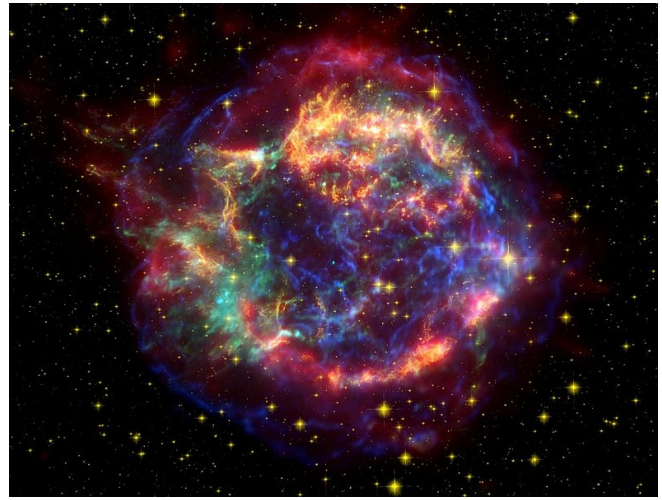

Neutrinos as a probe of supernova explosion dynamics

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Monash University

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I. Tamborra (Copenhagen)

Queen's University Belfast

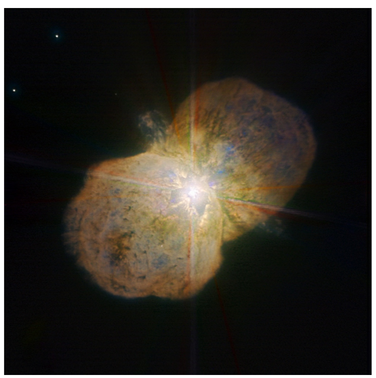
NCI PROVIDING AUSTRALIAN RESEARCHERS WITH WORLD-CLASS HIGH-END COMPUTING SERVICES

DiRAC Distributed Research utilising Advanced Computing

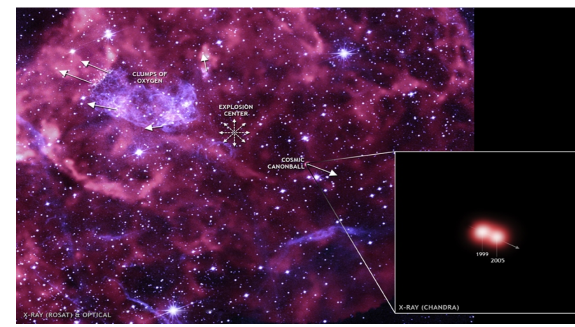
Direct probes of the first second of a core-collapse supernova

heavy elements

massive star

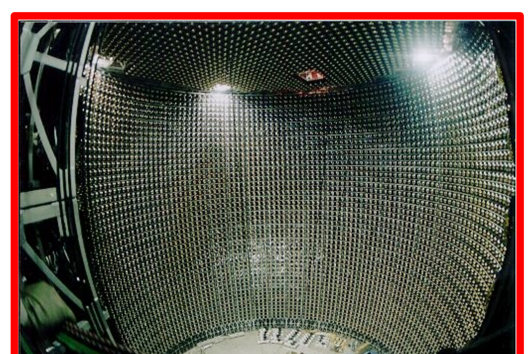


neutron stars & supernova remnants



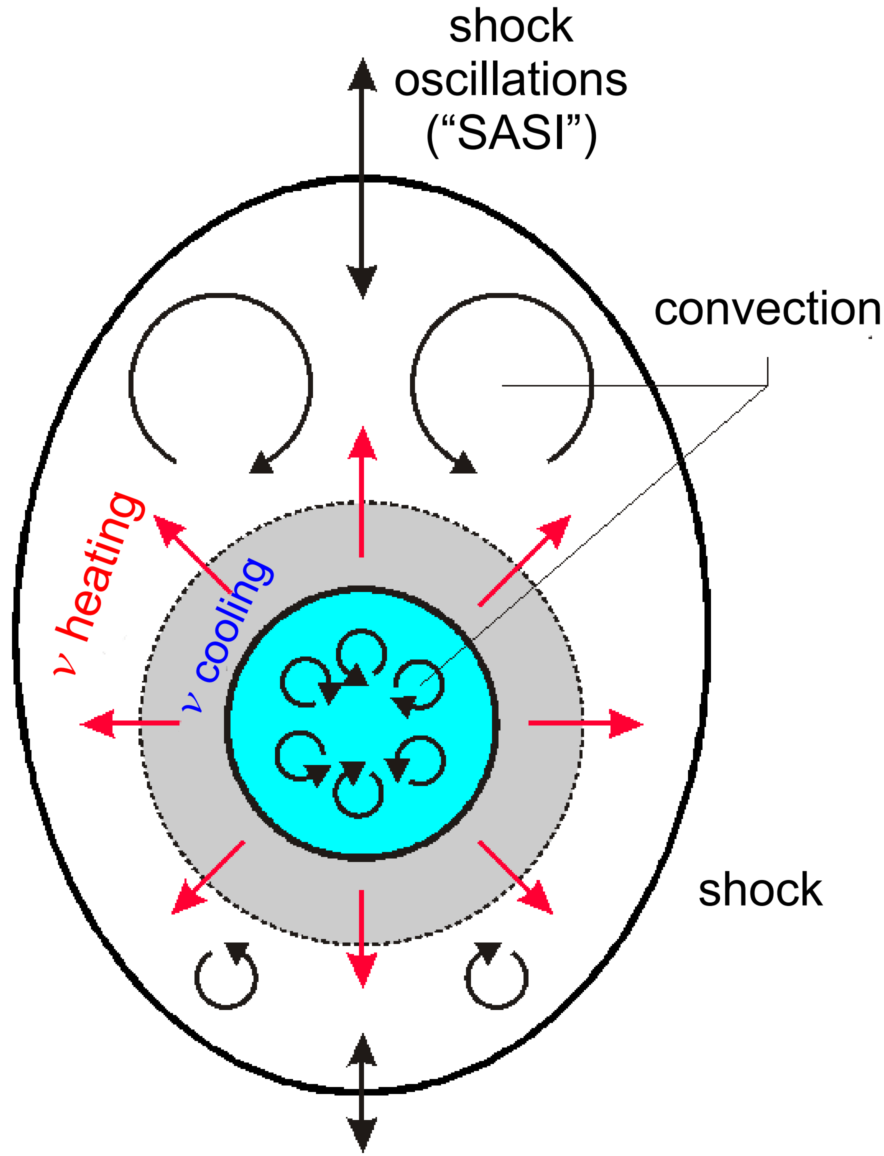
gravitational waves

neutrinos



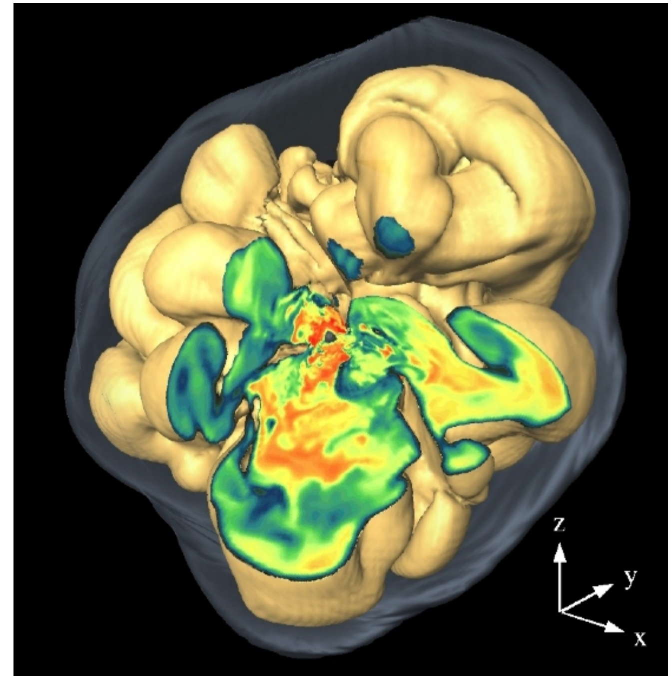
The neutrino-driven mechanism in its modern flavour

- Stalled accretion shock still pushed outward to ~150km as matter piles up on the PNS, then recedes again
- *Heating* or *gain* region develops some tens of ms after bounce
- Convective overturn & shock oscillations “SASI” enhance the efficiency of ν-heating, which finally revives the shock
- **Big challenge: Show that this works!**

