This class:

- **Life cycle of high mass stars**
- **Supernovae**
- **Neutron stars, pulsars, pulsar wind nebulae, magnetars**
- **Quark-nova stars**
- **Gamma-ray bursts (GRBs)**

Cas A
All Image & video credits: Chandra X-ray Observatory

Life cycle of stars - Review

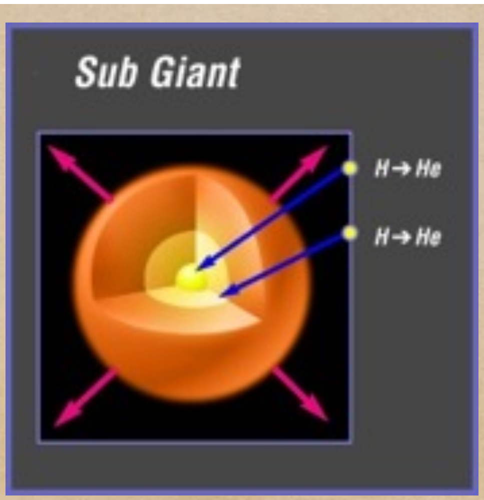
- Stars evolve differently based on their masses.
- Low mass star (eg. Sun) ends its life by gently expelling its outer layer into space. These ejected gases form a planetary nebula. The burned out core becomes a white dwarf.

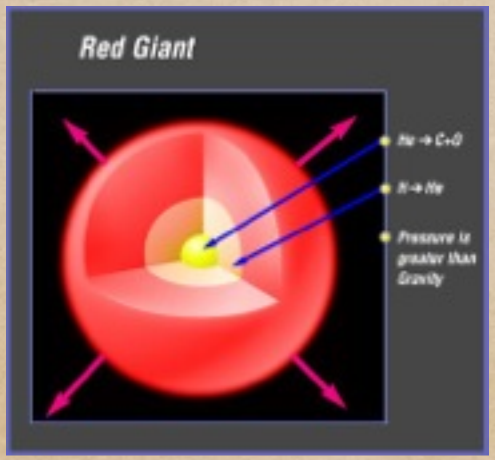
Review: Low mass stars (e.g., Sun)

TABLE 20.1 Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (Yr)	Central Temperature (10^6 K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	15	6000	10^5	7×10^5	1	Main-sequence star
8	10^8	50	4000	10^7	2×10^6	3	Subgiant branch
9	10^5	100	4000	10^8	7×10^7	100	Helium flash
10	5×10^7	200	5000	10^7	7×10^6	10	Horizontal branch
11	10^4	250	4000	10^8	4×10^8	500	Asymptotic-giant branch
12	10^5	300	100,000	10^{10}	10^4	0.01	Carbon core
		—	3000	10^{-17}	7×10^8	1000	Planetary nebula*
13	—	100	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

* *Values refer to the envelope.*





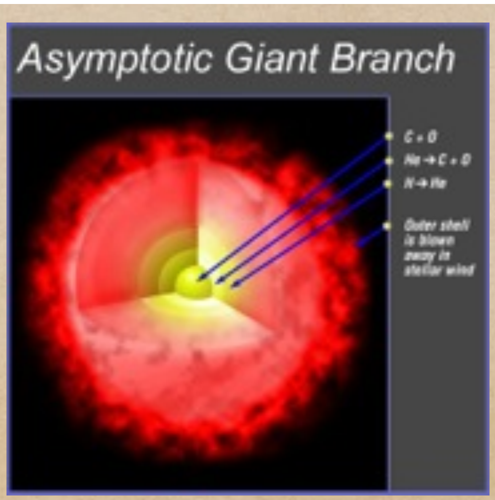
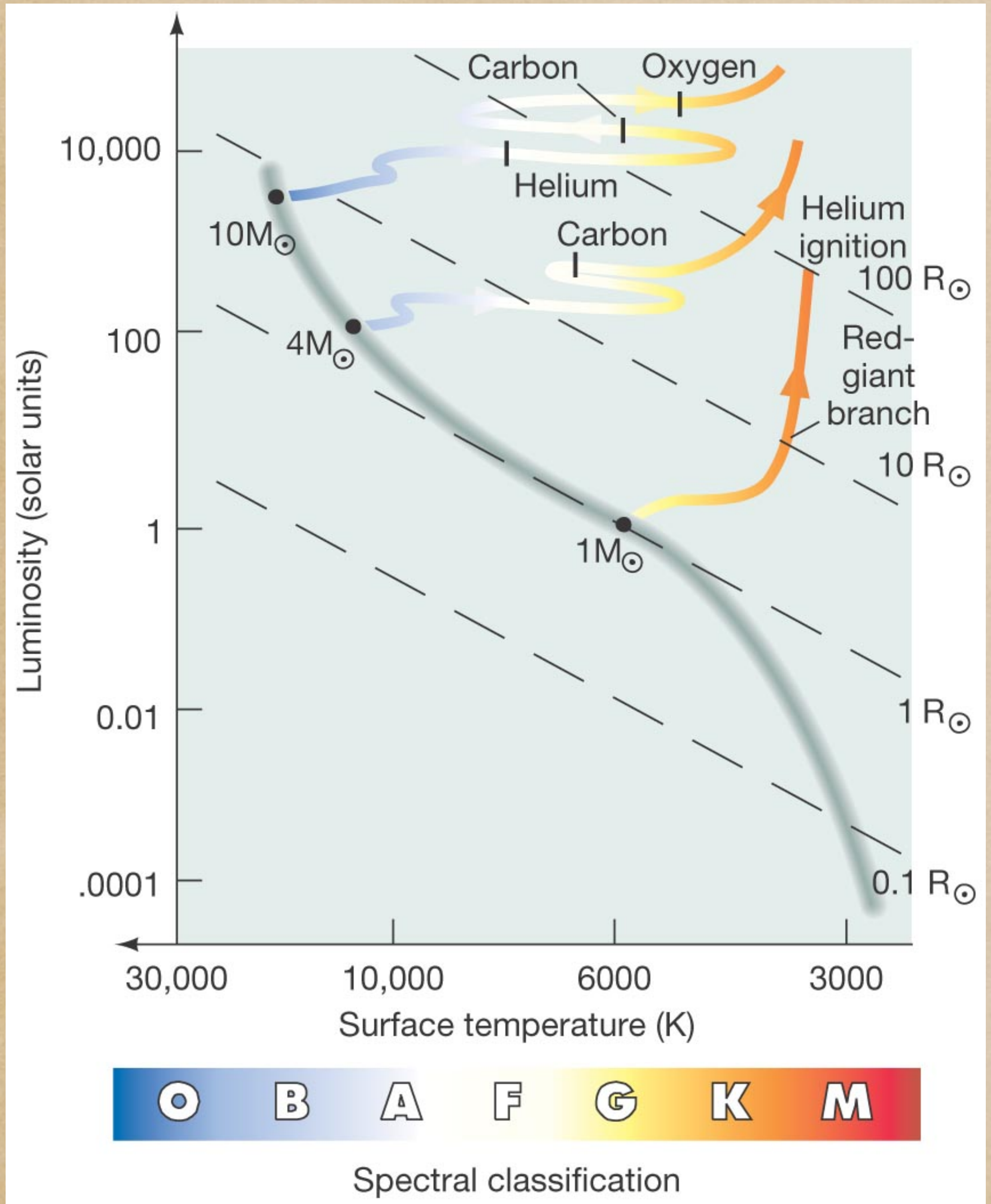


Image credit: http://www.bestthinking.com/articles/science/astronomy_and_space/astronomy/stellar-evolution-5-of-6-end-of-life-cycle-for-low-mass-stars

High mass stars (> 5 solarmass)



- Travel across top of HR diagram

- High-mass star ends its life by the sudden collapse of the core, triggering a supernova explosion.
- A white dwarf can also become a supernova, if it accumulates gas from a companion star in a close binary system (if stars are close, they can affect each other's evolution).

Supernova explosions

Massive stars undergo violent explosion - supernova explosions

- Luminosity comparable to the entire galaxy (~10^{11} stars).

- key source of heavy elements in our universe

- Two types (based on explosion mechanisms):
  *** Type Ia (thermonuclear supernovae)**
  *** Type II (core-collapse supernovae)**

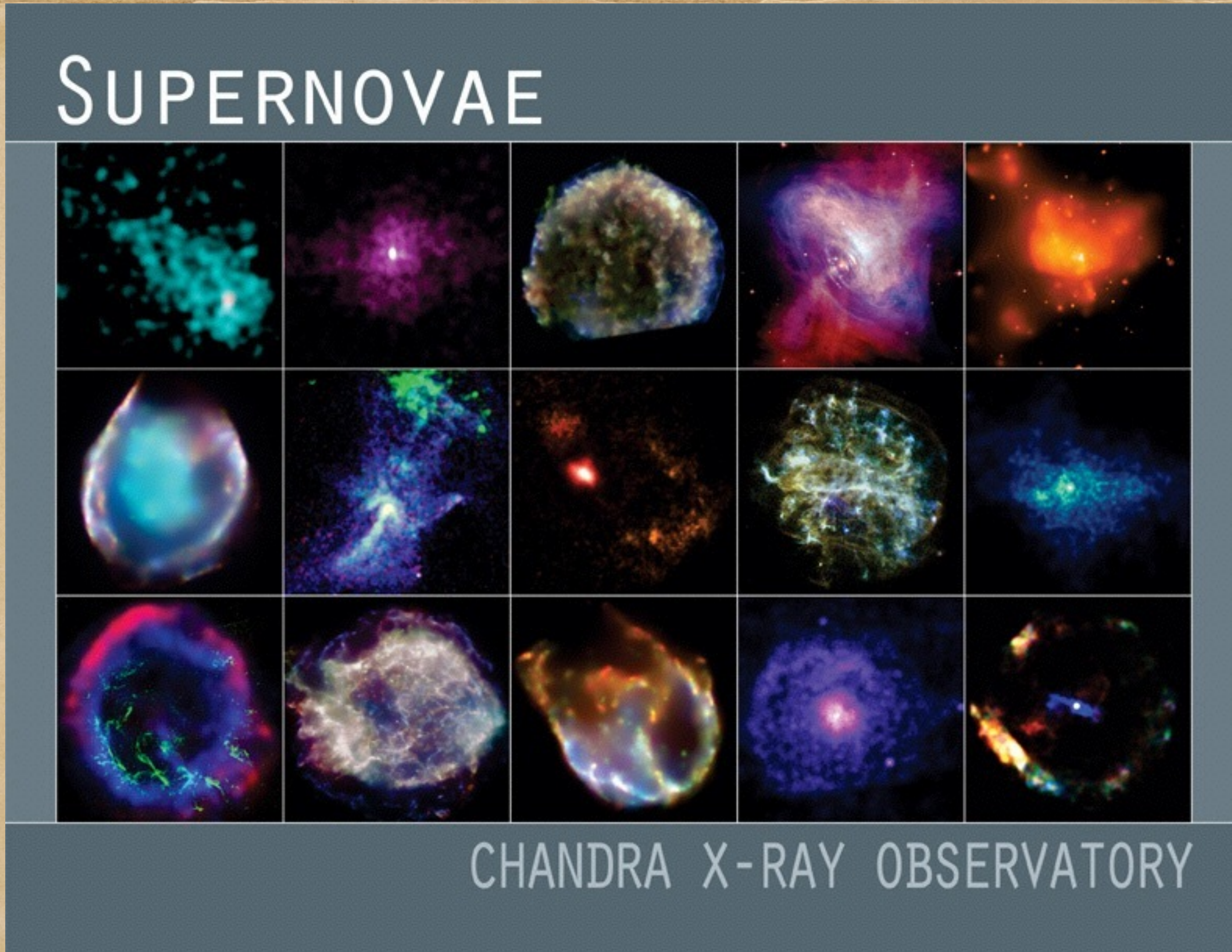
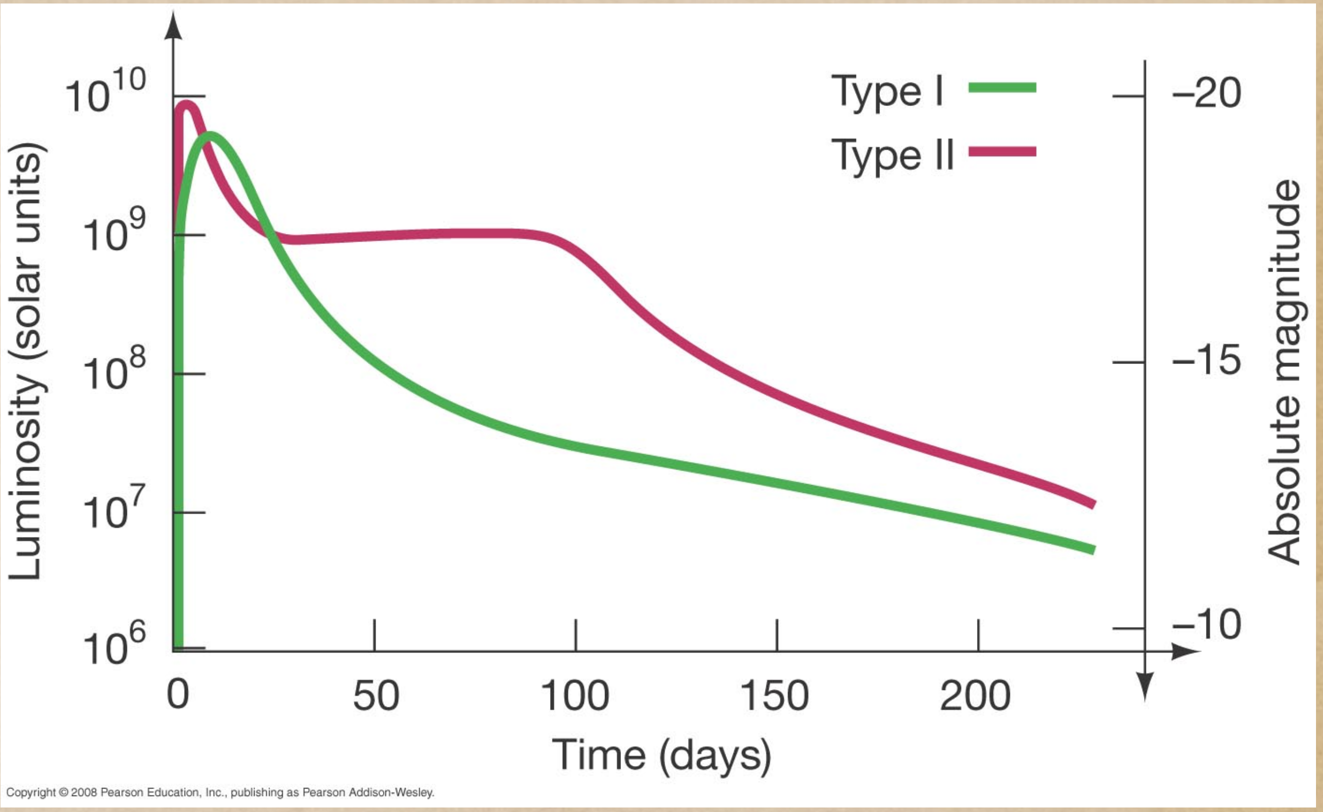


