O-Ne-Mg-Supernovae: Explosion Dynamics and Nucleosynthesis Conditions

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(work in collaboration with H.-Th. Janka, F. Kitaura, R. Hoffman, and R.Buras)

Outline

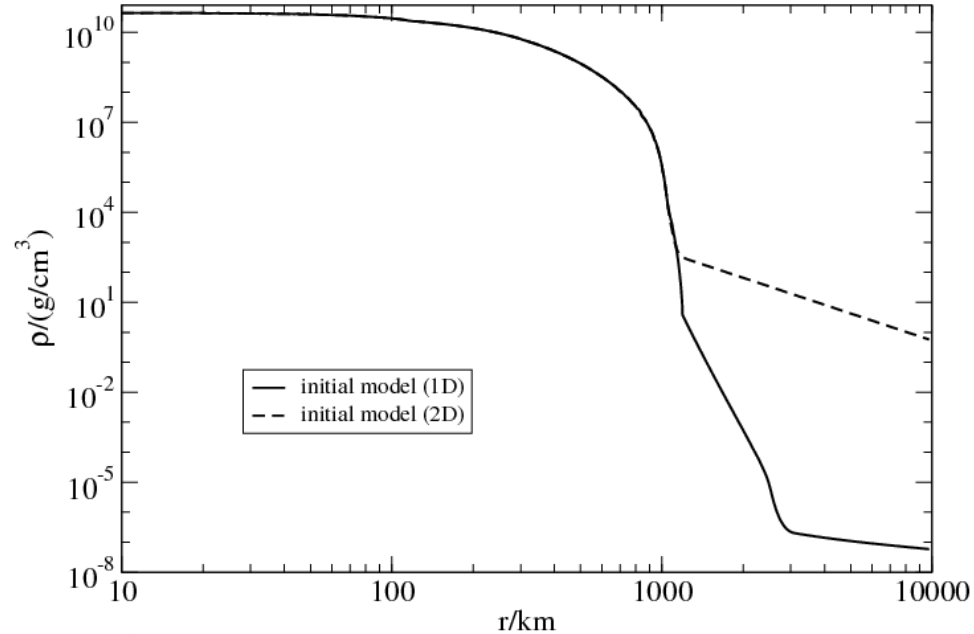
- Progenitor models for O-Ne-Mg supernovae
- Explosion mechanism (1D)
- Nucleosynthesis aspects (1D): r-process?
- Brief remarks on multi-dimensional effects
- Conclusions

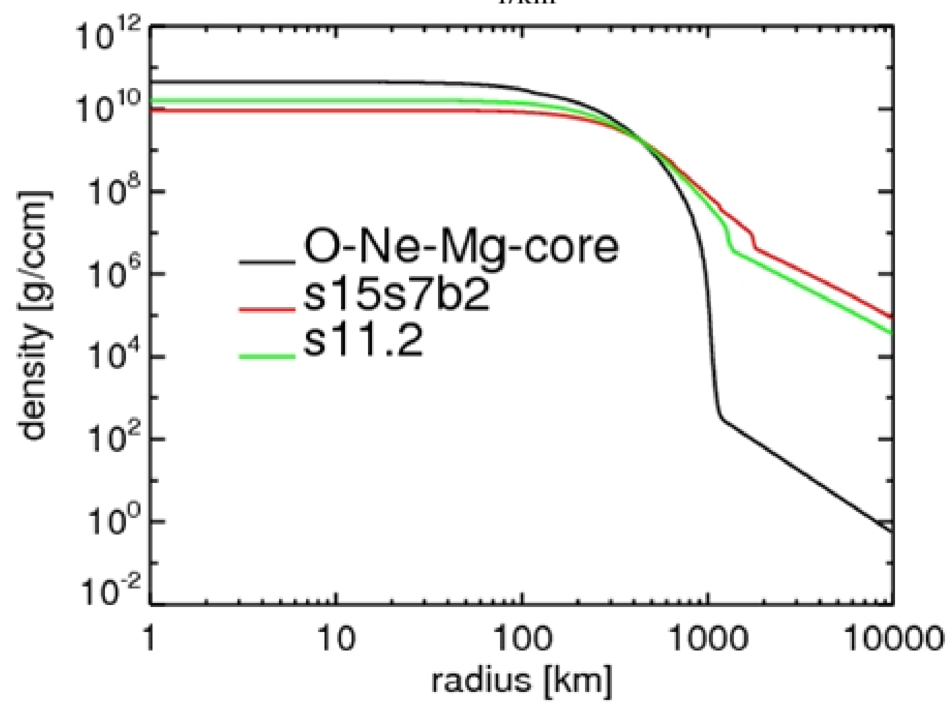
O-Ne-Mg Supernovae: Basic Facts

- O-Ne-Mg core of super-AGB stars (with M_{ZAMS} between $8M_{sun}$ and $10M_{sun}$) may undergo core collapse due to electron captures on ^{20}Ne and ^{24}Mg (i.e. without ever having formed an iron core)
- Possible rate:
  - up to 30% of all SNe (old estimate by Nomoto et al. (1982))
  - more narrow mass range suggested by Poelarends et al. (arXiv:0705.4643)
    - optimistic case: $9M_{sun}$..$9.25M_{sun}$ (<20% of all SNe)
    - best case: $8.75M_{sun}$..$9.M_{sun}$ (<4% of all SNe)

Progenitor Structure

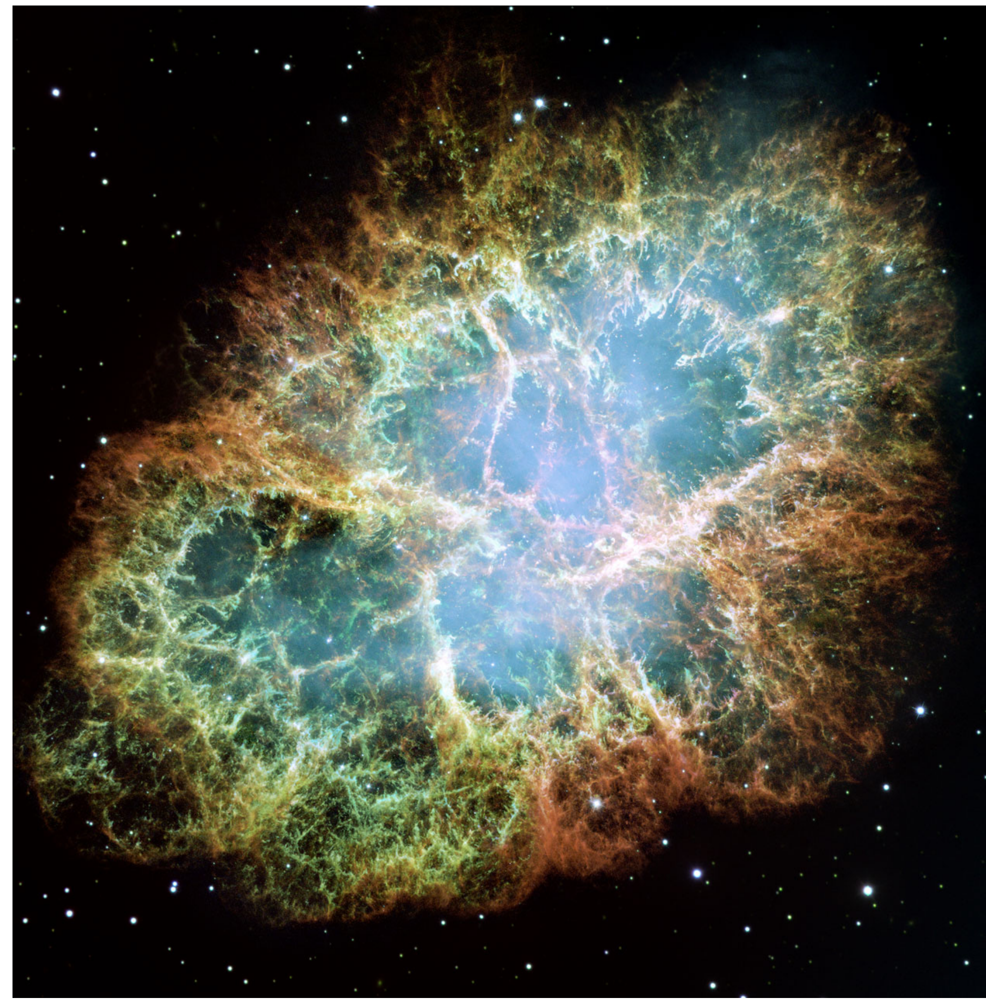
- Currently: only one progenitor model for SN modelling available, see Nomoto et. al (1984,1987), recently supplemented with hydrogen envelope
- Core exhibits steep density gradient at the surface
- mass accretion rate decreases rapidly after core bounce, hence:
  - continuous shock expansion and favourable conditions for explosion
  - growth behaviour of hydrodynamical instabilities different from more massive progenitors





