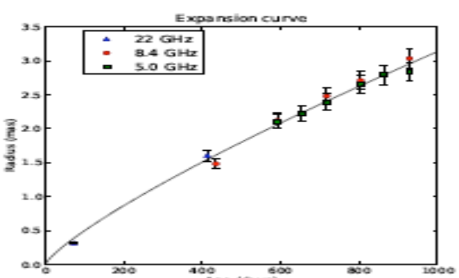
Supernova and SuperNova Remnants

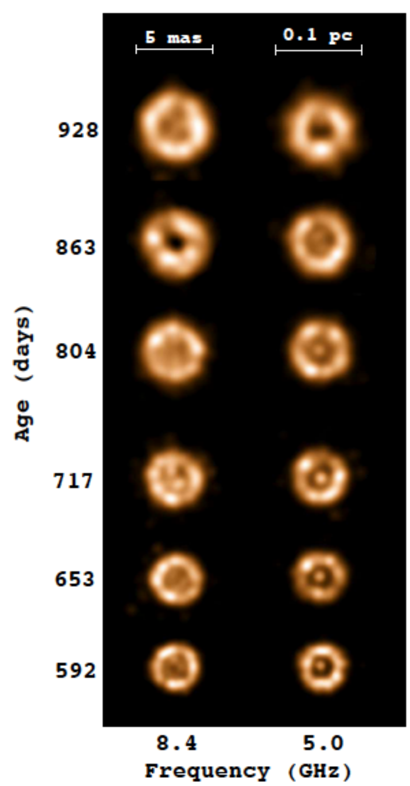
- We bid a fond farewell to clusters and start a new topic...

  supernova and supernova remnants

Super Nova and Super Nova Remnants

- Types of Super Nova
- Explosions
- Nucleosynthesis
- Physics of Supernova remnants
- Particle Acceleration
- Cosmology?





Radio images of SN2008 in M82 +Size vs time

Supernovae and Supernova Remnants

Supernovae

- T~ 5000 K effective temperature of photospheric optical emission during early period

- most of photon energy is in the is optical and infrared timescale ~ year

create a fair fraction of the elements

Supernovae and Supernova Remnants

Supernova remnants

powered by expansion energy of supernova ejecta, dissipated as the debris collides with interstellar material or stellar mass loss generating shocks

$T \sim 10^{6-7}$ K

characteristic thermal emission is X-rays

timescale ~100-10,000 years

SNR are multi-wavelength objects

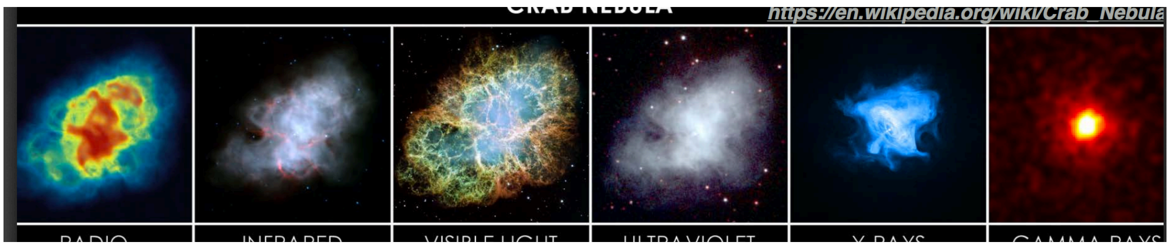
•SNR appearance in different energy bands depends on type of SN and the surrounding medium and age –SNR size/morphlogy is not a proxy for age

•X-ray-primary shock physics, thermal content, ISM density, ejecta abundances

•Optical- secondary shock physics, densities and (occasionally) shock speed and abundances

•Radio- particle acceleration

• To understand SNRs as a class, high quality data are required at multiple wavelengths



Why Study Supernova/Supernova Remnants?

Supernova explosion:
How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What and (how much) elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

Why Study Supernova/Supernova Remnants?

Shock physics:

How is energy distributed between electrons, ions, and cosmic rays in the shock?
How do electrons and ions share energy behind the shock?

Why Study Supernova/Supernova Remnants?

Interstellar medium:

How is the structure of the interstellar medium affected, and how does the shock interact with that structure?

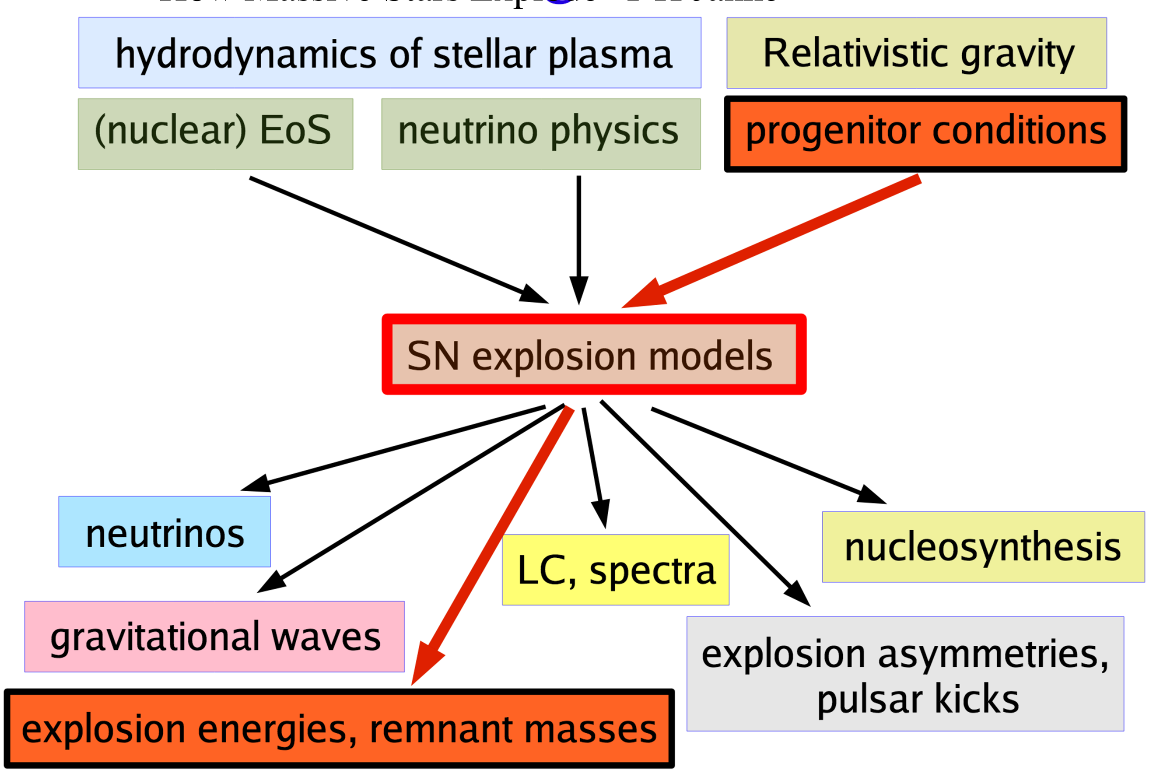
How is the ISM enriched and ionized- how are the metals created and distributed

