Max-Planck-Institut
für Astrophysik

Supernova 1987A: 20 Years After
Aspen, Colorado, February 19-23, 2007

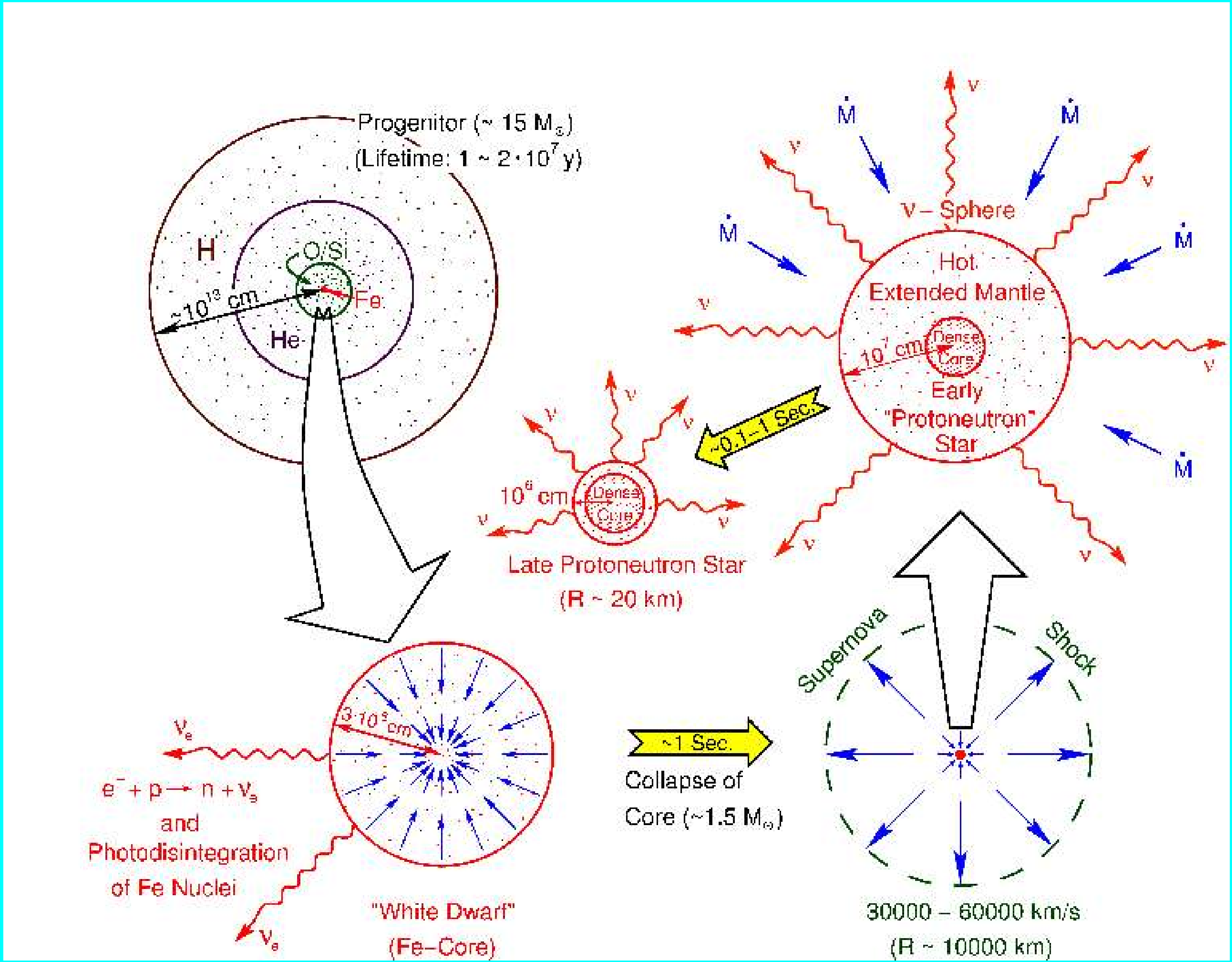
Theory of Core-Collapse Supernovae: Progress and Challenges

Hans-Thomas Janka
(MPI for Astrophysics, Garching, Germany)
Students and postdocs: A. Arcones, R. Buras, K. Kifonidis, F. Kitaura, A. Marek, B. Müller, L. Scheck & many collaborators

Contents

- Diversity of core-collapse events
- Explosions:
  - Neutrino-driven?
  - Acoustically-driven?
  - Magnetohydrodynamic?
- Status of modeling neutrino-driven explosions
  - 41 years after Colgate & White (1966)
  - 25 years after Wilson (1982)
- Neutrino-driven explosions work!
  - Explosion energies of 2D models
  - SN 1987A: What was it?
  - SN asymmetries
- Summary and outlook

Stellar Collapse & Explosion



(adapted from A. Burrows)

Supernova Explosion Mechanisms

- Neutrino-driven?
  Neutrinos carry away 100 times more energy than needed!

- Acoustically-driven?
  Accretion induces neutron star l=1 g-mode oscillations, which transfer energy outward by acoustic waves, power explosion (Burrows et al. 2006a,b)

  Are large-amplitude g-mode oscillations of the NS excited or not on the relevant timescale? (More comments later)

Apologies to J. Murphy
for how the discussion went yesterday after my remark!

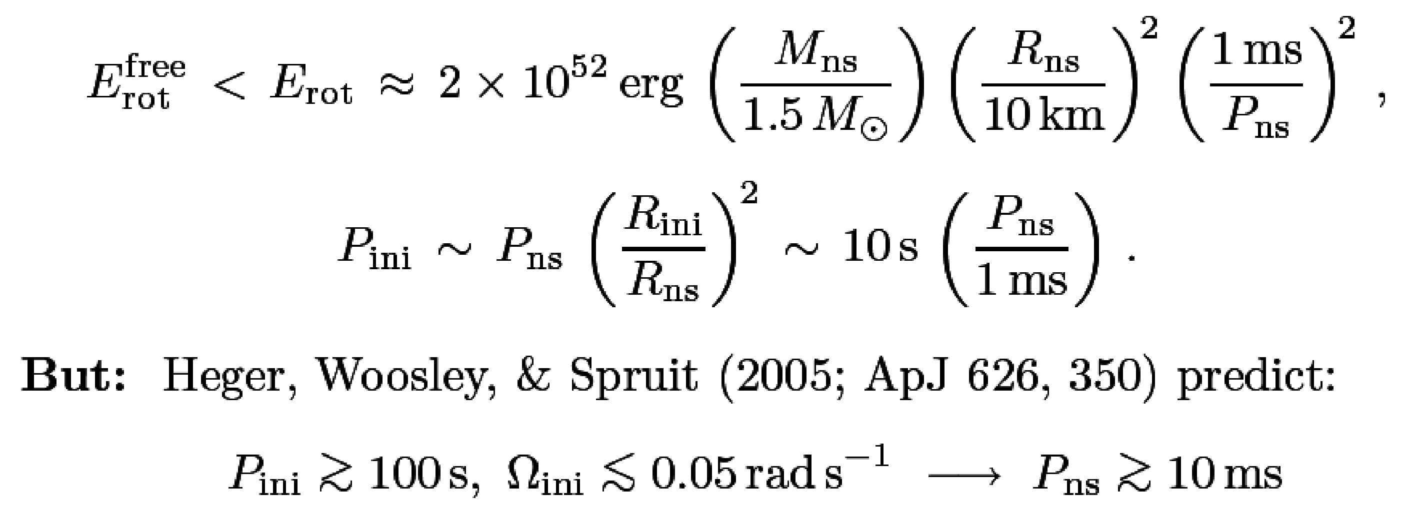
At the moment NOBODY's numerical scheme should be questioned without testing or should be trusted blindly!!!

Supernova Explosion Mechanisms

- Magnetohydrodynamic (MHD)?

  Free energy of rotation is converted to magnetic energy, magnetic pressure or dissipative heating via magnetorotational instability (MRI); can drive explosion! (e.g., Meier et al. 1976, Akiyama & Wheeler 2003, Kotake et al. 2004, 2005, Moiseenko et al. 2005, Thompson et al. 2005, Obergaulinger et al. 2006, Burrows et al. 2007)

  BUT: Requires a lot of rotational energy ====> fast initial rotation; probably at work in GRBs and possibly in magnetar-producing supernovae



$$E_{\mathrm{rot}}^{\mathrm{free}} < E_{\mathrm{rot}} \approx 2\times 10^{52}\,\mathrm{erg}\left(\frac{M_{\mathrm{ns}}}{1.5\,M_\odot}\right)\left(\frac{R_{\mathrm{ns}}}{10\,\mathrm{km}}\right)^2\left(\frac{1\,\mathrm{ms}}{P_{\mathrm{ns}}}\right)^2,$$

$$P_{\mathrm{ini}} \sim P_{\mathrm{ns}}\left(\frac{R_{\mathrm{ini}}}{R_{\mathrm{ns}}}\right)^2 \sim 10\,\mathrm{s}\left(\frac{P_{\mathrm{ns}}}{1\,\mathrm{ms}}\right).$$

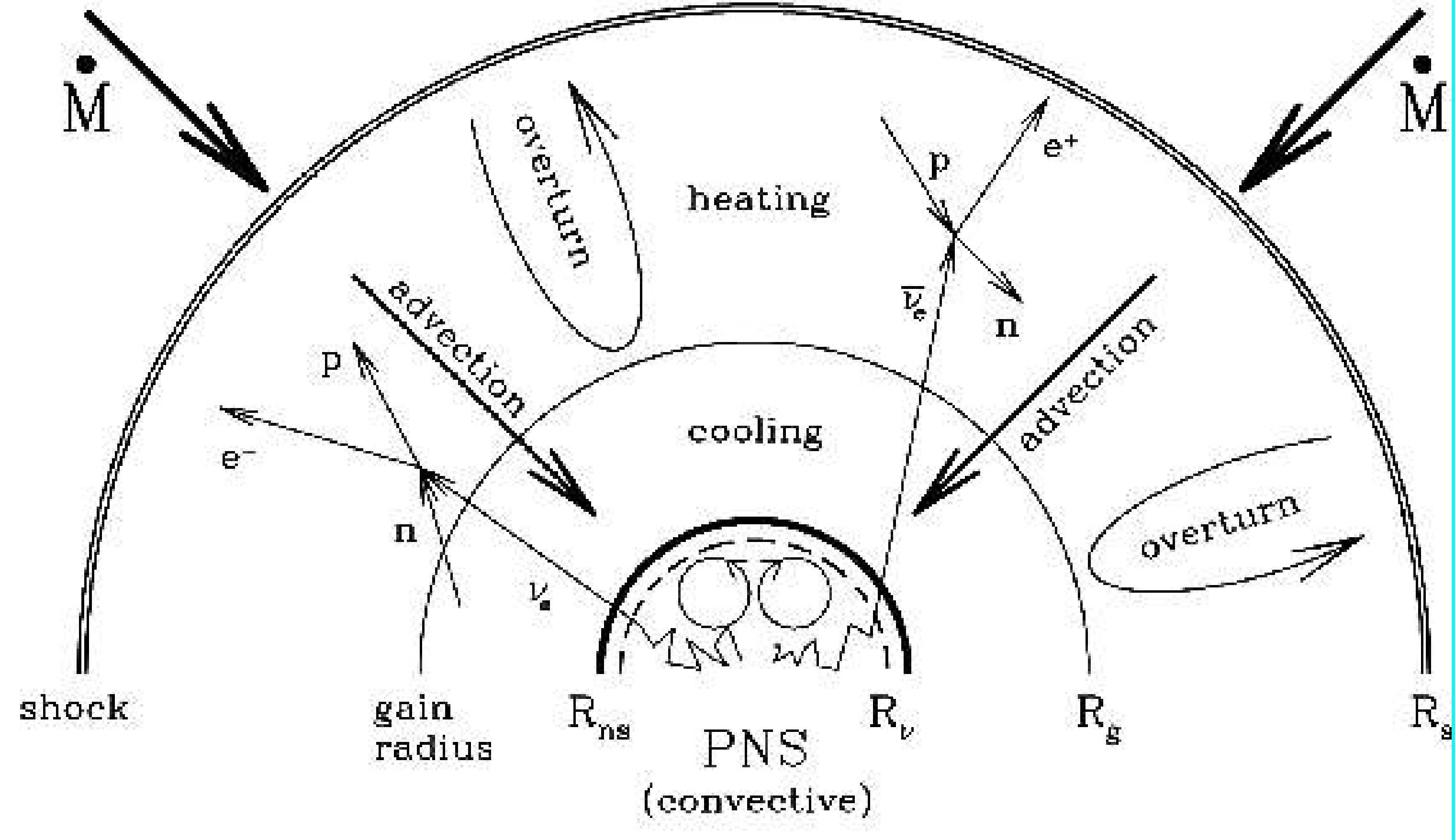
But: Heger, Woosley, & Spruit (2005; ApJ 626, 350) predict:

$$P_{\mathrm{ini}} \gtrsim 100\,\mathrm{s},\ \Omega_{\mathrm{ini}} \lesssim 0.05\,\mathrm{rad\,s}^{-1} \longrightarrow P_{\mathrm{ns}} \gtrsim 10\,\mathrm{ms}$$

Fe cores of ordinary SN progenitors rotate slowly (P_{ini} > 100 sec) (Heger et al. 2005), but MHD explosions need P_{ini} < 2 sec (Burrows et al., astro-ph/0702539; Thompson et al. 2005)

Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



- "Neutrino-heating mechanism": Neutrinos revive stalled prompt 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).

Brief Historical Outline of SN Modeling Progress

- 1966: Colgate & White suggest neutrinos as driving force for explosion
- 1970–1990: prompt explosions do not work
- 1982 (publ. 1985): Wilson finds “delayed” neutrino-driven explosions
- > 1989: Wilson claims neutron-finger convection in PNS to be crucial for neutrino-driven explosions
- 1985: Bruenn develops new 1D SN code with multi-group neutrino diffusion
- 1993: Boltzmann S_N-scheme first used in 1D core-collapse models (Mezzacappa & Bruenn)
- 1992–1996: Postshock convection discovered to be very important (Herant et al. 1992, 1994; Burrows et al. 1995; HTJ & Müller 1994, 1996)
- 2000 ff: Very sophisticated multi-group neutrino transport in 1D GR and Newtonian simulations (Rampp & HTH 2000, Liebendörfer et al. 2001, 2002,...; Thompson et al 2003; Sumiyoshi et al. 2005)
- 2002: First 3D models with grey neutrino diffusion (Fryer & Warren)
- 2003: Standing accretion shock instability (SASI) first recognised (Blondin et al.)
- 2003 ff: First 2D simulations with multi-group neutrino transport (MPA Garching)
- > 2005: Various efforts to push forward to full 2D energy-dependent transport
- > 20??: 3D models with full 3D energy-dependent transport?

Fryer & Warren 2002

Why is it so difficult??

- Highly complex combination of physics
- Numerically challenging
- Incompletely known ingredients (e.g. NS equation of state, initial conditions)

- Final conclusions about neutrino-driven mechanism need 3D simulations with GOOD neutrino transport!

Not possible yet!

