The Status of Core-Collapse Supernova Explosion Modelling

Bernhard Müller

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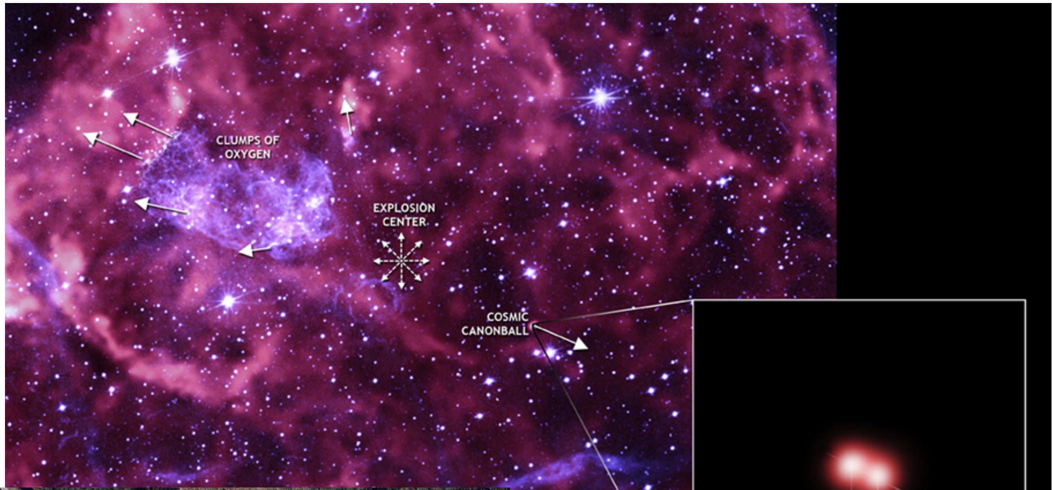
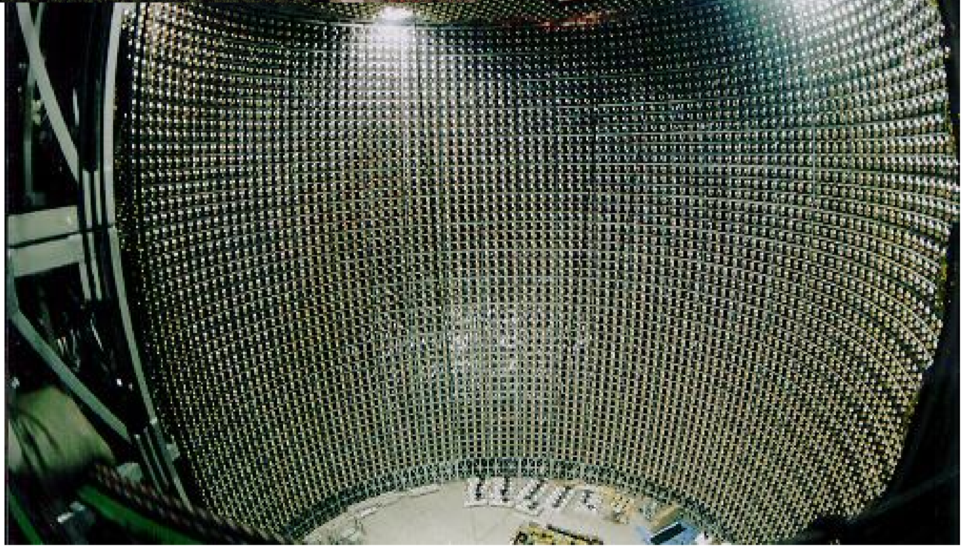
Major Questions in Supernova Theory

- How does the "engine" work? Is the ν-driven mechanism viable or do we need something else?
- What can we observe?
  - Neutrinos – from bounce to cooling
  - Gravitational waves (?)
  - Nucleosynthesis yields
  - Ejecta morphology, pulsar kicks, light curves...

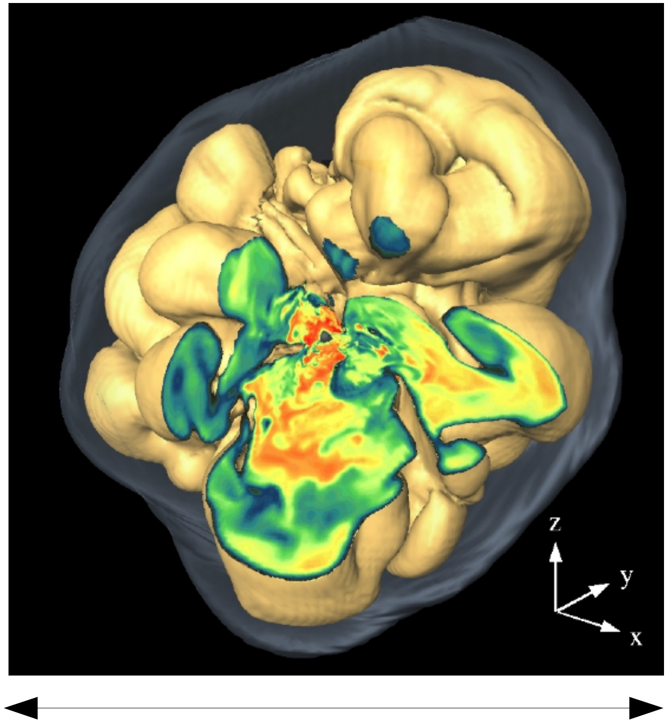




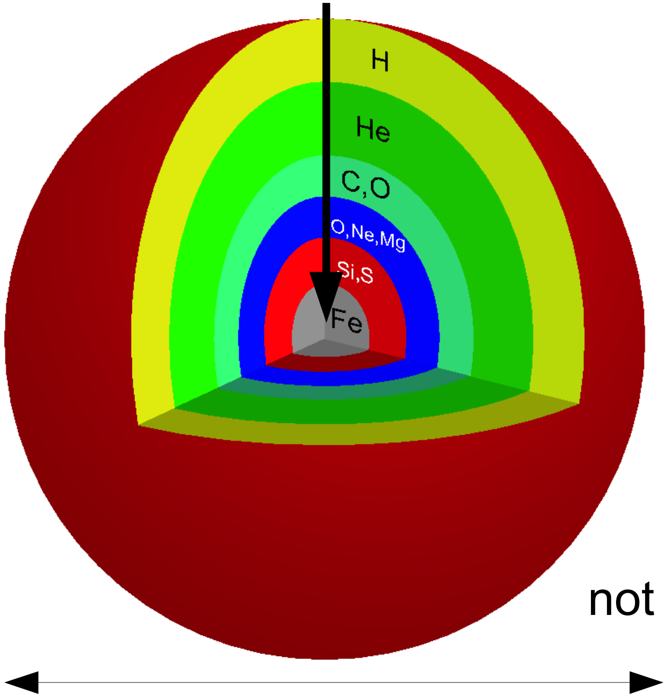
The Thorny Path towards Explosion Models

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 ($GM/rc^2 \approx 0.1\ldots0.2$) & high velocities → relativistic effects important
- Combine all this in a first-principle approach!
- The most ambitious 3D models currently take ~5000 core years



several 100 km



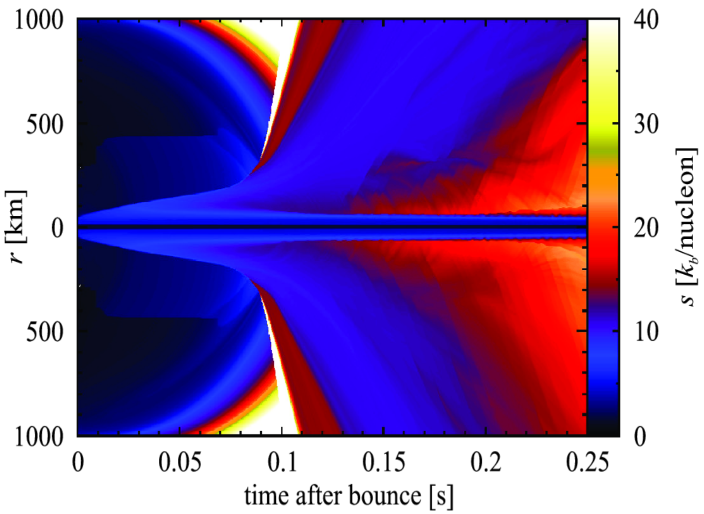
not to scale

~10^8km

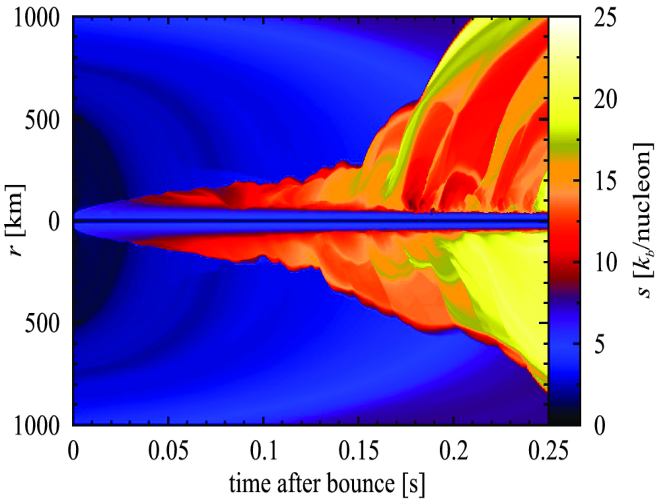
Why SN explosions have proved difficult to obtain (in simulations...)

- Delicate sensitivity of heating/cooling to neutrino interaction rates: $t_{adv}/t_{heat} \sim (L_{\nu} E_{\nu}^{2})^{5/3}$ → **importance of accurate transport**
- **General relativity** only recently included in multi-dimensional transport simulations (Müller et al. 2010; first attempts in 3D: Kuroda et al. 2012, Ott et al. 2013)
- **Long simulations** (~1s) and **3D models** not feasible until recently
- Too few models: impact of **progenitor variations** (in the innermost $<2M_{\odot}$) has long remained unexplored
- More successful results recently reported (results & methods cannot all be evaluated here):
  - MPA group: Marek & Janka (2009), Müller et al. (2012, 2013), Janka et al. (2012)
  - Suwa et al. (2010, 2012), Takiwaki et al. (2012), Kuroda (2012)
  - OakRidge group: Bruenn et al. (2009), Bruenn et al. (2012).

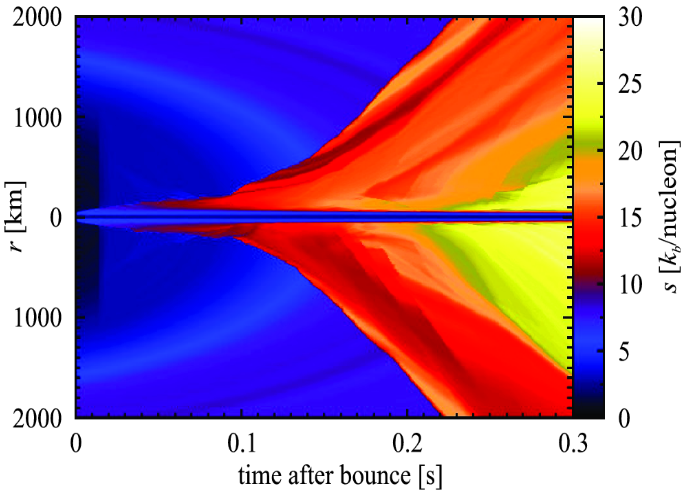
A Panoramic View of Multi-Group Neutrino Hydrodynamics Simulations (MPA Group)