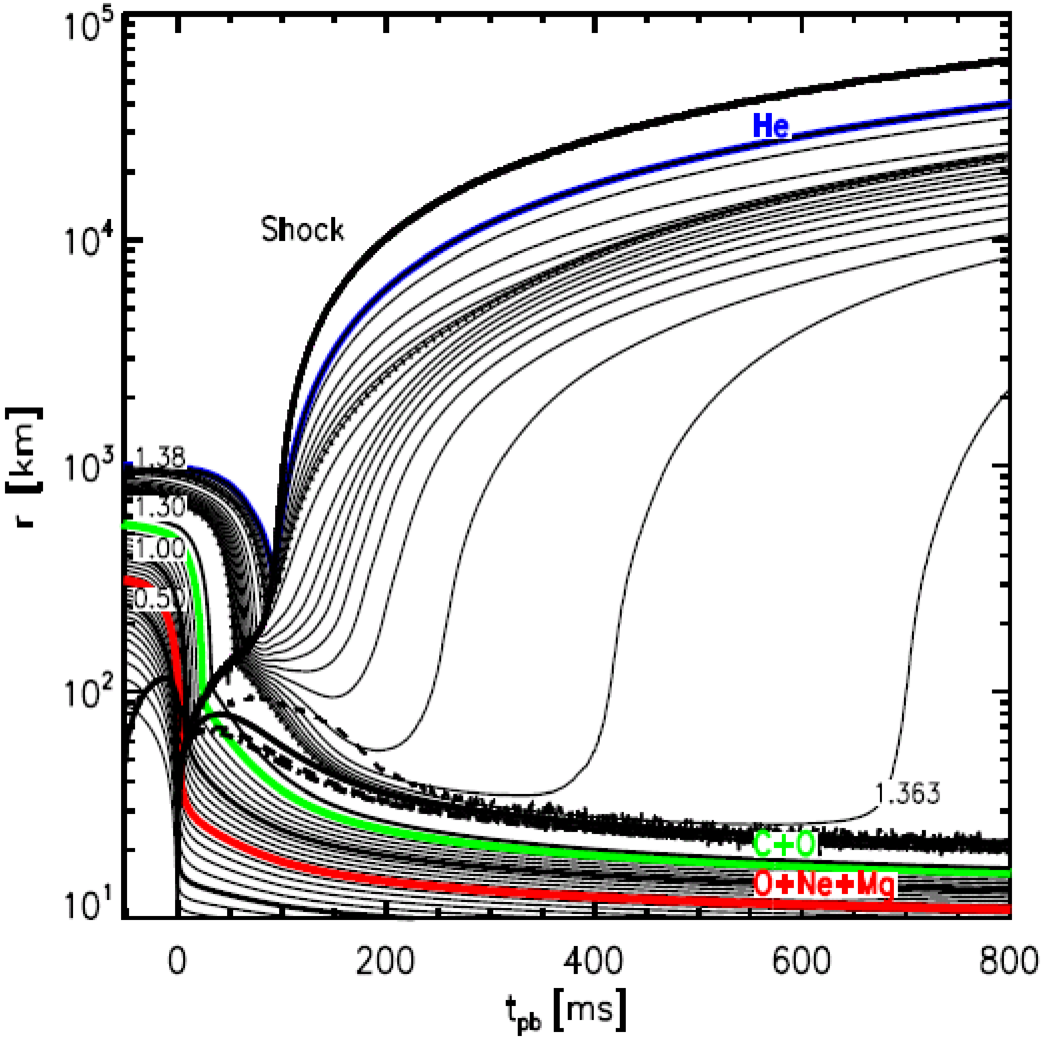
Possible Candidates

- Crab nebula:
  - low kinetic energy of remnant gas (0.1...0.2foe)
  - small Ni and O mass (<0.01 M_{sun})
  - low kick velocity
- Low Ni and O content seems to suggest a low-mass progenitor (Nomoto et al. 1982; Hillebrandt, 1982)
- However, a case can also be made for M_{progen}>9.5M_{sun} (MacAlpine&Satterfield, arxiv:0806.1342)

