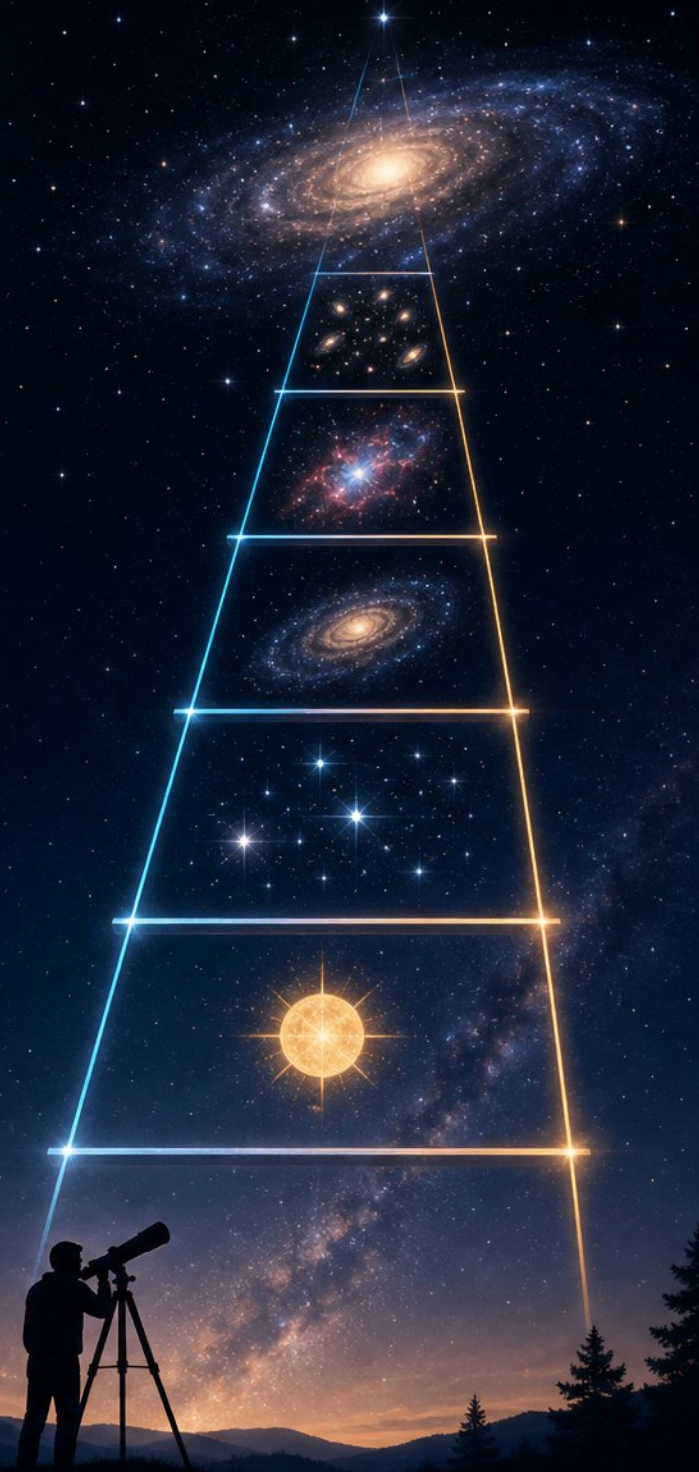


How Astronomers Measure Distance

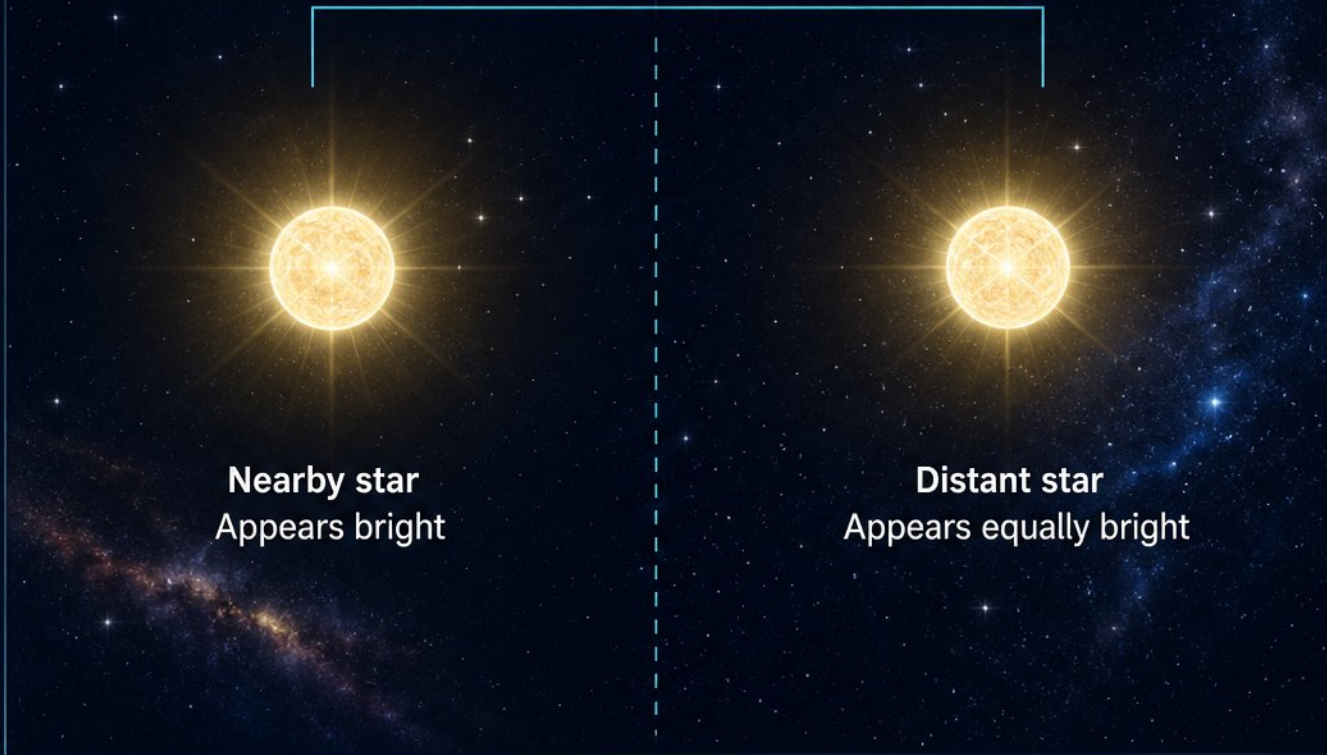
- - Distance is fundamental but extremely hard to measure accurately.
- - We use a cosmic distance ladder, not one single tool.
- - Each rung calibrates the next, from nearby stars to far galaxies.
- - By the end, you will explain the key methods and their ranges.