Supernova- sec 4.1-4.3 of Rosswog and Bruggen

- Supernova come in two types (I and II)
  - Type Ia is the explosion of a white dwarf pushed over the Chandrasekar limit- details are not well understood
    - However they are used as a 'standard candle' for cosmology
  - Type Ib and II is the explosion of a massive star after it has used up its nuclear fuel- massive $M>8M_\odot$ star
  - Type I supernovae do not show hydrogen in their spectra. Type Ia supernovae reach peak luminosities of about

    4 x10^{43} erg/s (e.g. $10^{10}L_\odot$, $M_B \sim -19.5$ at maximum light,) with very similar light curves
- Type II supernovae show hydrogen in their spectra. Their light curves are diverse, with peak luminosities having a wide range ~2x10^{42}-2x10^{43} erg/s

How Massive Stars Explode- T-H Janke



- Remember Project ?
- Due the week before the last day of classes..

Dec 3

~10 pages- double spaced- use figures if you want, but not to excess.

please cite your references

you can use internet resources but must reference them

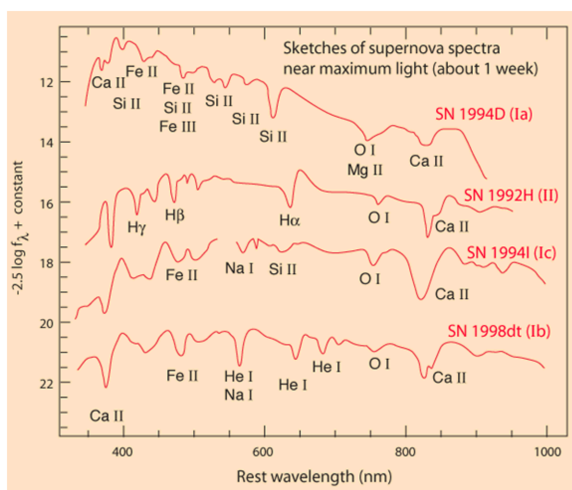
topic of your choice that you are excited about directly related to the class BUT not a topic that we covered in any depth.

Original research encouraged but <u>not required</u>

Optical classifications of SN

- I – No H in spectrum
  - Ia : No He either, but characteristic Si absorption
- II – Strong H in spectrum

K. Long



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

flux vs wavelength near maximum light for Ia and several core collapse (CC) types

Type Ias appear in all types of galaxies

Type Ia supernova, need several very specific events to push white dwarf over the Chandrasekhar limit.

Type II and Ib

Because massive stars are short lived these supernovae happen in star forming regions – never in elliptical galaxies

Type II events occur during the regular course of a massive star's evolution. (adapted from Type Ia Supernovae and Accretion-Induced Collapse Ryan Hamerly)

Types of Supernovae

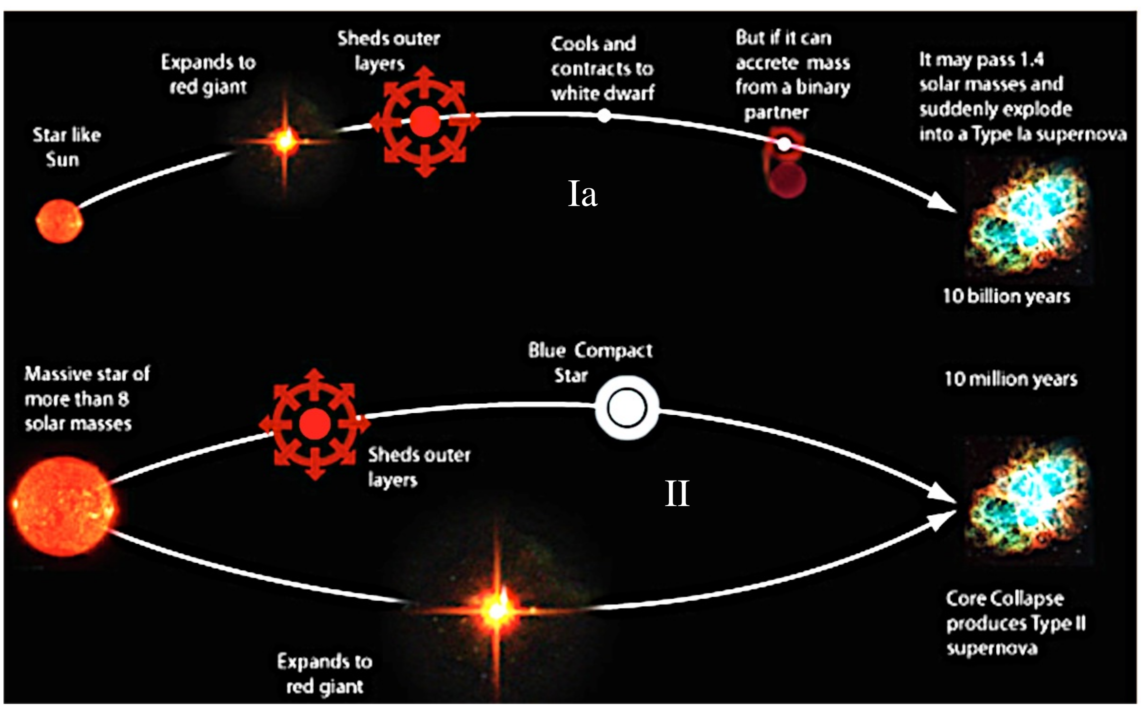
Type Ia	Type II
• No H, He in spectrum	Both H, He in spectrum
• No visible progenitor (WD)	Supergiant progenitor
• Kinetic Energy: 10^{51} erg	Kinetic Energy: 10^{51} erg
• EM Radiation: 10^{49} erg	EM Radiation: $10^{48\text{-}49}$ erg
• Likely no neutrino burst ?	Neutrinos: 10^{53} erg
• Rate: 1/300 yr in Milky Way Rate:	1/50 yr in Milky Way
• Occur in spirals and ellipticals	Occur mainly in spiral galaxies
• No compact remnant	NS or BHs
• most of the explosion energy is in heavy element synthesis and kinetic energy of the ejecta	vast majority of the energy is in neutrino emission
	decay of radioactivity keeps it bright for years.