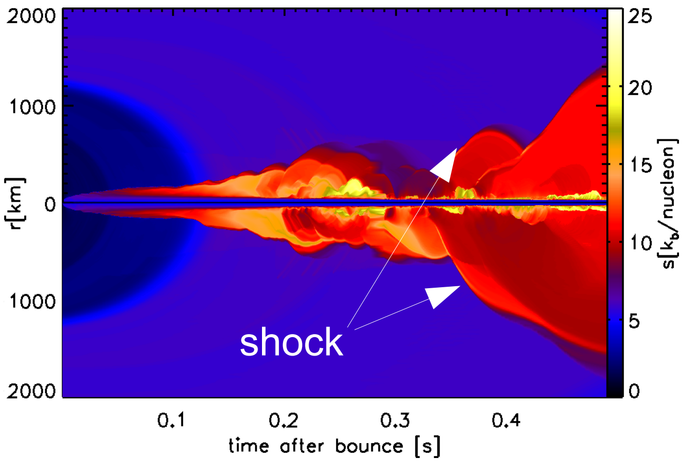
8.8 O-Ne-Mg core progenitor



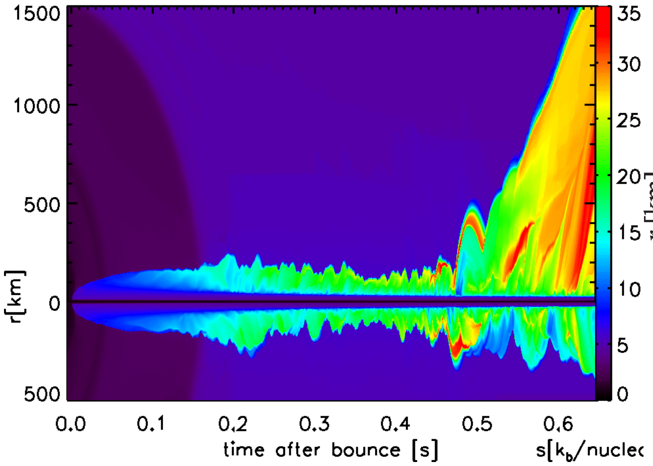
8.1 $M_\odot$, $Z=10^{-4}Z_\odot$



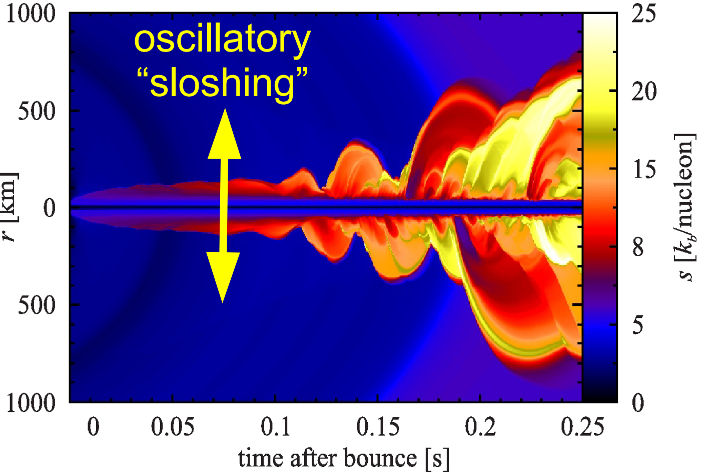
9.6 $M_\odot$, Z=0



11.2 $M_\odot$



15 $M_\odot$



27 $M_\odot$

Janka et al. (2012)

Evolution of the entropy along the polar axis
(show shock evolution, shell interfaces & neutrino-heated matter)

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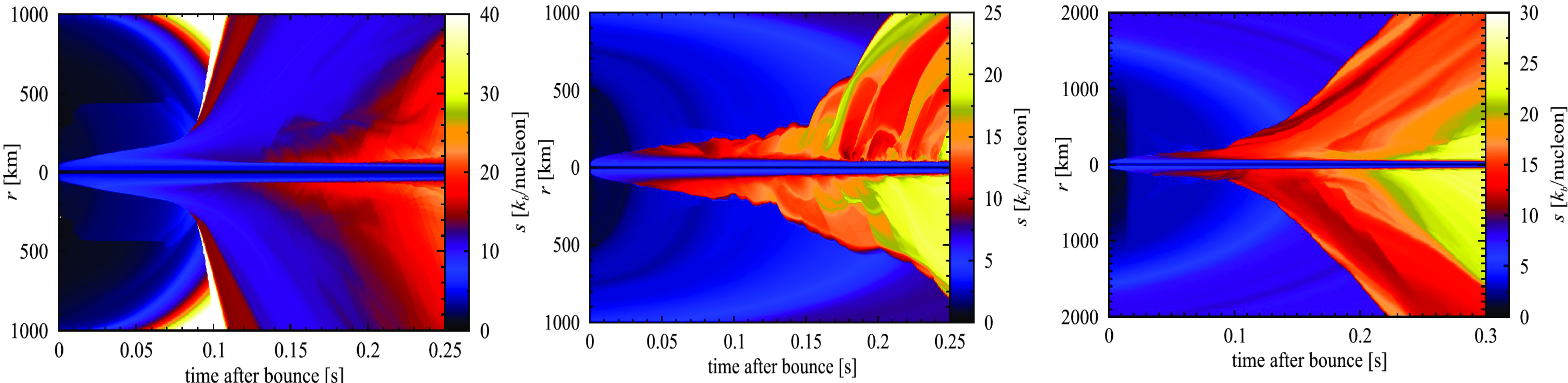

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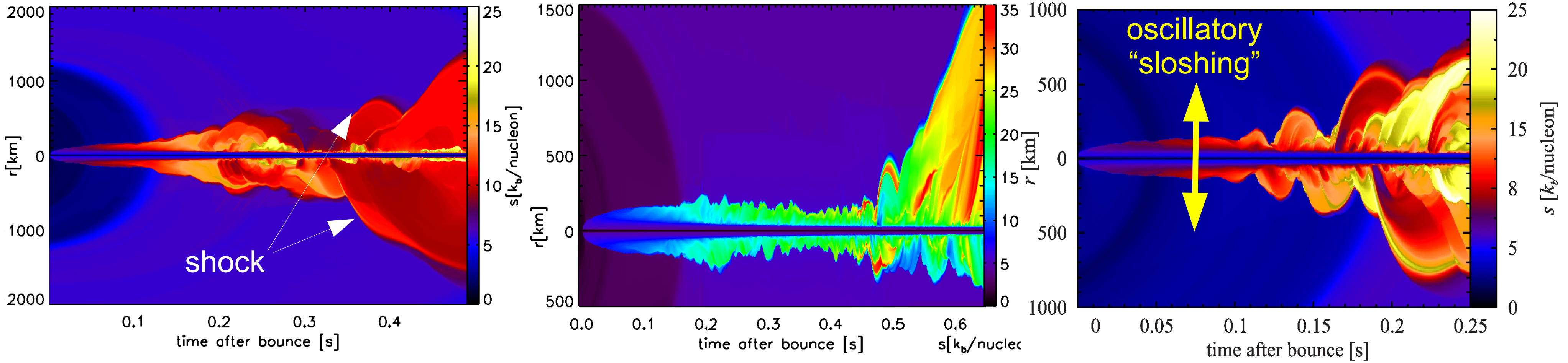

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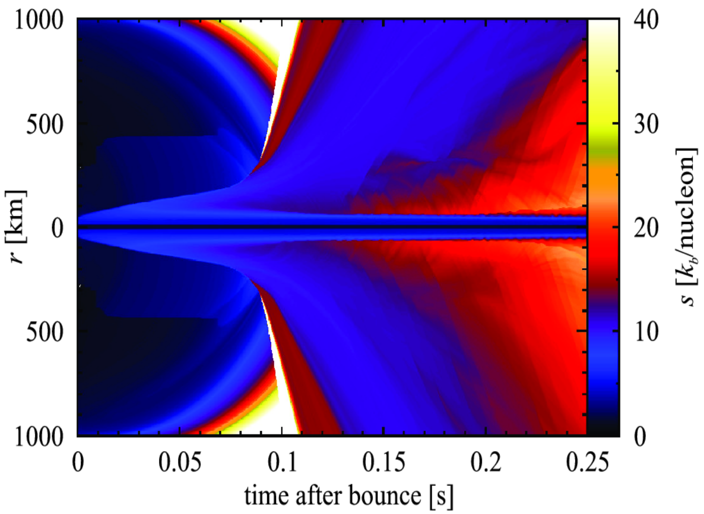

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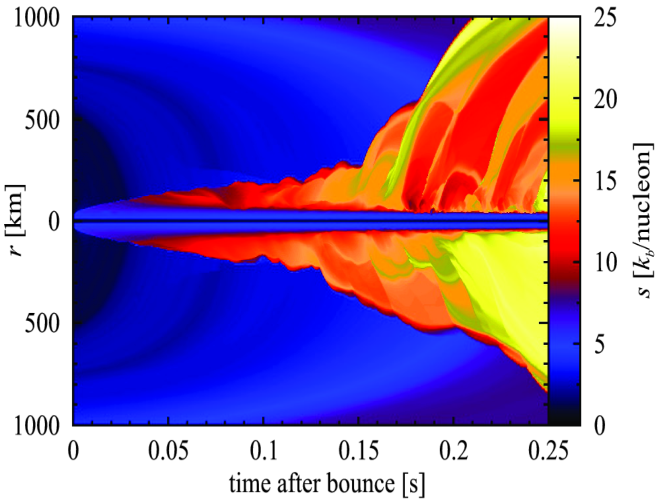

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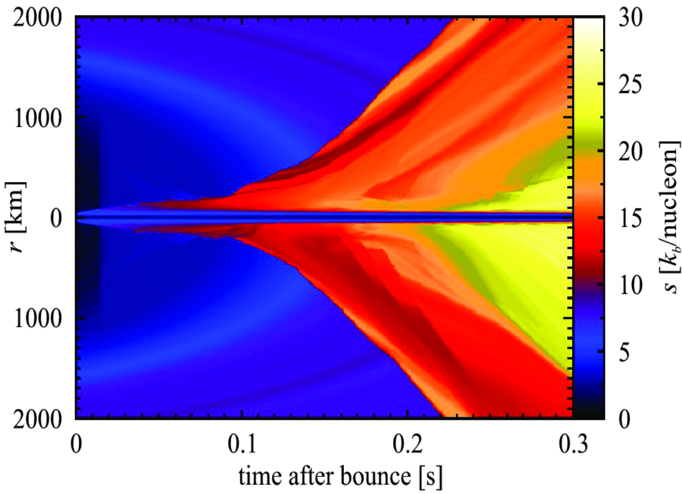

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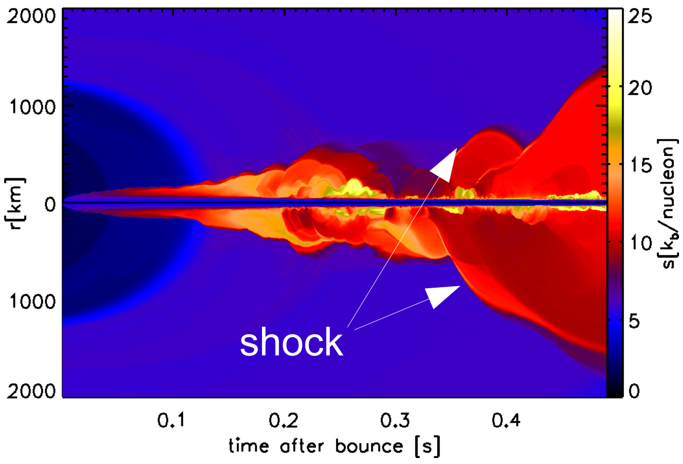

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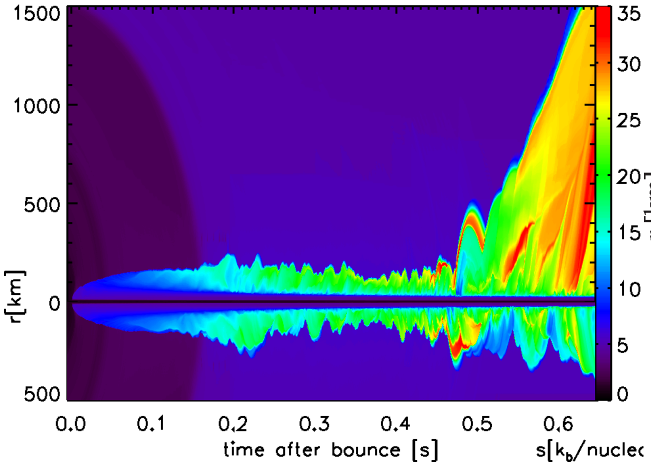

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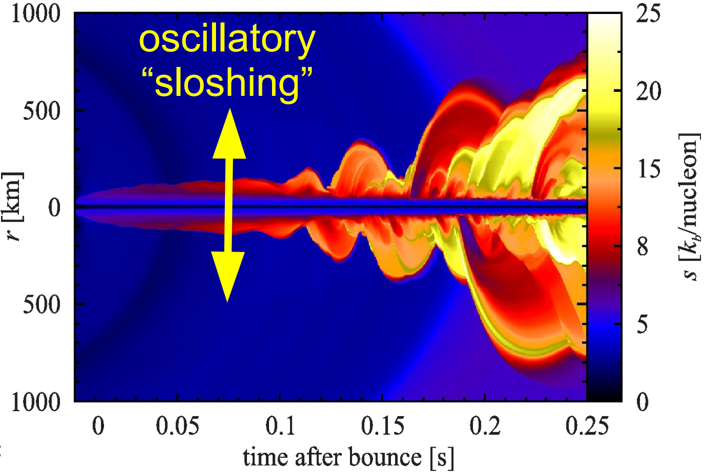

