Remnants of Massive Stars

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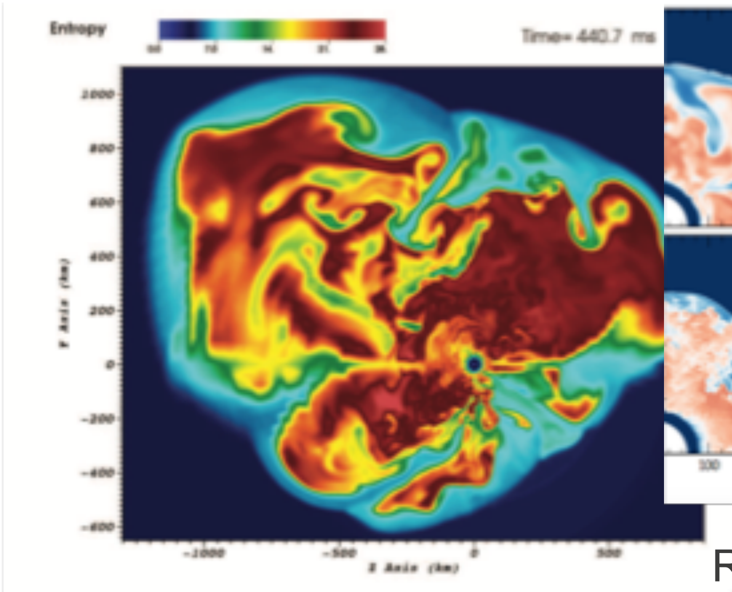
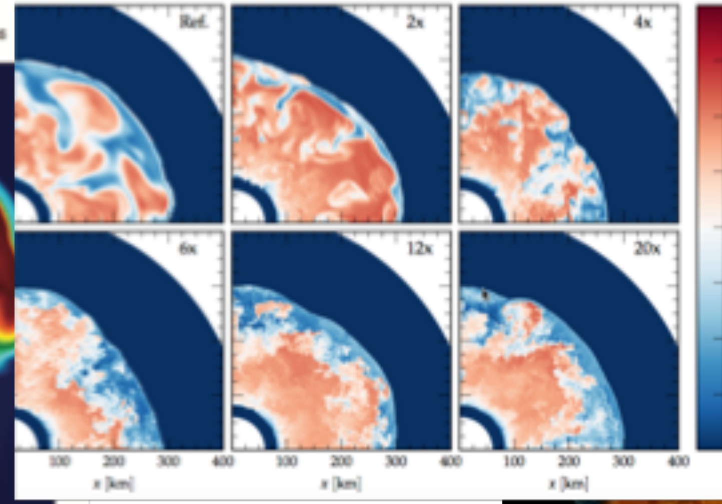
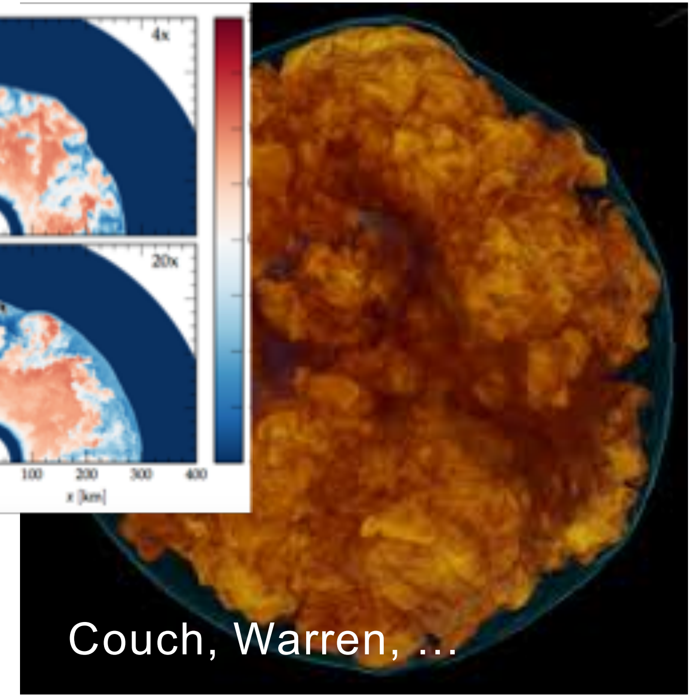
There is growing agreement that the “convective” engine is behind “normal” core-collapse supernovae*



Mezzacappa, Messer, Hix



Radice, Burrows, Dolence



Couch, Warren, …

*We do not agree on the exact physics or how to name it. There is also a general agreement that it is difficult to achieve quantitatively accurate results and, in general “our”<insert name of the team showing results> calculations are better than ”theirs”. The TEAMS Collaboration brings many groups together to work this “us” vs. “them” out.

