Is strong SASI activity the key to successful neutrino-driven supernova explosions?

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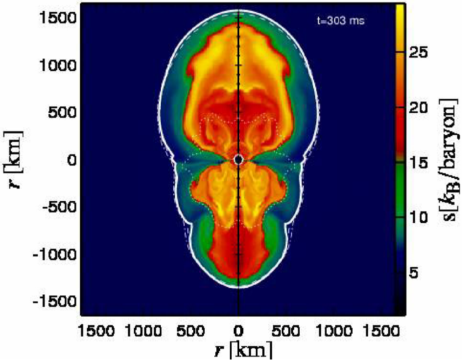
Current Status of Supernova Modelling

Recent simulations with sophisticated neutrino transport in 2D

- can yield supernova explosions (Marek & Janka 2009; Müller et al. 2012)
- ”marginal” explosions: relatively late and fairly underenergetic
- Burrows et al. (2006,2007): lack of neutrino-driven explosions

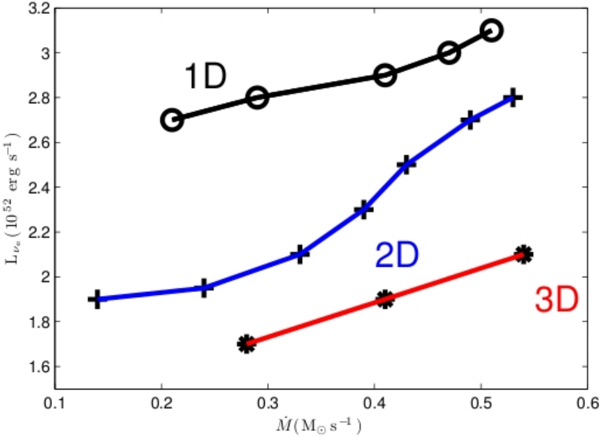


How does 3D change the fluid dynamics?

(Nordhaus 2010, Hanke 2011, Takiwaki 2011, Bruenn 2009, Liebendörfer 2010)

Inspired by results of Nordhaus et al. (2010)

- based on the concept of a critical luminosity (Burrows & Goshy 1993)



2D -> 3D:
another reduction of threshold luminosity by 15-25%

Numerical Setup

- hydrodynamical simulations with PROMETHEUS Code
- local source terms (Murphy & Burrows 2008; Nordhaus et al. 2010) for neutrino:
  - heating

$$Q_\nu^+ = 1.544 \cdot 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{T_{\nu_e}}{4\,\mathrm{MeV}}\right)^2 \left(\frac{100\,\mathrm{km}}{r}\right)^2 (Y_n + Y_p)\, e^{-\tau_{\mathrm{eff}}/2.7} \left[\frac{\mathrm{erg}}{\mathrm{g\,s}}\right],$$

  - cooling

$$Q_\nu^- = 1.399 \cdot 10^{20} \left(\frac{T}{2\,\mathrm{MeV}}\right)^6 (Y_n + Y_p)\, e^{-\tau_{\mathrm{eff}}/2.7} \left[\frac{\mathrm{erg}}{\mathrm{g\,s}}\right].$$

- collapse until 15ms post-bounce treated with full neutrino transport
- 15 $M_\odot$ and 11.2 $M_\odot$ progenitor star investigated

Numerical Setup

- hydrodynamical simulations with PROMETHEUS Code
- local source terms (Murphy & Burrows 2008; Nordhaus et al. 2010) for neutrino:
  - heating

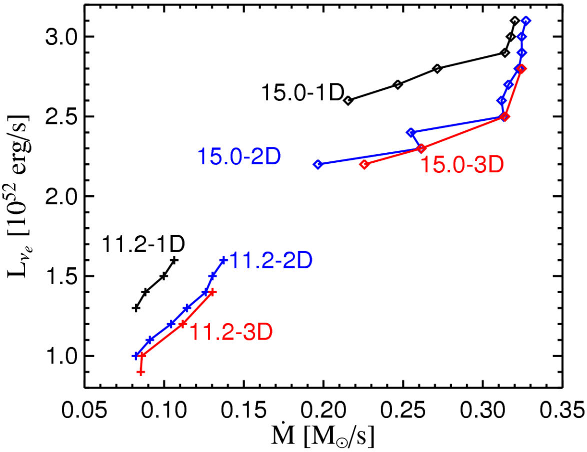
$$
\begin{aligned}
Q_\nu^+ &= 1.544 \cdot 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\,\mathrm{erg\,s^{-1}}} \right) \left(\frac{T_{\nu_e}}{4\,\mathrm{MeV}} \right)^2 \\
&\quad \left(\frac{100\,\mathrm{km}}{r} \right)^2 (Y_n + Y_p)\; e^{-\tau_{\mathrm{eff}}/2.7} \left[\frac{\mathrm{erg}}{\mathrm{g\,s}} \right] ,
\end{aligned}
$$

