Neutron Stars at the Crossroads of Fundamental Physics,
Vancouver, BC, 9–13 August 2005

Physics of Supernova Explosions and Neutron Star Formation

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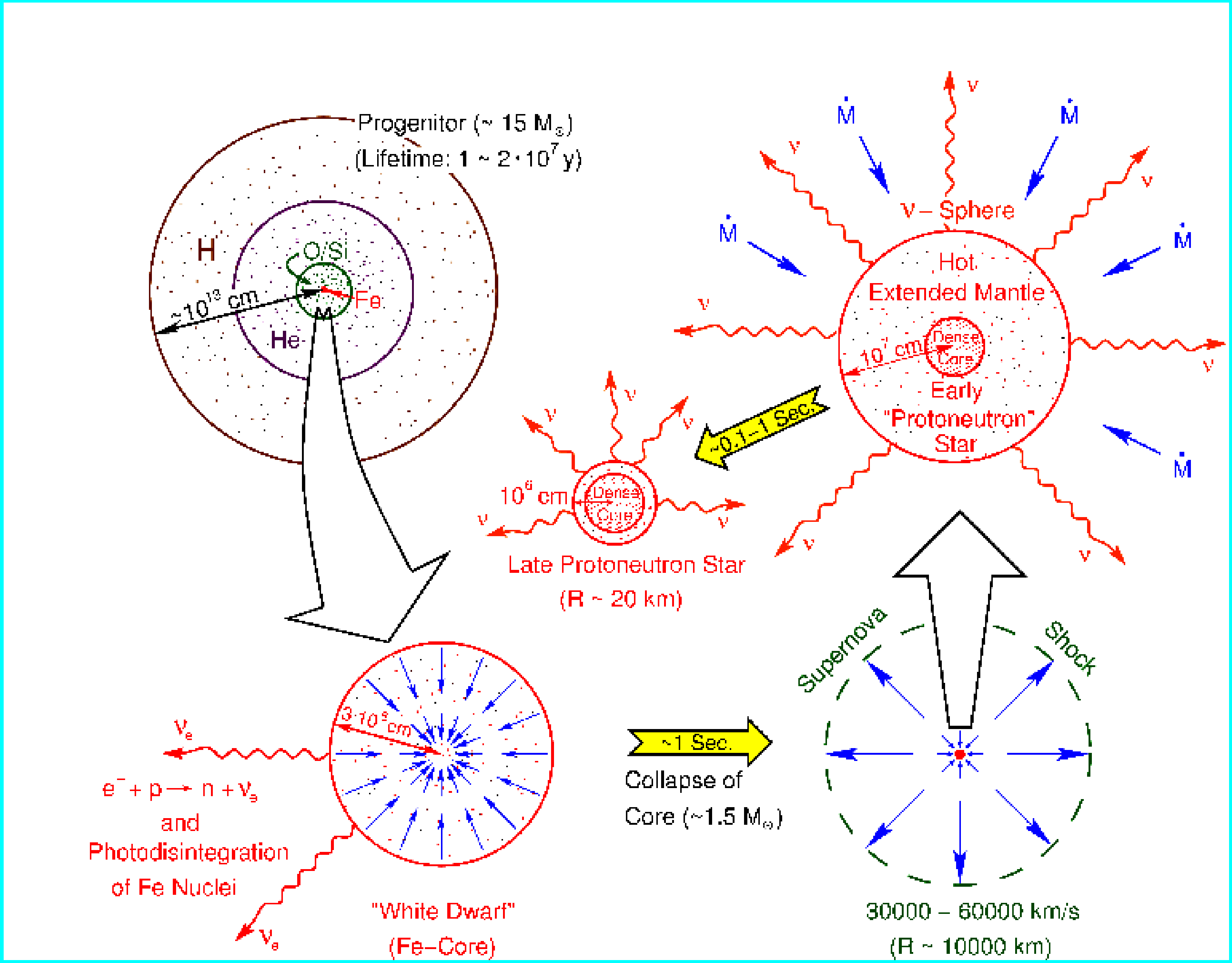
Supernovae & Neutron Stars

- Brief overview & motivation
- The tools: Hydrodynamics, neutrino transport, microphysics
- 1D simulations (spherical symmetry):
  - * collapse and explosion of ONeMg cores
  - * stars between 11 M_{sun} and 25 M_{sun}
- 2D simulations (axial symmetry):
  Rotation and large-mode convection
- 2D and 3D simulations with approximative neutrino transport:
  Global explosion asymmetries and pulsar kicks
- Summary and outlook

Neutron Star Formation: Overview

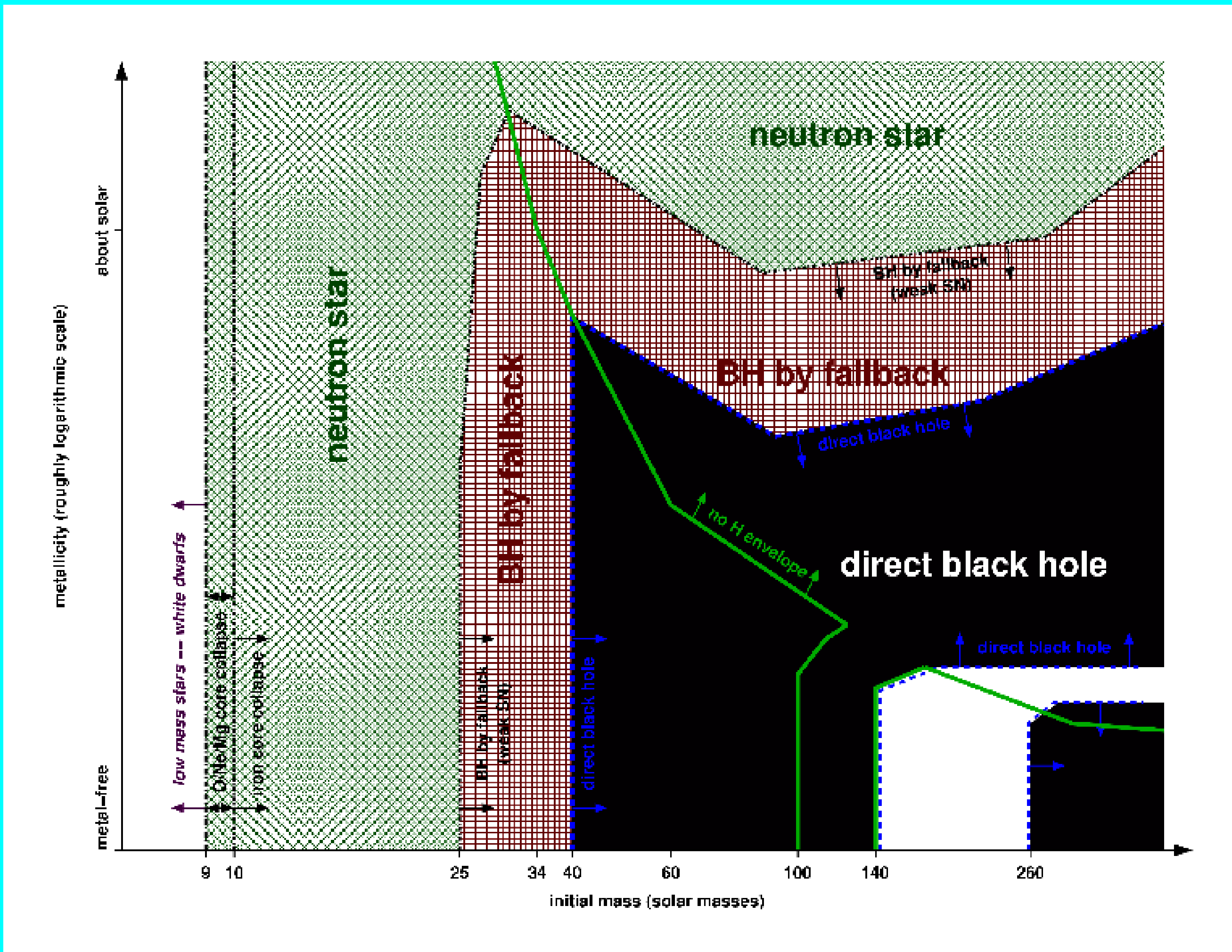


(adapted from
A. Burrows)

Numerical Modeling: Aims

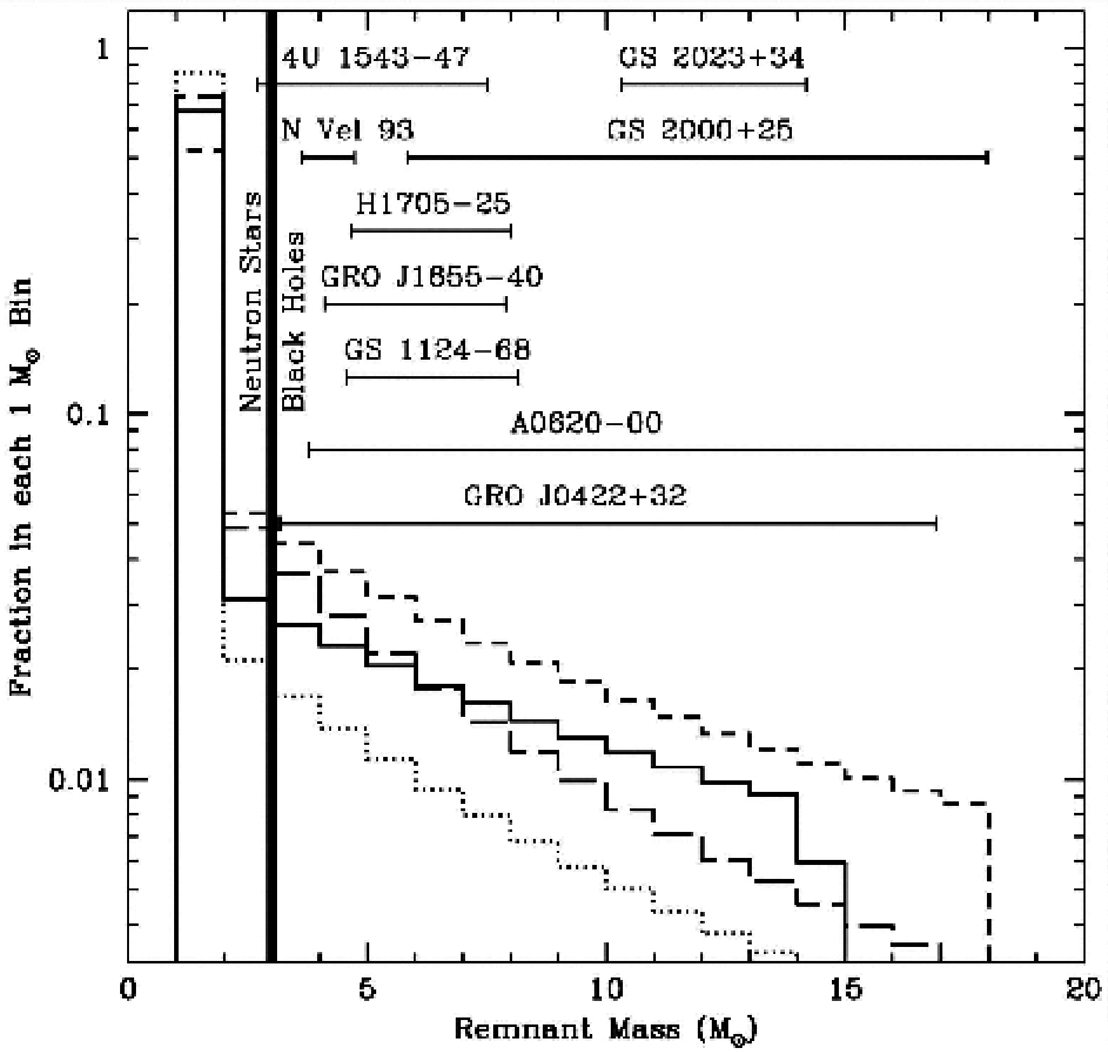
- Determine how massive stars blow up.
- Determine neutron star initial mass function.
- Determine progenitor mass limit for black hole formation.
- Determine neutron star initial rotation rate.
- Determine measurable signals associated with NS birth (neutrinos, gravitational waves, heavy elements, ...).
- Determine origin of pulsar kicks.
- ....

Massive Stars & Neutron Stars

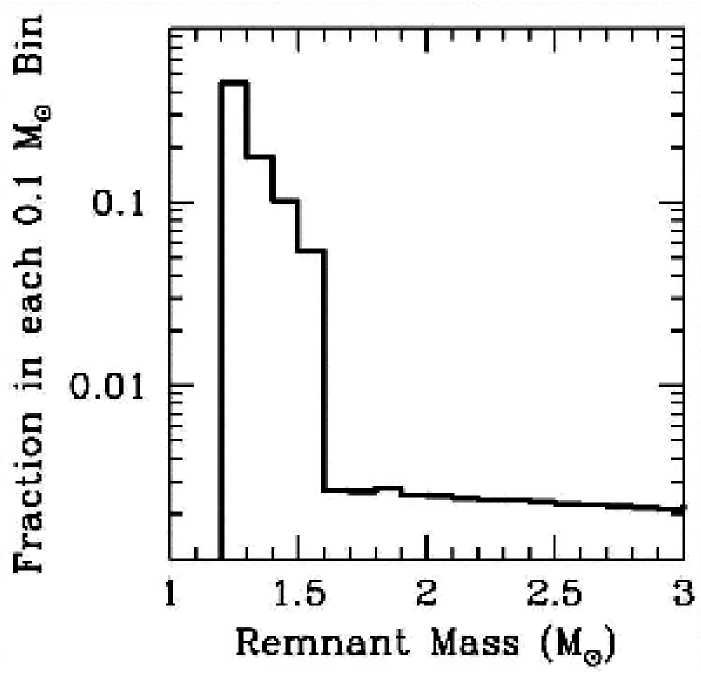


Heger et al.
(2003)

Massive Stars & Neutron Stars



Fryer & Kalogera (2001)



Massive Stars & Neutron Stars

But:

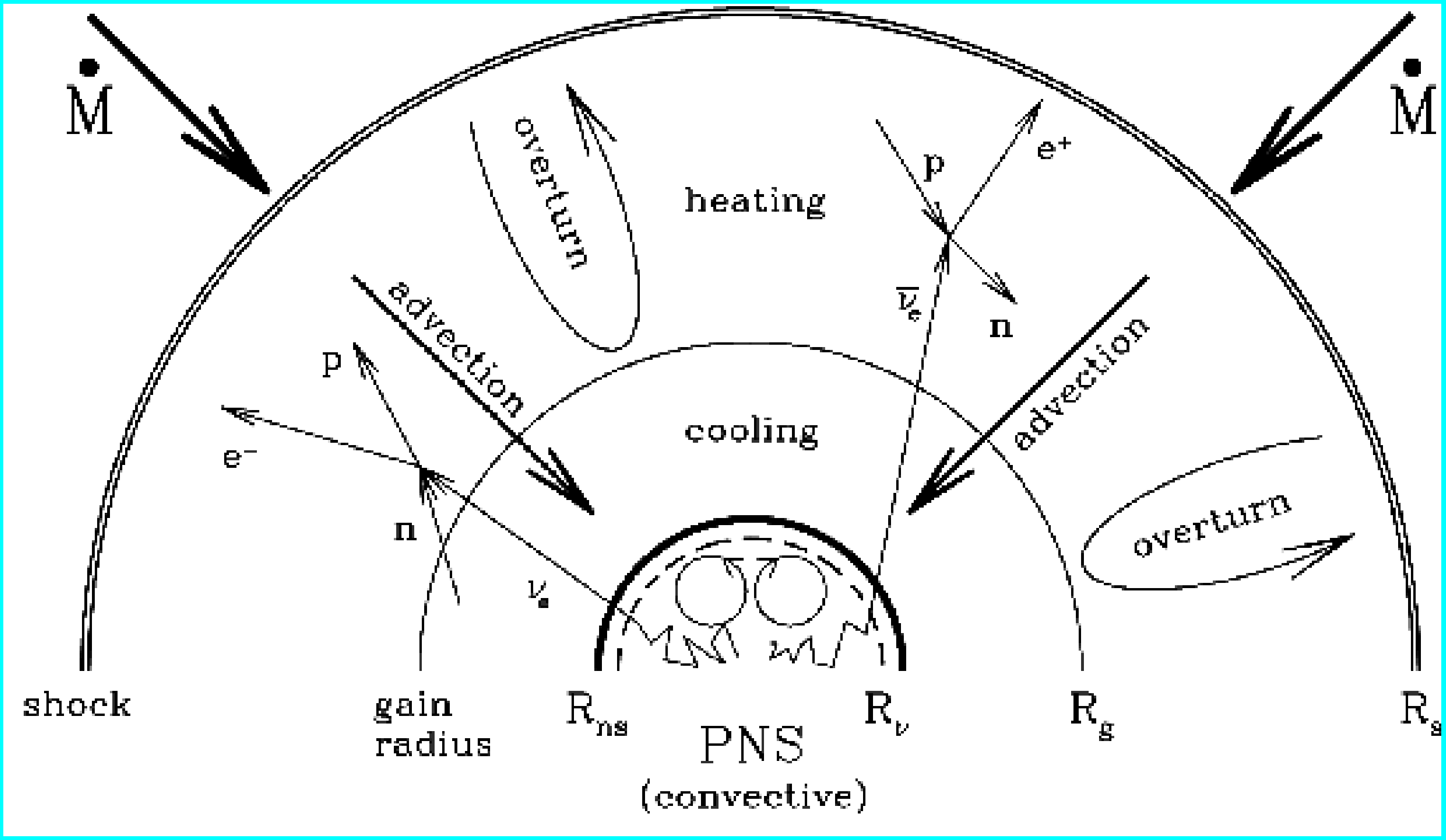
Current supernova models are still deficient or incomplete!

There is need for improvements, e.g.,
aspects of neutrino transport, nuclear EoS, stellar rotation & magnetic fields,.....

There is also need for a better understanding of the role of hydrodynamic instabilities, e.g. of convective processes.

Supernovae: Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



- "Neutrino-heating mechanism": Neutrinos revive stalled prompt shock by energy deposition (Colgate & White 1967, Wilson 1982, Bethe & Wilson 1985);
- Convective processes play an important role (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996).

