- We bid a fond farewell to black holes and start a new topic… supernova and supernova remnants

"Thank you, Blake, for that riveting presentation on black holes."

Why Study Supernova Remnants?

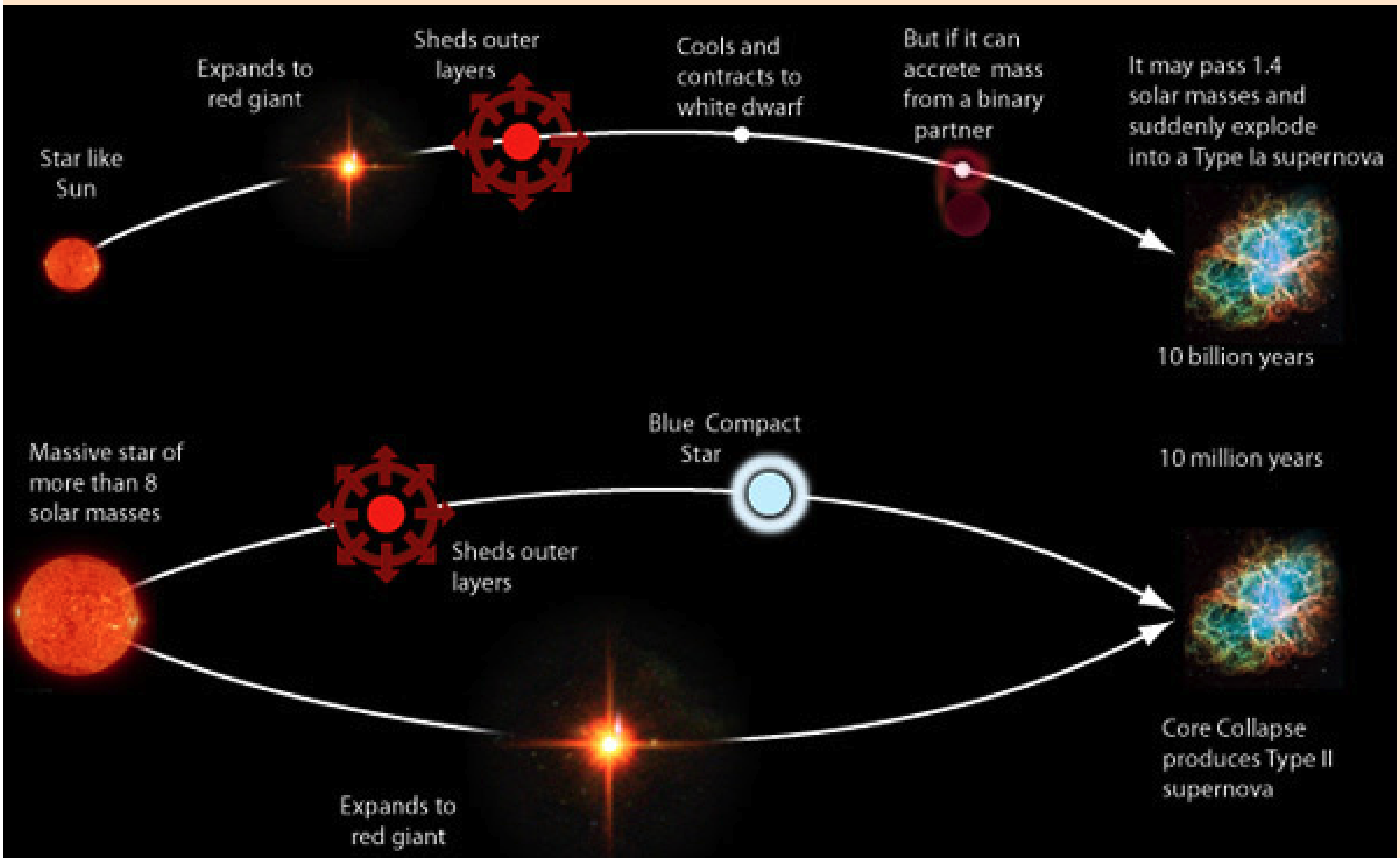
Supernova explosion:
How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What and (how much) elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

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?

Interstellar medium:
What is the structure of the interstellar medium, and how does the shock interact with that structure?
How is the ISM enriched and ionized

Supernova- See Ch 4 (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 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
- Type I supernovae do not show hydrogen in their spectra. Type Ia supernovae reach peak luminosities of about 2×10^{43} erg/s
- Type II supernovae show hydrogen in their spectra. Their light curves are rather diverse, and their peak luminosities are around 10^{42} erg/s


Star like Sun
Expands to red giant
Sheds outer layers
Cools and contracts to white dwarf
But if it can accrete mass from a binary partner
It may pass 1.4 solar masses and suddenly explode into a Type Ia supernova
10 billion years
Massive star of more than 8 solar masses
Sheds outer layers
Blue Compact Star
10 million years
Core Collapse produces Type II supernova
Expands to red giant

How to Get to a Type I

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

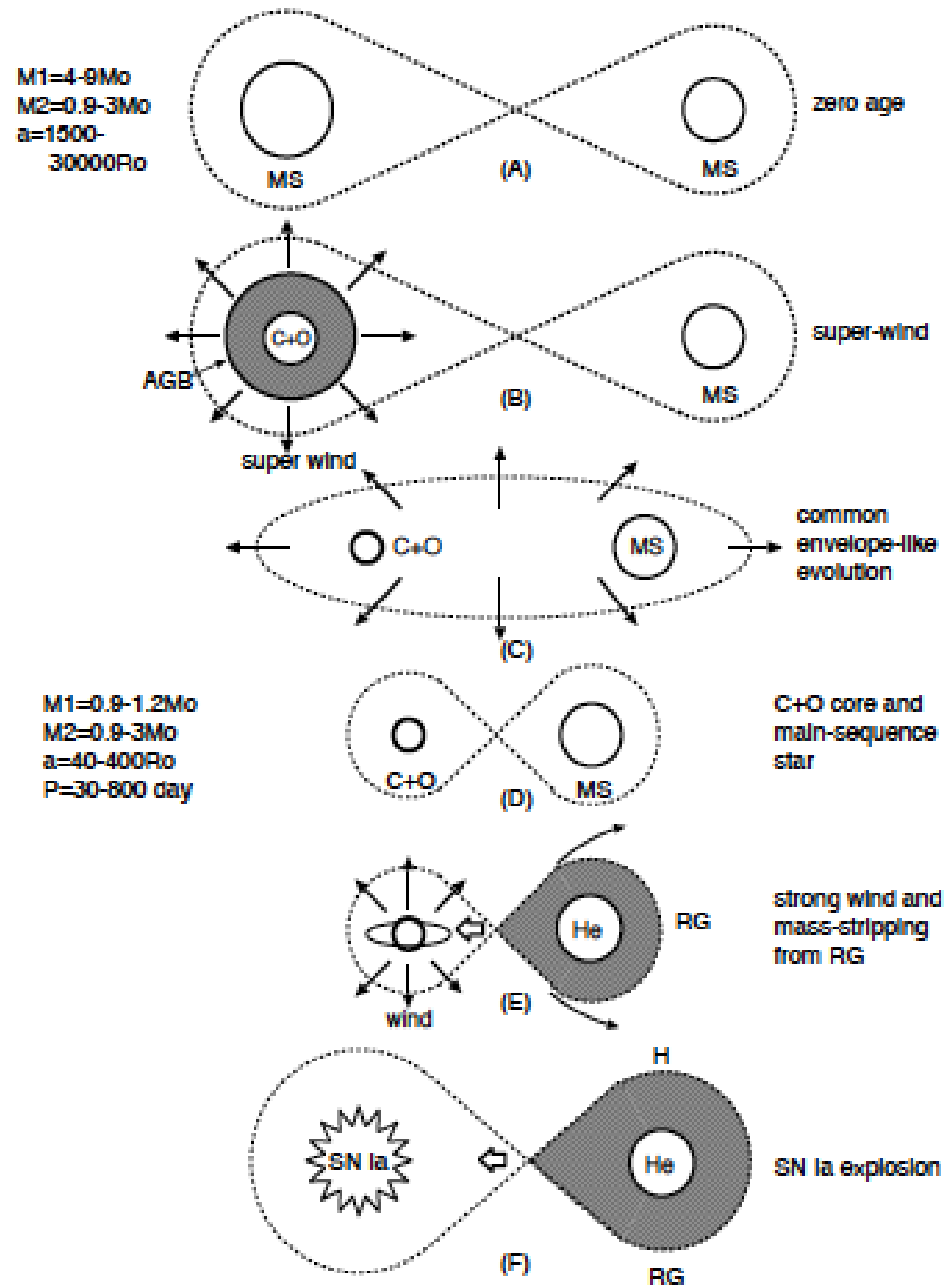


FIGURE 2. An illustration of the WD+RG (symbiotic) channel to Type Ia supernovae.

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^{48-49} 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 remnant	NS or BHs
• most of the explosion energy is into heavy element synthesis	vast majority of the energy is indirected neutrino emission
and kinetic energy of the ejecta	,

Type II events occur during the regular course of a massive star's evolution. a Type Ia supernova, needs several very specific events to push themwhite dwarf over the Chandrasekhar limit.(adapted from Type Ia Supernovae and Accretion-Induced Collapse Ryan Hamerly)

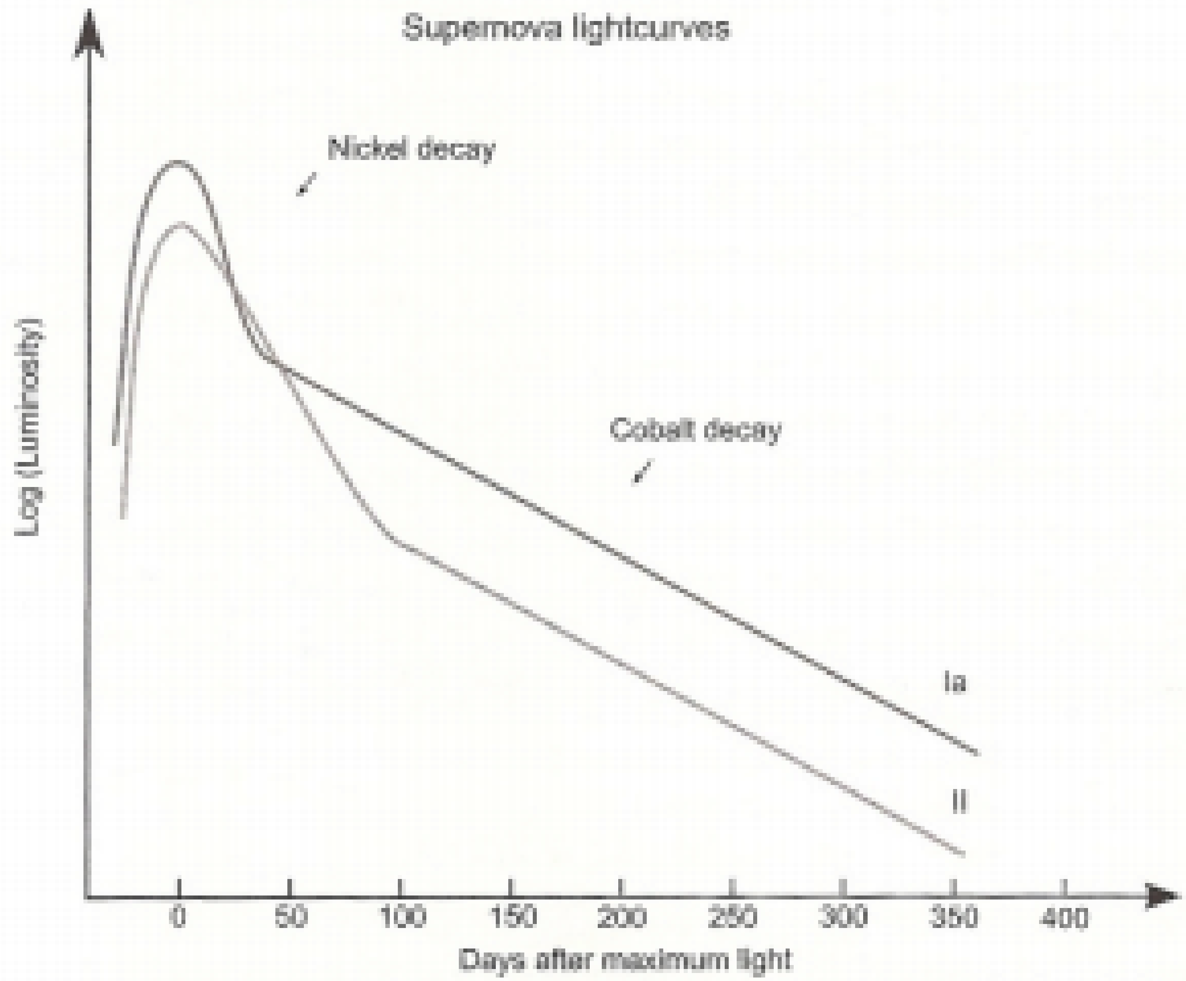
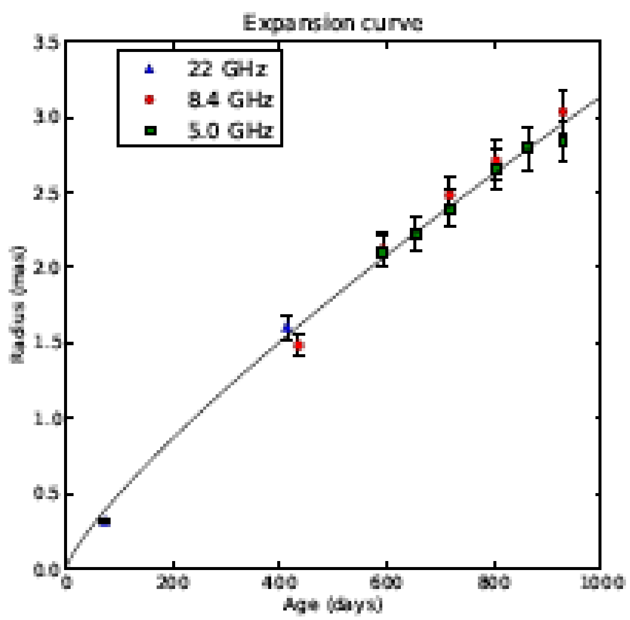


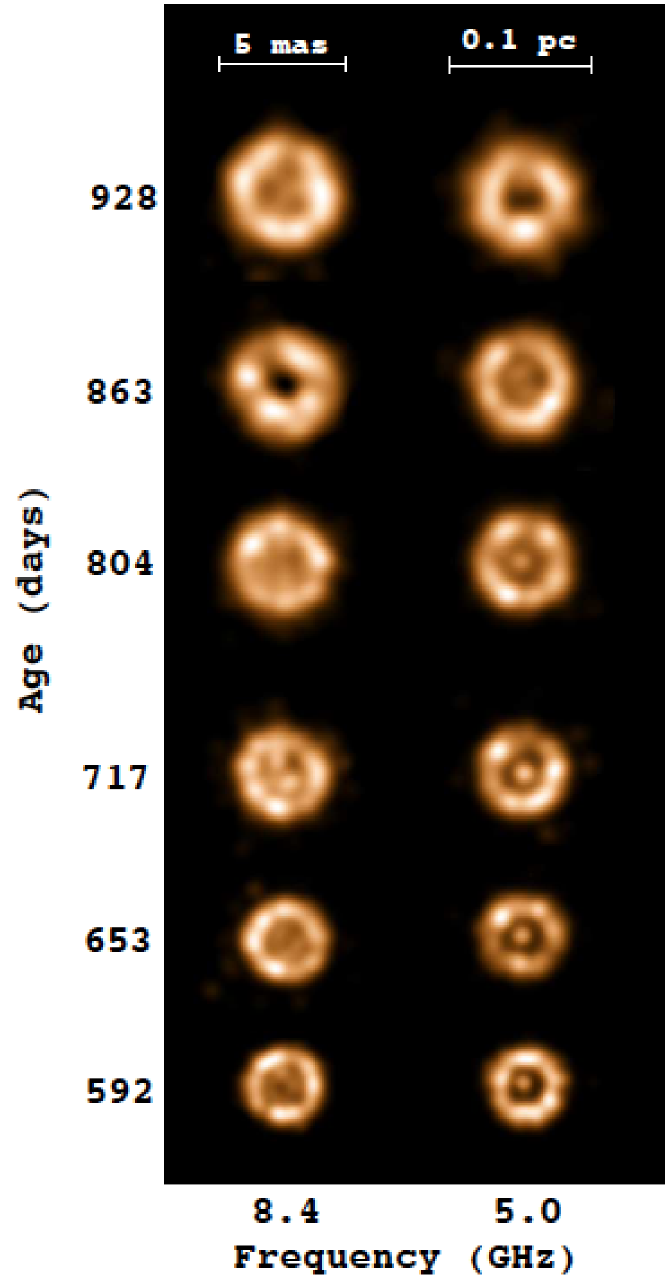
Figure 4.3 Supernovae light curves for Types Ia and II.

Rosswog and Bruggen fig 4.3

Super Nova and Super Nova Remnants

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





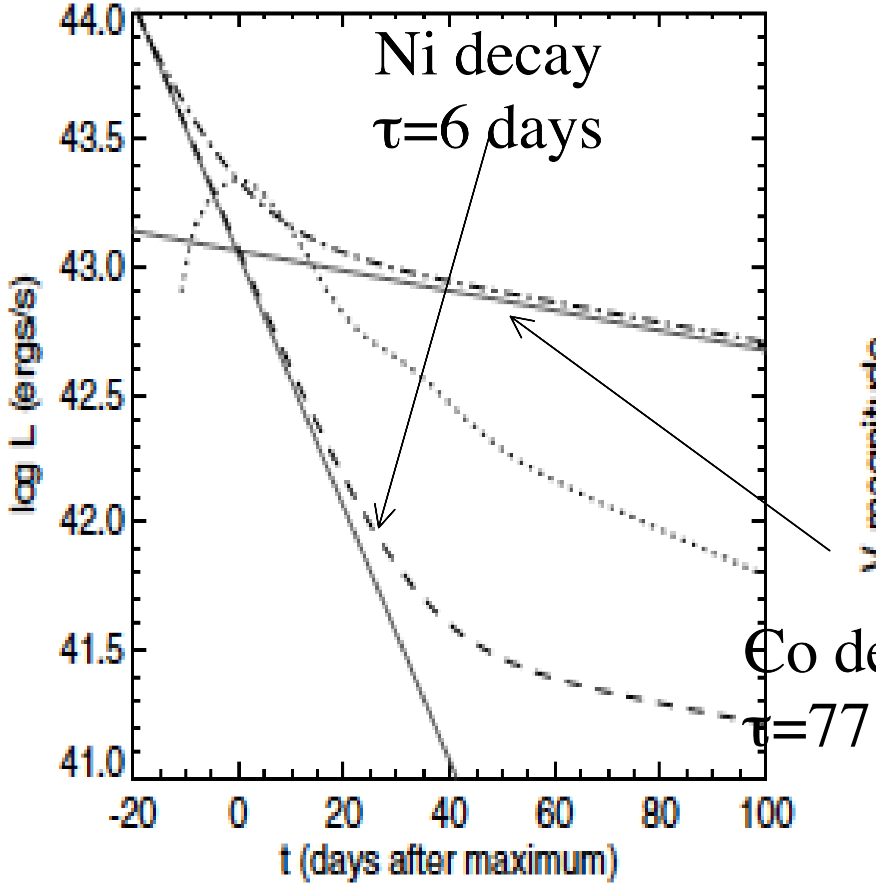
Radio images of SN2008 in M82 +Size vs time

