Todays Lecture

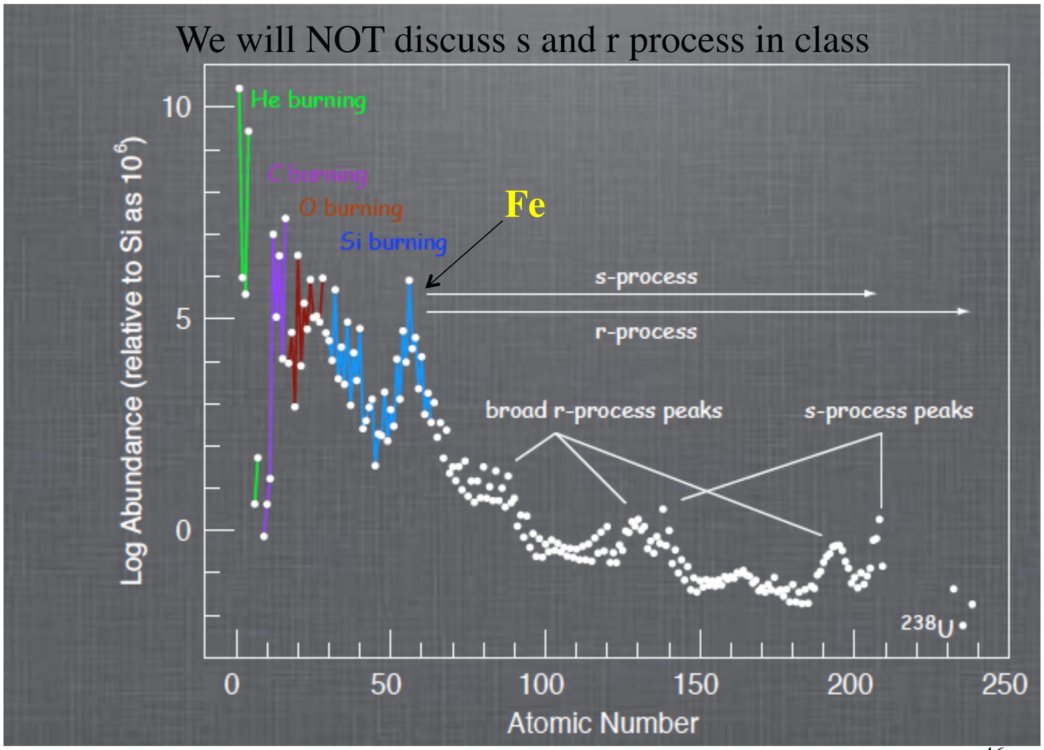
- Element Generation
- Supernova 'light curves'
- Start of SNR

This material WILL NOT be on the exam.

The exam will be qualitative in nature, and you will not need to know any formulas, but will need to understand concepts.

There will be choices of questions to answer

Element production in type II (generic)



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.

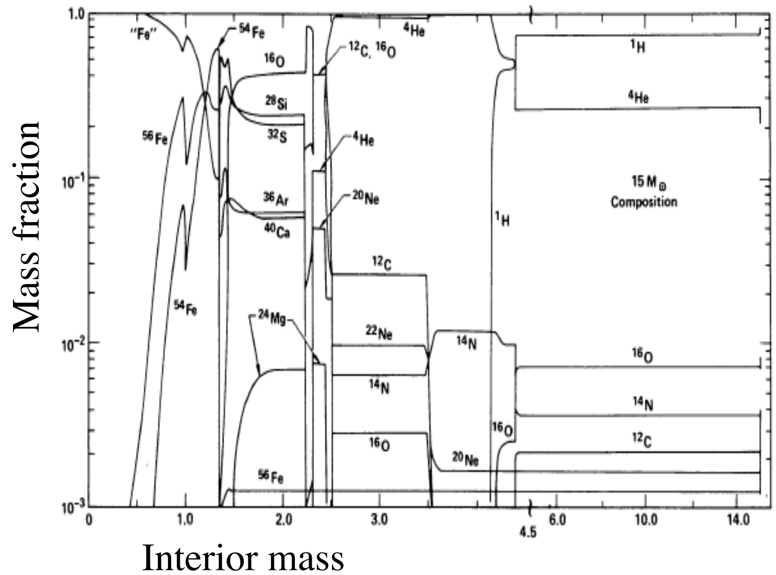


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge

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

Physics of SN Explosions

(Woosley and Weaver 1986 Ann Rev Astro Astrophy 24,205

- Supernova physics relates some of the most complicated physical processes from the explosion mechanisms to nucleosynthesis, radiation transport, neutrinos 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.

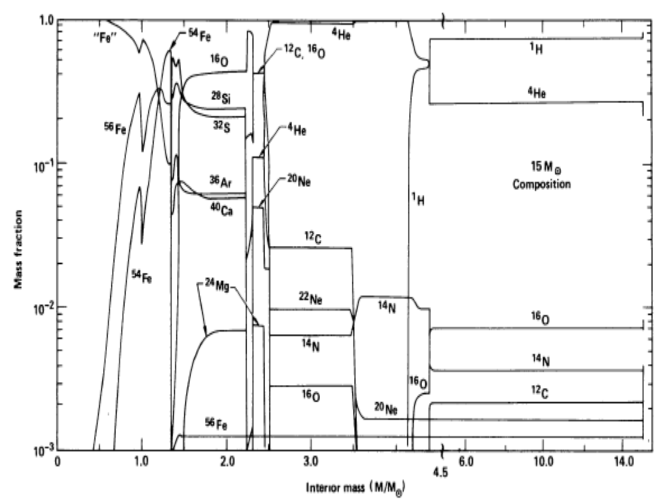


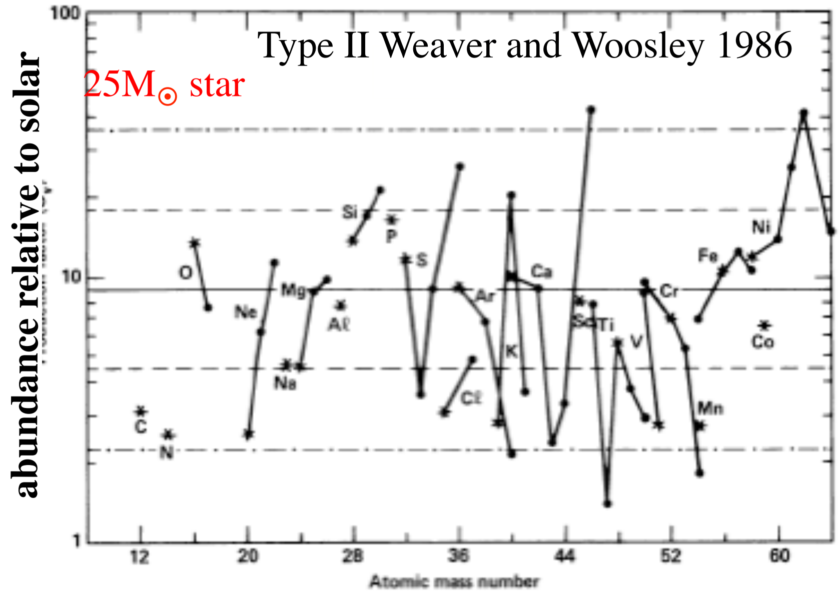
Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge

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

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

How Much Metals are Created as a Function of Stellar Mass

- As the mass of the exploding star increases more metals are created and the ratio of the amount of different elements that are created differs (linear in red)