The "Boltzmann" Supernova Code

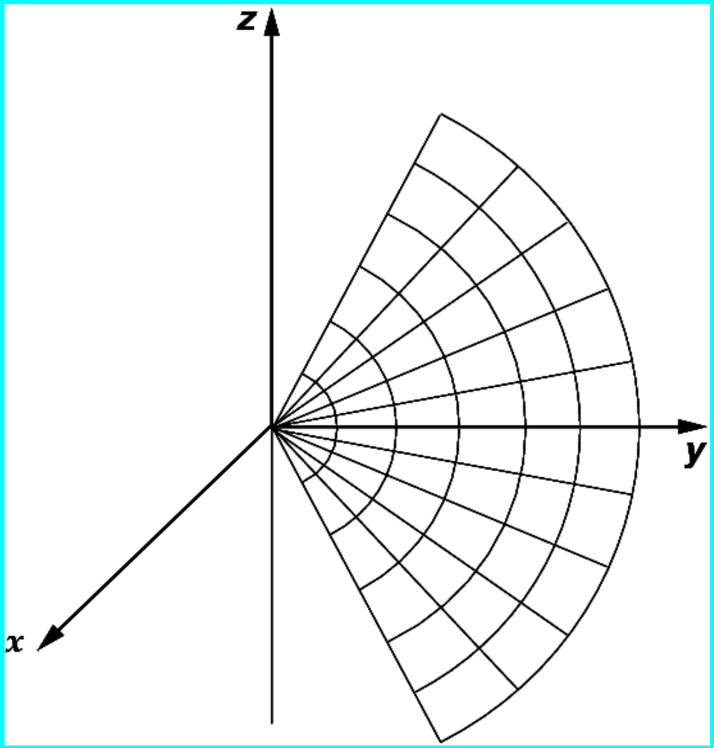
1D version: VERTEX,   multi-D version: MuDBaTH

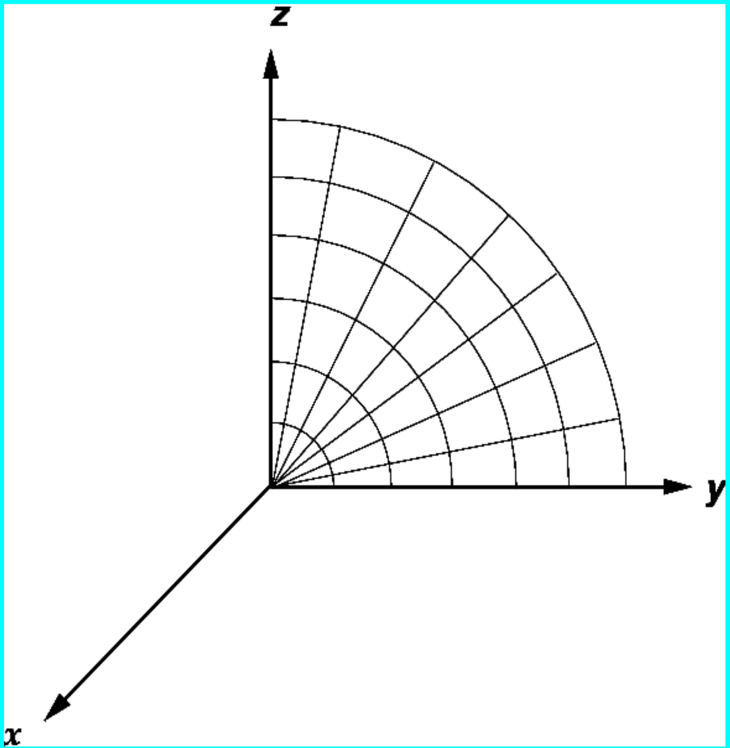
(Rampp & Janka 2002; Buras et al. 2005)

- 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)
  - * relativistic redshift and time dilation included
  - * state-of-the-art description of neutrino-matter interactions
- Neutrino transport in 2D: multi-energy, "ray-by-ray plus" scheme

The Supernova Code (cont'd)

- Multi-dimensional version:
  * spherical coordinates
  * in 2D axial symmetry assumed
  * azimuthally symmetric intensity and diagonal pressure tensor
  * neutrino transport radial in angular bins
  * lateral coupling by neutrino advection and pressure gradients





Our Codes: Input Physics

Neutrino rates:

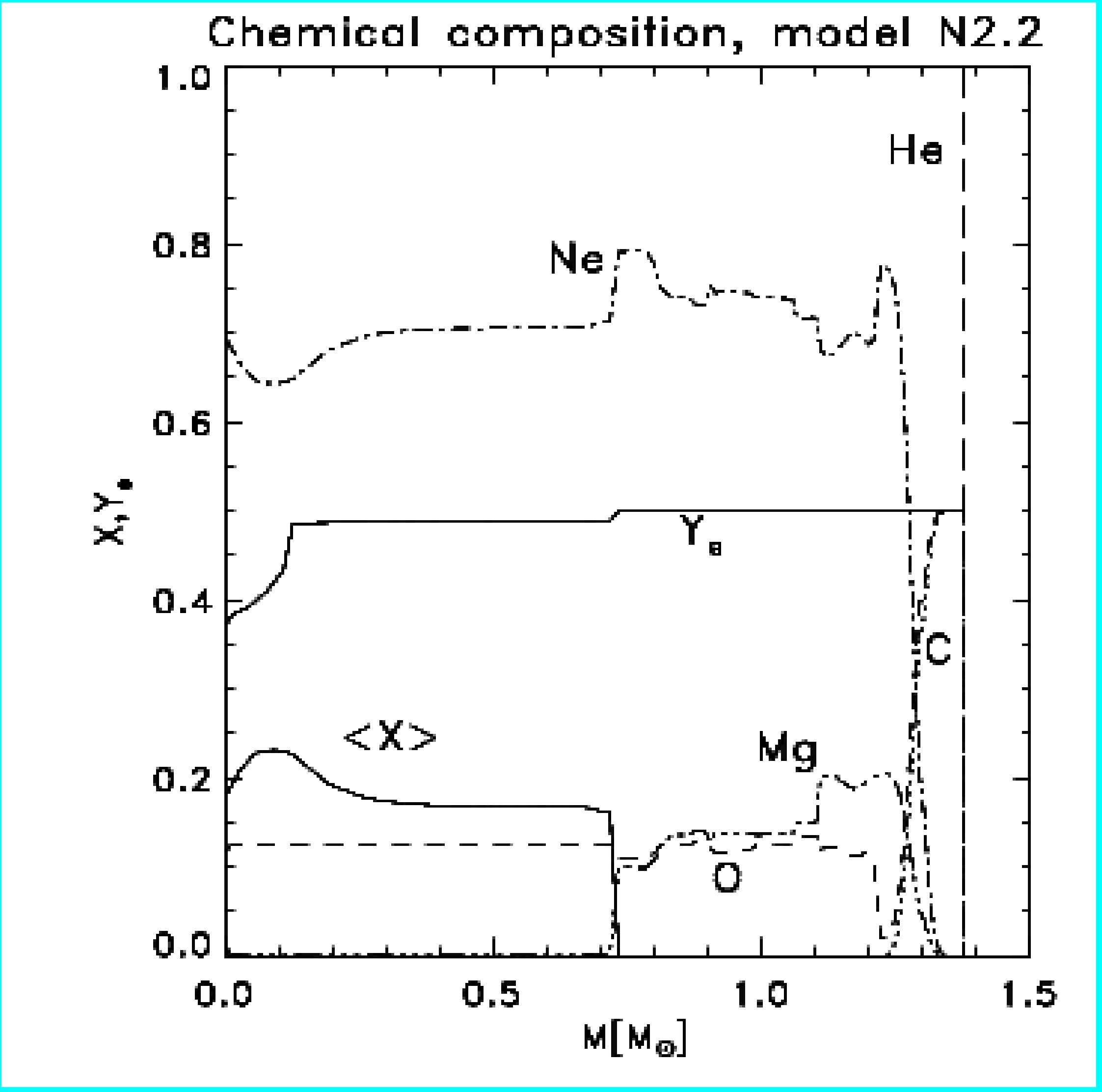
- Rate treatment mostly based on Bruenn (1985), Bruenn & Mezzacappa (1993a,b, 1997)
- Neutrino-nucleon interactions include recoil, fermion blocking, correlations, weak magnetism, effective nucleon mass
- Nucleon-nucleon bremsstrahlung (Hannestad & Raffelt 1998)
- Neutrino-neutrino interactions (Buras 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)

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

1D Simulations: ONeMg Core

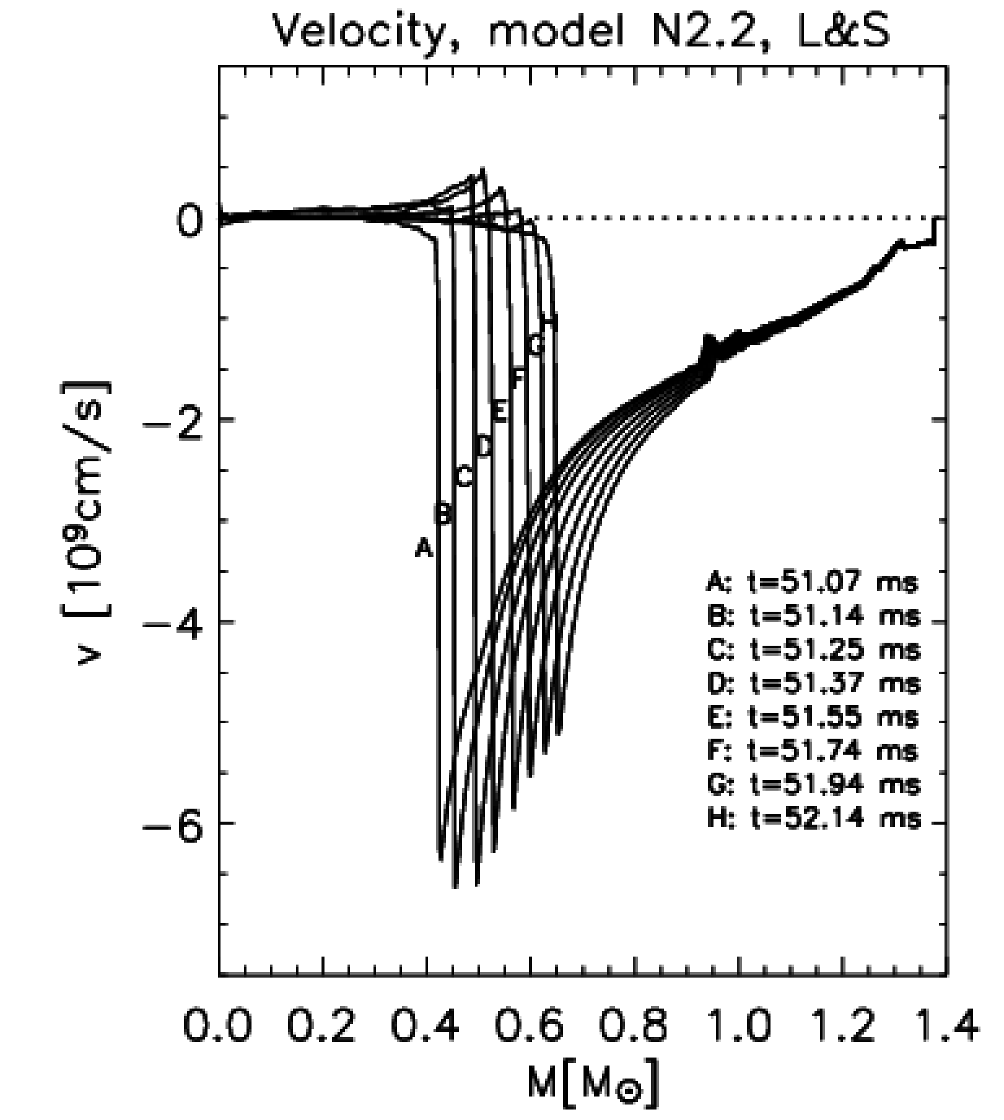
2.2 Msun He core, 1.38 Msun C core, 1.28 Msun ONeMg core (8 10 Msun stars, up to about 30% of all supernovae)

(Nomoto 1981, 84, 87)



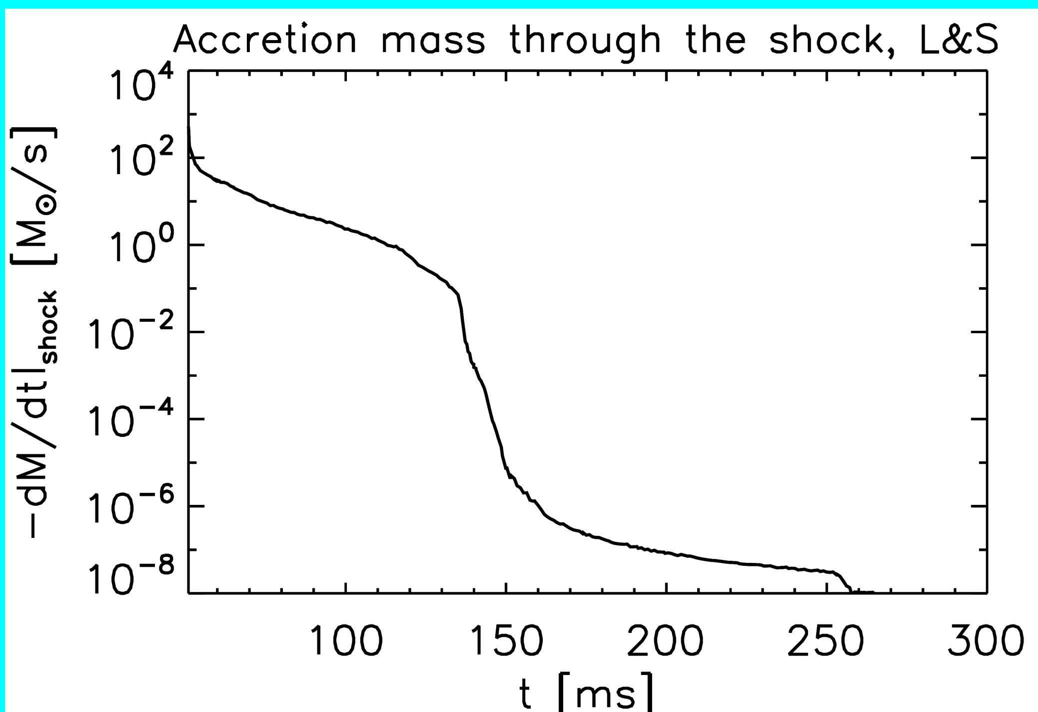
1D Simulations: ONeMg Core

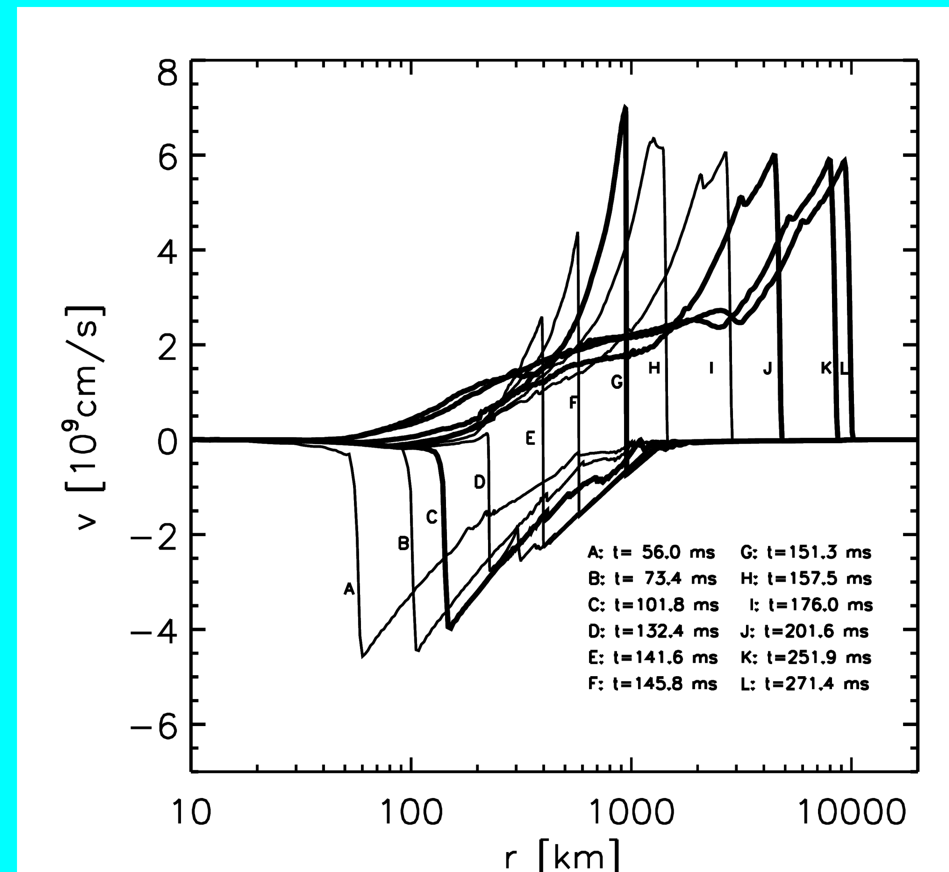
No prompt explosion!



