Less Traveled Roads in Supernova Nucleosynthesis

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- Nucleosynthesis Sites In Massive Stars (Gamma-Ray Bursts vs. Supernovae)
- r-Process: Well-Traveled Roads
- r-Process: Roads Not Taken
- More problems ahead

Sites For Nucleosynthesis in Massive Stars

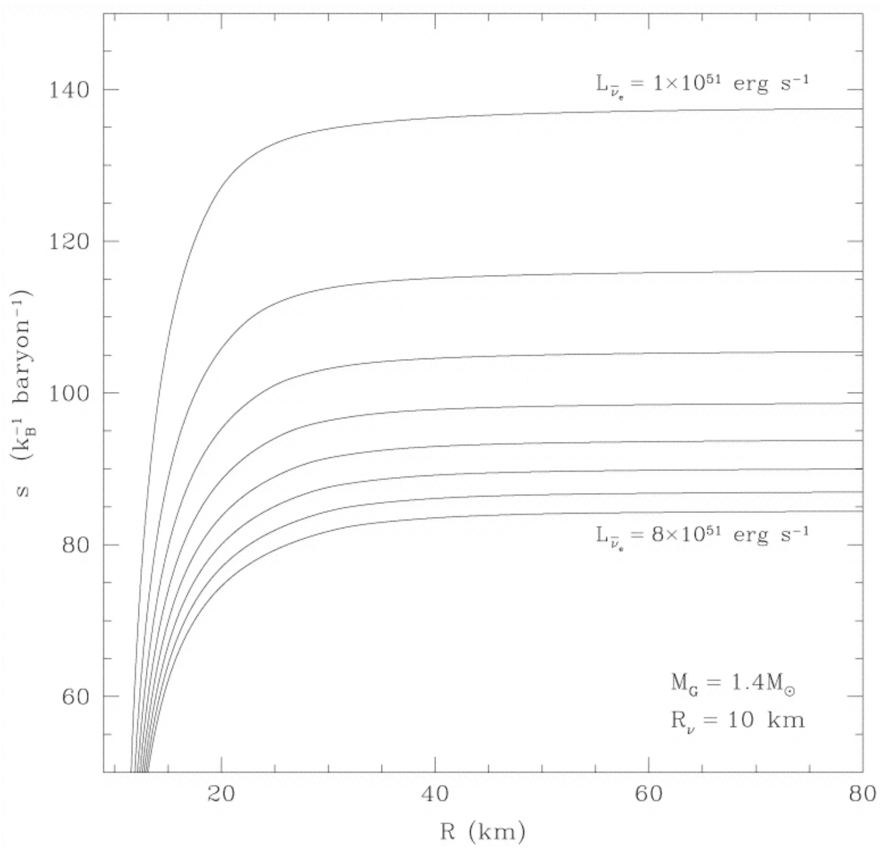
Core-Collapse Supernovae

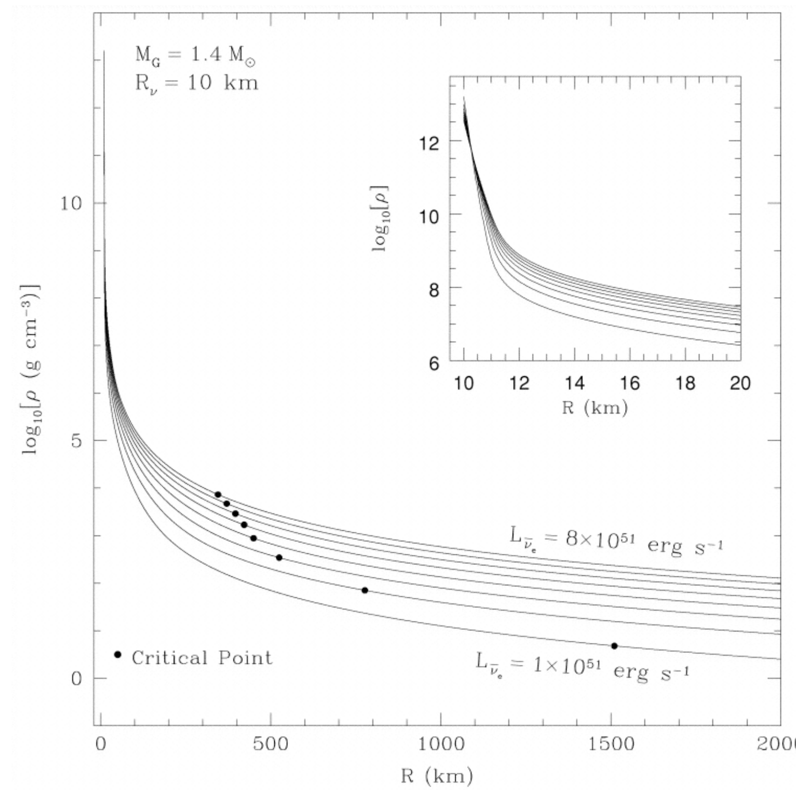
- Stellar Evolution (ejected in winds or SN explosion - Maeder & Meynet)
- Explosive Nucleosynthesis (traditionally 1D piston explosions - e.g. Woosley & Weaver 1995)
- Neutron Star Winds (r-Process?? 1D wind solution - Qian & Woosley)

Collapsar Gamma-Ray Bursts

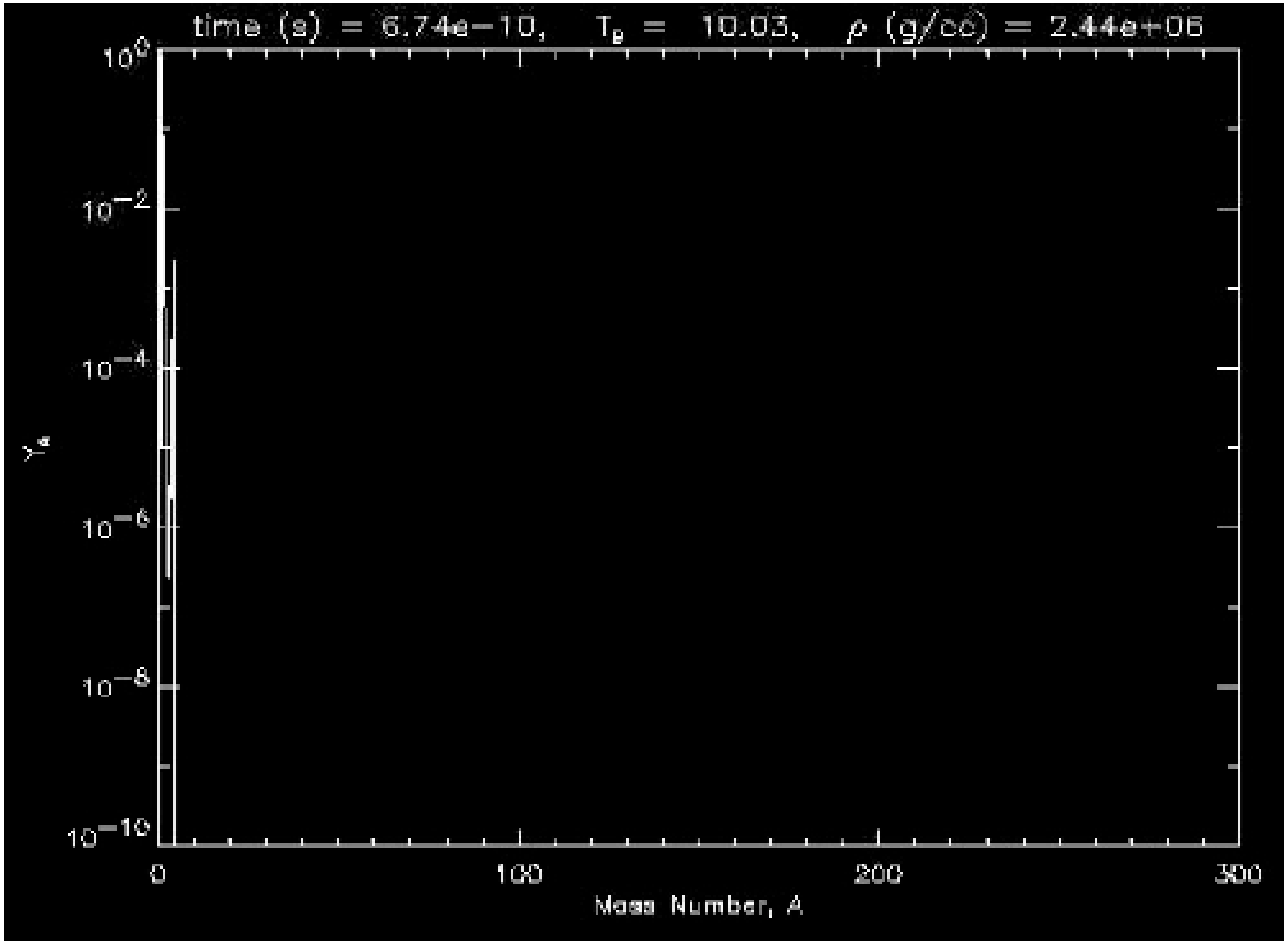
- Stellar Evolution (ejected in winds or SN explosion - M&M)
- Explosive Nucleosynthesis (multi-dimensional results - Maeda, Nomoto and collaborators)
- Black Hole Accretion Disks (r-process?? Wind solutions - Surman & McLaughlin, Pruet et al.)

