Part 2: Stars

- Thursday, February 9 — Reading: Chapter 6 [Ed. 9, 10, 11, 12]
  - The nature of light: How we use spectra to measure the properties of stars
- Tuesday, February 14 — Reading: Chapters 8, 9.1, 9.5 or Orion Nebula
  - Stars: distance, luminosity, mass, composition. Star formation. HW2 assnd
- Thursday, February 16 — Reading: Chapter 7.1 — 7.2 or 7.3 on the Sun
  - Stars: Our Sun.
- Tuesday, February 21 — Reading: Chapters 7 or 9 on fusion, 9.2 — 9.5
  - Stars: Stellar models, energy generation, main sequence life
- Thursday, February 23 — Reading: Chapters 10.1 — 10.3
  - Stars: Evolution from main sequence to white dwarf or Type II supernova
- Tuesday, February 28 — Reading: Chapters 10.4, 11 HW 2 due
  - Stars: Type I supernovae; white dwarf stars, neutron stars, black holes
- Wednesday, March 1 — Help session from 4 — 6 PM in Welch 3.502
- Thursday, March 2 — Exam 2 (Part 2)
- Monday, March 6 — Help session from 4 — 6 PM in RLM 4.102
- Tuesday, March 7 — Exam 3 (Parts 1 + 2)
- Thursday, March 9 — Exam 4 (Parts 1 + 2)

The contracting iron core has no further energy source via nuclear reactions.
So the central temperature rises.

Two causes of supernova explosions:

1 – As the growing core approaches its Chandrasekhar limit, it shrinks dramatically and gets very dense and hot.

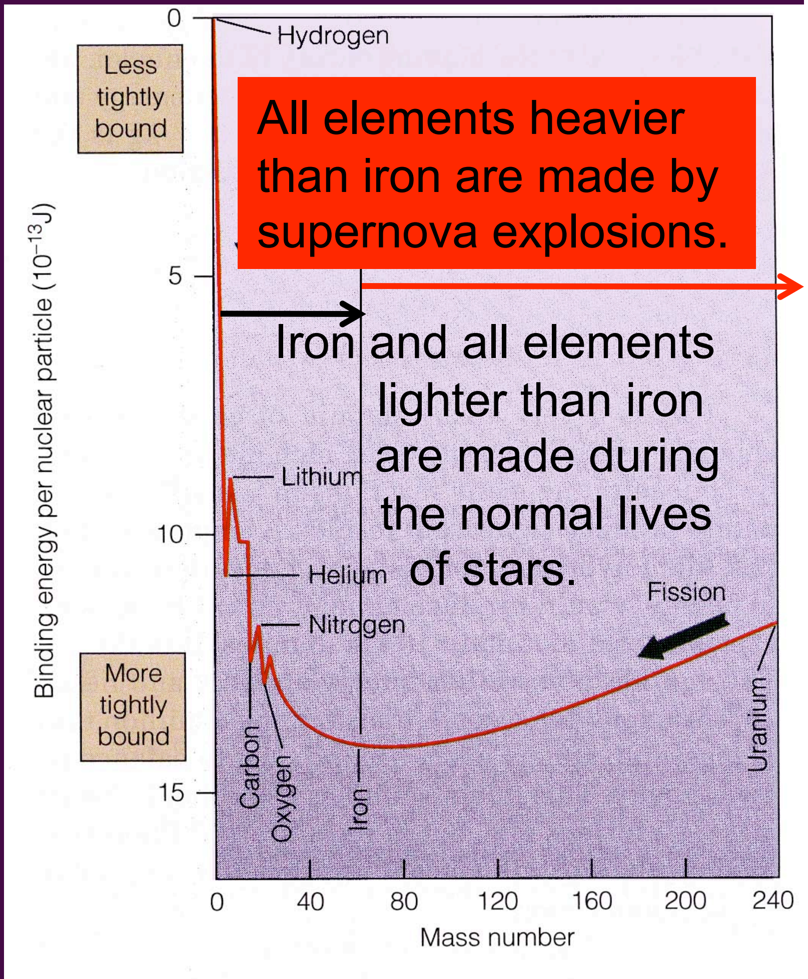
2 – At about 10 billion K,
photons that hit an iron nucleus smash it to pieces.
But the pieces are less tightly bound than iron.
So this uses up energy.

In other words, this uses up heat.

The iron core is suddenly refrigerated. Pressure disappears.
The core collapses in less than a second.
It may stabilize as a neutron star or it may become a black hole.
But the next layers out that crash onto it are still nuclear fuel;
they get superheated and explode as a supernova.

Review: Evolution of High-Mass Stars

Stars born with more than 8 — 10 $M_{\odot}$ cannot lose enough mass to become white dwarfs. These stars die by supernova explosions.



Ignition of "metals"

The core of an old high-mass star gets little support from electron degeneracy pressure, so it has to contract. Its temperature climbs to several billion K. Then nuclear reactions convert elements from carbon through silicon into iron. These late stages of nuclear burning produce relatively little energy and delay the end only briefly.

Formation of an iron core

Near the end, a high-mass star has an iron core supported by electron degeneracy pressure. No more nuclear energy is available. From the point of view of nuclear reactions, iron is a "dead end". <u>This is why the Universe produces so much iron.</u>

Review: Cosmic Abundances of the Elements

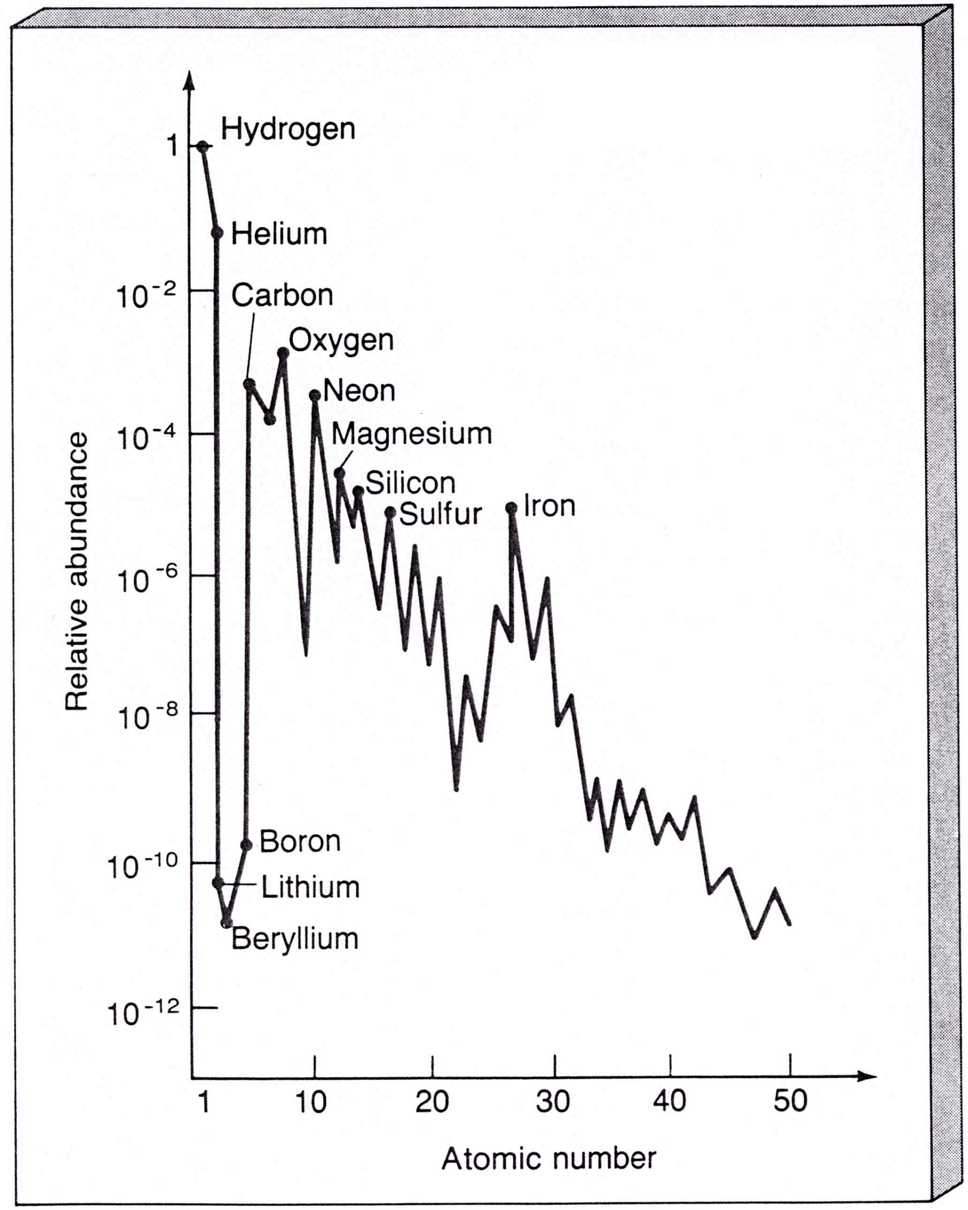
In the expanding supernova shock wave, nuclear reactions go berserk and cook up elements more massive than iron, all the way to platinum.

In the 15 billion year history of our Galaxy, about a quarter billion supernovae have each recycled about 10 $M_\odot$ of metal-enriched gas back into the interstellar medium.

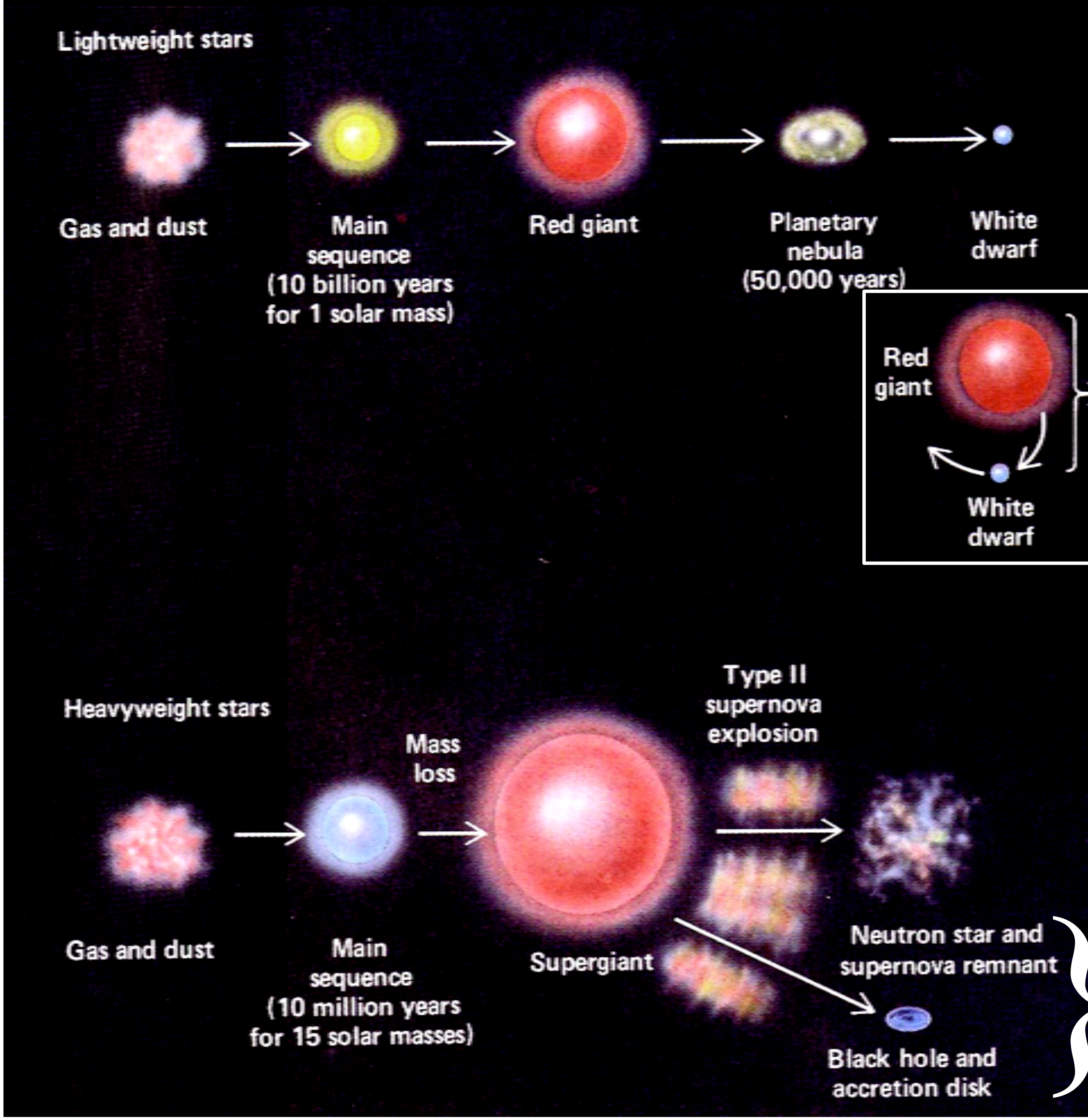
This is a total of more than 1 billion $M_\odot$ or more than 1 % of the mass of the Galaxy.

