- Show that P α nT

$$PV = n_{mol}RT$$

$$P = \frac{n_{mol}RT}{V}$$

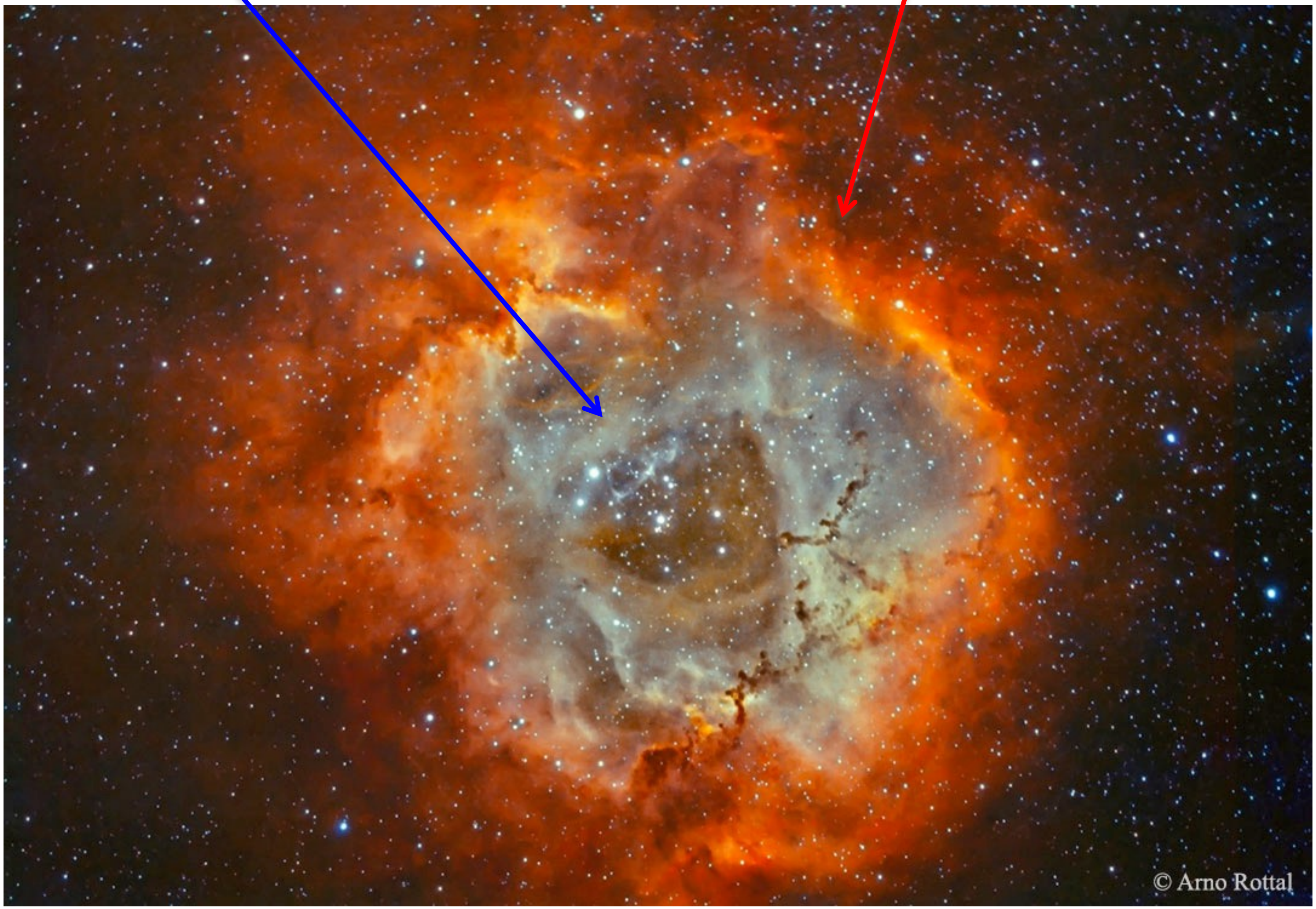
Now number density of particles is

$$n = \frac{n_{mol}N_A}{V} \quad \text{so}$$

$$P = \frac{nRT}{N_A} \qquad \text{i.e. } P \propto nT$$

H II Region $n \sim 10^{10}$ m^{-3}, $T \sim 10^4$ K

Molecular cloud $n \sim 10^{10}$ m^{-3}, $T \sim 30$ K



https://apod.nasa.gov/apod/ap150225.html

Supernovae

- Supernova explosions
- X-ray emission
- Radio synchrotron emission
- Hot phase of the ISM

