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SFB 375

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Max-Planck-Institute fuer Physik und Astrophysik

Supernova and Gamma-Ray Burst Remnants, Kavli Institute, Feb. 6-10, 2006

Asymmetric Supernovae

Modeling Explosions, Pulsar Kicks, & Ejecta Mixing

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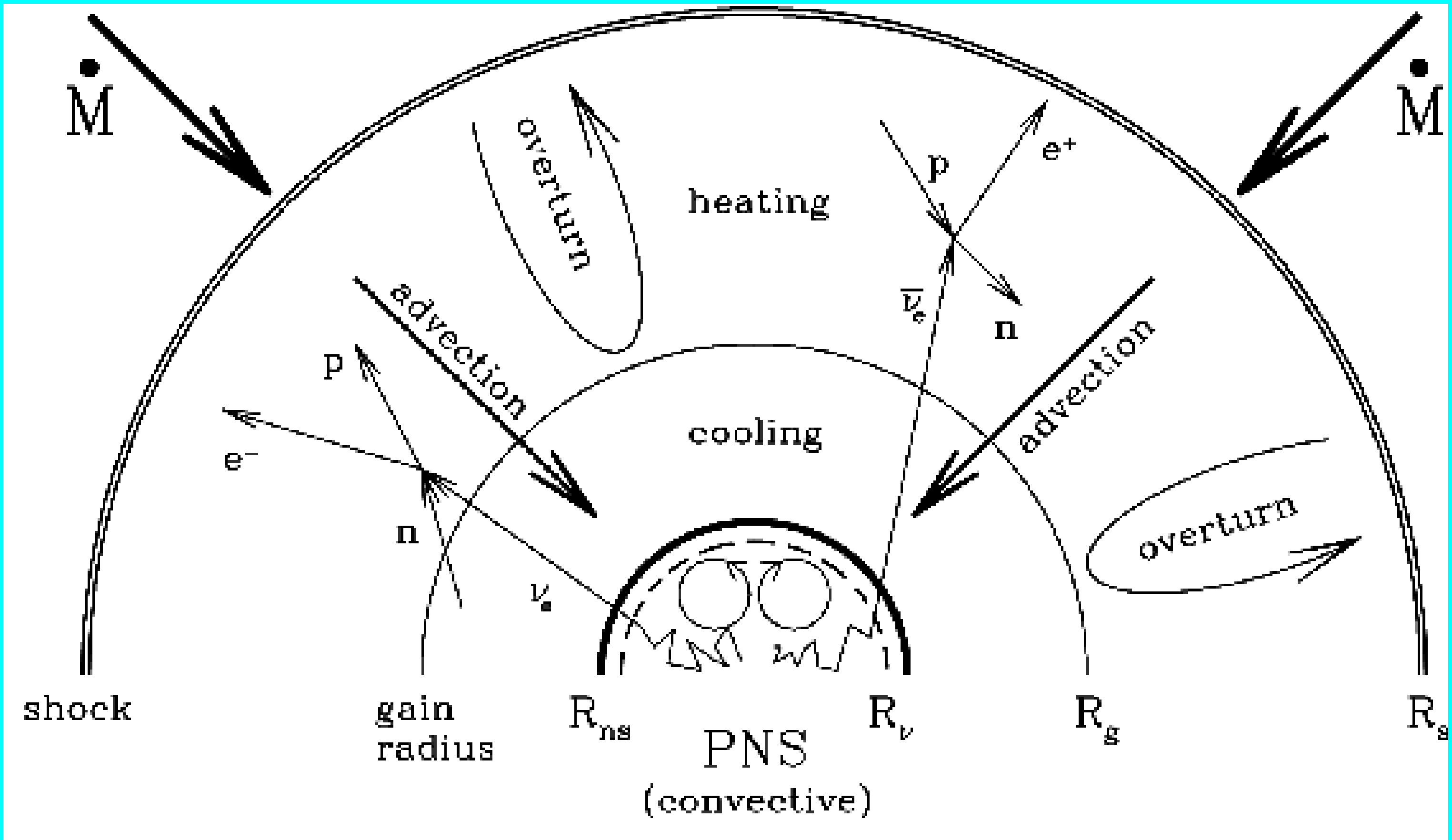
Contents

- Introduction & background
- The tools: Hydrodynamics, neutrino transport, microphysics
- Do neutrino-driven explosions work? “yes!” & “not (?) yet”
- What, if they worked? pulsar kicks, SN asymmetries, & mixing

Introduction

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).

Tools

The "Boltzmann" Supernova Code

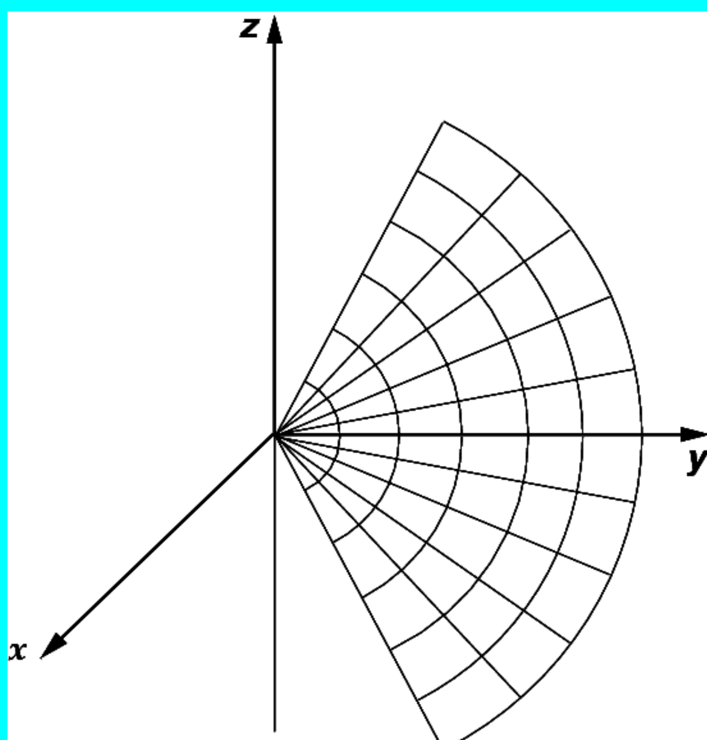
1D version: VERTEX,   multi-D version: MuDBaTH

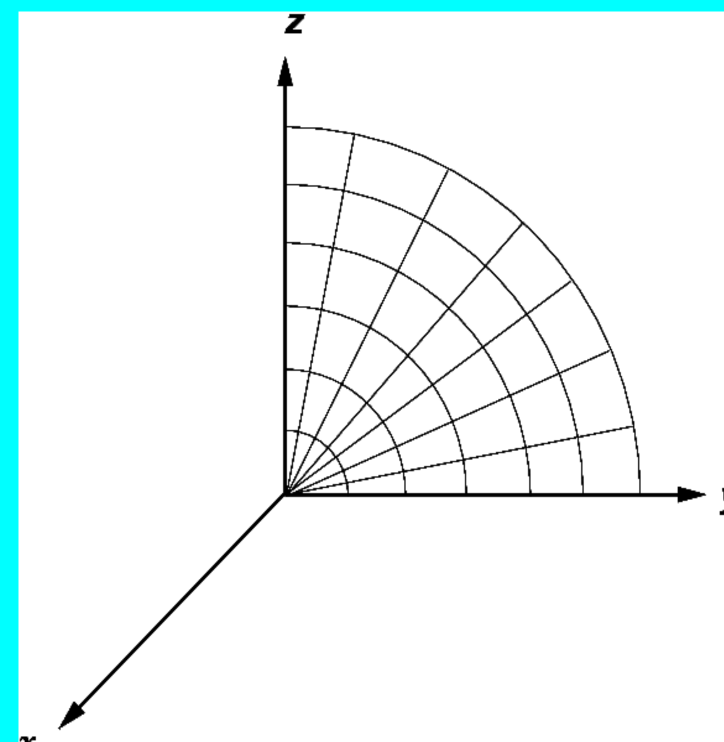
(Rampp & Janka 2002; Buras et al. 2005)

- 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)

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

Explosion Models

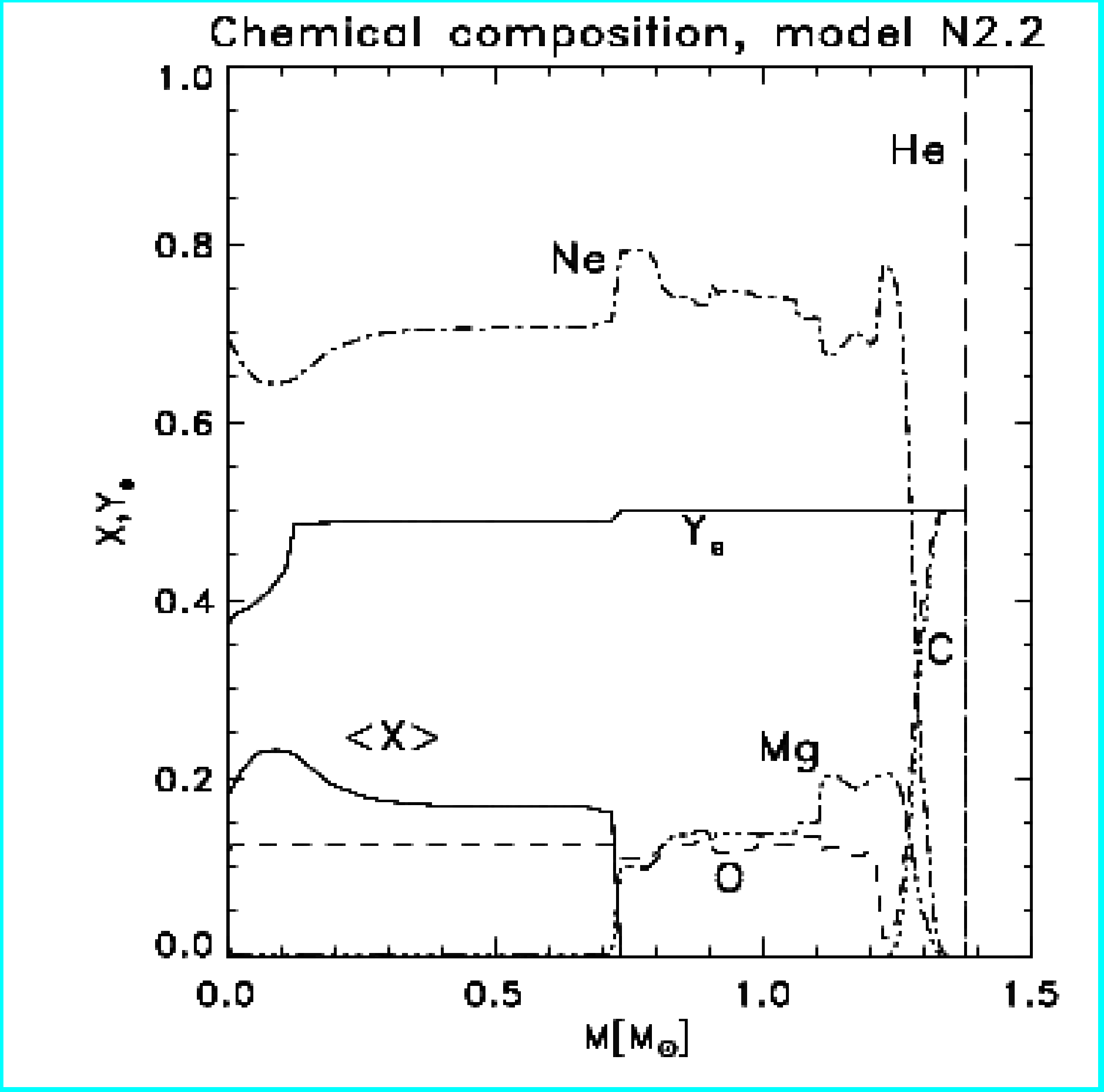
Do neutrino-driven explosions work?

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)

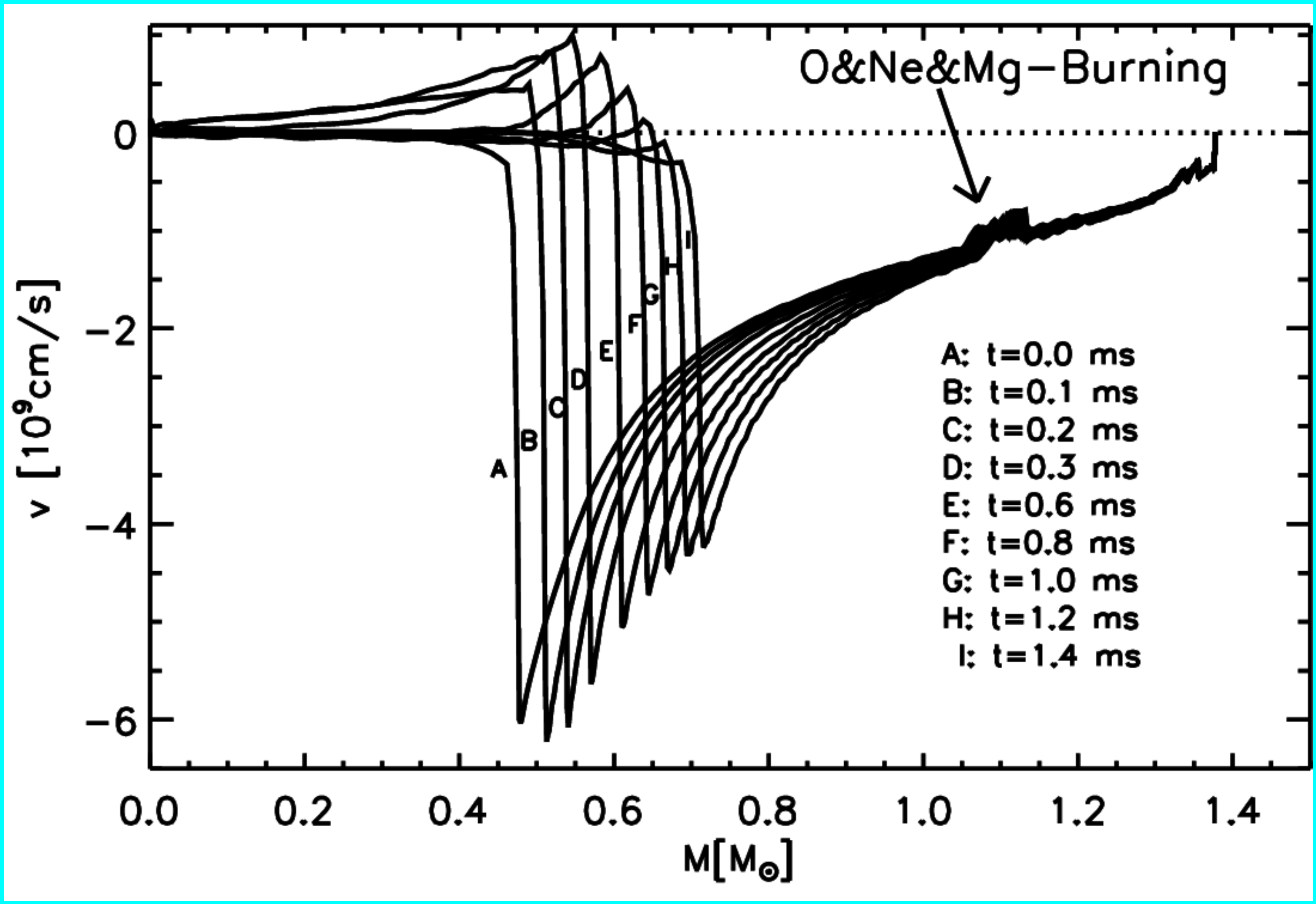
(Nomoto 1981, 84, 87)



