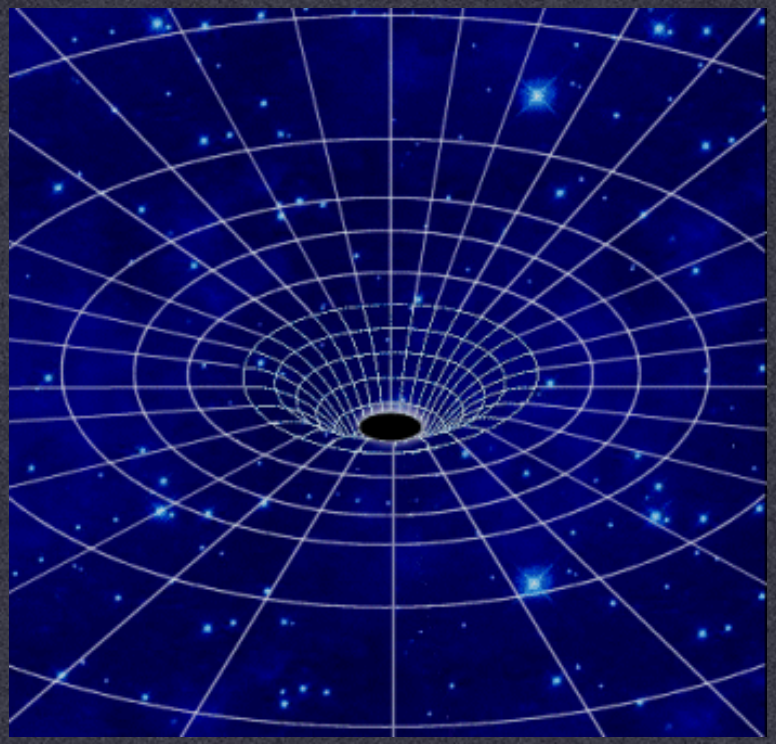
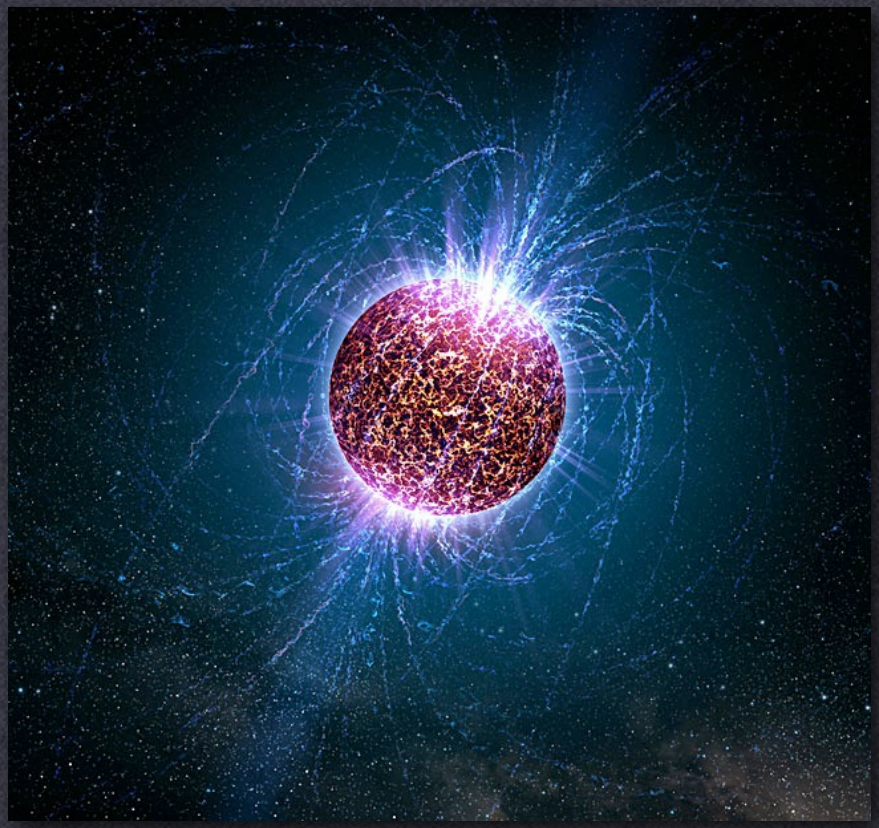
Stellar death:

White dwarfs, Neutron stars & Black Holes





Content Expectaions

E5.2x Stellar Evolution

Stars, including the Sun, transform matter into energy in nuclear reactions. When hydrogen nuclei fuse to form helium, a small amount of matter is converted to energy. These and other processes in stars have led to the formation of all the other chemical elements. There is a wide range of stellar objects of different sizes and temperatures. Stars have varying life histories based on these parameters.

E5.2e Explain how the Hertzsprung-Russell (H-R) diagram can be used to deduce other parameters (distance).

E5.2f Explain how you can infer the temperature, life span, and mass of a star from its color. Use the H-R diagram to explain the life cycles of stars.

E5.2g Explain how the balance between fusion and gravity controls the evolution of a star (equilibrium).

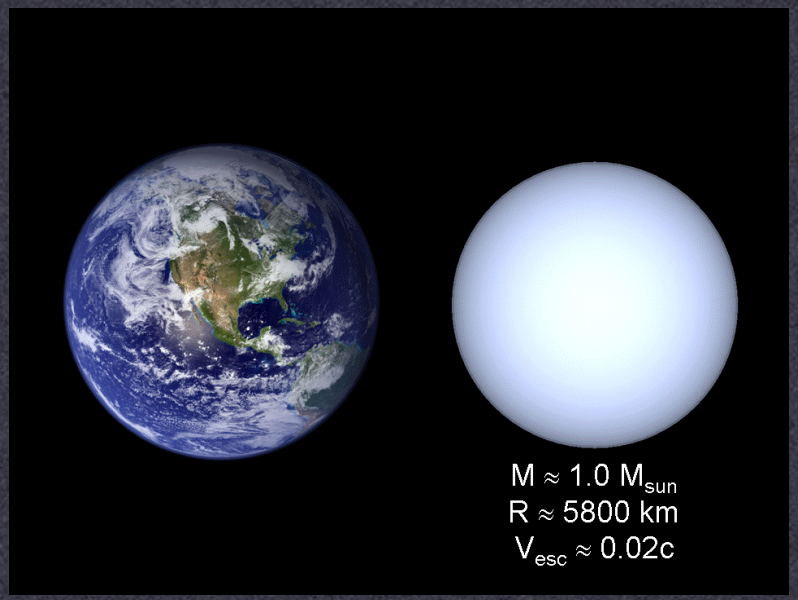
E5.2h Compare the evolution paths of low-, moderate-, and high-mass stars using the H-R diagram.

What happens when fusion stops?

- Stars are in balance (hydrostatic equilibrium) by radiation pushing outwards and gravity pulling in
- What will happen once fusion stops?
- The core of the star collapses spectacularly, leaving behind a dead star (compact object)
- What is left depends on the mass of the original star:
  - $<8\ M_\odot$: white dwarf
  - $8\ M_\odot < M < 20\ M_\odot$: neutron star
  - $> 20\ M_\odot$: black hole

Forming a white dwarf

- Powerful wind pushes ejects outer layers of star forming a **planetary nebula**, and exposing the small, dense core (white dwarf)
- The core is about the radius of Earth
- Very hot when formed, but no source of energy – will slowly fade away
- Prevented from collapsing by *degenerate electron gas* (stiff as a solid)

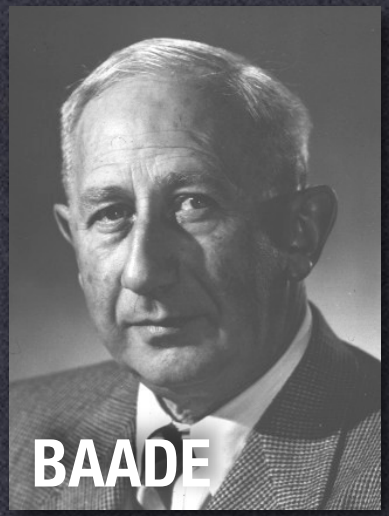


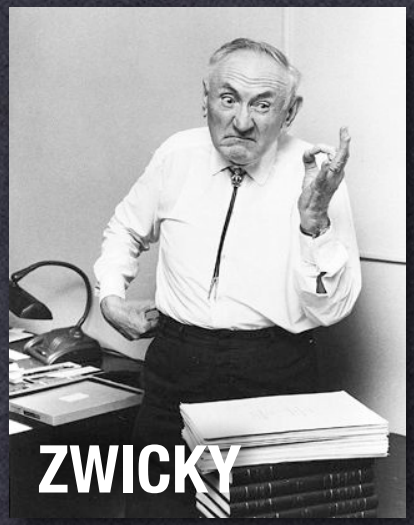
Planetary nebulae
(nothing to do with planets!)

