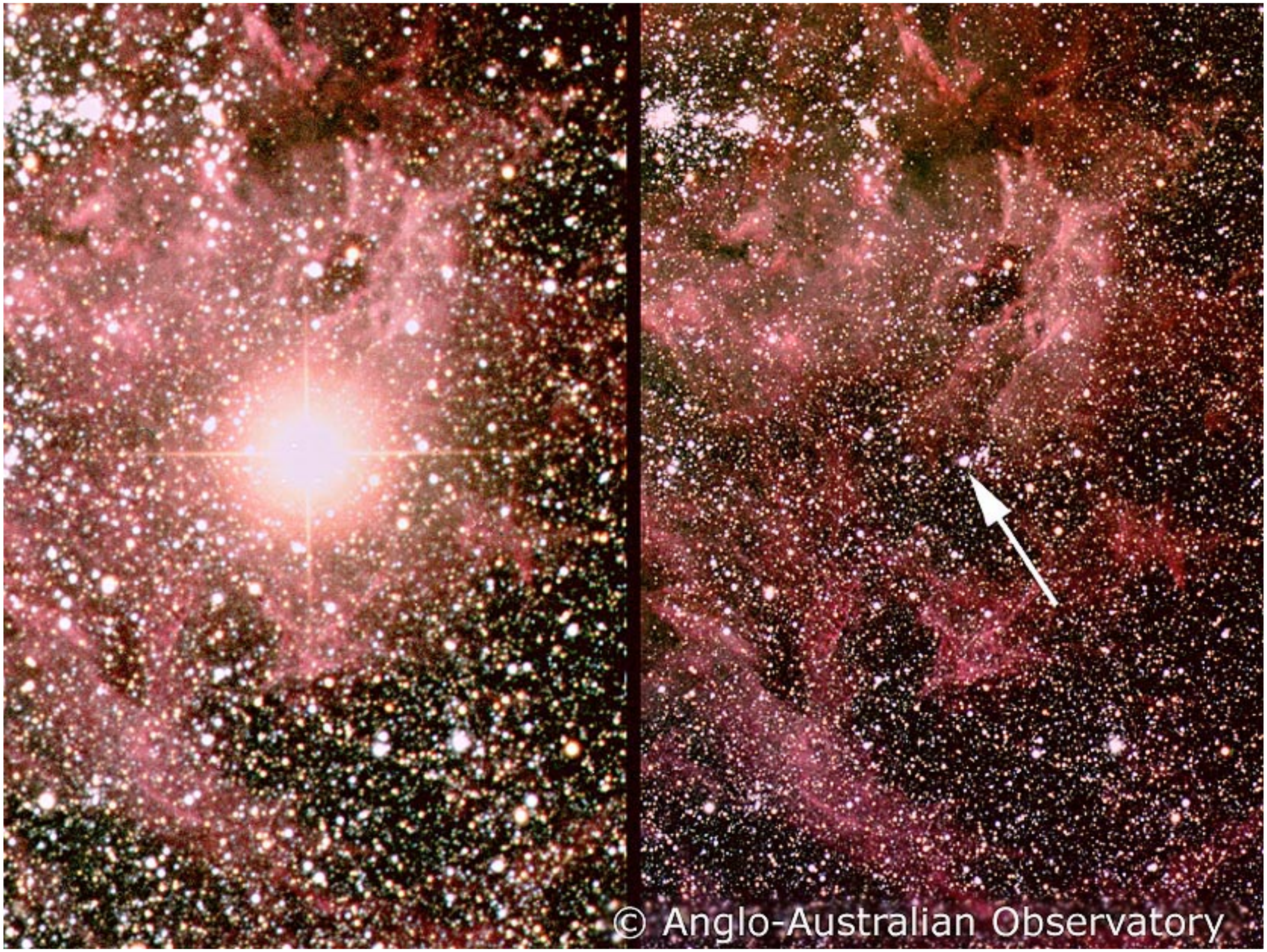
Probes of the Supernova Engine

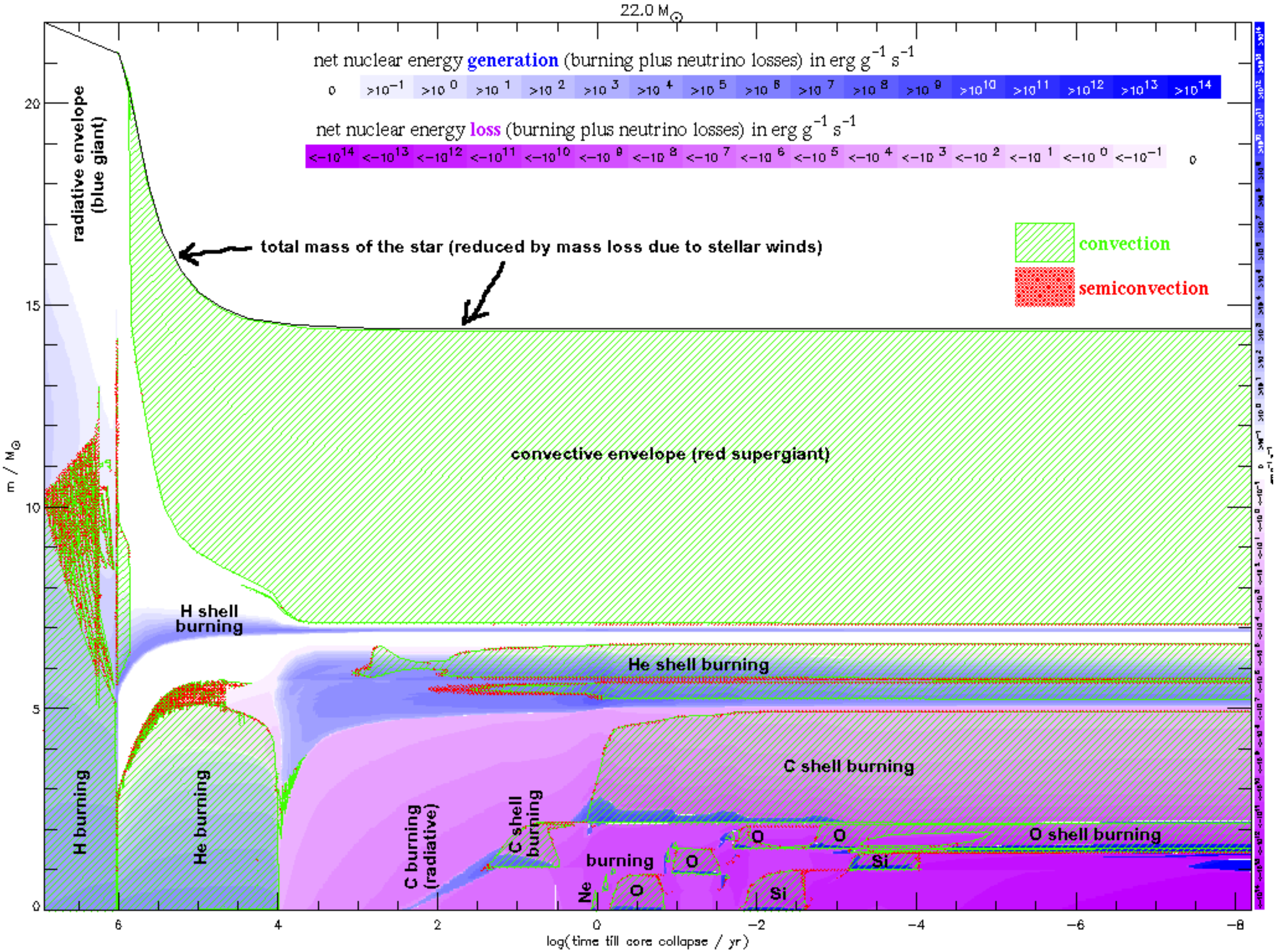
Chris Fryer (LANL) for LANL Multi-Messenger team, LANL light-curve team, NuGrid collaboration

- ➢ Direct Probes of the SN Engine
- • Neutrinos
- • Gravitational Waves
- ➢ Indirect Probes
- • Progenitors
- • Light Curves
- • Ejecta Remnants
- • Compact Remnants
- • Nucleosynthetic Yields

Supernova 1987A



After – SN 1987A
Before – Sanduleak -69 202



22.0 M⊙
net nuclear energy generation (burning plus neutrino losses) in erg g^-1 s^-1
0 >10^-1 >10^0 >10^1 >10^2 >10^3 >10^4 >10^5 >10^6 >10^7 >10^8 >10^9 >10^10 >10^11 >10^12 >10^13 >10^14
net nuclear energy loss (burning plus neutrino losses) in erg g^-1 s^-1
<-10^14 <-10^13 <-10^12 <-10^11 <-10^10 <-10^9 <-10^8 <-10^7 <-10^6 <-10^5 <-10^4 <-10^3 <-10^2 <-10^1 <-10^0 <-10^-1 0
convection
semiconvection
radiative envelope (blue giant)
total mass of the star (reduced by mass loss due to stellar winds)
convective envelope (red supergiant)
H shell burning
He shell burning
C shell burning
O shell burning
H burning
He burning
C burning (radiative)
C shell burning
burning
Ne
O
O
O
O
Si
Si
m / M⊙
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)

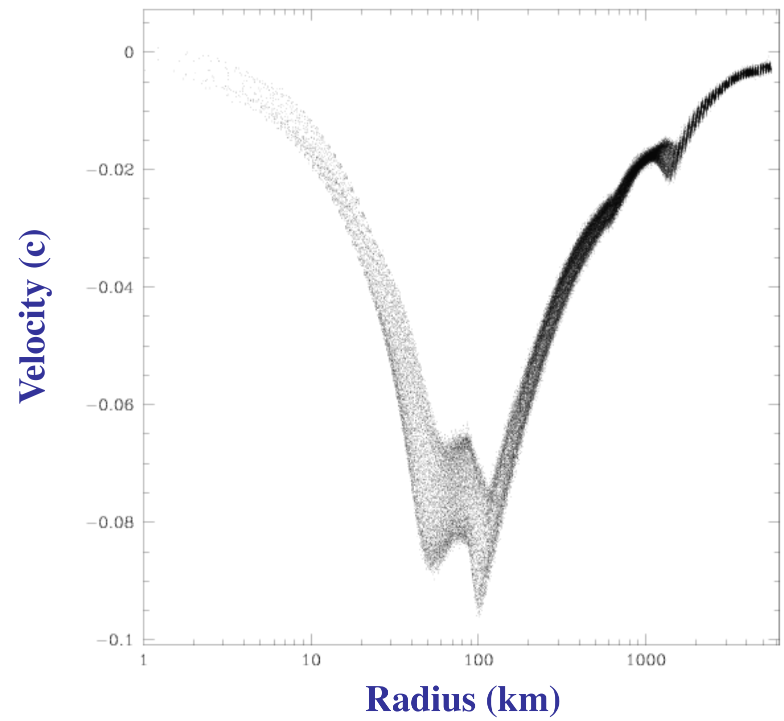
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:

Iron dissociates into alpha particles

Electrons capture onto protons

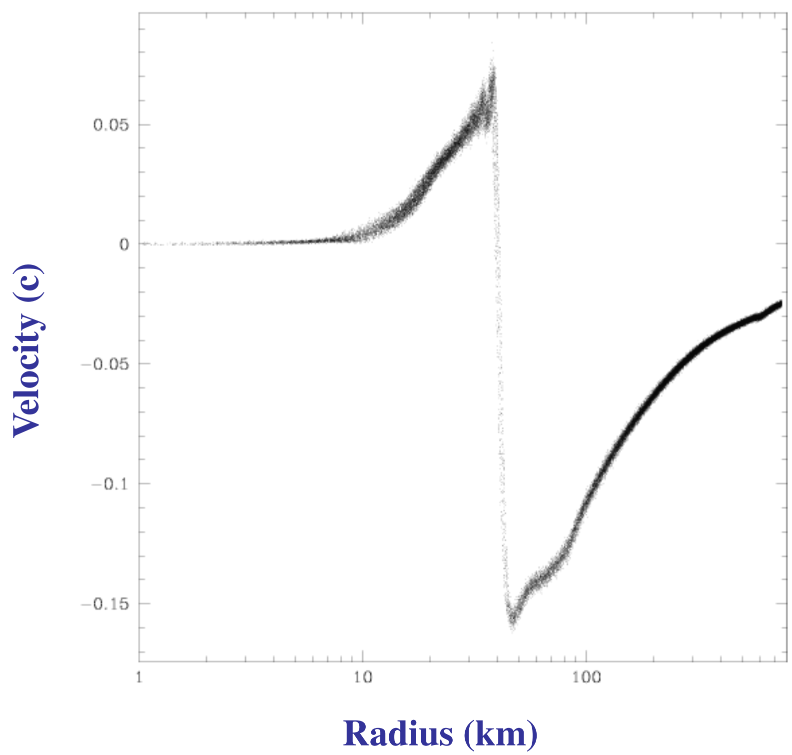
Core collapses nearly at freefall!