27 $M_\odot$

Evolution of the entropy along the polar axis
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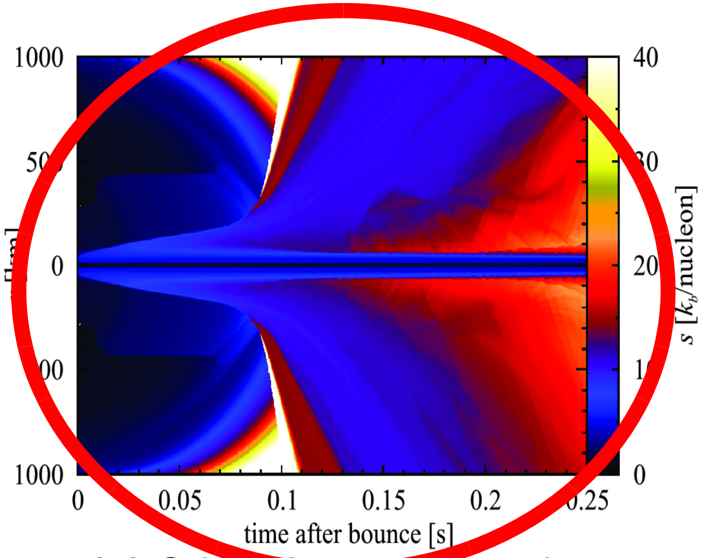
Janka et al. (2012)

A Large Variety of Ways Towards the Explosion



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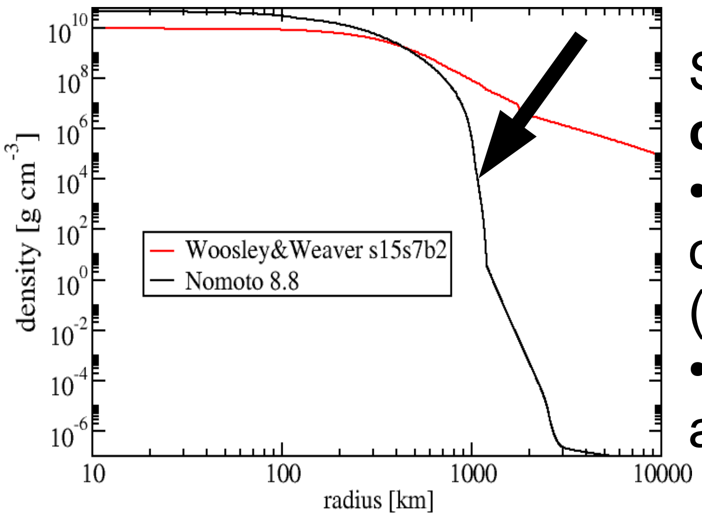
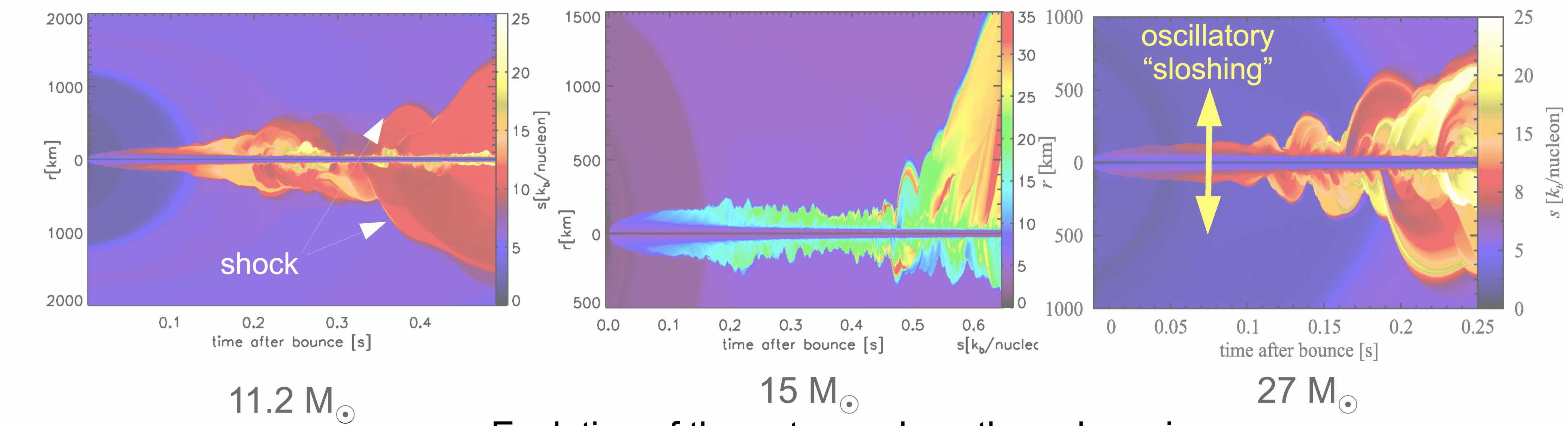


Supernovae with **O-Ne-Mg cores**:

- Robust explosions obtained by 3 groups (MPA, Arizona, Basel)
- Clue: **Tenuous envelope** around iron core



11.2 M$_\odot$ 15 M$_\odot$ 27 M$_\odot$

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Evolution of the entropy along the polar axis
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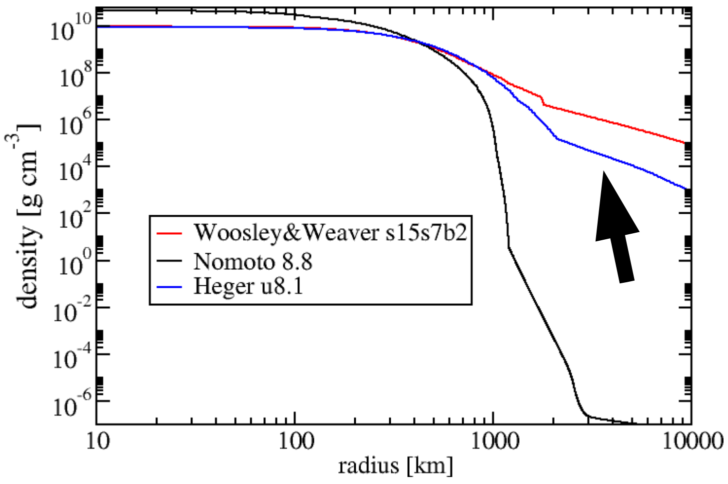
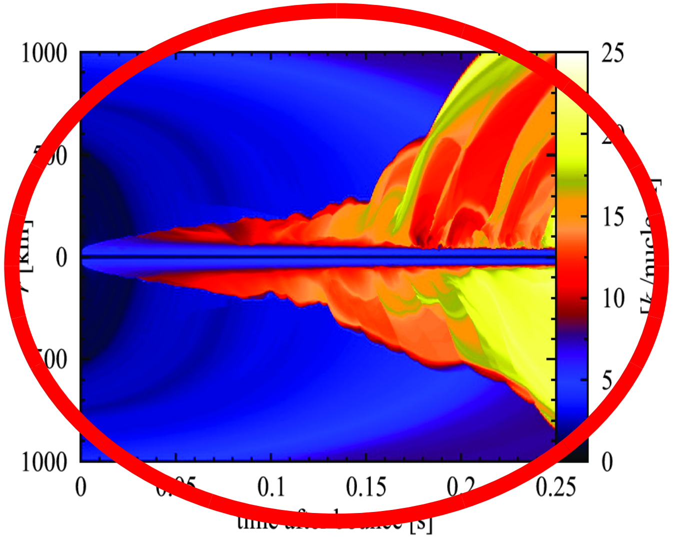
New Class of Fast-Exploding Low-Mass Progenitors with Iron Cores





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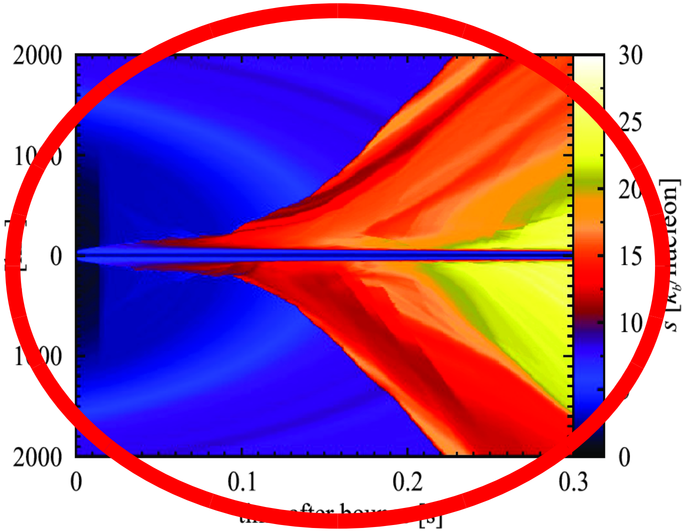

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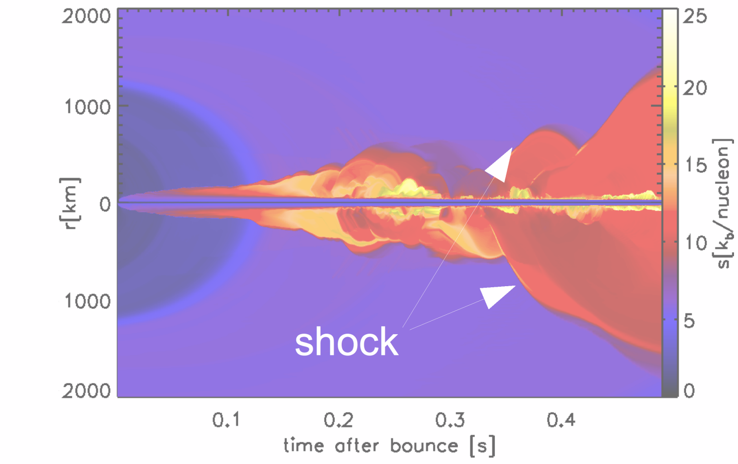

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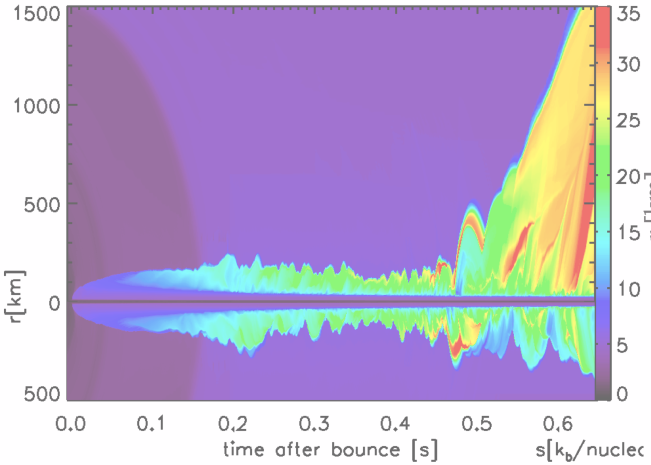

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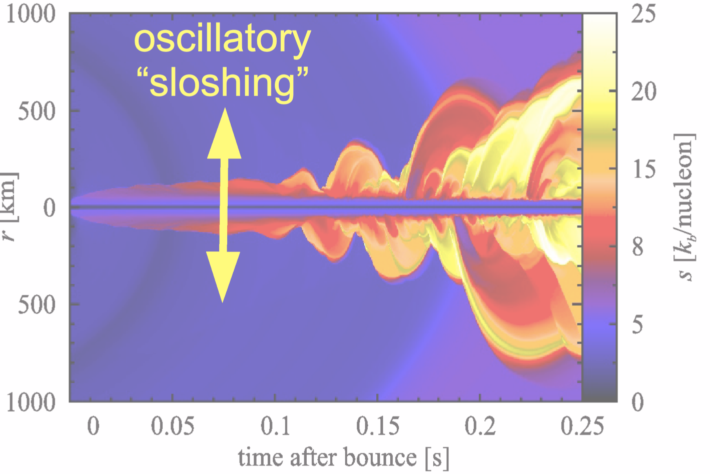

