

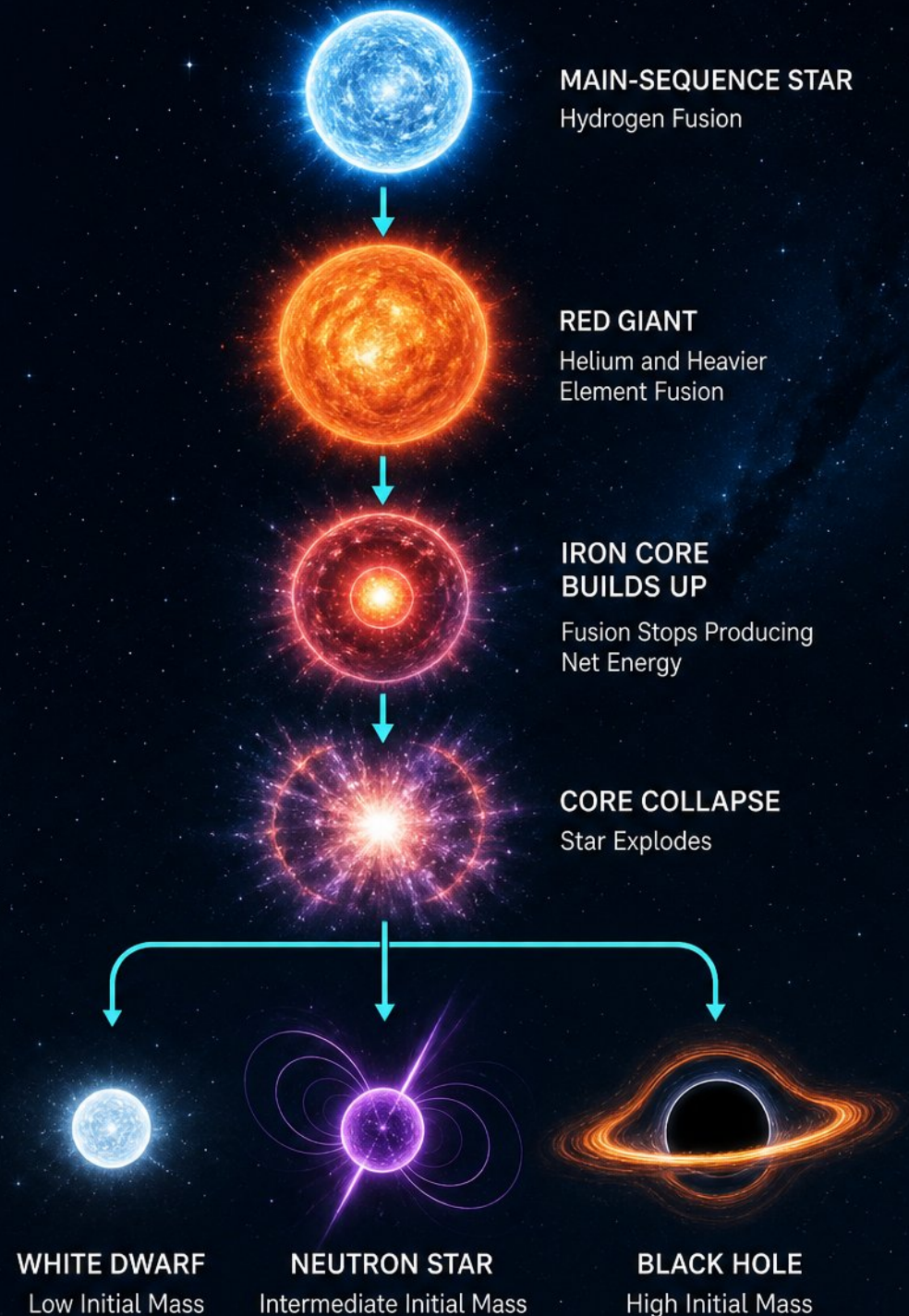
Neutron Stars and Stellar Remnants: An Introduction

- Stellar remnants: compact end states after nuclear fusion ceases
- Three main types: white dwarfs, neutron stars, black holes
- A star's initial mass determines its final remnant
- Training roadmap: evolution, supernovae, remnants, extreme physics



Stellar Evolution: The Road to a Remnant

- - Stars fuse hydrogen to helium, then heavier elements up to iron
- - Gravity pulls inward; radiation pressure from fusion pushes outward
- - When iron accumulates, fusion stops producing net energy
- - Core collapses once internal pressure can no longer support the star
- - Initial mass sets the final remnant: white dwarf, neutron star, or black hole



Supernovae:

The Birth of Neutron Stars

- Core-collapse: iron core stops fusing, gravity wins
- Thermonuclear: white dwarf explosions, often leave no remnant
- Collapsing core rebounds, forming a neutron star
- Shockwave and neutrinos eject the outer layers
- Very massive stars may collapse into black holes instead



What Is a Neutron Star?