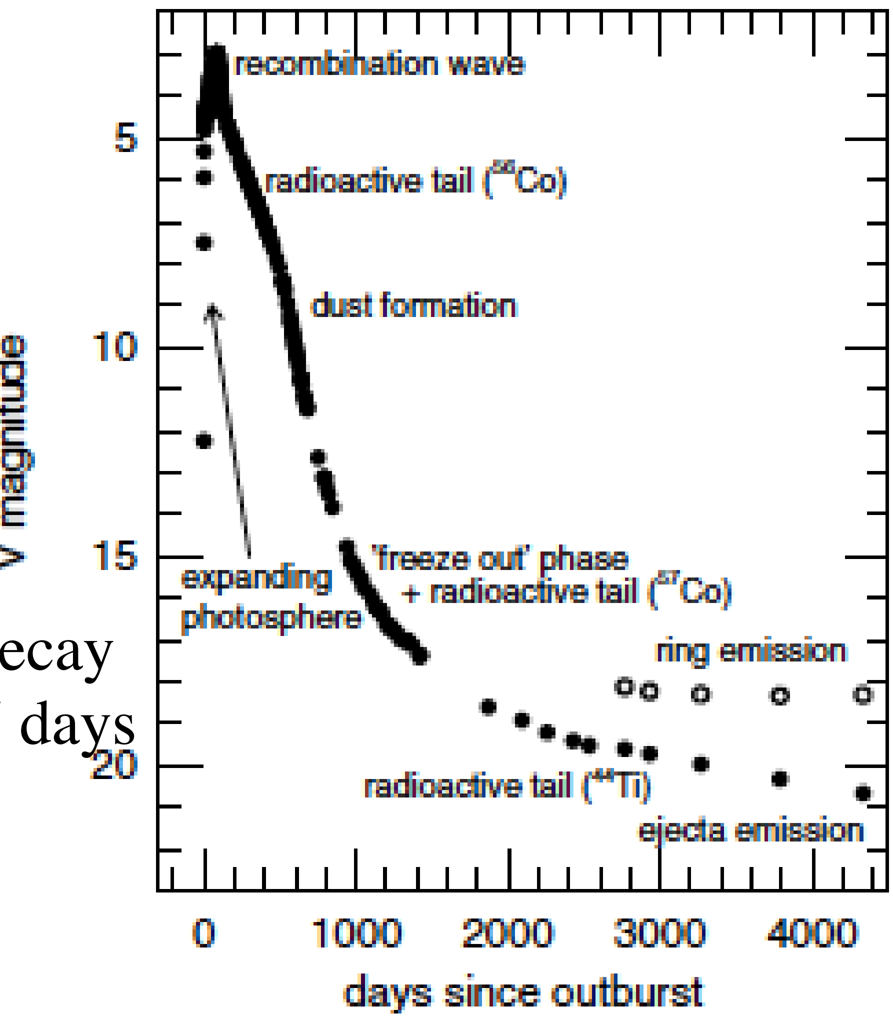
SN Light Curves

Type Ia

Bruno Leibundgut

Type II

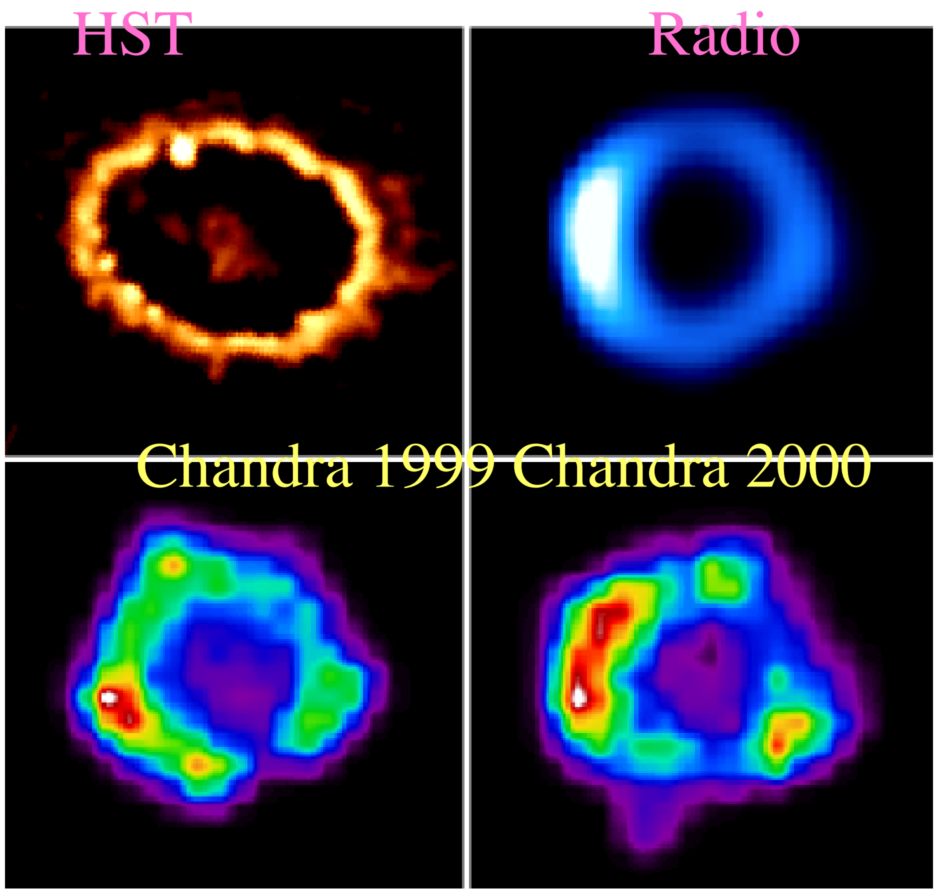




$^{56}Ni + e^-$ → $^{56}Co + \nu; ^{56}Co + e$ → $^{56}Fe + \nu$

SuperNova Remnants

- Supernova Occur in two types
  - I- primarily the explosion of a low mass (accreting white dwarf) star
  - II- Explosion of a massive $M>8M_{\odot}$ star
- 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

- 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..)

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

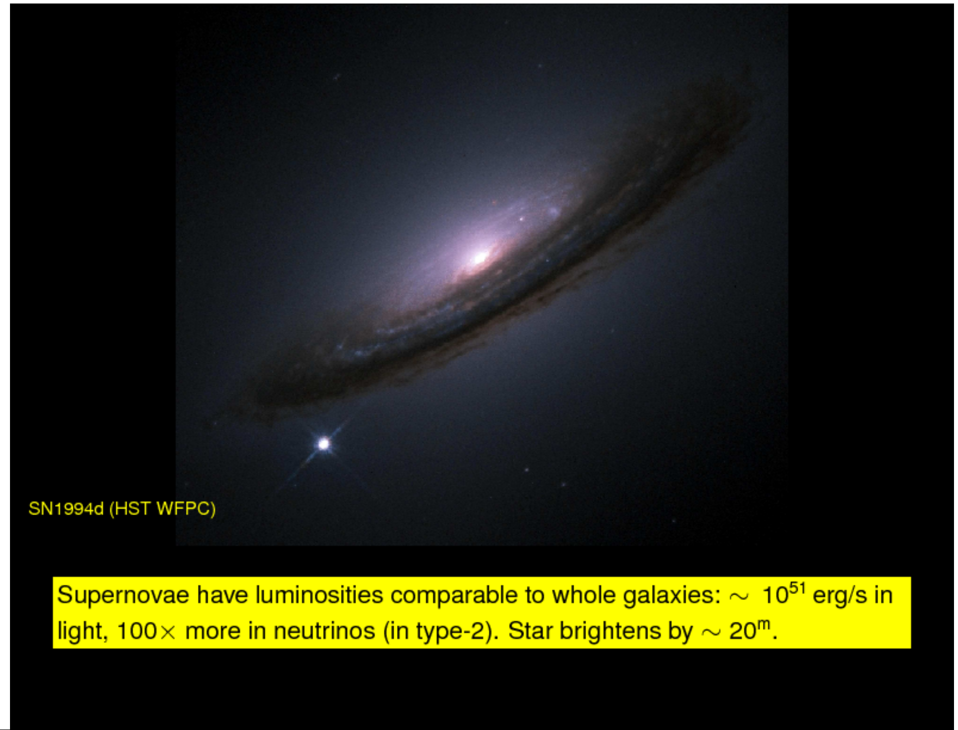
$Ni^{56} \Rightarrow Co^{56} \Rightarrow Fe^{56}$ (77 day 1/2 life)

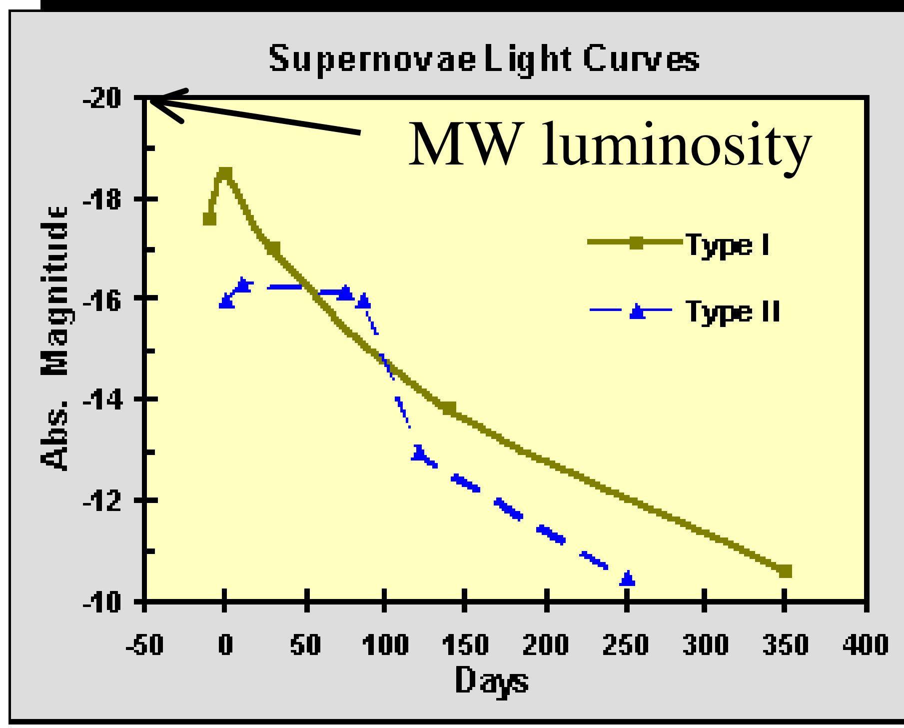
Velocities of gas seen in the optical is ~10^4 km/sec

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

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

v_4 in units of 10^4 km/sec





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

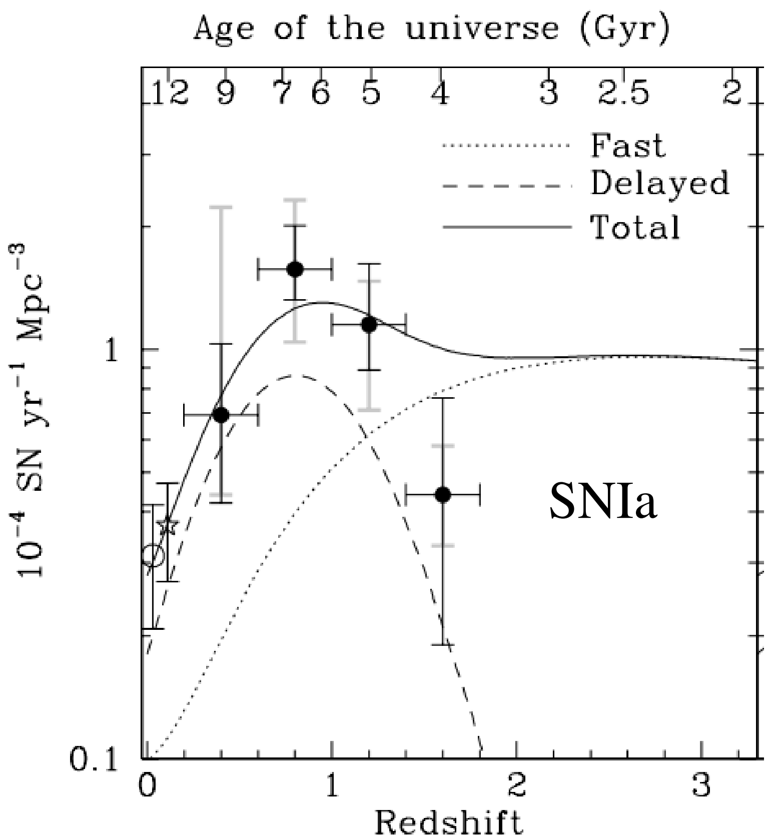
$T \sim 10^{6-7}$ K

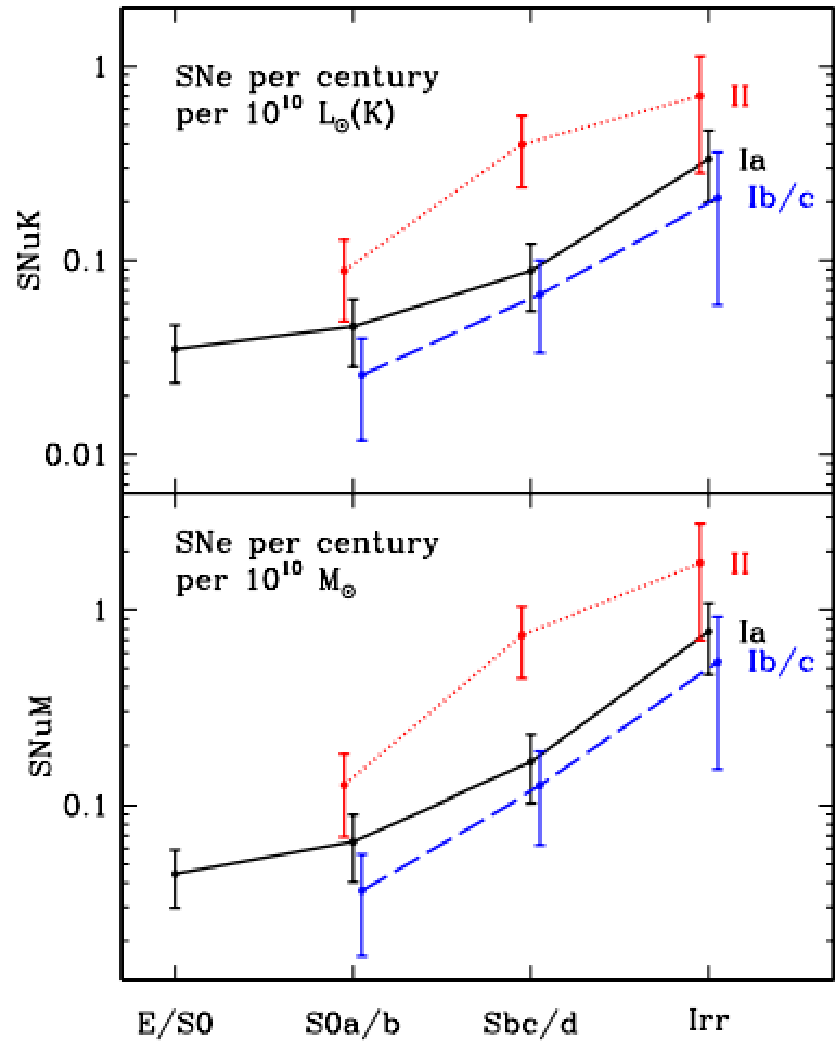
characteristic thermal emission is X-rays

timescale ~100-1000 years

SN Rate vs Time and Galaxy Properties

- the Ia SN rate per unit mass changes with galaxy morphology , colors and cosmic time
- it increases by a factor of about 4 from E/S0 to Sbc/d, up to a factor of about 17 in Irr galaxies
- Argues for 2 populations of SNIa (fast and slow)

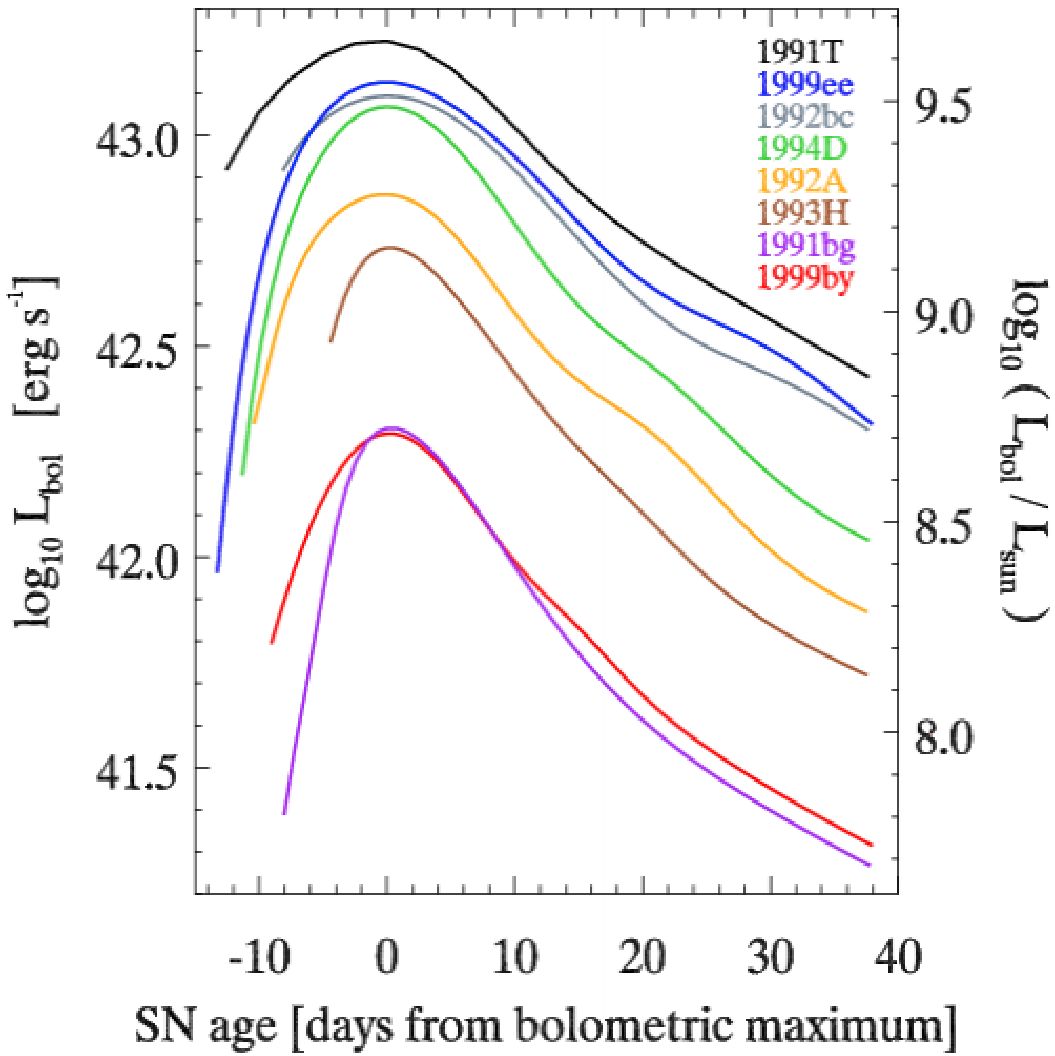




Mannucci 2005

Type Is

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



Type Ia's

- Why a thermonuclear explosion of a white dwarf?
  - Kinetic energy of ejecta ~5×10^{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 remant (e.g. NS or BH)
  - occurance in elliptical galaxies with no star formation
- But (Rosswog and Bruggen pg 136)
  - No consensus on
    - mass of WD or its composition
    - origin of accreted material
    - exact explosion mechanism

Supernova Explosions

Ia Thermonuclear Runaway

• Accreting C-O white dwarf reaches Chandrasekhar mass limit, undergoes thermonuclear runaway- have to accrete matter at the right rate (too slow and get burning on WD surface and produce a novae; need $dm/dt > 4 \times 10^{-8}$ M/yr)

•Type I supernovae: no hydrogen in their spectra- reach peak luminosities $\sim 2 \times 10^{43}$ erg/s

• Results in total disruption of progenitor (no remnant NS or BH)

• Explosive synthesis of Fe-group plus some intermediate mass elements (e.g., Si)

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

•Amount of Ni synthesized is not the same from object to object

➔**different ejecta mass**

➔**different explosion energies**

➔**asymmetries in the explosions**

➔**differences in the explosion physics**

Type Ia- How the Explosion Occurs

- Deflagration wave
- Deflagration-

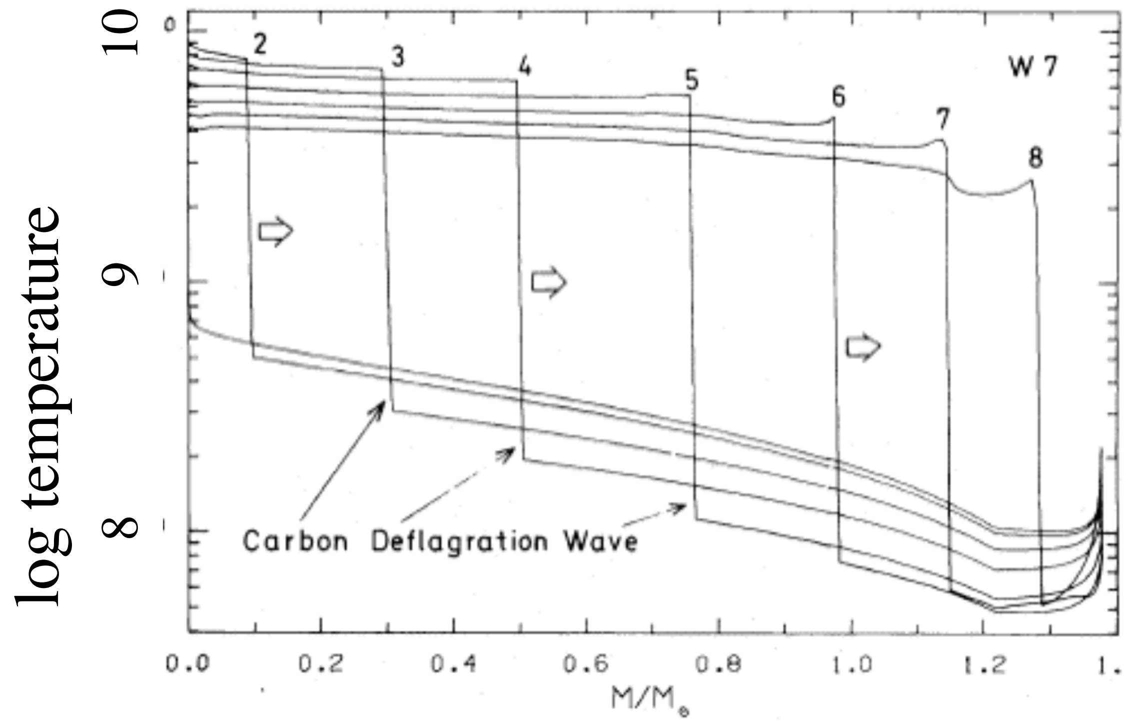
"Combustion" that propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.