1D Simulations: ONeMg Core

Shock stagnation 1ms after shock formation

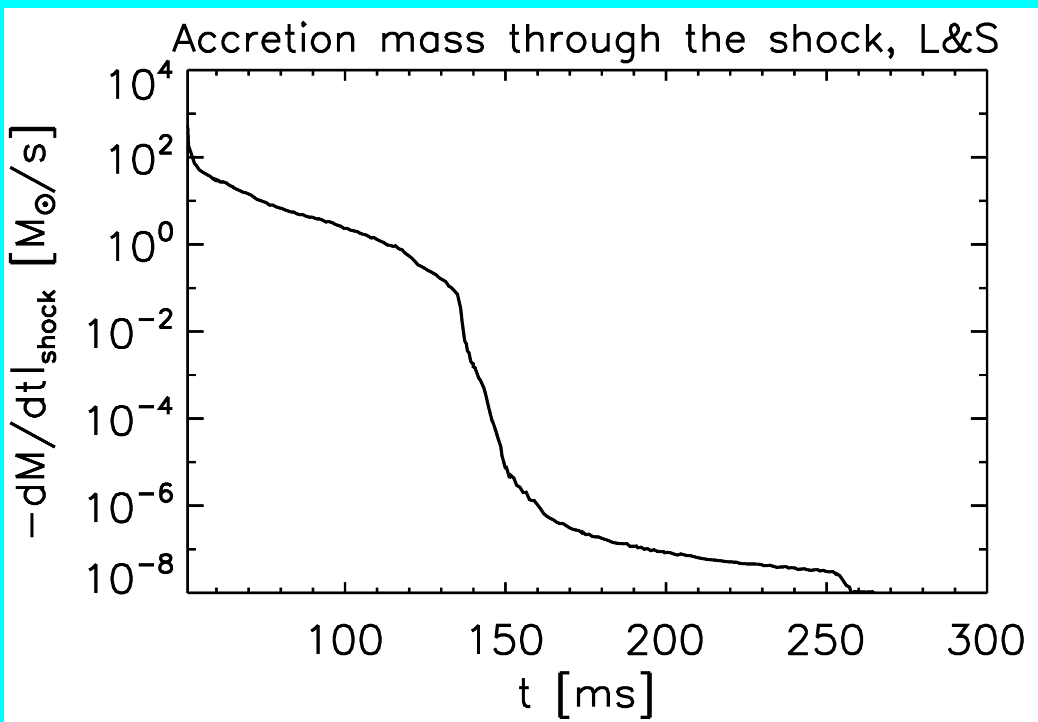
No ejection of low-entropy r-process material



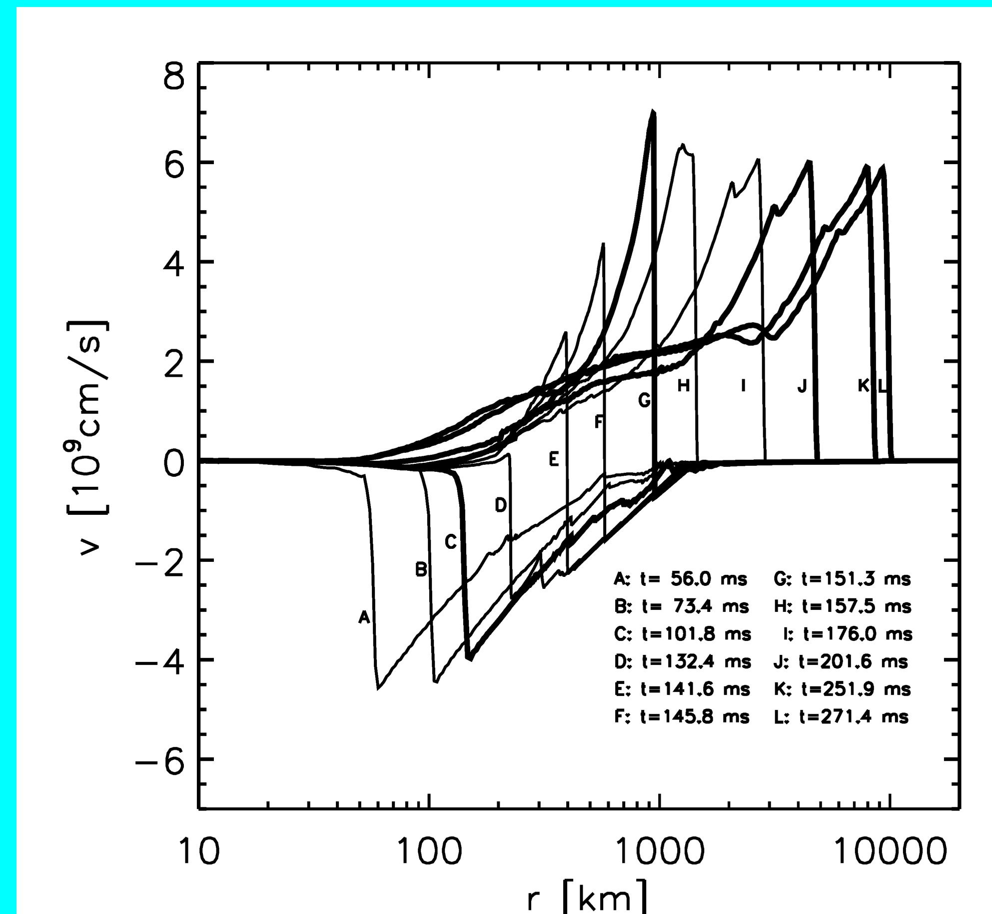
Kitaura et al., A&A, in press (2006)

No prompt explosion!

1D Simulations: ONeMg Core

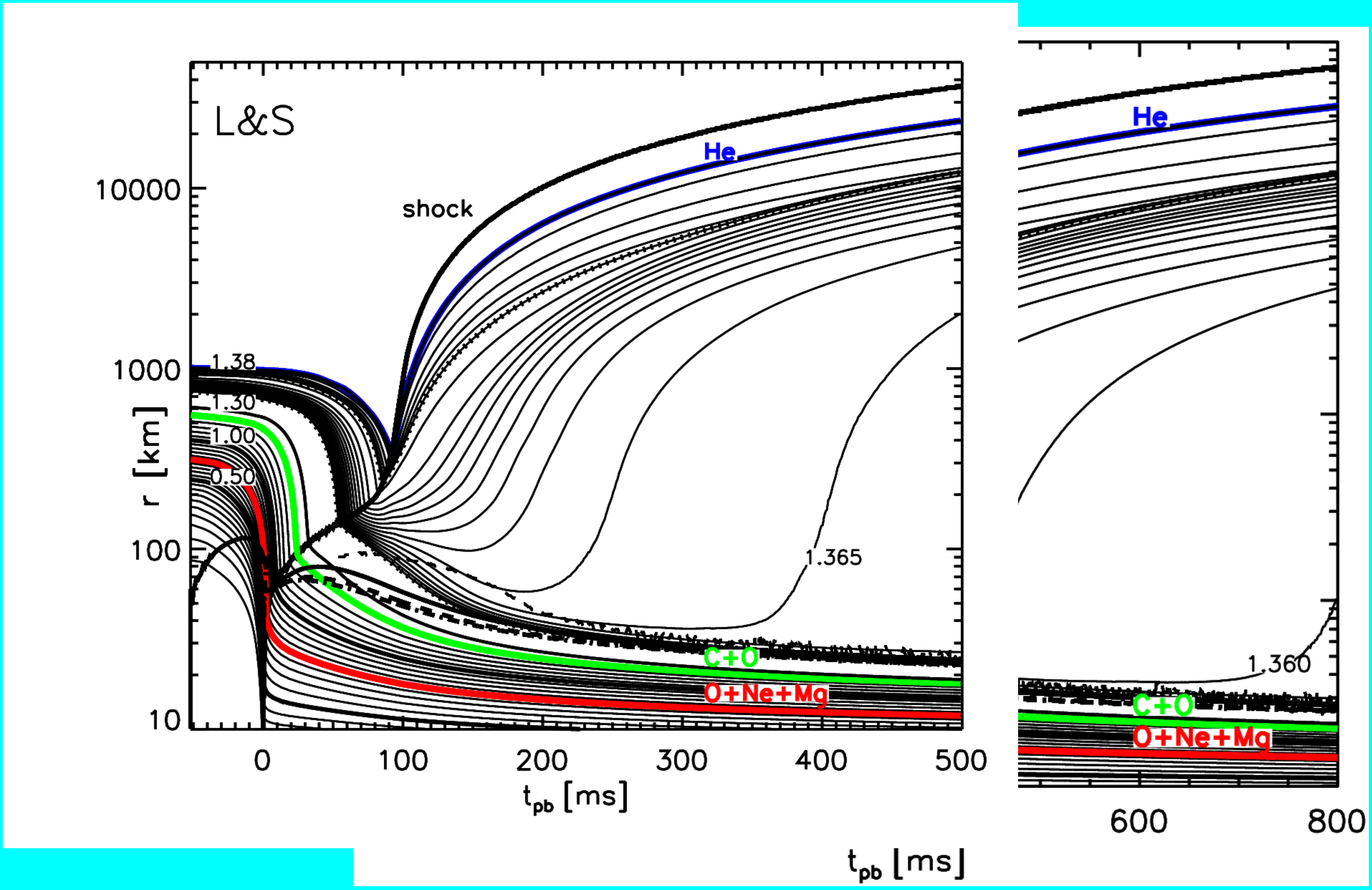


Rapidly decreasing mass accretion rate.

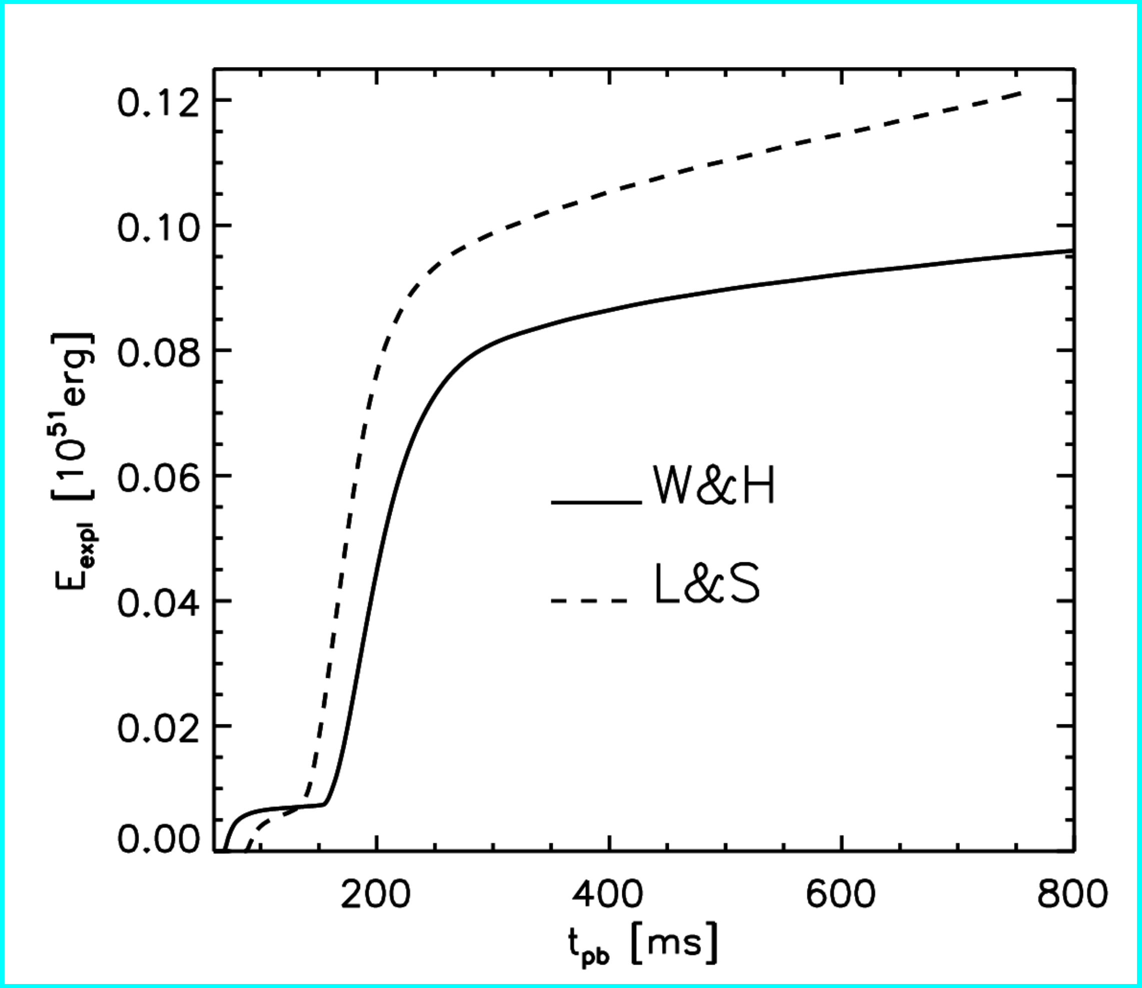


Continuing shock expansion due to decreasing mass accretion rate.

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 bethe), small Ni mass (~0.01 Msun), neutron star mass: ~1.35 M_{sun}

CRAB?   (Nomoto, Nature, 1984)

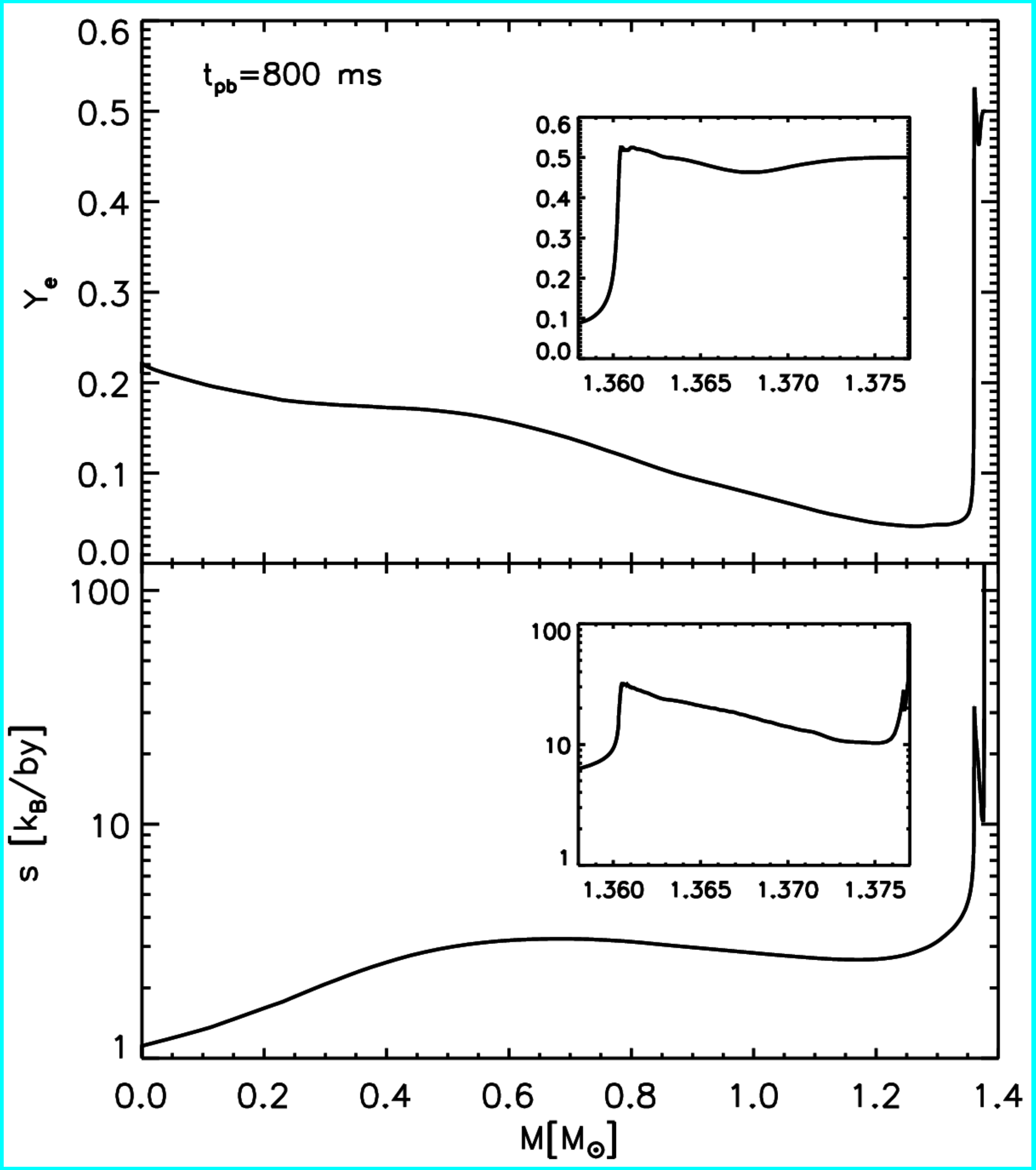
1D Simulations: ONeMg Core

During first second of the explosion:

$0.46 < Y_e < 0.53$
$10 < s/(k_B/N) < 30$

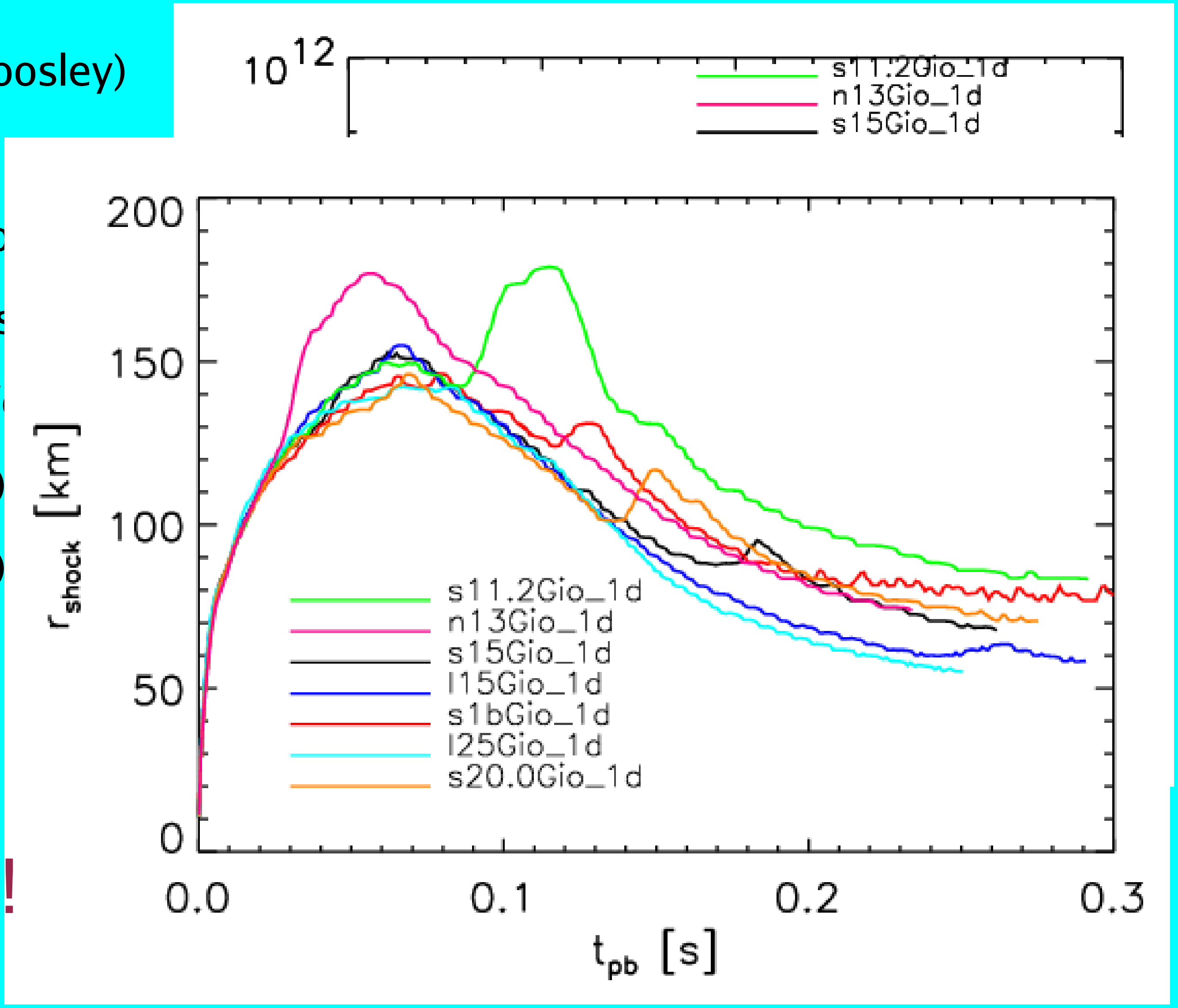
No high-entropy r-process

No overproduction problem of rare n-rich isotopes ==> no event rate constraints
(in contrast to Mayle & Wilson 1988)



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.)



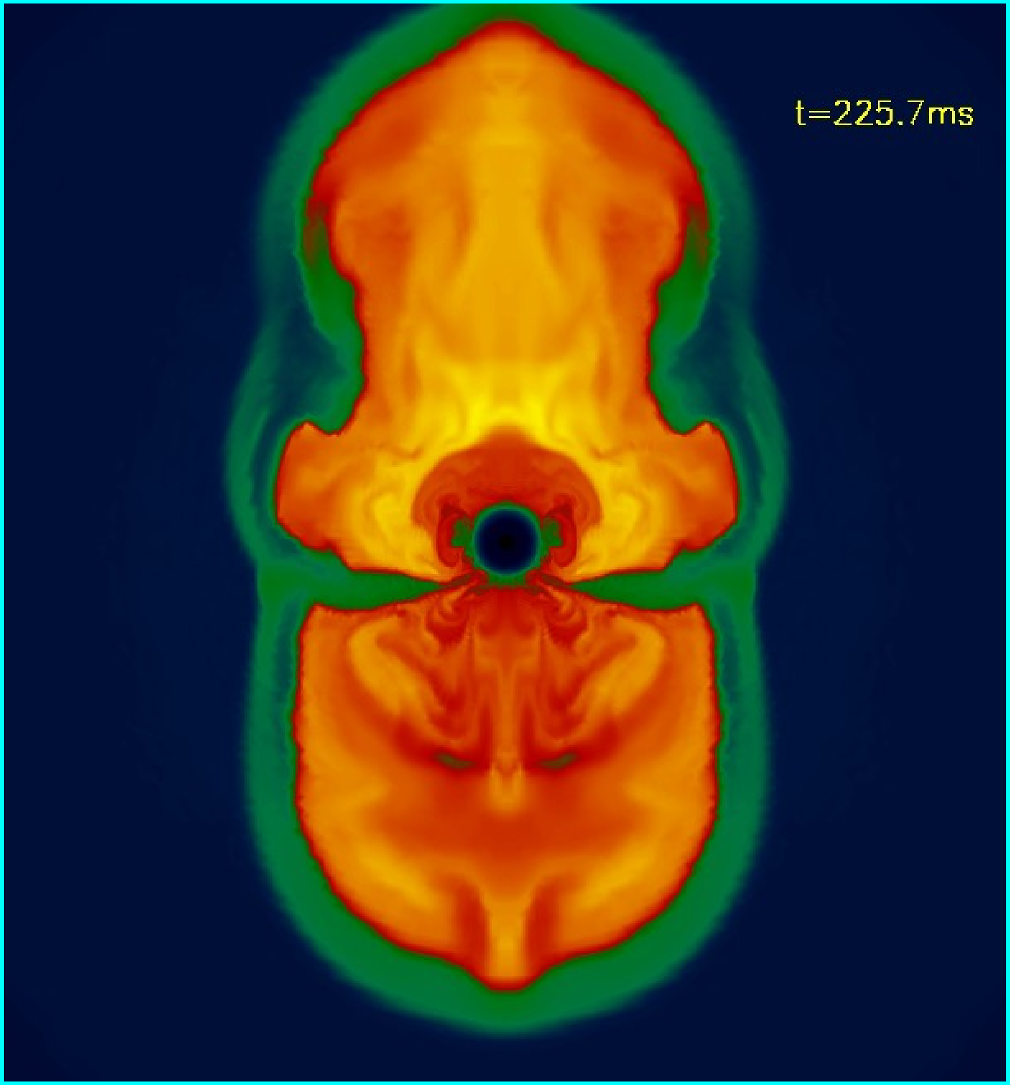
No 1D explosions!

2D Simulation: 11.2 Msun, 180° Grid

- Full 180º grid
- allows low-mode (l=1,2) convection to occur,
- global anisotropy develops,
- weak explosion takes place.

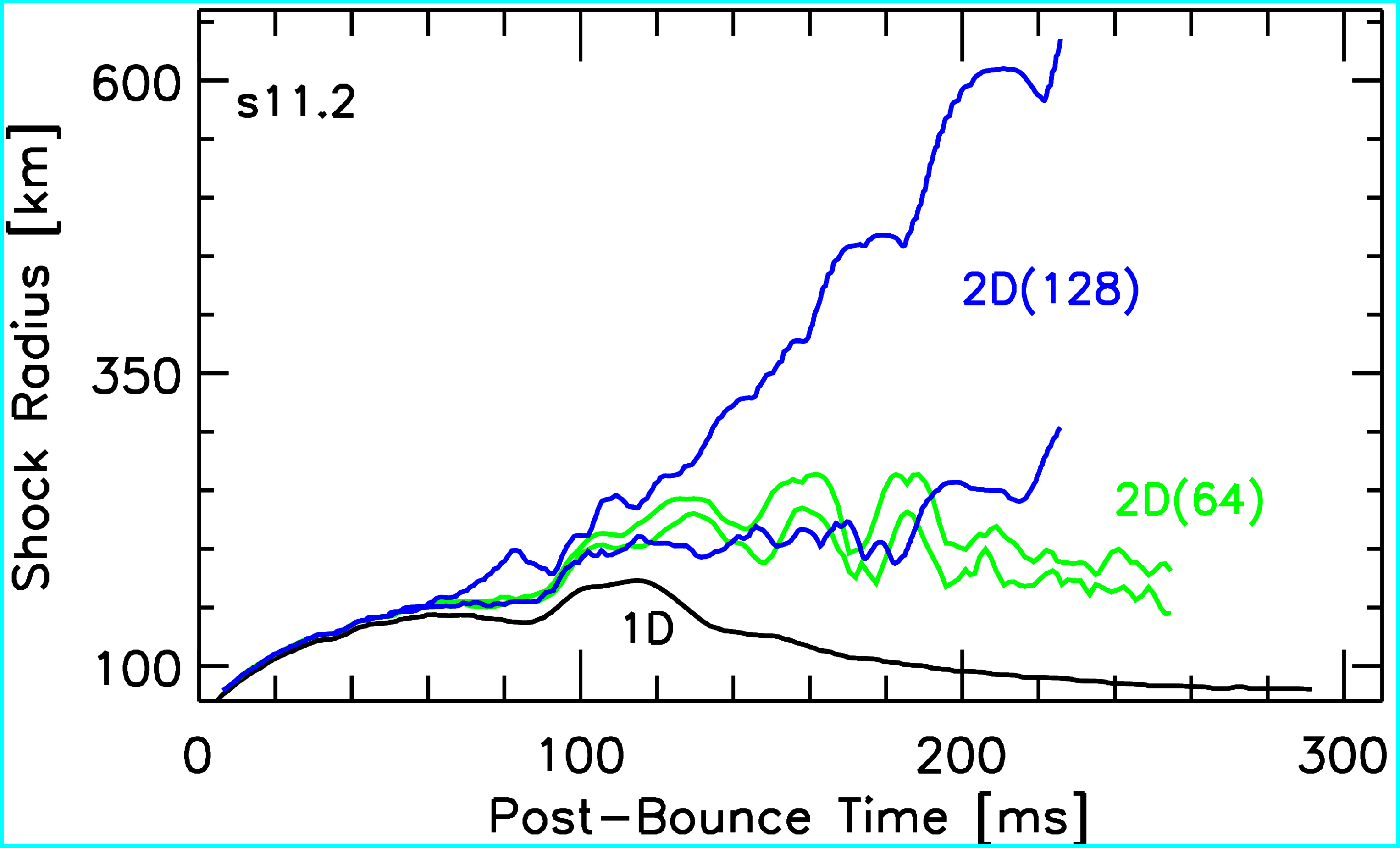
Supernovae can explode globally aspherically by the neutrino-heating mechanism even if rotation is absent!

(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 et al. (2005), A&A, submitted

