The Evolution of Supernova Remnants

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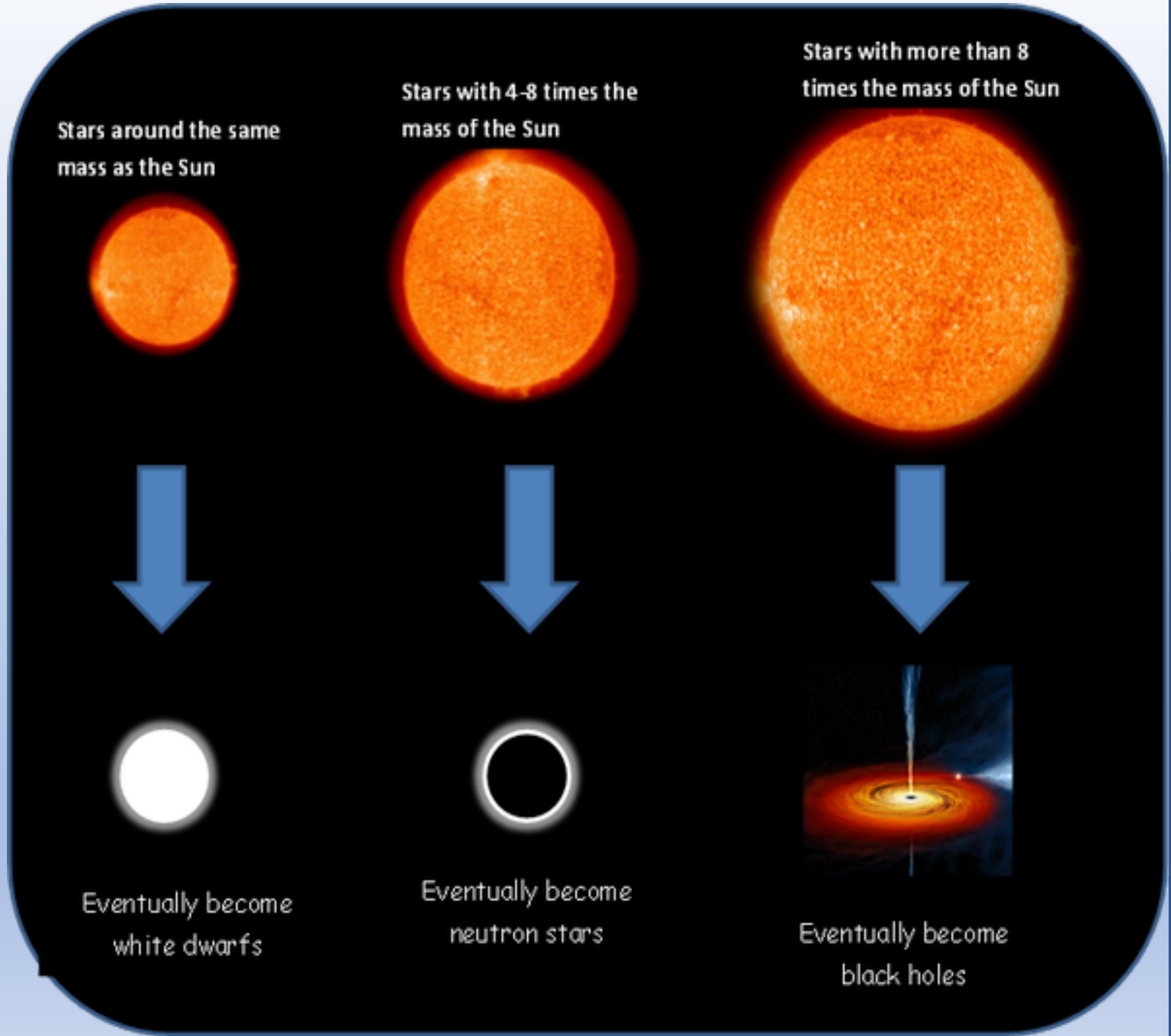
Post Main Sequence Stellar Evolution

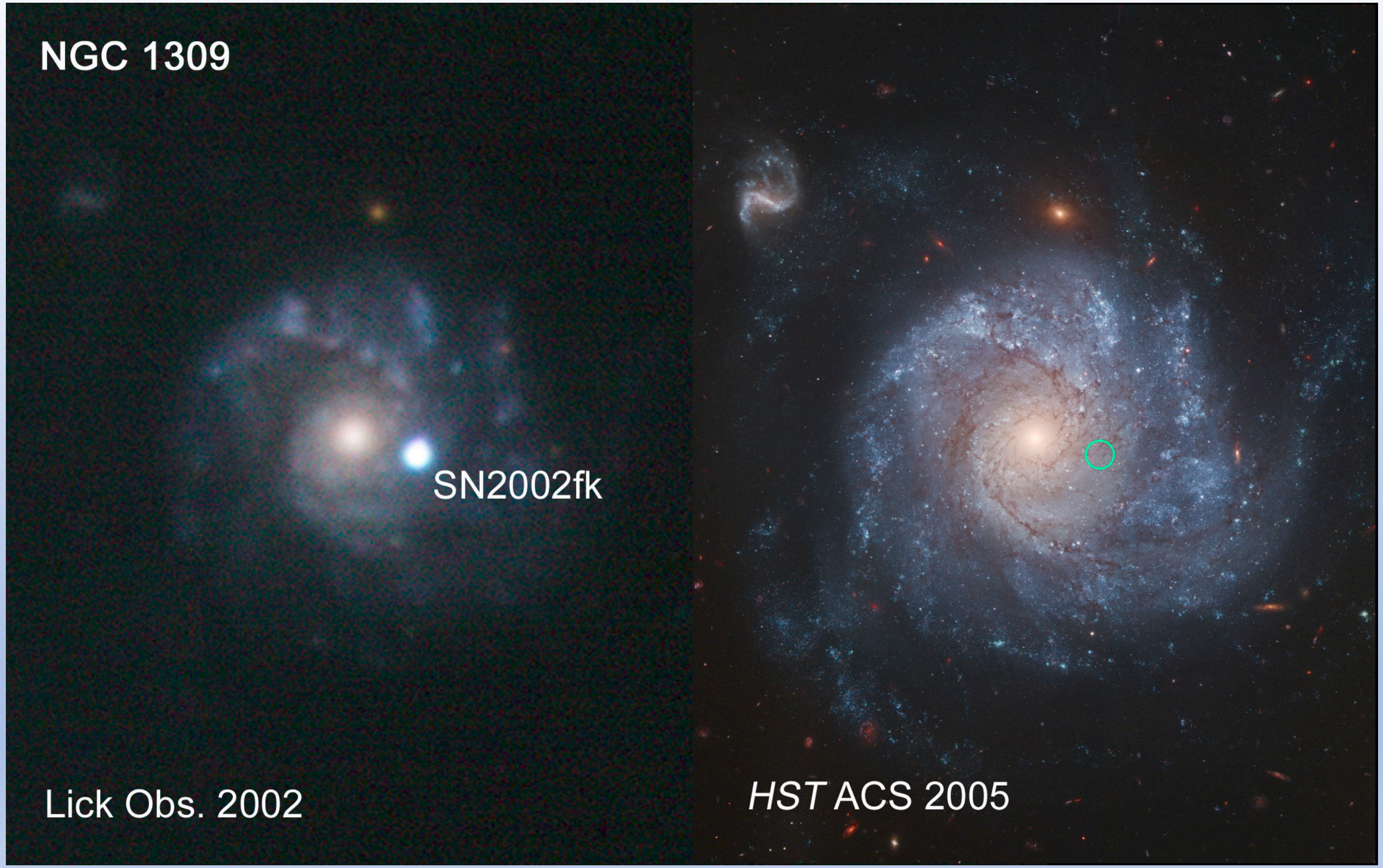
Remnant left depends on initial stellar mass:

- Up to 8 solar masses – planetary nebular and white dwarf.
- 8 - 25 solar masses – supernova and neutron star.
- 25 solar masses - Supernova and black hole



What is a Supernova?

- Super – very large or powerful
- Nova - a star showing a sudden large increase in brightness and then slowly returning to its original state over a few months.
- Explosion of a massive star
- Brightens by around ten orders of magnitude in a few hours – enough to outshine the whole galaxy.



SN2002fk as observed from Lick Observatory Kait 0.76 meter telescope in 2002. The location of the supernova is marked on the 2005 Hubble ACS image.
Credit:NASA, ESA, The Hubble Heritage Team, (STScI/AURA) and A. Riess (STScI)

What is a Supernova?

Two mechanisms:

- Type II - core collapse supernova

Iron rich core collapses under gravity, from a sphere roughly the size of the Earth (radius 6000km) to a ball of radius only 50km.

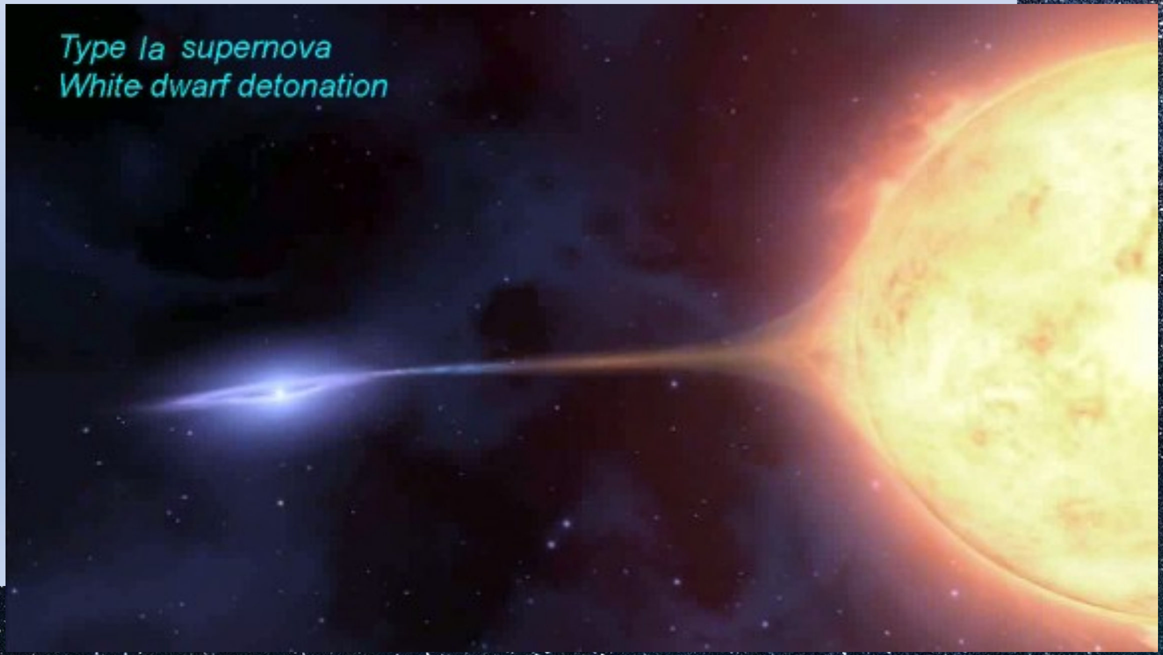
- Type Ia –

when a white dwarf in a binary

reaches 1.4 solar masses through

accreting mass from it’s larger

companion.



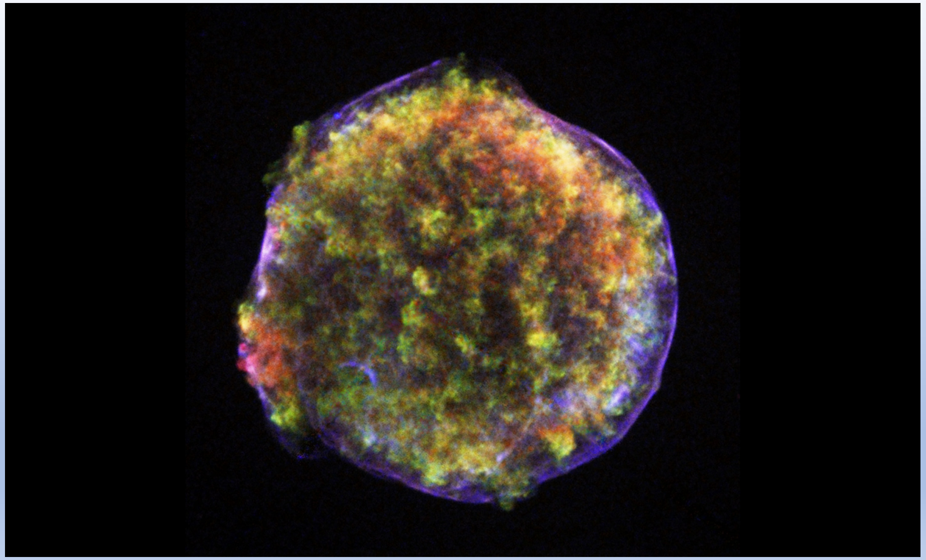
Supernovae

- Instantaneous release of 10^{51}erg (10^{31} Megatons). - this is the amount of energy a solar type star emits in it's whole lifetime!
- Blows the stellar material away from the stars at 30,000km/s (0.1c)
- Drives a shock wave into the surrounding gas
- Sweeps up the gas – see a supernova remnant.
- Create some elements heavy elements and spread them around the galaxy.

