Max–Planck–Institut
für Astrophysik

SFB-TR7

SFB-TR27

TUM
LMU
Excellence Cluster
Universe

Stellar Death and Supernovae Conference

Kavli Institute for Theoretical Physics, Santa Barbara, August 17–21, 2009

# Status of 8-10 Solar Mass Objects and Beyond

Hans-Thomas Janka
(Max Planck Institute for Astrophysics, Garching, Germany)

Student, postdocs, collaborators:
Lorenz Hüdepohl, Andreas Marek, Bernhard Müller, Nico Hammer, Ewald Müller,
Shinya Wanajo

Max–Planck–Institut
für Astrophysik

SFB-TR7

SFB-TR27

Excellence Cluster
Universe

Stellar Death and Supernovae Conference
Kavli Institute for Theoretical Physics, Santa Barbara, August 17–21, 2009

# Status of Core-Collapse Supernova Modeling in Garching

Hans-Thomas Janka
(Max Planck Institute for Astrophysics, Garching, Germany)

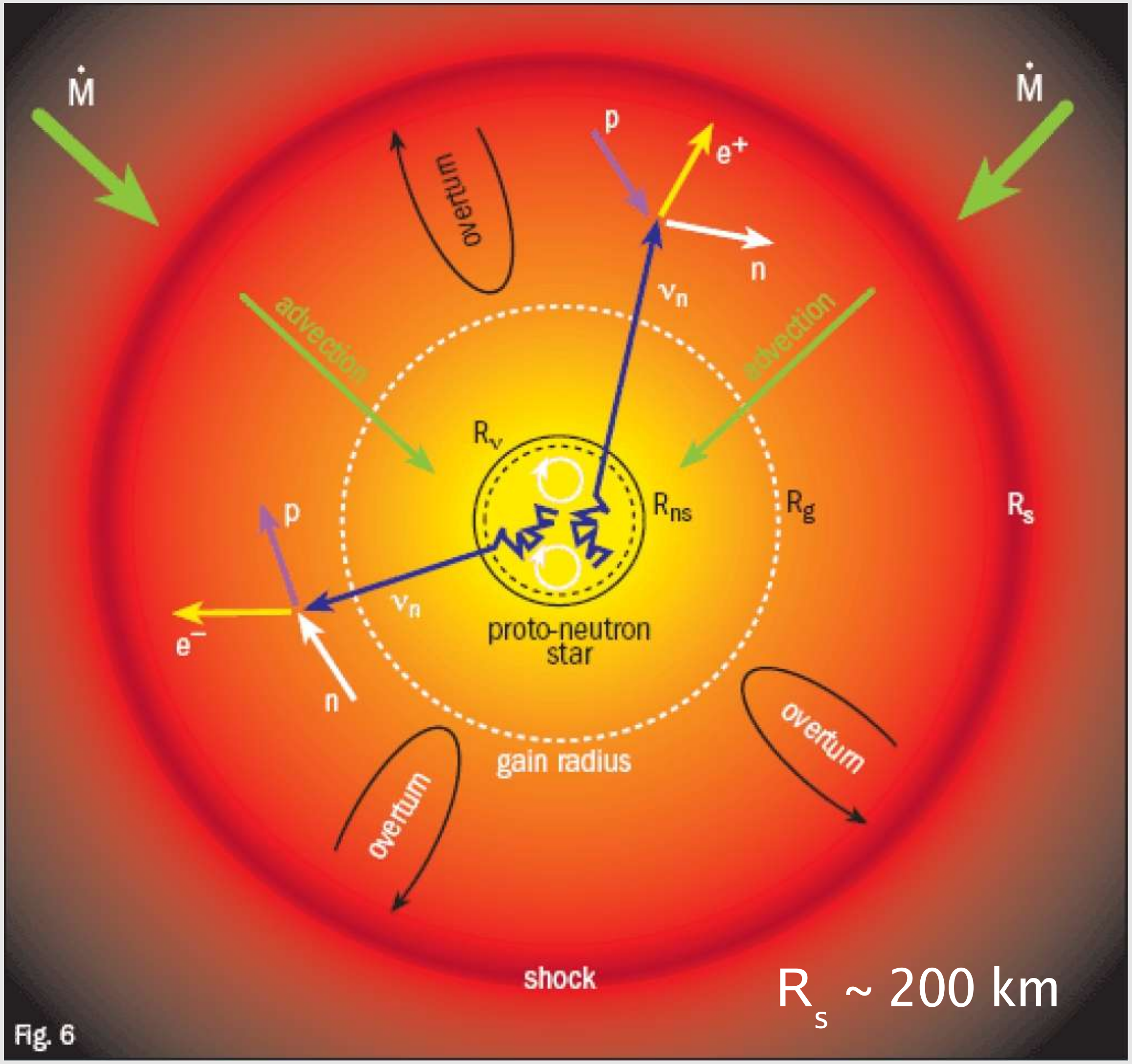
Student, postdocs, collaborators:
Lorenz Hüdepohl, Andreas Marek, Bernhard Müller, Nico Hammer, Ewald Müller,
Shinya Wanajo

# Exploration of neutrino-driven explosions

- 3D simulations of mixing instabilities in supernovae until shock breakout
- Explosion models for electron-capture supernovae of 8–10 $M_{sun}$ stars
- Neutrino-driven explosion models of 11 and 15 $M_{sun}$ stars

# Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



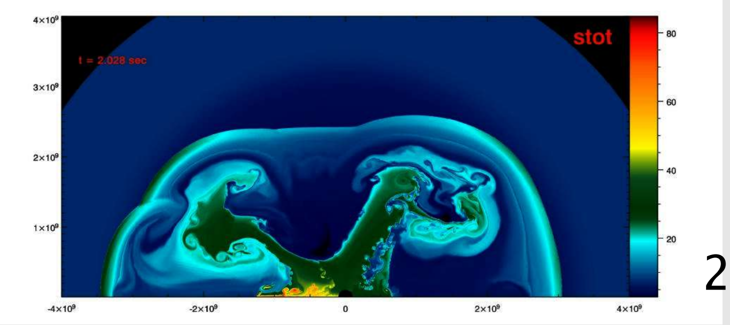
$R_s$ ~ 200 km

Fig. 6

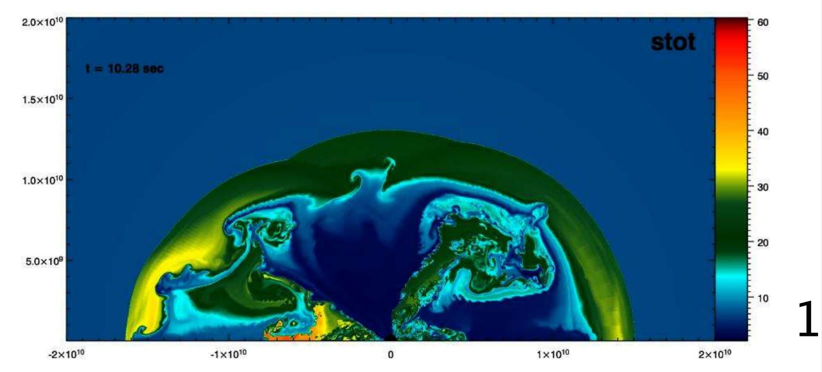
- “Neutrino-heating mechanism”: Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities play an important role (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08).

# 3D Models of CCSN Explosions

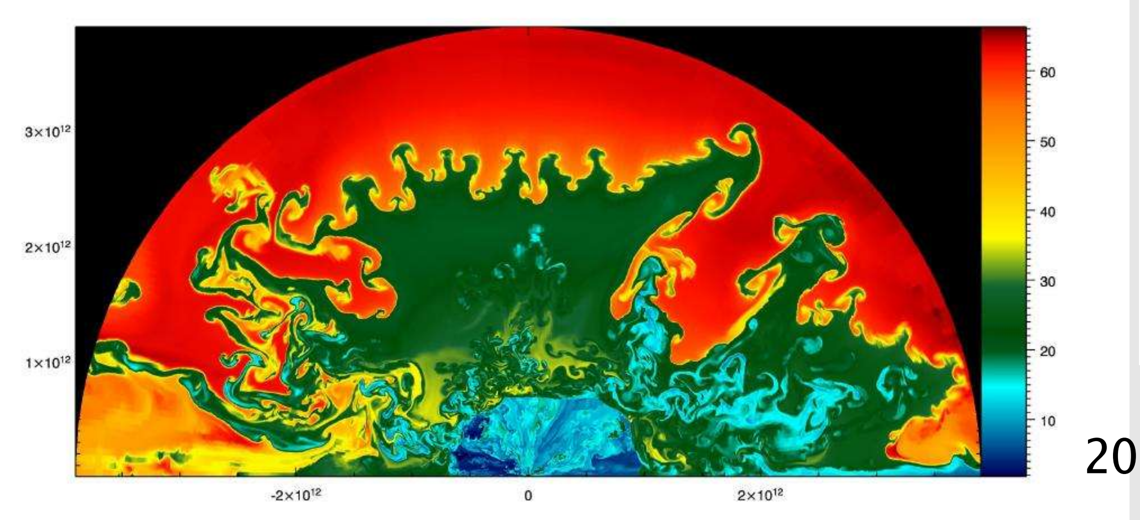
# Mixing Instabilities during SN Explosions



2 s



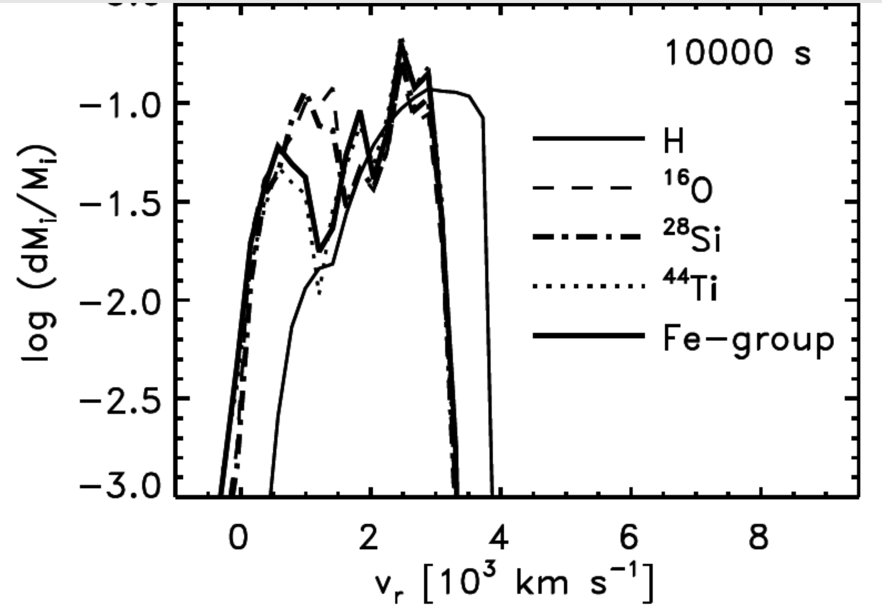
10 s



20000 s

## 2D models with large initial shock deformation:

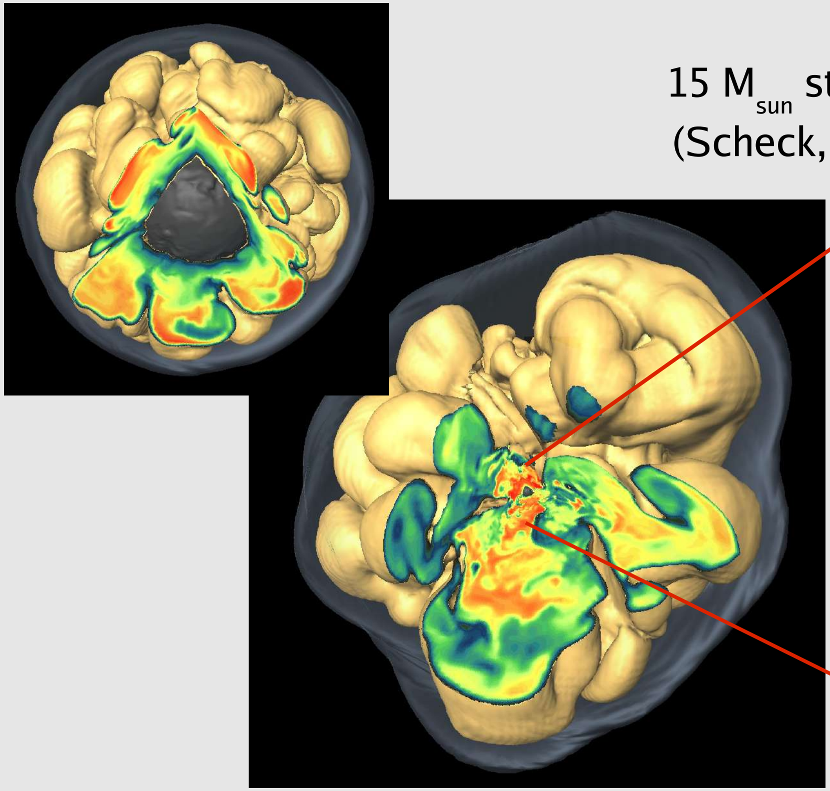
- Strong metal mixing into H envelope
- Strong H mixing deep into He layer
- large asymmetry of metal distribution
- High Ni velocities ($v_{max}$ > 3000 km/s as observed in SN 1987A)