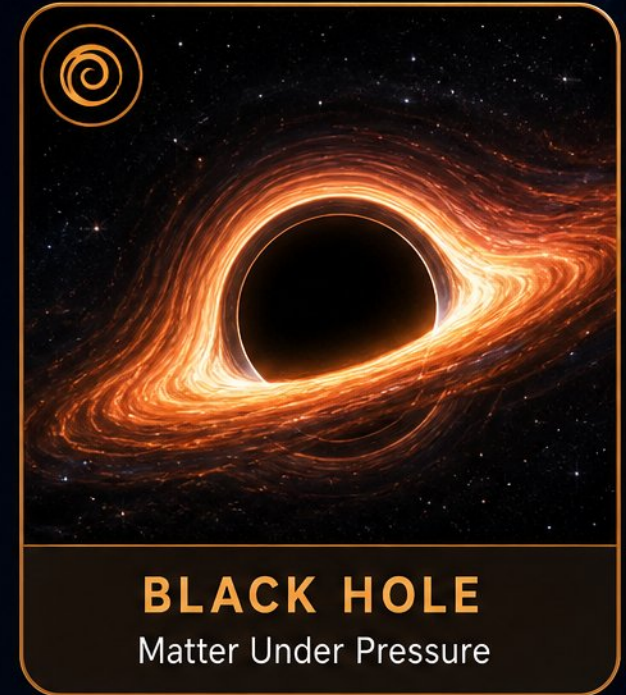
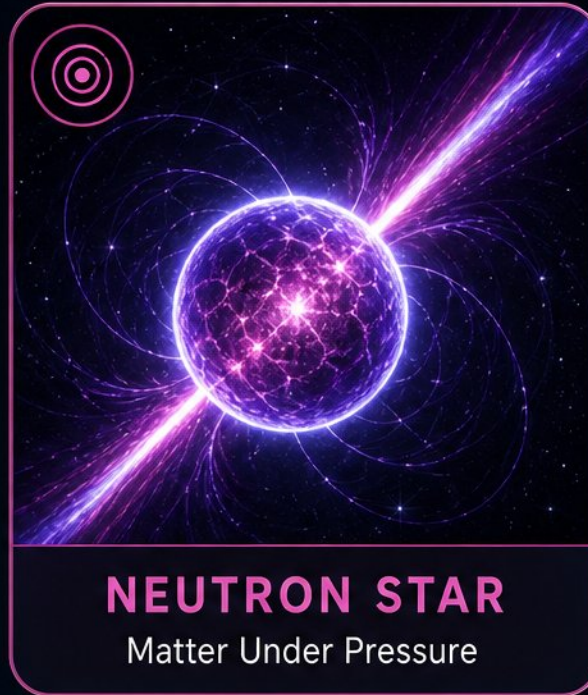
- City-sized object with roughly 1.4 solar masses
- Extreme density: a teaspoon weighs billions of tons
- Made of neutron-rich matter supported by degeneracy pressure
- Rotating neutron stars with strong magnetic fields are pulsars
- Current observations point to radii of about 11–13 km



