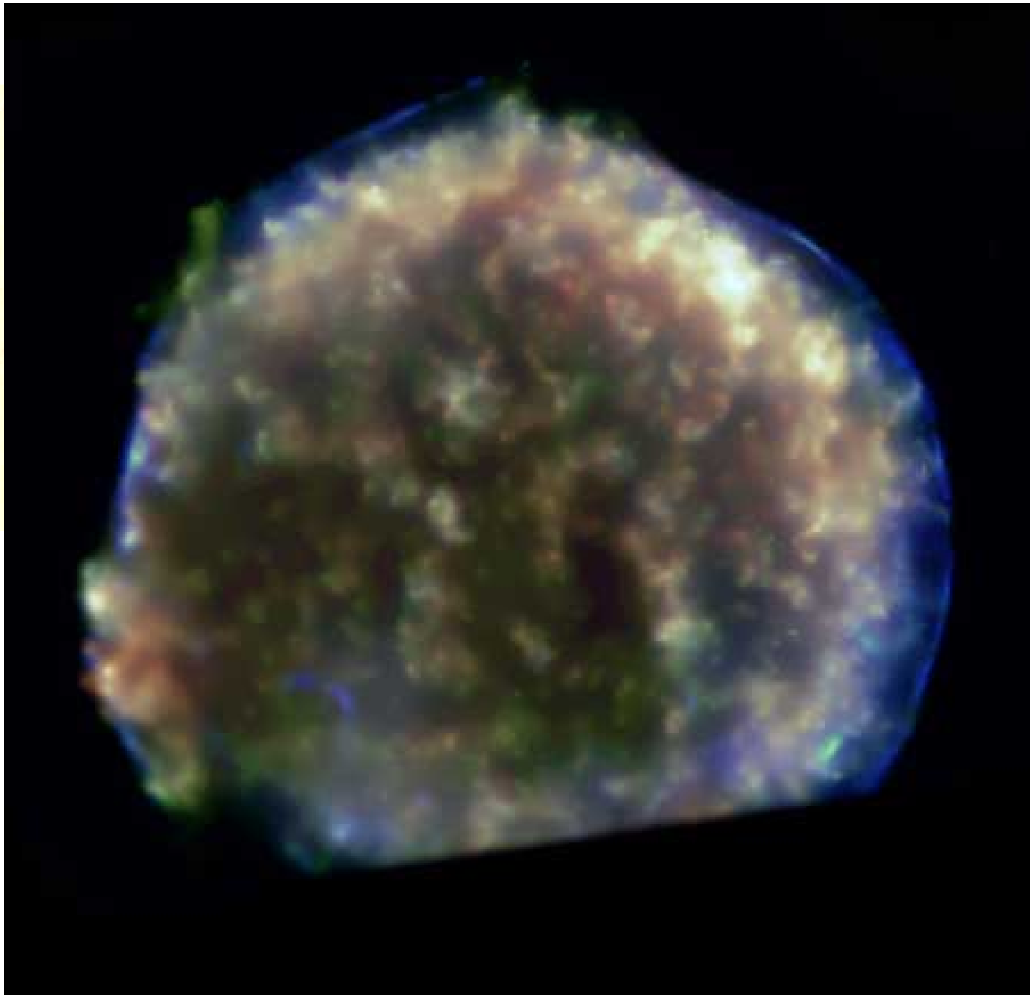
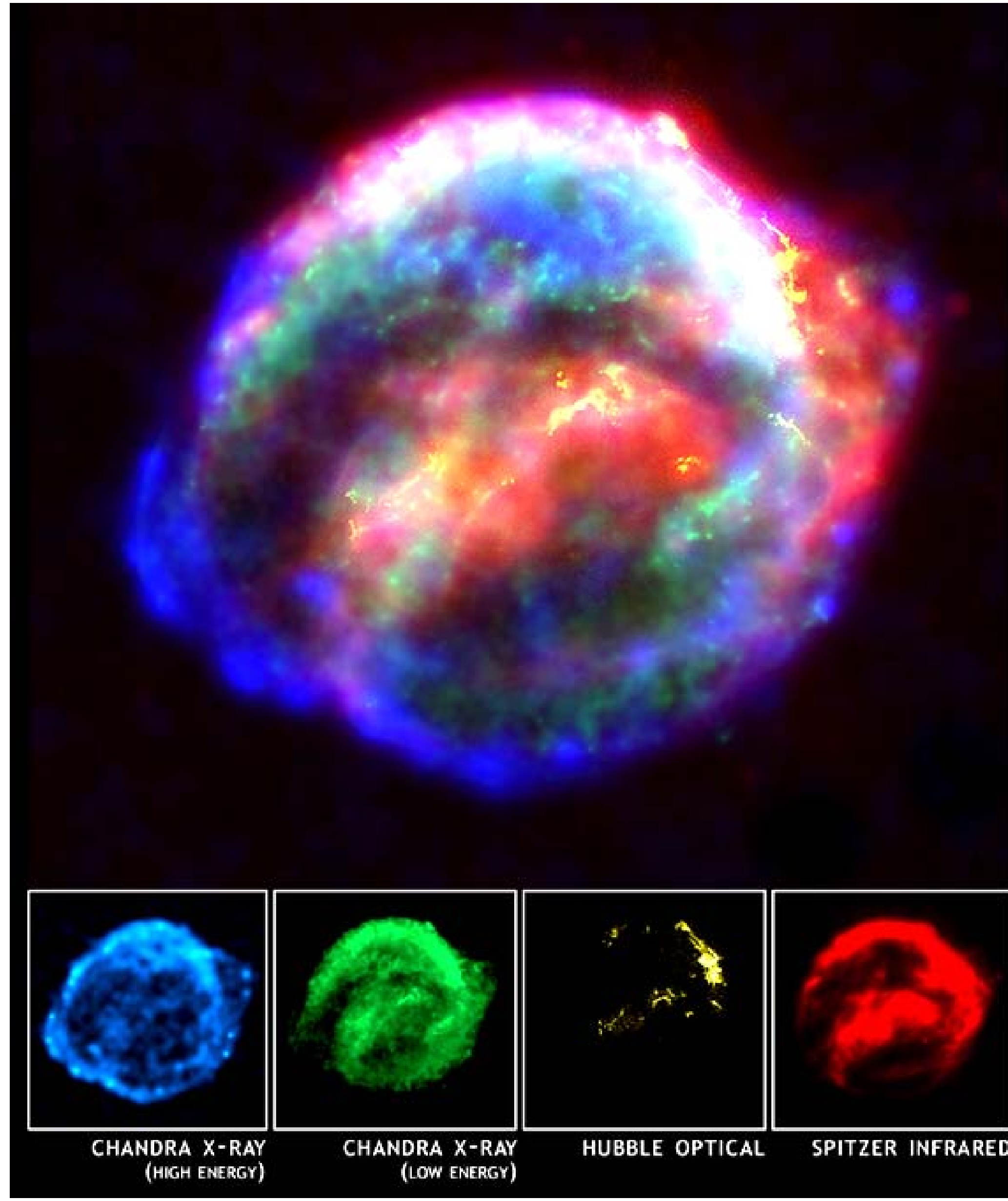
Lecture 8. Supernova remnants. Adiabatic (Sedov) and radiative (snow-plow) stages. X-ray observations, cosmic ray production…

• discovery by Tycho de Brahe (Nov 11, 1572)



