Multi-Dimensional Core-Collapse Supernova Simulations with Neutrino Transport

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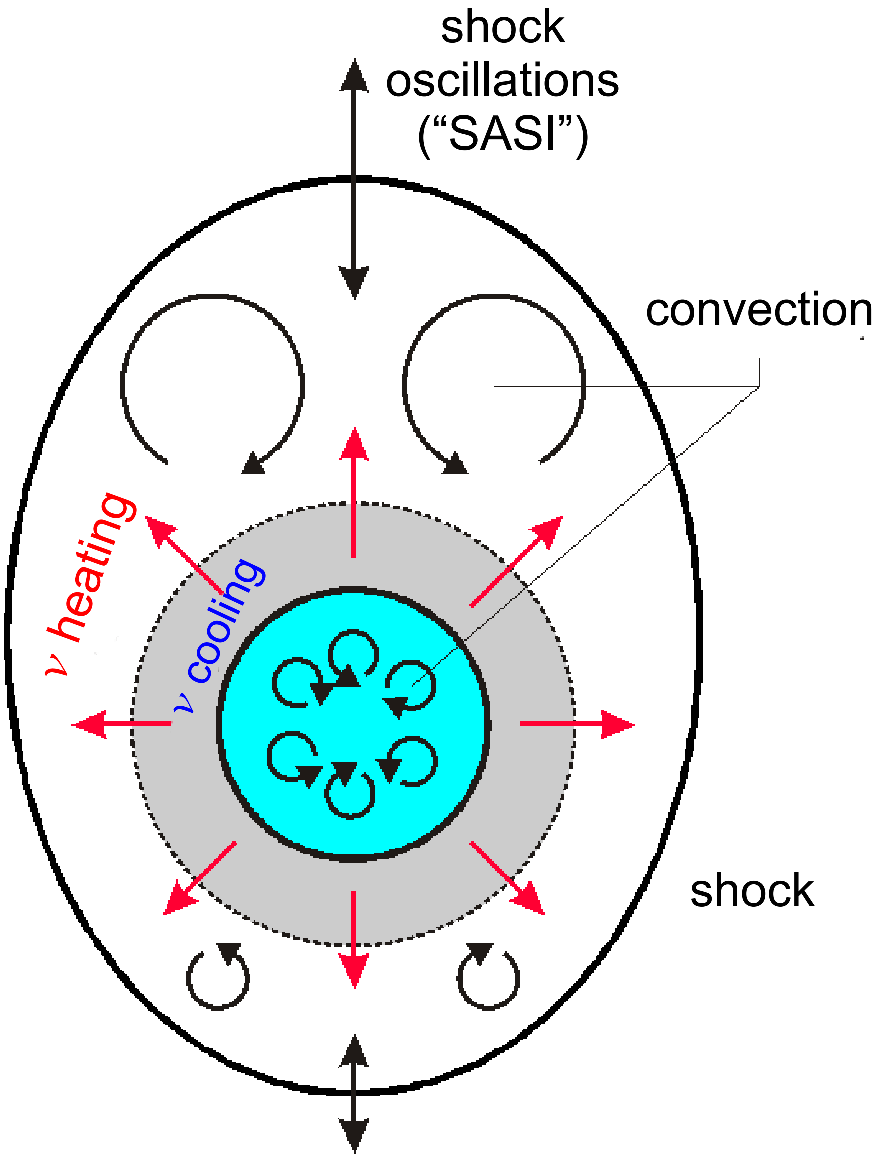
Part I

Introduction

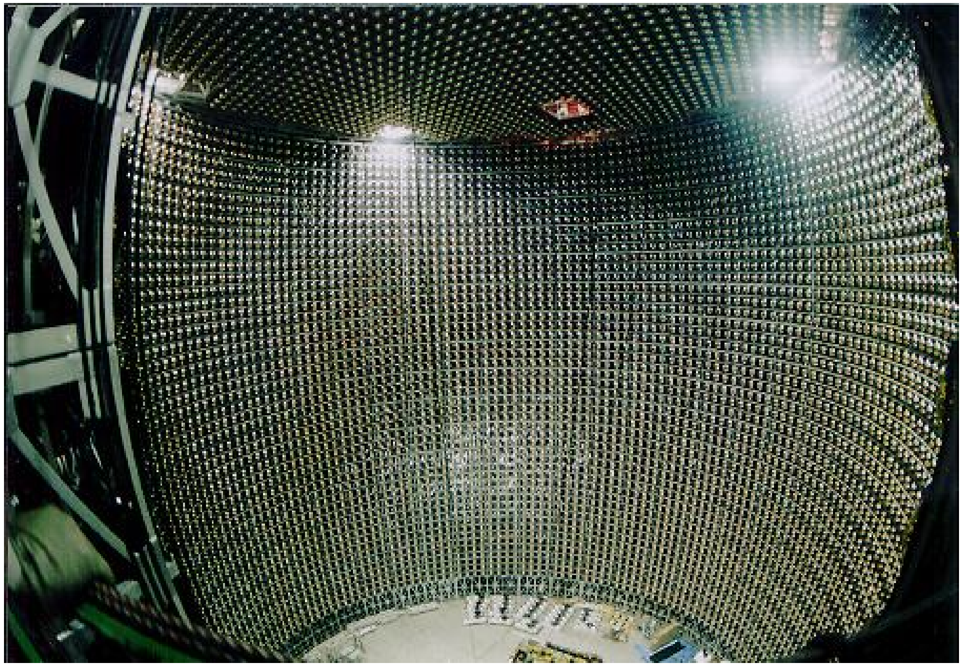
Core Collapse Supernovae

- Collapse of massive star to neutron star
- Shock wave launched when core rebounds, stalls after a few ms
- Different mechanisms for shock revival suggested: neutrino heating + convection, MHD, acoustic waves...
- Once shock wave reaches the stellar surface →optically visible as type II/type Ib,c supernova



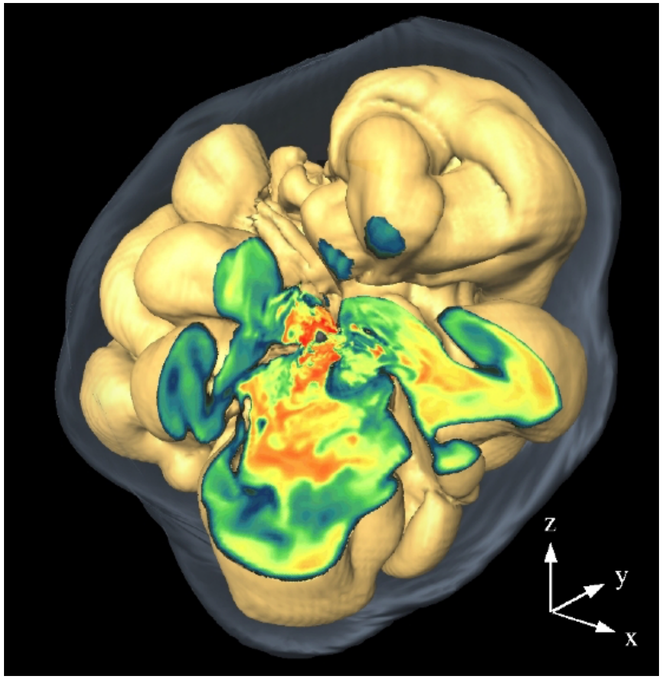
Major Issues

- How does the “engine” work? Can we predict explosion energies?
- What can we observe?
  - Neutrinos
  - Gravitational waves (?)
  - Nucleosynthesis yields
  - Ejecta morphology
  - Light curves

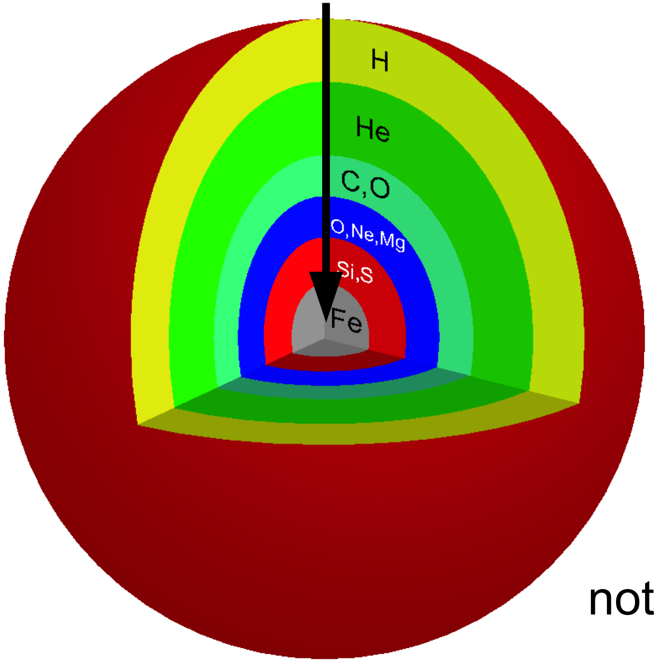


Challenges of the Supernova Problem

- Multi-dimensionality of the flow
- Multi-scale problem
- Nuclear physics input not yet fully determined
- Strong gravitational fields ($GM/rc^2 \approx 0.1 \ldots 0.2$) & high velocities → relativistic effects important
- Transition between the diffusion & free streaming regimes of the neutrinos → **kinetic theory required** → 6D problem



several 100 km



not to scale

~10^8km

Part II

Overview of Neutrino Transport Strategies in Multi-D Core-Collapse Supernova Simulations

Why Neutrino Transport Is Important

- Transport of energy, momentum & lepton number can be crucial for the dynamics of compact objects and their surroundings
- Rough criterion for importance: **evolution time-scale≈diffusion time-scale** (at a given density) or larger
- Role of neutrinos in the supernova problem:
  - Determine <u>heating</u> & neutron star <u>cooling</u> (contraction) → crucial for dynamics (explosion/no explosion)
  - Regulate <u>nucleosynthesis</u> conditions
  - Can produce sizeable <u>gravitational wave</u> signal
- Neutrino transport also relevant for other scenarios involving compact objects (winds from merger disks, gamma ray bursts)