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

Detailed physics is still controversial!

Fundamental reason: nuclear burning rate in SnIa conditions $\sim T^{12}$

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

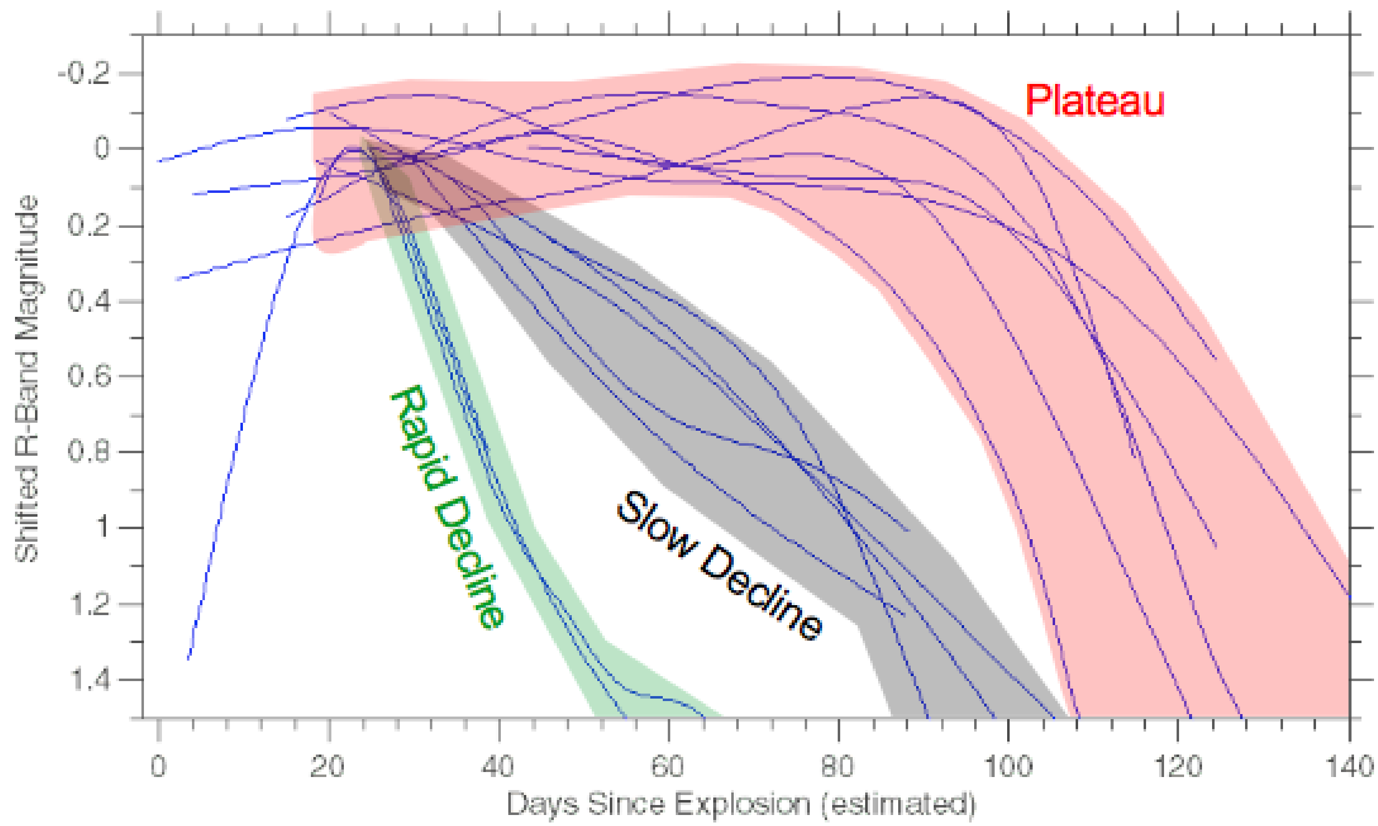


mass shell

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

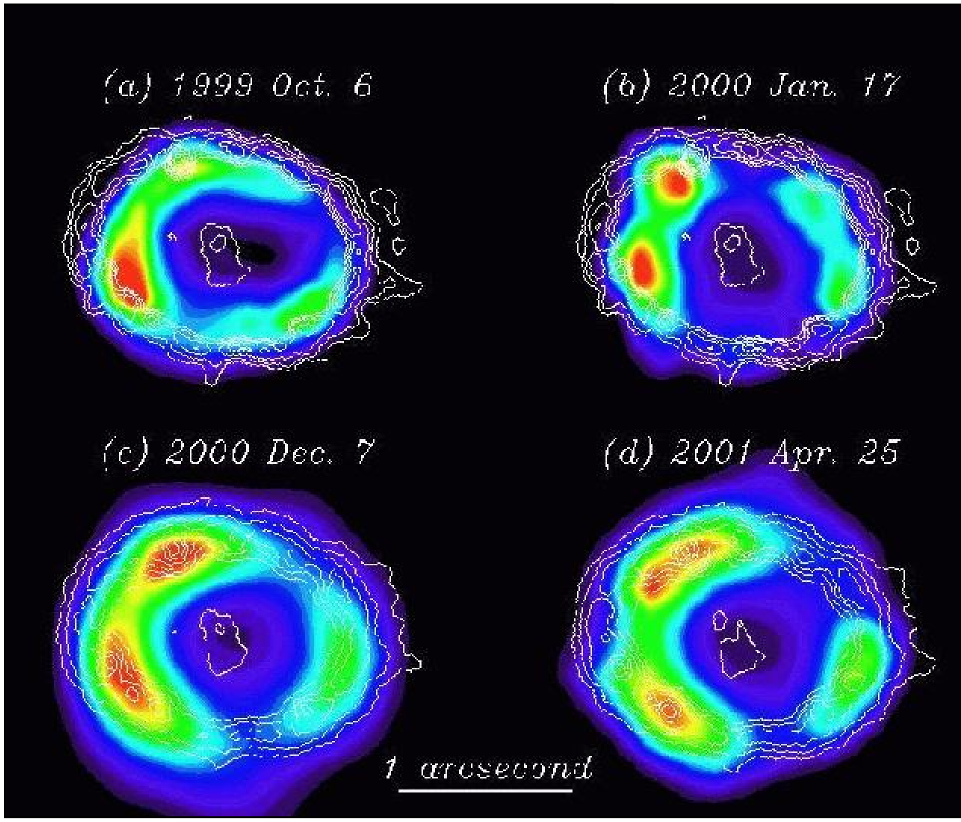
SN II

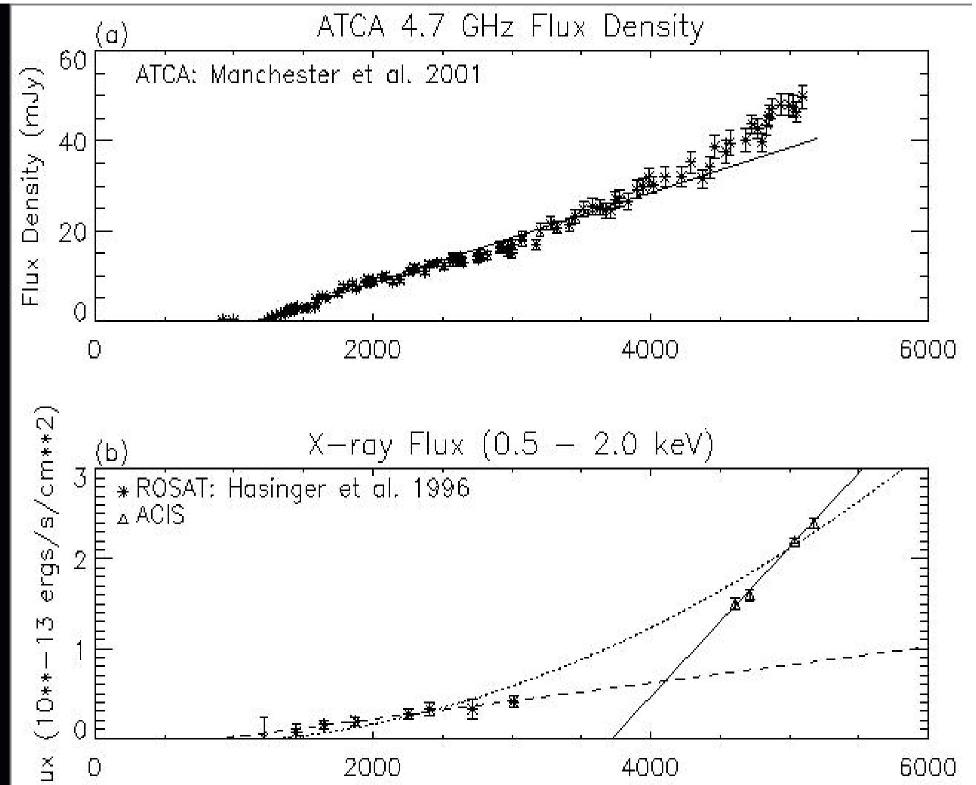
- Wide Variety of Light Curves- assume wide range of progenitors
- Type II supernovae - implosion-explosion events of a massive star. They show a characteristic plateau in their light curves a few months after explosion
- . This plateau is reproduced by models which assume that the energy comes from the expansion and cooling of the star's outer envelope as it is blown away



SNR 1987A in Large Magellanic Cloud-

Pre SN explosion images showed star that exploded





days since explosion

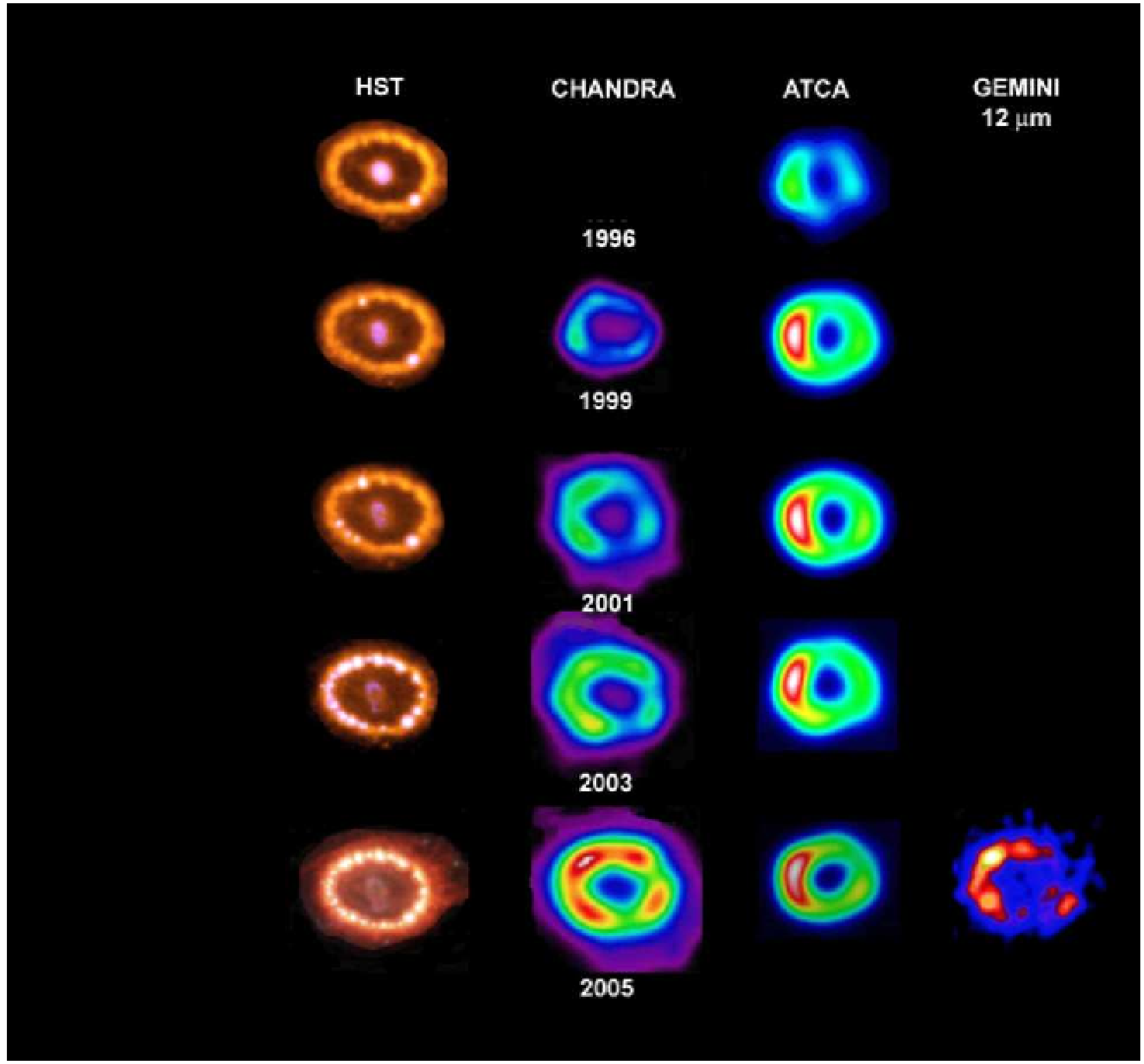
Park et al. 2002 , Burrows et al. 2001

X-ray emission is approaching inner circumstellar ring

X-rays correlate with radio

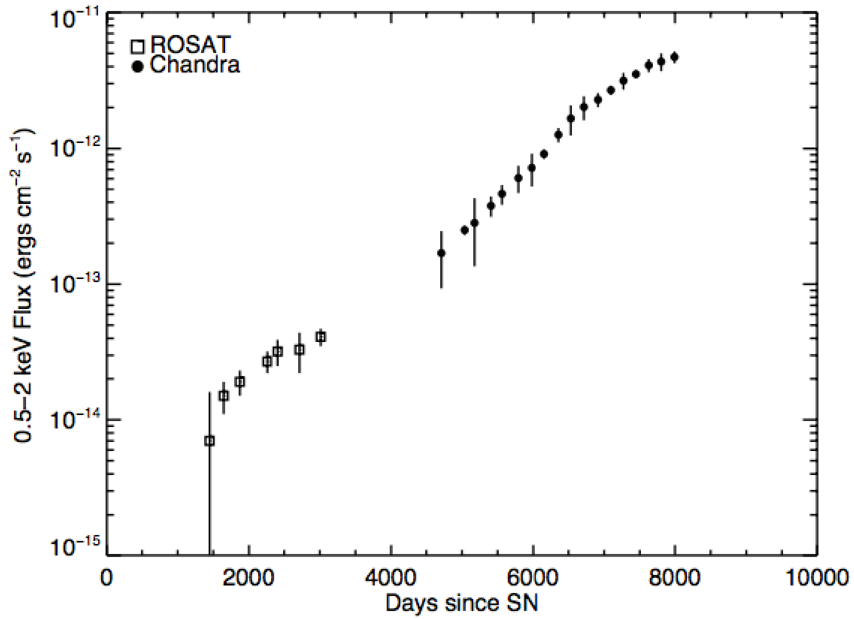
Young SN remnants evolve rapidly

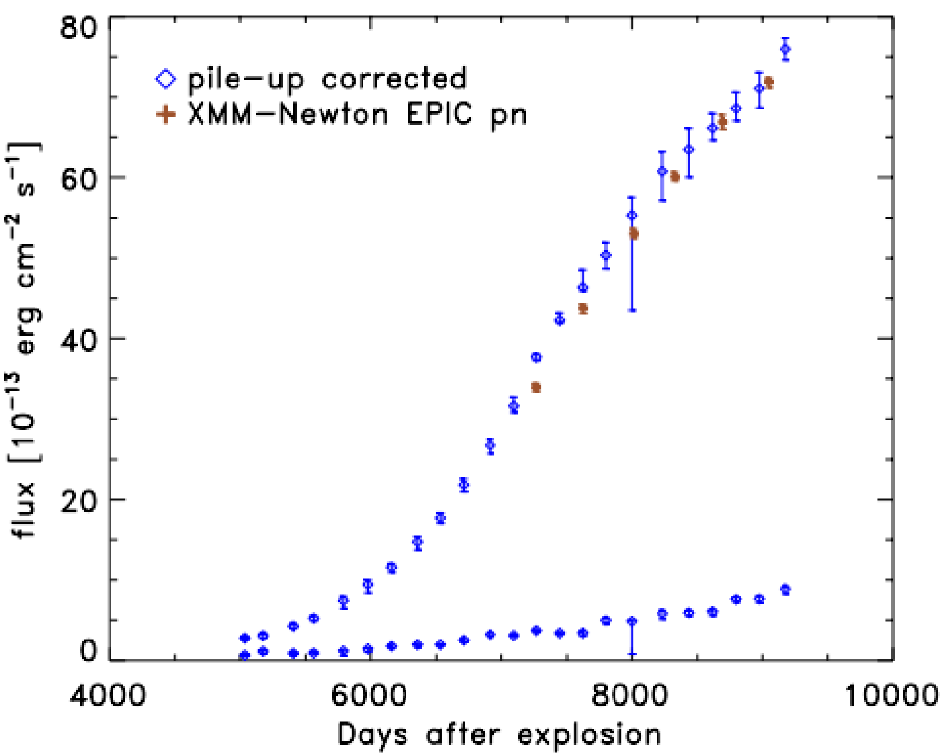
Some extragalactc SN have been followed for years