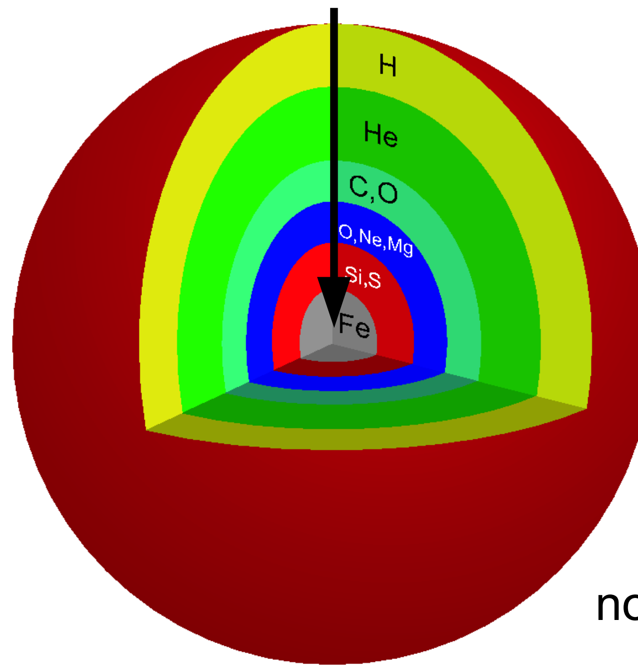


Computational Challenges

- Multi-dimensionality of the flow
- Multi-scale problem
- Transition between the diffusion & free streaming regimes of the neutrinos → kinetic theory required → 6D problem
- Nuclear & particle physics input partly undetermined
- Strong gravitational fields ($GM/rc^2 \approx 0.1...0.2$) & high velocities → relativistic effects important
- Combine all this in a first-principle approach!
- The most ambitious 3D models currently take ~50 million core hours



several 100 km



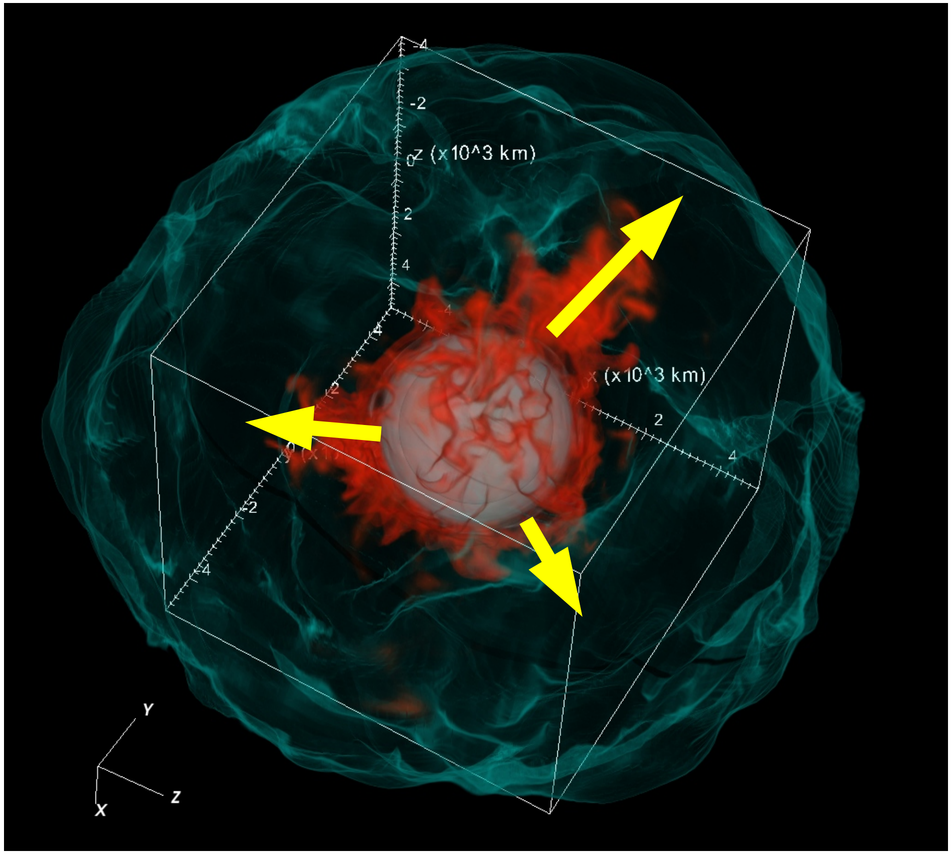
not to scale

~10^8km

The Road to 3D Explosion Models

- 3D models at the threshold & more reluctant to explode than in 2D (failure or delay)
- But first successes: Melson et al. (2015ab), Lentz et al. (2015)...
- Possible keys to more robust explosions:
  - Modified neutrino rates (e.g. Melson et al. 2015)?
  - Lower explosion threshold in SASI-dominated regime (Fernandez 2015)?
  - “Perturbation-aided” explosions (Couch et al. 2015, Mueller 2016)