Supernovae Explosions

- Supernovae come in two main types
  - Type II when the core of a single massive star collapses at the end of its life to form a neutron star or black hole
  - Type Ia when a white dwarf star explodes due to the accretion of matter in a binary star system pushing it over its maximum mass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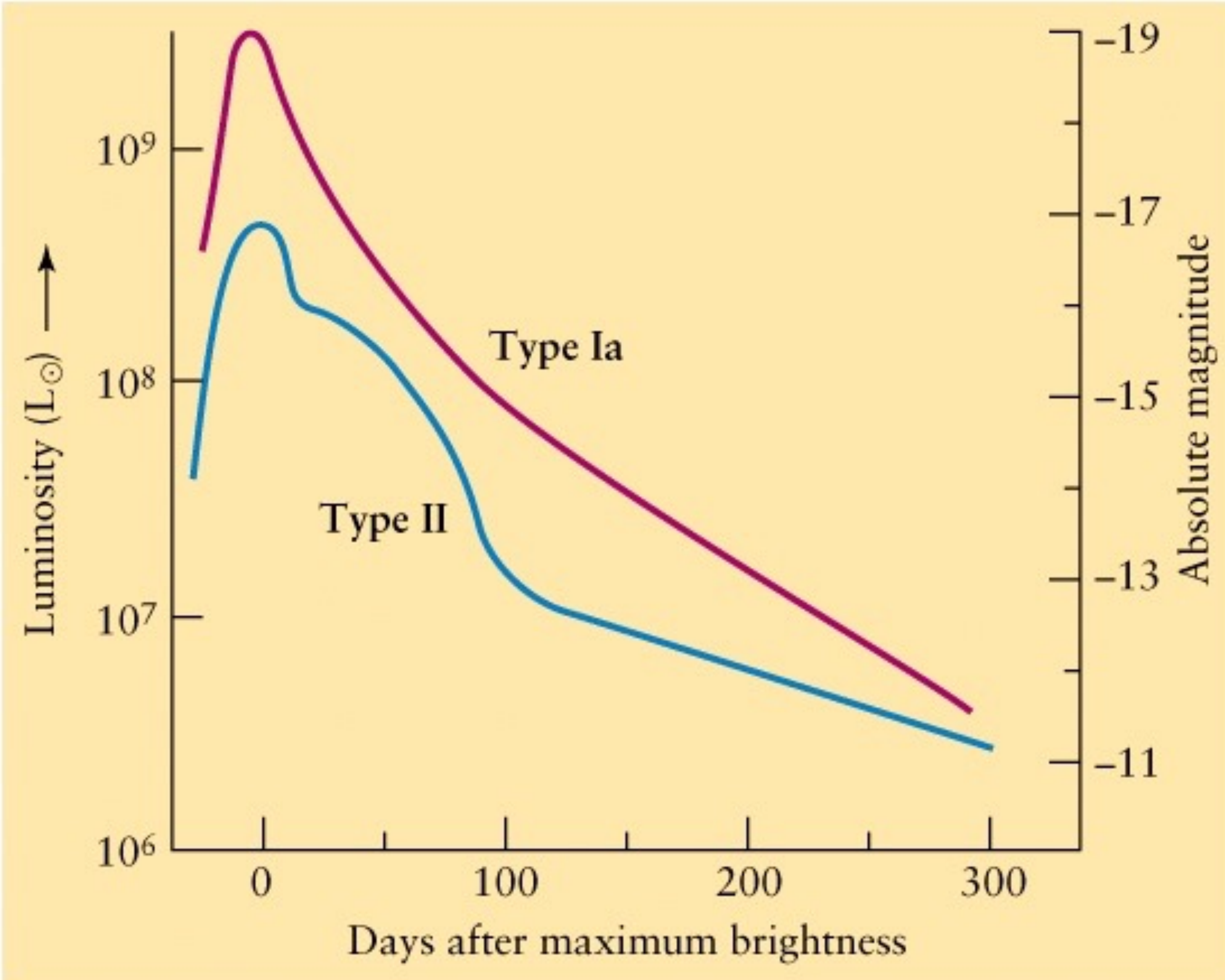
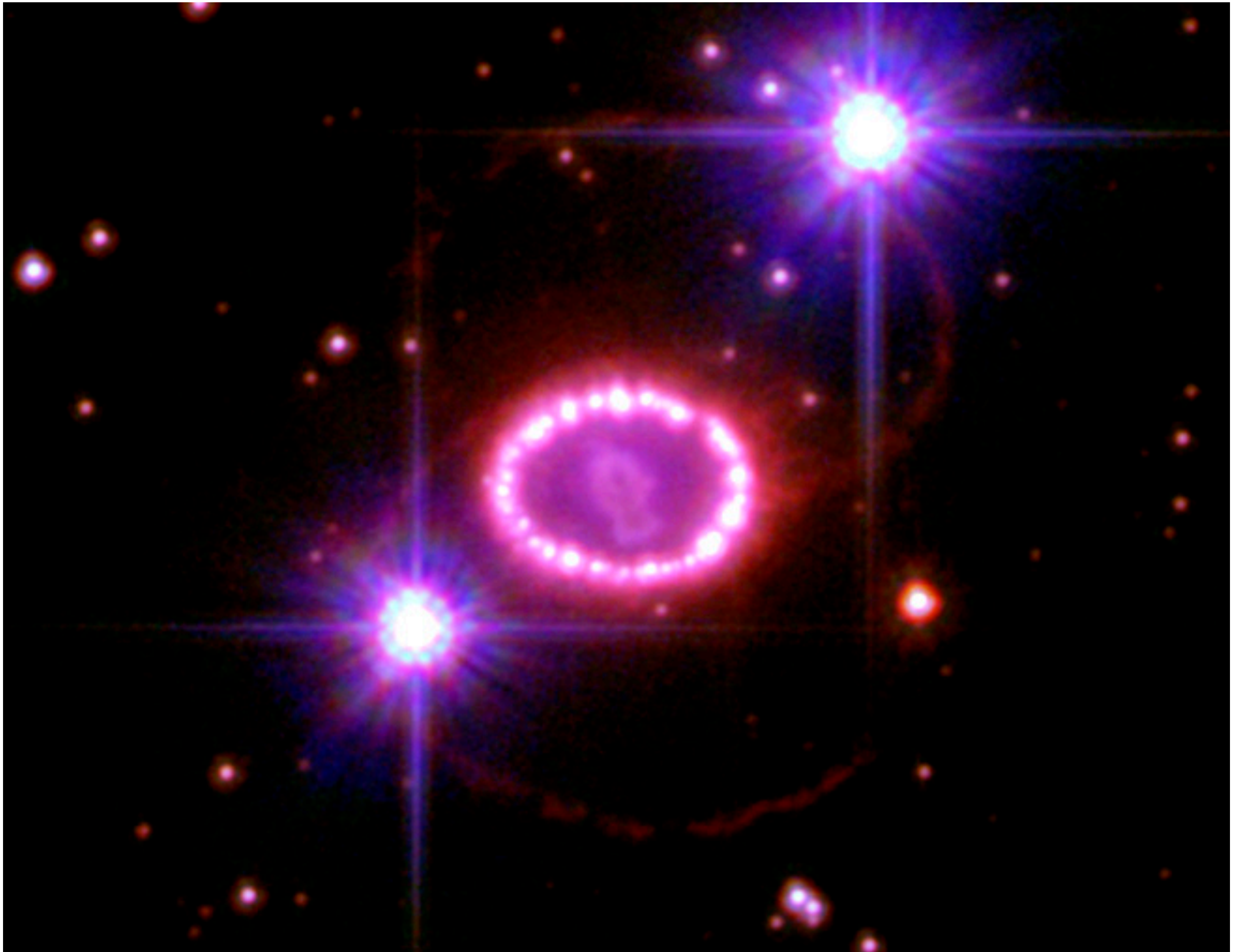


