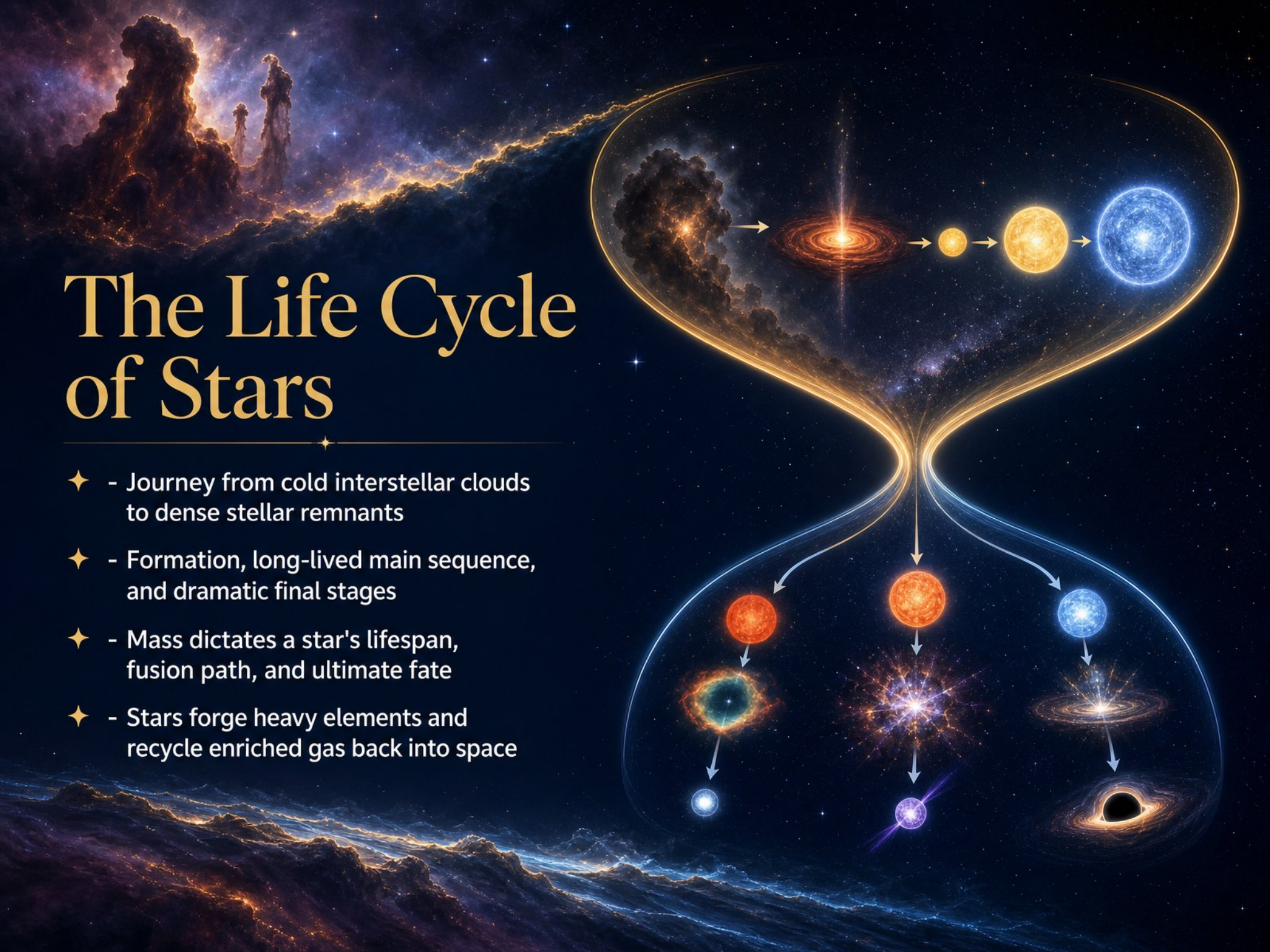
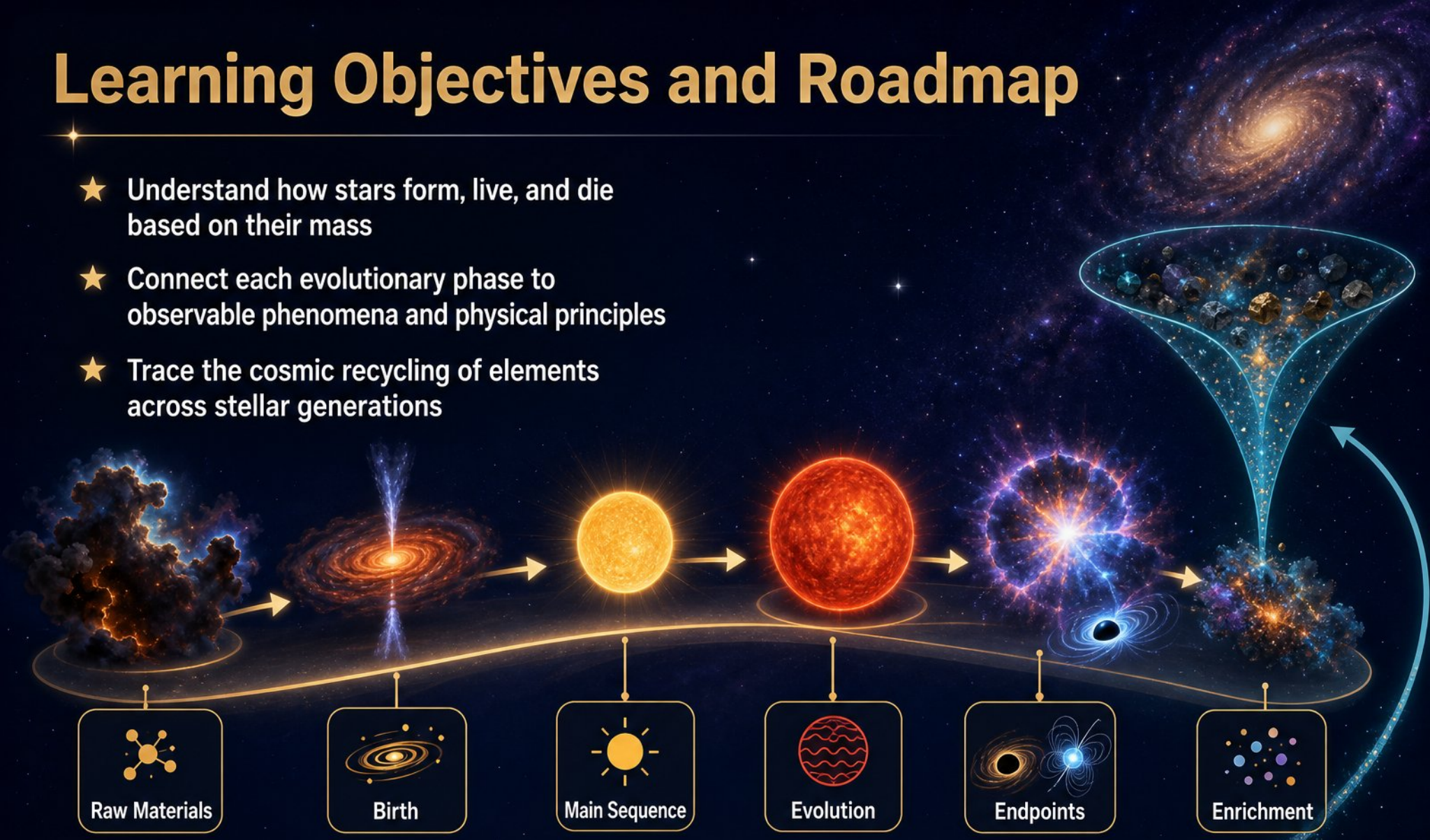
The Life Cycle of Stars