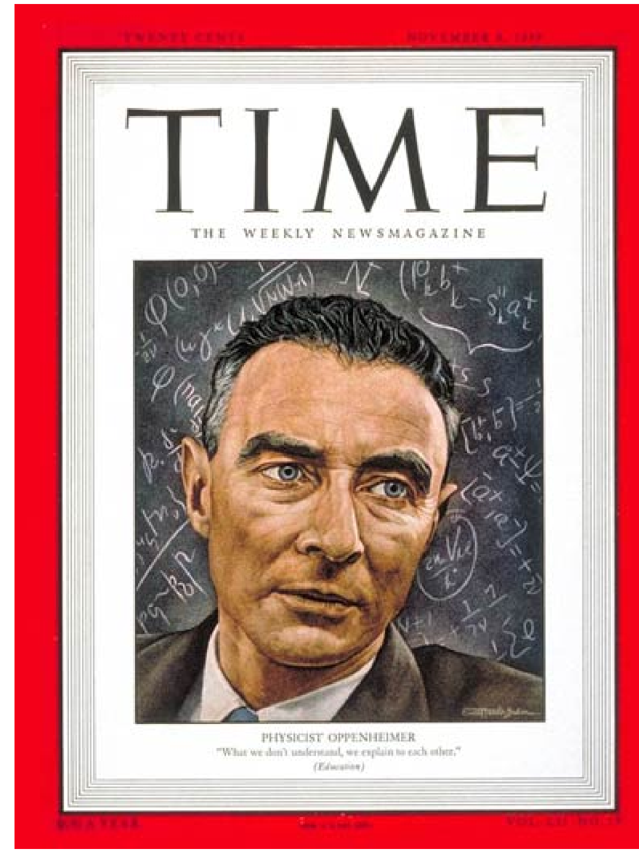
Tycho SNIa Remnant in X-rays



I.Kepler SN 1604

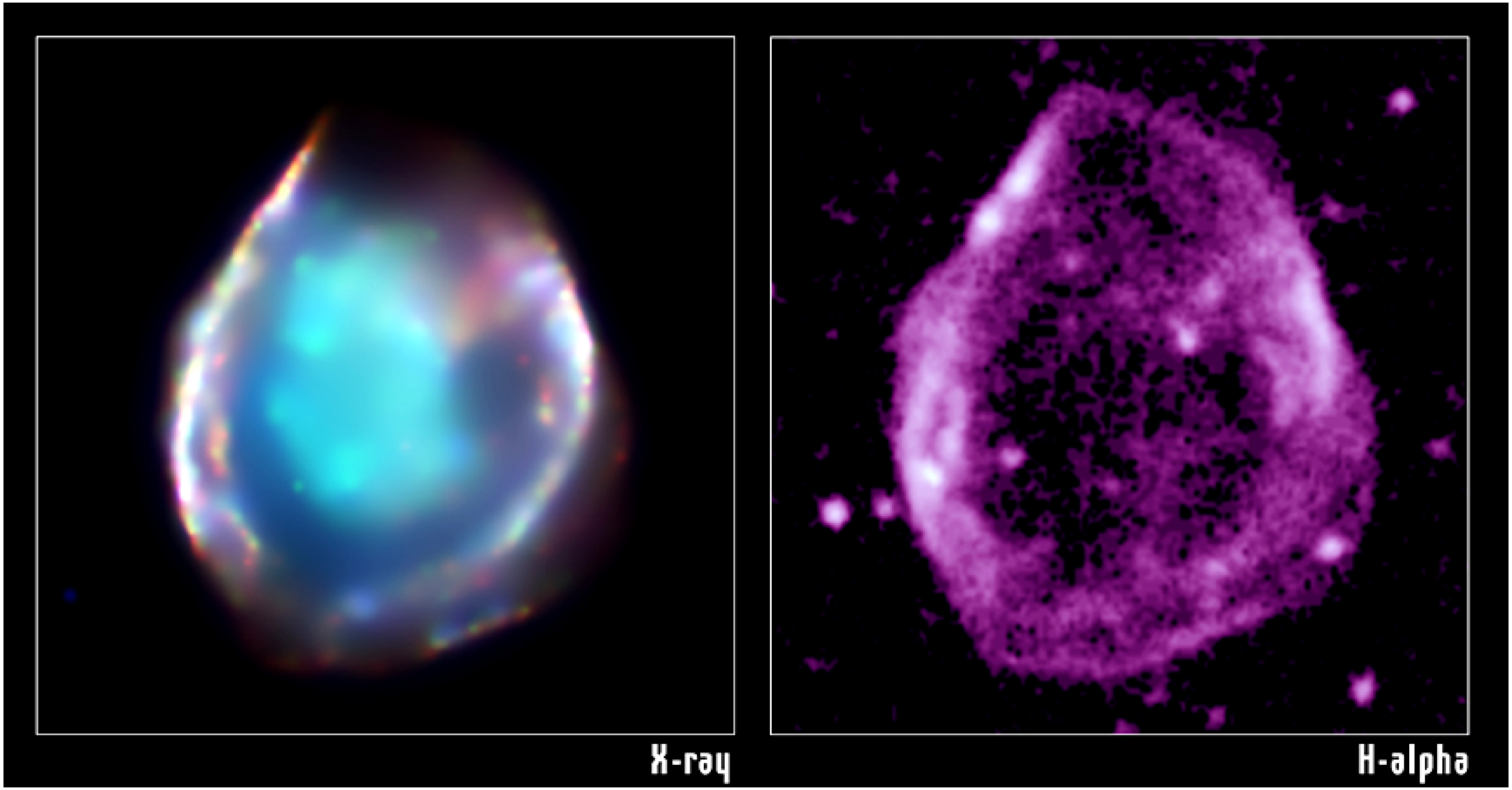
And on the Earth…

Trinity explosion, 16 July 1945



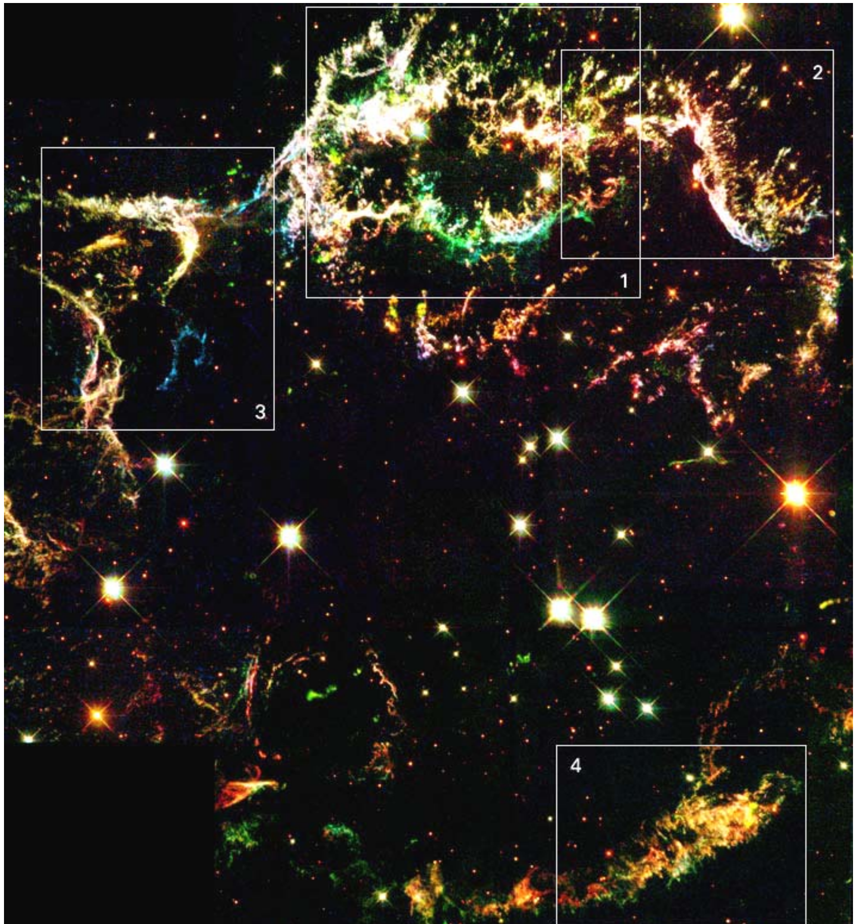
R. Oppenheimer.
Nov. 8 1948 issue

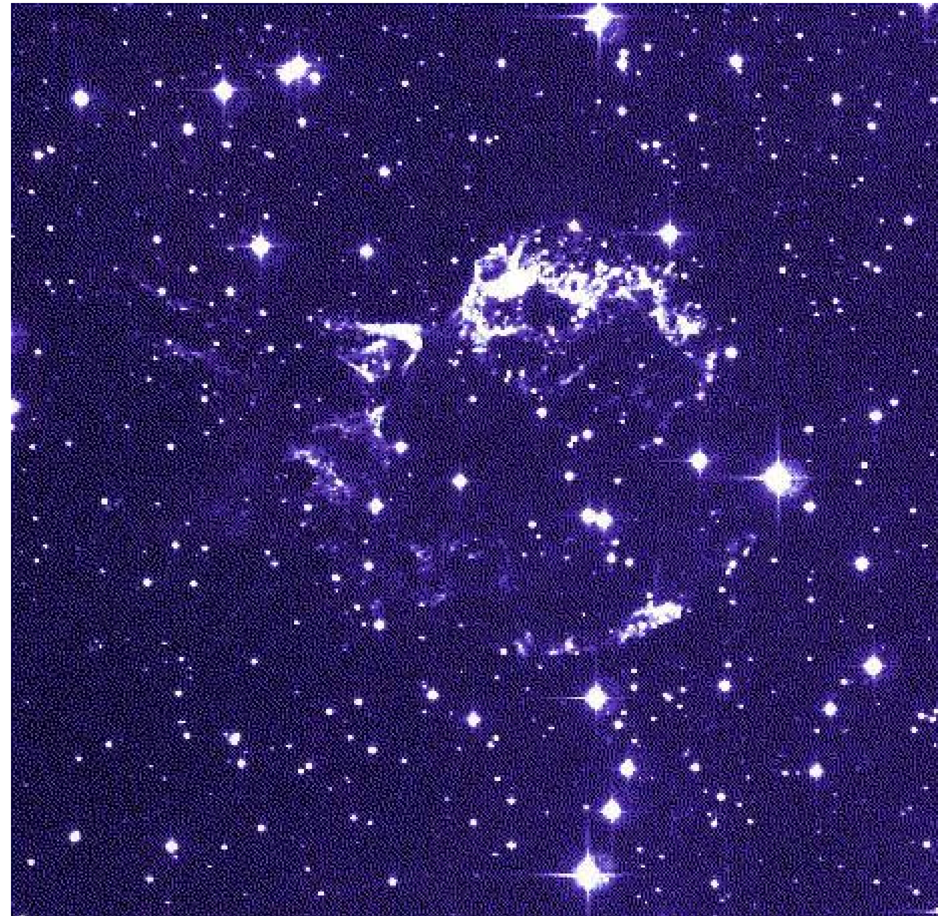
Deml71 - a SNIa SNR in LMC



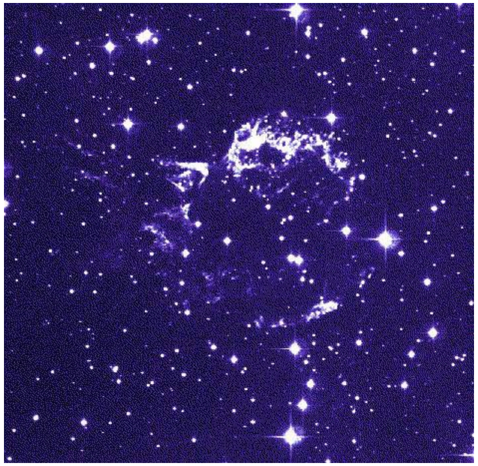
Chandra image

SNII remnants: Cas A

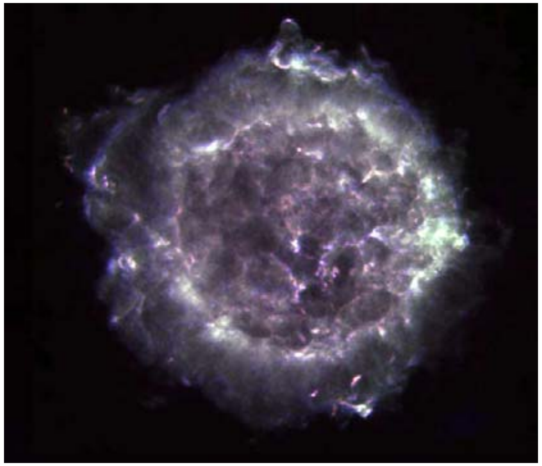




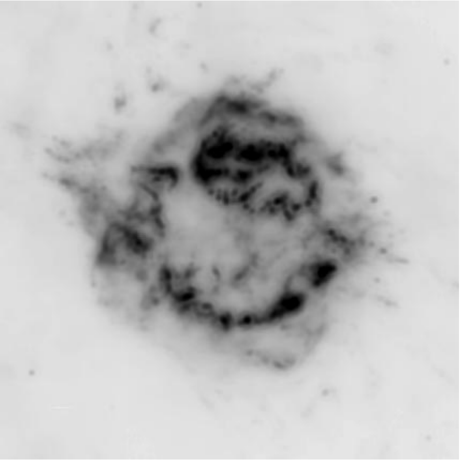
Explosion ca 320 yrs, M~10 $M_{\odot}$, now barely visible in the optical