Neutrino Transport: Basics

- In general: Boltzmann equation applicable (6D problem!):

$$p^{\alpha} M^{\beta}{}_{\alpha} \frac{\partial f}{\partial x^{\beta}} - \tilde{\Gamma}^{i}_{\alpha\beta} p^{\alpha} p^{\beta} \frac{\partial f}{\partial p^{i}} = C[f]$$

- Dimensionality may be reduced by introducing a hierarchy of angular moments of the distribution function (requires closure relation):

$$f \rightarrow J = \int f \, d\Omega \, , H^{i} = \int f n^{i} \, d\Omega \, , K^{ik} = \int f n^{i} n^{k} \, d\Omega \, , \ldots$$

- Diffusion approximation: truncate hierarchy at lowest level (only energy density J is evolved)
- Grey approximation is even more severe (detailed information on spectral distribution lost)

$$(J, H^{i}, K^{ik}, \ldots) \rightarrow \left(\int J \, d\epsilon, \int H^{i} \, d\epsilon, \int K^{ik} \, d\epsilon, \ldots\right)$$

Overview of Current Strategies for the Multi-D Supernova Problem

- **2D/3D hydro + parameterized source/sink terms** (e.g. 2D: Fernandez & Thompson 2009; 3D: Iwakami et al. 2008, Nordhaus et al. 2010) or **leakage schemes** (Sekiguchi 2010, GR)
- **2D/3D hydro + grey transport** (e.g. Fryer & Young 2007, Scheck et al. 2008) or **hybrid grey transport+leakage** (Kuroda et al. 2012, GR)
- **2D (3D) hydro + multi-energy transport:**
  - Discrete ordinate (S_n) method for Boltzmann equation without non-isoenergetic scattering & gravitational redshift: Livne et al. 2004 (2D), Sumiyoshi & Yamasaki 2012 (3D, stationary)
  - Ray-by-ray variable Eddington factor method (Buras et al. 2006, Müller et al. 2010, GR)
  - Multi-group flux-limited diffusion (full 2D: Walder et al. 2005, Swesty&Myra 2006; ray-by-ray: Bruenn et al. 2006)
  - Isotropic diffusion source approximation (Liebendörfer et al. 2009), ray-by-ray implementation by Suwa et al. 2010 (2D), Takiwaki et al. 2011 (3D)

Issues Relevant for Multi-Group Transport

- Choice of equations to be solved
  - Direct discretisation of the Boltzmann equation
  - Two-moment equations with prescribed closure or Boltzmann closure
  - Flux-limited diffusion
  - Isotropic Diffusion Source Approximation (IDSA)
- Comoving or mixed frame
- Full multi-angle treatment or ray-by-ray-method (radial flux vector)
- Energy bin coupling (Doppler shift, redshift, non-isoenergetic scattering)
- Linear solvers for implicit schemes

New Schemes for Radiation Hydrodynamics

- Disadvantage of rigorous approach: direct solution of Boltzmann equation introduces strong non-local coupling

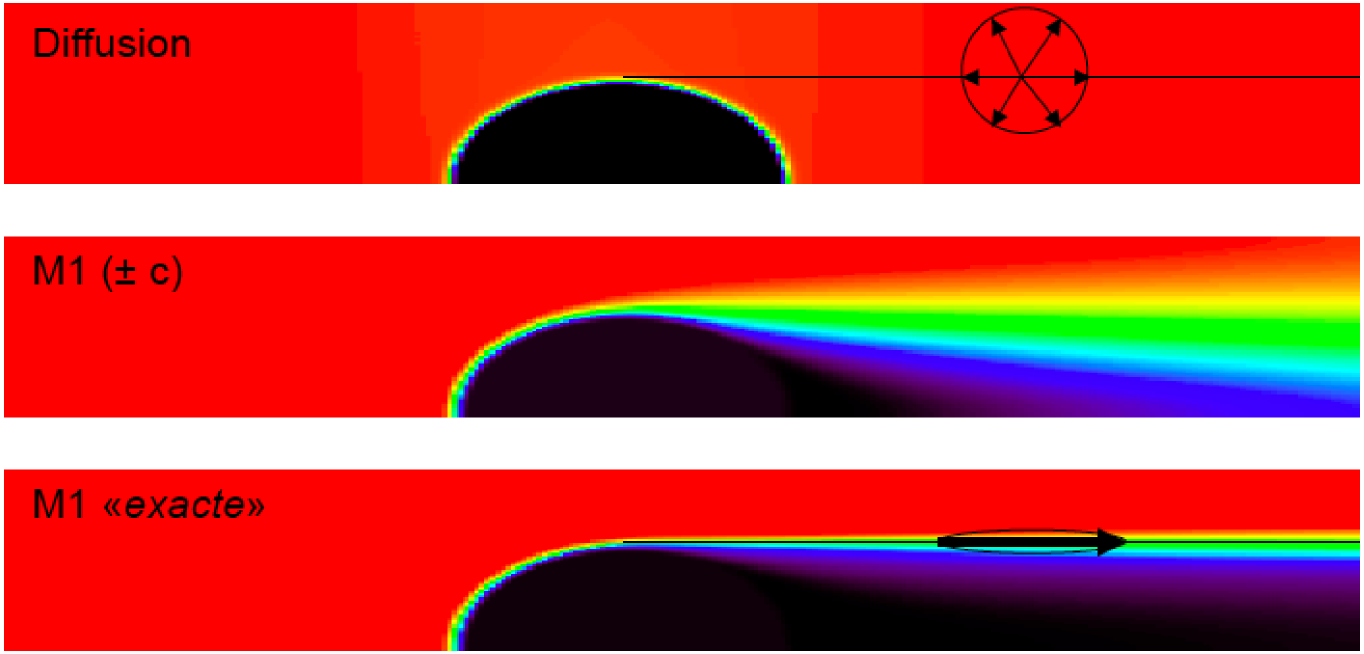
  → fully implicit schemes required

  → expensive, harder to parallelise

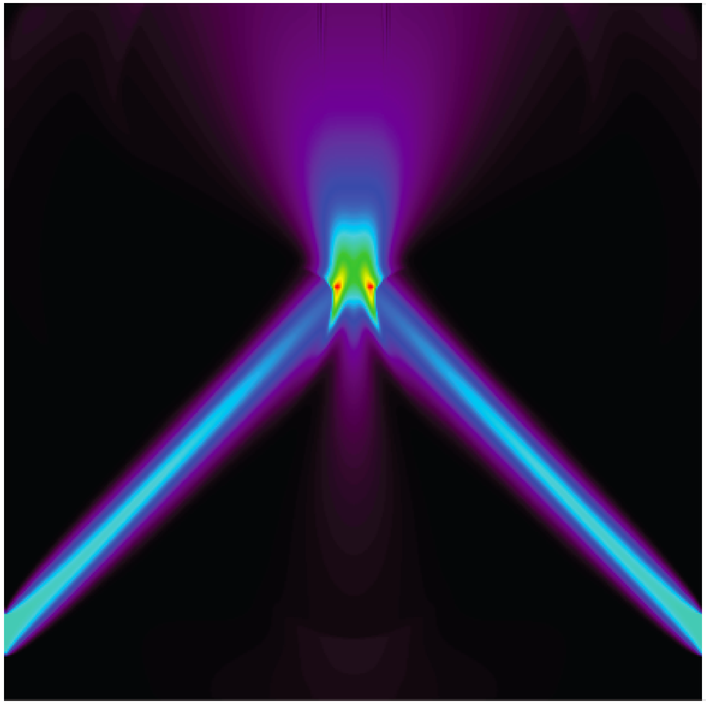
  BUT: only rigorous way to ensure correct flux factors & atmosphere solution a priori

- Isotropic Diffusion Source Approximation (IDSA)
  - Diffusion limit can be included by construction
  - Elegant use of different frames for streaming and trapped component
  - **BUT**: potentially expensive in multi-D, unless applied ray-by-ray
- Two-moment approach with prescribed closure
  - Explicit finite-volume discretisation→ fast, easy to parallelise
  - Potential problems: enforcement of diffusion limit may be necessary (Pons et al. 2000, Audit et al. 2002); critical points of PDEs? (Koerner & Janka 1992)

