Core-Collapse Supernovae: Moving Towards a Test-bed for Nuclear Physics

Chris Fryer (LANL)

- Basic Neutrino-Driven Core-Collapse Mechanism (Theory and Observational Support)
- Neutrino-Driven Mechanism and Asymmetries
- Moving toward realistic nucleosynthesis calculations

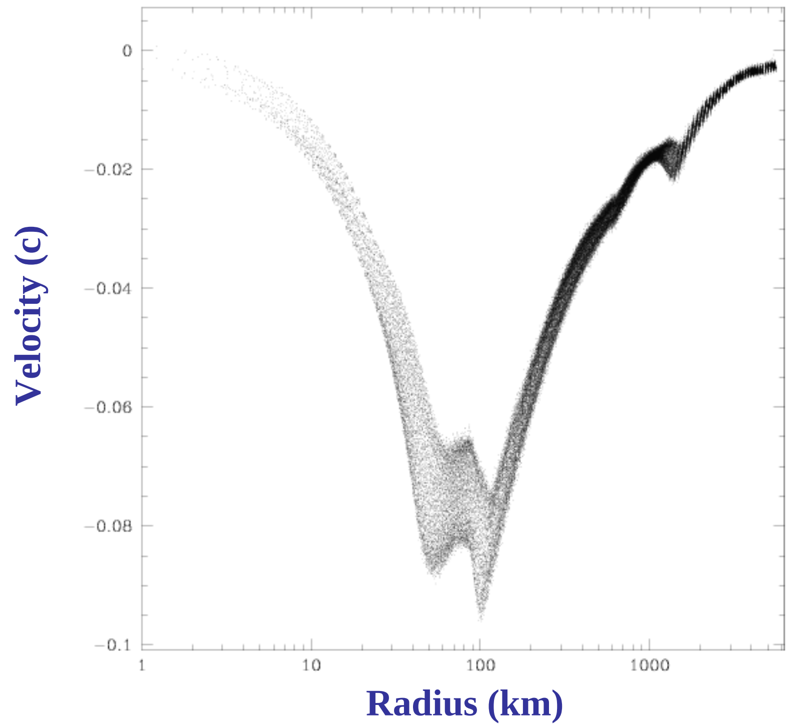
Neutrino-Driven Supernova Mechanism

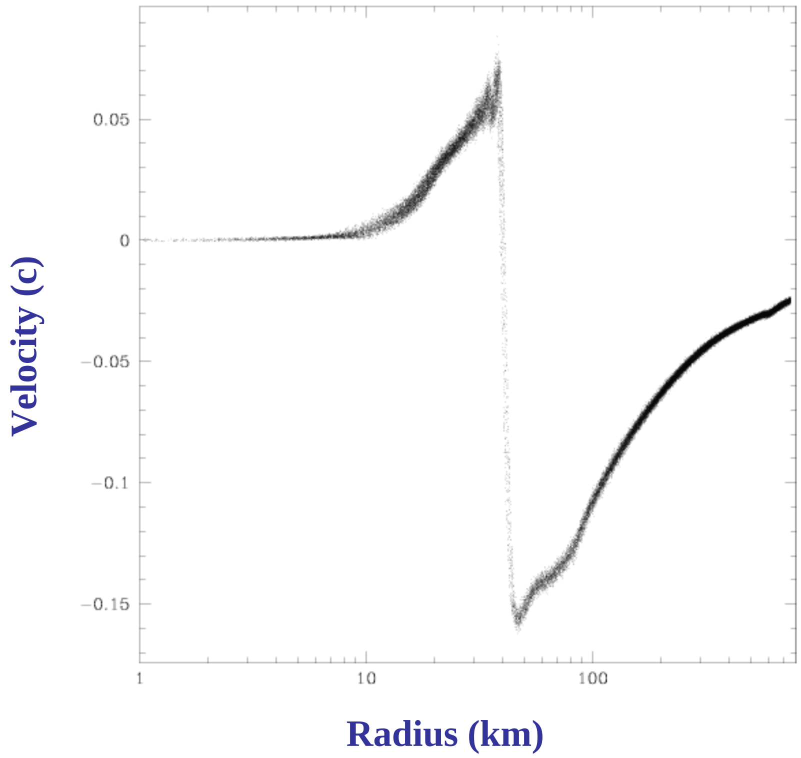
Temperature and Density of the Core Becomes so High that:

Iron dissociates into alpha particles

Electrons capture onto protons

Core collapses nearly at freefall!