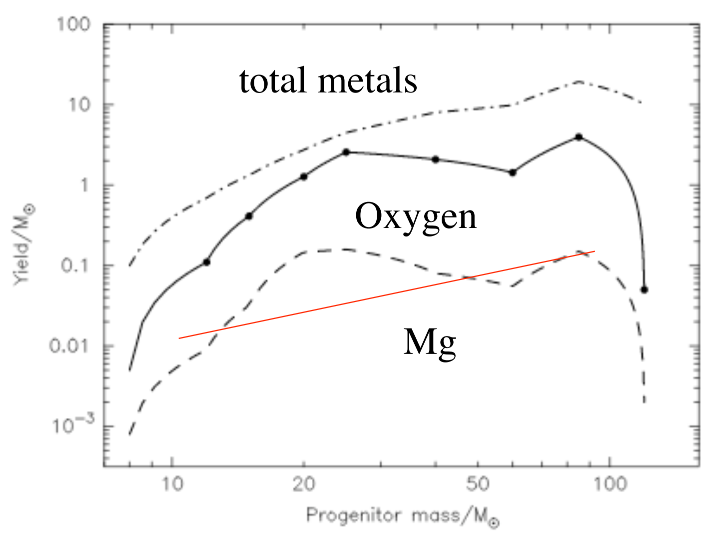
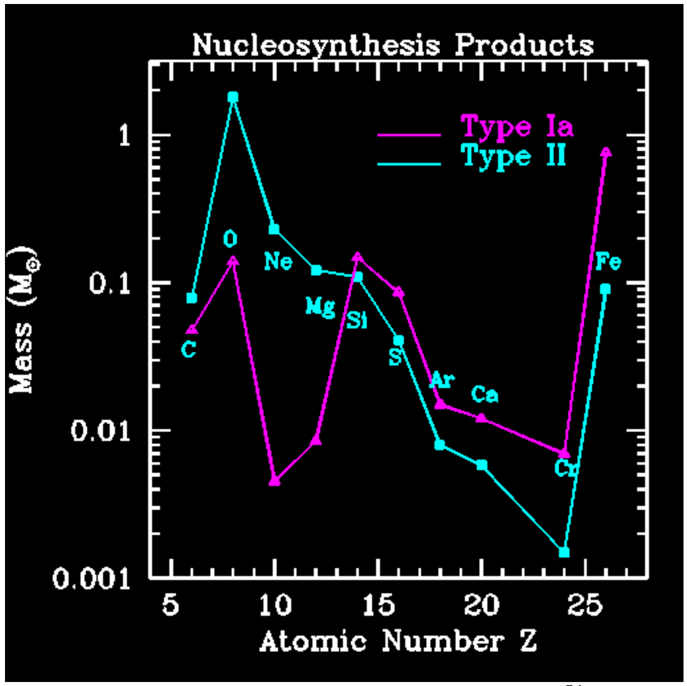


Figure 1. The yields of metals (dash-dot line), oxygen (full line) and magnesium (dashed line) against the initial stellar mass. Metal and oxygen yields

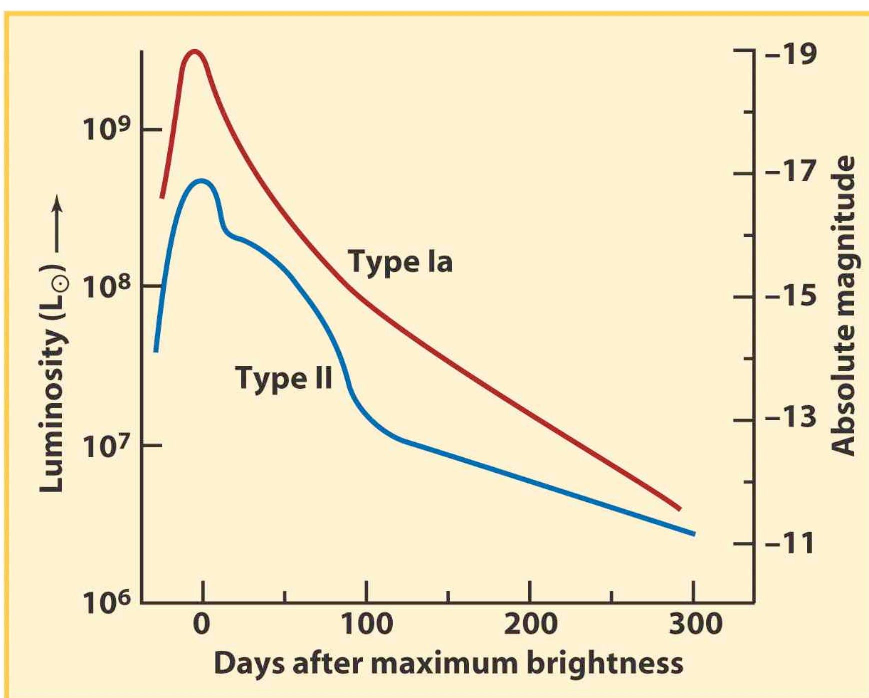
Goodwin and Pagel 2005

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 –graph is for a Saltpeter IMF