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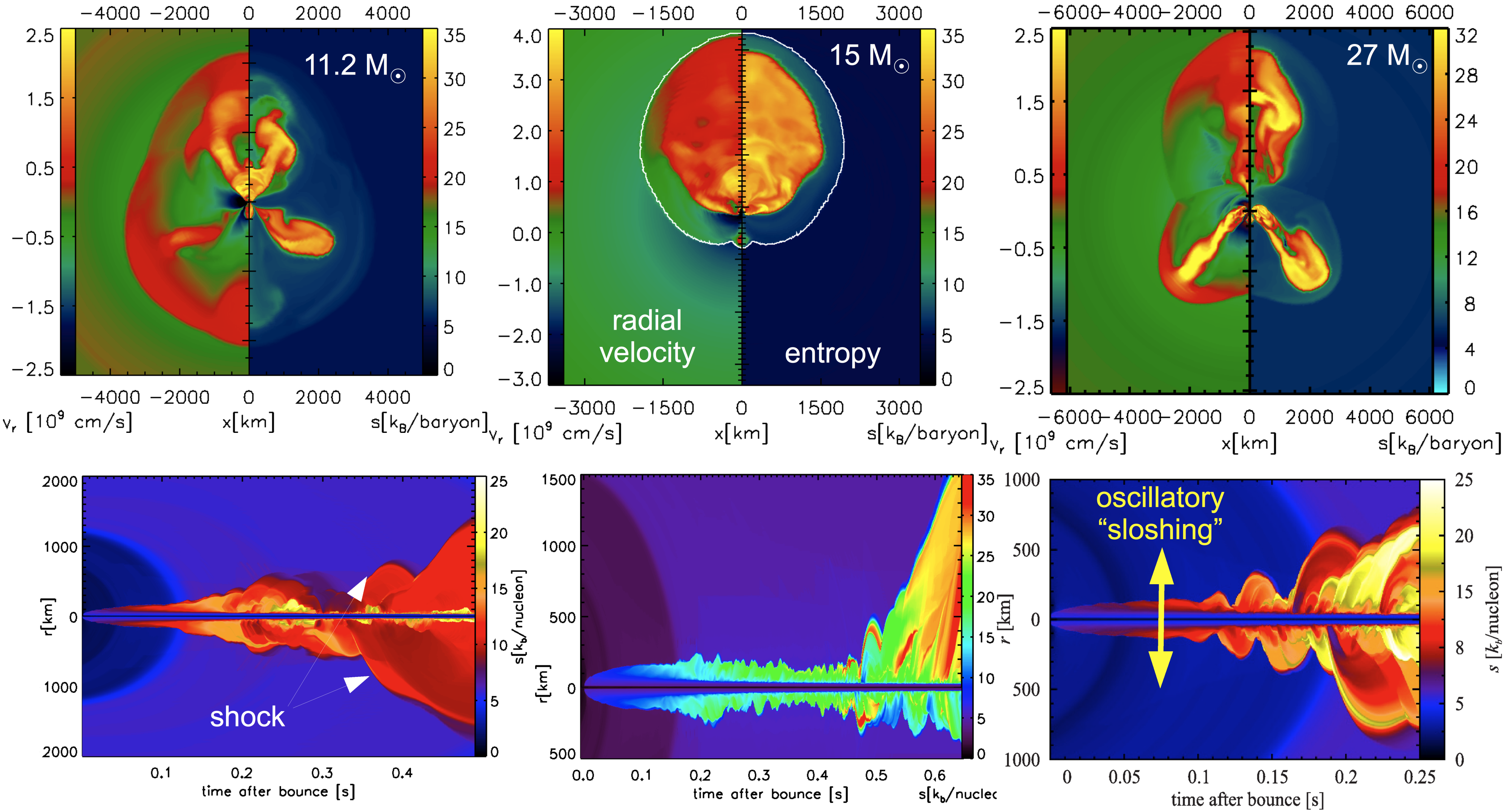
Janka et al. (2012)

The Hard Cases: More Massive Progenitors

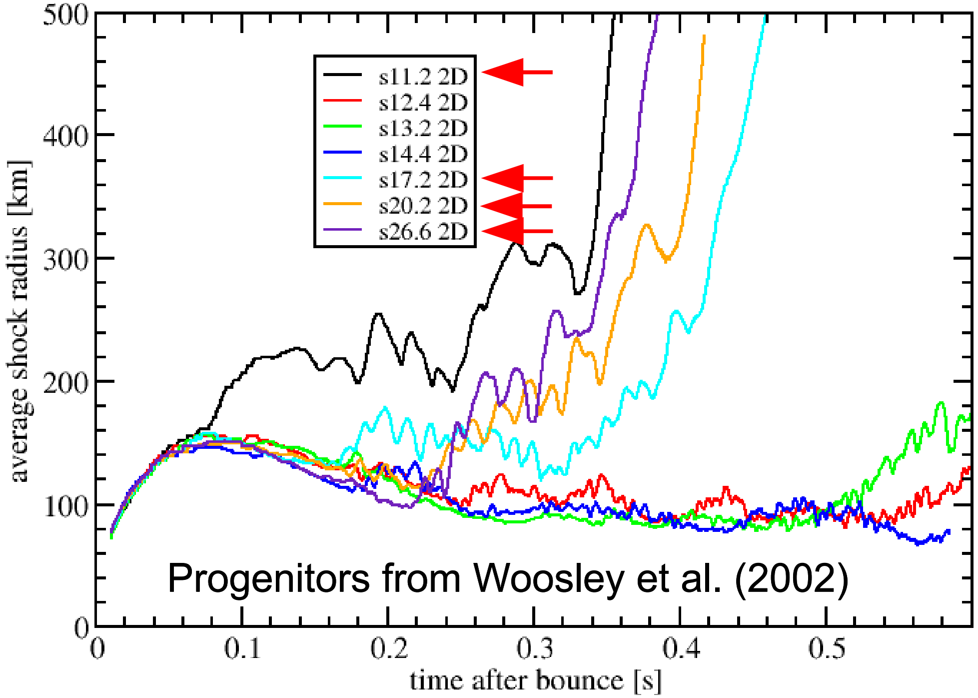


11.2 M☉ 15 M☉ 27 M☉

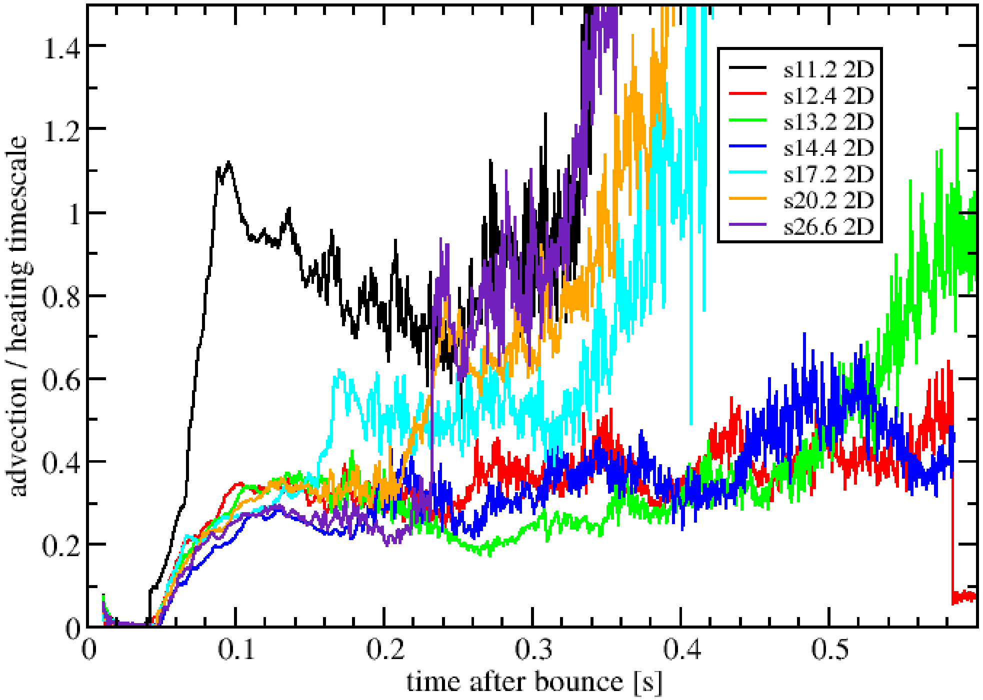
Janka et al. (2012)

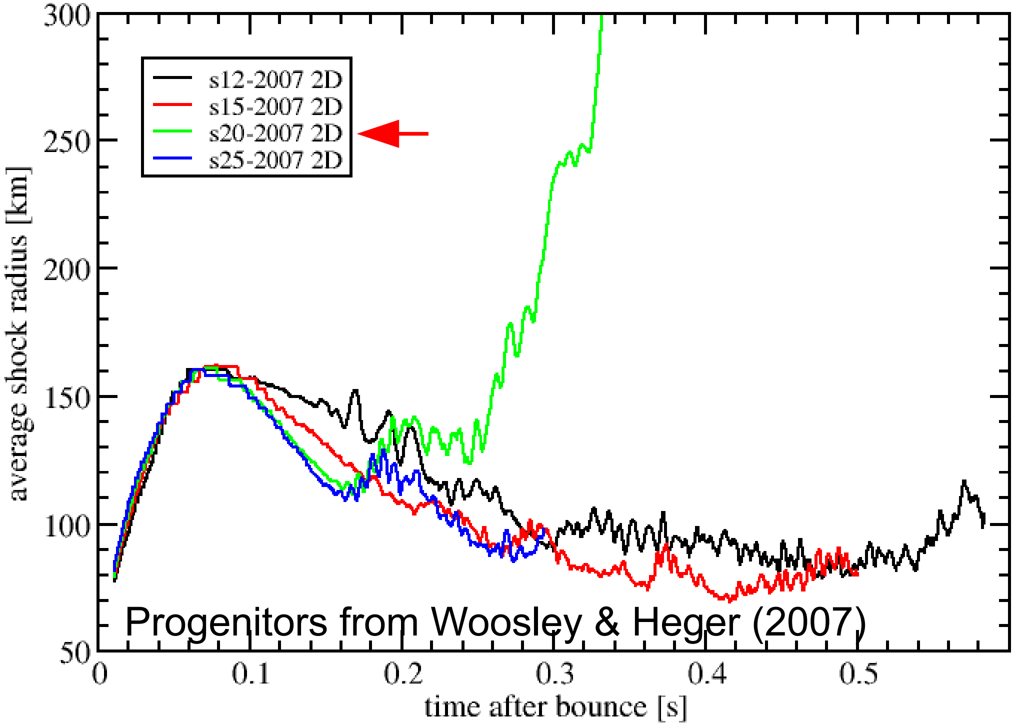
Key ingredients for the growing set of explosion models: general relativity, better neutrino transport & longer simulation times

More 2D explosions from 2013

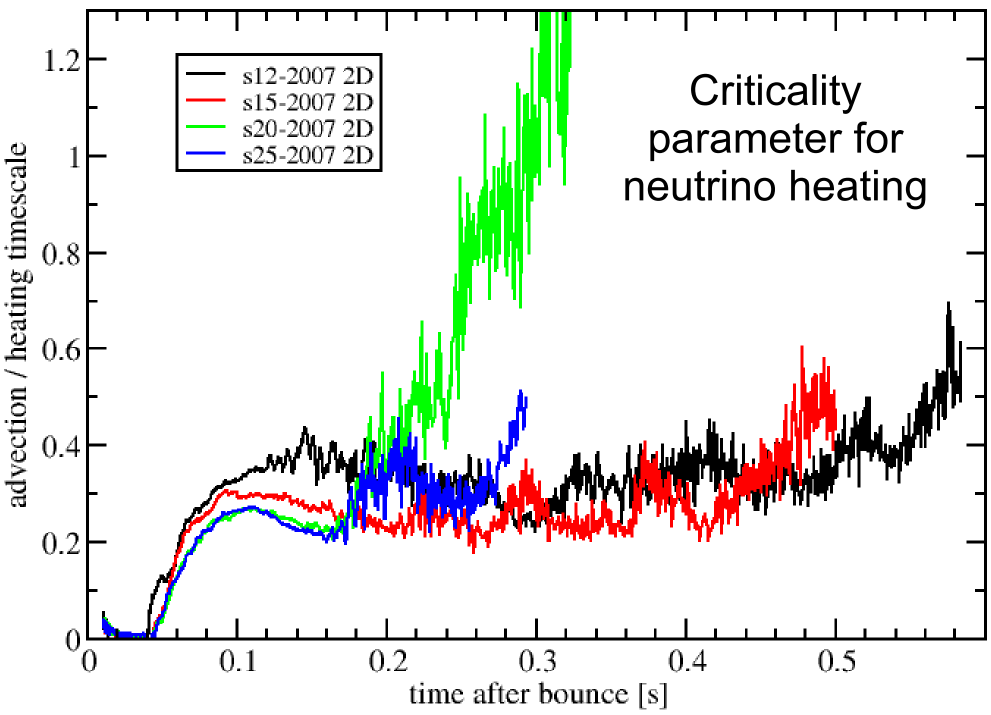


Progenitors from Woosley et al. (2002)





