Explosive Nucleosynthesis-Type IIs

(Details see 13.1.4 of Longair)

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

'α' products

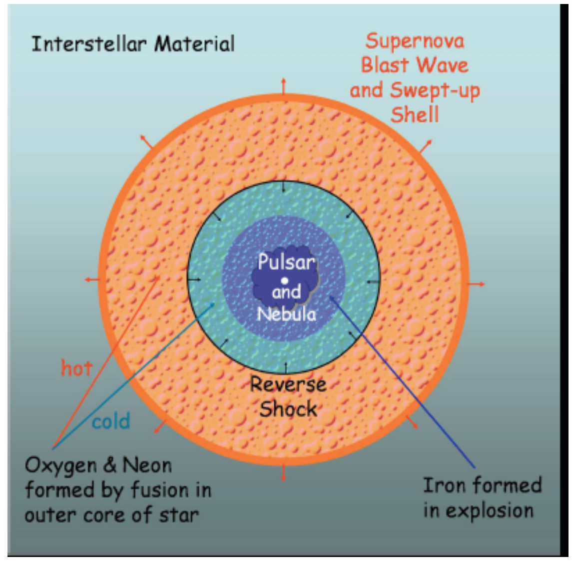
C burning produces O, Ne, Mg, etc
T ~ 2 x 10^9 K

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

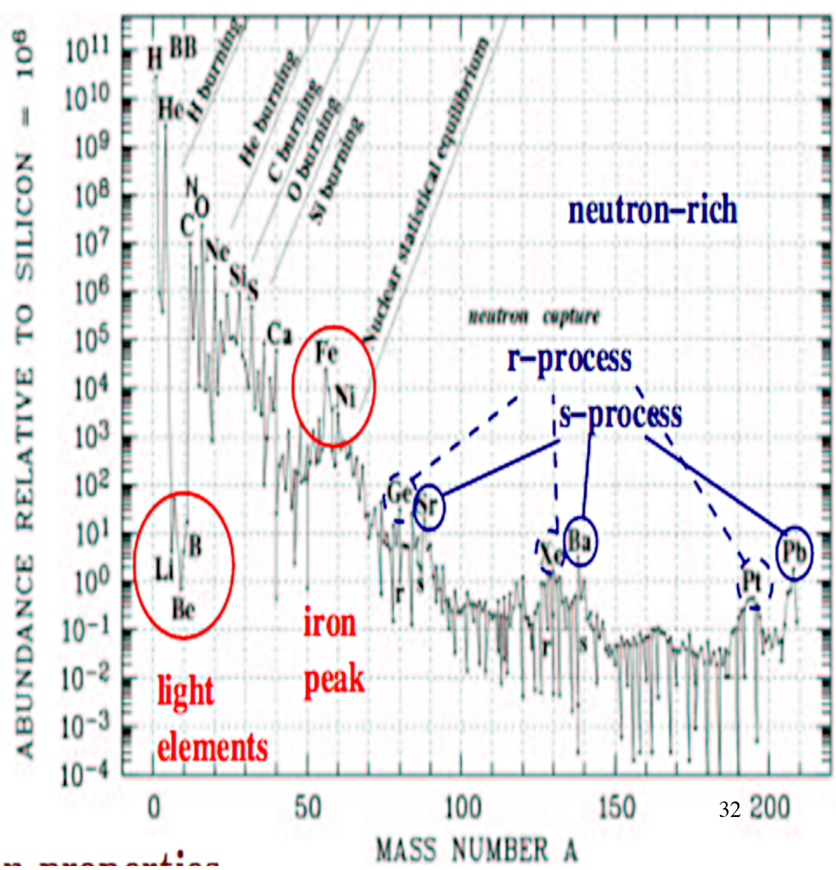
stops at Fe



- Thermonuclear burning changes the composition of the hottest regions of stars.
  - Diffusion of nuclei in the stellar plasma is too slow to remove gradients.
- heavier elements are more difficult

to form because of their larger Coulomb barrier-require higher energies(temperature)

during nuclear burning



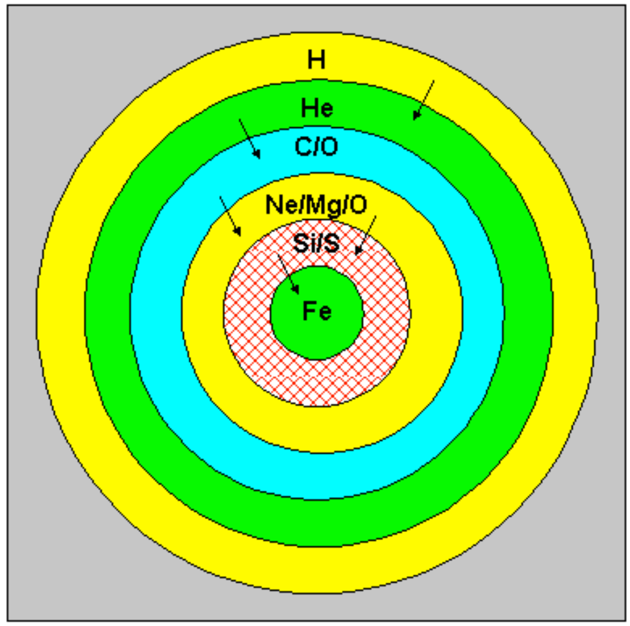
II/Ib/Ic Core-Collapse of Massive Progenitor

- Massive progenitor core forms neutron star or black hole

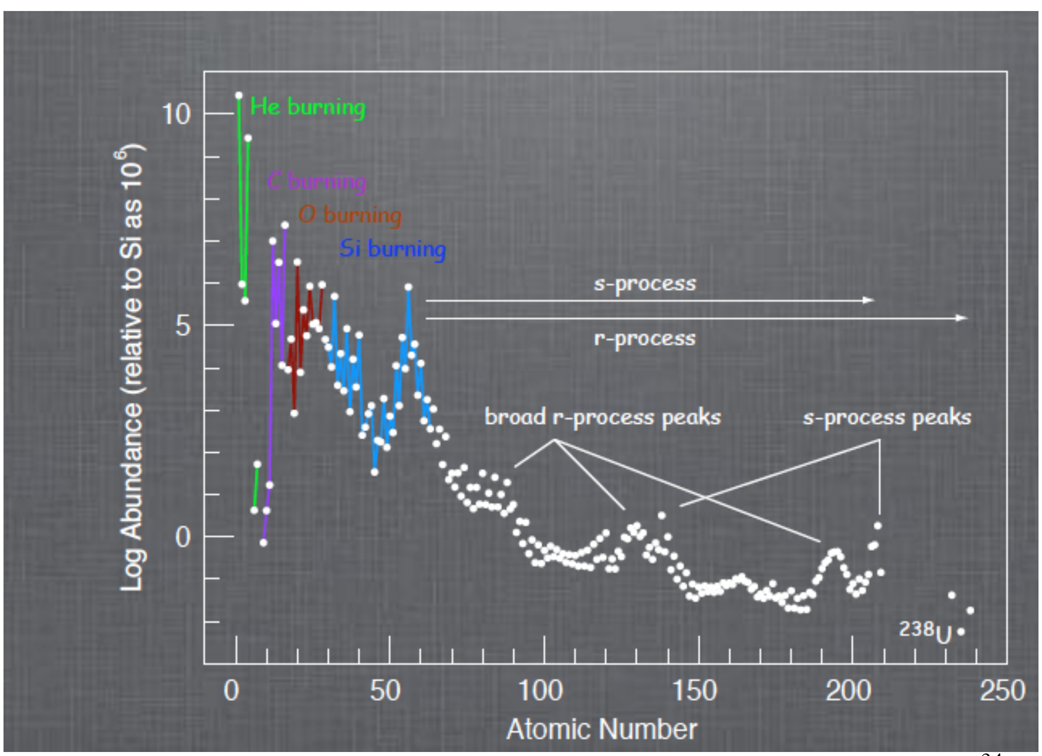
- Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled

- **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

Supernova Explosions



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



Physics of SN Explosions
(Woosley and Weaver 1986 Ann Rev Astro Astrophy 24,205

- Mass range for Type II SN bounded at lower end by most massive stars that can become white dwarfs ($8M_\odot$) and at upper by the most massive stars that can exist.
- Supernova physics relates some of the most complicated physical processes from the explosion mechanisms to nucleosynthesis, radiation transport, and shock physics
- SNe II are the main producer of O,Ne etc in the universe. Their progenitors have short life times, e.g. massive stars which become core-collapse supernovae.

