



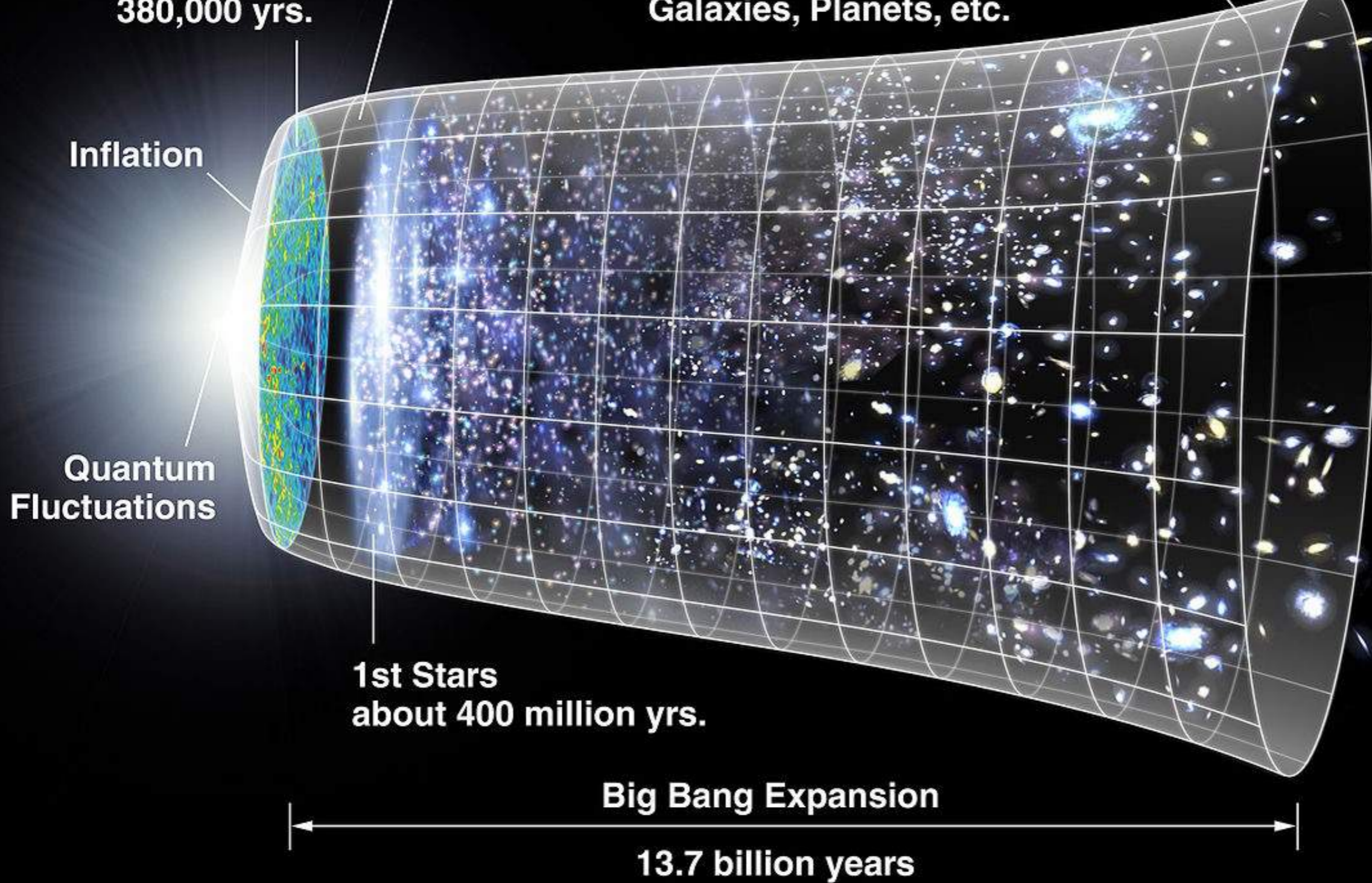
FROM UNIVERSE...

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 . . .

BIG BANG: STEP 1 OF 5

- ▶ No complete physical description of this era yet exists, but models suggest...
- ▶ During the first 10^{-43} s the four fundamental forces are unified (weak, strong, electromagnetic, and gravity).
- ▶ Temperature 10^{32} K.
- ▶ 10^{-43} s defines the time when gravity splits from the other forces.

Quantum
Fluctuations

BIG BANG: STEP 2 OF 5

- ▶ **Inflation** occurs (accelerated expansion of the Universe; lasts between 10^{-36} – 10^{-32} s).
- ▶ Up to 10^{-35} s, quarks and anti-quarks dominate the Universe.
- ▶ The strong force separates from the weak and electromagnetic forces.
- ▶ Temperature drops to 10^{27} K.
- ▶ At 10^{-12} s the four forces become distinct.



Inflation

**Quantum
Fluctuations**

BIG BANG: STEP 3 OF 5

- ▶ At 0.01 s, electrons and positrons form as the temperature drops to 10^{11} K.
- ▶ After 1 s, the Universe becomes transparent to neutrinos, which from now on hardly interact further with matter.

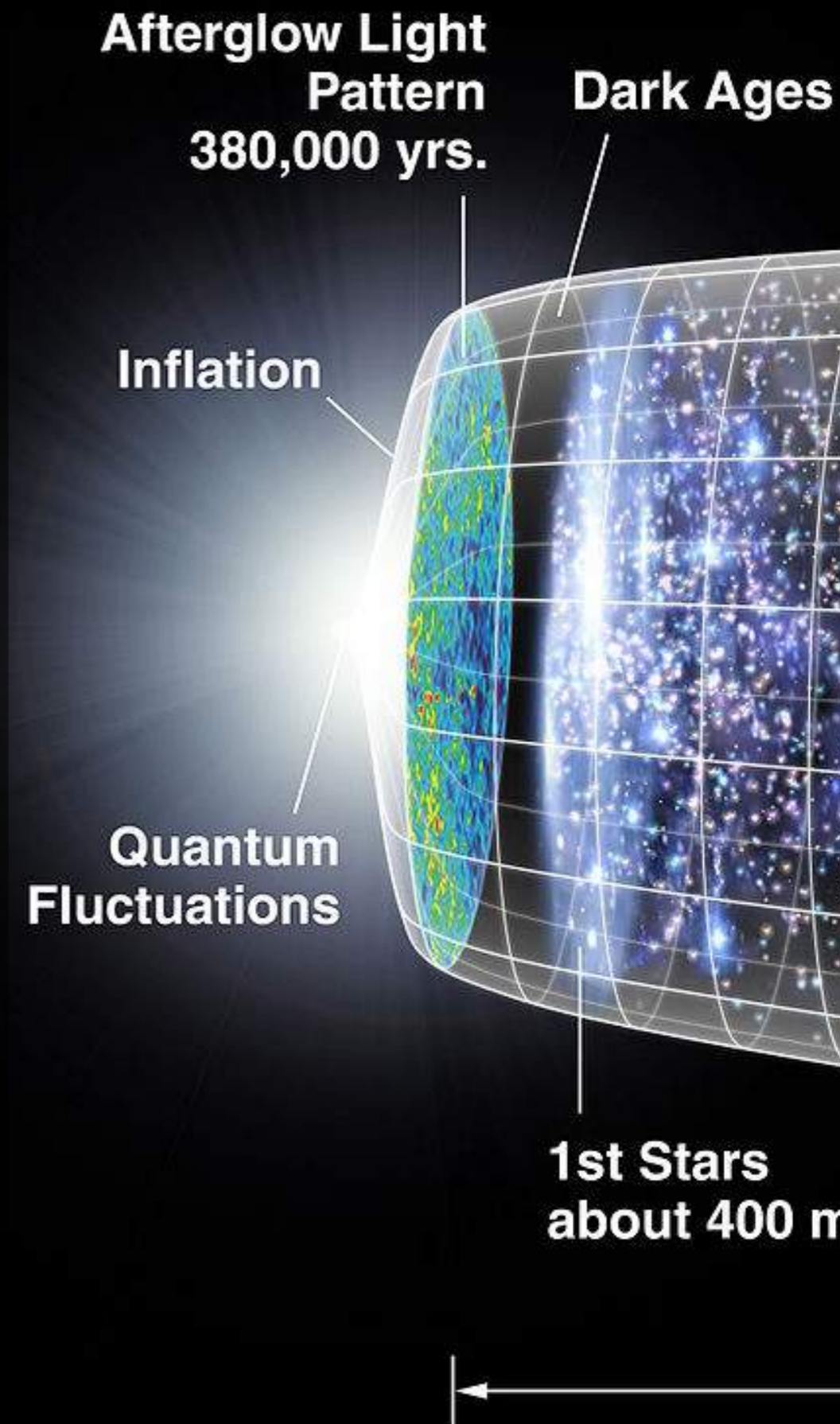
Inflation



**Quantum
Fluctuations**

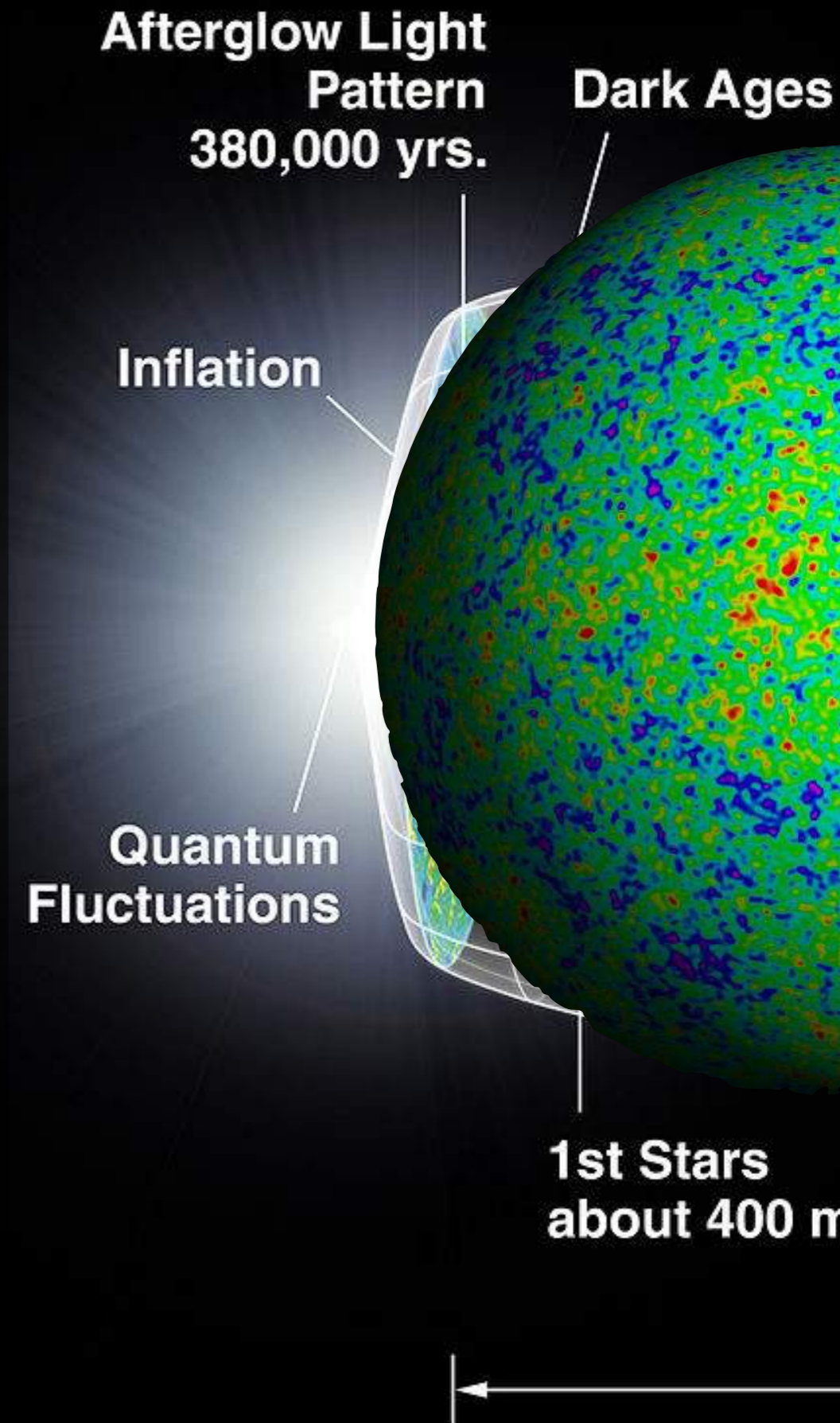
BIG BANG: STEP 4 OF 5

- ▶ At 3 minutes after the big bang, the temperature has reached 10^9 K, protons and neutrons start combining to form what will become the nuclei of elements.
- ▶ By 300 000 yrs, baryonic matter ("visible" matter) in the Universe consisted of about **75% H** and **25% He** (by mass).
- ▶ Trace amounts of heavy elements (starting from Li).



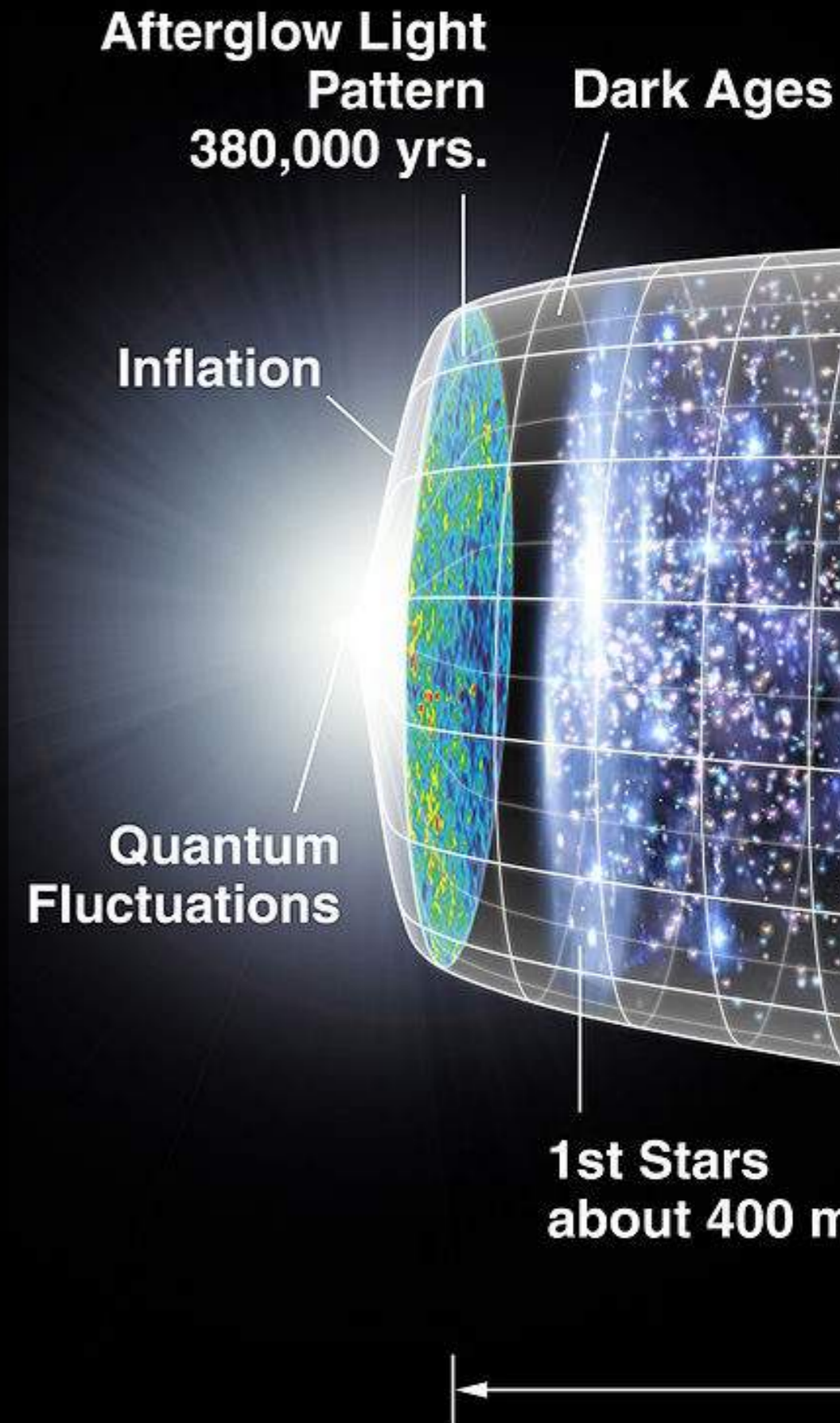
BIG BANG: STEP 4 OF 5 (CONTINUED)

- ▶ By 380 000 yrs the temperature has dropped below 3000 K and the electrons are captured by nuclei to form neutral atoms (**Epoch of Recombination**).
- ▶ Cosmic Microwave Background (**CMB**), the oldest electromagnetic radiation in the Universe.
- ▶ Isotropic with a black body temperature of 2.72548 ± 0.00057 K.



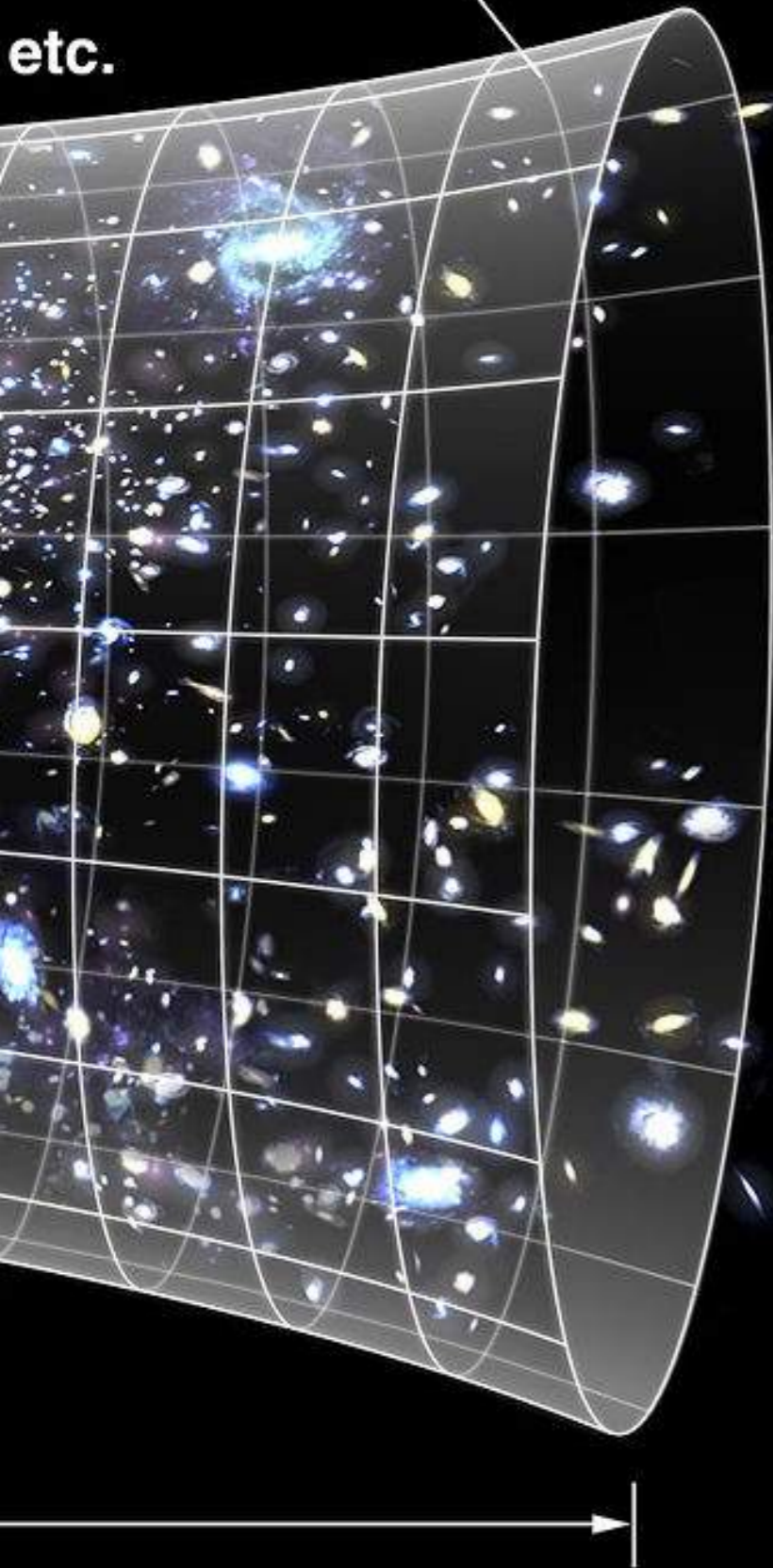
BIG BANG: STEP 4 OF 5 (CONTINUED)

- ▶ The Universe becomes transparent (no more free electrons to interact with photons; **Dark Ages**).
- ▶ Tiny variations in temperature produce over-densities in mass which eventually collapse due to gravity.
- ▶ The first stars form after ~400 million yrs and begin to heat up and ionise the surrounding gas (**Epoch of Reionisation**).