Flux-Limited Diffusion, Two-Moment Closure & Exact Radiative Transfer



M1 closure capable of capturing shadowing effects → superior to diffusion

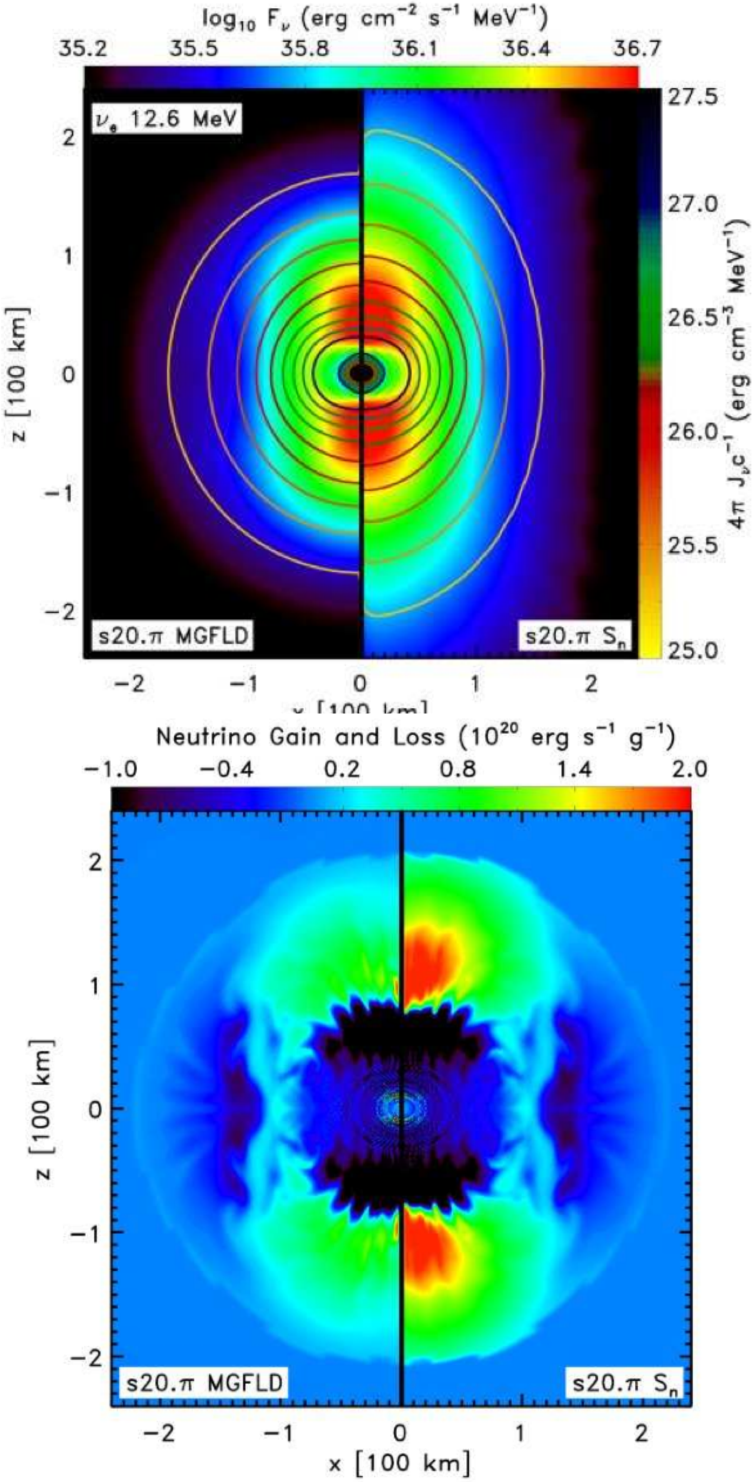


Breakdown of the approach: intersecting beams of radiation without any interaction

Examples from E.Audit, Conference Talk at the Workshop “Asymmetric Instabilities in Stellar Core Collapse” (2008)

Multi-Angle Transport

- Multi-angle effects explored by Ott et al. (2008) in dynamical 2D simulations and for stationary 3D configurations by Sumiyoshi & Yamada (2012)
- “Smearing” effect of flux-limited diffusion revealed → may have an impact on the heating rates for rapidly rotating aspherical proto-neutron stars
- Quantitative comparison to ray-by-ray approach still missing, but the flux asymmetry is qualitatively similar
- Advantages of ray-by-ray-transport: easy to parallelise (several 10,000 cores in 3D), re-utilisation of well-tested 1D modules with elaborate ν rates & full energy bin coupling



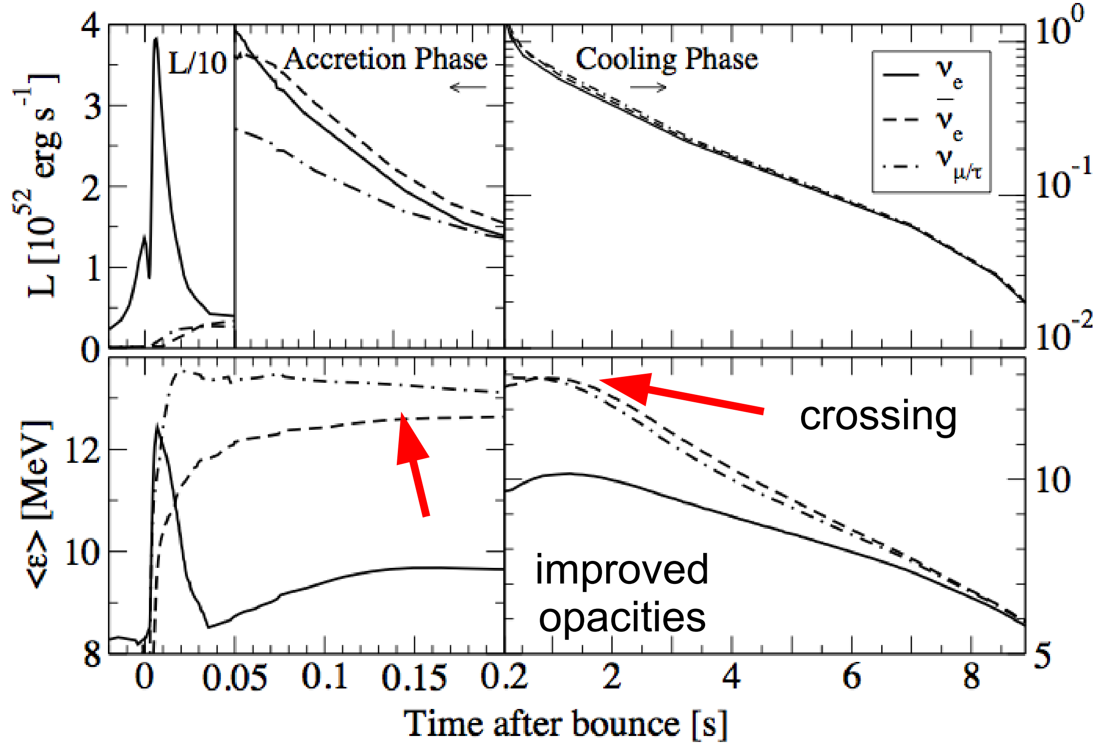
flux

heating rate

Figures from Ott et al. (2008)

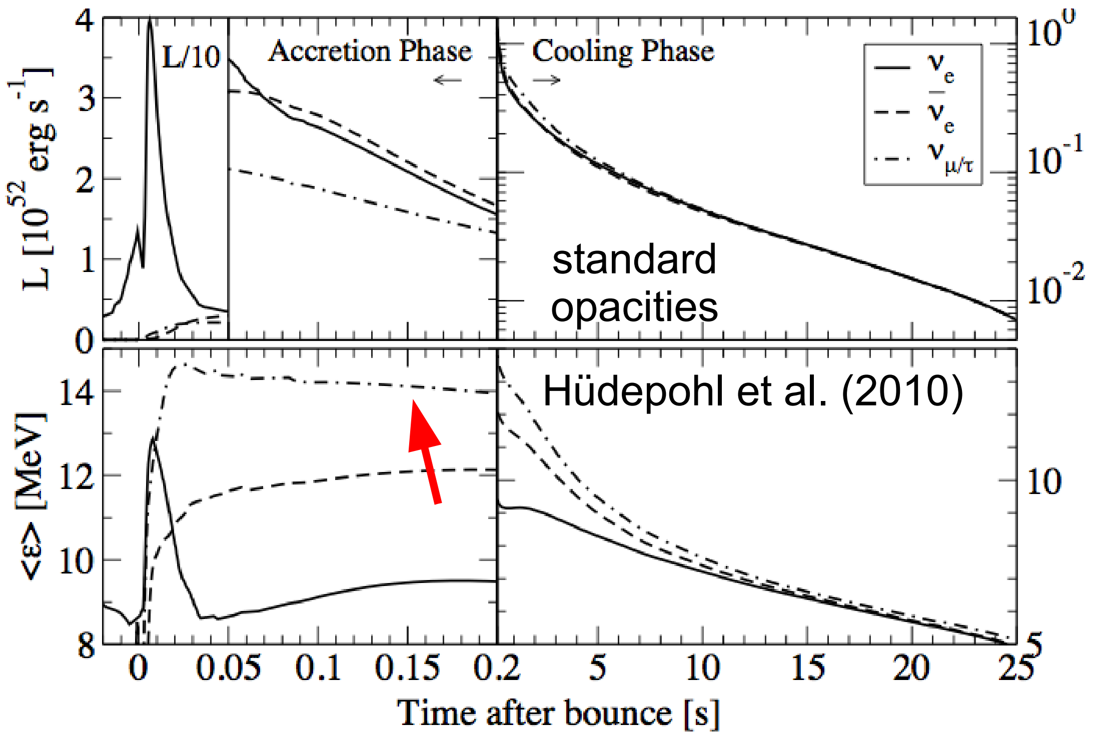
Input Physics: Neutrino-Nucleon Reactions

- "Standard" opacities (Bruenn 85) assume non-interacting nucleons & zero momentum-transfer
- Rates modified by recoil (small energy transfer to nucleon!) & correlations at high densities (→ lower opacity)
- Huge impact on cooling time-scale of proto-neutron star (shorter by factor ~2)
- Energy exchange in scattering reactions drastically reduces mean energies of μ/τ neutrinos
- νN scattering is only an (illustrative) example: do not forget NN bremsstrahlung, pair conversion...



crossing

improved opacities



standard opacities

Hüdepohl et al. (2010)

Summary: What Level of Precision in the Transport Sector is Required?

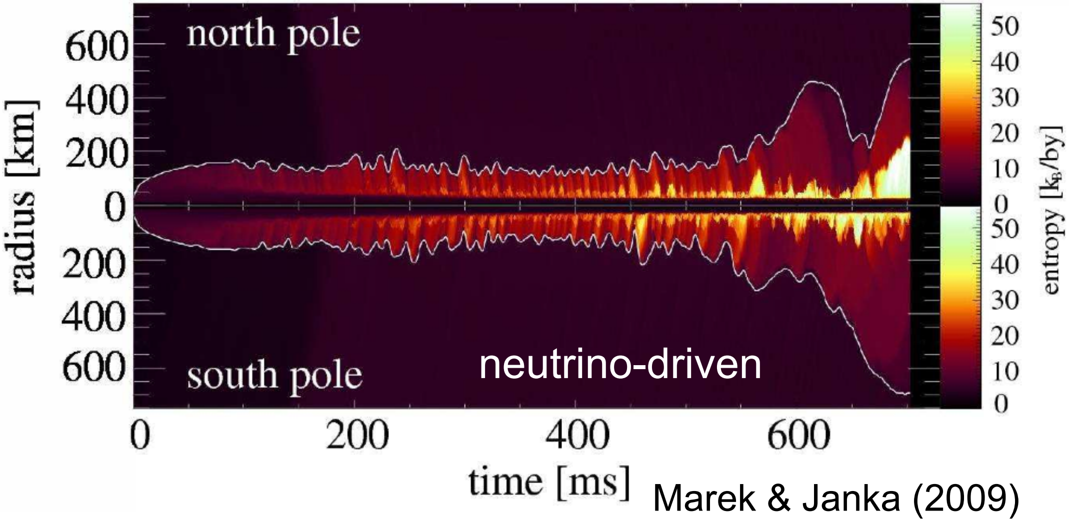
- Answer is problem-dependent!
- Studying general properties of hydrodynamical instabilities: parametrized schemes will *usually* do the job (caveat: feedback effects)
- Quantitatively accurate dynamics require accurate luminosities (within a few percent) - different multi-group methods may work well
- Neutrino wind nucleosynthesis & neutrino oscillation studies: up-to-date interaction rates indispensable!
- Thorough and comprehensive comparison of multi-D transport methods still missing & highly desirable