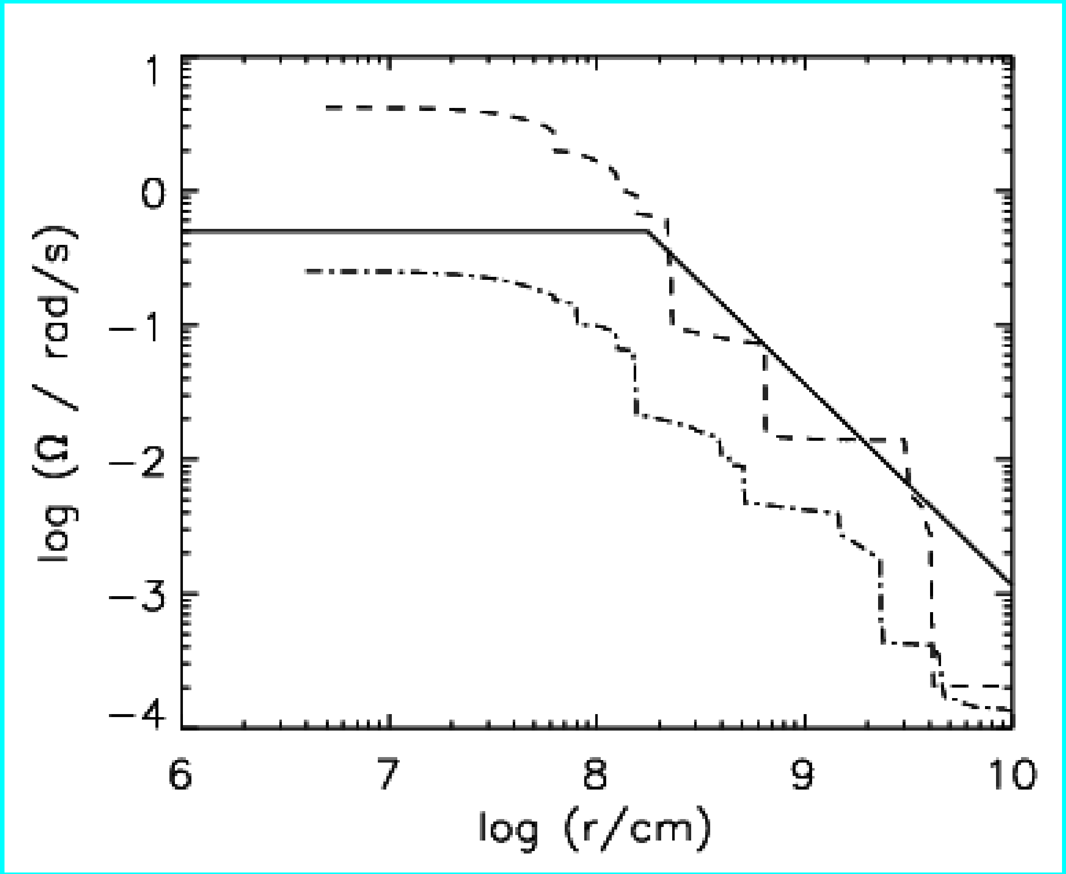
2D Simulation: 11.2 Msun, 180° Grid



R. Buras et al. (2005), A&A, submitted

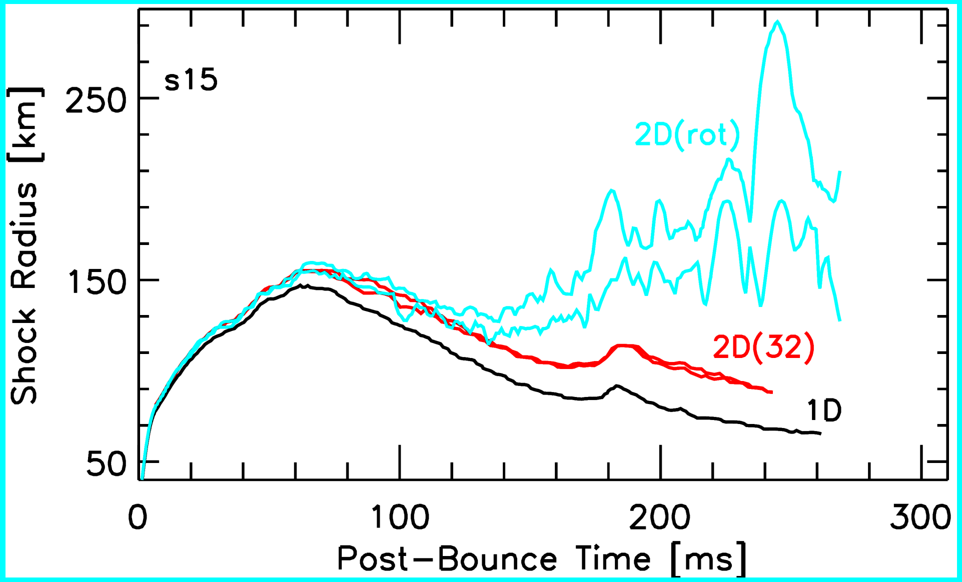
2D Simulations with Rotation

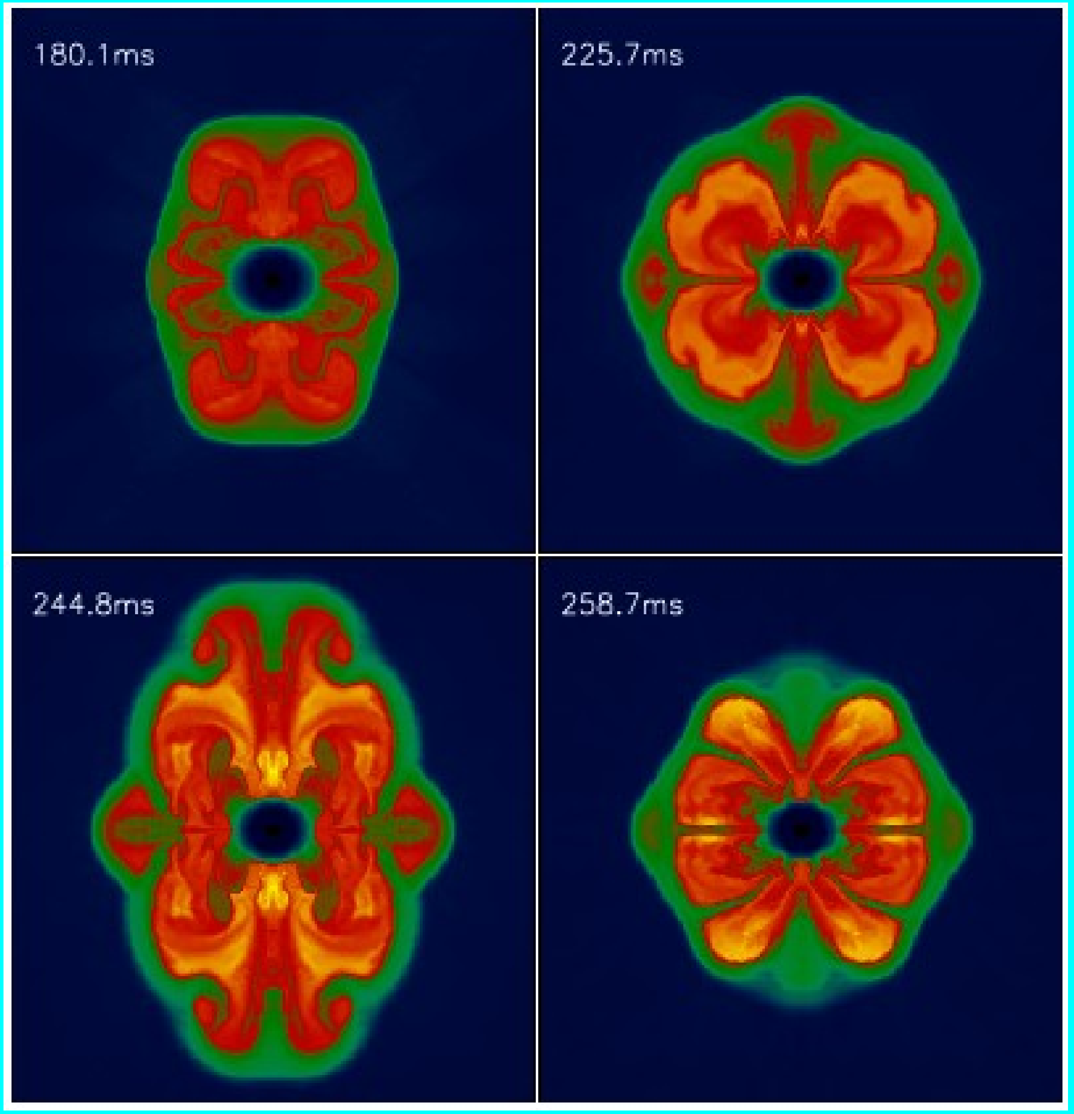
- Influence of convection and rotation on the neutrino-heating mechansim.
- “Moderate” initial iron core rotation of 15 Msun star assumed:
  period ~ 12 seconds,
  angular frequency ~0.5 rad/s.
- This rotation rate is between magnetic and nonmagnetic cores of Heger, Woosley & Spruit.
- Initially, centrifugal 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.





Summary and Outlook I

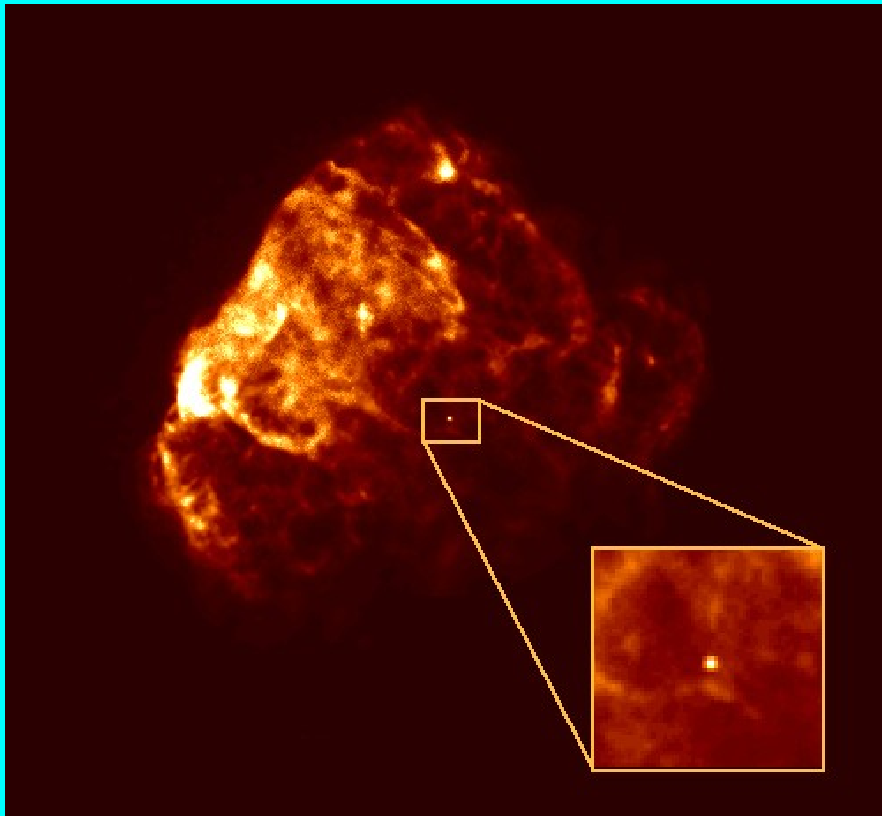
"Full models": On the road to massive star explosions:

- ONeMg core collapse (1D): shock expands, neutrino-driven wind;
  explosion for 8–10 solar mass stars with (0.1-0.2)*10^{51} ergs
- 11.2 M_{sun} star (180° grid): global l=1,2 modes, large asymmetry,
  weak explosion due to strong l=1 mode convection.
- Rotating 15 M_{sun} star: "near" explosion
  (neutrino heating ~factor 2 too low).
- More models with 180° grid and full spectral Boltzmann neutrino transport are on the computers, also runs for t > 500 ms post bounce.

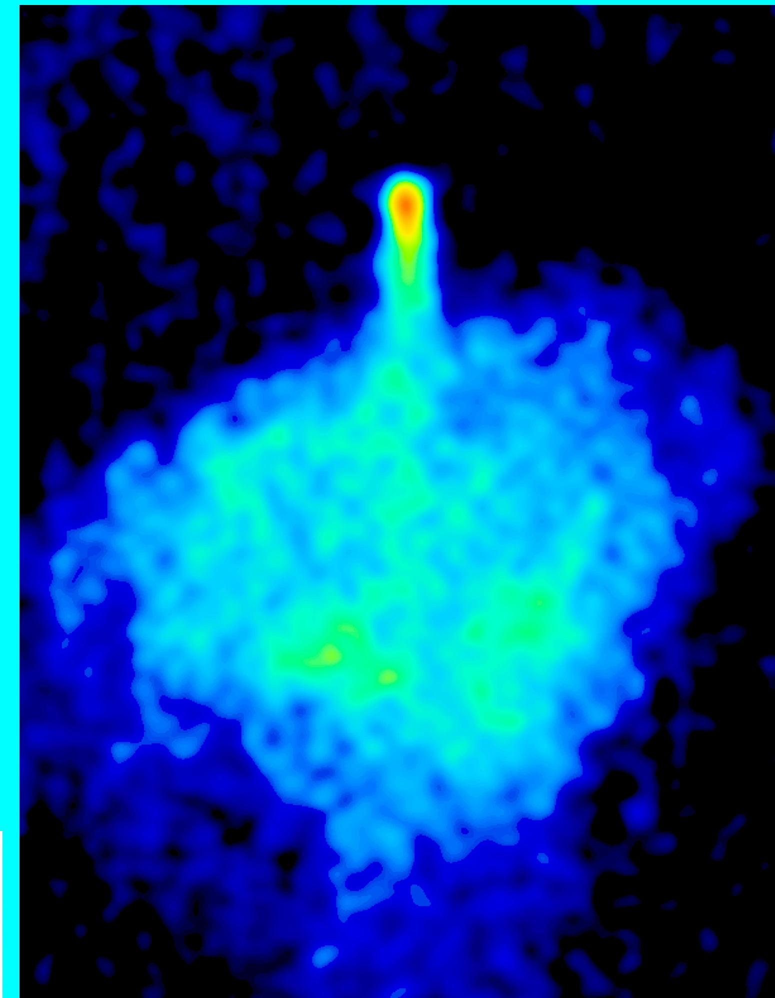
- Exploration in 3D needed (see below)!

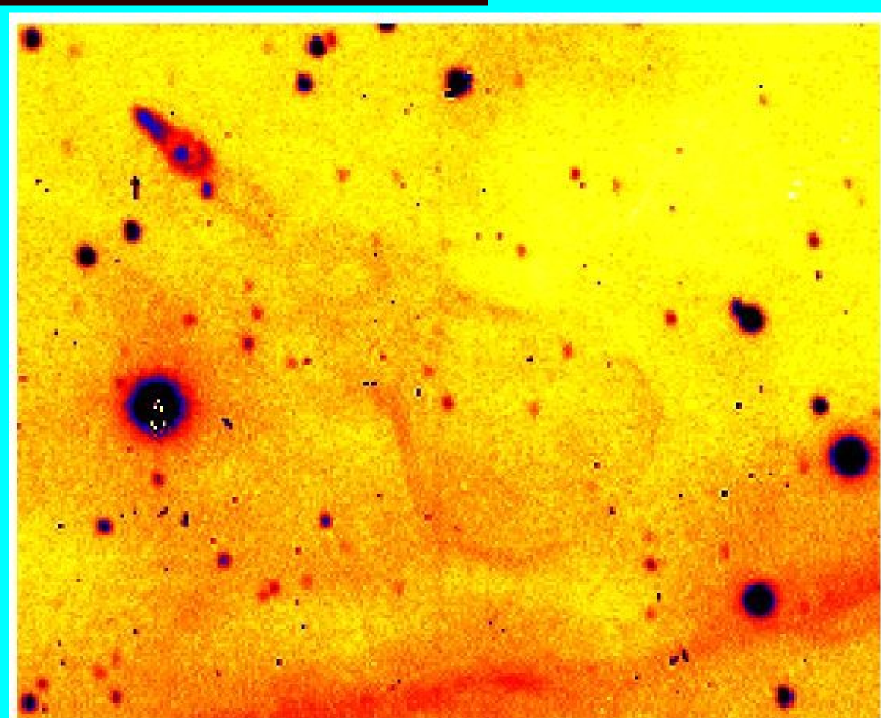
Neutron Star Recoil

What, if neutrino-driven explosions worked?



Puppis A





Guitar Nebula

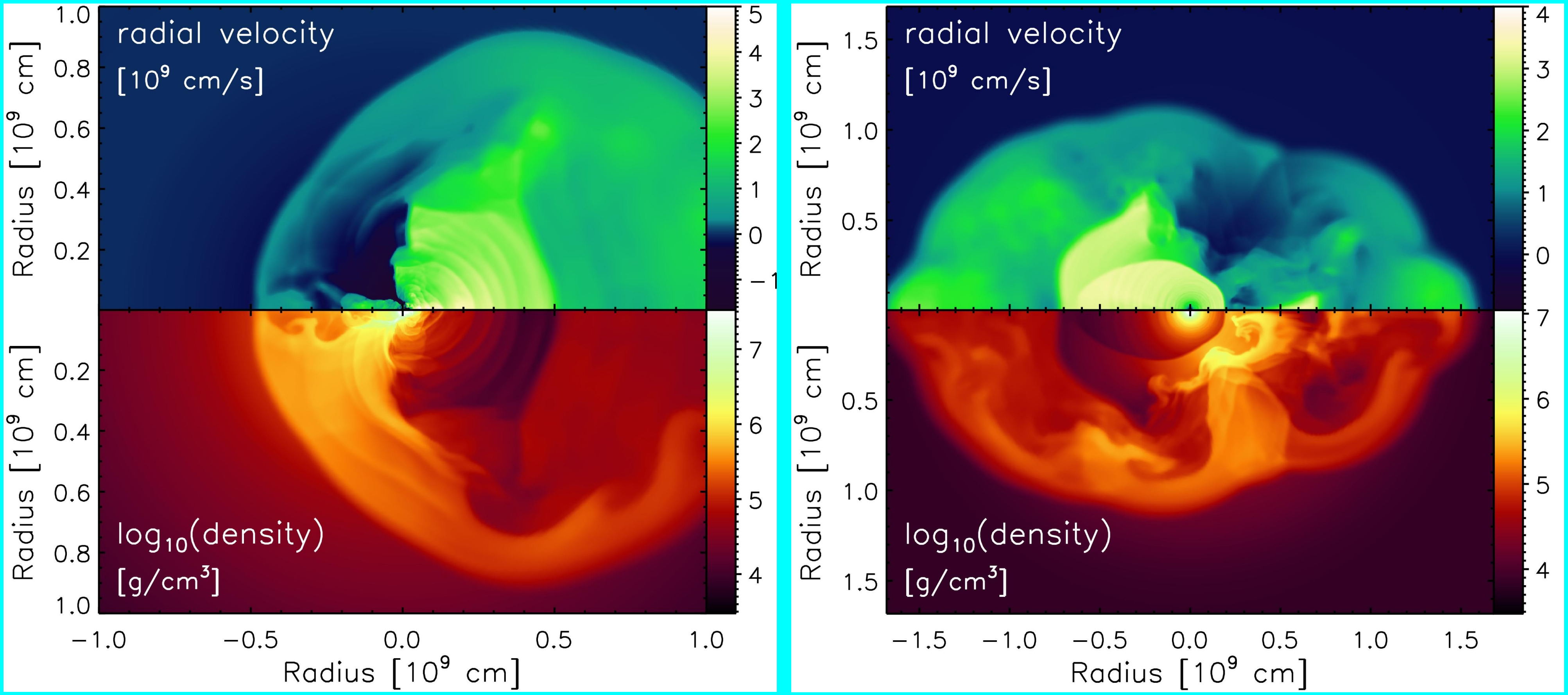
Parametric Explosion Studies

- 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!

Parametric Explosion Studies in 2D

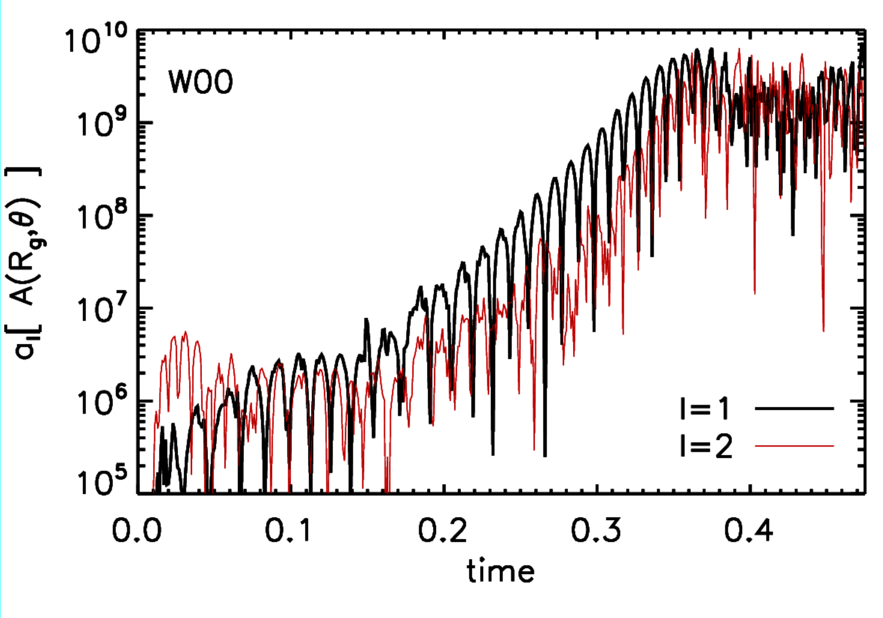
- If explosion develops slowly, convective structures have time to merge/develop to low-mode (l = 1,2) flow.
- Very asymmetric shock expansion and mass ejection although boundary neutrino flux isotropic.

