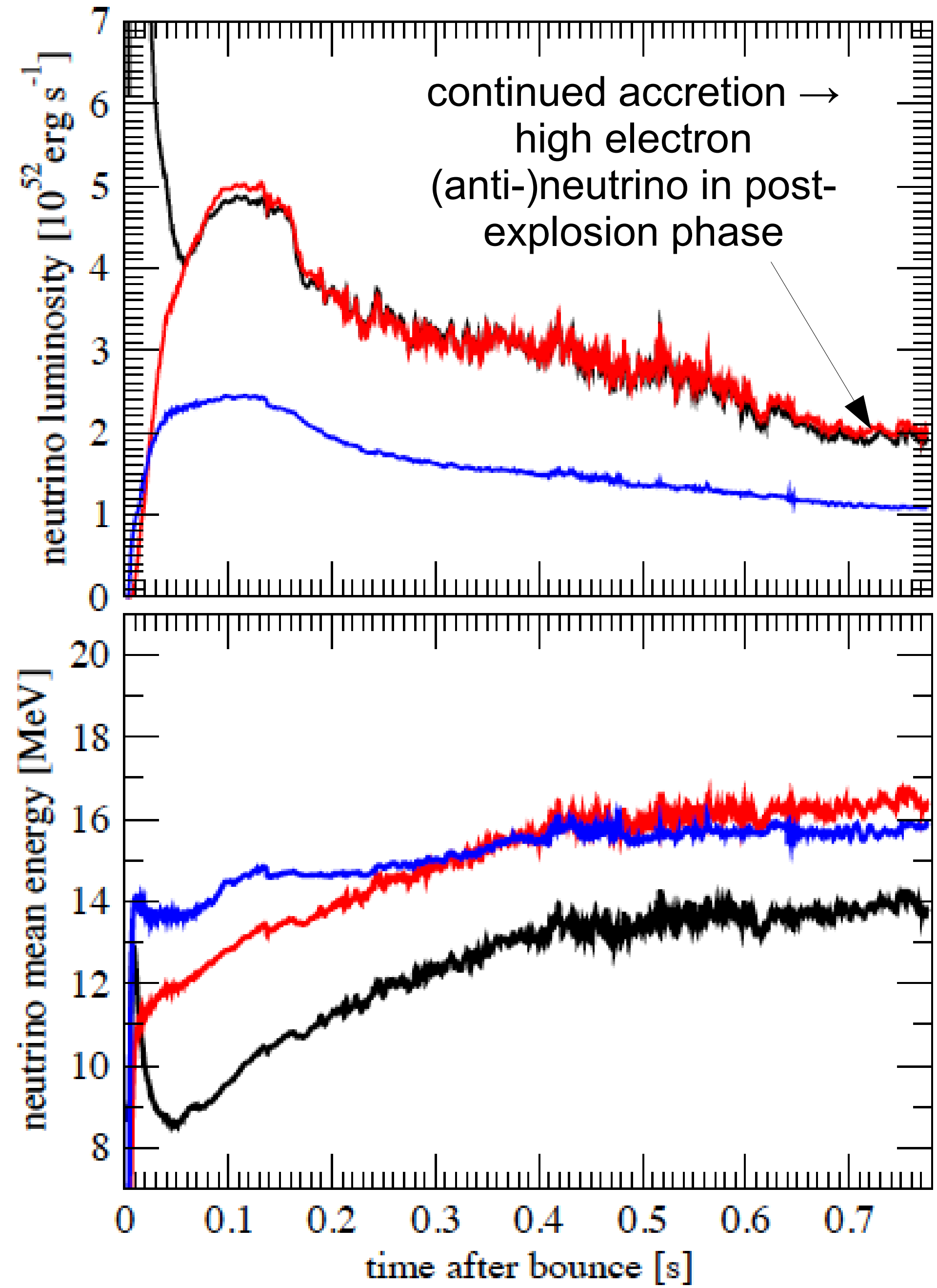


After Shock Revival: The Neutrino Signal

- Accretion can subsist long after the shock has been revived
- Decay of ν_e and anti-ν_e luminosities is slow – **no abrupt drop**