Anatomy of a Convective Engine

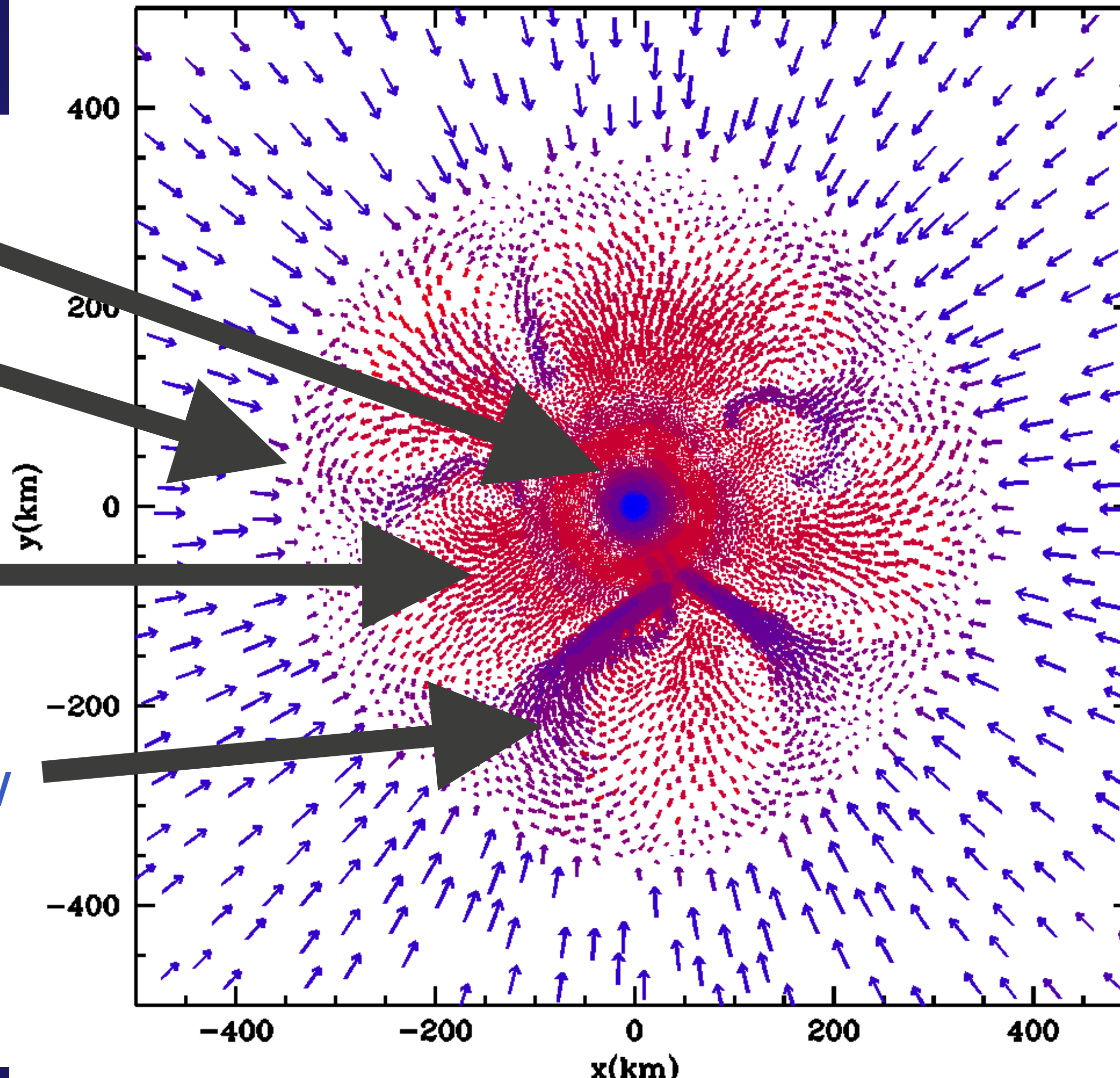
Proto-neutron star

Accretion shock

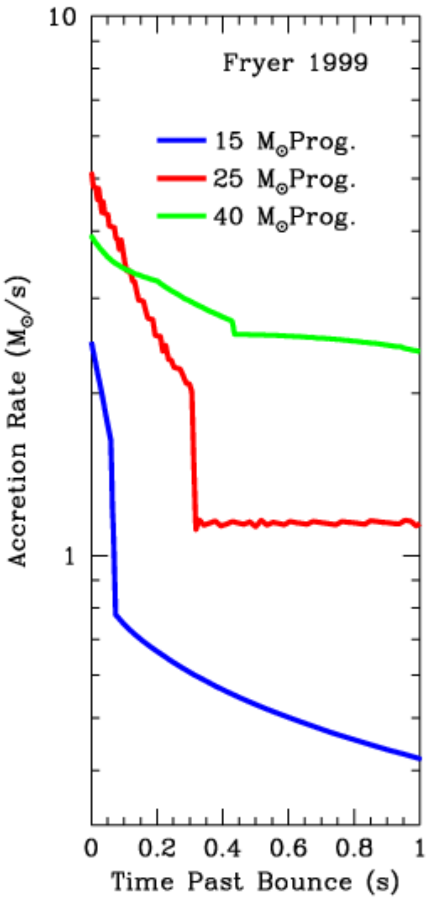
Motion is driven both by entropy gradient and standing shock accretion instabilities