Why Measuring Distance Is So Difficult

- Space is too vast for direct measurement
- Objects that appear close may be vastly distant
- Brightness alone is ambiguous: a nearby dim star can look like a distant bright one
- Key units: AU, light-year, and parsec

SAME APPEARANCE, VASTLY DIFFERENT DISTANCE



NESTED SCALES: FROM EARTH TO DEEP SPACE



Earth



Solar System



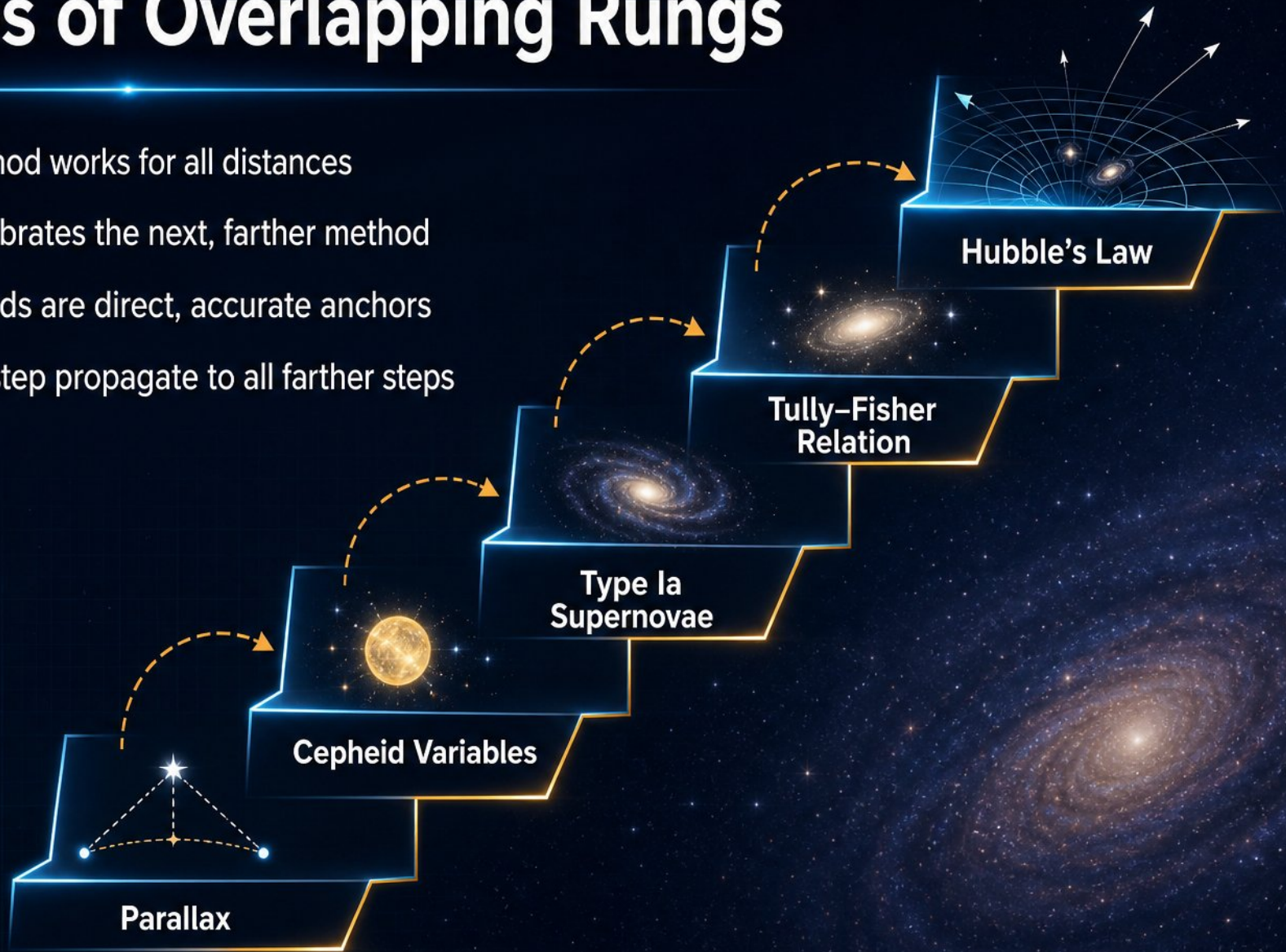
Milky Way Galaxy



Deep Space

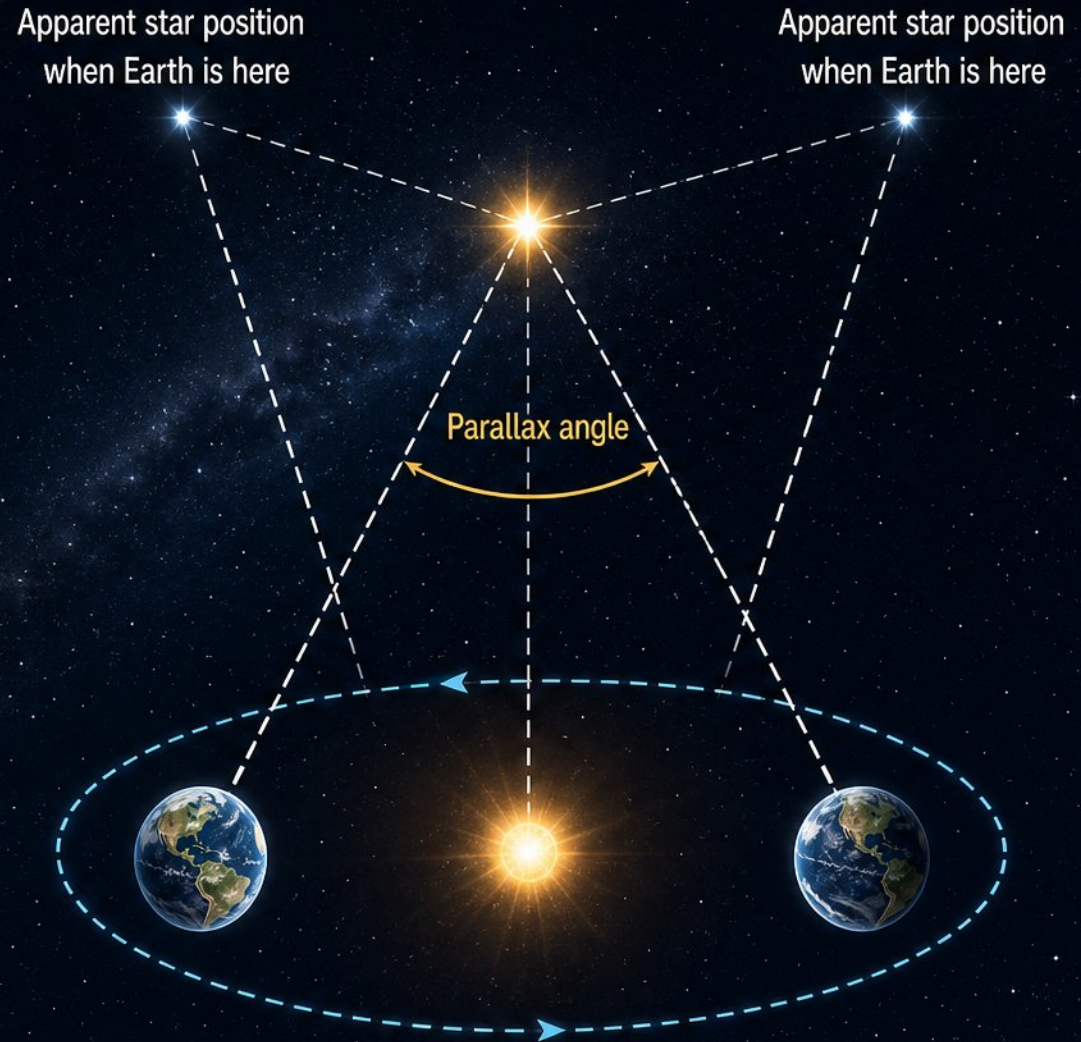
The Cosmic Distance Ladder: A Series of Overlapping Rungs

- No single method works for all distances
- Each rung calibrates the next, farther method
- Nearby methods are direct, accurate anchors
- Errors at one step propagate to all farther steps