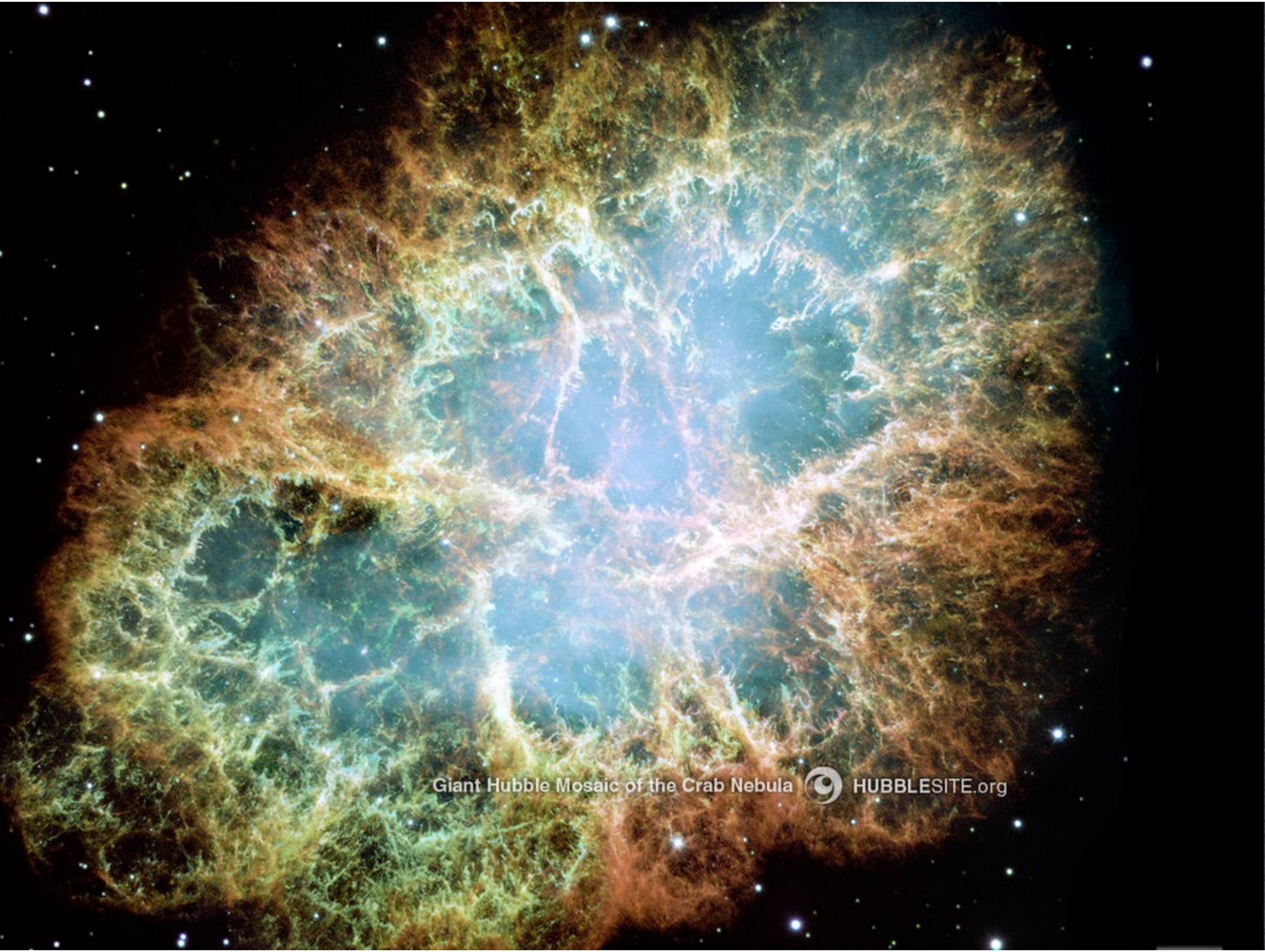
Planetary nebulae
(nothing to do with planets!)

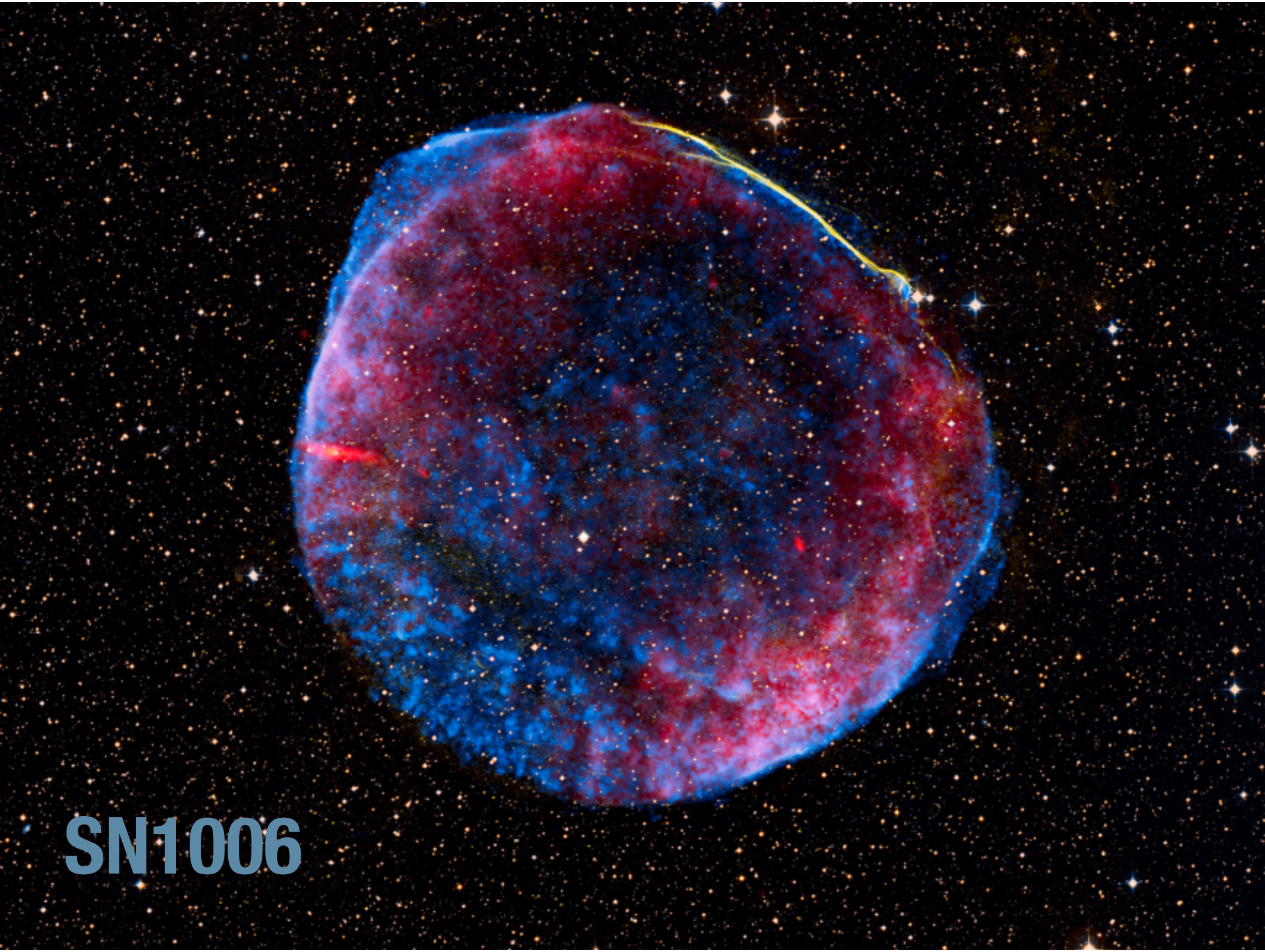
Death of massive stars

- When the core of a massive star collapses, it can overcome electron degeneracy
- Huge amount of energy released - big **supernova** explosion
- **Neutron star**: collapse halted by neutron degeneracy (1934: Baade & Zwicky)
- **Black Hole**: star so massive, collapse cannot be halted






Giant Hubble Mosaic of the Crab Nebula
HUBBLESITE.org


SN1006

1967: Pulsars discovered!

- Jocelyn Bell and her supervisor Antony Hewish studying radio signals from quasars
- Discovered recurrent signal every 1.337 seconds!
- Nicknamed LGM-1 now called PSR B1919+21