visible



radio



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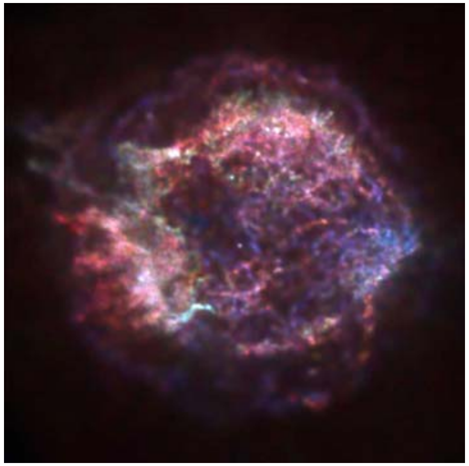
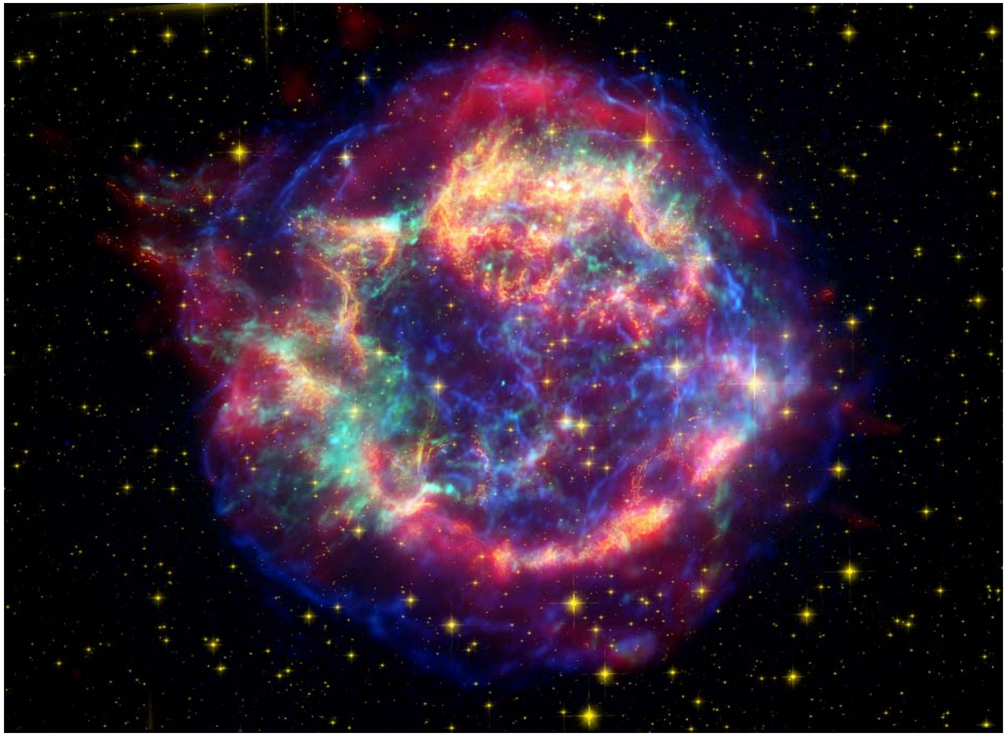
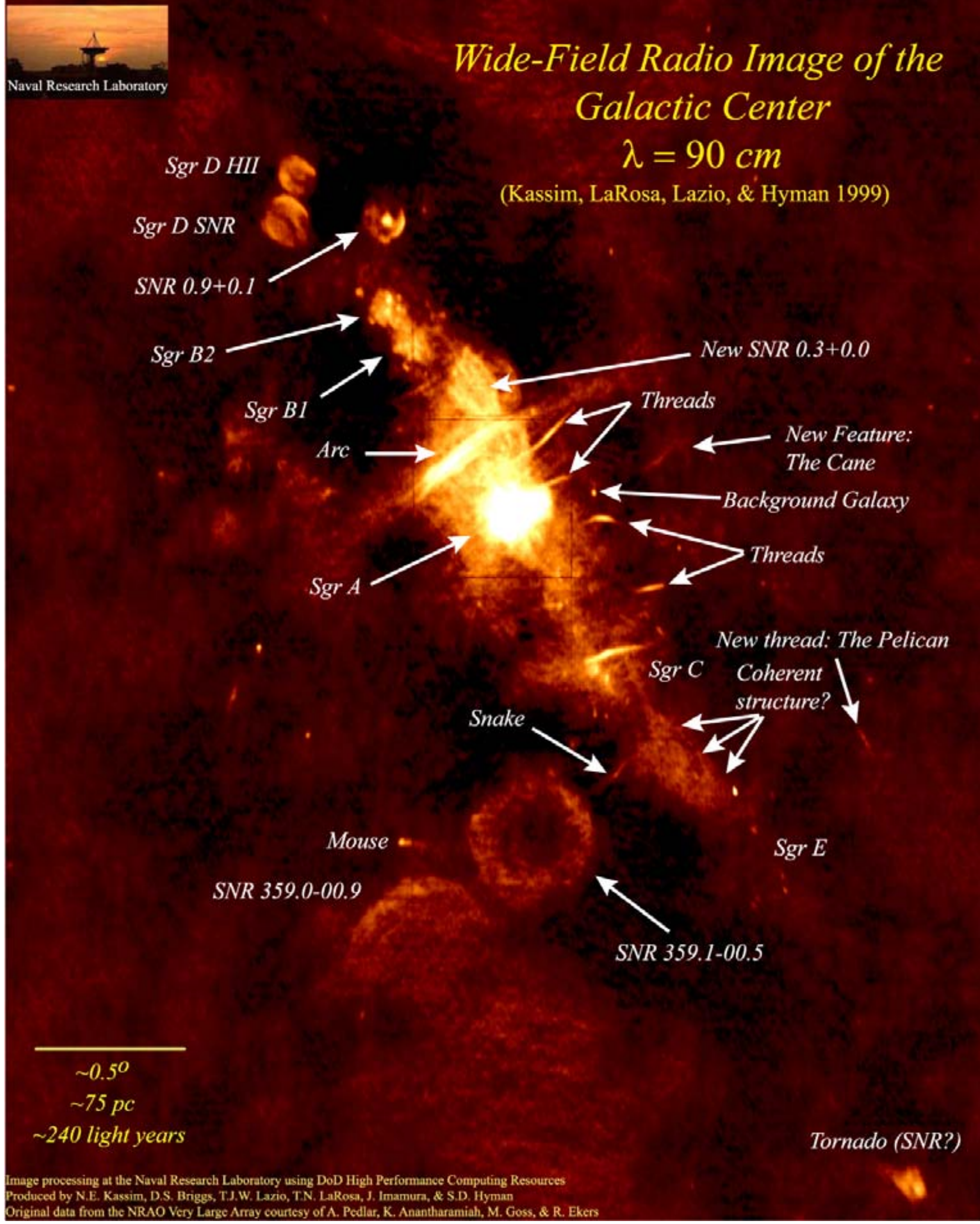


Chandra X-ray

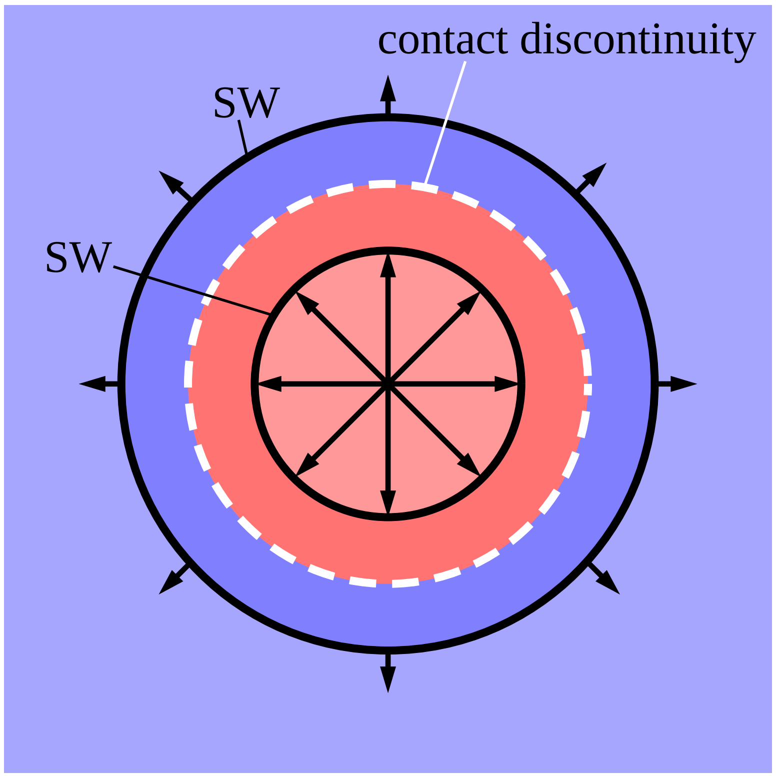


Look at the galactic plane in radio to see more…



Cygnus region.
Canadian Gal. Plane Survey

SN shocks

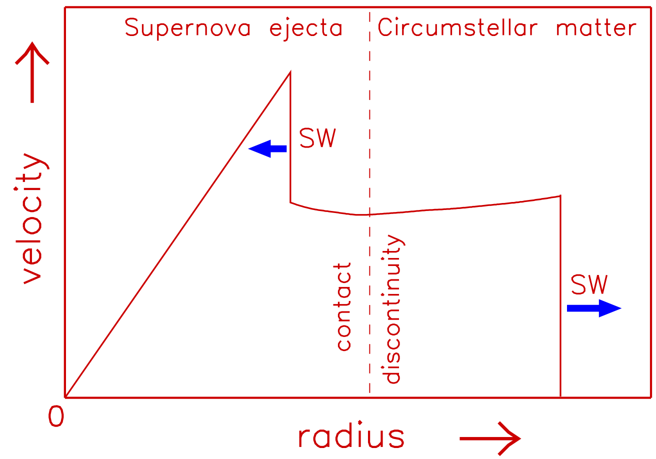


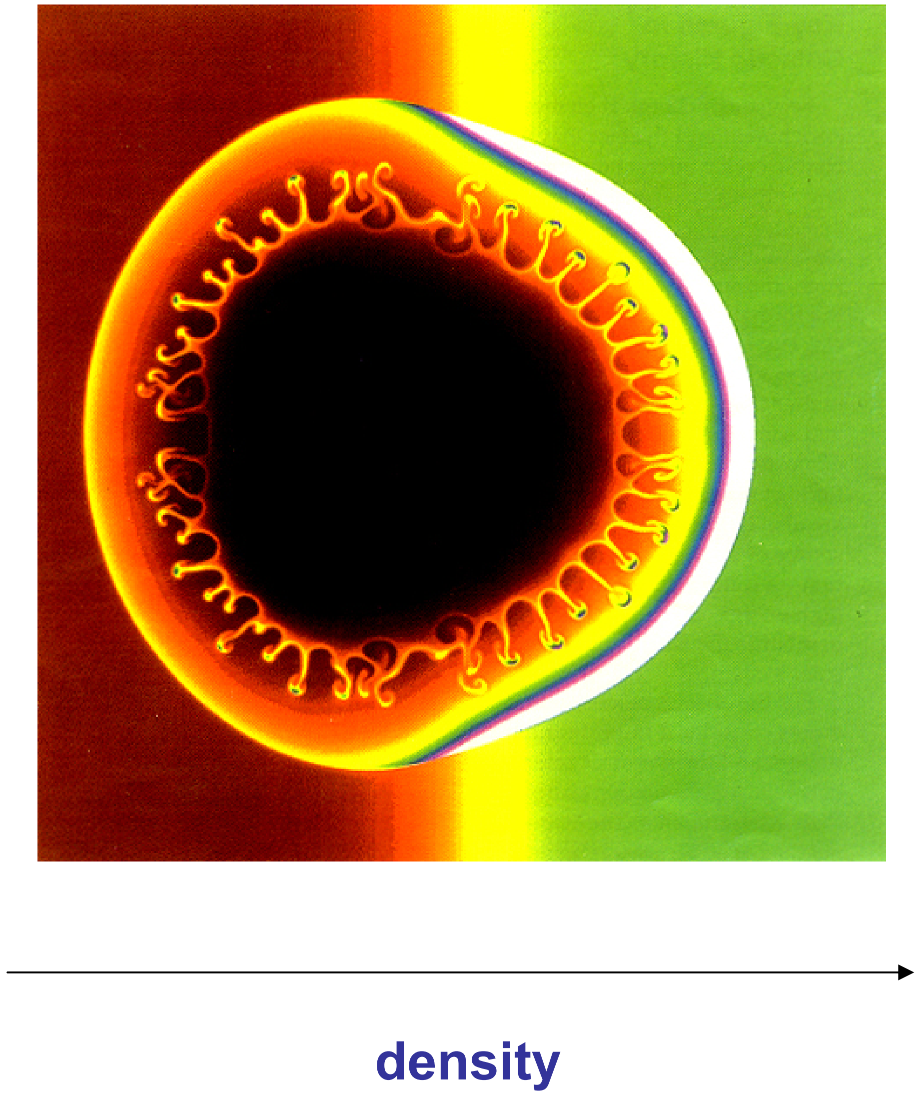
After explosion: energy in the kinetic energy of ejecta

$$\frac{1}{2}\mathrm{M_{ej}v_{ej}^2} = E_0 \Rightarrow v_{ej} \sim 10^4 \mathrm{km/s}\ \ \mathrm{E_{51}^{1/2}}(M / M_\odot)^{-1/2}$$