10^9
10^8
10^7
10^6
Luminosity (L☉) ⟶
Type Ia
Type II
0
100
200
300
Days after maximum brightness
−19
−17
−15
−13
−11
Absolute magnitude



NASA HST image of SN 1987A

NASA HST movie of SN 1987A

Extreme Energies

- We can estimate the energy in a supernova explosion from the gravitational potential energy released

$$E_{grav} \approx \frac{GM^2}{R}$$

$$\approx \frac{7\times10^{-11}\times\left(2\times10^{30}\right)^2}{15\times10^3} = 2\times10^{46}\ \mathrm{J}$$

Class Example

- Compare with the energy output of a typical galaxy in a year

- Energy output of a typical galaxy in a year
  - Typical galaxy has 10^{11} stars
  - Sun is an average star so

$$
\begin{aligned}
E &= Lt \\
&\approx 10^{11} \times 4 \times 10^{26} \times 3 \times 10^{7} \\
&\approx 10^{45}\ \text{J}
\end{aligned}
$$

SN 2013cu (iPTF13ast)

Gal-Yam et al. 2014; Nature, May 22, 2014

Supernova Remnant

- The exploding material is initial ejected at several 1000 km s^{-1} (mildly relativistic)
- As the shell expands it sweeps up interstellar material and slows down to a few 100 km s^{-1}
- They continue to expand for ~ million years before reaching equilibrium and hence can fill a large volume of the galaxy

X-ray Emission

- The expanding shell is moving much faster than the sound speed in the cool interstellar gas and so a shock wave results
- The shocked gas gets heated to a very high temperature
- This gas emits in the X-ray region via bremsstrahlung

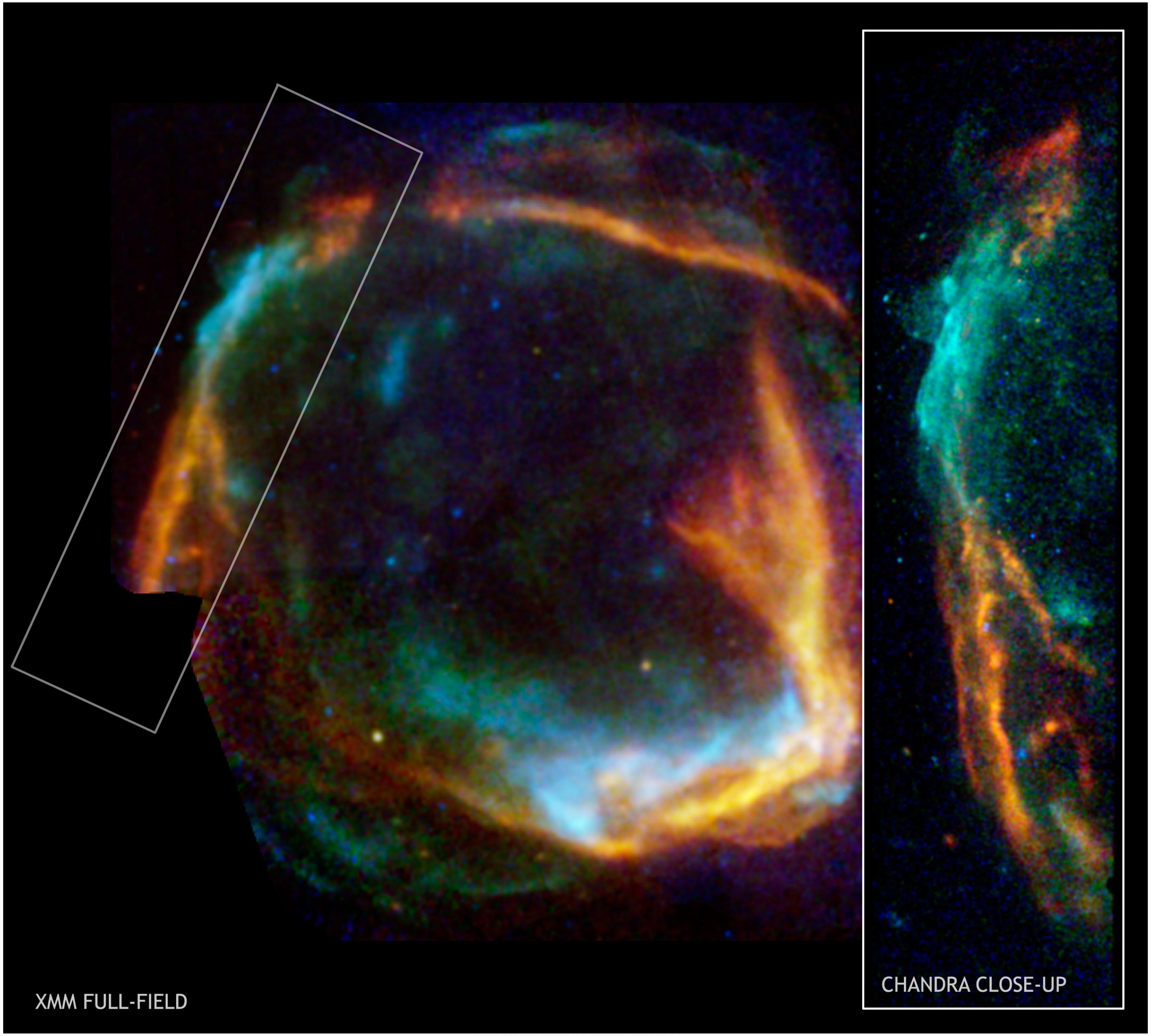
- Estimate temperature by equating the kinetic energy of a particle to the thermal energy it produces if stopped

