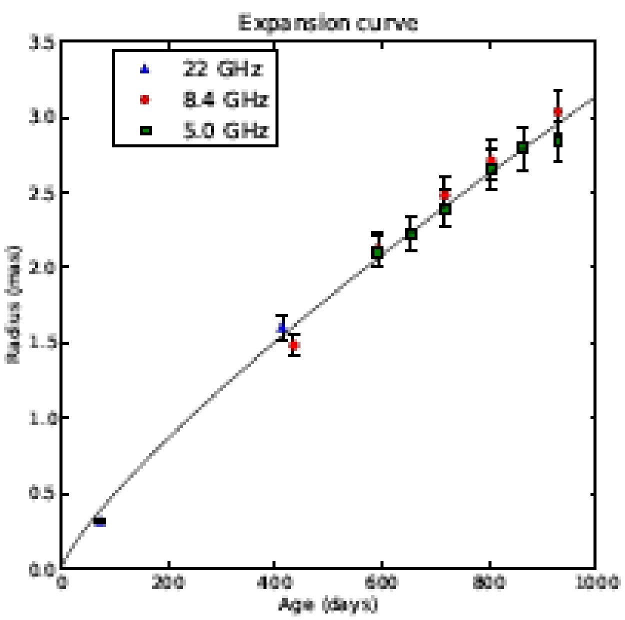
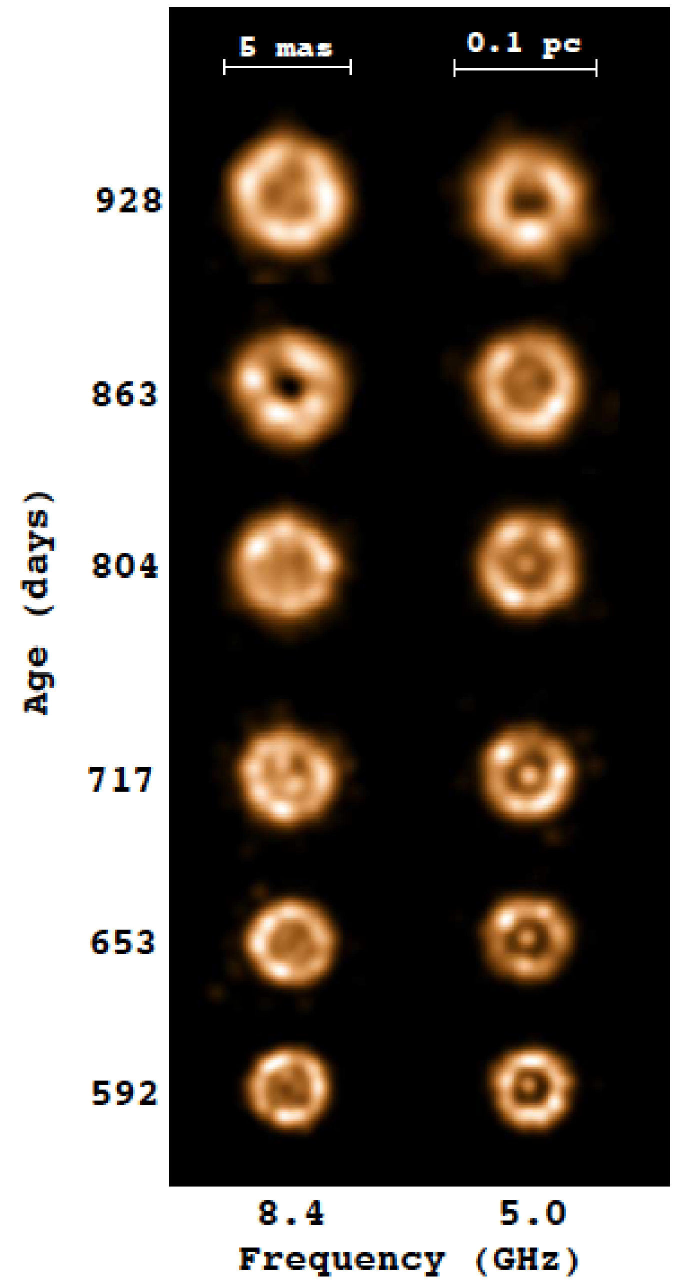
Super Nova and Super Nova Remnants

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

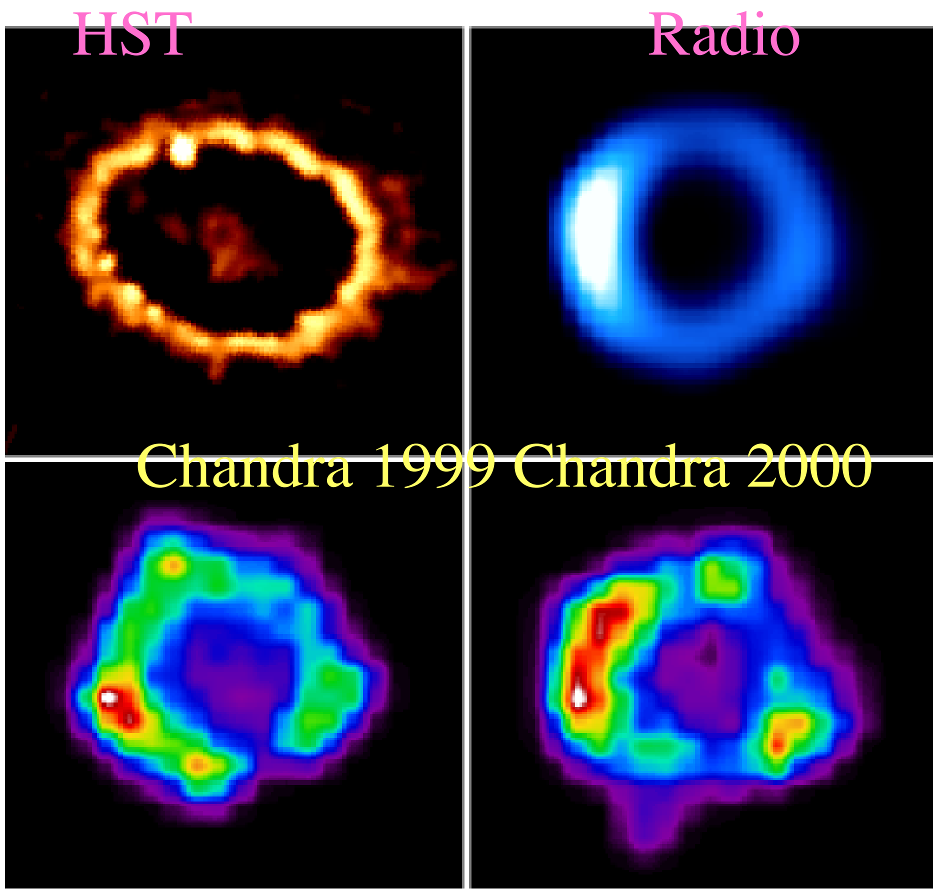


Radio images of SN2008
in M82 +Size vs time



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.

About 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..)

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

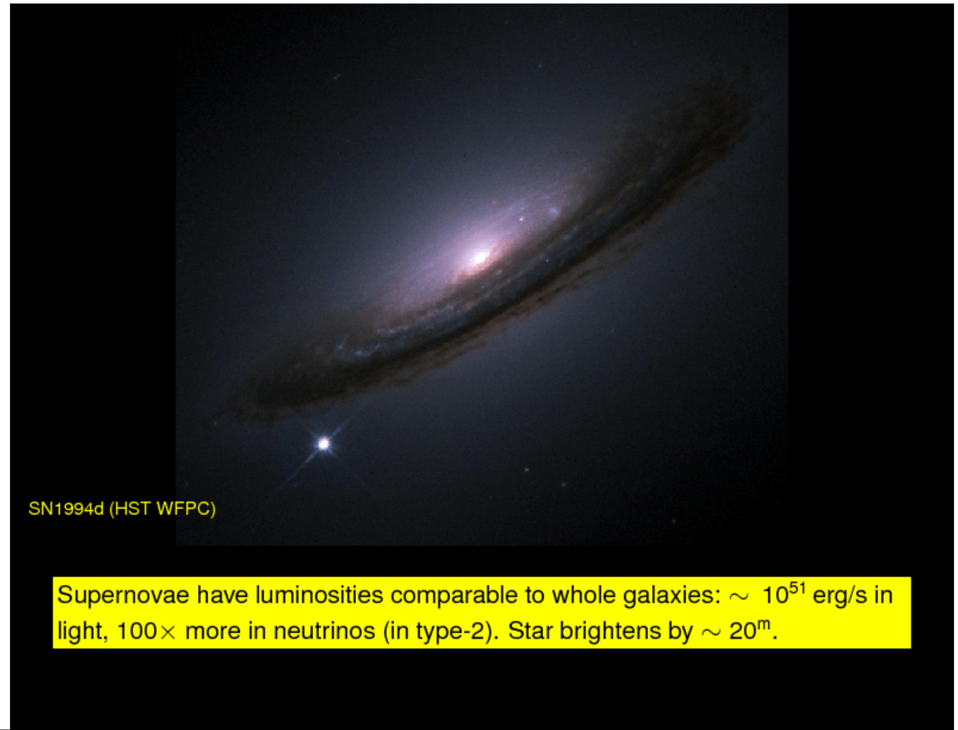
- For first ~1000 days the luminosity is driven by radioactive decay (type Ia)

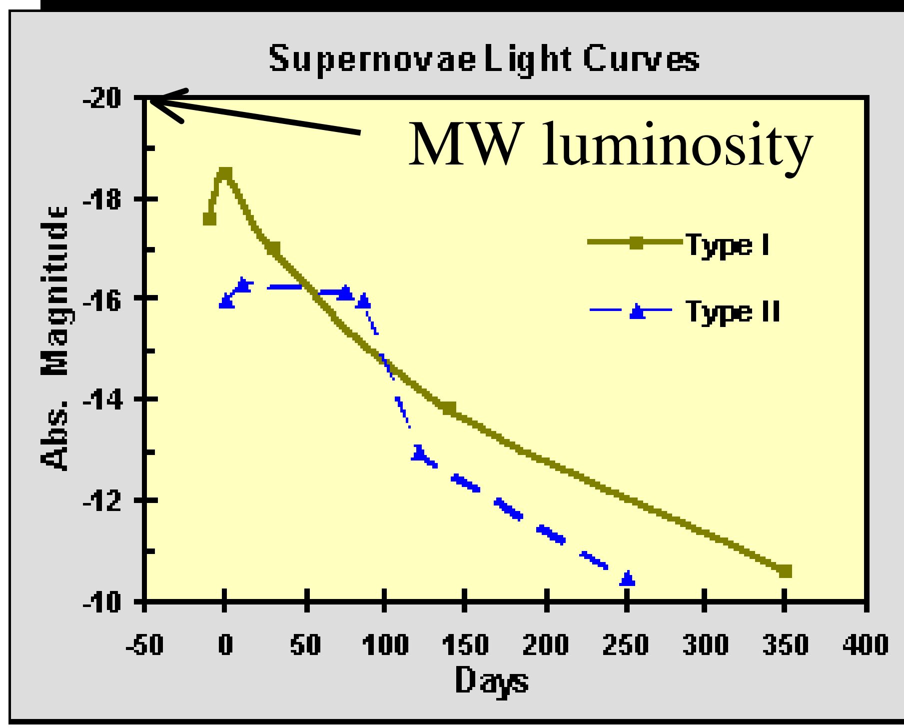
Ni^{56} → Co^{56} → Fe^{56} (77 day 1/2 life)

Velocites 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 can exceed that of the host galaxy- can be seem to z>1





Supernovae and Supernova Remnants

Supernovae

- powered mostly by radioactive decay: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$
- T~ 5000 K
- 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} K
- characteristic thermal emission is X-rays
- timescale ~100-1000 years

Supernova Explosions

Ia Thermonuclear Runaway

• Accreting C-O white dwarf reaches Chandrasekhar mass limit, 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)

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

•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**

II/Ib/Ic Core-Collapse of Massive Progenitor

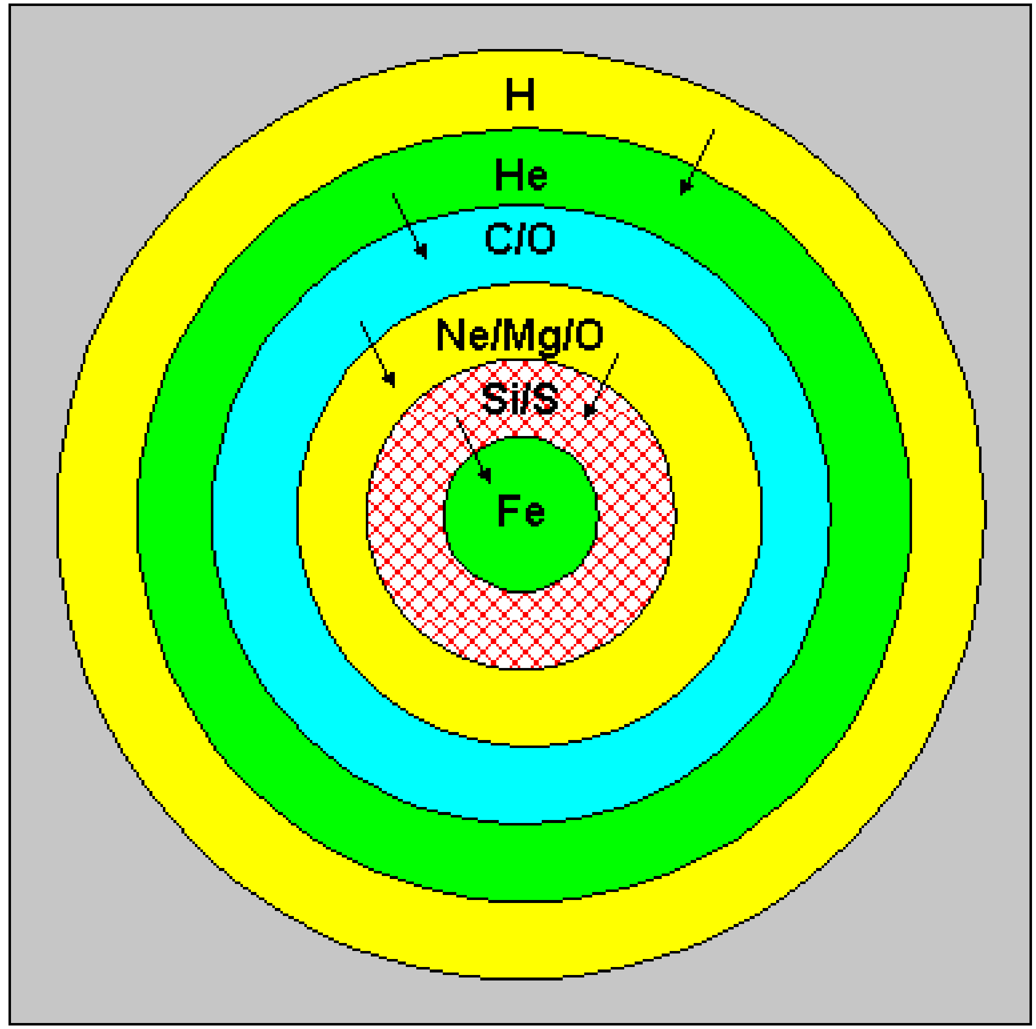
- Massive progenitor core forms neutron star or black hole

- <u>Explosive</u> 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 (kT sensitive) Nobel prize 2002