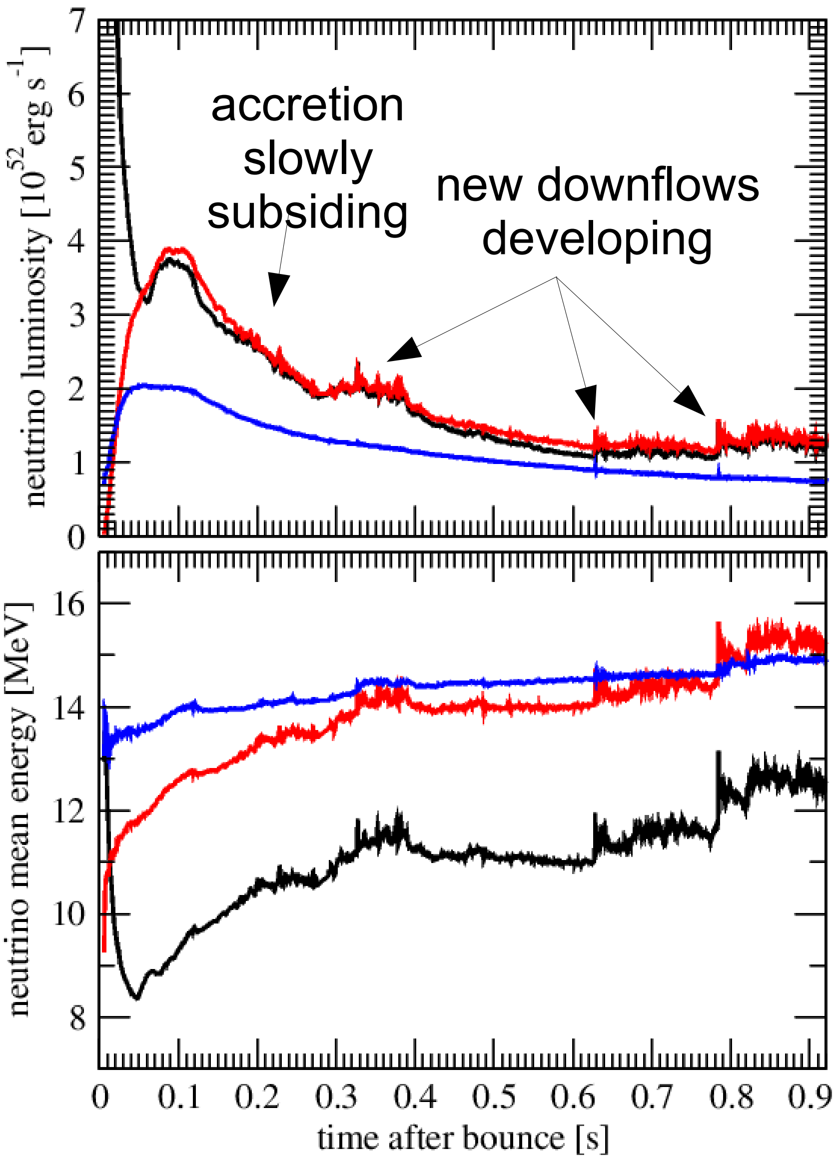


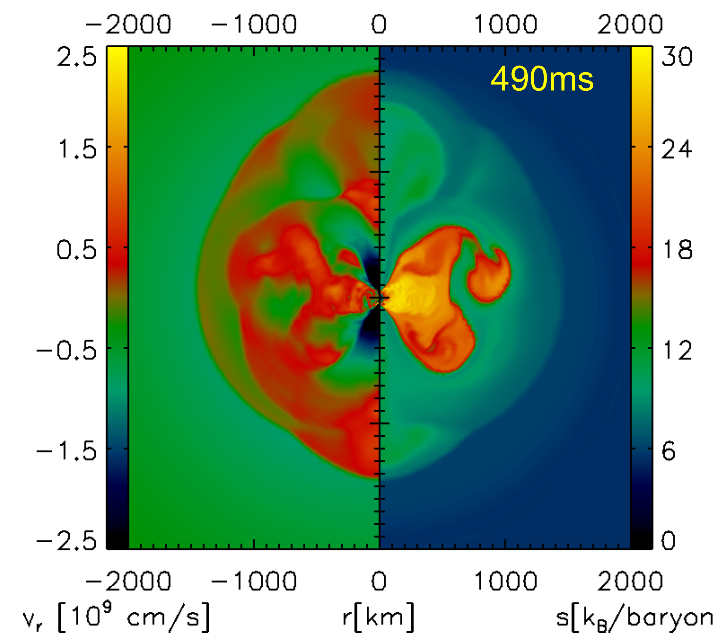
For comparison: artifical 1D explosion from Fischer et al. 2010

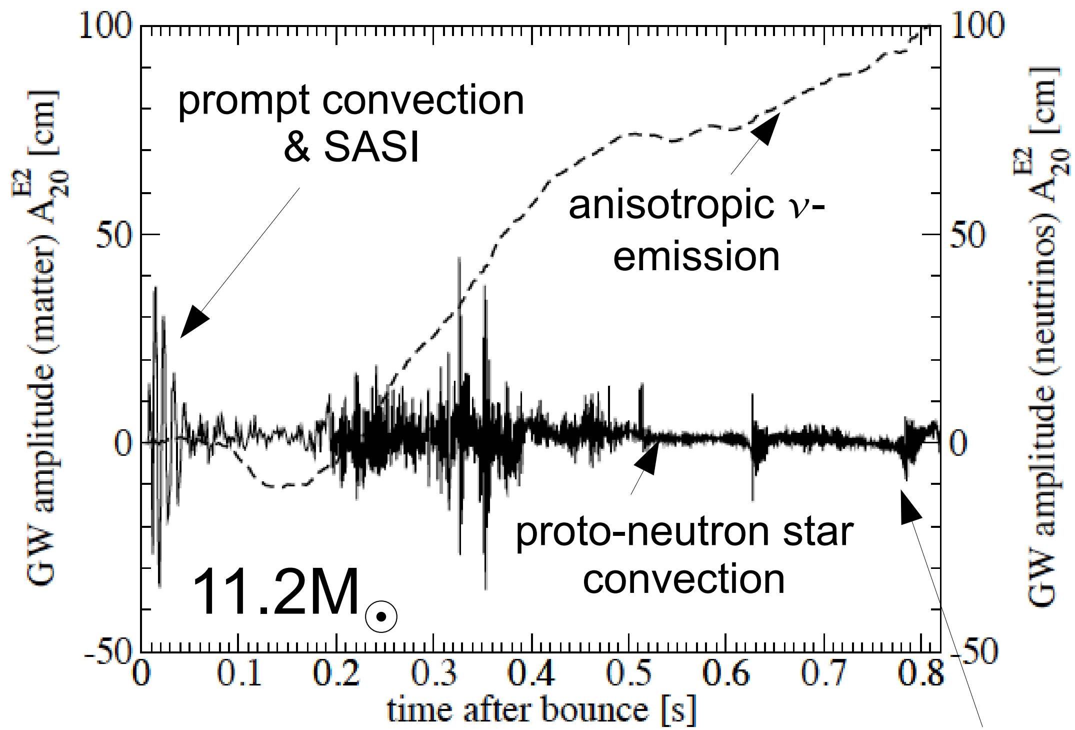


see Müller et al. (2012) in Proceedings of Haνse Workshop 2011

Neutrino & Gravitational Wave Signals after Shock Revival







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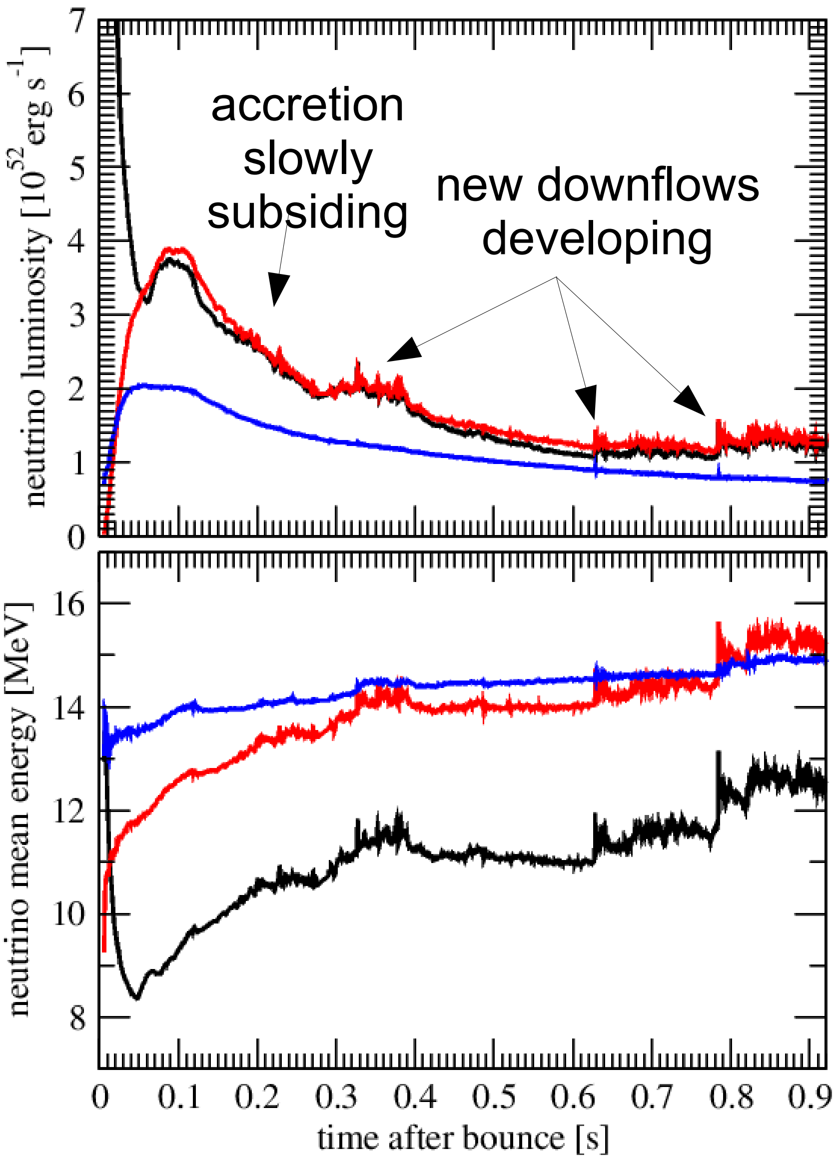

