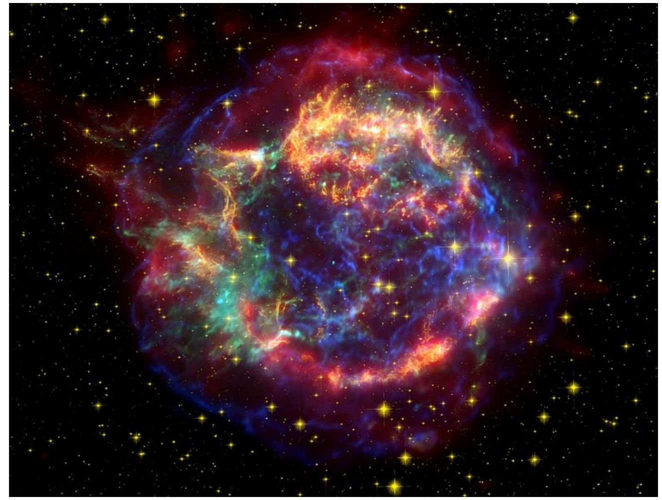
Queen's University Belfast



Simulating Electron-Capture Supernovae and their Cousins

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

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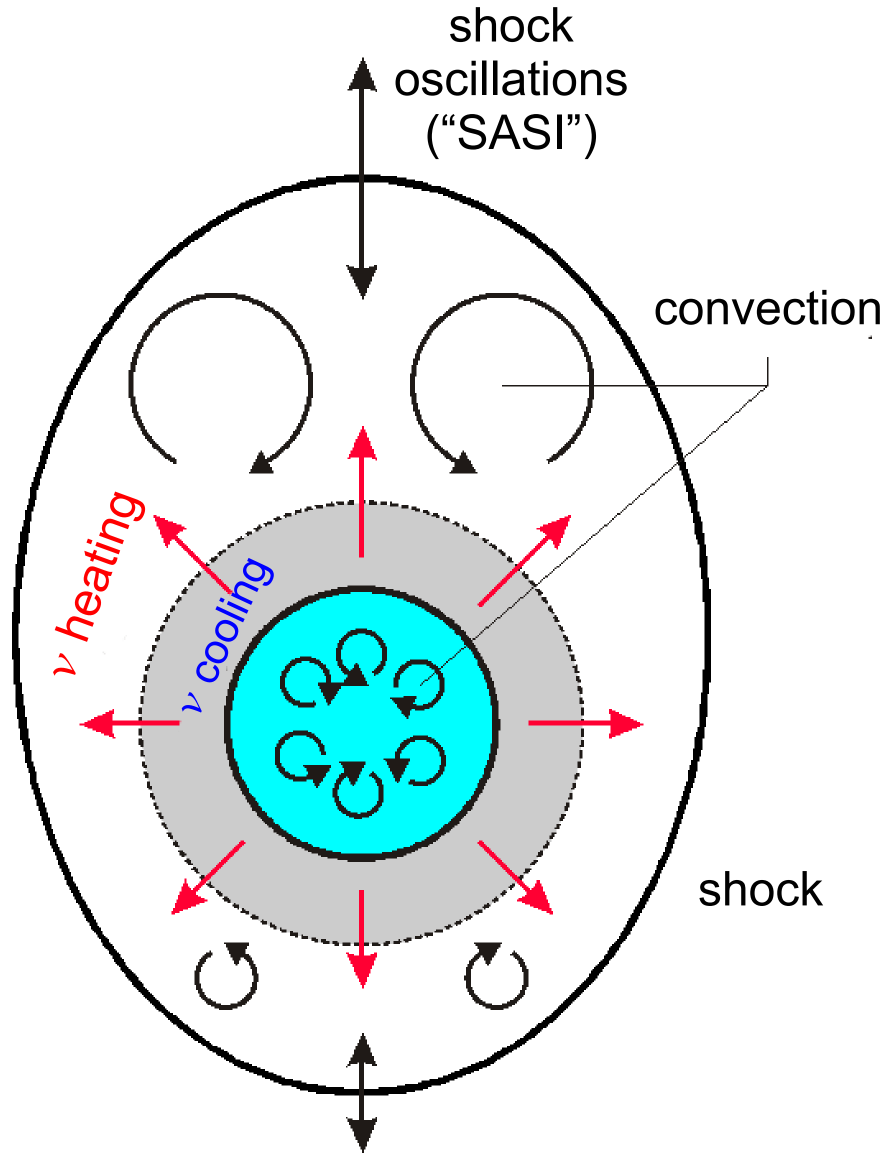
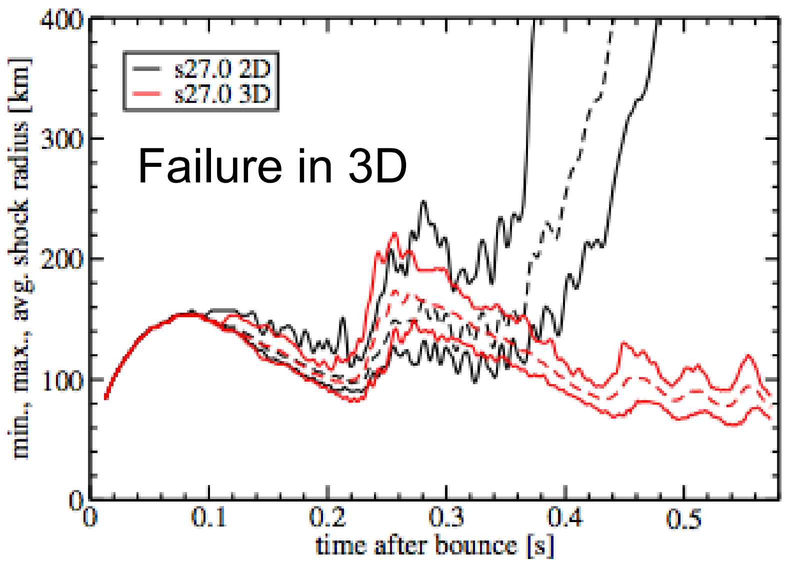
The neutrino-driven mechanism in its modern flavour

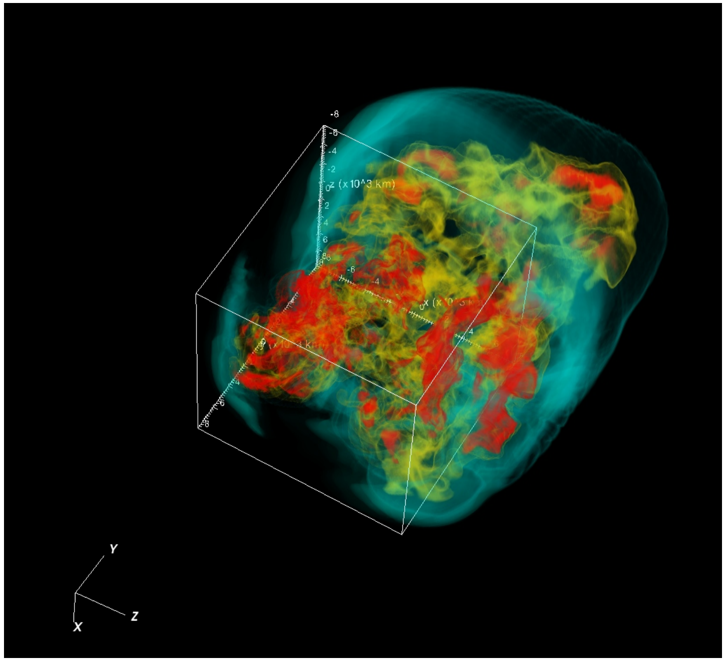
- Shock launched after inner core collapse to proto-neutron star and rebounds, quickly stalls
- Accretion shock pushed outward to ~150km after collapse, then recedes again
- *Heating* or *gain* region develops some tens of ms after bounce
- Convective overturn & shock oscillations "SASI" enhance the efficiency of ν-heating, which finally revives the shock



Status of 3D Neutrino Hydrodynamics Models

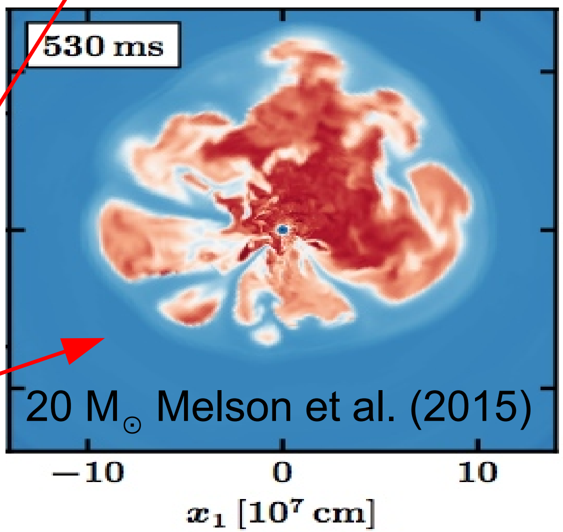


27 $M_\odot$ Hanke et al. (2013)

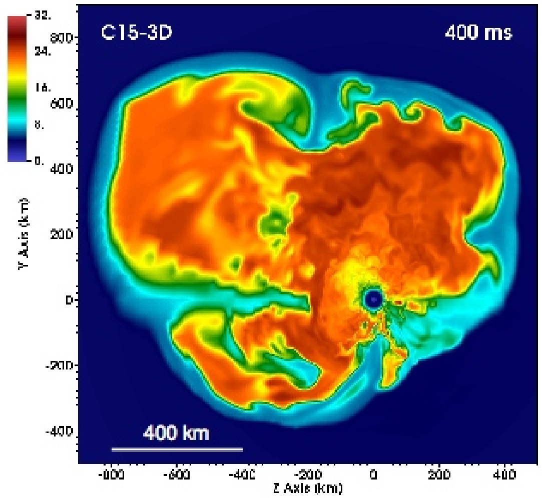


18 $M_\odot$ Müller (2016)

- Mixed record, some explosions, **delayed compared to 2D**
- Solution for shock revival may contain several elements:
    - Multi-D progenitor models
    - Uncertainties in high-density neutrino opacities
    - Numerics
    - etc.