Observation of a Rapidly Pulsating Radio Source

by

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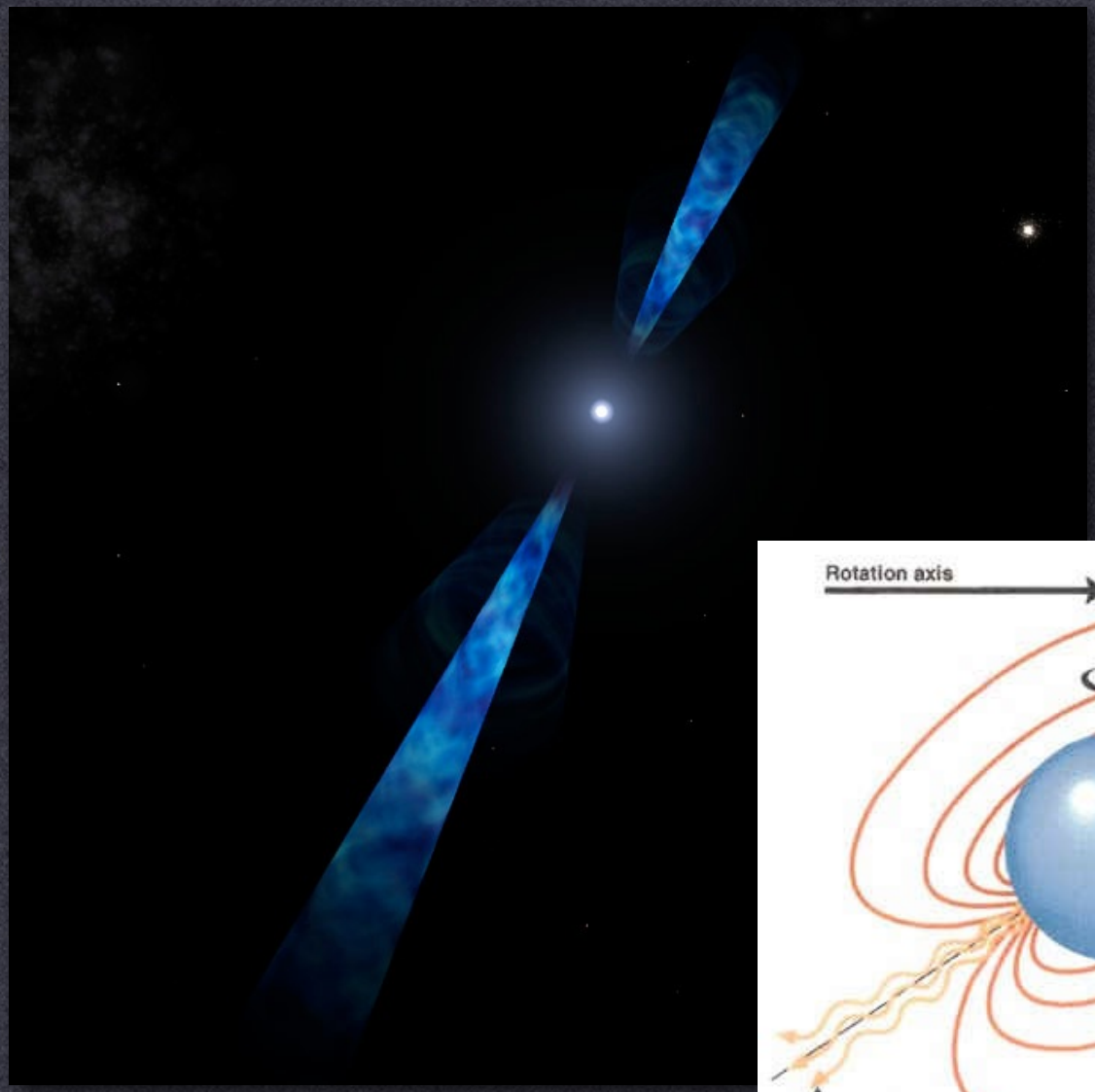
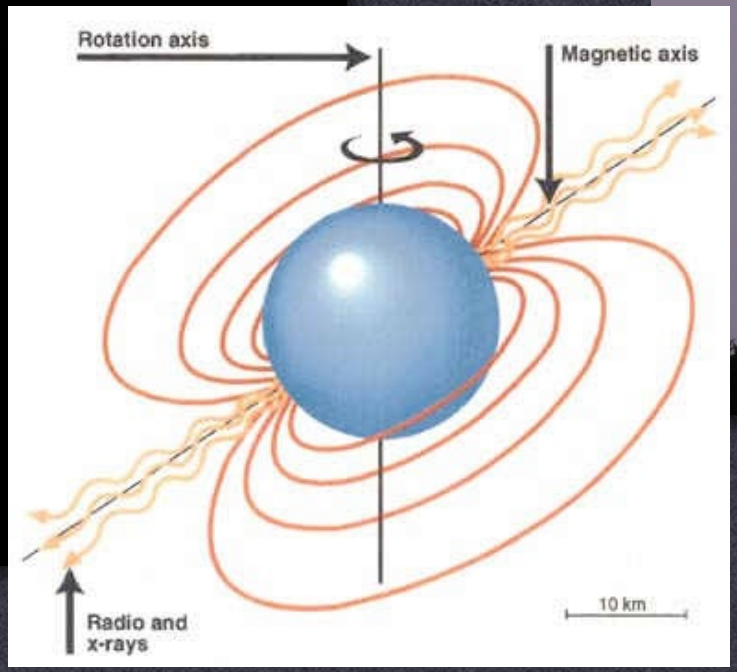
Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

NATURE, FEBRUARY 1968

1967: Pulsars discovered!