F. Kitaura (Diploma Thesis 2003)

1D Simulations: ONeMg Core

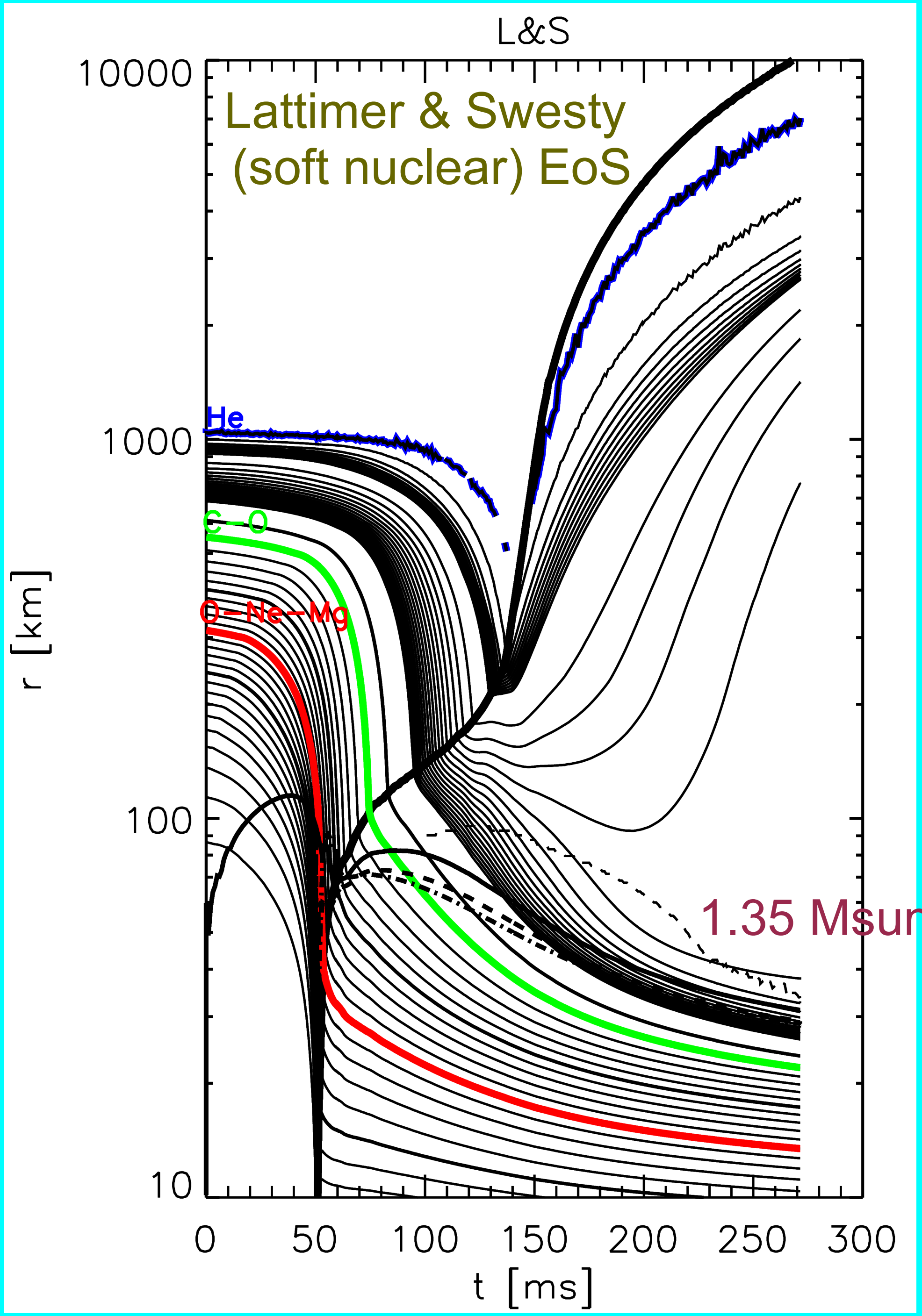


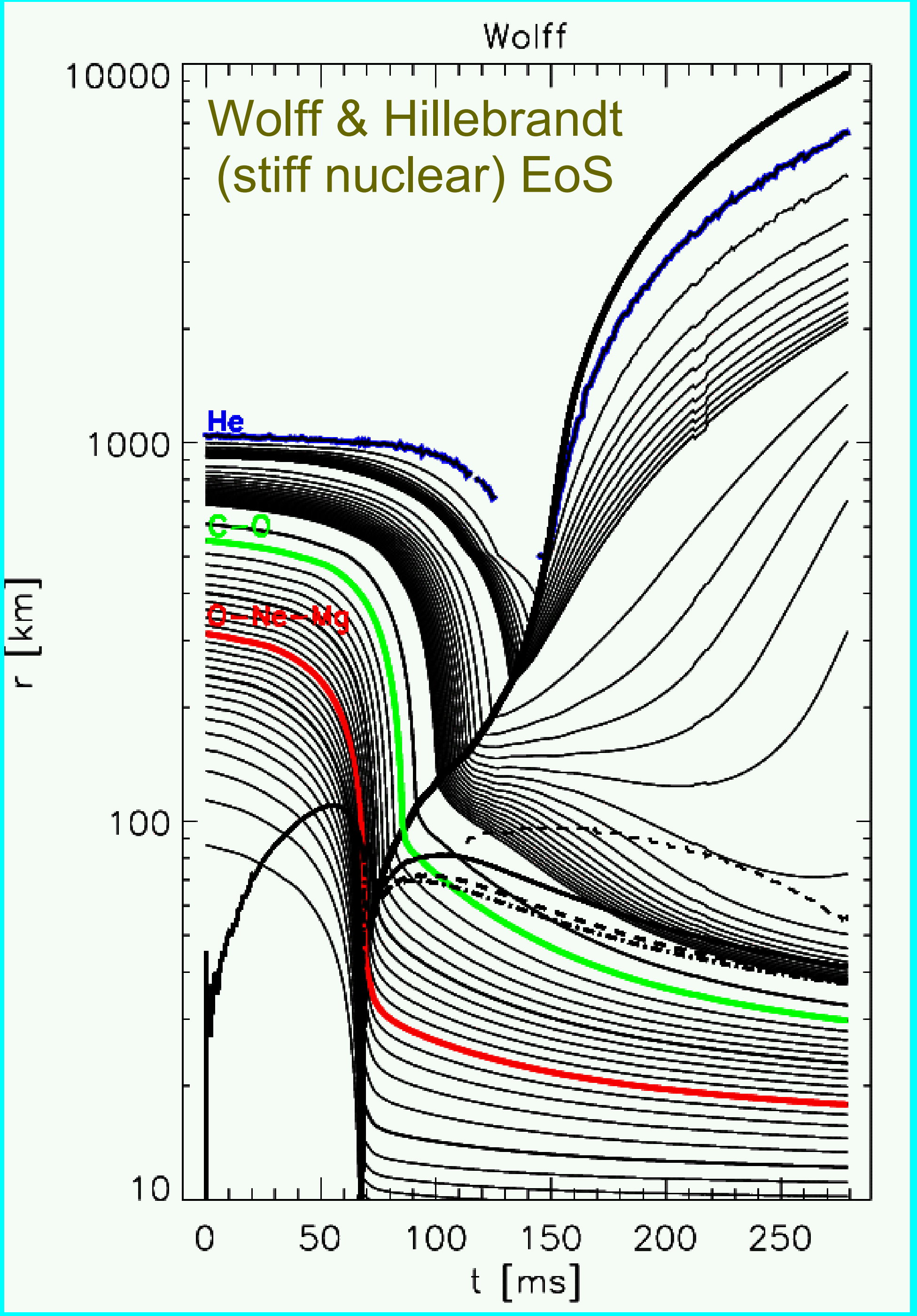


Rapidly decreasing mass accretion rate.

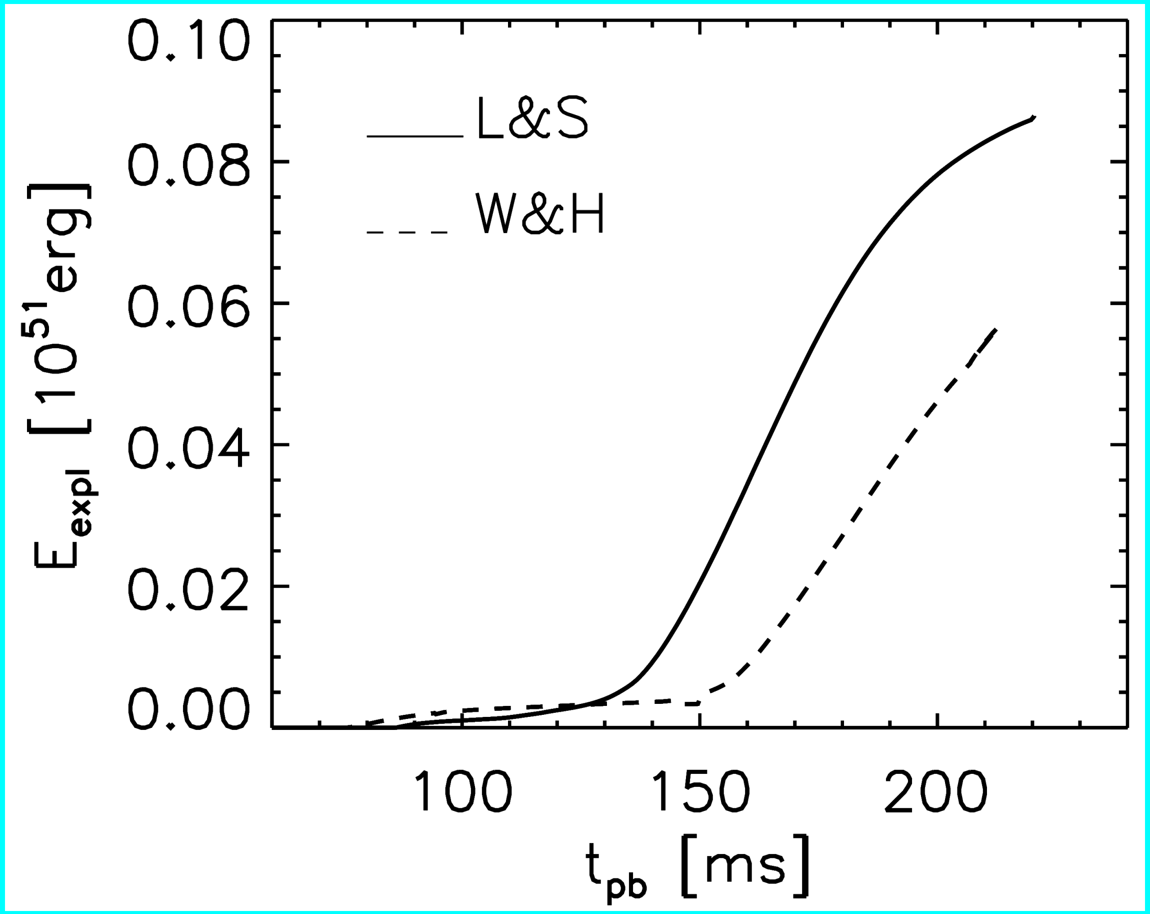
Continuous shock expansion due to decreasing mass accretion rate.

1D Simulations: ONeMg Core





1D Simulations: ONeMg Core

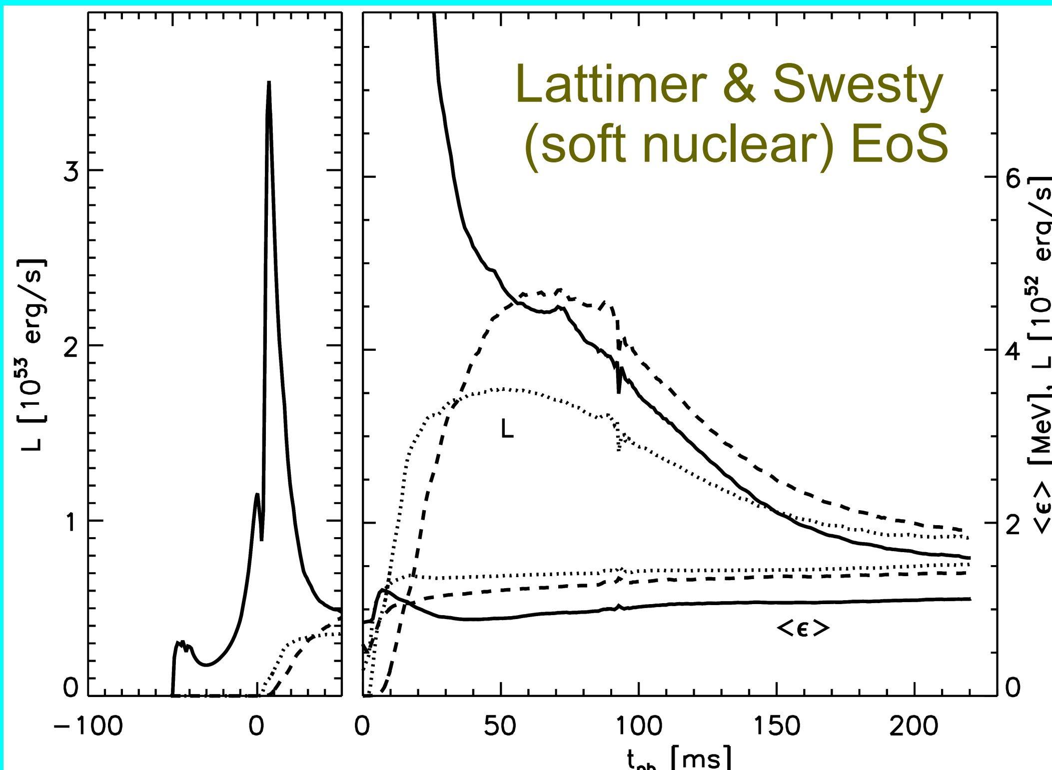


Mass ejection by neutrino-driven wind (similar to AIC of WD, Woosley & Baron 1992; also see Mayle & Wilson 1988; Fryer et al. 1999)

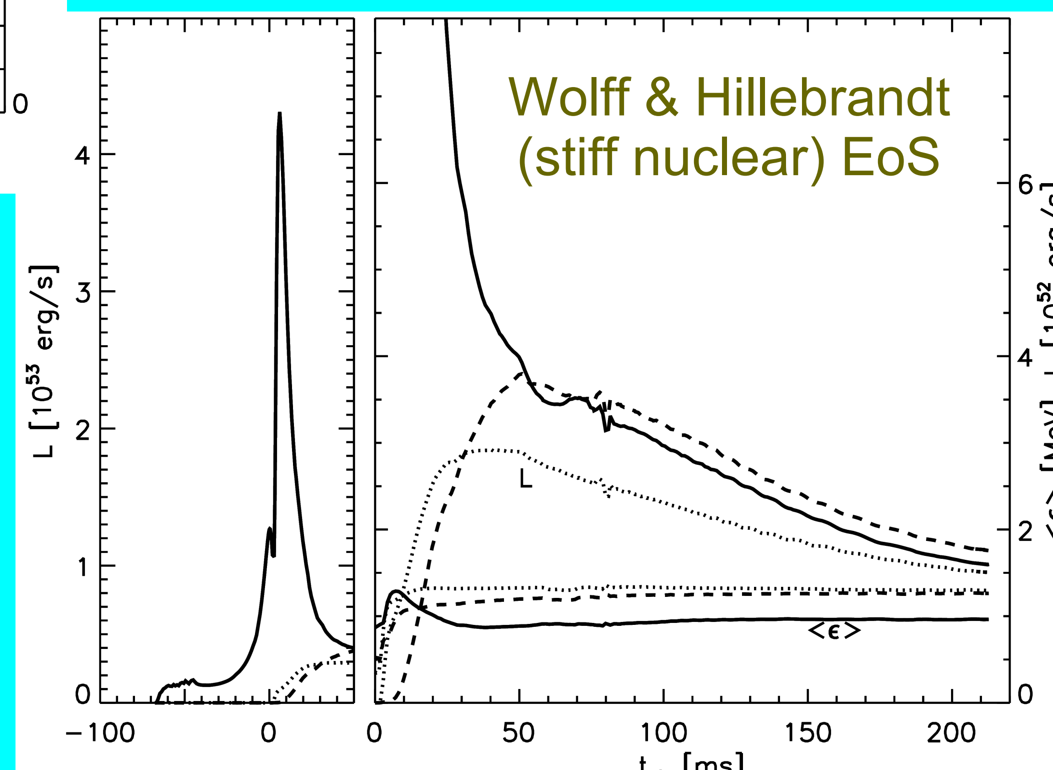
Low explosion energy (with long-time neutrino-driven wind: ~0.3–0.4 FOE), small Ni mass (~0.01 Msun), neutron star mass: 1.35 M_{sun}

CRAB?   (Nomoto, Nature, 1984)

1D Simulations: ONeMg Core



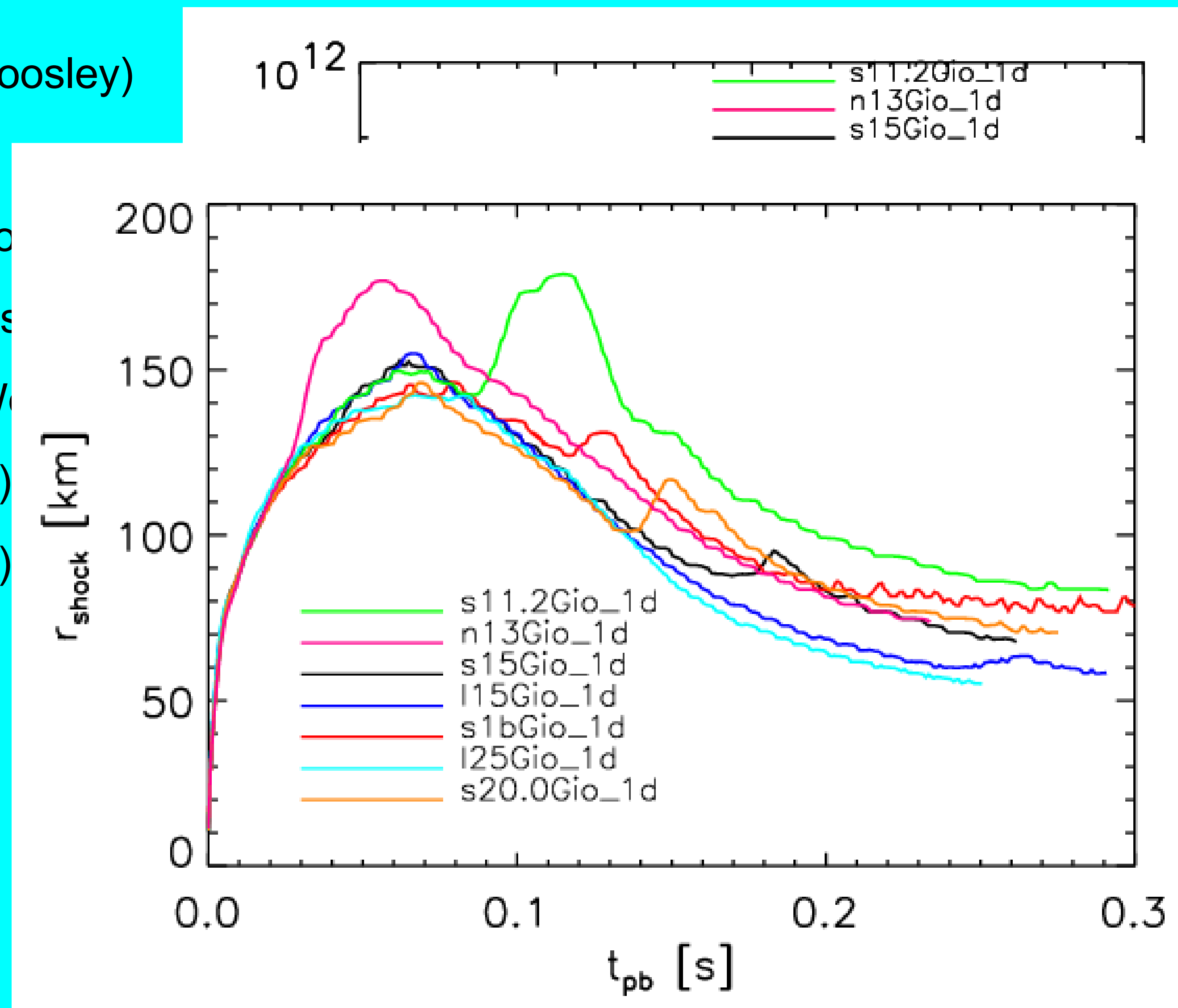
Neutrino luminosities
and
mean energies



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

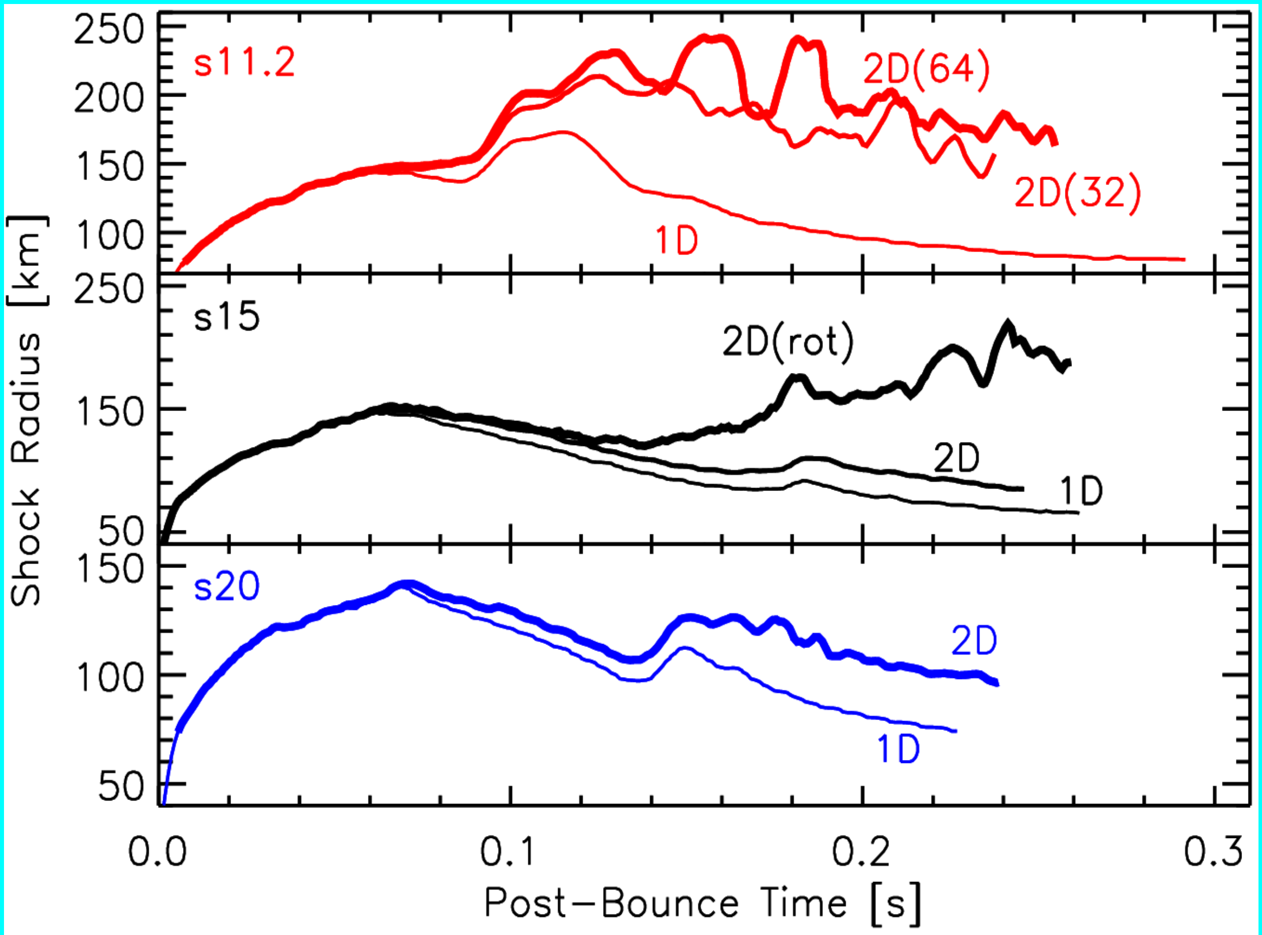
1D Simulations: 11–25 Msun Stars

- 11.2 Msun (Heger & Woosley)
- 13 Msun (Nomoto)
- 15 Msun (s15s7b2, Woo
- 20 Msun (Heger & Woos
- Type Ib progenitor (W
- 15 Msun (Limongi et al.)
- 25 Msun (Limongi et al.)