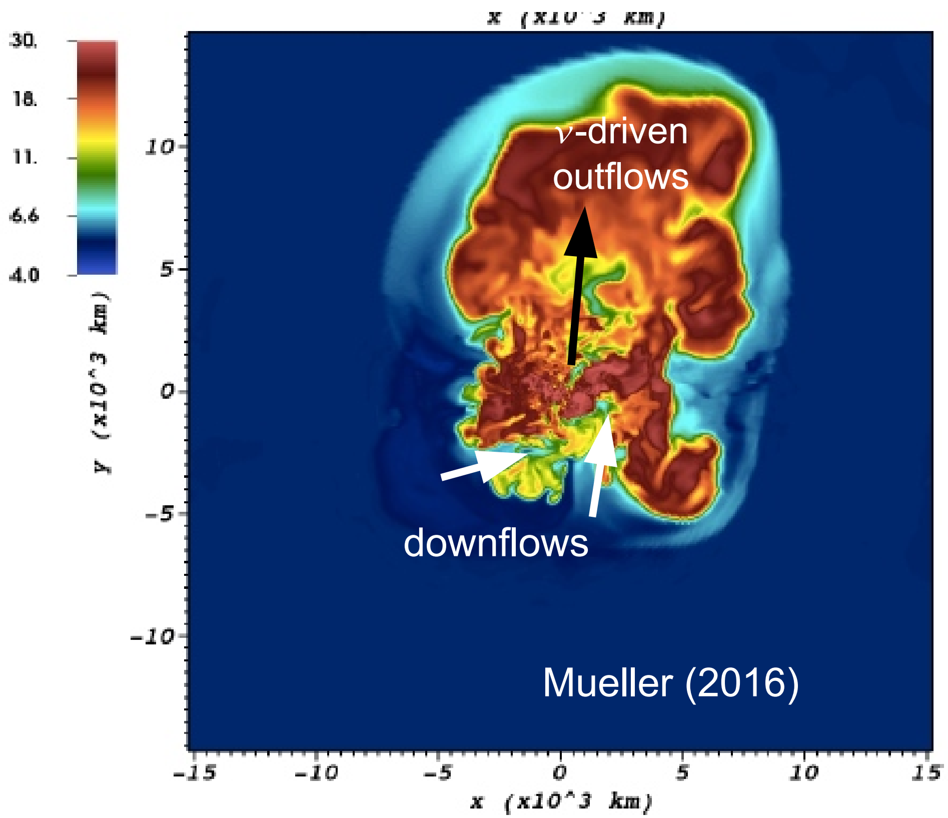
20 $M_\odot$ Melson et al. (2015)

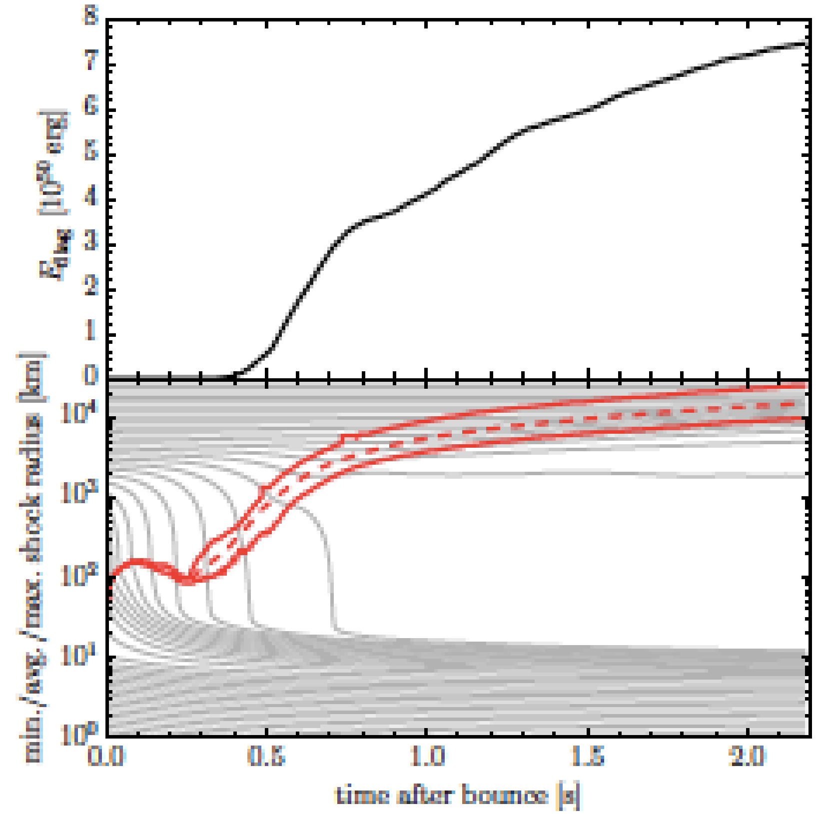


15 $M_\odot$ Lentz et al. (2015)

Or with simpler schemes: e.g. IDSA+leakage Takiwaki et al. (2014)

Explosion Dynamics of Typical Neutrino-Driven Supernovae





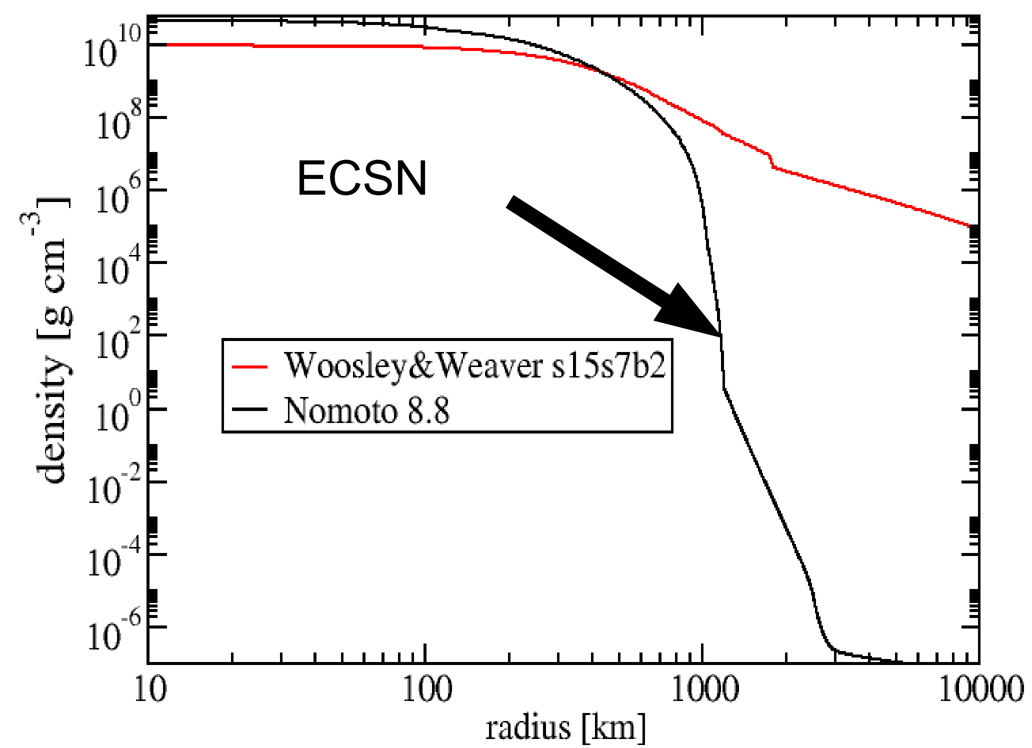
- Cycle of accretion & mass ejection can last >1s after shock revival
- Implies that large parts of the O shell may not be ejected
- Limits predictability of current 2D/3D models concerning energetics & nucleosynthesis

What Makes ECSNe Different?

Critical condition for explosion: $L > L_{\text{crit}}(\dot{M}, M)$

$$\dot{M} \approx 2\frac{M}{\tau_{FF}}\frac{\rho}{\bar{\rho}-\rho} \rightarrow \frac{8\pi\rho R^3}{3\tau_{FF}}$$

$$\rho \ll \bar{\rho} \Rightarrow \dot{M} \rightarrow \frac{8\pi\rho R^3}{3\tau_{FF}}$$



For modifications in multi-D, see Mueller & Janka (2015), Summa et al. (2016)

Dynamics of Electron Capture Supernova Explosion is Different

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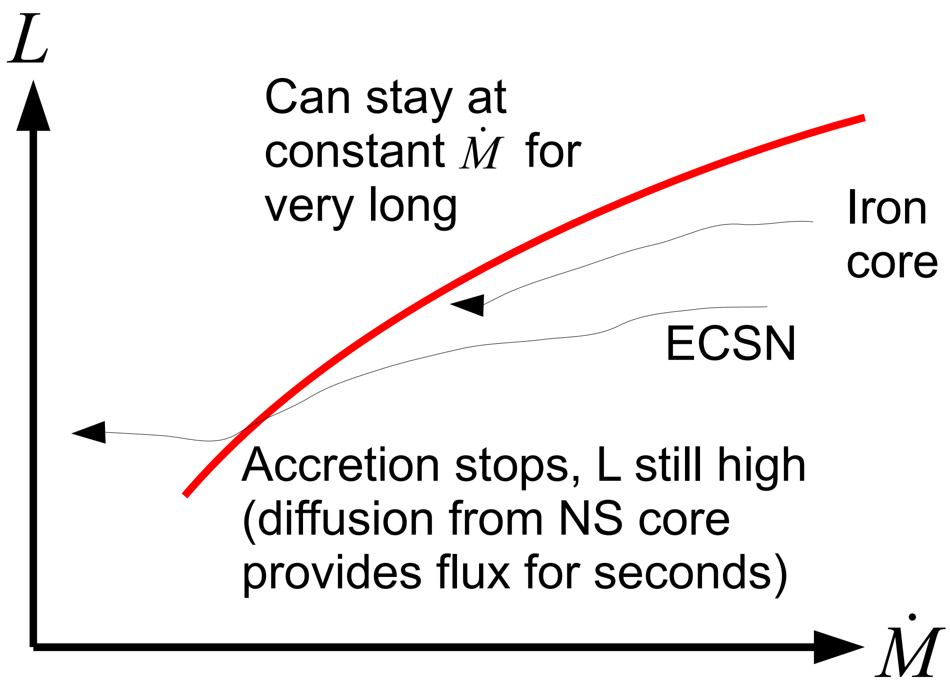

