Asymmetries in Core-Collapse Supernovae

Chris Fryer (LANL)

- Basic Core-Collapse Mechanism (Theory and Observational Support)
- Possible Mechanisms Driving Asymmetries
- A Few Observational Tests of those Mechanisms
- LANL's Light-Curve Program

Supernova 1987A

After – SN 1987A   Before – Sanduleak -69 202

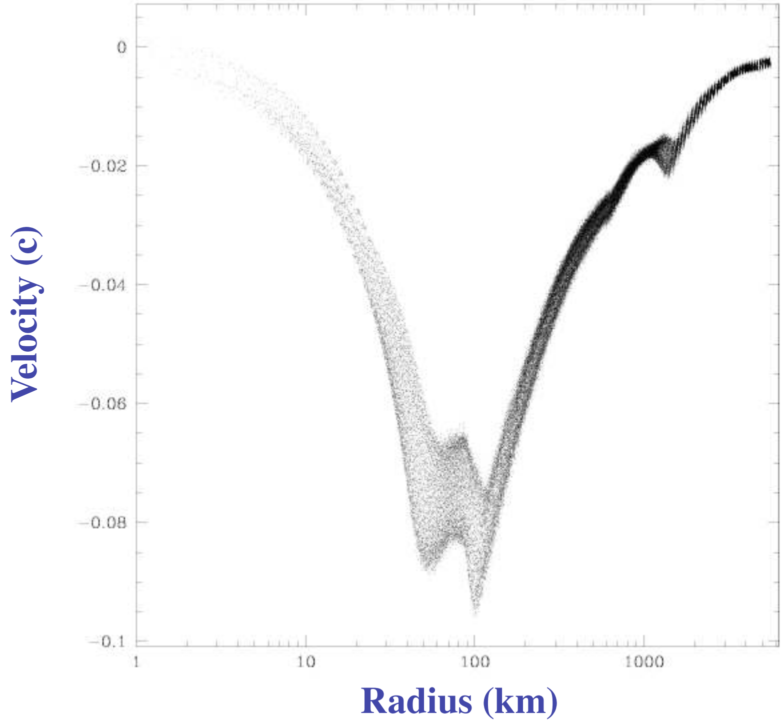
Neutrino-Driven Supernova Mechanism

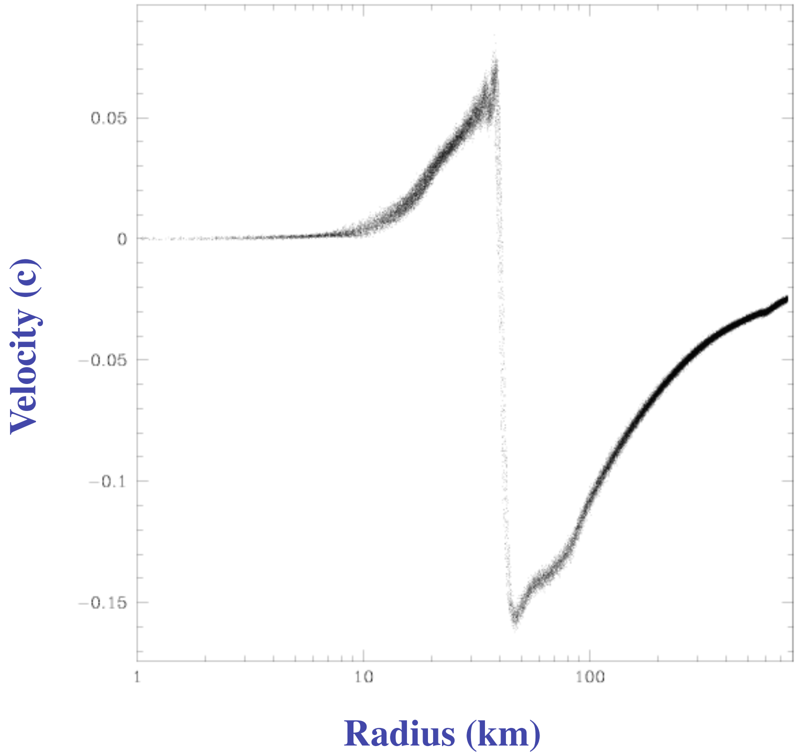
Temperature and Density of the Core Becomes so High that:

Iron dissociates into alpha particles

Electrons capture onto protons

Core collapses nearly at freefall!



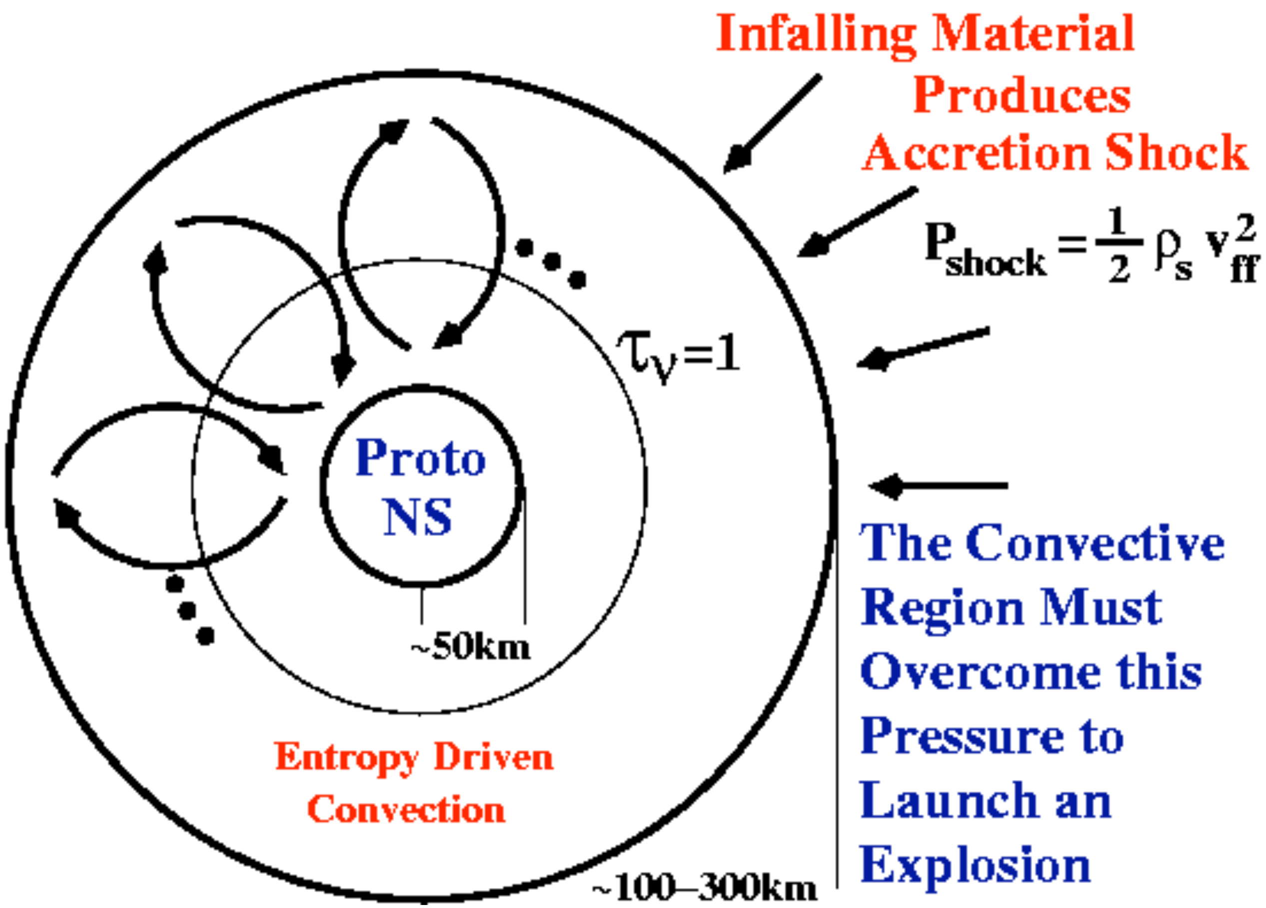


Core reaches nuclear densities

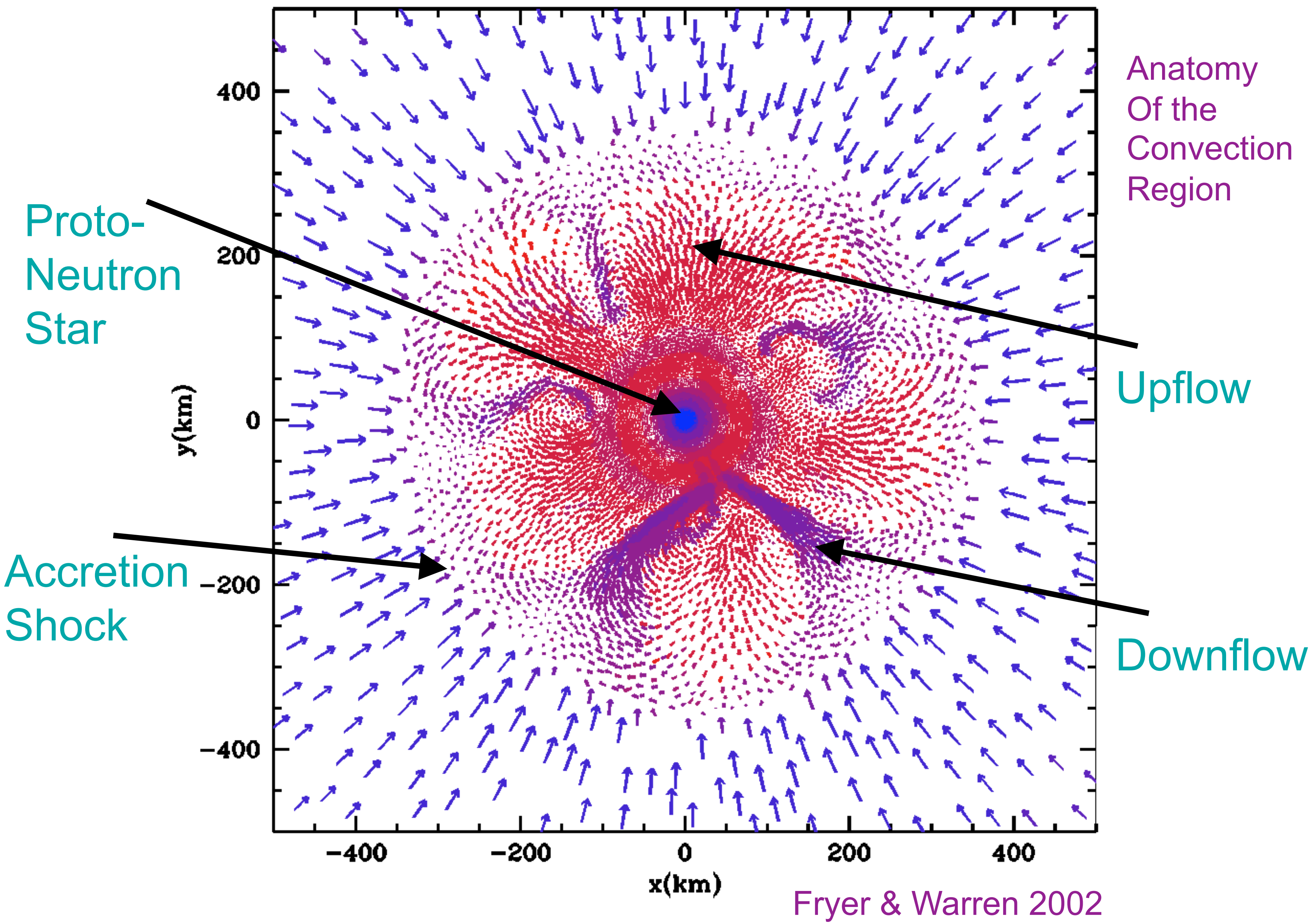
Nuclear forces and neutron degeneracy increase pressure

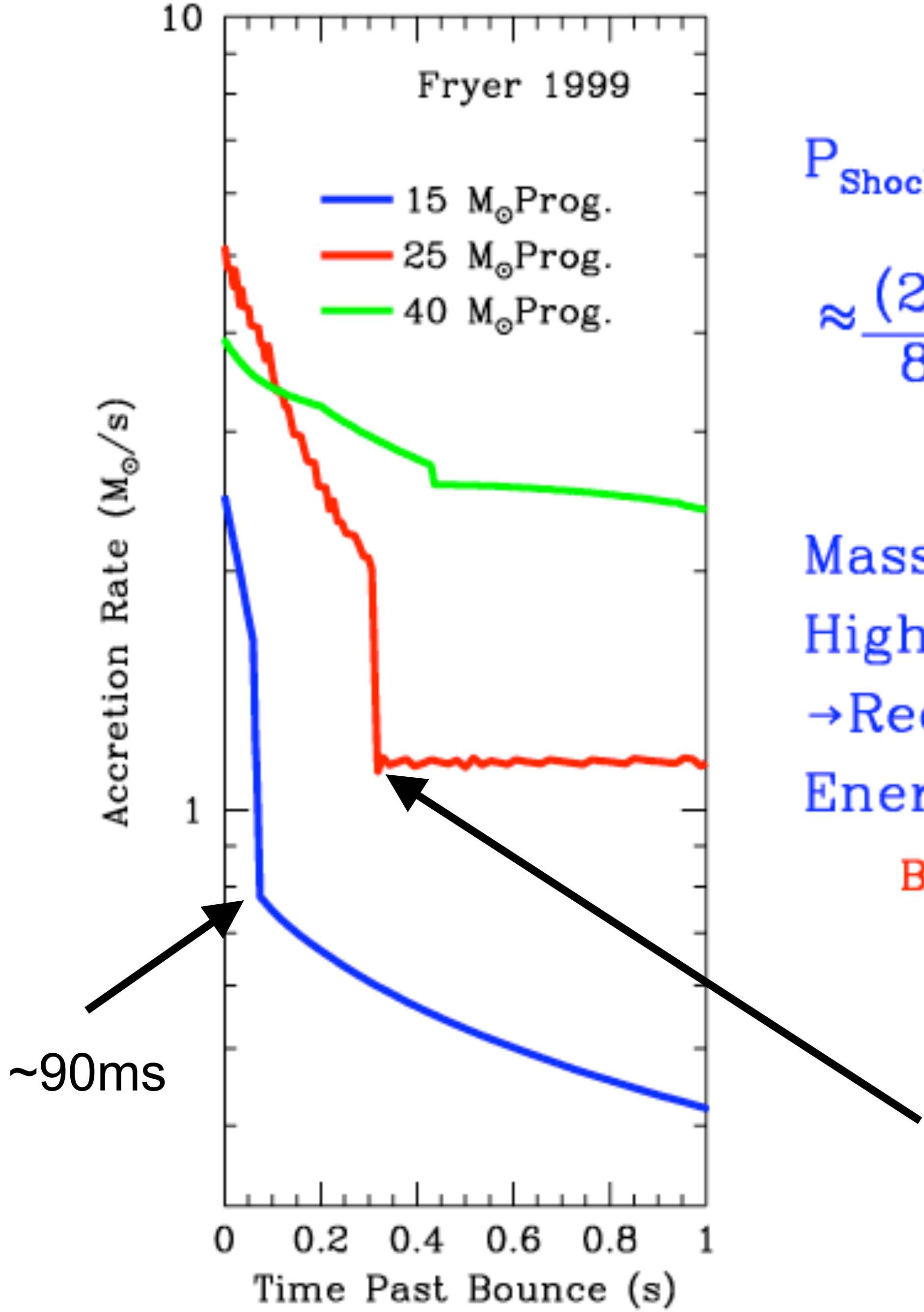
Bounce!