- Two classes of light curves



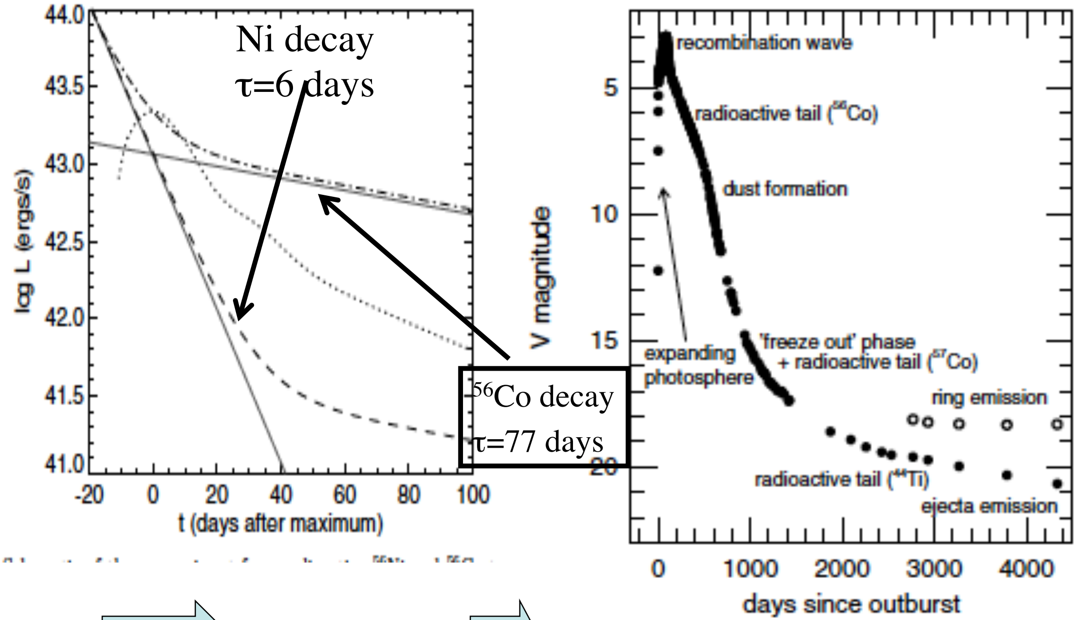
Rosswog and Bruggen fig 4.3

SN Light Curves- Notice Very Different Time scales

Type Ia

Bruno Leibundgut

Type II

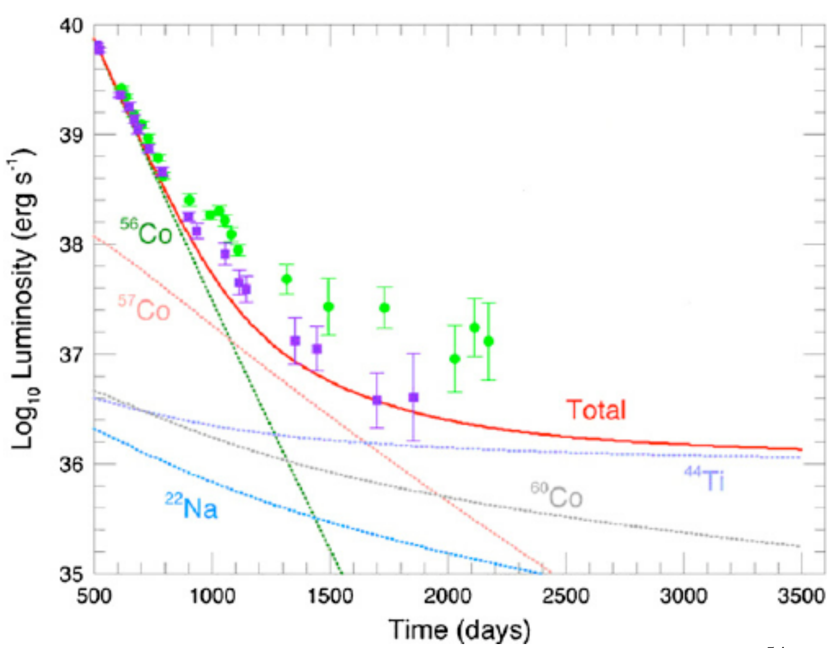


$^{56}Ni + e^- \Rightarrow {}^{56}Co + \nu; {}^{56}Co + e \Rightarrow {}^{56}Fe + \nu$

Fig 13.5 of Longair

SNII Light Curve at Late Times

- purple and green are data points
- Red Line is sum of decay products energy at late times



Radioactive Decay

- Exponential decay $N(t)=N_0 \exp^{-\lambda t}$ where the 'half life", $t_{1/2}$ (the time it takes to reduce the amount to ½) is defined as $t_{1/2}=\ln 2/\lambda$
- If one thinks in magnitudes $dM/dt=1.086\lambda$
- Given Ni half life of 6.1 days gives dM/dt= 0.11 mag/day
- See Handbook of Supernovae pp737-Light Curves of Type II Supernova-. Zampieri

- For first ~1000 days the luminosity is driven by radioactive decay (type Ia)

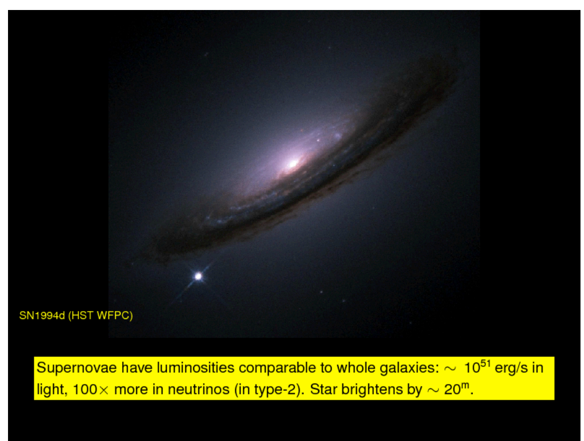
Ni^{56} → Co^{56} → Fe^{56} (77 day 1/2 life)

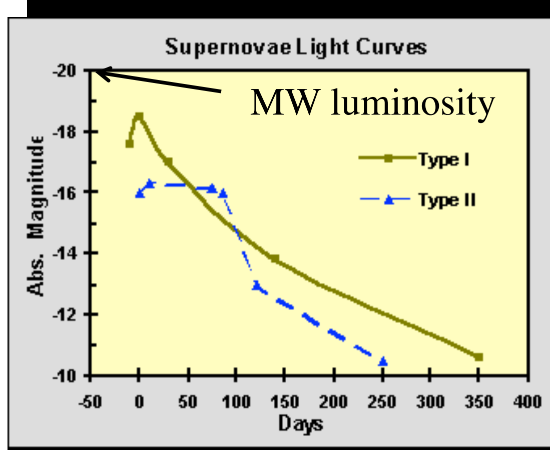
Velocities of gas seen in the optical is ~10^4 km/sec

$E \sim 1/2Mv^2 \sim 10^{51}\, M_\odot v_4^2$ ergs

Luminosity of SN ~ that of the host galaxy- can be seem to z>1

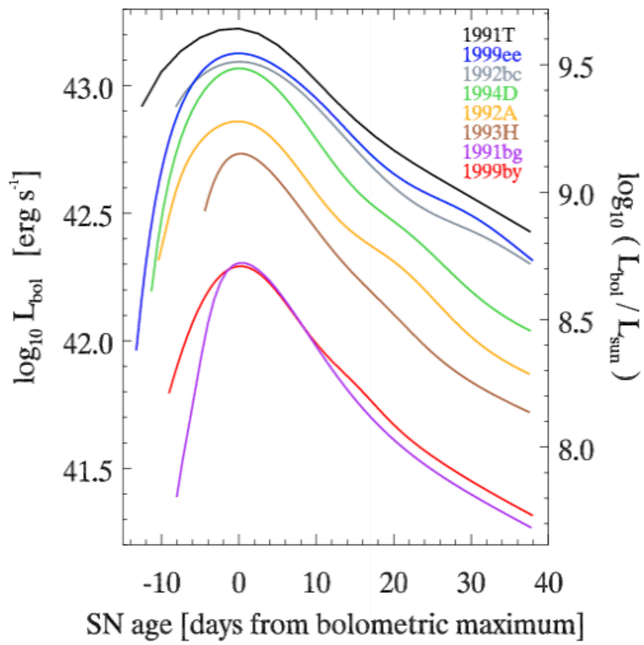
v_4 in units of 10^4 km/sec





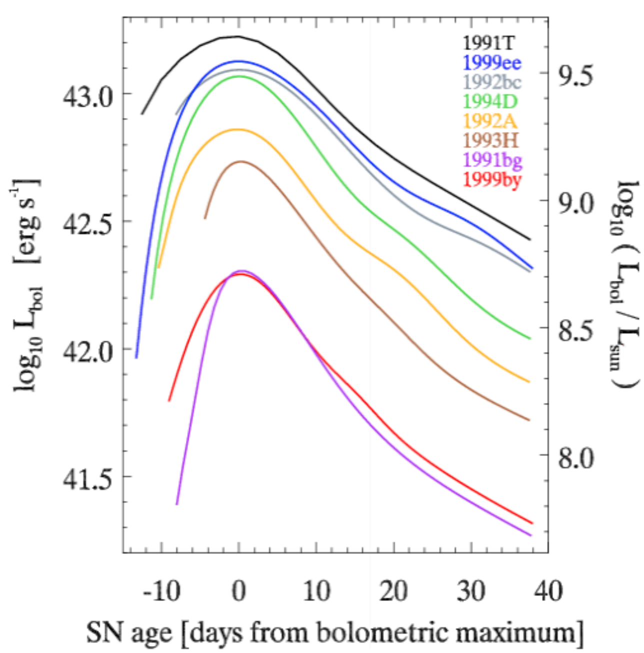
- From total luminosity derive M_{Ni} that has been synthesized and thus the amount of Fe that has been produced.
- SNe Ia :the main producer of iron in the universe. Their progenitors have long life times.