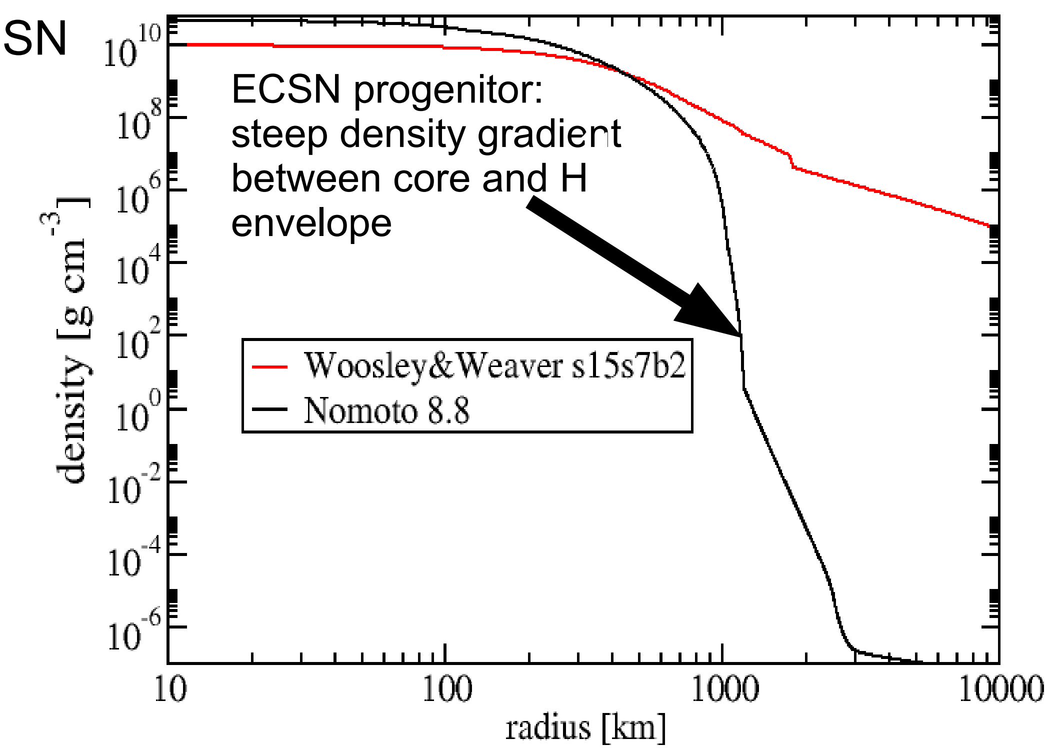

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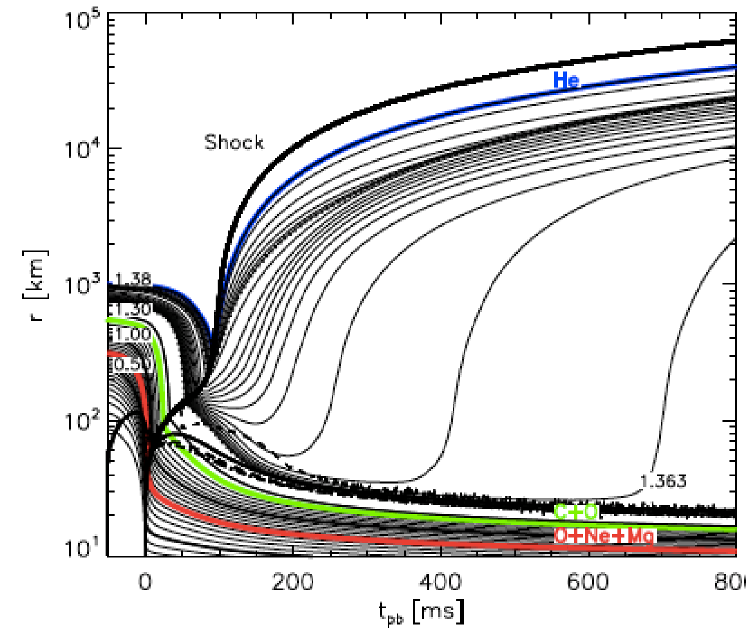
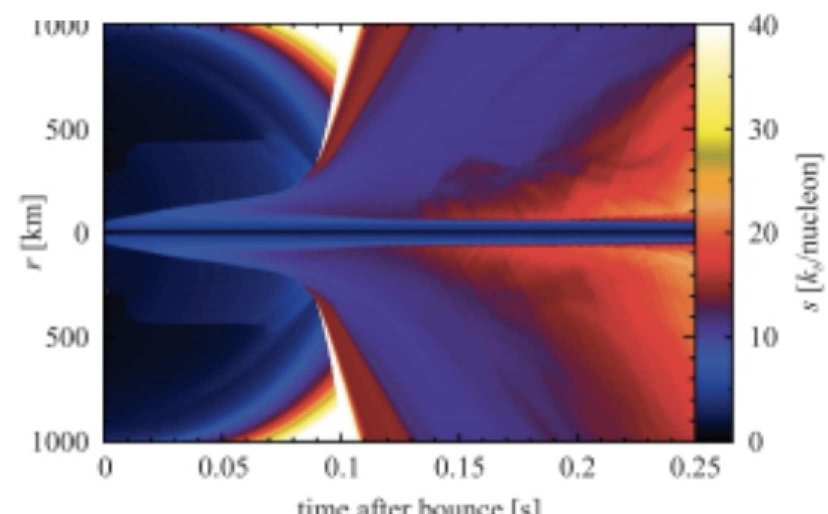
Dynamics of Electron Capture Supernova Explosion is Different

- Drop of accretion rate allows shock revival ~0.1s after bounce **(even in 1D)**
- ν-heating unbinds material in gain region ($0.005 M_\odot$)
- Only recombination energy of nucleons "left over" as net explosion energy (~10^{50}erg)
- ν-driven wind provides another ~10^{49}erg
- Simultaneous accretion & ejection over ~1s in more massive progenitors → more powerful, but more difficult to model





Entropy vs. radius: and time
(Janka et al. 2012)