SN 1987A (Type II) Through Time in Different Wave Bands

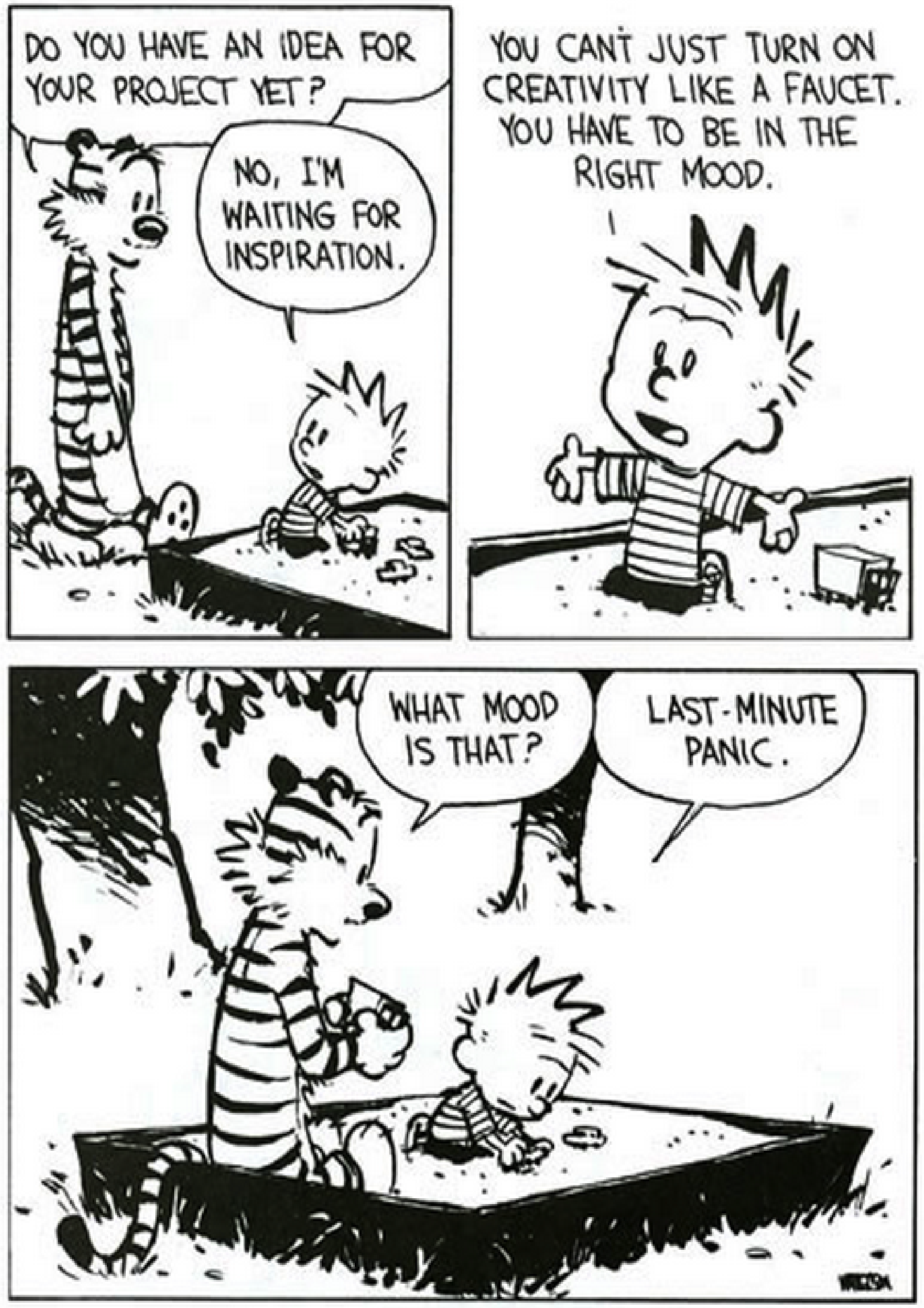
1987A - Latest X-ray Light Curves





- Remember Project
- Due the week before the last day of classes.. April 30
- Evalutions:

  CourseEvalUM will be open for student evaluations for this semester
- Apr. 23 through May 10 https://courseevalum.umd.edu/
- You all know the drill

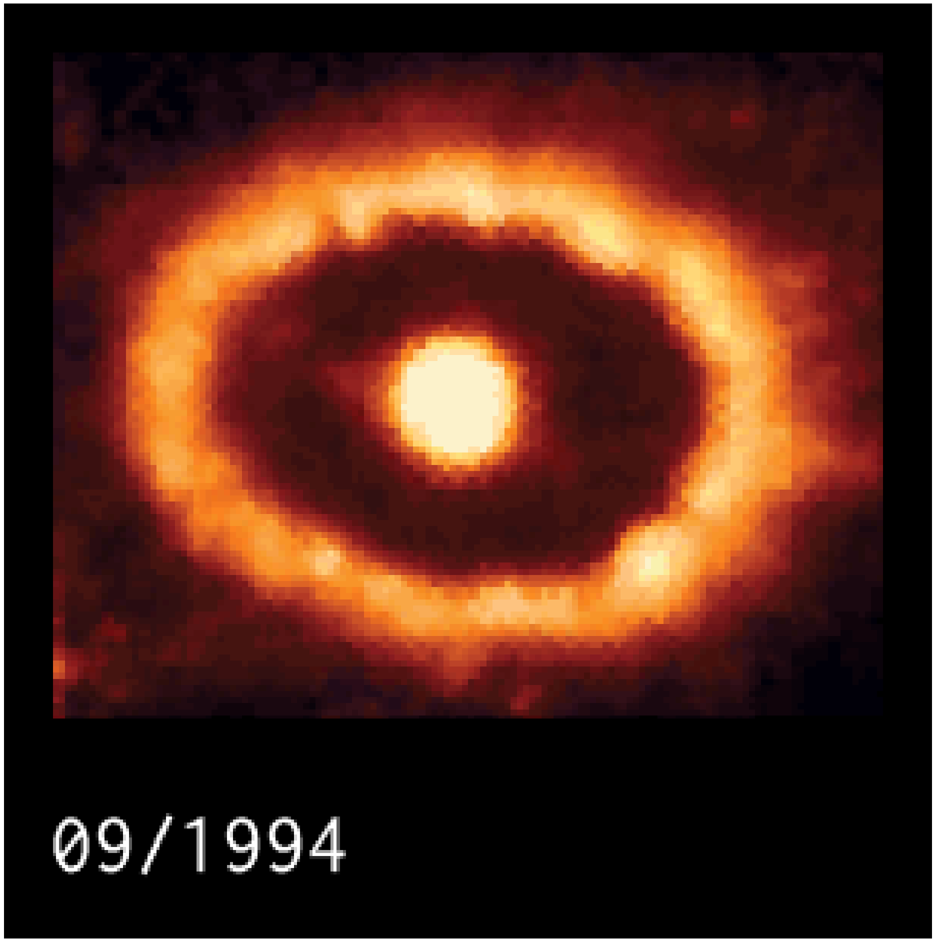


1987A

~24 neutrinos were detected within 12 hours before the optical light was detected-

confirmation that neutrinos carry most of the energy

Direct detection of ^{56}Co γ-ray lines



Evidence for Two Distinct Populations of Type Ia Supernovae

- Published in Science, yesterday (!)
- Type Ia supernovae (SNe Ia) have been used as excellent standardizable candles for measuring cosmic expansion, but their progenitors are still elusive... the spectral diversity of SNe Ia is tied to their birthplace environments. ...SNIa with high-velocity ejecta are substantially more concentrated in the inner and brighter regions of their host galaxies than are normal-velocity SNe Ia ... and are in larger and more luminous hosts... suggesting that high-velocity SNe Ia originate from younger and more metal-rich progenitors and are only found in galaxies with substantial chemical evolution.

Explosive Nucleosynthesis- Type IIs

(Details see Rosswog+Bruggen pg 134-135)

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

'α' products

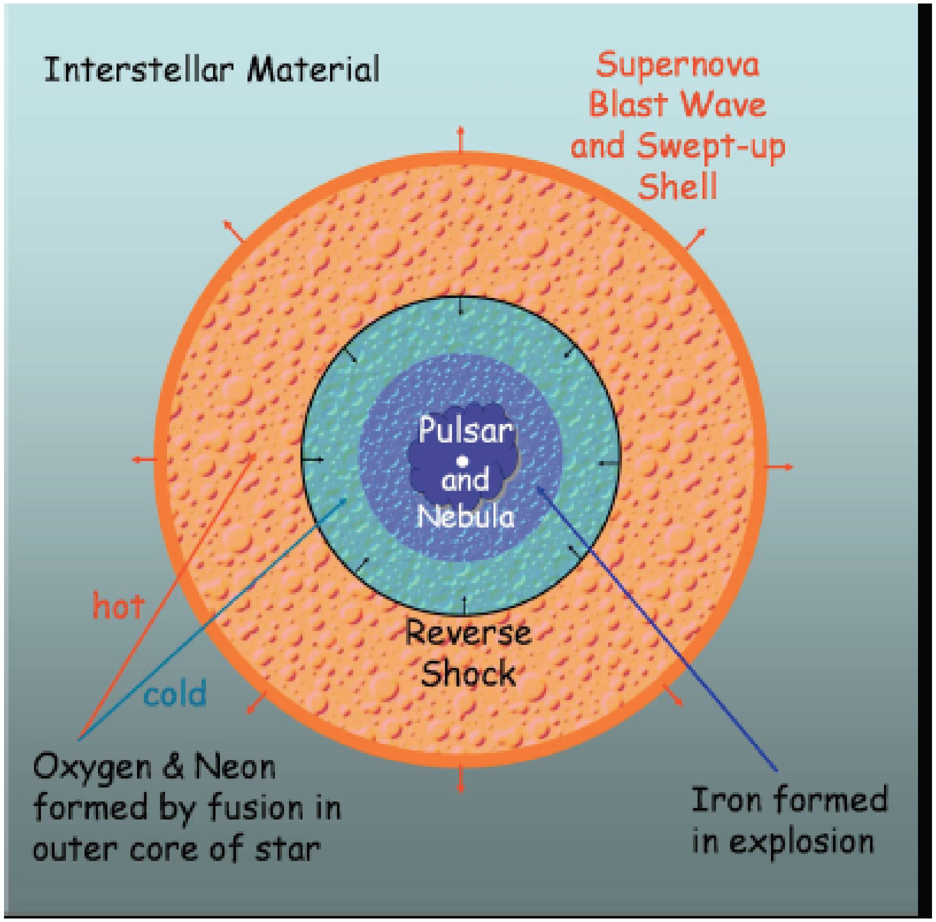
C burning produces O, Ne, Mg, etc
$T \sim 2 \times 10^9$ K

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

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

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

stops at Fe



II/Ib/Ic Core-Collapse of Massive Progenitor

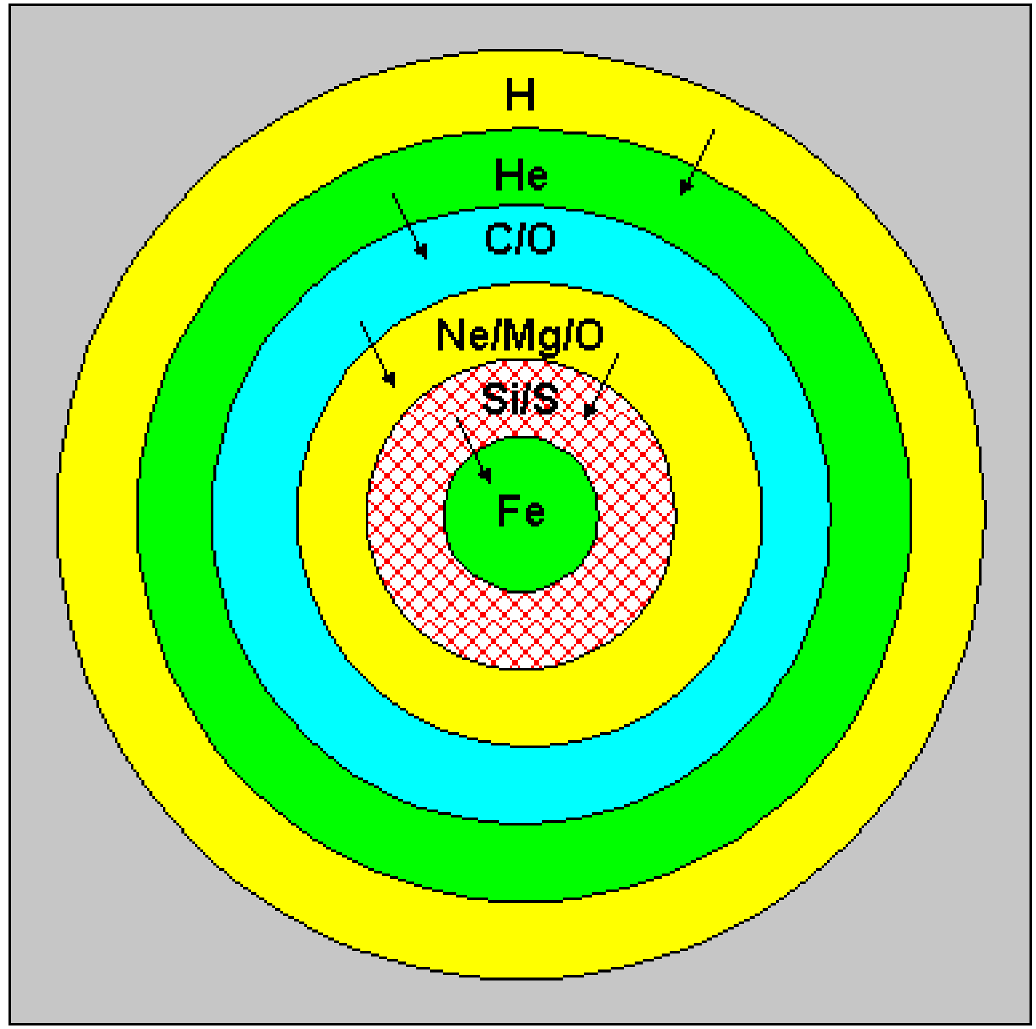
• Massive progenitor core forms neutron star or black hole

• 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.

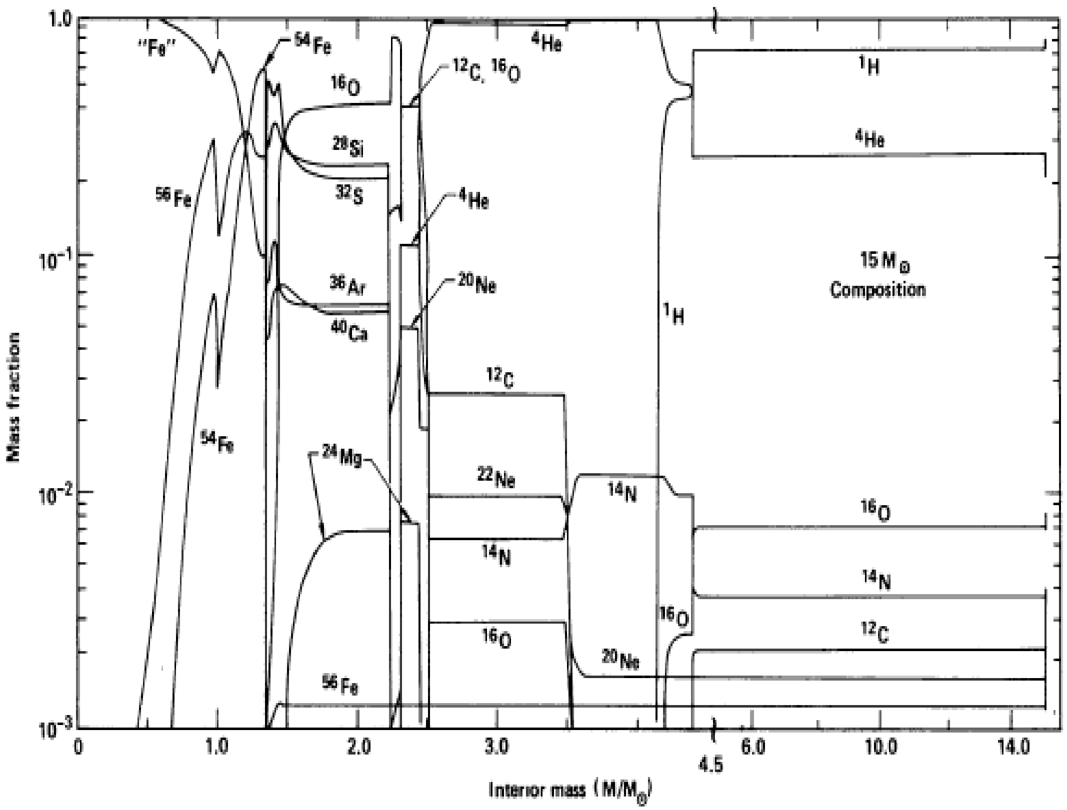


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge

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

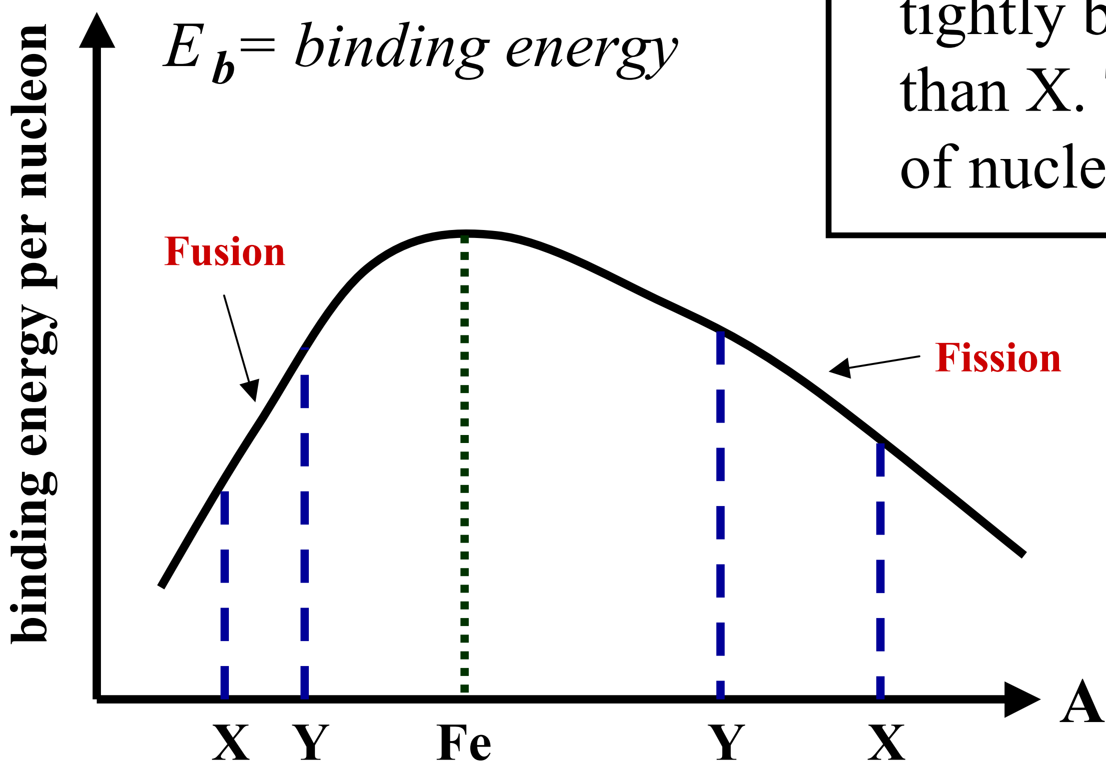
Binding energy of Nuclei - why stellar burning stops generating energy