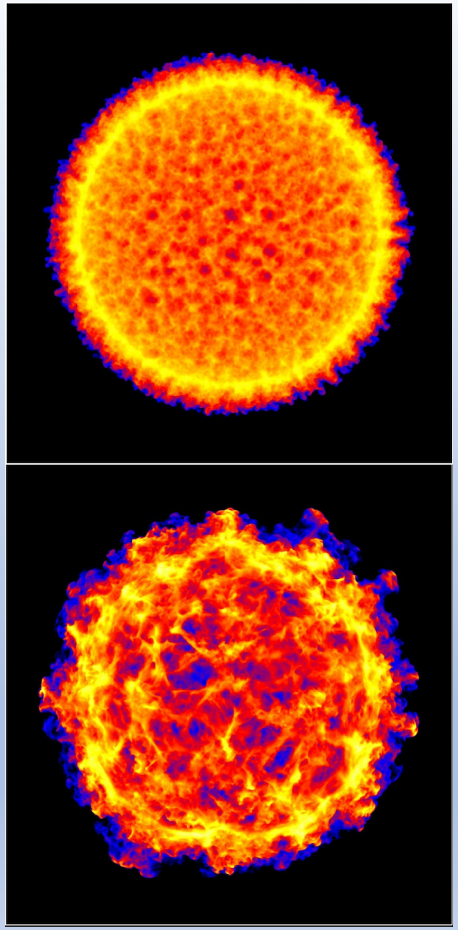
History of SN observations

- SN 185 - Observed by Chinese astronomers in 185 AD
- SN 1006 – brightest ever recorded, observed by astronomers in 1006 AD across China, Japan, Iraq, Egypt and Europe.
- Observed in the Milky Way galaxy – SN 1572 (Tycho Brahe) and SN 1604 (Johannes Kepler) – None have been observed in our galaxy since!
- Observations of the explosion are quite rare, we see around 300 SN a year in other galaxies (but there are many many galaxies!)
- We observe the remnants of the explosion.

Tycho's Supernova Remnant



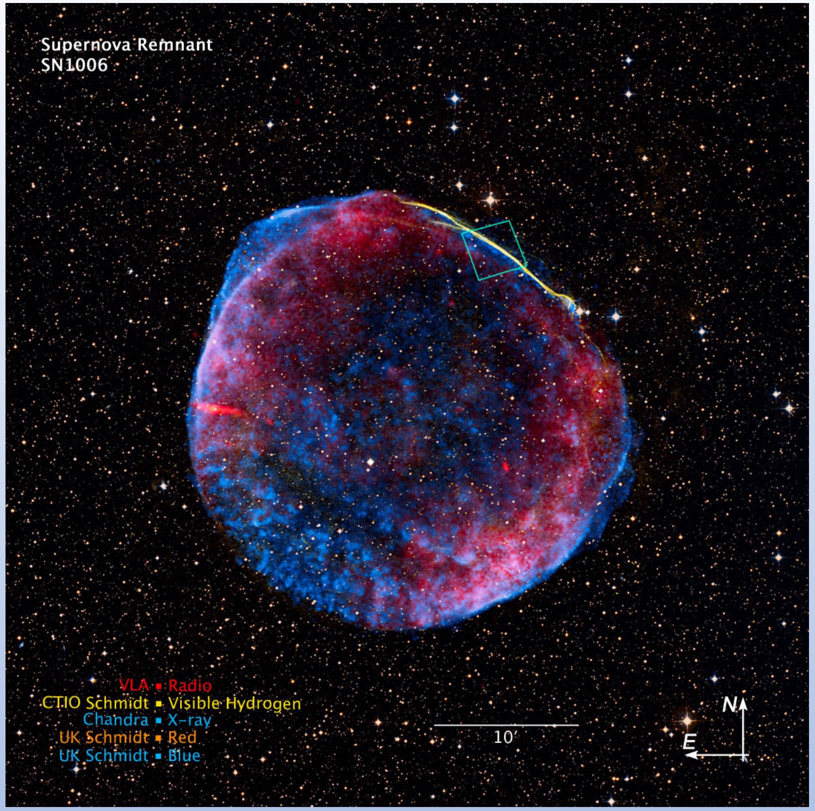
A false-color X-ray image by Chandra of the Tycho supernova remnant, first discovered in 1572. [NASA/CXC/Rutgers/J.Warren & J.Hughes et al.]



3D hydrodynamical simulations of Tychoejecta. [From Williams et al. 2017]

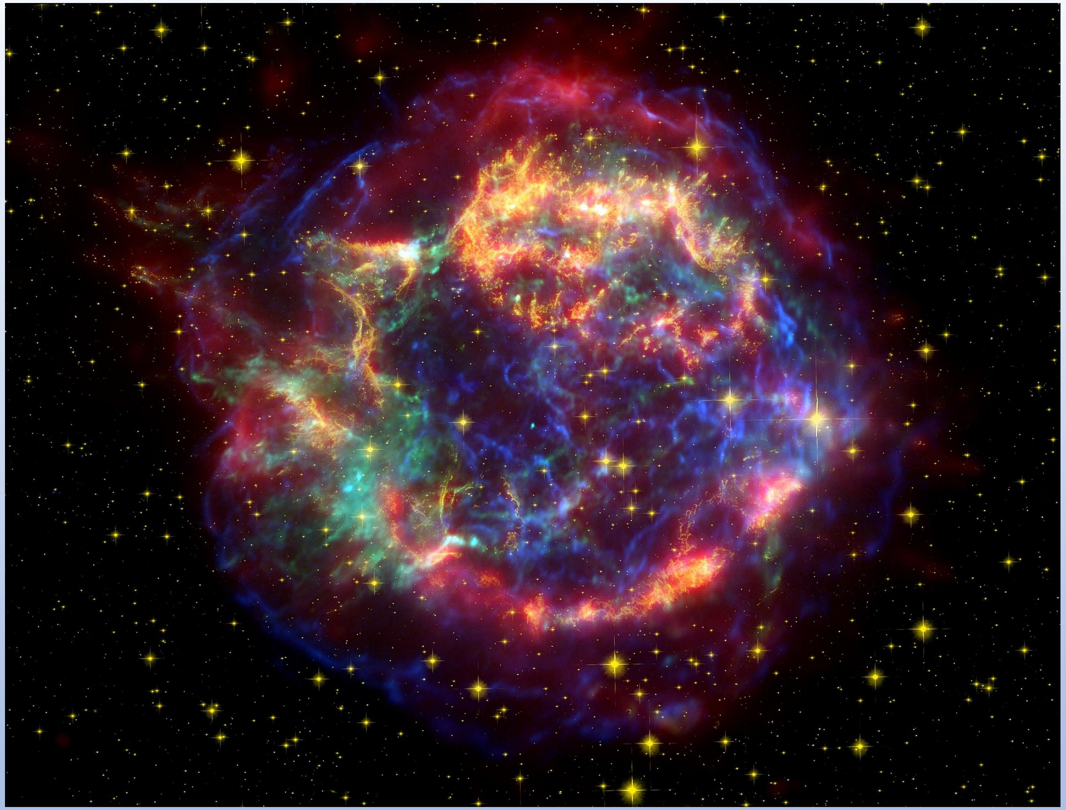
Supernova Remnants (SNRs)

SNR 0509 in the Large Magellanic Cloud (LMC). Red is the visible light taken by Hubble, green and blue colours is denser, heated gas emitting in X-rays, captured with Chandra. Credit: NASA, ESA, CXC, SAO, the Hubble Heritage Team (STScI/AURA), and J. Hughes (Rutgers University)



SN1006: This image is a composite of visible (or optical), radio, and X-ray data of the full shell of the supernova remnant from SN 1006. **Credit:**NASA, ESA, and Z. Levay (STScI).