Upflow

Downflow



The Progenitor and its Structure Matter

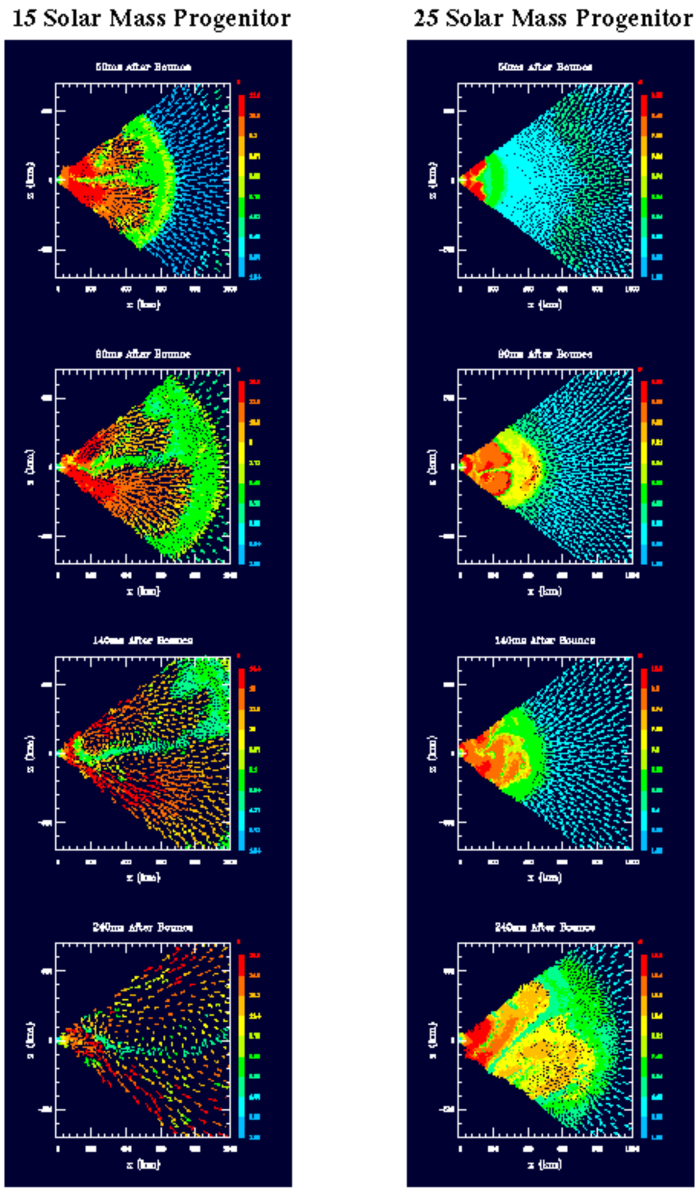


$$P_{Shock} \approx \frac{1}{2}\rho v_{ff}^2$$

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

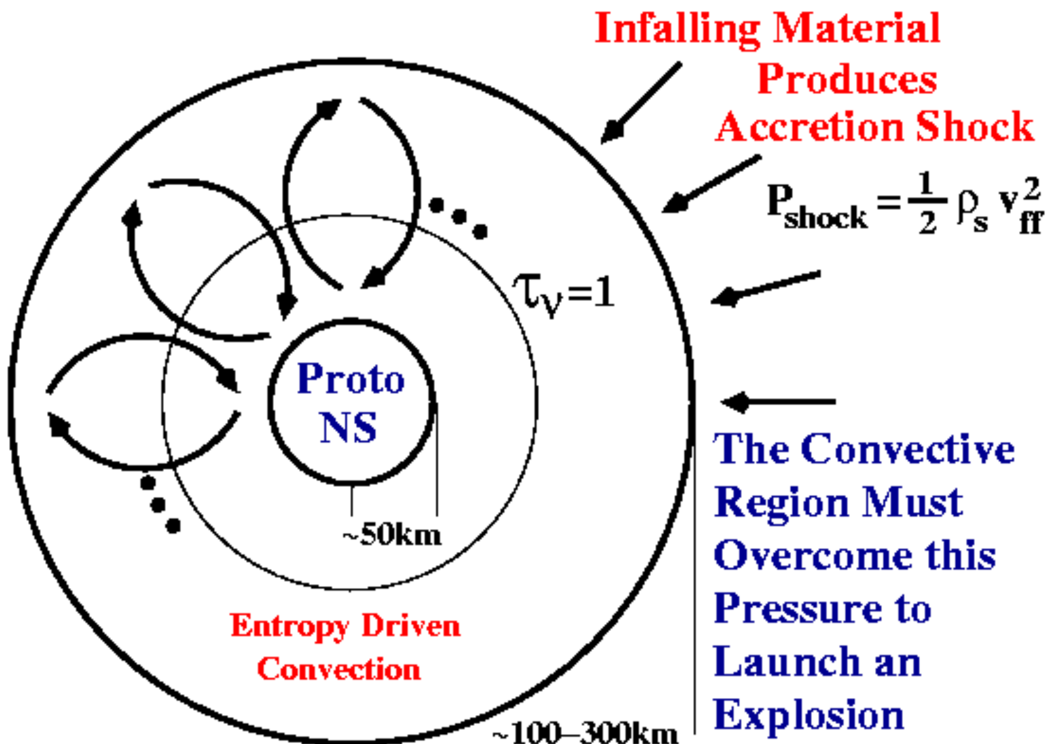
Massive Stars Have
Higher Infall Rates
→Requires More
Energy To Explode