Image credit: Chandra gallery

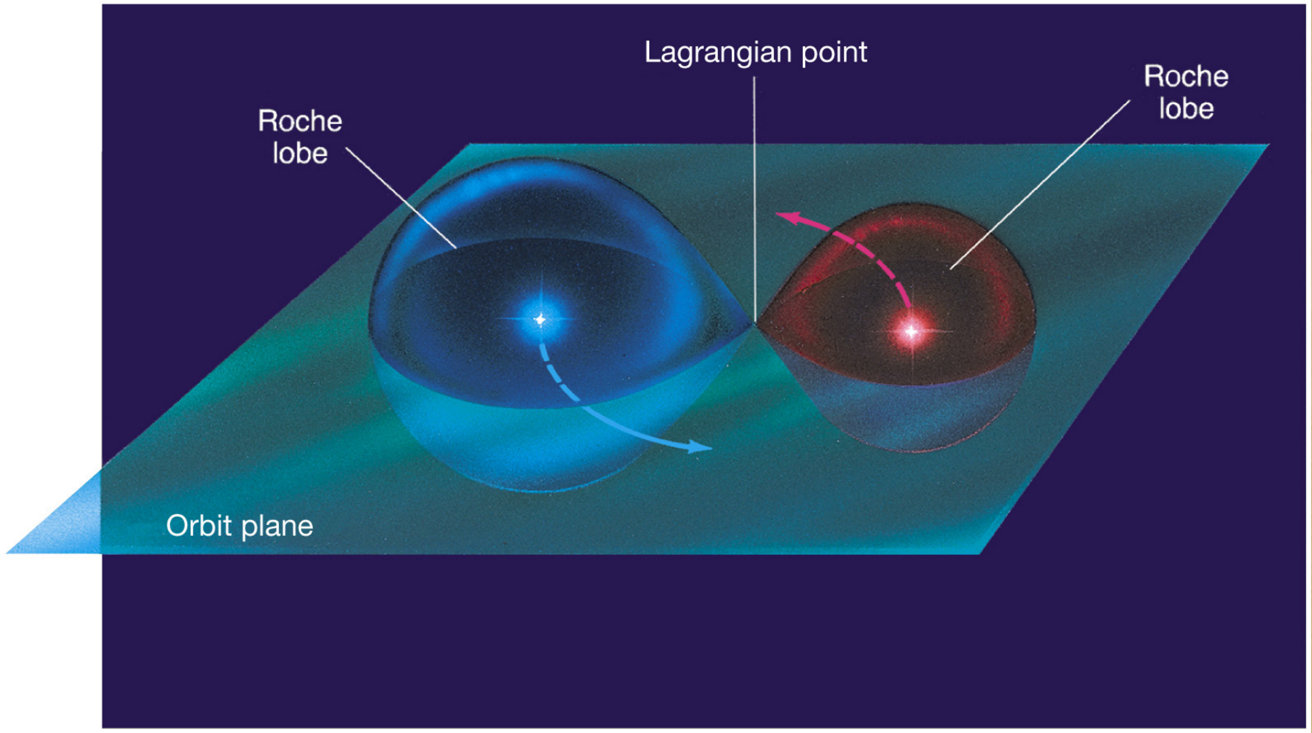
Light curves of Type Ia and II

- Shape of light curve (Luminosity Vs time plot) distinguishes SNe types.
- Type Ia —> a sharp maximum and a gradual decline.
- Type II —> a broader peak at maximum and declines more quickly.
- Spectra of SN type Ia DO NOT show any hydrogen lines.



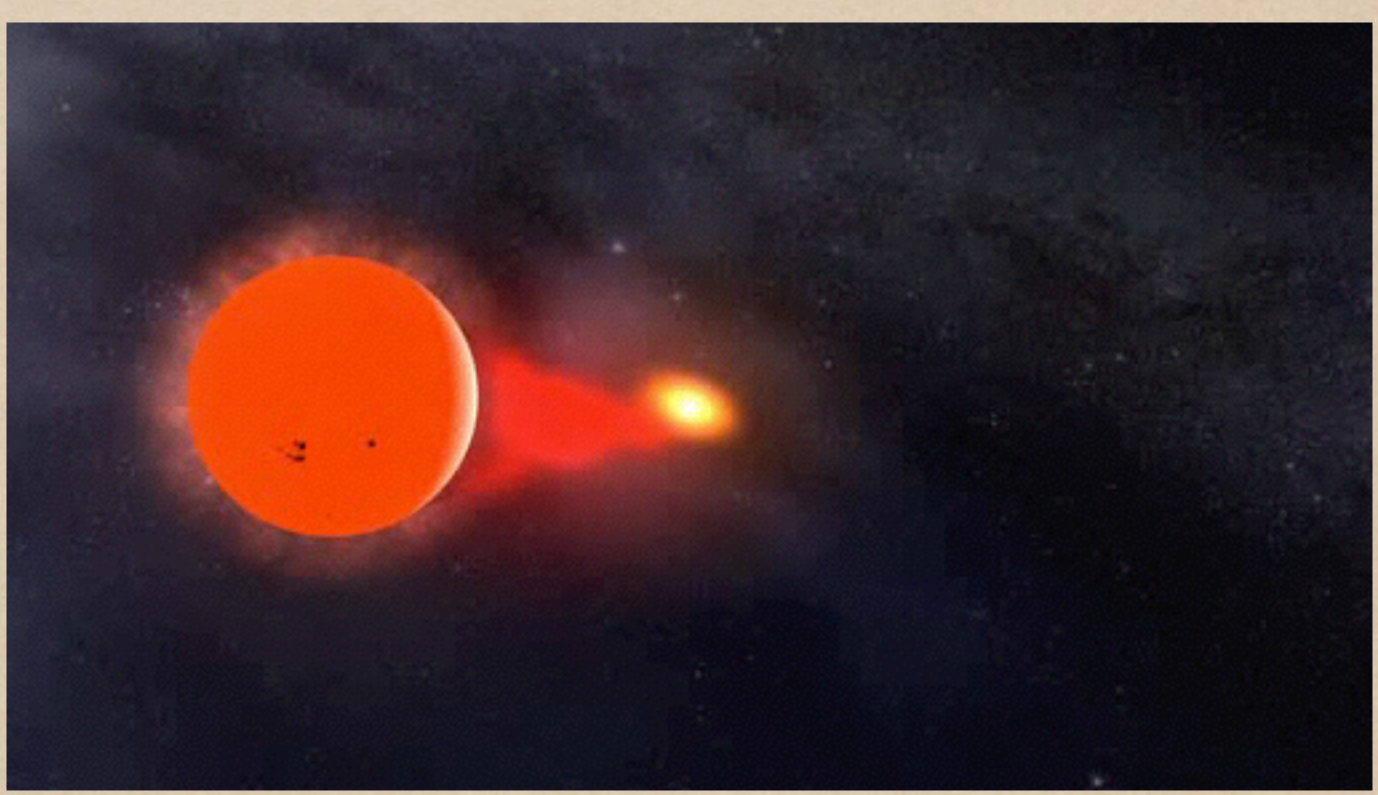
Supernovae type Ia - Thermonuclear SNe

- Most stars are in binary star systems.
- Two scenarios:
  - White dwarf and a high-mass star
  - Two white dwarfs
- One will evolve a bit faster than the other —> giant and a white dwarf.
- Tenuous outer material from the giant star falls onto the white dwarf.
- Limit to the amount of mass that a white dwarf can support.
- —> Chandrasekhar limit ~ 1.4 solar masses.



- In a binary system, each star controls a finite region of space, bounded by the Roche Lobes (i.e., zone of influence inside which matter is considered as being "part" of that star).
- Matter can flow from one star to another through the inner Lagrange point.

Supernovae type Ia animation

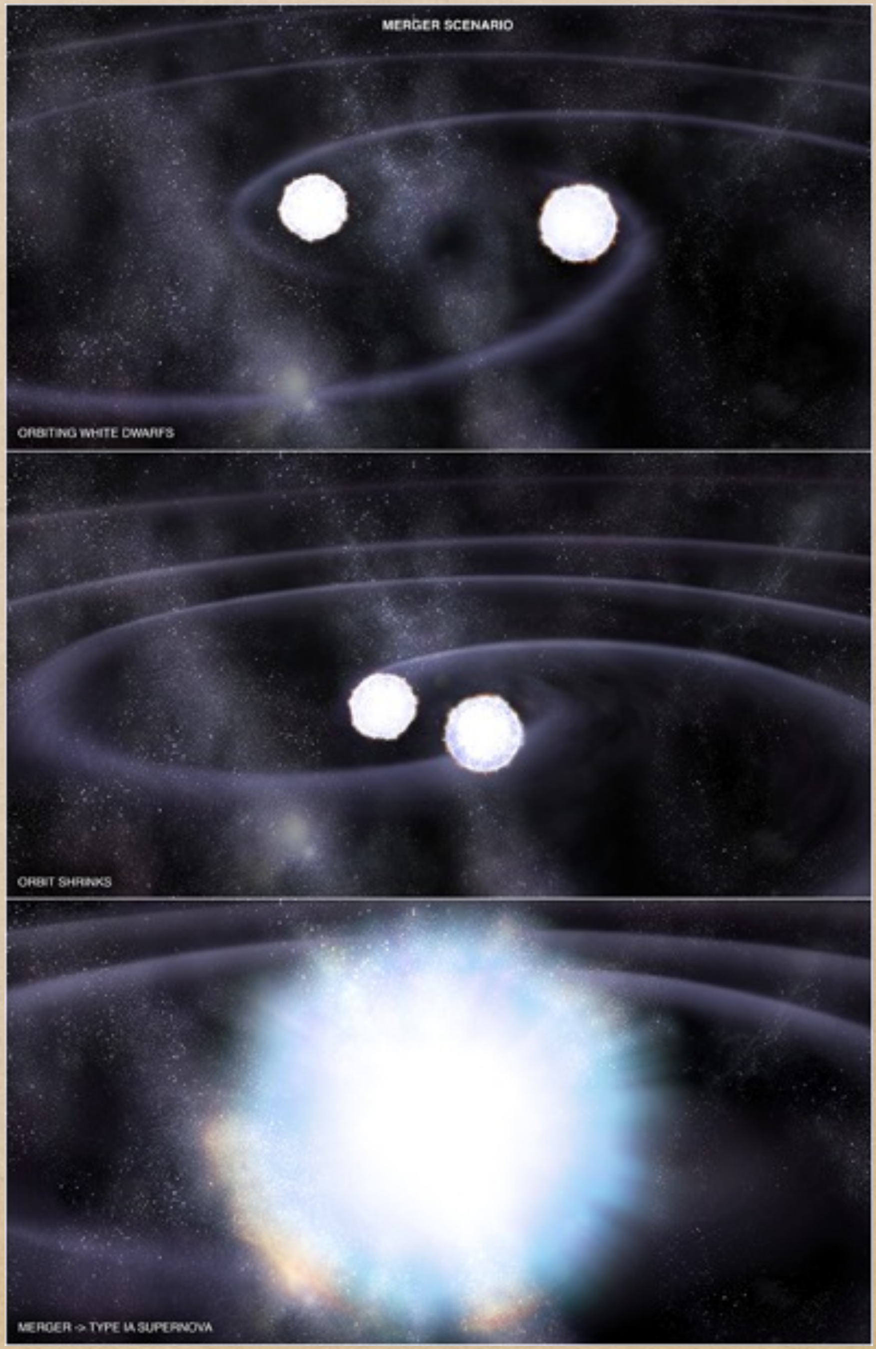


- Exceeding the Chandrasekhar limit results in a runaway fusion process that blasts the white dwarf apart, totally destroying it.