SCALE LADDER



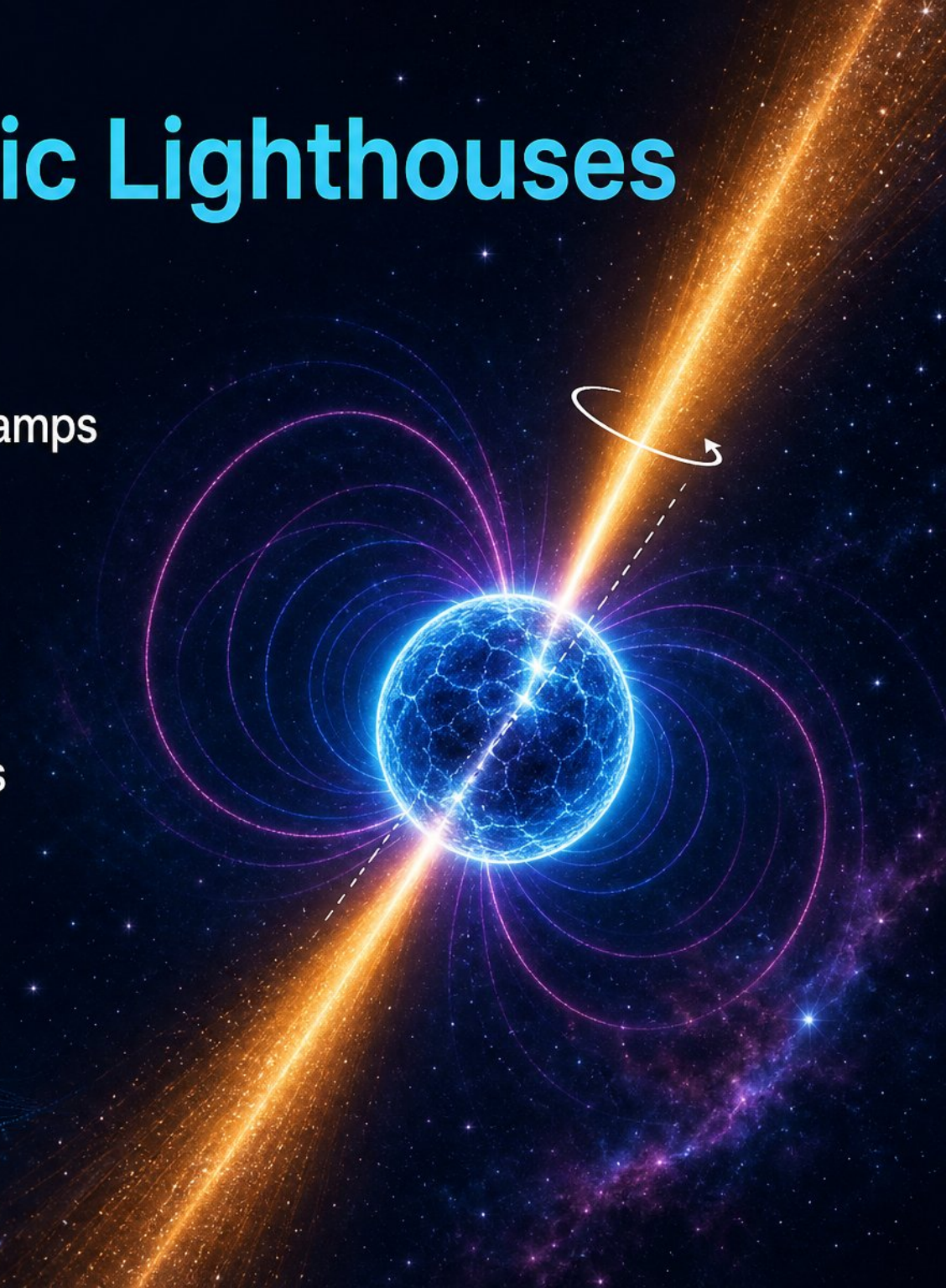
Other Remnants: White Dwarfs and Black Holes



- White dwarfs: end state for low- to intermediate-mass stars
- Neutron stars vs. stellar-mass black holes: key physical contrasts
- Chandrasekhar limit caps white dwarf mass
- Tolman-Oppenheimer-Volkoff limit bounds neutron star mass

Pulsars: Cosmic Lighthouses

- Misaligned magnetic poles sweep beams like lighthouse lamps
- Detection happens only when a beam crosses Earth
- Pulsar timing offers natural, extremely stable cosmic clocks
- 3,500+ known pulsars map the neutron star population



Magnetars:

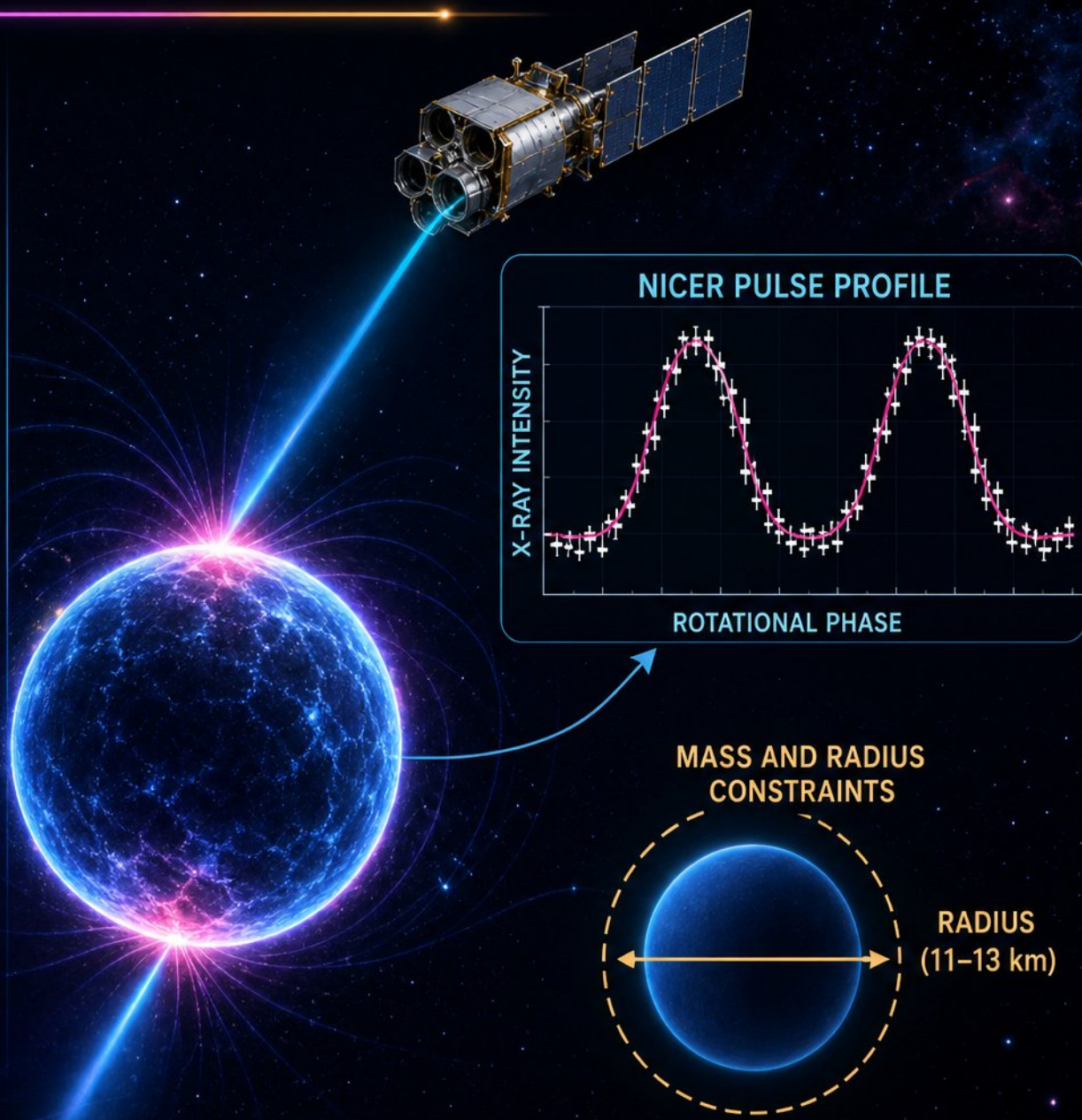
Neutron Stars with Extreme Magnetic Fields

- Neutron stars with magnetic fields a thousand times stronger than typical
- Ultra-strong fields power giant flares and burst outbursts
- Magnetar activity is linked to mysterious fast radio bursts
- SGR 1935+2154 is the most active magnetar of the past decade

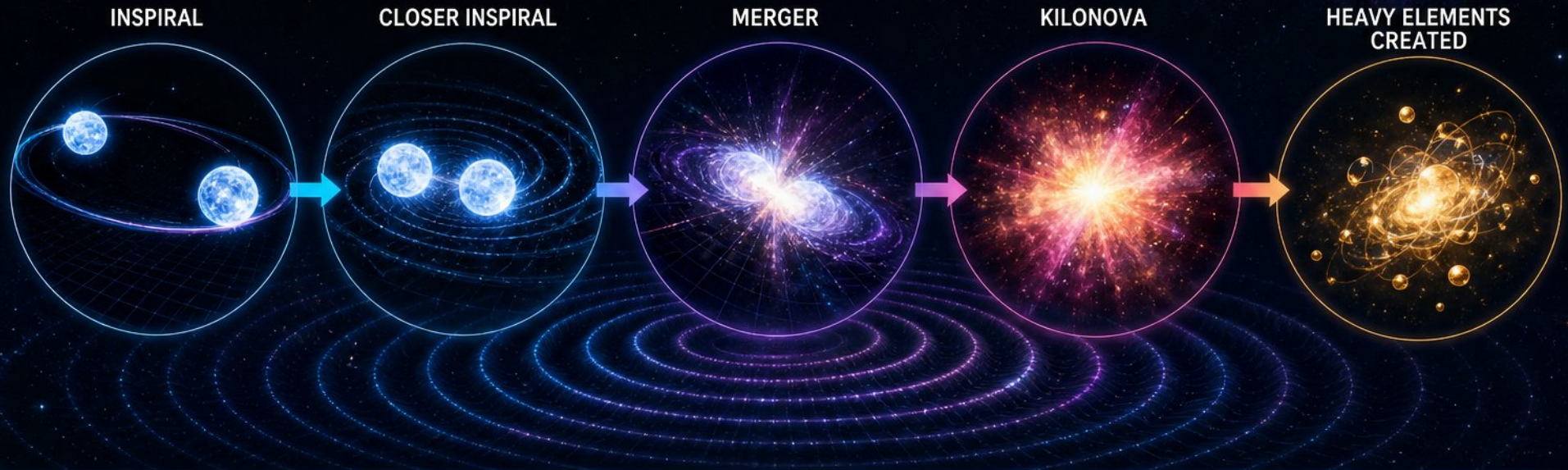


Measuring Neutron Stars: Mass and Radius

- NICER pulse profile modeling fits X-ray waveforms to constrain mass and radius
- PSR J0437-4715: tight radius at $\pm 7\%$ using radio mass priors
- J0740+6620 and J0030+0451 updated analyses agree with softer EOS
- Gravitational waves from GW170817 add complementary tidal deformability limits
- Emerging consensus: canonical neutron star radii cluster around 11-13 km



