FROM UNIVERSE…

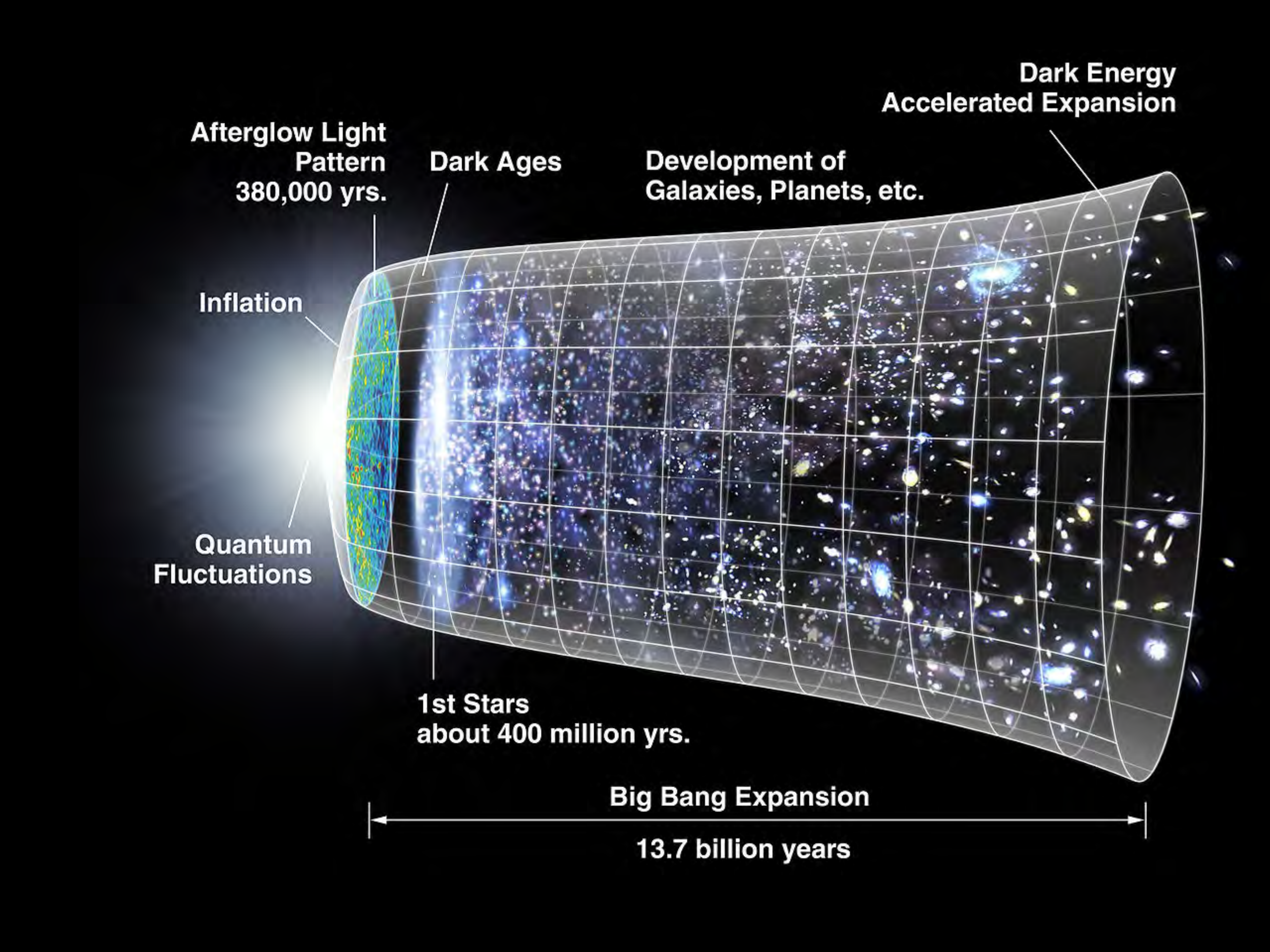
TO PLANETS

LECTURE 1.1: COSMOLOGICAL HISTORY

OUTLINE

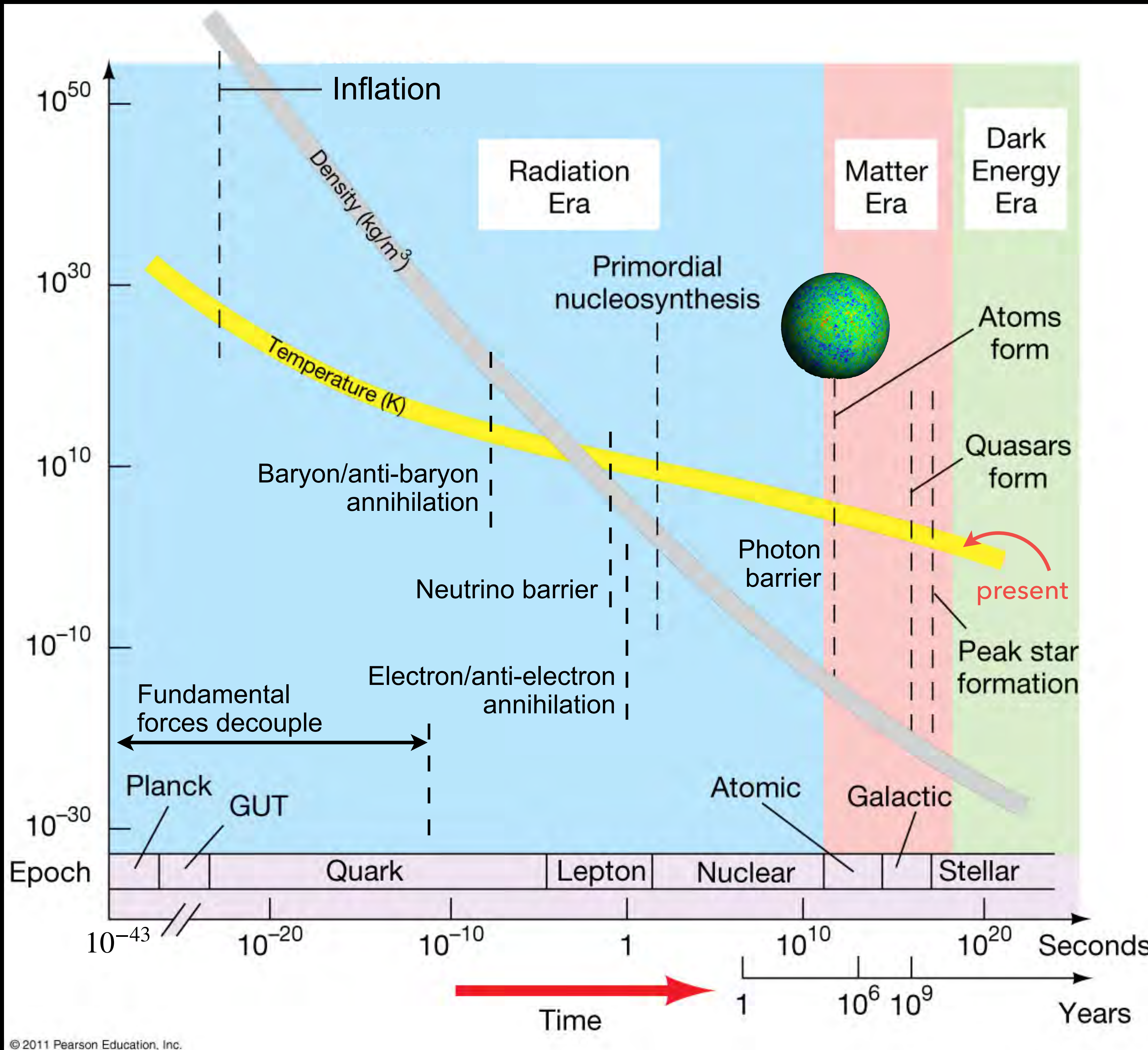
- Cosmological history:
  - From Big Bang to present day
- Stellar Nurseries:
  - The environment in which stars are born
- Star formation and evolution:
  - The life and death of stars

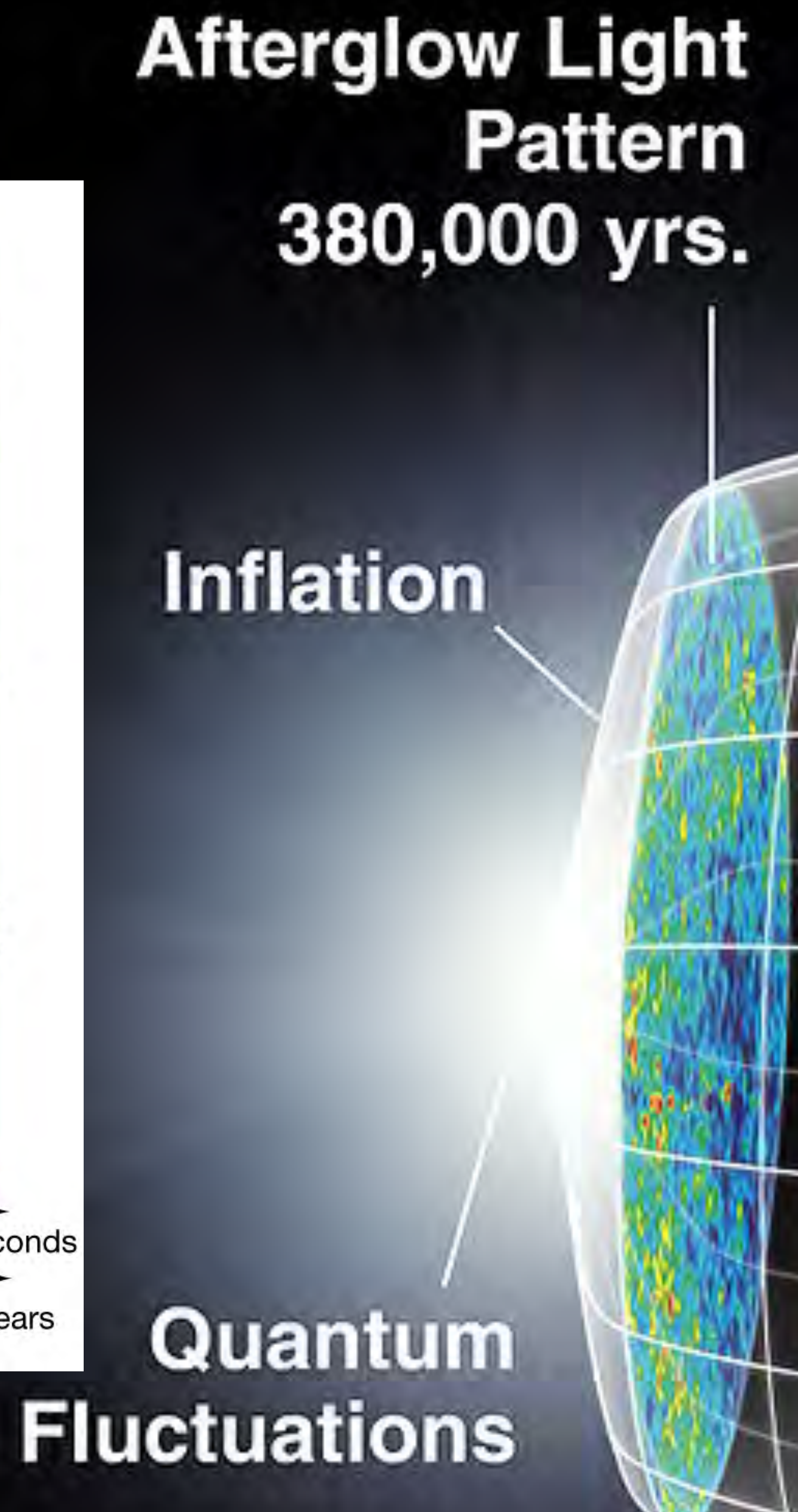
PREVIOUSLY...



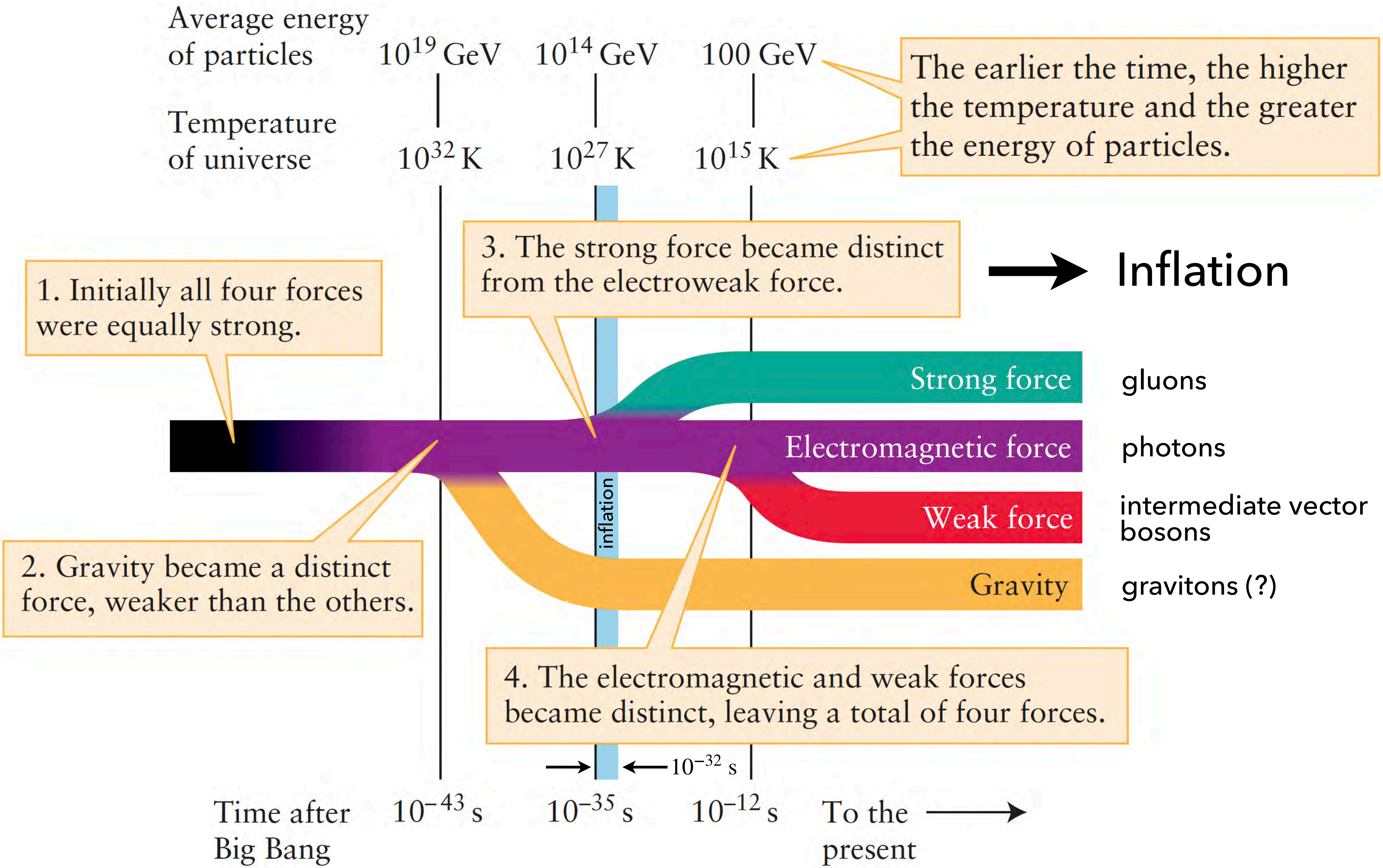
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

VERY EARLY UNIVERSE

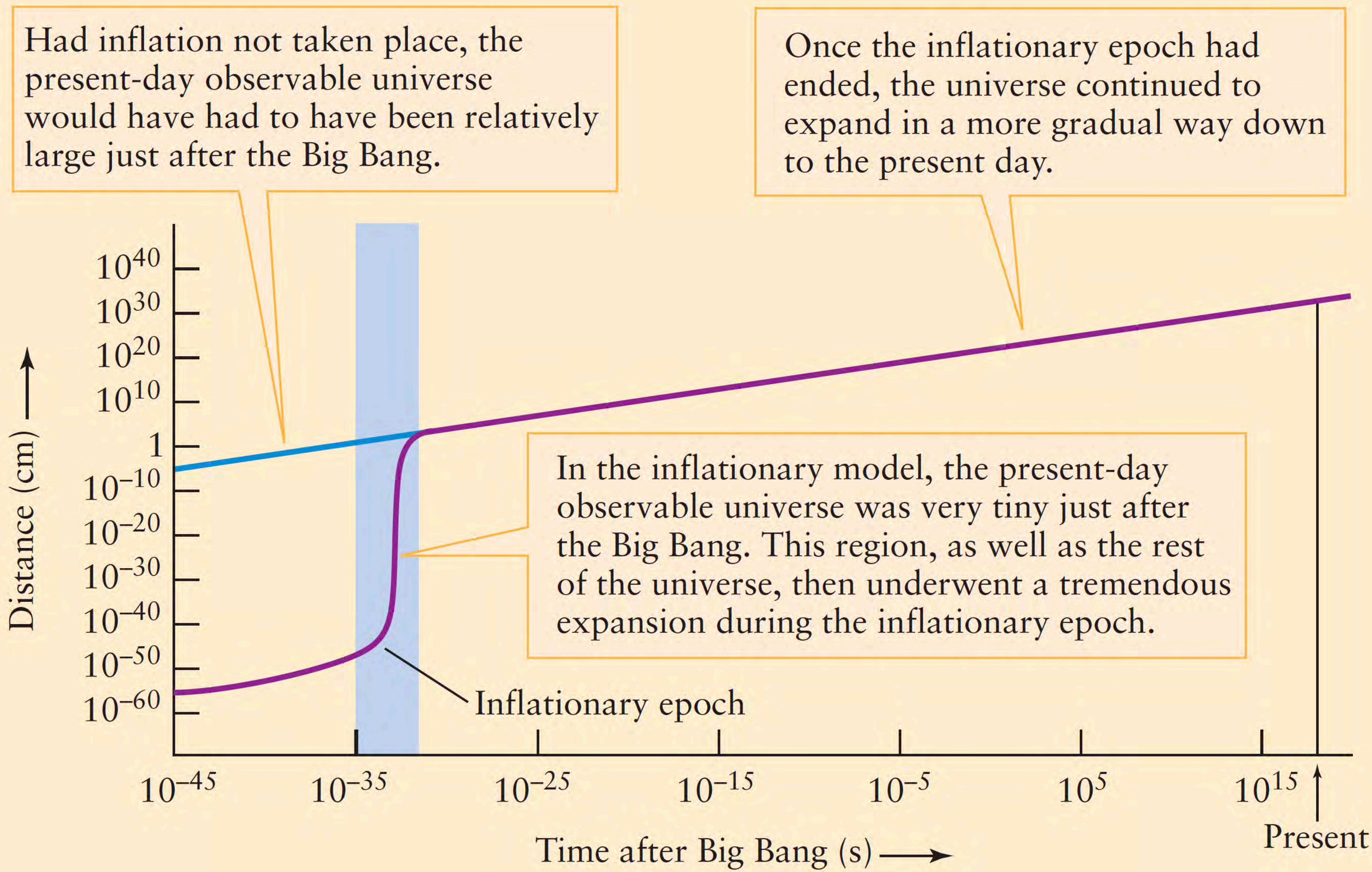




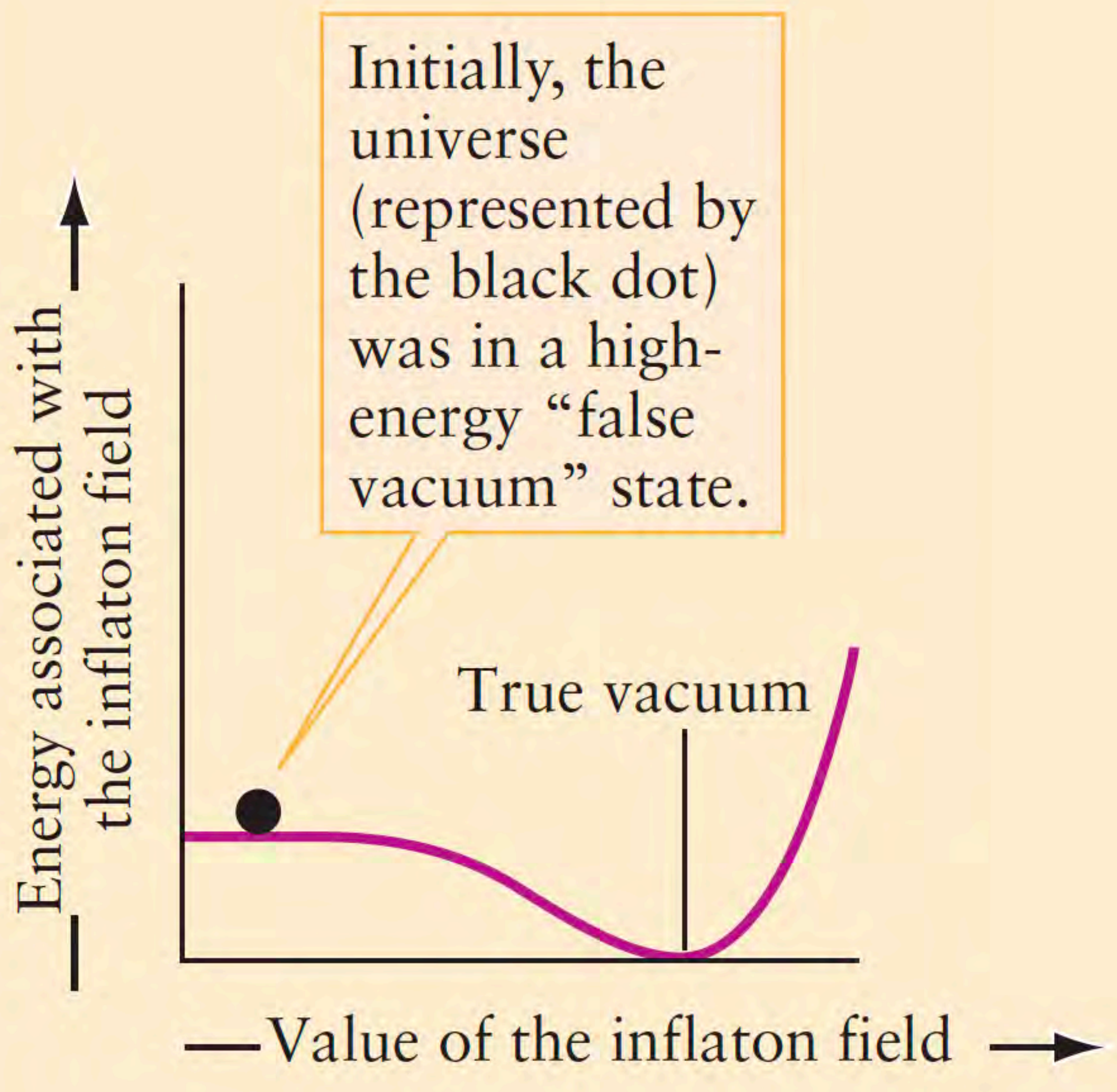
SEPARATION OF FORCES



WHAT IS INFLATION?

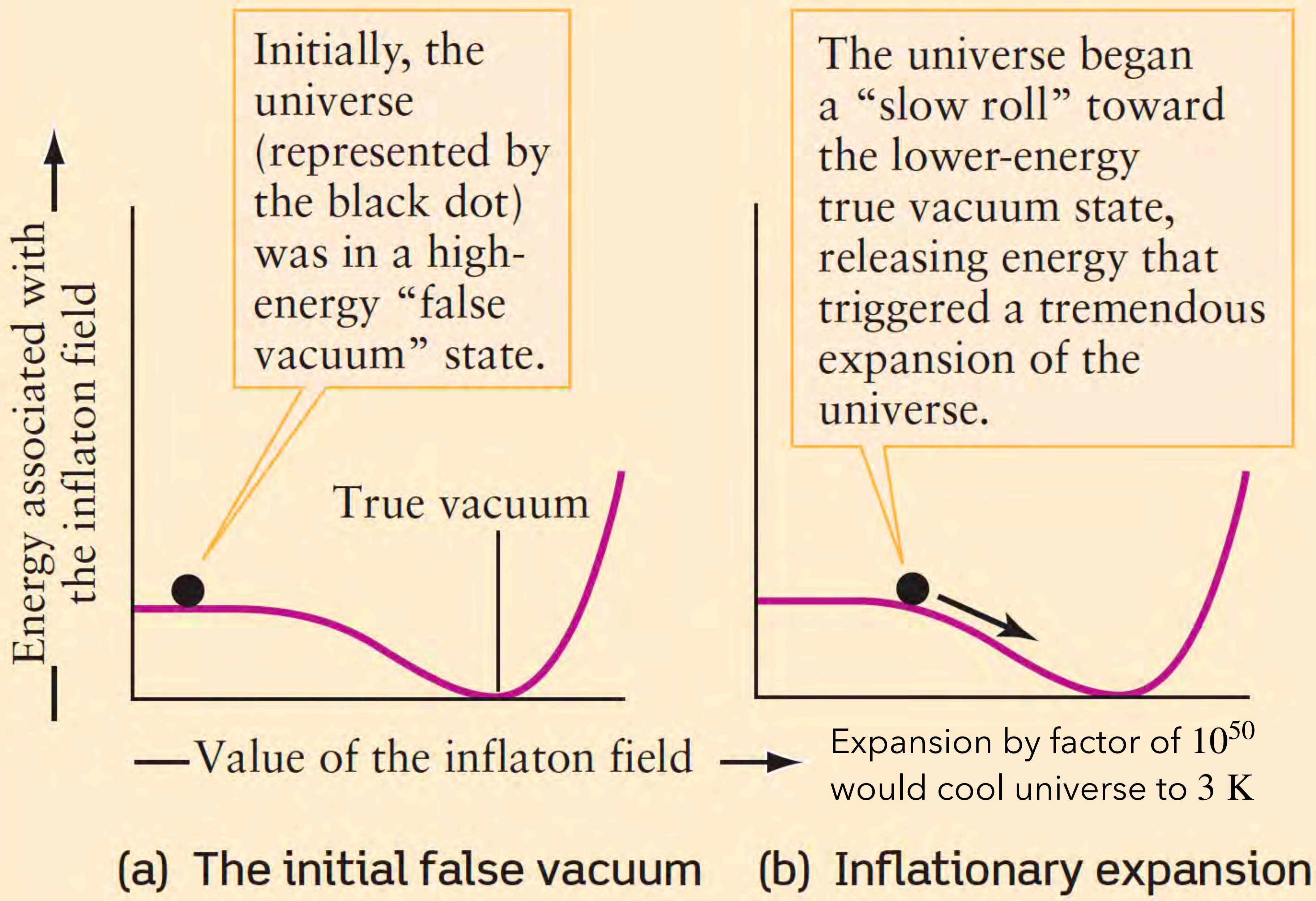


WHAT CAUSED INFLATION?

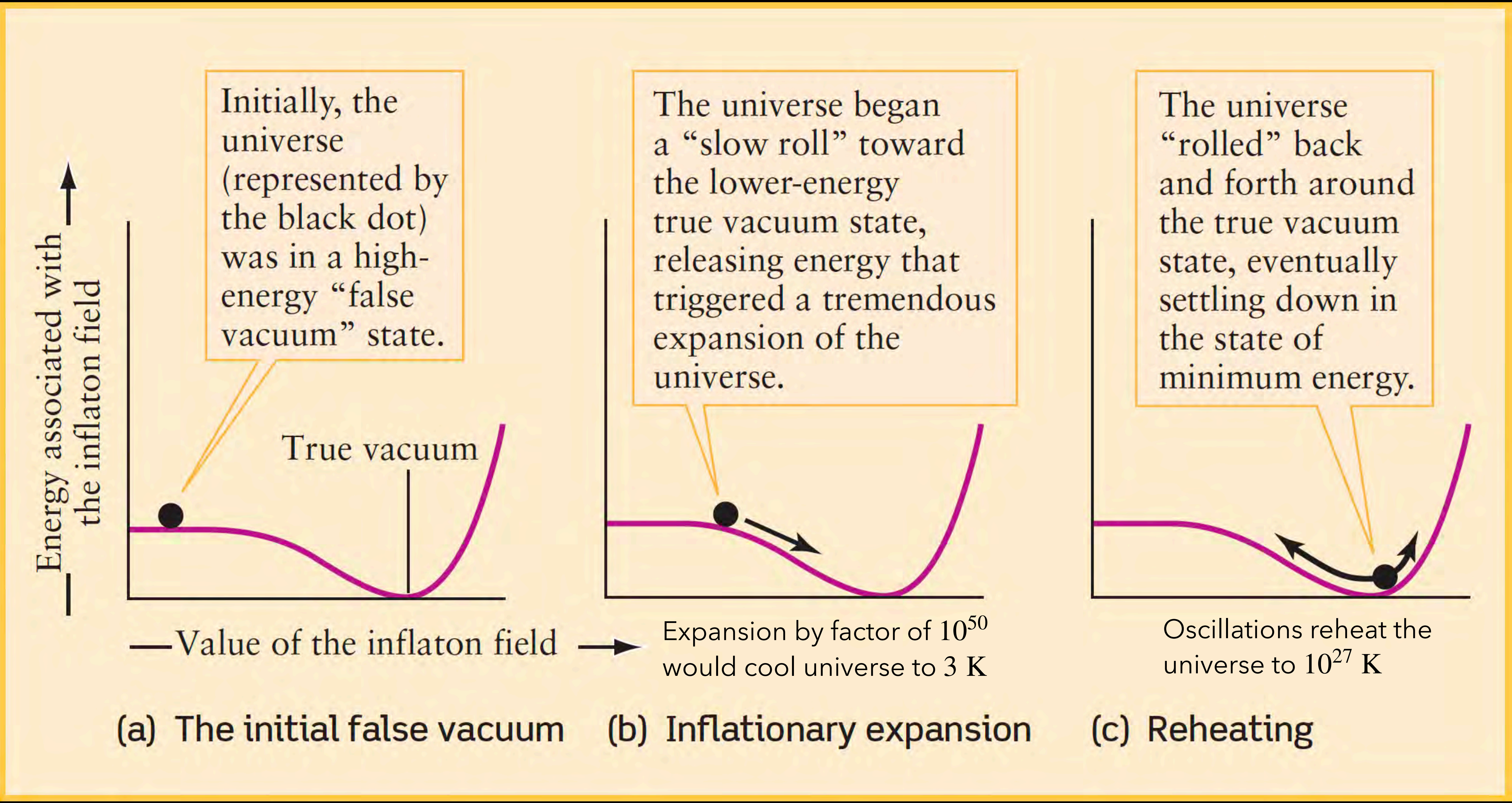


(a) The initial false vacuum

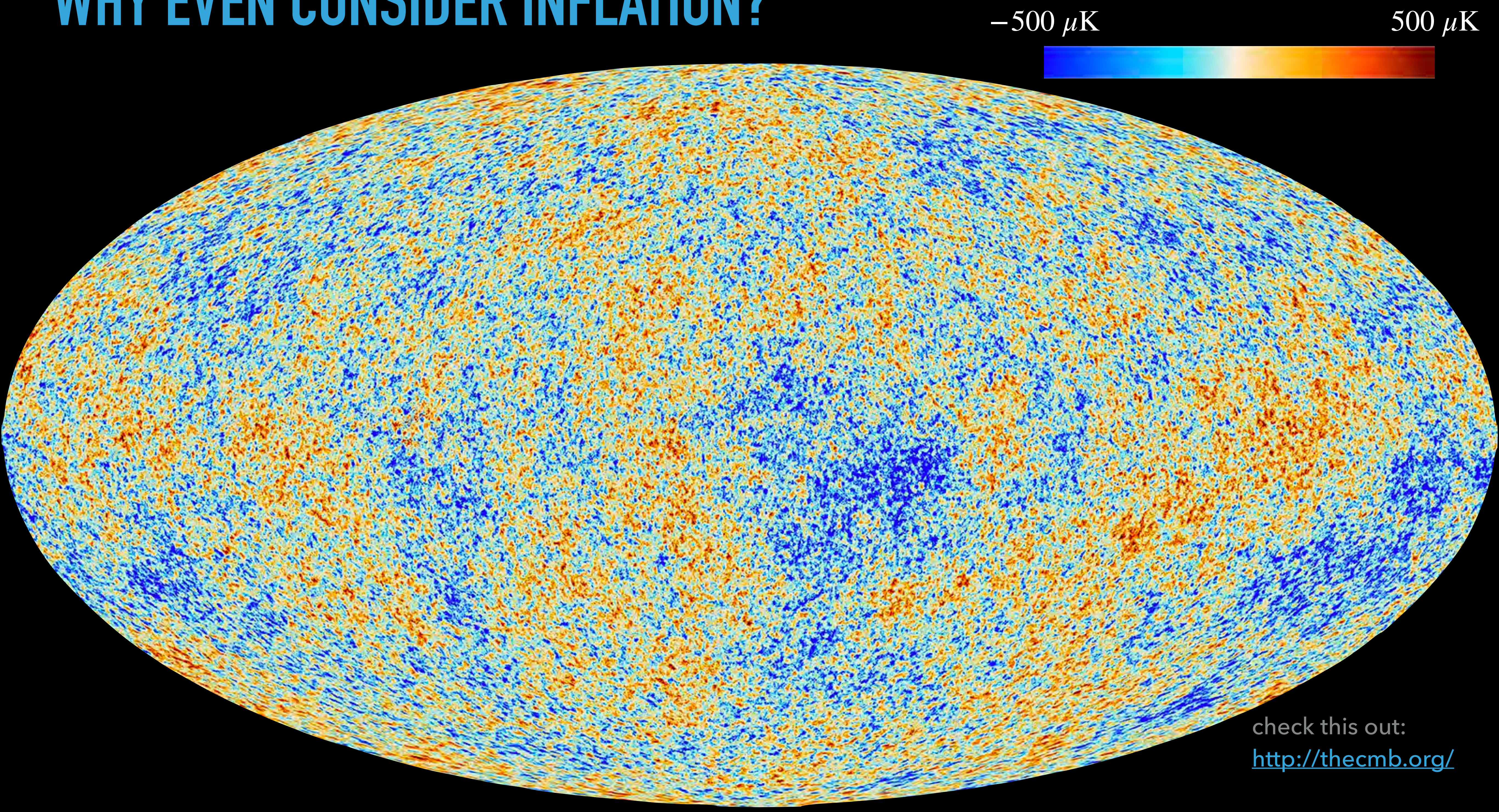
WHAT CAUSED INFLATION?



WHAT CAUSED INFLATION?

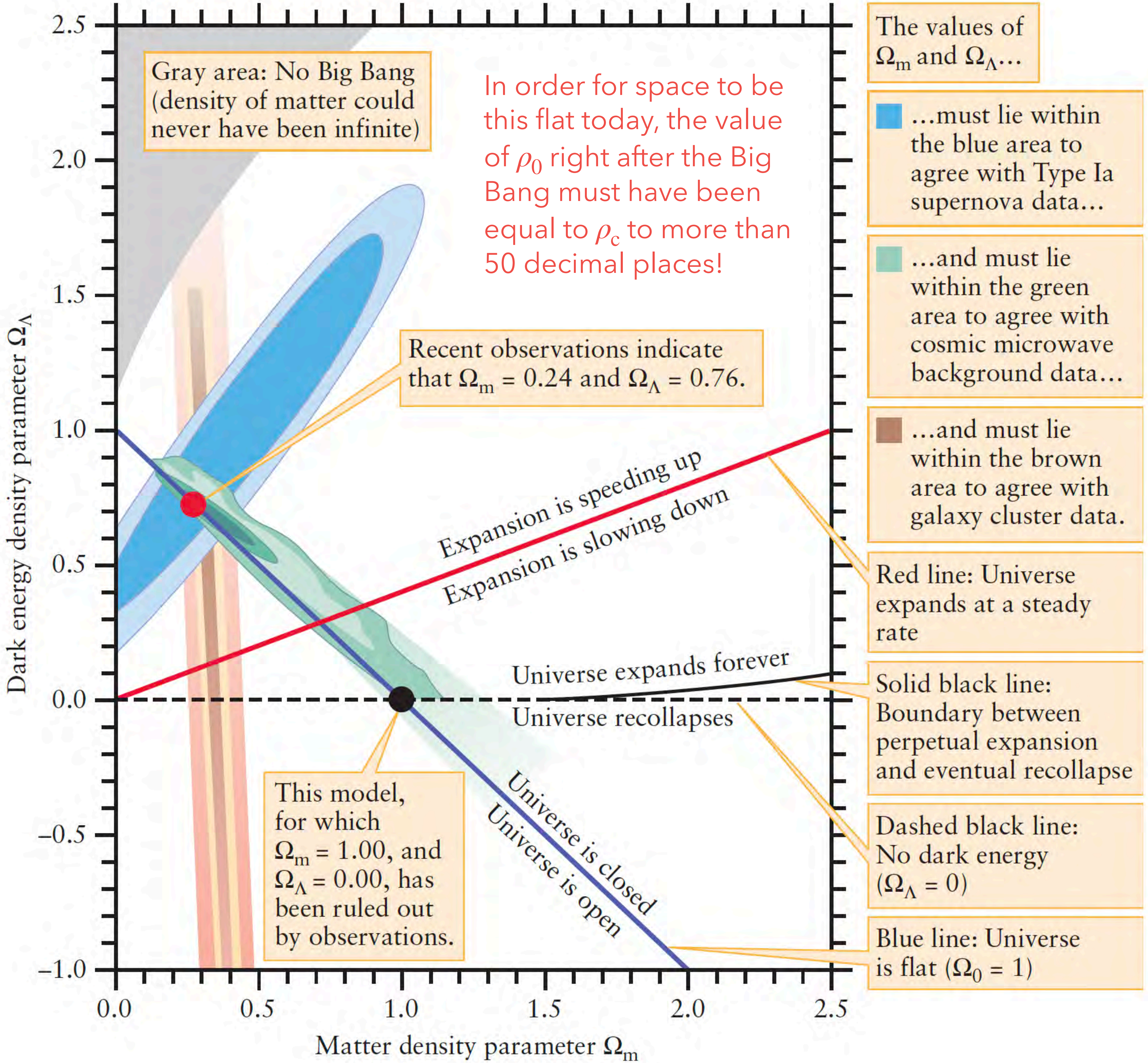


WHY EVEN CONSIDER INFLATION?



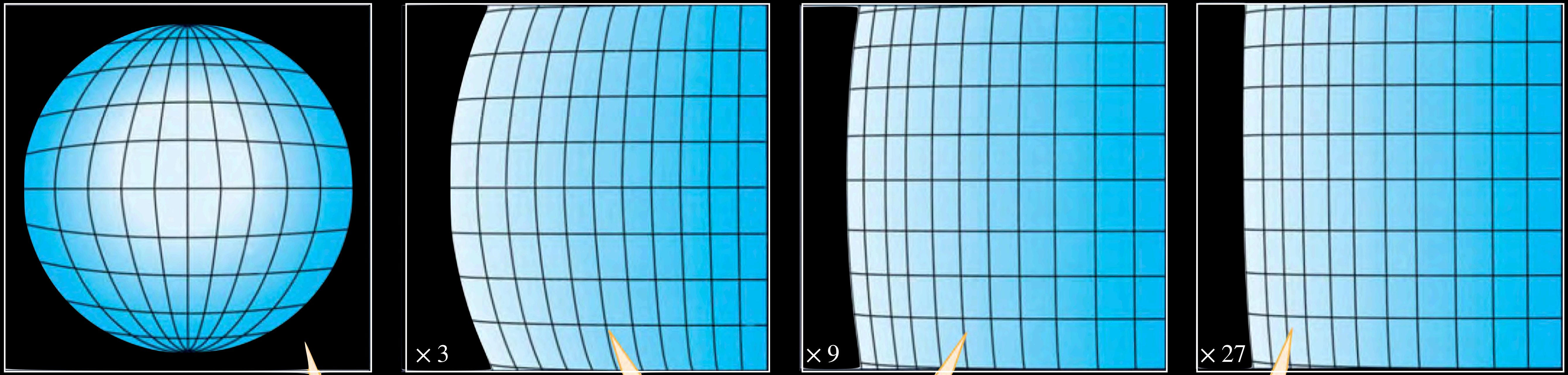
check this out:
http://thecmb.org/

- Especially when the oldest light is the cosmic microwave background (CMB) from 380,000 years after the Big Bang…



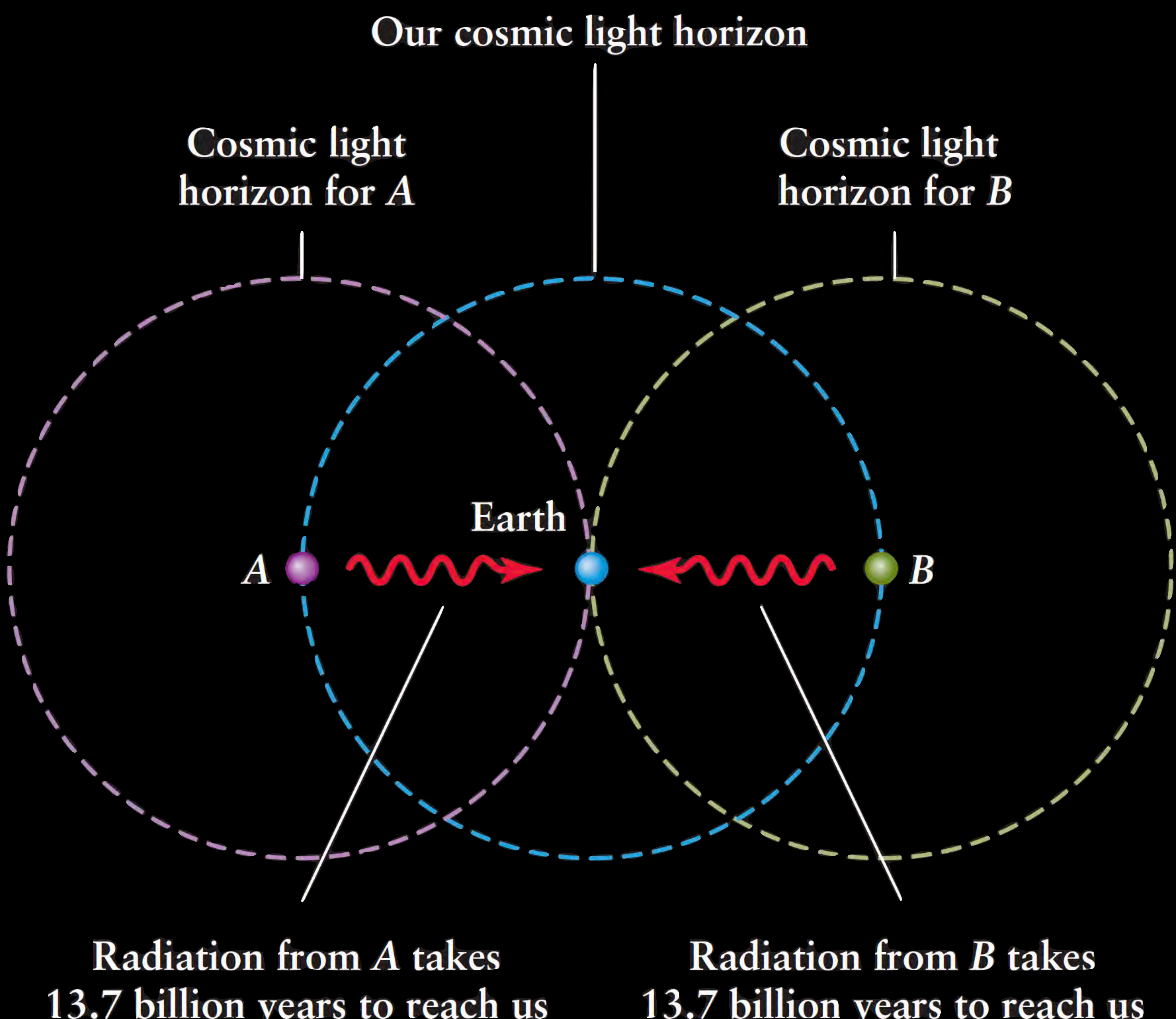
Gray area: No Big Bang (density of matter could never have been infinite)
In order for space to be this flat today, the value of ρ_0 right after the Big Bang must have been equal to ρ_c to more than 50 decimal places!
The values of Ω_m and Ω_Λ...
...must lie within the blue area to agree with Type Ia supernova data...
...and must lie within the green area to agree with cosmic microwave background data...
...and must lie within the brown area to agree with galaxy cluster data.
Recent observations indicate that Ω_m = 0.24 and Ω_Λ = 0.76.
Expansion is speeding up
Expansion is slowing down
Red line: Universe expands at a steady rate
Universe expands forever
Universe recollapses
Solid black line: Boundary between perpetual expansion and eventual recollapse
Dashed black line: No dark energy (Ω_Λ = 0)
This model, for which Ω_m = 1.00, and Ω_Λ = 0.00, has been ruled out by observations.
Universe is closed
Universe is open
Blue line: Universe is flat (Ω_0 = 1)
Dark energy density parameter Ω_Λ
Matter density parameter Ω_m
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
0.0
0.5
1.0
1.5
2.0
2.5

INFLATION: SOLVES THE FLATNESS PROBLEM…



As the sphere is inflated, its curvature eventually becomes undetectable and its surface appears flat.