Numerical Tools

used in Garching

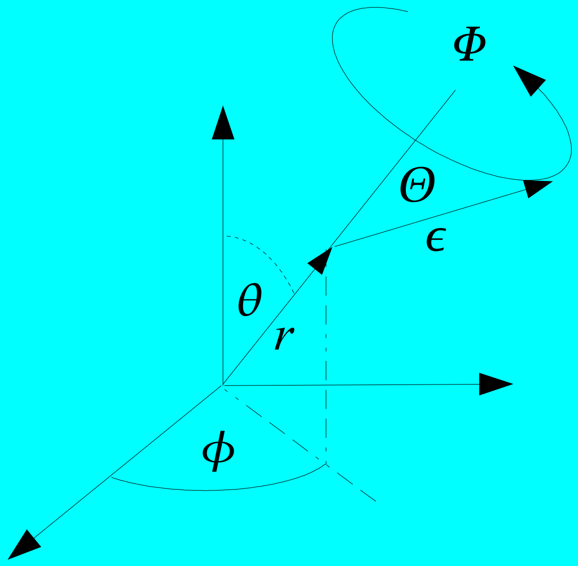
The Garching "Boltzmann" Supernova Code

1D version: VERTEX, multi-D version: MuDBaTH

(Rampp & Janka, A&A 2002, Buras et al., A&A 2006)

- Hydrodynamics: PROMETHEUS
  - * based on Riemann solver, 3rd order PPM
  - * general relativistic gravitational potential
  - * time-explicit
- Neutrino transport: variable Eddington factor technique
  - * moment equations of number, energy, momentum transport
  - * closure by solution of "model Boltzmann equation"
  - * fully time-implicit
  - * multi-frequency (energy-dependent)
  - * order v/c
  - * approx. GR version: relativistic redshift and time dilation included
  - * state-of-the-art description of neutrino-matter interactions
  - * in spherical symmetry: 3D problem

The Curse and Challenge of the Dimensions



- Boltzmann equation determines neutrino distribution function in phase space

$$f(r,\theta,\phi,\Theta,\Phi,\epsilon,t)$$

- Integration over momentum space yields source terms for hydrodynamics

$$Q(r,\theta,\phi,t),\dot{Y}_e(r,\theta,\phi,t)$$

Solution approach

- **3D** hydro + **6D** direct discretization of Boltzmann Eq. (no serious attempt yet)
- **2D** hydro + **5D** direct discretization of Boltzmann Eq. (planned by DoE's TSI/SSC)
- **2D** hydro + **"ray-by-ray-plus"** variable Eddington factor method (current method of MPA)

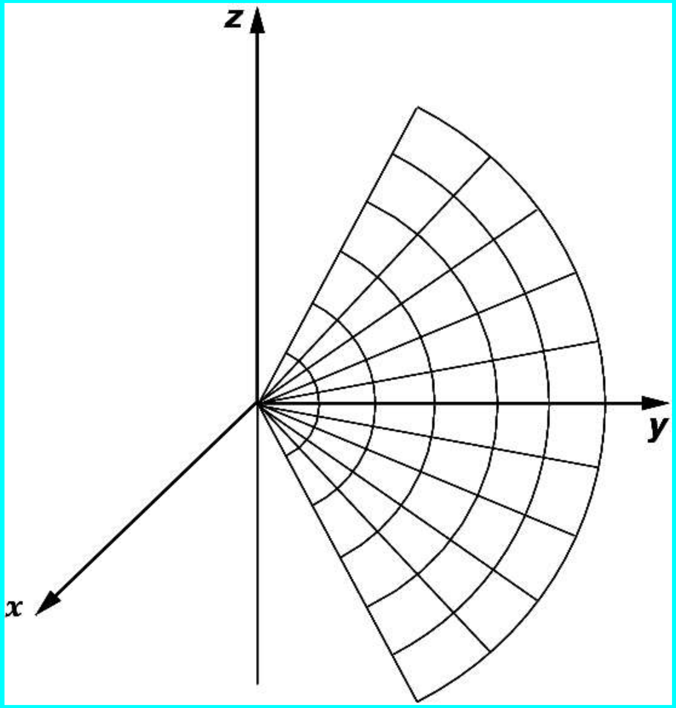
Required resources

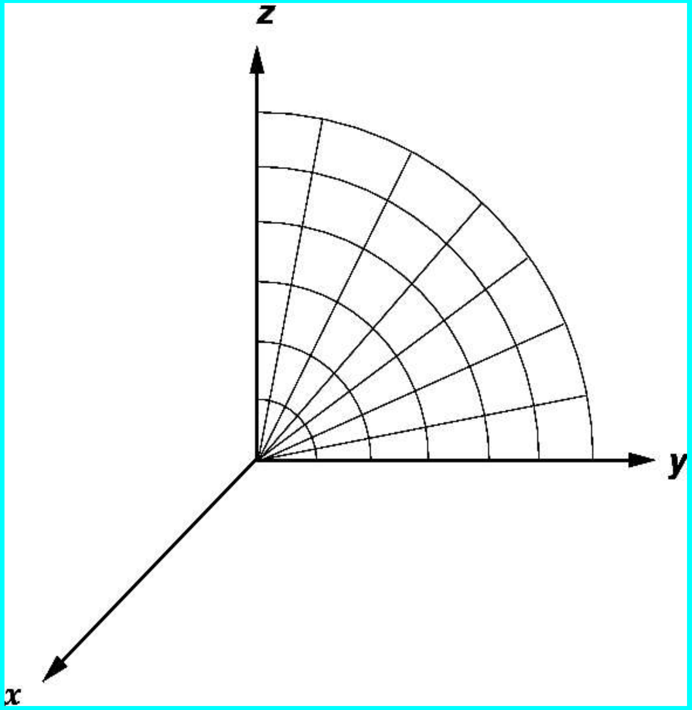
- ≥ 1–10 PFlops (sustained!)
- ≥ 10–100 Tflops, TBytes
- ≥ 1 TFlops, < 1 TByte

Time-dependent simulations: t > 1 second, > 10^6 time steps!

Garching Supernova Code (cont'd)

- Neutrino transport in 2D: multi-energy, “ray-by-ray plus” solution of 1D problems
  - * spherical coordinates
  - * in 2D axial symmetry assumed
  - * diagonal pressure tensor
  - * neutrino flux radial in angular bins
  - * lateral coupling by neutrino advection and pressure gradients
  - * approximation reduces dimensionality from 5 to 4

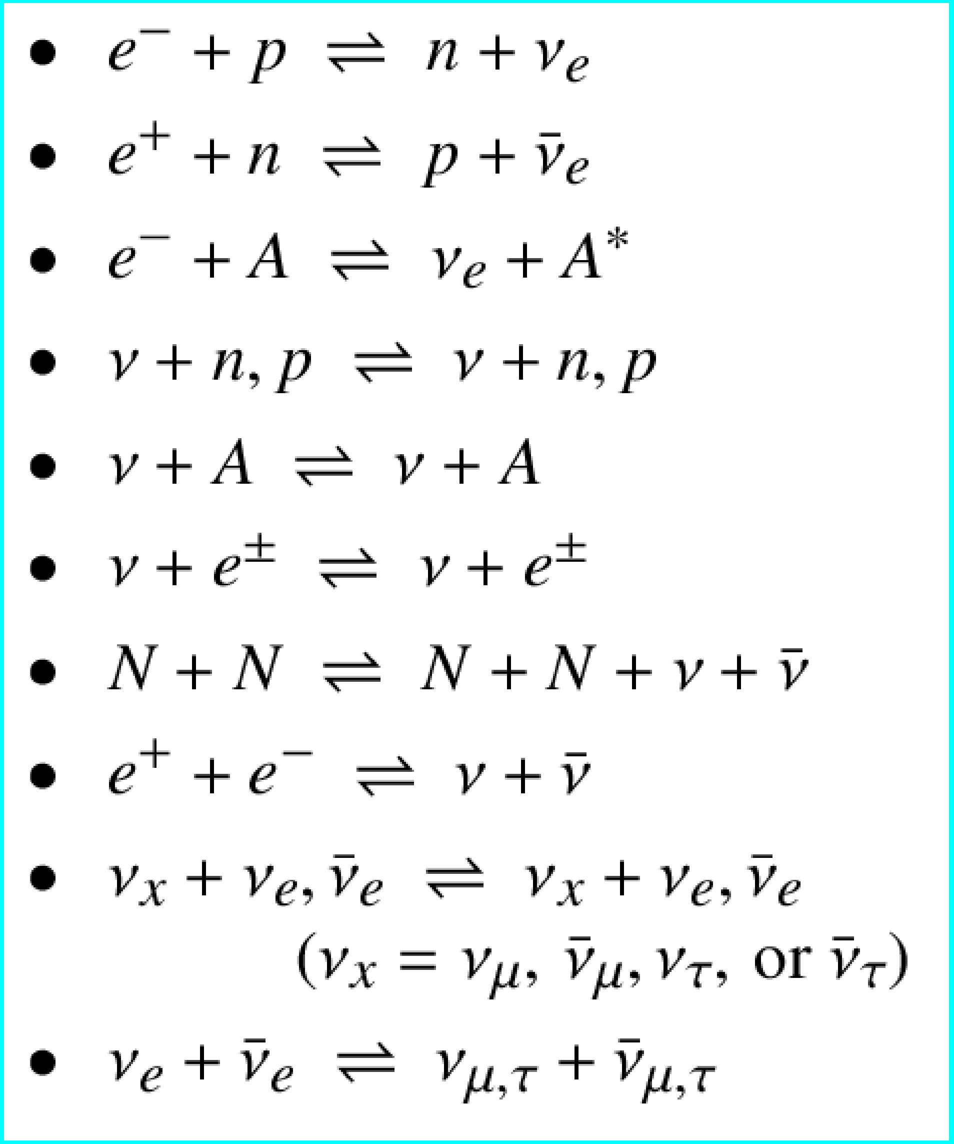




Garching SN Code: Input Physics

Neutrino rates:

- Rate treatment mostly based on Bruenn (1985), Bruenn & Mezzacappa (1993a,b, 1997)
- Neutrino-nucleon interactions include recoil, fermion blocking, correlations, weak magnetism, effective nucleon mass
- Nucleon-nucleon bremsstrahlung (Hannestad & Raffelt 1998)
- Neutrino-neutrino interactions (Buras et al. 2002)
- Electron capture on nuclei for >300 nuclei in NSE (A= 45–112) FFN+LMP+hybrid rates, SMMC calculations
(Langanke et al., PRL 2003)

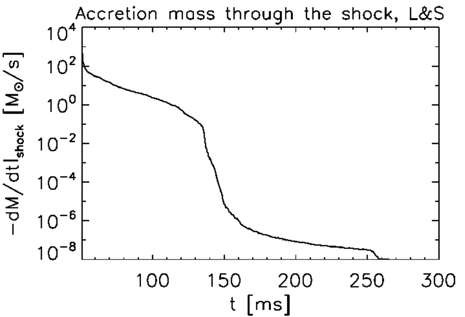


- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$
- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Status of Explosion Modeling

Do neutrino-driven explosions work?

SN Simulations: ONeMg Core

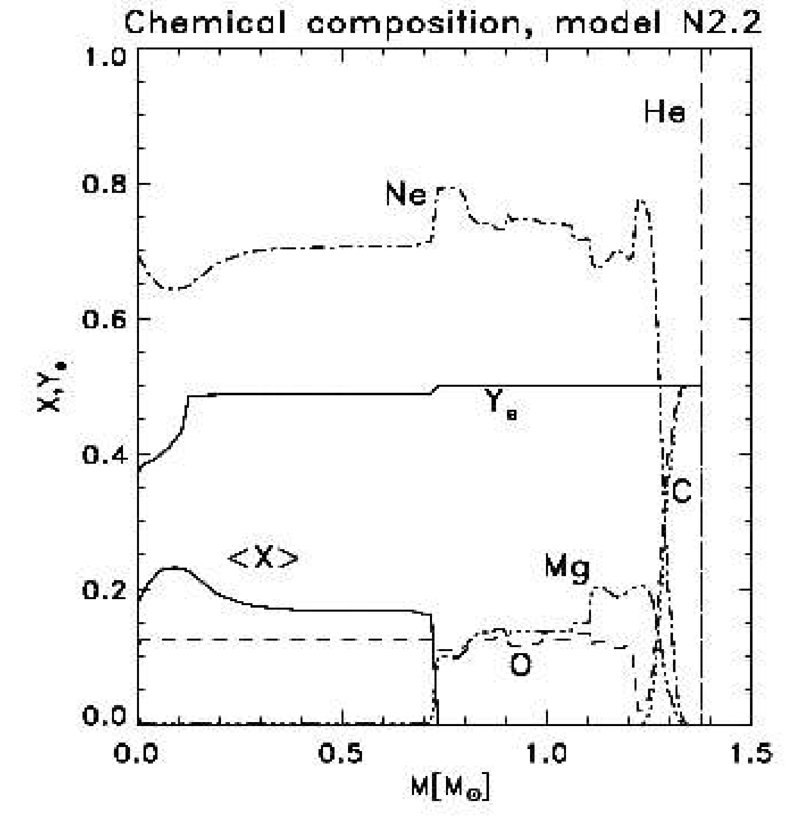


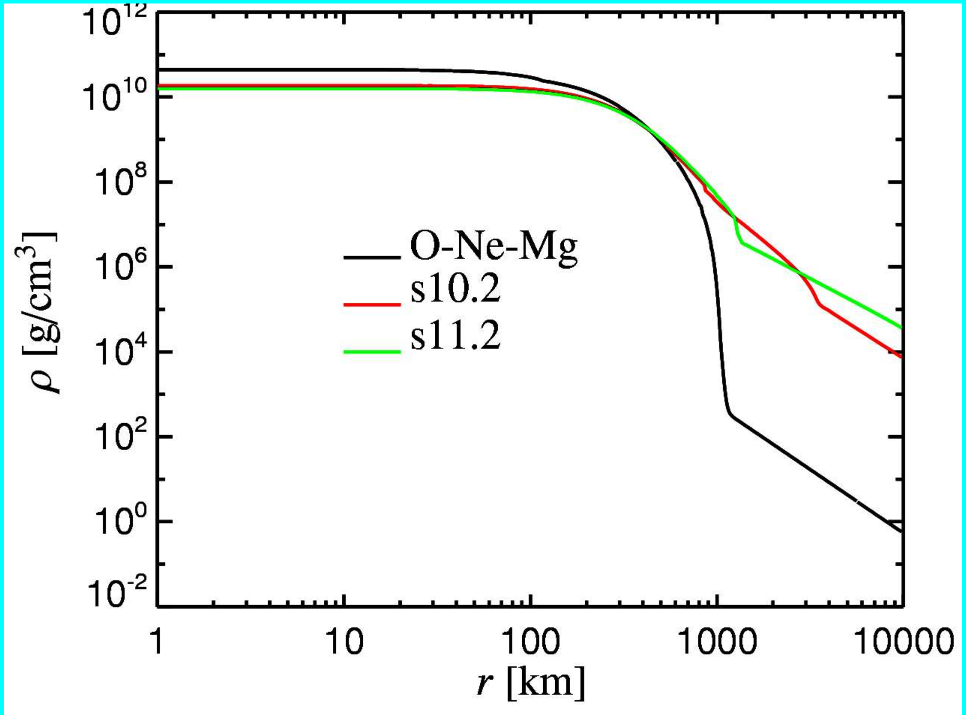
8–10 M_{sun} stars

with cores: 2.2 M_{sun} He, 1.38 M_{sun} C, 1.28 M_{sun} ONeMg,

about 30–35% of all supernovae

(Nomoto 1981, 84, 87)