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/

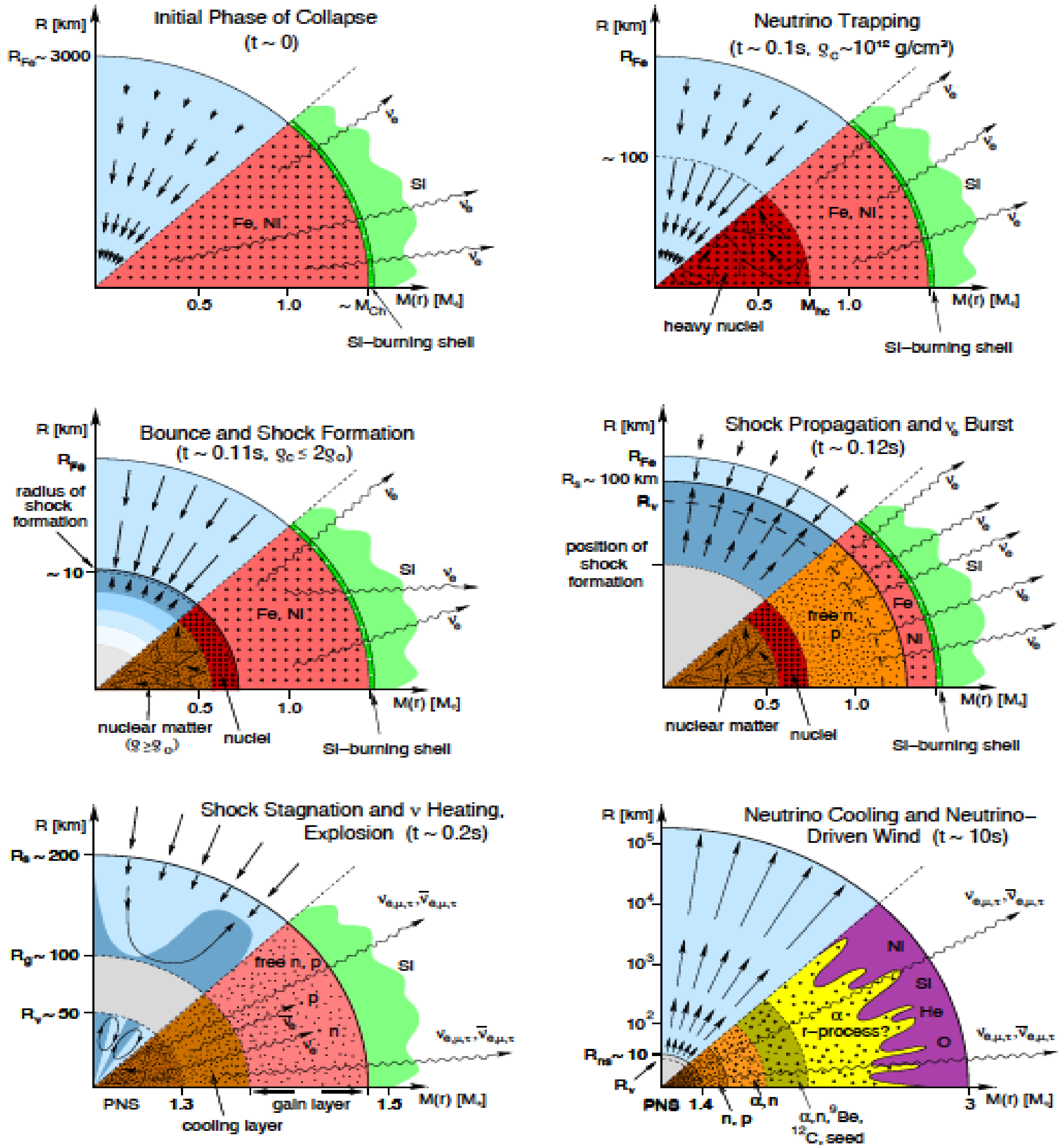
SNIIa
see sec 4.2.3 of R+B

- $E_{kinetic} \sim 10^{51}$ erg$<<E_{binding} \sim 3 \times 10^{53}$
- 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 ...

- 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

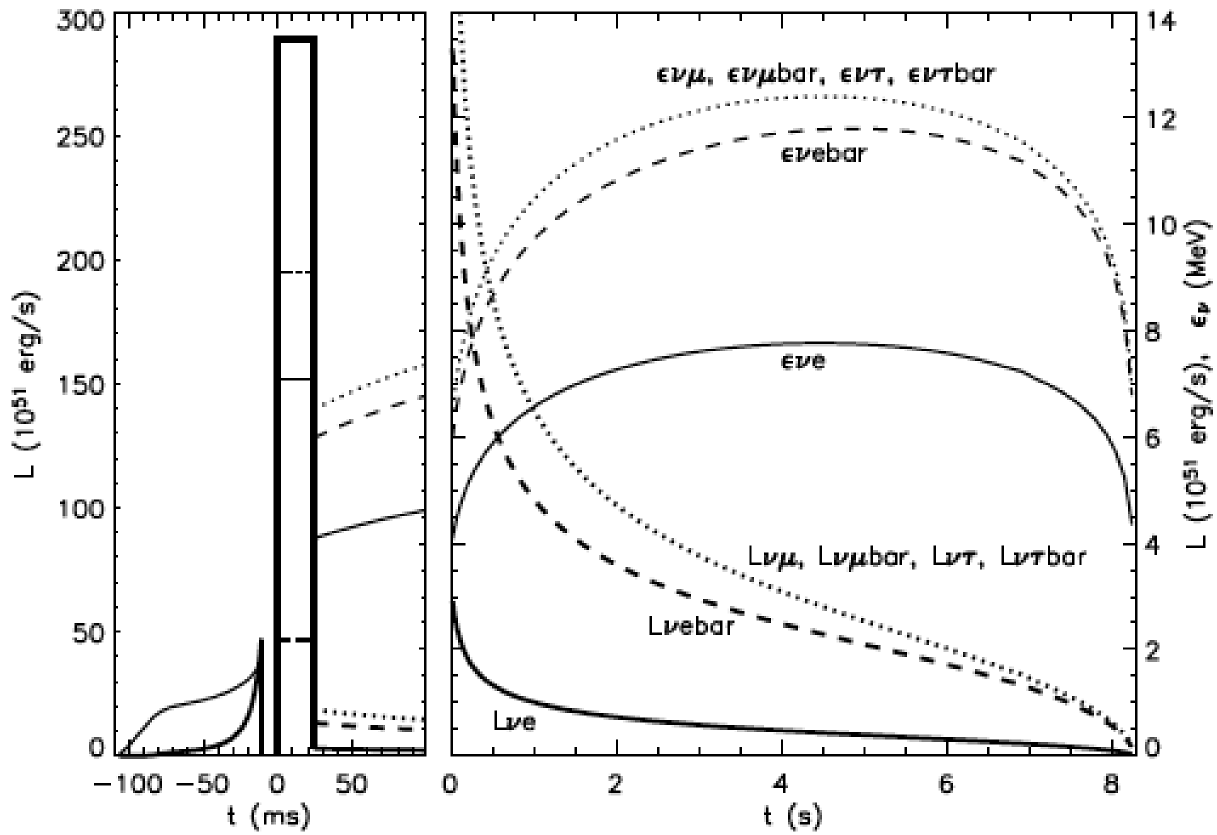
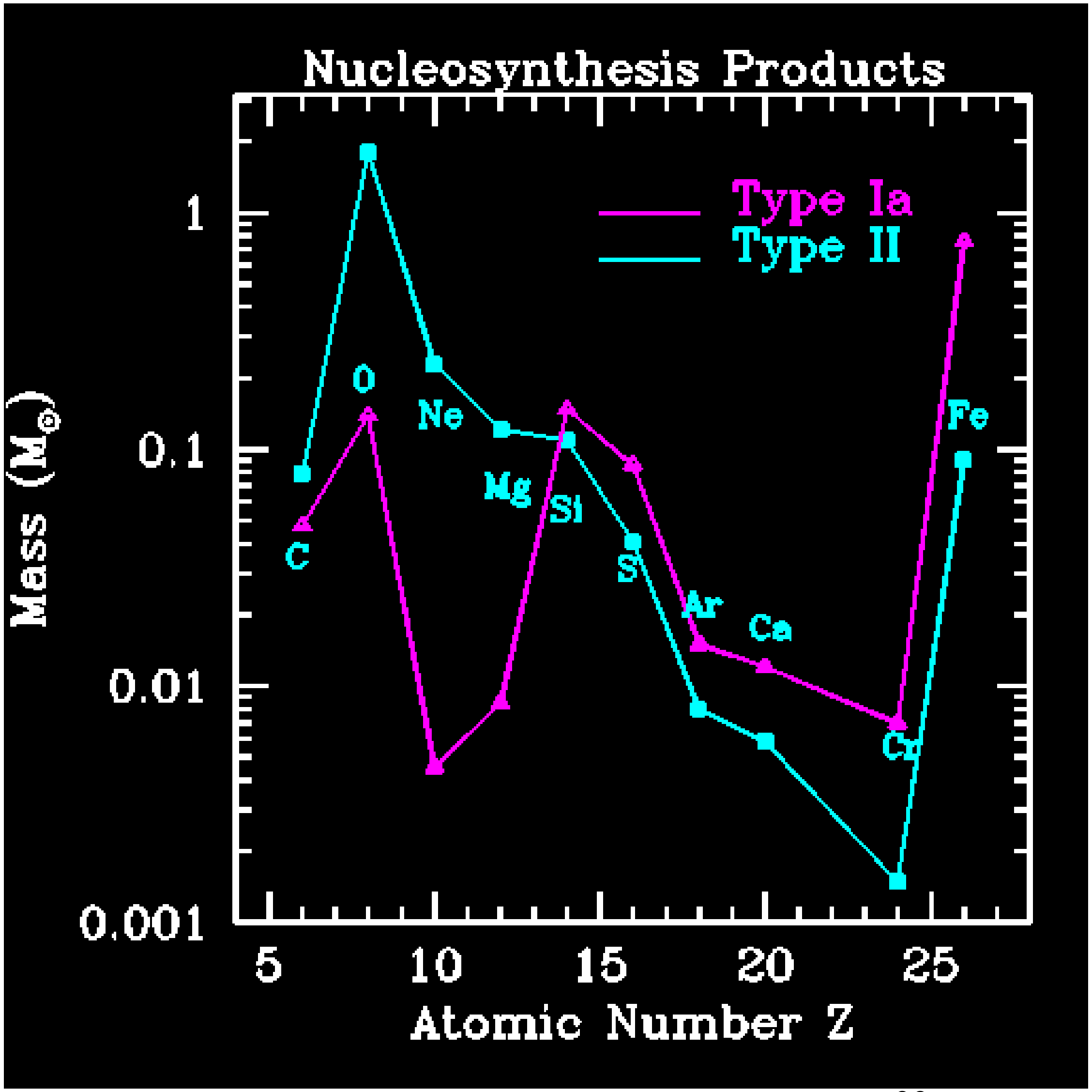


Figure 2. Crudely estimated neutrino luminosities (thick) and characteristic energies (thin). Note the change in time and luminosity (but not energy) scales between the left and right panels. The left panel is a close-up of infall and bounce at $t = 0$.

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}

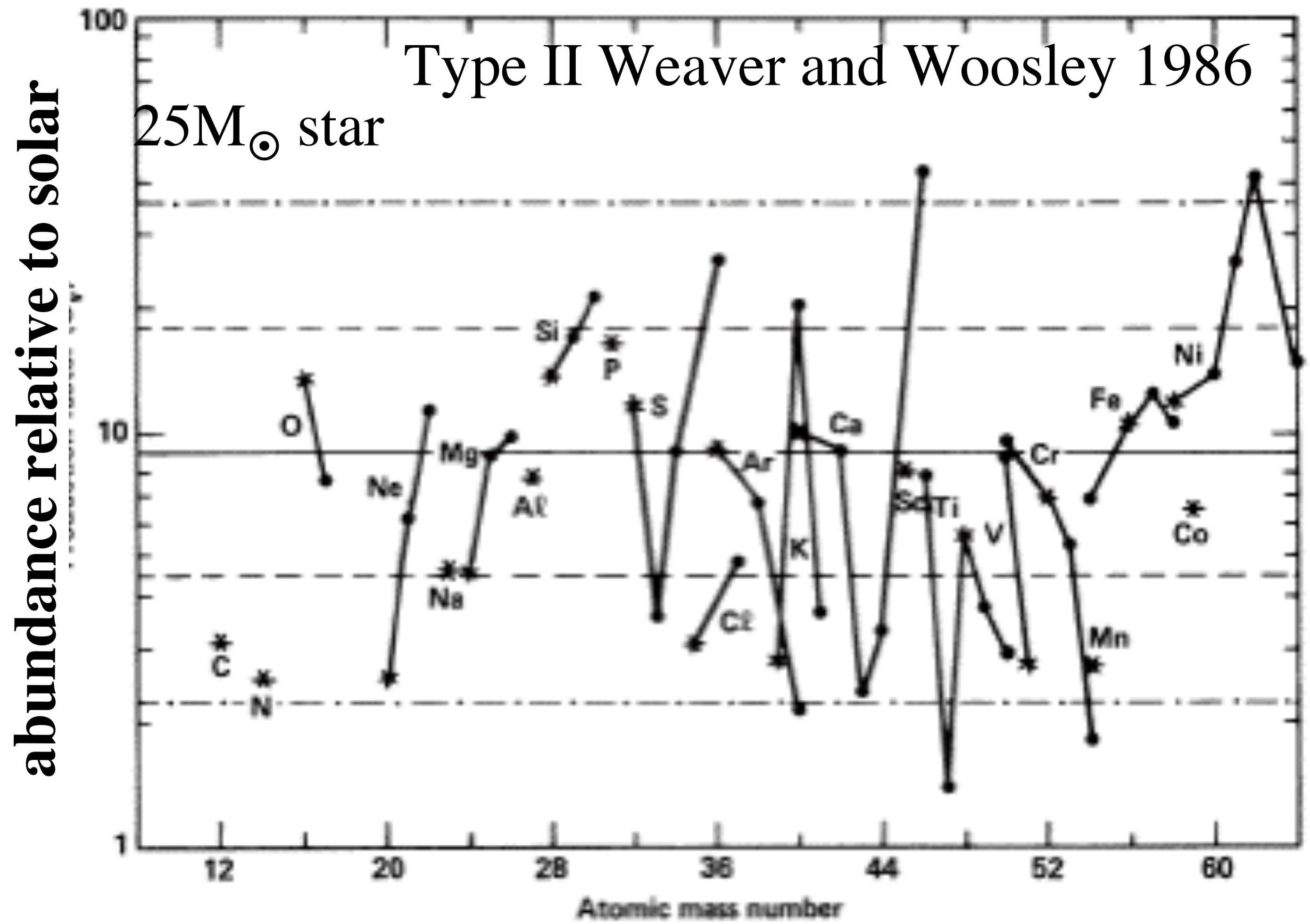
  - To get 'solar' composition need to add the sum of the two 'just right' and have the 'right' number of SN over cosmic times



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

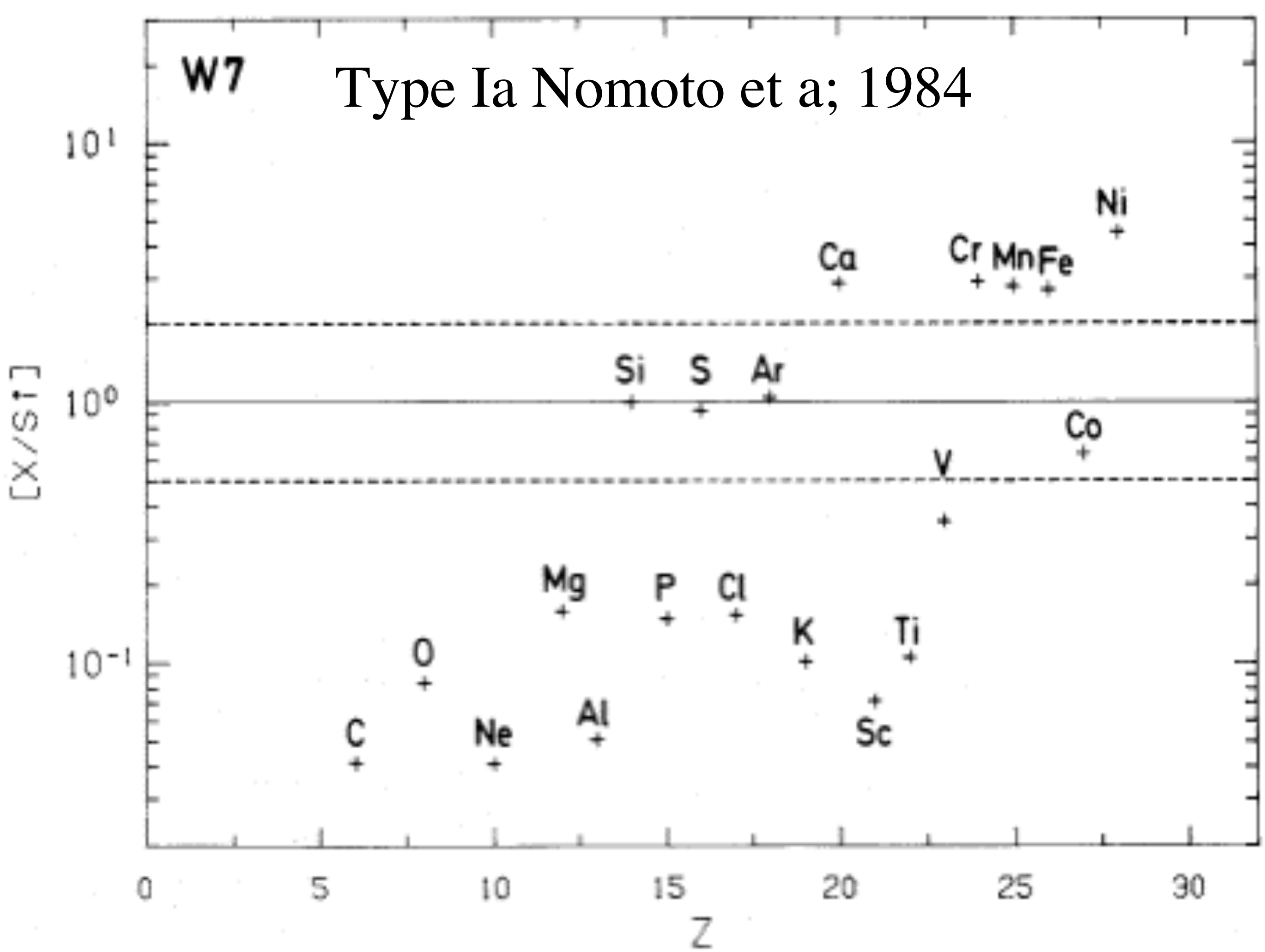


FIG. 10.—The abundances of elements relative to the solar values (W7). The ratio is normalized to Si.