Part III

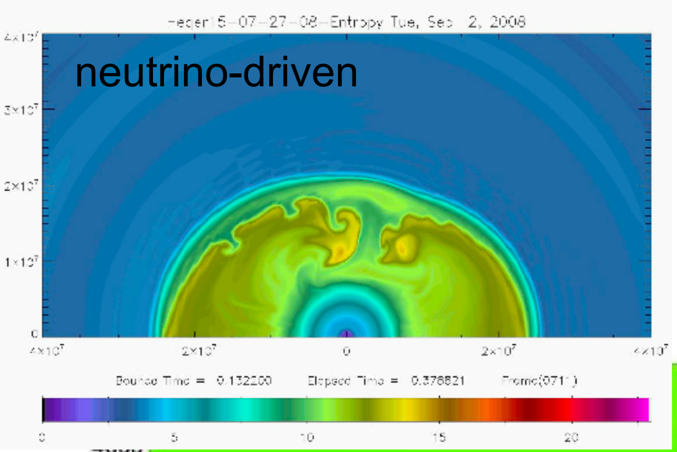
Status of Core-Collapse Supernova Simulations & Recent Results Obtained at MPA

Viability of the Neutrino-Driven Mechanism

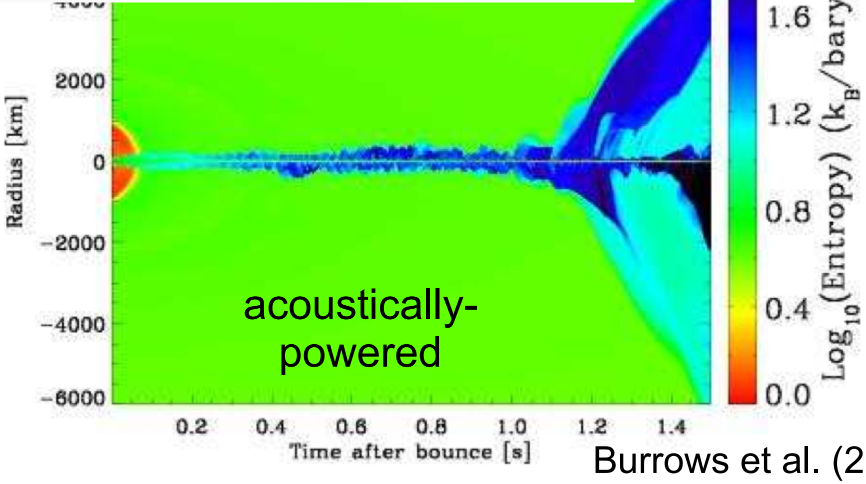
- Axisymmetric multi-group simulations by different groups not yet in agreement
- Concerns: some weak & late explosions, limited range of progenitors
- Potential ingredients for neutrino-driven explosions to be investigated in more detail:
    - 3D effects
    - Equation of state
    - General relativity
    - Neutrino physics
- Models need to be evolved further into the explosion phase (→ nucleosynthesis)



Marek & Janka (2009)

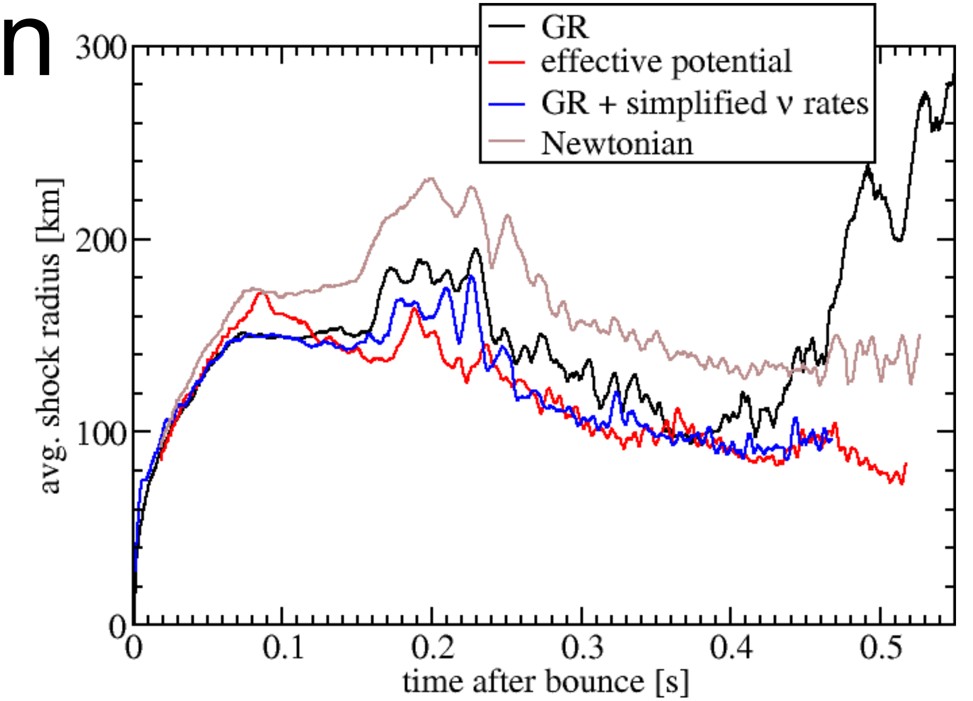


Bruenn et al. (2009)

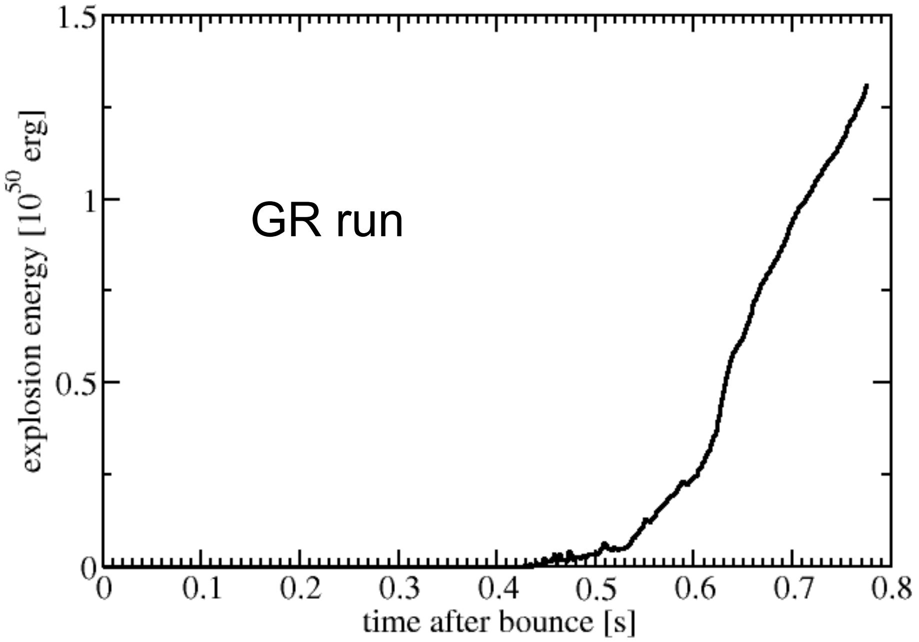


Burrows et al. (2007)