All iron was expelled from stars by supernovae.

Almost all elements heavier than iron
(e. g., all gold, lead, platinum, uranium)
were manufactured in supernova explosions.



Stellar Evolution



Supernovae of type I and …

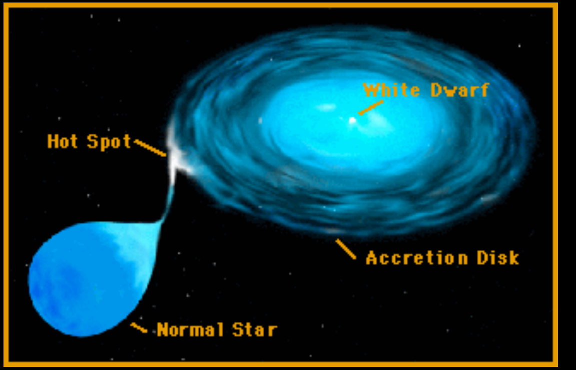
neutron stars and black holes are the subjects of the rest of this lecture.

Type I Supernovae

A white dwarf can gain mass from a companion star.
When it reaches 1.4 $M_\odot$, the dwarf collapses, triggering a nuclear explosion.
So a **Type I supernova** is a nuclear bomb with a gravity detonator.

Mass-Transfer Binaries

Stars that orbit each other closely can exchange mass. When one star of a binary becomes a red giant, then the gravity of the other star distorts the giant into an egg shape. As the giant swells, its outer gas starts to flow onto the other star.

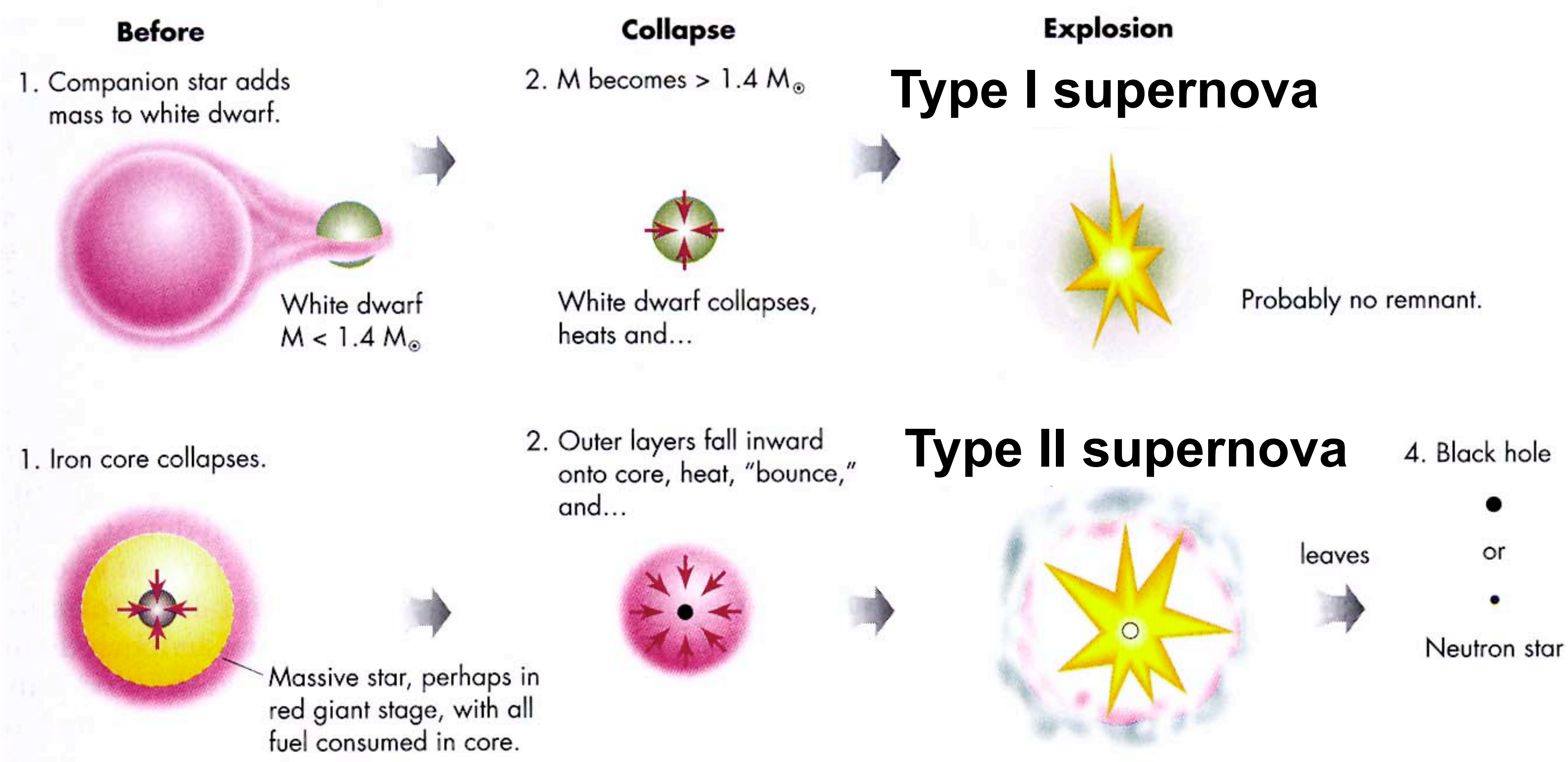


Carbon detonation

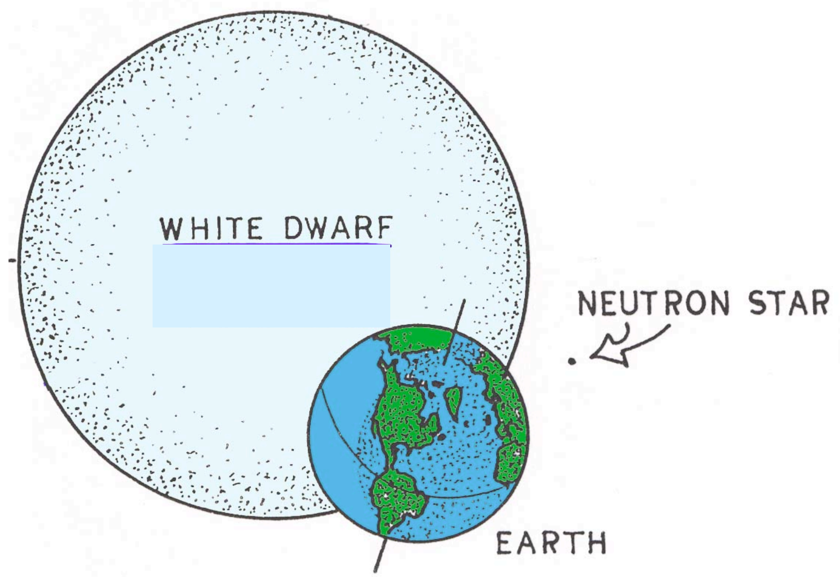
If the recipient star is already a white dwarf, then the mass that it gains brings it closer to the Chandrasekhar limit of 1.4 $M_\odot$. When it reaches this limit, the white dwarf collapses under its own gravity. It gets hotter. Carbon nuclei at the center fuse, and a wave of nuclear burning sweeps out through the star, reaching the surface about 1 second later. These reactions make iron-group elements and release about 0.001 $M_\odot$ worth of energy.

This is enough to blow the white dwarf apart.

Type I supernovae are more violent than type II supernovae because all of the progenitor white dwarf consists of nuclear fuel (e. g., carbon), whereas type II progenitors consist of iron cores that are not nuclear "fuel".



Corpses of Stars



	White dwarf	Neutron star	Black hole
Progenitor star mass:	0.08 — 8 $M_\odot$	8 — 20 $M_\odot$	>20 $M_\odot$
Corpse mass:	≤ 1.4 $M_\odot$	≤ 3 $M_\odot$	3 — 10 $M_\odot$
Corpse radius:	7000 km	~ 10 km	~ 10 km
Corpse density:	10^6 g cm^{-3}	10^{15} g cm^{-3}	-
1 teaspoonful on Earth:	5 tons	1 billion tons	-
Thickness of atmosphere:	~ 50 km	a few meters	-