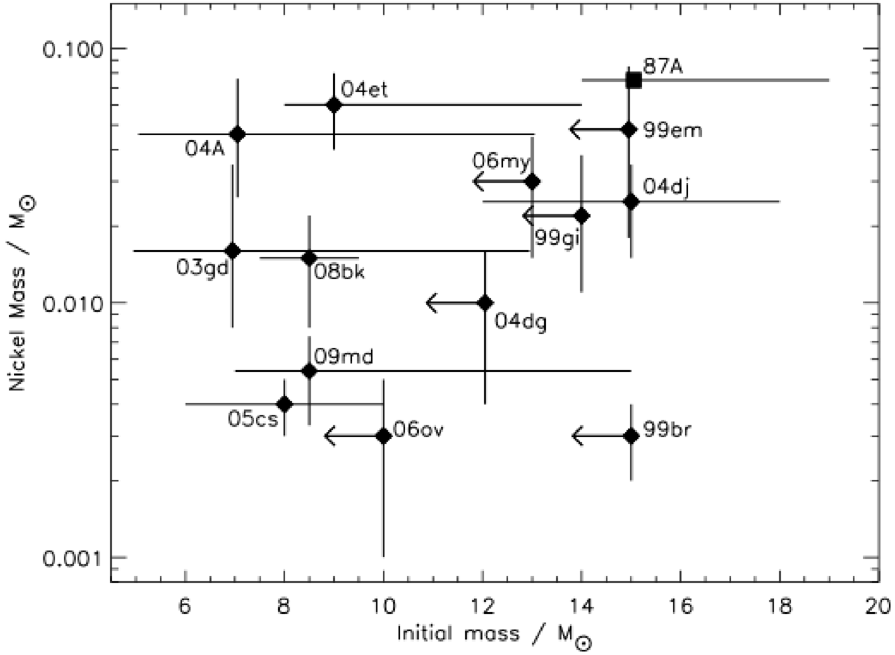
Progenitors from Woosley & Heger (2007)



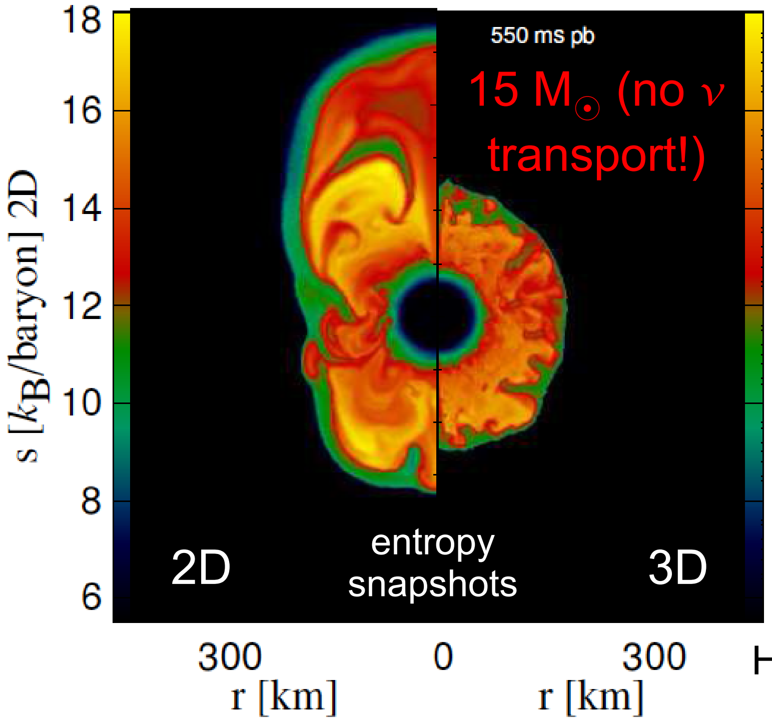
Criticality parameter for neutrino heating

Open Questions

- Explosions still difficult to obtain in 2D especially for some of the *less massive* progenitors!
- Mass ranges for successful/failed explosions compatible with observations?
- Explosion energies to low?
- Do the large-scale sloshing motions that facilitate explosions in 2D survive in 3D?
- Net effect of 3D helpful or even harmful? Opinions differ...



Eldrige & Smartt



Hanke et al. (2012)

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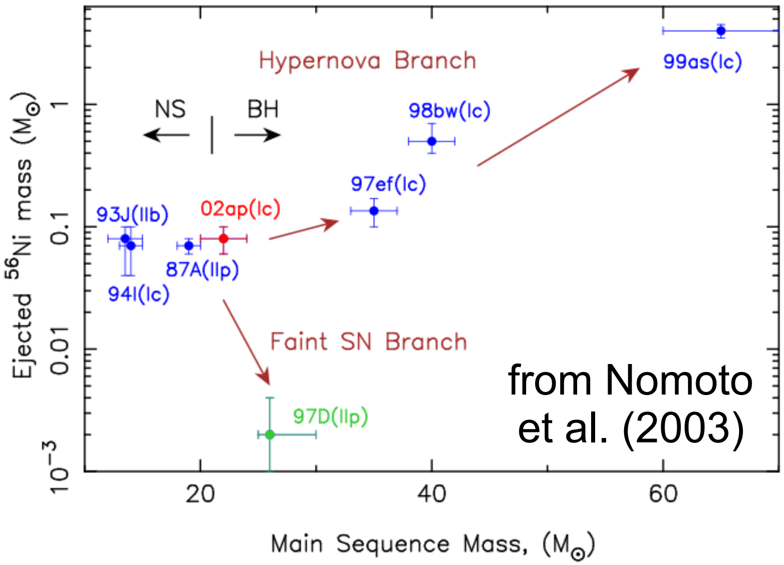
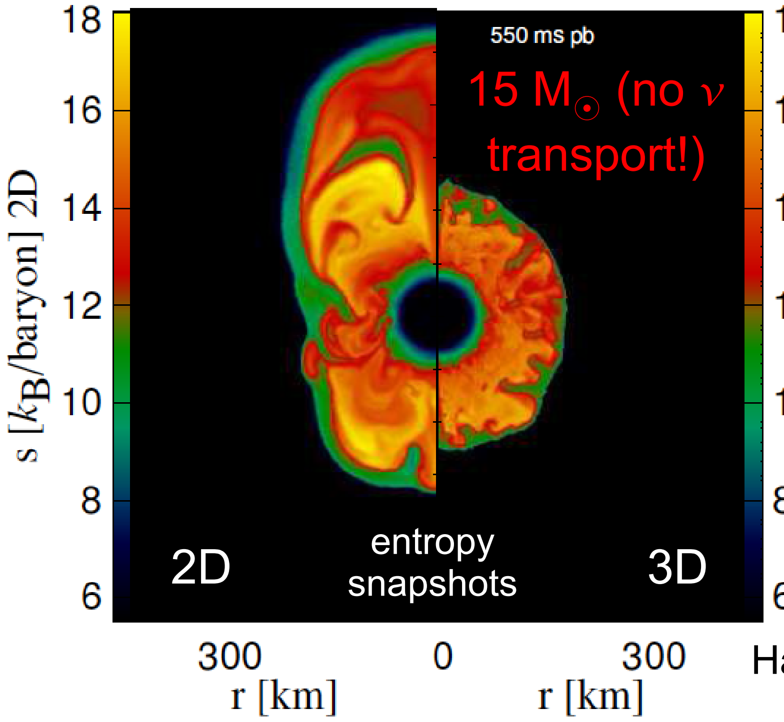
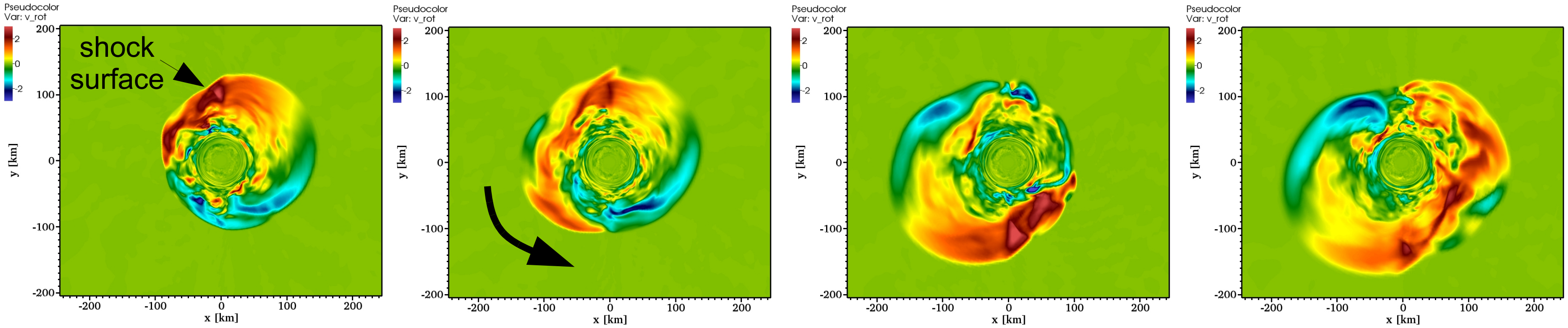


from Nomoto et al. (2003)



Hanke et al. (2012)

Does the SASI Survive in 3D?



velocity around spiral axis

Hanke et al. (2013)

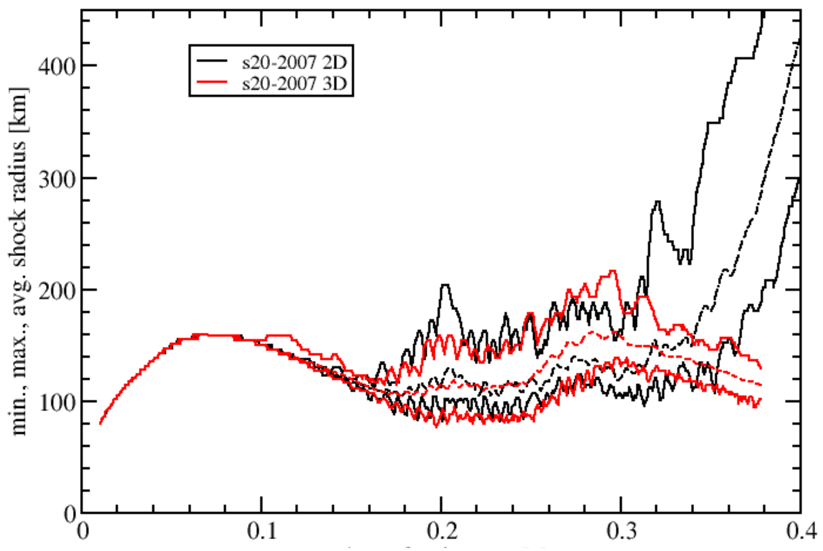
- Strong sloshing & “spiral” mode in two 3D models with full ν transport
- SASI looks even “cleaner” than in 2D
- Recent parametrized 3D models provide further confirmation (Couch & O'Connor 2013)

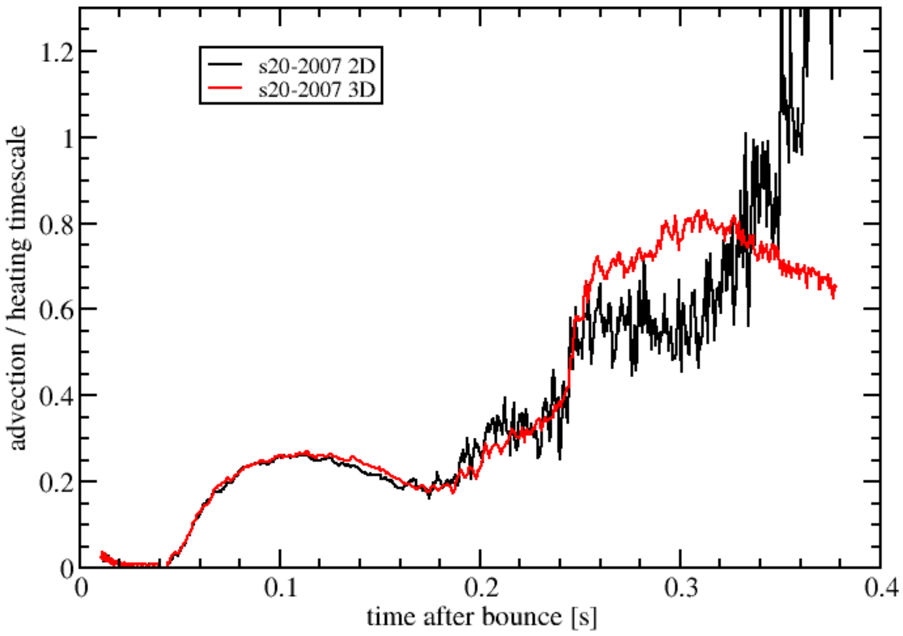
Computed on ~8000 cores of the CURIE computer (Paris)

