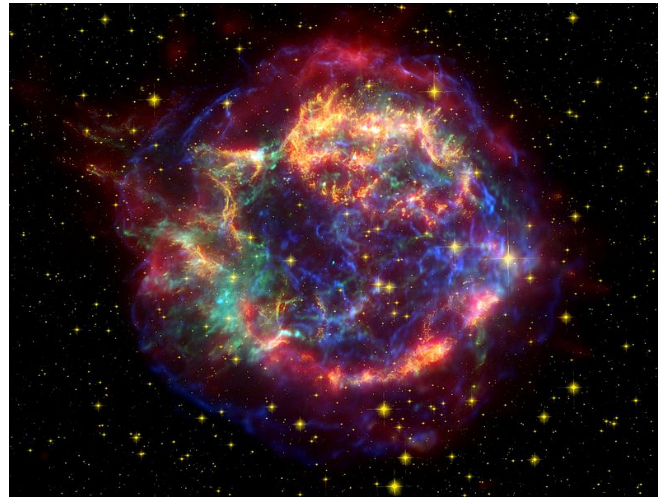

Australian Government
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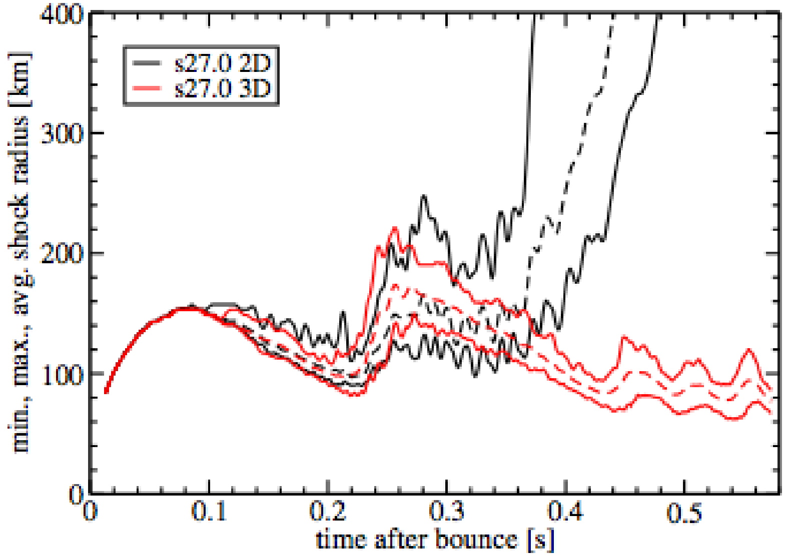
Multi-D Effects in Core-Collapse Supernovae Revisited

NCI
PROVIDING AUSTRALIAN RESEARCHERS WITH WORLD-CLASS HIGH-END COMPUTING SERVICES

Bernhard Müller
Monash University

Shock Revival in 3D – Where are we?



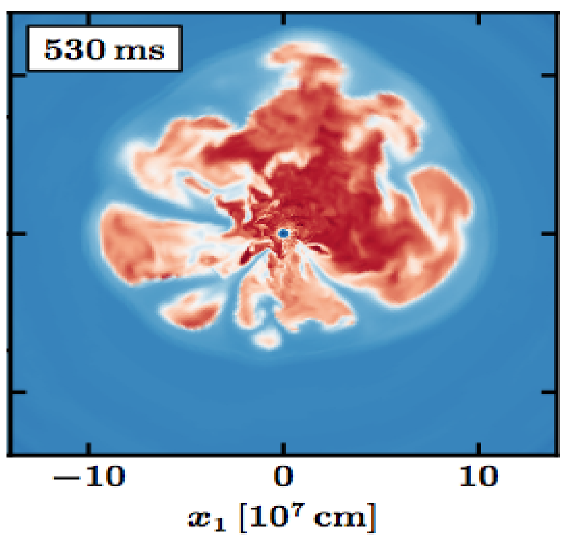
27 $M_\odot$ Hanke et al. (2013)

First-principle 3D models:

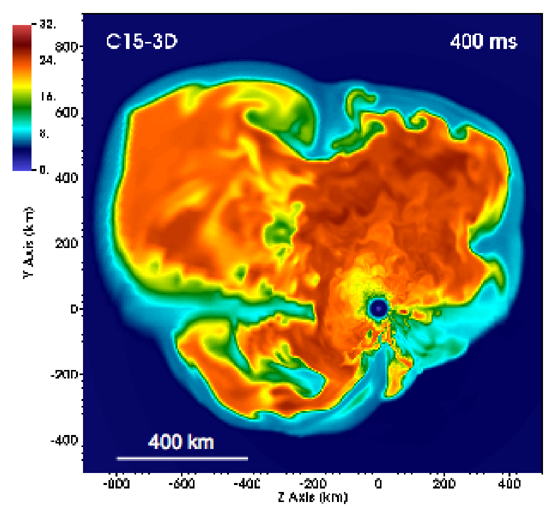
- Mixed record, some failures
- Some explosions, delayed compared to 2D
- Models close to the threshold

So what is missing?

- $L_{crit} \propto (\dot{M} M^2)^{3/5} (1 + 4\, Ma^2/3)^{-3/5}$
- Unknown/undetermined microphysics (e.g. Melson et al. 2015)?
- Lower explosion threshold in SASI-dominated regime (Fernandez 2015)?
- Better 1D/multi-D progenitor models?
- ???