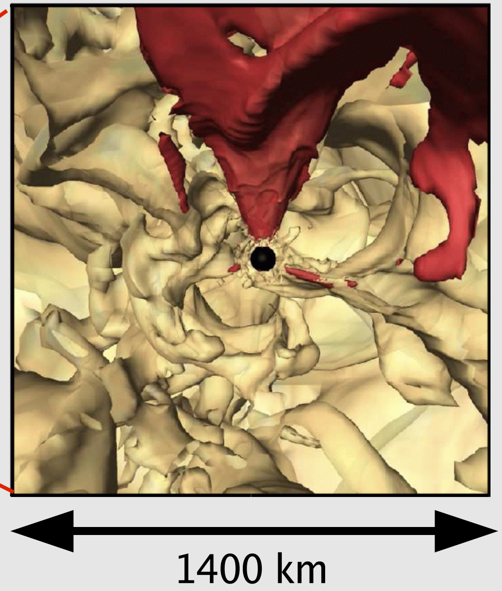


Kifonidis et al., A&A 453 (2005), 661

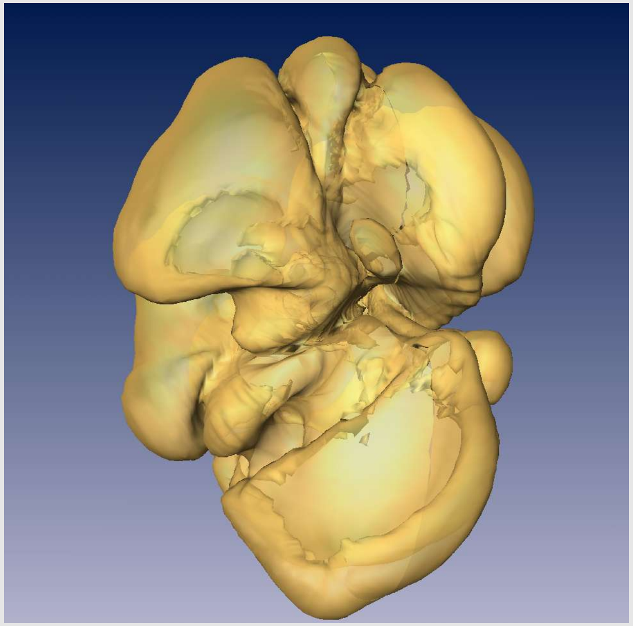
# Parametric Explosion Studies in 3D

- Explosions in 3D show also very large asymmetries
- Accretion flow to neutron star develops l = 1 mode also in 3D
- Should produce neutron star kicks similar to 2D

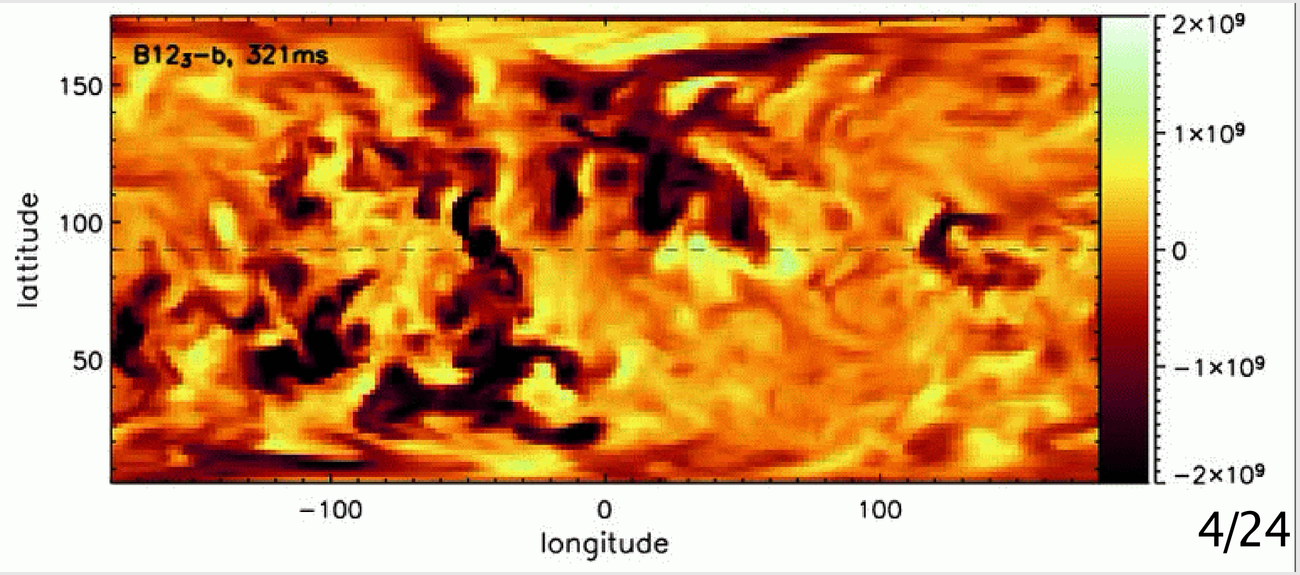




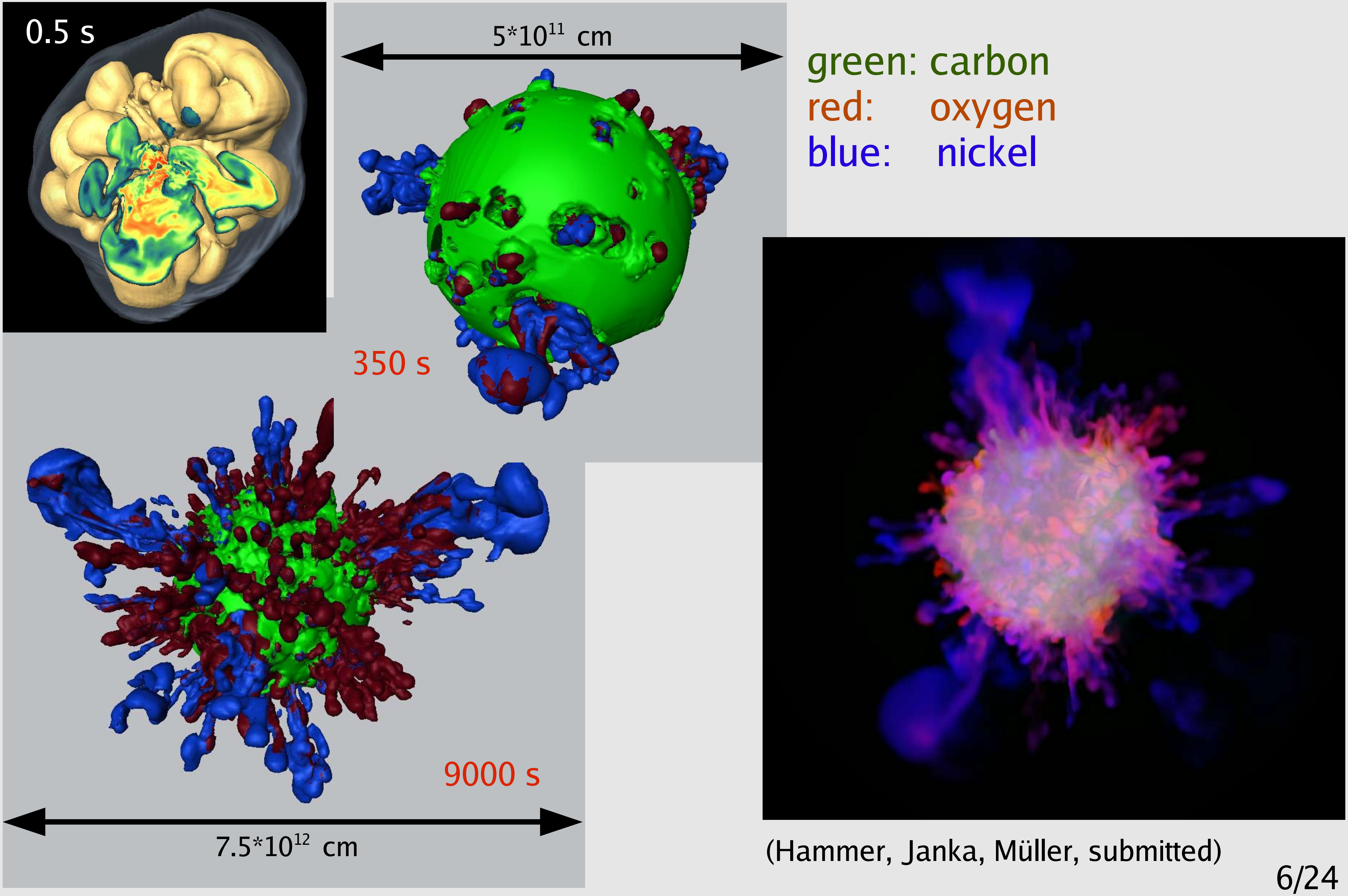
15 $M_{sun}$ star without rotation (Scheck, PhD Thesis 2006)



3D with rotation (Scheck, PhD Thesis 2006)



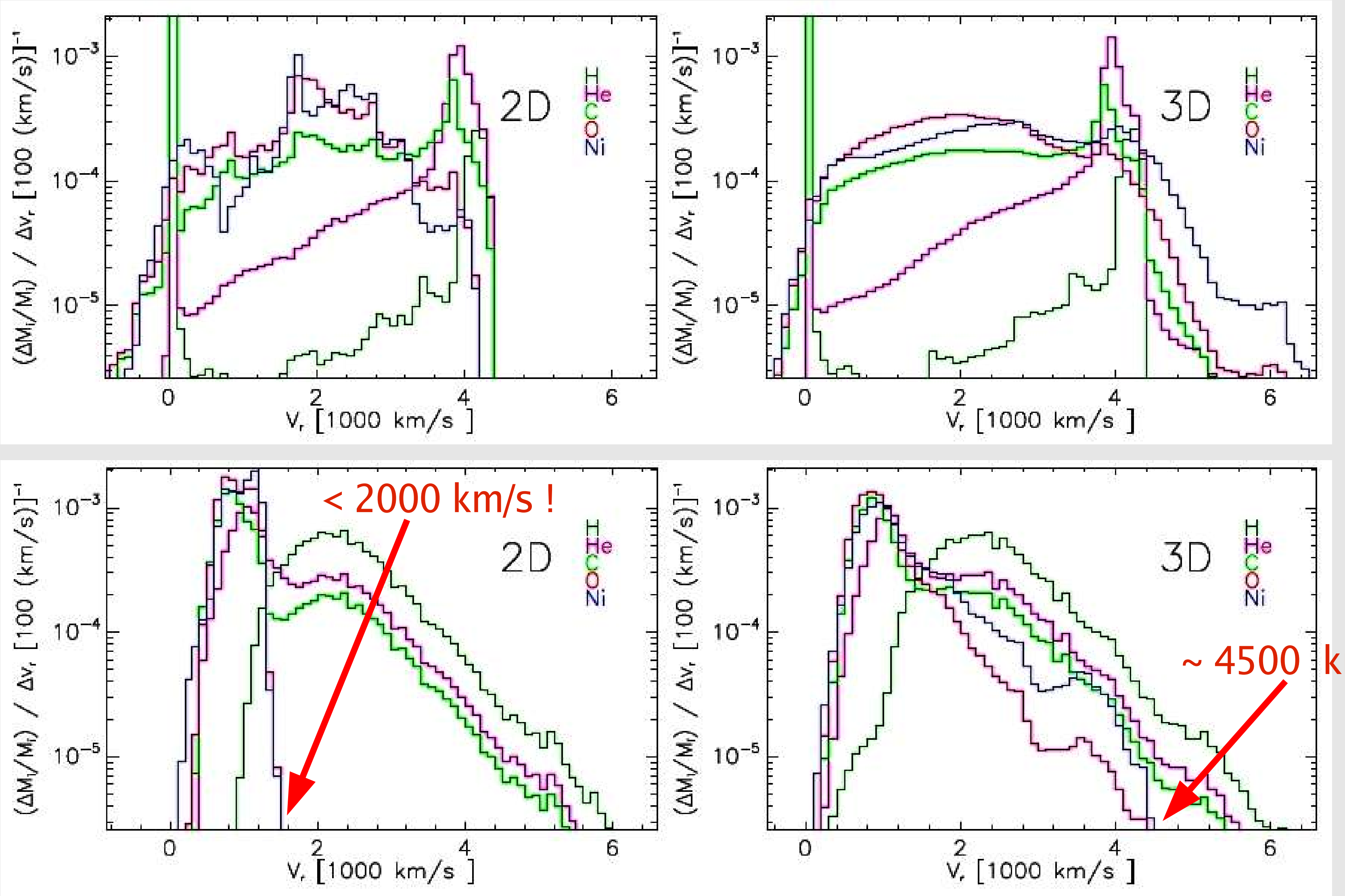
# Mixing Instabilities in 3D SN Models



green: carbon
red: oxygen
blue: nickel

(Hammer, Janka, Müller, submitted)

# Mixing Instabilities in 3D SN Models



< 2000 km/s !

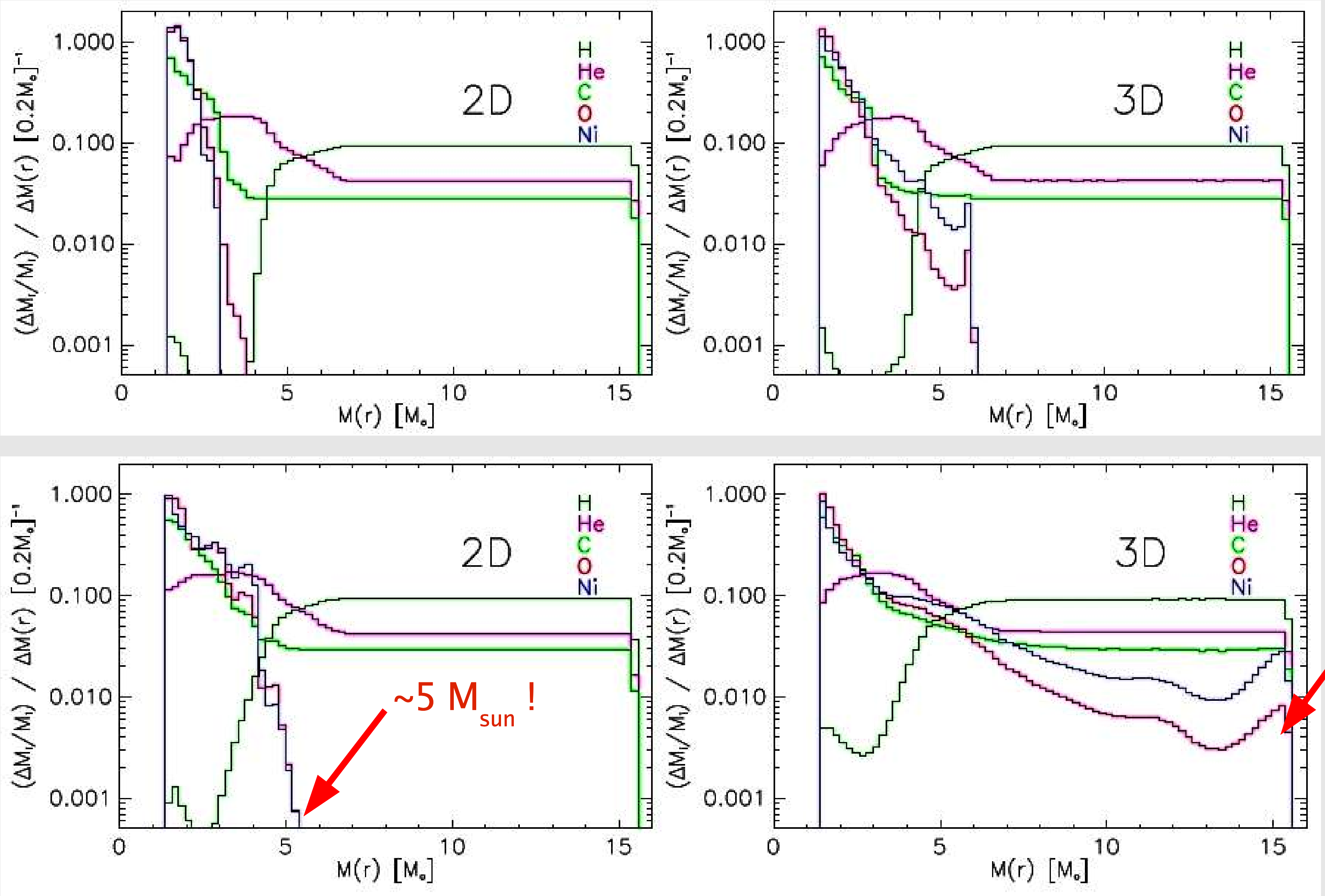
~ 4500 km/s !