Neutron Stars: Properties and Structure

Radii and Masses

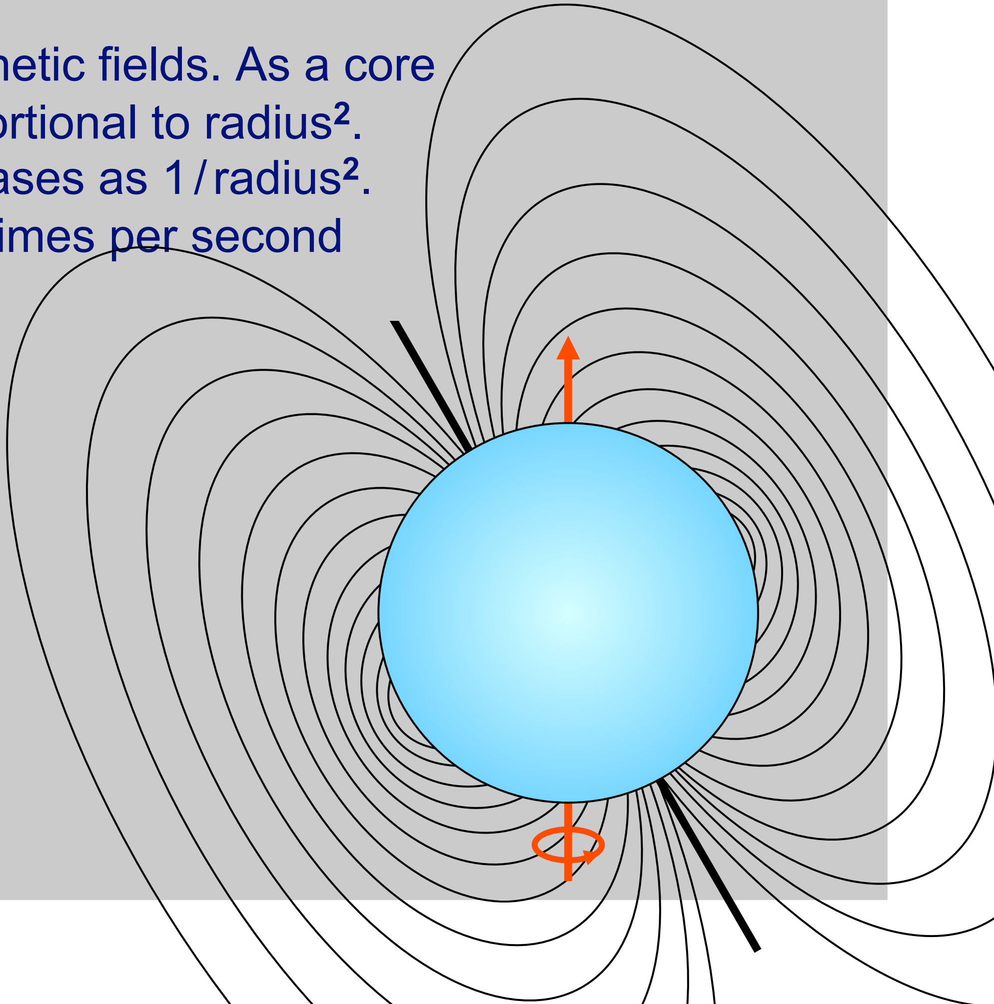
Neutron stars are smaller than white dwarfs by a factor of $m_{neutron}/m_{electron}$, because they are supported by degenerate neutrons, not degenerate electrons. They have radii of 10 to 30 km and masses greater than 1.4 $M_{\odot}$, the Chandrasekhar limit for white dwarfs.

Rotation and magnetic fields

Cores of massive stars rotate and have magnetic fields. As a core collapses, its rotation period decreases proportional to $radius^2$. Similarly, the magnetic field of the core increases as $1/radius^2$. So a newly-formed neutron star spins many times per second and has very strong magnetic fields.

Structure

On a neutron star surface, iron-group nuclei form a rigid crust several hundred meters thick. Below this, the interior consists of free neutrons + a few electrons and protons. At the center, the density exceeds nuclear densities.



Pulsars

A rotating, magnetized neutron star generates powerful electromagnetic fields. These fields create beams of radiation from radio to X-rays. As the neutron star rotates, the beams sweep through space like a spinning searchlight. Each time a beam passes the Earth, we detect a pulse of radiation.

Discovery

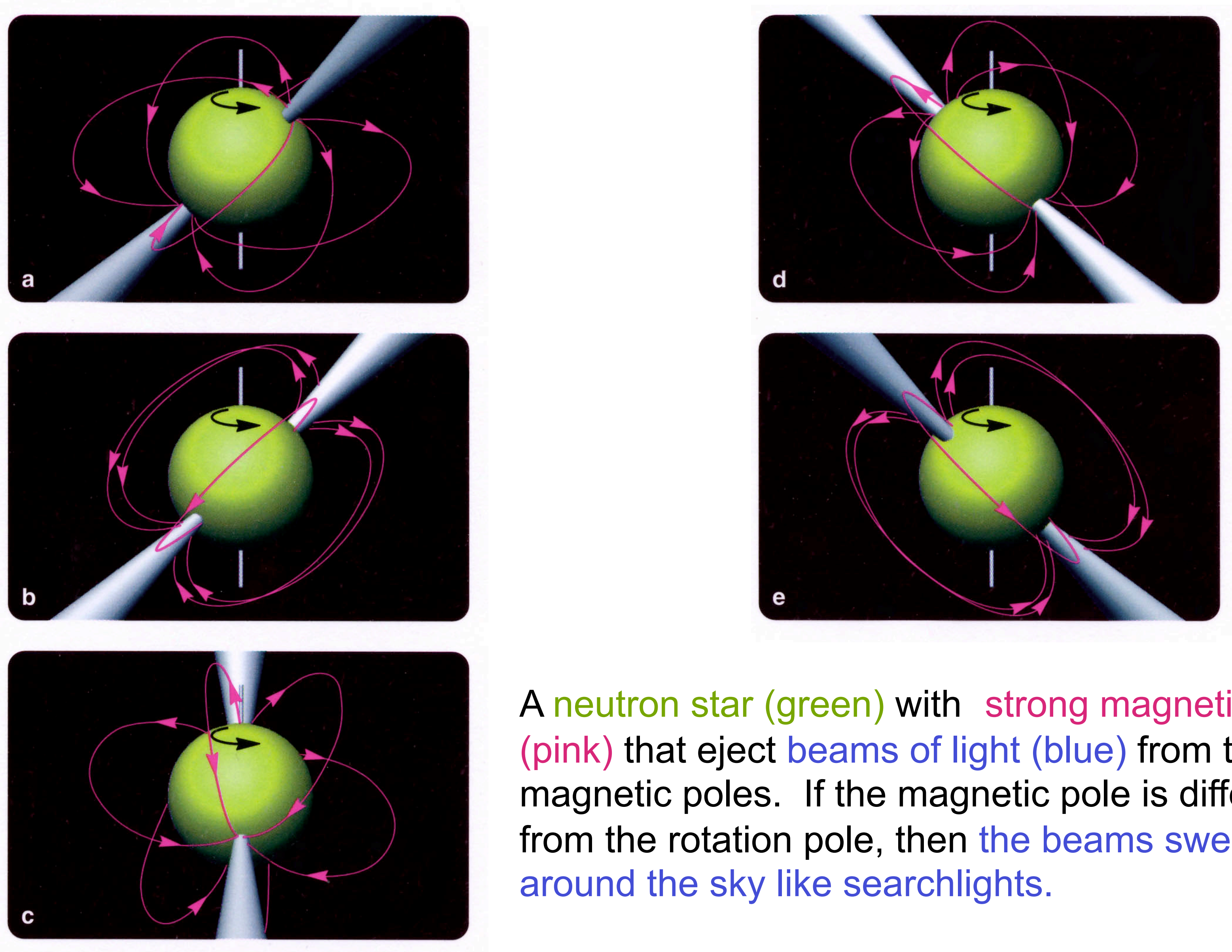
Pulsars were discovered by Jocelyn Bell in November 1967. She noticed regular sequences of pulses in signals detected by a radio telescope. The time between one pulse and the next is so constant that the pulses could only come from a rotating object.

The Crab Nebula Pulsar

The nature of pulsars was settled when one was discovered in the remnant of a supernova that was observed in 1054 AD. Only a neutron star could spin so fast — 30 times per second — without flying apart. This pulsar is the neutron star remnant of the star that exploded as the supernova.

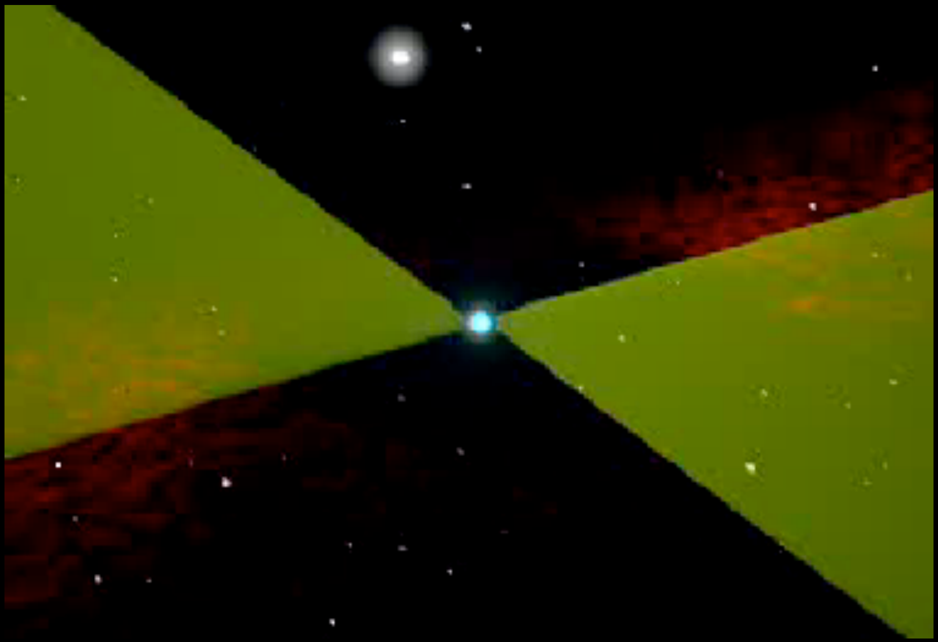
The period of the Crab Nebula pulsar is slowly increasing. The rate at which spin energy is lost is similar to the power emitted by the pulsar and the surrounding supernova remnant. So the neutron star acts as a flywheel, storing mechanical energy that powers the pulsar and the remnant.

