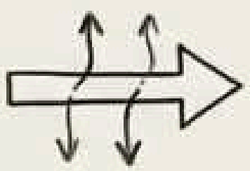
¶ 5.1

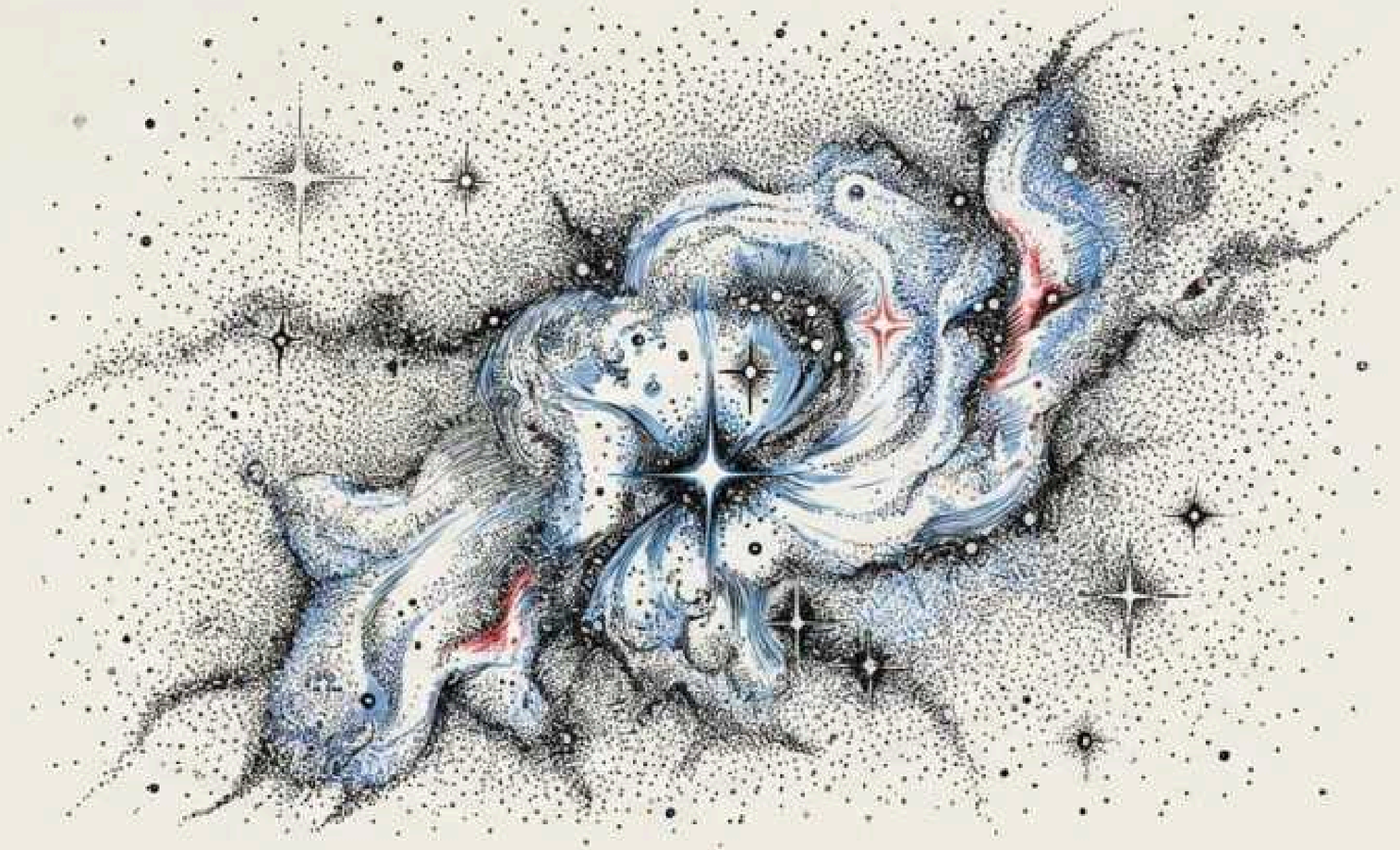
$$\vec{F}_g = G\frac{m_1 m_2}{r^2}$$

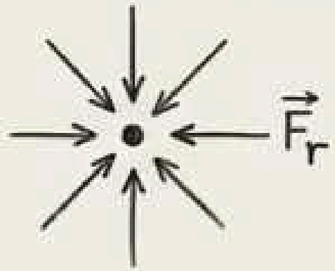
$\vec{F}$ m_1 $\vec{F}$

$\Delta S \geq 0$

$PV = nRT$

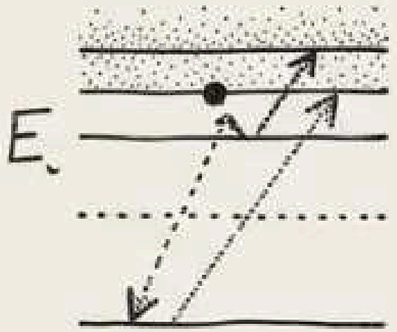






$$^1_4H \rightarrow 2e^+ + \gamma$$

$$^1_4H \rightarrow {}^4He + 2e^+ + 2\nu_e + \gamma$$



The Life and Death of Stars

ASTR 101 B – Lecture 5

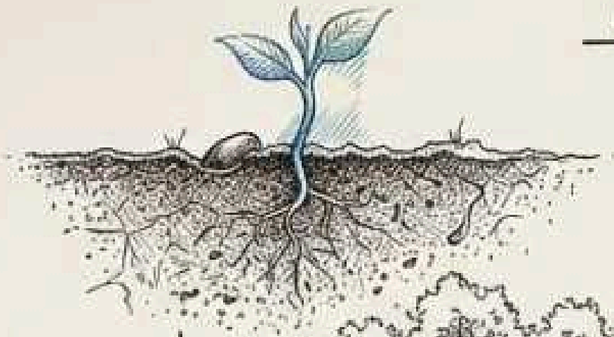
Star Birth, Life, and Death | White Dwarfs, Supernovae, Neutron Stars, and Black Holes | The Origin of the Elements

Gemini Notebook

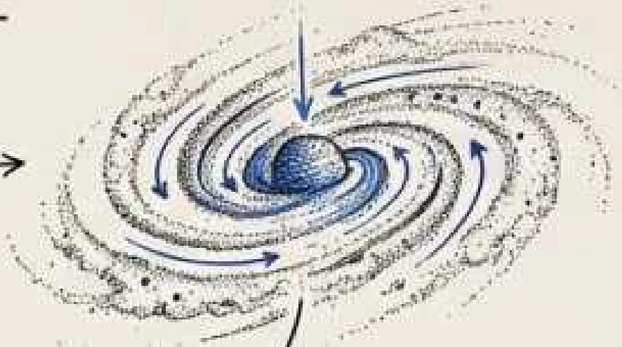
$M(t) = M_0(1 - e^{-kt})$

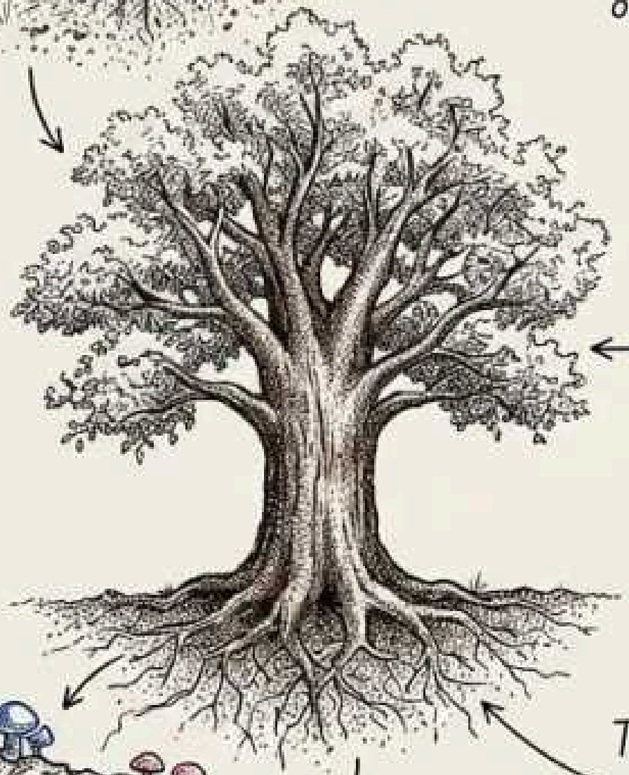
The Cosmic Forest

¶ 5.2

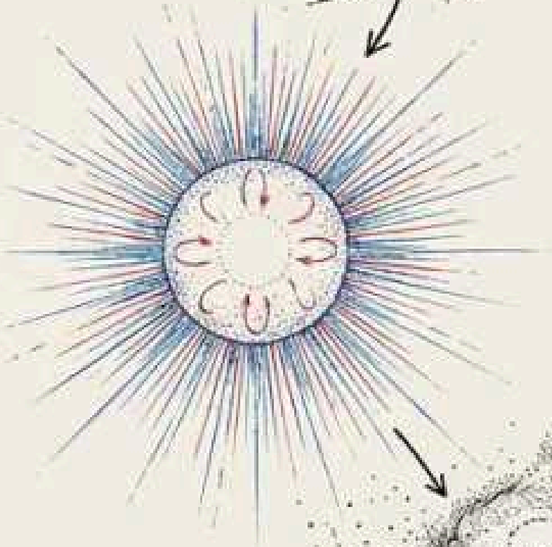


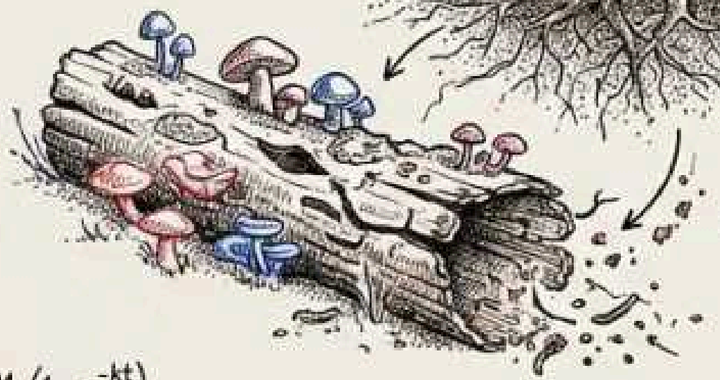
We cannot watch one star through its whole millions or billions of years of life.



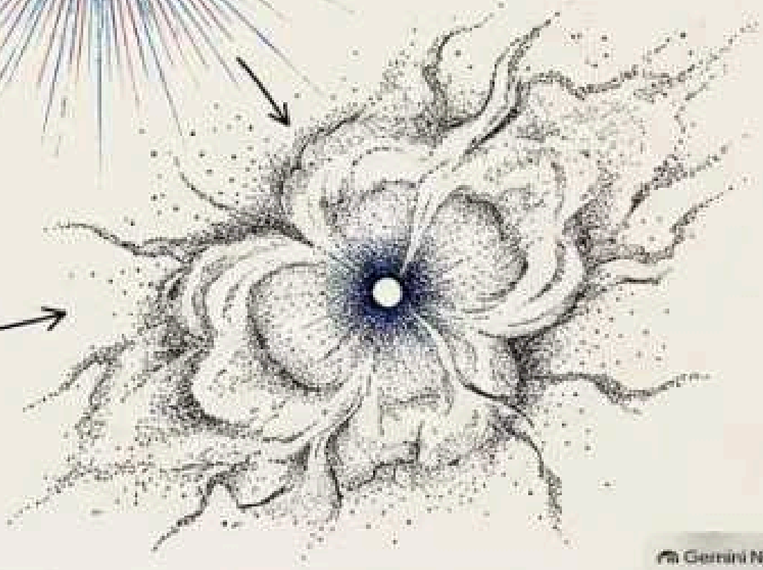


The sky holds stars of every age at once.