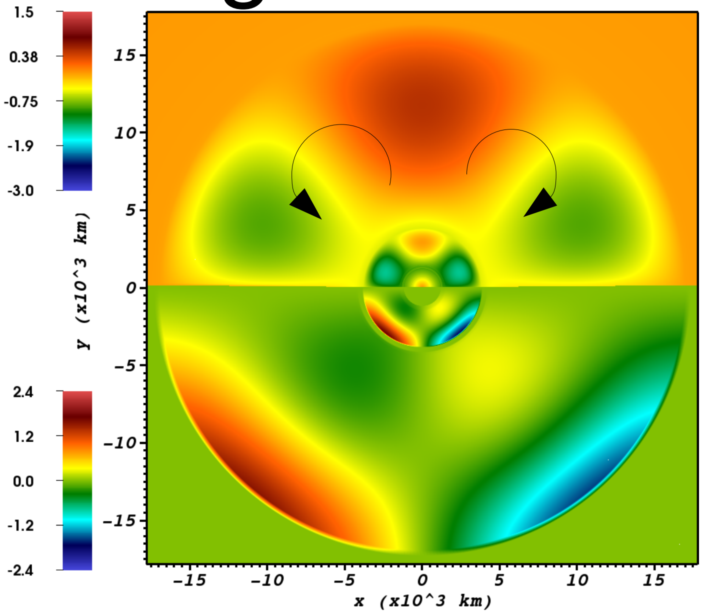
20 $M_\odot$ Melson et al. (2015)

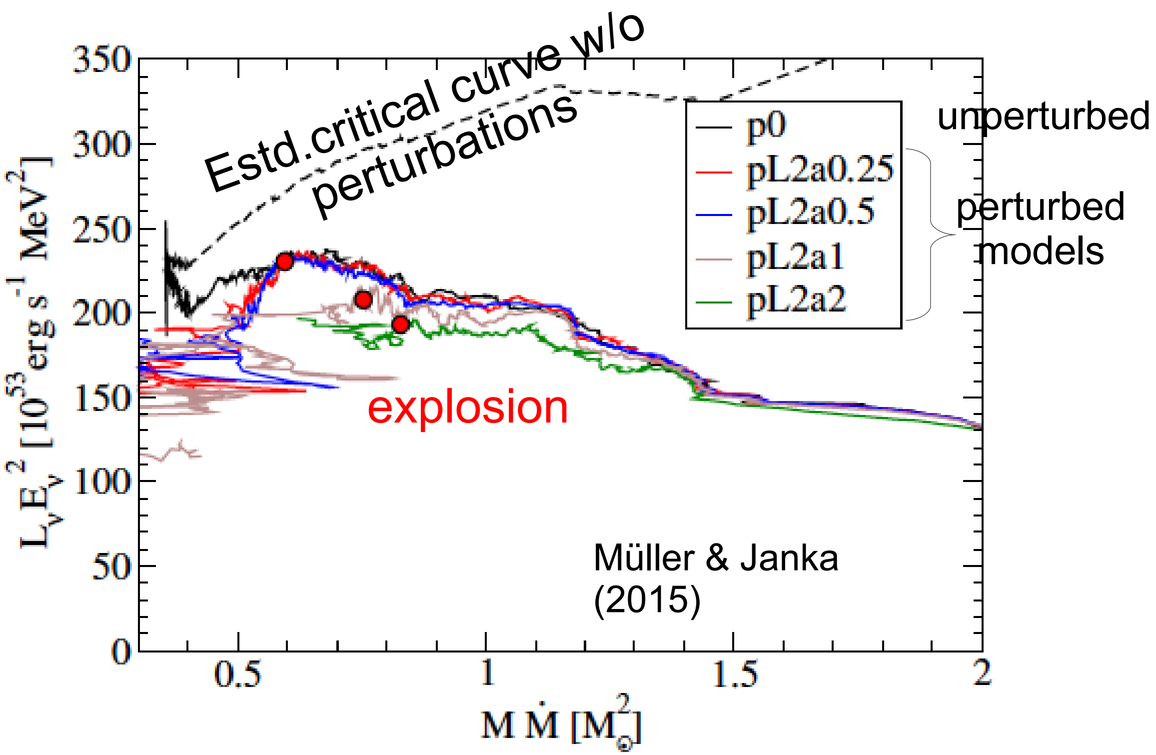


15 $M_\odot$ Lentz et al. (2015)

Solutions: Seed perturbations from convective burning?