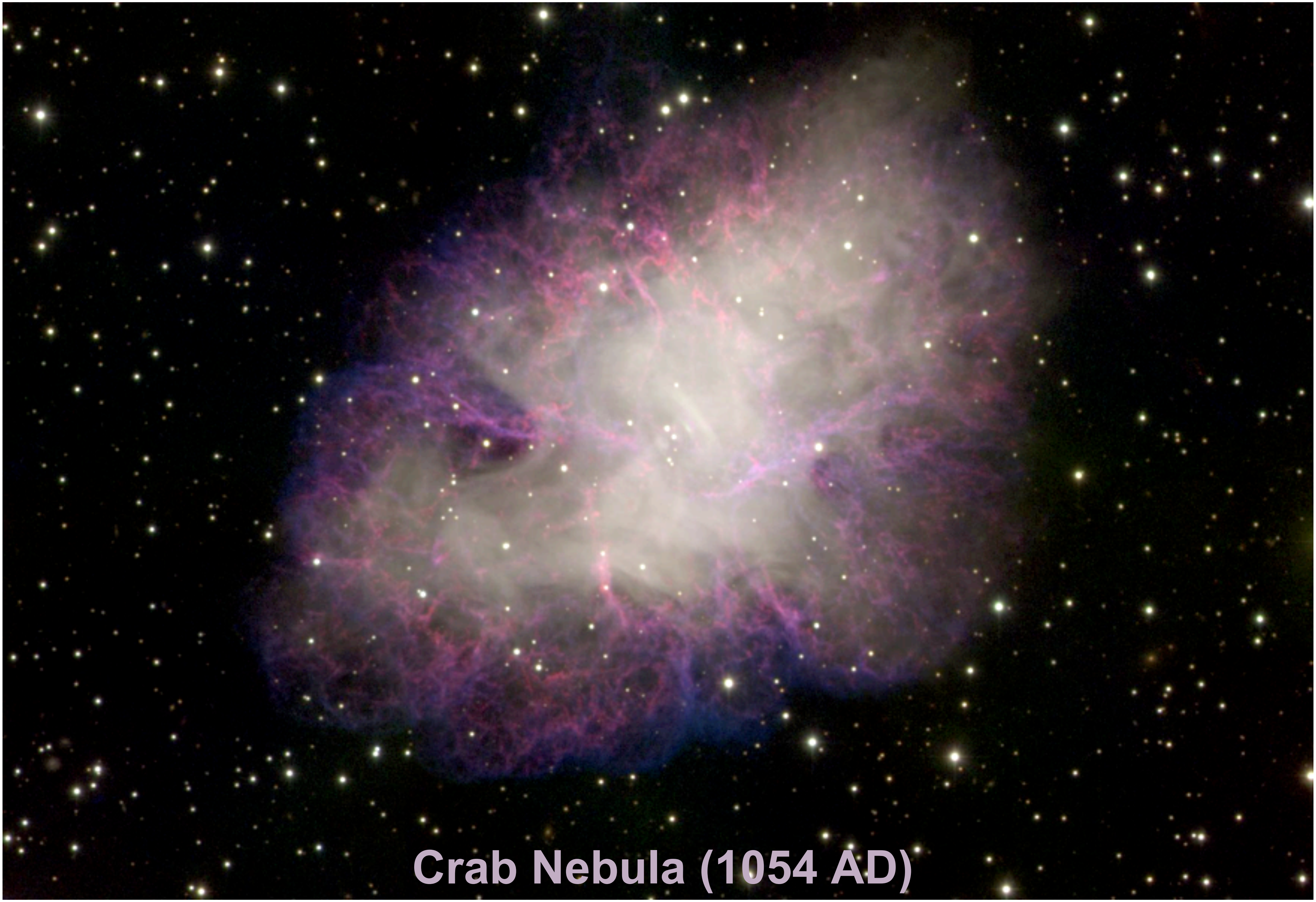
Spinning Neutron Star



A neutron star (green) with strong magnetic fields (pink) that eject beams of light (blue) from their magnetic poles. If the magnetic pole is different from the rotation pole, then the beams sweep around the sky like searchlights.

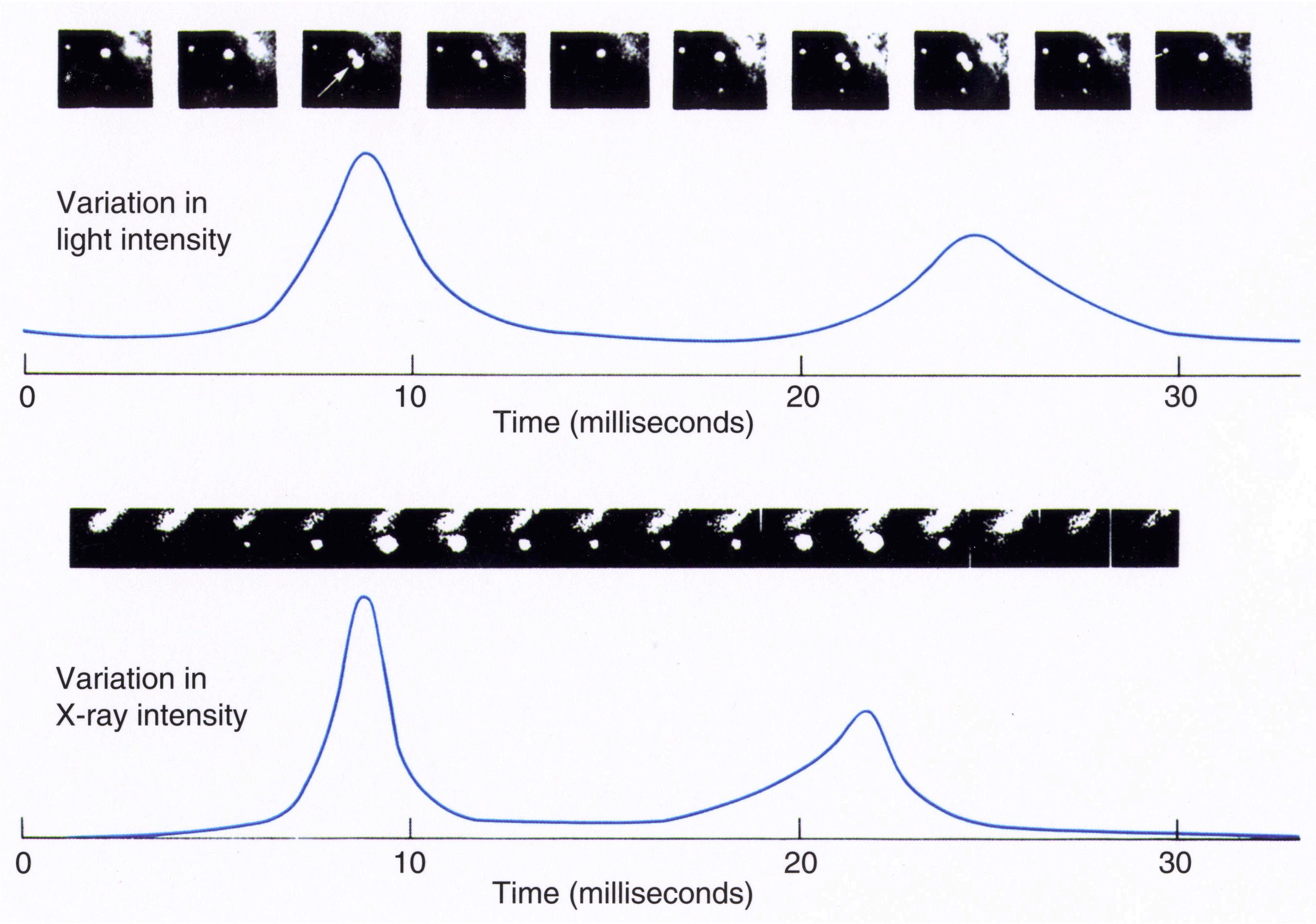
Neutron Star Model



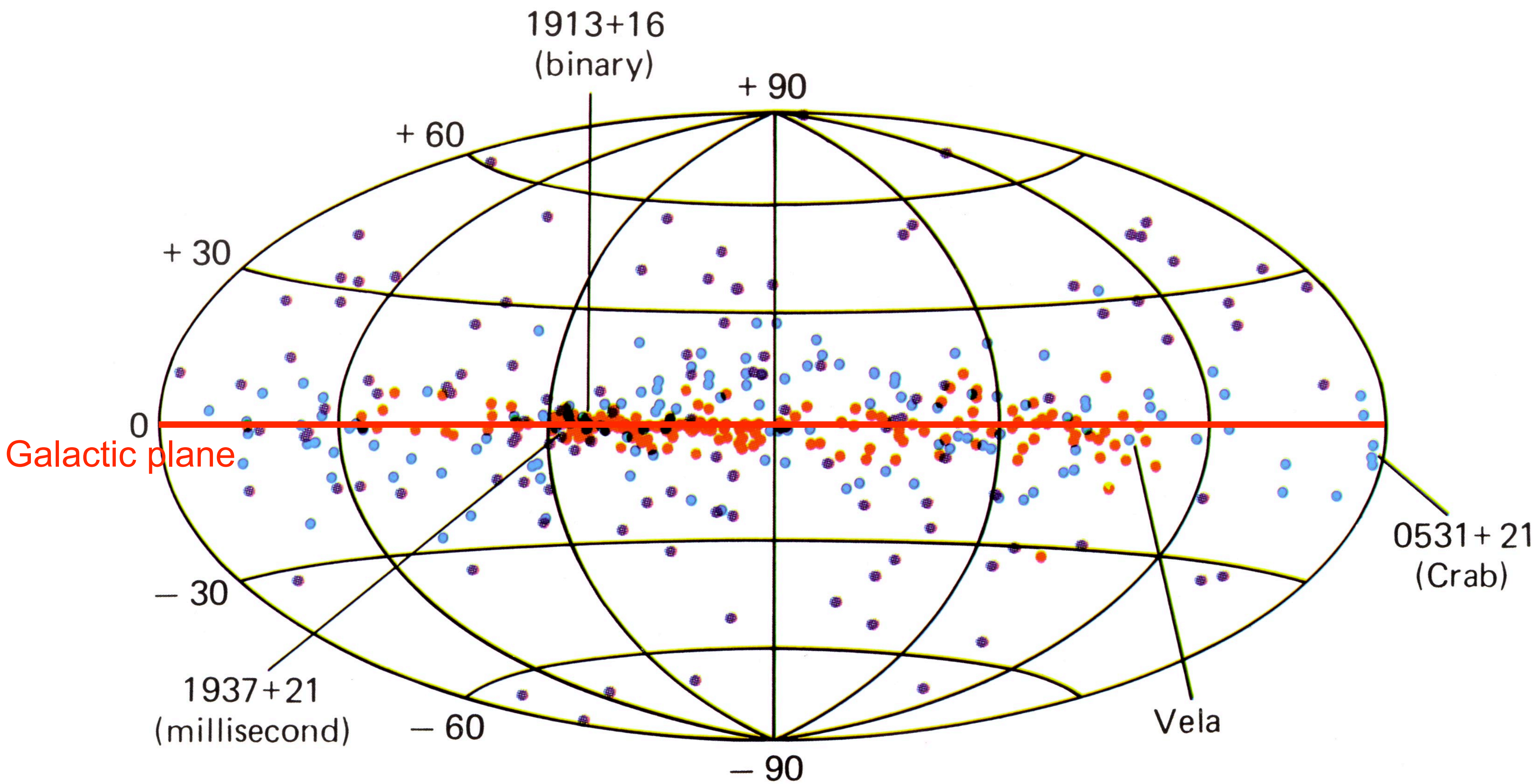


Crab Nebula (1054 AD)

Crab Nebula Pulsar — Light Curves

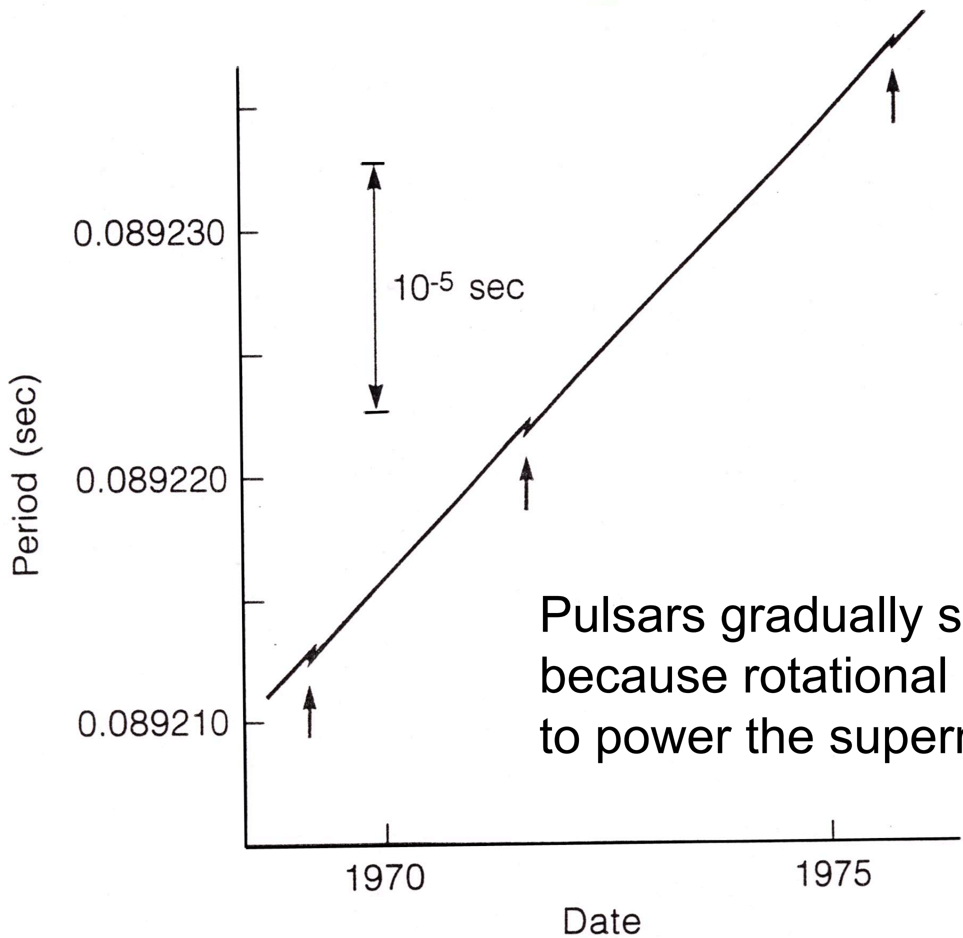


Distribution of Pulsars in Galactic Coordinates



This means that pulsars are in our Galaxy.