This is the story of that life cycle—ending with the origin of the atoms in our own bodies.



$M(t) = M_0(1 - e^{-kt})$

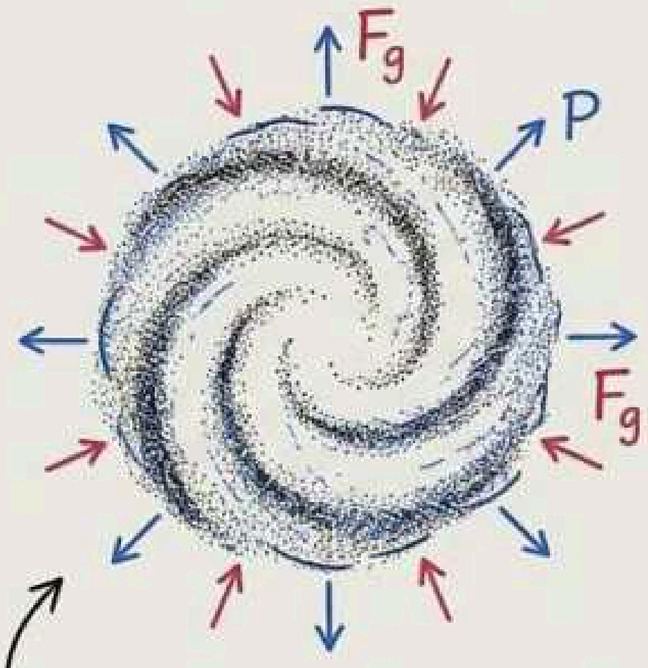
$M(t) = M_0(1 - e^{-kt})$

Gemini Notebook

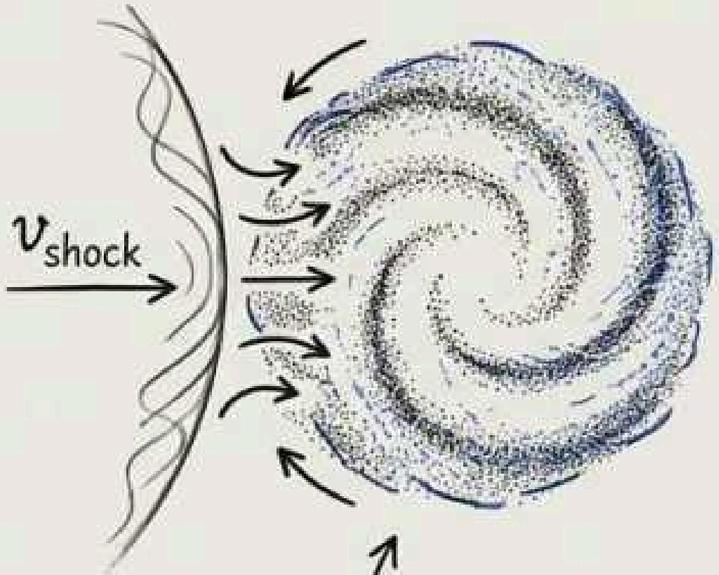
$P = nkt$

¶ 5.3

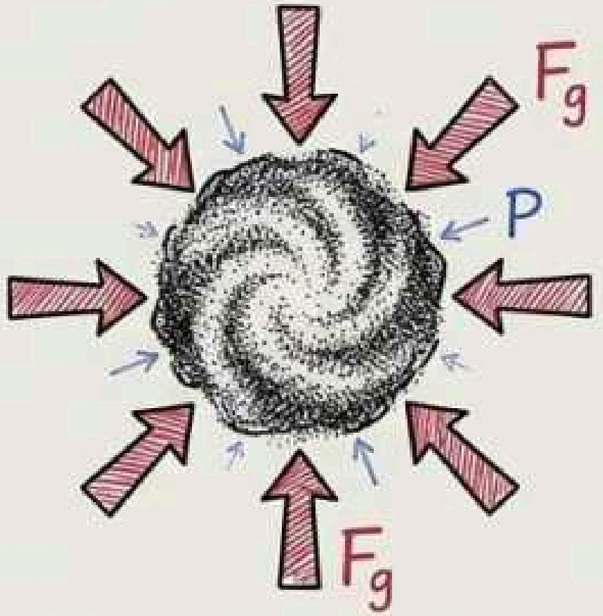
The Nursery: Molecular Clouds



Cold, dense clouds of gas and dust held up by own pressure.



A shock wave pushes a clump past the point where gravity wins.



Famous visible region: The Orion Nebula (visible with binoculars).

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

$$t_{ff} \approx \left(\frac{1}{G\rho}\right)^{1/2}$$

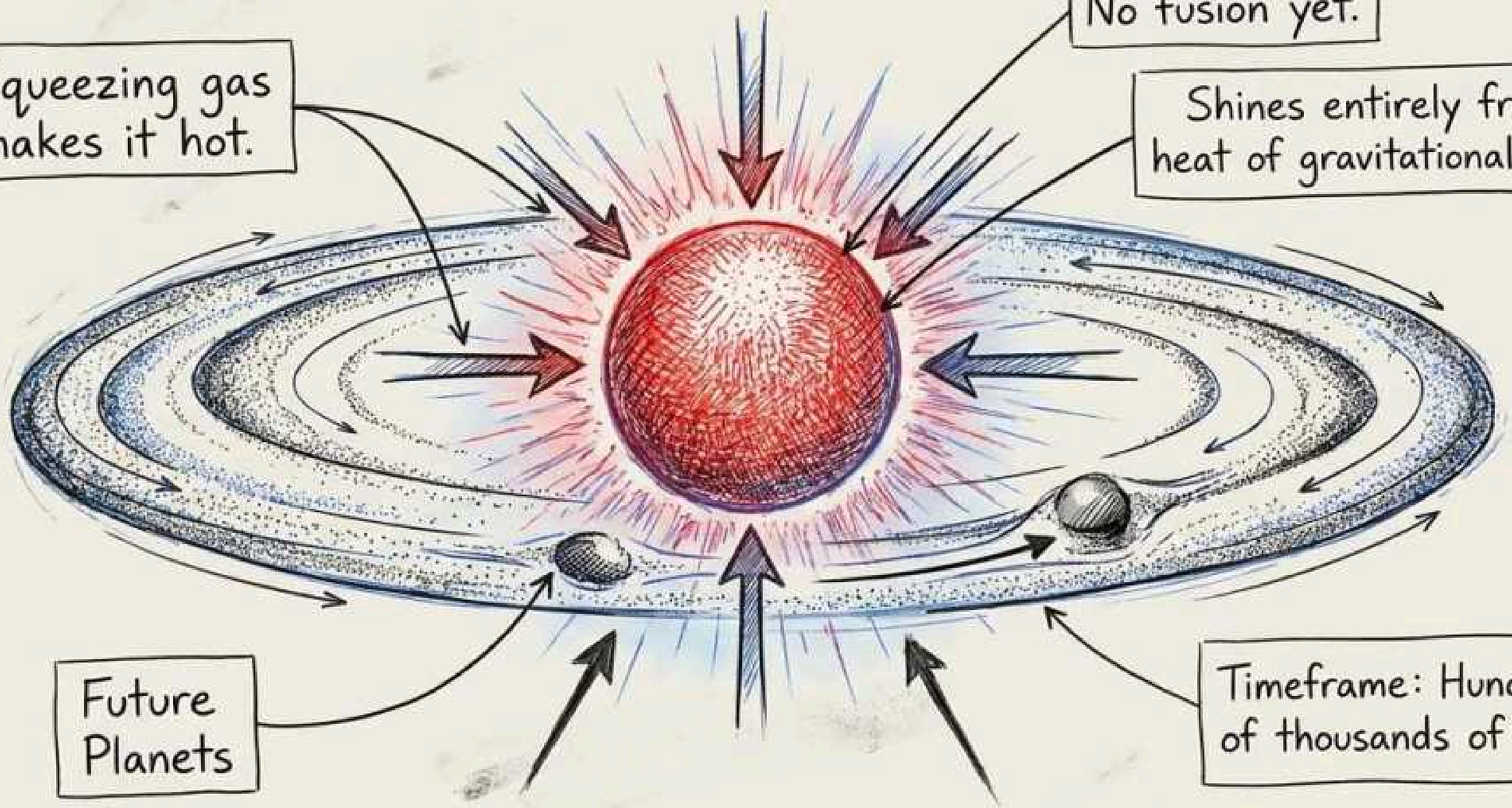
Gemini Notebook

$U = -\frac{GMm}{r}$

$E_{thermal} \propto T$

The Protostar

¶ 5.4



$U = -\frac{GMm}{r}$, $E_{thermal} \propto T$

$\tau_{KH} \approx \frac{GM^2}{RL}$

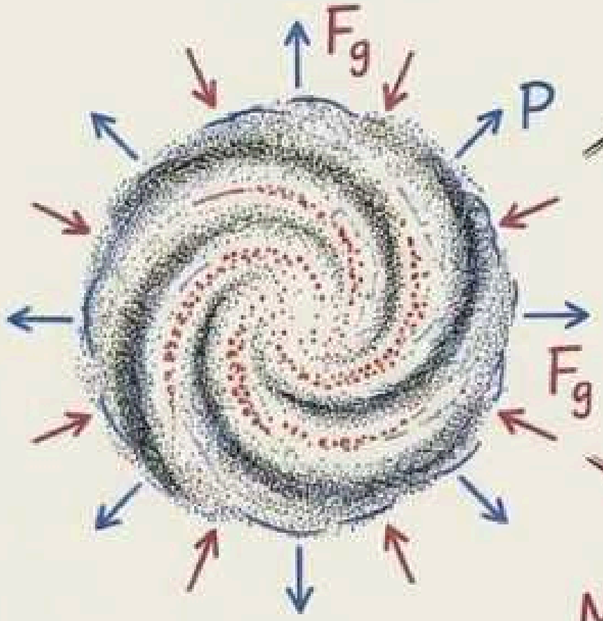
Gemini Notebook

$P \propto \rho T$

$P \propto \rho T$

¶ 5.5

The Ignition Threshold

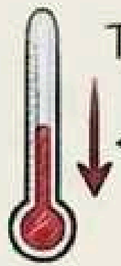


Protostar

Mass $< 0.08\ M_\odot$



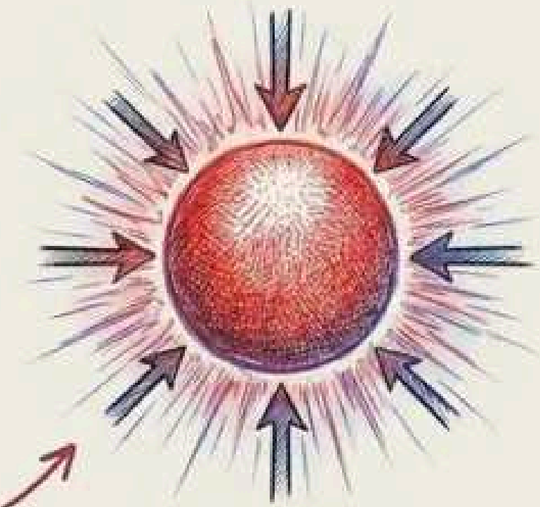
Brown Dwarf



Smaller balls never ignite (Brown Dwarfs). Cools forever.

