Week 13 Thursday

Today's Agenda
- Project Grading Rubric
- White Dwarfs
- Neutron Stars
- Black Holes
- Group Problem

Announcements / Reminders
- Read Chapter 20 (19 would be good too, but not required
- HW 9 due Friday 1min before midnight

- HEAP talk at 4pm on Thursday
  - Dark Sector Visible Signals in Neutron Star Mergers
- Colloquium at 2pm on Friday
  - Cosmic Rays at Heliospheric Extremes: Recent Measurements by Voyager and Parker Solar Probe

Project Grading Rubric

- Accuracy (50 pts): The scientific accuracy of the information you convey. The goal is to "communicate science," and it's important that the information presented is correct.

- Clarity (20 pts): How clearly the scientific information is conveyed. Again, the goal is to "communicate science," which means communicating effectively.

- Creativity (10 pts): The artistic aspect. Is the information conveyed in a novel or unique way? Is the information presented in an aesthetically pleasing way?

- Presentation (20 pts): The in-class presentation of the project during the last week of class. The project does not have to be 100% complete at this time, but it should be near completion, in a presentable state. The rubric for grading the presentation is:

  ○ Prepared (5 pts): Thought went into the presentation; it's not ad-libbed.
  ○ Concept clear (5 pts): The concept is obvious from the presentation.
  ○ Approach clear (5 pts): The approach of explaining the concept is obvious.
  ○ Significant progress on project (5 pts): Is the project >~90% complete?

Degeneracy Pressure

As stellar evolution proceeds, cores are supported by "degeneracy pressure" when there is no fusion to provide the necessary pressure to support the core against gravitational collapse.
—> acts as a "pressure floor"

Source of this pressure come from the rules of QM — Pauli exclusion & uncertainty principles

$$\Delta x \Delta p \geq \hbar$$

Material getting maximally compressed, so electron momentum/velocity driven by that compression, NOT the temperature of the material!

$$P_{\text{th}} = n_e kT \sim n_e m_e v_{\text{th}}^2 \qquad \text{b/c} \qquad v_{\text{th}} \approx \sqrt{\frac{kT}{m_e}}$$

$$v_{\text{th}} \approx \frac{\Delta p}{m_e} \sim \frac{\hbar n_e^{1/3}}{m_e} \qquad \text{b/c} \qquad \Delta x \sim V^{1/3} \sim n_e^{-1/3}$$

$$\boxed{P_{\text{degen}} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e}}$$

White Dwarfs

Leftover C core of a low mass ($M \sim 0.7 \ M_\odot$) star

$$P_{\text{degen}} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e} \longleftarrow \text{Set these equal} \longrightarrow P_{\text{c}} \sim \frac{GM^2}{R^4}$$

$$n_e^{5/3} = \left(\frac{M}{m_p R^3} \right)^{5/3}$$

Solve for R

More massive WDs are smaller!

Why?

$$R \sim \frac{\hbar^2}{G m_e m_p^2} \left(\frac{M}{m_p} \right)^{-1/3} \approx 0.01 R_\odot \left(\frac{M}{0.7 M_\odot} \right)^{-1/3}$$

Also, because they have *M*~M_{sun} but are 100x smaller, their surface gravity is much stronger, producing strongly pressure-broadened absorption lines
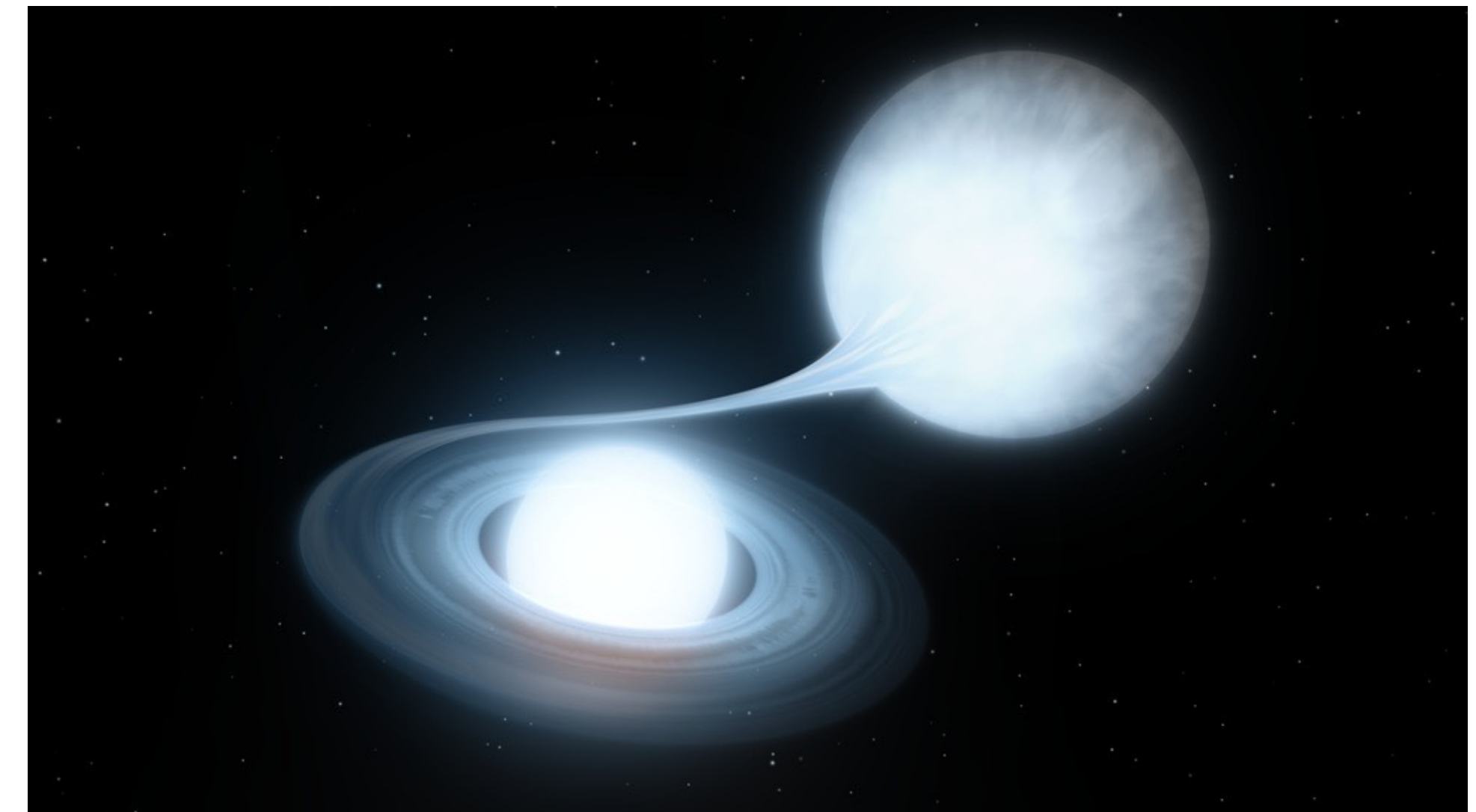
Can a White Dwarf have any mass?

$$P_{\text{degen}} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e}$$

As a WD becomes more massive, the pressure has to increase — what will cause the pressure to max out?

$$\Delta v \sim c$$

$$M_{\text{Ch}} \sim \left(\frac{\hbar^3 c^3}{G^3 m_p^4} \right)^{1/2} \sim 2 M_\odot$$

Called the Chandrasekhar mass
Modern calculations give 1.4 M$_{\text{sun}}$

Initial mass of star	WD type
$M < 0.5 M_\odot$	He
$0.5 M_\odot < M < 5 M_\odot$	C/O
$5 M_\odot < M < 7 M_\odot$	Ne/Mg