Pulsar glitches are caused by **starquakes**.



Pulsars gradually slow down, because rotational energy is used up to power the supernova remnant.

Sometimes a pulsar suddenly speeds up by a small amount. This is called a glitch. Three glitches in the period of the Vela pulsar happened in the above 8 years.

Pulsar Oddities

The crust of a neutron star is solid. Its highest mountains are only millimeters high. Why?

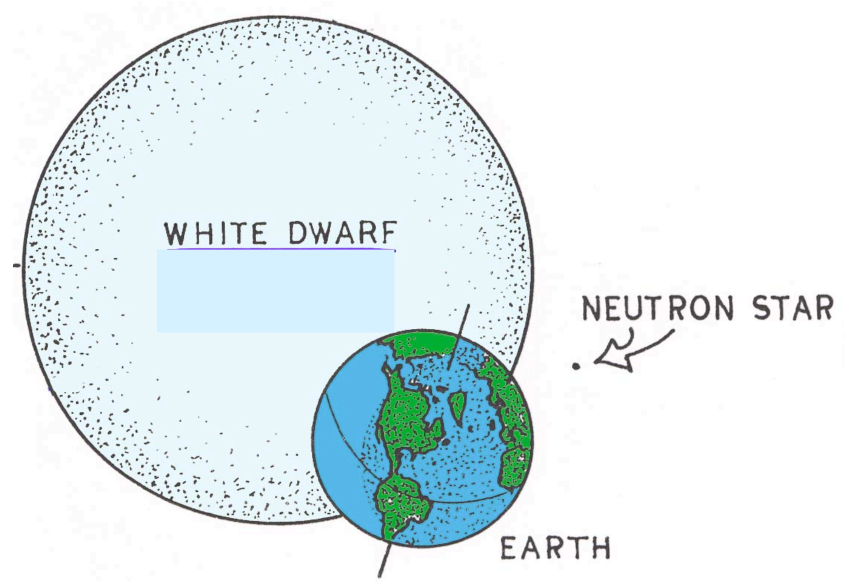
The surface gravity is so high that a 150 pound person would weigh a million tons. You would be squeezed flatter than a piece of paper.

The fastest pulsar known has a period of 0.0014 s. The star spins 642 times per second. Dozens of such “millisecond pulsars” are known. More are being discovered.

In 1974, J. H. Taylor and R. Hulse (Princeton University) discovered a 0.059 s pulsar in a binary system with an orbital period of 7.75 hr. The orbital radius is only 700,000 km. The masses of the two stars are ~ 2 and 0.8 $M_\odot$. They are probably a neutron star and a white dwarf. The binary pulsar allows us to test general relativity. E. g., the orbit is contracting at the rate expected if the system were giving off gravitational waves. Hulse and Taylor won the 1993 Nobel Prize in physics.

The first planets outside our Solar System were discovered orbiting a pulsar. The orbital radii are 0.19 AU, 0.36 AU, and 0.47 AU. The masses are ≈ 0.013 M_{Earth}, 3.4 M_{Earth}, and 2.8 M_{Earth}. They are VERY UNEXPECTED!

Corpses of Stars



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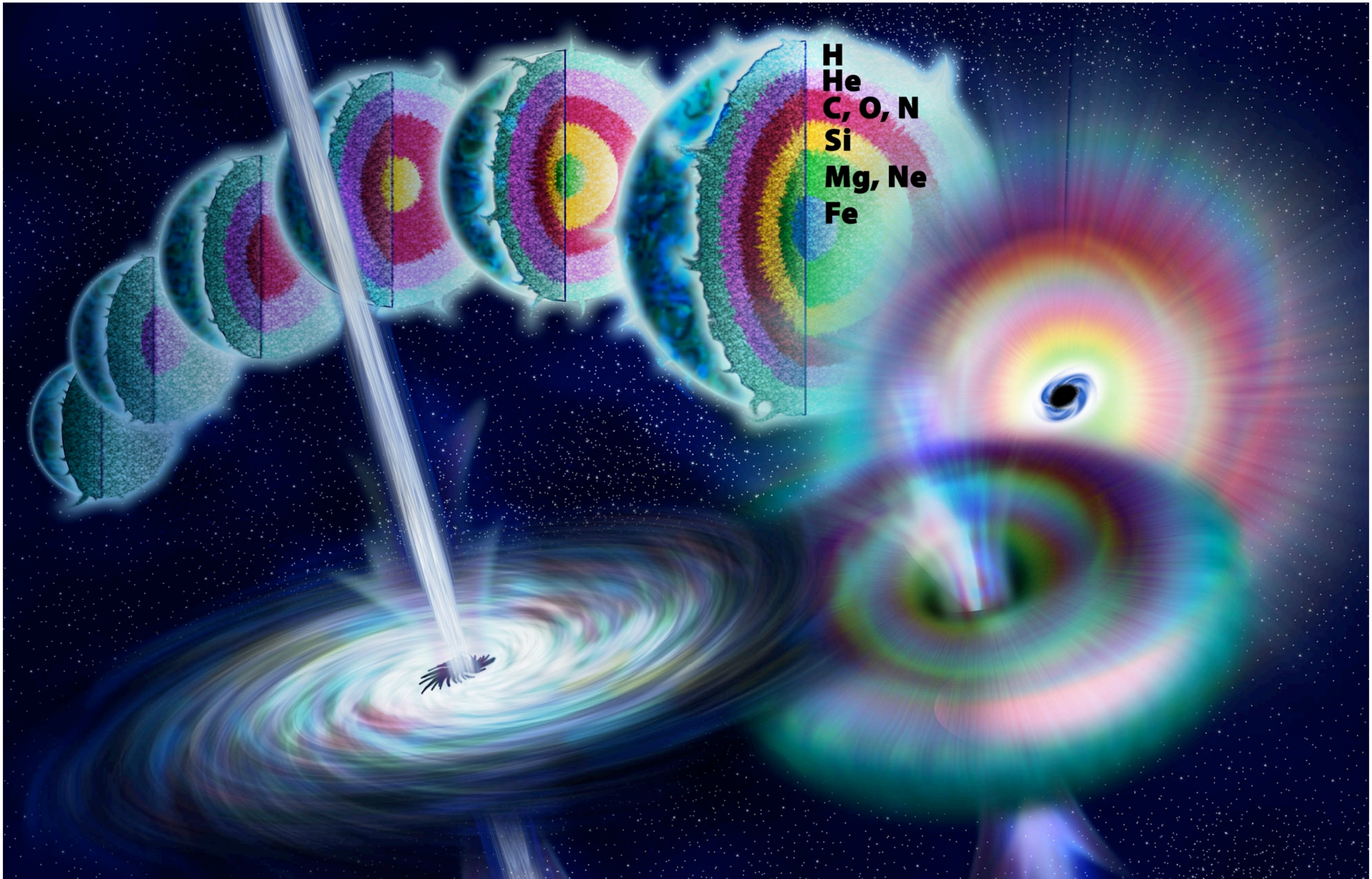


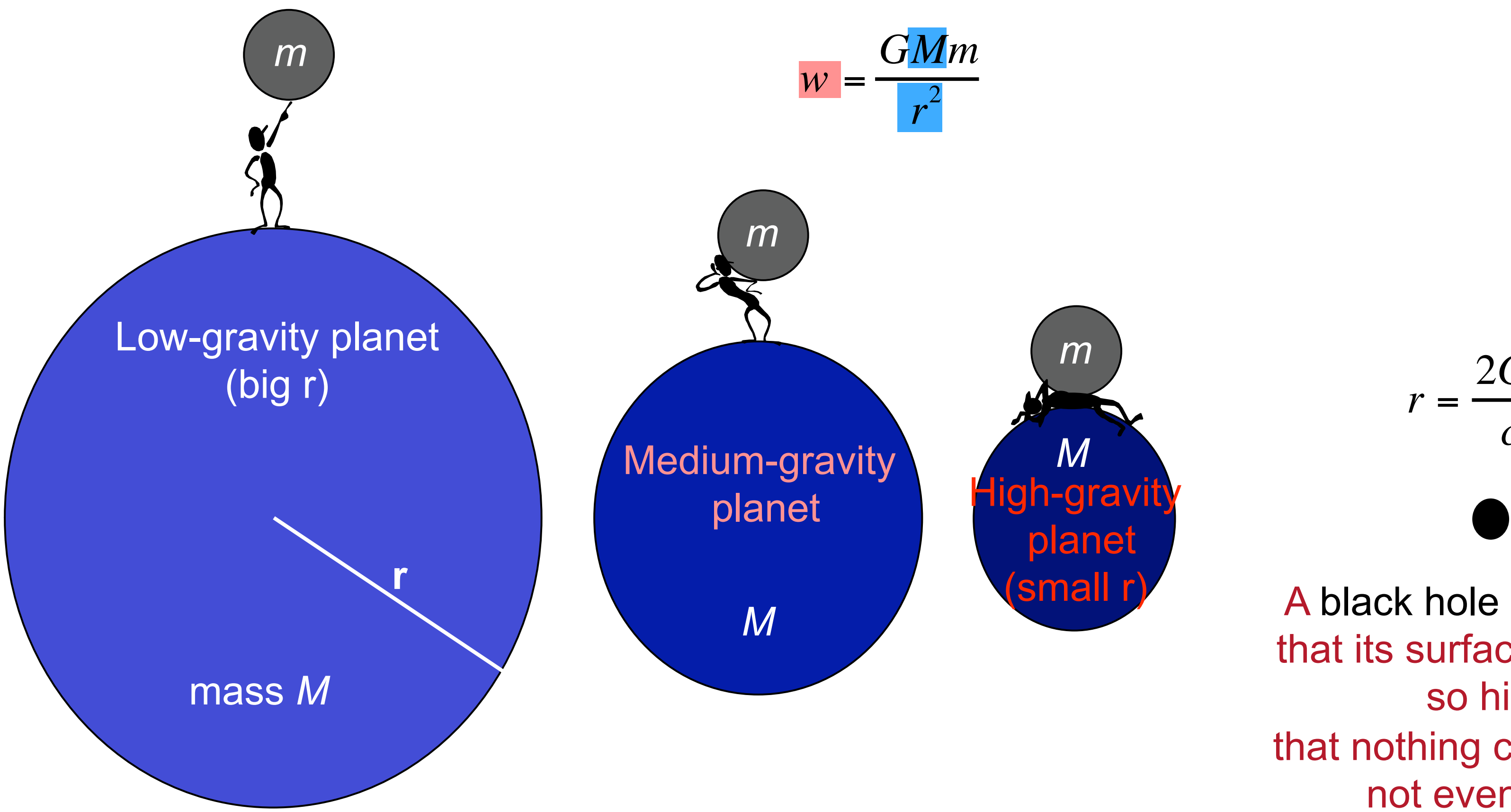
Stellar evolution to a supernova that produces a black hole and a gamma-ray burst

Black Hole

The gravitational force that an object of mass M exerts on something on its surface gets bigger as you make the object smaller.