Mass $\geq 0.08\ M_\odot$

$T_{core} = 10{,}000{,}000$ Kelvin



Main Sequence

Sufficient mass ignites fusion, settling into balance between gravity and pressure.

$L \propto M^3$

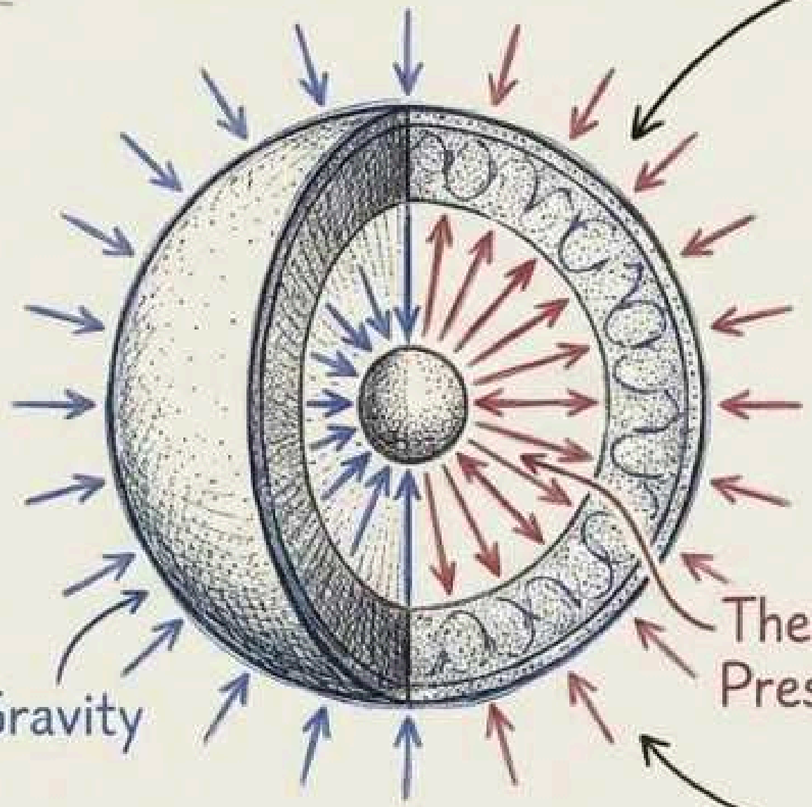
$t_{MS} \propto M^{-2}$

$P \propto \rho T$

Gemini Notebook

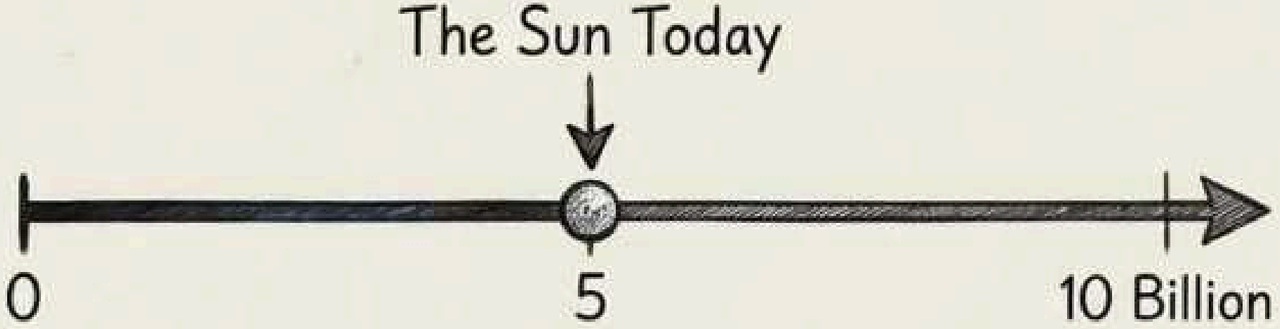
The Main Sequence

The Cosmic Balance



$^{4}_{1}H \rightarrow {}^{4}He + energy$

Spends ~90% of its life fusing Hydrogen into Helium.



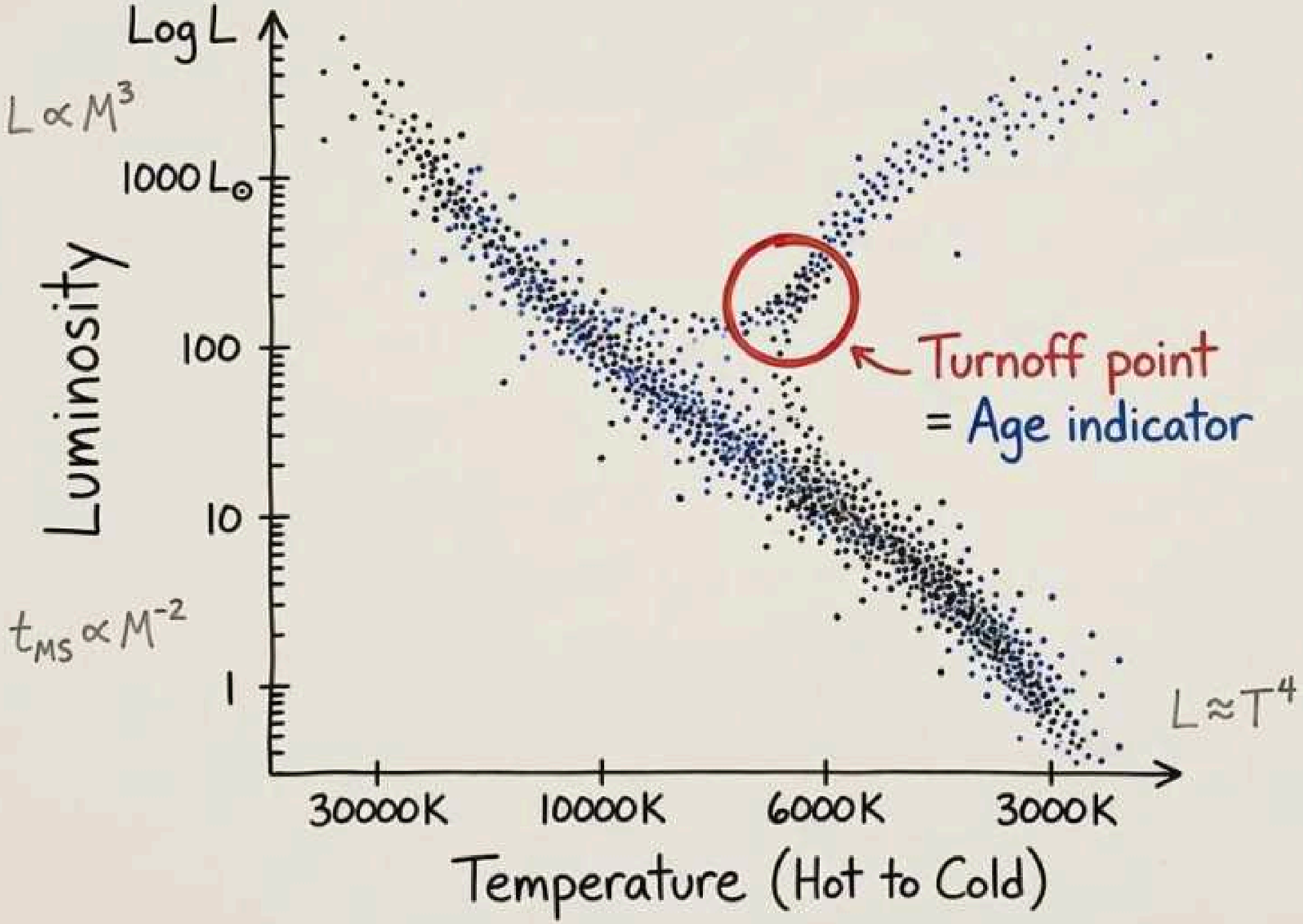
The Sun is roughly halfway through its 10-billion-year main sequence life.

Future path depends on mass: Sun-like stars are quiet compared to massive ones.

Gemini Notebook

Star Clusters as Laboratories

¶ 5.7



Born together from one cloud → Same age, same chemical makeup, differ only in mass.

Heaviest stars die first.

Oldest Milky Way clusters: ~13 Billion Years.

Gemini Notebook

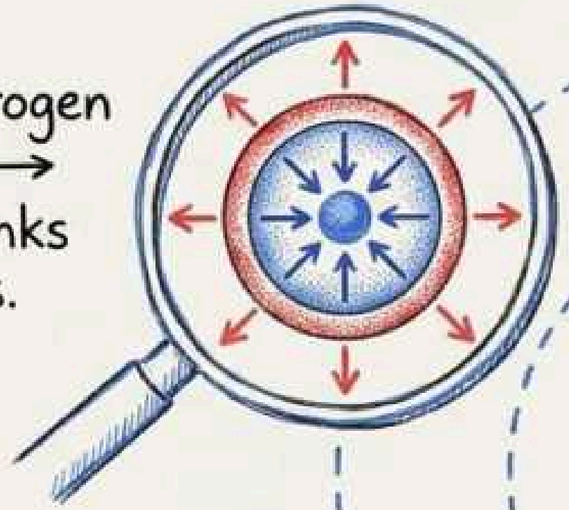
The Red Giant Phase

¶ 5.8

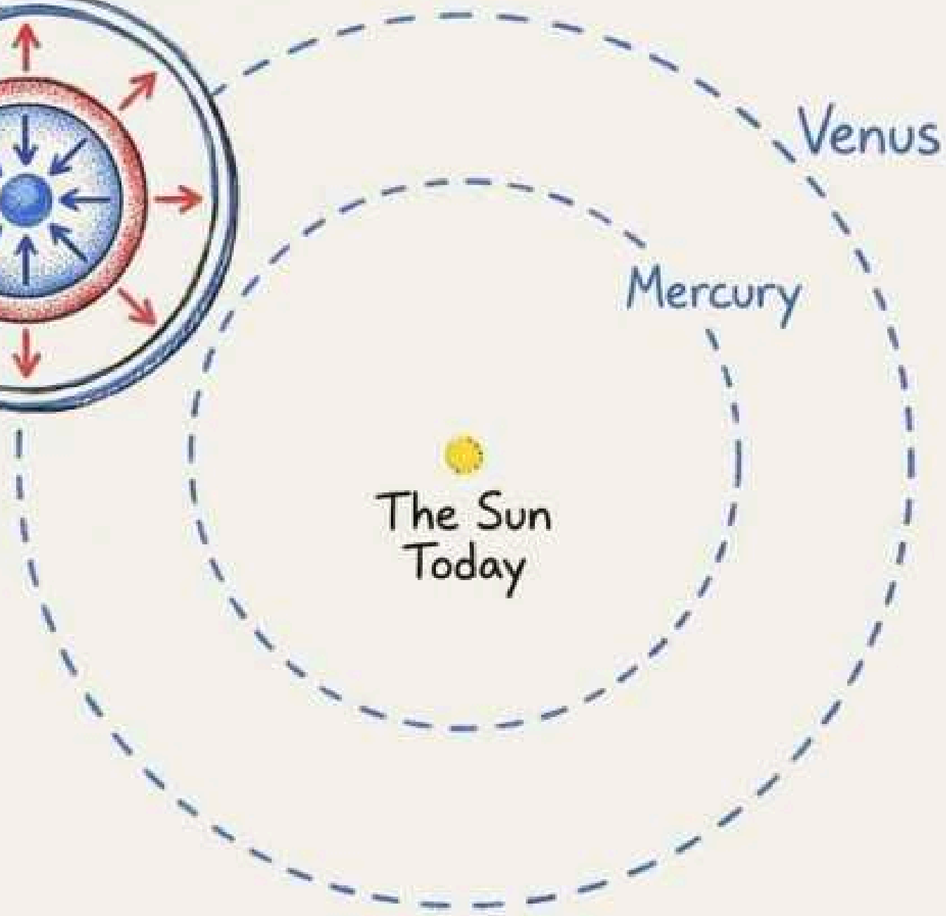
$R \propto T^{-2}$

$L \propto R^2 T^4$

Core hydrogen runs out → Core shrinks and heats.