Type Ias

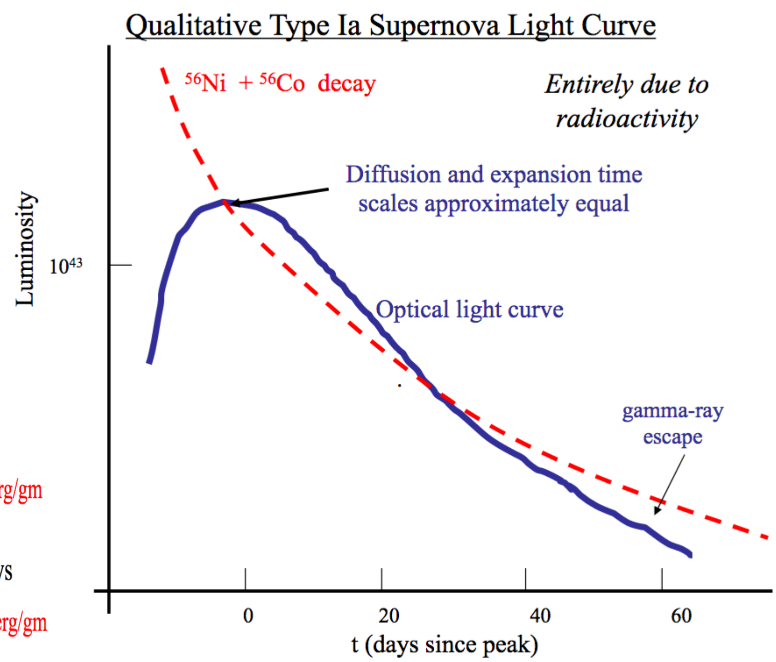


- L_{total}~1.1×10^{50} ergs~ $0.6 M_{\odot}$ of Ni
- Light curves are rather homogenous- suggesting little variation in the nature of the progenitor (?)
  - 2 possibilities
    - merger of 2 white dwarfs
    - or white dwarf collapse due to accretion

Type Ias



- SNIa Light Curve Entirely due to radioactivity
-



$^{56}Ni + e^{-} \rightarrow {}^{56}Co + \nu$ $\quad \tau_{1/2} = 6.1$ days

q = 3.0 x 10^{16} erg/gm

$^{56}Co + e^{-} \rightarrow {}^{56}Fe + \nu$ $\quad \tau_{1/2} = 77.1$ days

q = 6.4 x 10^{16} erg/gm

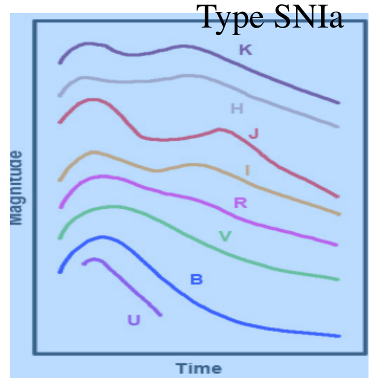
Woosley

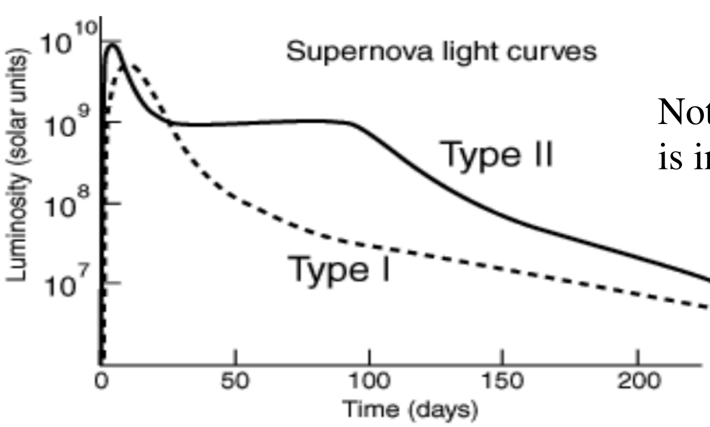
q= energy per gram available from radioactivity

SuperNova Light Curves-http://astronomy.swin.edu.au/cosmos/T/Type+Ia+supernova+light+curves

- Shape and amplitude depends on color (physics of atmosphere and velocity of expansion)
- SN are 'typed' by the amplitude, shape and color of their light curves
- Optical spectra

Type SNIa





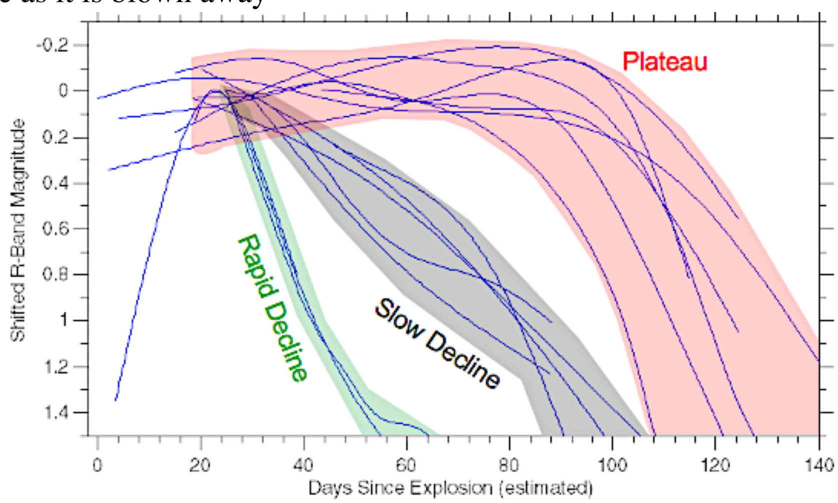
Adapted from Chaisson & McMillan

Notice absolute luminosity is in solar units

SN II

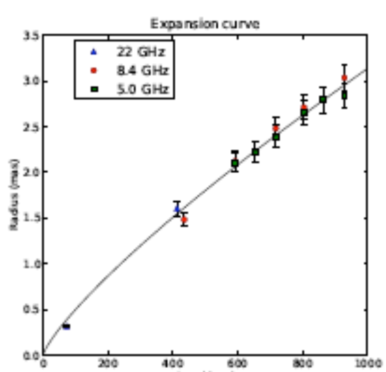
- Wide Variety of Light Curves- assume wide range of progenitors
  - see http://astronomy.swin.edu.au/cosmos/T/Type+II+Supernova+Light+Curves for details
- Type II supernovae - Some show a characteristic plateau in their light curves a few months after explosion

This plateau is due to the energ from the expansion and cooling of the star's outer envelope as it is blown away

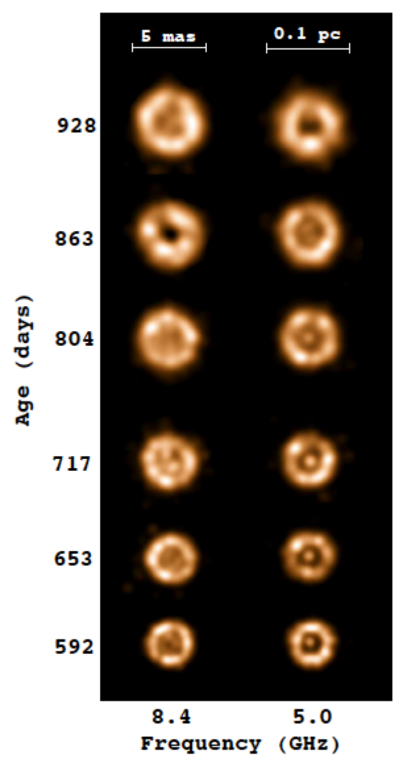


Super Nova and Super Nova Remnants

- Types of Super Nova ✔
- Explosions ✔
- Nucleosynthesis 1/2✔
- Physics of Supernova remnants
- Particle Acceleration
- Cosmology?