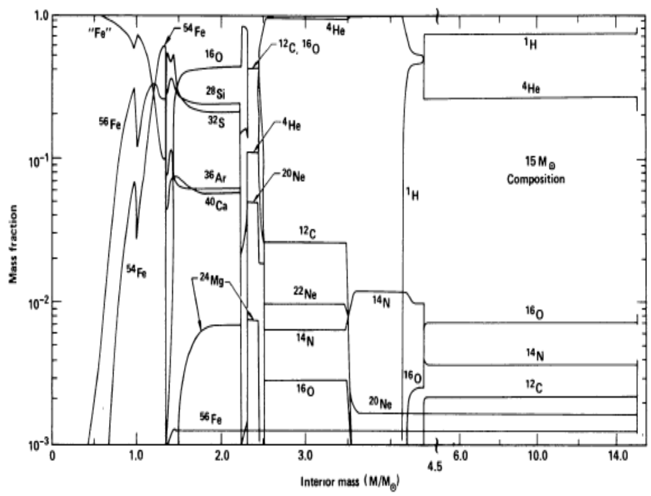


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge

Distribution of material in pre-supernova $15M_\odot$ star- notice the layer cake type distribution

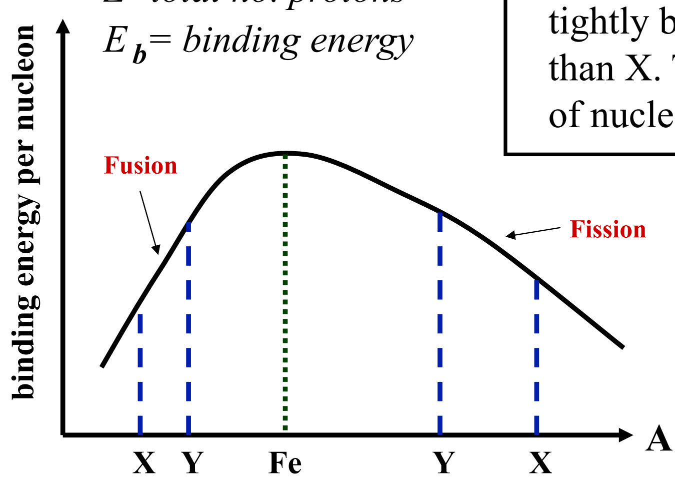
Binding energy of Nuclei - why stellar burning stops generating energy

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



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

SNIIa
see sec 4.2.3 of R+B

- $E_{kinetic}$~10^{51} erg<<$E_{binding}$~$3x10^{53}$
- Very difficult to make them explode in computer models

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)
- 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 ...*

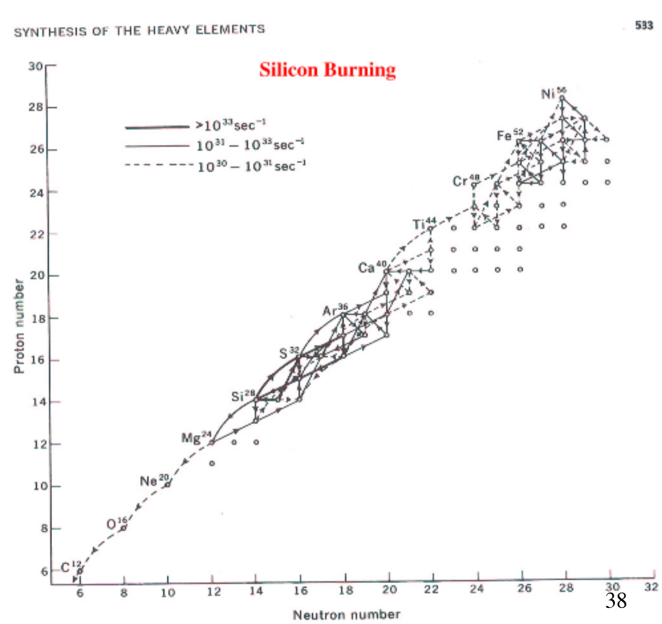
Complex Chain

- Schematic of the products and processes in Si 'burning"
  - all reactions occur in both directions (i.e. forward and

reverse reaction)

abundance pattern approaches nuclear statistical equilibrium (NSE)

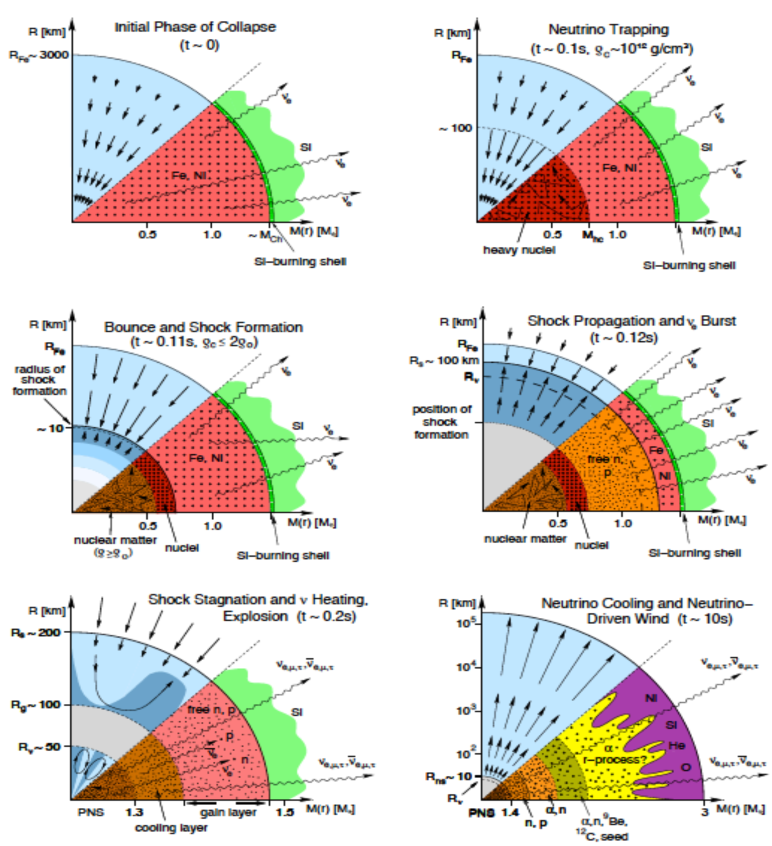
Synthesis of Si



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.

