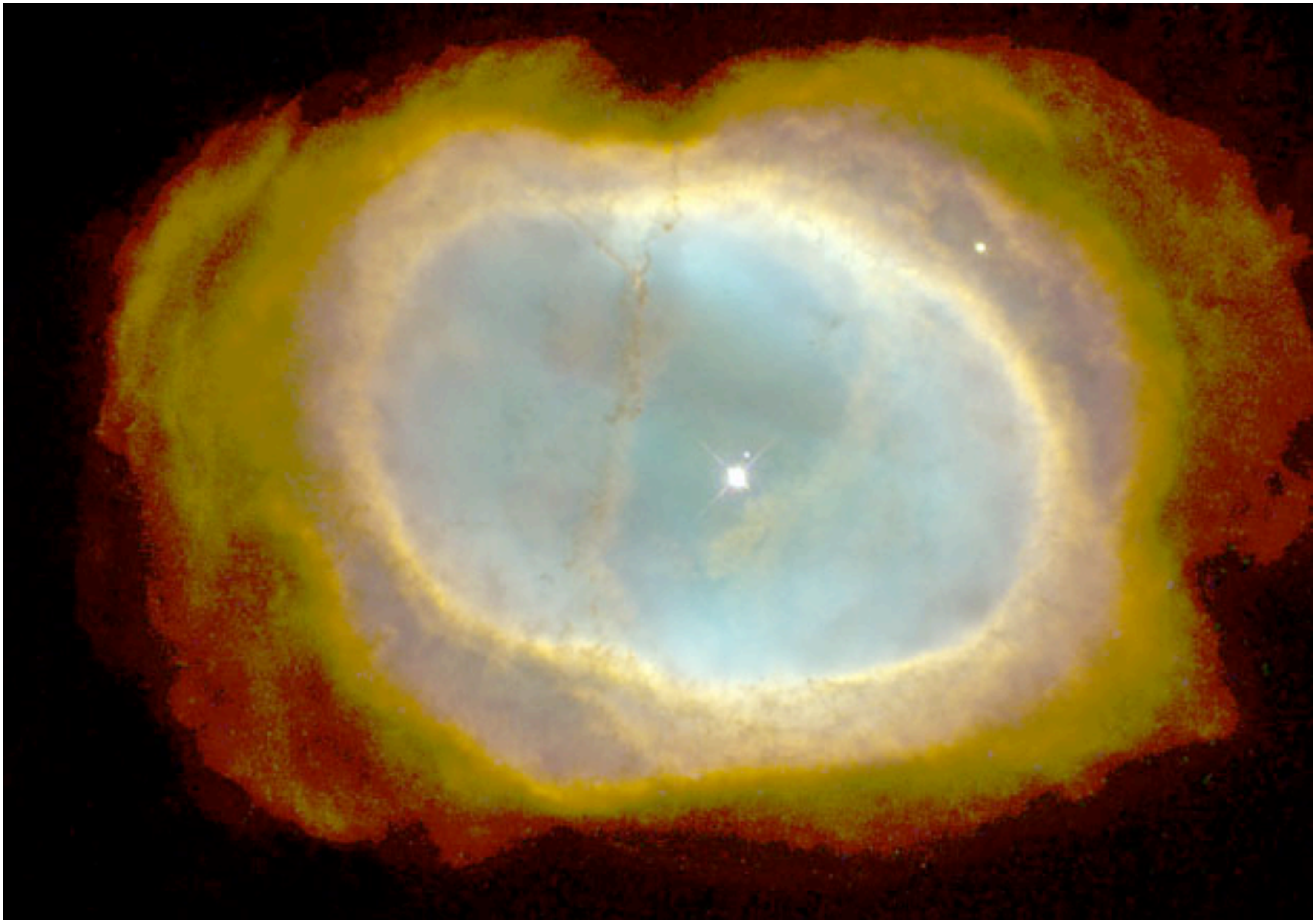
White Dwarf



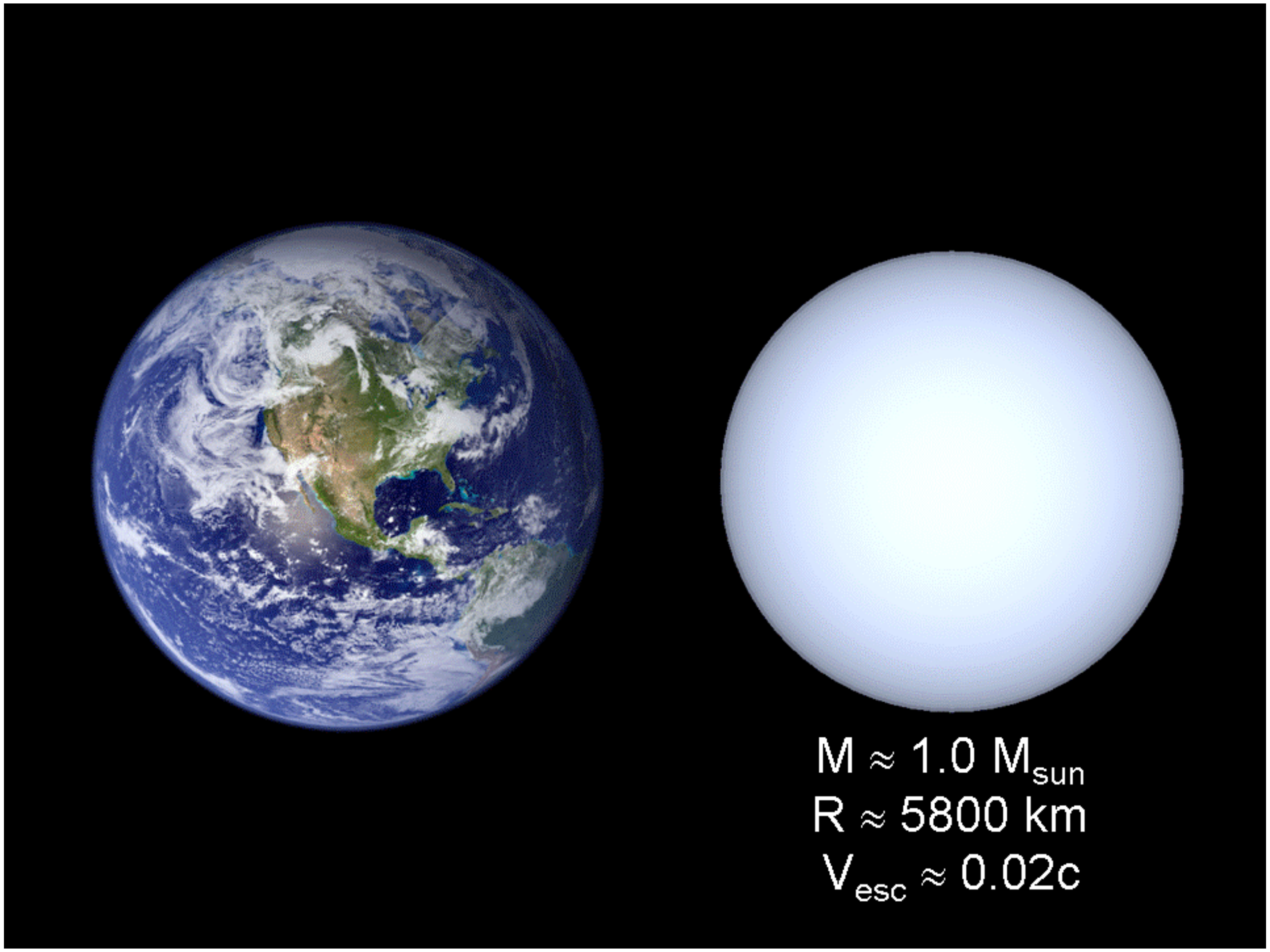
Properties of a White Dwarf

- Contains most of star's original mass
- Yet diameter is roughly Earth's diameter
- Density about 3×10^9 kg/m^3
  - ✶ One teaspoon would weigh 15 tons
  - ✶ Surface gravity = 1.3×10^5 g
  - ✶ $v_{esc} = 0.02$ x speed of light
- $T_{eff} = 10{,}000$ K, $M_V = +11$ (Sun is +4.8)

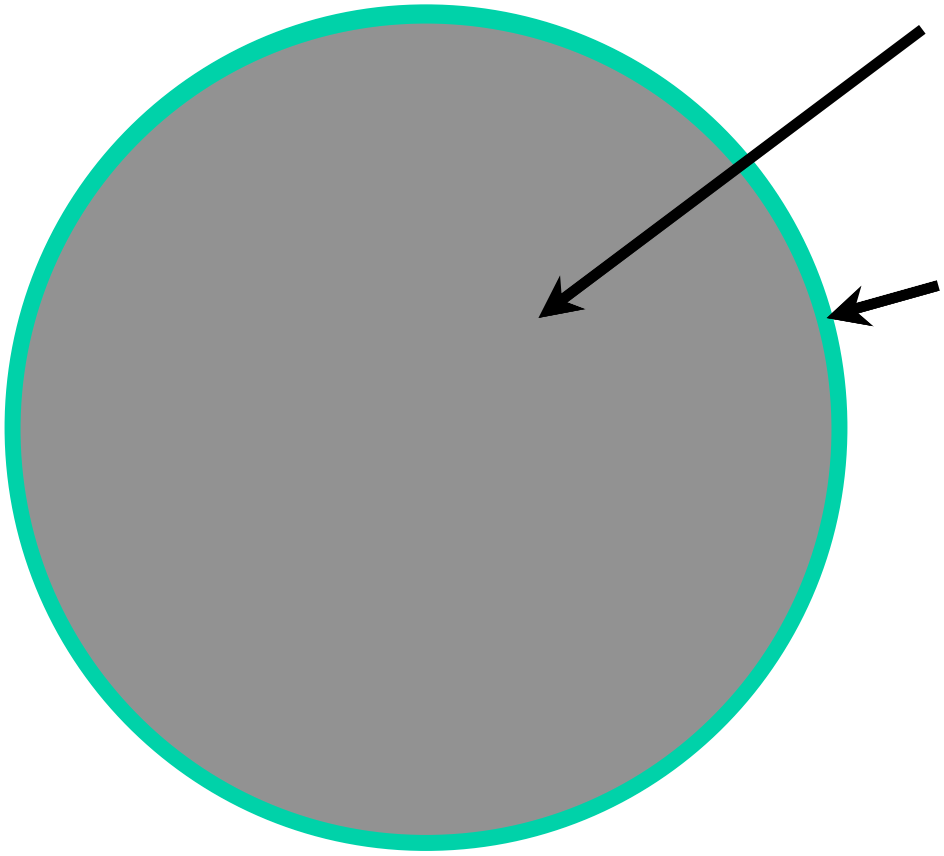
White Dwarf

- After planetary nebula dissipates, all that’s left is the hot degenerate core
- Remnant core of $M<8\ M_{sun}$ star
- $M<4M_{sun}$: C-O white dwarf (never ignited C)
- $M=4\text{-}8M_{sun}$: O-Ne-Mg white dwarf
- Supported by *electron degeneracy pressure*
- No fusion, no contraction, just cooling. For eternity.

Properties of a White Dwarf



Structure of isolated WD



Degenerate CO core
(5000 km)

Thin (100m) atmosphere

Structure of isolated WD

- At these densities, WD is supported by *electron degeneracy pressure*.
- This has a profound impact on its *structure* (M vs. R)

Structure of isolated WD

- WD consists of gas of ionized C+O nuclei and electrons (overall neutral)
- Electrons are *fermions*, i.e. spin±1/2 particles (protons & neutrons as well)
- 2 important quantum-mechanical things: Pauli exclusion principle; Heisenberg uncertainty principle

Structure of isolated WD

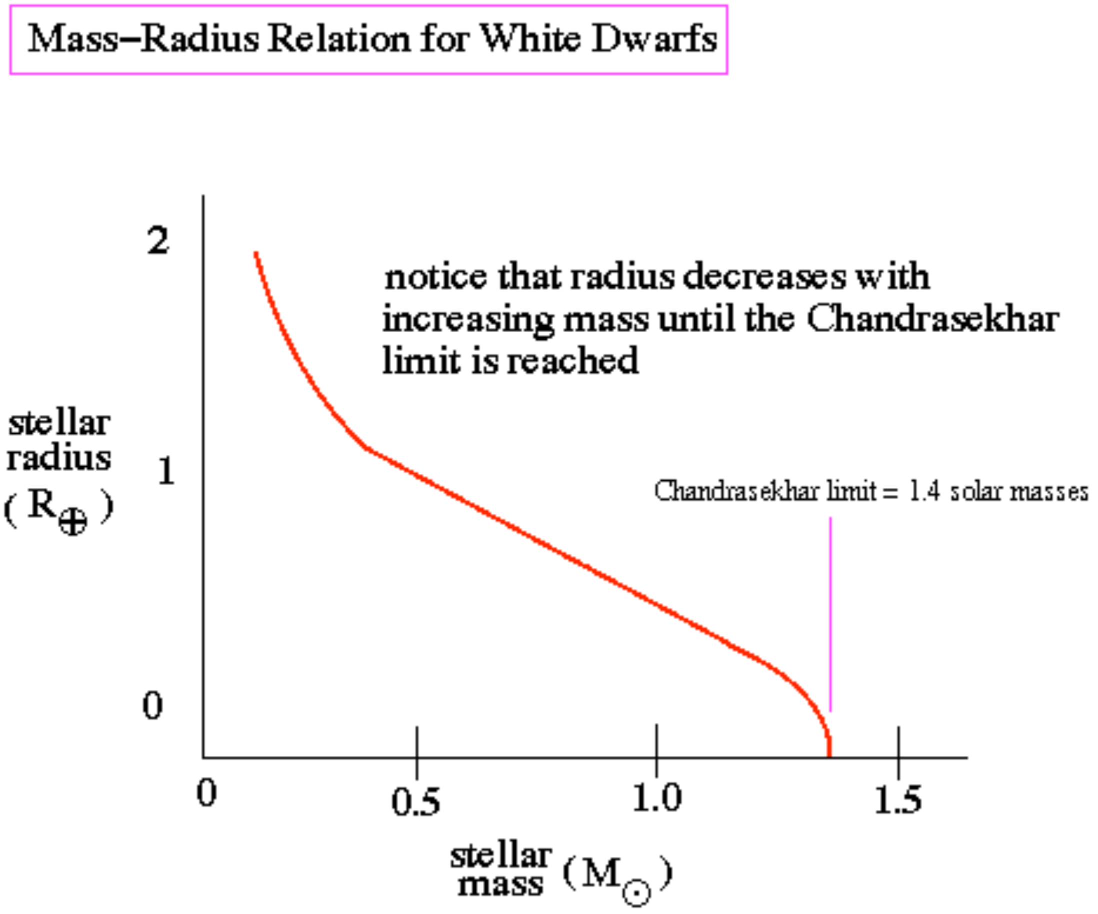
- **Pauli exclusion principle**: no 2 identical fermions can occupy exact same quantum mechanical state (e.g., energy, angular momentum, spin)