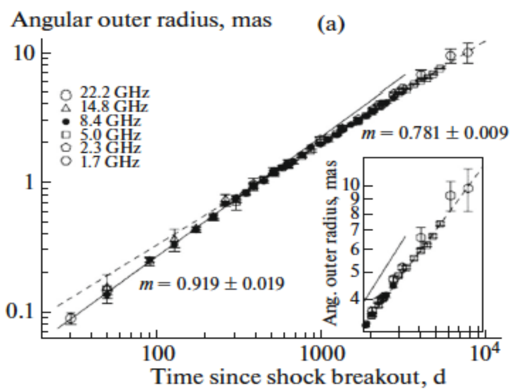


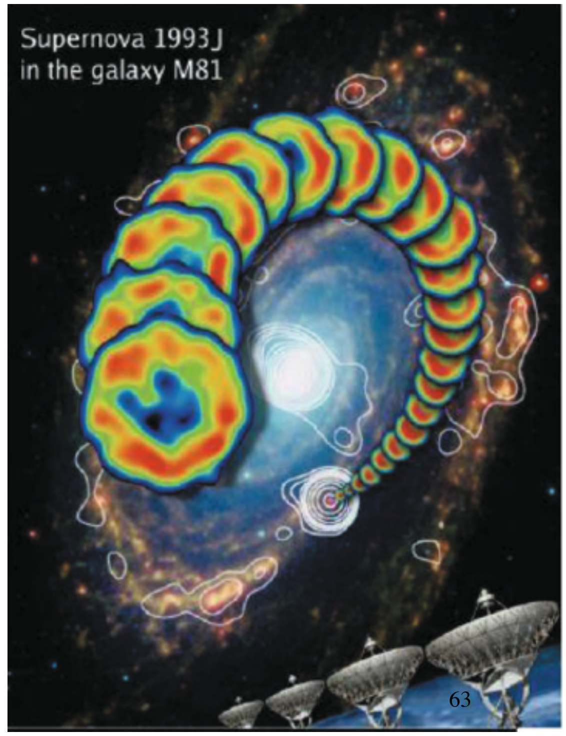
Radio images of SN2008 in M82 -Size vs time

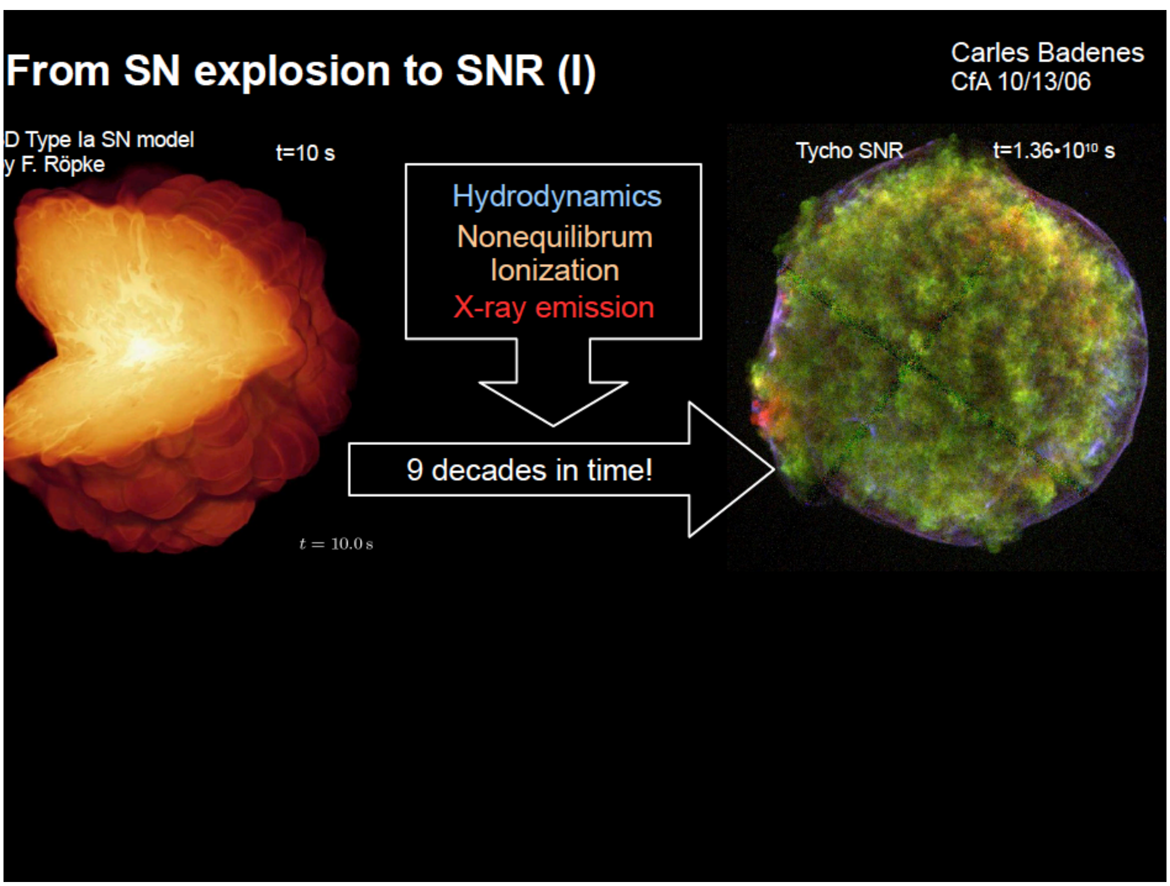


Evolution into a SNR-Radio Emission

- Radio VLBI has the sensitivity and resolution to map nearby SN as they turn into SNR (Bartel et al Astronomy Reports 2017 61,299)
- 50d-8 years of images of SN 1993J
- Directly measure expansion (m=1 free expansion)

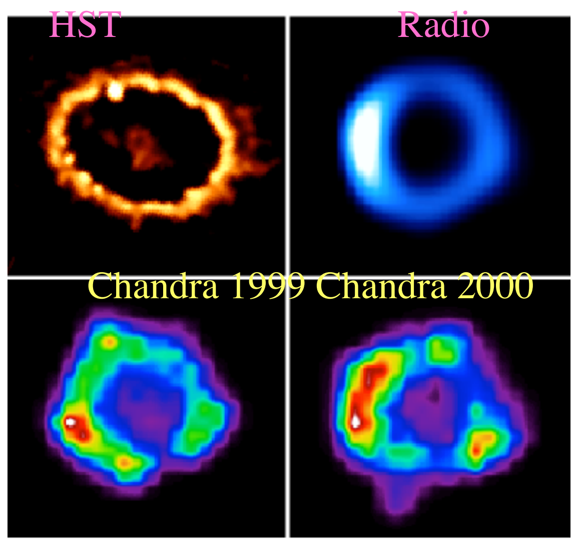






SuperNova Remnants

- We will distinguish between
  - SN explosions (the actual events and the next few years) and
  - Remnants - what happens over the next few thousand years.