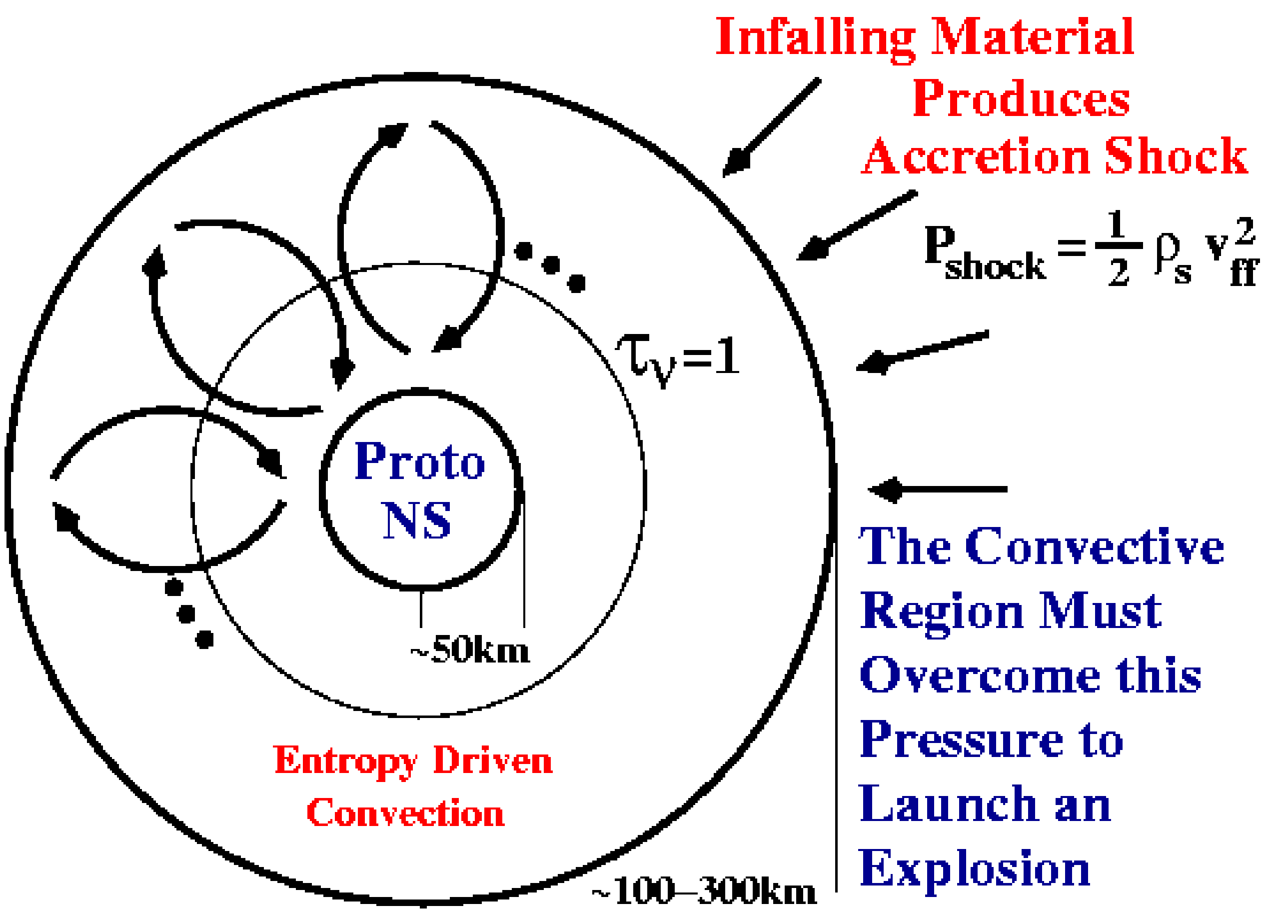


Core reaches nuclear densities

Nuclear forces and neutron degeneracy increase pressure

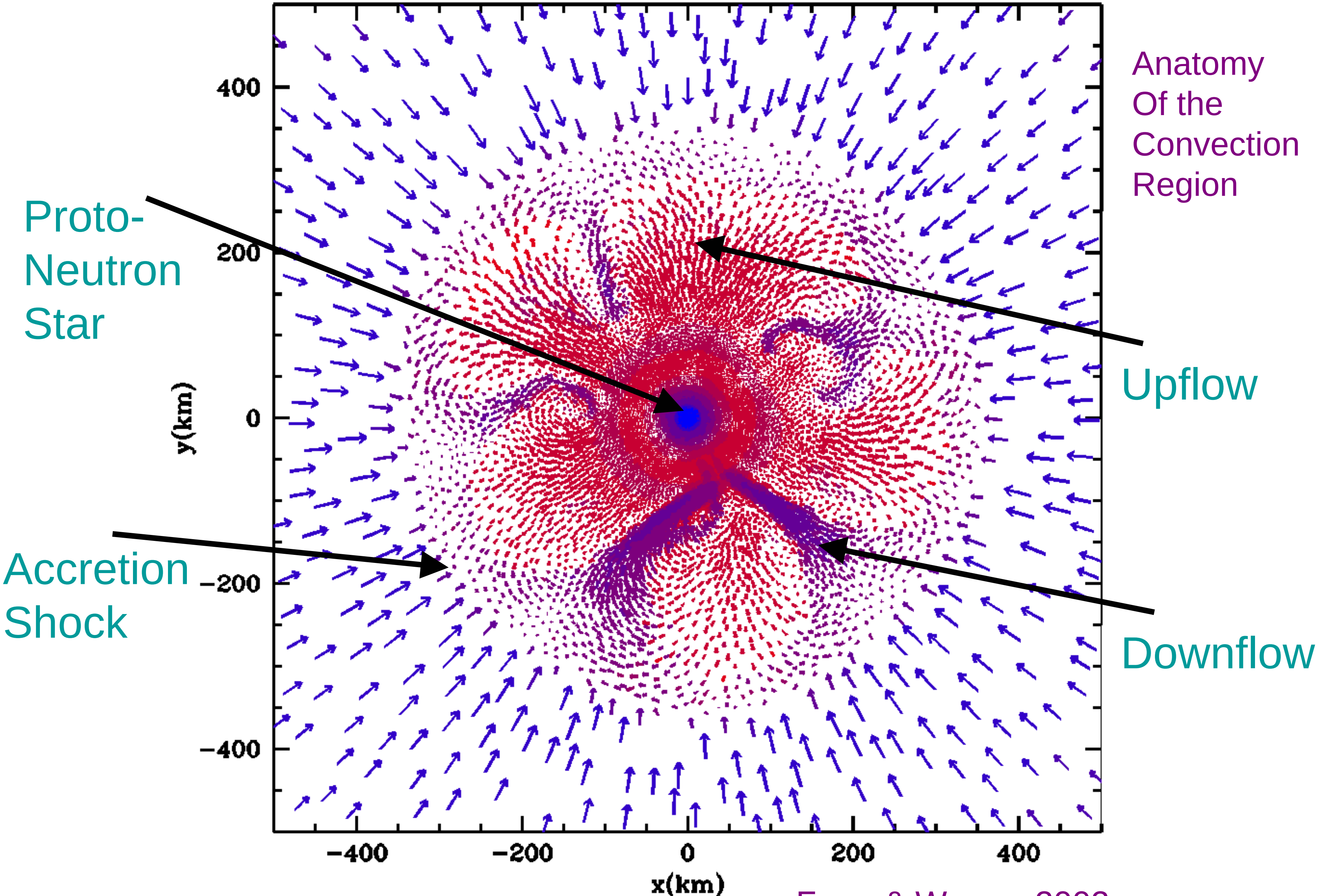
Bounce!

Neutrino-Driven Supernova Mechanism: Convection



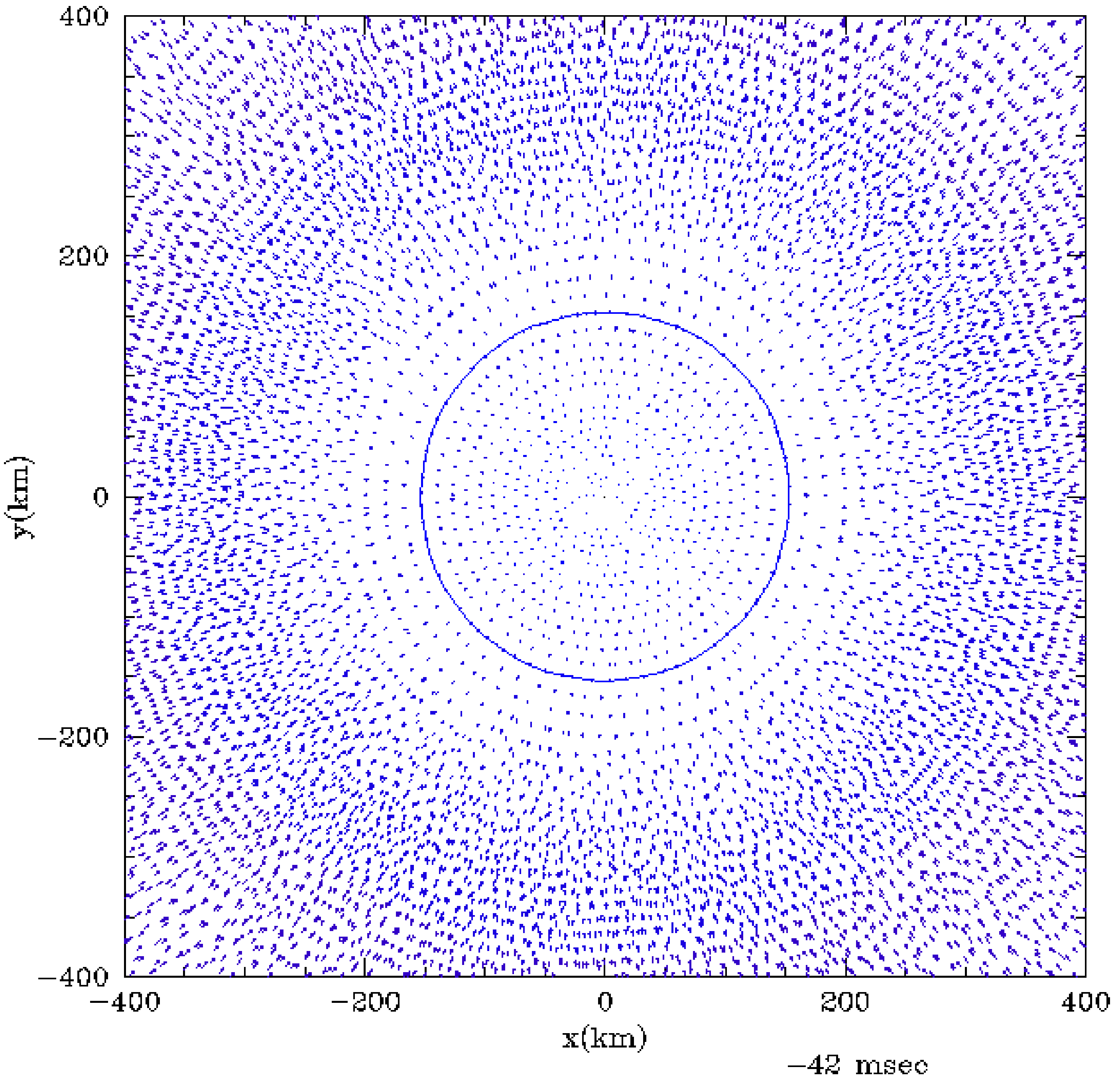
Fryer 1999

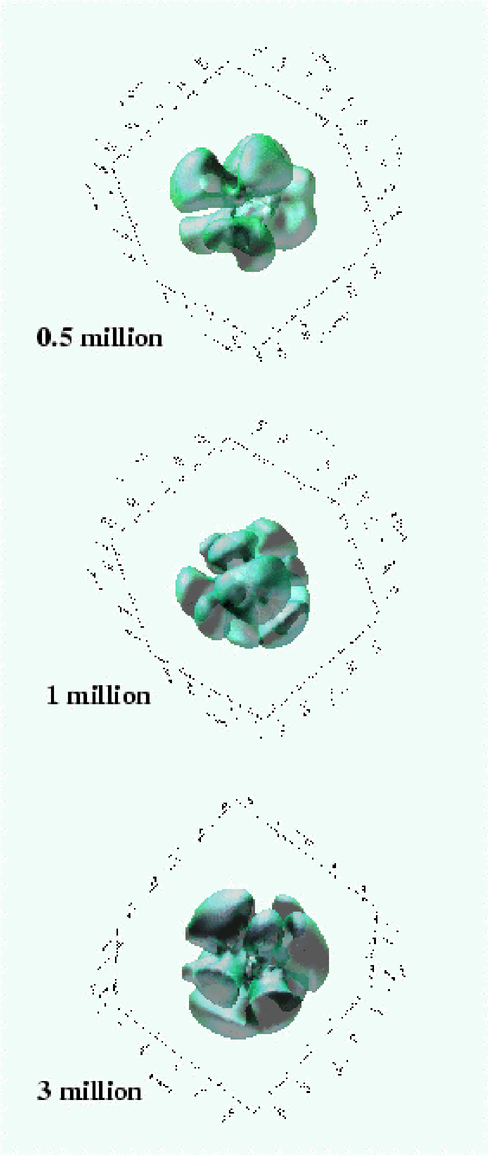
Anatomy
Of the
Convection
Region



Fryer & Warren 2002

Evolution Of a Collapse Simulation





Fryer & Warren 2002

Convection in 3–dimensions!

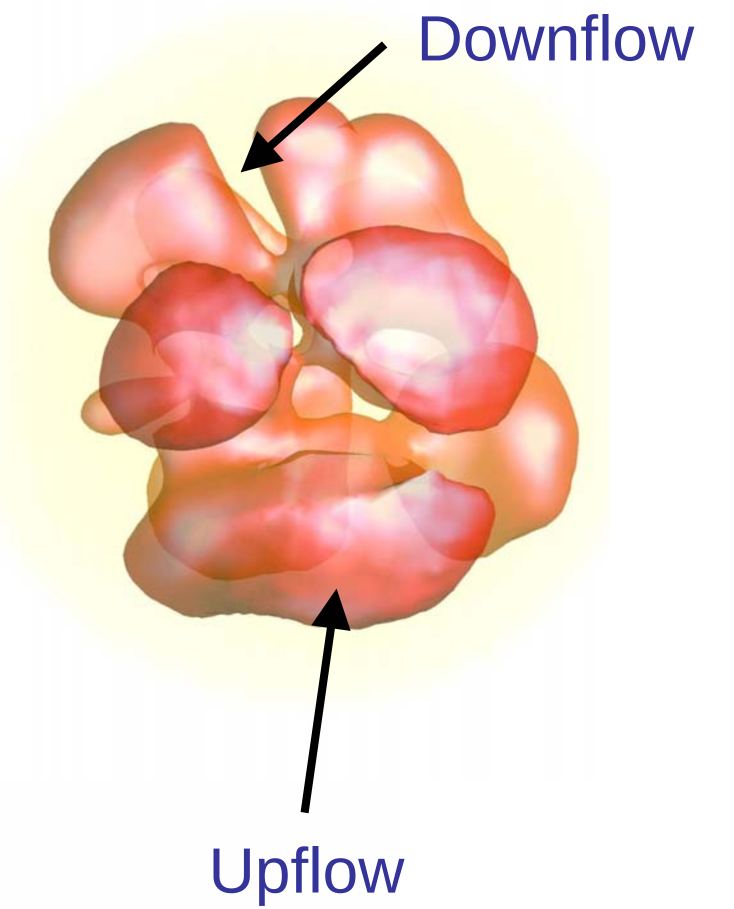
Even at Early Times, the Convection is Limited to a a Few Upflows.