**Dark Energy
Accelerated Expansion**

etc.



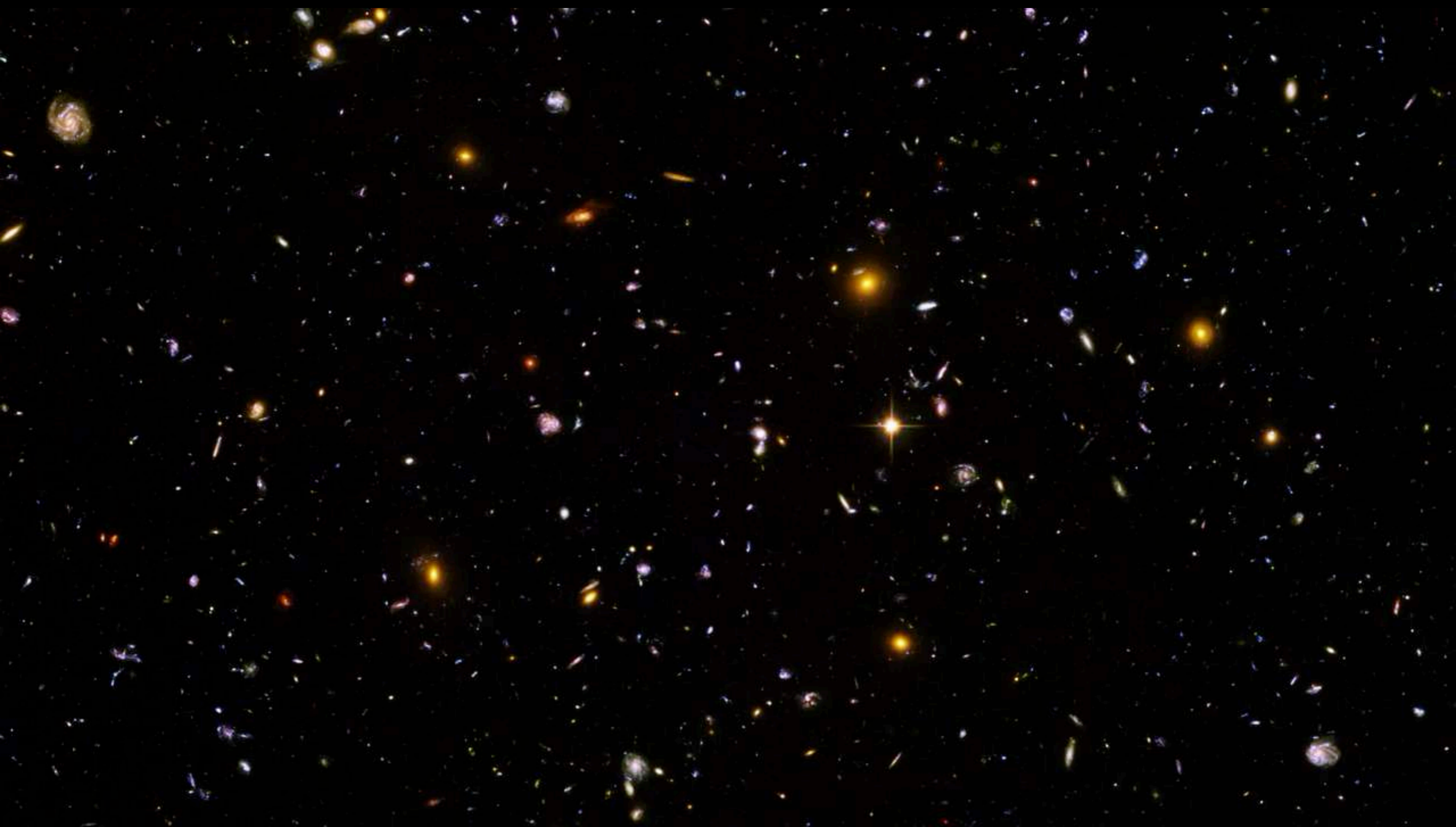
BIG BANG: STEP 5 OF 5

- ▶ After 1 billion yrs, the temperature is 20 K and galaxies and stars have begun to form in dark matter halos.
- ▶ Halos merge to form clusters and super clusters.
- ▶ At a few billion yrs our galaxy forms. At about 9 billion yrs after the Big Bang the Sun and Earth form.
- ▶ After ~13.8 billion yr we reach the present and a background temperature of ~3 K.

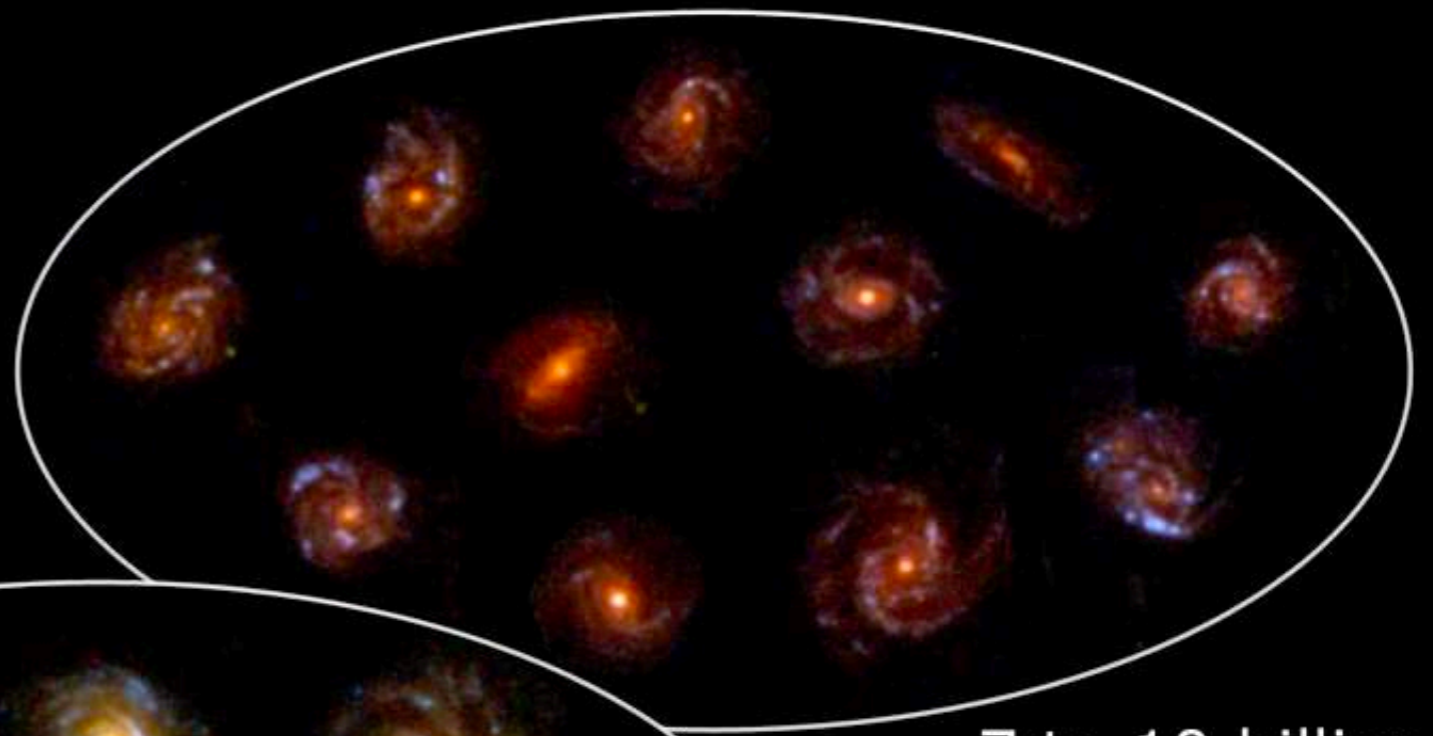
DARK MATTER SIMULATION



HUBBLE ULTRA DEEP FIELD



Evolution of Spiral Galaxies



7 to 10 billion
years ago



3 to 7 billion
years ago

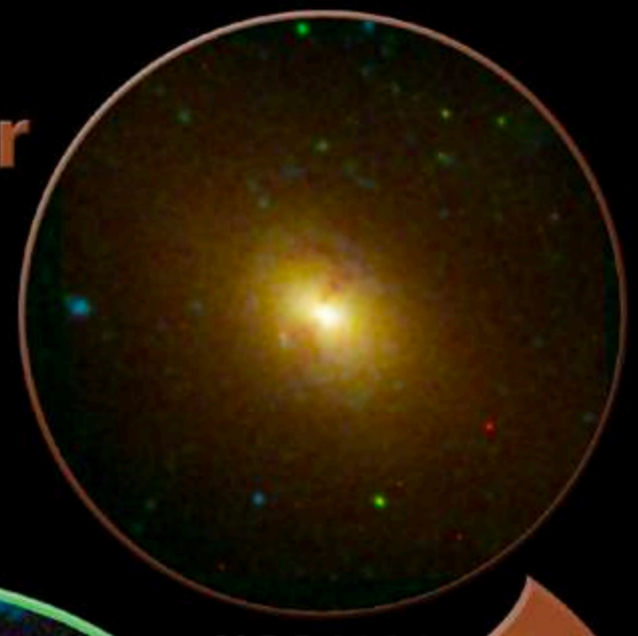


Present to
3 billion years ago



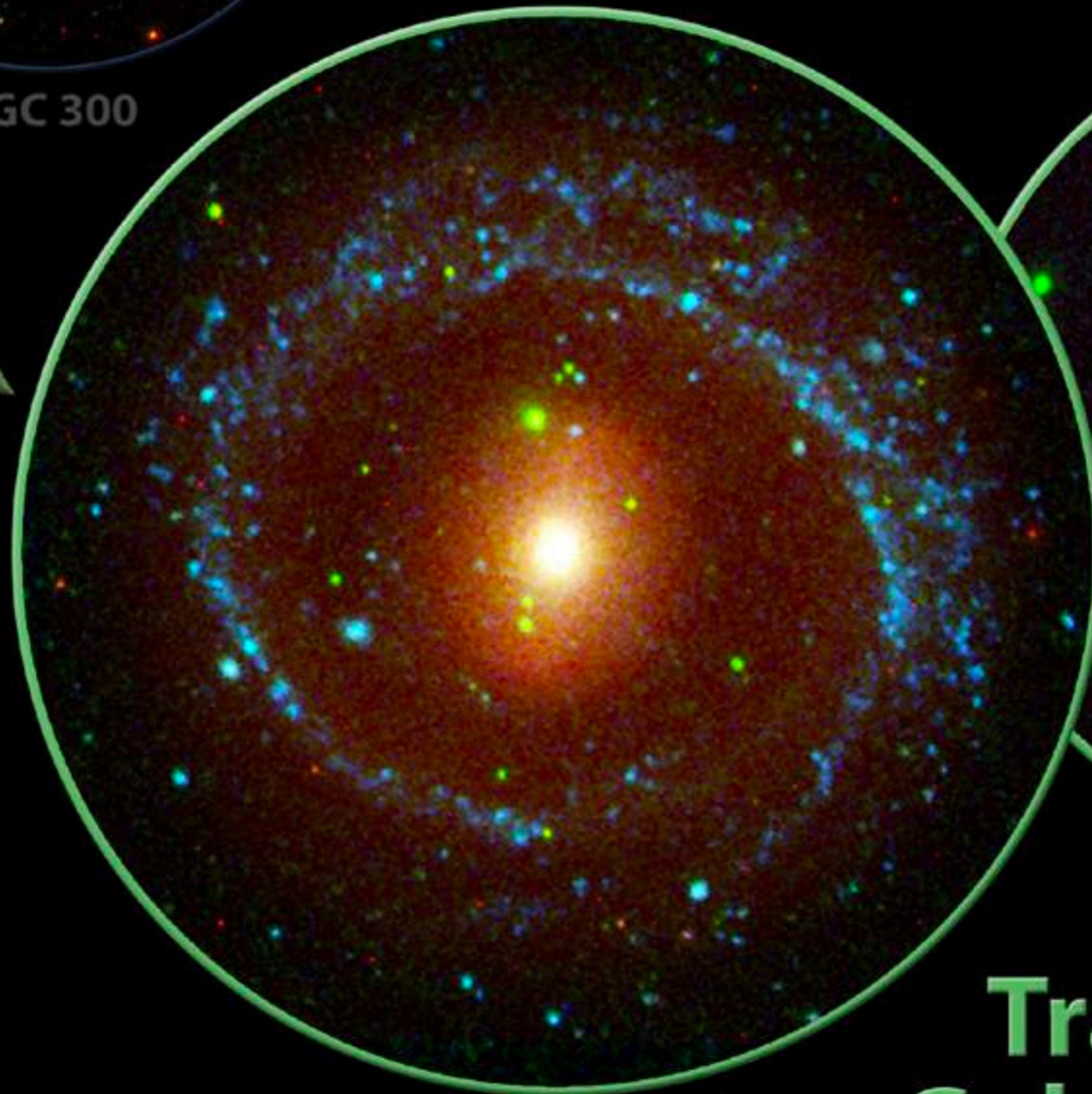
**Younger
Galaxies**

NGC 300

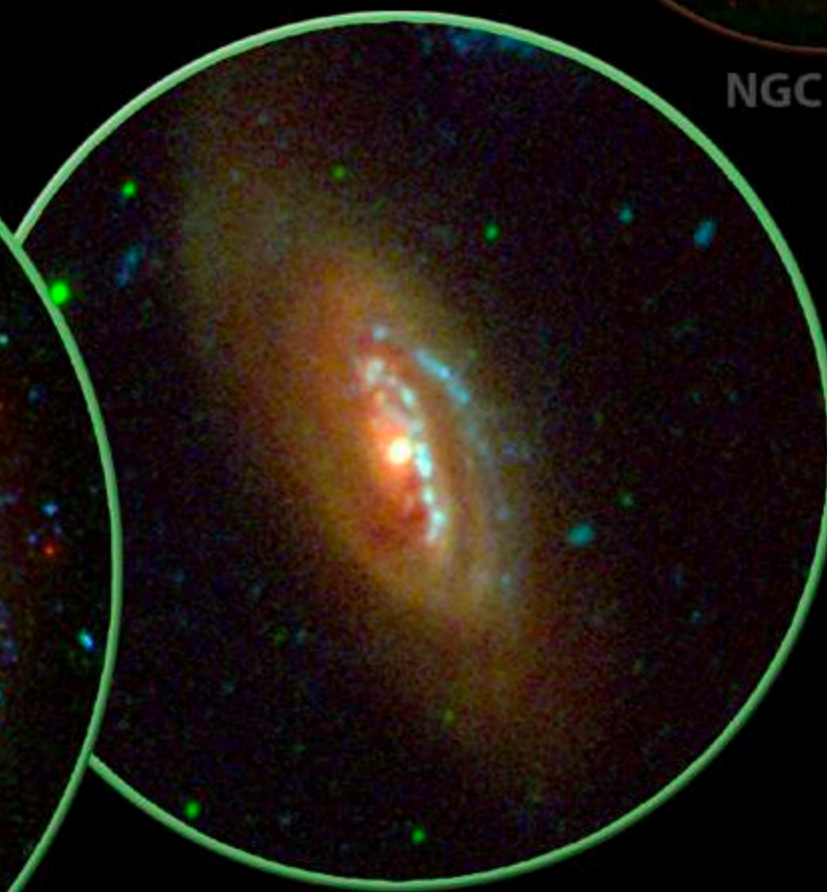


**Older
Galaxies**

NGC 1316



NGC 1291



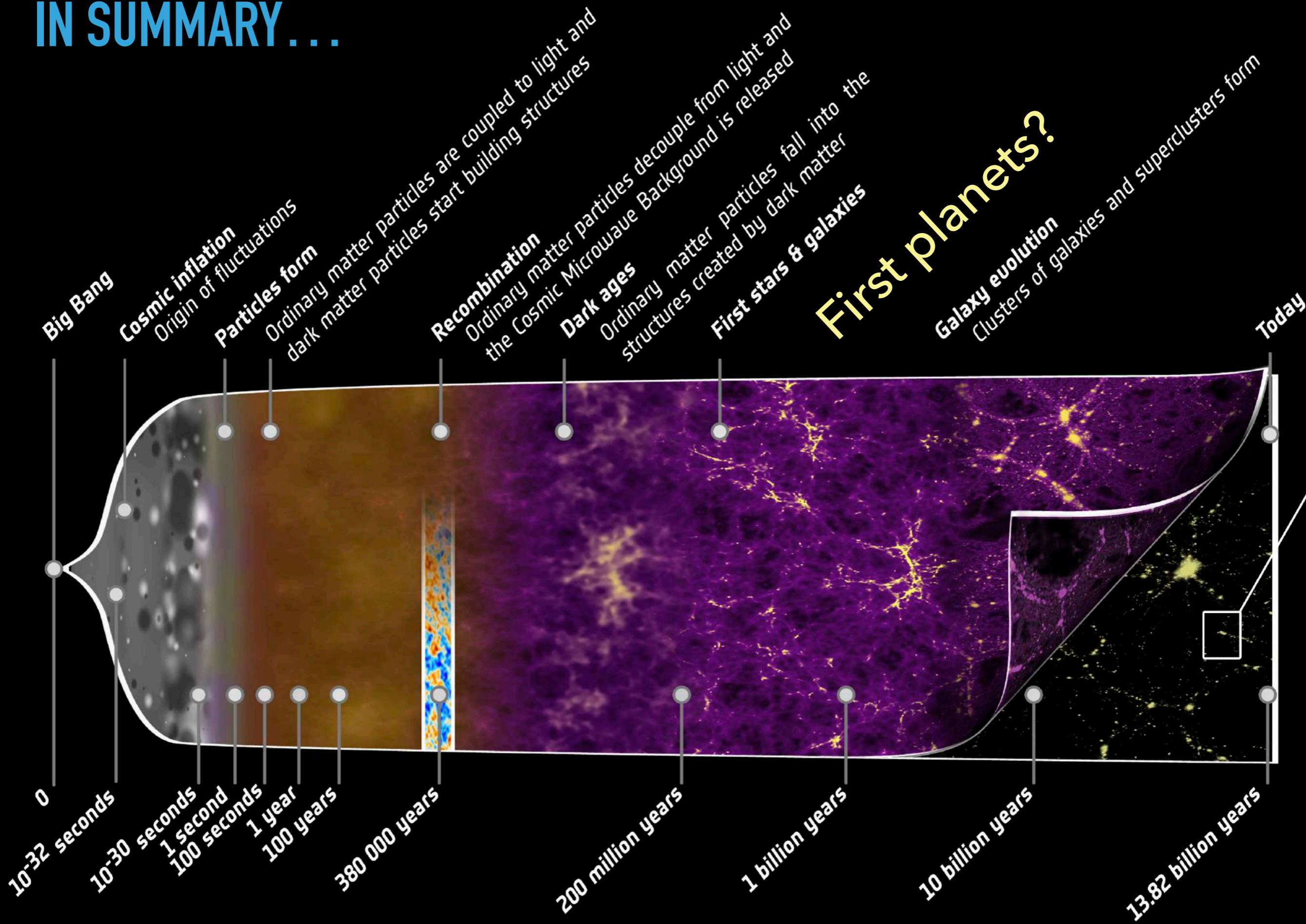
M90/NGC 4569

**Transitional
Galaxies**

Transitional Galaxy Populations

GALEX Galaxy Evolution Explorer **NUV**
FUV

IN SUMMARY...