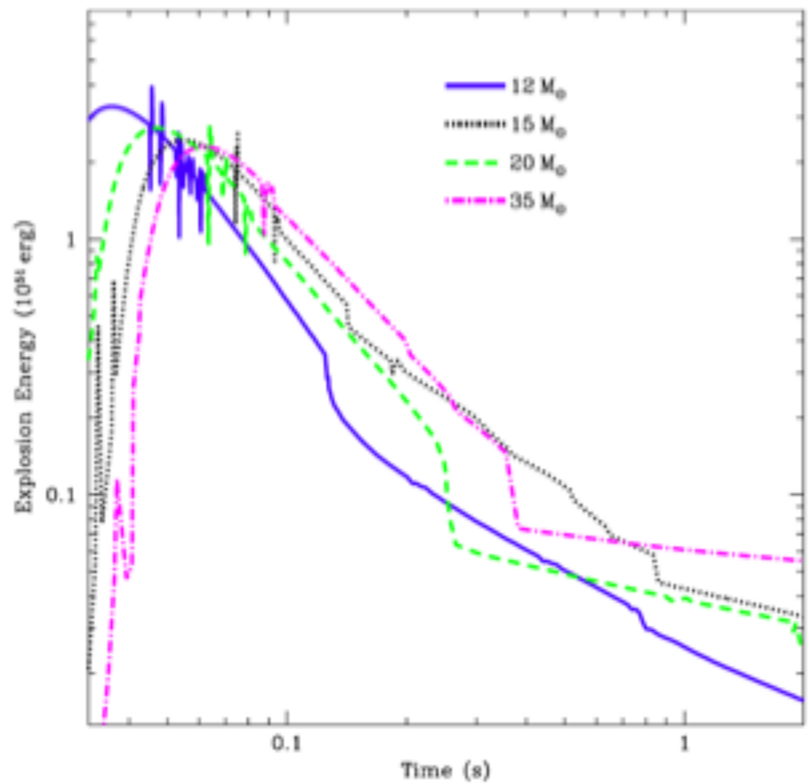
Burrows & Goshy 1993

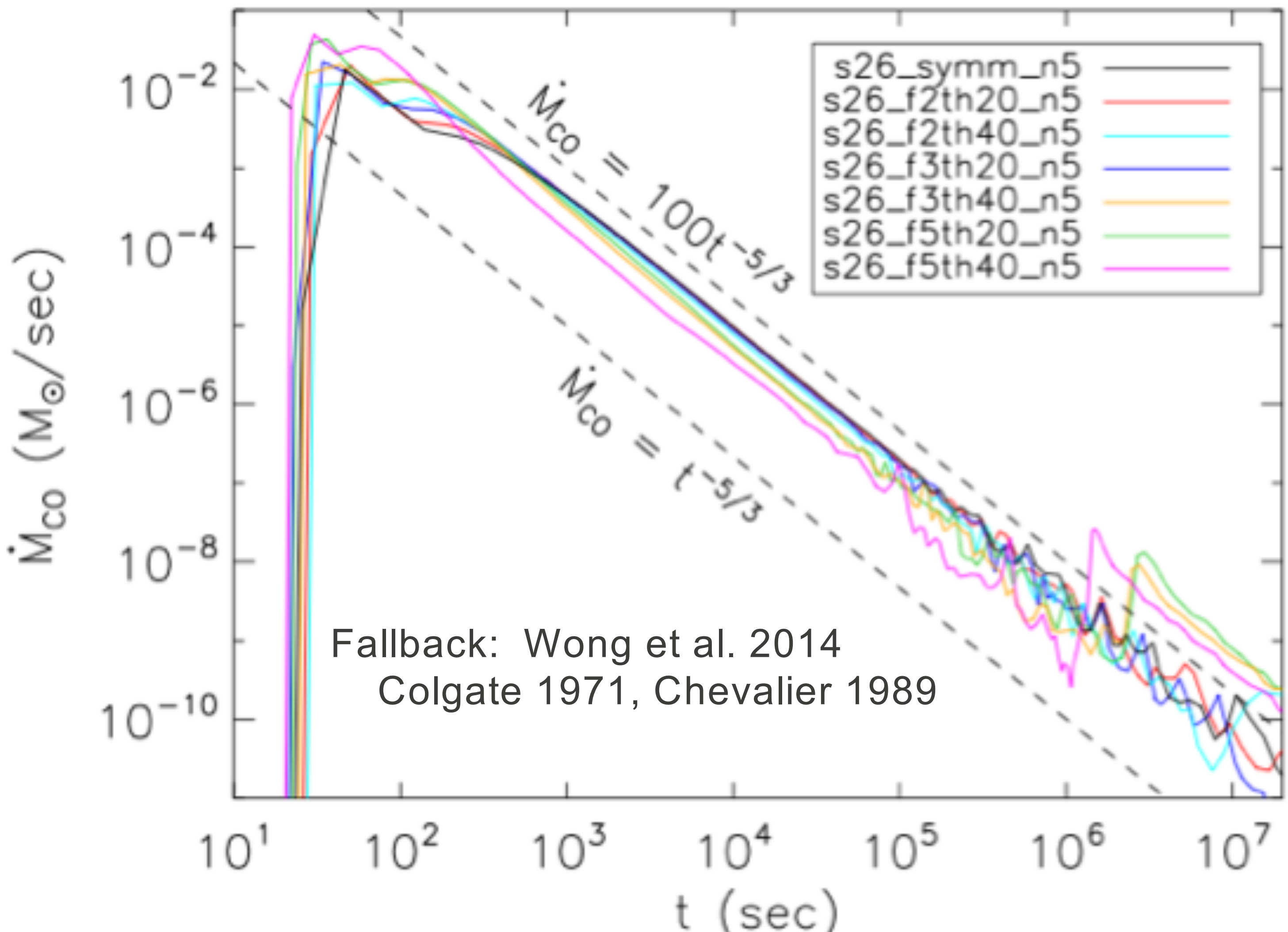


Trends in the Explosion

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



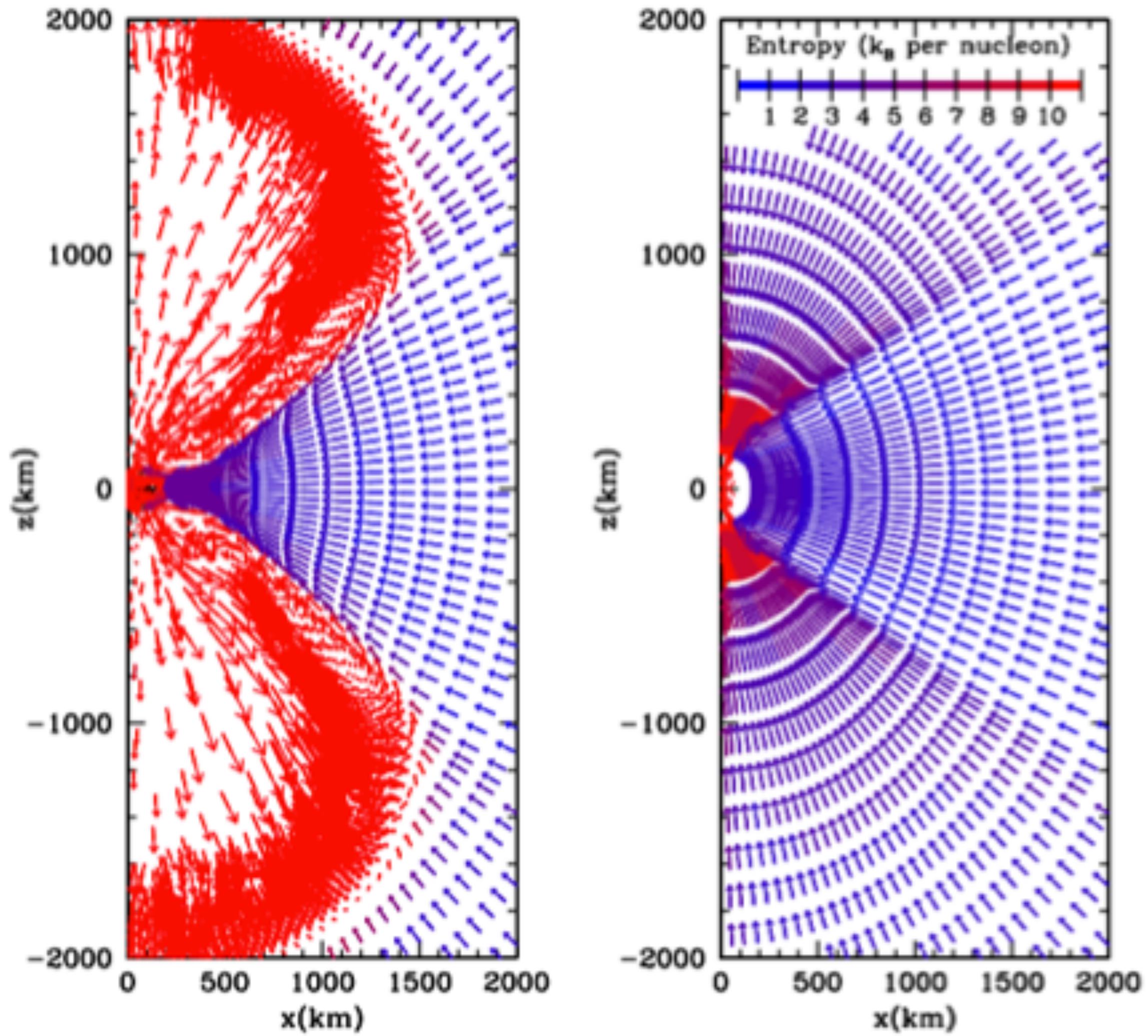




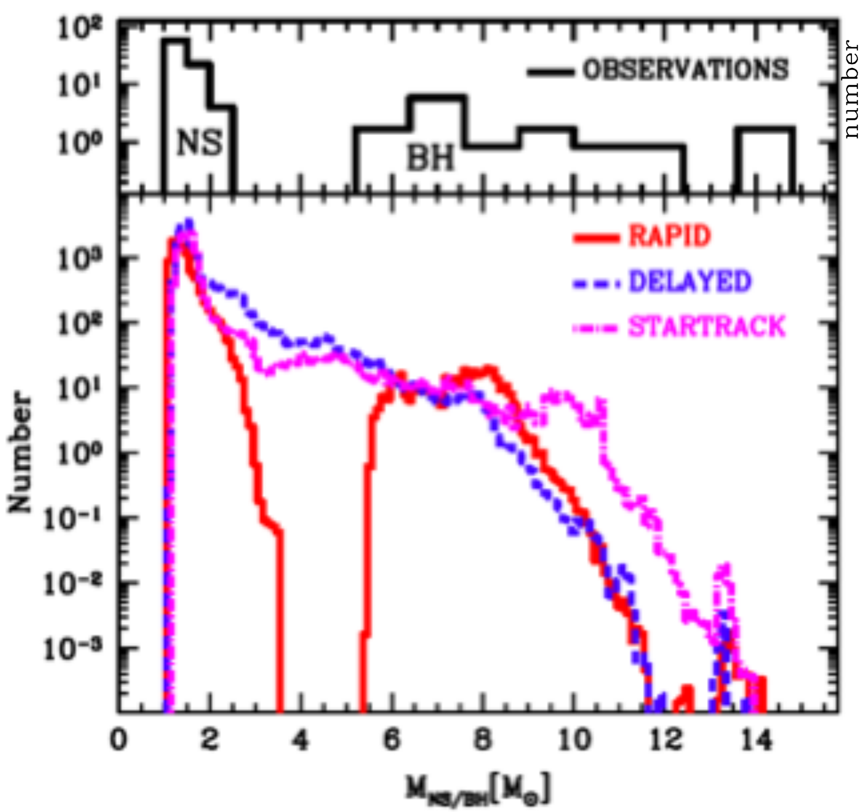
s26_symm_n5
s26_f2th20_n5
s26_f2th40_n5
s26_f3th20_n5
s26_f3th40_n5
s26_f5th20_n5
s26_f5th40_n5
$\dot{M}_{co} = 100t^{-5/3}$
$\dot{M}_{co} = t^{-5/3}$
$\dot{M}_{CO}$ ($M_\odot$/sec)