- **Heisenberg uncertainty principle**: it is impossible to define position and momentum simultaneously to accuracy better than ~Planck's constant for the product of the uncertainties:

$$(\Delta x)(\Delta p_x) \geq \hbar/2$$

p_x is x-component of momentum

Structure of isolated WD

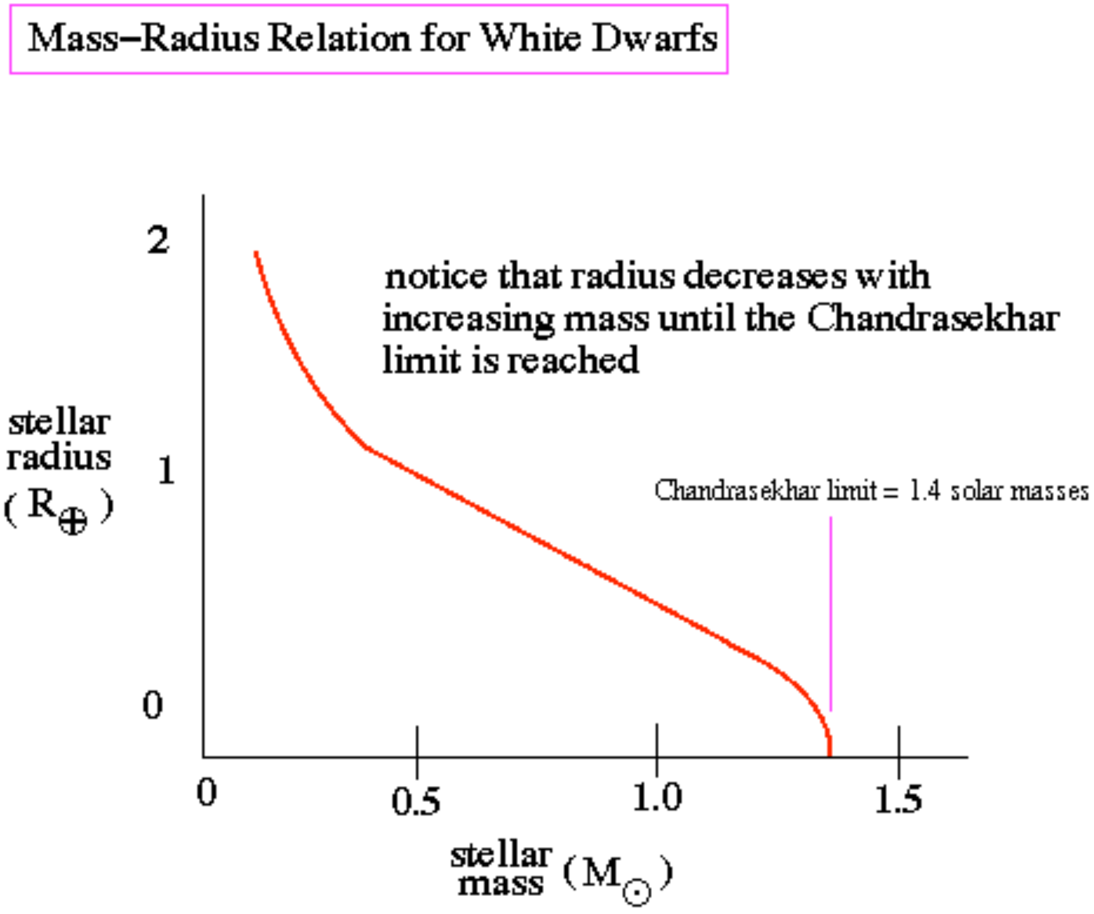


Chandrasekhar mass limit

There is an upper limit to the mass of a WD of 1.4 solar masses, set by electron degeneracy pressure…

Above this limit, WD is unstable

Upper limit on mass of white dwarfs

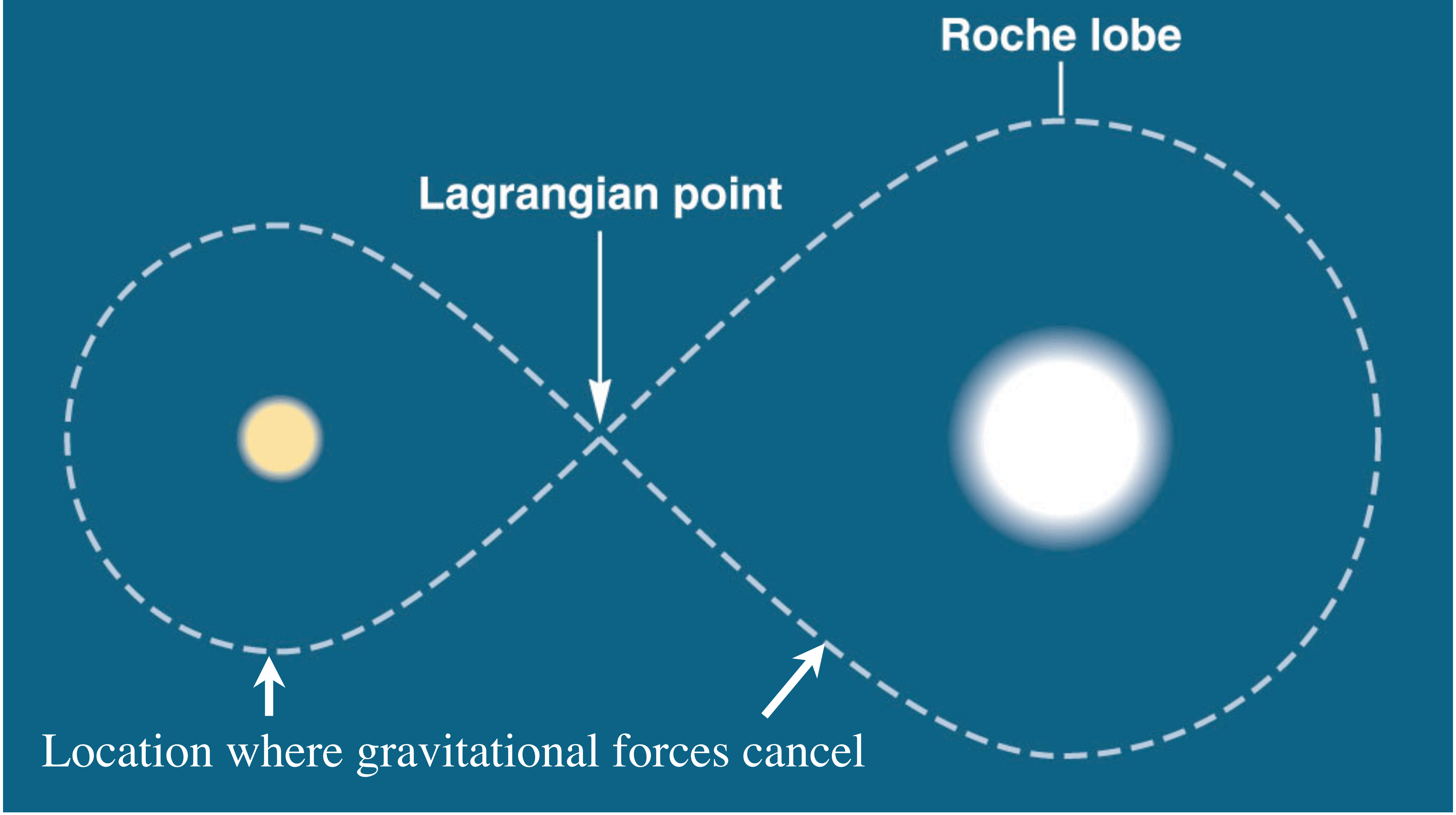


Electron degeneracy can't support more than 1.4 M_{sun}

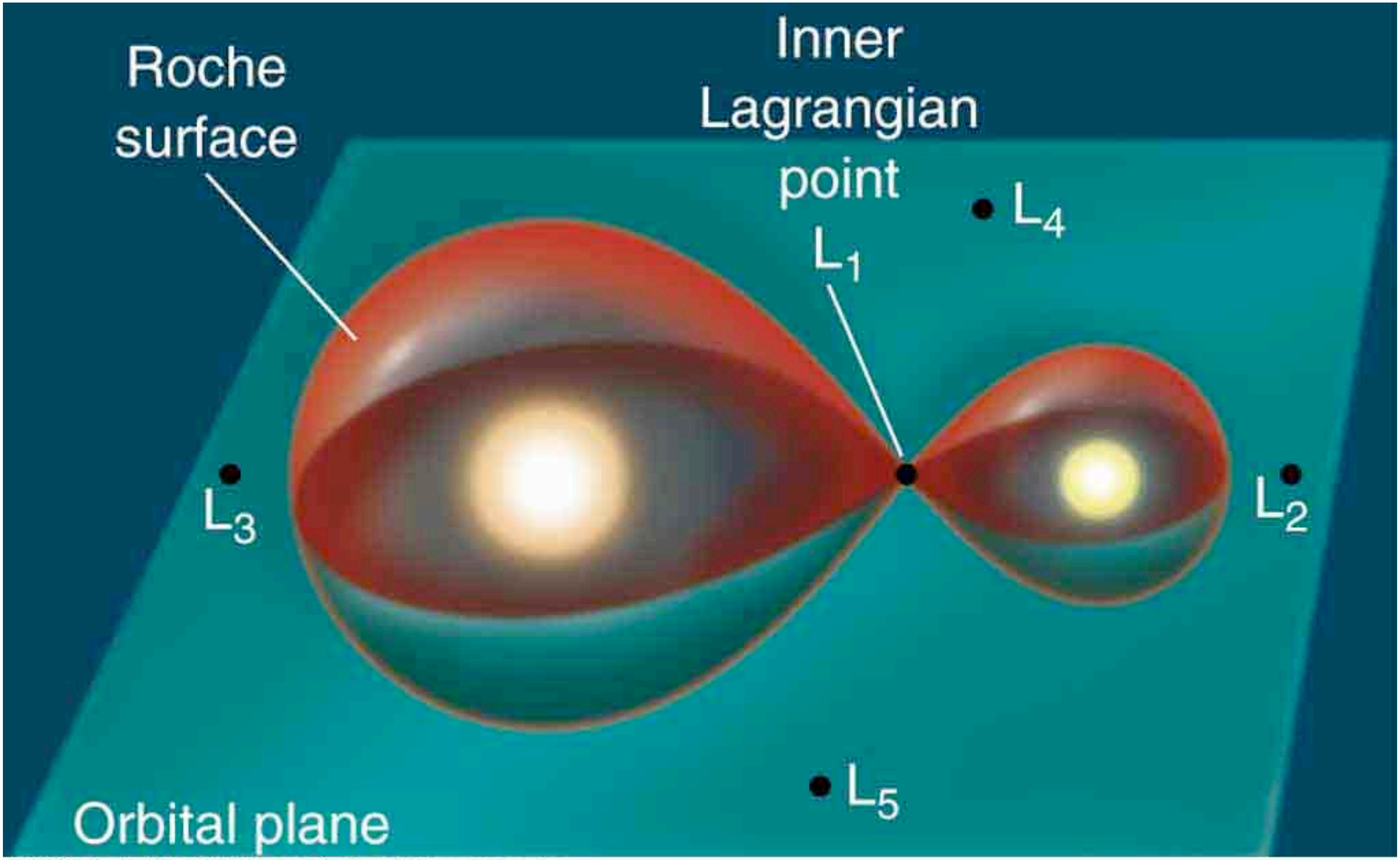
Mass transfer in binary systems

- Isolated white dwarf boring, simply cools forever (makes them good "clocks")
- White dwarfs in binary systems are more interesting
  - If binary stars are close enough (<1 AU), mass transfer can occur…

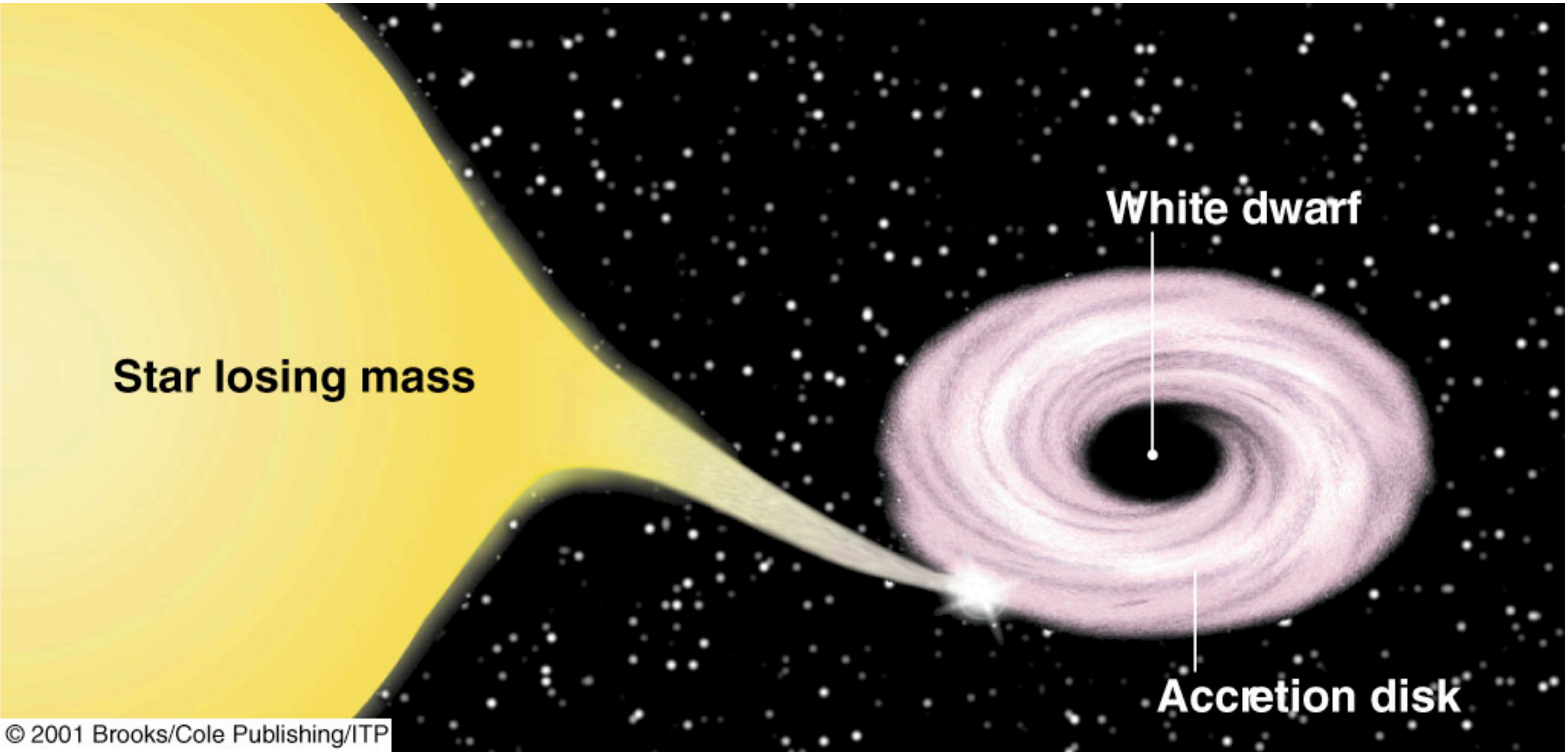
Stars in a binary system may have more complex evolution….



Location where gravitational forces cancel


Roche surface
Inner Lagrangian point
L_1
L_4
L_3
L_2
L_5
Orbital plane

Accretion on to white dwarf



Type Ia SN as white dwarf grows to M ~ 1.4 M_{sun}

Type Ia supernova

Thermonuclear explosion of entire WD near Chandrasekhar mass limit, with $L \sim 6 \times 10^9 L_{sun}$

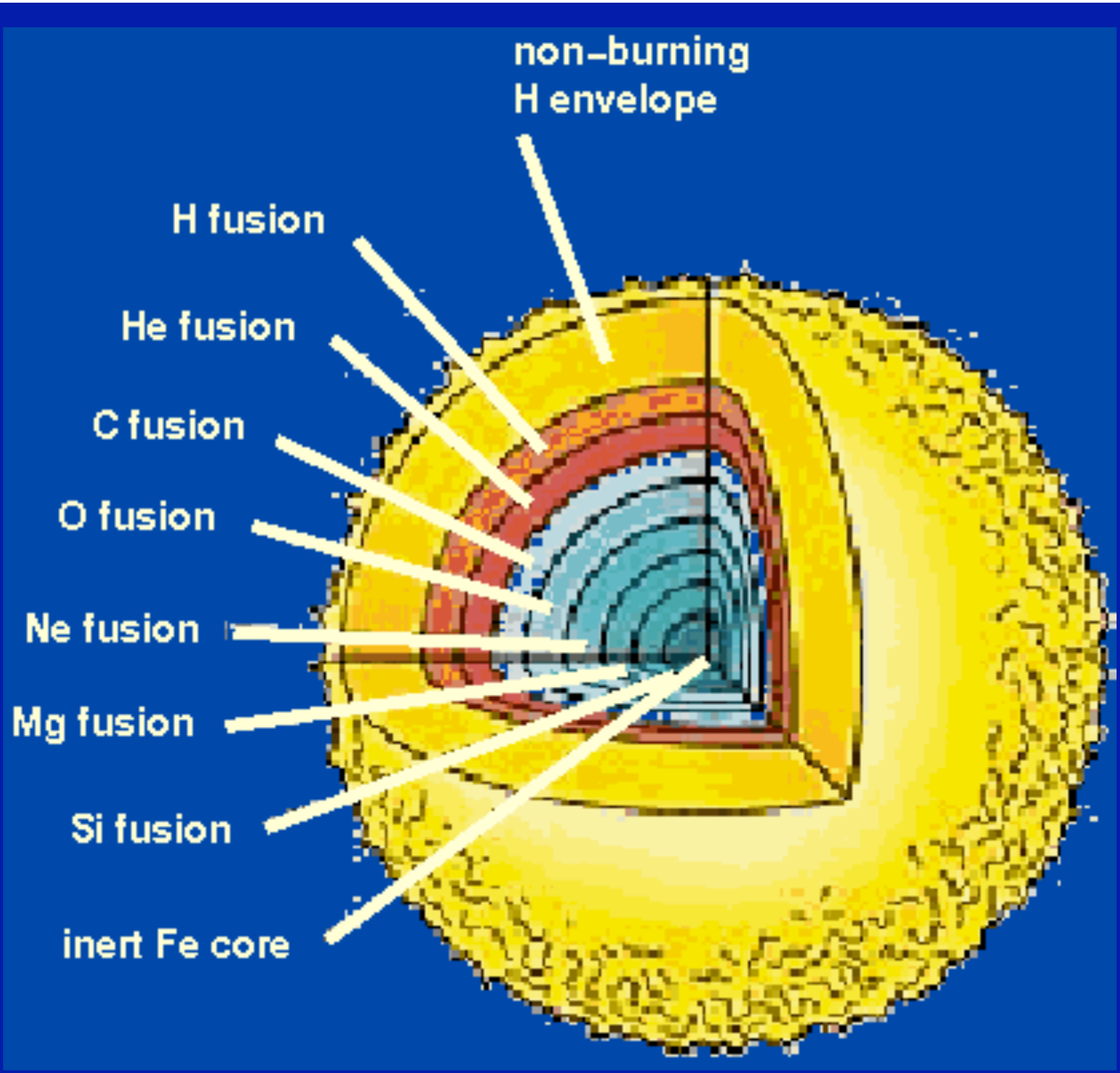
Since every Type Ia SN is the same size (~1.4 solar masses), they may be good *standard candles* for measuring distance