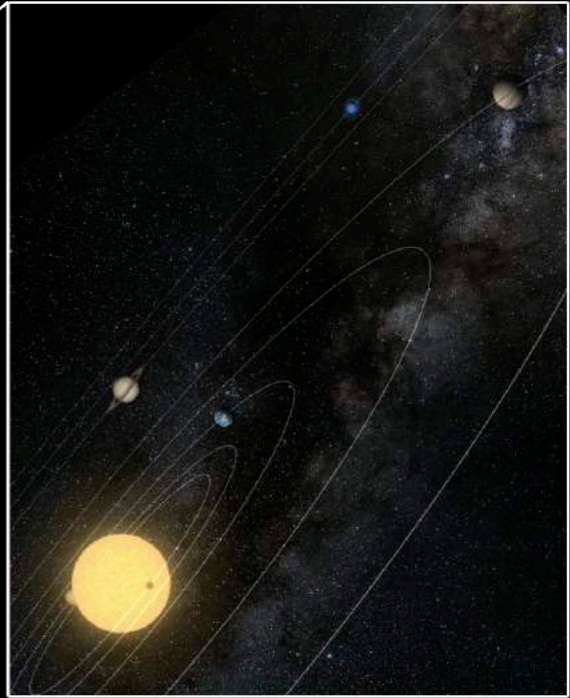
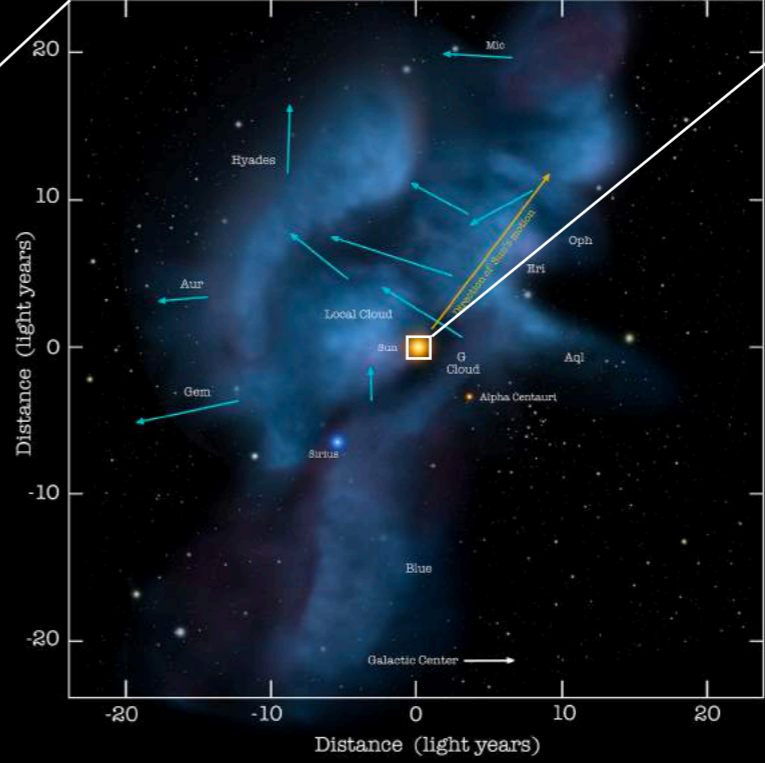
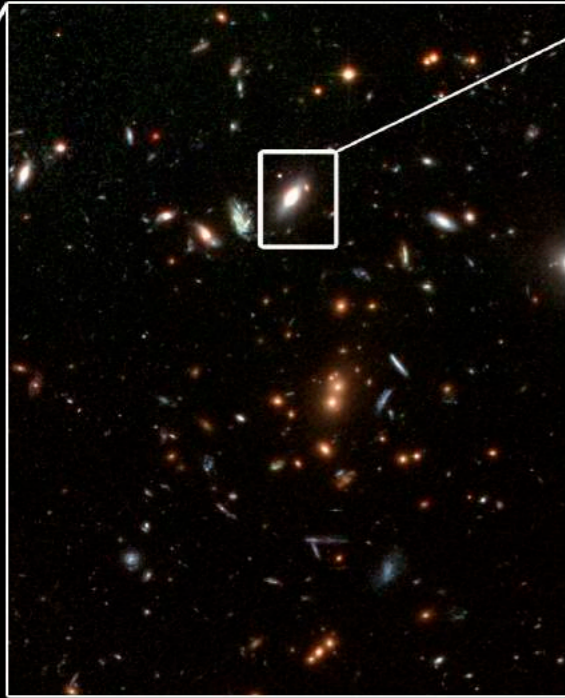


Clusters of galaxies

Galaxy

Local Neighbourhood

Solar System



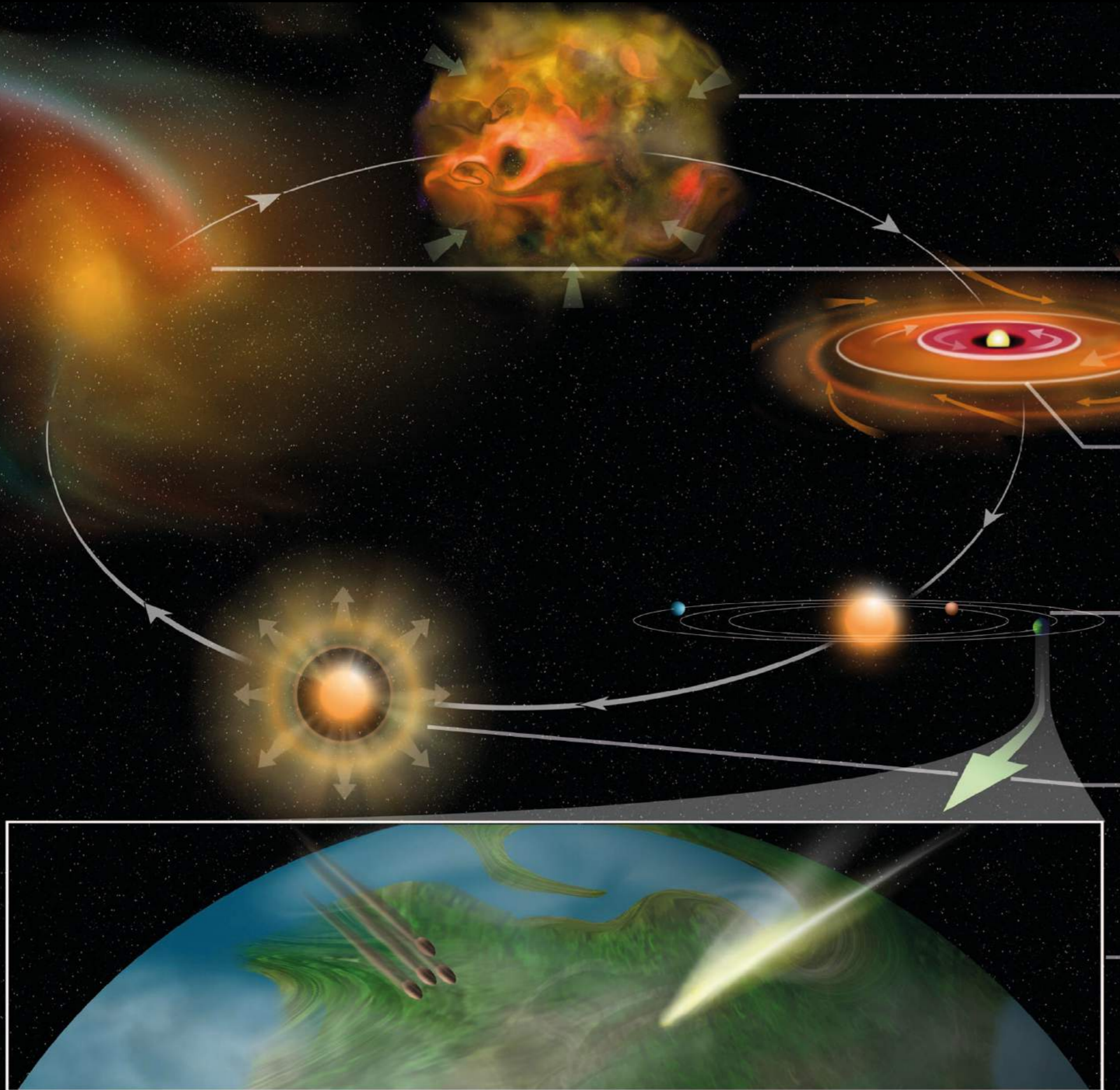


**THE INTERSTELLAR MEDIUM
AND GIANT MOLECULAR CLOUDS**

STELLAR NURSERIES

LECTURE 1.2

LIFE CYCLE



Dichte Wolke
Dense cloud

Diffuse Wolke
Diffuse cloud

Akkretionsscheibe
Accretion disc

Sonnensystem
Planetary system

Massenverlust
Mass loss

Zoom zum Planeten
Zoom to planet

INTERSTELLAR MEDIUM (ISM)



INTERSTELLAR MEDIUM (ISM)



INTERSTELLAR MEDIUM (ISM)

- ▶ The matter and radiation that exists in the space between the star systems in a galaxy. This matter includes gas in ionic, atomic, and molecular form, as well as dust and cosmic rays (highly energetic protons and atomic nuclei).
 - ▶ In cool, dense regions of the ISM, matter is primarily in molecular form with number densities of 10^6 cm^{-3} .
 - ▶ In hot, diffuse regions of the ISM, matter is primarily ionised, with number densities as low as 10^{-4} cm^{-3} .
- ▶ Gas is predominately in an ionised state (which is why we can see it).

INTERSTELLAR MEDIUM (ISM): GAS

- ▶ Gas is primarily composed of **H** (90% by number), followed by **He** (8%). All other elements are called "metals" (obviously not a metal in a chemical sense).
- ▶ Next most abundant elements are **C**, **O**, and **N** (respectively, 2.7, 4.9, 0.7×10^{-4} in relation to H).
- ▶ Nearly 200 different molecules have been detected over the past 45 years (not counting isotopologs).
 - ▶ From simple molecules (CO, H₂O and NH₃) to relatively complex (CH₃OCH₃ and C₃H₇CN); even unusual ion species (HCO⁺, N₂H⁺) and long carbon chains (HC₇N).

INTERSTELLAR MEDIUM (ISM): GAS

- ▶ Low densities → chemistry is *not* in **thermodynamic equilibrium**.
Two basic processes by which molecular bonds can be formed:
 - ▶ **Radiative association** of atoms or molecules, in which the binding energy of the new molecule is carried away through the emission of photons (three-body processes probably not important at low densities).
 - ▶ Formation of molecules on the **surfaces of dust grains** (the dust accommodates the released energy). The surface provides a reservoir where atoms/molecules can be stored and brought together on longer timescales than in the gas. They enable reactions that are too slow in the gas, such as the hydrogenation of atomic O, C and N to form H₂O, CH₄ and NH₃ (but dust is not catalytic in a chemical sense).

INTERSTELLAR MEDIUM (ISM): GAS

- ▶ Molecular bonds can be **photodissociated** by intense UV radiation or broken up by **dissociative recombination** (reaction with electrons).
- ▶ Reactions between ions and molecules are particularly fast at low temperatures (even at 10 K). Ions are created via:
 - ▶ **Photoionisation** of atoms like C, S and Fe by the ambient UV radiation at the edges of clouds
 - ▶ Cosmic rays can penetrate deep inside clouds and also ionise H, H₂, He, O and N, whose ionisation potentials are above 13.6 eV, the threshold where the interstellar UV radiation cuts off. H₂⁺ reacts quickly with H₂ to form H₃⁺, a cornerstone molecule which kick-starts the chemistry.

INTERSTELLAR MEDIUM (ISM): WATER EXAMPLE

- ▶ Low temperatures and densities: gas-phase ion-molecule reaction route, initiated by cosmic rays, dominates and produces a low fractional abundance of water (around 10^{-7} with respect to H).
- ▶ High temperatures (e.g. shocks): reaction barriers of O and OH with H_2 can be overcome and H_2O is rapidly formed by neutral-neutral reactions.
- ▶ Cold dense clouds: formation of water ice is very efficient and locks up the bulk of the oxygen. Water can be brought from the ice into the gas phase by thermal desorption at high temperatures and by photodesorption triggered by UV radiation in cold clouds.

INTERSTELLAR MEDIUM (ISM): DUST

- ▶ Dust: average interstellar extinction can be satisfactorily reproduced with two components (silicate and graphite) and a power-law grain-size distribution:

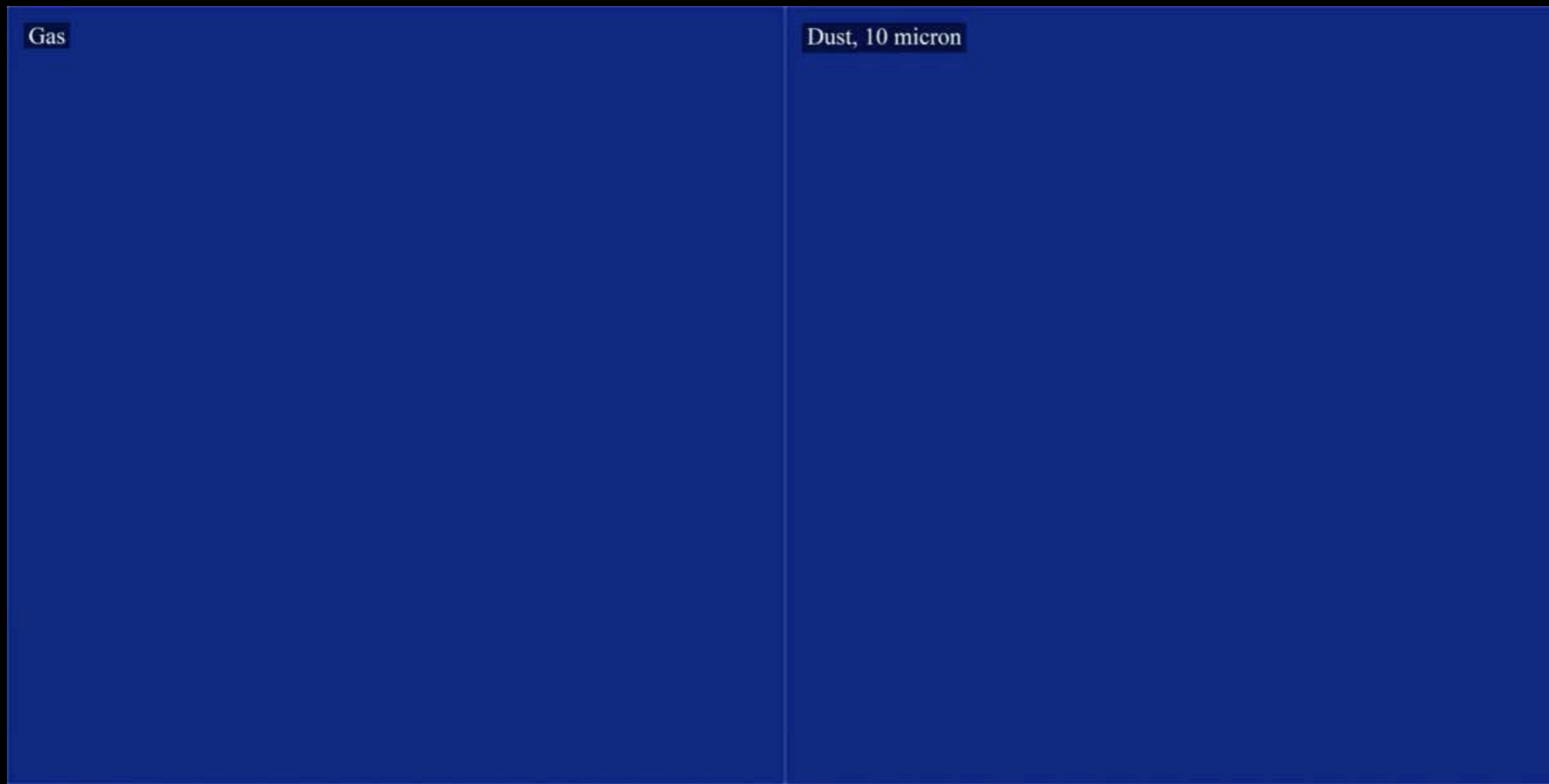
$$dn(a) \propto a^{-3.5} da,$$

truncated at a minimum and maximum size:

$$a_{\min} = 0.005 \mu\text{m} \quad a_{\max} = 0.25 \mu\text{m}$$

- ▶ Dust comprises approximately 1% of the ISM by mass (dust-to-gas ratio of 1:100).
- ▶ Turbulence influences spatial and size distribution.

INTERSTELLAR MEDIUM (ISM): DUST



GIANT MOLECULAR CLOUDS (GMC)

- ▶ Concentrations of gas and dust that are 15–600 light-years in diameter and contain between 10^4 – 10^7 solar masses.
- ▶ In the Milky Way, GMCs account for <1% of the volume of the ISM, but roughly half of the total gas mass interior to the Sun's galactic orbit.
- ▶ Primarily composed of H_2 , but are usually observationally traced using CO (or NH_3 in molecular cores).
- ▶ Cold, dense filaments or clumps are called **molecular cores** and are the usual breeding ground for stars. They typically have sufficient dust concentrations so as to block light from background stars, making them appear dark.

GIANT MOLECULAR CLOUDS (GMC)



GIANT MOLECULAR CLOUDS (GMC)



GIANT MOLECULAR CLOUDS (GMC): STABILITY

- ▶ The lifetime of GMCs do not exceed 3×10^7 yrs due to disruption by stellar feedback when stars are born.
- ▶ Cloud stability relies on balance between pressure and gravity (**hydrostatic equilibrium**):

$$\nabla P = \frac{dP}{dr} = -\frac{GM}{r^2}\rho = -\frac{d\phi}{dr}\rho$$

- ▶ Assuming an isothermal equation of state (ideal gas law):

$$P = nk_{\text{B}}T = \frac{k_{\text{B}}T}{m}\rho = c_s^2\rho$$

- ▶ Combining these two equations gives

$$\frac{d \ln \rho(r)}{dr} = -\frac{d}{dr} \left(\frac{\phi(r)}{c_s^2} \right) \quad \text{or} \quad \rho(r) = \rho_c e^{-\phi(r)/c_s^2}$$

GIANT MOLECULAR CLOUDS (GMC): STABILITY

- ▶ Meanwhile the gravitational potential is related to the density by: (assuming spherical symmetry)

$$\nabla^2 \phi = \frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{d\phi}{dr} \right) = 4\pi G \rho$$

- ▶ And we can define the cumulative mass with a sphere of radius r as:

$$M(r) = \int_0^r 4\pi r'^2 \rho(r') dr' \quad \text{or} \quad \frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

- ▶ Now it is useful to define the dimensionless variables:

$$u \equiv \frac{\phi}{c_s^2} \quad \text{and} \quad \xi \equiv r \left(\frac{4\pi G \rho_c}{c_s^2} \right)^{1/2}$$

- ▶ And substitute these into the top equation

GIANT MOLECULAR CLOUDS (GMC): STABILITY

- ▶ After substitution, we arrive at the Lane-Emden equation:

$$\frac{1}{\xi^2} \frac{d}{d\xi} \left(\xi^2 \frac{du}{d\xi} \right) = e^{-u}$$

- ▶ Likewise, the density becomes $\rho(r) = \rho_c e^{-u}$ and the mass:

$$M = 4\pi\rho_c \left(\frac{c_s^2}{4\pi G\rho_c} \right)^{3/2} \int_0^{\xi_0} e^{-u} \xi^2 d\xi$$

- ▶ Making use of the Lane-Emden equation, we find

$$\int_0^{\xi_0} e^{-u} \xi^2 d\xi = \xi^2 \frac{du}{d\xi}$$

- ▶ And that the mass becomes

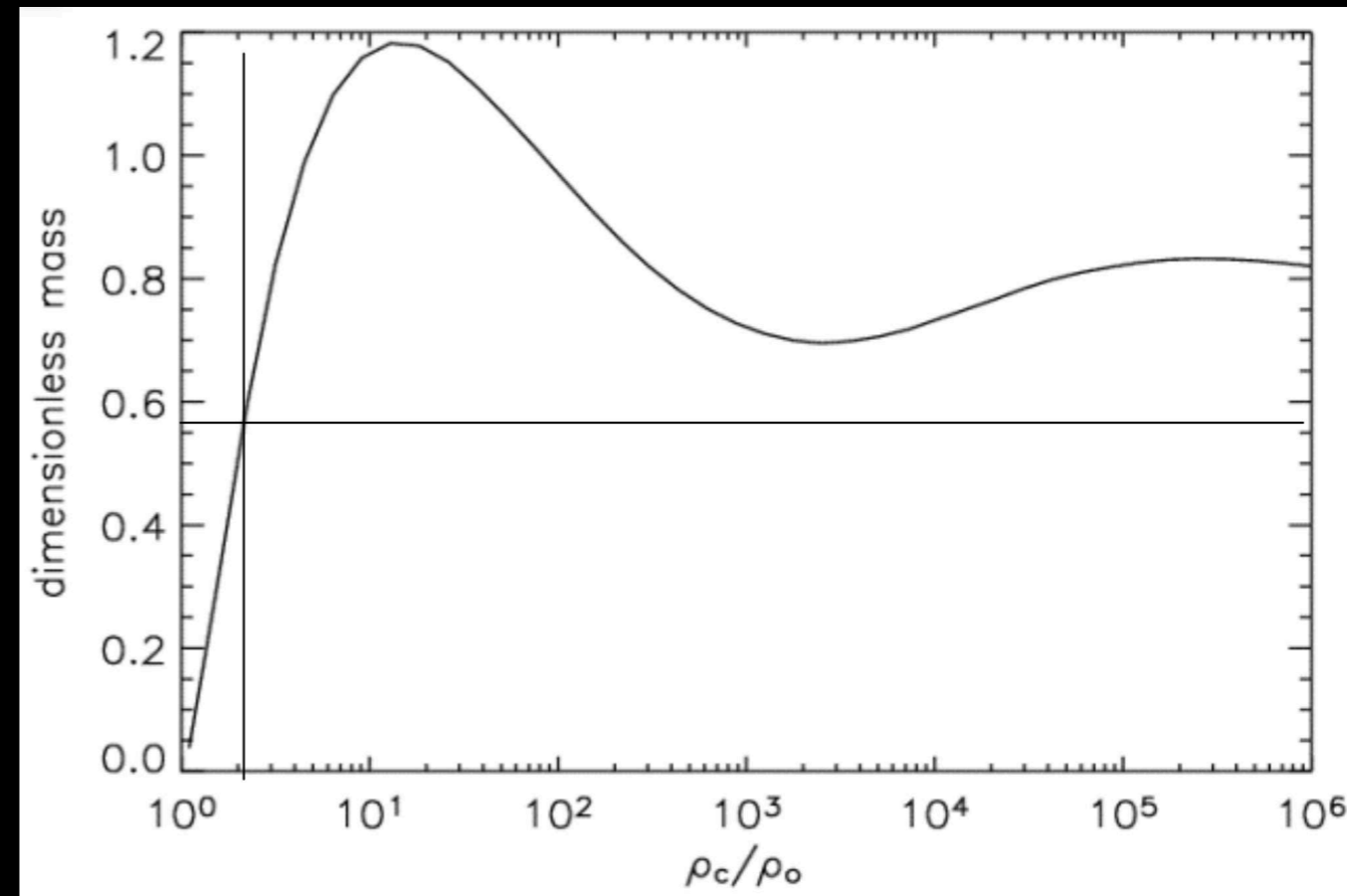
$$M = 4\pi\rho_c \left(\frac{c_s^2}{4\pi G\rho_c} \right)^{3/2} \xi^2 \frac{du}{d\xi} \quad \text{or} \quad m \equiv \frac{P_0^{1/2} G^{3/2} M}{c_s^4}$$

GIANT MOLECULAR CLOUDS (GMC): STABILITY

- ▶ The solution to the Lane-Emden equation is referred to as the **Bonner-Ebert Sphere**. To get the actual solution, we first have to define the boundary conditions:

$$u(0) = 0 \quad \text{and} \quad \left. \frac{du(\xi)}{d\xi} \right|_{\xi=0} = 0$$

- ▶ And then follow the recipe:
 - ▶ For a given pressure P_0 , find ρ_c/ρ_0 from the figure.
 - ▶ Use the dimensionless solution to find r_0 .
 - ▶ Make the BE sphere.