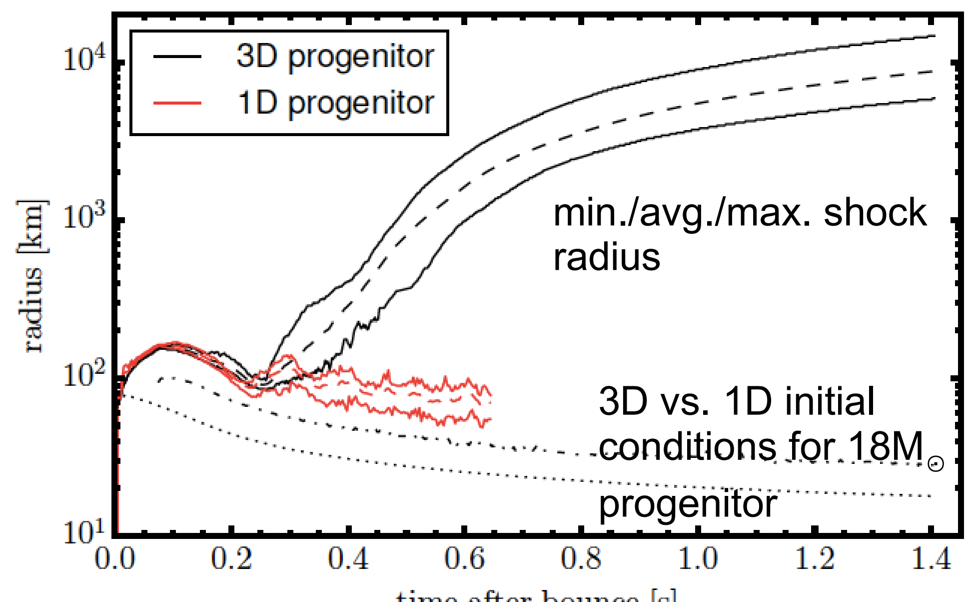
More in Tony Mezzacappa's talk

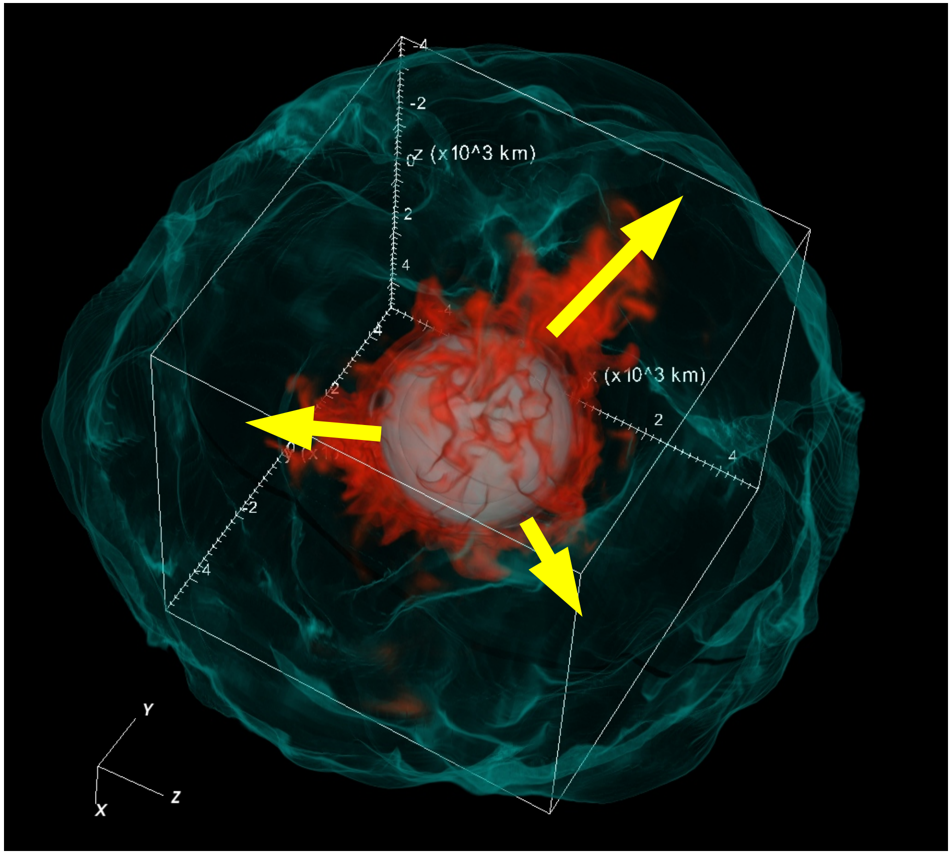


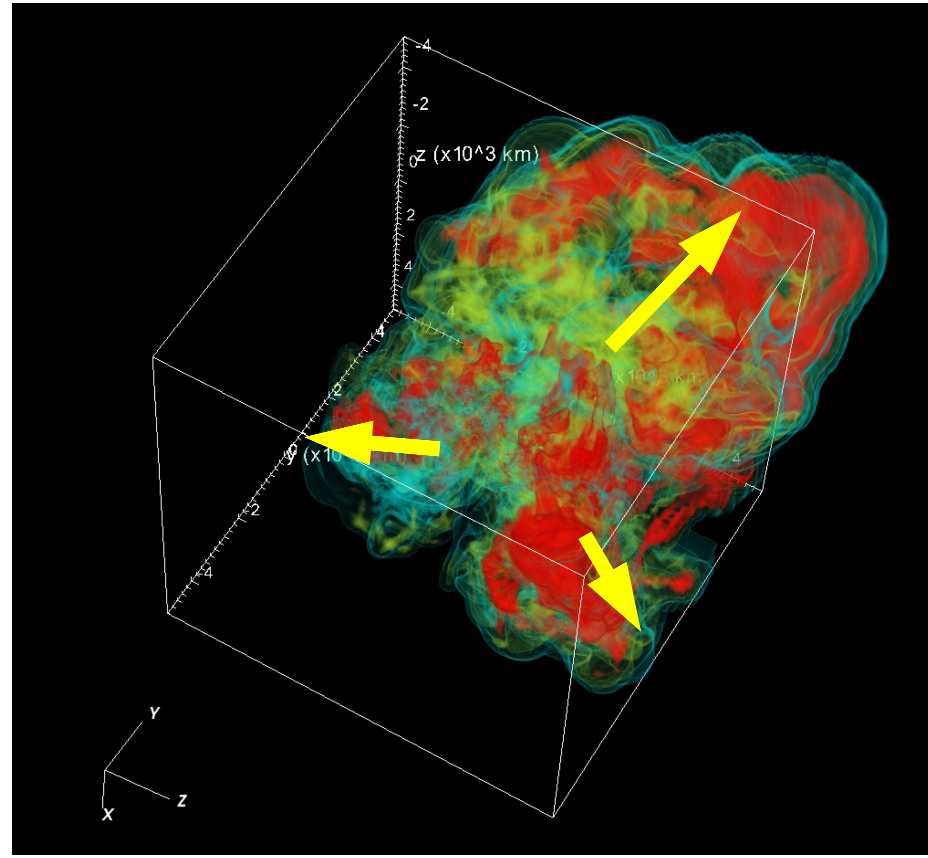
Red: Si-rich ashes
Cyan: Outer O shell boundary
Grey: Si core

Neutrino-heated bubbles in ensuing supernova (red/yellow)

- “Perturbation-aided” neutrino-driven mechanism quite efficient in first comparisons with multi-group neutrino transport (Müller 2016)
- Asymmetric infall facilitates asymmetric shock expansion
- Beware selection bias!
- Initial asymmetries in O shell imprinted on explosion







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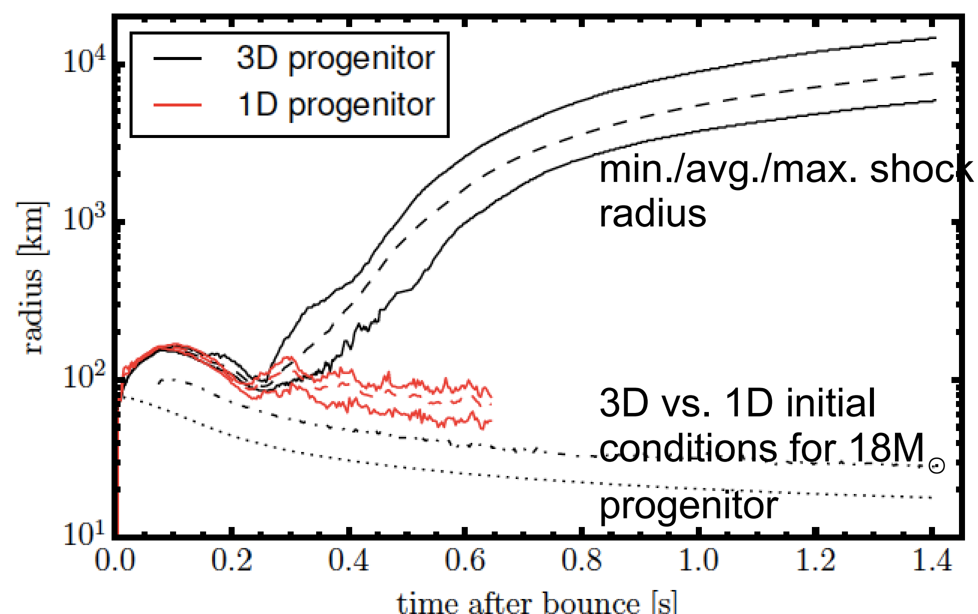
- "Perturbation-aided" neutrino-driven mechanism quite efficient in first comparisons with multi-group neutrino transport (Müller 2016)
- Beware selection bias!
- Forced shock deformation imprints O shell asymmetries on explosion



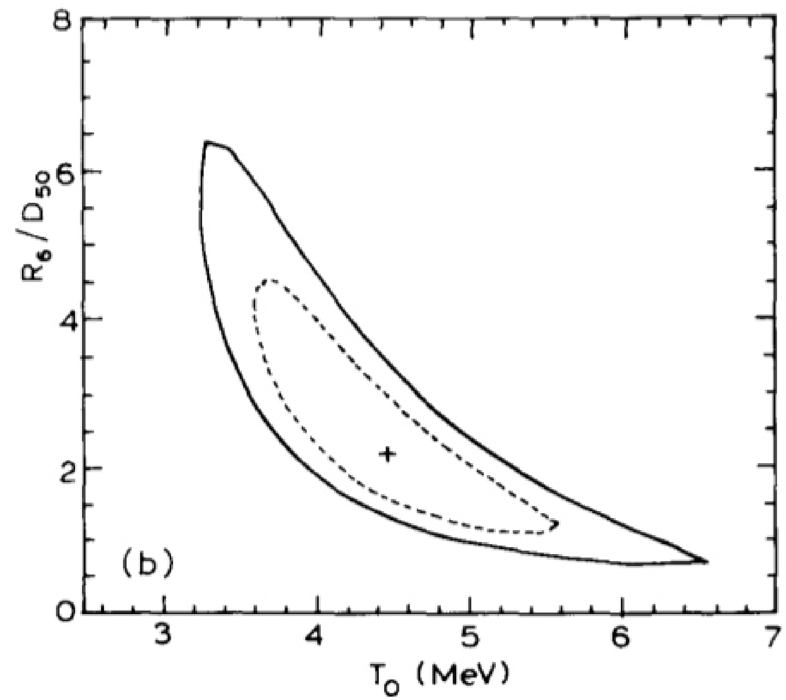
Fingerprints for multi-D flow dynamics in the supernova core?