350 s

9000 s

- In 3D Rayleigh-Taylor instabilities grow faster ===> clumps with higher initial velocities
- In 3D drag forces are smaller ===> less deceleration of propagating clumps

# Mixing Instabilities in 3D SN Models



350 s

~5 M$_{sun}$ !

~15 M$_{sun}$ !

9000 s

- In 3D mixing much more efficient; very fast metal clumps with up to several $10^{-3}$ M$_{sun}$
- Onion-shell structure of progenitor is turned over: Fe overtakes O, O faster than C

# Explosions of $M_{star} \sim 8–10\ M_{sun}$ Stars

# SN Progenitors: Core density profiles

~8–10 $M_{sun}$ (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface

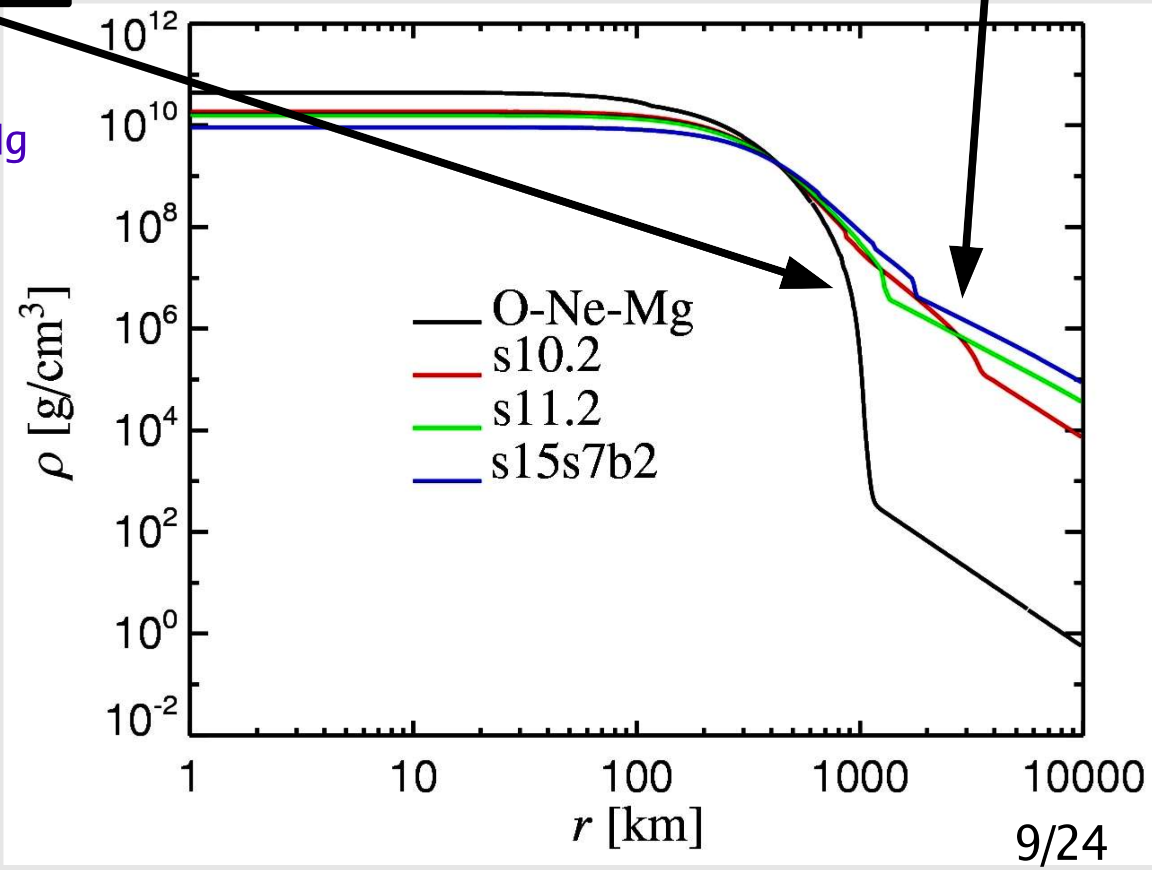
(====> rapidly decreasing mass accretion rate after core bounce)

>10 $M_{sun}$ stars have much higher densities outside of their Fe cores

(e.g. Heger et al., Limongi et al.,Nomoto et al., Hirschi et al.)

(====> ram pressure of accreted mass decreases slowly after core bounce)

8.8 $M_{sun}$ progenitor model (Nomoto 1984):
2.2 $M_{sun}$ H+He, 1.38 $M_{sun}$ C+O, 1.28 $M_{sun}$ ONeMg



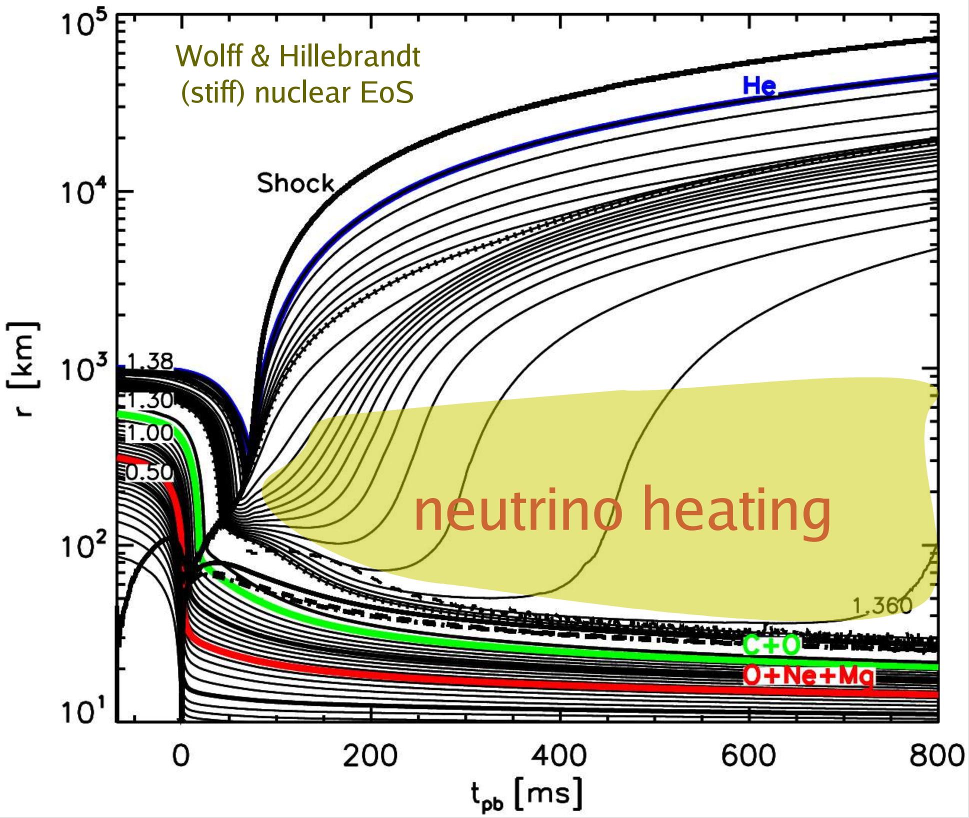
~30% of all SNe (Nomoto et al. 1981, 84, 87)

(8.75 $M_{sun}$ < $M_{ZAMS}$ < 9.25 $M_{sun}$: < 20% of all SNe; Poelarends et al., A&A 2006)

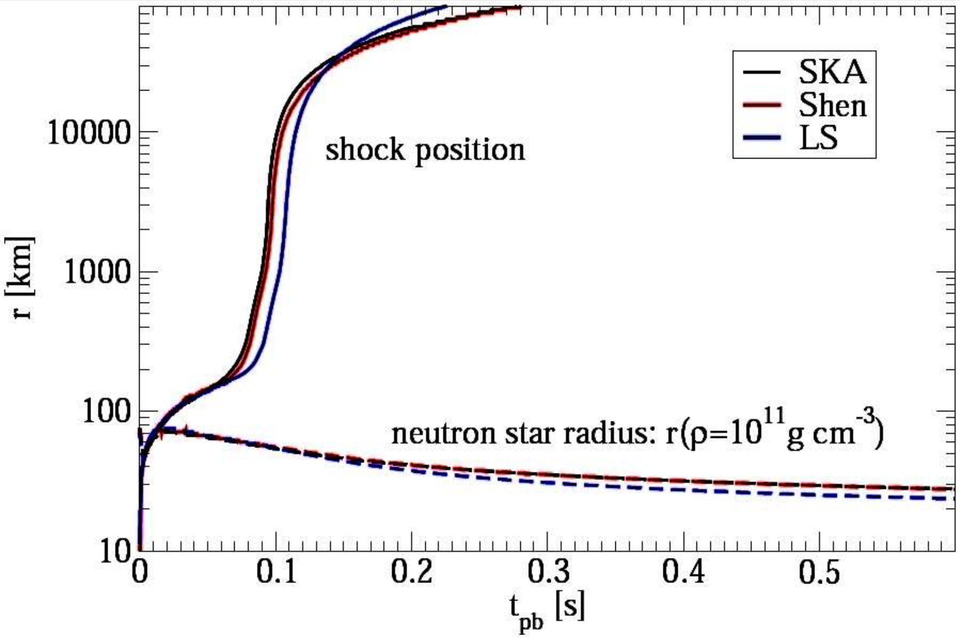
# SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

"Electron-capture supernovae"
or "ONeMg core supernovae"

- No prompt explosion !
- Mass ejection by “neutrino-driven wind”
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



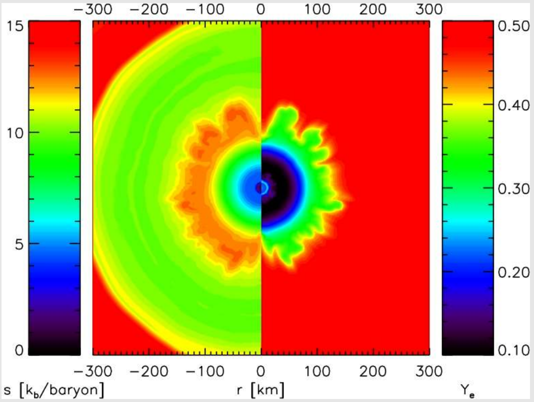
Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199



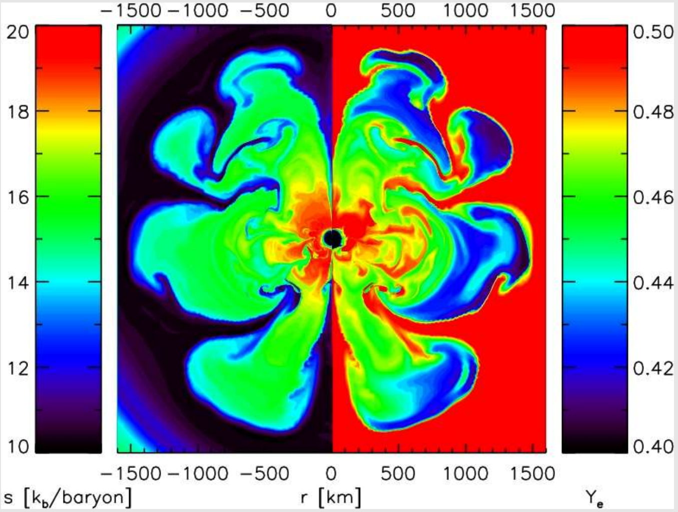
Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer

# SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

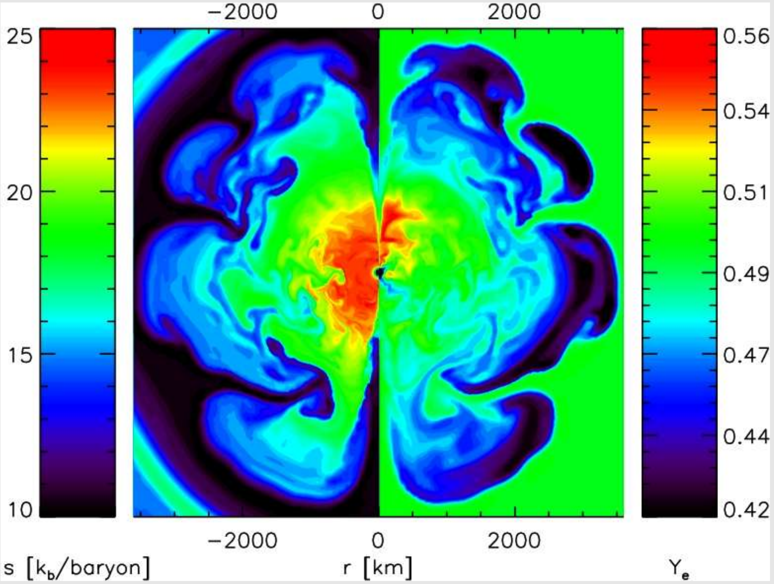
Convection leads to slight increase of explosion energy and causes explosion asymmetries