Hydrogen fusion moves to a shell around the core.



Outer layers swell enormously, creating a a cooler surface but far more luminosity.

$L \propto R^2 T^4$

$P_{core} \uparrow$

$T_{core} \uparrow$

In 5 billion years, the Sun will swallow Mercury and Venus, scorching the Earth.

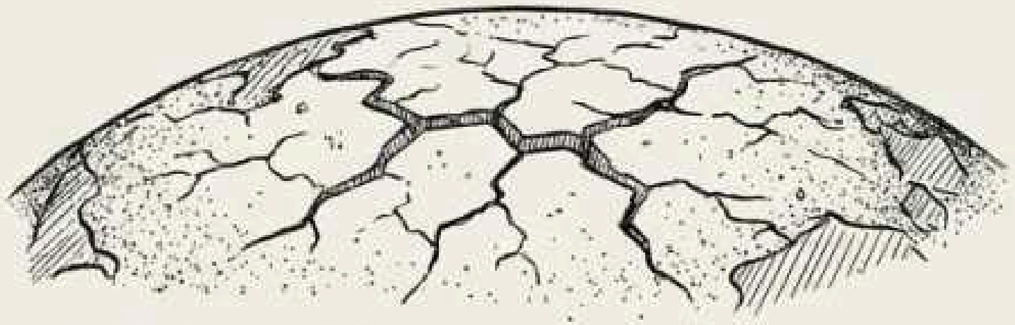
Gemini Notebook

The Fate of the Earth

¶ 5.9

1 Billion Years

$L \propto R^2 T^4$





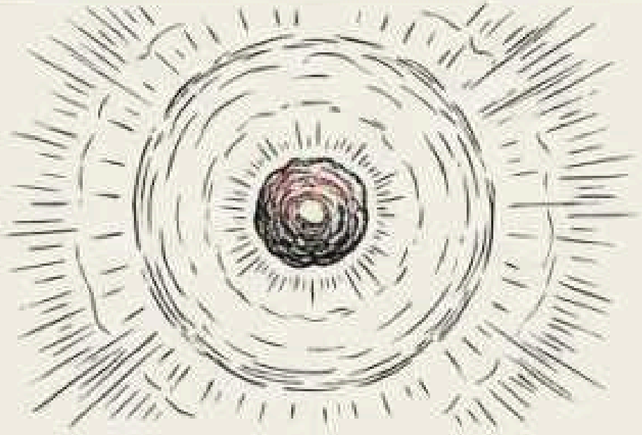
Sun grows bright enough to boil away the oceans.

Life must move.

$P \approx \frac{M^2}{R^4}$

5 Billion Years

$P \approx \frac{M^2}{R^4}$



$He \rightarrow \underbrace{C + O}_{+\ 100\ \text{Million Years of life}}$

Helium ignites in the core, fusing into Carbon and Oxygen.

$L \propto \frac{M^2}{R^4}$

This adds ~100 million years of life.

Gemini Notebook

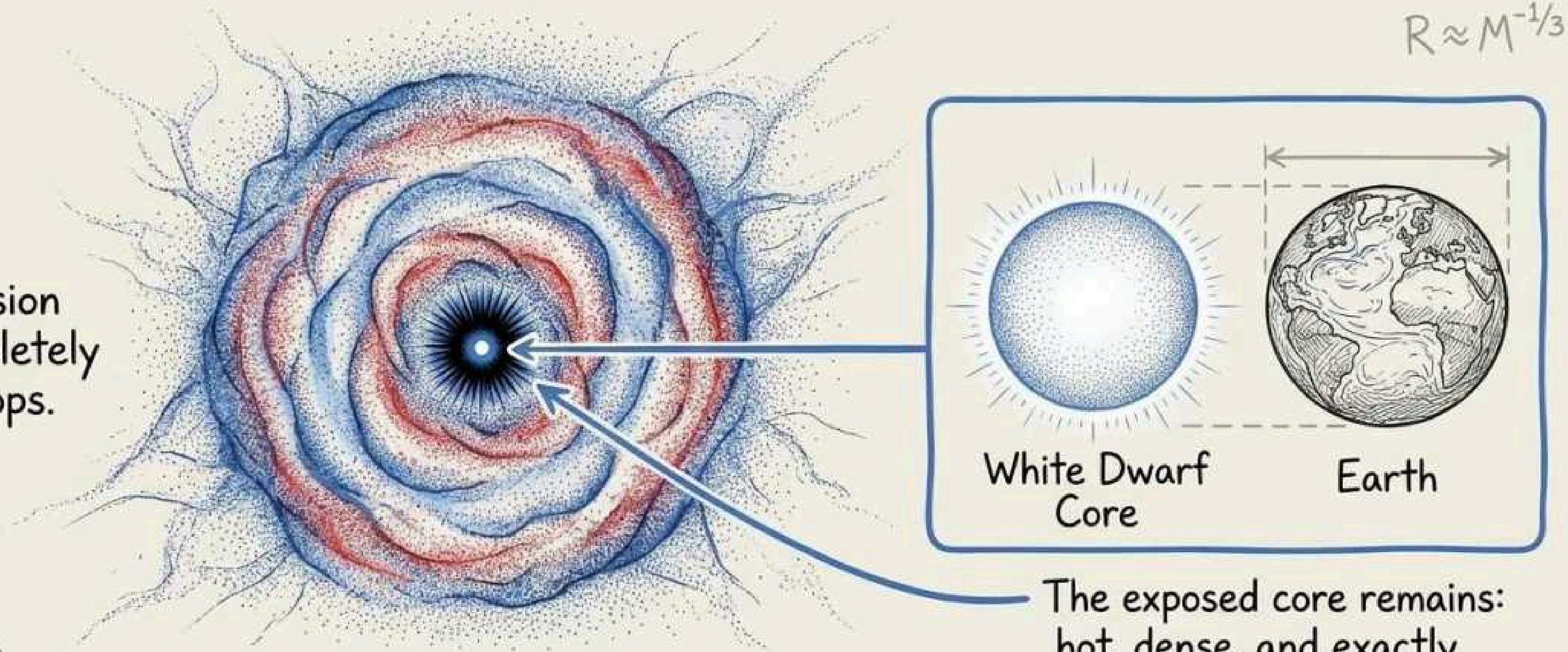
Planetary Nebula & White Dwarf

¶ 5.10

$L \approx M^3$

$R \approx M^{-1/3}$

Fusion completely stops.



The exposed core remains: hot, dense, and exactly the size of the Earth.

Outer layers drift away into a glowing shell (a "planetary nebula"—a historical misnomer with nothing to do with planets).

$L \approx M^3$

$R \approx M^{-1/3}$

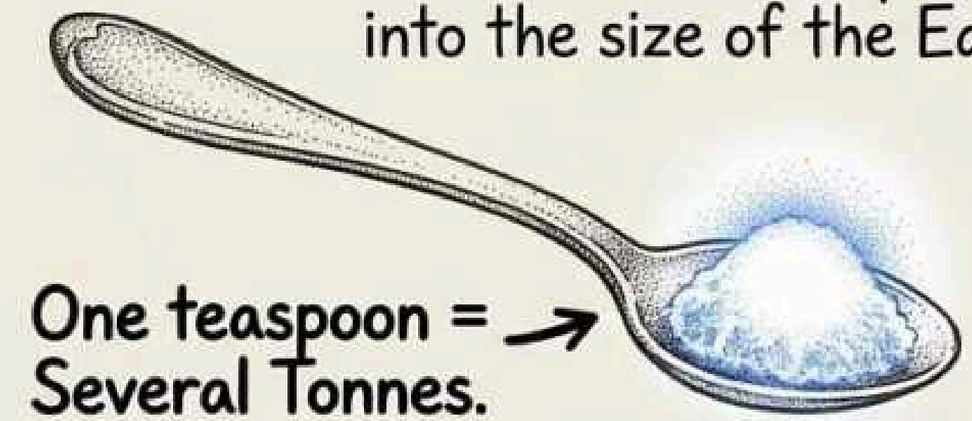
$\rho \sim 10^6 \frac{g}{cm^3}$

Gemini Notebook

Inside a White Dwarf

¶ 5.11

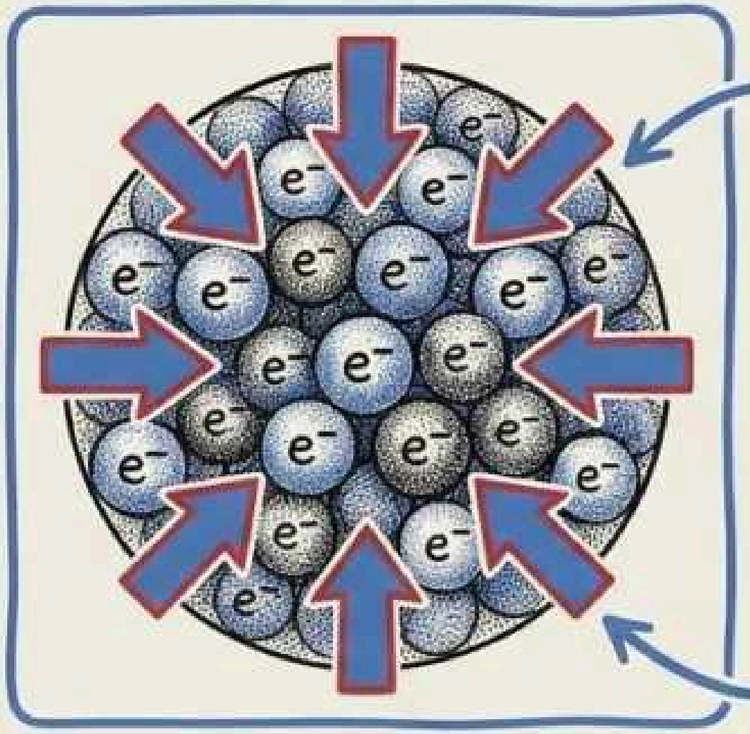
Mass of the Sun packed into the size of the Earth.