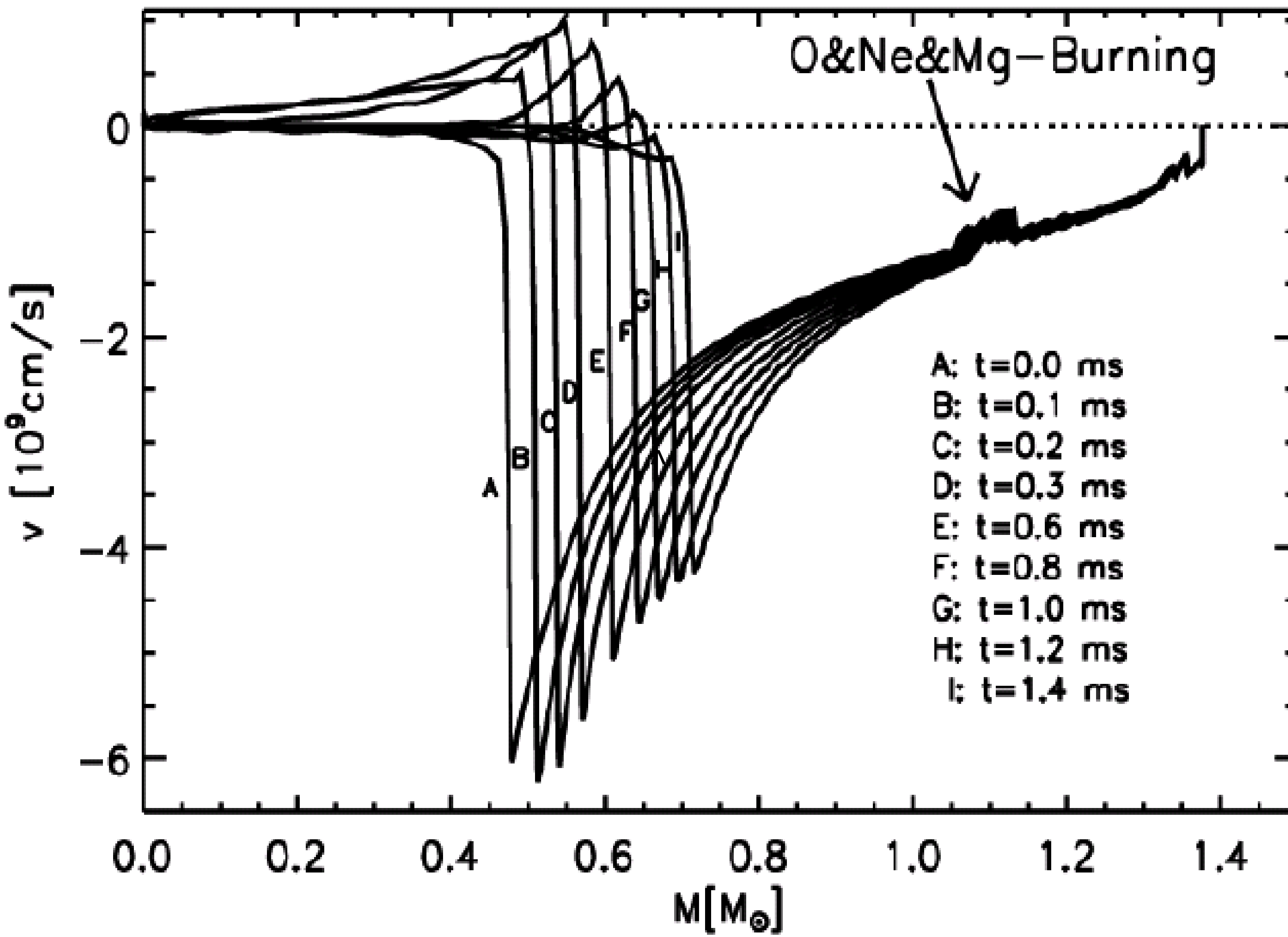


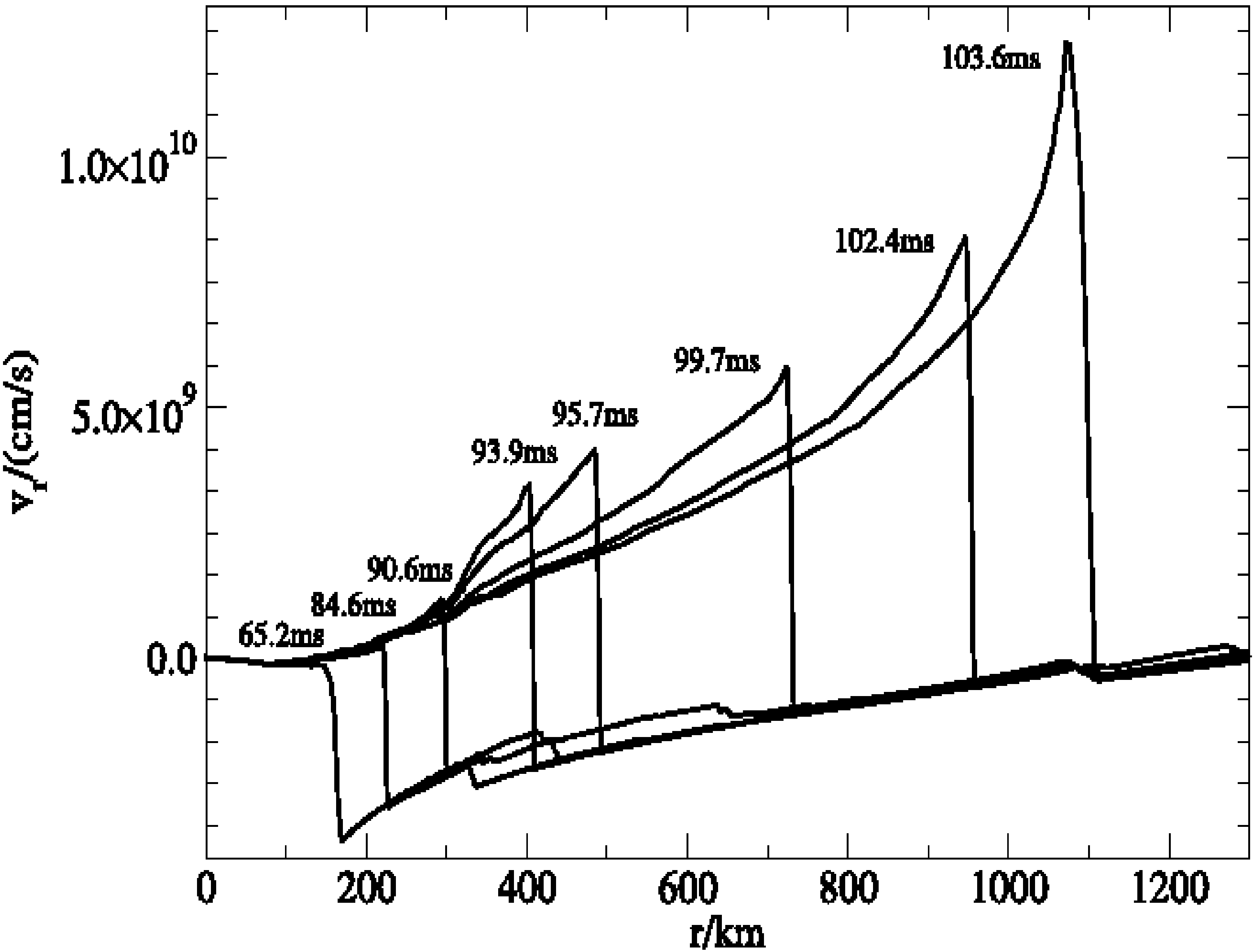
Dynamics of the Explosion

- Post-shock velocities become positive once the mass shells from the edge of the core reach the shock
- A small amount of matter ahead of the shock is unbound directly by PdV work (carrying around $1*10^{48}$erg)
- Ejection of post-shock material by neutrino-driven wind (-> explosion energy of the order of 0.1foe)



(model simulated with Wolff&Hillebrandt EoS) nota bene: no prompt explosion

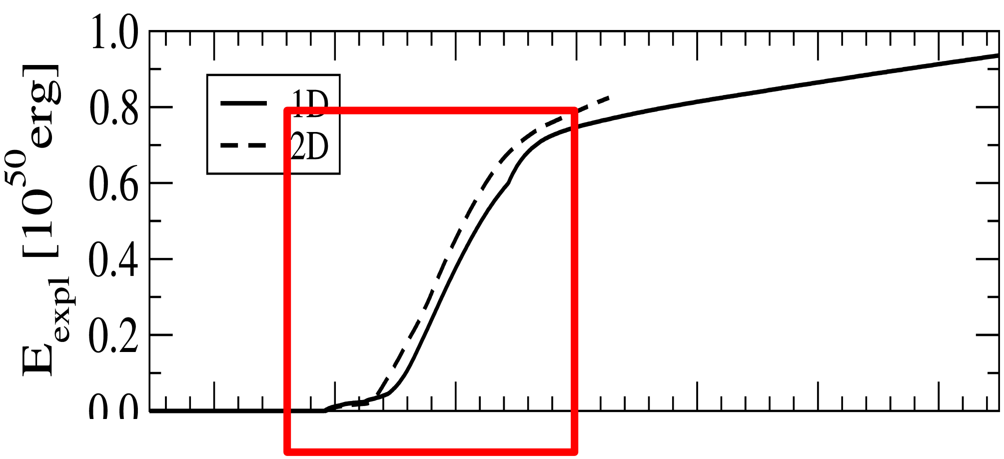




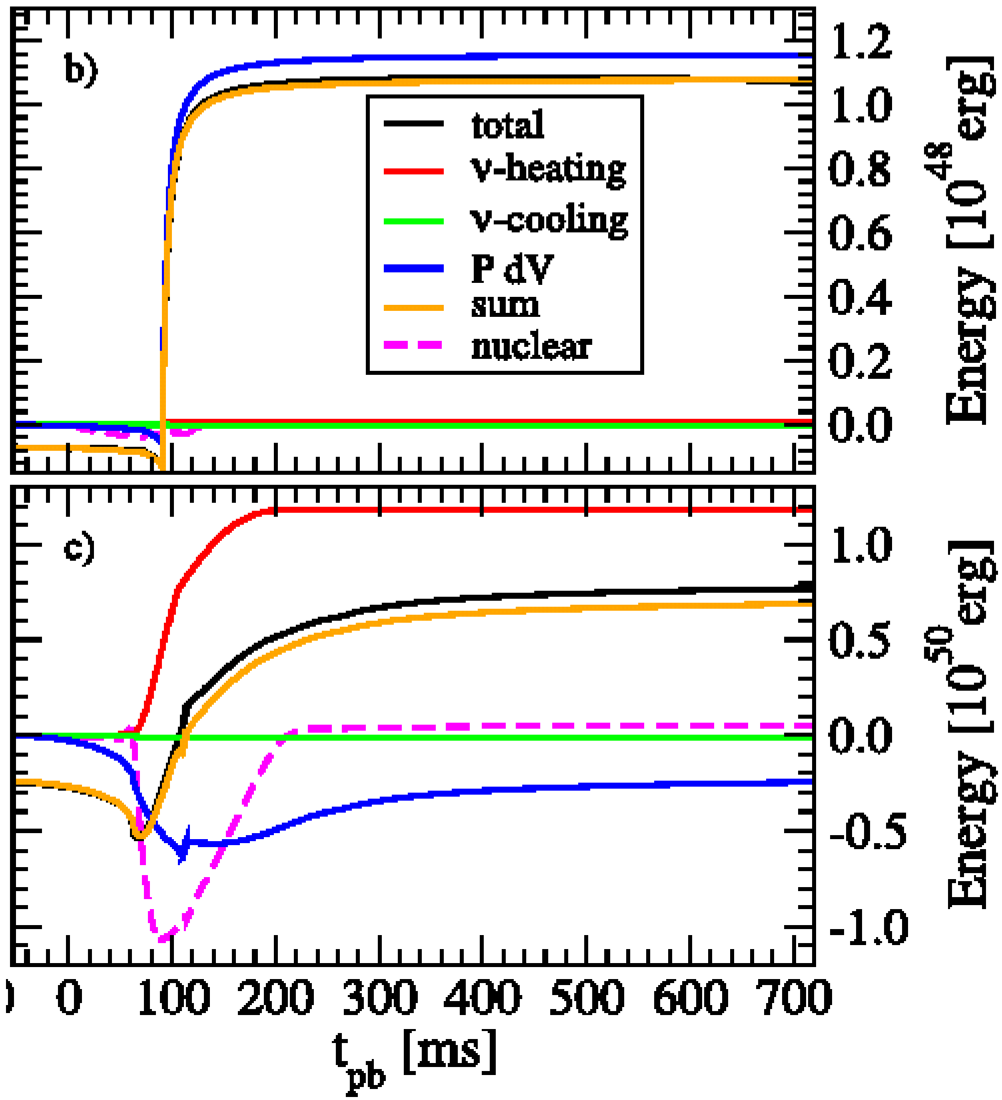
(model with L&S EoS, as on subsequent slides)