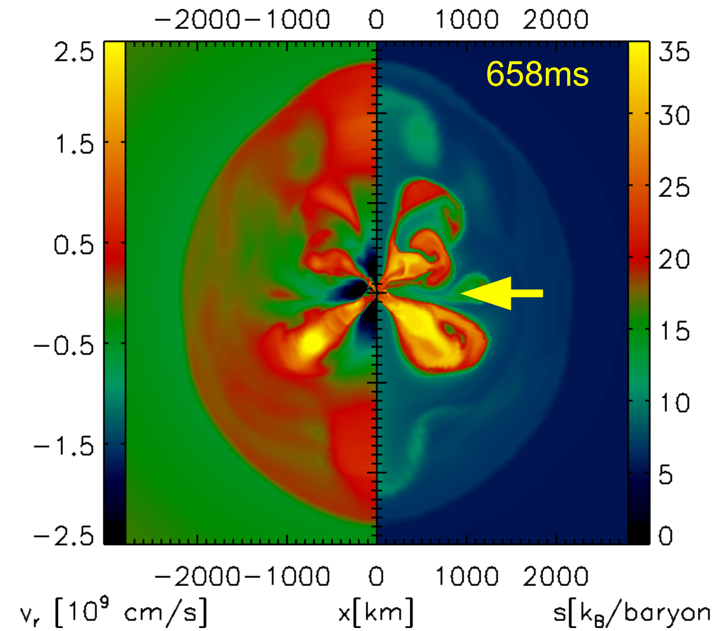

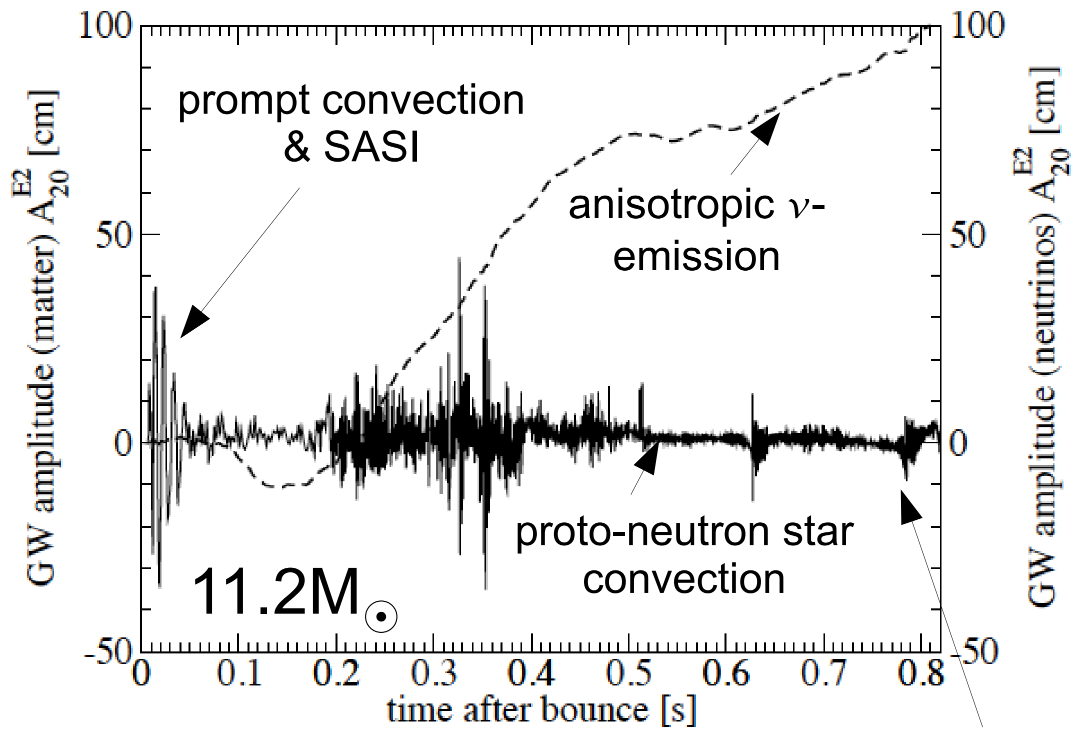

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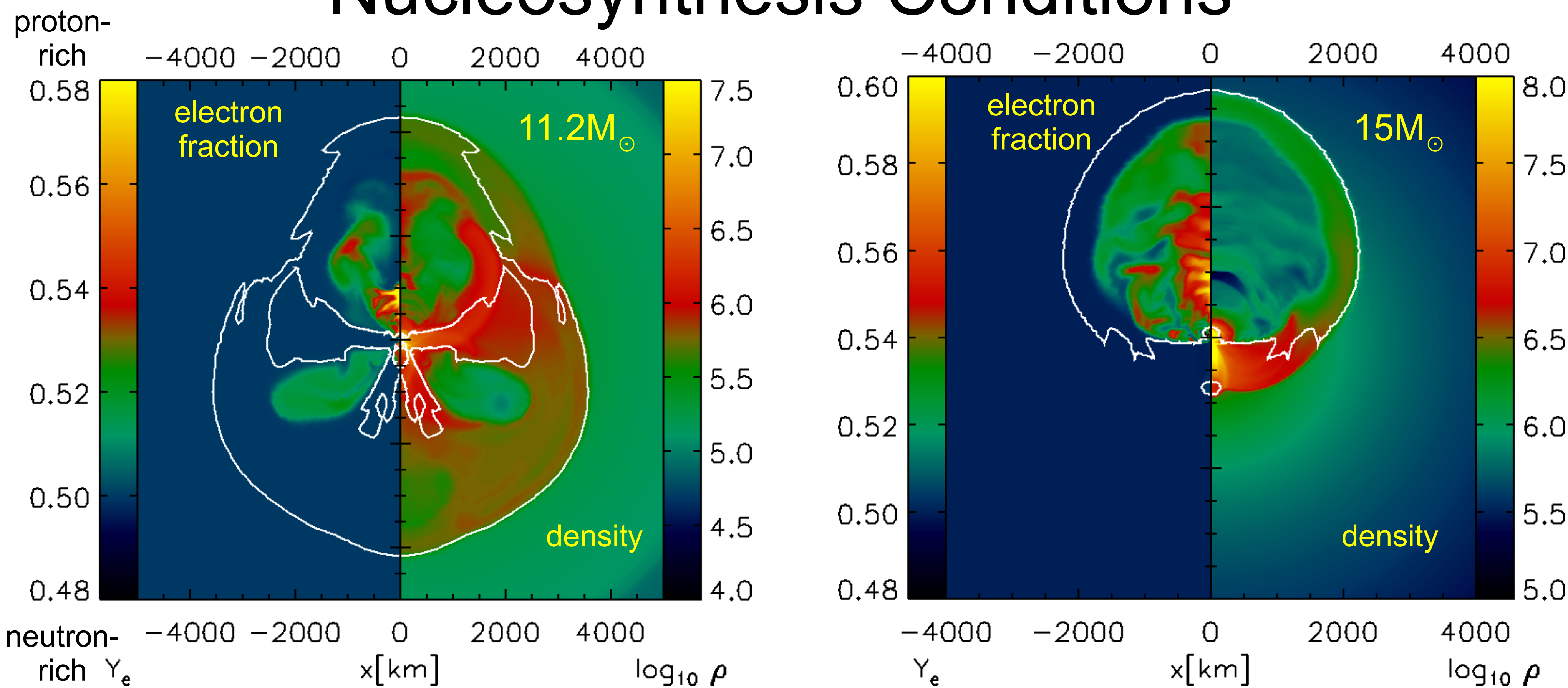
Nucleosynthesis Conditions