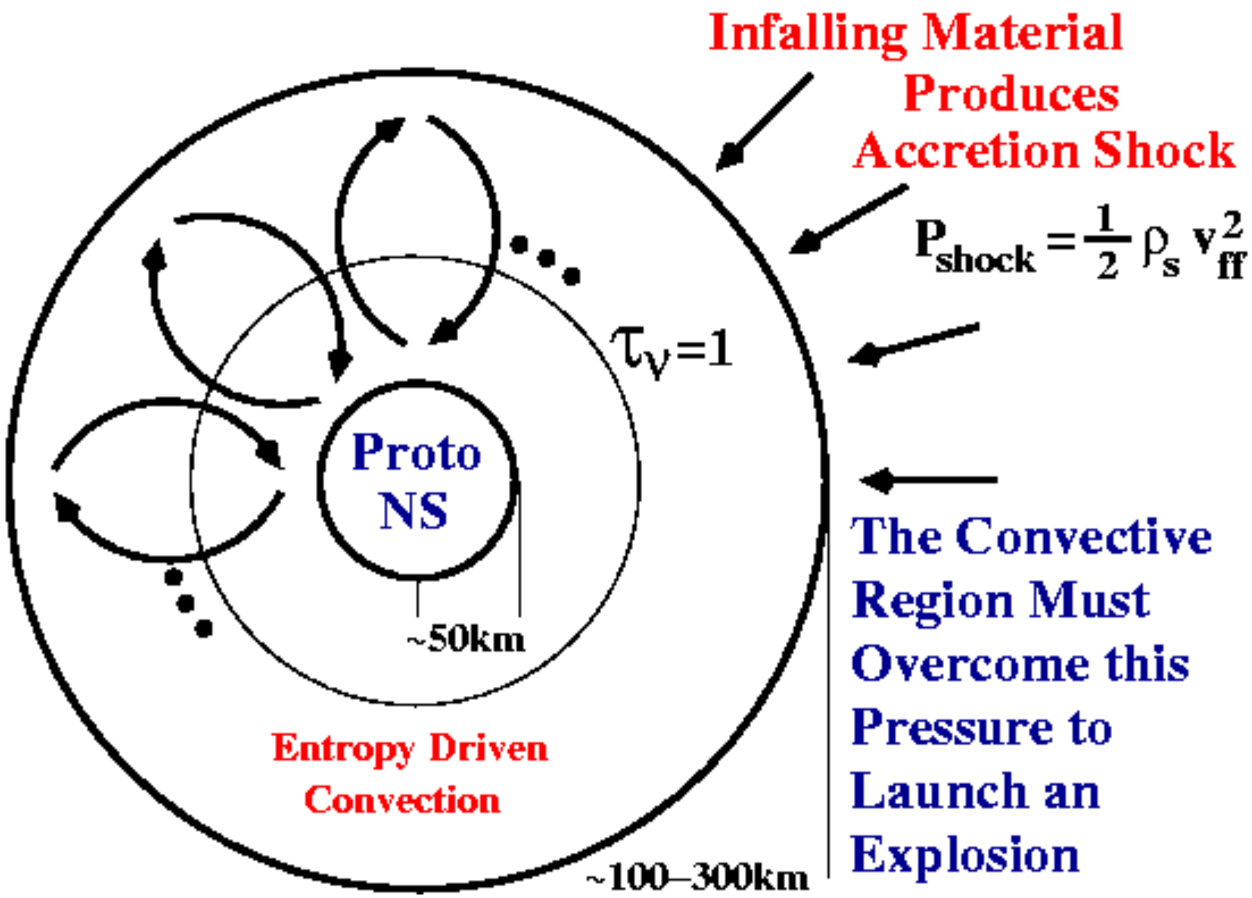
Core reaches nuclear densities

Nuclear forces and neutron degeneracy increase pressure

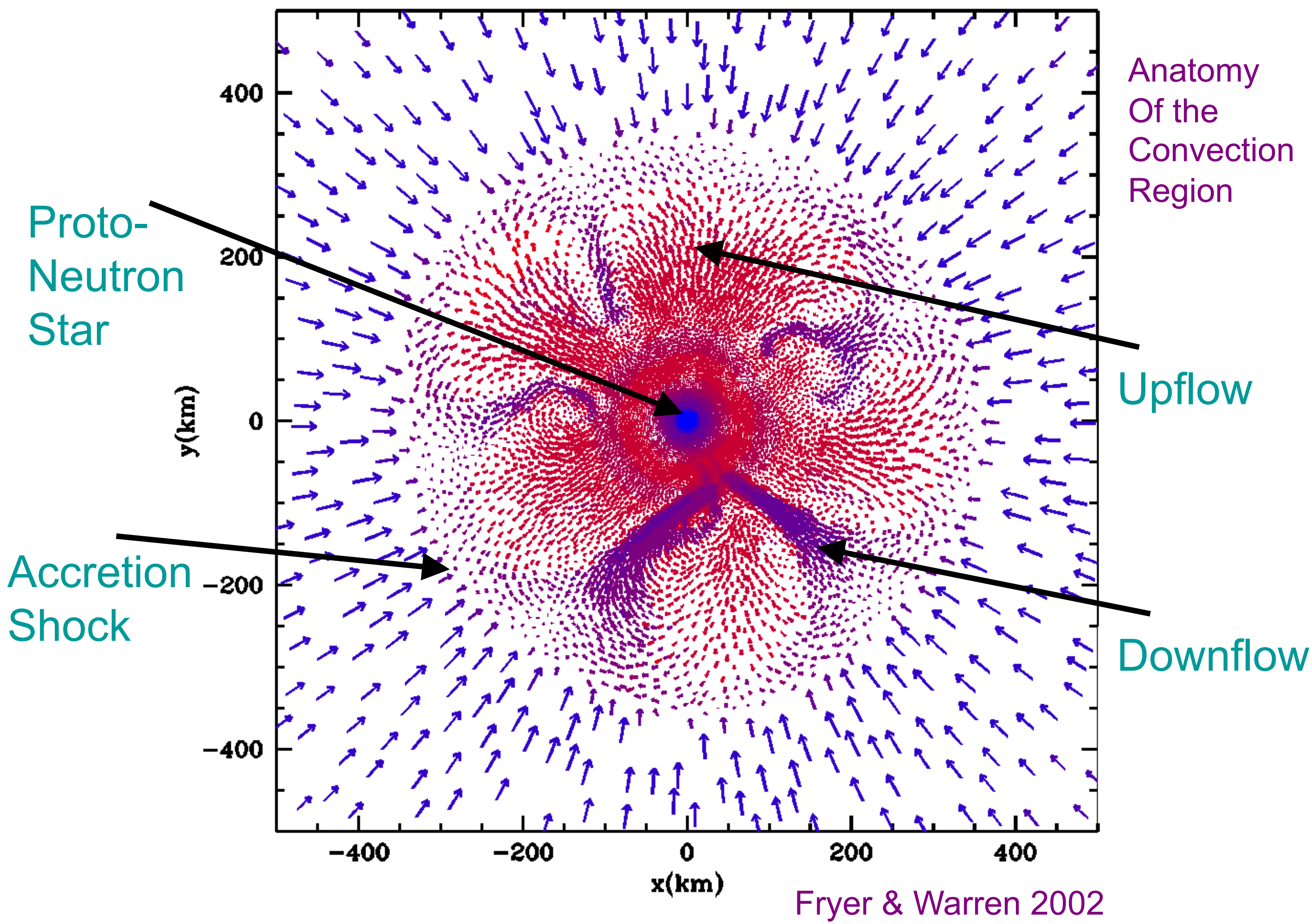
Bounce!



Neutrino-Driven Supernova Mechanism: Convection

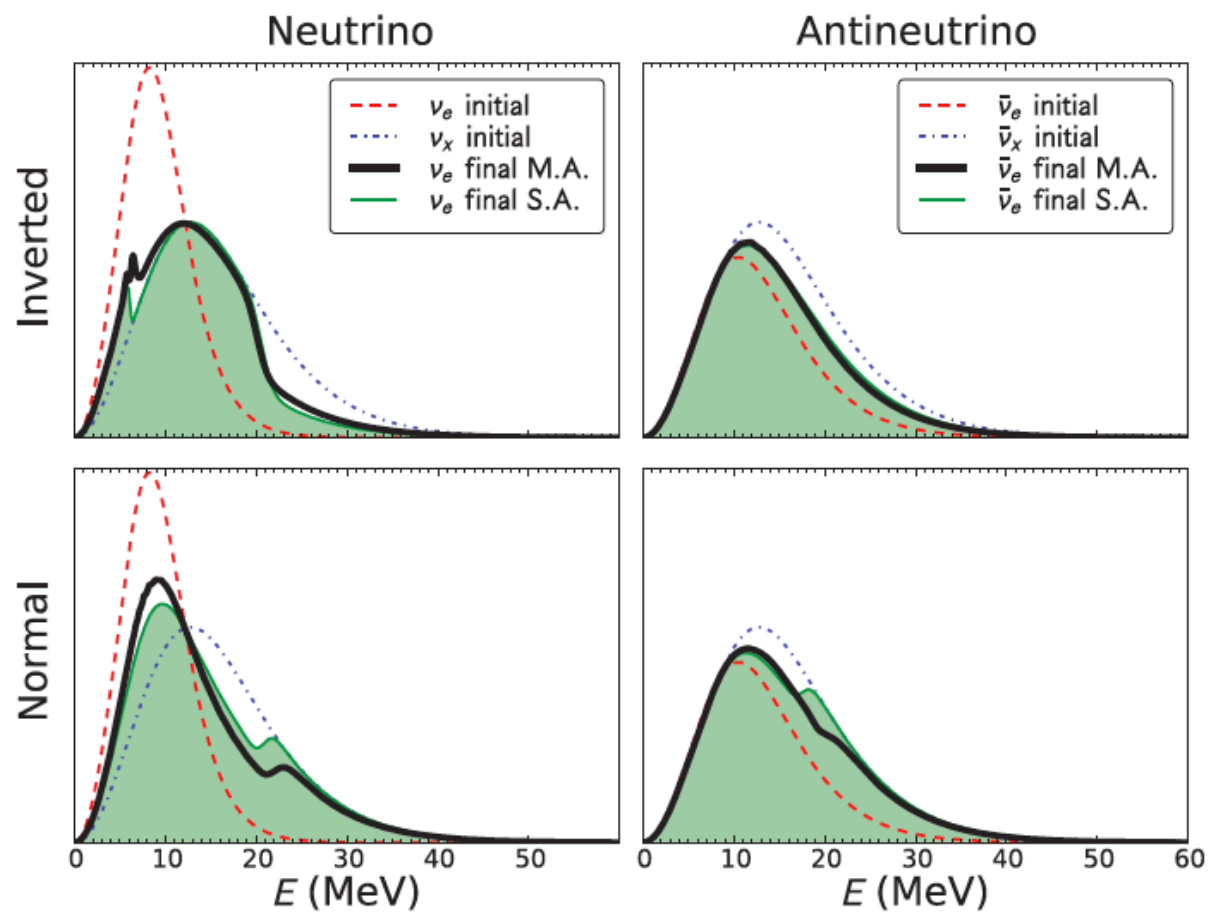


Fryer 1999


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

Neutrinos

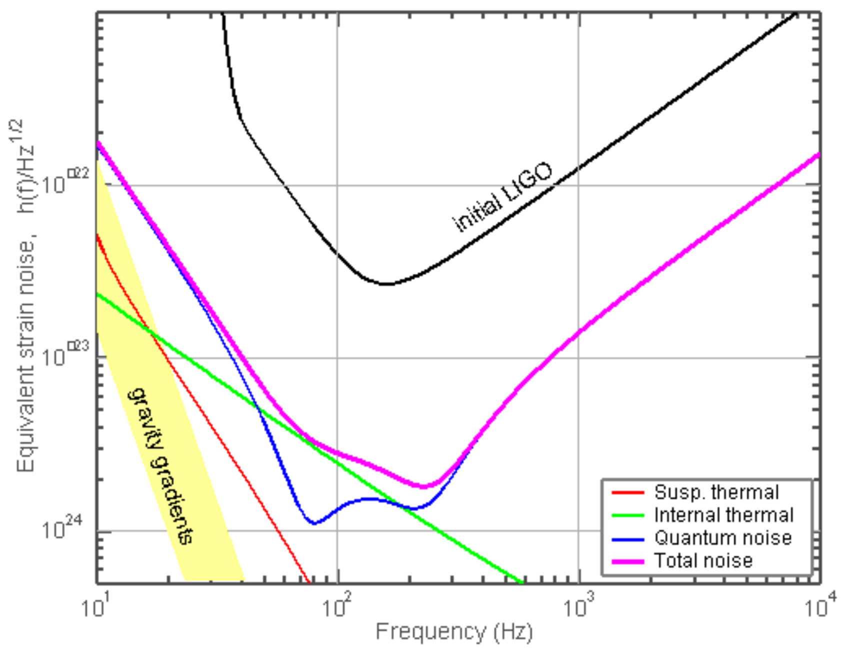
- Neutrinos probe the structure of the core and the behavior of matter at nuclear densities (e.g. Roberts et al. 2012, Reddy et al. 2012).
- With modern detectors, a Galactic supernova could be used to probe neutrino physics such as neutrino oscillations.