In the simple 1D neutron-star wind models, entropy, velocity, temperature and density all a function of neutrino luminosity.





2+1 parameter models:
Neutrino luminosity,
Electron fraction,
entropy



Courtesy of Brad Meyer

The Qian & Woosley "To Do" List

- General Relativity - Conclusion: Not Important
- Lower Ye (current estimates of neutrino fluxes suggest opposite)
- Increase heating (nucleon recombination, better neutrino annihilation)
- Neutrino Oscillations - Studied in detail by a series of thesis from Fuller's students
- Neutron Star Oscillations
- Fallback
- Magnetic Fields
- Break in Spherical Symmetry (not mentioned by QW)

Collapsar Disk - Outflow Model (Surman & McLaughlin)

Take velocity as a function of radial distance from the black hole to be

$$u = v_{\infty}\left(1 - \frac{R_o}{R}\right)^{\beta}$$

where 5,000 $< v_{\infty} <$ 50,000 km/s, 0.2 $< \beta <$ 2.5

Take flow to be vertical at first, then radial

Consider adiabatic flows with entropy 10 $< s <$ 50

GRBs

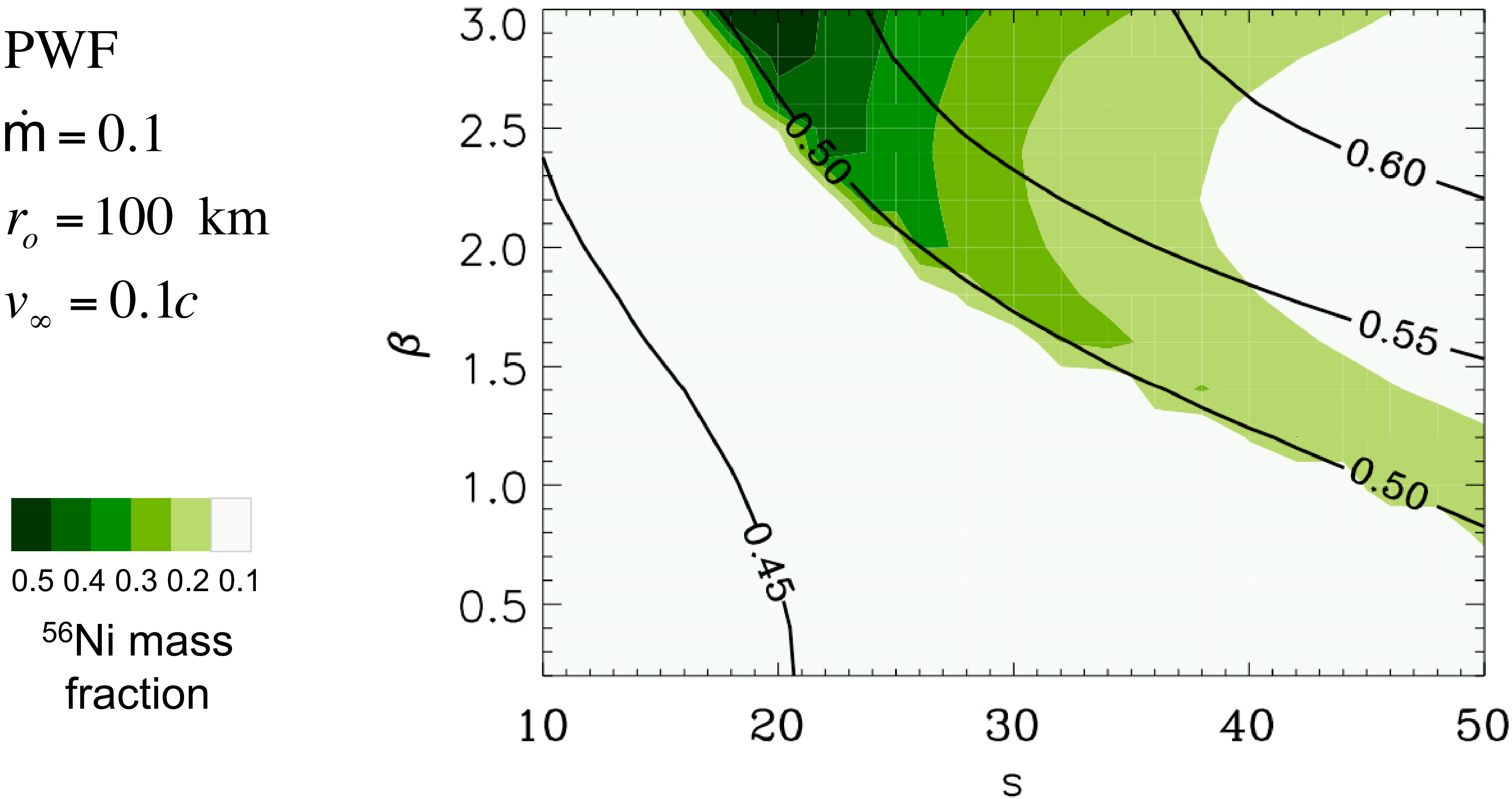
High Y_e => Nickel Synthesis

PWF

$\dot{m} = 0.1$

$r_o = 100 \text{ km}$

$v_\infty = 0.1c$



Surman & McLaughlin, astro-ph0509365, ApJ in press

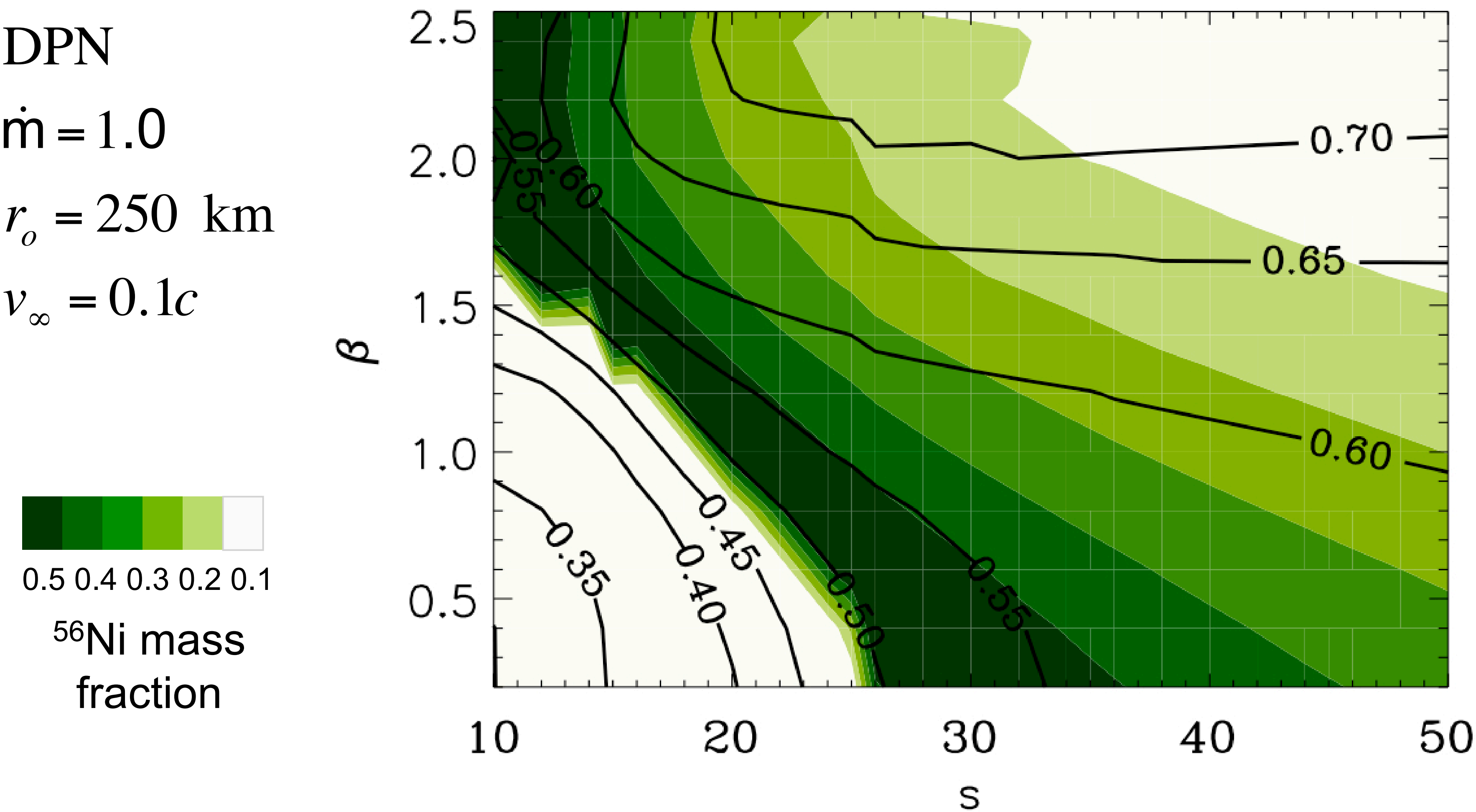
High Y_e => Nickel Synthesis

DPN

$\dot{m} = 1.0$

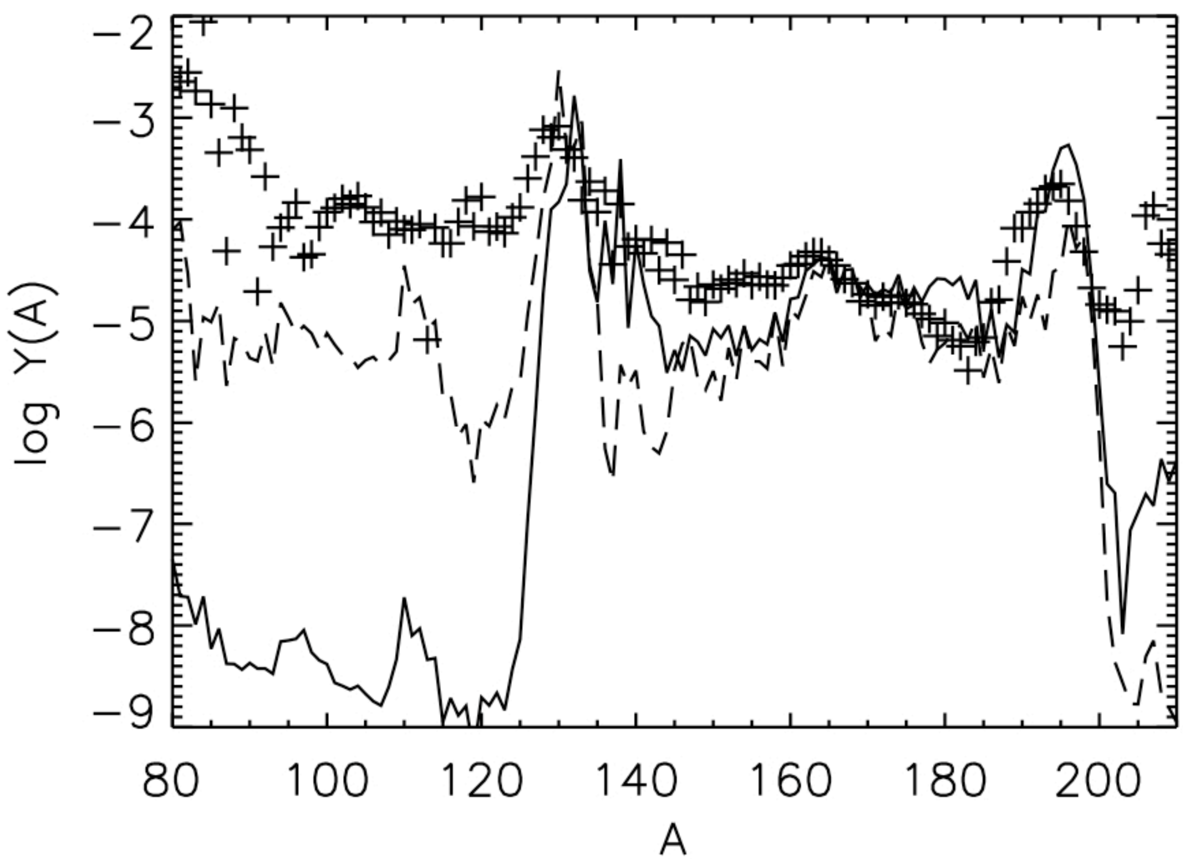
$r_o = 250\ \text{km}$

$v_\infty = 0.1c$



Surman & McLaughlin, astro-ph0509365, ApJ in press

Low Y_e => *r*-Process Nucleosynthesis!!