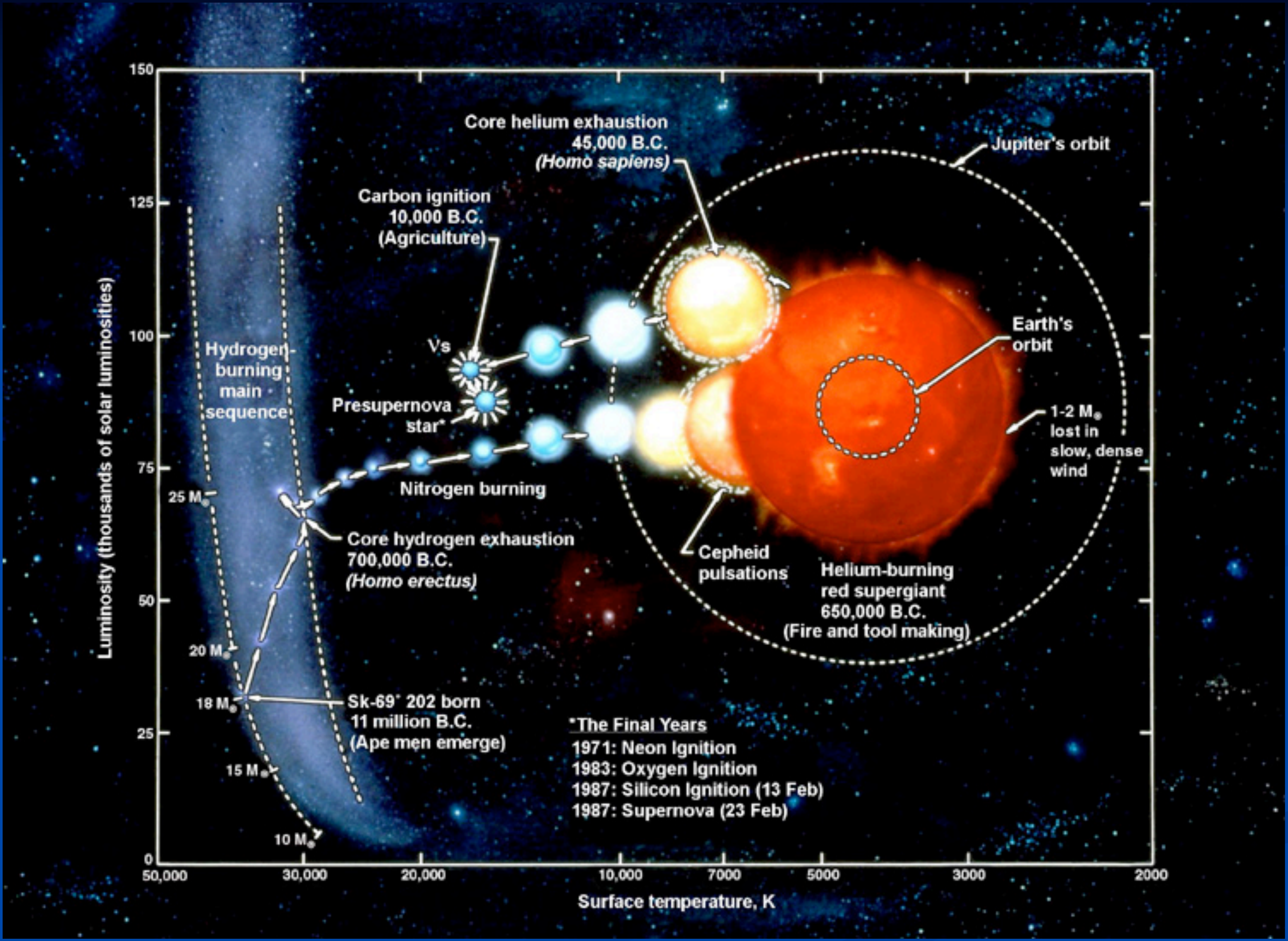
Standard candle is an object with known constant luminosity

SN1994D in NGC4526

Two ways to get a Supernovae

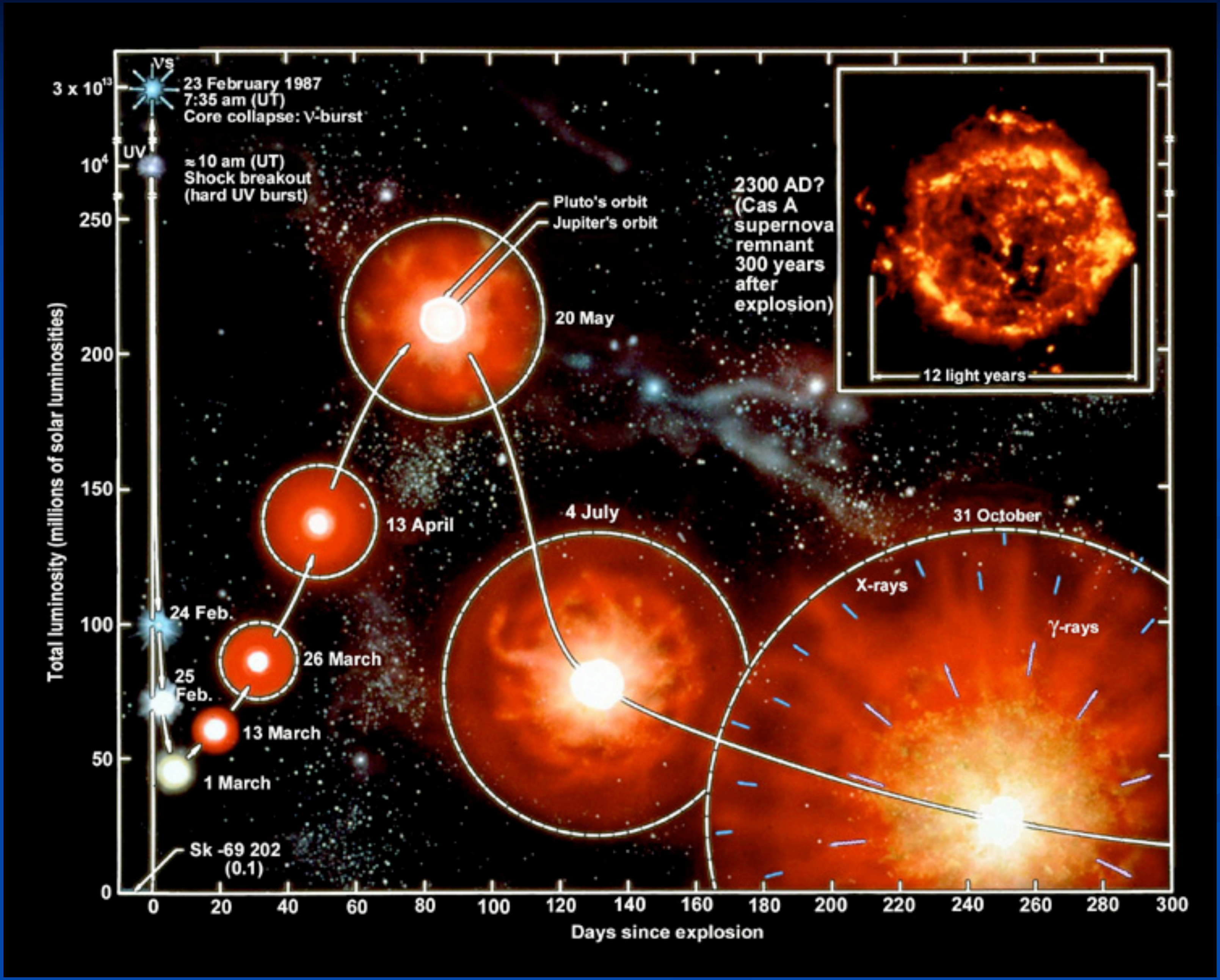
- Type Ia: WD explodes due to accretion from companion
  - ✶No hydrogen lines in spectrum
  - ✶Occur in old stellar populations
  - ✶Powered by nuclear burning (C -> Fe) @ 1.3 $M_\odot$
  - ✶Destroys WD (nothing left after explosion)
- Type II: Fe core collapse in high-mass star
  - ✶Hydrogen lines in spectrum
  - ✶Occur in regions of star formation
  - ✶Results in formation of NS (or perhaps BH)


non-burning
H envelope
H fusion
He fusion
C fusion
O fusion
Ne fusion
Mg fusion
Si fusion
inert Fe core

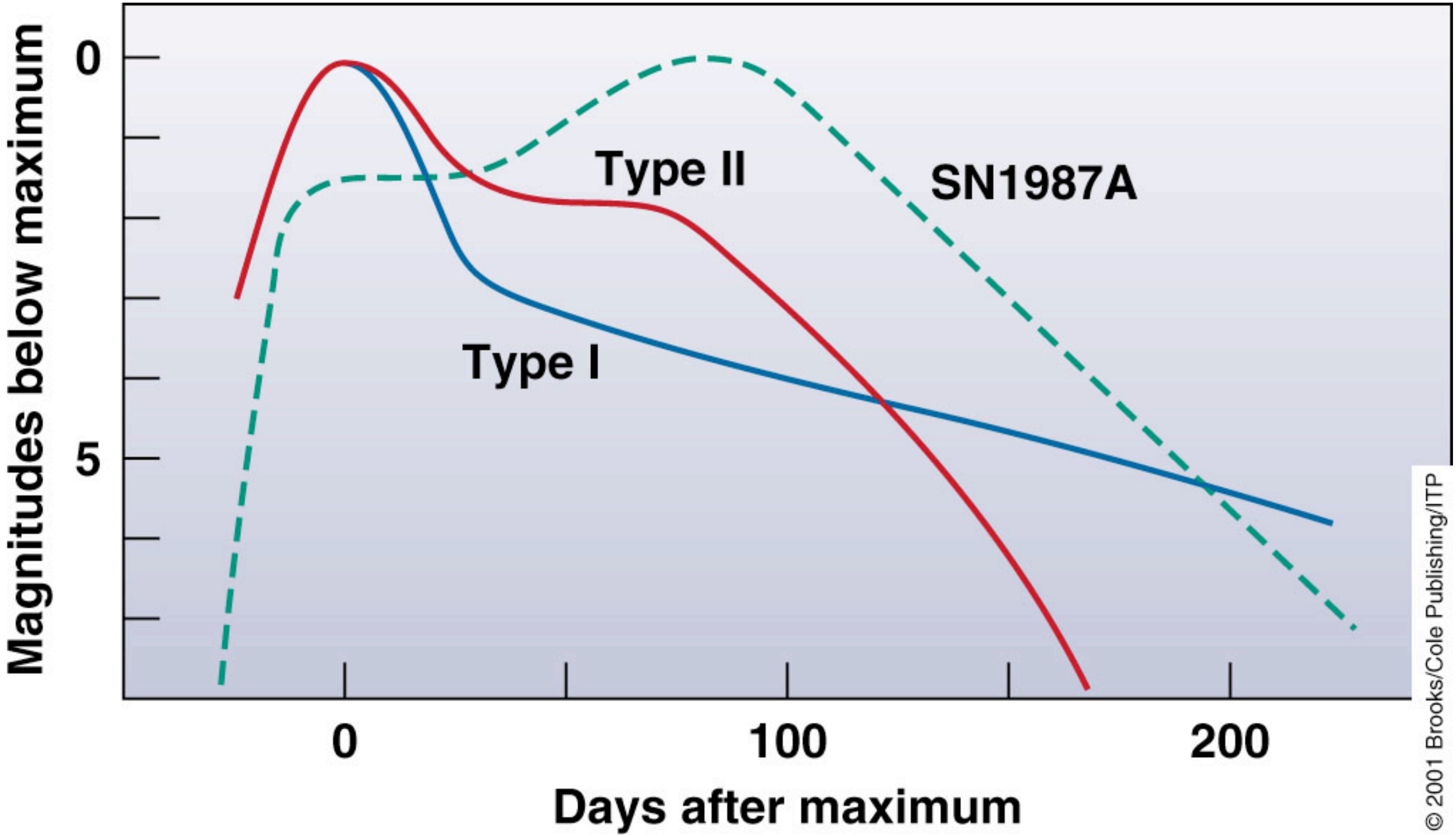


Courtesy of Tom Weaver

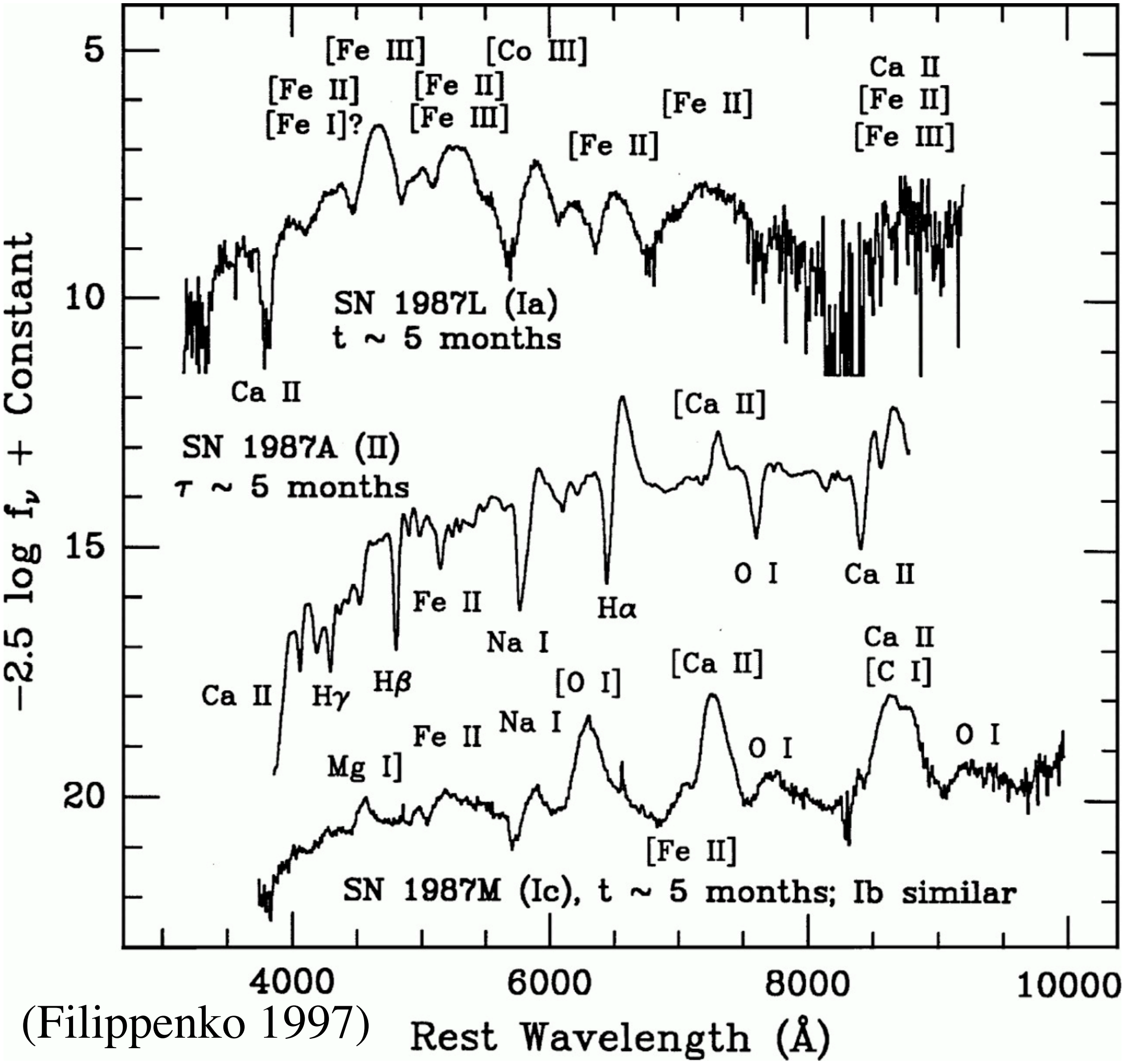
Core-Collapse Supernova Light Curve: SN1987A