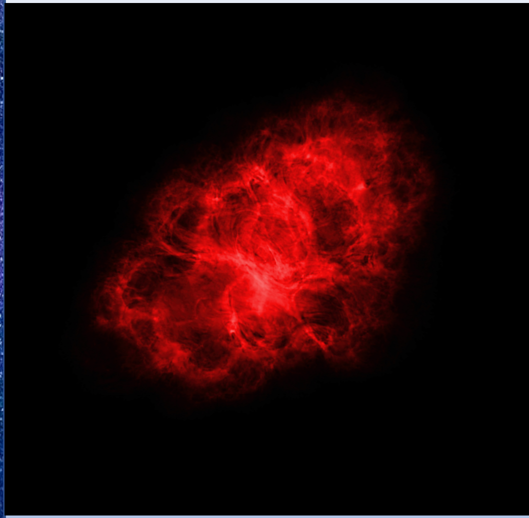
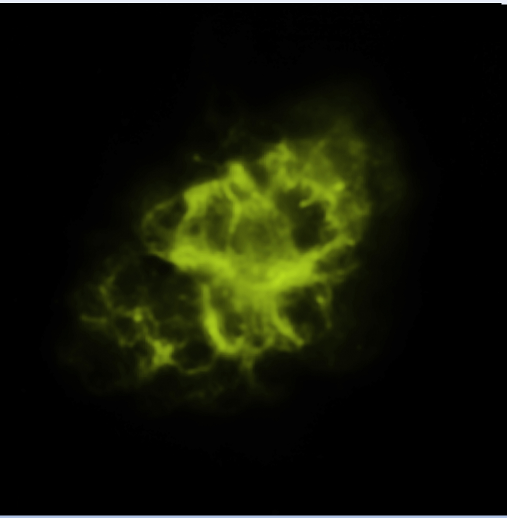
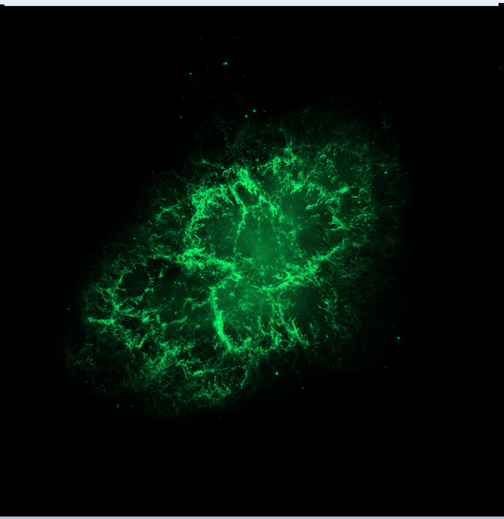
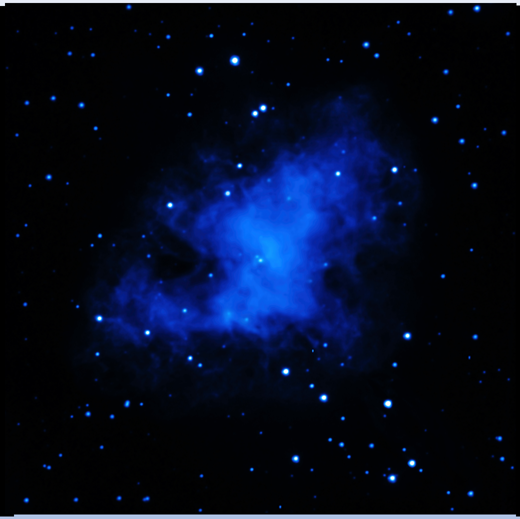
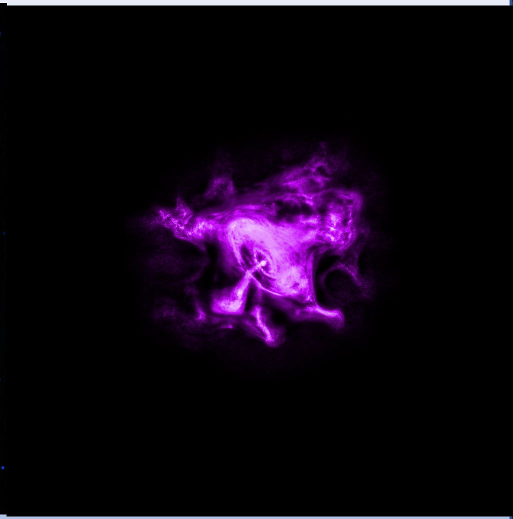
Supernova Remnants – Cas A



Cassiopeia A (Cas A) - the youngest known remnant from a supernova explosion in the Milky Way.
Left image: Optical data. **Right image:** Combination of radio, X-ray and optical emission.
Credit: NASA, ESA, and the Hubble Heritage Collaboration.