Gravitational Waves from Neutron Star Mergers

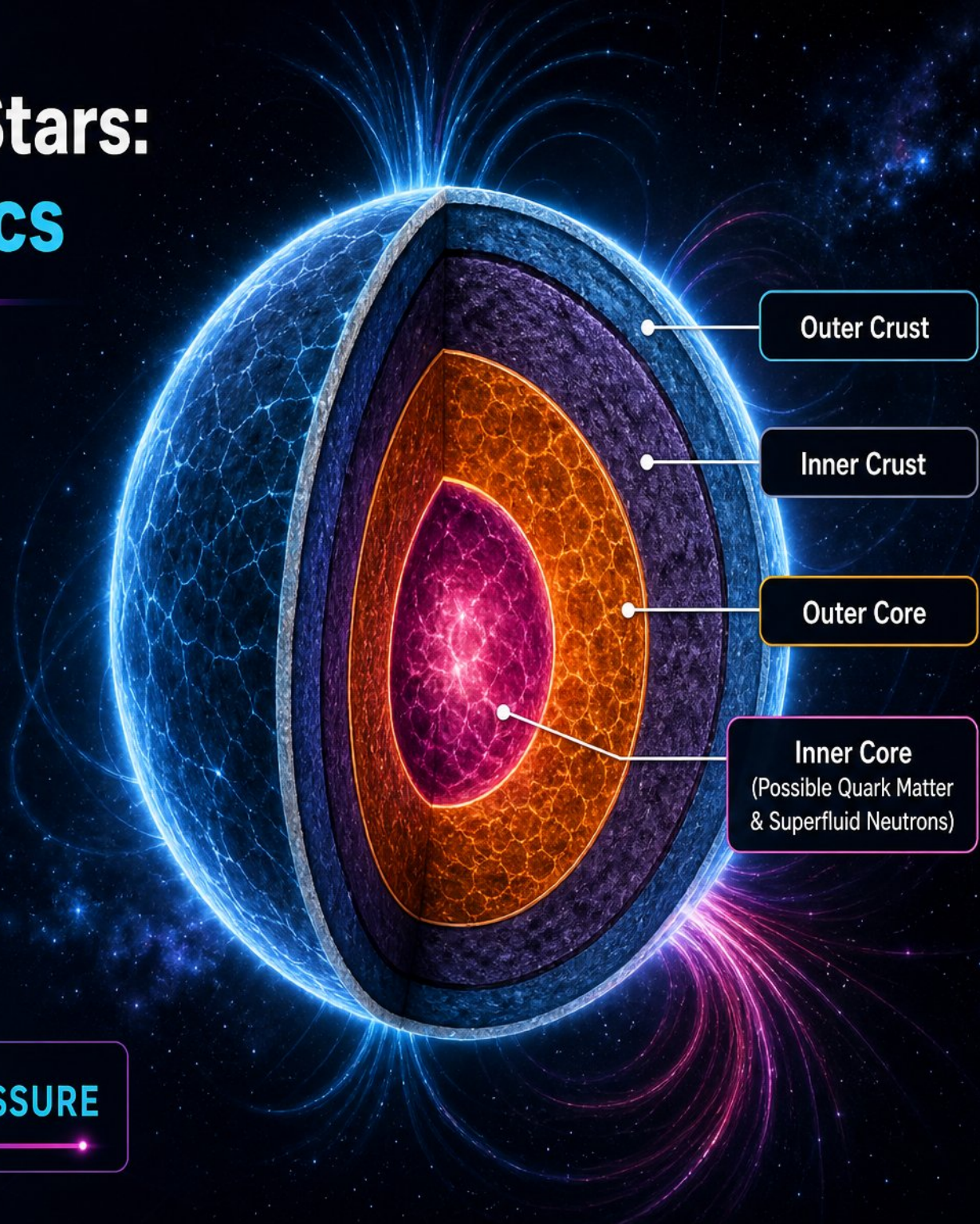


- Inspiring neutron stars emit gravitational waves, losing energy and merging
- GW170817 marked the first multi-messenger neutron star merger detection
- Mergers produce kilonovae, creating heavy elements like gold and platinum
- Recent events like S250206dm refine searches for these rare counterparts
- Merger observations constrain the neutron star equation of state