t (sec)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^1 10^2 10^3 10^4 10^5 10^6 10^7
Fallback: Wong et al. 2014
Colgate 1971, Chevalier 1989

Fallback outflows

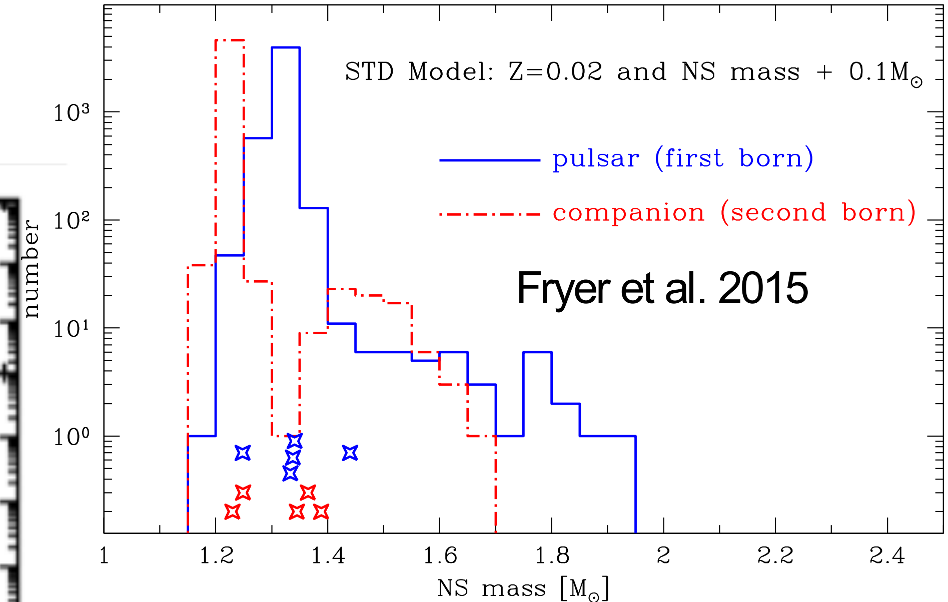
- Fallback can produce extensive ejecta (up to 30% of the fallback)
- With small amounts of angular momentum, this ejecta forms bimodal outflows.
- Except for very high angular momenta, fallback onto BHs produce no ejecta.