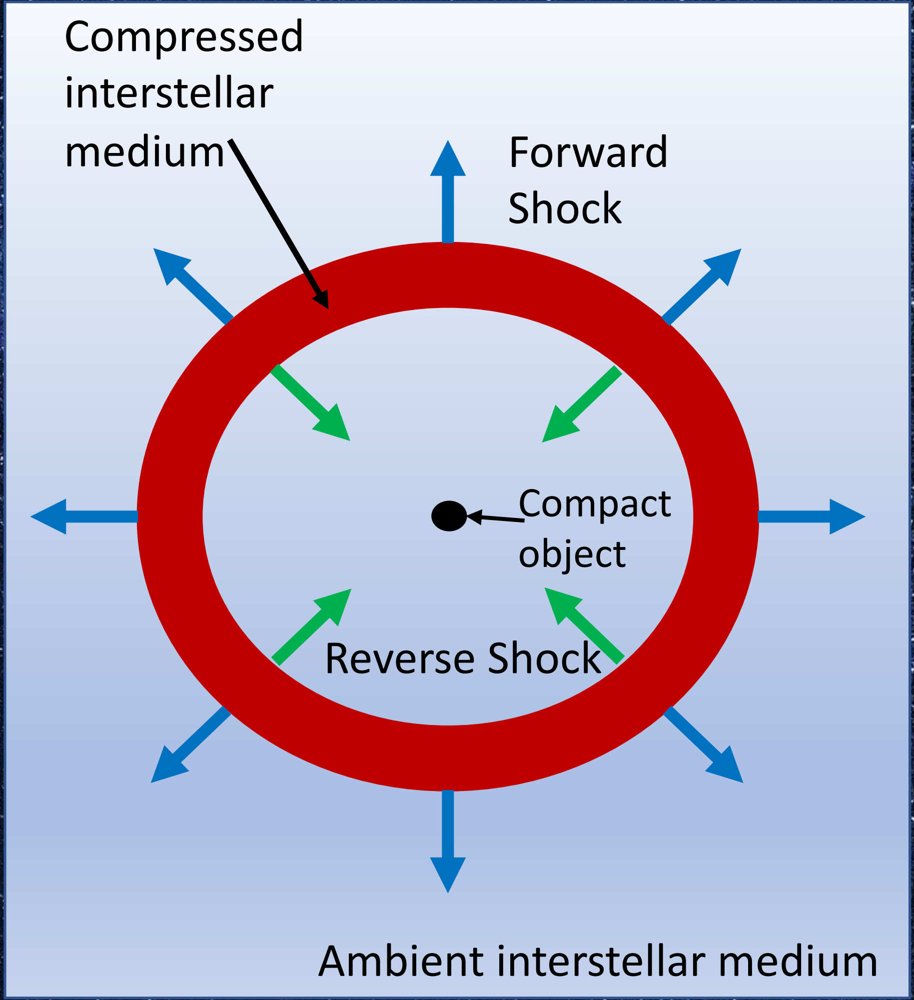
Nearby supernova remnant, N 63A,.
Credit: Image Credit: NASA, ESA, HEIC, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: Y.-H. Chu and R. M. Williams (UIUC).

The Crab Nebula

Radio	Infrared	Optical	Ultraviolet	X-ray
				
Very Large Array (VLA) **Credit:**NRAO/AUI /NSF	**Spitzer Space Telescope** **Credit:**JPL/Caltech	Hubble Space Telescope **Credit:**NASA, ESA/Hubble	XMM-Newton Space Telescope **Credit:**ESA	Chandra X-ray. Observatory **Credit:**CXC

Evolution of Supernova Remnants

- 99% of SN energy released in the form of energetic neutrinos
- The rest is converted into kinetic energy
- Outer stellar material is pushed out into the surrounding ISM
- Compresses and heat the gas and sweeps it up like a snow plough

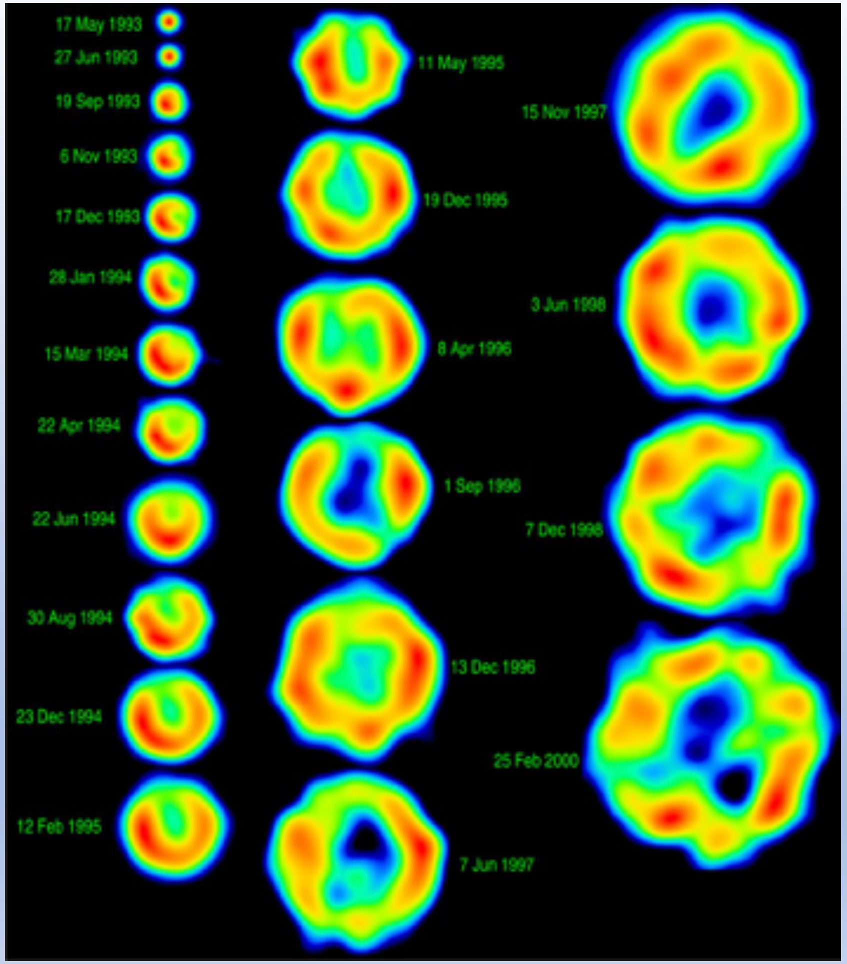


Evolution of a Supernova Remnant

Eight stills from the 3D supernova explosion animation (artist's impression).
Credit:NASA, ESA, and the Hubble Heritage (STScI/AURA)-
ESA/Hubble Collaboration. Acknowledgement: Robert A. Fesen (Dartmouth College, USA) and James Long (ESA/Hubble)

Evolution of a Supernova Remnant

- Evolution of a real Supernova remnant - SN1993J, over a period of 7 years, from May 1993 to February 2000. (Rupen et. Al.)



Modelling the Evolution of Supernova Remnants

Three Phases:

- Free expansion phase - Lasts ~100-1000 years
- Sedov-Taylor phase – Lasts 10 000 -20 000 years
- Cooling phase – Lasts until shell cools enough to mix with the ISM.