Surman & McLaughlin, astro-ph0509365, ApJ in press

DPN

$\dot{m} = 10$

$r_o = 250$ km

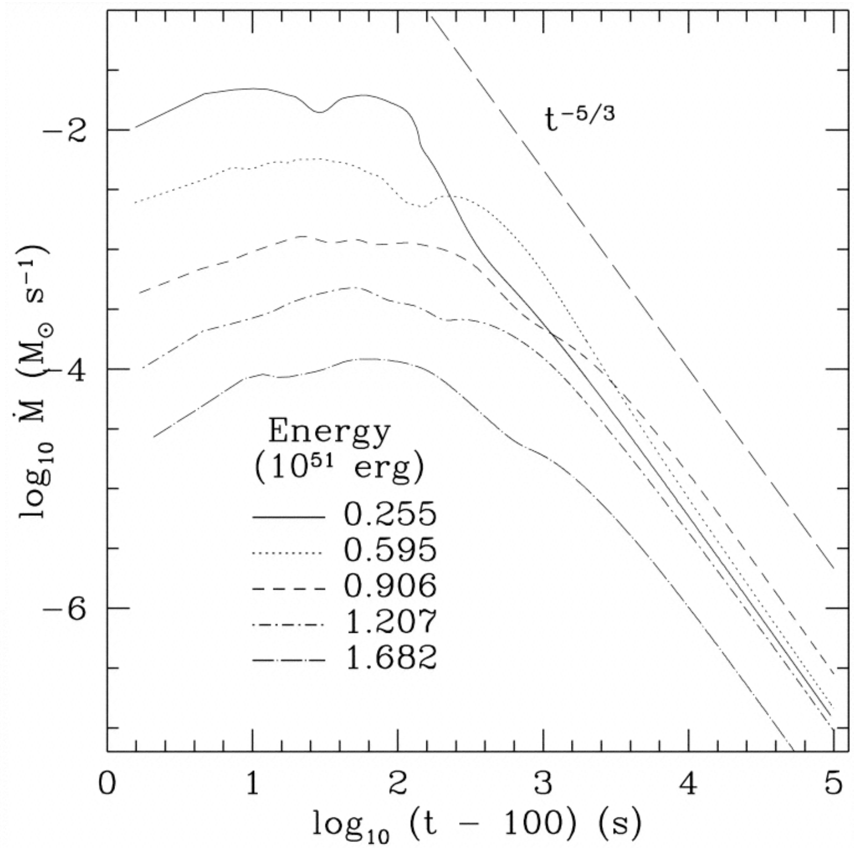
$v_\infty = 0.1c$

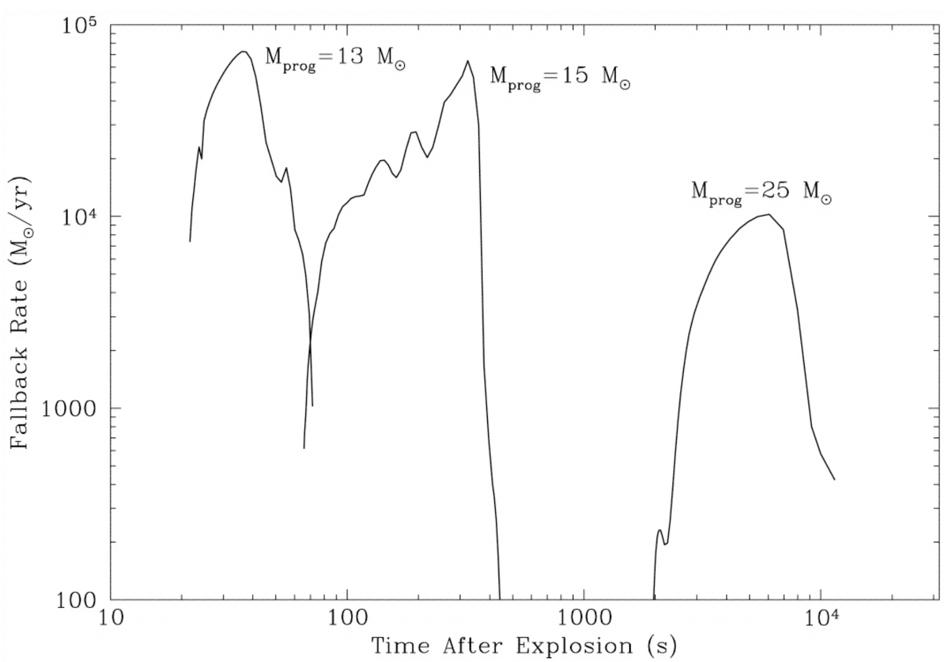
$s = 10, \quad \beta = 0.4$

$s = 50, \quad \beta = 2.2$

But these are still parameterized models!

Fallback in the 1-dimensional piston era: There can be a considerable delay between explosion and fallback.



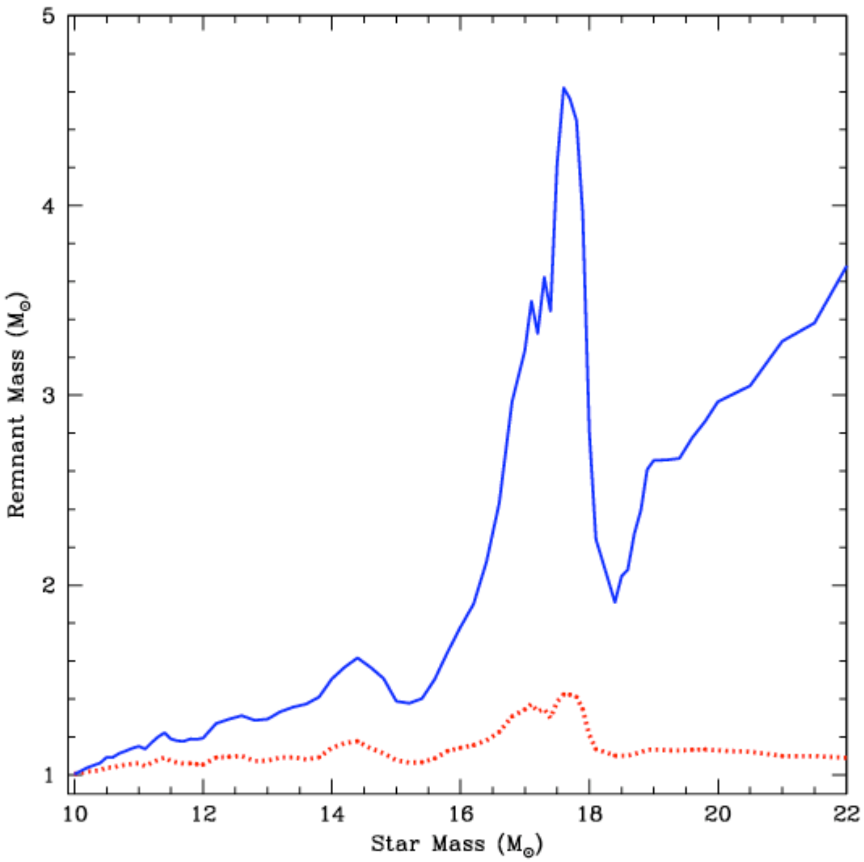


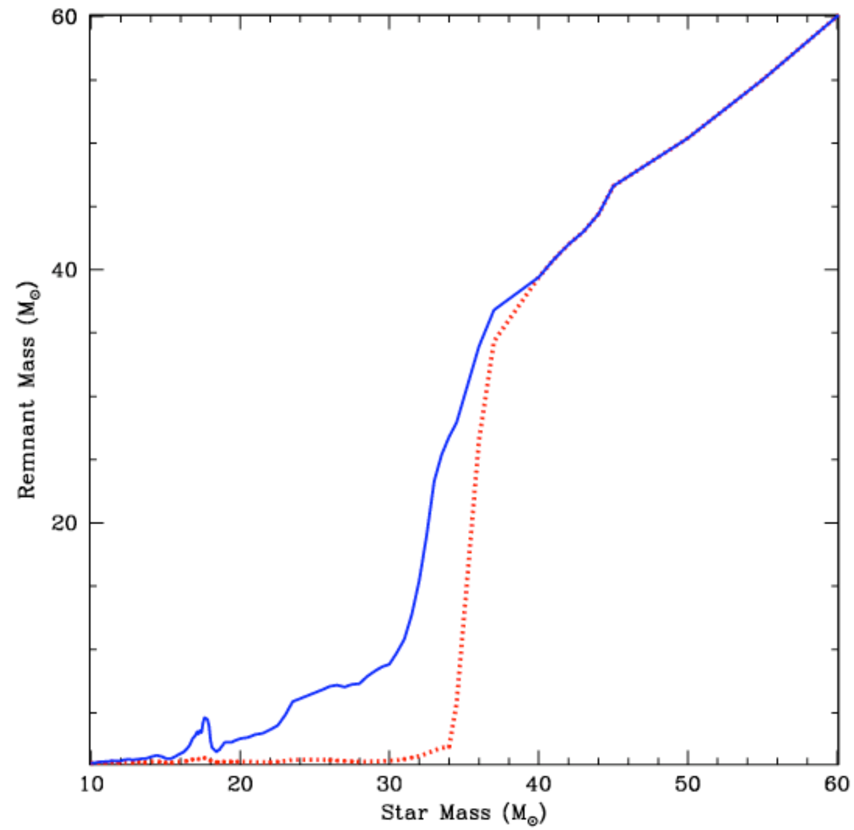
Fallback occurs in stars >12 solar masses for reasonable explosion energies (CLF opinion only - not accepted by all/any).