GIANT MOLECULAR CLOUDS (GMC): STABILITY

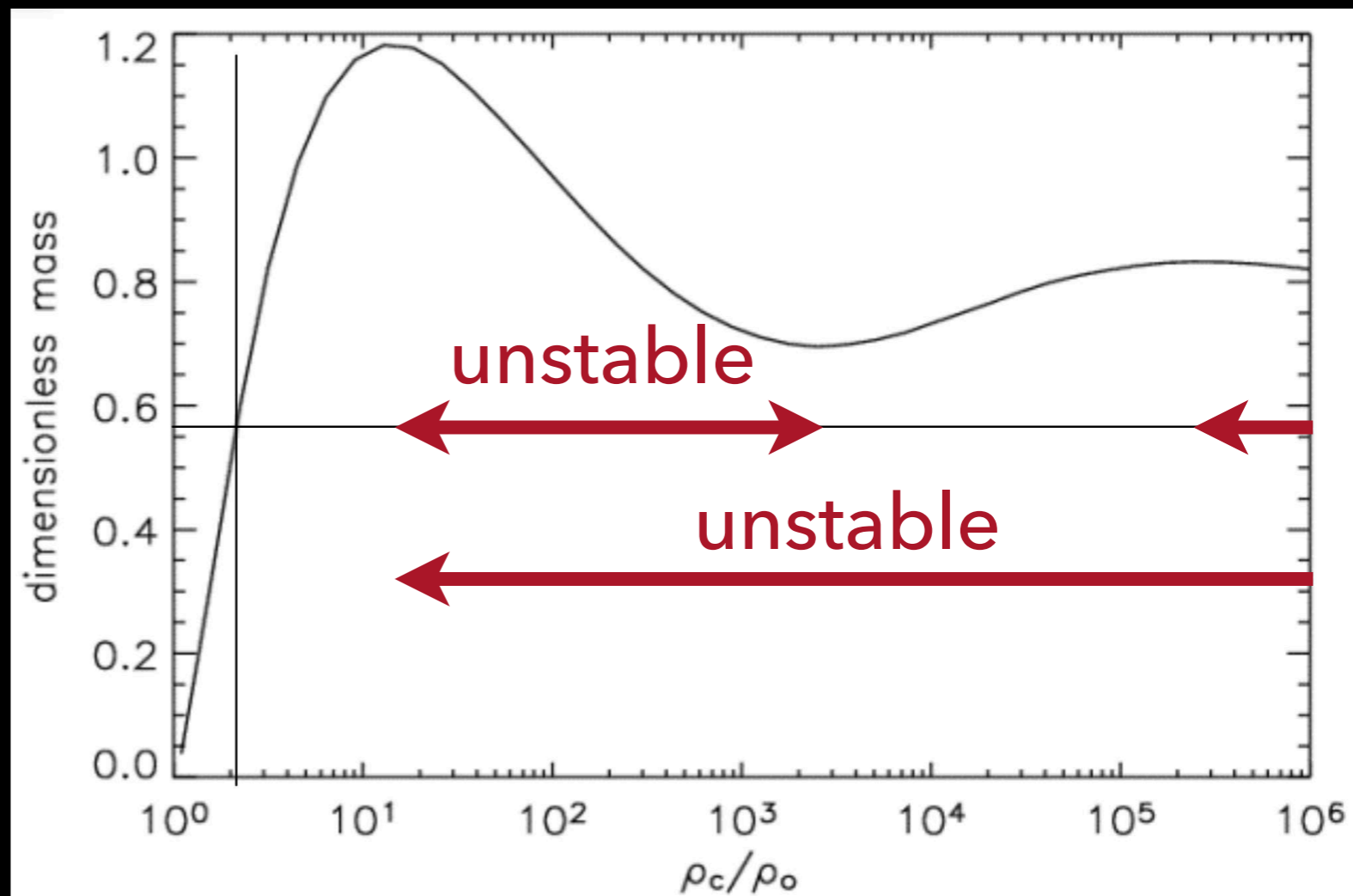
- ▶ We can then perturb the solution and look at the stability of the normal modes. The solution is unstable when:

$$\frac{dP_0}{dr_0} > 0 \quad \text{or} \quad \frac{dm}{d(\rho_c/\rho_0)} < 0$$

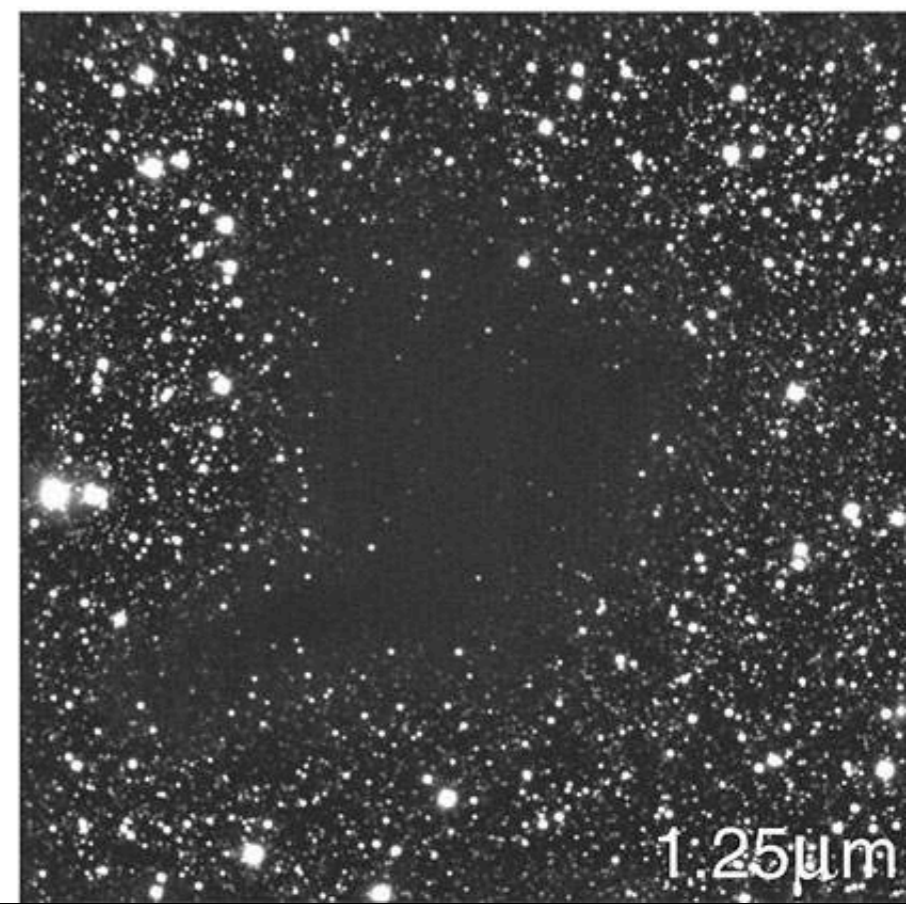
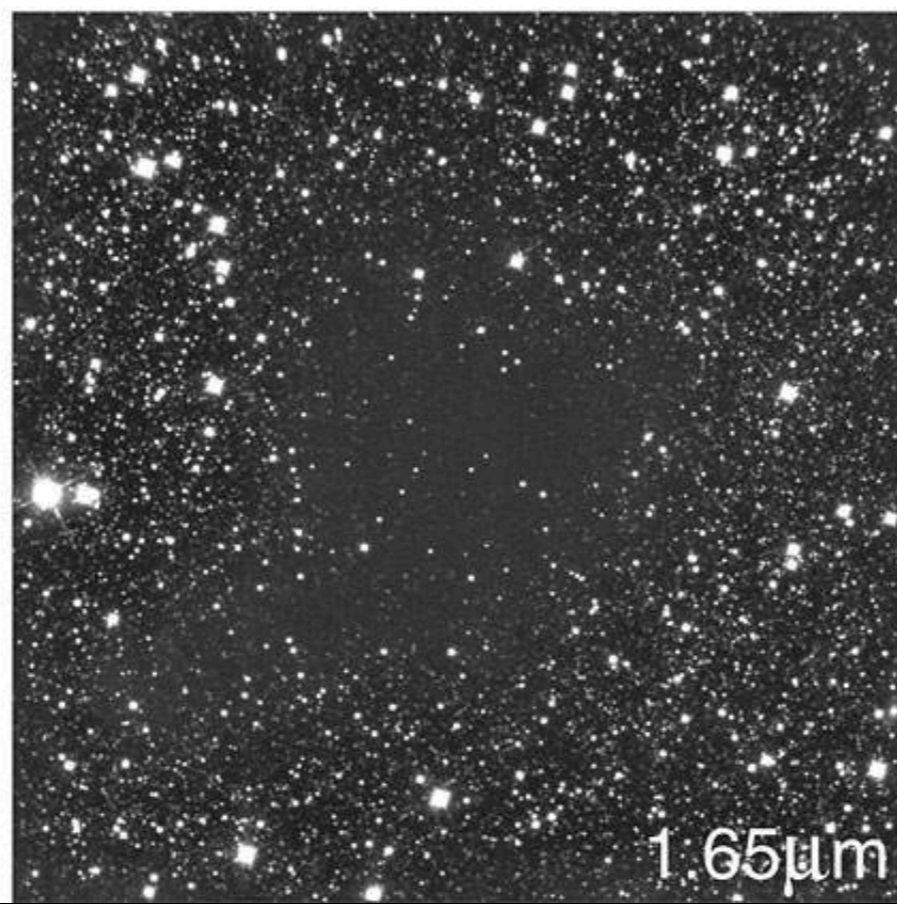
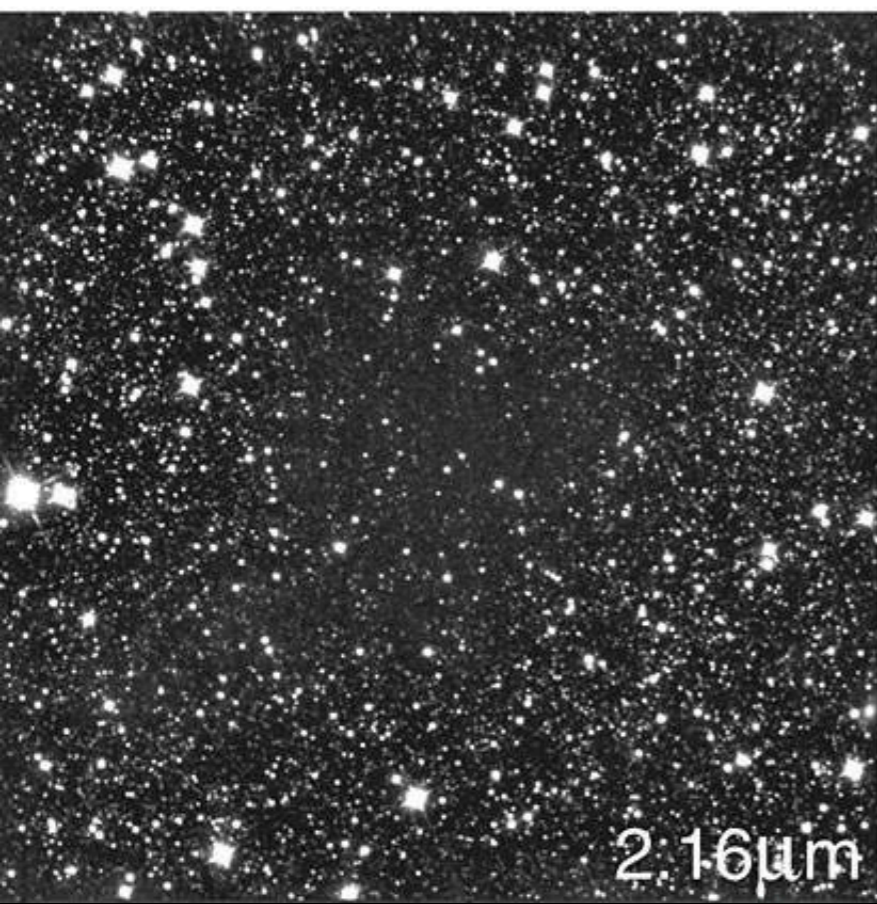
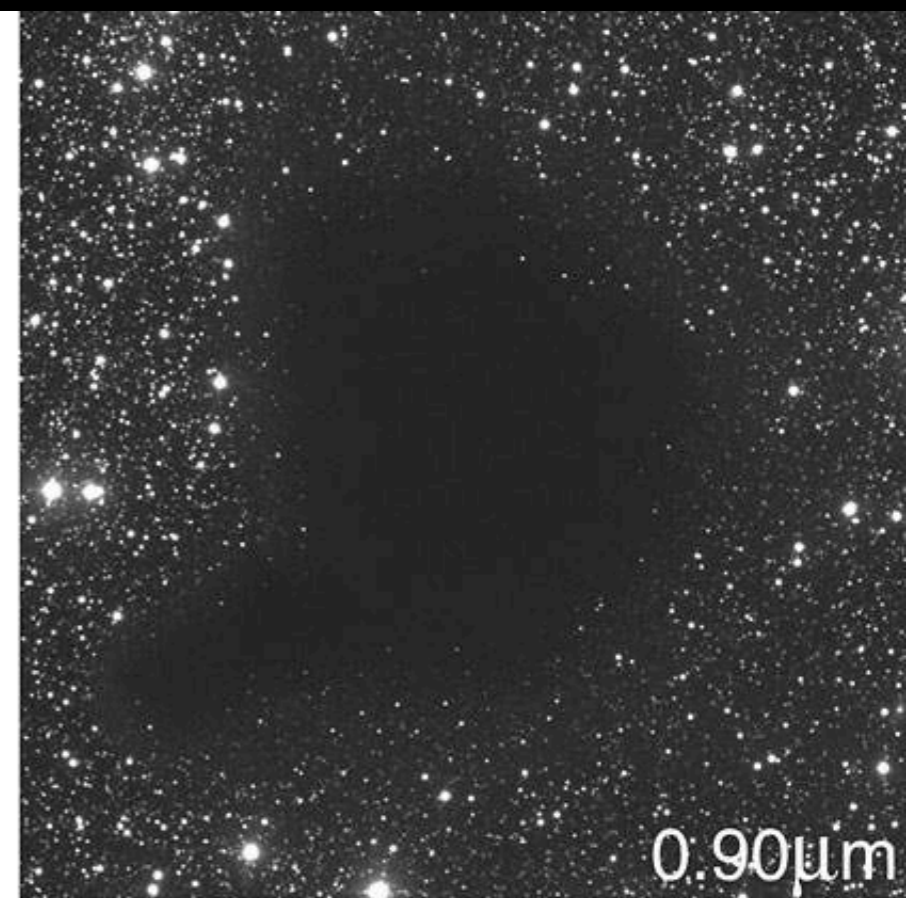
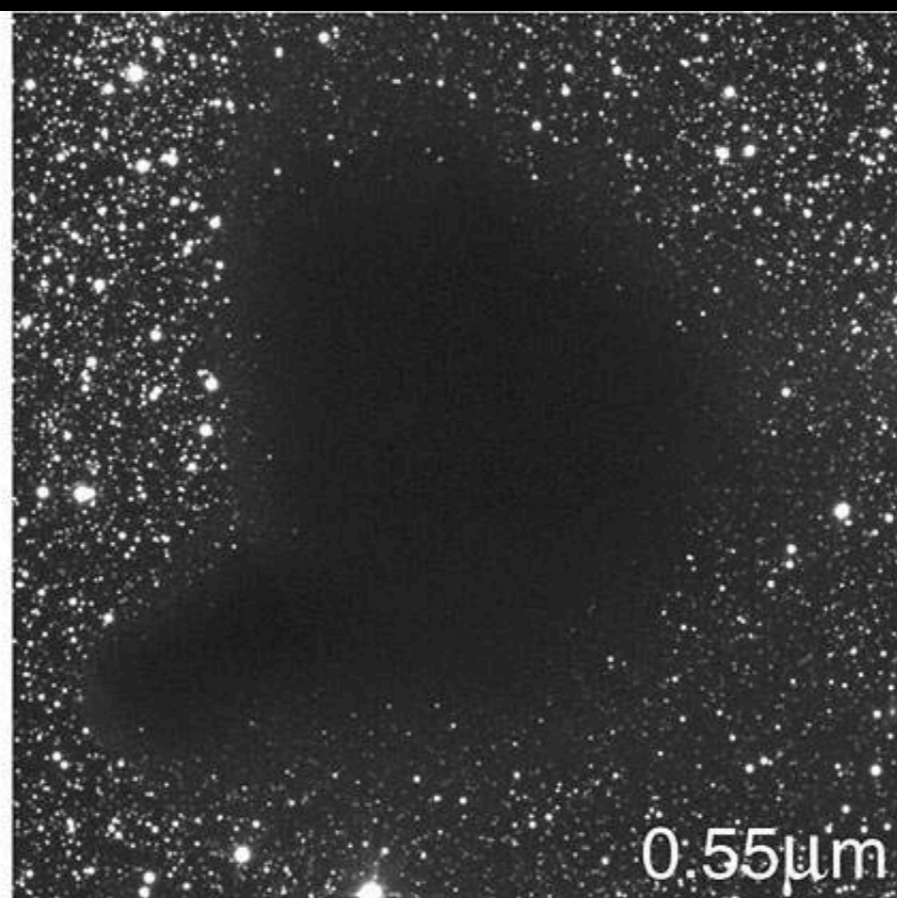
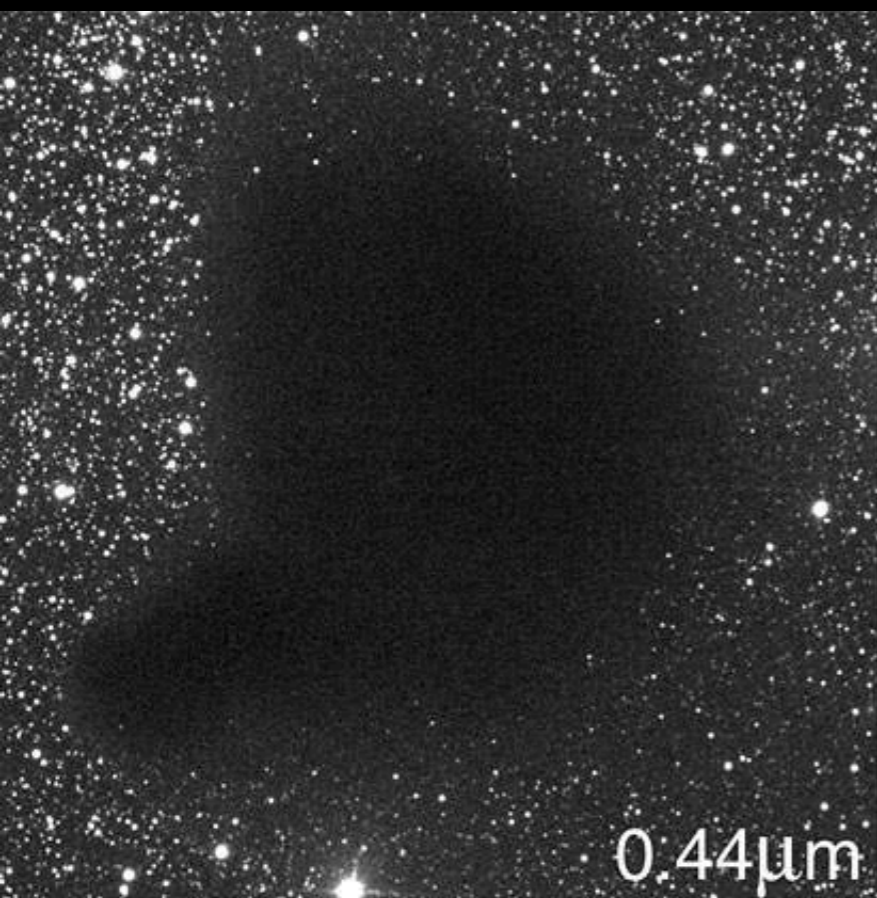
- ▶ Unstable if external pressure too high or mass too concentrated.