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

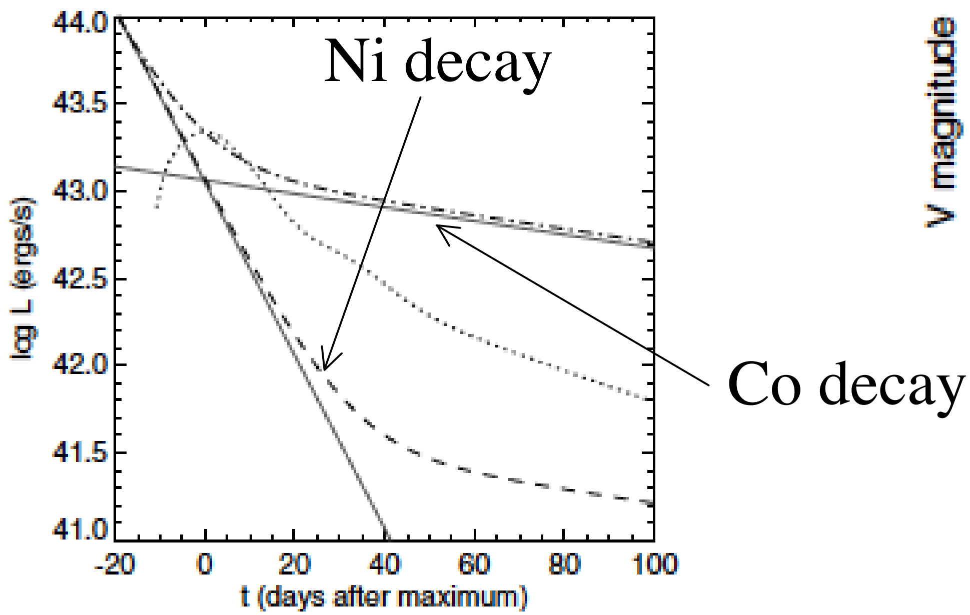
Supernova Explosions



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

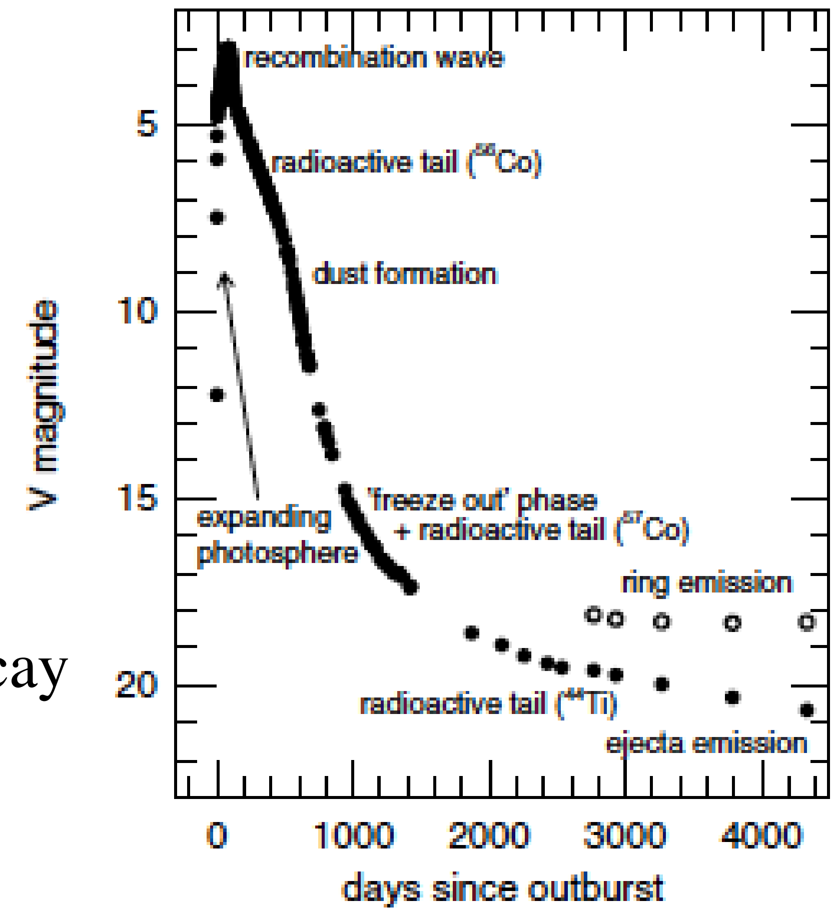
SN Light Curves

Type Ia

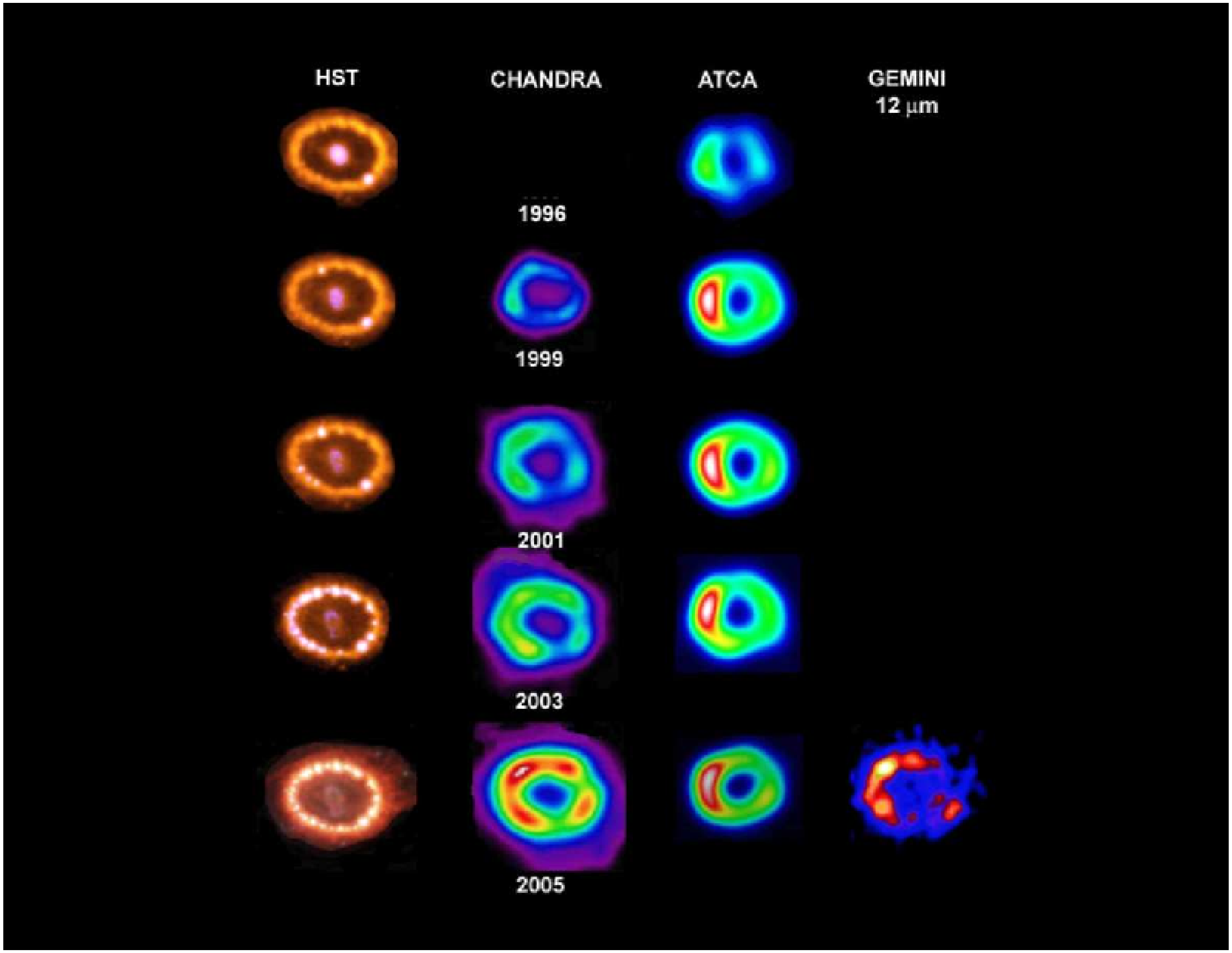


Type II

Bruno Leibundgut

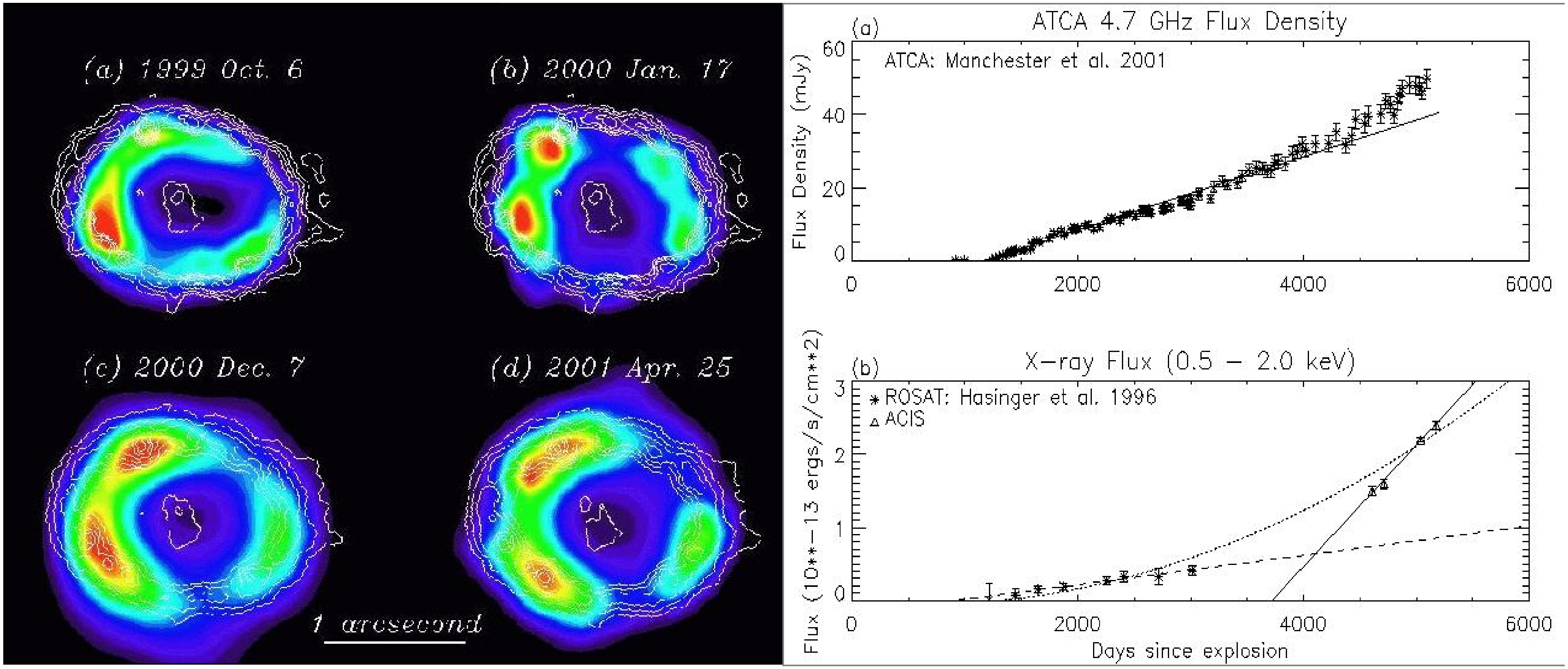


- Young SN remants evolve rapidly
- Some extragalactic SN have been followed for years



SN 1987A Through Time in Different Wave Bands

SNR 1987A in Large Magellanic Cloud



Park et al. 2002 , Burrows et al. 2001

X-ray emission is approaching inner circumstellar ring
X-rays correlate well with radio

Explosive Nucleosynthesis

Nuclear processing as the supernova shock wave propagates through the star (e.g., see Arnett 1996)

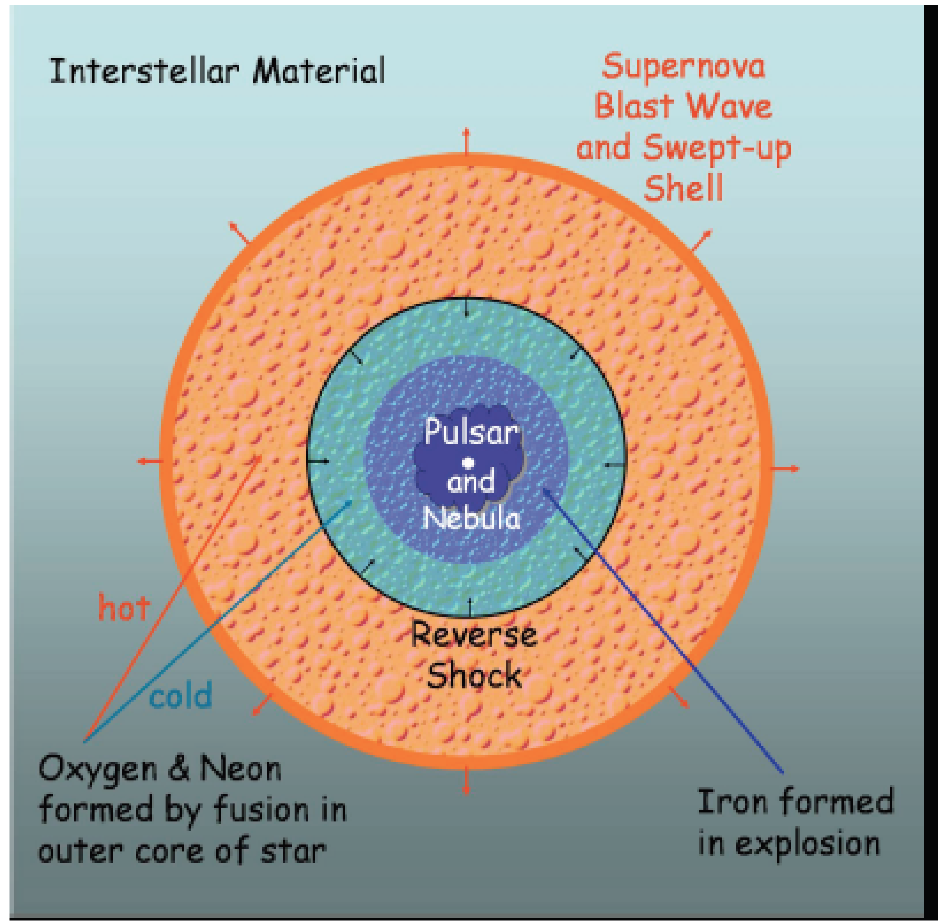
'α' products

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

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

- Mass range for Type II SN bounded by lower end of most massive stars that can become white dwarfs ($8M_\odot$) and 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 Ia are the main producer of iron in the universe. Their progenitors have long life times, compared to massive stars which become core-collapse supernovae.

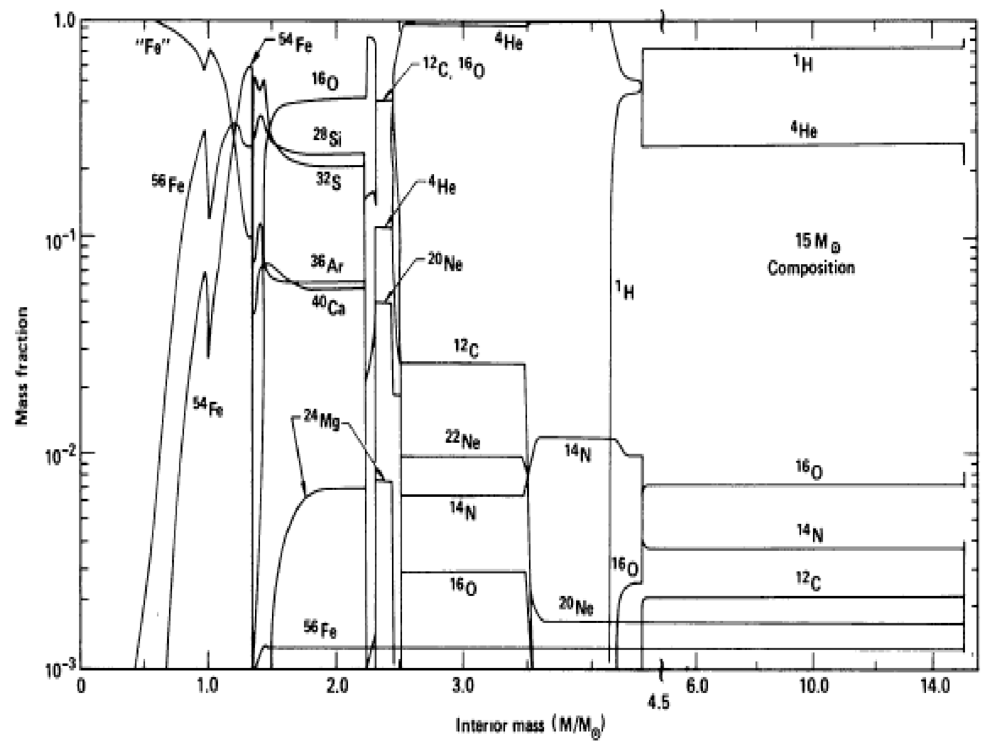
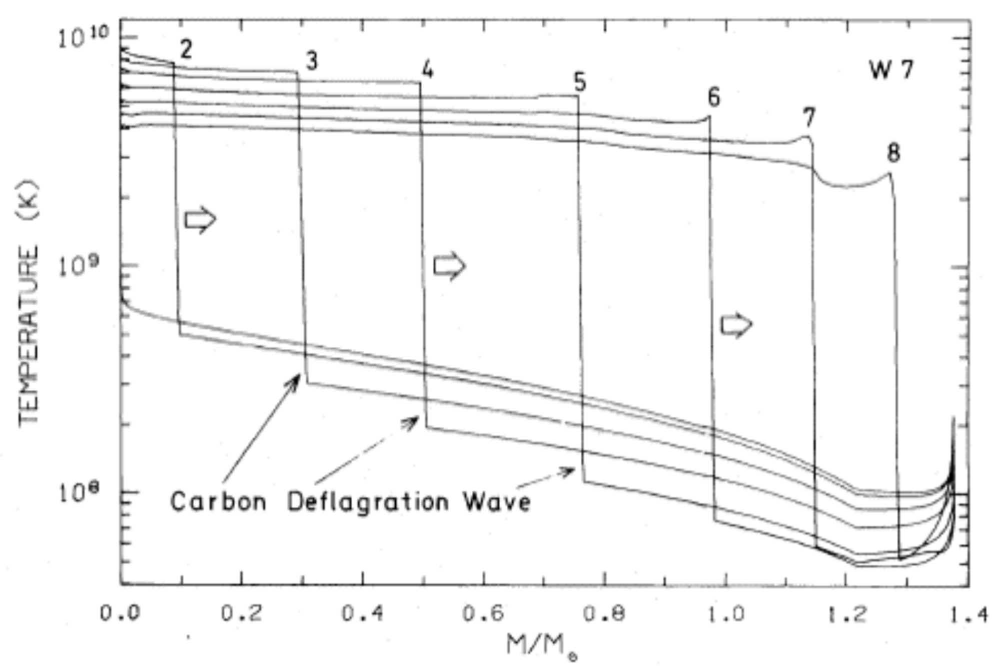


Figure 1 Structure and composition of a 15-$M_\odot$ presupernova star at a time when the edge