Scheck et al. (PRL, 2004), Scheck et al. (2006), A&A, submitted

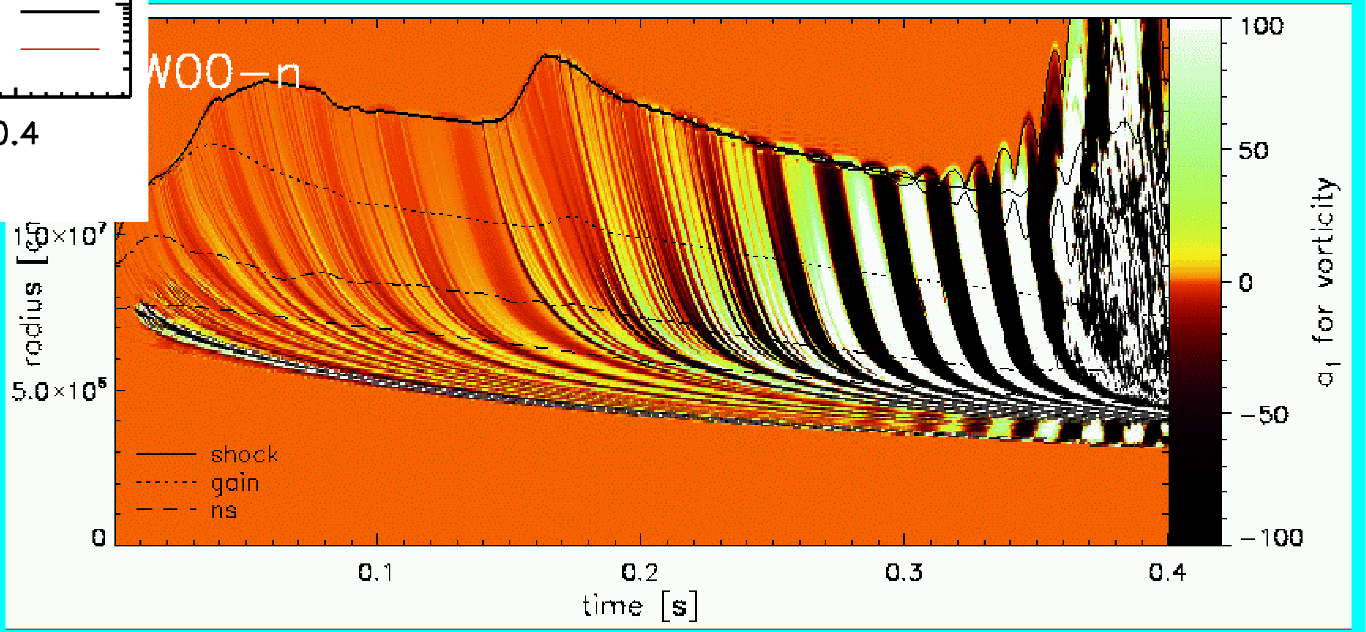


2D Models: Low-Mode Asymmetries

- Growth of asymmetry in the linear phase shows evidence for the action of the advective-acoustic cycle ala Foglizzo (2001, 2002)
- Amplitudes of spherical harmonics of vorticity and velocity field show characteristic oscillations on expected timescale.

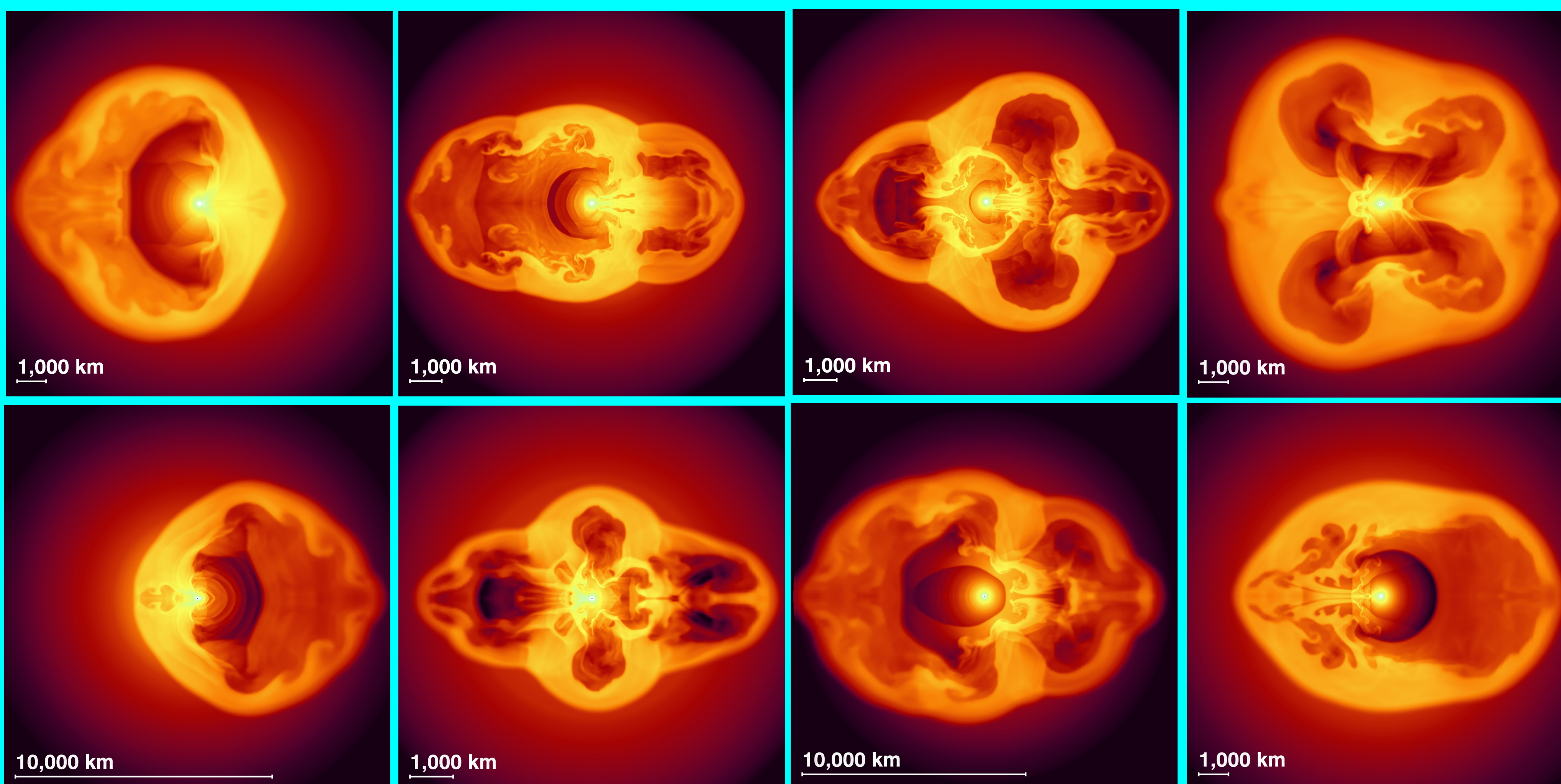


Scheck et al. (2006), A&A, in preparation



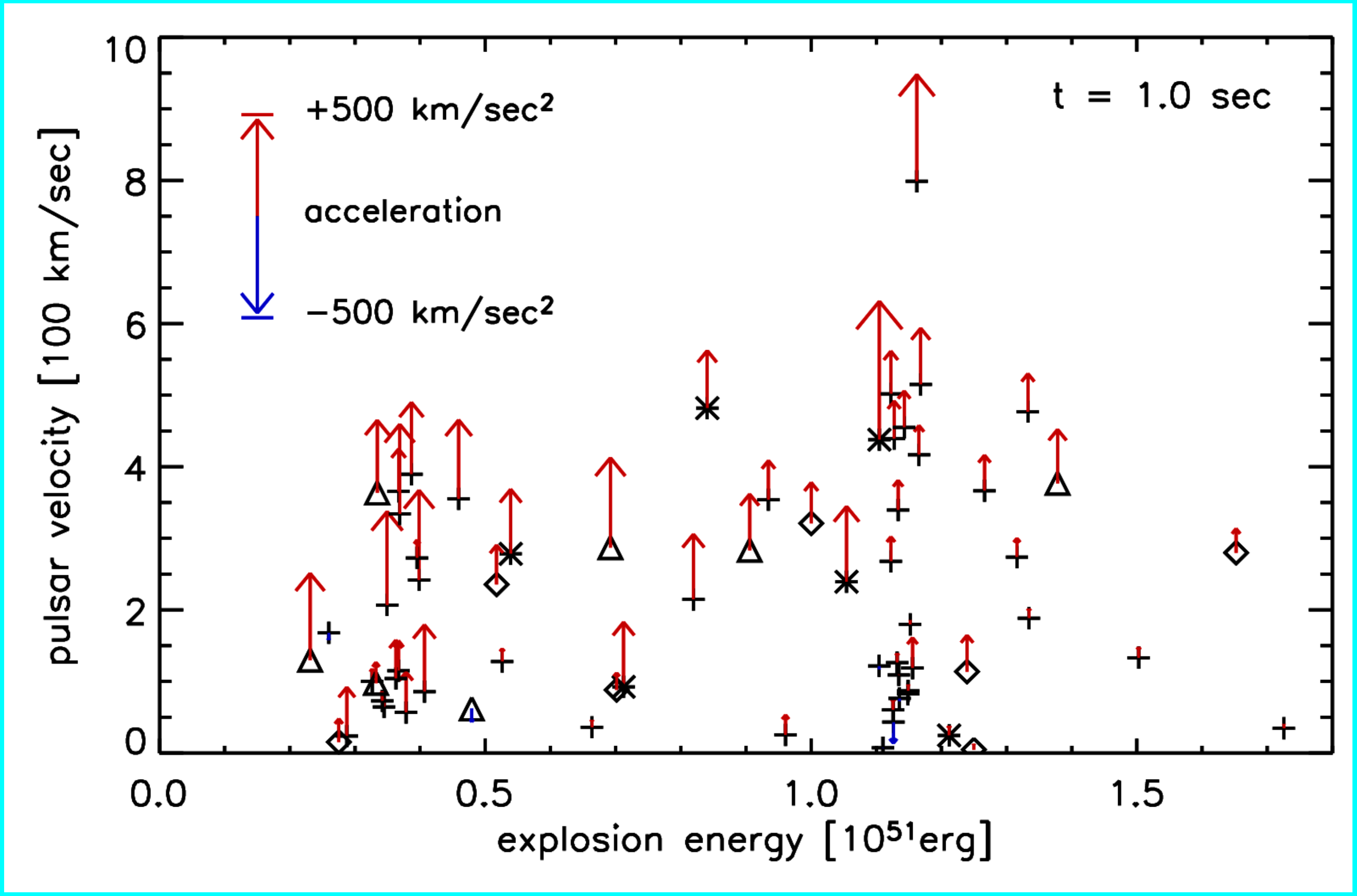
2D Models: Low-Mode Asymmetries

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



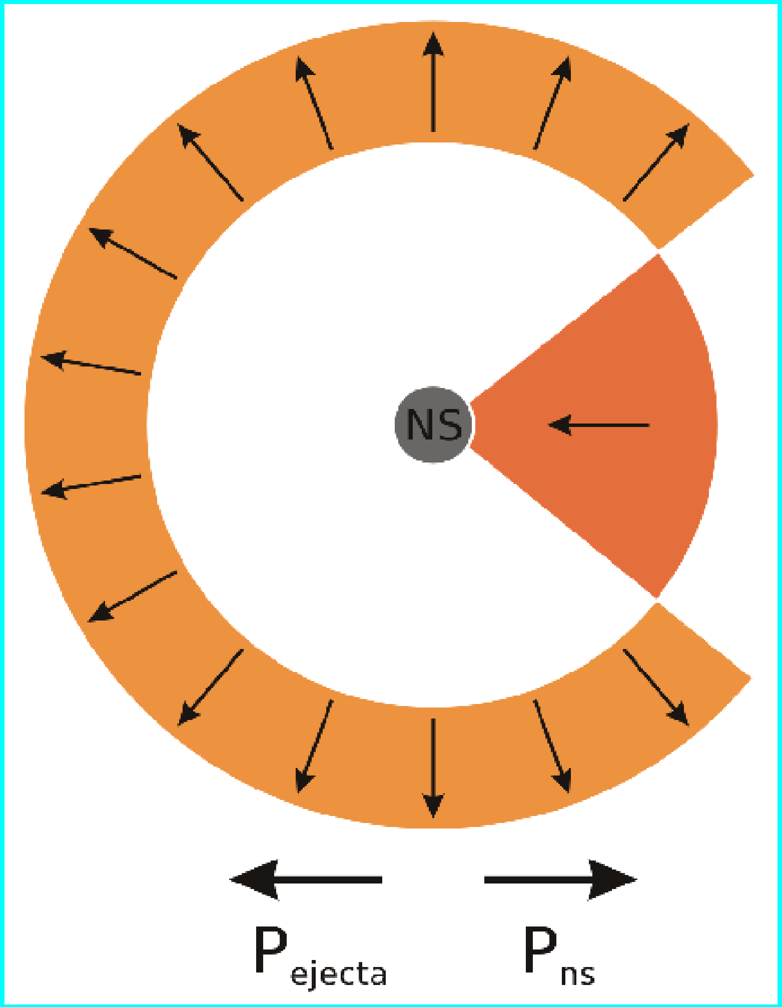
Parametric Explosion Studies in 2D

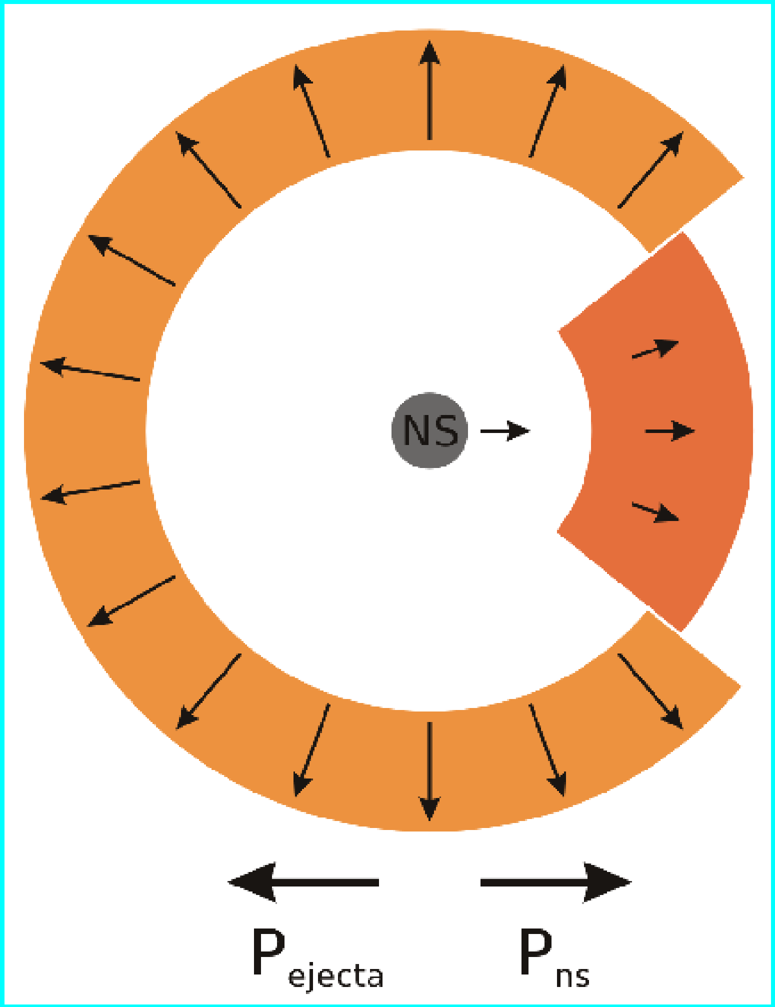
- Anisotropic mass ejection ==> neutron star receives recoil velocity.
- In 2D: v > 800 km/s at 1 second, large acceleration continues longer.