Supernova - Summary

- Type Ia
- No hydrogen
- Thermonuclear explosion of a white dwarf
- No bound remnant •
- ~10^{51} erg kinetic energy •
- v ~ 5,000 – 30,000 km s-1
- No neutrino burst
- $E_{optical}$ ~ 10^{49} erg
- L_{peak} ~ 10^{43} erg s-1 for 2 weeks
- Radioactive peak and tail (^{56}Ni, ^{56}Co)
- 1/200 yr in our Galaxy •
- Makes about 2/3 of the iron in the MilkyWay

•Type II
- Hydrogen in spectrum
- M > 8 solar masses
- Iron core collapses to a neutron star or black hole
- ~10^{51} erg kinetic energy
- v ~ 2,000 – 30,000 km s^{-1}
- Neutrino burst ~ 3 x 10^{53} erg
- $E_{optical}$ ~ 10^{49} erg
- L_{peak} ~ 3 x 10^{42} erg s^{-1}~ 3 months(varies from event to event)
- Radioactive tail (^{56}Co)
- 2/100 yr in our Galaxy
- Makes about 1/3 iron and all the oxygen plus many other elements

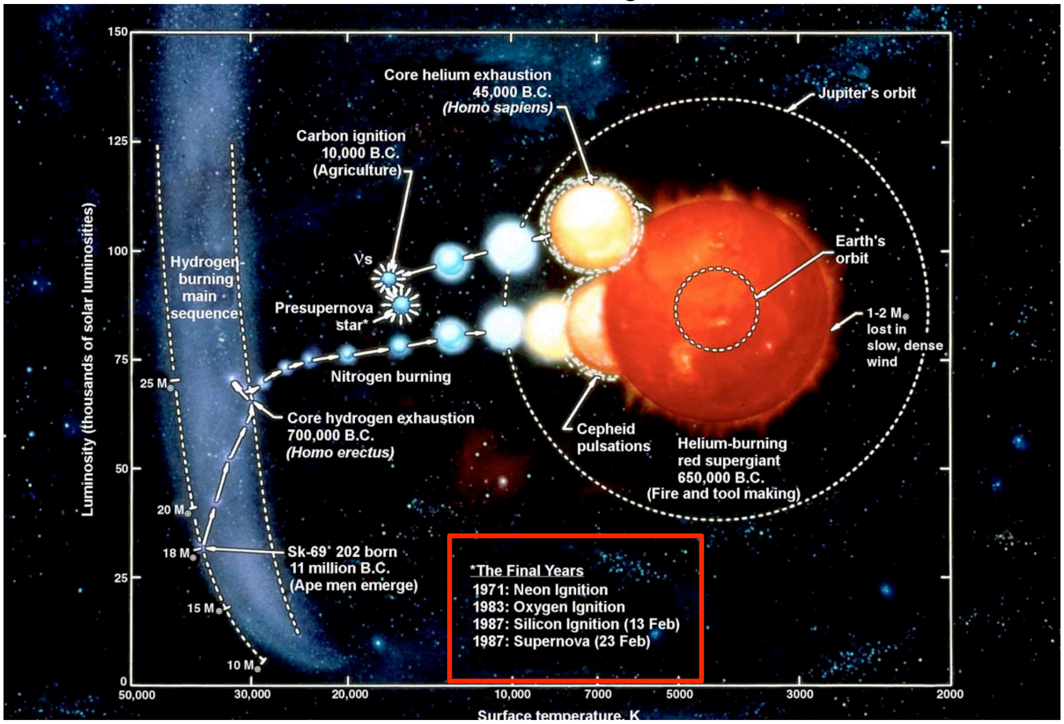
Two Paths to a SNe



The Life of SN1987A- AKA SK-69-202

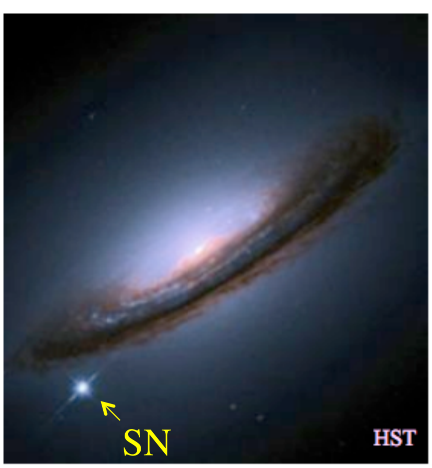
Progenitor star was a previously catalogued blue supergiant

Mass = 18 $M_\odot$



How to Get to a Type I

- Route to a type I is very complex and not well understood
- There maybe several evolutionary paths



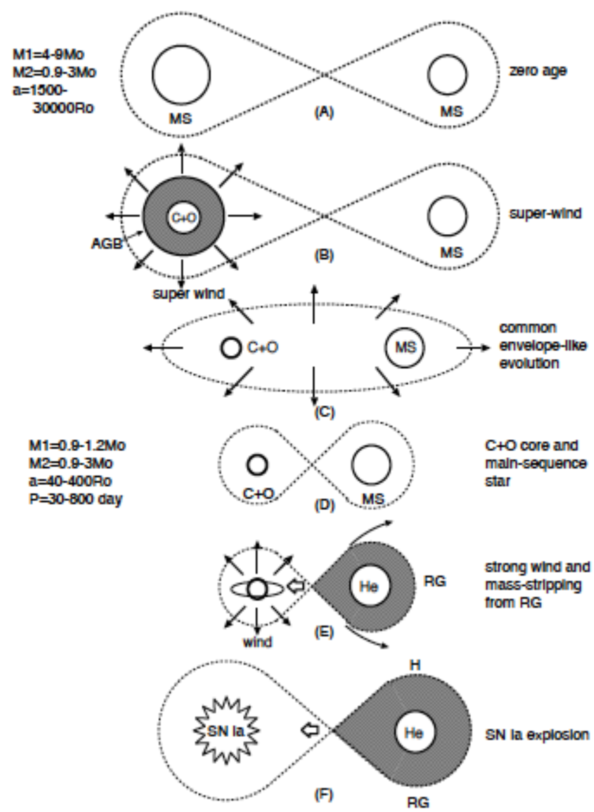


FIGURE 2. An illustration of the WD+RG (symbiotic) channel to Type Ia supernovae.