INFLATION: SOLVES THE ISOTROPY PROBLEM…



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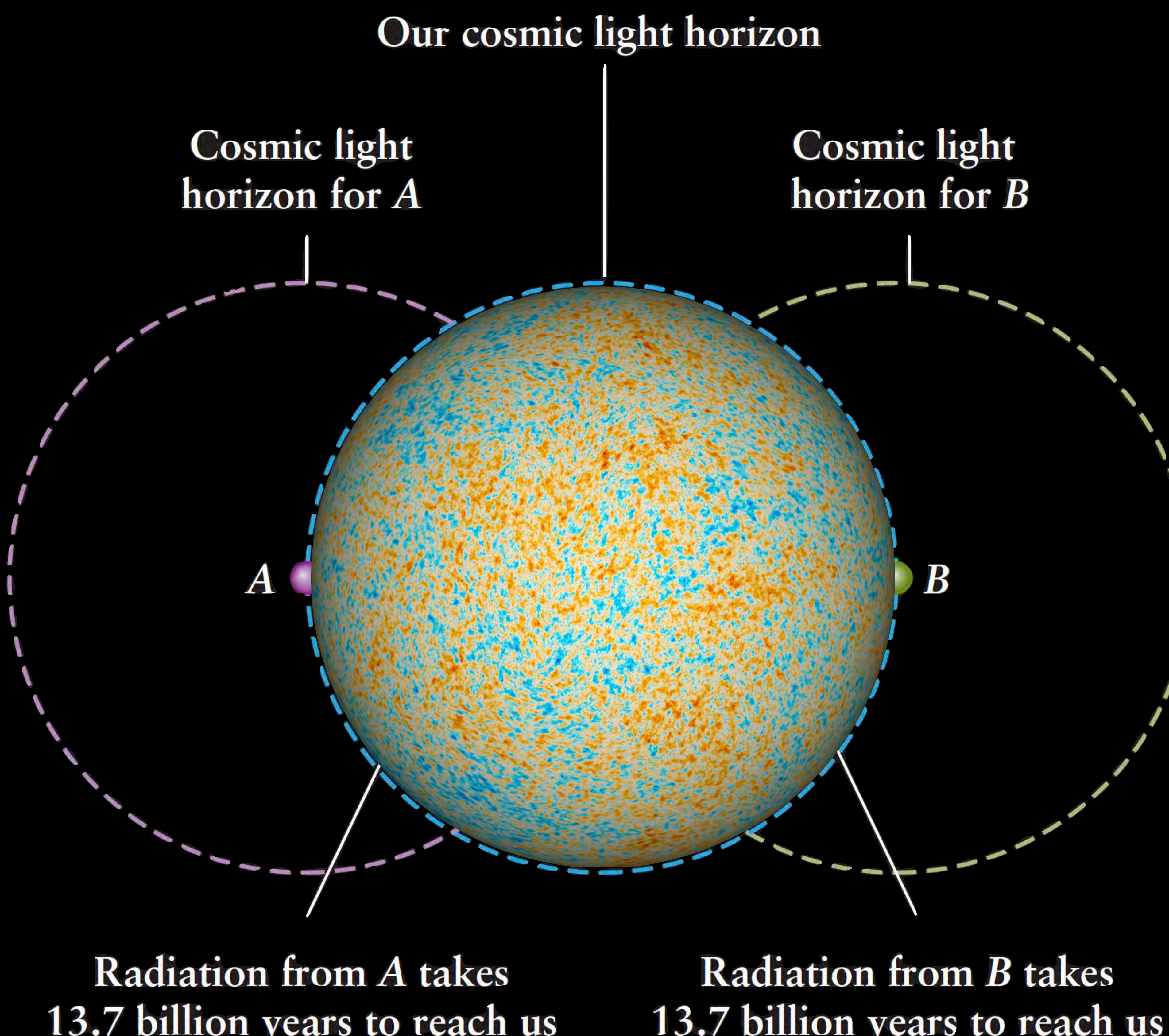
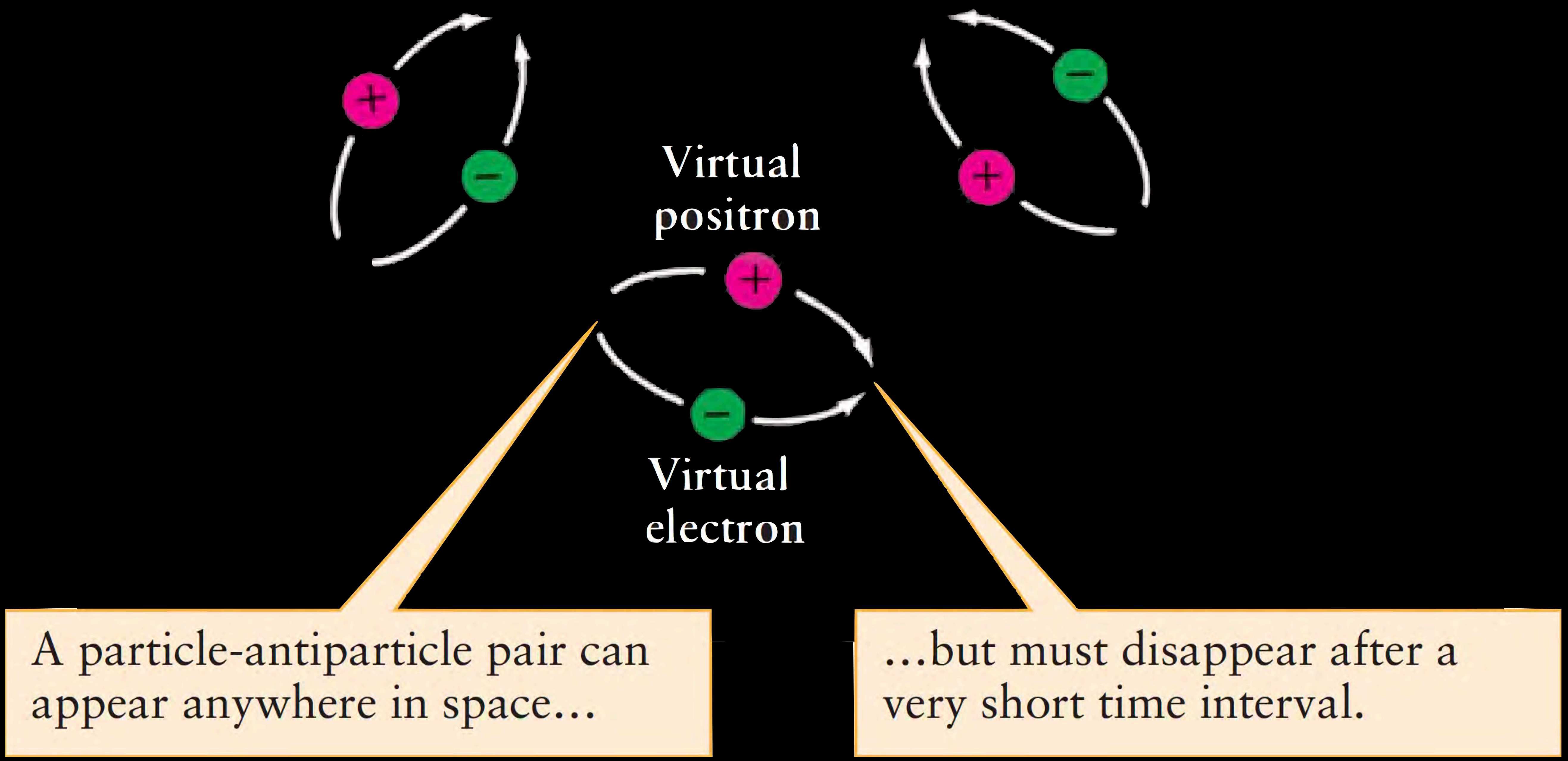


INFLATION: EXPLAINS WHERE MATTER COMES FROM…

$$\left.\begin{aligned} \Delta E \Delta t &= \frac{\hbar}{2} \\ E &= mc^2 \end{aligned}\right\} \longrightarrow \quad \Delta t = \frac{1}{\Delta m}\frac{\hbar}{2c^2} \quad \xrightarrow[e^-]{e^+} \quad 3.22 \times 10^{-22}\ \mathrm{s}$$



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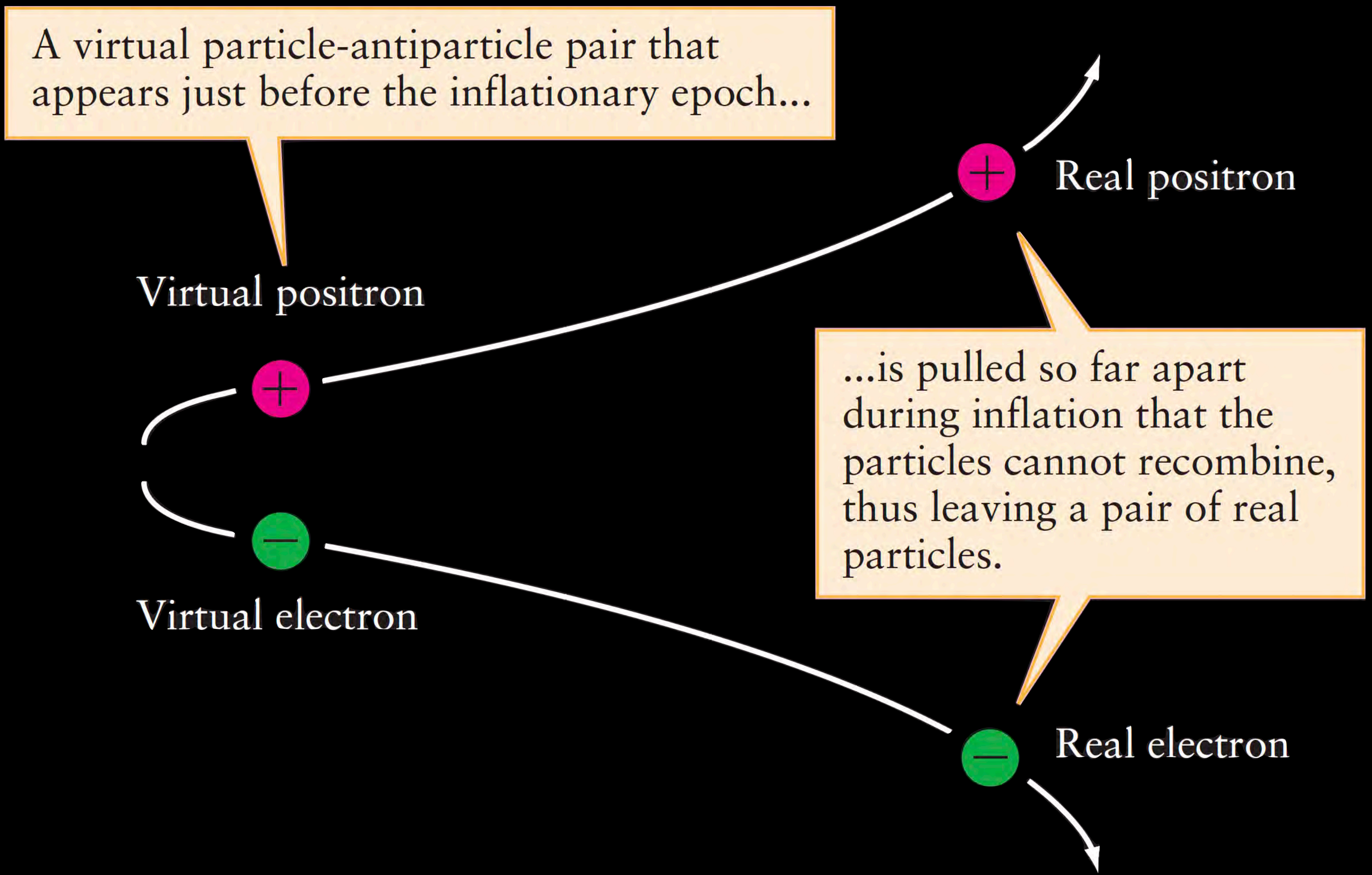
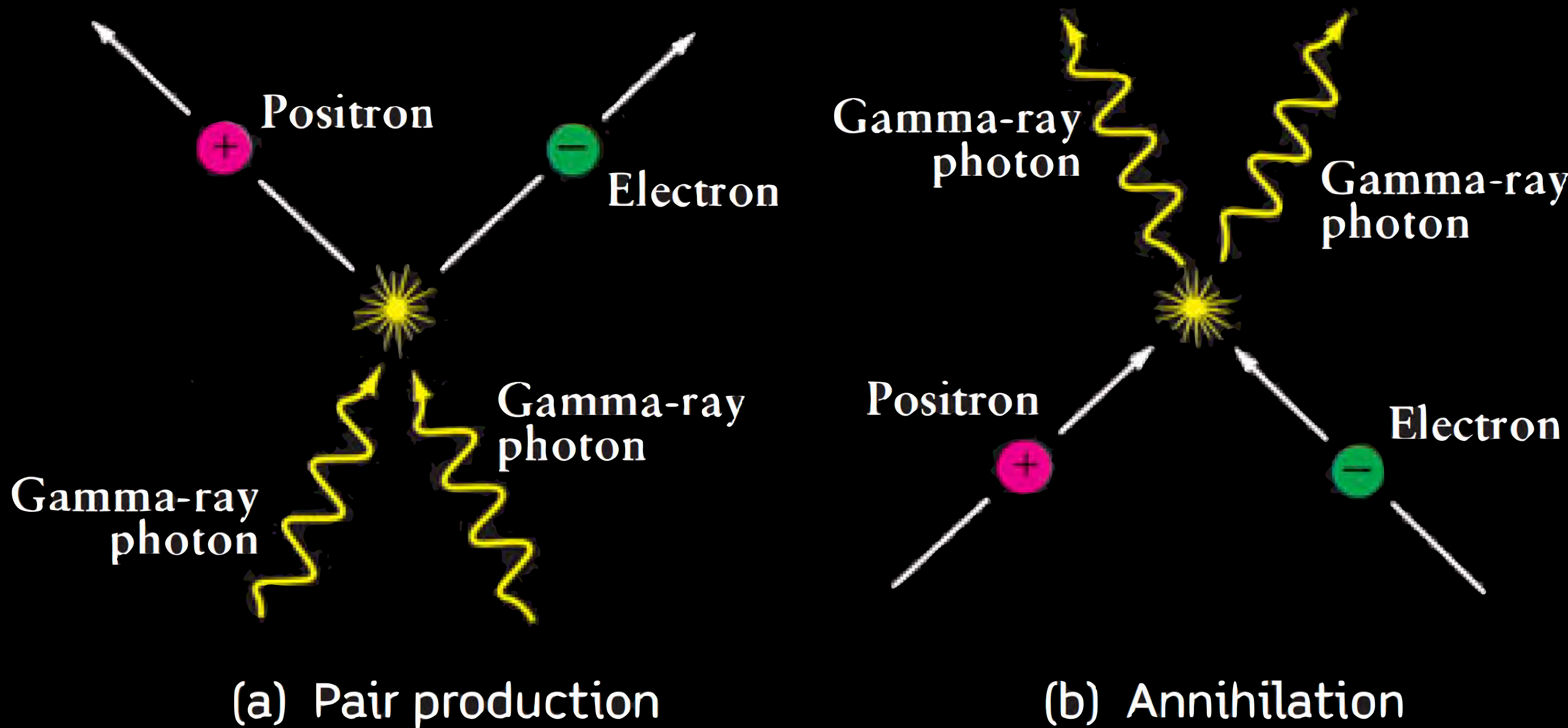
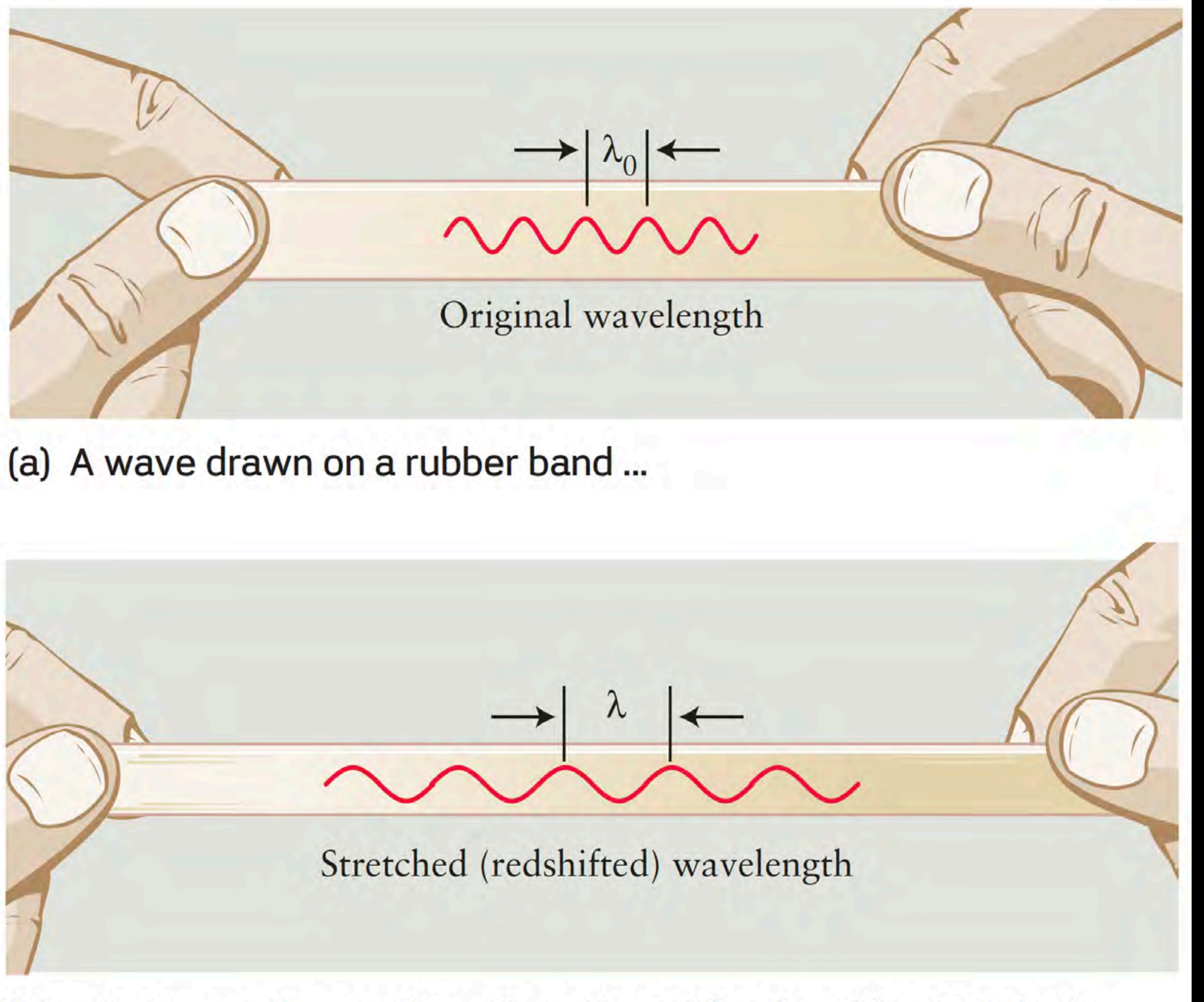


CREATING INTENSE RADIATION



- Thermal equilibrium between radiation and matter (Pair production rate = Annihilation rate)
- Expansion redshifted photons, lowering the temperature

EXPANSION AND ANNIHILATION REMOVE ANTIMATTER

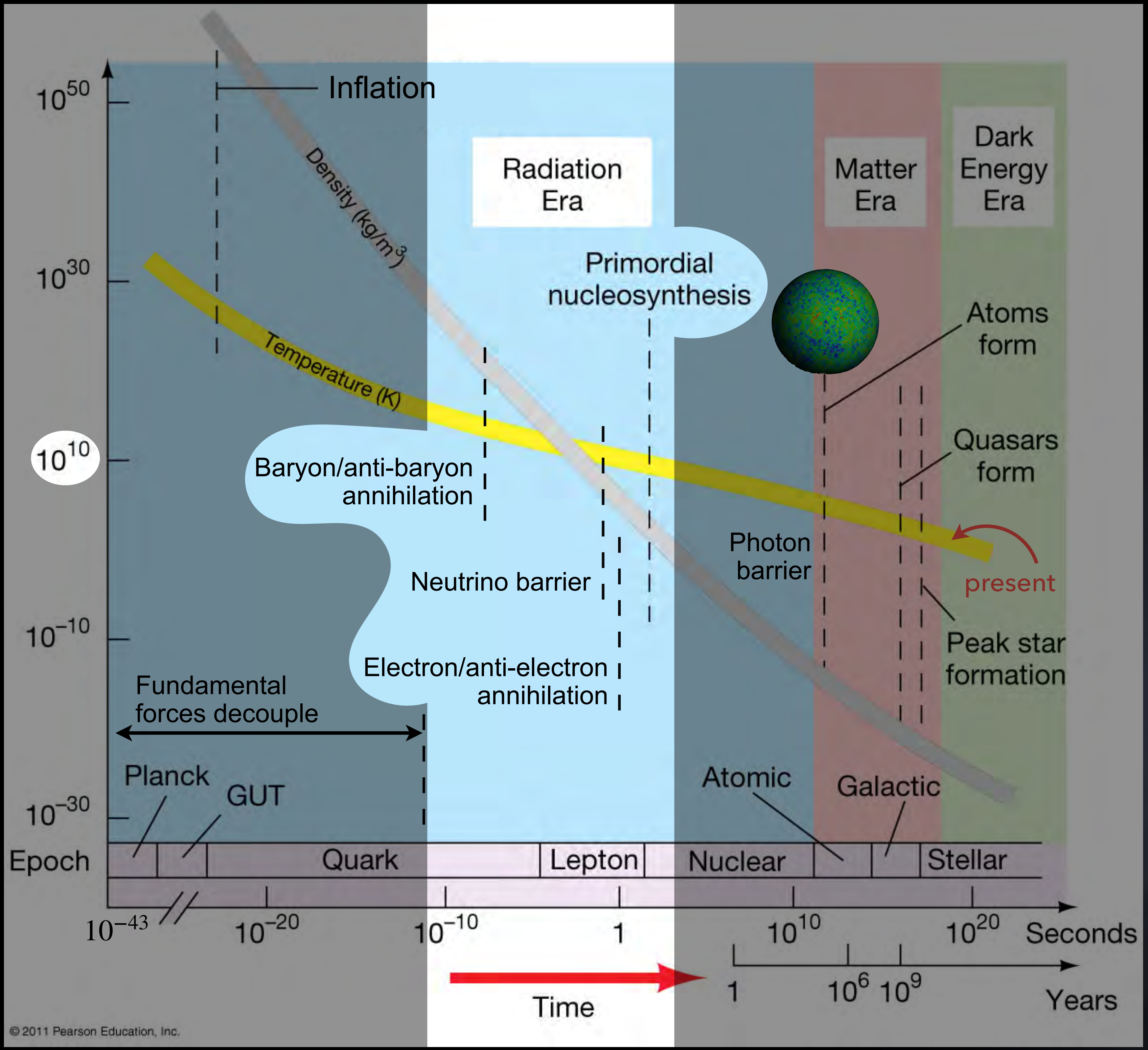


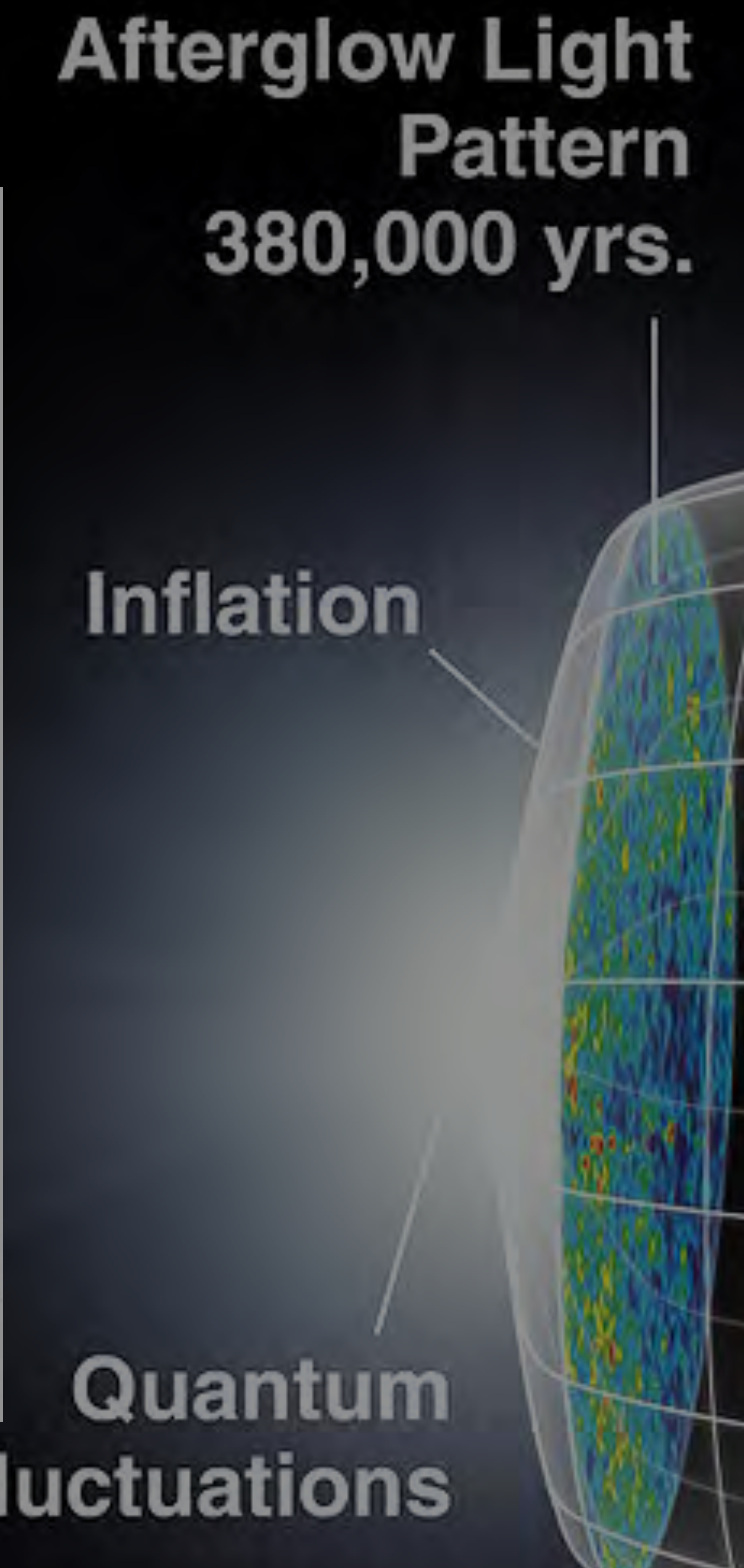
(a) A wave drawn on a rubber band ...

(b) ... increases in wavelength as the rubber band is stretched.

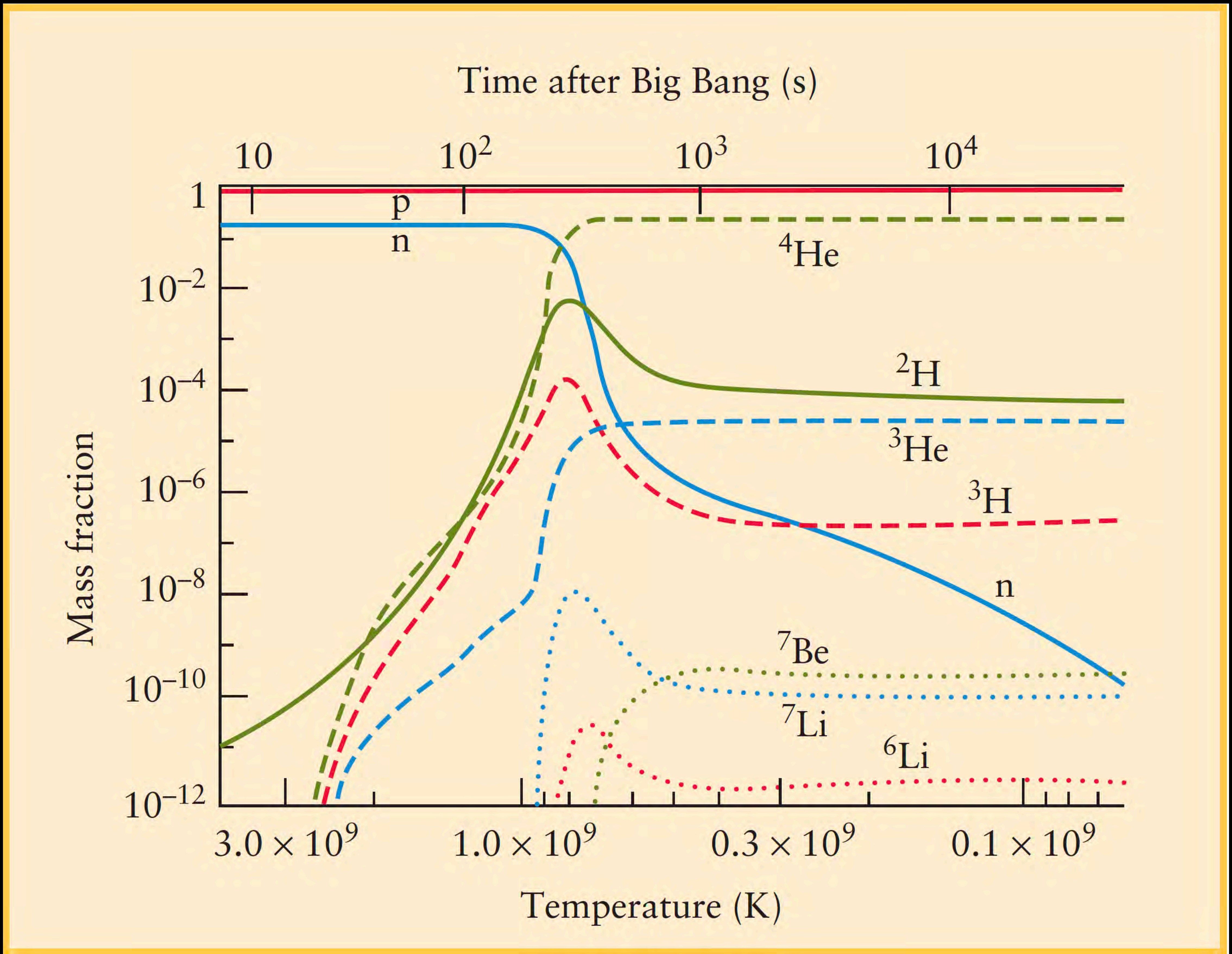
- Expansion
  $\rightarrow$ longer λ
  $\rightarrow$ lower energy
  $\rightarrow$ lower temperature
- Insufficient energy to create certain particles
  - $\rightarrow$ Annihilation events leaving only matter
  - Particle ratio: 10^9 antimatter to $10^9 + 1$ ordinary matter

AND EVENTUALLY SETS ABUNDANCES





NUCLEOSYNTHESIS



NUCLEOSYNTHESIS

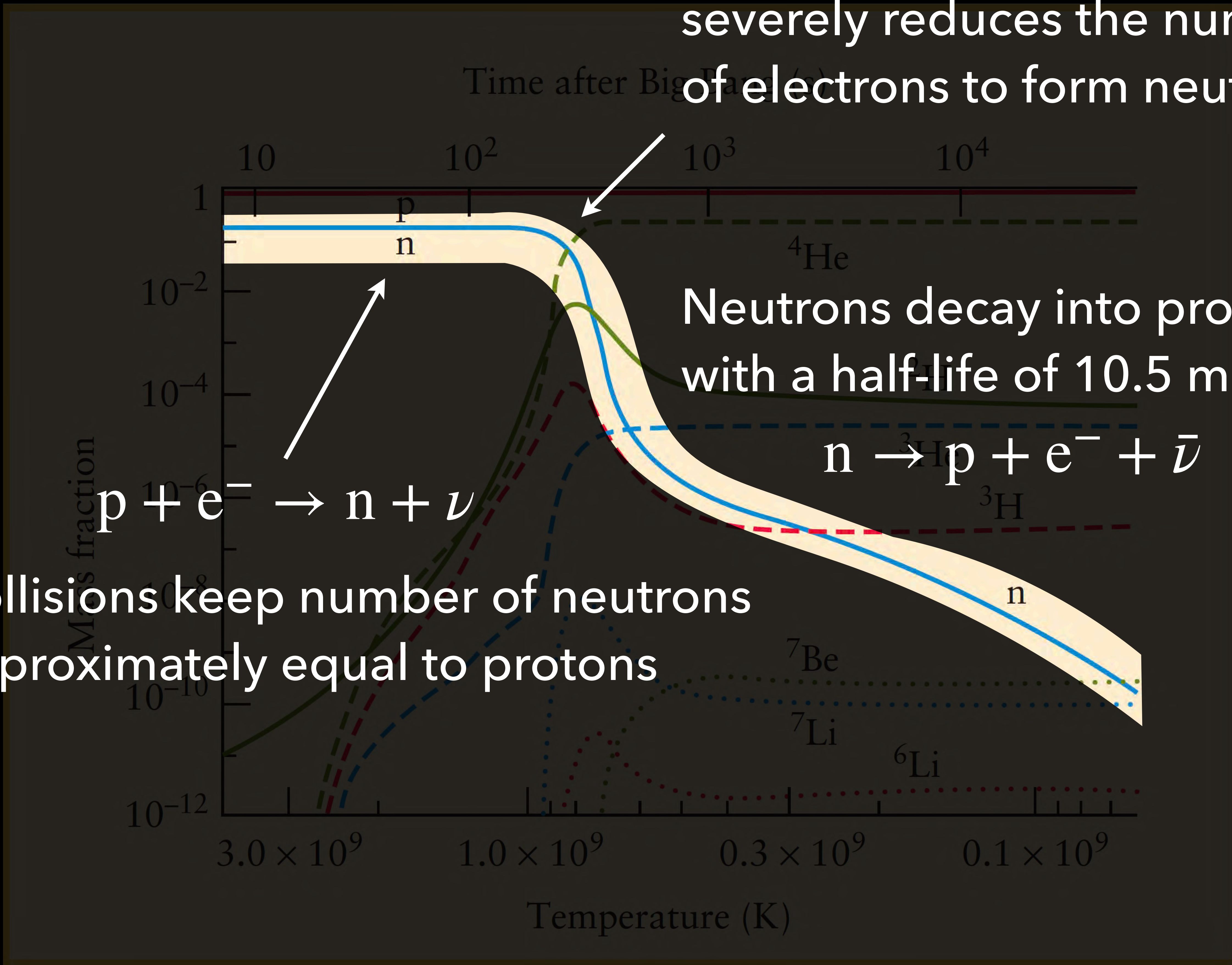
Electron-positron annihilation severely reduces the number of electrons to form neutrons

Neutrons decay into protons with a half-life of 10.5 minutes

$$n \rightarrow p + e^- + \bar{\nu}$$

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

Collisions keep number of neutrons approximately equal to protons



NUCLEOSYNTHESIS

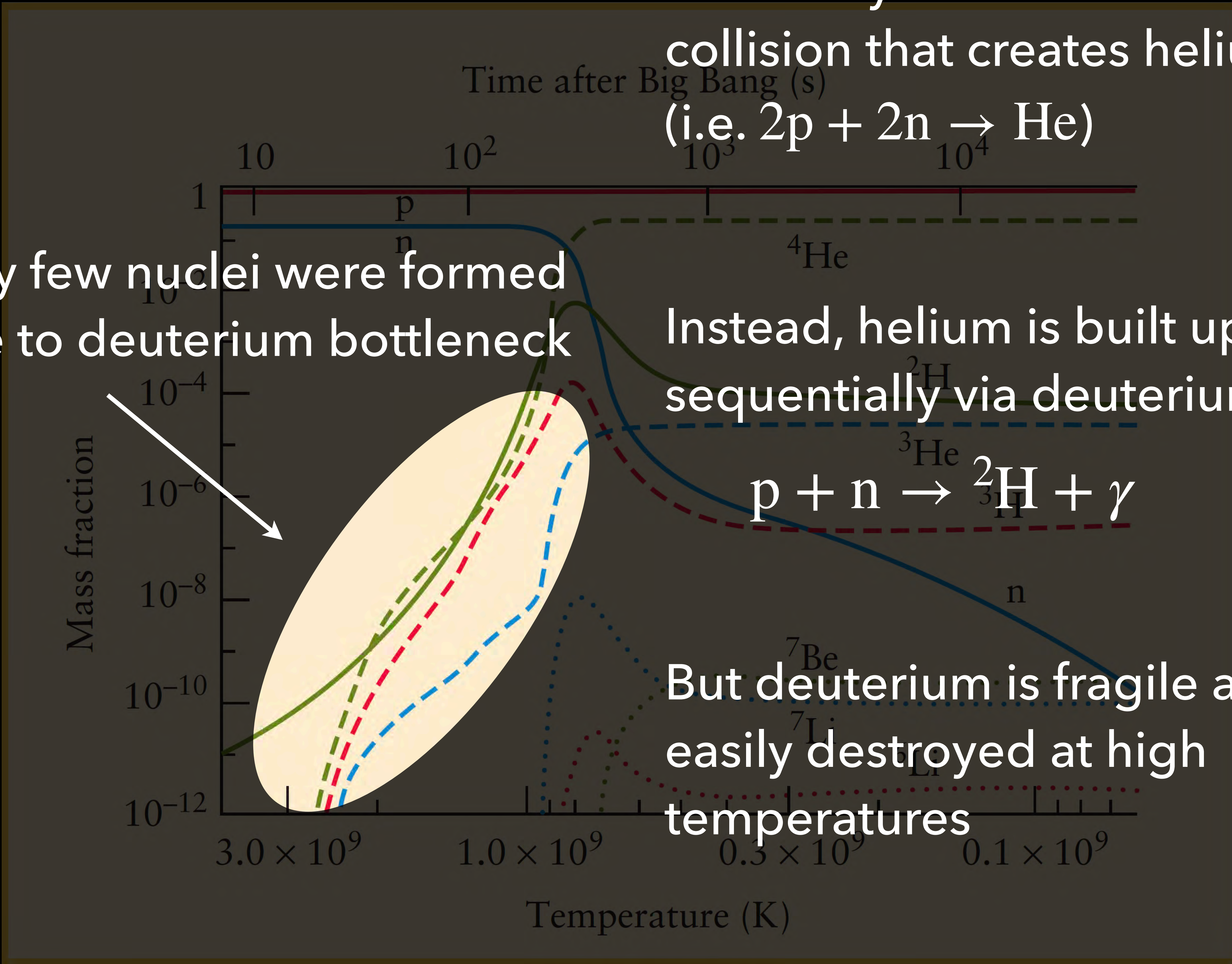
Extremely rare to have a 4-way collision that creates helium (i.e. $2\mathrm{p} + 2\mathrm{n} \rightarrow \mathrm{He}$)