Free Expansion Phase

- Explosion energy converted to kinetic energy – can calculate the initial velocity:

$$E_{SN} = \frac{1}{2} M_e v_e^2 \quad \Rightarrow \quad v_e = \left(\frac{2E_{SN}}{M_E} \right)^{1/2}$$

- Outer stellar material is pushed out, away from the central compact object.
- Shell expands with constant velocity (up to 0.1c). We can calculate the radius of the shell using the equation:

$$R_s(t) = v_e t$$

Free Expansion Phase

- The mass of gas swept up increases as the shell expands.
- When this mass is equal to the mass of the ejected stellar material, the expansion starts to slow down.
- The radius of the shell at the end of this phase, and the time taken to get there can be calculated from equations 5 and 6.

$$M_e = \frac{4\pi}{3} R_{SW}^3 \rho_0 \quad \Rightarrow \quad R_{SW} = \left(\frac{3M_e}{4\pi\rho_0} \right)^{1/3}$$

$$t_{SW} = R_{SW}/v_e$$

Sedov-Taylor phase

- When the mass of the swept up ISM = ejected stellar mass
- Interior of SNR so hot that energy loss via radiation is very small.
- Adiabatic expansion of shock heated gas due to high temperature of shock
- Medium is swept up into a shell of shocked gas with the explosion products behind it

- ~10^4 years
- ~30pc

Sedov-Taylor Phase

$$R_s(t) = \left(\frac{25E_{SN}}{4\pi\rho_0}\right)^{1/5} t^{2/5}$$

$$v_s(t) = \frac{2}{5}\left(\frac{25E_{SN}}{4\pi\rho_0}\right)^{1/5} t^{-3/5}$$

Cooling Phase – 'Snowplough Phase'

- SNR reaches a critical temperature where the energy loss via radiation becomes very important (~10^6K).
- Thermal pressure decreases and expansion slows down.
- Dense, cool shell forms directly behind the shock front.
- 'Snow plough' phase – keeps sweeping up more gas until the swept up mass is much larger than the ejected stellar mass.

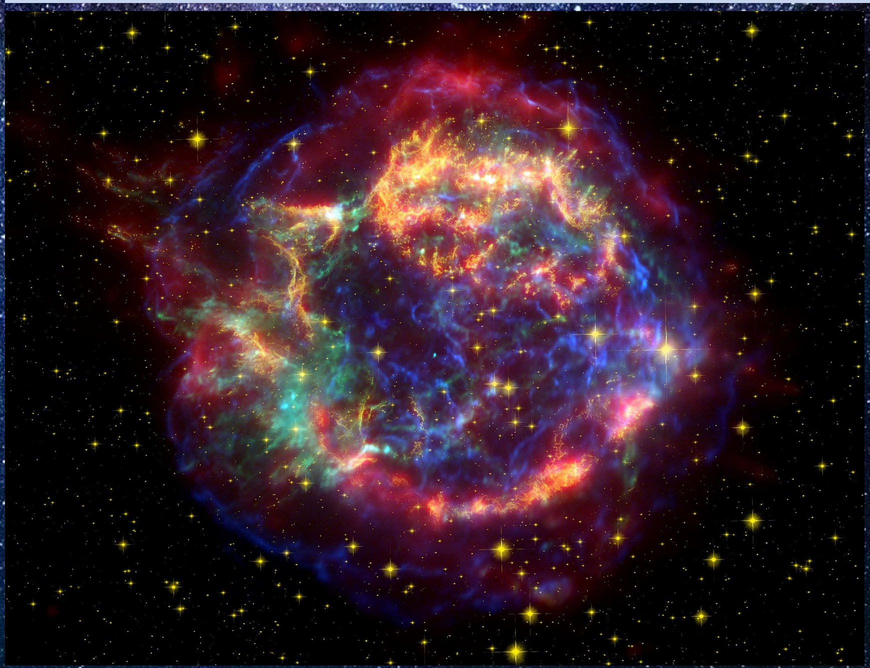
Cooling Phase – ‘Snowplough Phase’

- Eventually the shell starts to break up – Rayleigh-Taylor instabilities
- SNR mixes into the ISM as velocity of the gas drops to a values typical of the ISM gas (random motions ~10km/s)
- The SNR is ‘lost’ in the ISM and no longer visible
- ~10^9 years

Phases of Real SNRs

End of free expansion phase - Cas A.

- 300 years old
- v ~ 6000km/s
- R ~ 3pc



Sedov-Taylor Phase – Crab Nebula

- 1000 years old
- V ~ 1500km/s
- R ~ 3.4pc

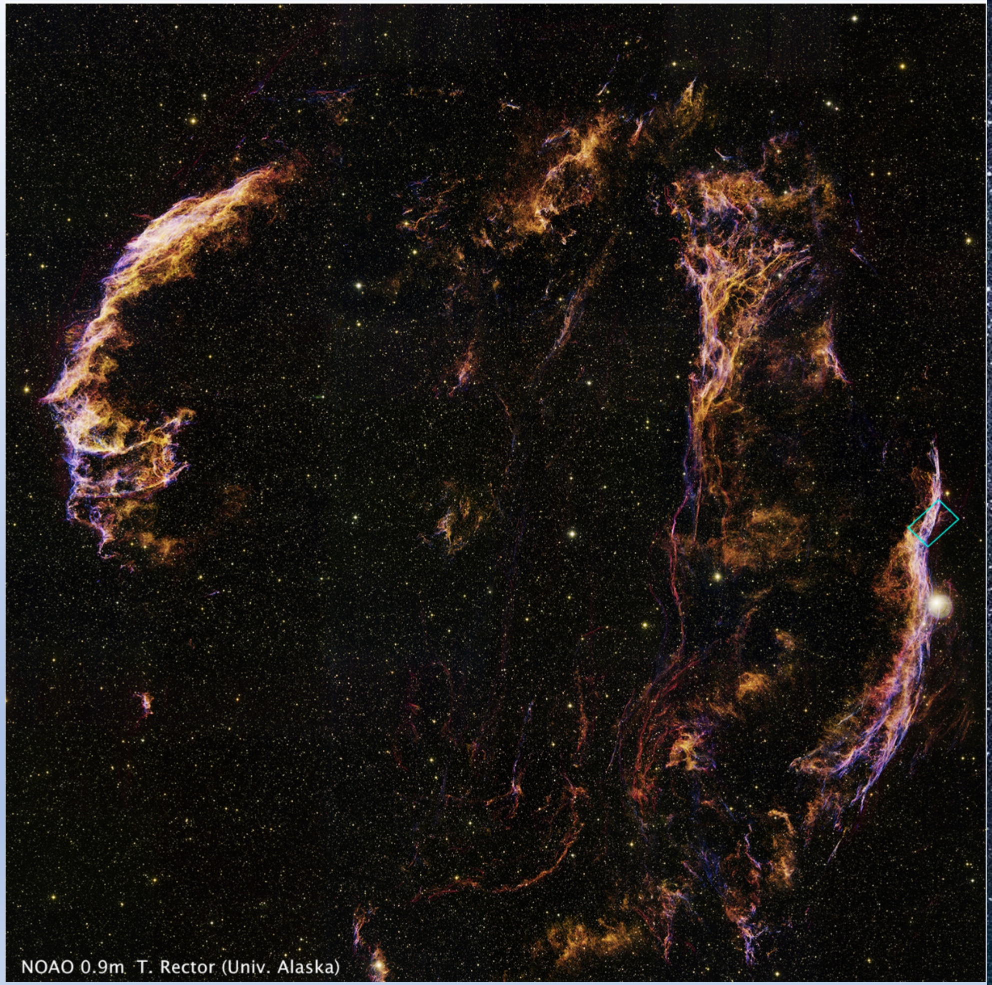
Phases of Real SNRs

Snowplough Phase:

The Cygnus Loop

- 20 - 40 thousand years old
- ~ 50pc
- ~20Msun

  progenitor



Do the models work for real SNRs?