- ▶ The fundamental breathing mode is unstable when the mass exceeds:

$$M_{\text{BE}} = 1.18 \frac{c_s^4}{P_0^{1/2} G^{3/2}}$$



A REAL BONNOR-EBERT SPHERE IN NATURE? ... BARNARD 68



GIANT MOLECULAR CLOUDS (GMC): JEAN'S INSTABILITY

- ▶ A similar, but equivalent analysis, yields what is called the **Jean's instability** criterion. Derived by looking at sound wave perturbations traveling through a homogeneous medium of density ρ_0 .
- ▶ Linear analysis of small amplitude waves gives a dispersion relation that predicts instability, when the wavelength exceeds a critical length:

$$\lambda_J > \sqrt{\frac{\pi c_s^2}{G\rho_0}}$$

- ▶ Differs by a factor of ~ 2 from the Bonner-Ebert sphere, understandably given the different initial conditions.

GIANT MOLECULAR CLOUDS (GMC): VIRIAL THEOREM

- ▶ The **Virial theorem** is yet another criterion used in the literature, this time with energy arguments...

$$\frac{1}{2} \frac{d^2 I}{dt^2} = 2T + 2U + 2\tau_{\text{int}} + M + \tau_M + W$$

(moment of inertia)

$$I = \int_V \rho r^2 dV$$

(surface pressure term)

$$\tau_{\text{int}} = \frac{1}{2} \oint_S x_i P \hat{n}_i dS$$

(bulk kinetic energy)

$$T = \frac{1}{2} \int_V \rho v^2 dV$$

(magnetic energy)

$$M = \frac{1}{8} \pi \int_V B^2 dV$$

(gravitational energy)

$$W = - \int_V x_i \rho \frac{\partial \phi}{\partial x_i} dV$$

(internal thermal energy)

$$U = \frac{3}{2} \int_V P dV$$

(magnetic stress at surface)

$$\tau_M = \frac{1}{r} \pi \oint_S x_i B_i B_j \hat{n}_j dS$$

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I (moment of inertia)

T (bulk kinetic energy)

U (internal thermal energy)

τ_{int} (surface pressure term)

M (magnetic energy)

τ_M (magnetic stress at surface)

W (gravitational energy)

IN SUMMARY...

- ▶ Possible ways to trigger collapse:
 - ▶ 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)



IN SUMMARY...

- ▶ Collapse is hindered by:
 - ▶ Turbulence
 - ▶ Macroscopic flows
 - ▶ Cloud geometry
 - ▶ **Rotation**
 - ▶ **Magnetic fields**





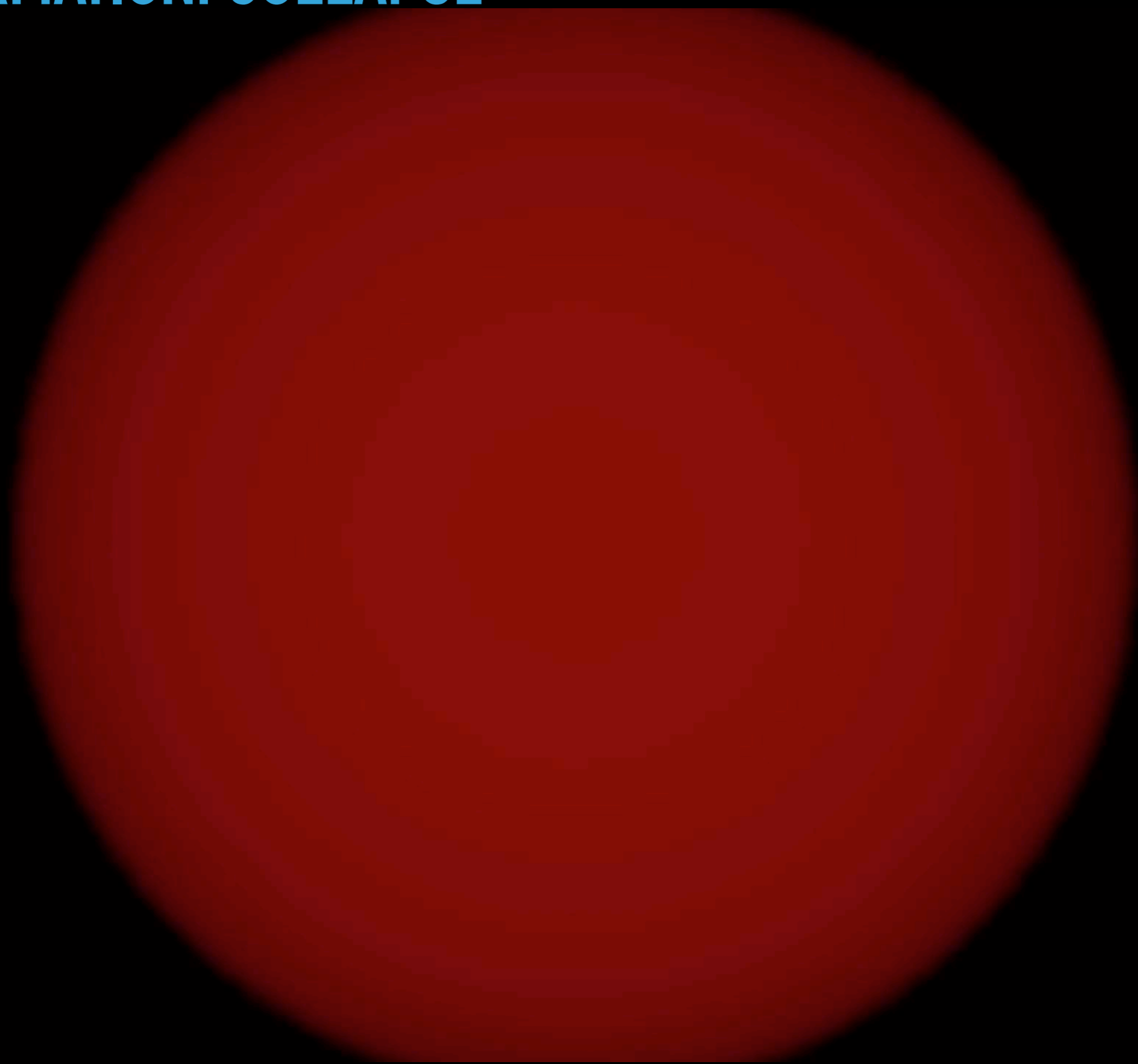
BIRTH, LIFE, AND DEATH

STELLAR EVOLUTION

LECTURE 1.3

STAR FORMATION: COLLAPSE

0 yrs



1000 AU

STAR FORMATION: COLLAPSE

0.1s

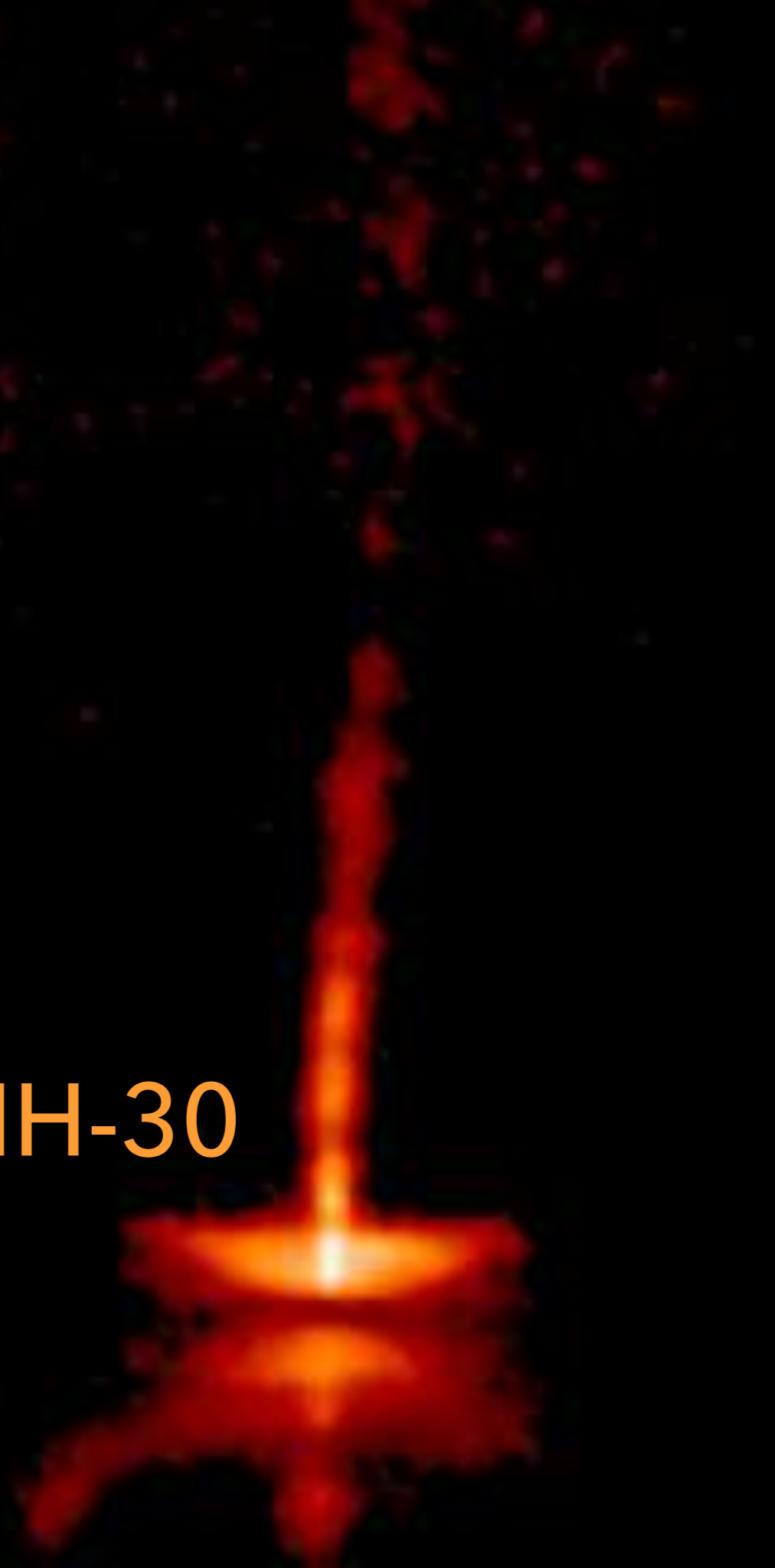
STAR FORMATION: COLLAPSE

- ▶ **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.

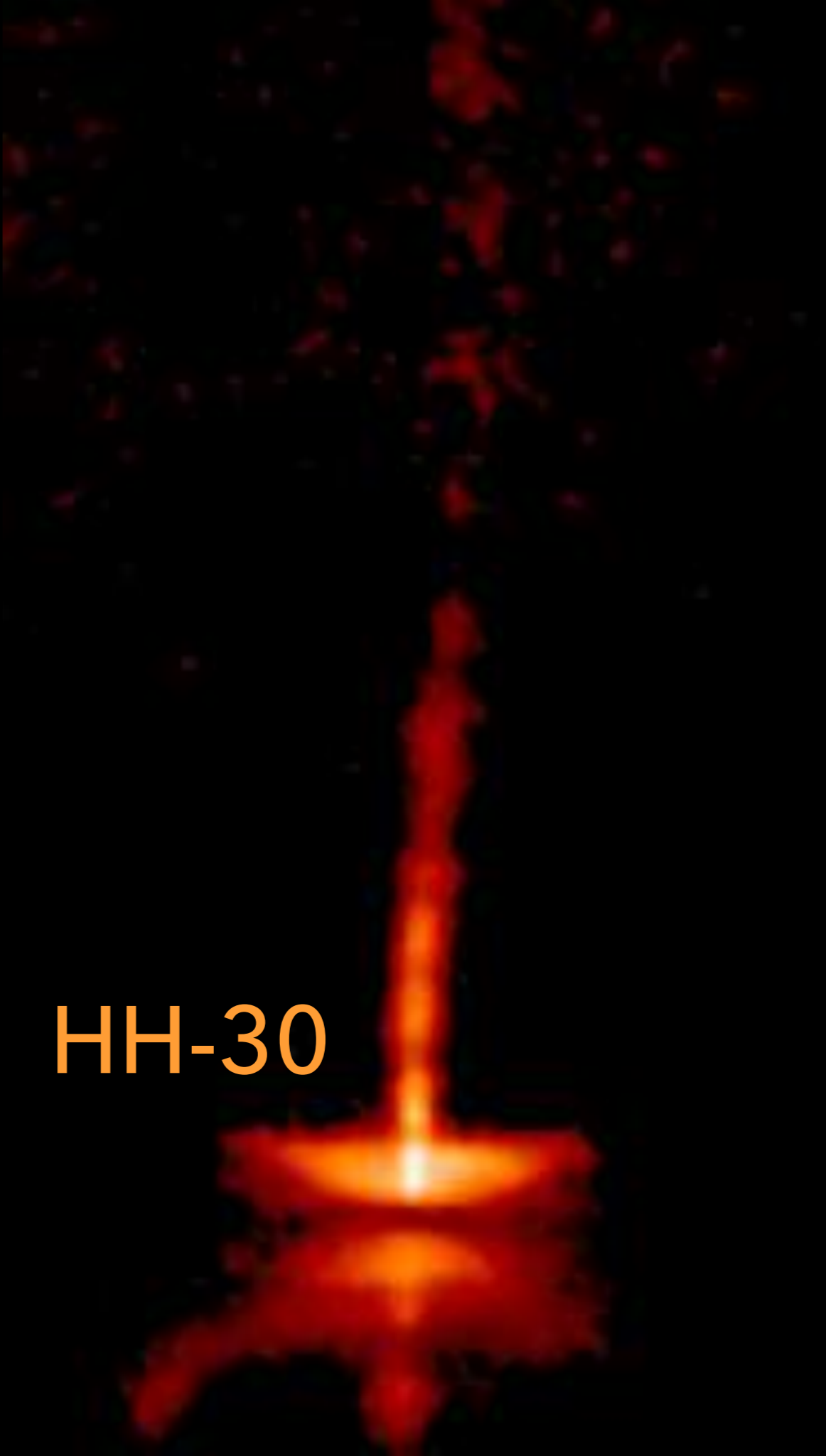
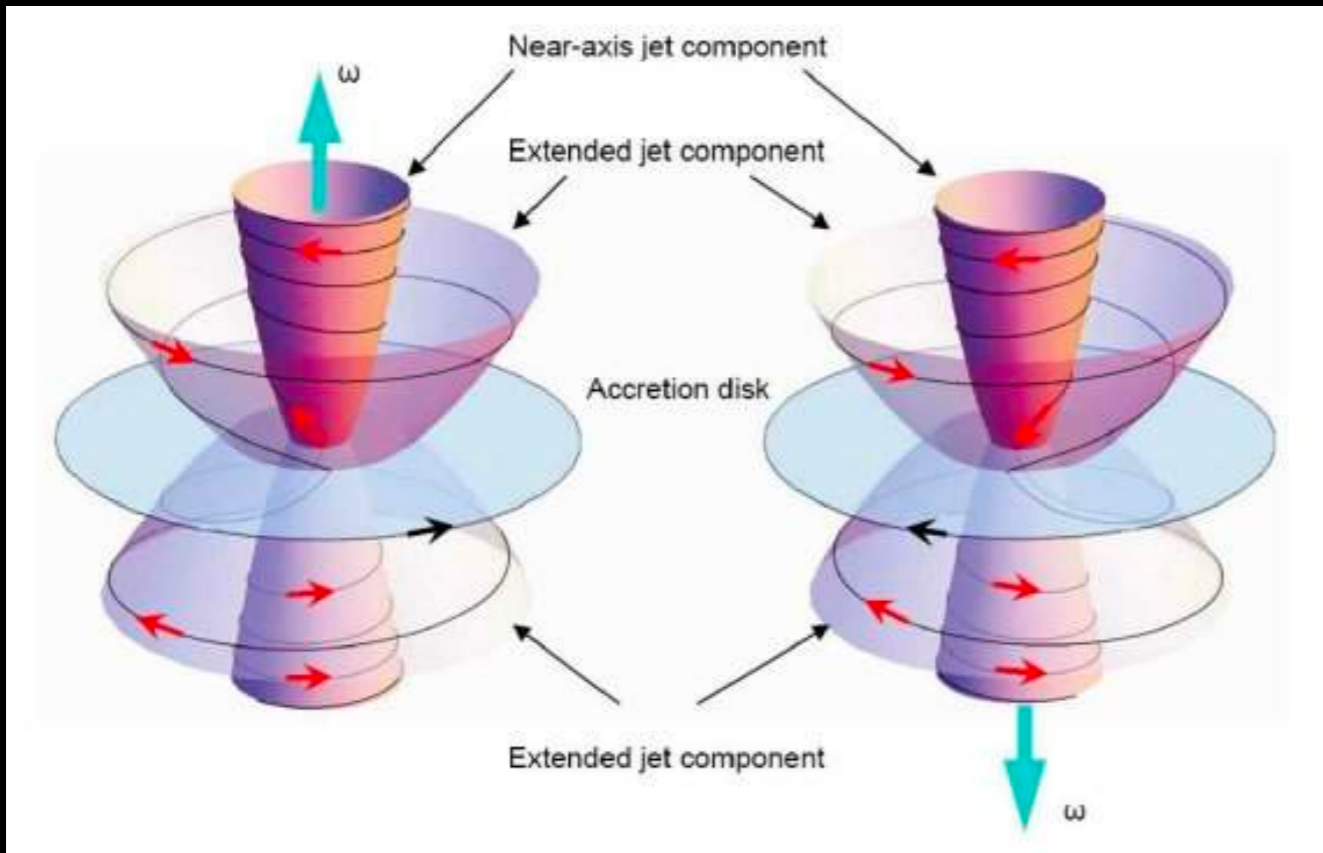
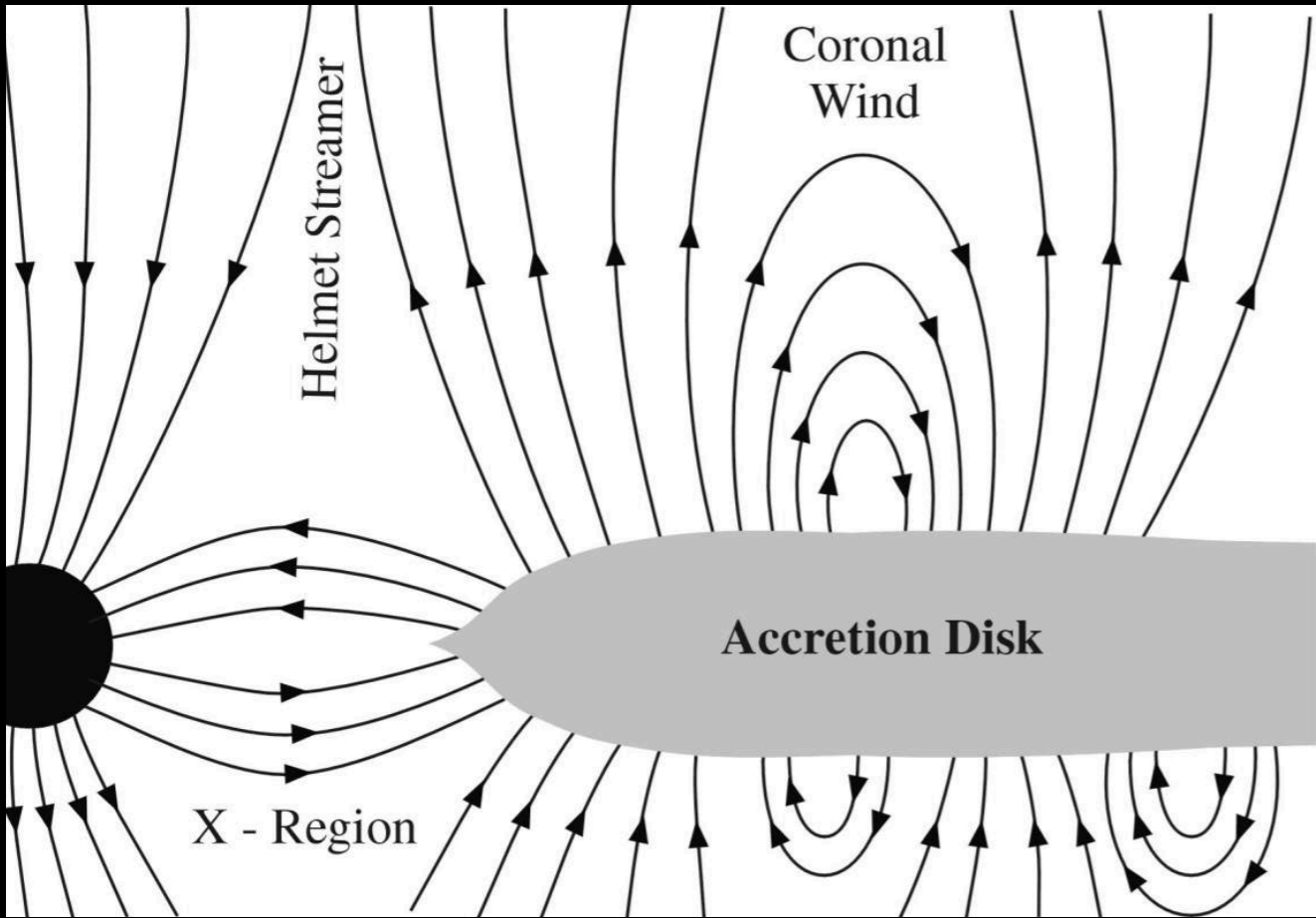
STAR FORMATION: JETS

- ▶ 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.