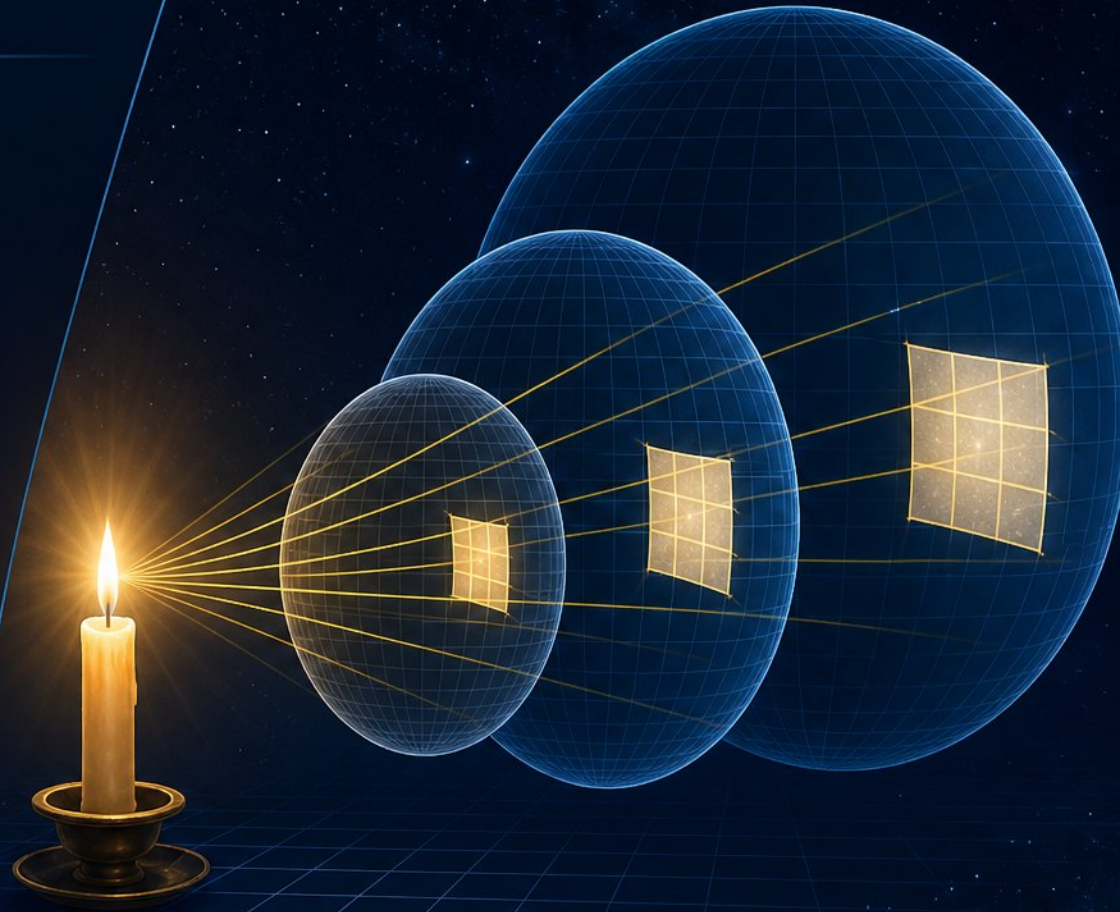
Parallax: The Gold Standard for Nearby Stars

- Earth's orbit creates a shifting perspective of nearby stars.
- The parallax angle lets you calculate distance geometrically.
- Ground-based parallax is limited by atmospheric turbulence.
- The Gaia space telescope measures precise parallax for billions of stars.



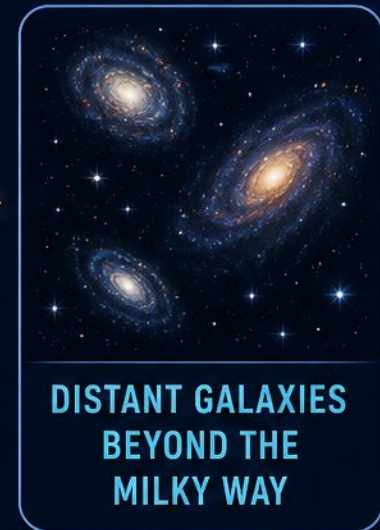
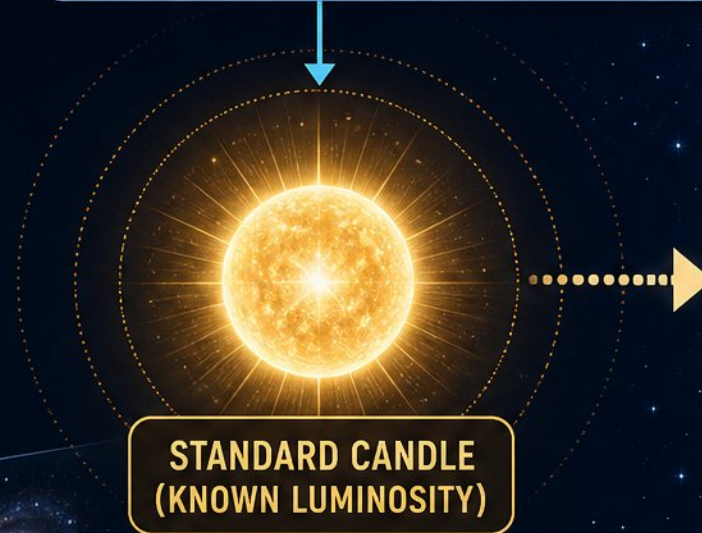
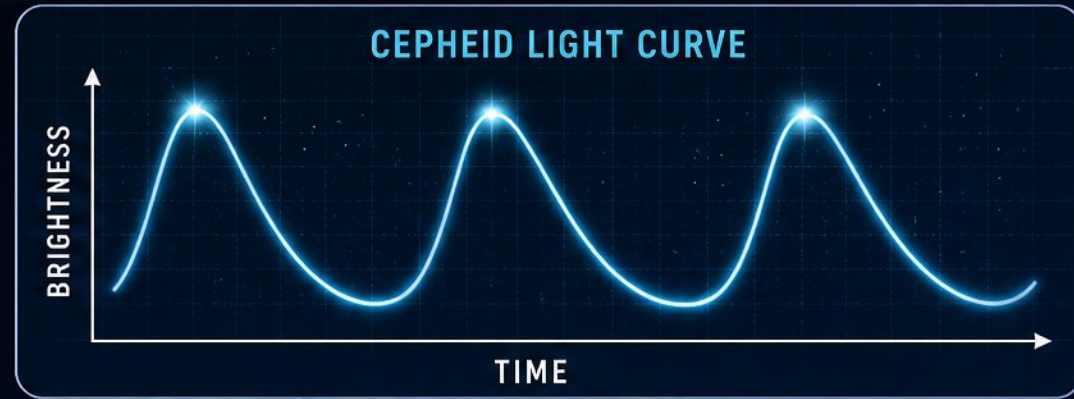
Standard Candles: Using Known Brightness