Very few nuclei were formed due to deuterium bottleneck

Instead, helium is built up sequentially via deuterium

$$\mathrm{p} + \mathrm{n} \rightarrow {}^{2}\mathrm{H} + \gamma$$

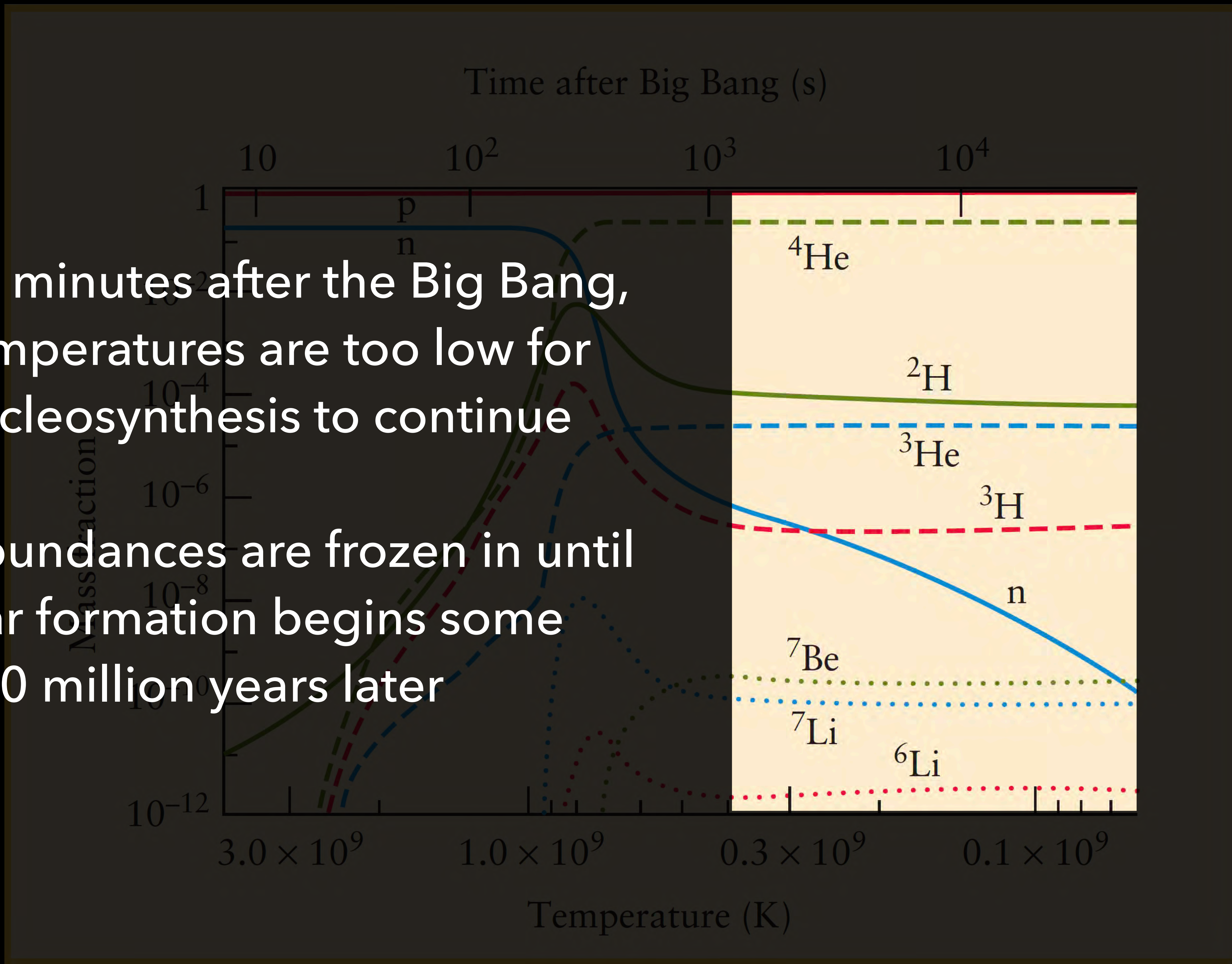
But deuterium is fragile and easily destroyed at high temperatures



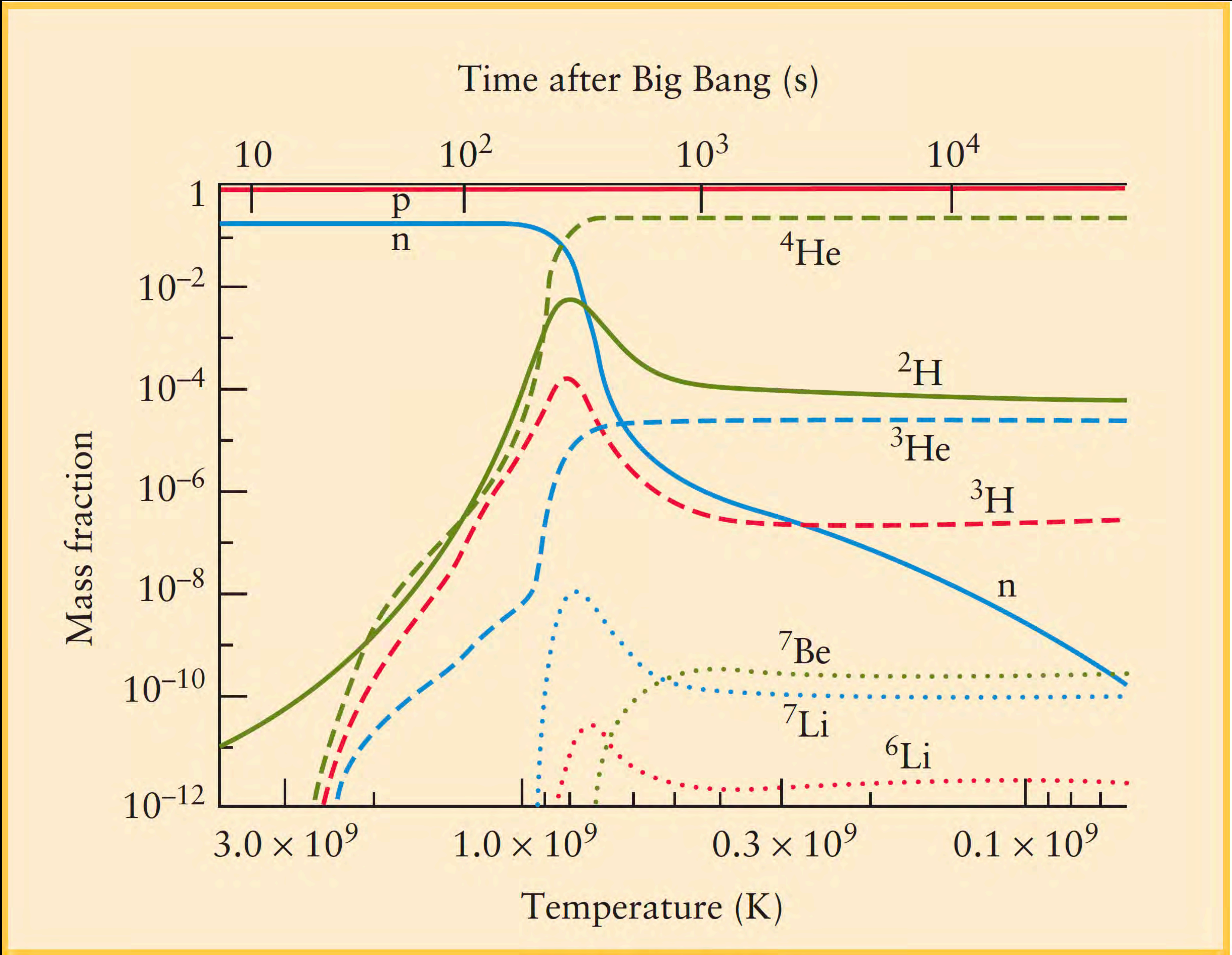
NUCLEOSYNTHESIS

15 minutes after the Big Bang, temperatures are too low for nucleosynthesis to continue

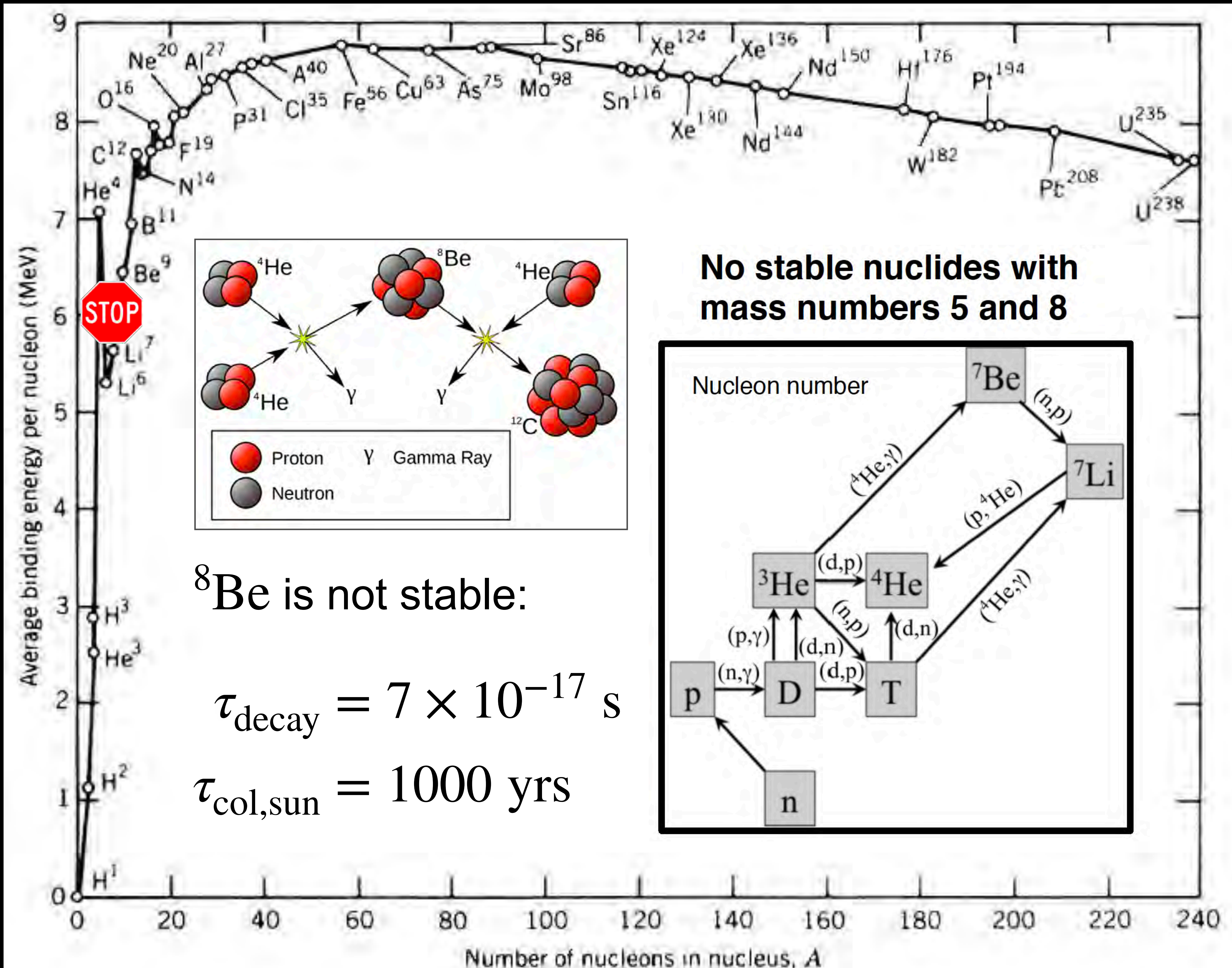
Abundances are frozen in until star formation begins some 400 million years later



NUCLEOSYNTHESIS



NUCLEOSYNTHESIS: VIRTUALLY NO HEAVY ELEMENTS



No stable nuclides with mass numbers 5 and 8

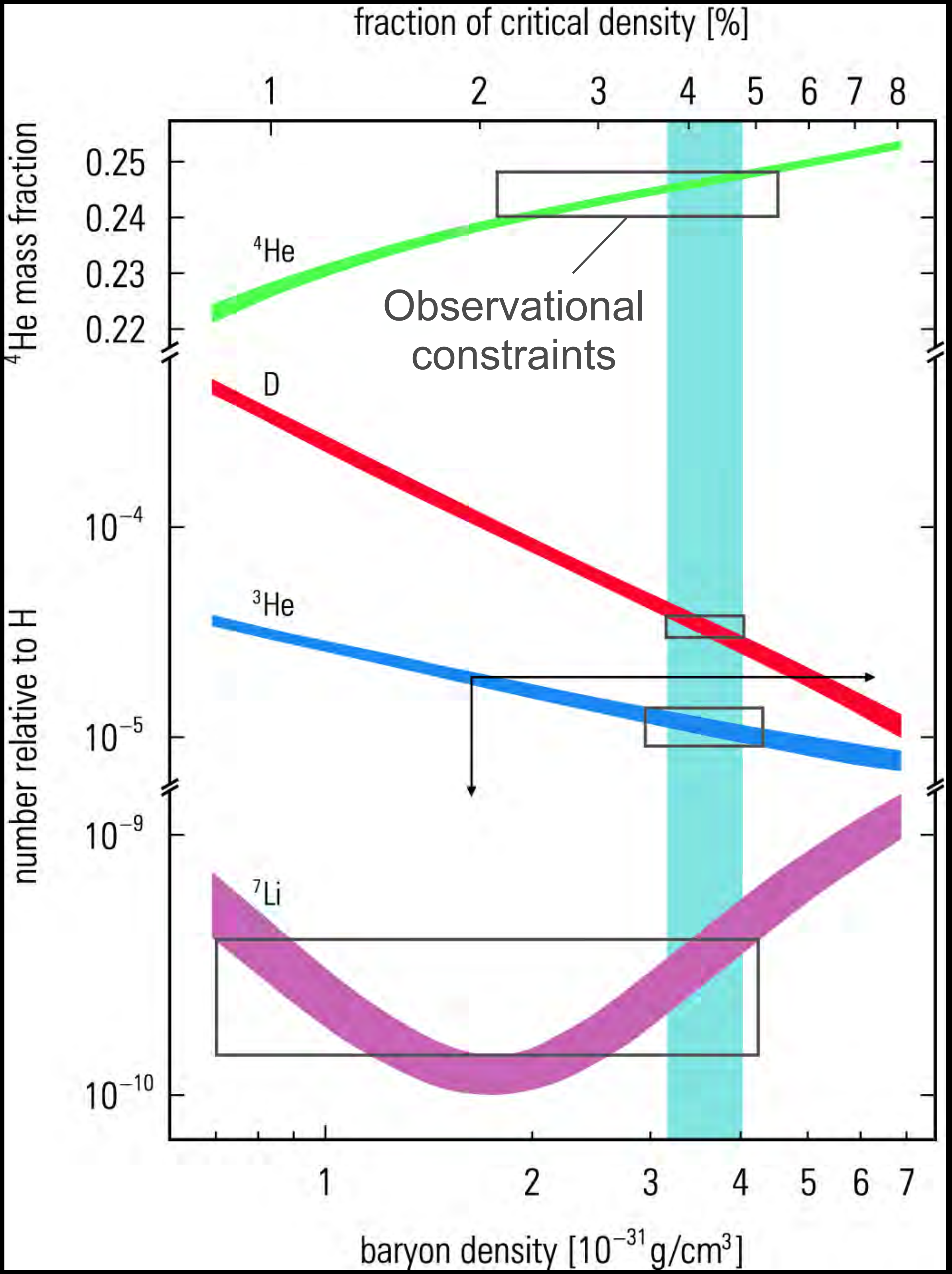
^{8}Be is not stable:

$$\tau_{\rm decay} = 7 \times 10^{-17}\ {\rm s}$$

$$\tau_{\rm col,sun} = 1000\ {\rm yrs}$$

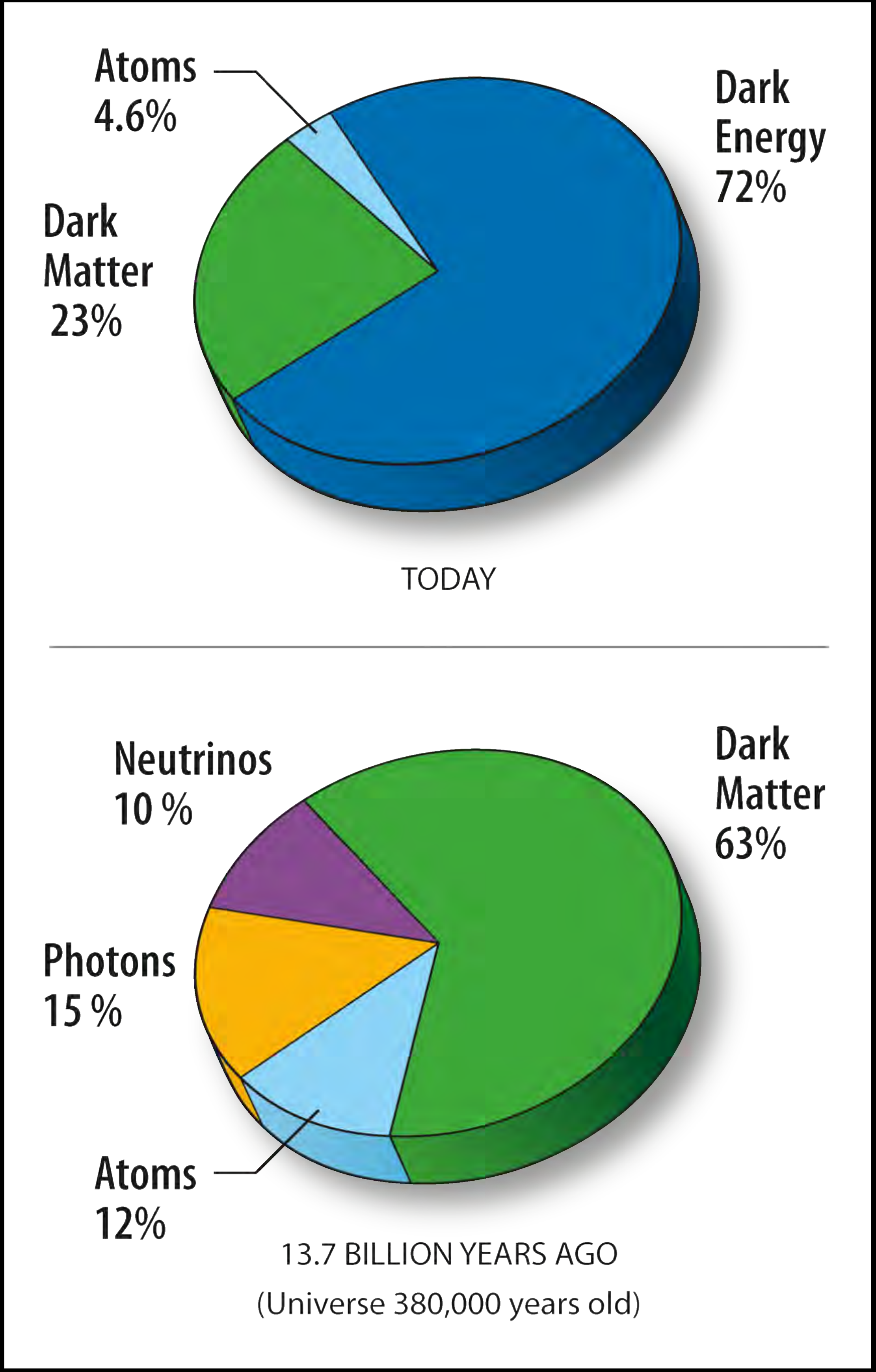
NUCLEOSYNTHESIS: OBSERVATIONS

- Observations at later times are consistent with models with low baryonic density
- However, the universe requires high densities to explain flatness
  - Most matter in the universe is non-baryonic (dark)!
  - Important for creating the large-scale structure we see today

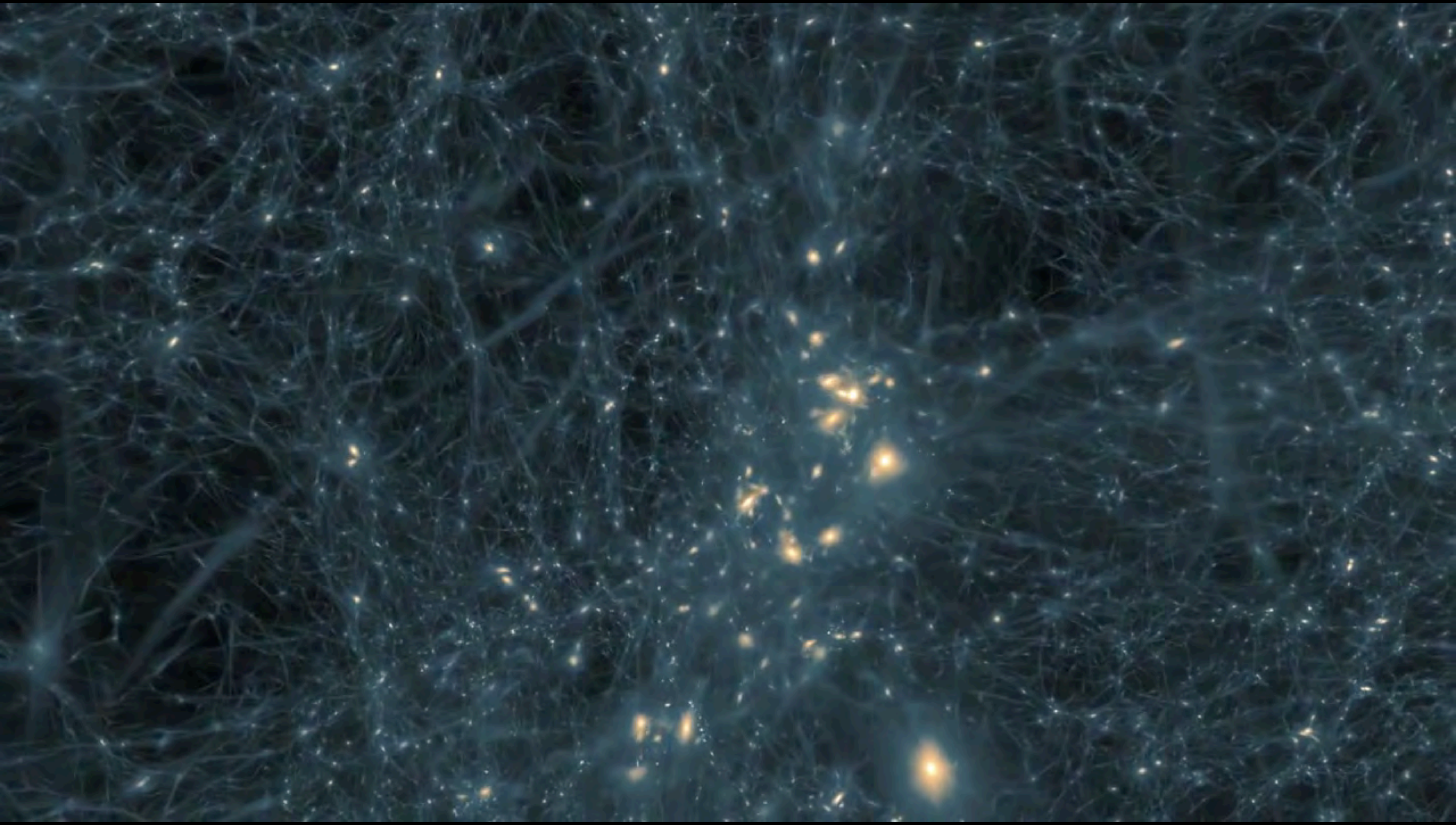


NUCLEOSYNTHESIS: OBSERVATIONS

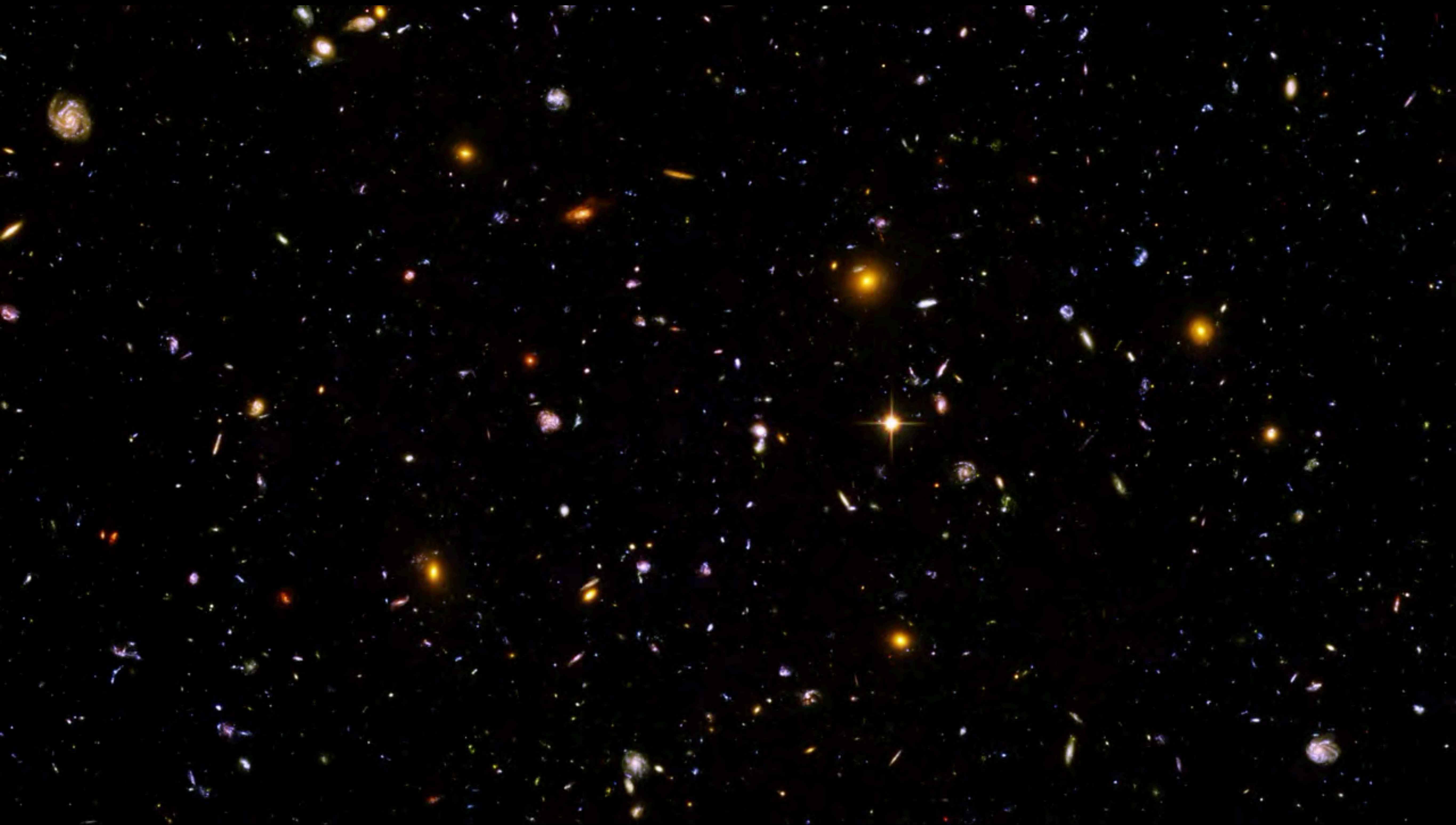
- Observations consistent with models if baryon density is low
- Universe requires high densities to explain flatness
  - Suggests most matter in the universe is non-baryonic!
  - "Dark" because it does not emit or interact with light
  - Can begin collapsing before regular matter → large-scale structure we see today

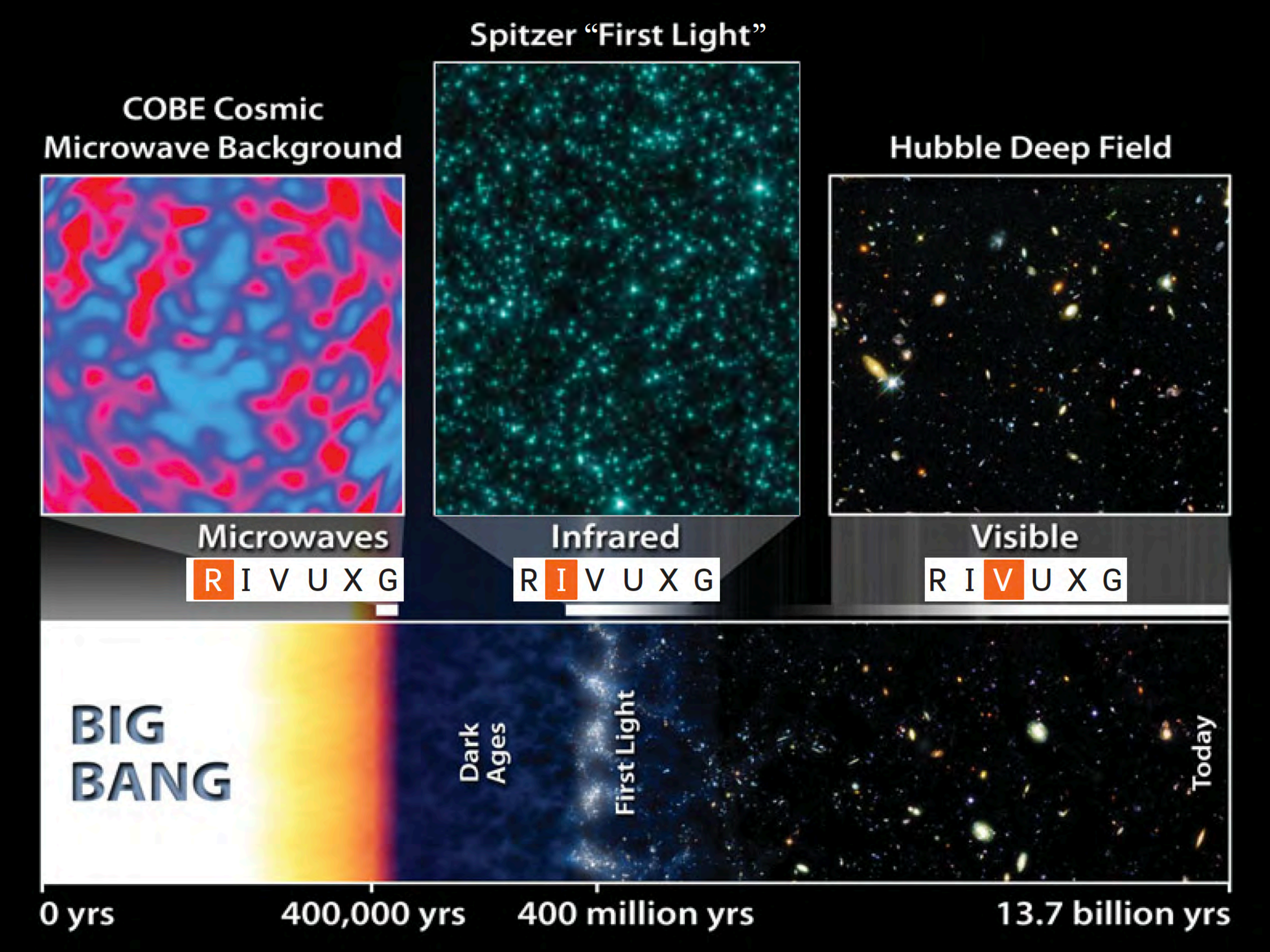


DARK MATTER SIMULATION

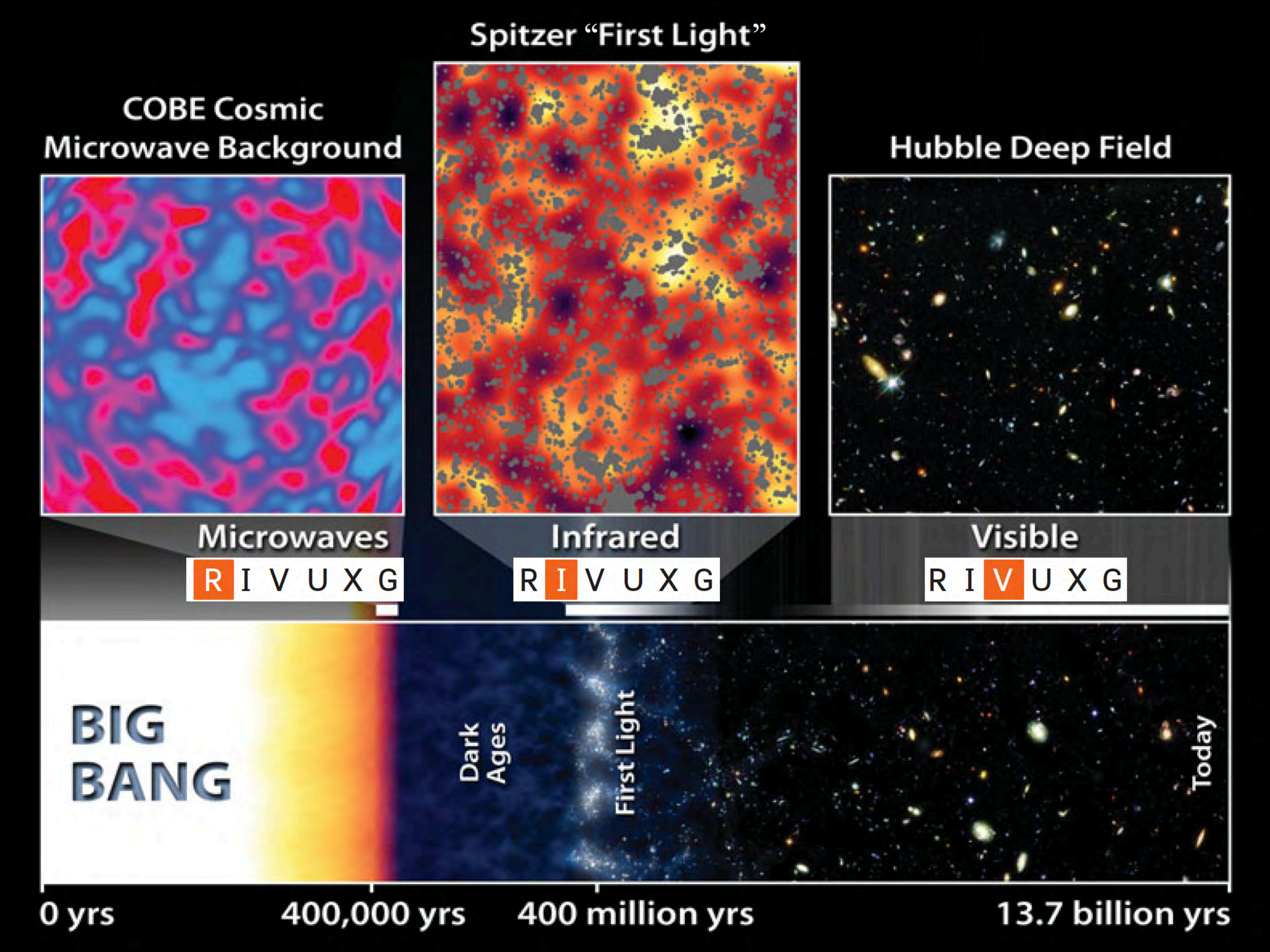


HUBBLE ULTRA DEEP FIELD





Spitzer "First Light"
COBE Cosmic Microwave Background
Hubble Deep Field
Microwaves
R I V U X G
Infrared
R I V U X G
Visible
R I V U X G
BIG BANG
Dark Ages
First Light
Today
0 yrs
400,000 yrs
400 million yrs
13.7 billion yrs



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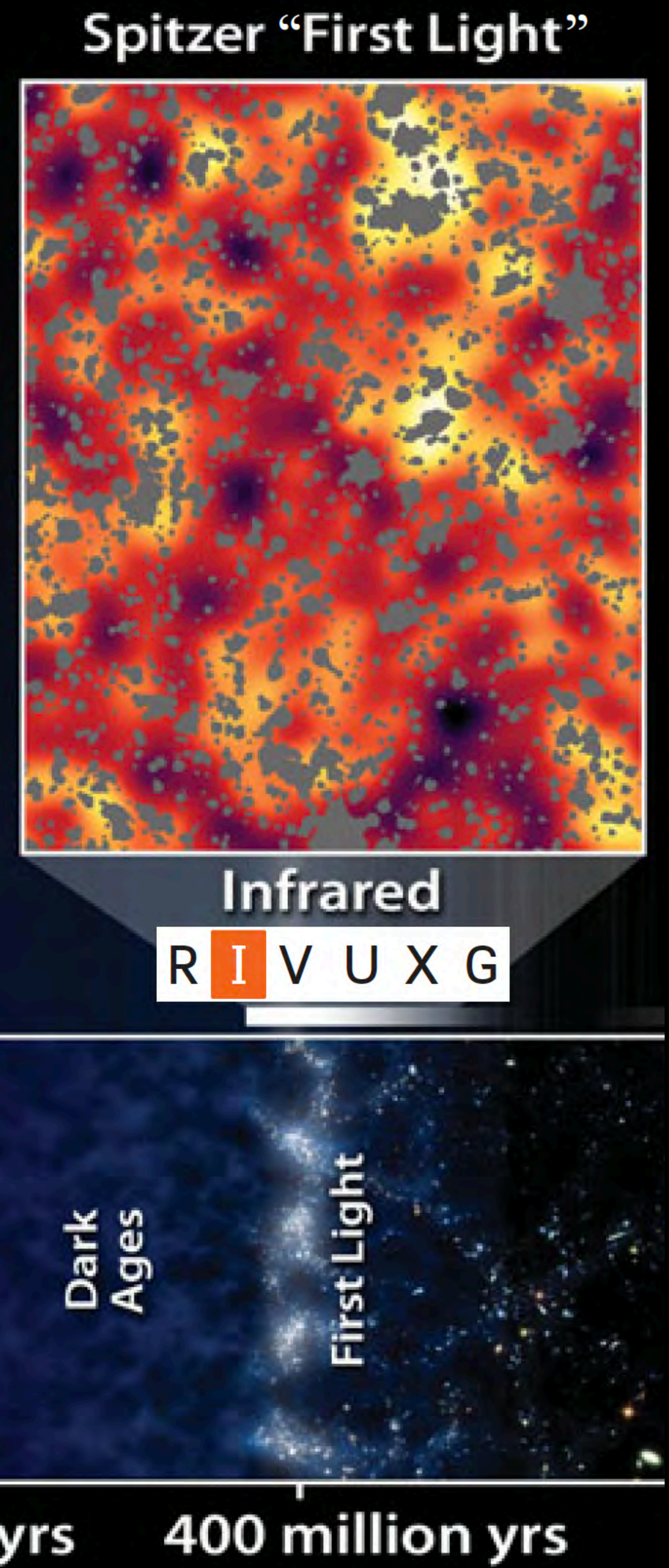
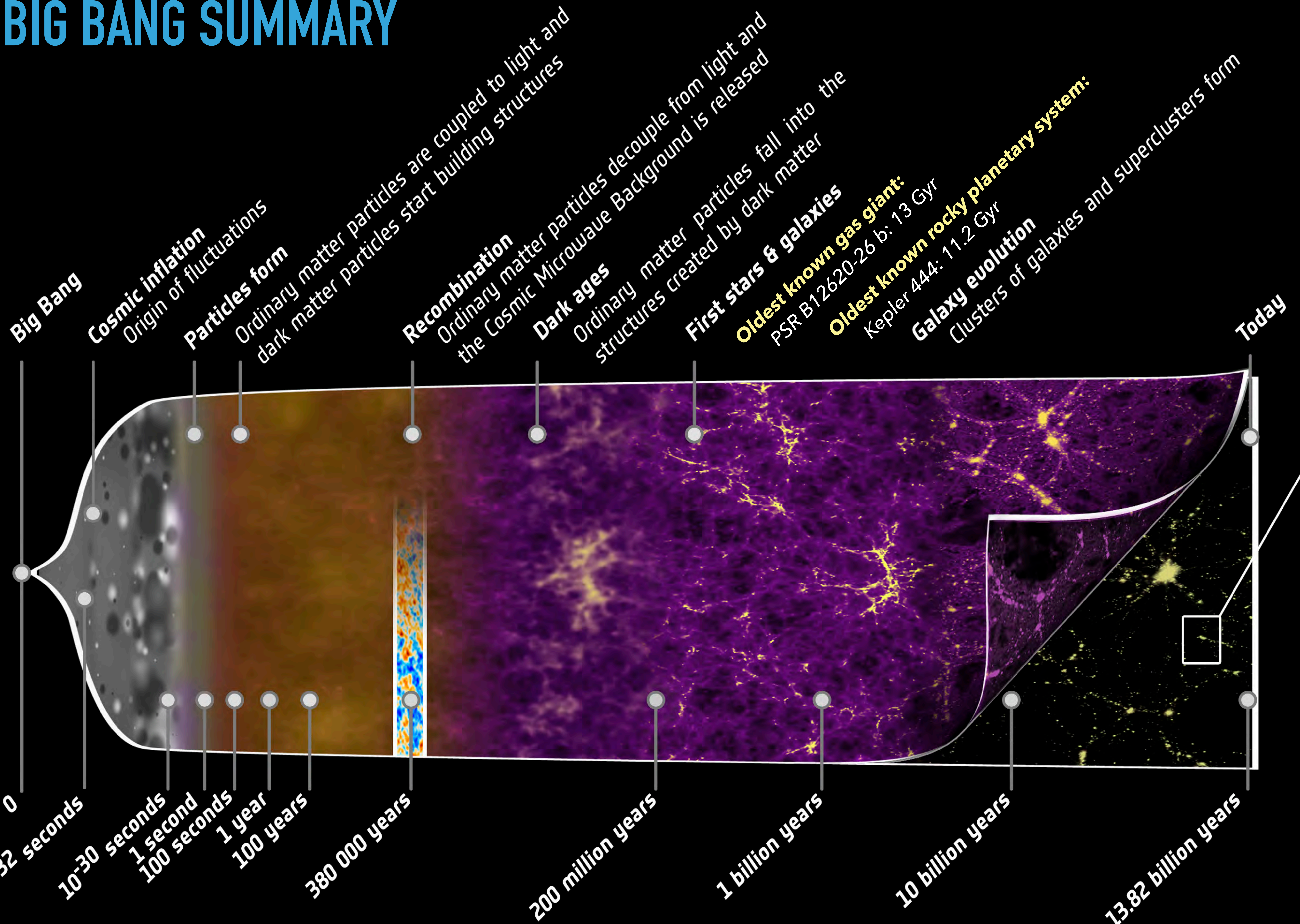


FIRST STARS

- With no heavy elements, the internal pressure of gas clouds would be higher
- Collapse requires greater mass
  - First stars: $30 - 1000\ M_\odot$
  - Short lifetimes with large supernova explosions → heavy elements
- Surface temperatures: 10^5 K
  - Flood of short wave radiation
  - Epoch of reionisation