27 $M_\odot$

Heating Conditions: 2D vs. 3D

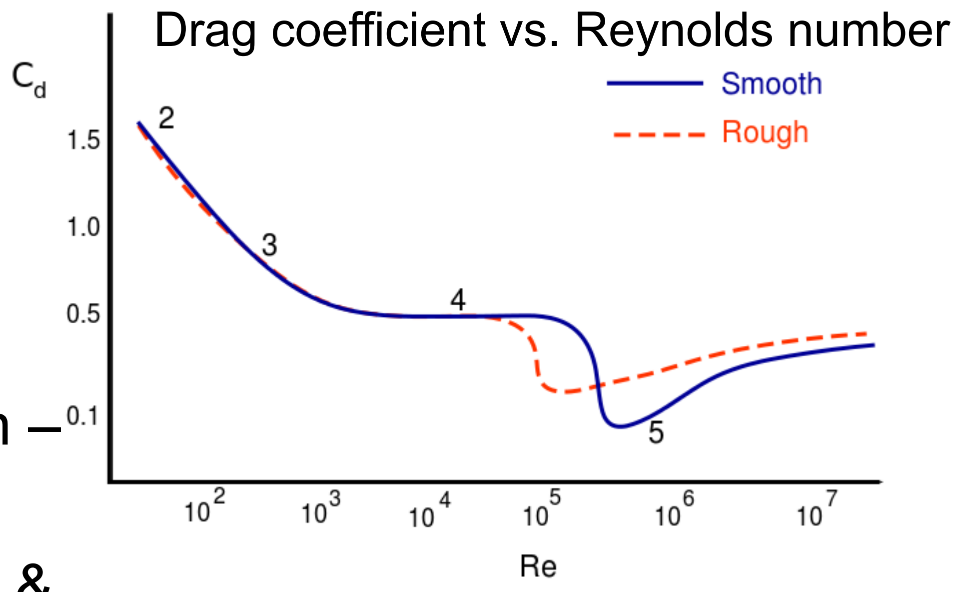
- 3D simulations for 11.2$M_\odot$, 20$M_\odot$ & 27$M_\odot$ with multi-group transport underway
- No explosions so far!
- Consistent picture:
  - Transient phase with better heating conditions than in 2D
  - Failure close to runaway threshold

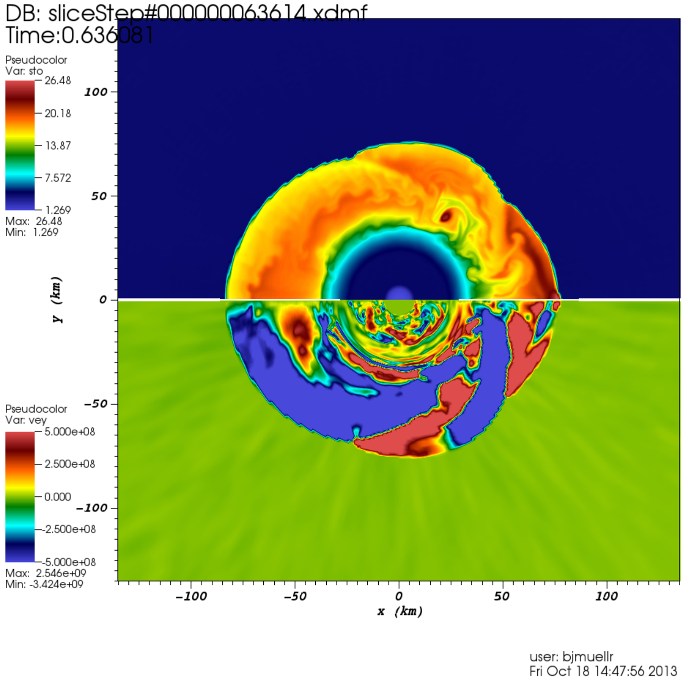




The Conundrum

- Ways to obtain robust bubble expansion in 3D:
  - Reduced drag at high resolution – but beware of analogies!
  - Progenitor asphericities (Couch & Ott 2013)? How large is the effect?
  - Magnetic fields? Weak rotation?
- Neutrino luminosities, mean energy & flux factors accurate within 10%?
  - Rate uncertainties at neutrinospheric densities?
  - Flavor conversion (multi-azimuthal angle instability...)?





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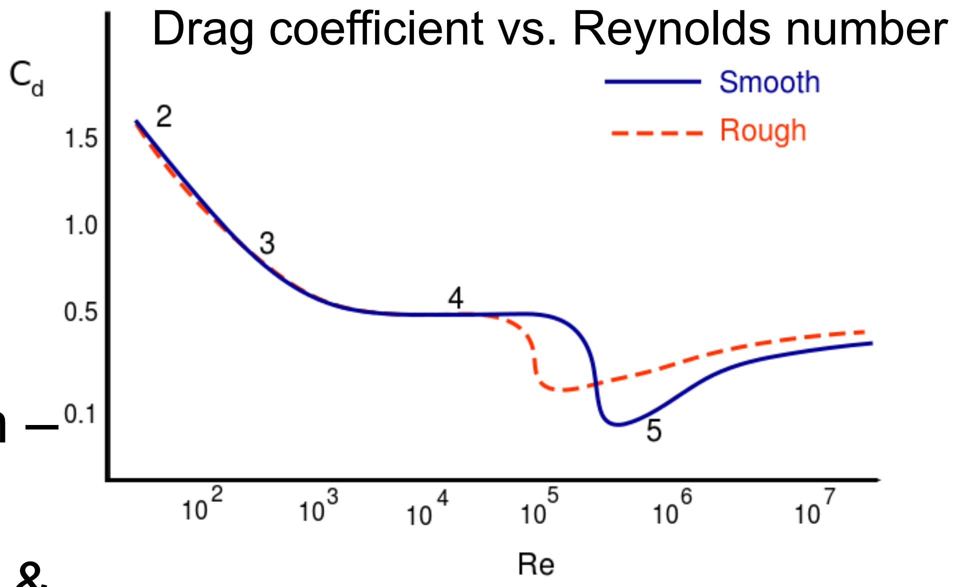
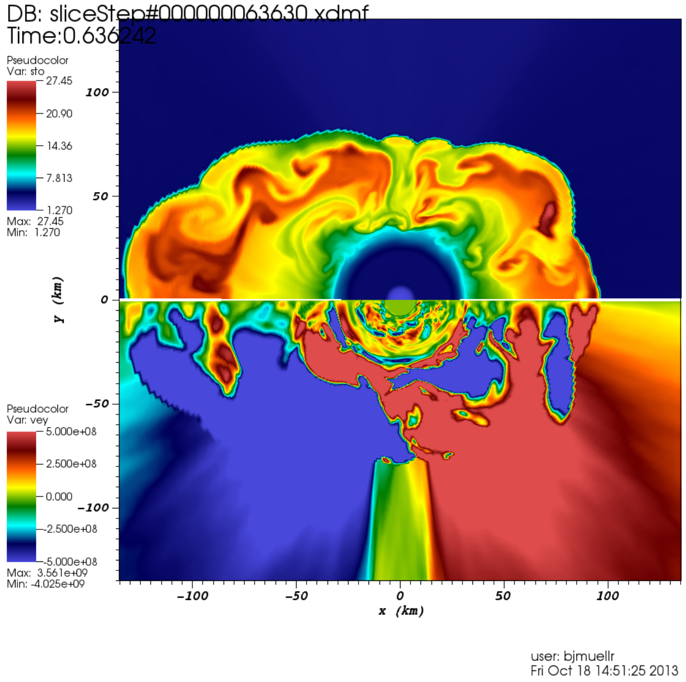

Drag coefficient vs. Reynolds number



Probing the Supernova Core with Neutrinos

What will observations of a Galactic supernova tell us about the supernova engine?

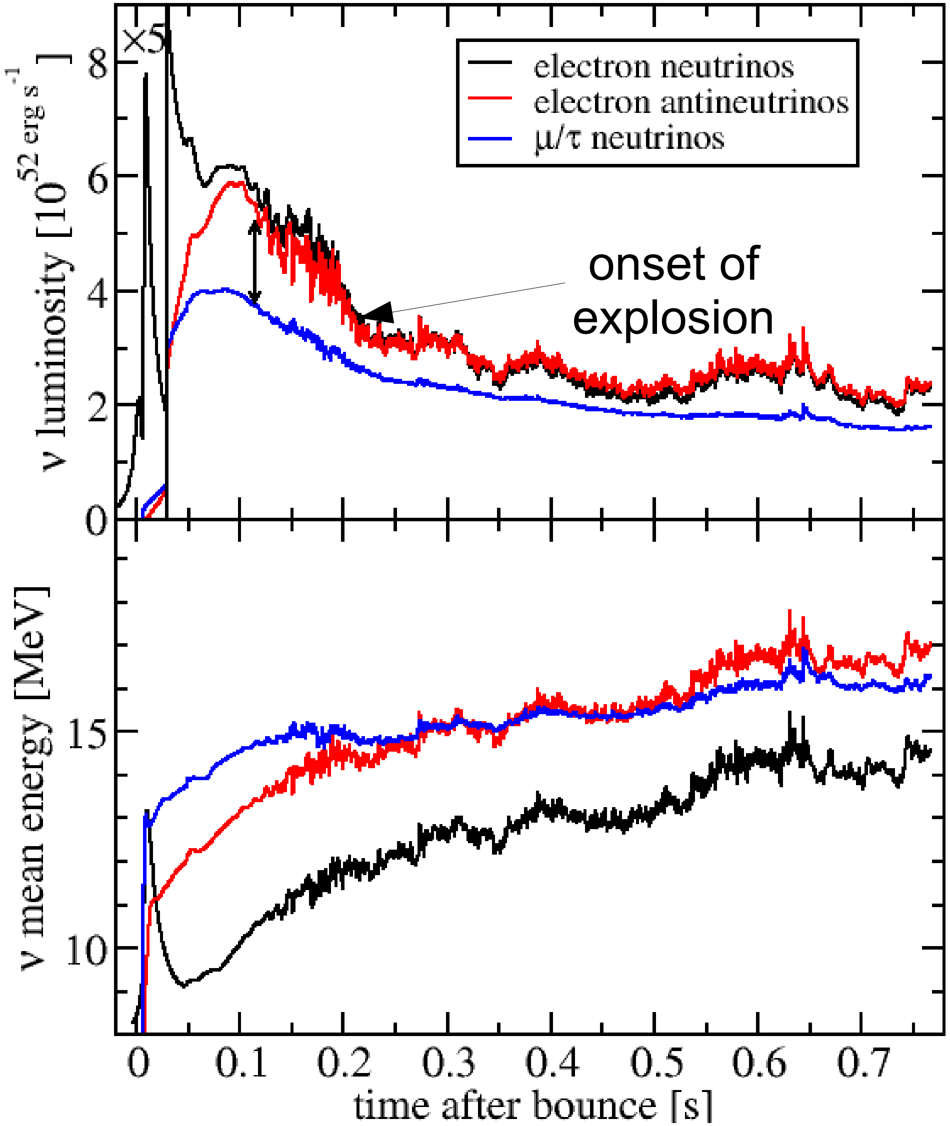
Neutrino Signal – Overview

- 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

    $L_{acc} \sim \alpha G M \dot{M} / R$

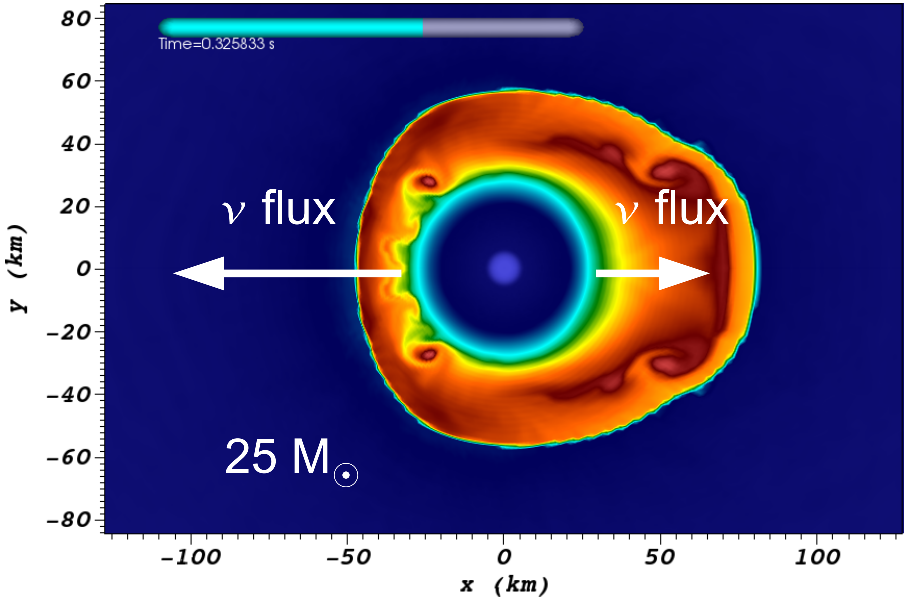
    for ν_e and $\bar{\nu}_e$
  - $\bar{\nu}_e$ mean energy~neutron star mass
- Signs of the explosion?