Distribution of Neutron and Black Hole Masses



Belczynski 2012



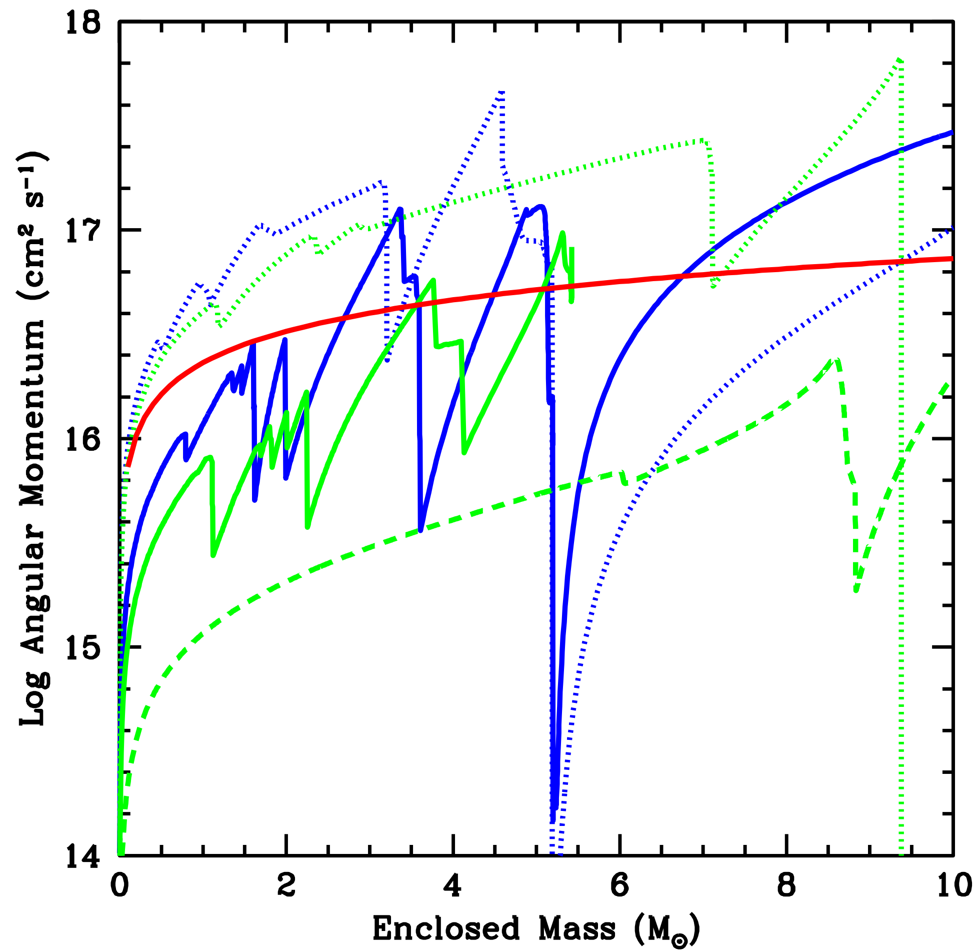
Both the NS-BH mass gap and the distribution of NSs must be fit by any explosion model. Since these masses have all evolved from close binaries, we must also include binary effects. A second gap should occur in the pair-instability gap.

Angular Momentum in Stars Depends upon Coupling

Different models produce different angular momentum profiles based on the recipe for their coupling:

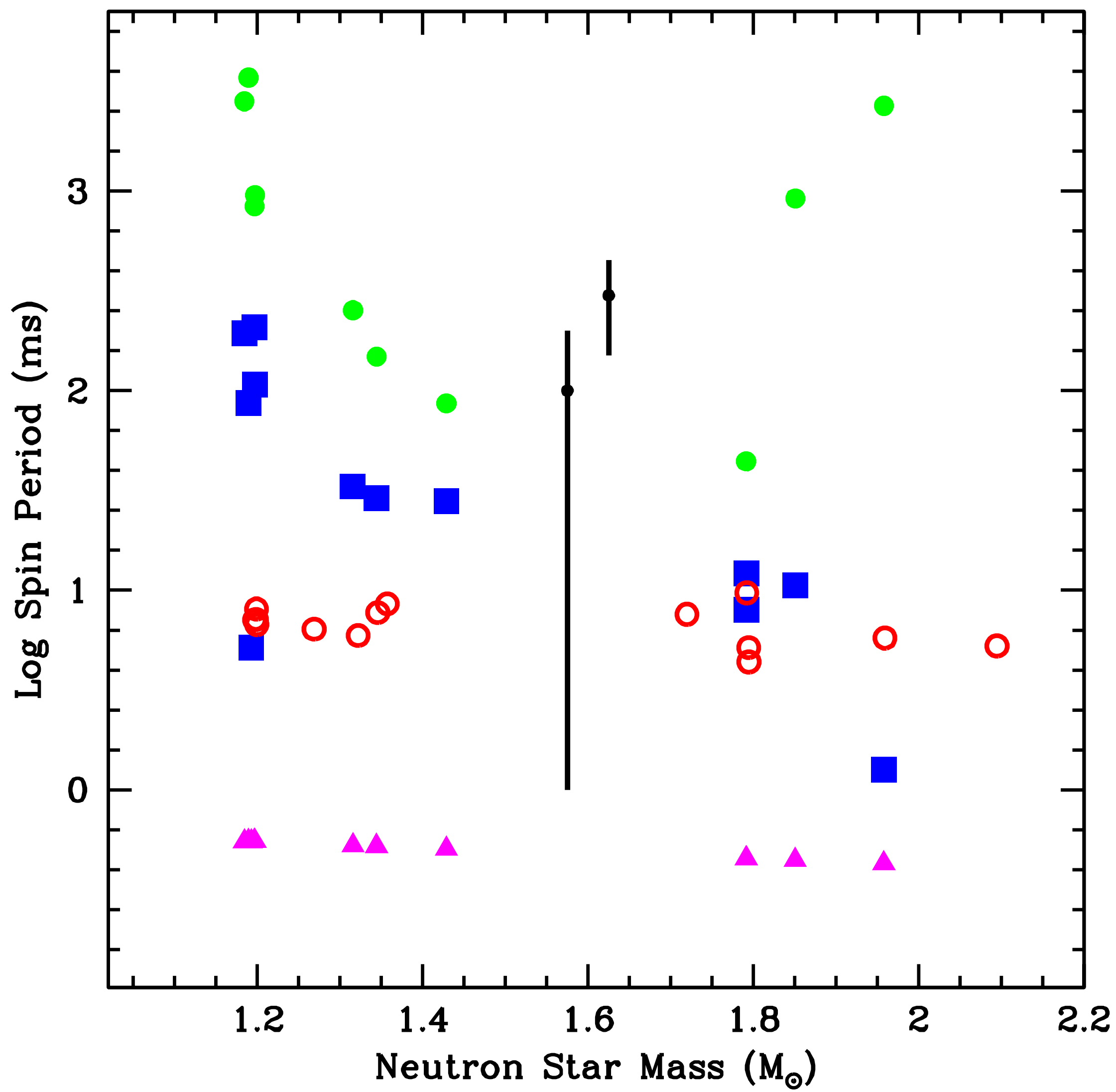
- Dotted: Meynet – no magnetic coupling
- Solid: Heger – Tayler-Spruit Dynamo
- Dashed: MESA

The red line shows the angular momentum required to make a 1000km disk. Strong coupling means no disk.