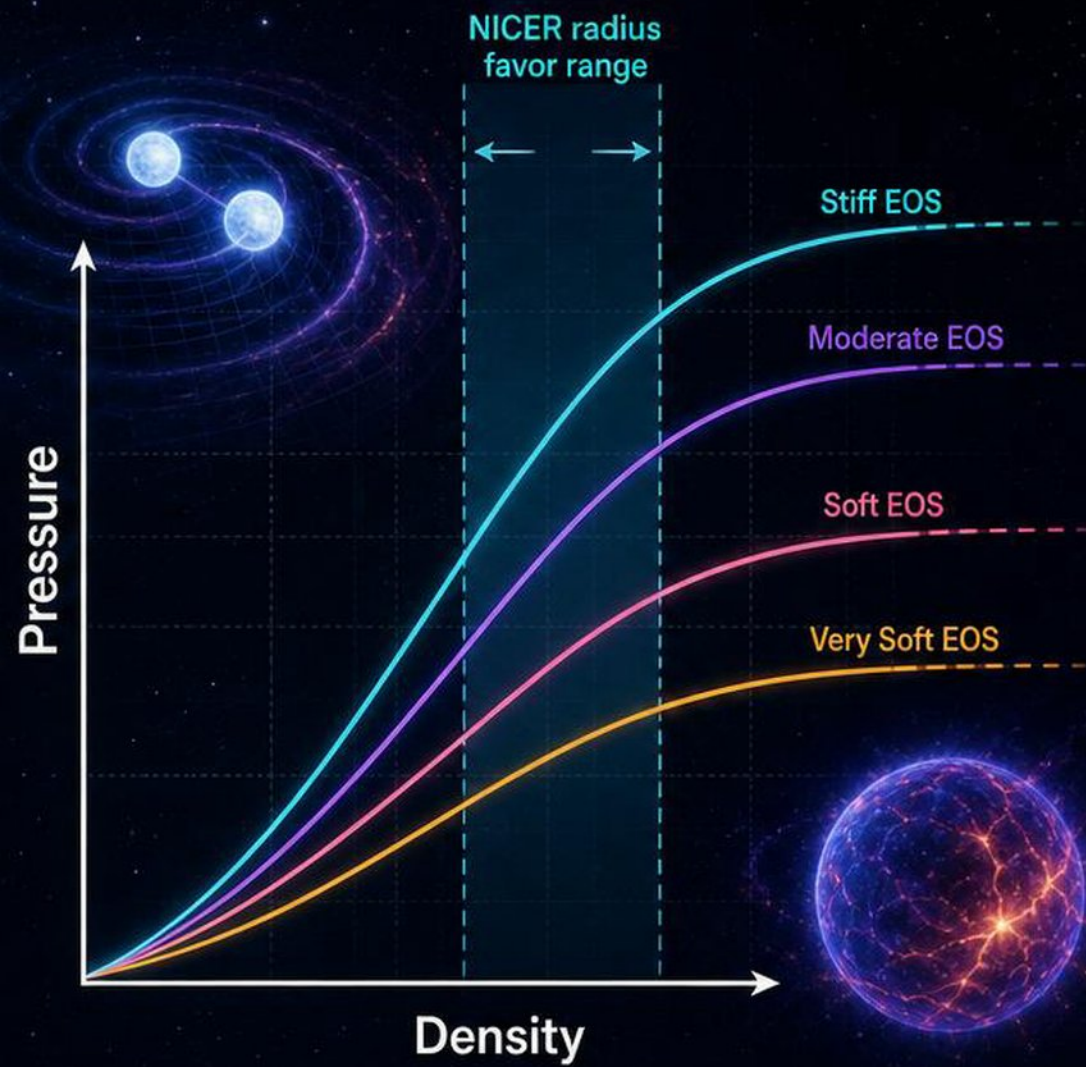
Inside Neutron Stars: Extreme Physics

- - Layered structure: outer crust, inner crust, outer core, inner core
- - Equation of state links pressure and density; details remain uncertain
- - Exotic possibilities include quark matter and superfluid neutrons
- - Nuclear physics experiments inform models of dense stellar interiors



MATTER UNDER PRESSURE

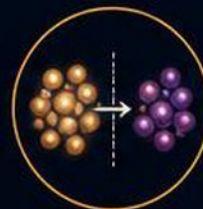
The Equation of State: Current Constraints



- Multi-messenger data converge on softer EOS



- NICER targets favor radii between 11 and 13 km



- Recent studies suggest density phase transitions possible



- Maximum mass ceiling now estimated below roughly 2.4 solar masses

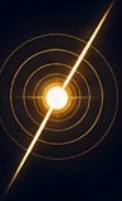
A diagram of a pulsar showing a central white dot with concentric blue circles representing light waves. Two bright blue beams of light extend from the poles, representing the pulsar's emission.

