

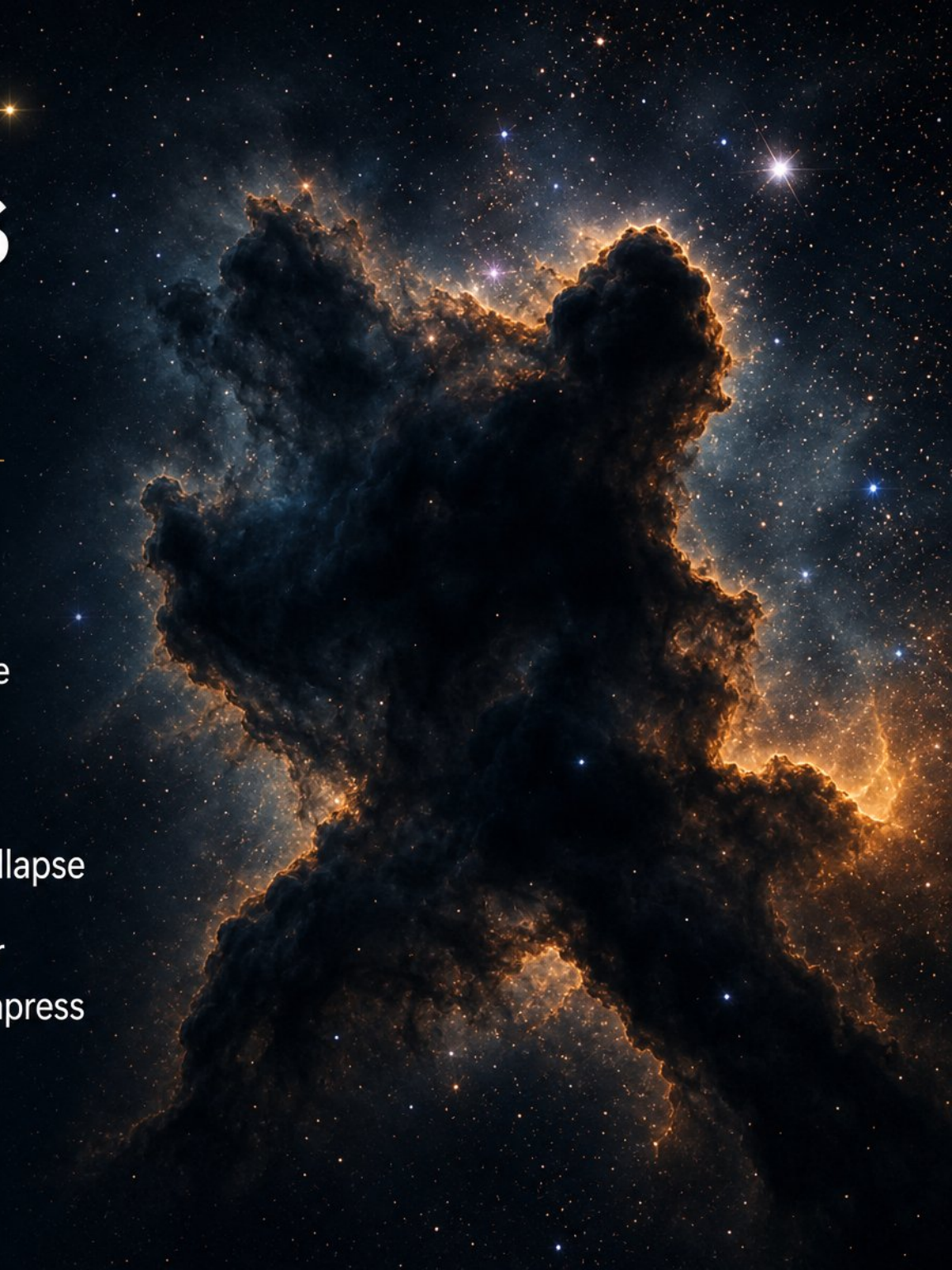
How Stars Form and Evolve

- Traces the full life cycle from interstellar clouds to stellar remnants
- Foundational framework for interpreting nearly all of observational astronomy
- Mass is the primary driver of every stage
- From protostar ignition to final fate as white dwarf, neutron star, or black hole



Birthplaces of Stars

- Molecular clouds: cold, dense regions rich in H₂ and dust
- Gravity compresses gas while turbulence and magnetic fields resist collapse
- Shock waves from supernovae, stellar winds, or cloud collisions can trigger collapse
- Only intermediate-speed shocks trigger collapse; extremes destroy or fail to compress
- Dense filaments within clouds often mark the next stage of star formation



