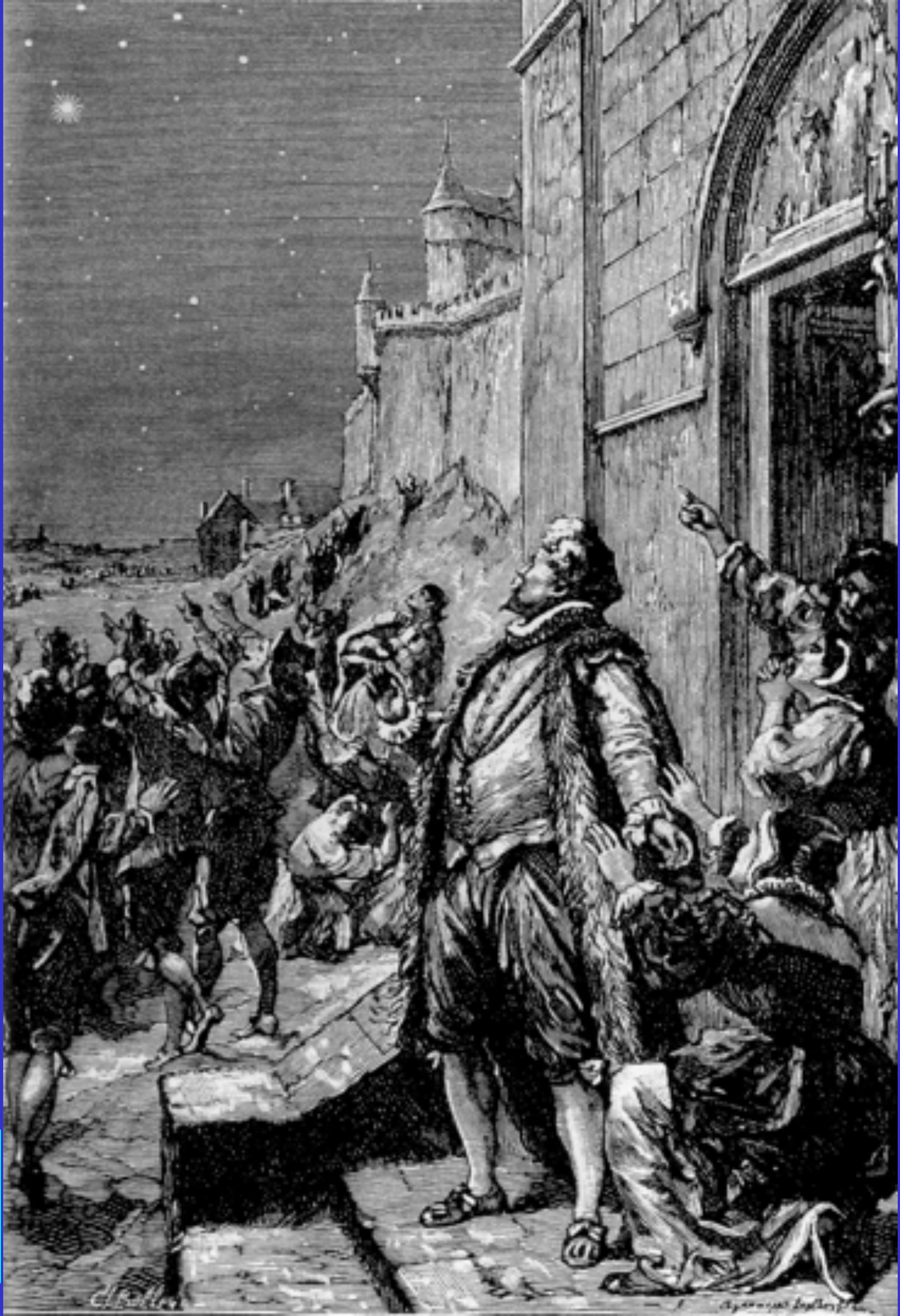
Supernovae - deaths of stars

Learning Outcomes

- What is a supernova
- Brief history of discovery
- The difference between Type I and Type II supernovae
- The two physical mechanisms for producing supernovae
- Learn how to use gravitational and nuclear potential energies to understand properties of the explosions
- Basic physics of the core-collapse process
- What stars produce the typical Type II and Type Ia
- The best studied supernova - SN1987A

Supernovae have been seen and recorded by humans for 2000 years



Drawing of the great Tycho supernova of 1572

Supernovae in the Milky Way

European and far eastern written records of the following Galactic events:

Supernova Remnant	Year	Peak Visual mag
CasA	1680	?
Kepler	1604	-3
Tycho	1572	-4
3C58	1181	-1
Crab	1054	-4
SN1006	1006	-9 ←
SN393	393	0
SN386	386	+1
SN185	185	-4

Brightest stellar event ever seen, visible in daytime.
Full moon : ~-13.

We've been waiting 335 years for a galactic SN

- Historical accounts of supernovae in our galaxy are coincident with supernovae remnants now visible

SN 1006 today

Expanding debris with $M \sim 1$ Msun, $V \sim 10^4$ km/s.

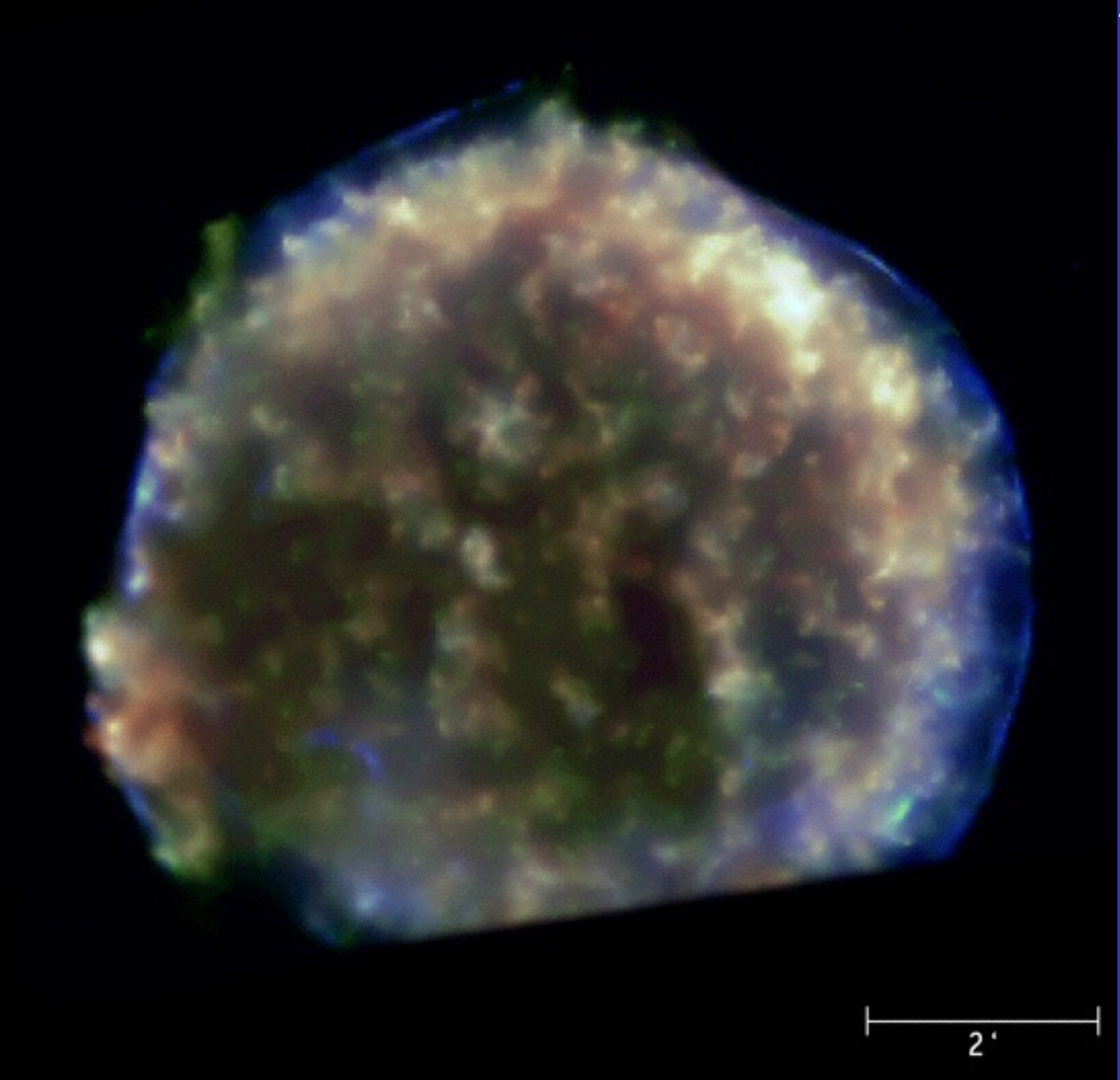
Death of a white dwarf

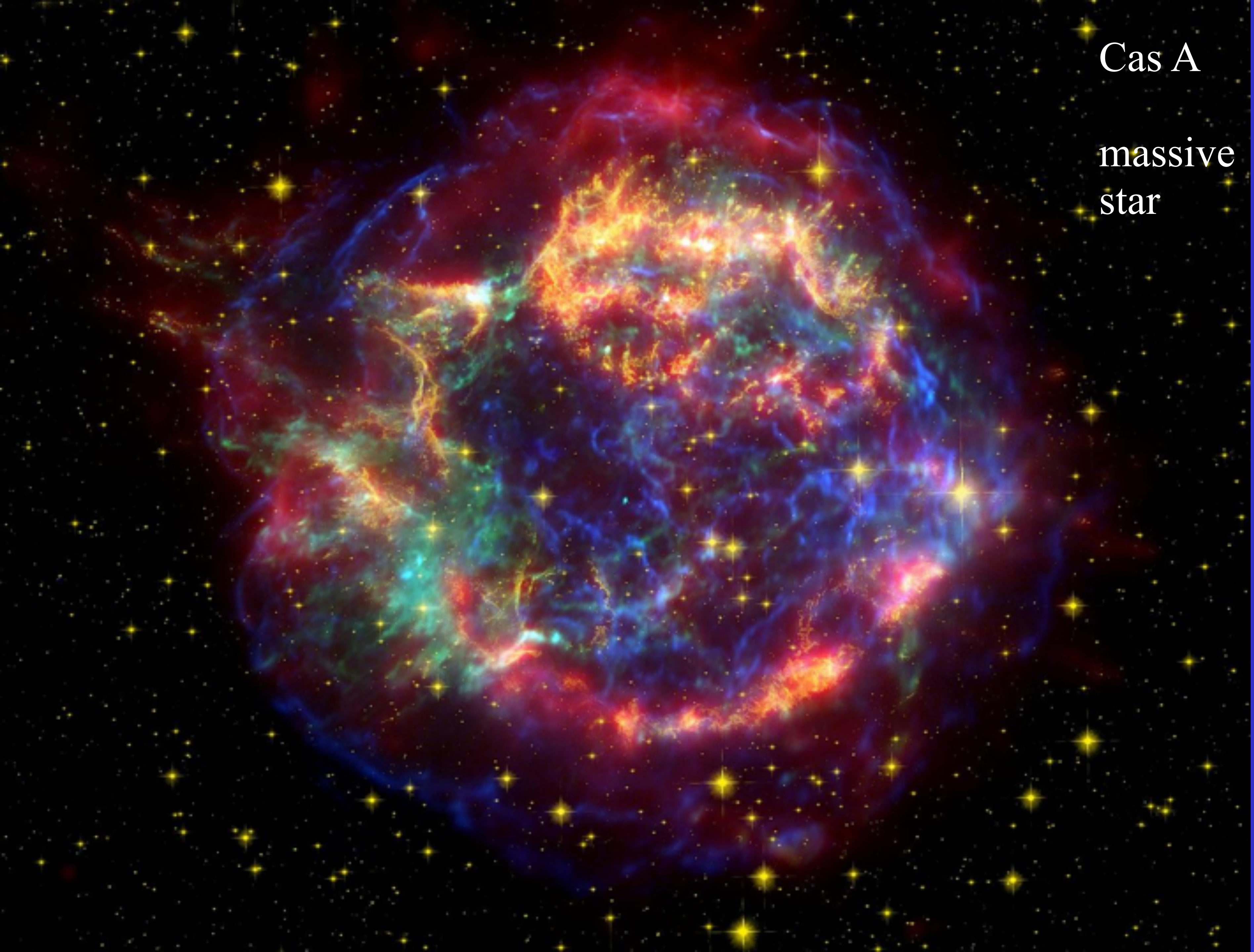
SN 1054 (The Crab nebula) today - optical (red) and X-ray (lilac) composite