Explosion Dynamics and Energetics

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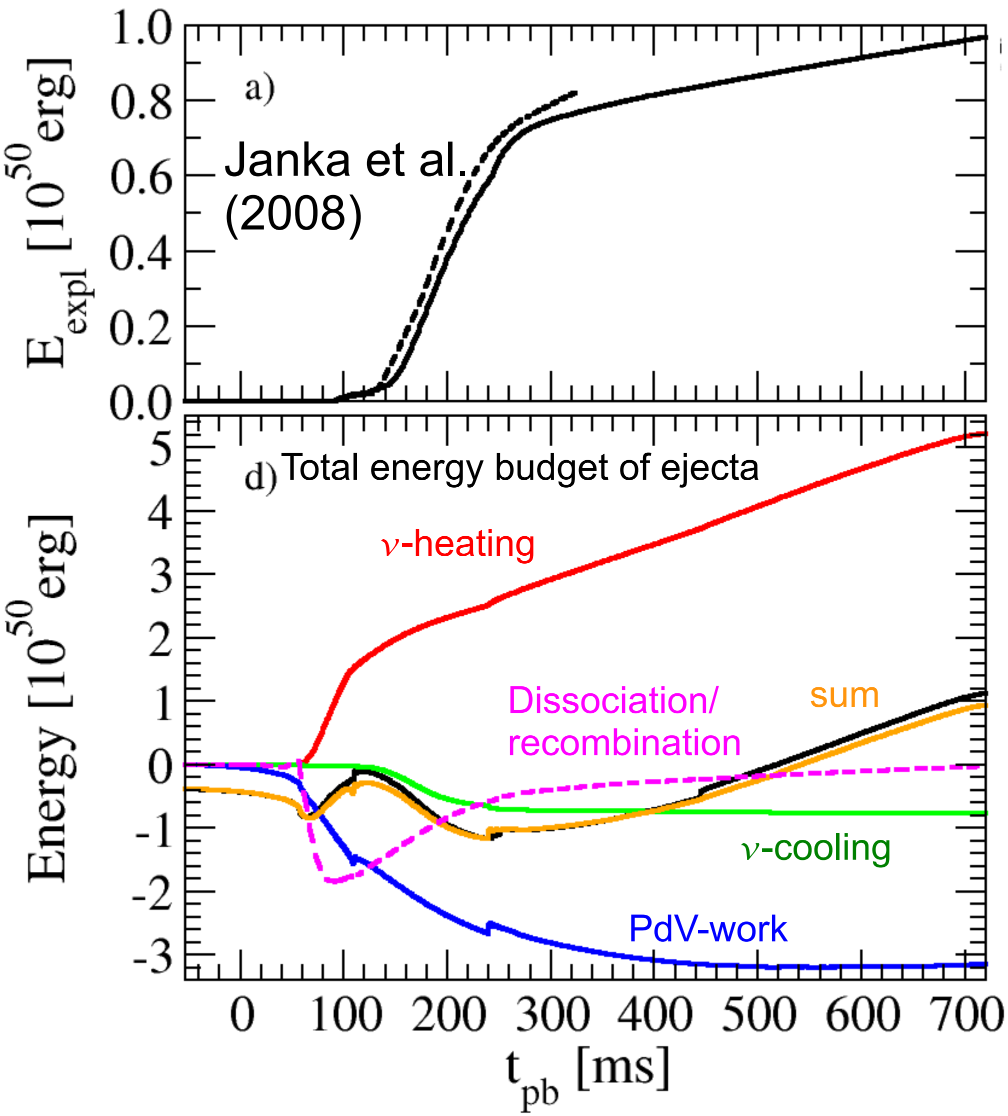
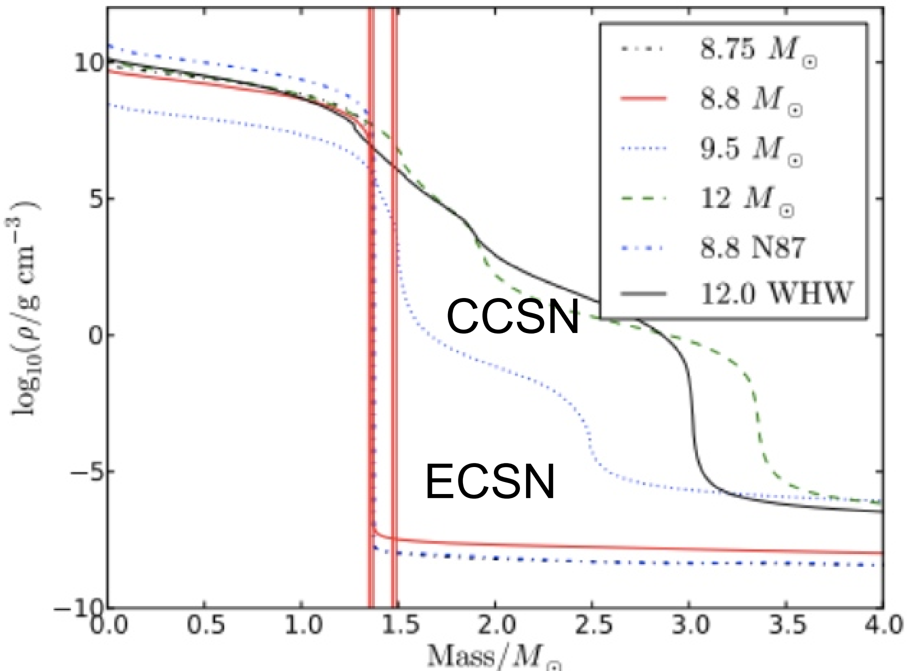
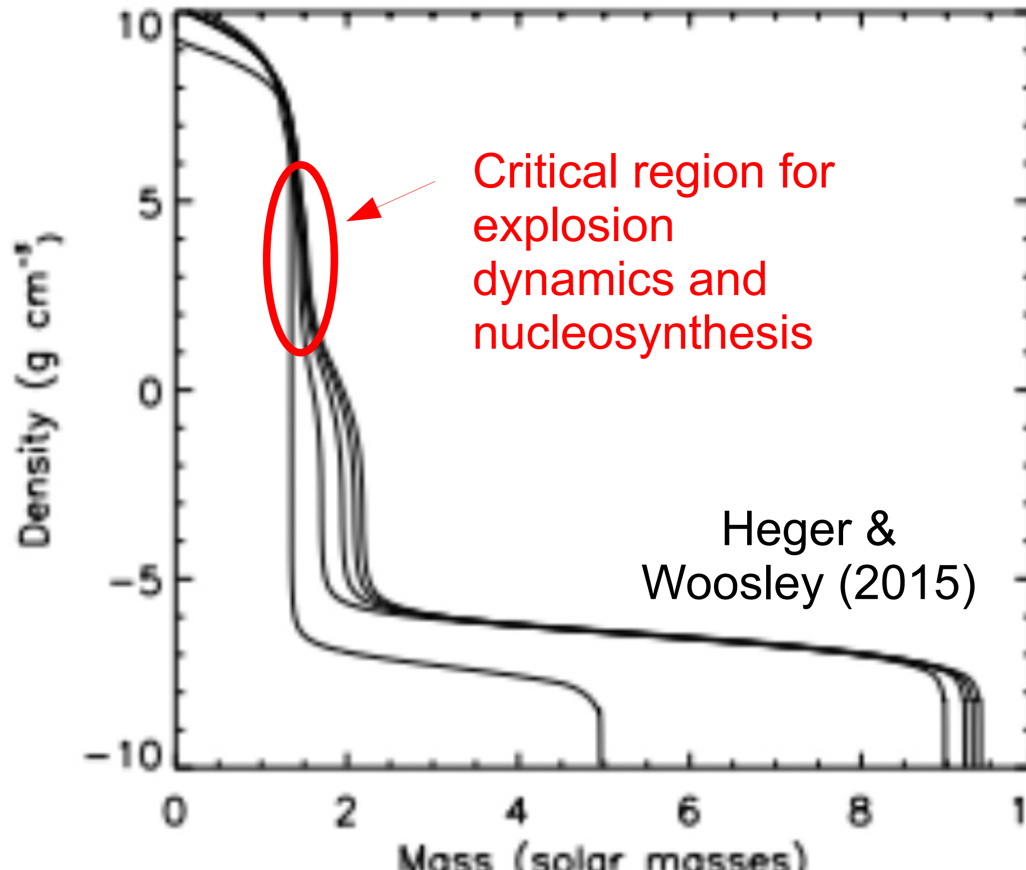


NB: Claims of E_{exp}~2.5×10^{50}erg (Radice et al. 2017, arxiv: 1702.03927) for different neutrino opacities appear problematic

Sensitivity to Core Structure



Jones et al. (2013)

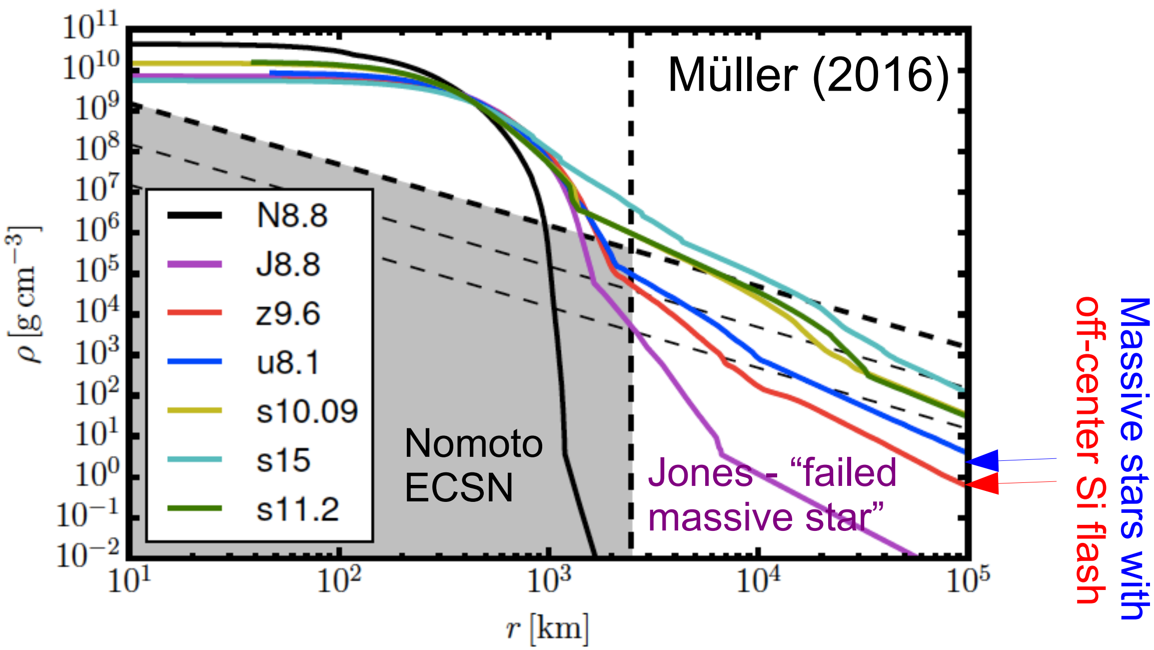


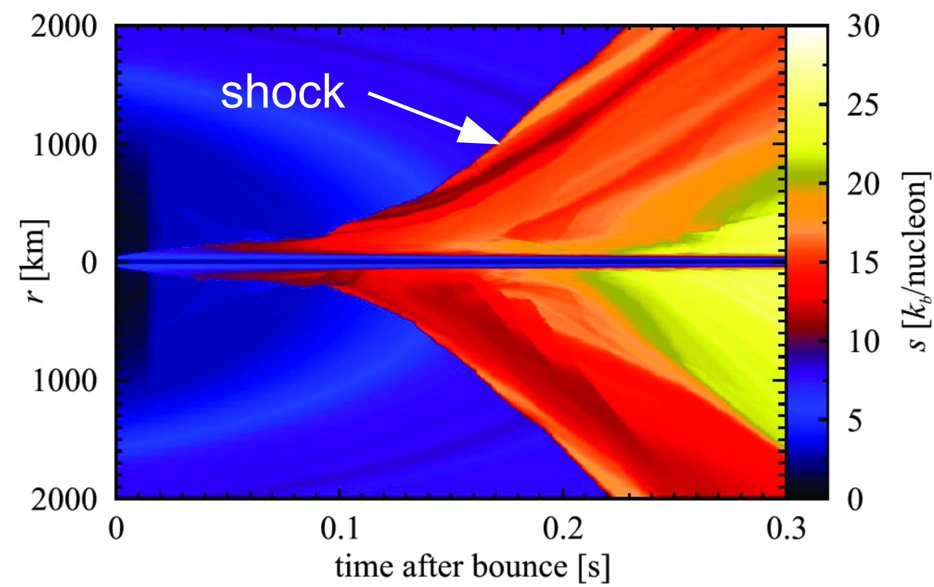
Recent work on the AGB-supernova mass transition reveals (see review by Doherty, Gil-Pons, Siess & Lattanzio 2017):

- Width of ECSN channel(s) uncertain
- But many paths to similar core structure (low-mass iron cores)

So how extreme a density profile is needed?