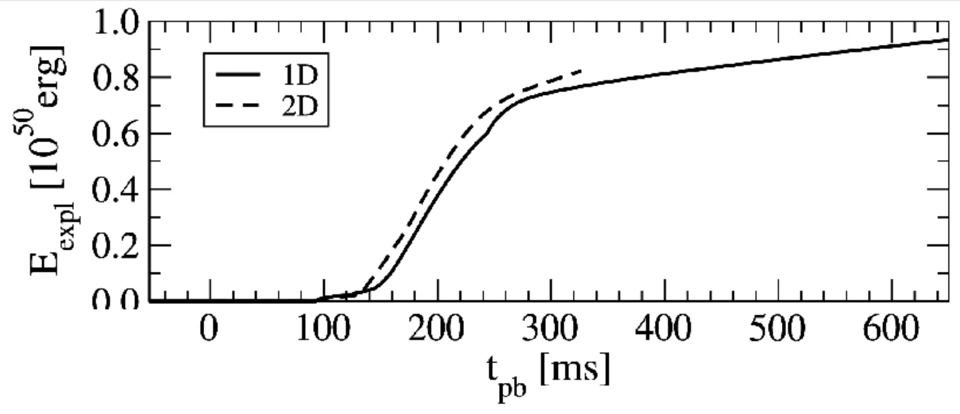
t = 0.097 s  after core bounce



t = 0.144 s  after core bounce



t = 0.262 s  after core bounce

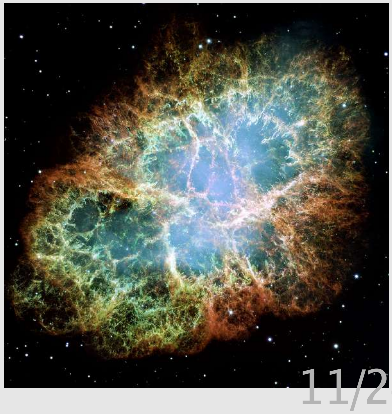


Müller et al.  (in preparation)

Low explosion energy and ejecta composition – little Ni, C, O – of CRAB (SN1054) is compatible with ONeMg core explosion

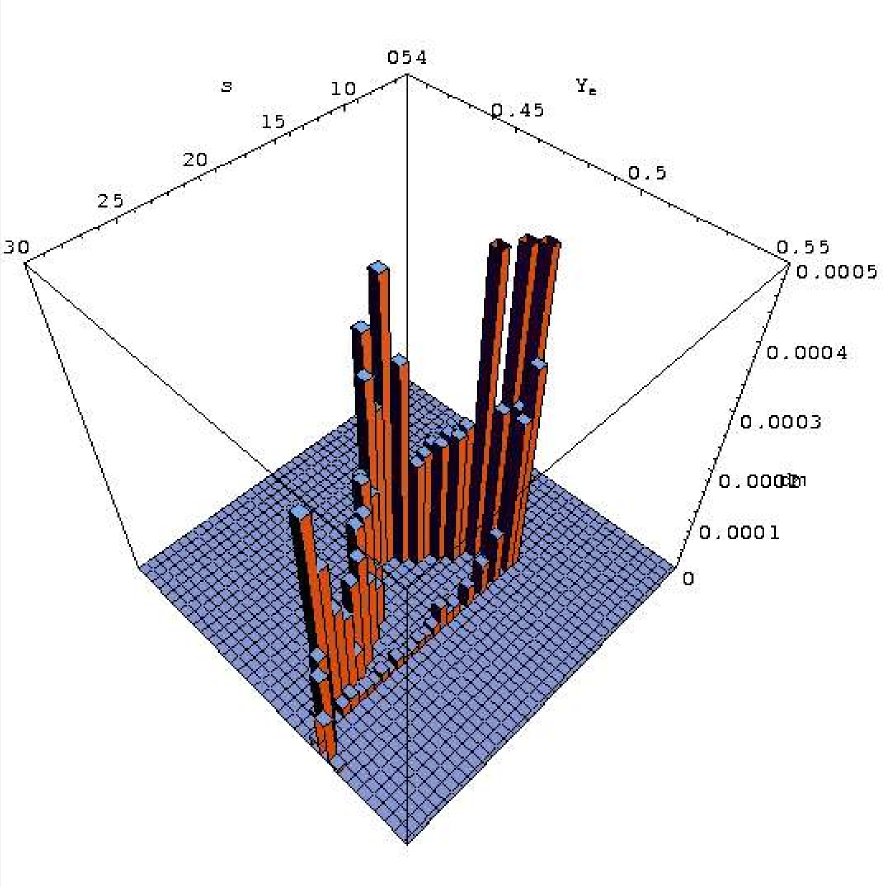
(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

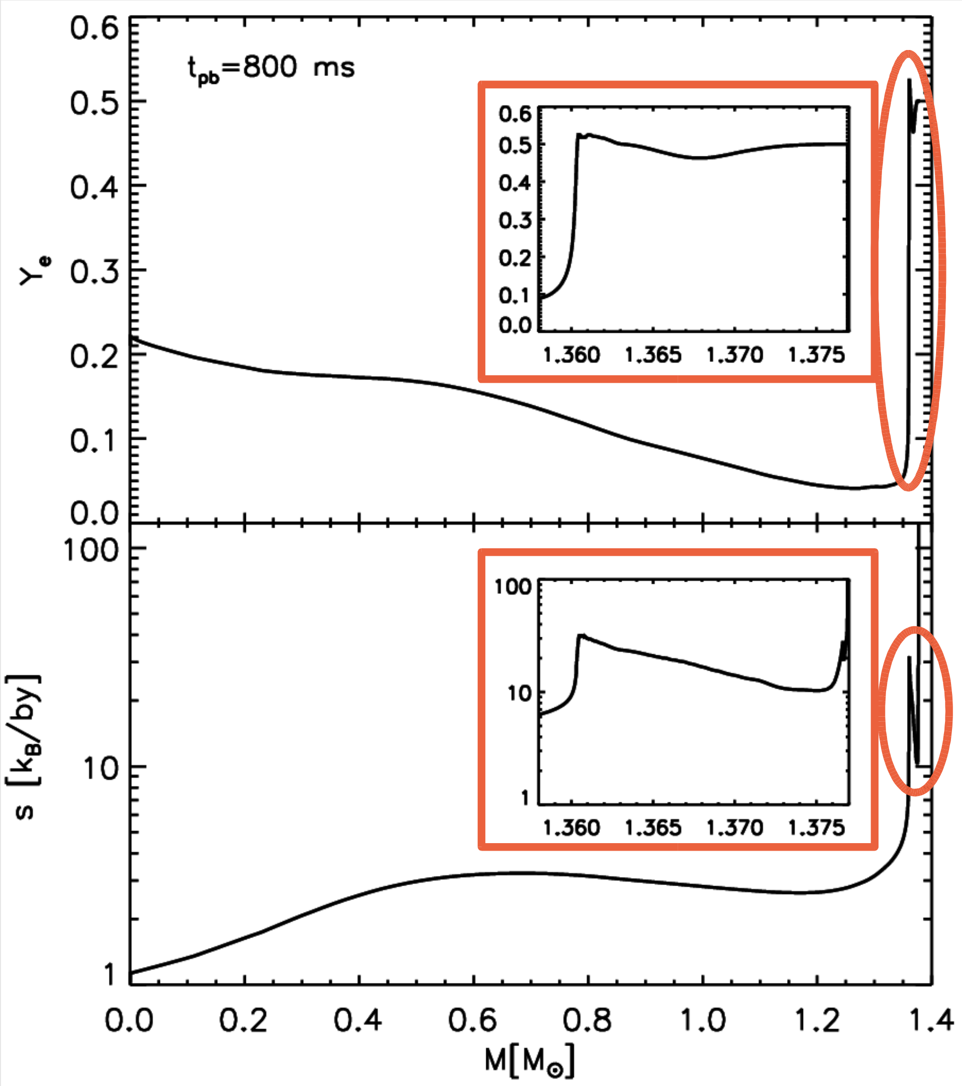
Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)



# O-Ne-Mg Core Supernovae: Ejecta

- Early SN ejecta have $Y_e$ around 0.5 and even $Y_e > 0.5$
- Entropies are ~10 $k_B$ per nucleon, but strong increase for ejected matter in steep gradient at core surface





# Nucleosynthesis in O-Ne-Mg Core SNe

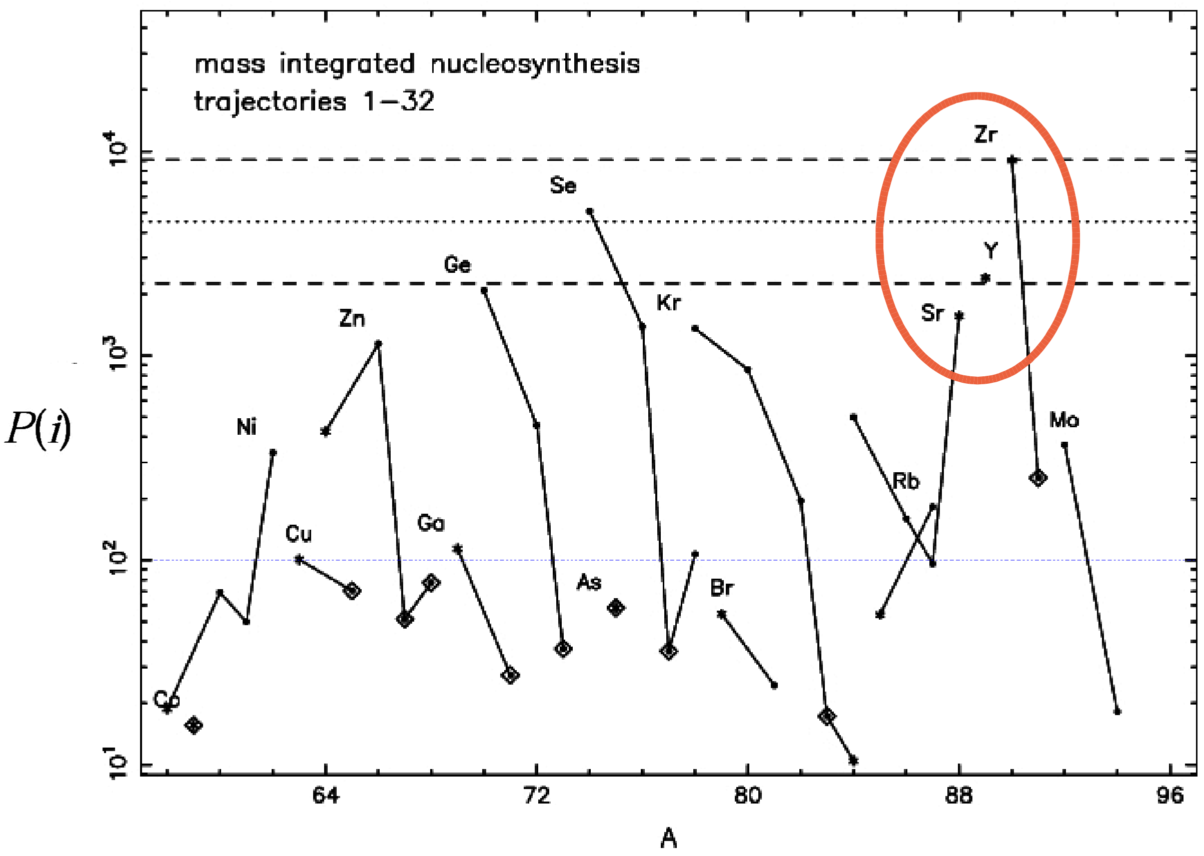
- No r-processing in the early ejecta

  (in contradiction to suggestion by Ning et al. 2007)

- Mass cut: $M_{cut} = 1.363\ M_{sun}$
- Ejecta mass: $M_{ej} = 1.263\ M_{sun}$
- Nucleosynthesis mass yield: $M_{nucsyn} \sim 1.5*10^{-2}\ M_{sun}$
- Mass-weighted production factors of nuclides i in all ejecta shells j, normalized to total amount of ejecta:

$$P(i) = \sum_j \frac{M_j}{M^{ej}} \frac{X_j(i)}{X_{\odot,i}}$$

Hoffman, Janka, Müller, ApJL (2008), similar results by Wanajo et al. (2009)

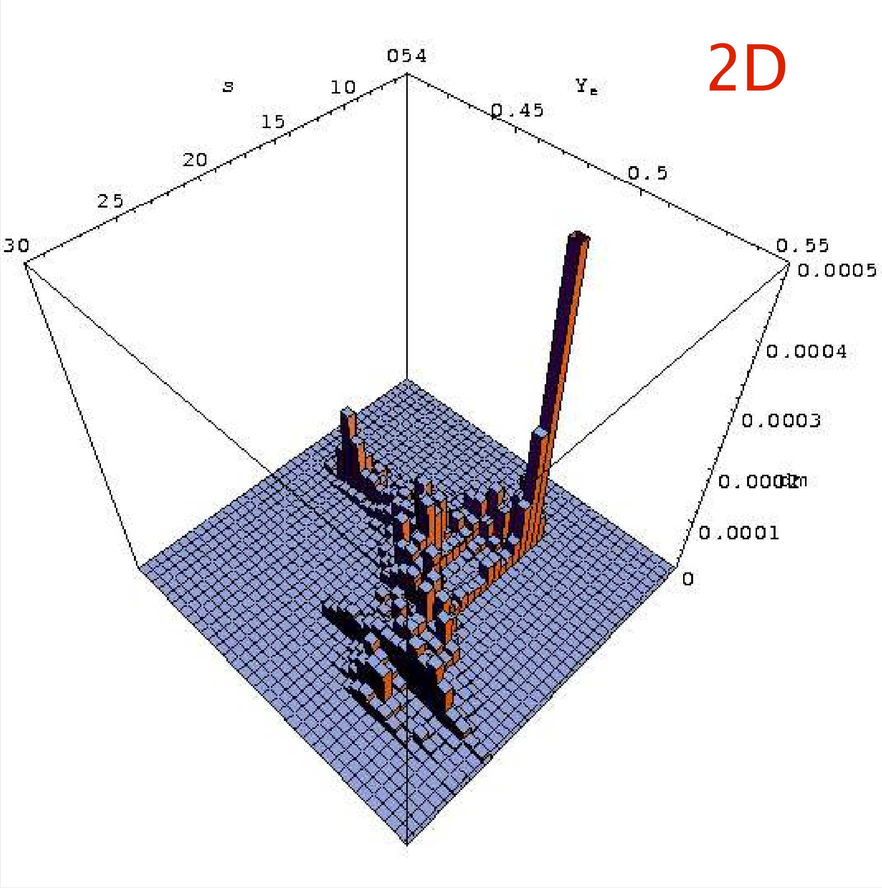


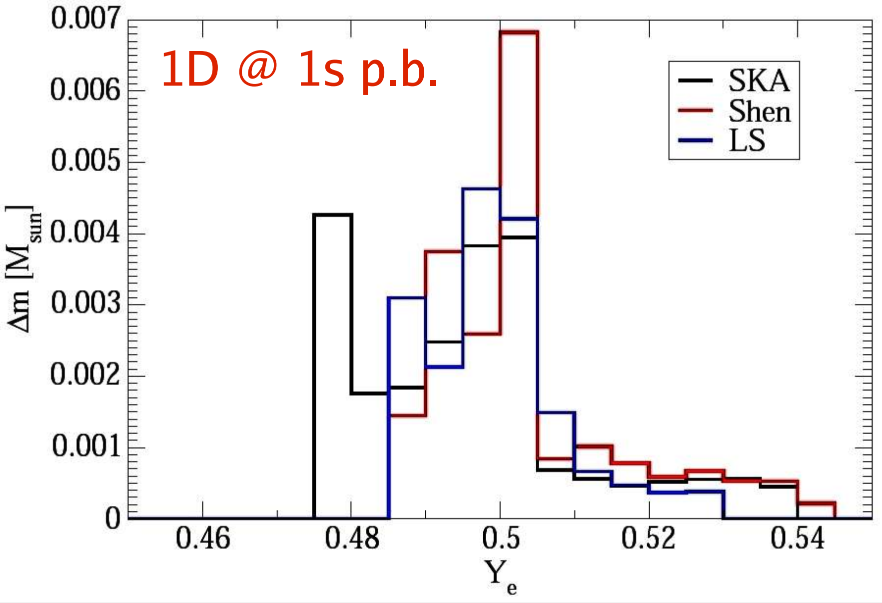
* To be compatible with Galactic chemical abundances: P(i) < 100 (if ~10% of all SNe are O-Ne-Mg core collapses).