Surface gravity is proportional to 1/radius^2.

$$w = \frac{GMm}{r^2}$$



$$r = \frac{2GM}{c^2}$$

A black hole is so small that its surface gravity is so high that nothing can escape, not even light.

To turn the Earth into a black hole,
we would have to squeeze it into the size of a grape.

Black holes with masses of a few Suns are well understood.

The most massive stars turn into such black holes when they die in supernova explosions.

The speed of light

$c = 2.997925 \times 10^{8}$ m s^{-1}

is a constant

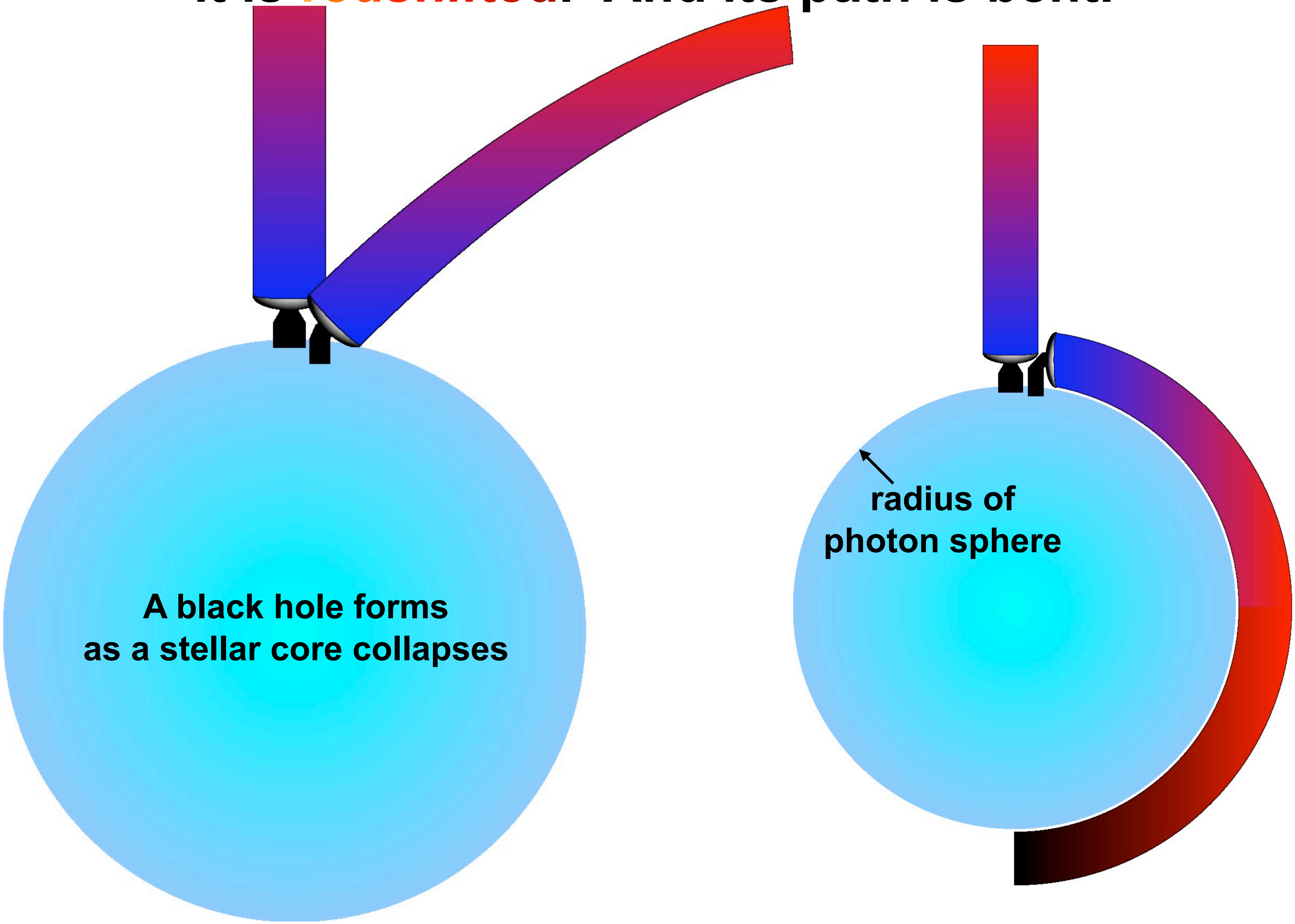
independent of the motion

of the observer

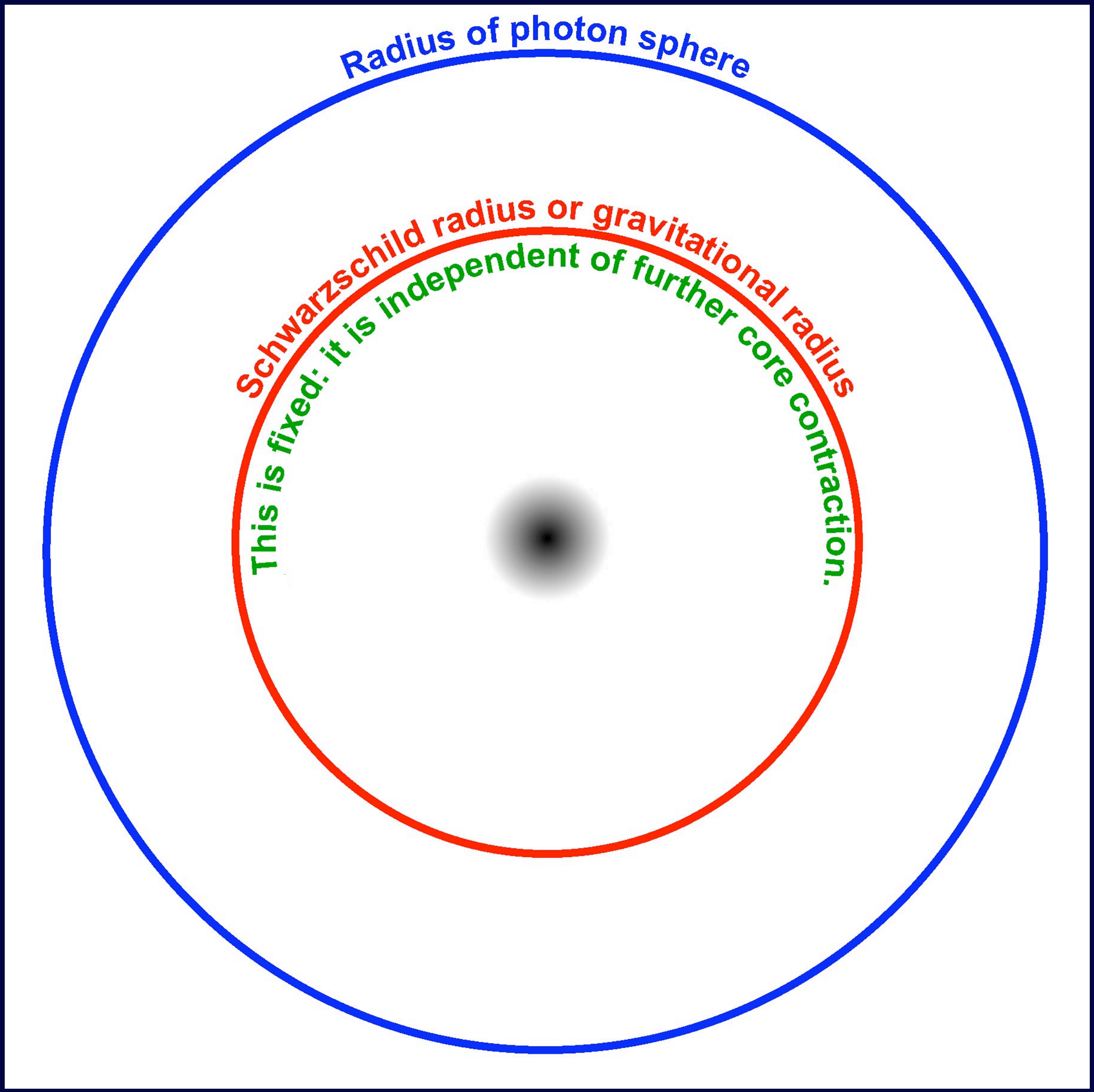
or the emitter.

So:

Light that fights gravity does not slow down; it is redshifted. And its path is bent.