Sensitivity to Core Structure





Janka et al. (2012): 9.6$M_\odot$ iron core progenitor (zero metallicity)

ECSN-like explosions will occur roughly when the mass accretion rate drops to $\dot{M}$ <0.05 $M_\odot$ early on (~100ms after bounce)

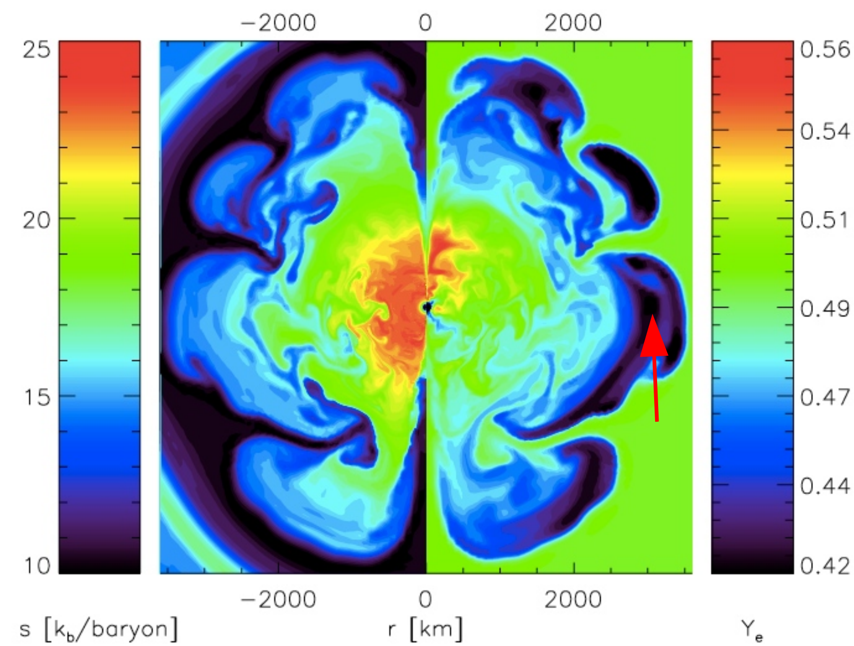
Prerequisite is to have no more than a thin O and C shell

→ don't need SAGB structure (i.e. can have quite a bit of He) for ECSN-like explosion dynamics

→ E_{exp} and Ni mass won't be smoking guns for "real" ECSN (but spectra could be → talk by A. Jerkstrand)

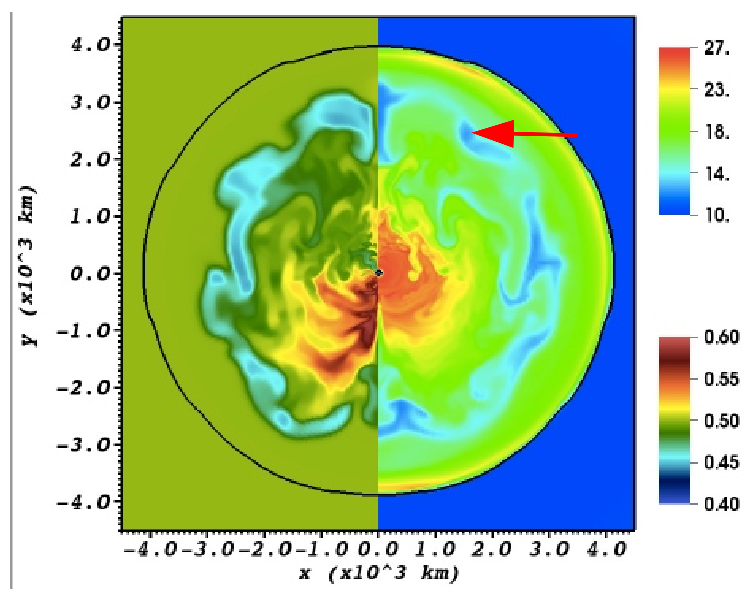
Multi-D Effects

- Shock revival and development of Rayleigh-Taylor instability practically coincident
- One single overturn
- Very different from more massive models (where convection is quasi-stationary)
- Modest enhancement of explosion energy (less for more extreme core structure)
- Buoyant plumes are also **neutron-rich** → nucleosynthesis



entropy electron fraction

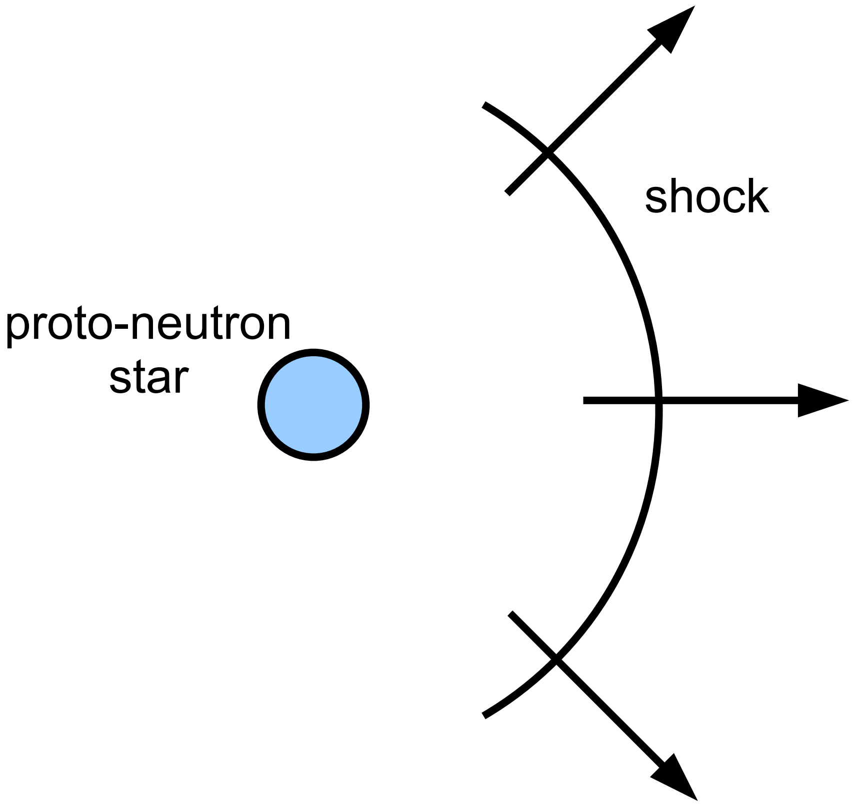
ECSN channel: Wanajo et al. (2011)



Case of low-mass iron cores: Wanajo et al. (2017)

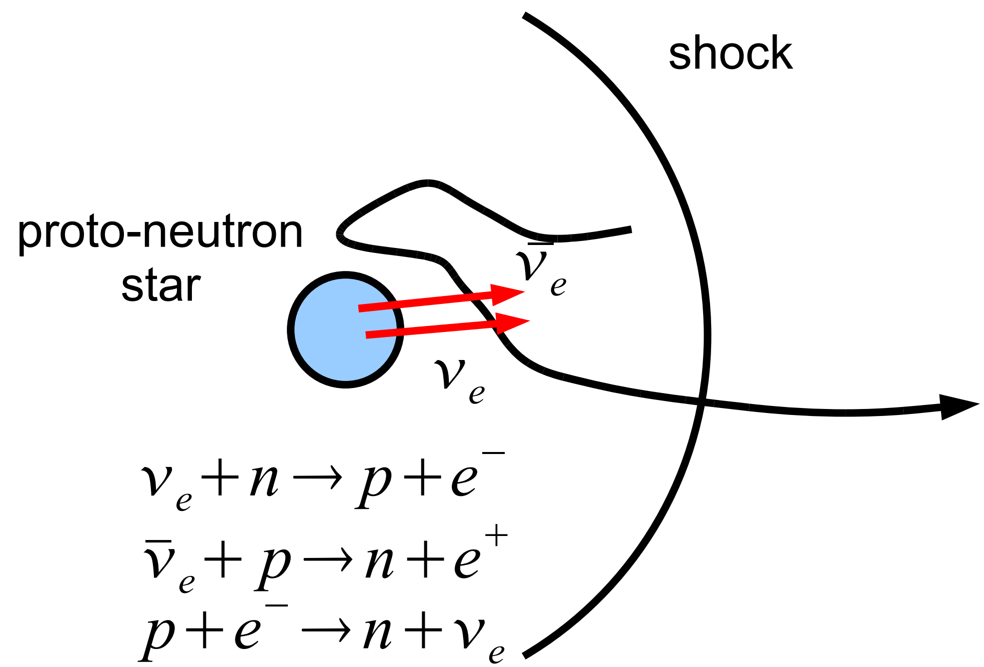
The Innermost Ejecta of Core-Collapse Supernovae

Classical explosive burning (can also be studied by piston/thermal bomb models)



Y_e mostly set by progenitor composition. Nucleosynthesis regulated by *initial* Y_e, composition, maximum T & expansion time-scale.