Neutrino-Driven Supernova Mechanism: Convection



Fryer 1999


Anatomy
Of the
Convection
Region
Proto-
Neutron
Star
Upflow
Accretion
Shock
Downflow
400
200
0
−200
−400
y(km)
−400
−200
0
200
400
x(km)
Fryer & Warren 2002



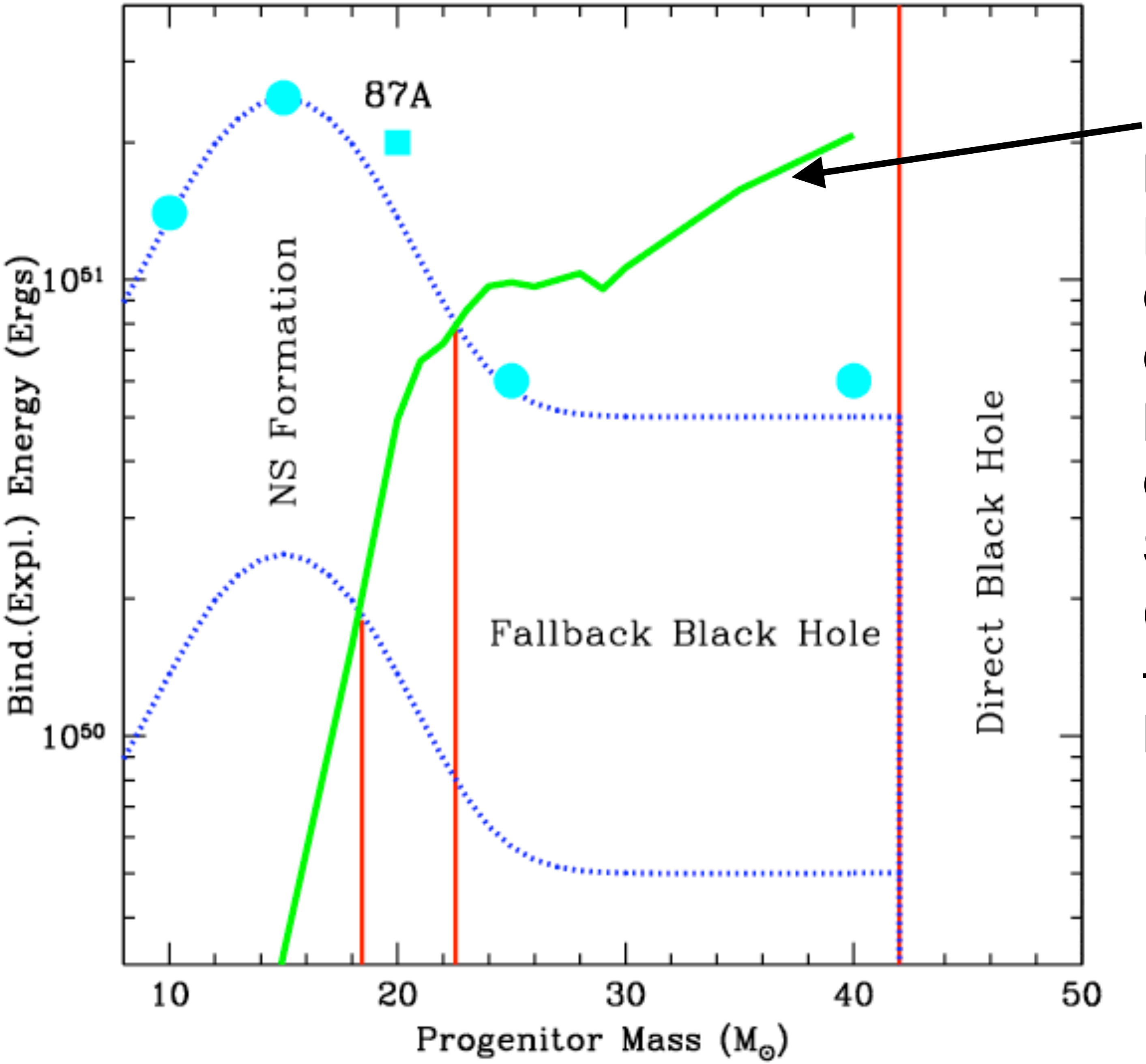
$$P_{Shock} \approx \frac{1}{2}\rho v_{ff}^2$$

$$\approx \frac{(2GM_{encl})^{1/2}}{8\pi R_S^{2.5}}\dot{M}_S$$

Massive Stars Have
Higher Infall Rates
→Requires More
Energy To Explode

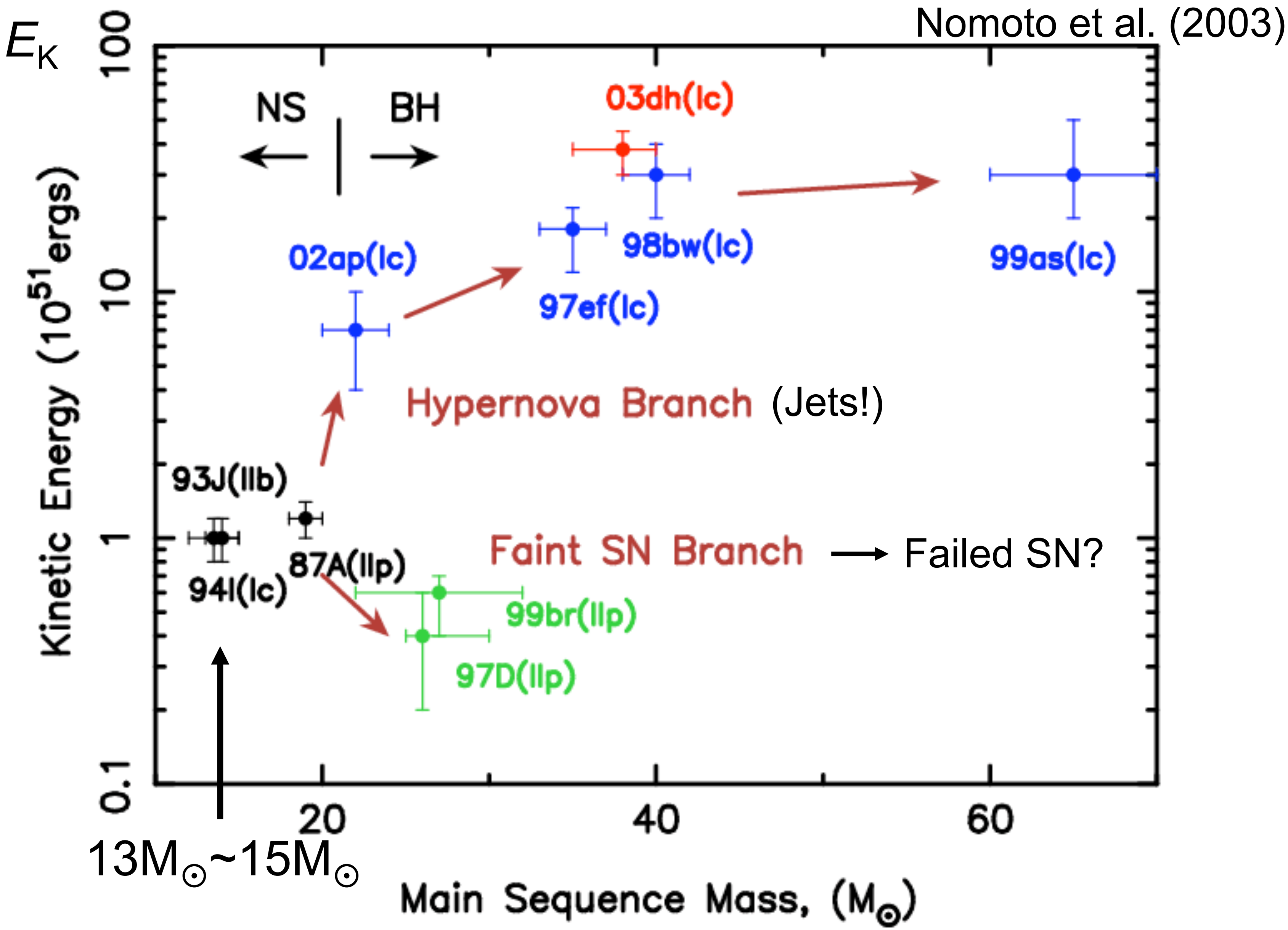
Burrows & Goshy 1993

Fryer 1999

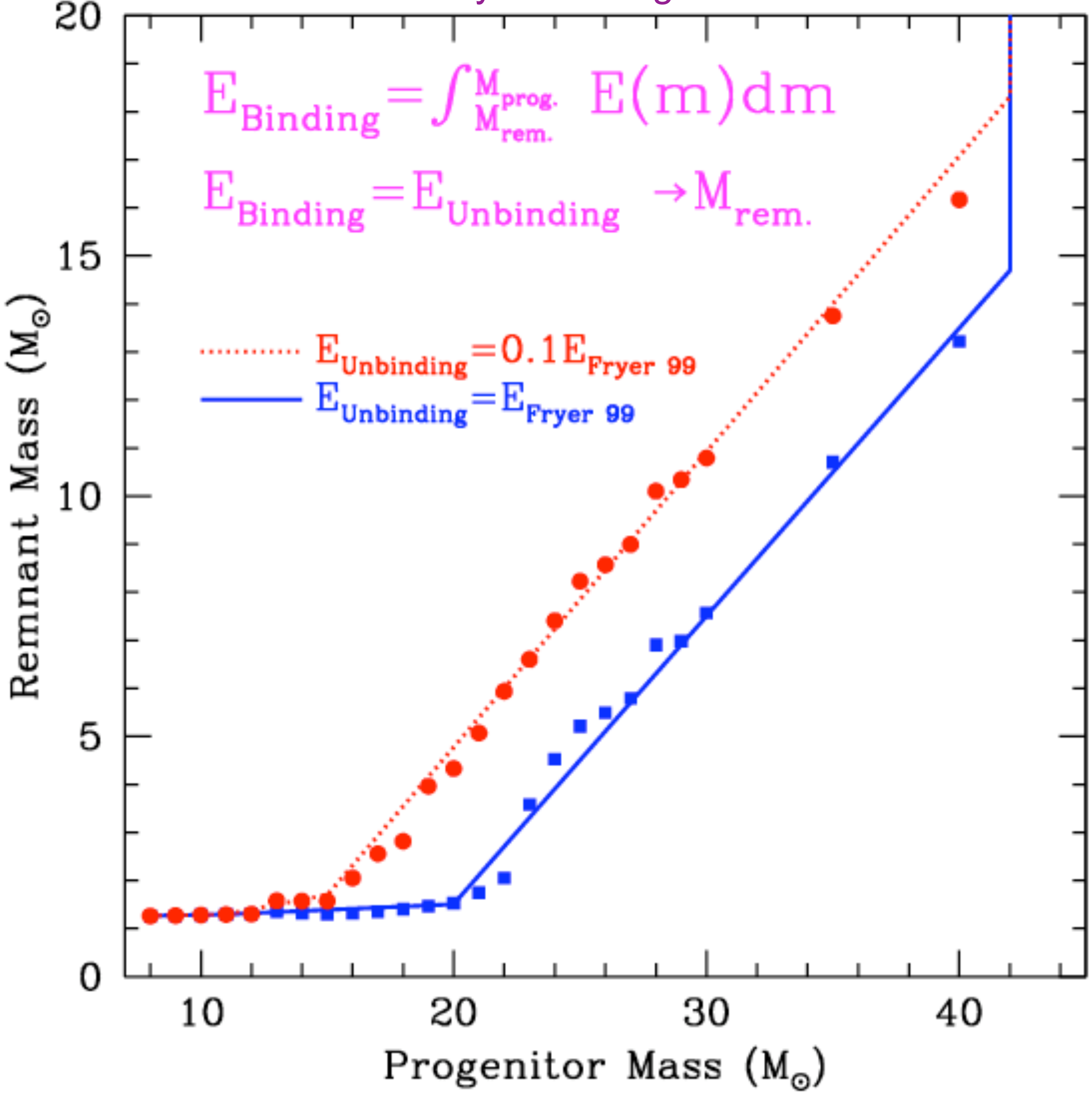


Binding Energy Of the Outer Layers Of the Star (M_{star} -3 solar Masses)

Supernovae/Hypernovae

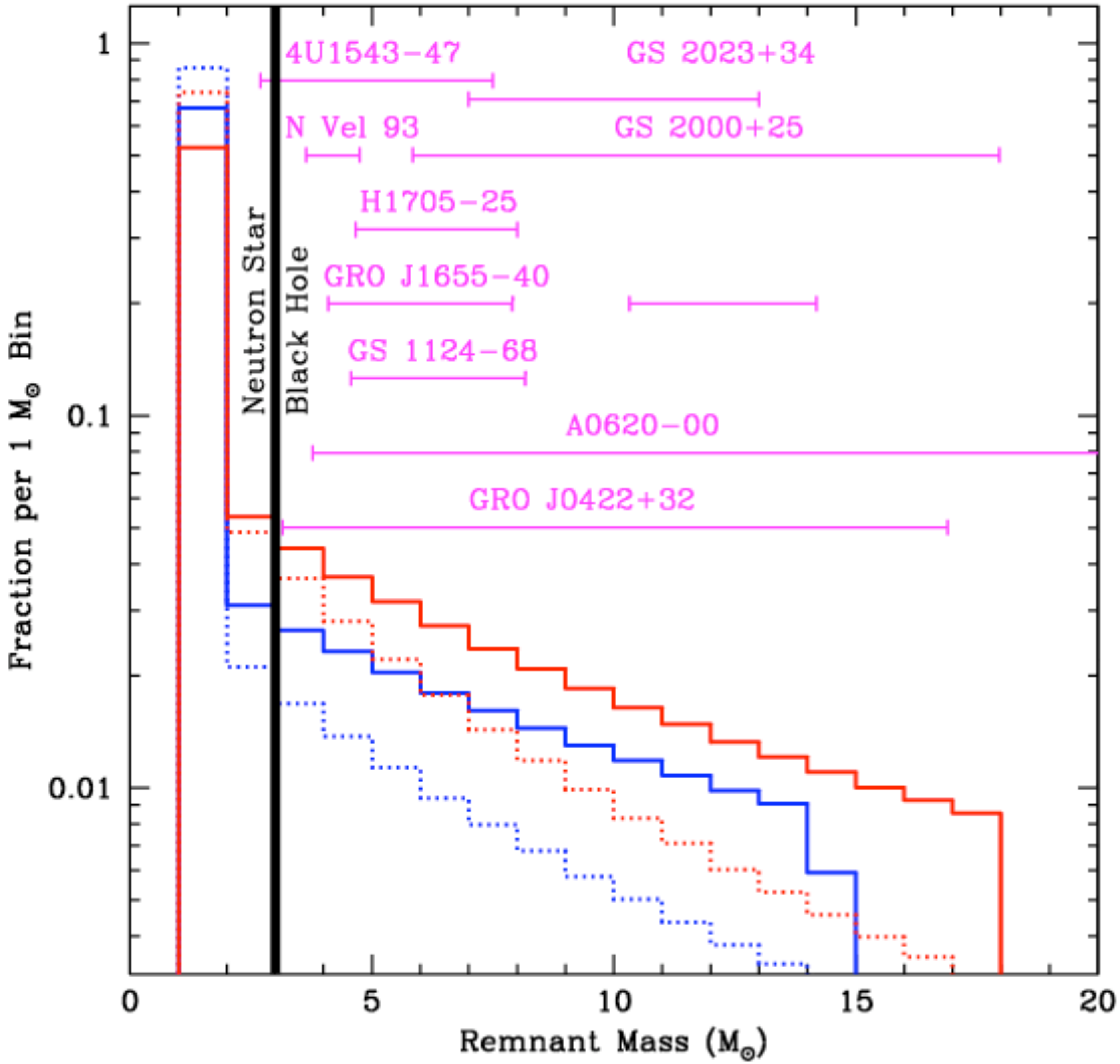


Fryer & Kalogera 2000



Assuming The Explosion Energy Effects Matter With a 10,100% Efficiency, We can Estimate The Remnant Mass

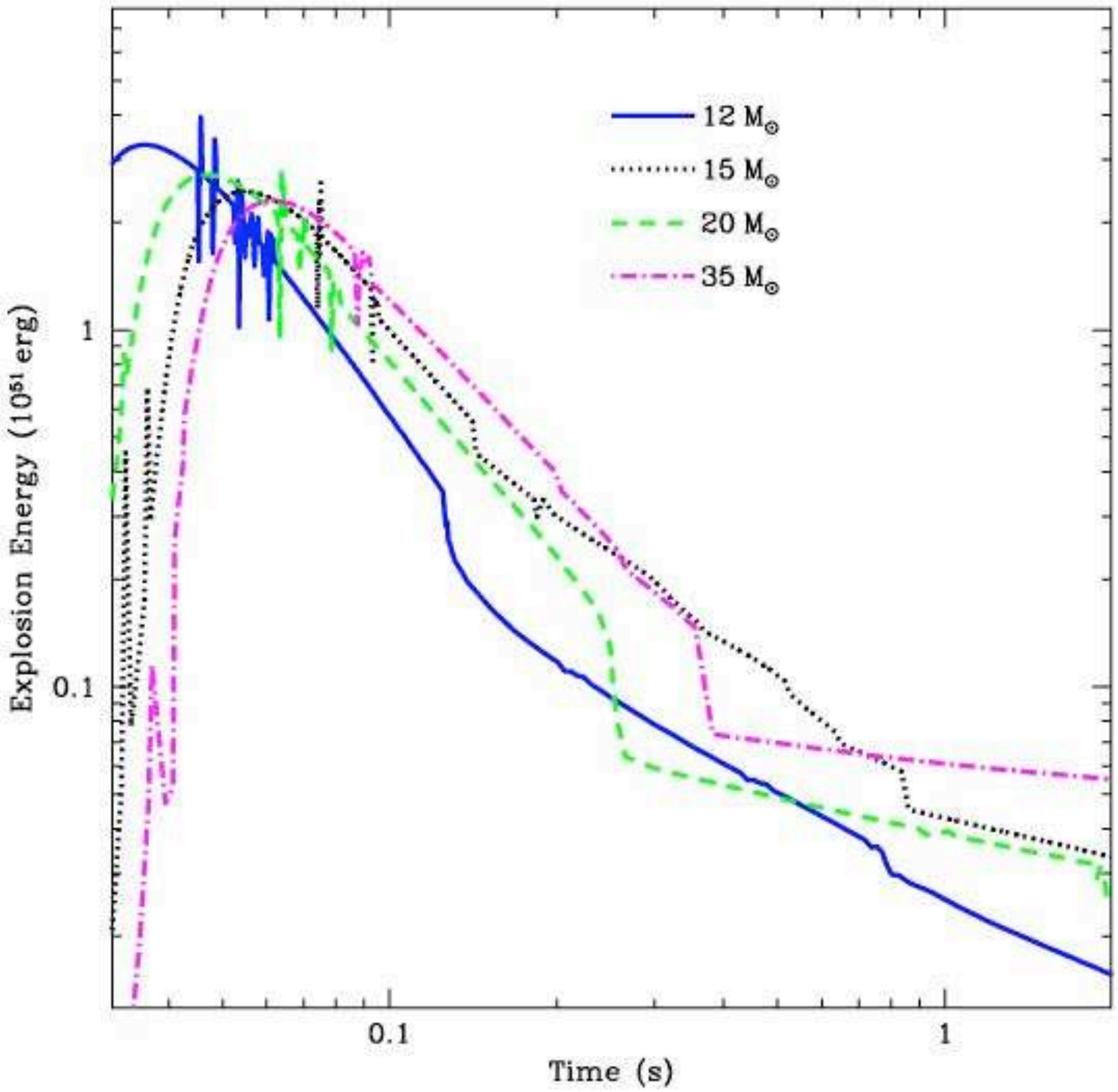
Fryer & Kalogera 2000



Remnant Mass Distribution

(Using An initial Mass Function)

The convective engine mechanism may not be able to explain high-energy explosions. Although the collapse releases 10^{53} ergs of energy, the convective region can only store a few times 10^{51} ergs.