- Known true brightness enables distance calculation from apparent brightness
- Light intensity follows the inverse square law
- Luminosity is intrinsic power; magnitude measures brightness
- Standard candles have predictable, uniform luminosity for reliable distance estimates



Cepheid Variables and the **Period-Luminosity Relation**

- Cepheids pulse in a cycle tied directly to their true brightness.
- Measure the period to know the star's actual luminosity.
- Leavitt discovered this pattern, unlocking the extragalactic distance scale.
- Hubble used Cepheids to prove galaxies exist beyond the Milky Way.



Type Ia Supernovae: The Brightest Standard Candles

- Explode with highly uniform peak luminosity across the universe
- Outshine entire galaxies, visible from billions of light-years away
- Key evidence for dark energy and accelerating cosmic expansion



EARTH



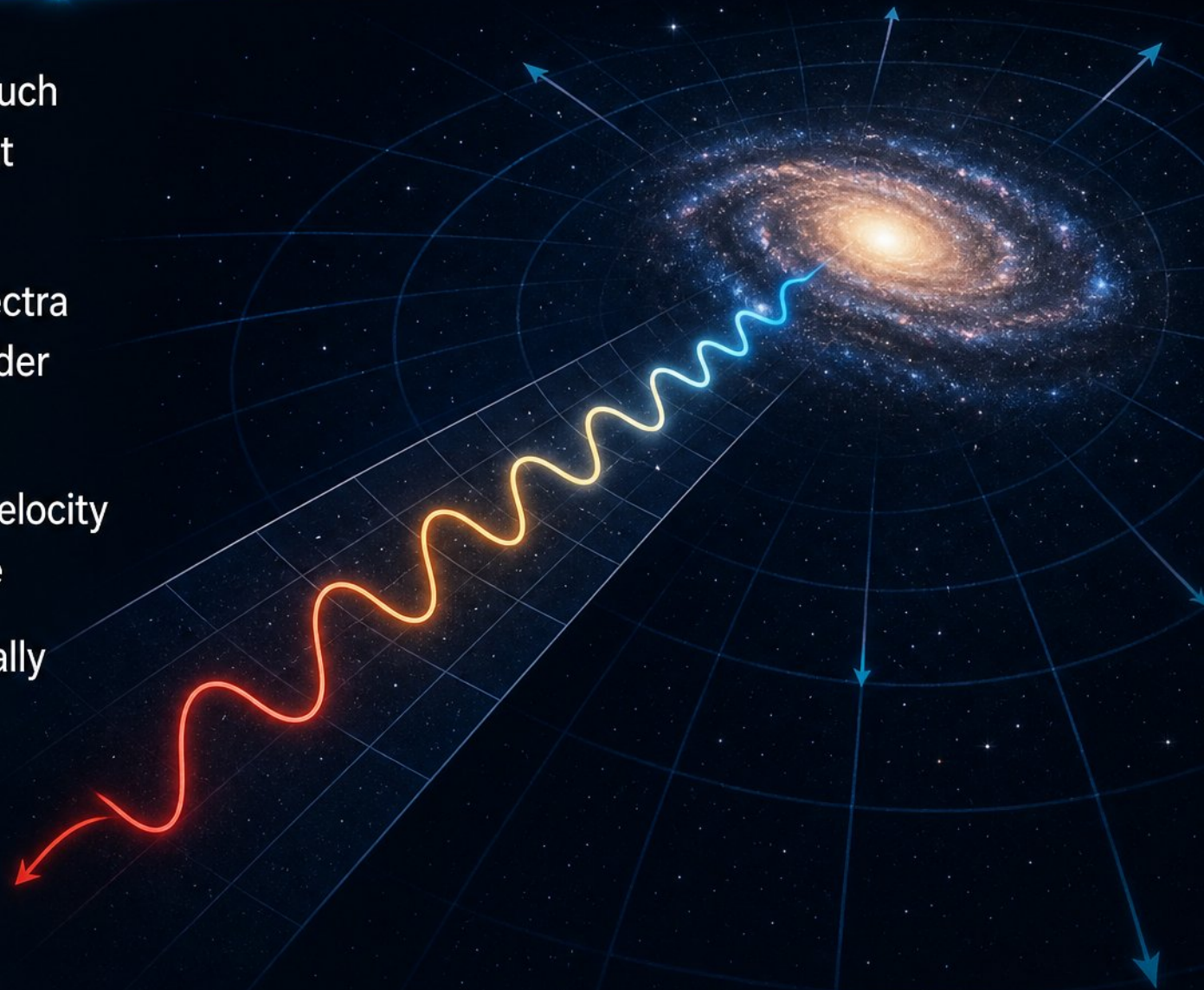
HOST GALAXY



DISTANT SUPERNOVA

Redshift and Hubble's Law for the Farthest Galaxies

- Redshift measures how much space stretched while light traveled to us
- Distant galaxies show spectra shifted toward longer, redder wavelengths
- Hubble's Law: recession velocity is proportional to distance
- JWST now spectroscopically confirms galaxies out to $z \approx 14$



Putting It All Together: The Distance Ladder in Action

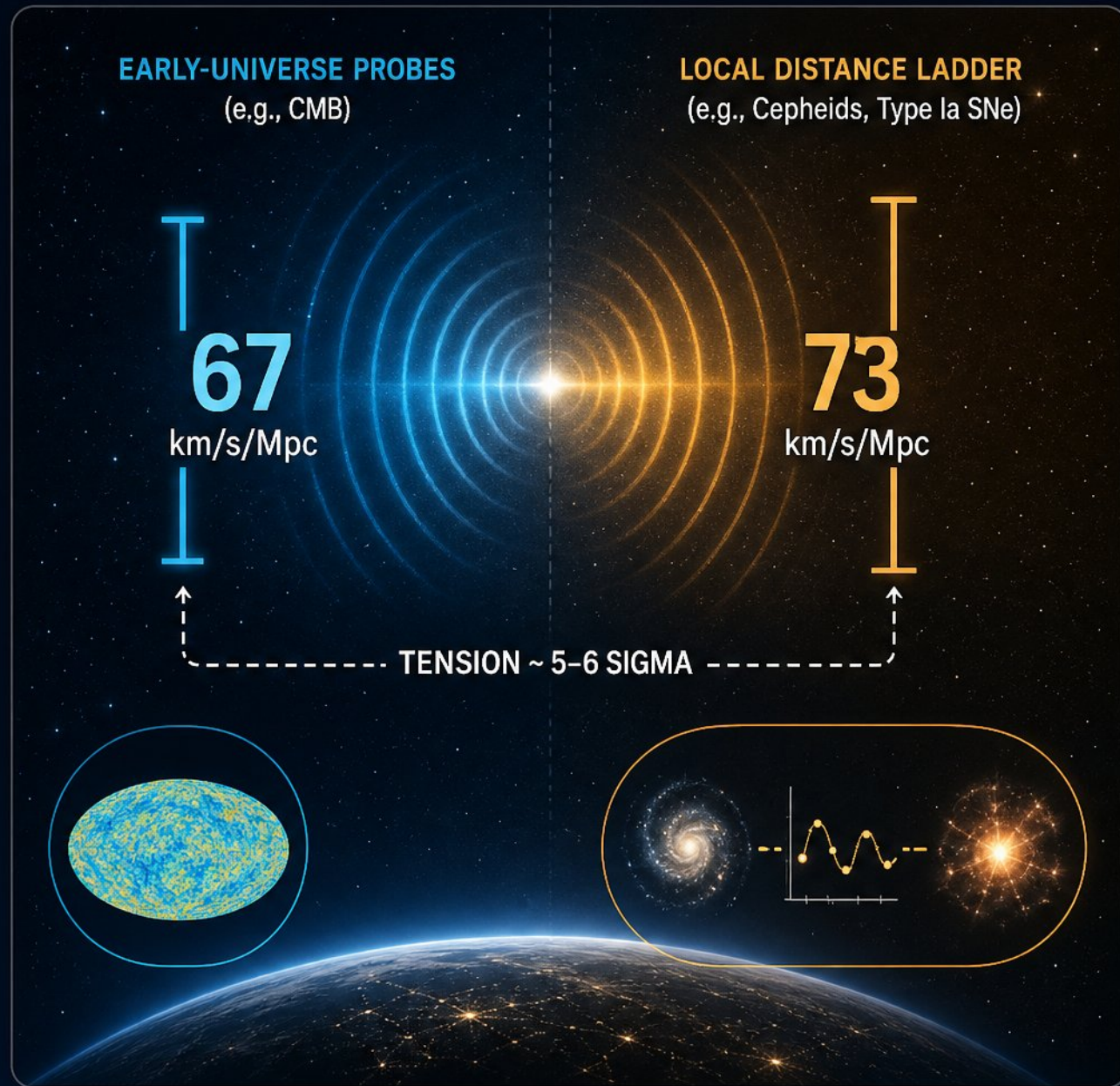


- Each method covers a limited range; overlaps allow calibration.
- Cross-check methods where ranges overlap to confirm accuracy.
- Recalibrating a lower rung improves all farther measurements.
- Gaia parallax calibrates Cepheids; Cepheids calibrate Type Ia supernovae.