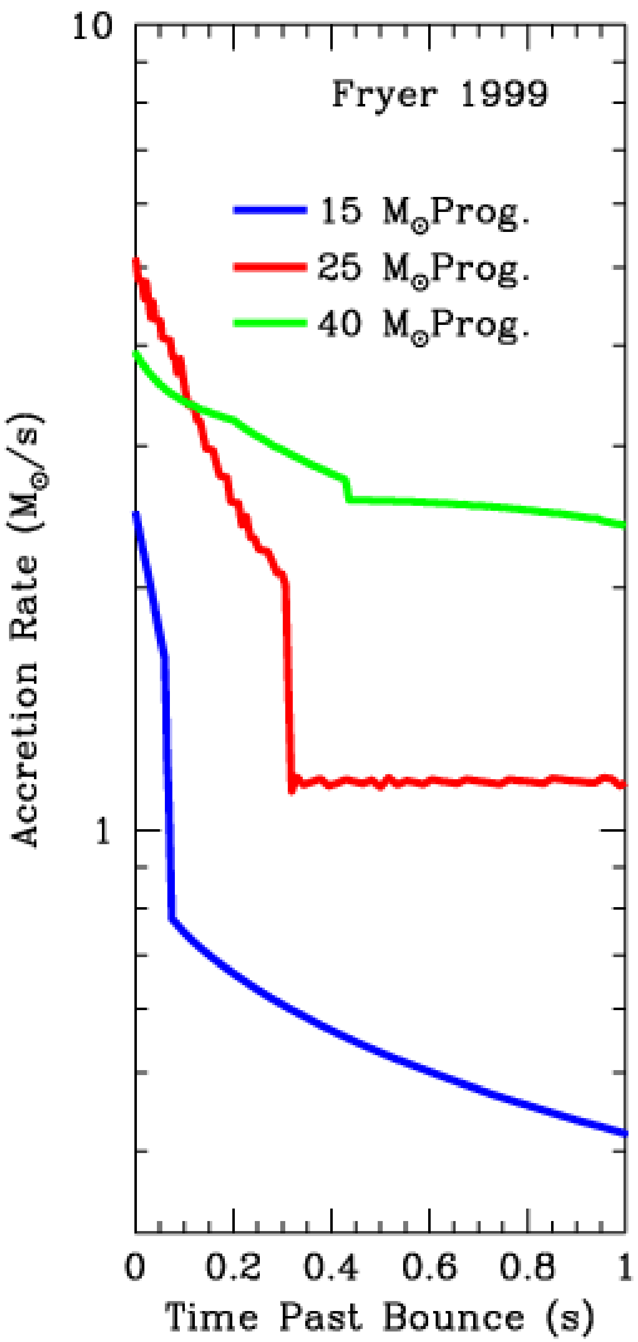
The Explosion Energy in All of these Simulations Agree at the 10% level.

At Late Times, the Rising Bubbles May Merge, Leading to Fewer and Fewer Upflows.

(Janka 2002)

Isosurfaces of outward Moving bubbles





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

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

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

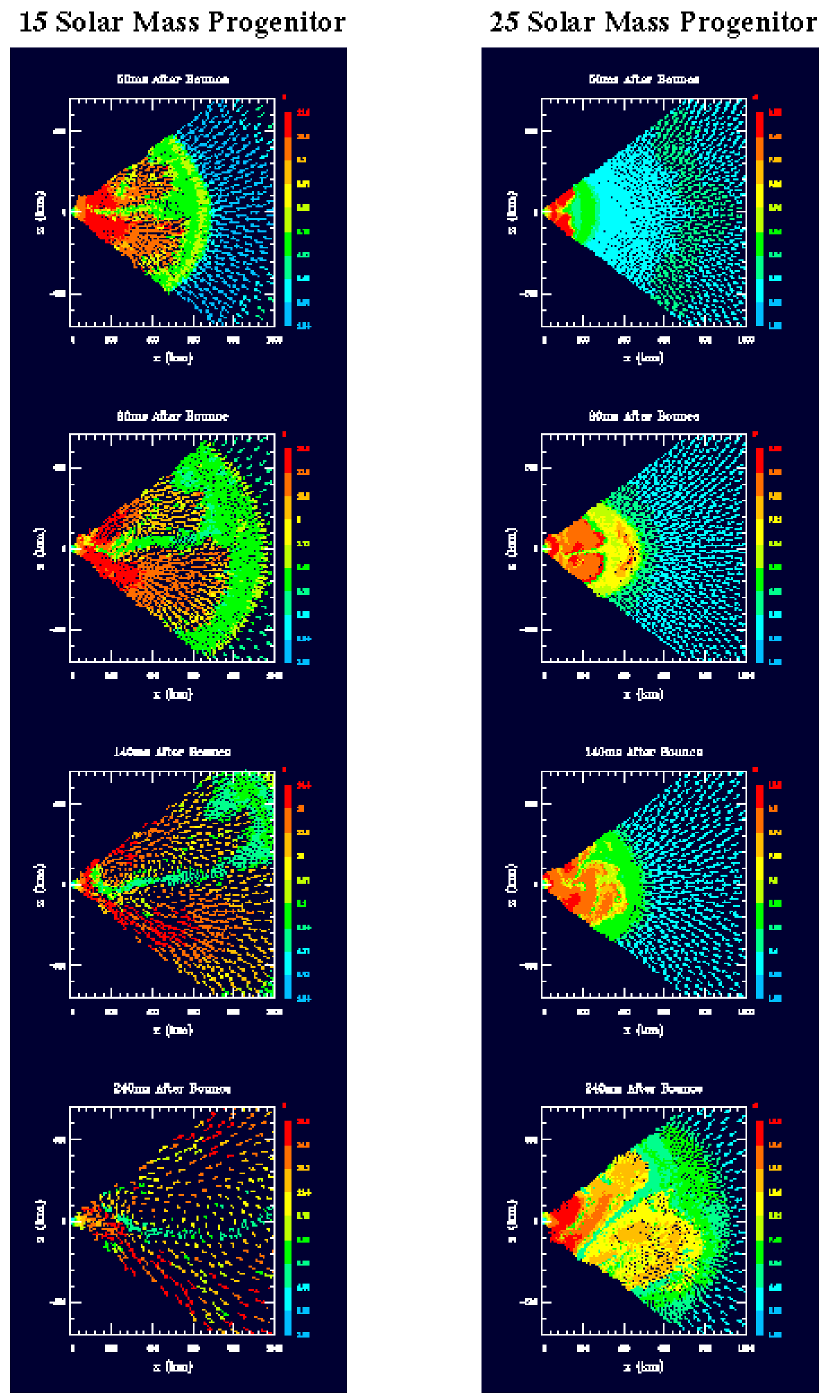
Burrows & Goshy 1993

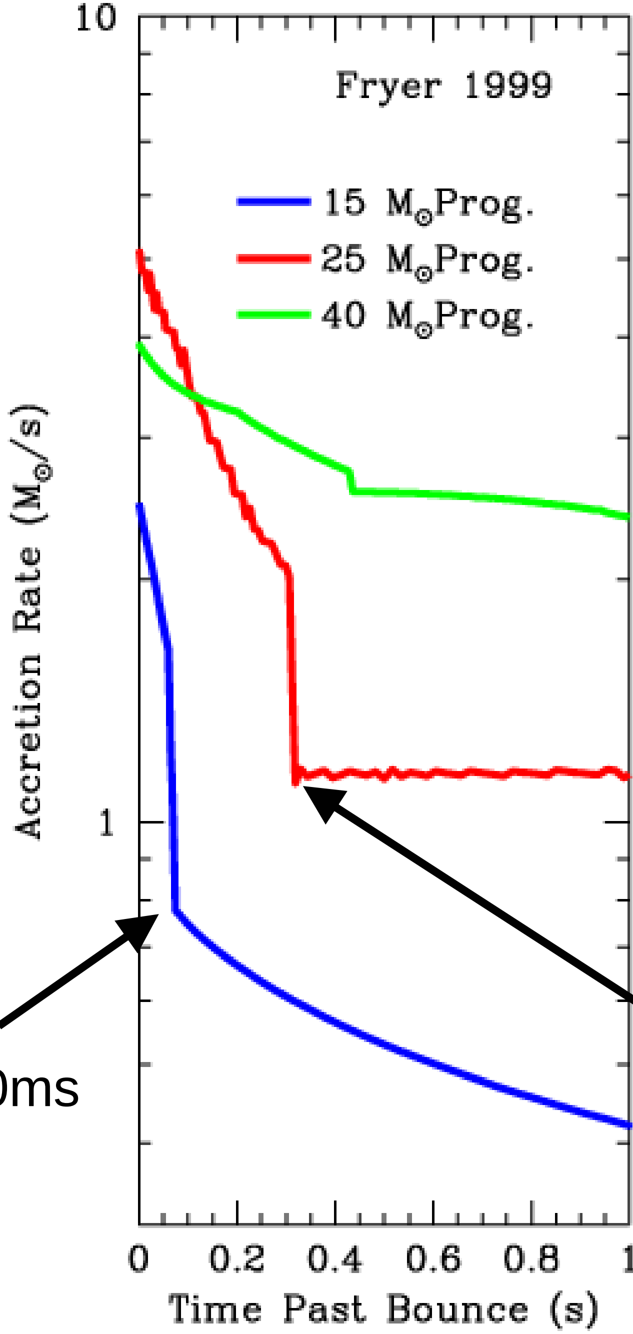
15 vs. 25 Solar Mass Collapse

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

15 solar mass star explodes At ~90ms.