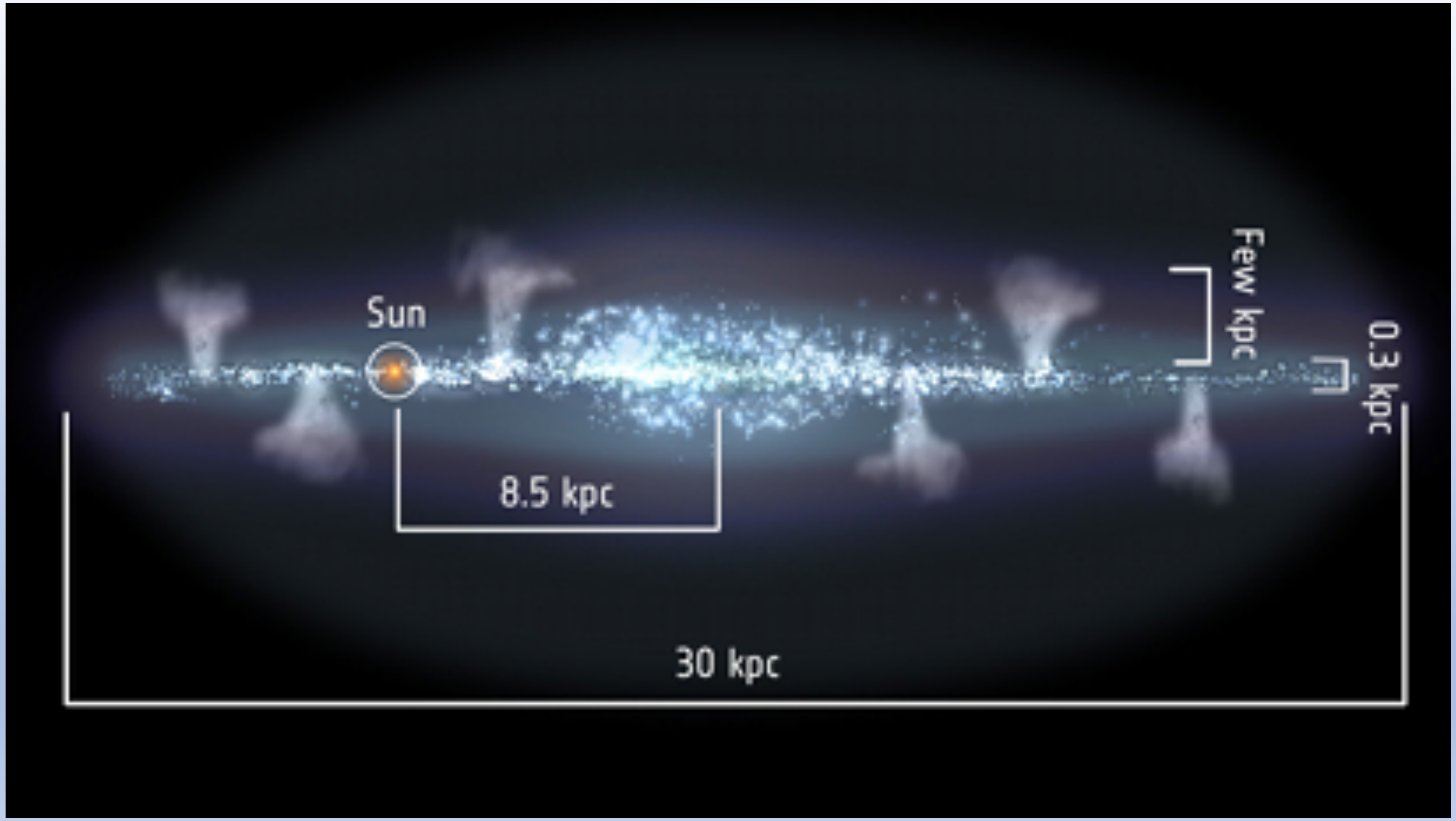
- The winds from massive stars make the ISM low density. - free expansion phase can be longer.
- ISM is generally not uniform resulting in non-spherical SNRs
- Massive stars are usually born in stellar associations – neighbouring SNRs may merge together to form a single ‘superbubble’.
- Reality is much more complicated!

SN and Galaxy Evolution

- Sweeps up the ISM gas and pushes it out to large distances.
- Heats the ISM gas, preventing it from collapsing to form more stars.
- Spreads heavy elements around the galaxy
- Can remove gas from the galaxy disk

Galactic Fountains

- Hot gas can be pushed so far it leaves the thin galactic disk.
- Ejected gas can form part of the Galactic halo
- If gas can cool it can fall back onto the disk and mix more efficiently.