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

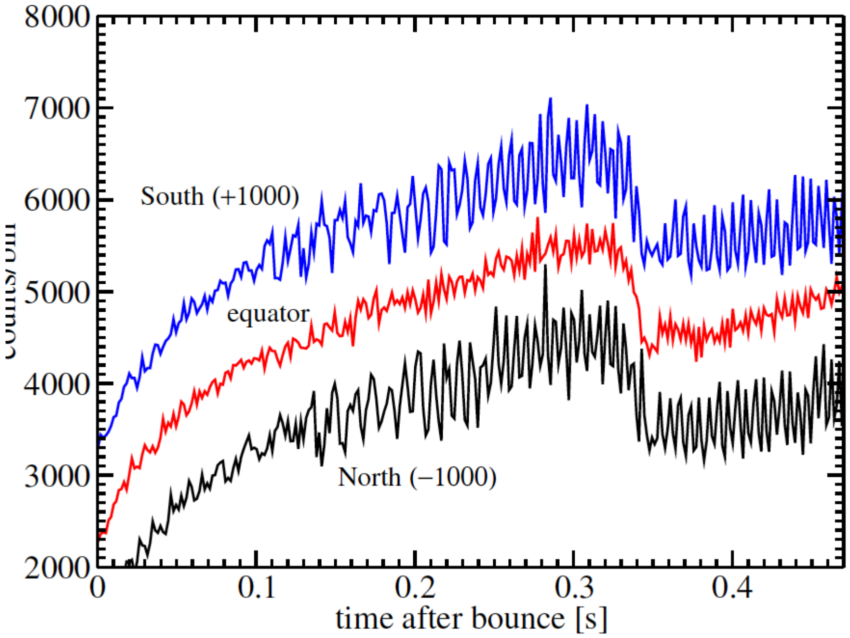
Can we learn more about the dynamics?

- Exploit *temporal variations* of the ν signal as fingerprints of multi-D instabilities!
- Exemplary cases:
  - Supernova models as seen by the IceCube detector at a distance of 10kpc
  - No non-linear flavor conversion & ordinary mass hierarchy assumed



Detecting Shock Oscillations

- Sloshing motions result in quasi-periodic and asymmetric neutrino emission
- Sloshing frequency related to shock and proto-neutron star radius
- Modulations survive in 3D (Tamborra et al. 2013)
- Detectable in IceCube for up to ~10 kpc
- Opportunity to reconstruct shock trajectory!



Non-exploding 25 $M_\odot$ model

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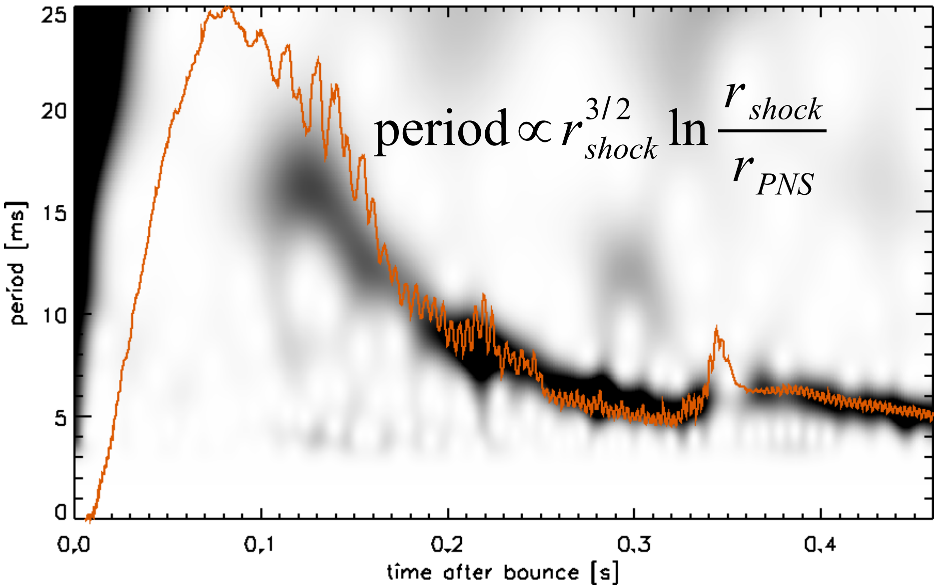
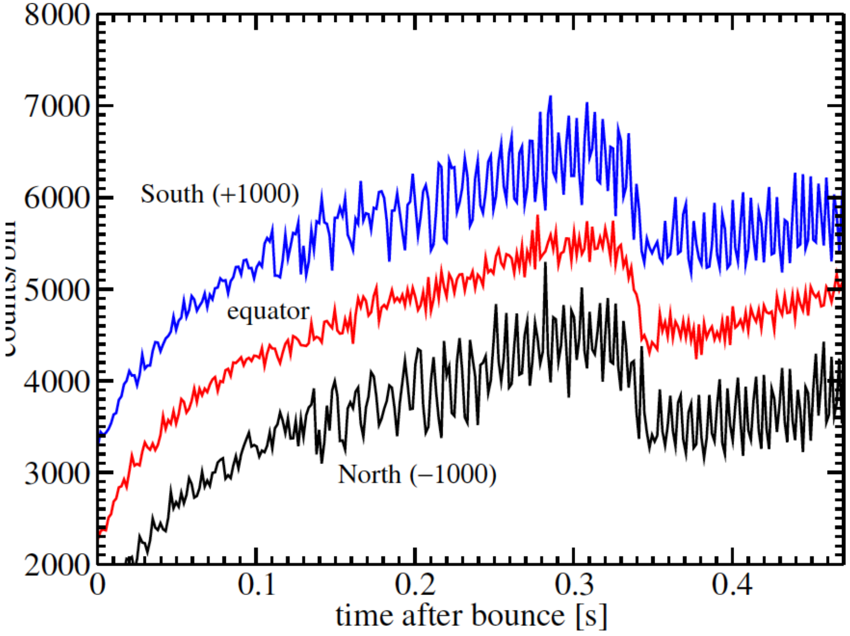
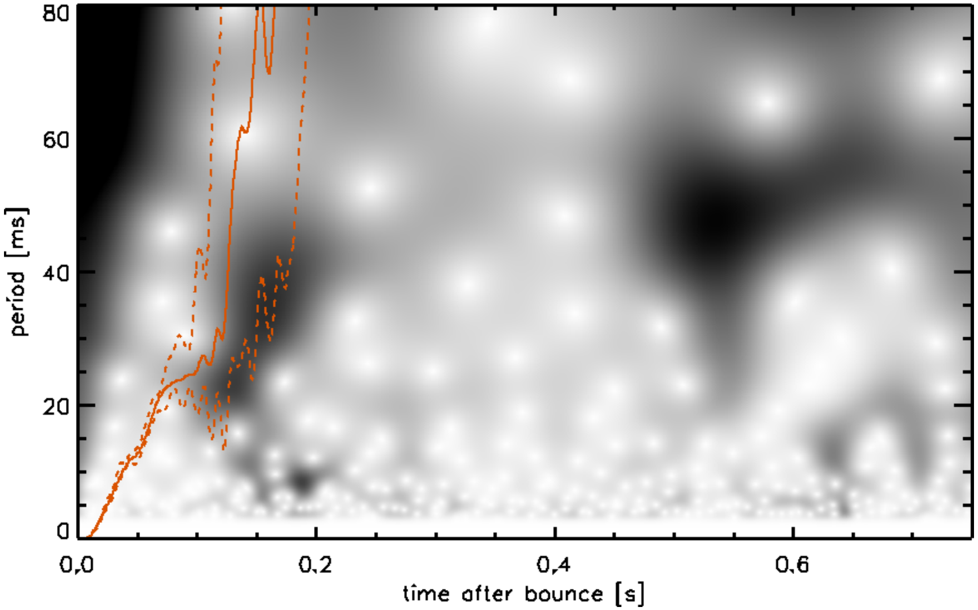
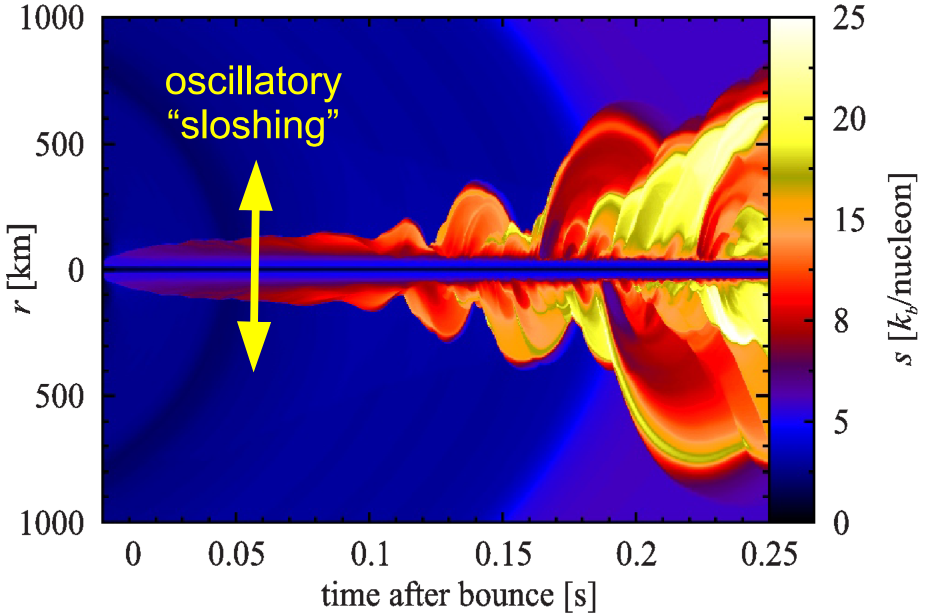




Signatures of the Explosion

- Explosion phase characterized by slowly-changing large-scale anisotropies
- → emission modulation periods >20 Hz
- Weak explosions: possible emission spikes due to “early fallback”

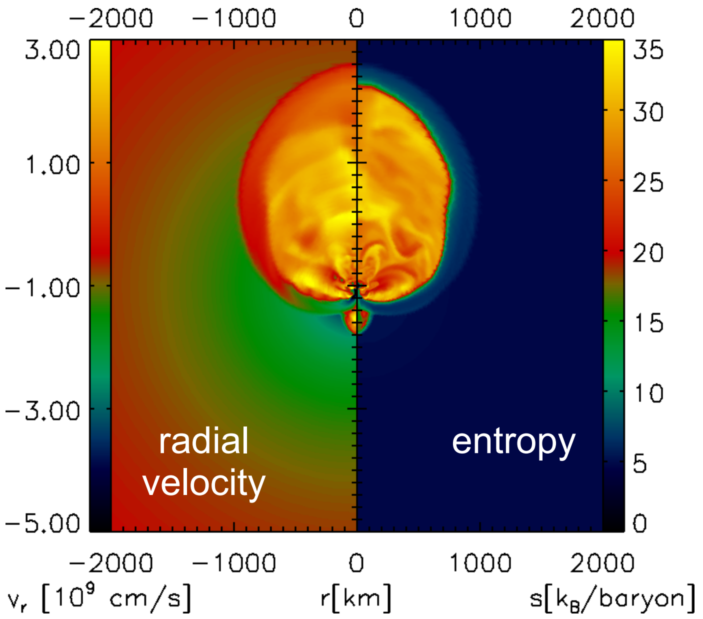


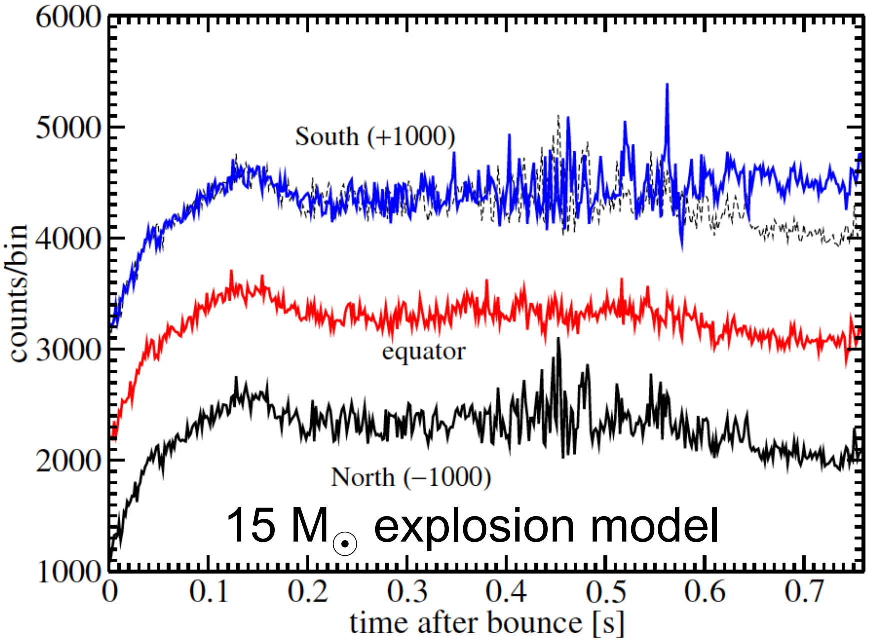


27 $M_\odot$ explosion model

Signatures of the Explosion

- Explosion phase characterized by slowly-changing large-scale anisotropies
- → emission modulation periods >25ms