Dynamics of the Explosion

- Only a small amount of matter ahead of the shock is unbound directly by PdV work (carrying around $1*10^{48}$erg)
- Shocked layers can reach rather high entropies due to high shock velocity



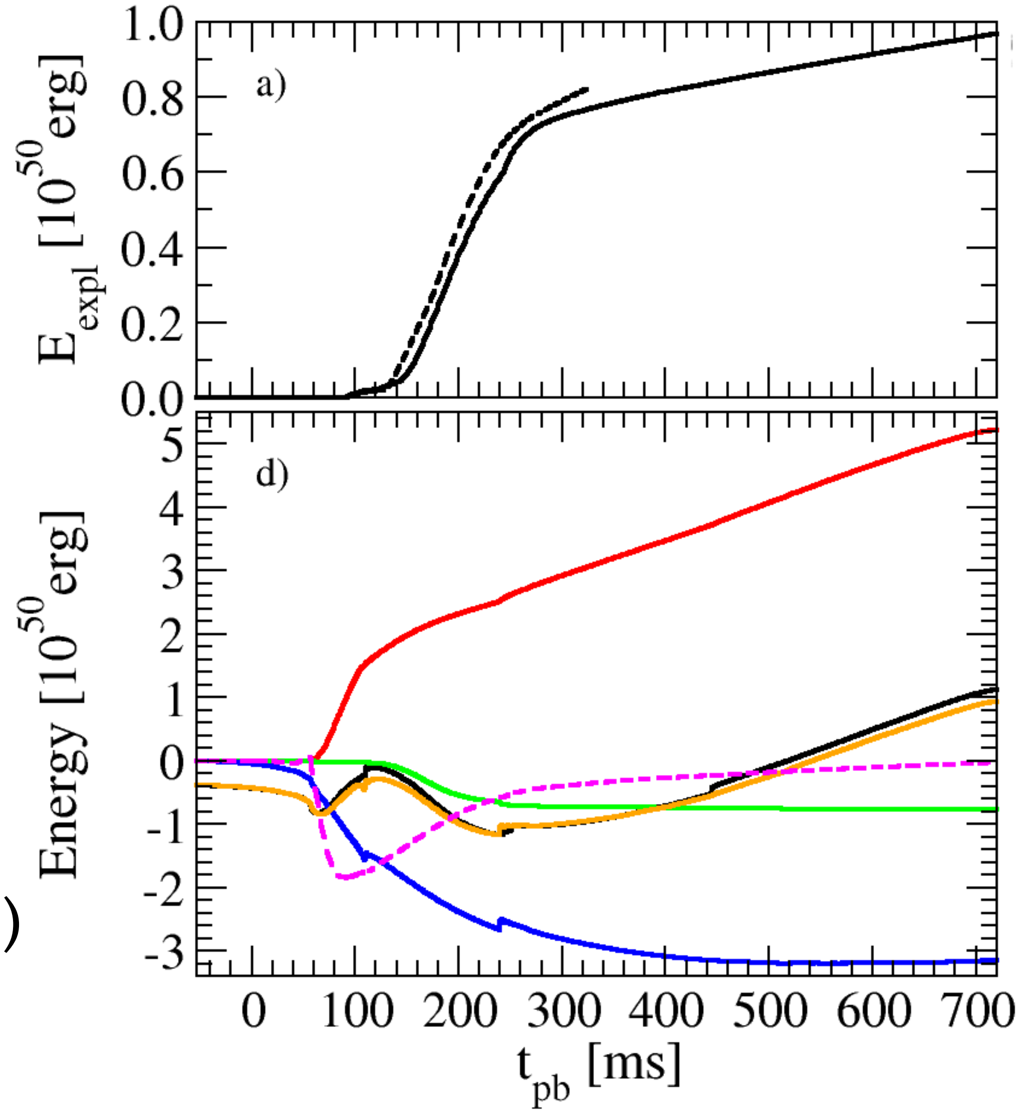
$1.376913M_{sun}$



$1.3675M_{sun}$

Dynamics of the Explosion

- Only a small amount of matter ahead of the shock is unbound directly by PdV work (carrying around $1*10^{48}$erg)
- Shocked layers can reach rather high entropies due to high shock velocity
- Ejection of post-shock material by neutrino-driven wind (at comparatively low entropies of 10...25k_b/baryon)



mass cut :$1.3626M_{sun}$

r-process Conditions?

- Ning, Qian & Meyer (ApJL 2007) suggested the C+O layer around the O-Ne-Mg core as a possible r-process
- Motiviation: favourable thermodynamic conditions due to extremely high shock velocity
- Basic ingredients of their model:
  - Y_e closely below 0.5 (0.49..0.495 leads to a solar r-process pattern: requires the production of ^{13}C in the progenitor
  - high entropies s~150k_b/nucleon
  - short expansion time-scale (time spent between T_9=5 and T_9=5/e) around 1ms
  - analytic model for shock propagation
- Crucial question: Are these conditions really reached?