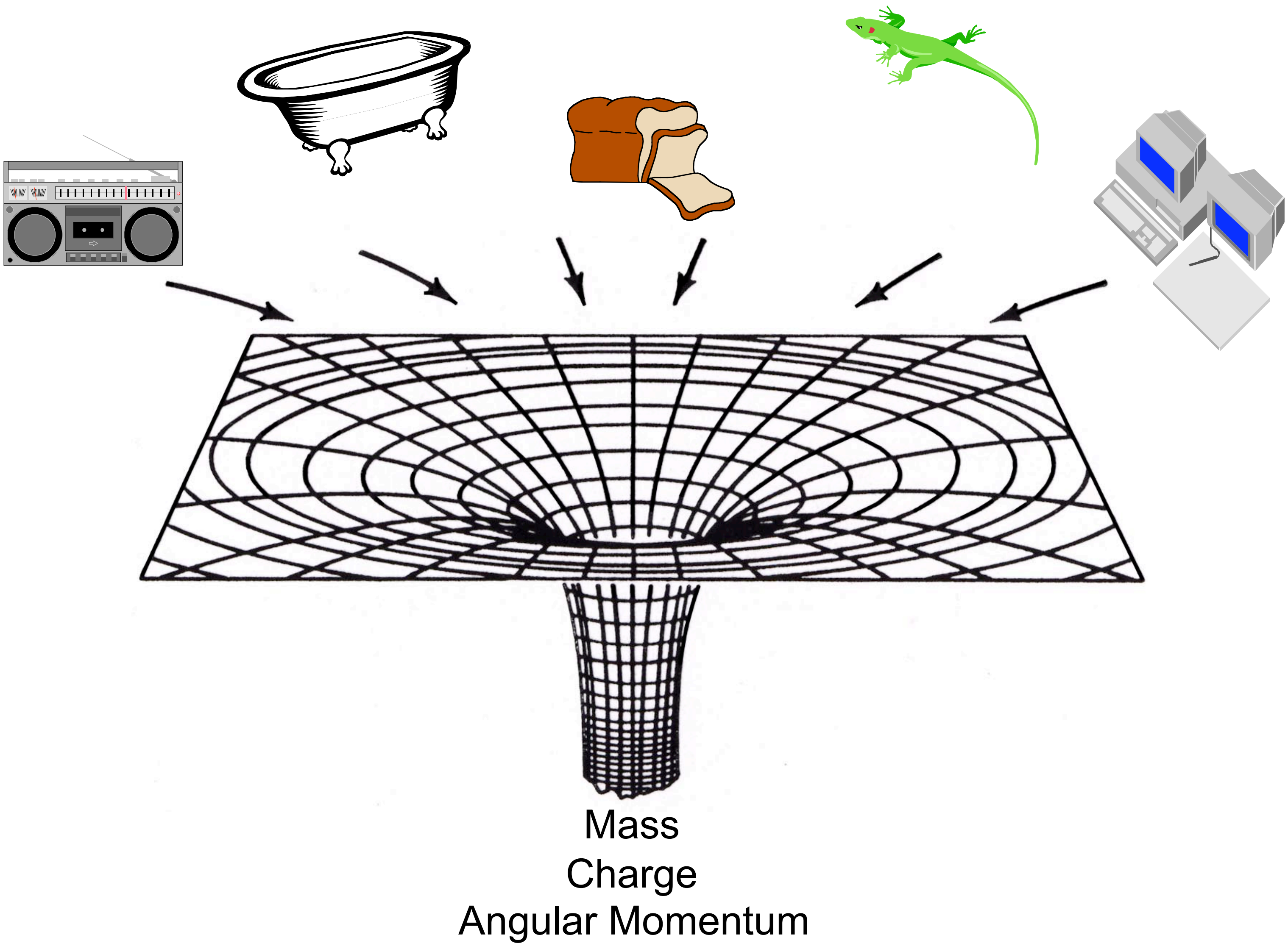
Black Hole



Once the core has shrunk inside its gravitational radius, nothing can prevent it from collapsing to a singularity (size = 0)!

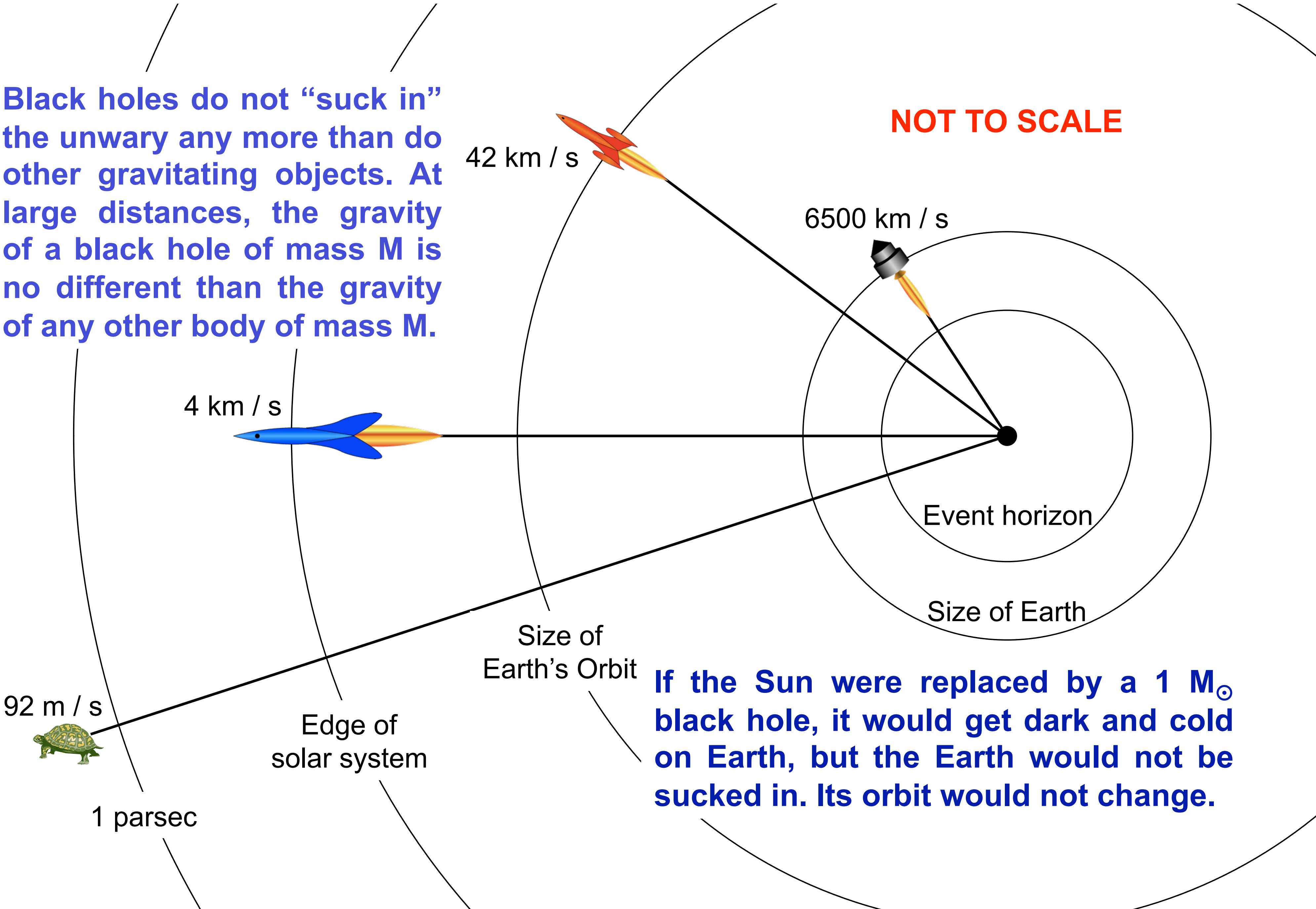
All physical laws
break down
at a singularity.

“A black hole has no hair.”



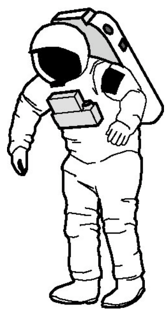
Black Hole Escape Velocity

Black holes do not "suck in" the unwary any more than do other gravitating objects. At large distances, the gravity of a black hole of mass M is no different than the gravity of any other body of mass M.

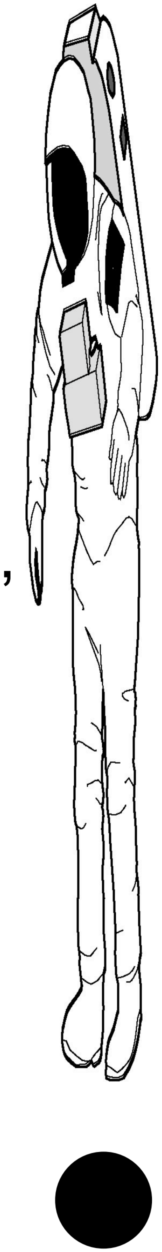


If the Sun were replaced by a 1 $M_{\odot}$ black hole, it would get dark and cold on Earth, but the Earth would not be sucked in. Its orbit would not change.

Gravitational Tides



200 km from a stellar-mass black hole, a human body would be torn apart by tidal forces.



Do Black Holes Exist?

We are confident that very massive black holes exist at the centers of most galaxies.

Black holes of a few solar masses are believed to form when massive stars undergo core collapse if the collapsed core exceeds the maximum of ~ 3 $M_{\odot}$ permitted for neutron stars. The best evidence for such black holes comes from **binary stars**.

Single-line spectroscopic binaries

Some stars have spectral lines that shift back and forth periodically. Most such systems show two sets of lines, one from each star. But in others, we cannot see any light from one of the stars. If the dark star has a mass greater than 3 $M_{\odot}$, then it is a black hole.

Irregular X-ray sources

Just like a neutron star, a black hole can attract matter from an ordinary star. This matter settles into an accretion disk around the hole and slowly spirals in, radiating X-rays as it does so. Cygnus X-1 is the best black hole candidate. Its X-rays are emitted from the vicinity of an object with a mass of 5 to 10 $M_{\odot}$ and a diameter of less than 300 km. Such an object is almost certainly a black hole.

Cygnus X-1

Cygnus X-1’s brightness “flickers” in a thousandth of a second. For something to blink so quickly, it must be very small, less than 200 miles in diameter.

In 1971, radio astronomers measured the position of Cygnus X-1 accurately.
It coincides with the giant blue star HDE 226868.
Such a large star could not be the source of X rays that flicker so rapidly.
So … what is the source?

Spectra show that HDE 226868 has an unseen companion.
The two objects rotate around each other in 5 $^{1}/_{2}$ days.
Kepler’s third law tells us that the mass for the companion is more than 4 times the mass of our Sun. But no light from the companion is visible.

Astronomers believe that the companion of HDE 226868 is a black hole.

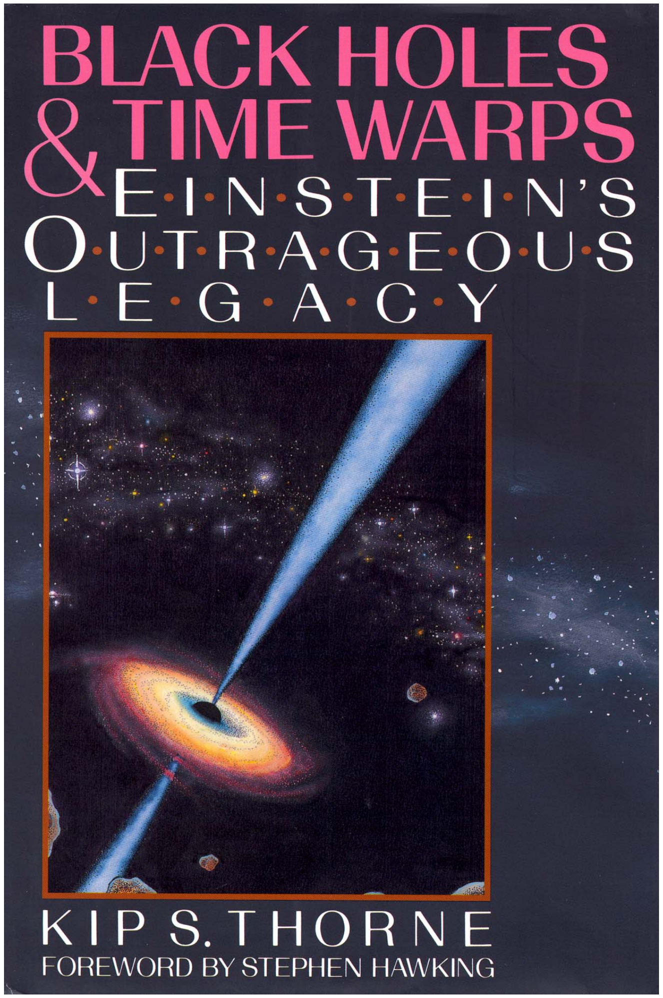
CYGNUS–X1 *Black hole*

Tens of millions of stellar-mass black holes are floating unseen among the billions of stars in our Galaxy.