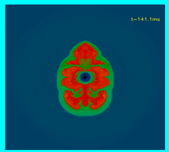


2D Simulations: 11.2, 15, 20 Msun

- Simulations with ~90º wedge do not explode.
- Convection causes big effect on shock expansion in case of 11.2 Msun star.
- Rotation causes big effect on shock expansion in case of 15 Msun star.

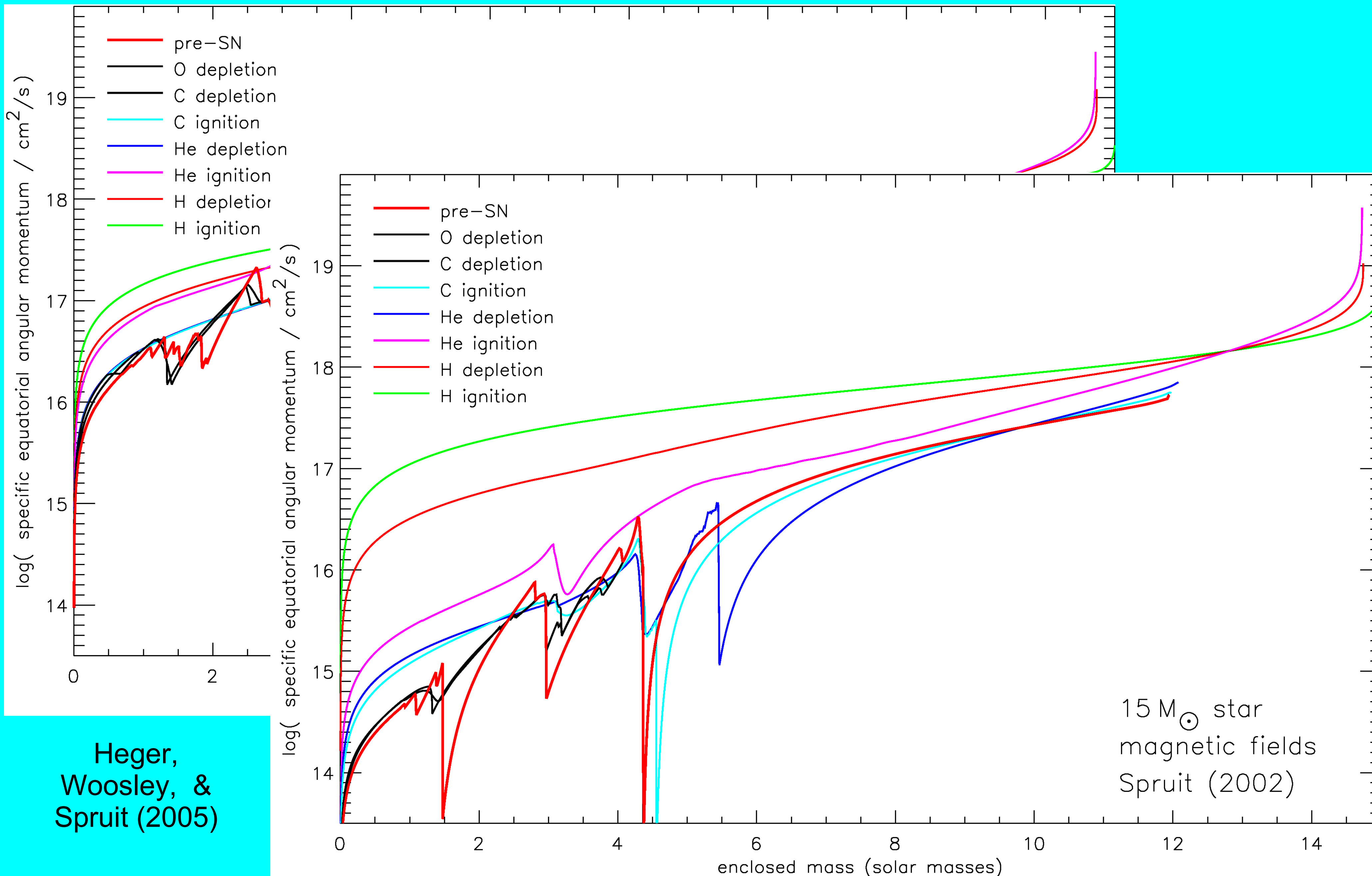


All 2D simulations with L&S EoS



Buras et al. (PRL 2003),
R. Buras (PhD Thesis 2004)

Stellar Rotation & Magnetism



Heger, Woosley, & Spruit (2005)

Stellar Rotation & Magnetism

Mass	Baryon[b] ($M_\odot$)	Gravitational[c] ($M_\odot$)	$J(M_{\rm bary})$ (10^{47} erg s)	BE (10^{53} erg)	Period[d] (ms)
12 $M_\odot$	1.38	1.26	5.2	2.3	15
15 $M_\odot$	1.47	1.33	7.5	2.5	11
20 $M_\odot$	1.71	1.52	14	3.4	7.0
25 $M_\odot$	1.88	1.66	17	4.1	6.3
35 $M_\odot$ [e]	2.30	1.97	41	6.0	3.0

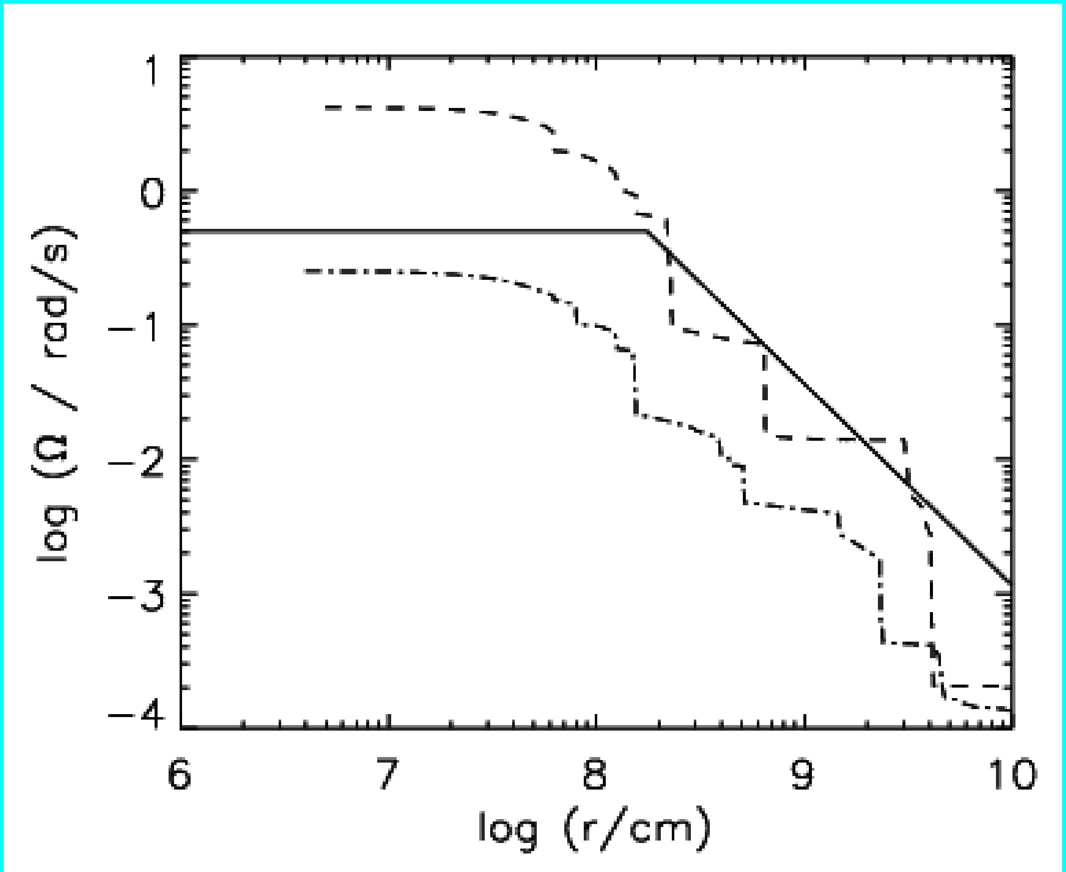
[a] Assuming a constant radius of 12 km and a moment of inertia $0.35MR^2$ (Lattimer & Prakash 2001)
[b] Mass before collapse where specific entropy is $4\,k_{\rm B}$/baryon
[c] Mass corrected for neutrino losses
[d] Not corrected for angular momentum carried away by neutrinos
[e] Became a Wolf-Rayet star during helium burning

Heger, Woosley, & Spruit (2005)

Stellar models with magnetic fields produce neutron star with rotation rates roughly as expected from observations.

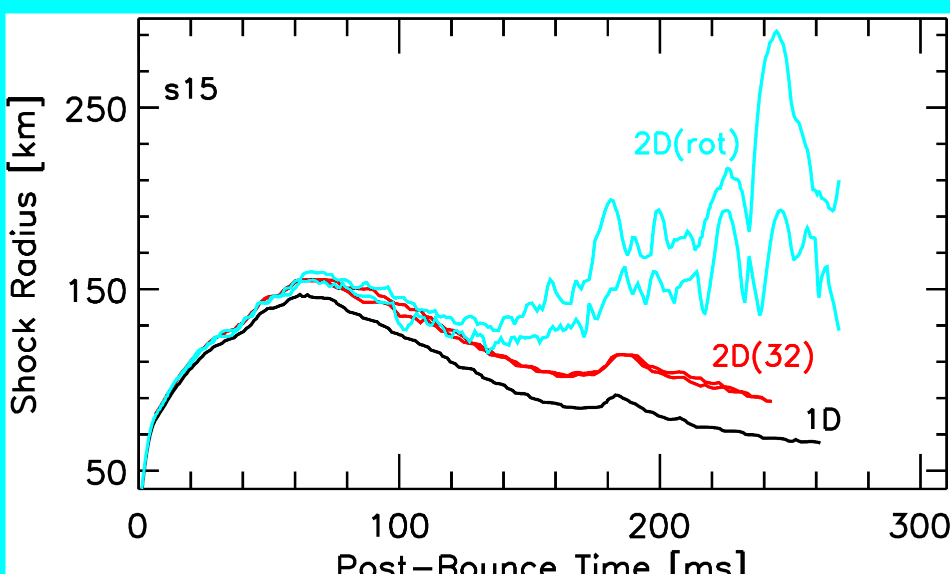
2D Simulations

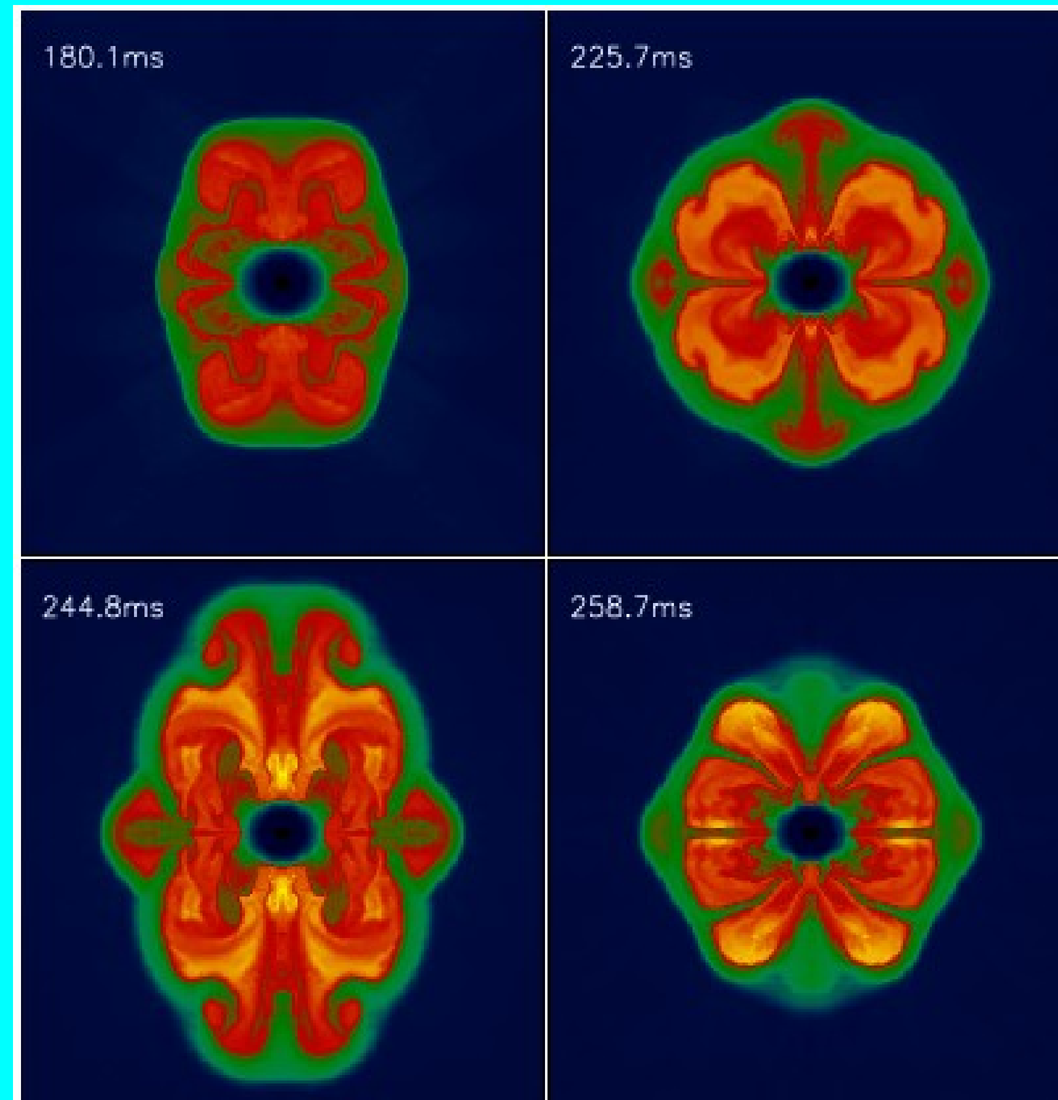
- Influence of convection and rotation on the neutrino-heating mechansim.
- Initial iron core rotation assumed to be rather “moderate”:
period ~ 12 seconds,
angular frequency ~0.5 rad/s.
- This rotation rate is between magnetic and nonmagnetic cores of Heger, Woosley & Spruit.
- Initially, centrifugal force < 1% of gravitational force;
maximizes angular momentum effects at late post-bounce times;
for j = const, NS will have period P >1 ms.



2D Simulations: Rotation (15 Msun)

- Without rotation postshock convection is suppressed by shock recession.
- Rotation helps shock expansion and enhances postshock convection.



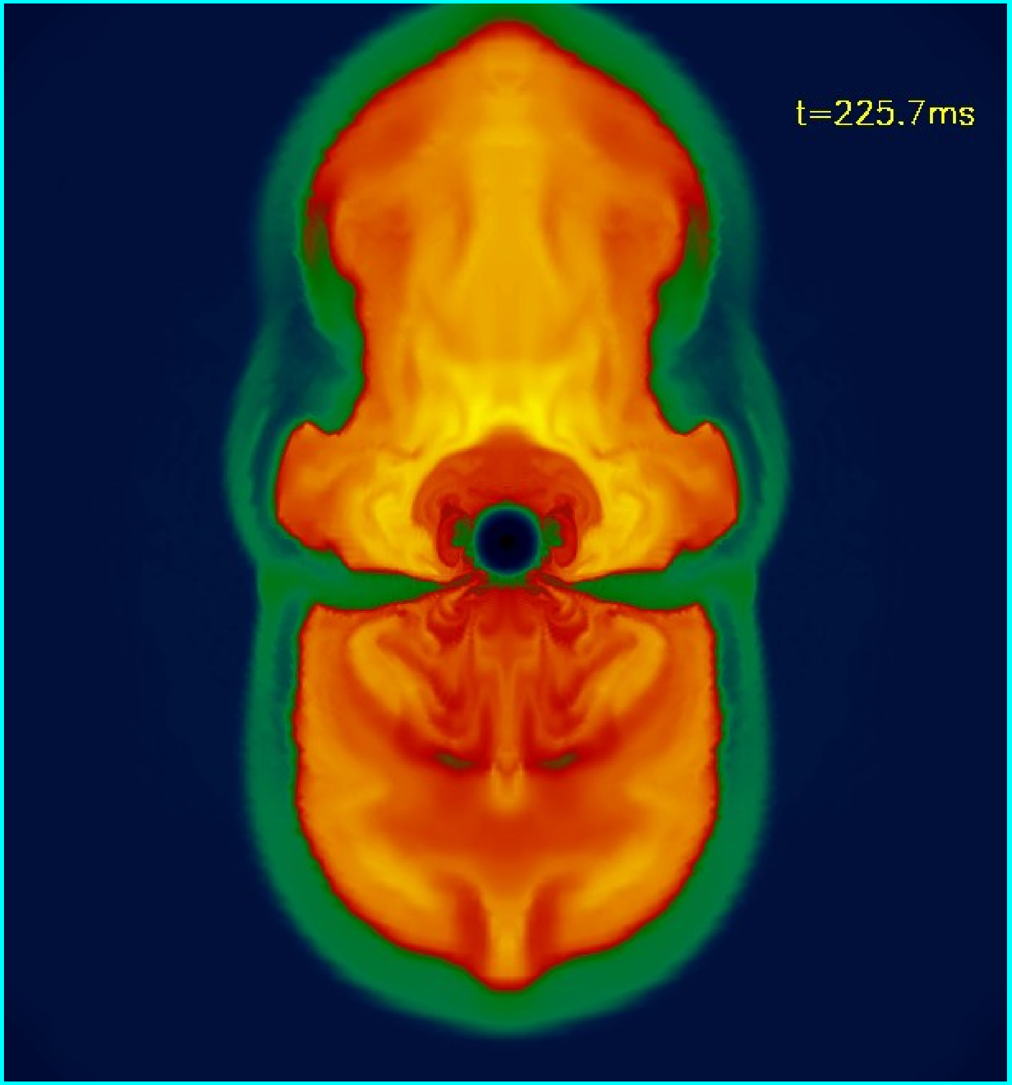


2D Simulation: 11.2 Msun, 180° Grid

- Full 180º grid makes big difference for postshock convection and shock expansion,
- allows low-mode (l=1,2) convection to occur,
- global anisotropy develops,
- weak explosion takes place.