- Journey from cold interstellar clouds to dense stellar remnants
- Formation, long-lived main sequence, and dramatic final stages
- Mass dictates a star's lifespan, fusion path, and ultimate fate
- Stars forge heavy elements and recycle enriched gas back into space



Learning Objectives and Roadmap

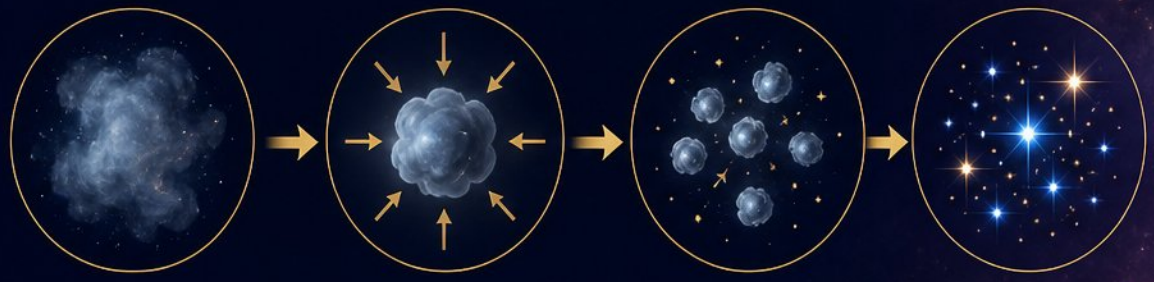
- ★ Understand how stars form, live, and die based on their mass
- ★ Connect each evolutionary phase to observable phenomena and physical principles
- ★ Trace the cosmic recycling of elements across stellar generations



Course roadmap: Raw Materials → Birth → Main Sequence → Evolution → Endpoints → Enrichment