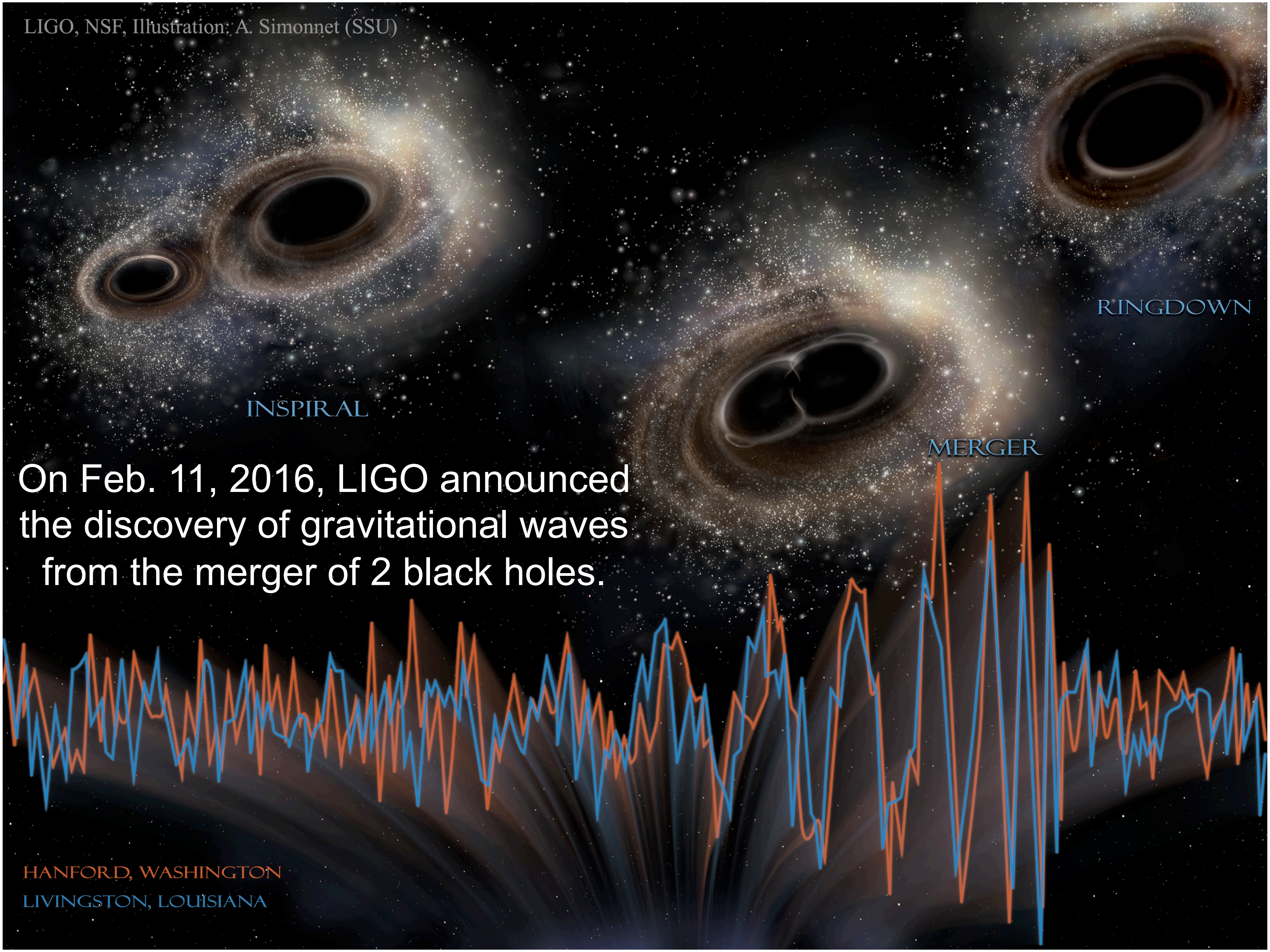
Supermassive Black Holes

For more information about supermassive black holes,
see http://chandra.as.utexas.edu/bhsearch.html
and especially the "review article for the general public" there.

For more information about black holes in general, I recommend:



Kip Thorne,
Feynman Professor of
Physics Emeritus at Caltech,
produced the movie
Interstellar.

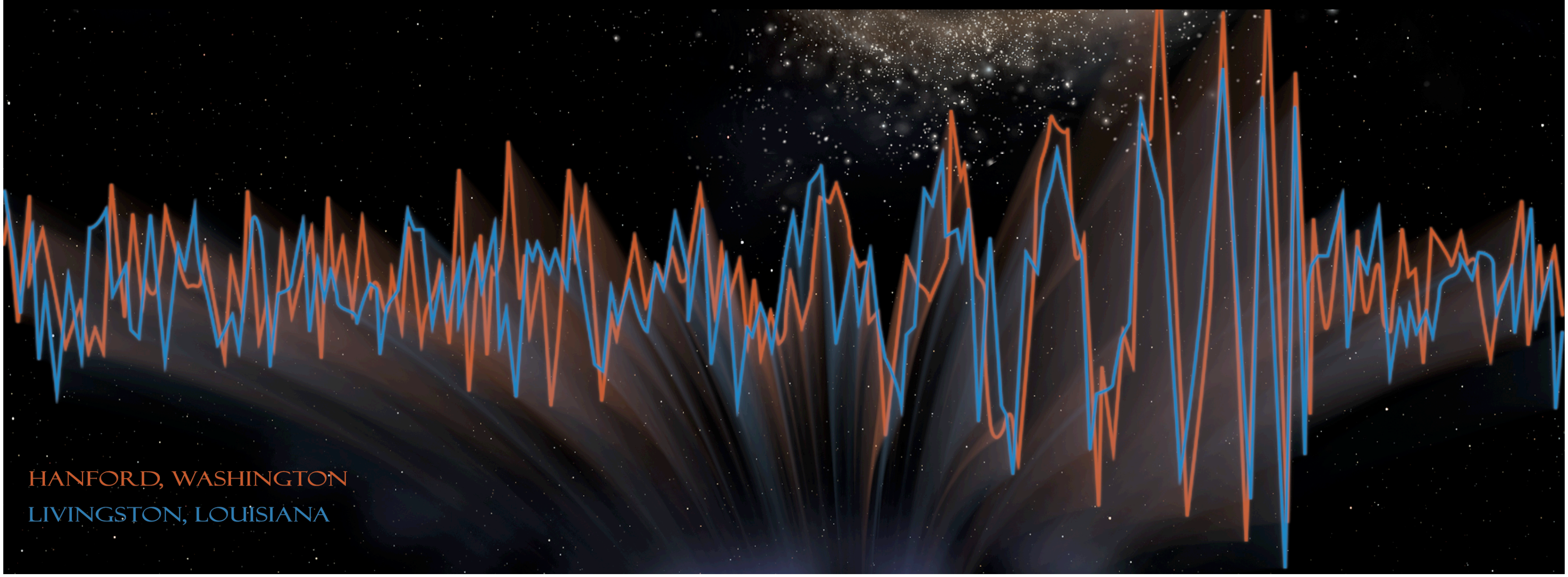

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
On Feb. 11, 2016, LIGO announced the discovery of gravitational waves from the merger of 2 black holes.
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

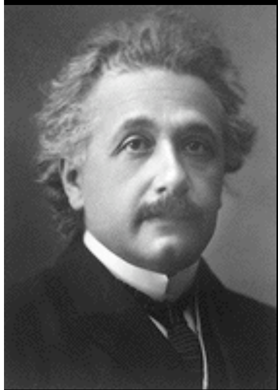
Distance to the merging black holes ≈1.3 billion light years!

Signal = wiggle in 2.5-mile-long arm of LIGO by 4/1000 of proton diameter. Equivalent to wiggle in distance to α Cen of width of human hair in 4.3 lyr.

Data sequence is 0.3 sec long and includes the inspiral from ~30 orbits per second to ~ 250 orbits per second when black hole speeds ≈ ½ speed of light.

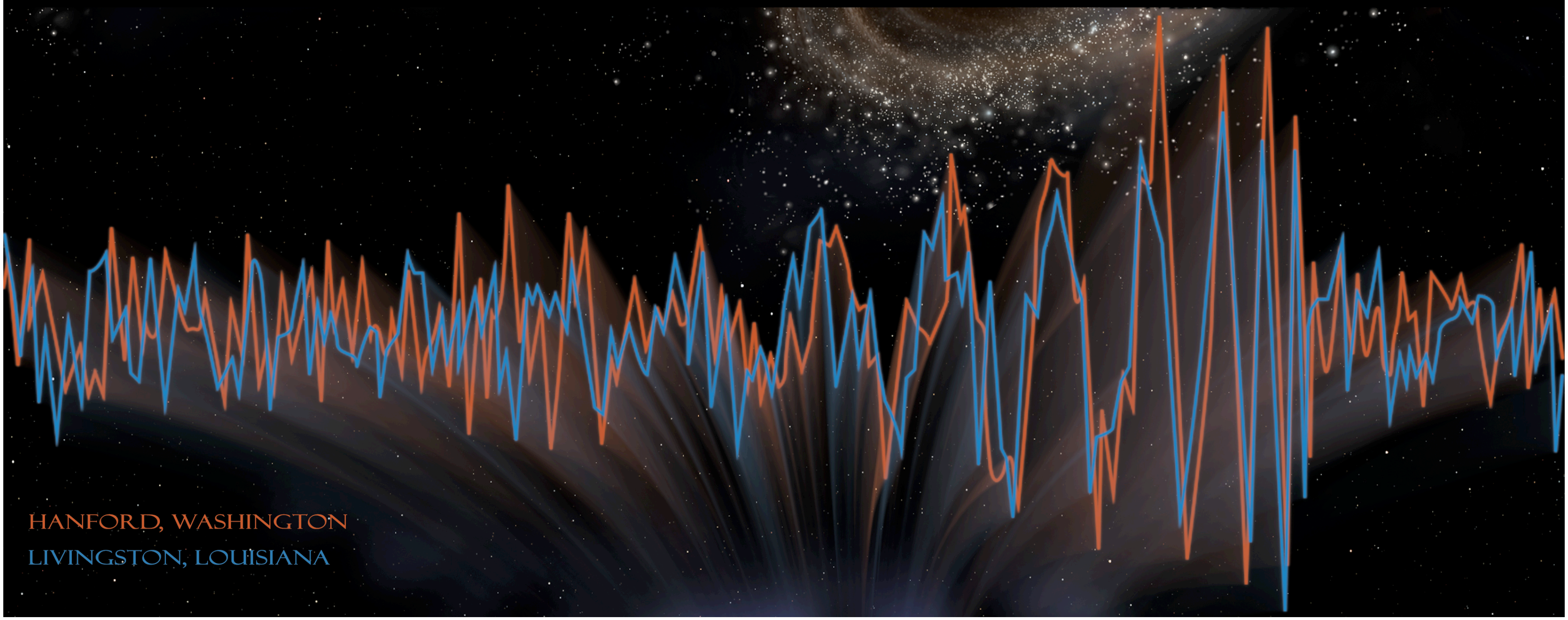
Black holes with masses 29 and 36 $M_\odot$ merged into 62 $M_\odot$ black hole; $3M_\odot c^2$ of energy was radiated in gravitational waves at a maximum power ≈ 50 times total power of all stars in observable Universe.





This is robust proof that black holes exist.

It is a successful test of
Einstein's 1916 prediction of gravitational waves
based on his General Theory of Relativity.



And this is a “window” on the origin of supermassive black holes:

Biggest stars in the early Universe were bigger then the biggest stars now.
When they died as supernovae, they left behind bigger black holes
than the typical 10-$M_\odot$ black holes now.

We believe that supermassive black holes got their start
because many stellar-mass black holes merged together
when protogalactic fragments merged to build today’s galaxies.