SN 1987A observed in 1999, 2000

SNRs enrich the ISM by dispersing material produced both during the star's life and at the moment of the SN event.

~2 per century for Milky Way (all types)

SNRs are probes both of their progenitor star (and of their pre-supernova life) and of the medium into which they explode (the ISM)

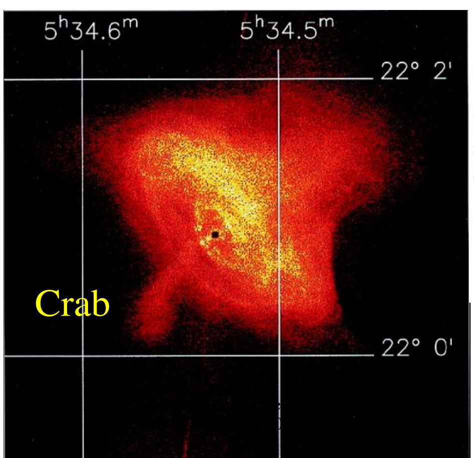
They are also cosmic accelerators (cosmic rays).

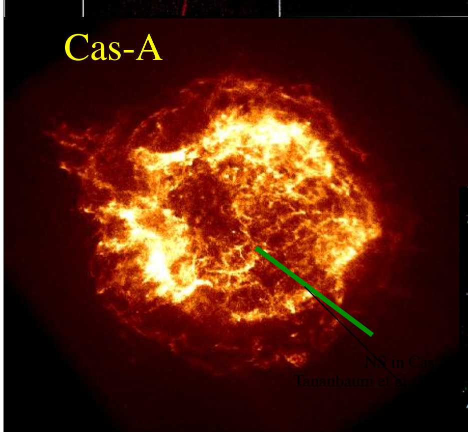
Birth places of neutron stars and stellar mass black holes.

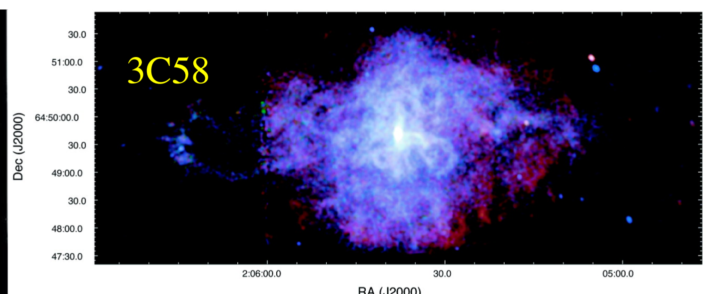
laboratories for study of magnetic fields, shock physics, jets, winds, nuclear physics etc

Sites of ejection of enriched material

- SNR evolution (and their appearance now) depends on many factors:
  - age
  - environment (density)
  - total energy of the explosion
  - progenitor star (mass, type of SN associated..)



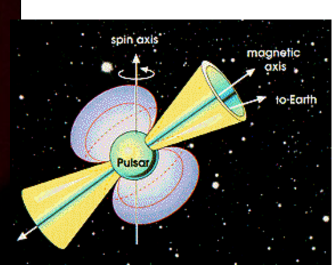




Neutron Stars in SNRs

Pulsars are highly magnetized NS: beacons of light emitted along axis are detected as pulsations

Infer energy loss rate, B field from pulsation characteristics



Relativistic wind is seen as a nebula around pulsar

Thermal (blackbody) emission can also emitted from the surface of the NS

Supernovae and Supernova Remnants

Supernovae
T~ 5000 K characteristic kT of photospheric emission during early period
characteristic emission is optical and infrared
timescale ~ year

Supernova remnants
powered by expansion energy of supernova ejecta,
dissipated as the debris collides with interstellar material generating shocks
T ~ 10^{6-7} characteristic thermal emission is X-rays

timescale ~100-10,000 years (youngest SN in MW is ~110years old)

In our Galaxy there are~300 identified SNRs

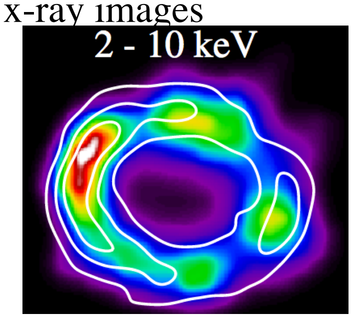
~ 8% detected in the TeV range
~ 10% in the GeV range
~ 30% in optical wavelengths
~ 40% in X-rays
~ 95 % in radio

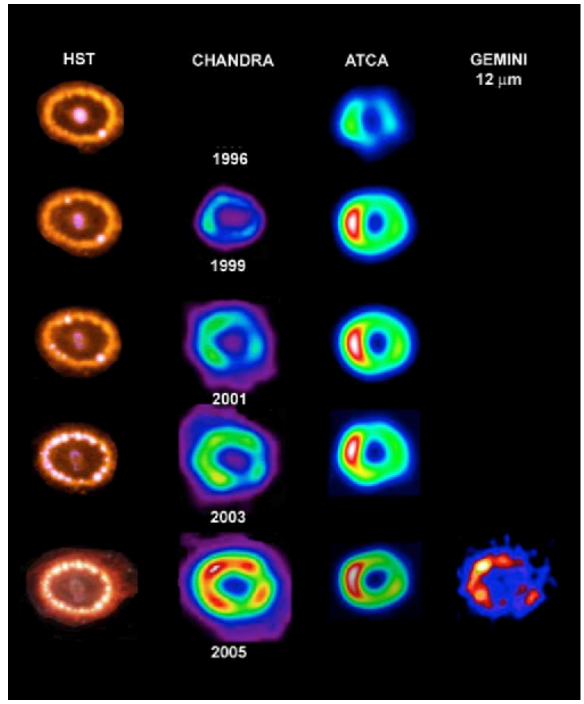
Young SN remnants evolve rapidly

- see [1989 ARA&A..27..629A](#)