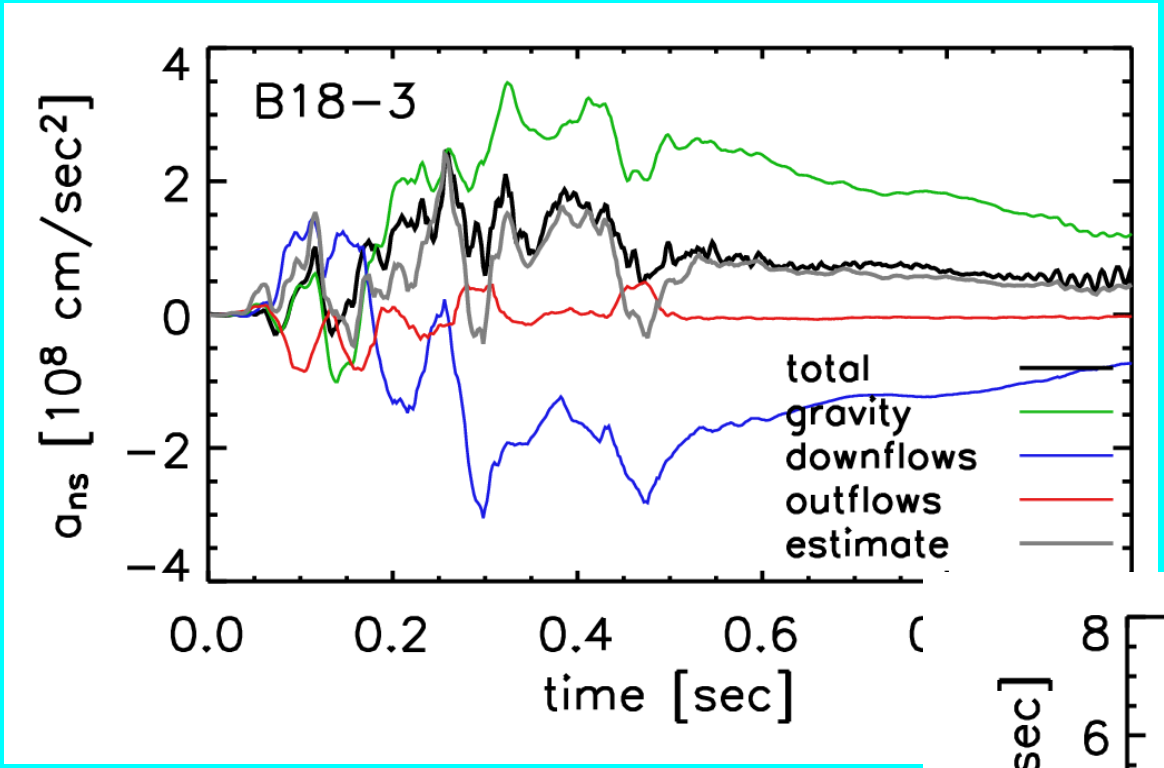
Parametric Explosion Studies in 2D

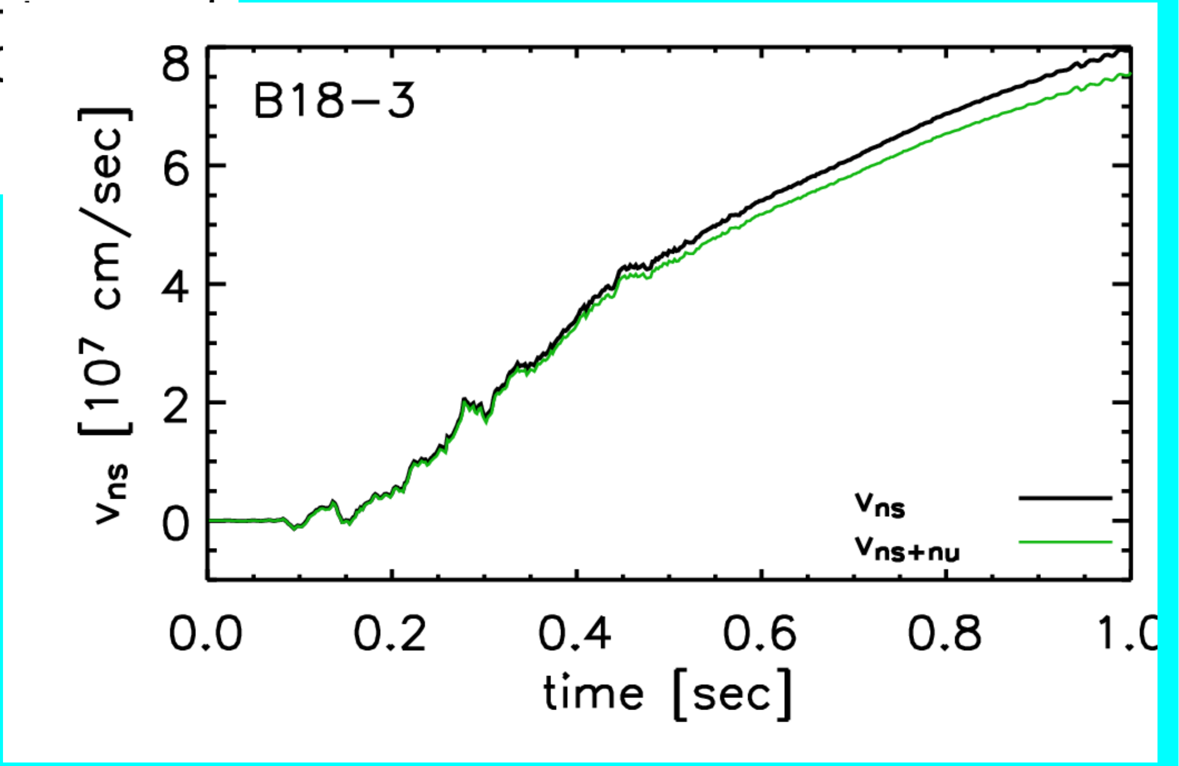
- Neutron star acceleration mainly by gravitational forces, also hydrodynamic forces, neutrinos are of minor importance.





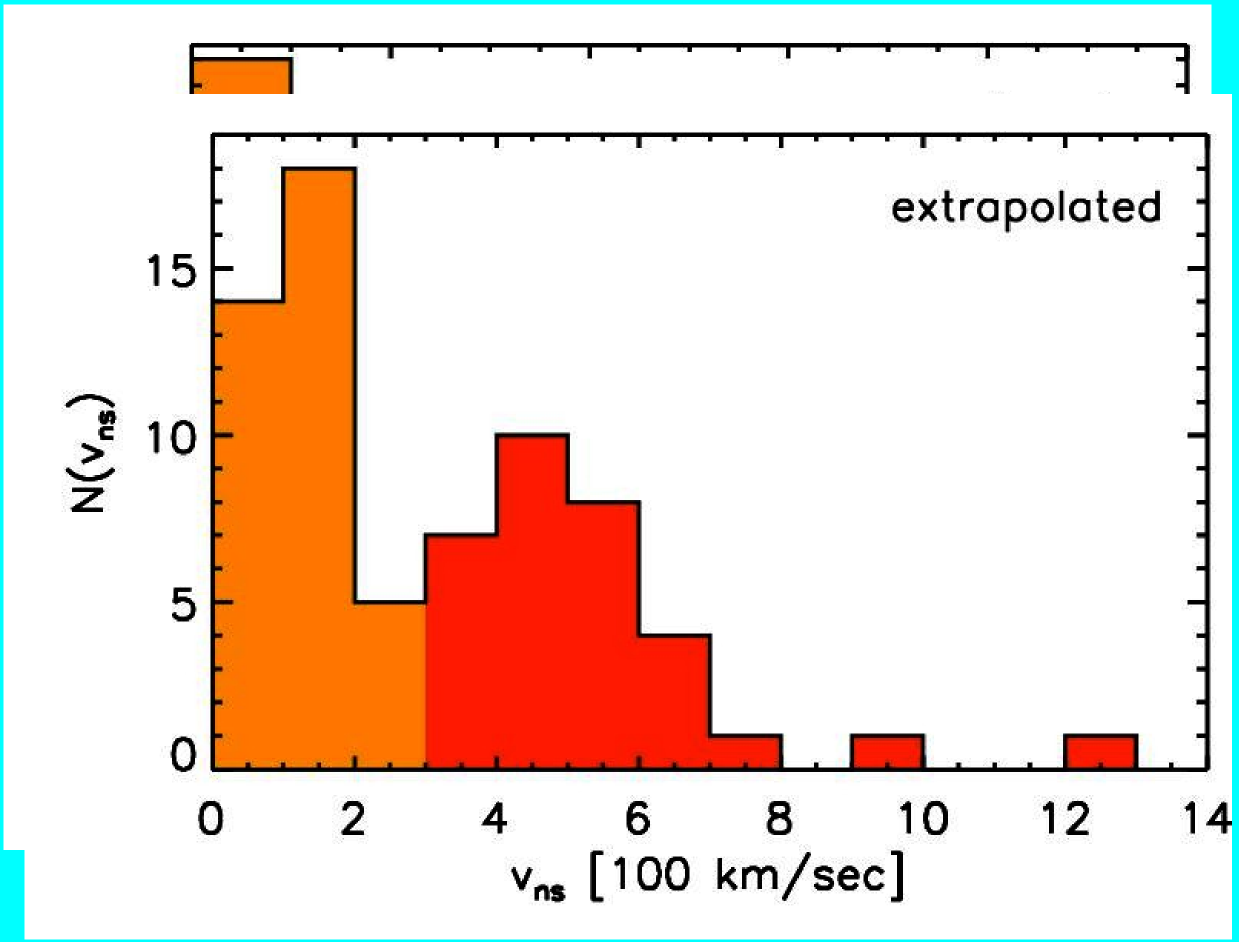
Parametric Explosion Studies in 2D





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:

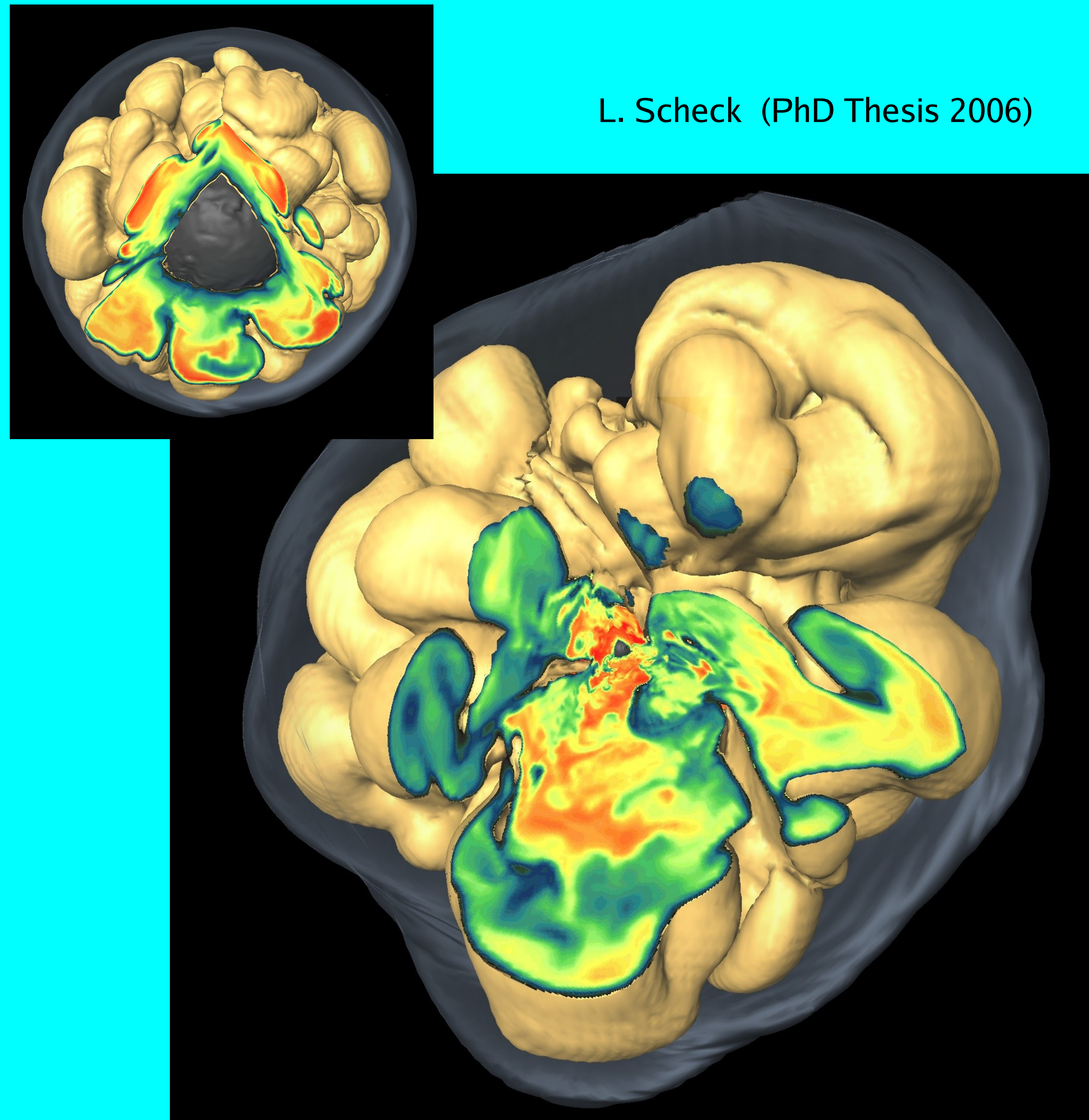
!! Fryer et al. (1997) and Arzoumanian et al. (2002) claim evidence,

?? 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: 1.5°–3°.

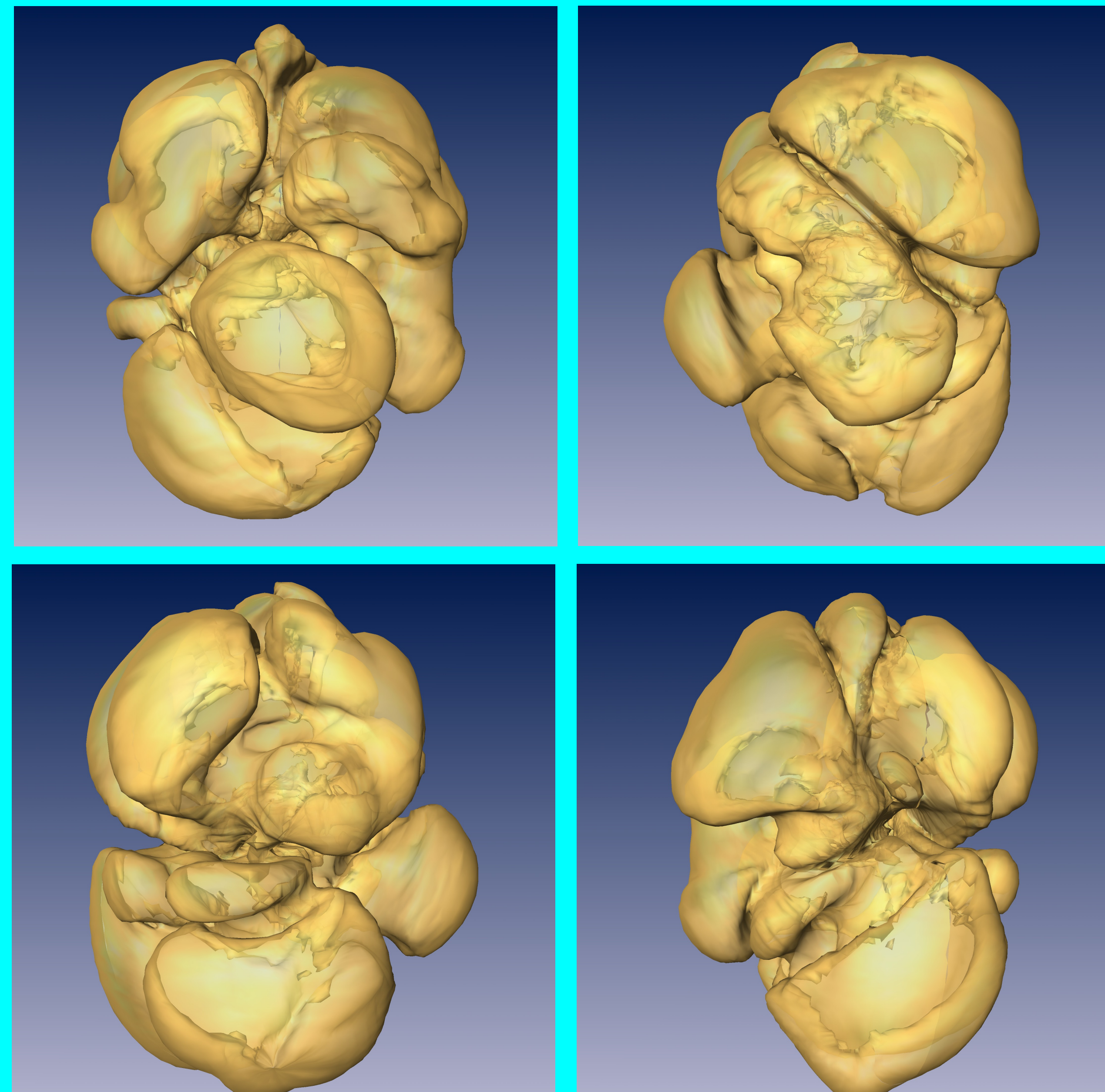
L. Scheck (PhD Thesis 2006)



