Explosions From Stellar Collapse

Chris Fryer
Los Alamos National Laboratory

Supernova

- "Super-nova" termed by Baade & Zwicky (1934) to describe the extra-luminous novae.
- With the discovery of the neutron, Zwicky (1938) proposed that the collapse of a massive star to a star composed of neutrons could power these supernovae.
- 10^{53} erg released, but most supernovae are 10^{51} erg = 1 foe = 1 Bethe.

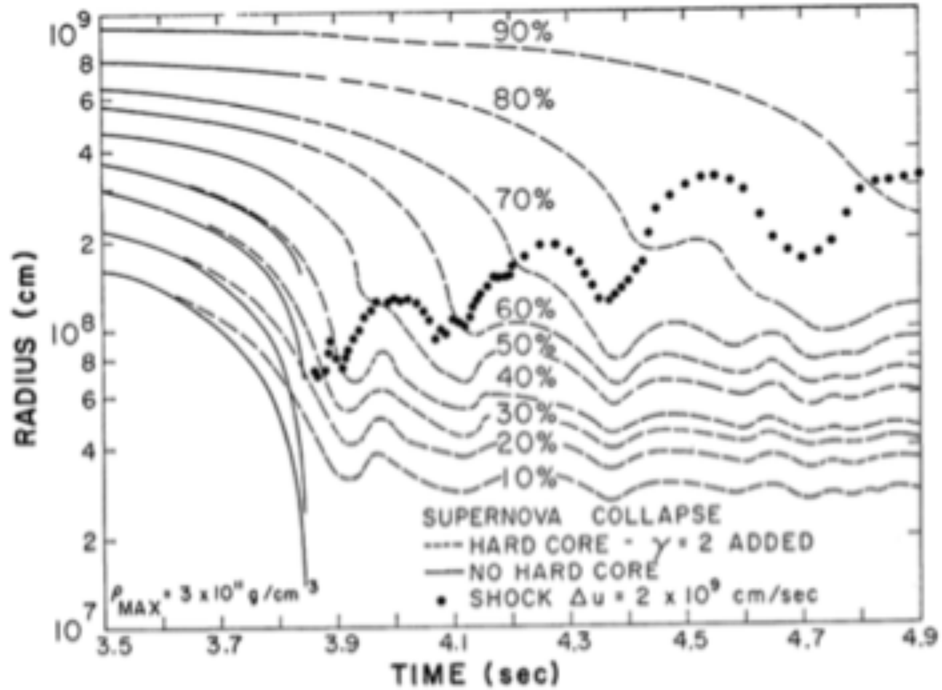
$E_{released} = GM_{core}/r_{NS} - GM_{core}/r_{core} =$ ~10^{53} erg

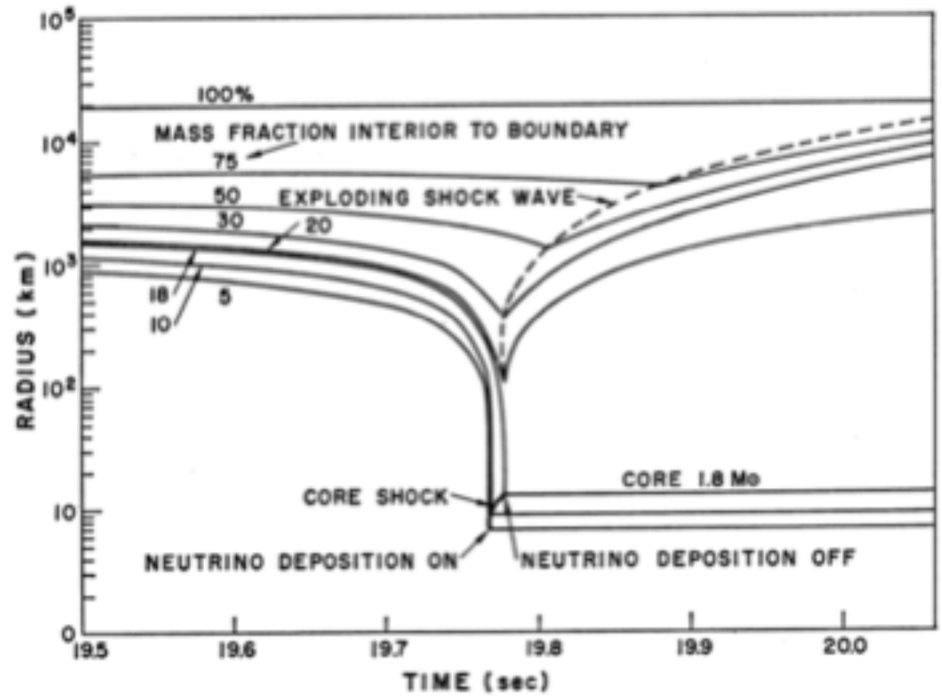
Fritz Zwicky

Hans Bethe

Core-Collapse Supernovae and Neutrinos

- Although considerable energy is released in the collapse, extracting that energy to drive an explosion is more difficult.
- The bounce shock tends to stall or produce weak explosions (dissociation of heavy elements, neutrino losses).
- Colgate & White (1966) proposed that neutrinos from the hot, collapsed core (proto-neutron star) could revive explosion.





Supernova Engines

SNe as standard candles proposed in 1938 (Zwicky),
but this didn't become a reality for nearly 5 decades.

2 Standard Engines

- Collapse of a normal star down to a neutron star (Baade & Zwicky - 1934)
- Thermonuclear explosion of a star (Hoyle & Fowler 1960)
- Both Models Exist in Nature - determing the progenitor has been the hard part.

"That which is not forbidden is compulsory"
-T.H. White

- Many models (and progenitors) have been proposed, but many require extreme conditions (rulled out by Occam's Razor) may explain peculiar transients.

"Pluralitas non est ponenda sine neccesitatem"
"Plurality should not be posited without necessity"
- William of Ockham

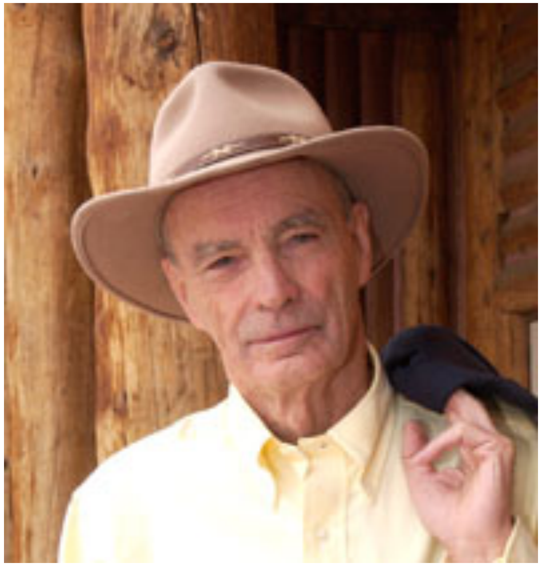
"We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances."
- Isaac Newton

White's Mandate

- Everything which is not forbidden is compulsory
- If the laws of physics do not forbid a phenomenon, Nature will find a way to make it.

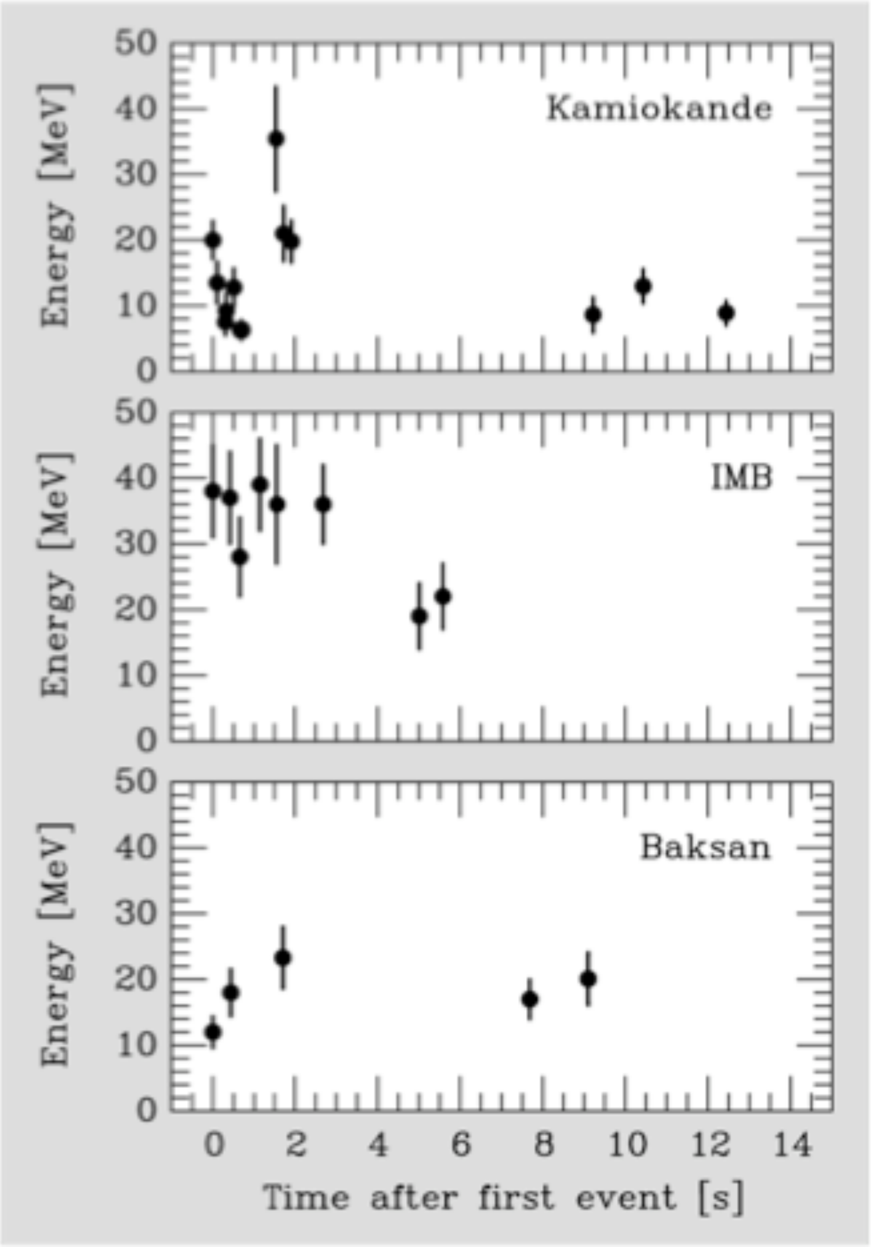
Core-Collapse versus Thermonuclear Supernovae

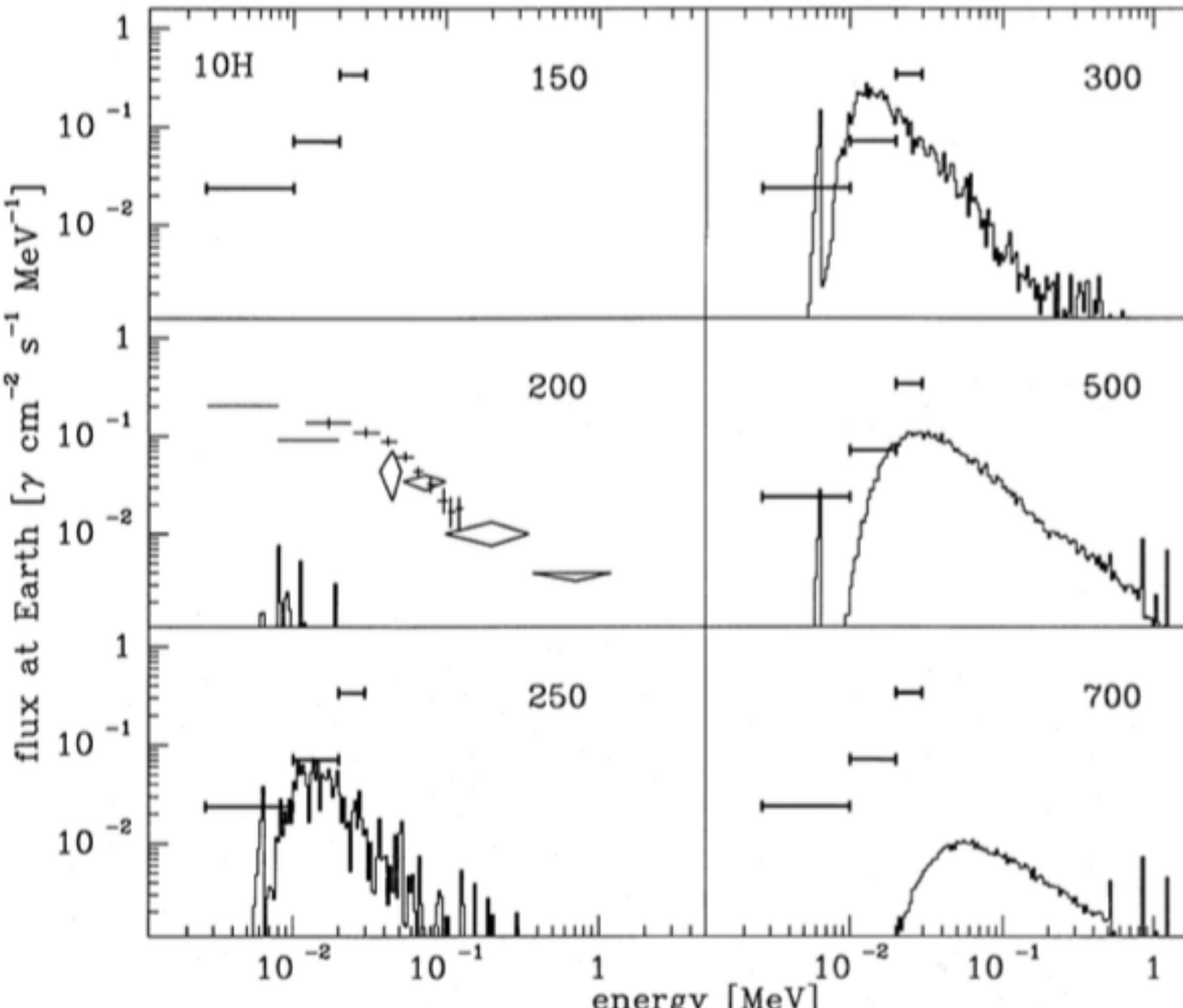
- Early debates on supernova fleshed out many of the properties of supernovae:
- Importance of equation of state (Colgate & White 1966, Arnett 1966)
- Nucleosynthesis (issues of neutronization in core-collapse Arnett & Cameron 1967)
- Fallback (Colgate 1968)
- …