Variation of Supernova Light



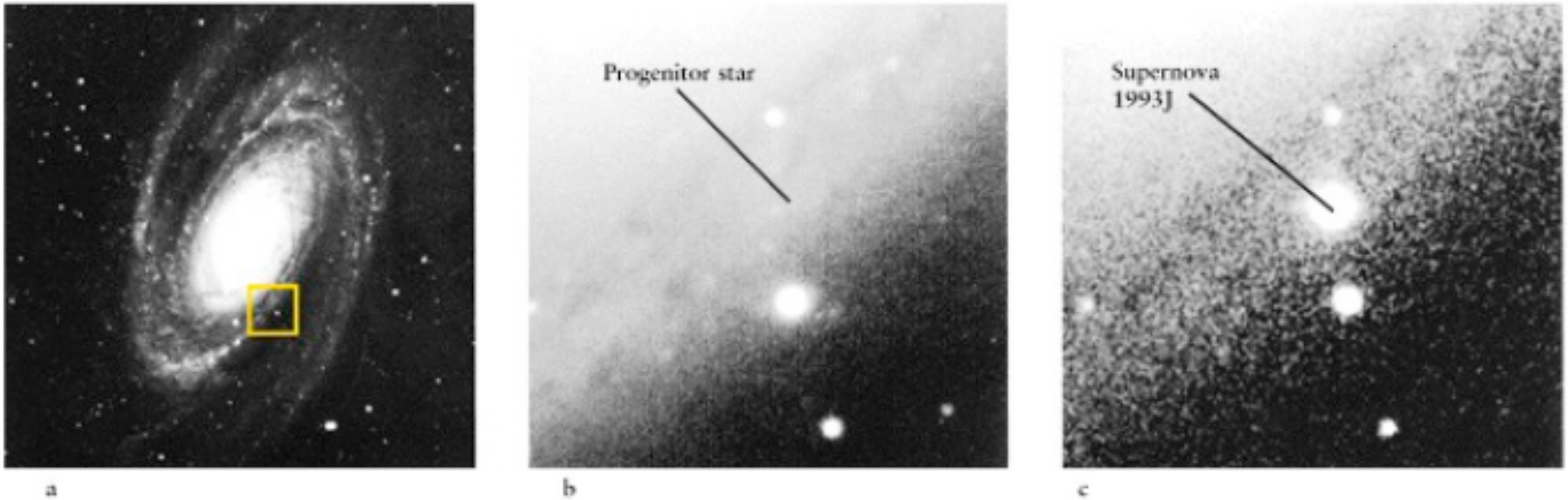
Types of Supernova Spectra



(Filippenko 1997)

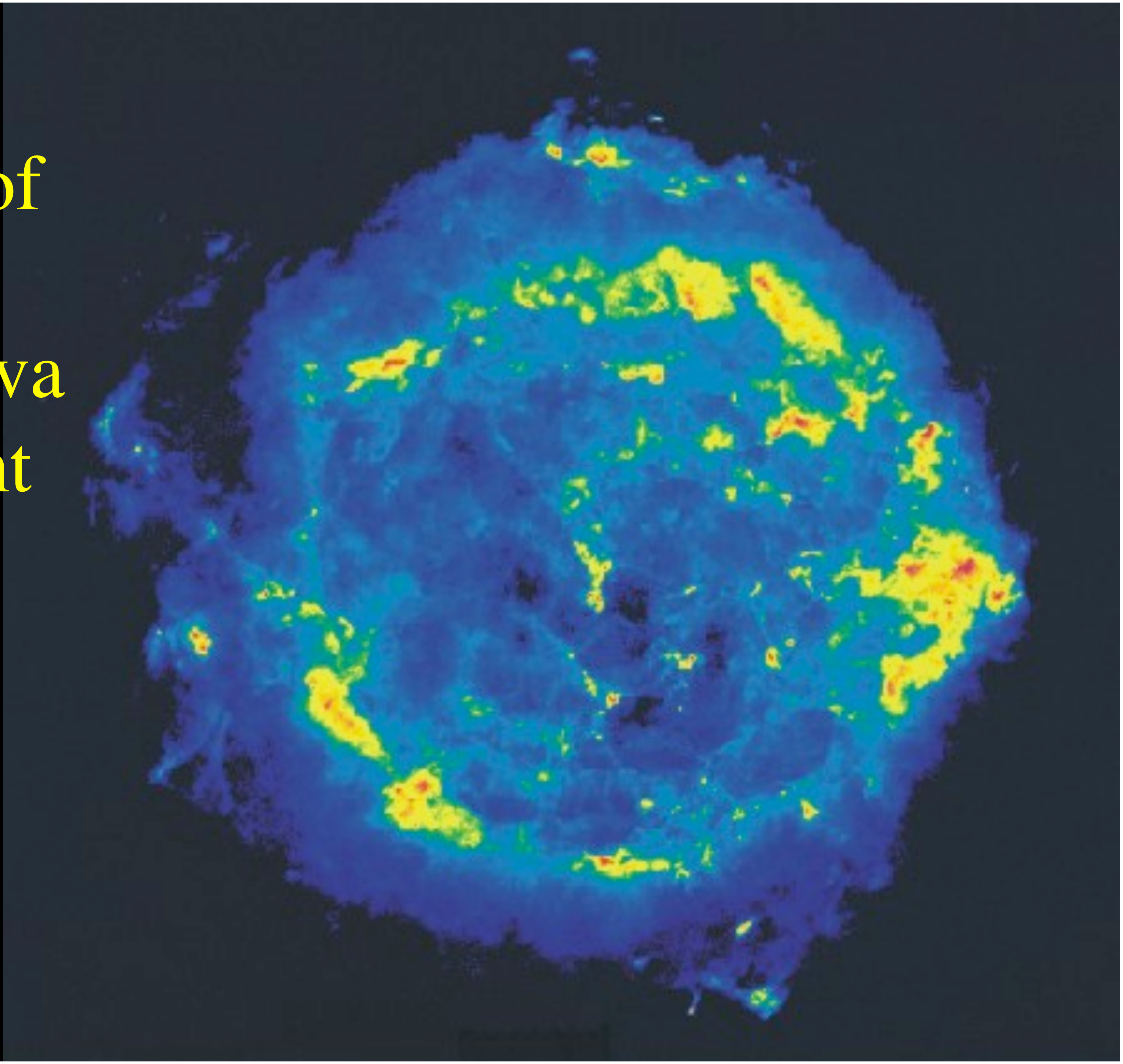
- **Type II** (core collapse) have H lines
- **Type I** (a,b,c) do not
- **Type II** and **Type Ib,c** probably from massive star death

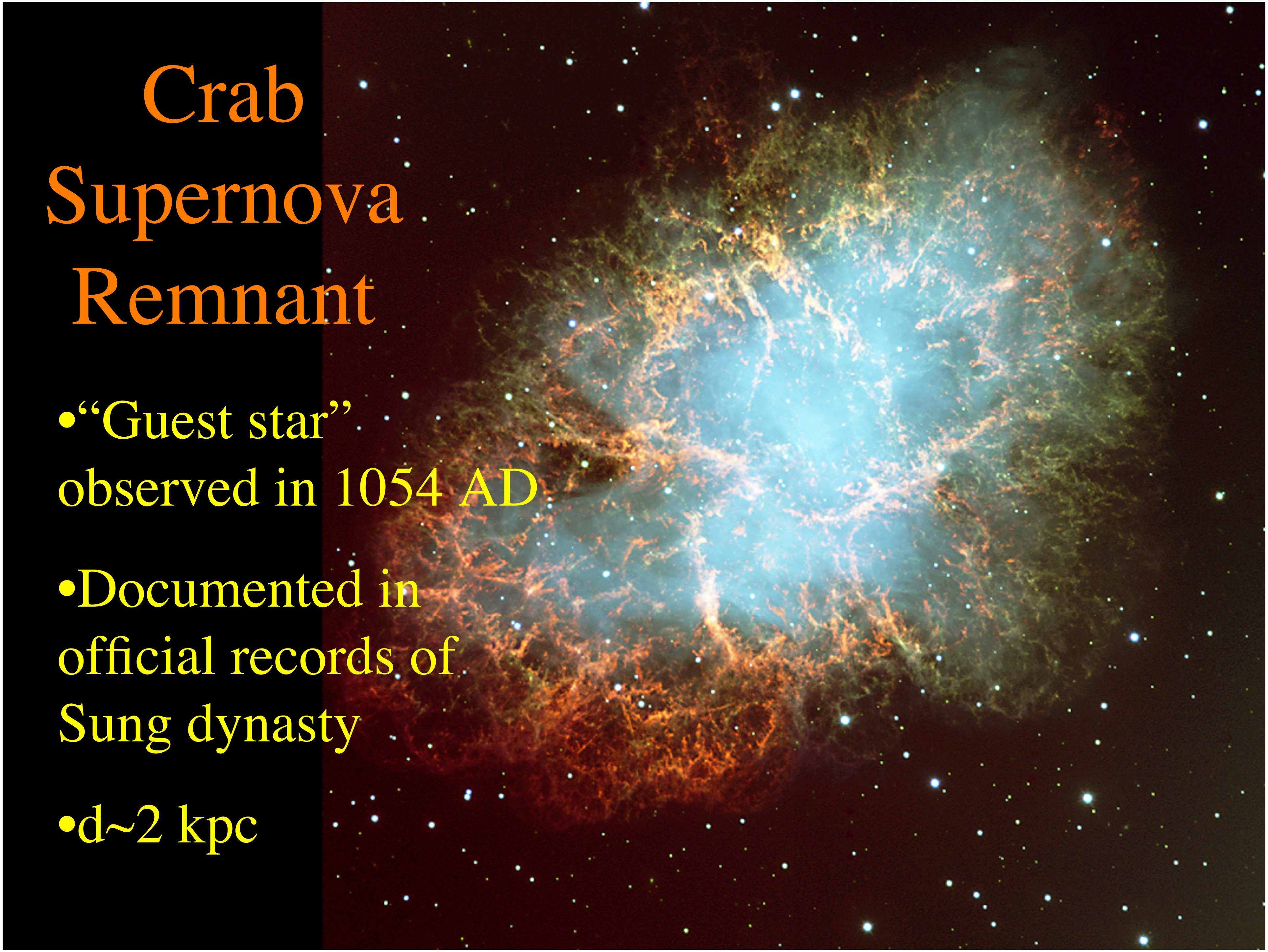
Massive-Star Supernova



Supernova 1987A

Radio image of Cas A supernova remnant





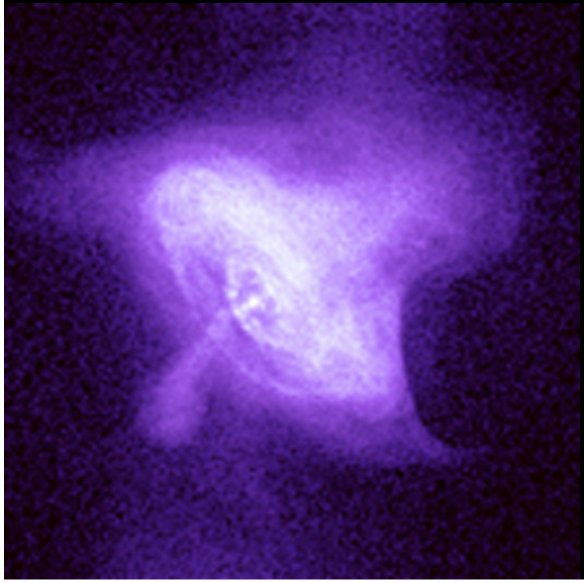
Crab Supernova Remnant

- "Guest star" observed in 1054 AD
- Documented in official records of Sung dynasty
- d~2 kpc