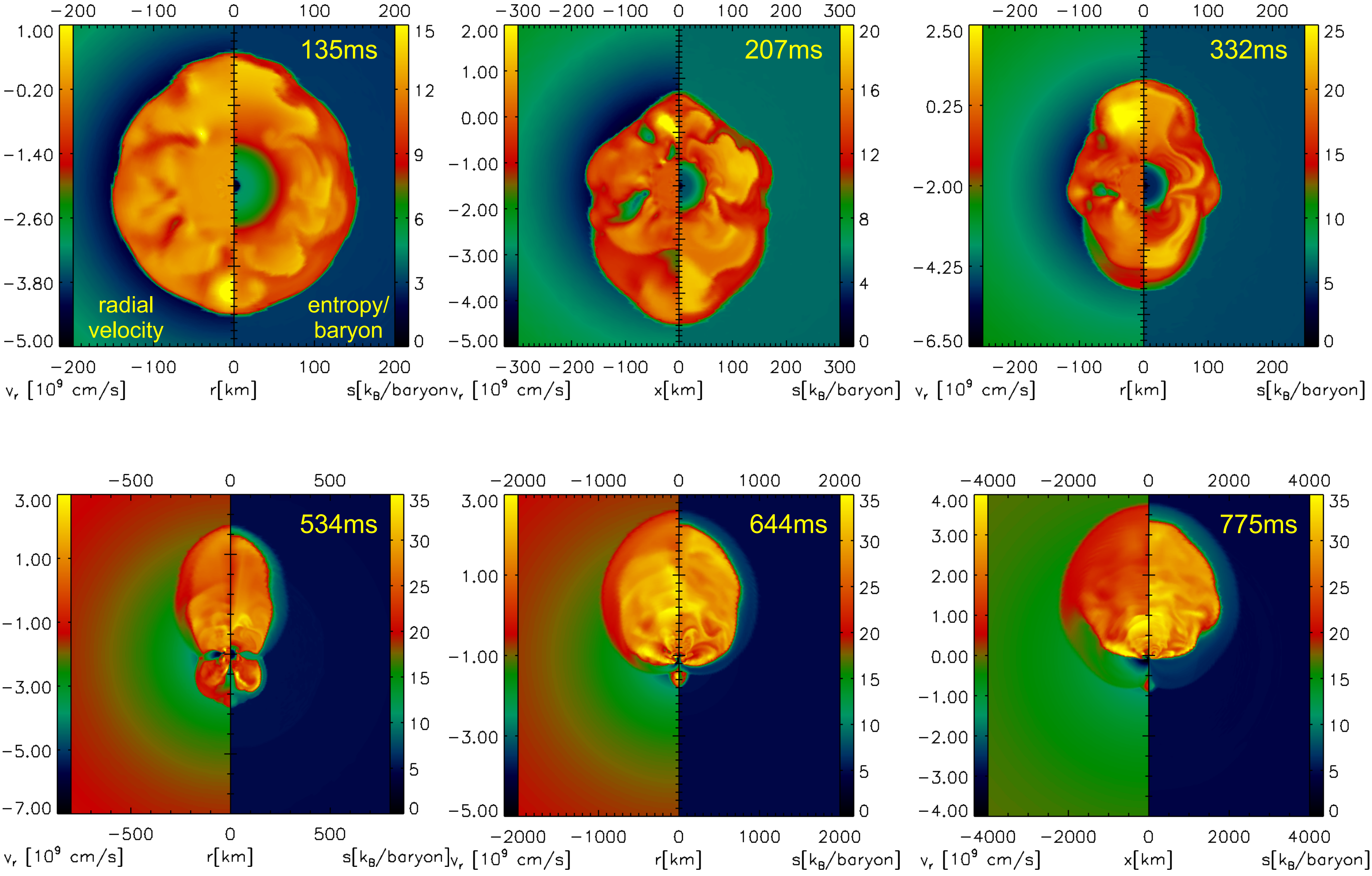
Ingredients for ν-driven Explosions



- Tool for testing the influence of GR (in xCFC approximation) and the neutrino microphysics in 2D available: VERTEX-CoCoNuT code (Müller et al. 2010, 2D ray-by-ray variable Eddington factor method)
- Detailed comparison of four models using the 15$M_\odot$ 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)
- GR and ν rates can make a difference!



GR run


135ms
radial velocity
entropy/ baryon
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
1.00
−0.20
−1.40
−2.60
−3.80
−5.00
15
12
9
6
3
0
−200
−100
0
100
200
207ms
v_r [10^9 cm/s]
x[km]
s[k_B/baryon]
2.00
1.00
0.00
−1.00
−2.00
−3.00
−4.00
−5.00
20
16
12
8
4
0
−300
−200
−100
0
100
200
300
332ms
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
2.50
0.25
−2.00
−4.25
−6.50
25
20
15
10
5
0
−200
−100
0
100
200
534ms
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
3.00
1.00
−1.00
−3.00
−5.00
−7.00
35
30
25
20
15
10
5
0
−500
0
500
644ms
v_r [10^9 cm/s]
r[km]
s[k_B/baryon]
3.00
1.00
−1.00
−3.00
−5.00
35
30
25
20
15
10
5
0
−2000
−1000
0
1000
2000
775ms
v_r [10^9 cm/s]
x[km]
s[k_B/baryon]
4.00
3.00
2.00
1.00
0.00
−1.00
−2.00
−3.00
−4.00
35
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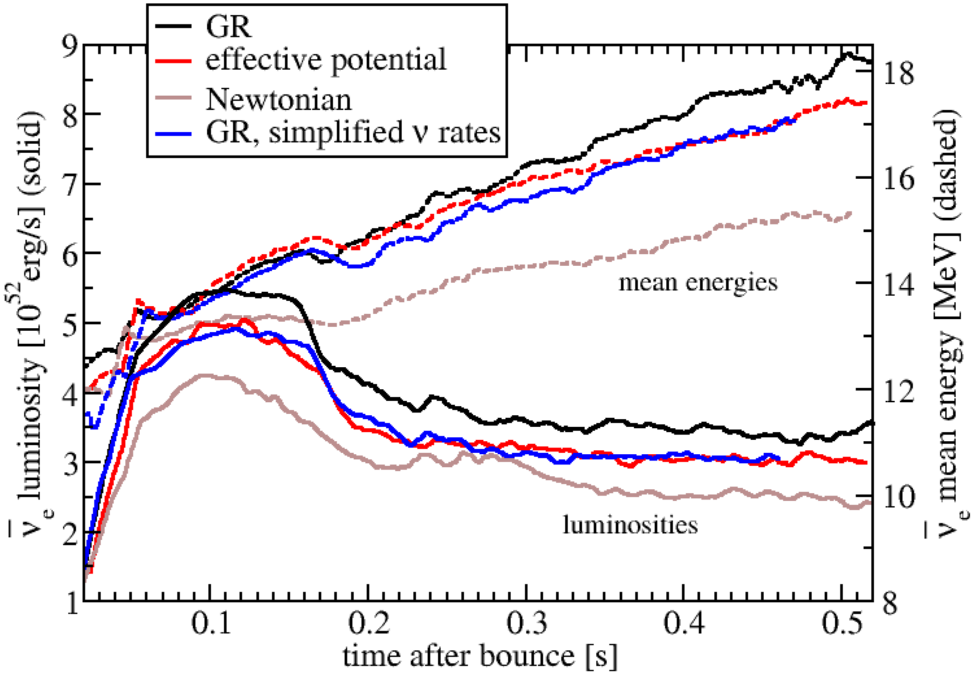
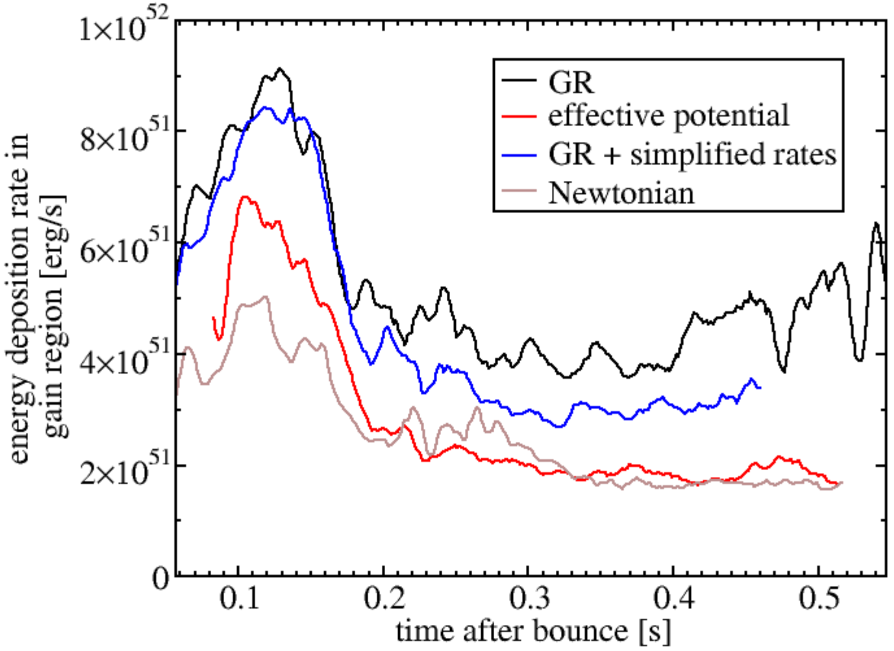
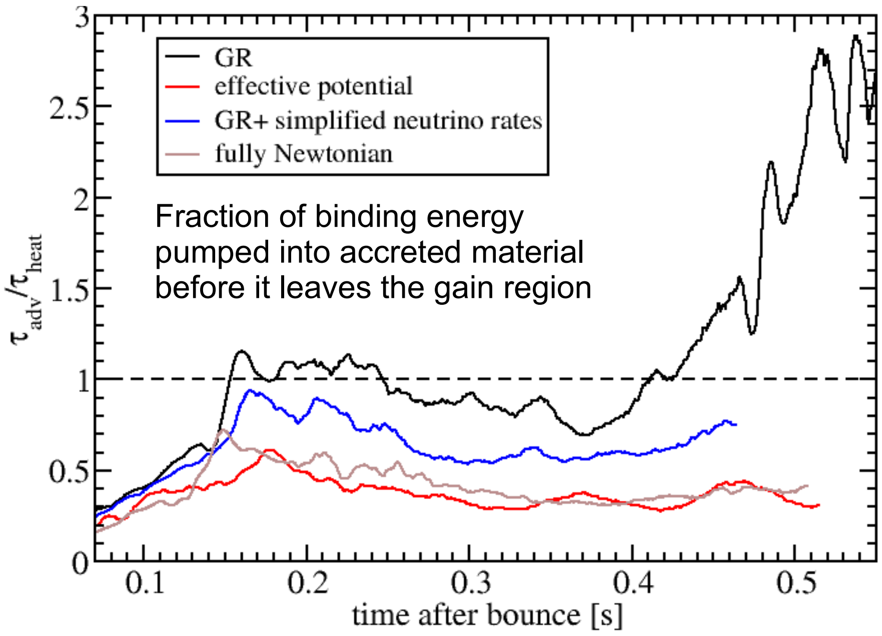
15
10
5
0
−4000
−2000
0
2000
4000