- Couch & Ott (2013, 2014): lateral velocity perturbations, no eddies
- Müller & Janka (2015): ~40 models with neutrino transport, mimicking convective eddies
- Couch et al. (2015): Convective Si burning with artificially accelerated deleptonization

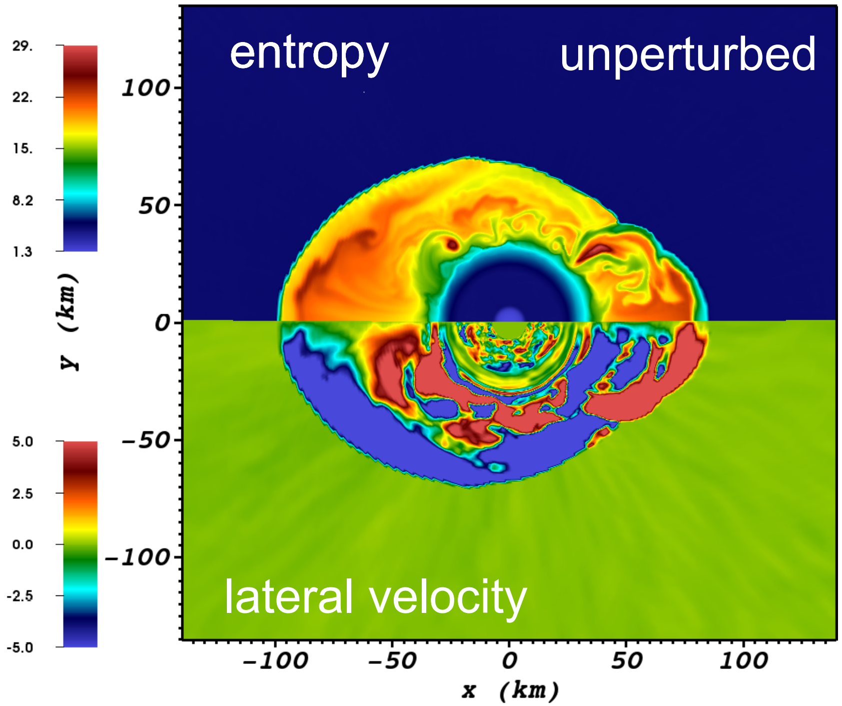


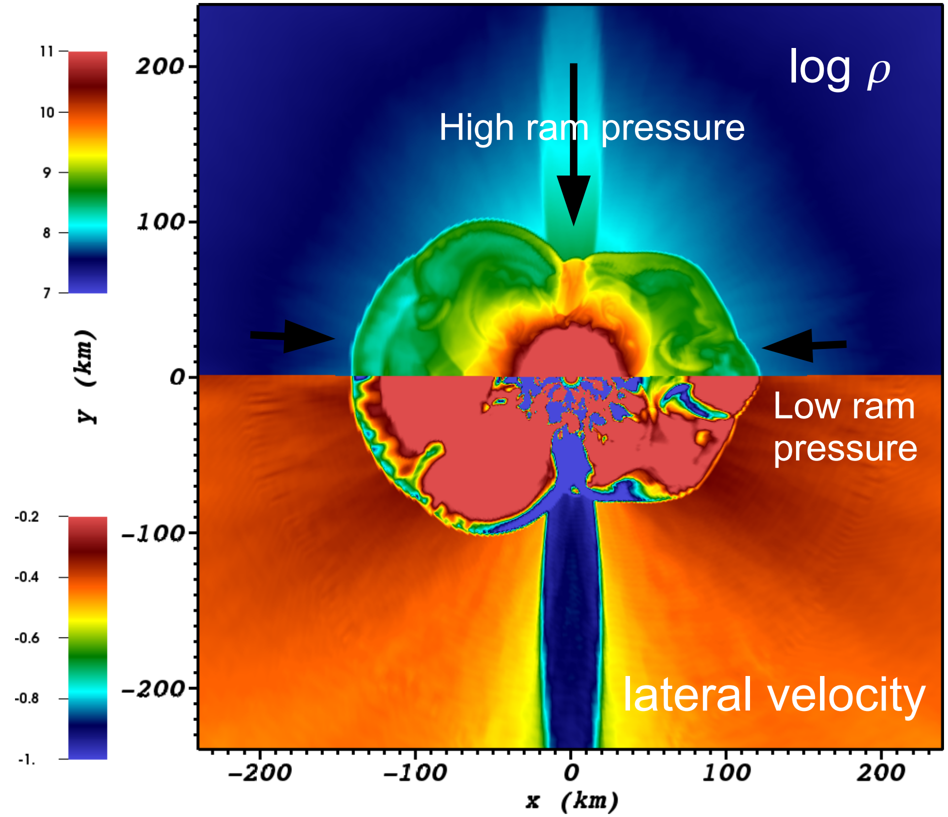


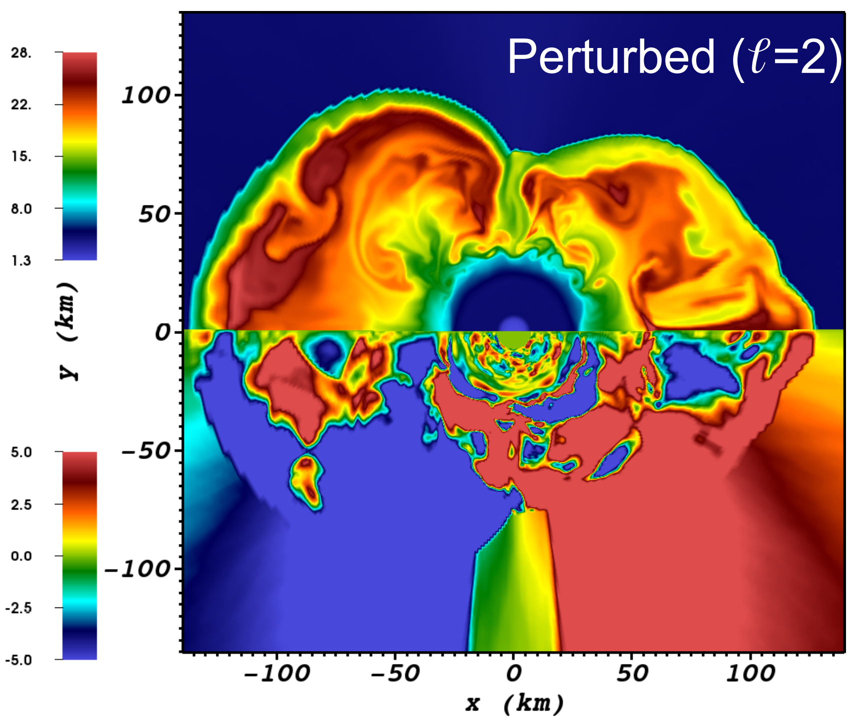
Reduction of critical luminosity by up to several 10% possible if:

- Large convective velocities ~10^8cm/s
- Large-scale structures (ℓ=1,ℓ=2)
- Extended burning shell

Caveat: HUGE variations in pre-collapse nuclear energy generation rates & shell structure







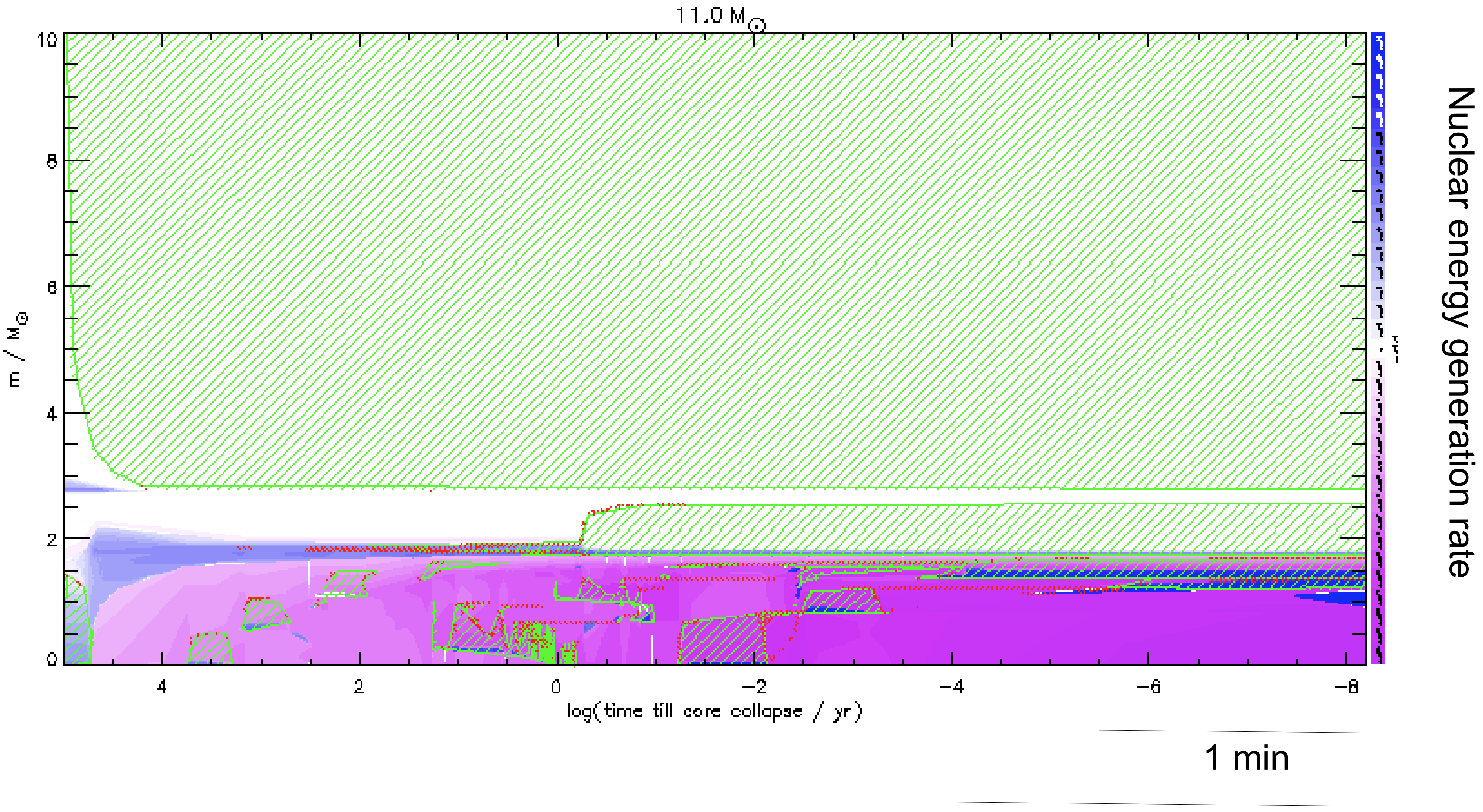
Generation of density perturbation during infall:

$$\delta\rho/\rho \sim v_{conv,ini}\, t_{infall} \frac{d\ln\rho}{d\ln r} \sim Ma \frac{d\ln\rho}{d\ln r}$$