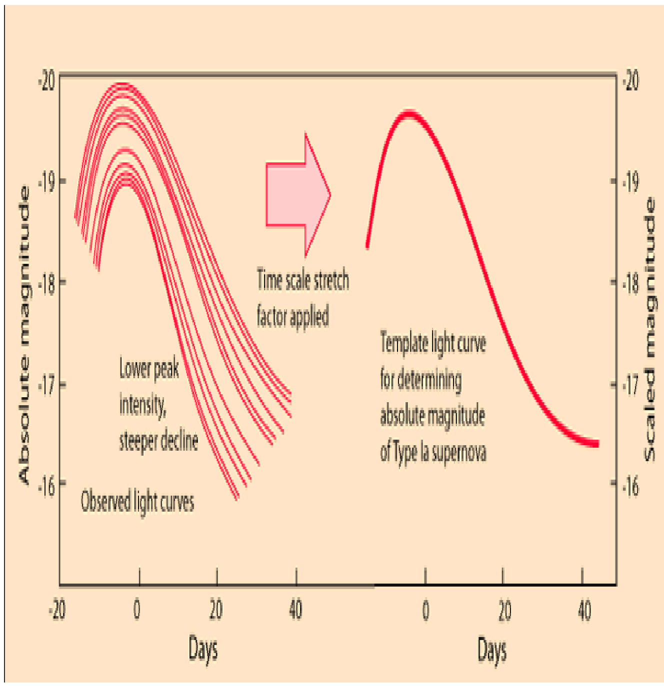
Type I SN and Cosmology

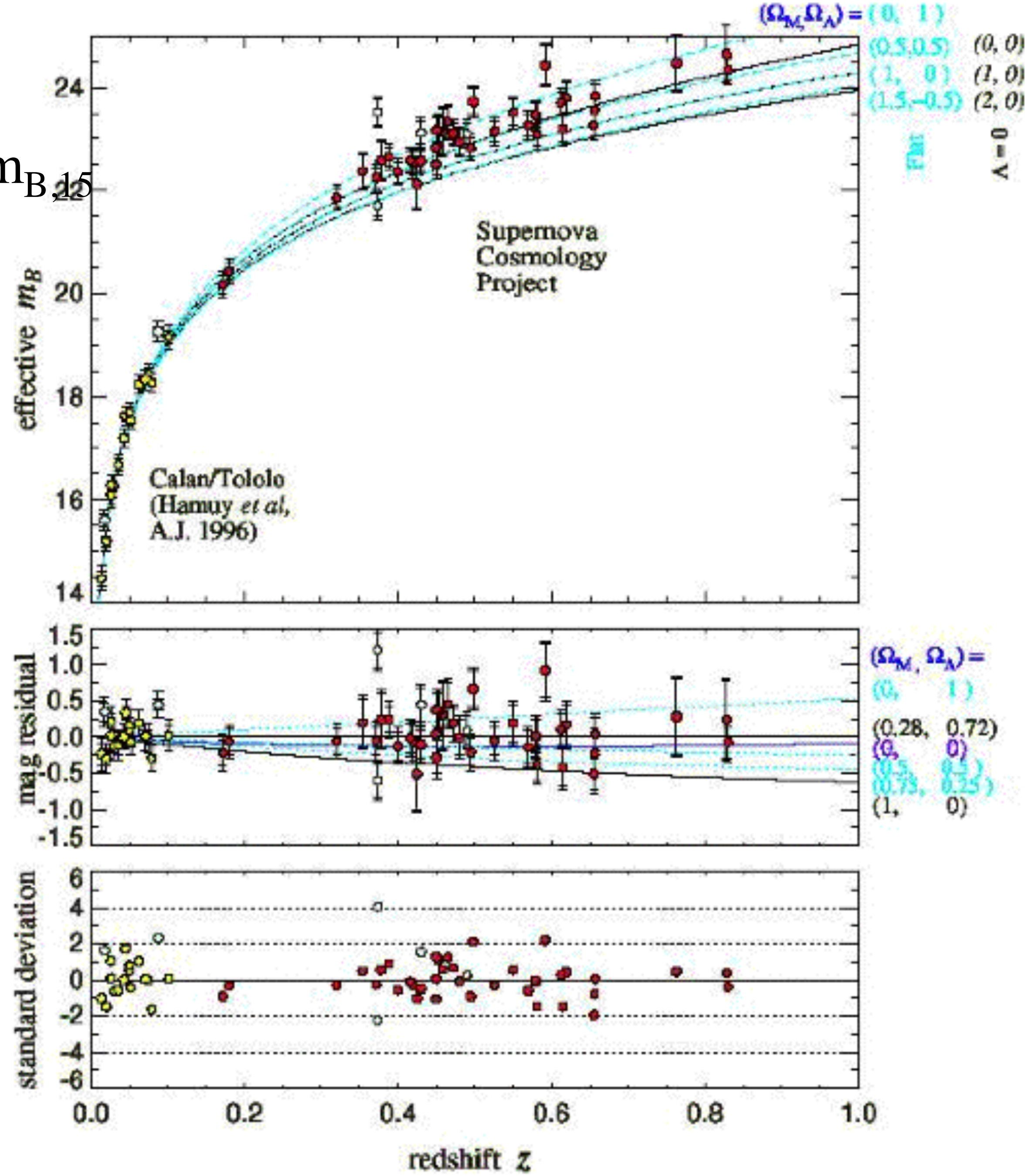
- how old is the universe, how fast is it expanding, how much material and of what type is in it, what is its fate?
- Need to determine the relationship between distance and redshift
  - Redshift (‘z’) is the measure of Doppler shift by the expansion of the universe- (1+z)~v/c
  - In General relativity 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 candle'- 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

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





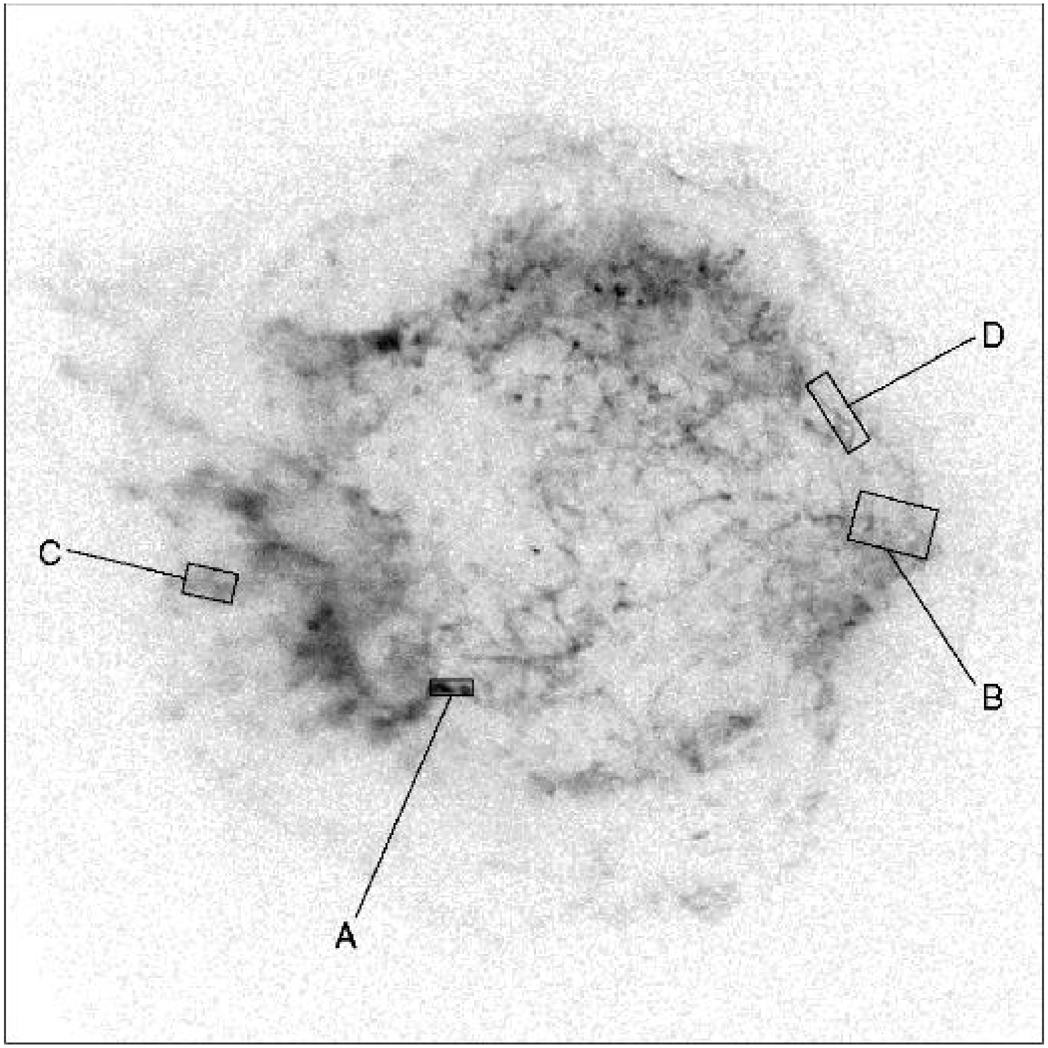
Perlmutter 2003

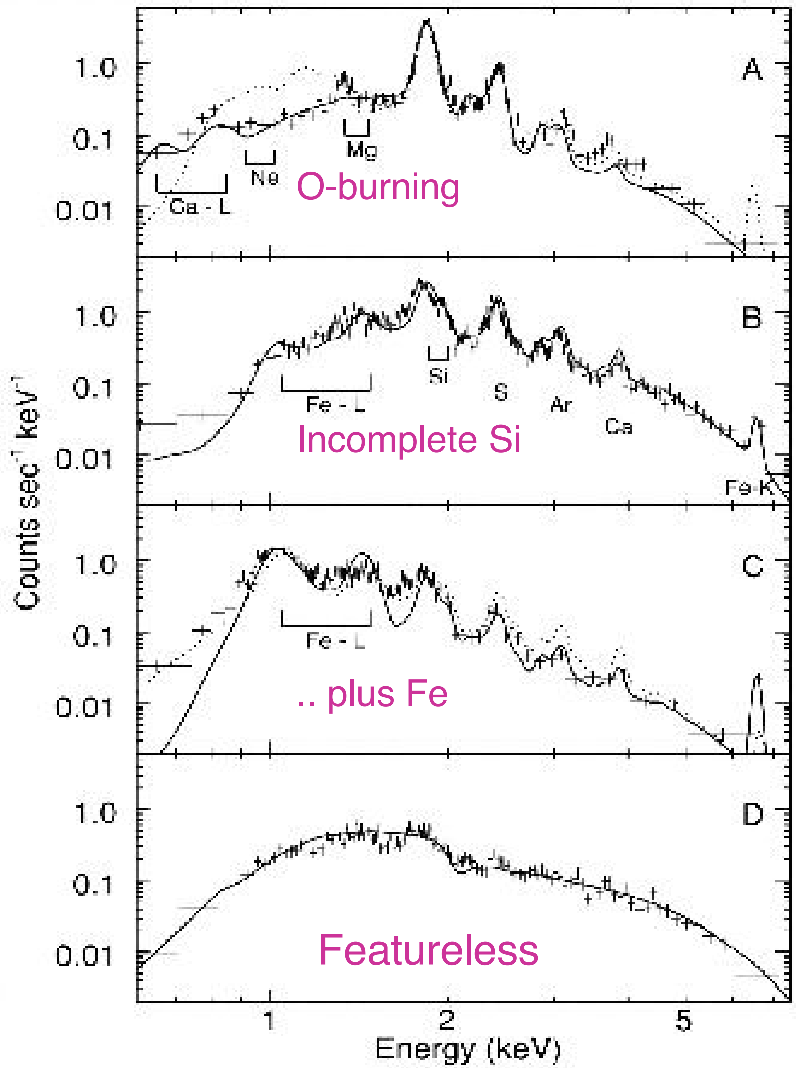
X-ray Emission from Supernova Remnants

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

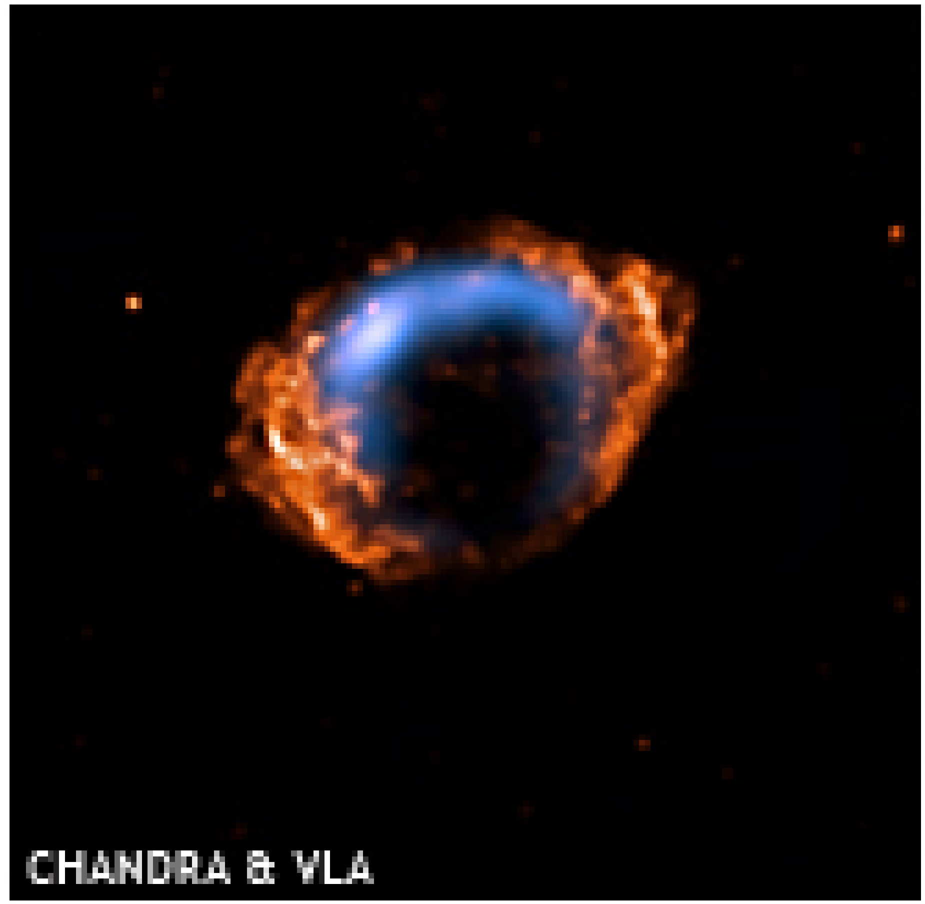


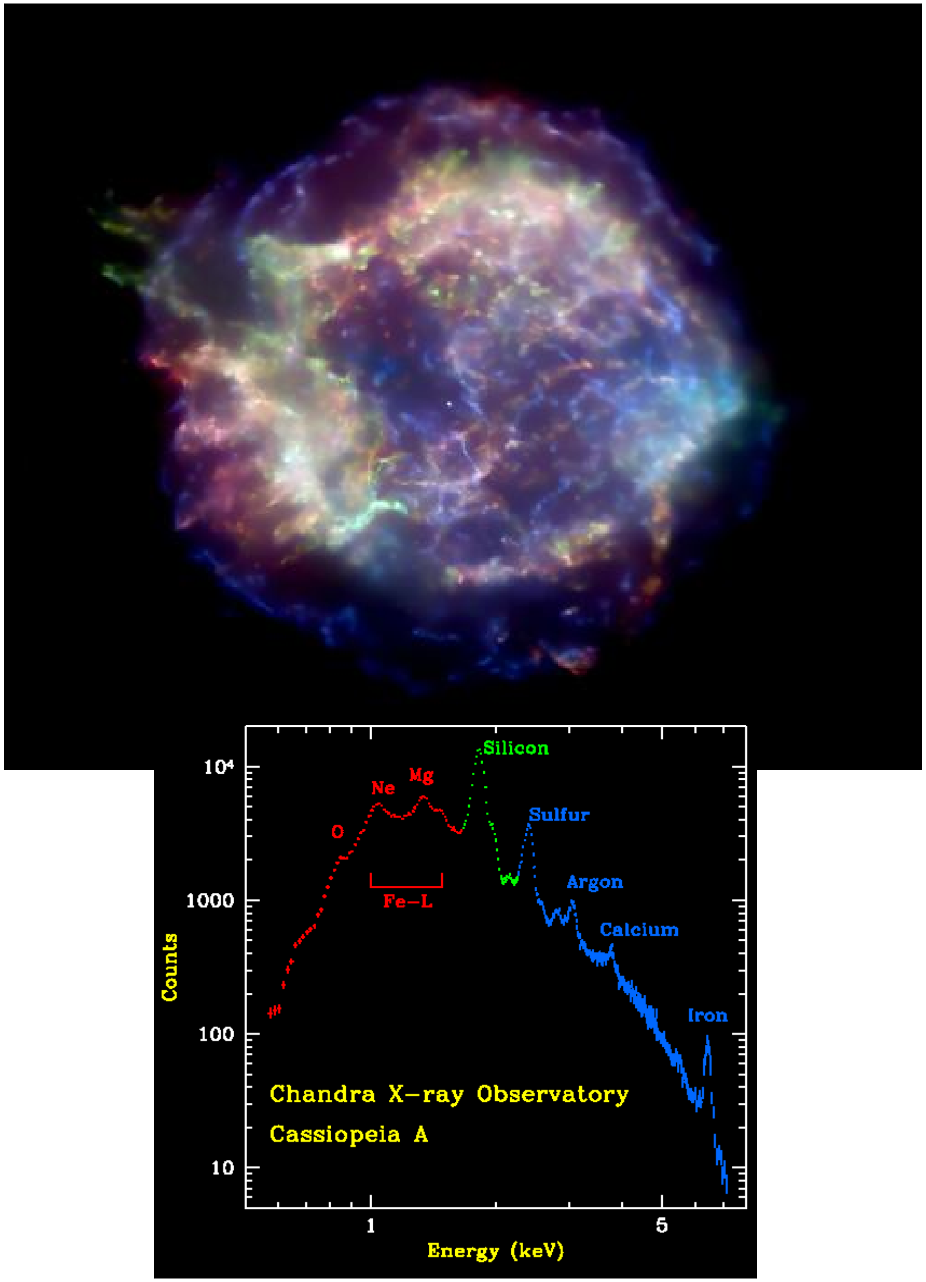


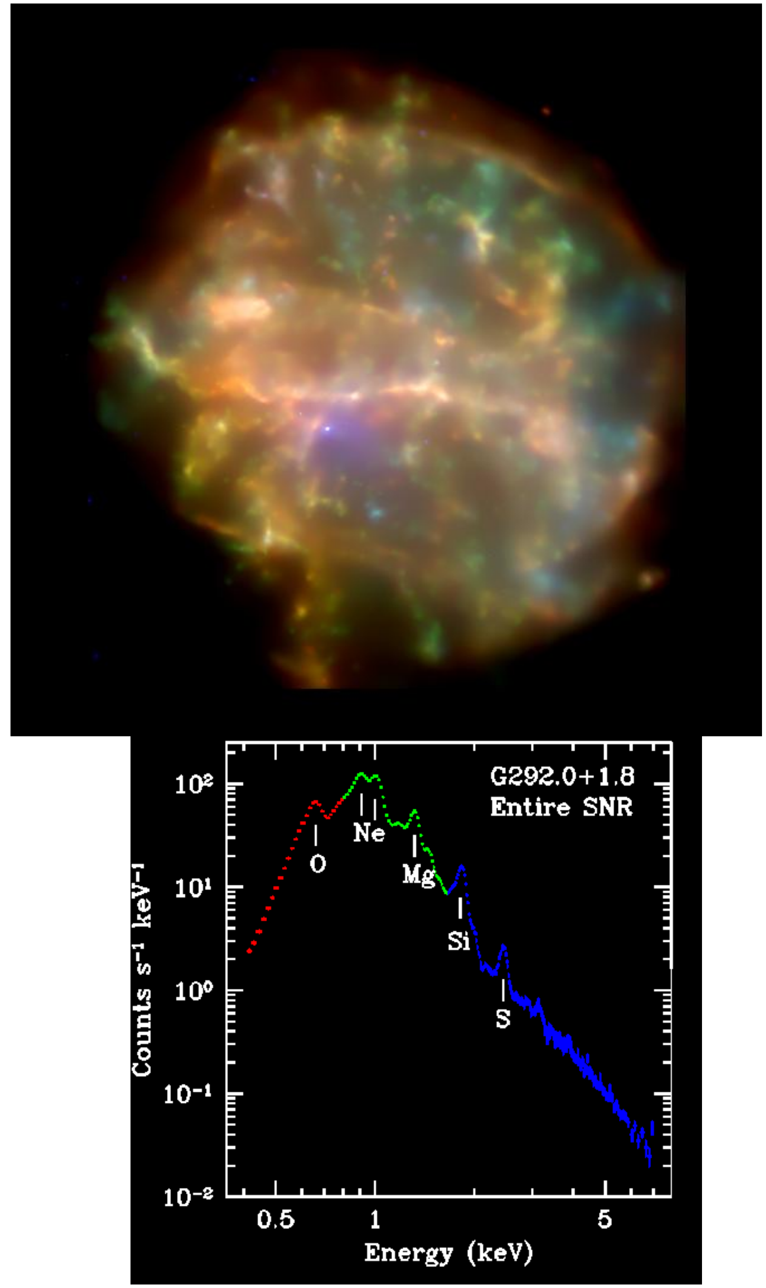
(Hughes et al. 2000 ApJ, 518, L109)

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.