Supernova Explosions

Ia Thermonuclear Runaway

• Accreting C-O white dwarf reaches Chandrasekhar mass limit (more when we study NS and BHs), undergoes thermonuclear runaway

• Results in total disruption of progenitor (no remnant NS or BH)
• Explosive synthesis of Fe-group plus some intermediate mass elements (e.g., Si)

Type Ia Supernova Explosion

Uncertain mechanism and progenitor: probably a delayed detonation* (flame transitions from subsonic to supersonic speed) or deflagration*

•Amount of Ni (which drives the long term light curve) synthesized is not the same from object to object

➔**different ejecta mass**

➔**different explosion energies**

➔**asymmetries in the explosions**

➔**differences in the explosion physics**

*Detonation is the violent reignition of thermonuclear fusion in a white dwarf star . It is a runaway thermonuclear process which spreads through the white dwarf in a matter of seconds,

*Deflagration-"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat

Type Ia's

- Why a thermonuclear explosion of a white dwarf?
  - Kinetic energy of ejecta ~$5x10^{17}$ erg/gm (~$1/2v^2$~$(10^4$km/sec$)^2$) is similar to nuclear burning energy of C/O to Fe (~1 Mev/ nucleon)
  - lack of remnant (e.g. NS or BH) or progenitor in both pre and post explosion observations.
  - occur in elliptical galaxies with no star formation
- <u>But</u> (Rosswog and Bruggen pg 136)
  - No consensus on
    - mass of WD or its composition before explosion
    - origin of accreted material (either mass from a 'normal' companion or the merger of 2 white dwarfs)
    - exact explosion mechanism

Type Ia- How the Explosion Occurs

- Deflagration wave
  - Deflagration-

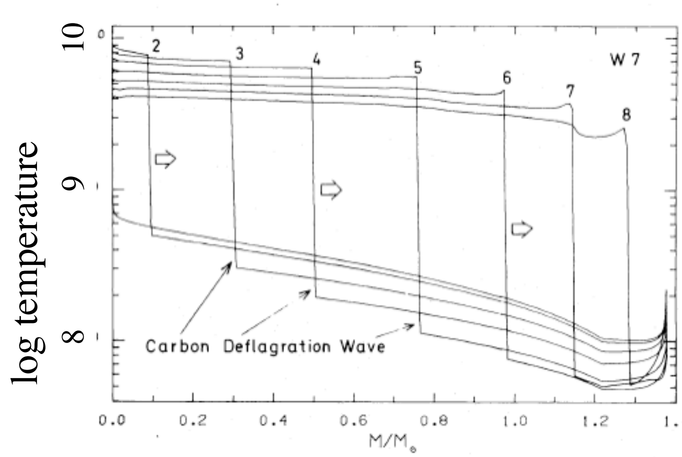
"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.

In main sequence stars T_c~ 10^8 K to ignite helium core burning- in SNIa T_{core}~10^{10} K

Detailed physics is still controversial!

Fundamental reason: nuclear burning rate in SnIa conditions ~T^{12} *!!*

'flame' ~ 1cm thick, White dwarf has r~10^8cm



mass shell

Deflagration wave in WD
time steps are at **0, 0.6, 0.79, 0 .91, 1.03, 1.12, 1.18, 1.24 sec !!**

Detailed Yields for a SNIa model

Abundances are relative to solar

We will come back to this later....

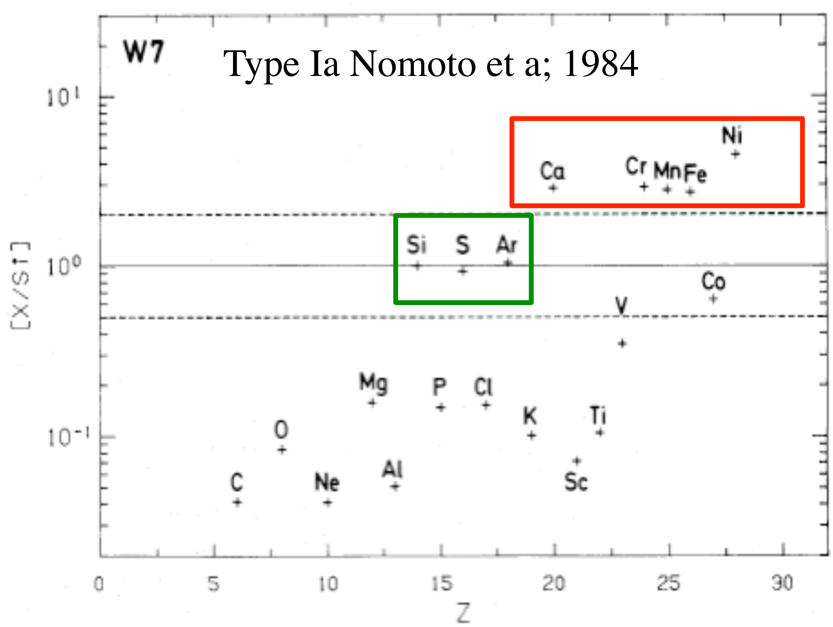
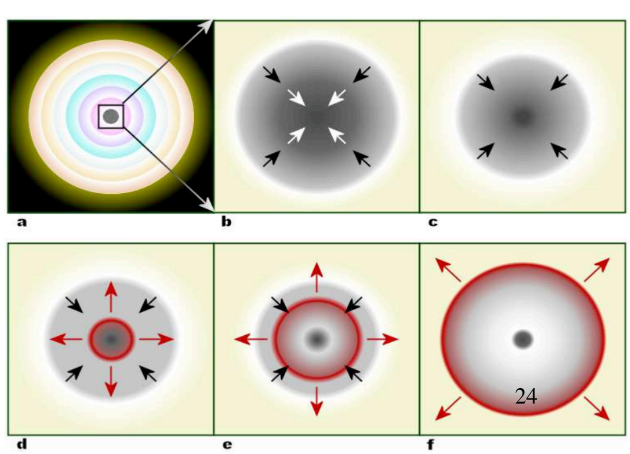


FIG. 10.—The abundances of elements relative to the solar values (W7). The ratio is normalized to Si.