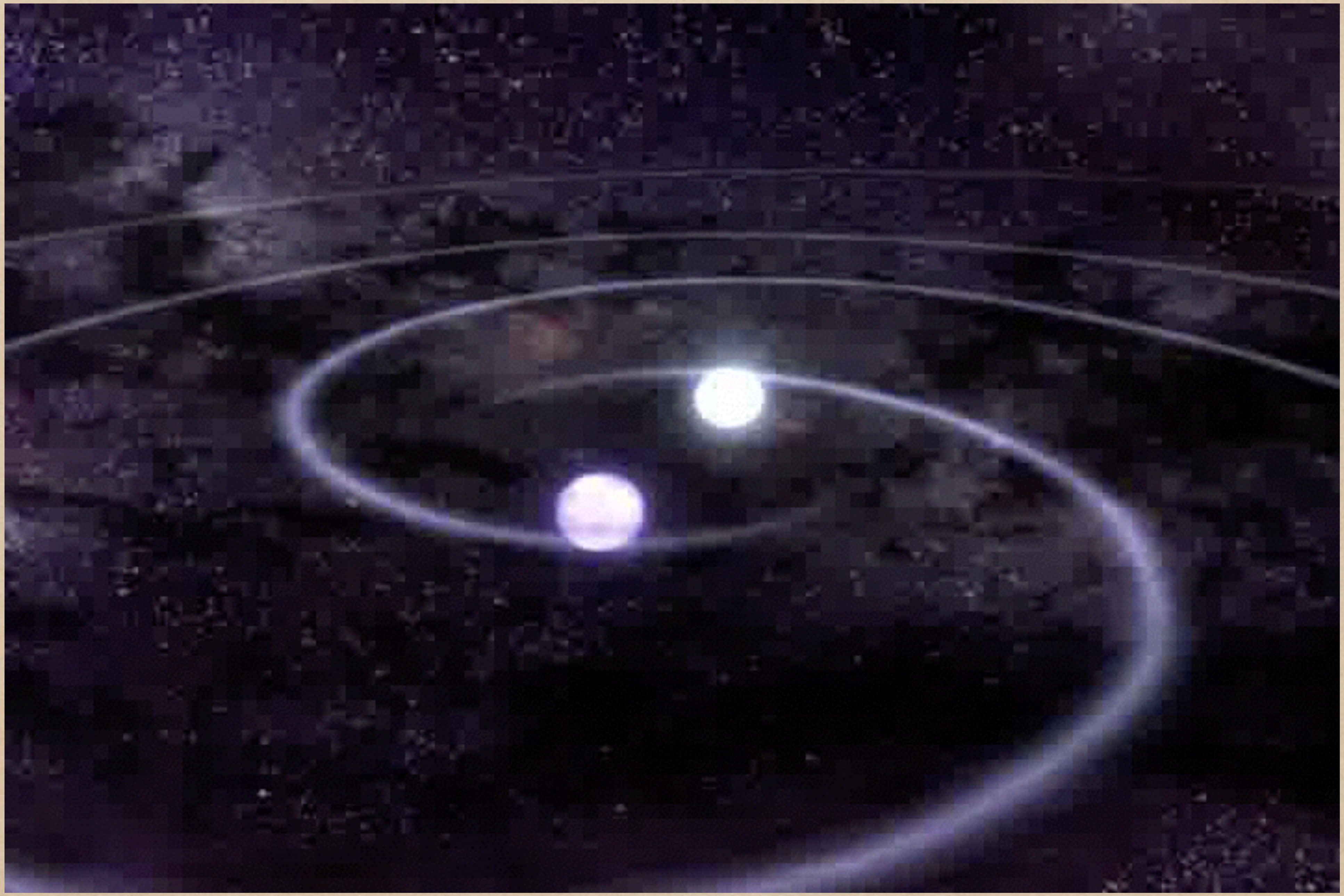
Video credit: Chandra X-ray Observatory

Supernovae Type Ia

- A second scenario:
- Two white dwarfs in binary orbit.
- Merge together
- Limit to the amount of mass that a white dwarf can support
- Chandrasekhar limit ~ 1.4 solar mass.
- Explosion exceeding Chandrasekhar limit.

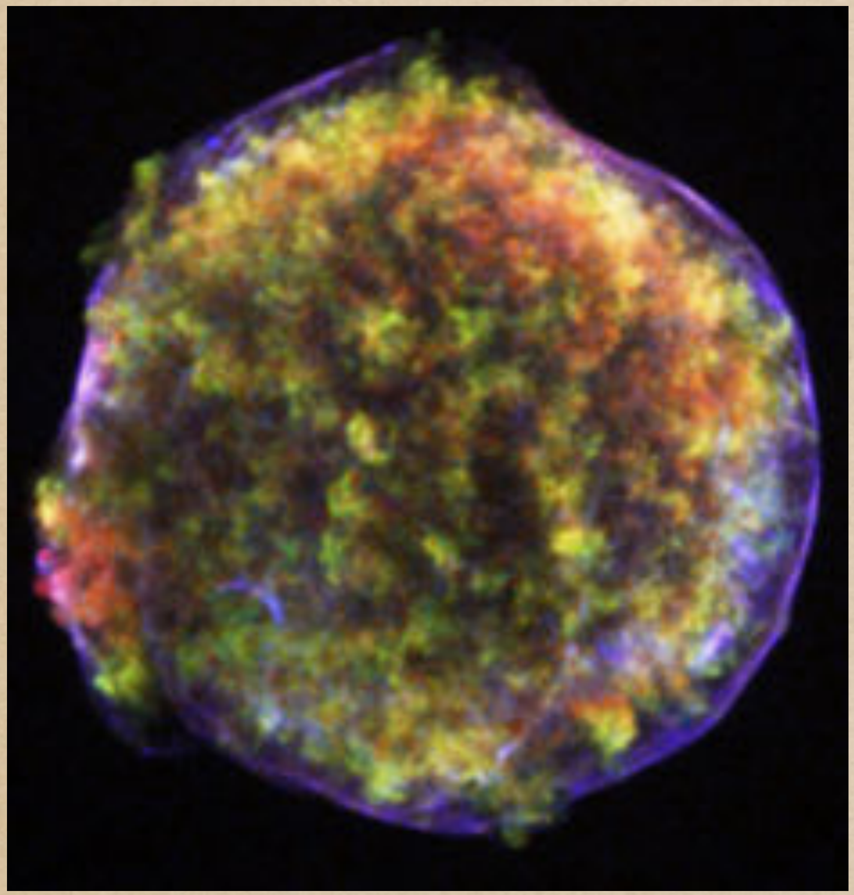


Animation of two white dwarfs merging

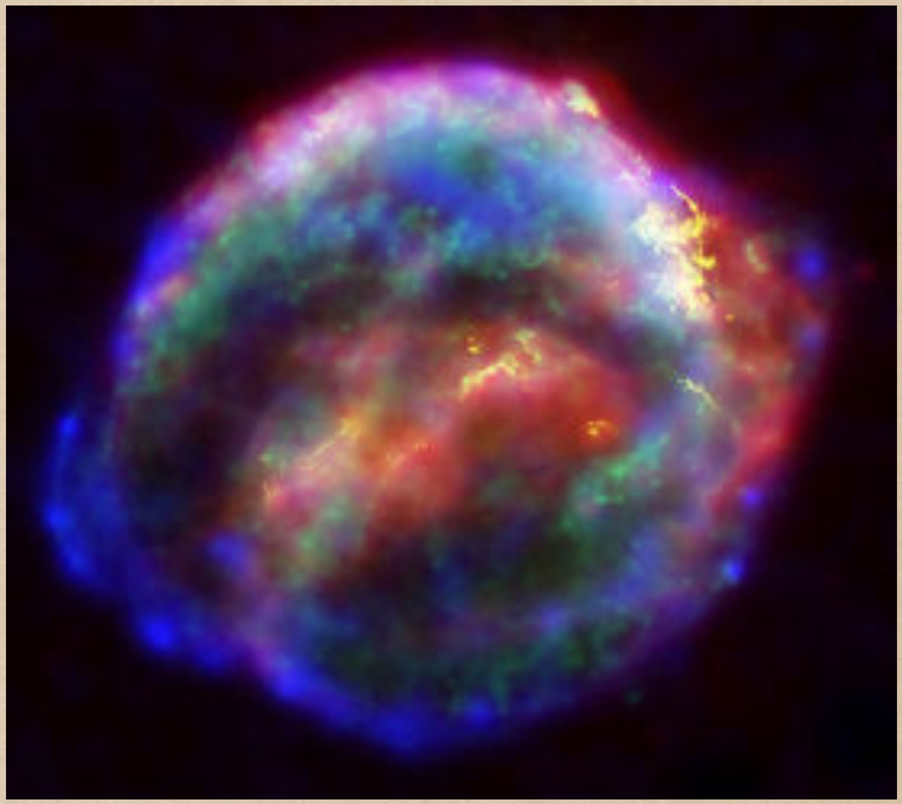


http://chandra.harvard.edu/photo/2005/j0806/wd_sm.mov

Examples of type Ia



Tycho's SN, 1572, 7500 ly away

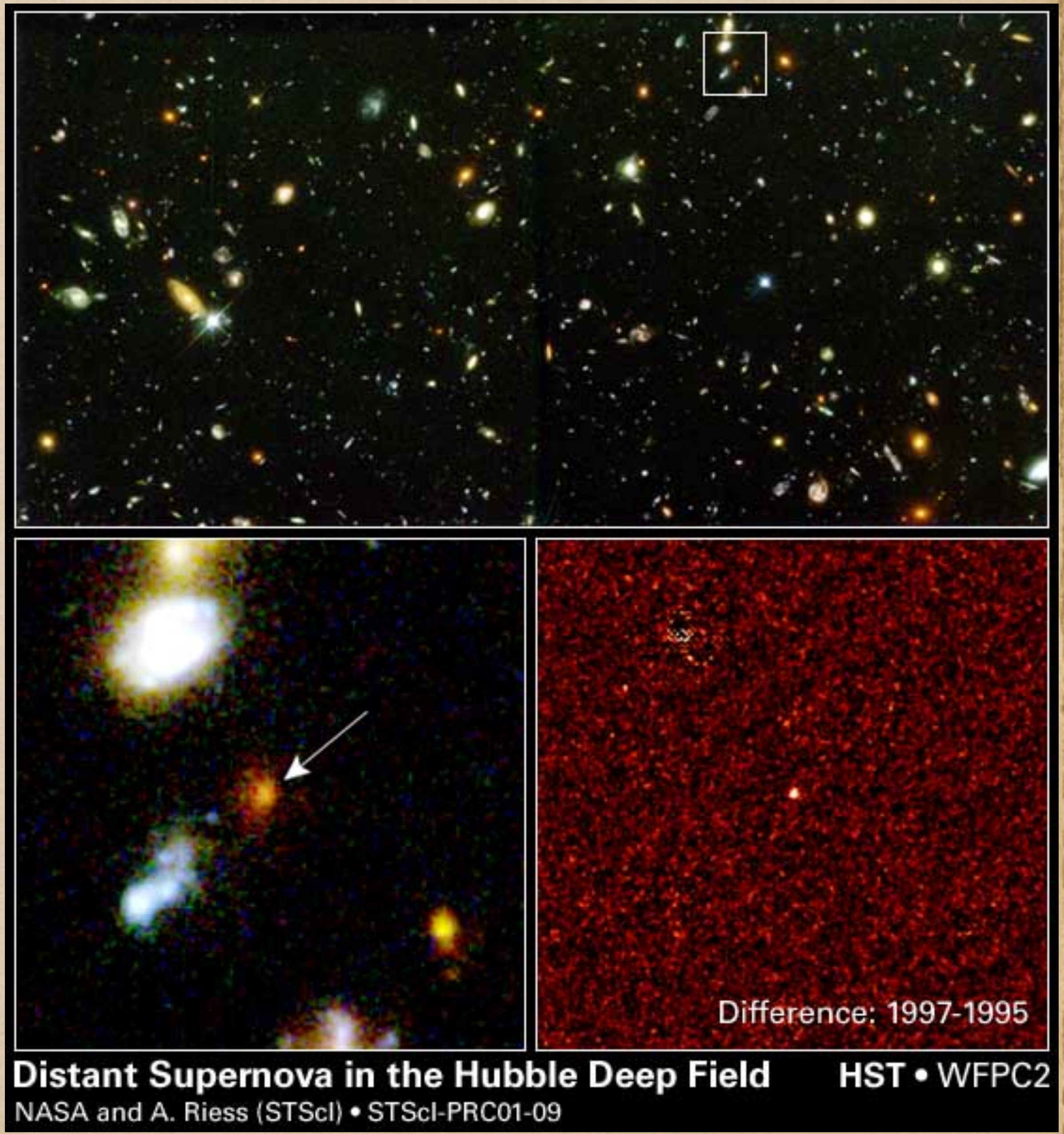


Kepler's SN, 1604, 20000 ly away

Image credits: Chandra X-ray Observatory

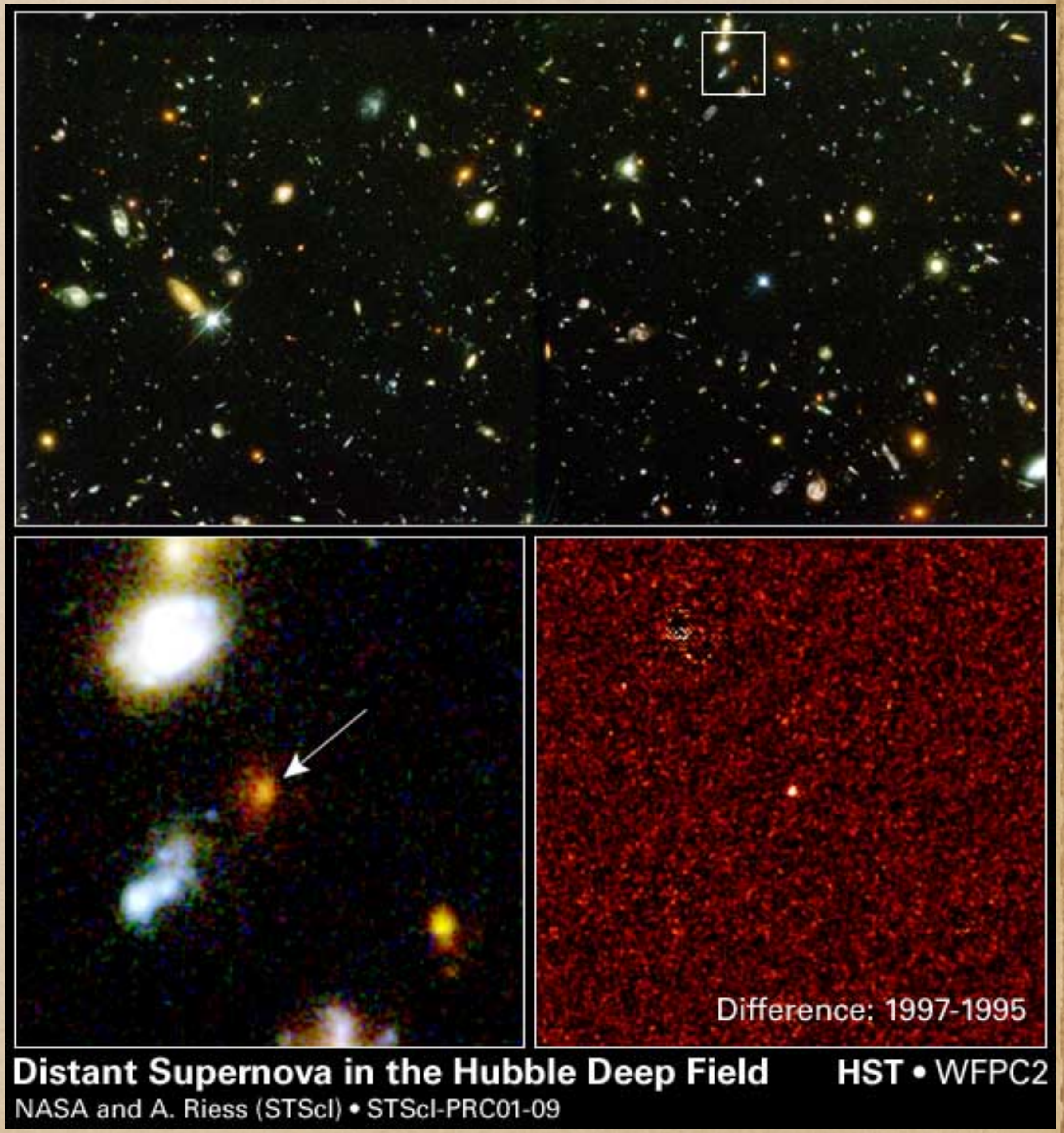
Supernova type Ia

- Standard candles - source that has a known luminosity.
- For distances too large to measure using parallax, astronomers use ‘standard candles’.
- 1.4 solar masses converts to a small range of energies —> a small range of intrinsic luminosity. Which particular luminosity, within this range, can be determined from the shape of the light curve.
- Use the inverse square brightness law to get the distance to the galaxy hosting the explosion.