The Hoped-For Outcome

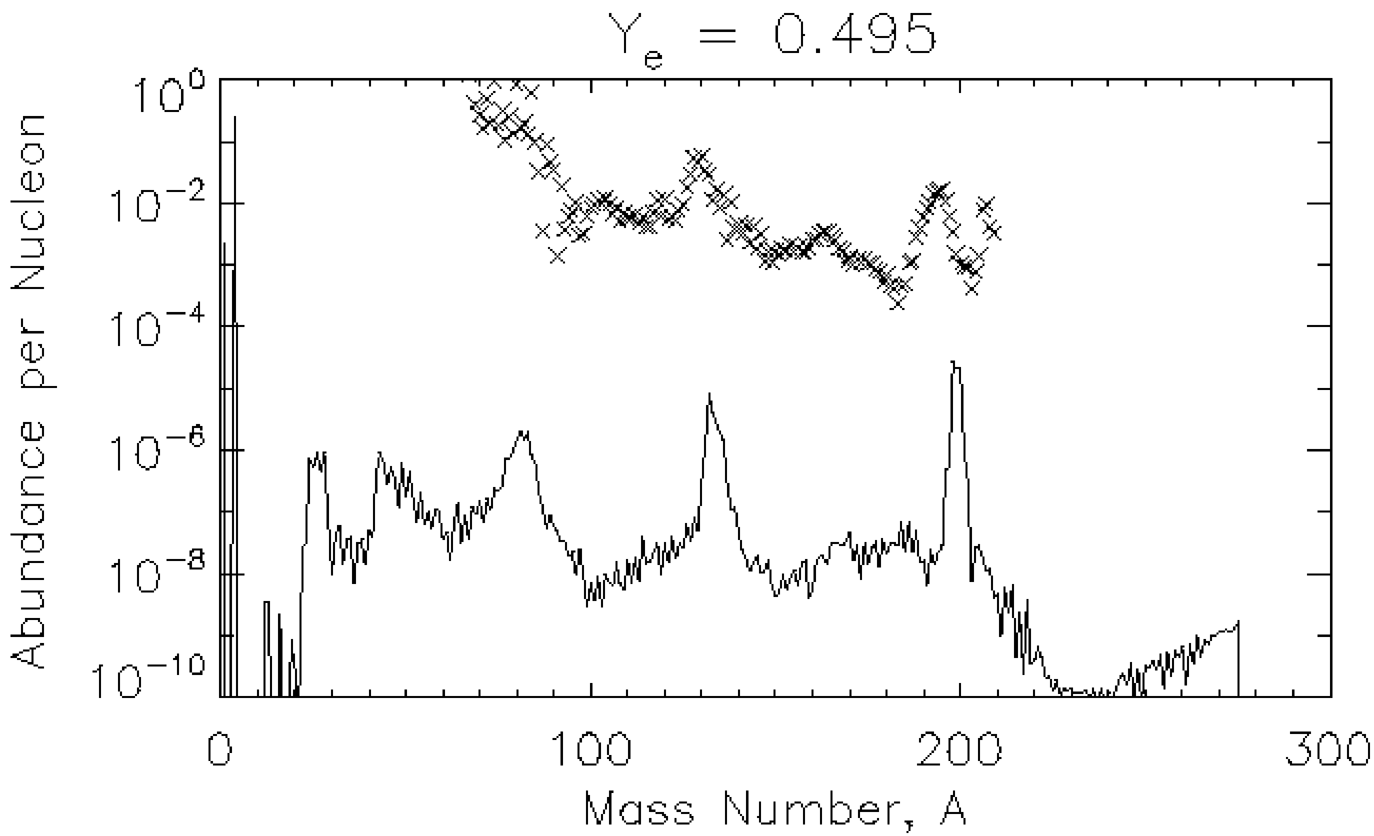
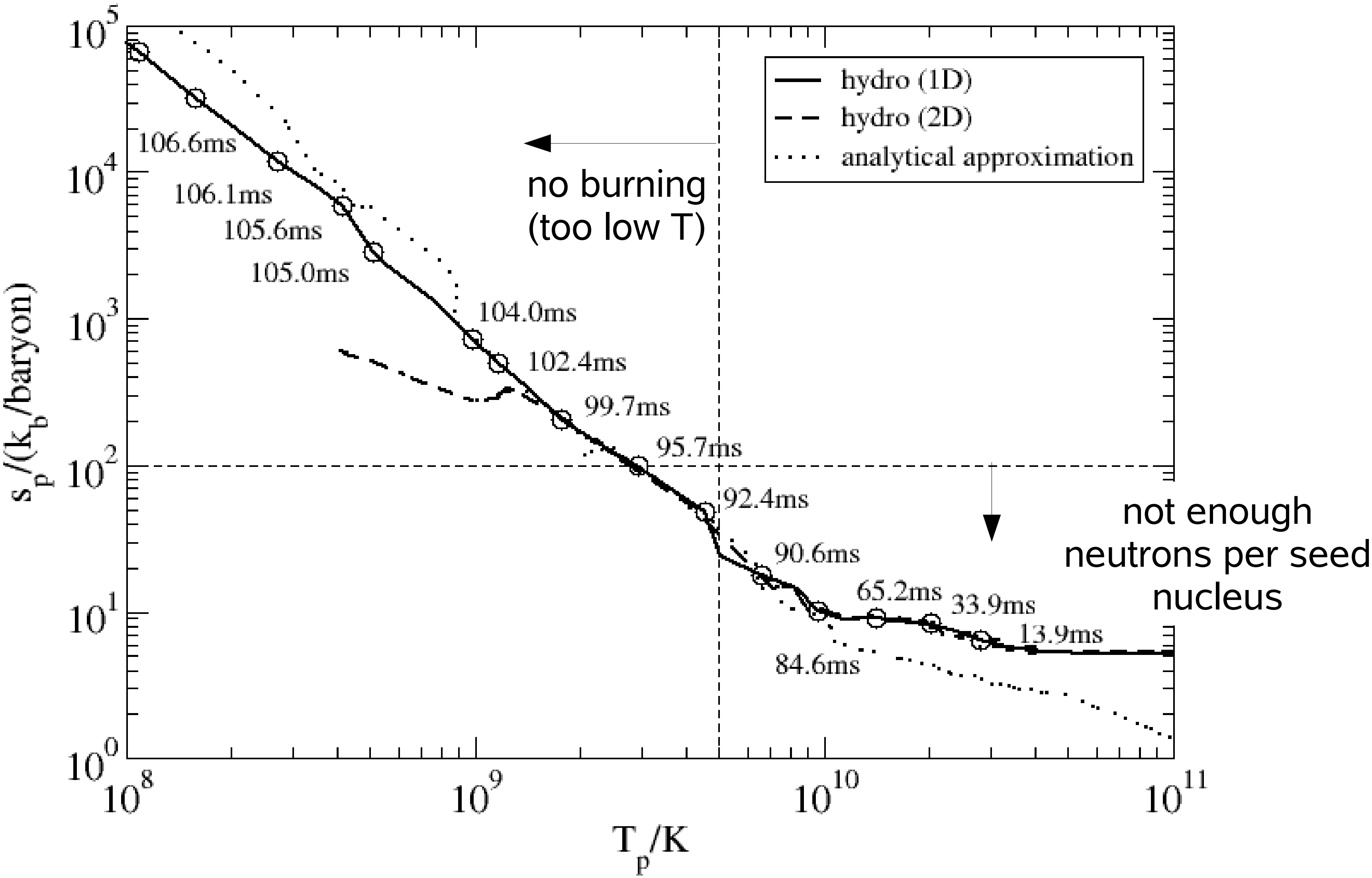


Fig. 1.— Final abundances versus mass number for trajectories 1 (top panel) and 2 (bottom panel). The (arbitrarily scaled) solar r-process abundances (Kappeler et al. 1989) are shown as $\times$'s for comparison. The final mass fractions resulting from both trajectories are $\approx$ 98% α-particles and $\approx$ 2% heavy nuclei.