25 solar mass star explodes At ~240ms.





~90ms

~240ms

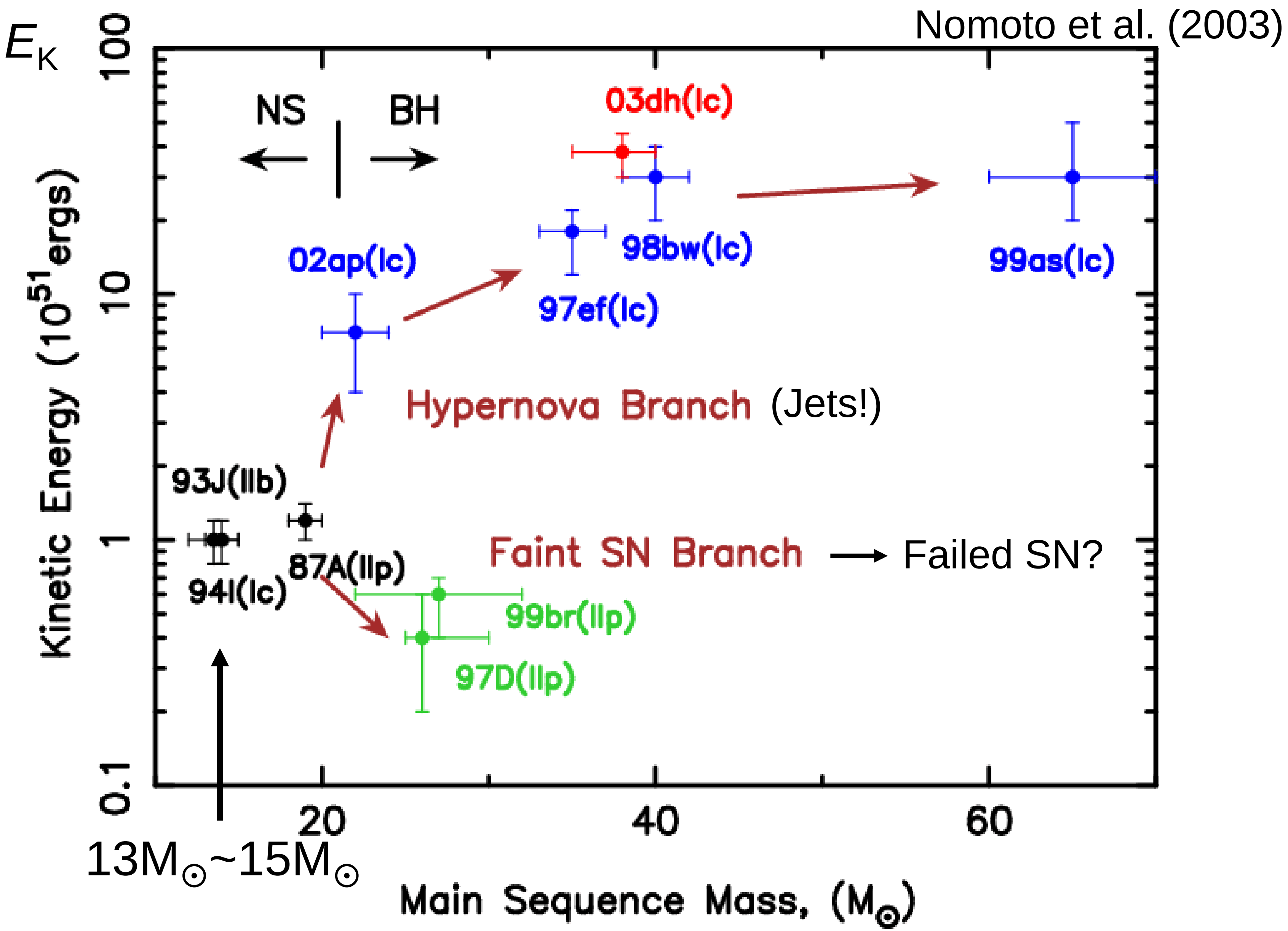
$$P_{Shock} \approx \frac{1}{2}\rho v_{ff}^2$$