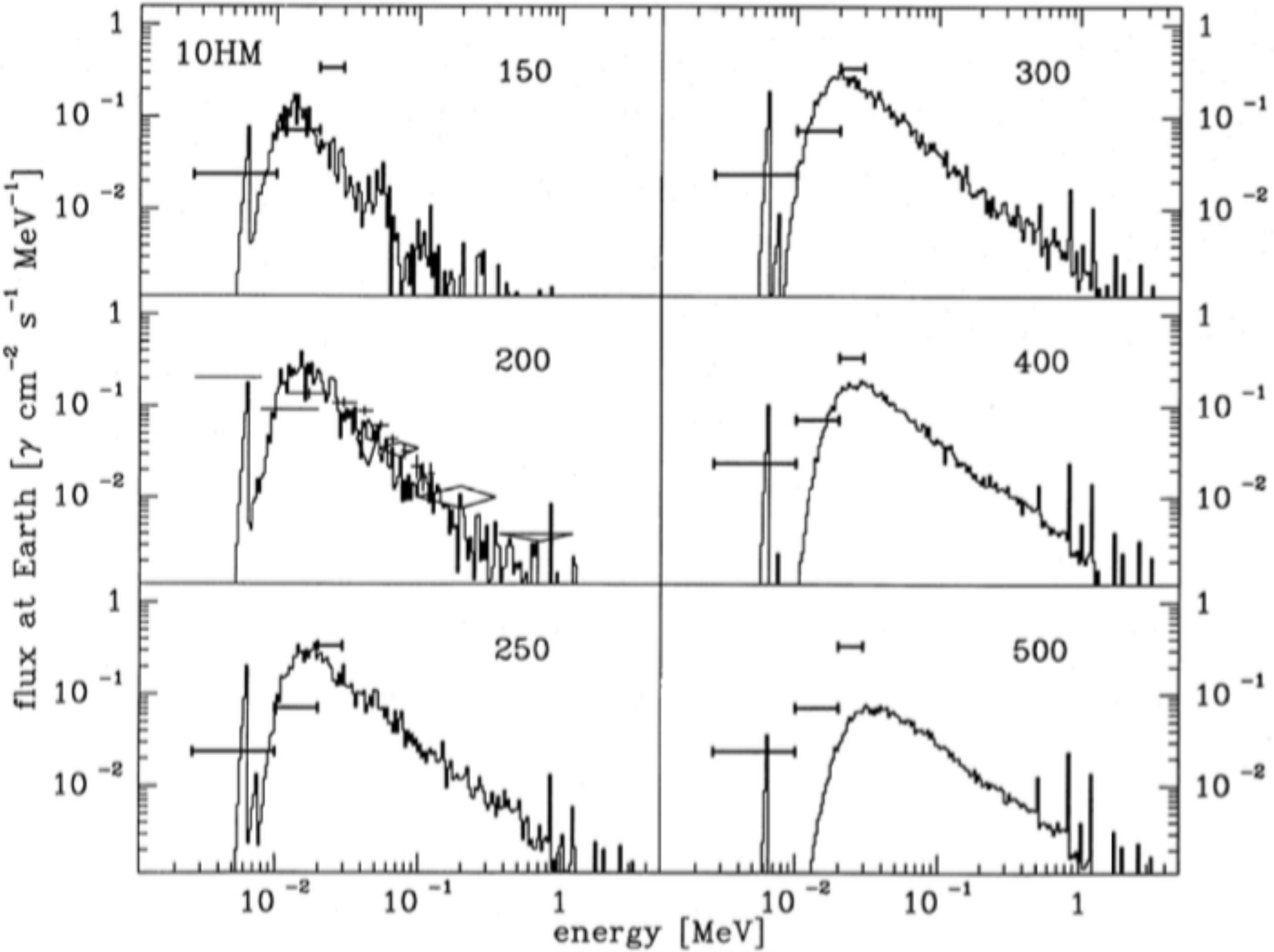
Discoveries from SN 1987A

- Neutrinos detected matching collapse calculations.
- Progenitor star observed – it IS a massive star!
- But the progenitor isn't a red supergiant
- But the gamma-rays appeared early
- But there were redshifted lines
- But, but, but….



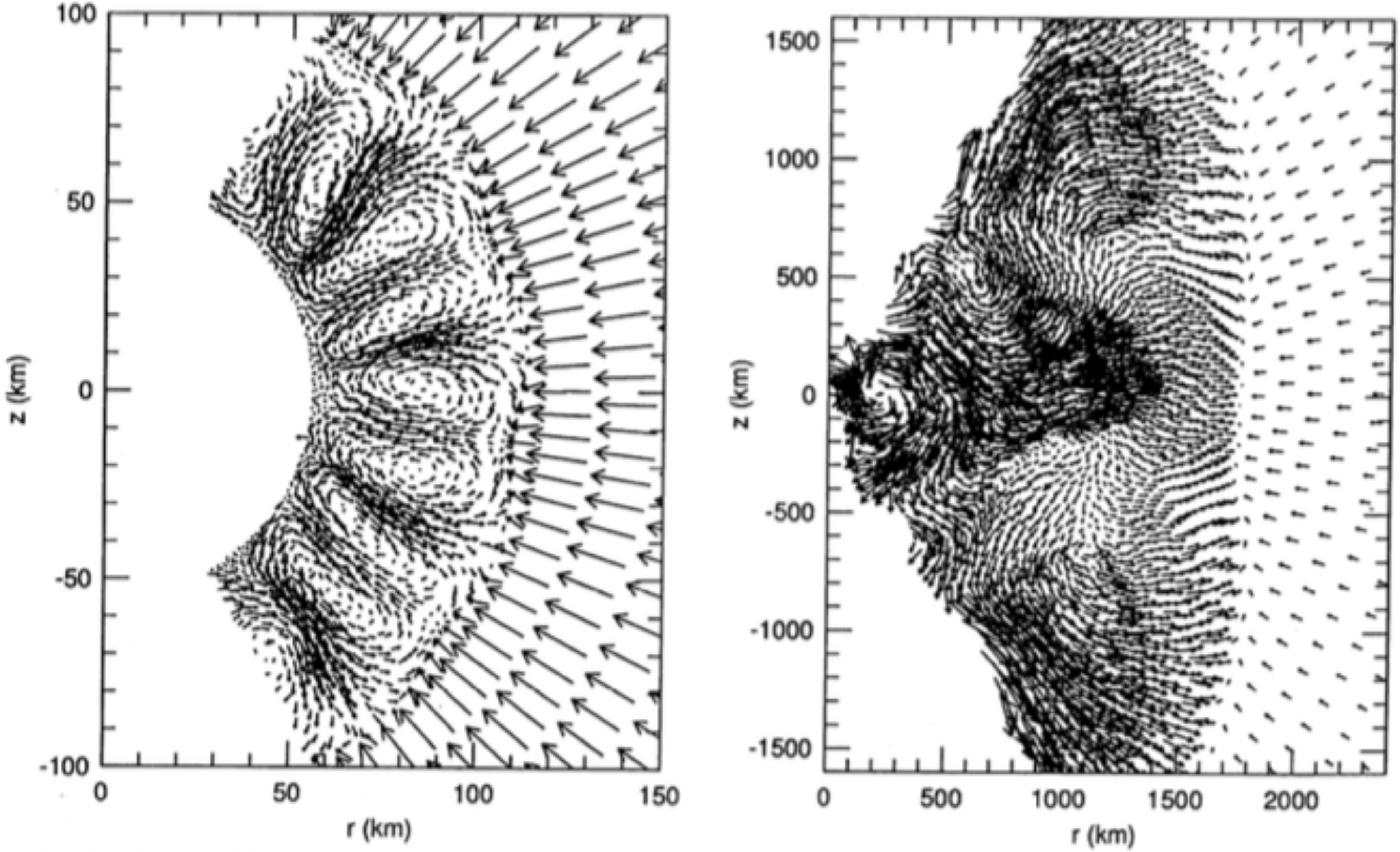


10H
150
300
200
500
250
700
flux at Earth [γ cm^{-2} s^{-1} MeV^{-1}]
energy [MeV]
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1



10HM
150
200
250
300
400
500
flux at Earth [γ cm^{-2} s^{-1} MeV^{-1}]
energy [MeV]
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1

To explain this mixing, Herant et al. (1992) needed early seeds – the birth of the convective engine (Herant et al. 1994)

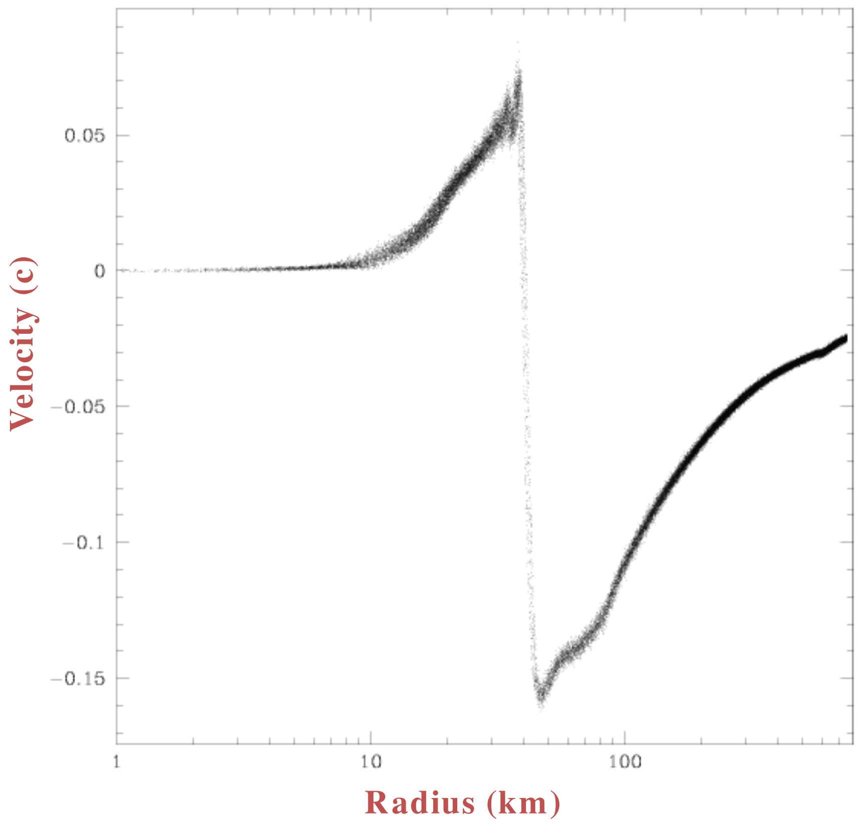


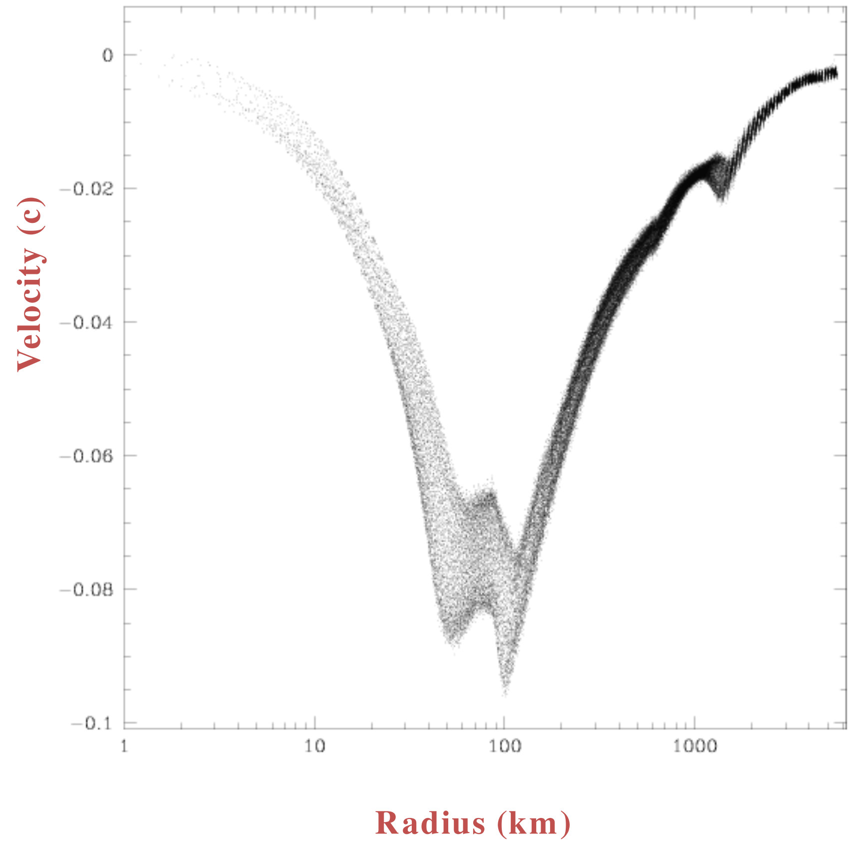
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:

- Iron dissociates into alpha particles
- Electrons capture onto protons

Core collapses nearly at freefall!