- Proton-rich ejecta at least for several 100ms
- Potential for νp-process (Fröhlich et al. 2006, Pruet et al. 2006) to be investigated
- Note: simple wind models inapplicable during this phase due to high accretion luminosity & aspherical dynamics

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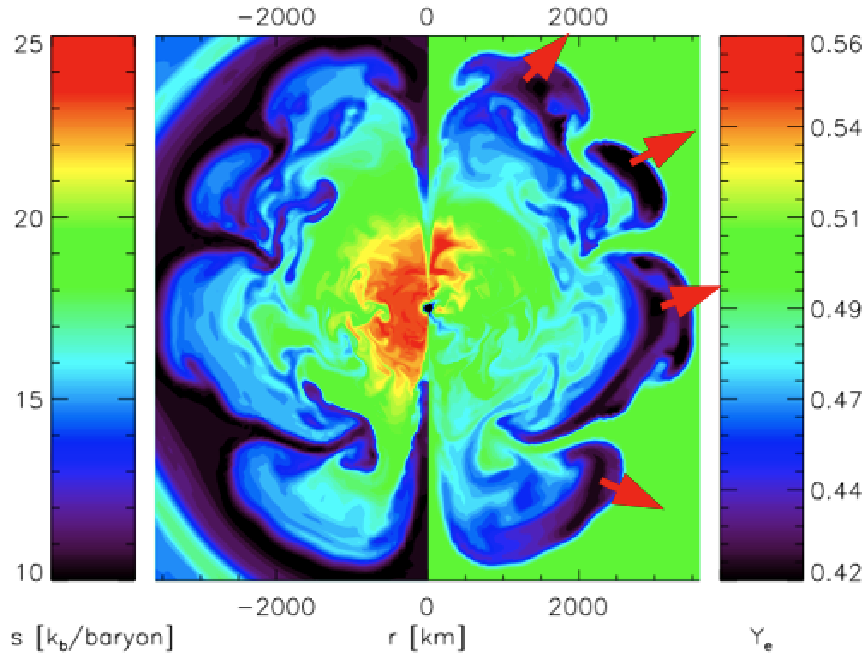
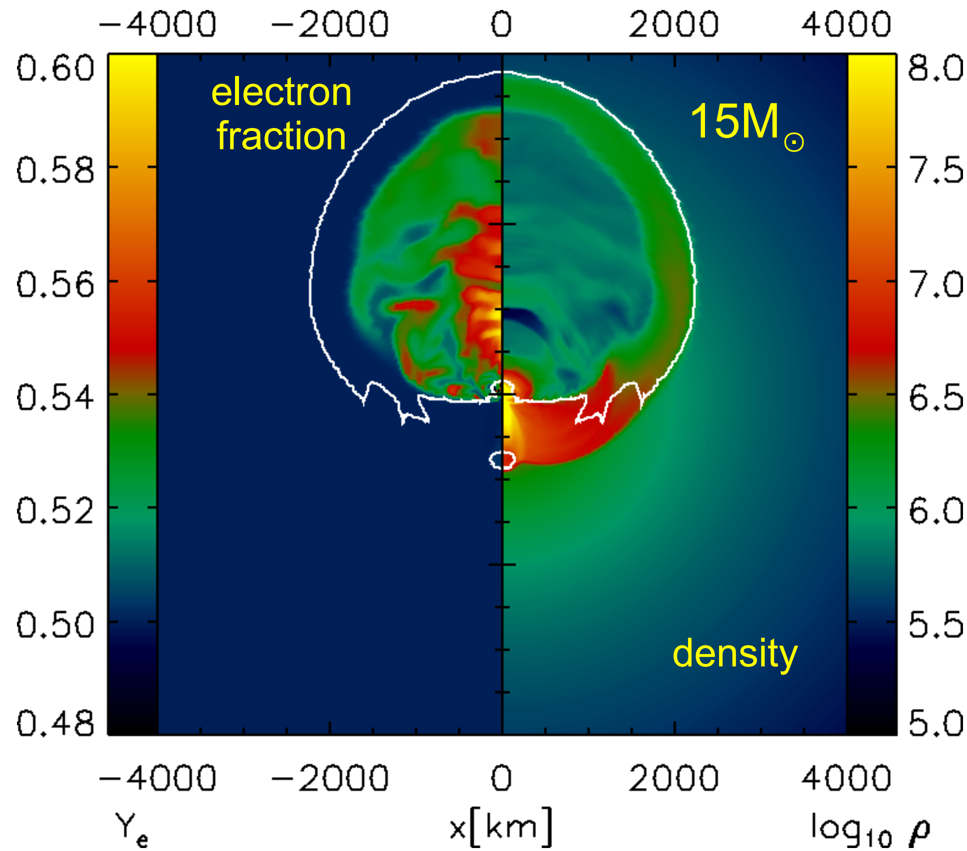


8.8M$_\odot$ progenitor with O-Ne-Mg-core: neutron-rich plumes (Wanajo et al. 2011)