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

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

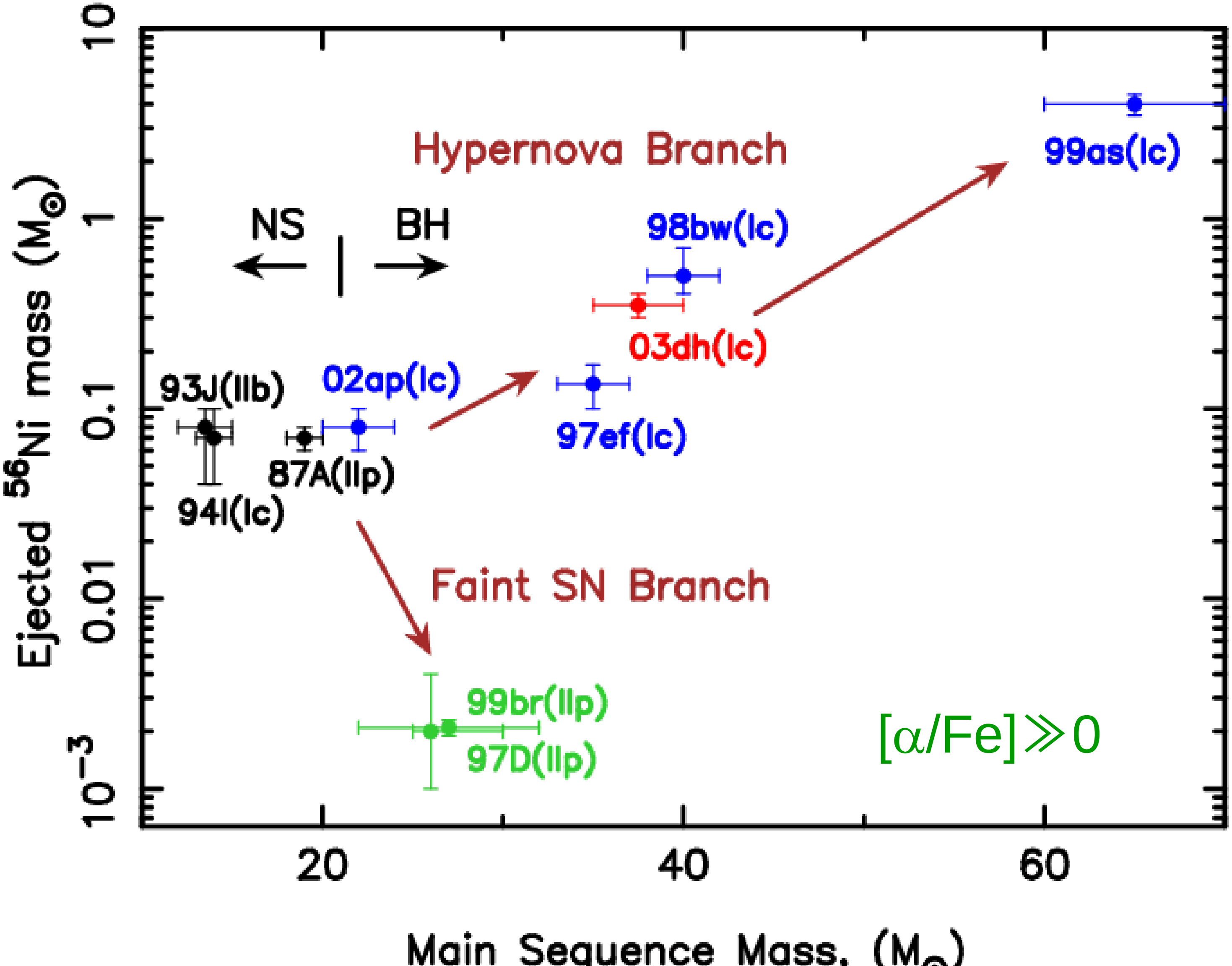
Burrows & Goshy 1993

Supernovae/Hypernovae



$M(^{56}Ni)/M_\odot$

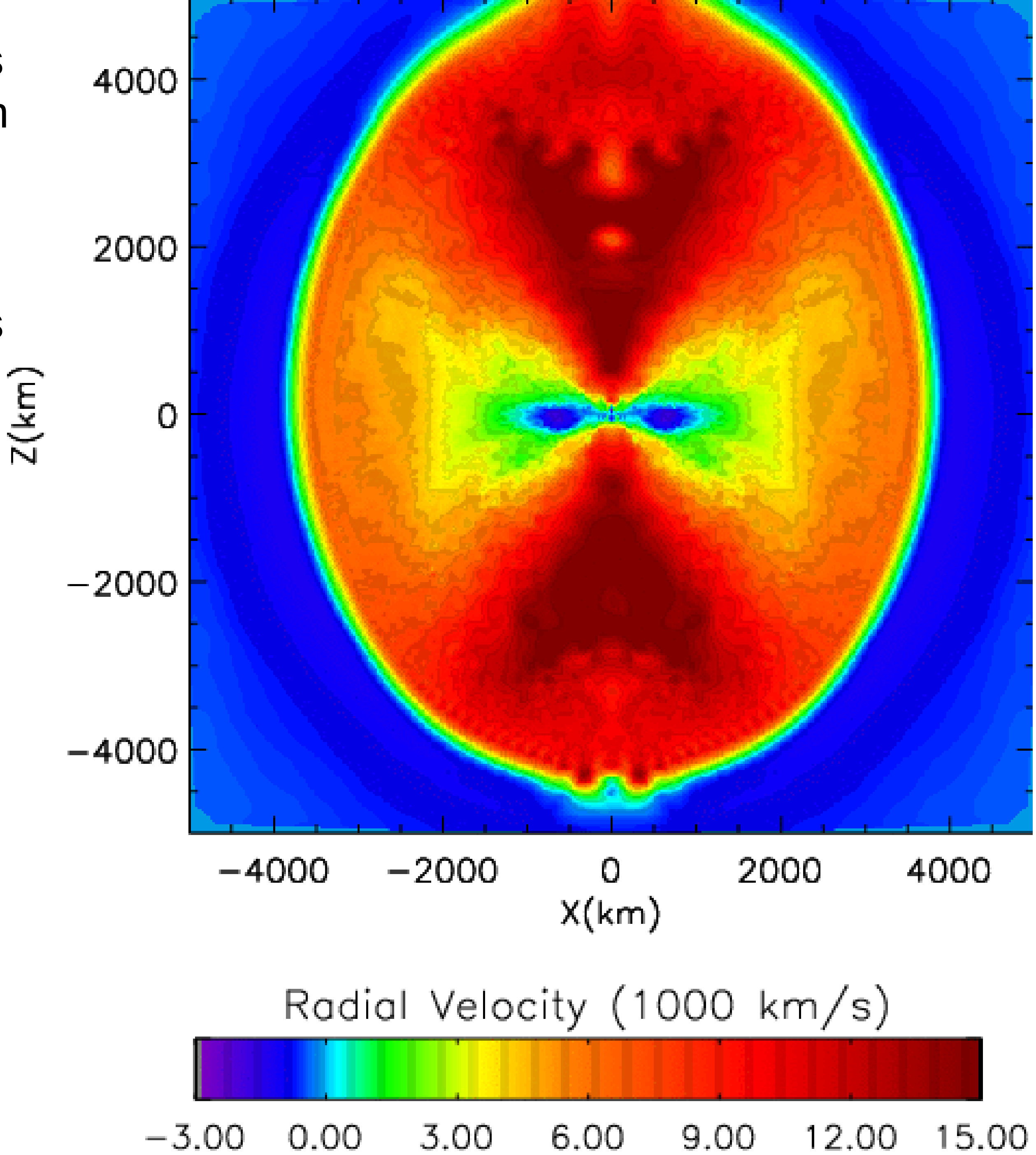
Nomoto et al. (2003)



$[\alpha/Fe] \gg 0$

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!

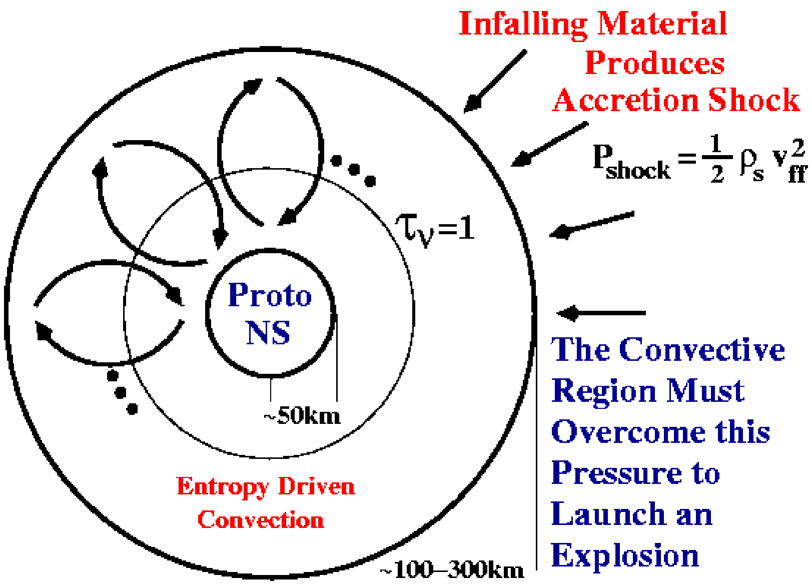


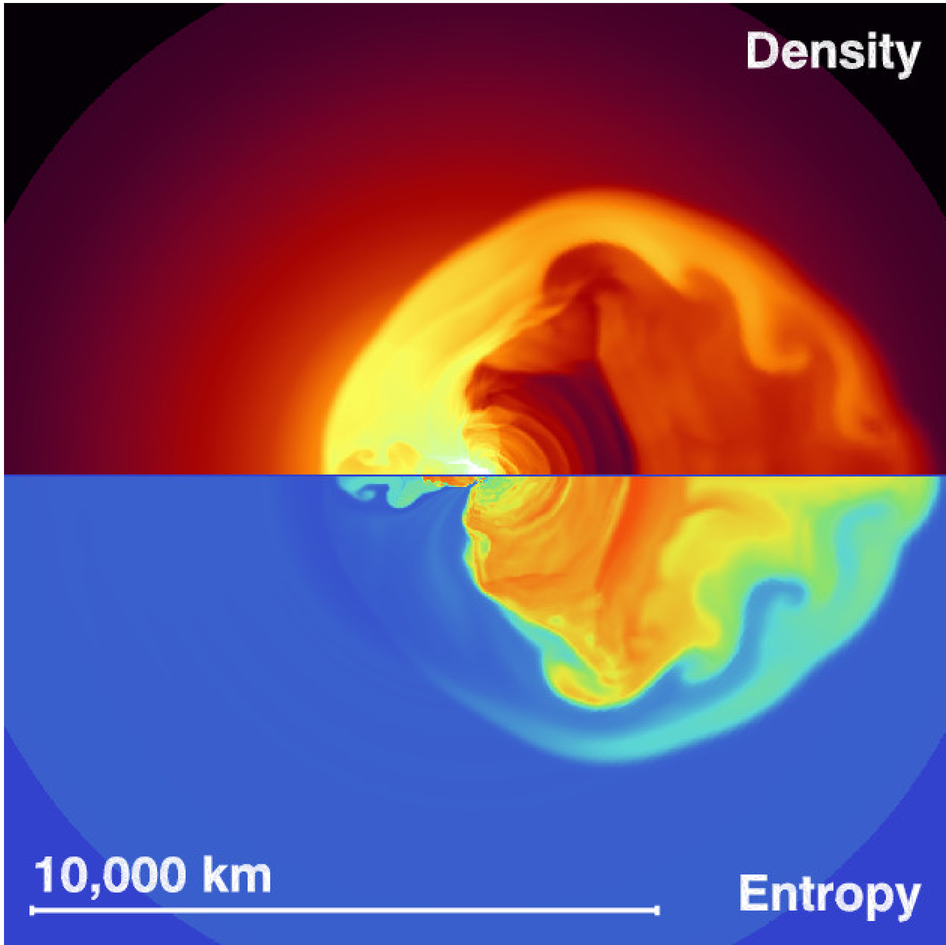
Single-Lobe Convection

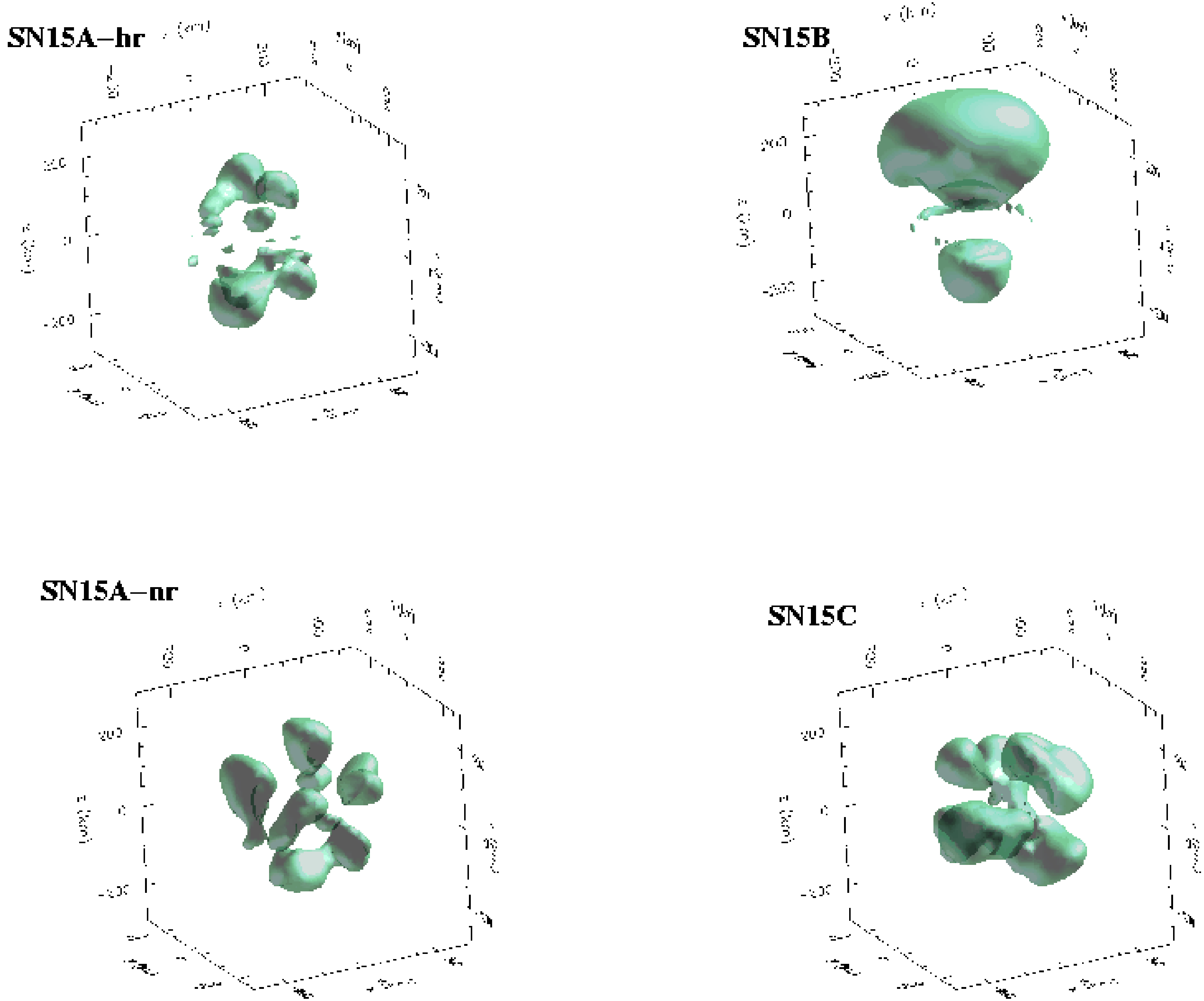
- Convection Drives explosion.
- The convective cells merge with time.
- With sufficient time, Low-Mode convection develops.