Neutron Stars are supported by neutron degeneracy pressure

More massive than the Sun
R ~ 10 km

Neutron Star

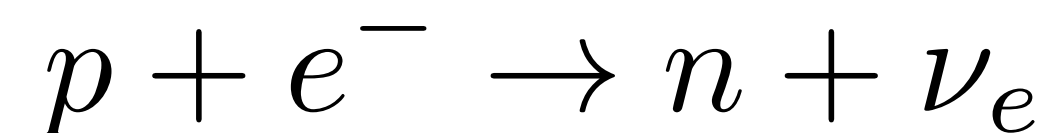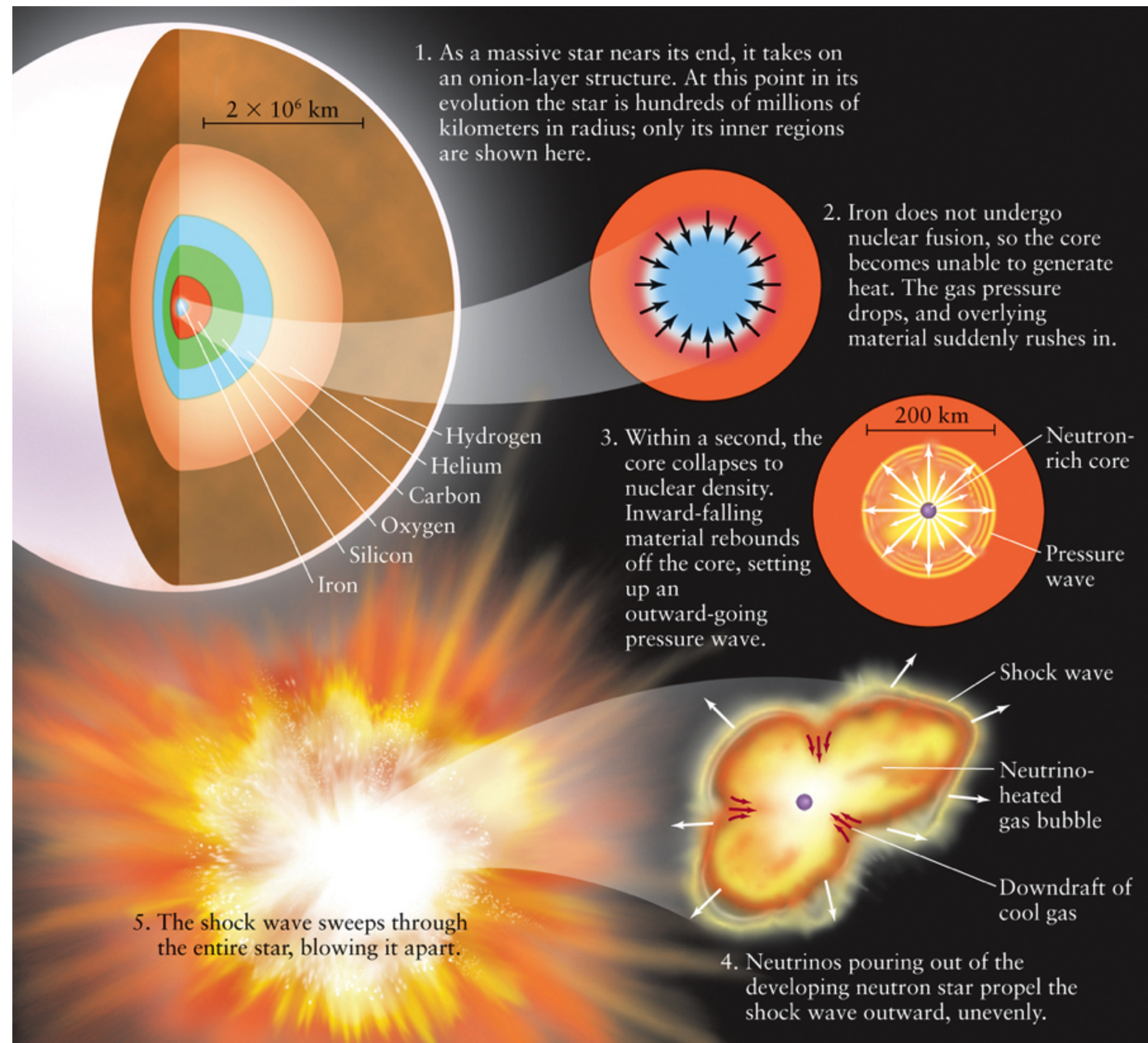Vancouver

www.kindaroomy.com

Supernovae!

Electron degeneracy pressure fails

Electrons absorbed into protons in nuclei creating neutrons

$$p + e^- \rightarrow n + \nu_e$$

Outer layers bounce off of forming NS (or pressure wave), causing star to explode

1. As a massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

2×10^6 km

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

- Hydrogen
- Helium
- Carbon
- Oxygen
- Silicon
- Iron

200 km — Neutron-rich core

3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.

Pressure wave

Shock wave

Neutrino-heated gas bubble

5. The shock wave sweeps through the entire star, blowing it apart.

Downdraft of cool gas

4. Neutrinos pouring out of the developing neutron star propel the shock wave outward, unevenly.
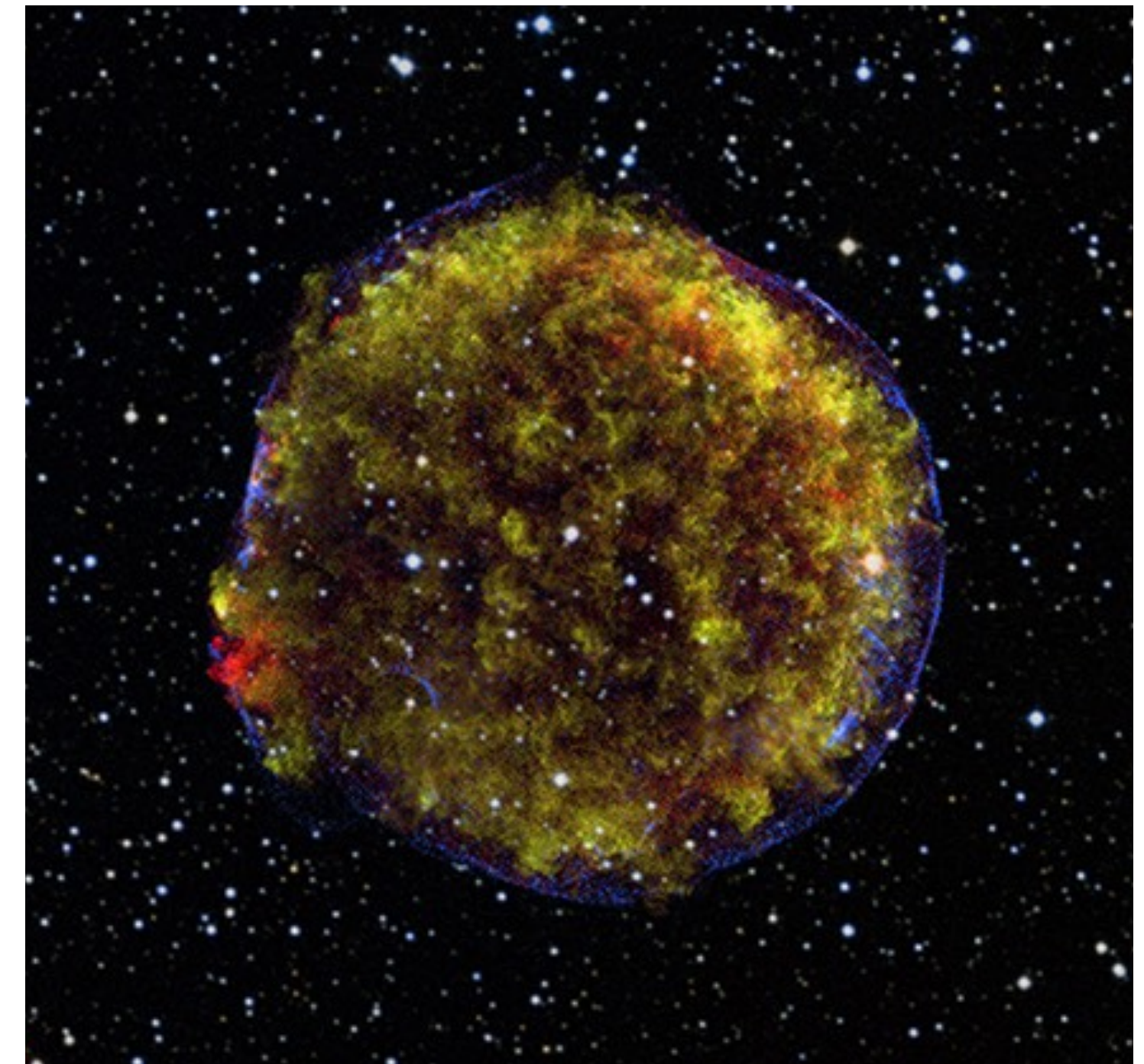
Historical SNe are now Supernova Remnants (SNRs)
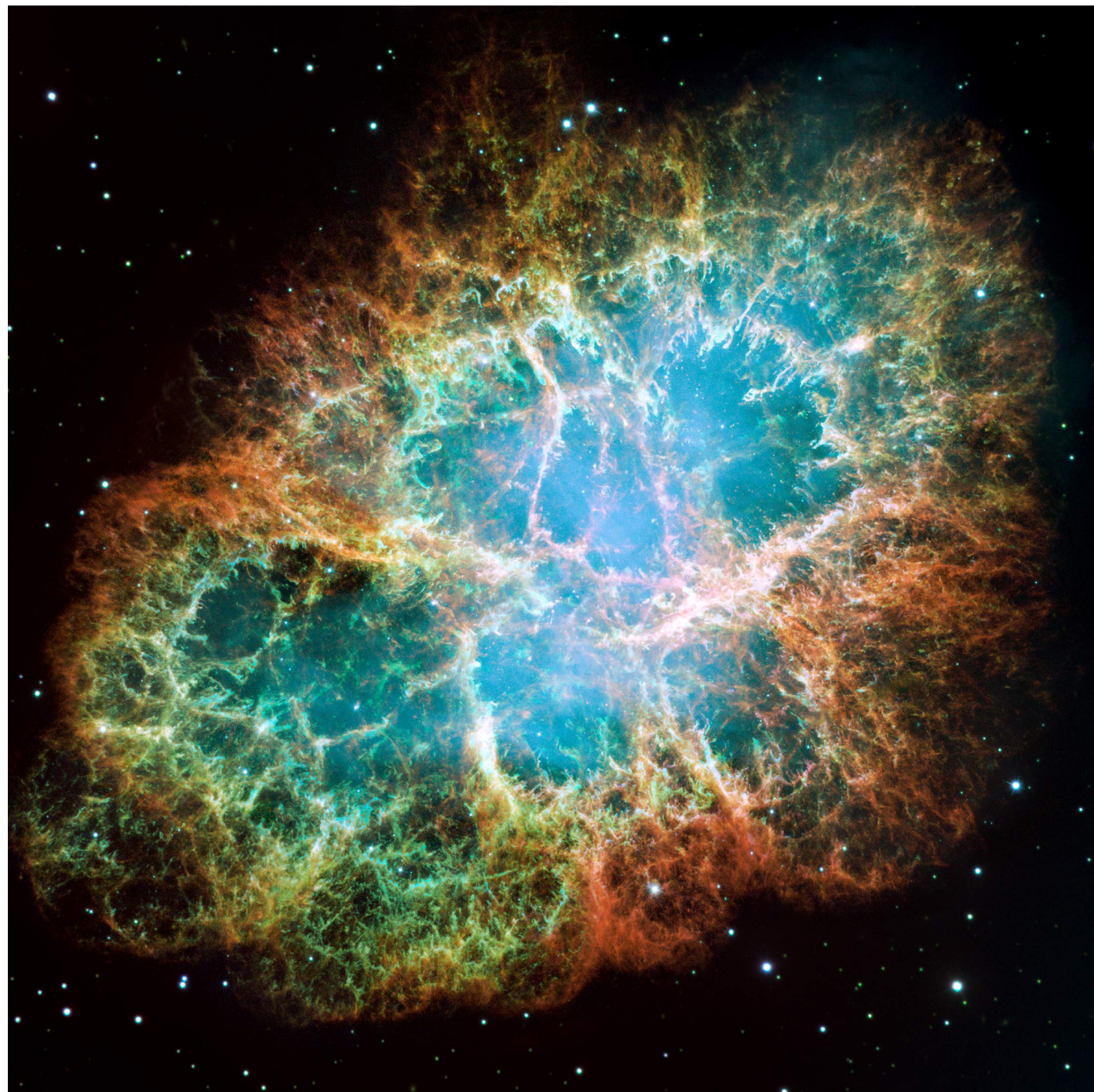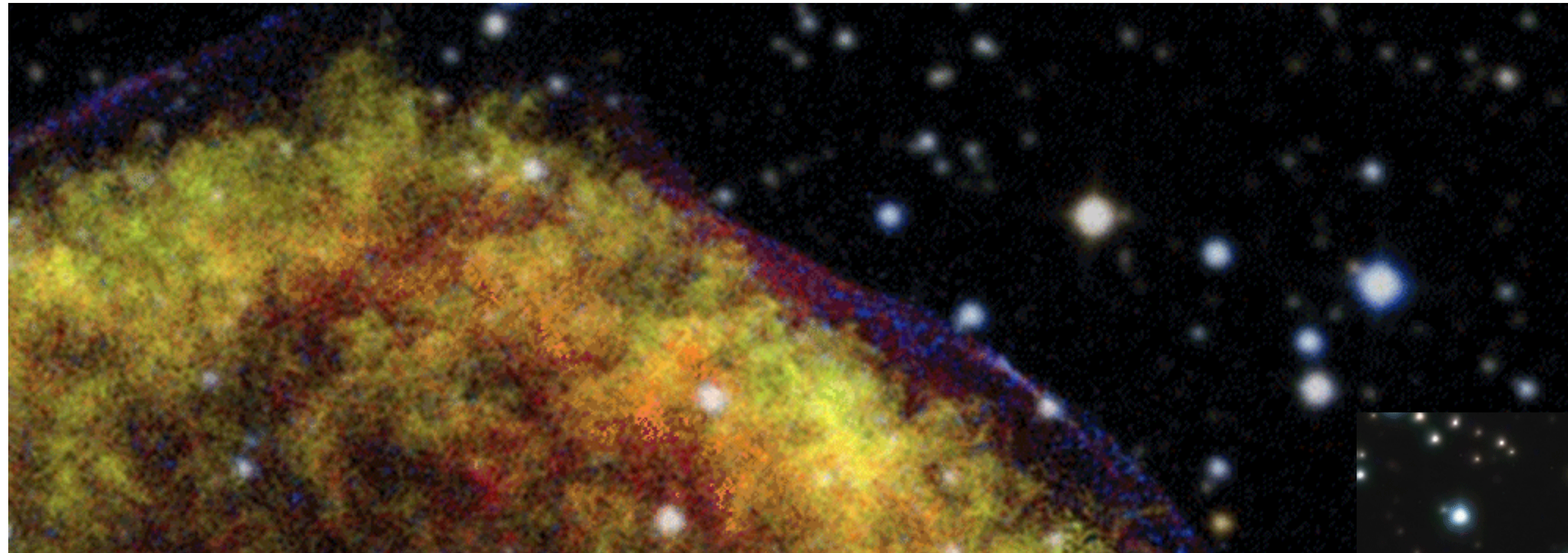