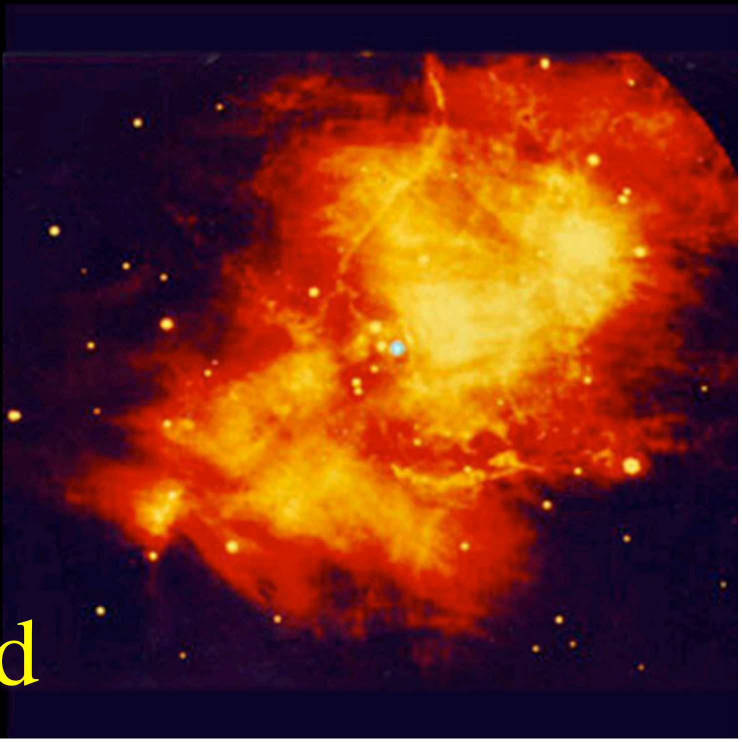
Crab supernova remnant

radio

visible

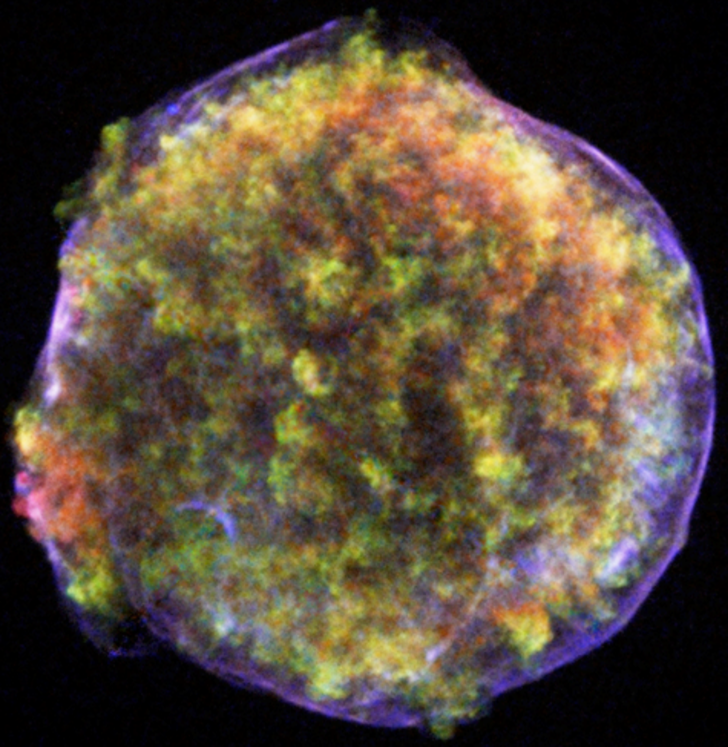


X-ray



Infrared

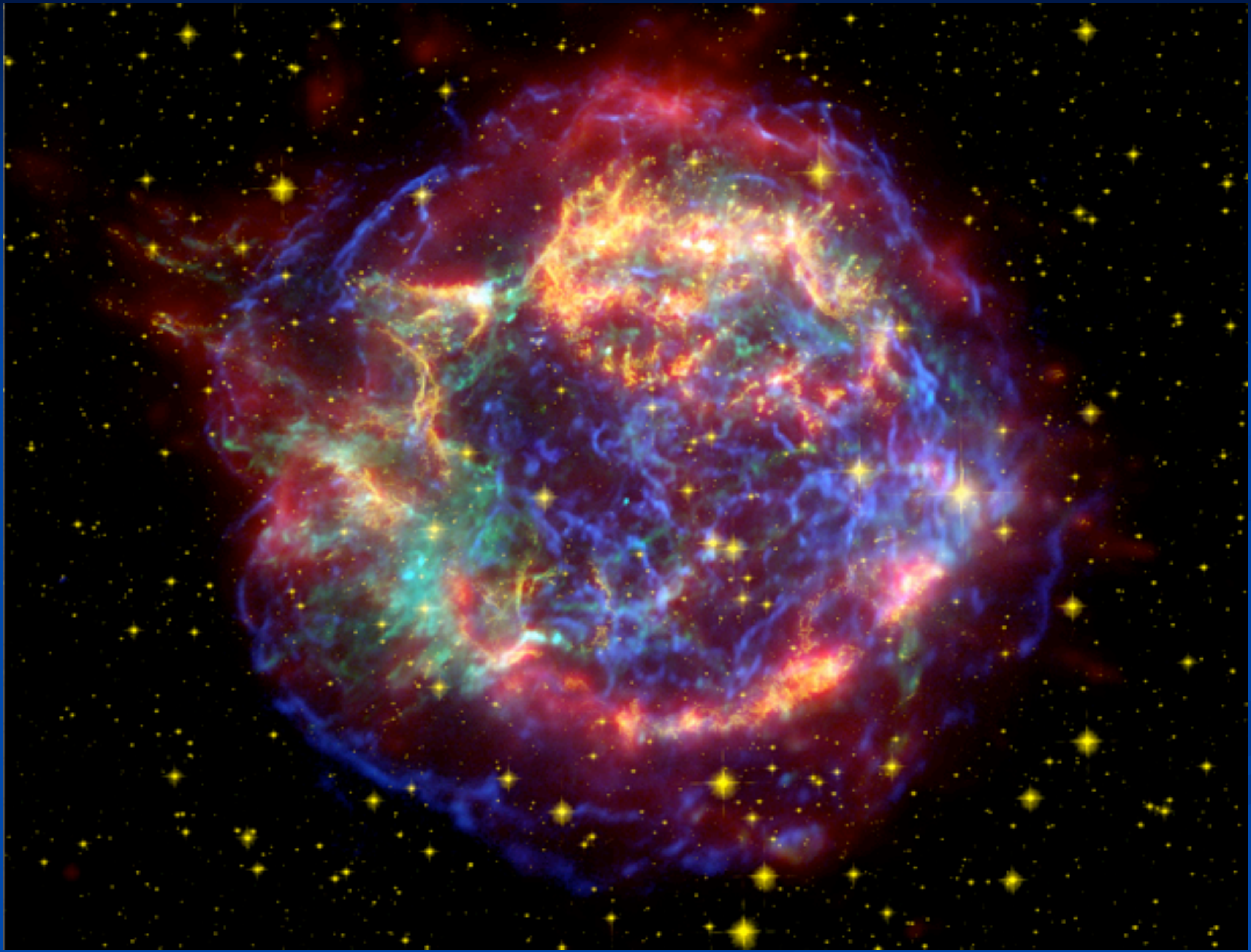
Tycho's SNR



- Tycho observed SN explosion in 1572
- d~2.4 kpc

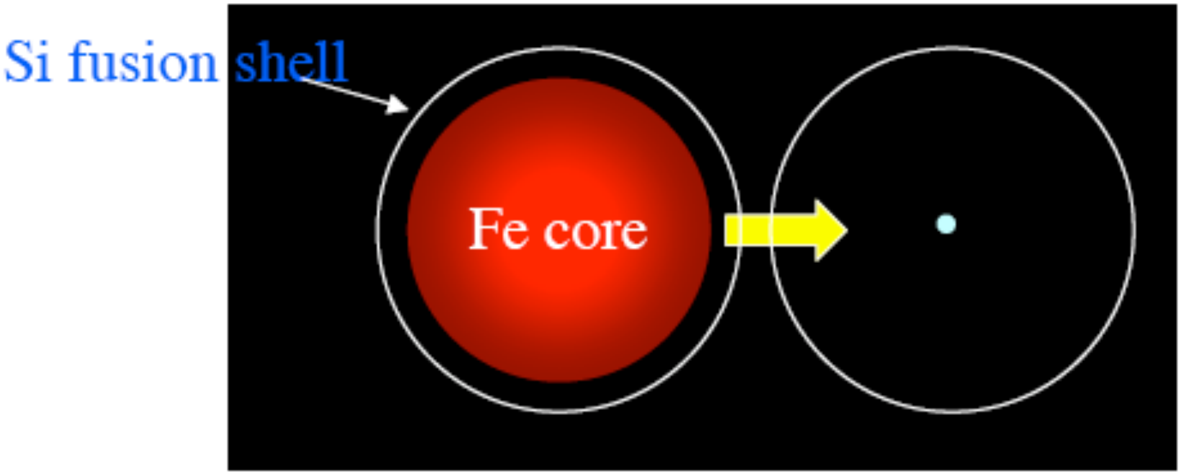
- X-ray image, 10.5 arcmin across

Supernova Remnant Cas A in X-rays



Properties of a Neutron Star

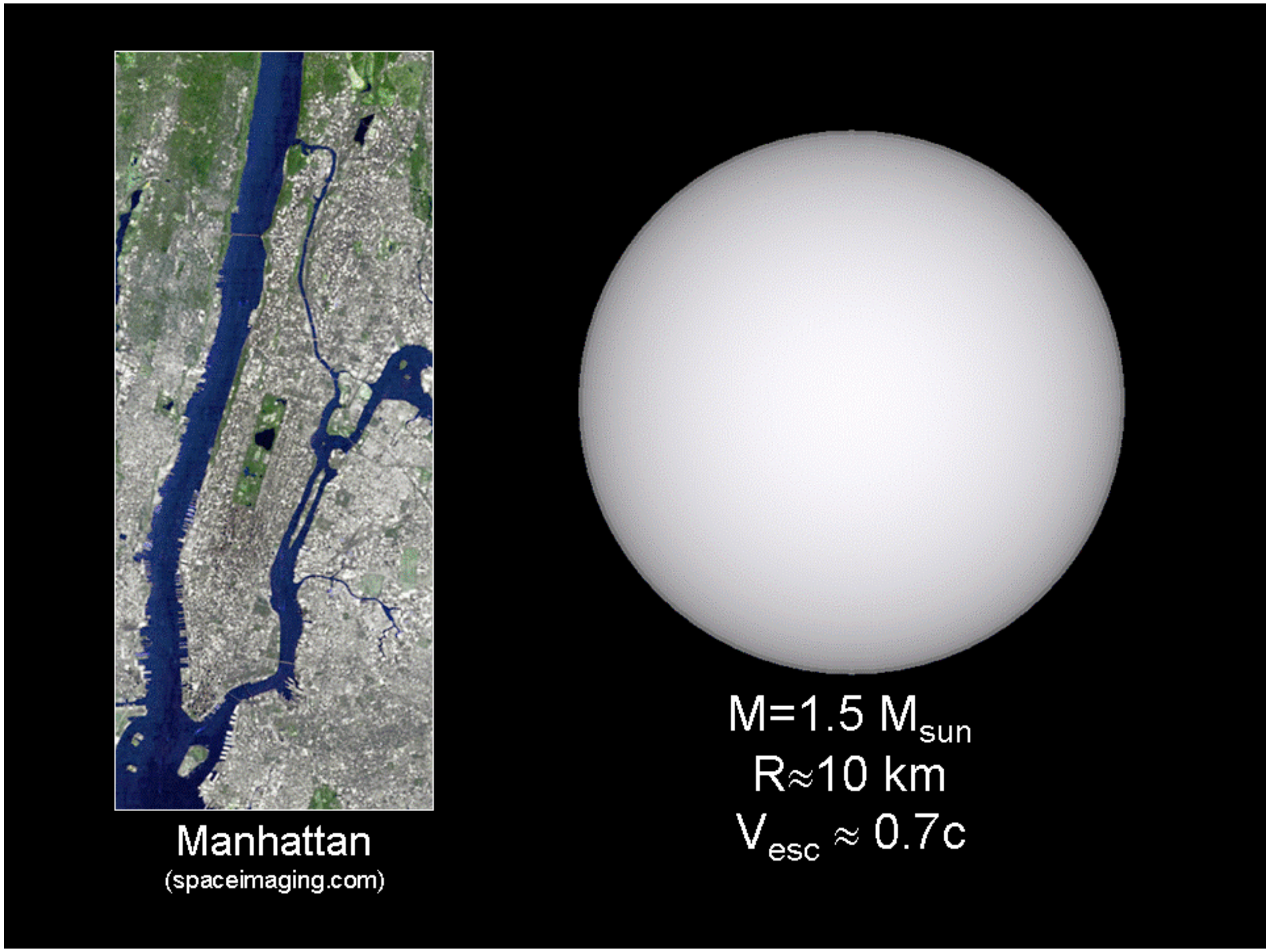
- Electrons and protons merge to make neutrons in Fe core collapse (Type II Supernova)



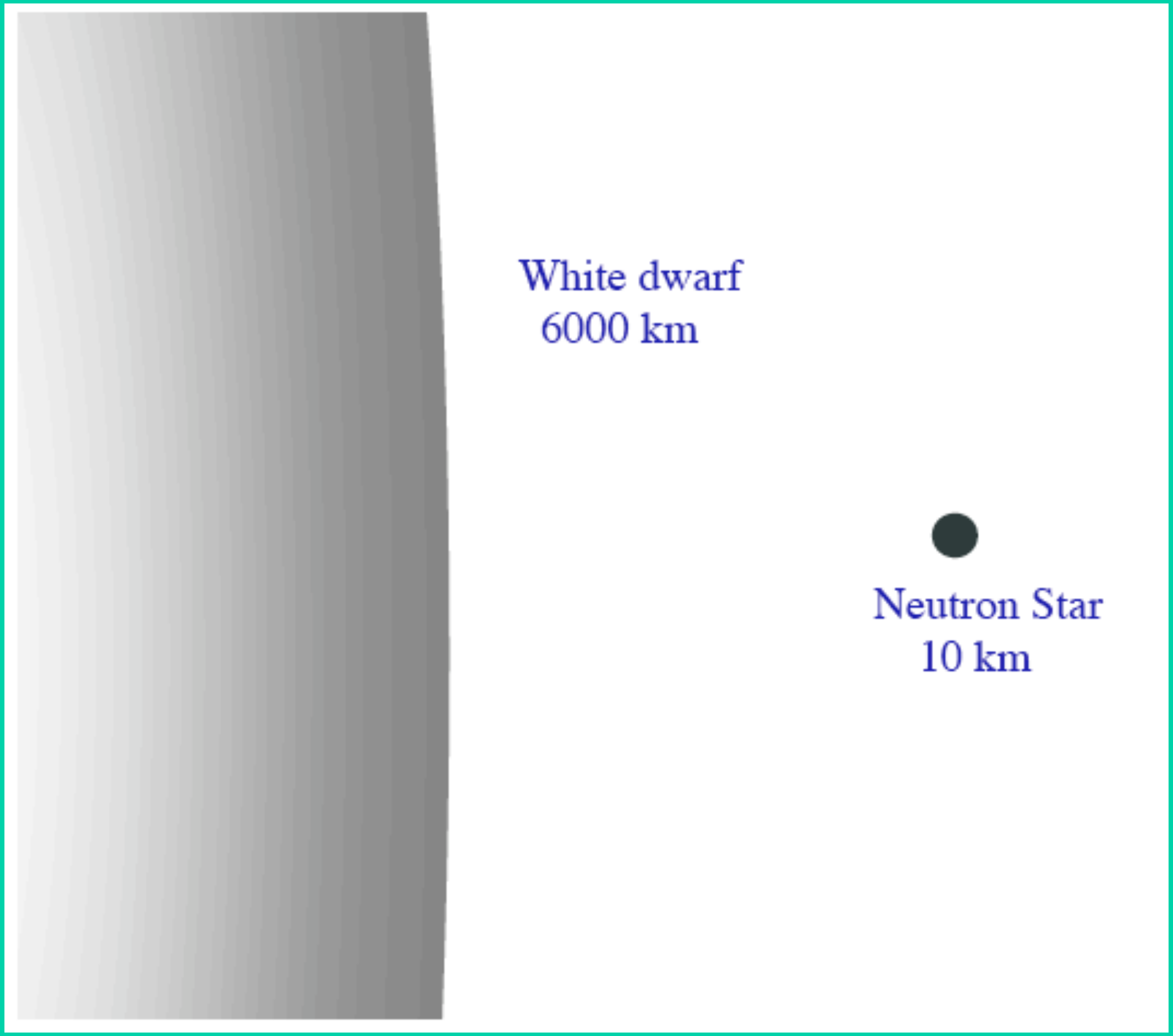
Properties of a Neutron Star

- Electrons and protons merge to make neutrons in Fe core collapse
- Supported by *neutron degeneracy pressure*
- Maximum mass ~ 3 $M_\odot$
- Radius is ~ 10 km
  - Density is $>10^{17}$ kg/m^3
  - Squeeze all humans into volume of sugarcube
- Escape speed close to c: highly relativistic
- Should be born rapidly rotating with strong B

Properties of a Neutron Star

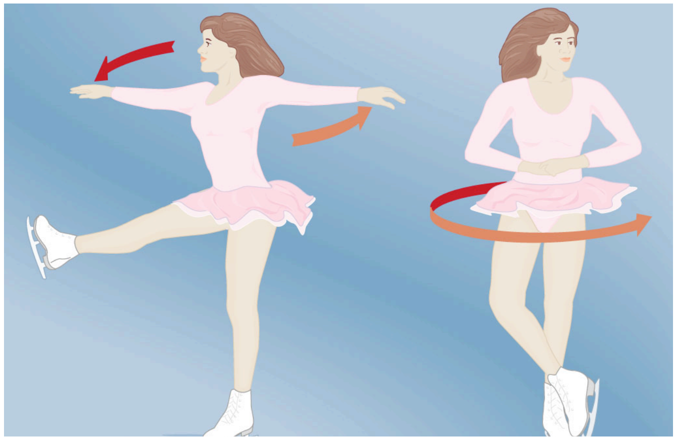


Properties of a Neutron Star



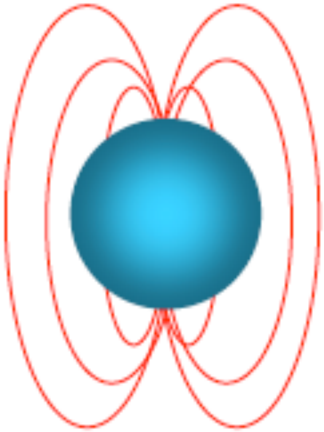
Neutron Star Spin

- As Fe core collapses, it will spin faster (conservation of angular momentum)
- NS spin rate = Core spin rate * $(R_{core}/R_{NS})^2$
  - ✶ So a newborn neutron star is expected to spin with a period of about 0.001 second

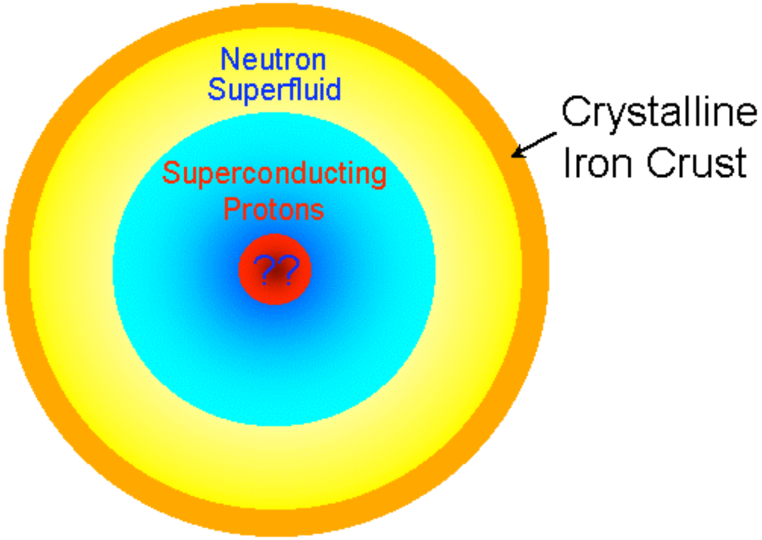


Neutron Star B-field

- As Fe core collapses, magnetic field lines, and total magnetic flux are conserved, i.e. $B*4\pi R^2$ ~conserved
- B becomes very strong (10^8 T), as R shrinks