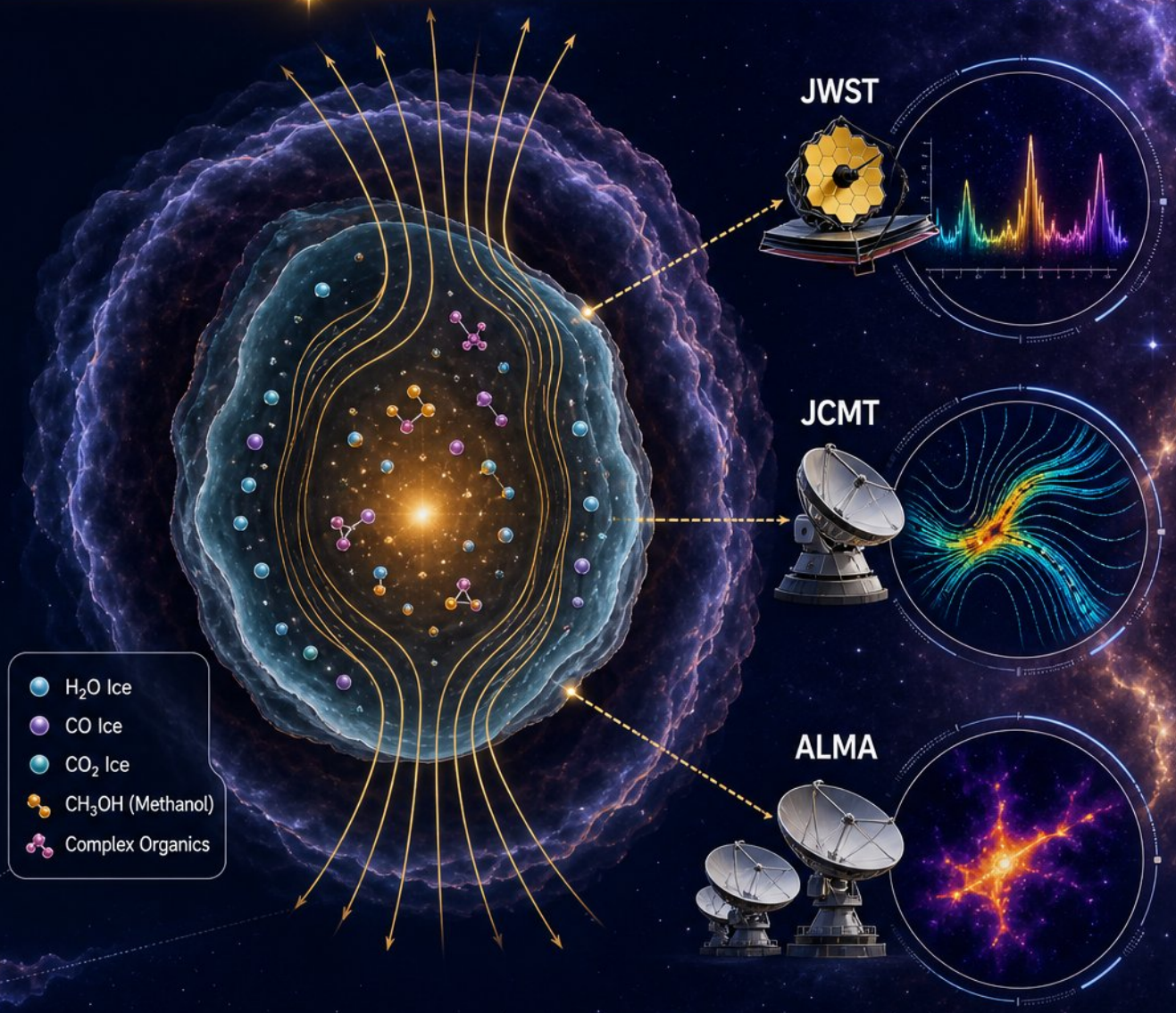
Cosmic Raw Materials: Giant Molecular Clouds

- Composed of cold gas (~10-20 K) and dust, up to millions of solar masses
- Gravity triggers collapse when mass exceeds the Jeans instability criterion
- Fragmentation causes a single cloud to form entire star clusters
- Orion Molecular Cloud Complex: the nearest massive star-forming region



Inside Orion's Stellar Nursery: Latest Discoveries

- **JWST** reveals ice chemistry and structure of prestellar cores in Orion A
- **Deuterium fractionation** acts as an evolutionary clock for starless cores
- **JCMT** and **ALMA** map magnetic fields shaping filament fragmentation
- **Methanol and complex organics** are common in cores, suggesting prebiotic chemistry



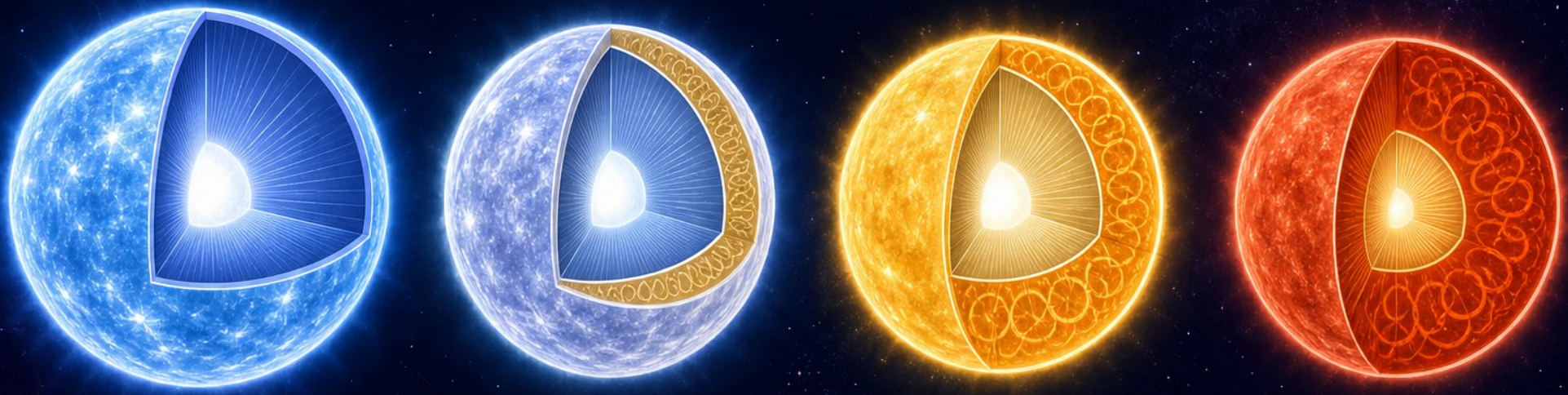
Protostars:

The Birth of a Star

- Collapsing core evolves through Class 0 to Class III stages
- Accretion disks feed mass while jets eject excess material
- Hydrostatic equilibrium begins, balancing gravity and pressure
- Observed via infrared and millimeter-wave telescopes penetrating dust