Temperature, Entropy & Expansion Time Scale in Detailed Models



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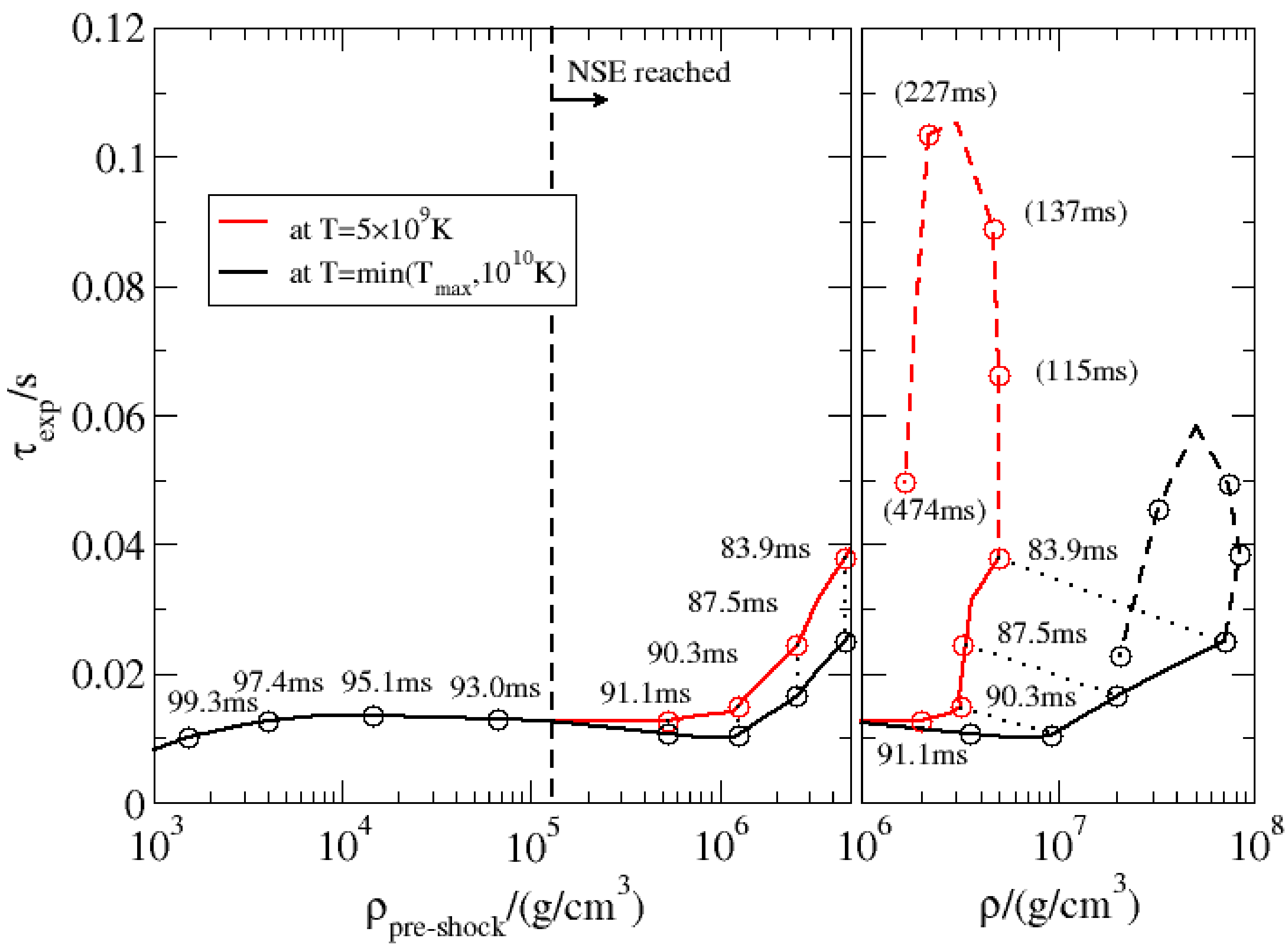
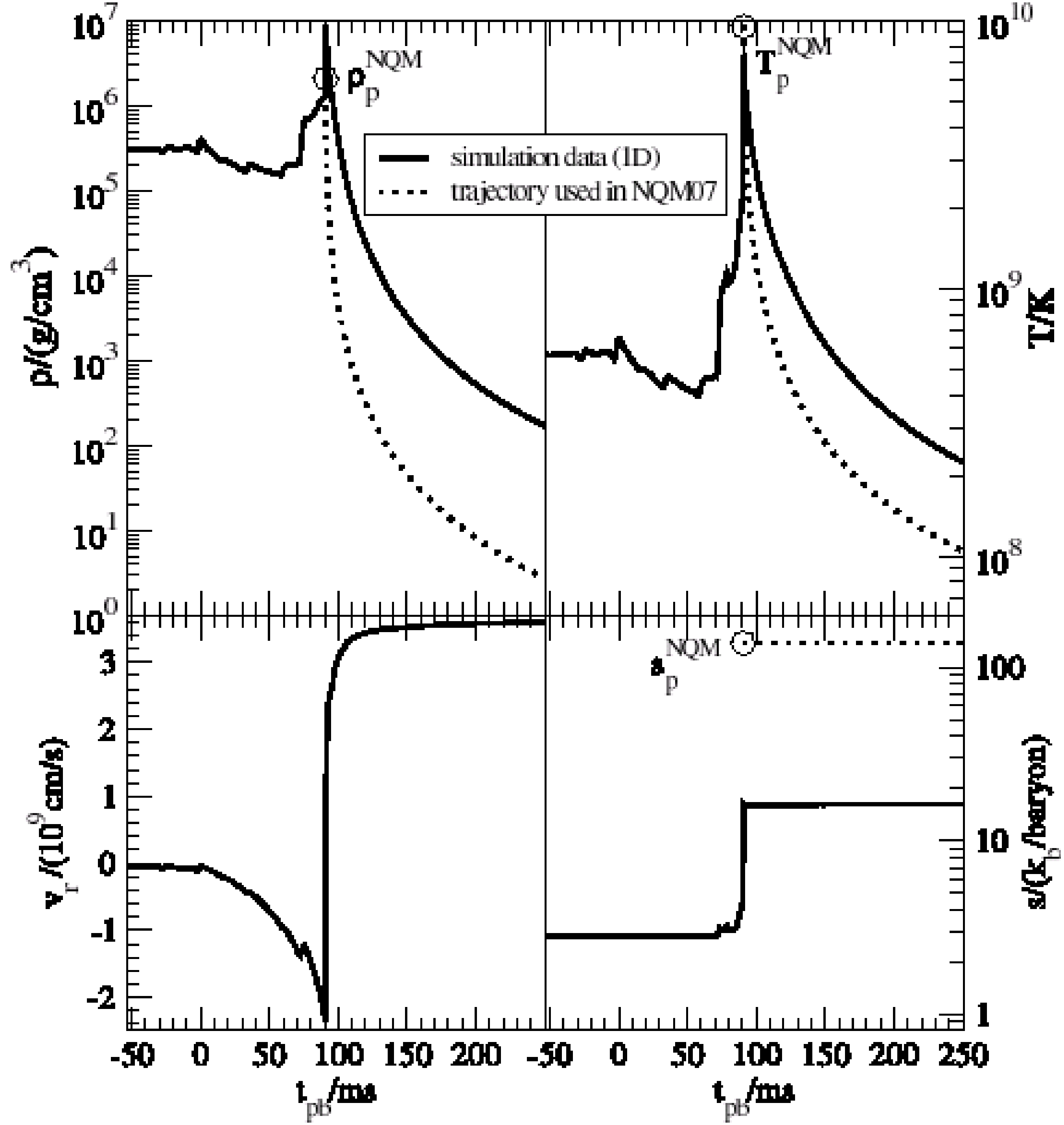
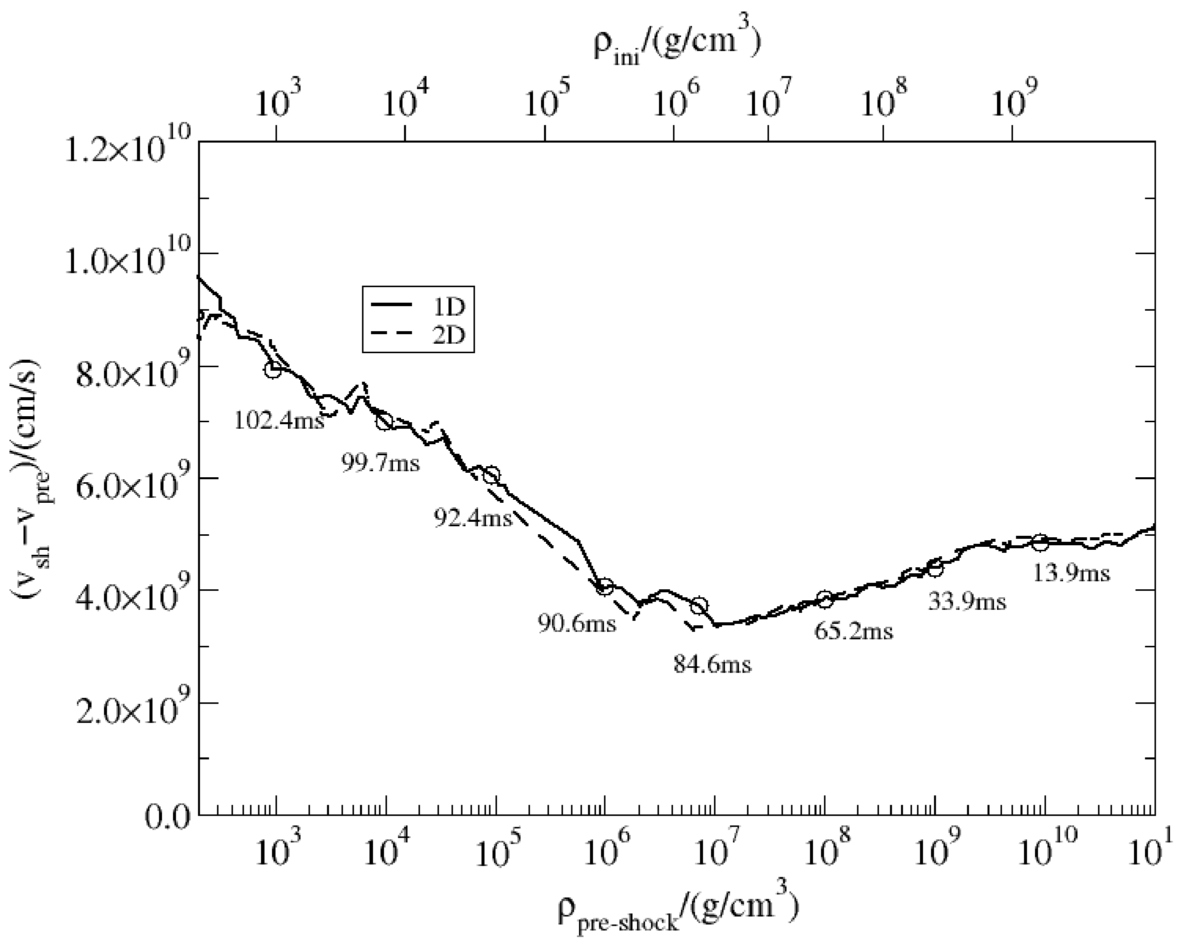




simulation data (1D)
trajectory used in NQM07
ρ/(g/cm^3)
T/K
v_r /(10^9 cm/s)
s/(k_b /baryon)
t_pb/ms