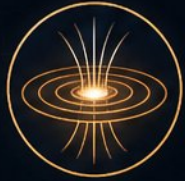
From Cloud Core to Protostar



- Gravitational collapse begins when gravity overcomes thermal pressure



- A dense, opaque core forms, trapping heat and slowing collapse



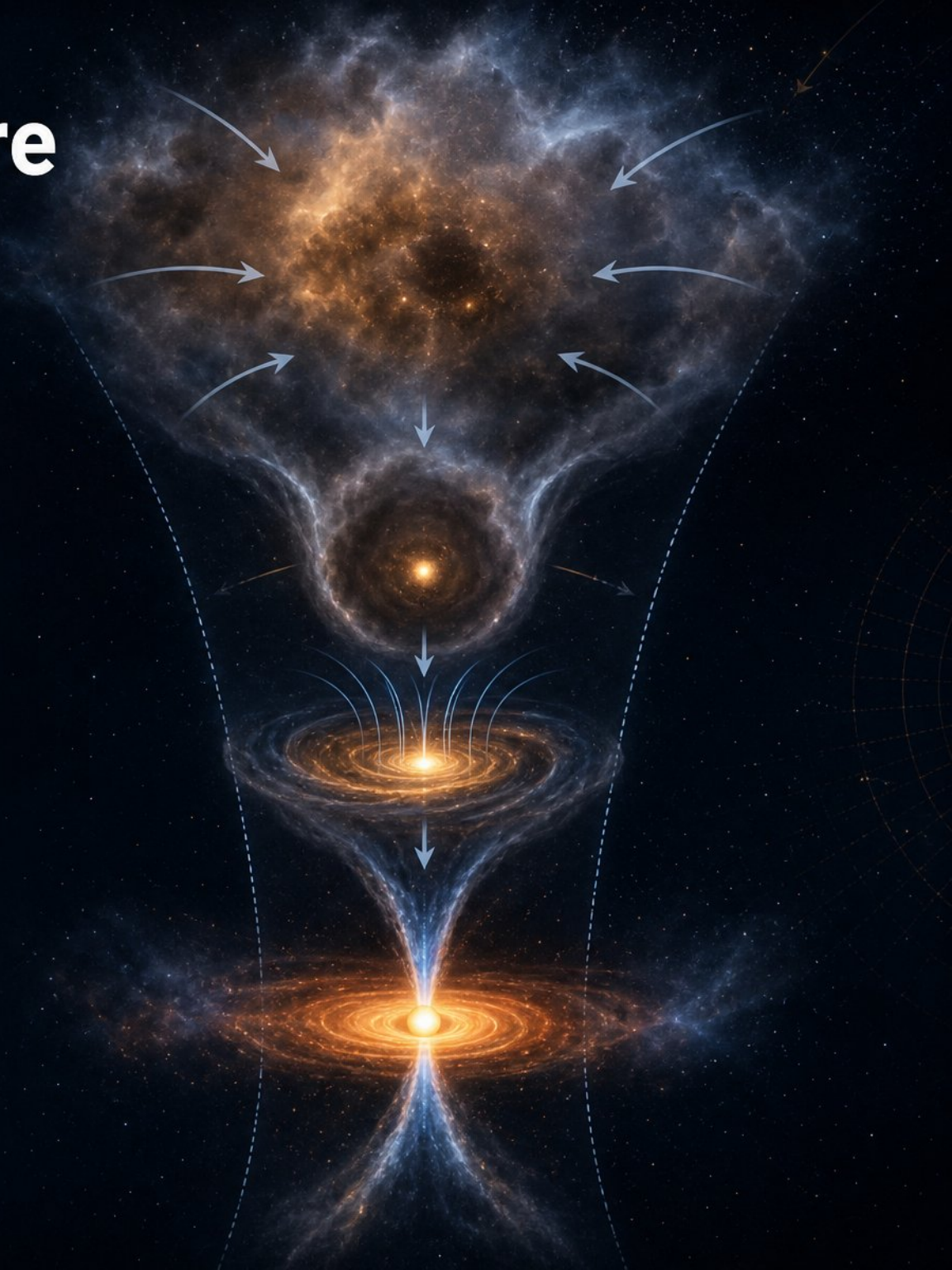
- Rotation and magnetic fields channel infalling gas into a disk