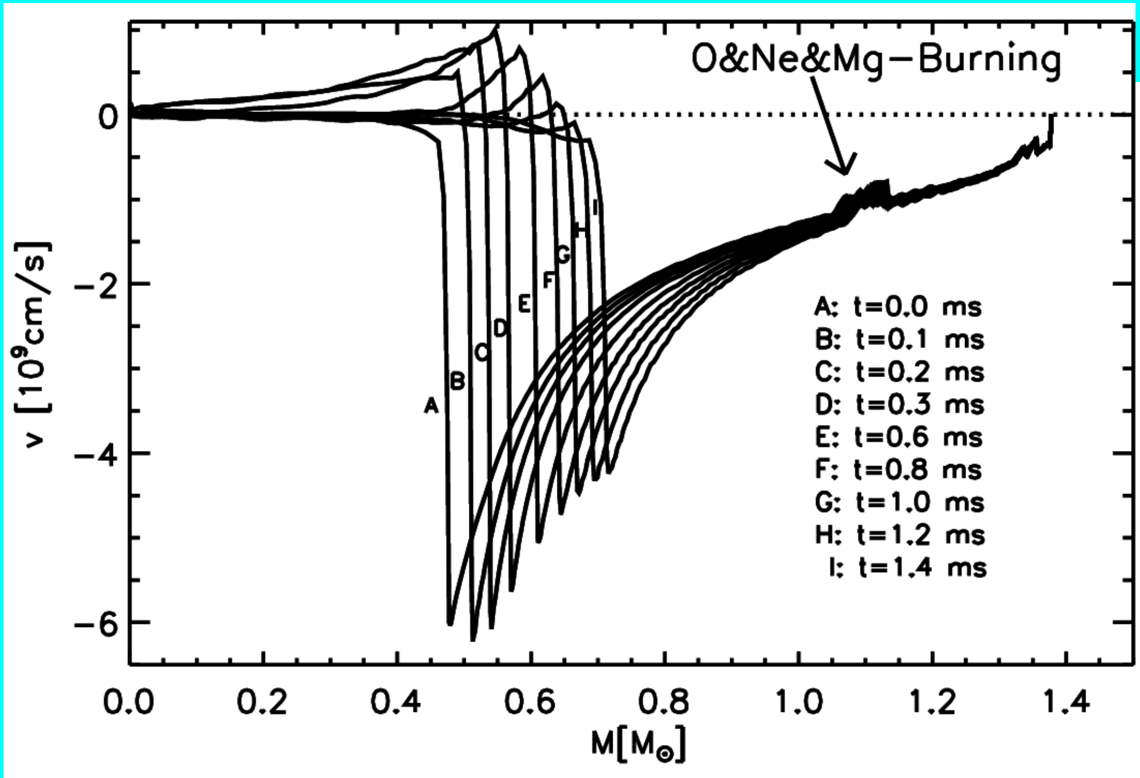


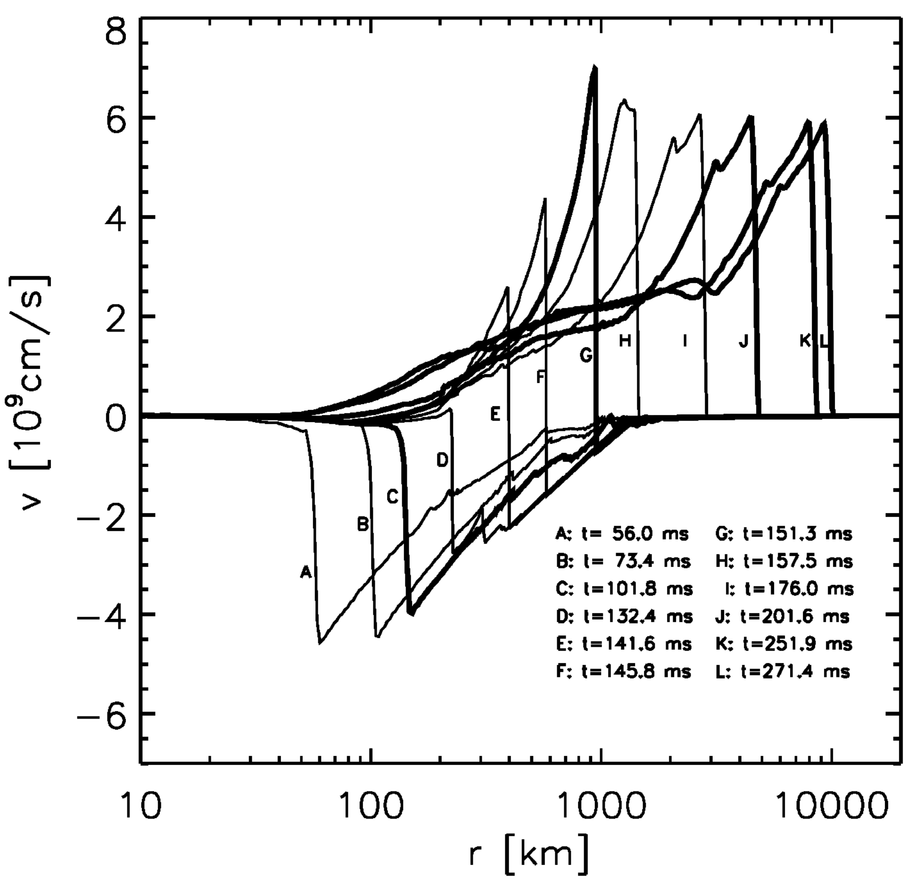


Very steep density gradient outside of ONeMg core and therefore rapidly decreasing mass accretion rate

Kitaura et al., A&A 450 (2006) 345

SN Simulations: ONeMg Core





No prompt explosion!
No low-entropy r-process!

Continuing shock expansion due to decreasing mass accretion rate
--------> delayed explosion!!

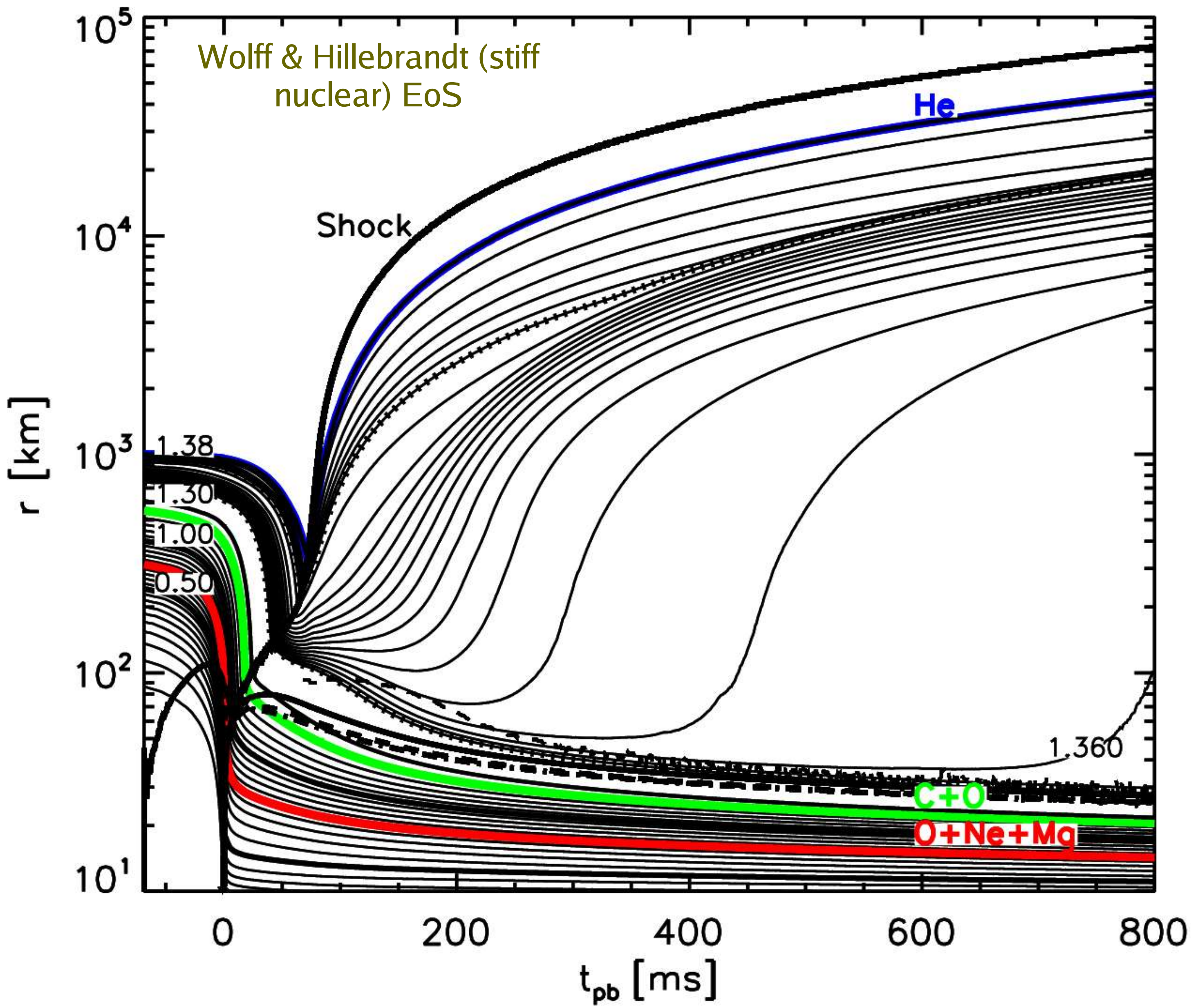
Kitaura et al., A&A 450 (2006) 345

SN Simulations: ONeMg Core

Mass ejection by neutrino-driven wind

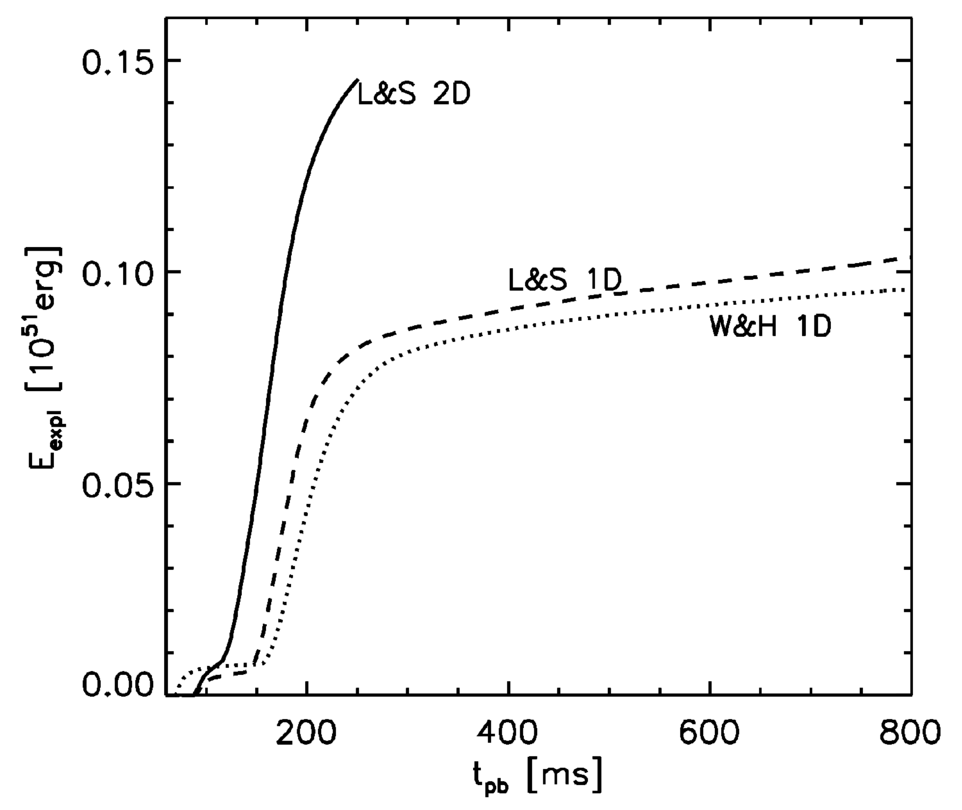
(like Mayle & Wilson 1988 and similar to AIC of WDs; see Woosley & Baron 1992, Fryer et al. 1999; Dessart et al. 2006)

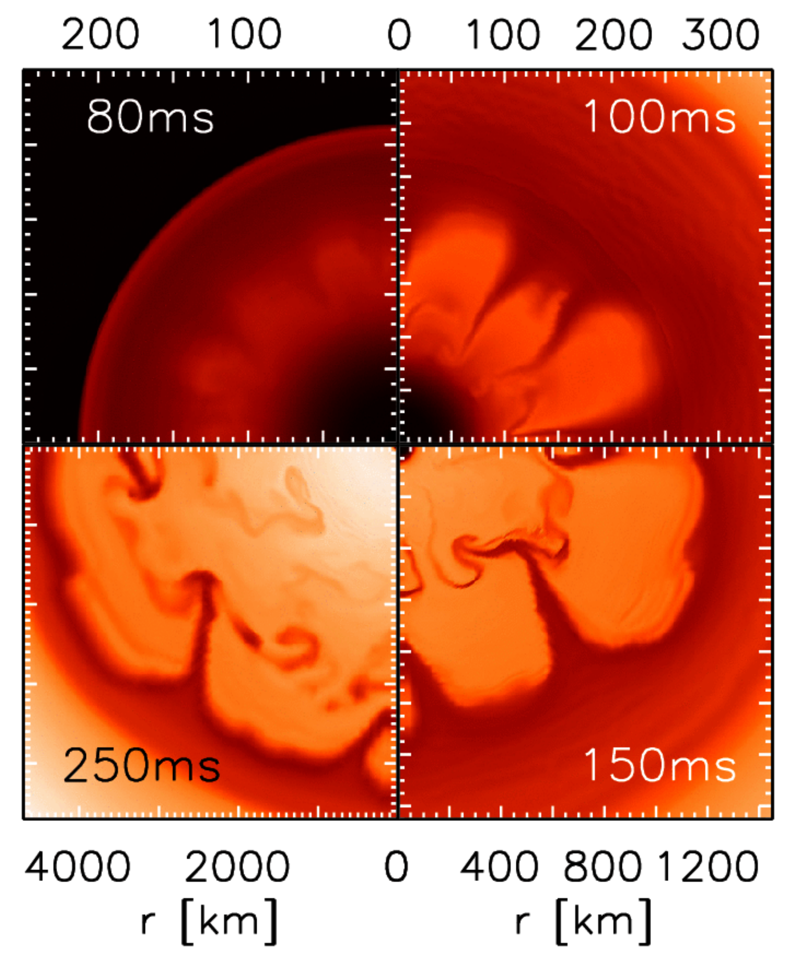
Kitaura et al., A&A 450 (2006) 345



SN Simulations: ONeMg Core

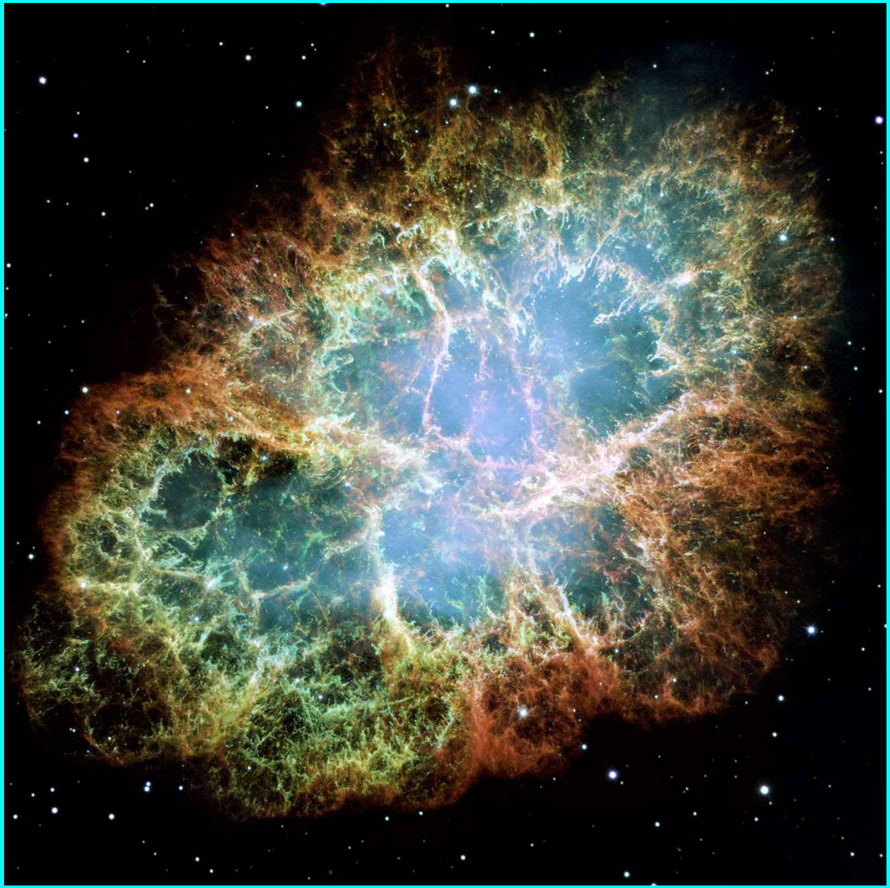
- Convection enhances the explosion energy and creates anisotropies
- Convection is not essential for explosions of small stars





Kitaura et al., to be published

SN Simulations: ONeMg Core

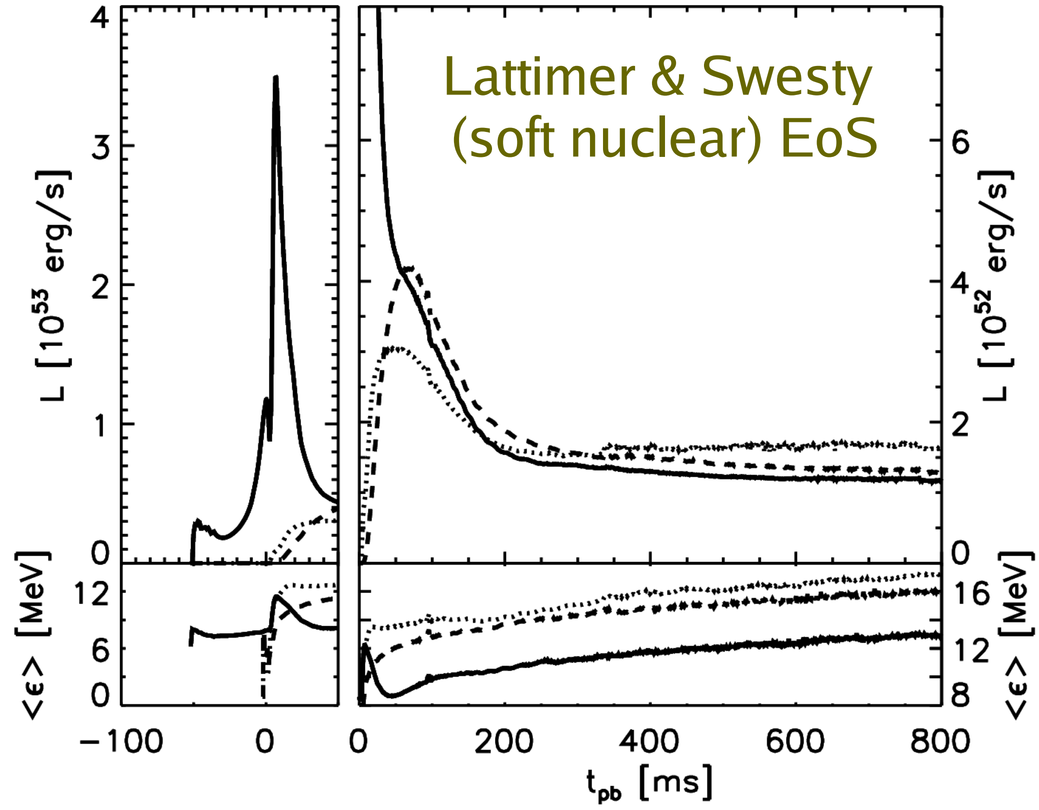


Source: http://www.spacetelescope.org/images/html/heic0515a.html;
Credit: NASA, ESA and Allison Loll/Jeff Hester (Arizona State University).
Acknowledgement: Davide De Martin (www.skyfactory.org)