Type IIs

- Collapse of a massive star- the cores mass 'burns' into iron nuclei and has a maximum size determined by the Chandrasekhar limit, ~1.4 $M_\odot$. (see late slides on what this is)
- Natural from stellar evolution
- Leaves NS or BH or maybe no remnant
- Wide range of masses, metallicities, binarity etc make for wide range of properties

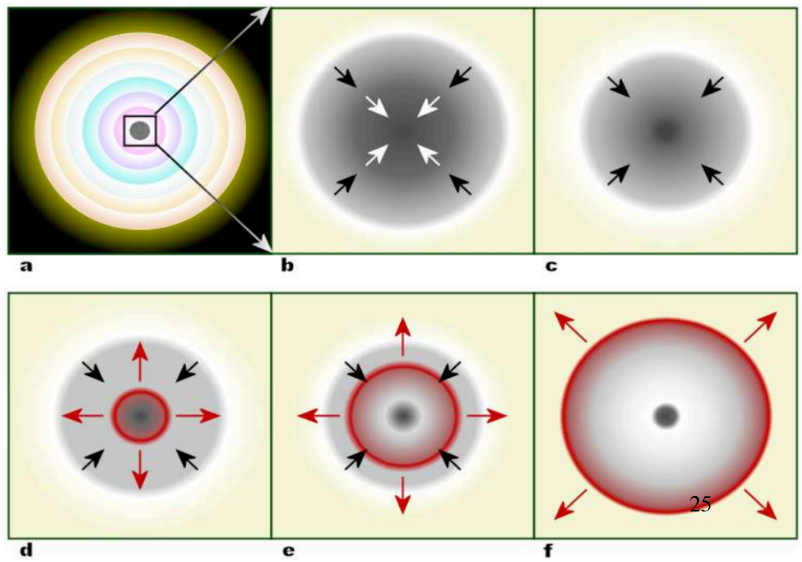


Lattimer- http://www.astro.sunysb.edu/lattimer/AST301/lecture_snns.pdf

Type IIs

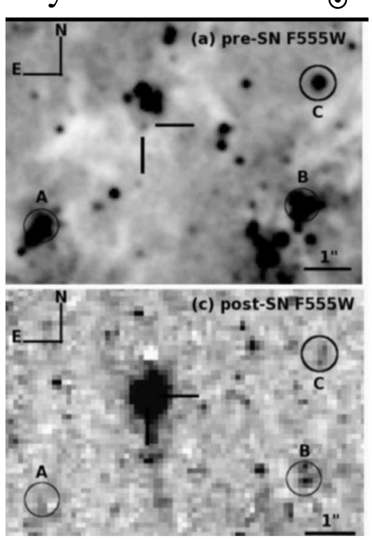
- total "optical" energy ~10^{49}erg.
- several solar masses ejected at ~1%c
- •The kinetic energy ~10^{51}erg

Collapse of massive star to a SN- central density reaches ~3×10^{14} gm/cm^3- several times that of nuclear density



Type II Progenitors

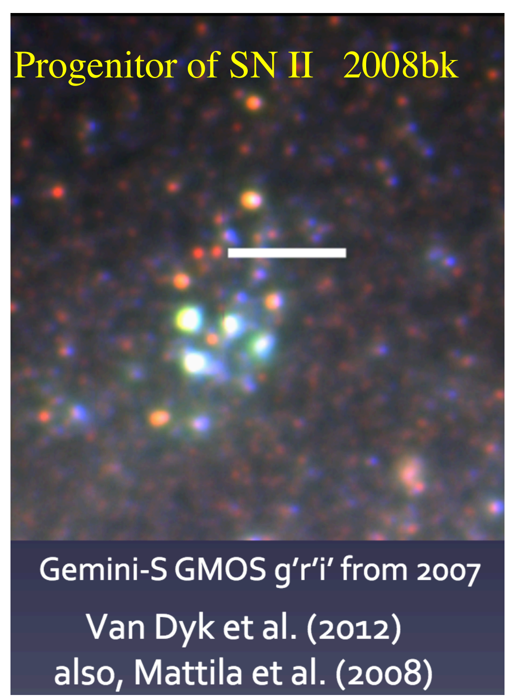
- In a few cases HST has directly observed the progenitor - has to be very luminous ~$10^5 L_\odot$ to detect



before

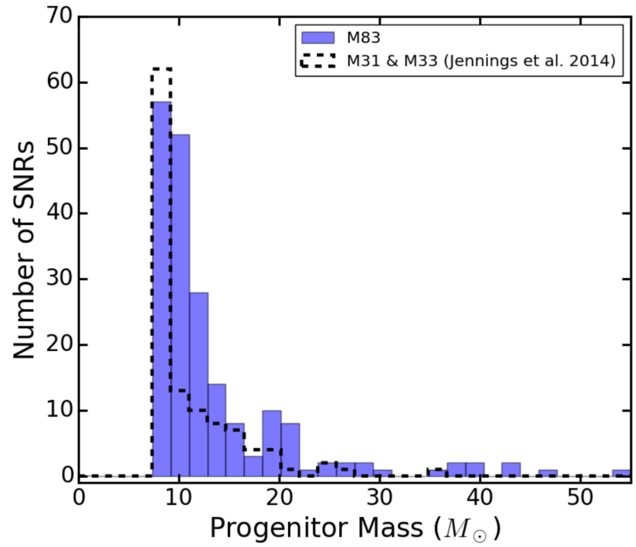
after

SN2008cn in NGC 4603
(Elias-Rosa et al.2009)



Type II Progenitors

- In nearby galaxies HST data can constrain the age of the stars near to (50pc)supernova remnants
- The most massive stars have shortest lives and explode 'first'
  - the mass of the oldest *living* star provides a lower bound to the mass of the star that exploded as a type II SN