The Main Sequence: A Star's Longest Chapter

- **Hydrogen fusion:** p-p chain for low-mass, CNO cycle for high-mass stars
- **Mass–luminosity relation:** more mass means exponentially more light
- **Internal structure:** radiative vs. convective zones by spectral type
- **ZAMS** marks the start; slow, steady changes during core hydrogen burning



O
Hot, Massive
Mostly Radiative

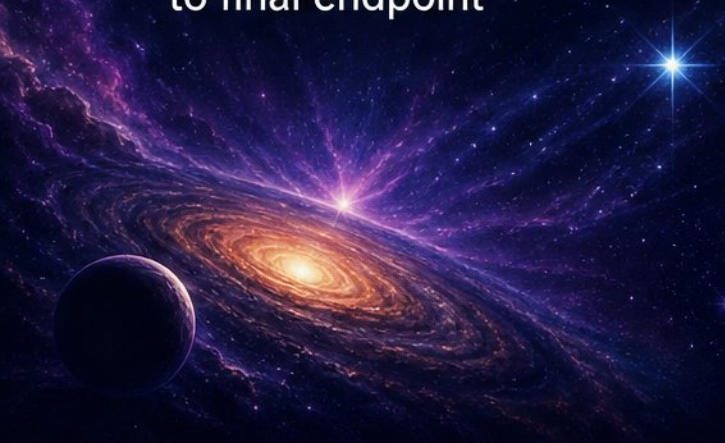
A
Hot, Intermediate
Radiative Core, Thin Convective Envelope

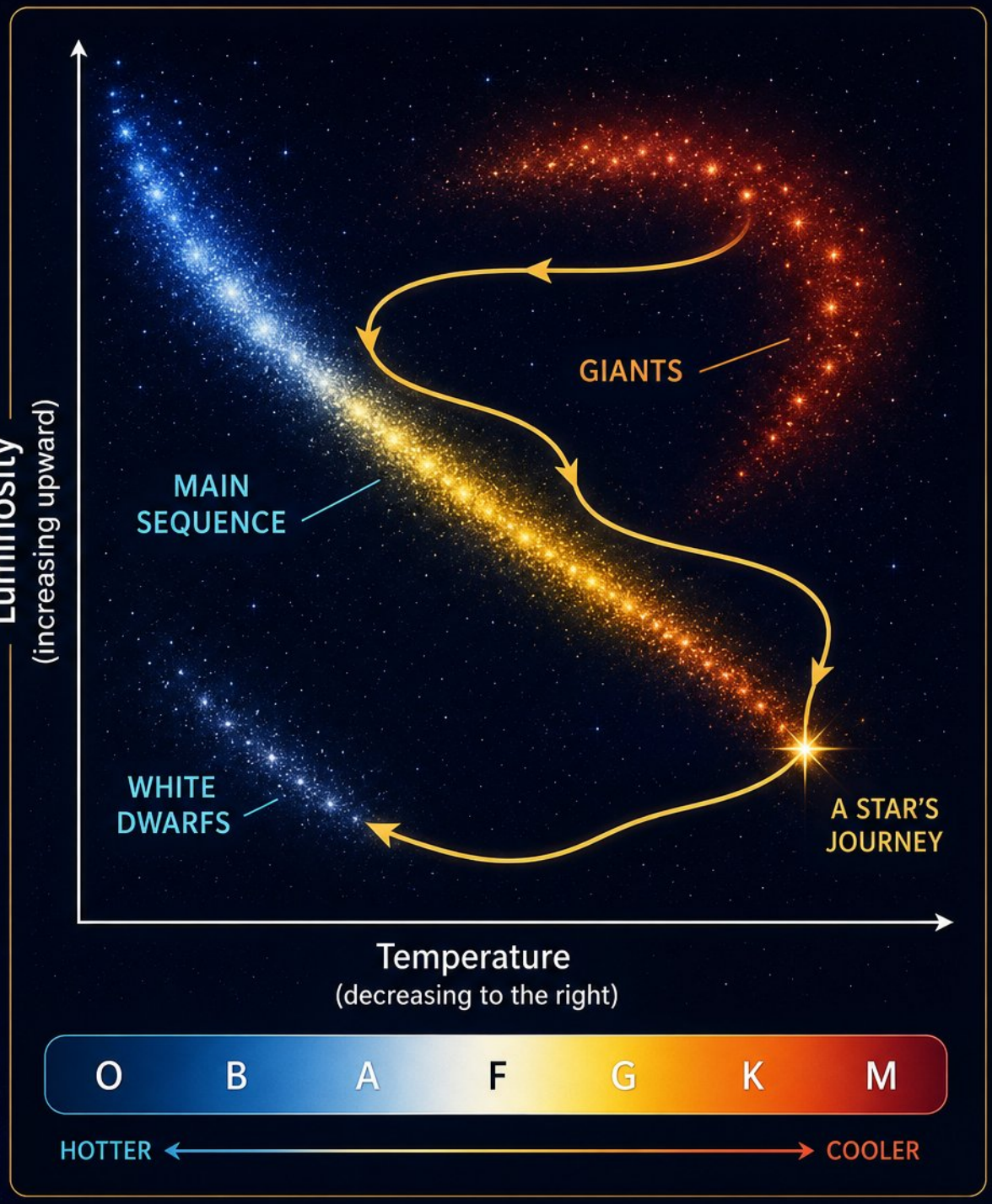
G
Sun-like
Radiative Core, Thick Convective Envelope