Contact discontinuity btw ejecta and ISM ==> Shock wave

(sound velocity in T~$10^4 K$ ISM is ~ 10 km/s)





- Shock propagates more slow in higher density regions → asymmetric shape

- Deceleration of the shock acts as effective gravity → RT instability develops

Three phases of SNR evolution

- Free expansion   R=vt

  Ends when

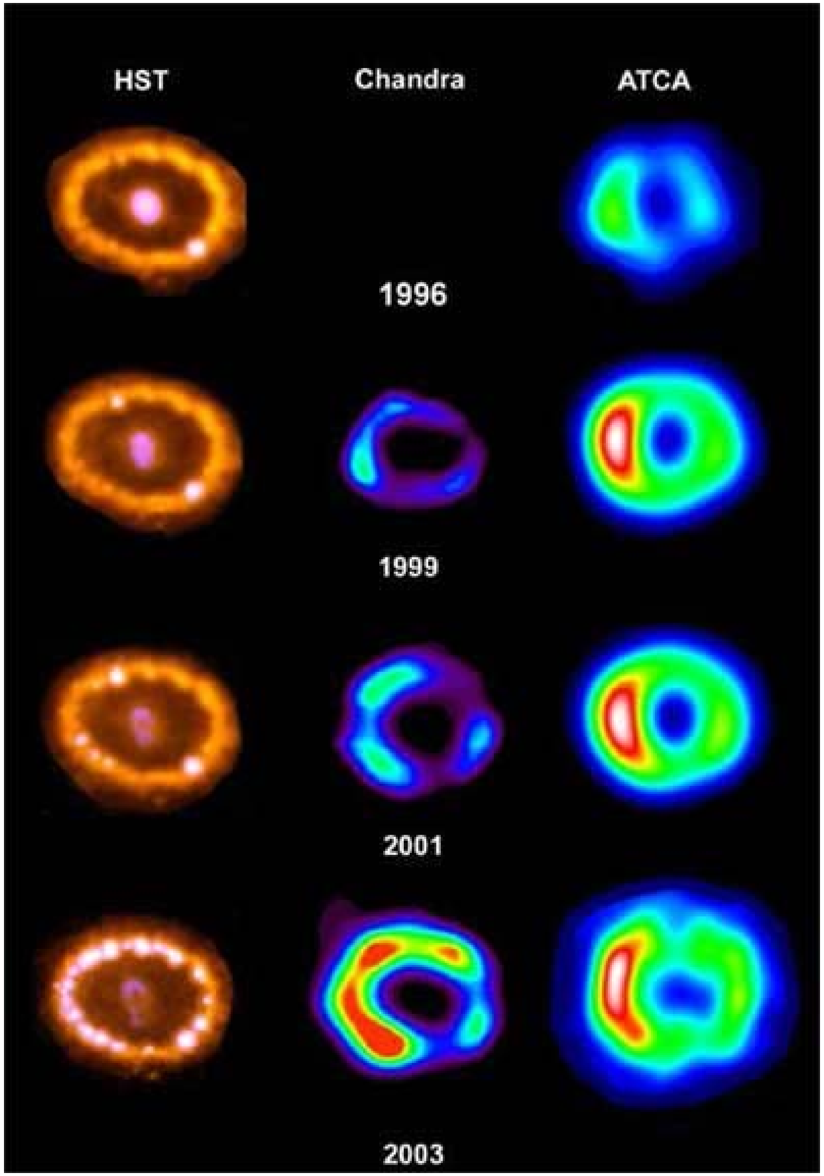
  swept-up mass ~ ejected mass

$$\mathrm{M_{sw}} = \frac{4\pi}{3}\rho_{ISM} R_{free}{}^{3} \sim \mathrm{M_{ej}}$$

$$R_{free} \sim 2\mathrm{pc}\,(\mathrm{M_{ej}} / M_{\odot})^{1/3} (\rho_{ISM} / 10^{-24}\,\mathrm{g/cm^3})^{-1/3}$$

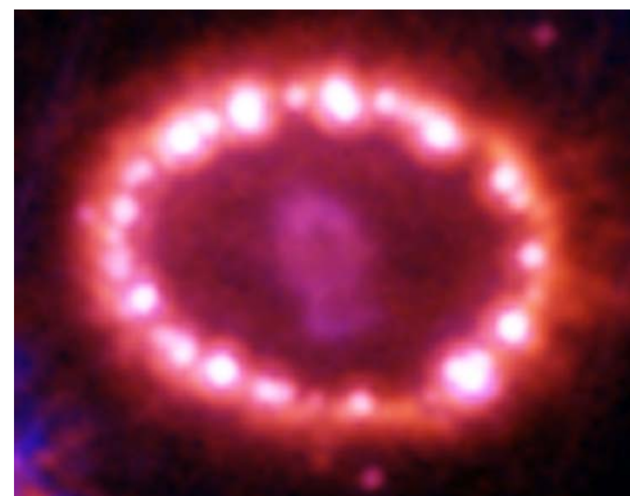
$$t \sim \frac{R_{free}}{v_{ej}} \sim 200\,\mathrm{yr}\,(\mathrm{M_{ej}} / M_{\odot})^{5/6} E_{51}^{-1/2} \rho_{-24}^{-1/3}$$

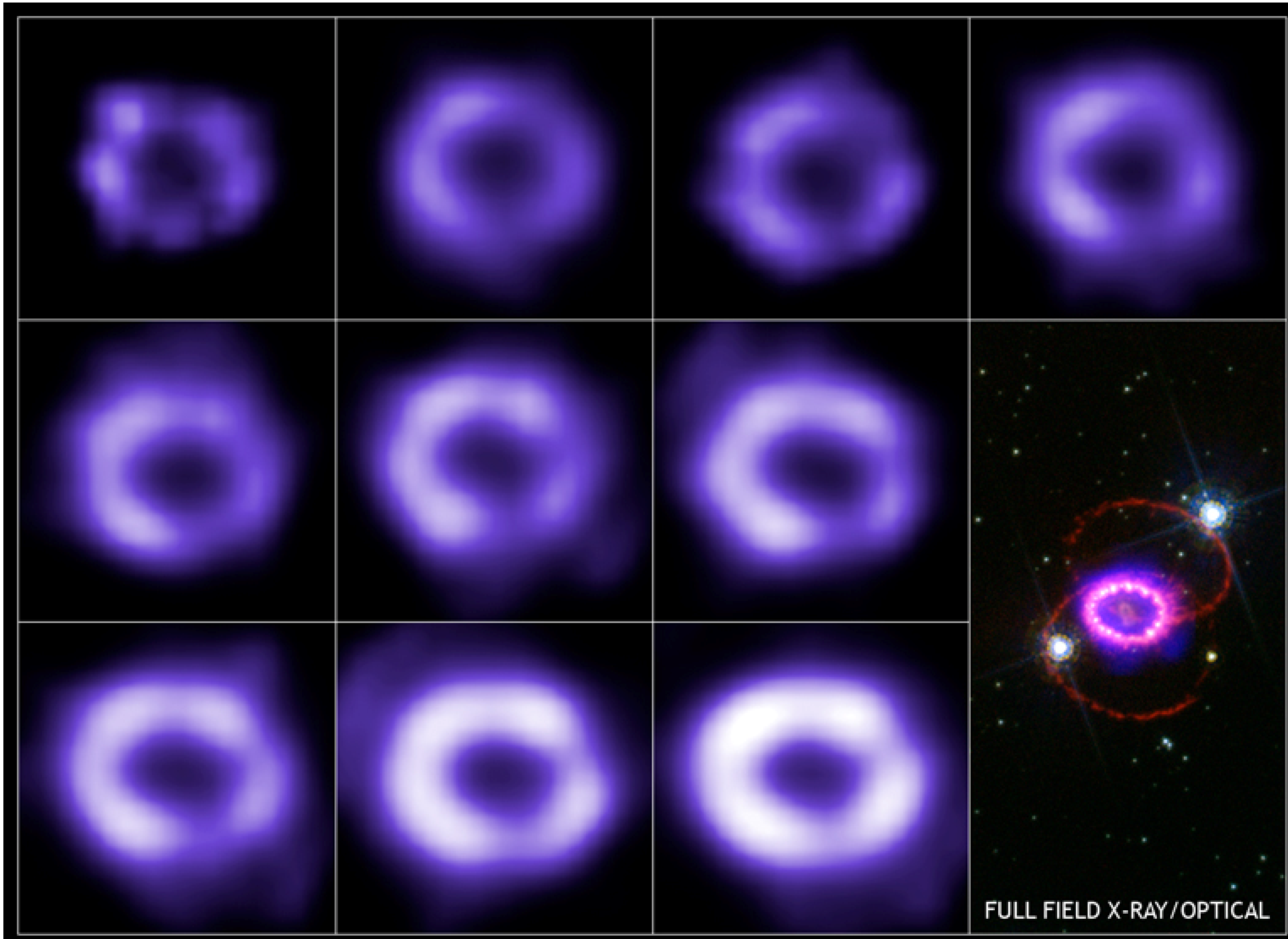
Of nearby SNR, ONLY SN 1987A is observed at this stage!