Neutron Stars

in the Milky Way and Beyond

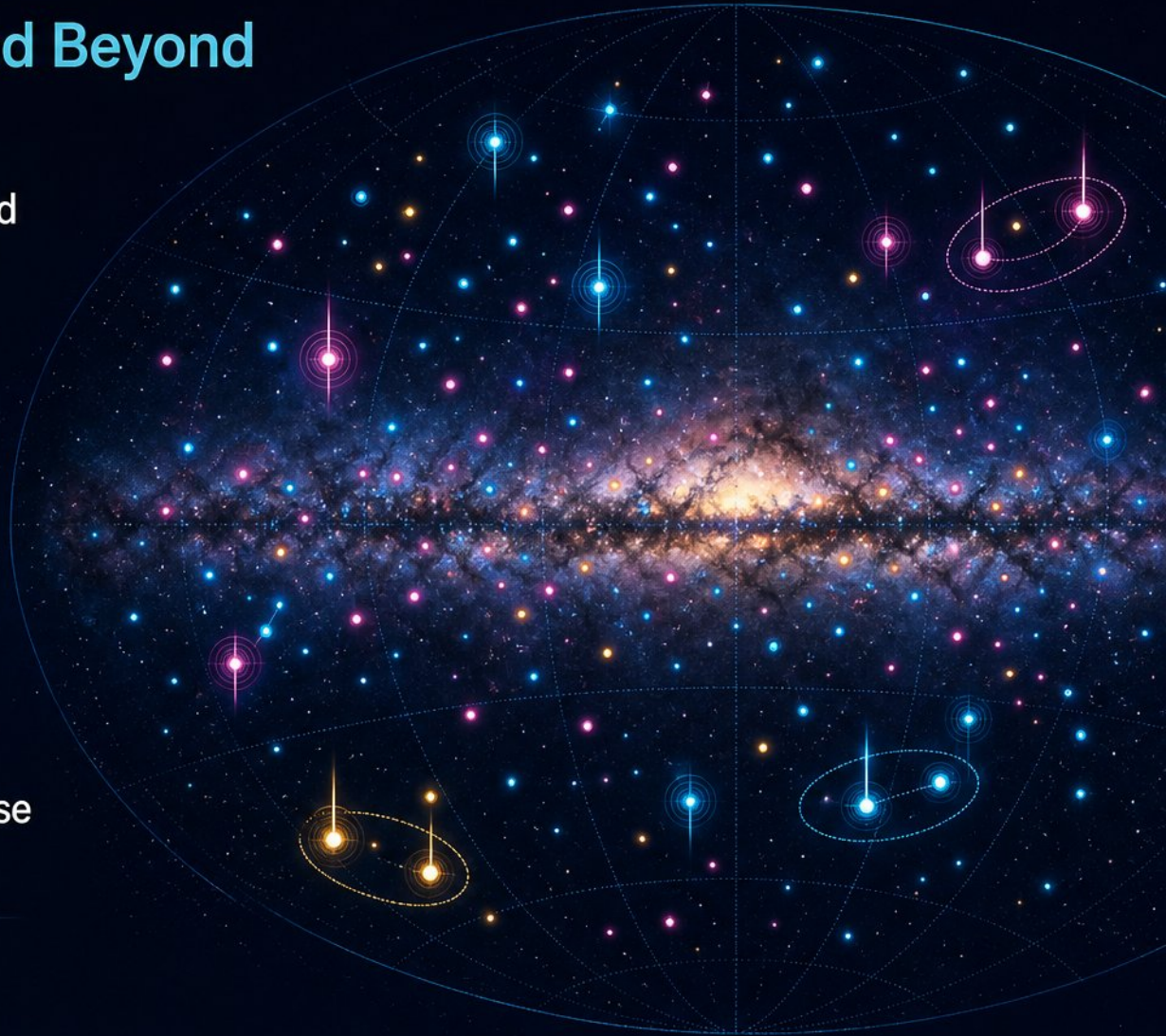
- 
- A diagram of a pulsar with a central white dot and concentric blue circles. Two bright blue beams of light extend from the poles.
- Over 3,500 rotation-powered pulsars are now known

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- A diagram of a pulsar with a central white dot and concentric purple circles. Two bright purple beams of light extend from the poles.
- FAST has discovered more than 1,000 new pulsars

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- A diagram of a pulsar with a central white dot and concentric orange circles. Two bright orange beams of light extend from the poles.
- Surveys locate isolated and binary neutron stars

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- A diagram of a pulsar with a central white dot and concentric blue circles. Two bright blue beams of light extend from the poles.
- Binary pulsars provide precise mass measurements