Neutron Star Structure

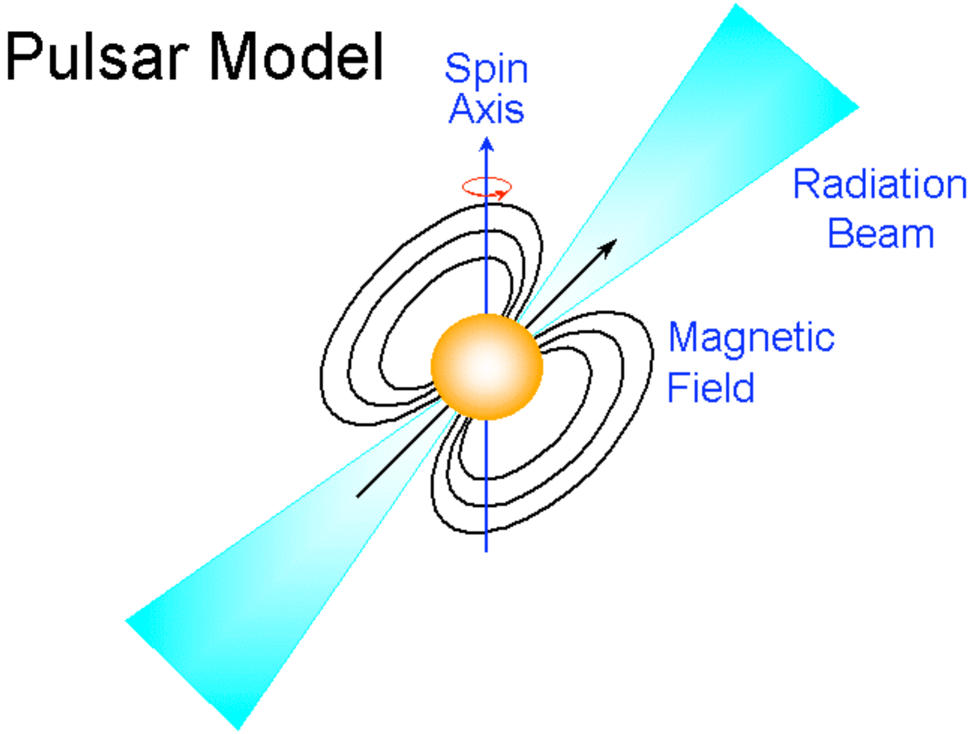


- Outer crust of heavy nuclei (e.g. Fe)
- Interior: superfluid neutrons and, at even higher densities a mix of superfluid neutrons and superfluid, superconducting protons (pairs of free neutrons and protons: bosons)
- Core: $\rho > \rho_{nuc}$, ????
- Uncertainties in model

Pulsars Make Good Clocks

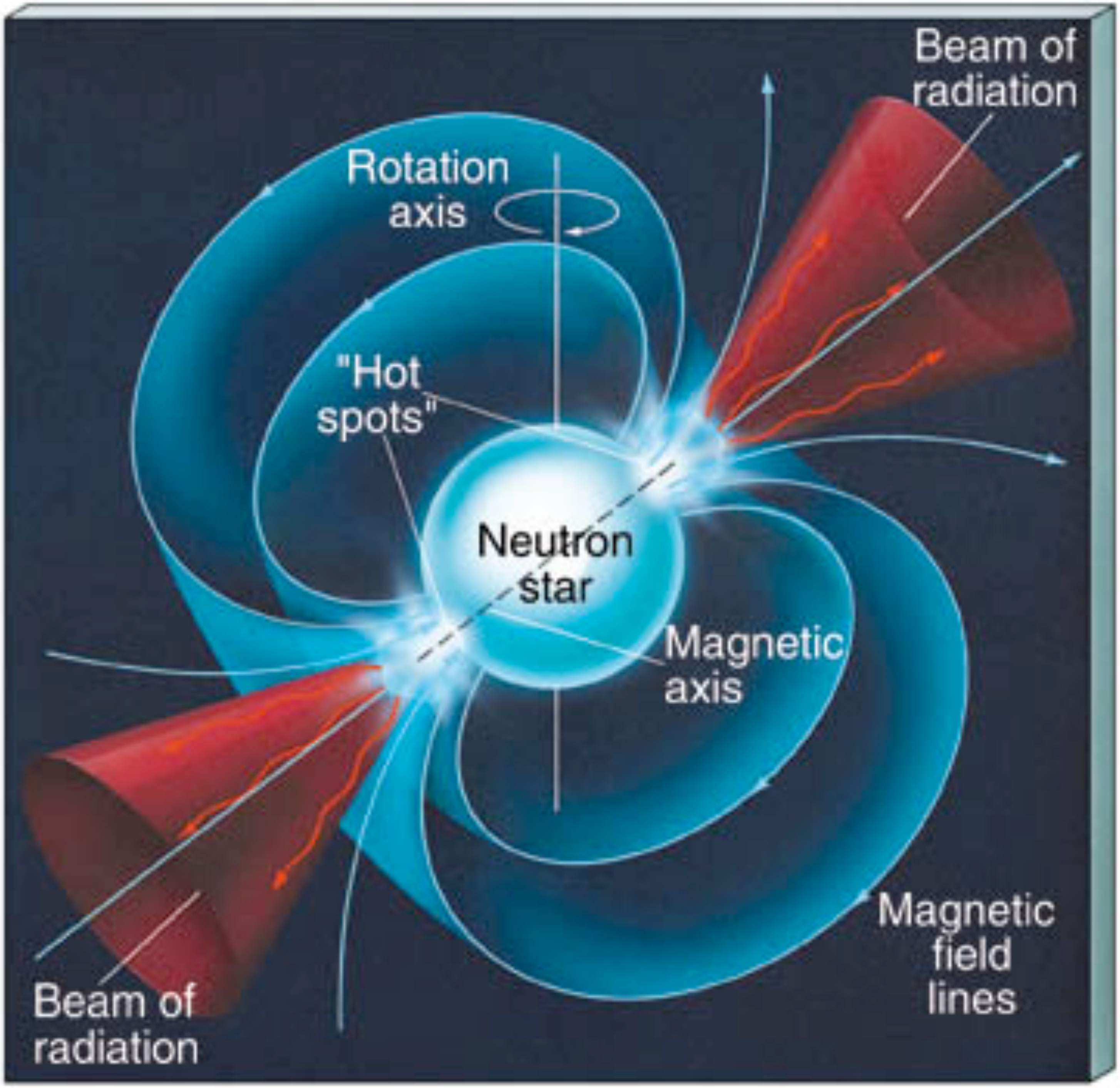
- Pulse period is quite fast: 1.4 ms $< P <$ 12 s
  - Most have .25 s $< P <$ 2 s, avg. ~0.8 sec
- Pulses slow down with time, very gradually:
  - Change in P per unit time, dP/dt $\sim 10^{-15}$ s/s = 0.03 μs/yr
- Individual pulse arrival times can be measured with μs = 10^{-6} s precision.
  - A precision tool for dynamics, especially GR
- P is very stable, can be determined up to accuracy of 10^{-17} s (e.g. PSR 1937+214 has P=0.00155780644887275 s)!

Pulsars as Lighthouse Beacons



- Magnetic field axis and rotation axis are misaligned
- Light (not blackbody) emitted in a cone along magnetic field
- Radiation enters our line of sight once per rotation period (if we are aligned correctly)
- Shape of pulse tells us about the structure of the cone, e.g. how narrow and how many peaks.

- Pulsars are spinning, magnetized neutron stars that emit light in direction of mag. field.
- >1700 Pulsars known today in our Galaxy, must be small fraction of neutron stars

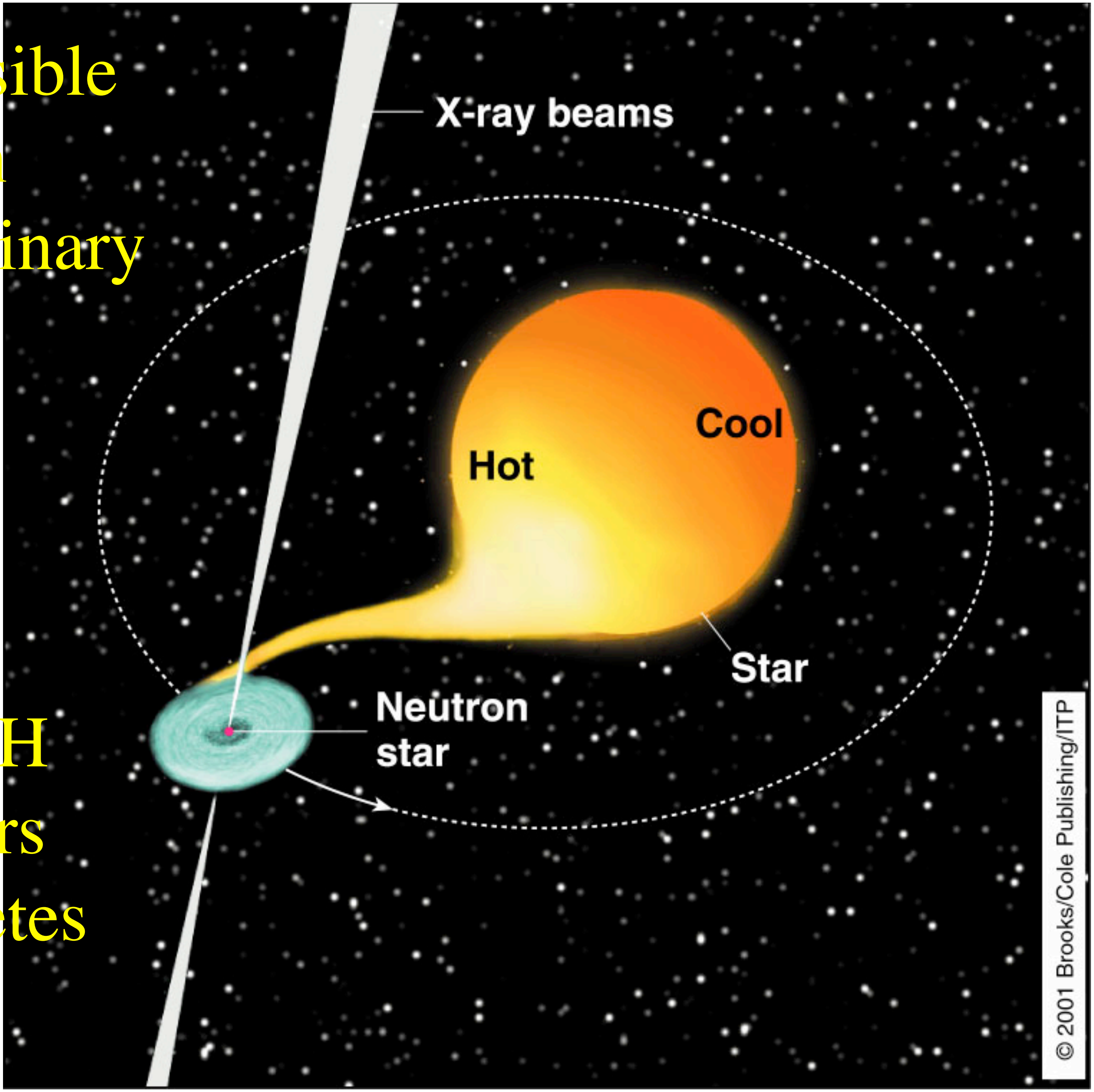

Beam of radiation
Rotation axis
"Hot spots"
Neutron star
Magnetic axis
Magnetic field lines
Beam of radiation

Pulsars in Supernova Remnants

- Supernova (SN) explosions glow for $\sim 10^5$ yr
- Neutron stars pulse for $\sim 10^7$yr
- Some young pulsars should be in SN remnants: 3 are found!
- Confirms the connection between pulsars & SN.

Crab Nebula, remnant of a supernova that appeared on July 4, 1054 A.D., an event recorded by Chinese and Anasazi Indian astronomers. It was visible in daylight for 23 days!

NS also visible if accretion occurs in binary system



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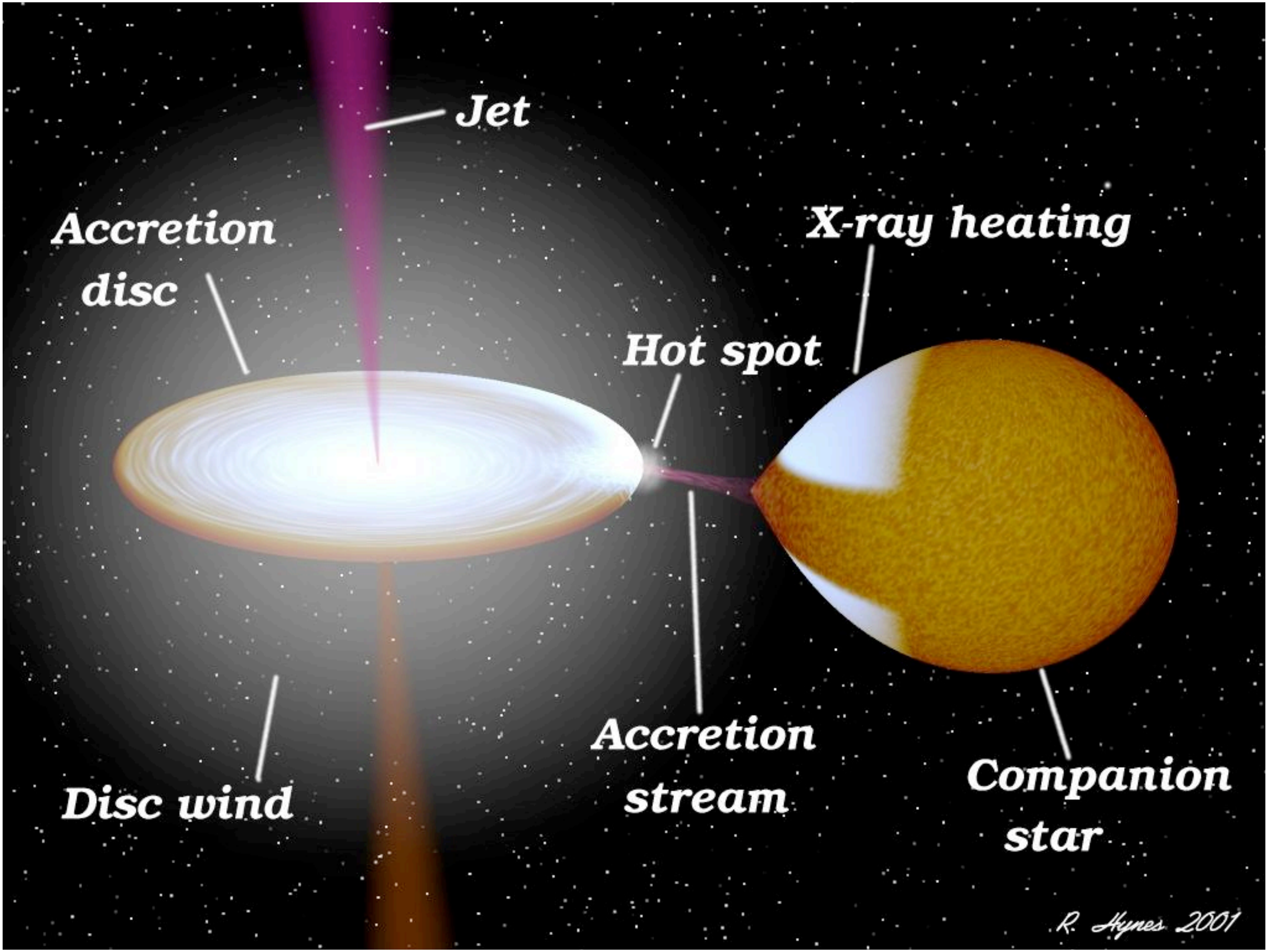
No nova outbursts – H fusion occurs *as* gas accretes


Jet
Accretion disc
X-ray heating
Hot spot
Accretion stream
Companion star
Disc wind
R. Hynes 2001