1989 **Supernova 1987A.**
Arnett, Bahcall, Kirshner, Woosley

Strong overlap between radio and x-ray images

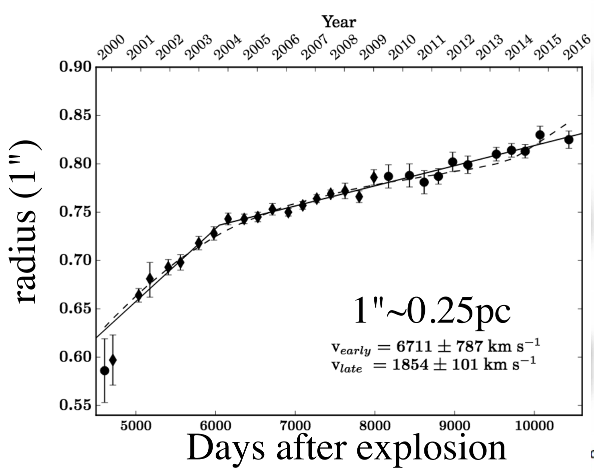


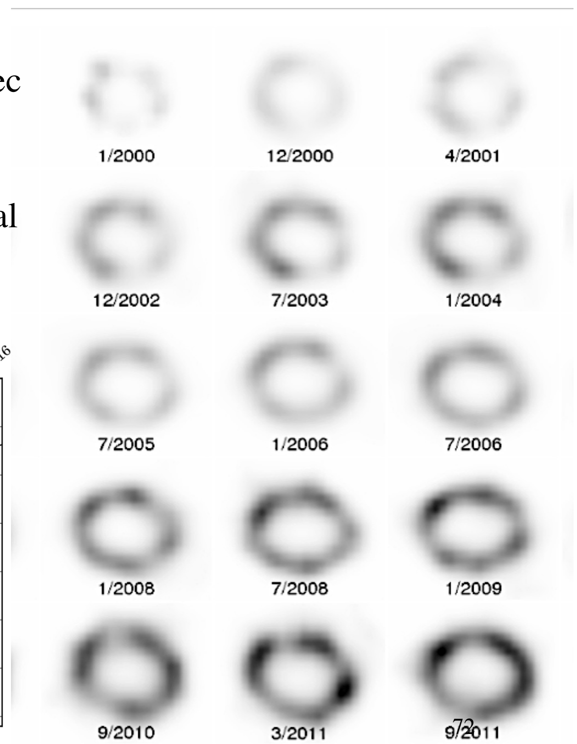


SN 1987A (Type II) Through Time (9 years) in Different Wave Bands
ATCA is radio, Gemini is in IR, HST-optical, Chandra X-ray

SN 1987A X-ray Evolution

- a velocity of 8500 km/sec until day 5900 then a slow down to 1820 km/sec (r=vt)
- the shock started to interact with a equatorial ring at day ~6000- e.g. local medium is non-uniform



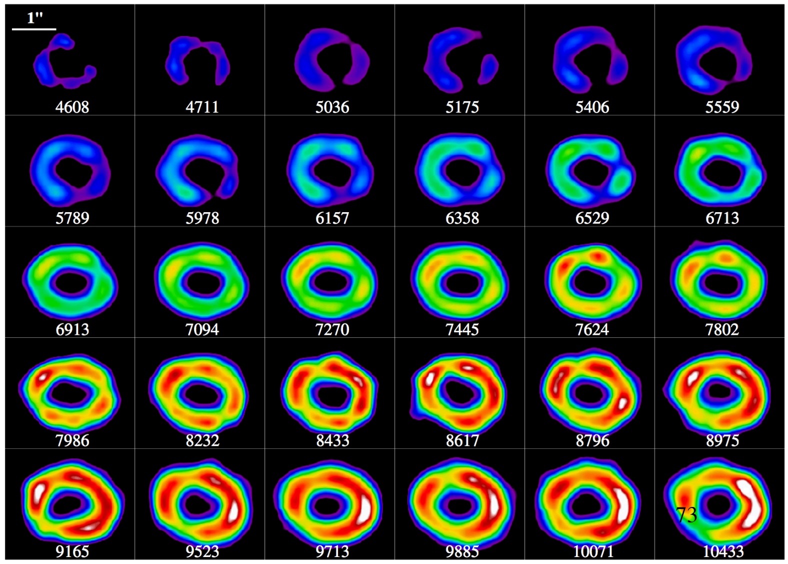


c morphology (corrected for the *Chandra* PSF) of SN 1987A at all epochs u

And More...

- The emitting region can be modeled as a smooth ring with n~10^3cm^{-3}and very dense clumps, n~10^4cm$^{-3,}$ distributed around the ring

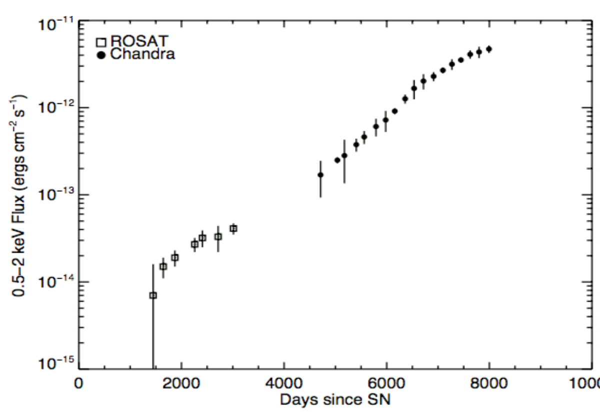
Still no central point source (NS or BH) visible after 28 years



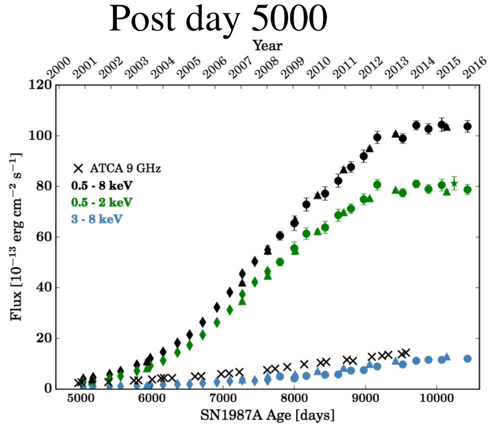
1987A - X-ray Light Curves

- Keeps getting brighter-thermal X-ray emission is a tracer of the density of the material into which the shock is expanding

See SNaX: A Database of Supernova X-Ray Light Curves Ross and Dwarkada AJ 153:246 2017



Post day 5000



Notice radio and hard x-ray light curves are very similar

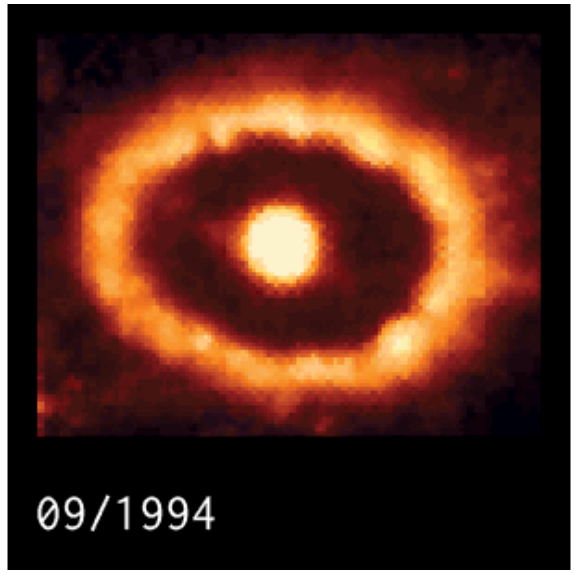
1987A Neutrinos

~24 neutrinos were detected ~ 12 hours before the optical light was detected-Noble Prize 2002

(https://www.nobelprize.org/uploads/2018/06/koshiba-lecture.pdf)

confirmation that neutrinos carry most of the energy with about 2 to 4 x 10^{53} ergs emitted in neutrinos

also direct detection of ^{56}Co γ-ray lines verifying radioactivity driven light curve