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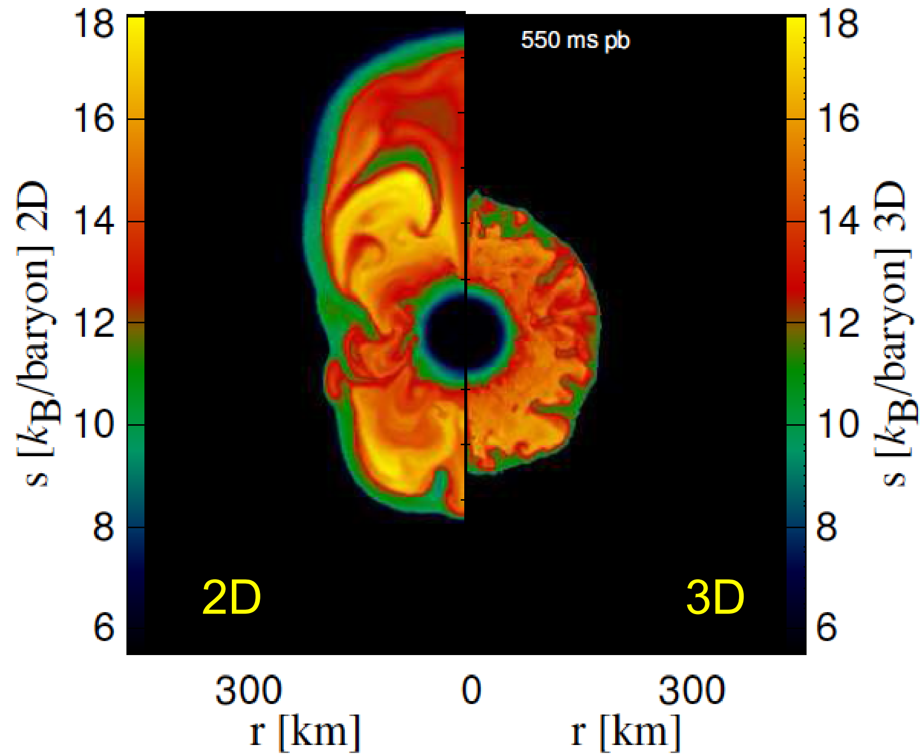
- Potential for νp-process (Fröhlich et al. 2006, Pruet et al. 2006) to be investigated
- Note: simple wind models inapplicable during this phase due to high accretion luminosity & aspherical dynamics
- **Pronounced difference** between massive progenitors and low-mass progenitors (for which case see Wanajo et al. 2011)

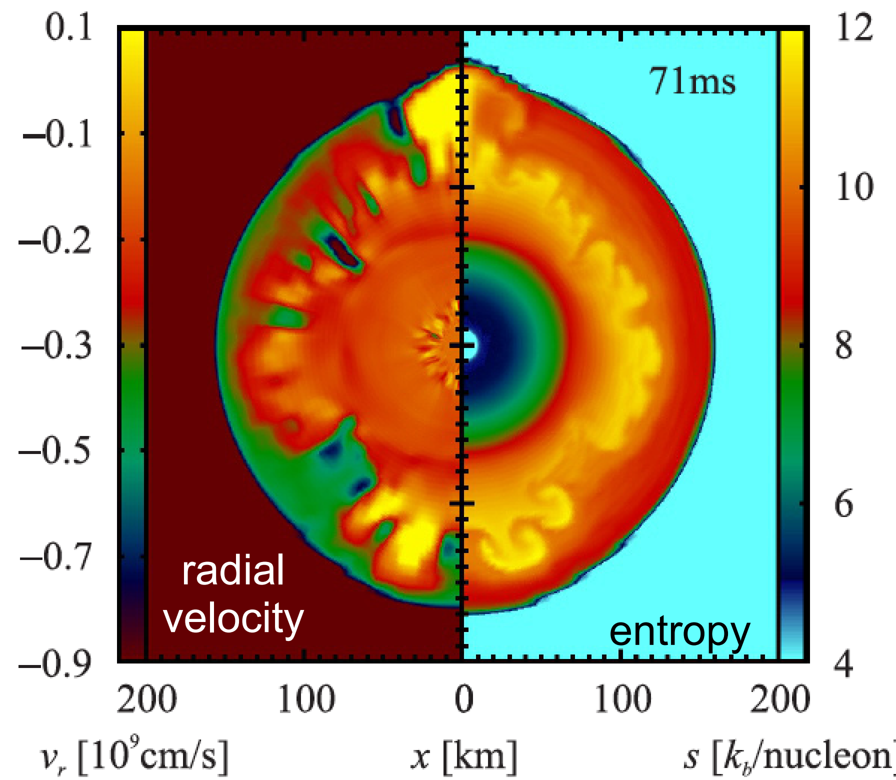
Convection vs. SASI and the Possible Role of General Relativity in the Debate

Convection vs. SASI

- Instabilities well-distinguished in linear regime only
- Large-scale structures and kinetic energy of convection may be reduced in 3D due to turbulent cascade (Hanke et a. 2012)
- But: large-scale modes may be important for explosion (more energy stored)
- Convection usually grows first



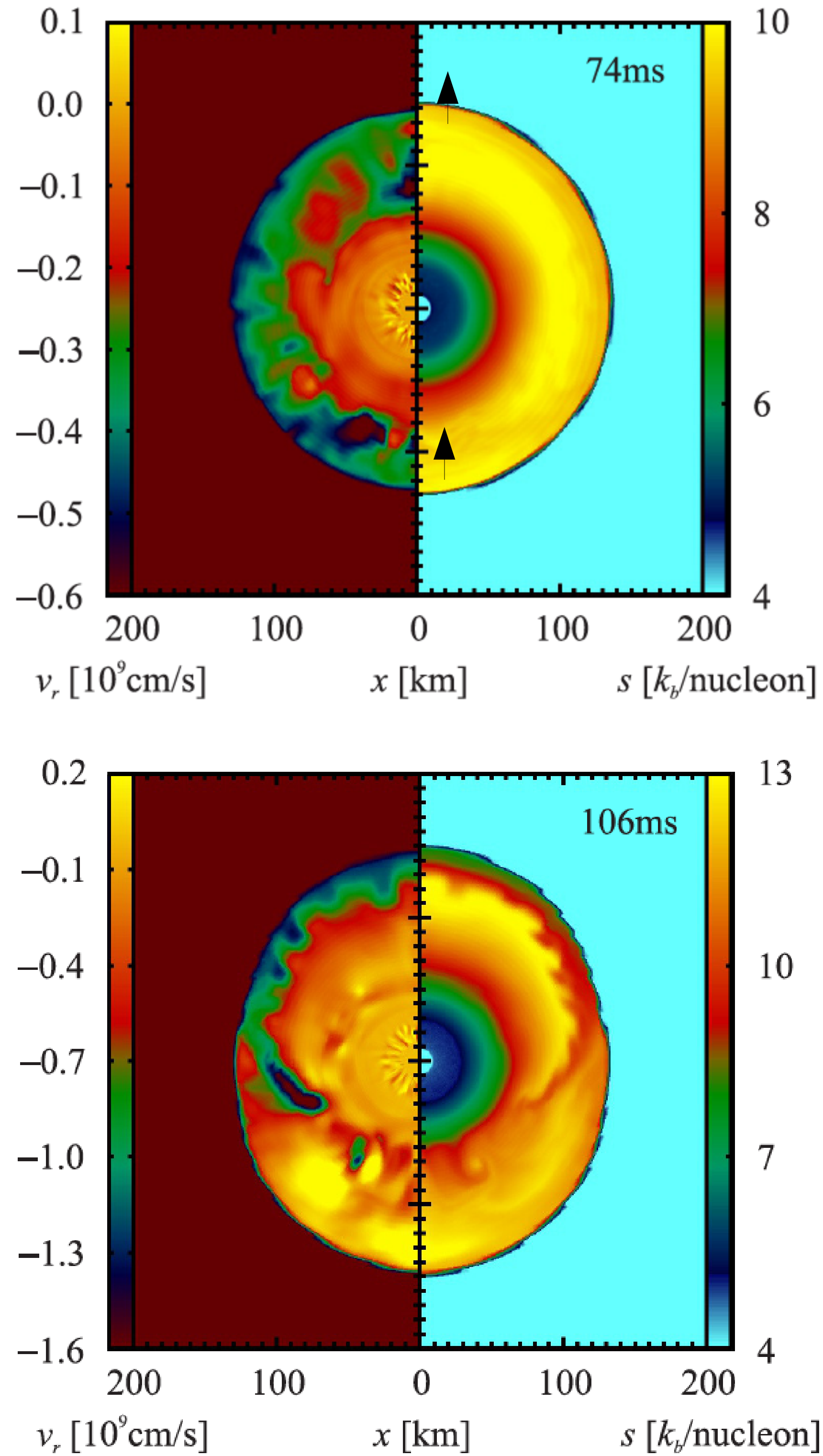
Hanke et al. (2011), arXiv:arXiv:1108.4355