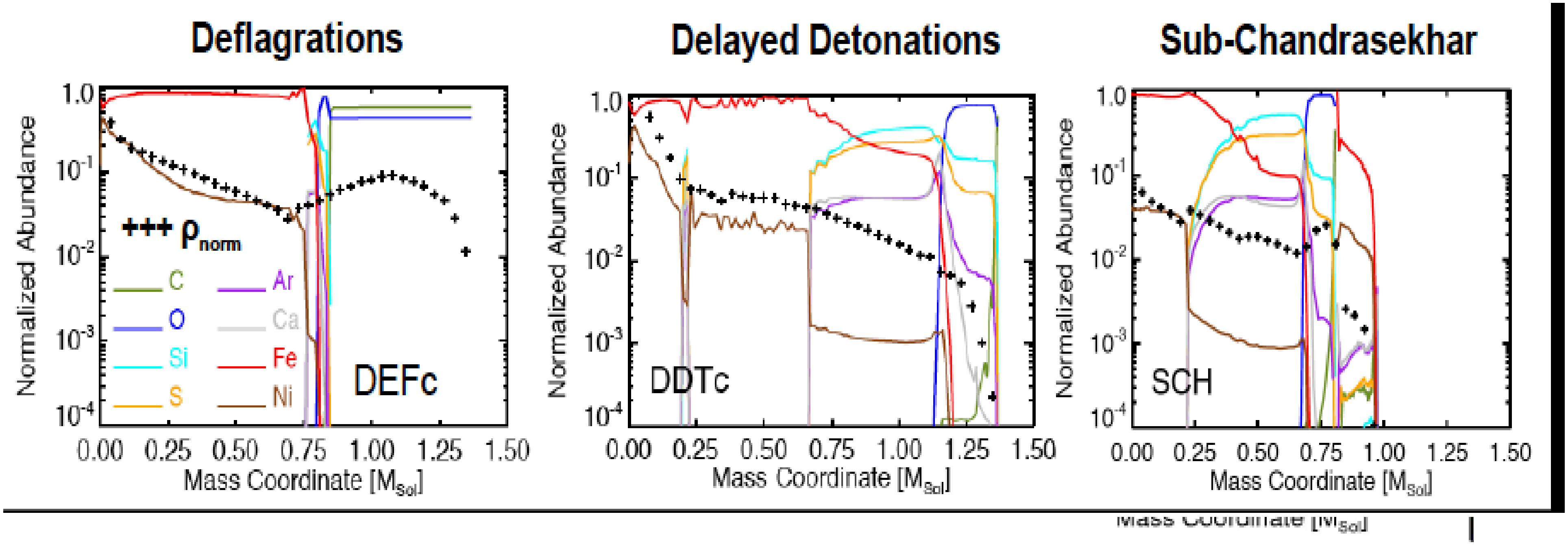






- Type Ia produce mainly Fe -- low O/Fe ratio.
- Type II produces: mainly 0 -- high O/Fe ratio

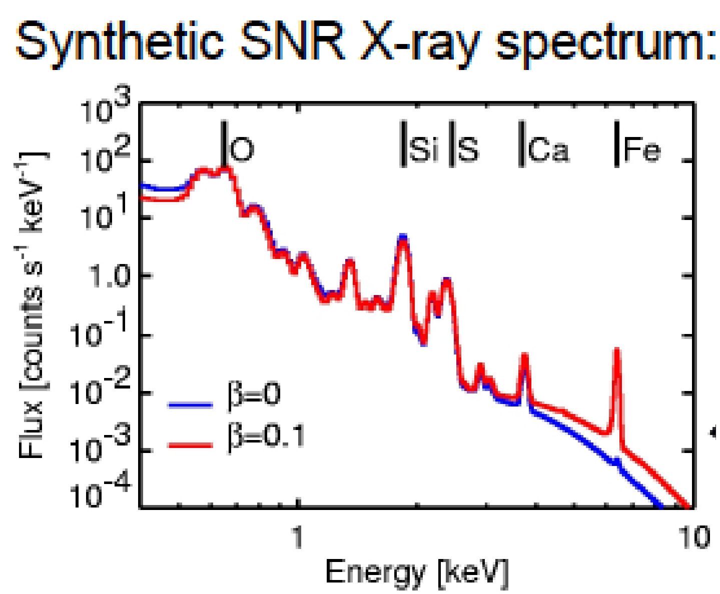
Examples of Yields from 3 Type Ia SN Models



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

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

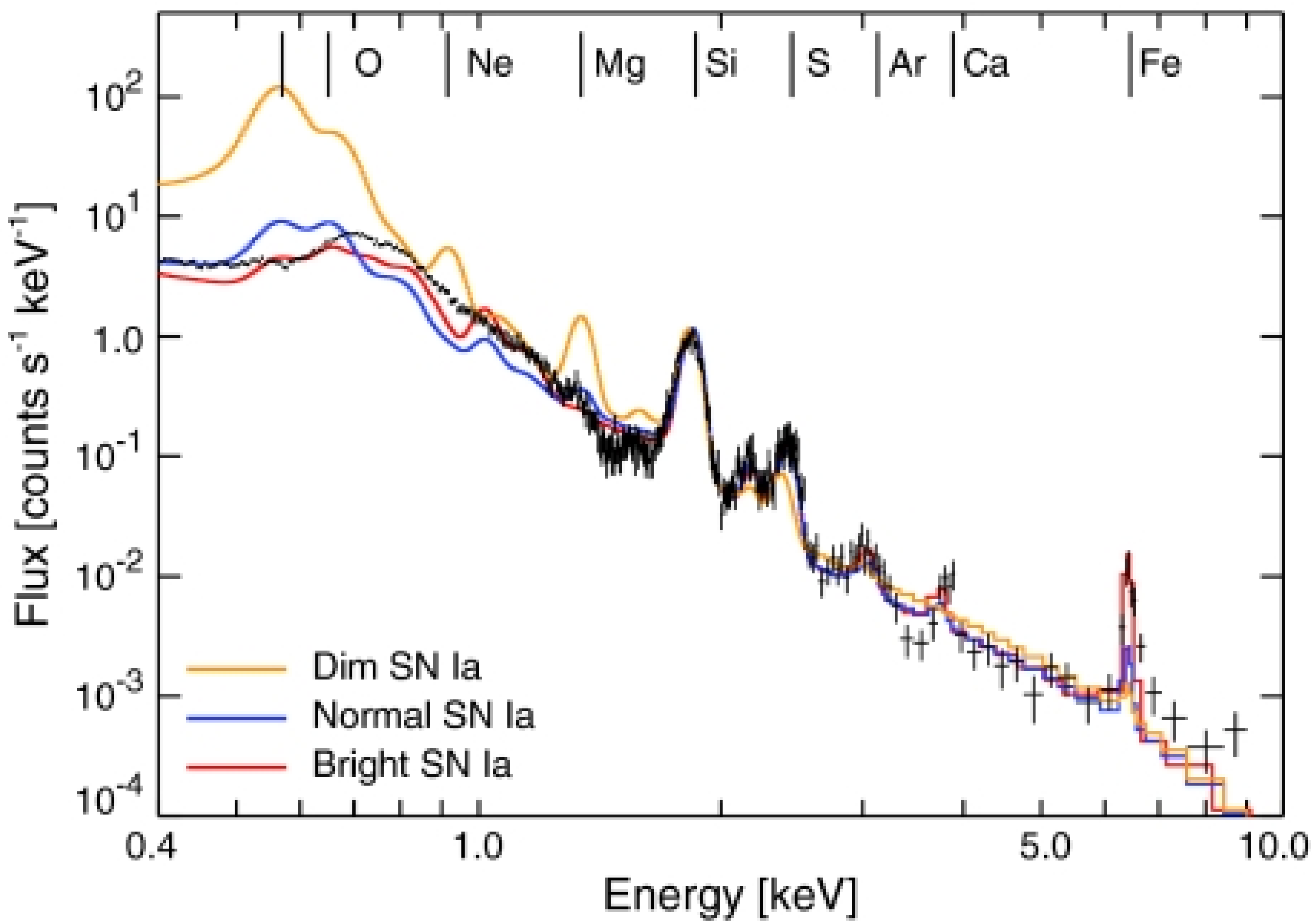
- $M_{Fe}=0.8\ M_{\odot}$, $M_{O}=0.12\ M_{\odot}$, $M_{Si}=0.17\ M_{\odot}$, $M_{S}=0.13\ M_{\odot}$, $M_{Ar}=0.033\ M_{\odot}$, $M_{Ca}=0.038\ M_{\odot}$



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

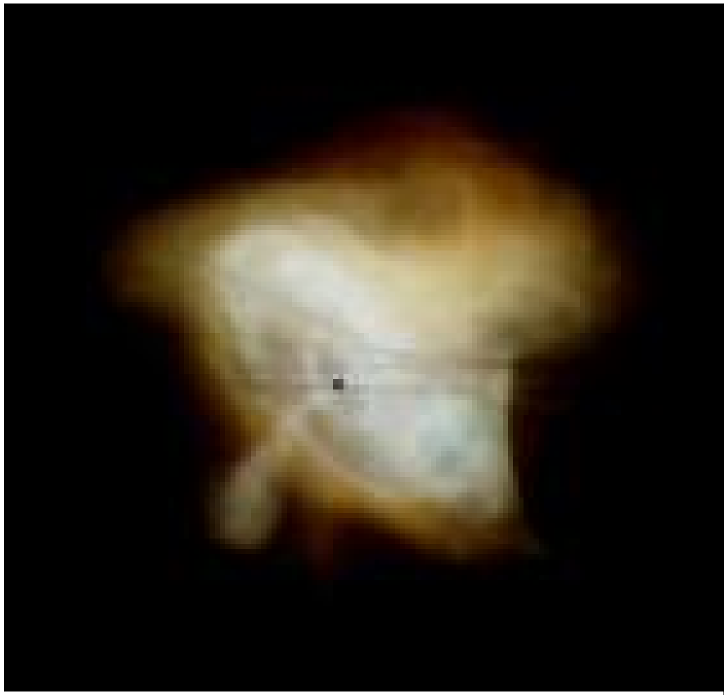
C. Badenes

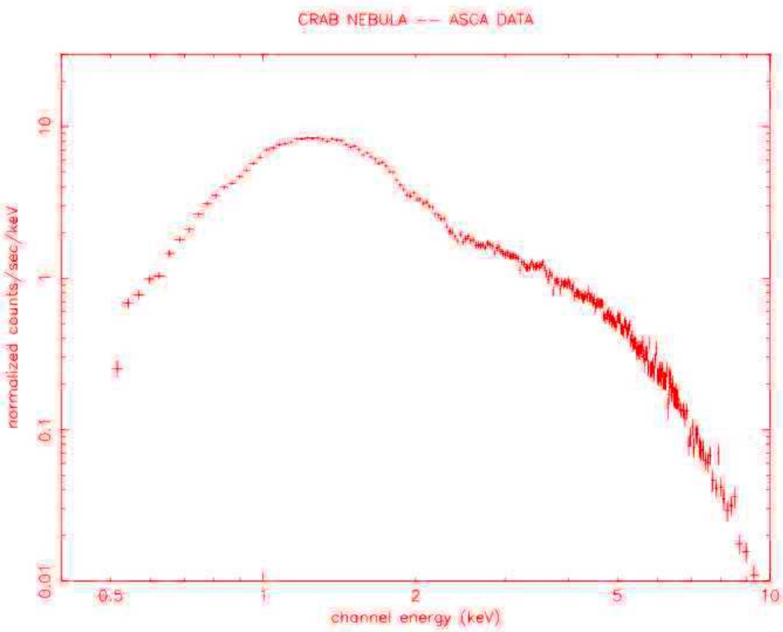
Proc Natl Acad Sci U S A. 2010 107(16): 7141–7146.



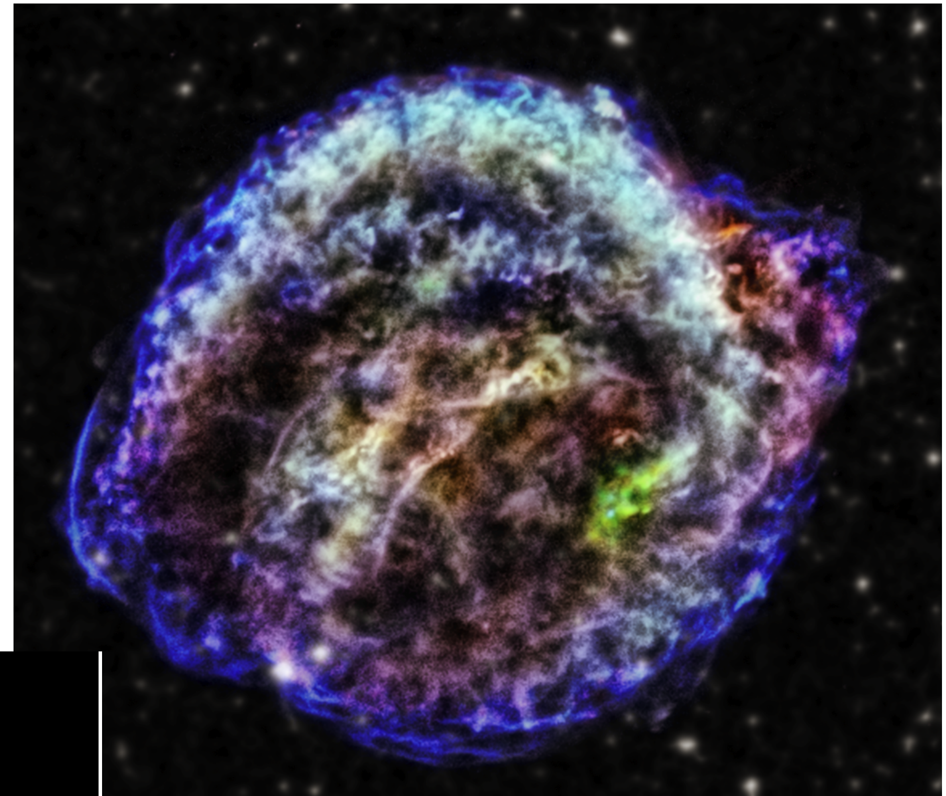
Non-Thermal Remnants

- 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

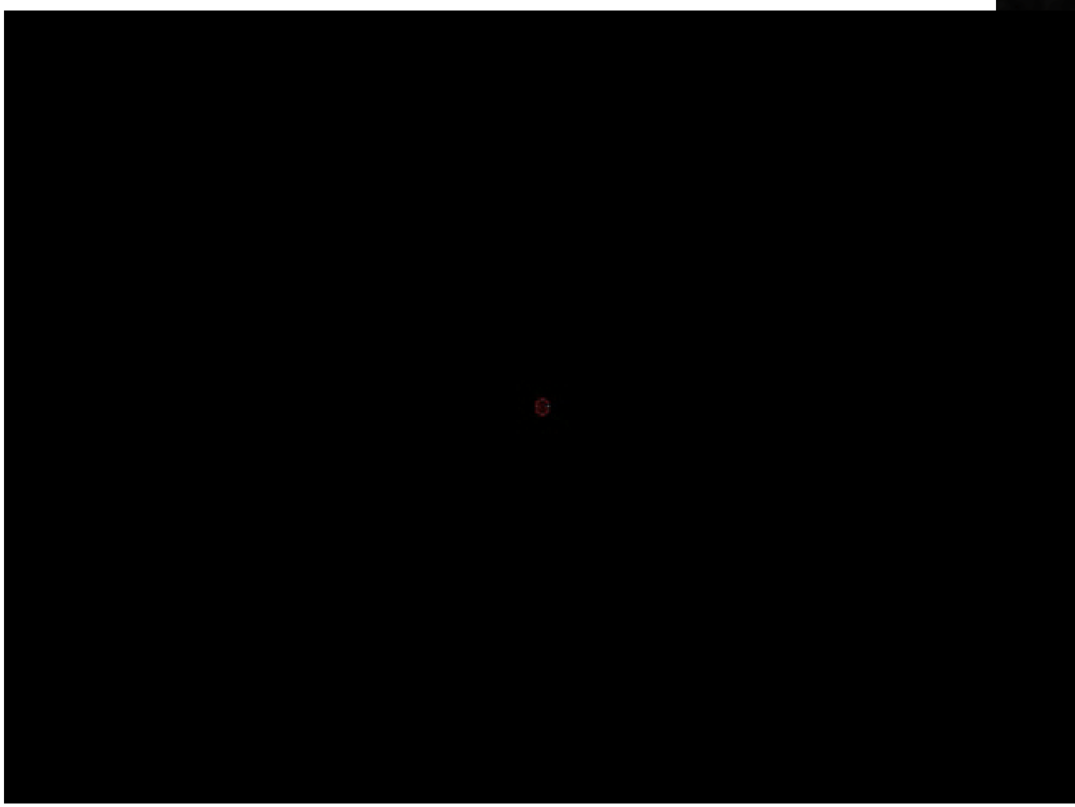




- Kepler SNR- remnant of a type Ia
- Chandra analysis indicates that the Kepler supernova was likely triggered by an interaction between a white dwarf and a red giant star.



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

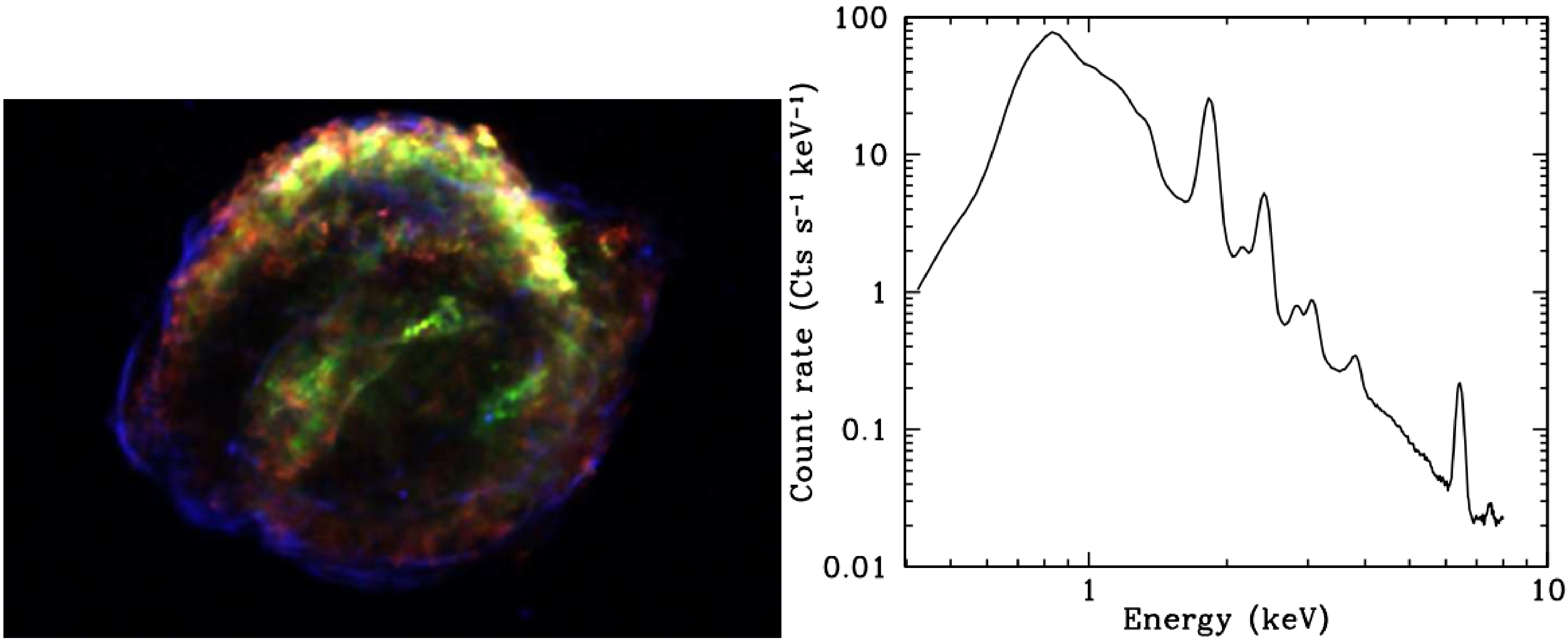
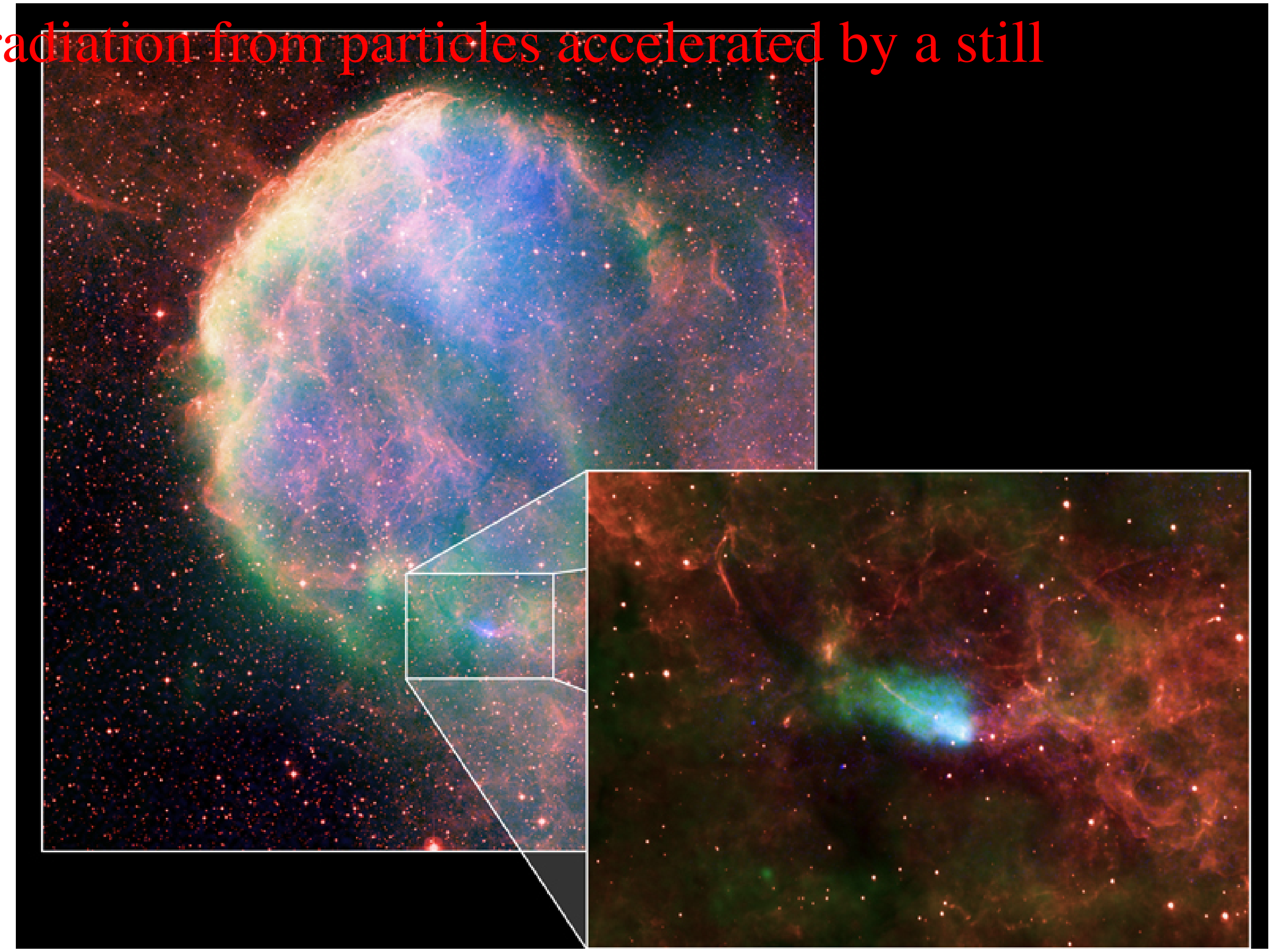