Forced shock deformation increases non-radial kinetic energy (works best for unstable SASI modes ℓ=1,2)

Müller & Janka (2015)

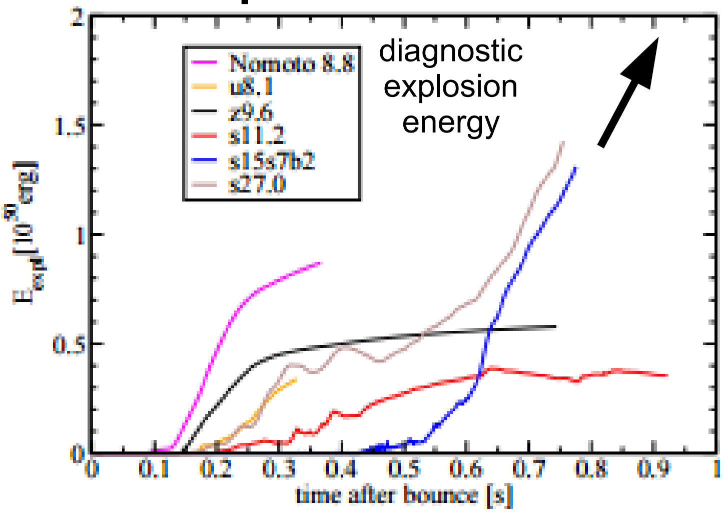
Reminder: Strong variations in shell configurations & nuclear energy generation rate



hatched: convection

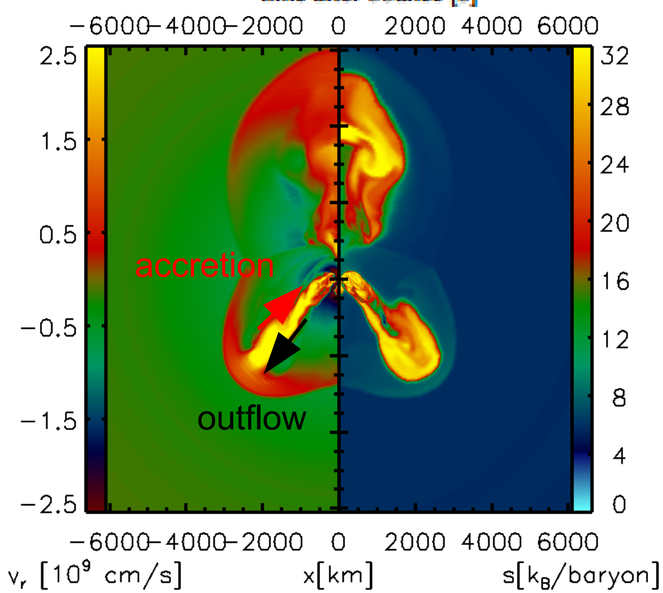
Credit: Alex Heger (2sn.org)

But even many of the exploding 2D models have problems...



Several 10^{50}erg with sustained accretion

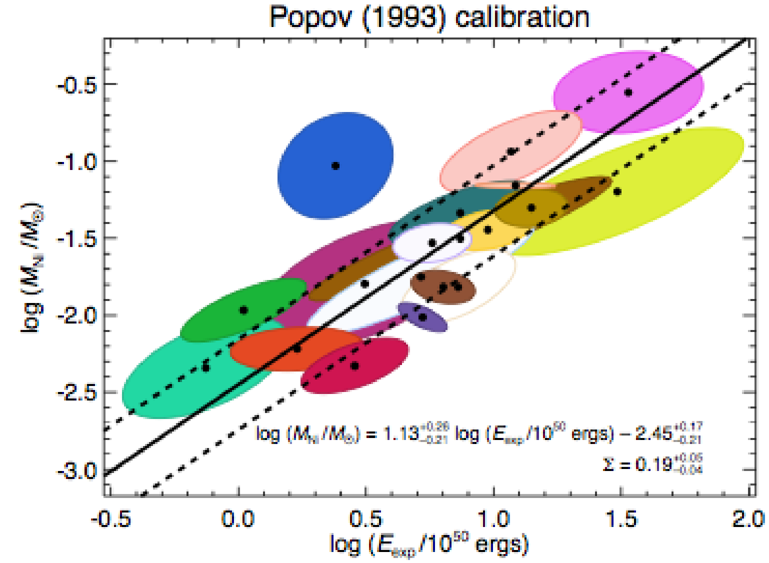
Janka et al. (2012)



Hard to reach several 10^{50}erg in many 2D simulations – considerable accretion needed → high neutron star masses