- 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



- Neutrino emissivity
  Cardall astro-ph 0701831
- Because of their low interaction cross sections neutrinos escape rapidly
- Photons bounce around a lot and take days to escape

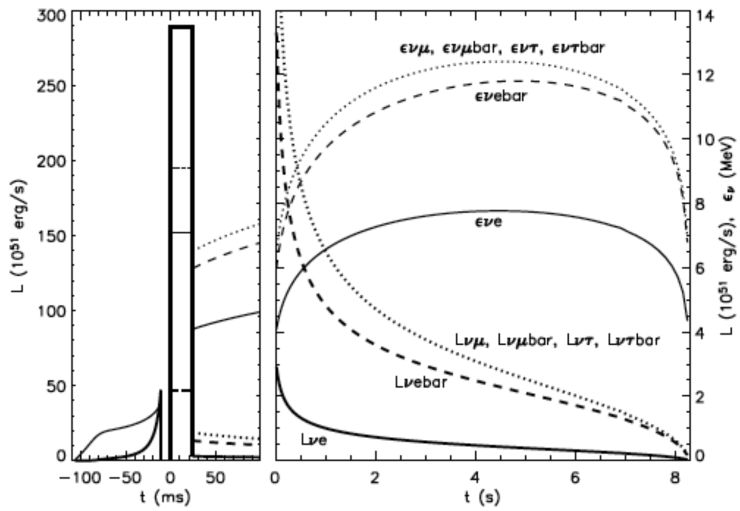
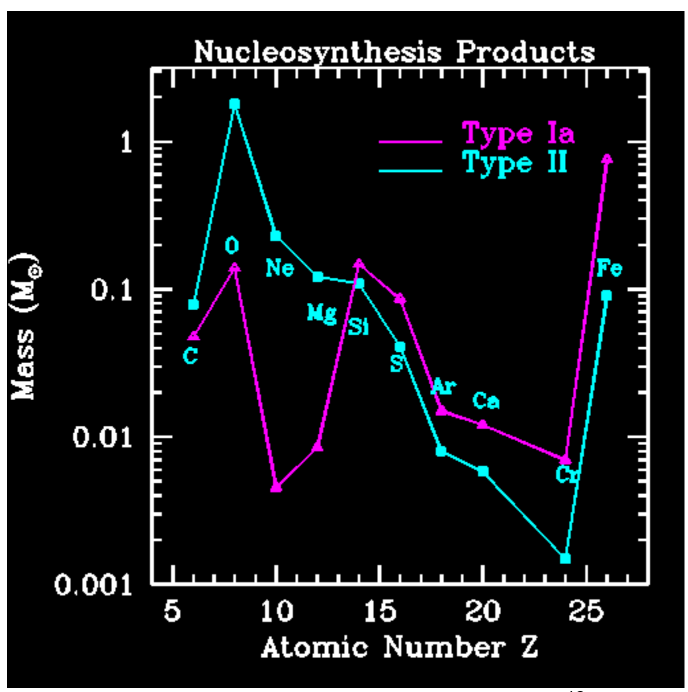


Figure 2. Crudely estimated neutrino luminosities (thick) and characteristic energies (thin). Note the change in time and luminosity (but not energy) scales between the left and right panels. The left panel is a close-up of infall and bounce at $t = 0$.

Elemental Production in Type Is and IIs

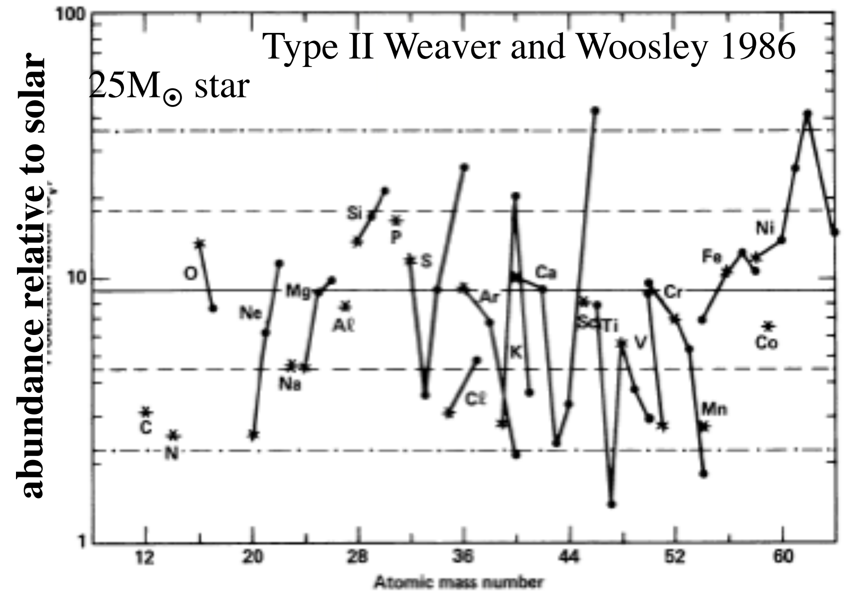
- To simplify
  - Type Is produce mostly Fe and a little Si and S
  - Type IIs produce O and α+O e.g. add a α particle to O^{16}
  - To get 'solar' composition need to add the sum of the two 'just right' and have the 'right' number of each SN type over cosmic times



Examples of Detailed Yields

Different SN of different intial mass (Type II) have different yields.

Net elememtal production due to type IIs requires summing over the initial mass function



igure 3 Isotopic nucleosynthesis in a 25-$M_\odot$ explosion. Final abundances in the ejecta are lotted for isotopes from ^{12}C to ^{64}Ni compared with their abundances in the Sun (Cameron

Detailed Yield for a SNIa model

Abundances are relative to solar

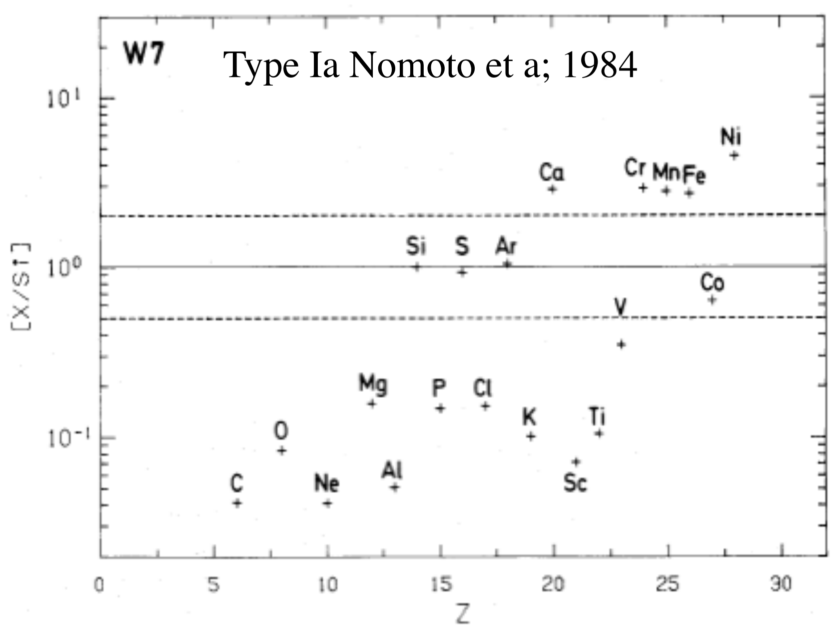


FIG. 10.—The abundances of elements relative to the solar values (W7). The ratio is normalized to Si.