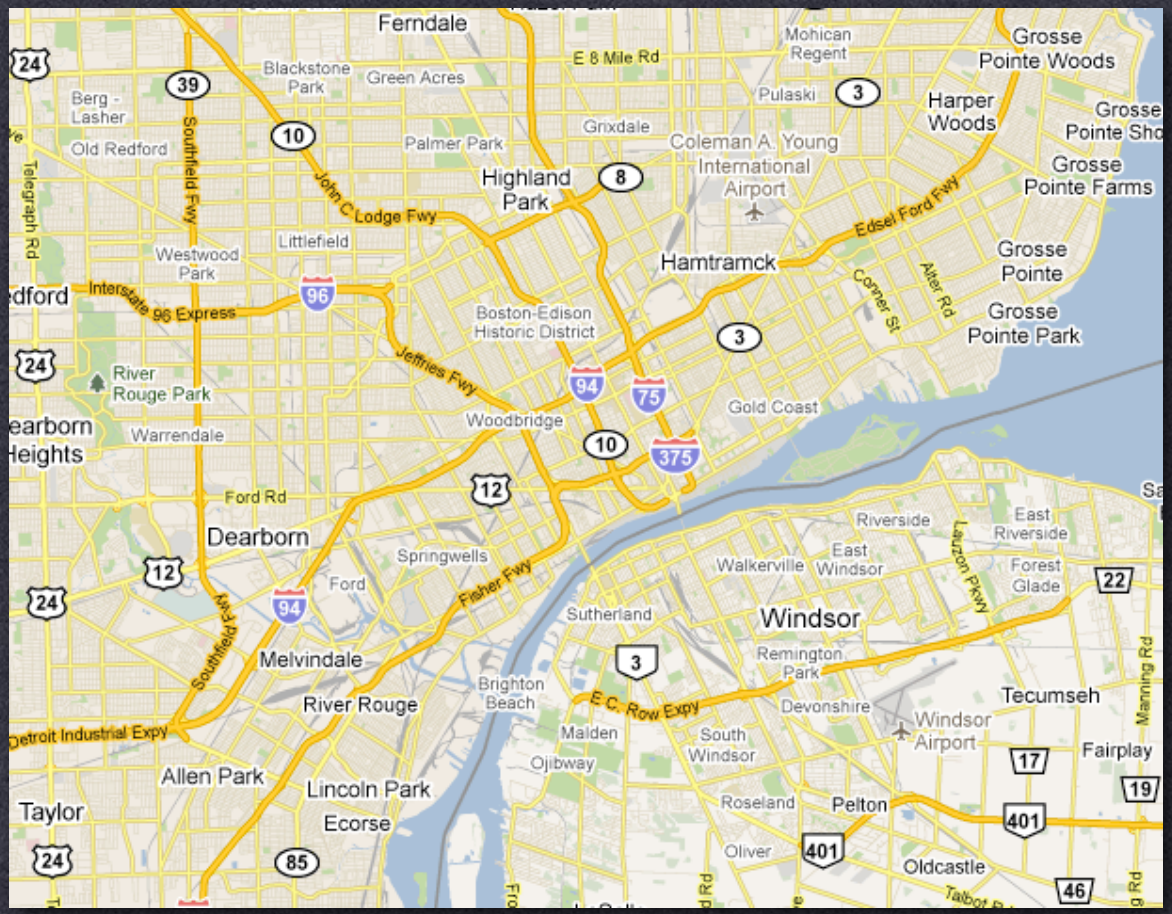


- Beams of radiation from spinning neutron star
- Like a lighthouse

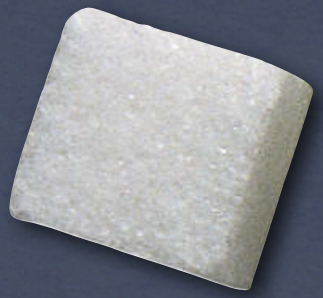


Neutron stars: key facts

- ***Mass:*** About 1.5 times the mass of the Sun
- ***Radius:*** 10 - 15 km



Neutron stars: key facts



HUMANITY in a SUGAR CUBE

ABOUT 10 TIMES MORE DENSE THAN ATOMIC NUCLEI

Neutron stars: key facts

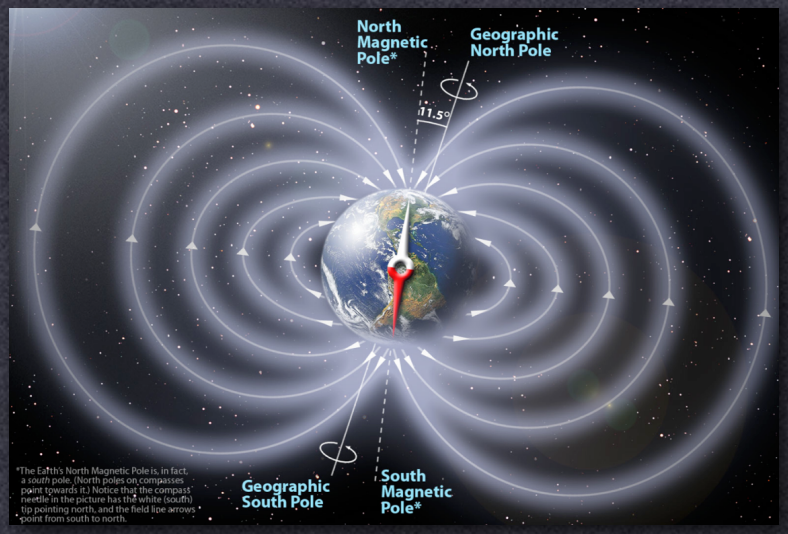
NEUTRON STARS CONTAIN:
DENSEST DIRECTLY OBSERVABLE
MATTER IN THE UNIVERSE

HUMANITY IN A SUGAR CUBE

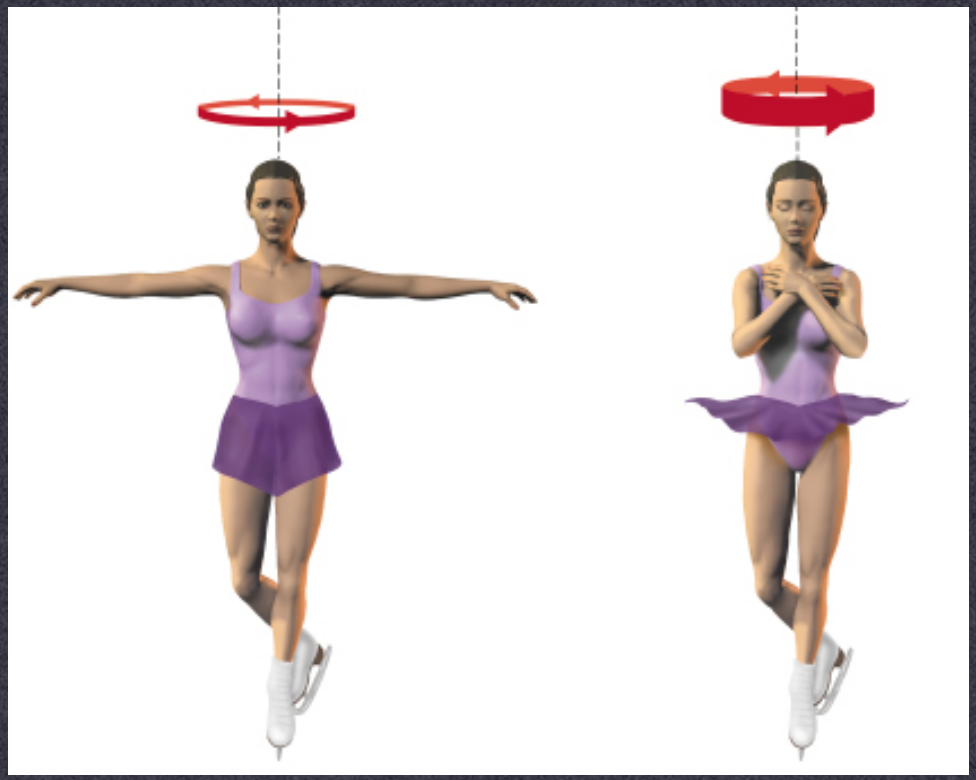
ABOUT 10 TIMES MORE
DENSE THAN ATOMIC NUCLEI

Neutron stars: extreme objects

- **Magnetic field:**
  - about trillion times Earth's!
- **Surface gravity:**
  - > 100 billion times Earth's
- **Rotation:**
  - spin up to 700 times a second (60 million times faster than Earth)

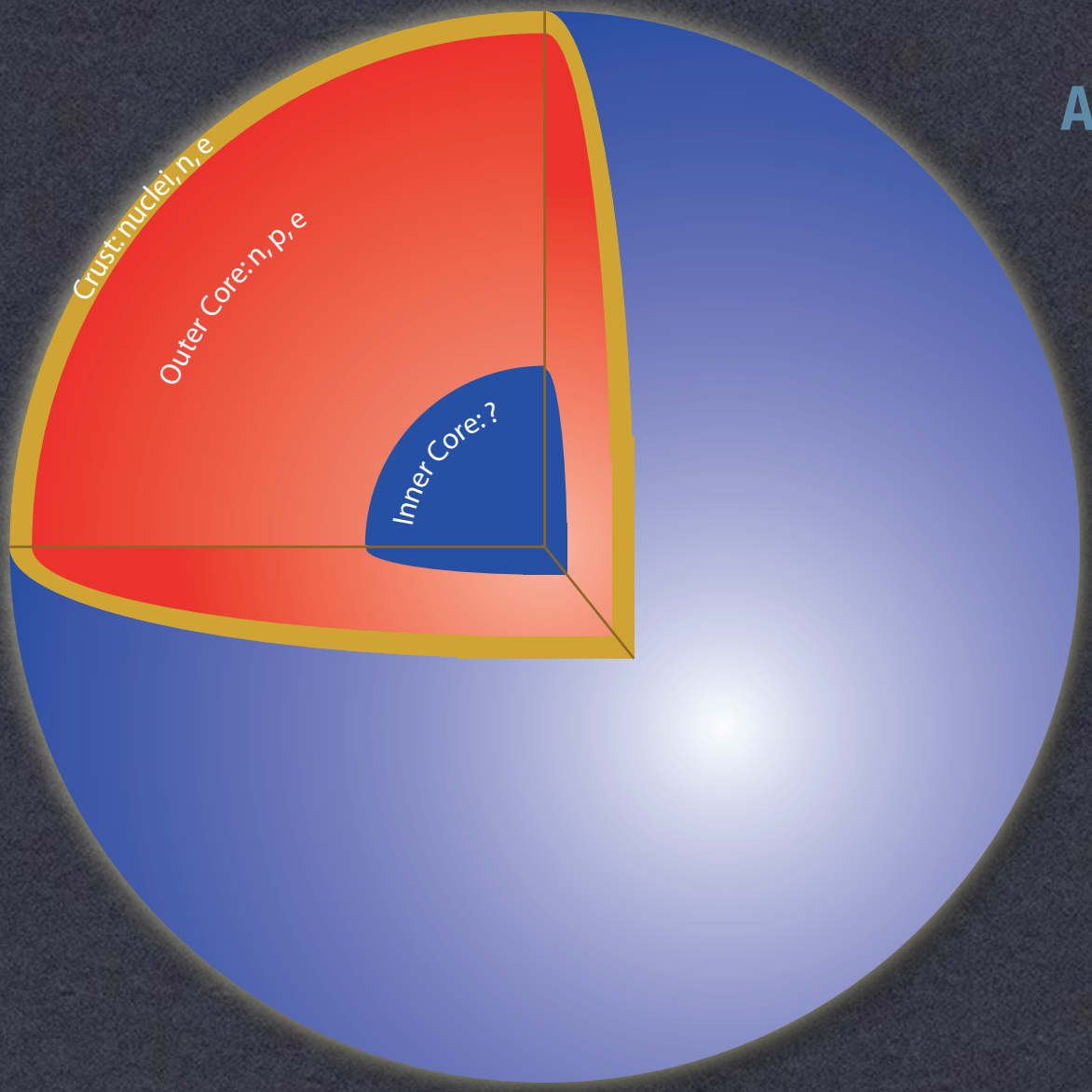


Why do neutron stars rotate so quickly?



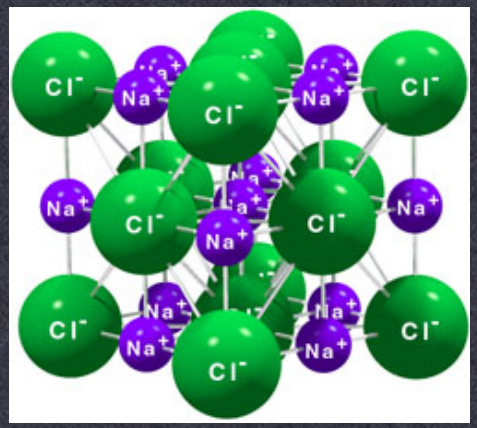
- Conservation of angular momentum means that smaller objects will rotate more quickly

What are neutron stars made of?



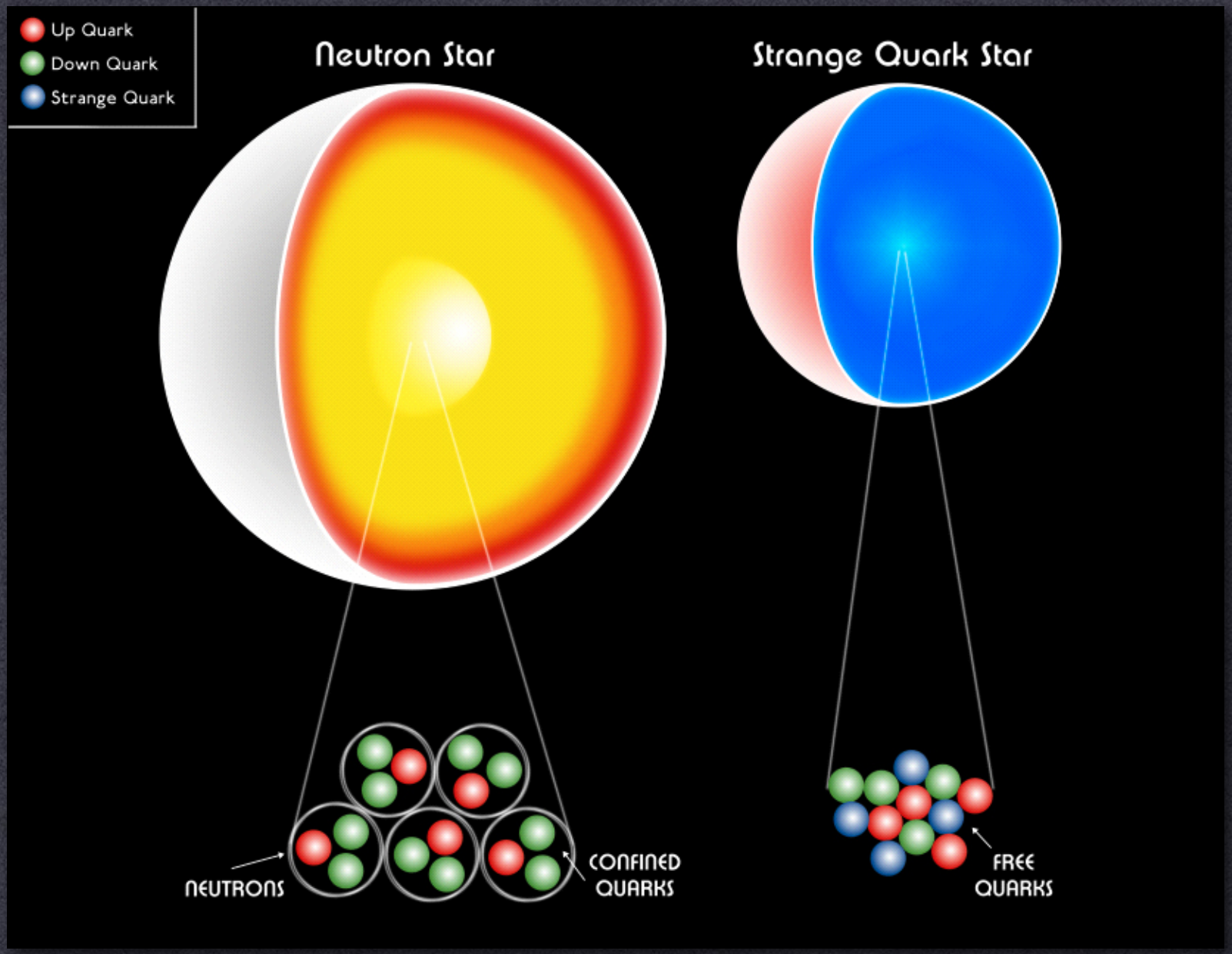
ATMOSPHERE: HYDROGEN

CRUST: SOLID LATTICE (OF IRON?)