The Neutrino Signal – Historical Background

Neutrinos already detected from SN1987 (two dozen):

- ~3×10^{53}ergs radiated in νs
- Avg. temperature: 4MeV
- Neutrinosphere radius ~20km
- $\bar{\nu}_e$ lifetime >5×10^{12}s
- $\bar{\nu}_e$ mass <30eV
- Maybe indication of modest core mass (Bruenn 1987, later revisited by O'Connor & Ott 2013)
- Constraints on hypothetical axion mass (Ellis & Olive 1987, Keil et al. 1997)

Neutrinosphere radius [10km]



Initial neutrinosphere temperature [MeV]

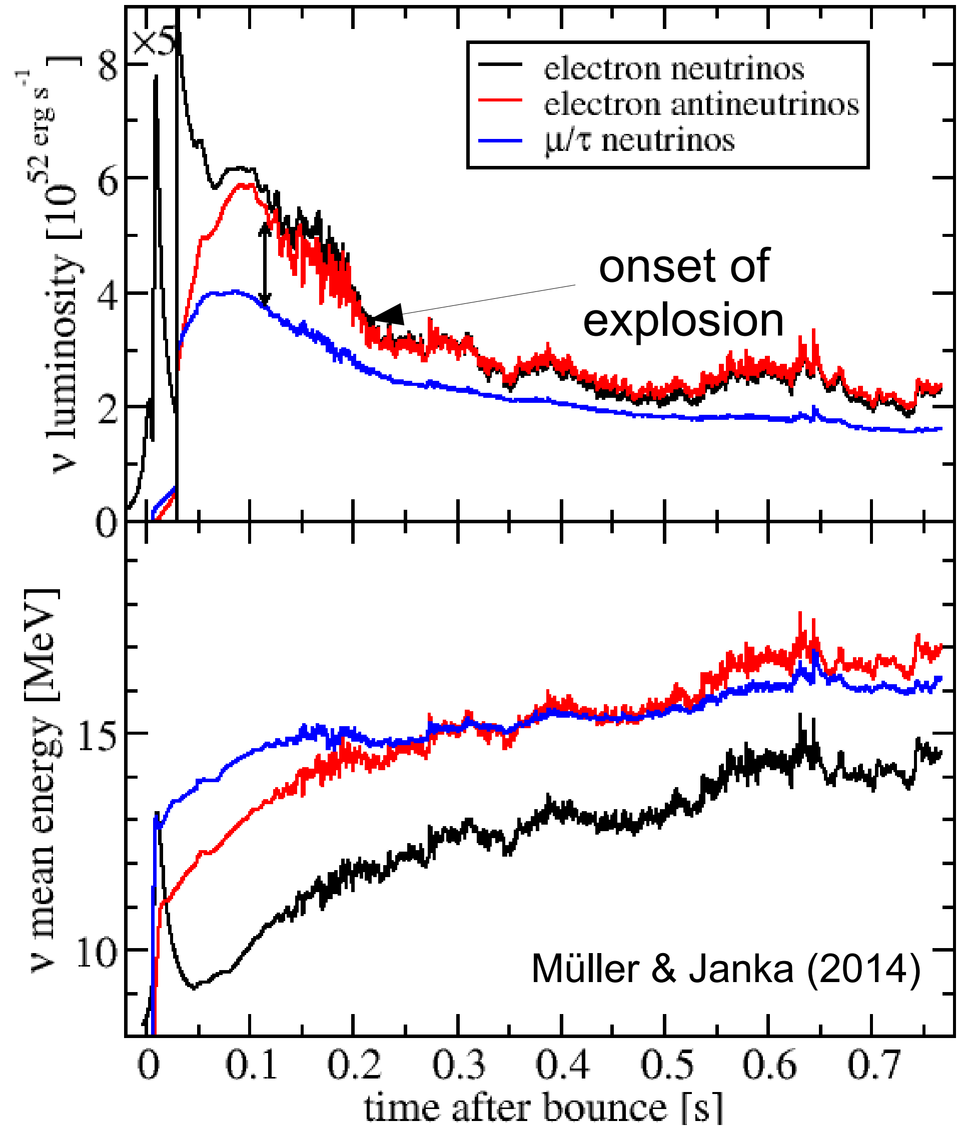
adapted from Loredo & Lamb (1998)

Can we learn more about the supernova engine?

The Time-Dependent Neutrino Signal

- Electron neutrino burst after bounce
- Accretion phase:
  - Gray-body law for $\nu_{\mu/\tau}$:
    $$L \sim 4\pi\epsilon\sigma R^2 T^4$$
  - Additional accretion contribution
    $$L_{acc} \sim \alpha G M \dot{M} / R$$
    for ν_e and $\bar{\nu}_e$
  - $\bar{\nu}_e$ mean energy~neutron star mass
- Signs of the explosion?

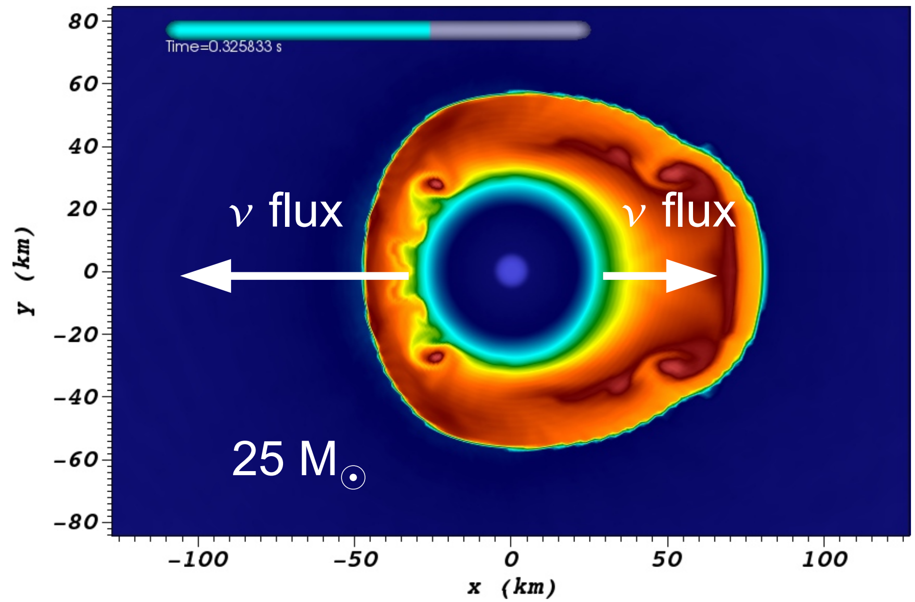
Tricky observables because of flavour conversion (MSW/non-linear)



27 $M_\odot$ model, spherical integration of the total neutrino flux

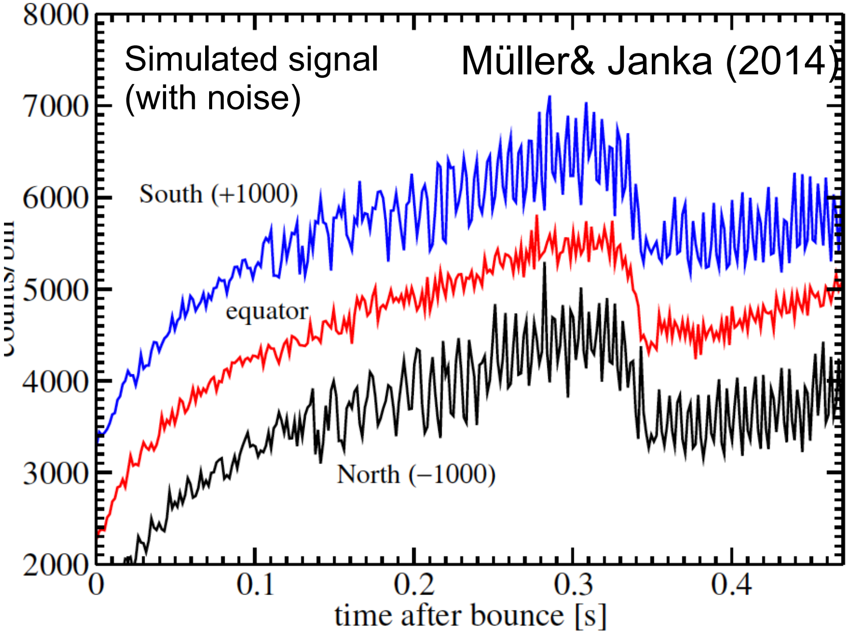
Can we learn more about the dynamics?