  - cooling

$$
Q_\nu^- = 1.399 \cdot 10^{20} \left(\frac{T}{2\,\mathrm{MeV}} \right)^6 (Y_n + Y_p)\; e^{-\tau_{\mathrm{eff}}/2.7} \left[\frac{\mathrm{erg}}{\mathrm{g\,s}} \right] .
$$

- enhanced net cooling to reproduce values of Murphy & Burrows (2008)

Critical curves



1D -> 2D: critical luminosities reduced by 15-25%

confirms Murphy & Burrows (2008), Nordhaus et al. (2010)

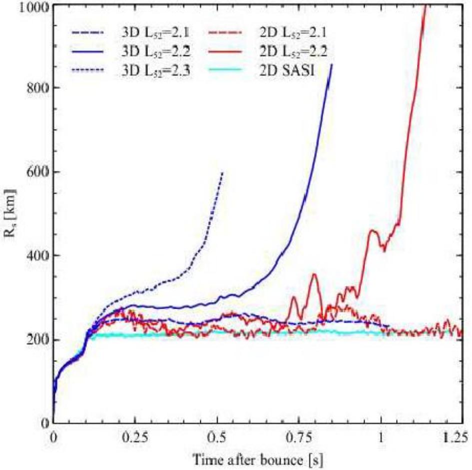
2D -> 3D: no more favorable conditions for explosions

Comparison to Nordhaus et al. (2010)

possible reasons for discrepancy

- different treatment of neutrino cooling
- different employed hydrodynamics scheme (PROMETHEUS vs. CASTRO)
- differences in the exact structure of infall region due to different treatment of collapse phase (full neutrino transport vs. simple deleptonization scheme)

New results of Burrows et al. 2012

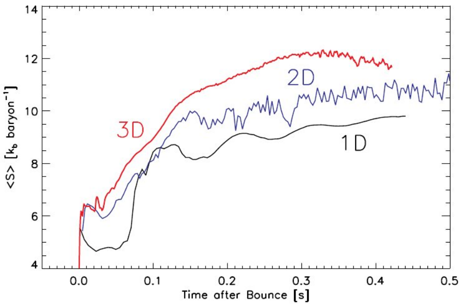


now: 2D -> 3D: reduction of threshold luminosity almost vanished

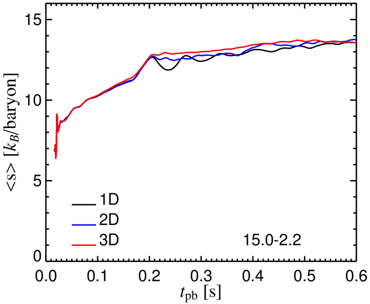
2D-3D Differences

averaged entropy of gas in gain layer <s(t)>

- Nordhaus et al. (2010): clear hierarchy in dimension



- our results: no distinction between dimensions

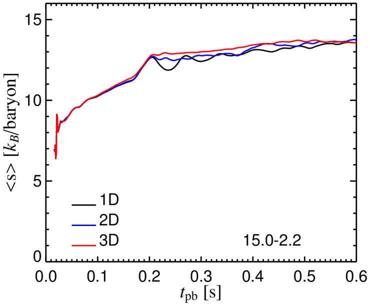


2D-3D Differences

averaged entropy of gas in gain layer <s(t)>

- neutrino energy deposition rises entropy
- however, <s(t)> encompasses downdrafts with cool matter, much denser, hardly heated by neutrinos
- not higher than 1D by convective overturn

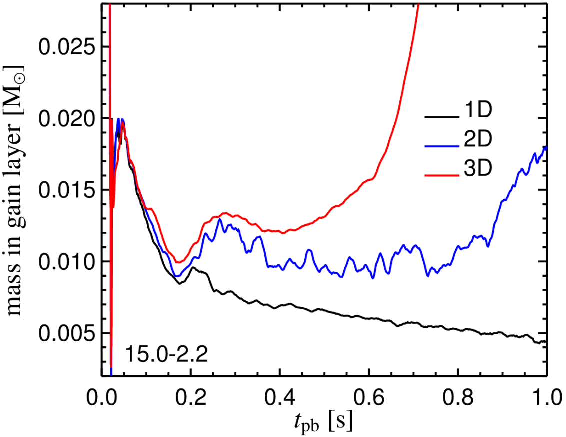
- our results:
  no distinction between dimensions



2D-3D Differences

dominant effect of multi-D?