Neutrino-processed ejecta (innermost ~0.01 to 0.1$M_\odot$ of ejecta)



“Memory” of initial Y_e and composition **lost.** Y_e and composition determined by neutrino processing & expansion time-scale

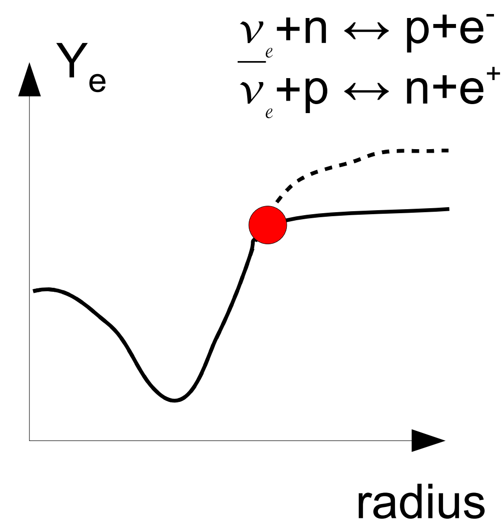
Origin of Neutron-Rich Ejecta

- Freeze-out of final Ye set by competition between expansion and neutrino processing

Heating rate

Total/average electron flavour luminosity and mean energy

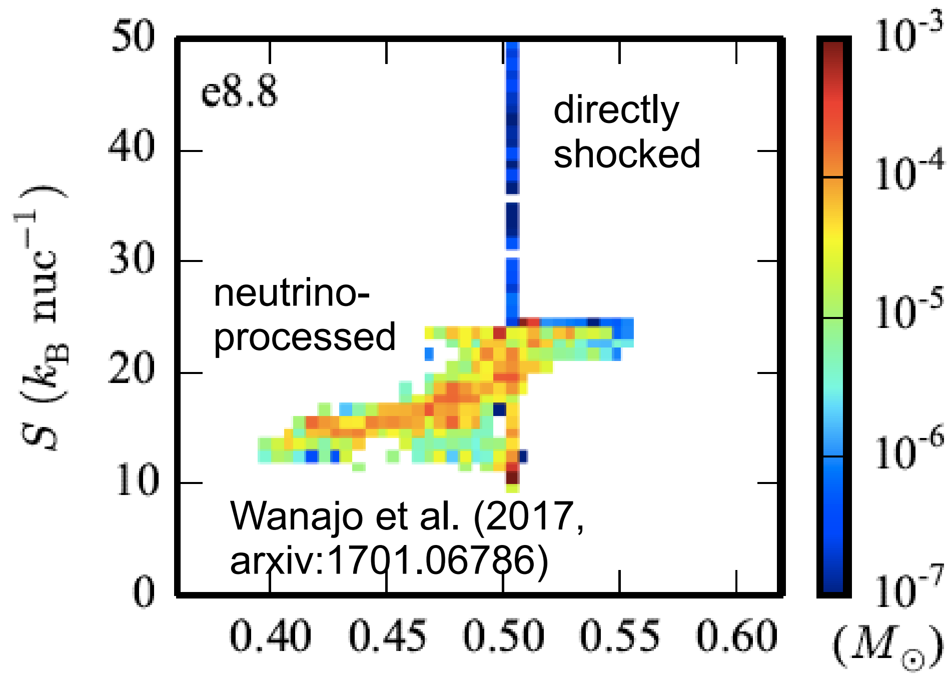
Expansion time-scale
$$\frac{v_r}{r} \approx \frac{2 m_n \dot{q}_\nu}{\langle E_\nu \rangle} \propto \frac{L_\nu \langle E_\nu \rangle}{r^2}$$

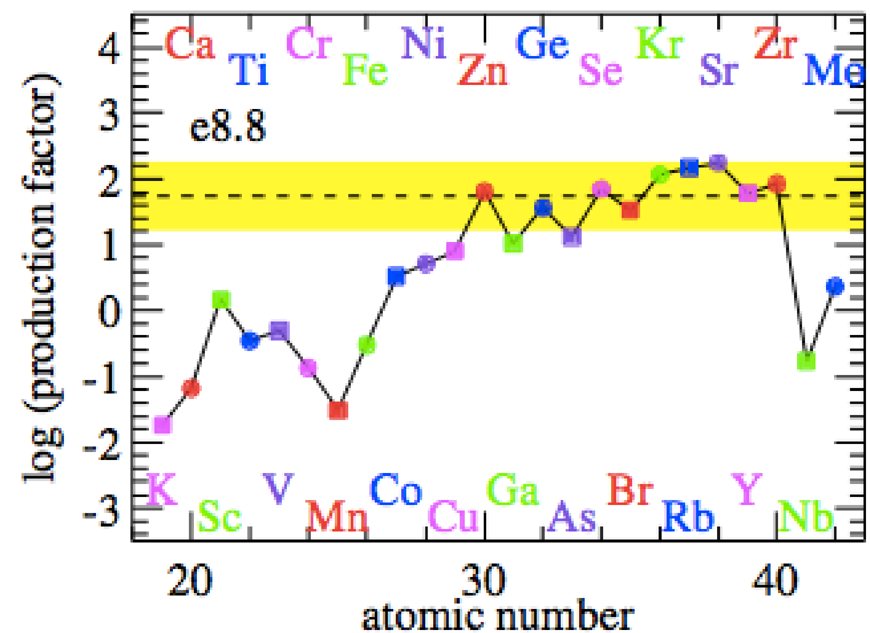


- Neutrino heating alone typically drives Y_e to >0.5 for r⟶∞ in modern models, so need high v_r (⟶ early freeze-out) to make ejecta neutron rich

Nucleosynthesis Conditions in 2D

- Nucleosynthesis in n-rich ejecta dominated by freeze-out from NSE/QSE (nuclear quasi-equilibrium)
- Highest production factors between Zn and Zr
- In line with idea of idea of separate origin for Sr, Y, Zr from heavy r-process ("LEPP": Travaglio et al. 2004, "weak r-process": Wanajo & Ishimaru 2006)





Wanajo et al. (2017)

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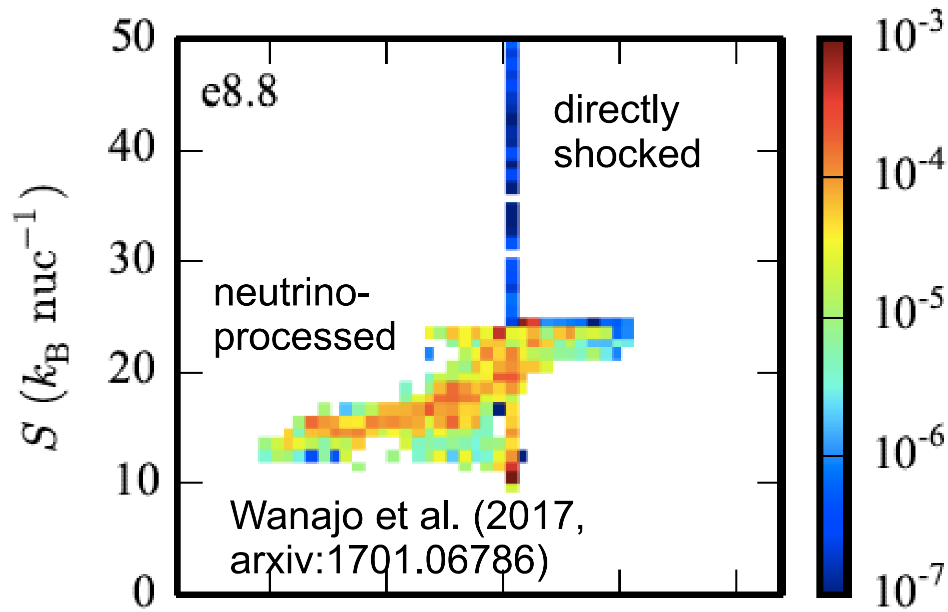
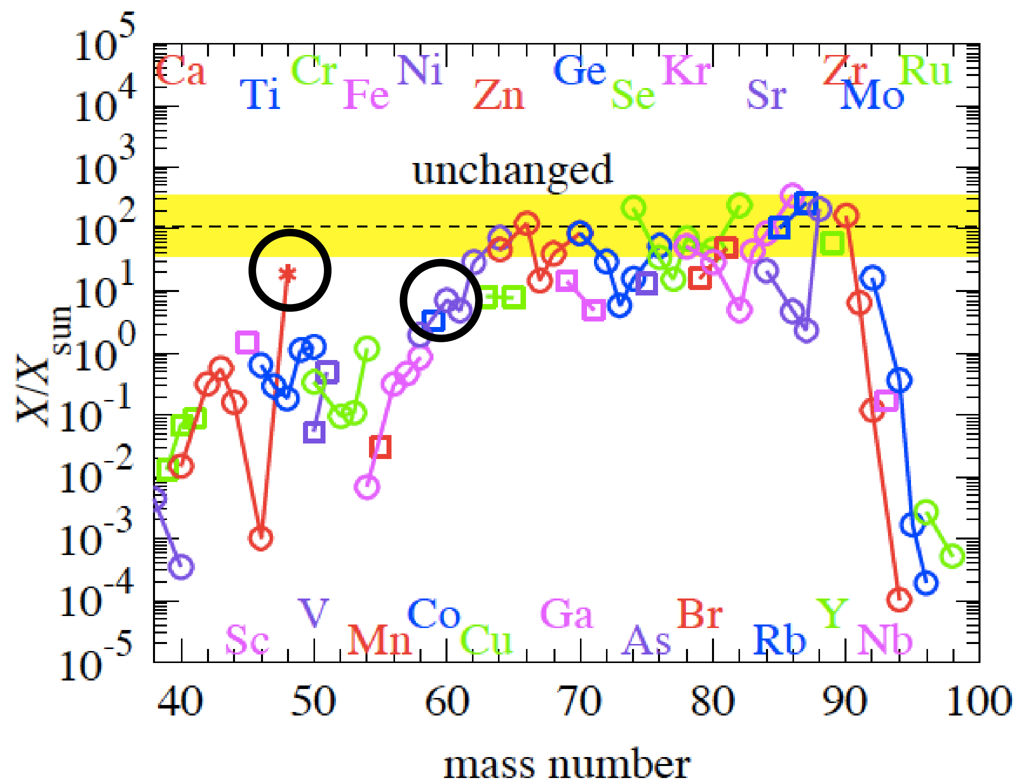
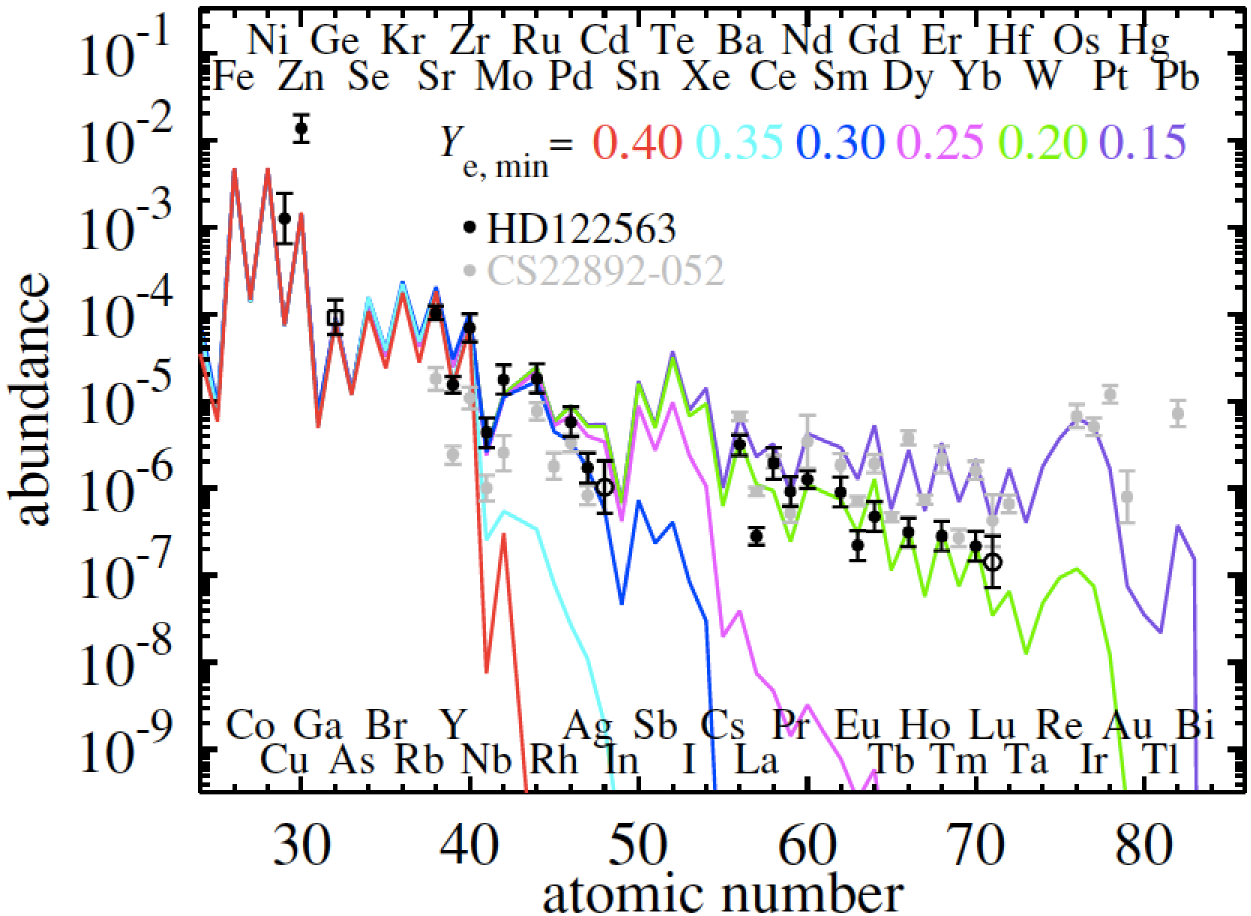
- Possible contribution to galactic inventory of ^{48}Ca and ^{60}Fe