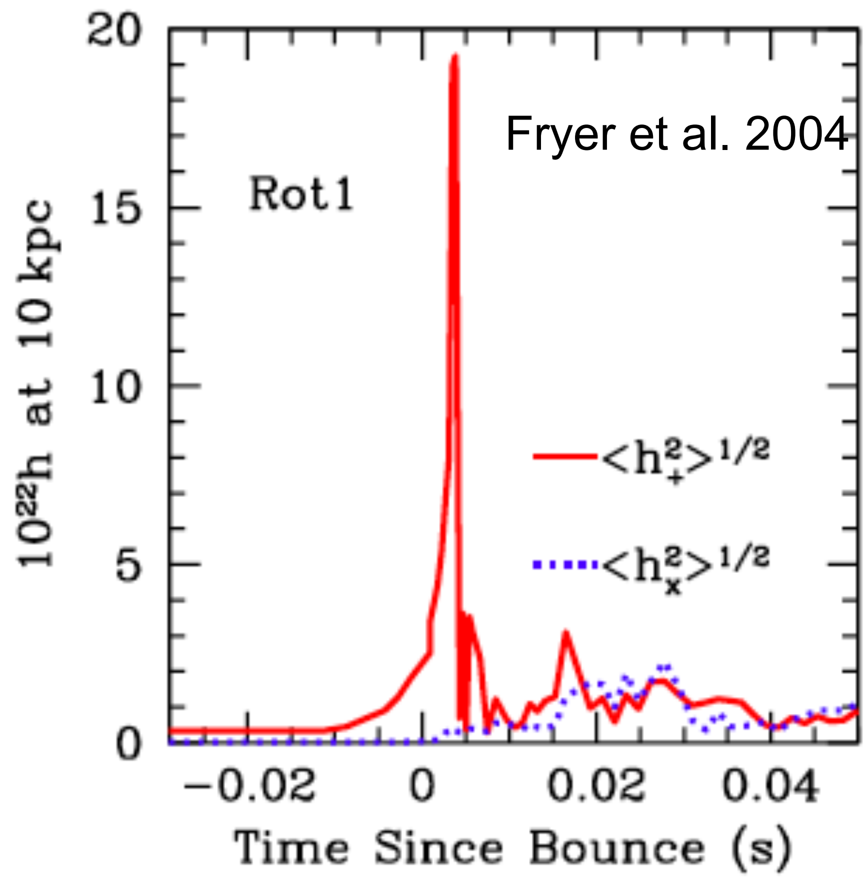


Flavor-State Coupling (Duan & Friedland 2011)

Gravitational Waves

- One of the uncertainties limiting what we can learn from neutrinos is the core rotation.

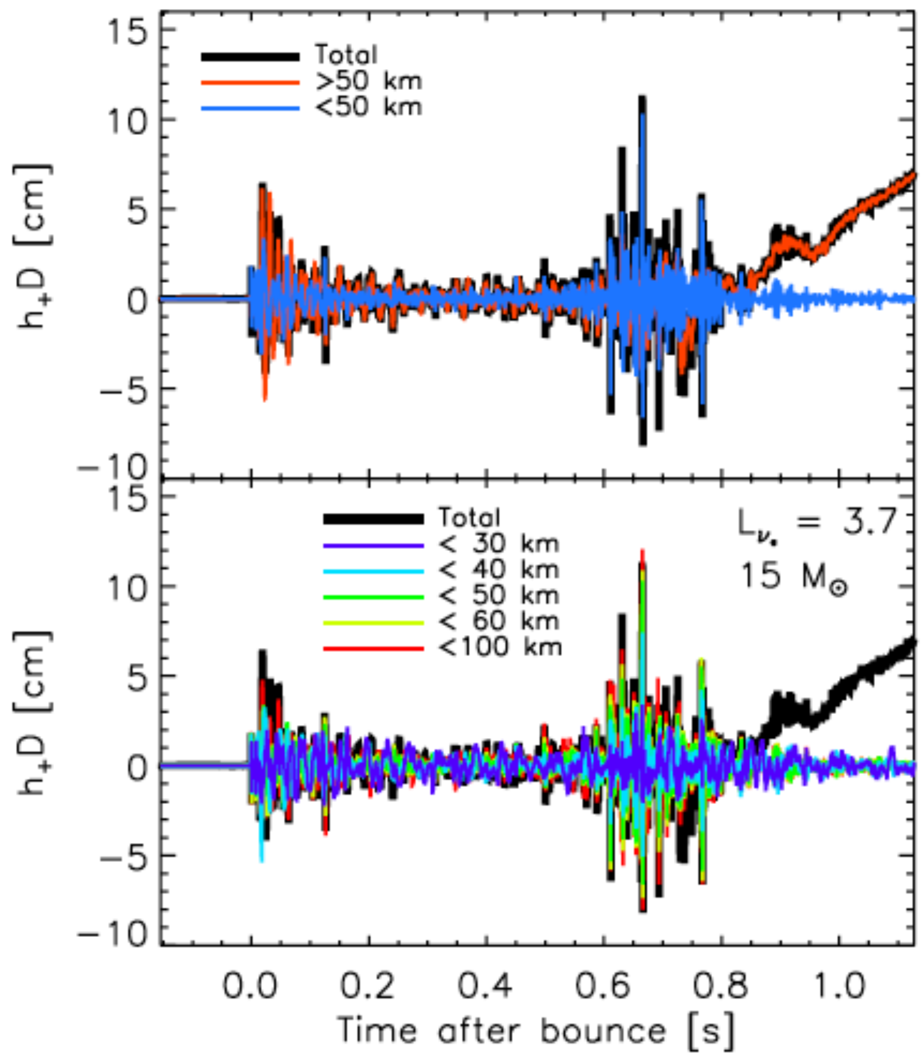




- Gravitational Waves are direct probes of this rotation.

Gravitational Waves

- For a sufficiently strong signal, we could even probe the nature of the convection.
- Unfortunately, even with the next generation of detectors, such detailed neutrino and gravitational wave signals are limited to Galactic (or local group) supernovae.



Murphy et al. 2009

Indirect Probes

- With indirect probes, we will have to use theory to connect the observations to the physics we want to study.
- With these tests, errors can multiply. Need to constrain the initial conditions and include multiple diagnostics to minimize the errors.

Observing the Progenitor

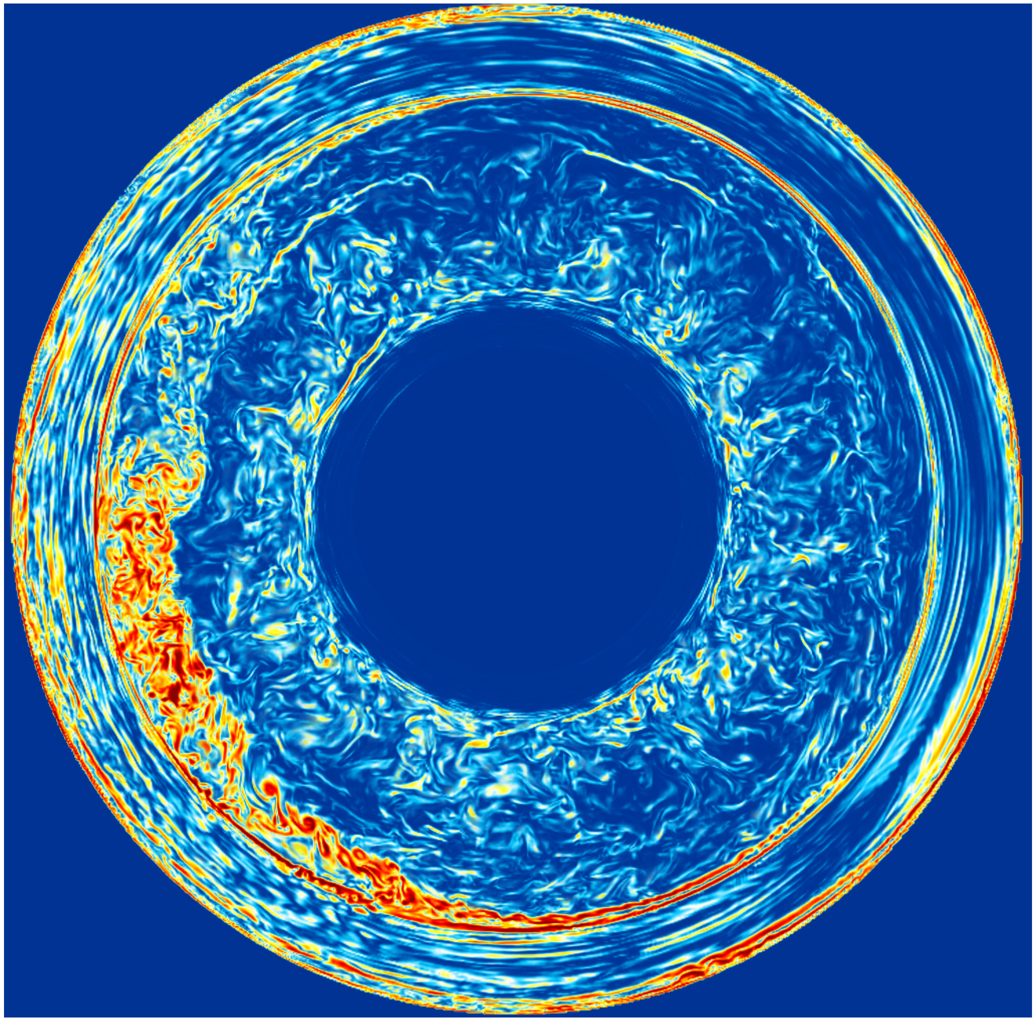
- Thanks primarily to the HST archive, we now have a growing list of supernovae whose pre-explosion progenitor has been observed.
- However, even with observations, the errors can still be large.
- Better theory is needed to take advantage of this data.