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

How the Explosion Occurs

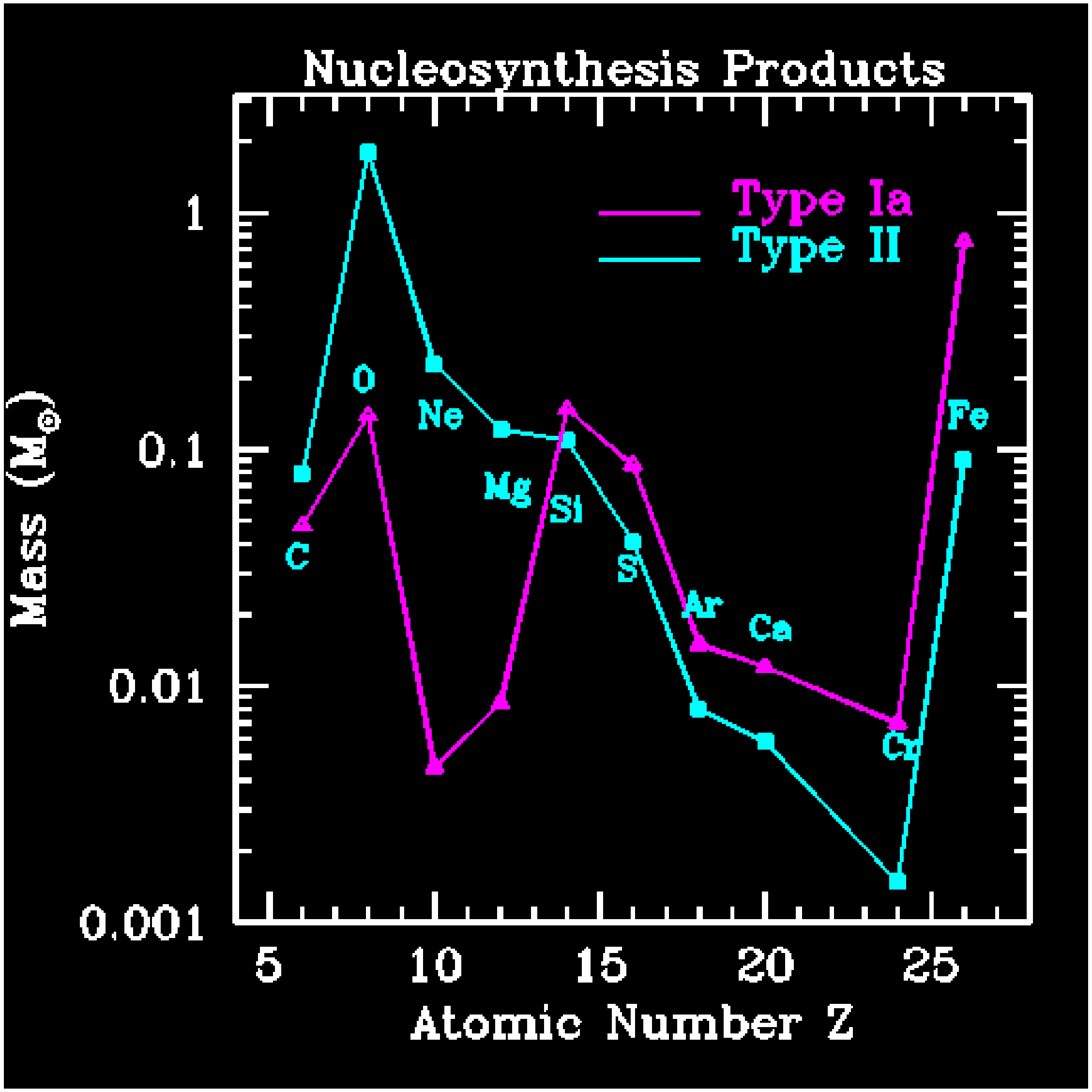
- Deflagration combustion that propagates through a gas or along the surface of an explosive at a rapid rate driven by the transfer of heat



Deflagration wave in WD
time steps are at 0, 0.6, .79, .91, 1.03, 1.12, 1.18, 1.24 sec

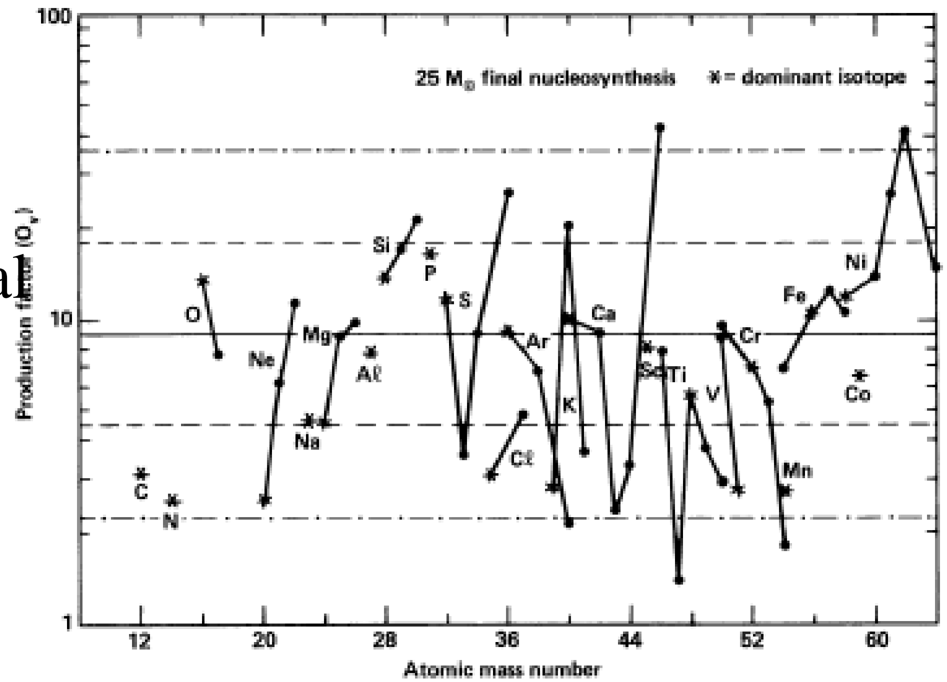
Elemental Production in Type Is and IIs

- 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.



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

Type Ia Nomoto et a; 1984

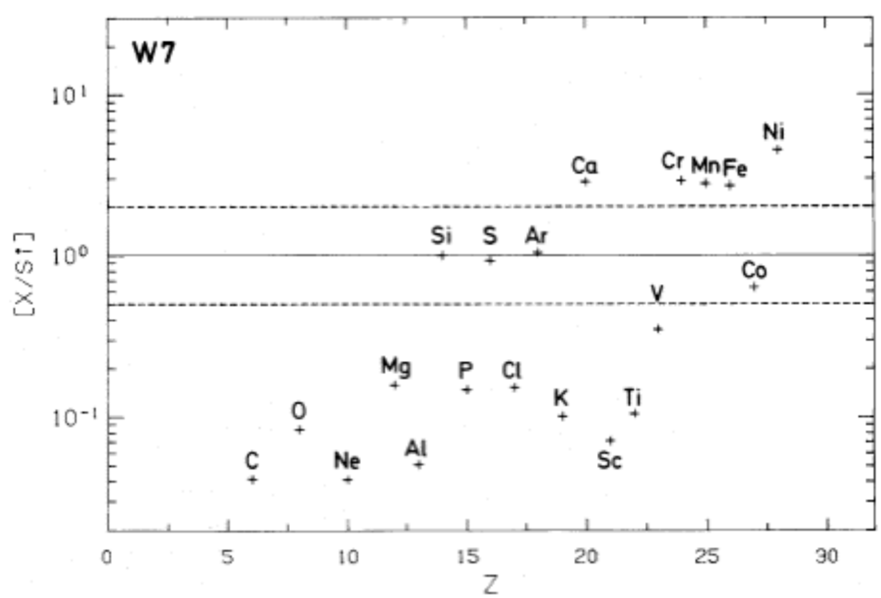
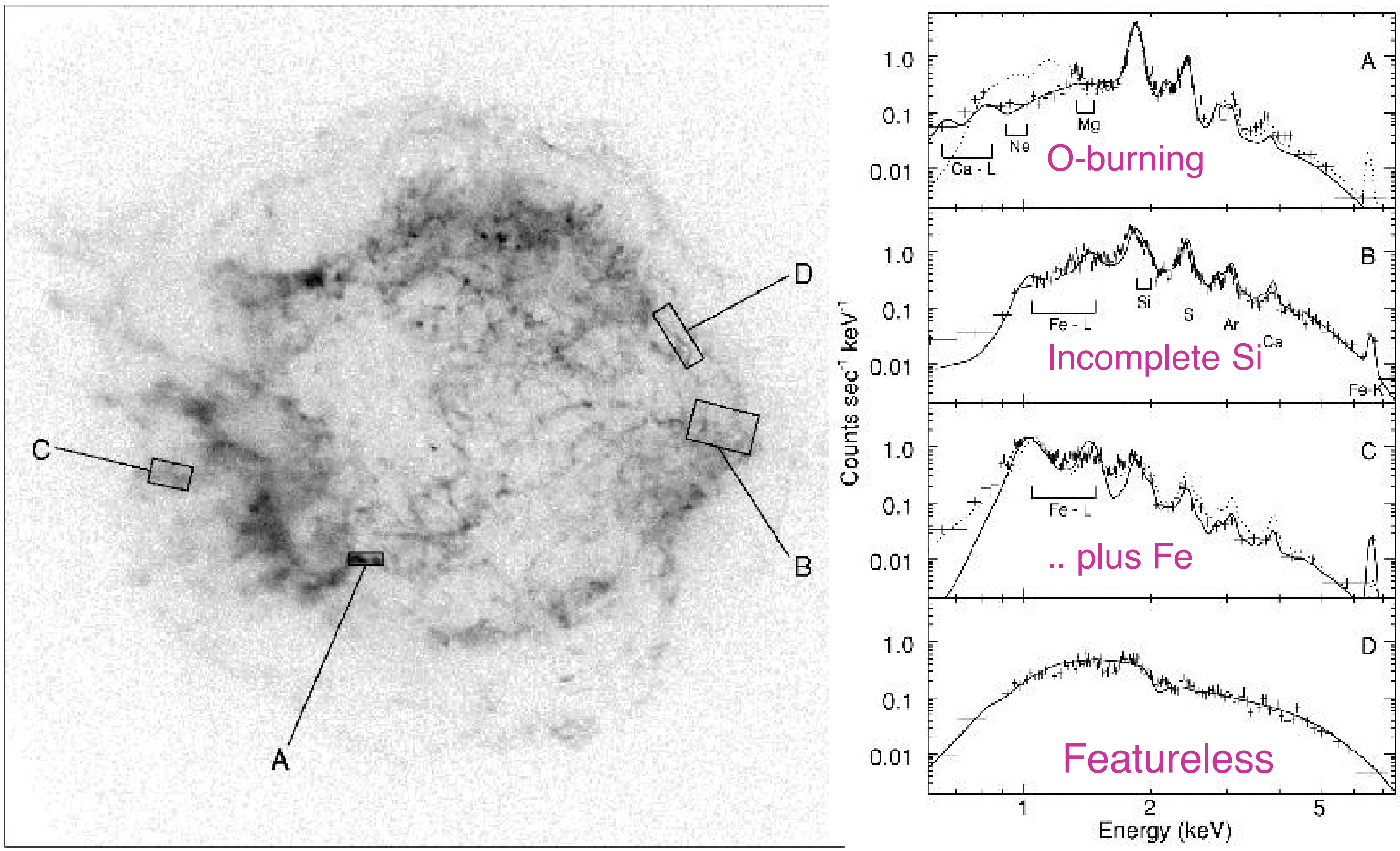


FIG. 10.—The abundances of elements relative to the solar values (W7). The ratio is normalized to Si.

Type II Weaver and Woosley 1986

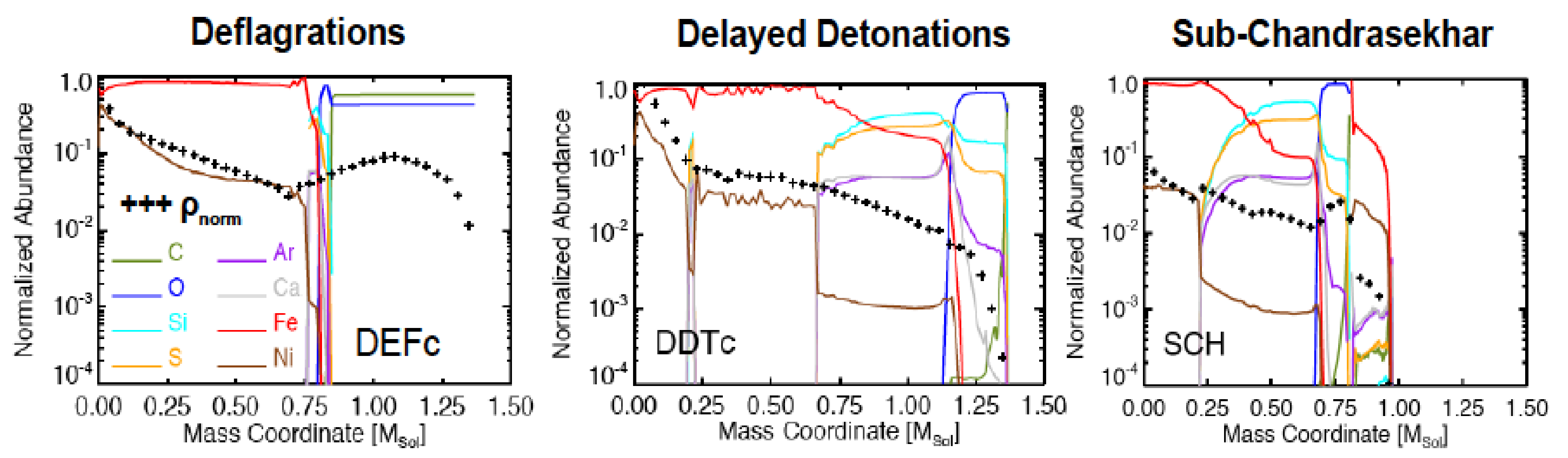
Physics of type Ia is not well understood
delayed detonation,
deflagration etc

Cassiopeia A: Explosive Nucleosynthesis



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

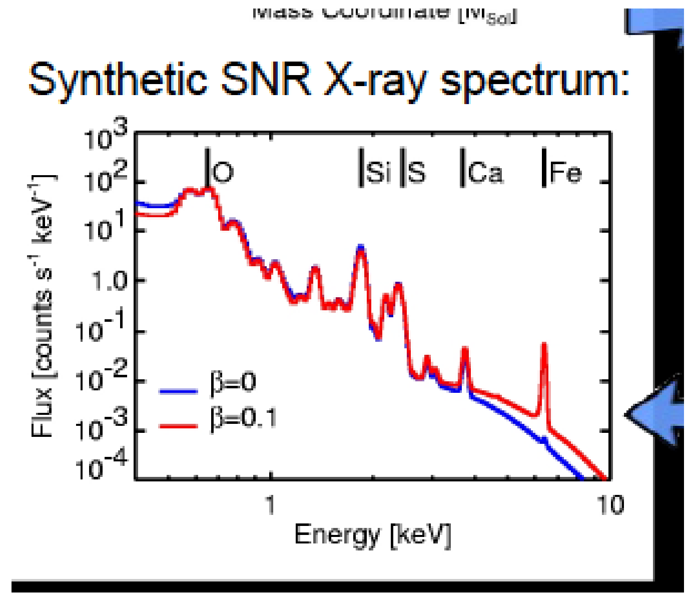
Examples of Yields from 3 Type Ia SN Models



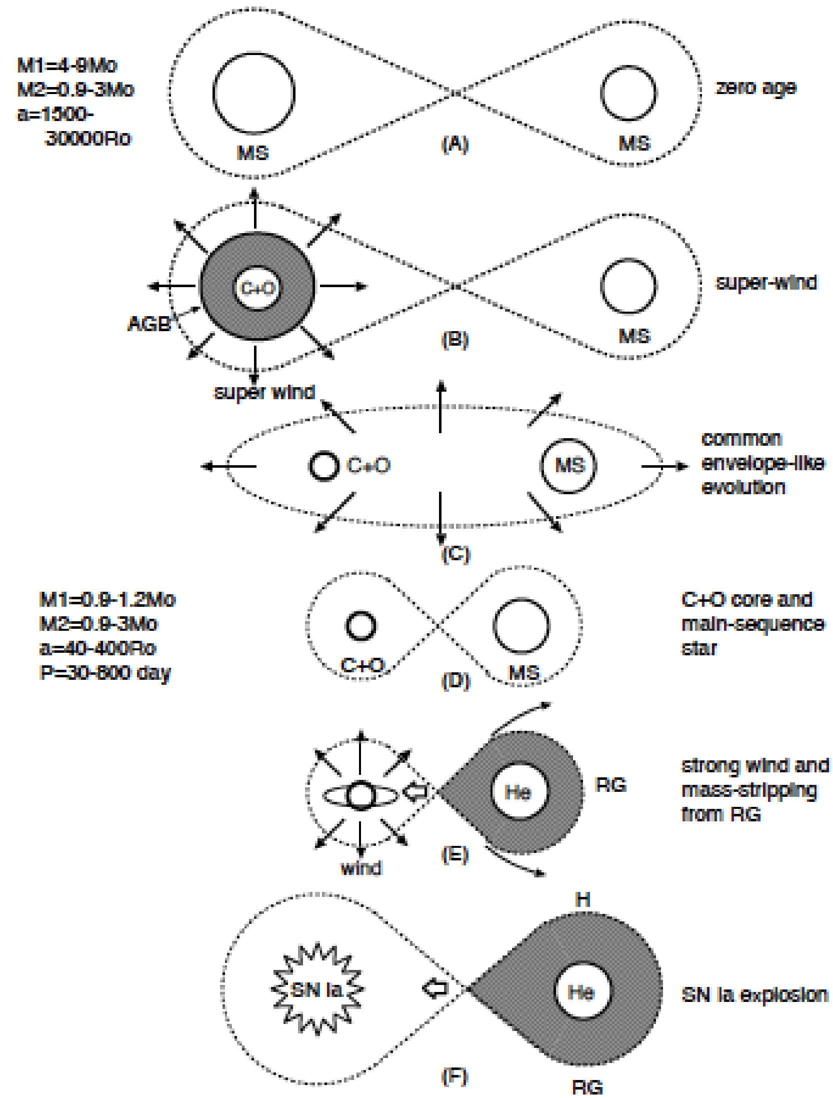
- Check of these yields against analysis of chemical abundance of SNR favors Delayed detonations.