CORE: MOSTLY NEUTRONS, OR SOMETHING MORE EXOTIC?

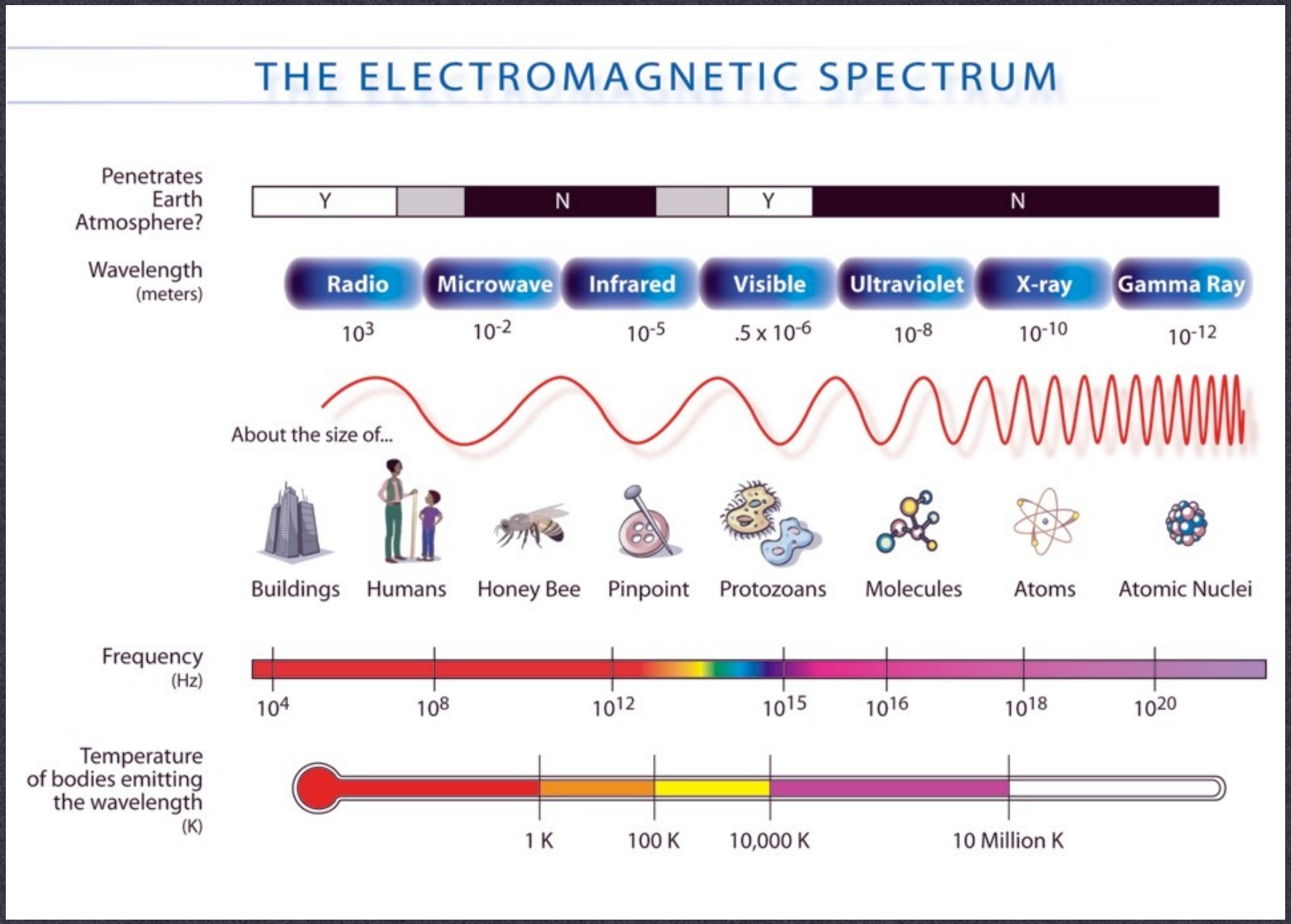
NEED TO MEASURE NEUTRON STAR MASSES AND RADII



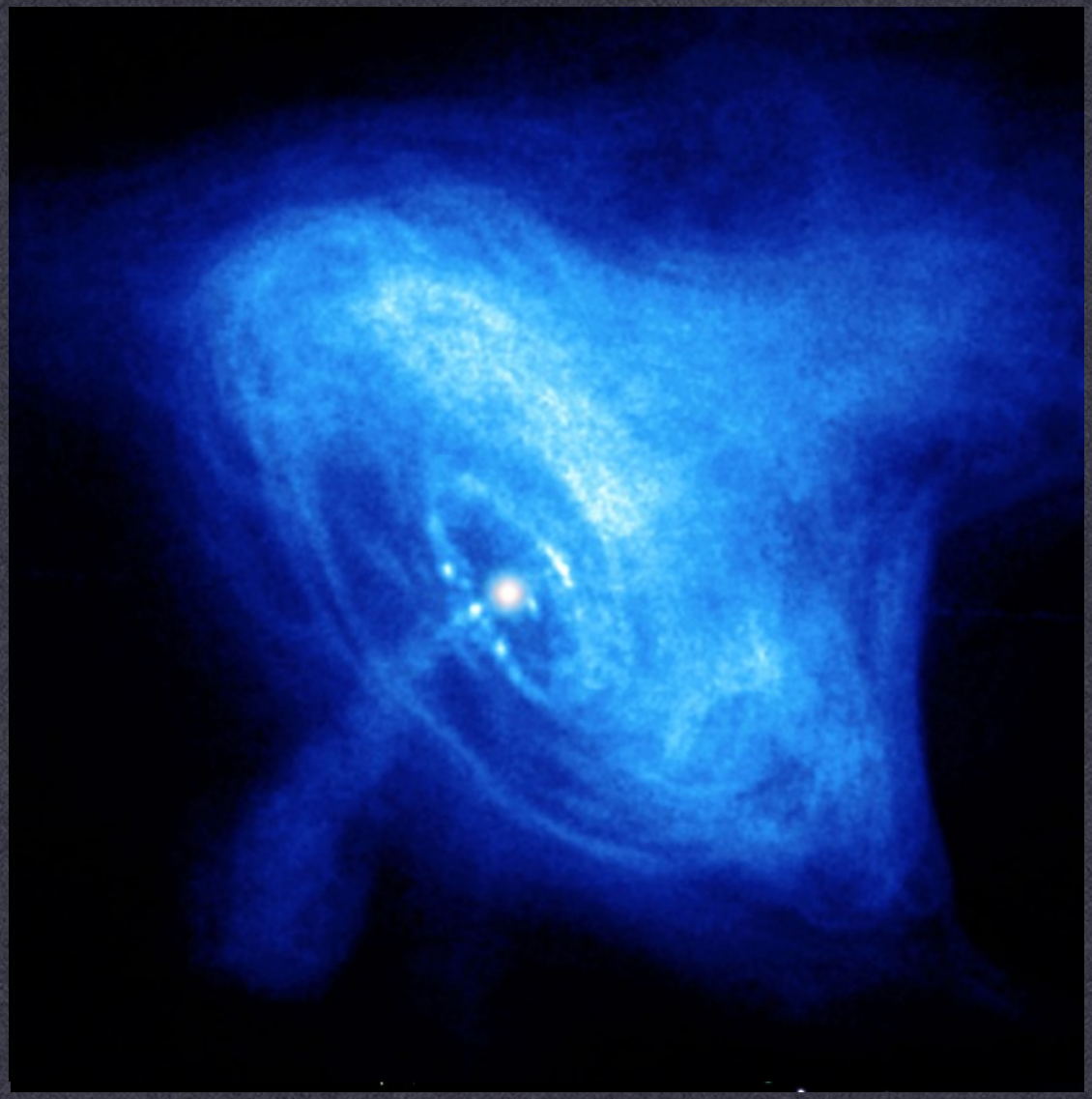
Measuring a neutron star radius is.....

like measuring the width of a DNA helix on the Moon

How/where do we see neutron stars?