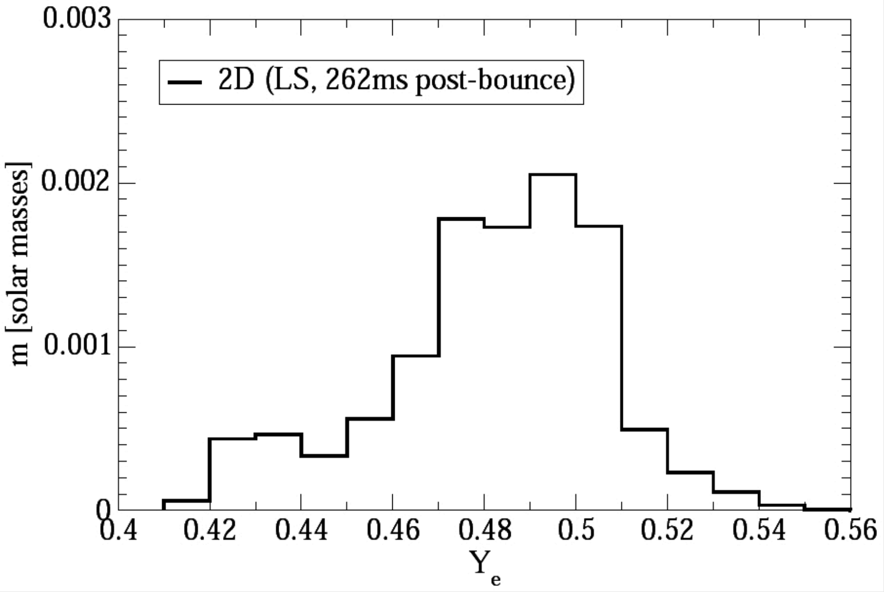
* Massive overproduction (10–50 times solar value over history of Galaxy) of N=50 closed neutron-shell nuclei $^{88}$Sr, $^{89}$Y, $^{90}$Zr, because $\sim 5.5*10^{-3}\ M_{sun}$ are ejected with $Y_e < 0.47$ and low entropies (s ~ 20 $k_B$/nucleon).

# Nucleosynthesis in O-Ne-Mg Core SNe

- ~2% increase of minimum $Y_e$ removes overproduction problem (Wanajo et al. 2009)
- Slightly improved neutrino treatment indeed causes required $Y_e$ increase!
- But: 2D effects go in opposite direction!



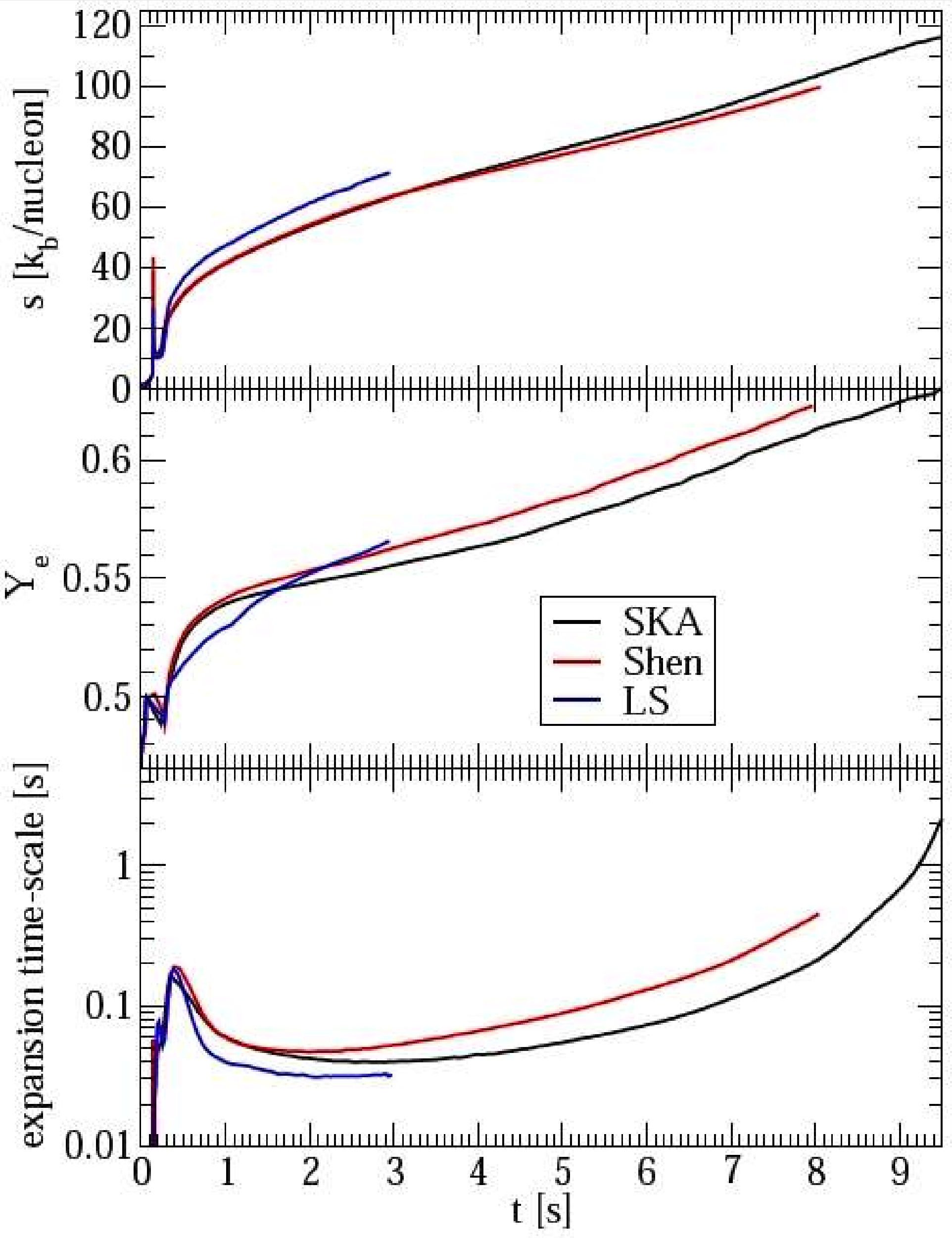




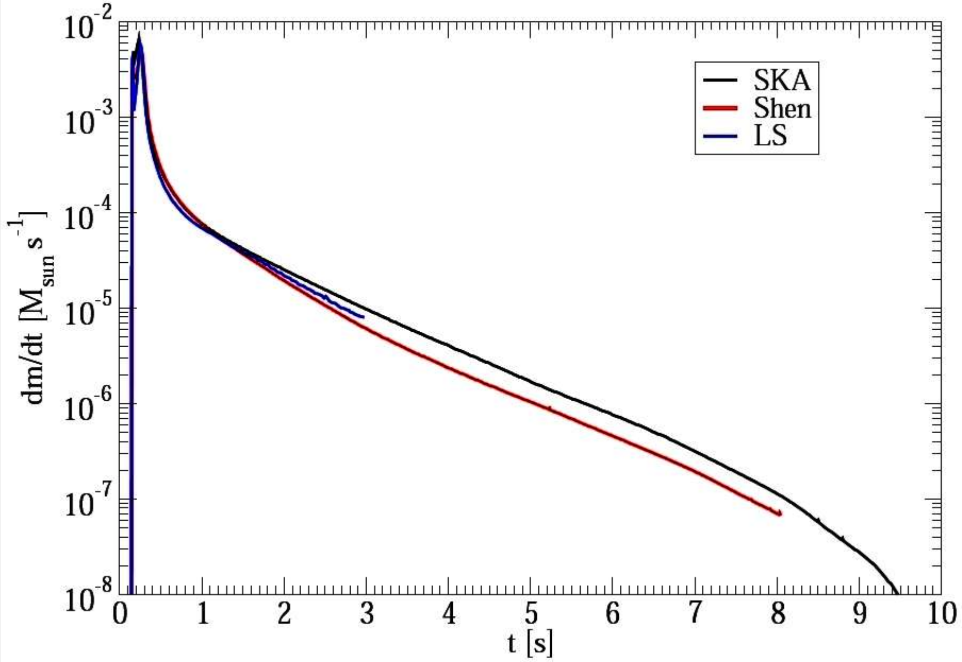
(Müller & Janka, in preparation)

# Nucleosynthesis in O-Ne-Mg Core SNe

- Neutrino-driven wind remains p-rich for >10 seconds!
- No r-process in the late neutrino-driven wind!



Hüdepohl (Diploma Thesis 2009)



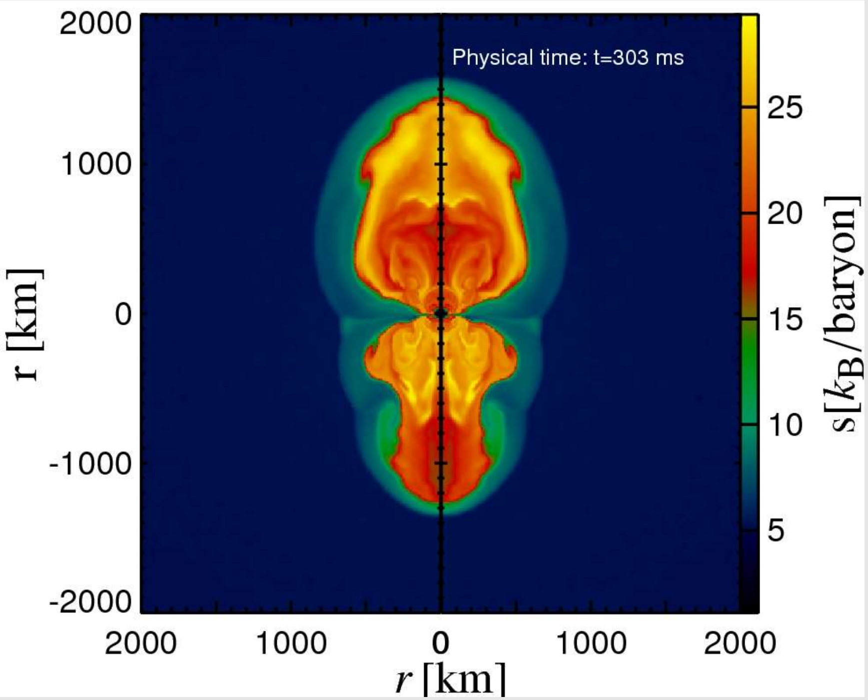
# Explosions of $M_{star} > 10\ M_{sun}$ Stars

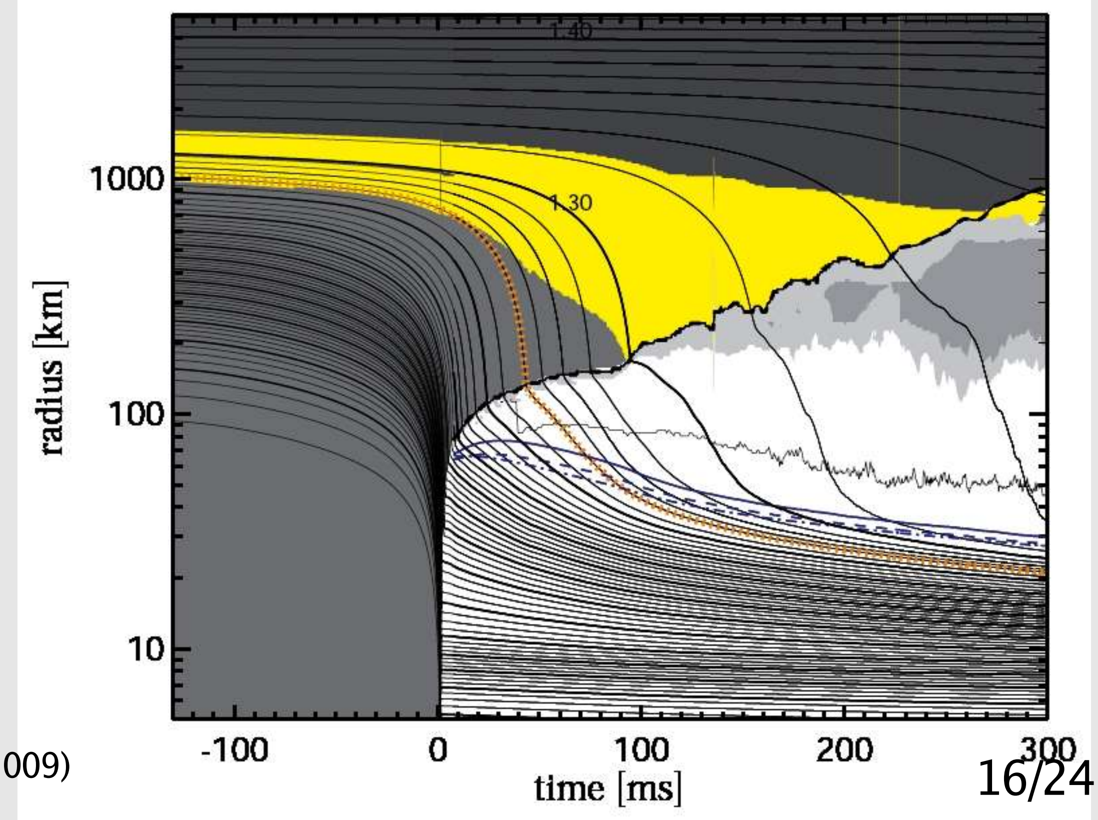
# 2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

For explosions of stars with $M > 10\ M_{sun}$ multi-dimensional effects (nonradial hydrodynamic instabilities) are crucial !