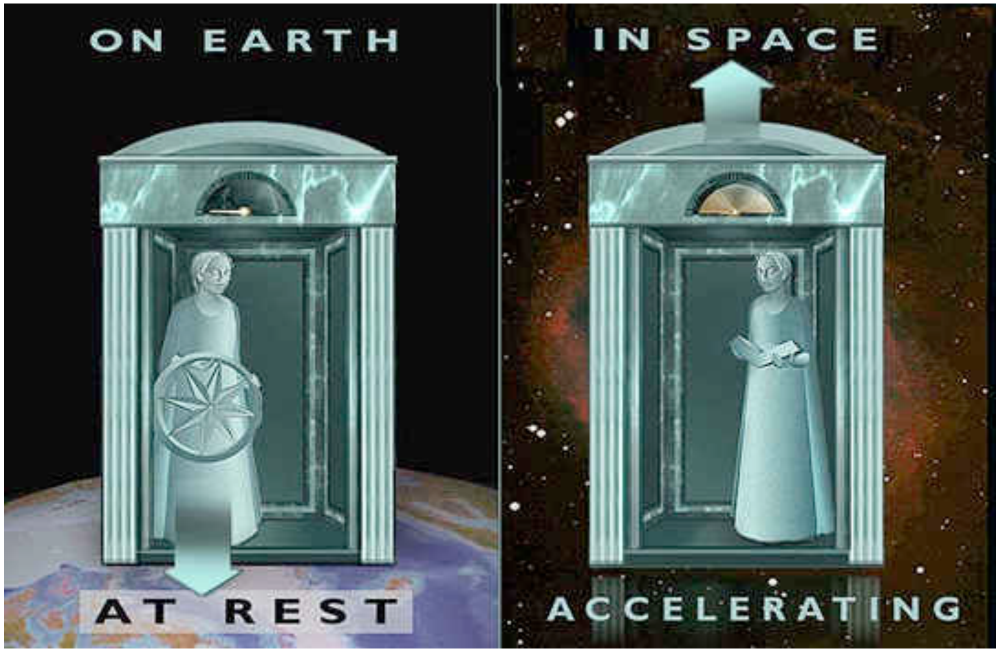
Black hole

- Maximum mass of neutron star is ~ $3\ M_{sun}$
- What if mass of collapsing core > $3\ M_{sun}$?
- No known force can halt collapse
  → *black hole*
- One of many strange but true consequences of Einstein’s Relativity Theories

General Relativity

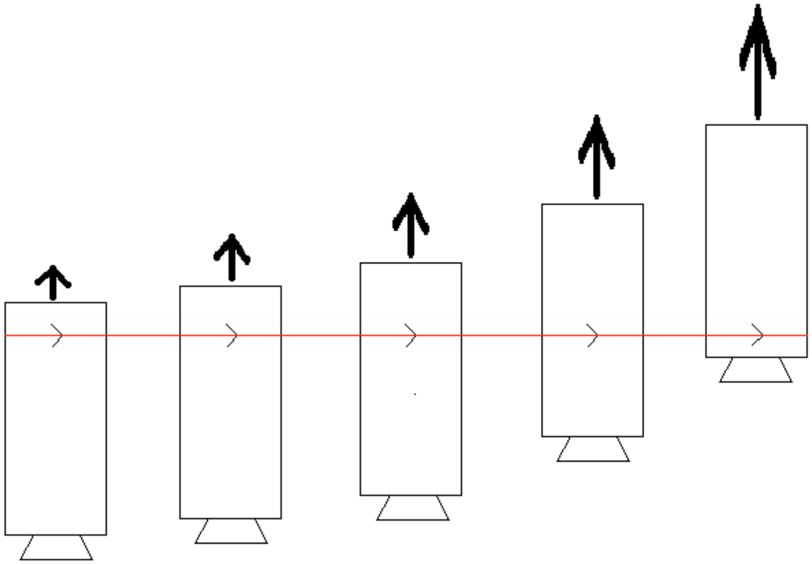
- Einstein's "most beautiful thought":

  "If a person falls freely he will not feel his own weight."

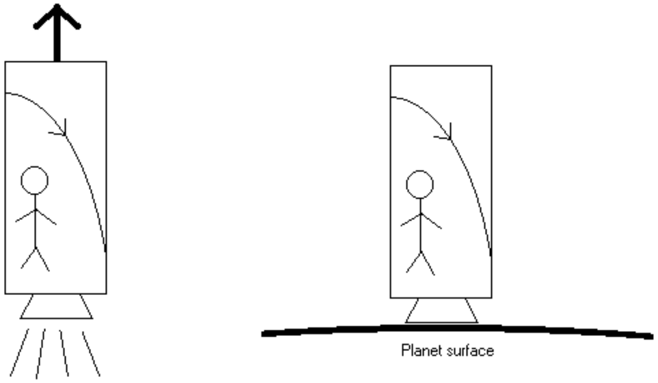


- Equivalence Principle:
  - ✶ Physics is the same in all freely falling frames.
  - ✶ Gravity is equivalent to acceleration.
- Free-fall is the natural way to describe physics.
- Gravity is an illusion!

“Bending” of light by “gravity”



View of our accelerating elevator. The beam of light travels in a straight line (as respresented by the red line); it is the elevator that is accelerating. The time interval between each view of the elevator is the same. We can thus imagine that if we were standing in the elevator, the beam of light would thus appear to follow a curved path, as show below (lower left).



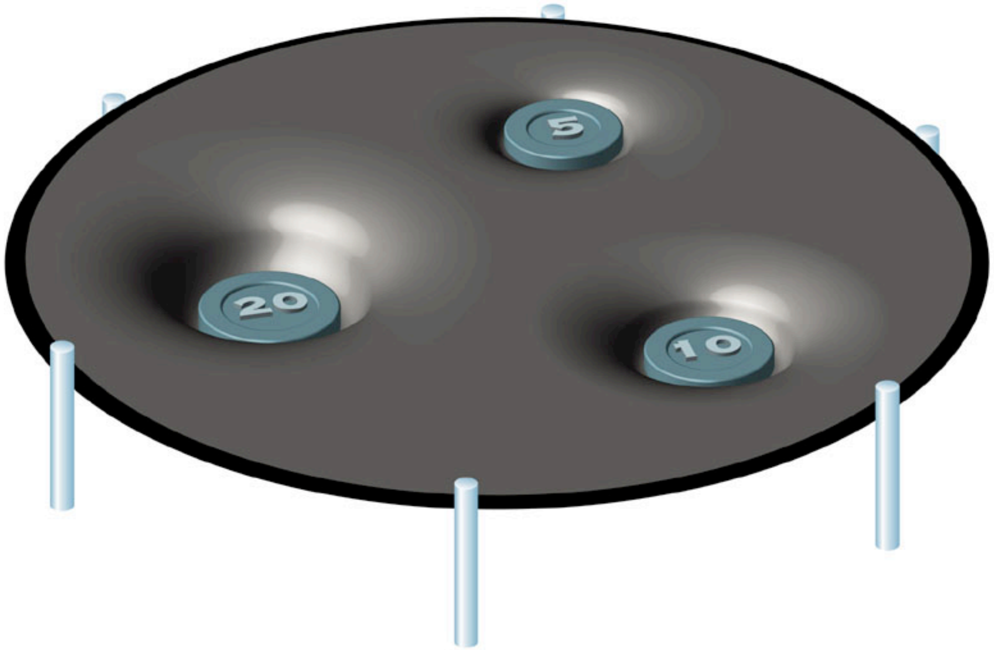
Due to the "equivalence principle," if you were to stand inside the elevator, it would not be possible to tell whether you were accelerating (above left) or whether you were instead placed in a gravitational field, on a planet's surface (above right). And because we know that in an accelerating frame like that in the elevator on the left, a beam of light would appear to follow a bent path, we ought to observe the same bending of light if we were on a planet's surface. (The effect of bending is extremely exaggerated here.) That's how we can conclude that gravity bends light!

- Light travels in straight lines
- Spacetime curves in response to matter
- Particles follow the straightest possible path (called a geodesic).

Curved Spacetime

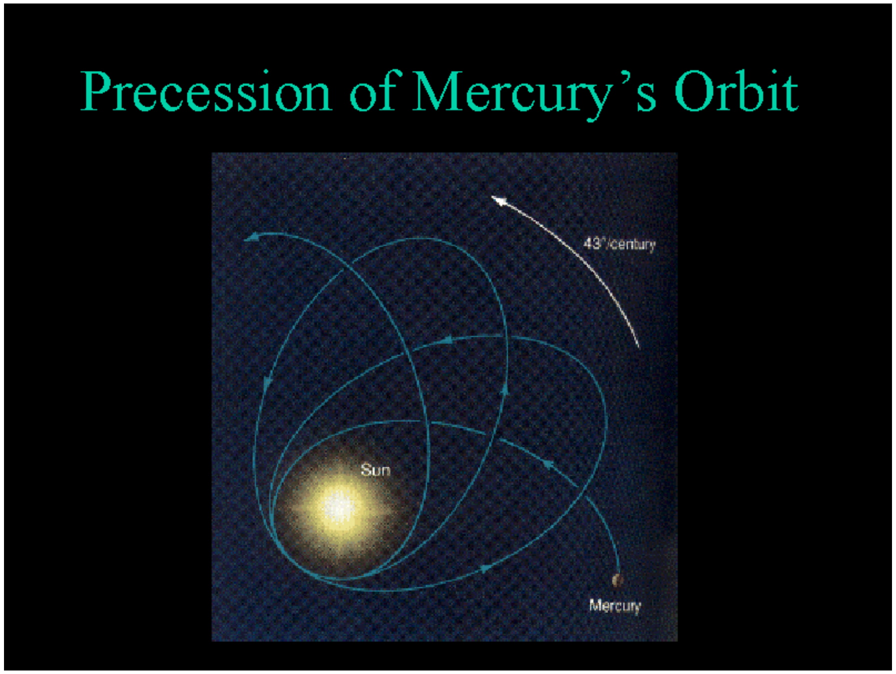

THE EINSTEIN FIELD EQUATION

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

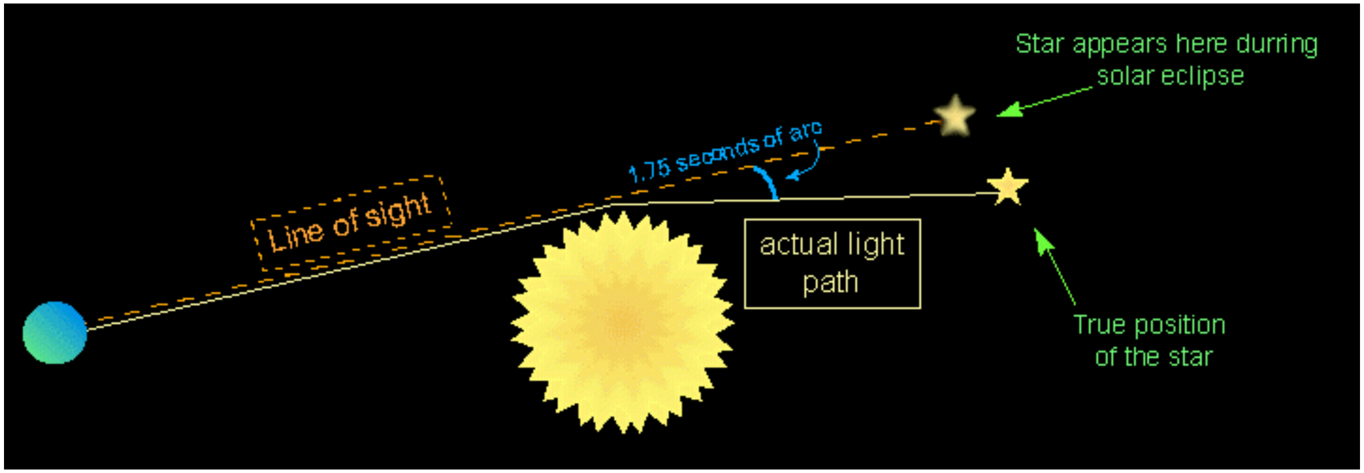


- Matter (and energy) tell spacetime how to curve
- Spacetime tells particles how to move
  - ✶ Freefall follows geodesics
- Eliminates action at a distance
- Curvature becomes infinite for BH

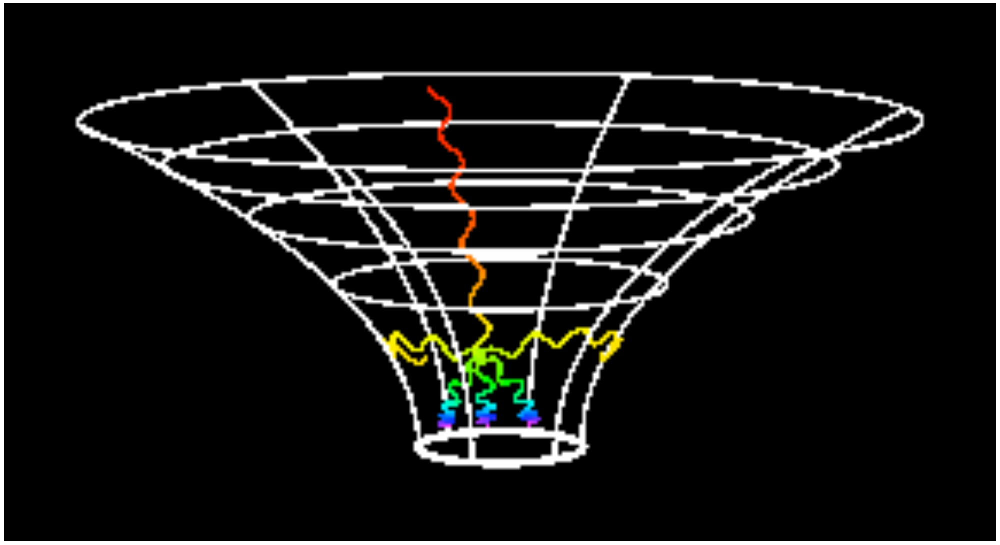
Famous Tests of GR

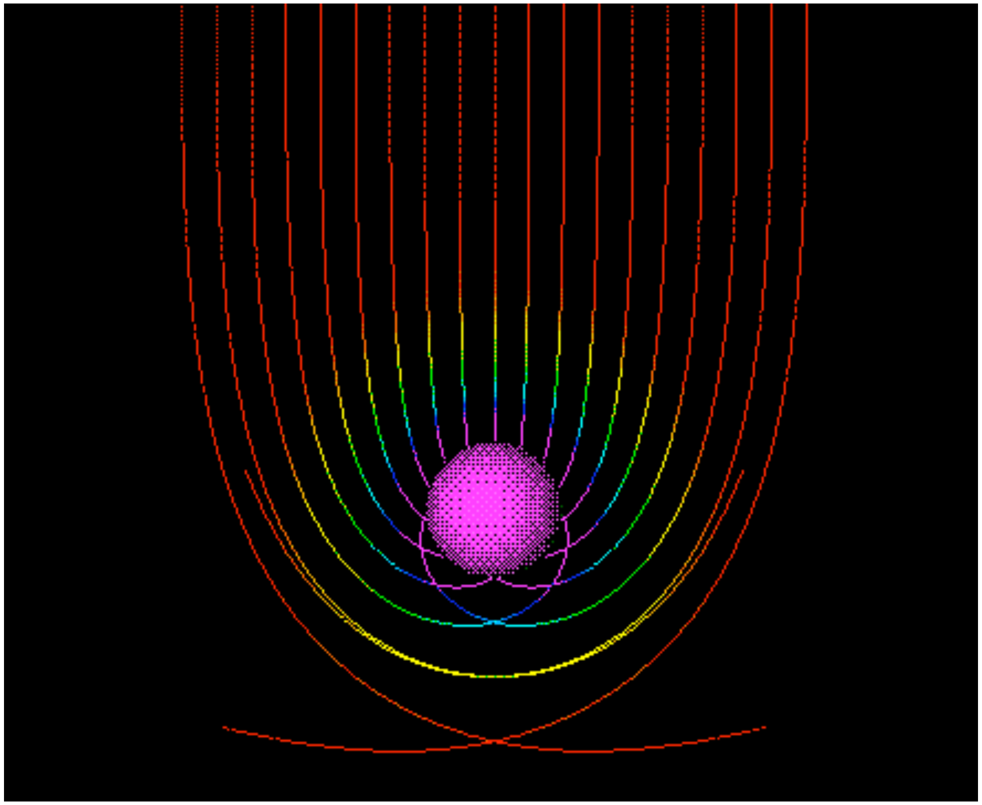


- Keplerian orbits stationary, GR needed to explain precession.
- Eddington's eclipse expidition of 1919
- Predictions spectacularly confirmed