Estimated mass of progenitor in nearby galaxies

Energy Release in Supernovae

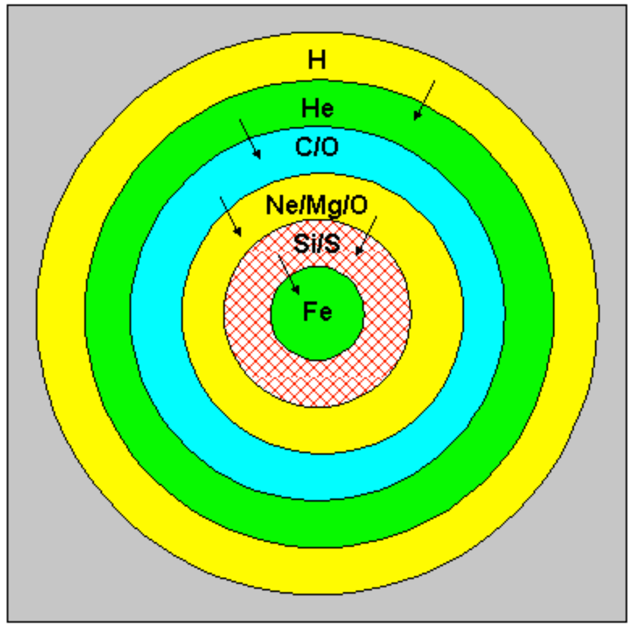
- Basic idea
- Once the core density has reached 10^{17} -10^{18} kg m^{-3} , further collapse impeded by nucleons resistance to compression
- Shock waves form, collapse => explosion, sphere of nuclear matter bounces back.

Types II/Ib/Ic Core-Collapse of Massive Progenitor

• Massive progenitor core forms neutron star or black hole or perhaps nothing left

• Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled

TYPE II Supernova Explosion



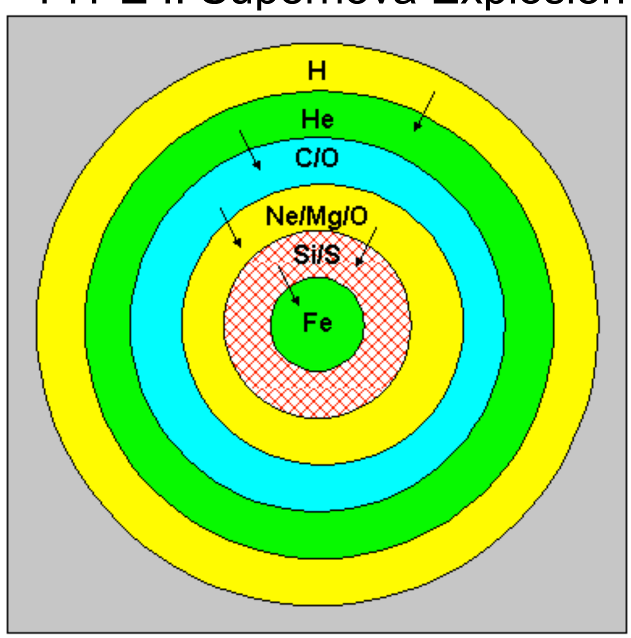
Initially in core-collapse supernovae (type II) the energy comes from the gravitational energy freed in the collapse- later times from radioactive decay

Types II/Ib/Ic Core-Collapse of Massive Progenitor

• **Most of the explosion energy is carried away by neutrinos-**
  - Detection of neutrinos from SN 1987A confirmed basic physics Nobel prize 2002 (Cardall astro-ph 0701831)

• Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields

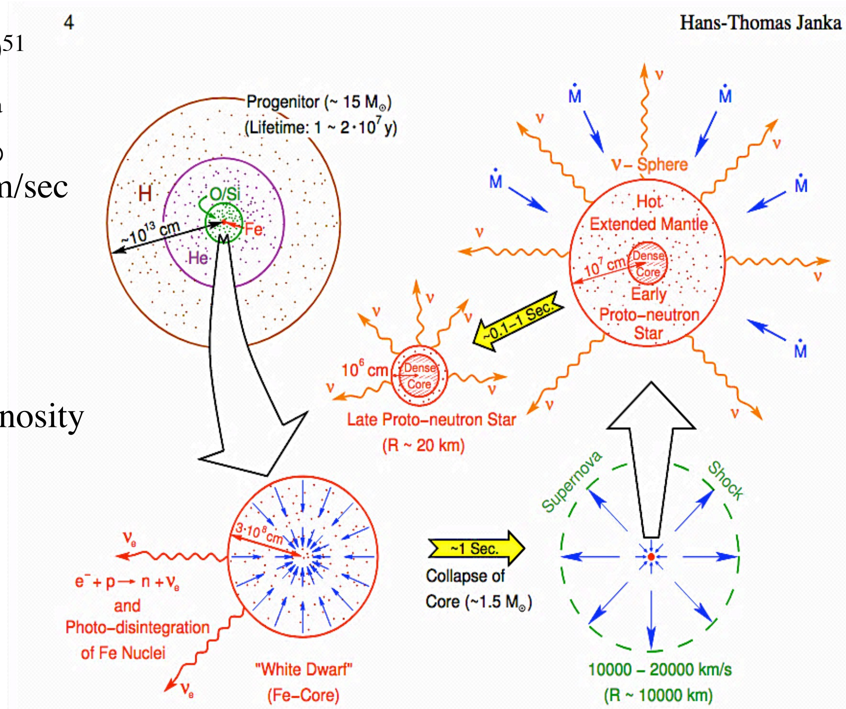
TYPE II Supernova Explosion



Initially in core-collapse supernovae (type II) the energy comes from the gravitational energy freed in the collapse- later times from radioactive decay