Crab Nebula
1054
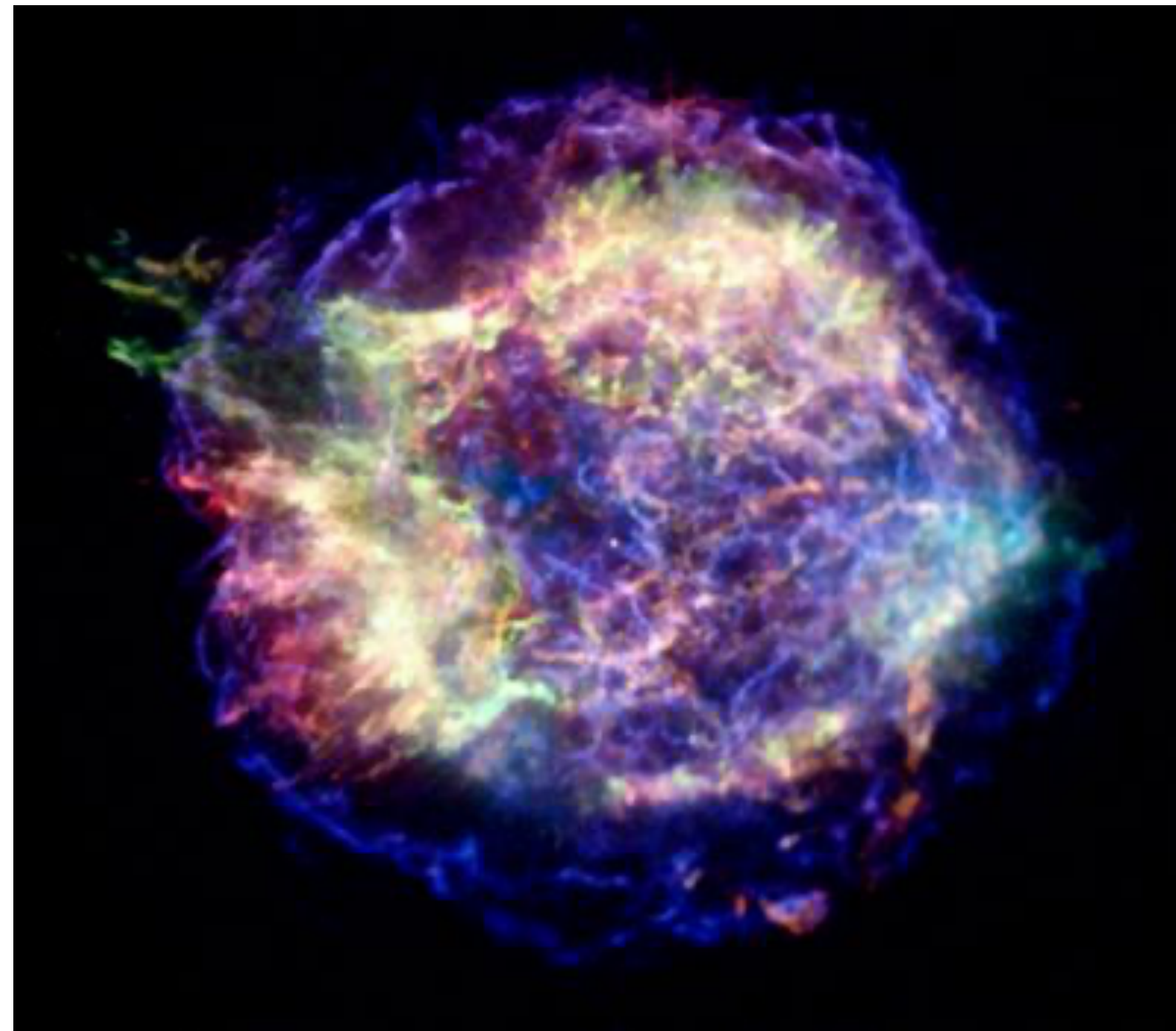
Cassiopeia A
~1680
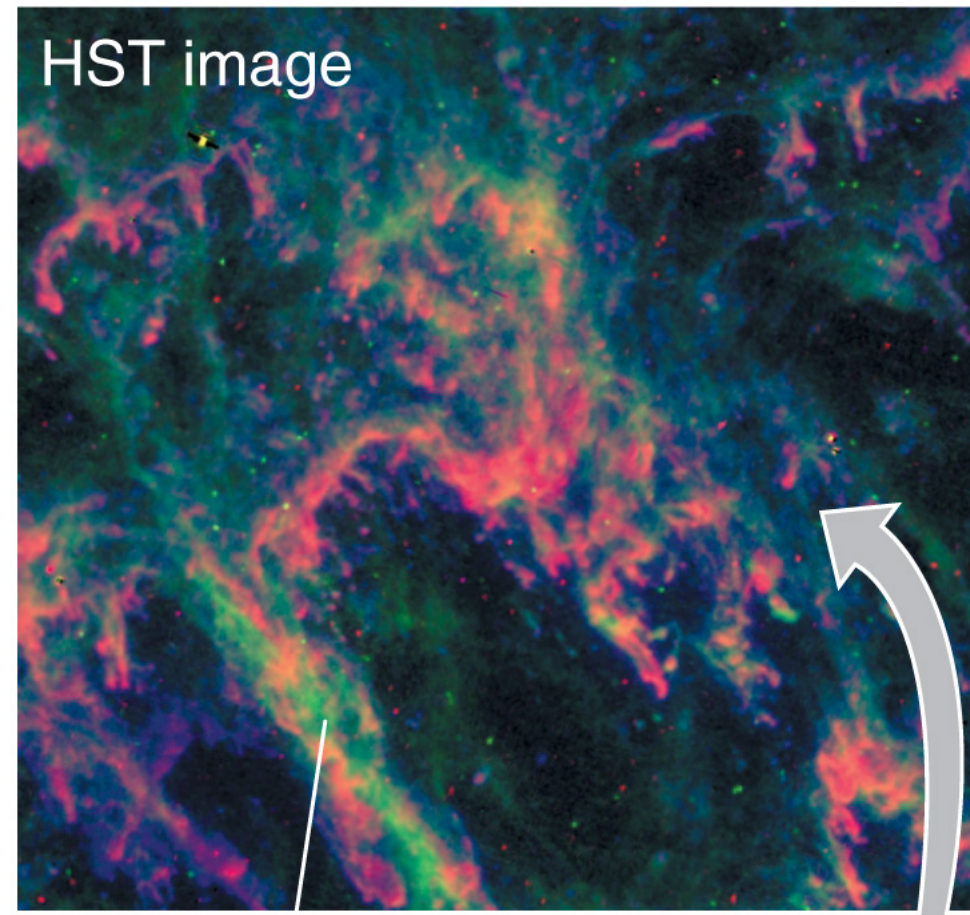(not clearly recorded)