10 years of 1987A with HST

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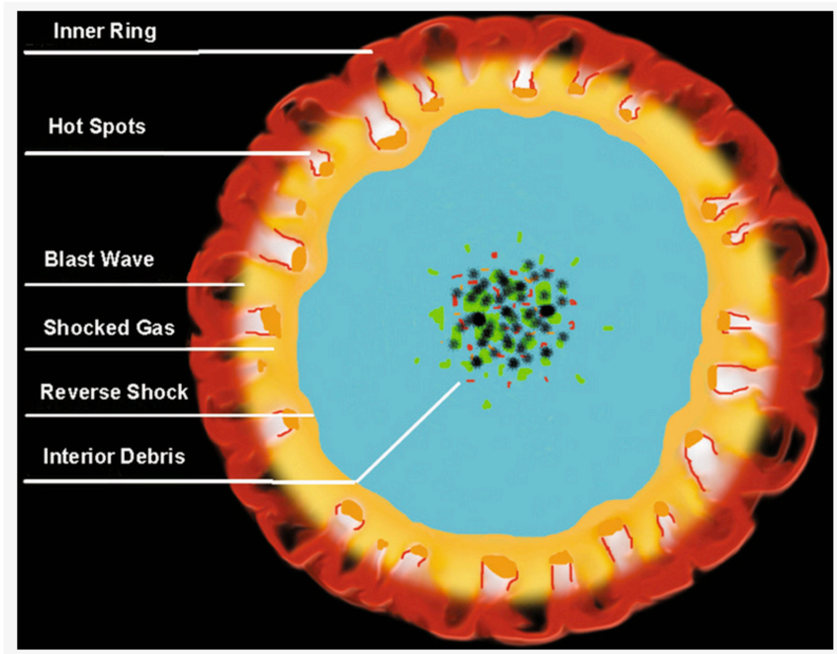
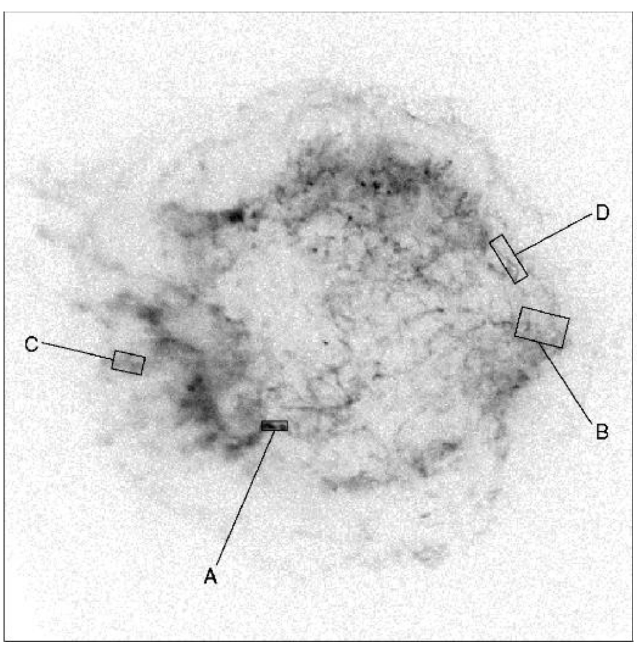
The Young SNR

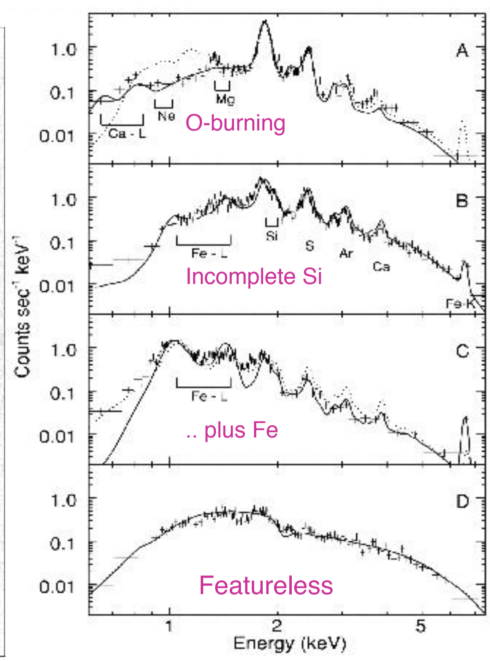
The nucleosynthesis products in the interior debris are confined mostly within a sphere expanding with velocity ~ 2000 km s^{-1}



The blue-yellow interface represents the reverse shock , while the yellow annulus represents the X-ray-emitting gas, bounded on the outside by the blast wave . The white fingers represent protrusions of relatively dense gas.

Cassiopeia A: Observations of Explosive Nucleosynthesis Spectral/Spatial Decomposition





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

Notice inhomogeneity of element distribution

Origin of the Elements- repeat

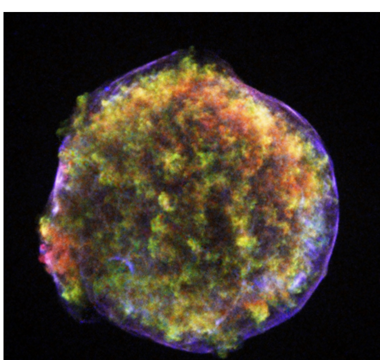
C burning produces O, Ne, Mg, etc $\qquad T \sim 2 \times 10^{9}$ K

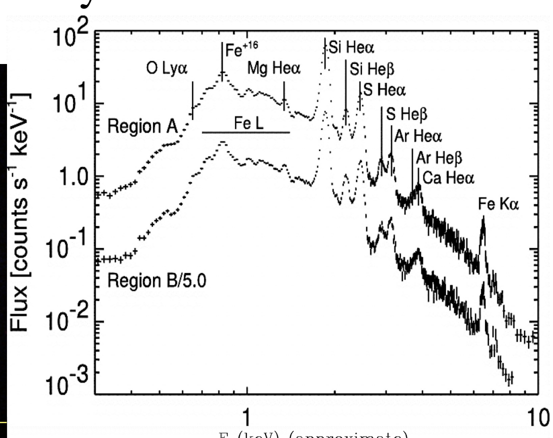
Ne burning produces O, Mg, etc $\qquad T \sim 2.3 \times 10^{9}$ K

O burning produces Si, S, Ar, Ca, etc $\qquad T \sim 3.5 \times 10^{9}$ K

Si burning produces Fe, Si, S, Ca, etc $\qquad T \sim 5 \times 10^{9}$ K

Nucleosynthesis Products in SNRs

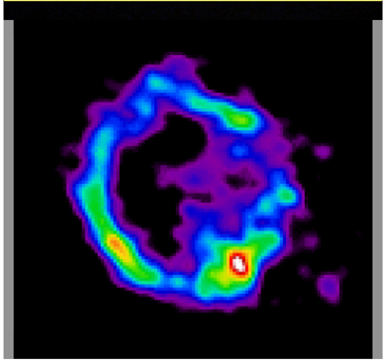


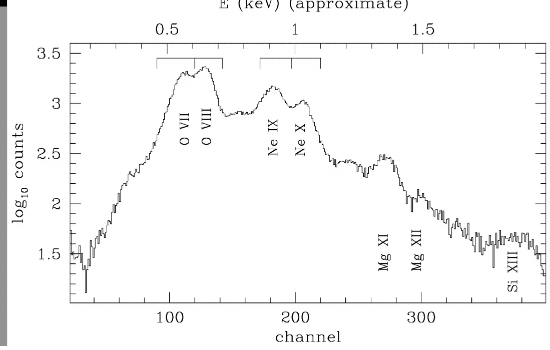


Tycho's SNR

Type Ia
White dwarf + companion

Si, S, Ar, Ca
Expect lots of Fe: most not yet shocked





E0102-72

Core-collapse
~25 M_{sun}
mostly O, Ne, Mg