- Accretion feeds the central protostar, releasing gravitational energy

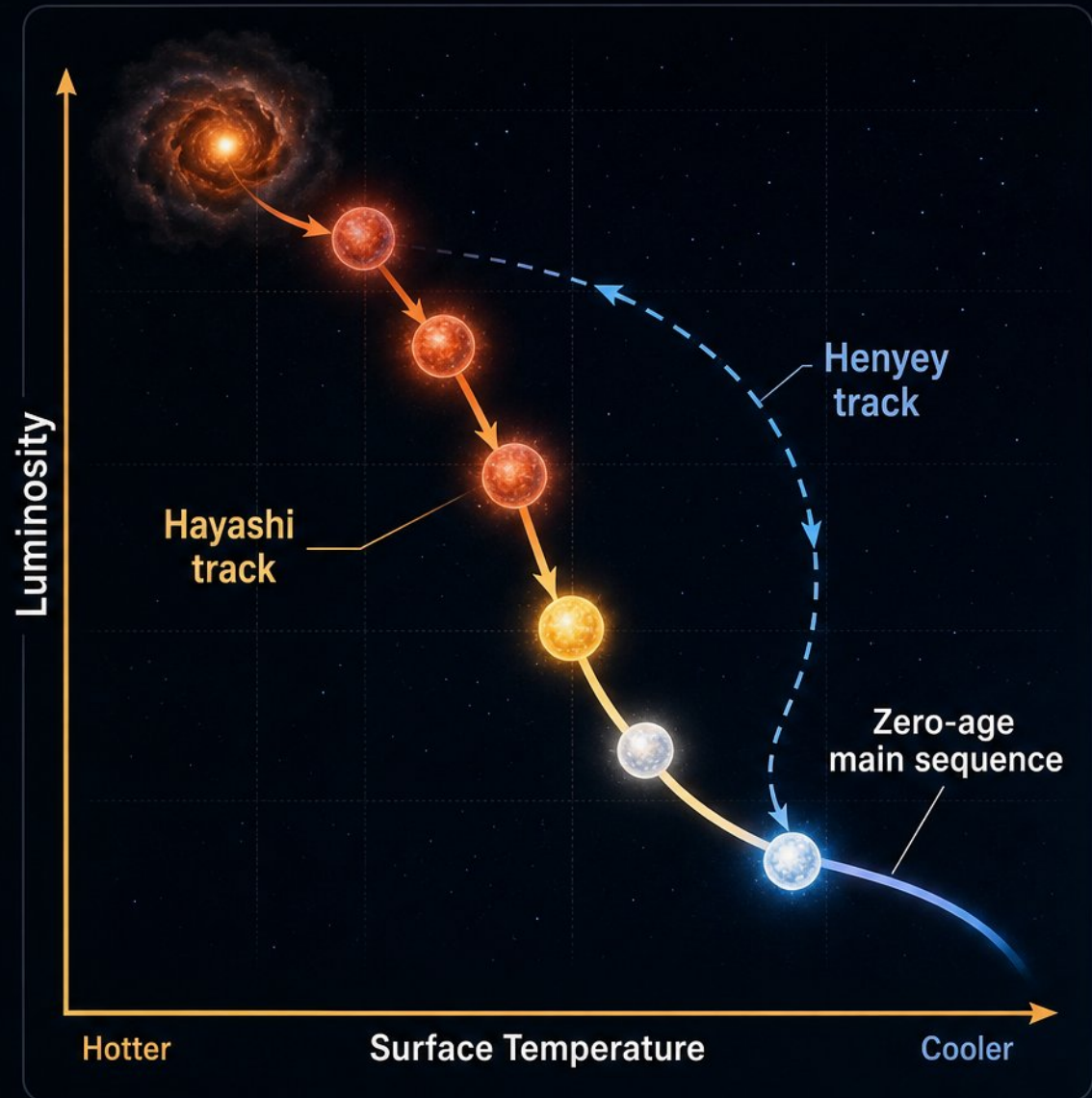


- Bipolar outflows and jets carry away excess angular momentum



The Road to the Main Sequence

- Protostars contract, converting gravitational energy into heat
- Hayashi track: fully convective, nearly constant surface temperature
- Henyey track: radiative core forms, moving toward higher temperatures
- Core reaches ~ 12 million K, igniting hydrogen fusion
- Arrival on the zero-age main sequence marks stable equilibrium



Life on the Main Sequence

- Core hydrogen fusion defines the main sequence
- Mass drives luminosity, temperature, and radius
- Hydrostatic equilibrium balances gravity and pressure
- $L \approx M^{3.5}$ for main-sequence stars
- Low-mass stars burn fuel slowly, lasting billions of years



Why **Massive Stars** Live Fast and Die Young

- Luminosity rises steeply with mass: $L \propto M^{3.5}$
- A 10-solar-mass star is about 10,000 times brighter than the Sun
- More mass means higher core temperature and much faster fusion
- Main-sequence lifetime: $t \propto M / L$, roughly $M^{-2.5}$
- A 10-solar-mass star lasts only ~20 million years
- A 0.5-solar-mass star lasts ~200 billion years, older than the universe