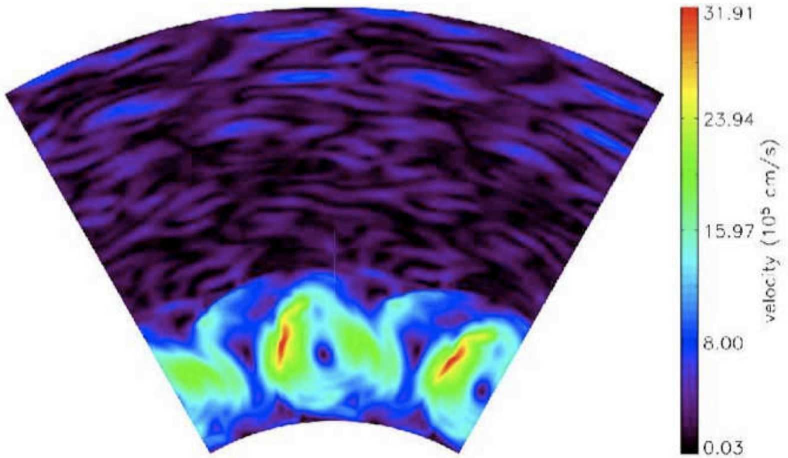


Mechanisms for Asymmetries

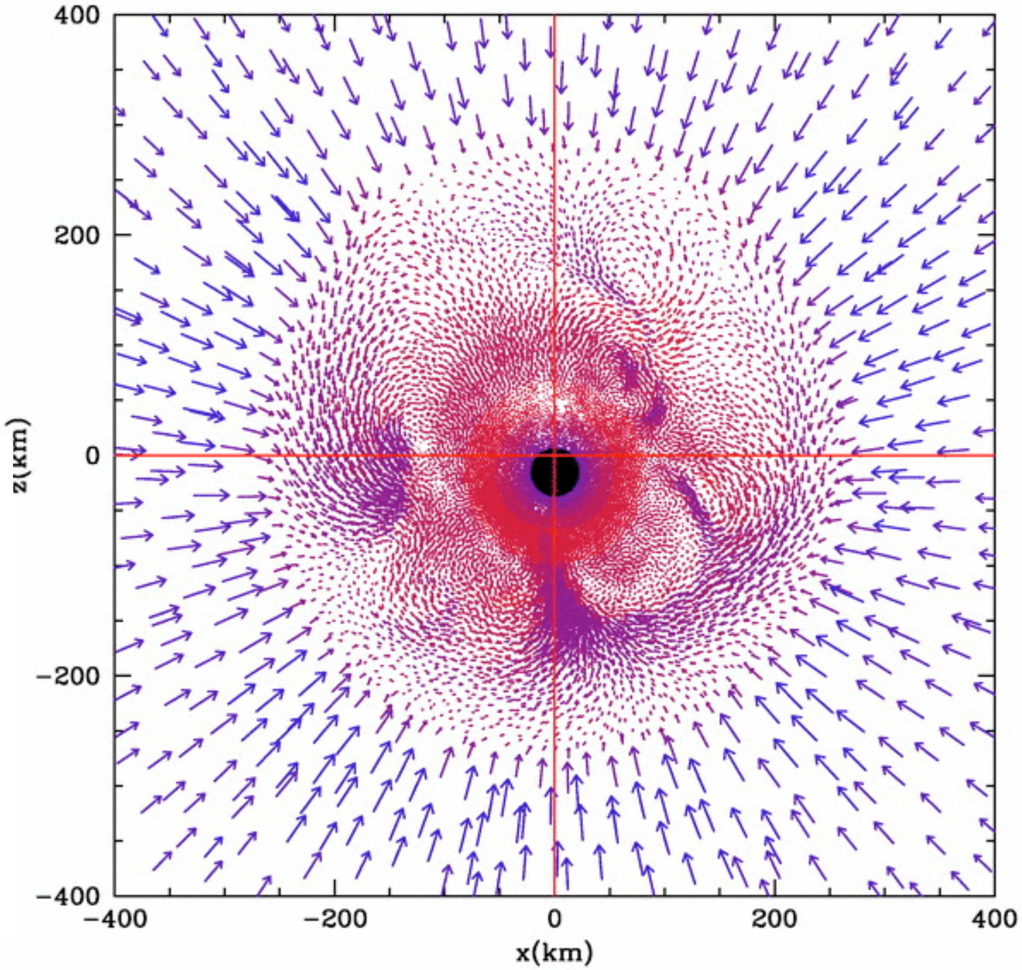
- Asymmetries in Collapse
- Matter Asymmetries in the Convective Engine
- Asymmetries in the Neutrino Emission

Asymmetries in the Collapse may cause kicks

Large-scale mixing in the Oxygen/Silicon burning can cause asymmetries that can be magnified in the collapse and cause kicks.



Meakin & Arnett 2007

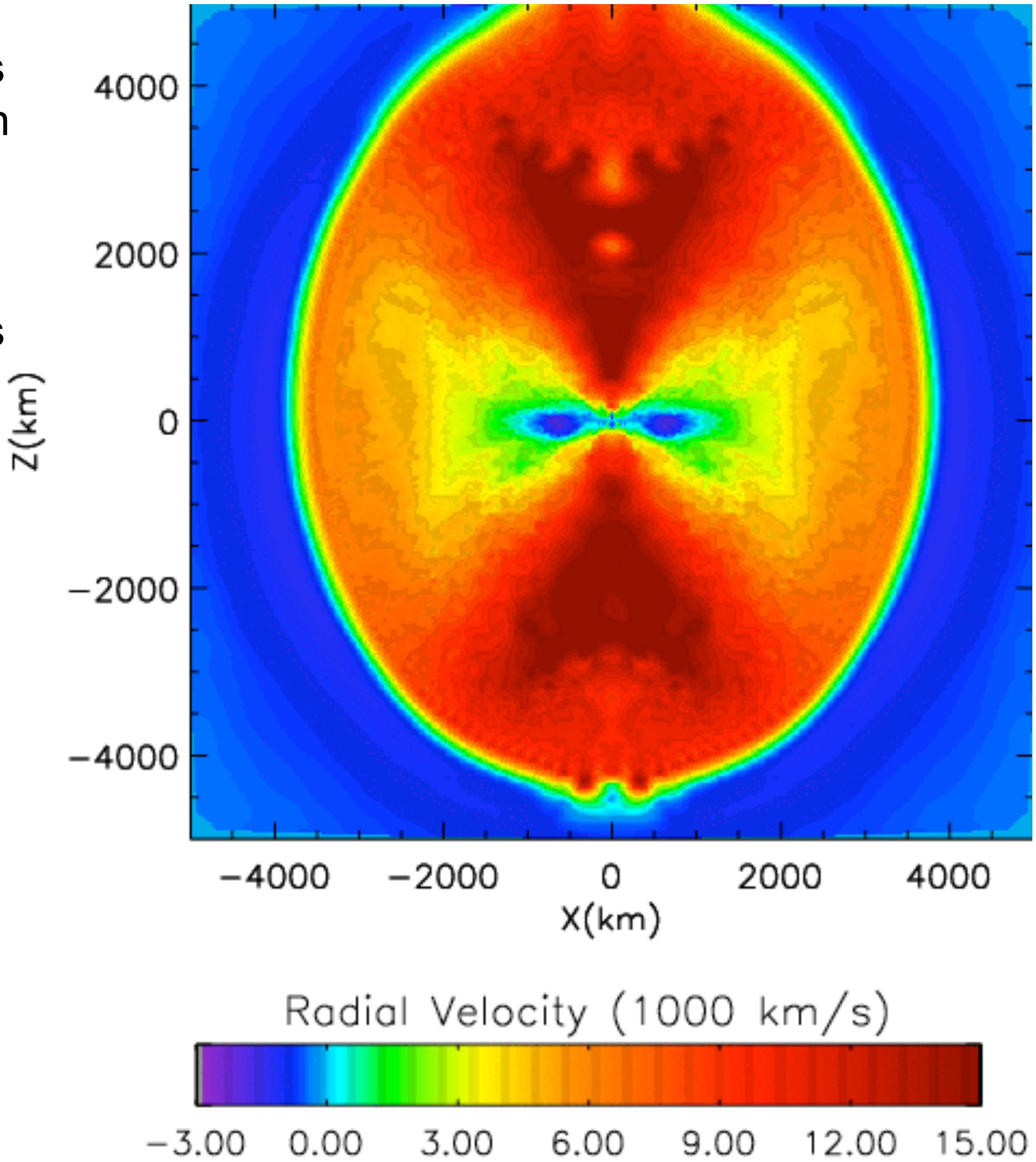


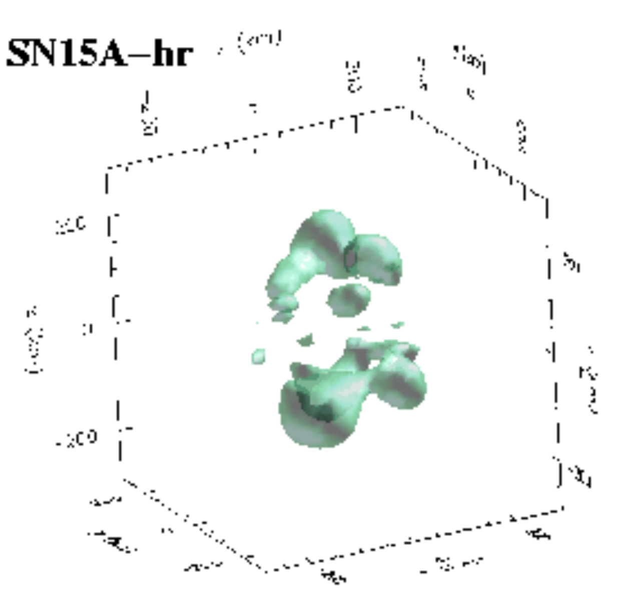
Fryer 2004

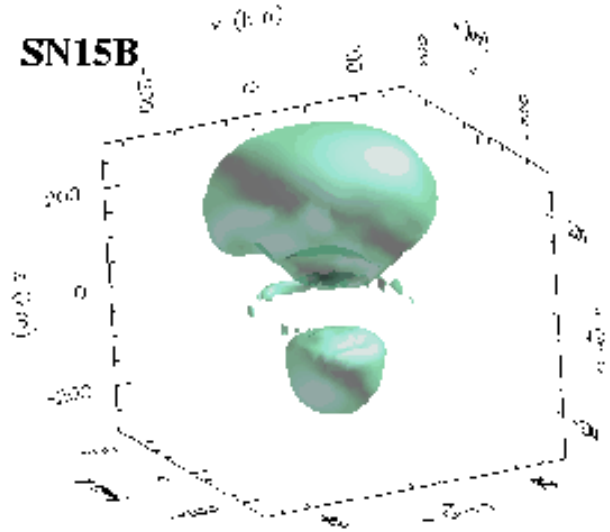
Asymmetries from Rotation

Asymmetries
In convection
And neutrino
Heating
Cause
Asymmetries
In the
Supernova
Explosion!

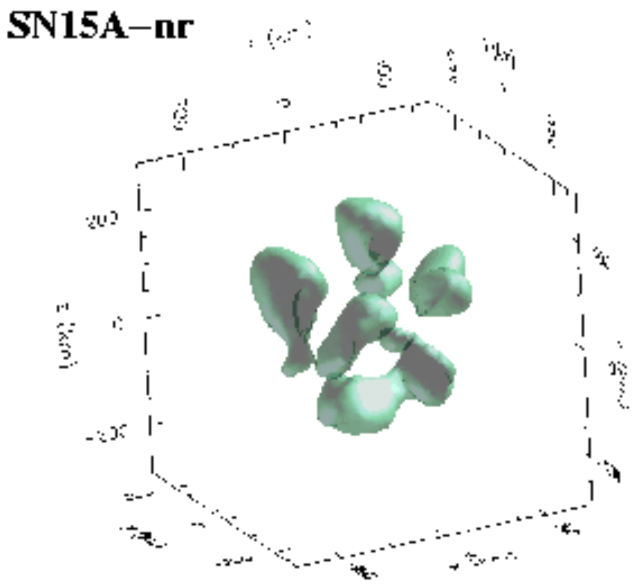
Explosion
Velocities
Can be
Twice as
Strong along
The rotation
Equator than
Along the
Pole!

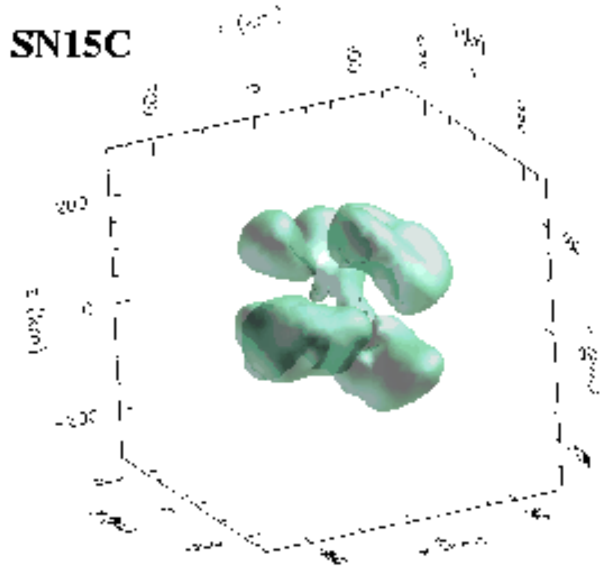






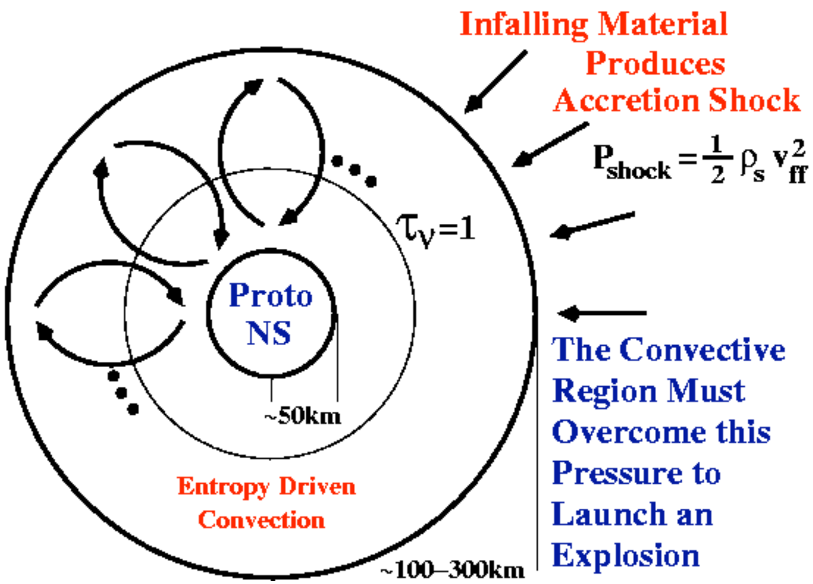
Rotational Asymmetries in 3D



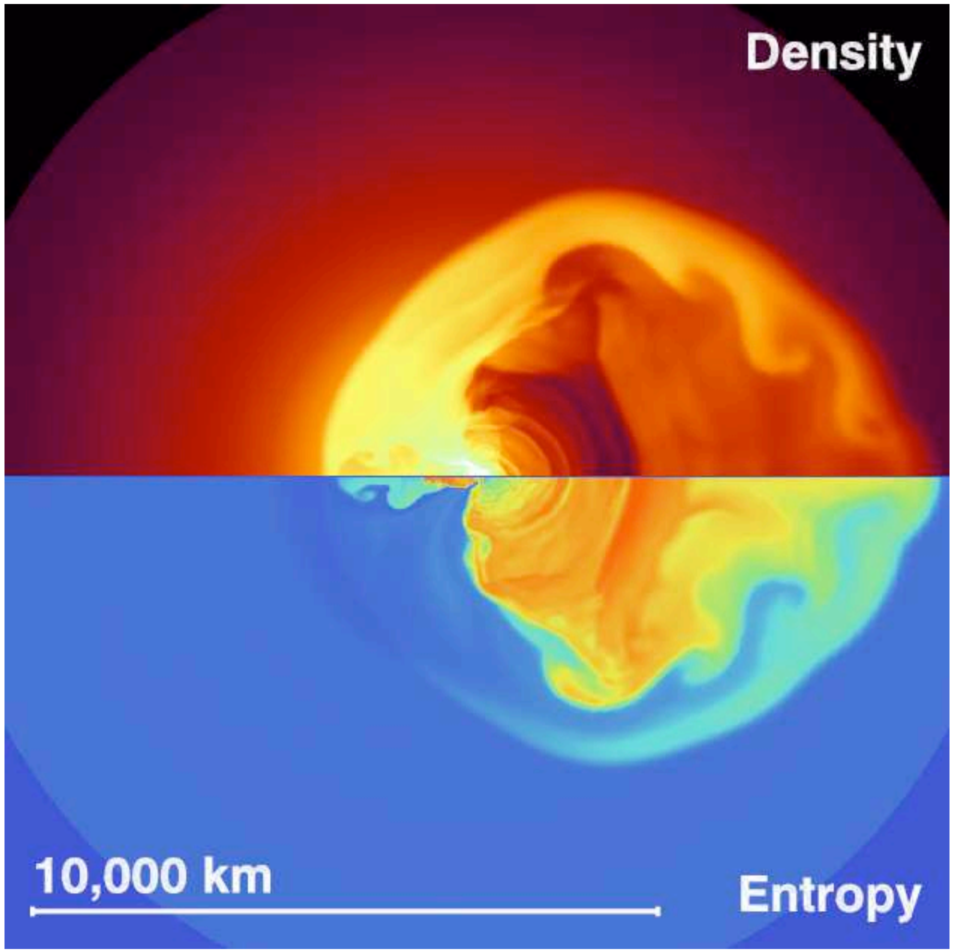


Asymmetries from Single-Lobe Convection

- Convection Drives explosion.
- The convective cells merge with time.
- With sufficient time, Low-Mode convection develops.
- Neutron Star Kicks for Slow Explosions