Death of a massive star

Tycho’s supernova remnant in X-rays

Death a white dwarf



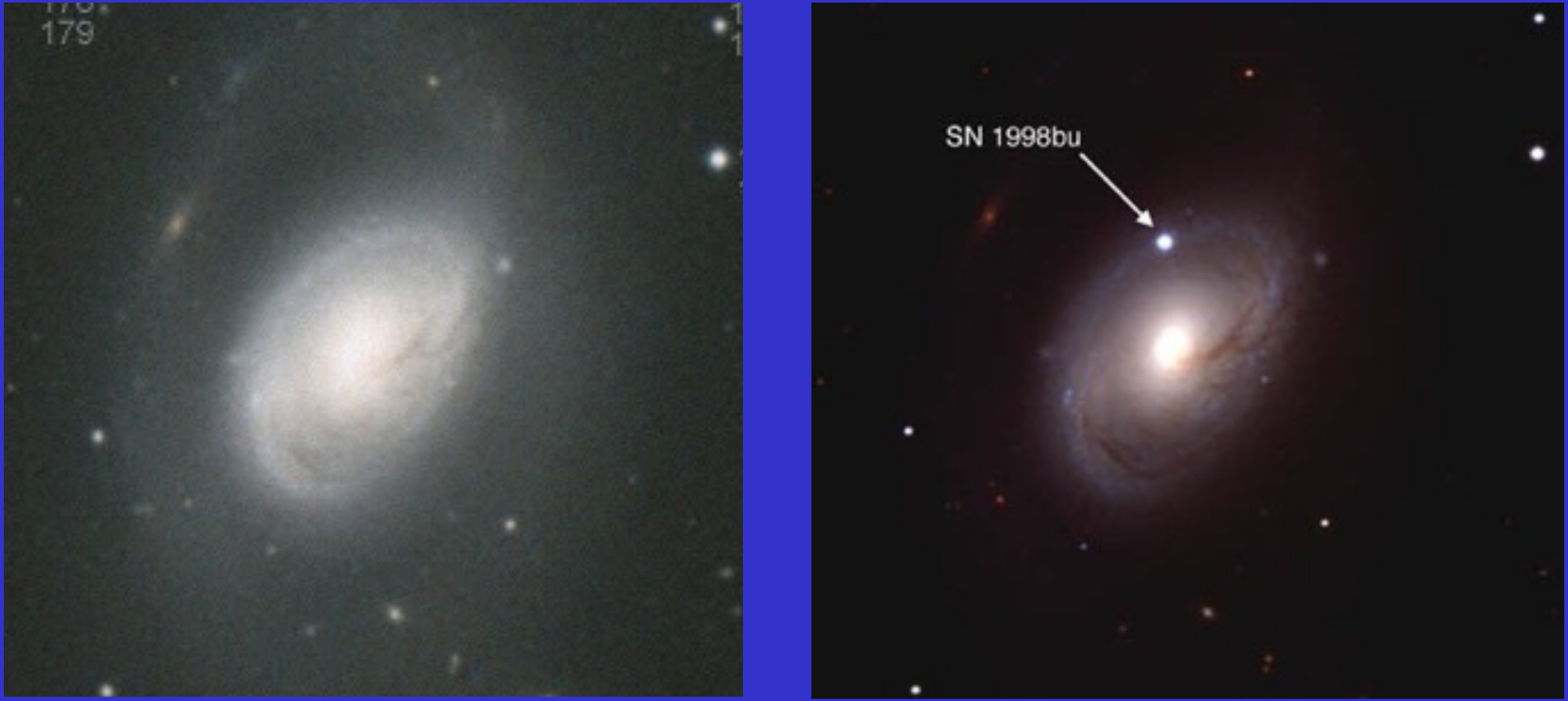


Cas A

massive
star

A supernova in a modern telescope

For a few weeks or months, the luminosity is comparable to that of the entire galaxy (which comes from ~100 billion stars)



SN1998bu in M96: left DSS reference image (made by O.Trondal), right BVI colour image from 0.9m at CTIO (N. Suntzeff)

Supernovae : history

In the 1930's ***supernovae*** were recognised as a separate class of objects to ***novae*** (meaning new stars).

- So-called by Fritz Zwicky, after Edwin Hubble estimated distance to Andromeda galaxy (through Cepheids)
- Hence the luminosity of the "nova" discovered in 1885 in Andromeda was determined :a billion solar luminosities!
- Supernovae outbursts last for short periods: typically months to a few years
- Typical galaxies like the Milky Way appear to have a rate of 1-2 SNe per 100 years (compare with ~50 novae per year). But the last one in our galaxy was in 1680.

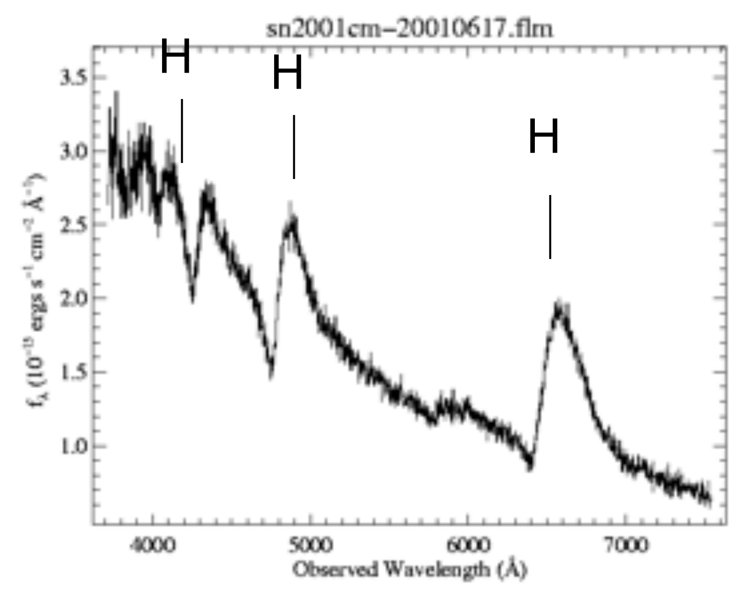
The observed types of supernovae

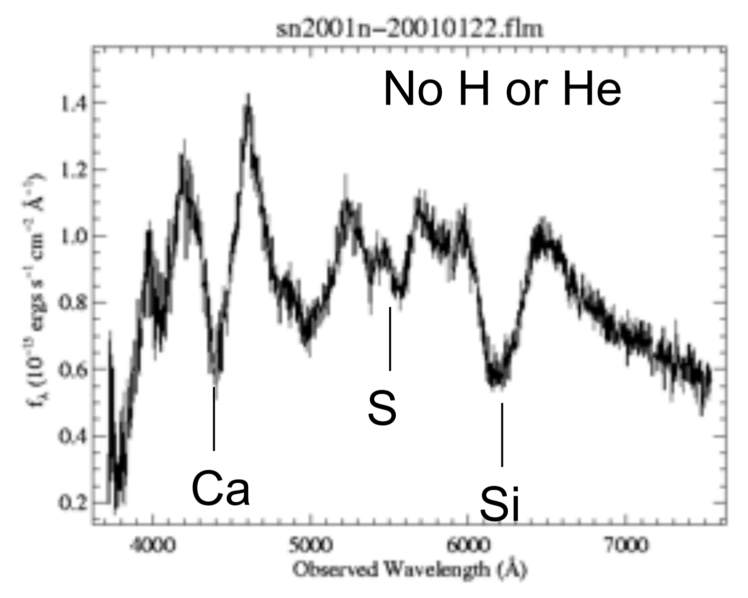
Supernovae explosions classified into **types** according to their *observed* properties. The two main types are ***Type I*** and ***Type II*** which are distinguished by the presence of hydrogen lines in the spectrum.

Without hydrogen lines
↓
Type I
↙ ↓ ↘
Si He no He or Si
↓ ↓ ↓
Ia Ib Ic

With hydrogen lines
↓
Type II
↓
Lightcurve and spectral properties
↓
II-P, II-L, IIn, IIb

Example spectra of Type II and Type I SNe



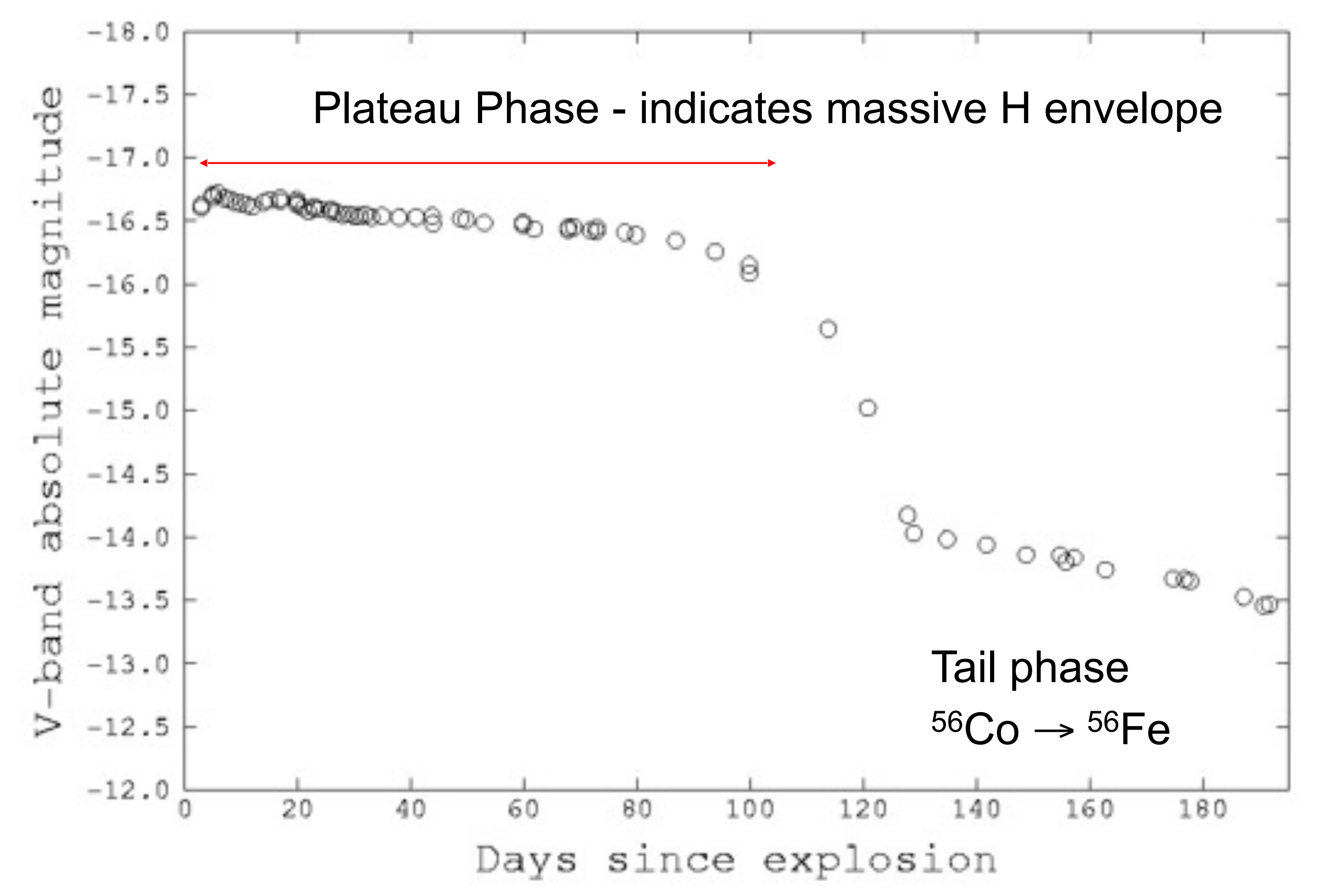


Typical Type II SN observed within a few weeks of explosion

Typical Type Ia supernova observed near maximum light (i.e. when SN is at its brightest)

Observed light curve of a Type II SN

SN1999em (Hamuy et al. 2001)

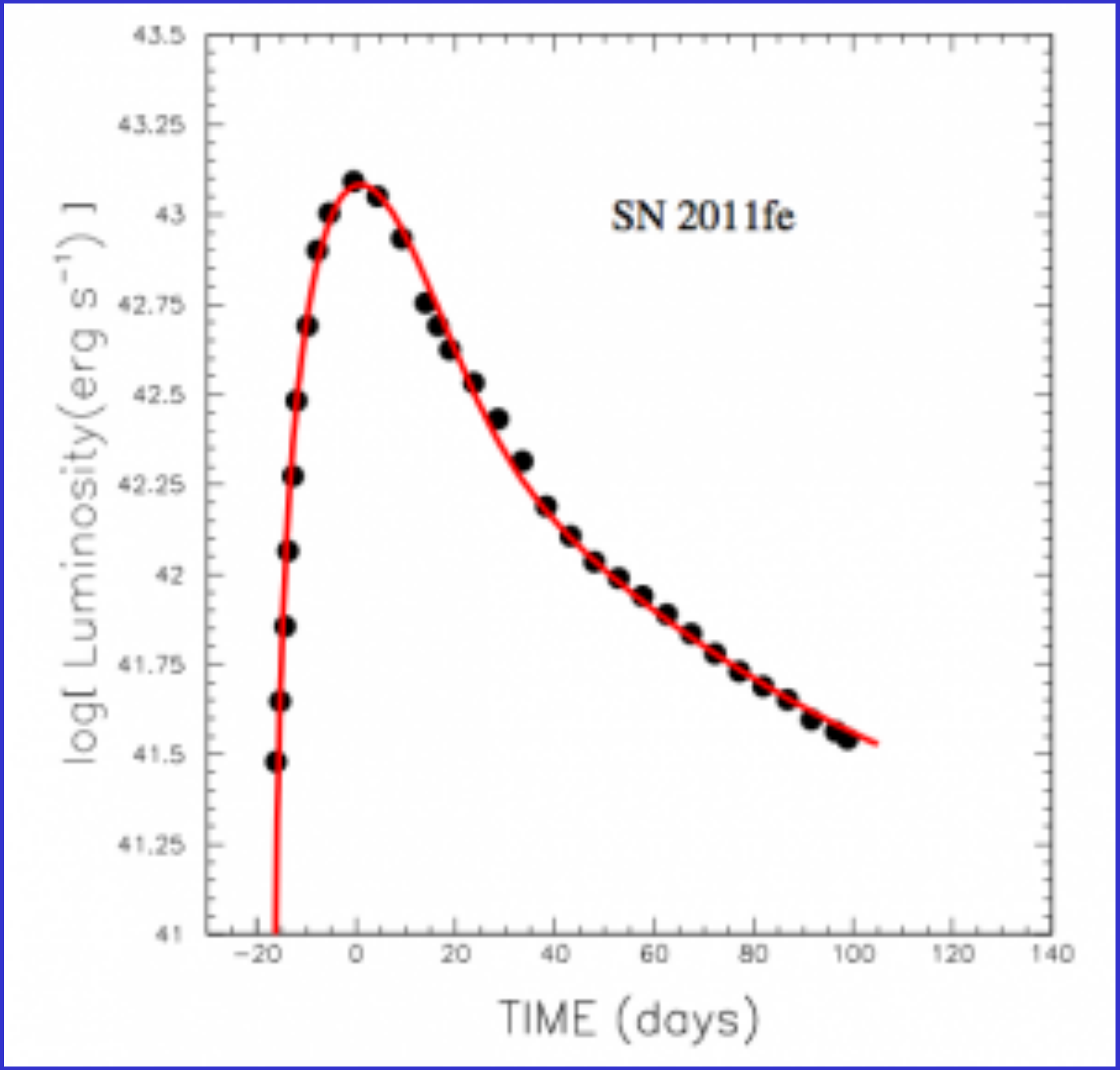


Plateau Phase - indicates massive H envelope

Tail phase

^{56}Co → ^{56}Fe

A Type Ia light curve



Exponential tails

- Discovered in 1940s.
- Decay time of ~100 days.
- Borst 1950 : Radioactivity!
- Colgate & McKee 1969 : ^{56}Ni —> ^{56}Co —> ^{56}Fe!