Low-mode nonradial (dipole, l=1, and quadrupole, l=2) "standing accretion shock instability" ("SASI"; Blondin et al. 2003) develops and pushes shock to larger radii

===> This stretches residency time of matter in neutrino heating layer and thus increases neutrino energy deposition;
Initiation of globally aspherical explosion by neutrino heating even without rotation

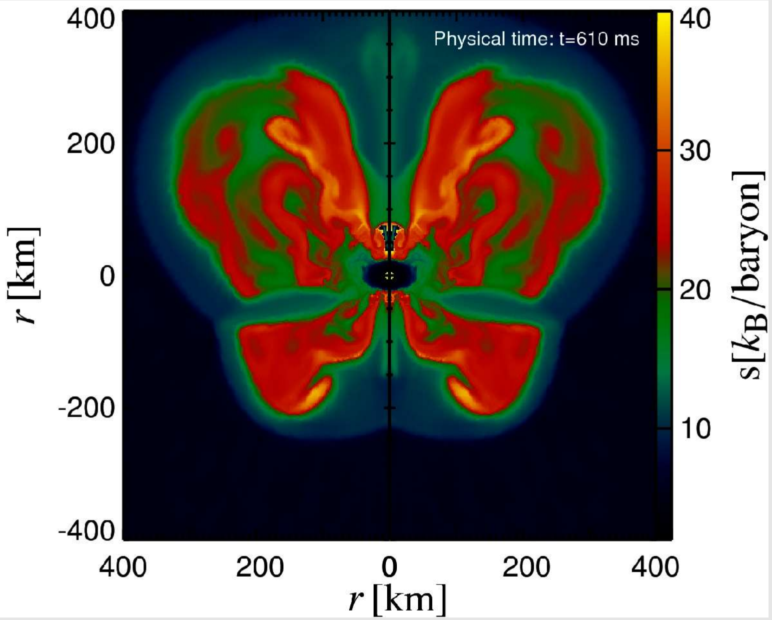


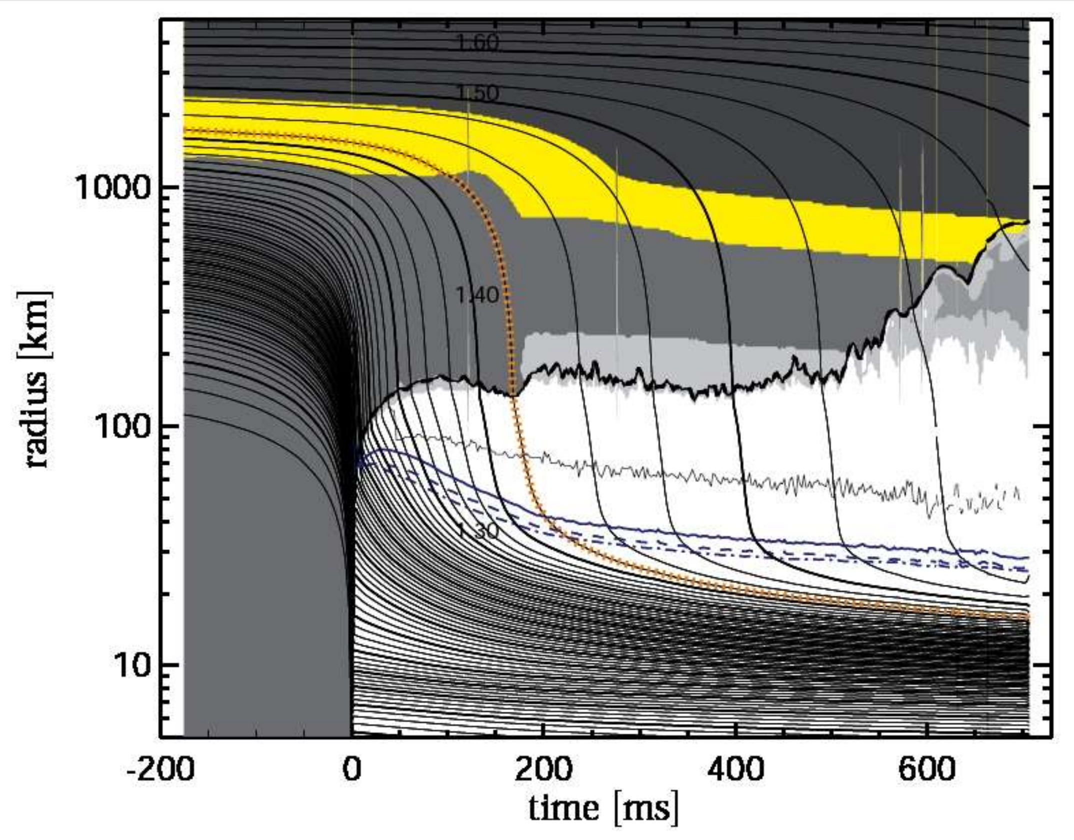


Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2009)

# 2D SN Simulations: $M_{\mathrm{star}} = 15\ M_{\mathrm{sun}}$

Violent SASI oscillations,
ν-driven explosion sets in
at t ~ 600 ms after bounce





(Marek, PhD Thesis 2007;
Marek & THJ, ApJ, 2009)

# Explosion Energies and NS masses

$$E_{\rm exp} \approx \dot{E}_\nu \tau_{\rm acc} + E_{\rm wind} + E_{\rm burn} - E_{\rm bind}$$

$$\begin{aligned}\dot{E}_\nu &\sim \zeta \dot{M}_{\rm acc} \dot{q}_\nu \tau_{\rm adv} \\ &\sim 2 \times 10^{51}\, \frac{\rm erg}{\rm s} \left(\frac{\zeta}{0.5}\right) \left(\frac{\dot{M}_{\rm acc}}{0.2\, M_\odot/{\rm s}}\right) \times \\ &\quad \times \left(\frac{\dot{q}_\nu m_{\rm B}}{300\,{\rm MeV/s}}\right) \left(\frac{\tau_{\rm adv}}{30\,{\rm ms}}\right)\end{aligned}$$

($E_{exp}$ depends on the duration of simultaneous accretion & outflow after onset of explosion: $t_{acc}$~0.5 sec)

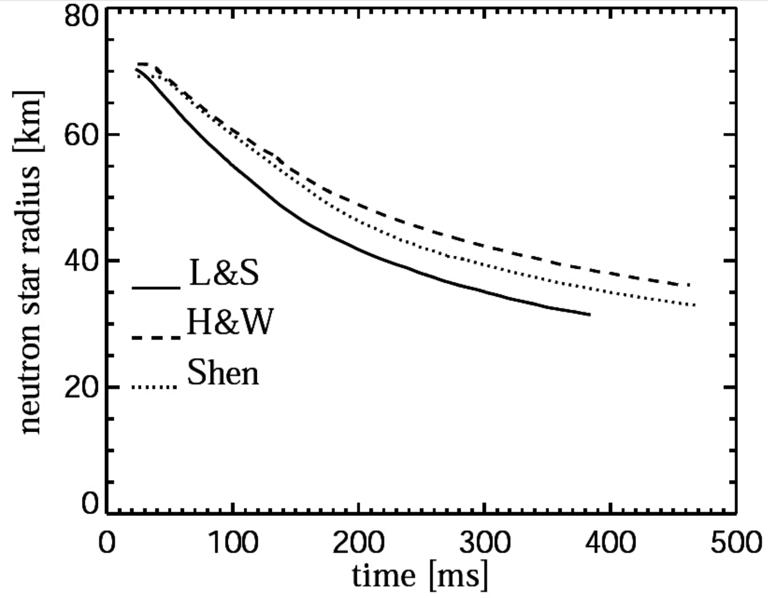
$$\tau_{\rm acc} \approx \frac{R_{\rm esc}}{v_{\rm s}} \sim 0.5\,{\rm s}\; M_{1.5}\, v_{\rm s,9}^{-3}$$

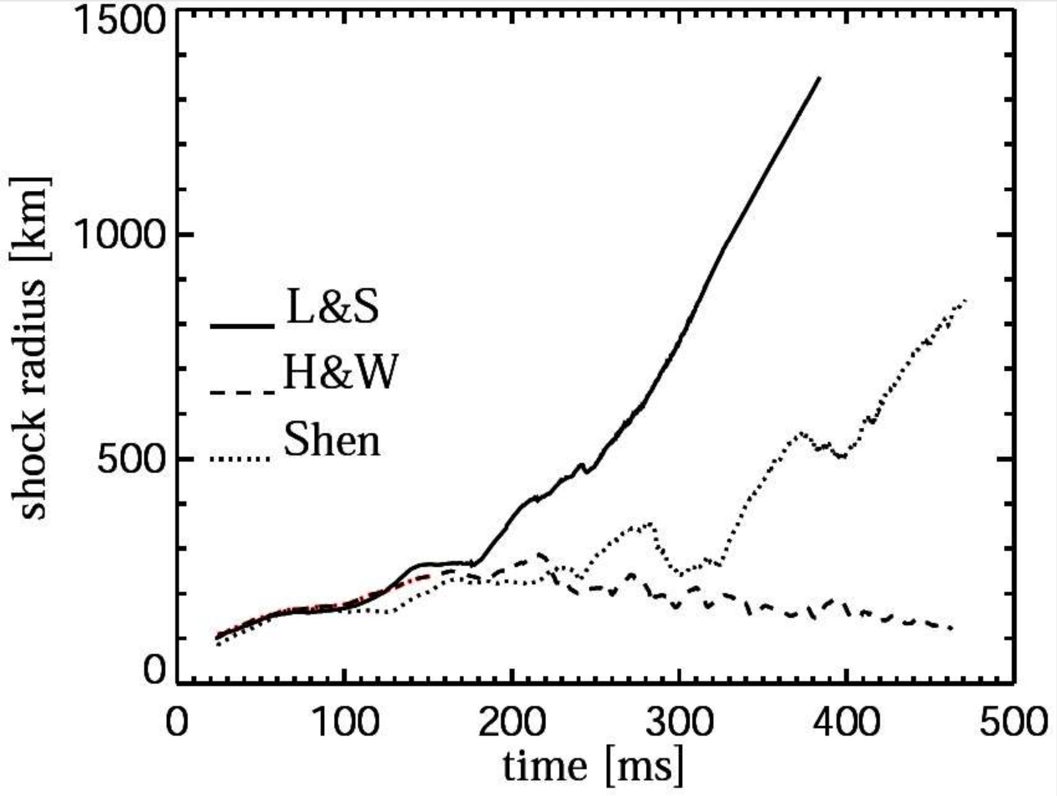
| Stellar mass<br>[$M_{sun}$] | $t_{exp}$<br>[ms] | $\Delta M_{gain}$<br>[$M_{sun}$] | $E_{exp}$<br>[B] | $M_{ns}$(baryonic)<br>[$M_{sun}$] |
|---|---|---|---|---|
| 8 – 10 | 150 | < 0.01 | 0.1 – 0.2 | 1.35 |
| ~11 | 250 | 0.01 | 0.2 – 0.4 | 1.30 |
| 15 | 620 | 0.08 | ~ 1.0 | 1.55 |

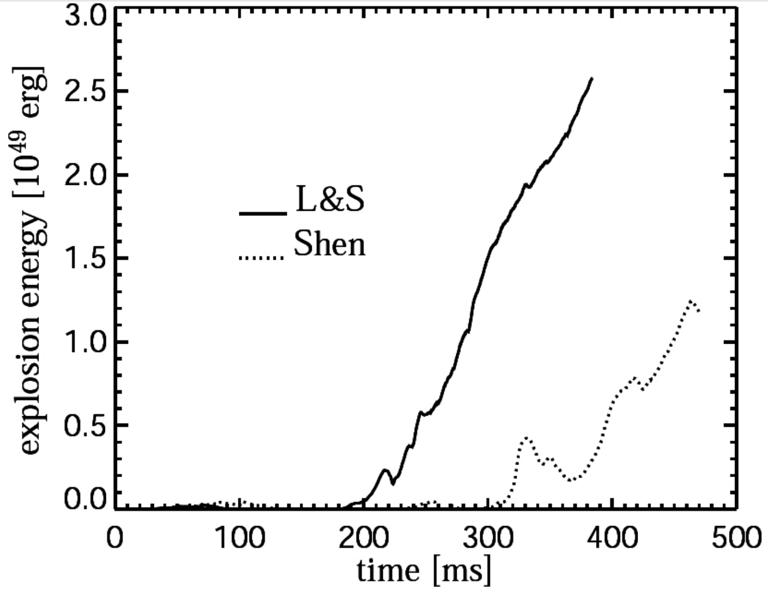
NOTE: The stellar properties do not vary monotonically with the progenitor mass (cf. Woosley, Heger, & Weaver 2005)

# 2D Explosions of 11.2 $M_{sun}$ star : Test of EoS Influence

- Simulations for 3 different nuclear EoSs: Lattimer & Swesty (L&S), Hillebrandt & Wolff (H&W), Shen et al.
- “Softer” (L&S) EoS and thus more compact PNS leads to earlier explosion