- Mass motion ~10^{51} ergs $(\sim M_\odot v^2)_{ejecta}$
  - SNII $M=4M_\odot$ v_{ejecta}=5000km/sec
  - Neutrino luminosity is ~3×10^{53} ergs $(0.15M_\odot c^2)$

    photon luminosity ~10^{49}

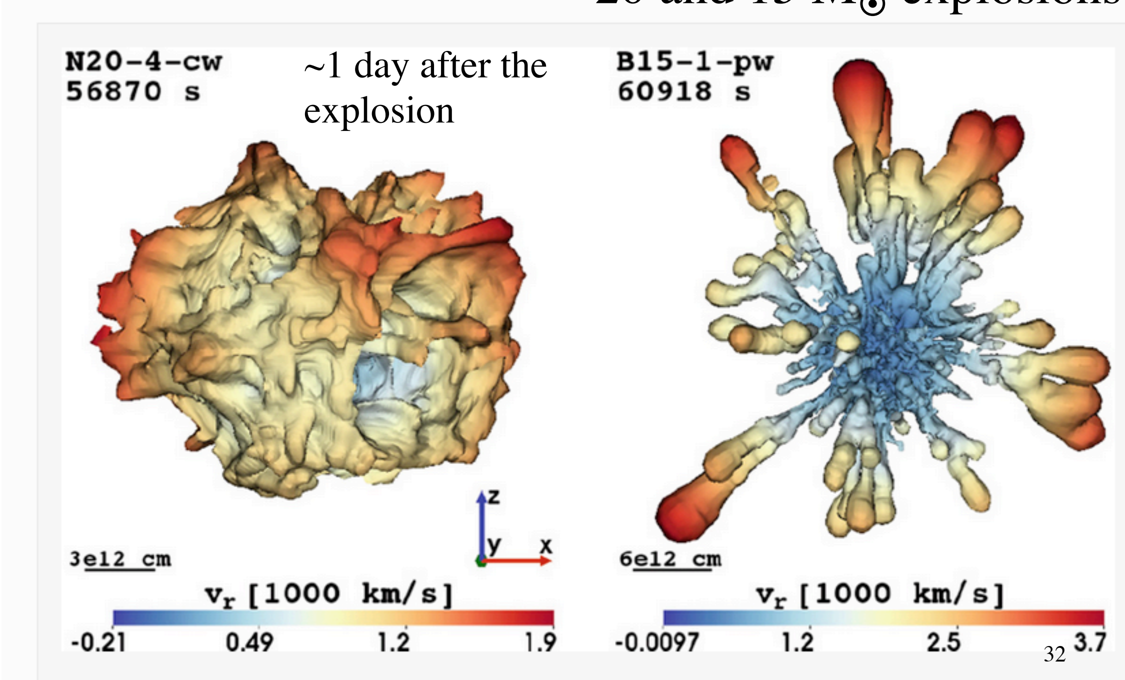


Evolution of a massive star from core collapse to NS

SNII Explosions- Not Spherical Cows

Wongwathanarat et al. 2015

20 and 15 $M_\odot$ explosions



STOP

- What are 4 differences between type Ia and II supernova
- 1 item per group- I will call on the groups randomly and no repetitions!

33

In massive stars, nucleosynthesis by fusion of lighter elements into heavier ones via
sequential hydrostatic burning processes called helium burning, carbon burning, oxygen burning, and silicon burning, in which the ashes of one nuclear fuel become, after compressional heating, the fuel for the subsequent burning stage.

During hydrostatic burning these fuels synthesize overwhelmingly the alpha-nucleus (A = 2Z) products.

And so the type II SN **ejects** the previously made elements -some heavier elements are made in the explosion (zinc, silver, tin, gold, mercury, lead and uranium etc-)

Explosive Nucleosynthesis- Type IIs

Nuclear processing as the supernova shock wave propagates through the star (see Arnett 1996)

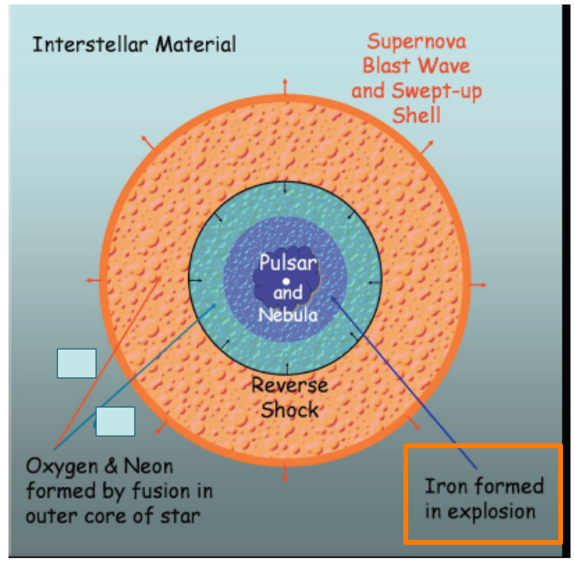
'α' products

C burning produces O, Ne, Mg, etc
T ~ 2 x 10^9 K

Ne burning produces O, Mg, etc
T ~ 2.3 x 10^9 K

O burning produces Si, S, Ar, Ca, etc
T ~ 3.5 x 10^9 K

Si burning produces Fe, Si, S, Ca, etc T ~ 5 x 10^9 K



stops at Fe, sort of

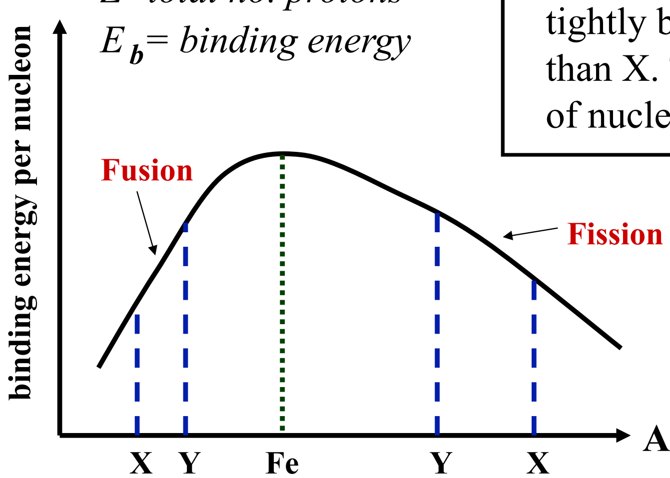
Binding energy of Nuclei - why stellar burning stops generating energy

A=total no. nucleons

Z=total no. protons

E_b= binding energy

Change from X to Y emits energy since Y is more tightly bound per nucleon than X. This is a function of nucleon mass