Fallback occurs in most supernovae:

Red - Mass at explosion

Blue - Final remnant mass

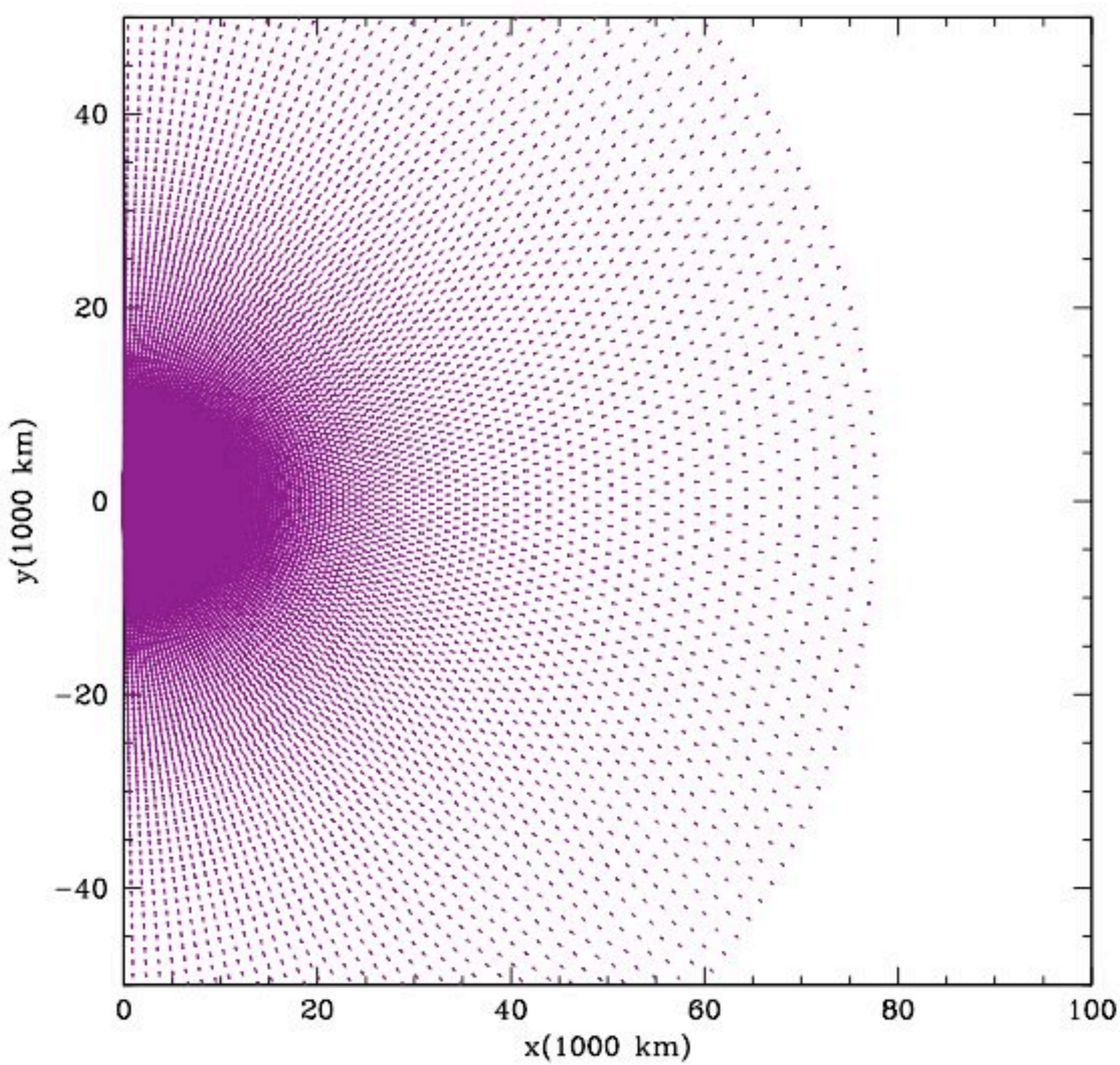


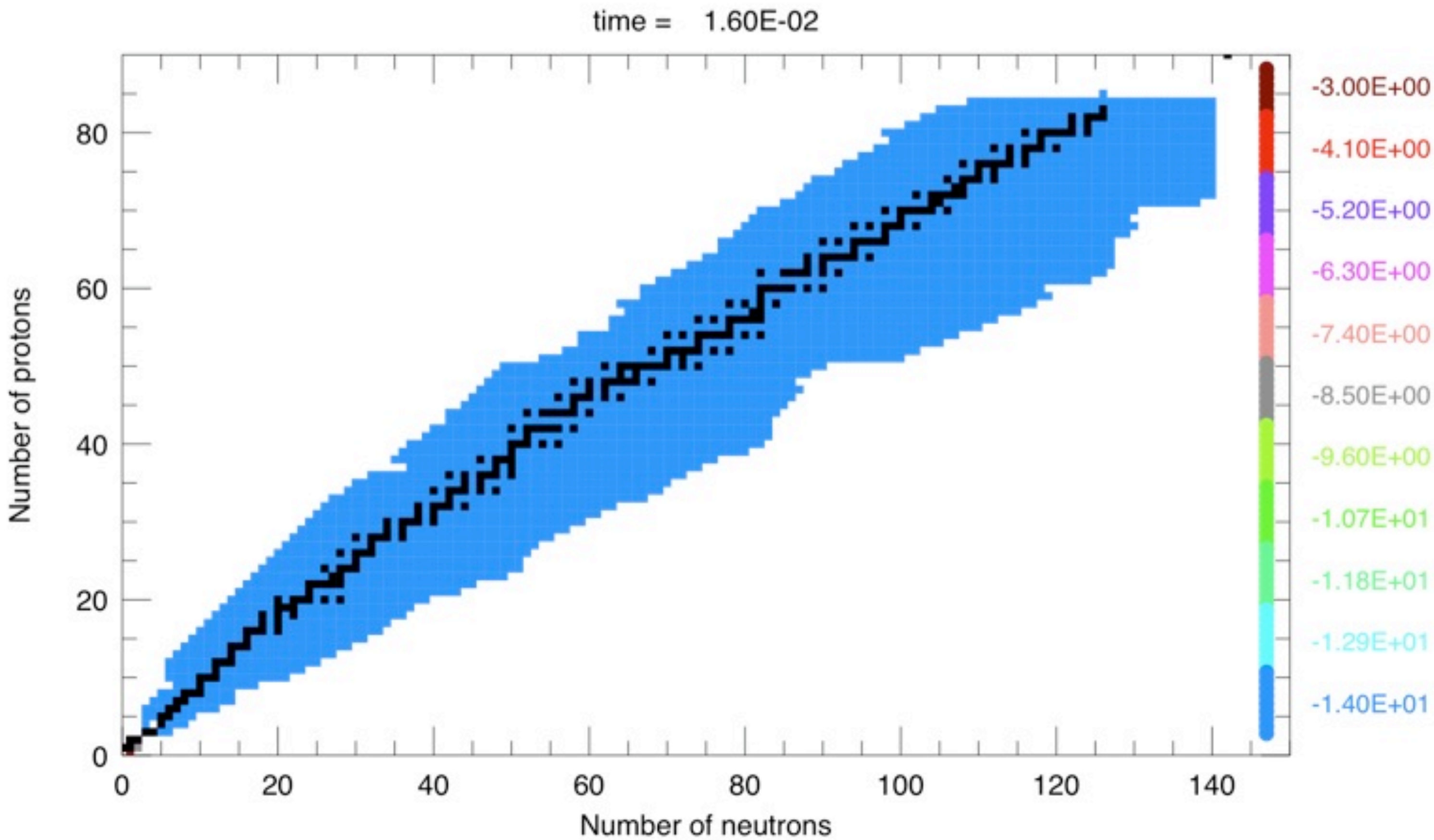


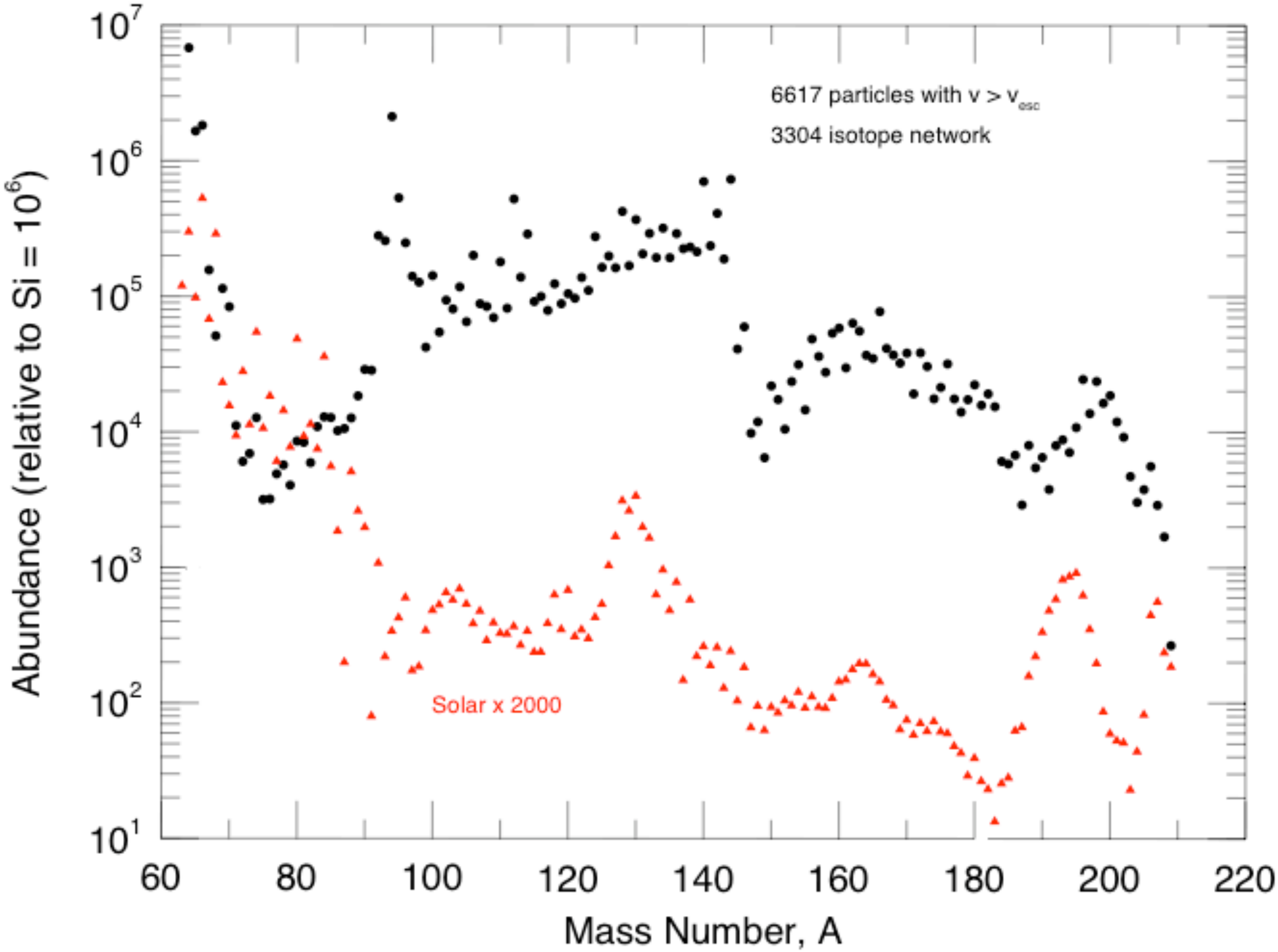
Belczynski et al. 2005

Fallback far from the 1D (spherically symmetric) picture.

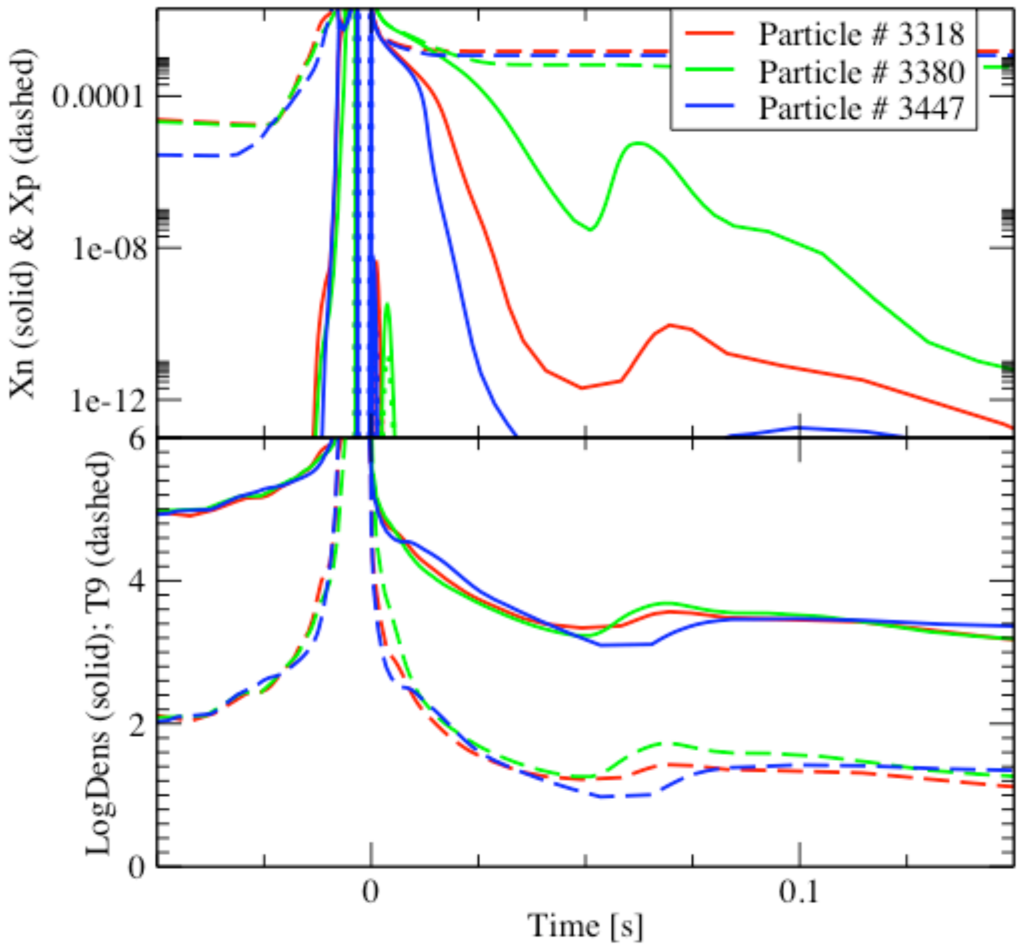
Fryer, Herwig, Hungerford, & Timmes 2006




time = 1.60E-02
Number of protons
Number of neutrons
0
20
40
60
80
100
120
140
-3.00E+00
-4.10E+00
-5.20E+00
-6.30E+00
-7.40E+00
-8.50E+00
-9.60E+00
-1.07E+01
-1.18E+01
-1.29E+01
-1.40E+01



6617 particles with v > v_esc
3304 isotope network
Solar x 2000
Abundance (relative to Si = 10^6)
Mass Number, A
10^7
10^6
10^5
10^4
10^3
10^2
10^1
60
80
100
120
140
160
180
200
220