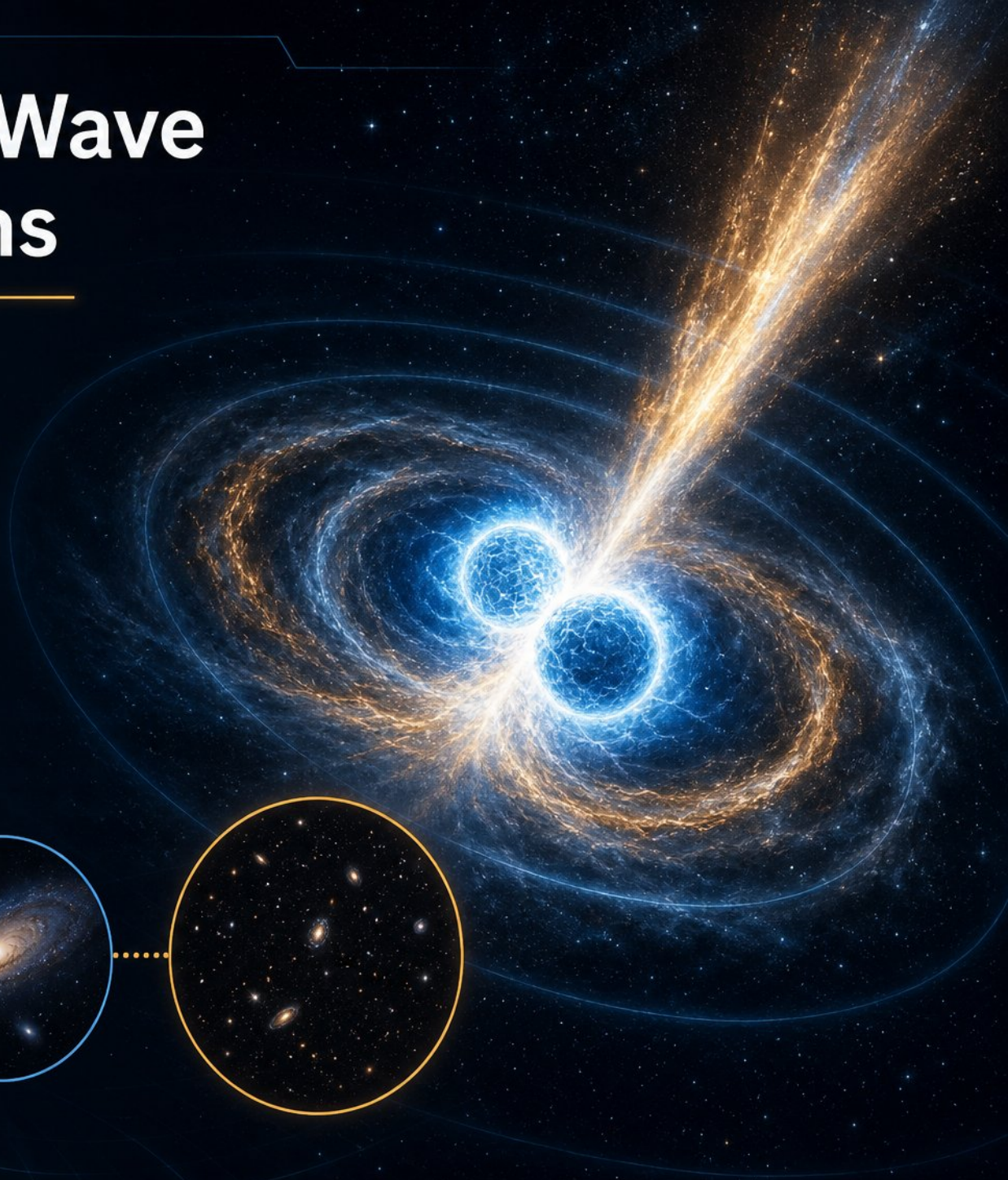
Current Frontiers: The Hubble Tension

- - Local ladder and early-universe probes disagree on expansion rate.
- - Tension now roughly 5-6 sigma: 73 vs 67 km/s/Mpc.
- - JWST observations test Cepheid and supernova measurements.
- - Cepheid calibration refinements affect the local H_0 value.