MASS COMPARISON



10-solar-mass star
Very massive



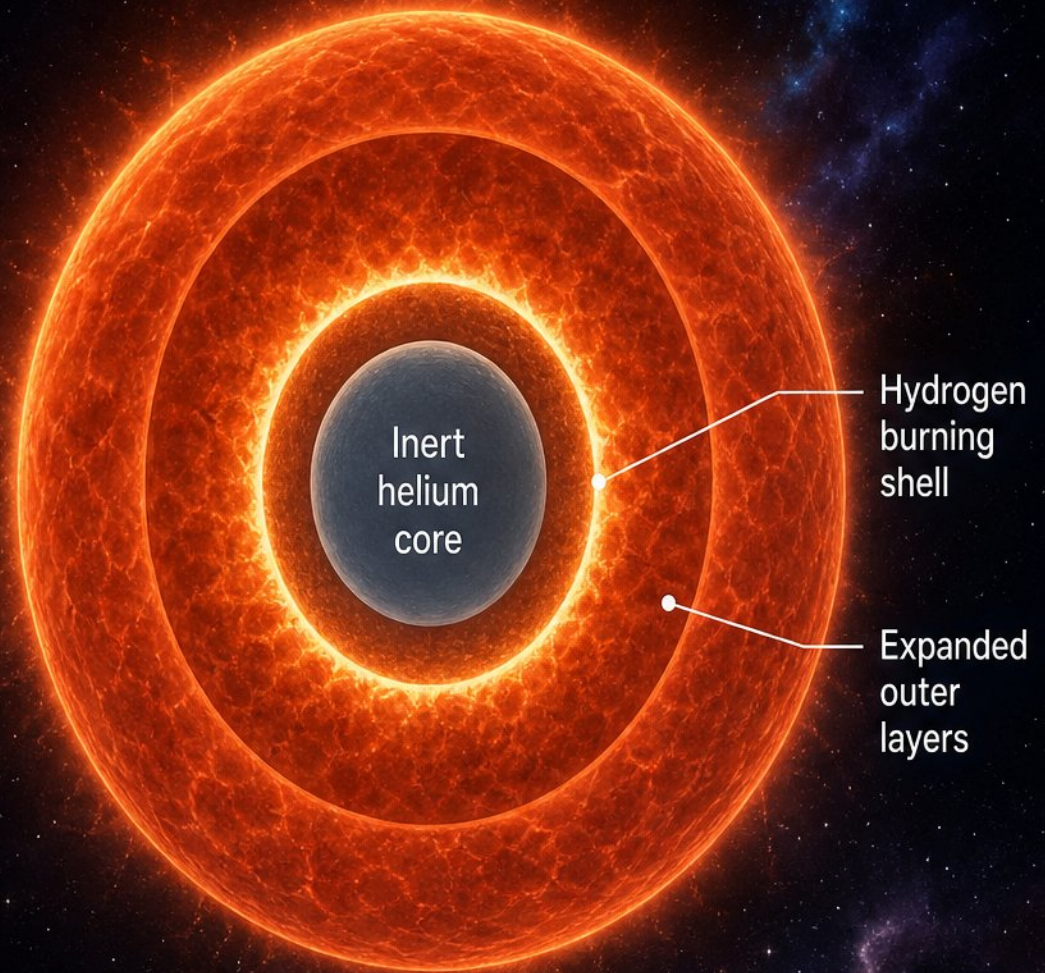
1-solar-mass star
Like the Sun



0.5-solar-mass star
Low mass

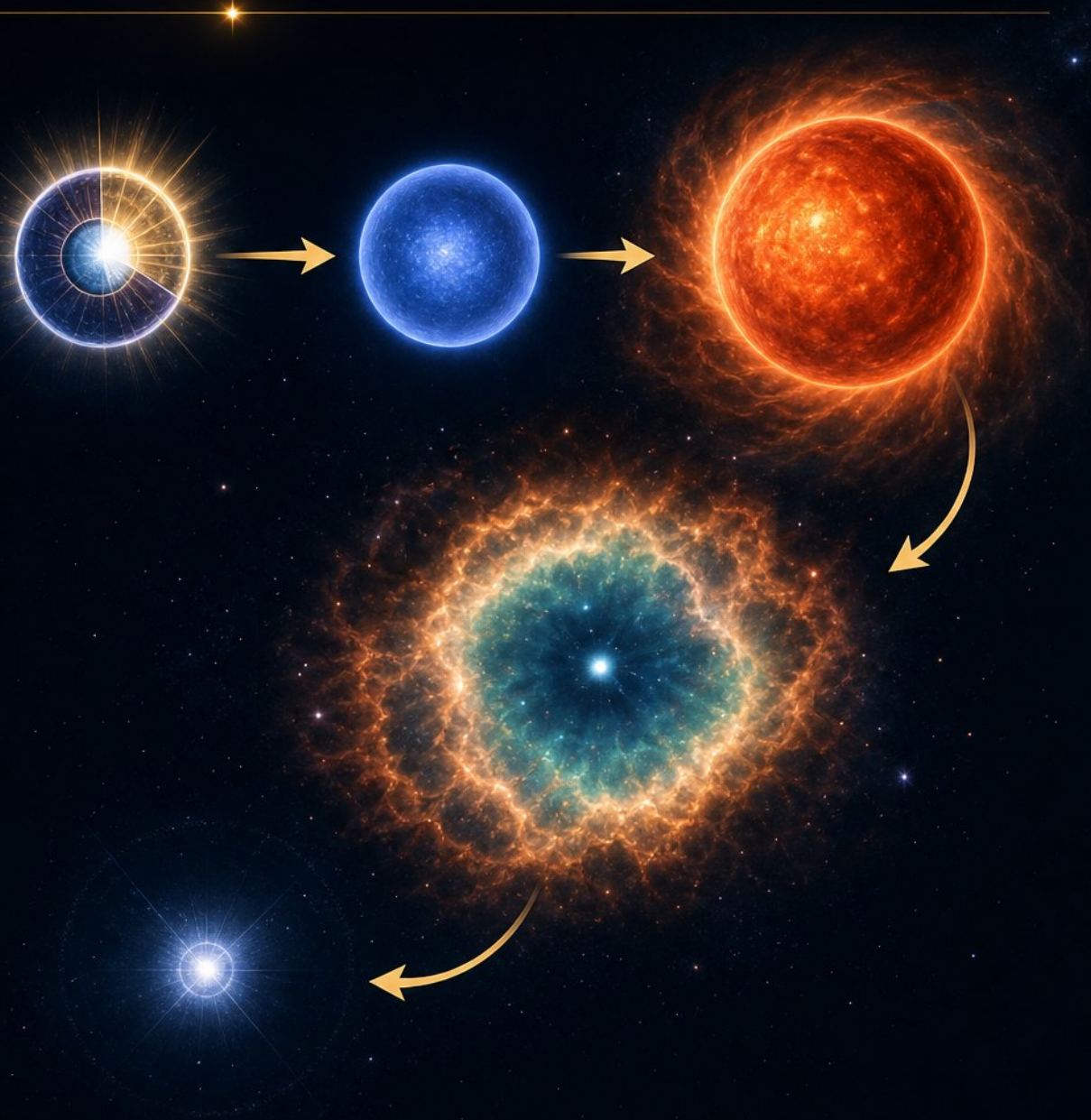
Leaving the Main Sequence

- Core hydrogen exhausted; inert helium core contracts and heats