One teaspoon = Several Tonnes.



Electron Degeneracy Pressure



Held up not by heat, but by a quantum effect: electrons cannot be squeezed beyond a certain point.

Slowly cools forever—unless it crosses the 1.5 Solar Mass limit.

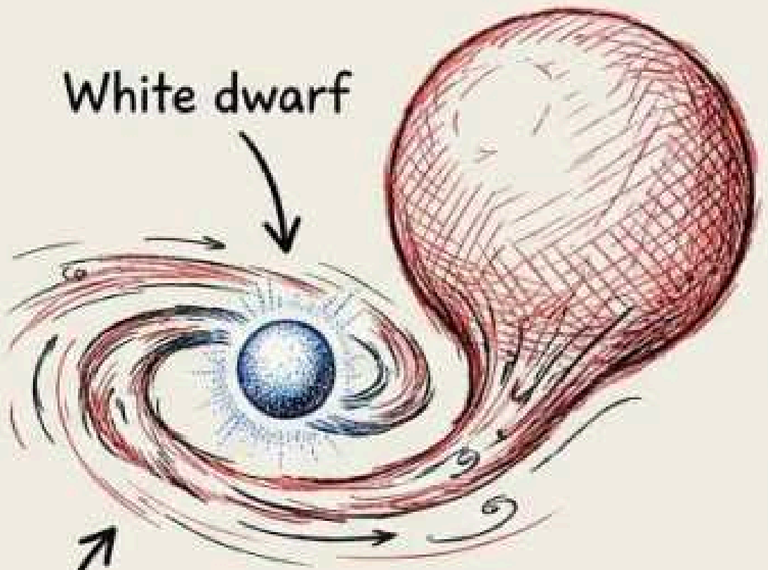
$M \leq 1.4\ M_{\odot}$ (Chandrasekhar Limit)

Gemini Notebook

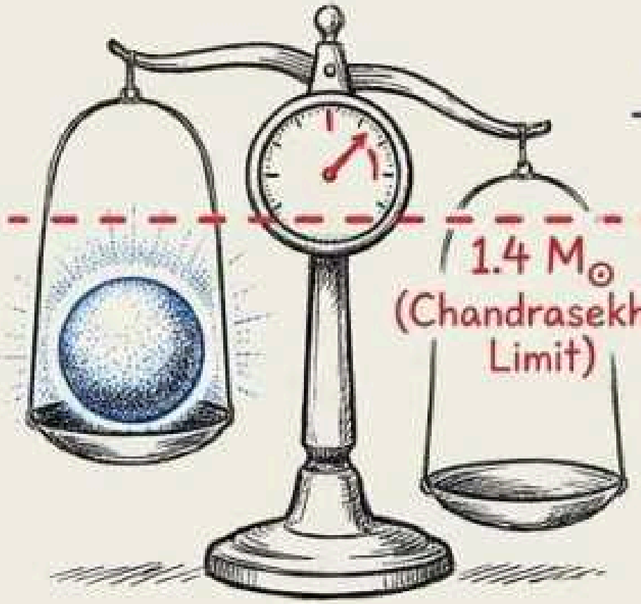
$E_{kinetic} \approx 10^{51}$ ergs $v_{ejecta} \approx 10{,}000$ km/s

Type Ia Supernovae

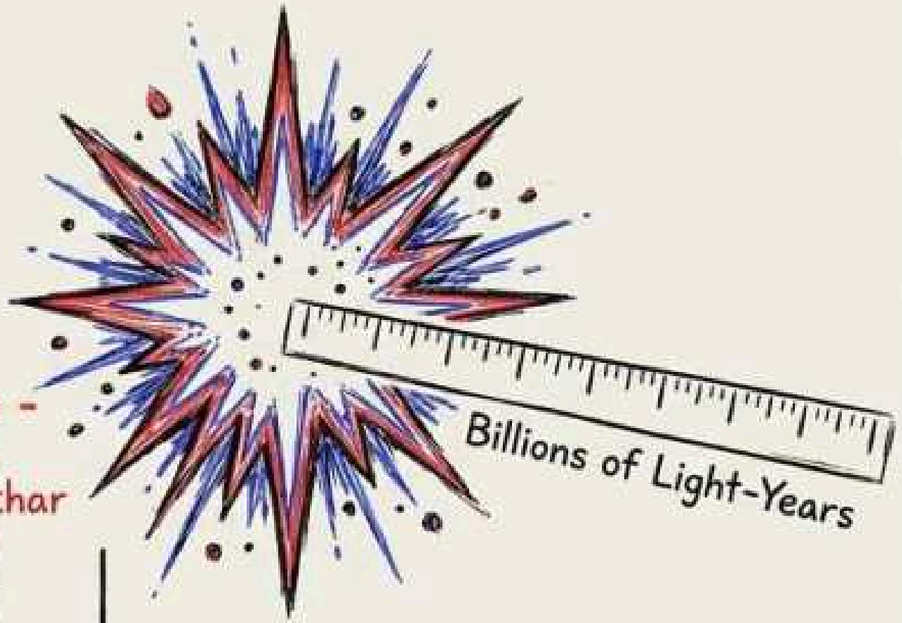
¶ 5.12



If a white dwarf in a close pair pulls gas from a companion, it can approach the 1.4 $M_\odot$ limit.



Result: Runway ignition and complete explosion.



Because they explode at the exact same mass limit, they reach the same peak brightness every time.

Astronomers use them as "Standard Candles" to measure the universe.

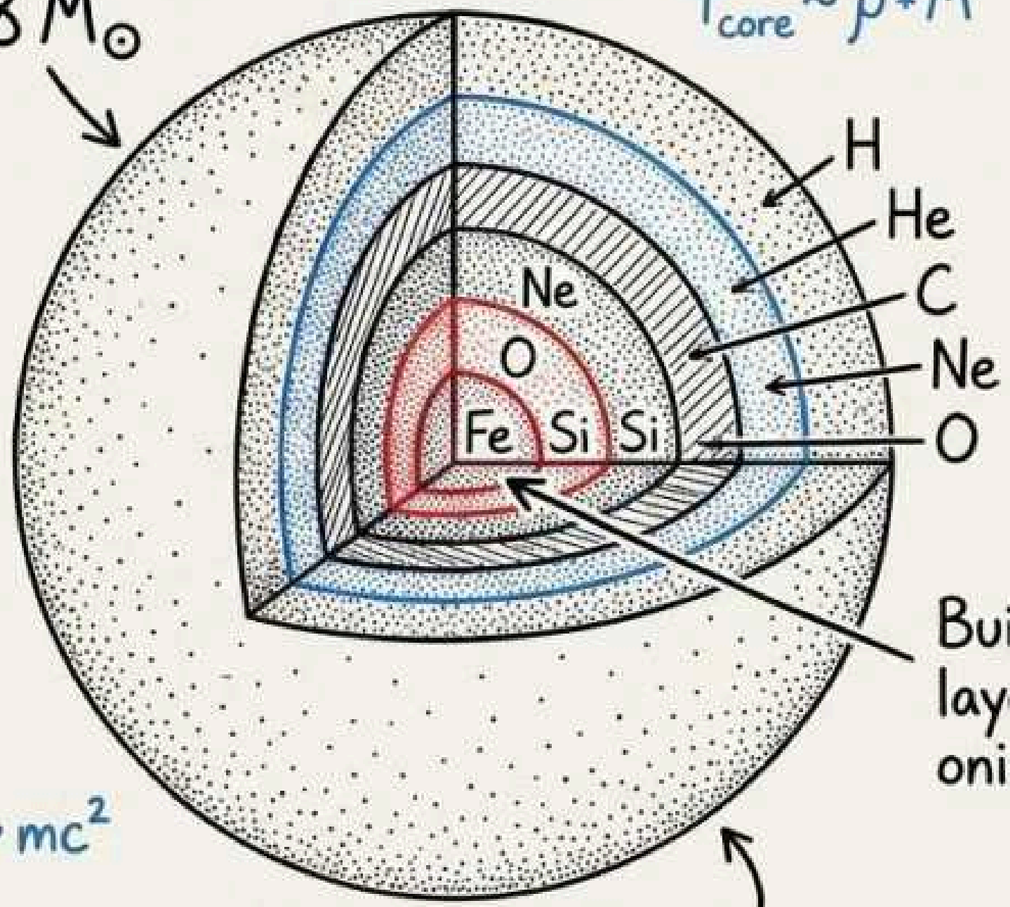
$E_{kinetic} \approx 10^{51}$ ergs $v_{ejecta} \approx 10{,}000$ km/s
$E_k \approx 10^{51}$ ergs $v_{ejet} \approx 0{,}50$ km/s
$E_{kinetic} \approx 10^{51}$ ergs $v_{ejecta} \approx$
Gemini Notebook

Massive Stars: Live Fast, Die Young

¶ 5.13

$>8\,M_\odot$

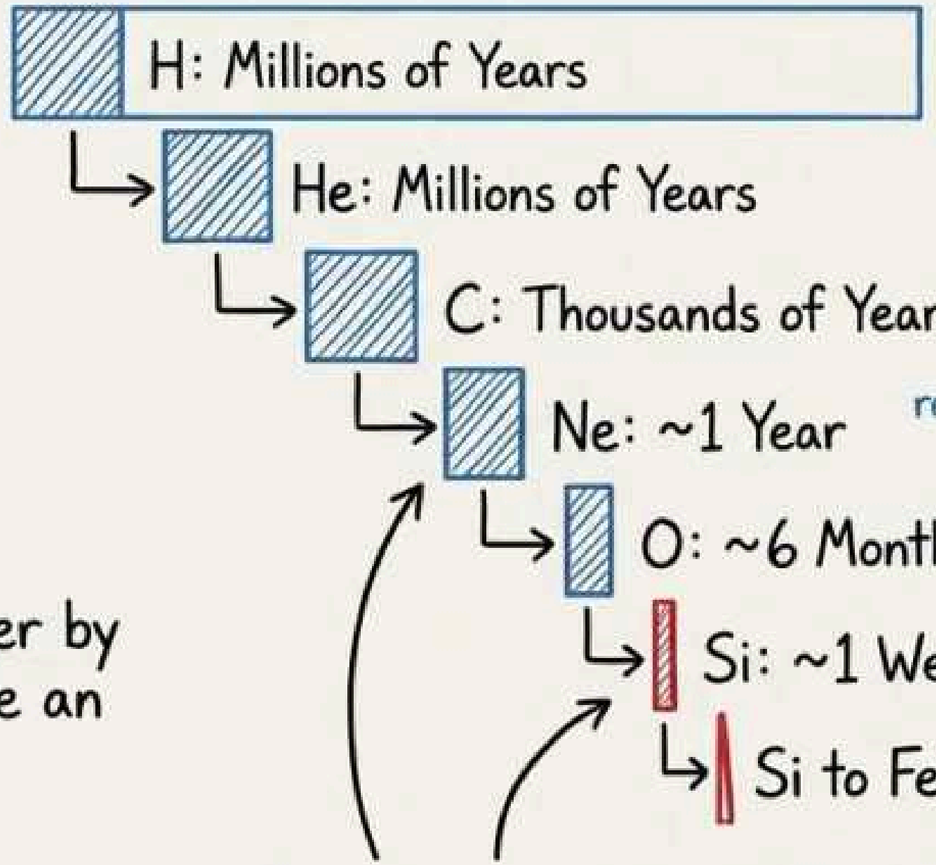
$T_{core} \sim \rho * M$



Built layer by layer, like an onion.