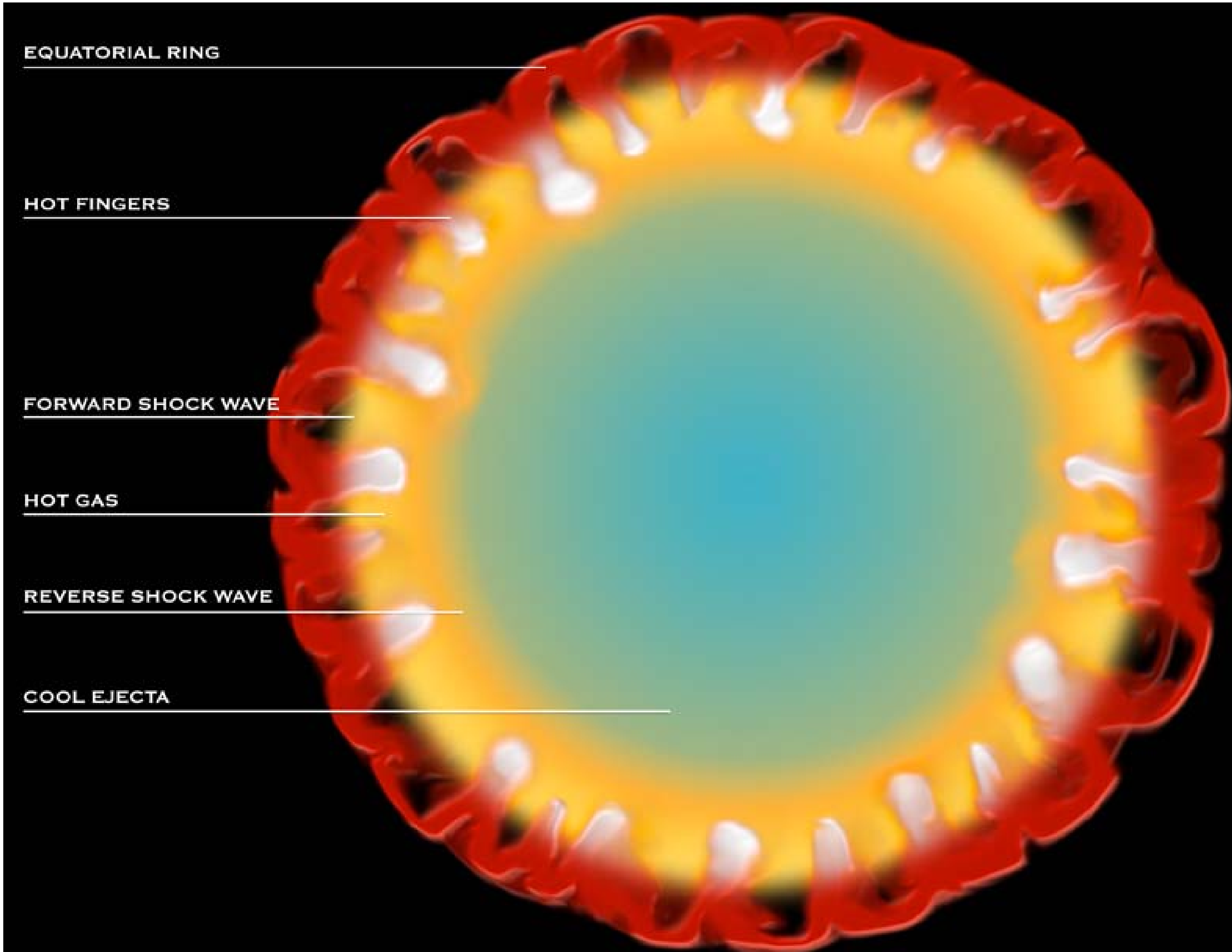


1”.66

Shocked clumpy
stellar wind left
by pre-SN supergiant
start glowing (C, N ions)
when the blast wave from
SN 1987a reached it (by 2000)

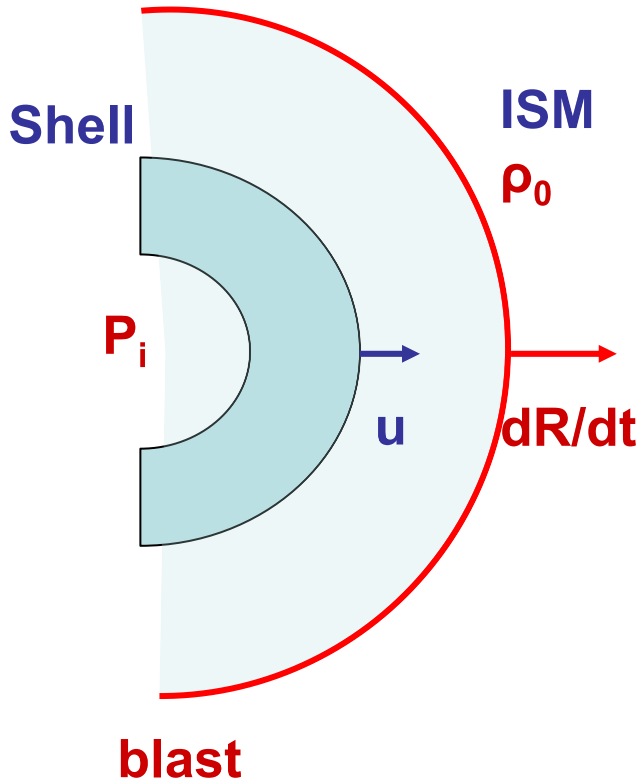



FULL FIELD X-RAY/OPTICAL



(Credit: NASA/CXC/M.Weiss)

2. Adiabatic (Sedov-Taylor-von Neumann) stage



$$R = 0.31\,\mathrm{pc}\left(\frac{E_{0,51}}{n_0}\right)^{1/5}\left(\frac{t}{\mathrm{yr}}\right)^{2/5}$$

Swept-up mass is confined within a thin shell:

$$M(t) = M_0 + \frac{4\pi}{3}\rho_0 R(t)^3$$

Shell motion is driven by internal pressure:

$$\frac{d}{dt}(Mu) = 4\pi R^2 P_i$$

Total energy is conserved (adiabatic stage!):

$$\frac{1}{2}Mu^2 + \frac{4\pi}{3}\frac{P_i}{(\Gamma-1)}R^3 = E_0$$

(Γ is the adiabatic index)

Strong shock: $P_i \gg P_{external}$

$$\frac{dR}{dt} = \frac{\Gamma+1}{2}u$$

In the approximation $M \gg M_0$ one finds Sedov's solution (1946):

$$R(t) = \xi\left(\frac{E_0}{\rho_0}\right)^{1/5} t^{2/5}, \quad \xi \approx 1.152 \quad \text{for } \Gamma=5/3.$$

X-ray emission from young SNR

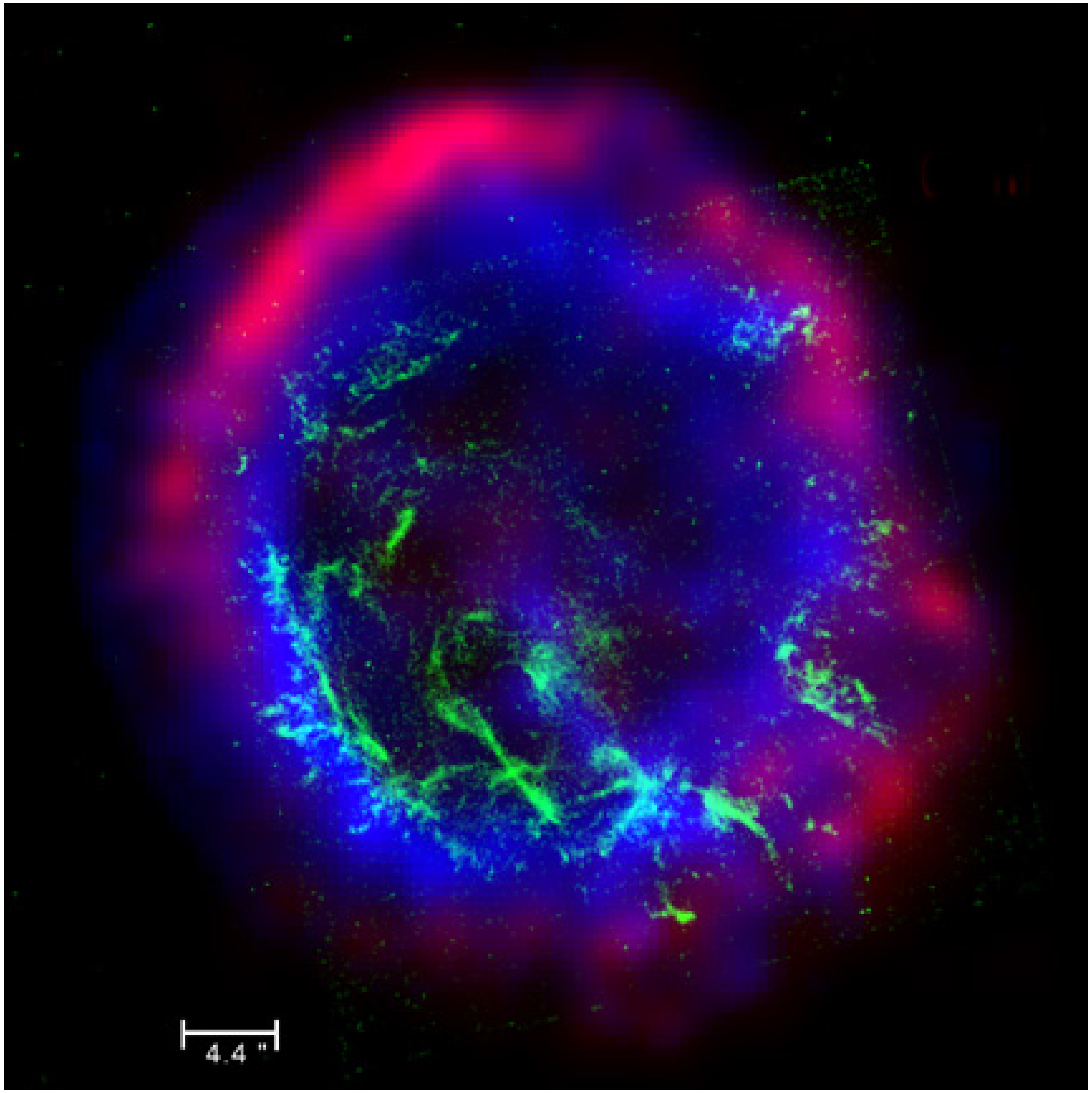
If energy of kinetic motion of particles behind the shock dominates the thermal energy of fully ionized plasma, temperature of the shocked matter is

$$k_B T_{sh} = \frac{3}{16}\mu\left(\frac{dR}{dt}\right)^2$$

At the Sedov stage $dR/dt \sim R/t$ so

$$\boxed{T_s \simeq 1.8\cdot 10^5 \ \mathrm{keV} \left(\frac{\mathrm{R/pc}}{t/\mathrm{yr}}\right)^2}$$

Young SNR ($t \geq 100$ yrs) must shine mostly in X-rays!