Supernova type Ia

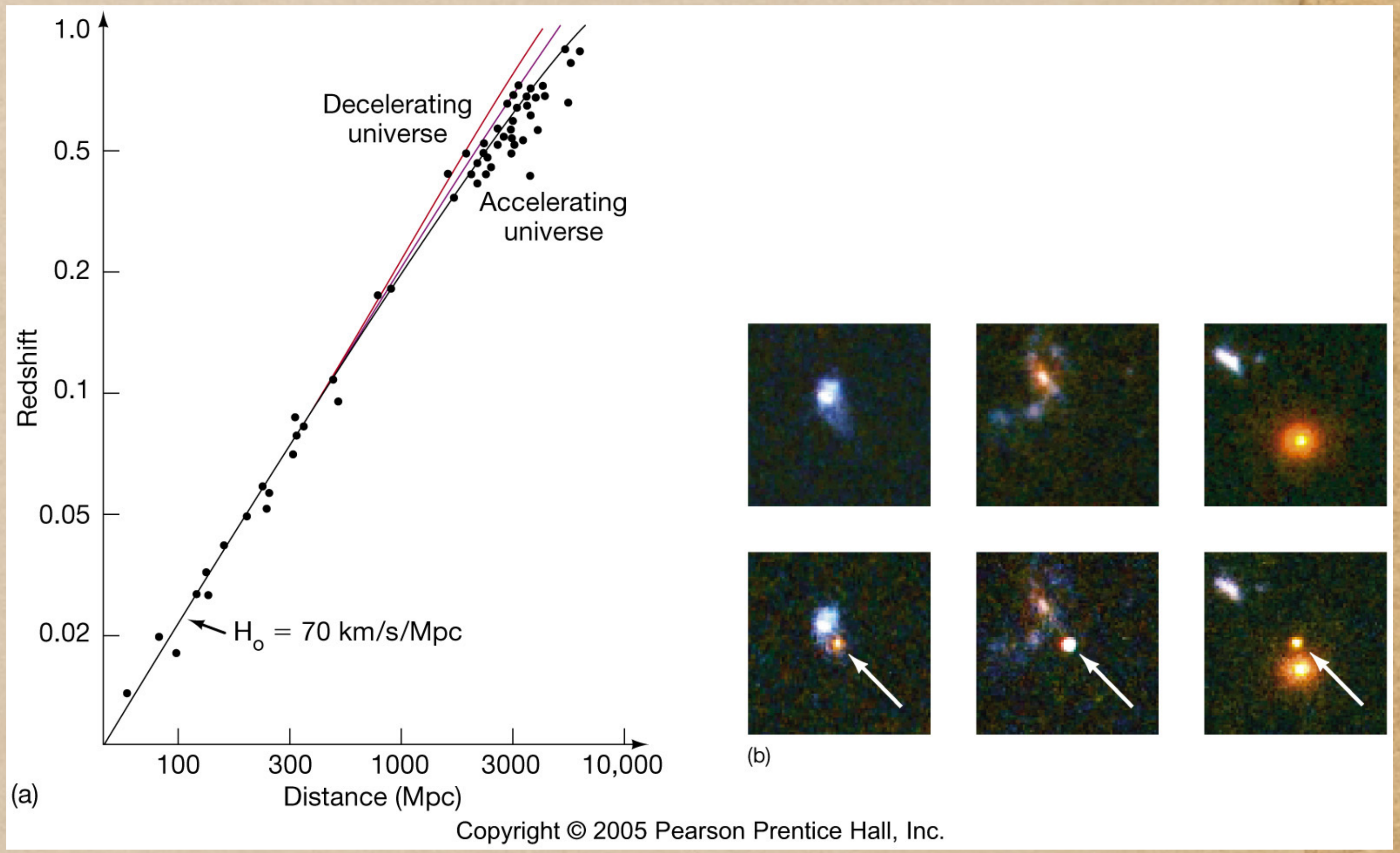
- Using these very bright explosions —> distance to galaxies very far away (e.g., galaxies in the Hubble Deep Field).
- What can we get from knowing the distance?



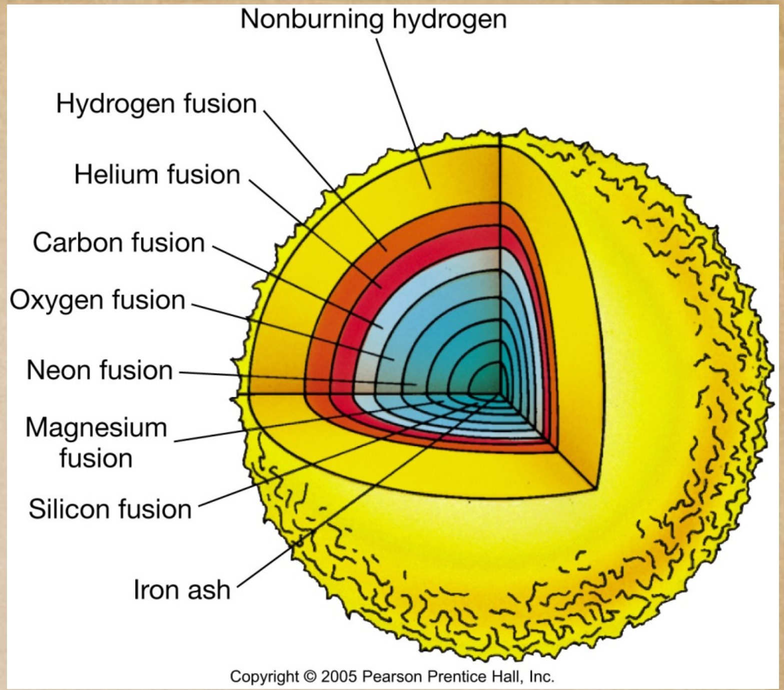
Big Bang: the Expansion of the Universe

- The expansion is **accelerating**.
- Distance determined from SNe versus the velocity (redshift = v/c) of the host galaxy determined from observations of the doppler shift.
- Can assess this for an understanding of Dark Energy.

Observations

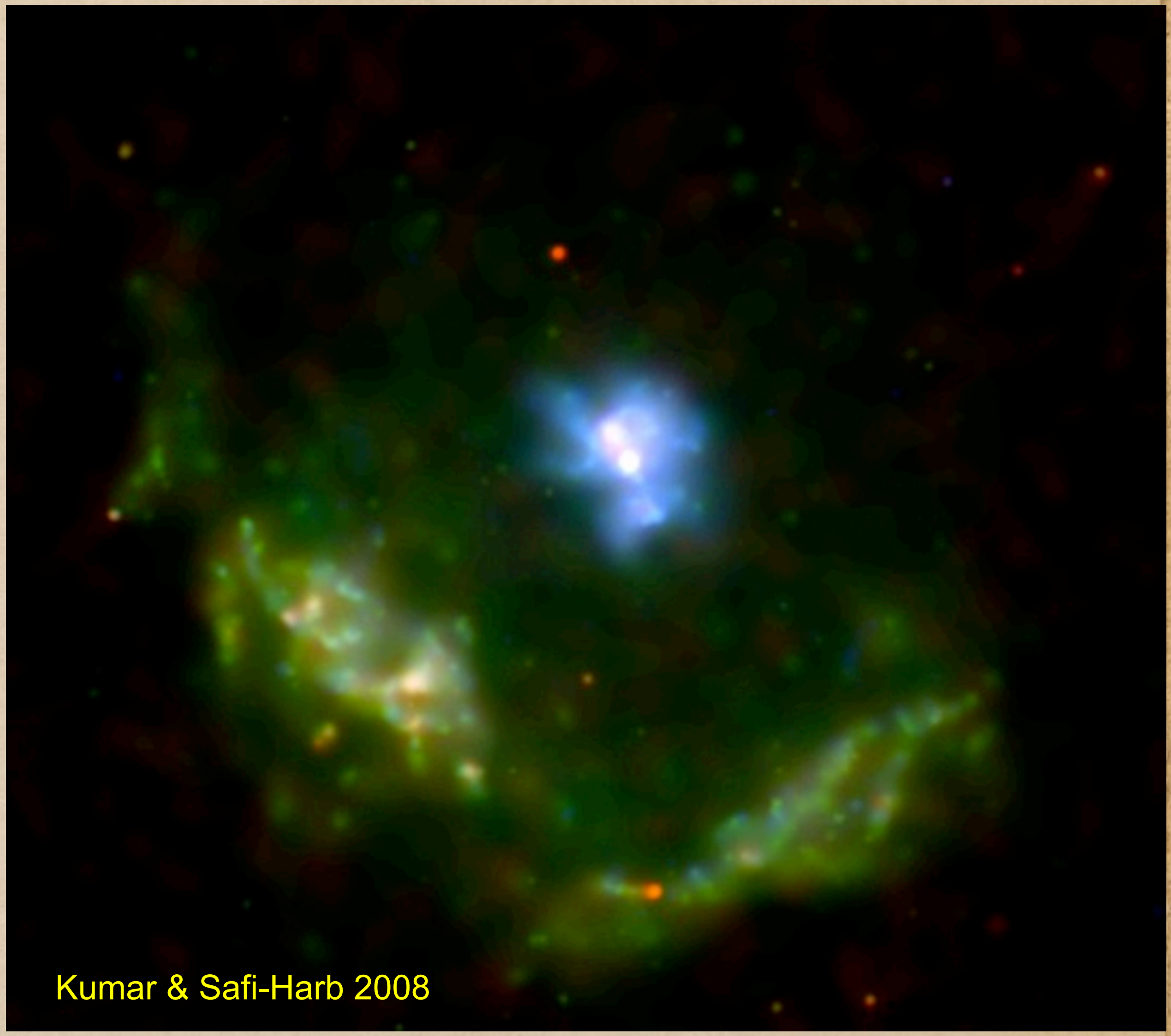


Supernovae Type II (Core-collapse)



- Initially evolve the same way as low mass stars turning into red giants and undergoing He-core burning.
- However, fusion doesn't stop with C-O core.
- Core progressively fuses elements.
- Fe fusion requires energy —> no supporting outward pressure to balance inward pull of gravity.
- Core collapses —> implosion.
- Protons & electrons crushed together —> neutrons.
- Degenerate gas of neutrons.
- Infalling material hits dense core and bounces outwards.
- Outward shock wave - blasts outermost layers into space at the velocity of light!

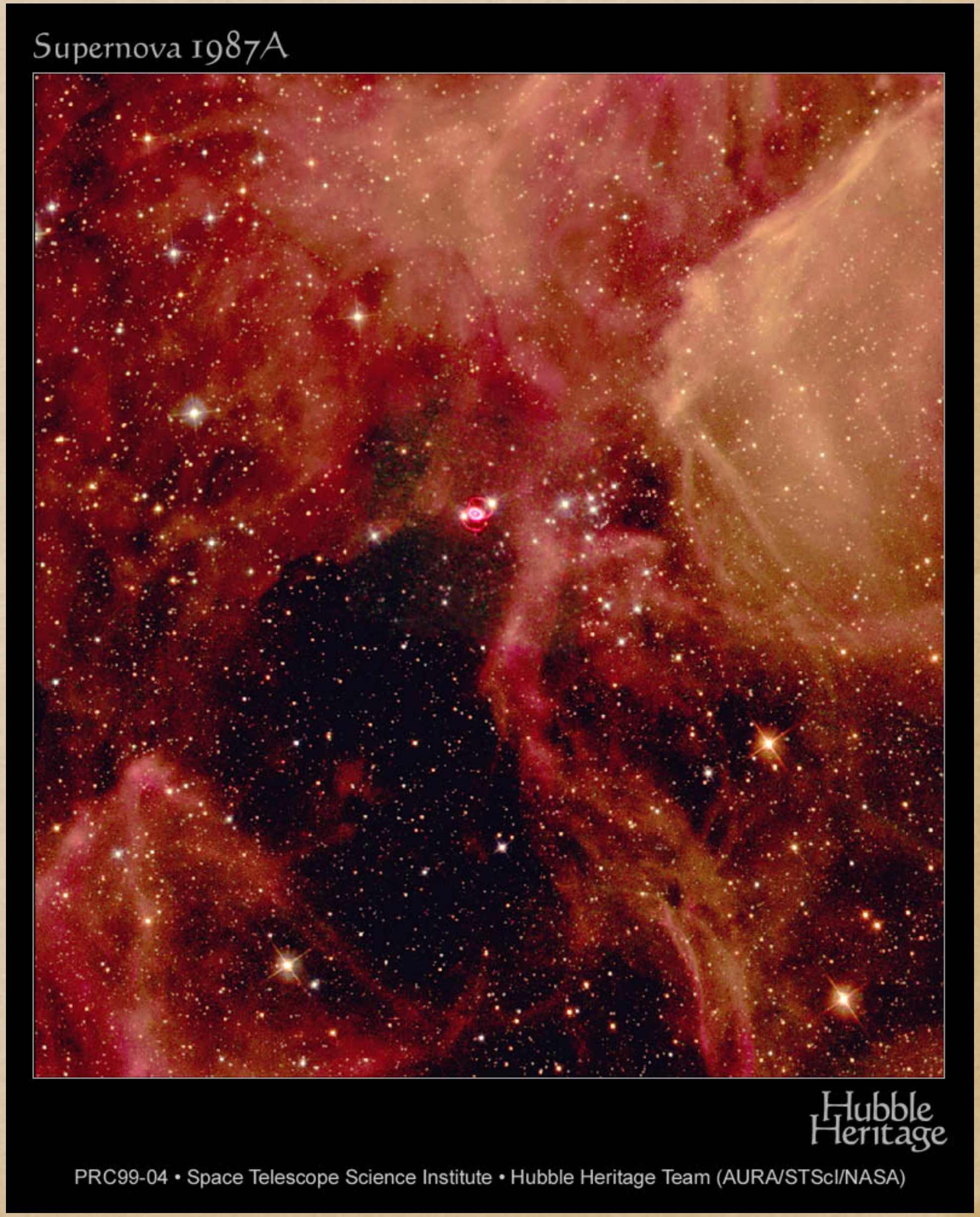
- **Supernova remnants:** the relics of a supernova explosion
- When supernova explodes, outer material is thrown into space with great velocities of ~ 10000 km/s.
- Blast wave interacts with the interstellar medium and pre-SN ejecta.
- Core: neutron star or a black hole