Explosion models yield: Low explosion energy (~0.2–0.3 bethe),
small Ni mass (~0.01 M_{sun}), little oxygen (< 0.01 M_{sun}) ,
neutron star mass: ~1.35 M_{sun}

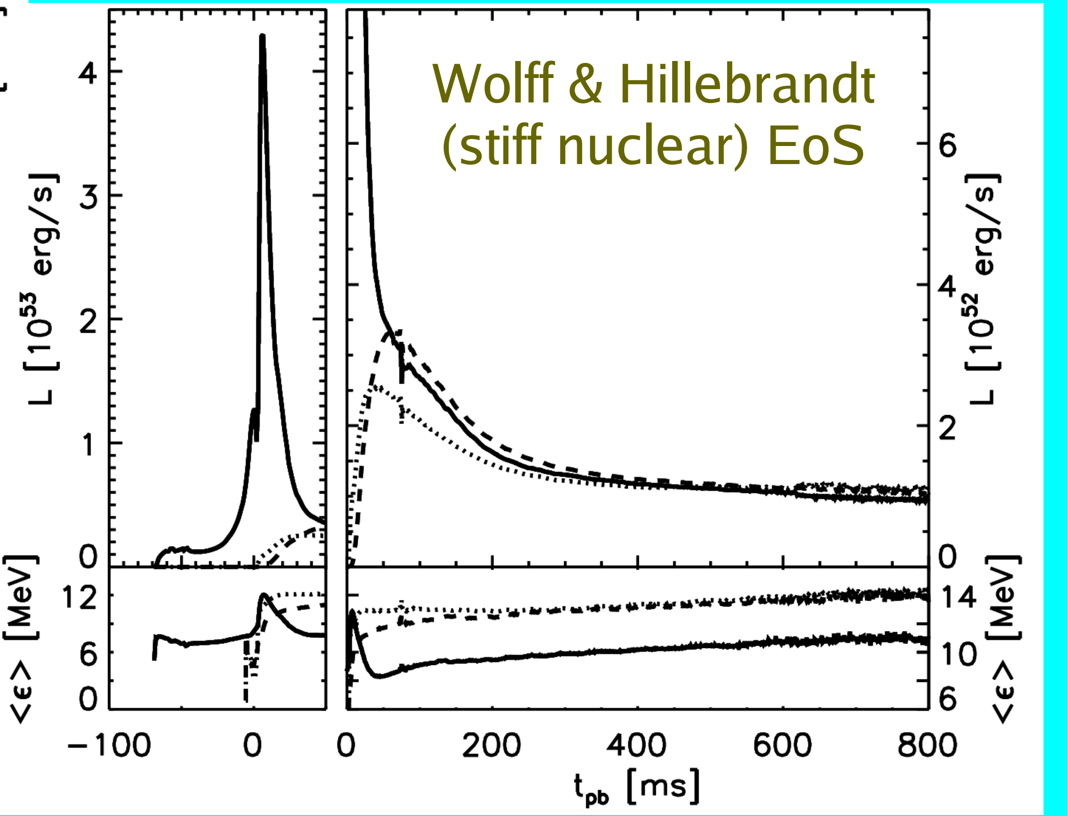
In agreement with observations of CRAB? (Nomoto et al., Nature, 1984)

SN Simulations: ONeMg Core



Neutrino luminosities
and
mean energies

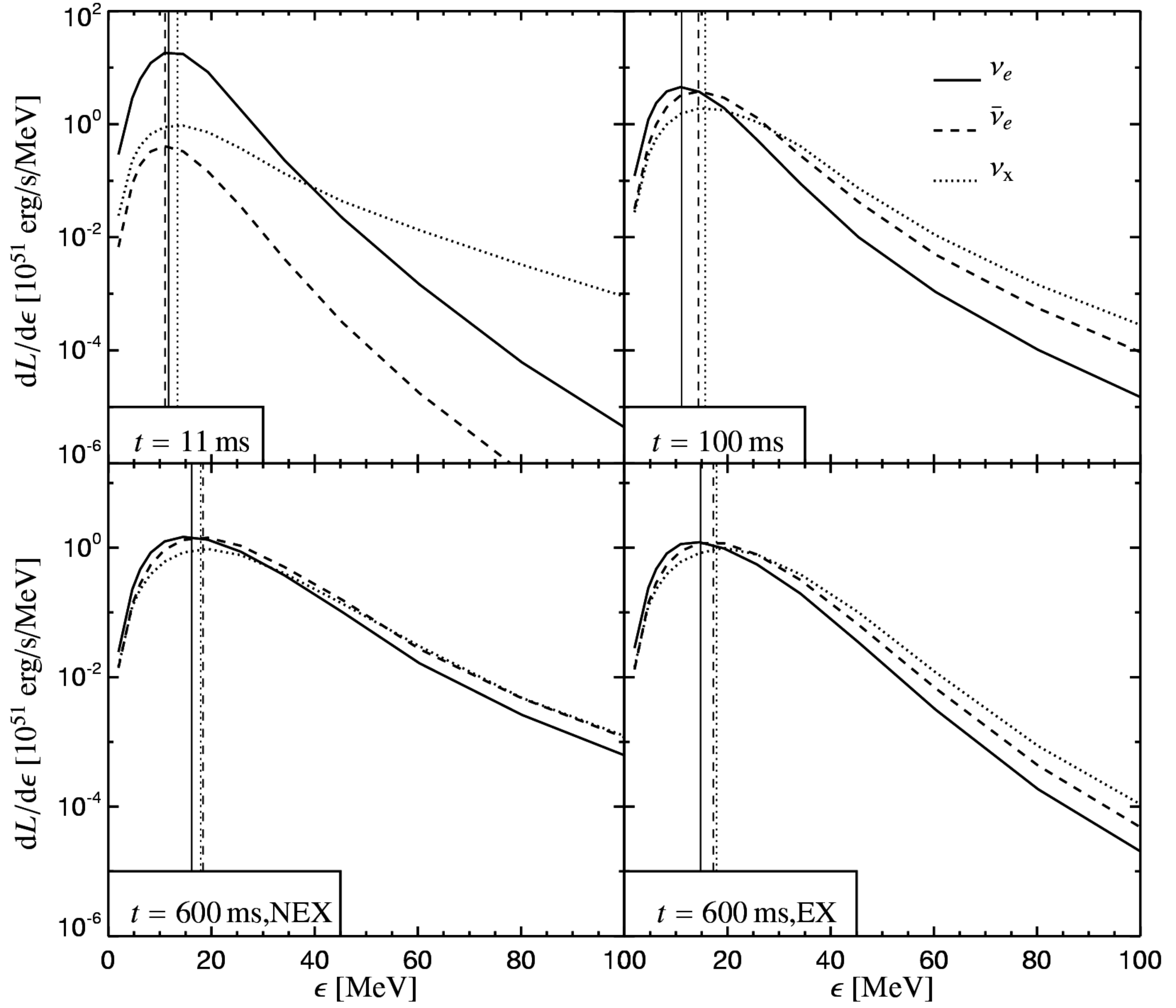
Kitaura et al., to be published



- solid: electron neutrinos
- dashed: electron antineutrinos
- dotted: heavy-lepton neutrinos

Improved Neutrino Treatment

- more accurate spectra
- muon and tau neutrinos are more similar to electron antineutrinos
- electron antineutrinos less energetic



A. Marek, PhD Thesis

SN Ejecta Composition

Electron neutrino and antineutrino interactions with neutrons and protons determine n/p-ratio in SN outflows:

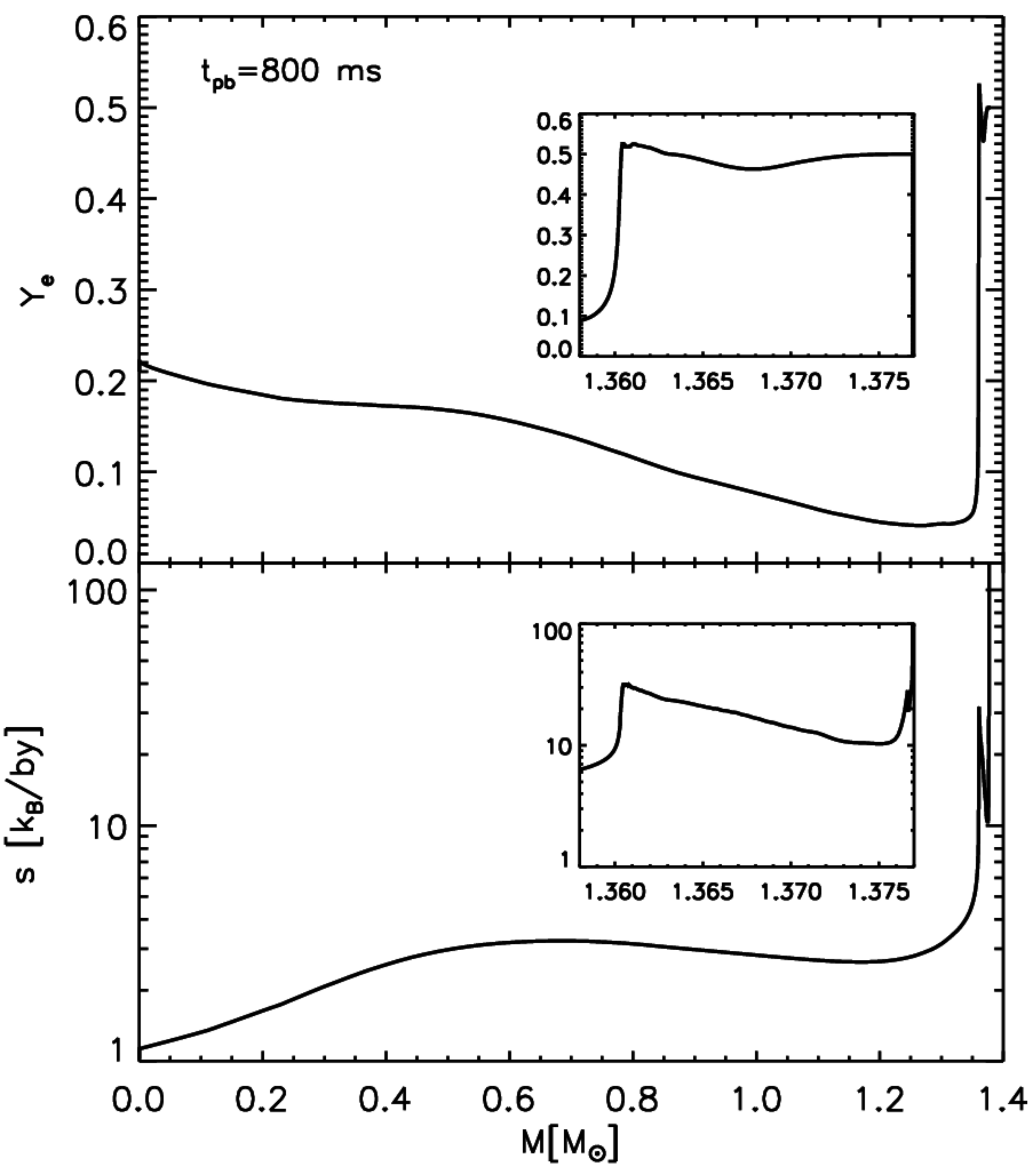
$$\begin{aligned} \nu_e + n &\longrightarrow e^- + p \\ \bar{\nu}_e + p &\longrightarrow e^+ + n \end{aligned}$$

Very approximately (Qian & Woosley 1996):

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e} \langle \epsilon_{\bar{\nu}_e} \rangle}{L_{\nu_e} \langle \epsilon_{\nu_e} \rangle} \right]^{-1}$$

Improved Neutrino Treatment

- Early SN ejecta have $Y_e \sim 0.5$ and even $Y_e > 0.5$ instead of $Y_e << 0.5$ in previous models with simplified grey neutrino treatment
- Very important for SN nucleosynthesis!
- Prevents massive overproduction of N=50 closed n-shell nuclei seen in previous models!



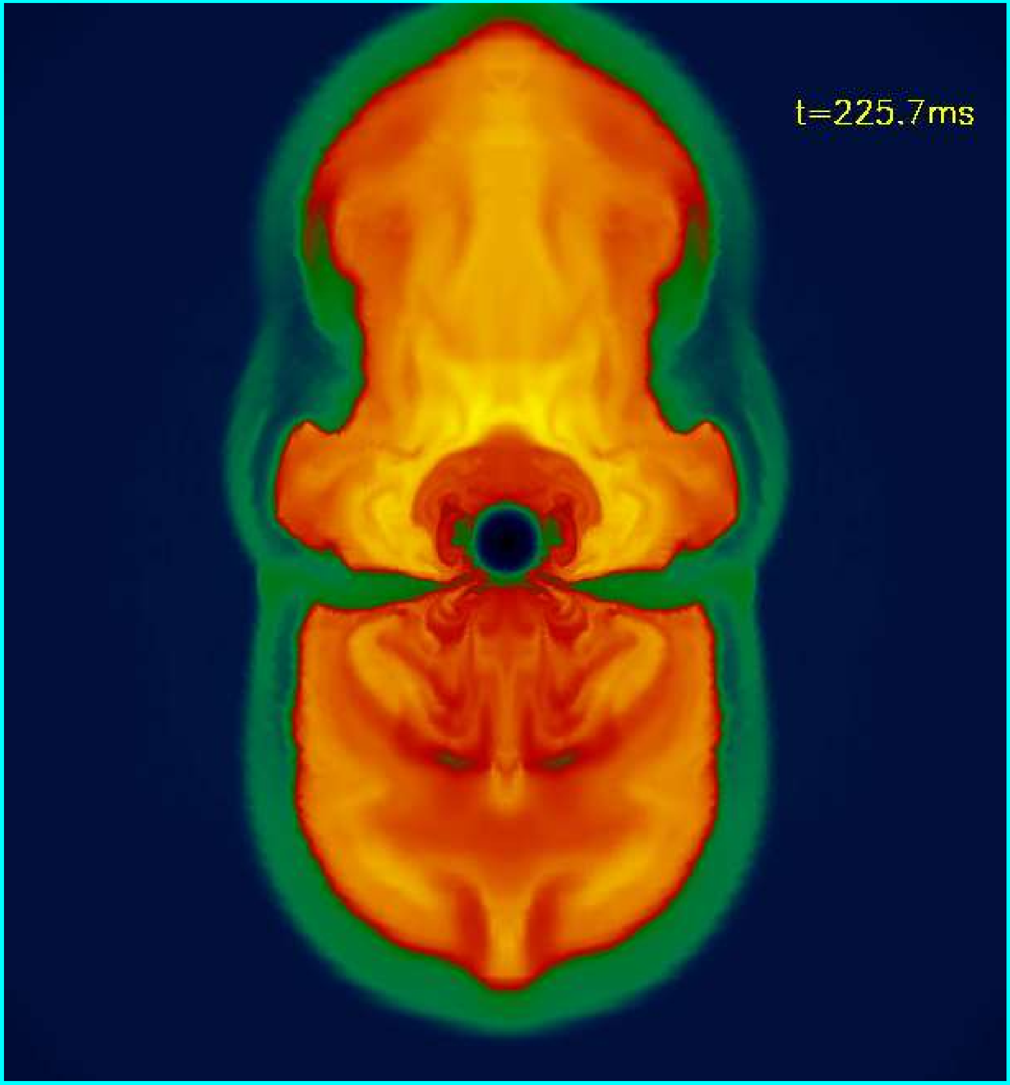
Kitaura et al., A&A 450 (2006) 345

SN Simulations: $M > 11\ M_{sun}$

- $M = 11.2\ M_{sun}$ (Woosley et al. 2003)
- Full 180° grid
- allows low (dipolar and quadrupolar, l=1,2) modes to occur
- global anisotropy develops
- weak explosion takes place