- Exploit *temporal variations* of the ν signal as fingerprints of multi-D instabilities (Lund et al. 2010, Tamborra et al. 2013, Müller & Janka 2014)
- Exemplary cases:
  - Supernova models as seen by IceCube at a distance of 10kpc
  - Only total PMT count rate used (no measurement of energy & direction for MeV neutrinos)
  - Shot noise from dark current included
  - No non-linear flavor conversion & ordinary mass hierarchy assumed
  - HyperK will also be able to this and provide spectral information as well



Detecting Shock Oscillations

- Sloshing motions result in quasi-periodic and asymmetric neutrino emission
- Sloshing frequency related to shock and proto-neutron star radius
- Detectable in IceCube for up to ~10 kpc
- Opportunity to reconstruct shock trajectory!
- Flavour conversion only affects modulation amplitude



Non-exploding 25 $M_\odot$ model

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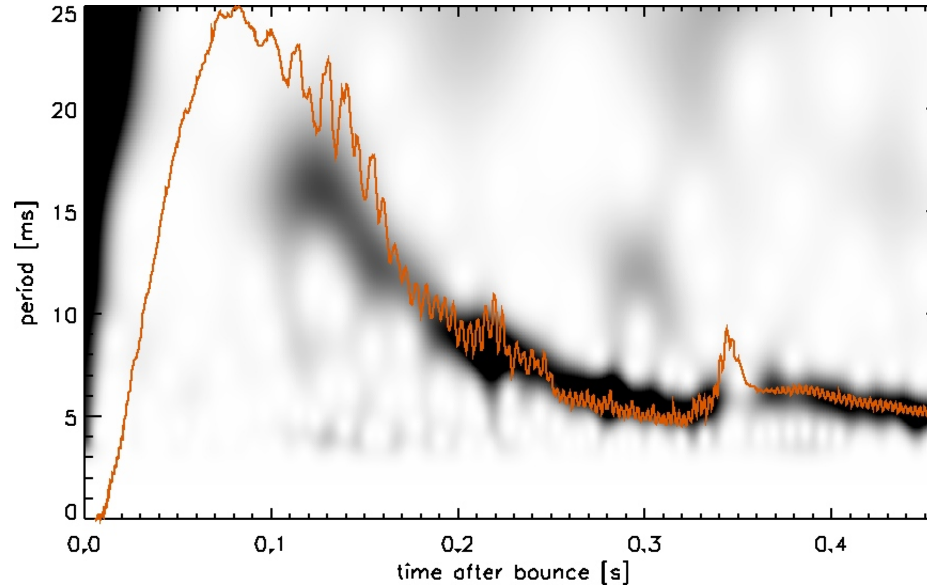
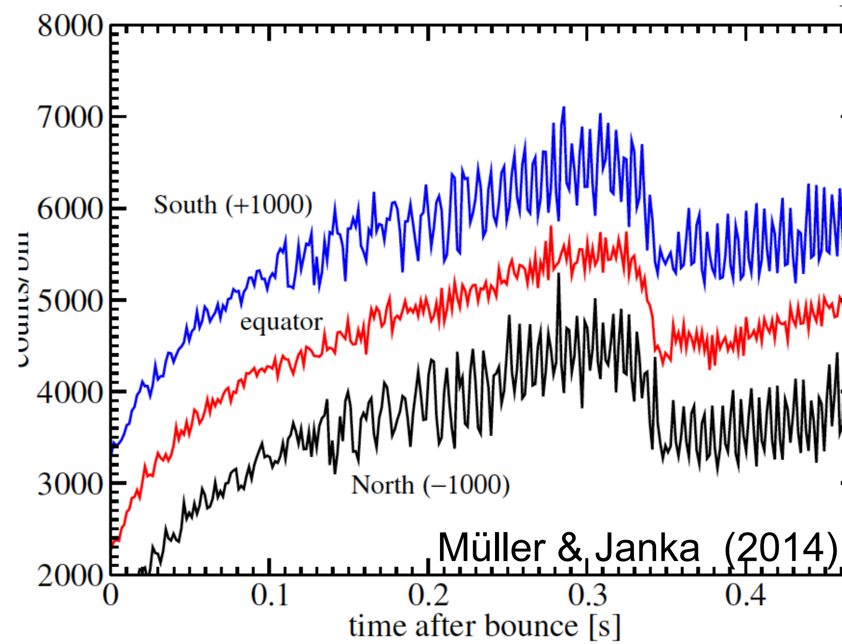


$$\text{period} \approx 19\,\text{ms}\,(r_{\text{shock}}/100\text{km})^{3/2} \ln \frac{r_{shock}}{r_{PNS}}$$



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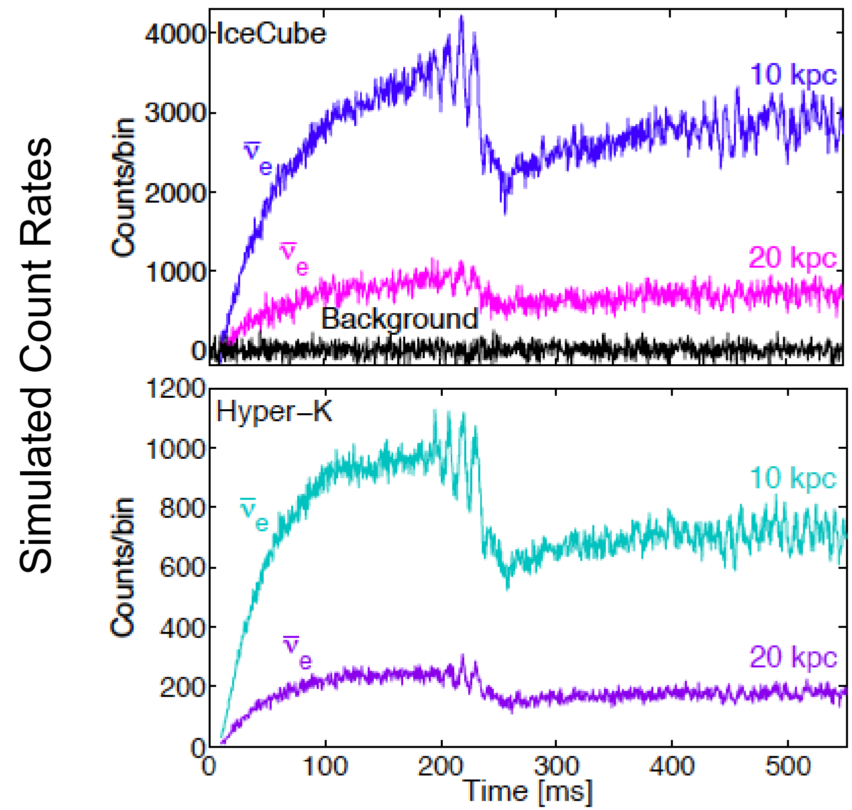
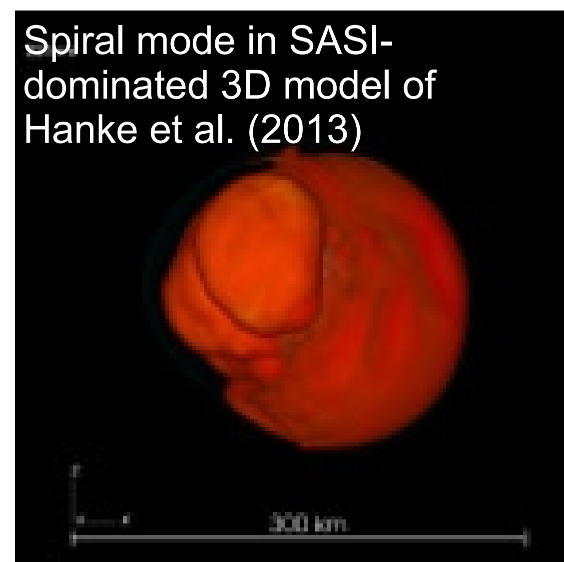


Tamborra et al. (2013)