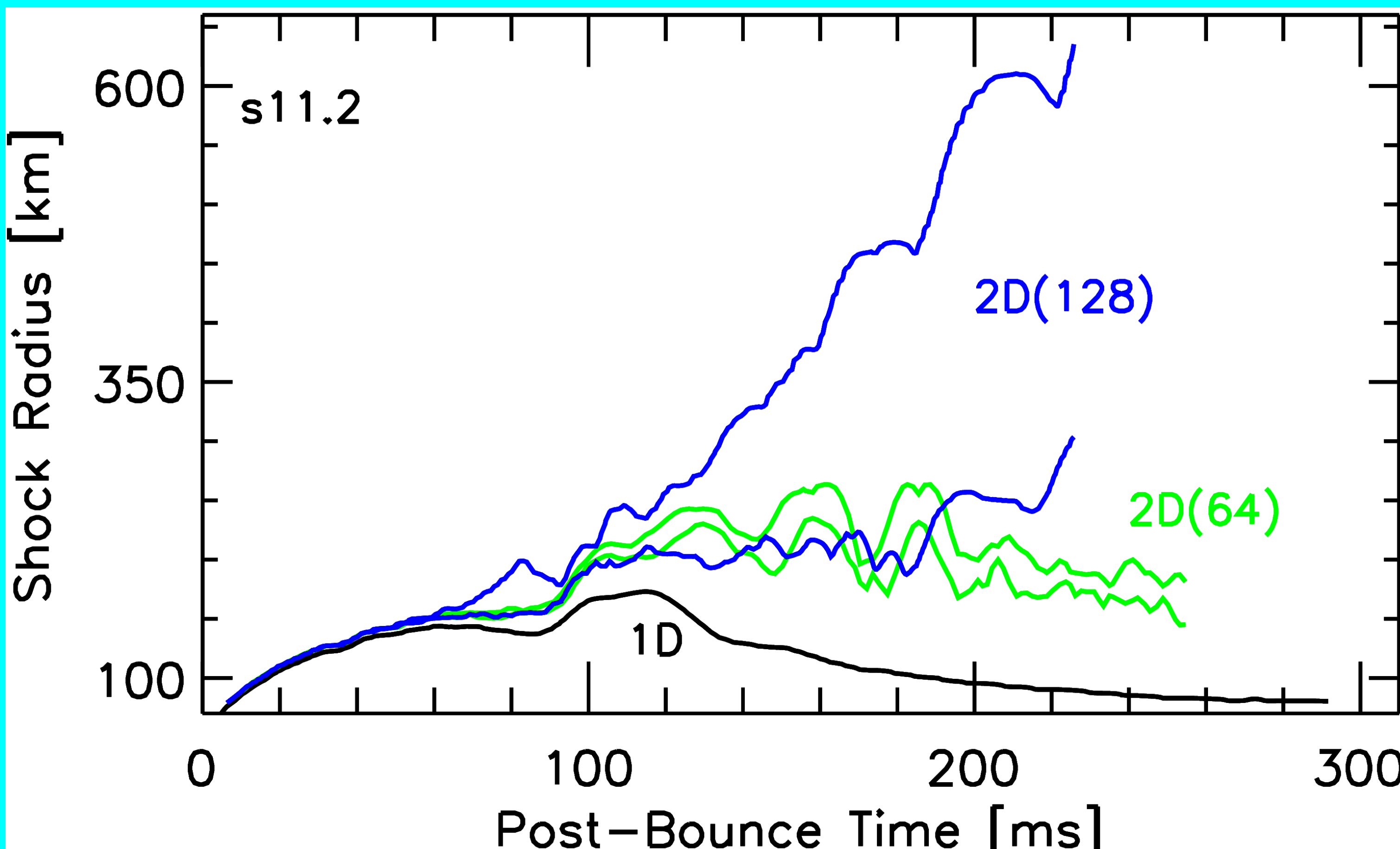
Supernovae can explode globally aspherically by the neutrino-heating mechanism even if rotation is absent!

(cf. l=1 mode shock instability pointed out by Blondin, Mezzacappa and DeMarino (ApJ 584 (2003) 971); Foglizzo 2002; Thompson 2001; Chandrasekhar 1980)



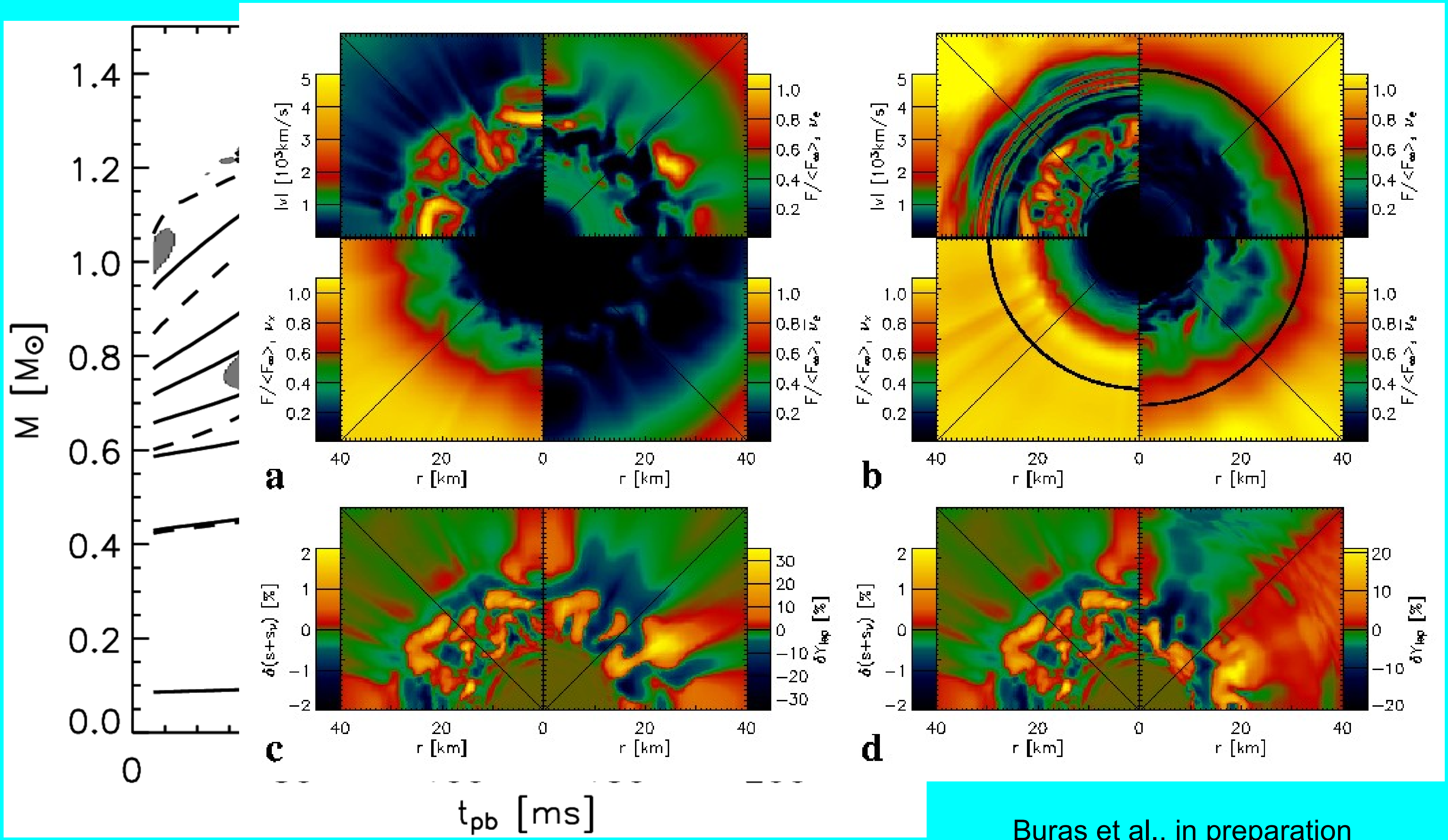
R. Buras (PhD Thesis 2004)

2D Simulation: 11.2 Msun, 180° Grid



R. Buras (PhD Thesis 2004)

Convection inside the Proto-NS



Buras et al., in preparation

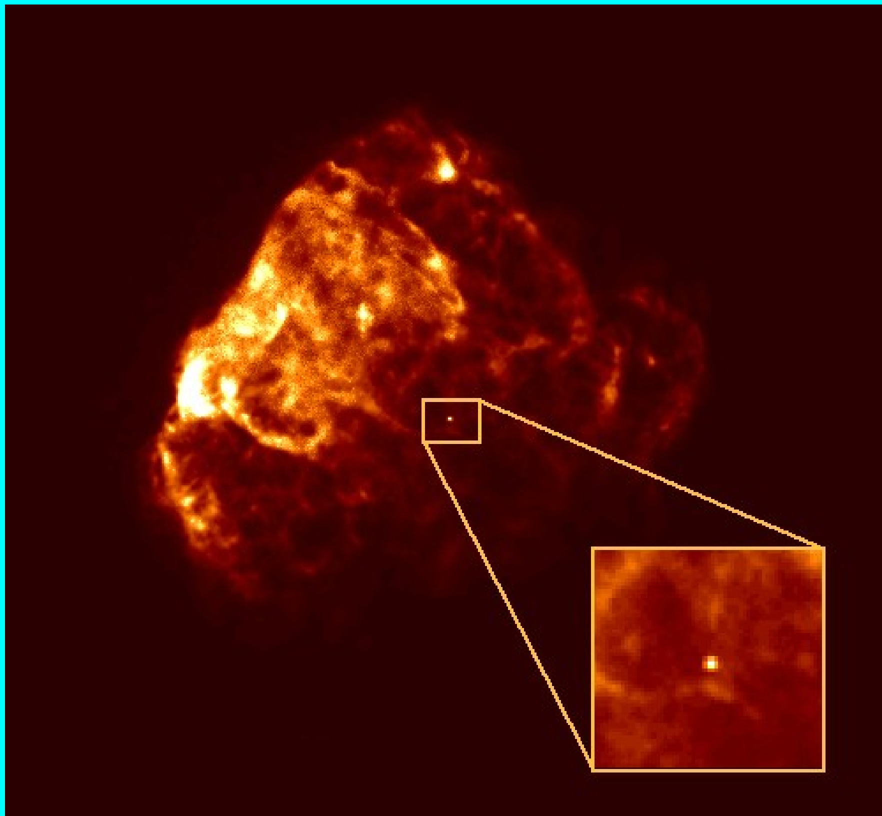
Summary and Outlook I

"Full models": On the road to massive star explosions:

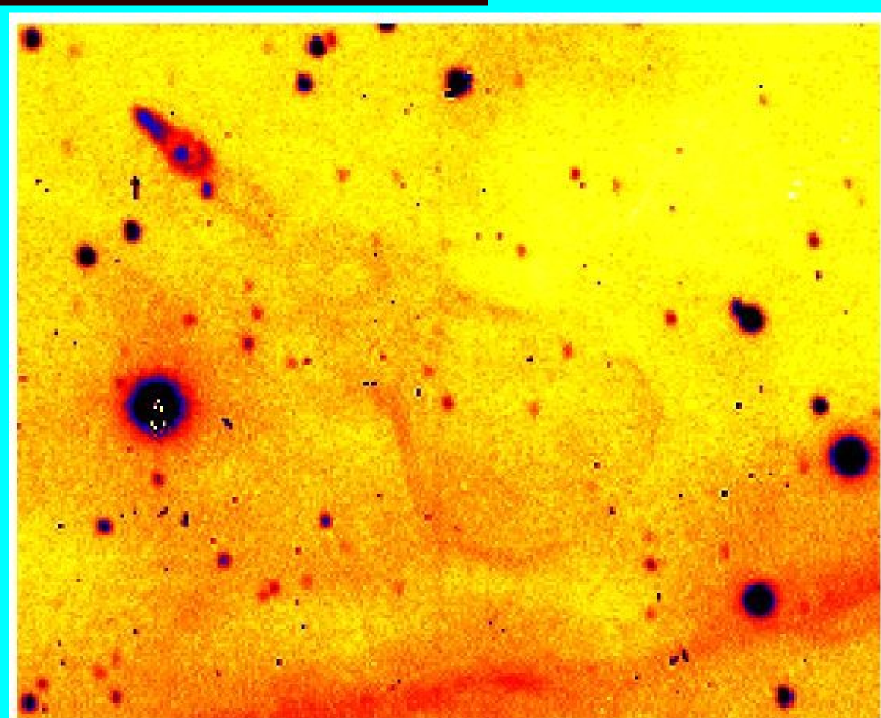
- Helpful for explosions:
  Rotation, even at a moderate rate,
  low-mode (l=1,2) convection (large explosion asymmetry) ,
  stiff nuclear equation of state (larger shock radius) ?
- ONeMg core collapse (1D): shock expands, neutrino-driven wind;
  Explosion for 8 – 10 solar mass stars!
- 11.2 Msun star (full 180º grid): global mode, weak explosion;
- Rotating 15 Msun star (90º quadrant): "near" explosion.
- More models with 180º grid and full spectral Boltzmann neutrino transport are on the computers, but require a lot of CPU time!
- Exploration in 3D needed (see below)!

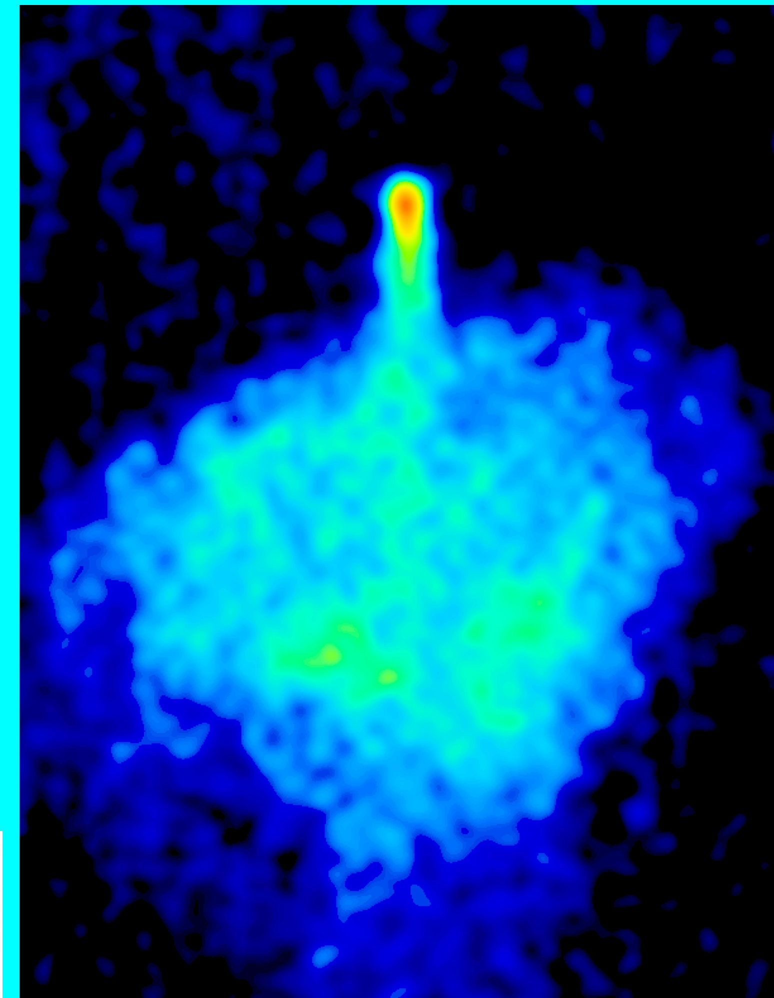
Parametric Explosion Studies

- Contracting neutron star interior replaced by boundary condition
  (Motivation: Physics at very high densities – e.g., nuclear EoS, nonradial instabilities, neutrino opacities □ incompletely understood).
- At this boundary: Neutrino number and energy fluxes prescribed.
- Systematic variation of neutrino luminosities and progenitors.
- Simplified neutrino transport
  (by time-dependent, radial integration of energy equation for neutrinos and antineutrinos of all flavors; NO “lightbulb” approximation: L not constant !).
- Advantages:
  * CPU-time efficient computations with reasonably accurate neutrino treatment,
  * allows for large number of explosion simulations in 2D to study multi-D effects and their consequences in SN explosions,
  * 3D simulations affordable NOW!