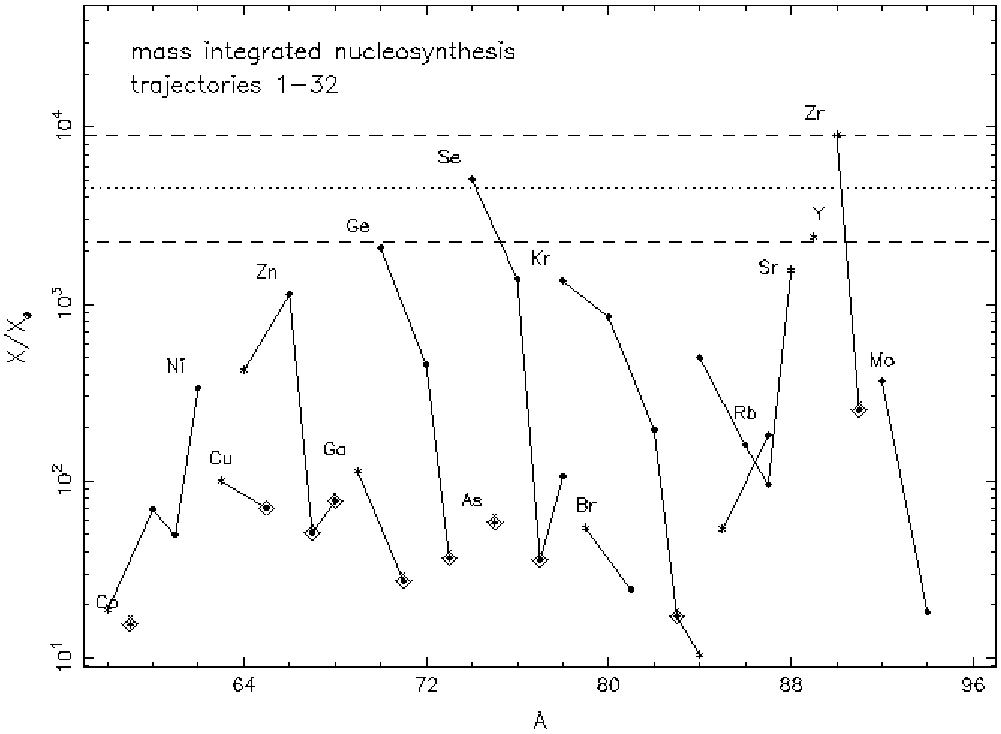
Why the Idea Fails

- Shock velocity overestimated by a factor of 4-5 in analytic model ($1.5*10^{10}$ cm/s instead of $<4*10^{10}$cm/s for a pre-shock density of around 10^6g/cm^3)
- As $s_{final} \sim (v_{sh} - v_{pre\text{-}shock})^{3/2}$ the entropies in the analytic model are grossly overestimated



Detailed Nucleosynthesis Calculations

- no r-process from high-entropy material (in fact, no significant nuclear processing at all)
- however: p-process occurs
- massive production of N=50 closed neutron shell nuclei (^{88}Sr, ^{89}Y, ^{90}Zr) in material with low Y_e (<0.47)

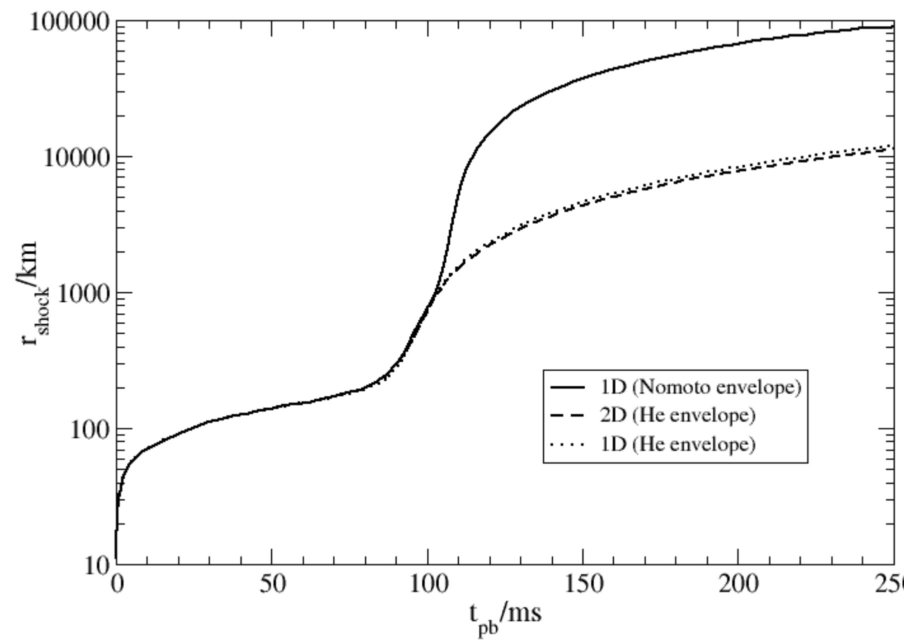


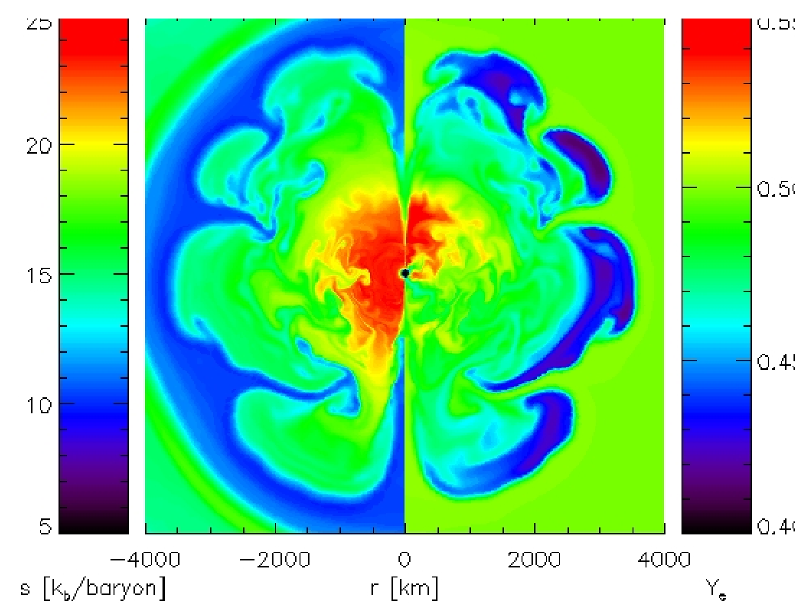
Problems with Chemo-Galactic Evolution

- Assuming 10% of all SNe to originate from O-Ne-Mg core collapse events, an upper limit on the allowed production factor can be established
- If $5.5*10^{-3}M_{sun}$ with $Y_e<0.47$ and moderate entropies (~$20k_b$/nucleon), the abundances of ^{88}Sr, ^{89}Y, ^{90}Zr would be overestimated by a factor of 10-50.
- Possible explanations for this discrepancy:
  - Nuclear physics: unlikely, reaction flow near the valley of the stability
  - Supernova model: not impossible, lowest value of Ye would only have to changed by about 0.01
  - Progenitor model: possibly, many difficulties (mass loss, dredge-up, thermal pulses)

Role of Multi-Dimensional Instabilities

- Explosion develops already at 100ms post-bounce
- Hence: SASI growth not fast enough to be of importance
- hot-bubble convection sets in shortly after the onset of the explosion and increases the explosion energy slightly.
- Significant impact of mixing on the composition of the ejecta!