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- Sloshing frequency related to shock and proto-neutron star radius
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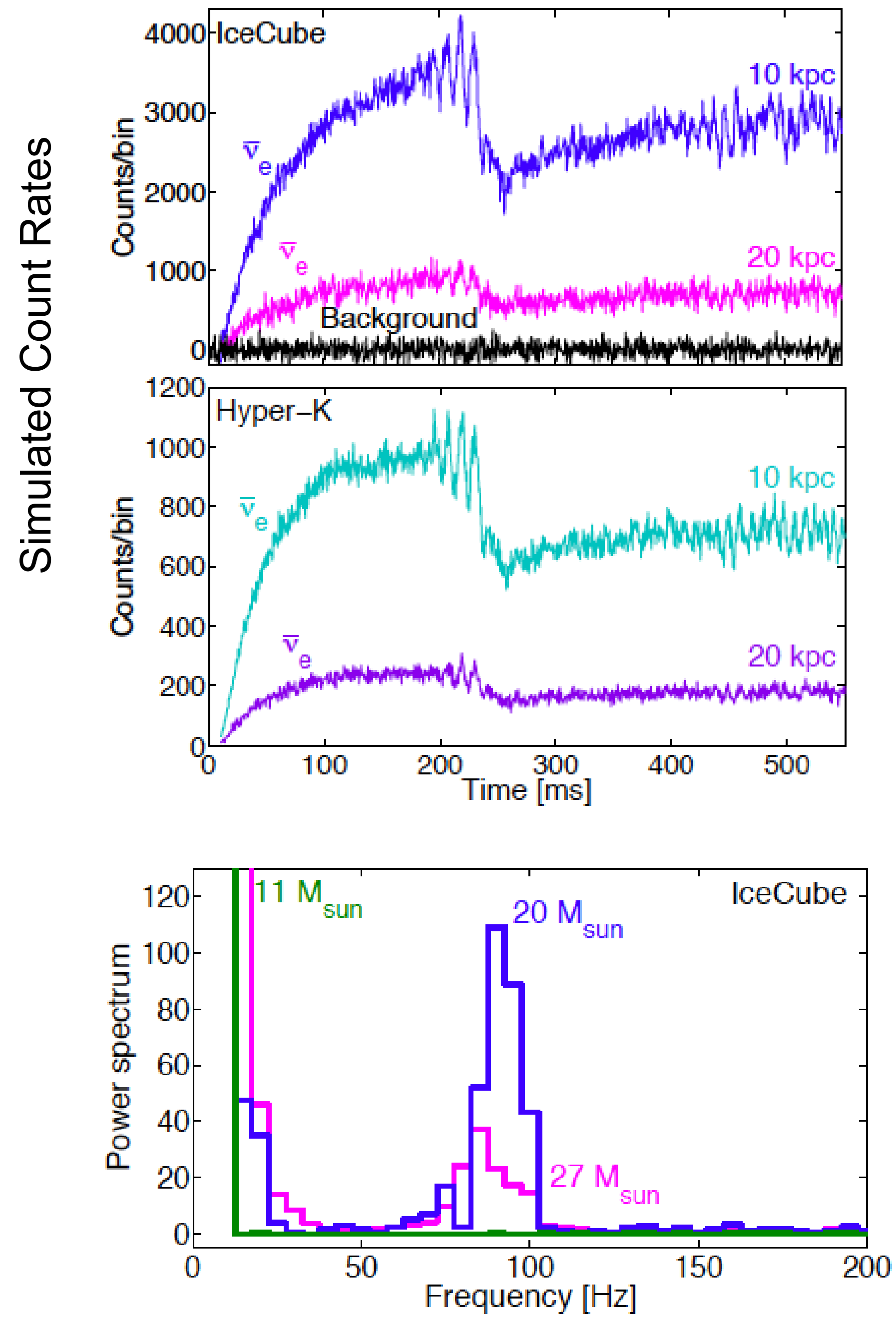
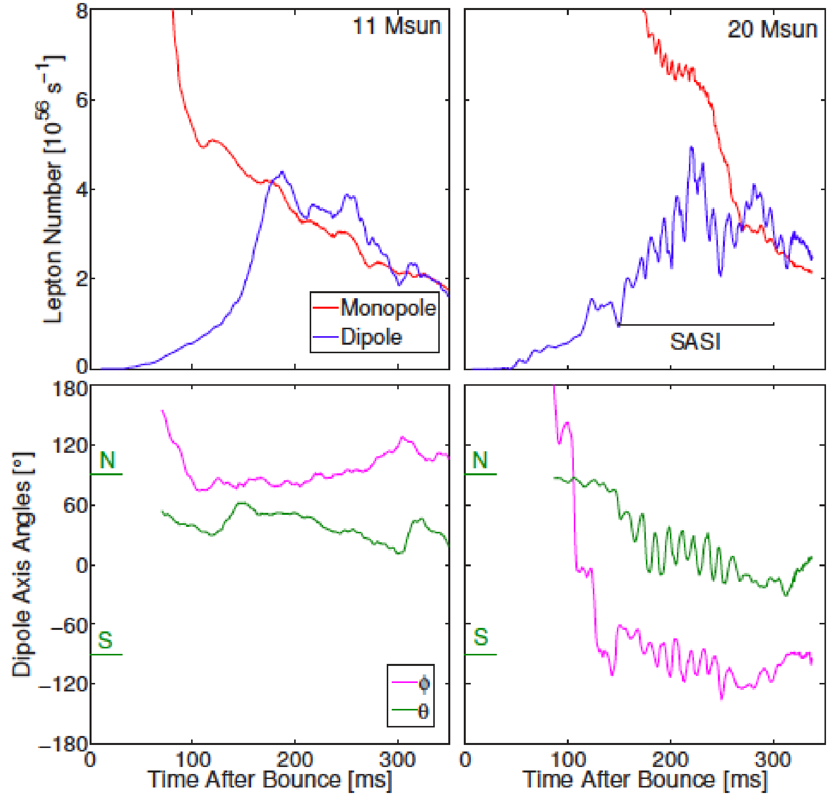
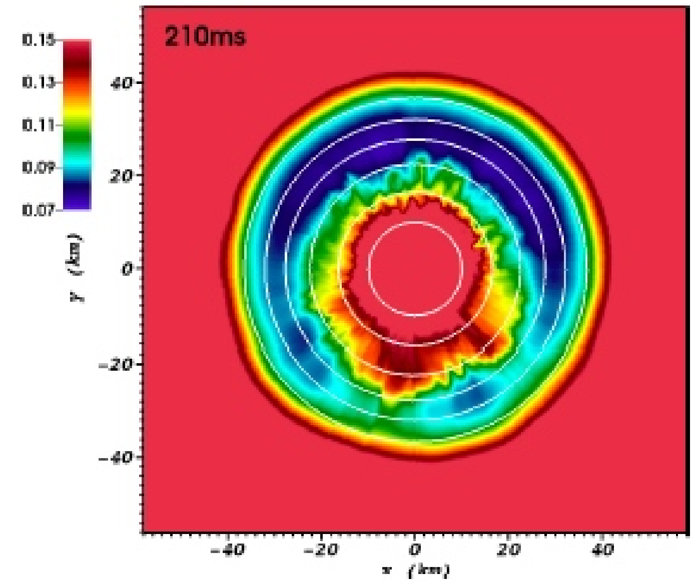
- Opportunity to reconstruct shock trajectory!
- Modulations survive in 3D (Tamborra et al. 2013)



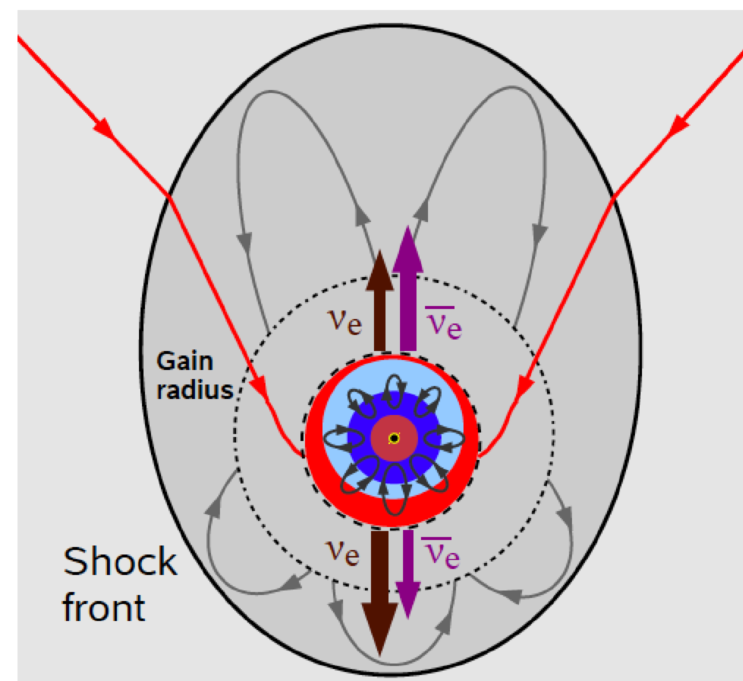
Tamborra et al. (2013)