Puppis A



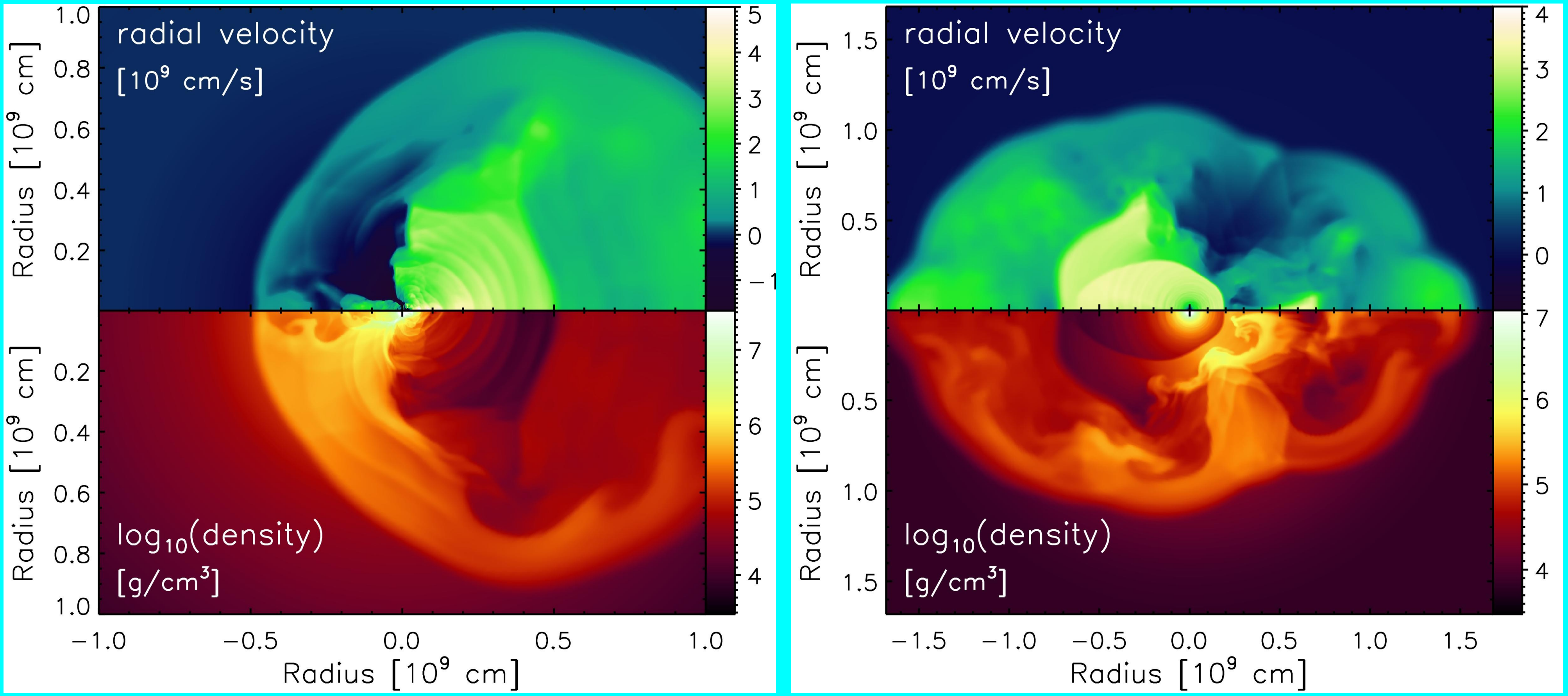


Guitar Nebula

Parametric Explosion Studies in 2D

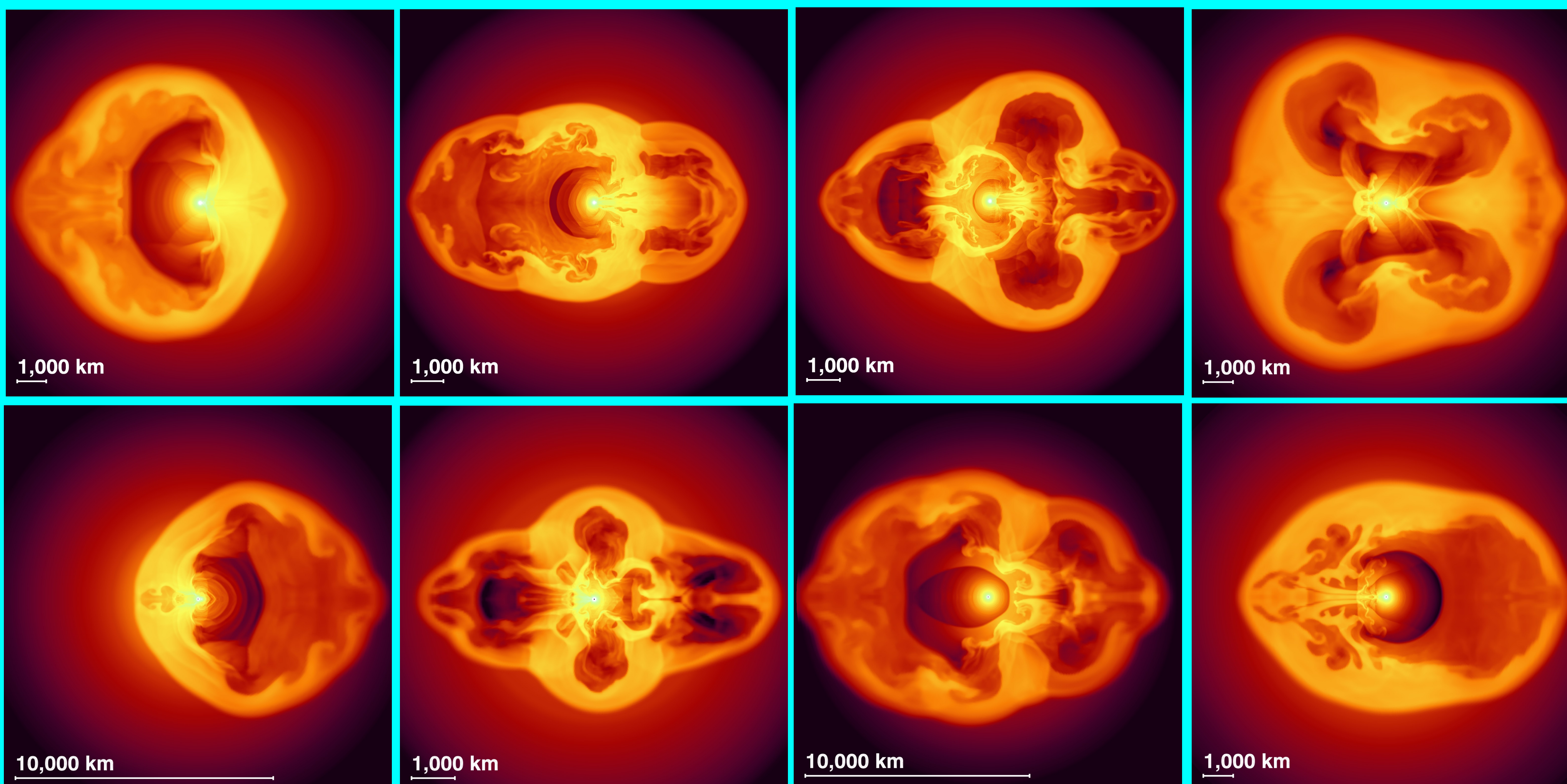
- If explosion develops slowly, convective structures have time to merge/develop to low-mode (l = 1,2) flow.
- Very asymmetric shock expansion and mass ejection although boundary neutrino flux isotropic.

Scheck et al. (PRL, 2004), Scheck (PhD Thesis 2004)



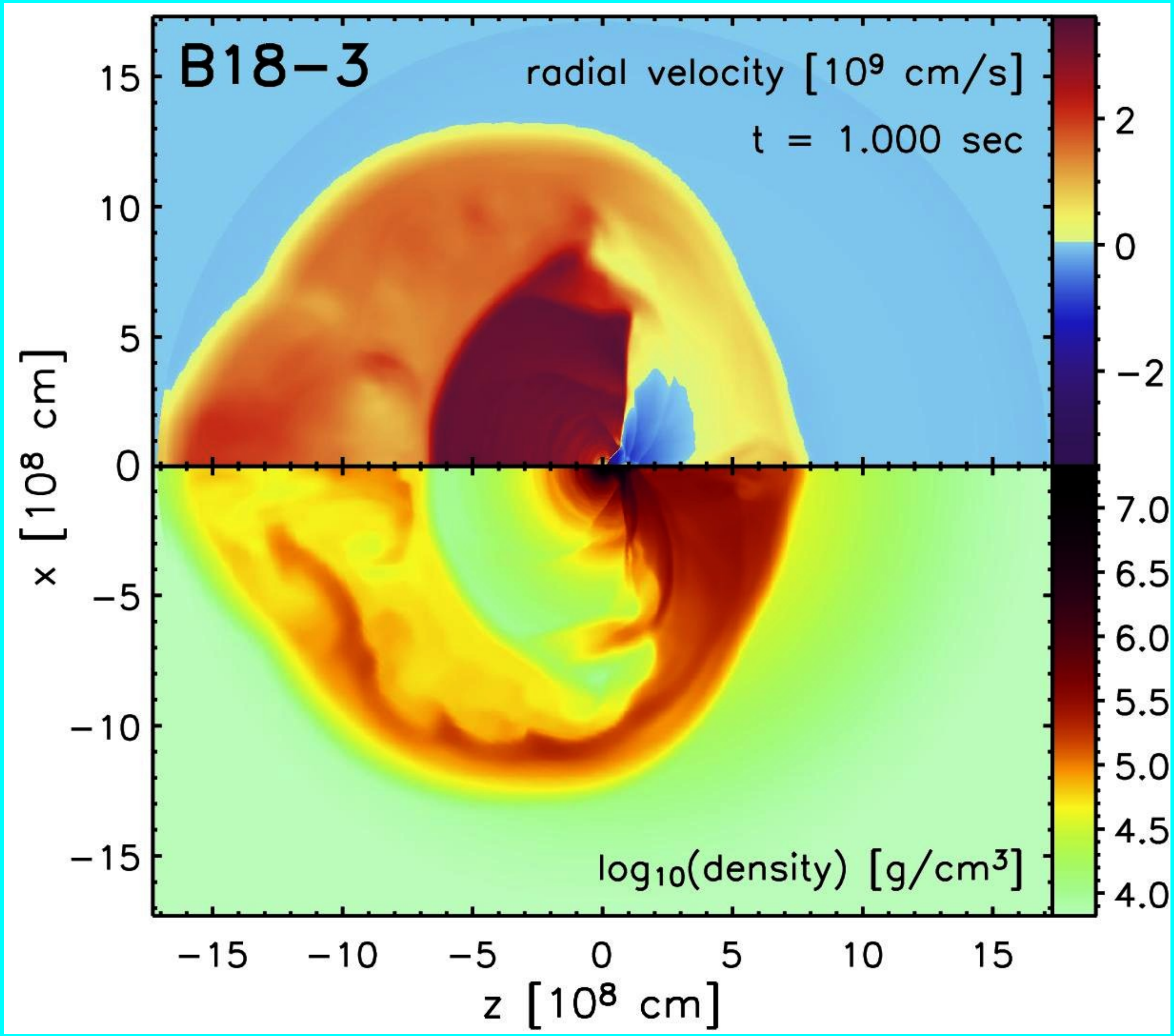
2D Models: Low-Mode Asymmetries

- Stochastic and chaotic growth of instabilities ====> different morpologies
- Explosion asymmetries 1 second after core bounce:



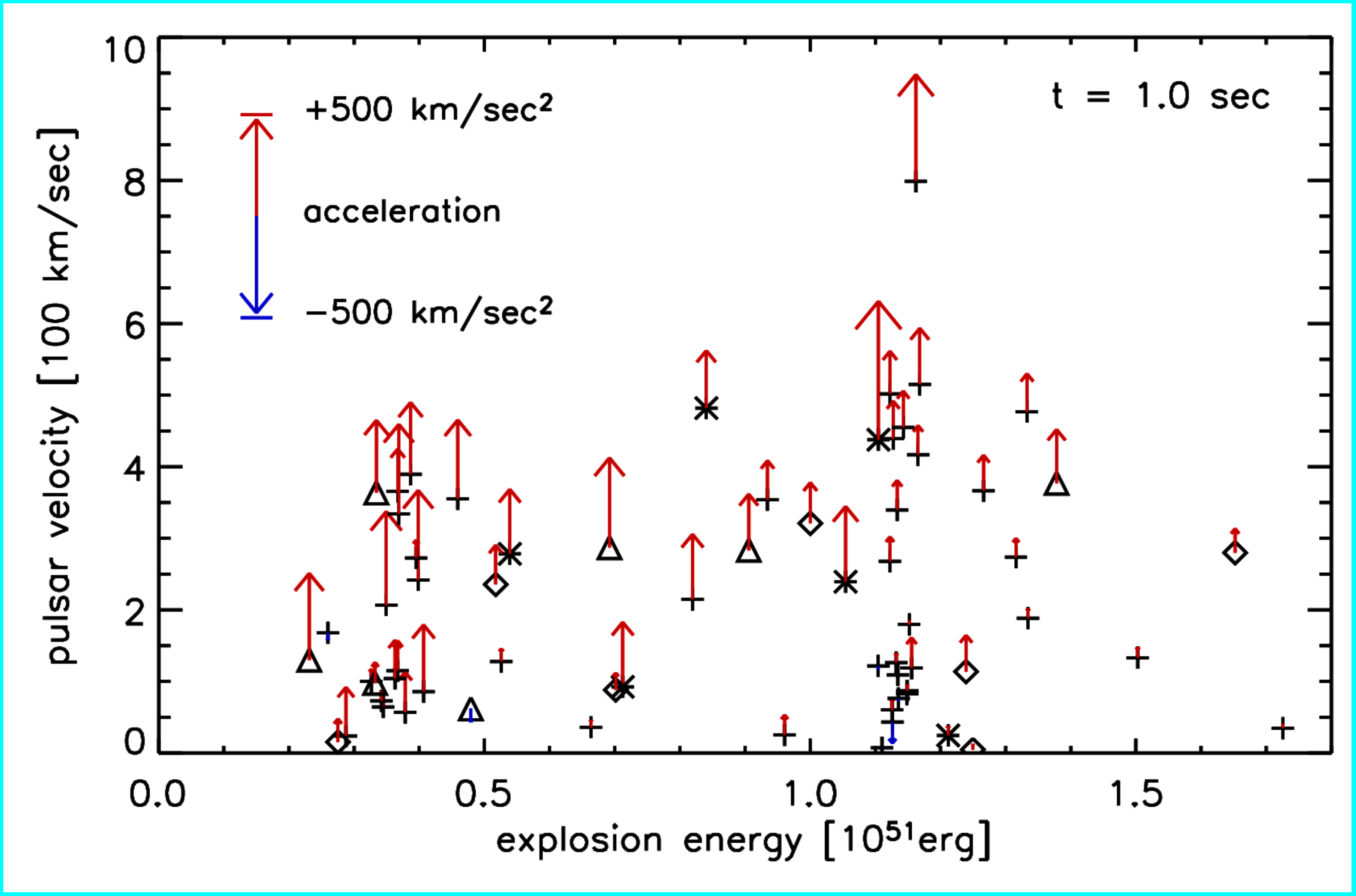
Parametric Explosion Studies in 2D

- World record for simulated kicks
- E_{exp} ~ 1.2 foe
- v_{ns} ~ 800 km/s at 1 second post bounce
- a_{ns} ~ 550 km/s^2 at this time



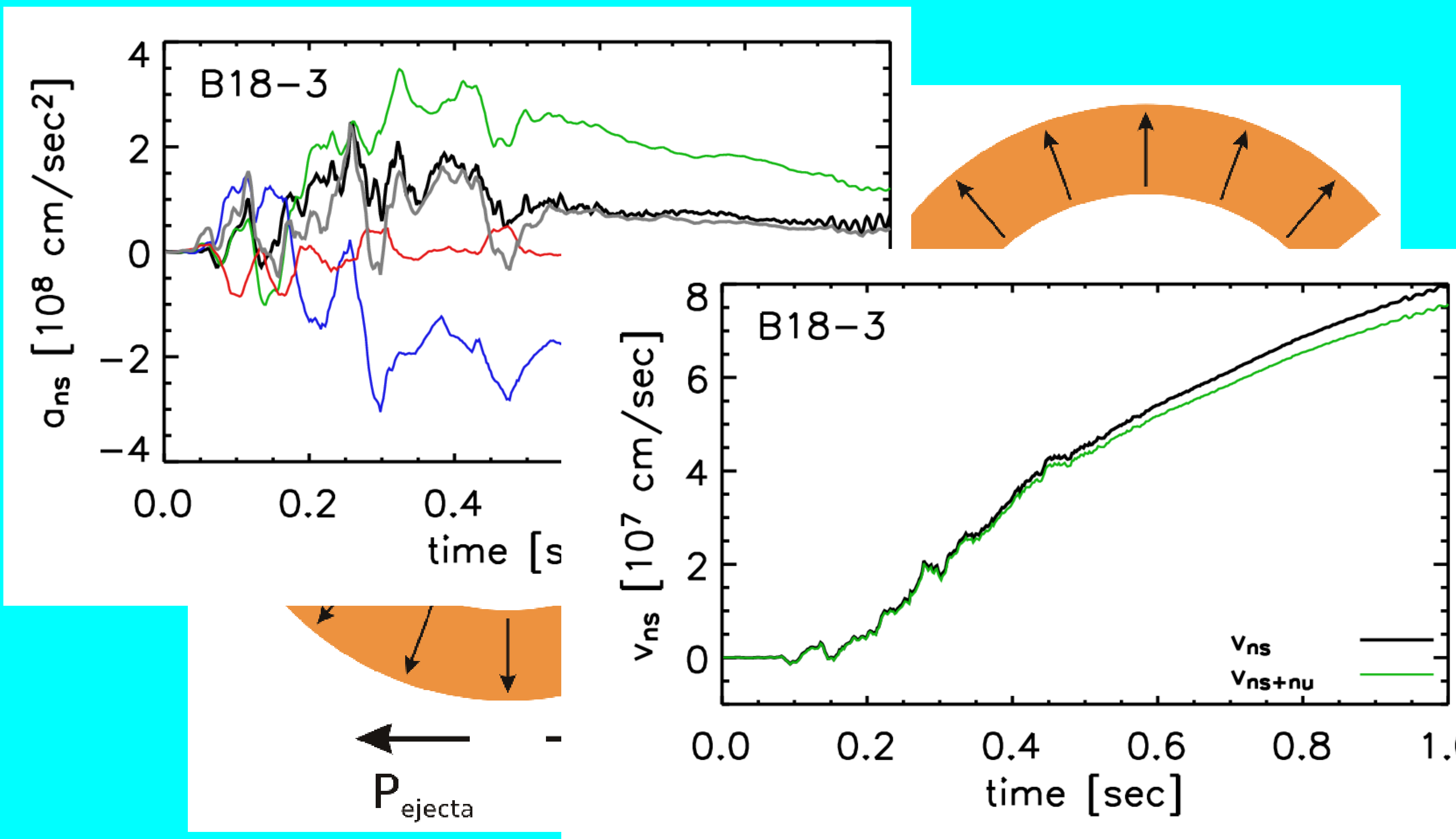
Parametric Explosion Studies in 2D

- Anisotropic mass ejection ==> neutron star receives recoil velocity.
- In 2D: v > 800 km/s at 1 second, large acceleration continues longer.



Parametric Explosion Studies in 2D

- Neutron star acceleration mainly by gravitational forces, also hydrodynamic forces, neutrinos are of minor importance.