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http://www.mssl.ucl.ac.uk/

SNIIa

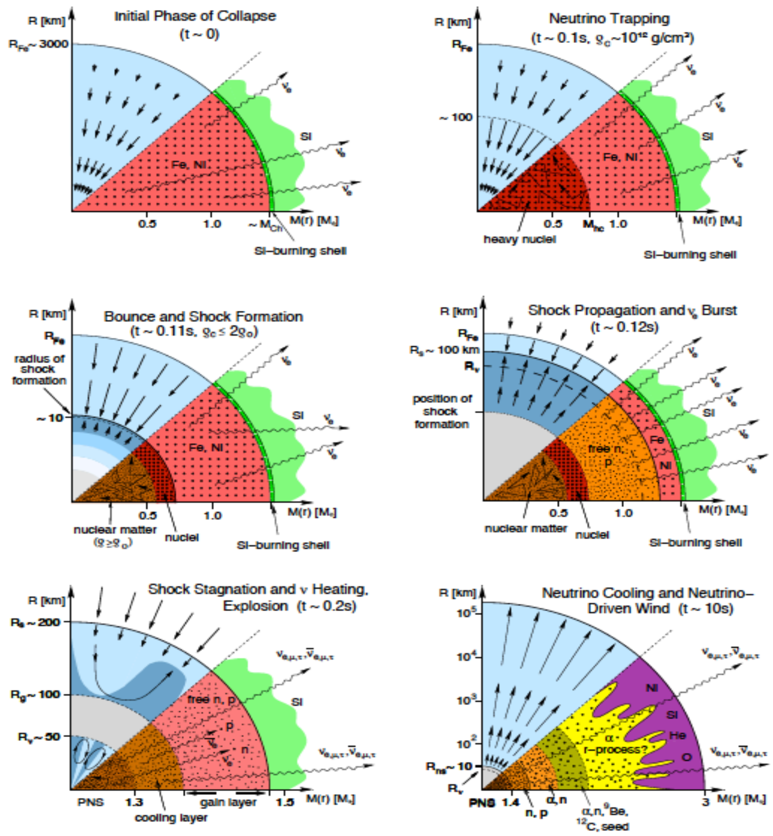
On the way to explosion

- Oxygen burning goes very fast (~2 weeks) Si even faster ~1 day.
- Photon energy leaks out very slowly (cross sections for interaction very large), neutrinos escape rapidly (during final collapse opacity high even for neutrinos)-
- not understood how the burst of neutrinos transfers its energy to the rest of the star producing the shock wave which causes the star to explode-
  - only 1% of the energy needs to be transferred to produce an explosion, but explaining how that one percent of transfer occurs has proven extremely difficult

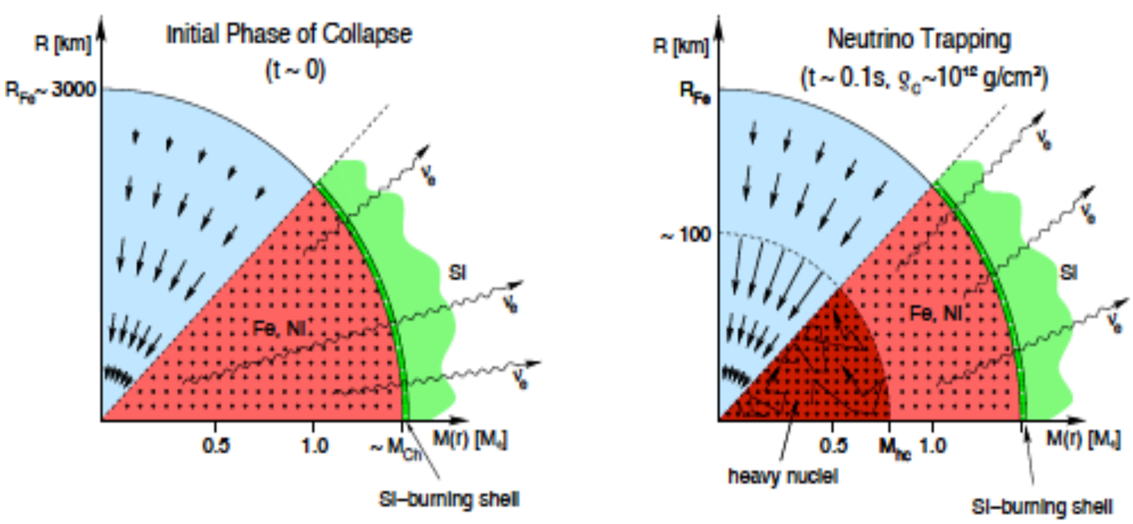
SNII

- Once Fe core reaches Chandrasekar mass electrons are relativistic, and unstable to gravitational collapse.
- Core temperature extremely high- elements photo-disintegrate; this lowers pressure increasing runaway (R+B pg 129-130)
- Core collapses (v~r) and outer parts of star fall in supersonically
- ***Then things get hideously complicated ...***

- Present understanding of explosion of massive star (Janka et al 2007)
- importance of hydrodynamic instabilities in the supernova core during the very early moments of the explosion



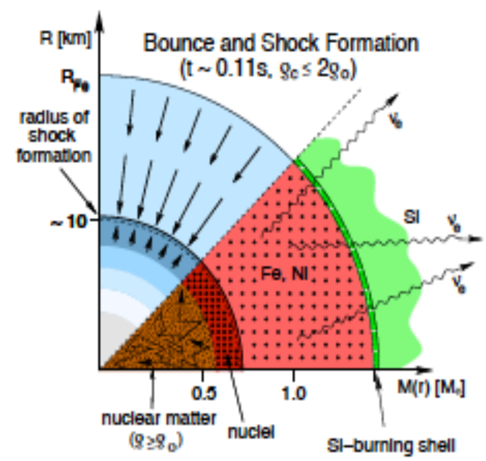
SNII Snapshots over the first 0.10- sec

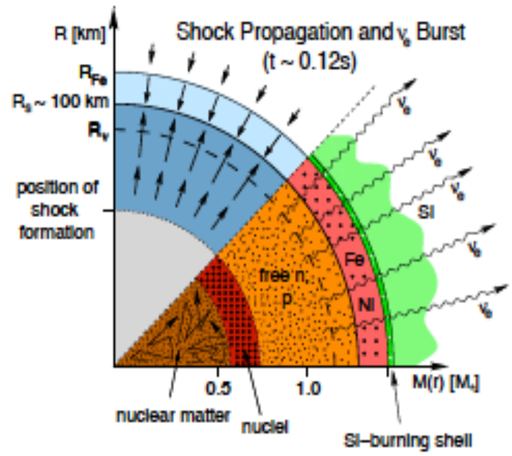


Left side of panel shows velocities
Right side the elements and neutrinos (ν)

0.1-0.12 Secs

- infall and neutrino burst





0.2-10sec

- Start of outflow