Tycho SNR
1572

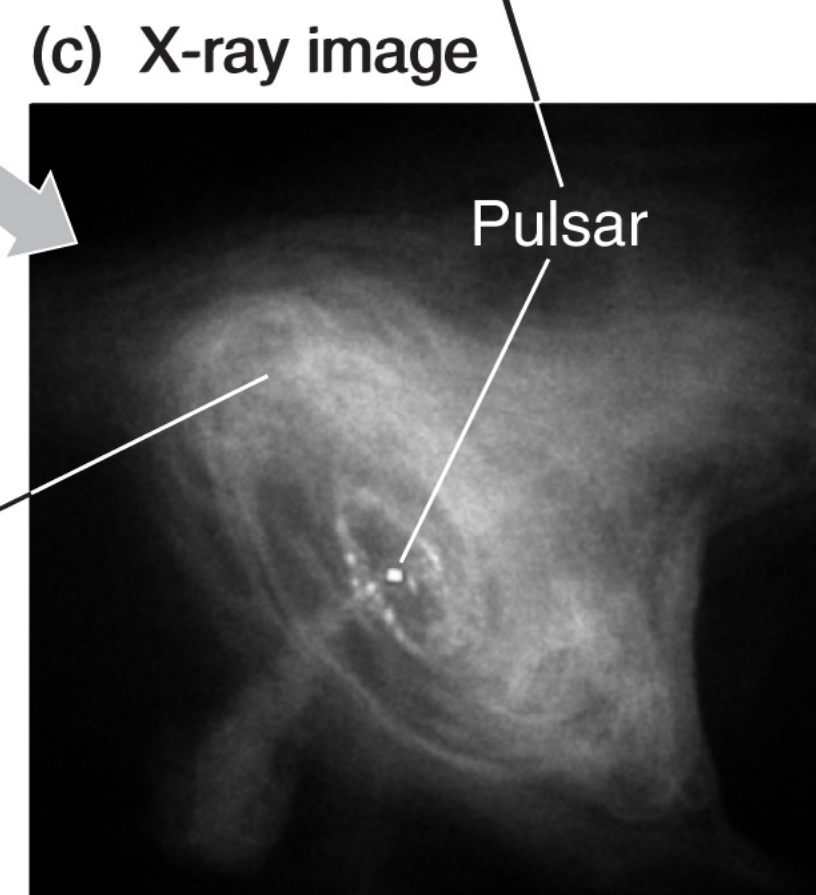# Can watch them expand!
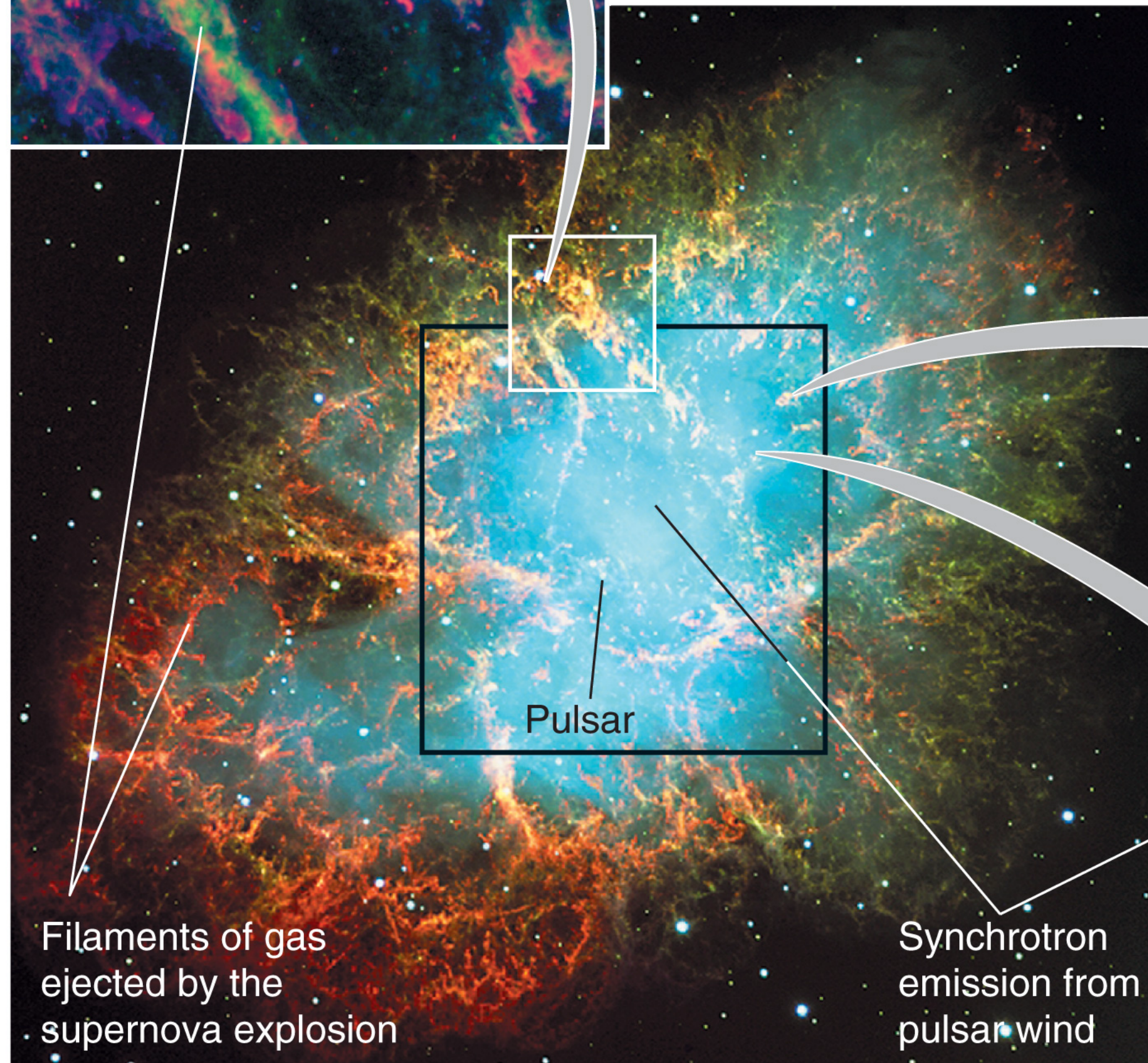