SNR Kes 75 with a pulsar at the center

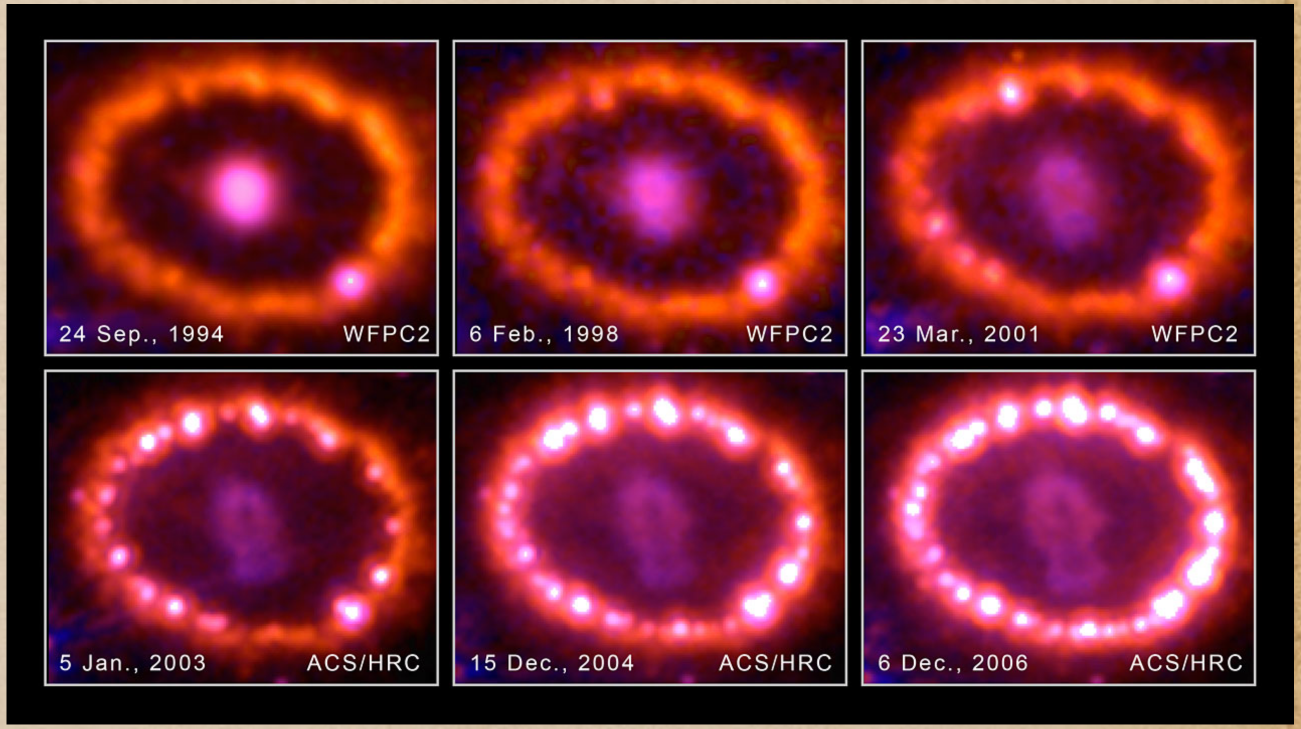
Supernova 1987A

- Discovered by UM alumnus Ian Shelton.
- The first SN in the year 1987.
- The first naked eye SN in ~380 years.
- Occurred in a neighbouring galaxy called the Large Magellanic Cloud.



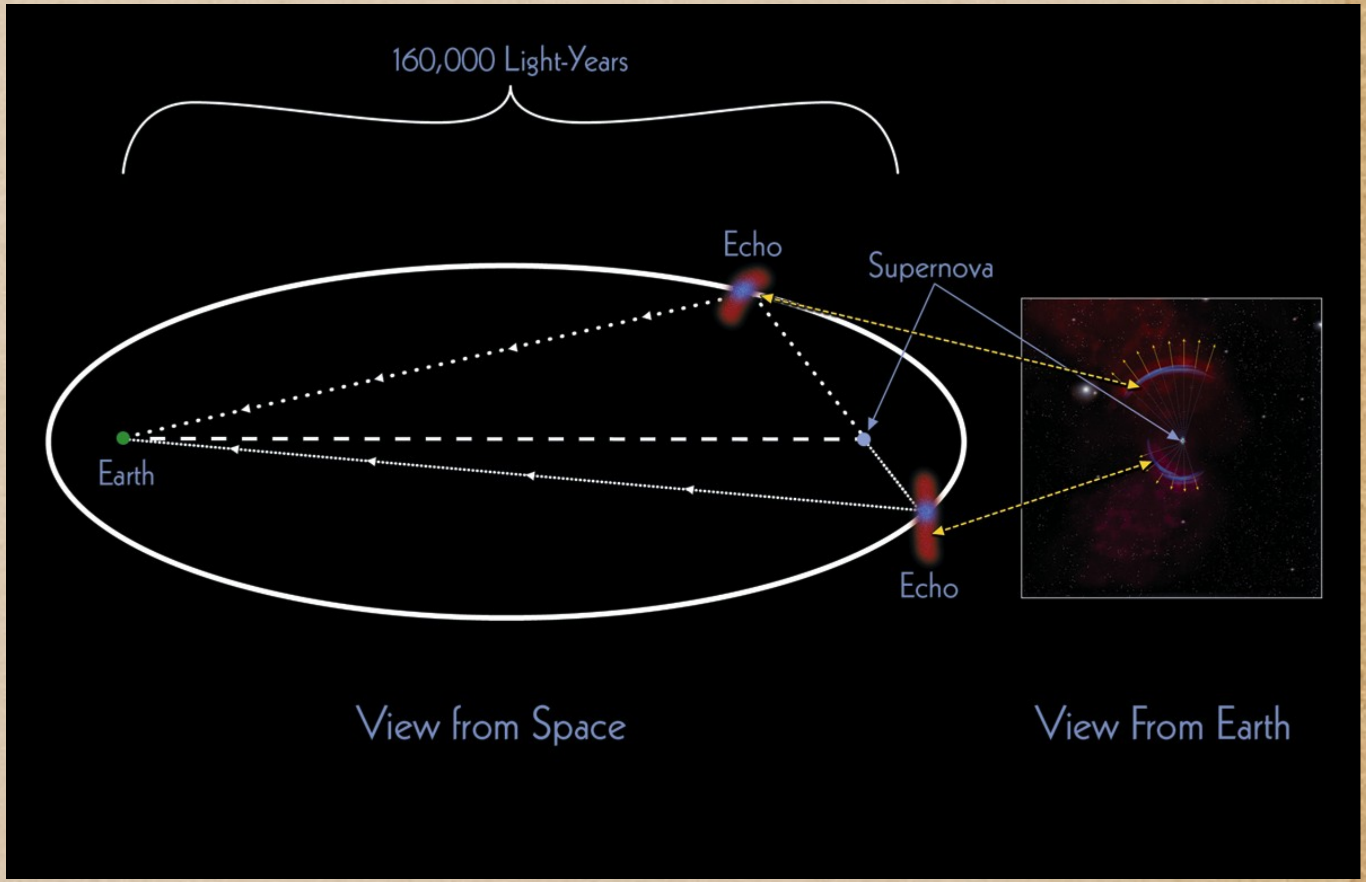
SN 1987A

- The ring consists of material ejected from the progenitor star thousands of years before it blew up.
- The brightening of the ring occurs as the supernova blast wave interacts with the ejected material.



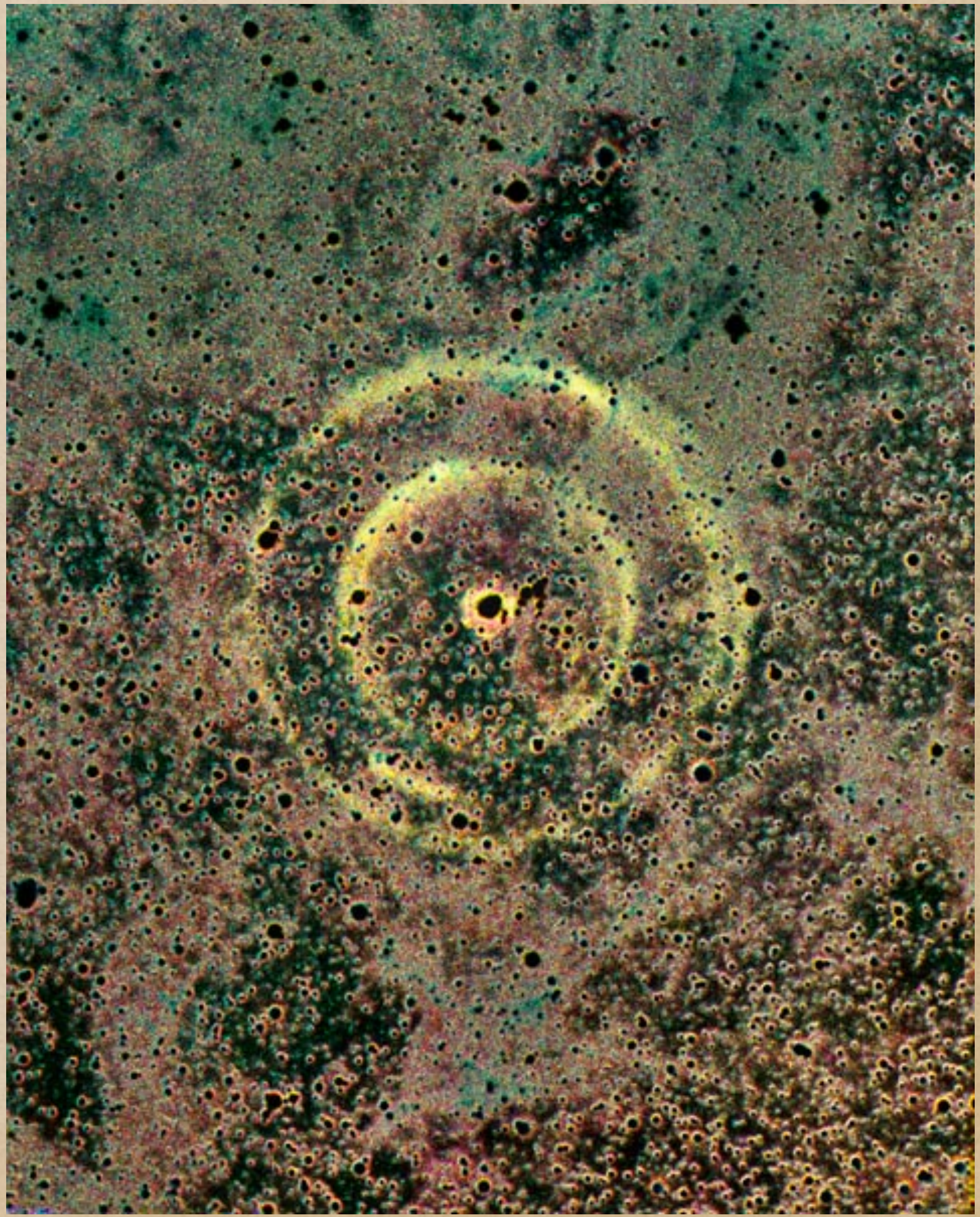
Supernova light echo

- Light moving outwards at constant speed.
- Consider the light paths not along out line of sight.
- Some of these intersect dust.
- Light is reflected off the dust into our telescopes.
- How the echo occurs for us on Earth can be derived using an ellipse with Earth at one focus and the supernova at the other focus.



Supernova light echo

- Light from SN 1987A interacts with dust in ISM.
- Picture was made by photographically subtracting negative and positive images of plates of the region taken before and after the supernova appeared.