Neutron Star Spins

- From pulsar observations (plus assumptions on ages and spin-down formulae), we have rough estimates of the birth spins of neutron stars: Faucher-Giguere & Kaspi 2006, Popov & Turolla 2012, Igoshev and Popov 2013
- We can use these spins to measure the coupling between burning layers



Black Hole Spins

- Black hole spins are a cleaner measurement: straightforward estimate on angular momentum that goes into the black hole (less ejecta), no pulsar spin-down mechanisms, etc.
- Spins of X-ray Binaries suggest very fast spins: many of these systems have spins (a) above 0.8-0.9
- What we see in LIGO black holes is very different…. See Chris Belczynski's talk

Conclusions

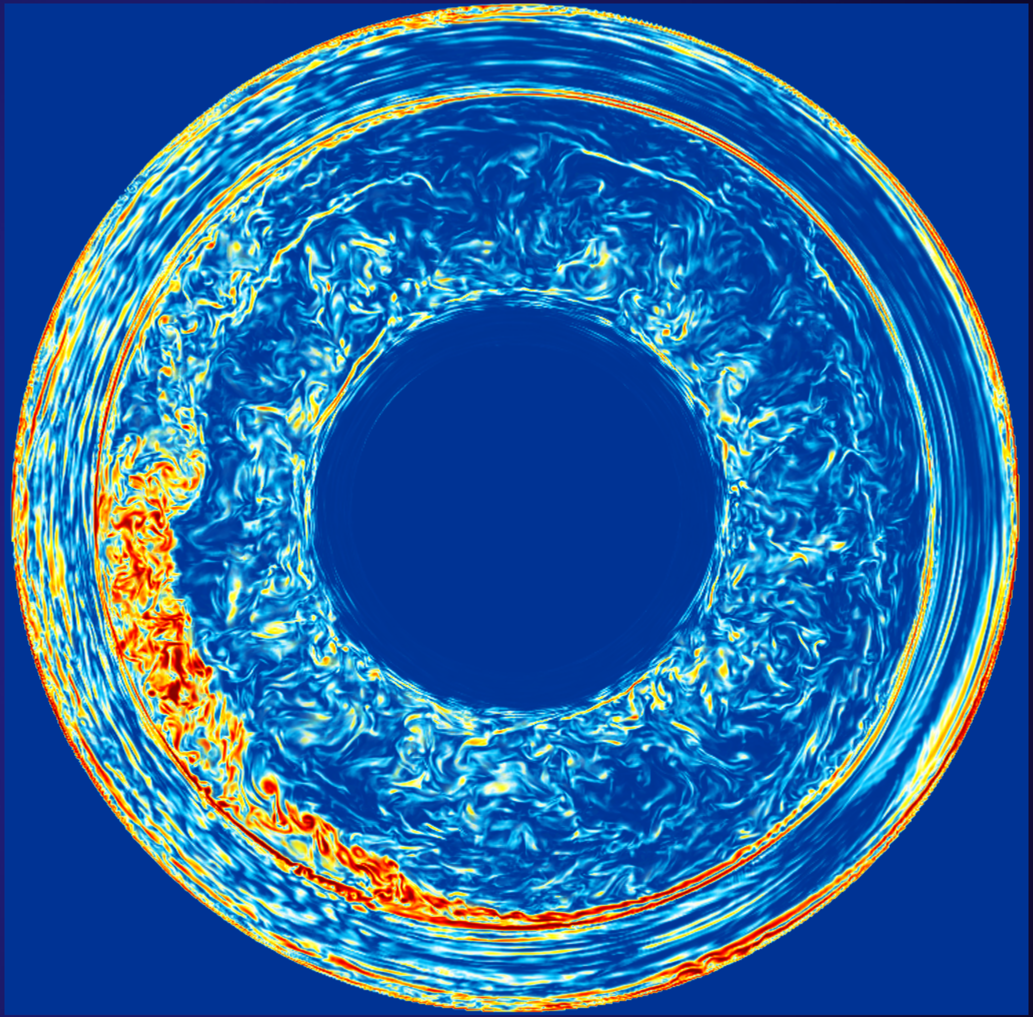
- Compact remnant mass and spin distributions can be made under the current paradigm for the supernova engine.
- But there are a lot of uncertainties: stellar models, neutrino physics, stellar models, equation of state, stellar models, multi-physics modeling, stellar models….

Table 5. Pulsational Pair-Instability Supernovae

M_{init} [$M_\odot$]	M_f [$M_\odot$]	τ [sec]	E [10^{50} erg]	M_{ej} [$M_\odot$]	M_{rem} [$M_\odot$]	M_{Fe} [$M_\odot$]
60	29.53	6.4(4)	0.015	0.02	29.51	2.32
62	30.56	6.1(4)	0.020	0.05	30.51	2.36
64	31.57	5.8(4)	0.022	0.07	31.50	2.49
66	32.60	5.7(4)	0.030	0.10	32.50	2.55
68	33.63	5.8(4)	0.038	0.18	33.45	2.67
70	34.66	6.7(4)	0.060	0.43	34.23	2.84
75	36.83	8.0(4)	0.36	0.66	36.17	2.95
80	39.38	4.1(5)	1.5	1.95	37.43	3.22
85	41.95	9.4(5)	4.6	3.78	38.17	2.99
90	44.54	2.3(6)	5.6	5.78	38.76	2.62
95	47.13	1.1(7)	5.8	6.37	40.76	2.52
100	49.75	1.1(8)	5.7	7.15	42.60	2.73
100*	50.22	8.6(7)	4.1	7.29	42.93	2.22
105	52.24	9.1(9)	5.2	7.21	45.03	1.73
105*	52.82	7.6(9)	3.1	6.83	45.99	2.04
110	54.79	5.8(10)	5.2	10.57	44.22	2.58
110*	55.43	7.3(10)	5.9	10.63	44.80	2.14
115	57.42	1.5(11)	14.8	16.07	41.35	2.63
120	60.12	1.2(12)	35.6	56.61	3.51	1.76