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

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



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



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

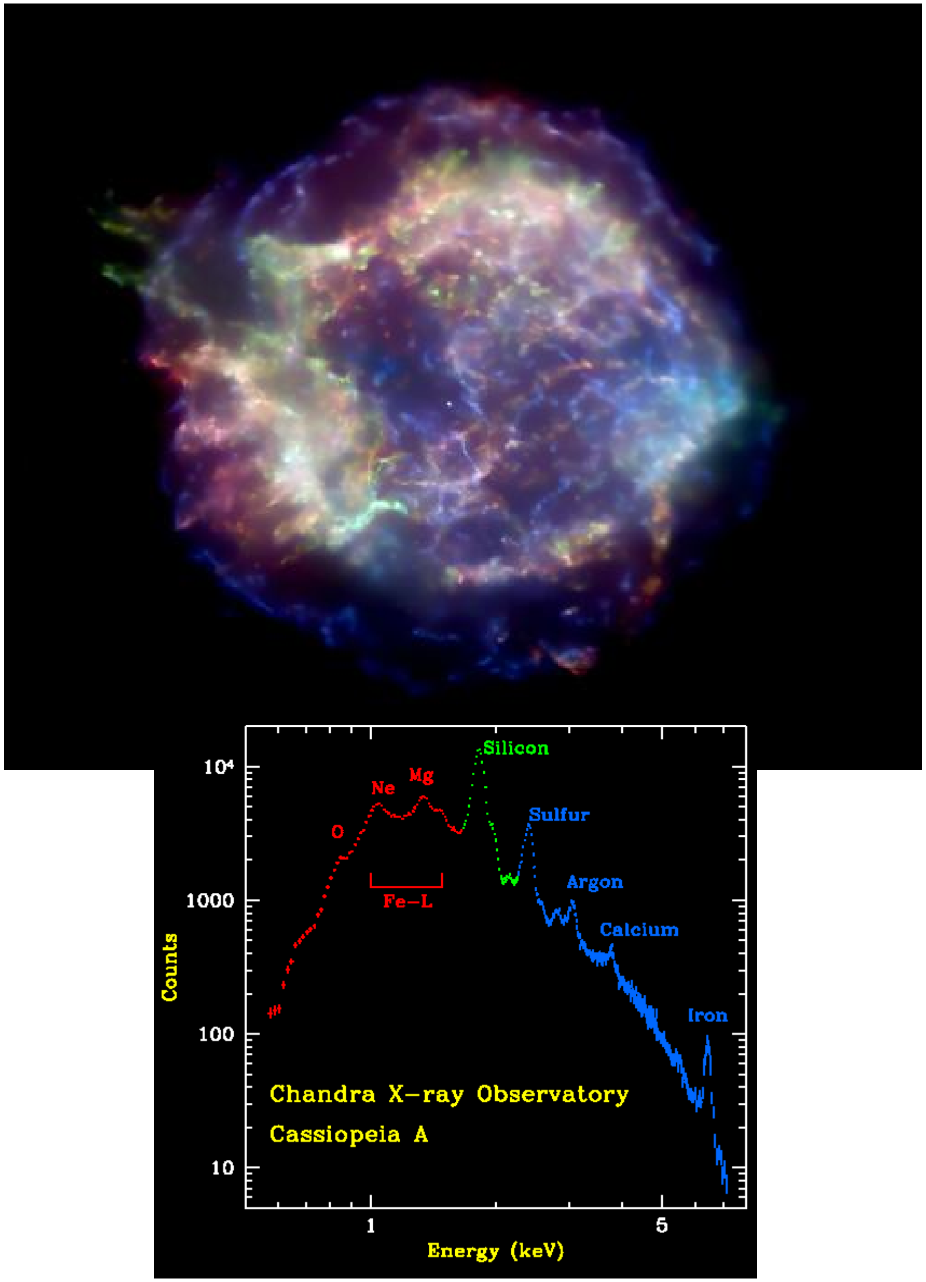
X-ray Emission from Supernova Remnants

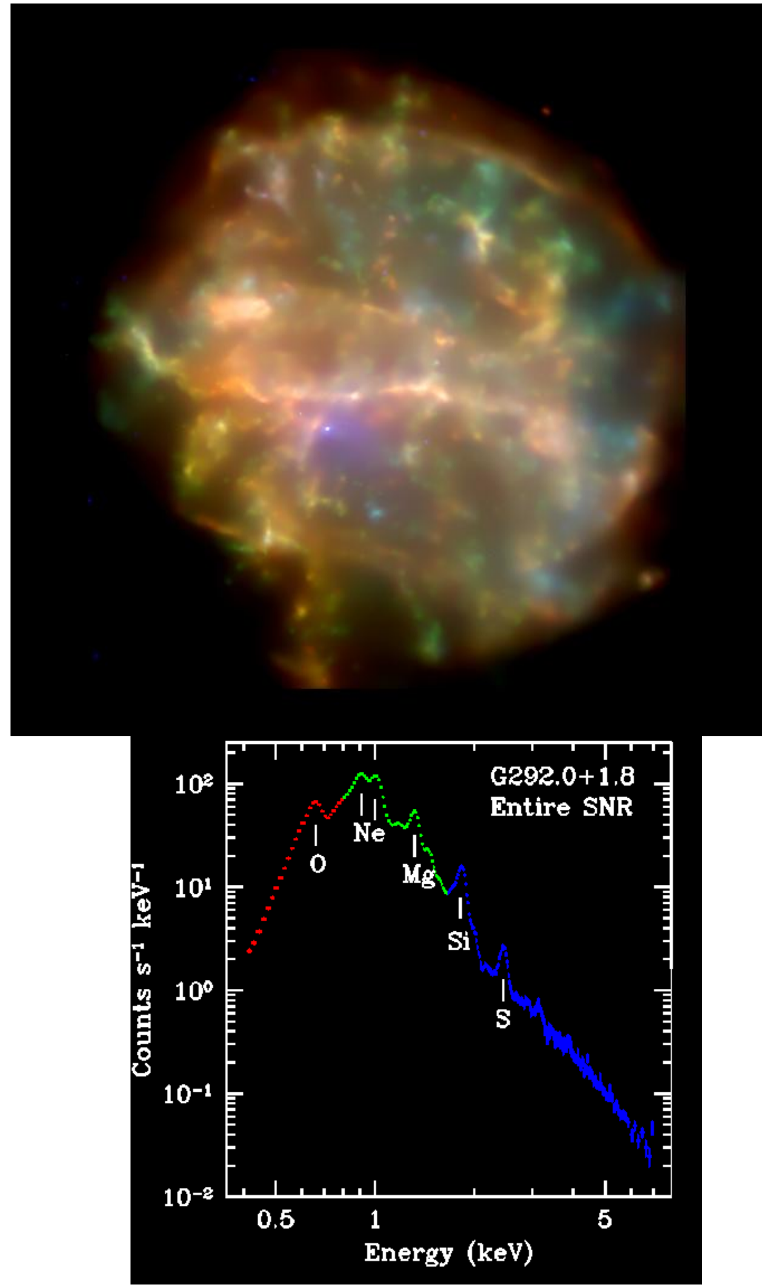
Thermal Emission

- 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)

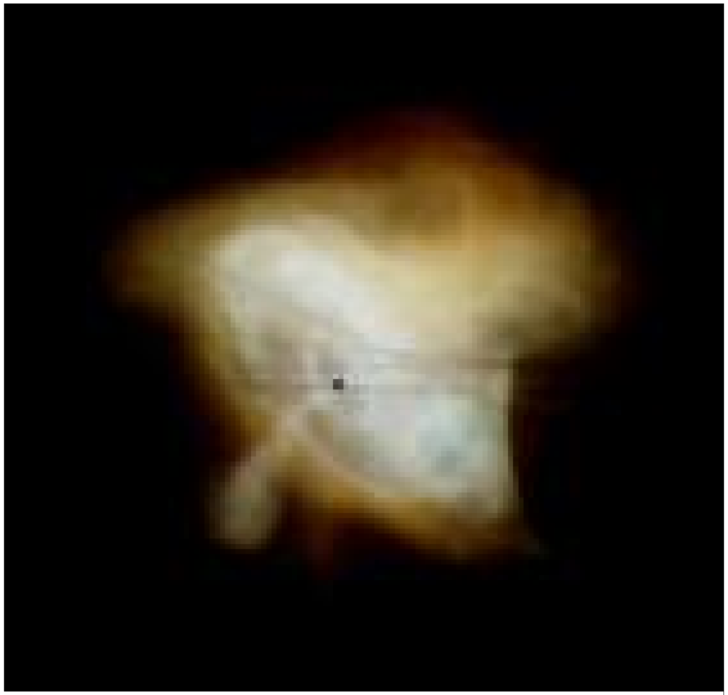


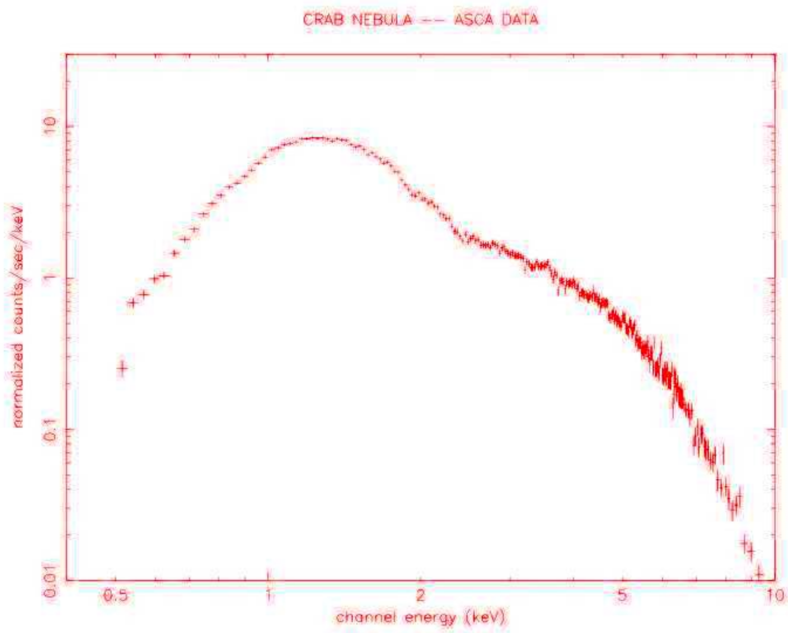


- Type Ia produce mainly Fe -- very low O/Fe ratio.
- Type II produces: mainly 0 -- very high O/Fe ratio

Non-Thermal Remants

- 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.
  - There can be synchrotron emission from shock accelerated electrons in other SNR





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)

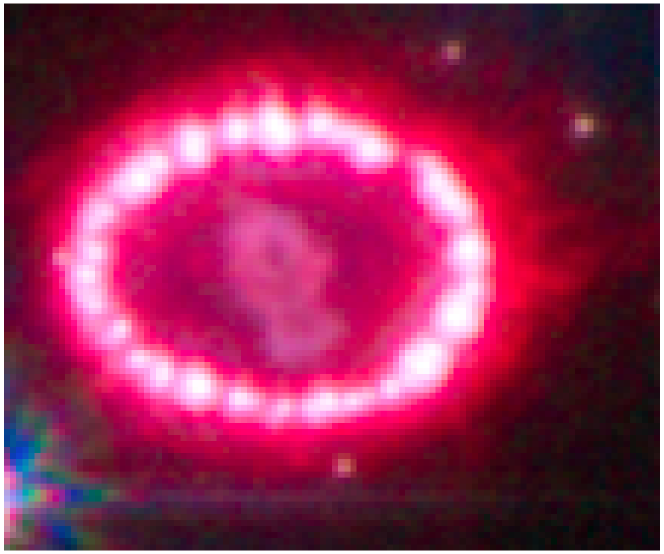
and then … Merge with the ISM

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

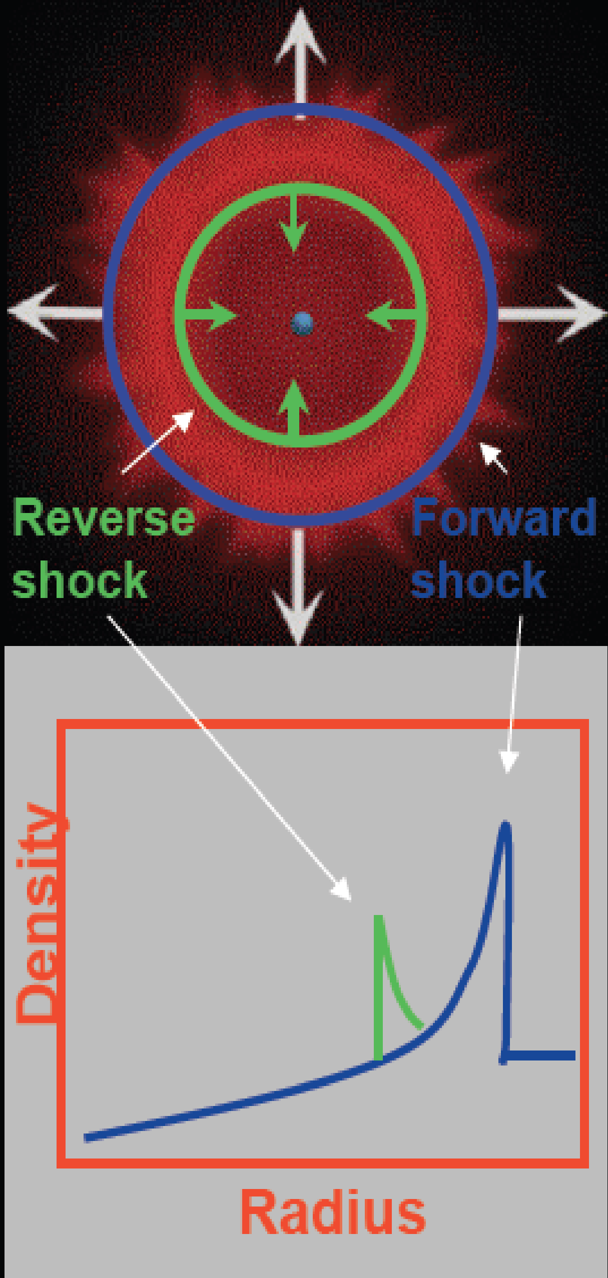
Remnant Evolution

Free Expansion
Ejecta expand without deceleration r~t

Adiabatic (Sedov-Taylor, or “atomic bomb”)
Ejecta are decelerated by a roughly equal mass of ISM $r \sim t^{2/5}$
Energy is conserved
Evolution of density, pressure is self-similar
Temperature increases inward, pressure decreases to zero

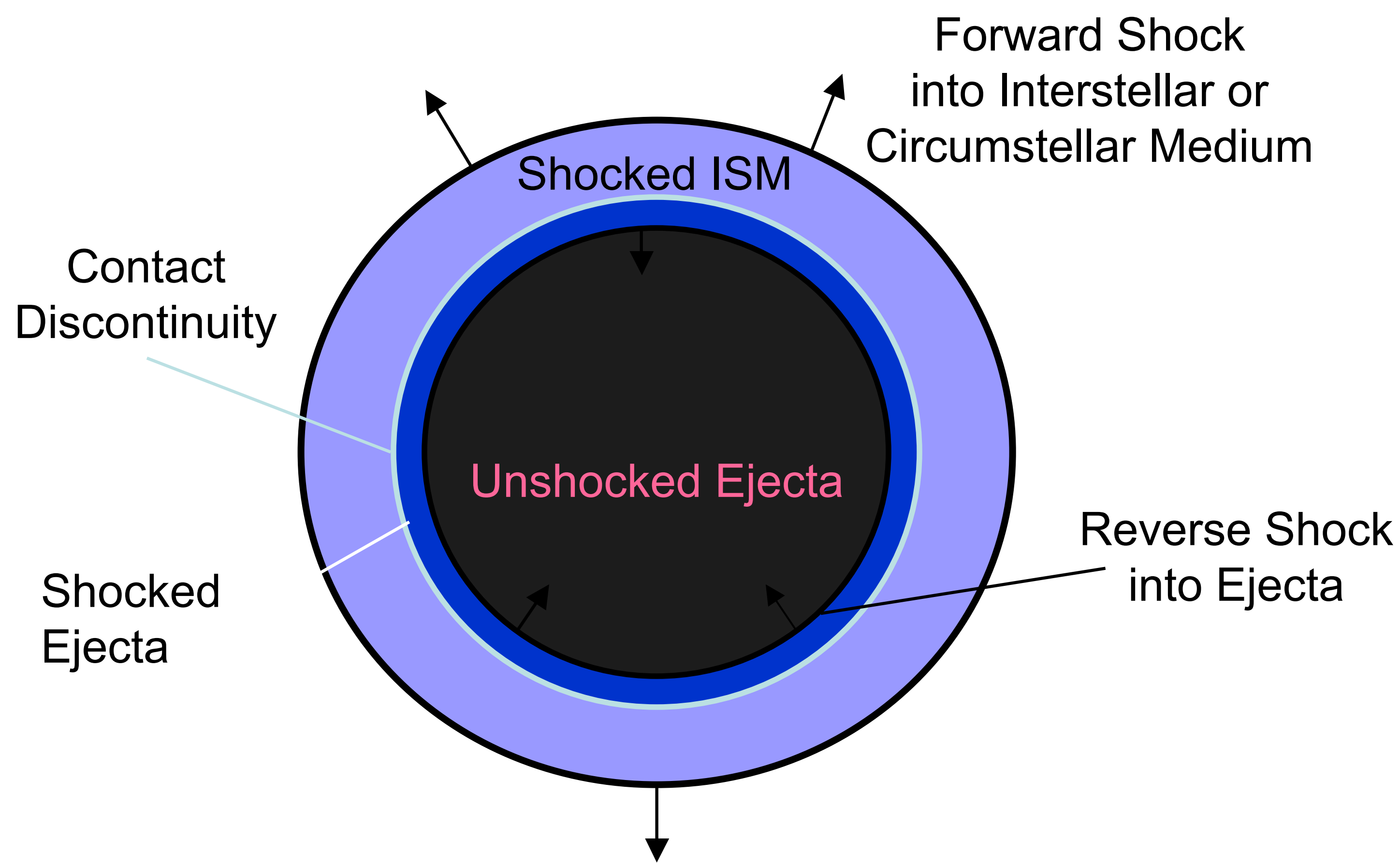
Radiative
Dissipation of remnant energy into ISM
Remnant forms a thin, very dense shell which cools rapidly
Interior may remain hot