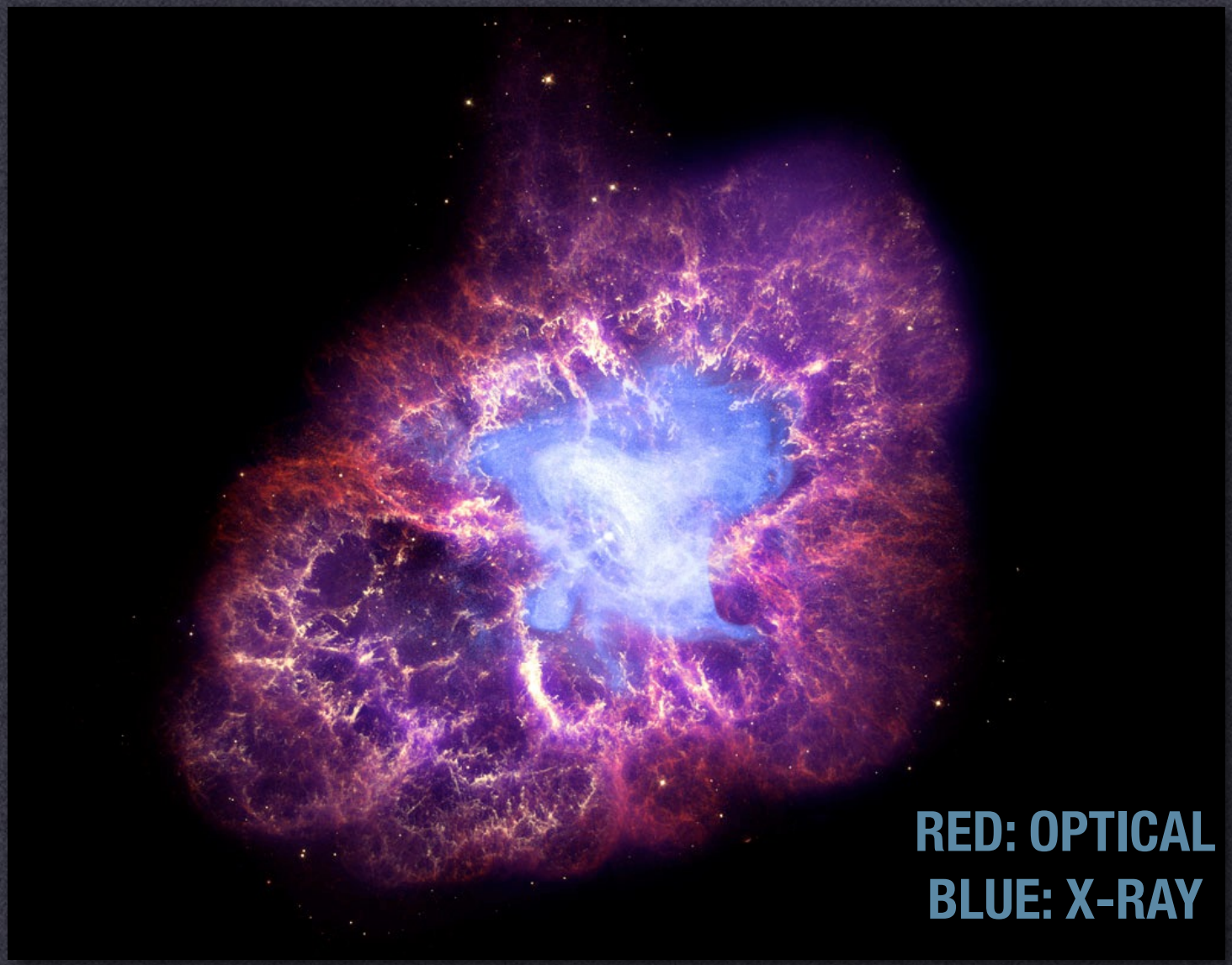
Where do we see neutron stars?



Crab nebula: 1054 AD

SUPERNOVA REMNANTS

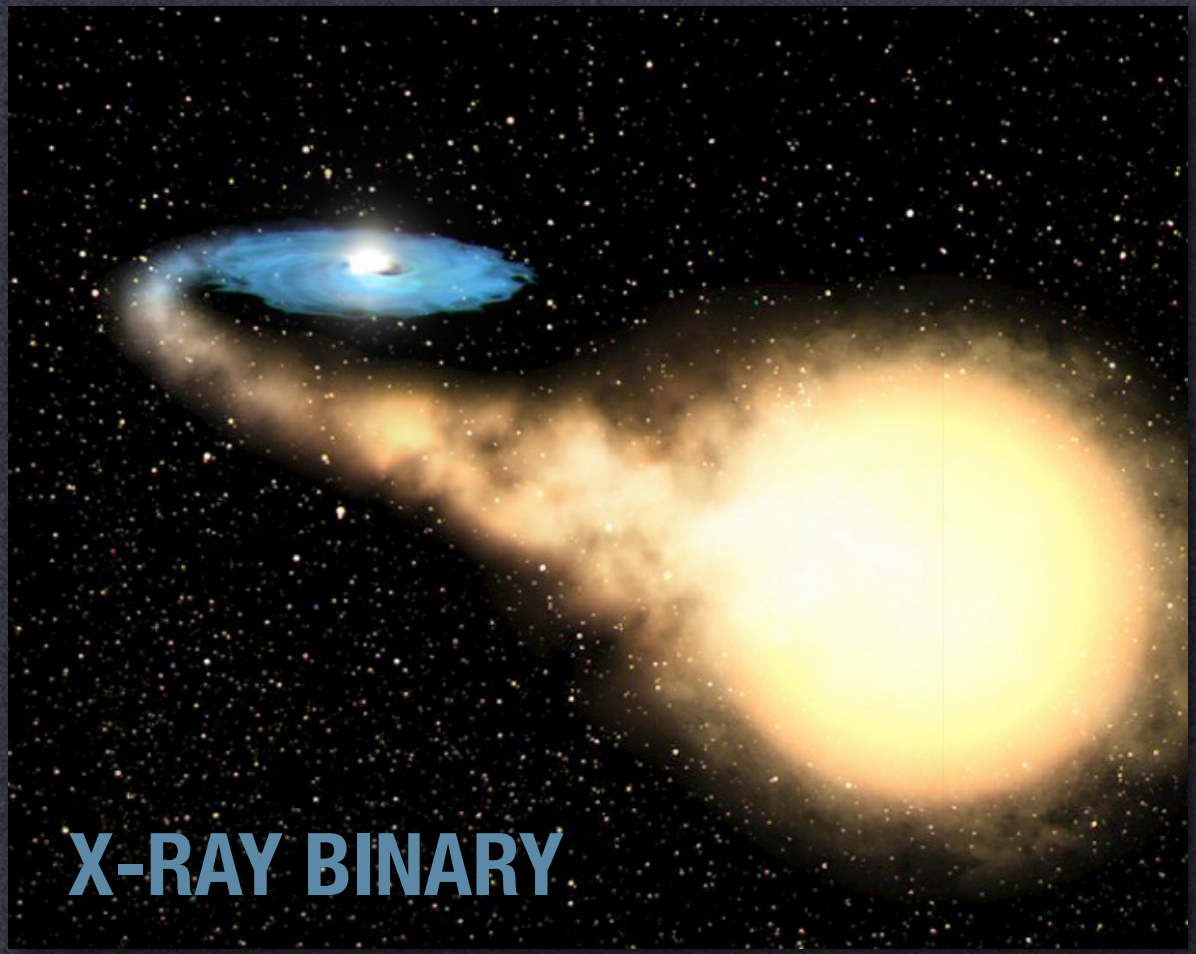
- Youngest neutron stars are at the centre of supernova remnants
- But, to see neutron star need to look in X-rays!


RED: OPTICAL
BLUE: X-RAY

Where do we see neutron stars?