Name	Mass
Serendipitous	
SN1987A	14-20$M_\odot$
SN1993J	$\sim 15M_\odot$
Gold Set	
SN2003gd	6-12$M_\odot$
SN2005cs	6-10$M_\odot$
SN2008bk	7.5-9.5$M_\odot$ $\rightarrow$ 11.2-14.6$M_\odot$ [54]
SN2004dj	12-20$M_\odot$
SN2004am	9-19$M_\odot$
Silver Set	
SN1999ev	15-18$M_\odot$
SN2004A	7-12$M_\odot$
SN2004et	8-14$M_\odot$
Bronze Set	
SN1999an	$<18M_\odot$
SN1999br	$<15M_\odot$
SN1999em	$<15M_\odot$
SN1999ev	12-22$M_\odot$
SN1999gi	$<14M_\odot$
SN2001du	$<15M_\odot$
SN2002hh	$<18M_\odot$
SN2003ie	$<25M_\odot$
SN2004dg	$<12M_\odot$
SN2005cs	6-10$M_\odot$
SN2006my	$<13M_\odot$
SN2006ov	$<10M_\odot$
SN2007aa	$<12M_\odot$
SN2008bk	8-12$M_\odot$
New	
SN2008ax	$10-14M_\odot$ or $\sim 28M_\odot$ [55]
SN2008cn	$13-17M_\odot$ [56]
SN2009md	$7-15M_\odot$ [57]
SN2011dh	$13-22M_\odot$ [58–60]
SN2012aw	$\sim 17-18M_\odot$ [61]
iPTF13bvn	$\sim$31-35$M_\odot$ [62, 63]

Smartt 2009 + Fryer et al. 2014

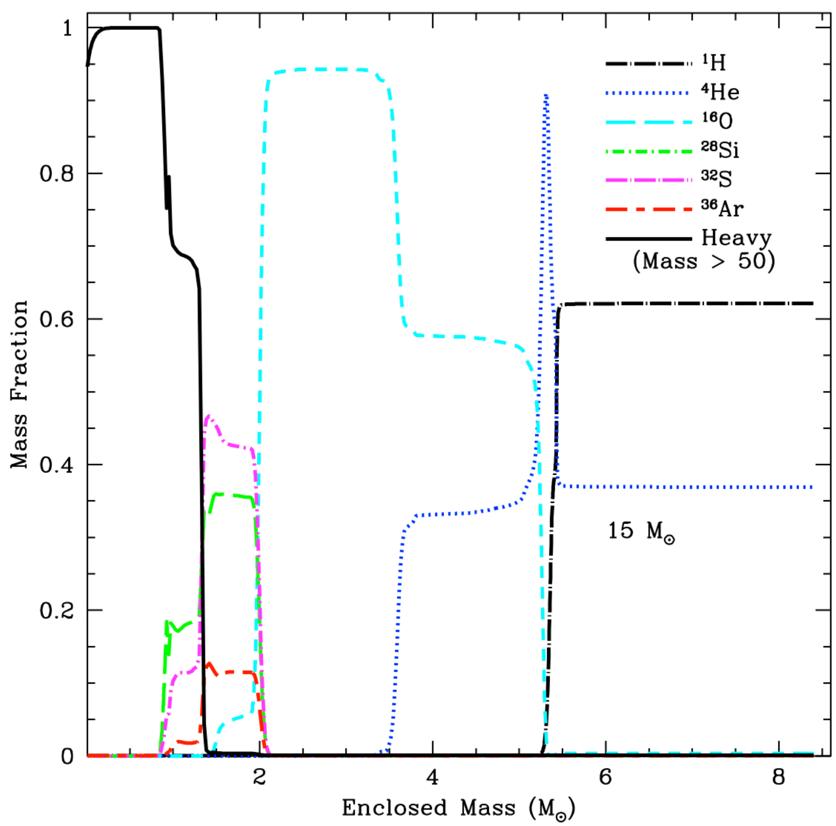
Shell Burning

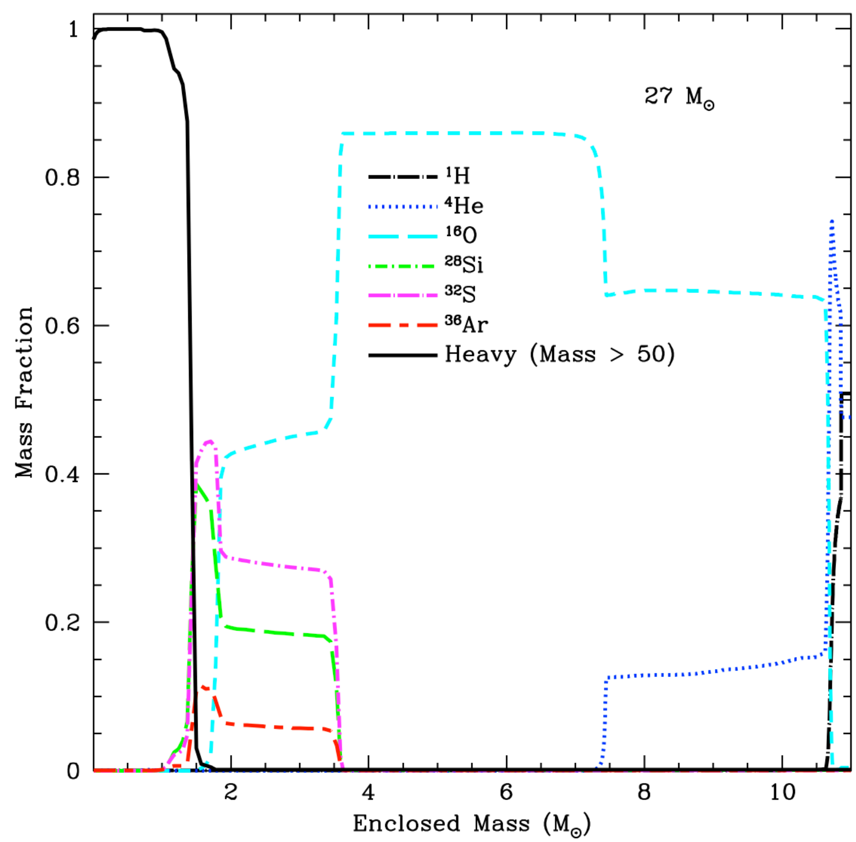
- Shell burning can be explosive (Smith & Arnett 2013, Arnett et al. 2014, Herwig et al. 2014). This will alter the core masses as well as the circumstellar medium.



Stellar Models Key

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

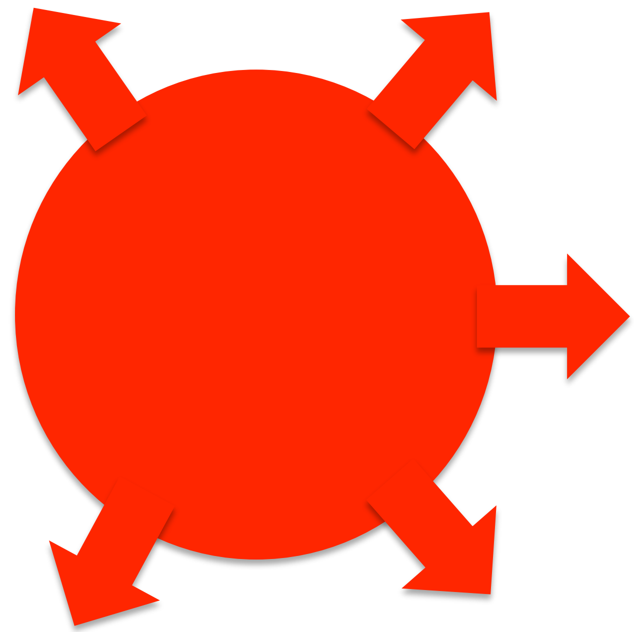




Binaries and mass loss

- Binary searches in clusters suggest that >50% of massive stars are in close binaries (Kobulnicky et al. 2012, Sana et al. 2012).
- Mass transfer, Common envelope will affect circumstellar media and, in some cases, stellar structure.
- The strength and asymmetries in wind mass loss has also changed over the last decade.
- All these, mixing, winds, binary effects, can dramatically alter the light curves and we have a lot of work to understand these effects.

Supernova Light Curves



- First Pass, an expanding sphere:

$$L = 4\pi r^2 \sigma T^4$$

- If we assume adiabatic expansion:

$$S \propto aT^3/\rho \rightarrow T \propto S^{1/3} M^{1/3} r^{-1}$$
$$\rightarrow L \propto r^{-2} M^{4/3} S^{1/3}$$

- What is missing?
  - ➢ Entropy at photosphere is not constant: Transport, ^{56}Ni decay, shock heating.
  - ➢ Photosphere doesn't expand with ejecta. Is a photosphere even well-defined?

Applying Early Light-Curve Models

Litvinova and Nadezhin (1985) derived relations for ejecta mass (m), radius (r) and explosion energy (E) as a function of V magnitude, time since explosion (t) and photospheric velocity (v) based on their simulations:

- $\lg(E(\mathrm{foe})) = 0.135\ V + 2.34\lg(t) + 3.13\lg(v) - 4.205$
- $\lg(M(\mathrm{solar})) = 0.234\ V + 2.91\lg(t) + 1.96\lg(v) - 1.829$
- $\mathrm{Lg}(R(\mathrm{solar})) = -0.572V - 1.07\lg(t) - 2.74\lg(v) - 3.350$

TABLE 3

OBSERVED AND PHYSICAL PARAMETERS FOR TYPE II SUPERNOVAE

SN	t_0 (JD−2,400,000)	t_p (JD−2,400,000)	V_p	v_p (±300 km s^{-1})	Energy ($\times10^{51}$ ergs)	Ejected Mass ($M_\odot$)	Initial Radius ($R_\odot$)
1969L.........	40550.5(5)	40660.0(7)	13.34(06)	4562	$2.3^{+0.7}_{-0.6}$	28^{+11}_{-8}	204^{+150}_{-88}
1973R	42008.5(15)	42119.0(7)	14.61(05)	4823	$2.7^{+1.2}_{-0.9}$	31^{+16}_{-12}	197^{+128}_{-78}
1986L.........	46707.9(4)	46813.0(7)	14.64(05)	4037	$1.3^{+0.5}_{-0.3}$	17^{+7}_{-5}	417^{+304}_{-193}
1988A	47163.0(7)	47305.0(35)	15.04(05)	3537	$2.2^{+1.7}_{-1.2}$	50^{+46}_{-30}	138^{+80}_{-42}
1989L.........	47650.0(15)	47790.7(7)	15.68(05)	2800	$1.2^{+0.6}_{-0.5}$	41^{+22}_{-15}	136^{+118}_{-65}
1990E.........	47932.6(5)	48063.9(10)	16.00(20)	4552	$3.4^{+1.3}_{-1.0}$	48^{+22}_{-15}	162^{+148}_{-78}
1991G	48280.0(5)	48403.0(7)	15.61(07)	3030	$1.3^{+0.9}_{-0.6}$	41^{+19}_{-16}	70^{+73}_{-31}
1992H	48661.0(10)	48777.5(10)	15.07(04)	5084	$3.1^{+1.3}_{-1.0}$	32^{+16}_{-11}	261^{+177}_{-103}
1992am	48778.1(11)	48951.1(29)	18.78(05)	5097	$5.5^{+3.0}_{-2.1}$	56^{+40}_{-24}	586^{+341}_{-212}
1992ba	48883.2(5)	49015.3(7)	15.56(05)	2954	$1.3^{+0.5}_{-0.4}$	42^{+17}_{-13}	96^{+100}_{-45}
1999cr	51221.5(10)	51347.5(10)	18.50(05)	3858	$1.9^{+0.8}_{-0.6}$	32^{+14}_{-12}	224^{+136}_{-81}
1999em	51474.0(3)	51598.0(5)	14.02(05)	3290	$1.2^{+0.6}_{-0.3}$	27^{+14}_{-8}	249^{+243}_{-150}
1999gi	51474.0(3)	51645.0(5)	14.98(05)	3168	$1.5^{+0.7}_{-0.5}$	43^{+24}_{-14}	81^{+110}_{-51}

Hamuy (2003) fits with this formulae predict extremely high masses (too high to be believed).