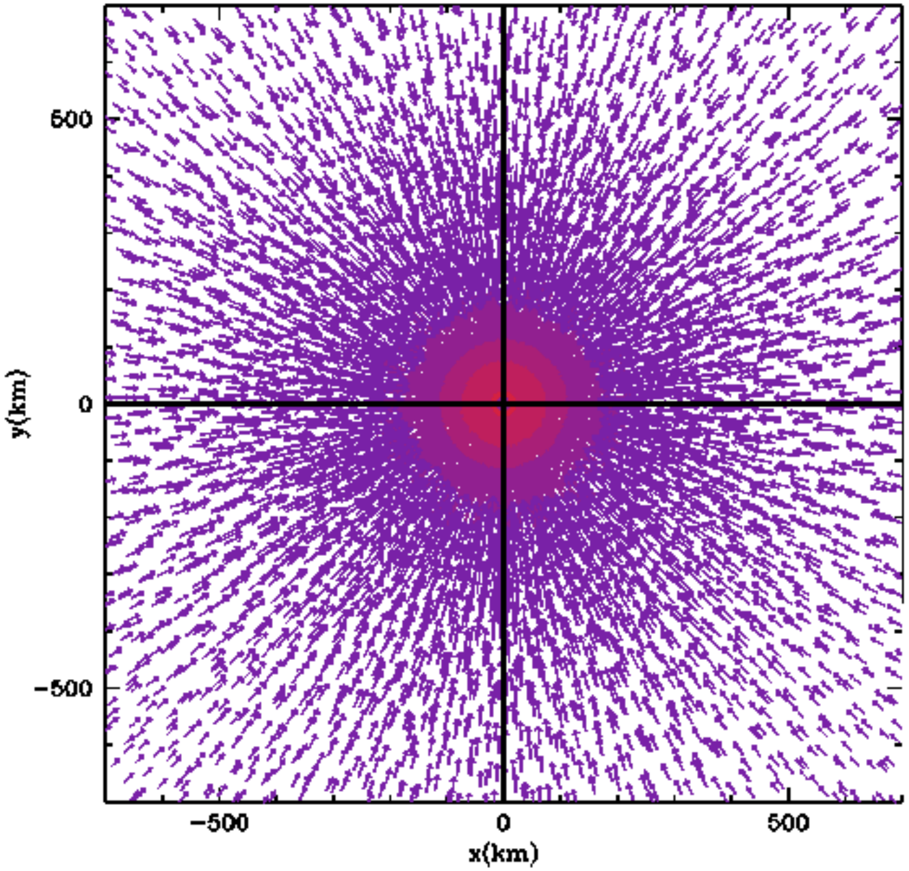


Scheck et al. 2003



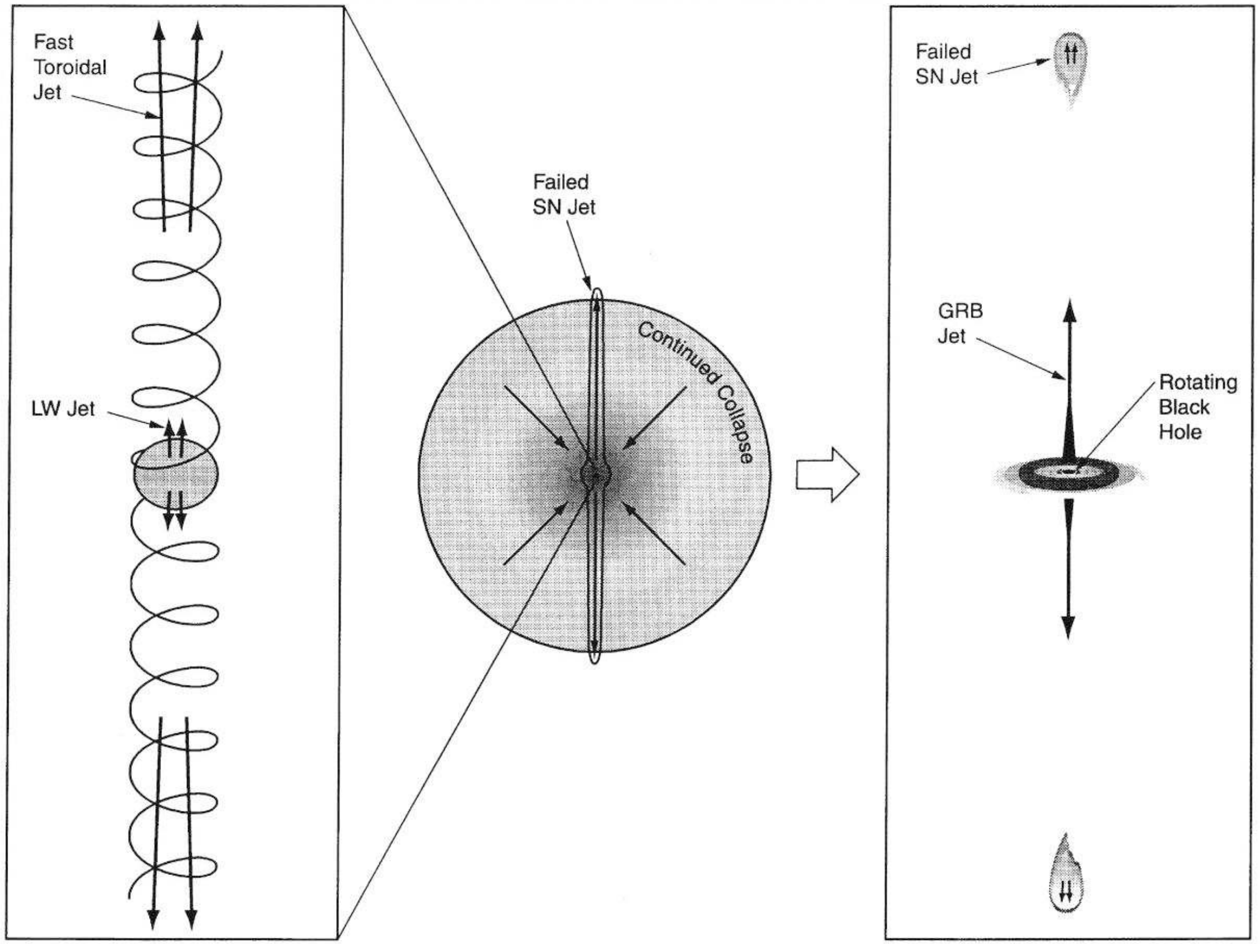
In 3-dimensions, the asymmetry is not quite as big.

These instabilities are evident in 3-dimensions, but the kick and the explosion asymmetry is not so dramatic (Fryer & Young 2007).



Magnetic Fields Can Also Produce Asymmetries if they drive the explosion

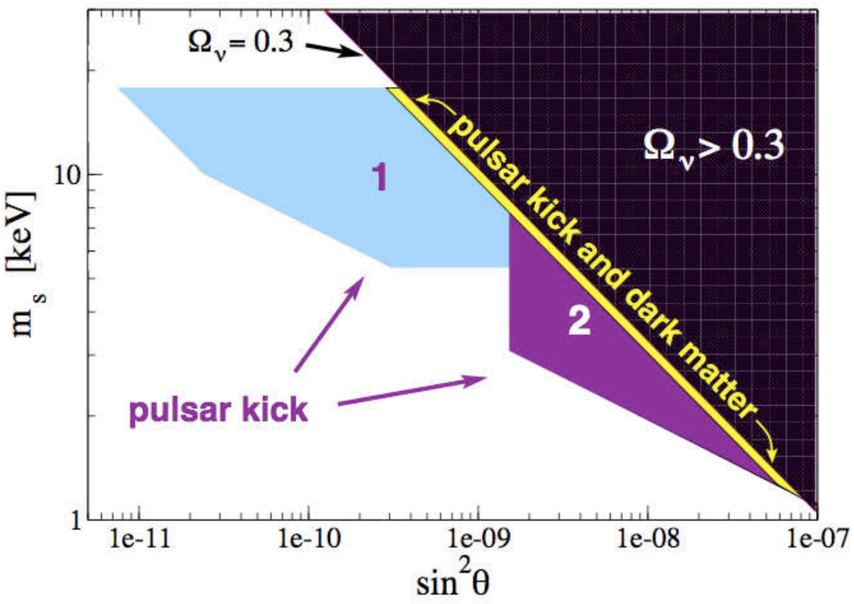
I would argue that this mechanism is more important for broad-lined supernovae and hypernovae, not normal supernovae



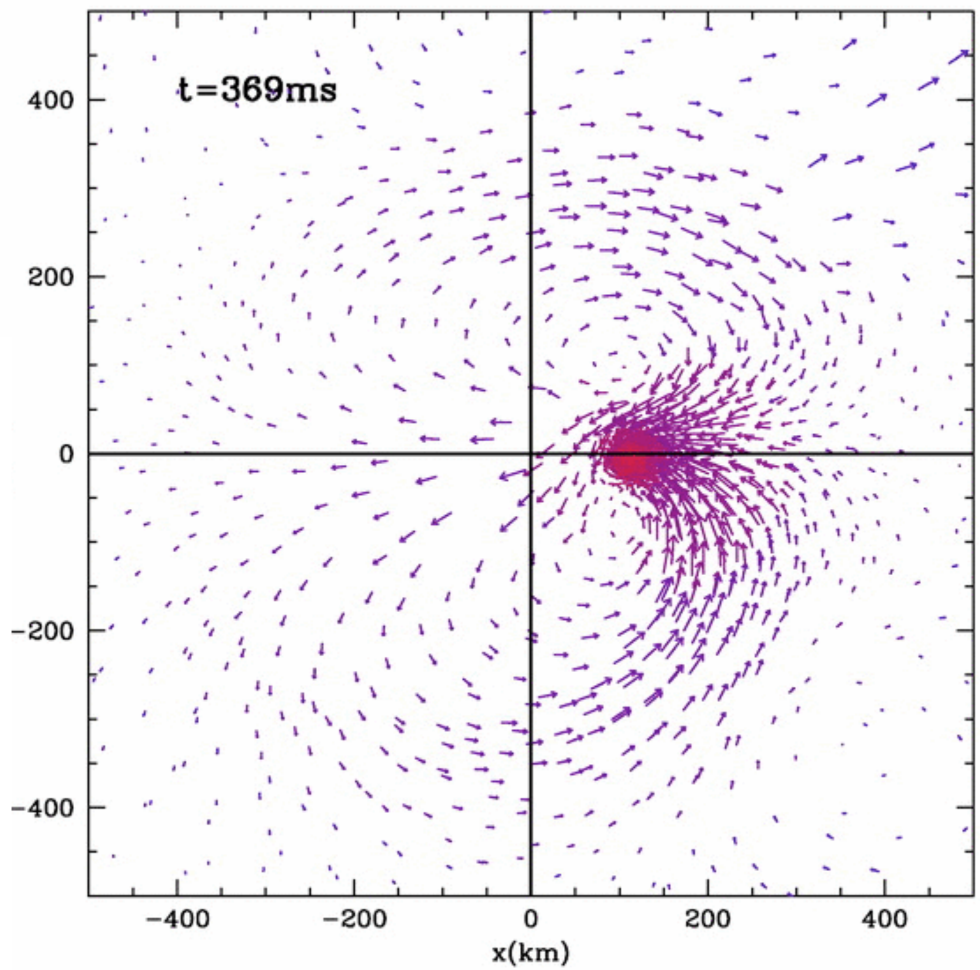
Wheeler et al. 2002

Asymmetries from Anisotropic Neutrino Emission

Neutrino oscillation to sterile neutrinos in a highly magnetized core can produce kicks.