M
Cool, Low-mass
Mostly Convective

Reading the H-R Diagram

- The most important map in stellar astrophysics
- Main sequence, giants, and white dwarfs in distinct zones
- Luminosity vs. temperature reveals evolution stage
- OBAFGKM sequence links color, temperature, and fusion
- Track a star's path from birth to final endpoint



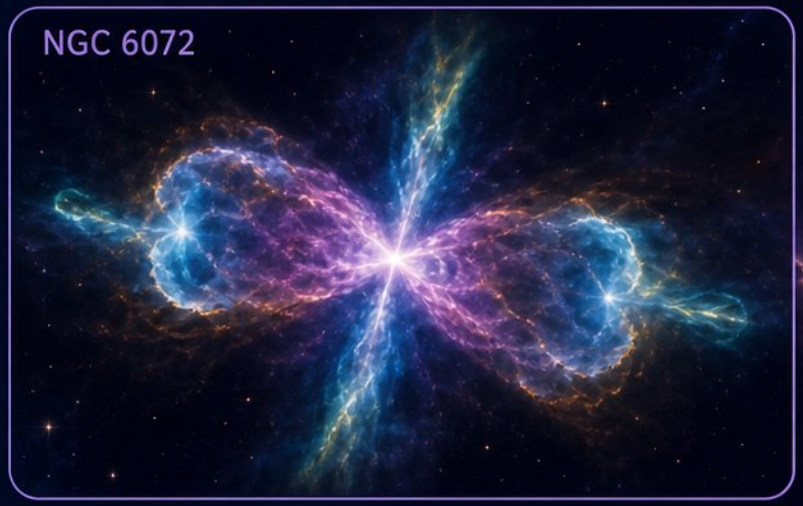


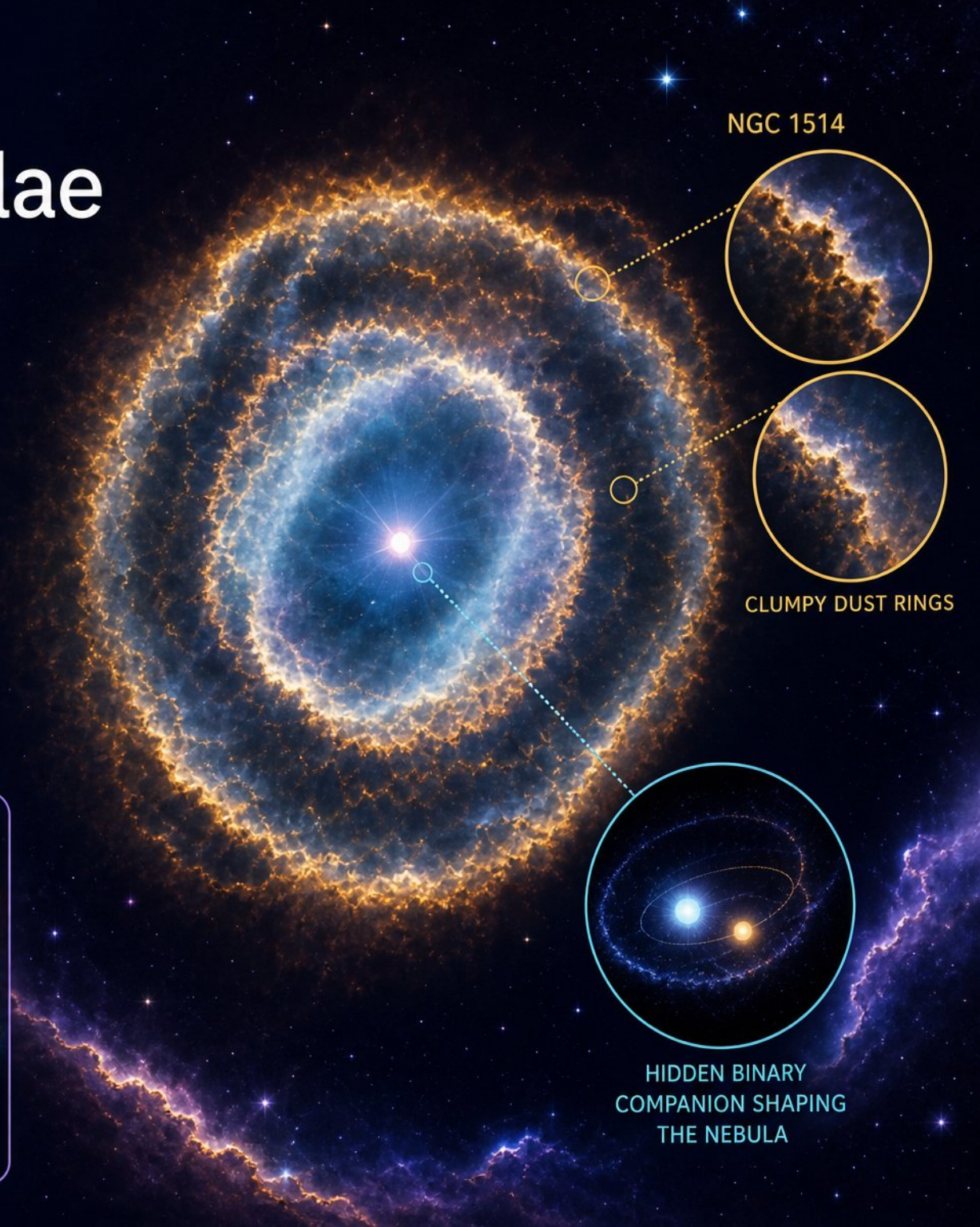
When the Core Runs Out: Post-Main-Sequence Evolution