Environments

All types of SNe apart from Type Ia are not observed in old stellar populations (such as elliptical galaxies). In particular Type II are observed mostly in the gas and dust rich arms of spiral galaxies. Star formation is ongoing and young stars are abundant. By contrast Type Ia SNe are found in all types of galaxies.

Hence the strong circumstantial evidence suggests:

- Type II supernovae are associated with the deaths of massive stars - the collapse of the Fe core at end of evolution
- These stars have large H-rich envelopes, hence the presence of H in the spectra
- Type Ia SNe do no come exclusively from young massive stars, but from an older population.

The energy budget of supernovae

Spectra —> Velocities ~ 10,000 km/s

Light curves —> Mass ~ few solar masses

Then:

E ~ 1/2 M V^2 ~ **10^{44} J**.

Where does the energy come from?

Gravitational:

E ~ GM^2/R

Would need collapse of star to R <~ 1000 km << R_earth

Nuclear:

E ~ (0.001-0.01) M_fuel c^2

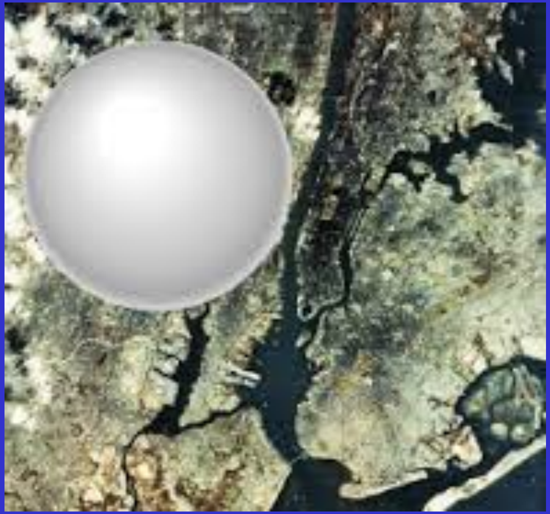
Need M_fuel >~ M (100-1000) (v/c)^2 ~ (0.1-1)*M

Hoyle and Fowler 1960: two sources:

Core-collapse (Type II and Ib, Ic)

Thermonuclear (Type Ia)

Stellar collapse?



- 1926 : R. Fowler explains how white dwarfs can be so small (quantum degeneracy pressure)
- 1932 : Chadwick detects the neutron
- 1934 : Baade and Zwicky : May supernovae be due to the release of gravitational energy as *neutron stars* are born, the equivalent of white dwarfs for neutron matter?
- Degenerate stars : size of quantum states and thereby size of whole star inversely proportional to the mass of degenerate particle —> R(neutron star) / R(white dwarf) = m_electron / m_neutron ~ 1/2000 —> R(neutron star) ~ 10,000 km/ 2000 ~ 5 km.
- $E = GM^2/R \sim 10^{46}$ J! Even 100 times more than needed.
- Note that black holes existed in theory since Einsteins general theory of relativity in 1916 and Schwarzschilds solutions the same year, but at this time noone thought they existed in Nature.
- 1968 : Bell discovers the first neutron star.
- 1971 : Webster/Murdin/Bolton discovers first black hole.

Thermonuclear SNe

- 1931 : Chandrasekhar derives upper mass limit to white dwarfs (~1.4 M_{sun}). Raised question what would happen if a white dwarf accretes matter beyond this limit.
- A C/O white dwarf has a nuclear energy potential of E_nuclear ~0.001 $Mc^2 = \underline{2*10^{44}\ J}$ (burn C/O to Si/Fe)
- Degenerate conditions —> this energy is released fast once ignition temperature is reached.
- Gravitational binding energy GM^2/R ~ $\underline{0.3*10^{44}}$ J << E_nuclear —> explosion and disruption with E_SN ~ 10^{44} J OK!

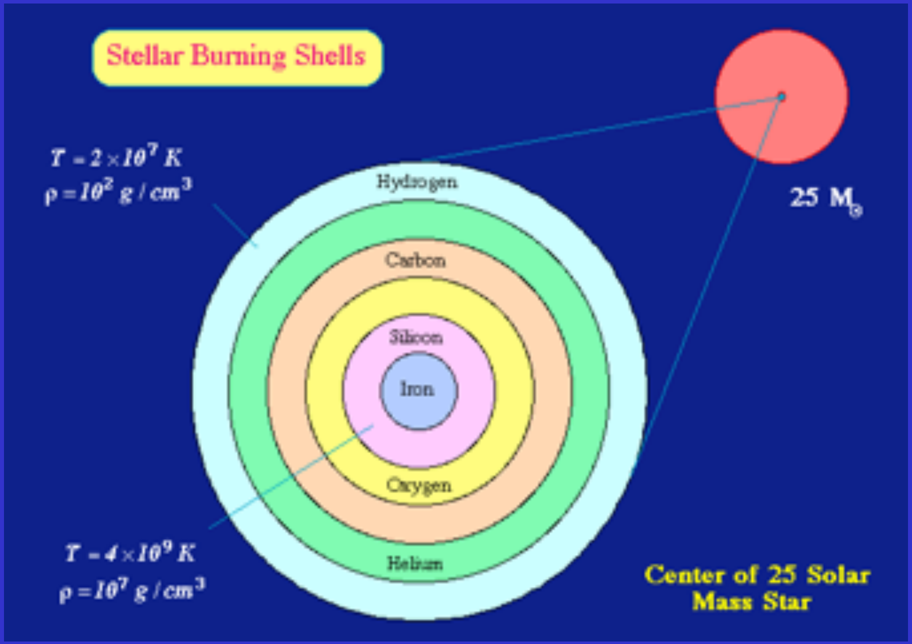
Review, late stellar evolution of massive stars

From the main-sequence to He burning

1. The cores of massive stars are *convective,* hence newly formed He is evenly mixed in the core.
2. As the hydrogen is consumed, the core contracts and also shrinks in mass.
3. The convective core becomes exhausted homogeneously, while it contracts to a smaller volume and becomes hotter.
4. The star also develops a H-burning shell around the He dominated core.
5. The temperature at the bottom of the hydrogen envelope is too high to sustain hydrostatic equilibrium. The envelope expands and the star becomes cooler, moving to the red region of the HRD. It becomes a red supergiant star.
6. Due to the rapid drop in temperature throughout the outer atmosphere, the criterion for convection is reached in this region and a convection zone develops, reaching deep into the star.
7. It dredges up some of the material from the original convective core. This core material can appear at the stellar surface in the atmosphere of the red supergiants.

From helium core to iron core

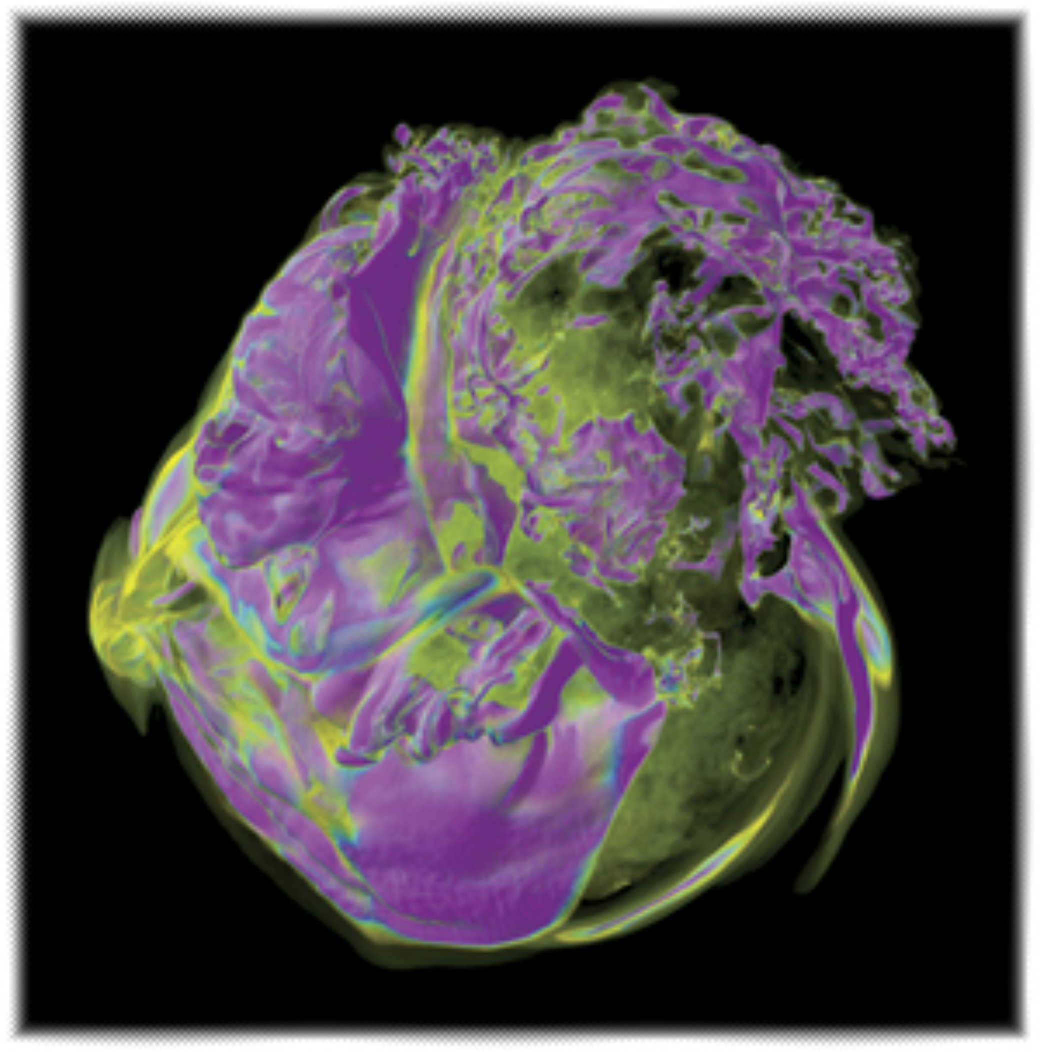
1. The triple-α process liberates less energy per unit mass than for H-burning (~10%). Hence the lifetime is shorter, around 10% of H burning.
2. Carbon ignition at T=8E8 K. Temperatures now high enough that cooling changes from radiative diffusion to neutrino emission. This is much more efficient as neutrinos can freely escape —> burning becomes more furious and time scales shorten. Star has less than 1000 years left.
3. Neon and oxygen burn around T=2E9 K, ~1 year each.
4. Silicon and sulphur burn at T=4E9K, make an iron core in a few days.
5. These late stages believed to be the main source of O, F, Ne, Na, Mg, Al, P in Universe.



Overview late burning phases

Central burning phase	time (yrs)	T_{core}(K)	Cooling	T_{surf}(K)	HR diagram
Hydrogen	10^7	10^7	photon	20,000-40,000	O, B
Helium	10^6	10^8	photon	3,000-4,000	K,M
Carbon	10^3	$8*10^8$	neutrino	3,000-60,000	O-M
Neon	1	$1.8*10^9$	neutrino	3,000-60,000	O-M
Oxygen	1	$2.1*10^9$	neutrino	3,000-60,000	O-M
Silicon	10^{-2}	$3.7*10^9$	neutrino	3,000-60,000	O-M

Core-collapse



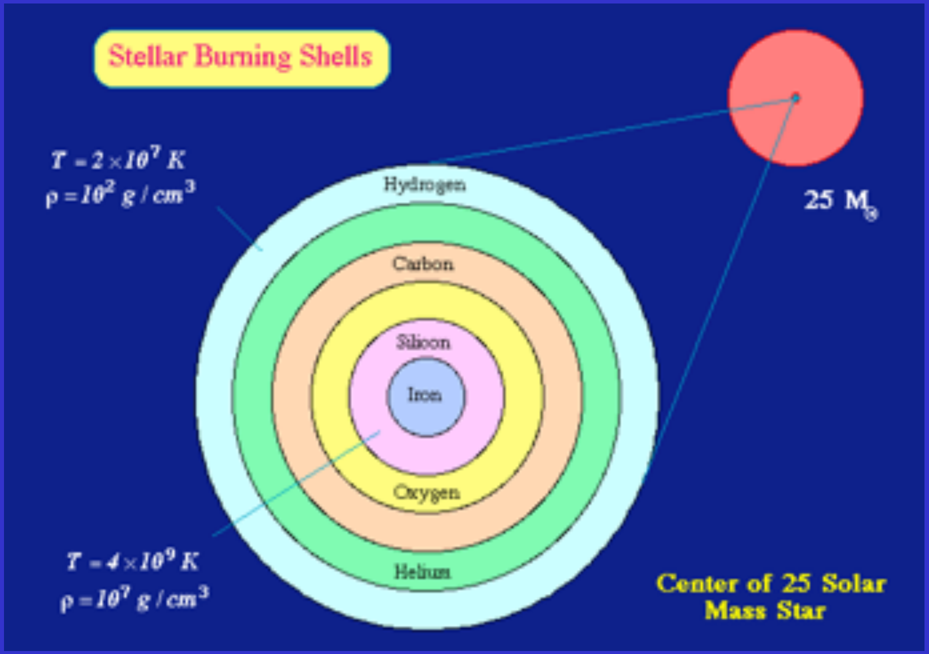
3D simulation from
Oak Ridge group

Fe core masses at the end of Si burning

M_{ZAMS}	***M(Fe core)***
12 M_{sun}	***1.2 M_{sun}***
15	***1.3***
20	***1.4***
25	***1.6***

- T ~ 4*10^9 K, ρ ~ 10^{11} kg m^{-3} —> electron degeneracy pressure dominates.
- R ~ 1500 km.

Fe core collapse



The core contracts further and increases its density and temperature.

Eventually **electron captures** occur.

$$e^- + p \rightarrow n + \nu_e$$

This leads to catastrophic loss of degeneracy pressure (higher density —> more electron captures —> even higher density etc) —> **free-fall collapse.**

High temperatures also lead to **photo disintegration**

$$^{56}Fe \rightarrow 13\,^4He + 4n - 100\text{MeV}$$

which takes away energy and accelerates the collapse.