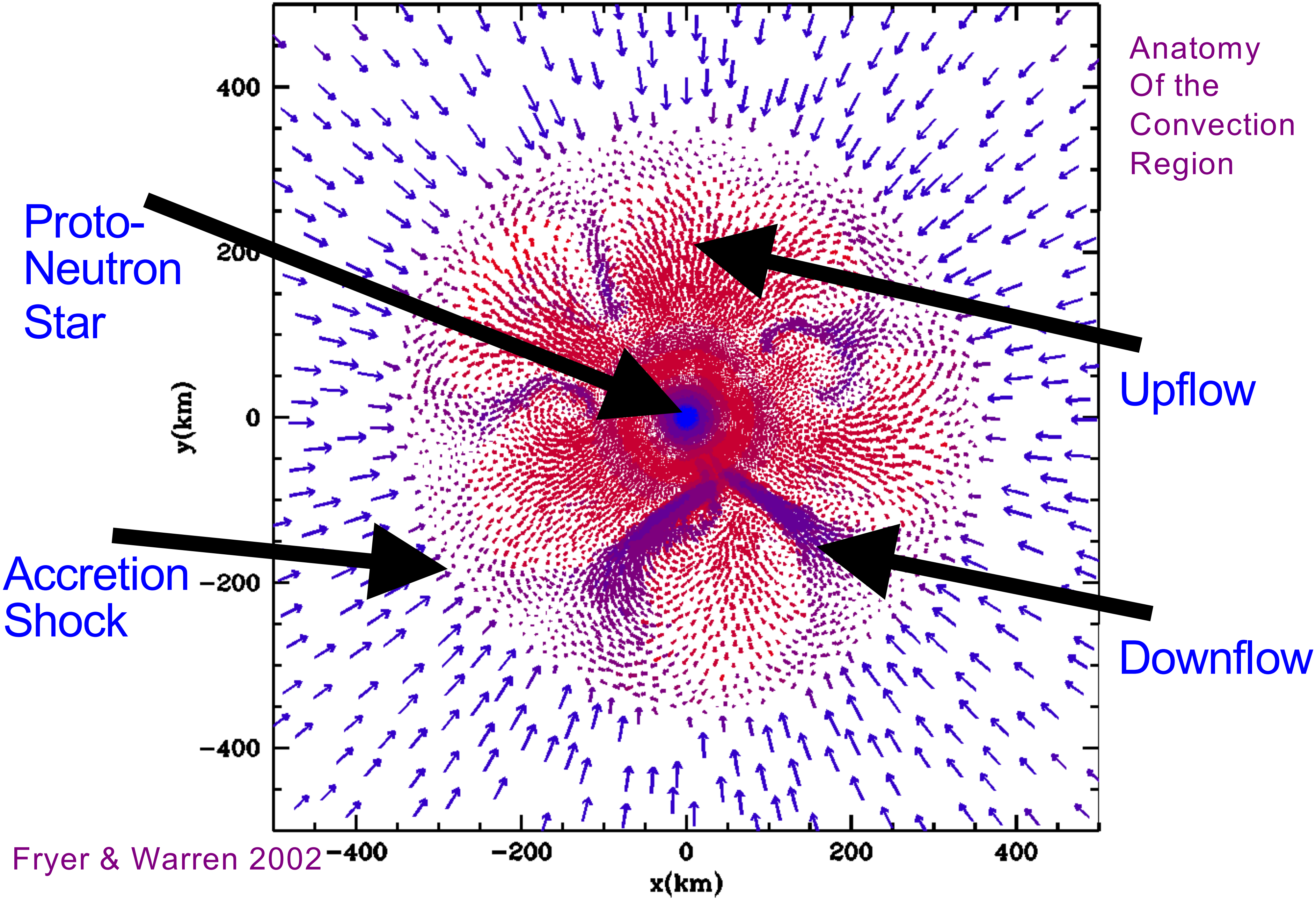


Core reaches nuclear densities

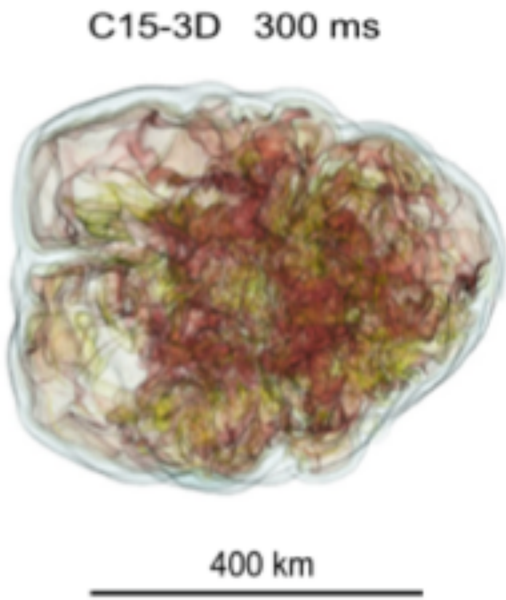
Nuclear forces and neutron degeneracy increase pressure

Bounce!

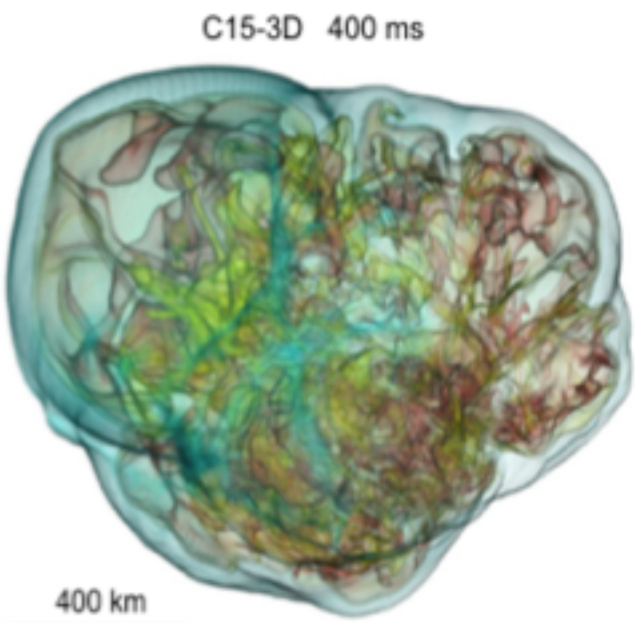
The Herant et al. (1994) Convective Supernova Engine



Fryer & Warren 2002



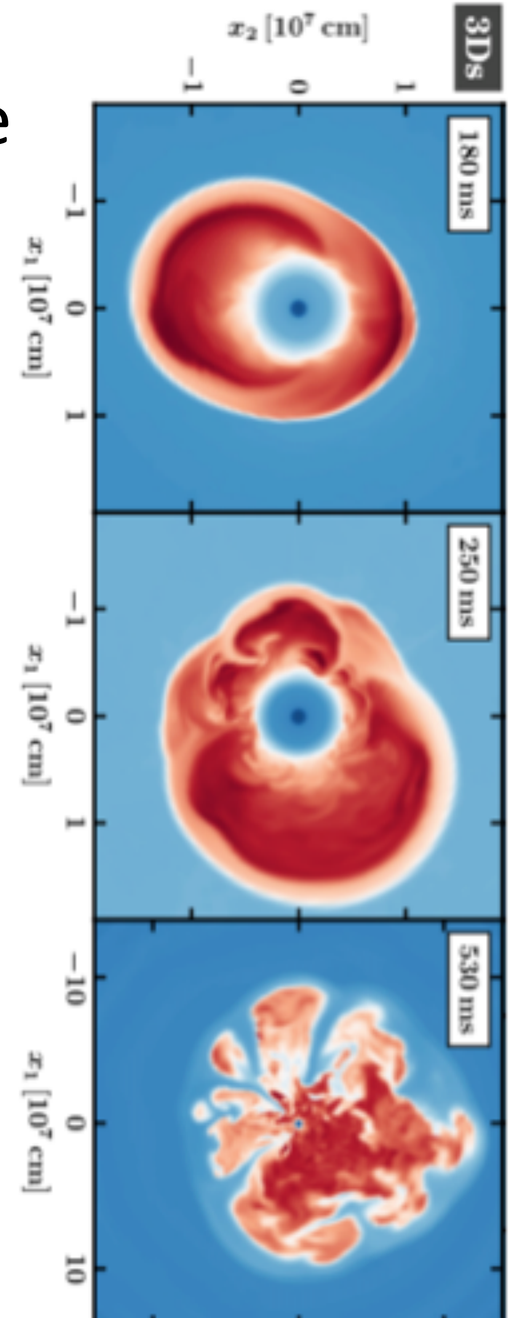
Lentz et al. 2015



Depending on the physics, most groups now produce explosions with this convective engine.

Most arguments focus on the:

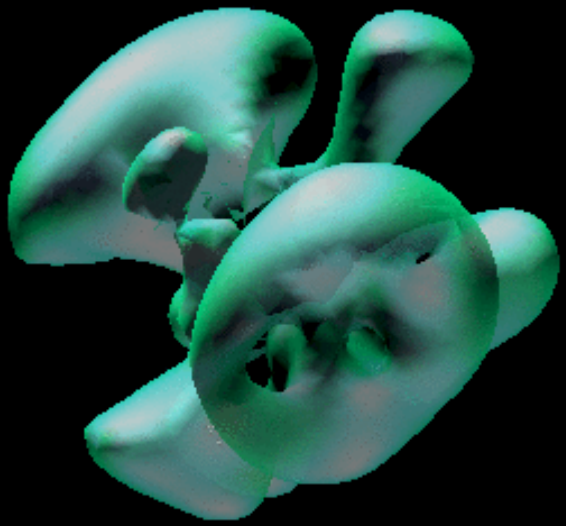
- Most important physics
- Source of instabilities



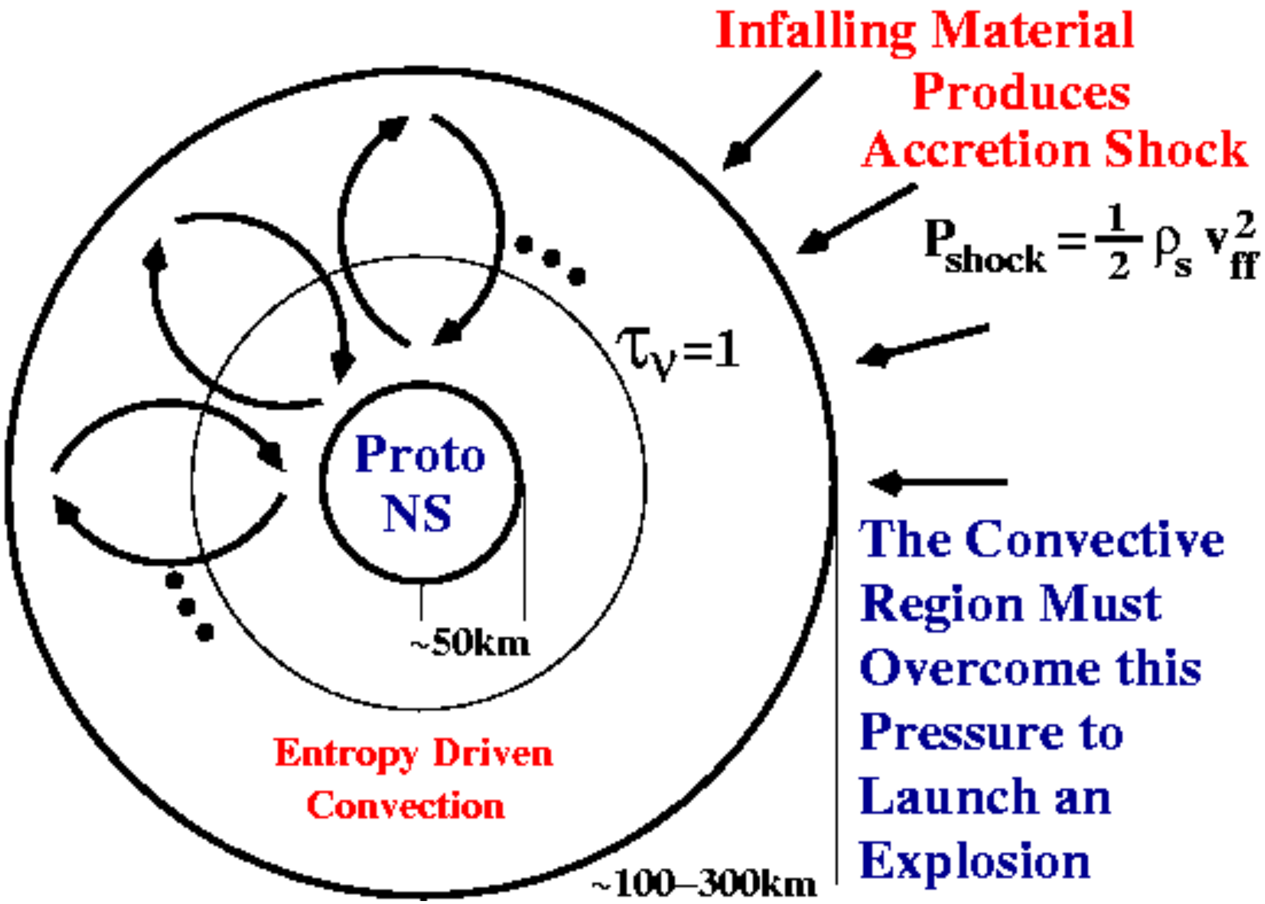
Melson et al. 2015

Ejecta Remnants – Probing Low Mode Convection

- In most simulations, low mode convection driven by Rayleigh-Taylor or advective-acoustic instabilities seem to dominate the flows.
- Although this has dominated the focus of theorists for nearly 20 years, until recently, we had no evidence of such flows.