LESA Instability





Electron fraction in proto-neutron star

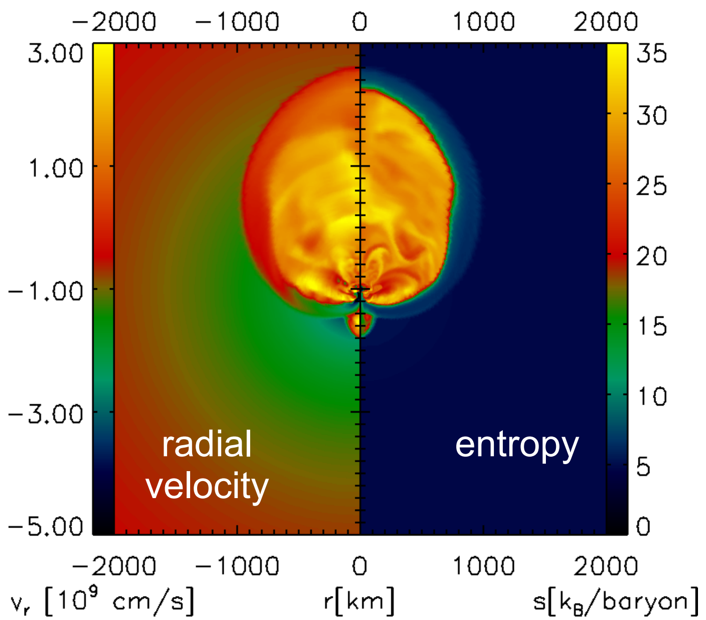


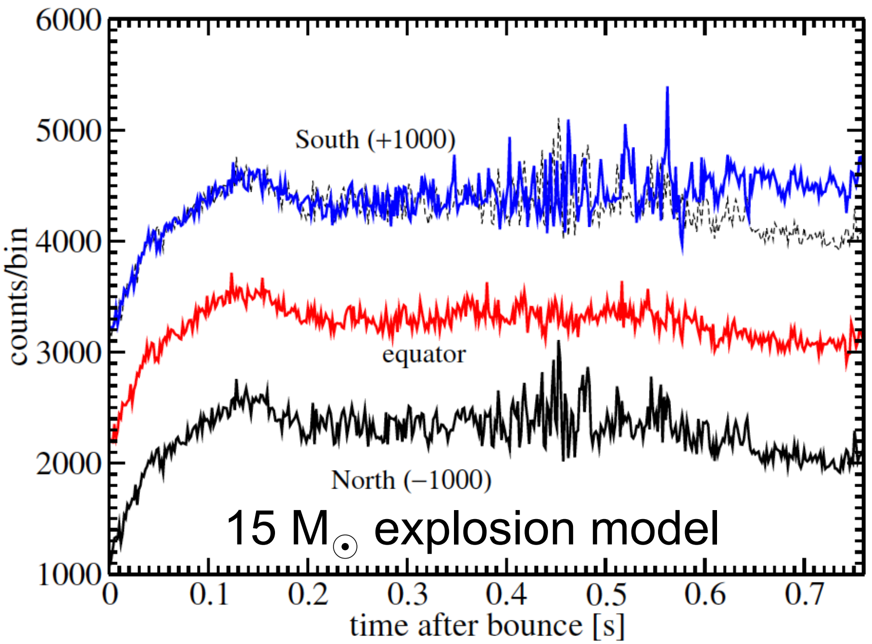
Tamborra et al. (2014)

- Global lepton flux asymmetry in recent 3D models of the MPA group (Tamborra et al. 2014)
- Nature of LESA still unclear: Accretion instability or low-mode nature of PNS convection responsible?
- May lead to very slow modulation of detected signal – likely not detectable
- But will affect nucleosynthesis (Y_e in outflow)

Signatures of the Explosion

- Explosion phase characterized by slowly-changing large-scale anisotropies
- → emission modulation periods >30ms (~advection time-scale when recombination radius is reached)





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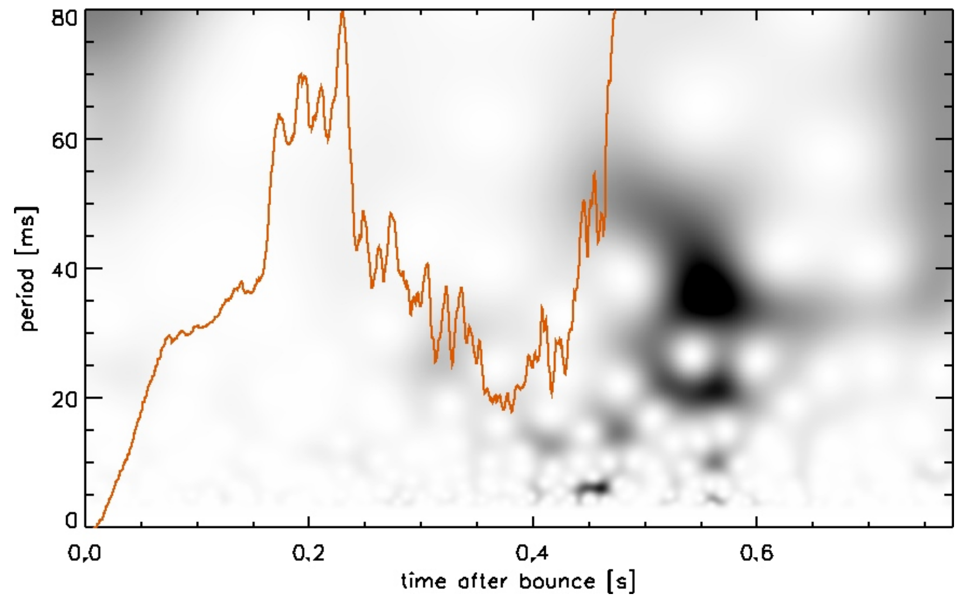