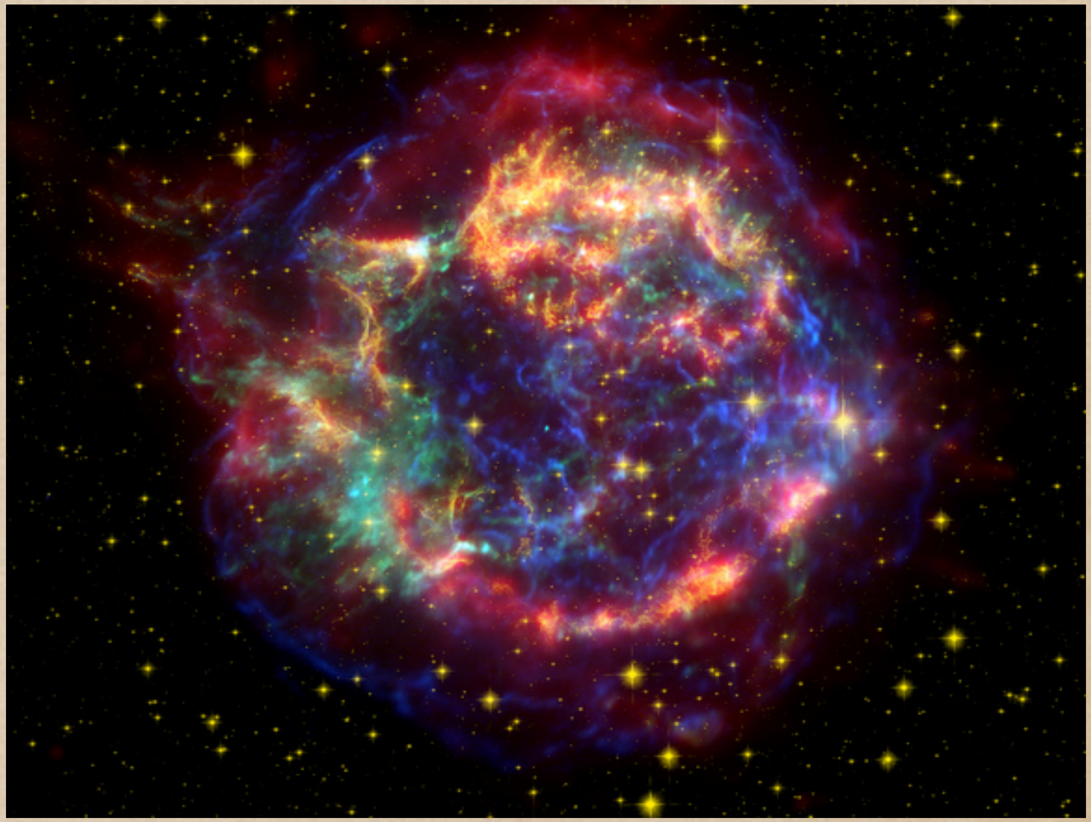


AAT; David Malin

Examples of core-collapse SNe

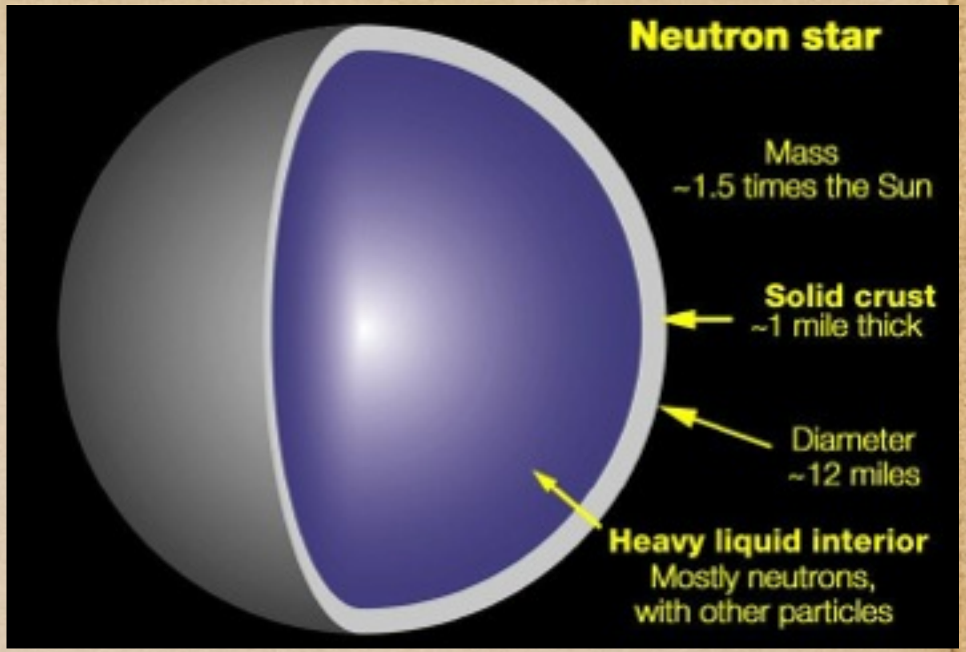
Crab nebula

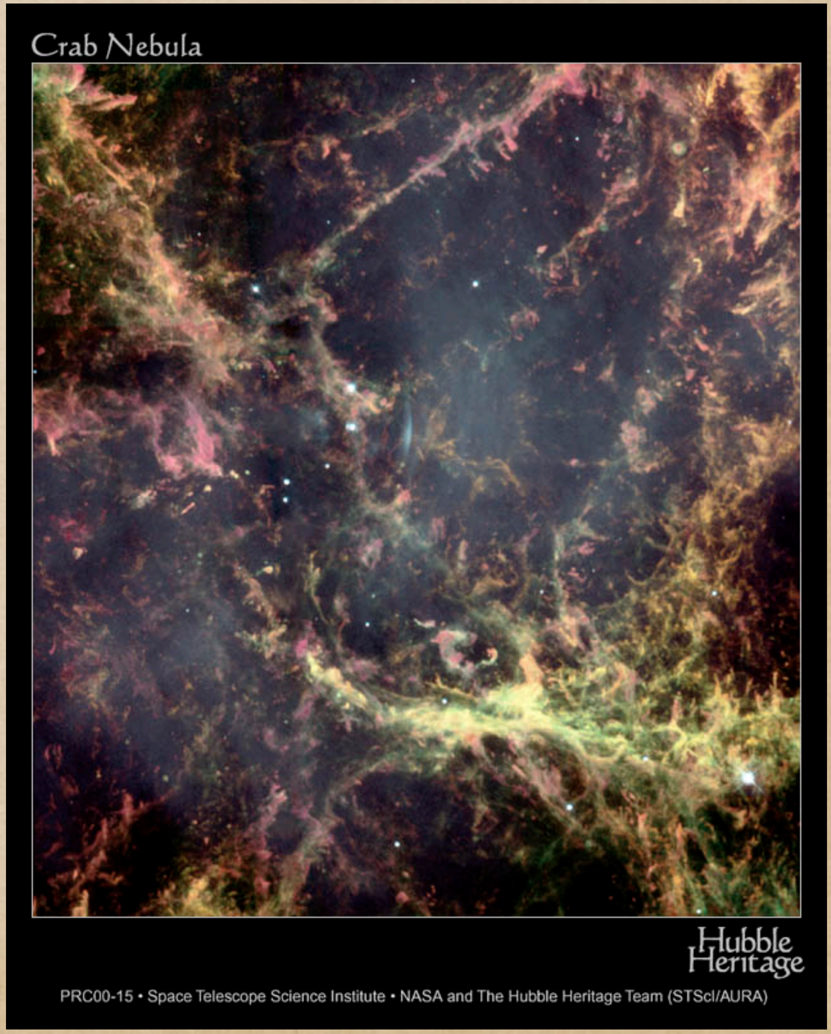
Cas A



SNe Type II:
Neutron stars, pulsars, magnetars

- Neutron stars:
  - radius ~ 10 km, Mass ~ 1.4 to 2 Msun.
- Highly dense
  - a spoonful of neutron star material weighs ~ million tons.
- electron crust surrounding neutron degenerate gas.
- Rapidly rotating - conservation of angular momentum





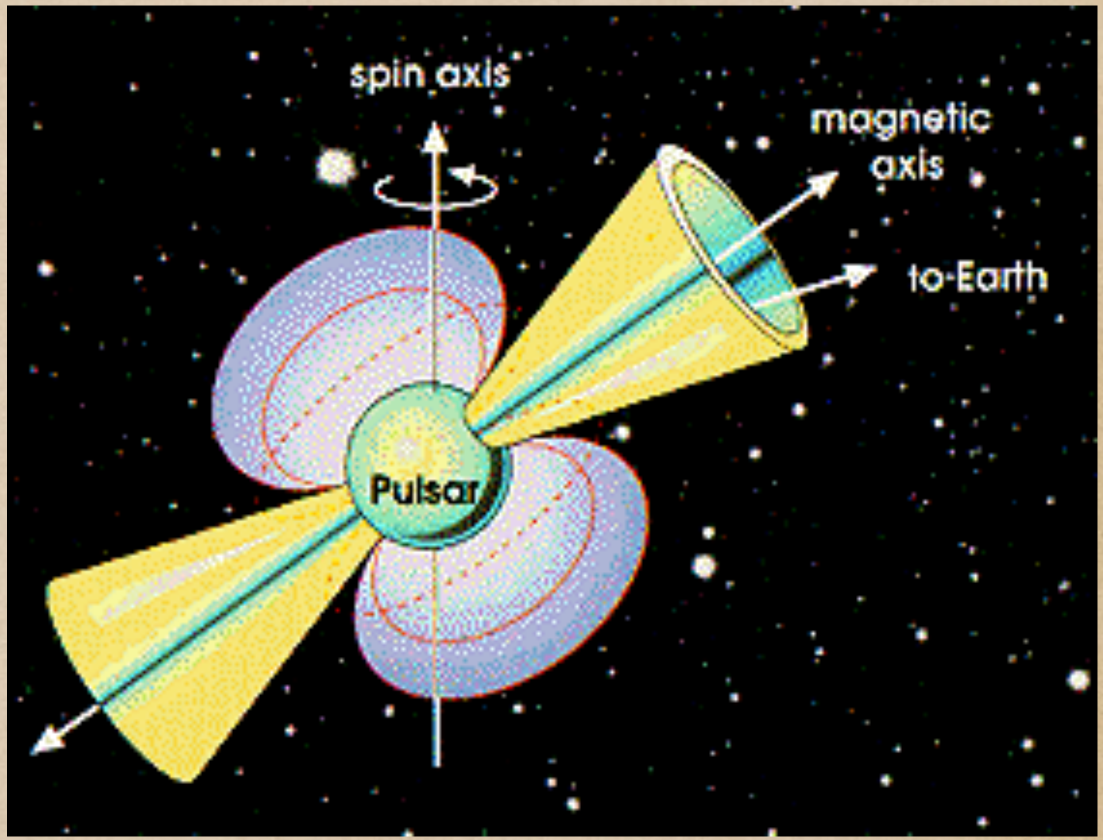
Heart of Crab nebula
- Lower star of the pair just left of center

Neutron stars

- High magnetic field (~10^{12} G).
- Neutron stars mainly made of neutrons.. So, how is the magnetic field generated?? Something to think about…

Pulsars

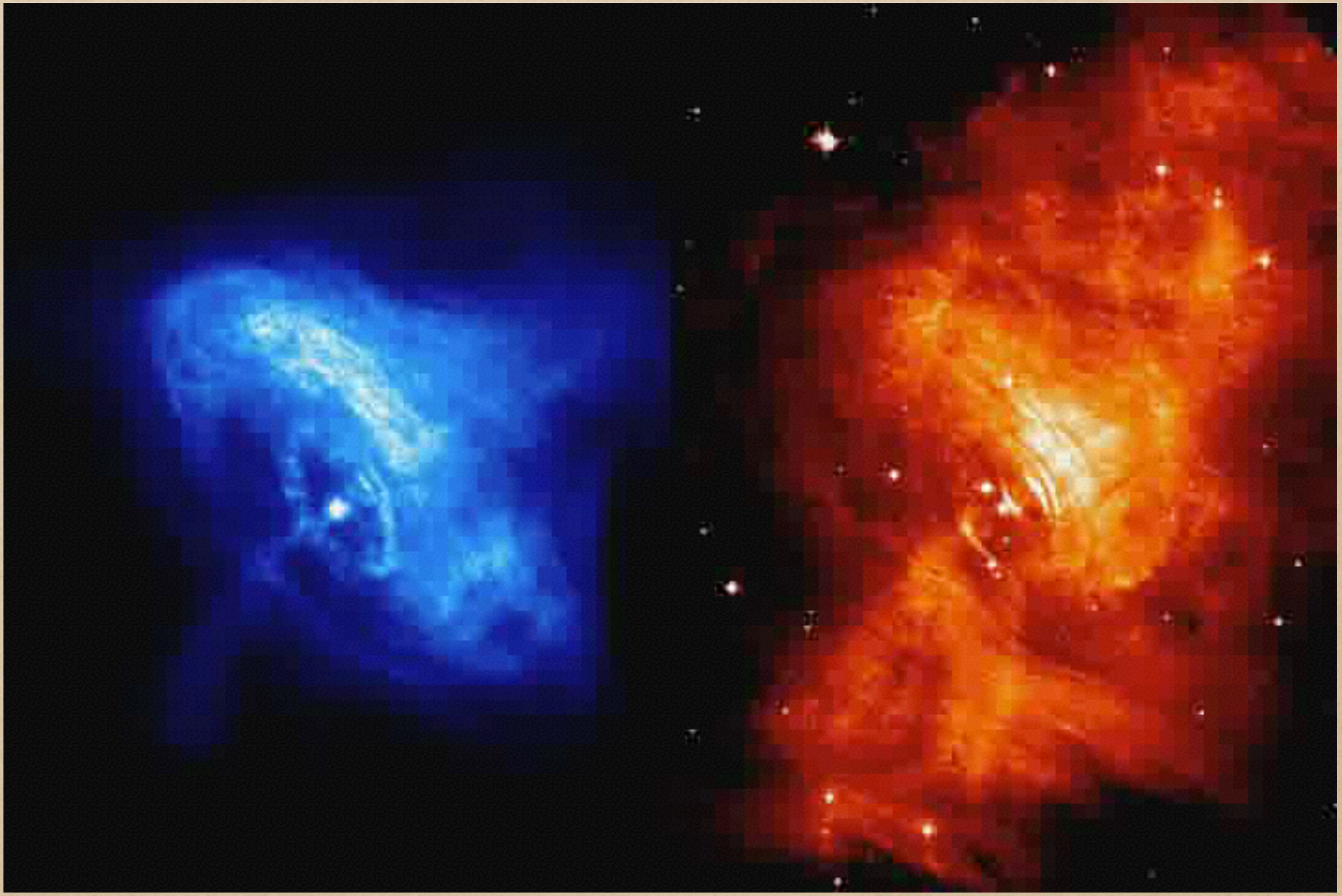
- Rapidly rotating neutron stars emit beams of radiation along the line of sight of an observer on earth.
- Electrons on the surface accelerated by magnetic field and jettisoned along the magnetic poles - synchrotron emission.
- **If beam is not perpendicular to our line of sight, then we do not observe a pulsar (they are just neutron stars).**
- Why do we see jets??



Pulsar wind nebula (PWN)

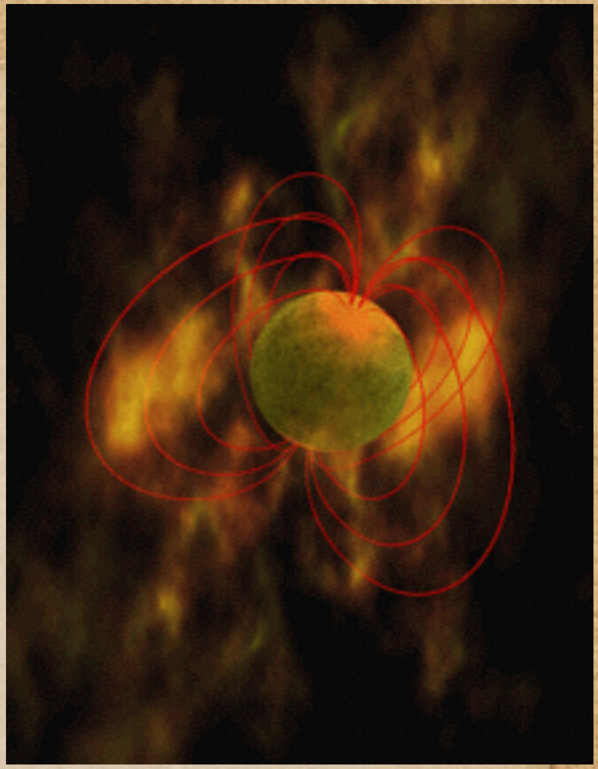
- Highly relativistic (v ~ c) particles emanating from the pulsar —> pulsar wind nebula (PWN).