Müller, Janka & Heger (2012) arXiv:1205.7078

Convection vs. SASI

- Can we find conditions for strong SASI growth In supernova cores?
- Recent relativistic $27M_\odot$ explosion model (Müller et al. 2012) constitutes such a case
- Incidentally: Explosions now also with LS220 equation of state



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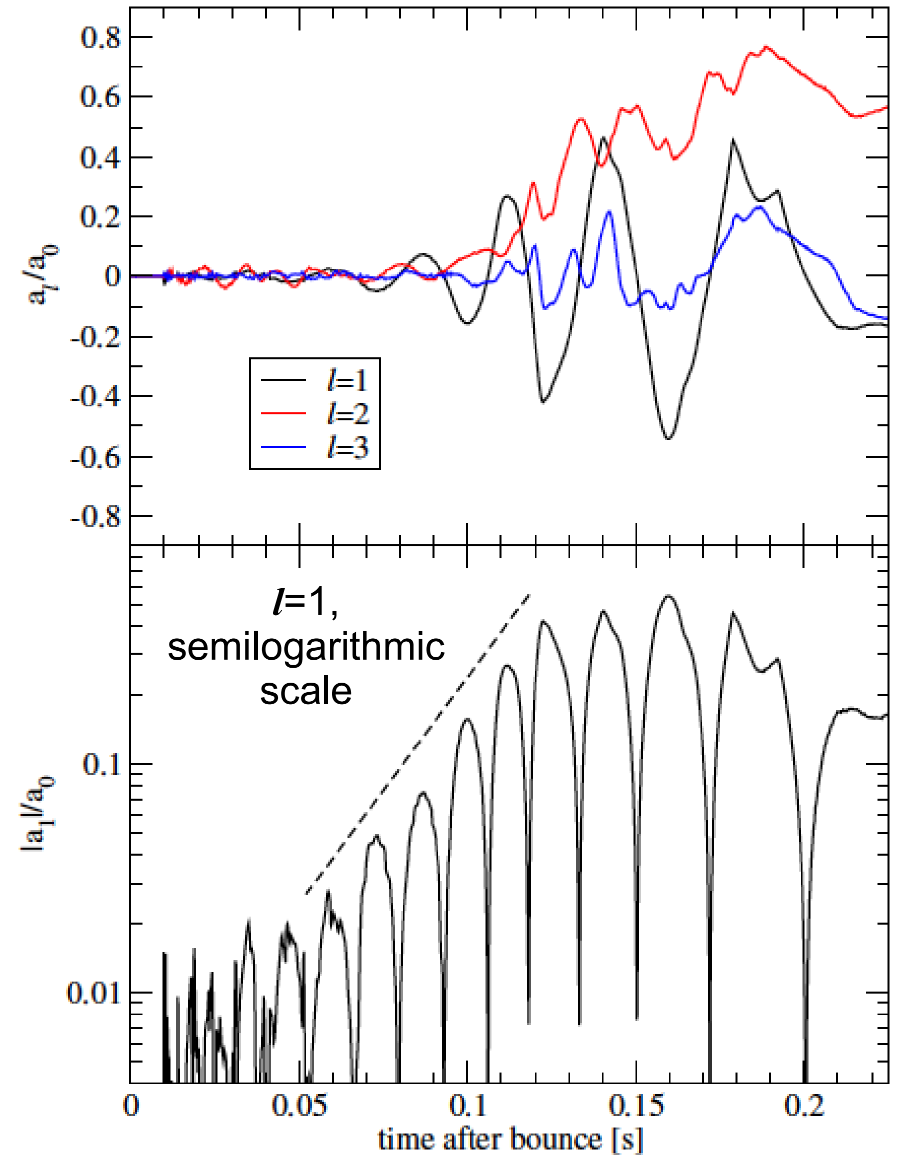

Decomposition of the shock surface into spherical harmonics

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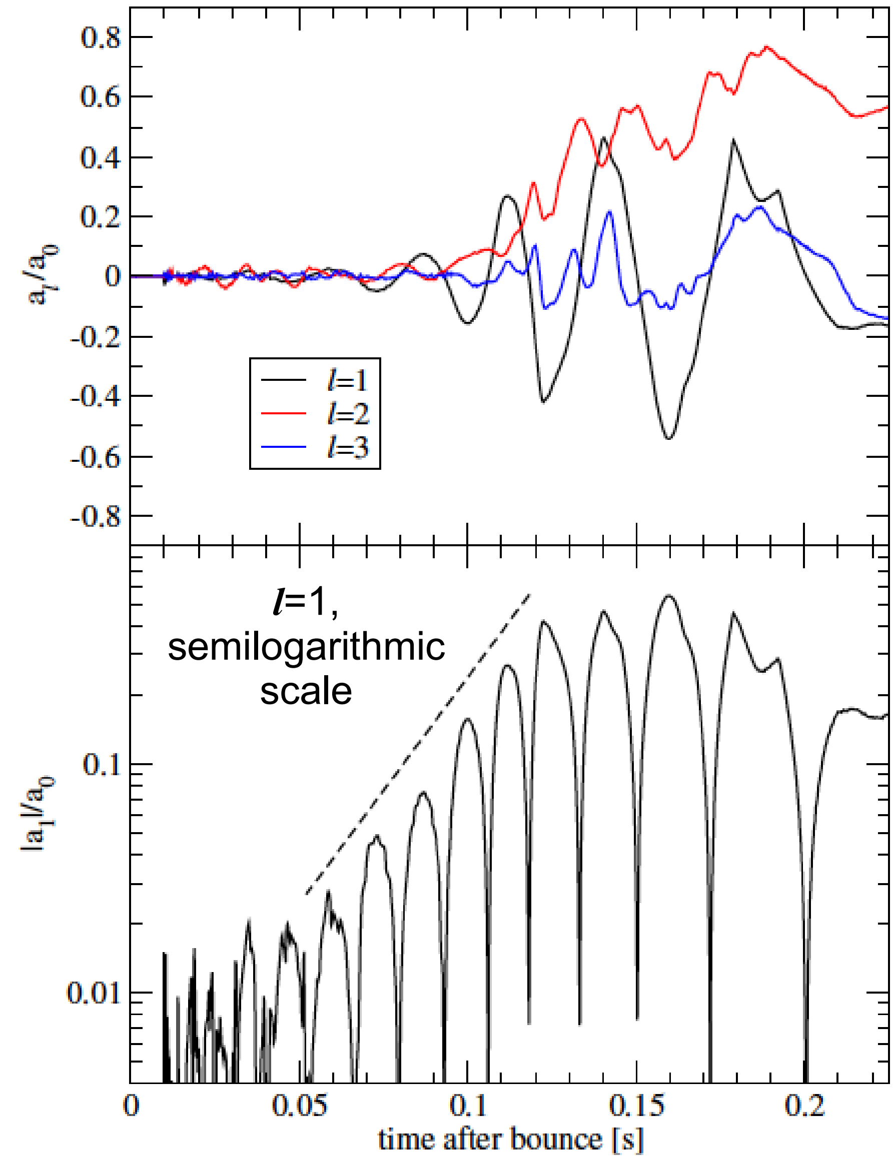