$$\frac{1}{2}mv^2 \approx \frac{3}{2}kT$$

$$T \approx \frac{1}{3}\frac{mv^2}{k}$$

$$\approx \frac{1}{3}\frac{1.7\times10^{-27}\left(200\times10^{3}\right)^2}{1.4\times10^{-23}}$$

$$\approx 2\times10^{6}\ \mathrm{K}$$

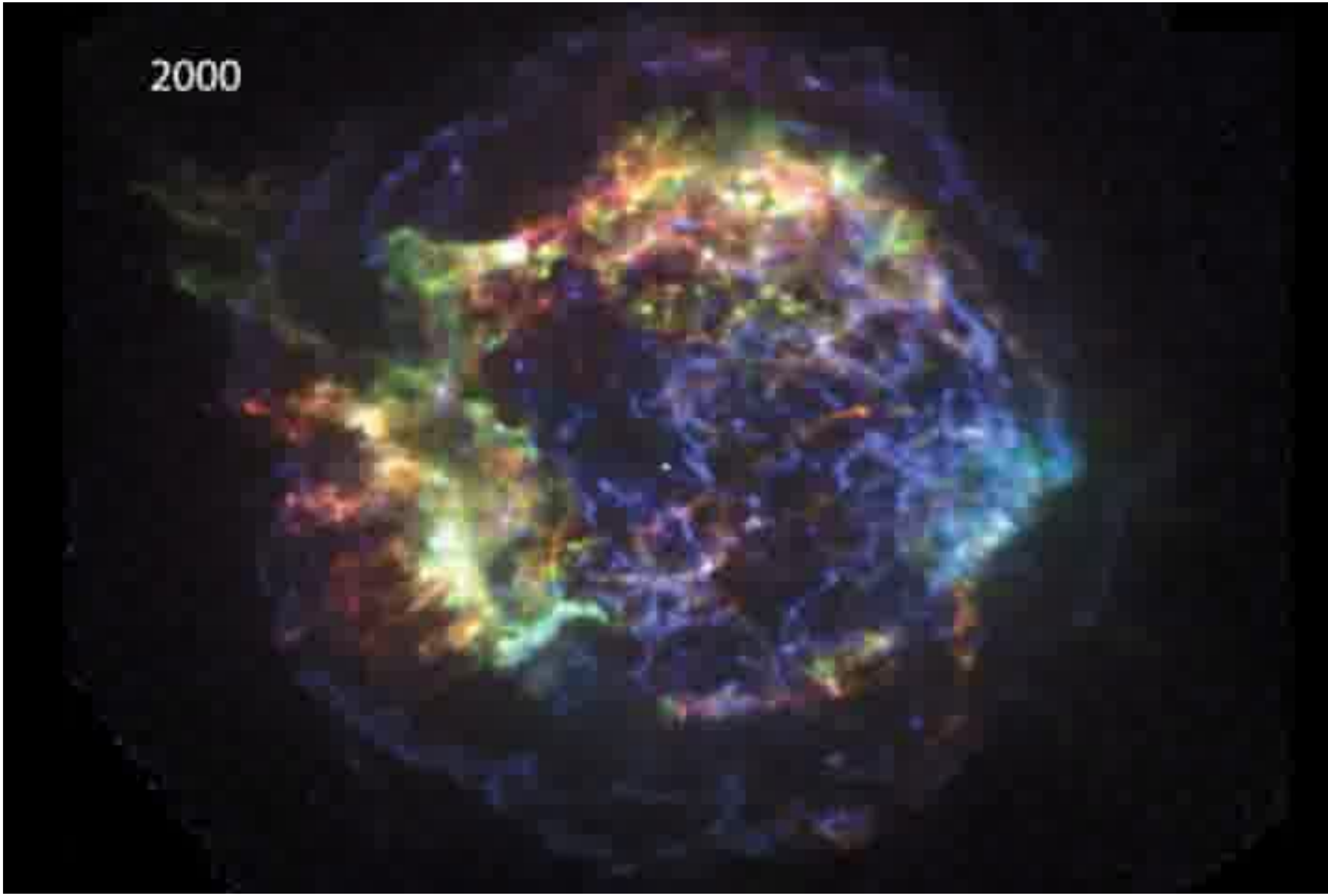


Oldest-recorded supernova unveiled by XMM-Newton and Chandra

Image courtesy of Jacco Vink (SRON Utrecht)

European Space Agency

Credit: Chandra: NASA/CXC/Univ. of Utrecht/J.Vink et al. XMM-Newton: ESA/Univ. of Utrecht/J.Vink et al.