Neutrino-Driven Supernova Mechanism: Convection

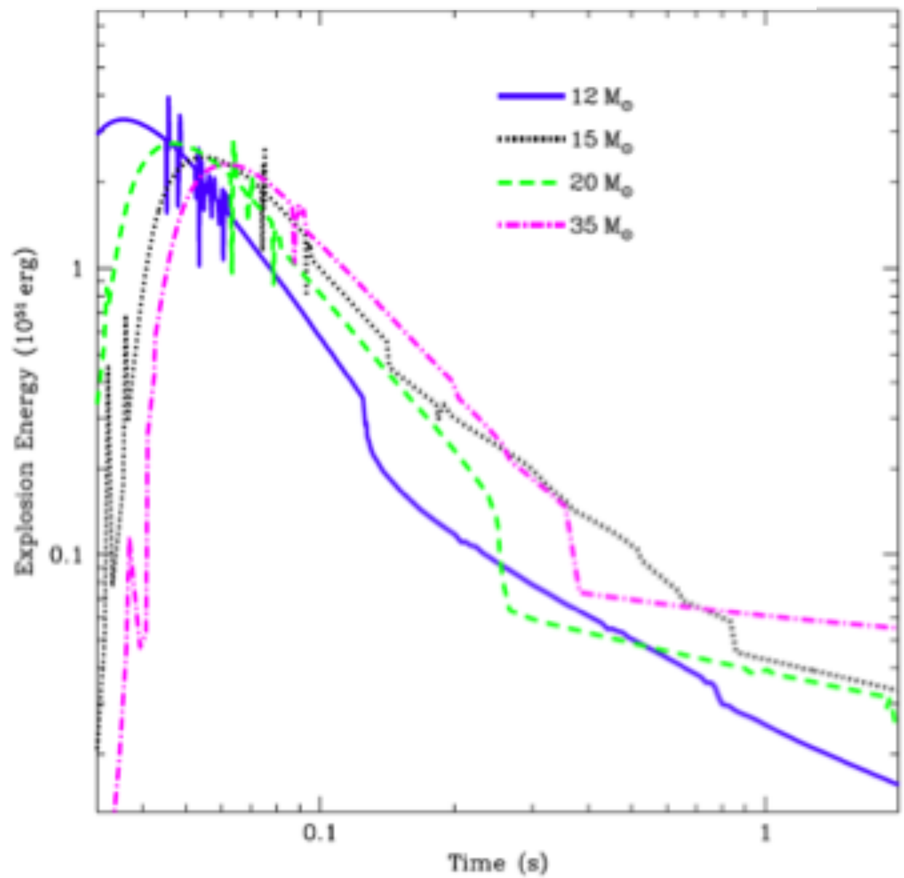


Fryer 1999

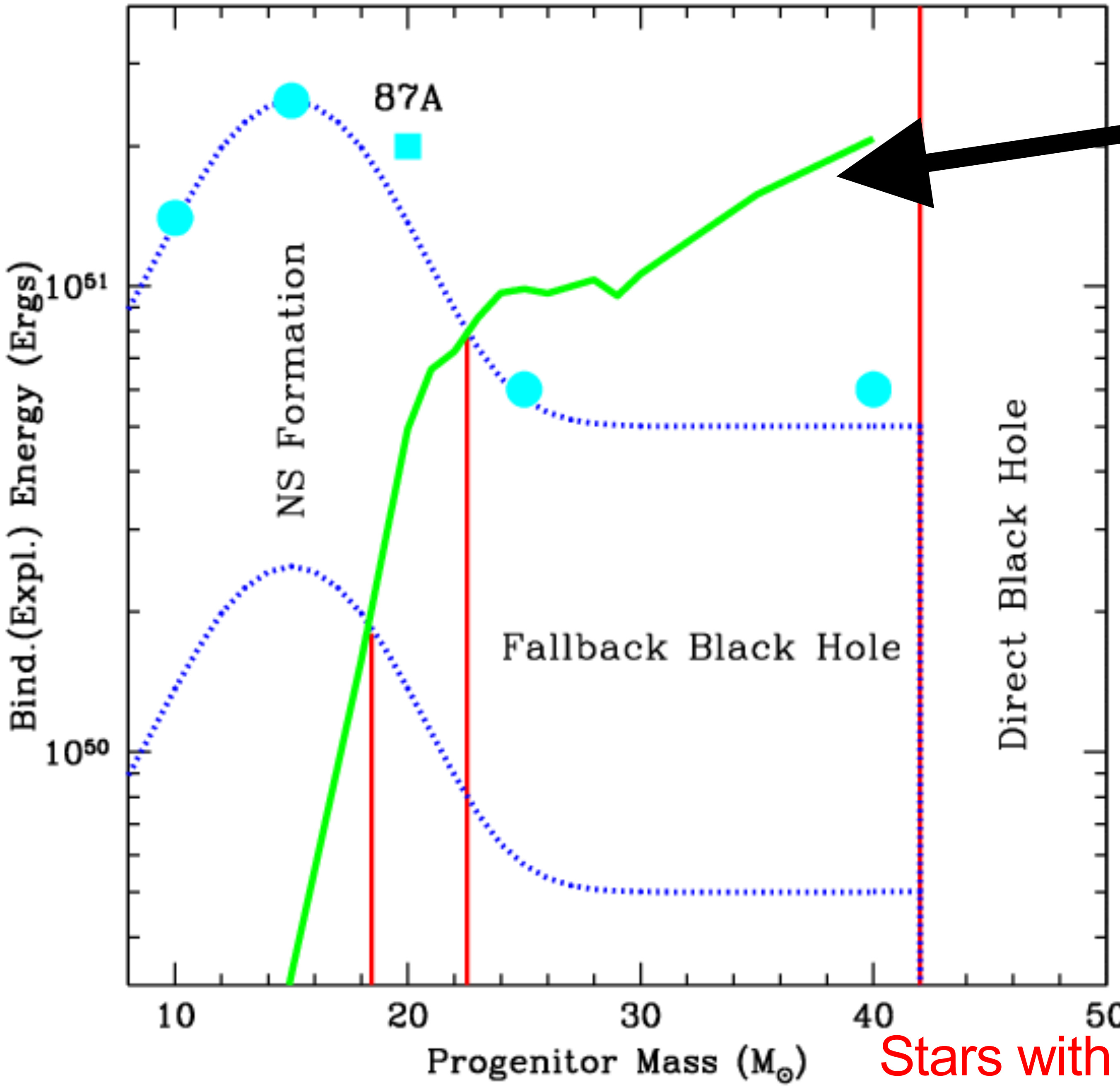
$$P_{\text{shock}}(r) = 1/2\rho_{\text{shock}}v_{\text{free-fall}} = (2GM_{\text{NS}})^{0.5}\dot{M}_{\text{acc}}/(8\pi r_{\text{shock}}^{2.5})$$

$$u_{\text{convection}}(r) = 3\left[4.7\times10^{8}\frac{M_{\text{NS}}}{M_{\odot}}\frac{10k_{\text{B}}\text{nucleon}^{-1}}{S_{\text{rad}}}\left(\frac{10^{6}\text{cm}}{r}-\frac{10^{6}\text{cm}}{r_{\text{shock}}}\right)+\right.$$
$$\left.1.2\times10^{6}\left(\frac{M_{\text{NS}}}{M_{\odot}}\frac{\dot{M}_{\text{acc}}}{M_{\odot}\text{s}^{-1}}\right)^{1/4}\left(\frac{2\times10^{7}\text{cm}}{r_{\text{shock}}}\right)^{5/8}\right]^{4}\text{erg cm}^{-3}.$$

- For most stars, the maximum energy is a few times 10^{51} erg. Fallback can increase this value, but not by much.
- This is a natural explanation for the energy, but it means that this engine can not explain hypernovae.



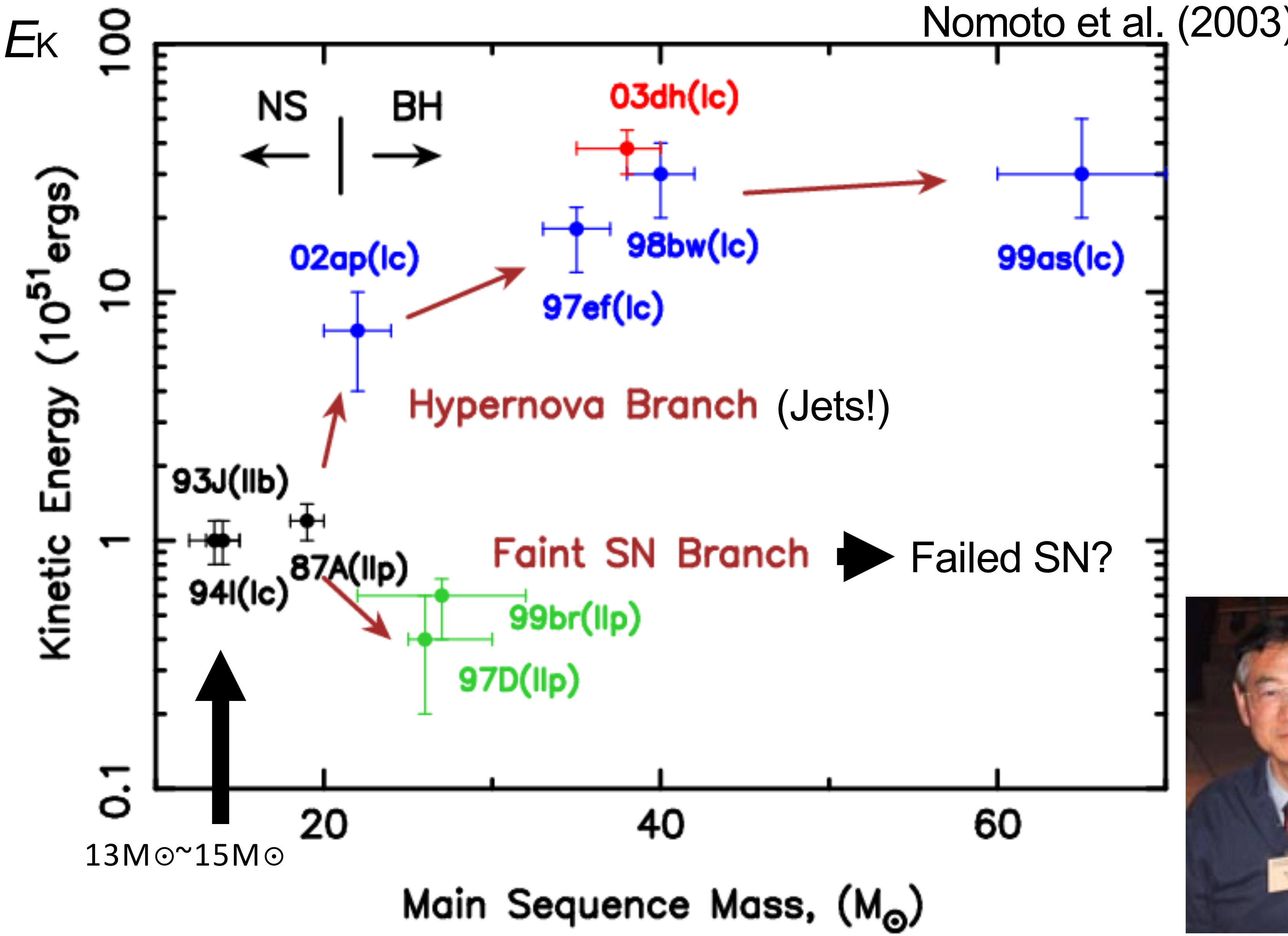
Fryer 1999



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

Stars with NO mass-loss

Supernovae/Hypernovae



Description of Physics

The difficulty in modeling core-collapse engines lies in the fact (based both on simulations and the observed NS/BH distribution) that the success or failure of this engine depends sensitively on a broad range of physics:

- Hydrodynamics and Turbulence
- Equation of State – Dense Nuclear Matter w/ phase transitions
- Neutrino Transport and Cross Sections
- Nuclear Burning
- Magnetic Fields
- General Relativity

Fluid Mechanics (Lagrangian Formalism)

I) Mass Conservation (Continuity Equation)

$V = 1/\rho = 4\pi r^2\, \partial r/\partial m$

II) Momentum Conservation

$dv/dt = -4\pi r^2 \partial P/\partial m$

III) Energy Conservation

$d\epsilon/dt = -PdV/dt = P/\rho^2\, d\rho/dt$

With $d\rho/dt = -\rho\nabla\cdot\vec{v} = -\rho/r^2\, \partial(r^2 v)/\partial r$

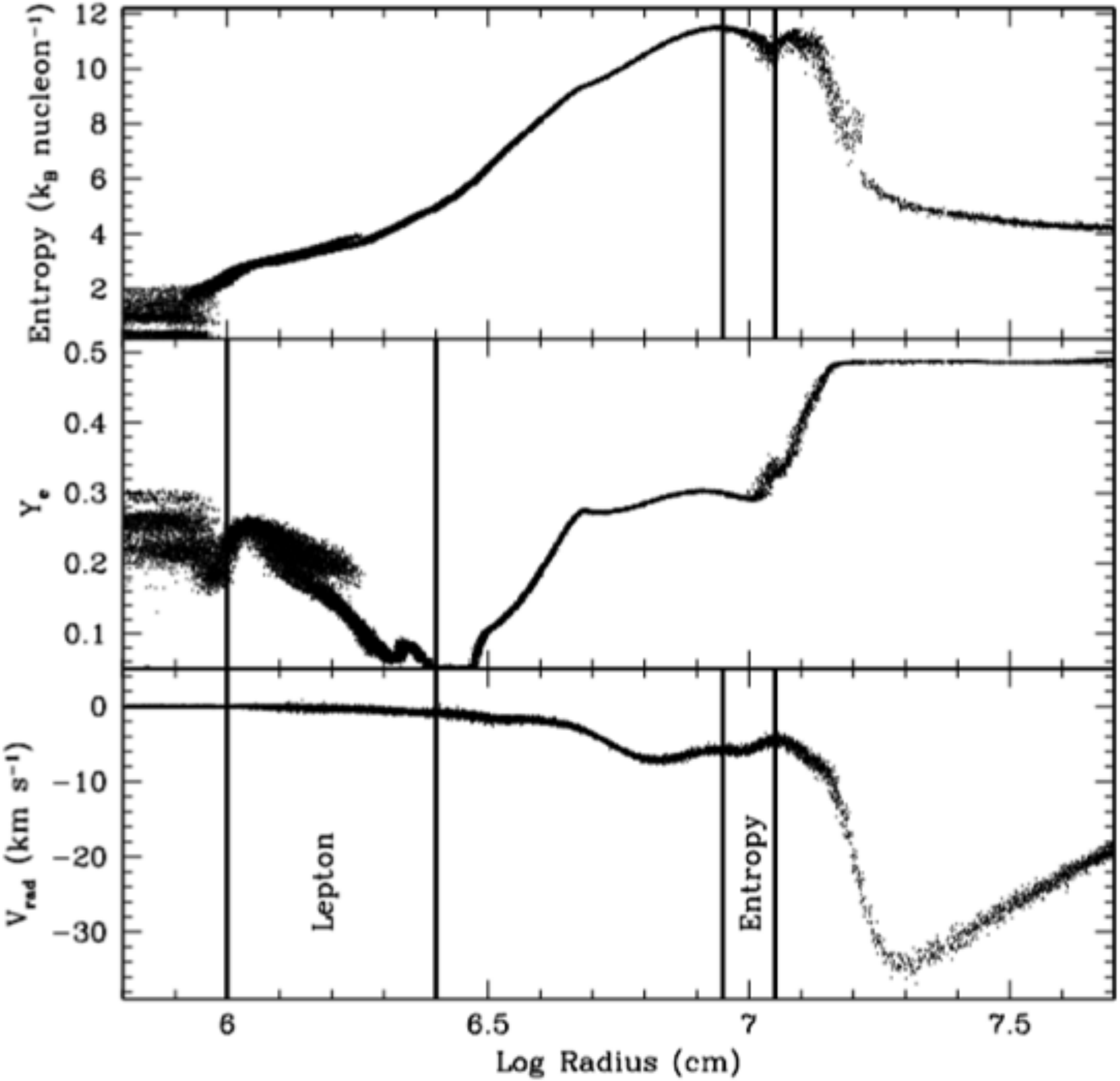
and $dm = 4\pi r^2 \rho dr$, the energy equation is:

$d\epsilon/dt = -4\pi P\partial(r^2 v)/\partial m$

IV) Equation of State

e.g. $P=(\gamma-1)\rho\epsilon$

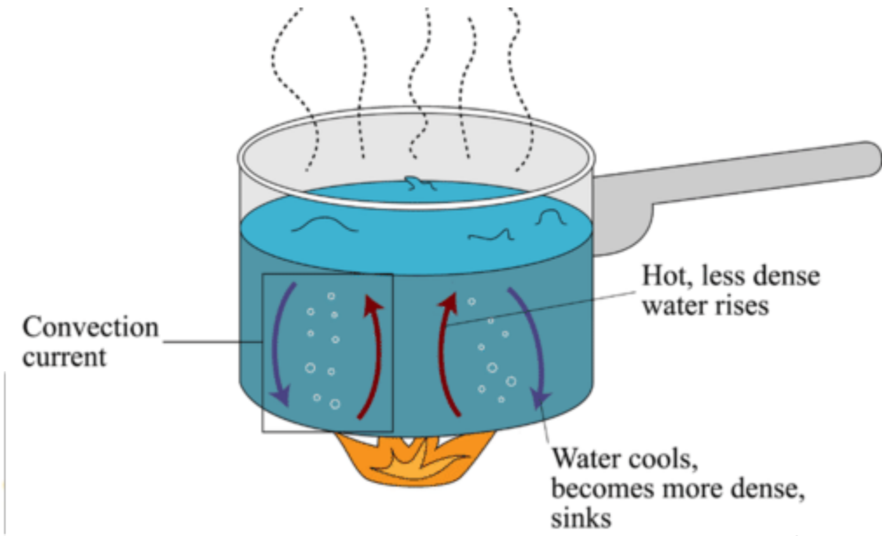
Post-Bounce Conditions: Two regions of Instabilities