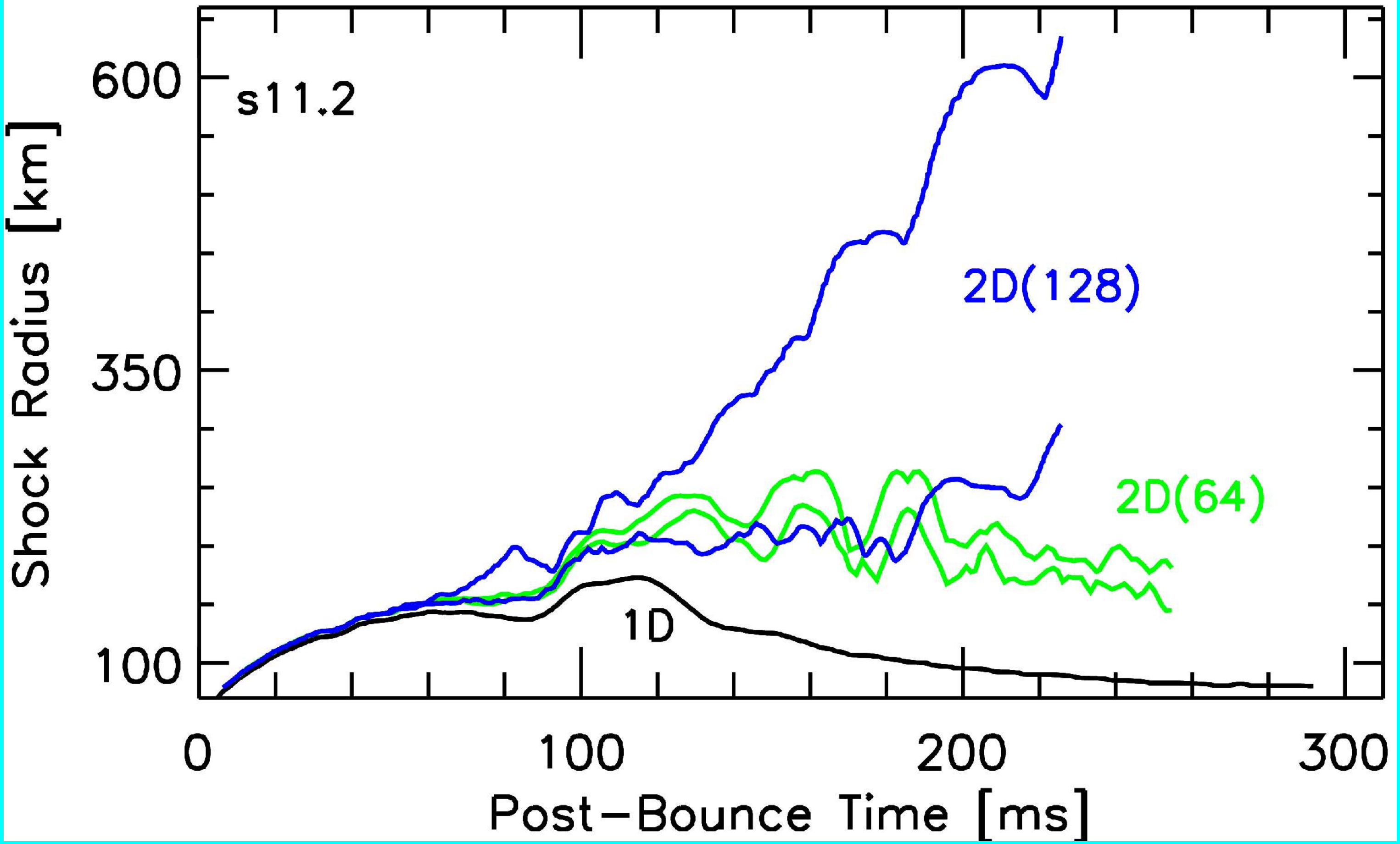
Globally aspherical explosion by the neutrino-heating mechanism without rotation!

l=1 mode standing accretion shock instability (SASI)
recognized by Blondin, Mezzacappa and DeMarino (ApJ 584 (2003) 971);
suggested to be caused by an "advective-acoustic feedback cycle" by Foglizzo (2002), Foglizzo & Galletti (2005)



Buras et al., A&A 457 (2006) 281

SN Simulations: $M = 11.2\ M_{sun}$



Buras et al., A&A 457 (2006) 281

Explosion Criterion

- Compare advection timescale with heating timescale
  (Janka et al. 2001; Thompson et al. 2005)

$$\tau_{\mathrm{adv}} = \frac{R_{\mathrm{shock}} - R_{\mathrm{gain}}}{|\langle v_r \rangle|}$$

$$\tau_{\mathrm{heat}} = \frac{E_{\mathrm{bind}}[R_{\mathrm{gain}},\, R_{\mathrm{shock}}]}{Q_{\mathrm{heat}}}$$

R_{shock} : shock radius

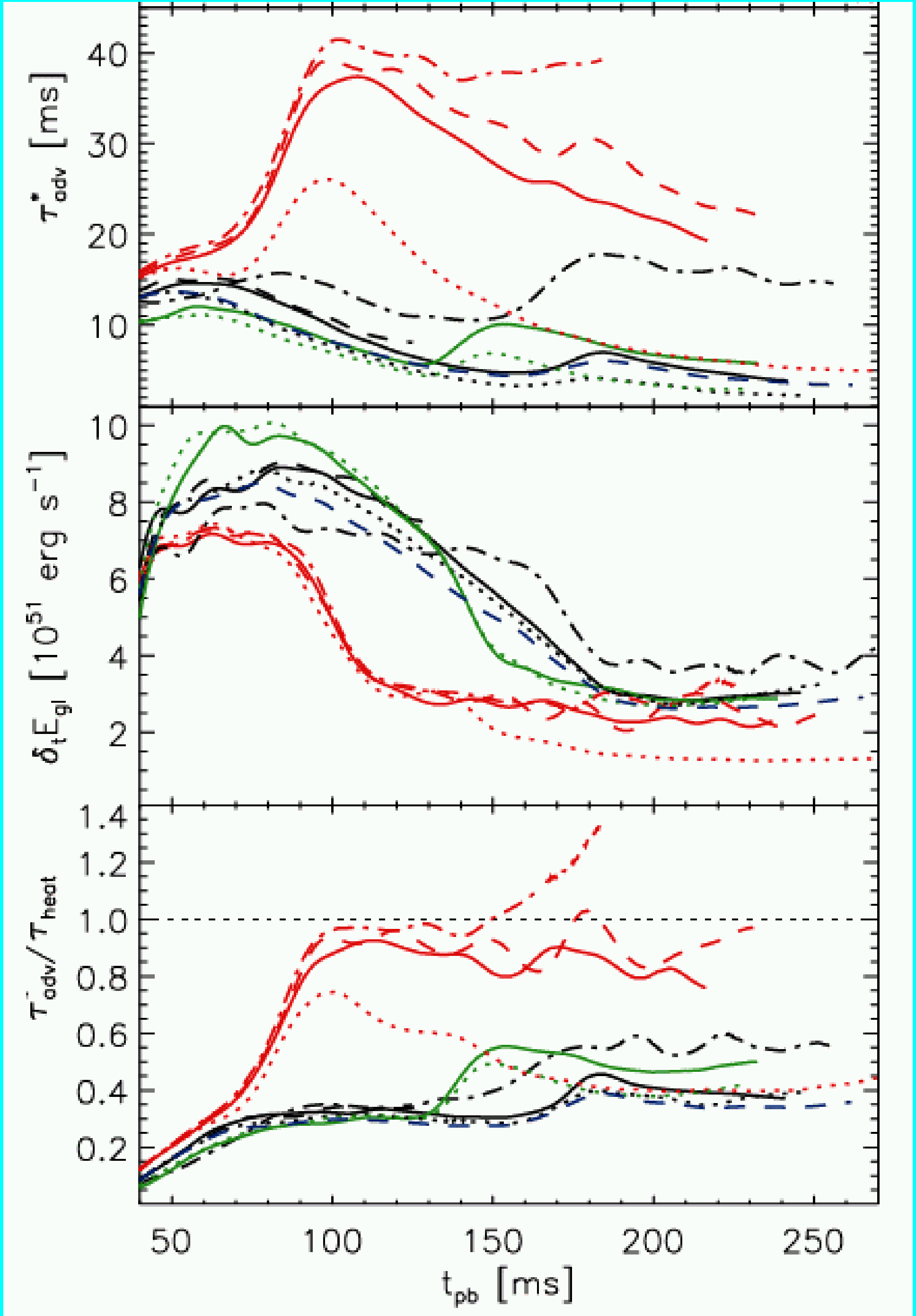
R_{gain} : gain radius

$|\langle v_r \rangle|$: mean radial velocity

E_{bind} : gravitational binding energy

Q_{heat} : net neutrino heating rate

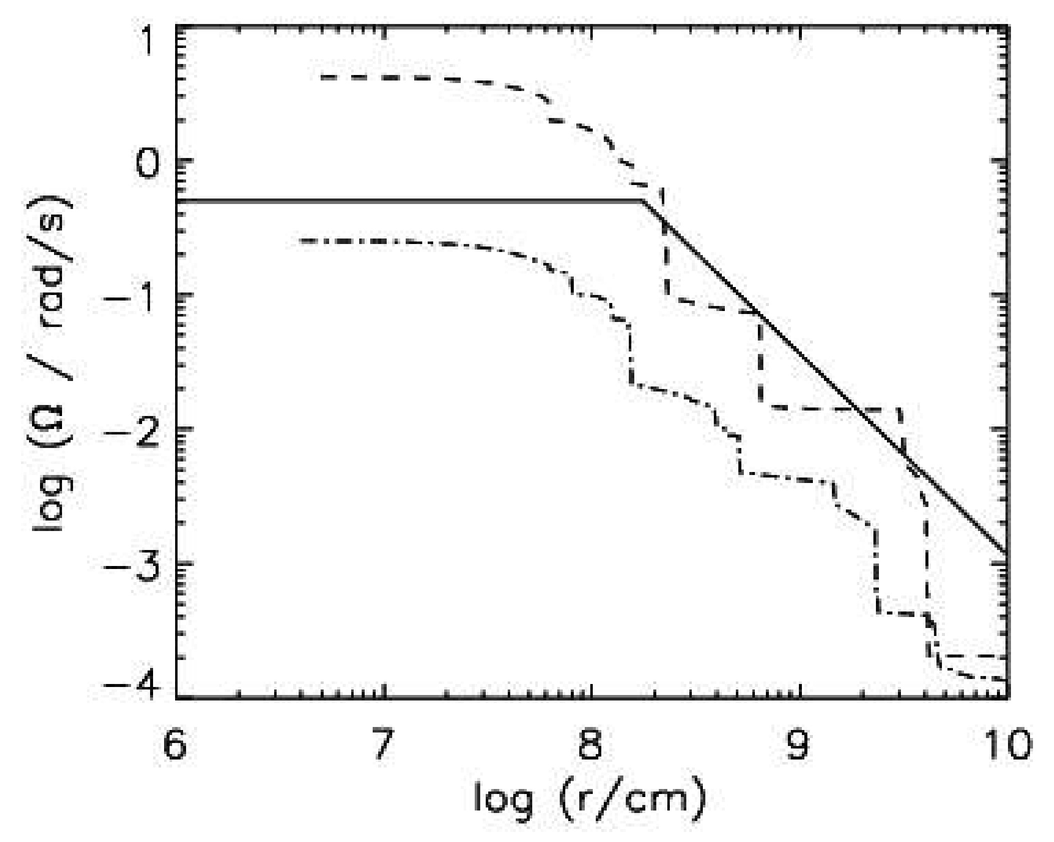
- If $\tau_{\mathrm{adv}} > \tau_{\mathrm{heat}}$: conditons are favorable for explosion



Buras et al., A&A 457 (2006) 281

SN Simulations: $M = 15\ M_{sun}$

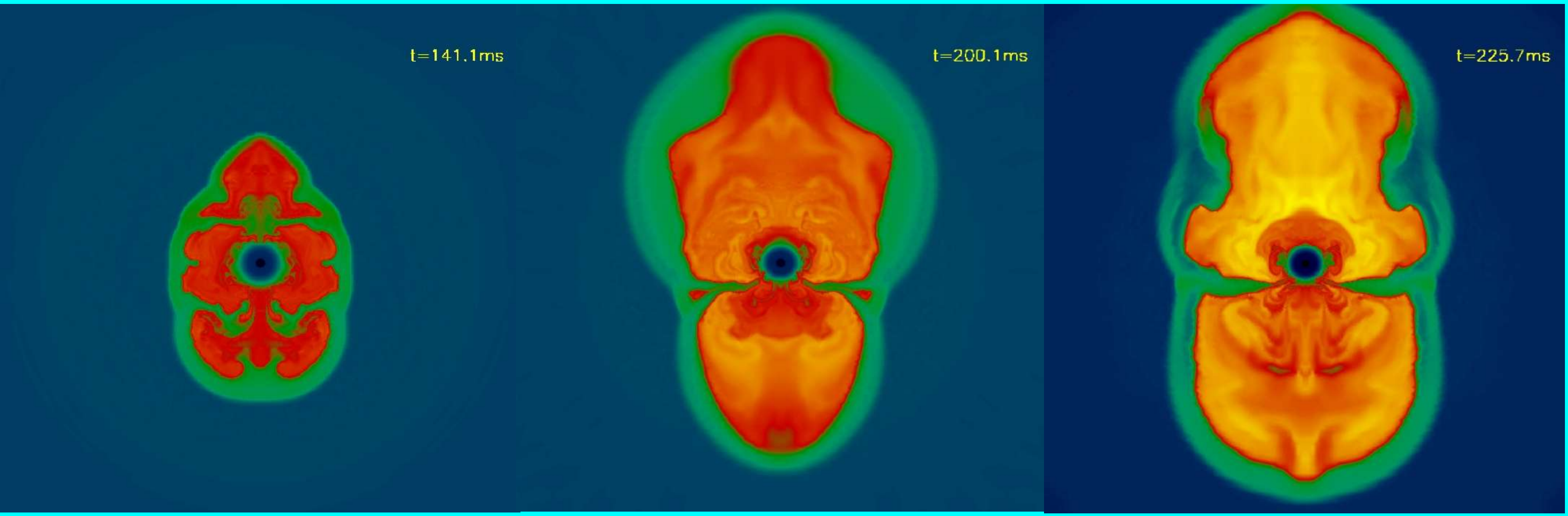
- Influence of convection and rotation on the neutrino-heating mechanism.
- Initial Fe core rotation assumed to be "rather slow":
  $P_{ini} \sim 12$ seconds,
  angular frequency ~ 0.5 rad/s,
  (β_{ini} of Fe core ~ 3×10^{-4});
  NS period will be >1 ms (for j = const)



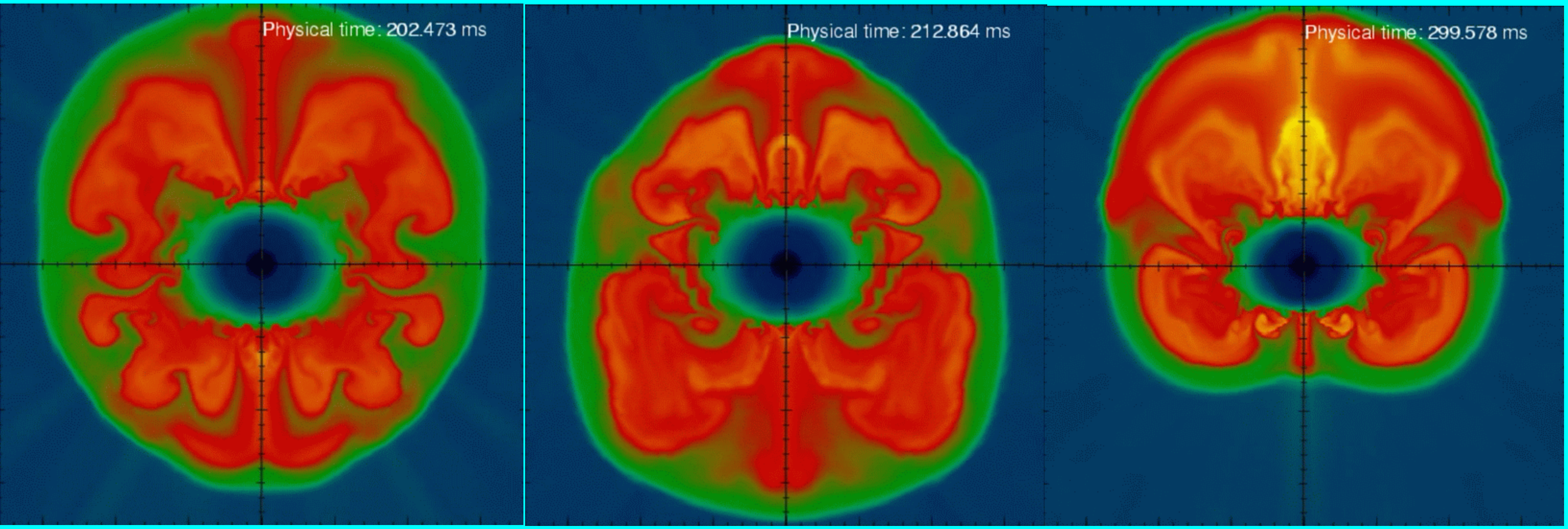
- This rotation rate is between magnetic and nonmagnetic cores of Heger, Woosley, Langer & Spruit.
- Initially centrifugal force < 1% of gravitational force.
- maximizes angular momentum effects at late post-bounce times.