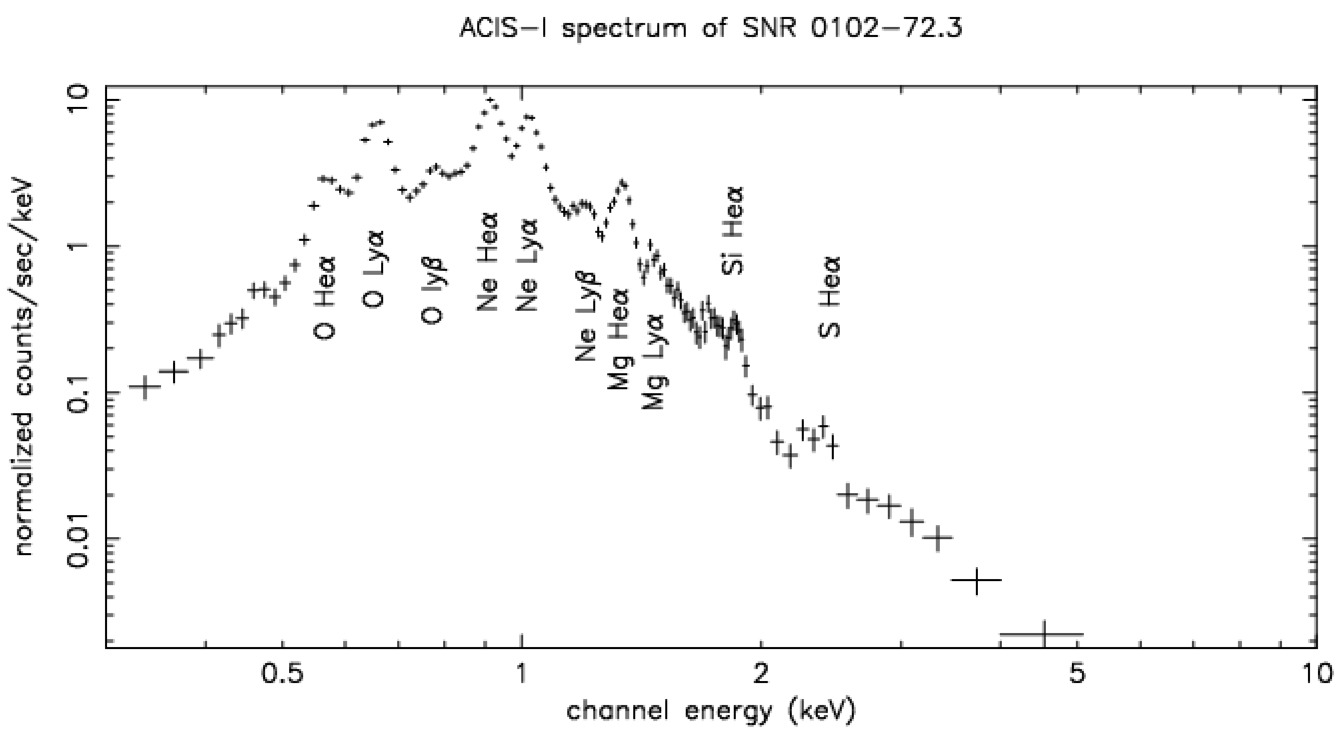


Example of core-collapse SNR (~10 $M_\odot$) at the Sedov stage

E0102-72.3 in SMC.
190,000 yrs old.
Red – radio synchrotron emission by electrons accelerated in the forward shock (ATCA).

Blue – X-ray emission of ejecta heated to 10^9K by reverse shock (Chandra).

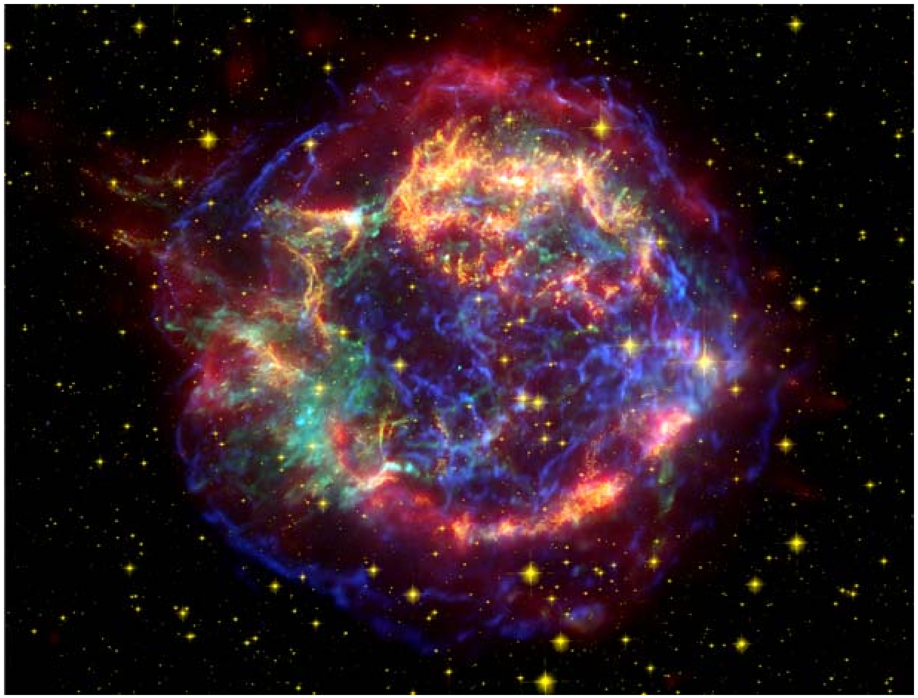
Green – optical filaments (HST).



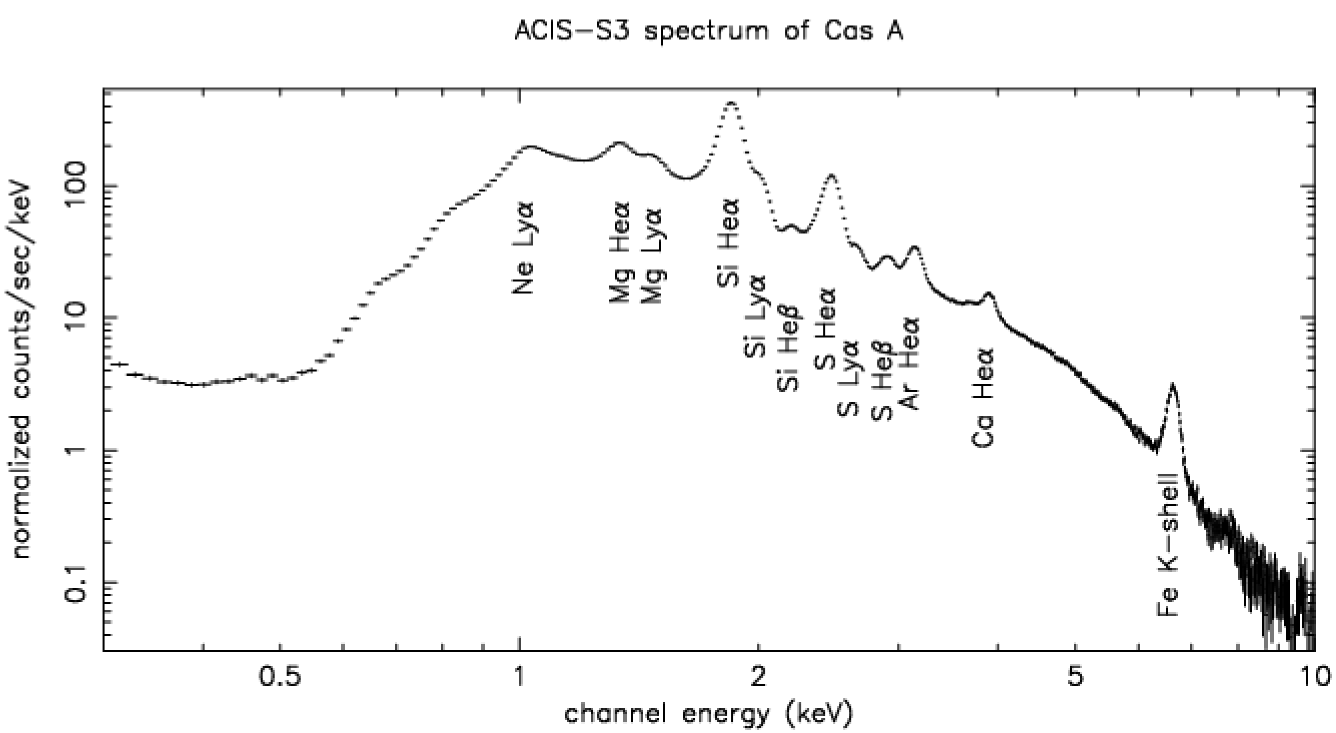
X-ray emission lines evidence collisionally excited thermal plasma

O, Ne and Mg dominate the X-ray spectrum → type Ib?

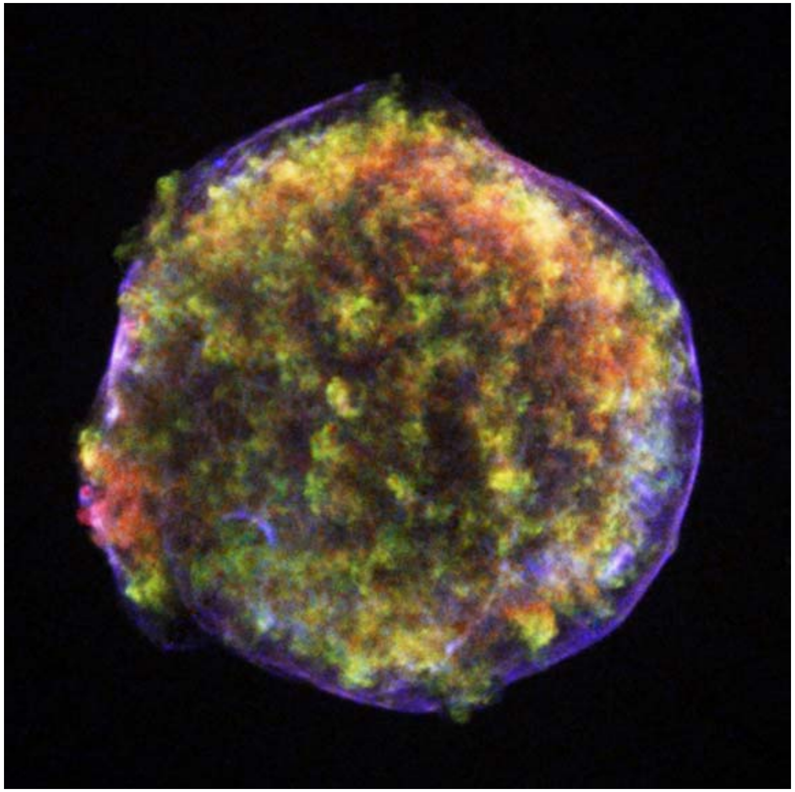
Another example: Cas A



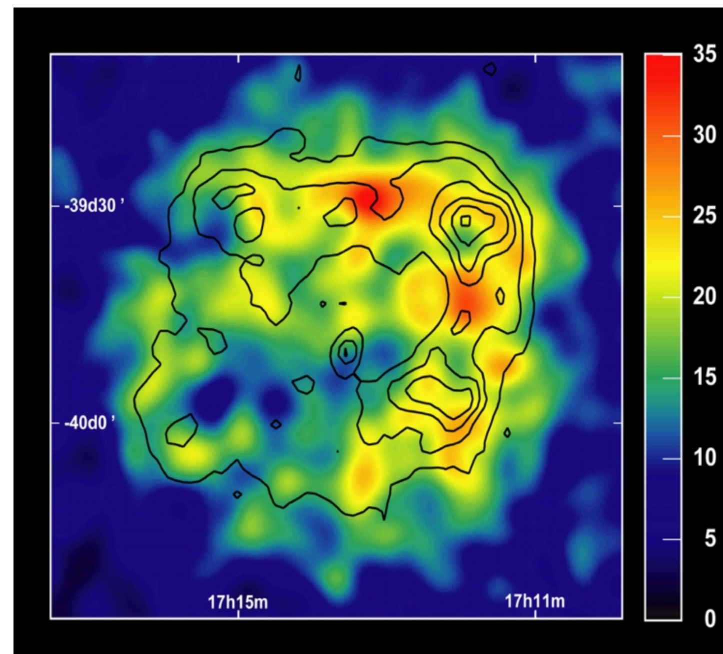
- Young shell-like SNR (~1670)
- No optical explosion was noted (dim SN)
- From optical observations $M \sim 10\ M_{\odot}$ - type II?
- 2000: Chandra found central point source (NS), thus confirming SNII nature.