Tycho

Crab

2008

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Neutron Stars / Pulsars

HST image

(a) Ground-based image

(b) Visible-light image

(c) X-ray image

Pulsar

Pulsar

Filaments of gas ejected by the supernova explosion
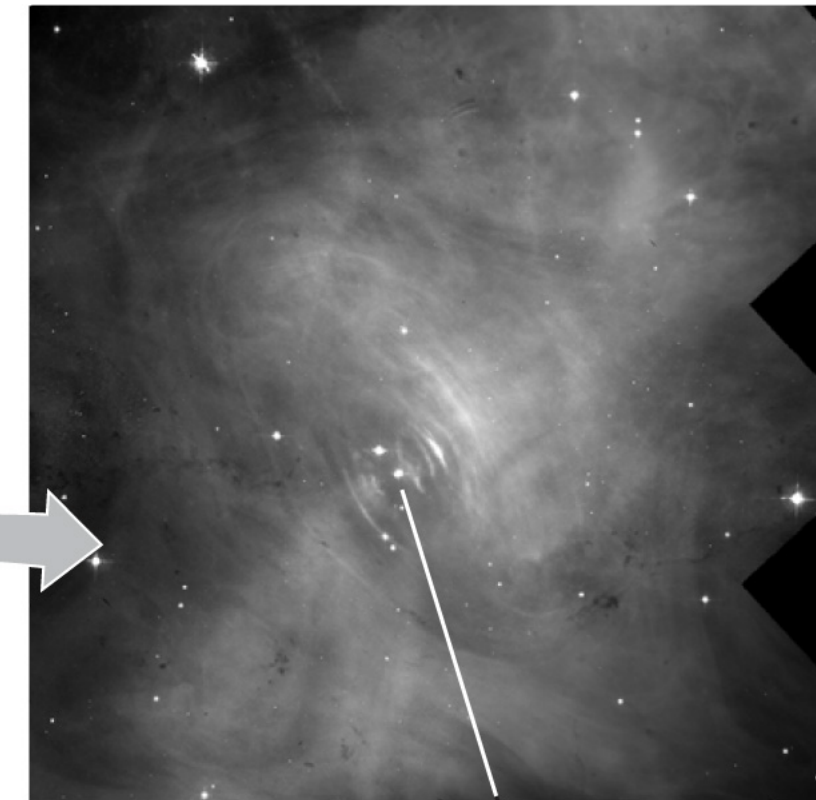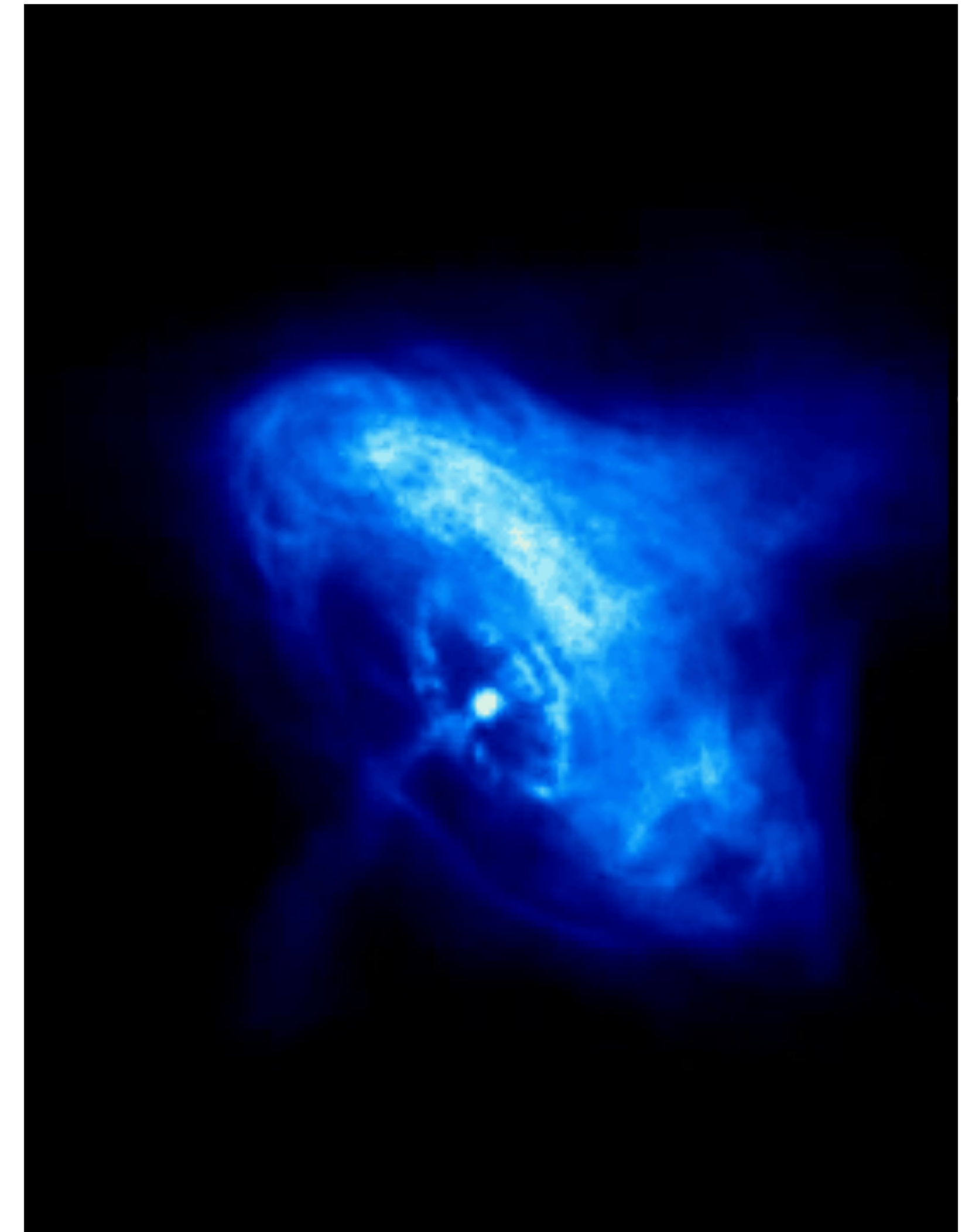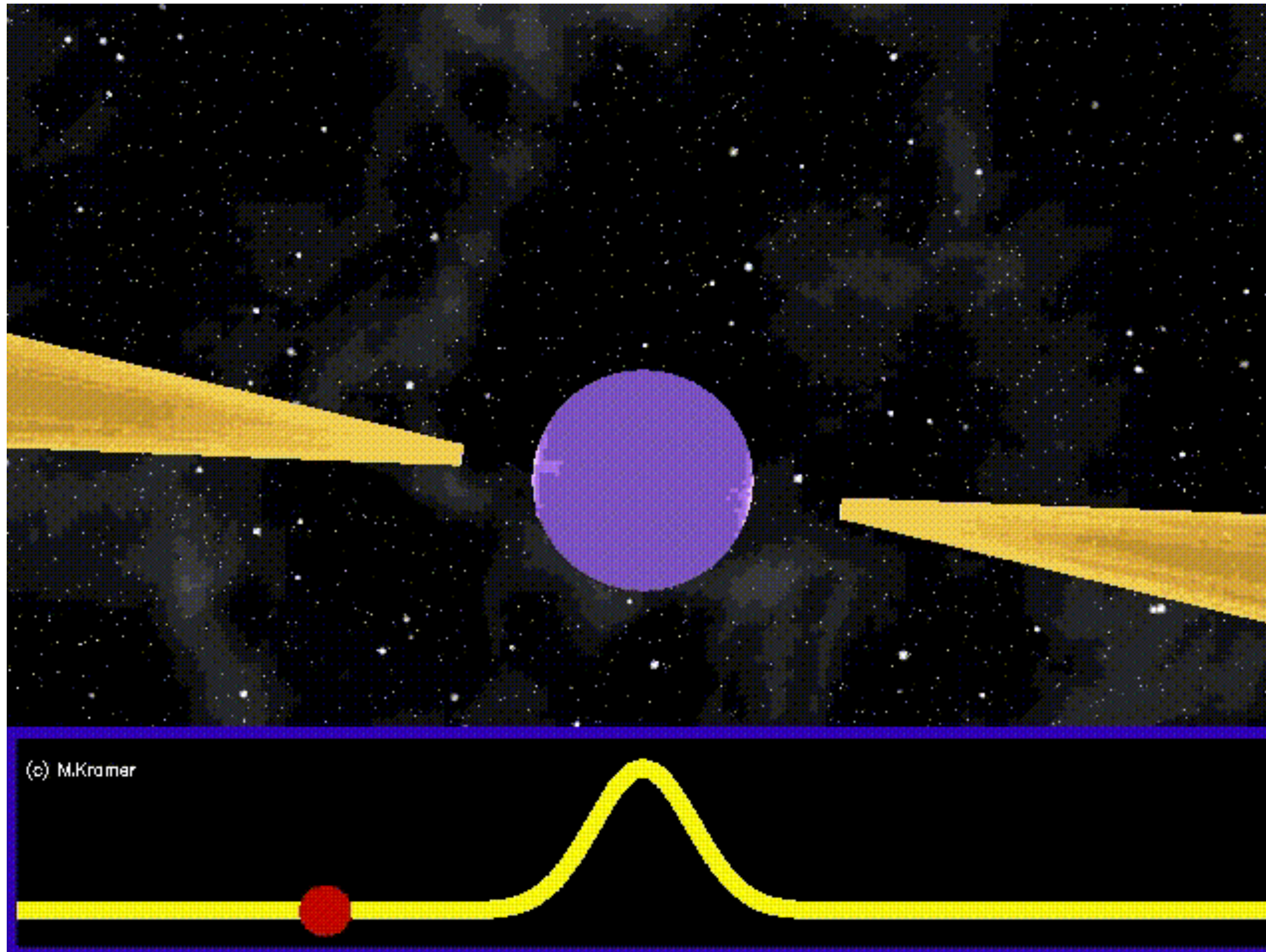
Synchrotron emission from pulsar wind

Exploded 1054

Pulsars emit pulses at all wavelengths

When formed, rotates with a period of ~ 10-100 ms

Realistic simulation of the magnetic field of a pulsar:

https://www.youtube.com/watch?v=jwC6_oWwbSE

Millisecond Pulsar:
https://www.youtube.com/watch?v=MPpDTvYL5ik

Black Widow Pulsar:

https://www.youtube.com/watch?v=-SoZ1xvCpMw

1 Neutron stars have enormously strong magnetic fields.

2 Electrons and positrons moving in the neutron star's magnetic field produce radiation that is beamed away from the poles of the neutron star.