Difficulties in Modeling Supernovae

- Initial Conditions
  - Progenitor structure, circumstellar medium (progenitor mass ejections), explosion energy, explosion asymmetry
- Radiation Transport
  - Simplifications in solving the Boltzmann Equation
  - Opacities: number of levels, LTE vs. NLTE, steady state approximations
  - Ion/electron coupling
- Radiation Hydrodynamics
  - 1T, 2T, 3T (radiation/matter decupling)
  - Hydrodynamic shocks and radiation
  - Radiation effects on hydrodynamics

Radiation Transport

Streaming and Removal Term

$$\frac{1}{c}\frac{\partial I}{\partial t} + \Omega \bullet \nabla I + (\sigma_a + \sigma_s)I =$$

Scattering Term

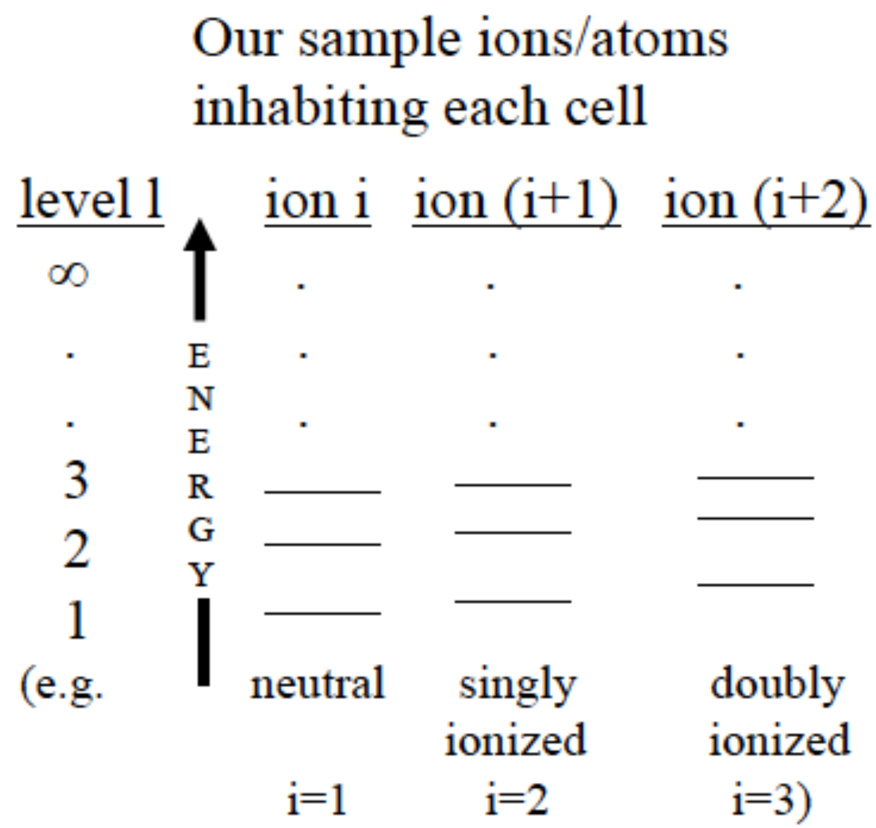
Source Term

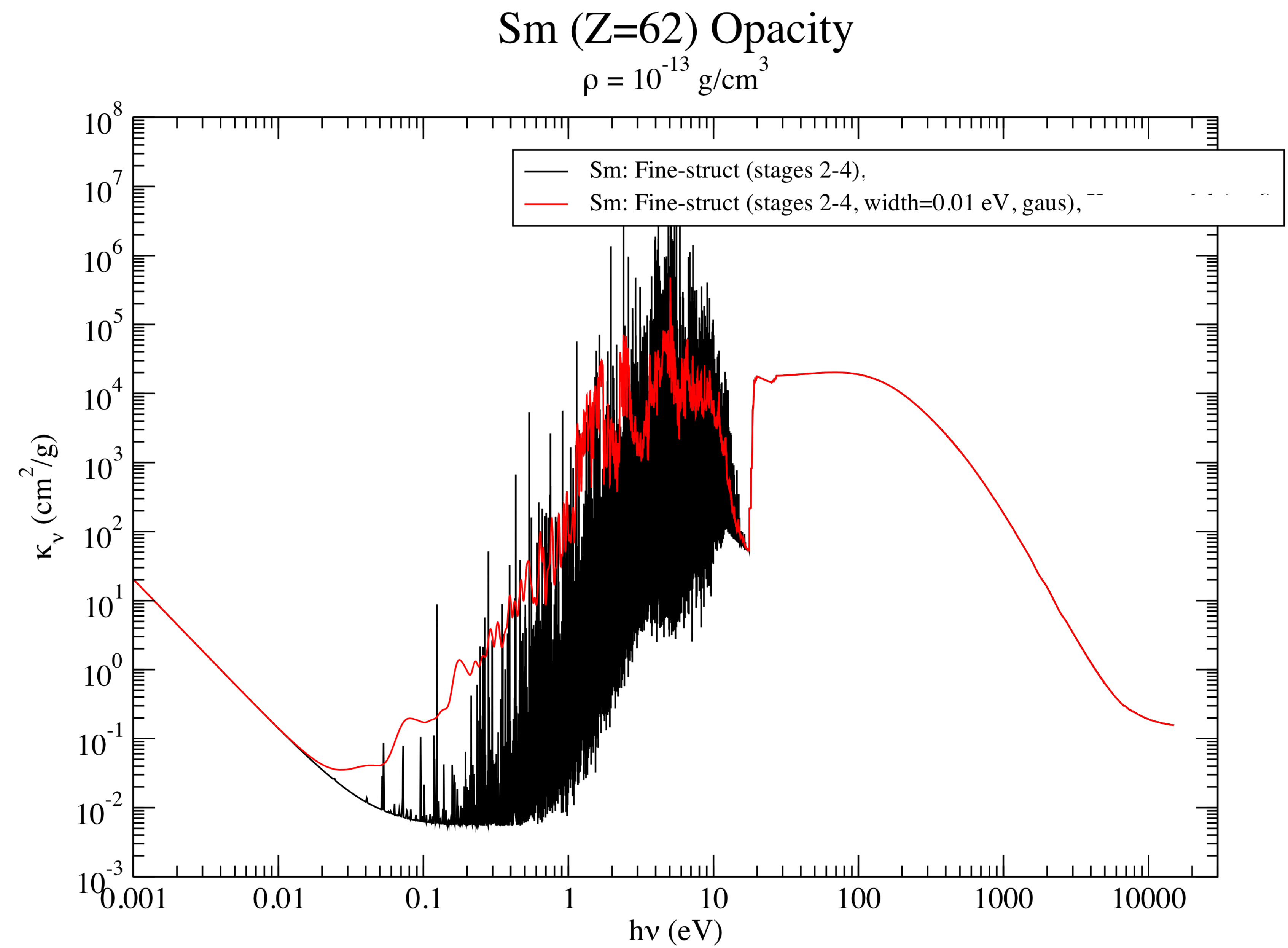
$$\int\int I(r,t,\Omega',E')\sigma(E' \rightarrow E,\Omega' \rightarrow \Omega)\,d\Omega'\,dE' + S(r,t,\Omega,E)$$

- Average over angle:
  - First moment: diffusion
  - Second moment: Variable Eddington Factor
- Average over Energy Group: Gray (Rosseland, Planck)
- Remove time dependent term
- Ignore Spatial Terms

Accurate Opacities critical: the kilanova example

- The presence of heavy elements at such cold temperatures requires the calculation of near-neutral ions with many (> 50) bound electrons.
- Furthermore, the presence of the $4f^4$ subshell (lanthanides) requires the seniority quantum number to properly account for the angular momentum coupling when calculating the fine-structure levels (extra code development was required to obtain atomic structure)
- Just 25 configurations leads to 27,000 levels and 300,000,000 lines.