Low-mode nonradial standing accretion shock instability (SASI) present in all simulated cases

(in agreement with Blondin et al. 2003, Scheck et al. 2004, Blondin & Mezzacappa 2006, Ohnishi et al. 2005):



Weak ν-driven explosion with global anisotropy in 11.2 M_{sun} star (Janka et al. 2004, Buras et al. 2006)

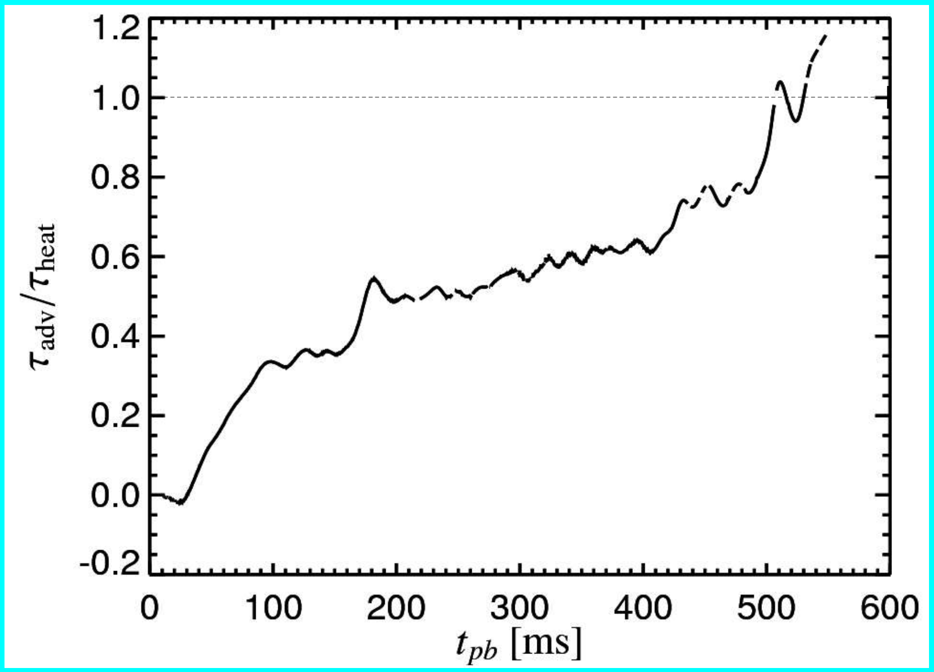


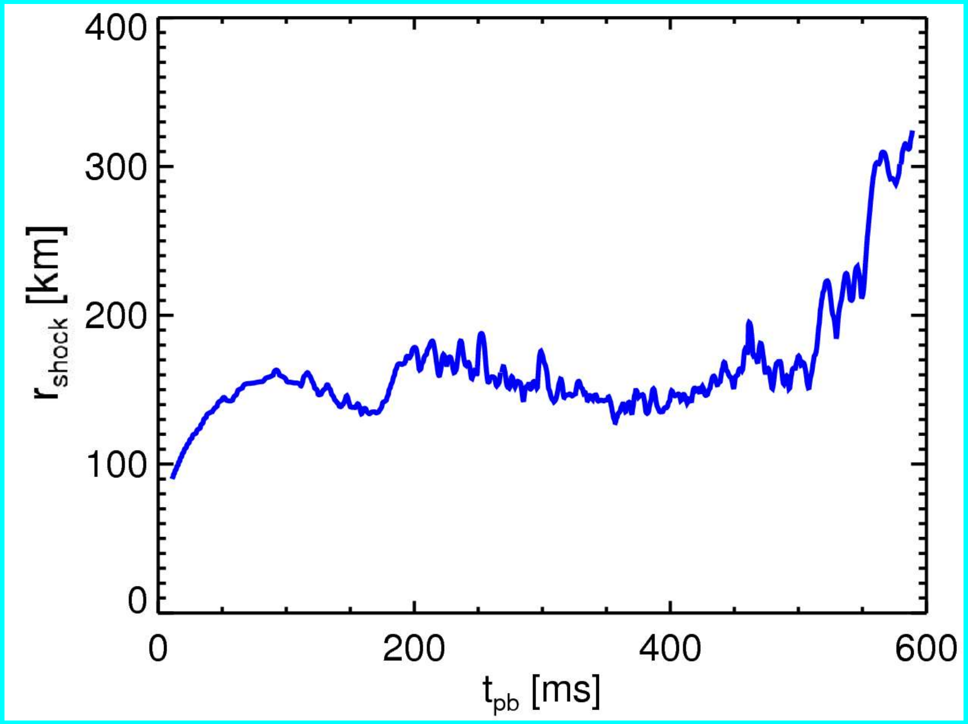
Violent shock oscillations, ν-driven explosion sets in at 570 ms p.b. in rotating 15 M_{sun} star (Marek et al., 2007)

SN Simulations: $M = 15\ M_{sun}$

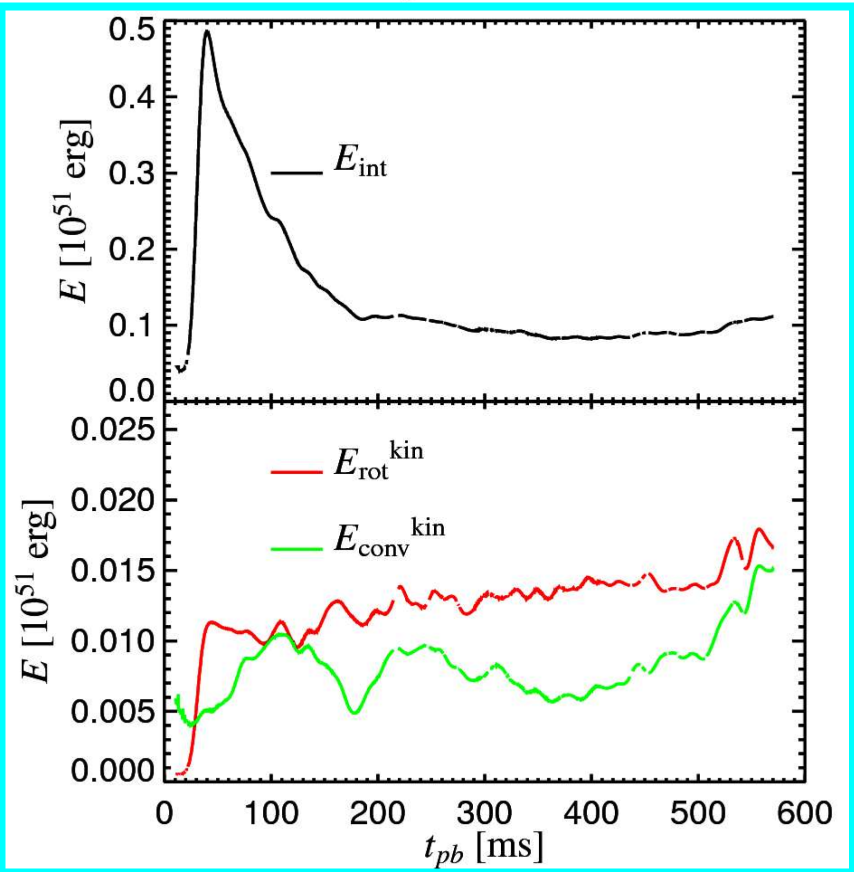
Centrifugal force and SASI l=1,2 modes help to increase the advection timescale
---> longer neutrino heating!

Critical timescale ratio $\tau_{adv} / \tau_{heat} > 1$:
conditons favorable for explosion
at ~600 ms after bounce





A. Marek, PhD Thesis (2007)



Explosion Energies and NS masses

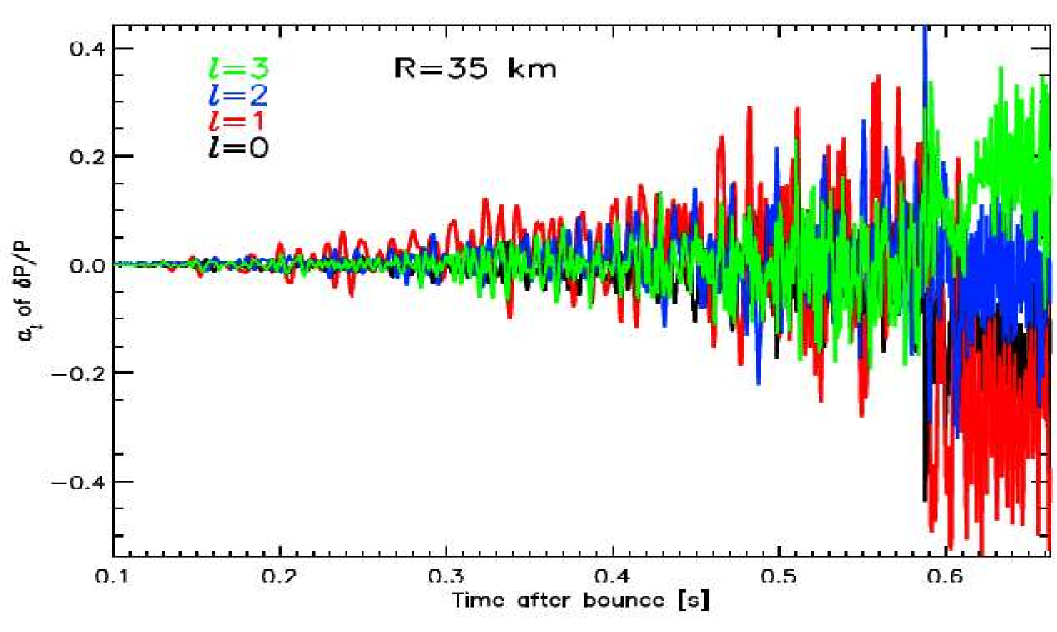
$$E_{\rm exp} = E_{\rm recomb} + E_{\rm wind} + E_{\rm burn} - E_{\rm bind}$$

where $$E_{\rm recomb} \approx 1.8 \times 10^{51}\,{\rm erg}\left(\frac{\Delta M_{\rm gain}}{0.1\,M_\odot}\right) .$$

Stellar mass	$t_{\rm exp}$	$\Delta M_{\rm gain}$	$E_{\rm exp}$	$M_{\rm ns}$ (baryonic)
[$M_{\rm sun}$]	[ms]	[$M_{\rm sun}$]	[B]	[$M_{\rm sun}$]
8–10	150	< 0.01	~0.3	1.35
~11	200	0.01	0.3–0.4	1.30
15	600	0.05	~1	1.55

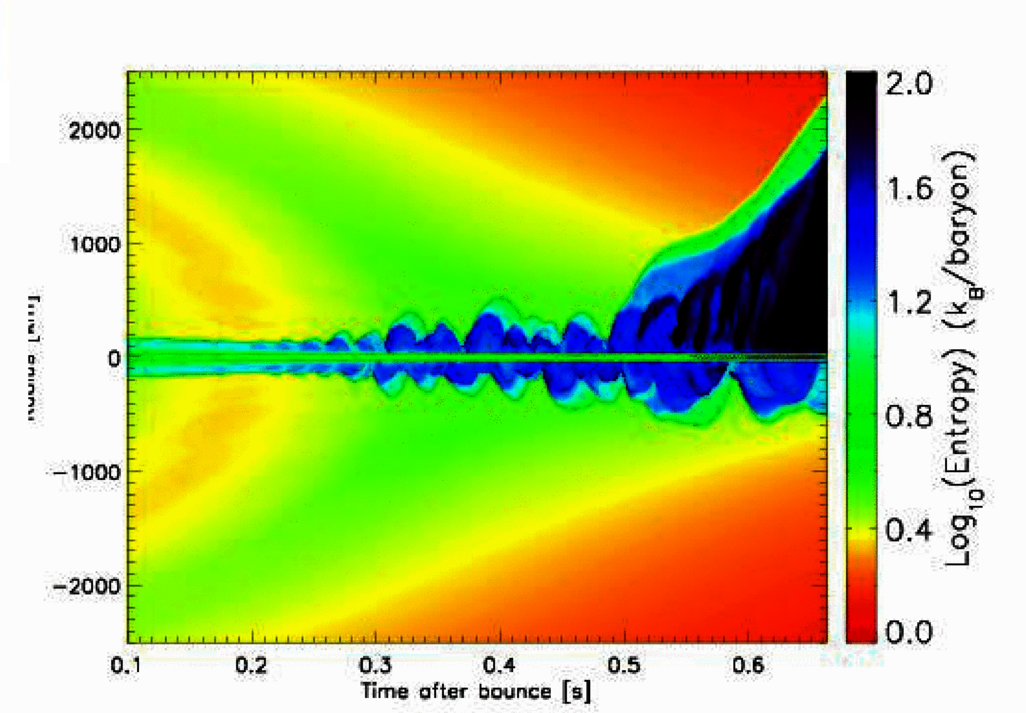
BUT NOTE: the stellar properties vary non-monotonically with the progenitor mass (cf. Woosley, Heger, & Weaver 2005)

Acoustic Explosion Mechanism



- Neutron star is excited to l=1 g-mode oscillation by non-steady accretion
- Transfers accretion power by acoustic waves to explosion

(Burrows et al., ApJ, 2006)

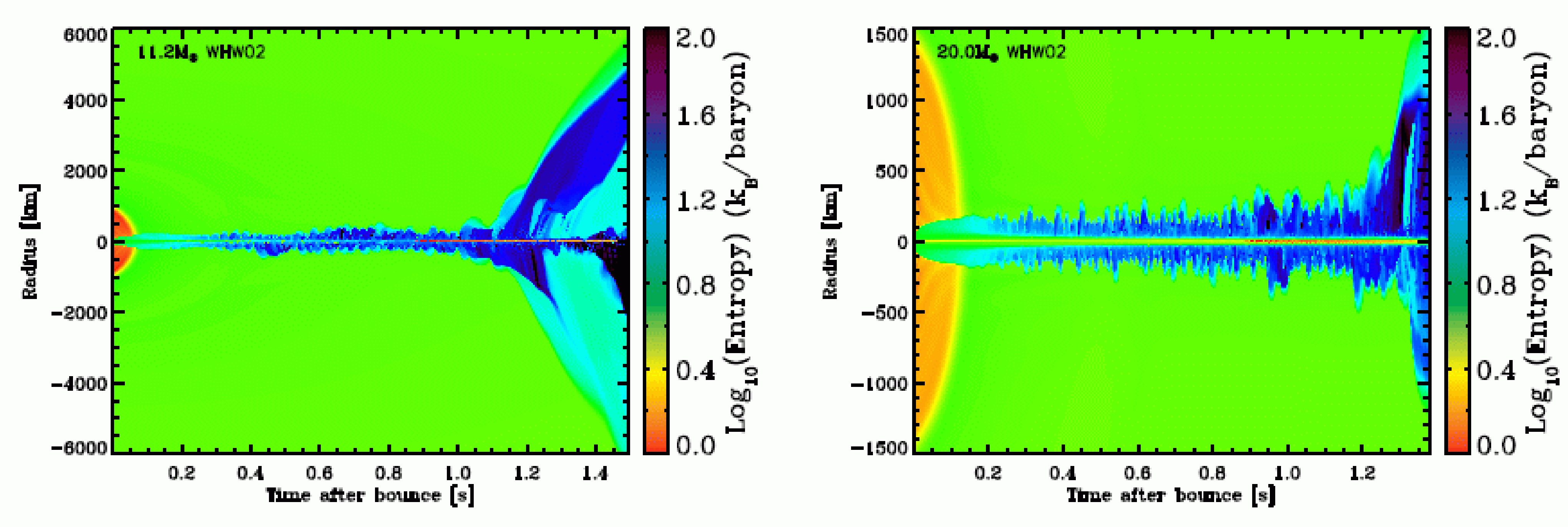


- For 11 M_{sun} Weaver & Woosley (1995) star explosion occurs at 500 ms after core bounce

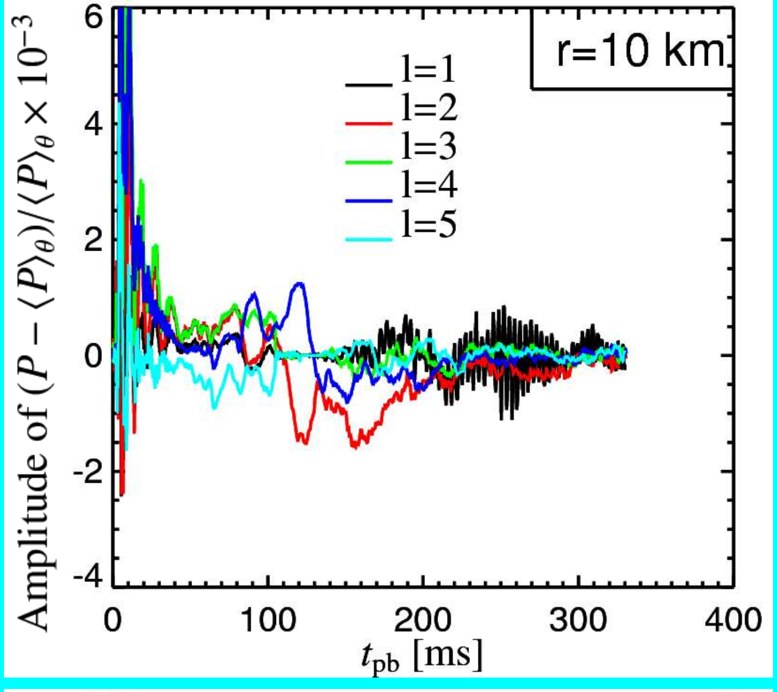
Acoustic Explosion Mechanism

- Other progenitors ====> explosions later than 1 second
- Question: Is a large g-modes of neutron star really excited?
  and is it excited before a neutrino-driven explosion occurs?