- Hydrogen shell ignites, pushing outer layers outward
- Star expands and cools, becoming a red giant
- Luminosity rises as the star climbs the red giant branch



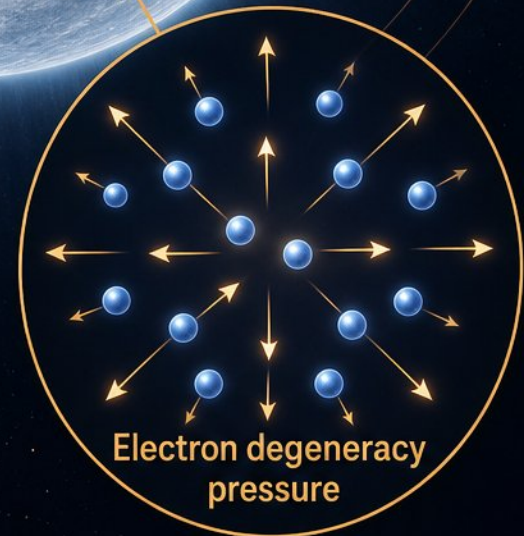
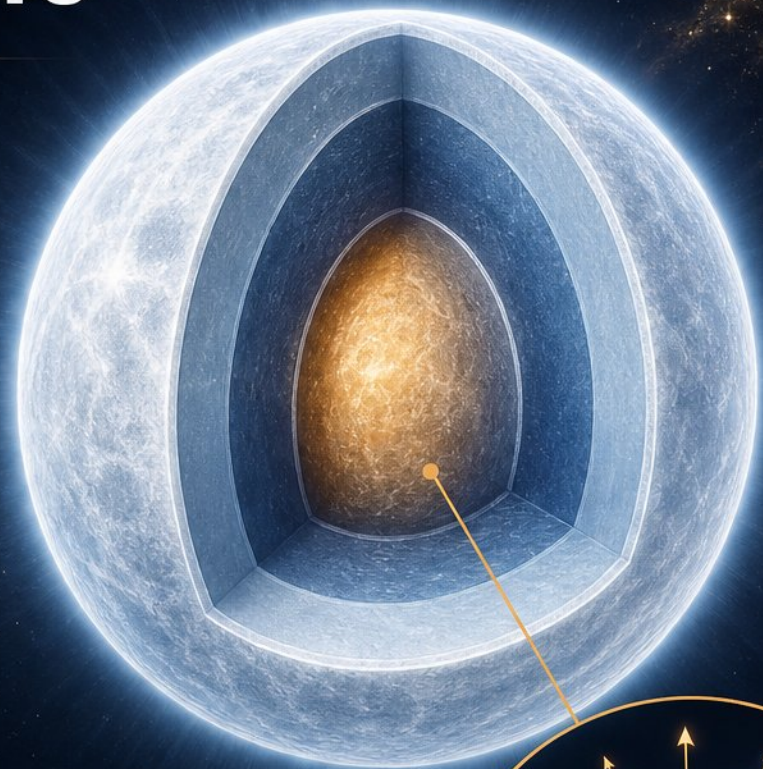
The Fate of Low- and Intermediate-Mass Stars