Crab nebula movie: Pulsar wind nebula (Formed in 1054 AD)



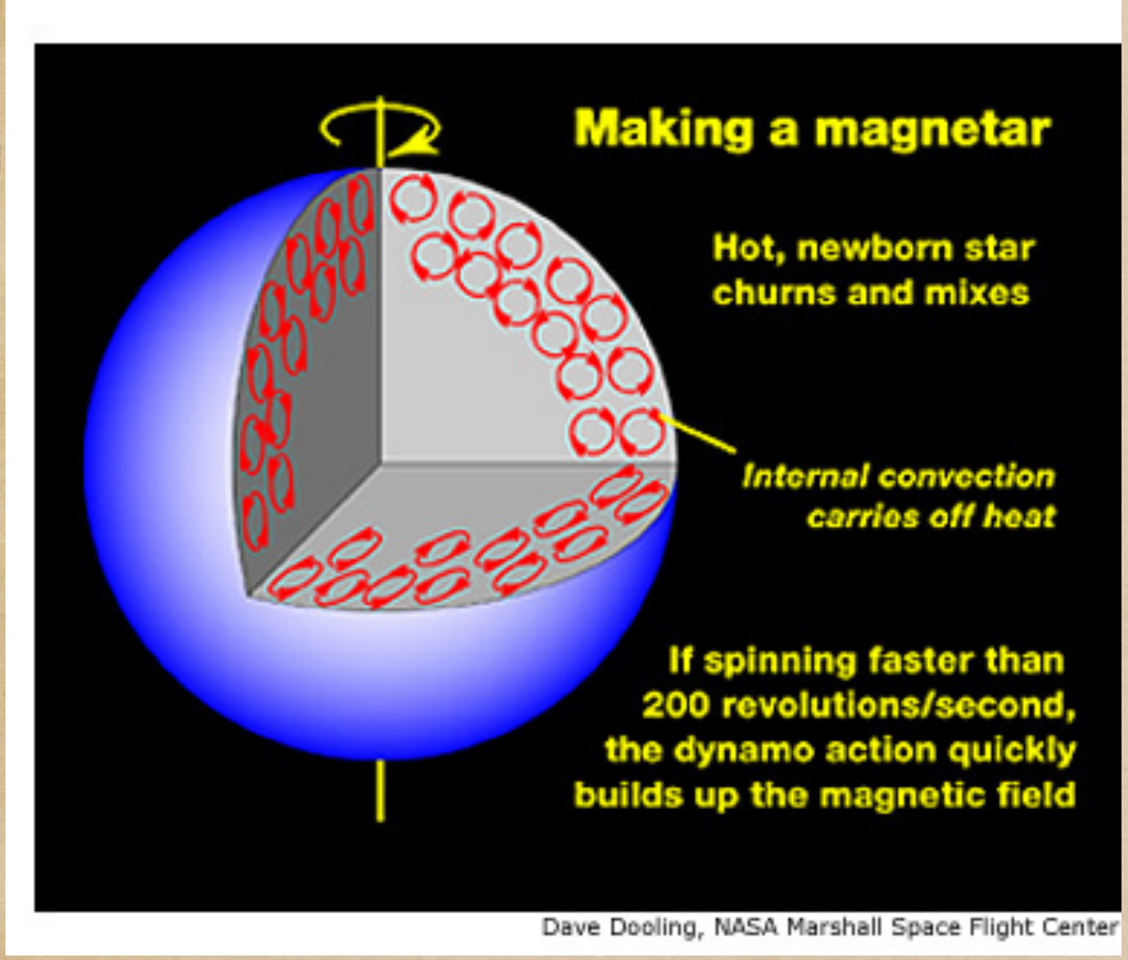
Left is X-ray. Right is Visual. Synchrotron radiation
Pulses 30 times a second

Magnetars

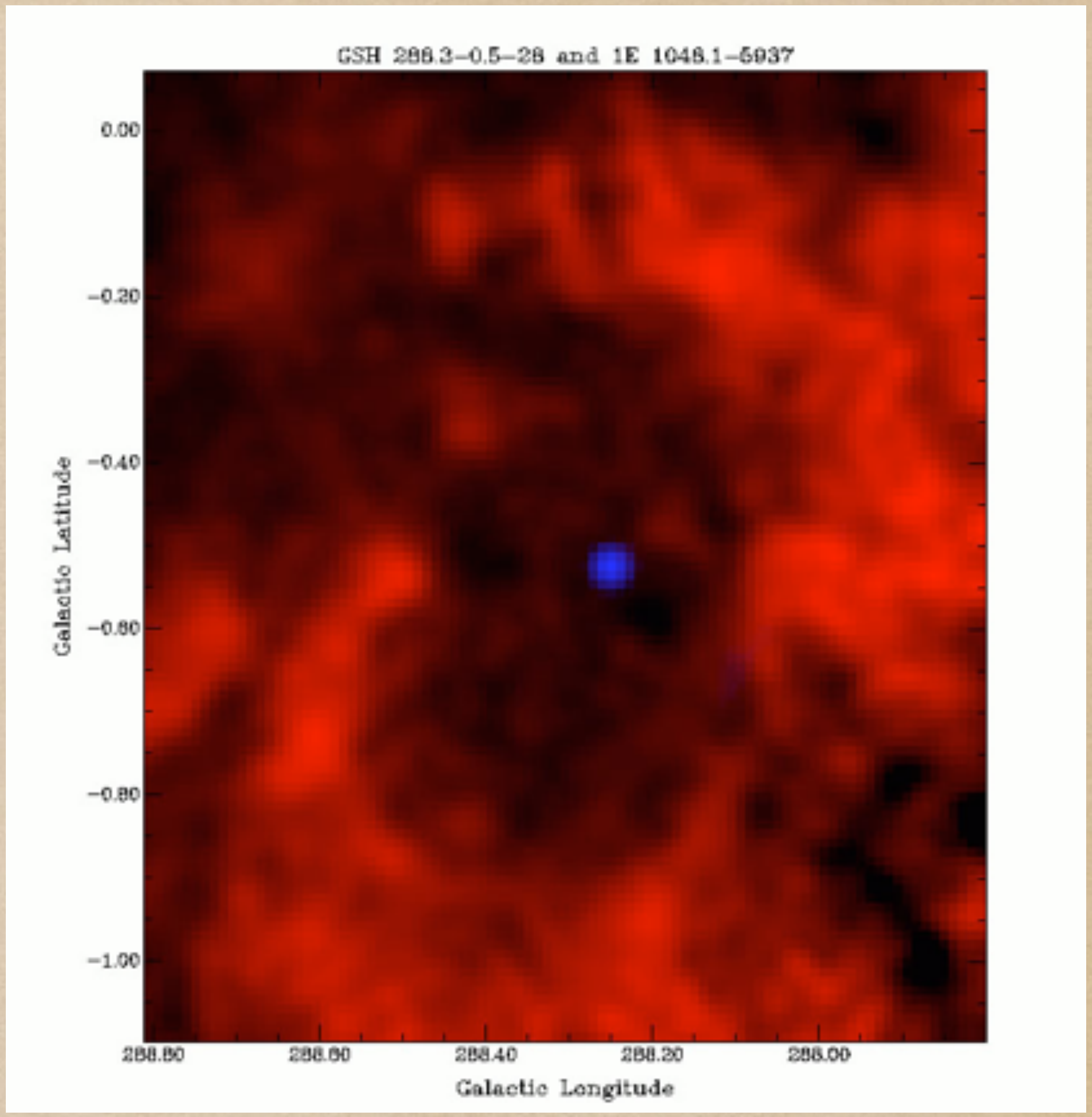


- Another kind of neutron stars!
- Most magnetic objects known so far in the universe!
- Radius ~ 10 km (city of Winnipeg).
- Magnetic field ~ 10^{14-15} G —> equivalent to a hundred trillion refrigerator magnets.
- Super-strong magnetic field stresses the neutron star surface causing the crust to crack open - star quakes!
- Observed as bursts of X-ray and gamma radiation.

Magnetars: Origin of high-magnetic fields



Credit: http://solomon.as.utexas.edu/~duncan/magnetar.html



Credit: ATNF/CXC/B. Gaensler (CfA)

- Dynamo amplification
- Inherited from its massive progenitor (> 25 Msun)

What about stars with M > 40-45 Msun?
Quark Novae (QNe)

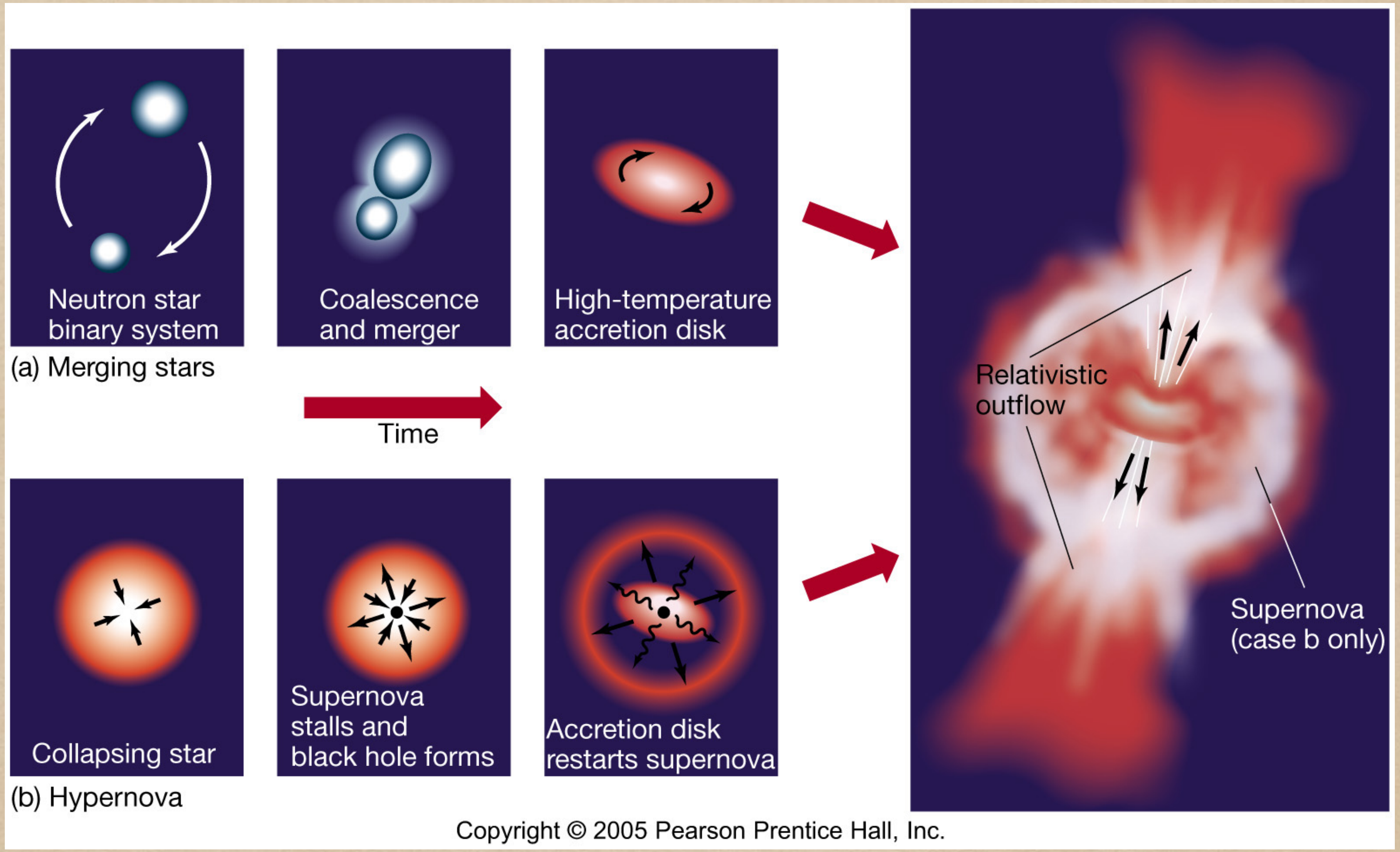
- M ~ 45 - 60 Msun.
- Neutrons contain even more fundamental particles called quarks.
  - Particles composed of quarks —> hadrons; includes protons, neutrons.
- SN type II and NS - neutrons are composed of quarks.
- Quark deconfinement
  - compressed, neighbouring neutrons share quarks —> quark state.
  - beam from magnetic poles quenched.
- quark state moves outward releasing energy (photons & neutrinos)
  - as approaches less dense surface of NS, neutrinos escape.
- P decrease in core - core collapse.
- exiting energy lifts off outer layer of neutron star within day to weeks.
- Quark nova - energizing SNR; create heavy & light elements.
- Quark star!