simulations

observations



Pejcha & Prieto (2015): Explosion energies vs. Nickel masses

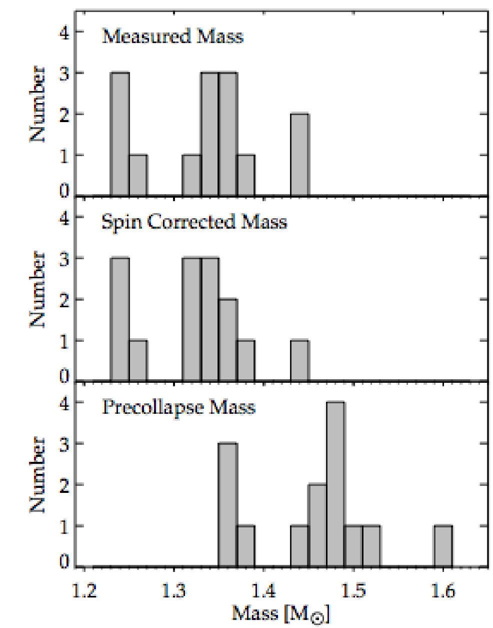


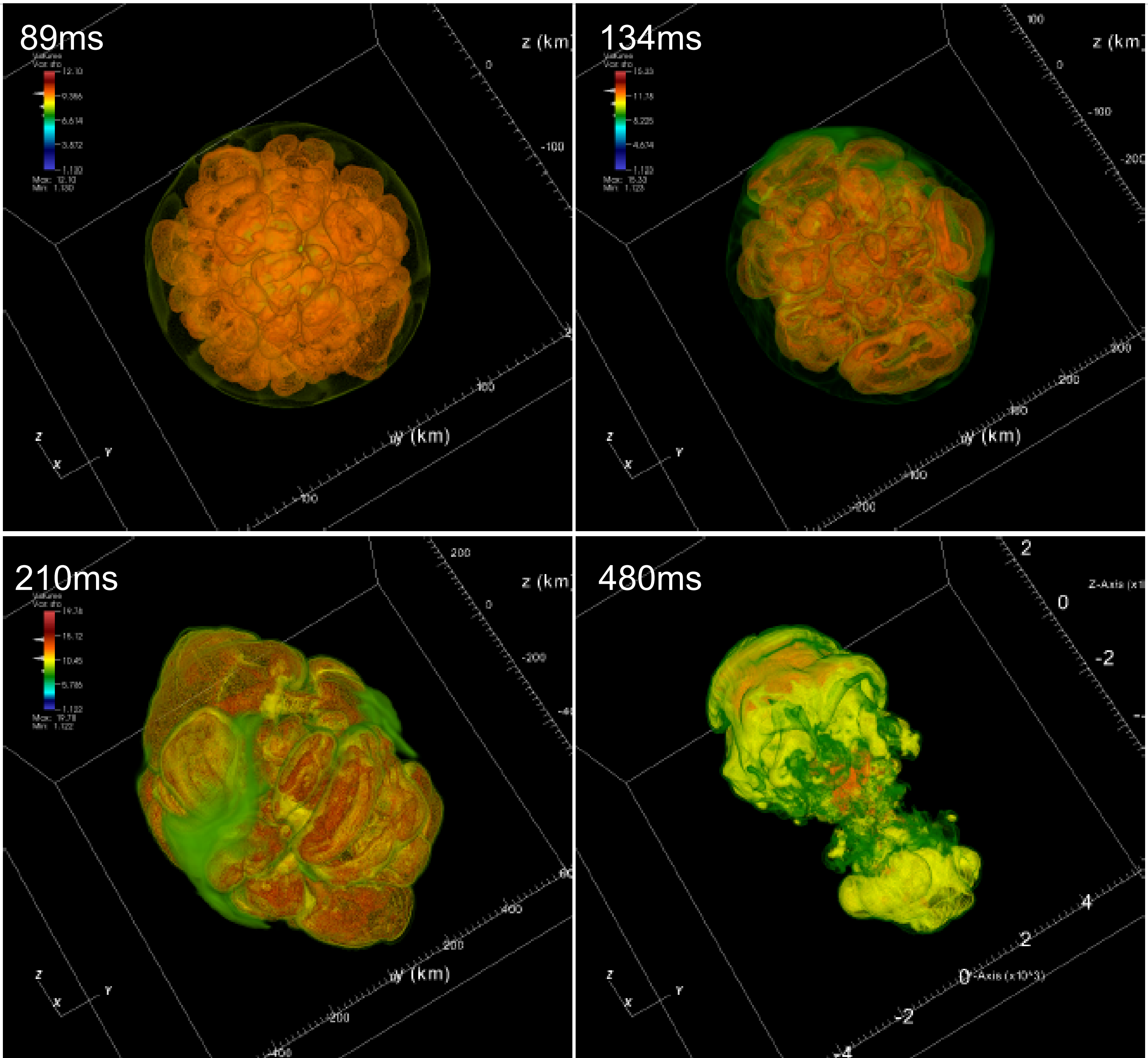
Figure 1. Mass histograms for the sample of 14 neutron stars. (*Top Panel*): The measured (gravitational) masses of the neutron stars. (*Middle Panel*): The masses of the neutron stars corrected for accretion as discussed in the text. (*Bottom Panel*): The precollapse (baryonic) masses of the neutron stars, based on one particular illustrative neutron-star equation of state.