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

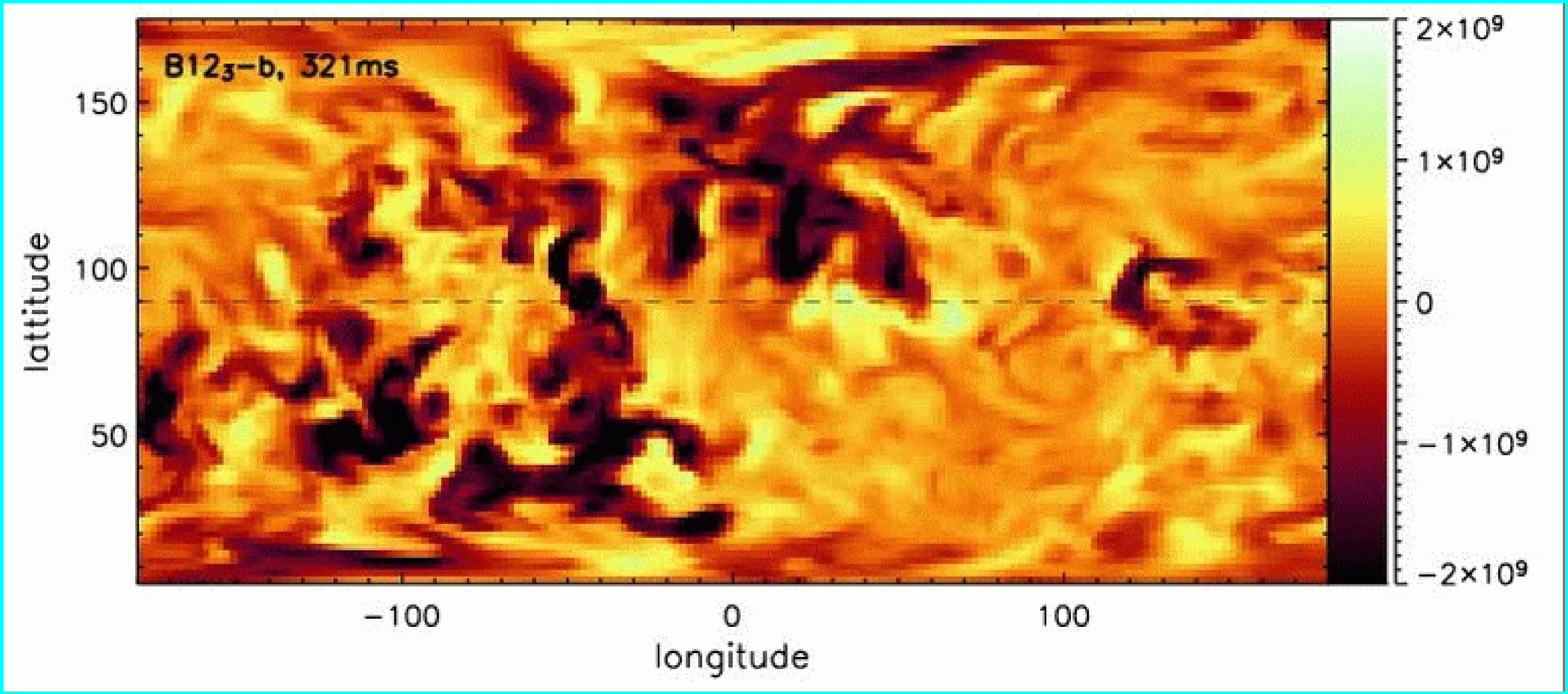
Parametric Explosion Studies in 3D

- 3D with rotation
- Significant prolate asymmetry



L. Scheck (PhD Thesis 2006)

Parametric Explosion Studies in 3D

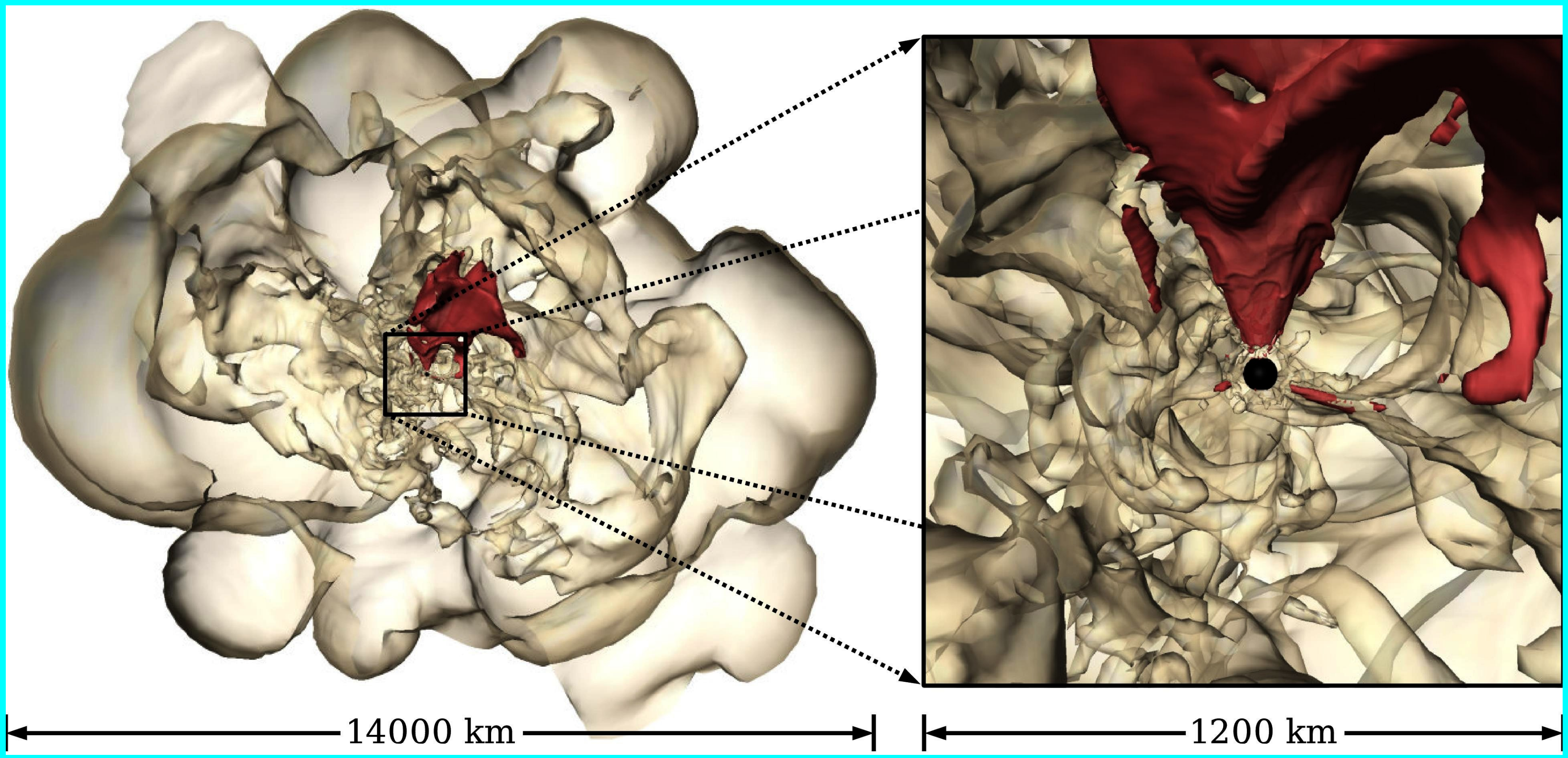


L. Scheck (PhD Thesis 2006)

Growth of low modes during convective overturn

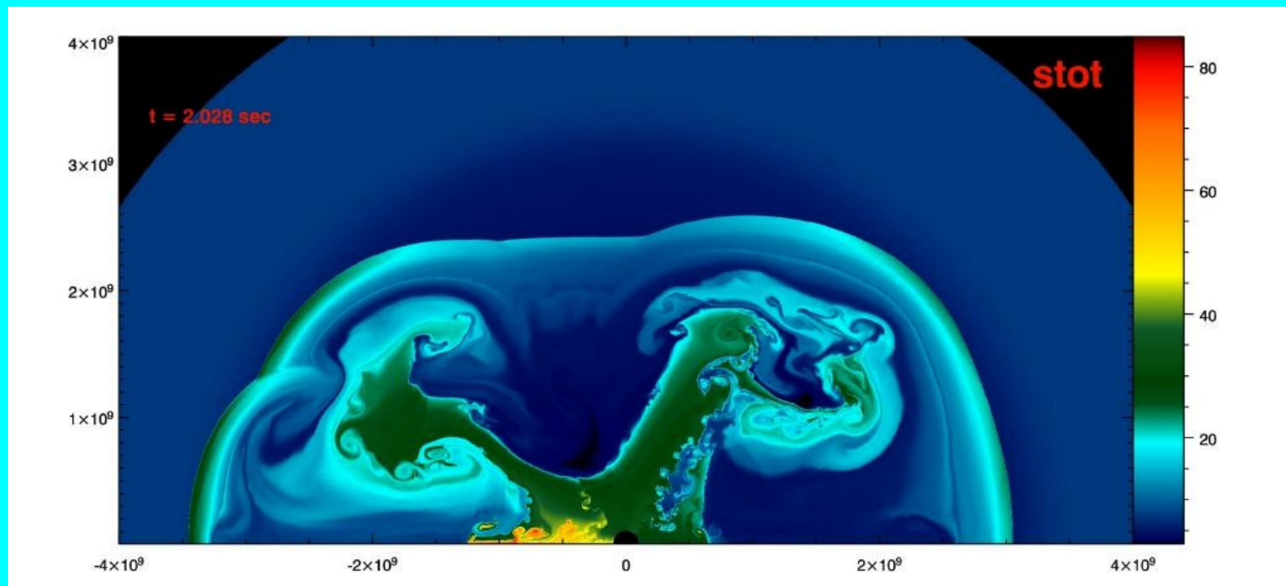
Parametric Explosion Studies in 3D

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

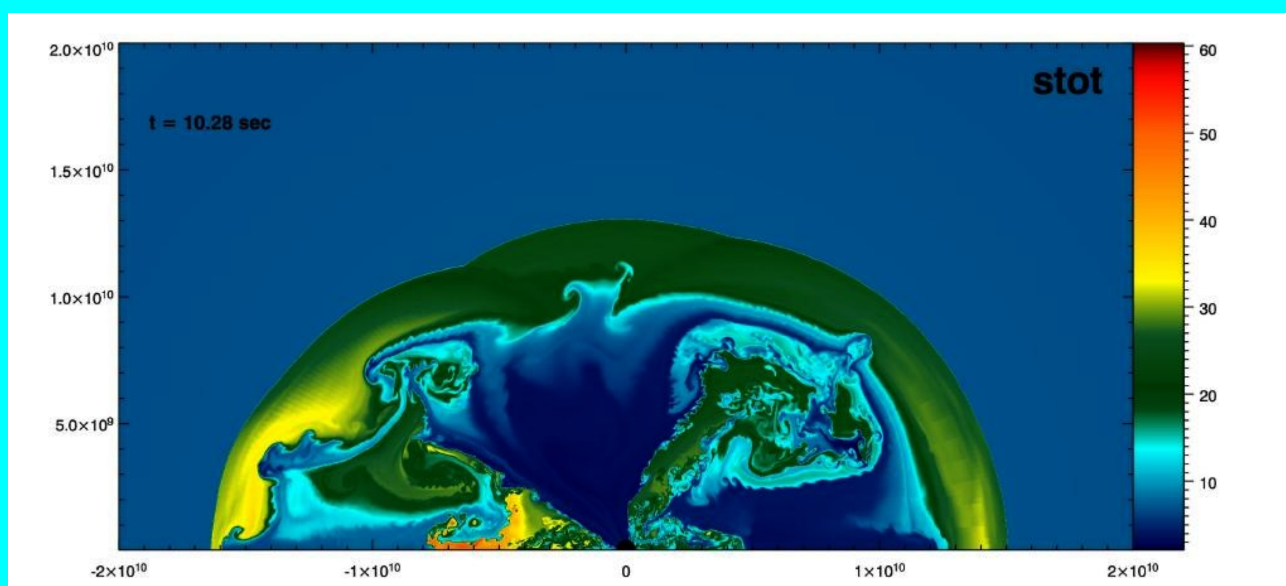


Ejecta Mixing

Long-Time SN Evolution in 2D



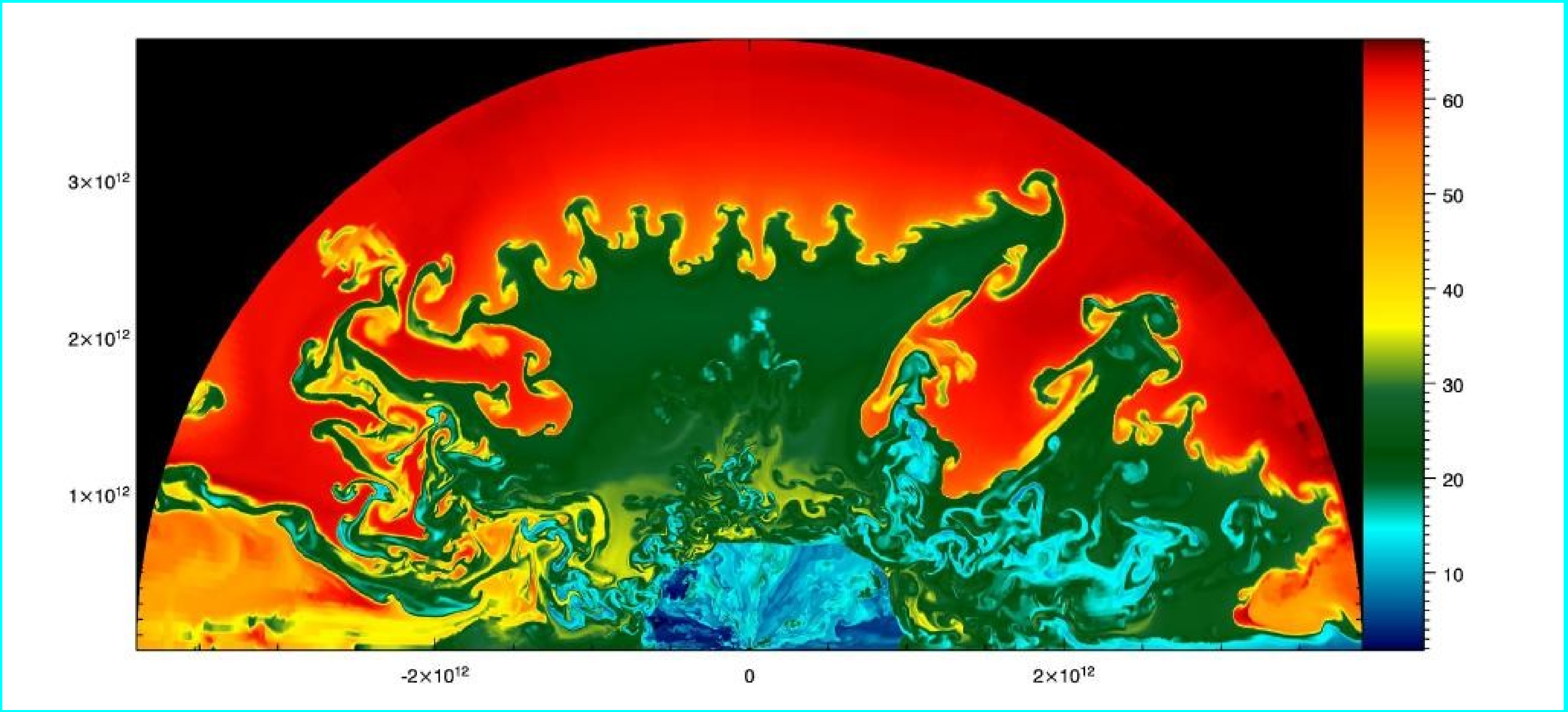
2 seconds



Kifonidis et al. (2005), A&A, submitted

10 seconds

Long-Time SN Evolution in 2D

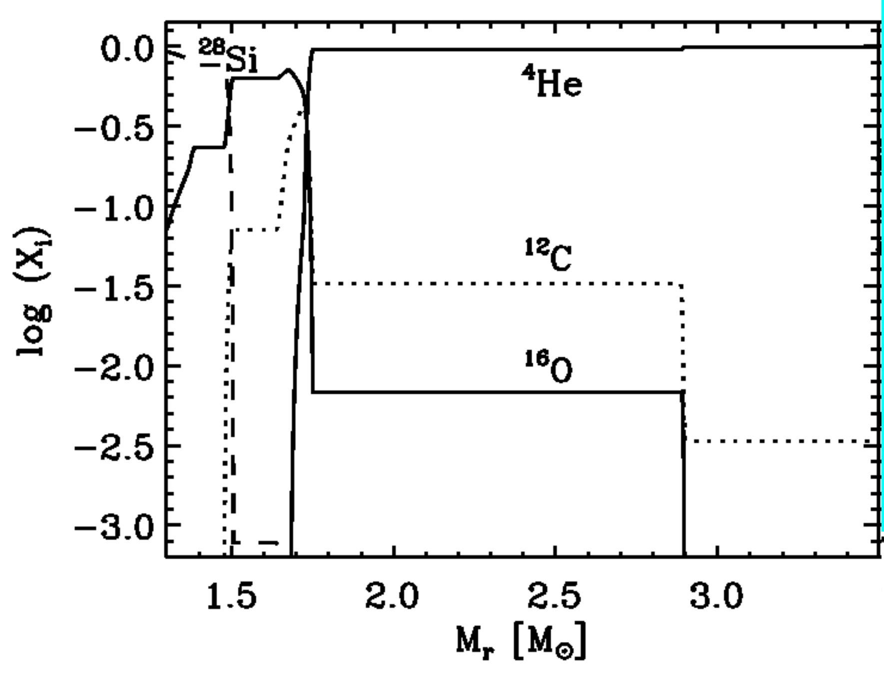


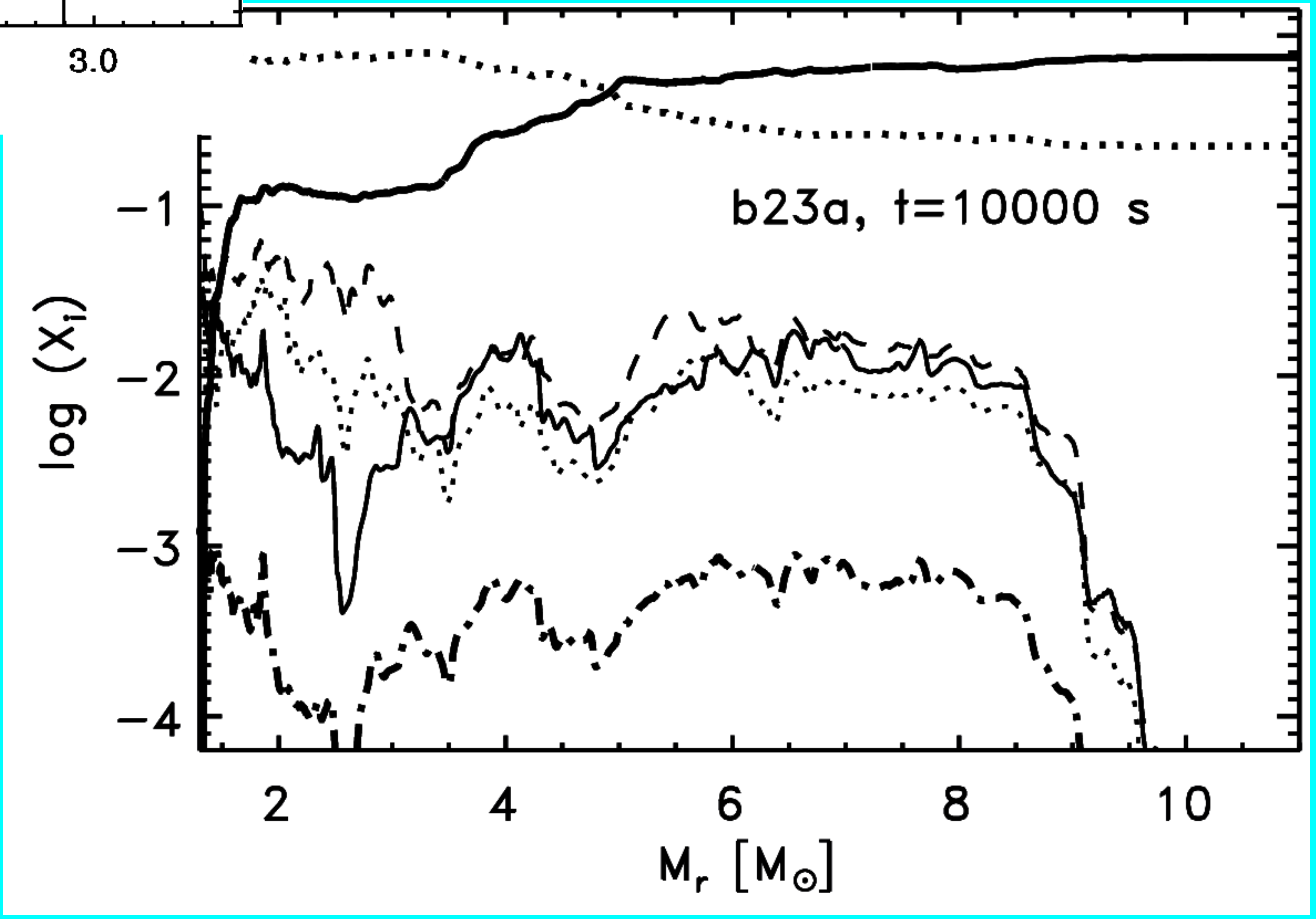
Kifonidis et al (2005), A&A, submitted

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

Long-Time SN Evolution in 2D