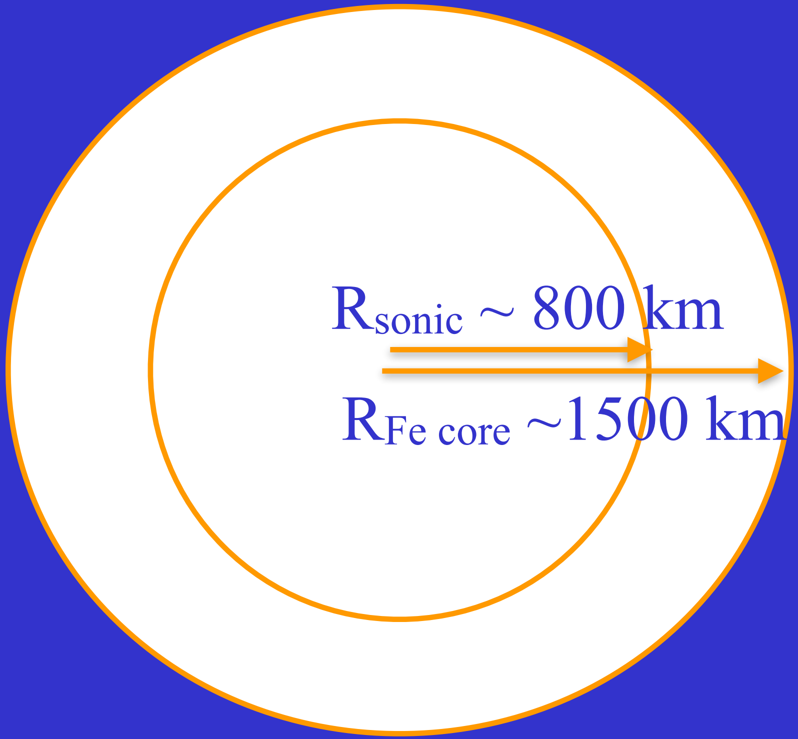
These two processes lead to collapse.

The collapse time-scale

- $t = R/V$ (R = radius of core, V = infall velocity)
- Gravitational potential energy converts to kinetic energy: $1/2MV^2 \sim GM^2/R$ —> $V \sim \mathrm{sqrt}(2GM/R)$
- Then $t = 1/\mathrm{sqrt}(2GM/R^3) = 1/\mathrm{sqrt}(8\pi/3\ G\ \rho)$ $= 4428$ <u>/ $\mathrm{sqrt}(\rho)$ seconds</u>
- Typically $\rho \sim 10^{11}$ kg m^{-3} —> **<u>$t \sim 0.1$ sec</u>**.

Collapse dynamics

- Sonic communication within R_sonic = V_sound *t_collapse
- V_sound = $(4/3\ P / \rho)^{1/2}$
- EOS for degenerate relativistic matter : $P = K\ \rho^{4/3}$
- —> V_sound = 400 * $\rho^{1/6}$ km/s.
- $\rho \sim 10^{11}$ kg m^{-3} —> V_sound ~ 8000 km/s —> R_sonic ~ 800 km,about half the core. This part collapses with structural integrity.
- Outside “shell-by-shell” in-fall on longer time-scale.



$R_{sonic} \sim 800$ km

$R_{Fe\ core} \sim 1500$ km

EOS stiffening and shock formation

- The Equation of state stiffens dramatically when nuclear densities (rho ~ 10^{18} kg m^{-3}) are approached due to two contributions :
    1. Neutron degeneracy

       Quantum states have size ~ dx dp ~ $1/m_{neutron}$ —> degeneracy at R ~ 5 km instead of ~10,000 km as for electron supported stars.
    2. Repulsive nuclear force

       Effective at ~ 10^{-15} m. Makes neutron stars somewhat larger than pure degeneracy model predicts (~10 km).
- This new pressure enough to halt collapse and formation of a **proto-neutron star** from the inner core (mass ~ 0.5 M_{sun}). A **shock wave** is created at the interface between inner and outer cores, but has initially a negative velocity in observer frame.
- Outer core accretes through shock and continues onto proto-neutron star which grows in mass : **all of Fe core becomes part of the NS**.
- Shock builds energy and starts to move out : **layers outside Fe core are reversed and exploded**. Exact dividing point (the “mass cut”) uncertain.

The bounce mechanism

- Can gravitational potential energy of lower layers be mechanically transferred to outer ones through this prompt shock, reversing and ejecting them?
- Firm answer today : no. The shock loses too much energy and does not get out —> accretion continues until neutron star exceeds its maximum limit and black hole forms with no supernova.

Need additional energy input… neutrinos?

- Proto-neutron star (R ~ 30 km) shines with L ~ 10^{45} W for a few seconds…comparable to the light output by the rest of Universe.
- All three neutrino (and anti-neutrino) flavors emitted.
- Emission processes:
  - $e^- + p \longrightarrow n + \nu\_e$
  - $e^+ + n \longrightarrow p + \text{bar}(\nu\_e)$
  - $e^- + e^+ \longrightarrow \nu + \text{bar}(\nu)$

Observed SN energies mean most gravitational binding energy must emerge as neutrinos

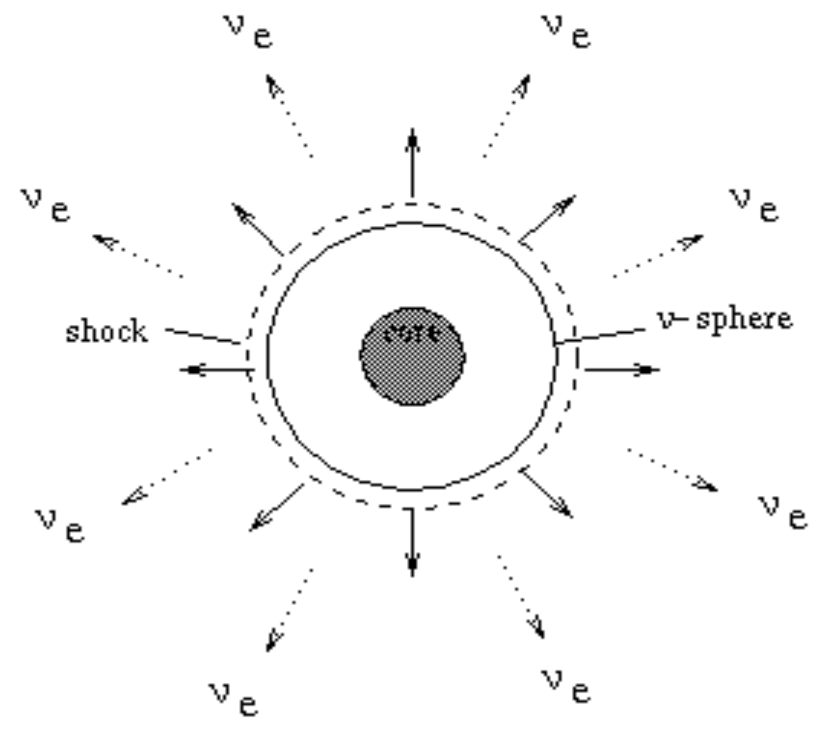
Energy source	Energy
Gravitational potential energy available from collapsing core	**Approx 3*10^{46} J**
Energy absorbed in Fe photodisintegration to p+n (~1.5 solar masses)	-3*10^{45} J (0.01*1.5*c^2) (the binding energy of Fe nuclei is ~1% of rest mass)
Energy gained from fusion in Si and O layers (~0.5 solar masse)	+10^{44} J (0.001*0.5*c^2) (the binding energy difference between O/Si and Fe nuclei is ~0.1% of rest mass)
Energy required to eject mantle and envelope from grav potential	-10^{44} J (G*M_ns*M/R with M_ns = 1.4 M_{sun}, M ~ 3 M_{sun}, R ~10,000 km (typical radius of ejected matter in pre-SN structure)
Observed Kinetic energy of the SN (v_{exp}~10^4 kms^{-1})	-10^{44} J
Observed electromagnetic radiation from the SN	-10^{42} J
Missing energy	Essentially all of the original 3***10^{46} J! Must emerge as neutrinos**

The neutron star is a bright neutrino star for a few seconds

- $t_{diffusion} \sim \lambda$ N_scatt / c
- N_scatt ~ τ^2 = $(R/\lambda)^2$
- $\lambda = 1/(\sigma n)$

$t_{diffusion} = (3/4\pi)\, \sigma(M/m_p) / Rc$
$= 1.3\ s\ (M/1.4\ M_{sun})(R/10\ km)^{-1}$

Here
λ = mean-free path,
τ = optical depth,
σ = interaction cross section
$\sim 10^{-44}\ m^2$.



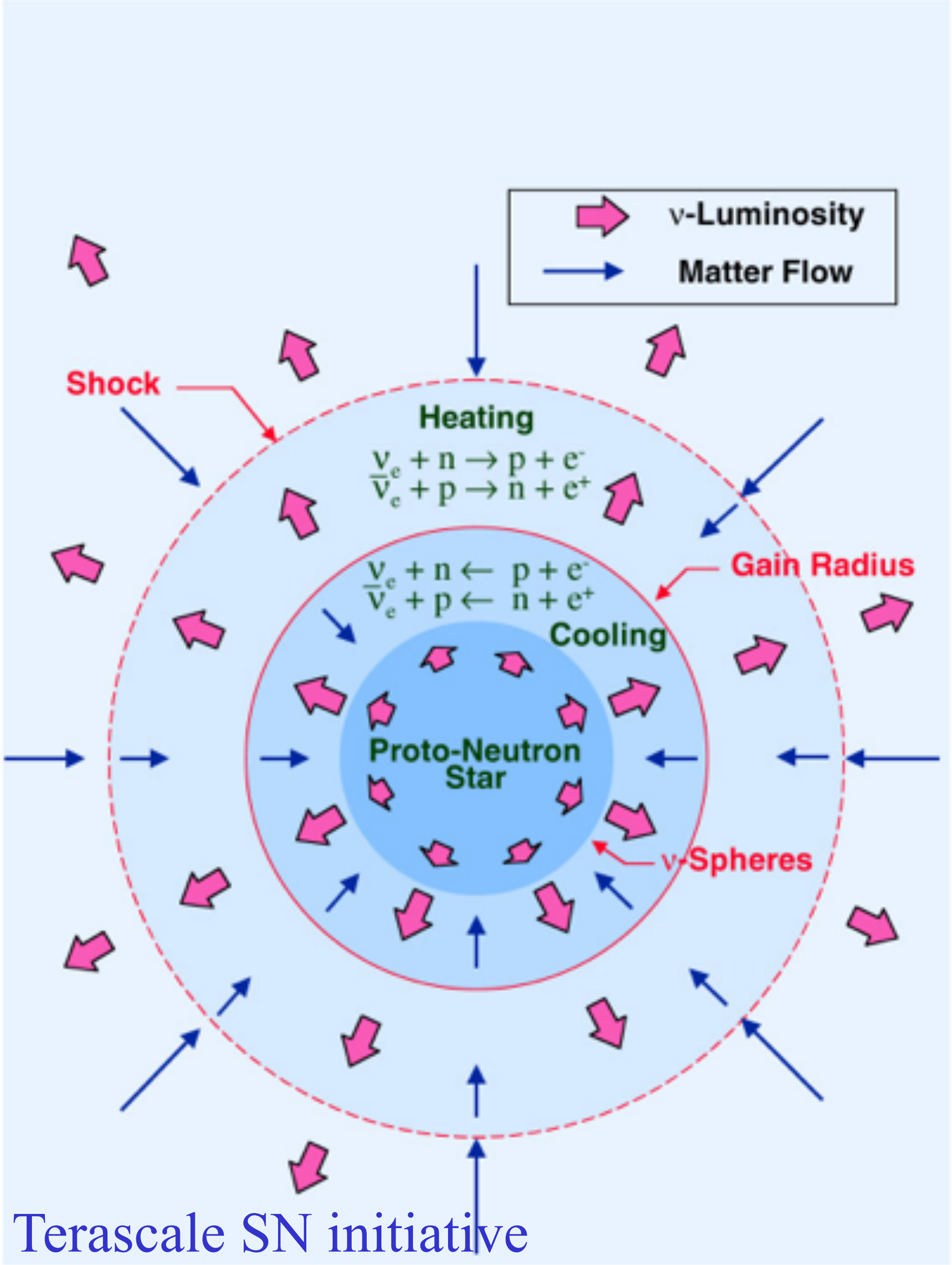
The neutrinos diffuse out on a time scale of seconds (compare free streaming time t = R/c = 10^{-4} seconds). The neutron star has a neutrino-sphere for a few seconds.

Neutrino deposition in mantle

- Cross section for neutrino-matter interaction $\sigma \sim 10^{-44}$ m^2 (interactions are bar(υ) + p and υ + n)
- Optical depth $\tau = \sigma * n * R \sim \sigma * (M/m_p)/R^2$
- Earth (M = $6*10^{24}$ kg, R = 6000 km), $\tau = 10^{-6}$, only 1 in a million neutrinos interact.
- Massive stellar core mantle (M ~ $6*10^{30}$ kg, R ~ 6000 km), $\tau \sim 1$, a significant fraction will interact.

The neutrino-driven explosion mechanism

- Colgate and White 1966 : can neutrinos deposit a small fraction of their energy into infalling mantle and explode it?
- Hard computational problem. Initial results in 1970s : does not seem to work.
- But Bethe and Wilson 1985 : yes but takes long time, t >> t_collapse! This so called ***delayed neutrino heating mechanism*** is currently the favoured scenario to explain supernova explosions.