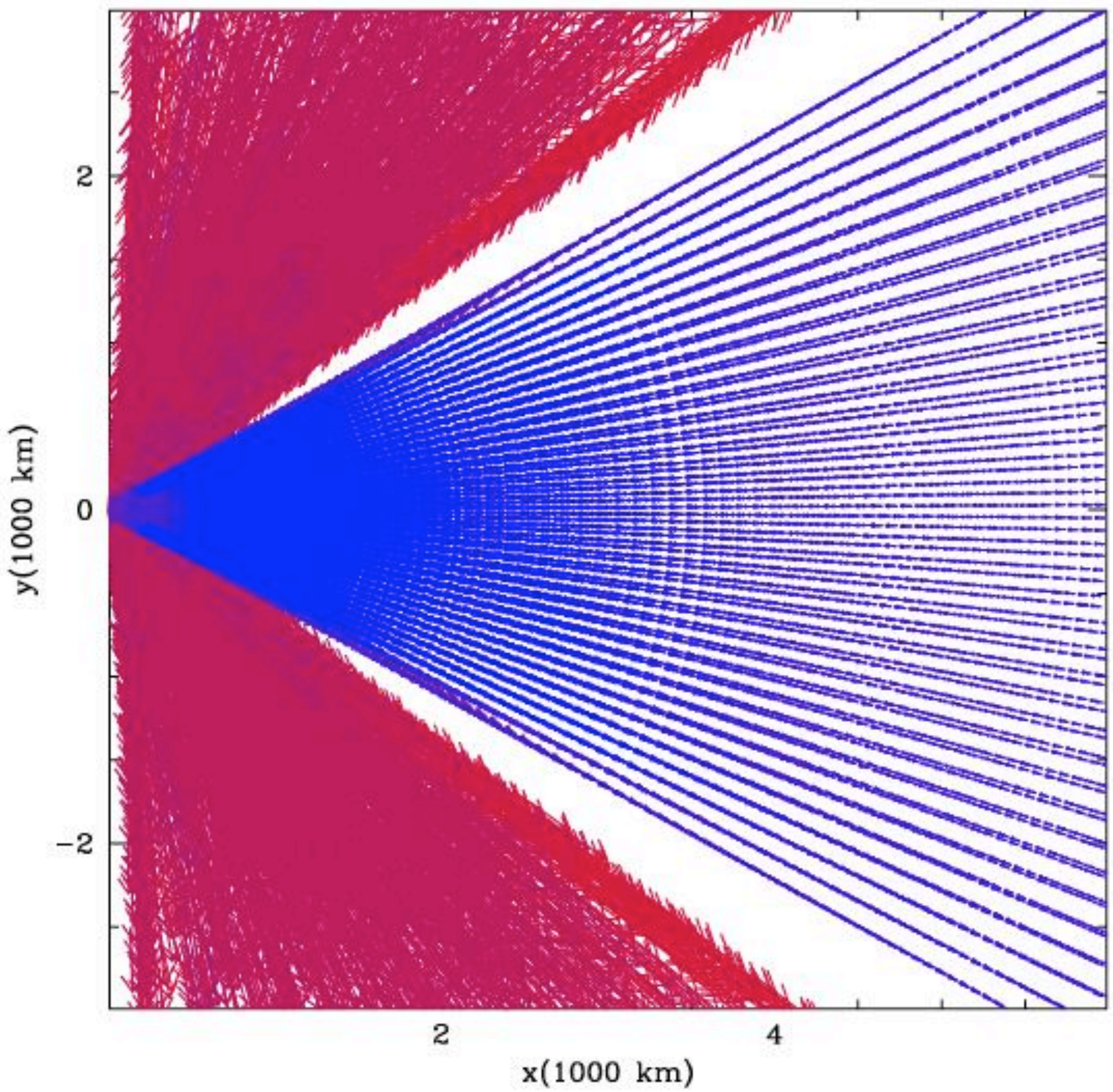


Small changes in the particle trajectory can dramatically alter the free neutron number and, hence, the final yield!

But I think (hope) Brad will understand this.

r-Process from Fallback - First Pass

- Can get the A~195 peak
- But we are not doing r-process (there is a combination of rapid proton plus neutron capture)
- As such, we may not get the observed r-process abundance ratios
- What's left: Understanding ejecta from fallback, Understanding the origin of fallback (that is, understanding the supernova mechanism)



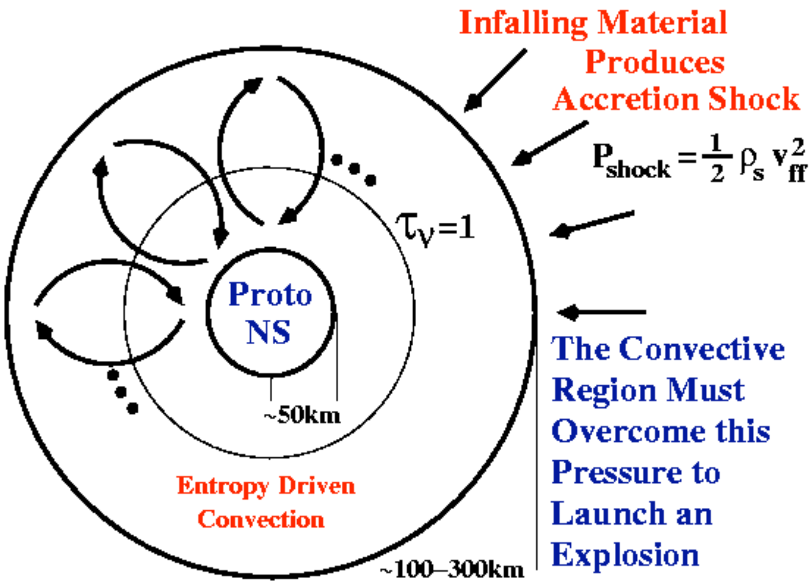
2
0
−2
y(1000 km)
2
4
x(1000 km)