Supernova Remnants

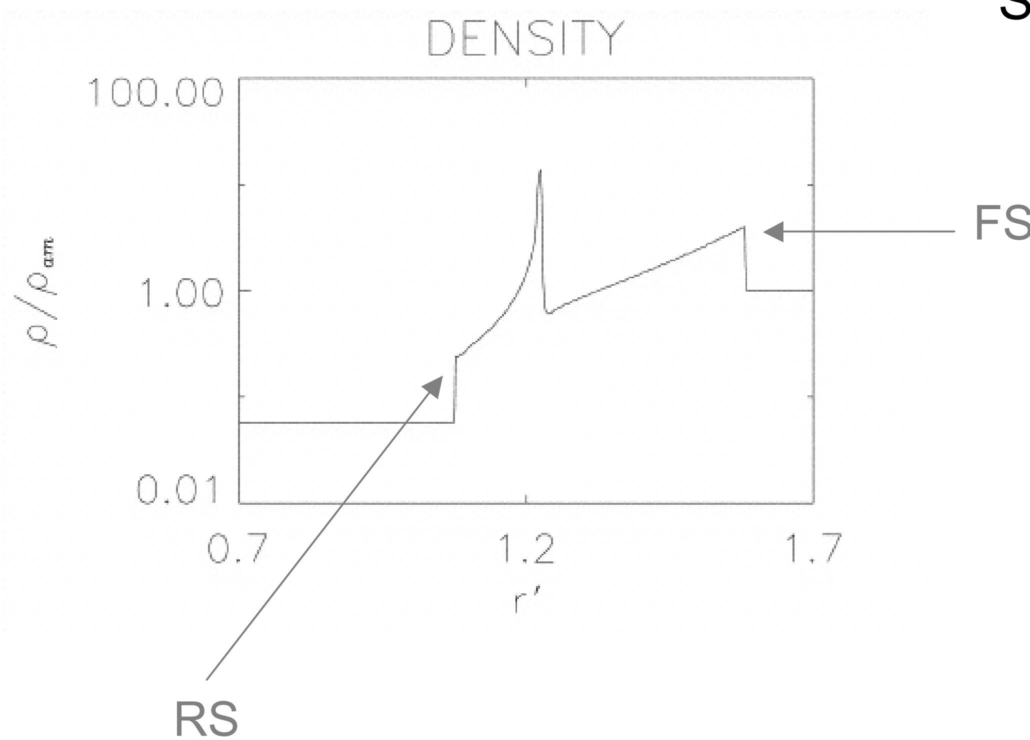


- Explosion blast wave sweeps up CSM/ISM in forward shock
  - spectrum shows abundances consistent with solar or with progenitor wind
- As mass is swept up, forward shock decelerates and ejecta catches up; reverse shock heats ejecta
  - spectrum is enriched w/ heavy elements from hydrostatic and explosive nuclear burning

Supernova Remnant Cartoon



Forward shock moves supersonically into interstellar/circumstellar medium
Reverse shock propagates into ejecta, starting from outside



Shocks compress and heat gas

Mass, momentum, energy conservation give relations (for γ=5/3)

$\rho = 4\rho_0$

$V = 3/4\ v_{shock}$

$T = 1.1\ m/m_H\ (v/1000\ km/s)^{2}$ keV

X-rays are the characteristic emission

These relations change if significant energy is diverted to accelerating cosmic rays

The shock is "collisionless" because its size scale is much smaller than the mean-free-path for collisions (heating at the shock occurs by plasma processes) coupled through the structure of turbulence in shocks and acceleration

Collisions do mediate ionizations and excitations in the shocked gas

The Shock

- A key ingredient in SNR dynamics is the strong (high Mach number) shock which is "collisionless"
- the effect of the shock is carried out through electric and magnetic fields generated collectively by the plasma rather than through discrete particle–particle collisions
- the shock system is given by the synonymous terms "adiabatic" and "non-radiative" to indicate that no significant energy leaves the system in this phase
- a "radiative" shock describes the case where significant, catastrophic cooling takes place through emission of photons

Plasma takes time to come into equilibrium

- particle (“Coulomb”) collisions in the post-shock plasma will bring the temperature of all species, including the free electrons, to an equilibrium value:
- $k^{-}T = 3/16 \mu m v_s^2$
- However it takes time for the system to come into equilibrium and for a long time it is in non-equilibrium ionization (NEI) $\tau > n_e t \sim 3 \times 10^{12} cm^{-3} s$

if the plasma has been shocked recently or is of low density it will not be in equilibrium

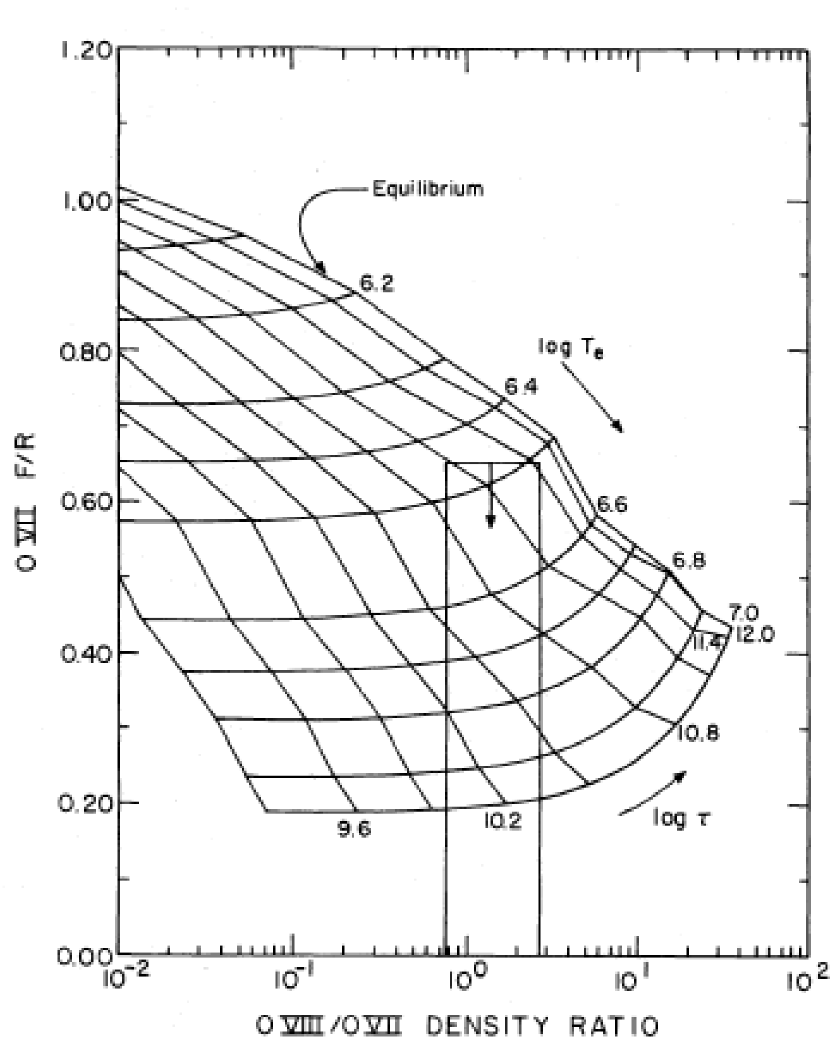
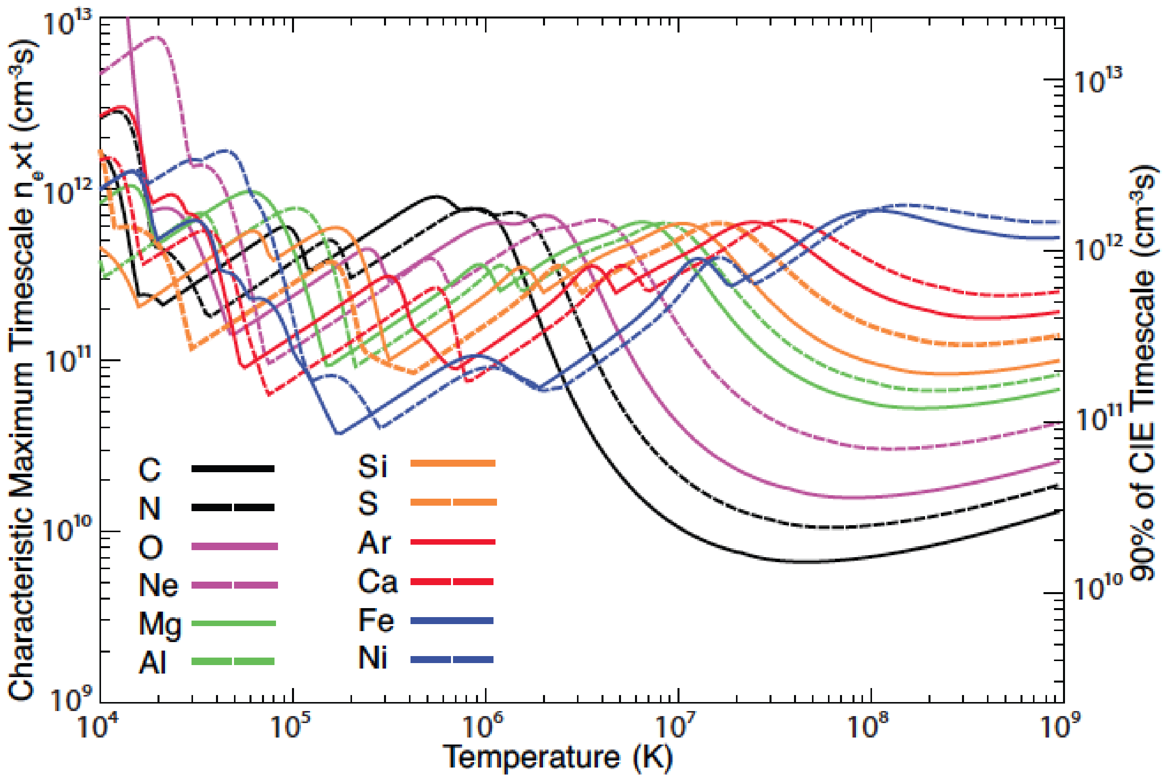


FIG. 3.—The results of our ionization nonequilibrium model (see text). The

- Timescale to reach equilibrium depends on ion and temperature- solution of coupled differential equations.

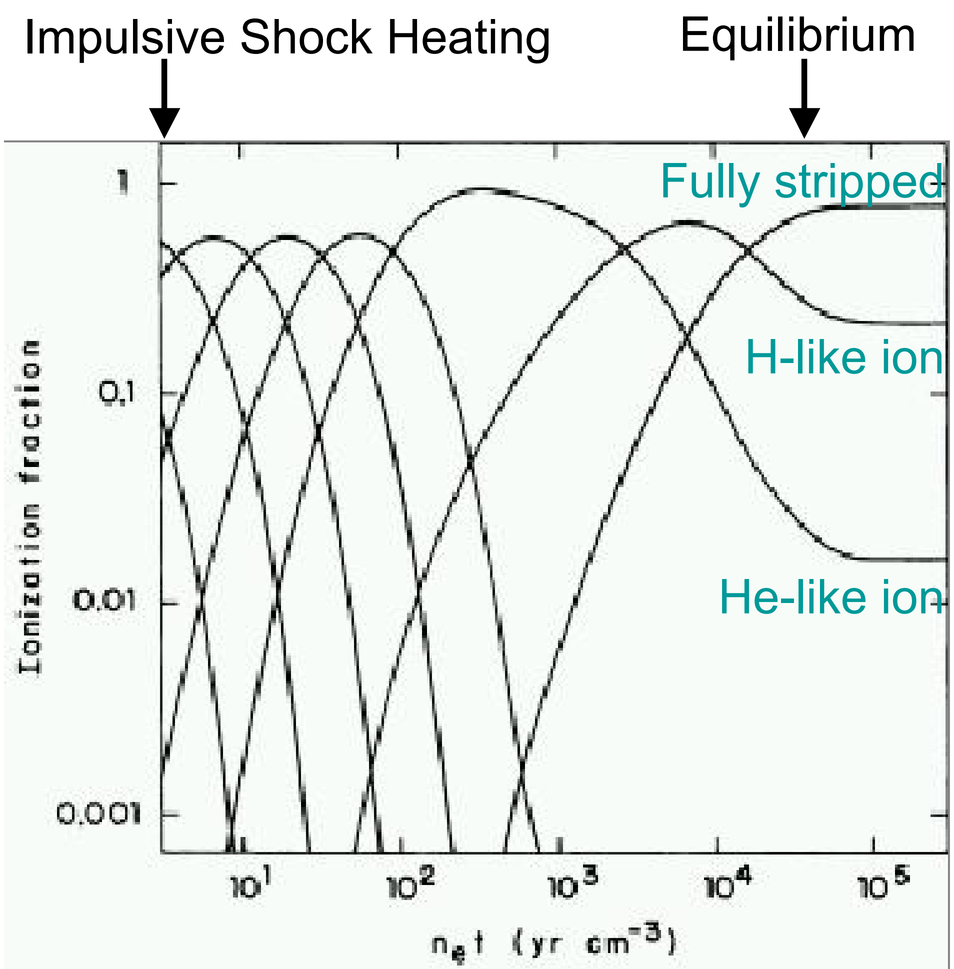


G. 1.— [Left axis] Density-weighted timescales (in units of cm^{-3} s) for C, N, O, Ne, Mg, Al, S, Si, Ar, Ca, Fe, and Ni to achieve one lding (e^{-1}) towards ionization equilibrium in a constant temperature plasma. [Right axis] Density-weighted timescale for all ions to be in 10% of their equilibrium value.

Smith and Hughes 2010

Time-Dependent Ionization

Oxygen heated to 0.3 keV
(Hughes & Helfand 1985)



Ionization is effected by electron-ion collisions, which are relatively rare in the ~1 cm^{-3} densities of SNRs

Ionization is time-dependent

Ionization timescale = $n_e t$
electron density x time since impulsively heated by shock

Ionization equilibrium attained at $n_e t$ ~ 10^4 cm^{-3} yr

Ionizing gas can have many more H- and He- like ions, which then enhances the X-ray line emission

Inferred element abundances will be too high if ionization equilibrium is inappropriately assumed for an ionizing gas

Sedov-Taylor phase

This solution is the limit when the swept-up mass exceeds the SN ejecta mass -the SNR evolution retains only vestiges of the initial ejecta mass and its distribution.

The key word here is SELF SIMILAR *(solutions can be scaled from solutions elsewhere)*

===> $f(r, t)$ becomes $f(r/r_{ref)}$ $*f(r_{ref})$

(skipping the equations) R_s=12.4 pc $(KE_{51}/n_1)^{1/5}\ t_4^{\ 2/5}$

t =390 yr $R_s\ T_{meas}^{-1/2}$

In the Sedov-Taylor model one expects thermal emission coming from a thin shell behind the blast wave. As the shock expends the pressure drops between the shock wave and the material ejected.

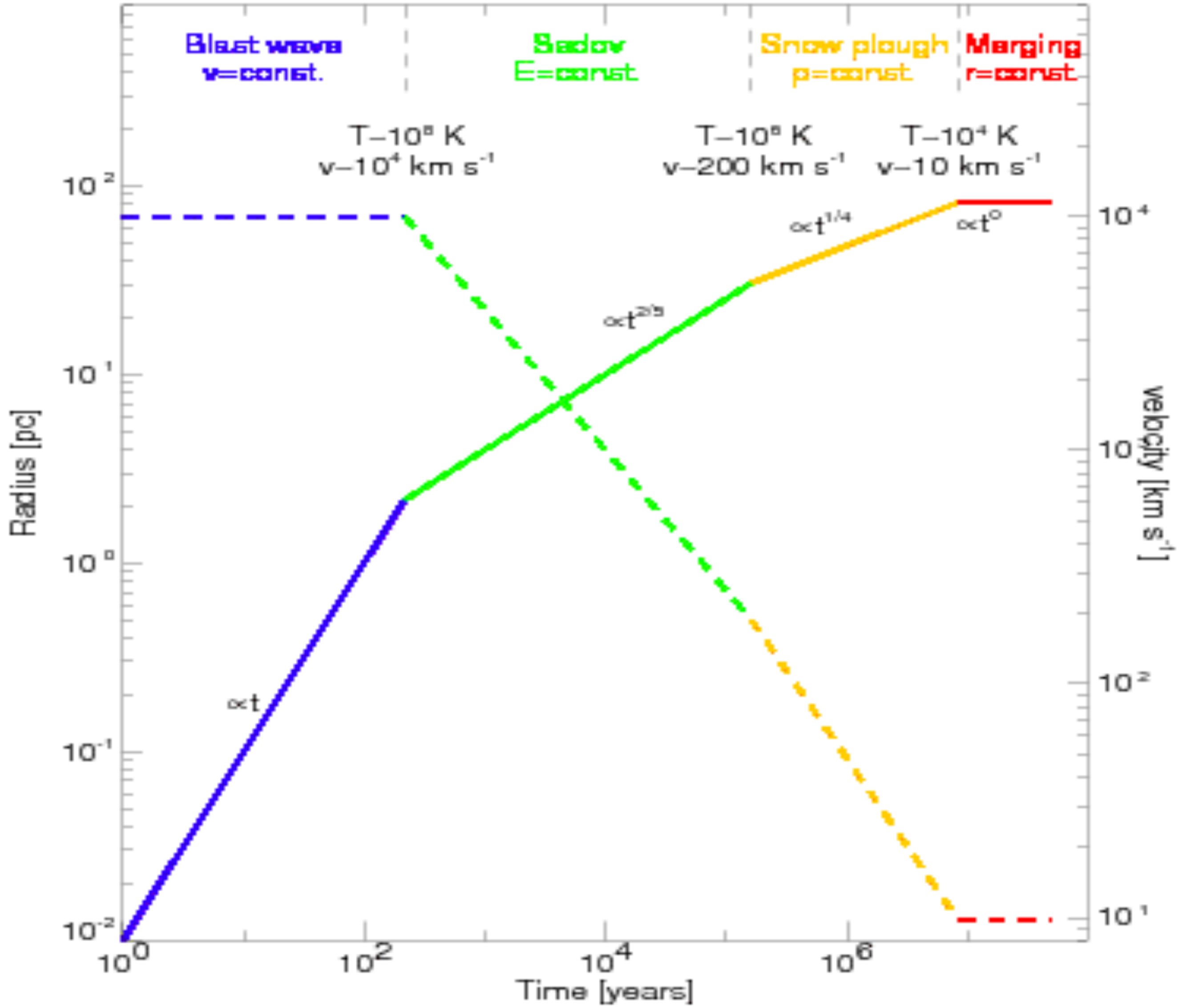
- Kinetic energy of expansion (KE) is transfered into internal energy - total energy remains roughly the same (e.g. radiative losses are small)
- The temperature of the gas is related to the internal energy
- $T \sim 10^6 k\, E_{51}{}^{1/2}\, n^{-2/5} (t/2x10^4 yr)^{-6/5}$