Fryer & Young 2007

Convective Instabilities

Growth time is relatively well known: Brunt-Vaisala frequency

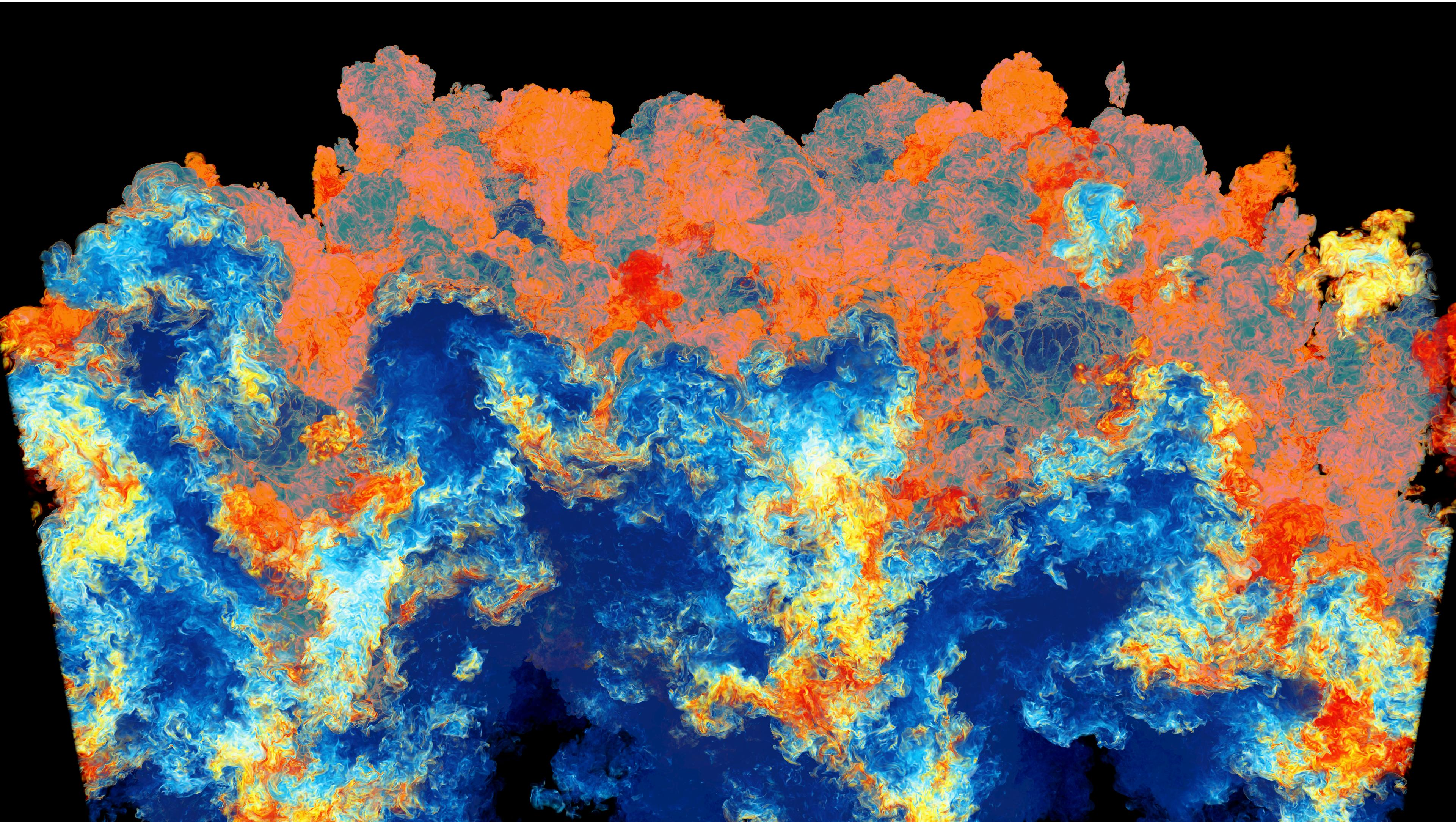


$$\omega^2 = g/\rho(\partial\rho/\partial S)_{\mathrm{P}}(\partial S/\partial r)$$

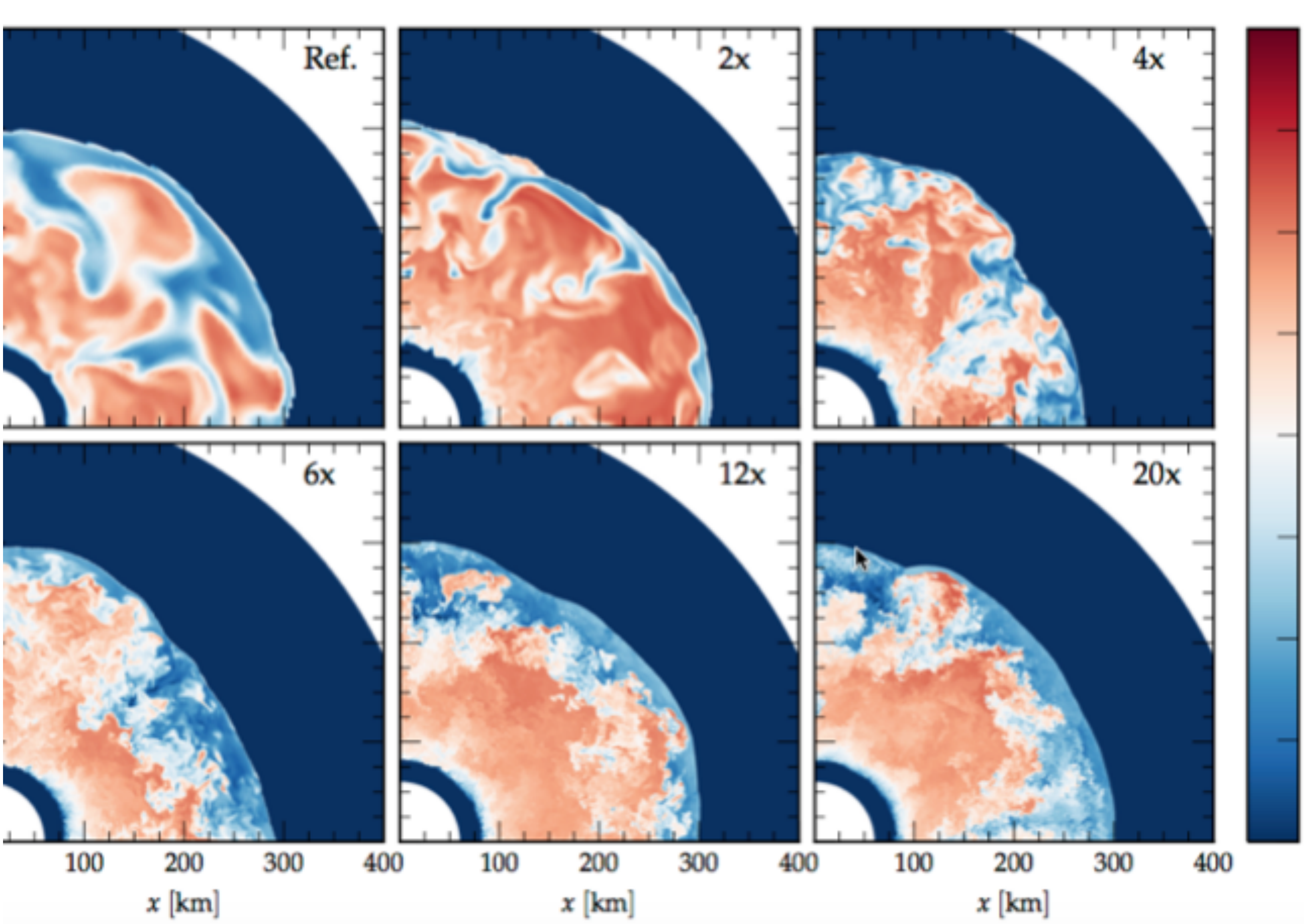
$$\omega^2 = g/S(\partial S/\partial r) \approx (1/S)\left(GM_{\mathrm{enclosed}})/r^2\right)(\Delta S/\Delta r)$$

For Supernovae, the growth time is 2ms – most calculations have too much numerical viscosity and damp this convection.

High-resolution is needed



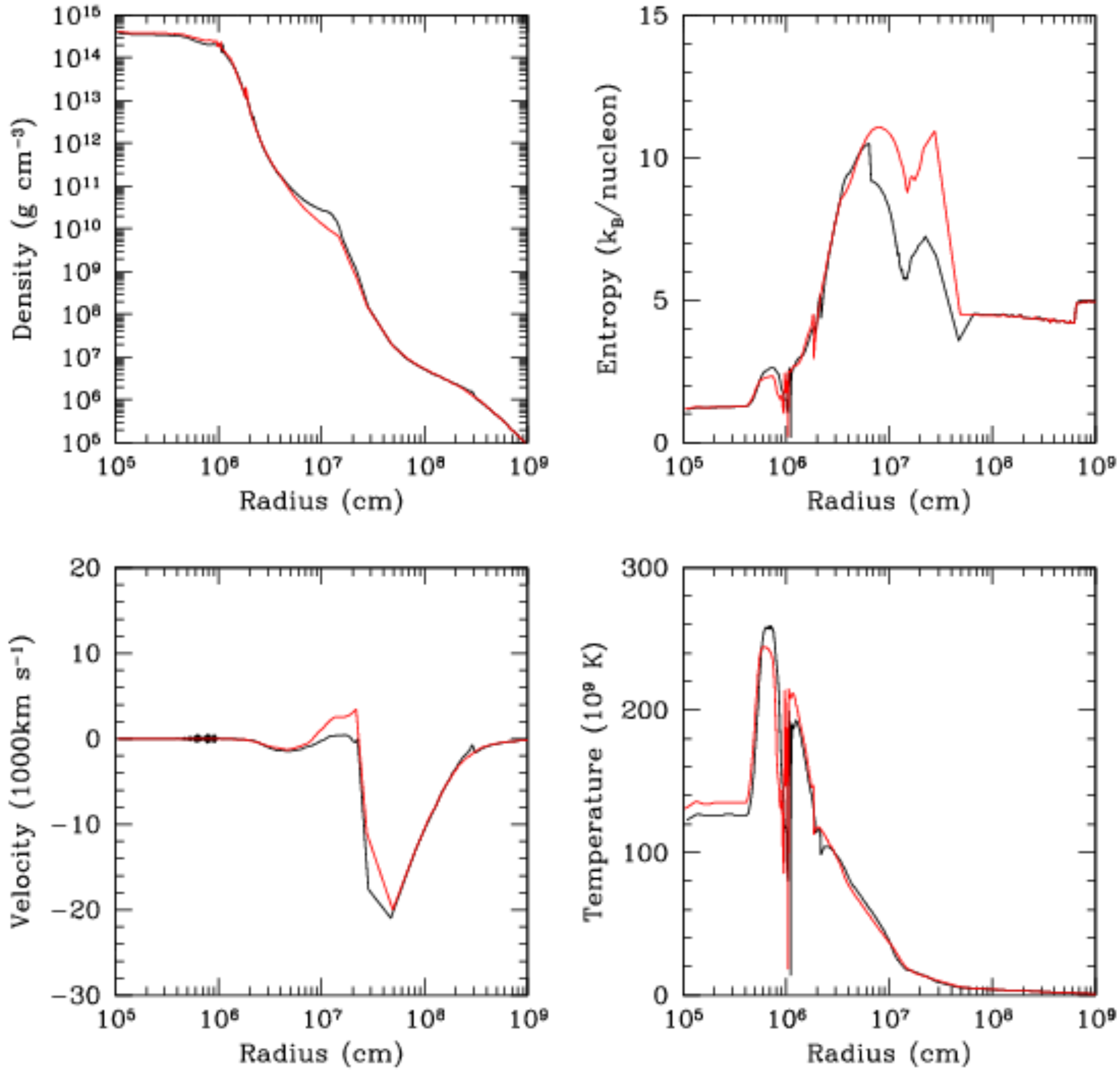
8000x8000x1000 zone, enhanced PPM models, Dimonte et al. 2010



Radice et al. 2016

Why did it take so long to reach an agreement?

- Most SN experts were transport experts and didn't realize the convective seeds mattered.
- Another issue with the nuclear energies in the Lattimer & Swesty equation of state at modest densities led altered the collapse slightly. But this change in entropy profile makes a huge difference in the early convection.



Neutrino Transport (Boltzmann Equation)

$$1/c\ \partial I/\partial t = j + \int_0^\infty \int_{4\pi} K_s(E'\rightarrow E,\ \Omega'\rightarrow\Omega)\ I(E',\Omega')\ d\Omega'\ dE'$$
$$-\ \Omega\cdot\nabla I - \sigma_t\ I$$

With dP (the differential phase–space volume),

A: $1/c\ \partial I/\partial t dP$ (p/s) represents the time rate of change of particle number in dP.

B: $j dP$ (p/s) represents the rate at which particles are created in dP.

C: $\int\int K_s \ldots dP$ (p/s) represents the rate at which particles scatter into dP.

D: $\Omega\cdot\nabla I dP$ (p/s) represents the rate at which particles acvect out of dP.
Recall that: $\int \Omega\cdot\nabla I\ dV = \oint I\ \Omega\cdot n\ dA$
where n is the unit vector out of the volume.

E: $\sigma_t\ I dP$ (p/s) represents the rate at which particles leave dP through scatter or absorption.

Transport Techniques (Numerical Schemes)

Moments and Moment Closure

Integrate $\mu^a \, d\Omega (a=0,1,...)$

a=0: $1/c \; \partial J/\partial t = (j-\sigma_a)J - \nabla H$

a=1: $1/c \; \partial H/\partial t = C_1 \, H - \nabla K$

...

Flux-Limited Diffusion

$H = -c\Lambda\nabla J$ (Λ is the Flux Limiter)

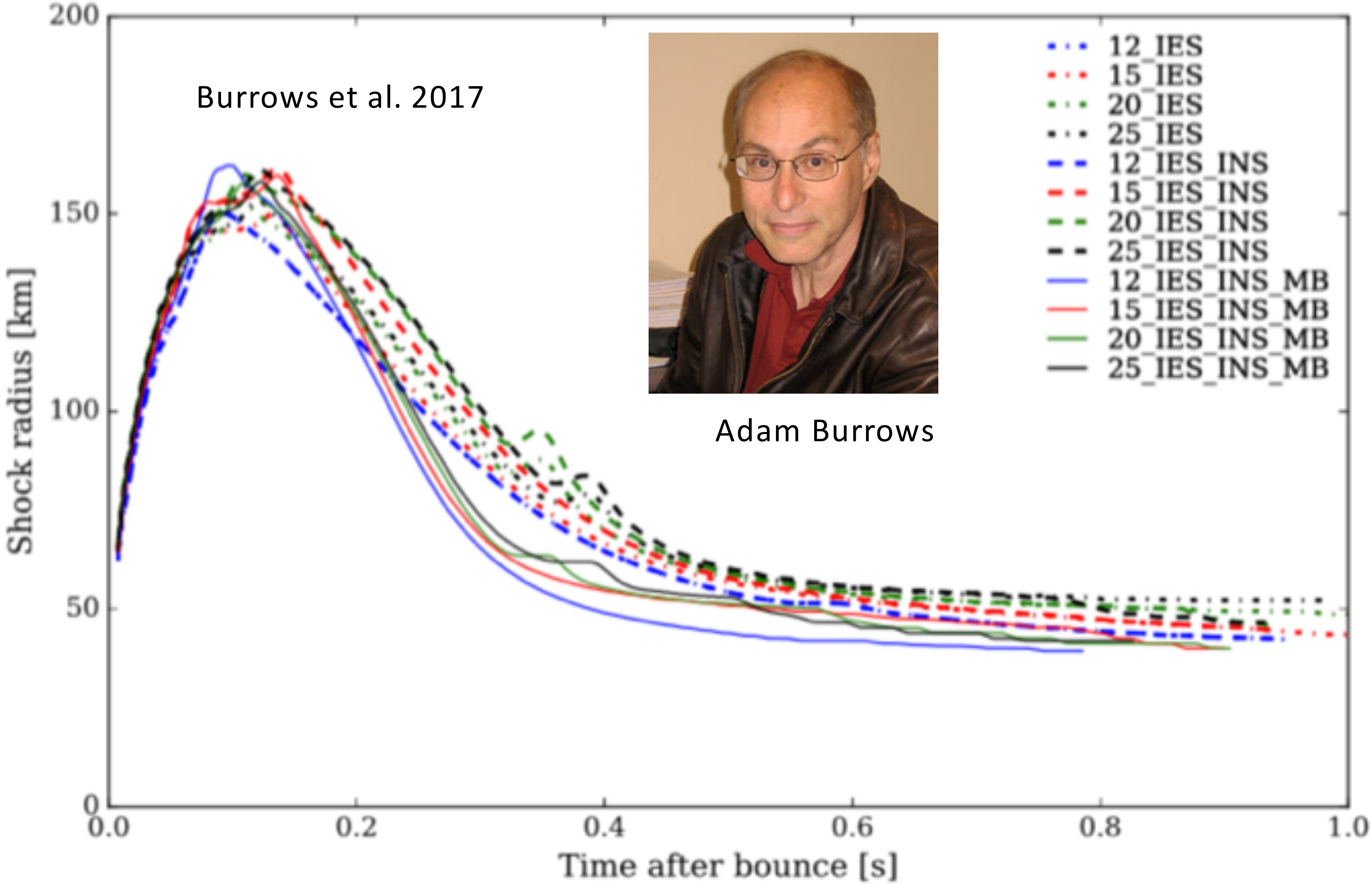
Variable Eddington Factors

Close with K (Solve by iteration)

Can Also Solve Full Boltzman Eq.