- Neutron Star Kicks for Slow Explosions

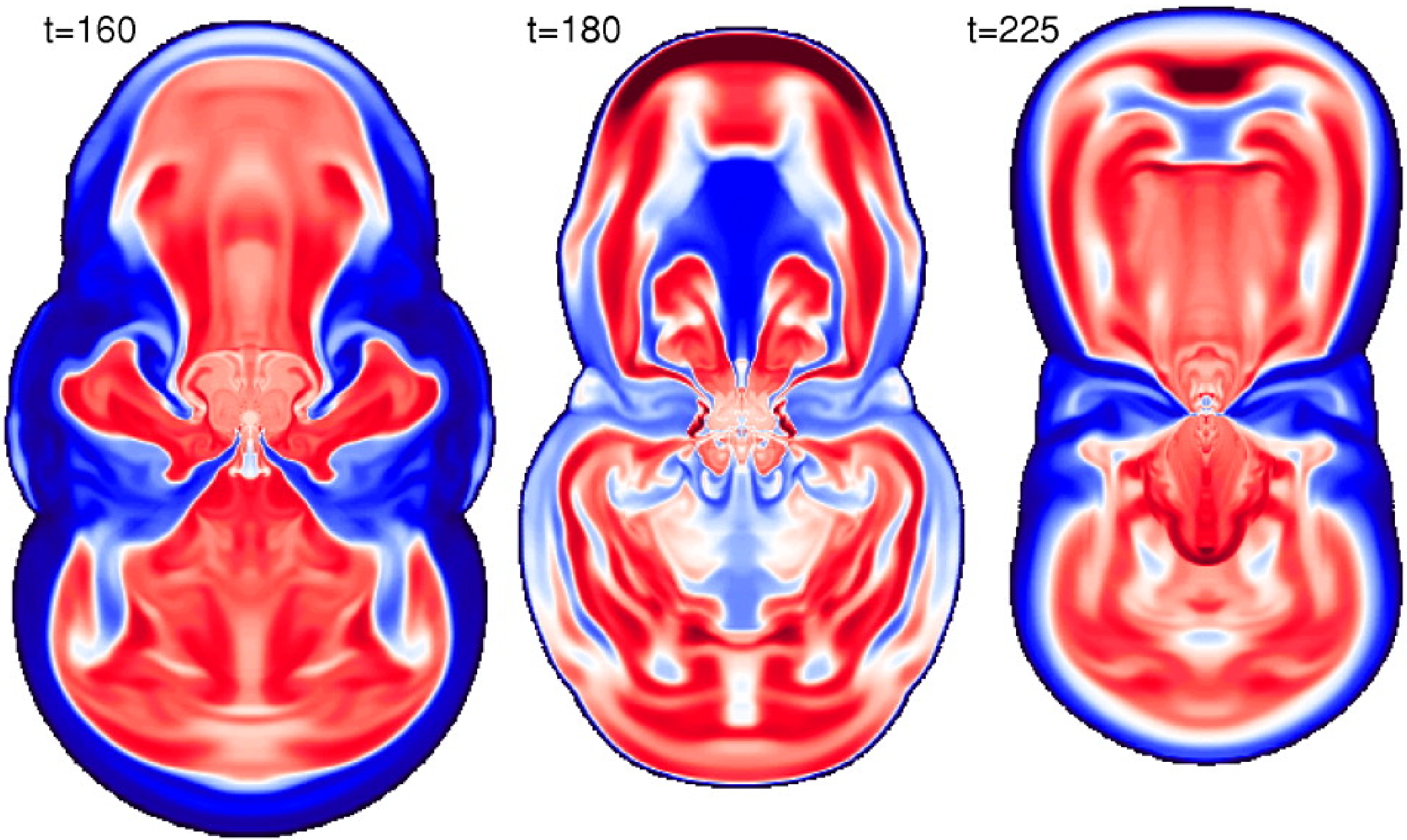
Scheck et al. 2003





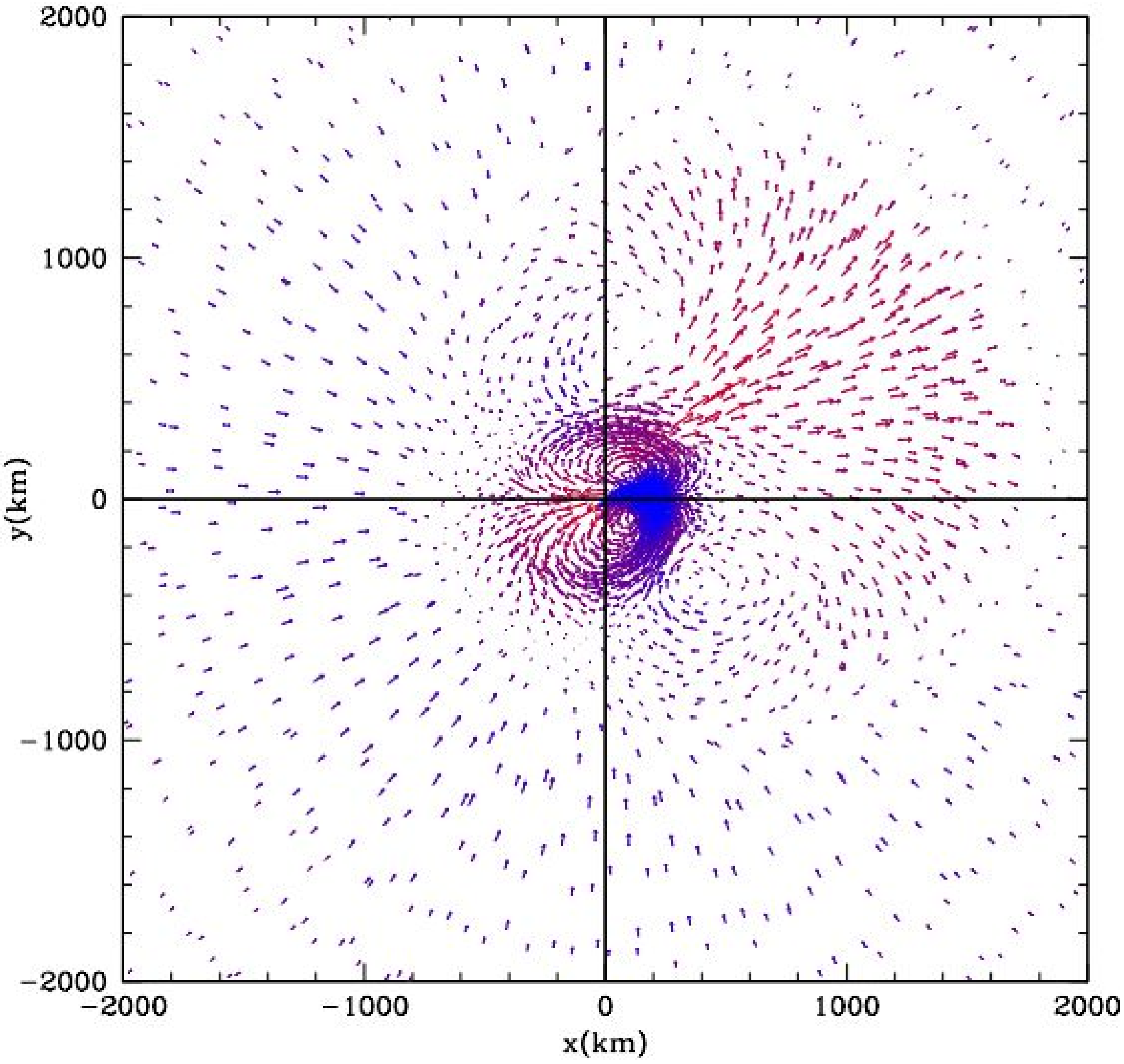

SN15A–hr
SN15B
SN15A–nr
SN15C

Instabilities in the Accretion Shock



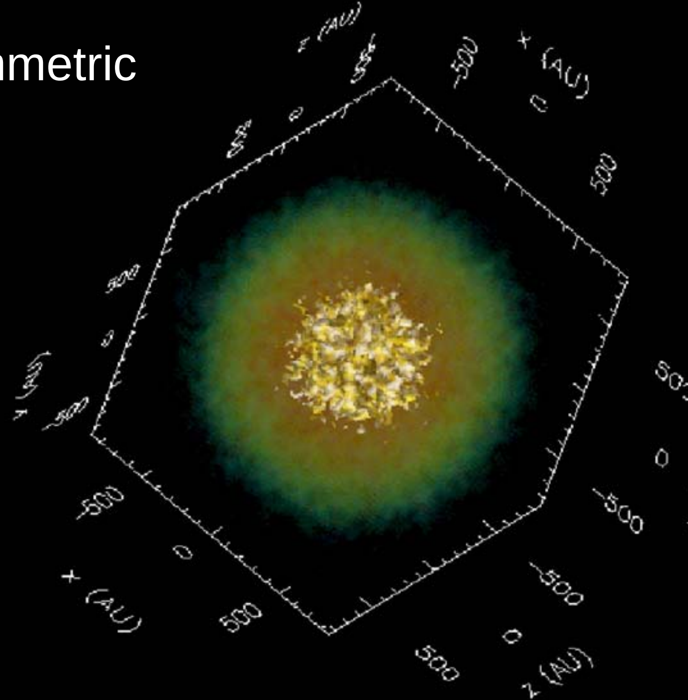
Blondin et al. 2003

Neutrino-Driven Mechanism takes on a new flavor (sterile neutrinos)