Schwab & Podsiadlowski (2010): inferred neutron star birth mass distribution

3D Effects After Shock Revival

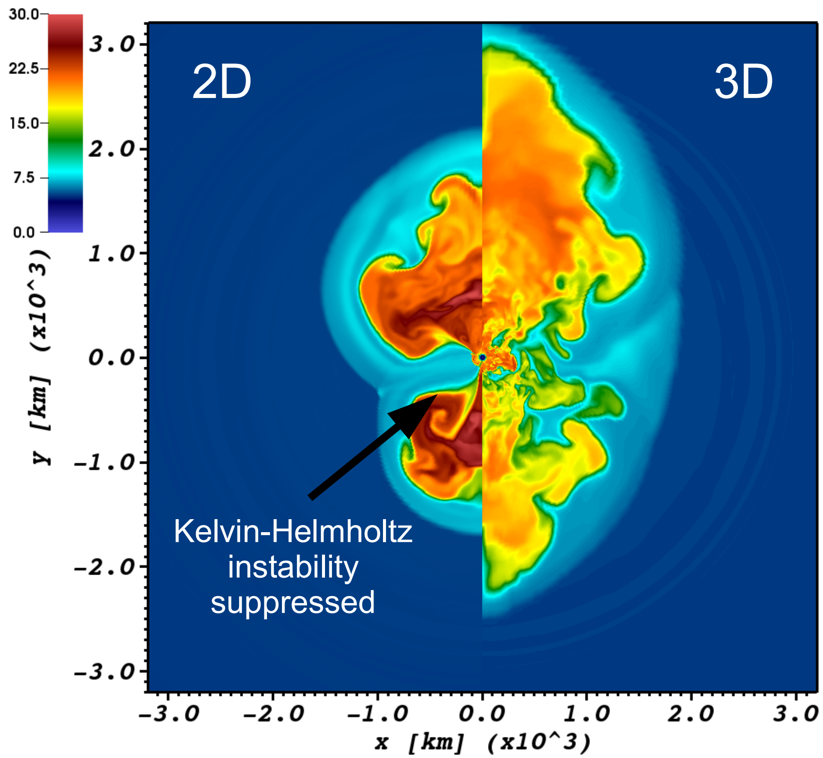
Could the problem be part of the solution?

Results from a 3D simulation of an 11.2$M_\odot$ progenitor with CoCoNuT-FMT code (GR hydro, simplified (fast) multi-group neutrino transport)