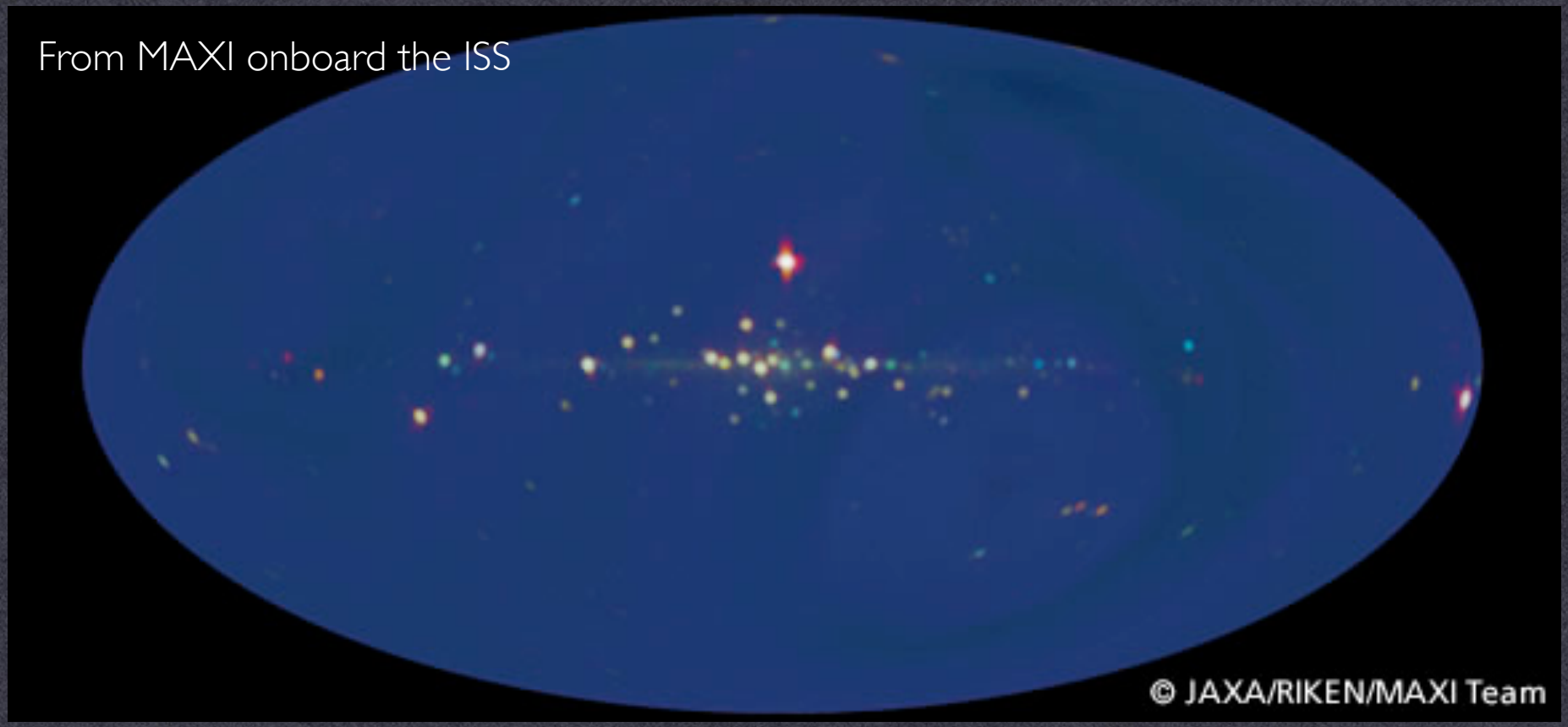
NEUTRON STAR & SUN-LIKE STAR ORBITING EACH OTHER

- Gravitational field of neutron star pulls gas towards it
- Form a very hot disc of in-spiralling gas
- They are some of the brightest X-ray sources in the sky!



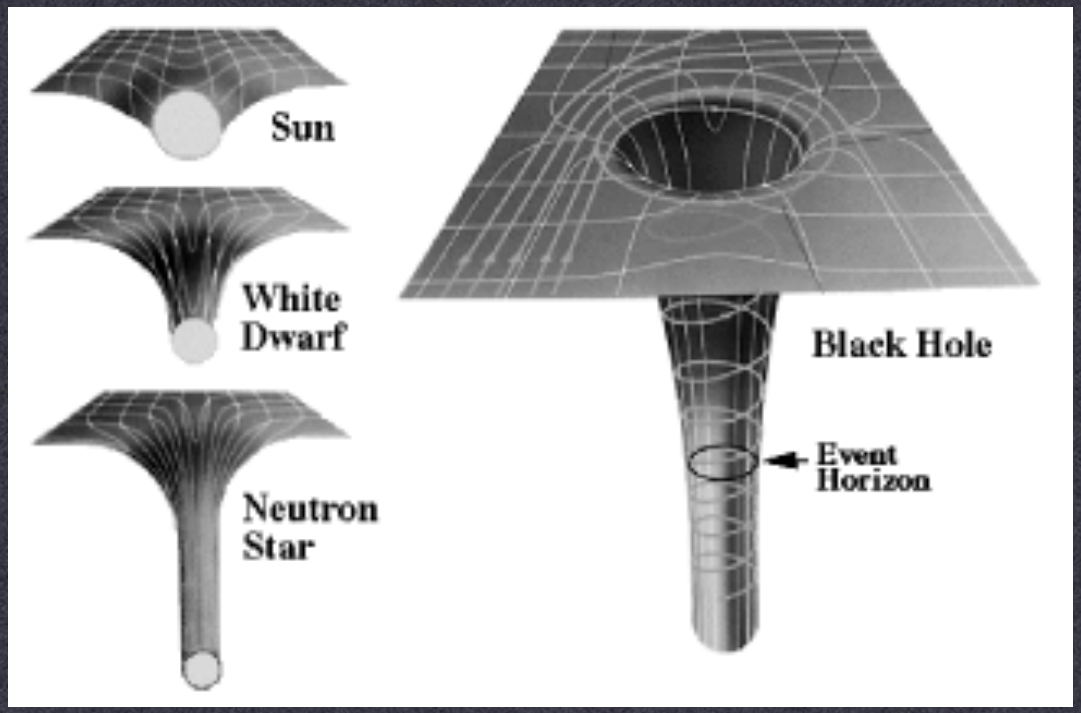
All-sky X-ray image

The brightest X-ray sources in the sky come from accretion onto black holes and neutron stars



Black Holes

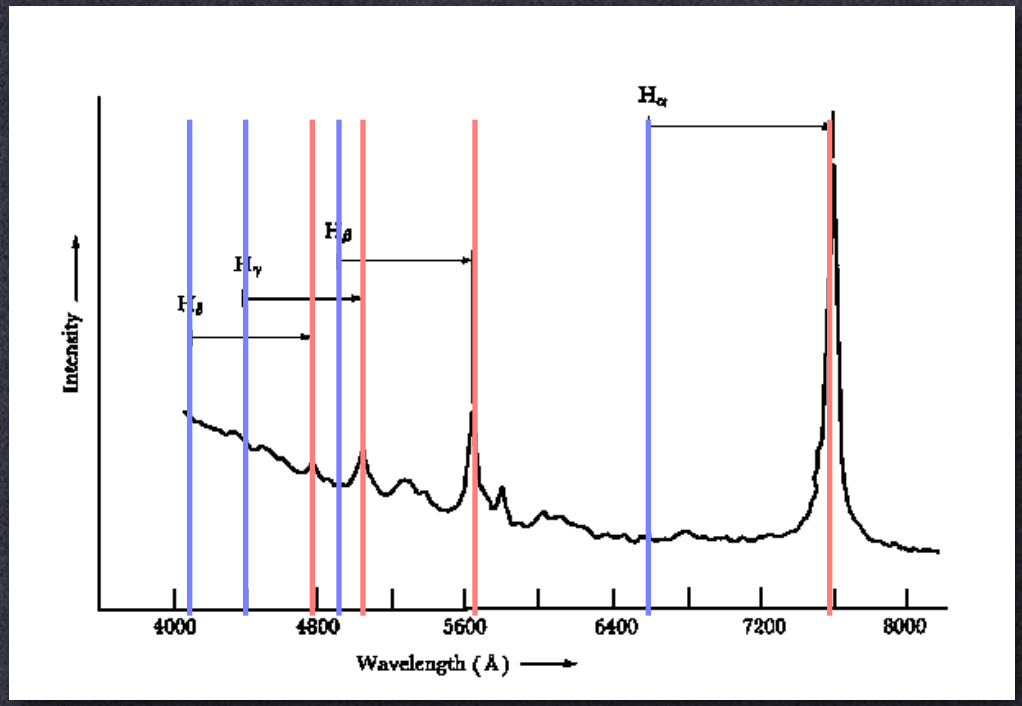
- First suggested by John Michell in 1783! *A object whose gravity is strong enough that even light cannot escape*
- Einstein's General Relativity (1916): mass bends space and time
- Karl Schwarzschild (1916): discovered a 'singularity' - what we know call black holes
- John Wheeler coined the phrase 'black hole' in 1960s
- *How might we see indirect evidence of black holes?*



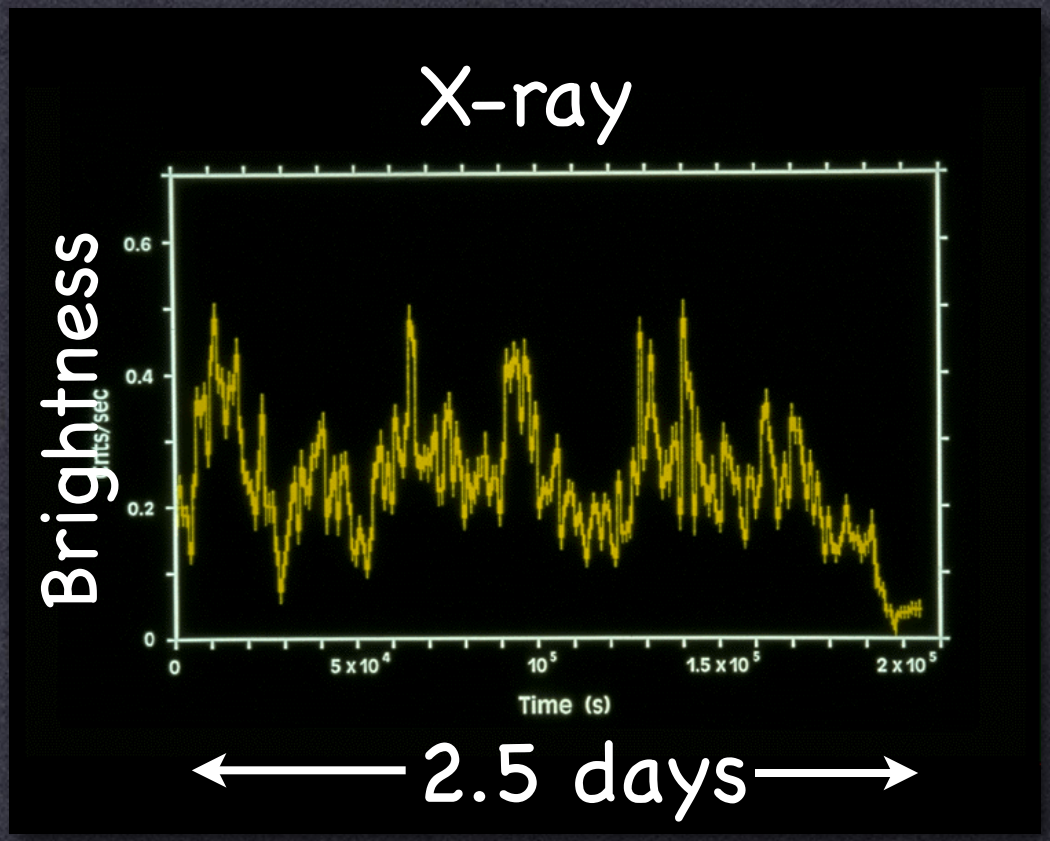
Quasars

Quasi-stellar radio sources

- Bright stellar-like objects that were also bright radio sources
- But, weird *non-stellar* spectra
- Realized they were redshifted so must be a huge distances (U is expanding, bigger the redshift, further the distance)