Cas A SNR Movie

Credit: NASA/CXC/SAO/D.Patnaude et al.

Class Example

- The Crab nebula has an angular radius of about 150” at a distance of 2 kpc. Knots of emission in the nebula are moving radially away from the centre with a proper motion of 0.15”/year. What is the expansion velocity and when did the explosion take place? See movie at:

https://apod.nasa.gov/apod/ap180104.html

Distance travelled in one year

$$l = \theta d$$

$$= \frac{0.15}{206265} \times 2000 \times 3.1 \times 10^{16}$$

$$= 4.5 \times 10^{13} \text{ m}$$

$$v = \frac{l}{t} = \frac{4.5 \times 10^{13}}{3.1 \times 10^{7}} = 1.5 \times 10^{6} \text{ ms}^{-1}$$

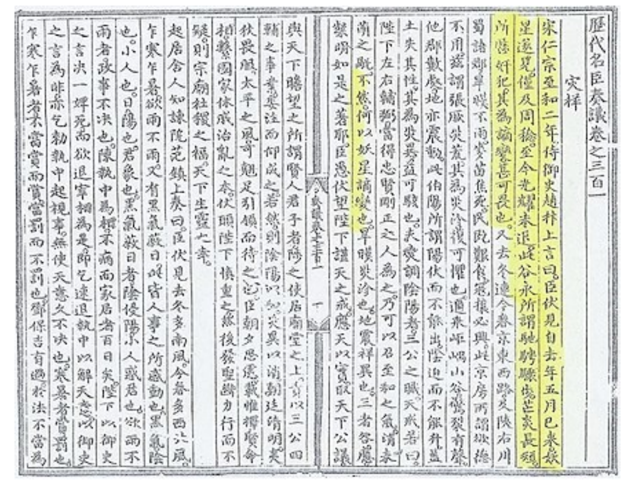
$$= 1500 \text{ kms}^{-1}$$

$$t = \frac{\text{angular distance}}{\text{angular velocity}} = \frac{\theta}{\dot{\theta}}$$

$$= \frac{150}{0.15}$$

$$= 1000 \text{ years}$$

https://en.wikipedia.org/wiki/SN_1054


歷代名臣奏議卷之三百一

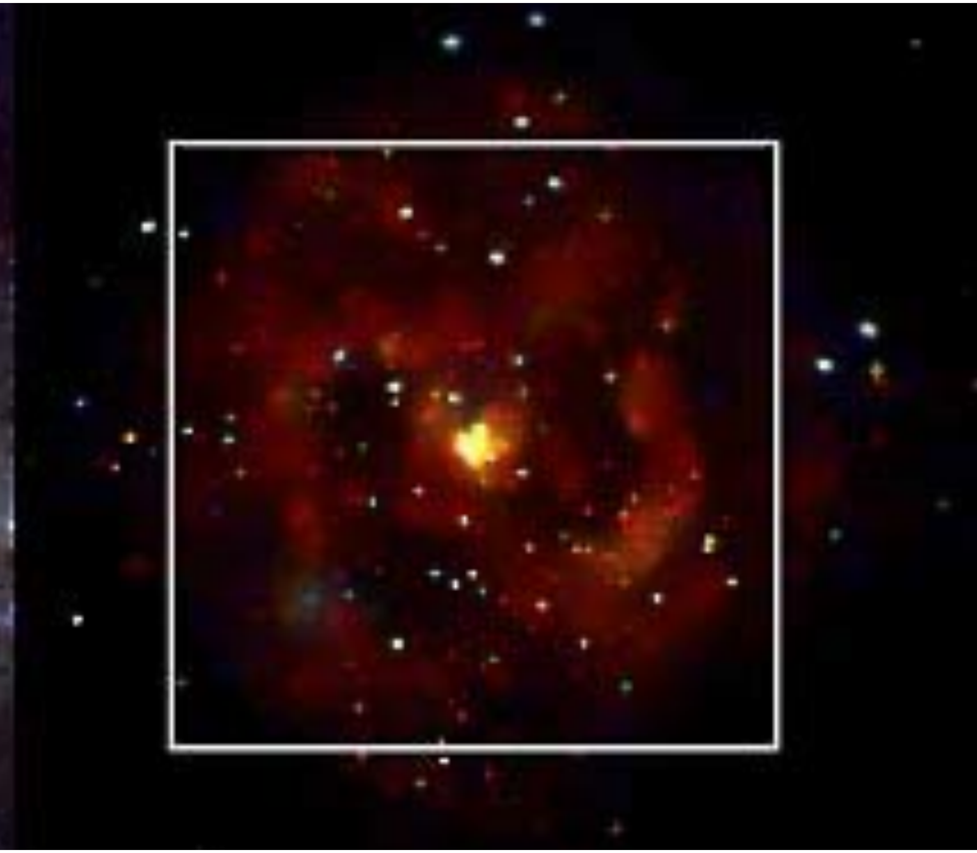
灾祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖

- Explosion took place ~1020 AD
- Actually recorded in 1054 AD by Chinese, Japanese, Arab, Native American and Aboriginal scholars

Hot Phase of the ISM

- Most of the volume of interstellar space in a gas-rich galaxy is taken up by very low density (10^3 m^{-3}) and very hot gas (10^6 K)
- Observed as weak, diffuse X-ray emission
- Due to the cumulative effect of many expanding supernovae remnants