- **Helium flash:** explosive ignition in a degenerate core
- **Horizontal branch:** stable core helium fusion phase
- **AGB:** double-shell burning of hydrogen and helium
- **Planetary nebula:** ejected glowing outer layers
- **White dwarf:** Earth-sized carbon-oxygen stellar remnant

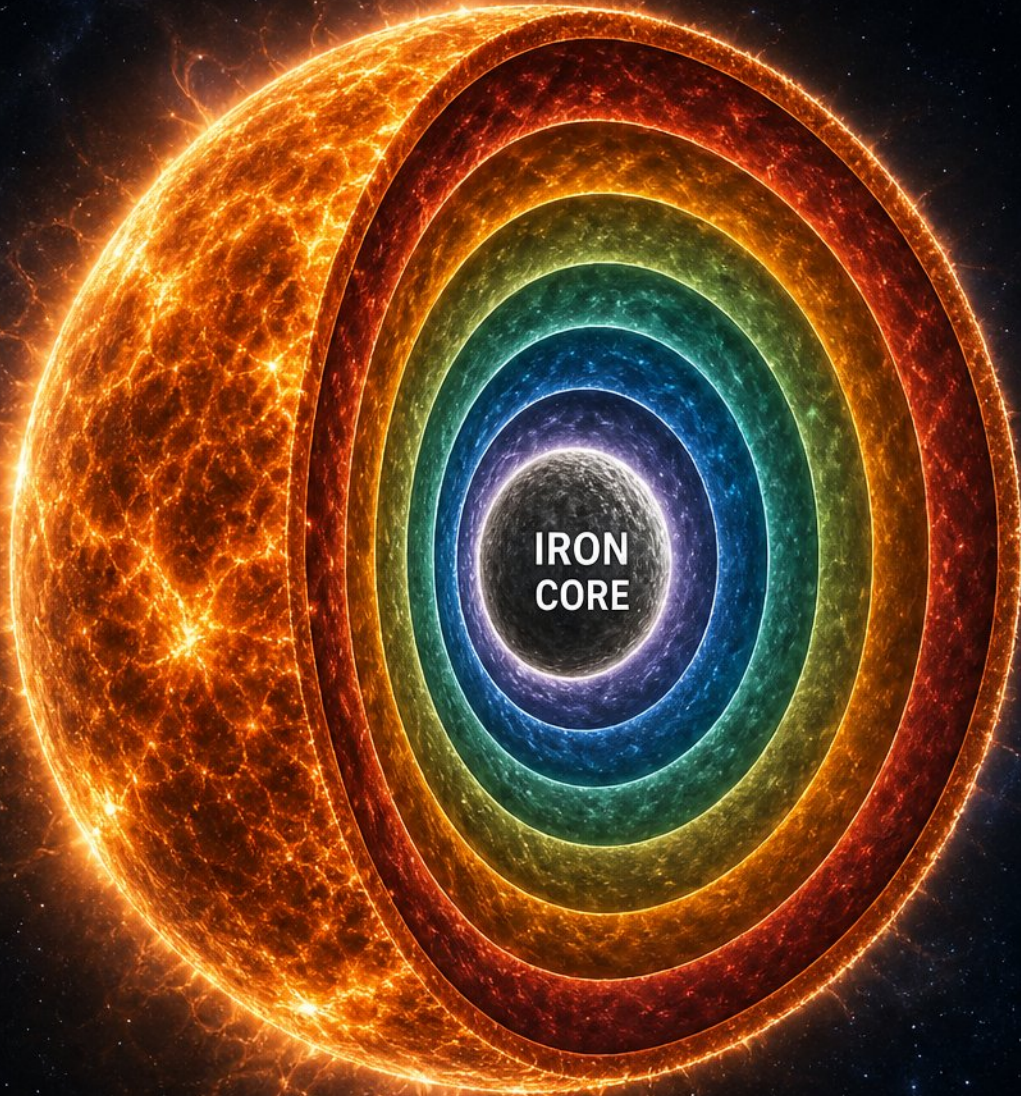


Inside White Dwarfs

- Exposed C-O core: Sun-like mass, Earth-like radius
- Density about a million times that of water
- Supported by electron degeneracy pressure, not fusion
- Chandrasekhar limit: maximum stable mass ~ 1.4 solar masses
- Cools over billions of years, fading toward a black dwarf