$E \sim mc^2$

Stars $>8\,M_\odot$ grow hot enough to fuse heavier and heavier elements.



$E \sim mc^2$

reaction rate $\sim T^n$

Each stage is faster than the last. The final stage (Silicon to Iron) lasts only about a day.

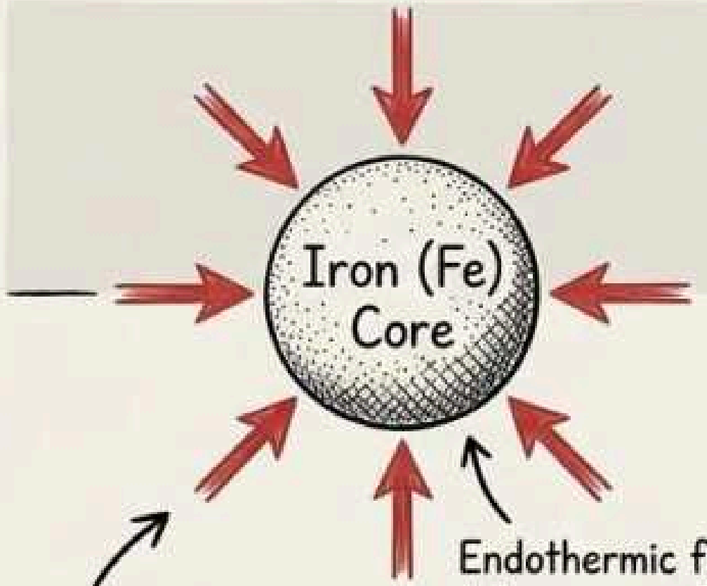
Gemini Notebook

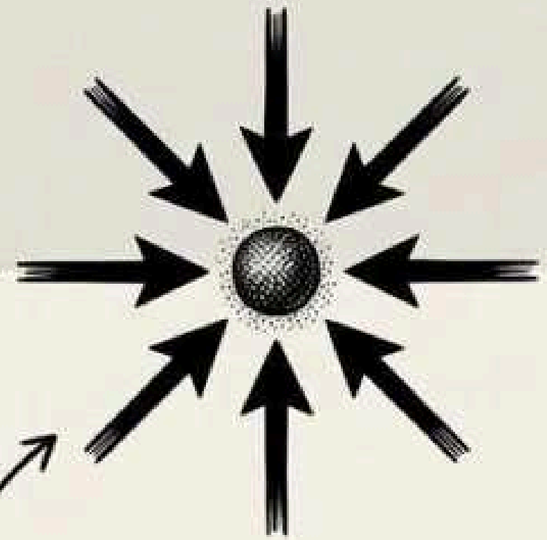
Core Collapse

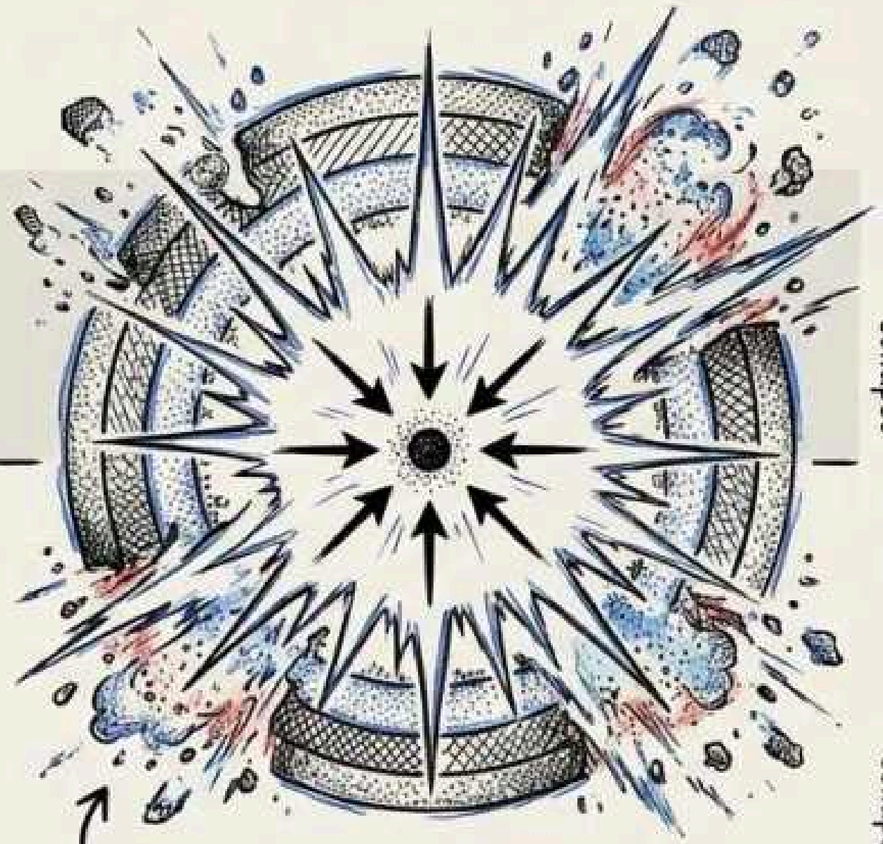
¶ 5.14

$T_{core} > 5$ GK

(Fraction of a second)







$\rho_{core} \approx 10^{14}$ g/cm^3

$T_{core} > 5$ GK

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse} \approx 100$ms

Iron is the end of the line. Fusing lighter elements releases energy, but fusing iron TAKES energy IN.

The core loses its outward pressure and collapses in a fraction of a second.

Outer layers rebound in a titanic explosion: A Supernova.

For a few weeks, it shines as brightly as a whole galaxy.

$E_{grav} \approx 10^{53}$ ergs

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse}$

Gemini Notebook

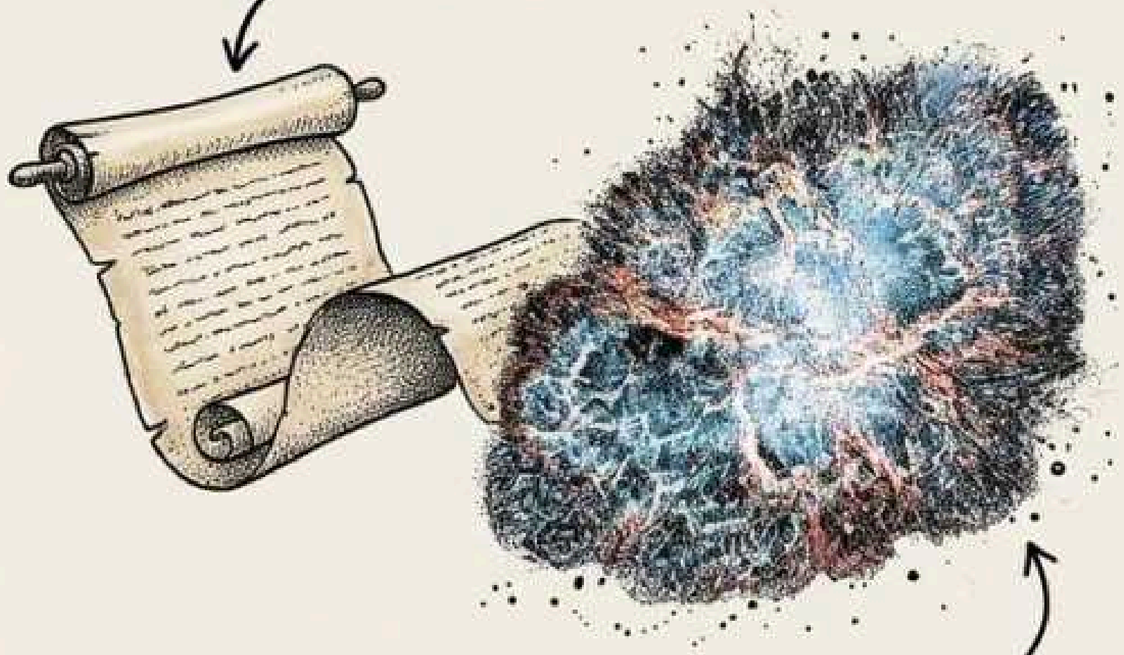
Supernovae in Human History

$E \sim mc^2$

Rare: perhaps 1 or 2 per century in any galaxy.

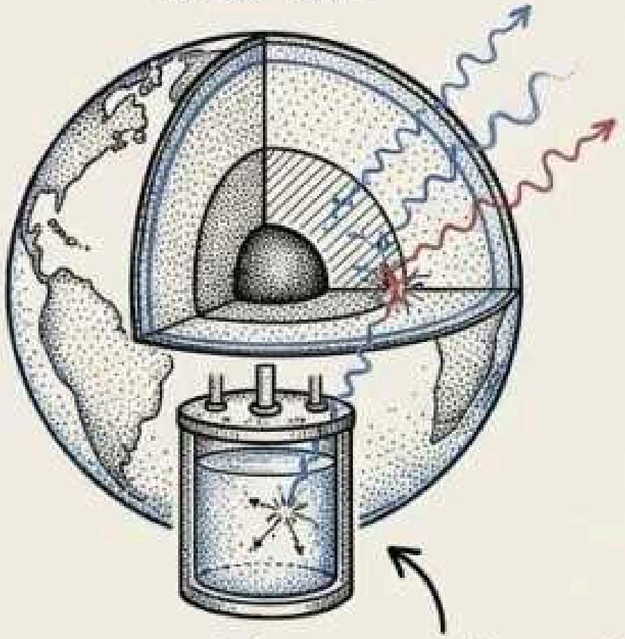
$\rho_{core} \approx 10^{14}$ g/cm^3

1054 AD



Recorded by Chinese astronomers.
Remains still glow today (Crab Nebula).

1987 AD



Explosion in a neighboring galaxy. Earth detectors caught a burst of neutrinos, confirming core collapse theory.