BIG BANG SUMMARY



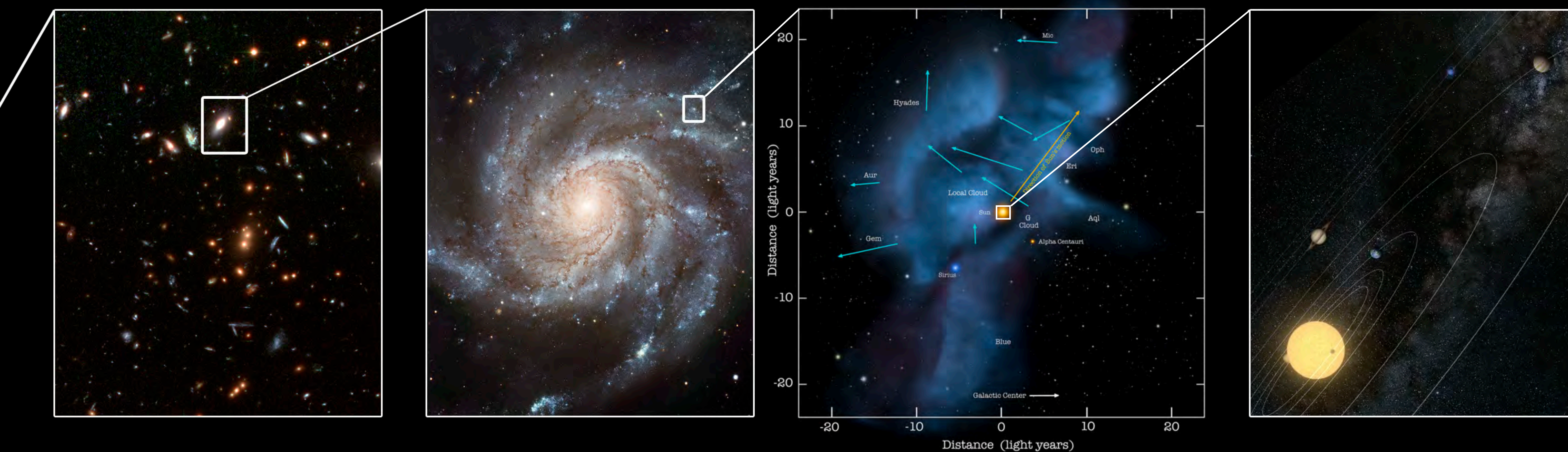
BIG BANG SUMMARY

Clusters of galaxies

Galaxy

Local Neighbourhood

Solar System

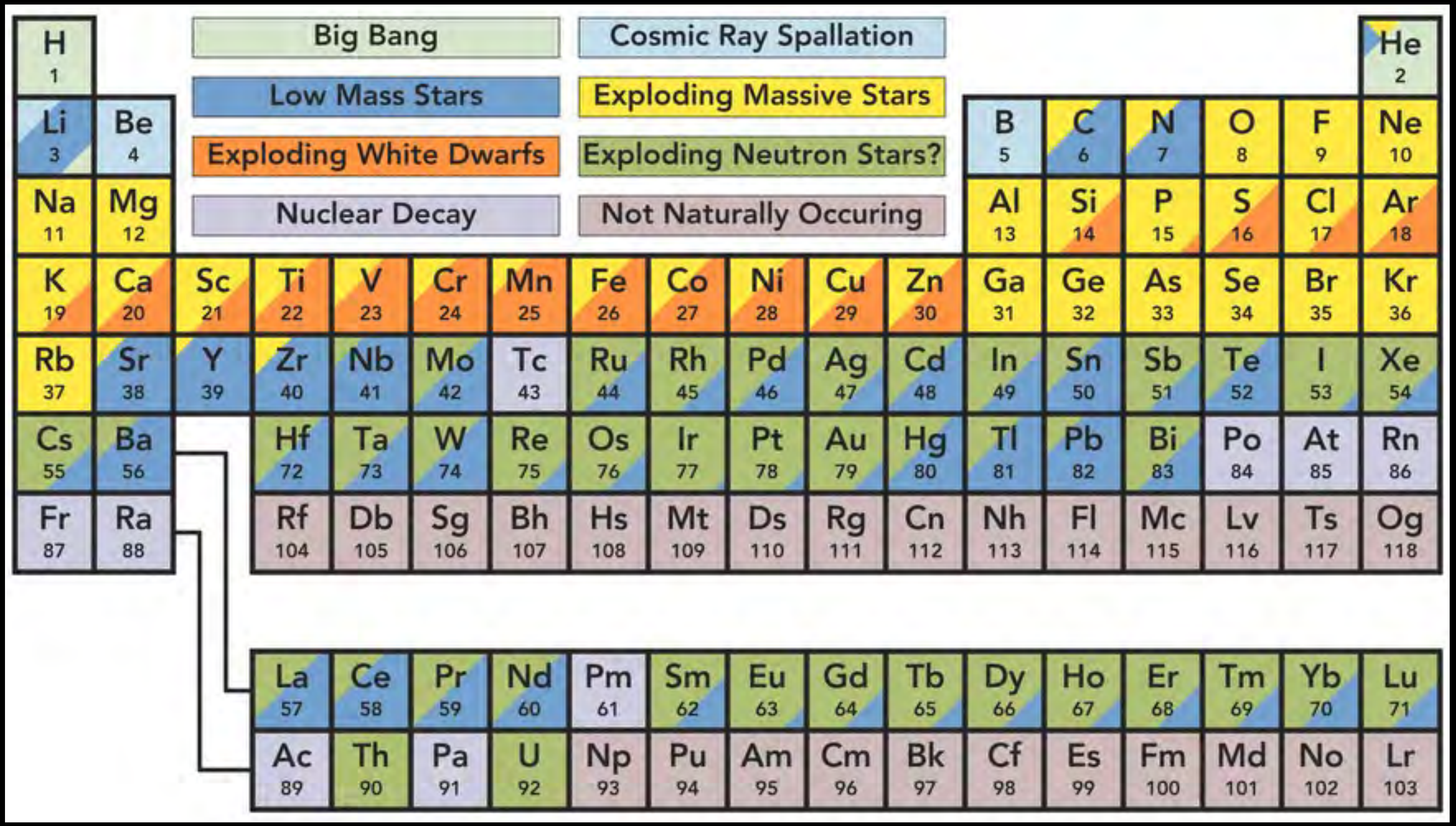


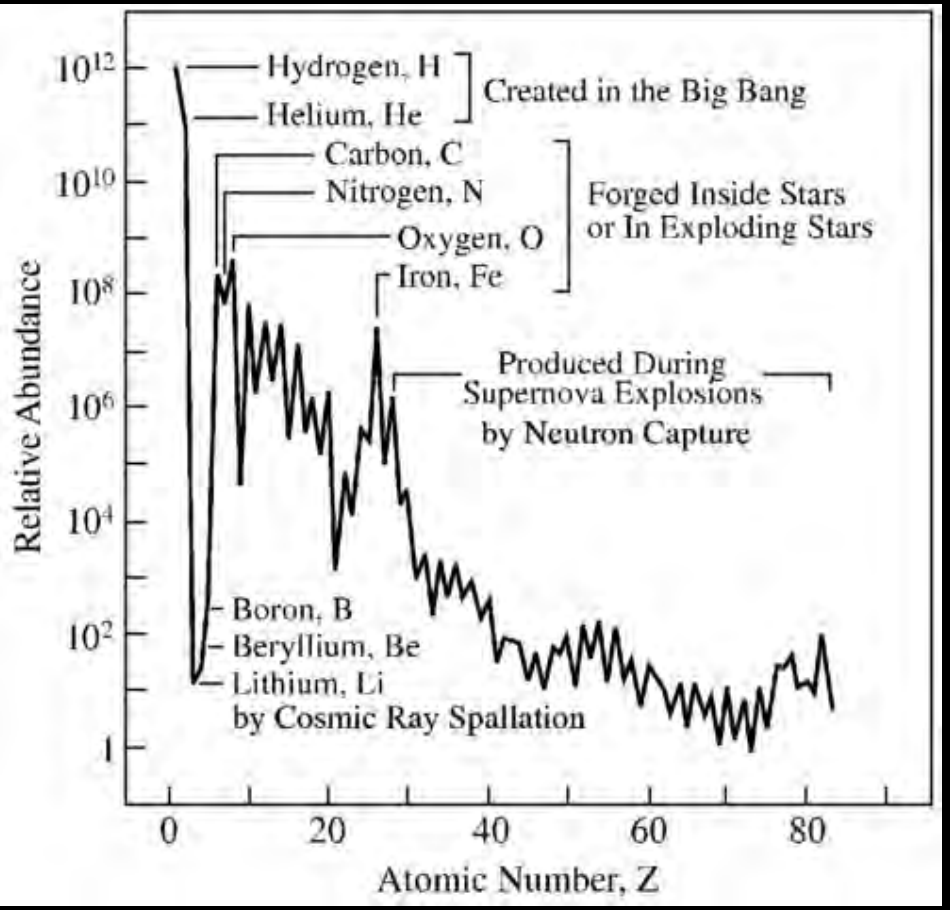
BIG BANG SUMMARY: GATHERING THE INGREDIENTS

BIG BANG SUMMARY: GATHERING THE INGREDIENTS

- Although instead of apple pie, we are more interested in the ingredients needed for life
  - Human composition (by number):

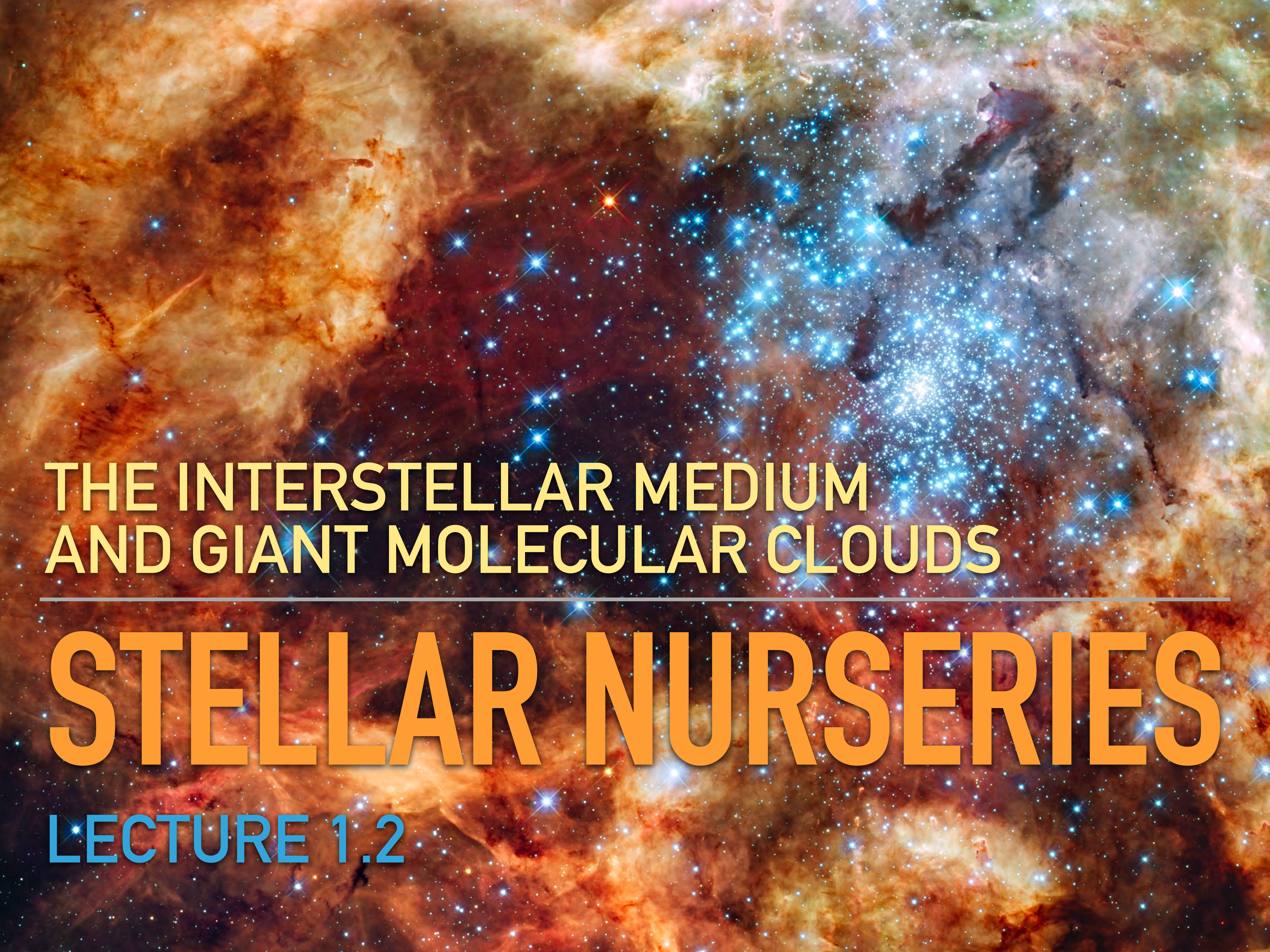
H : 63 %
O : 25.5 %
C : 9.5 %
N : 1.4 %
other : 0.6 %





BIG BANG SUMMARY: GATHERING THE INGREDIENTS

- We need a hot, dense beginning to generate the elemental abundance we see in the universe today
- We need the universe to rapidly expand through inflation (not just regular expansion)
  - To create the space between astronomical objects today (crowded environments are anyway not suitable for life)
  - To cool down: energy $\longrightarrow$ particles $\longrightarrow$ structures
  - To inflate tiny quantum fluctuations into large scale structures that can later collapse due to gravity

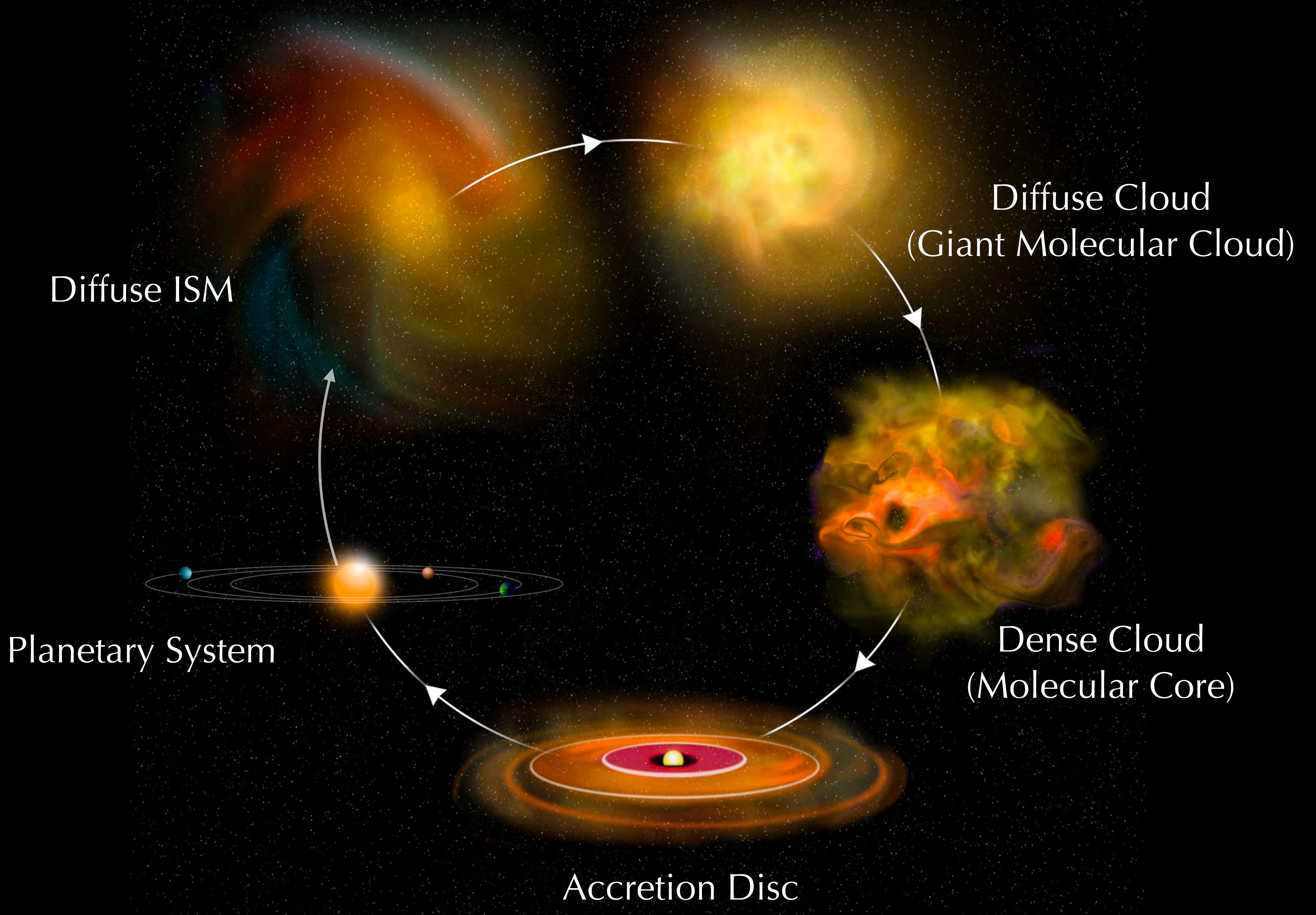


THE INTERSTELLAR MEDIUM AND GIANT MOLECULAR CLOUDS

STELLAR NURSERIES

LECTURE 1.2

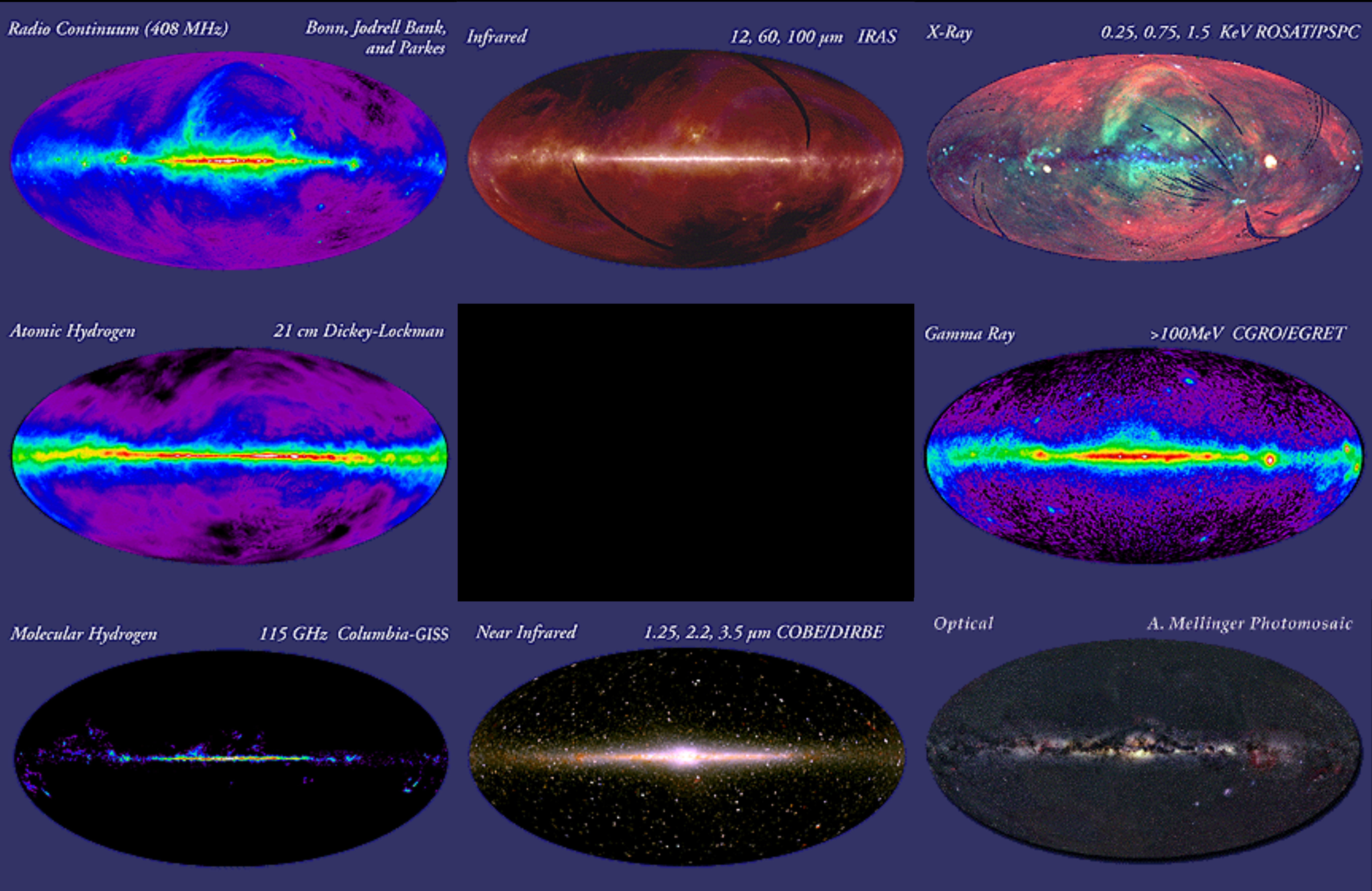
LIFE CYCLE


Diffuse ISM
Diffuse Cloud
(Giant Molecular Cloud)
Dense Cloud
(Molecular Core)
Accretion Disc
Planetary System

INTERSTELLAR MEDIUM (ISM)

INTERSTELLAR MEDIUM (ISM)

INTERSTELLAR MEDIUM (ISM)



INTERSTELLAR MEDIUM (ISM): COMPOSITION AND PHASES

- Hydrogen is the dominant element in the ISM followed by helium and other 'metals'
- Gas in the ISM comes in several different phases depending on the temperature and density

Element	Abundance/H
He	0.1
C	3.6×10^{-4}
N	1.1×10^{-4}
O	8.5×10^{-4}
Si	3.6×10^{-5}

Phase	n (cm^{-3})	T (K)	M ($10^9 M_\odot$)	Filling factor	Pressure (~nT)
molecular	>300	10	2	0.01	3000
cold atomic	50	80	3	0.04	4000
warm atomic	0.5	8×10^3	4	0.3	4000
warm ionised	0.3	8×10^3	1	0.15	2400
hot ionised	3×10^{-3}	5×10^5	tiny	0.5	1800
HII regions	1 - 10^4	10^5	tiny	tiny	10^5 -10^9

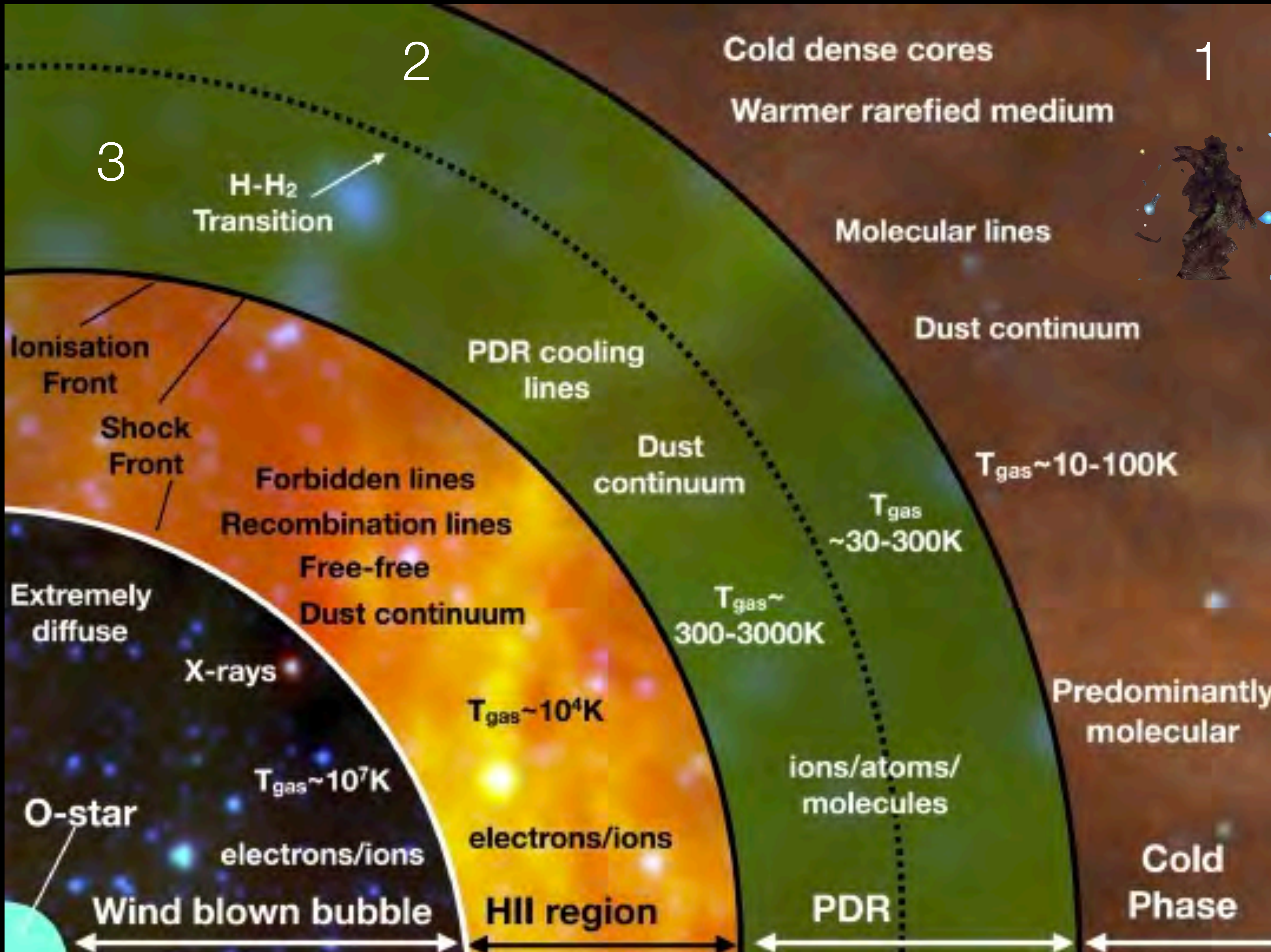
Sites of star formation

Most mass in HI
Sets the ISM pressure

Feedback from massive stars

- Despite the huge range of conditions, most phases are in approximate pressure balance

INTERSTELLAR MEDIUM (ISM): COMPOSITION AND PHASES



GIANT MOLECULAR CLOUDS (GMC)

https://www.youtube.com/watch?v=gpZtlAPQ2QU

GIANT MOLECULAR CLOUDS (GMC)

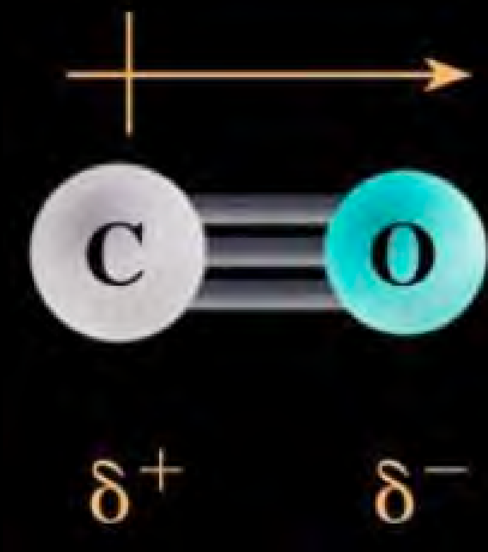
MOLECULAR GAS TRACER: CO

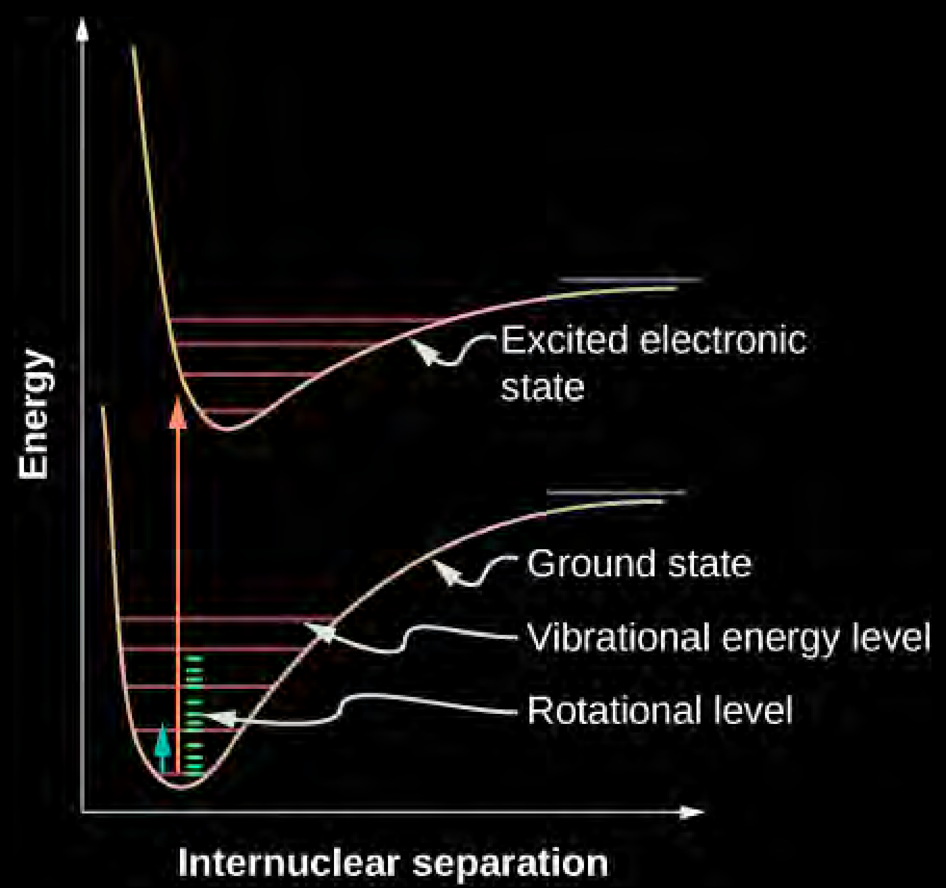
- Because H_2 is a symmetric molecule, it has zero dipole moment in the ground state
- It cannot radiate unless excited, but molecules are only formed in cold, shielded regions so gas is usually in the ground state

Molecular Hydrogen cannot be observed directly in cold clouds

- We can instead observe molecular CO, which has a permanent dipole moment
- Requires less energy to excite rotational and vibrational transitions (sometimes rovibrational) of a non-symmetric molecule

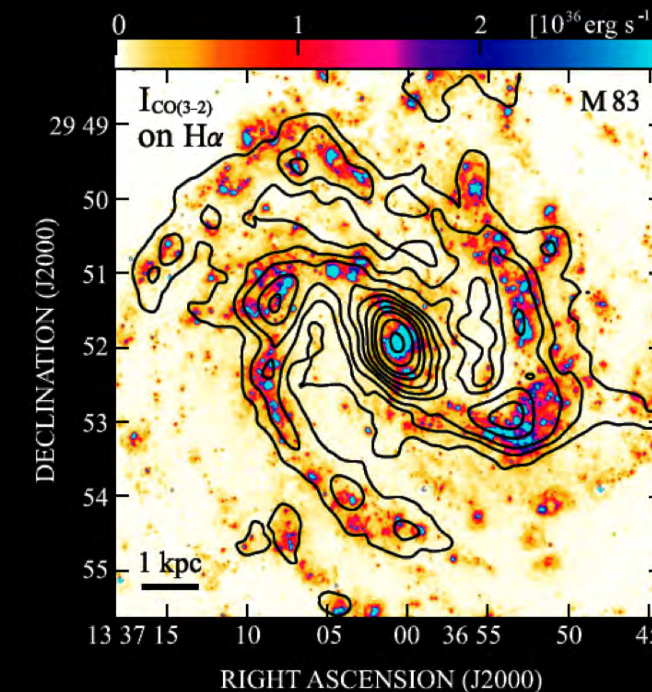
Assume that the ratio of CO to H_2 is constant!
(not always true at very high densities)

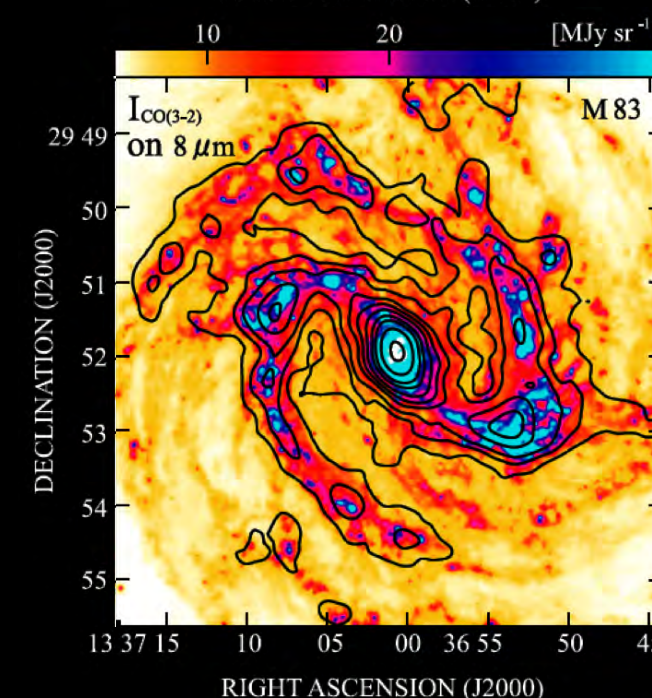


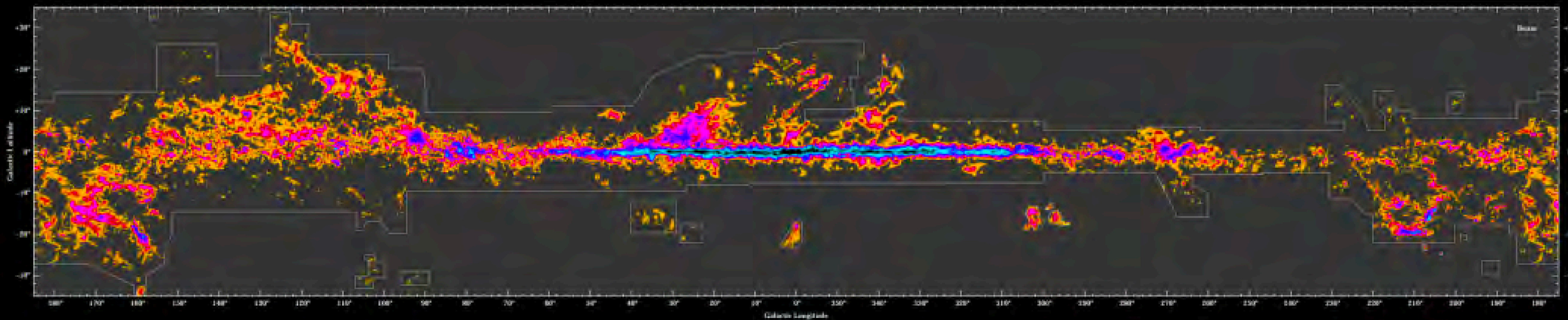


GALACTIC CO DISTRIBUTION

- Observations show that most molecular gas is found in molecular clouds that are concentrated in spiral arms located in the galactic plane
- Total mass of molecular hydrogen: $\sim 2\text{–}3 \times 10^9\ M_\odot$
- This is ~25 - 50% of the total gas mass in the galaxy
- Molecular gas is destroyed by photodissociation (UV radiation and cosmic rays) and dissociative recombination (reaction with electrons)
- Need a high column density ($\gtrsim 10\ M_\odot\ \mathrm{pc}^{-2}$) of atomic gas to shield molecular hydrogen

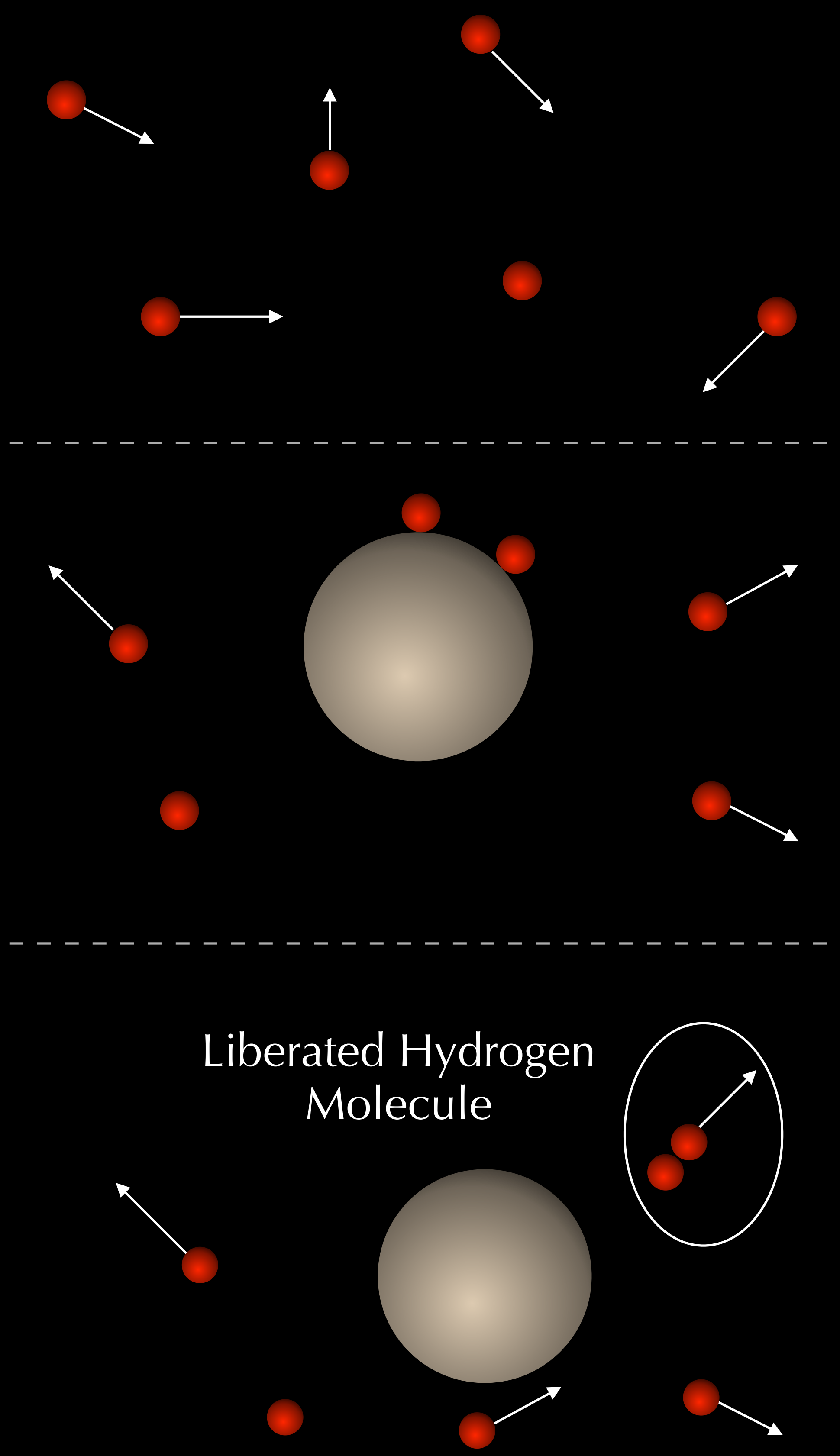


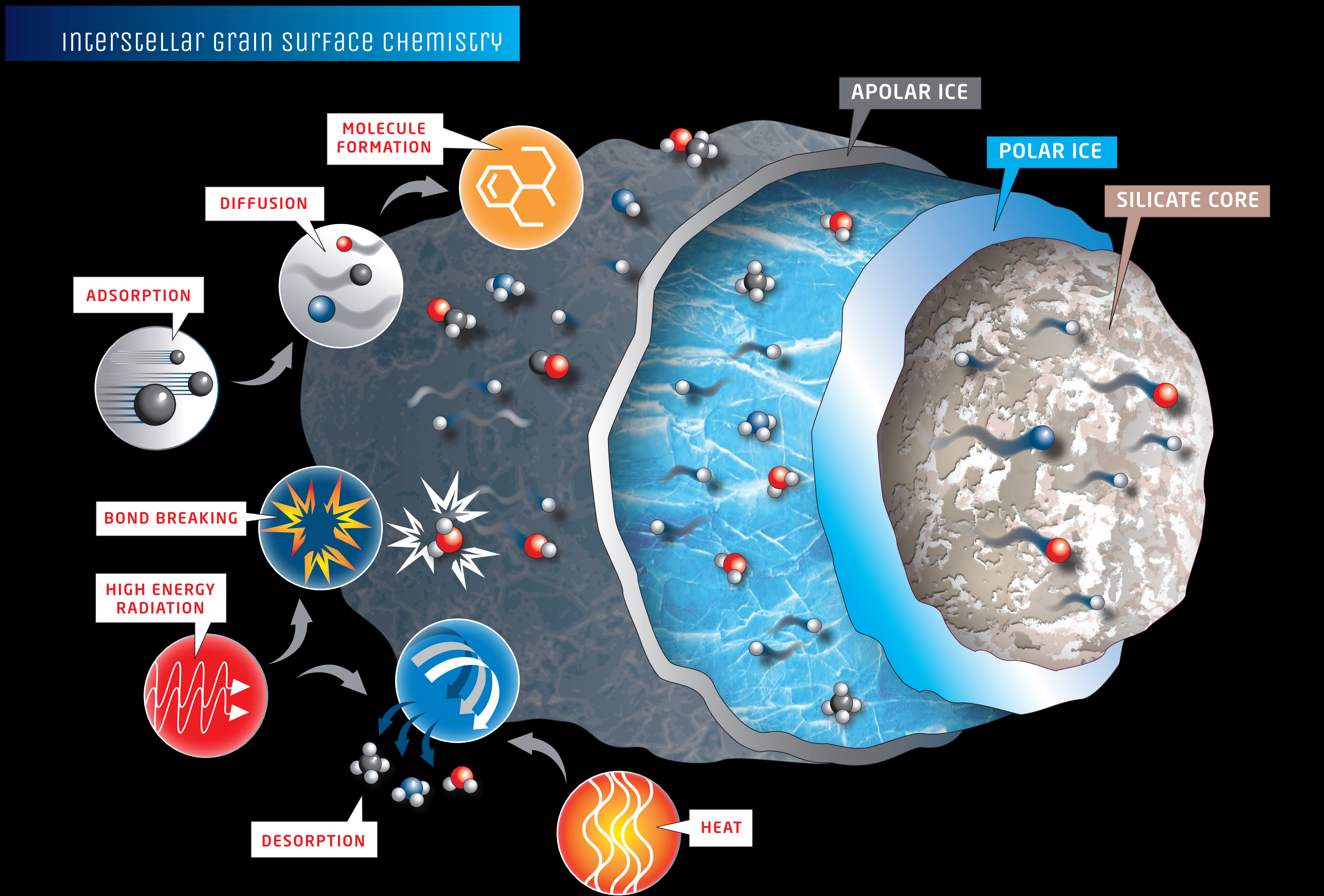




THE FORMATION OF MOLECULES

- Two-body collisions of atomic H is too inefficient to explain the amount of molecular hydrogen in the Milky Way, even in the denser spiral arms
- The surface of dust grains provides a reservoir where atoms/molecules can be stored and brought together on longer timescales than in the gas
  - Enables reactions that are too slow in the gas (e.g. hydrogenation of atomic O, C and N to form H_2O, CH_4 and NH_3)
- Liberated energy helps to release the molecule from the dust surface