ACIS−S3 spectrum of Cas A
normalized counts/sec/keV
channel energy (keV)
0.1
1
10
100
0.5
1
2
5
10
Ne Lyα
Mg Heα
Mg Lyα
Si Heα
Si Lyα
Si Heβ
S Heα
S Lyα
S Heβ
Ar Heα
Ca Heα
Fe K−shell

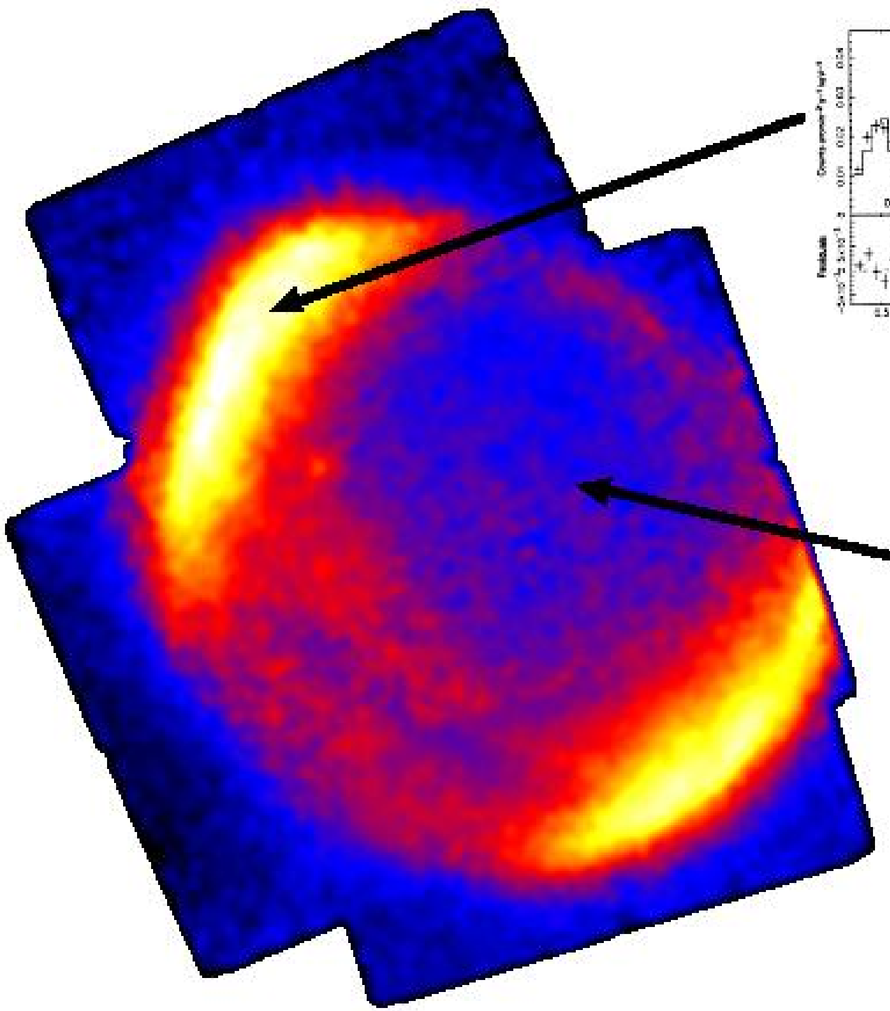
Tycho SNR (SN1a, 1572)

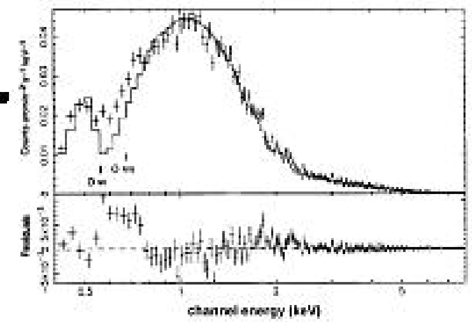


- New findings (Chandra, 2005) – forward shock front (in blue) and ejecta keep pace much closer than expected → forward shock energy spent to accelerate nuclei to relativistic energies (CR formation)
- CR formation is directly confirmed by recent H.E.S.S. discovery of TeV photons from SNRs (image below)

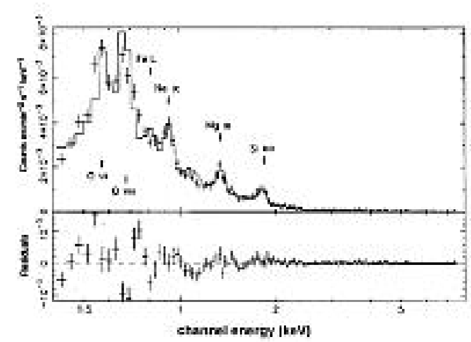


ASCA view of SNR 1006: *CR* production by SNR shock



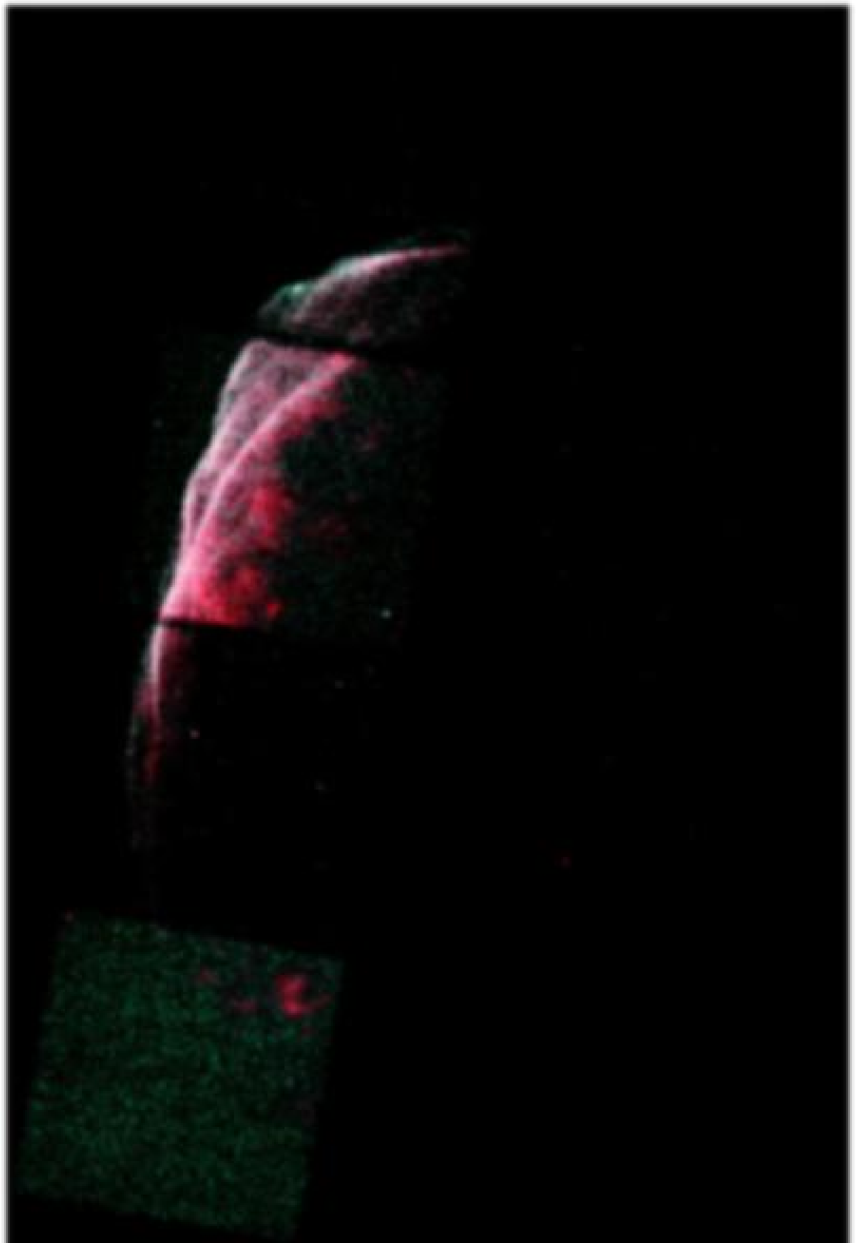


Non-thermal emission of relativistic electrons in magnetic field



X-rays from thermal plasma

SNR 1006



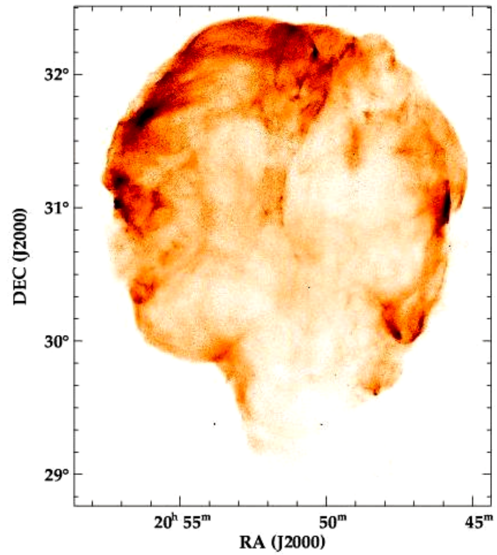
…and Chandra resolves the shock where particles are accelerated.

Plerionic (Crab-like) SNRs

Crab Nebula after SN 1054 –
No shock shell.
Synchrotron nebula is
powered by the central pulsar

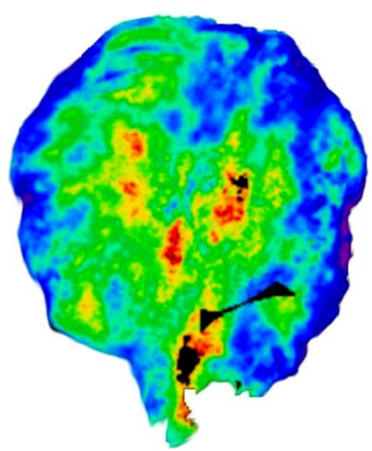
Cnandra found extended shell around plerionic SNR G21.5-0.9 explosion in ISM swept up by the SNR progenitor wind?