Terascale SN initiative

Neutrinos heat the infalling mantle in a gain layer

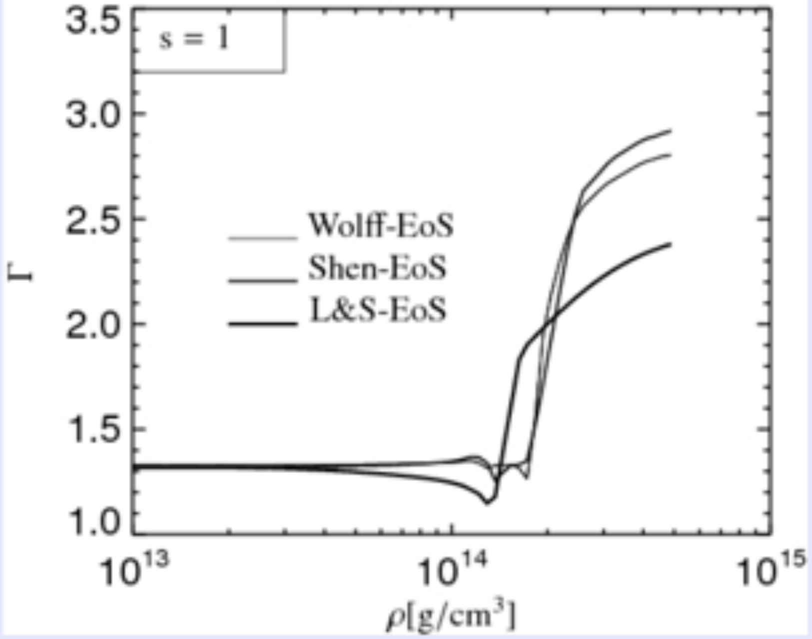
Modelling neutrino-driven explosions

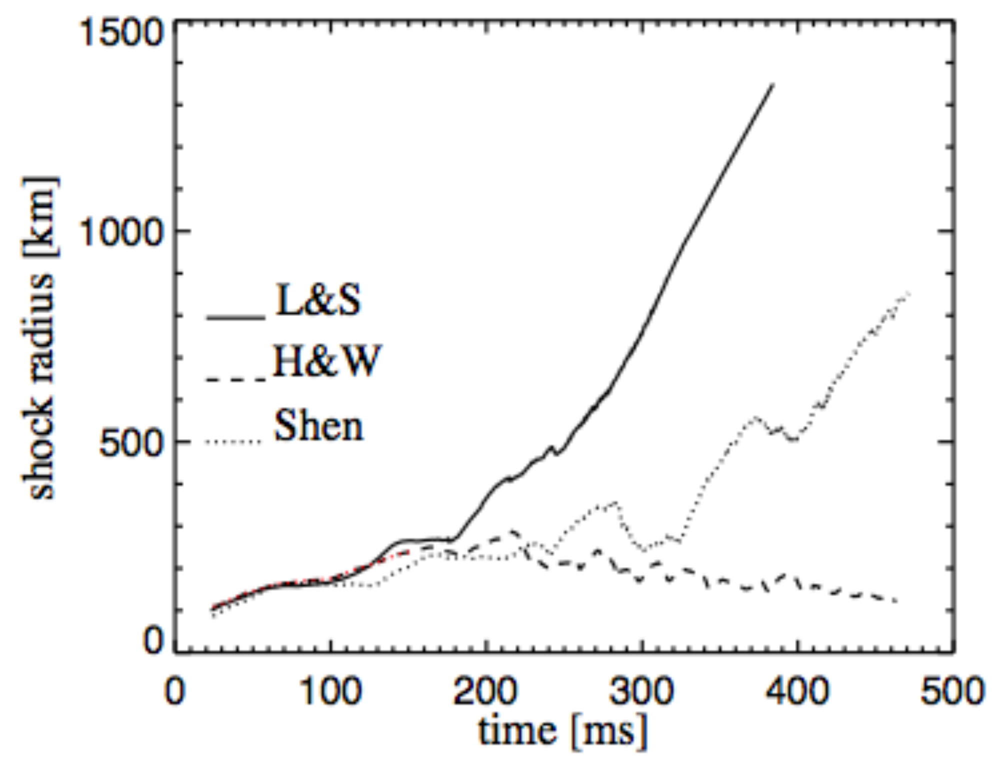
A difficult computational problem. Important physics:

- Equation of state for neutron star matter
    - Not well known..
- Gravity
    - Newtonian, general relativity, approximate GR,…
- Hydrodynamics
    - Eulerian, Lagrangian, 1D, 2D, 3D, resolution,..
- Magnetic fields
- Rotation
- Neutrino transport

Example : Different equations of state give very different results

Three different EOSs give very different shock propagations.



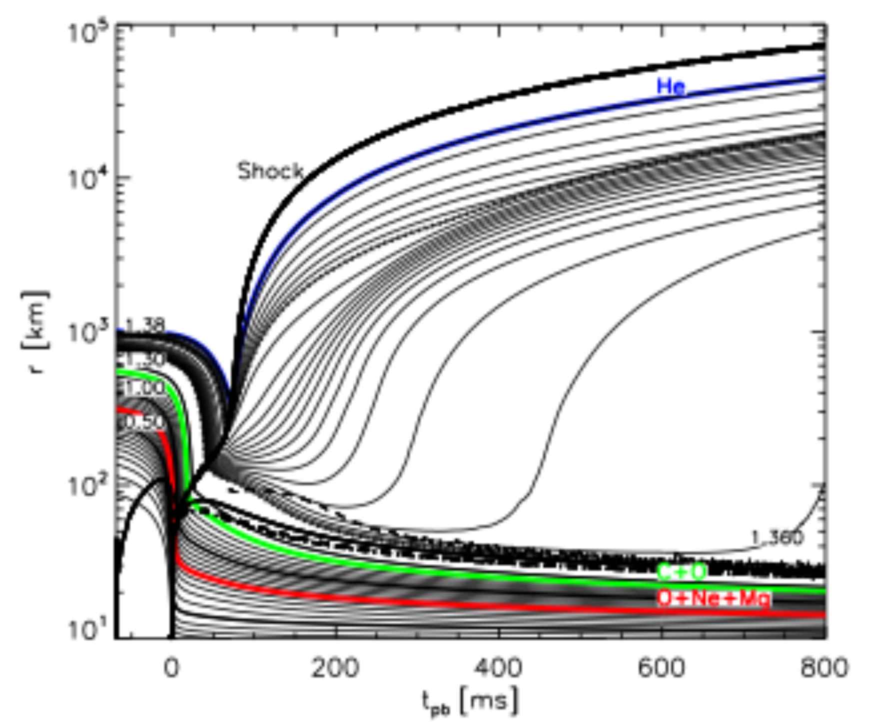


Marek 2003

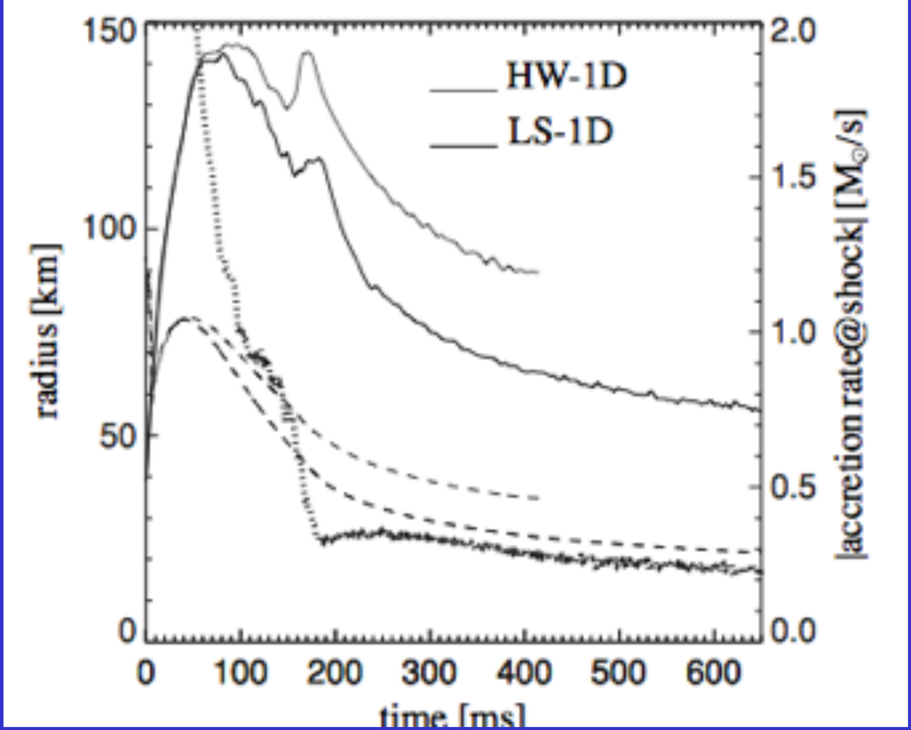
Janka+2012

Neutrino-driven explosions in 1D

- Turn out to only work for "light massive stars" (M_{ZAMS} = 8-9 M_{sun}).
- For these $E_{SN} \sim 10^{43}$ J is obtained.