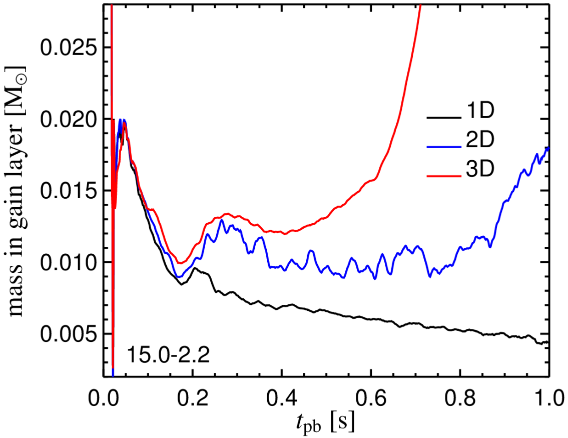
- associated with inflation of shock radius and postshock layer
- driven by buoyant rise and expansion of plumes of neutrino-heated plasma
- more mass is heated, not same mass more heated!



2D-3D Differences

dominant effect of multi-D?

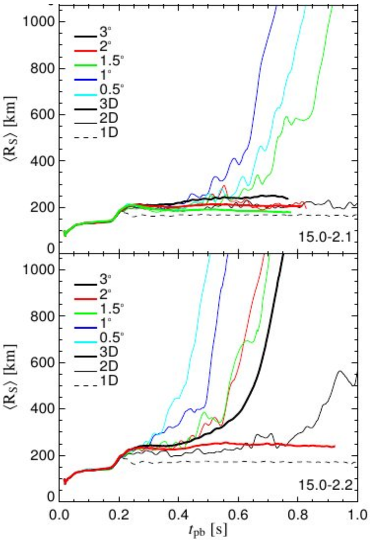
- M_{gain} increases for models closer to explosion
- longer dwell times of matter in gain layer drives explosion
- better indicator of proximity to explosion



Effects of resolution

very interesting trend:

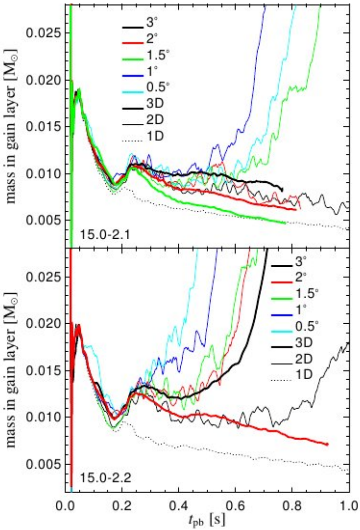
- higher angular resolution fosters explosions in 2D
- but delays or prevents explosions in 3D
- confirmation of our results with moderate resolution



Effects of resolution

very interesting trend:

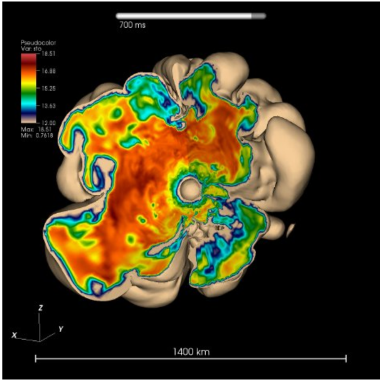
- reflected in diagnostic quantities
- 3D more similar to 1D with higher resolution



2D-3D resolution dependence

convective structure of an 11.2 $M_{\odot}$ explosion model

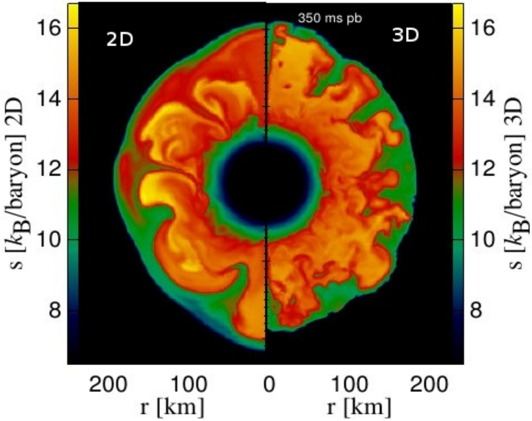
- more fine structures on small spatial scales in 3D
- no improved conditions for explosion



Interpretation I

turbulent energy cascade: redistributes energy into the flow in opposite direction in 2D and 3D