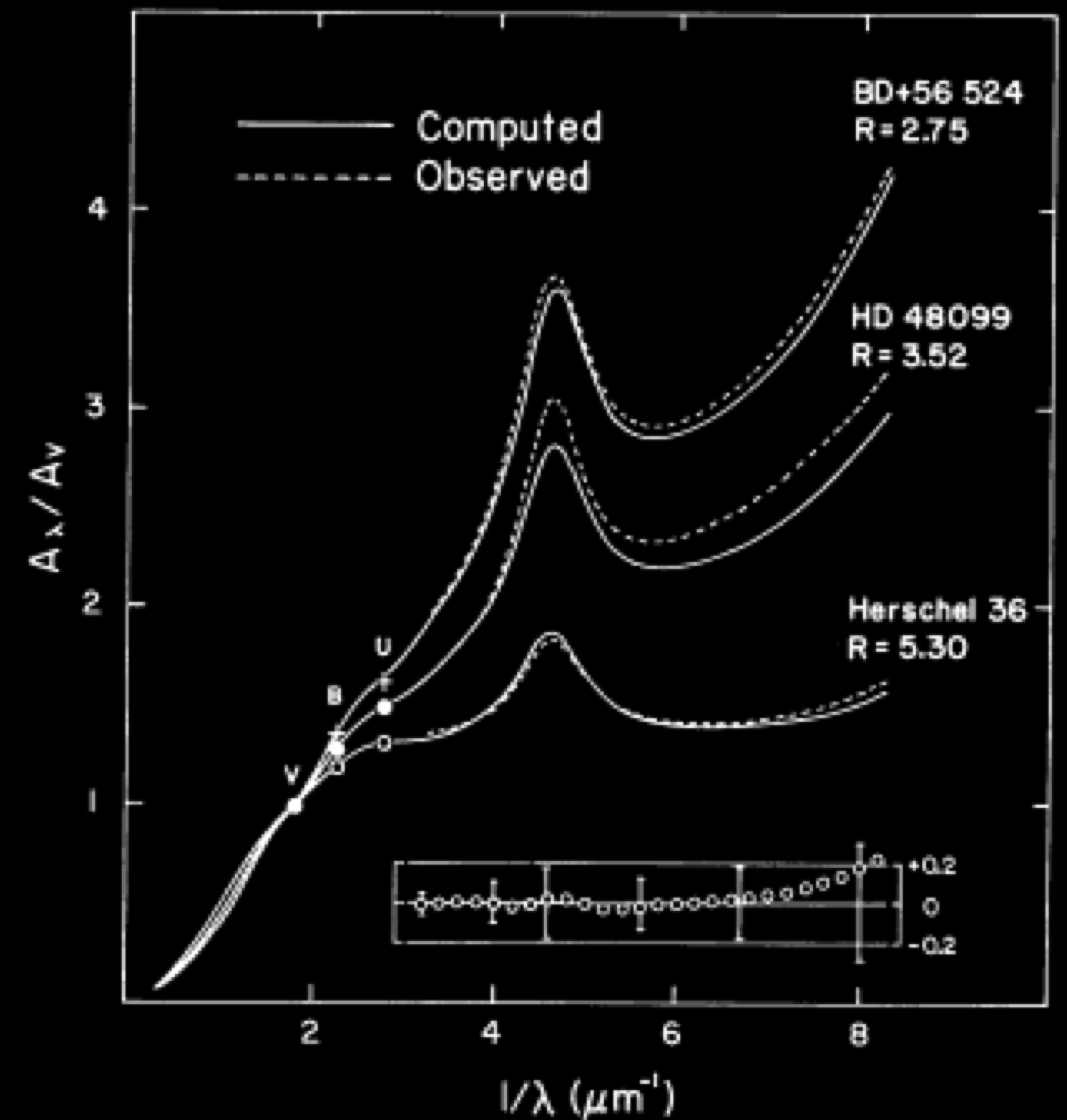

Interstellar Grain Surface Chemistry
APOLAR ICE
POLAR ICE
SILICATE CORE
MOLECULE FORMATION
DIFFUSION
ADSORPTION
BOND BREAKING
HIGH ENERGY RADIATION
DESORPTION
HEAT

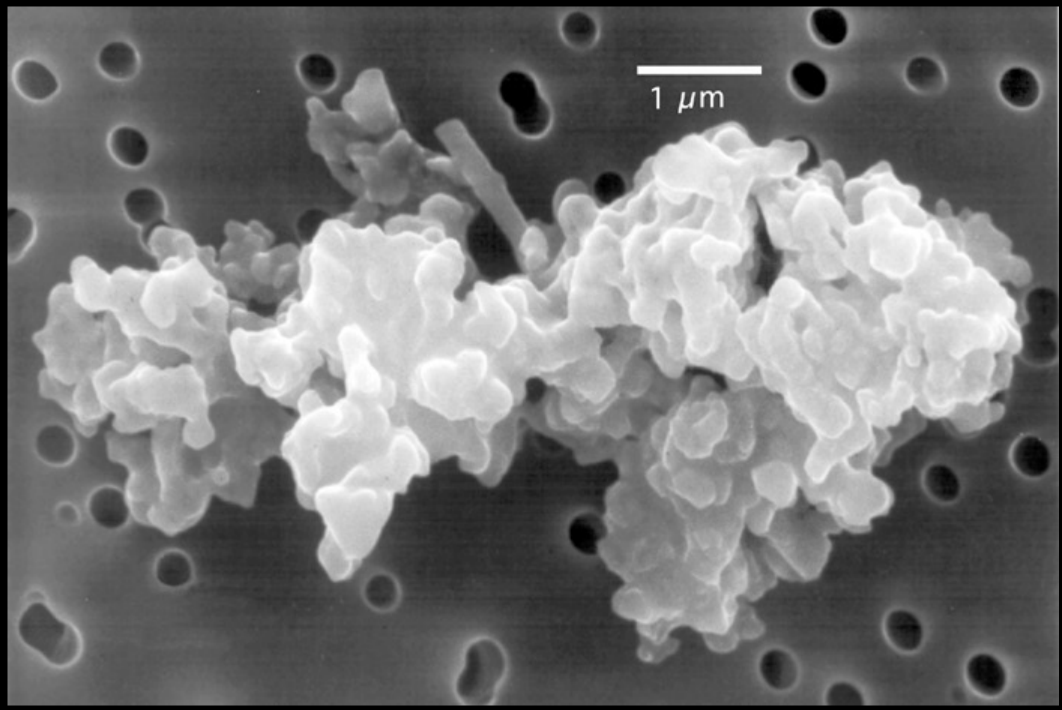
INTERSTELLAR MEDIUM (ISM): DUST

- Dust comprises only ~1% of the ISM by mass, but is an important source of opacity and cooling
- Average interstellar extinction can be satisfactorily reproduced with two components (silicate and graphite) and a power-law grain-size distribution:

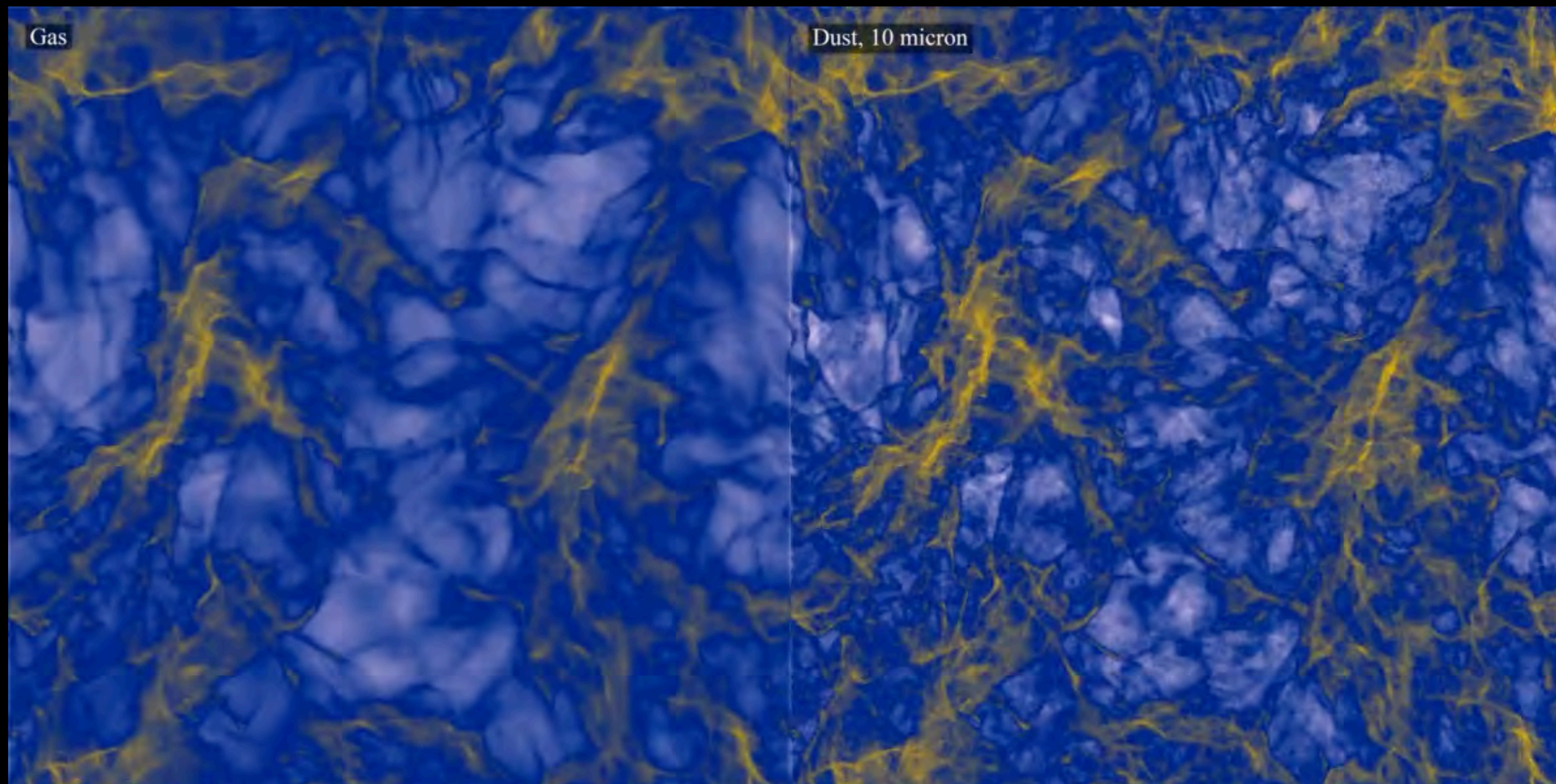
$$dn(a) \propto a^{-3.5} da \qquad \begin{cases} a_{\min} = 0.005\ \mu\mathrm{m} \\ a_{\max} = 0.25\ \mu\mathrm{m} \end{cases}$$

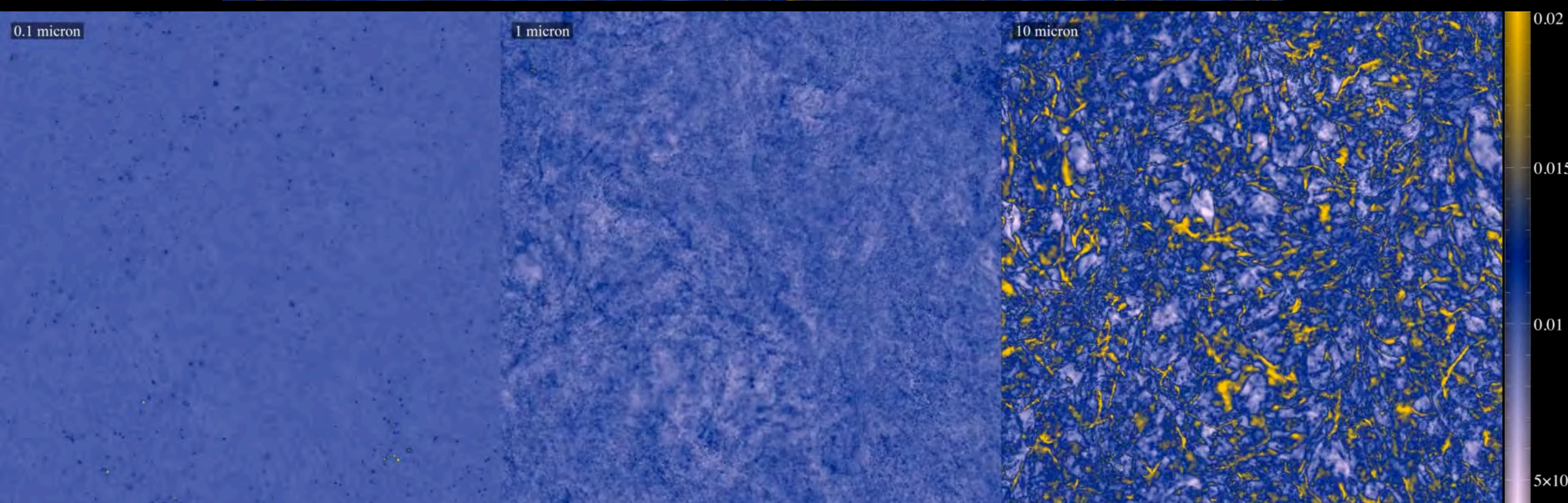
- Turbulence influences spatial and size distribution





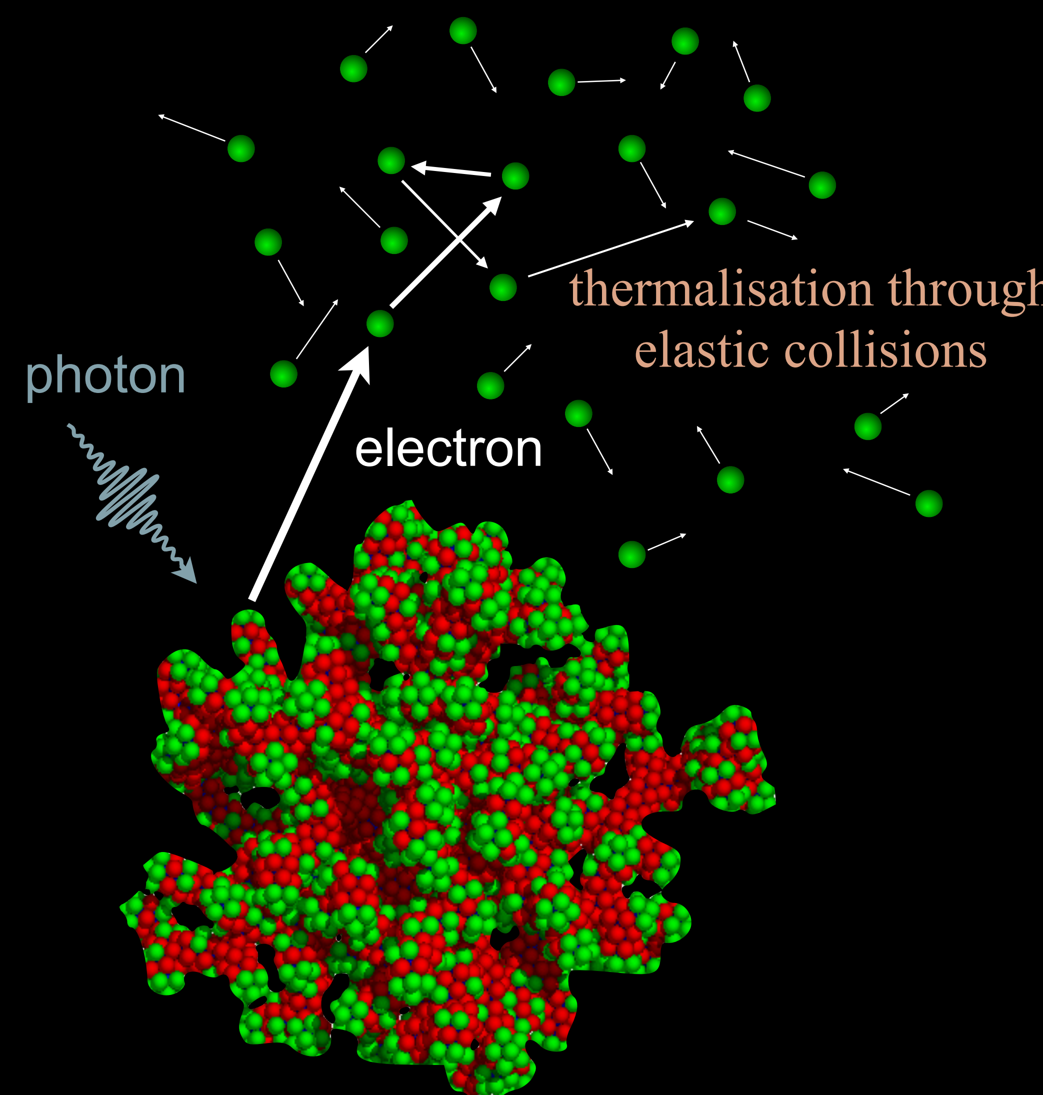
INTERSTELLAR MEDIUM (ISM): DUST

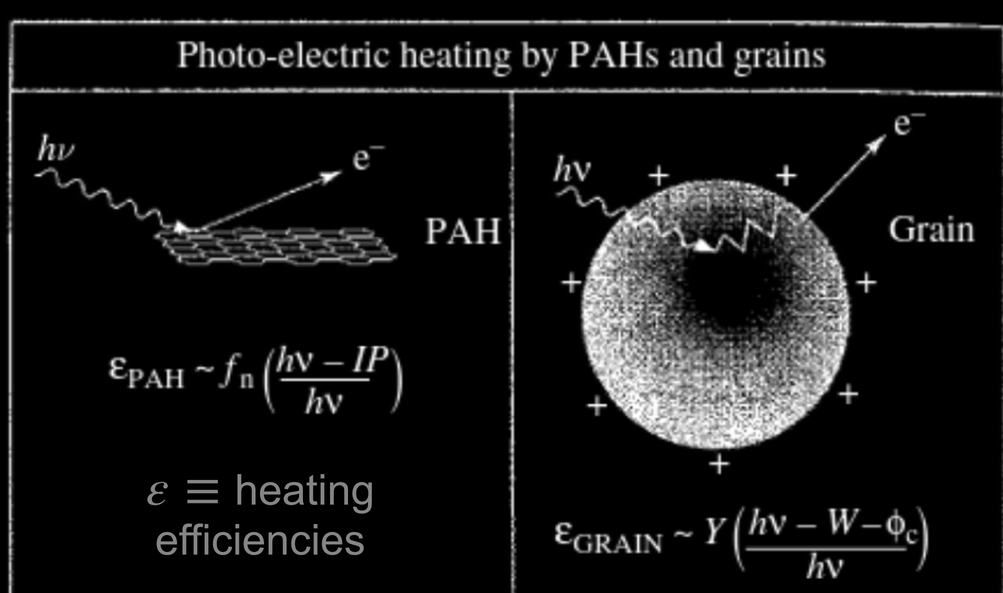


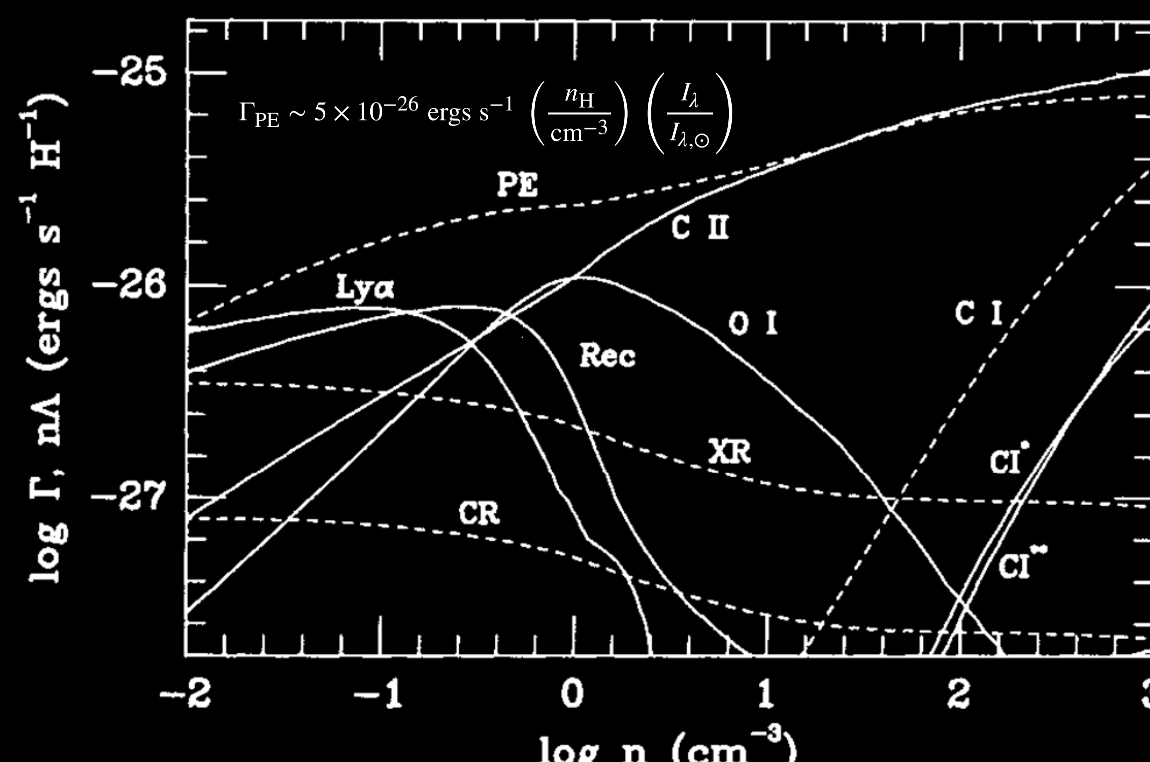


THERMAL PHYSICS OF ISM: HEATING

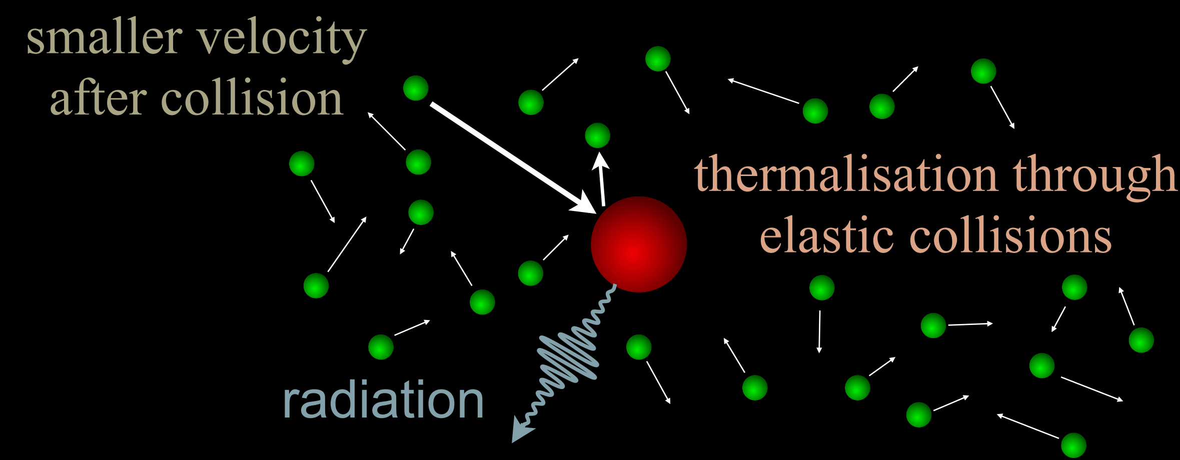
- Heating in the diffuse ISM is dominated by photoionisation (UV, X-ray, cosmic ray) of dust (photoelectric effect) and gas
  - ~100 times more electrons from dust (despite dust-to-gas ratio being 1:100)
- The electron receives a large fraction of the photon energy
- Subsequent collisions of the electron with other atoms redistributes the energy (i.e. thermalisation)

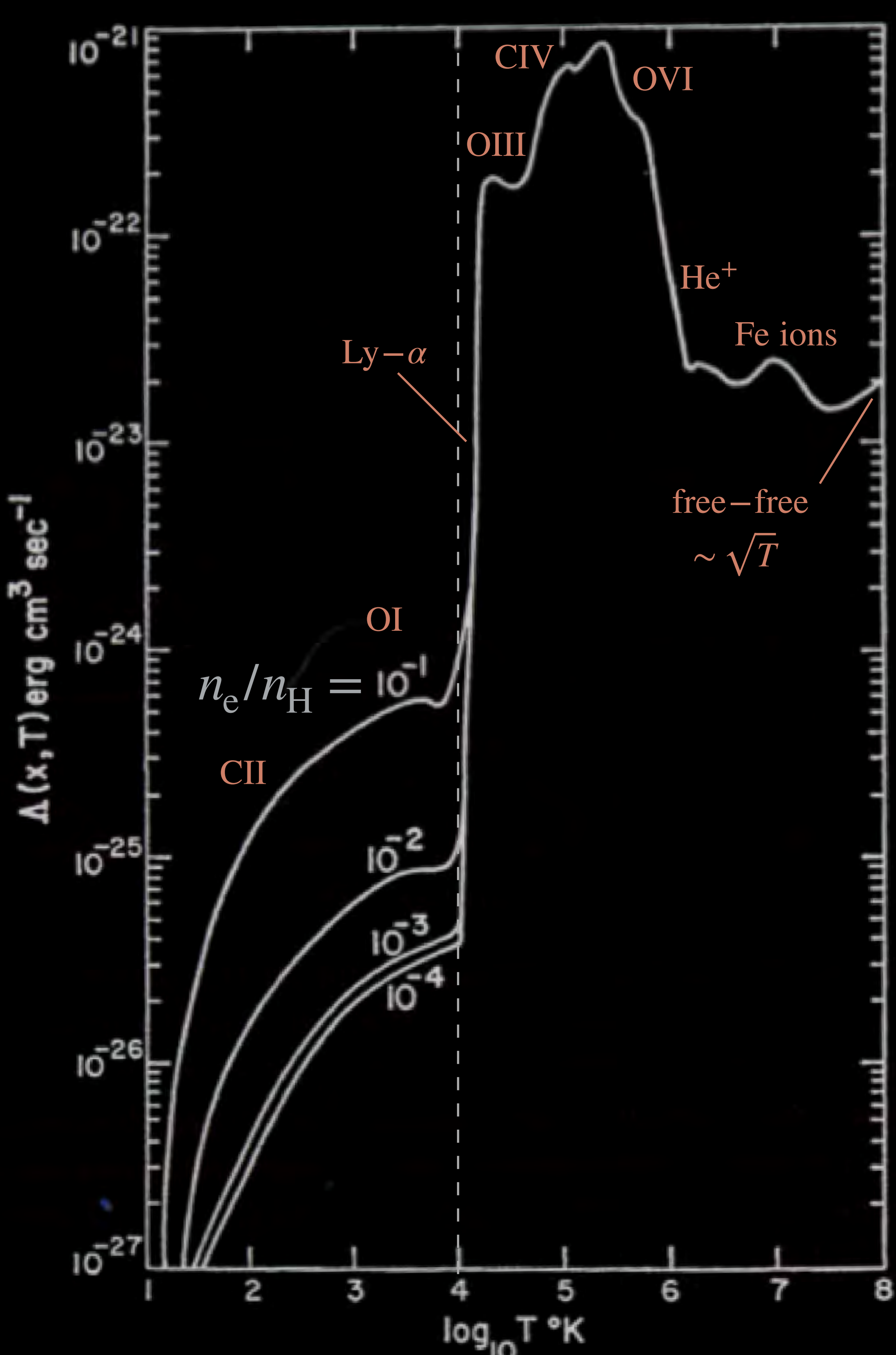






THERMAL PHYSICS OF ISM: COOLING

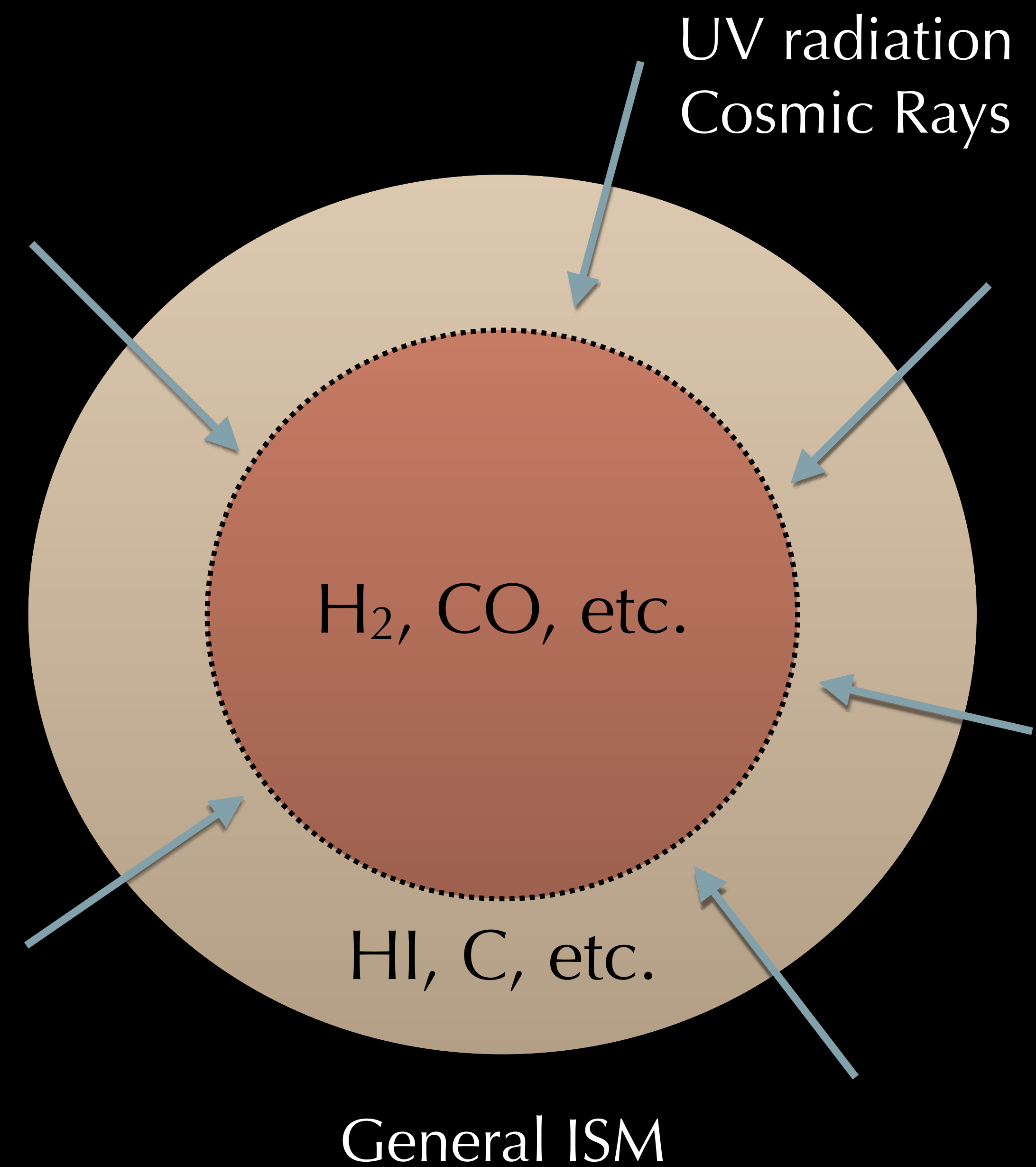




- Cooling is usually dominated by collisional de-excitation
  - Fine structure lines
  - Electron recombination lines
  - Resonance and metastable lines
- Cooling rate, Λ, per n^2
- $T < 10^4$ K, excitation of CII and OI dominate cooling
- The step at 10^4 K corresponds to cooling by the Lyman-alpha line of H
- $T > 10^4$ K, cooling due to various lines and bremsstrahlung

COLLAPSE OF MOLECULAR CLOUDS

- Molecular clouds form when a dense enough region of gas forms in the ISM to become optically thick from UV radiation (which would otherwise destroy the molecules)
- This results in a "UV shield" of atomic (or ionised) gas
- Molecules then form on dust grains and are ejected into the cloud
- The cooling is often dominated by dust emission in the infrared
- The cores of these clouds are extremely cold (~10 K) allowing gravity to overpower internal gas pressure



SIMPLEST CASE: FREEFALL

- Consider the gravitational collapse of a cold (isothermal), pressureless fluid of uniform density ρ_0 and radius R_0 initially at rest
- The gravitational acceleration at any point is:

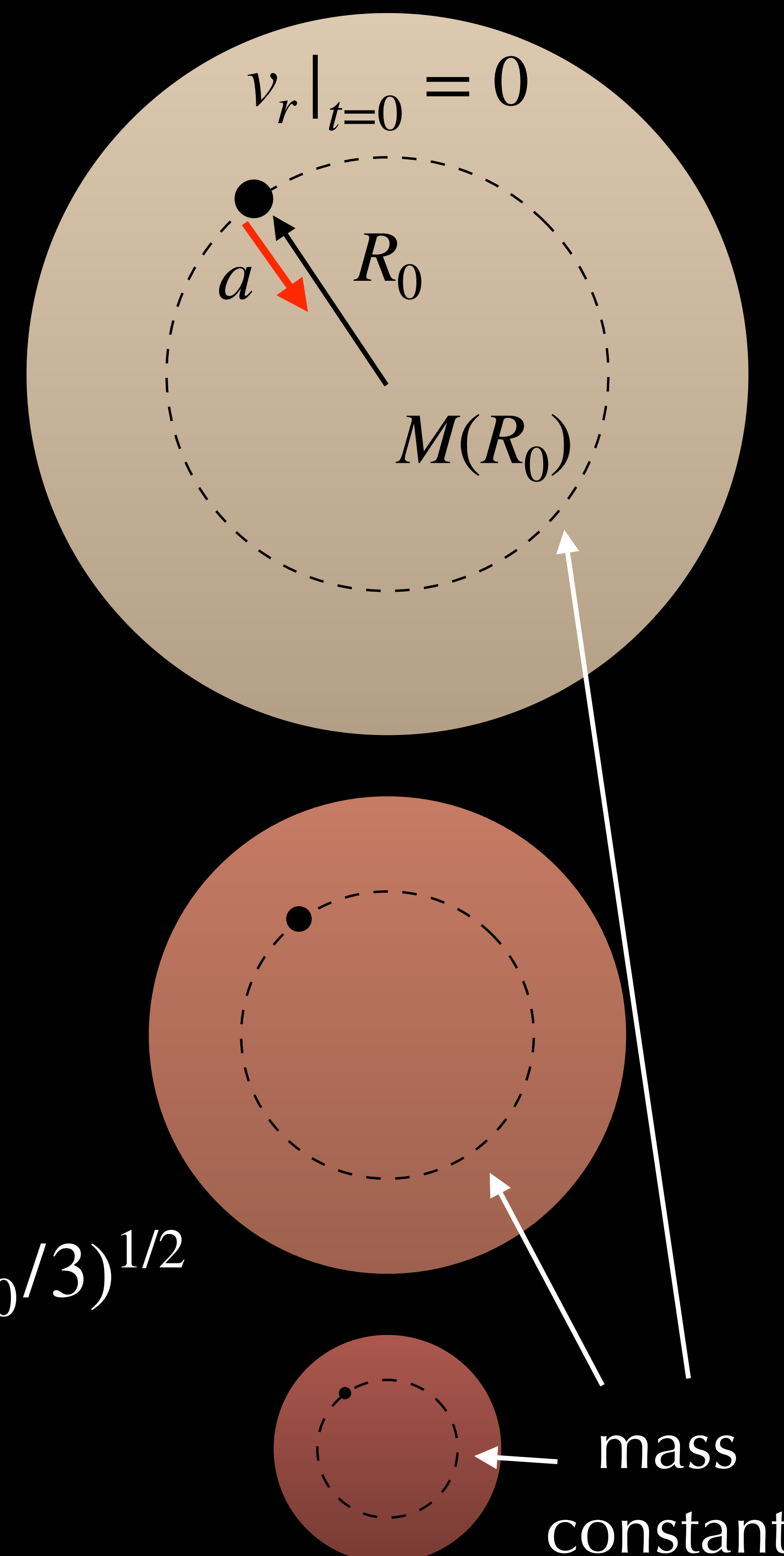
$$a_{\rm grav} = \frac{d^2 r}{dt^2} = -\frac{GM(R_0)}{r^2}$$

- Multiplying by v_r and integrating we find

$$\frac{dr}{dt} = -\sqrt{\frac{8\pi}{3} G\rho_0 R_0^2 \left(\frac{R_0}{r} - 1\right)}$$

- Making substitutions $\theta = r/R_0$ and $\chi = (8\pi G\rho_0/3)^{1/2}$ and integrating again gives

$$\sqrt{\theta(1-\theta)} + \cos^{-1}\sqrt{\theta} = \chi t$$



- Rewriting the mass in terms of density and multiplying by v_r

$$\frac{dr}{dt}\frac{d^2r}{dt^2} = -\left(\frac{4\pi}{3}G\rho_0 R_0^3\right)\frac{1}{r^2}\frac{dr}{dt}$$

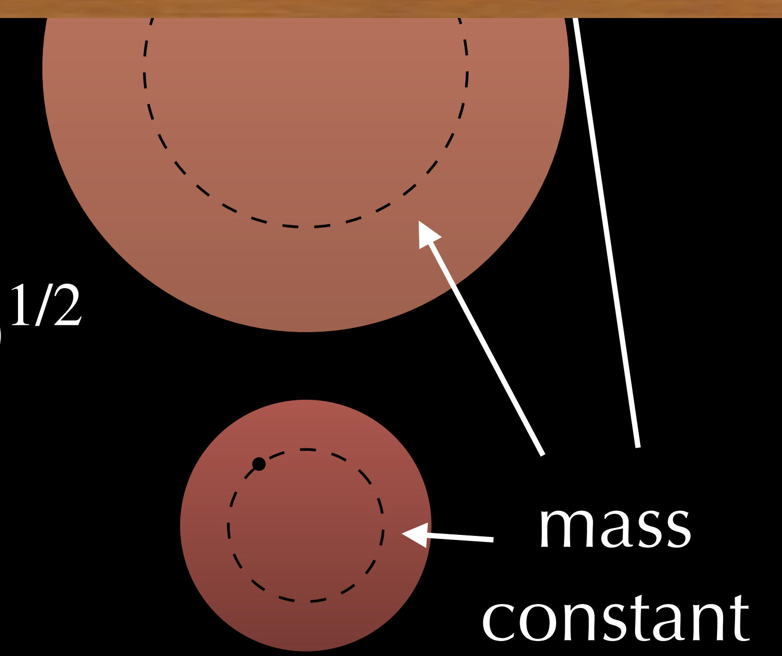
- Integrating with respect to time

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \left(\frac{4\pi}{3}G\rho_0 R_0^3\right)\frac{1}{r} + C$$

- The integration constant is fixed by the initial condition $\dot{r} = 0$ at $r = R_0$

$$C = -\frac{4\pi}{3}G\rho_0 R_0^2$$

$$\frac{dr}{dt} = -\sqrt{\frac{8\pi}{3}G\rho_0 R_0^2\left(\frac{R_0}{r} - 1\right)}$$



- Making substitutions $\theta = r/R_0$ and $\chi = (8\pi G\rho_0/3)^{1/2}$ and integrating again gives

$$\sqrt{\theta(1-\theta)} + \cos^{-1}\sqrt{\theta} = \chi t$$

SIMPLEST CASE: FREEFALL

- This predicts that $M(R_0)$ collapses to infinite density (i.e. $r = 0$) on the free-fall timescale

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho_0}}$$

- Independent of initial radius so the density profile increases at the same rate everywhere (homologous or self-similar)
- Neglects pressure, rotation, turbulence, magnetic fields, and radiation
- For centrally condensed clouds, the free-fall time is shorter near the centre (inside-out collapse)

$$t_{\rm ff} = 2.1 \times 10^3 \text{ s} \left(\frac{\rho}{\text{g cm}^{-3}}\right)^{-1/2}$$
$$= 50 \text{ Myr} \left(\frac{n}{\text{cm}^{-3}}\right)^{-1/2}$$

Estimated ISM Freefall Times

Phase	n (cm^{-3})	$t_{\rm ff}$ (Myr)
molecular	>300	< 3
cold atomic	50	7
warm atomic	0.5	70
warm ionised	0.3	90
hot ionised	3×10^{-3}	900

FLUID DYNAMICS

- Molecular clouds are complex, non-linear systems due to the large number of different physical processes that happen simultaneously
- If we wish to study the stability of the gas and to know what happens under certain physical conditions, we need to solve them accurately
- If we only consider hydrodynamics and gravity…it's already complicated

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

The Equation of Continuity (or Mass Conservation)

$$\frac{D\mathbf{v}}{Dt} = \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla P}{\rho} - \mathbf{g}$$

The Momentum Equation (or the Euler Equation)

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u = -\frac{P}{\rho}\nabla \cdot \mathbf{v}$$