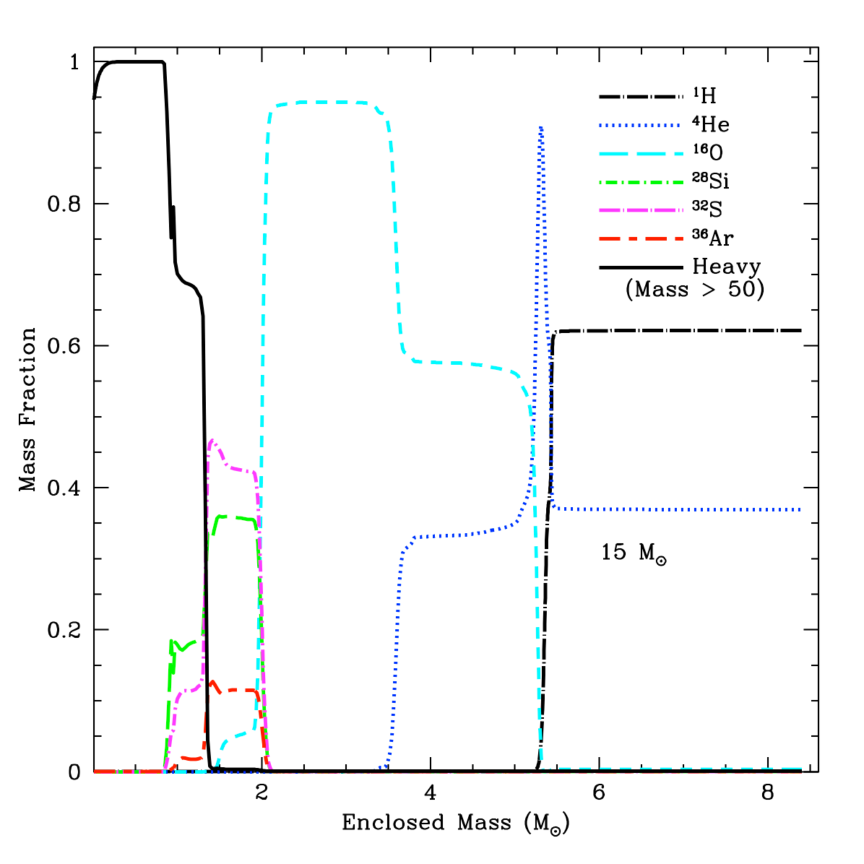
Woosley 2019

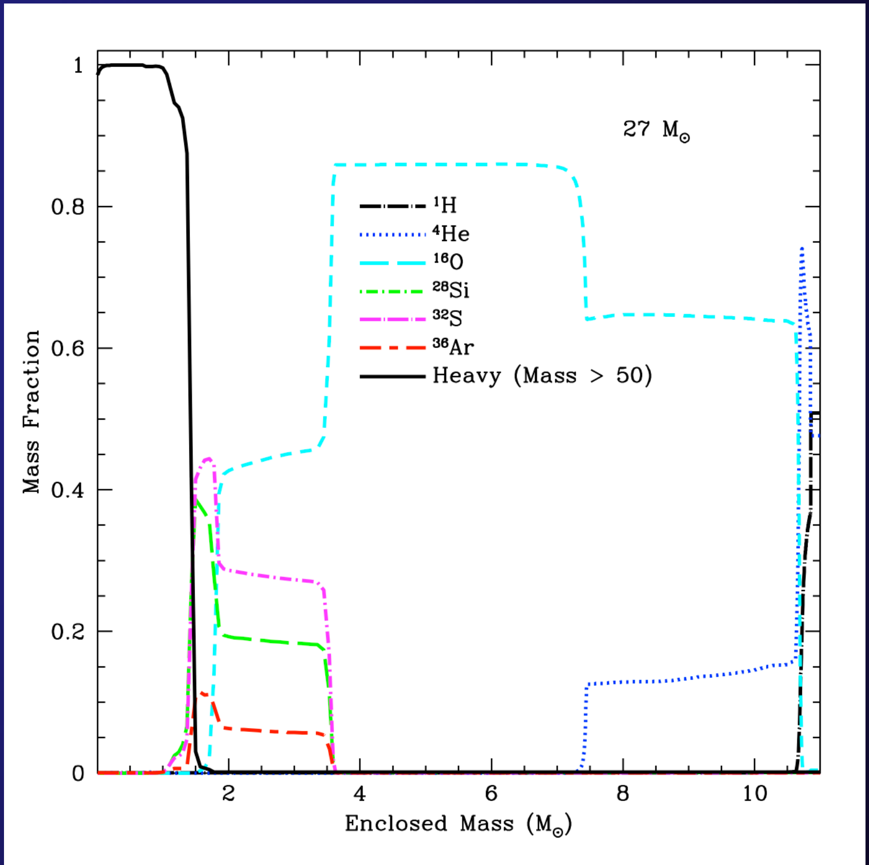
- **Shell burning can be explosive (Smith & Arnett 2013, Arnett et al. 2014, Herwig et al. 2014). This will alter the core masses as well as the circumstellar medium.**



Stellar Models Key

- **New mixing algorithms may burn helium (through more dynamic shell burning), increasing the Ic/Ib ratio (Frey et al. 2013)**





The core is perhaps more affected by the code than the initial conditions.

- Total mass from stellar models:
- Heger Solar – 12.9
- Heger Zero – 24.9
- Limongi Zero – 24.7

What Causes these differences?

- Prescriptions for Mixing and Mixing+Rotation
- Prescriptions for Mass-Loss