(Burrows et al., ApJ 2006)

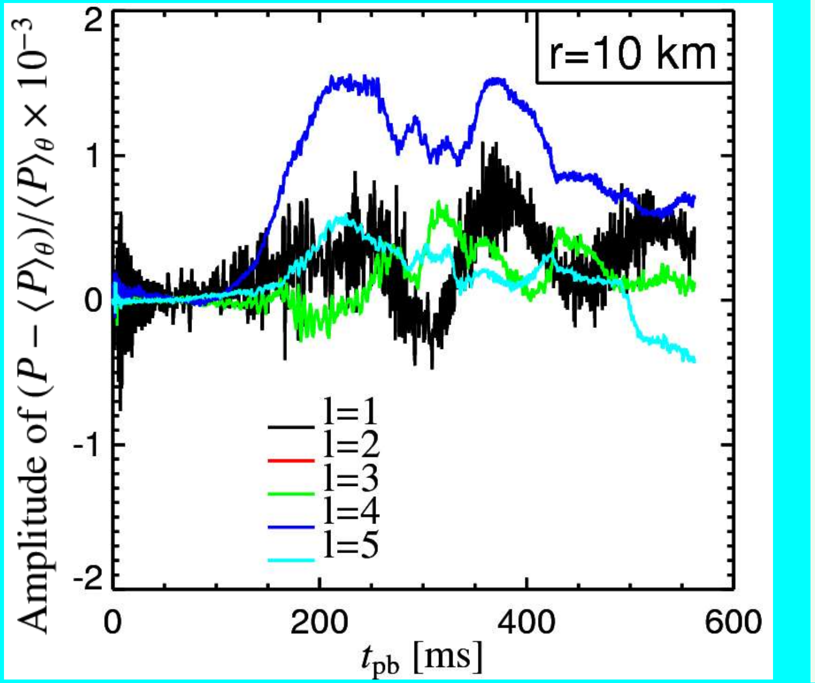


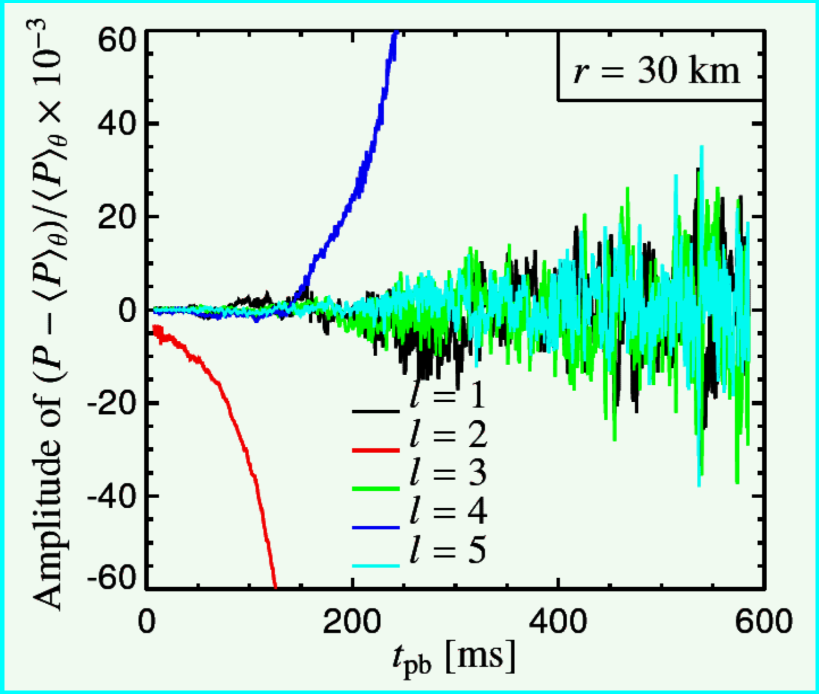
Acoustic Explosion Mechanism?



- Garching simulations give factor 10–100 smaller amplitudes of l=1 to l=5 modes in the proto-NS
- acoustic mechanism not causal for explosions!

A. Marek, PhD Thesis (2007)

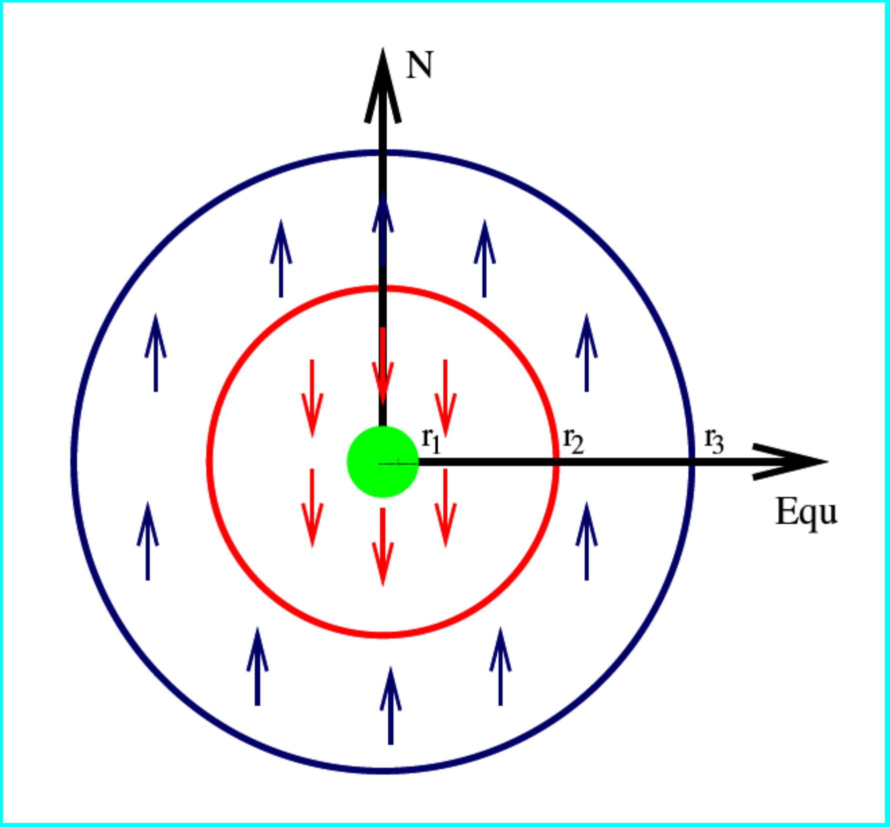




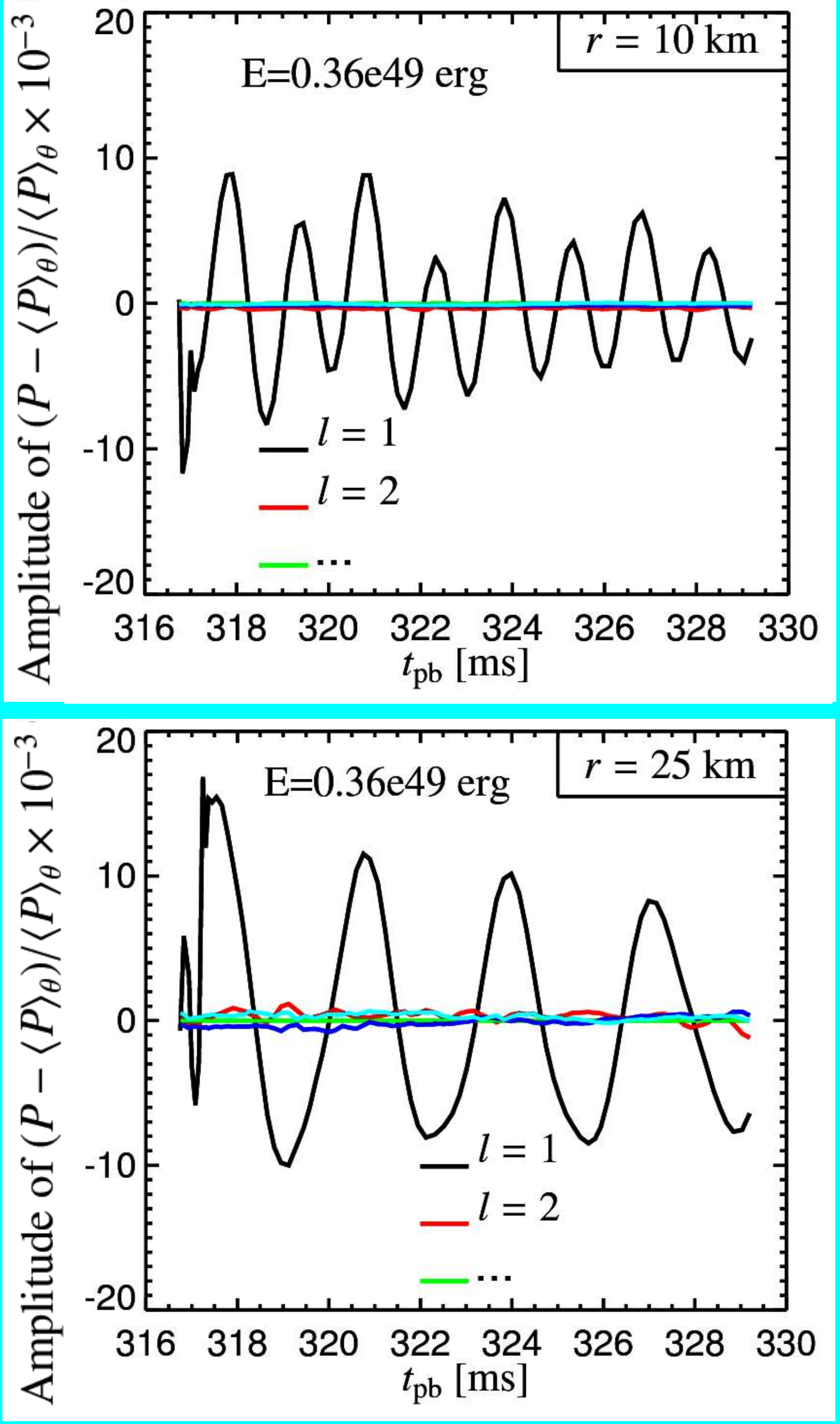
Acoustic Explosion Mechanism?

- Garching simulations give 1–2 orders of magnitude smaller amplitudes of l=1 to l=5 modes in the proto-NS.
- But can the Garching code follow such (e.g., dipole l = 1) oscillations?
- There are claims in the literature that " a code with spherical grid is unable to compute l=1 mode oscillations".
- We performed numerical experiments by exciting artificially l=1 oscillations with energies of $E_{osc} = 3.7*10^{48}$ erg and $E_{osc} = 5.9*10^{49}$ erg.

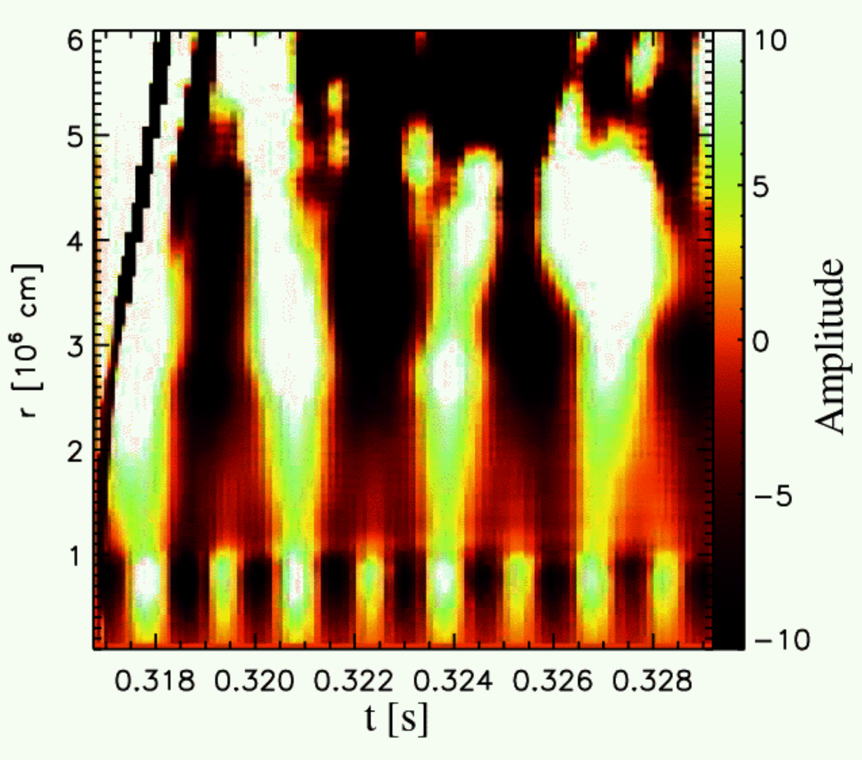
Chosen initial condition for numerical experiment:



Acoustic Explosion Mechanism?



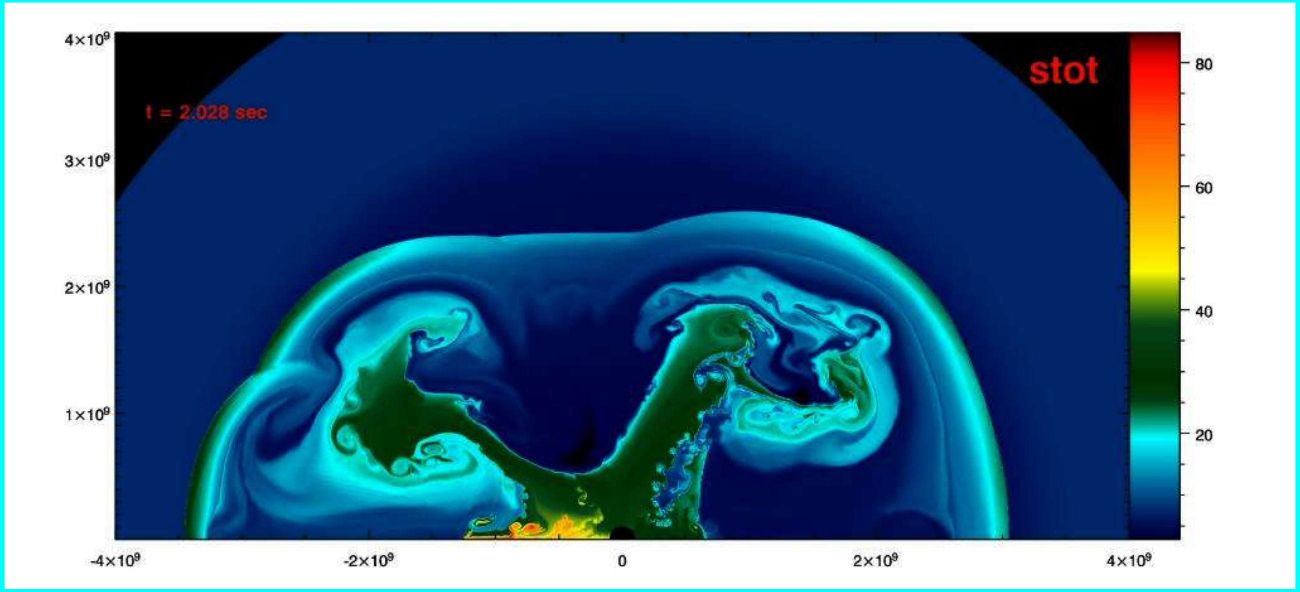
- Test of Garching SN code reveals that excited l=1 mode is stable and can well be followed over many cycles!