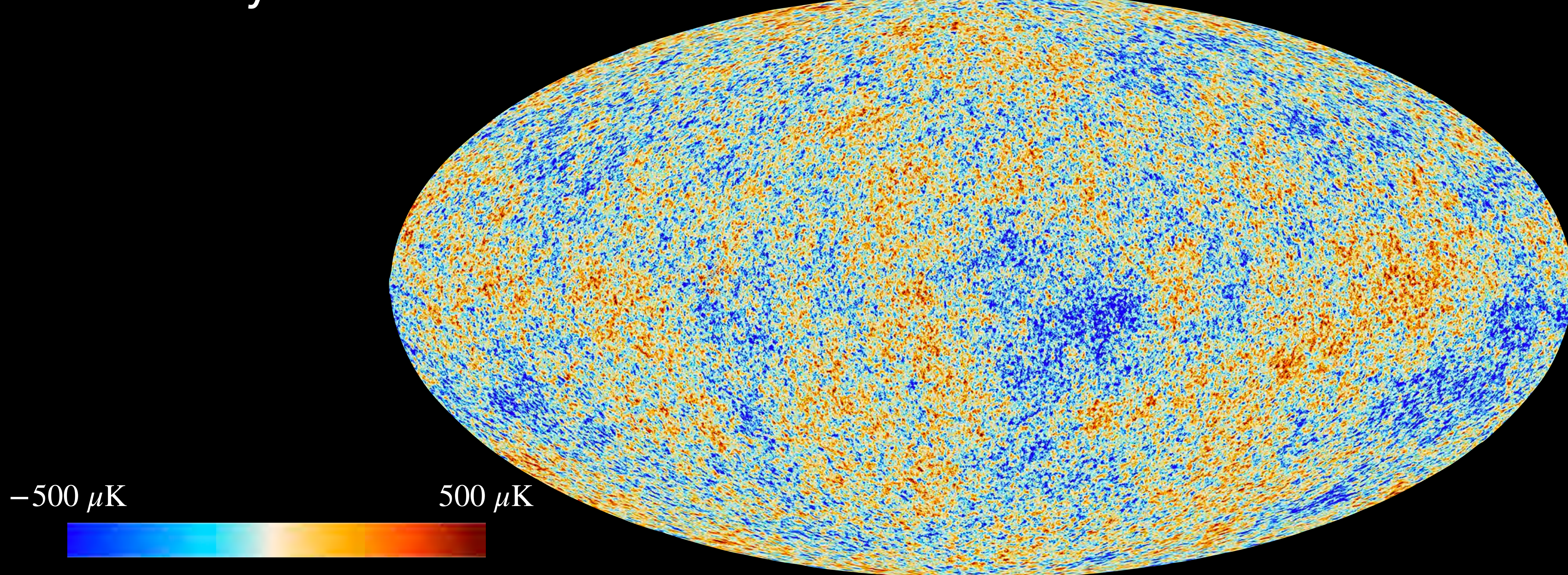
The Energy Equation (or Energy Conservation)

$$P = (\gamma - 1)\rho u$$

Equation of State (EOS)

SOUND WAVES

- Solution to the fluid equations for the simplest possible scenario
  - 1D hydrodynamics (NO gravity) with isothermal EOS ($P = c_s^2 \rho$)
- A trivial solution can be obtained with constant values of density, velocity and pressure, i.e. ρ_0, v_0 and P_0
- If we perturb the solution we get sound waves, something we actually saw earlier…



THE JEANS INSTABILITY

- Now consider a cloud where the pressure gradient acts against the attractive force of gravity

- For simplicity, assume an isothermal EOS, i.e. $P = c_s^2 \rho \equiv \dfrac{k_B T_0}{\bar{m}} \rho$

$$\nabla P \sim \frac{P_{\mathrm{centre}} - \cancel{P_{\mathrm{edge}}}}{R_0} \sim \frac{c_s^2 \rho_0}{R_0}$$

acceleration

$$a \sim \frac{c_s^2}{R_0} - \frac{4\pi}{3} G \rho_0 R_0$$

- For small values of R_0 (very little mass), the pressure term dominates

$$a \sim \frac{c_s^2}{R_0} \qquad t \sim \left(\frac{R_0}{a}\right)^{1/2} \sim \frac{R_0}{c_s}$$

Cloud expands and dissolves on sound-crossing timescale

- Conversely for large values of R_0 (large mass), the gravitational term dominates

$$a \sim -\frac{4\pi}{3} G \rho_0 R_0 \qquad t \sim \left(\frac{3}{4\pi G \rho_0}\right)^{1/2} \sim (G\rho_0)^{-1/2}$$

Cloud collapses on freefall timescale

THE JEANS LENGTH AND JEANS MASS

- At what length scales do we get gravitational collapse, i.e. $a < 0$?

$$\frac{c_s^2}{R_0} - \frac{4\pi}{3} G\rho_0 R_0 \lesssim 0 \qquad R_0 \gtrsim R_J \sim \left(\frac{c_s^2}{G\rho_0}\right)^{1/2}$$

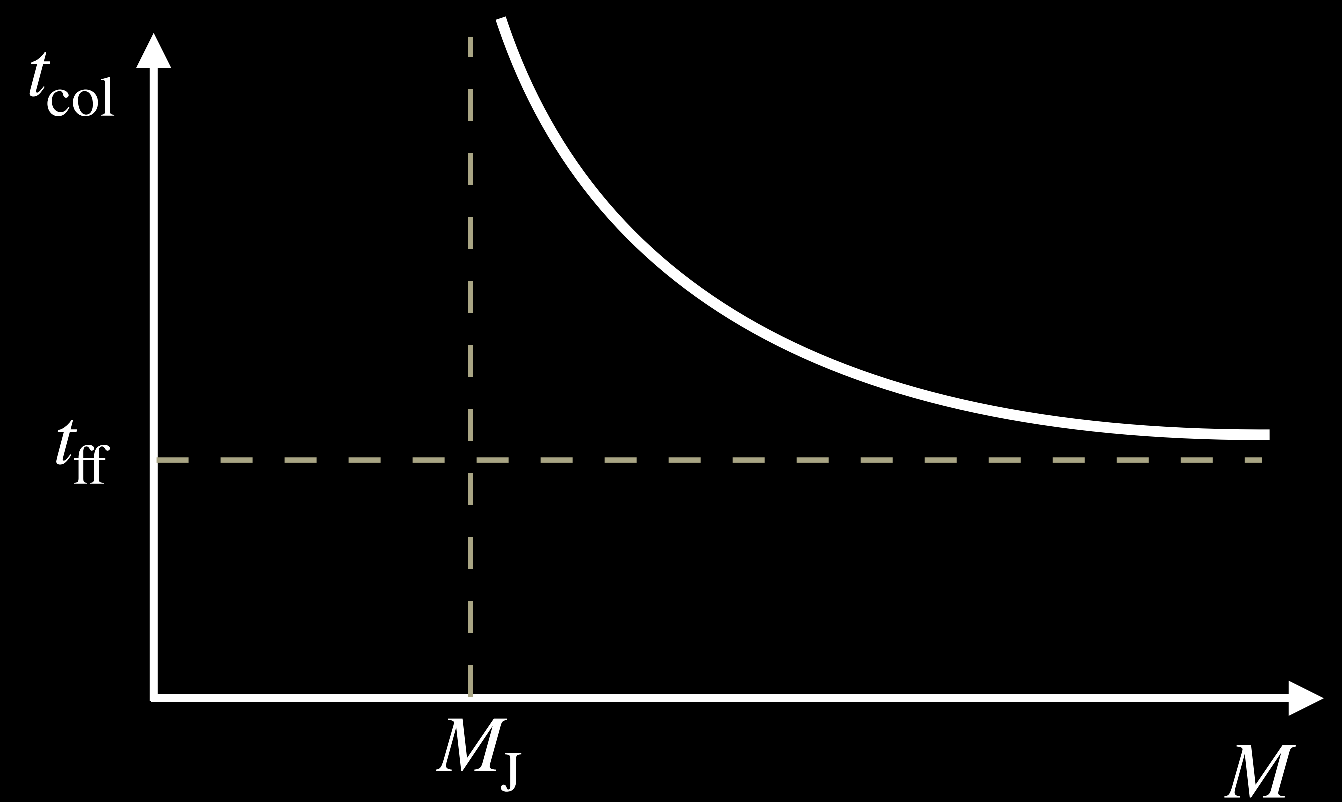
Jeans Length

- We can also define the mass: $M_0 \gtrsim M_J \sim \left(\frac{c_s^6}{G^3\rho_0}\right)^{1/2}$

Jeans Mass

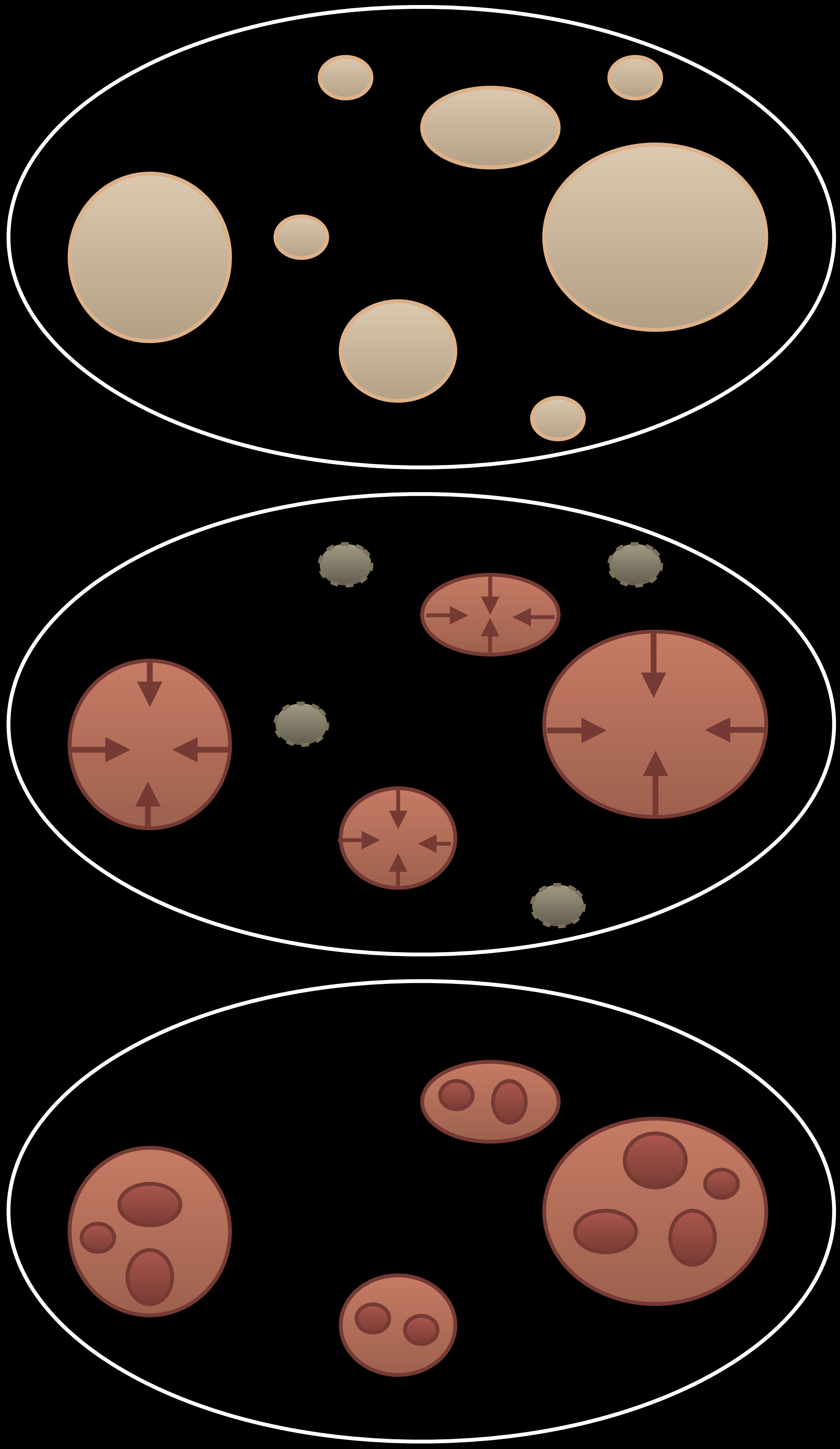
- The collapse timescale varies as

$$t_{col} \sim t_{ff} \left[1 - \left(\frac{M_0}{M_J}\right)^{-2/3}\right]^{-1/2}$$



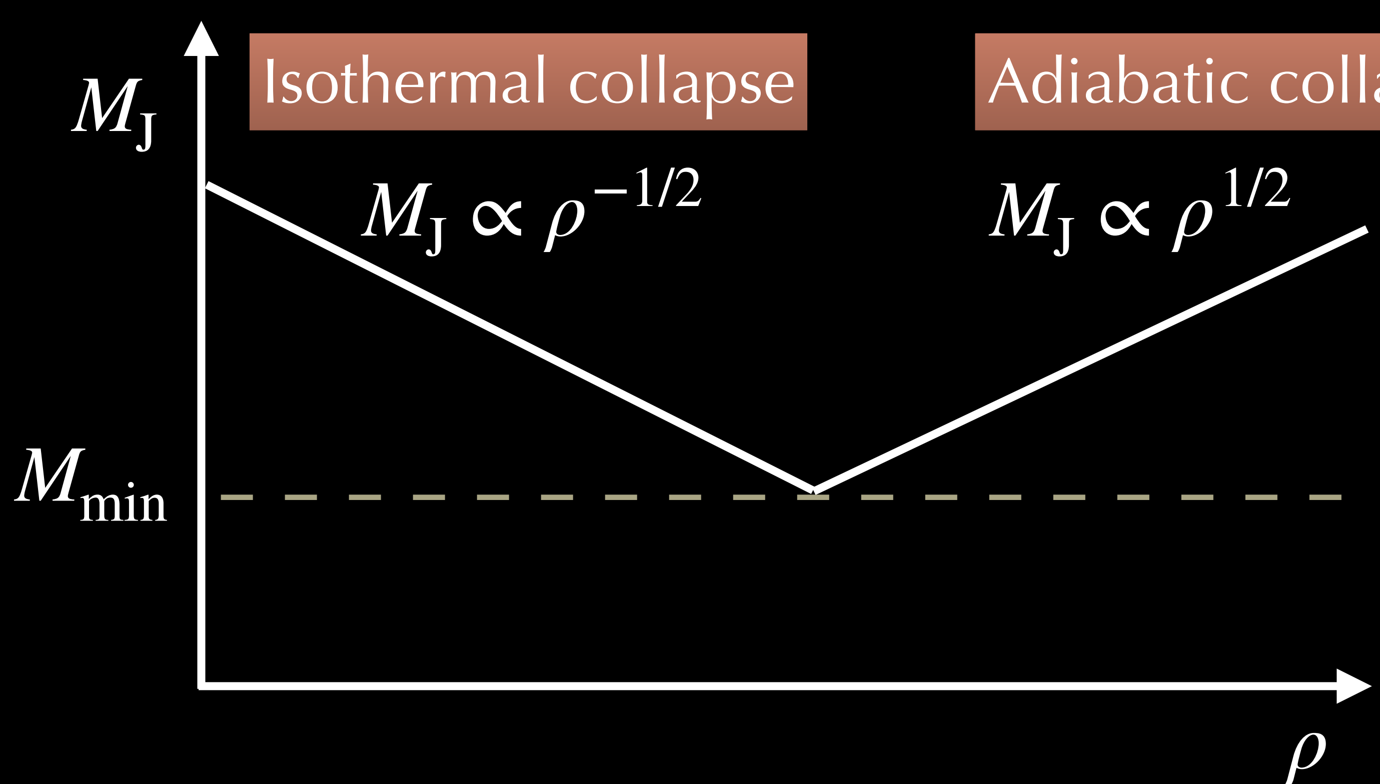
HIERARCHICAL FRAGMENTATION

- Imagine an infinitely large cloud with small density fluctuations on various size scales
- Smaller fluctuations will "dissolve" away as sound waves
- Larger fluctuations will collapse without affecting the larger cloud
- For sufficiently small densities, the cloud remains isothermal where $M_{\rm J} \propto \rho^{-1/2}$
- The fragmentation scale gets arbitrarily small as density increases
- Originally thought to be the origin of clusters, but this neglects heating



A MINIMUM MASS FOR STAR FORMATION?

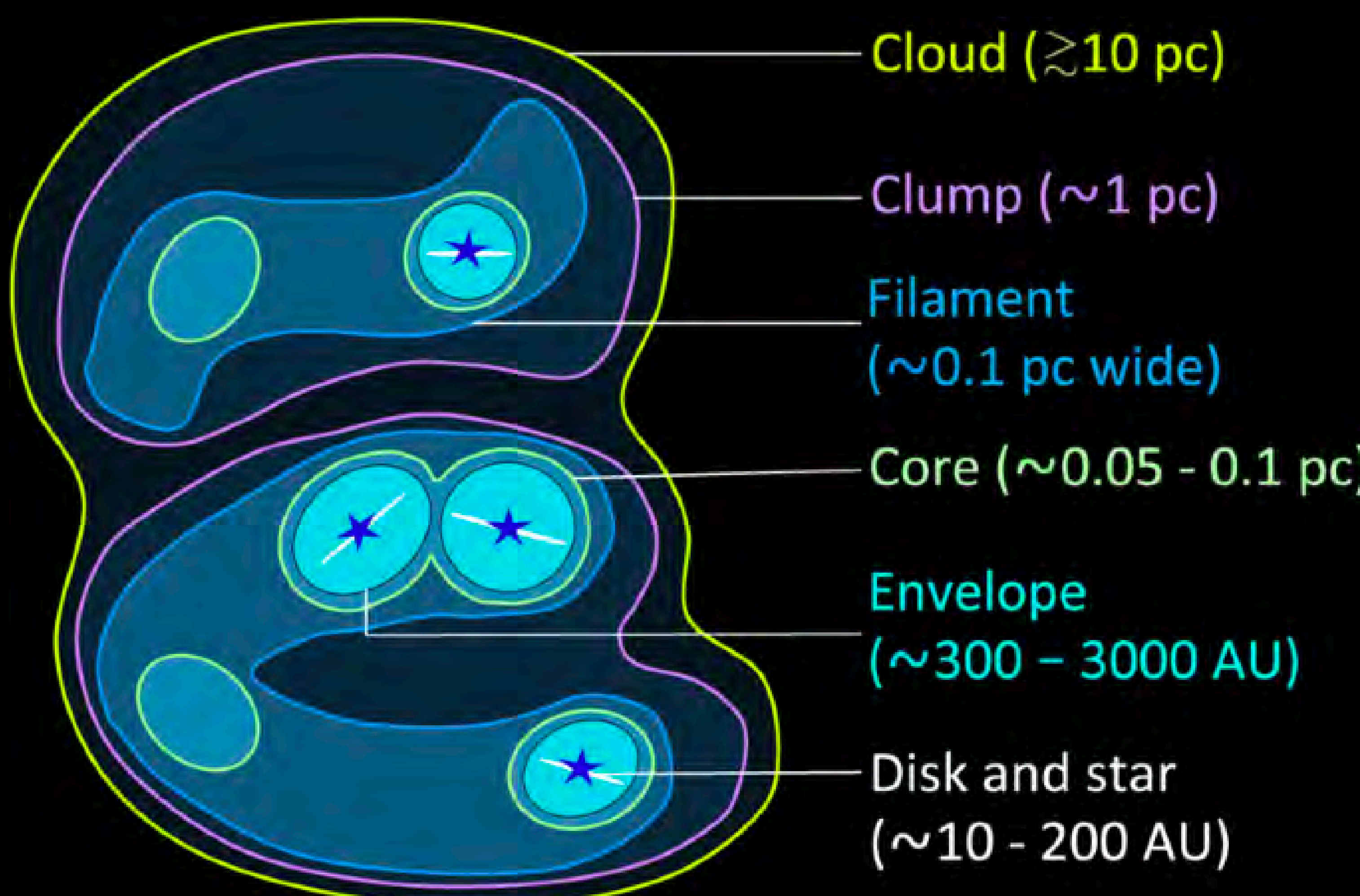
- As the cloud gets denser it eventually becomes optically thick to its own cooling radiation from dust
- The Jeans mass now increases with increasing density (approximately adiabatic contraction)
- The intersection of these curves gives a minimum Jeans mass



$$M_{min} \sim \left(\frac{R^9}{G^3 \sigma_B T^4} \right)^{1/2} \sim 0.5\ M_\odot$$

STAR FORMING CORES

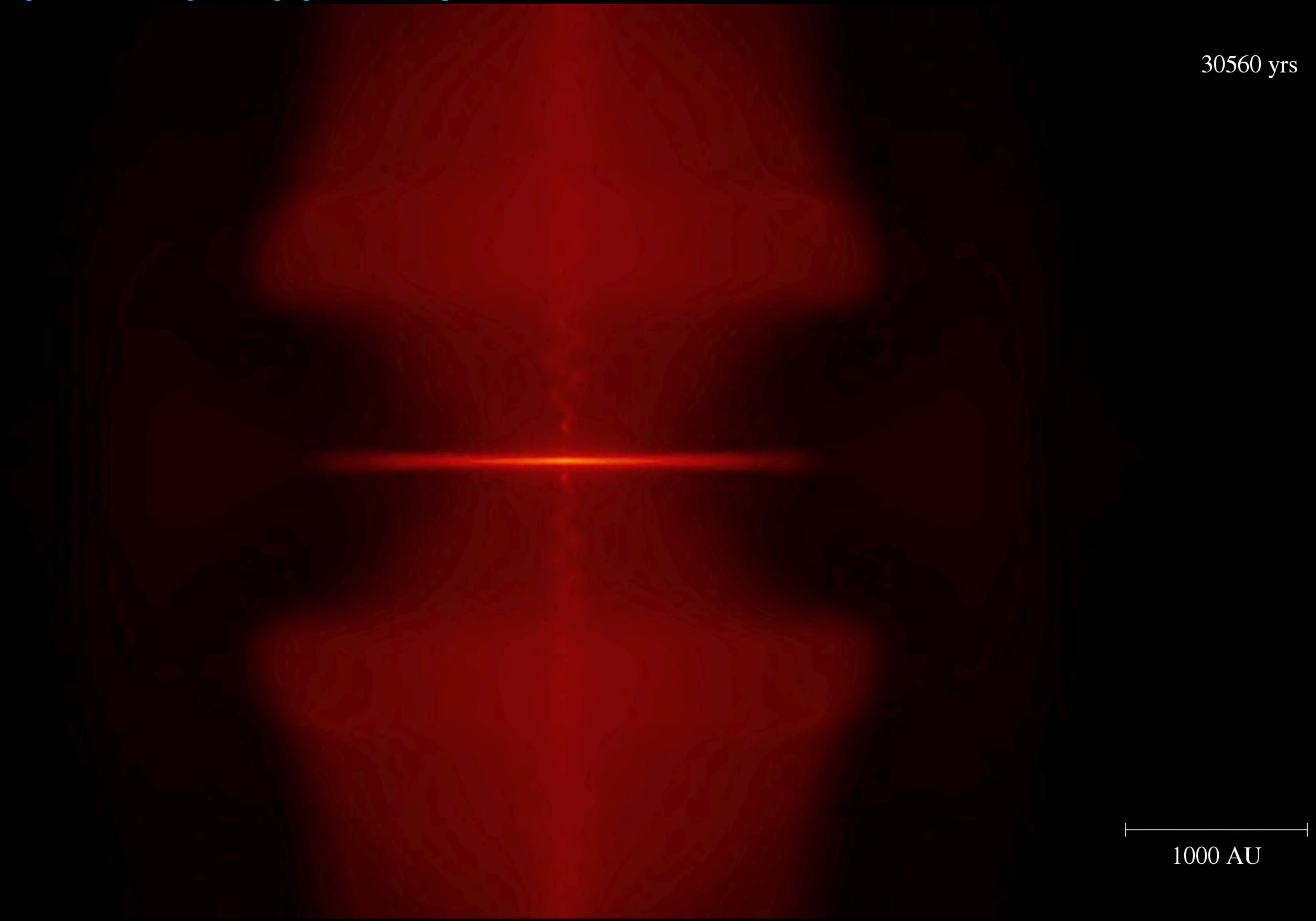
- At small scales (~0.1 pc), the gas has condensed into star-forming cores
- Each core is the progenitor of either an individual star or a binary/multiple system
- Initially, the core can only be seen in the sub-mm
- As it forms a central protostar, it starts to emit at shorter and shorter wavelengths until eventually becoming a star



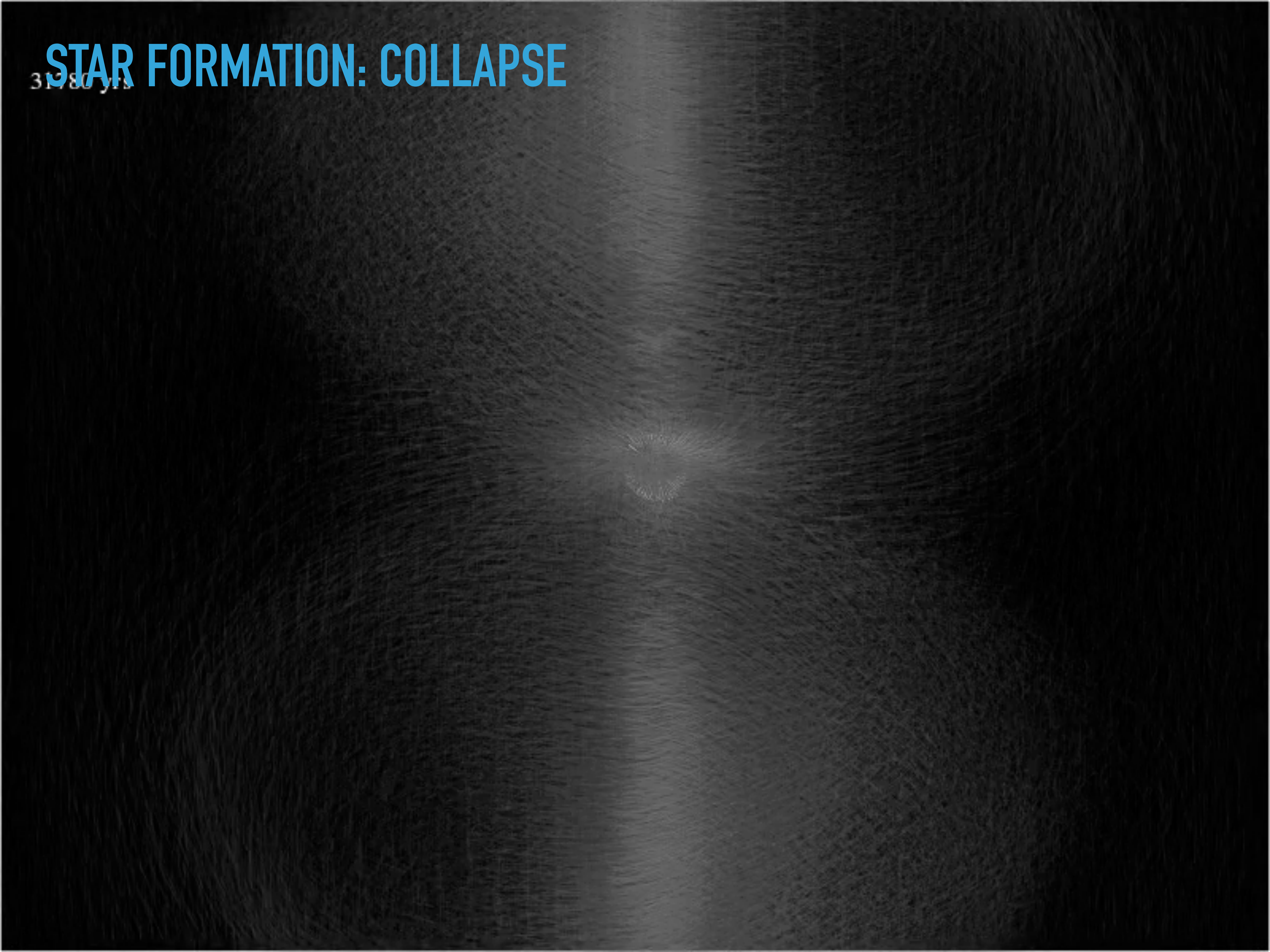
GIANT MOLECULAR CLOUD STABILITY

- Collapse triggered by:
  - Cloud-cloud collisions (including galactic collisions)
  - Shocks from nearby supernova explosions
  - Passage through a spiral arm of the galaxy
  - Collapse is facilitated by low temperatures and high densities (e.g. regions full of dust)
- Collapse is hindered by:
  - Turbulence
  - Macroscopic flows
  - Cloud geometry
  - Rotation
  - Magnetic fields

STAR FORMATION: COLLAPSE



STAR FORMATION: COLLAPSE

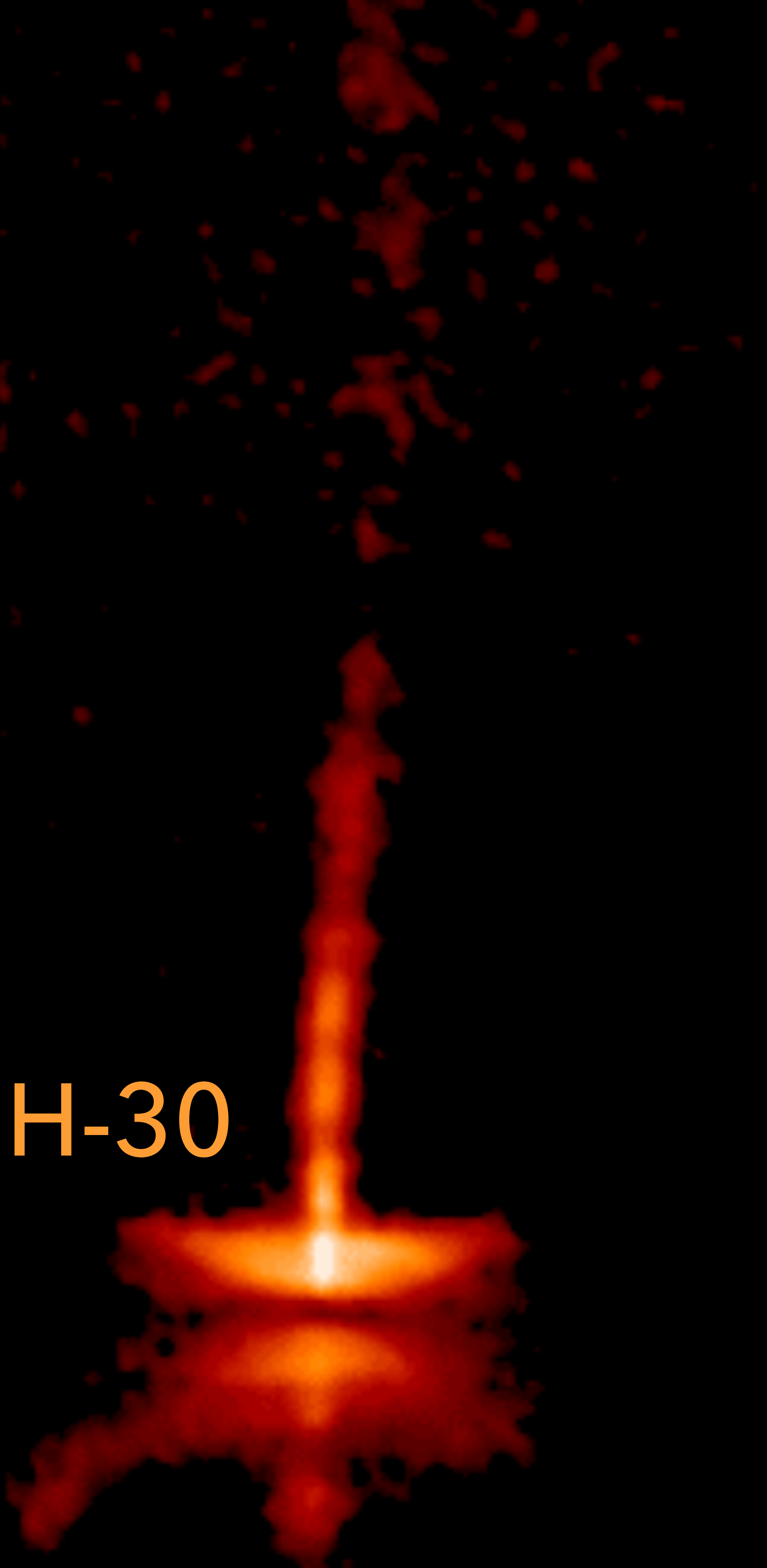


STAR FORMATION: COLLAPSE

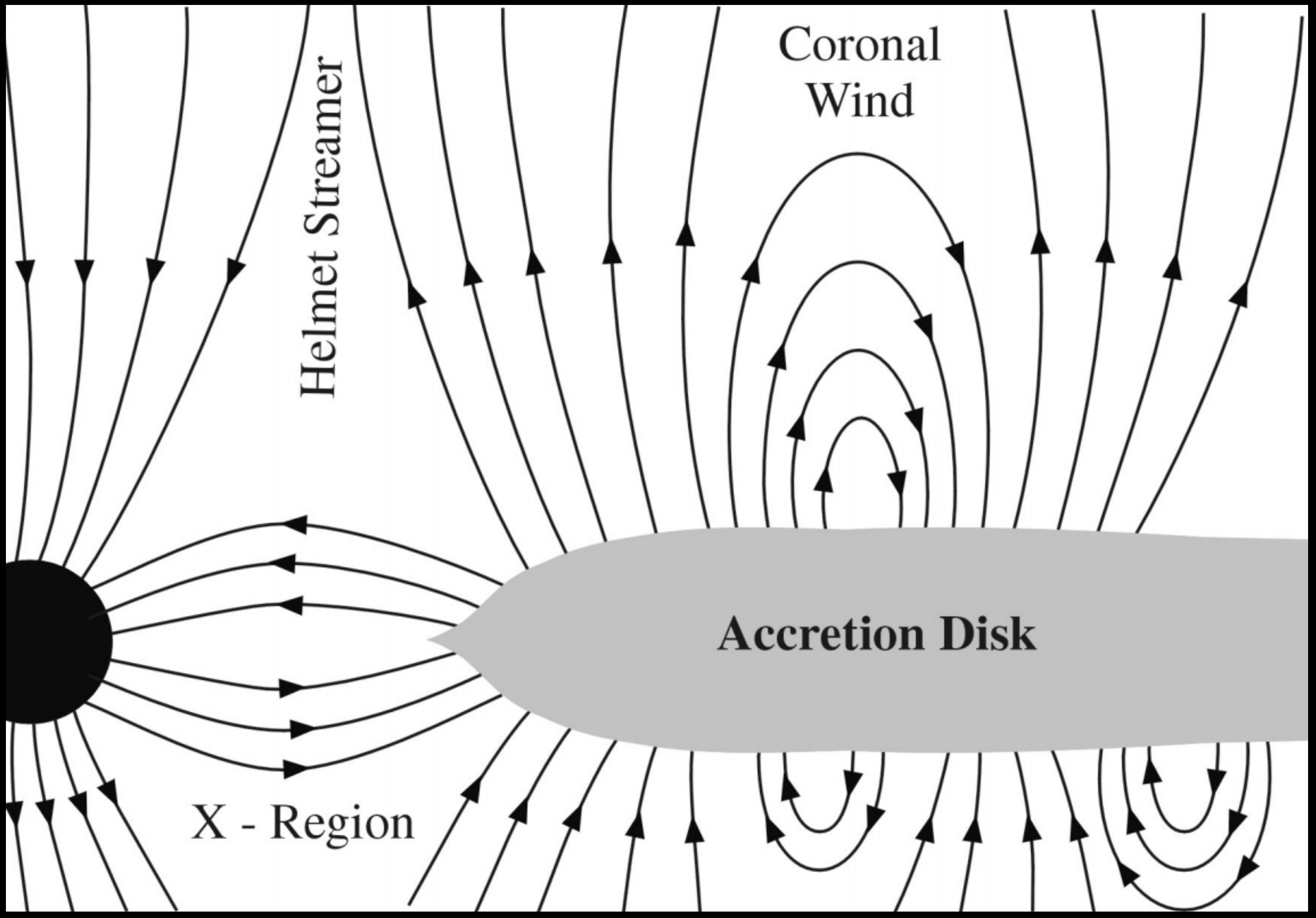
- Conservation of angular momentum leads to rapid rotation in the central region, suppressing further collapse and promoting the formation of a circumstellar disc
- The magnetic field can effectively transfer the excess angular momentum from the center of the cloud by magnetic braking and jets, thus promoting further collapse
    - If too efficient, magnetic braking can prevent a circumstellar disc from even forming (labeled the magnetic braking catastrophe)
- Observations show evidence for both magnetic fields and circumstellar discs, so the "catastrophe" is only numerical

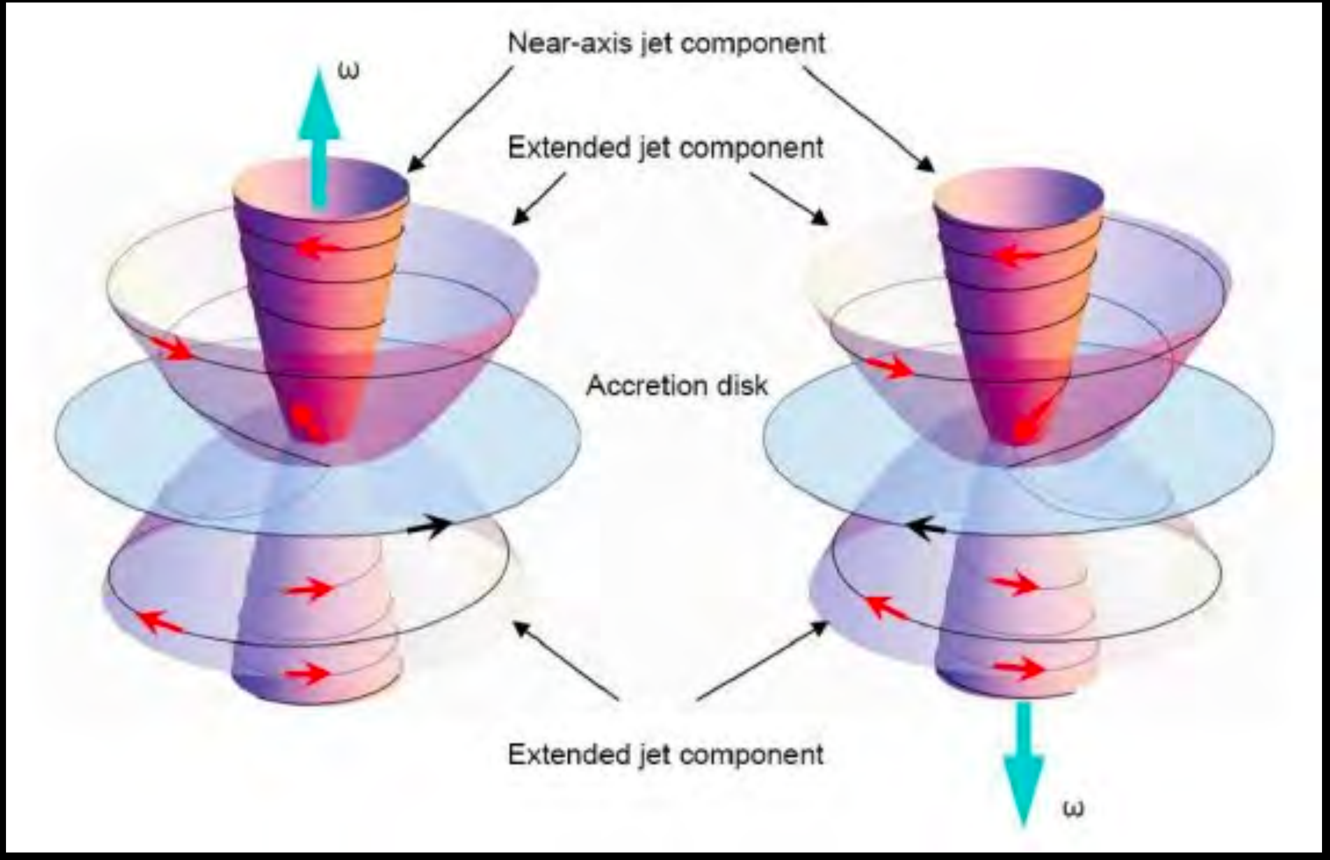
STAR FORMATION: JETS

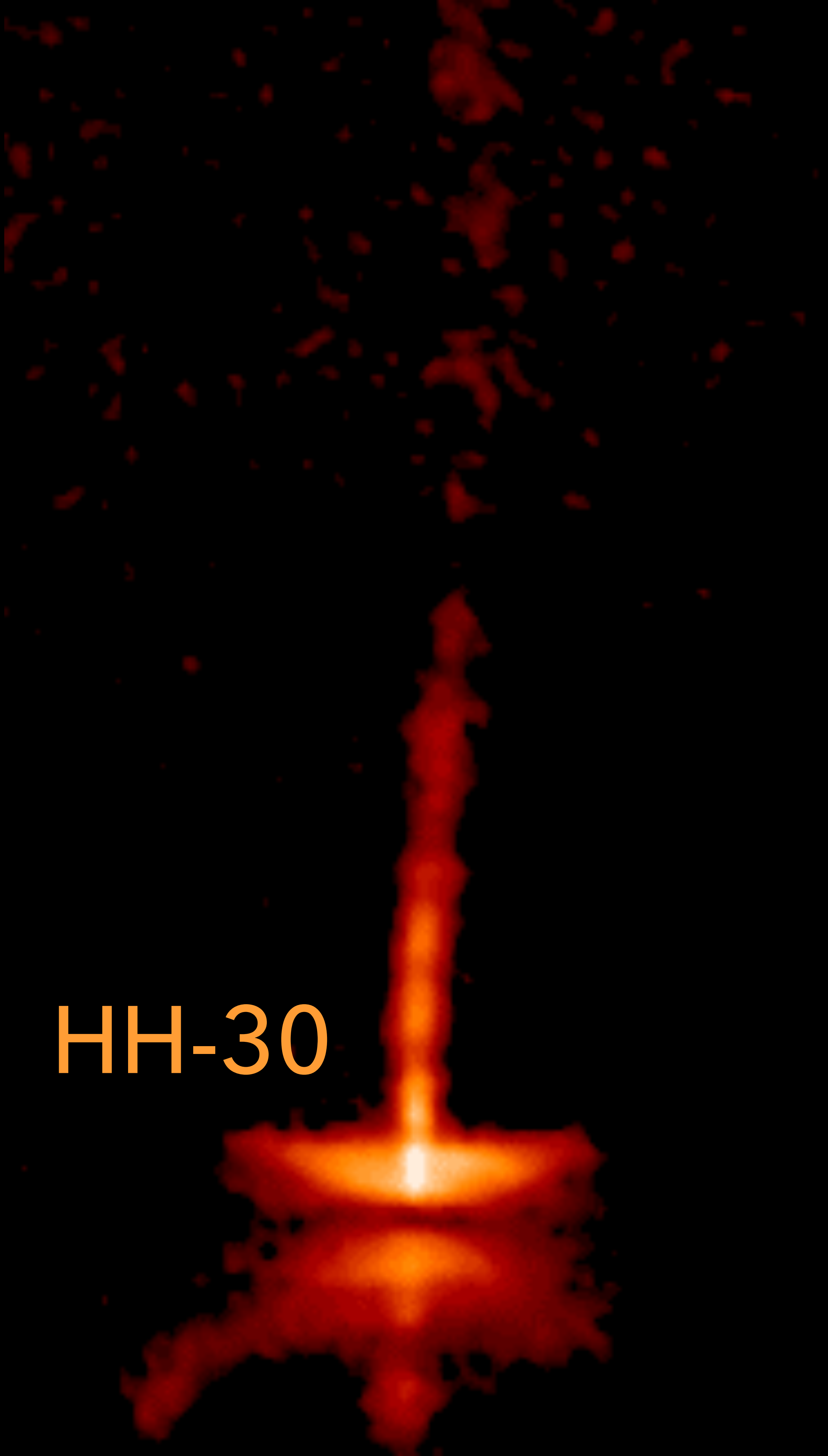
- Outflows of ionised matter emitted along the axis of rotation.
- Dynamic interactions between compact central objects (e.g. stars and black holes) and a surrounding accretion disc.
- Almost always associated with magnetic fields that twist up and collimate the beam.
- Ionised particles are attached to the field lines like “beads on a wire” and are centrifugally accelerated.