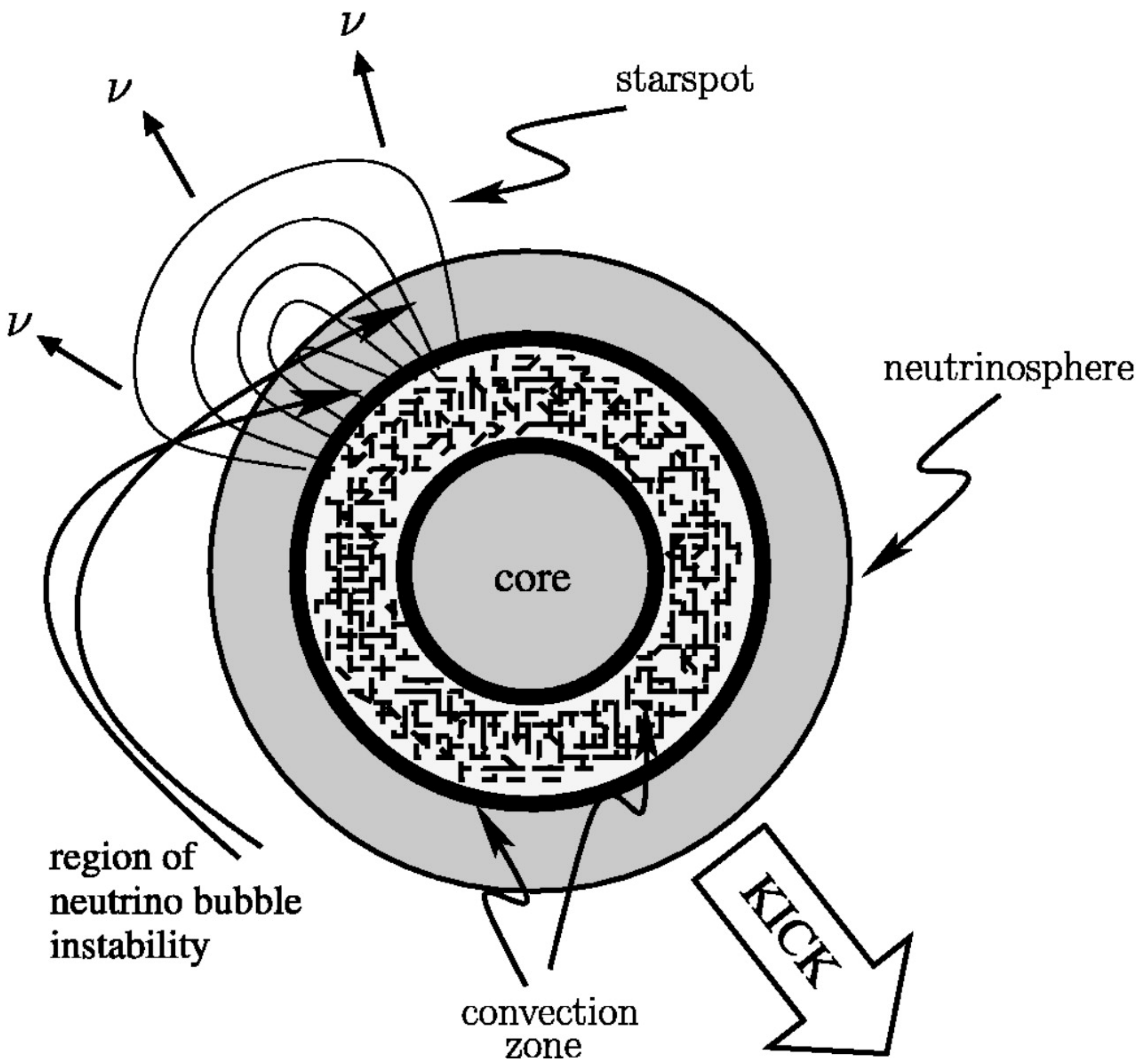


Fuller et al. 2003



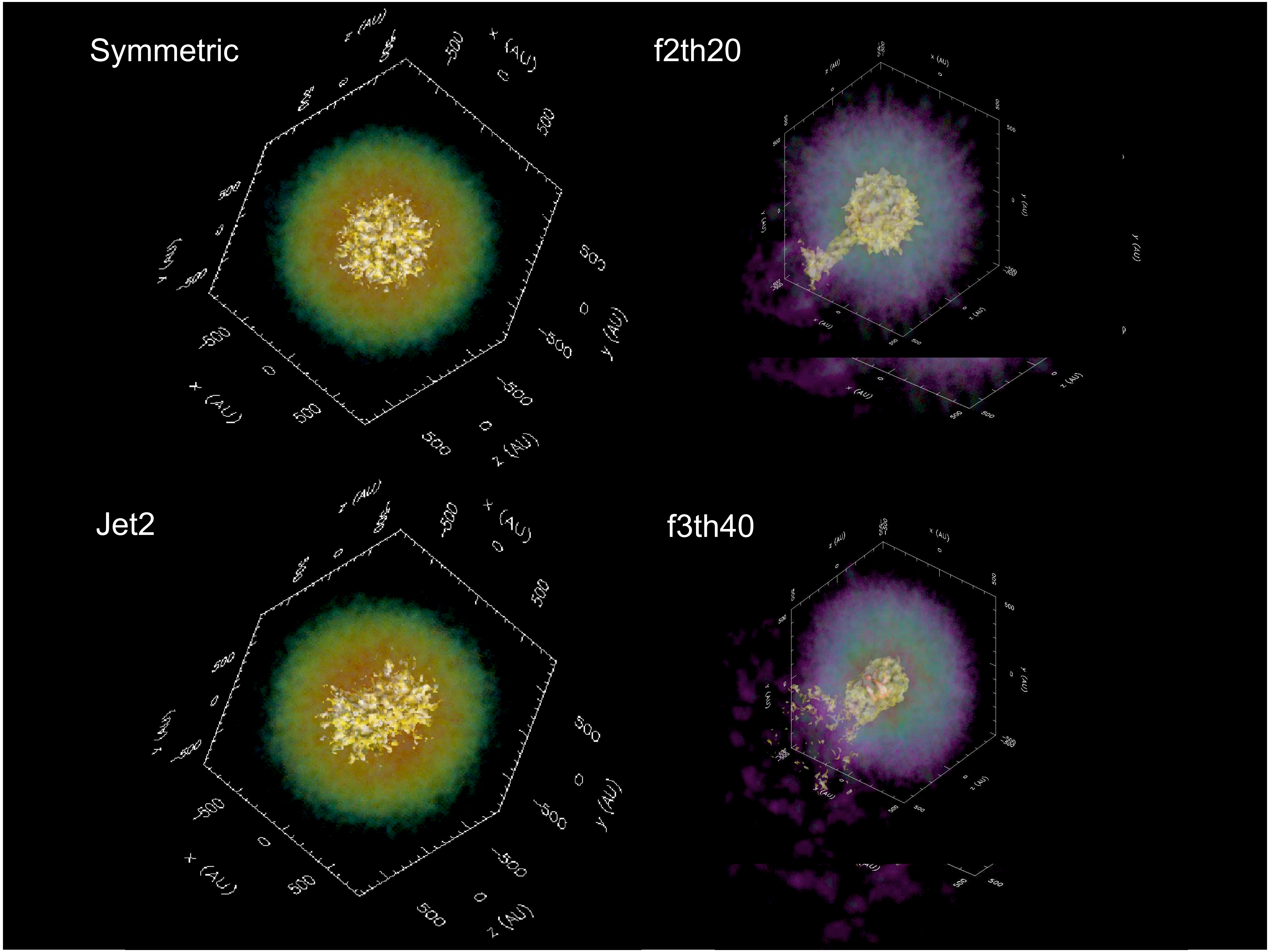
Fryer & Kusenko 2006

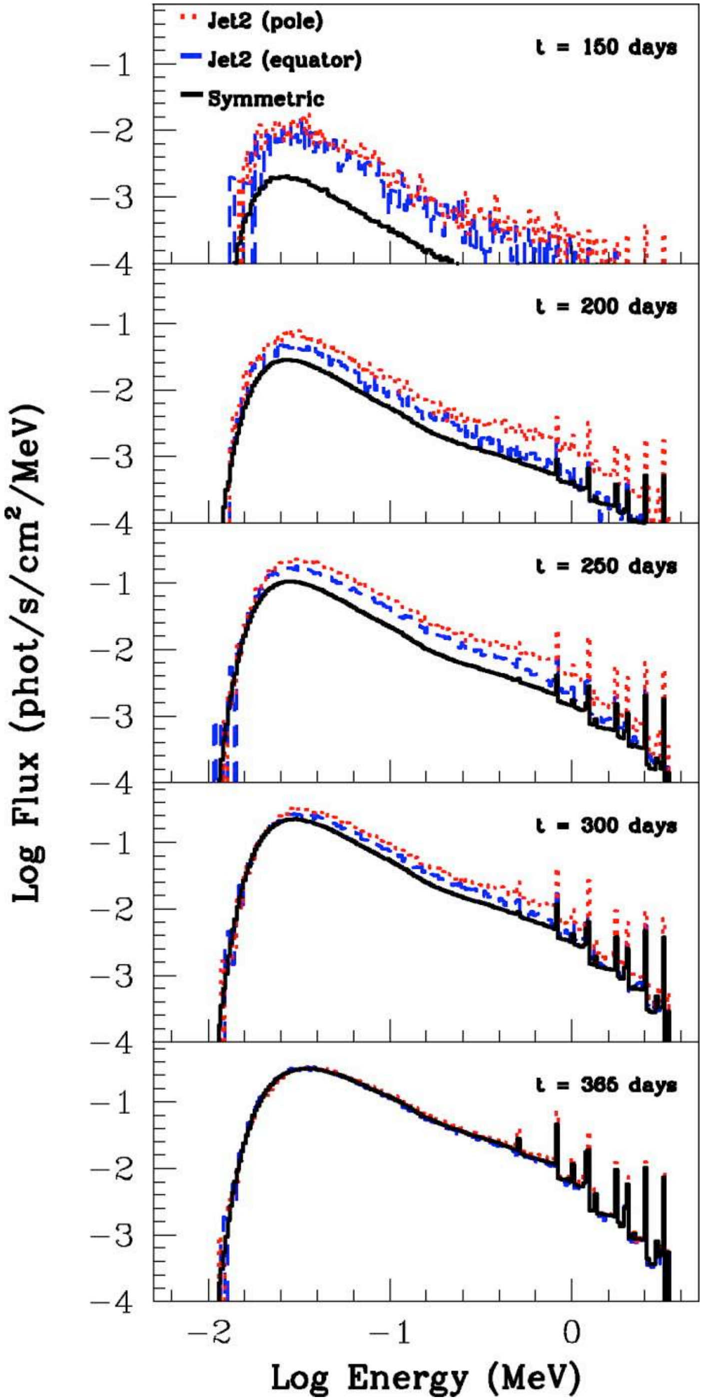
Magnetic fields near the neutrinosphere can also produce asymmetric neutrino emission, producing neutron star kicks (not necessarily aligned with the explosion ejecta).



Observational Tests

- Pulsar Velocities (Asymmetric Collapse & Mode Merger)
- Explosive Asymmetries and Gamma-Ray Emission
- Gravitational Waves and Neutrinos
- Nucleosynthesis
- Light Curves and Spectra


Symmetric
f2th20
Jet2
f3th40
x (AU)
y (AU)
z (AU)
500
0
-500



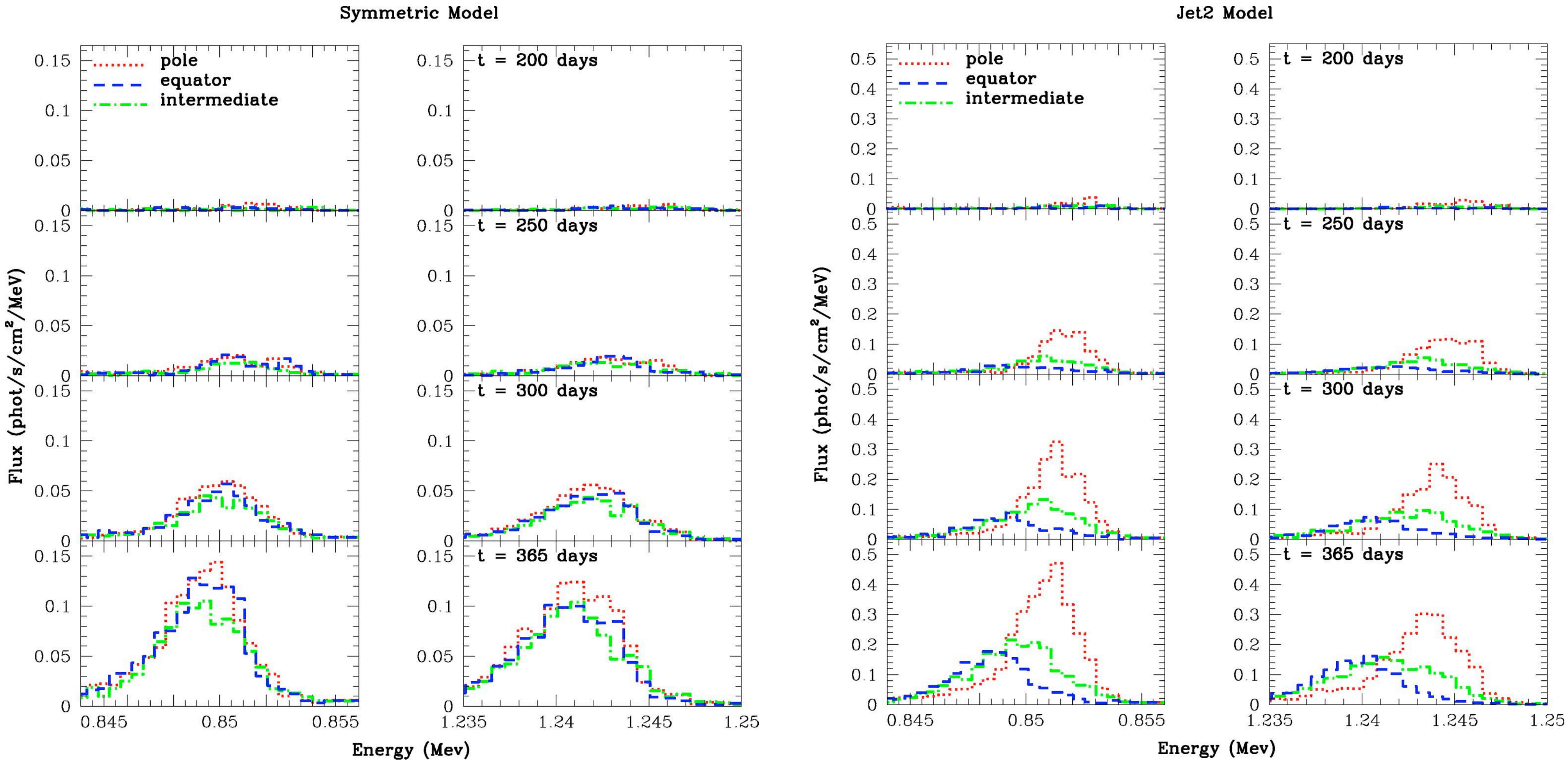
Bipolar Explosion

Hard X-ray continuum
Is brighter at early times for the asymmetric explosion regardless of viewing angle

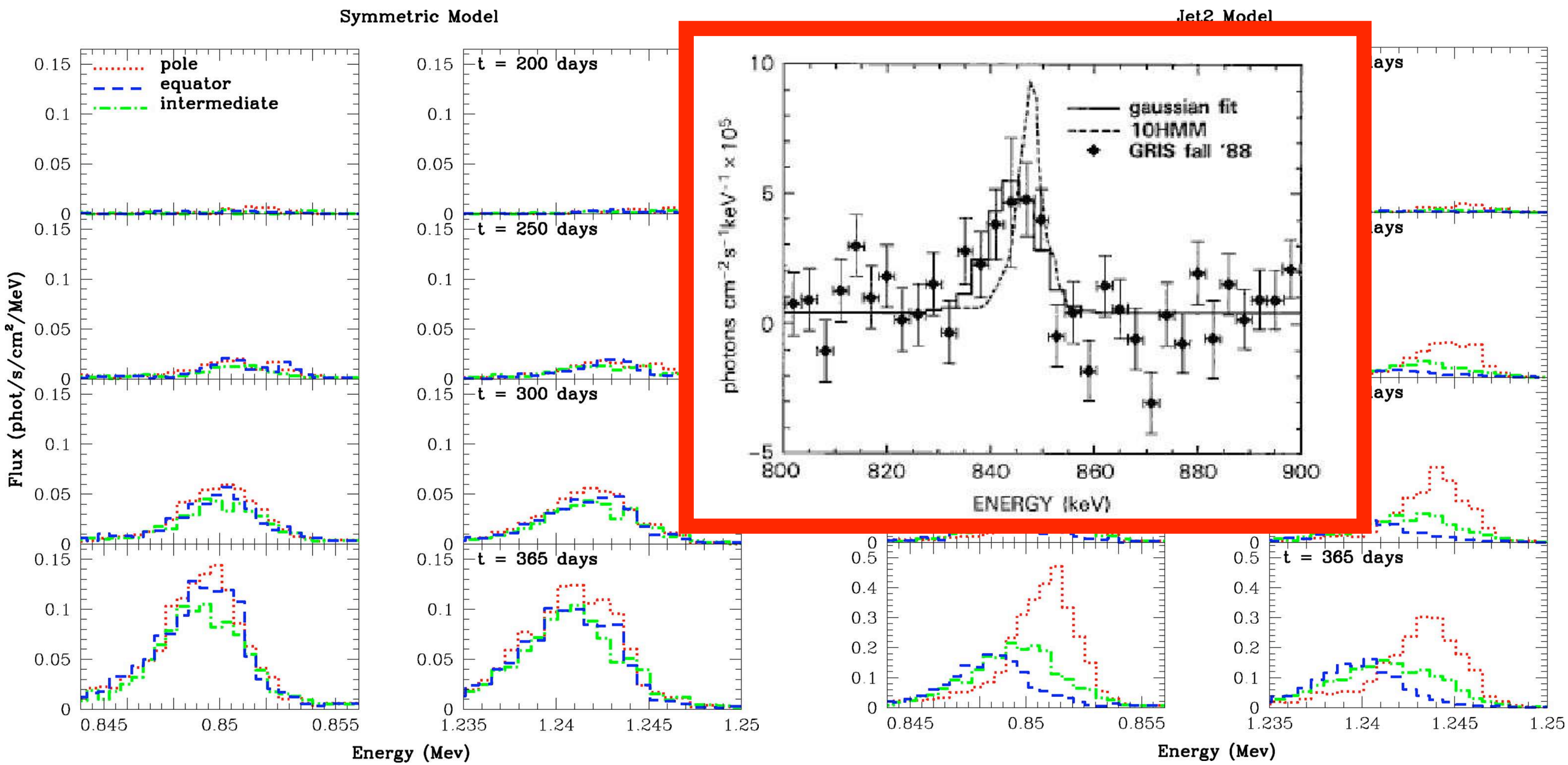
Global asymmetry does result in earlier emergence of Hard X- & gamma-rays

Level of hard X-ray continuum is roughly same for equator and pole views

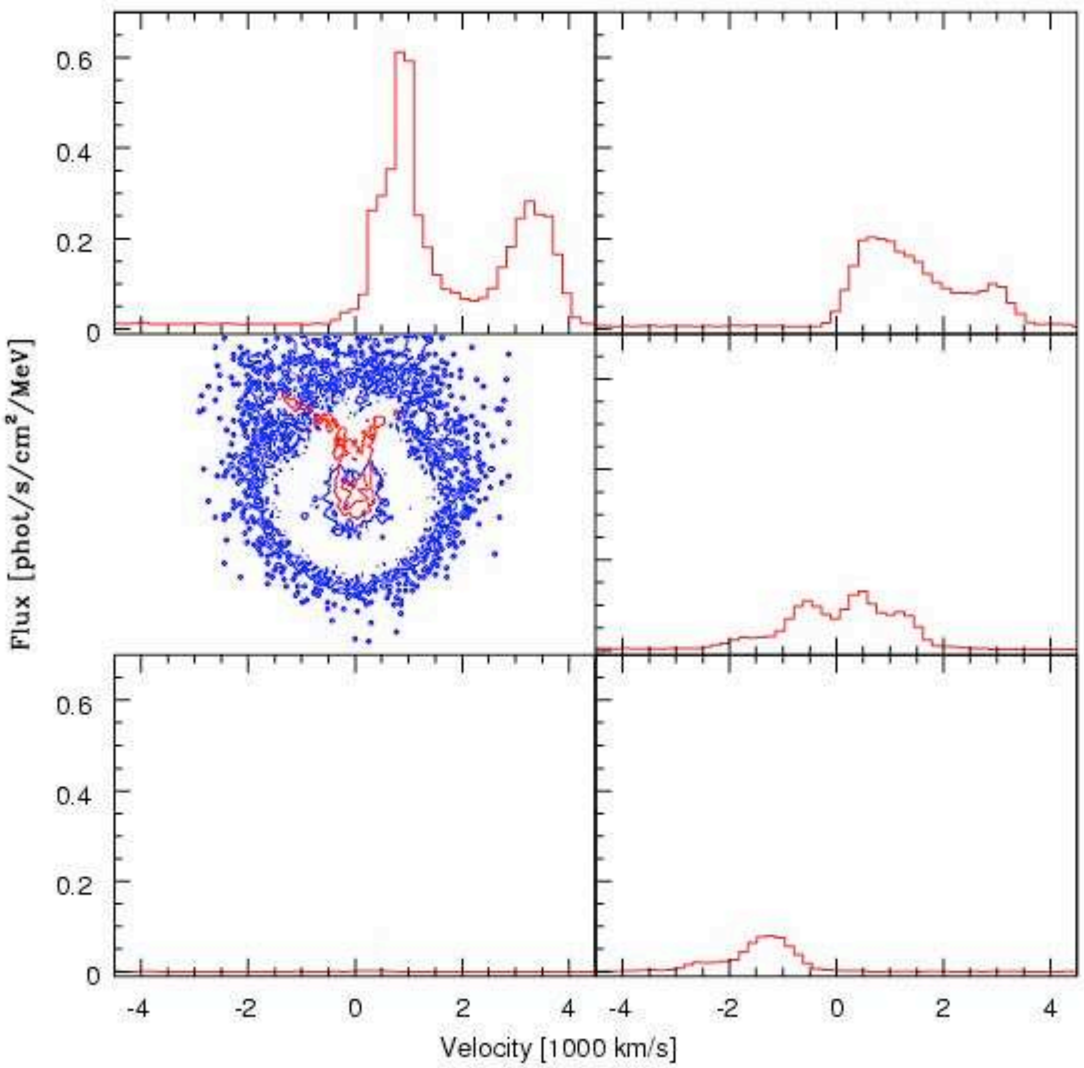
Line profiles of Co-56 decay emission differ with viewing angle for the Jet2 explosion. We see blueshifts due to opacity effects.



Line profiles of Co-56 decay emission differ with viewing angle for the Jet2 explosion. We see blueshifts due to opacity effects.



Single Lobe Explosions



Depending upon the Line-of-site, single-Lobe explosions can Produce red-shifted Gamma-ray emission.

The line profile will Change with time. Observations of the Temporal evolution Critical!

Hungerford et al. 2004

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Nucleosynthetic Dependence on Asymmetries

- Yields vary with explosion energy
- Mixing Allows material that would otherwise fall back to be ejected!