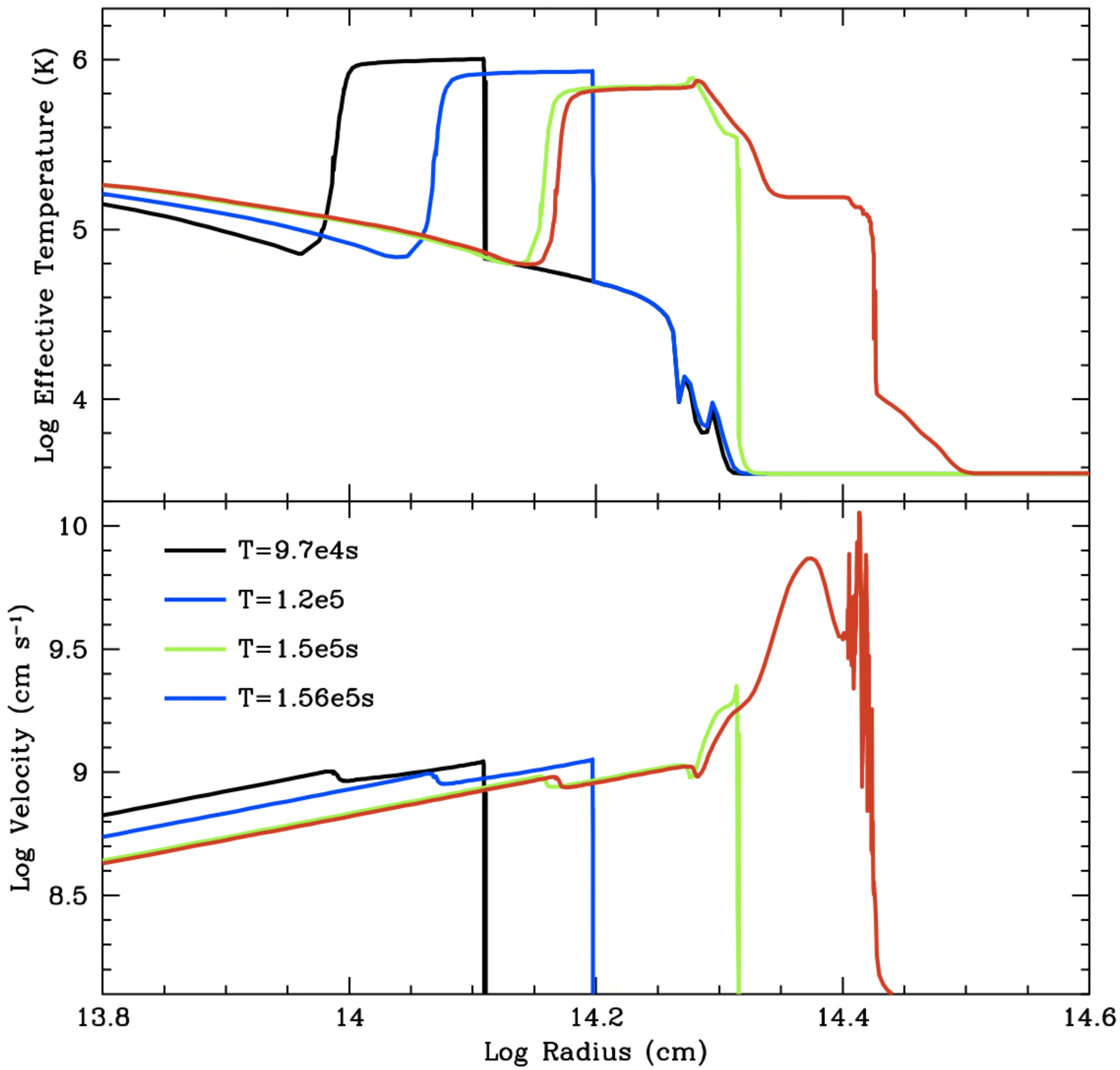




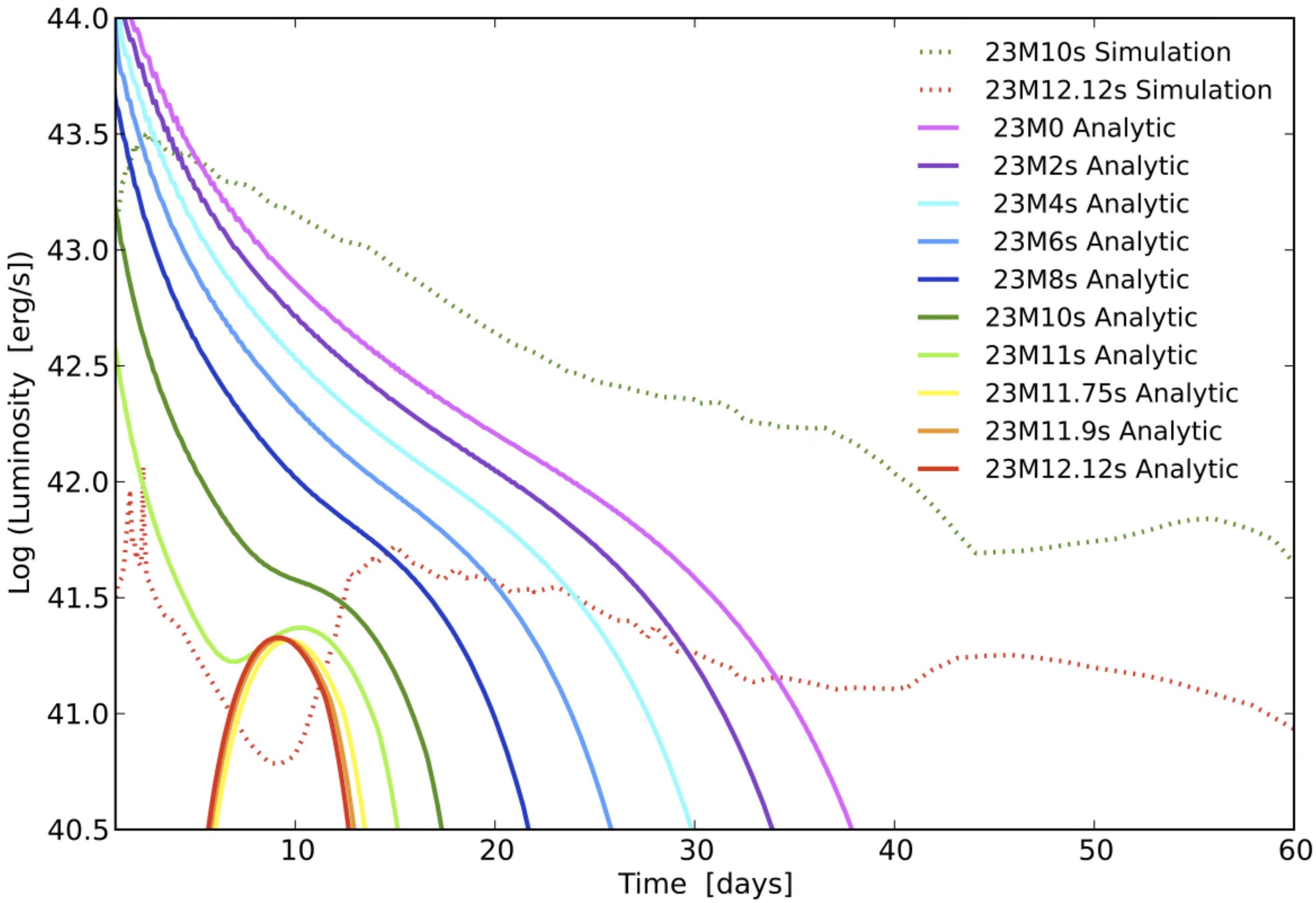
Sm (Z=62) Opacity
ρ = 10^-13 g/cm^3
Sm: Fine-struct (stages 2-4),
Sm: Fine-struct (stages 2-4, width=0.01 eV, gaus),
κν (cm^2/g)
hν (eV)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
0.001
0.01
0.1
1
10
100
1000
10000

Radiation Hydrodynamics in Shock Breakout

- Even when the radiation is trapped, it can lead the shock – the shock position moves faster than Sedov solution would predict.
- After breakout, the radiation begins to decouple from the material.



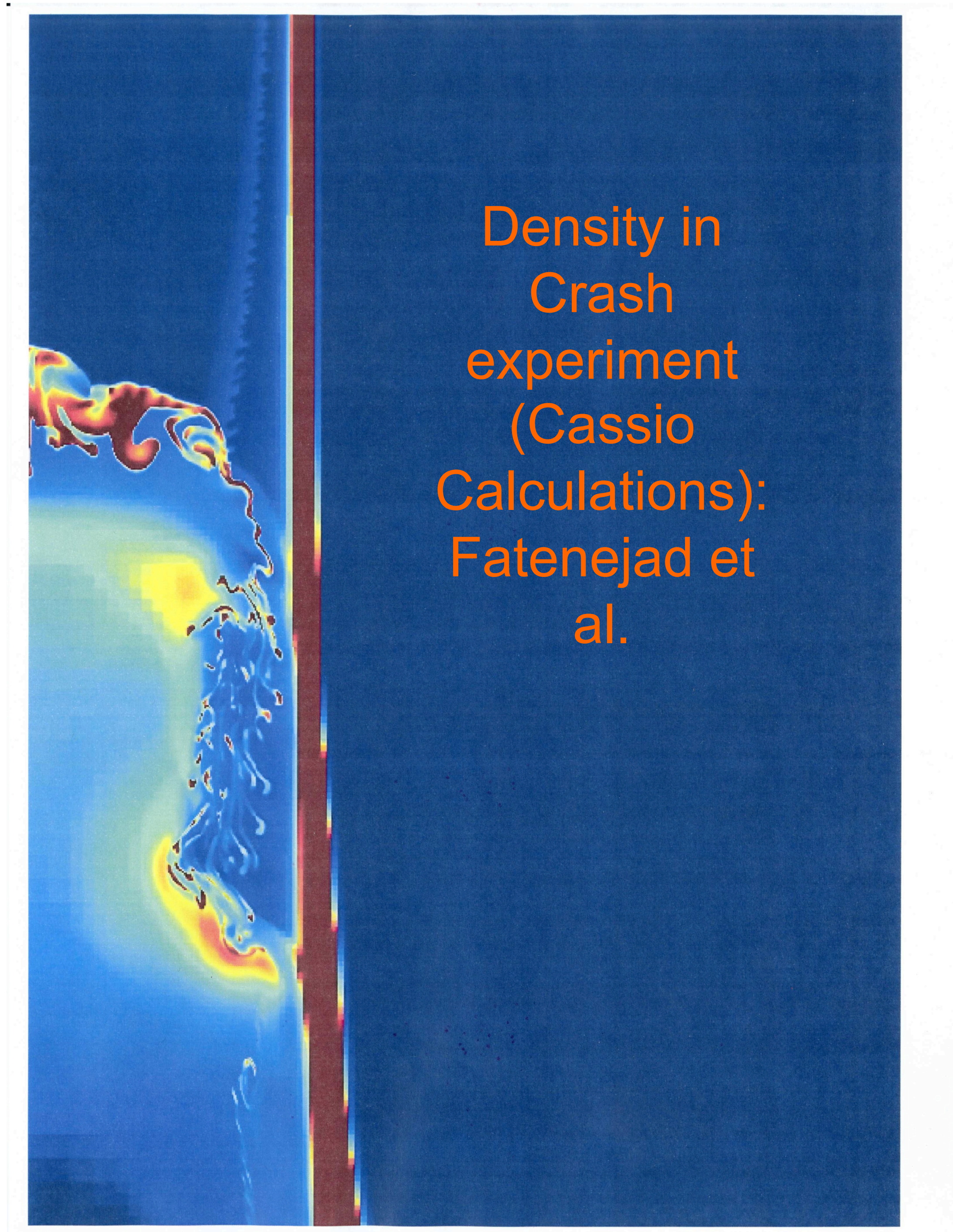
In most core-collapse supernovae, shocks are more important than ^{56}Ni in powering the light curve.



Bayless et al. 2014

Testing our codes: Physics experiments of Shock Breakout

- The Univ. of Michigan CRASH center developed an experiment to test shock breakout.
- This experiment demonstrated many of the difficulties with modeling shock breakout: radiation pre-heat, turbulence, ….



Opacity Experiments

- Early results showed good agreement with iron measurements, but the most recent iron experiments do not agree with state-of-the-art atomic physics.
- Kurucz results have trouble getting agreement with the atomic physics community.

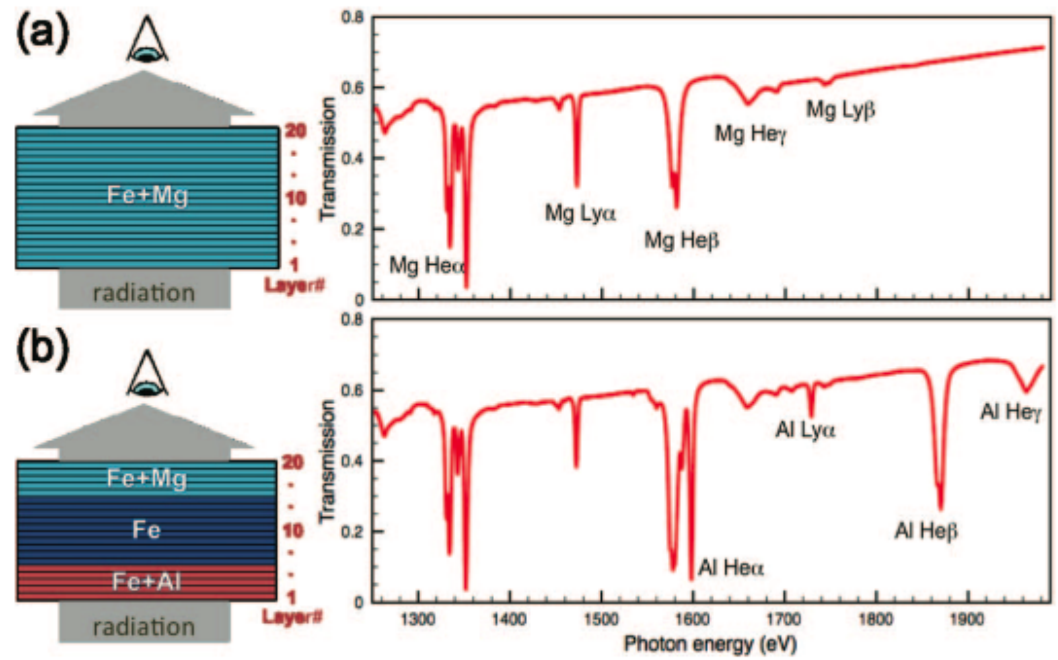
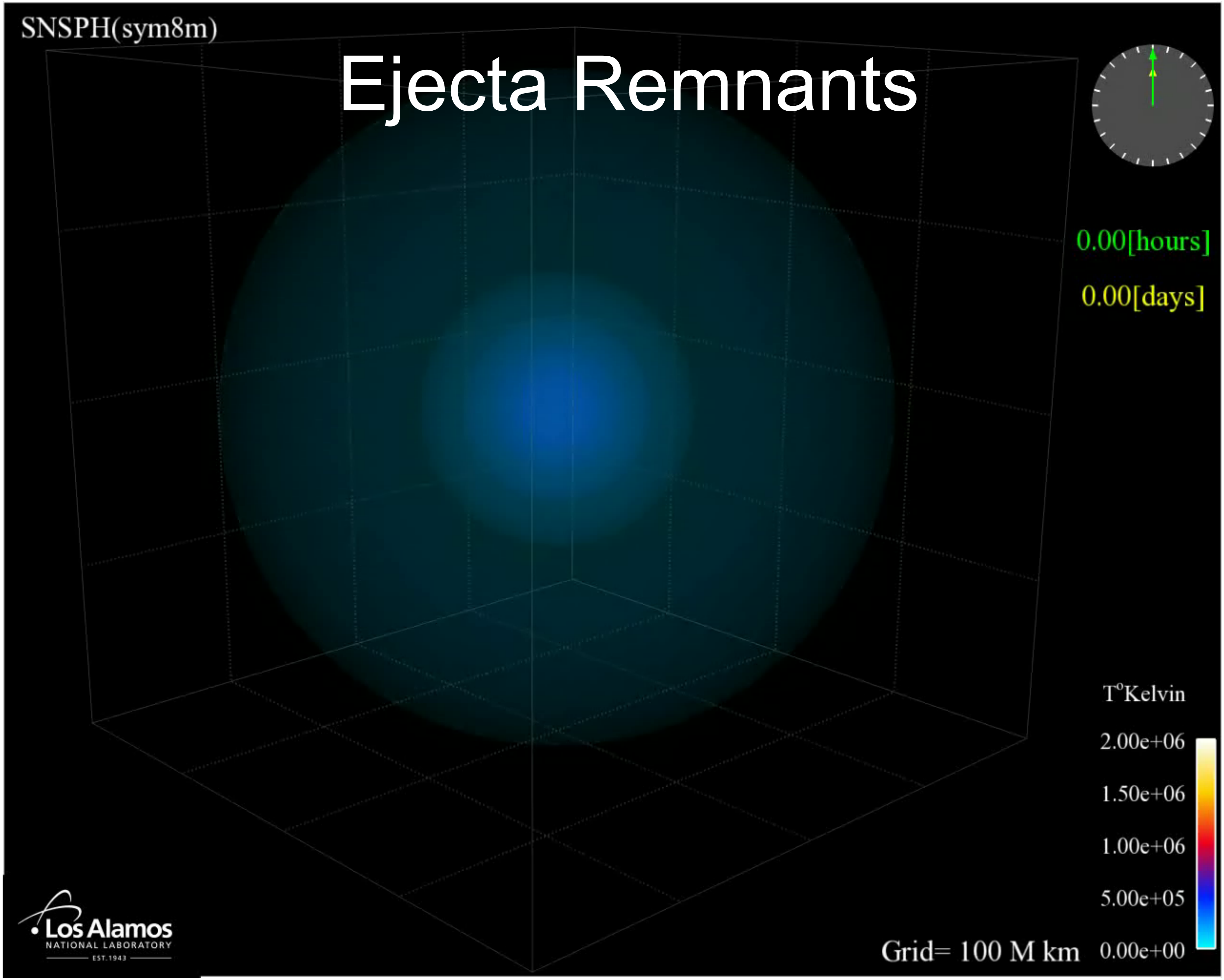


FIG. 1. The sample composition for (a) an Fe+Mg sample and (b) an Al+Fe+Mg sample and their synthetic transmission spectra under 10% gradient with the average T_e and n_e of 195 eV and 8×10^{22} cm^{-3}. Layer numbers correspond to the subscript i in Eqs. (1) and (2).