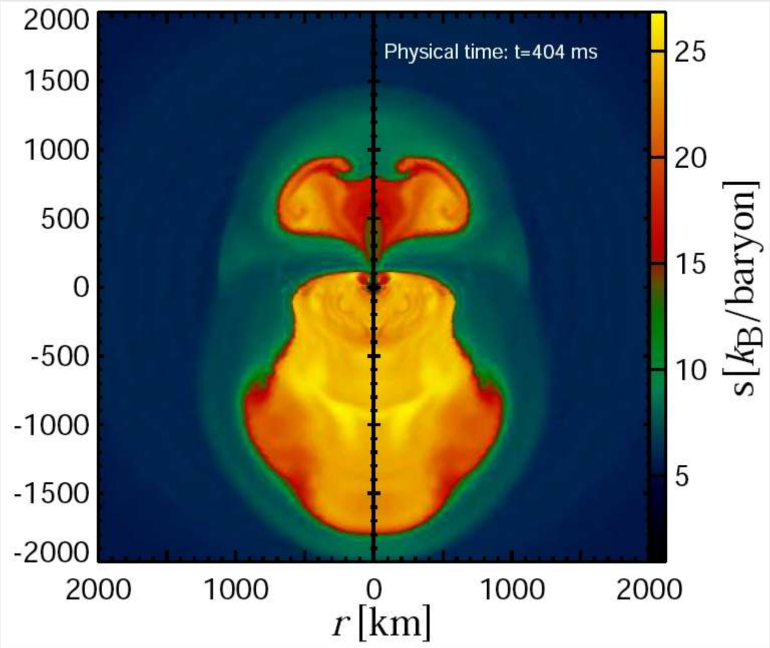




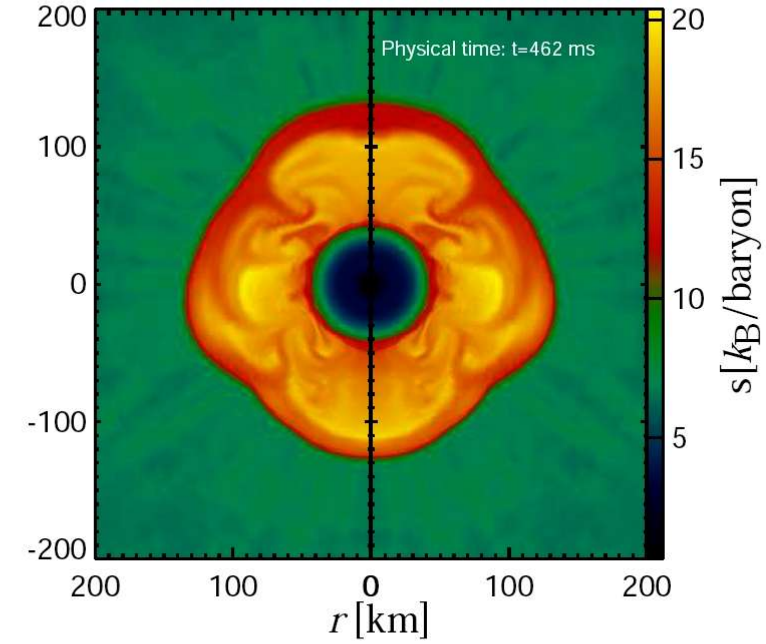


(Marek & THJ, 2009, in preparation)

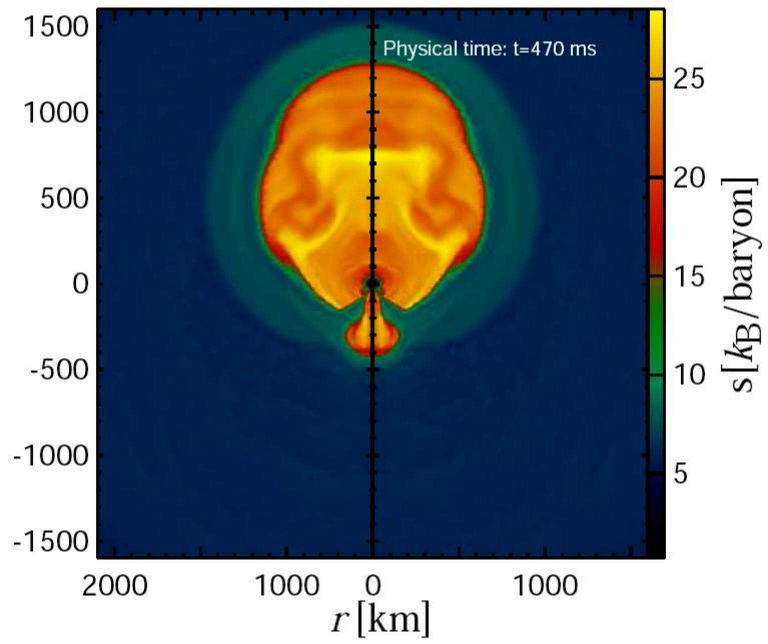
# 2D Explosions of 11.2 $M_{sun}$ star : Test of EoS Influence



L&S EoS, t ~ 400 ms p.b.



H&W EoS, t ~ 460 ms p.b.

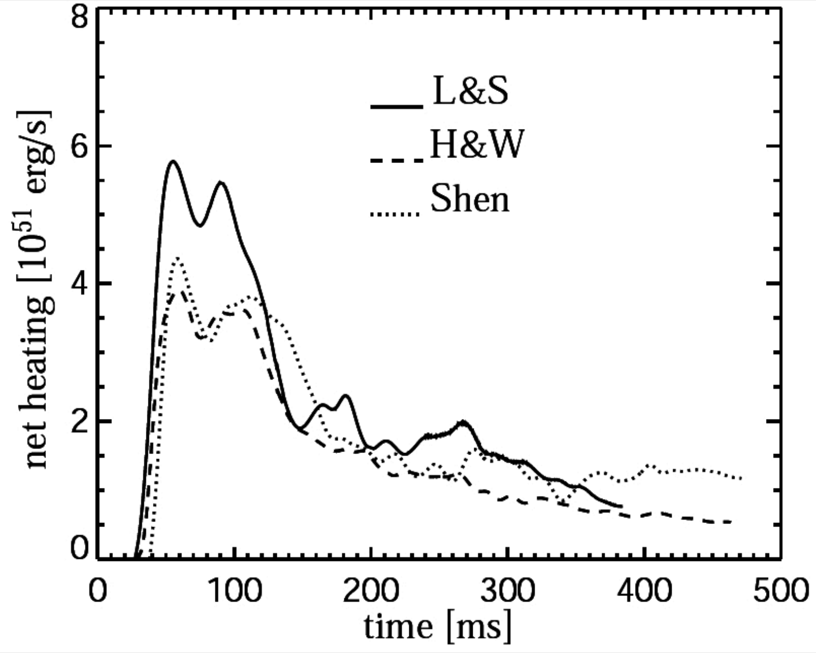


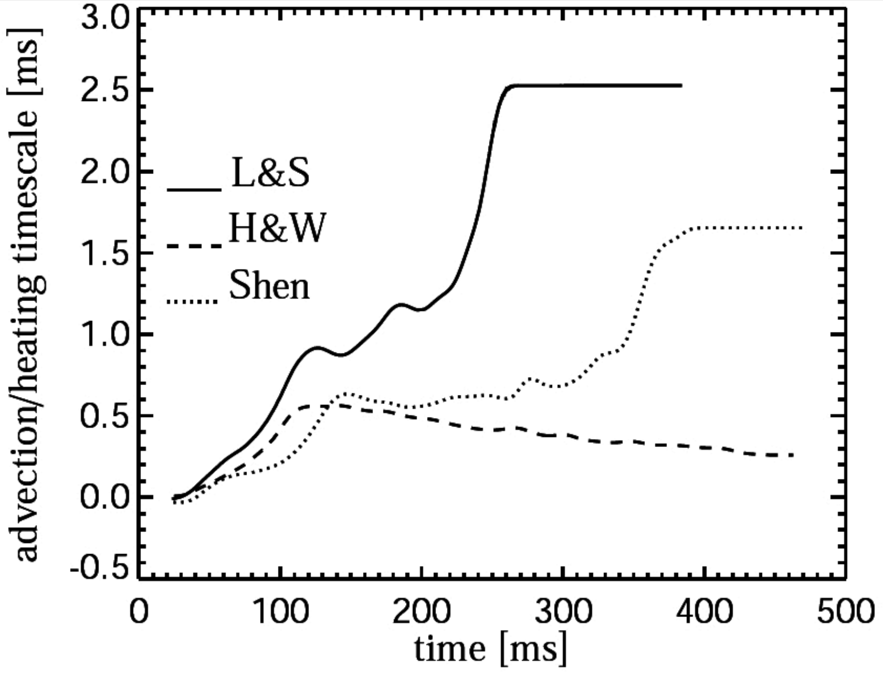
Shen EoS,
t ~ 470 ms p.b.

(Marek & THJ, 2009,
in preparation)

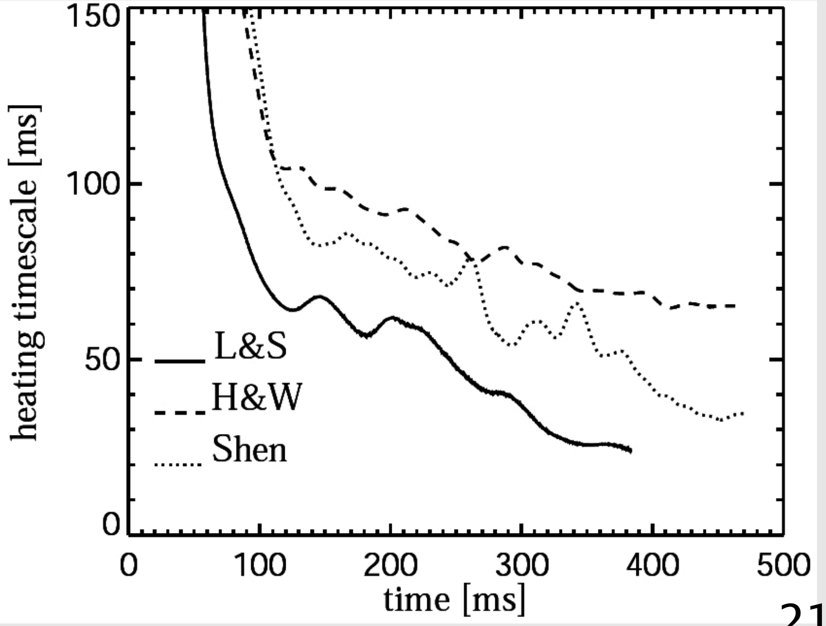
# 2D Explosions of 11.2 $M_{sun}$ star : Test of EoS Influence

- Neutrino-heating timescale decreases with time.
- Advection timescale of matter from shock to neutron star surface increases with time.
- Both evolve favorably for explosion at later times after core bounce.





(Marek & THJ, 2009, in preparation)



# 2D GR Models with Neutrino Transport

- New 2D general relativistic supernova code with ray-by-ray 2D neutrino transport was developed by Bernhard Müller

  (combining CoCoNuT CFC hydrodynamics code of Dimmelmeier with VERTEX neutrino transport program of Rampp & Janka, Buras)

- Excellent agreement of results in 1D with AGILE-BOLTZTRAN (Liebendörfer & Mezzacappa) and VERTEX

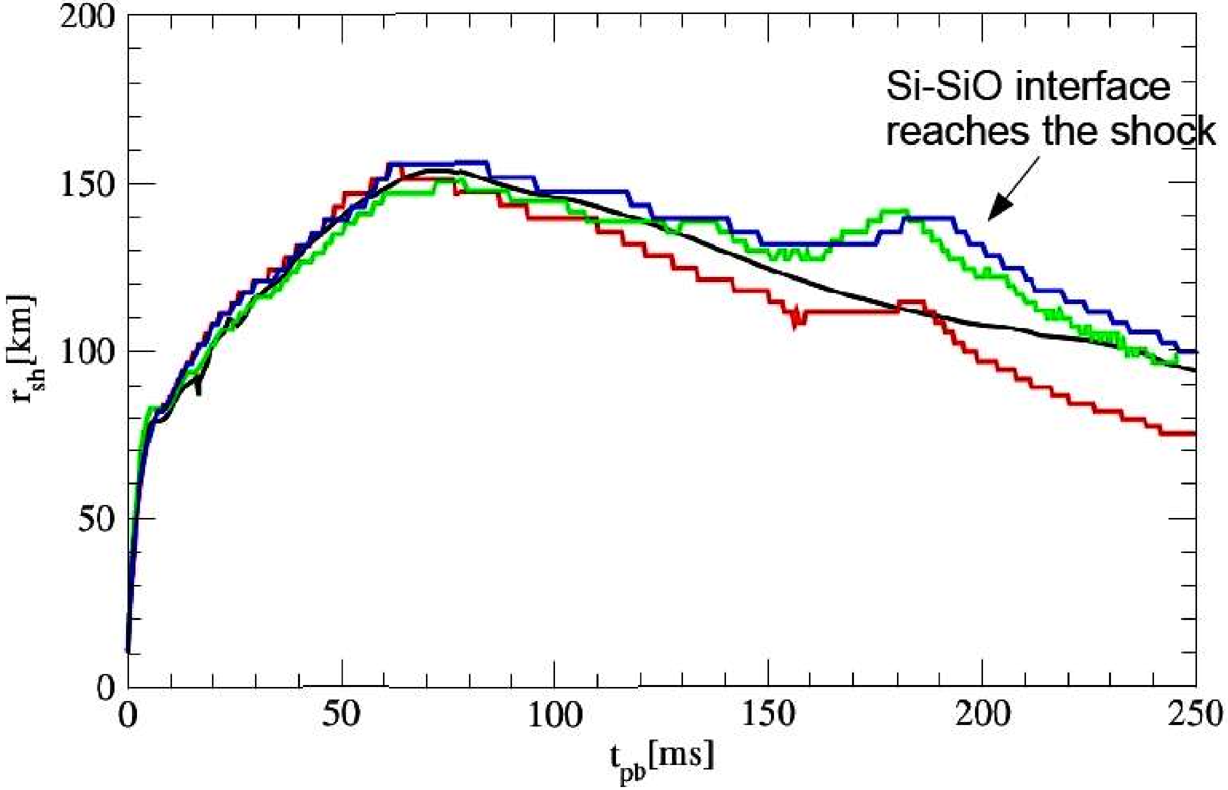


Figure 4.9.: Time evolution of the shock position for model G15 in AGILE-BOLTZTRAN (black), VERTEX-CoCoNuT (green), and VERTEX-PROMETHEUS with the effective potentials A and R (blue, red).