Wanajo et al. (2013)

A Weak r-Process in Electron Capture Supernovae?

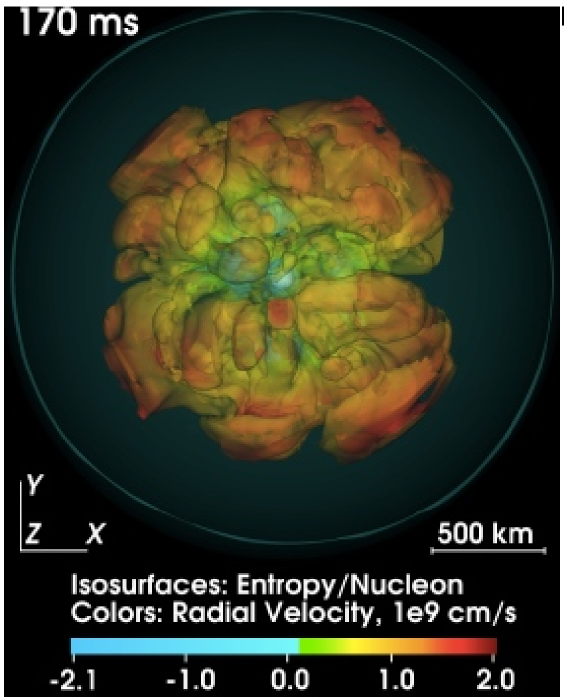


Wanajo et al. (2011)

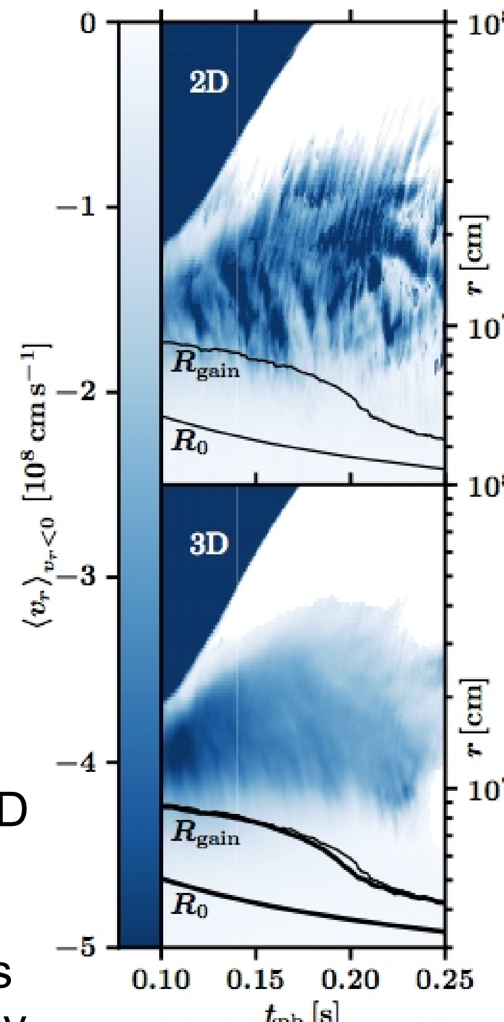
Comparison of model abundances with rescaled Y_e-distribution in metal-pooer halo stars CS22892-052 (enriched with heavy r-process) and HD122563 (no/little heavy r-process enrichment)

A weak r-process would require lower Y_e – so what are uncertainties in Y_e ?

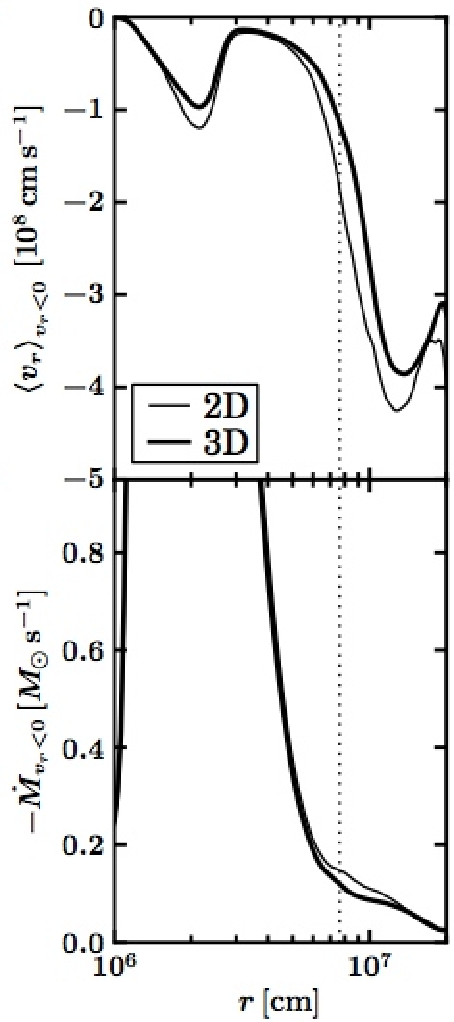
3D Effects in ECSN-like Supernovae



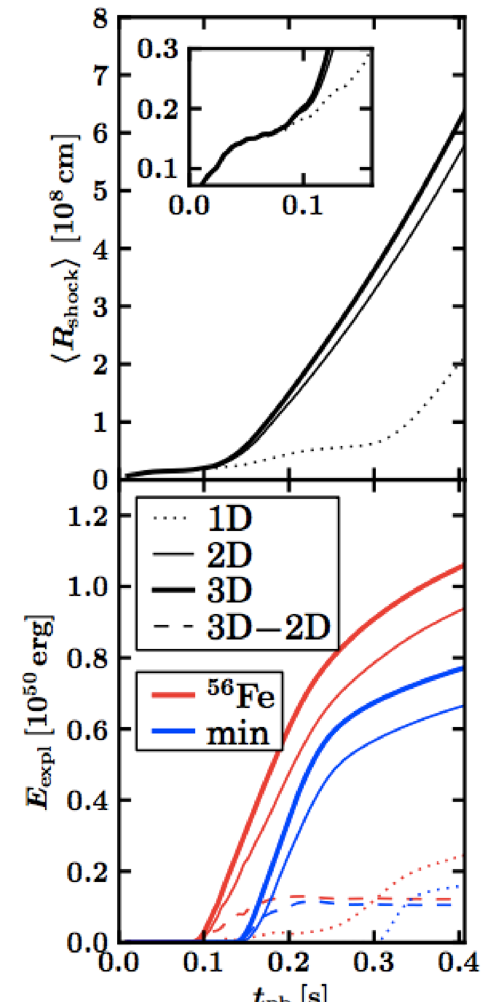
Downflows more strongly braked by turbulence in 3D and dragged along by outflows
→ larger total ejecta mass
→ higher explosion energy (by ~10%)