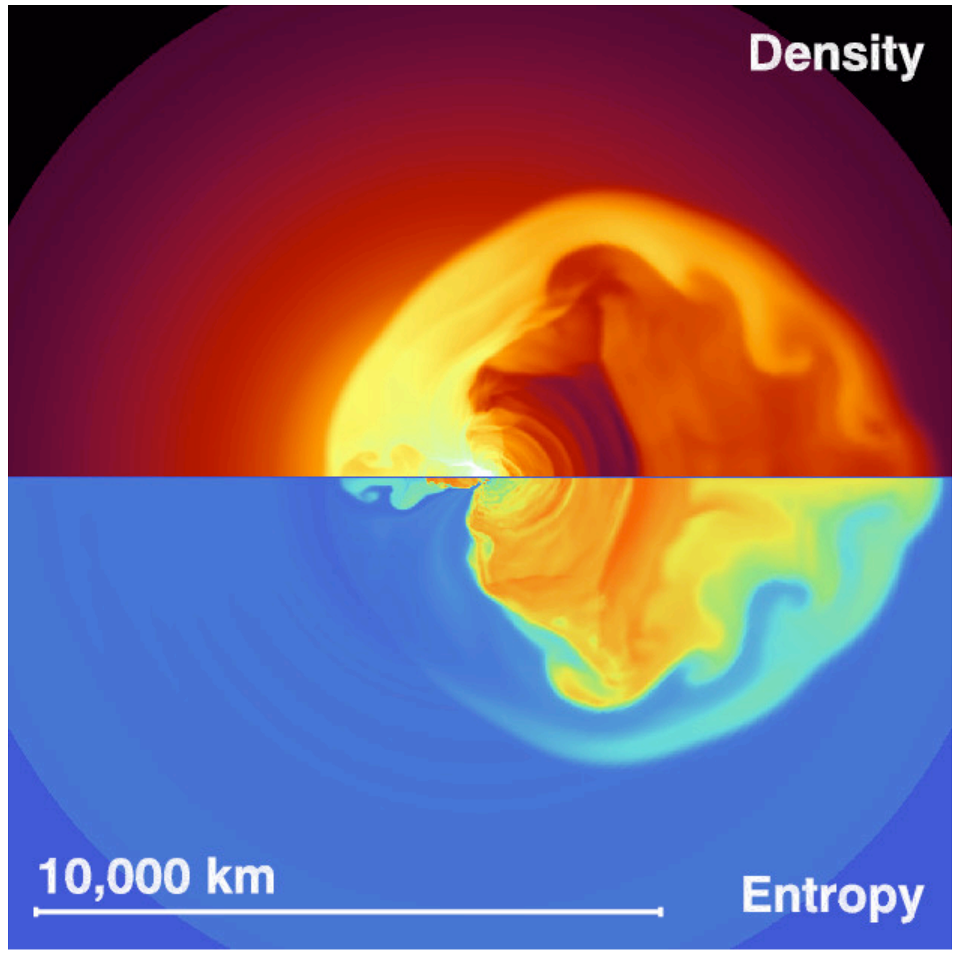
Single-Lobe Convection

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

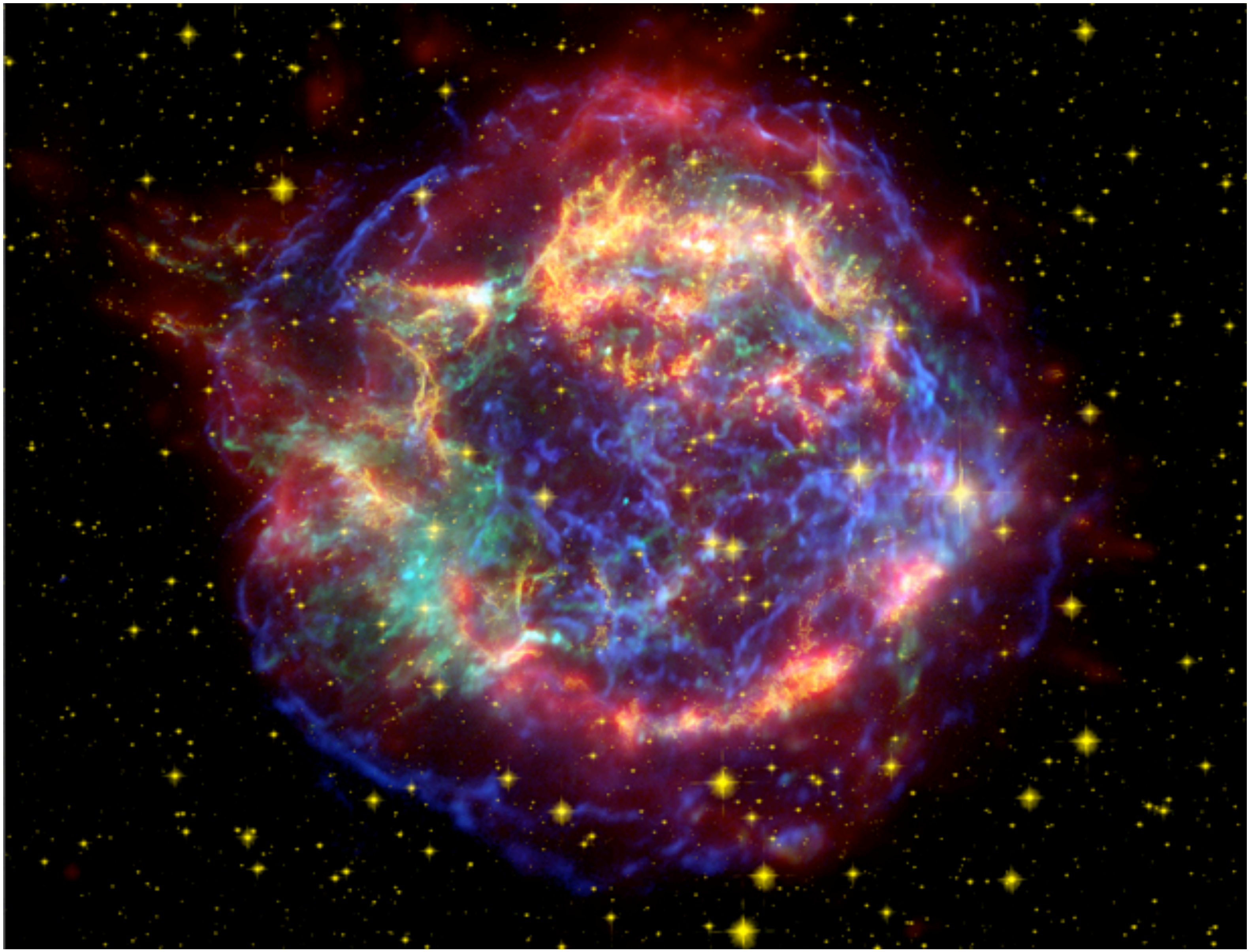
- Neutron Star Kicks for Slow Explosions

Scheck et al. 2003





Cas A: A strongly constrained supernova! VALIDATION

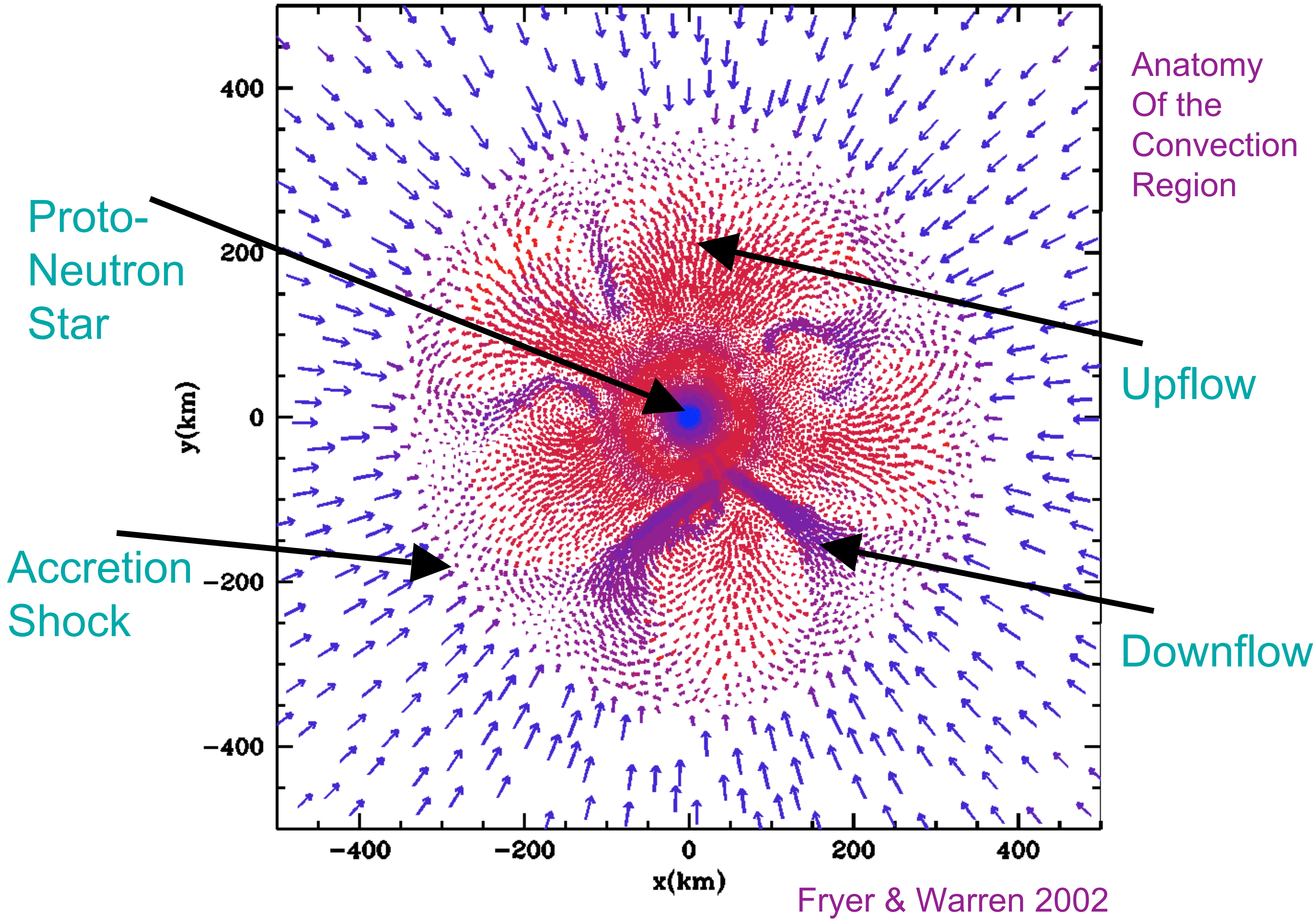


Conclusions

- Lots more to r-Process than neutrino-driven winds.
- Details of the explosion matter (asymmetries, fallback etc.). Indeed, the yields may depend very sensitive to the trajectories.
- No doubt, the yields will also depend sensitively on the rates.
- It is a hard problem, but validation tests exist and are being refined!

“So we did not solve the problem. In a way, we are as confused as you are. However, we believe our confusion is on a higher platform and about more important things.”

-Car Talk (courtesy of Y.-Z. Qian)


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