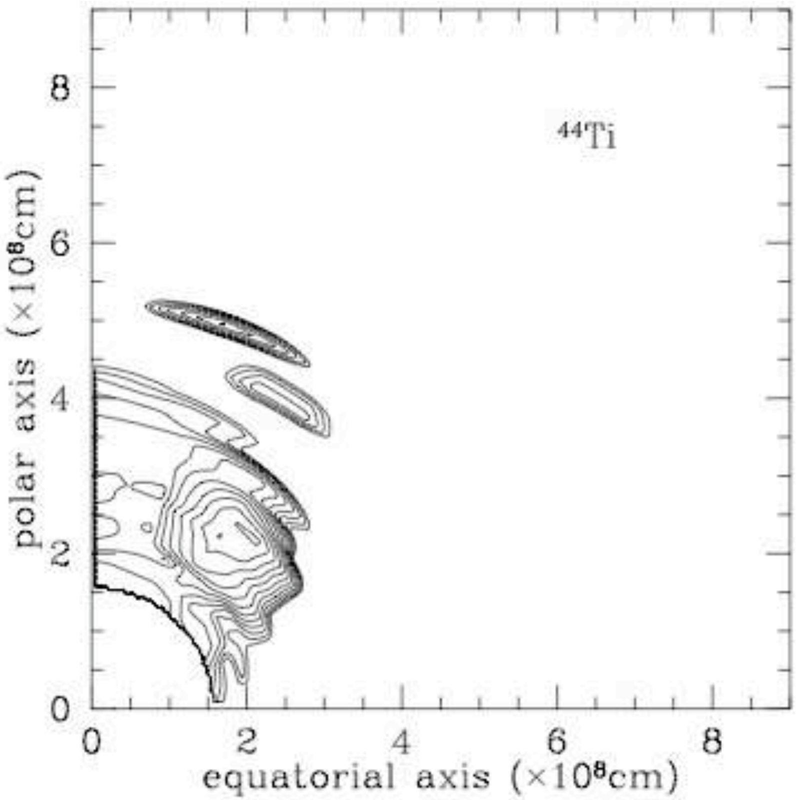
Table 1
^{44}Ti and ^{56}Ni Yields for a Range of 1-dimensional Supernovae

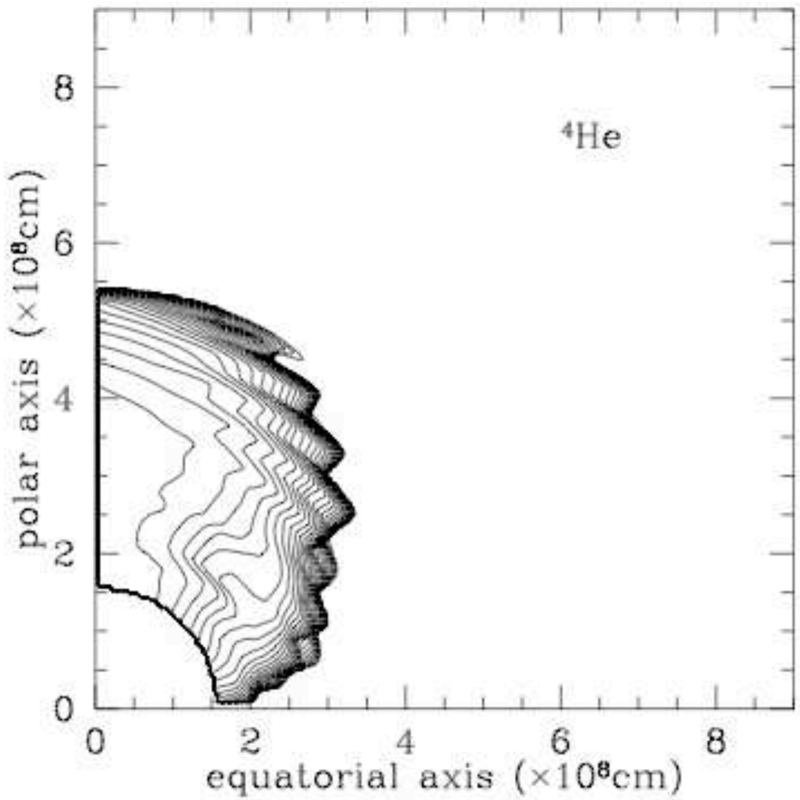
Explosion Energy (10^{51} erg)	$^{44}Ti^a$ $M_\odot$	$^{56}Ni^a$ $M_\odot$	$^{44}Ti^b$ $M_\odot$	$^{56}Ni^b$ $M_\odot$
0.1^c	4.2×10^{-5}	0.082	4.7×10^{-5}	0.059
1.35	5.3×10^{-5}	0.41	7.4×10^{-5}	0.28
1.8	3.5×10^{-6}	0.42	2.3×10^{-6}	0.30
6.5	1.6×10^{-6}	0.40	3.0×10^{-6}	0.63
0.1^d	3.4×10^{-5}	0.083	4.7×10^{-5}	0.060
1.35	1.6×10^{-5}	0.43	7.4×10^{-5}	0.30
1.8	1.7×10^{-6}	0.44	2.3×10^{-6}	0.32
6.5	6.8×10^{-7}	0.41	1.7×10^{-6}	0.29

[a] $Y_e = 0.50$
[b] $Y_e = 0.495$
[c] Weak and (p,n) Reactions On
[d] Weak and (p,n) Reactions Off

Asymmetries produce Asymmetric Yield Distributions (and alter the total yields)

Lots of ground-breaking work by Nagataki, Maeda, Tominga, …

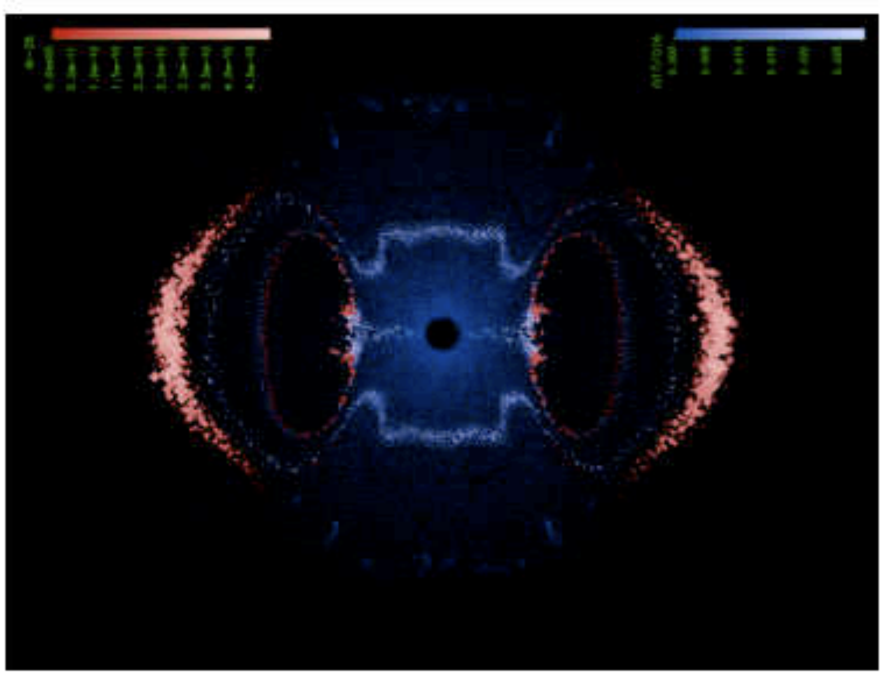


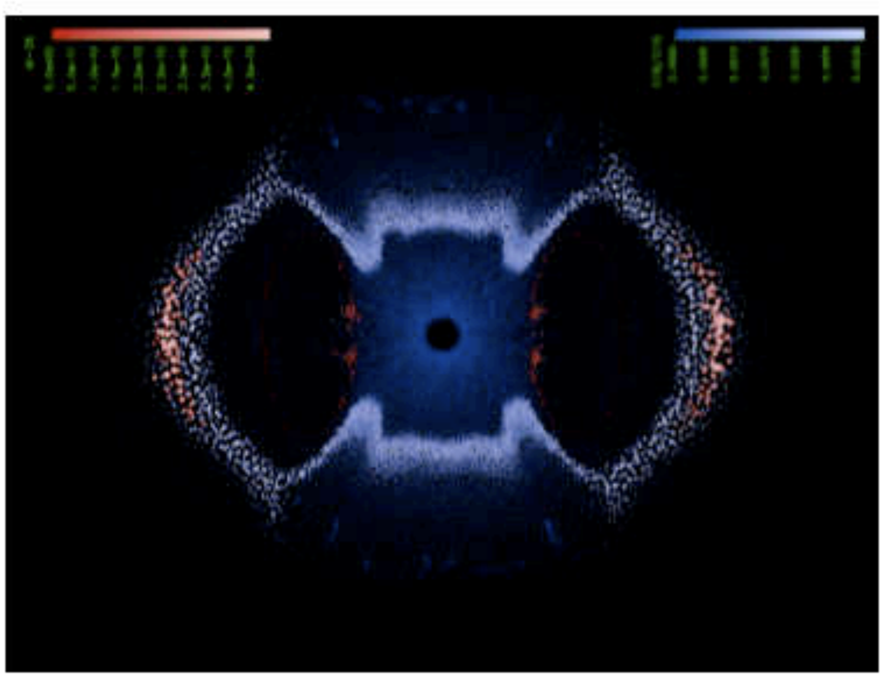


Nagataki et al. 2003

Carola, Young et al. 2008 found that asymmetries help to explain the Al and O distributions in the Cas A SNR. They may also explain the ratios of Oxygen isotopes!

We must understand asymmetries to study nuclear rates!





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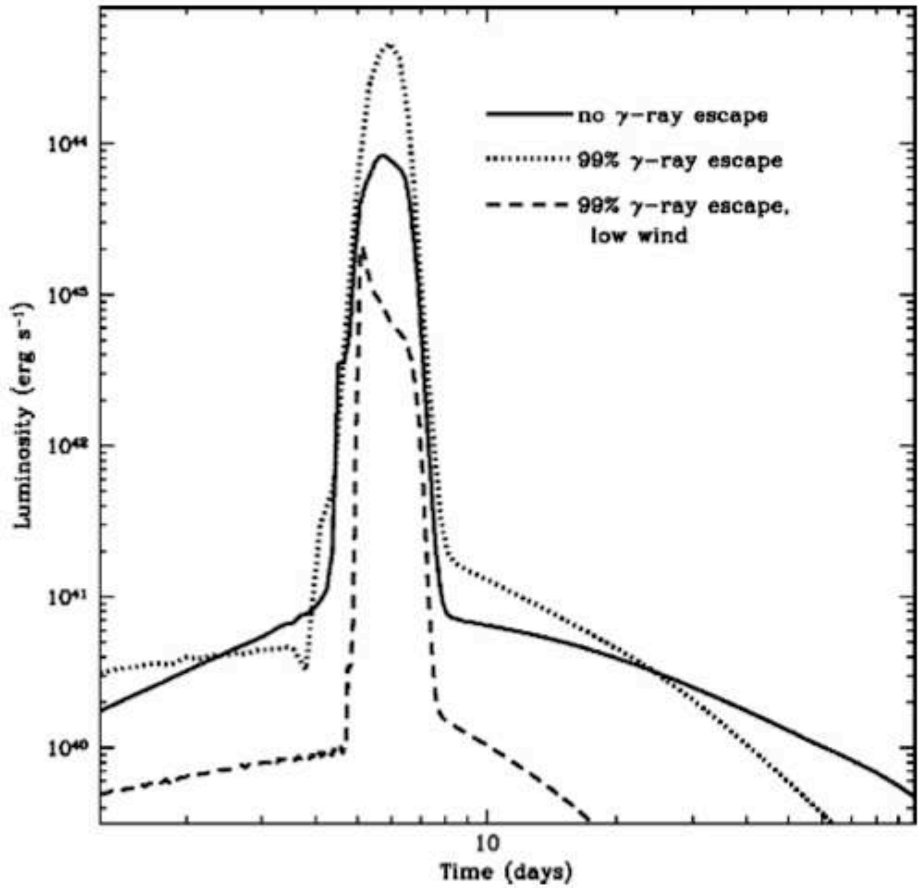
We can calculate these light-curves using RAGE

- RAGE - Radiation Adaptive Gride Eulerian
- Adaptive Mesh Refinement Scheme
- Multi-group flux-limited diffusion scheme
  – we emphasize gray simulations here
- Connected with LANL opacities and equations of state
- 1,2, and 3 dimensions
  – we emphasize 1D spherical results here
- Preliminary implementation of LANL's implicit Monte Carlo package Wedgehog (in support of new code package Cassio.)
- Preliminary implementation of linear, Sn, gamma-ray transport for in-line nickel and cobalt decay energy deposition.

Importance of Rad Hydro (Rage 1D GFLD Calculations)

- RAGE calculations of a hypernova explosion in 1D are complete.
- Radioactive decay heating has been included in situ, though the light curve peak is fairly insensitive to gamma-ray deposition.
- The strength of the circumstellar wind has a larger effect on the peak luminosity.

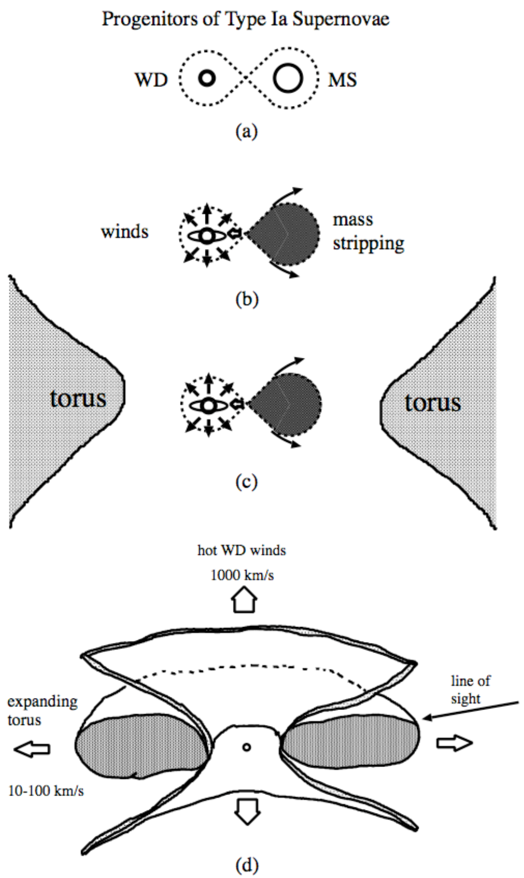


Importance of Rad-Hydro (Hachisu Progenitor for Ia)

- Recent important results from SNIa
  - young population exists for Ia supernovae
  - Circumstellar material can be seen in some spectral observations.

- Proposed progenitors show wind like material surrounding the white dwarf.

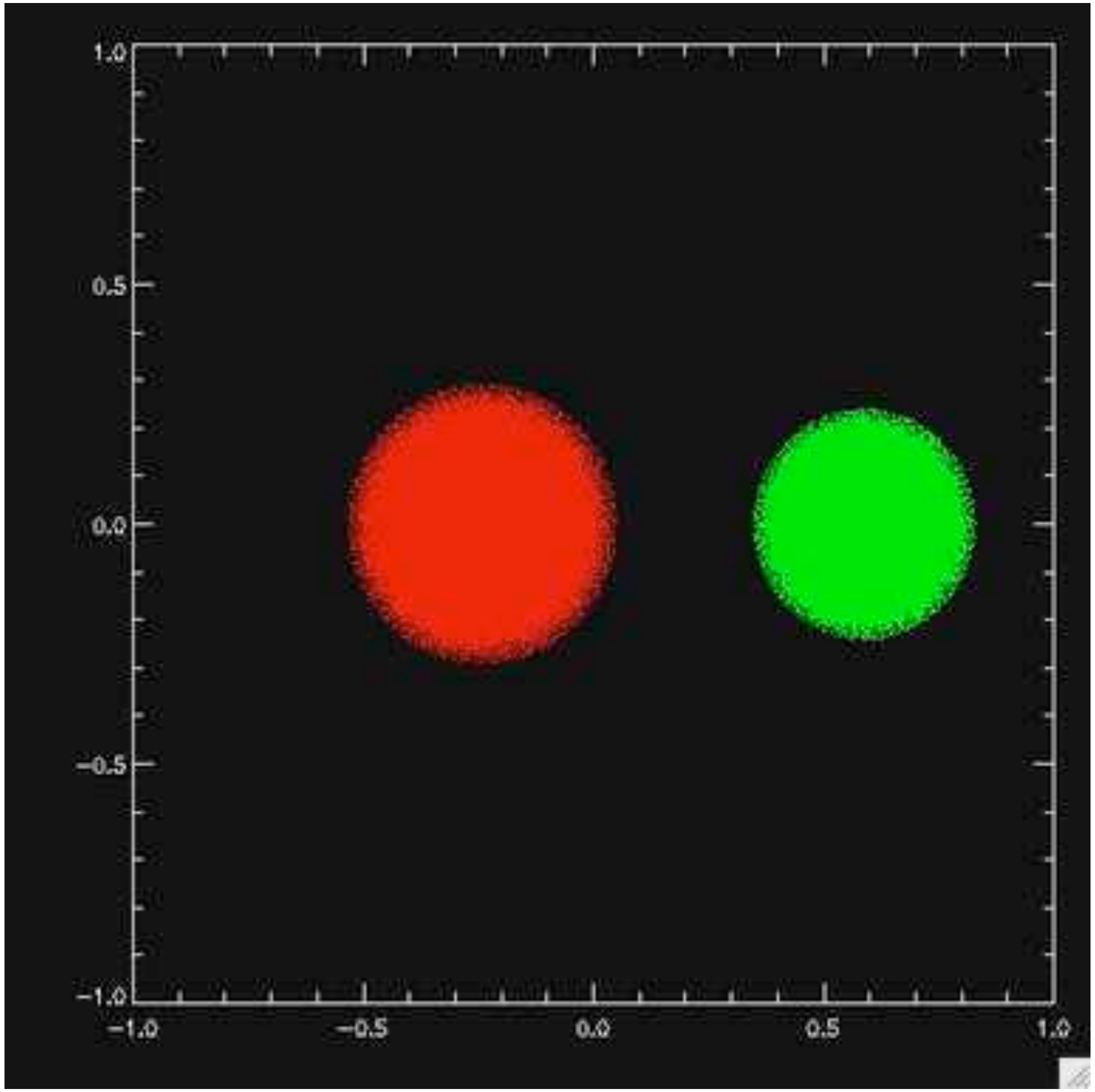
- Light curve shape may be altered by shock energy contributions in the accretion wind.



To study shock effects, we need to study the environment.