Avg. radial velocity of downflows



Accretion rate

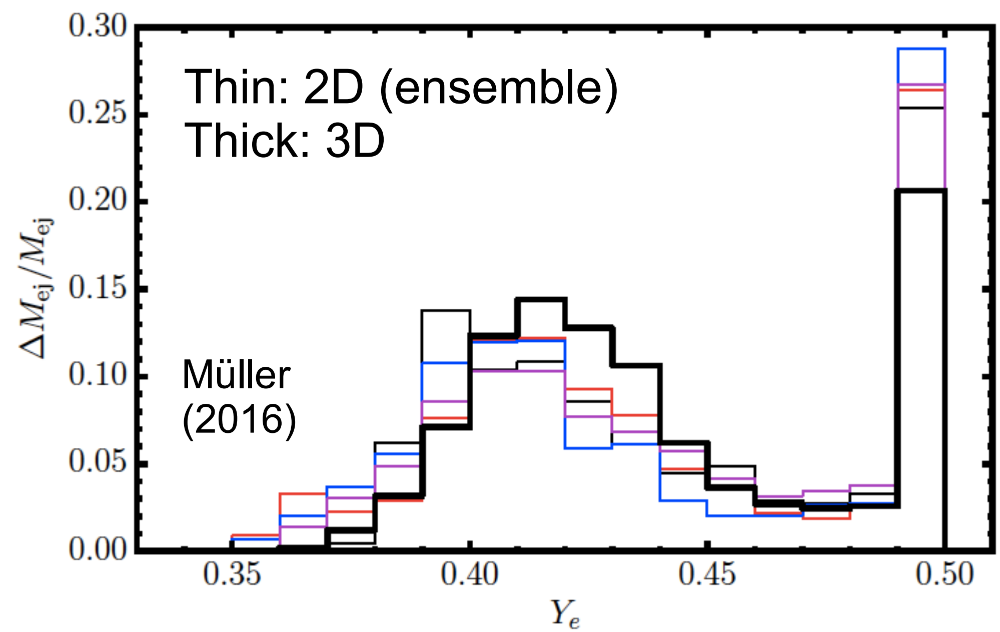


Shock propagation & explosion energy (red: assuming full nucleon recombination)

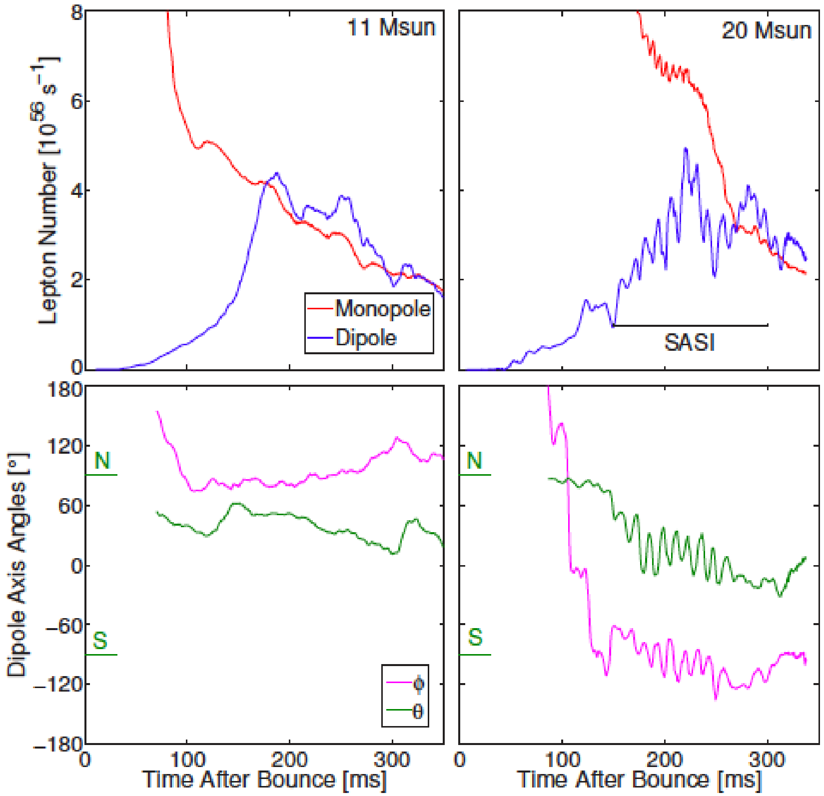
Melson et al. (2015)

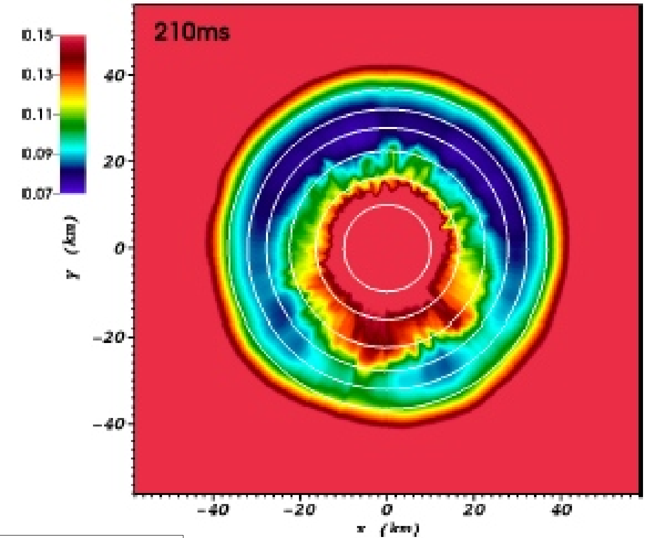
Effect on Nucleosynthesis Conditions?

- Net effect of 3D appears to brake n-rich bubbles
- Resulting Y_e distribution is shifted up slightly (Müller 2016)
- Caveat: Simplifications in transport for differential 2D/3D study
- Initial seed perturbations may also play a role (→ multi-D O deflagration models of Jones et al. 2016 and Shing Chi Leung)



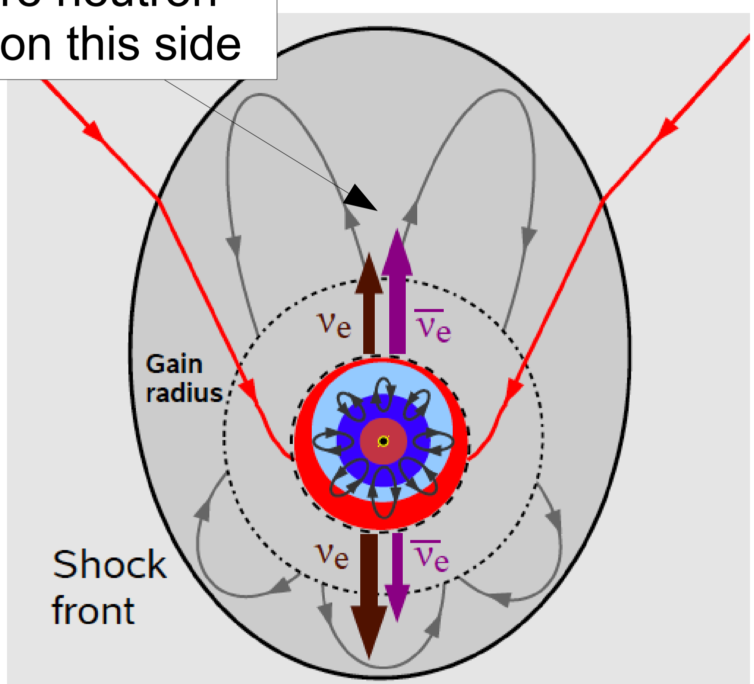
Lepton-Number Emission Asymmetry





Asymmetric Y_e-distribution in PNS

Outflows will be more neutron rich on this side



Tamborra et al. (2014)

- LESA: Global lepton flux asymmetry in recent **3D models** of the MPA group (Tamborra et al. 2014)
- Also seen in numerical simulations of other groups (O'Connor & Couch w/ leakage
- Accretion instability or low-mode nature of PNS convection responsible? Mathematical model for instability needed!
- Should lead to asymmetric Y_e in outflows.

Summary

- Neutrino-driven mechanism is robust for ECSNe – no help from multi-D effects required
- Different supernova channels (ECSN vs. low-mass iron core SN) above the AGB-SN mass transition hard to distinguish based on explosion dynamics & nucleosynthesis
- Small explosion energy ($\sim 10^{50}$erg), small Nickel mass (a few $0.001 M_\odot$)
- ECSN-like explosions as promising source for neutron-rich nucleosynthesis beyond iron (especially Sr, Y, Zr) – here multi-D is important (neutron-rich bubbles)
- Potential for weak r-process up to Ag & Pd, but would require more neutron-rich ejecta
- More n-rich ejecta conceivable within uncertainties: LESA instability, seed perturbations, neutrino interaction rates & flavour conversion, resolution → need new 3D models