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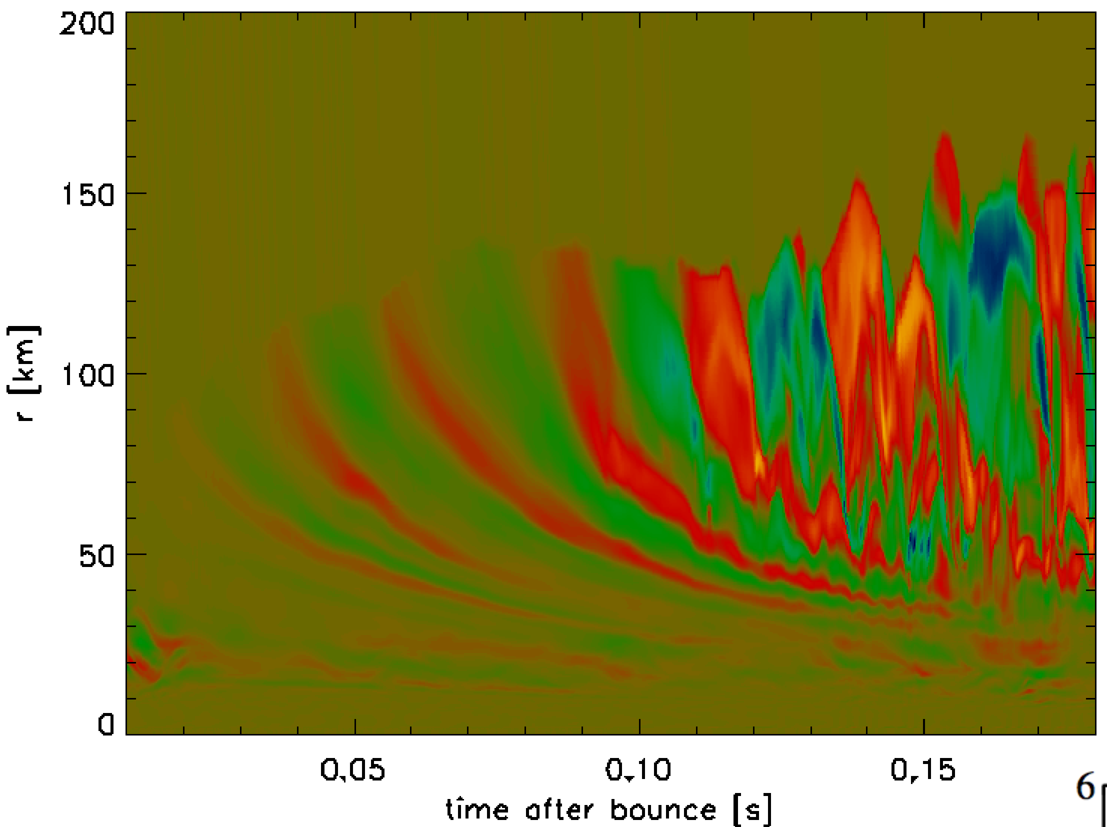
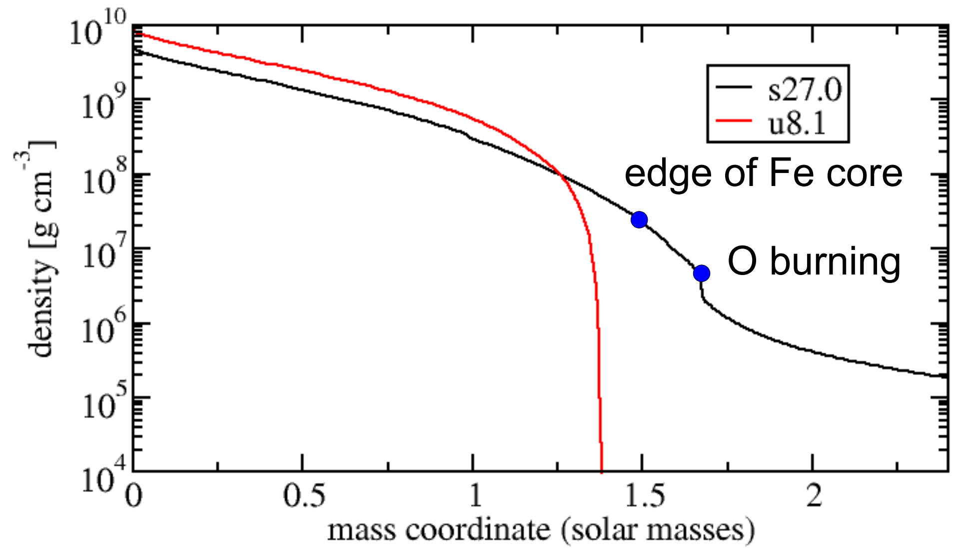
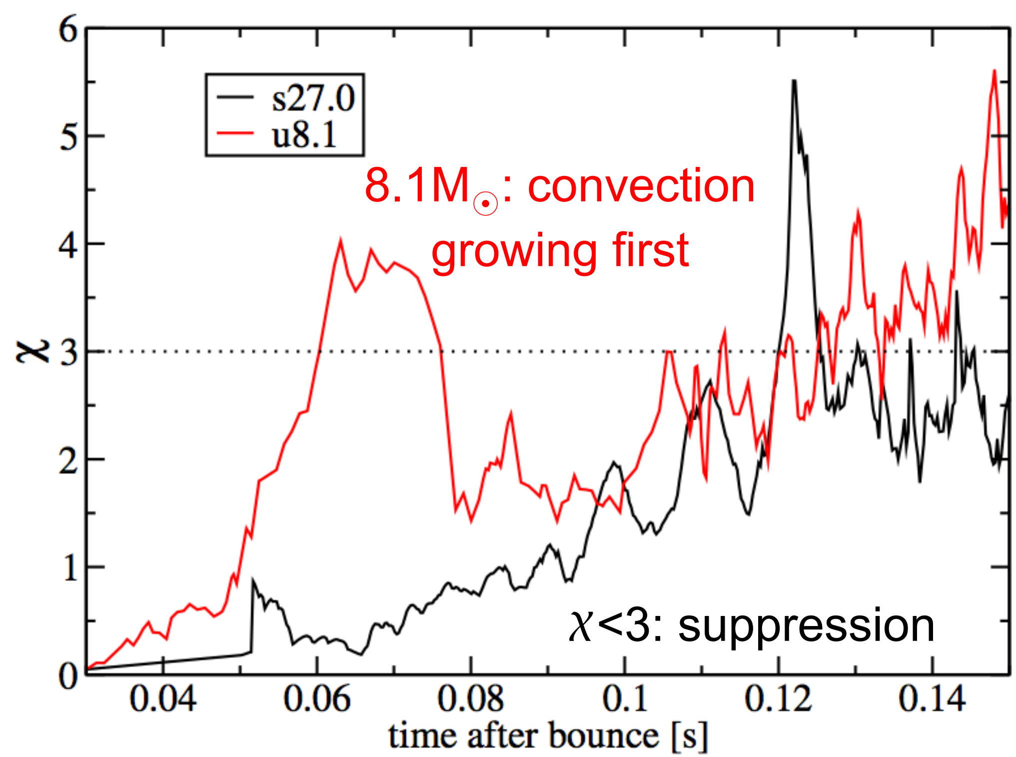