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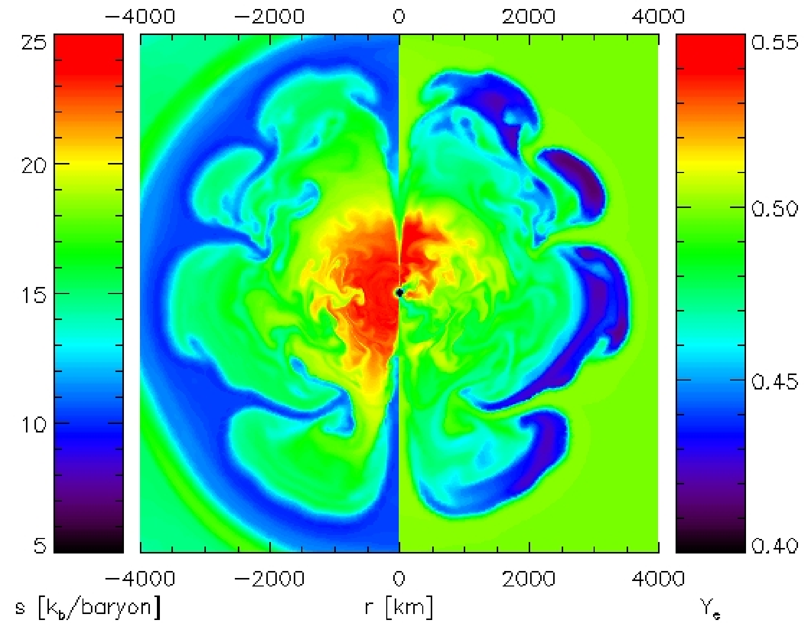

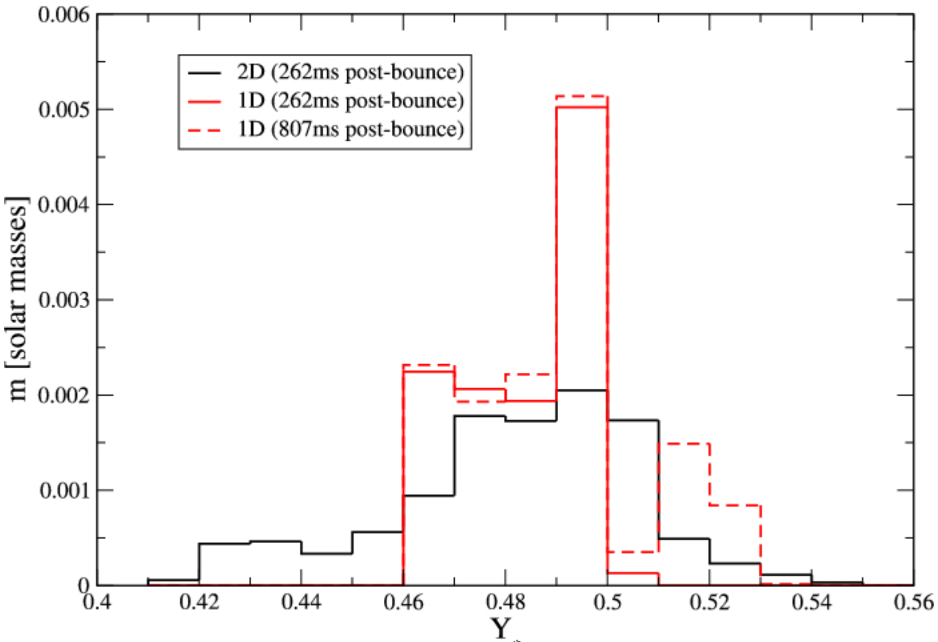

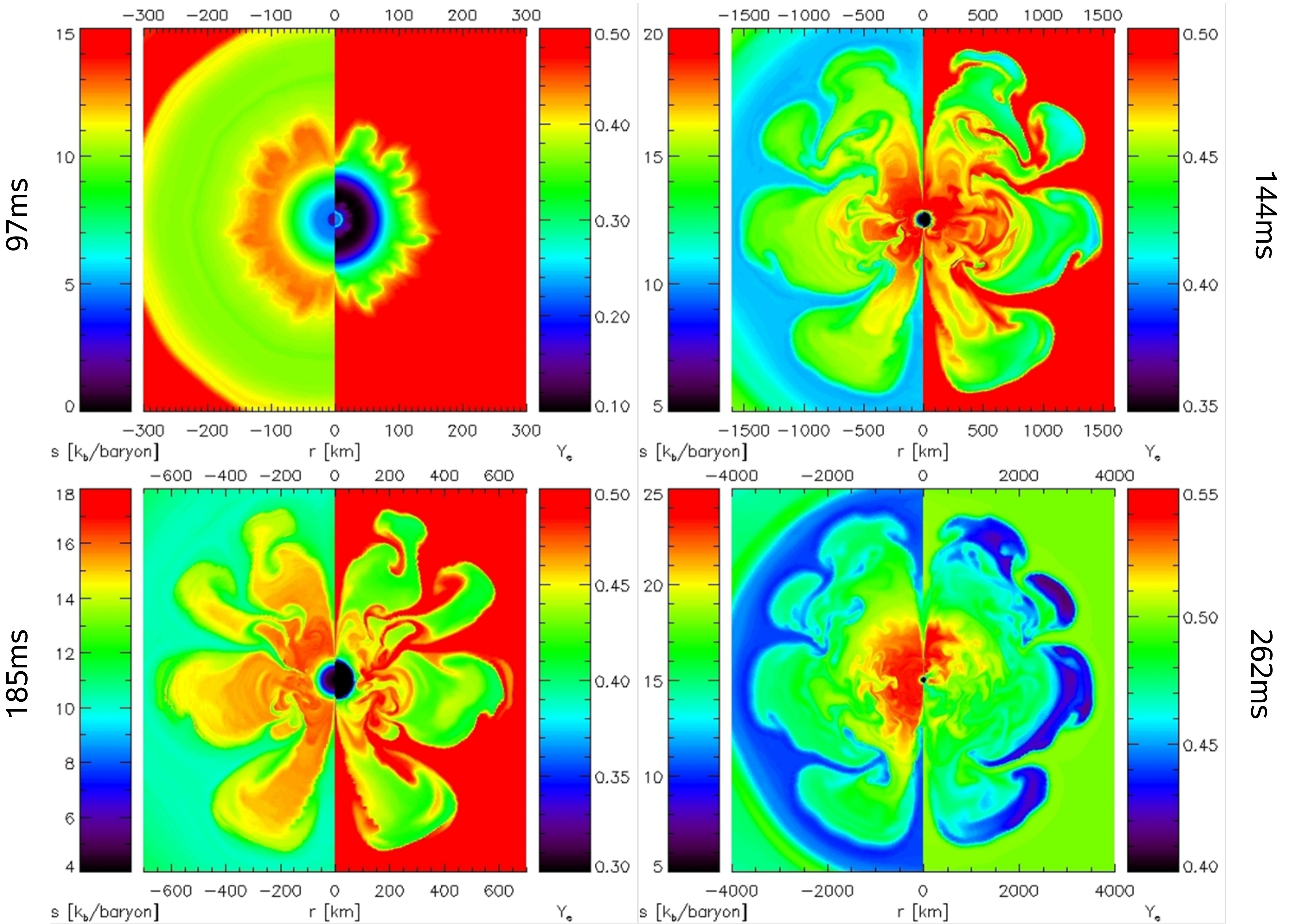
97ms
144ms
185ms
262ms
s [k$_b$/baryon]
r [km]
Y_e

Implications for Nucleosynthesis

- Can the r-process scenario be resuscitated in multi-D?
  - answer for non-rotating models: NO
  - no higher shock velocities reached
  - material in fast-rising bubbles has neither high enough entropies nor short enough expansion time-scales for r-processing
- Overproduction of N=50 closed-shell nuclei: problem seems even worse in 2D!

Conclusions & Open Questions

- O-Ne-Mg supernova provide an interesting opportunity for testing *successful* explosion models (nucleosynthesis yields, etc.)
- The explosion mechanism in these low-mass progenitors does not have to rely on multi-dimensional instabilities.
- However, multi-dimensional modelling is still crucial for determining observable signatures.
- Up-to-date progenitor models badly needed.