- Hydrogen-depleted core shrinks; hydrogen-burning shell ignites around it
- Shell burning dramatically inflates the star into a red giant or supergiant
- Evolutionary path splits by mass: low-mass, solar-type, and massive stars
- Helium ignition begins a new fusion phase, sometimes via the helium flash

Gentle Endings: Planetary Nebulae

- Late thermal pulses eject the stellar envelope as an expanding shell
- Exposed hot core ionizes the ejected gas, making the nebula glow
- JWST reveals NGC 1514's clumpy dust rings and NGC 6072's multi-polar outflows
- Complex morphologies often point to hidden binary companions



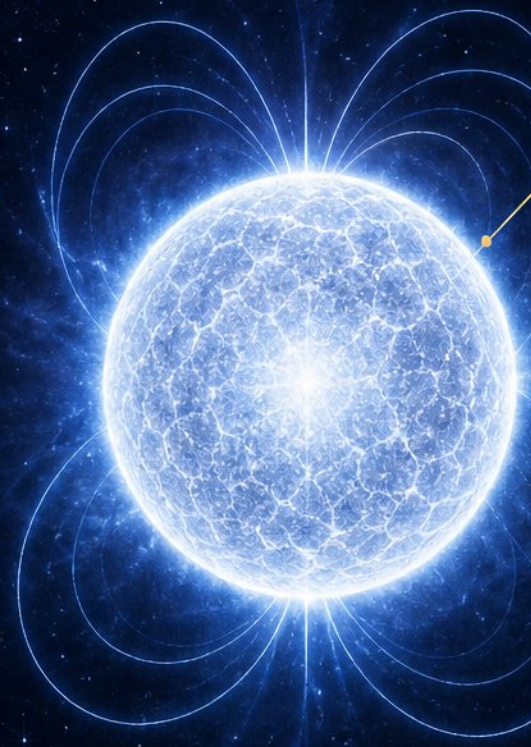


White Dwarfs:
The Fading Embers

- Exposed stellar core supported by electron degeneracy pressure—no ongoing fusion
- Chandrasekhar limit (~1.4 solar masses) marks the maximum stable white dwarf mass
- Cools and fades over billions of years, serving as a cosmic clock
- Composition layers record the nuclear burning history of the progenitor star

FIELD GUIDE: STELLAR REMNANT

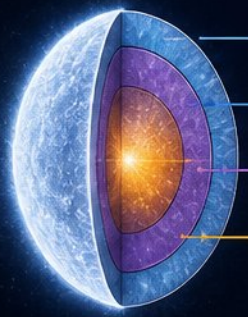
WHITE DWARF



MASS
~1.4 solar masses (maximum stable mass)

TEMPERATURE
Extremely hot surface

COOLING AGE
Billions of years and counting



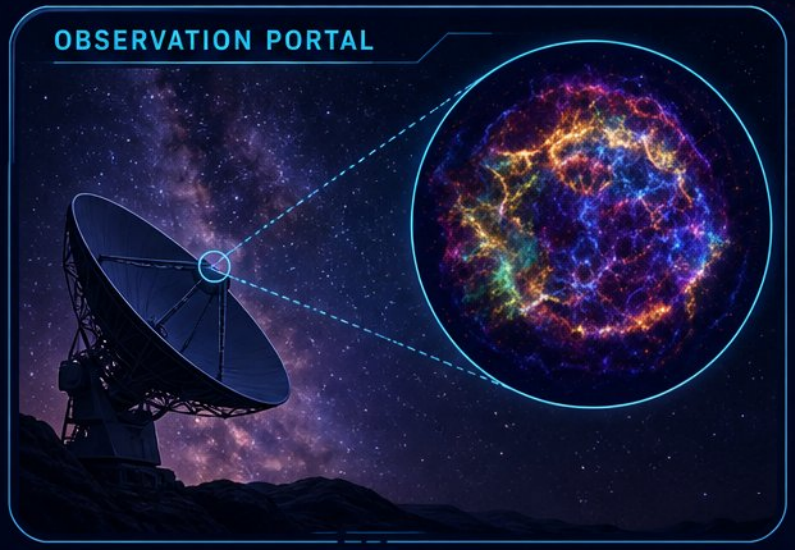
Layers preserve the chemical makeup and nuclear burning history of the progenitor star.