Cygnus loop: At the end of Sedov stage

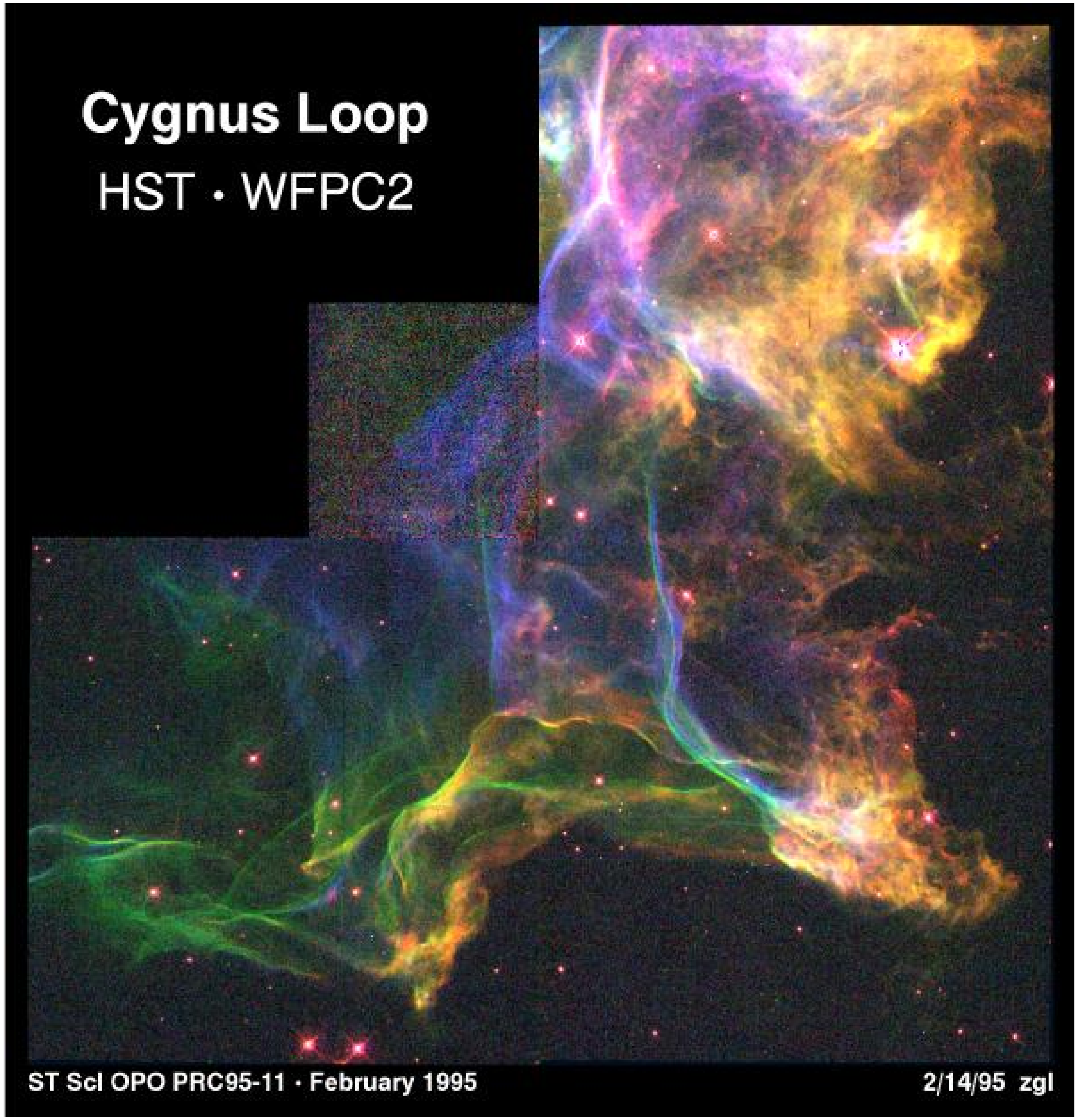


- 20,000 yrs old

ROSAT HRI X-ray composite image.
Asymmetric shape due to inhomogeneous surroundings



ROSAT PSPC temperature map.
Hotter gas is in the center



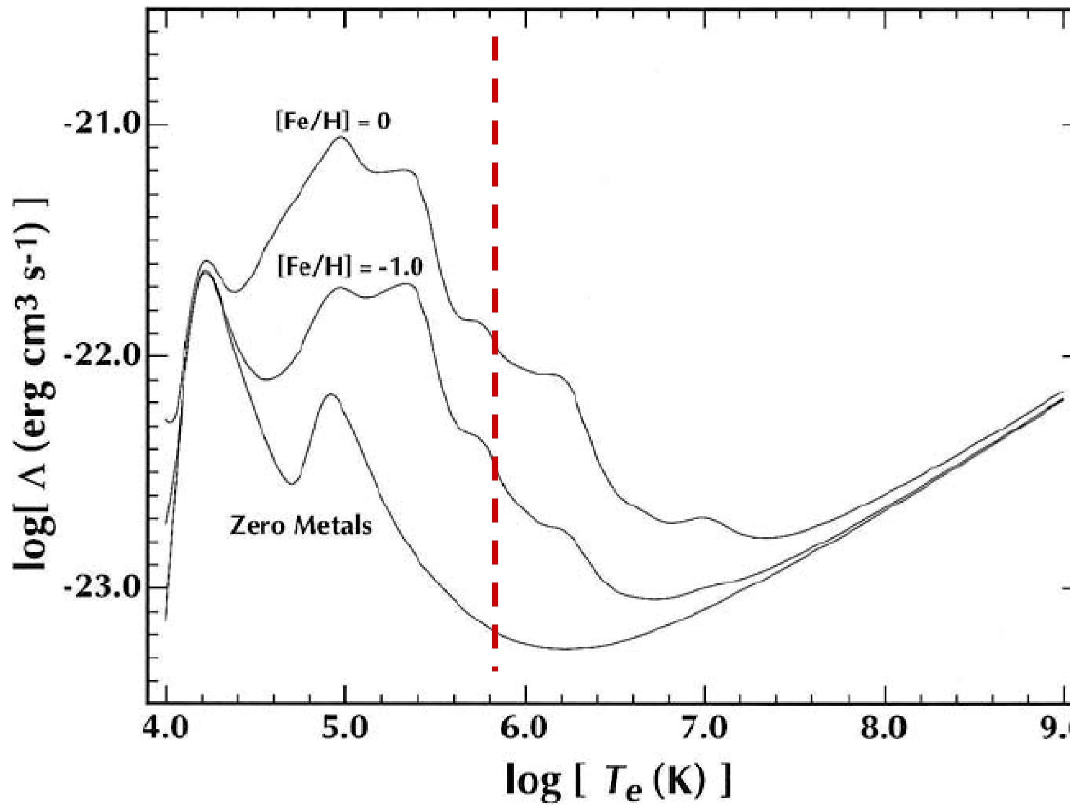
Optical filaments appears as thermal instability starts to operate in dense plasma.

3. Radiative (snow-plow) stage

Adiabaticity breaks when radiation losses from the shell become dynamically important. This occurs when temperature drops below $T_r \sim 6\times10^5$K.

Cooling function of thermal plasma:

$$\frac{dE}{dtdV} = n_e^2 \lambda(T)$$



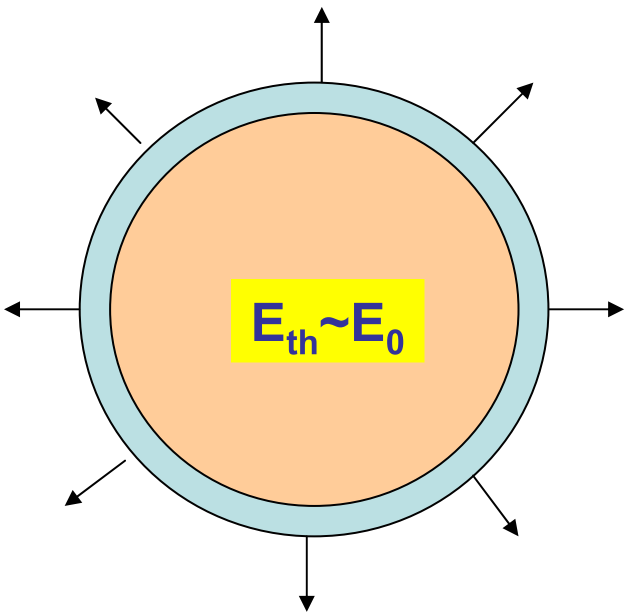
Cooling function of collisionally excited thermal plasma

At the Sedov stage: $T_s \sim (R/t)^2 \sim \left(\frac{E_0}{\rho_0}\right)^{2/5} t^{-6/5}$

Transition to radiative stage: $T_s = T_r \quad \Rightarrow$ transition radius:

$$R_c \approx 24\text{pc} \left(\frac{E_{0,51}}{n_0}\right)^{2/5}$$

Fast cooling occurs for $R > R_c$ and mass becomes condensed in a thin shell driven by the pressure work of the internal hot rarefied gas. The shell ploughs into the ISM due to its intrinsic momentum.



$$\mathbf{R \approx 35pc\left(\frac{E_{0,51}}{n_0}\right)^{5/21}\left(\frac{t}{10^5\,yrs}\right)^{2/7}}$$

Thermal energy evolution: $dE_{th} = -PdV, \quad E_{th} = \frac{4\pi}{3} R^3 \frac{P}{\Gamma - 1}$

For $\Gamma = \frac{5}{3}$: $\qquad \frac{\dot{E}_{th}}{E_{th}} = -2\frac{\dot{R}}{R} \;\Rightarrow\; \frac{E_{th}}{E_{th,c}} = \left(\frac{R_c}{R}\right)^2$

Expansion: $\qquad \frac{d}{dt}(M\dot{R}) = 4\pi R^2 P, \quad M = \frac{4\pi}{3} R^3 \rho_0$

Inserting $P \sim E_{th}/R^3 \propto 1/R^5$ we arrive at

$$\frac{d^2}{dt^2} R^4 \sim \frac{1}{R^3}$$

with the solution $\quad \mathbf{R \propto t^{2/7}} \quad \left(cf.\; R \propto t^{2/5} \text{ at the Sedov stage}\right)$

Thermal energy is a fraction of the explosion energy E_0.

At the adiabatic stage, $E_{th} = 0.72\,E_0$ (for Γ=5/3)

At the radiative stage, $E_{th} \approx 0.24\,E_0$

Once velocity of SNR drops to 10-100 km/s (as in ISM), it merges with ISM. This occurs typically after 10^4yrs.

HST image of many old merged SNRs around Hodge 301 young stellar cluster in LMC