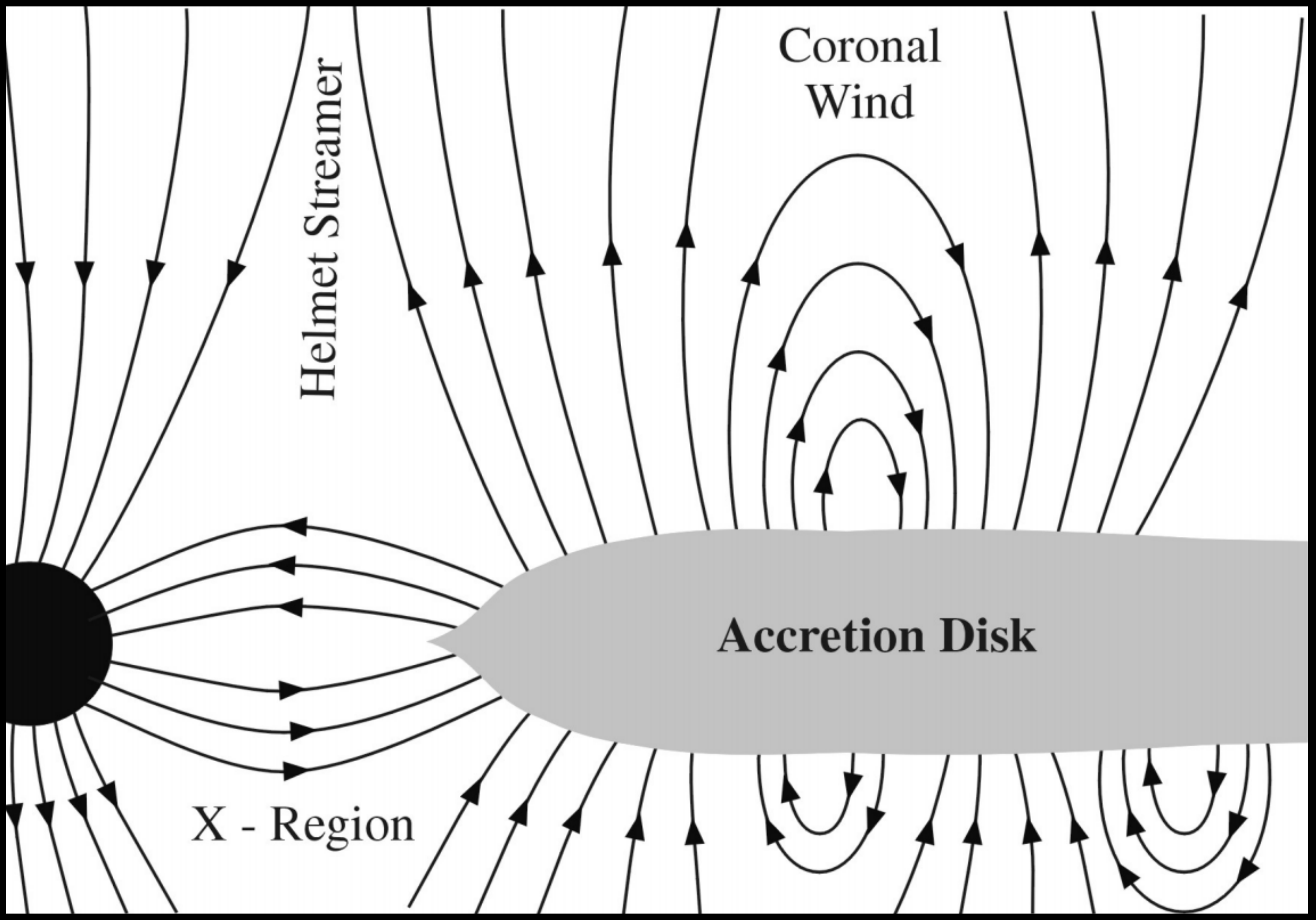
STAR FORMATION: JETS

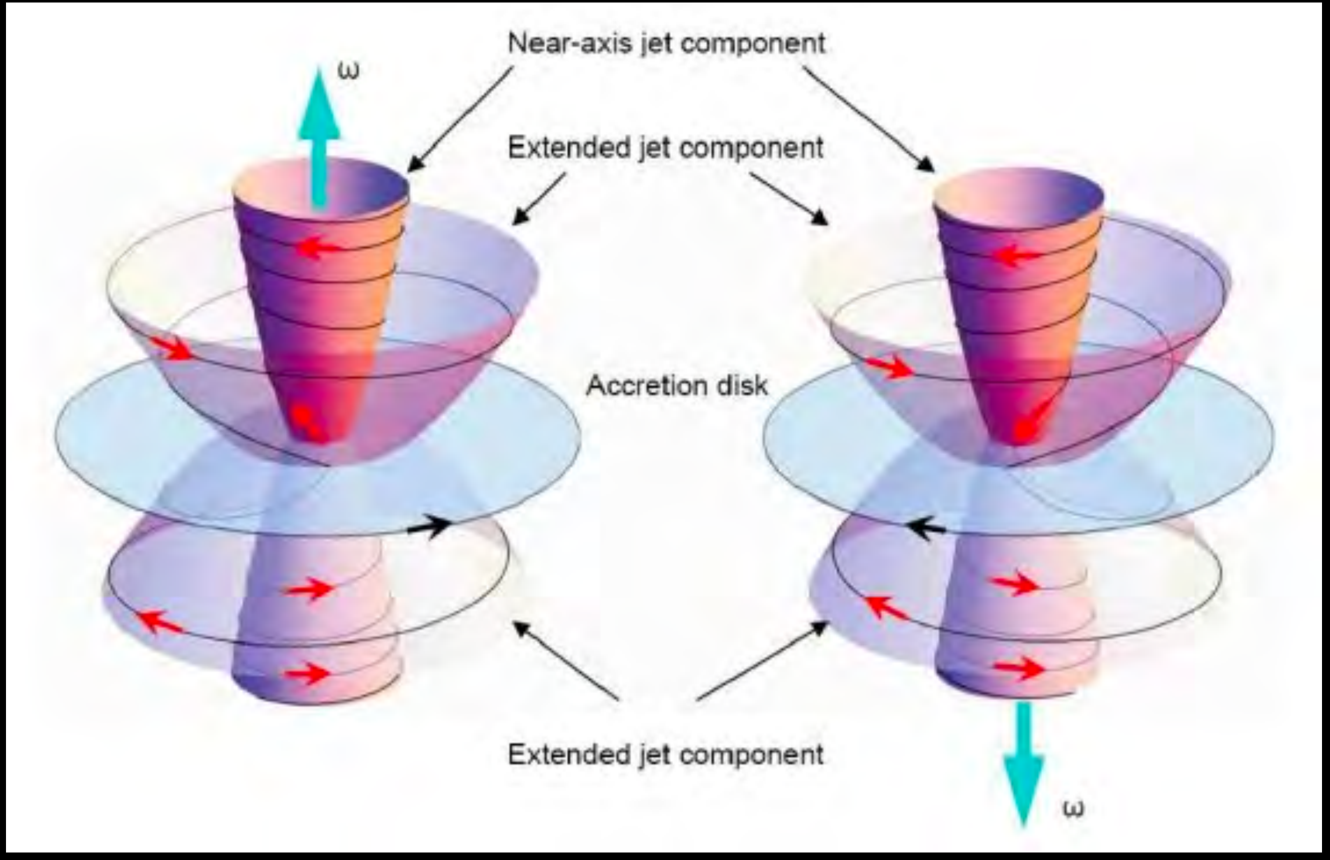


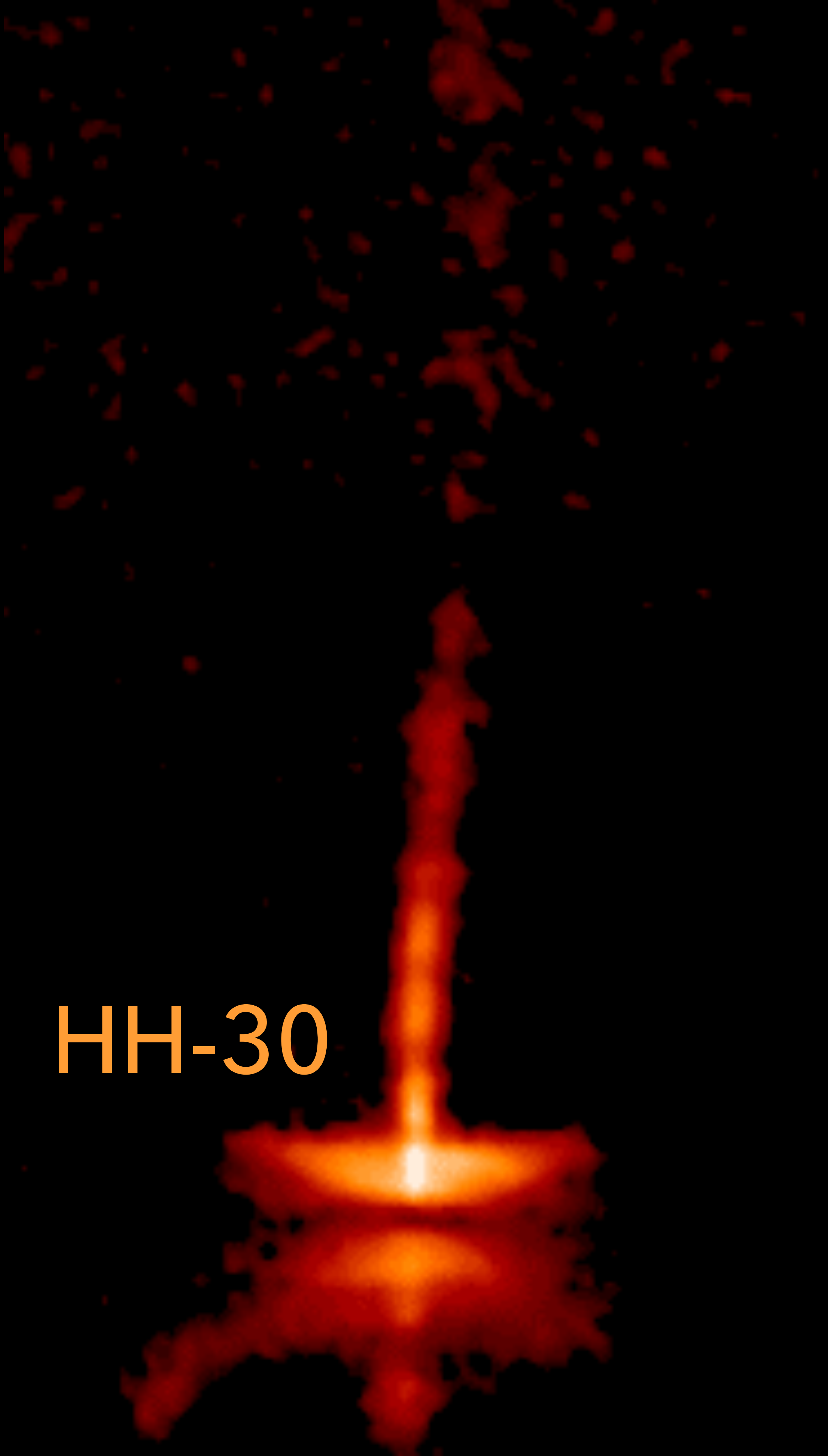




STAR FORMATION: JETS







STAR FORMATION: JETS

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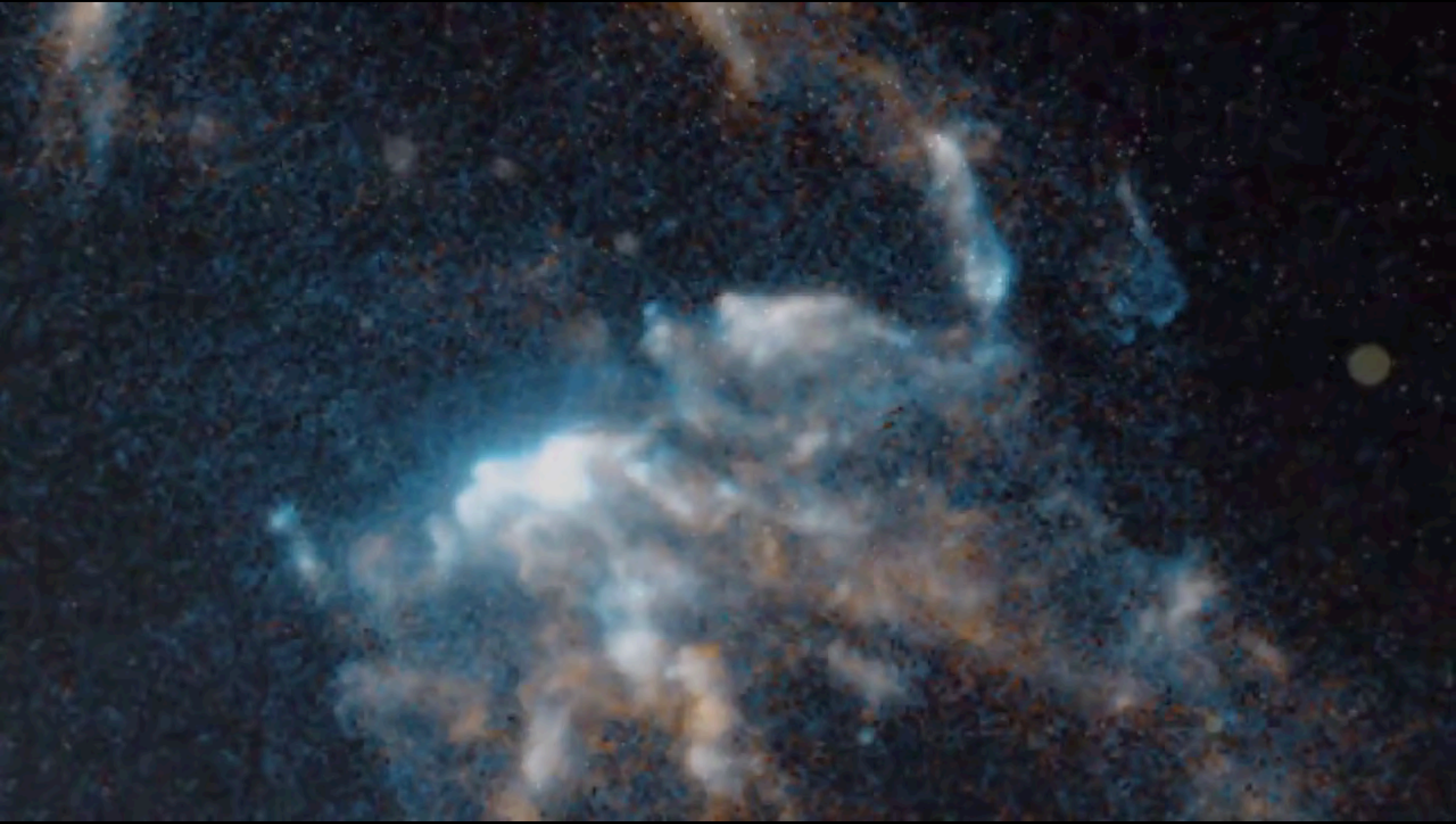

STAR FORMATION: JETS

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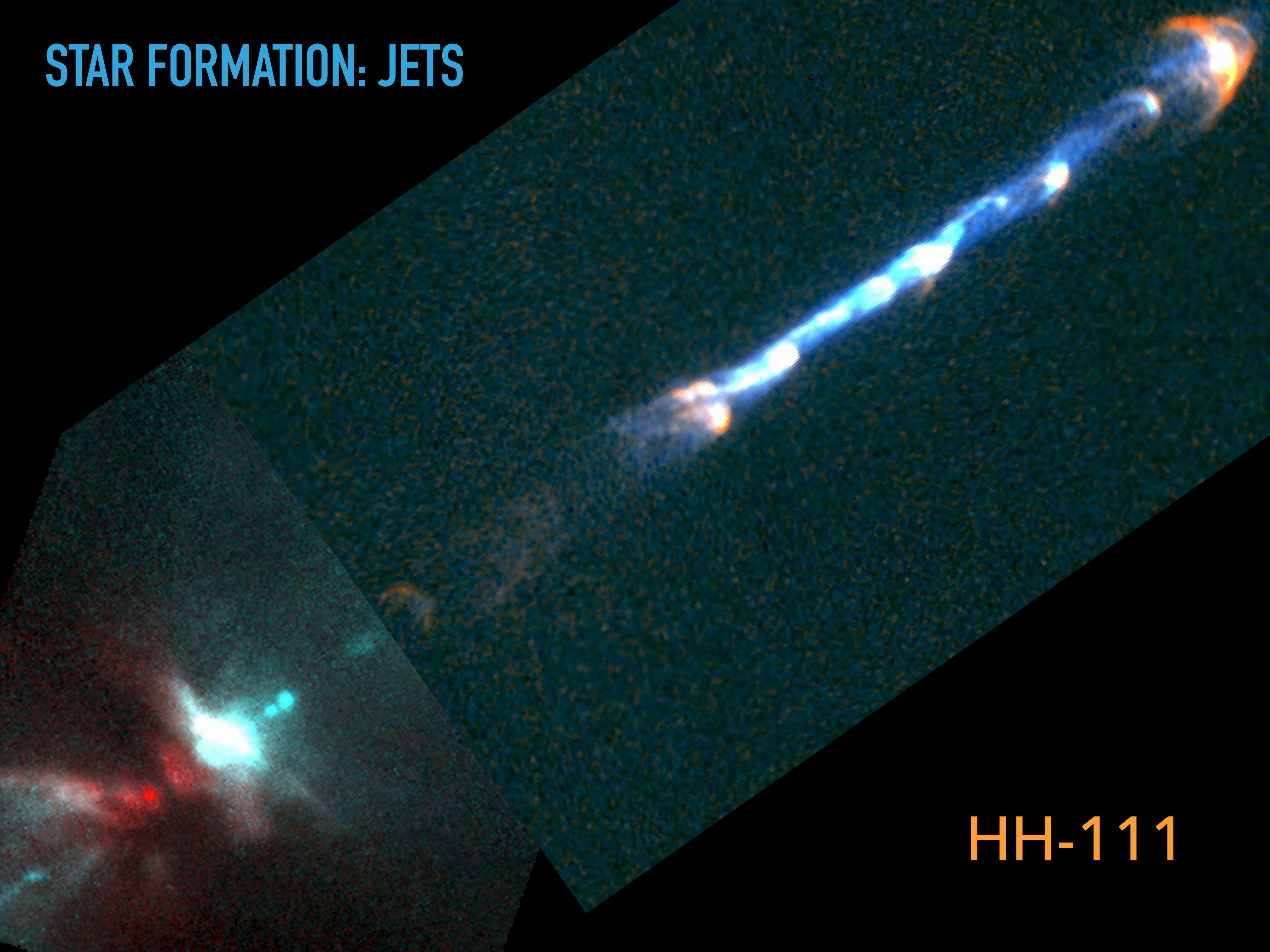


STAR FORMATION: JETS

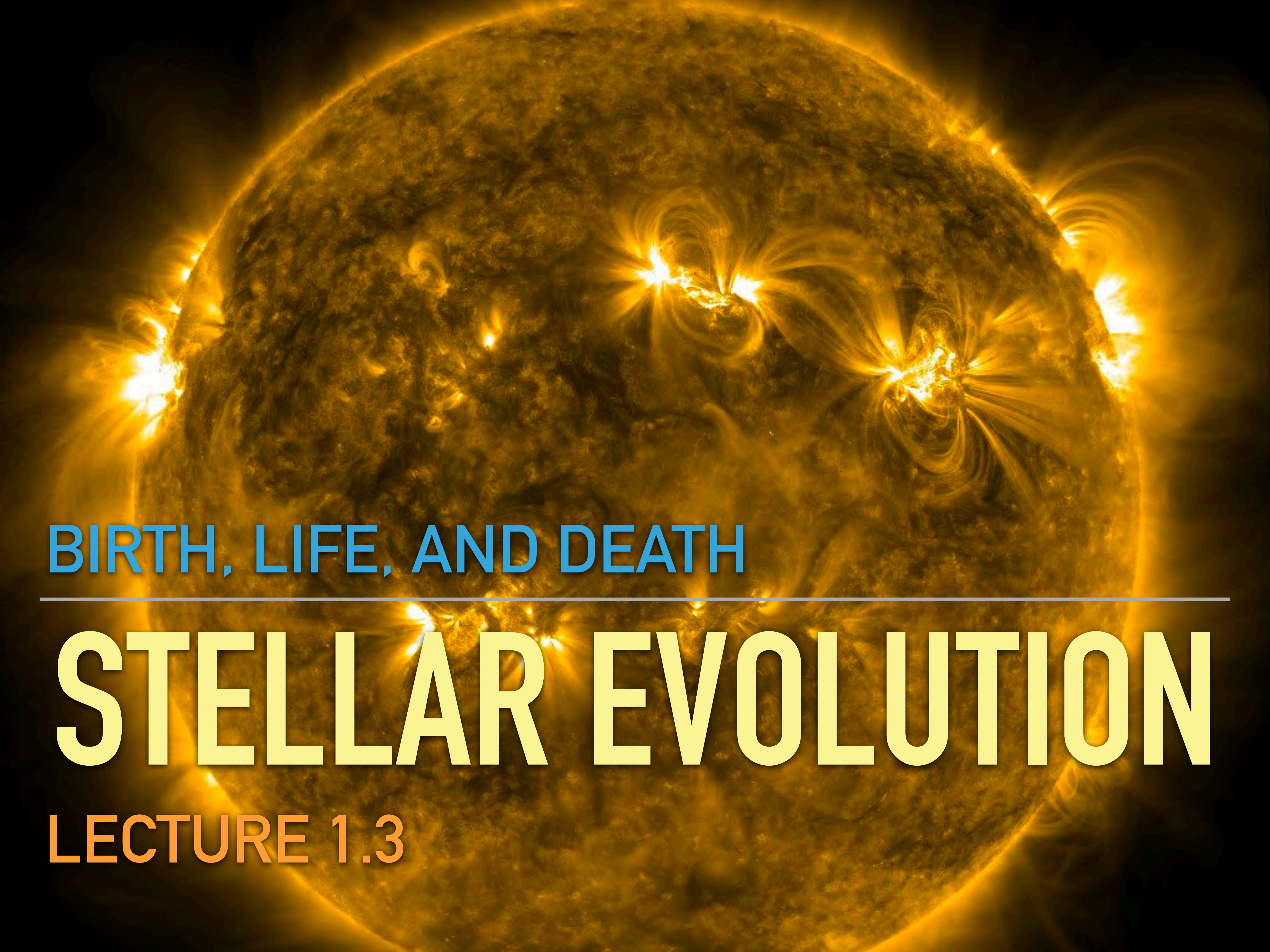
STAR FORMATION: CIRCUMSTELLAR DISCS

STAR FORMATION: CIRCUMSTELLAR DISCS

BIRTH, LIFE, AND DEATH

STELLAR EVOLUTION

LECTURE 1.3



STAR FORMATION: PROTOSTARS

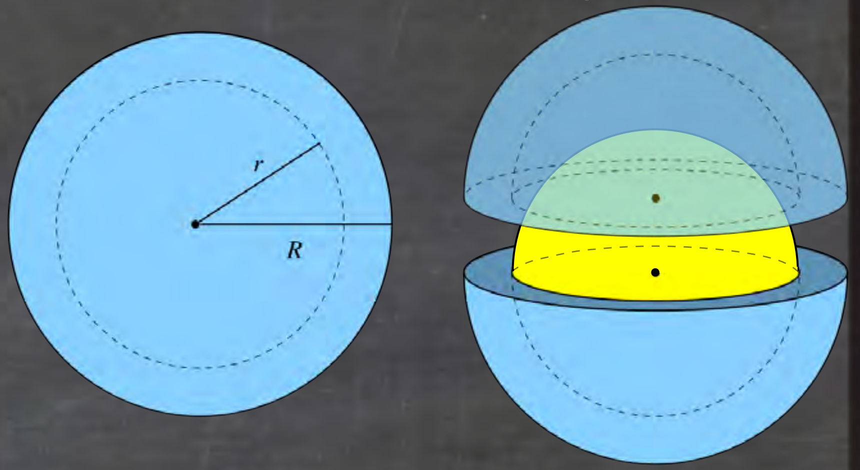
- Core that is still gathering mass from its parent molecular cloud (envelope). Material initially falls directly onto the protostar, but this later transitions to the surrounding disc.
- Gravitational contraction releases energy. About half the energy is radiated away by photons, the other half goes into heating the interior.
- The ratio of the energy produced to the energy lost is known as the Kelvin-Helmholz timescale:

$$\tau_{\mathrm{KH}} = \frac{\text{gravitational binding energy}}{\text{luminosity}} = \frac{GM^2}{RL}$$

- The time spent in the gravitational contraction phase depends on the mass of the protostar.

- The gravitational binding energy can be estimated by considering a sphere of radius R and imagine pulling it apart successively by removing thin shells to infinity.

$$m_{\text{shell}} = 4\pi r^2 \rho dr \quad \text{and} \quad m_{\text{interior}} = \frac{4\pi}{3} r^3 \rho$$



- The energy required for removing one shell is the negative gravitational potential energy

$$dU = +G\frac{m_{\text{shell}} m_{\text{interior}}}{r}$$

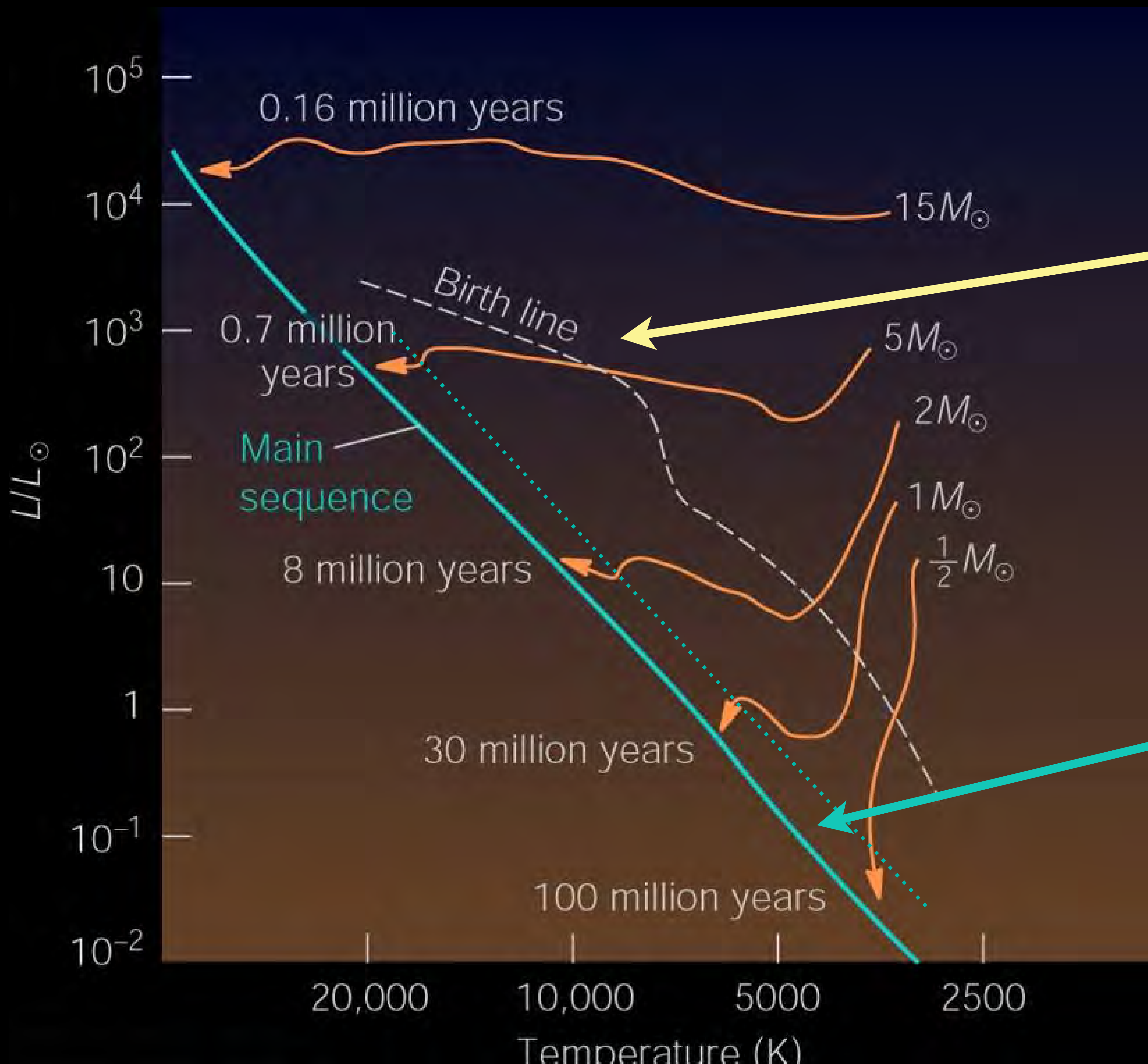
- Integrating over all shells (assuming ρ is constant):

$$U = G\frac{16\pi^2}{3}\rho^2 \int_0^R r^4 dr = G\frac{16\pi^2}{15}\left(\frac{M}{\frac{4\pi}{3}R^3}\right)^2 R^5 \sim \frac{GM^2}{R}$$

STAR FORMATION: PROTOSTARS

- Cores start out (relatively) low density and transparent. They shine because they are hotter than their surroundings, but are too cool for nuclear fusion.
    - Photons can leak out, keeping the interior cool, allowing collapse to continue. The surface area and luminosity decrease, but the surface temperature remains almost constant.
- Eventually the protostar builds up enough density and it becomes opaque (i.e. photons become trapped). The pressure builds, and hydrostatic equilibrium is reached (but not thermal equilibrium).
    - Changes in the star now keep the luminosity roughly constant, but the surface temperature starts to build up.

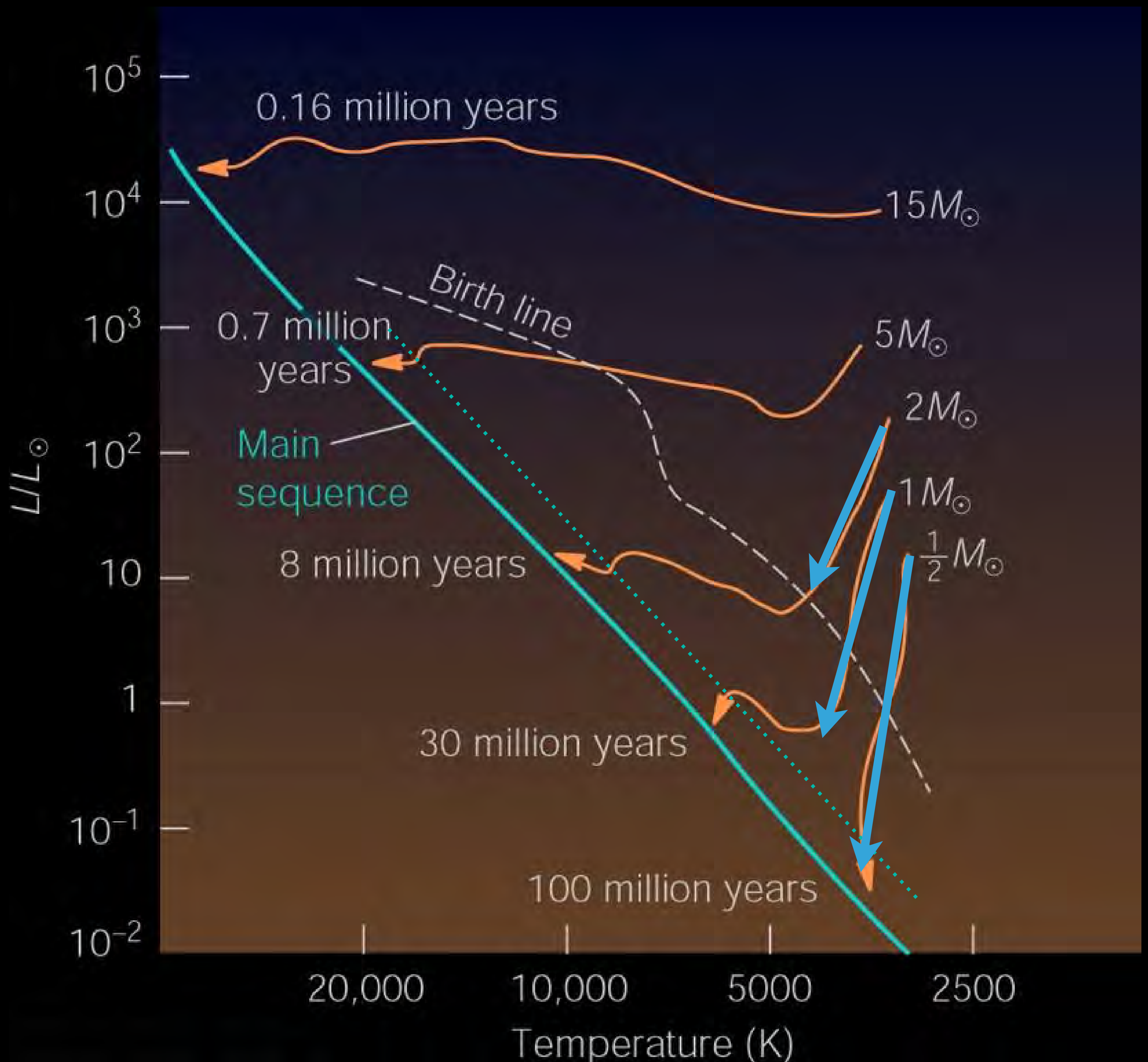
PRE-MAIN-SEQUENCE PHASE



Star emerges from the enshrouding dust cocoon

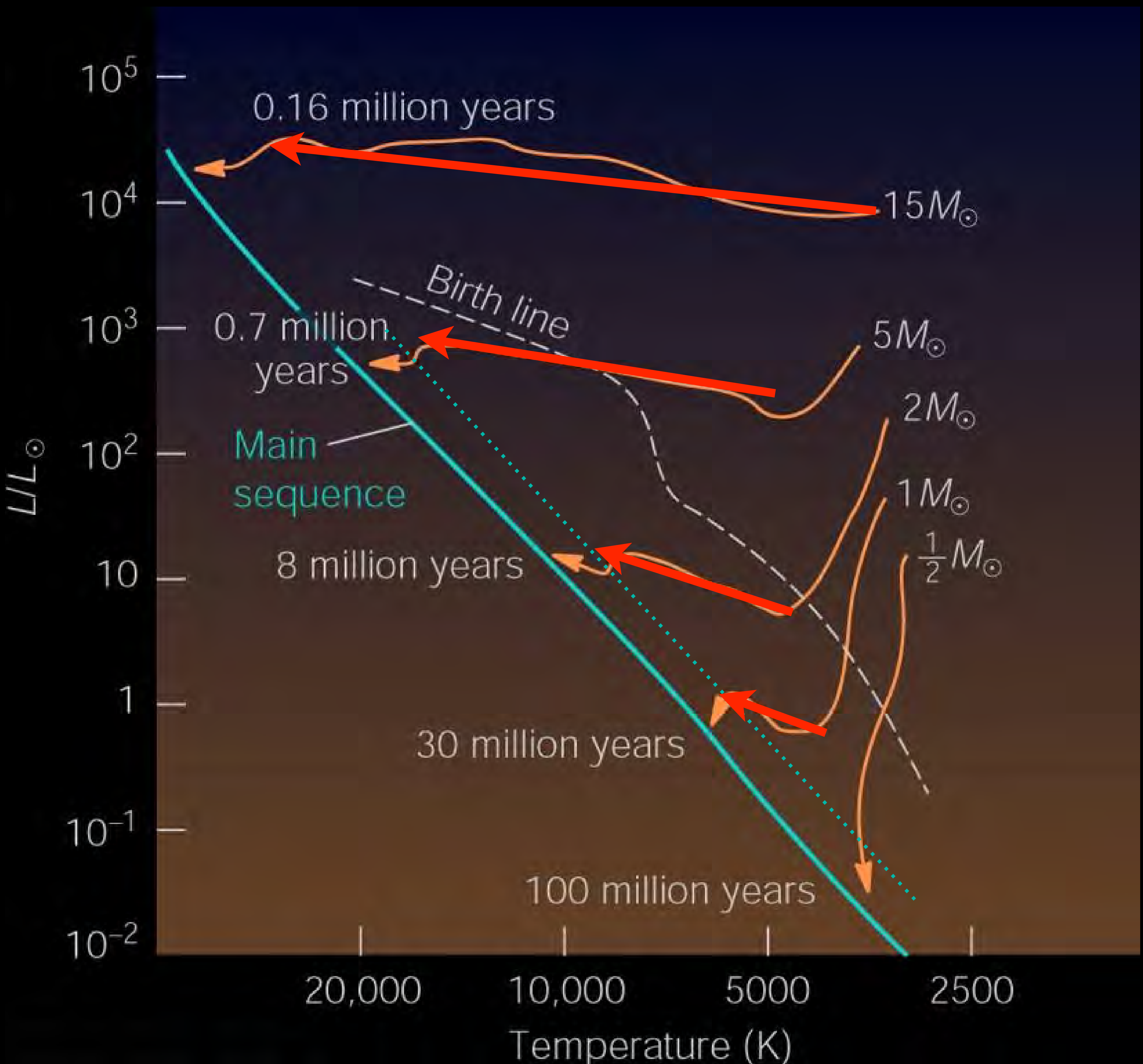
Hydrogen burning begins

HAYASHI TRACKS



- Near vertical track in the pre-main-sequence phase for $M \lesssim 3\ M_\odot$
- Convective interior: energy released by contraction on the interior is convected to the the surface (nearly constant in time)
- The loss of energy at the surface allows the star to further collapse
- Smaller radii with a constant temperature produces smaller luminosities

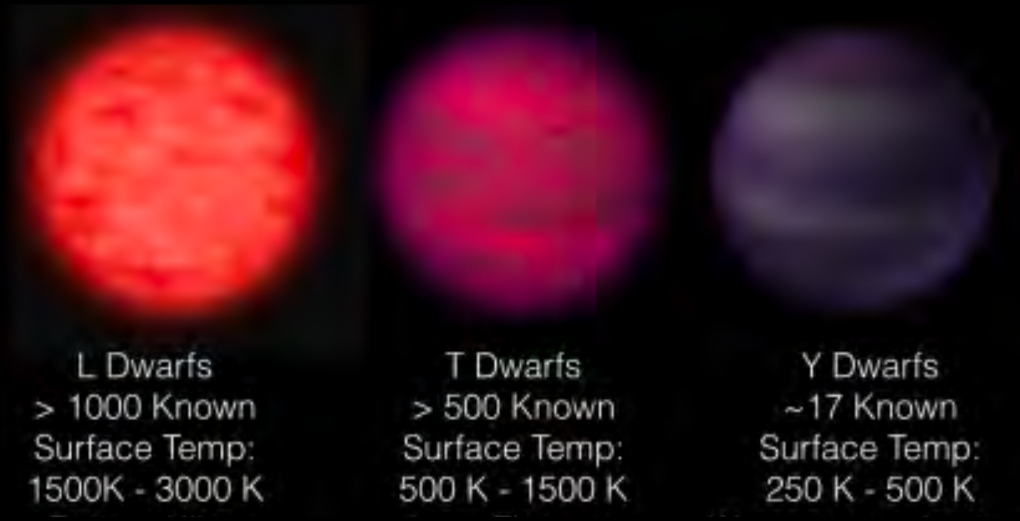
HENYEY TRACKS



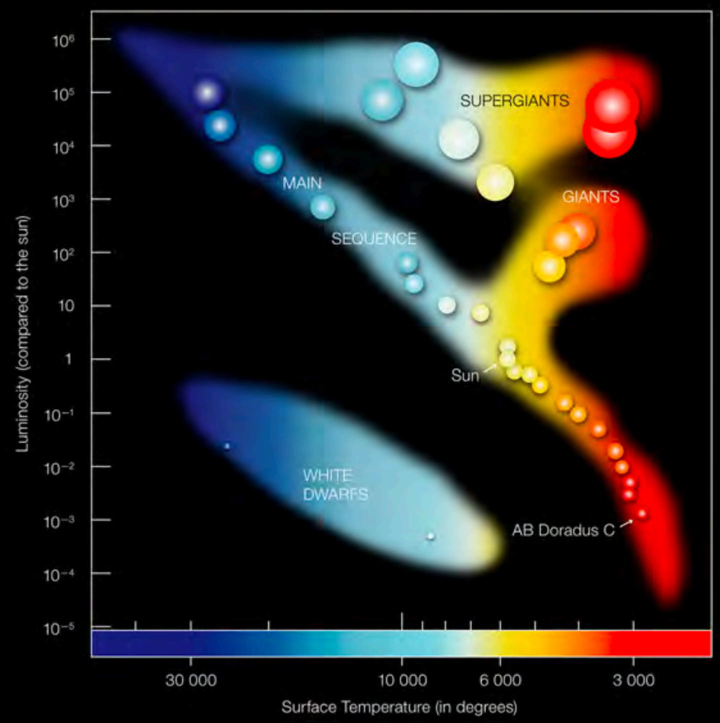
- Near horizontal track in the pre-main-sequence phase for $0.5\ M_\odot \lesssim M \lesssim 10\ M_\odot$
- Radiative interiors: energy loss limited by radiative diffusion (takes time for energy to diffuse out from the interior)
  - Steady increase in surface temperature
- Slow contraction with increasing surface temperature leads to a near constant luminosity with time

THREE POTENTIAL OUTCOMES

1. Brown dwarfs: below $\sim 0.08\ M_{\rm sun}$ the core never gets hot enough to ignite H fusion
   - May fuse deuterium (^{2}H) and lithium (^{7}Li) if mass is > 65 $M_{\rm J}$.