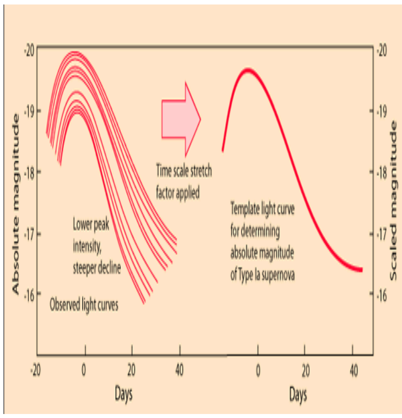
Type I SN and Cosmology

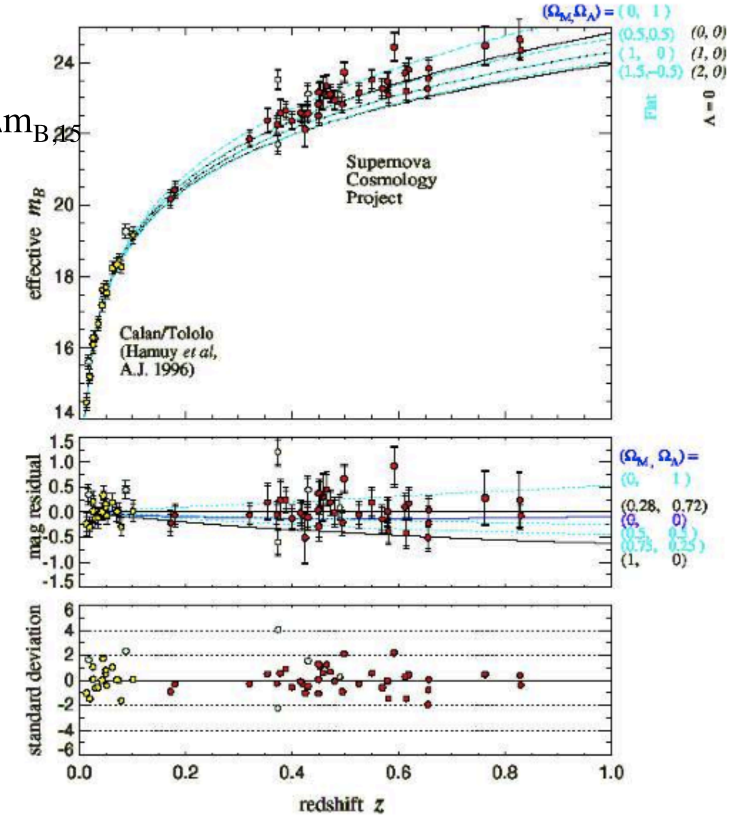
- how old is the universe, how fast is it expanding, how much material and of what type is in it, what is its fate?
- Need to determine the relationship between distance and redshift
  - Redshift ('z') is the measure of Doppler shift by the expansion of the universe- (1+z)~v/c
  - In General relativity there are 3 distances of relevance
  - The proper distance D_P that we measure to an object is the distance we would get if we were to take a snapshot of the universe and directly measure (e.g., pace off) the distance between where we are and where the object is, at some fixed time
  - .•The luminosity distance D_L is how far an object of known luminosity L (measured in energy per time) would have to be in Euclidean space so that we measure a total flux F (measured in energy per area per time), $D_L = \mathrm{sqrt}(L/(4\pi F))$.
  - The angular diameter distance D_A is the distance an object of known size l (say, one meter) would have to be in Euclidean space so that it appeared to be its measured angular size θ;

More Cosmology

- Each of these distances depends on cosmological parameters * in a different way
  - * in classical cosmology one has the Hubble constant (H(z))- how fast the universe is expanding at a given redshift
  - The density of the universe $-\rho-\Omega_M$
  - And now the 'cosmological constant' Λ
- Back to type Ia SN-
  - It turns out (when I say that it means a huge amount of work by many people over many years- Nobel prize 2011) that type Ia SN are 'standardizable candles' - one can use their brightness, color and speed of decay to determine an 'absolute' luminosity to ~10% accuracy.
  - `With a measured redshift and absolute luminosity one can get the luminosity distance

$$M_{B,max} = -19.3 + 5\,(\log H_{60})$$
$$M_{B,max} = -21.726 + 2.698\Delta m_{B,15}$$





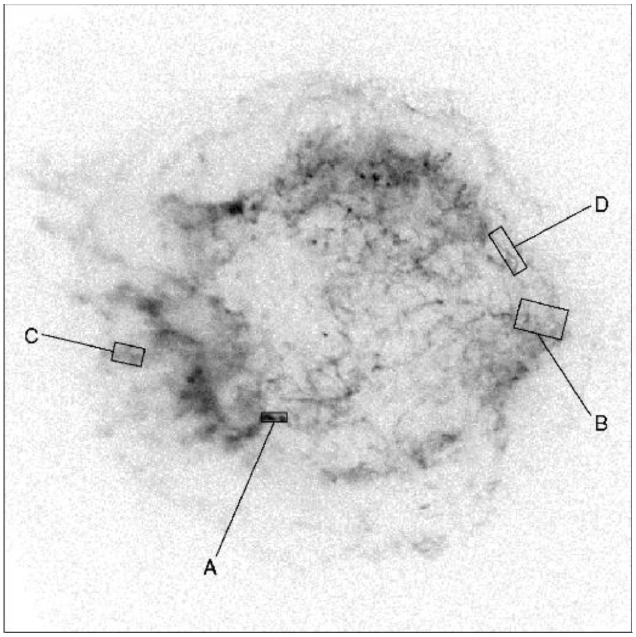
Perlmutter 2003

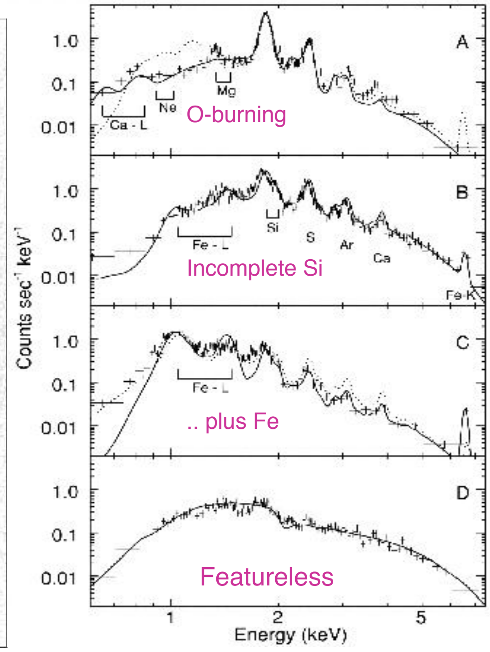
X-ray Emission from Supernova Remnants

Thermal Emission
- characterized by electron temperature, ionization timescale, element abundances
- primarily bremsstrahlung continuum
- collisionally excited emission lines

Nonthermal Emission
- blackbody or power law from pulsar/neutron star if present (across electromagnetic spectrum)
- synchrotron emission from electrons accelerated at the shock (usually radio, sometimes up to X-rays)
    - some SNR are dominated by NT emission (Crab-like, plerions)

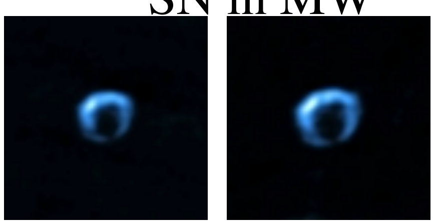
Cassiopeia A: Observations of Explosive Nucleosynthesis