3 As the neutron star rotates, these beams sweep around like the beam of a lighthouse.

Neutron star

Magnetic field

4 As the beams sweep past an observer, the neutron star appears to pulse on and off, earning it the name *pulsar*.
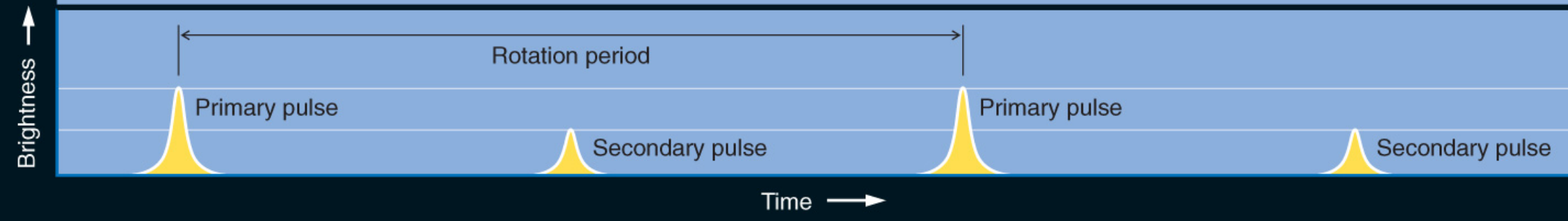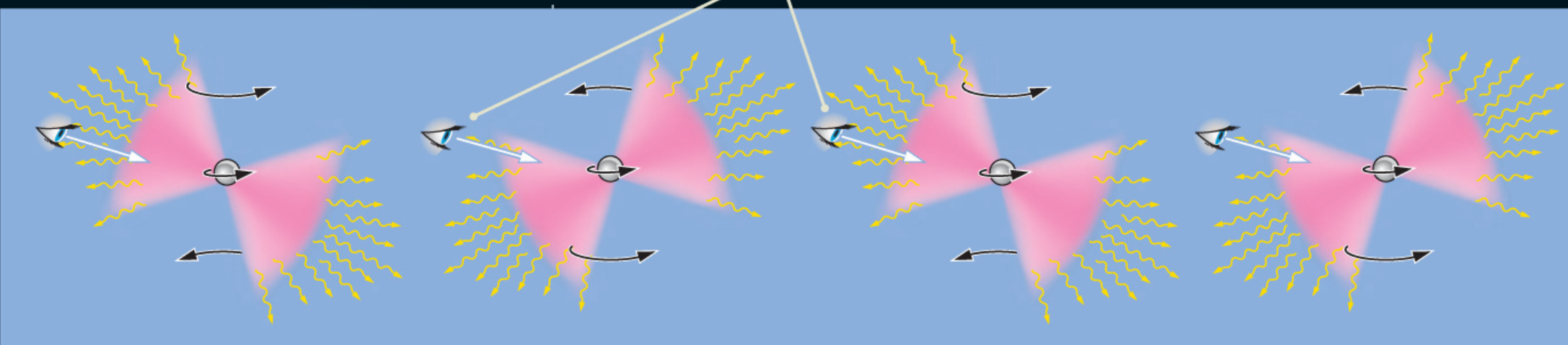
Lighthouse beam

Neutron Stars are born with strong magnetic fields (get stronger as the core collapses)

Field accelerates electrons and positrons, which causes them to emit radiation across the spectrum

We see the beam once or twice each time the star rotates

Rotation period

Primary pulse

Secondary pulse

Primary pulse

Secondary pulse

Brightness

Time

Can a Neutron Star have any mass?

Neutron degeneracy pressure will also eventually fail

$$M_{\mathrm{max,NS}} \approx 3M_\odot$$

Once a NS reaches the critical mass, its collapse can no longer bed stopped. All of its mass will end up (as far as we know) in a single point at the center of the black hole, called the <u>singularity</u>.

Why is it called a singularity?

Roger Penrose won the Nobel Prize last year for mathematically proving that black holes must have singularities at their centers, *IF* general relativity is the correct theory of gravity.
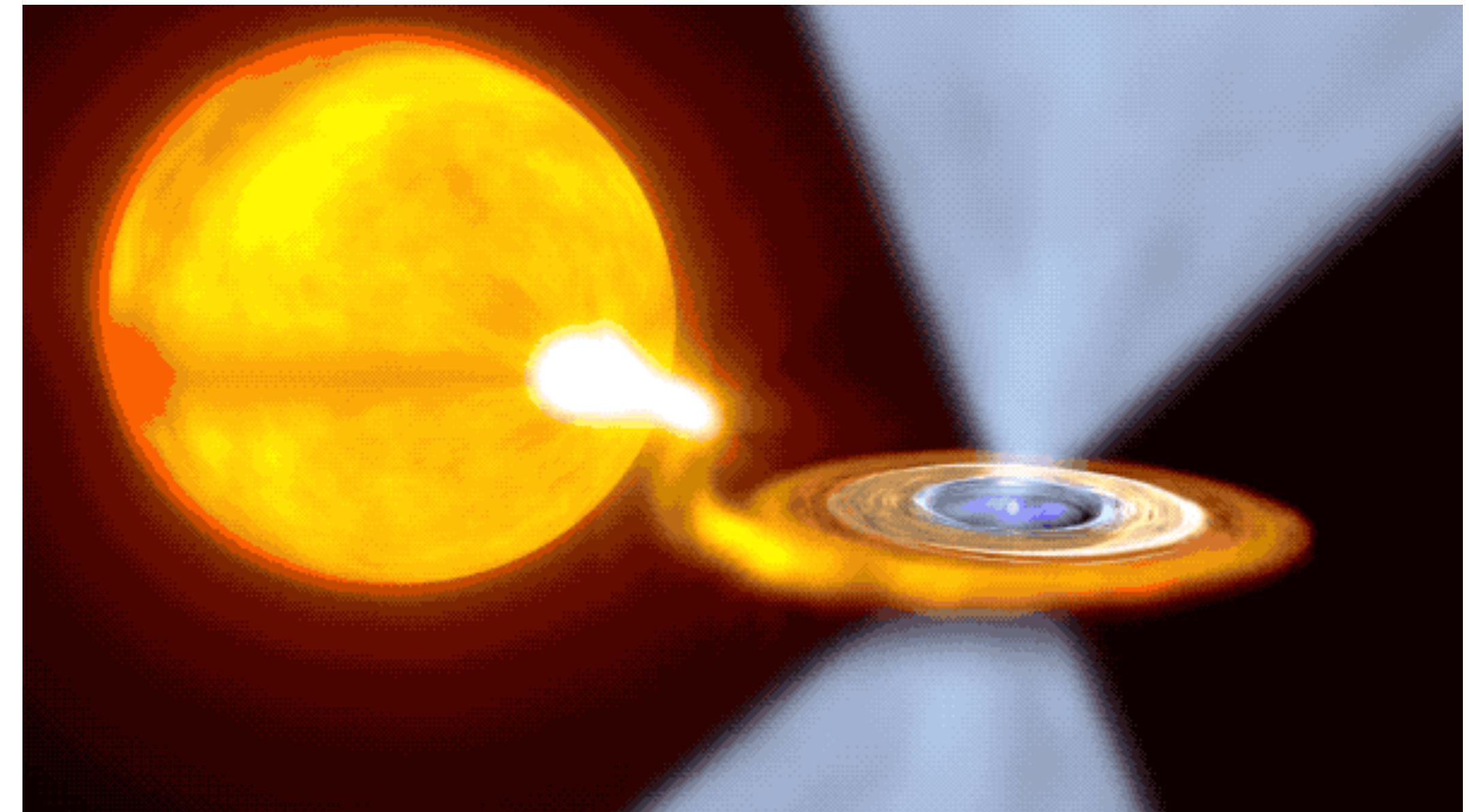
$$f(x) = \frac{1}{x}$$
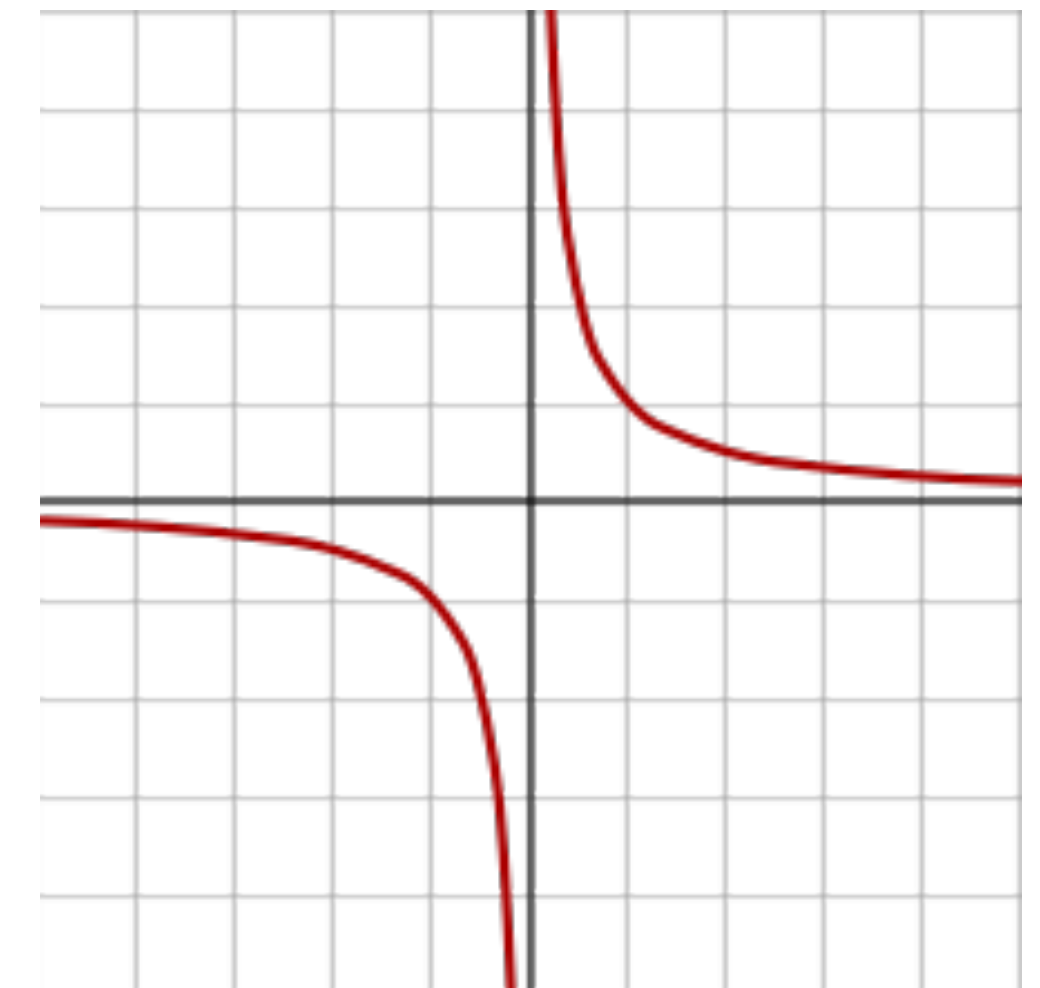
Black Holes