HH-30



STAR FORMATION: JETS



HH-30

STAR FORMATION: JETS



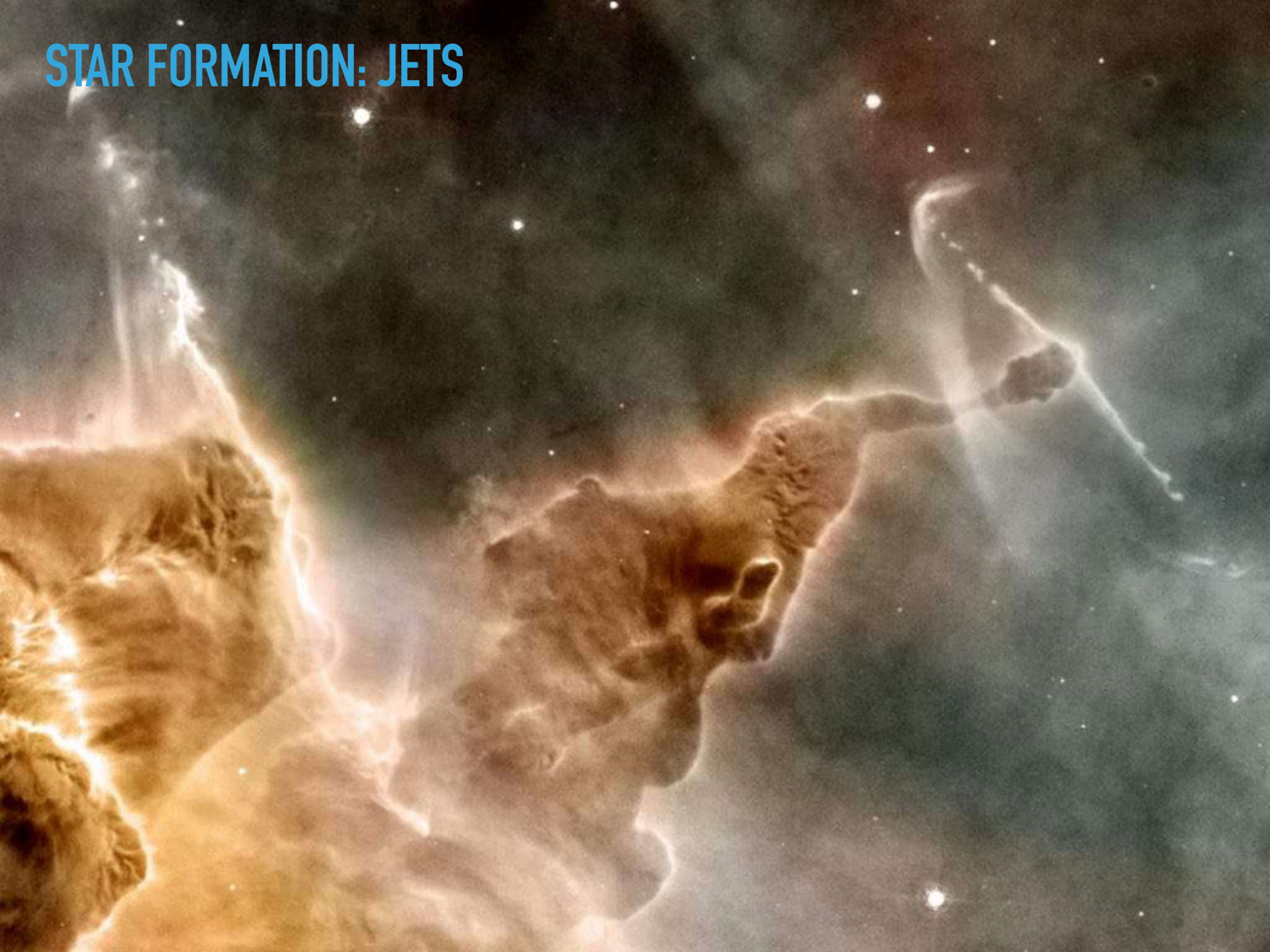
STAR FORMATION: JETS



STAR FORMATION: JETS



STAR FORMATION: JETS

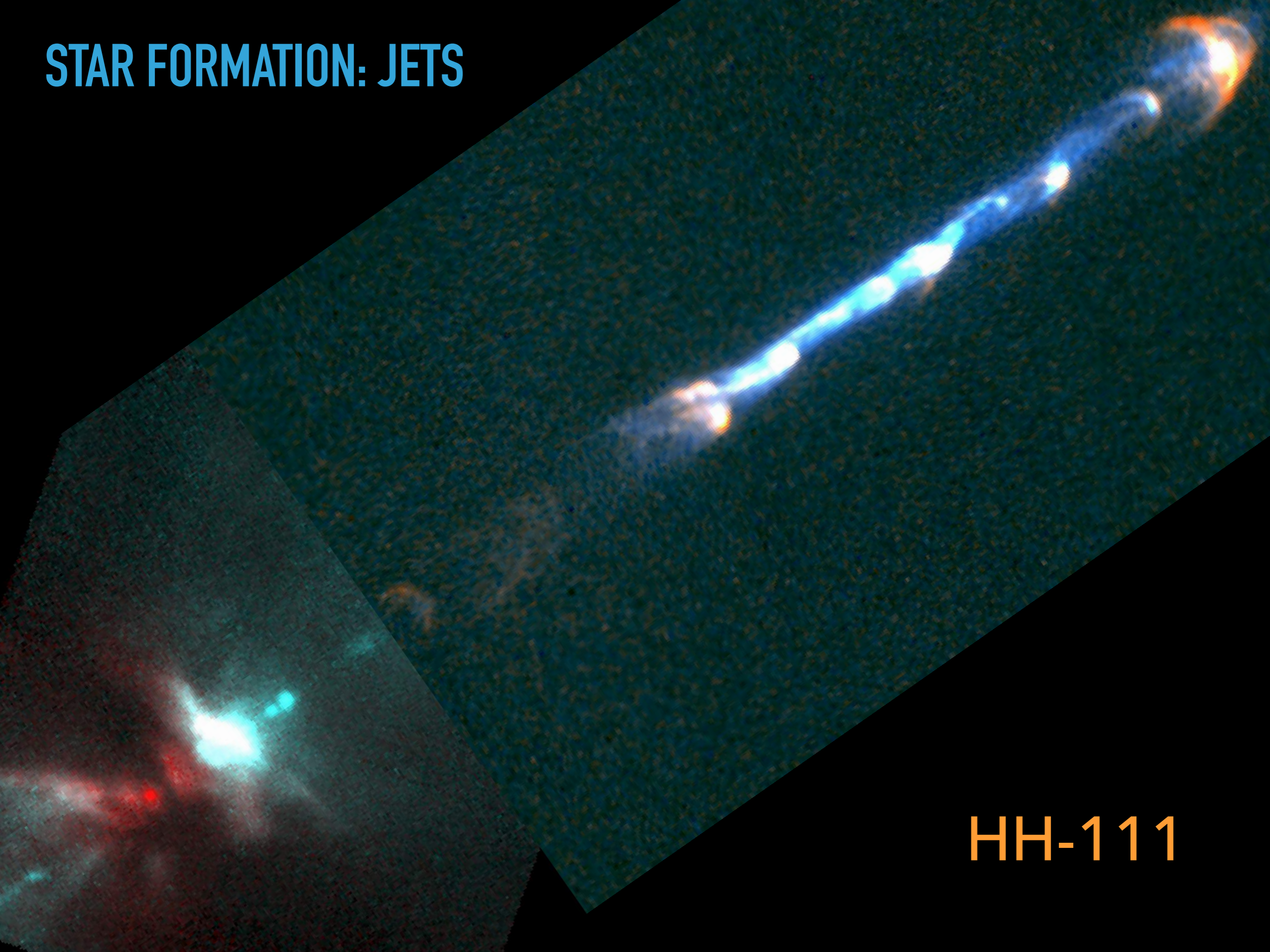


STAR FORMATION: JETS

HH-47



STAR FORMATION: JETS



HH-111

STAR FORMATION: JETS



STAR FORMATION: CIRCUMSTELLAR DISCS



STAR FORMATION: CIRCUMSTELLAR DISCS



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**:

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

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

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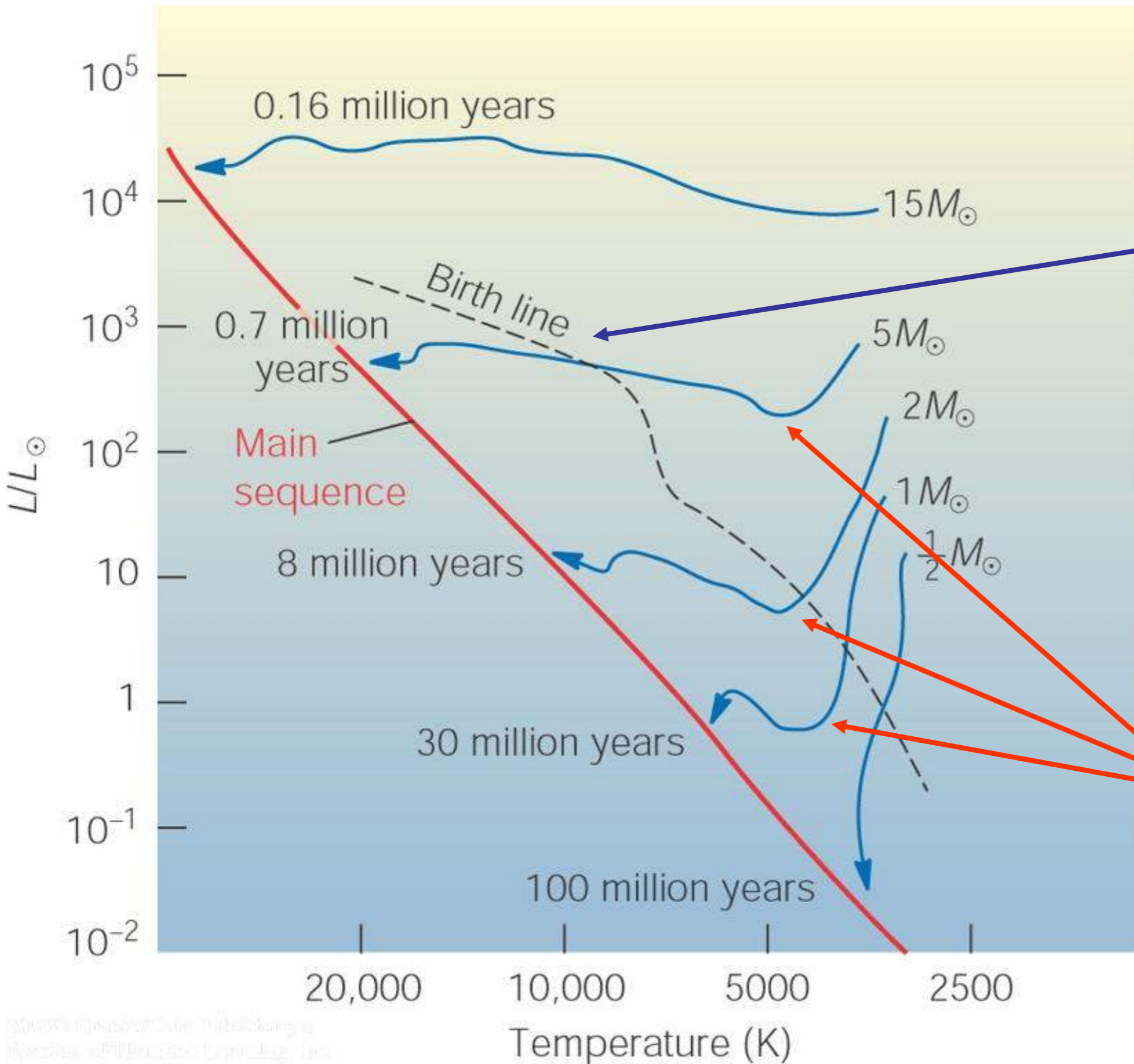
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STAR FORMATION: PROTOSTARS

- ▶ 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.

STAR FORMATION: PROTOSTARS



Star emerges from the enshrouding dust cocoon

Ignition of H \rightarrow He fusion processes

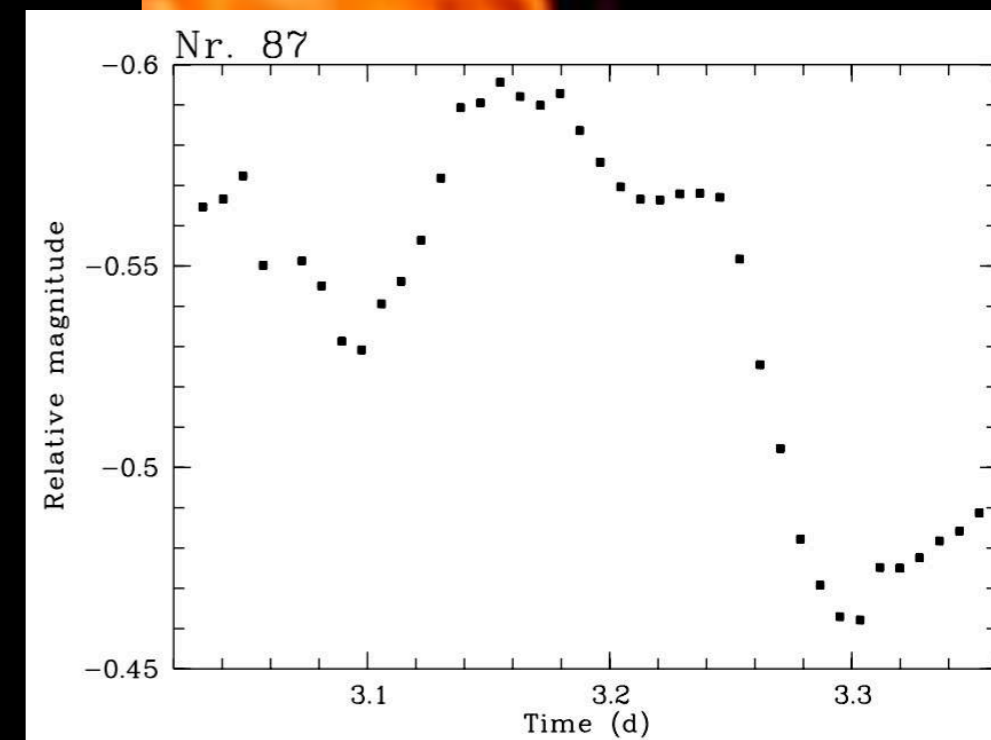
STAR FORMATION: PROTOSTARS

- ▶ Below $\sim 0.08 M_{\text{sun}}$ the core never gets hot enough to ignite H fusion → **Brown Dwarf**
- ▶ Above $\sim 100\text{--}150 M_{\text{sun}}$ the core gets so hot that radiation pressure overcomes gravity. The star becomes unstable and disrupts itself (rare).
- ▶ Gravitational collapse continues until the core reaches ~ 10 million K (zero-age **main sequence**).
 - ▶ Core temperature and pressure rise
 - ▶ Pressure = gravity and core collapse halts
 - ▶ Energy created by P-P chain fusion = luminosity

STAR FORMATION: T TAURI STARS

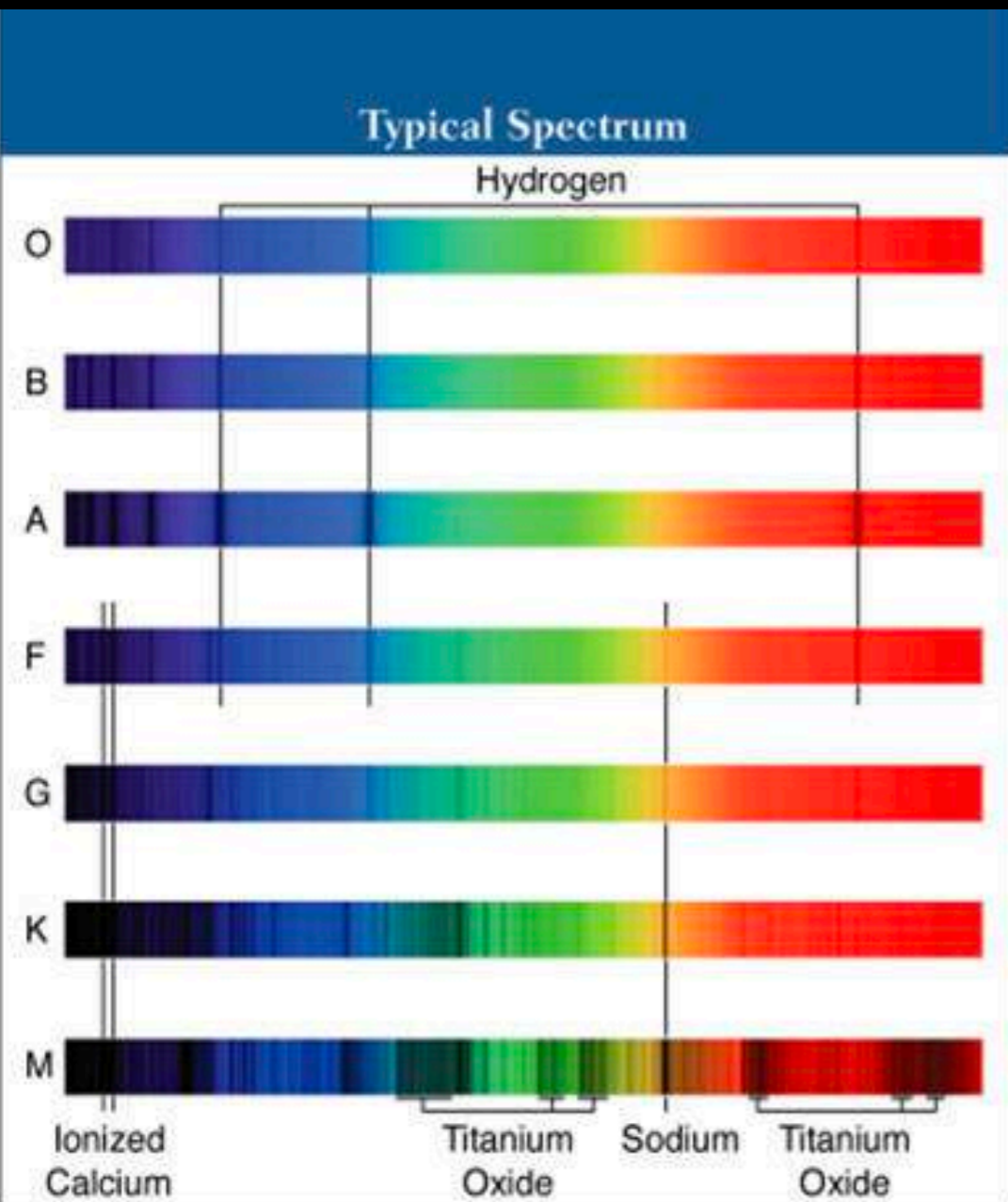
- ▶ **Variable stars** with $< 2 M_{\text{sun}}$ and < 10 million yrs old (still contracting on Hayashi track). Named after the prototype star T Tauri in the Taurus star-forming region.
- ▶ Similar surface temperatures to main-sequence stars of the same mass, but they are significantly more luminous because their radii are larger.
- ▶ Typically have rotation periods of 1–12 days, (compared to a month for the sun). They are very **active** (ejections, flares, and strong $L_{X\text{-ray}}$).