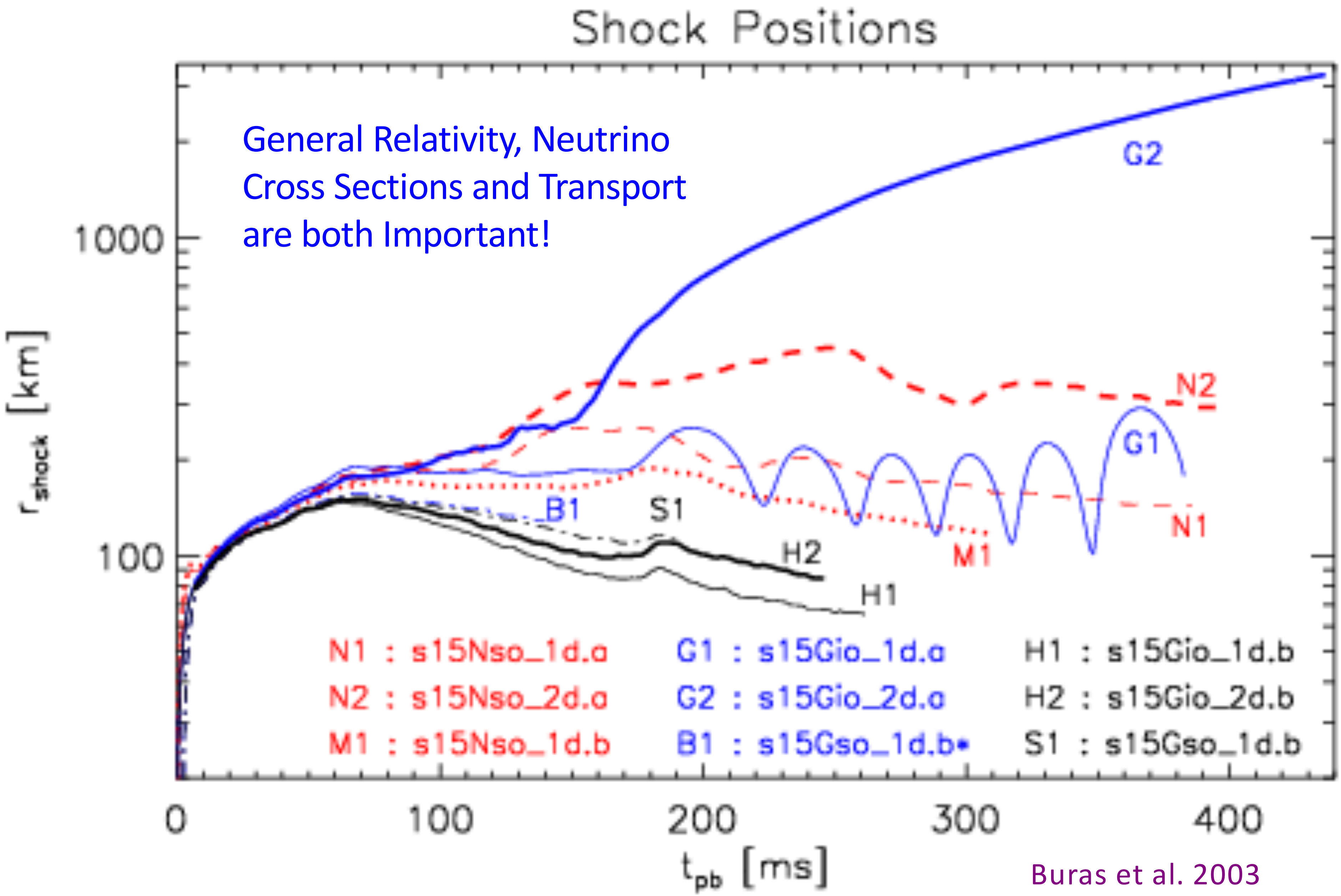
S_n methods, Boltztran (Mezzacappa et al.), ...

Neutrino Effects: As we add many-body effects, the shock moves



Adam Burrows

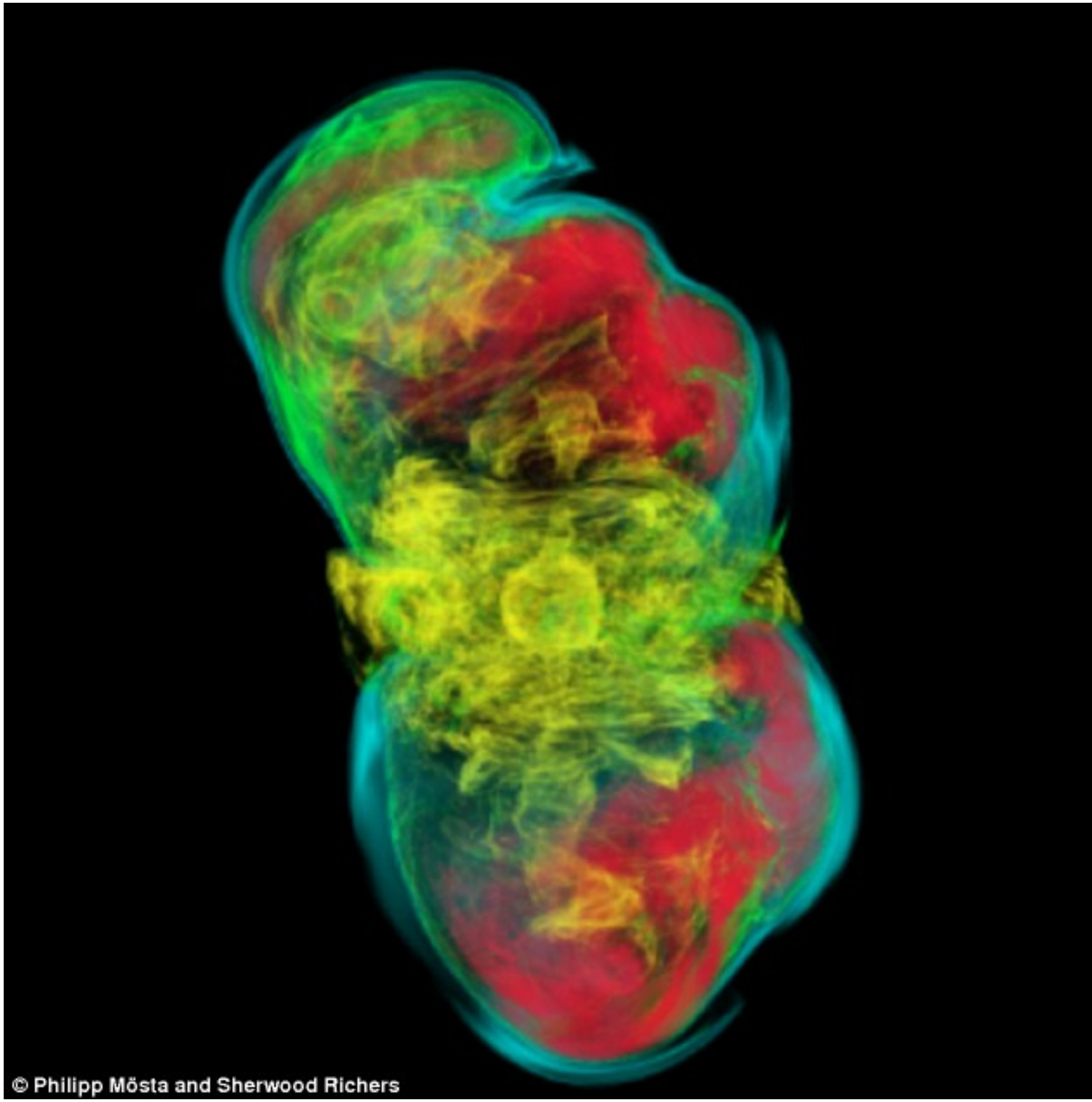
The Bad News – Explosions are NOT Robust!



Buras et al. 2003

Magnetic Fields

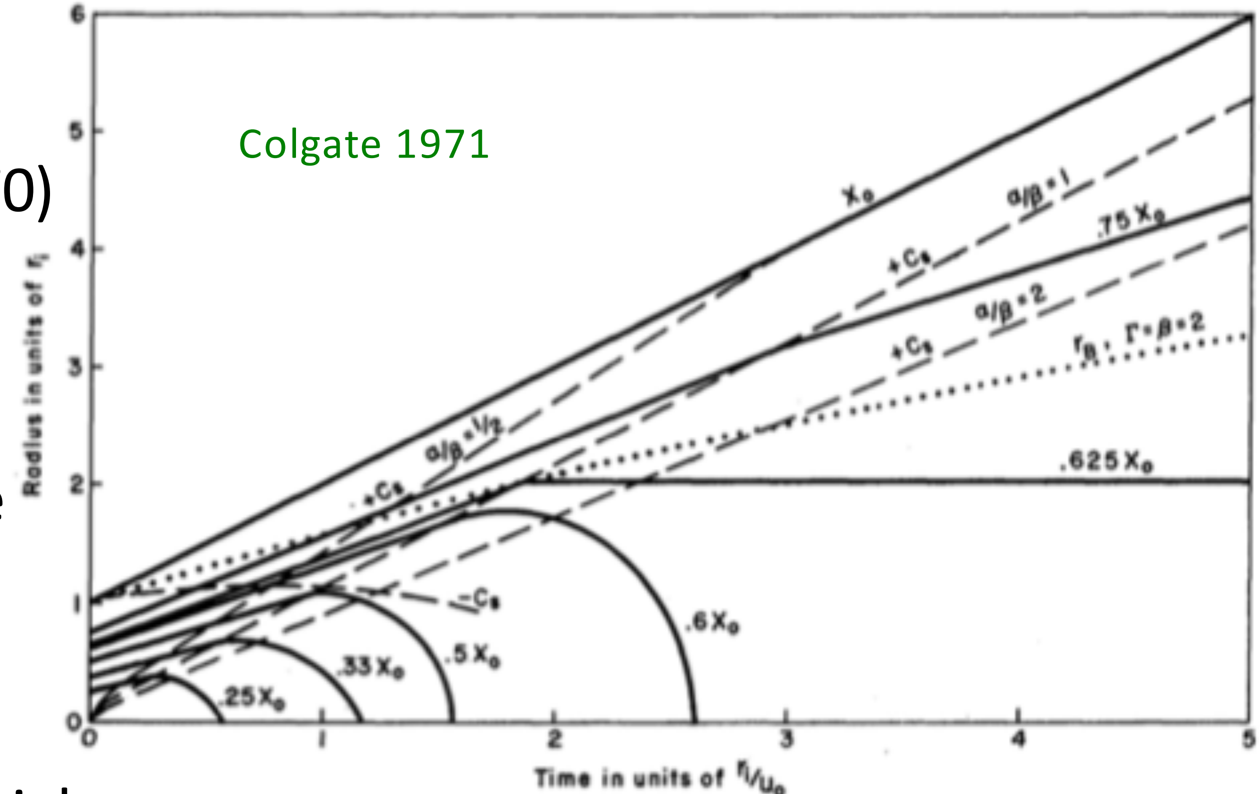
- Even if the magnetic fields are not strong enough to drive a jet, they can affect the fluid flow.
- Strong magnetic fields in the proto-neutron star can alter the neutrino transport.



Mosta et al. 2014

Fallback

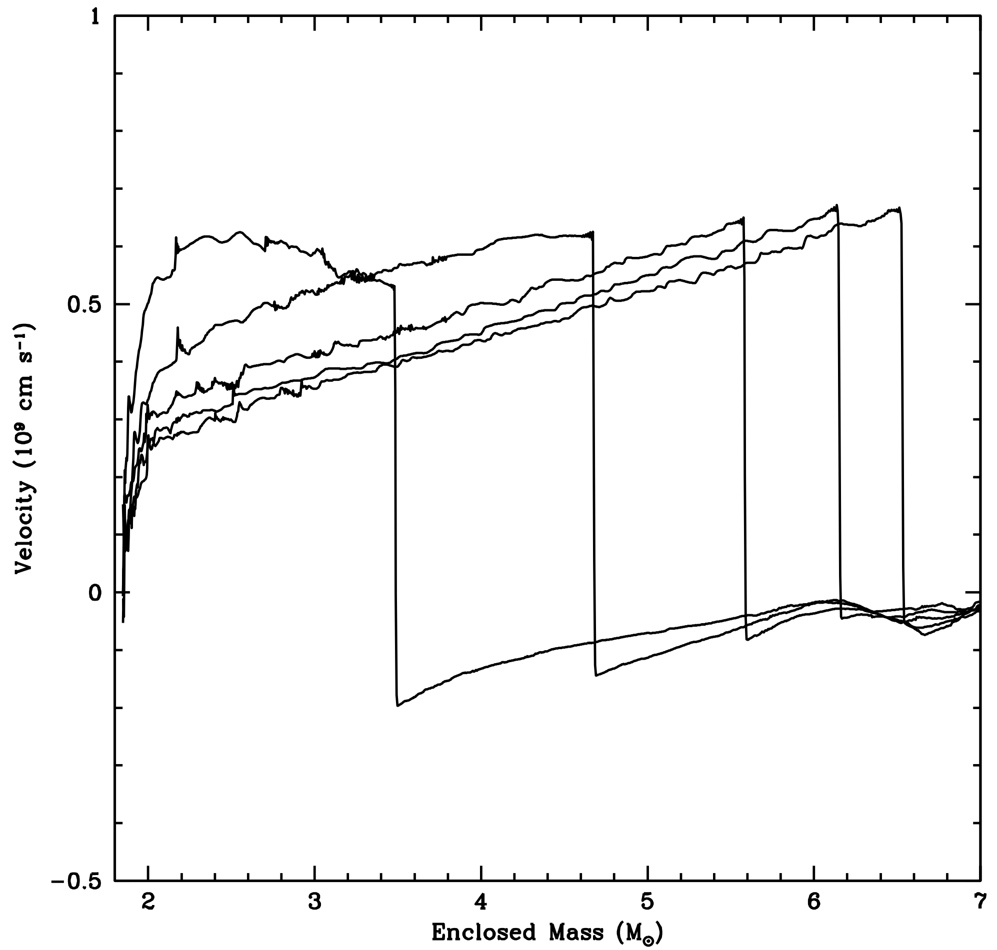
- Arnett & Truran (1970) argued that the conditions near the PNS would produce exotic elements. We do not see these elements.
- Colgate (1971) response: this material falls back (note that an alternate solution is that neutrinos reset the composition such that this material can be ejected).