If the Sun suddenly collapsed and formed a black hole, what would happen to the Earth?

For a spherically symmetric object, its gravitational force (outside the object) is identical to that of an object with the same mass all at $r = 0$ —> exactly the case of a black hole!

The escape speed for a BH is the same as usual then, but b/c we can get much closer to them, the escape speed can get really high

$$v_{\text{esc}} = \left(\frac{2GM}{r} \right)^{1/2}$$

Set $v_{\text{esc}} = c$ (speed of light)
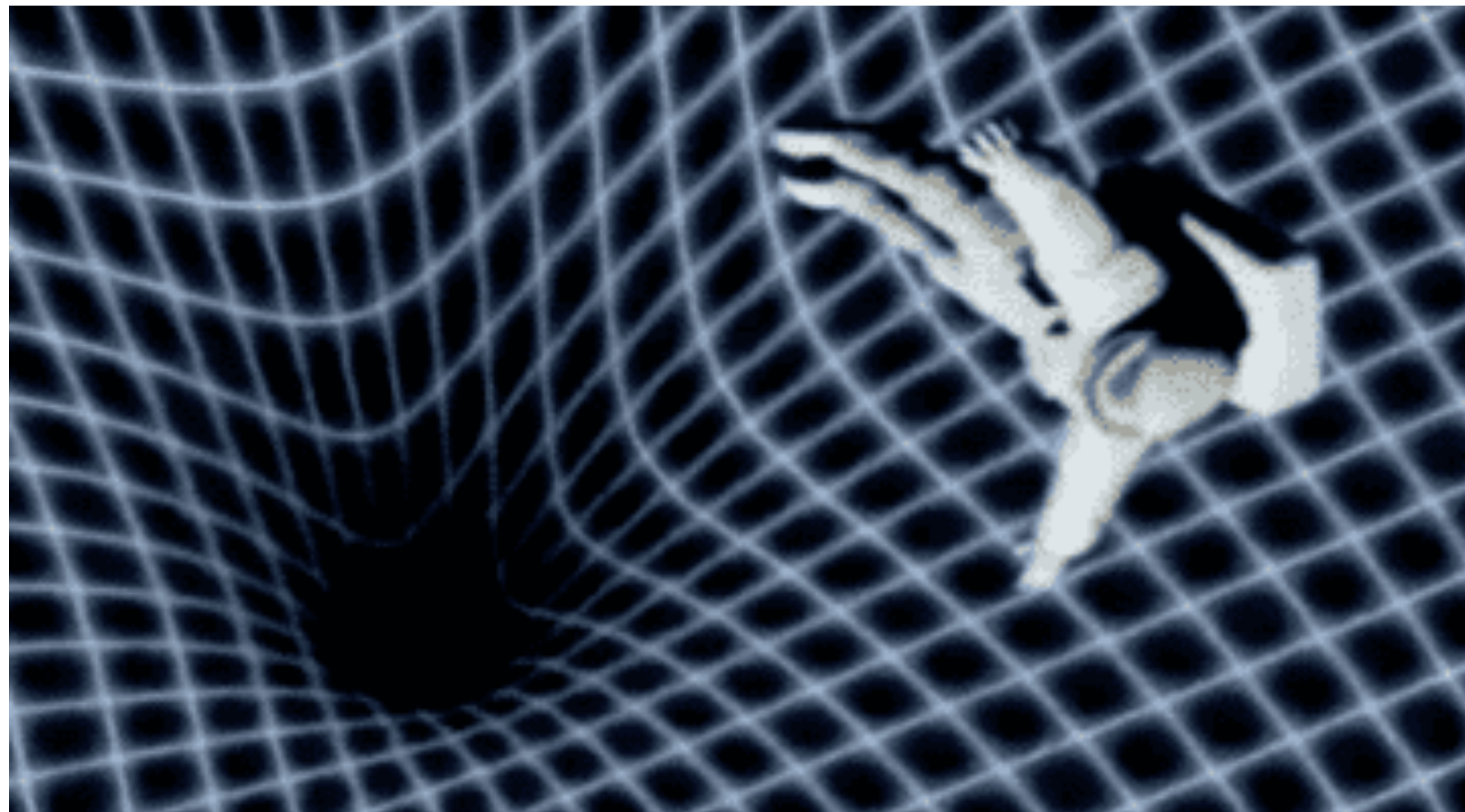
$$r_{\text{Sch}} = \frac{2GM}{c^2}$$

<u>Schwarzschild radius</u>
The spherical surface defined by this radius is called the <u>event horizon</u>

Black Holes

Spaghettification

F_g changes so quickly with radius that gravitational tidal forces (the difference in F_g between your head and your feet) become strong enough to rip you apart as you fall towards a BH's singularity
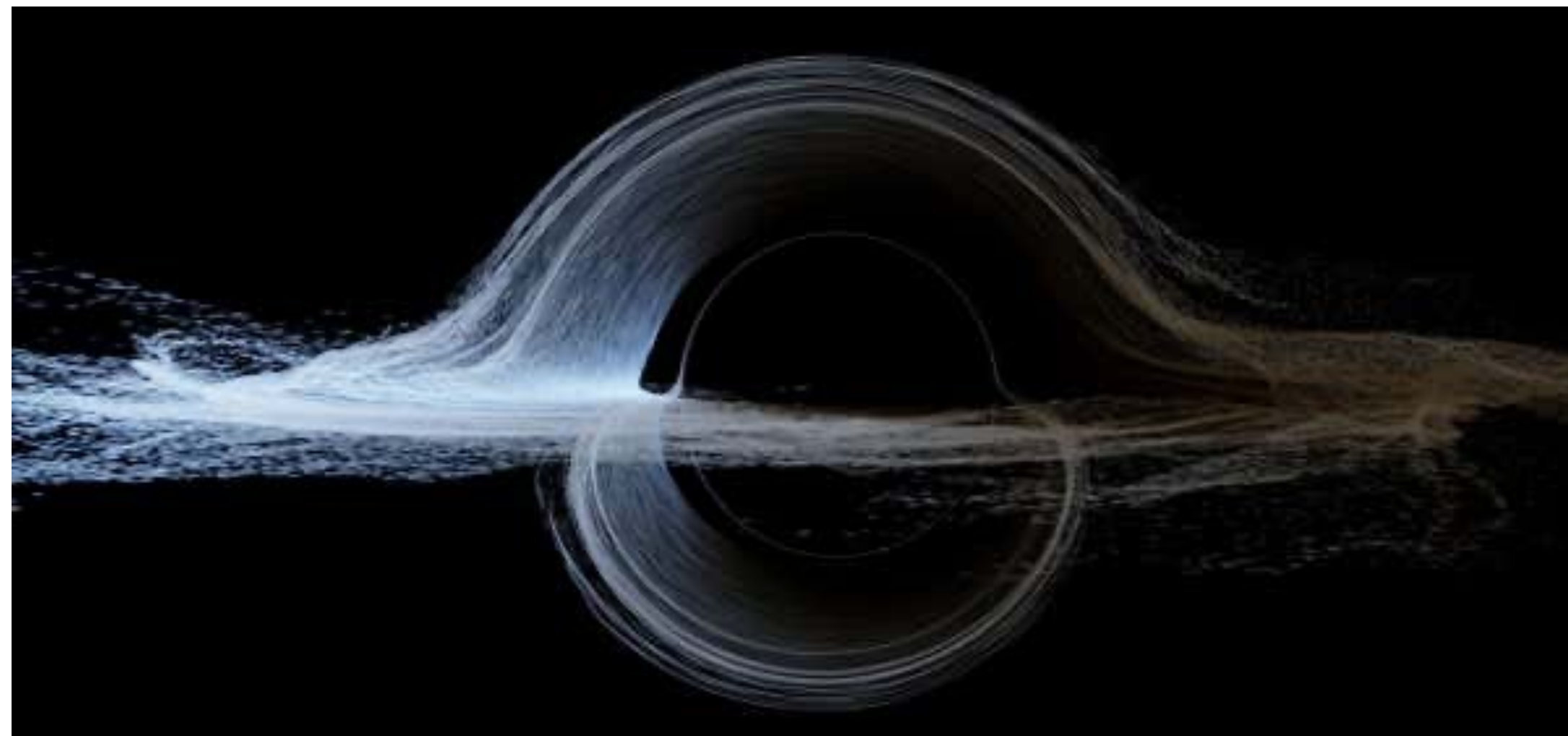
$$\Delta F \approx \frac{GMm}{r^3}\ell$$