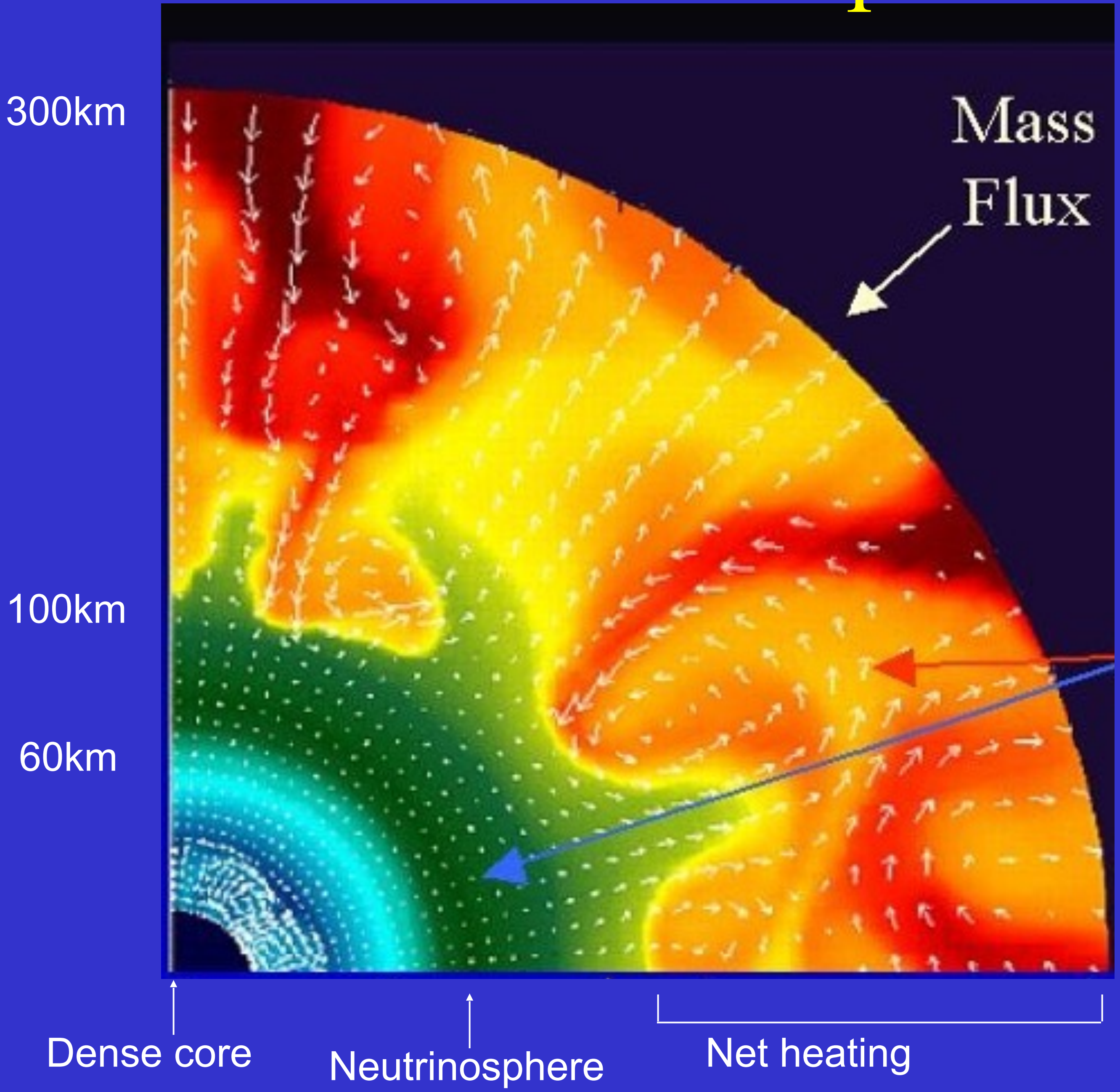


9 M_{sun} explodes (Kitaura 2006)



15 M_{sun} fails(Marek and Janka 2009)

Neutrino-driven explosions in 2D/3D



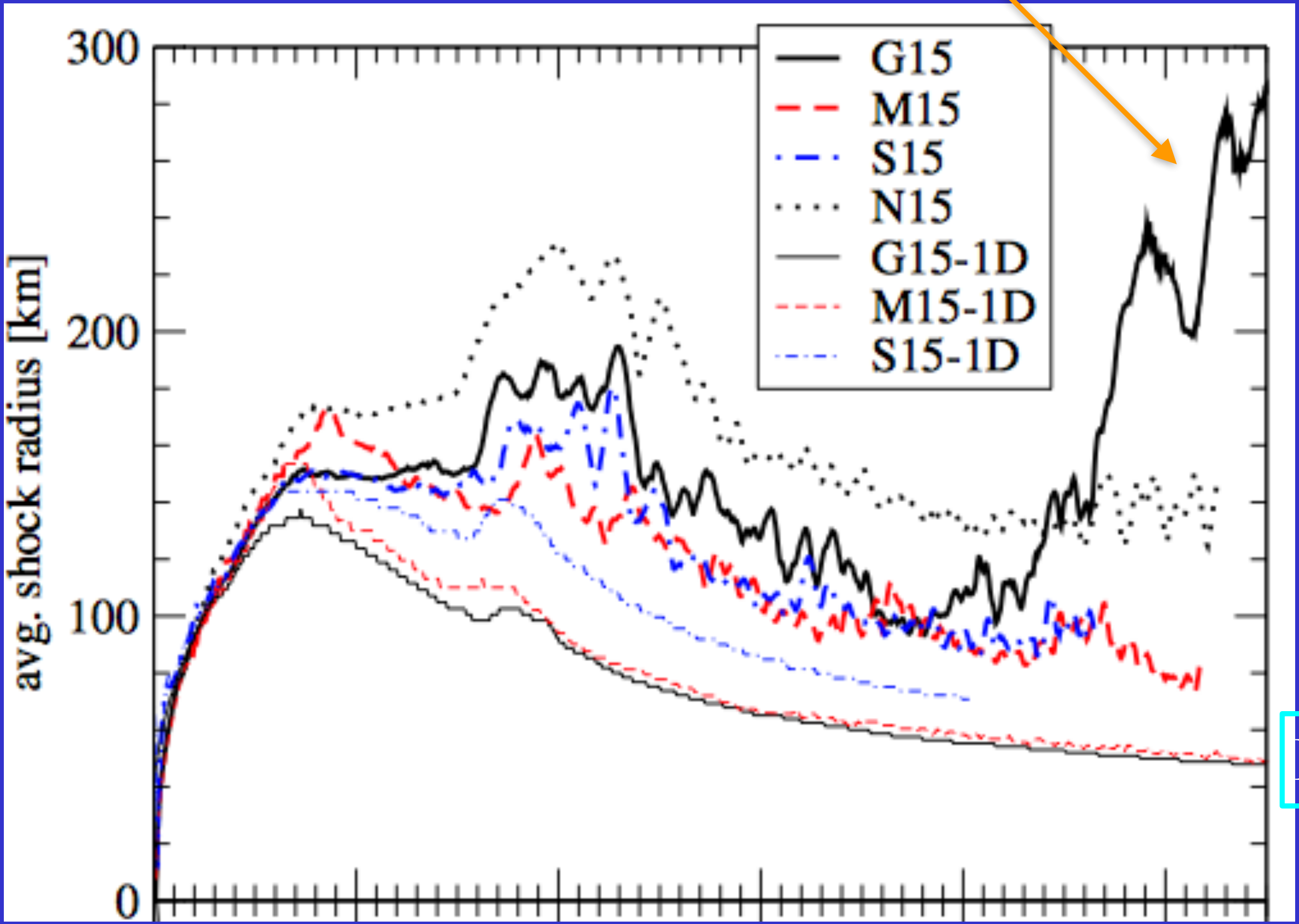
Multi-D hydrodynamical effects aid the neutrino deposition —> explosions also for higher masses

Heating and cooling regions

Janka & Mueller (1996):

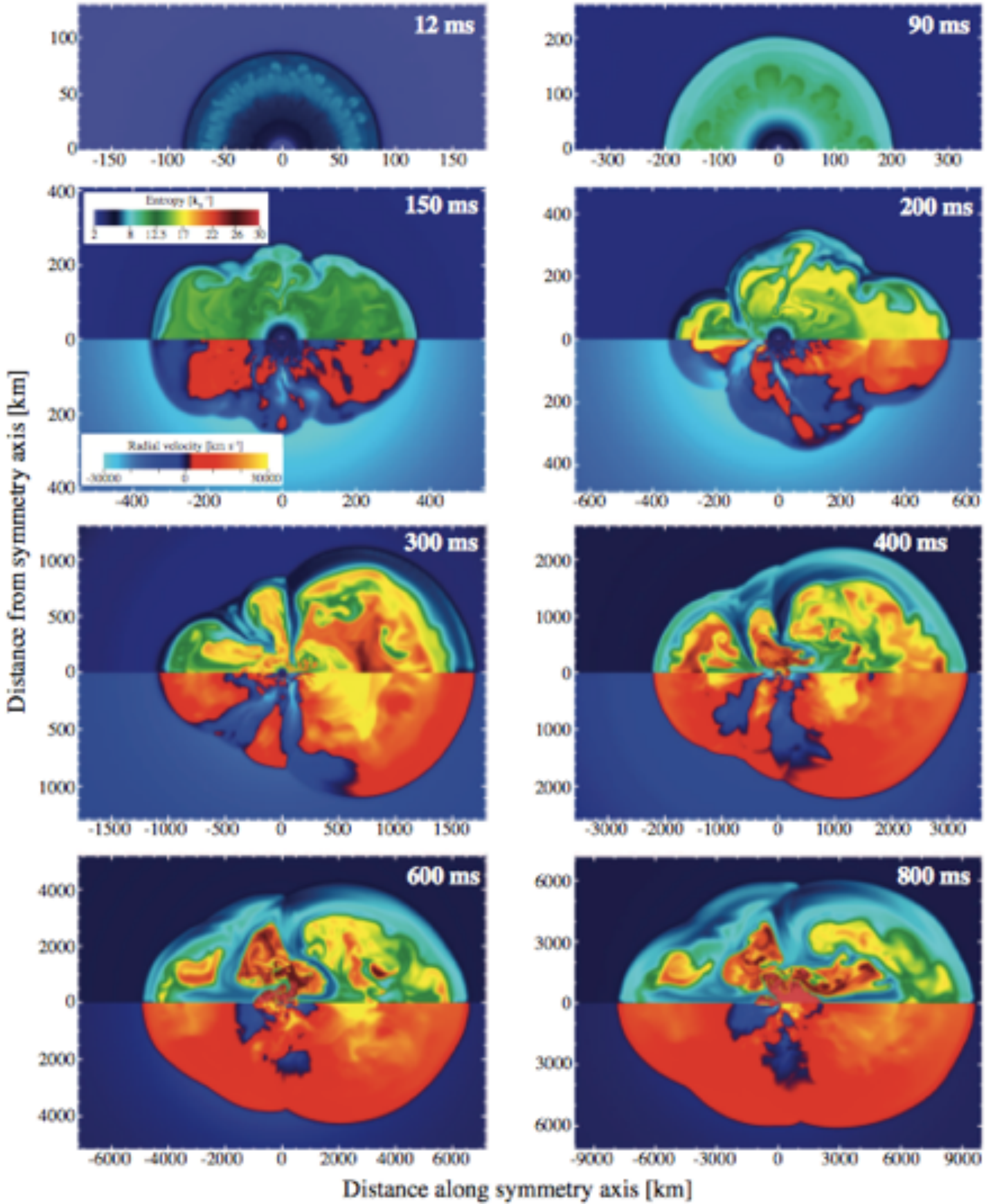
2D : 15 M_{sun} star explodes

Explosions also obtained for 11, 20, 27 M_{sun} stars in last few years



Time

From Mueller+2012



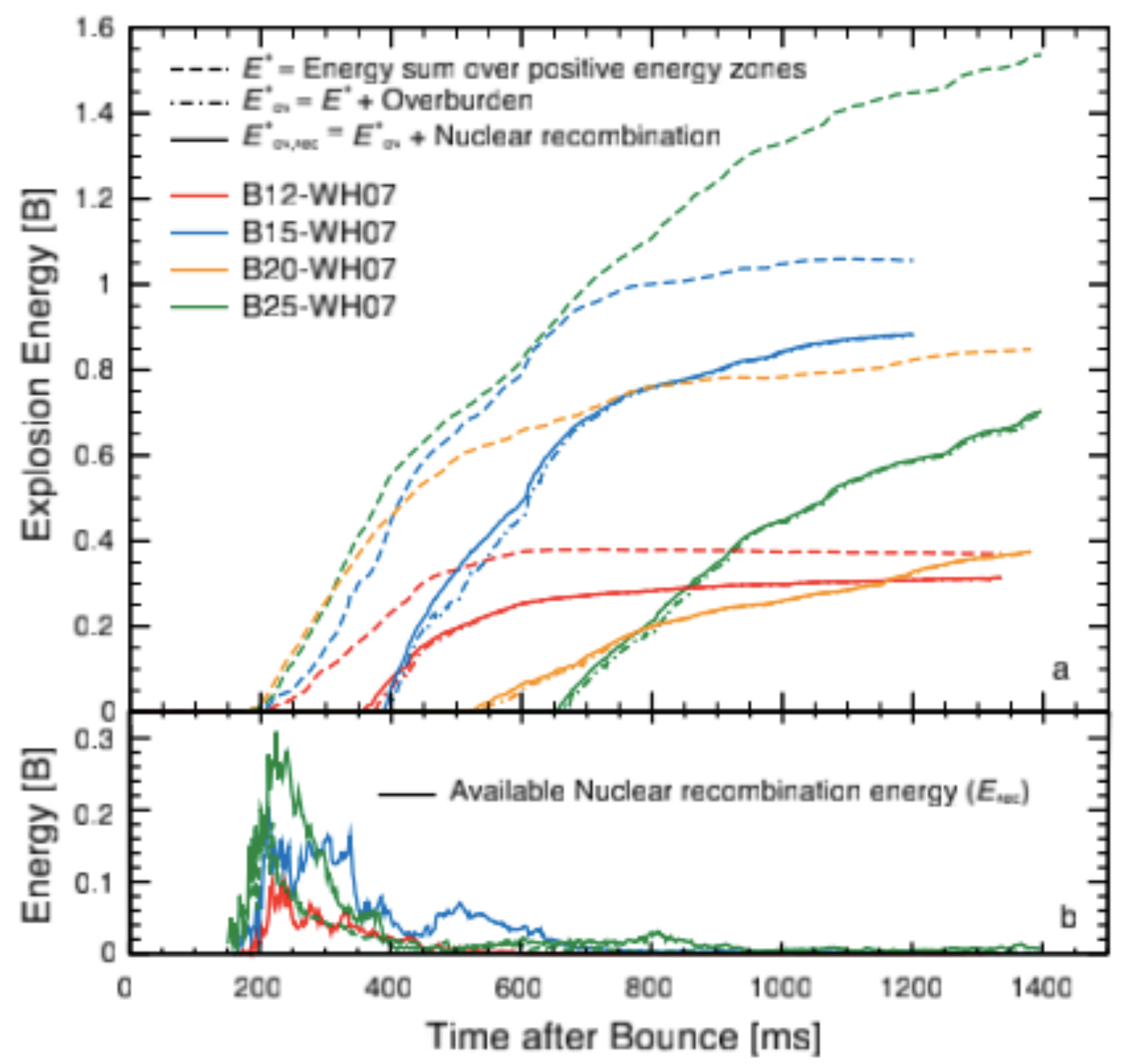
2D explosion of a 12 M_{sun} star (Bruenn 2013).

Upper half : entropy
Lower half: radial velocity

The explosion energy

- If the explosion occurs by a *self-regulating mechanism*, the explosion energy will be of the same order as the gravitational binding energy of the mantle. Once this amount is deposited the star expands away and the deposition efficiency decreases.
- So we expect E_SN ~ E_grav ~ M^2/R : *this quantity grows with* M_{ZAMS}.
- The neutrino mechanism is such a self-regulating process.

Modelled explosion energies



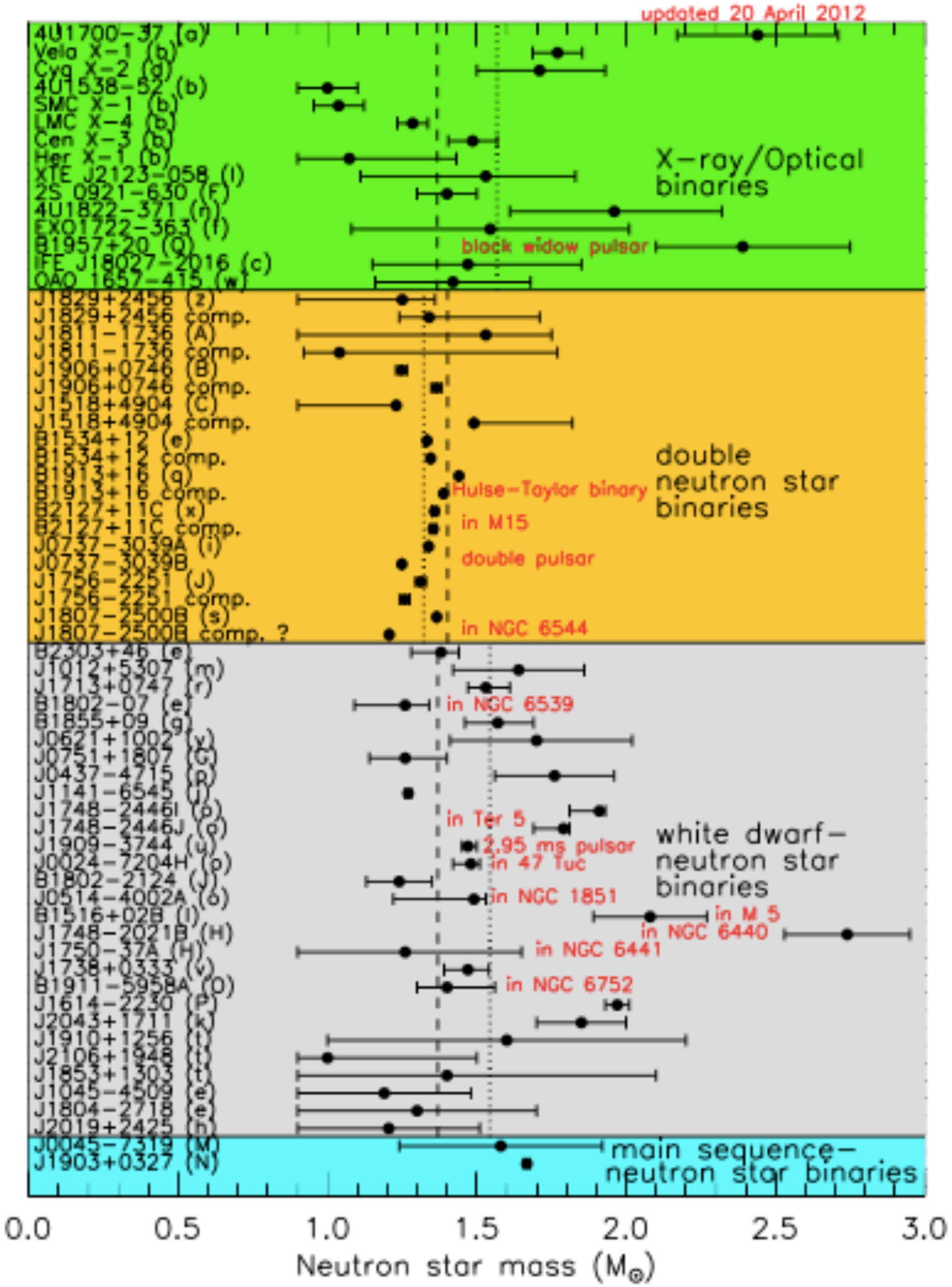
Bruenn 2014 (2D)

12 M_{sun} is done :
E ~ 0.3*10^{44} J

15 M_{sun} almost done:
E ~ 0.9*10^{44} J

Confirms neutrino mechanism gives higher E for higher mass progenitors.