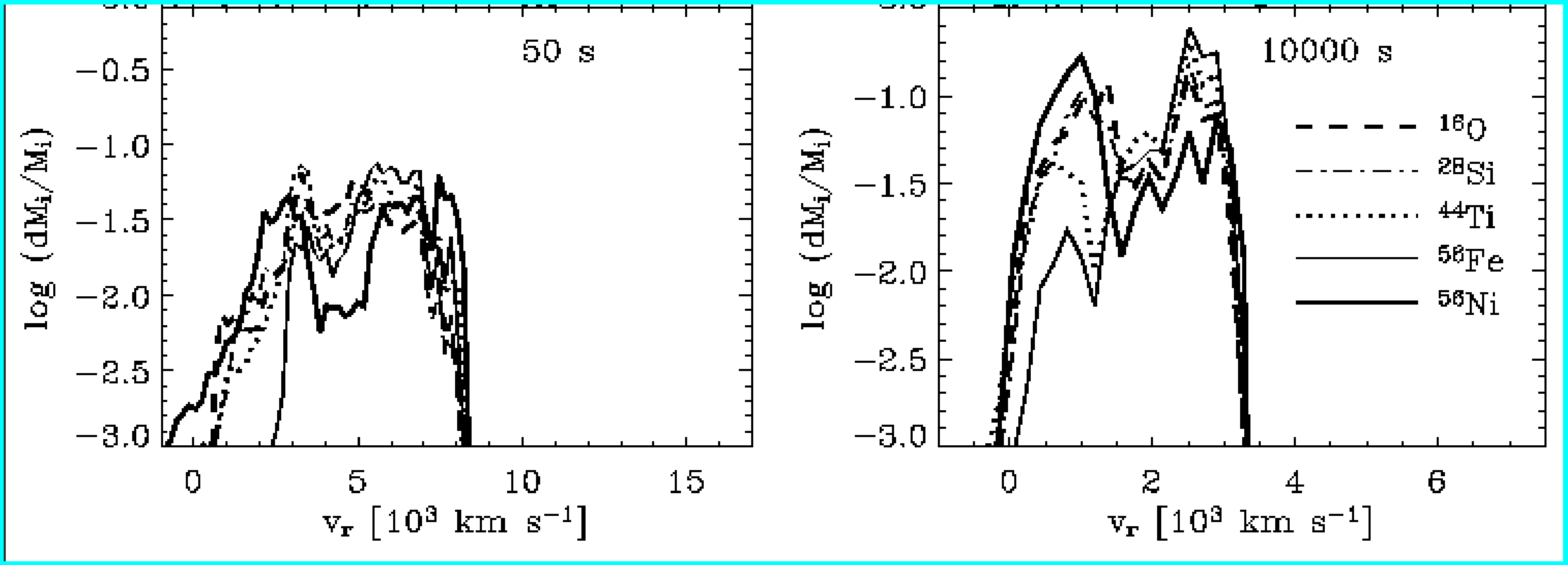




Composition is strongly mixed in radial direction:

H: bold solid
^{4}He: bold dotted
^{16}O: thin dashed
^{28}Si: thin dotted
^{44}Ti: bold dashed-dotted
Fe-group: thin solid

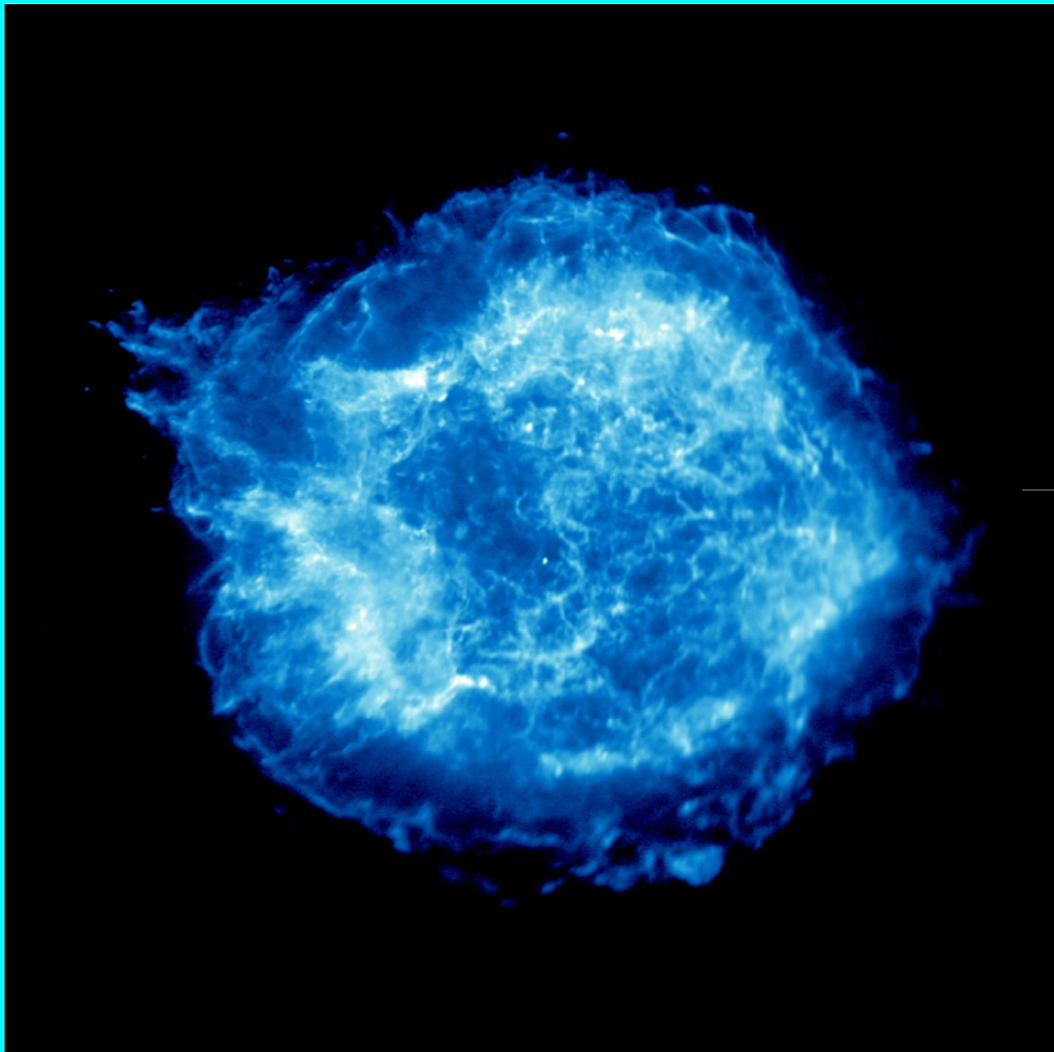
Long-Time SN Evolution in 2D

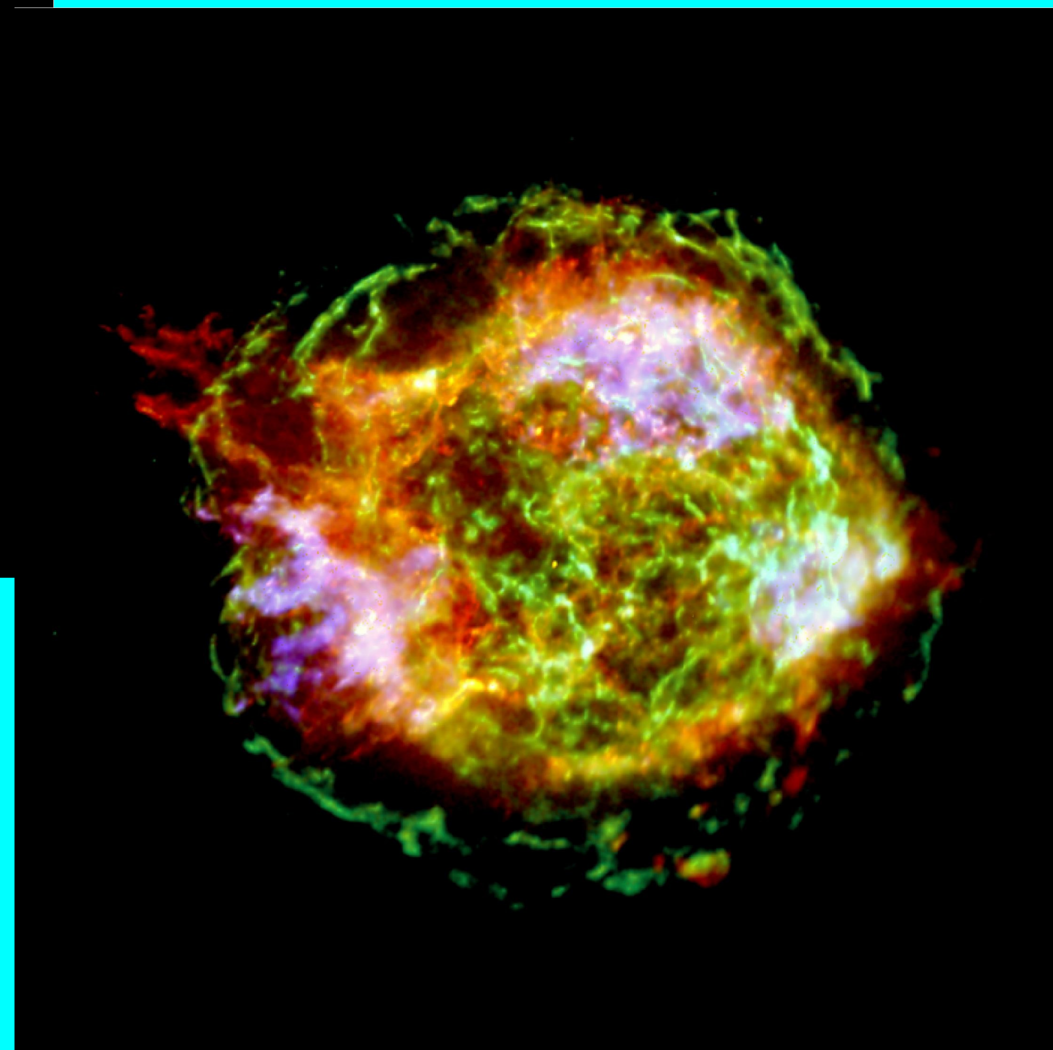


Kifonidis et al (2005), A&A, submitted

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

SN Remnant Cassiopeia A





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

Summary and Outlook II

Parametric explosion studies:

- When explosion starts "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 1987A asymmetries and observed element mixing can be explained.
- Can global deformation & polarization of most/all SNe be explained?
- Role of "advective-acoustic" cycle (Foglizzo 2002) for amplifying non-radial modes in convective environment needs more studies.