- so for typical explosion energies and life times the gas emits in the x-ray band
- measuring the size (r), velocity (v) and temperature T allows an estimate of the age
- $t_{Sedov} \sim 3x10^4 T_6{}^{-5/6} E_{51}{}^{1/3} n^{-1/3} yr$
- at $T \sim 10^6$-10^7 k the x-ray spectrum is line dominated

- Forward shock into the ISM- is a 'contact discontinuity'- outside of this the ISM does not yet 'know' about the SN blast wave

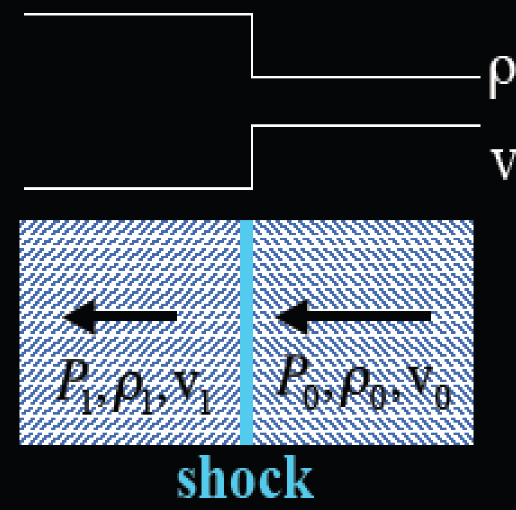
- Reverse shock- information about the interaction with the ISM travels backwards into the SN ejecta
- Shell like remnants
- **Shell velocity much higher than sound speed in ISM, so shock front of radius R forms.**

- Pabmanabhan 2002 (Fig 4.6) fromWilms 2010



:, Fig. 4.6)

Shocks in SNRs



- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with $\gamma=5/3$)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

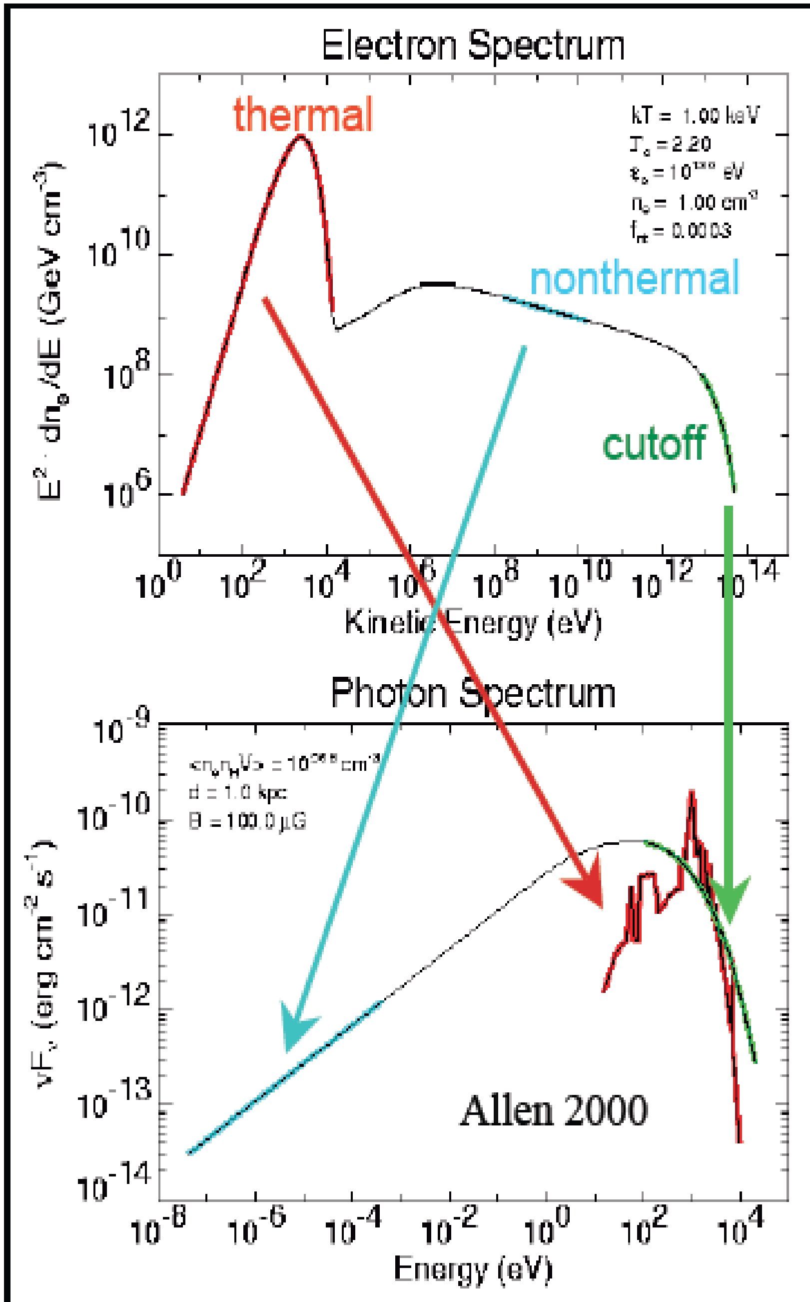
$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

$$v_{ps} = \frac{3v_s}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g. cosmic rays), the temperature will be lower than this



Shocked Electrons and their Spectra

- Forward shock sweeps up ISM; reverse shock heats ejecta
- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons

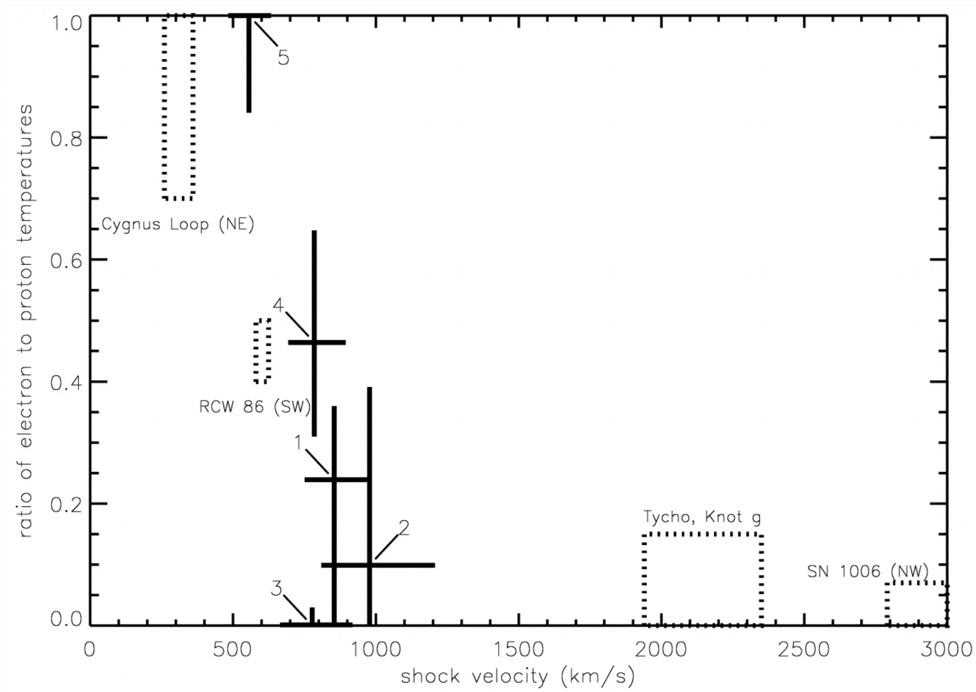
Electron Heating at SNR Shocks
Compare T_e to T_p

Temperatures behind shock are proportional to mass

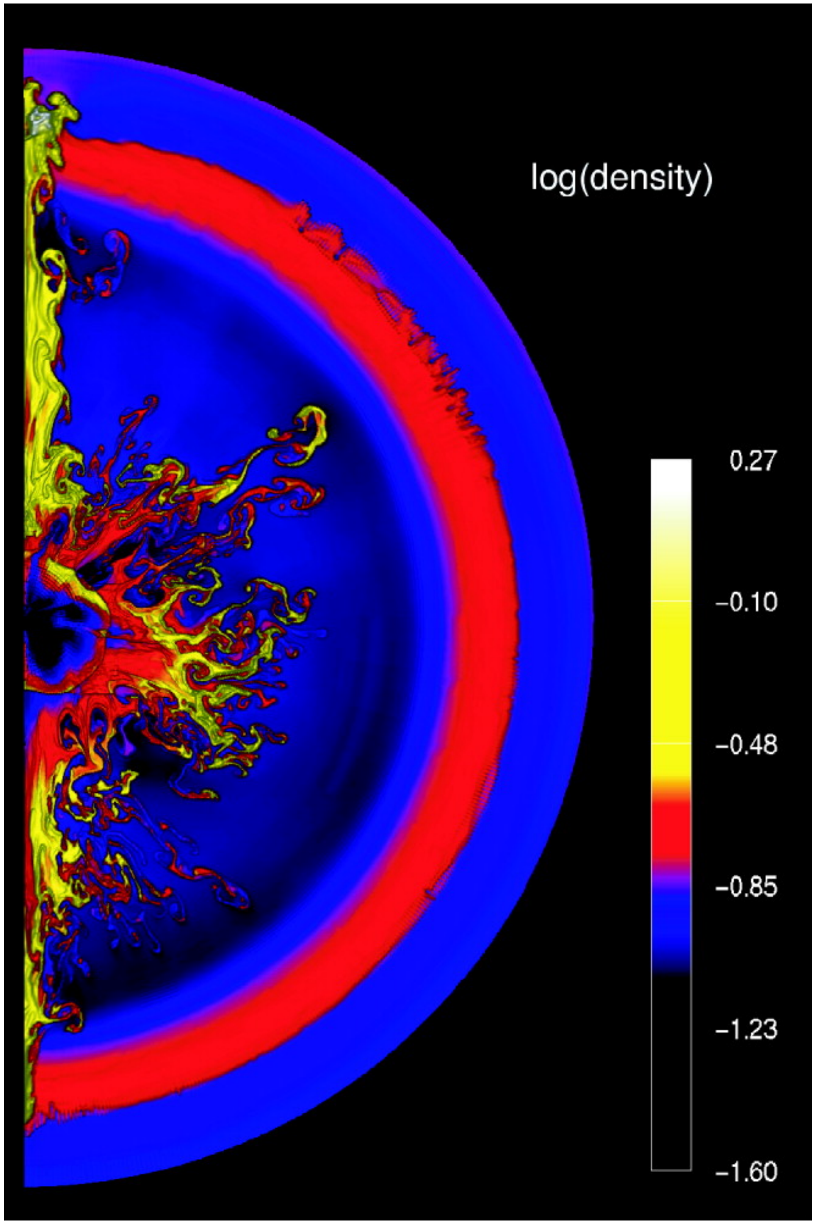
$kT_{i,e} \sim m_{i,e} \, v_{sh}^2$

Electrons and ions will equilibrate their temperatures by Couloumb collisions, but possibly more quickly by complicated collisionless plasma processes

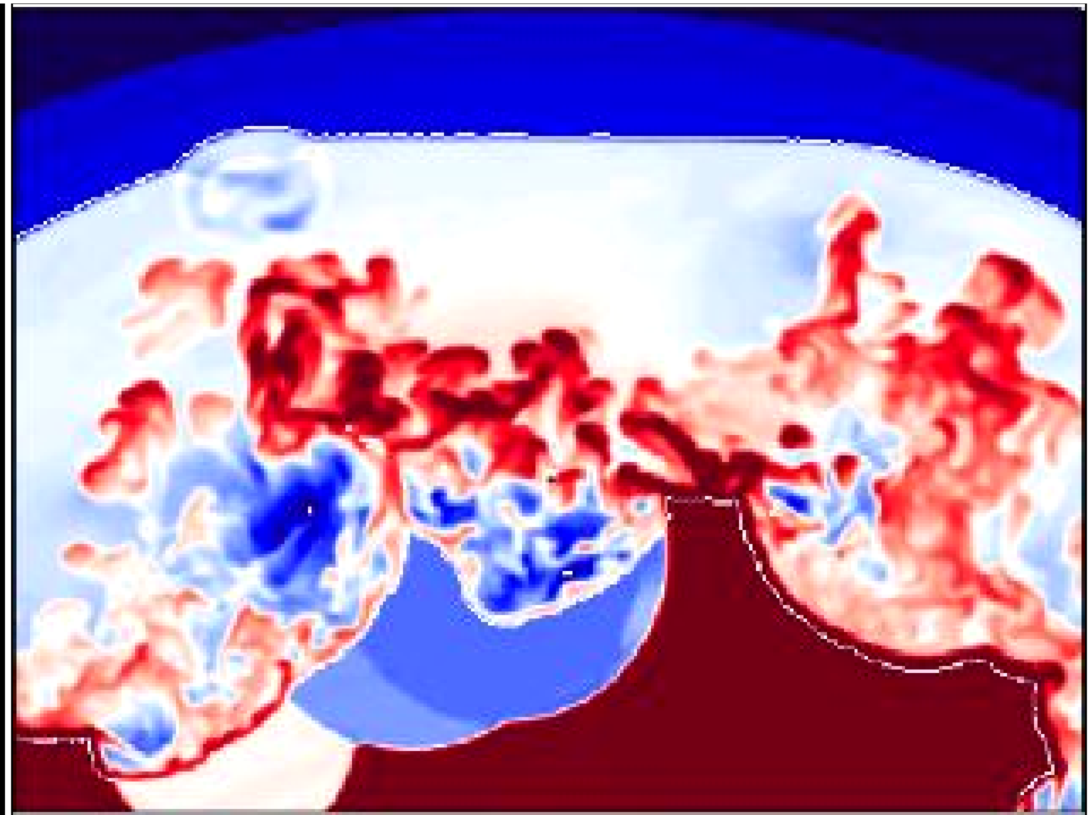
The efficiency of heating depends on the Mach number (shock velocity): faster electron heating in slower shocks



Rakowski et al. 2003



Kifonidis et al. 2000


Fe bubbles Blondin et al. 2001

Instabilities

irregular shock boundaries
mixing between ejecta layers
mixing between ejecta and ISM

Radiative/Snow plough phase

T drops as a steep function of radius

===> at some point, T is below T_{recomb} ~ 1 keV- the cooling function increases steeply and the gas recombines rapidly

Age of SNR when this happens depends on models for cooling functions, explosion energy and density.

roughly $t_{cool} \sim nkT/n^2 \Lambda(T)$ -~$4 \times 10^4 yr T_6^{3/2}/n$-

($\Lambda(T)$ is the cooling function)

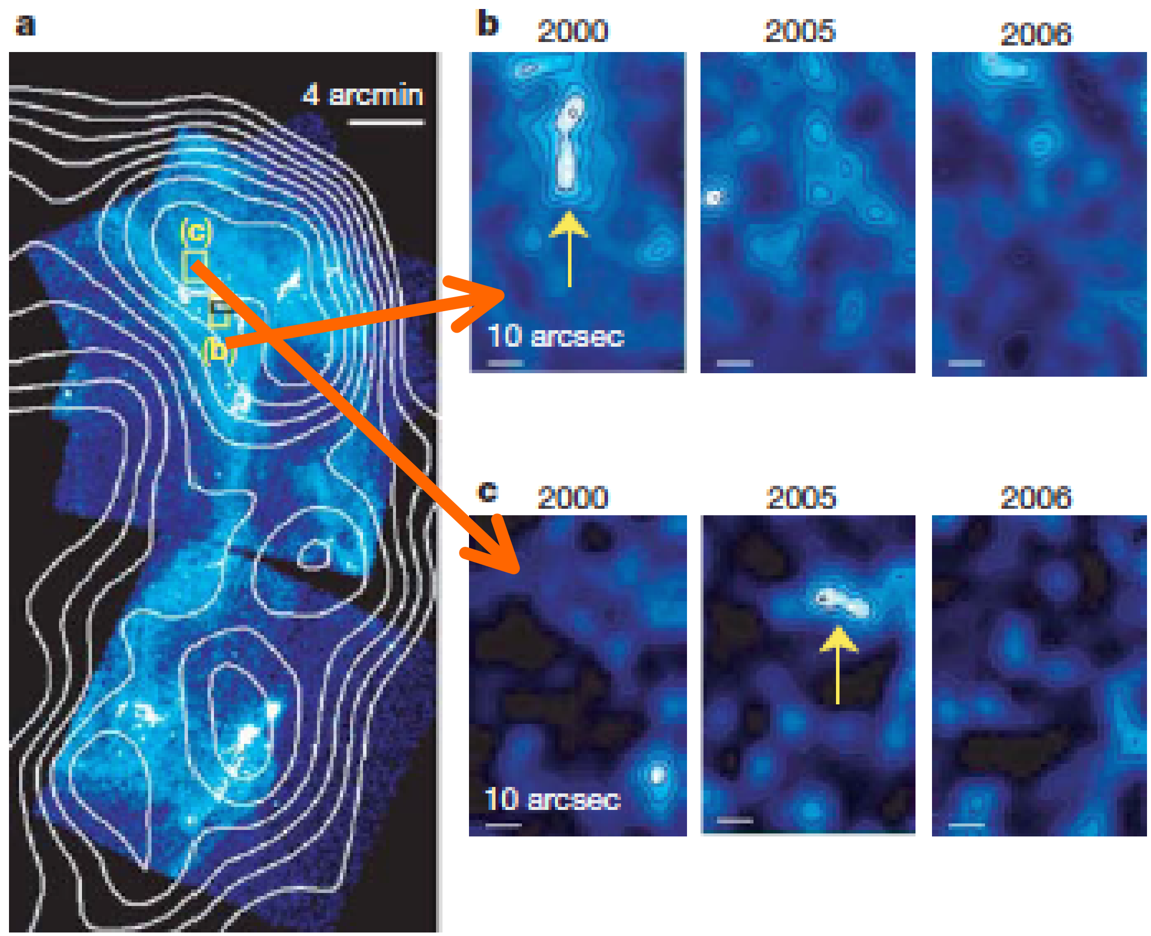
phase starts when $t_{cool} < t_{Sedov}$ $T_6 < E^{1/7} n^{2/7}$