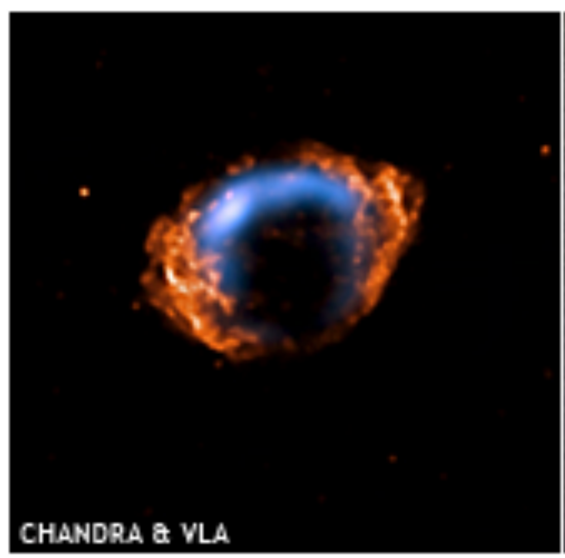


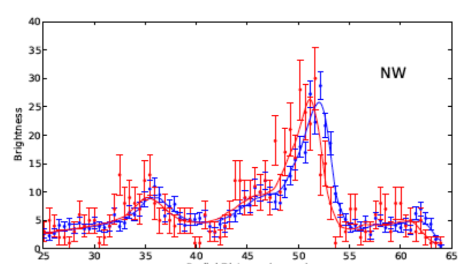
(Hughes et al. 2000 ApJ, 518, L109)

G1.9+0.3 Most Recent SN in MW



- 2 radio images separated by 13 years showing expansion and implied explosion epoch 140 years ago
- Not noticed because near galactic center, region of high extinction
- A simple uniform-expansion model describes the data well, expansion rate of 0.642% ± 0.049% yr-1 Without deceleration, the remnant age would then be 156 ± 11 yr, G1.9+0.3 is the only Galactic SNR increasing in flux, with implications for the physics of electron acceleration in shock waves.





Schematic Structure of Young SNR

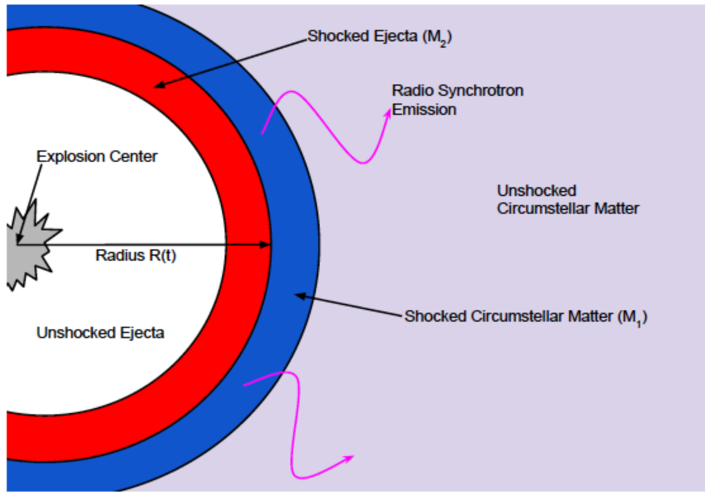
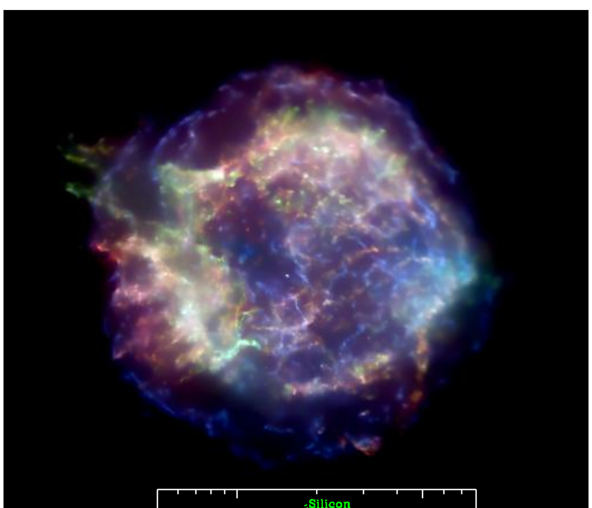
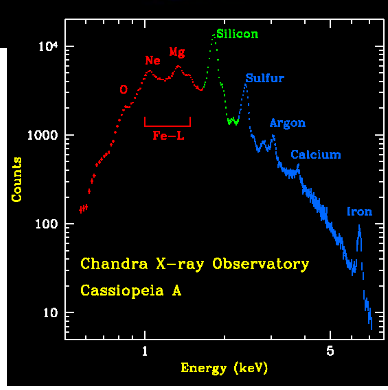


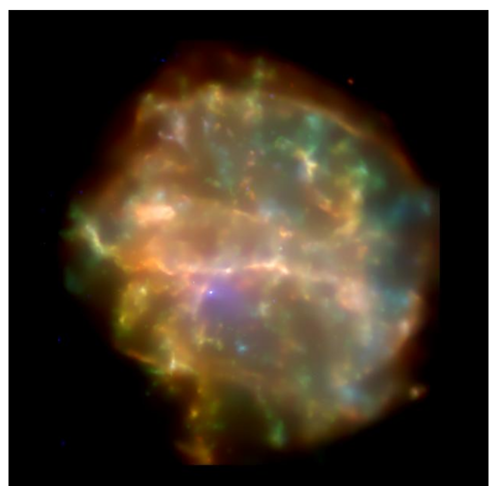
FIG. 1.— Schematic representation of the model used to predict the size and flux density evolution of young supernova remnants.

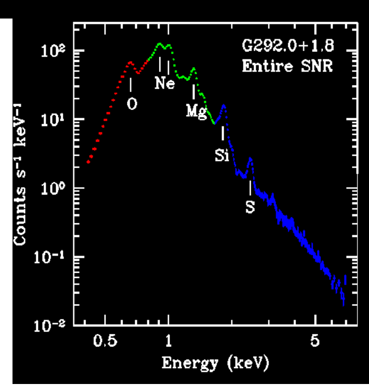
Chakraborti et al 2015



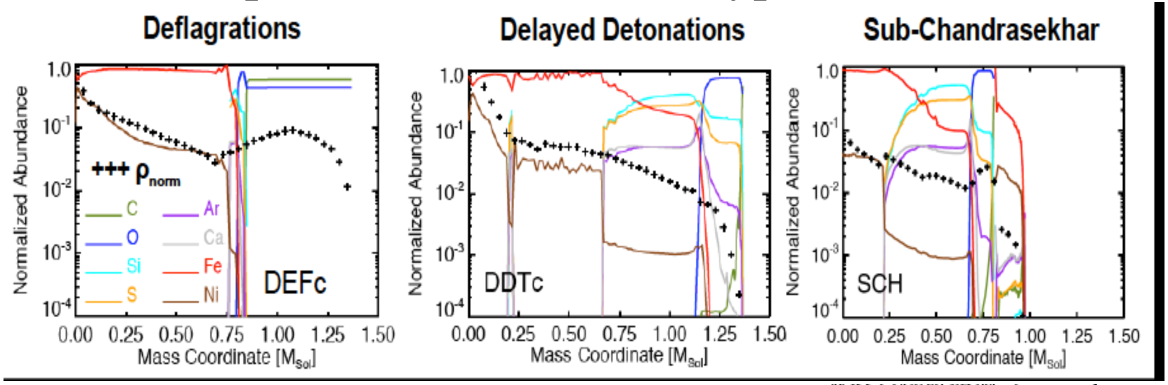


- Type Ia produce mainly Fe -- low O/Fe ratio.
- Type II produces: mainly O -- high O/Fe





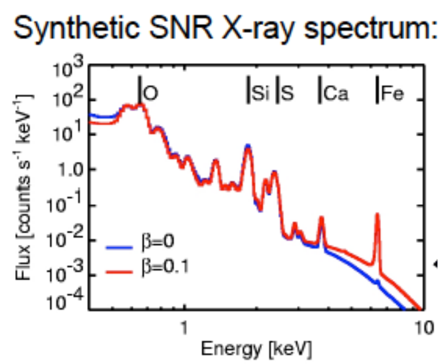
Examples of Yields from 3 Type Ia SN Models



- Check of these yields against analysis of chemical abundance of SNR favors Delayed detonations.