20 and 25 M_{sun} model not done at end of simulation.



Neutron star masses

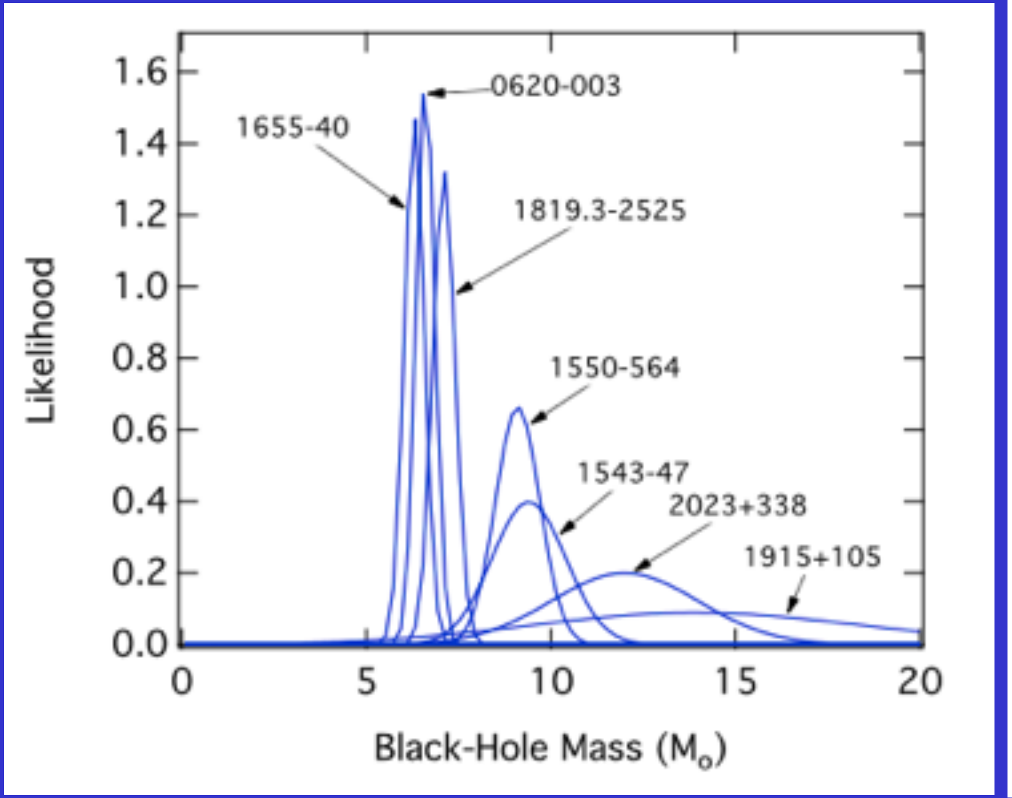
Theoretical upper limit:
2-3 M_{sun} (Tolman-Oppenheimer-Volkoff limit)

Nothing observed below ~ 1 M_{sun} because no stellar evolution channels to form such small Fe cores.

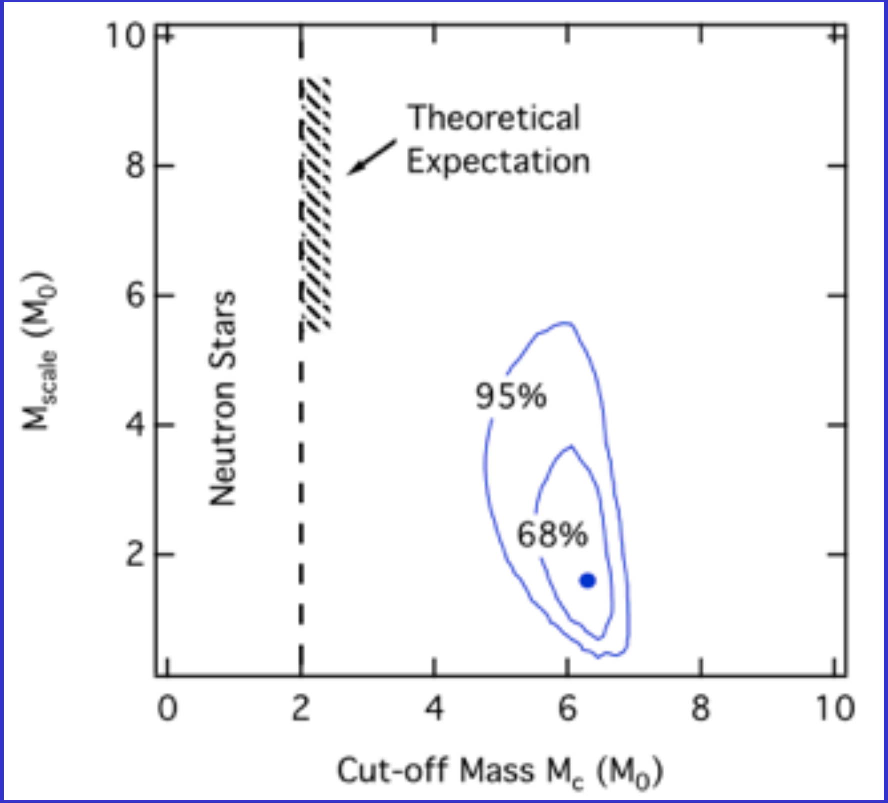
Explosion models give good agreement with observed masses.

Lattimer 2013

Observed black hole masses



Masses



Minimum mass probability distributions

All above 5 M_{sun} so far
—> no remnants in 3-5 M_{sun} range:
challenge for explosion models to explain.
But small sample still.

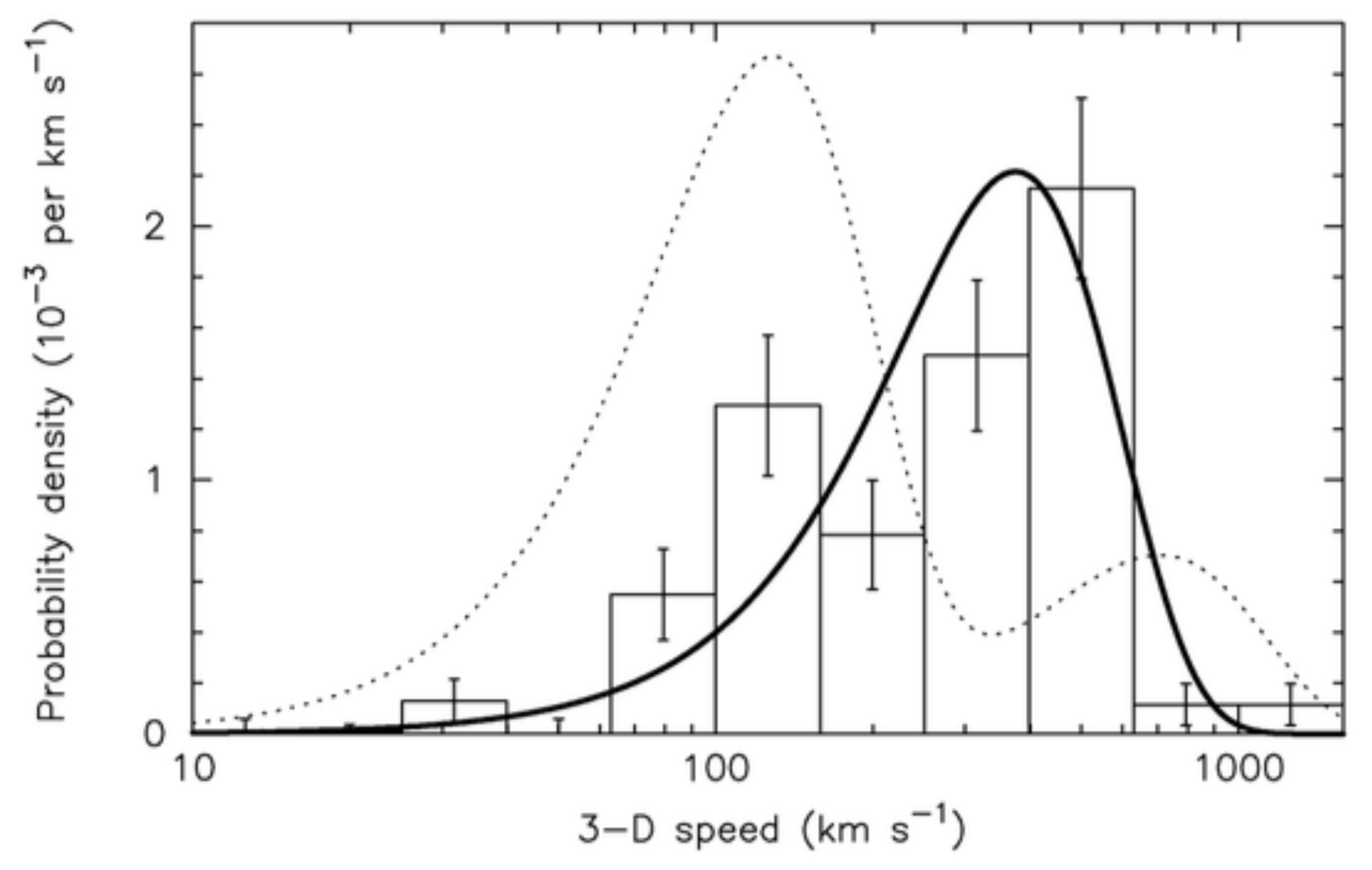
Ozel 2010

Neutron star spins

- 2D/3D simulations —> birth periods of >~ 100 ms for zero angular momentum progenitors: comes from hydrodynamical sloshing.
- Observed pulsars : born with periods down to 10-20 ms. Current belief there must be rotation in progenitor to achieve this.

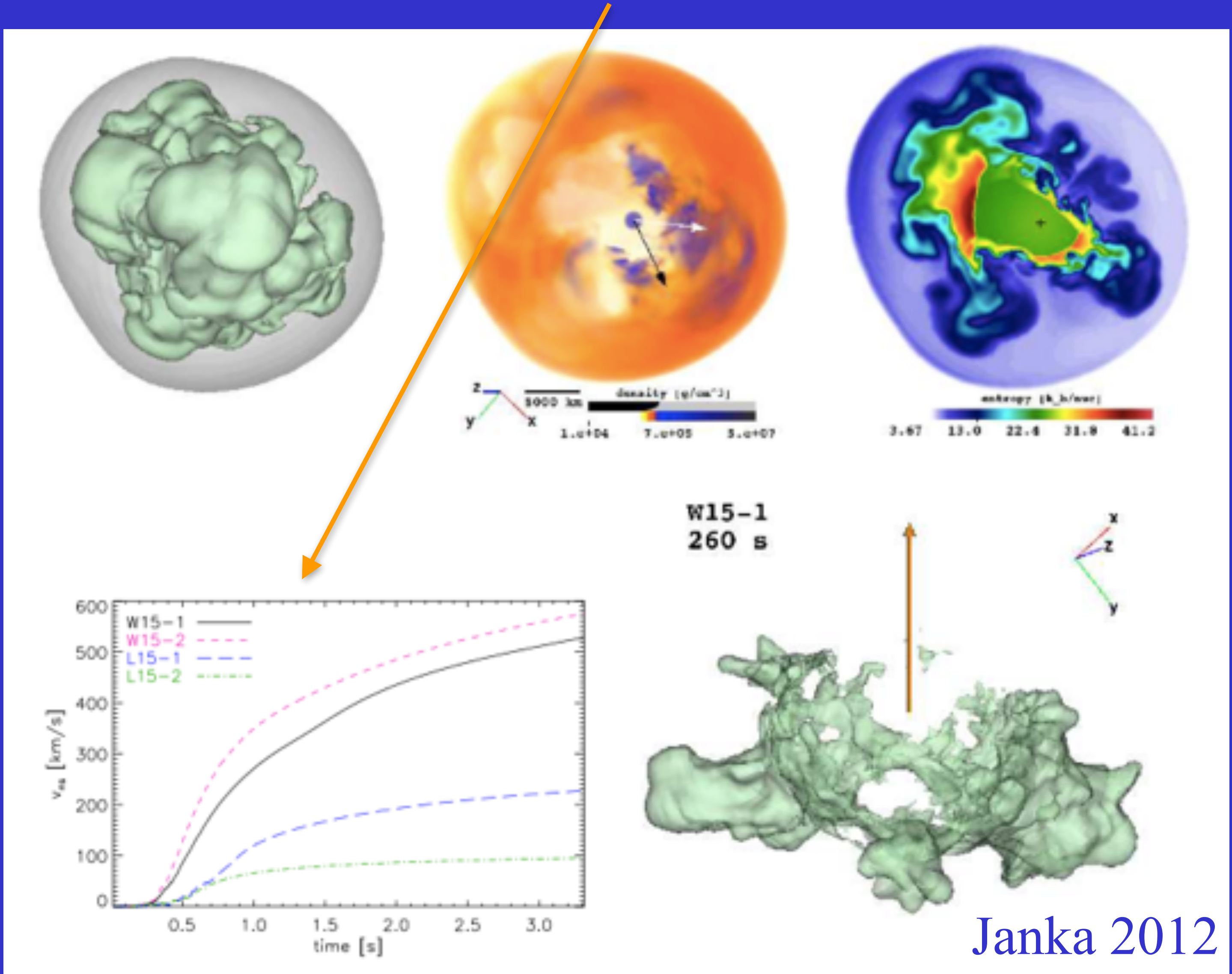
Observed neutron star kicks

Typically a few 100 km/s



From Hobbs 2005

Neutron star kicks : models successful



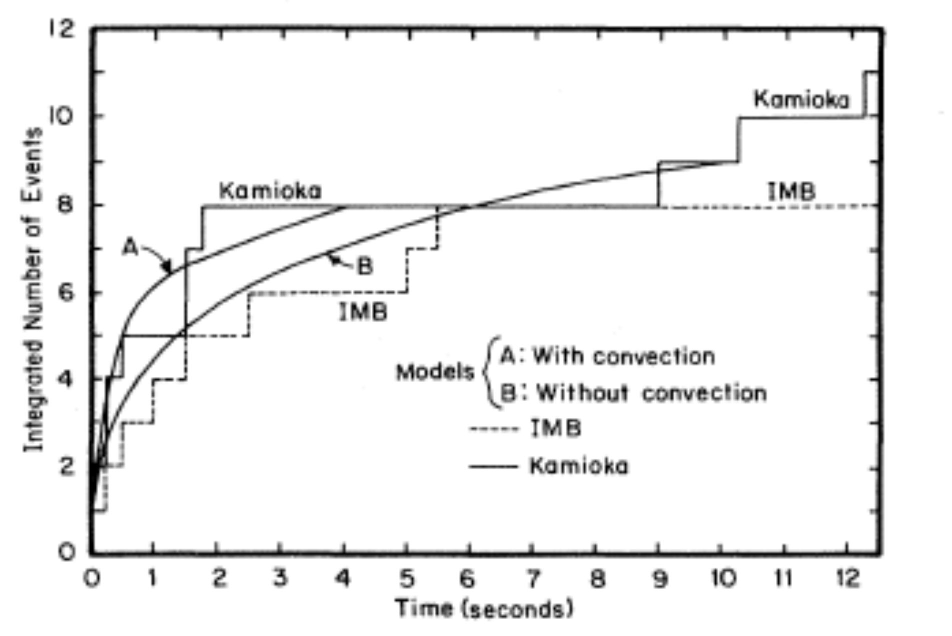
Janka 2012

Testing the model: SN1987A

Unique opportunity to test the core-collapse neutrino generating theory was the supernova of February 1987 in the Large Magellanic Cloud.