- Neutrinos can also reset this yield (Janka has championed this solution).

Fallback Mechanisms

- Innermost ejecta decelerates below the escape velocity as it pushes outward. Ultimately, this material falls back (Colgate idea).
- Shock decelerates, driving a reverse shock (derived through dimensional analysis):



- E_{exp}, $\rho=A/r^{\omega}$

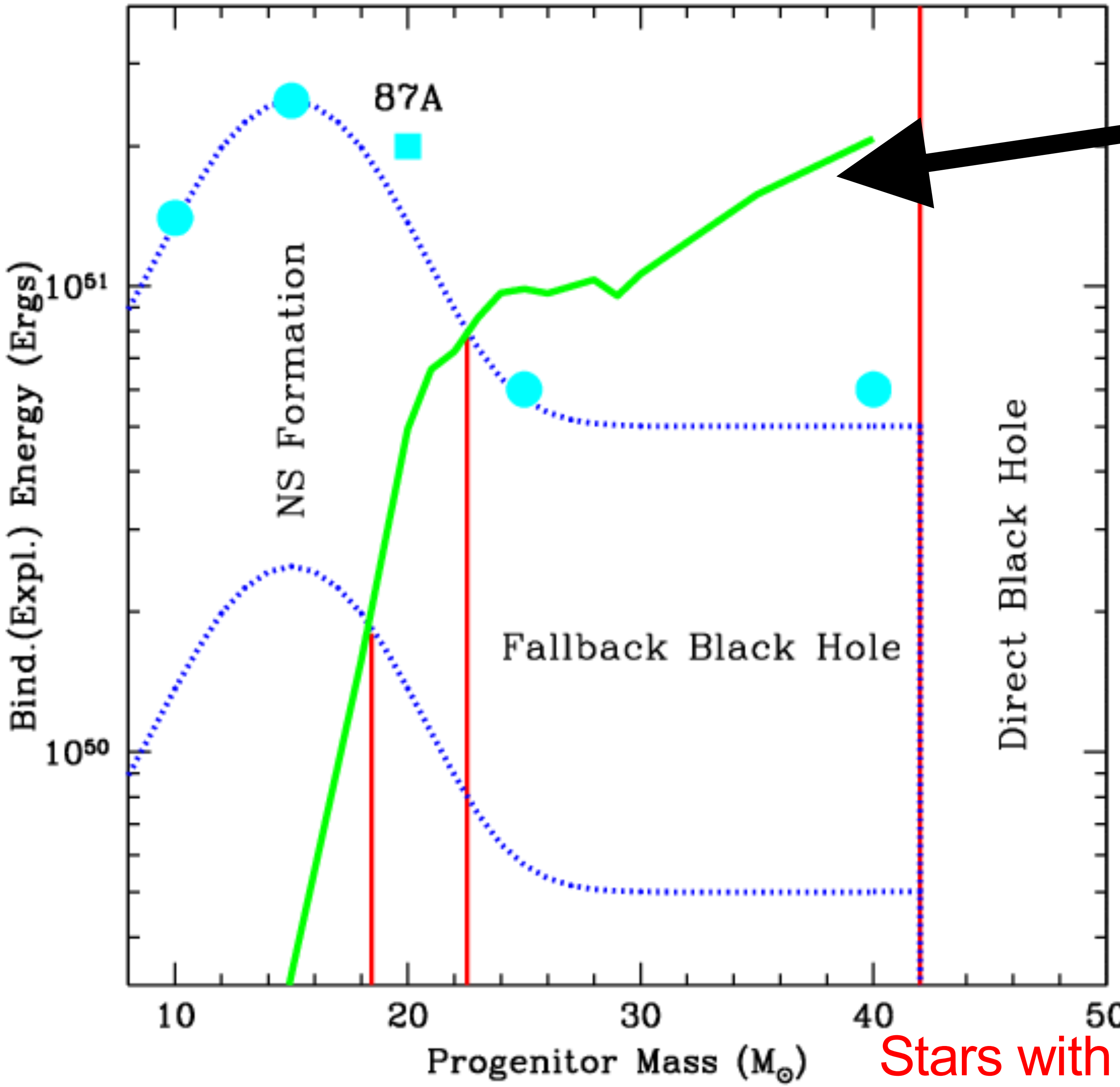
  $[E]=m\ r^2\ t^{-2}$, $[A]=m\ r^{-3+\omega}$

$r=A^{1/(\omega-5)}E_{exp}{}^{1/(\omega-5)}t^{2/(\omega-5)}$

$dr/dt=2/(\omega-5)$

$A^{1/(\omega-5)}E_{exp}{}^{1/(\omega-5)}t^{(\omega-3)/(\omega-5)}$

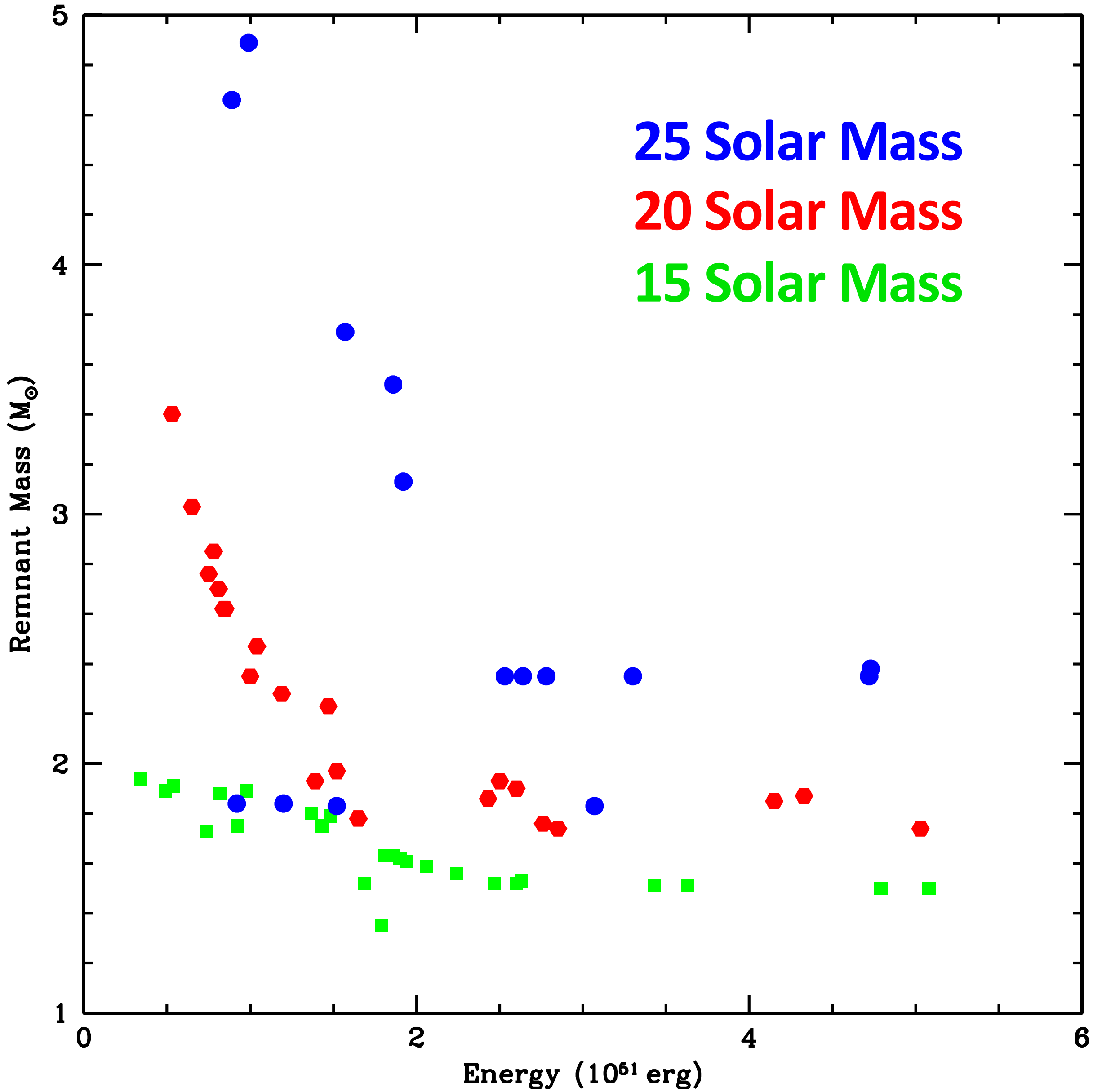
Fryer 1999



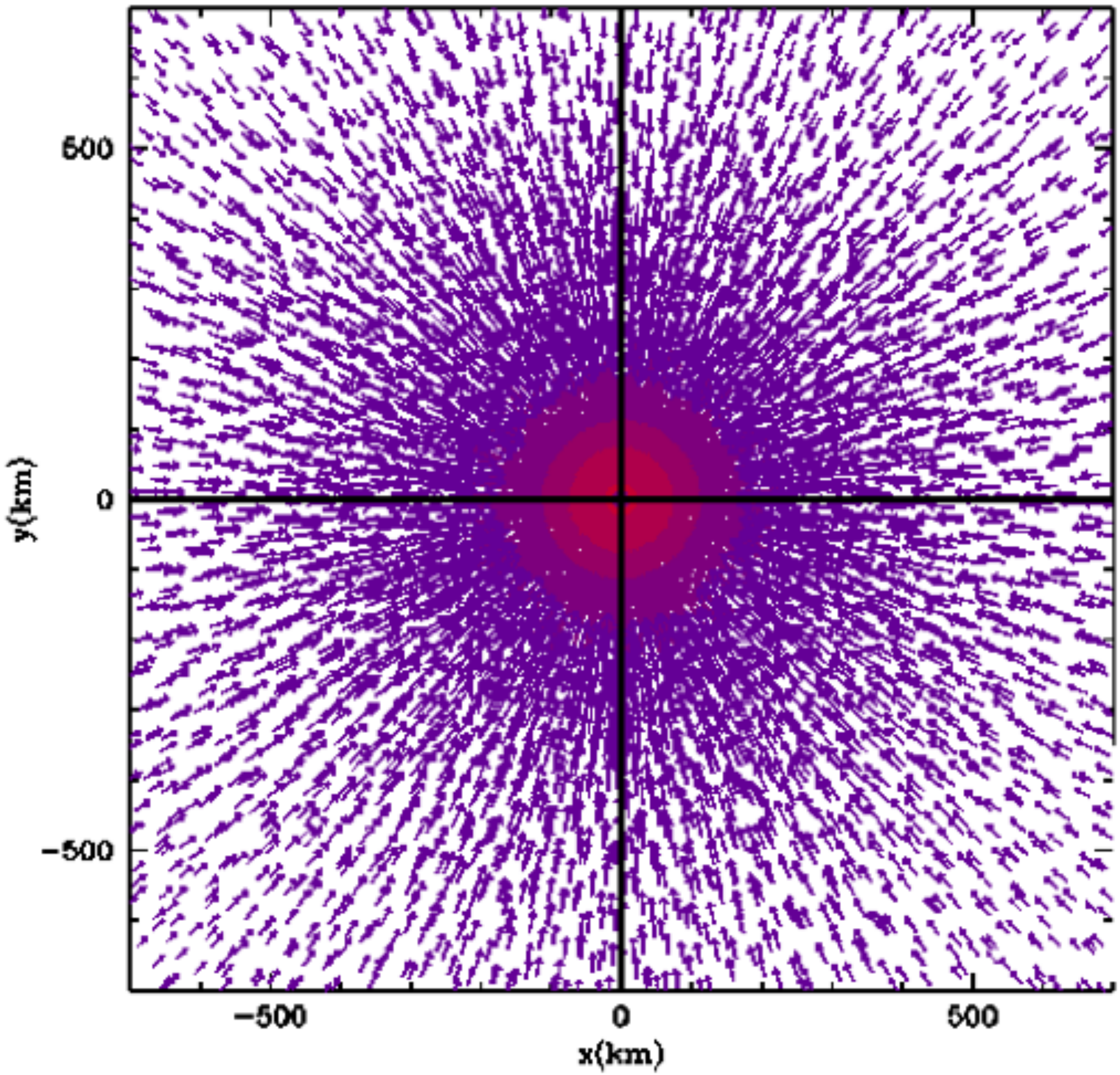
Binding Energy Of the Outer Layers Of the Star (M_{star} -3 solar Masses)