The Violent End of High-Mass Stars



- Advanced fusion builds an inert iron core
- Fusing iron absorbs energy, triggering collapse
- Core rebounds, launching a shock wave
- Neutrinos power the supernova explosion
- Remnant becomes neutron star or black hole

Neutron Stars and Black Holes

- Born from massive star core collapse in supernova explosions
- Neutron stars: ultra-dense, supported by neutron degeneracy pressure
- Pulsars: rotating neutron stars emitting regular radiation beams
- Black holes: gravity wins; no known force stops collapse
- Black hole evidence: X-ray binaries with unseen massive companions



Comparing Stellar Remnants

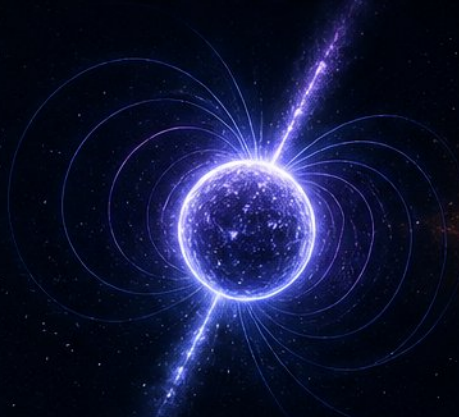
WHITE DWARF



EARTH-SIZED

~ The size of Earth

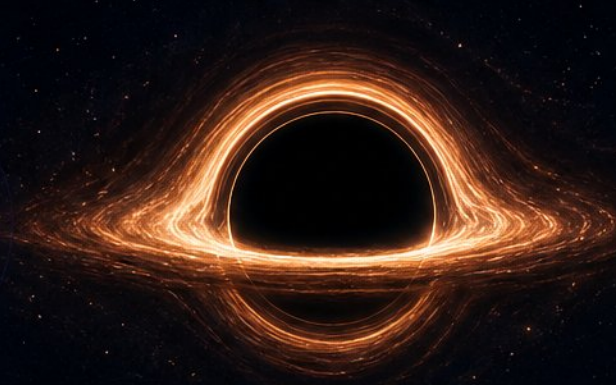
NEUTRON STAR



CITY-SIZED

~ The size of a city

BLACK HOLE



MUCH LARGER

~ Far beyond a star or planet

MASS COMPARISON

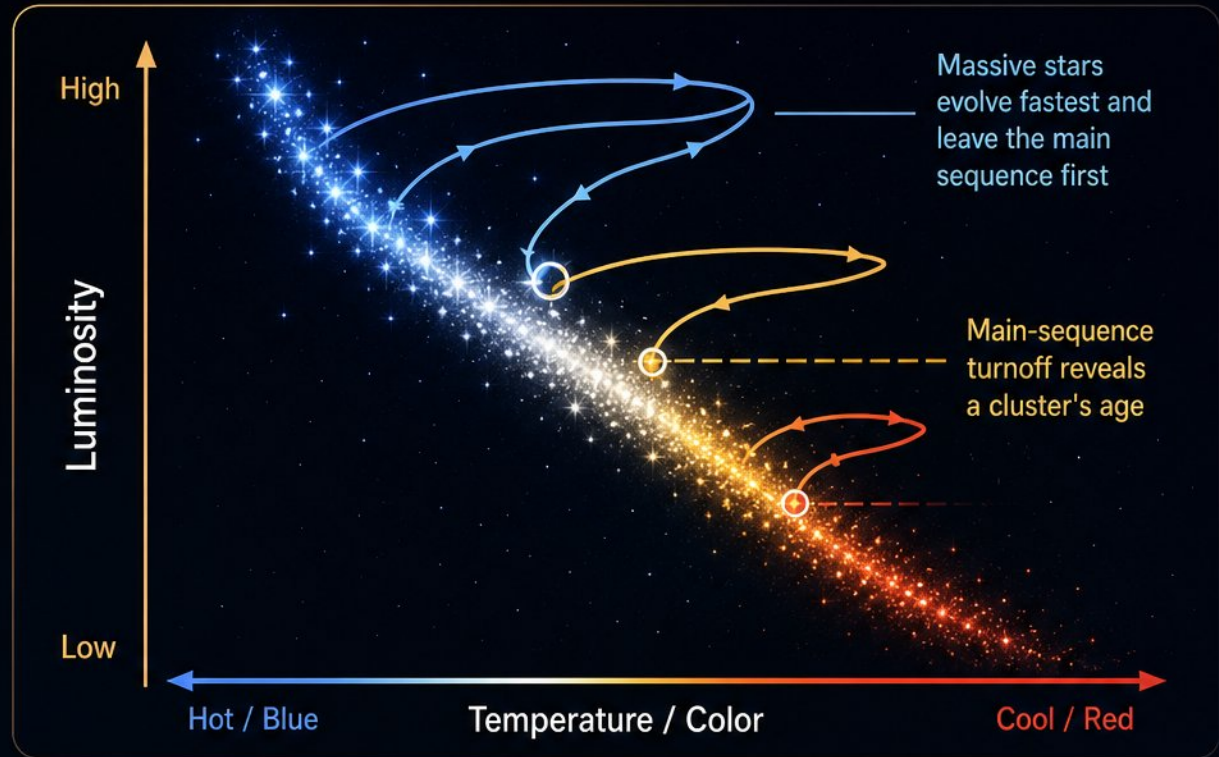


INCREASING MASS

- White dwarfs: Earth-sized, electron degeneracy pressure, max ~1.4 solar masses
- Neutron stars: city-sized, neutron degeneracy pressure, born in core collapse