Systematic Differences in the Heating Conditions



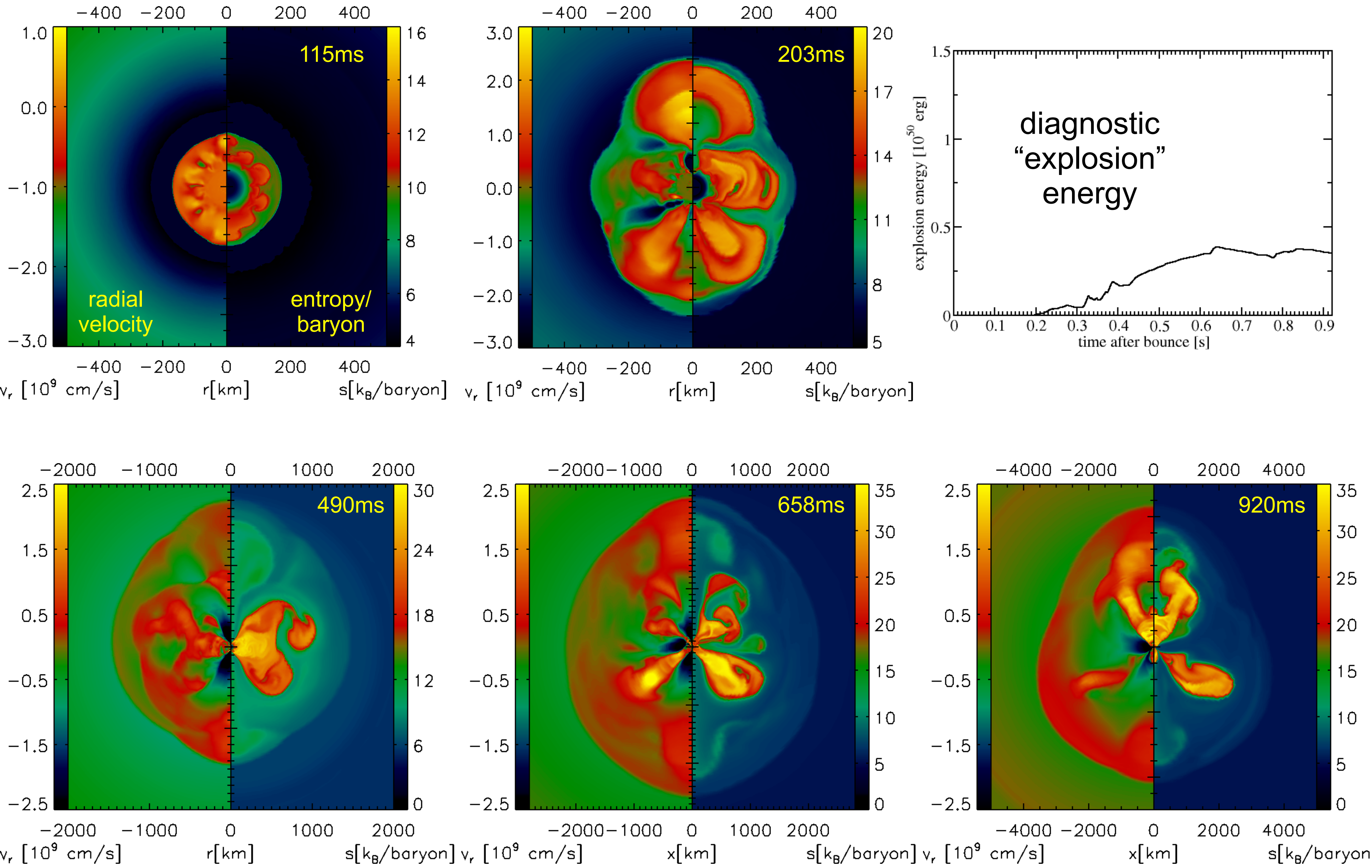


- Increased electron (anti-)neutrino luminosity L and mean energies $\langle E_\nu \rangle$ in GR (hotter neutron star surface)
- Local heating rate ~$L\langle E_\nu \rangle^2$, but feedback effects (stronger convection, larger shock radius) further increase the integrated heating rates (up to ~100%)
- 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



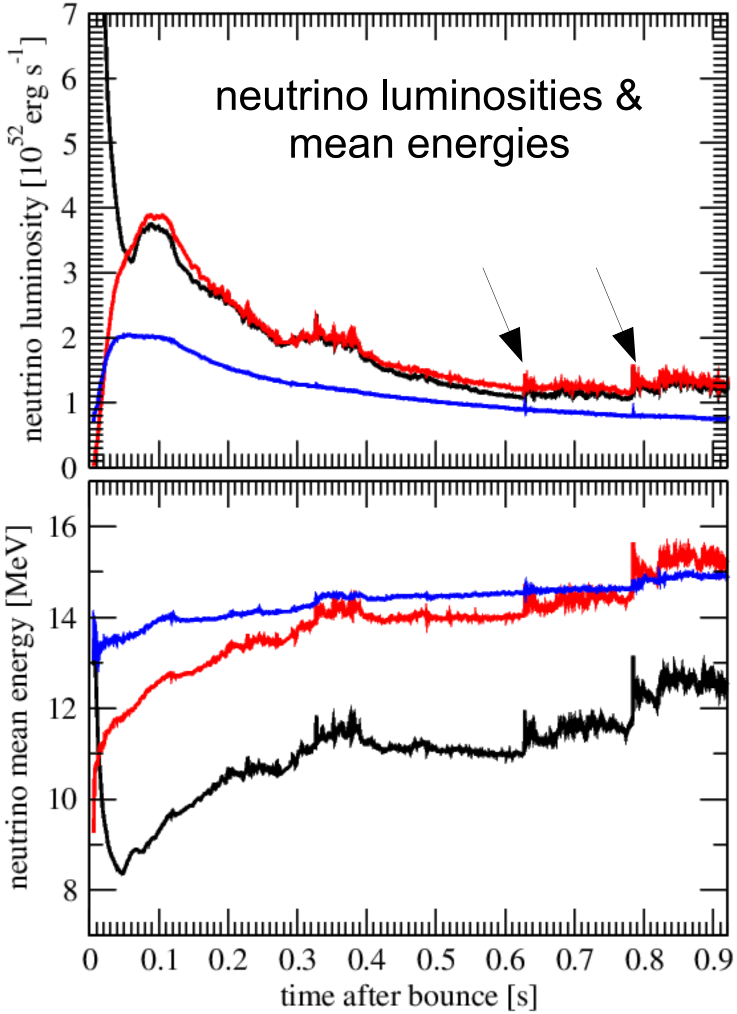
Fraction of binding energy pumped into accreted material before it leaves the gain region

Simulating into the Explosion Phase: An $11.2M_\odot$ Star

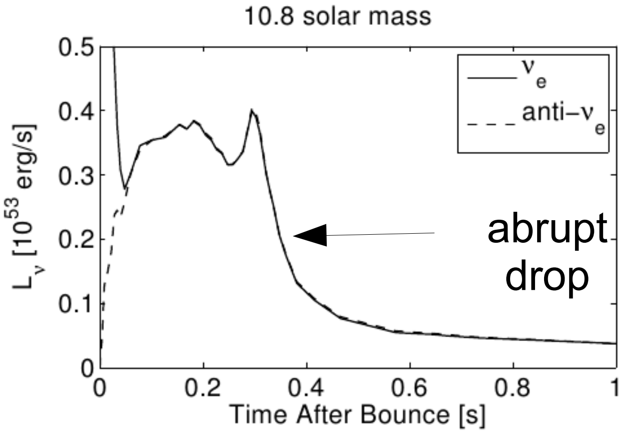


Simulating into the Explosion Phase

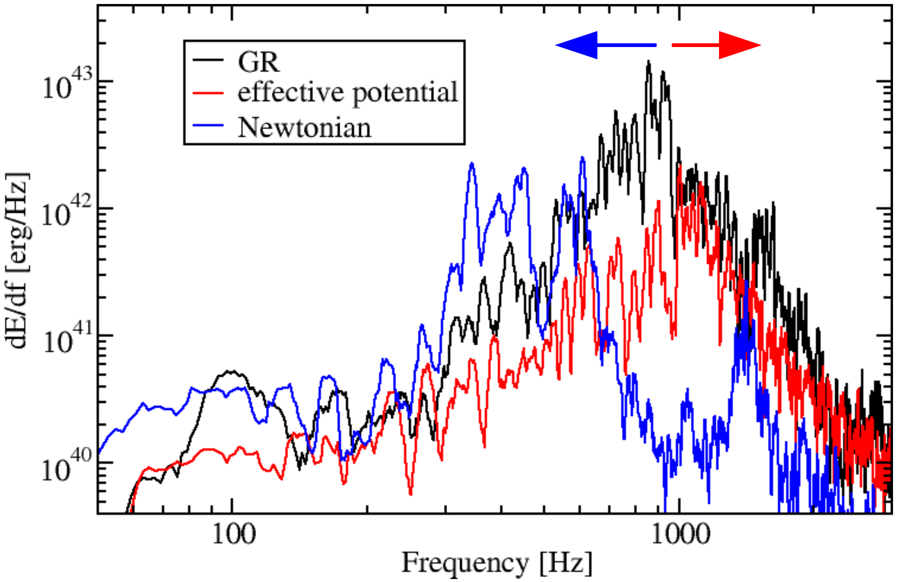
- First several hundreds of milliseconds of the explosion phase now accessible
- No final predictions for explosion energies (with outer envelope) yet – additional ~0.5s required
- Nonetheless: explosion of $11.2M_\odot$ progenitor definitely weak (as found by Buras et al. 2006), indications of early fallback
- Progress towards “complete” neutrino and and gravitational wave signals (including specific signatures of early fallback)


neutrino luminosities & mean energies

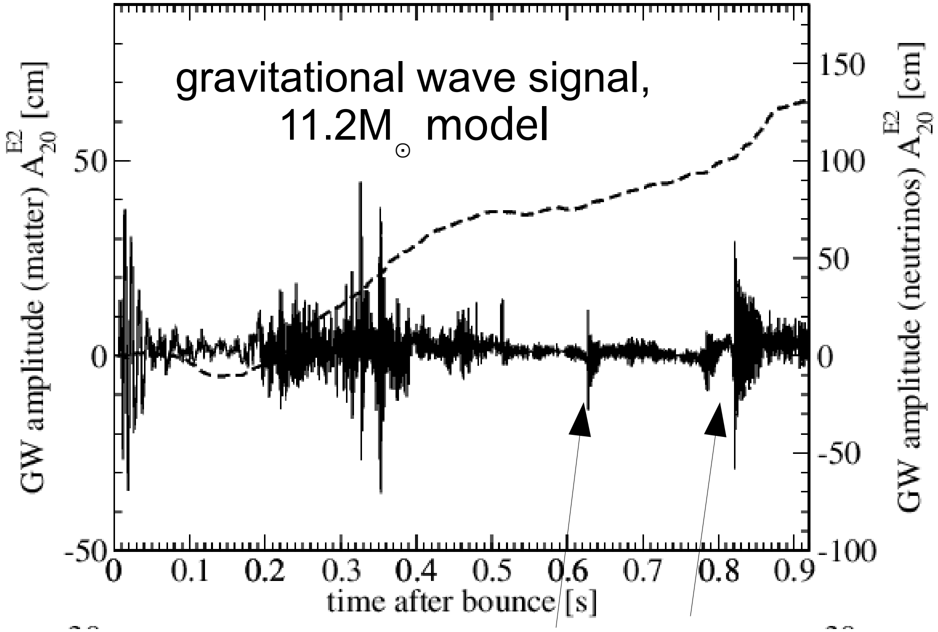
For comparison: artifical 1D explosion from Fischer et al. 2010