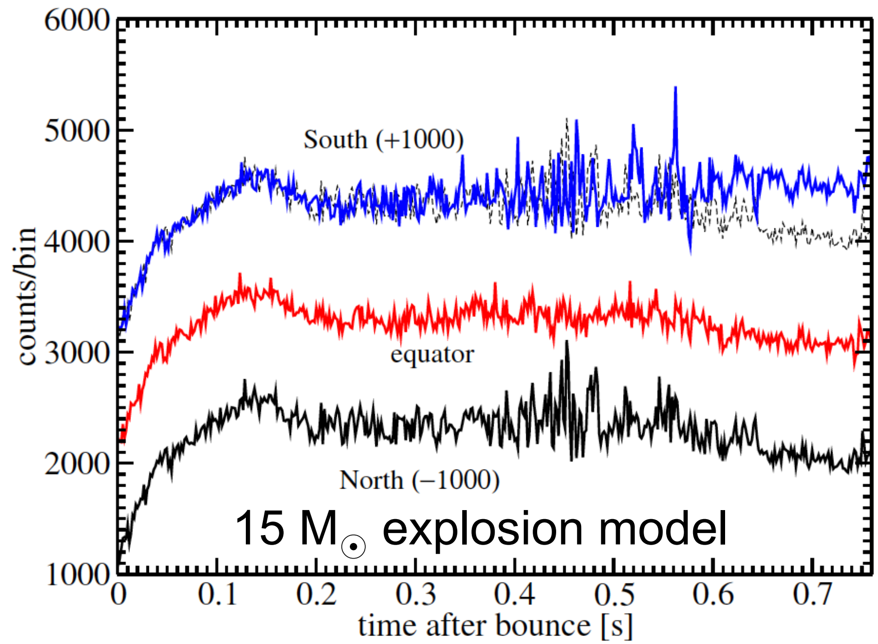

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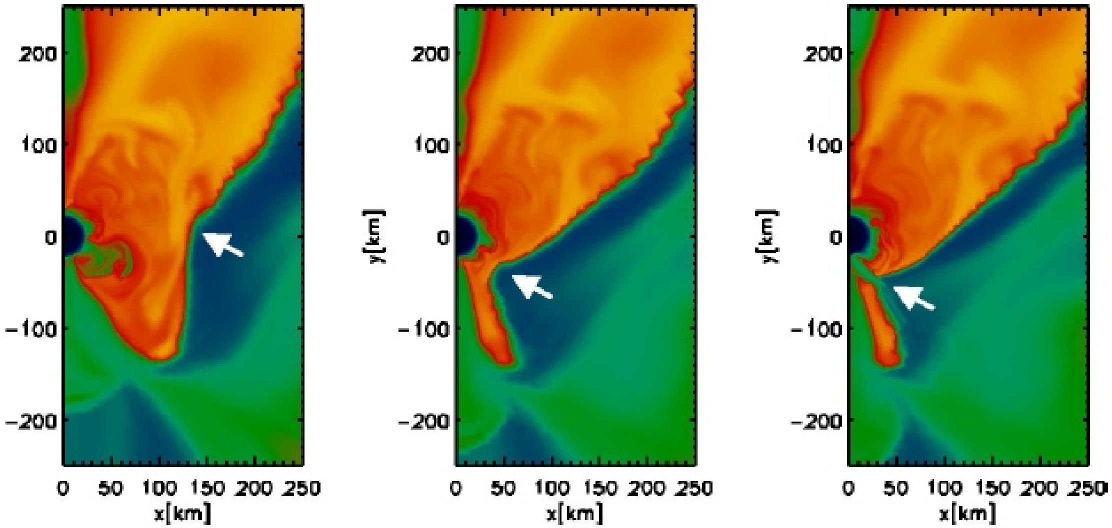
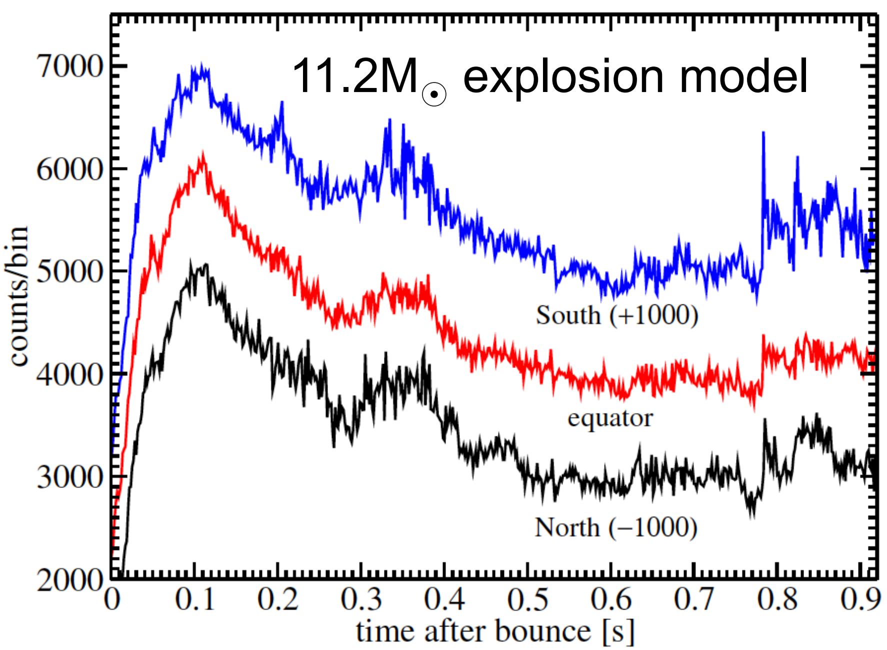
- Weak explosions: possible emission spikes due to "early fallback"





Müller & Janka (2014)

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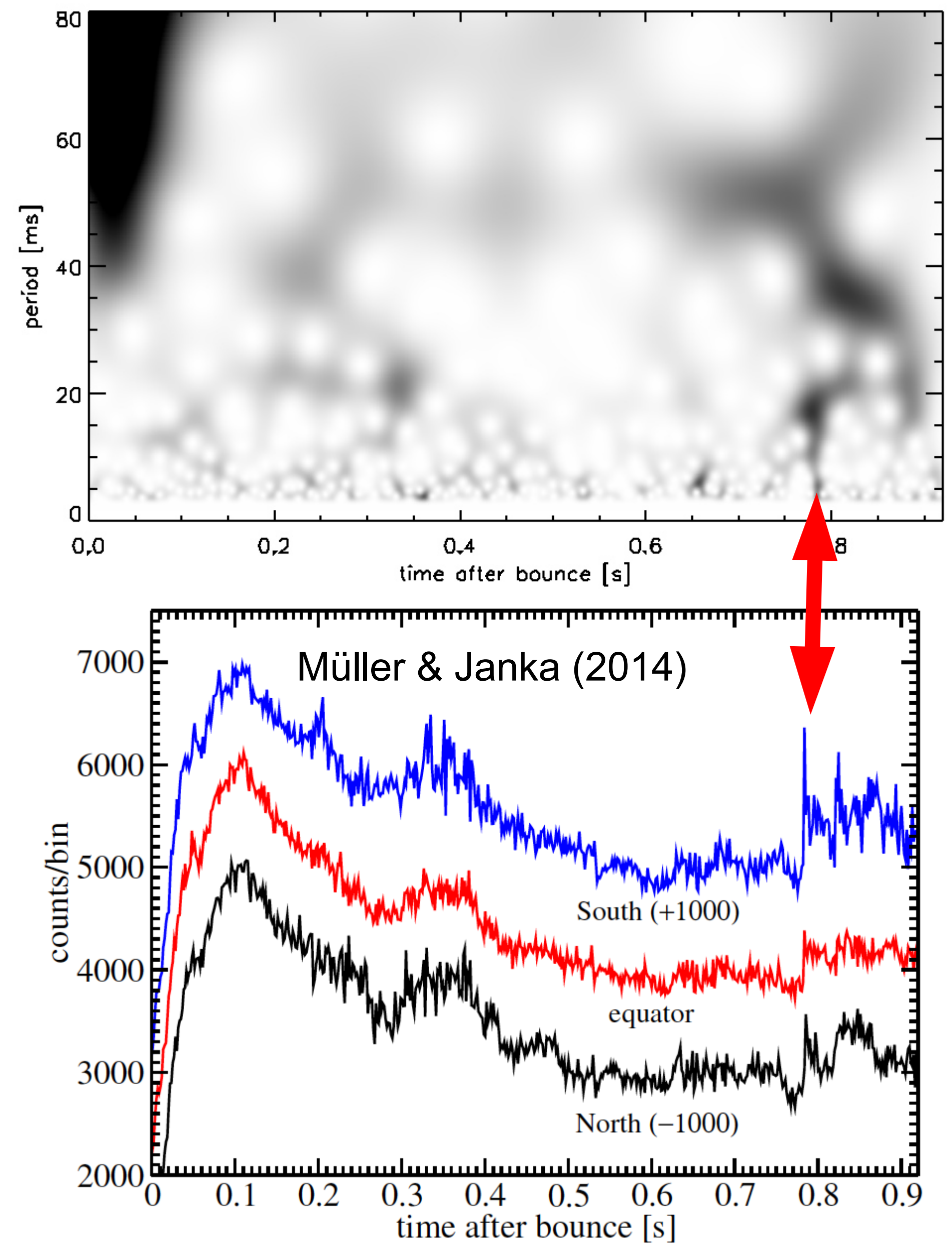

Conclusions

- First successful 3D simulations of core-collapse supernovae with self-consistent neutrino transport after initial setbacks
- 3D explosion models still need to become more robust – likely due to a **combination** of improved physics (3D initial conditions, better neutrino rates...)
- Neutrinos may be *the* prime messenger from the next Galactic supernova, will reveal:
  - Neutron star mass ($\propto E(\nu_e)$) & accretion rate as a function of time
  - Temporal modulation of neutrino signal reveals nature of hydrodynamics instabilities (SASI vs. convection) – but need to reinvestigate models with 3D initial conditions
  - Time of explosion (decrease in modulation frequency)
  - For SASI: time-dependent shock radius (!)
- Other goals of neutrino astronomy (not covered here):
  - Early proto-neutron star cooling (time scale → EoS properties, e.g. symmetry energy,...)
  - Clues about mass hierarchy, presence of sterile neutrinos...