XZ Tauri



STELLAR EVOLUTION: MAIN SEQUENCE

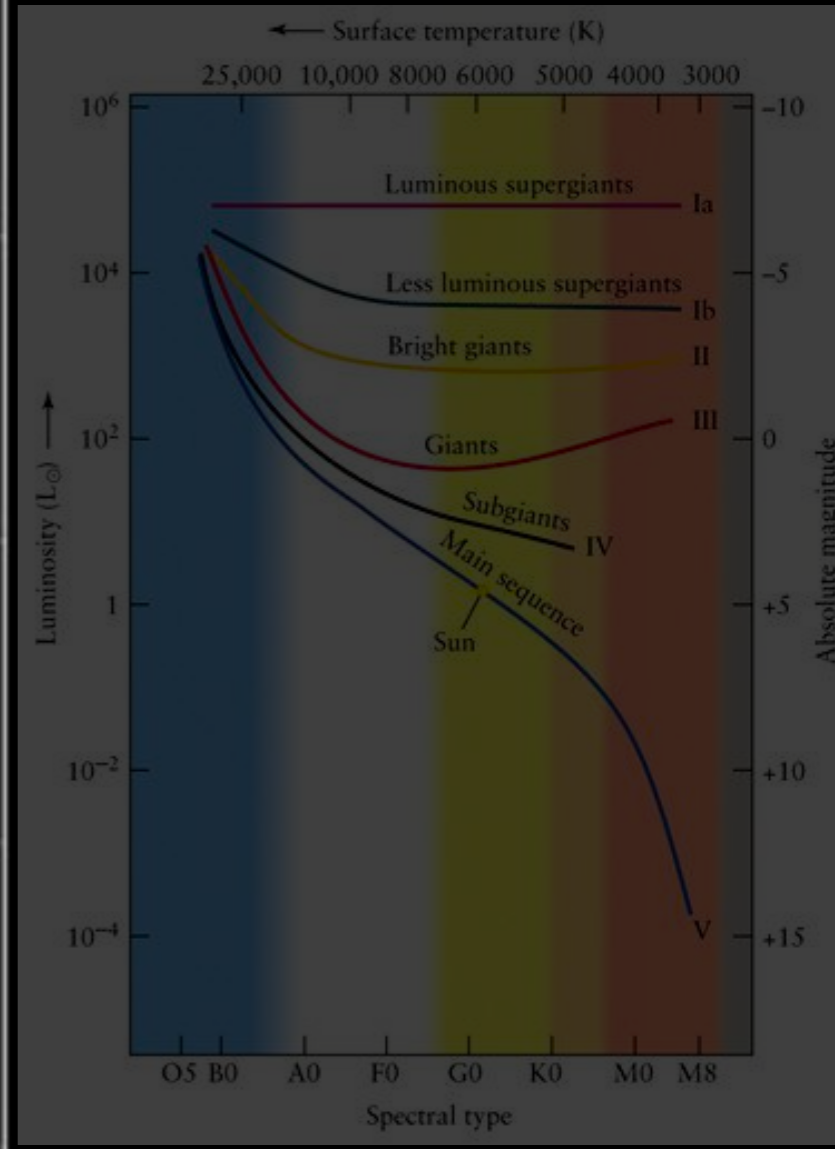
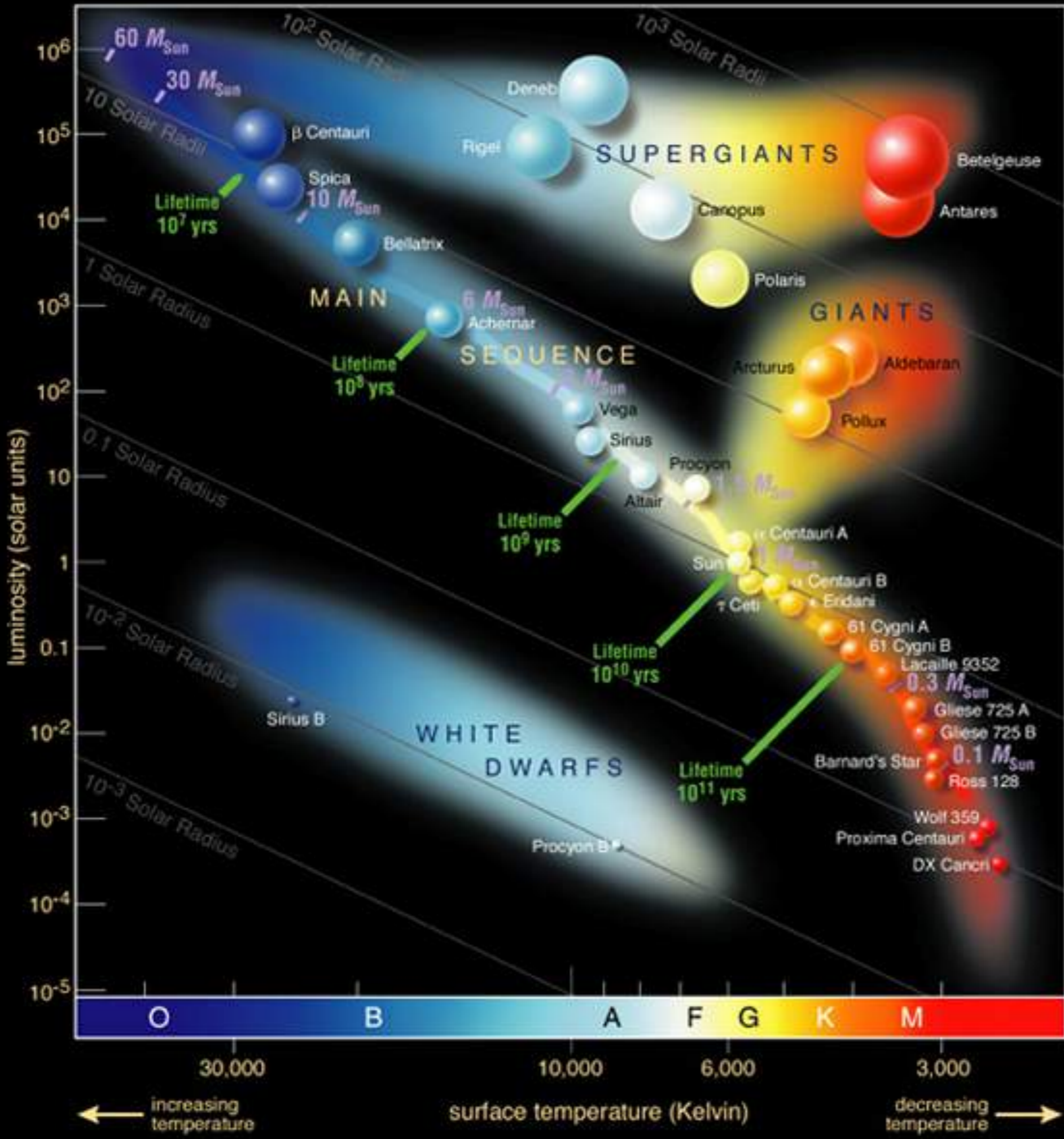
- Stars are classified by their **spectra** (the elements that they absorb) and their temperature. Seven main types of stars. In order of decreasing temperature, O, B, A, F, G, K, and M.



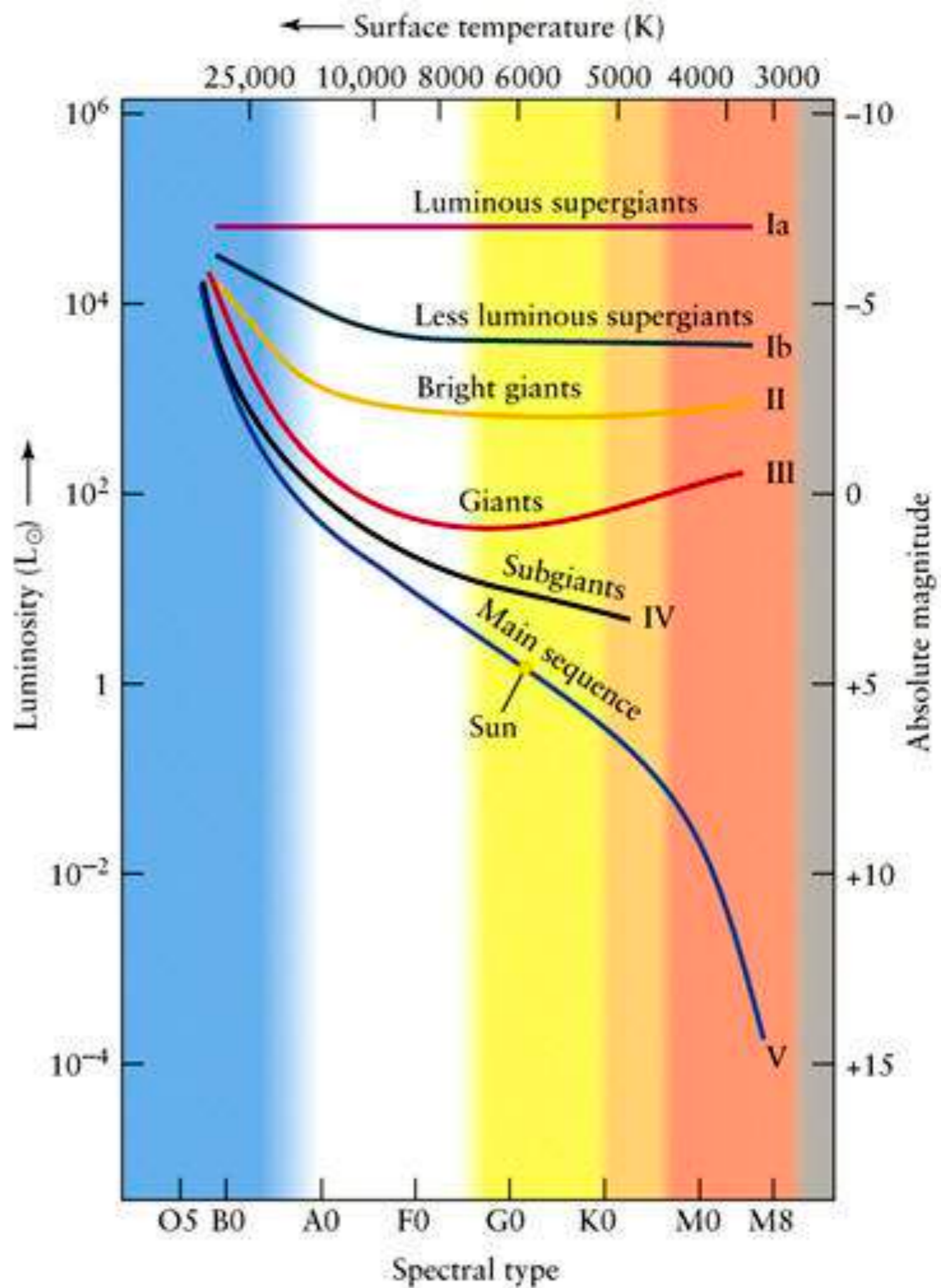
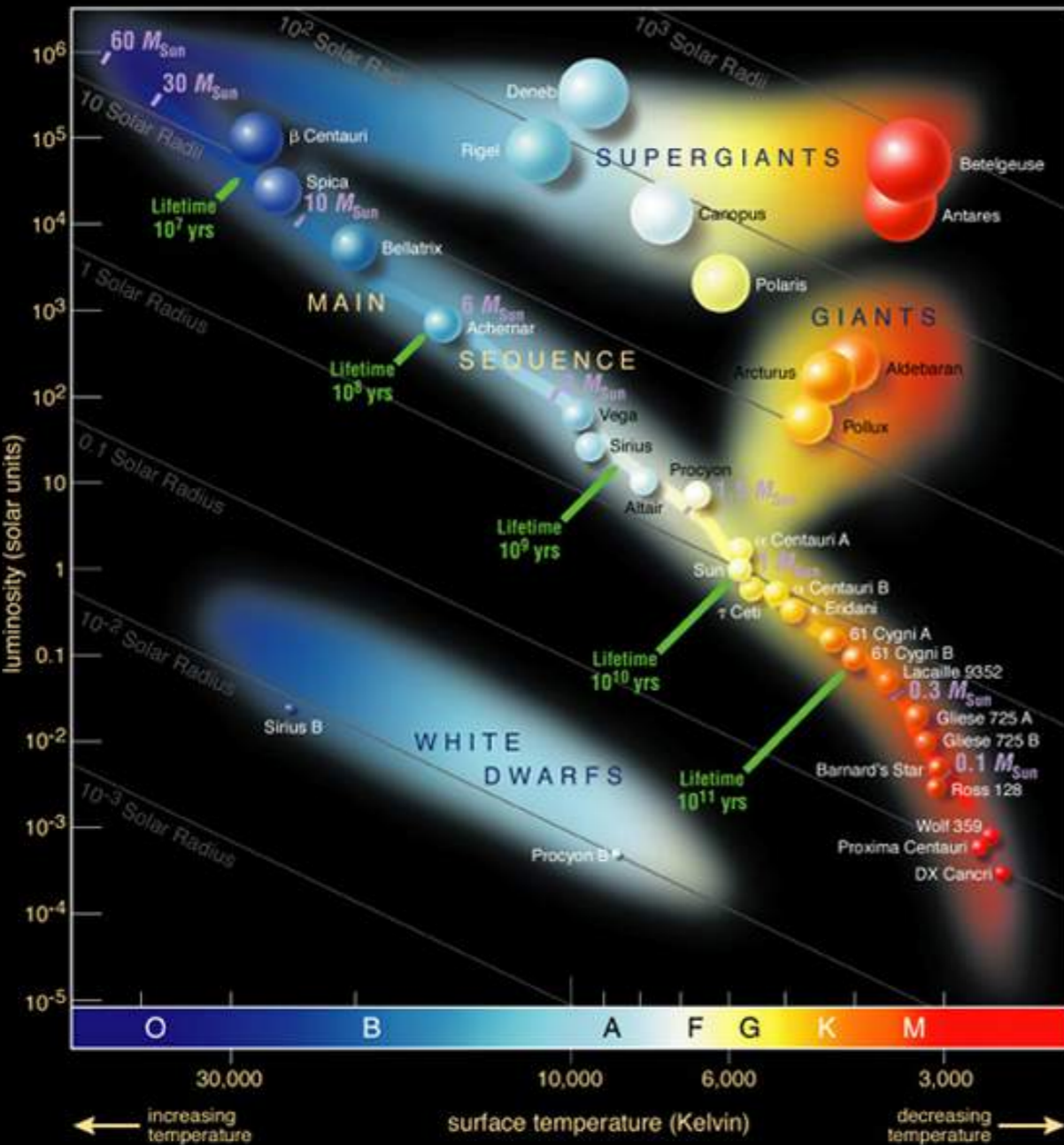
Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	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

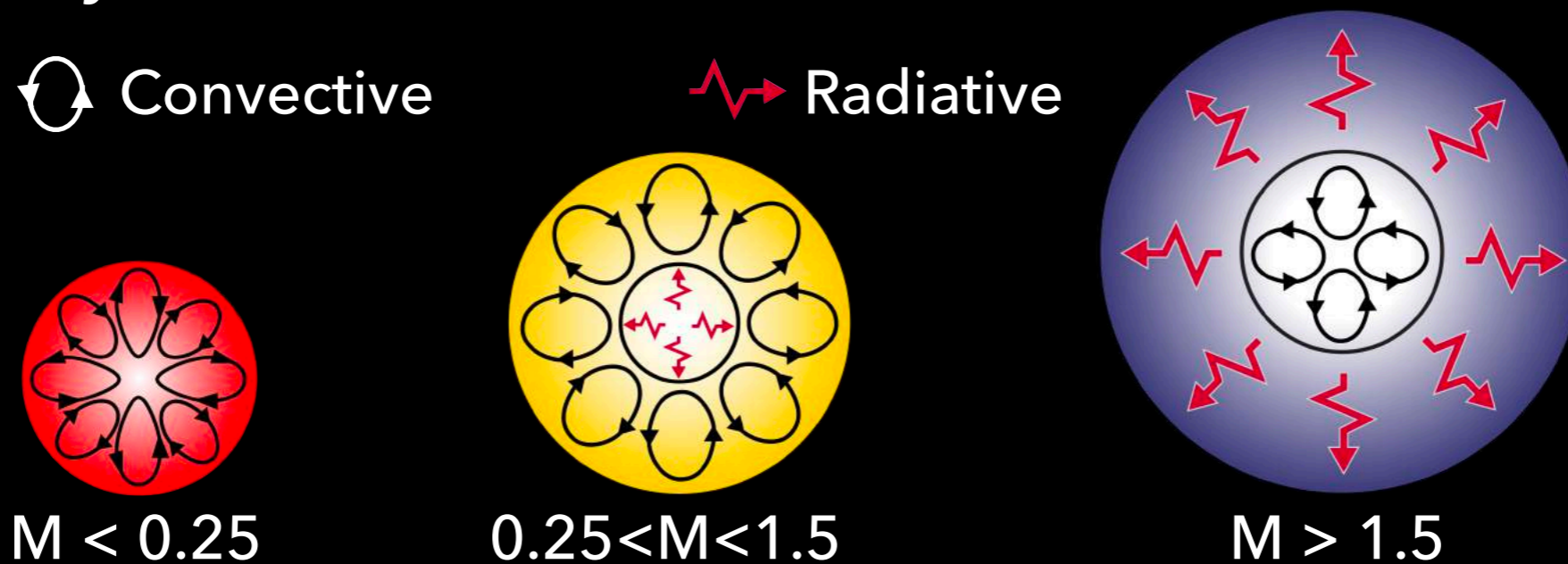


HERTZSPRUNG–RUSSELL DIAGRAM



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 $H \rightarrow He$.
- ▶ The mass of the star determines the internal structure and, ultimately, how the star will die.



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

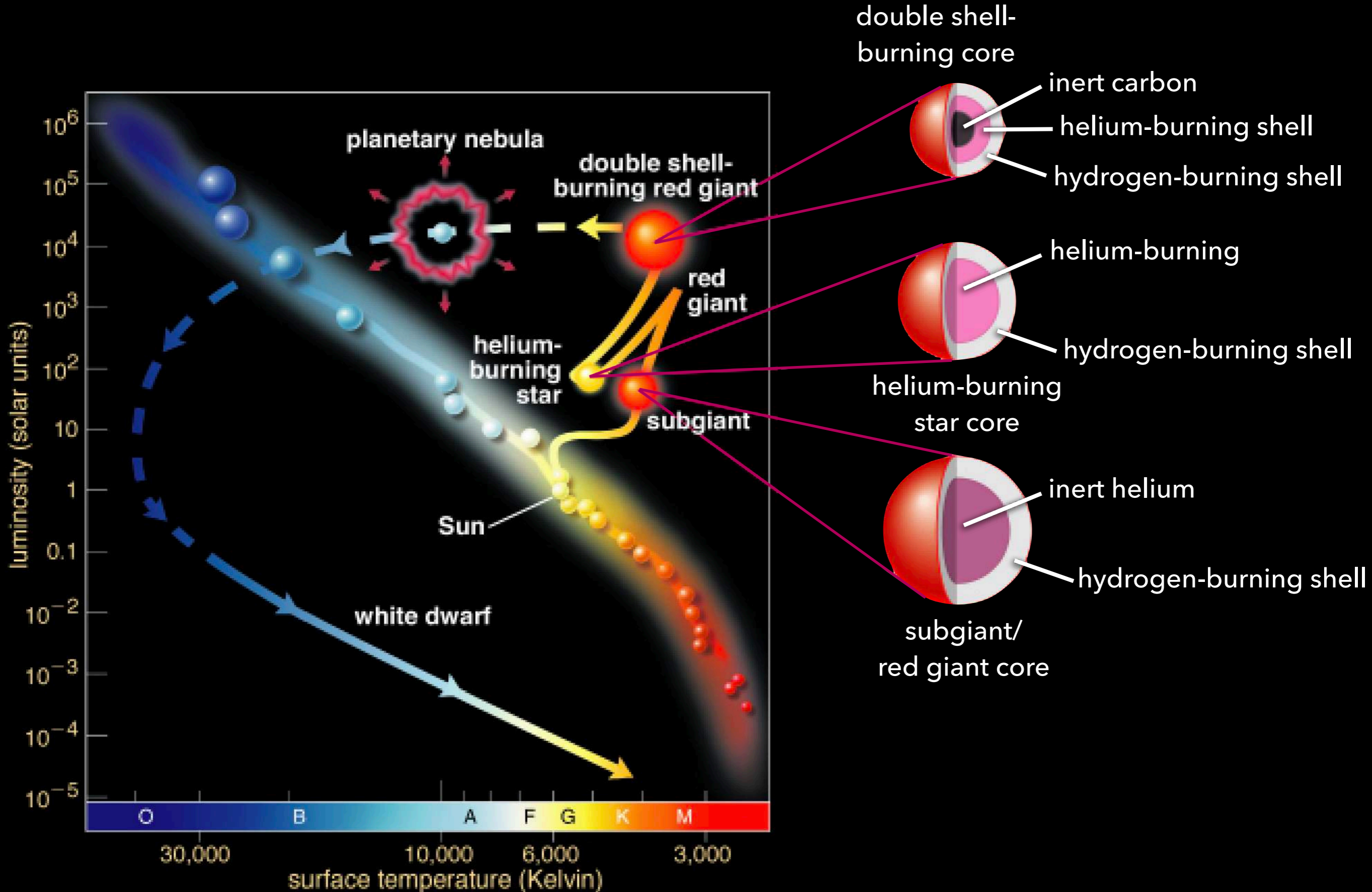
STELLAR EVOLUTION: LOW-MASS STARS

- ▶ 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 $10\text{--}100 \times$ 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).