Very bright and very small

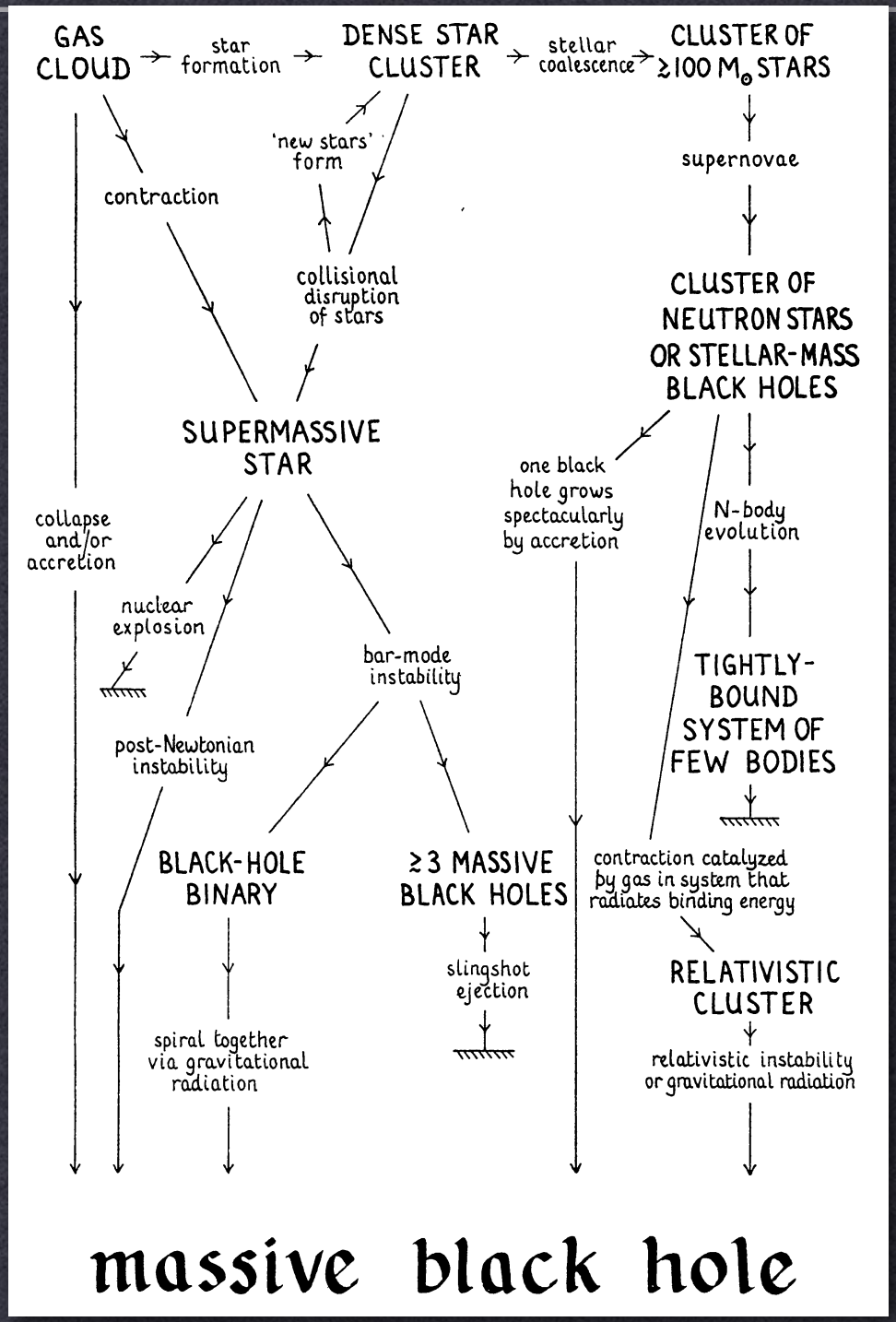


- Quasars are extremely luminous (> 100 billion Suns)
- Highly variable - size of light emitting region must be a few light-minutes across!
- What is the power source?!

Powered by what?

- Nuclear fusion?
  - No
- Dense star cluster?
  - No
- Accretion onto a massive black hole?

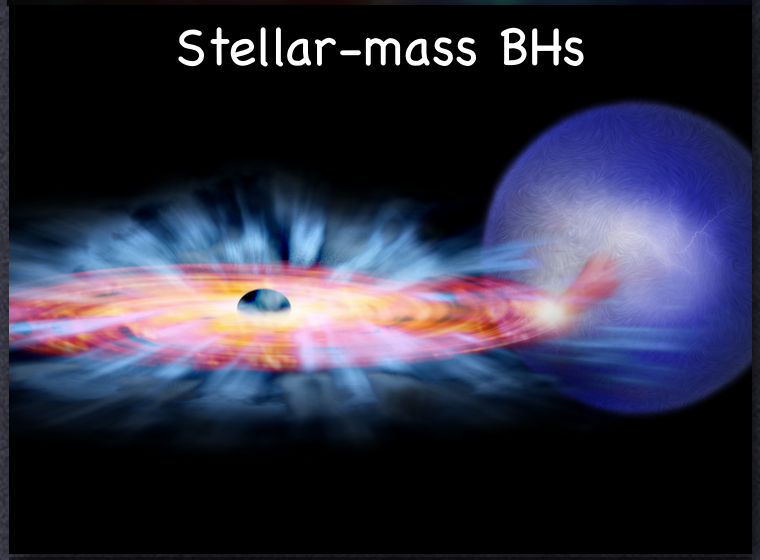
✓ Yes!



Martin Rees (1984)

Accretion

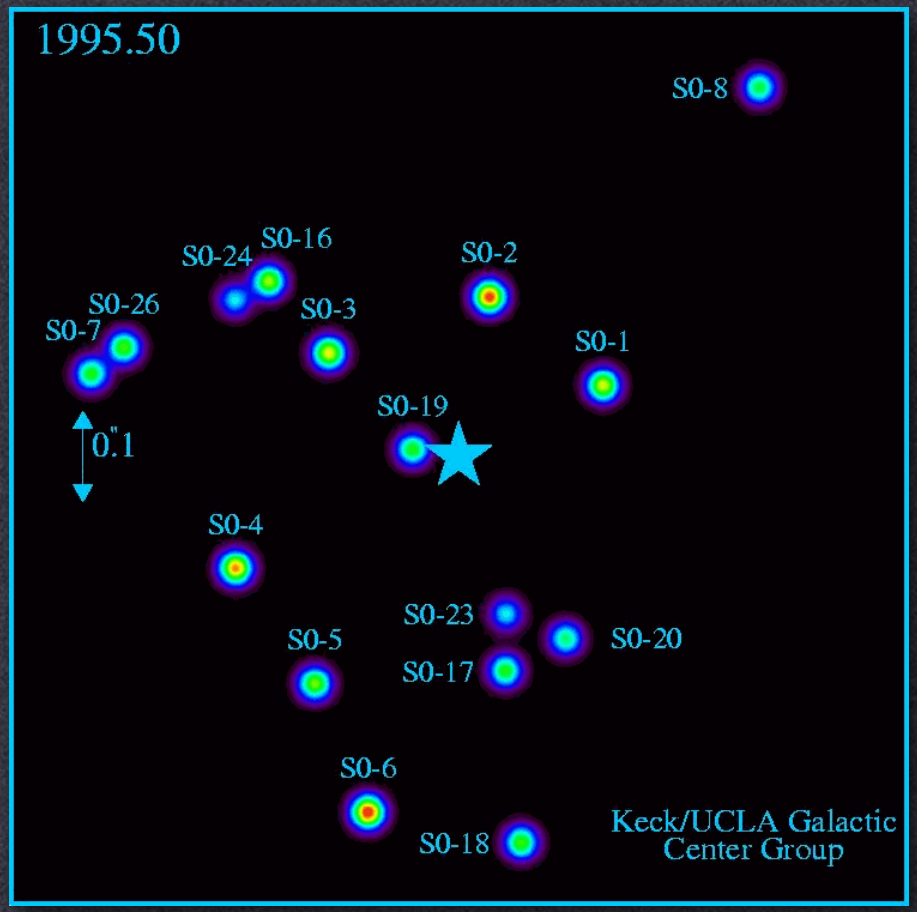
- Accretion is seen on many scales in the Universe
- *Infall of gas releases gravitational potential energy as radiation*
- Angular momentum lost through friction in a disk
- As mass accretion rate varies, brightness varies
- 10 times more efficient than nuclear fusion!



Credit: CXC/NASA

Black holes at the center of every galaxy?

- Look at the stars at the center of our own Galaxy (Milky Way)
- Orbits include a black hole with mass of 4 million Suns!



Stars at the center of the Milky Way

Different types of black holes

- Stellar-mass black holes: formed in supernovae
- Supermassive black holes: at the centers of galaxies

Key Questions:

- How do black holes grow?
- How do supermassive black holes form?
- How do they affect their environment?

Indirect evidence for black holes

- So, why we can't see them directly we know they exist
  - we can see evidence of them 'feeding'
  - we can see stars orbiting around an 'empty' place at the center of our own Galaxy