abrupt drop

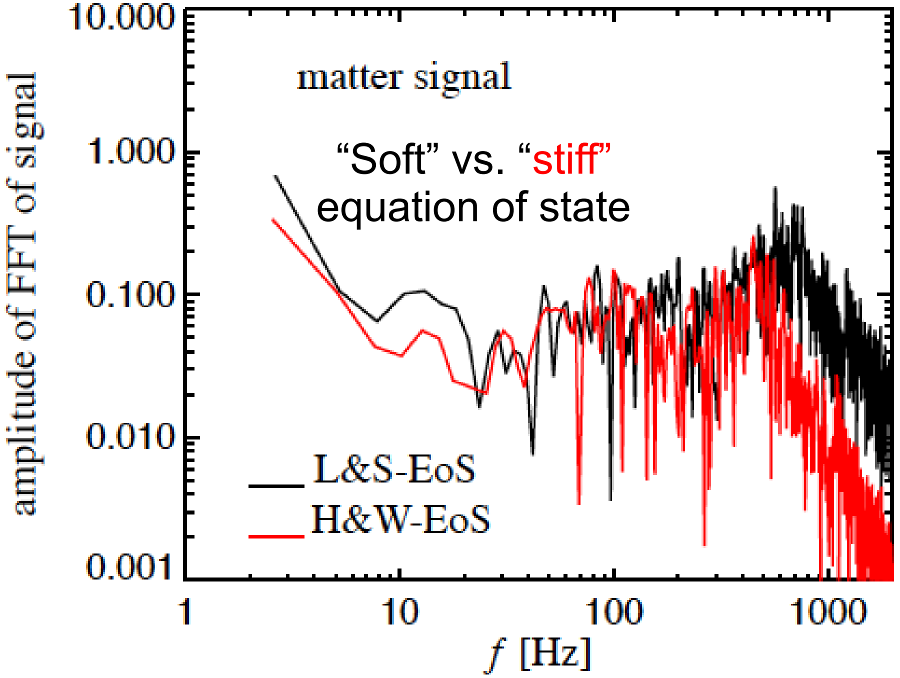
Gravitational wave signals: late explosion phase & impact of GR effects



GW energy spectra for a $15M_\odot$ progenitor (Müller et al. 2011): frequency shift due to different buoyancy frequency in neutron star surface region (cp. Murphy et al. 2009)


gravitational wave signal, $11.2M_\odot$ model

new downflows excite neutron star g-mode oscillations


“Soft” vs. “stiff” equation of state

For comparison: EOS dependence (Marek et al. 2009)

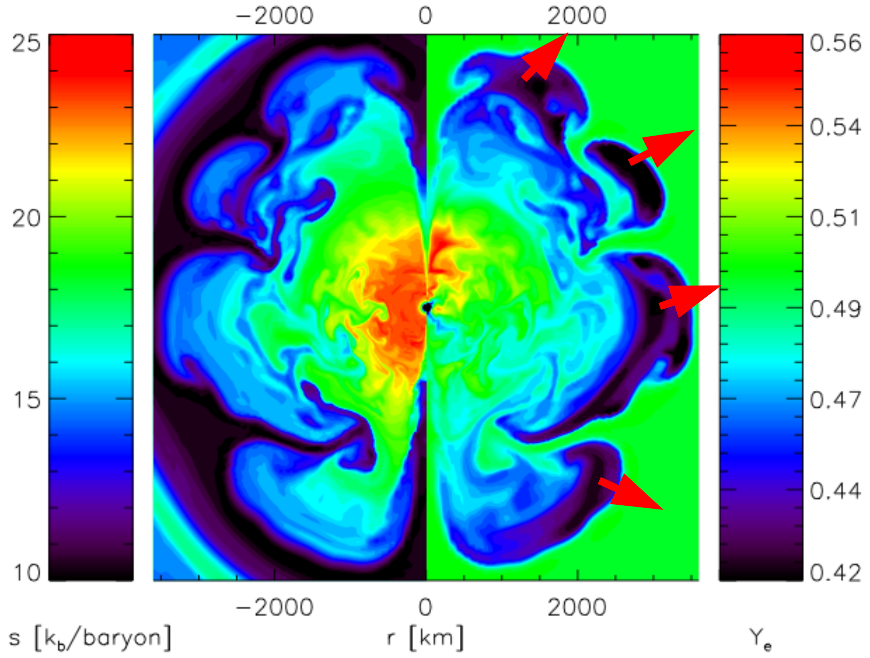


FIG. 1.— Snapshot of the convective region of the 2D simulation of an ECSN at 262 ms after core bounce with entropy per nucleon (s; left) and Y_e (right). Mushroom-shaped lumps of low-Y_e matter are ejected during the early phase of the explosion.

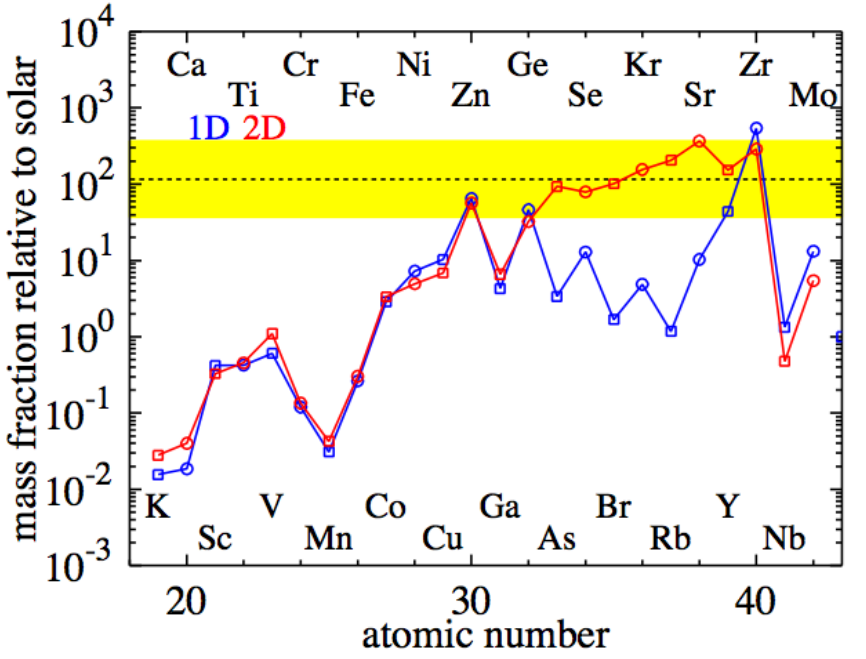
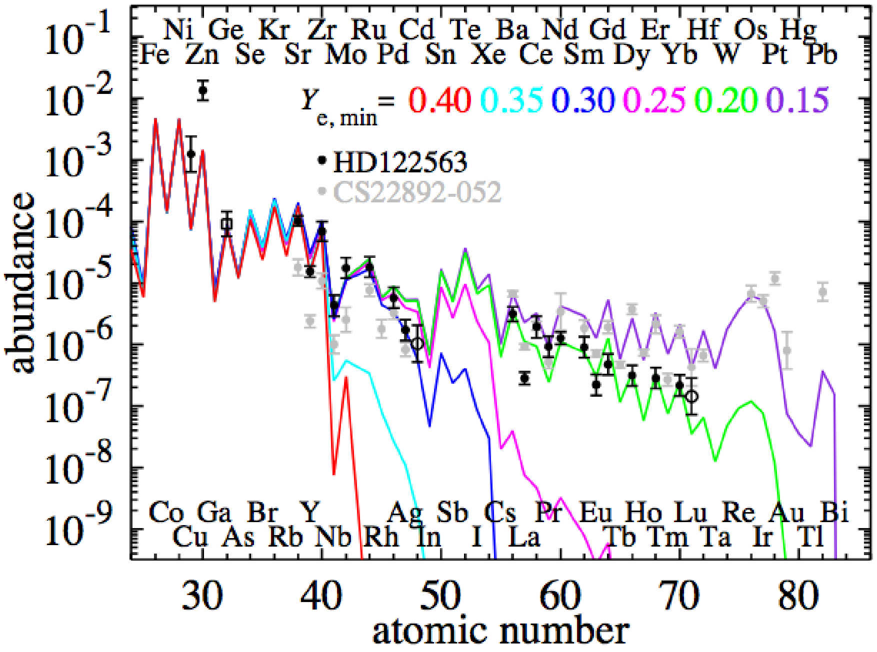