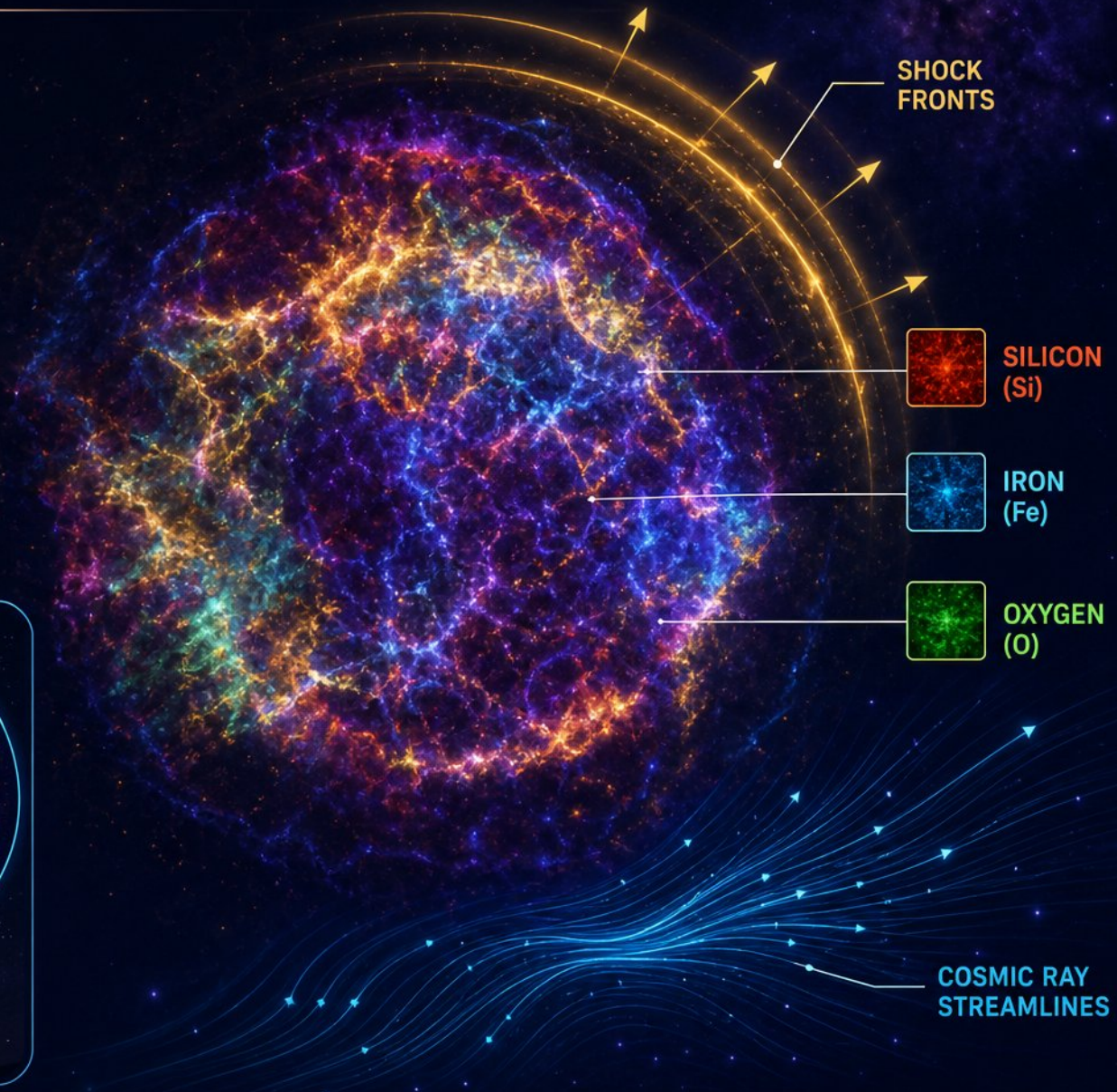
Catastrophic Finales: Core-Collapse Supernovae

- Massive stars build onion-like fusion shells, ending with inert iron
- Iron core collapse triggers a rebound shockwave that destroys the star
- Light curves reveal explosion energy and newly synthesized elements
- Remnants: ultra-dense neutron stars or stellar-mass black holes

Supernova Remnants: Shocks and Enrichment in Action

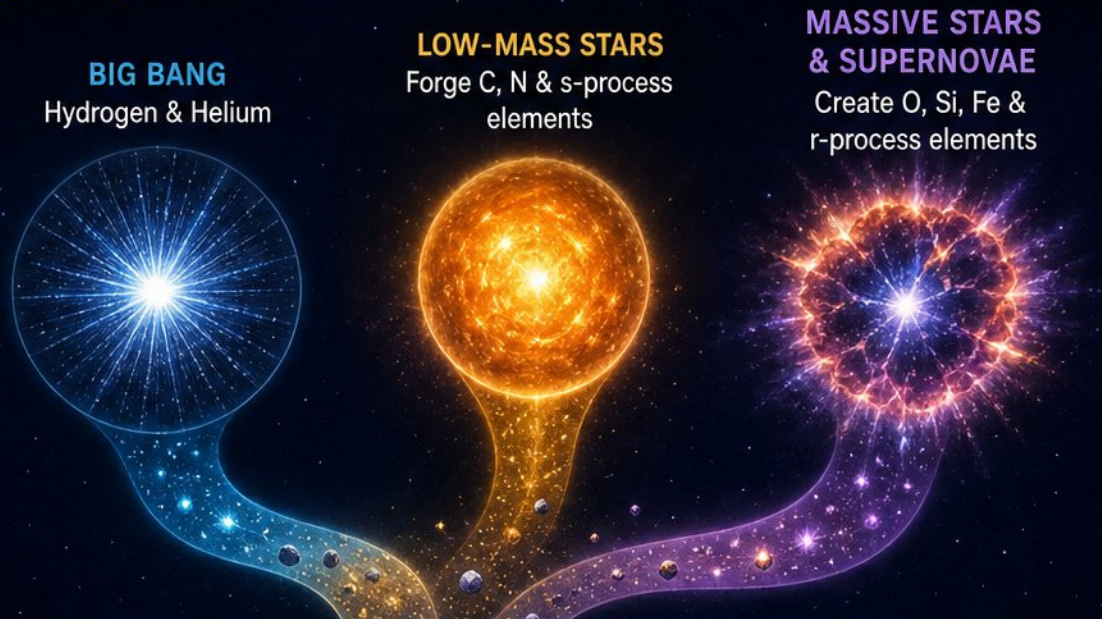
- Remnants expand and collide with surrounding interstellar gas
- Shock fronts heat gas to millions of degrees and accelerate cosmic rays
- Cassiopeia A maps reveal distribution of newly forged elements
- Orion BN/KL outflows serve as a nearby shock-physics laboratory