- Black holes: gravity wins completely, no known force prevents collapse
- Initial mass is the primary factor determining the final remnant
- Type Ia: exploding white dwarf; core-collapse: dying massive star

Reading Stellar Evolution in the H-R Diagram

- H-R diagram plots luminosity versus temperature or color
- Massive stars evolve fastest and leave the main sequence first
- Main-sequence turnoff reveals a cluster's age
- Young clusters retain bright blue stars; old clusters do not
- Globular clusters show ancient ages over 11 billion years



YOUNG CLUSTER



Retains bright blue stars

INTERMEDIATE-AGE CLUSTER



Fewer bright blue stars

OLD / GLOBULAR CLUSTER



Does not retain bright blue stars

Key Takeaways and Common Misconceptions



- Mass is the primary driver of stellar evolution



- Stars don't explode simply because they run out of fuel



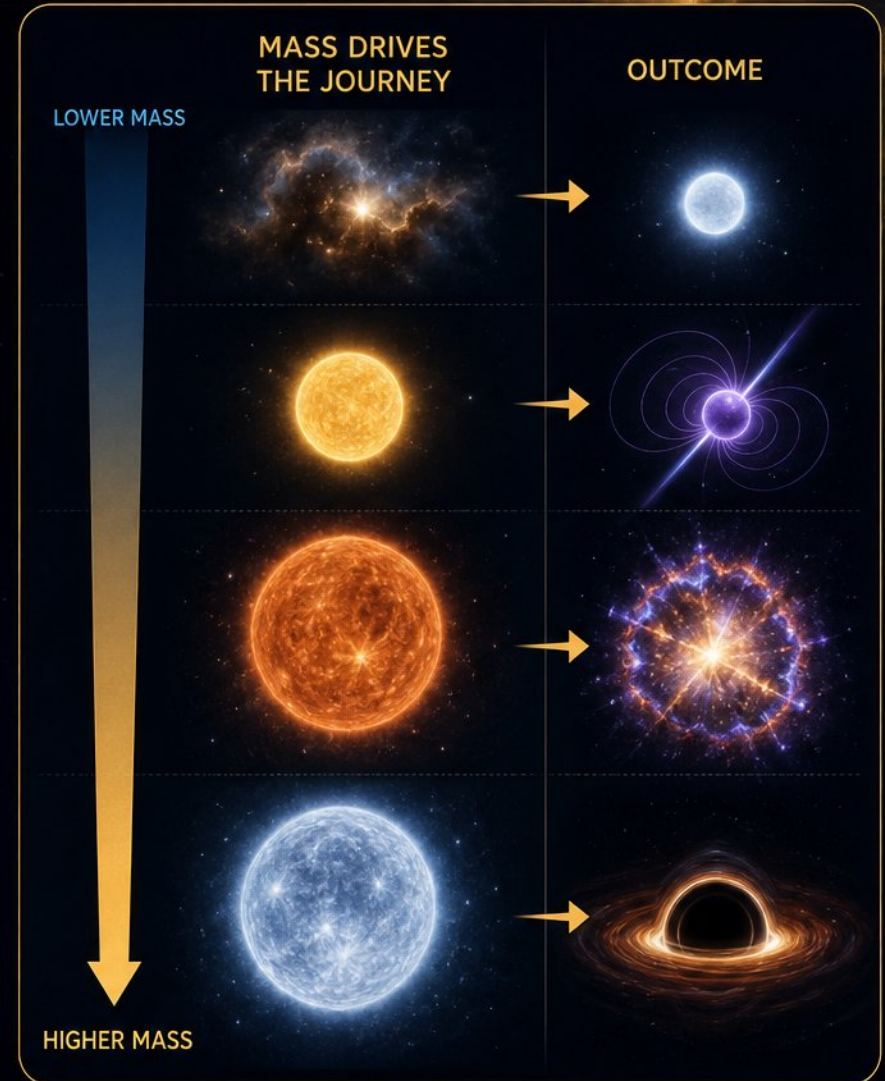
- Supernovae create, not just destroy, heavy elements



- H-R diagrams link observations to stellar life cycles



- White dwarfs, neutron stars, and black holes are normal endpoints



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