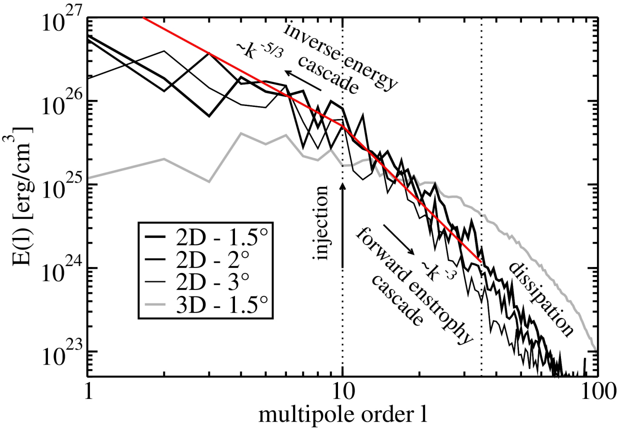
- 2D: from small to large spatial scales
- 3D: turbulent flow from large to small scales
- consequence of opposite resolution dependence



Interpretation I

turbulent energy cascade: redistributes energy into the flow in opposite direction in 2D and 3D

- decompostion of angular kinetic energy in spherical harmonics



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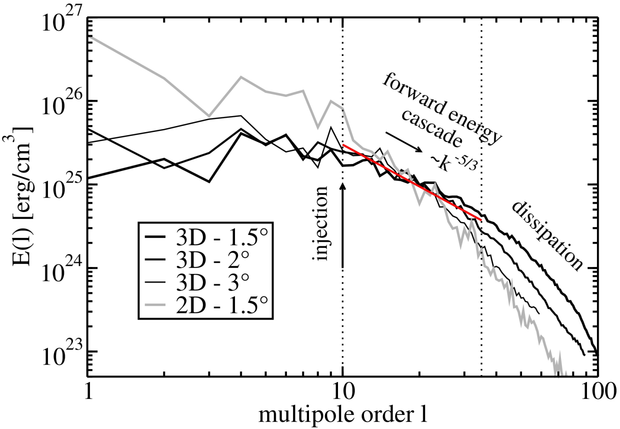
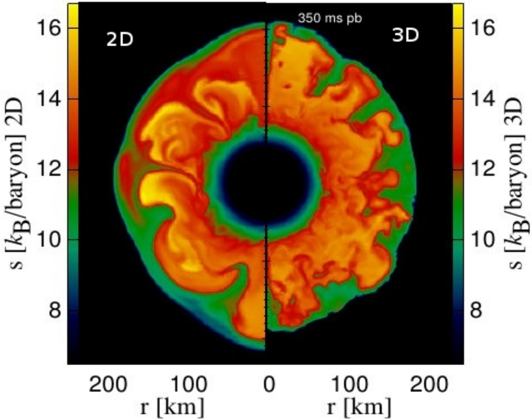


Interpretation II

large-scale mass flows associated with strong SASI activity favorable for explosion

- no support by enhanced fragmentation of structures on small scales
- typical for strong SASI activity



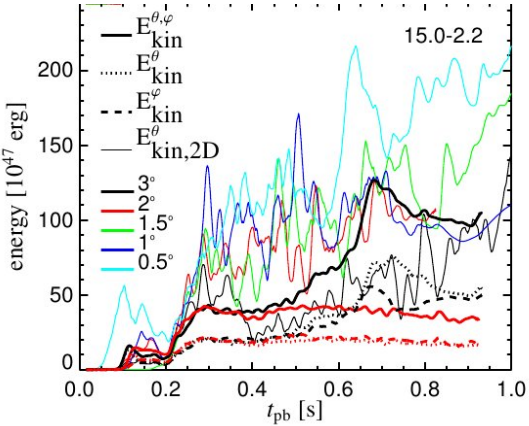
Interpretation II

large-scale mass flows associated with strong SASI activity favorable for explosion

strength of SASI activity in 2D

increases with higher resolution correlated with earlier explosion!

- higher angular kinetic energy
- spiky maxima and minima



Summary

systematic study of post-bounce evolution of supernova cores

- simple neutrino heating and cooling terms with varied values of driving luminosity
- 1D->2D: lowers driving luminosity
- 2D->3D: no significant further reduction
- resolution study: 2D models with higher resolution explode earlier,
  3D models show opposite trend
- connected to large-scale motions due to SASI activity in 2D,
  3D models develop weaker low-order SASI modes
- consequence of opposite turbulent energy cascades in 2D and 3D.

supernova physics in 3D is in its very infancy!