Animation of Quark Nova

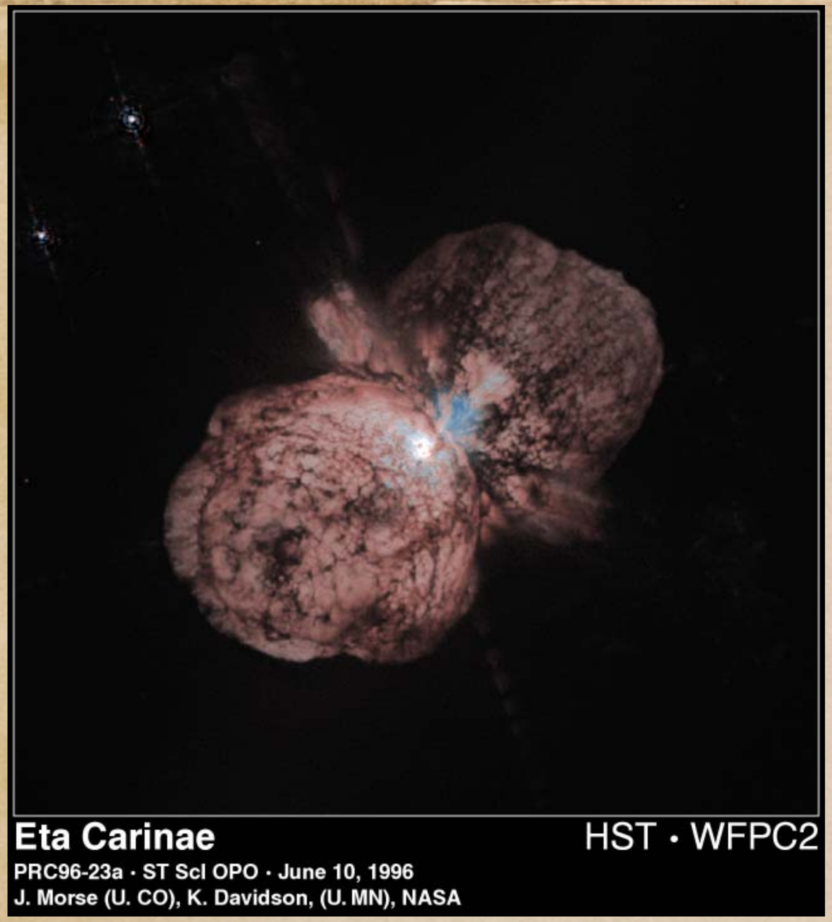
More massive stars! (M > 50 Msun) Gamma-ray bursts (GRBs)

- Bright flashes of gamma-rays coming from random locations in the sky for short period of time duration (< 100 s).
- Discovered in 1967 by US spy satellite.
- Most luminous explosions in the universe.
- Occurs at the rate of about 1 a day.
- They are at very large distances (z upto 8!) —> extremely luminous!
- Two types based on their duration:
  - short gamma-ray bursts: Bursts shorter than 2 s.
    - Binary mergers? (no evidence yet)
  - long gamma-ray bursts: Bursts longer than 2 s.
    - Super-Duper Supernovae!

Formation scenario

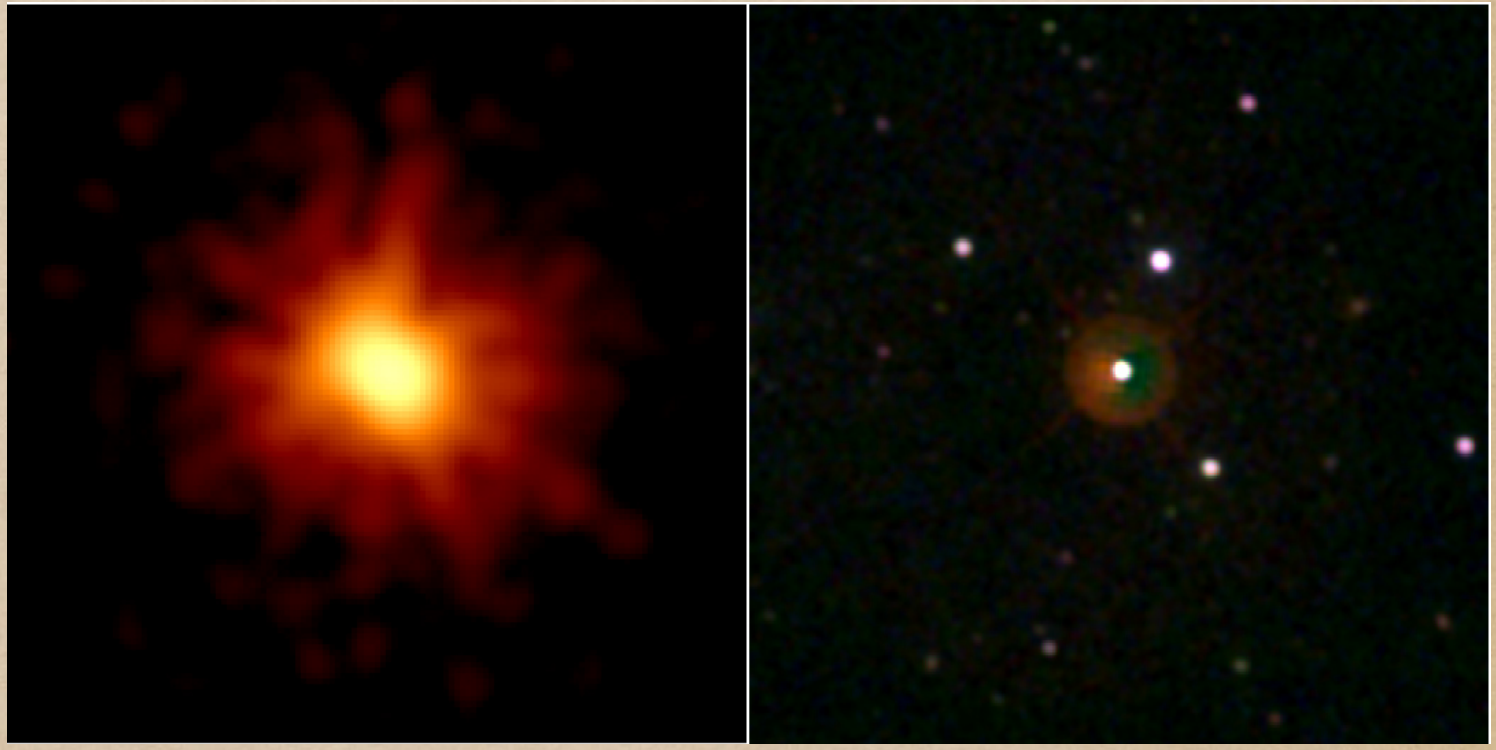


When a black hole forms from the collapsing core, the explosion sends a blast wave moving through the star with v ~ c. Gamma-rays are created when blast wave collides with stellar material inside the star and burst out from the star's surface just ahead of the blast wave.



Eta-Carinae system: Two stars in binary orbit
- a luminous blue variable ~ 150 Msun
- a hot supergiant ~ 30 Msun
- Expected to go supernova or Super-Duper nova due to it large mass and stage of life.

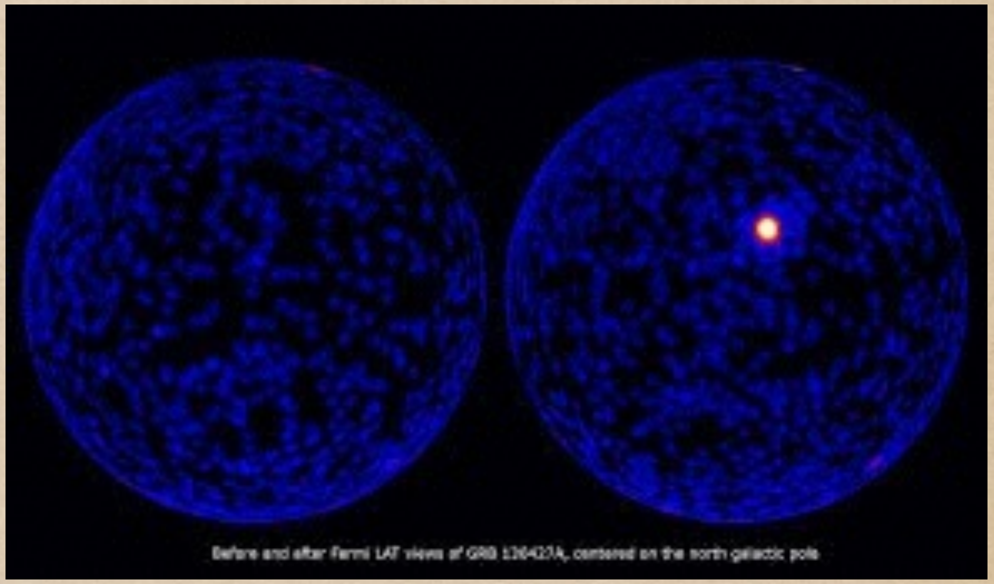
Swift satellite capturing a gamma-ray burst



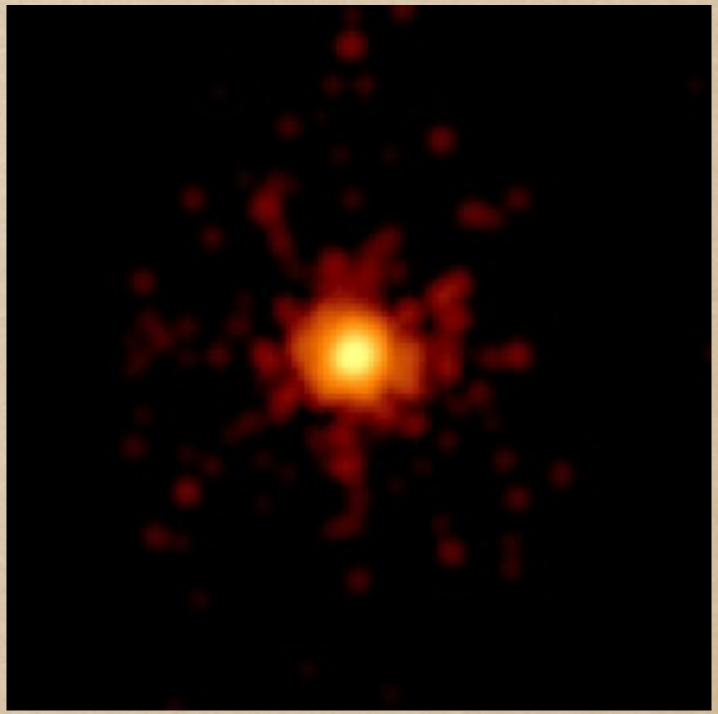
Gamma-rays **Optical**

Light curve shows GRB —> Super Duper Nova

New RECORD BREAKING GRB discovered!!
GRB 130427A



- Discovered on Apr 27, 2013, ~3.6 billion light years away.
- ~20 hrs long!
- Highest energy output ever recorded.
    - Energy of atleast 94 billion electron volts or ~ 35 billion times the energy of visible light!

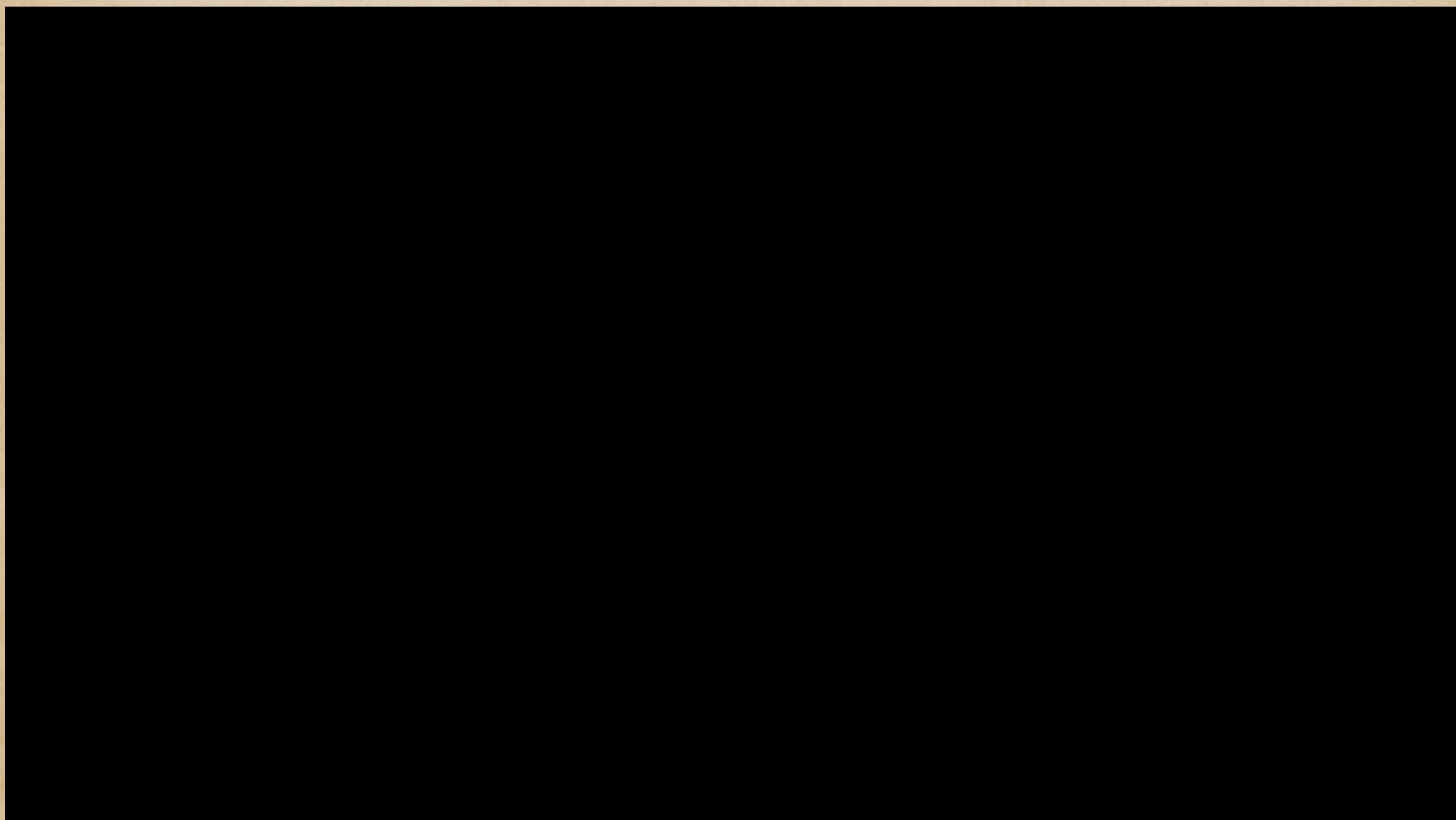


Swift-XRT image of the GRB

Credit: NASA/Swift/Stefan Immler.

http://www.universetoday.com/101944/bright-long-lasting-grb-sets-energy-output-record/

New RECORD BREAKING GRB discovered!!
GRB 130427A



Animation showing the burst from GRB 130427A

- Stars more massive: > 80-100 Msun —> Core collapses to Black Hole!!

Life cycle of stars - Summary