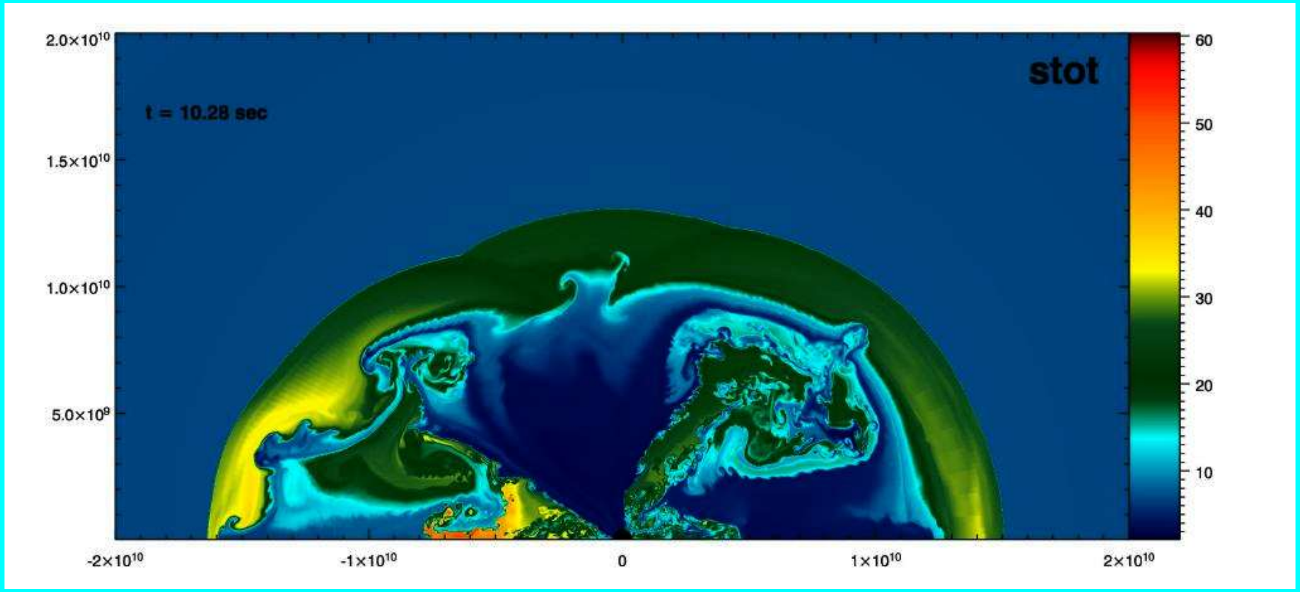
A. Marek, PhD Thesis (2007)

Long-time Evolution and Anisotropies

Long-Time SN Evolution in 2D



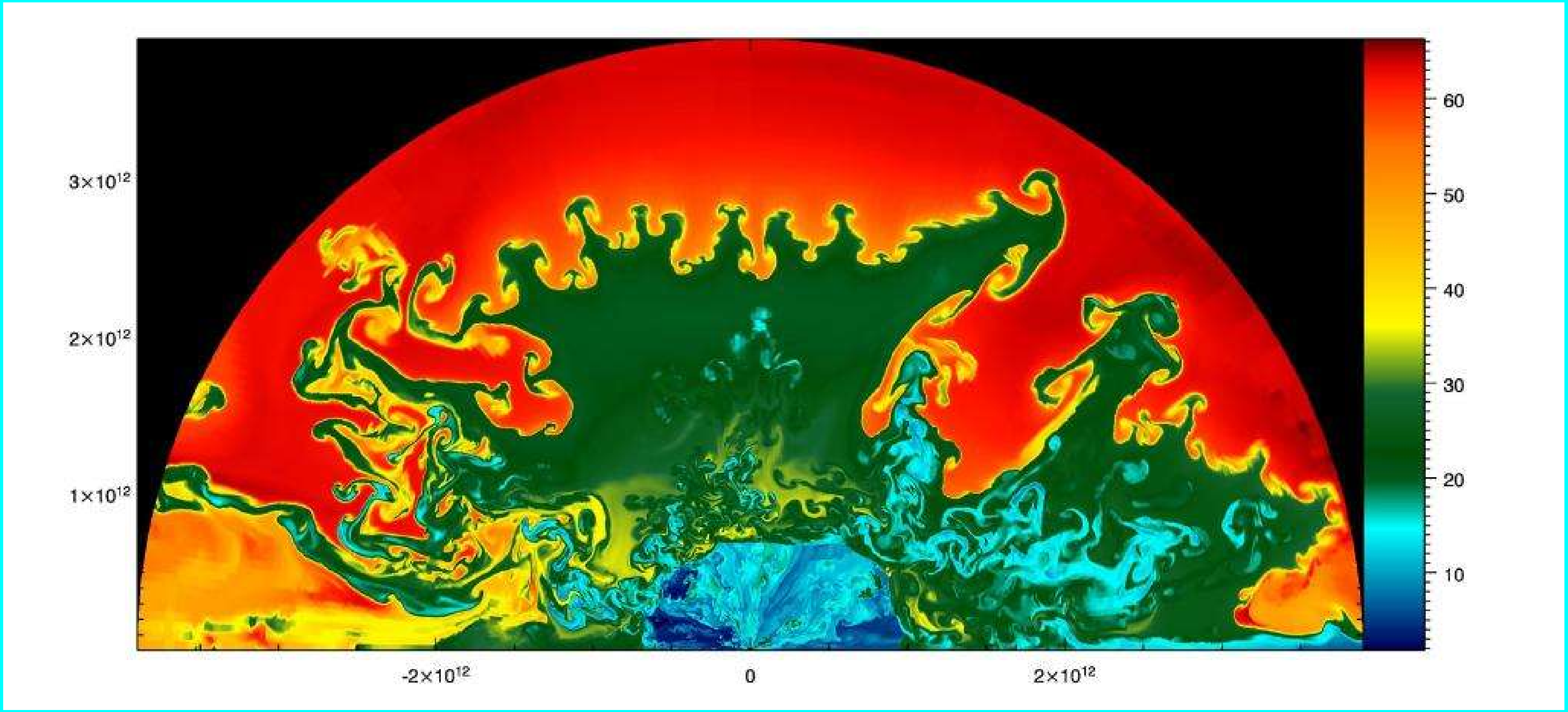
2 seconds



10 seconds

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

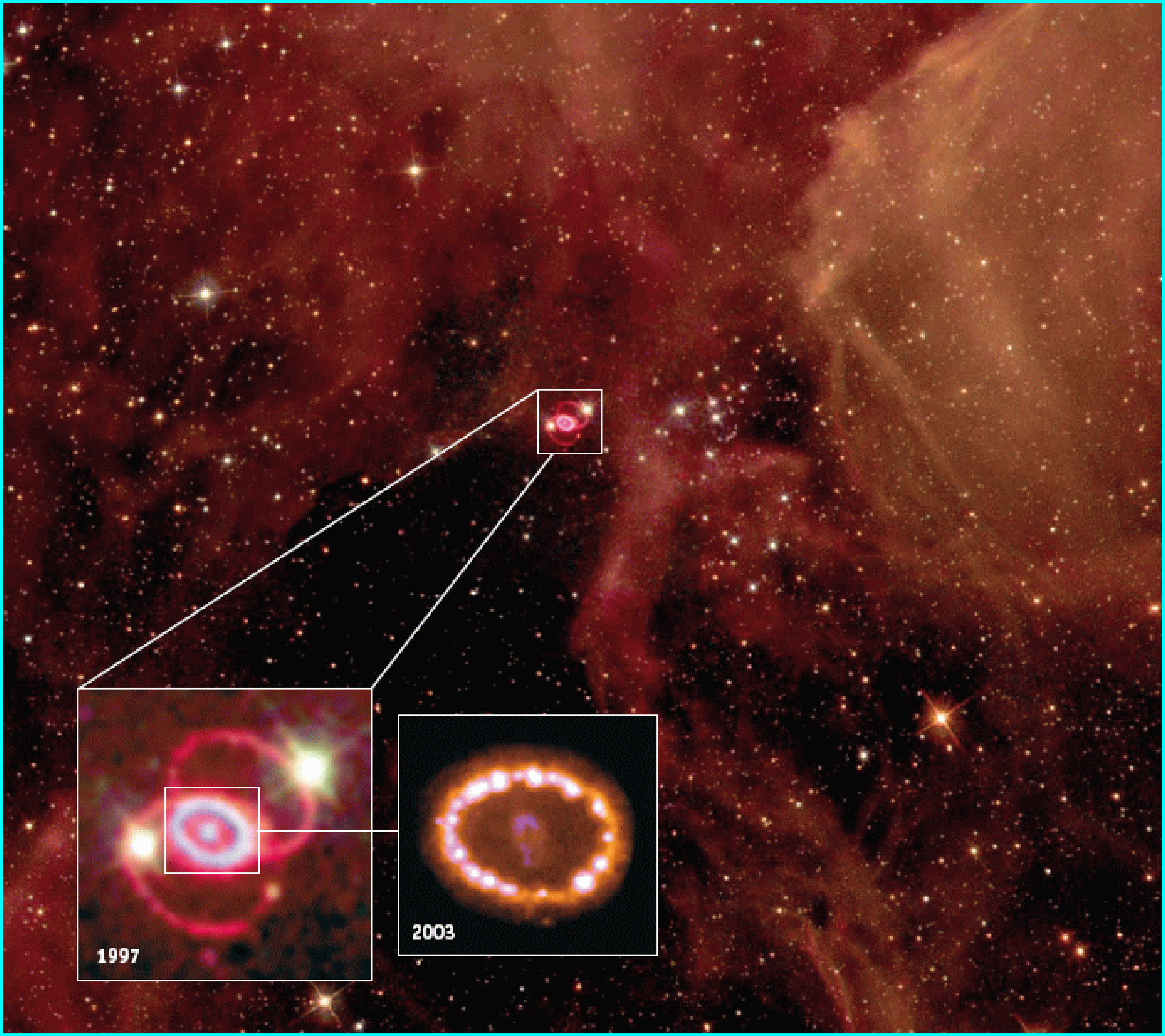
Long-Time SN Evolution in 2D



Kifonidis et al., A&A 453 (2006) 661

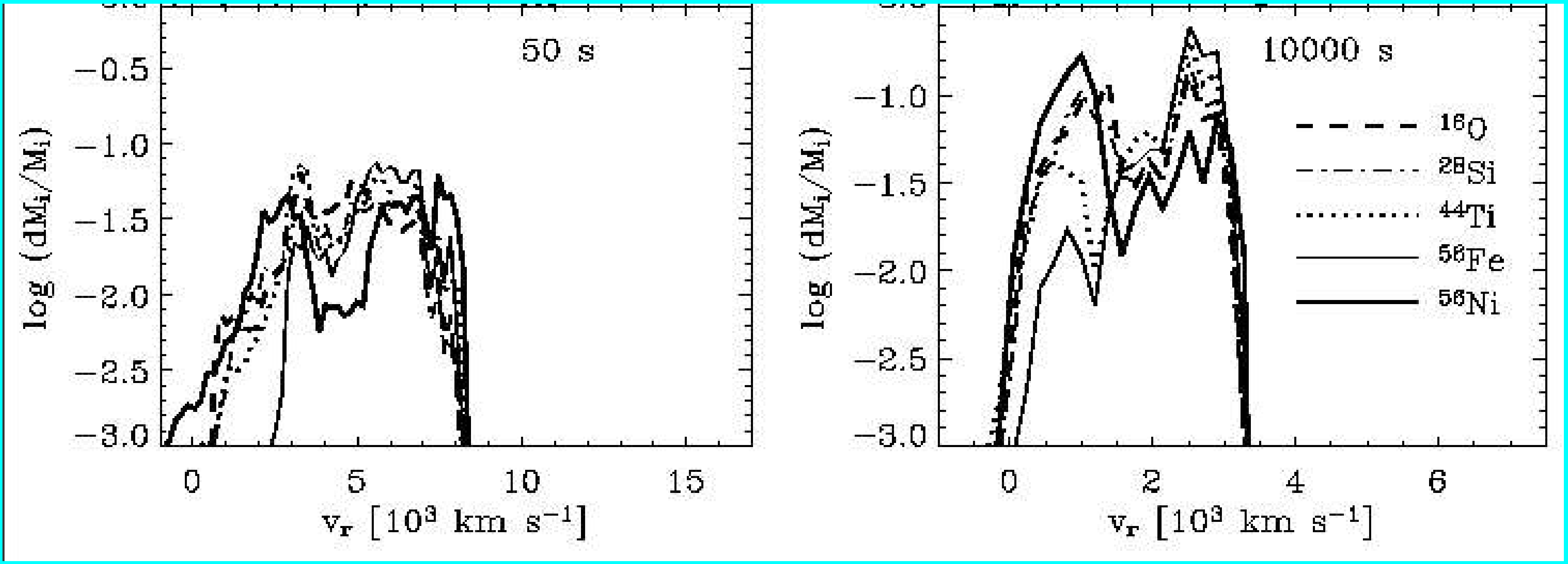
20000 seconds

- Strong metal mixing into H envelope [v_{max}(metals) ~ 3500 km/s]
- Strong H mixing deep into He layer
- large asymmetries of metal distribution



Supernova 1987A

Long-Time SN Evolution in 2D



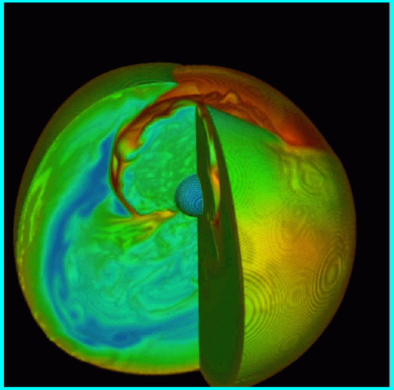
Kifonidis et al., A&A 453 (2006) 661

Element distribution in velocity space: Nickel velocities > 3000 km/s as observed in SN 1987A.

Neutrino-Driven Explosions

"Full models": Neutrino-driven explosions in 2D:

- ONeMg core collapse (8–10 solar mass stars):
  neutrino-driven wind drives explosion with ~0.3*10^{51} ergs, little Ni, O;
  Crab-like case.
- ~11 M_{sun} stars (180° grid) with small core and steep density gradient outside of iron core: weak neutrino-driven explosion, supported by a global l=1,2 mode instability ——> large asymmetry.
- 15 M_{sun} star (with modest rotation) develops explosion about 600 ms after bounce, supported by huge SASI-mode.



Blondin & Mezzacappa (2006)

- Exploration in 3D needed (see below)!
  New degrees of freedom in 3D may help explosion to develop!
  Do l =1 SASI modes or NS g-mode oscillations also grow in 3D?

So: What happened in SN 1987A?

- The progenitor of SN 1987A was probably a binary merger remnant (talk by Podsiadlowsky)
- BUT: How fast was its Fe+Si core spinning?
- Was it an MHD-driven explosion?
- Pro's (?): Rapid rotation and strong B-fields might reduce mean energy of radiated neutrinos and thus be more compatible with observations
- Con's (?): Explosion energy and Ni mass are normal
  No bright pulsar
  Neutrino-driven mechanism can provide explosion energy, anisotropy, mixing, Ni velocities

- Nucleosynthesis may provide indirect evidence
- For future galactic SN: Neutrino and gravitational wave measurements will be extremely valuable to get direct evidence of core physics!!