Between 17,000 and 25,000 years (assuming standard E_o and n_1)

Then: THE END… SNR merges with surrounding medium

SNR are Thought to Be the Source of Galactic cosmic rays

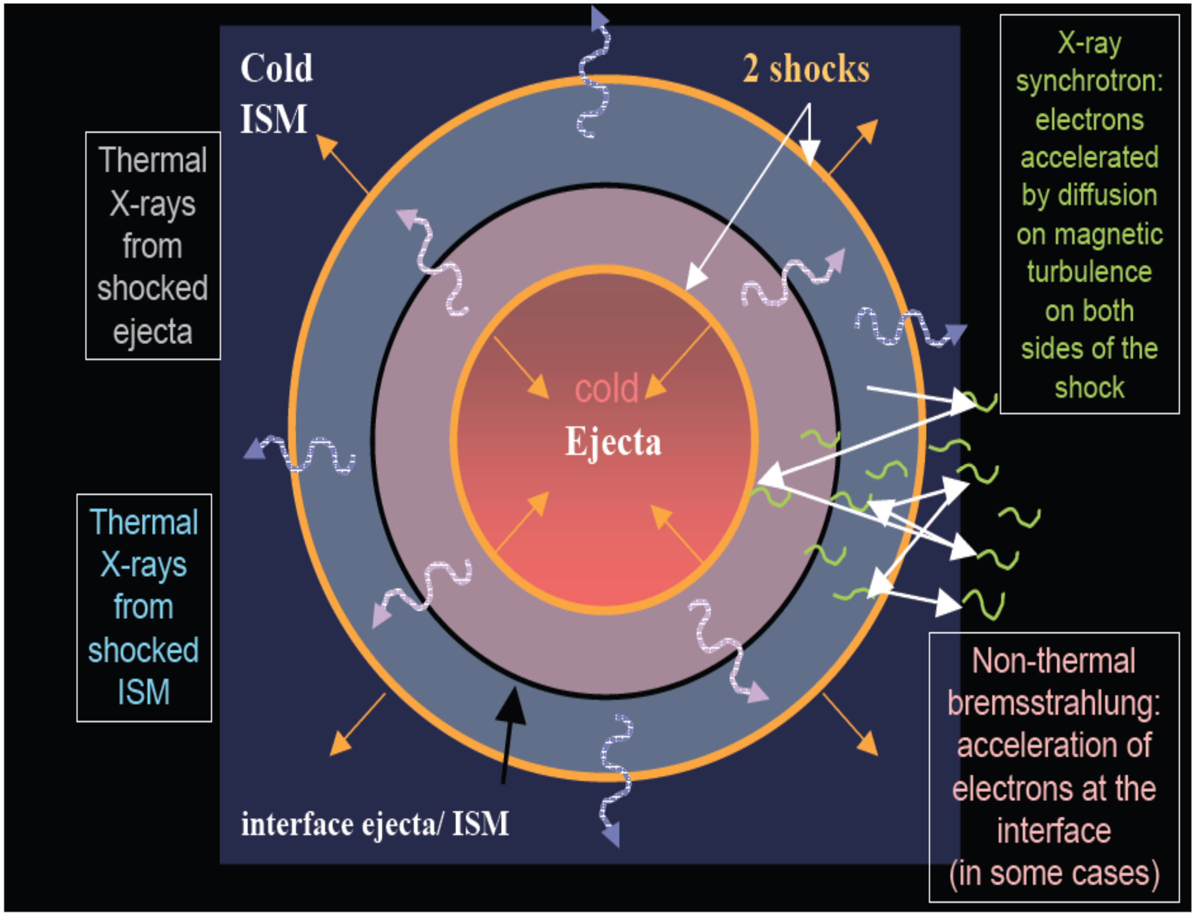
- They need to put ~ 5-20% of their energy into cosmic rays in order to explain the cosmic-ray energy density in the Galaxy (~2 eV/cm^3 or 3x10^{38} erg/s/kpc^2) , the supernova rate (1-2/100yrs), the energy density in SN (1.5x10^{41} ergs/sec~2x10^{39} erg/s/kpc^2)
- particles are scattered across the shock fronts of a SNR, gaining energy at each crossing (Fermi acceleration)
- Particles can travel the Larmor radius
- $R_L \sim E_{17}/B_{10\mu G}$ Z kpc



many young SNRs are actively accelerating electrons up to 10-100TeV, based on modeling their synchrotron radiation

See Melia sec 4.3

- Fermi acceleration-1949:
- charged particles being reflected by the moving interstellar magnetic field and either gaining or losing energy, depending on whether the "magnetic mirror" is approaching or receding. energy gain per shock crossing is proportional to velocity of shock/speed of light - spectrum is a power law

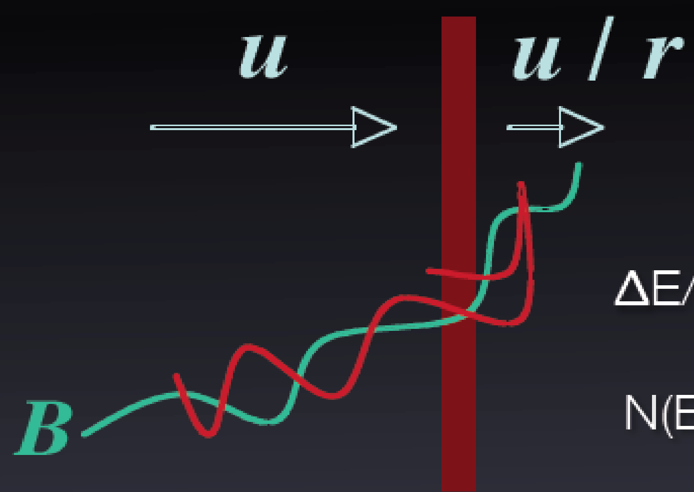


DeCourchelle 2007

Nice analogy- ping pong ball bouncing between descending paddle and table

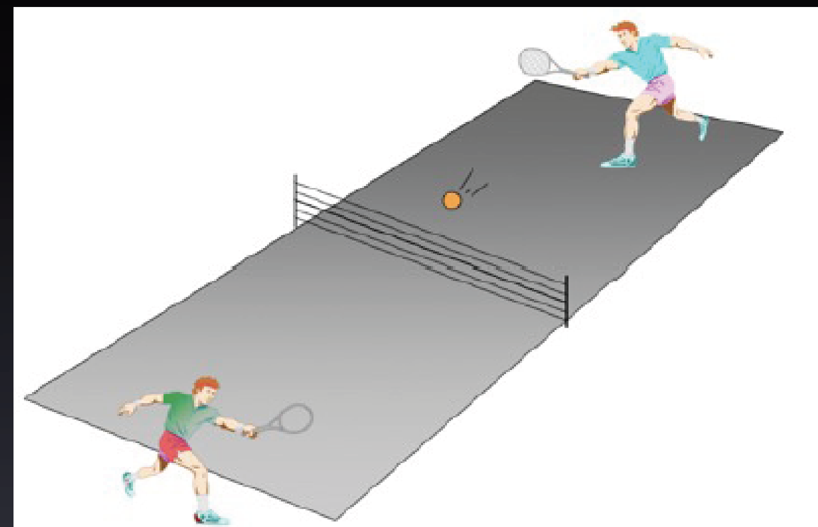
Spitovsky 2008

Particle acceleration:



$\Delta E/E \sim v_{shock}/c$

$N(E) \sim N_0 E^{-K(r)}$



Free energy: converging flows

Acceleration mechanisms:

- First order Fermi
  - Diffusive shock acceleration
  - Shock drift acceleration
  - Shock surfing acceleration
- Second order Fermi

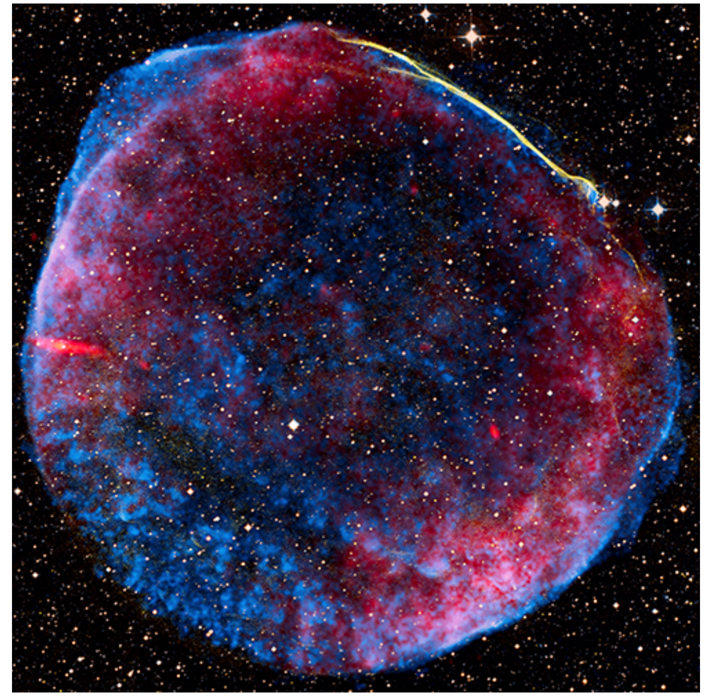
Efficient scattering of particles is required. Monte Carlo simulations of rel. shocks show that this implies very high level of turbulence $\delta B/B$(Ostrowski et al). Is this realistic? Are there specific conditions?

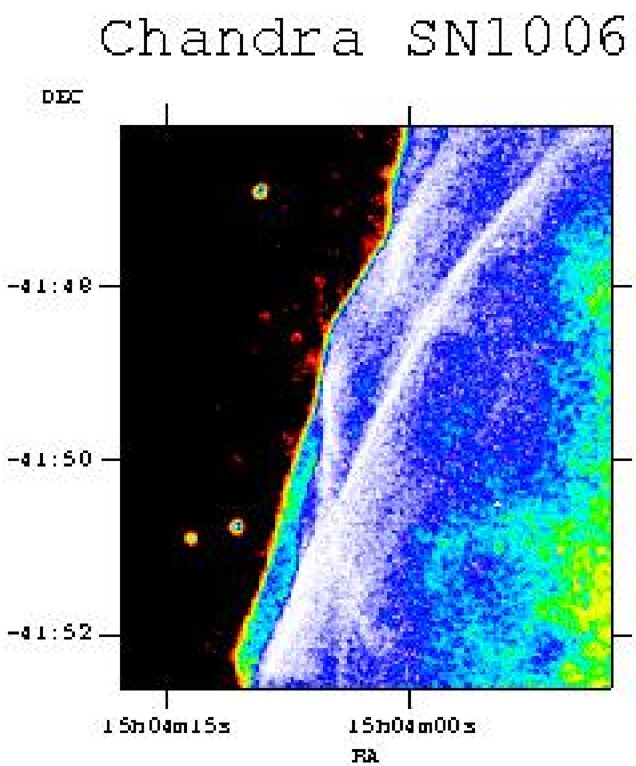
Requires turbulence for injection into acceleration process and to stay near the shock

Needs spectrum of turbulent motions (waves) downstream.

Sn1006

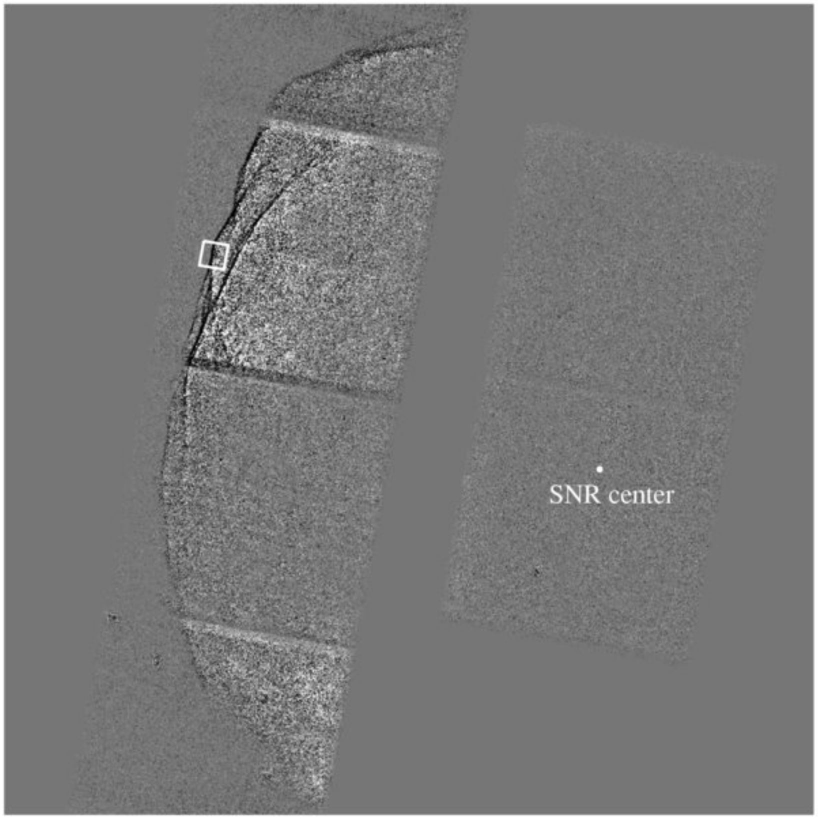
- The first SN where synchrotron radiation from a 'thermal' remnant was detected- direct evidence for very high energy particles