C. Badenes et al 2006 fit in Tycho SN for $E_{kinetic}=1.16\cdot10^{51}$ erg,

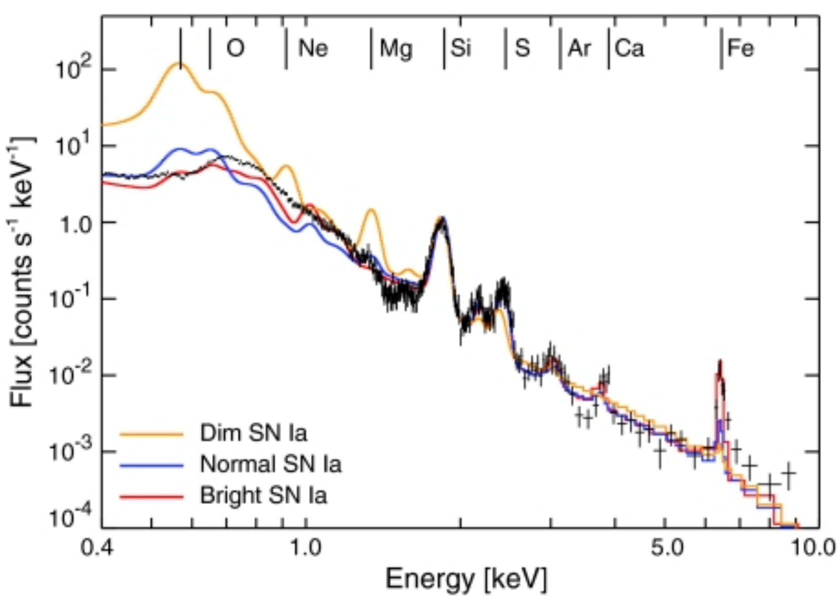
- $M_{Fe}=0.8\ M_\odot$, $M_O=0.12\ M_\odot$, $M_{Si}=0.17\ M_\odot$, $M_S=0.13\ M_\odot$, $M_{Ar}=0.033\ M_\odot$, $M_{Ca}=0.038\ M_\odot$



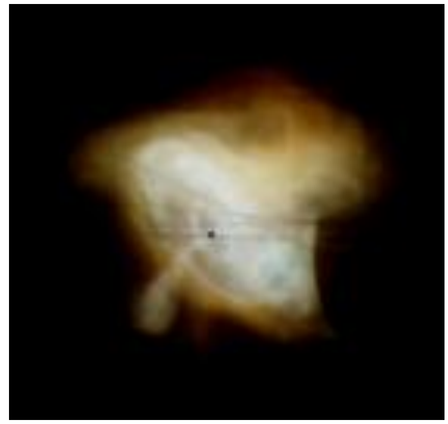
Comparison of Yields From Different Type Ia Models with X-ray Spectral data

C. Badenes

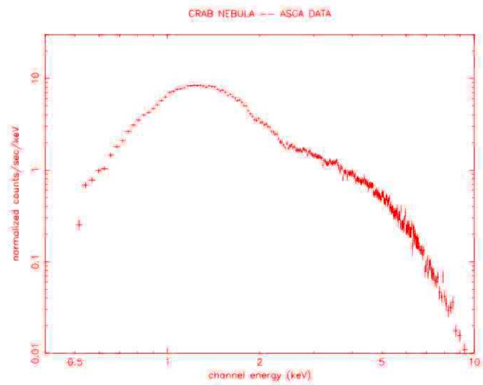
Proc Natl Acad Sci U S A. 2010 107(16): 7141–7146.



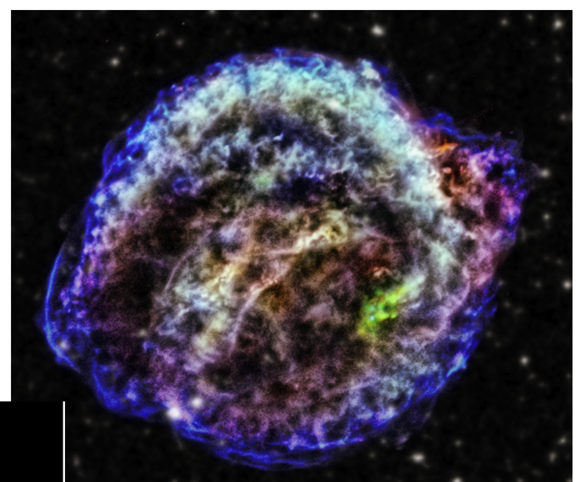
Non-Thermal Remnants



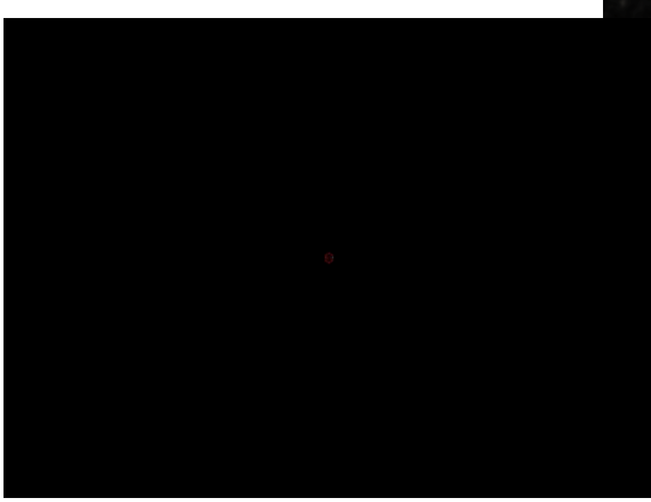
- Sometimes the explosion does not seem to produce lots of hot gas and instead one detects synchrotron emission from relativistic particles produced by a central Neutron star
  - these are called plerions or 'Crab-like' SNR.
  - in 'thermal' remnants there can be synchrotron emission from shock accelerated electrons in other SNR



- Kepler SNR- remnant of a type Ia
- Chandra analysis indicates that the Kepler supernova was likely triggered by an interaction between a white dwarf and a red giant star.



x-ray and optical image



Kepler SNR

- Fe Emission in the x-ray band in blue, IR emission due to dust in pink.
- Notice strong asymmetry in Fe emission

Kepler SNR

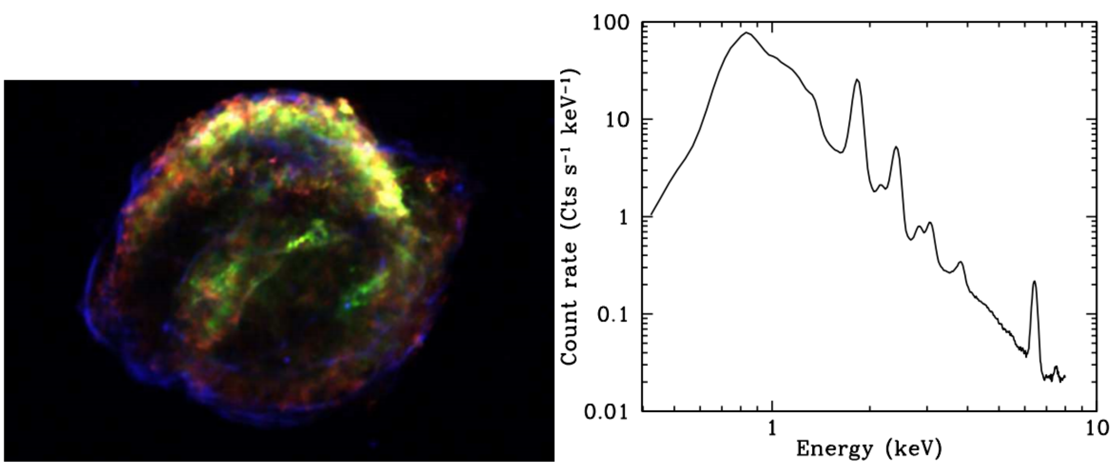


Figure 24: Left: *Chandra* image of Kepler's SNR, with red indicating Si-K α emission (1.75-1.95 keV), L emission (0.8-1.6 keV), and blue continuum emission (4-6 keV). The image is based on a deep, 750 ks,