Stars with NO mass-loss

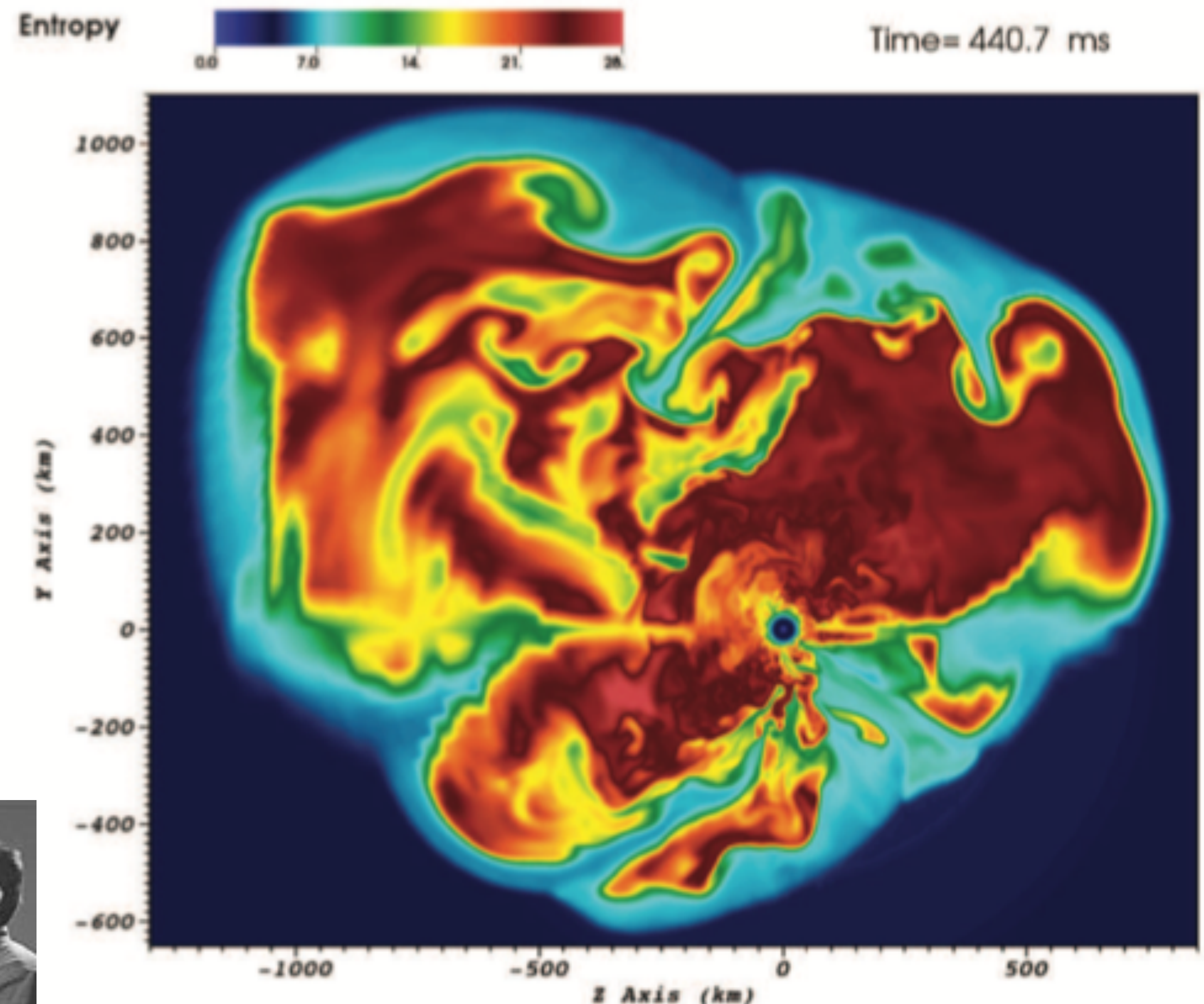
- In 1-dimension, we can alter the energy deposition to get a wide range of remnant masses.
- In the end, we have to be guided by 3D simulations and observations.



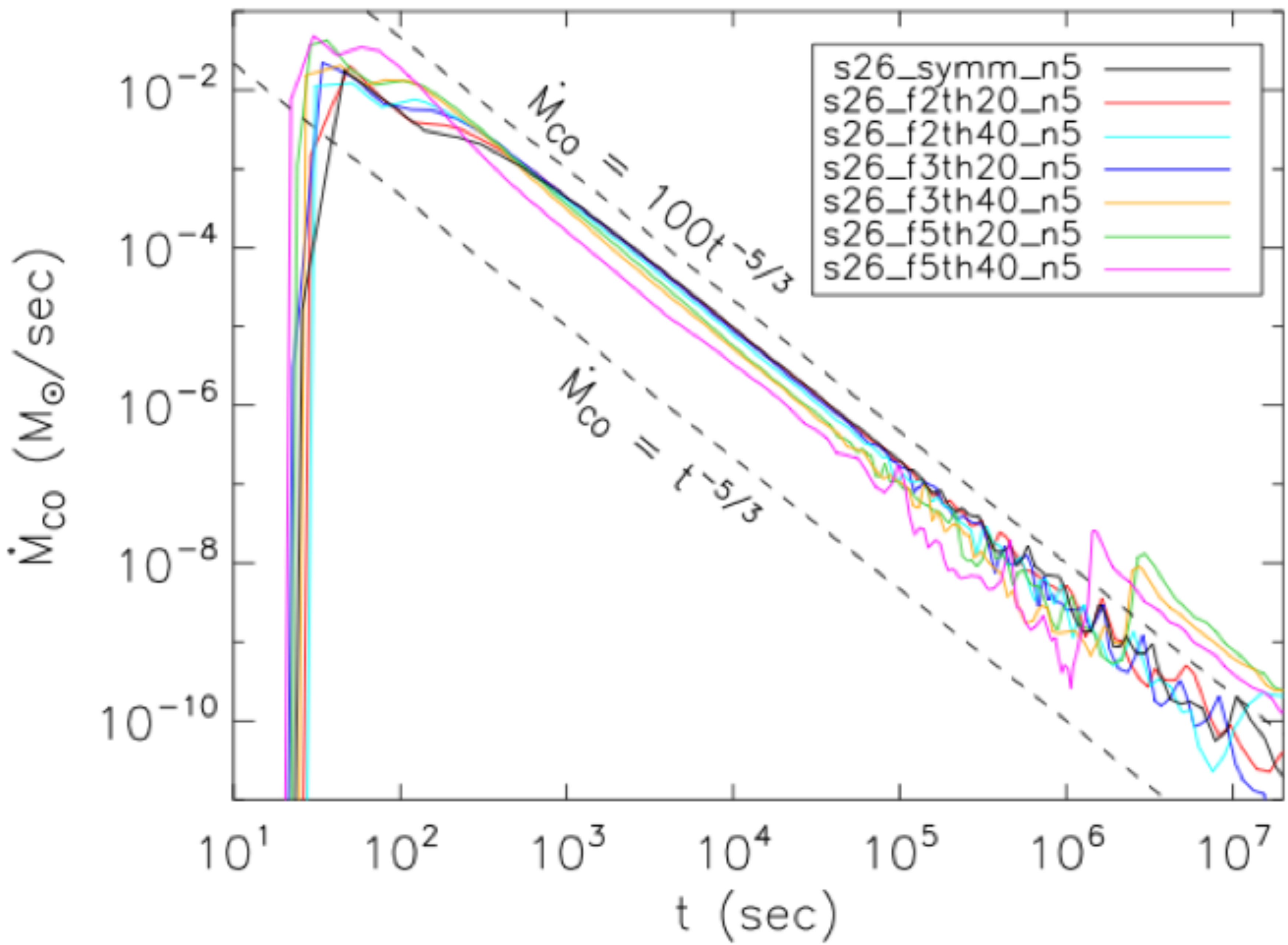
Even as the Supernova is exploding, material is still accreting onto the proto-neutron star.



Fallback could be a misnomer – Most 3D simulations just continue to accrete as the explosion is launched.



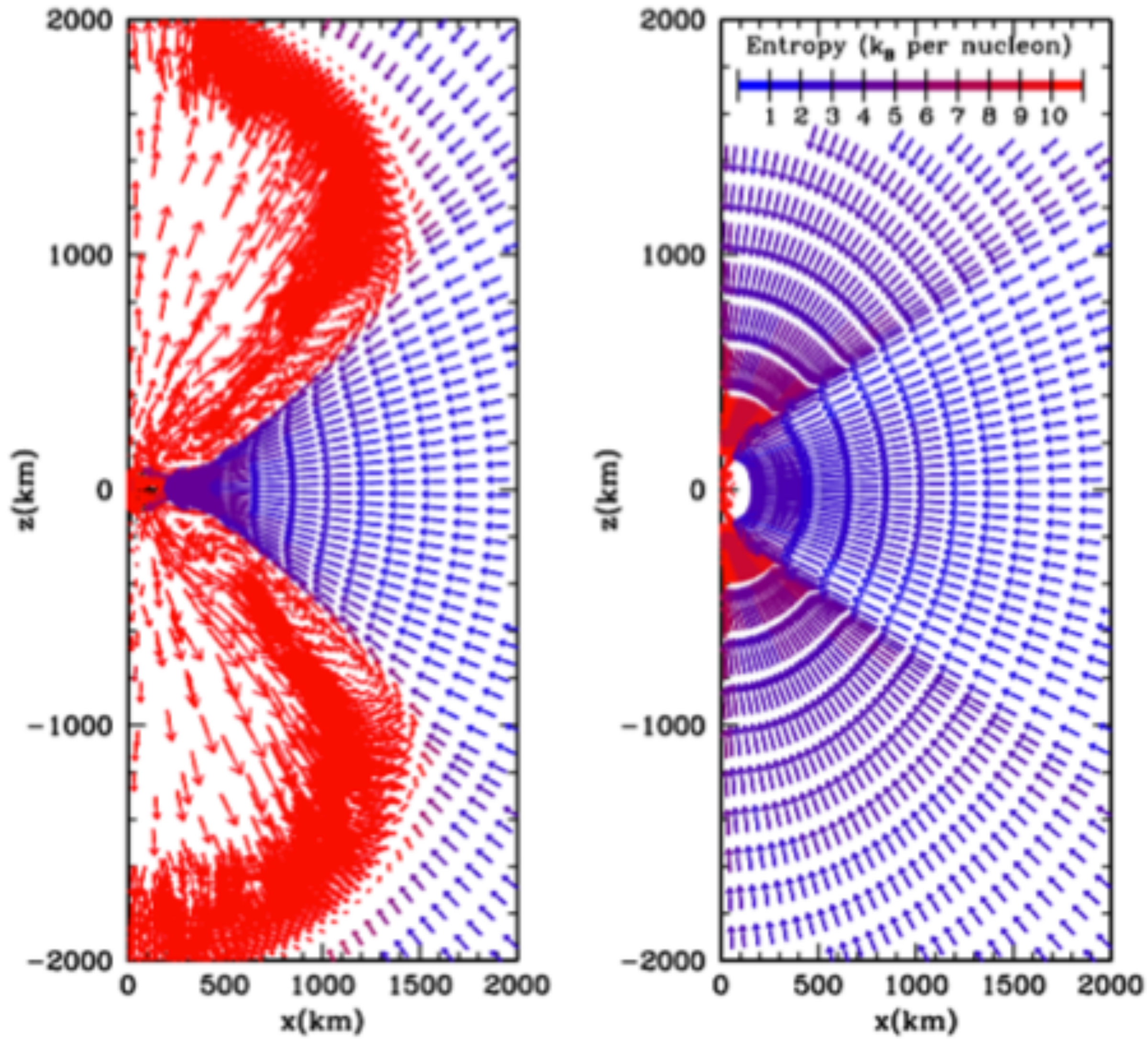
Mezzacappa 2015



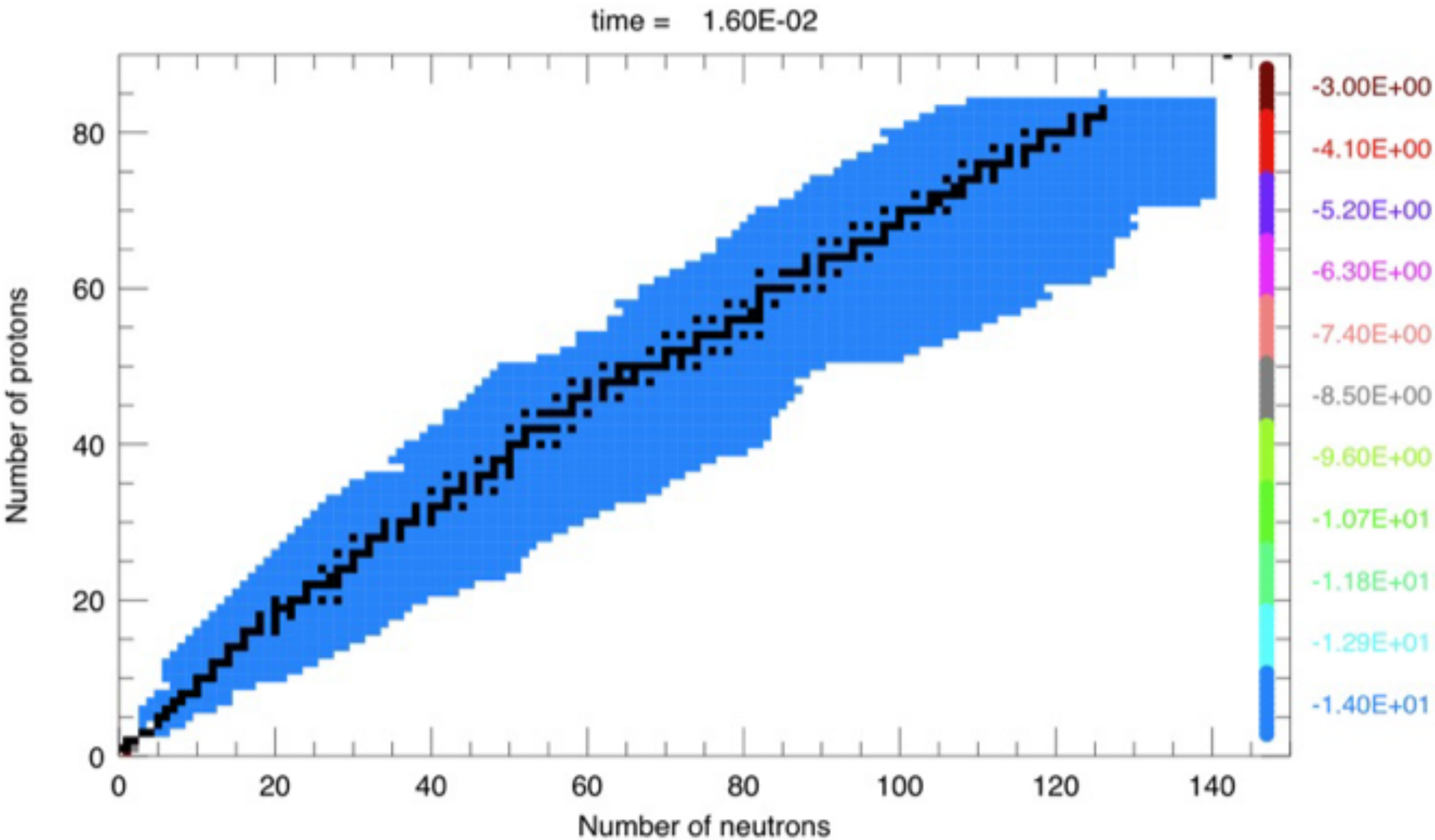
s26_symm_n5
s26_f2th20_n5
s26_f2th40_n5
s26_f3th20_n5
s26_f3th40_n5
s26_f5th20_n5
s26_f5th40_n5
$\dot{M}_{CO} = 100t^{-5/3}$
$\dot{M}_{CO} = t^{-5/3}$
$\dot{M}_{CO}$ ($M_\odot$/sec)
t (sec)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

Fallback outflows

- Fallback can produce extensive ejecta (up to 30% of the fallback)
- With small amounts of angular momentum, this ejecta forms bimodal outflows.
- Except for very high angular momenta, fallback onto BHs produce no ejecta.



Intermediate Process Ejecta



Conclusions

- Understanding the core-collapse engine is truly a multi-physics problem.
- Including the physics is difficult, and the path to a quantitative solution requires slowly improving upon approximations.
- This model explains why only 1% of the energy released in the collapse is in normal explosions, it also explains the remnant mass distribution.
- Does it explain all the yields???

NuGrid Data Set

In addition to the grid of yields in set 1, we have yields for 3 stars with a wide range of explosion energies.
Can we use these yields to rule out some explosions?