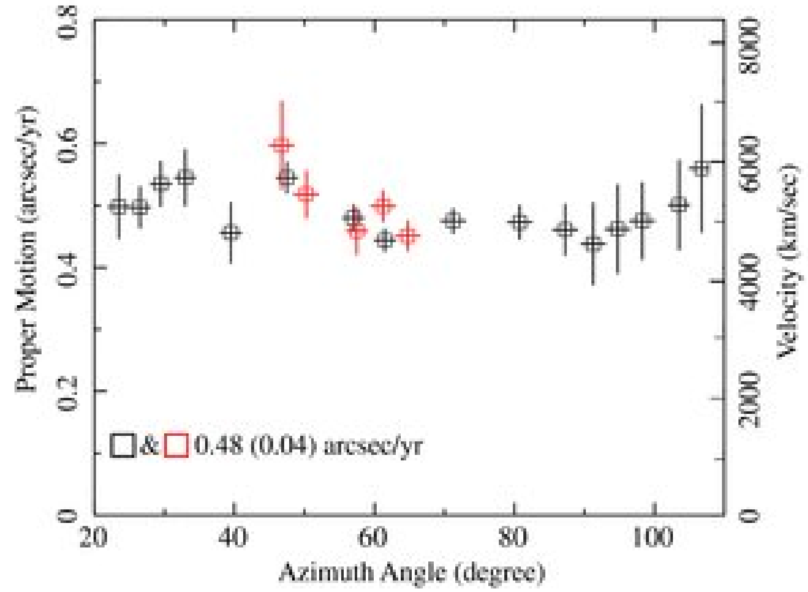


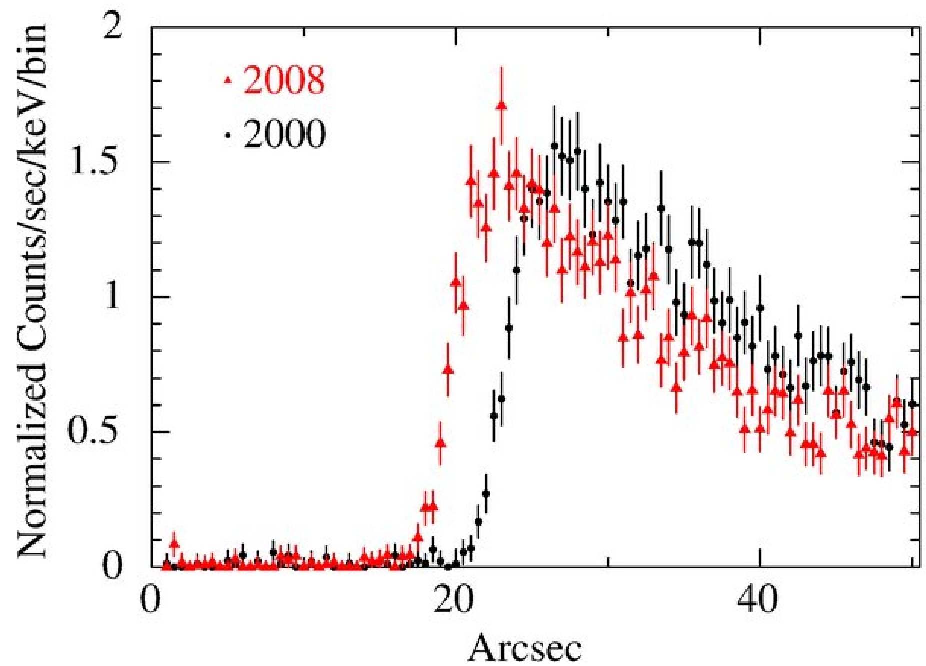
Enlarged SN filaments

Sn1006

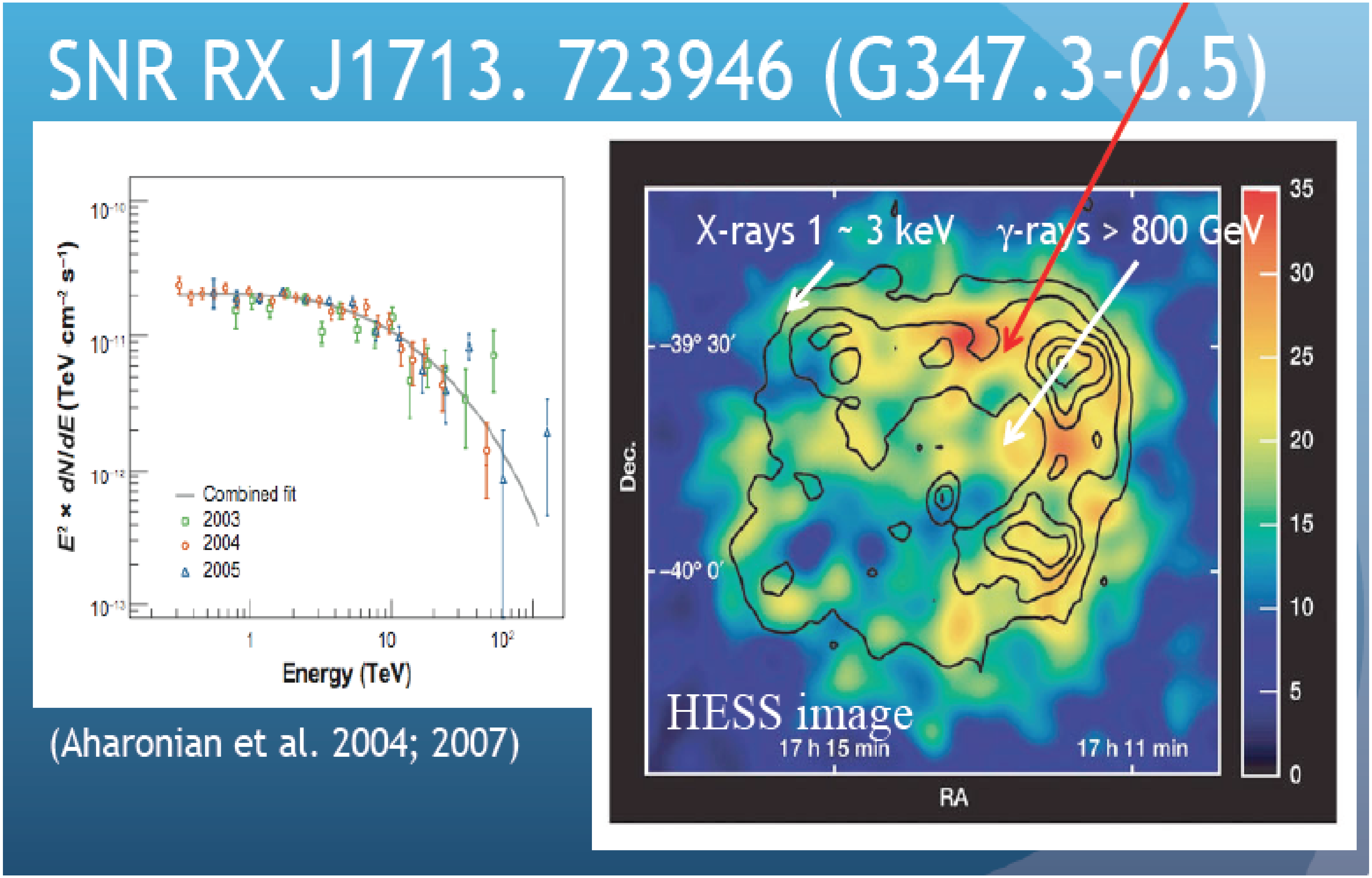


Difference Imag





Evidence for Particle Acceleration- Tev Emission + X-ray Synch

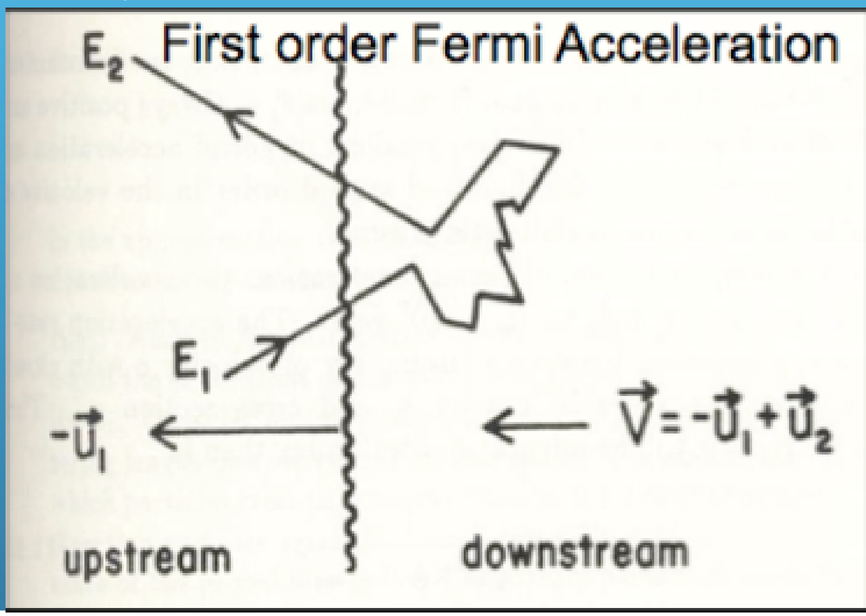


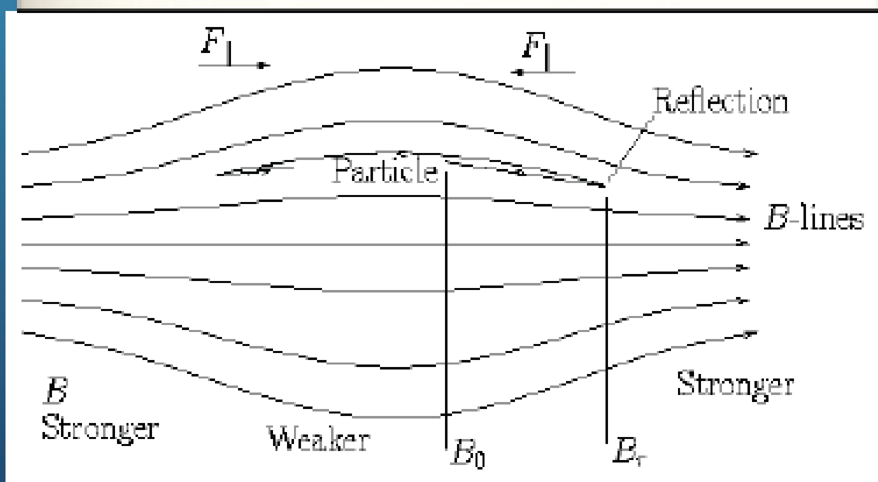
Diffusive Shock Acceleration (Fermi Mechanism)

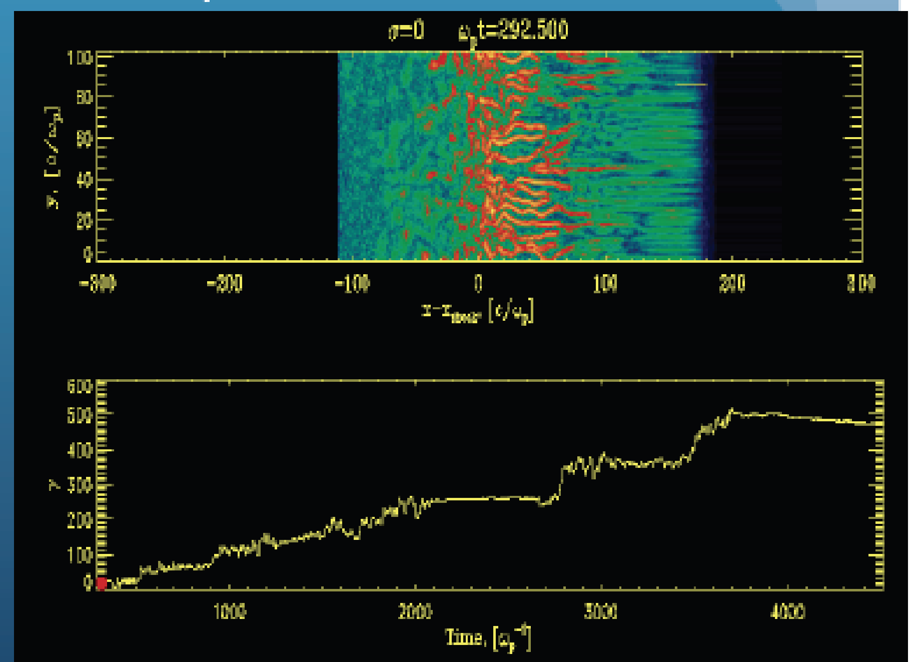
Fermi 1949;
Spitkovsky 2008;

V_s $\rightarrow$ $\leftarrow$ V_e

$V_s > 0$ gain energy
$V_s < 0$ lose energy
$\Delta\varepsilon \sim \beta$







Janfei Jang

3-D Structure

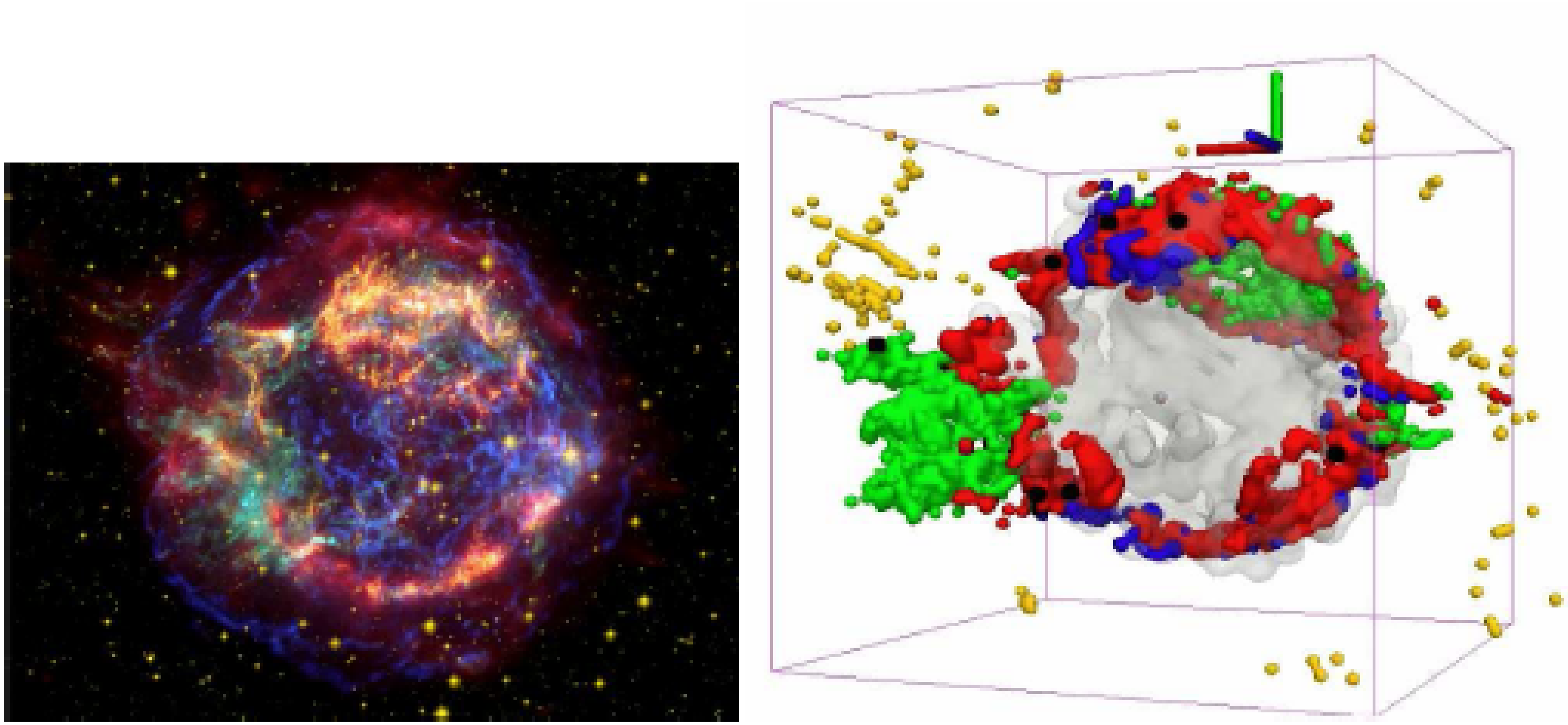


Fig. 2 Cas A present. Left: Composite view of Cas A in X-ray (*Chandra*, green & blue), visible (HST, yellow), and the IR (Spitzer, red); from *Chandra* Photo album, released June 2005. Right: A detailed 3D reconstruction of Cas A also in X-ray (black & green), optical (yellow), and IR (red, blue & gray.) Doppler shifts measured in X-ray and infrared lines provided the third dimension, from DeLaney et al. (2010).

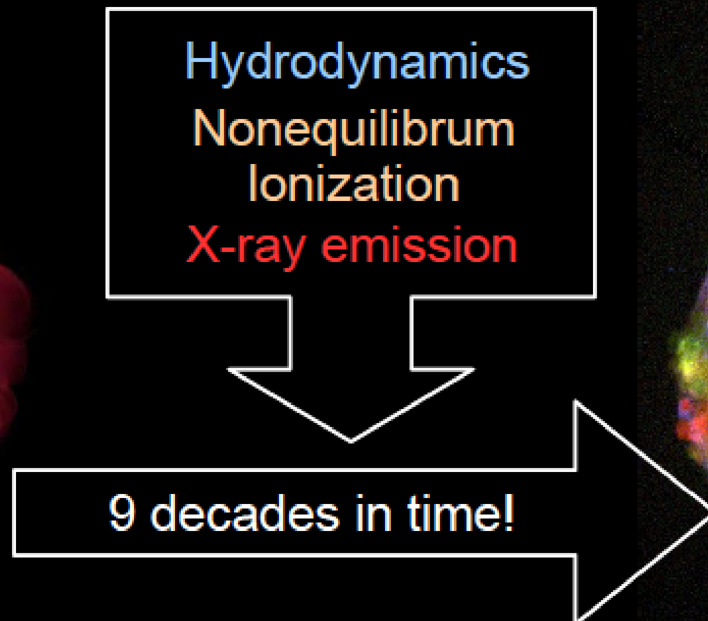
Velocity data allows an inversion of the 2-D to 3-D structure

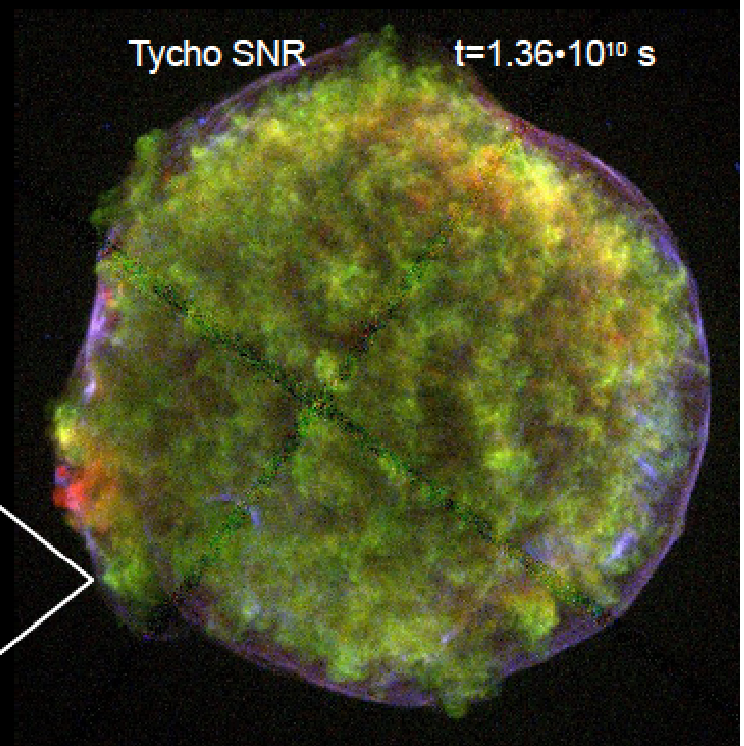
From SN explosion to SNR (I)

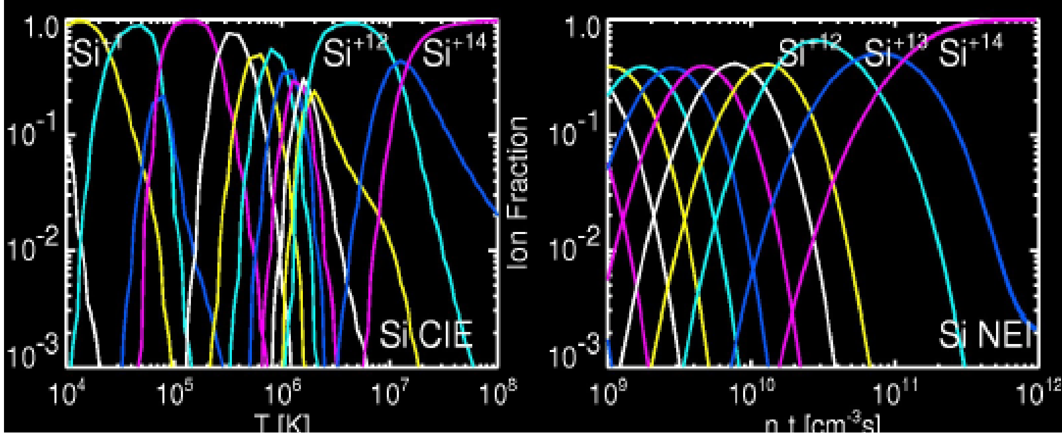
Carles Badenes
CfA 10/13/06

D Type Ia SN model
y F. Röpke

t=10 s







- Low ρ plasma in SNRs is in Nonequilibrium Ionization (NEI).
- Hydrodynamic evolution and X-ray emission are coupled by the NEI processes! [Badenes et al. 2003, ApJ 593, 358; 2005, ApJ 624, 198]