- Vink 2012

Elemental Creation Processes 13.1.4, 2.7.2

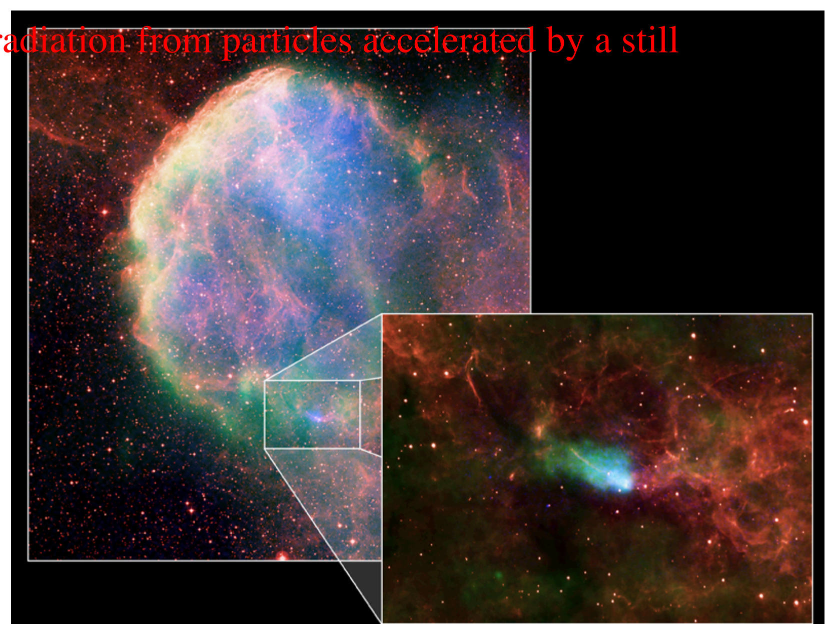
- The S-process is believed to occur mostly in asymptotic giant branch stars; occuring over time scales of thousands of years, passing decades between neutron captures. Producing heavy elements beyond Sr and Y, and up to Pb,

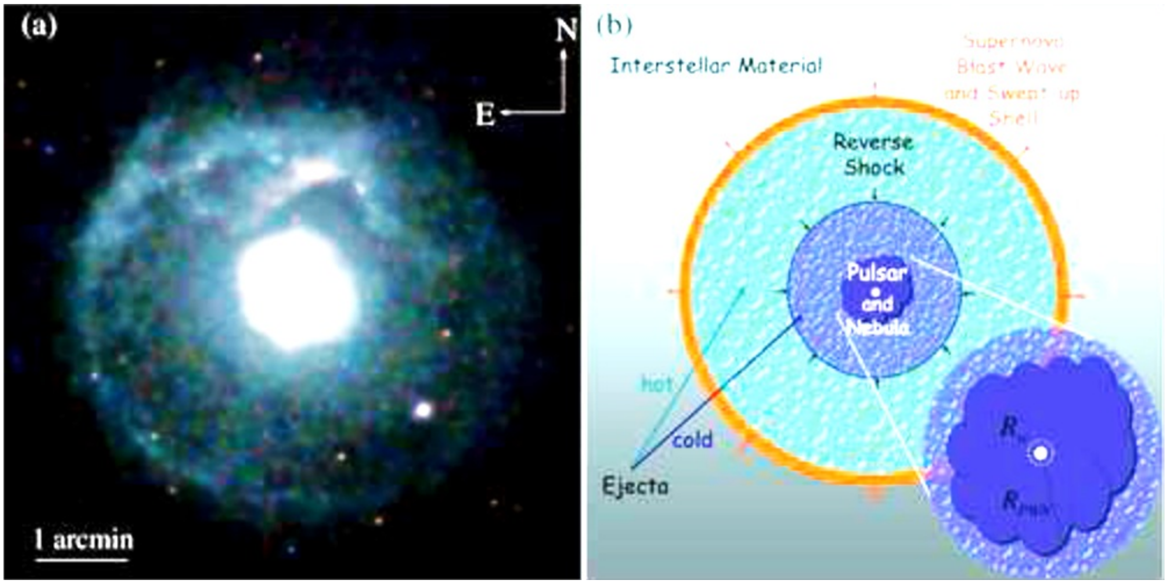
- R-process creating conditions in which elements of the iron group are irradiated by neutrons which are successively added to these nuclei before they undergo β decays. As a result the neutron excess found in heavy elements beyond the iron group can be synthesised, but it requires an environment in which a large flux of neutrons is created.

believed to occur over time scales of seconds in explosive environments (core-collapse supernovae). Radioactive isotopes must capture another neutron faster than they can undergo beta decay in order to create abundance peaks at germanium, xenon, and platinum

Combining Bremmstrahlung and Synchrotron Radiation

- In some supernova remnants one sees both processes at work
  - Bremmstrahlung from electrons that are shock heated by the SN blast wave +line emission
  - Synchrotron radiation from particles accelerated by a still active pulsar





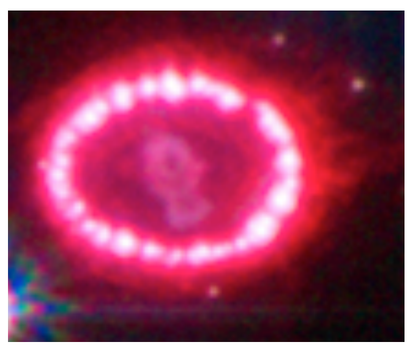
- Composite SNR G21.5- 0.9
  (Matheson & Safi-Harb 2005).

Free expansion phase

- Independent of the nature of the SN explosion
- No deceleration
- Evolution only depends on E_o the initial energy.
- Velocity of ejected shell ~ 10^4 km s^{-1}
- Mass swept-up small until $M_{sN} \sim M_{eje} \sim 1\ M_\odot$