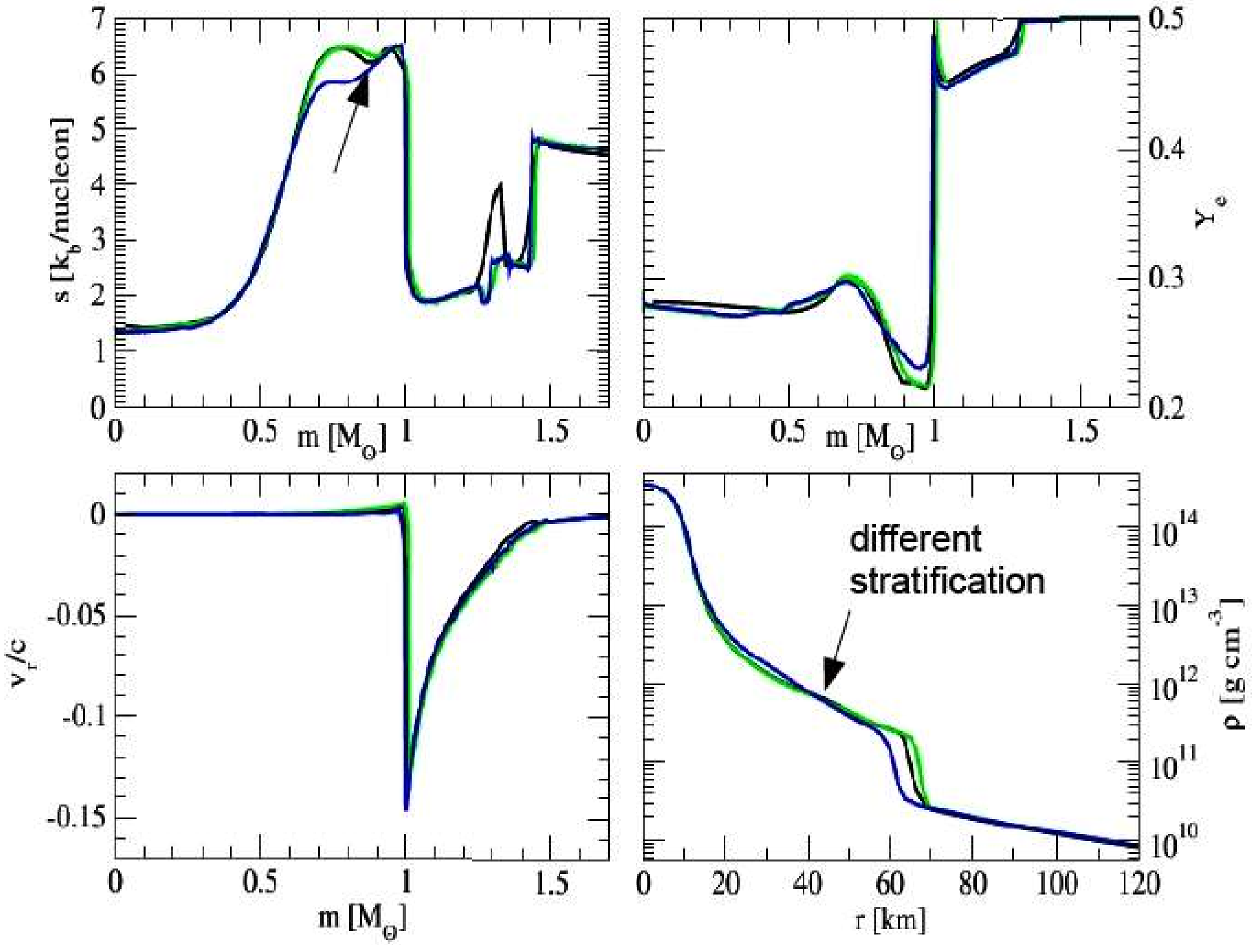
(B. Müller, PhD Thesis, 2009)

# 2D GR Models with Neutrino Transport

- New 2D general relativistic supernova code with ray-by-ray 2D neutrino transport was developed by Bernhard Müller

  (combining CoCoNuT CFC hydrodynamics code of Dimmelmeier with VERTEX neutrino transport program of Rampp & Janka, Buras)

- Excellent agreement of results in 1D with AGILE-BOLTZTRAN (Liebendörfer & Mezzacappa) and VERTEX



Profiles entropy, electron fraction, velocity and density 3ms after bounce obtained with AGILE (black), CoCoNuT (green), and PROMETHEUS (blue)

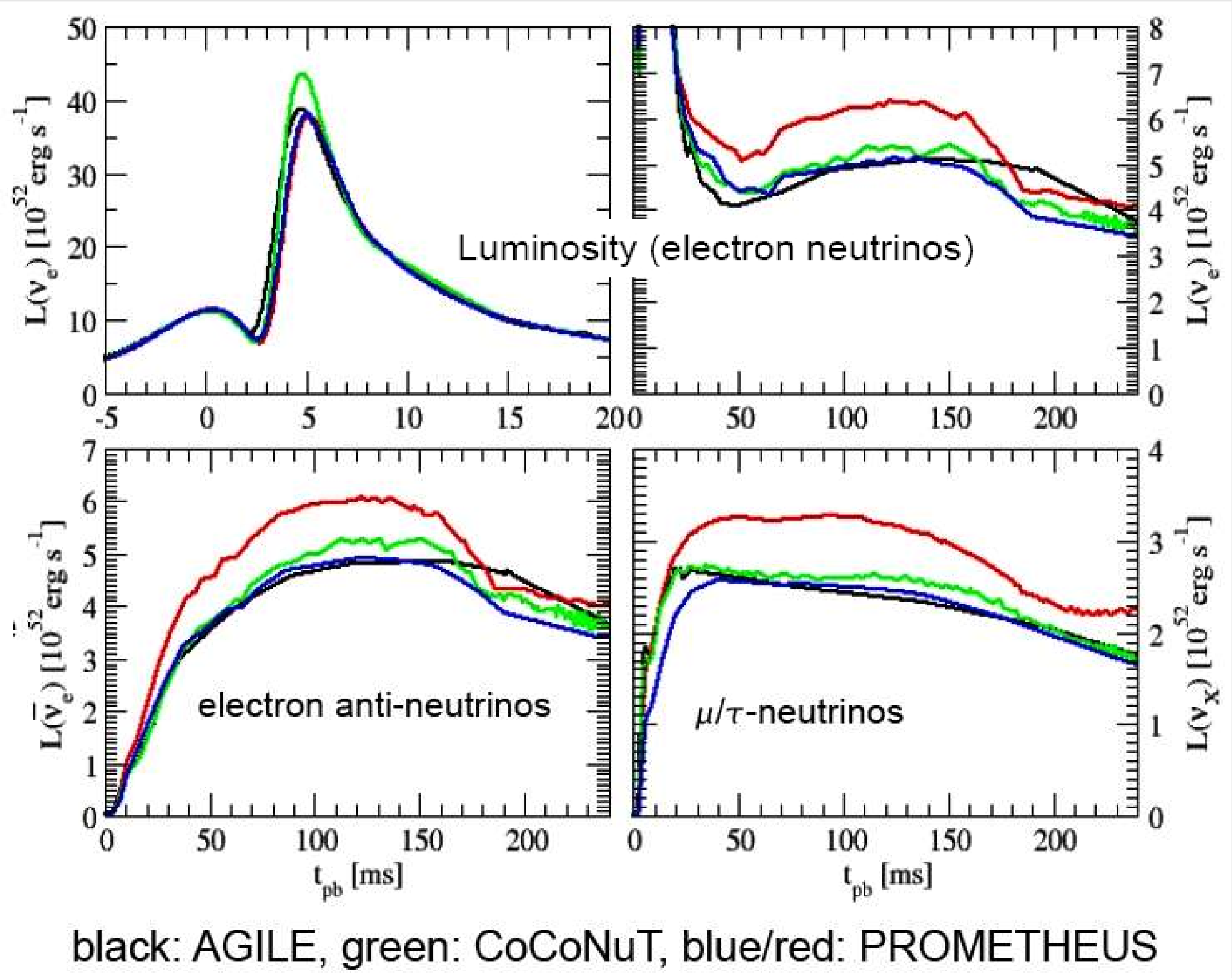
(B. Müller, PhD Thesis, 2009)

# 2D GR Models with Neutrino Transport

- New 2D general relativistic supernova code with ray-by-ray 2D neutrino transport was developed by Bernhard Müller

  (combining CoCoNuT CFC hydrodynamics code of Dimmelmeier with VERTEX neutrino transport program of Rampp & Janka, Buras)

- Excellent agreement of results in 1D with AGILE-BOLTZTRAN (Liebendörfer & Mezzacappa) and VERTEX

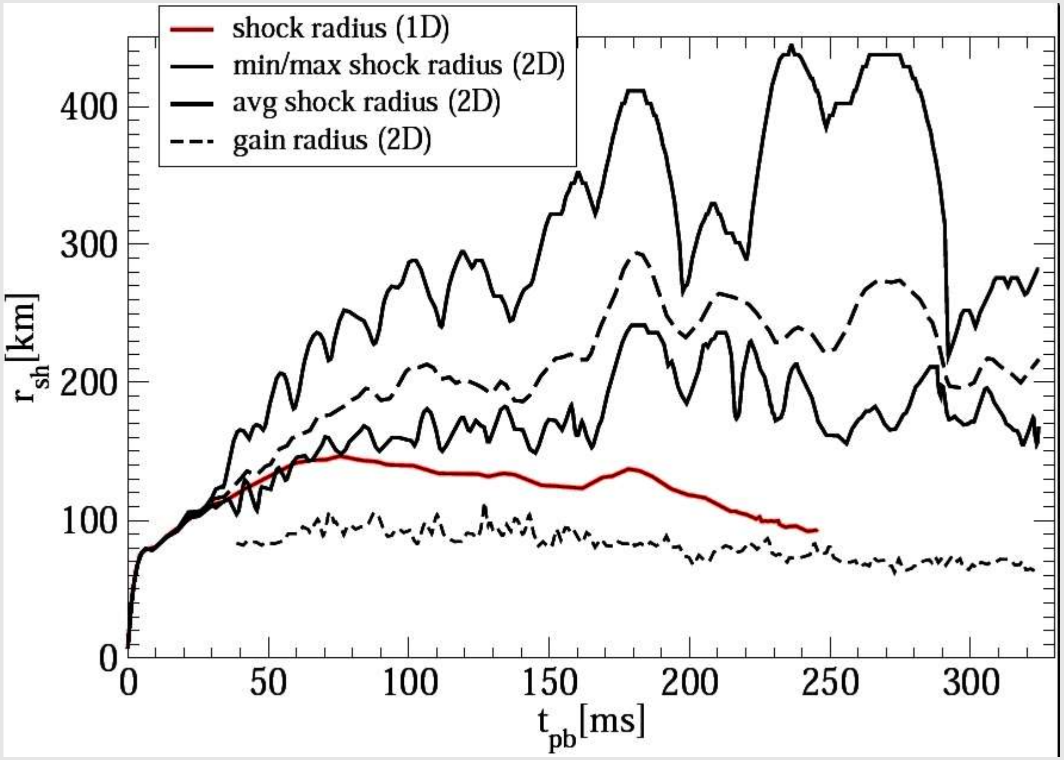


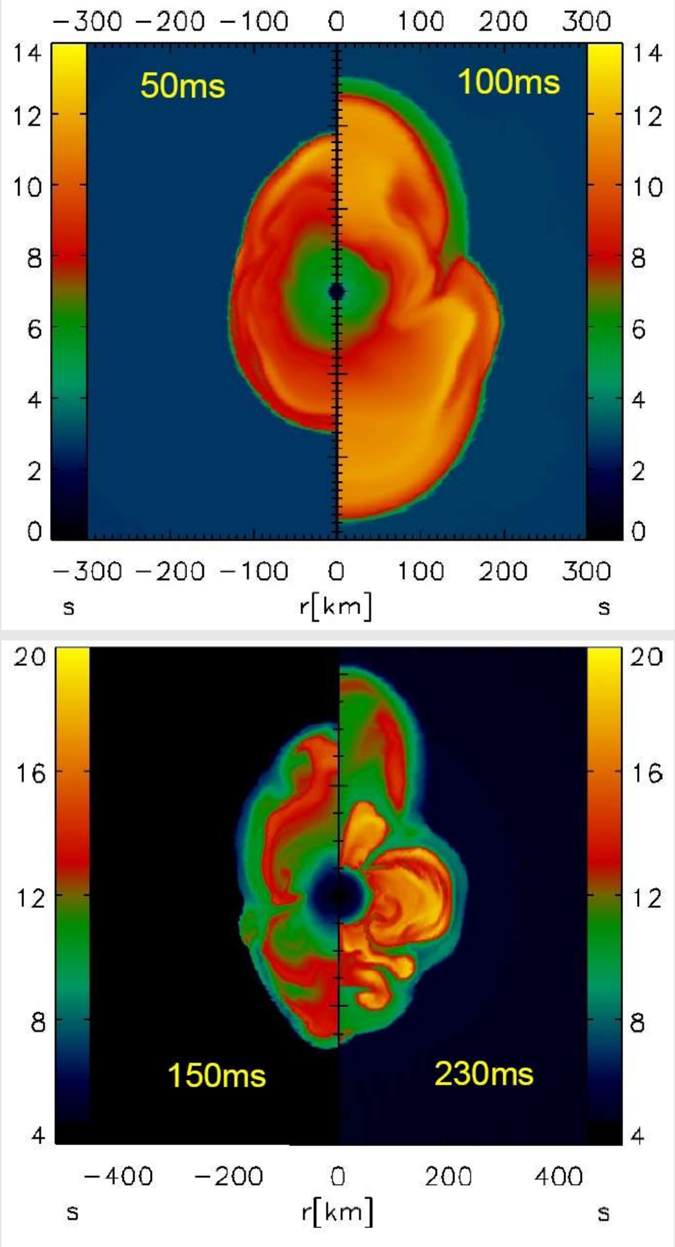
black: AGILE, green: CoCoNuT, blue/red: PROMETHEUS

(B. Müller, PhD Thesis, 2009)

# 2D GR Models with Neutrino Transport

- 15 M$_{sun}$ progenitor (s15s7b2 of Weaver & Woosley) does not show any explosion within 350 ms of post-bounce evolution in 2D GR simulation
- GR simulations with new hydrodynamics code and improved neutrino scheme qualitatively confirm results by Marek & Janka (2009)!





(B. Müller, PhD Thesis; publication in preparation)

# Conclusions

- Neutrino heating can power explosions of 8–10 $M_{sun}$ stars with ONeMg cores ------> Crab-like supernovae (agreement of results from different groups).

- Electron-capture supernovae don't provide conditions for r-processing.

- Our most sophisticated present 2D models show that SASI & convectively supported neutrino-driven mechanism may work at least for 11–15 $M_{sun}$ stars.
  Explosions occur fairly late after core bounce
  Need to verify robustness and need independent confirmation!

- 3D simulations are needed! Hydrodynamic instabilities in 3D supernova explosion models lead to higher velocities of metal clumps and stronger mixing.