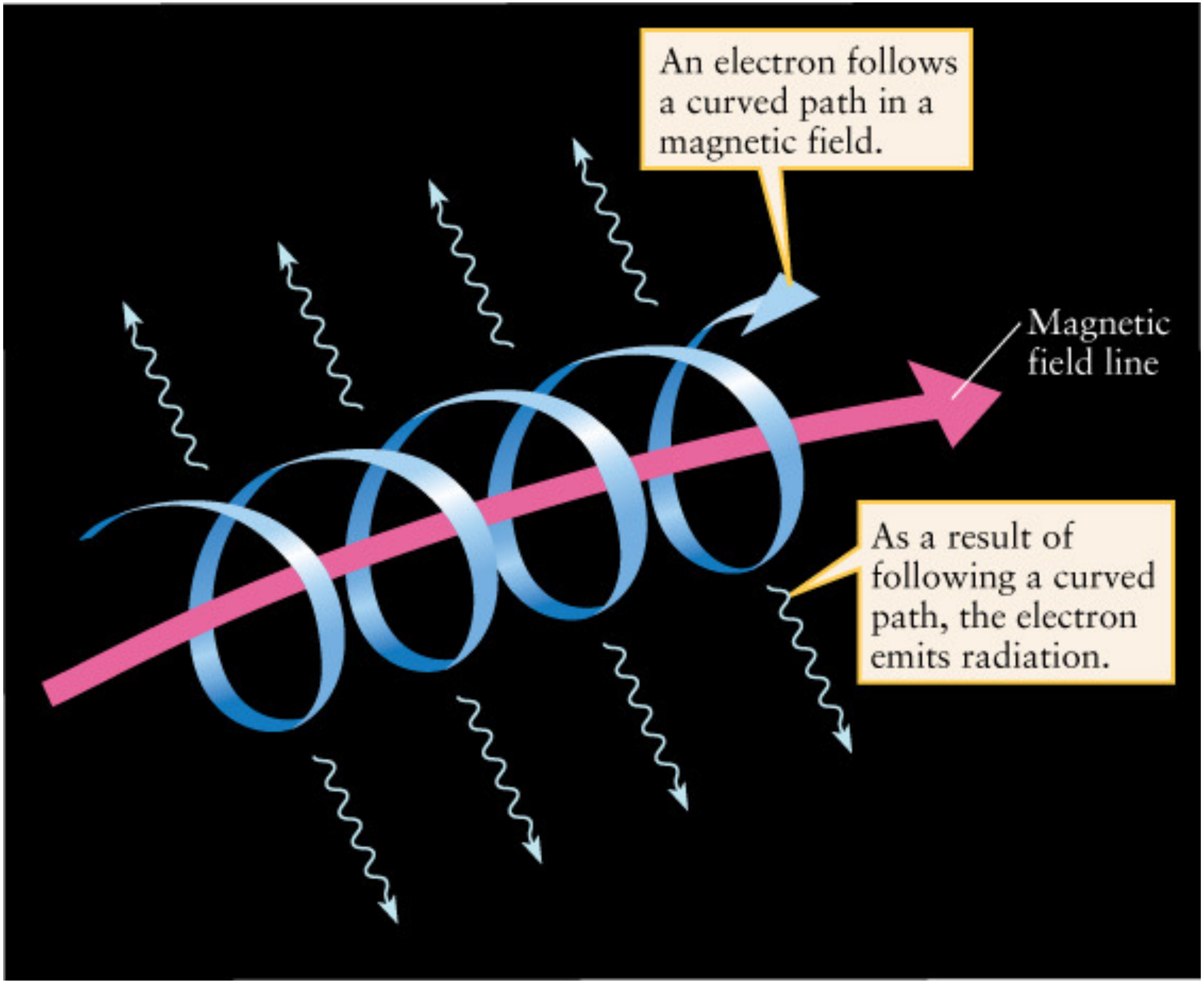
Optical from ESO

X-rays from NASA Chandra Satellite

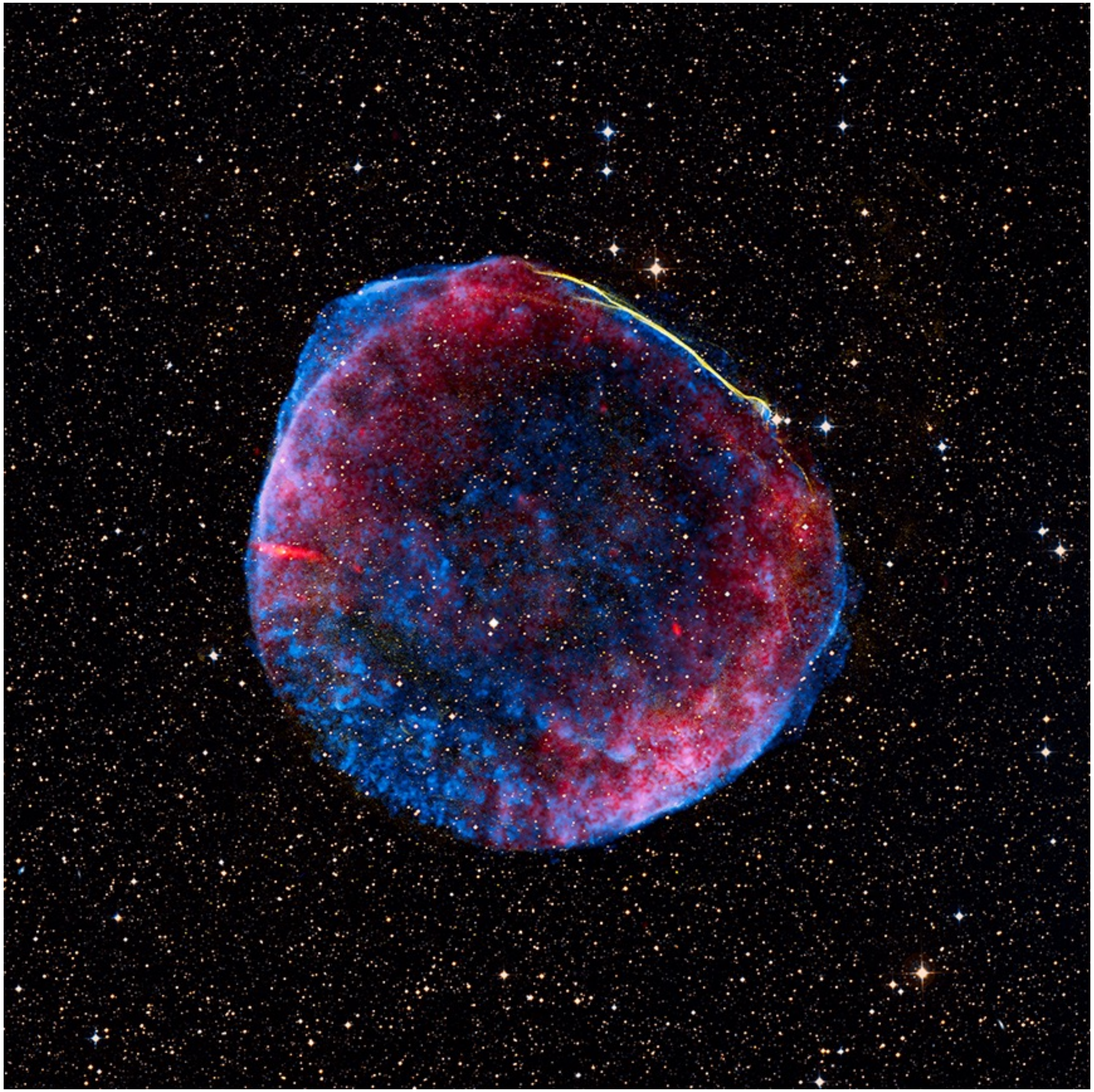
Spiral galaxy M83 showing diffuse X-ray emission along the spiral arms from hot phase of the ISM

Radio Emission

- Supernovae also emit strongly at radio wavelengths