How Stars Forge the Elements

- Big Bang gave us hydrogen and helium; stars made everything else
- Low-mass stars forge carbon, nitrogen, and heavy s-process elements
- Massive stars and supernovae create oxygen, silicon, iron, and r-process elements
- JWST and ALMA detect complex molecules and dust in star-forming regions



BIG BANG
Hydrogen & Helium

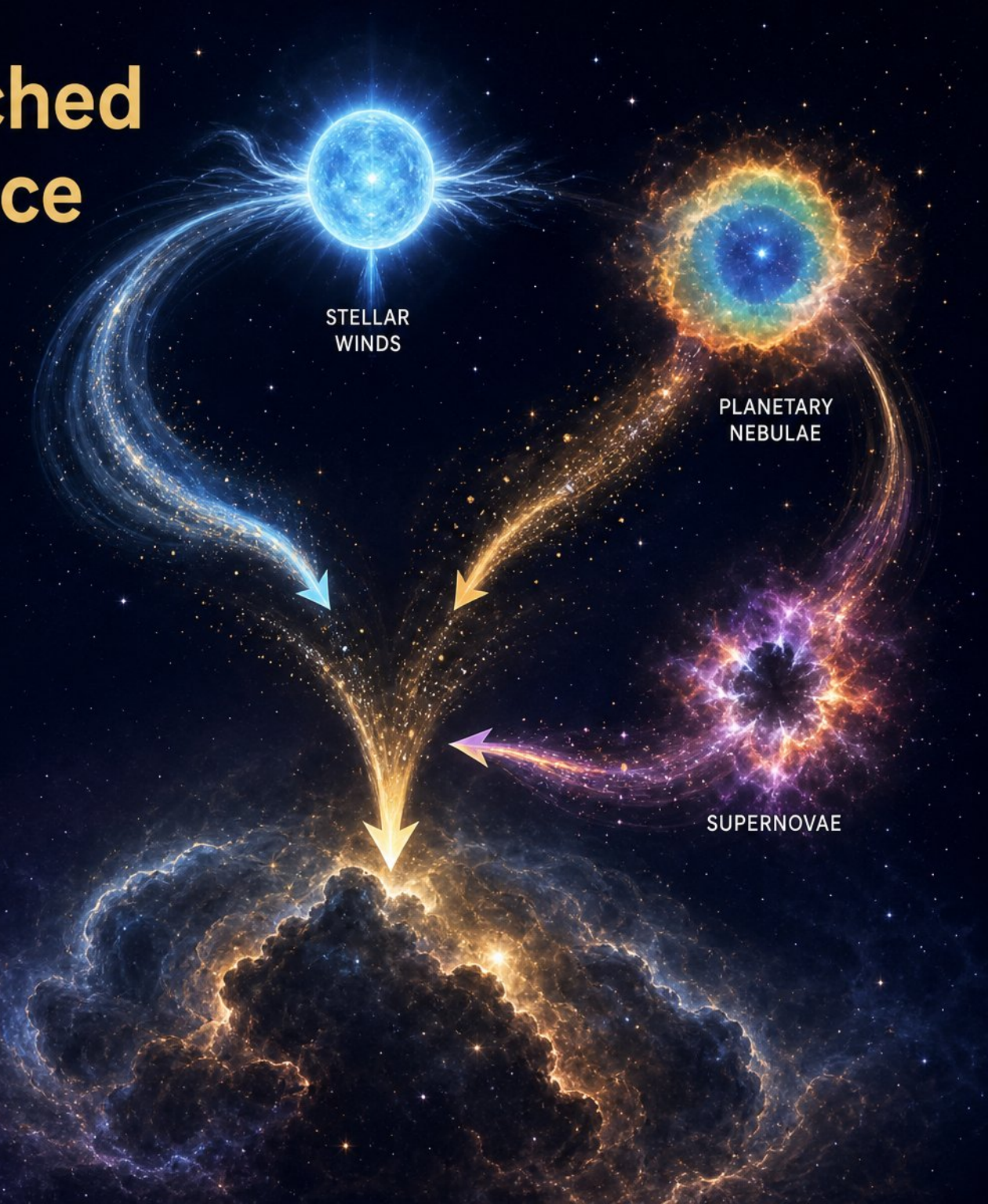
LOW-MASS STARS
Forge C, N & s-process elements

MASSIVE STARS & SUPERNOVAE
Create O, Si, Fe & r-process elements

H																	He
He												B	C	N	O	F	Ne
Li	Be											Al	Si	P	S	Cl	Ar
Na	Mg											Ga	Ge	As	Se	Br	Kr
Rb	Sr	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	In	Sn	Sb	Te	I	Xe
Cs	Ba	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg						Og
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Returning Enriched Material to Space

- Stellar winds, planetary nebulae, and supernovae recycle gas and dust
- Mass-loss rates and composition vary dramatically by stellar type
- Supernova ejecta mix into the interstellar medium over millions of years
- The Orion-Eridanus superbubble shows local feedback and enrichment in action



The Grand Cycle: From Stardust to Stardust

- Recycled gas and dust seed new generations of stars and planets
- Successive stellar generations drive the chemical evolution of galaxies
- Heavy elements in later-generation stars like our Sun provide observable evidence
- Every atom in our bodies (except hydrogen) was forged in a star that died

Summary and Key Takeaways

- Stars undergo continuous birth, evolution, death, and rebirth
- Mass determines lifespan, fusion path, and final remnant
- Stars are the universe's element factories and chemical engines
- Modern observatories reveal details at every stage

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