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse} \approx 100$ms

$T_{core} > 5$ GK

$E_{grav} \approx 10^{54}$ ergs

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse}$

Gemini Notebook

Neutron Stars & Pulsars

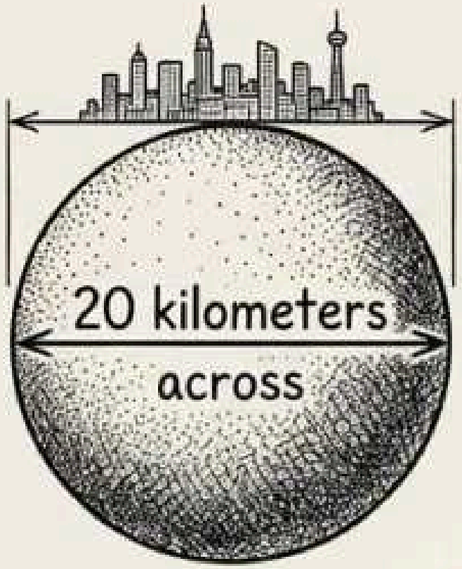
¶ 5.16

$E \sim mc^2$

$\rho_{core} \approx 10^{14}$ g/cm^3

$T_{core} > 5$ GK

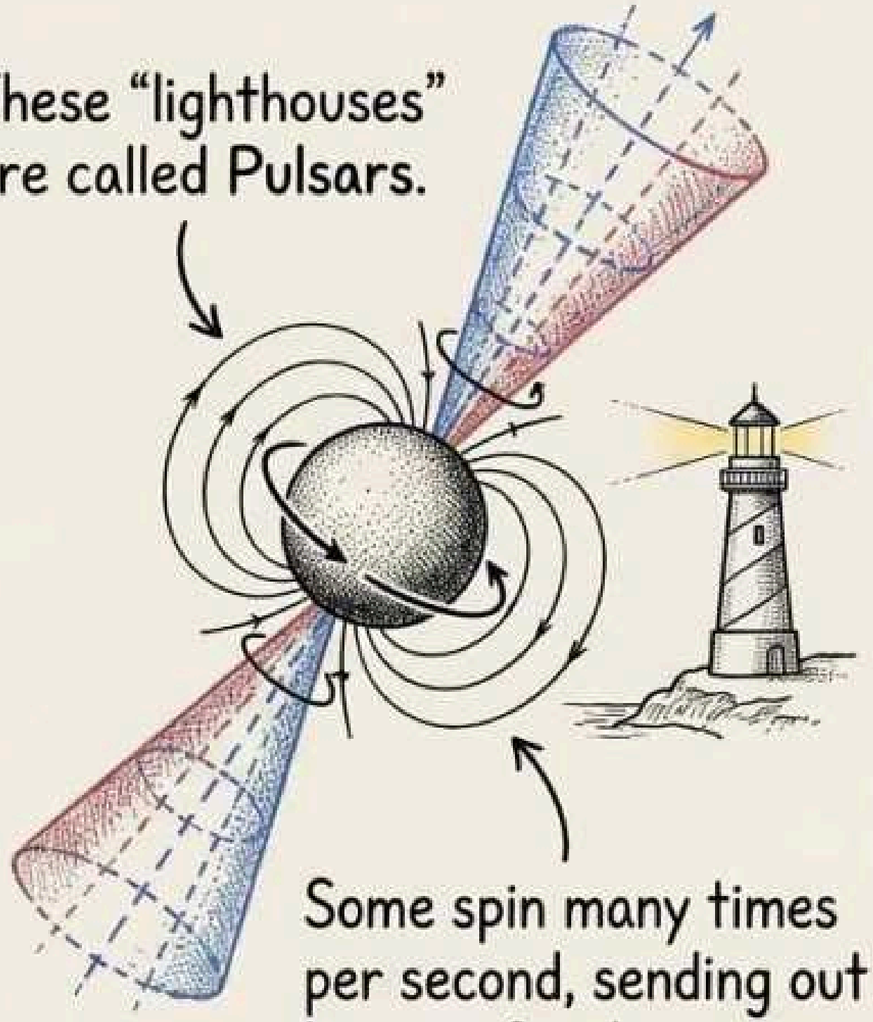
$p^+ + e^- \rightarrow n^0$



20 kilometers
across

If the collapsed core is not too heavy,
it becomes a Neutron Star.

These "lighthouses"
are called Pulsars.



Some spin many times
per second, sending out
beams of radio waves.

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse} \approx 100$ ms

$E_{grav} \approx 10^{54}$ ergs

$v_{collapse} \approx 0.2c$

$\Delta t_{collapse}$

Gemini Notebook

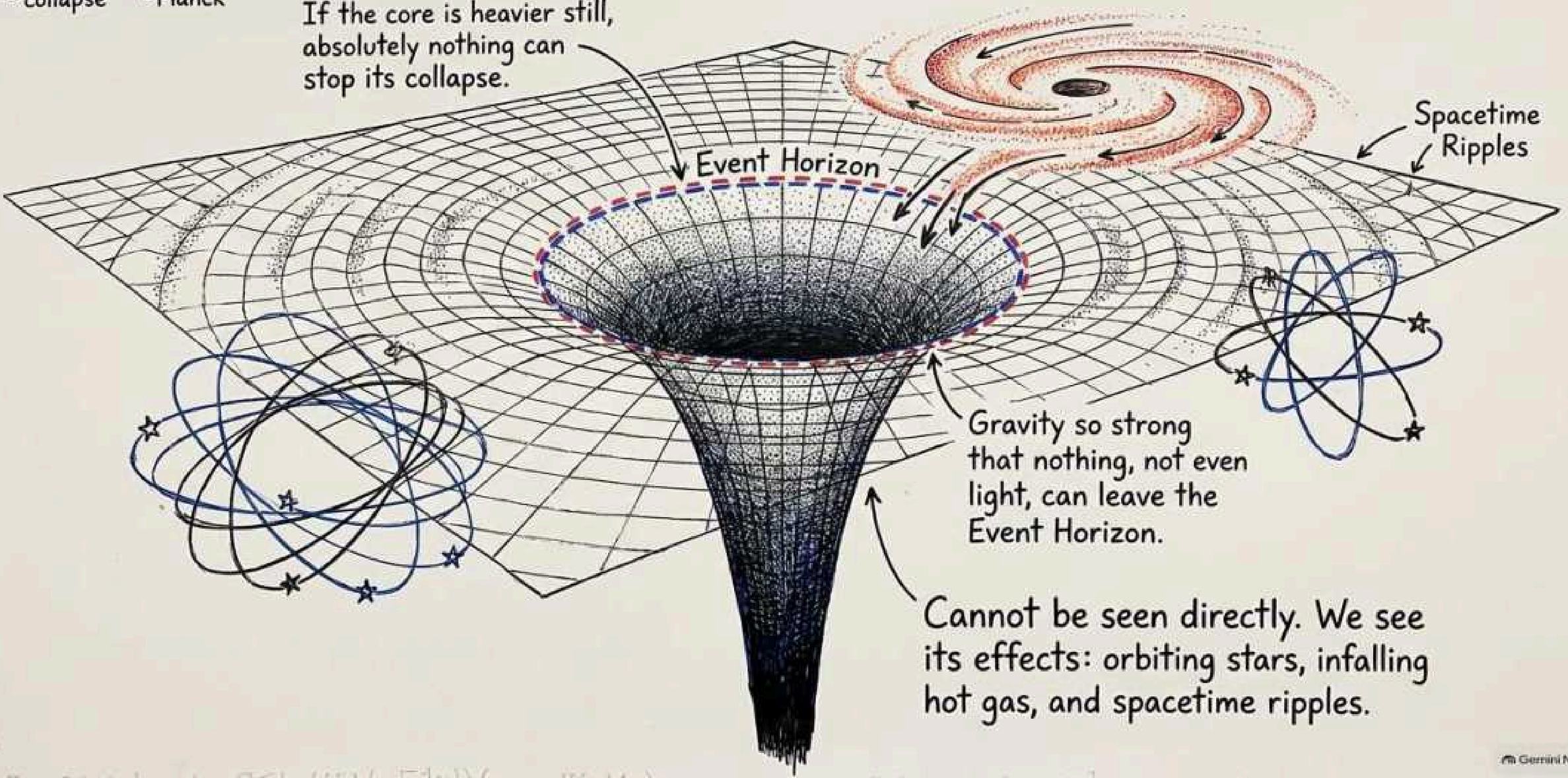
$E_{grav} \approx 10^{54}$ ergs

$v_{collapse} \approx c$

$\Delta t_{collapse} \approx t_{Planck}$

Black Holes

¶ 5.17

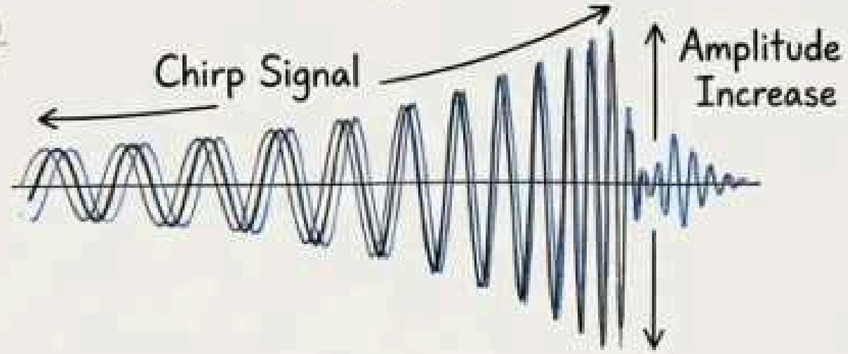


Gemini Notebook

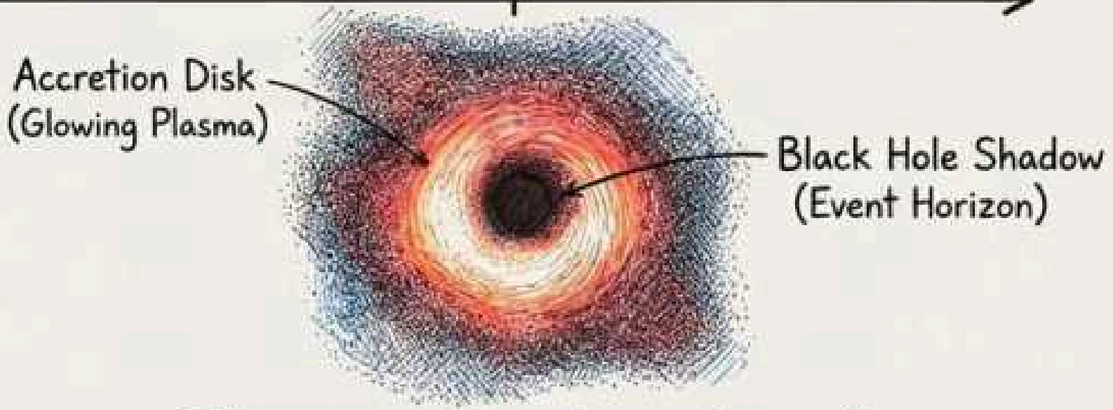
Seeing the Unseen: Waves and Shadows

2015 — 2019

$c = 3 \times 10^8 \frac{m}{s}$



LIGO detects Gravitational Waves from two merging black holes >1 billion light-years away.



Telescope network produces the first image of a black hole's shadow (Messier 87).

$c = 3 \times 10^8 \frac{m}{s}$

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



4,000,000 $M_\odot$ Black Hole sits at the center of our own Milky Way.