comparison of density profiles

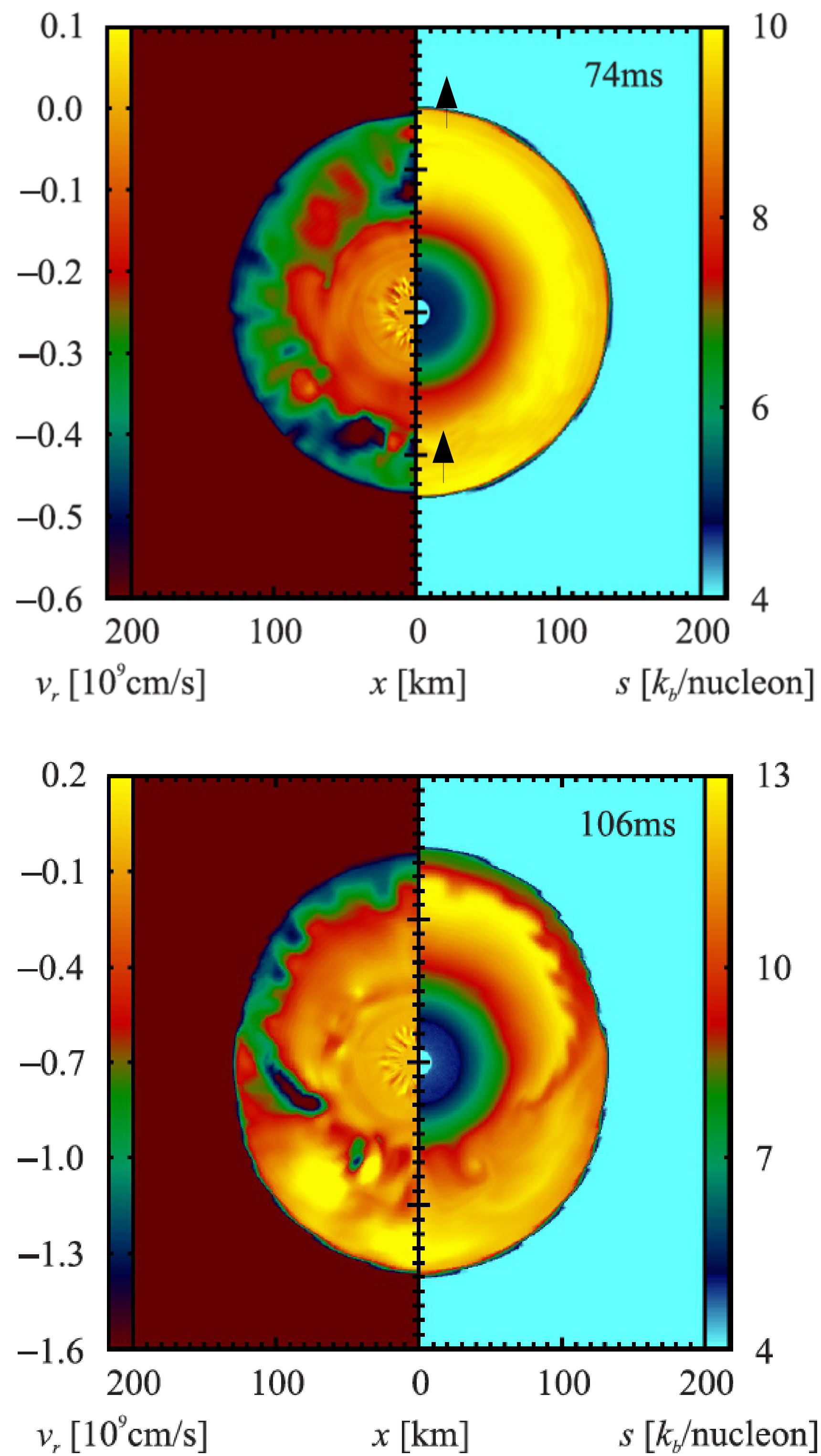
lateral velocity in equatorial plane revealing vorticity perturbation in SASI cycle

critical parameter χ for growth of convection ($\sim$buyoancy time scale/advection time scale)



Implications & Questions

- Compact proto-neutron stars with strong gravitational field beneficial for SASI growth (→ short advection time-scale)
- General relativity, the progenitor structure, the equation of state and a correct neutrino treatment at high optical depth (→ PNS contraction) may be crucial for vigorous SASI activity
- Is there an *intermediate* regime (SASI+convection)?
- Can “convectively-dominated” flows become “SASI-dominated” as the conditions change?
- What happens in 3D? Comparable or lower amplitudes? Spiral mode?



Summary

- General relativity (GR) and a good neutrino treatment emerge as important ingredients for successful explosions:
  - Higher neutrino luminosities & mean energies due to hotter proto-neutron star result in **more heating in GR**; effect outweighs different accretion shock radius
  - GR may even play a role for obtaining conditions conducive to strong SASI growth (behaviour in 3D to be investigated)
  - Seemingly minor rate effects (nucleon recoil in ν-nucleon scattering) may have an appreciable impact as well
- Large (50%) systematic GR effect on the typical gravitational wave frequency
- Conclusion: GR (at least on the level of the “effective potential approximation”) and up-to-date neutrino rates should be included for correct dynamics & accurate signal predictions
- Progress of explosion models: Growing set of progenitors, GW & neutrino signal predictions beyond shock revival now available, better connection to nucleosynthesis studies