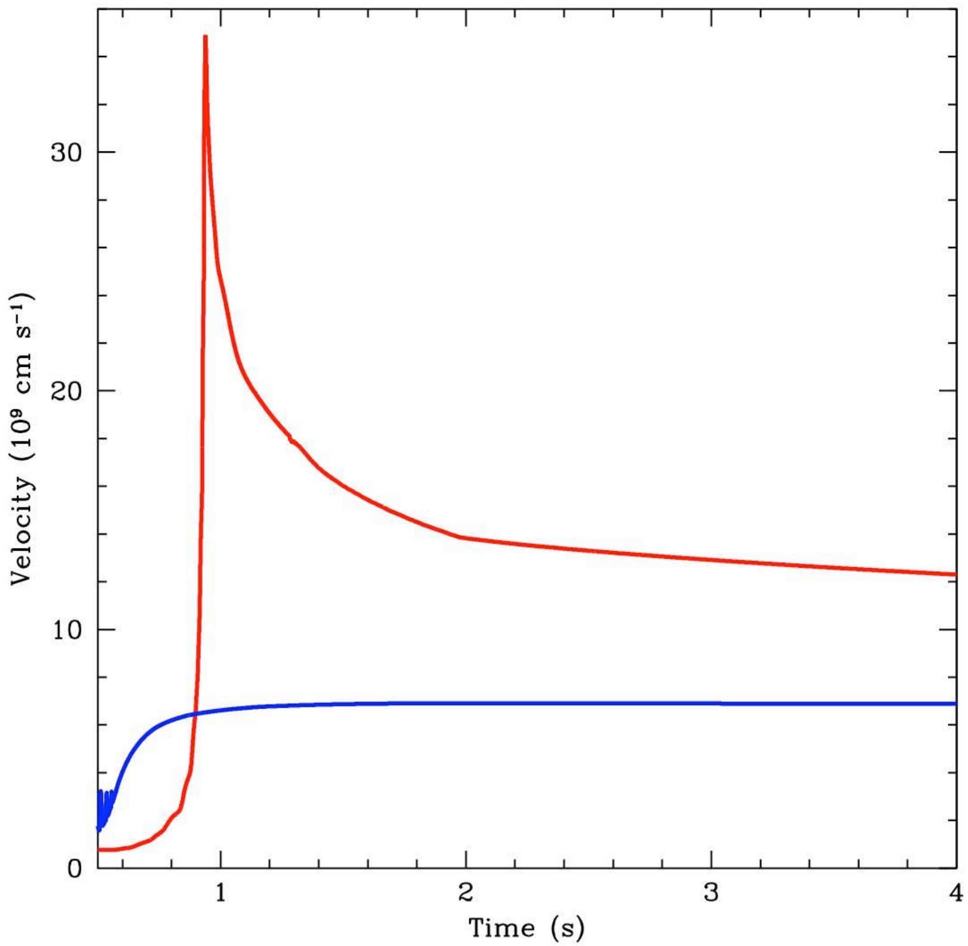
Merger of 2 “white dwarfs” (we are actually using an ideal gas EOS). Note the creation of an atmosphere around the larger star (Diehl et al. 2008)

Diehl has now added Timmes EOS.

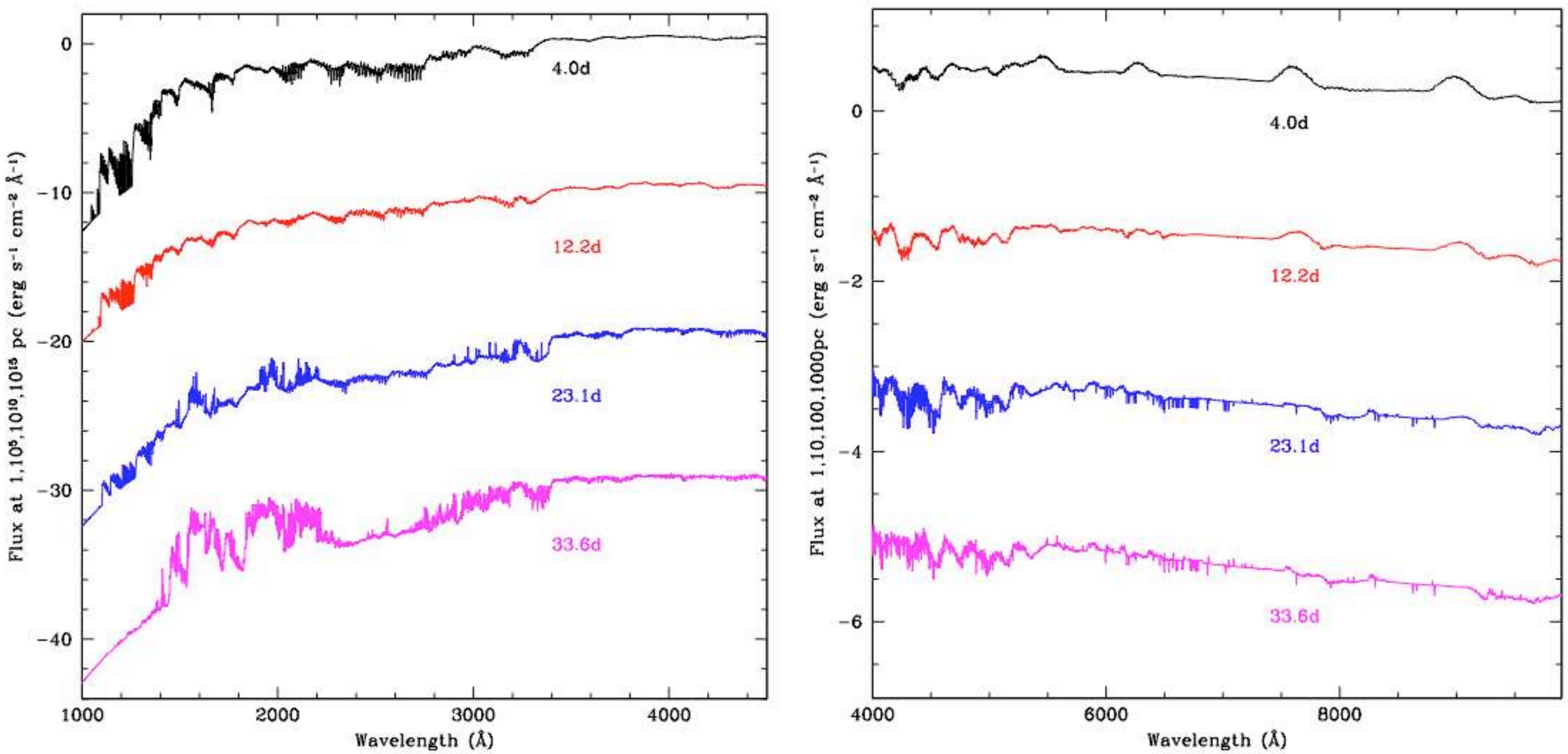


Radiative Cooling WILL change the nature of the Ejecta

- As the shock breaks out of the star, the high pressure at the boundary leads to an incredible acceleration of the shock (Matzner & McKee 1999 argued this could for relativistic ejecta).
- If radiative losses are included, the acceleration is much less dramatic.

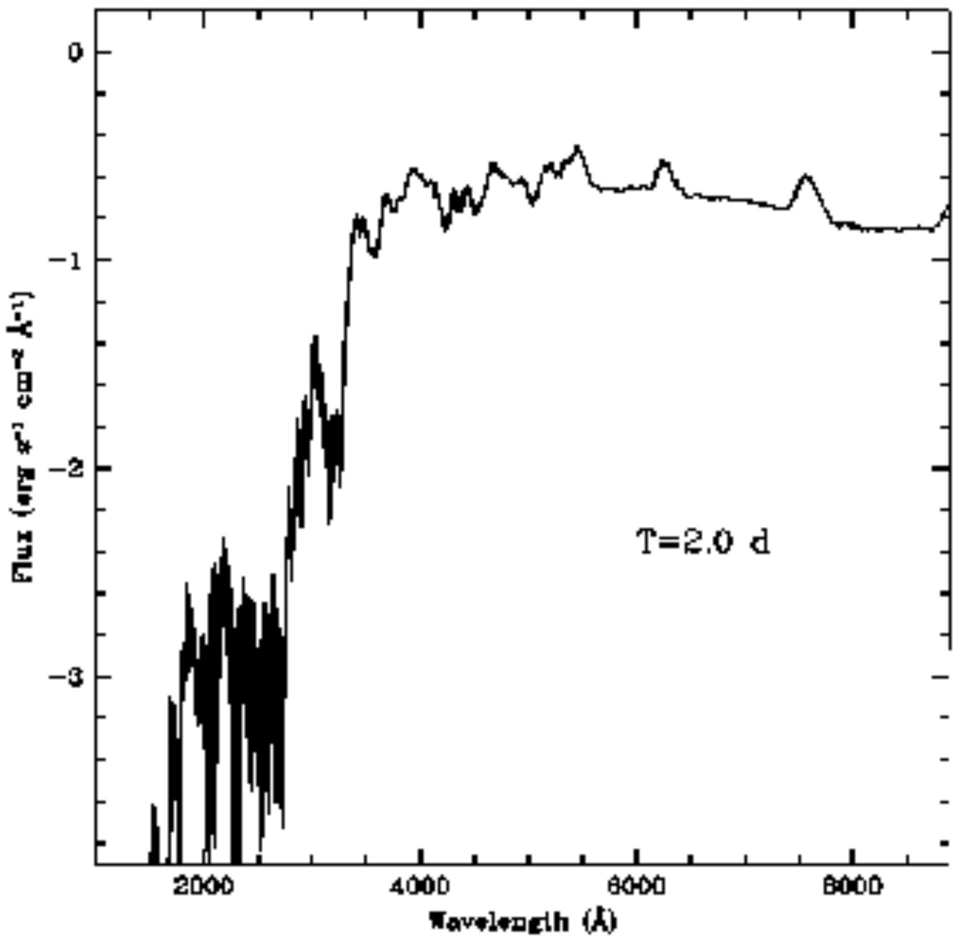


Spectrum
(16H with He Wind)



Spectrum Evolution (16H with He Wind)

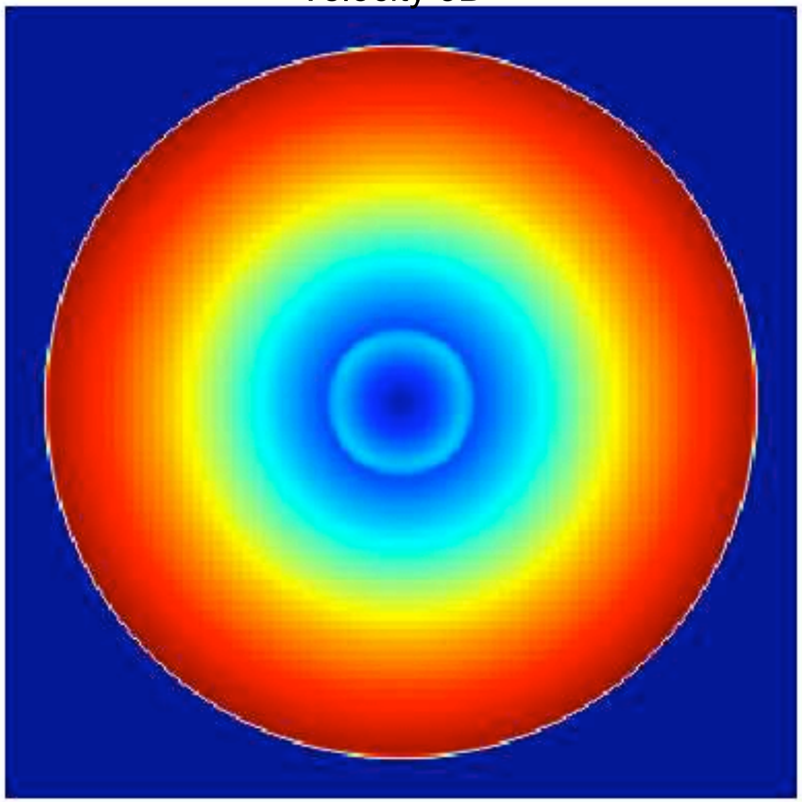
- Luminosity is rising for the times shown here, as was seen in the UBV lightcurves as well.
- As ejecta expand and cool, absorption features from the wind become noticeable



Multi-D Gray Flux Limited Diffusion

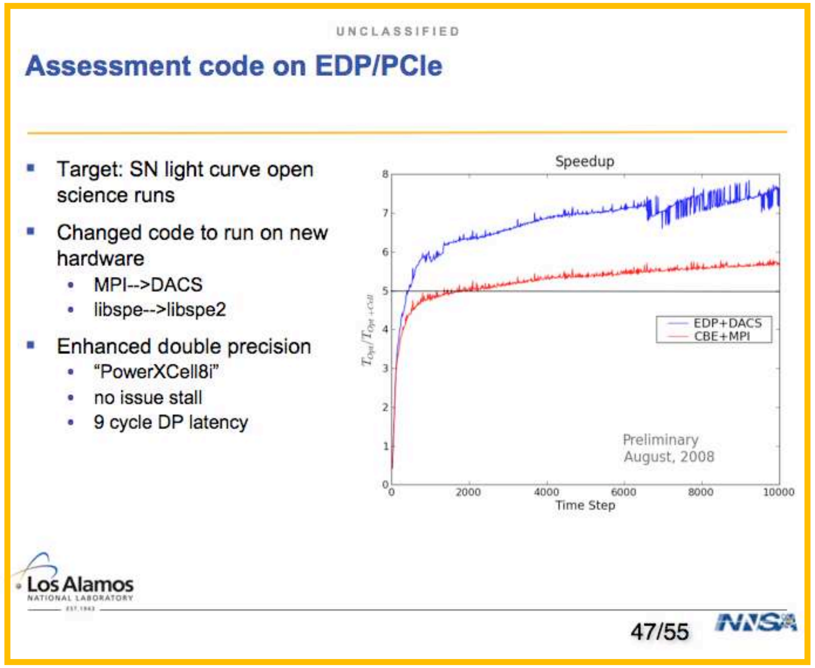
- Multi-D simulations are now being run with GFLD.
- Overlay capability in RAGE allows for remapping seemlessly.
- Boundary problems that impact the radiation flow have encouraged 3D simulation of full sphere.

Velocity 3D



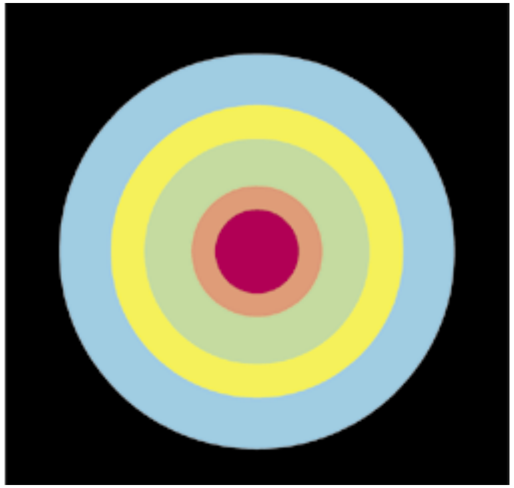
Ultimate Goal and Petascale Needs

- The real goal is to push this simulation effort to
  - Multi space dimensions
  - Multi frequency groups
  - Transport
- Lightning (~10 teraflops)
  - 1D, gray, FLD = 8,000 cpu-hrs
  - 3D, gray, FLD = 6e7 cpu-hrs
    1/20th the resolution of 1D
  - MG IMC(10X GFLD) = 6e8 cpu-hrs
  - ~10 years using the Lightning cluster
- Roadrunner (1 petaflops)
  - ~1 month using Roadrunner
    assuming efficient use of cell accelerators.

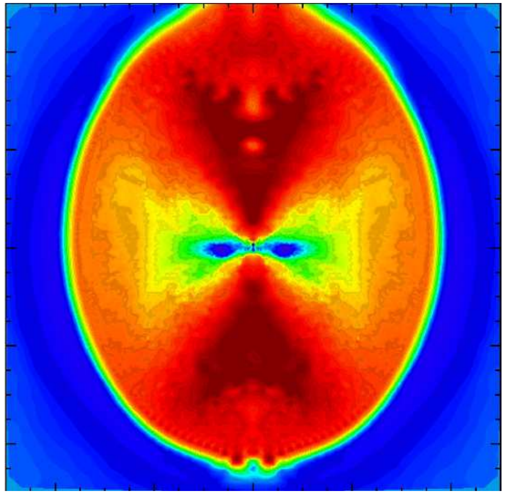


But are explosions symmetric? Models actually suggest a variety of asymmetries.

Spherically
Symmetric



Fryer & Heger 2000

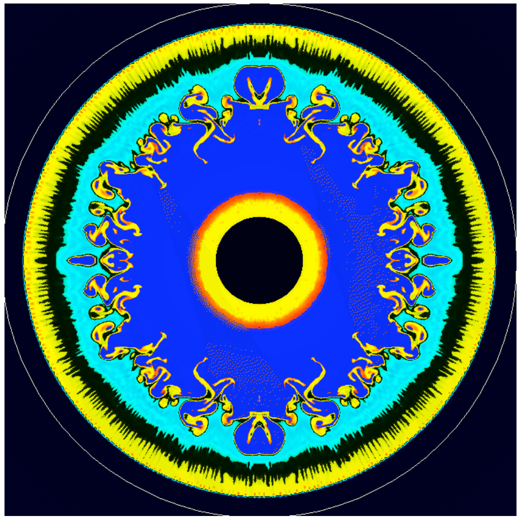


Globally
Asymmetric
What level is
required?
(bipolar)