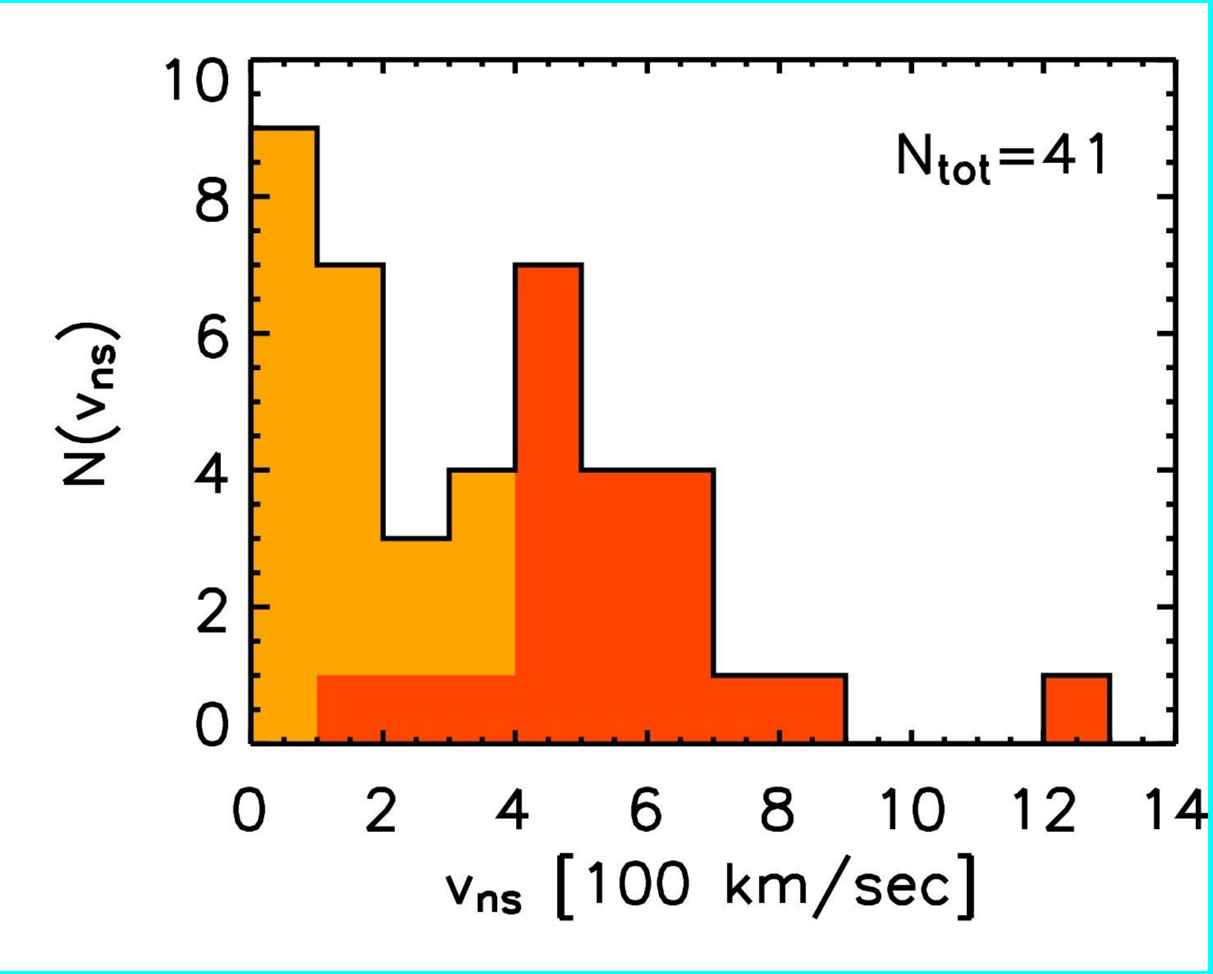
Parametric Explosion Studies in 2D

- Bimodality by separation between cases with and without l = 1 mode?
- Fastest stars typically have highest accelerations at 1 second and gain more speed on timescale of 1–3 seconds.
- More simulations needed, also for other than 15 M_{sun} progenitors!
- 3D simulations necessary!

NOTE: Bimodality is still observationally ambiguous:

!! Fryer et al. (1997) and Arzoumanian et al. (2002) claim evidence,

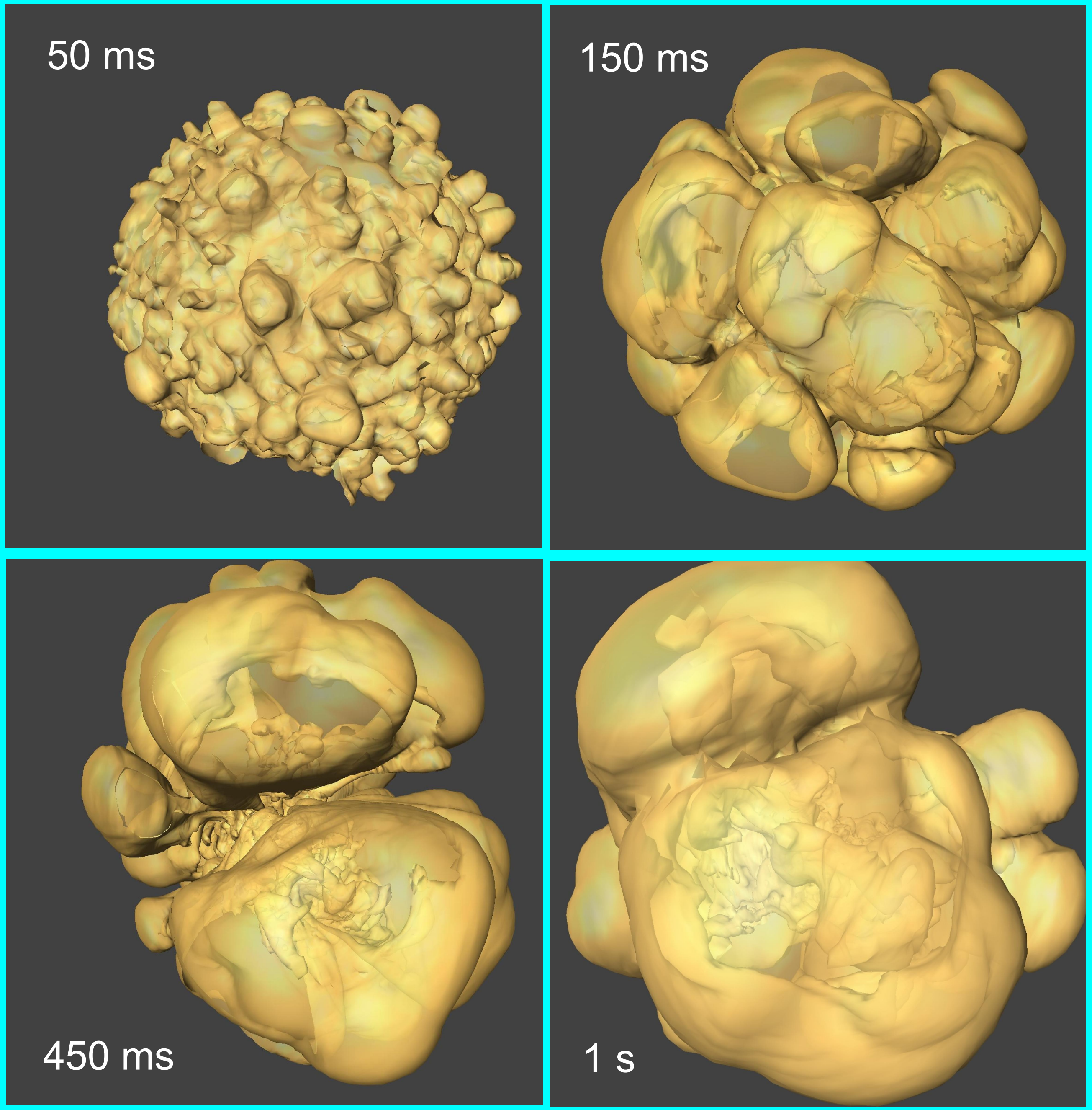
?? Lyne & Lorimer (1994), Phinney et al. (1998) and Lorimer et al. (2005) find best fits for single Gaussian distribution.



Parametric Explosion Studies in 3D

- Explosions in 3D show also very large asymmetry.
- Convection grows faster than in 2D.
- Explosion energy somewhat higher.
- Resolution: 3°, desired: 1°.

First 3D models by Fryer & Warren (ApJ, 2002, 2004)

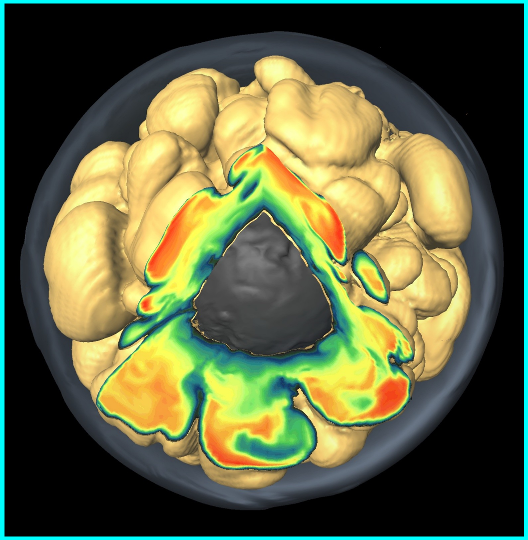


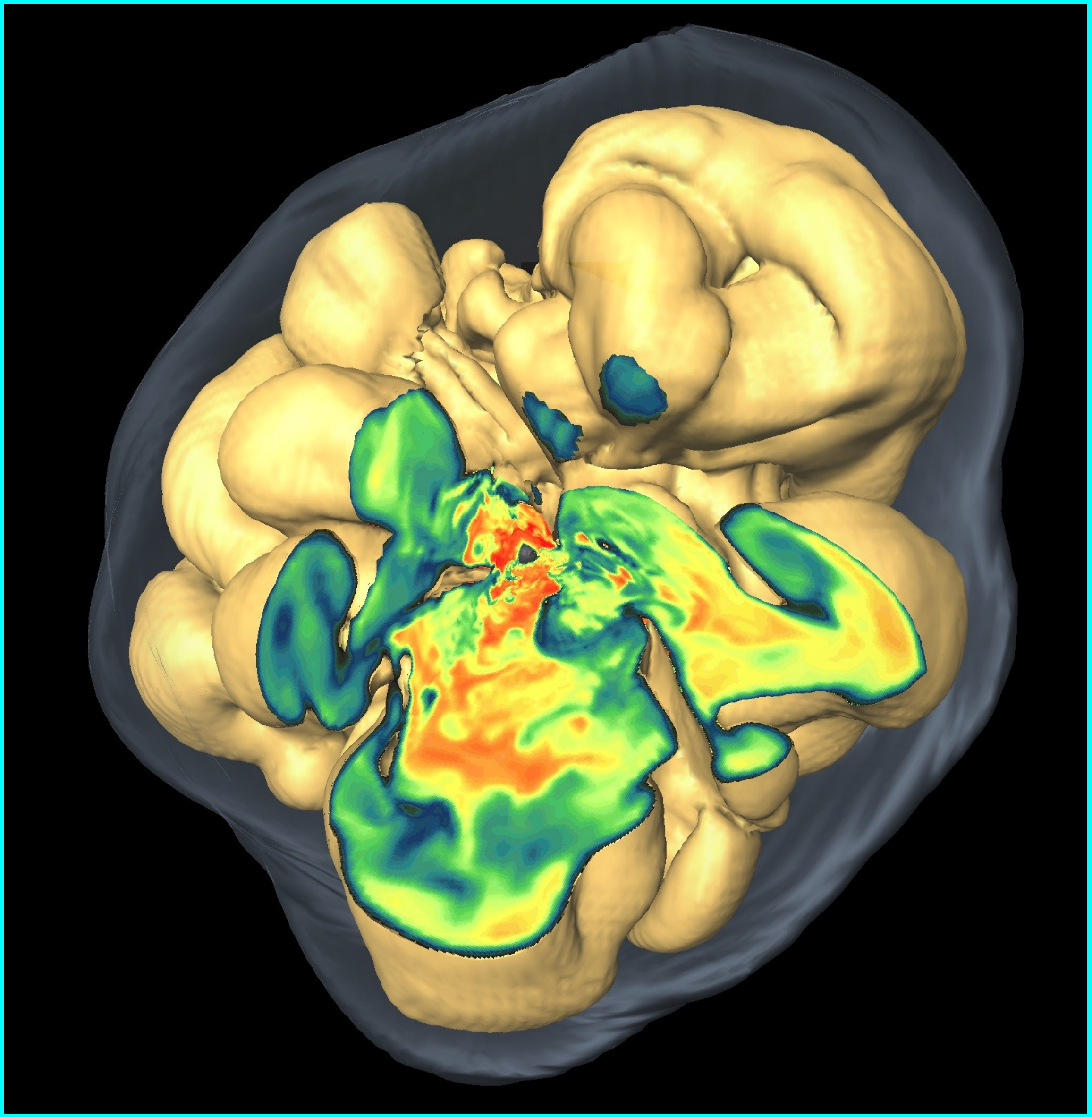
L. Scheck (PhD Thesis 2005)

Parametric Explosion Studies in 3D

Simulation with 1.5 degree angular resolution:

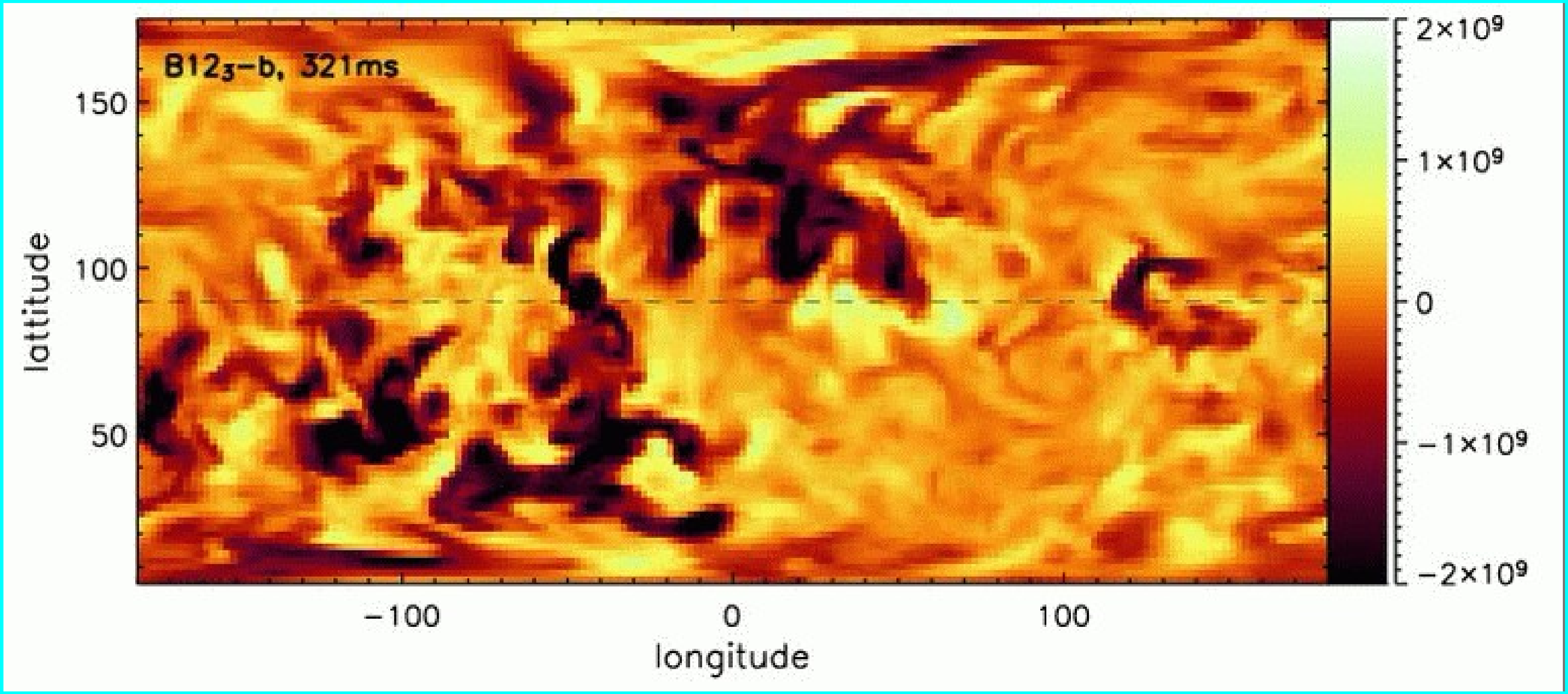
Growth of neutrino-heated bubbles





L. Scheck (PhD Thesis 2005)

Parametric Explosion Studies in 3D

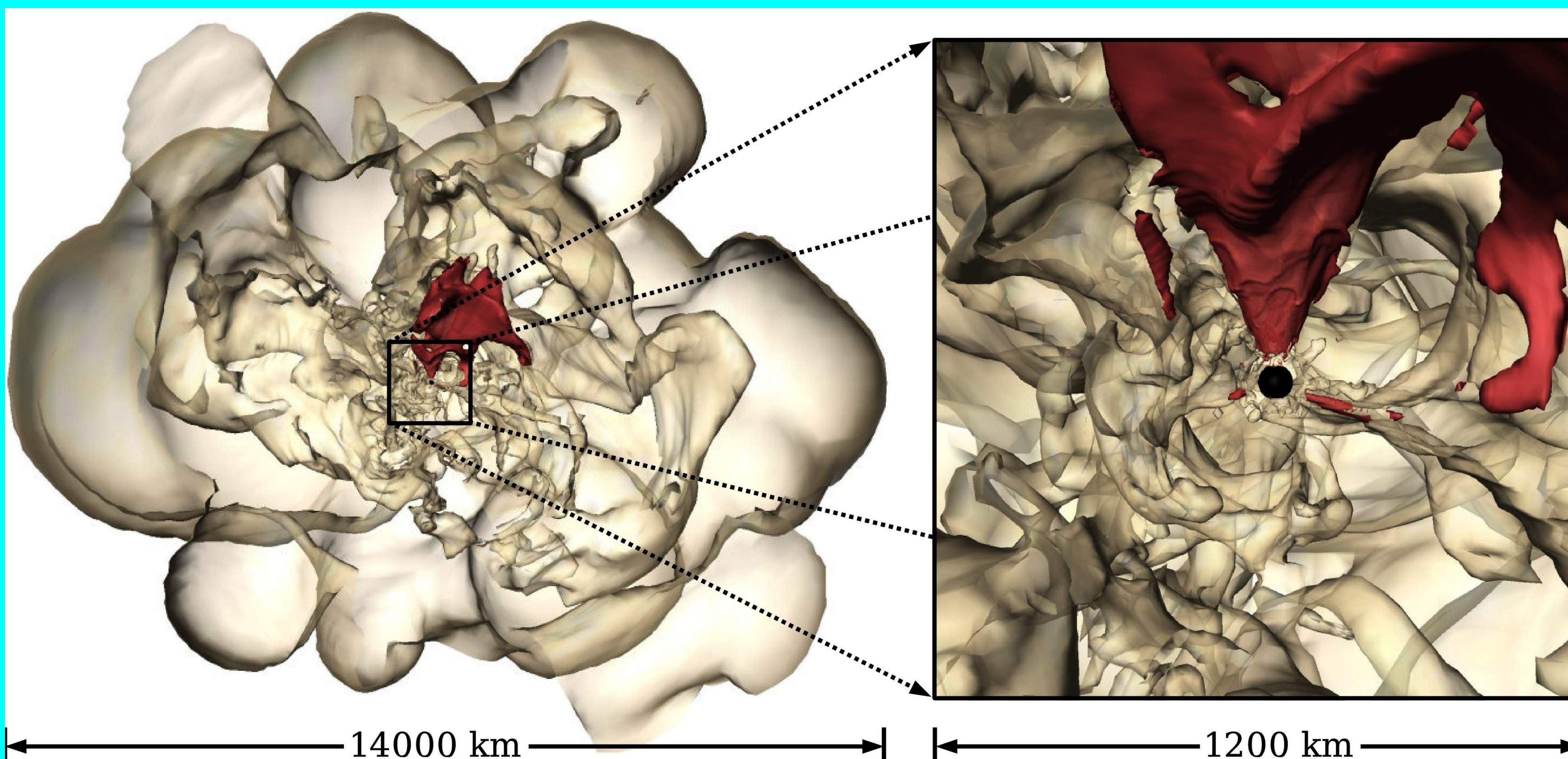


L. Scheck (PhD Thesis 2005)

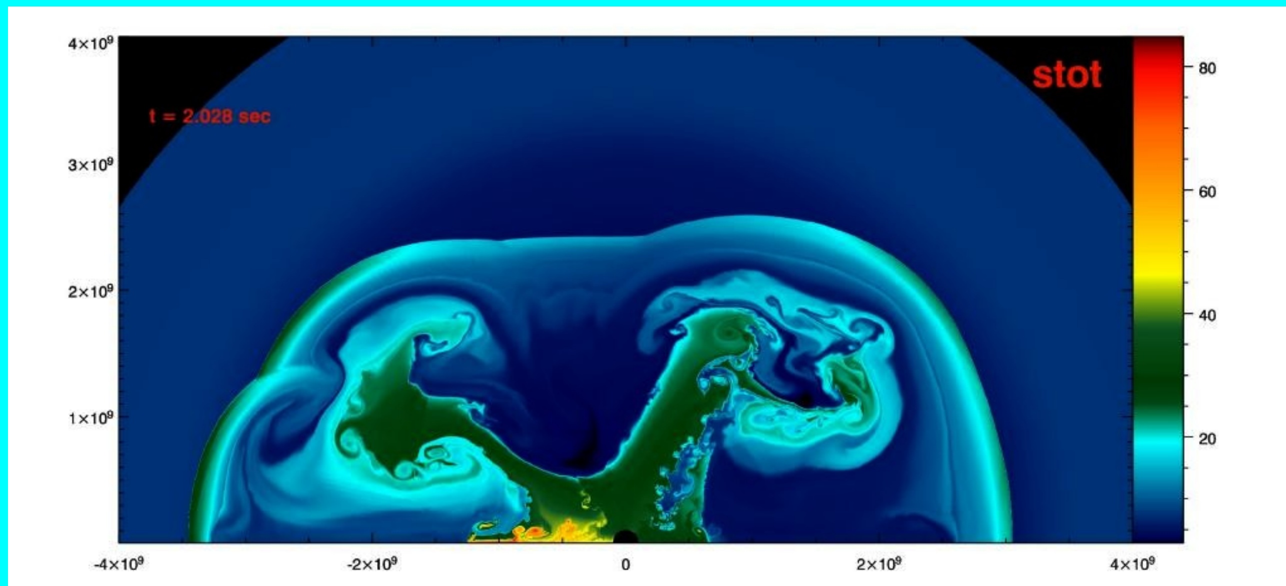
Growth of modes in convective overturn

Parametric Explosion Studies in 3D

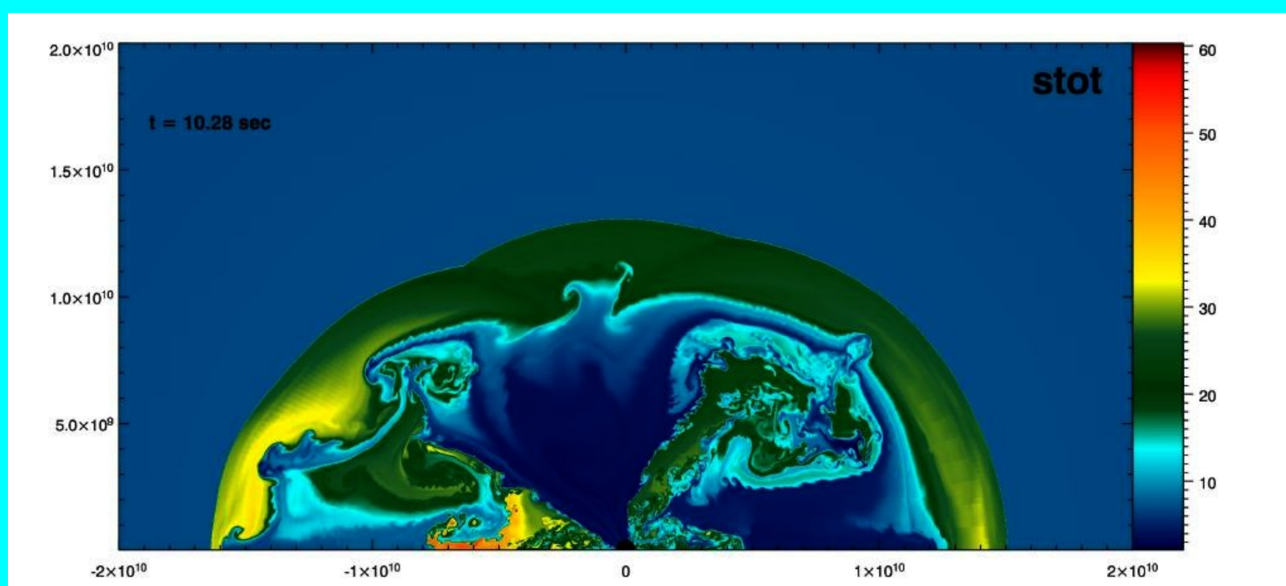
- Accretion flow to neutron star develops l = 1 mode also in 3D.



Long-Time SN Evolution in 2D



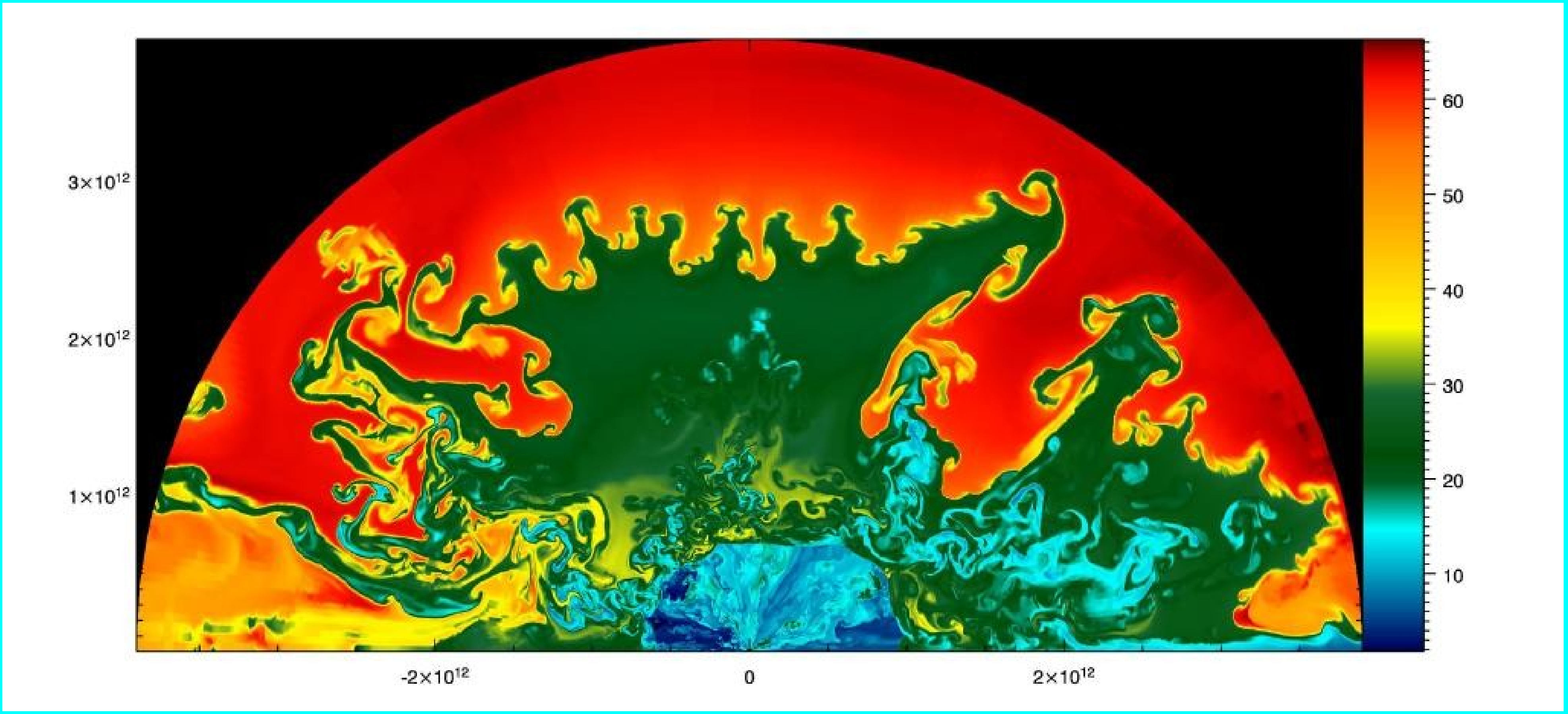
2 seconds



10 seconds

Kifonidis 2005

Long-Time SN Evolution in 2D

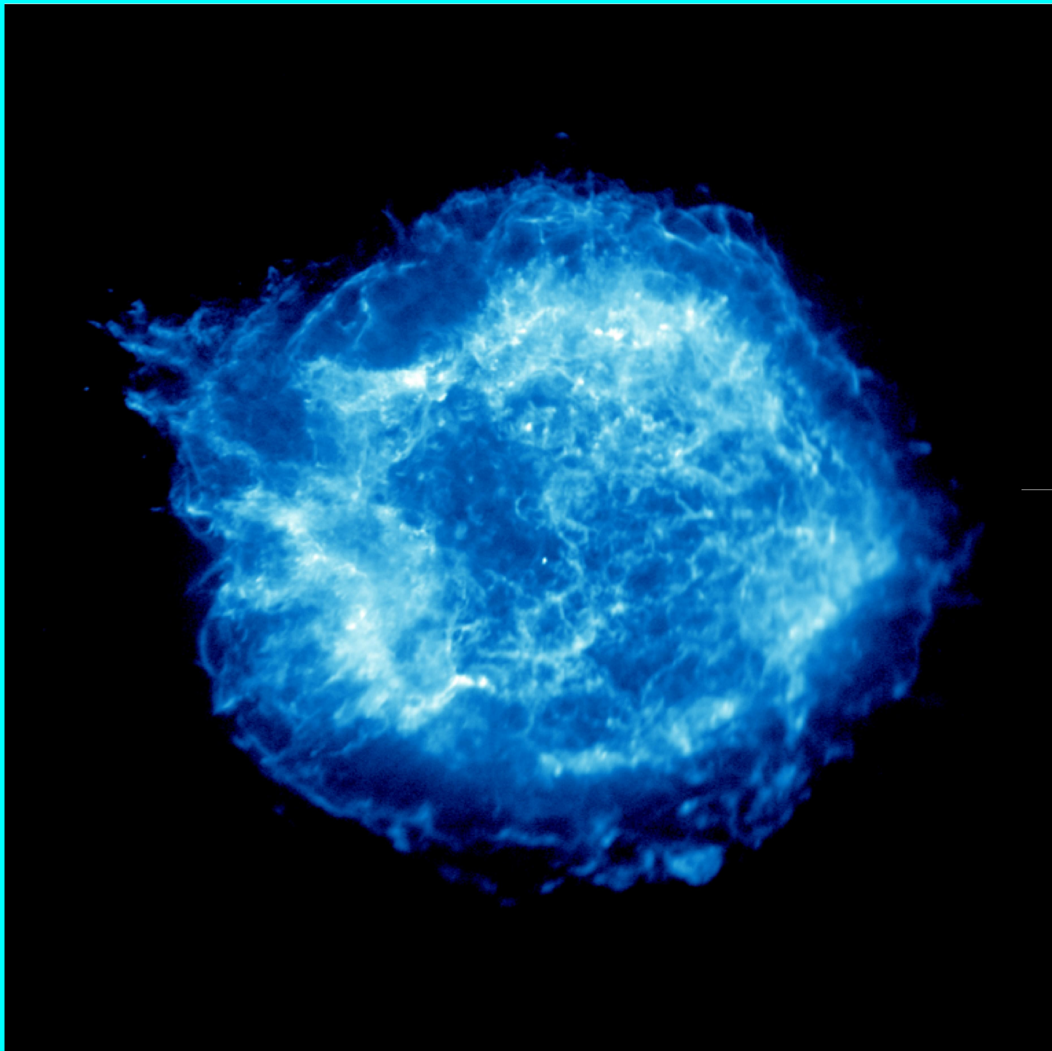


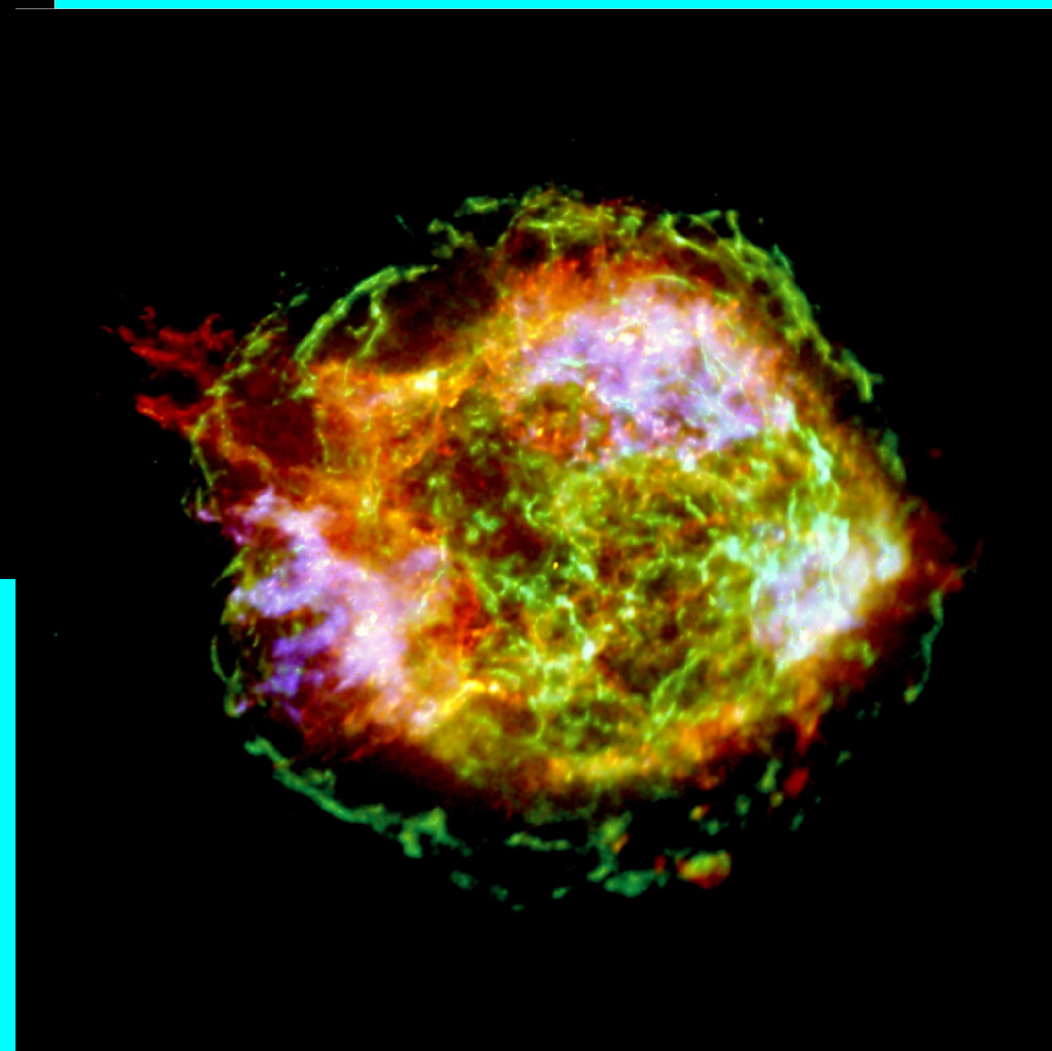
Kifonidis 2005

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

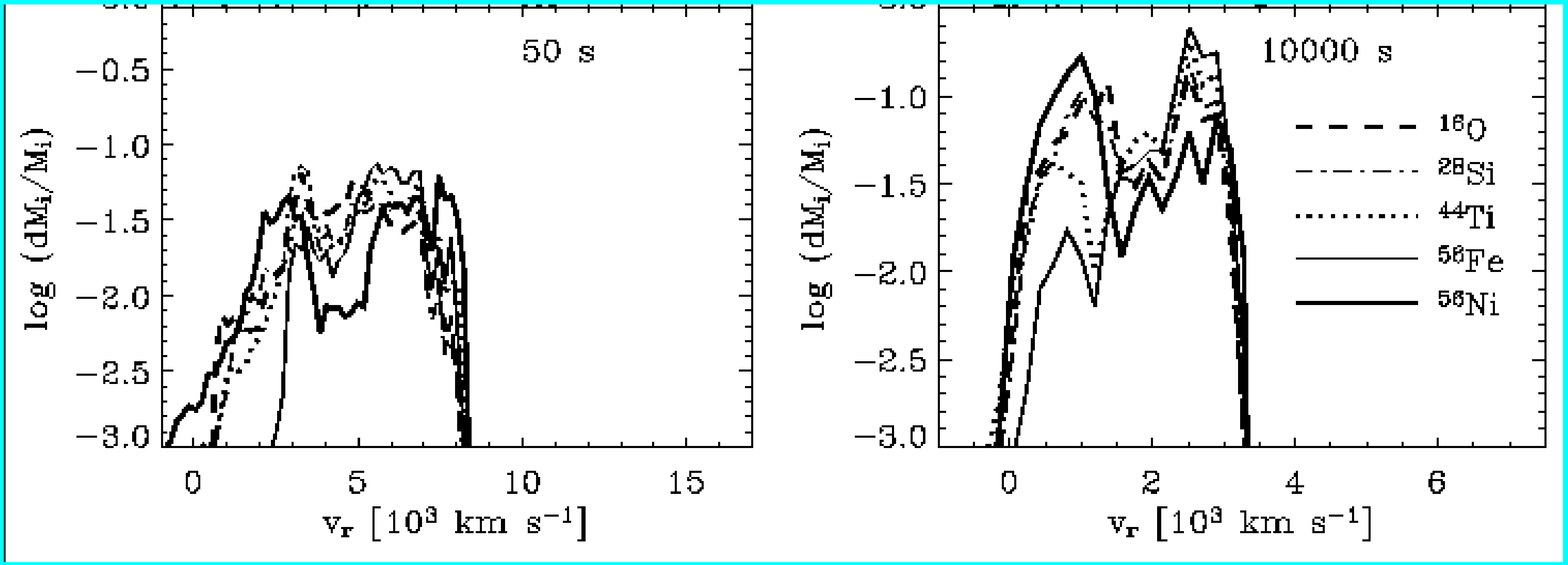
SN Remnant Cassiopeia A





A Million Second CHANDRA View of Cassiopeia A
(Hwang et al., ApJL, 2004)

Long-Time SN Evolution in 2D



Kifonidis 2005

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

Summary and Outlook II

Parametric explosion studies:

- If explosion develops slowly: low-mode flow dominates in 2D and 3D.
- In 3D explosions “easier” than in 2D.
- Large asymmetry of ejecta ==> pulsar kicks > 1000 km/s (in 2D)
- NS kick in opposite direction to main mass ejection.
- SN asymmetries and observed element mixing can be explained.
- Can global deformation (polarization) of observed SNe be explained?
- Role of “advective-acoustic” cycle (Foglizzo 2002) for amplifying non-radial modes in convective environment?