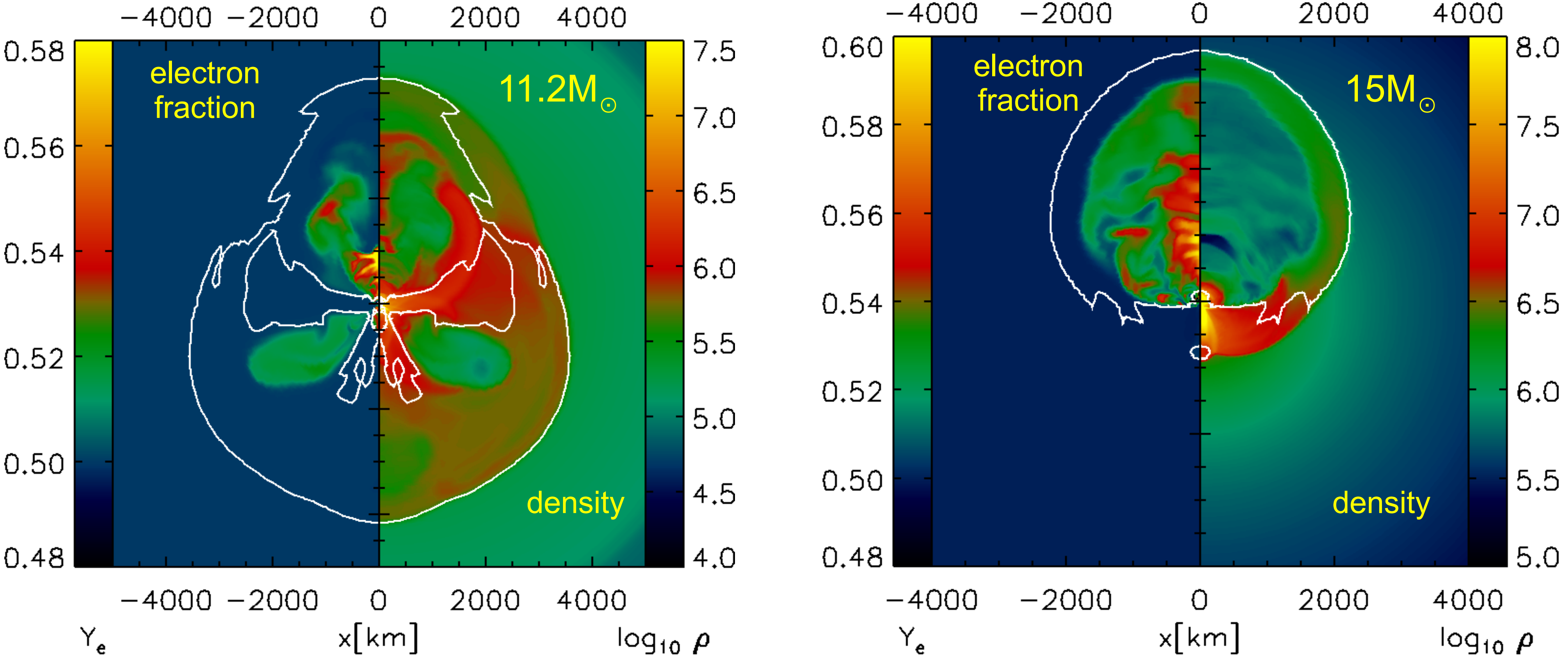
FIG. 3.— Elemental mass fractions in the ECSN ejecta relative to their solar values (Lodders 2003), comparing the 2D results (red) with the 1D counterpart (blue) from Wanajo et al. (2009). Even-Z and odd-Z elements are denoted by circles and squares, respectively. The normalization band (see text) is marked in yellow.

Connecting to Nucleosynthesis Studies

- First-principle models ready for nucleosynthesis calculations
- Interesting yields for electron capture supernovae due to ejection of neutron-rich Rayleigh-Taylor plumes (Wanajo et al. 2011)
- Model variations might allow “weak r-process”
- Later ejecta proton-rich for EC supernovae

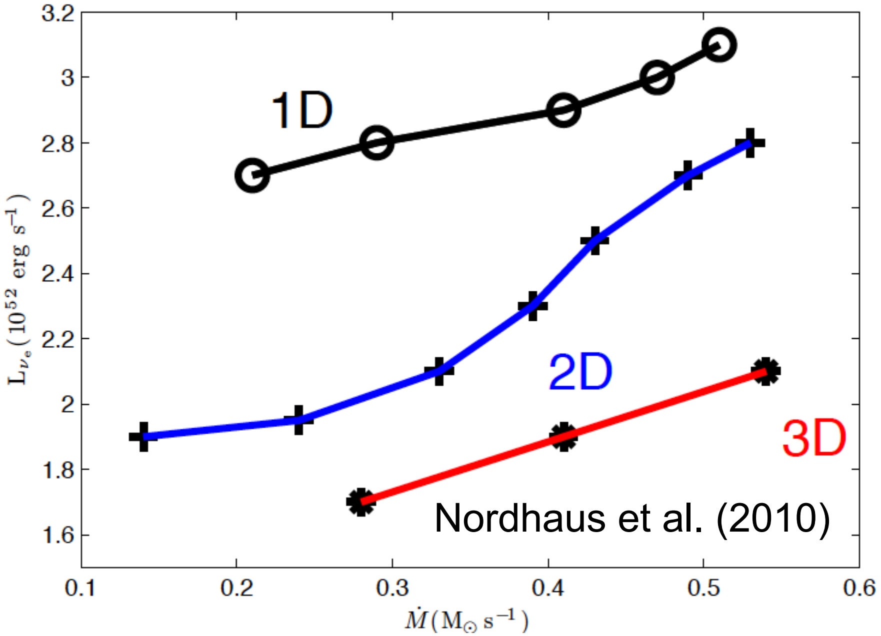


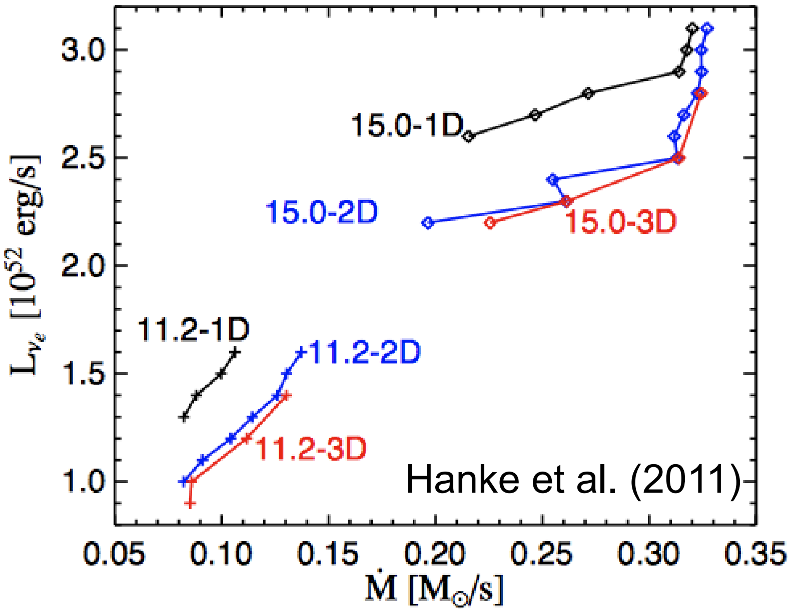
Connecting to Nucleosynthesis Studies



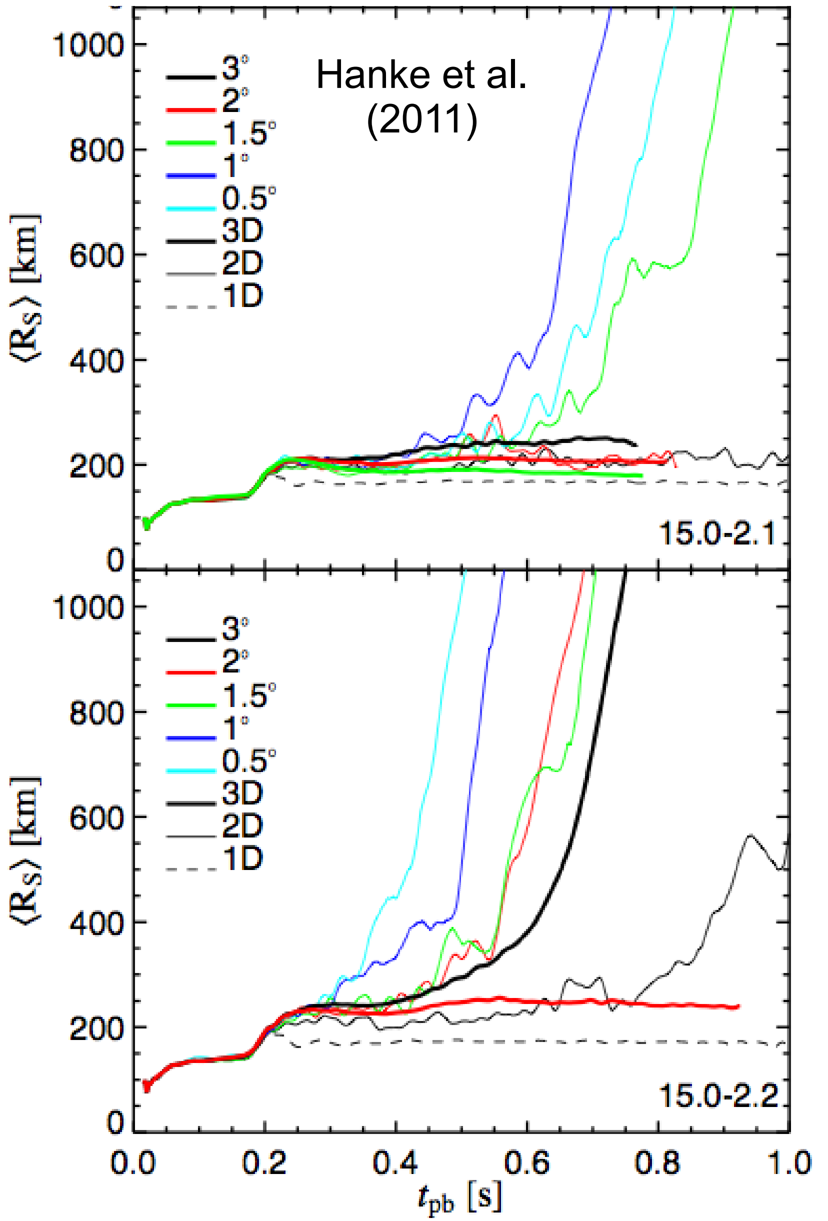
- Iron-core progenitors: Proton-rich early and late ejecta
- Consequence: prospects for (standard) r-process in supernovae increasingly bleak
- Potential for νp-process (Frohlich et al. 2006, Pruet et al. 2006) to be investigated
- Pronounced difference between massive progenitors and low-mass progenitors (electron capture supernovae)

What Will 3D Simulations Have in Store?





"Critical" luminosity for explosion



A non-trivial resolution dependence due to the different direction of the turbulent energy cascade in 2D and 3D?

Conclusions

- GR and neutrino microphysics identified as possible factors for more robust neutrino-driven explosion
- 2D supernova simulations with sophisticated transport proceeding further into the explosion phase
- Hence: better templates for neutrino and gravitational wave signals now available
- Connection from first-principle models to photon-based astronomy (light curves) is more difficult - better prospects for nucleosynthesis yields
- Understanding of 3D effects yet in its infancy: considerable technical development & exploratory studies required