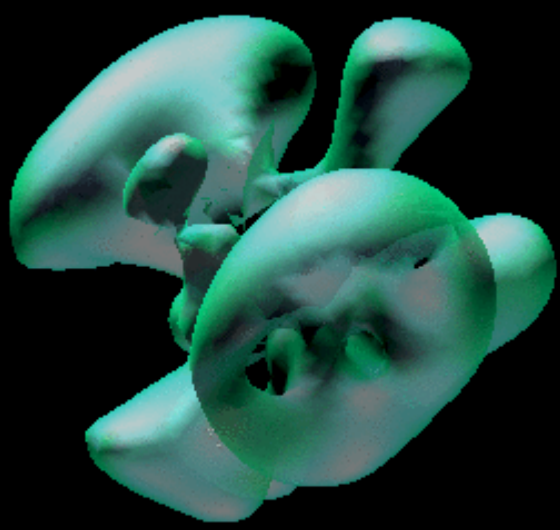
Nagayama et al. 2012

Ejecta Remnants

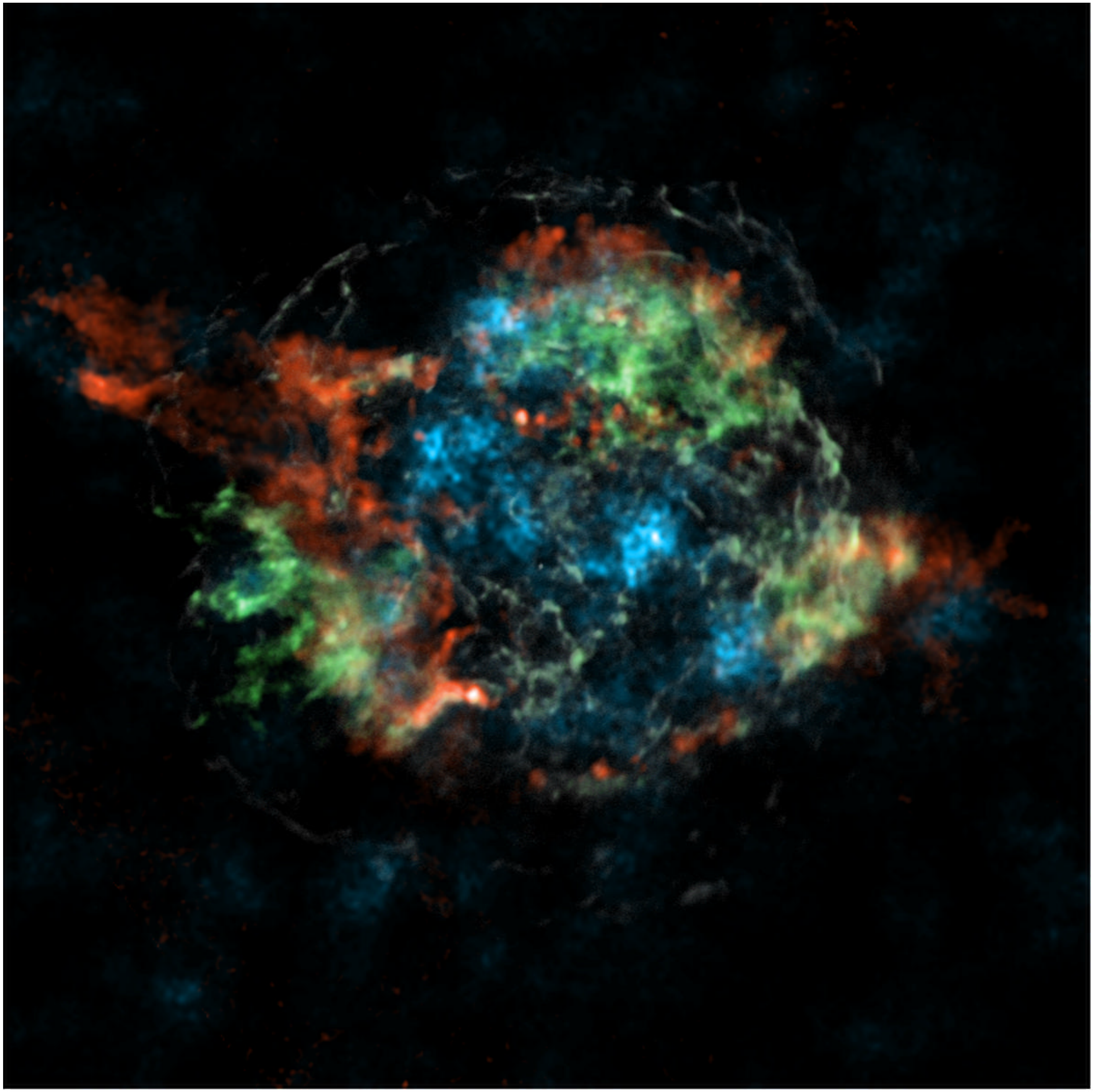


Ejecta Remnants – Probing Low Mode Convection

- 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.

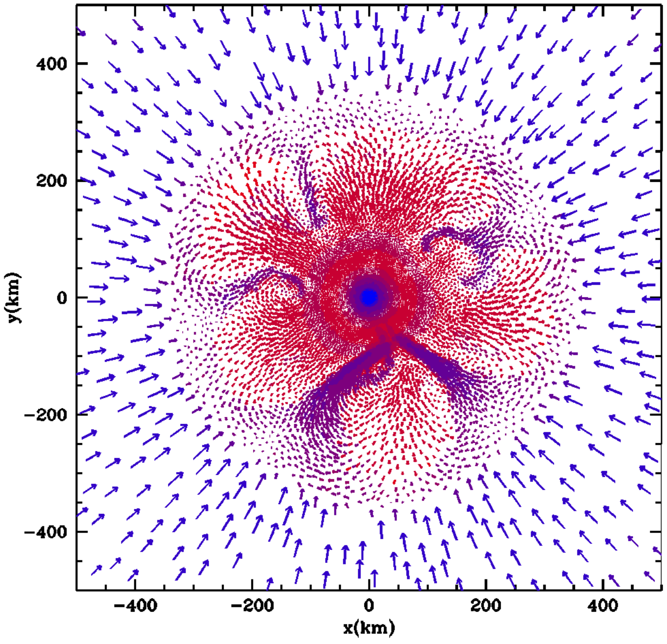


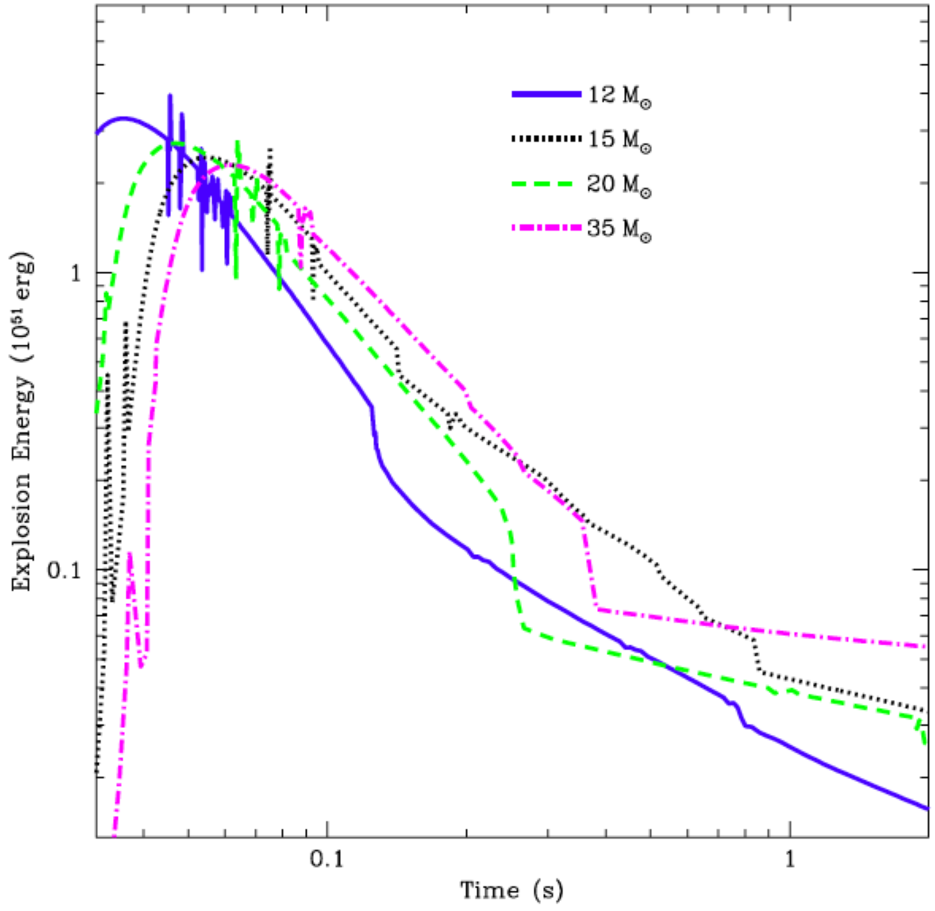
NuSTAR has provided a new window in the supernova mechanism
Greffenstette et al. 2014