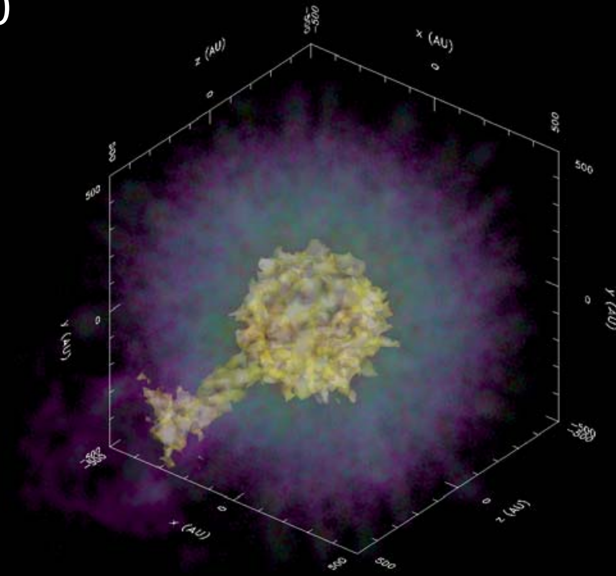


Fryer & Kusenko 2005

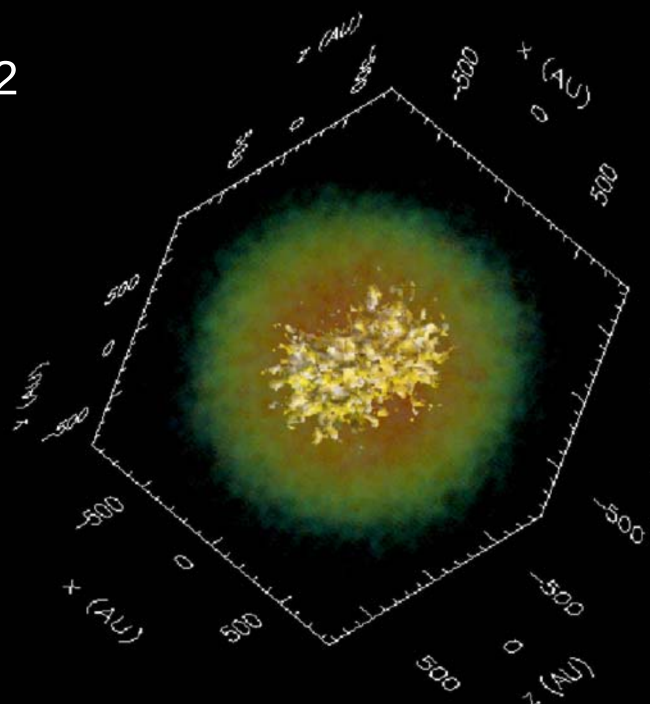
Symmetric



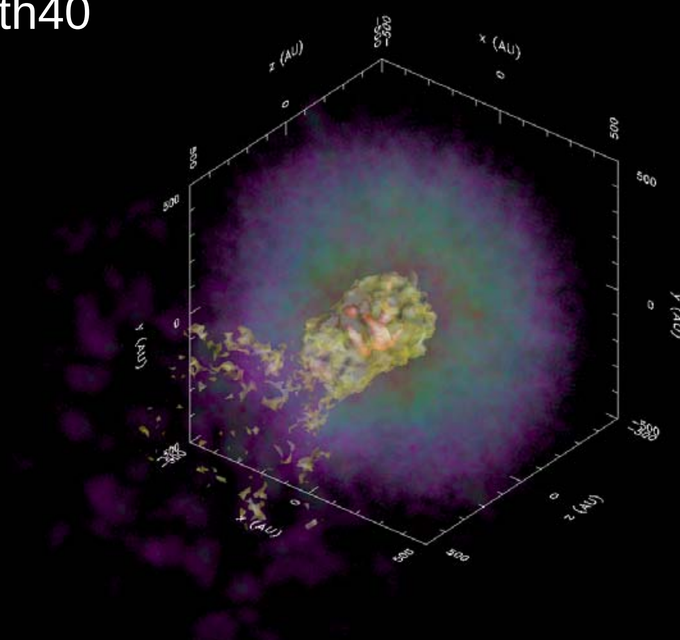
f2th20



Jet2



f3th40



Nucleosynthetic Dependence on Asymmetries

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

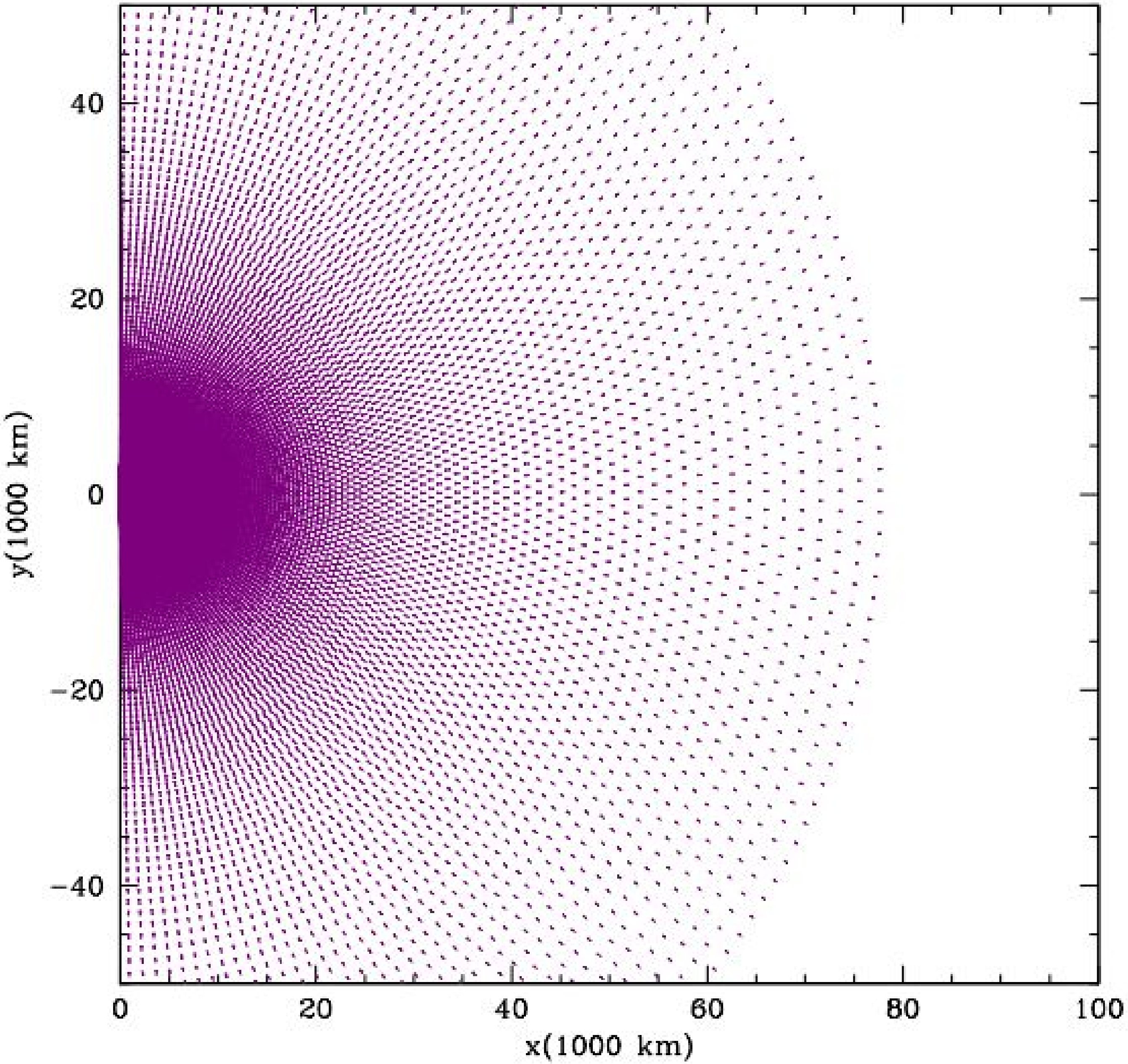
Table 1
^{44}Ti and ^{56}Ni Yields for a Range of 1-dimensional Supernovae