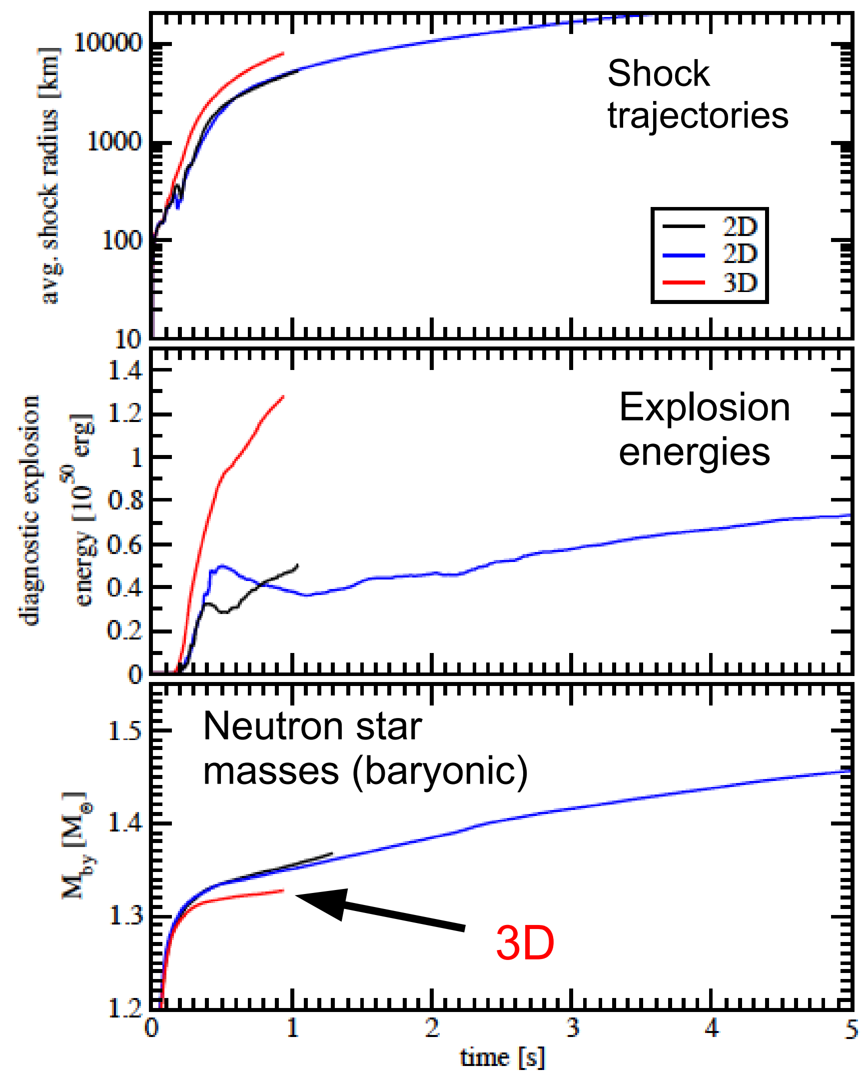


89ms
z (km)
y (km)
134ms
z (km)
y (km)
210ms
z (km)
y (km)
480ms

Energetics of 2D and 3D Explosions



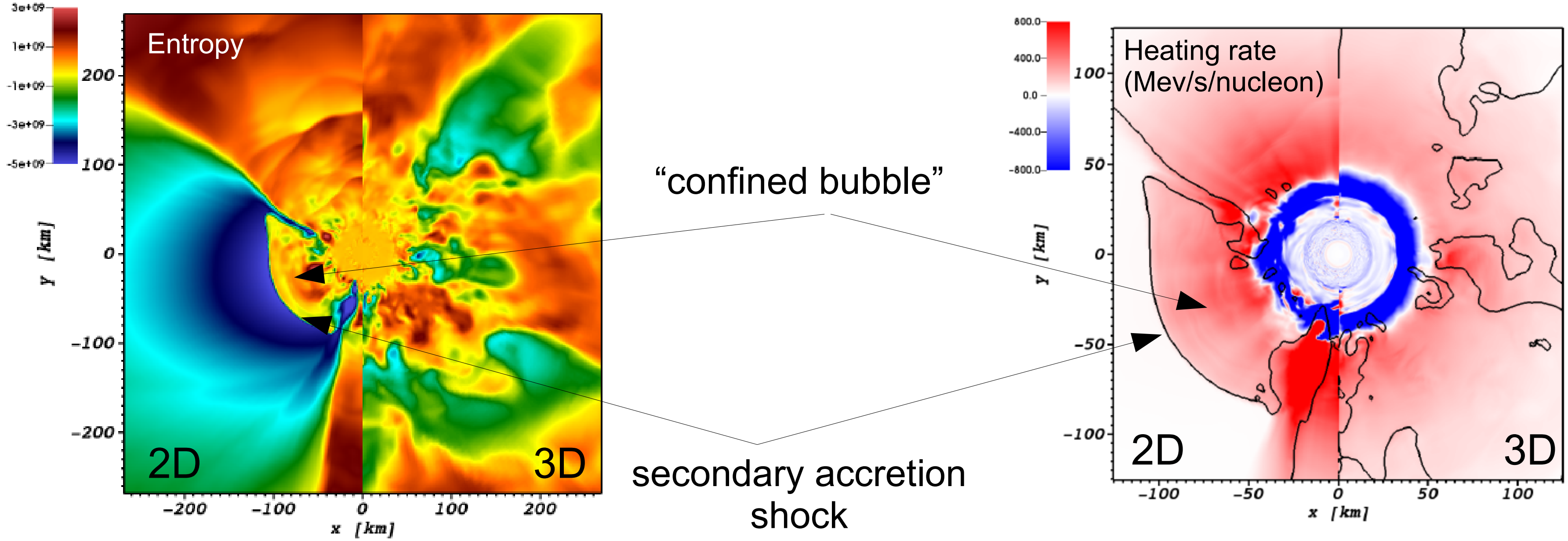
Müller 2015, to be submitted

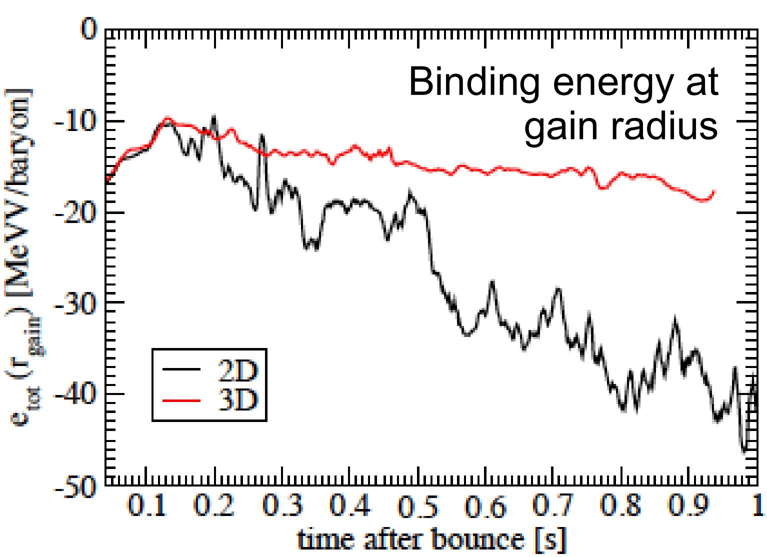


Faster & more robust growth of explosion energy in 3D

Long-time evolution in 2D: Cp. Raph Hix' question about the end of the explosion

Reasons for Weak Explosions in 2D





- g-mode excitation at PNS surface provides additional energy loss
- → matter bound more tightly at gain radius before ejection → lower outflow rate for given heating rate
- Heating in fast downflows and "confined bubbles" wasted – doesn't drive outflows

Different outflow surface fraction in 2D and 3D also seen by Handy et al. (2014) & Melson et al. (2015), but effect is more dramatic for persistent accretion.

Conclusions

- Several ingredients may be needed for robust core-collapse supernova explosion models in 3D
- Multi-D progenitor structure may be one of them – very complex problem
- Once shock revival is achieved:
  - 3D effects may *help* (while hurtful for shock revival)
  - Faster rise of explosion energy
  - Residual accretion reduced
  - How generic is this effect?
  - Can it compete against the “penalty” from delayed shock revival?
- Quest for explosion mechanism bound to remain tough – no simple answers from a few simulations

“Vers l’Orient compliqué, je volais avec des idées simples”
“Toward the complicated Orient I flew with simple ideas.”
Charles de Gaulle

General Sir John Monash, GCMB, KCB, VD
1865-1931