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- A diagram of a pulsar with a central white dot and concentric purple circles. Two bright purple beams of light extend from the poles.
- SKAO will greatly expand the known population

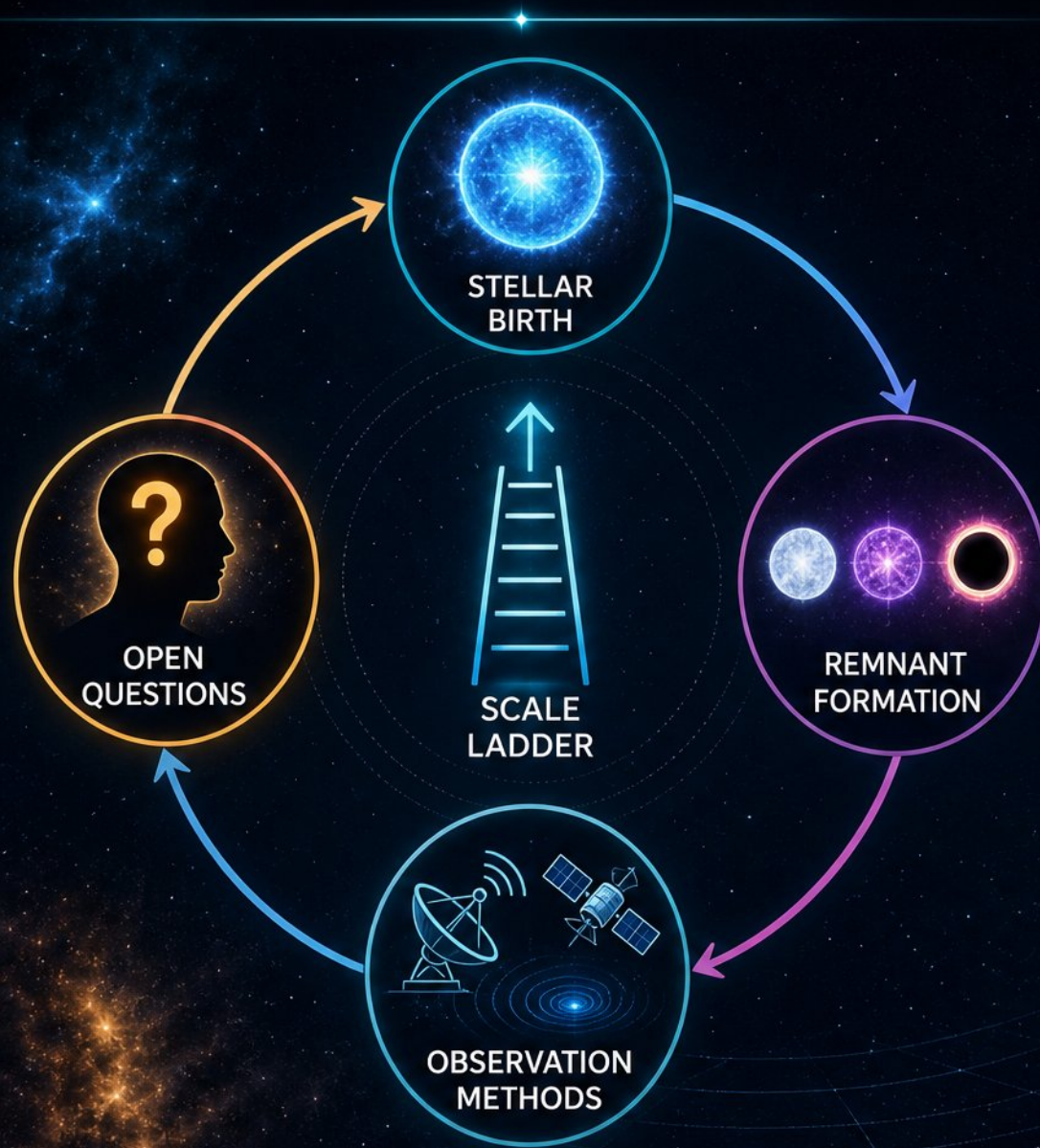


Why Neutron Stars Matter: Cosmic Laboratories

- - Test physics under extreme density, gravity, and magnetism
- - Source of heavy elements through neutron star mergers
- - Multi-messenger astronomy links light, waves, and particles
- - Natural laboratories for nuclear and quantum physics
- - Resources: NASA, ESO, LIGO, and SKAO websites



Key Takeaways and Next Steps



- Stellar mass determines whether a star becomes a white dwarf, neutron star, or black hole



- Pulsar timing, NICER, and gravitational waves probe neutron star physics



- Open questions include the equation of state and maximum neutron star mass



- Continue learning through observatory websites, journals, and public talks

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