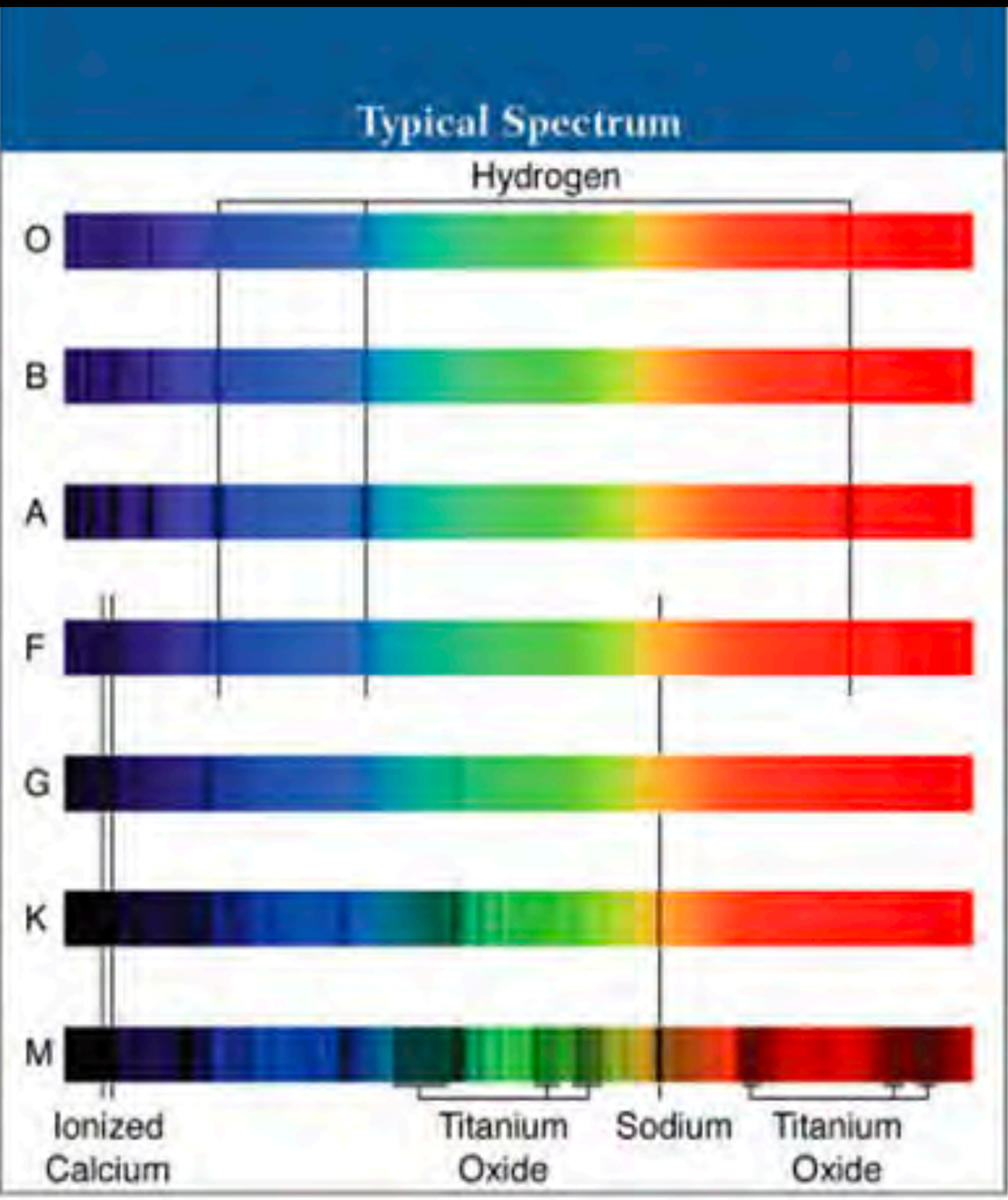
2. Zero-age main sequence (ZAMS): gravitational collapse continues until core reaches ~10 million K
   - Core temperature and pressure rise
   - Pressure = gravity and core collapse halts
   - Energy created by P-P chain fusion = luminosity



3. Eddington limit: luminosity so large that radiation pressure pushes away the gas (via the dust)
   - Difficult to make stars $> 20\ M_\odot$
   - Most massive stars ever observed $\sim 150\text{–}300\ M_\odot$

STELLAR EVOLUTION: MAIN SEQUENCE

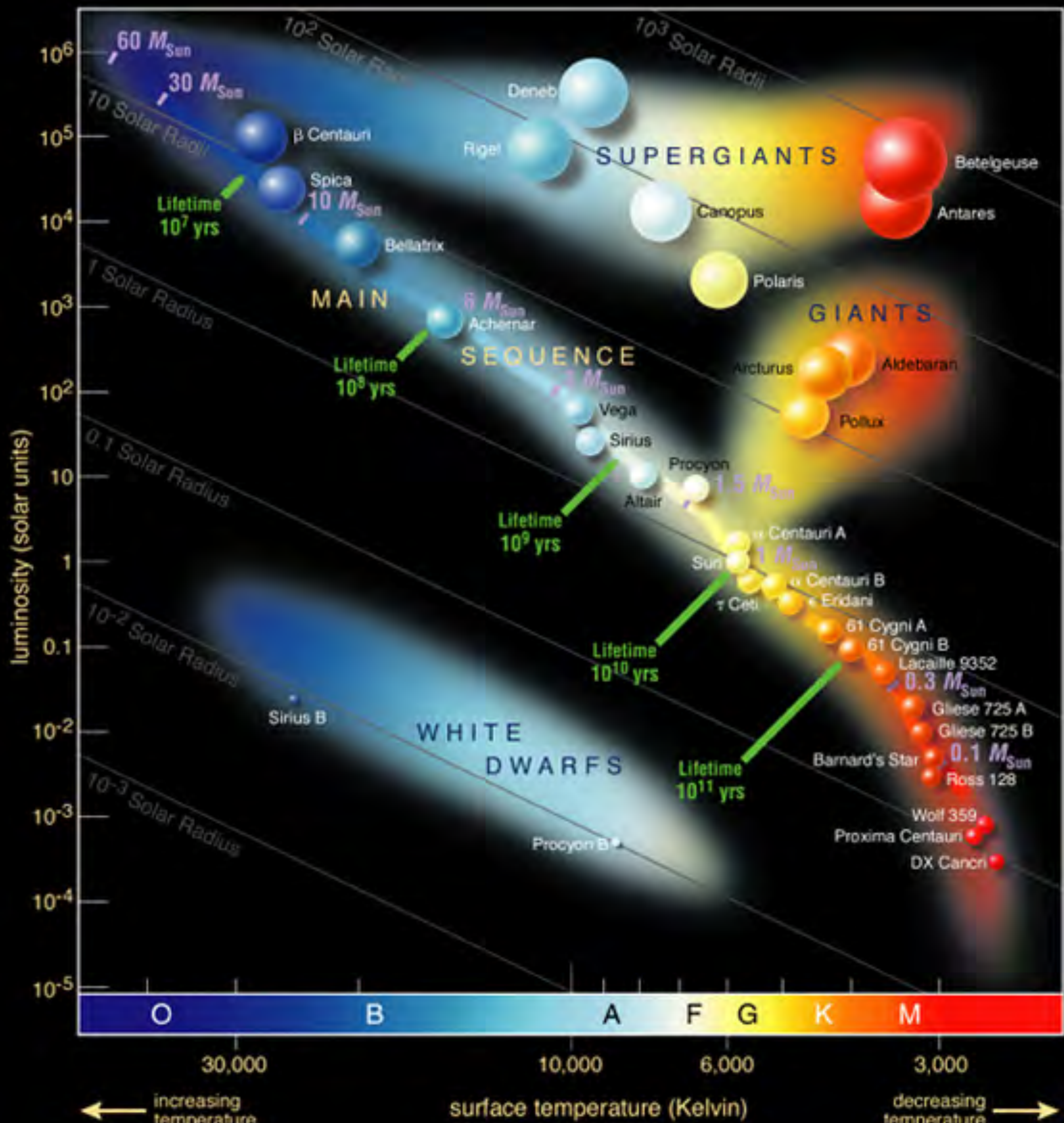
- Stars are classified by their spectra (the elements that they absorb) and their temperature. Seven main types of stars. In order of decreasing temperature, O, B, A, F, G, K, and M.



Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)

* All stars above 6,000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

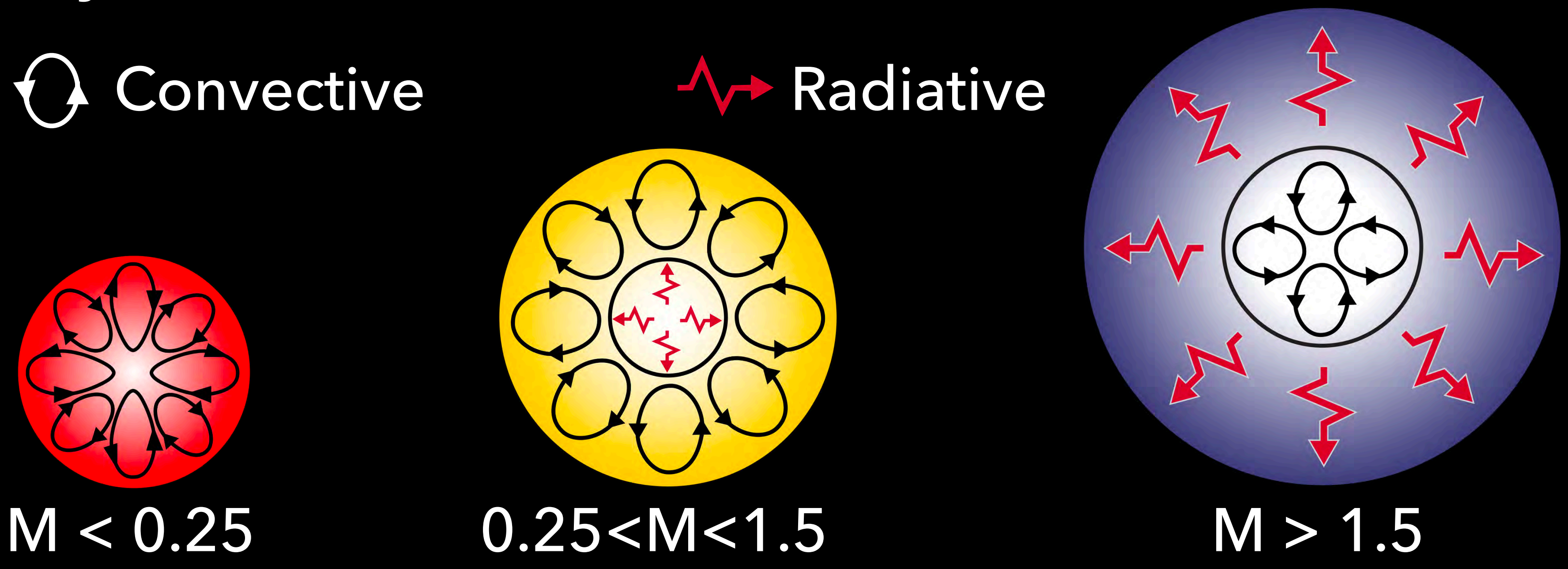
HERTZSPRUNG-RUSSELL DIAGRAM



STELLAR EVOLUTION: LOW-MASS STARS

- About 90% of stars are on the main-sequence (most of those are red dwarfs smaller than sun). Energy comes from nuclear fusion, as they convert H→He.

- The mass of the star determines the internal structure and, ultimately, how the star will die.



- Below $\sim 0.25\ M_{\rm sun}$ convection dominates, the surface temperatures and luminosities gradually increase, and the star quietly transitions into becoming a white dwarf.

STELLAR EVOLUTION: LOW-MASS STARS

- Higher masses develop an inert He core (not hot enough for fusion). The core slowly contracts and heats up, causing intense H burning in a shell surrounding the core.
- Increased radiation pressure causes the surface to expand $10{-}100\times$ its original size and cool down, making it appear more red (hence the name Red Giant Branch or RGB).
- The core also contains free electrons. At some point the Pauli exclusion principle (electrons cannot occupy the same energy level with identical quantum numbers) prevents further gravitational collapse due to electron degeneracy pressure.
- When degeneracy pressure is stronger than thermal pressure, the gas is said to be degenerate and no longer behaves like an ideal gas (pressure no longer depends on temperature).

STELLAR EVOLUTION: LOW-MASS STARS

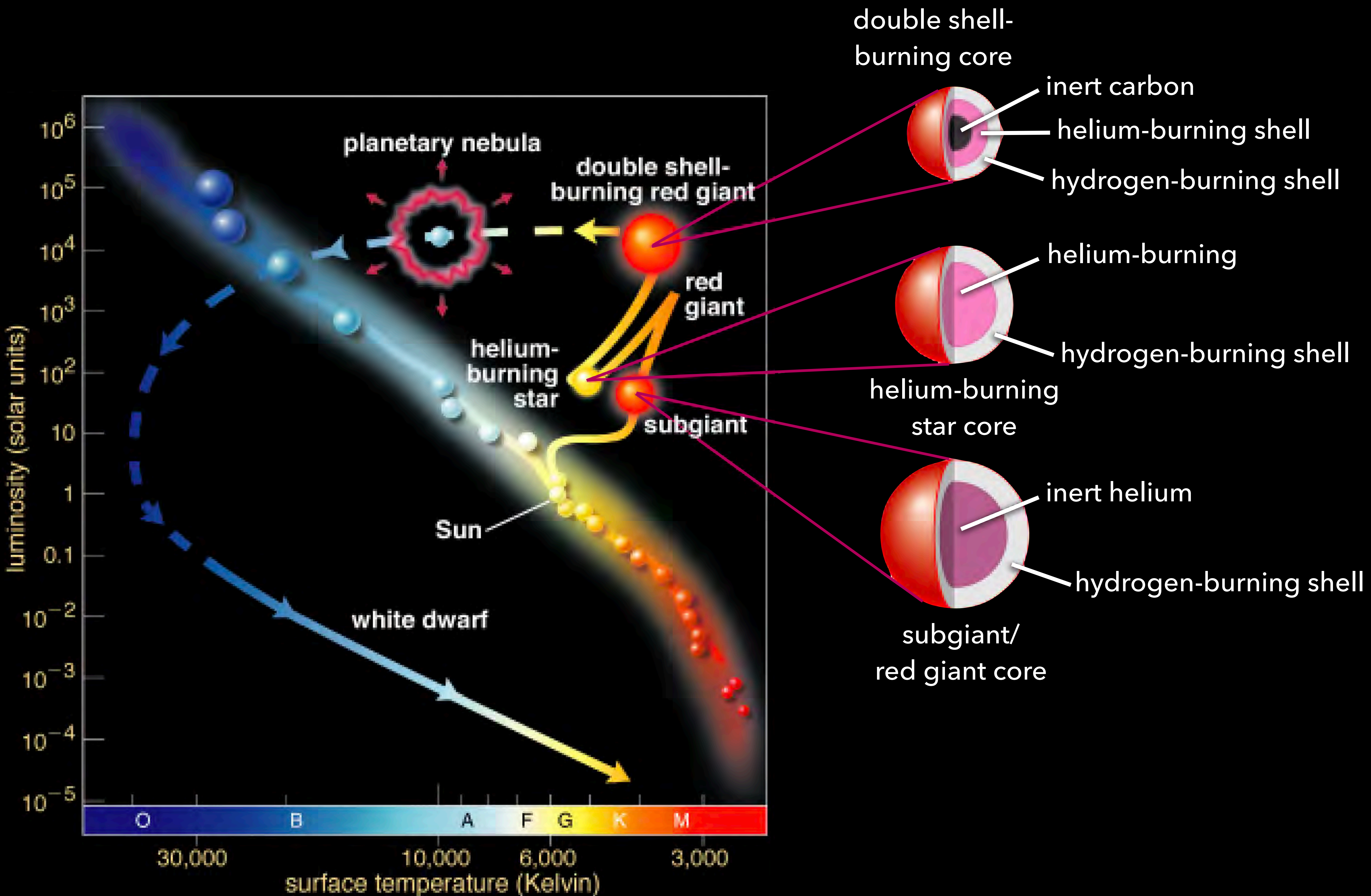
- Nuclear reactions in degenerate cores tend to be explosive because the gas does not expand and cool down when the temperature increases.

- However, nuclear reactions are still very temperature dependent. Runaway burning ensues until the core temperature lifts the degeneracy.

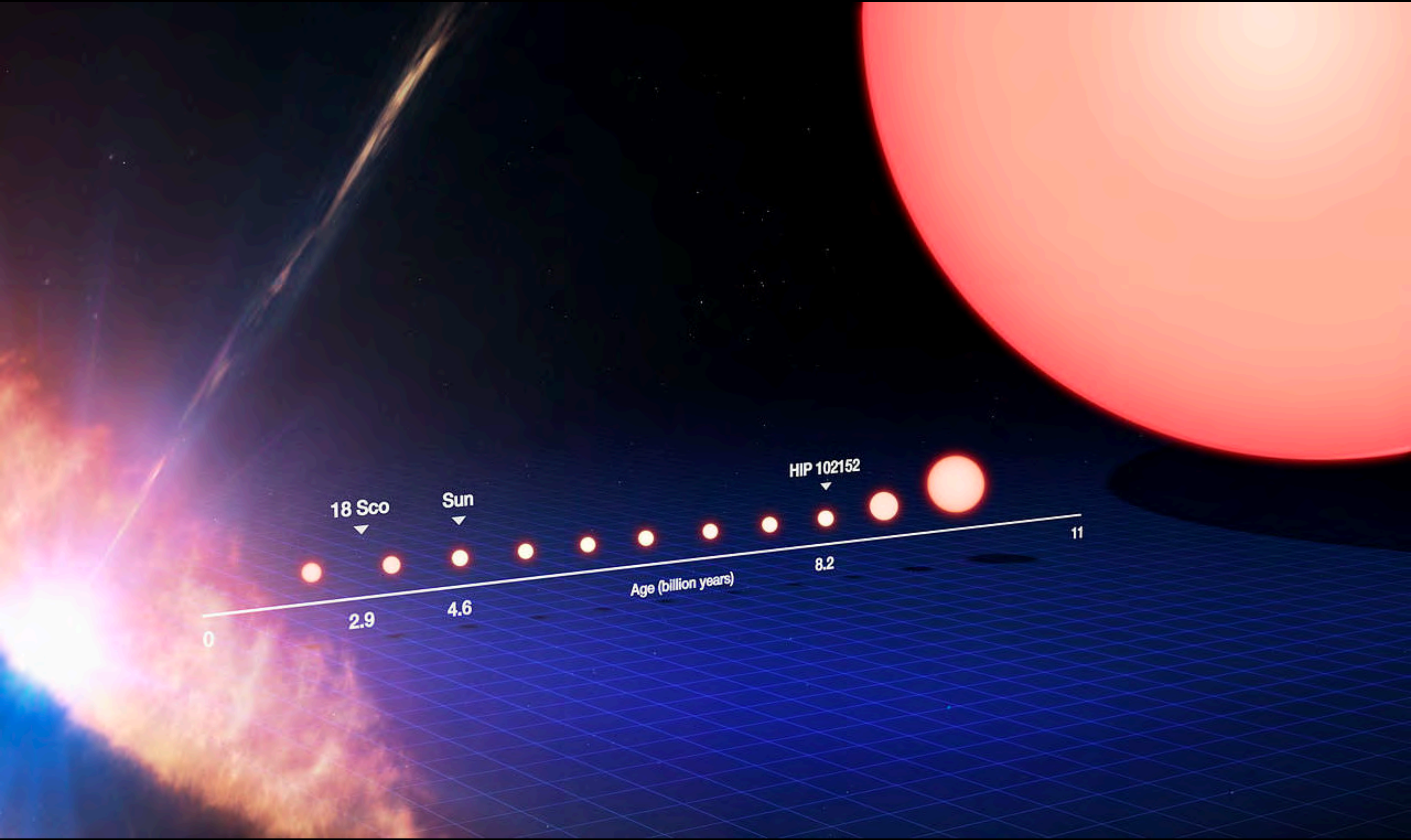
- The ignition of He in low-mass stars is explosive (called a helium core flash). Large amounts of He fuses to C in a matter of seconds. After the flash, the luminosity decreases and the outer layers of the star shrink.

- The process repeats, expanding along the Asymptotic Giant Branch (AGB), but cannot ignite C burning. He shell burns in a series of flashes, shedding its outer layers (planetary nebuae).

STELLAR EVOLUTION: LOW-MASS STARS

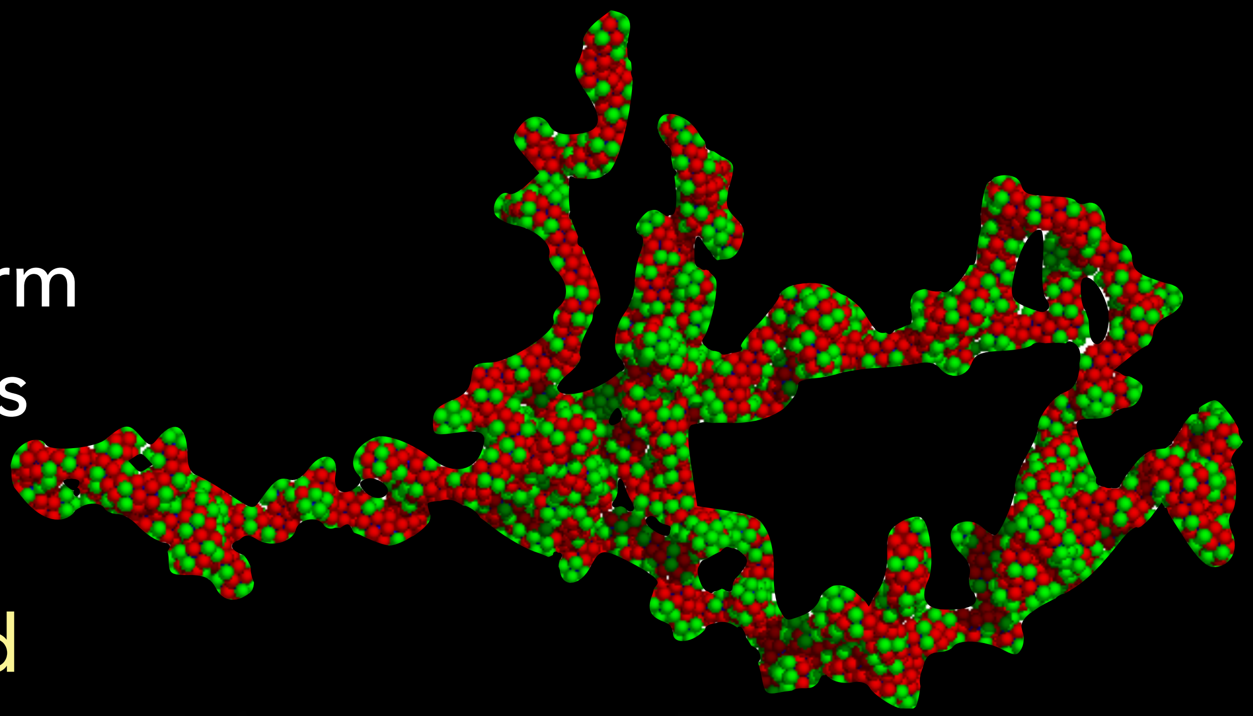


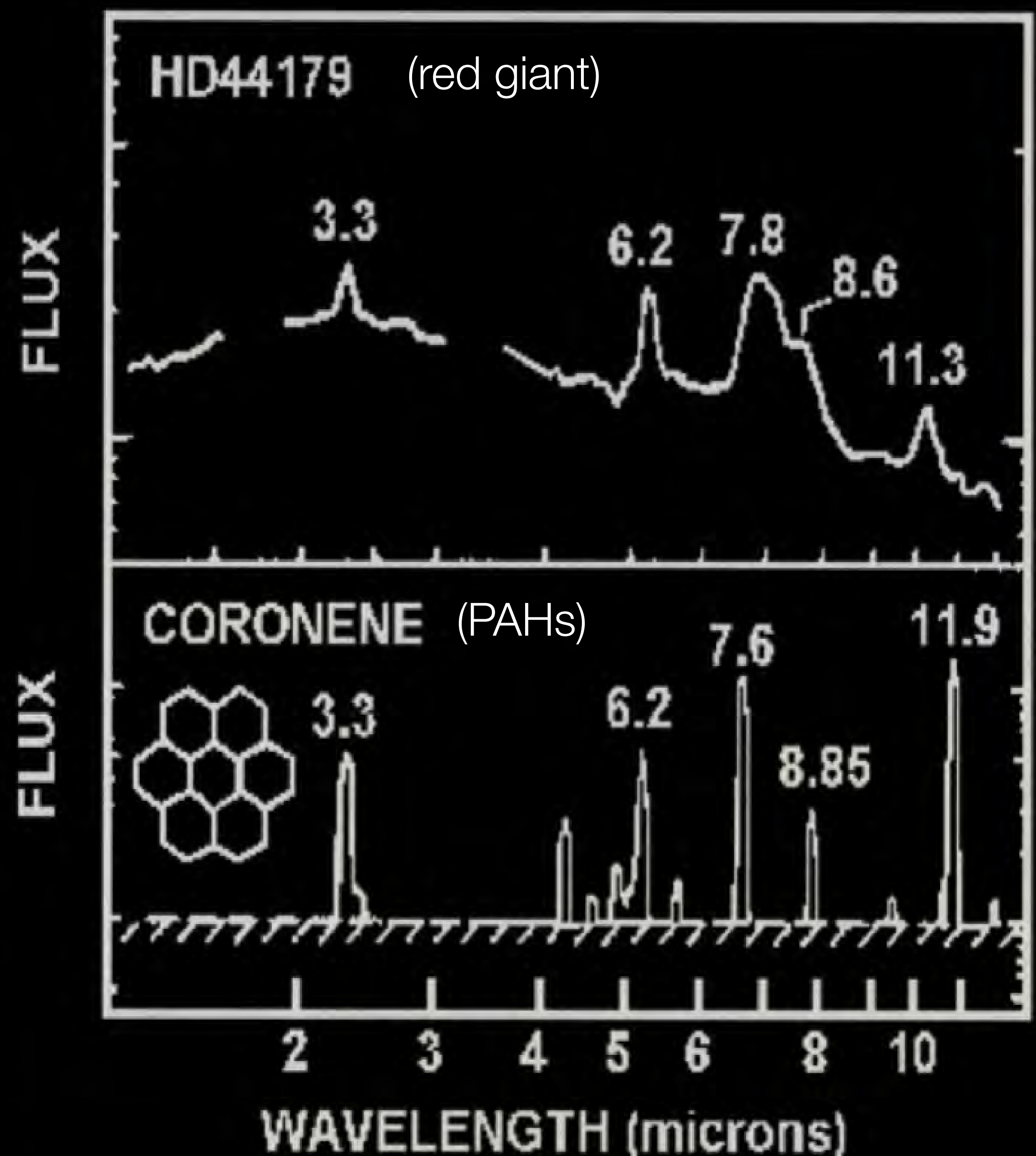
STELLAR EVOLUTION: LOW-MASS STARS



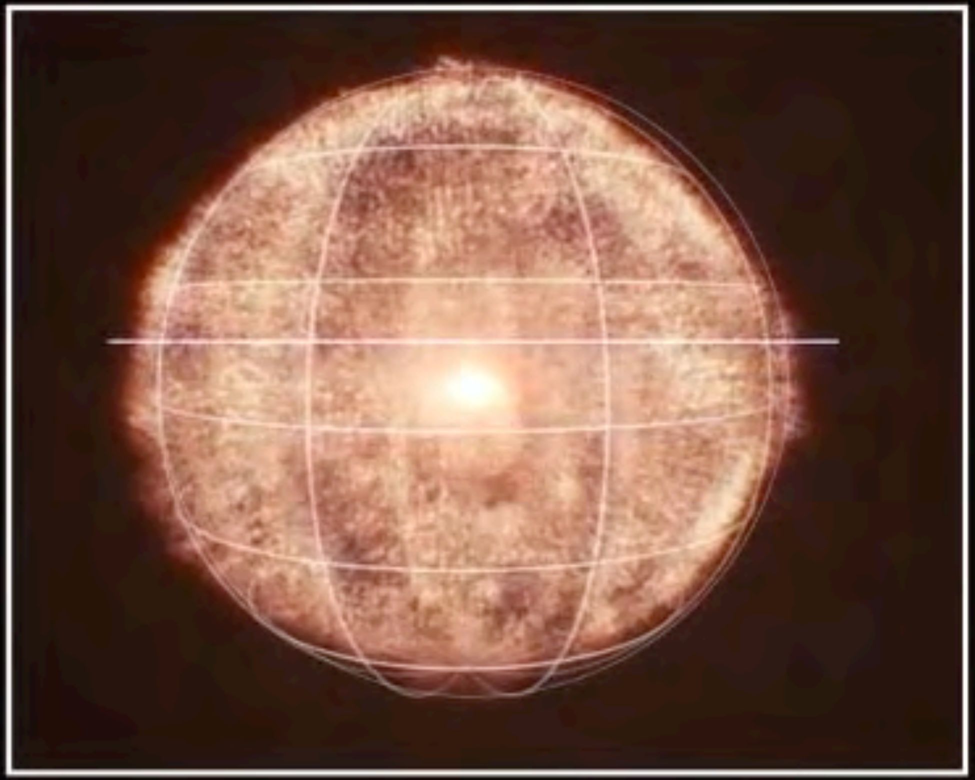
DUST FORMATION

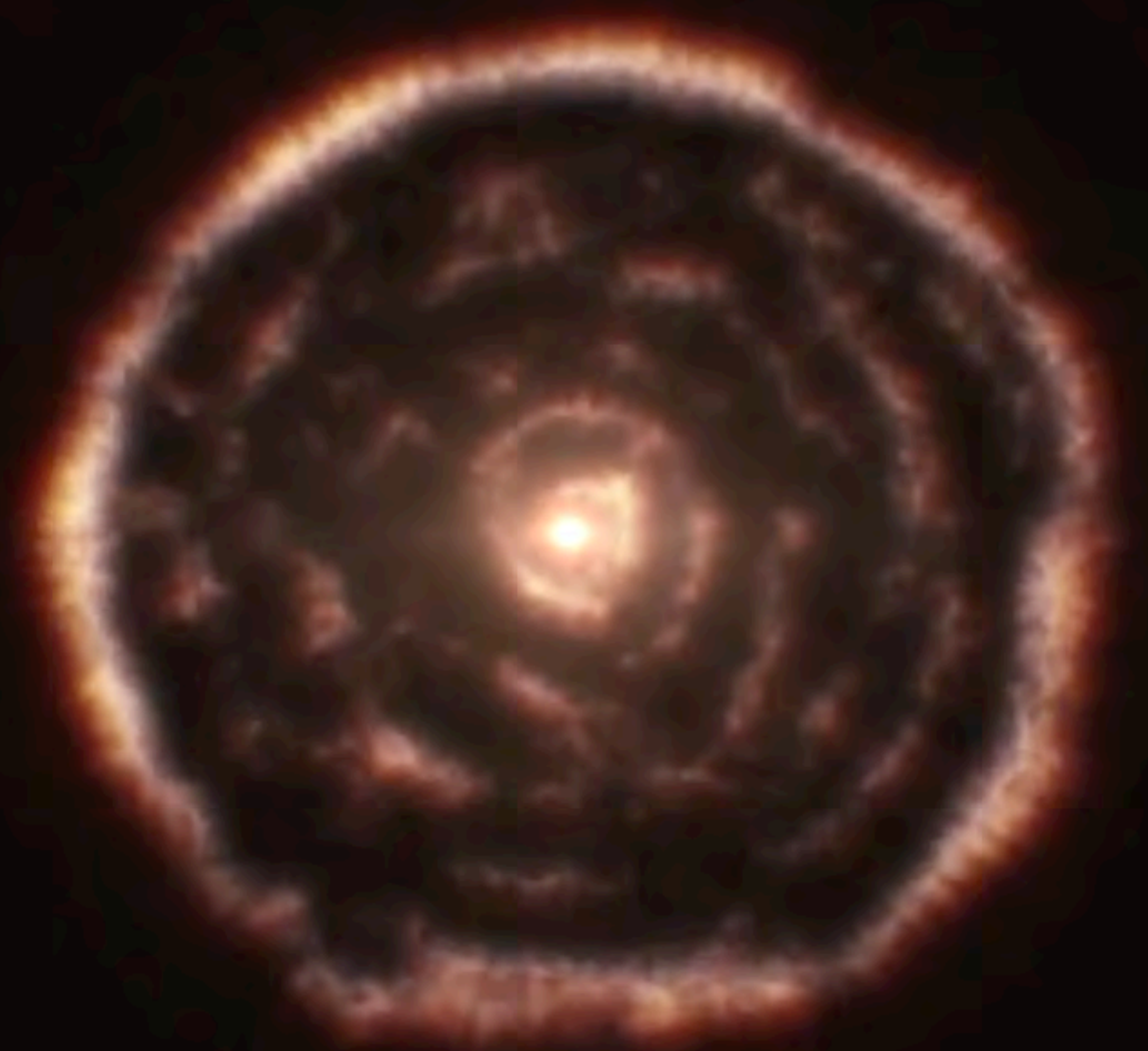
- The ISM is not dense enough to form complex interstellar dust molecules efficiently
- The interior of stars are too hot and destroy complex molecules
- Dust condenses out of stellar outflows:
    - Red giant and AGB stars
    - Wolf-Rayet stars
    - Supernovae
    - Neutron star mergers
- Compare the spectrum of red giant atmospheres to PAHs in the lab





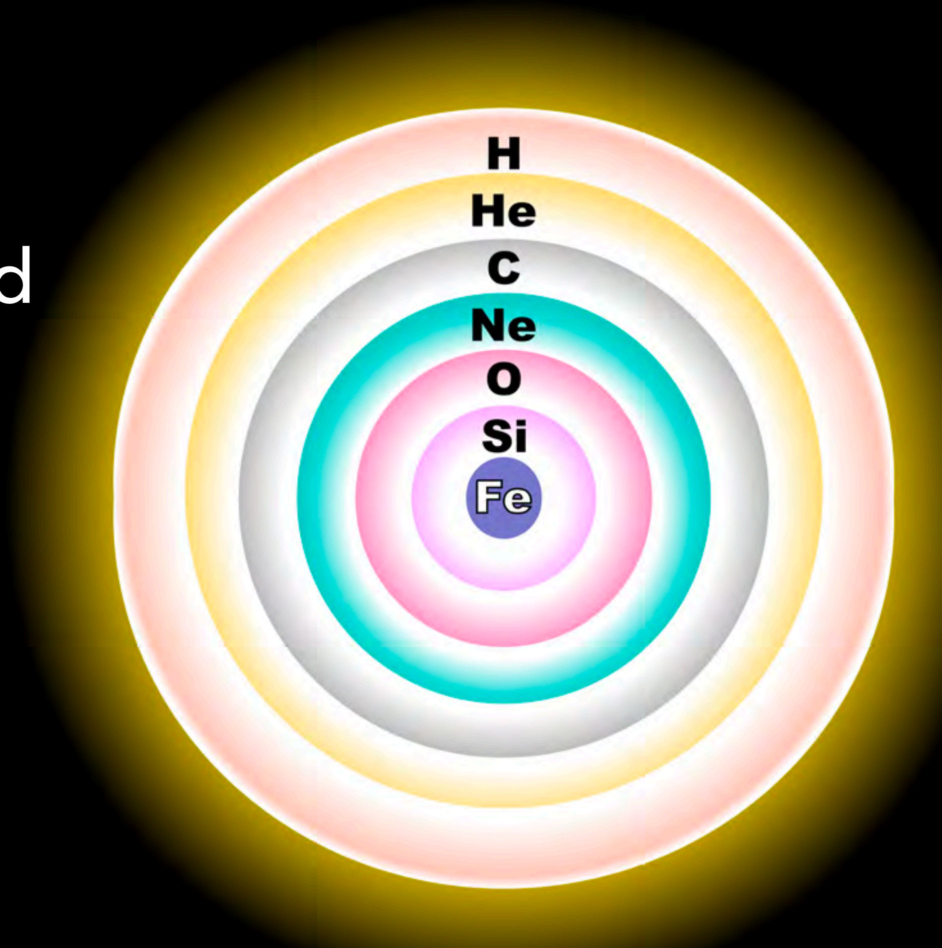
STELLAR EVOLUTION: AGB STARS





R SCULPTORIS

STELLAR EVOLUTION: HIGH-MASS STARS

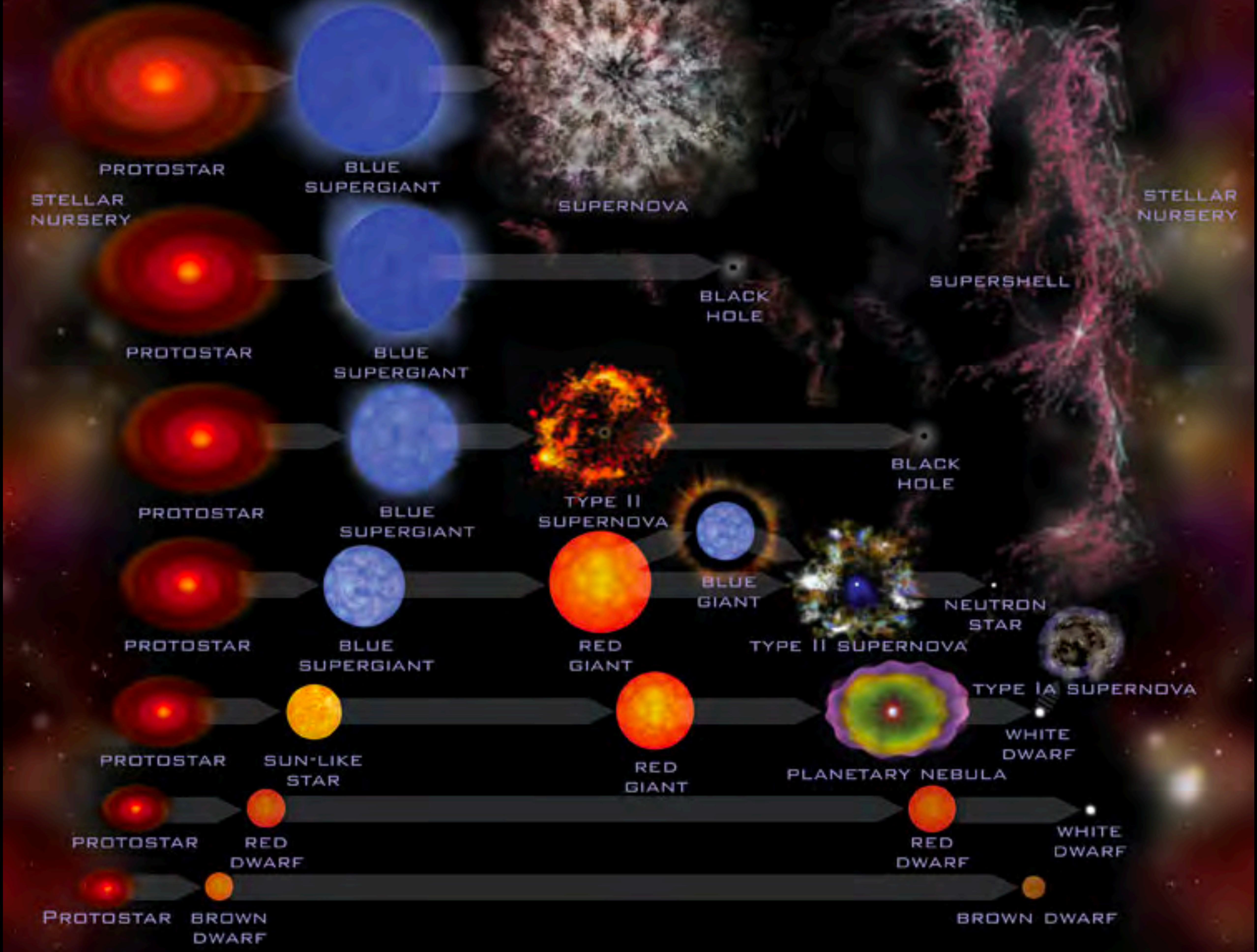


- Massive stars continue nuclear burning beyond C, but the process becomes progressively less efficient until Fe, which requires more energy than it releases
- At this point, the internal structure is made up of concentric layers of different elements
- If the mass of the iron core exceeds the Chandrasekhar limit (maximum mass for an electron-degenerate system; $\sim 1.4\, M_{\rm sun}$), the star collapses, rebounds, and explodes in a core-collapse or Type II supernova. The envelope is ejected with typical speeds of about 10^4 km/s (~0.03c).
- At peak brightness (lasting weeks), their luminosities can compete with the luminosity of their entire host galaxy
- Supernovae are responsible for a large fraction of the ionised gas and heavy elements in the ISM and regulate star formation rates in galaxies

SUPERNOVAE AND PLANETARY NEBULAE




IN SUMMARY . . .



PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

MAIN POINTS

- H and He are by far the most prevalent elements in the Universe (provides the fuel for sustaining life, i.e. stars), but there is still a rich amount of chemistry to consider
- The life cycle of stars is crucial to planet formation
    - Formation: concentrate gas/solids in accretion discs where planets are formed
    - Destruction: produce the building blocks for future planets (eject solids/heavy elements into the ISM)
- Environment is key! Location in the galaxy, what material is available, neighbouring stars, etc. all play an important role in planet formation