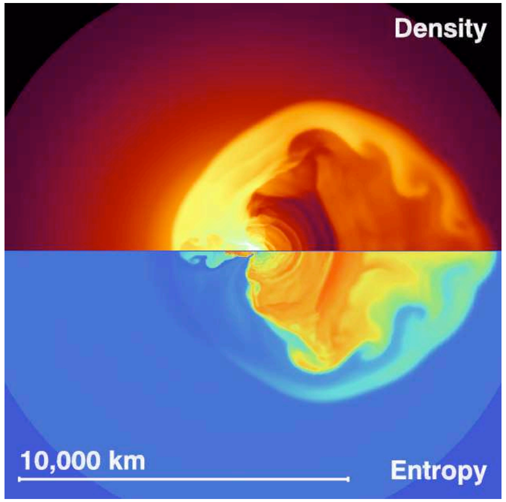
Symmetric

or

Globally
Symmetric



Burrows et al. 1995



Scheck et al. 2004

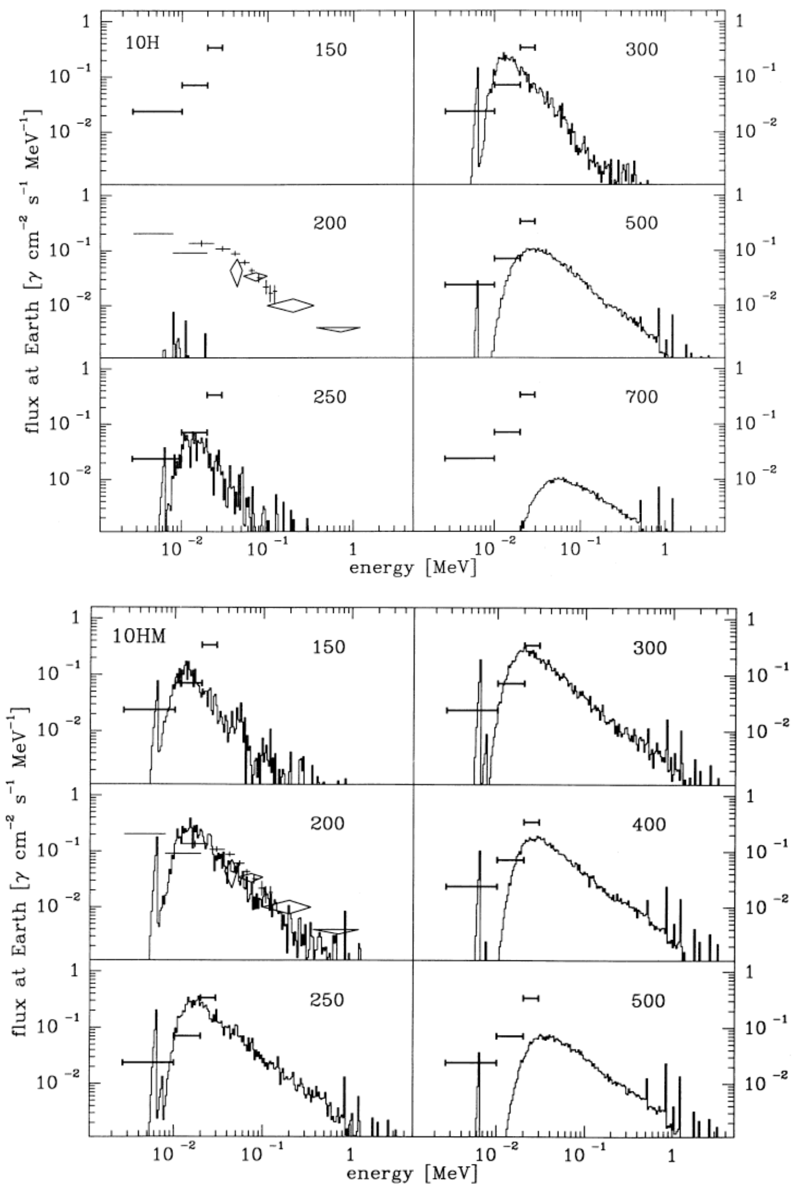
Globally
Asymmetric

(single lobe)

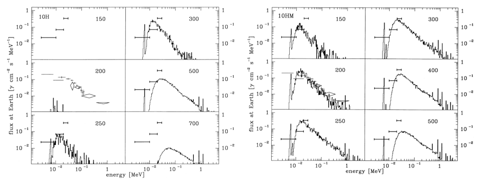
Observational Evidence

Global Asymmetry	Break in Spherical Symmetry

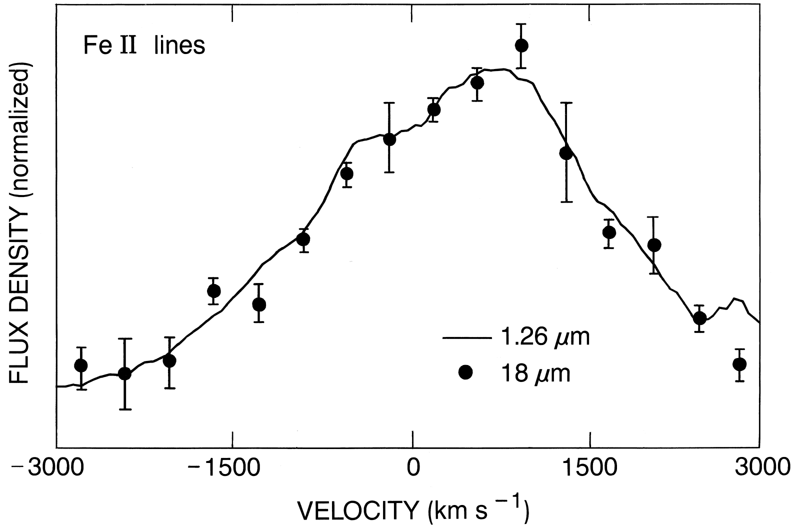
Theoretical fits to hard X-ray Spectra from SN 1987A



Observational Evidence

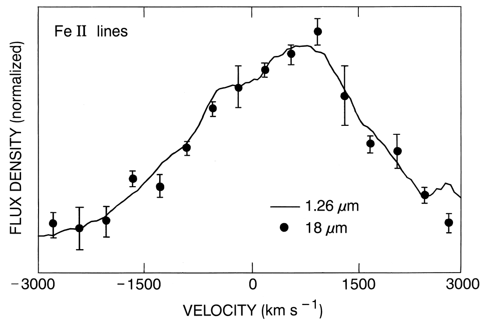
Global Asymmetry	Break in Spherical Symmetry
	

Broad lines of [Fe II] and [Ni II]
Implied presence of Fe and Ni
Into the hydrogen "layer" of SN87A



Hydrodynamic modelling of this
Mixing in symmetric models cannot
Achieve such broad lines, BUT
Global asymmetry might fix this!

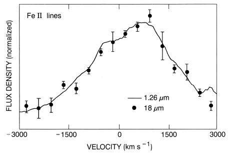
+



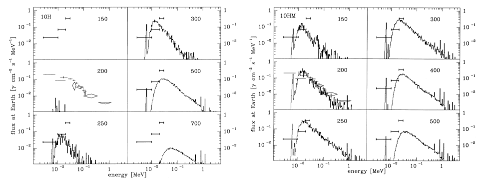
Observational Evidence

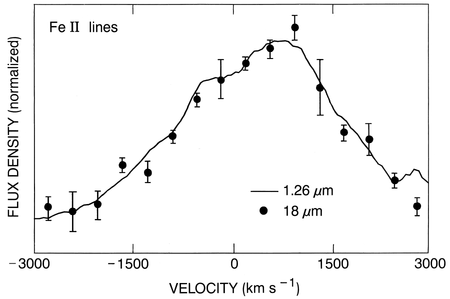
Global Asymmetry

+



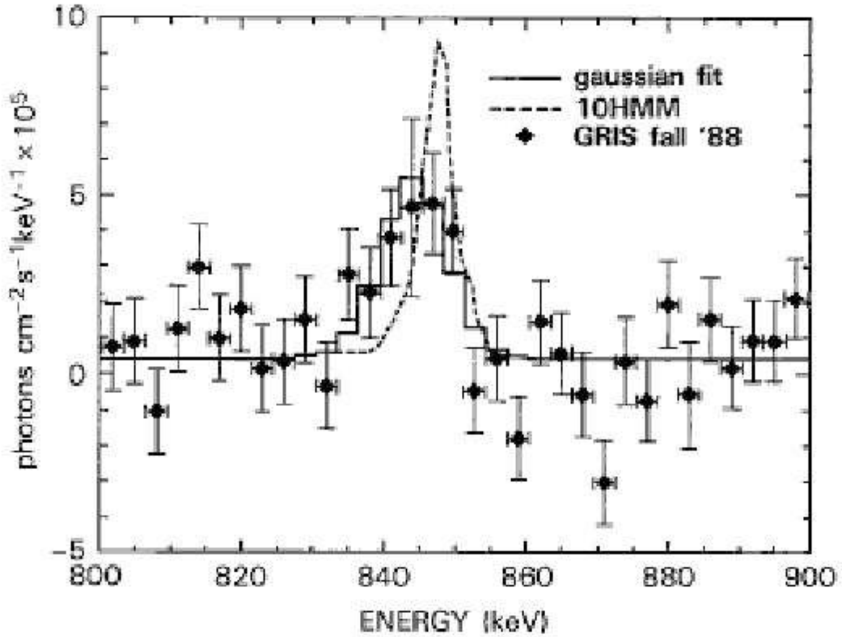
Break in Spherical Symmetry





Redshifted gamma-ray lines!

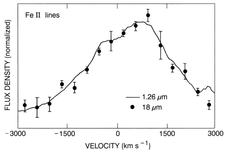
And also broad gamma-ray lines…

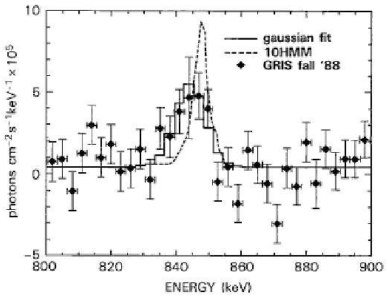


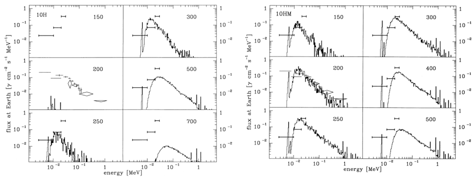
Observational Evidence

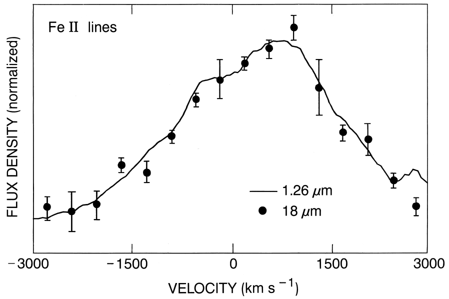
Global Asymmetry	Break in Spherical Symmetry

+



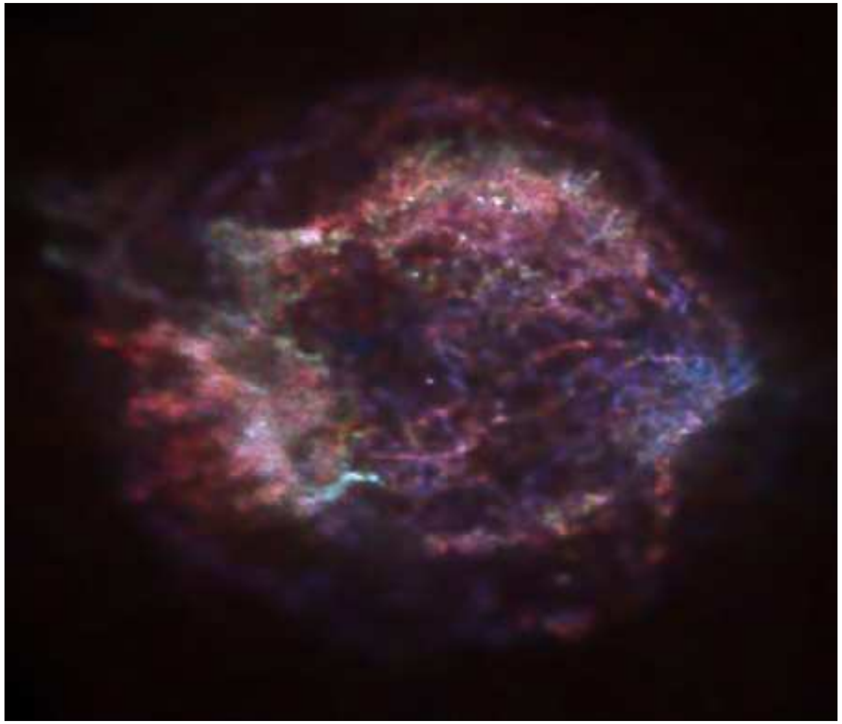






Red = Fe-rich material
White = Si-rich material

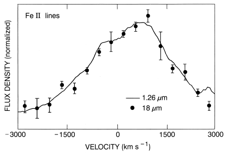
Why is Fe outside of Si?

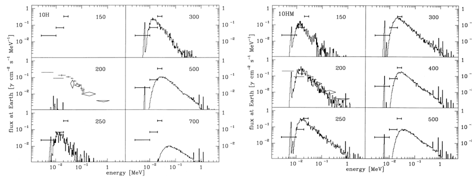


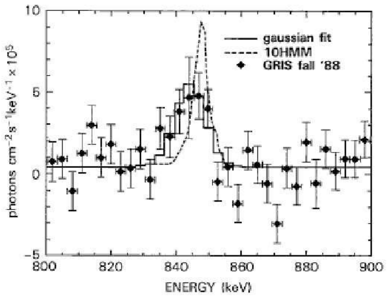
Jet-like structure to the North East …
But iron is just outside jet

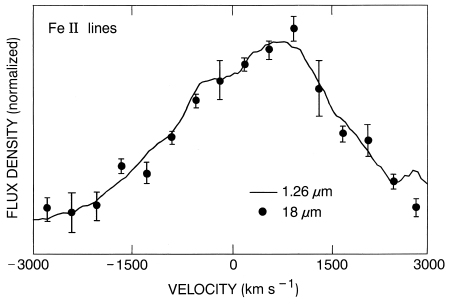
Observational Evidence

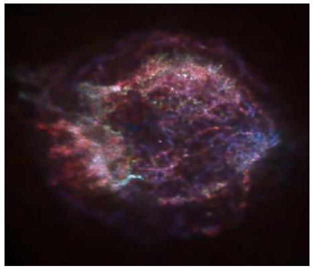
Global Asymmetry	Break in Spherical Symmetry

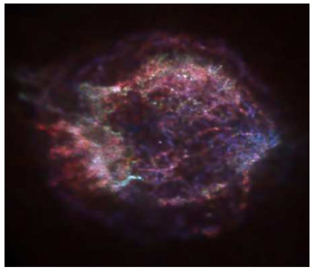

+


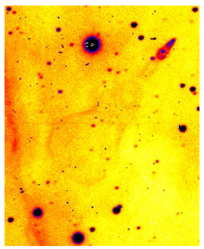


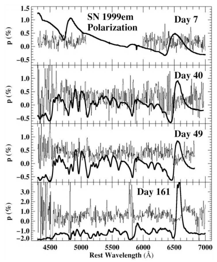












Polarization and Pulsar Velocities

3 Mechanisms for Asymmetry

- Rotation: Drives bi-polar explosion along rotation axis
- Merger of Convective Cells: Drives single-mode explosion

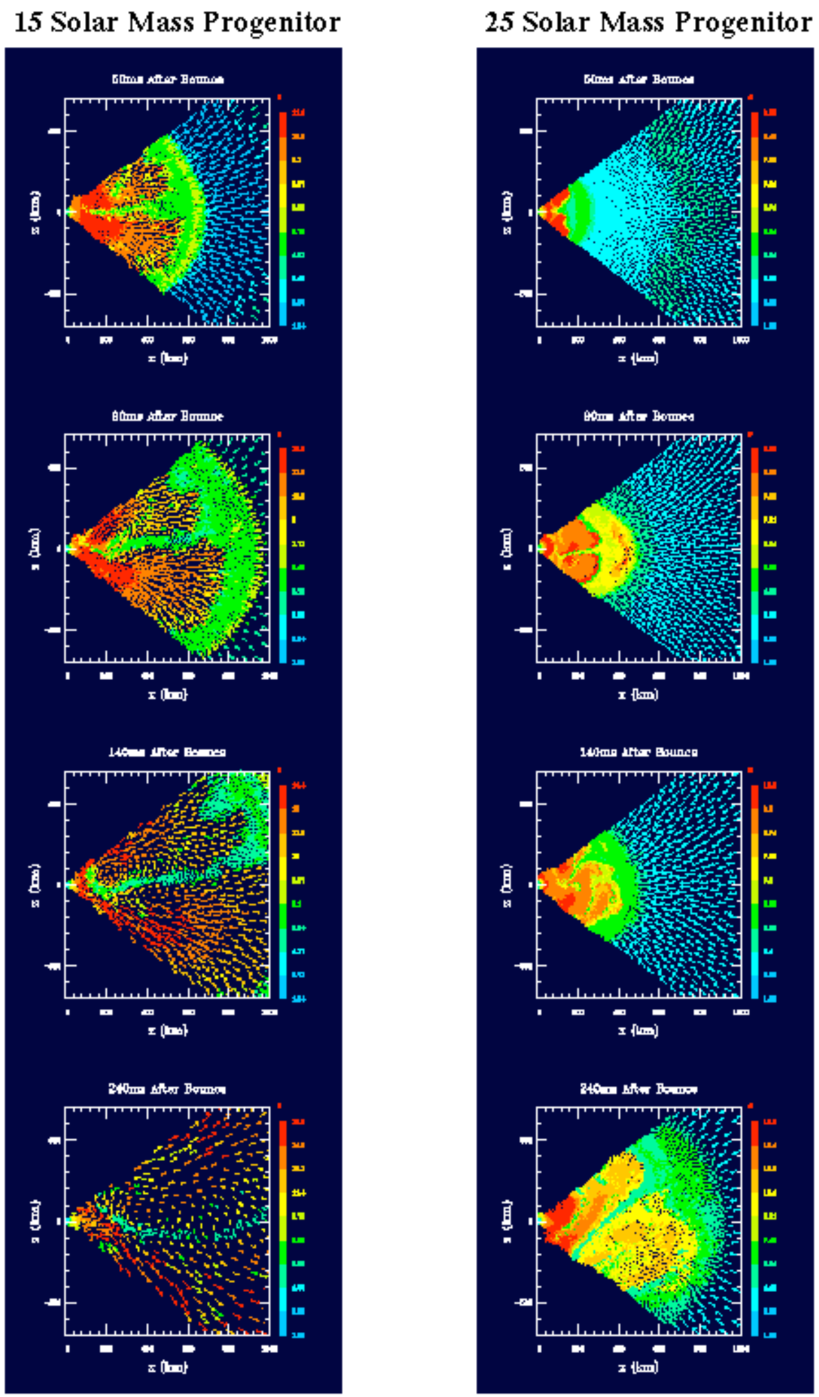
Theory

15 vs. 25 Solar Mass Collapse

Time steps: 50ms, 90ms, 140ms, 240ms

15 solar mass star explodes At ~90ms.

25 solar mass star explodes At ~240ms.



Rotation and Convection

Angular Momentum Stabilizes the Core Against Convection

$$\Delta a = \Delta a_{buo} + [j^2_{blob} - j^2(r+\Delta r)]/(r+\Delta r)^3$$

$$j_{blob} = j(r)$$

$$j^2(r+\Delta r) = j(r)^2 + (\partial j^2/\partial r)\Delta r$$

$$\partial a/\partial r = -g/\rho[(\partial \rho/\partial r)_{ad} - \partial \rho/\partial r)] + (\partial j^2/\partial r)/r^3$$