- The combination of fast moving electrons and magnetic fields gives rise to synchrotron radiation
- The electrons spiral around the magnetic field



From Universe textbook



SN1006

X-ray: (blue)

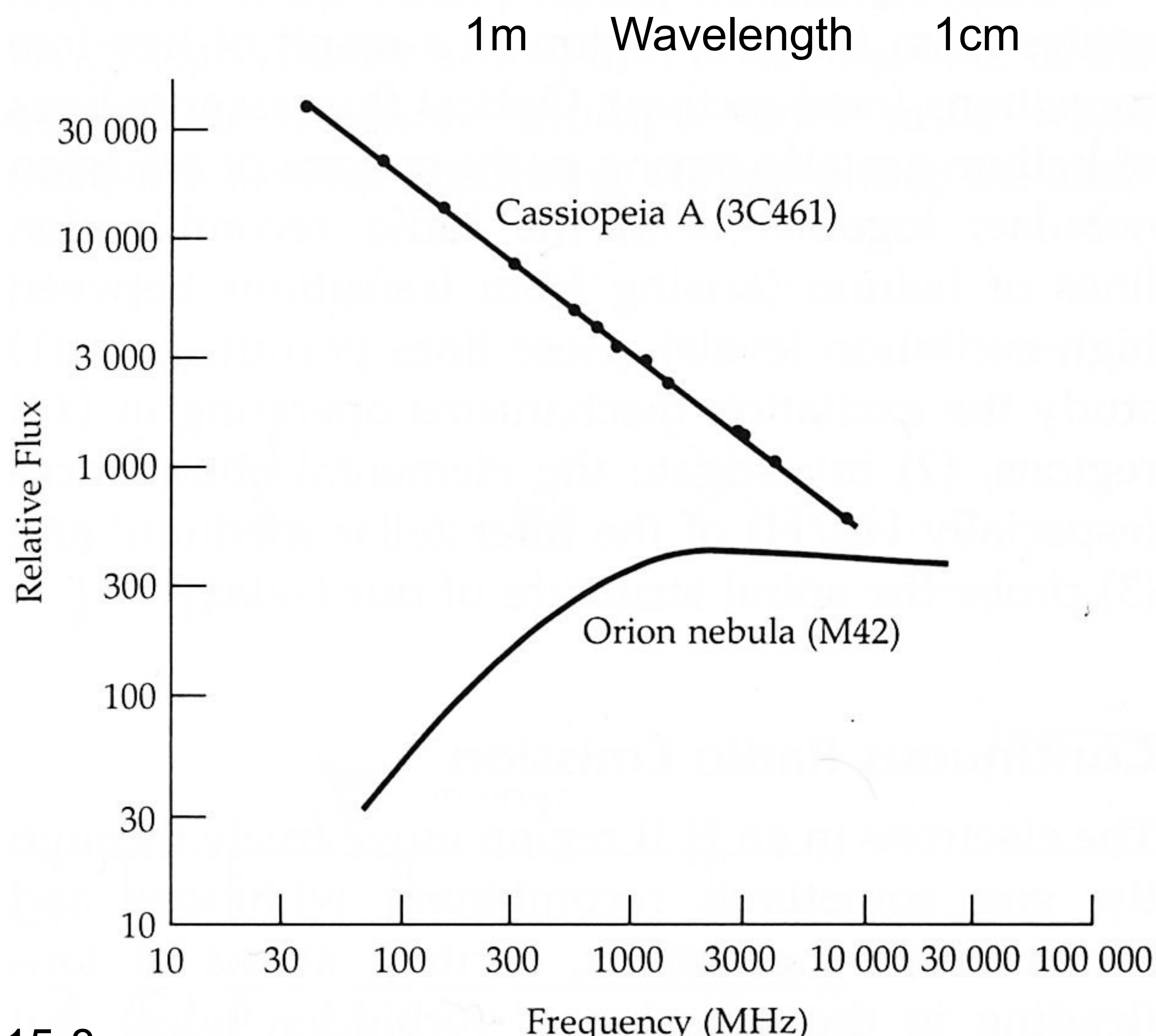
Radio: (red);