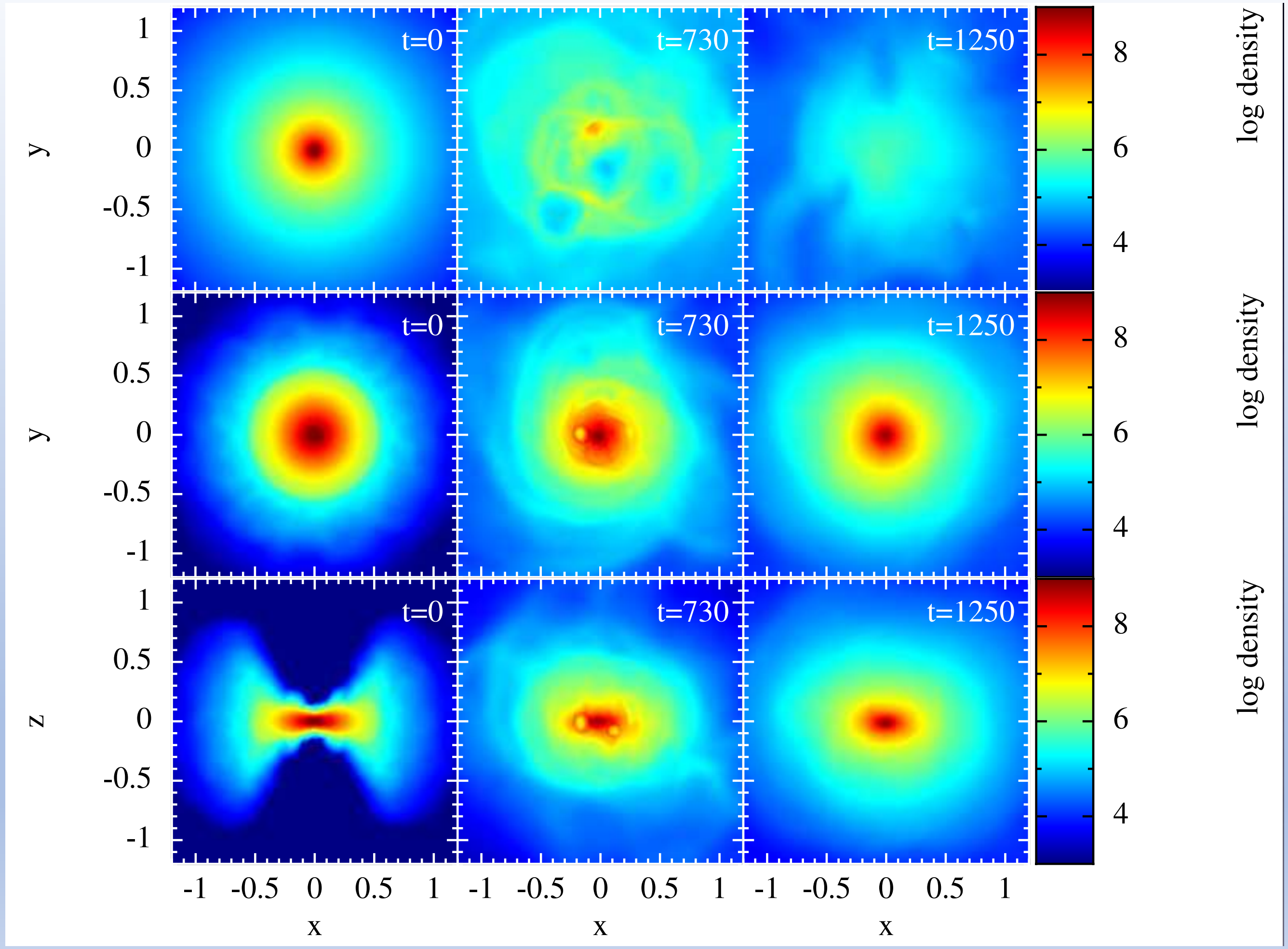
Modelling Supernova in Simulations

- Can use simulations to see what happens when a large amount of energy is put into a small region of gas.
- Allow it to expand and follow it’s evolution – explore the effects on the galaxy.
- Large cosmological simulations need supernova feedback (SN FB) to produce galaxies like those we observe (otherwise stellar masses are too high!)
- Efficient SN FB is needed to slow down star formation

Dwarf galaxies

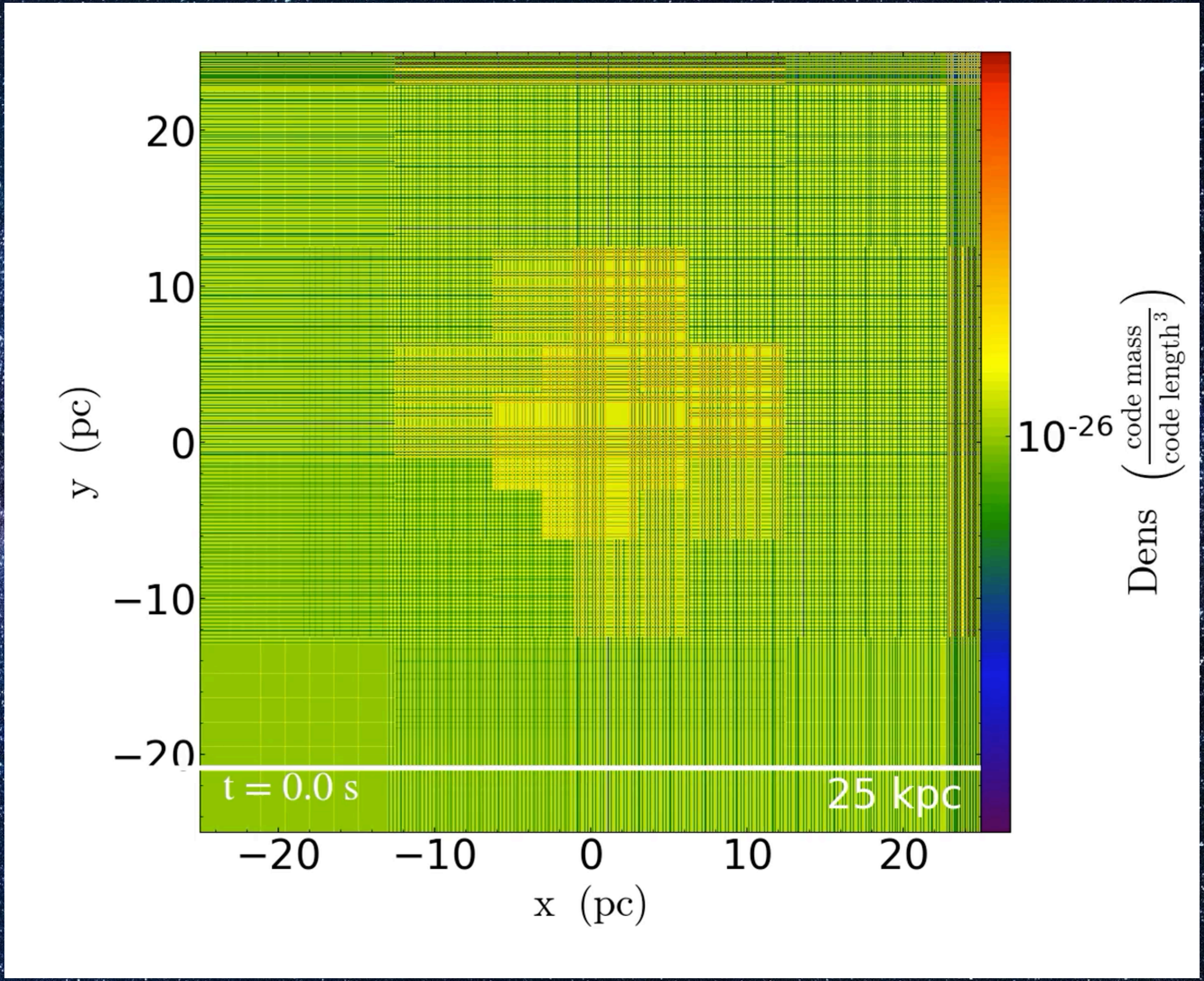
- Small galaxies – easy to remove gas as they have shallower gravitational potential wells and so lower escape velocities
- SN can easily accelerate the ISM to velocities sufficient to escape the galaxy completely
- Shut off star formation
- Gas contributes to the intergalactic medium (IGM)

Simulating Supernova Feedback



Summary

- Supernova explosions are very energetic events – powerful enough to influence the evolution of the whole galaxy
- Enrich the galaxy ISM with metals formed in nucleosynthesis (both in the stellar core and some from the explosion) by transporting them far away and mixing with the ISM.
- Heat up the ISM - important to regulate amount of star formation



y (pc)
x (pc)
t = 0.0 s
25 kpc
10^{-26}
Dens $\left(\frac{\text{code mass}}{\text{code length}^3}\right)$