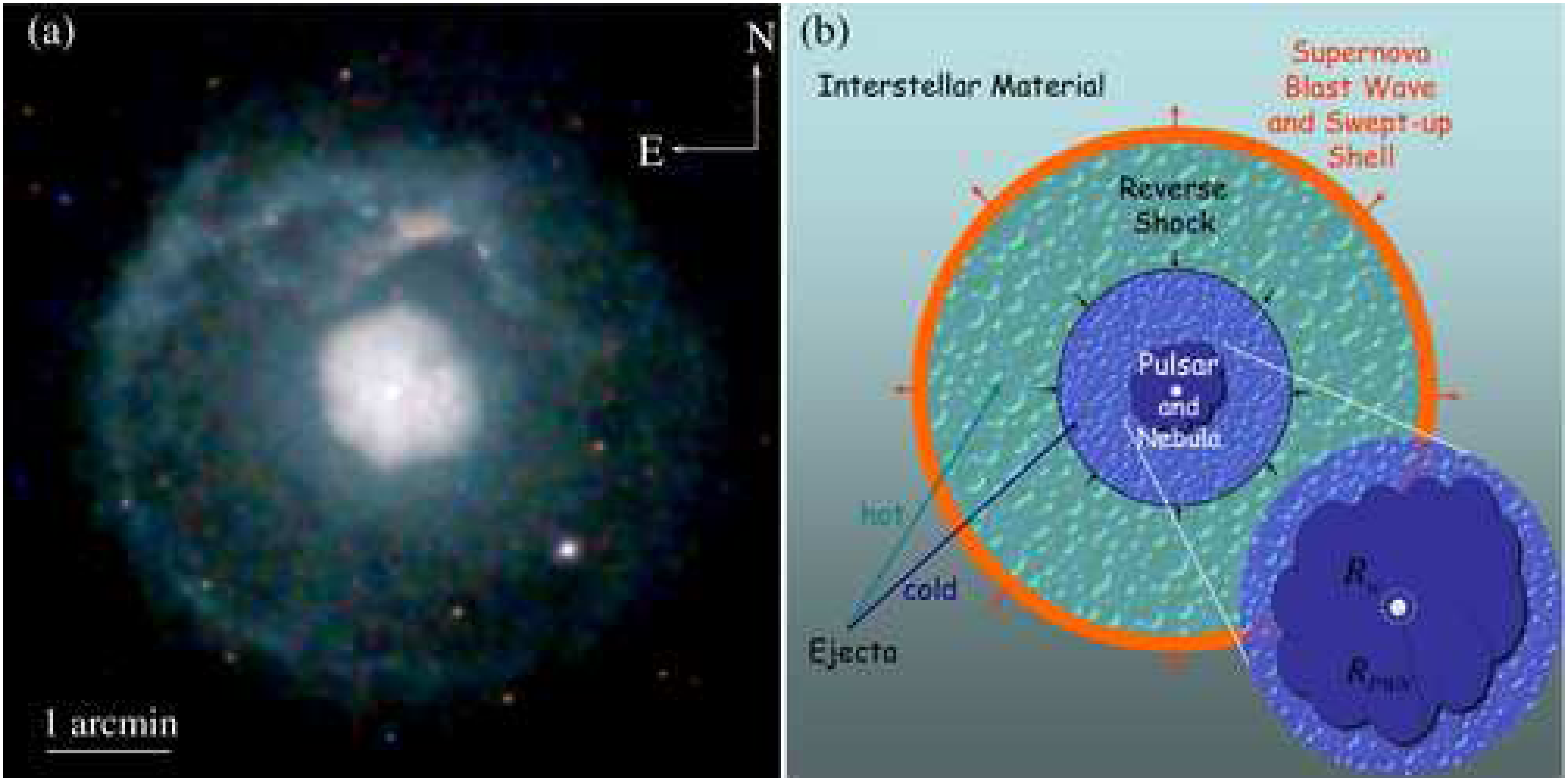
Figure 24: Left: *Chandra* image of Kepler's SNR, with red indicating Si-K α emission (1.75-1.95 keV), L emission (0.8-1.6 keV), and blue continuum emission (4-6 keV). The image is based on a deep, 750 ks,

- Vink 2012

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).

3 phases in SNR's life.

- Free expansion (less than 200-300 years)
- Adiabatic or "Taylor-Sedov" phase (about 20,000 years)
- Radiative or Snow-plow phase (up to 500,000 years)

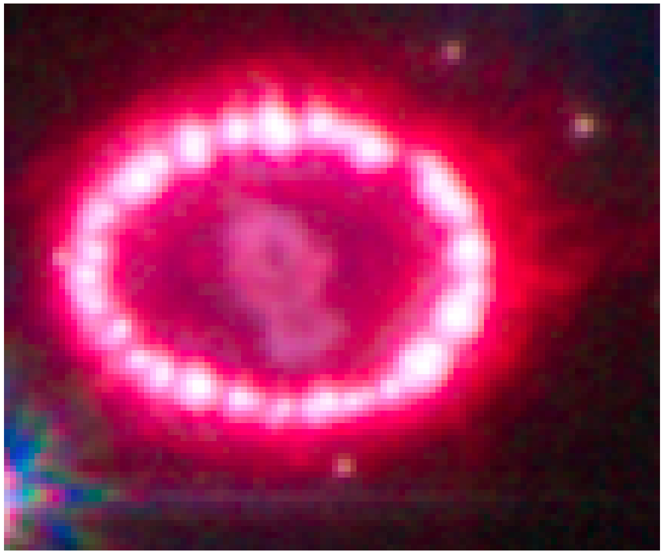
and then … Merge with the ISM

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 negligible 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

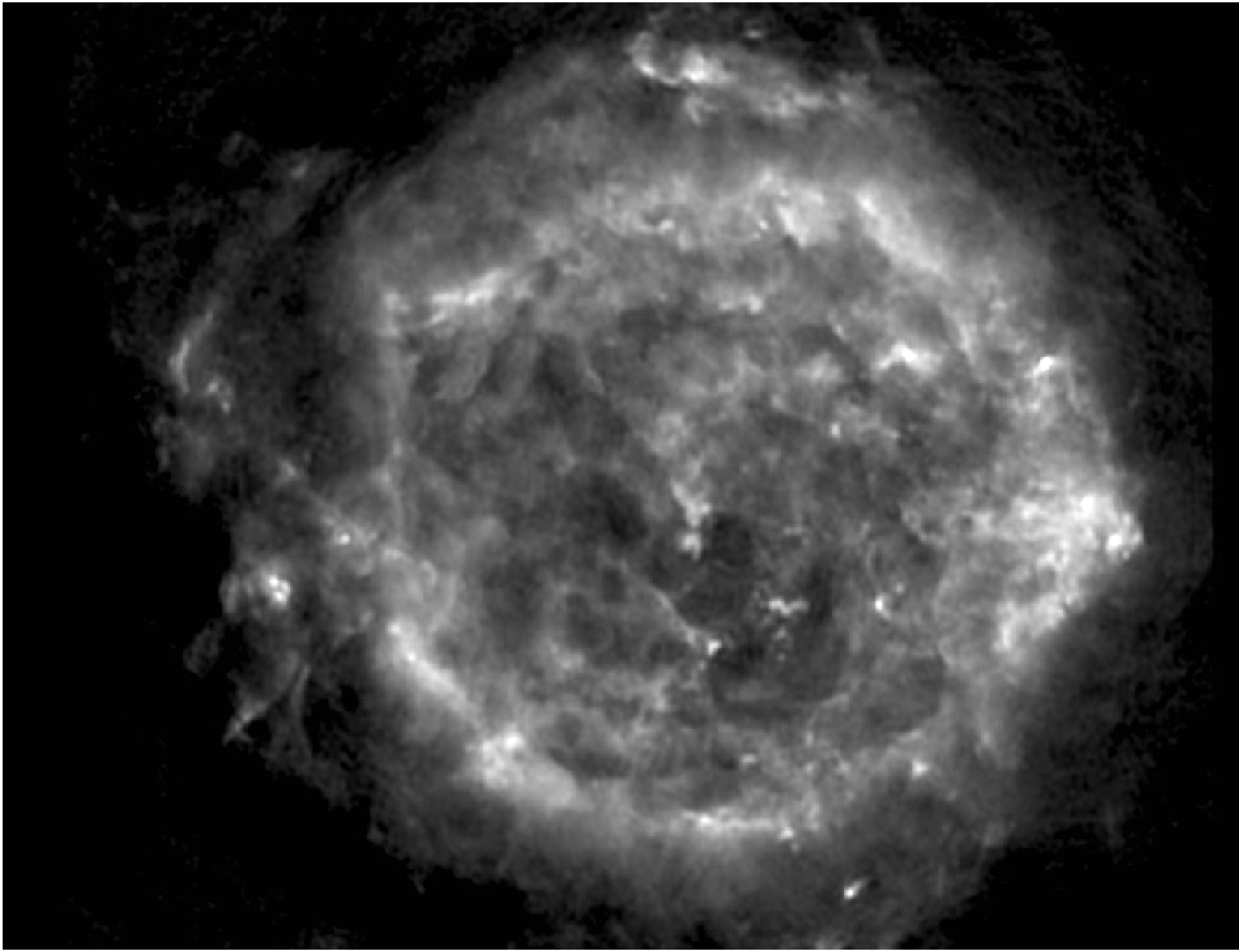
Temperature increases inward, pressure decreases to zero

Radiative

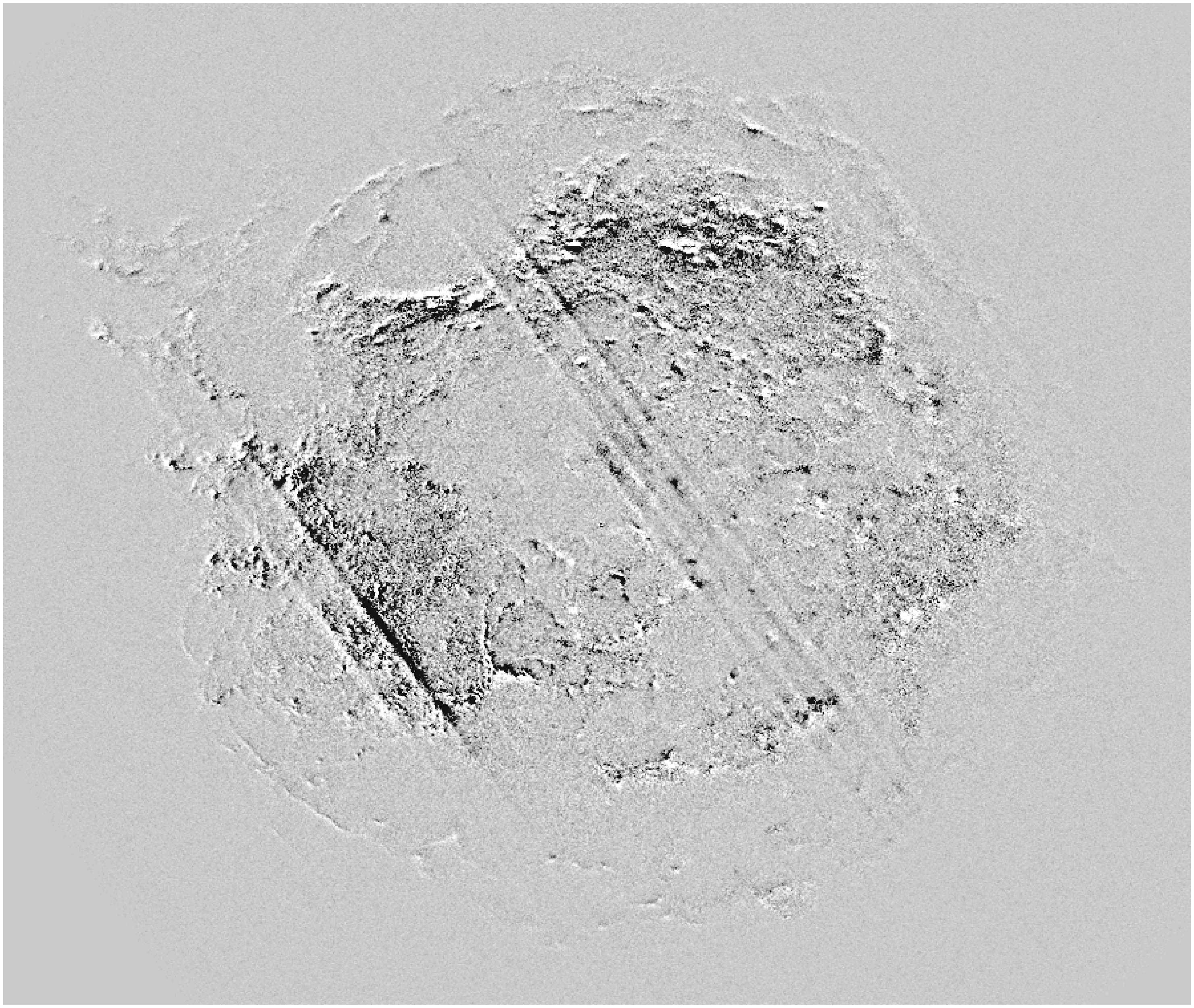
Dissipation of remnant energy into ISM

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

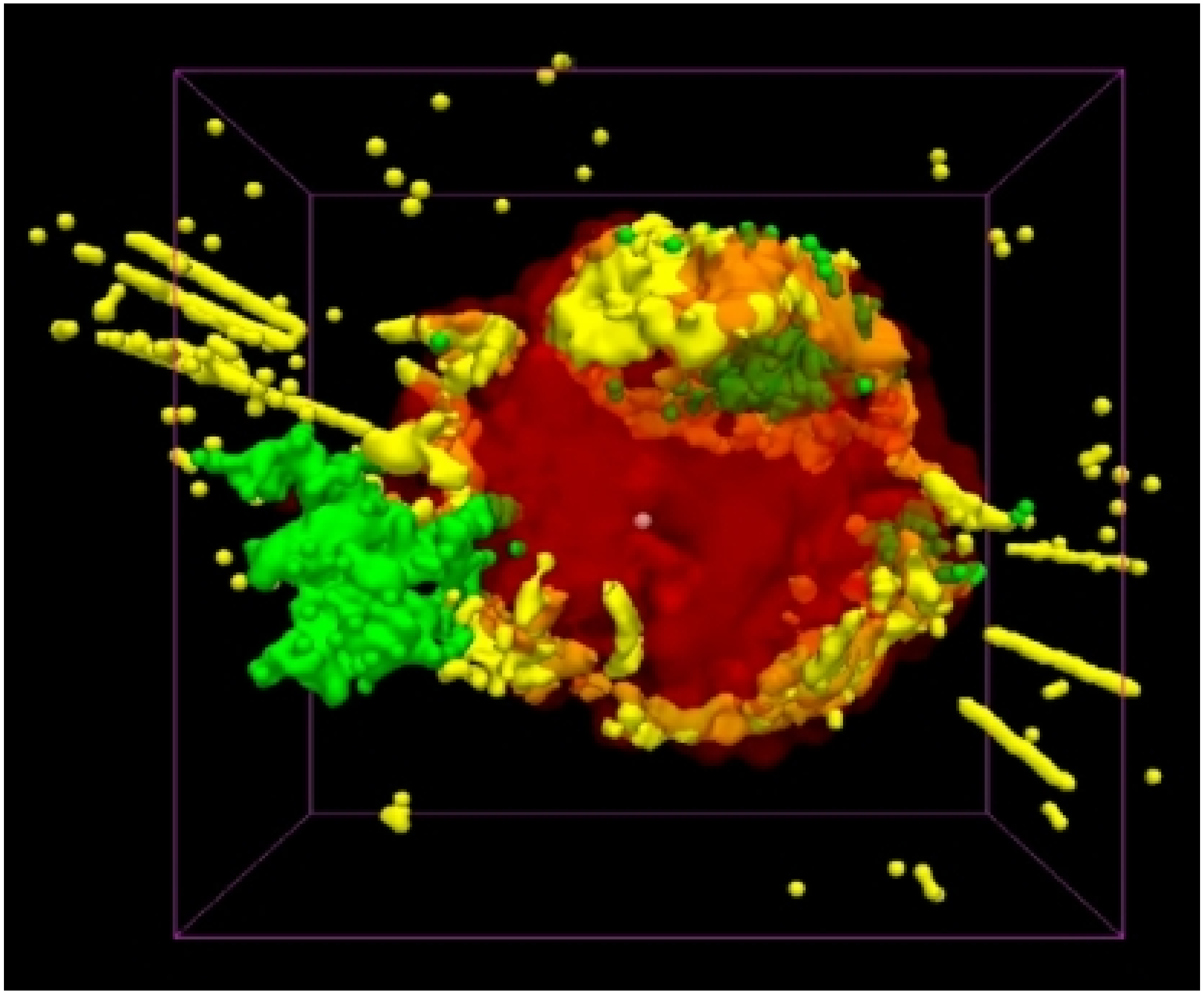


Cas-A Difference of X-ray Images Taken 2 Years Apart Delaney e al 2005



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