Optical:(yellow)

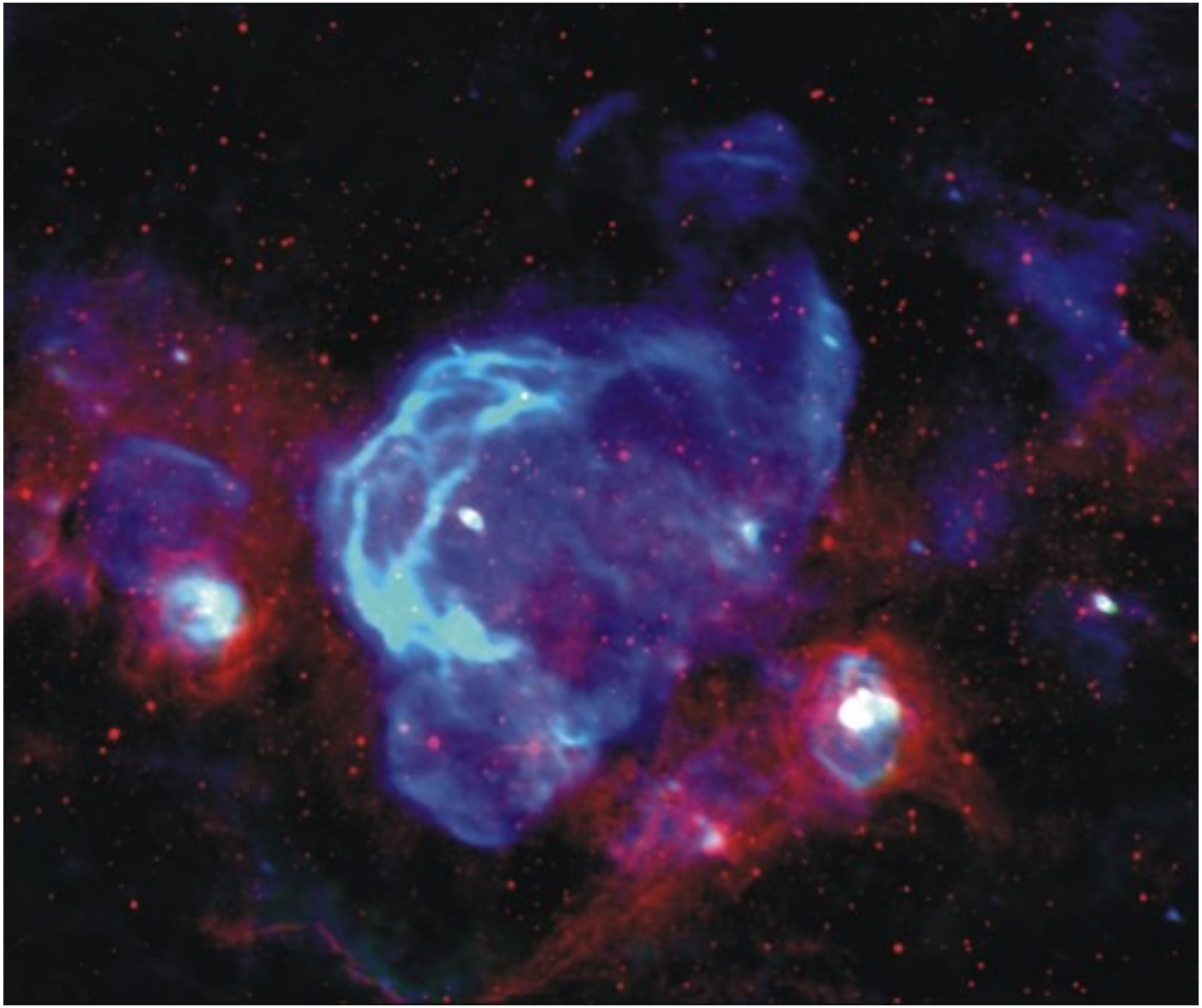
Credit: X-ray: (blue) NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.; Radio: (red) NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: (yellow) Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

- The synchrotron radiation is strongest at long radio wavelengths (λ~ 1 m)
- Also referred to as non-thermal radio emission to distinguish it from thermal bremsstrahlung
- Note the different slopes of the radio spectra for thermal and non-thermal sources

- Note the different slopes of the radio spectra for thermal sources like the H II region M42 and non-thermal sources like the SNR Cas A



Zeilik Fig 15-8



W28 region with SNRs and H II regions

Blue: radio 90 cm; Red mid-infrared 8 microns

Image courtesy of NRAO/AUI and Brogan et al.

Where do they occur?

- The Type II supernovae resulting from massive stars will occur in spiral arms and irregulars, i.e. Population I
- The Type Ia supernovae result from the evolution of old, low mass stars and are therefore Population II

Summary

- Supernova remnants are one of the main sources of energy input into the interstellar medium
- They can be observed at X-ray and long wavelength (m) radio wavebands
- They are responsible for the hot phase of the interstellar medium

Class Example

- A supernova remnant will expand for about 1 million years before being halted by the interstellar medium. If it expands at an average speed of 100 kms^{-1} how far will it have travelled in that time?