Gravitational Redshift

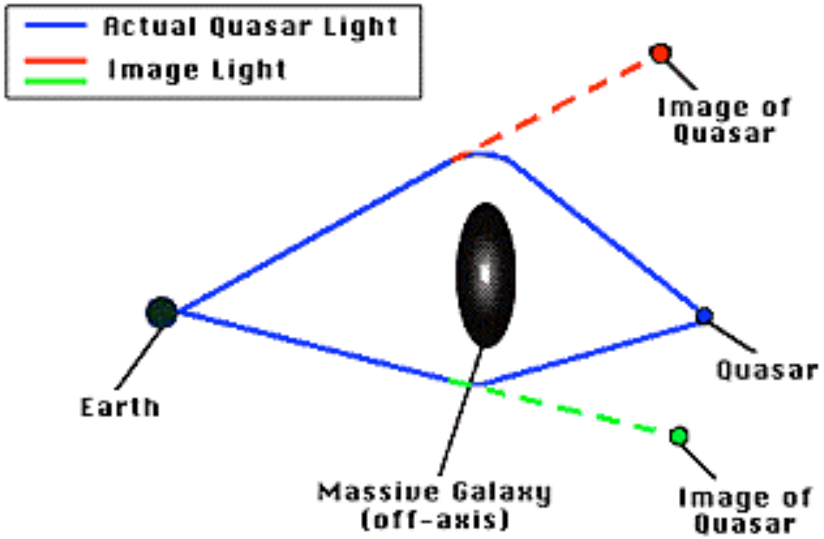


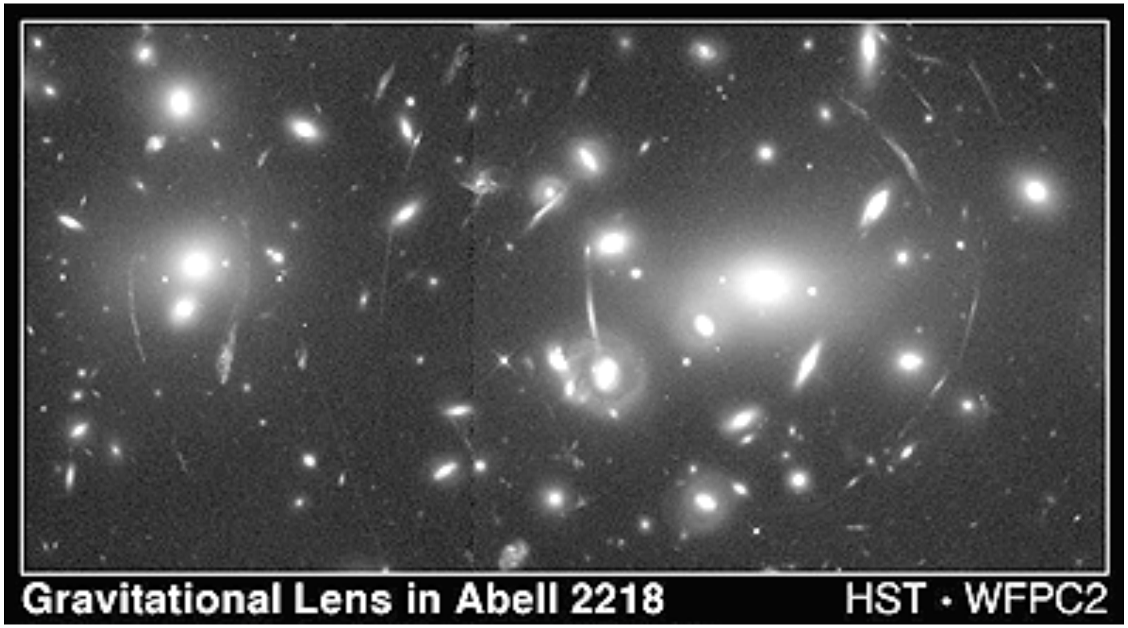


- Photons lose energy as they climb out of gravitational potential
- A consequence of relativistic time dilation
- Measurable on Earth
- Larger for WD, NS
- Infinite for BH

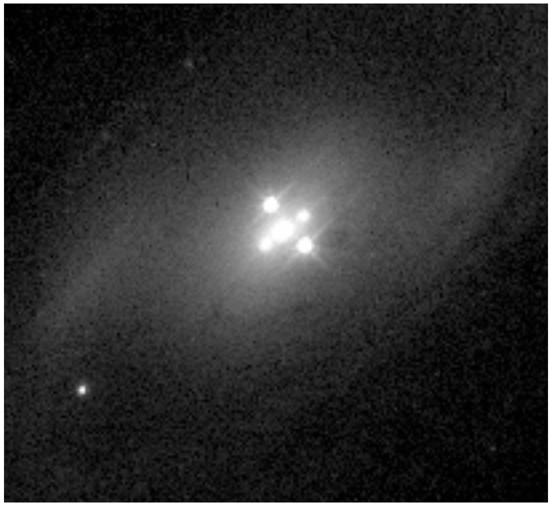
Gravitational Lensing

- Light from background object amplified by curved space time.
- Effects: transient magnification, multiple images, arcs





Einstein Cross

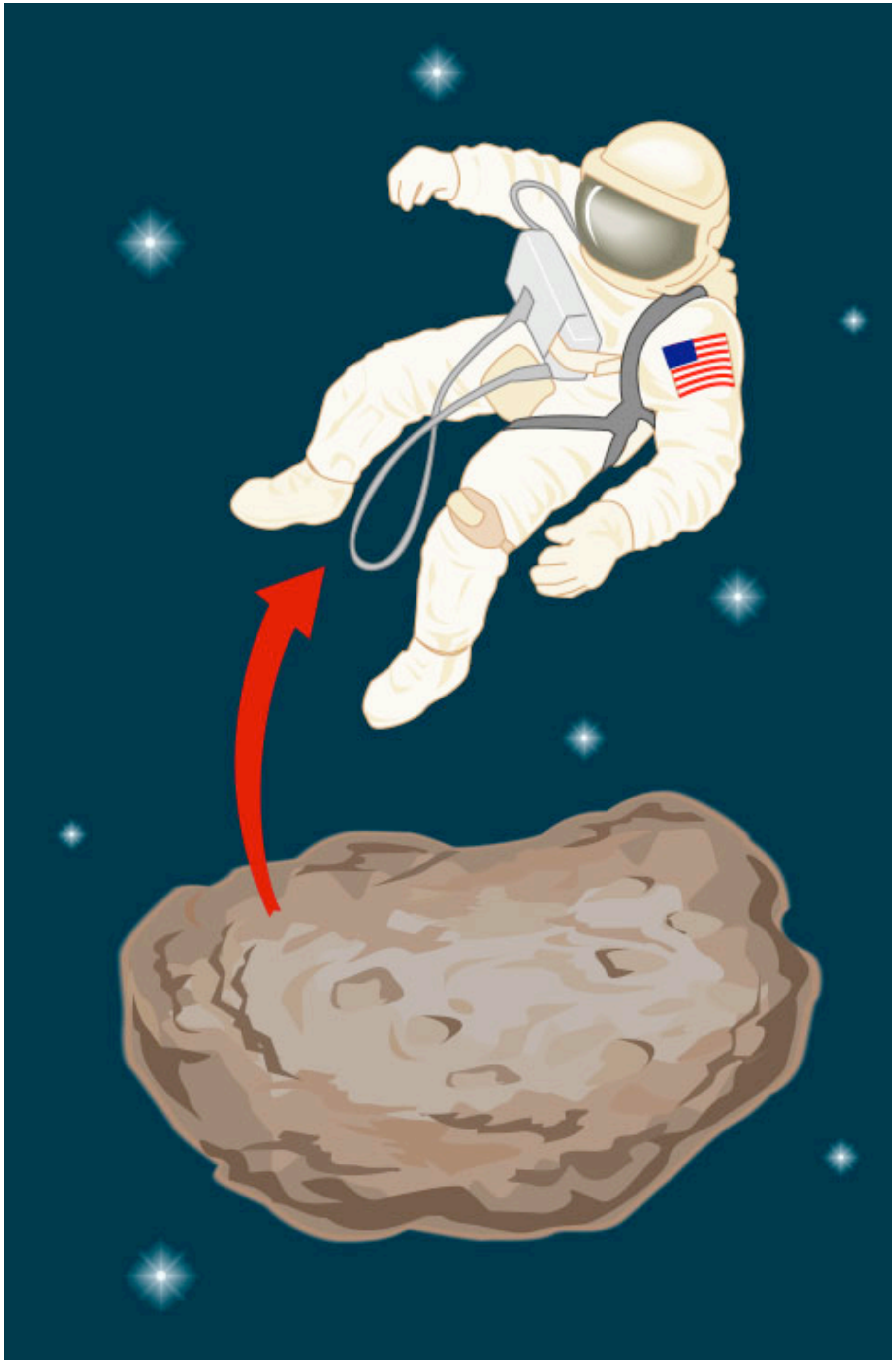


Escape Speed

$$\boxed{V_{escape} = \sqrt{2GM/R}}$$

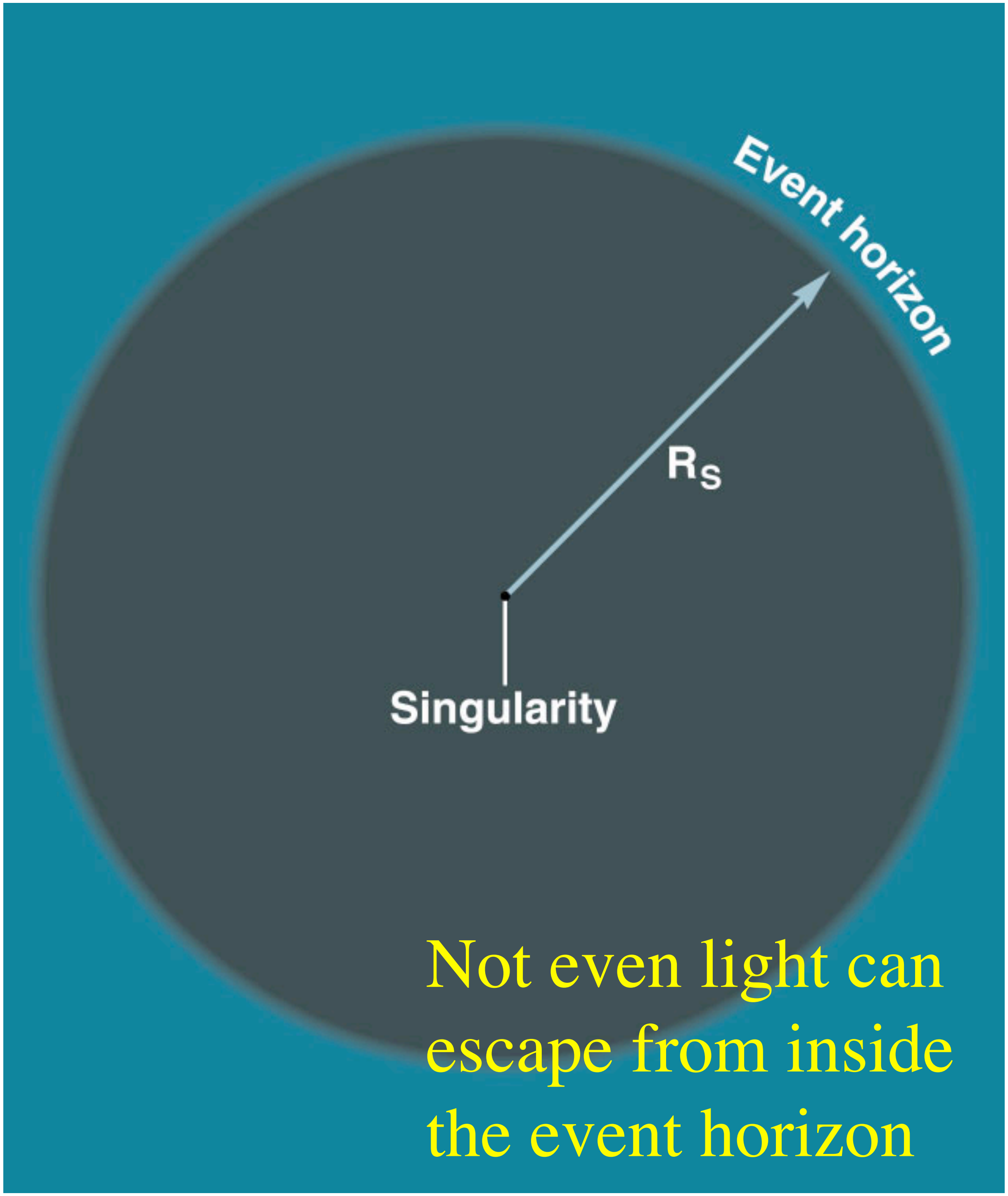
- Earth: $V_{esc} = 11$ km/s
- Sun: $V_{esc} = 600$ km/s

- For fixed M, V_{esc} increases as R decreases



Black Hole

- If R becomes small enough, escape speed at “surface” equals speed of light



Not even light can escape from inside the event horizon

Size of event horizon (*Schwarzschild Radius*) = $2\,G\,M / c^2$

- 0.9 cm for M_{Earth}
- 3 km for $M_{\odot}$
- $4\ R_{\odot}$ for $10^6\ M_{\odot}$
- 20 AU for $10^9\ M_{\odot}$

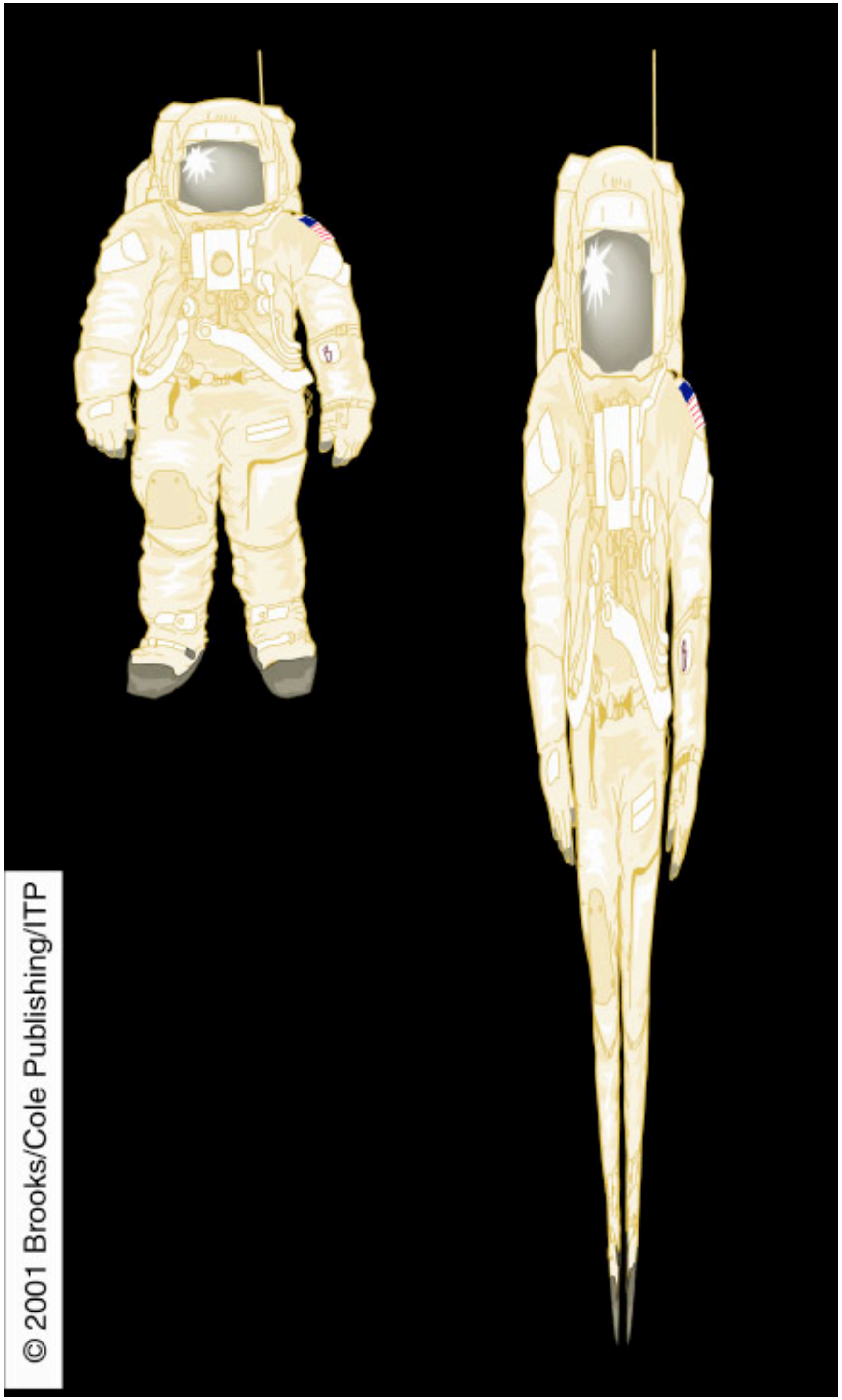
Falling into a black hole

An outside observer:

- Time dilation
- Gravitational redshift

The poor astronaut:

- Tidal forces kill
- Notices nothing special at event horizon
- Inexorably drawn to singularity



There is even better evidence for a supermassive black hole at the center of the Milky Way galaxy…and many others

Another singular solution to GR gives us the Big Bang and the expanding universe

… stay tuned!