Expected neutrino flux for the SN at this distance (about 50 kpc) was 10^{13} m^{-2}.

Two experiments (Kamiokande and IMB) simultaneously detected neutrino burst, and the entire neutrino capture event (24 neutrinos captured) lasted 12s. This occurred 3 hours *before* the SN was optically detected. The reason is that the time for the shock wave to reach the stellar surface is ~3 hours.

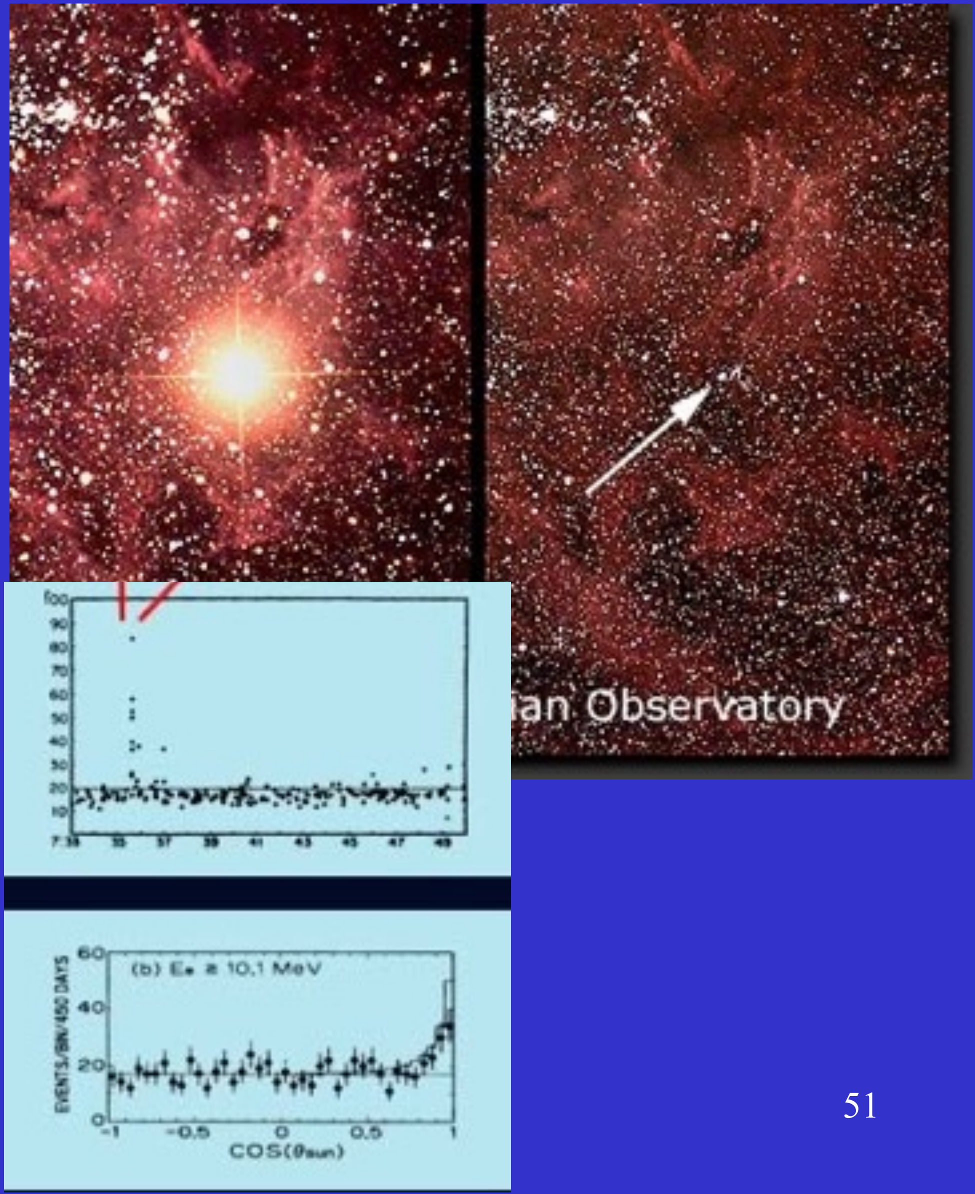


Spread-out arrival times (12s) —> neutrinos must have been trapped —> neutrino diffusion confirmed.

SN1987A - confirmation of core collapse

Core-collapse of massive star

- Catalogued star SK-69 202
- $M=17M_\odot$
- $T_{\mathrm{eff}}=17000$
- $\log L/L_\odot = 5.0$
- Star has disappeared
- Neutrinos confirm neutron star formation
- No pulsar or neutron star yet seen



Explosive nucleosynthesis

Shock wave moves through layers of Si and the lighter elements increasing temperature to $T \sim 5 \times 10^9$ K. This has following implications:

- Nuclear Statistical Equilibrium (NSE) reached on timescale of milliseconds
- As with slow core nuclear burning the products are Fe-group elements
- But main product is ^{56}Ni rather than ^{56}Fe as outer layers are less neutron rich.
- Timescale too short for β-decays to occur to change ratio of p/n
- Fuel (e.g. ^{28}Si) has $Z/A=1/2 \Rightarrow$ product must have $Z/A=1/2$
- ^{56}Ni has $Z/A=1/2$ but ^{56}Fe has $Z/A=26/56<1/2$
- As shock wave moves out, and $T < \sim 2 \times 10^9$ K (around ONe layer) explosive nuclear synthesis stops
- Elements heavier than Mg produced during explosion. Lighter elements produced during preceding stellar evolution
  - After the “photospheric” stage, the luminosity is powered by the decay of radioactive ^{56}Ni and its daughter nucleus ^{56}Co.

β-decays release energy:

3x10^{12} JKg^{-1} for ^{56}Ni

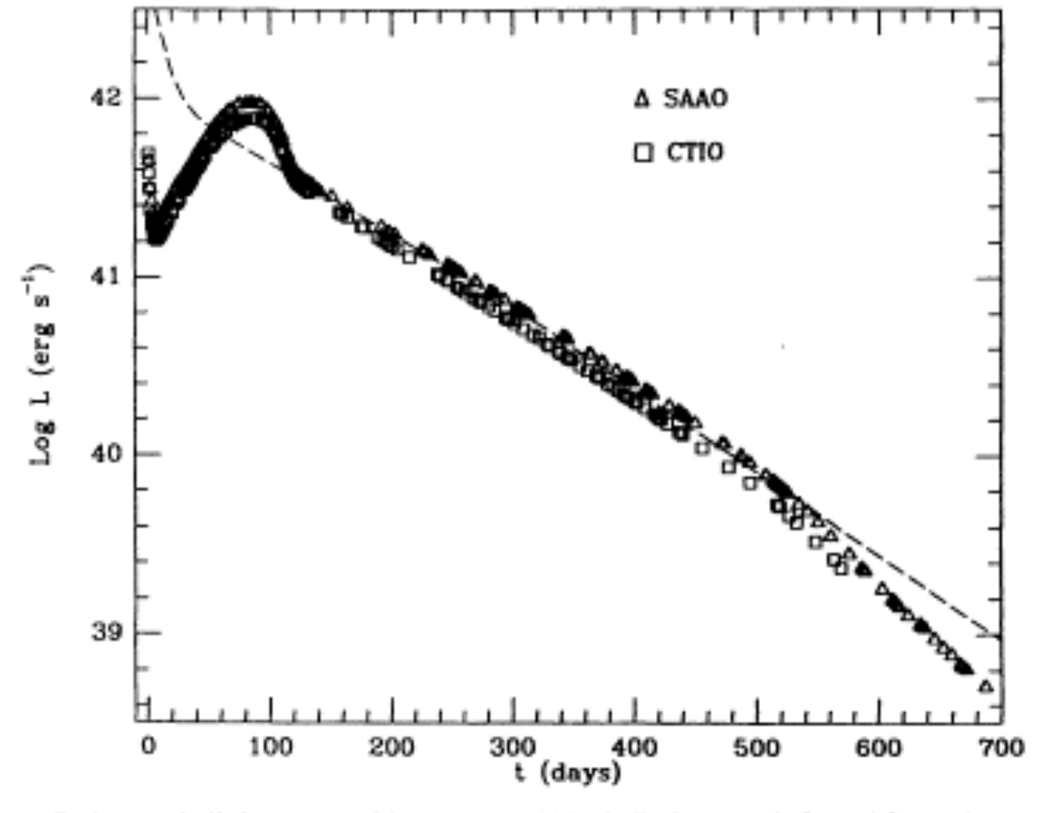
6.4x10^{12} JKg^{-1} for ^{56}Co

γ-ray lines (1.24Mev from ^{56}Co decay) detected by space and balloon experiments between 200-850 days.

Rate of lightcurve decline gives excellent match to the radioactive energy source half-life.

If distance is known, the mass of ^{56}Ni can be determined. For SN1987A:

M(^{56}Ni)= 0.075M$_\odot$

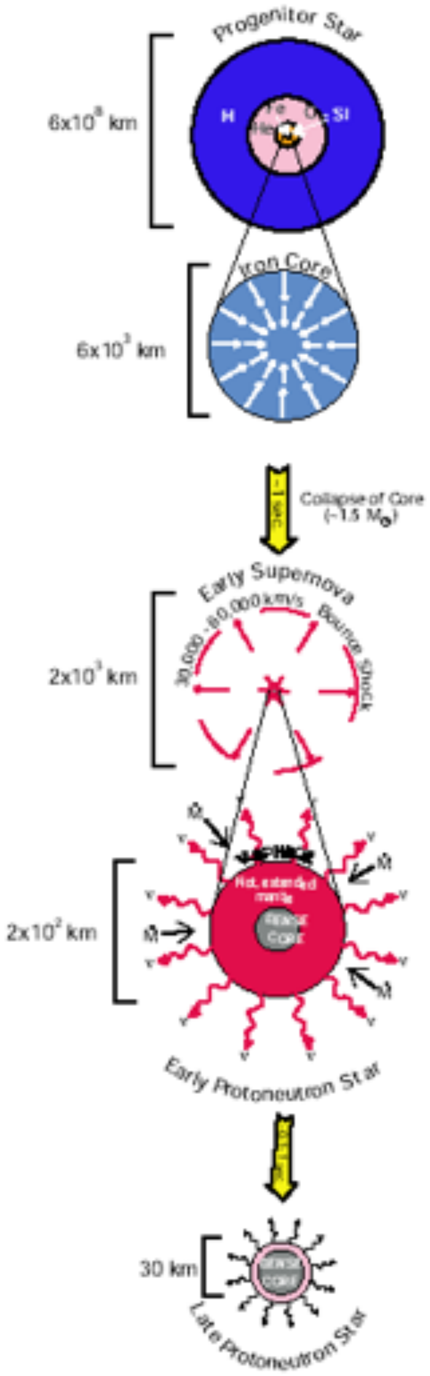


$$^{56}Ni \rightarrow {}^{56}Co + e^+ + \nu_e + \gamma \quad (\tau_{1/2} = 6 \text{ days})$$

$$^{56}Co \rightarrow {}^{56}Fe + e^+ + \nu_e + \gamma \quad (\tau_{1/2} = 77.1 \text{ days})$$

Summary 1

- Supernovae are stellar explosions, ejecting 1-10 solar masses at about 10,000 km/s.
- They occur about once per century in a galaxy.
- The origin are either thermonuclear explosion of a white dwarf (Type Ia) or collapse of the iron core in a massive star ($M > 8\ M_{sun}$) to a neutron star or black hole (Type II, Ib, Ic). Type II SNe have hydrogen, type I do not.
- The core collapses because electron captures and photodisintegration of ^{56}Fe take away pressure support.
- The core collapses on a time scale of 0.1 seconds, and a neutron star forms with R ~ 10 km. It is held up by both neutron degeneracy pressure and the strong nuclear force.
- Bounce at nuclear density initiates outward shock
- Shock must have further energy input
- Likely this comes from neutrinos, which radiate the released gravitational binding energy on a time-scale of seconds. Neutrinos detected directly in SN 1987A - their energies and arrival time dispersion in line with neutron star formation theory.



Summary 2

- Full modelling of core-collapse is a formidable supercomputing problem; explosions have been obtained only in the last few years. Multidimensional hydrodynamical effects crucial for successful explosions.
- Supernovae produce radioactive elements in explosive burning. At late times they are powered by ^{56}Ni —> ^{56}Co —> ^{56}Fe. Main source of iron in the Universe. Direct detection of this radioactive decay process in SN 1987A.