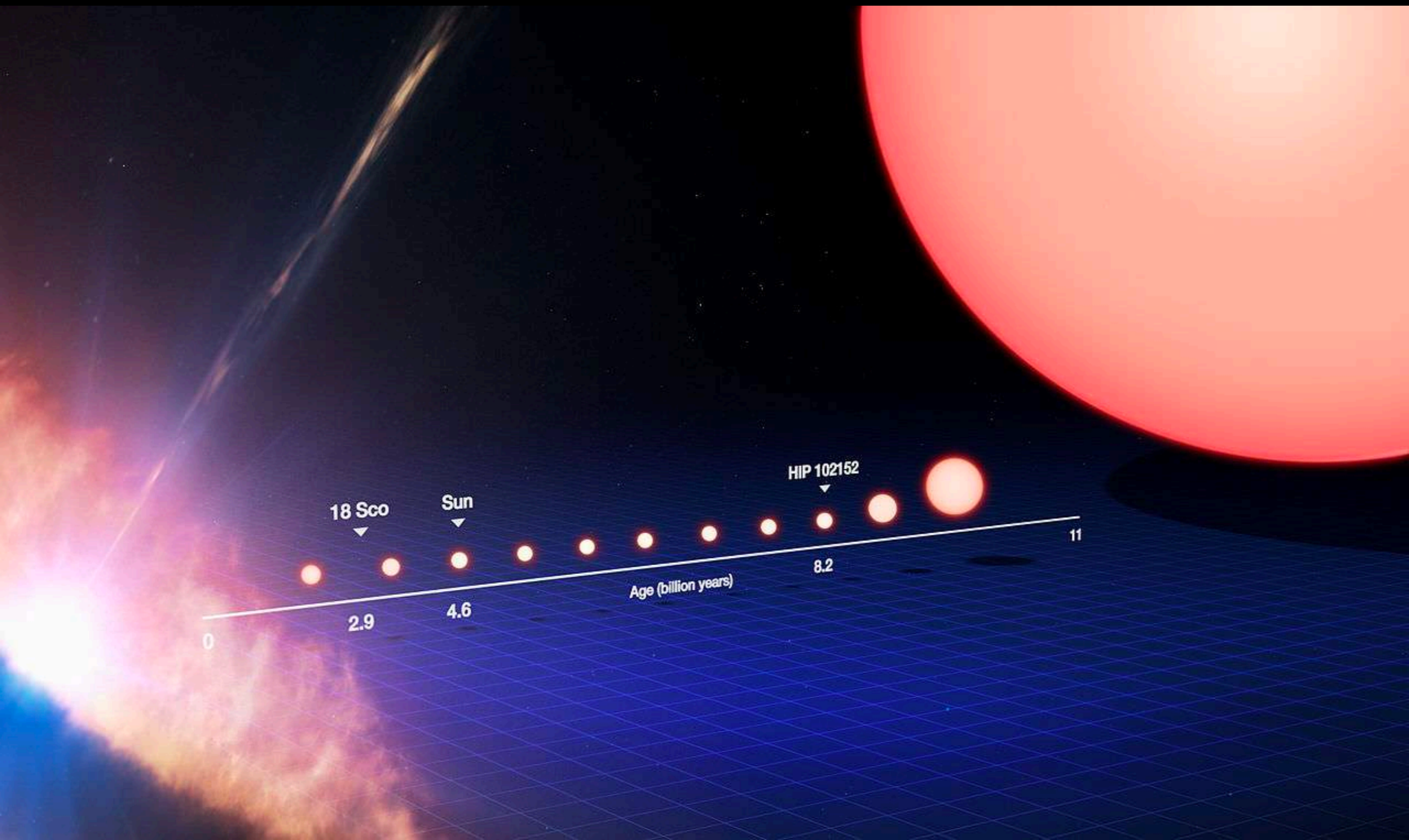
STELLAR EVOLUTION: LOW-MASS STARS

- ▶ 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 ensures 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 nebulae**).

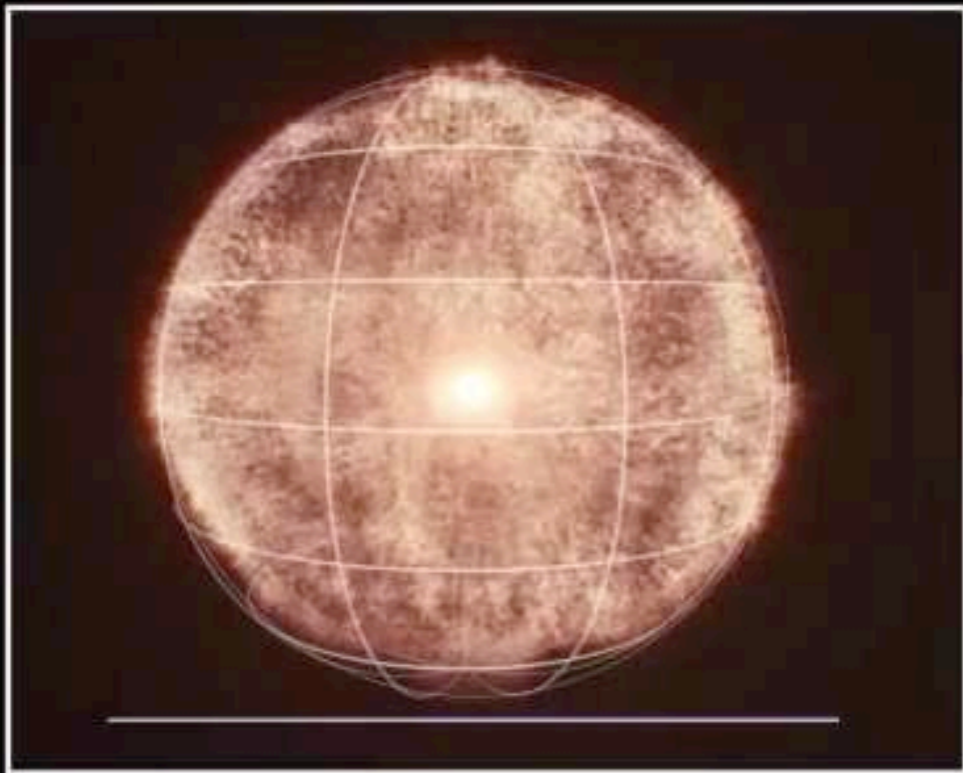
STELLAR EVOLUTION: LOW-MASS STARS



STELLAR EVOLUTION: LOW-MASS STARS

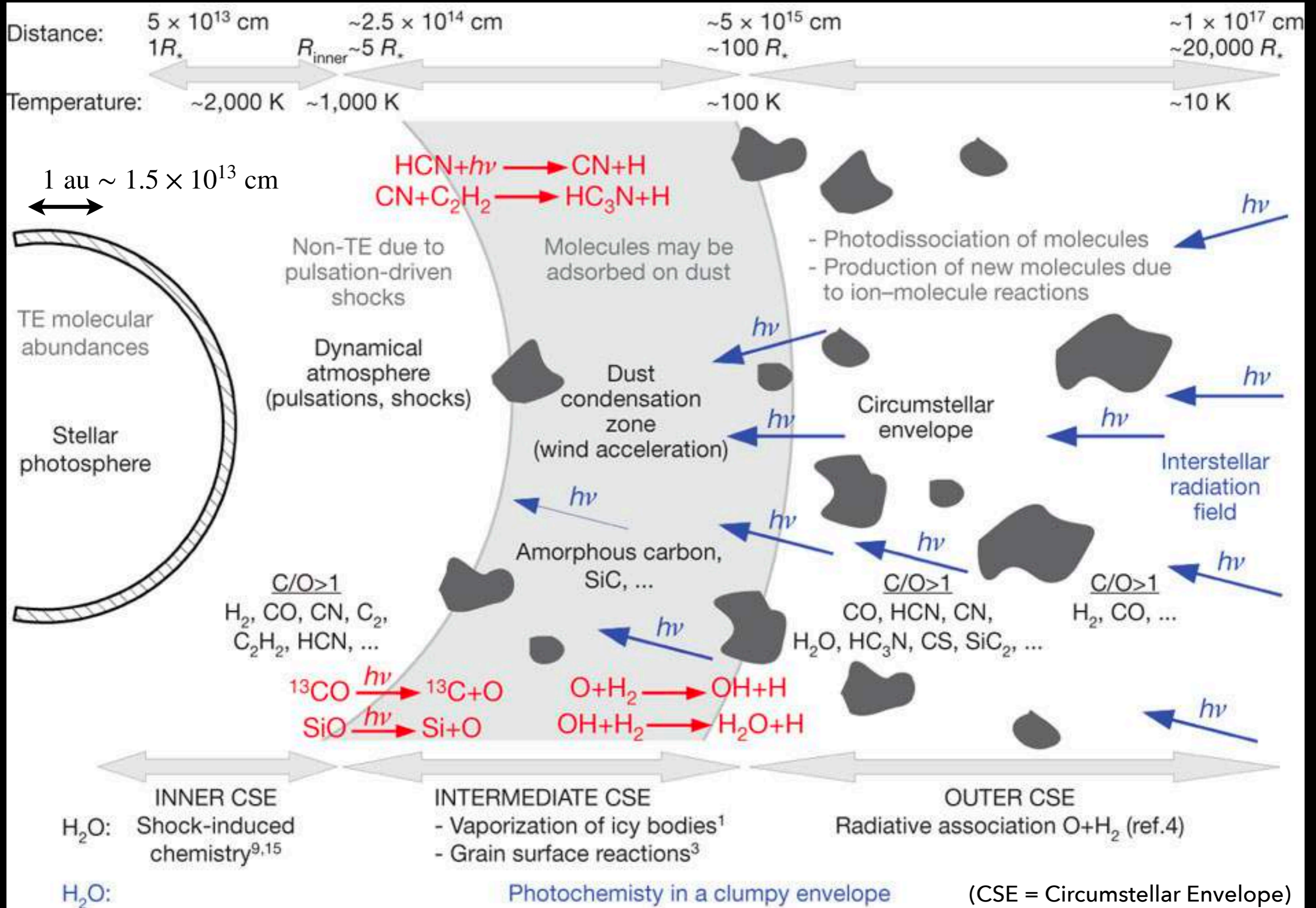


STELLAR EVOLUTION: AGB STARS



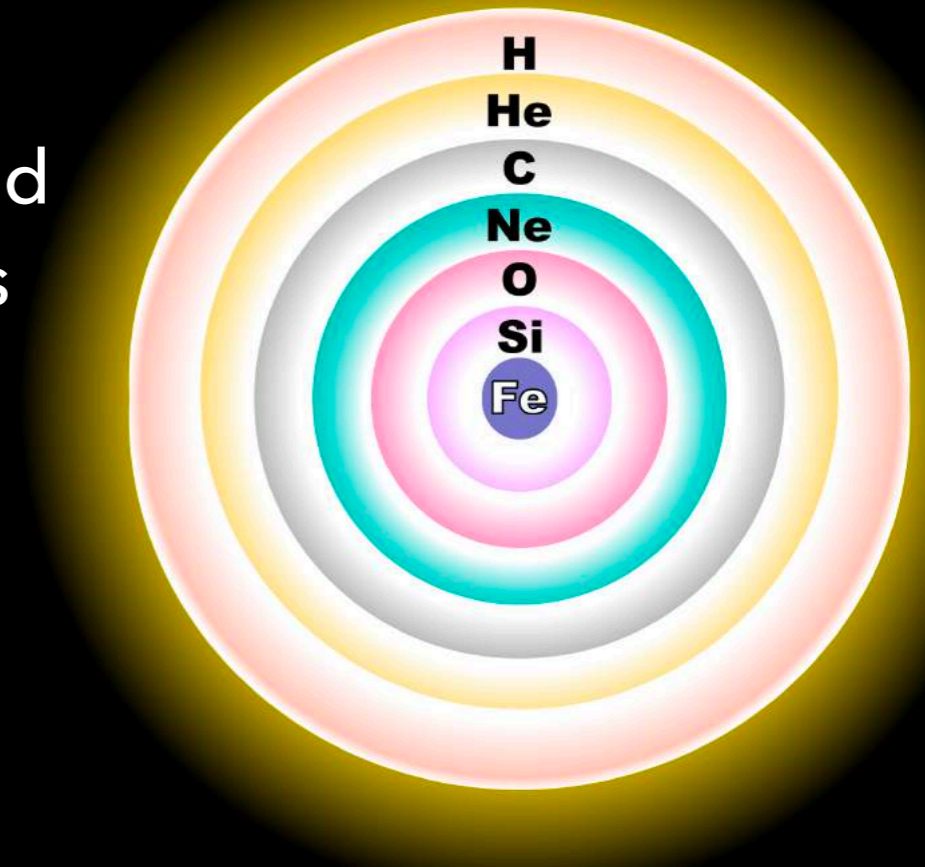
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STELLAR EVOLUTION: AGB STARS

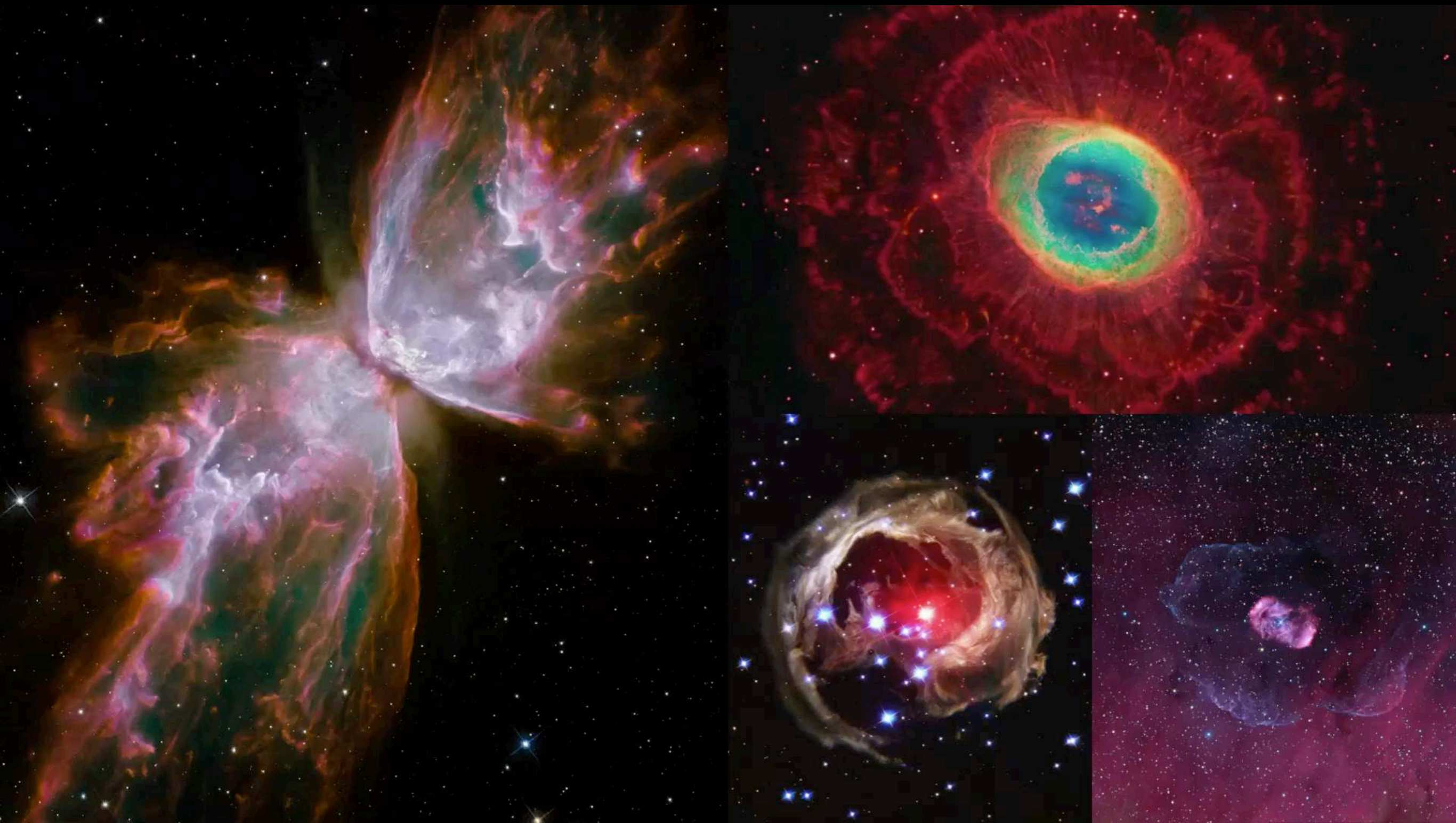


STELLAR EVOLUTION: HIGH-MASS STARS

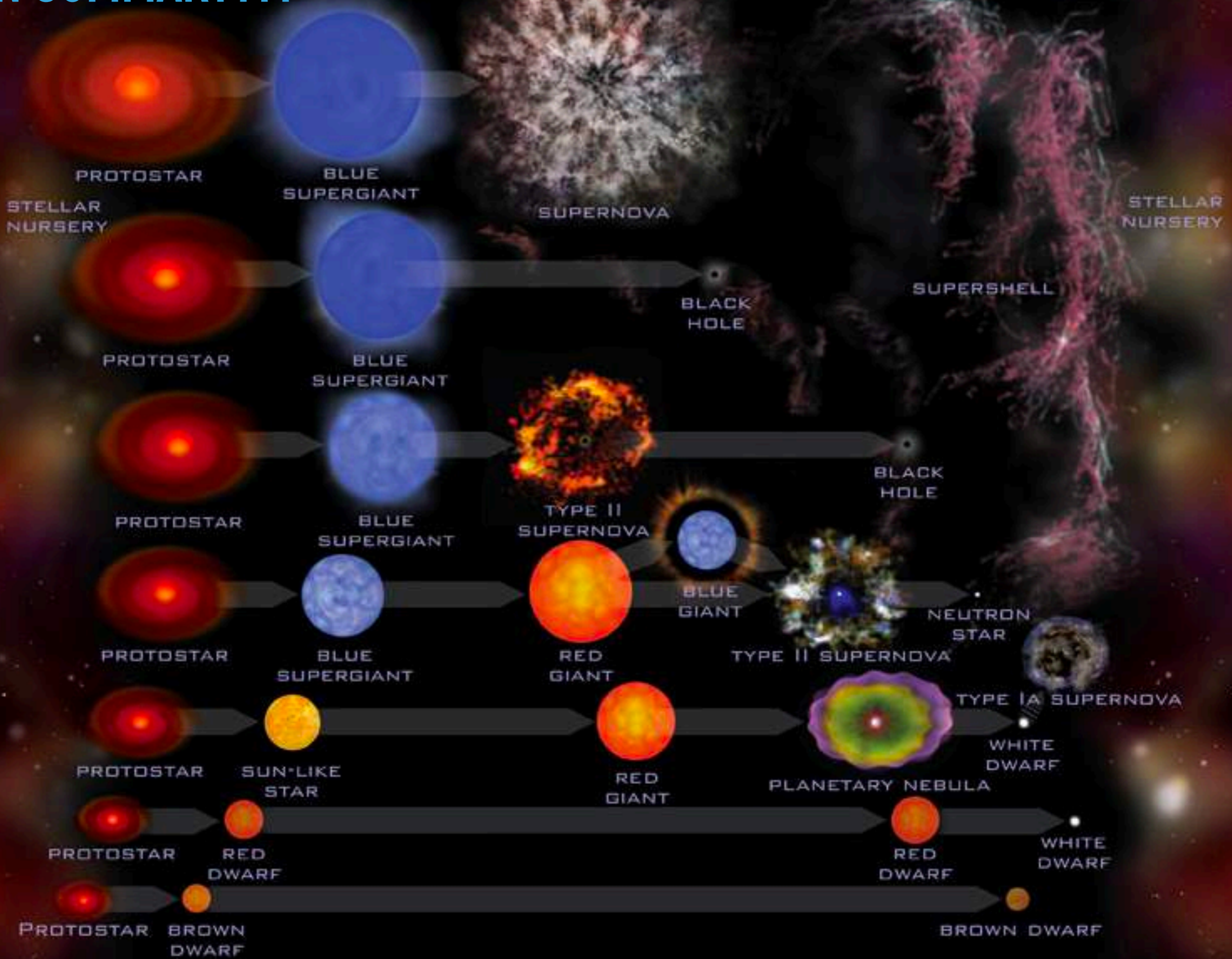
- ▶ Massive stars continue nuclear burning beyond C, but the process becomes progressively less efficient until Fe, which requires more energy than it releases.
- ▶ At this point, the internal structure is made up of concentric layers of different elements.
- ▶ If the mass of the iron core exceeds the **Chandrasekhar limit** (maximum mass for an electron-degenerate system; $\sim 1.4 M_{\text{sun}}$), 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 ($\sim 0.03c$).
- ▶ 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...



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.