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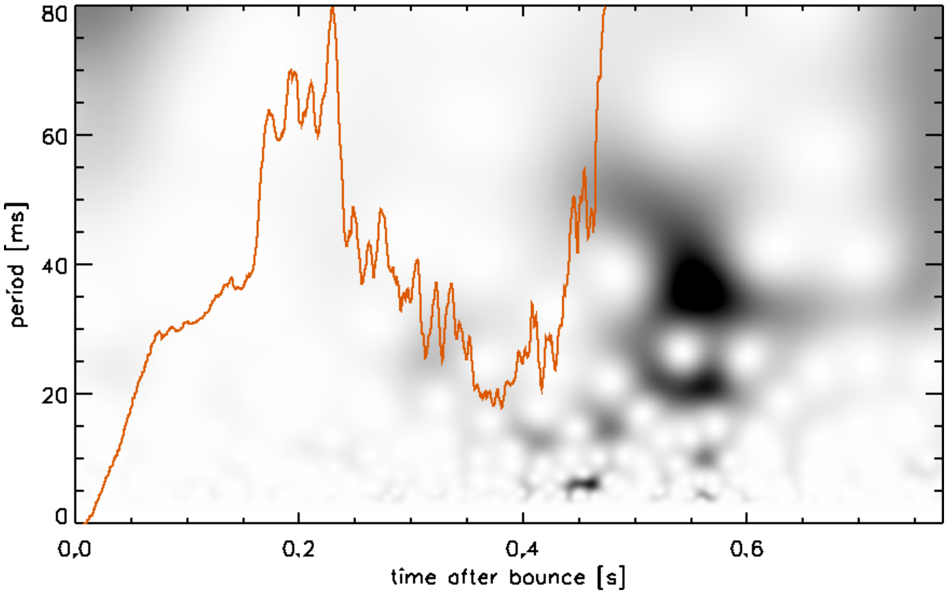
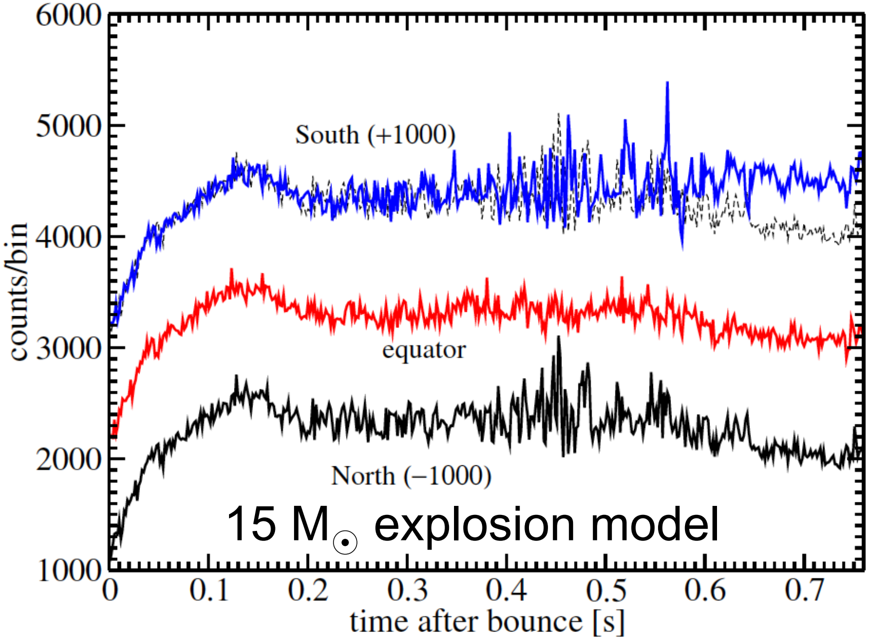
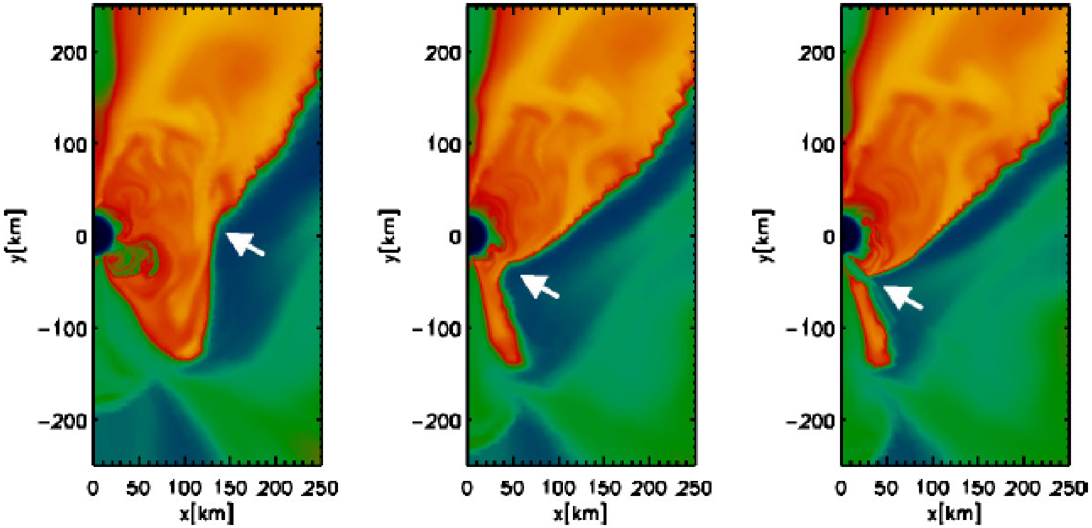
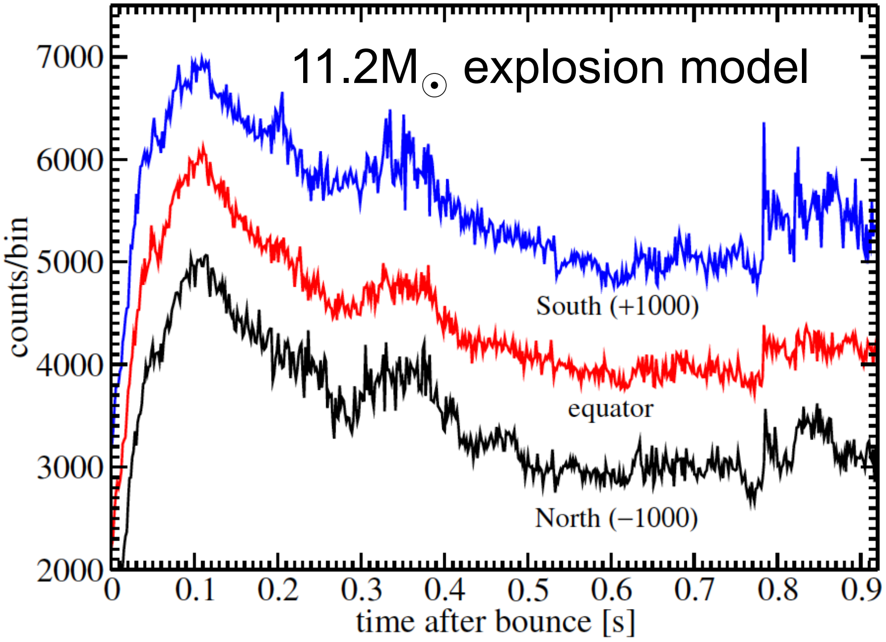




Signatures of the Explosion

- Explosion phase characterized by slowly-changing large-scale anisotropies
- → emission modulation periods >25ms
- Weak explosions: possible emission spikes due to “early fallback”





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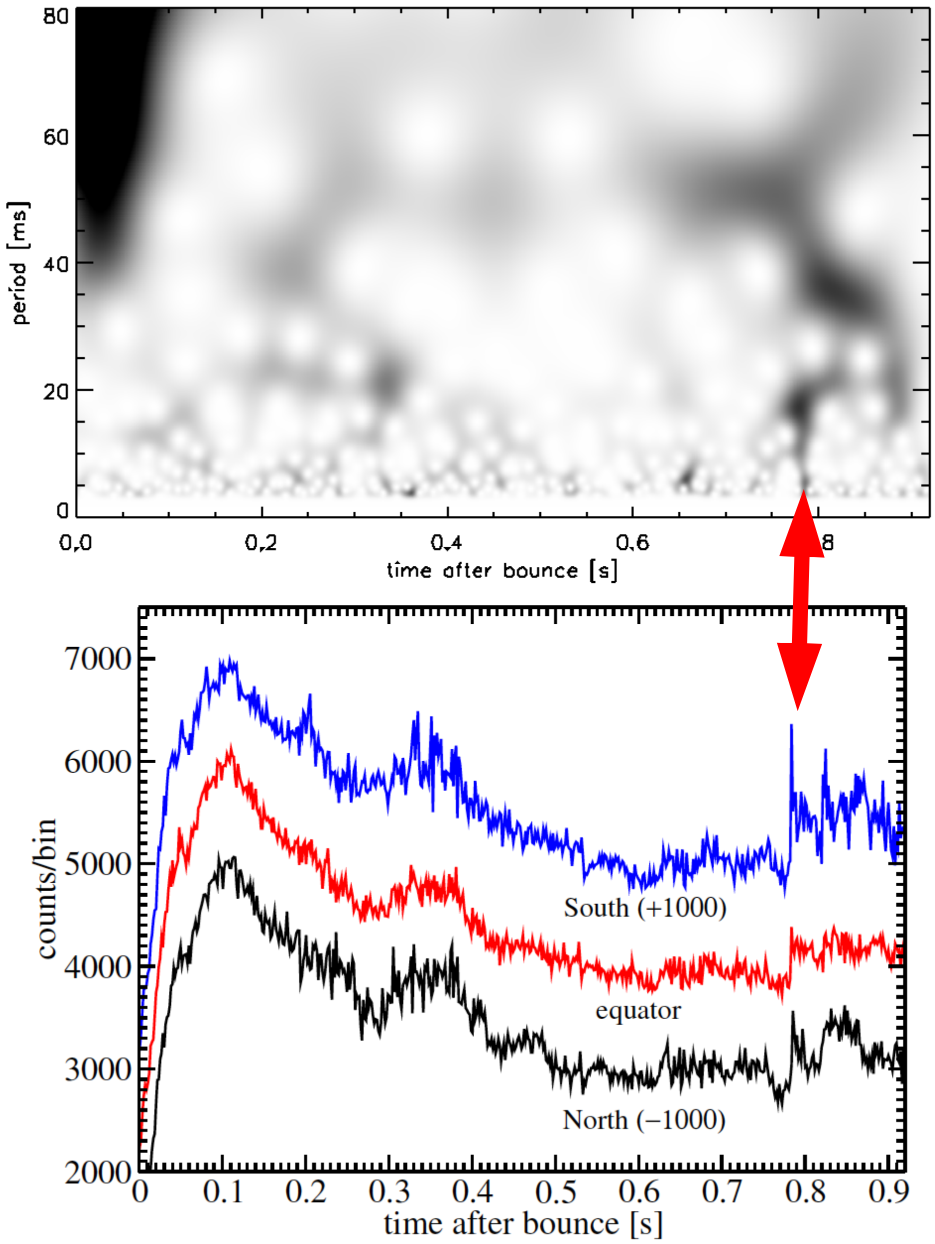

Summary & Outlook

- The neutrino-driven supernova mechanism works for a host progenitor models in 2D (from 8.1$M_\odot$ to 27$M_\odot$) thanks to GR, good ν transport and improved ν rates
- But: first self-consistent 3D models with VERTEX fail to explode, though not by far!
- Conclusions:
  - 3D supernova models may bring up more questions than they answer
  - Cross-comparisons of model needed to ensure the accuracy of current simulations
  - Don't shirk from questioning the input physics (progenitors, high-density physics, neutrino physics) and current simulation methodology
- Direct observations of supernova neutrinos would help a lot to validate or correct multi-D simulations:
  - Time evolution of luminosities & rise of neutrino mean energies reflect the accretion history (→ progenitor structure)
  - SASI activity & shock recession/expansion directly reflected in time-frequency structure of the neutrino signal
  - Emission modulations at frequencies < 40 Hz mark the onset of the explosion
  - Early fallback in weak explosions will produce emission spikes