Your mass

Your height

Other effects (e.g., explaining *Interstellar*)

BH with accretion disk (no gravitational lensing)

What it would actually look like

Gravitational Lensing
Light follows shortest path b/t 2 points, but space-time curved, so light rays are curved

Time Dilation
Time passes slower the closer you are to a massive object (GPS satellite clocks "have more ticks" than our clocks in a given interval of time)

Gravitational Redshift
Light has to "climb out" of a gravitational potential well, losing energy — light with less energy has a longer wavelength (just outside the event horizon, light is nearly infinitely redshifted)

Observing real NSs and BHs

X-ray

Optical / UV

Andromeda Galaxy
(M31)
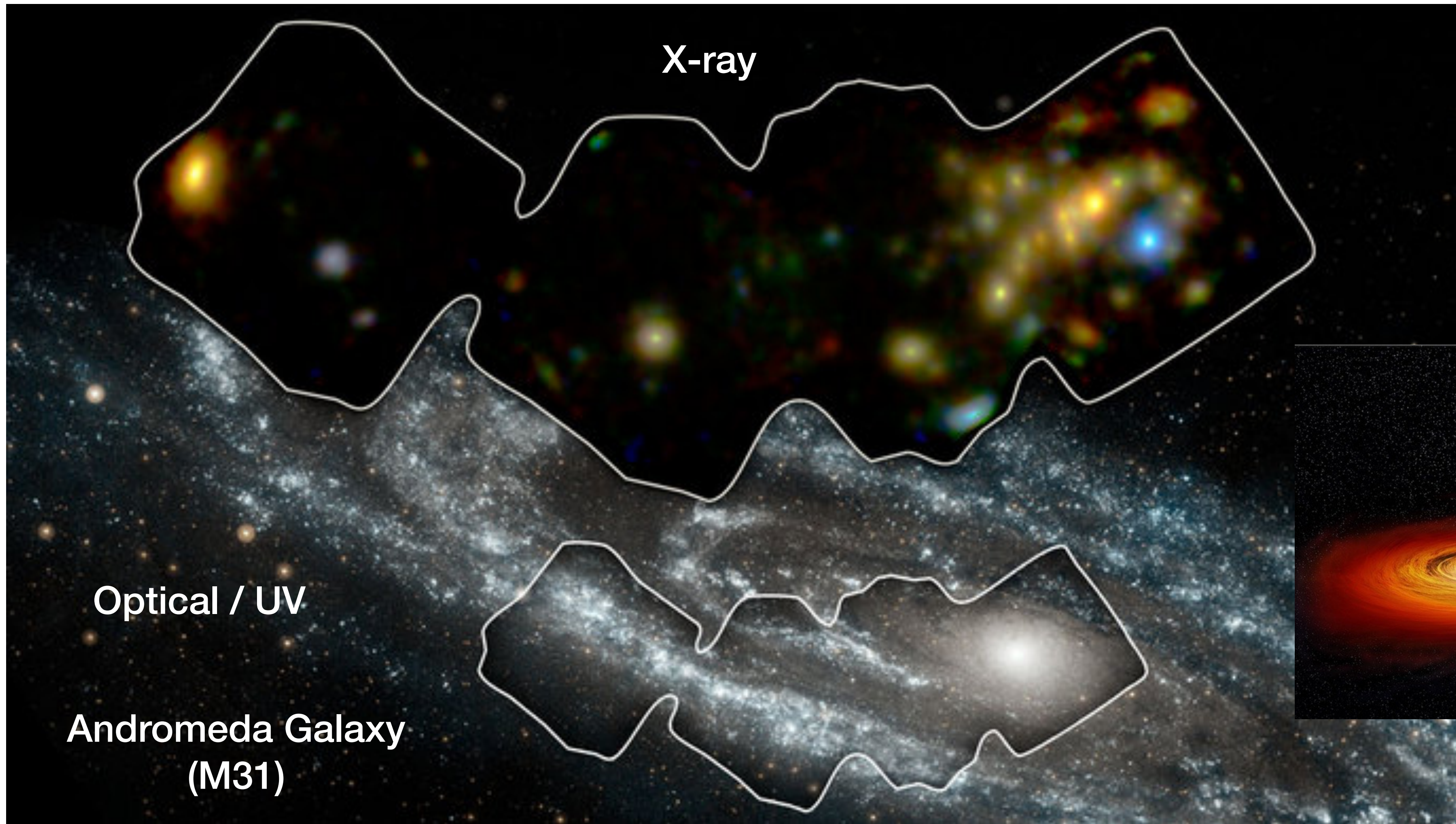
X-ray Binaries
Close binary stars where 1 star has exploded and is now accreting matter from its companion
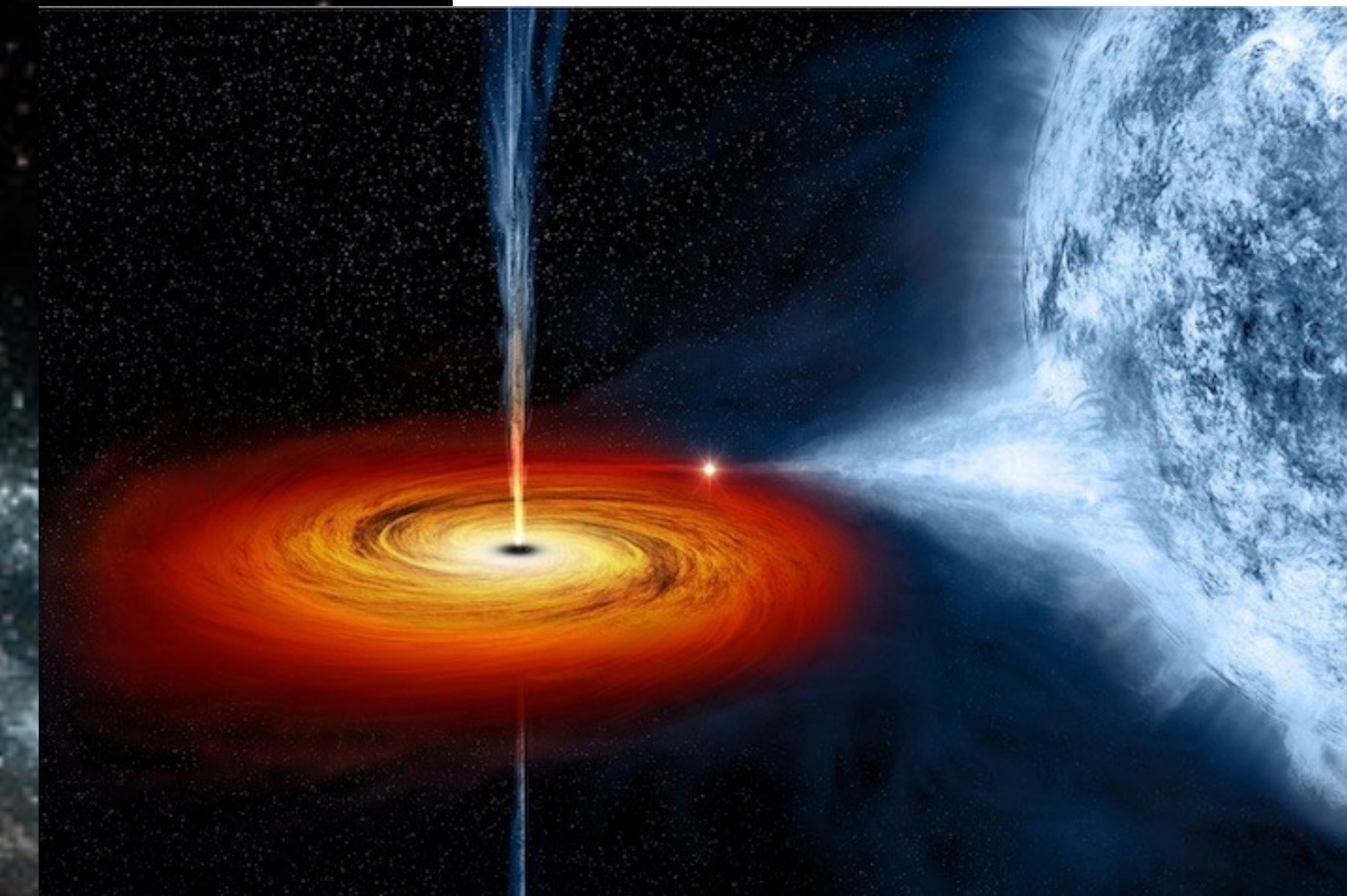
Group Discussion Problem

The radiation powering pulsars results from high energy processes due to the very strong magnetic field of the star.

What is the origin of the large magnetic field?

As the pulsar radiates, the star must lose energy assuming energy conservation. What is the effect of that lost energy on the star?

If the pulsar was formed with a mass very close to its Chandrasekhar Mass, will it eventually become a black hole (assuming it remains isolated, accreting a trivial amount of matter of that time)?

Star's life determined mostly by its initial mass

White Dwarf:

$M < 7M_\odot$

Neutron Star:

$7M_\odot < M < 18M_\odot$

Black Hole:

$M > 18M_\odot$