===> R_s = 250 yrs $M_{eje}{}^{5/6}\ n_1{}^{-1/3}\ E_{51}{}^{-1/2}$

SNR enters then its Adiabatic Phase



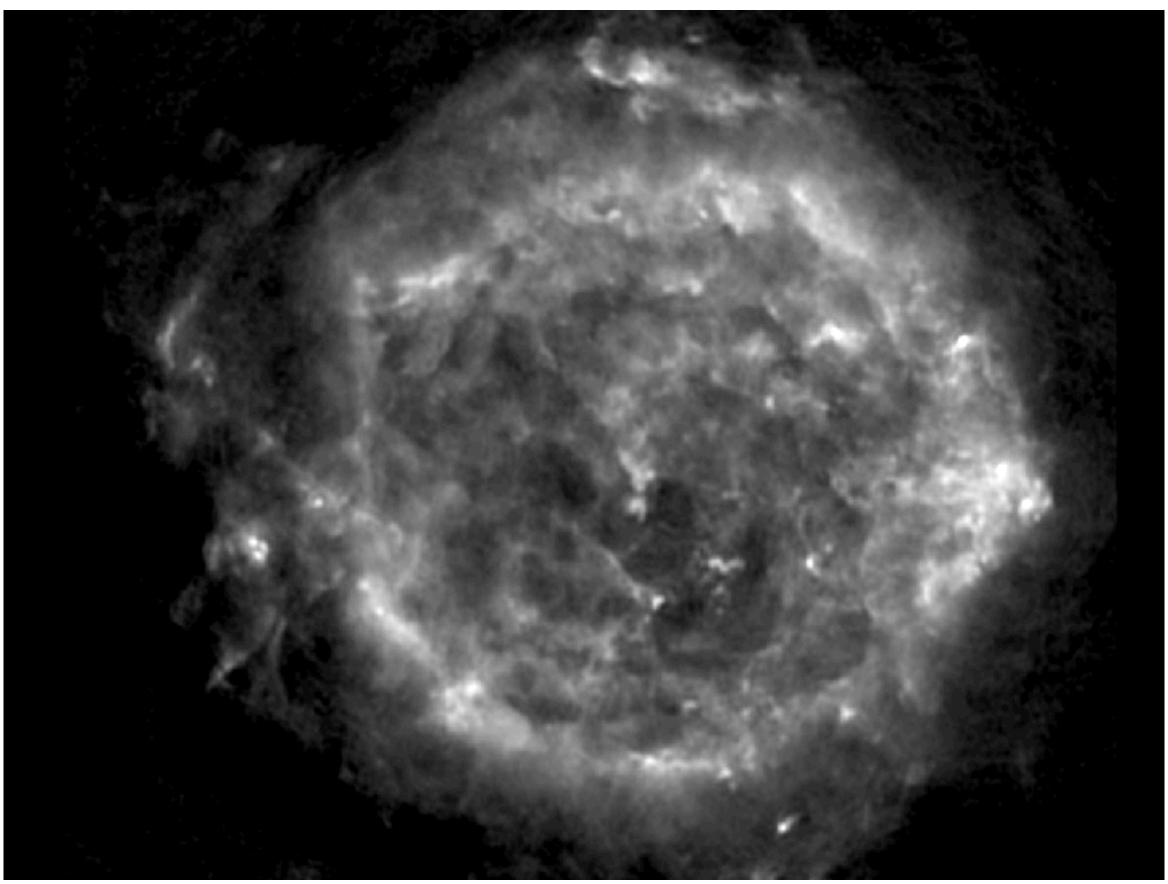
1987A HST in 2010

Remnant Evolution

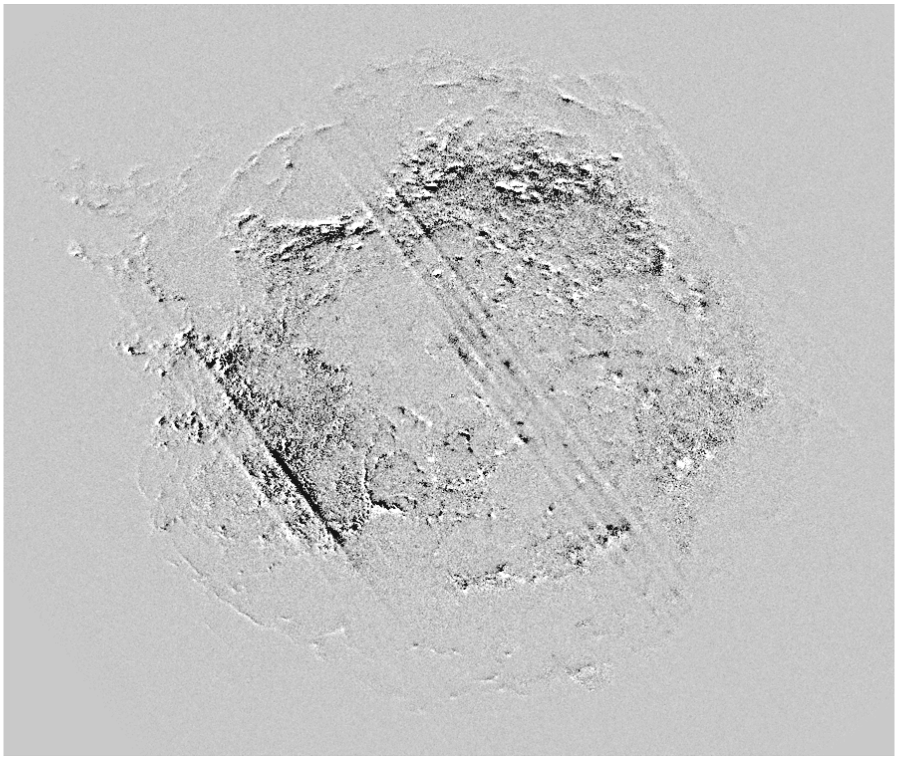
Free Expansion
Ejecta expand without deceleration r~t (see movie Rudnick et al., 1996, BAAS, 188.7403.) - Core collapse SN have initial velocities of ~5000km/sec and several $M_\odot$ of ejecta , SN Ia ~10,000 km/sec, ~1 $M_\odot$

Adiabatic (Sedov-Taylor, or "atomic bomb")
Ejecta are decelerated by a roughly equal mass of ISM- $r \sim t^{2/5}$
Energy is conserved-(Cooling timescales are much longer than dynamical timescales, so this phase is essentially adiabatic e.g. net heat transfer is zero).
Evolution of density, pressure is self-similar
Temperature increases inward, pressure decreases to zero

Radiative
Dissipation of remnant energy into ISM
Remnant forms a thin, very dense shell which cools rapidly
Interior may remain hot- typically occurs when shock velocities vs drop to around 200 km/sec

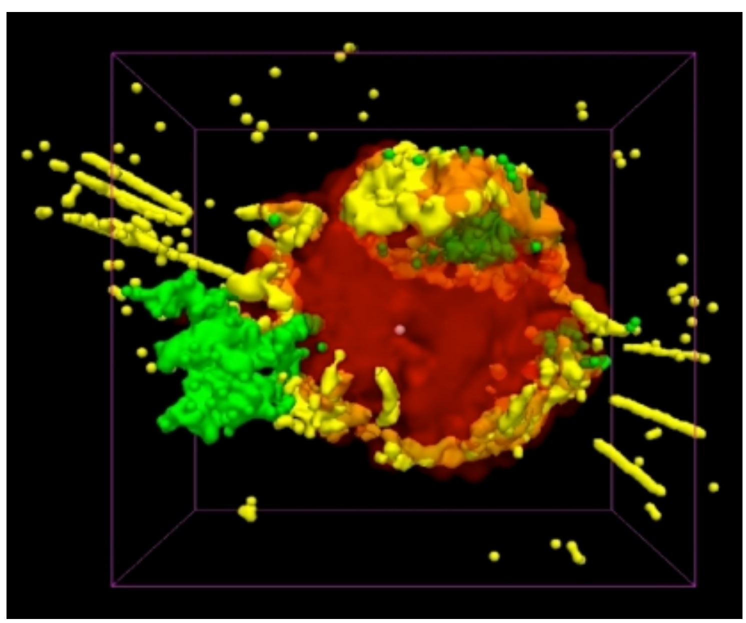


Cas-A Difference of X-ray Images Taken 2 Years Apart Delaney e al 2005



3-D View of Cas-A

- green is X-ray emitting Fe; yellow is X-ray, optical and infrared emitting Ar and Si;
- red is infrared emitting unshocked ejecta;
- the pink dot represents the compact object.



T. Delaney