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

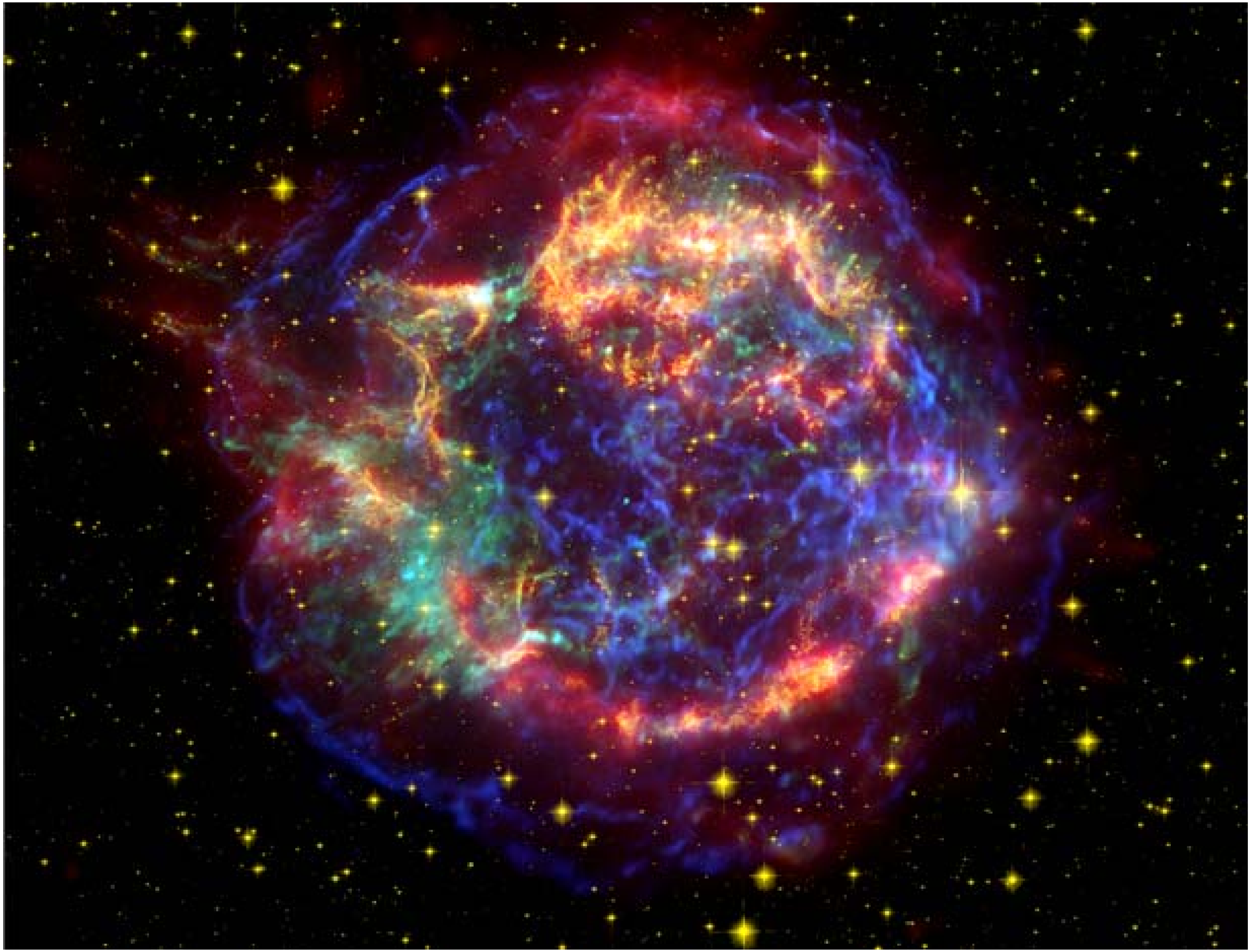
[a] $Y_e = 0.50$
[b] $Y_e = 0.495$
[c] Weak and (p,n) Reactions On
[d] Weak and (p,n) Reactions Off

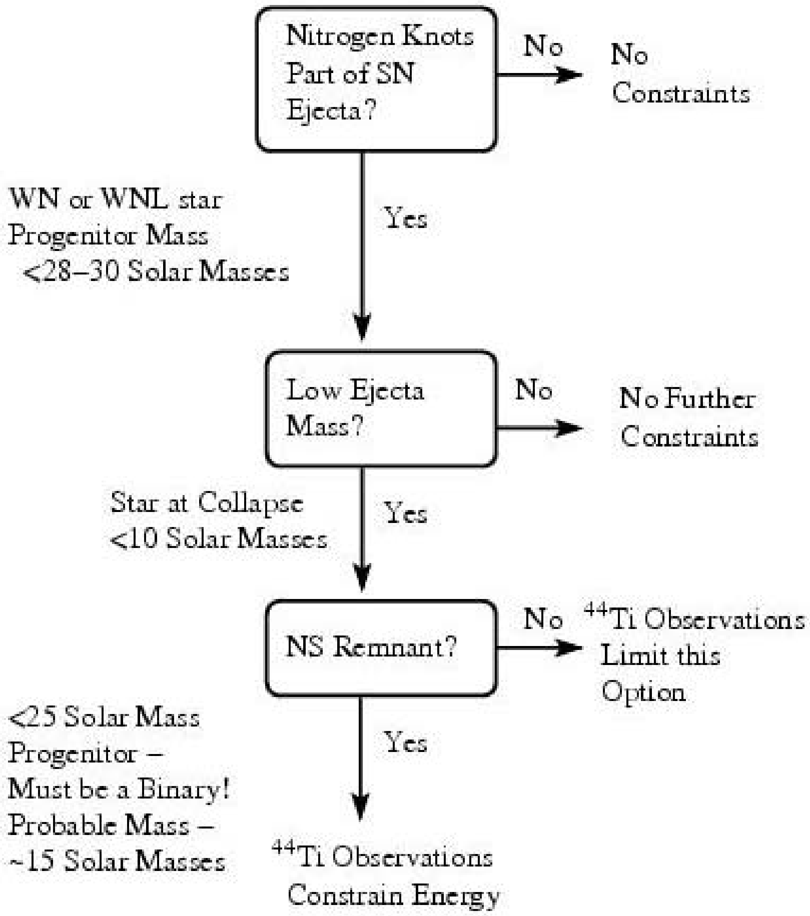
Asymmetries and the r-process:

Here we must also move away from the spherically symmetric paradigm!

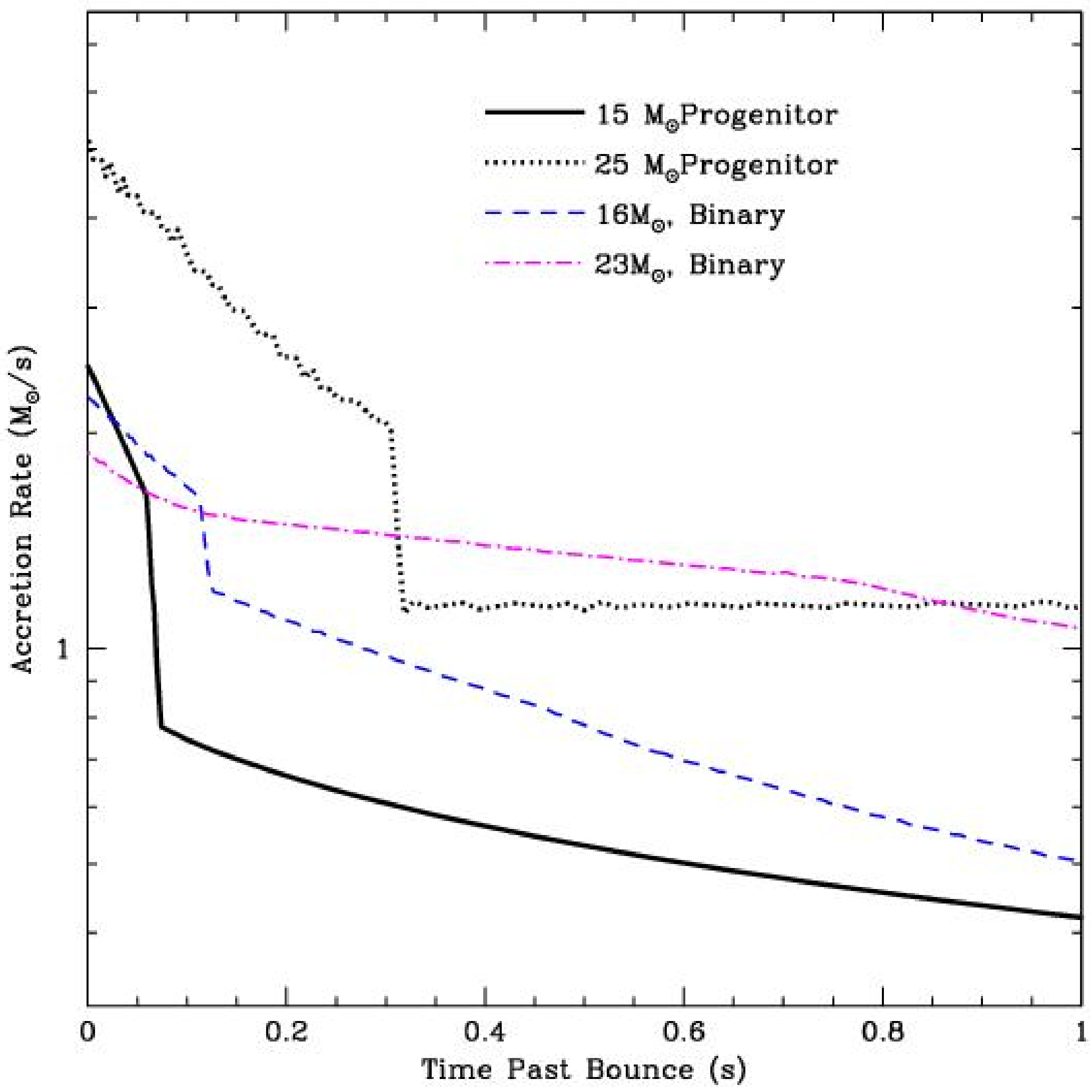


Cas A: A strongly constrained supernova!





The many observations of Cas A do not allow us much wiggle room as to the nature of its progenitor.



The Cas A supernova had an explosion energy of 2-4 foe. We now know that the progenitor was a 16-23 solar mass binary star.

Any supernova code must be validated against these observations!