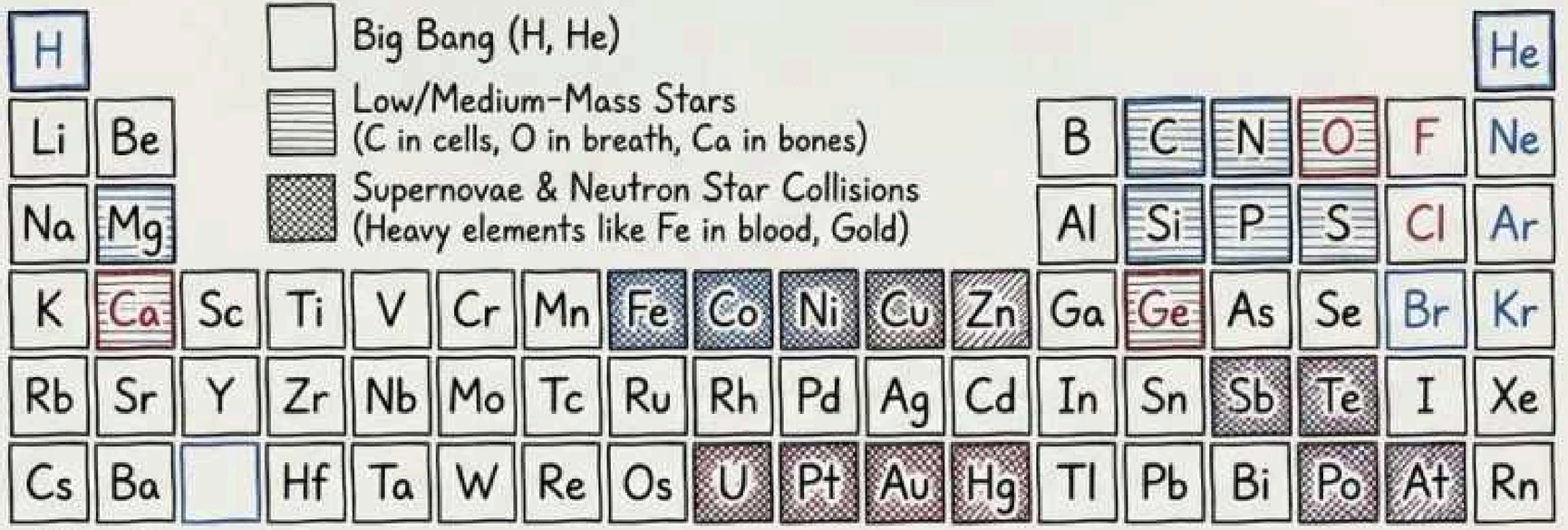
$M_\odot \approx 2 \times 10^{30}$ kg

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

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The Origin of the Elements

¶ 5.19



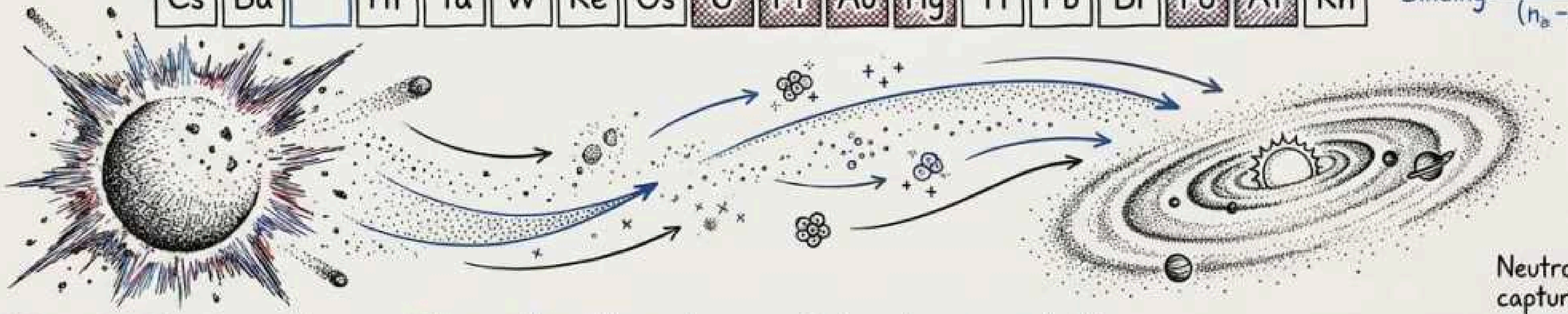
$4\,^1H \rightarrow {}^4He + 2e^+ + 2\nu_e +$ energy

$^3He + {}^3He \rightarrow {}^4He + 2\,^1H$

$^9H + {}^4He \rightarrow {}^{16}Ei^+ +$ + energy

$^{12}C + {}^4He \rightarrow {}^{16}O + \gamma$

$\text{Binding} = \frac{(\mu_t\, m_\alpha}{(n_s - ne^b)}$



$^1H \rightarrow {}^4He + 2e^+ + 2\nu_e +$ energy

Neutron capture

$^{12}C \rightarrow {}^4He \rightarrow {}^{16}O + \gamma$

After the Big Bang, the universe held almost only Hydrogen and Helium.

Every other element was made inside stars or in their explosions.

Dying stars spread this material through space to be gathered into new stars and planets.

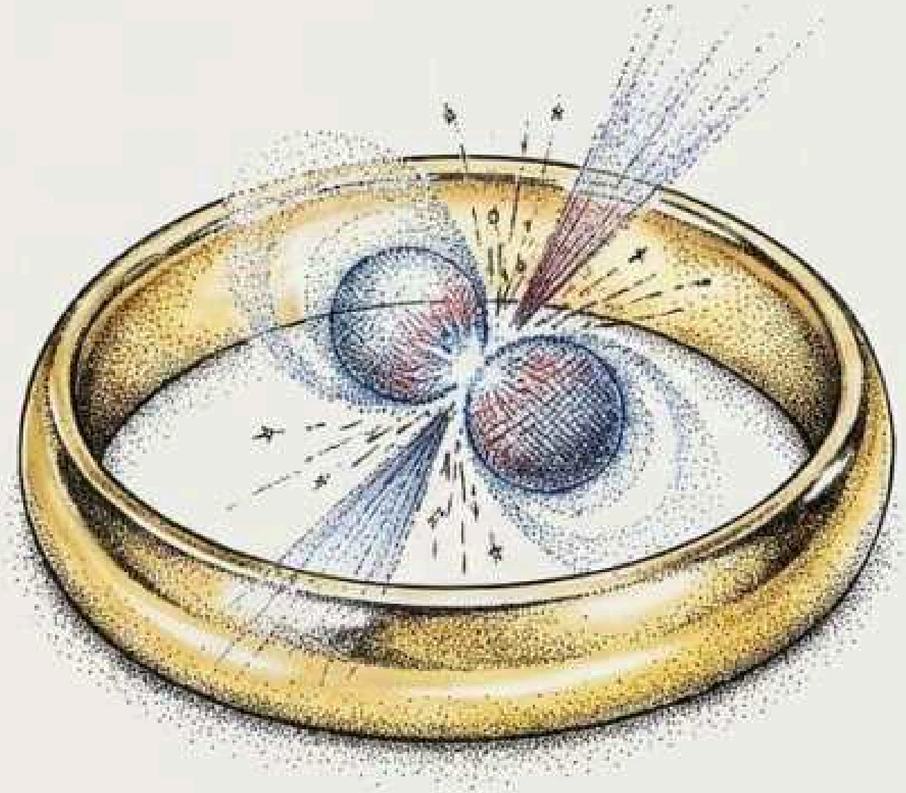
We are, literally, made of star stuff.

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A Question to Take Away

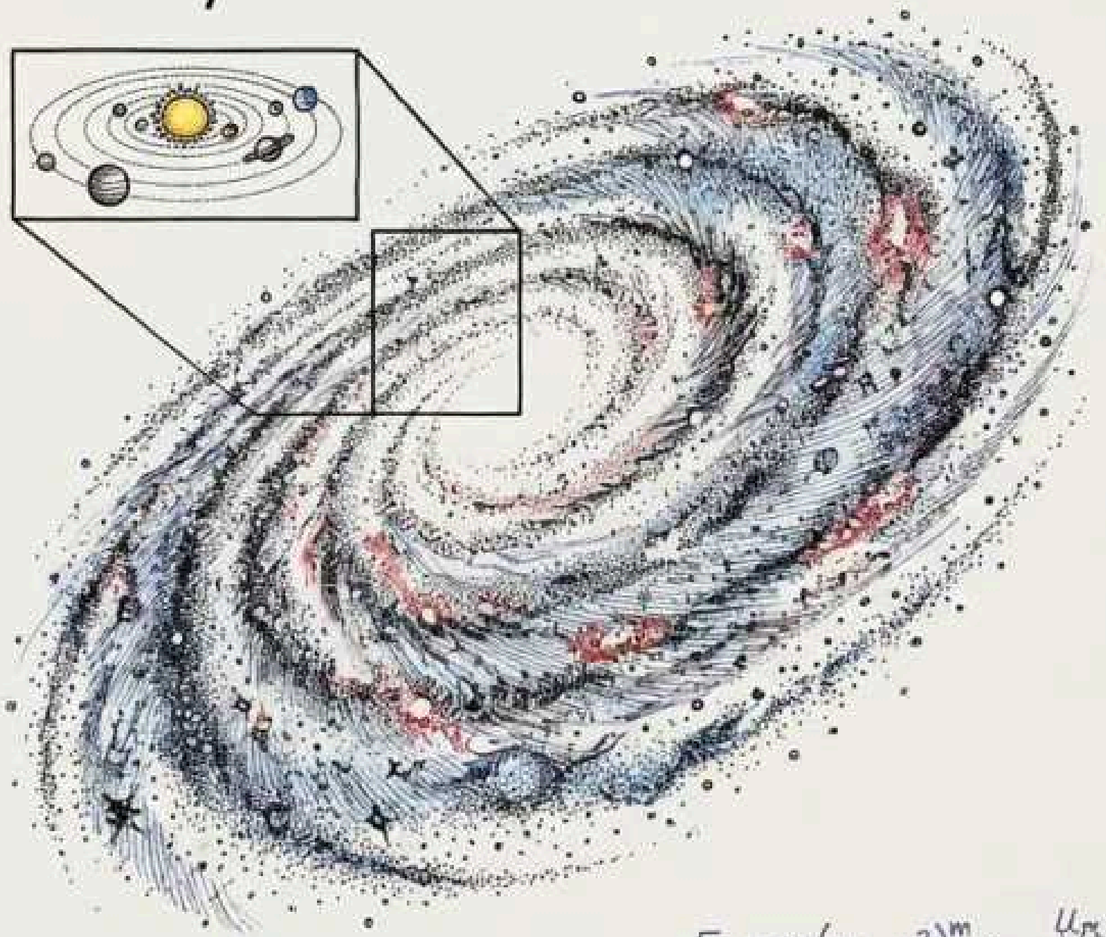
¶5.20

The gold in a wedding ring could not have been made in the Sun. Why not?



Hint: Think about what the Sun can and cannot fuse.

Next in Lecture 6: Stepping back to the largest scales—Galaxies and the history of the universe.



$E = mc^2$

$E = \frac{(\mu\varepsilon_r m_0)}{(n_a - ne^{\beta})}$

Binding energy $H_i = \left(\frac{\mu\varepsilon_r m_0}{(n_a - ne^{\beta})}\right)$

$\ddot{H}_{eland} = \frac{2M}{c^2} + \left(-\frac{m_0}{\chi c^2}\right)$

$E_e = mv^2 - \left(\frac{24T}{\sqrt{-\Lambda_m}^2} + \frac{\phi}{c^2}\right)$

$E_0 = \gamma (m_m v^2)^m \leftarrow -\frac{4\pi}{\lambda}$

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