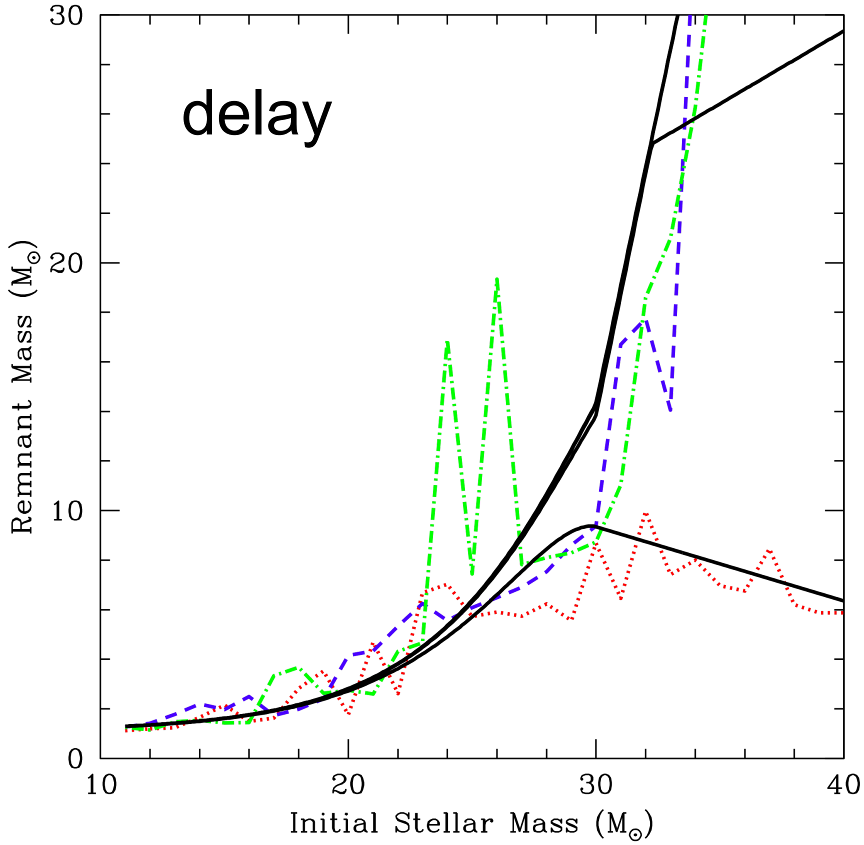
Compact Remnants

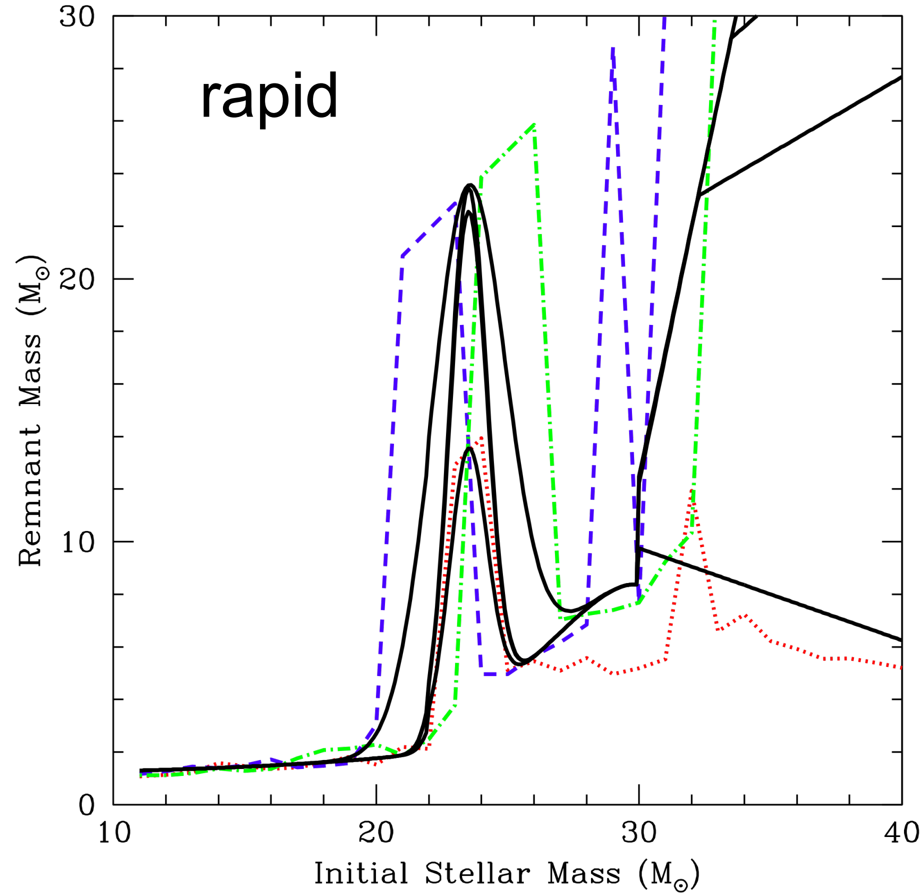
• The mass distribution of compact remnants (black holes, neutron stars) depends on the nature of the explosion engine. For example, the delay in the engine: 100ms vs. 1s can have a big effect on the long-term masses.





Remnant Masses and the Explosion

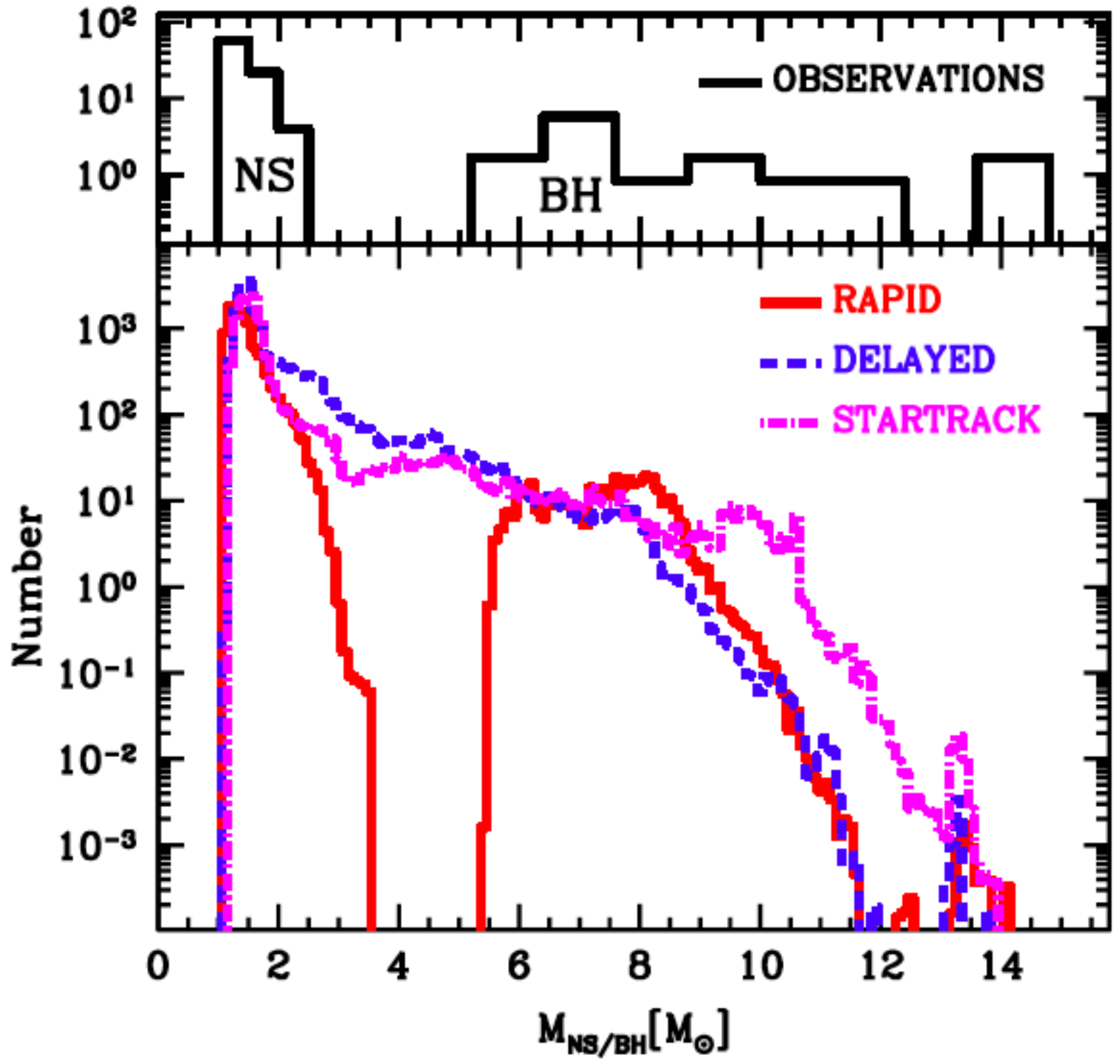




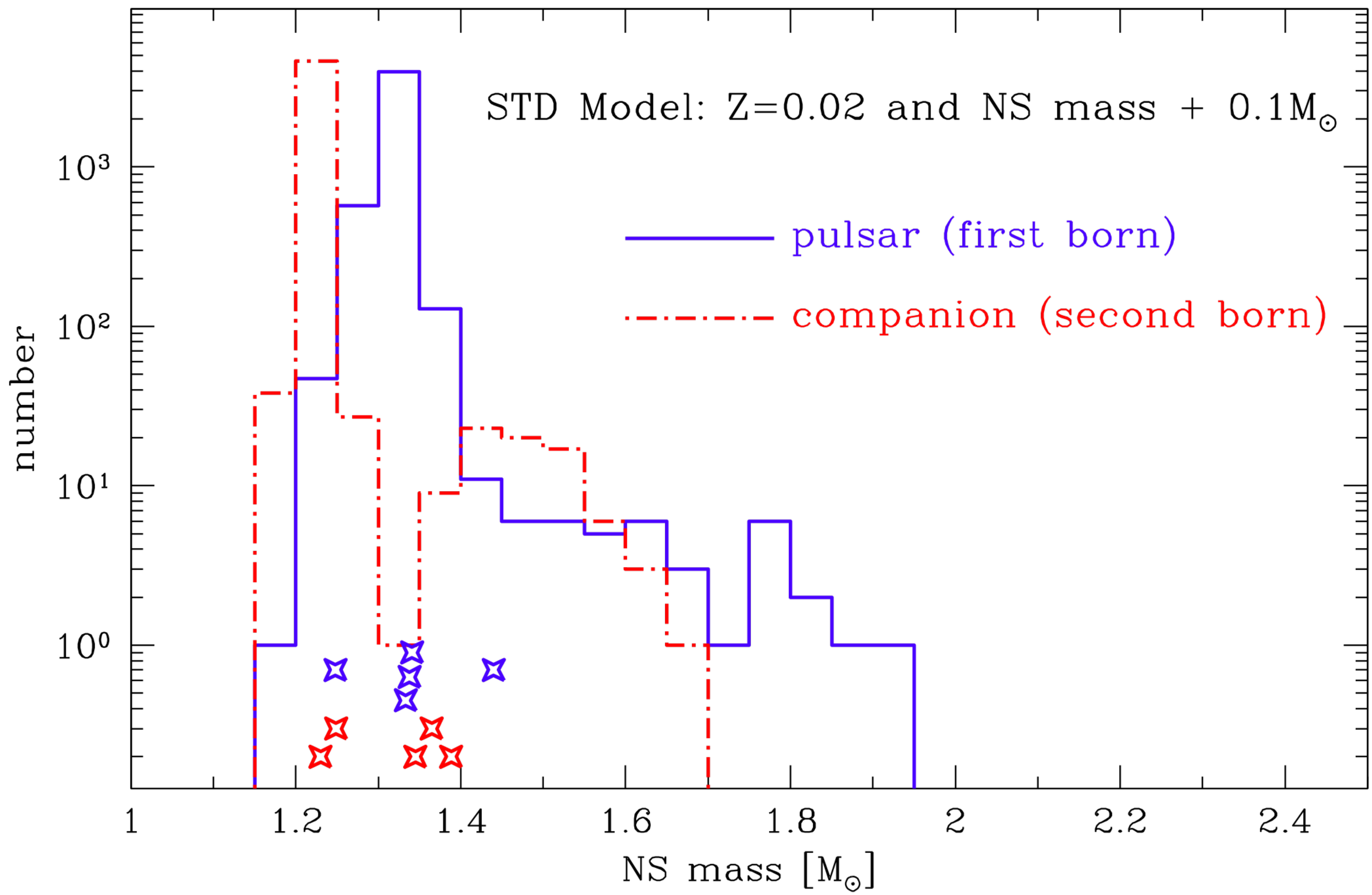
Note that, even at low metallicity, variability in stellar mixing can cause the remnant mass to decrease with increasing mass.

Compact Remnants

- The masses of compact remnants can be measured in binary systems (e.g. binary pulsar systems and X-ray binaries) and these observations are producing a growing list of masses.
- Advanced LIGO could dramatically increase these mass estimates



Distribution of BNS Masses



Remnant Masses

By combining

- population synthesis
- merger models
- EOS understanding

we can predict fractions of HMNS, direct BHs, and systems which collapse to a BH after a given time.

If we can distinguish between these events, we ultimately will have a nice probe of the maximum NS mass. Preliminary results argue that we are quite sensitive (but stay tuned).

Probing the Supernova Engine

- Direct probes (neutrinos, gravitational waves) can both probe the supernova engine and nuclear physics. Their drawback is that we need a local group SN for these probes to be effective.
- Indirect probes must be coupled to theory and theoretical uncertainties must be considered in interpreting results.
- BNS mergers are probes of both the lower (determined by progenitor/core-collapse calculations) and maximum (EOS) neutron star masses.