Gravitational-Wave Standard Sirens

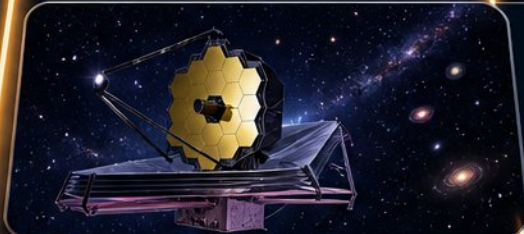
- - GW events provide distance markers independent of the cosmic ladder
- - Waveform amplitude and shape directly encode luminosity distance
- - GW170817: first bright siren with identified electromagnetic counterpart
- - Recent standard siren results favor SH0ES without full resolution
- - Einstein Telescope expected to push toward percent-level H_0 precision



Recent Advances and Next-Generation Tools



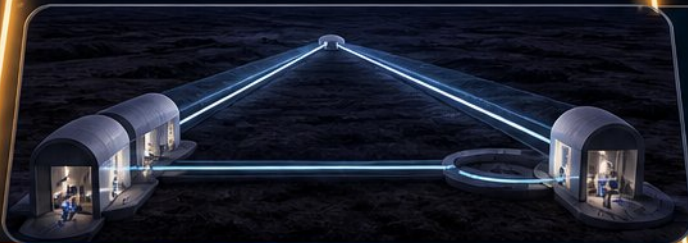
- Gaia Data Release 4 planned for December 2, 2026



- JWST spectroscopically confirms galaxies out to $z \approx 14$



- Vera C. Rubin Observatory and LSST will transform supernova cosmology



- Einstein Telescope promises percent-level distance measurements

Key Takeaways and Practical Skills



- - Match distance methods to ranges: parallax, Cepheids, Type Ia supernovae



- - Explain ladder calibration: each rung anchors the next



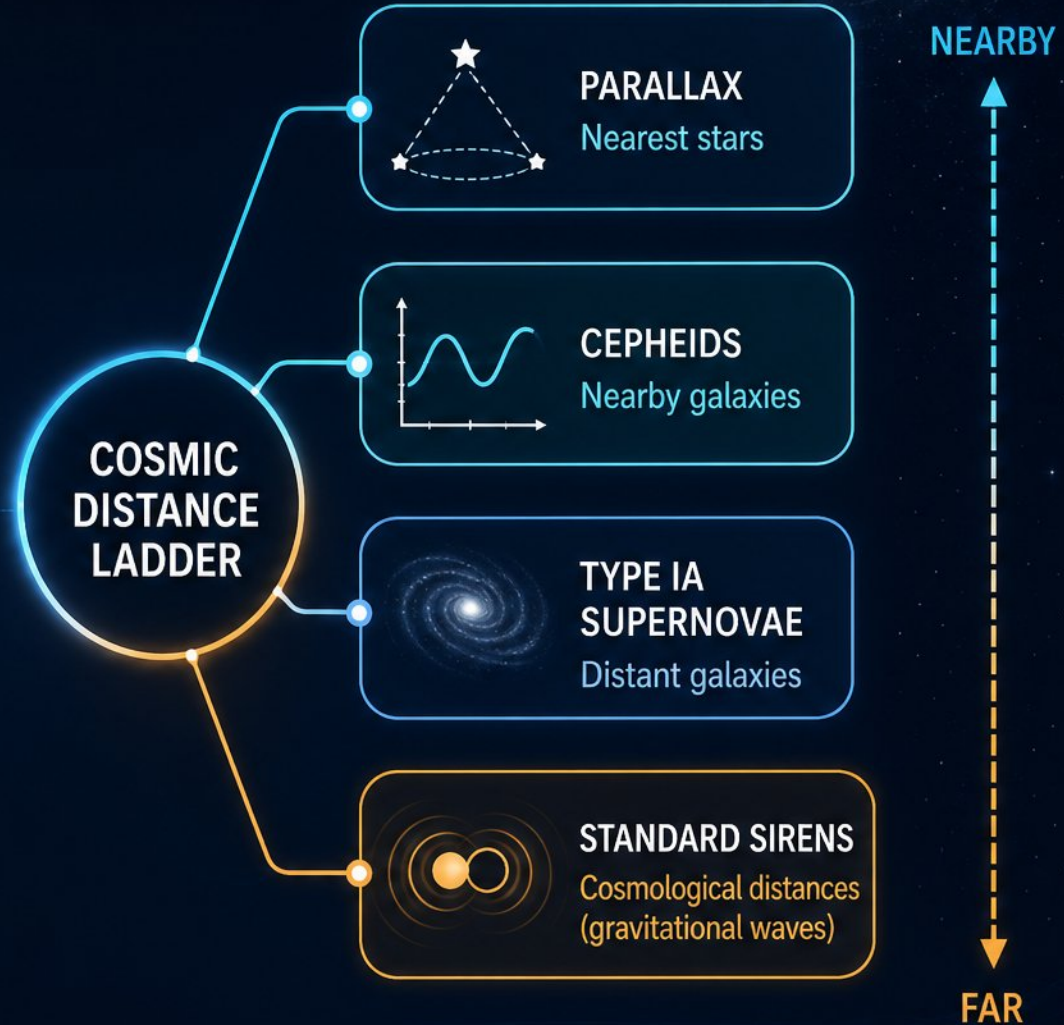
- - Identify standard candles (Cepheids, Type Ia) and standard sirens



- - Describe the Hubble tension and its significance as a 5–6 sigma discrepancy



- - Choose the right tool for nearby stars, galaxies, and $z \approx 10$ sources



Discussion and Further Exploration



- - What unresolved questions remain in distance measurement?



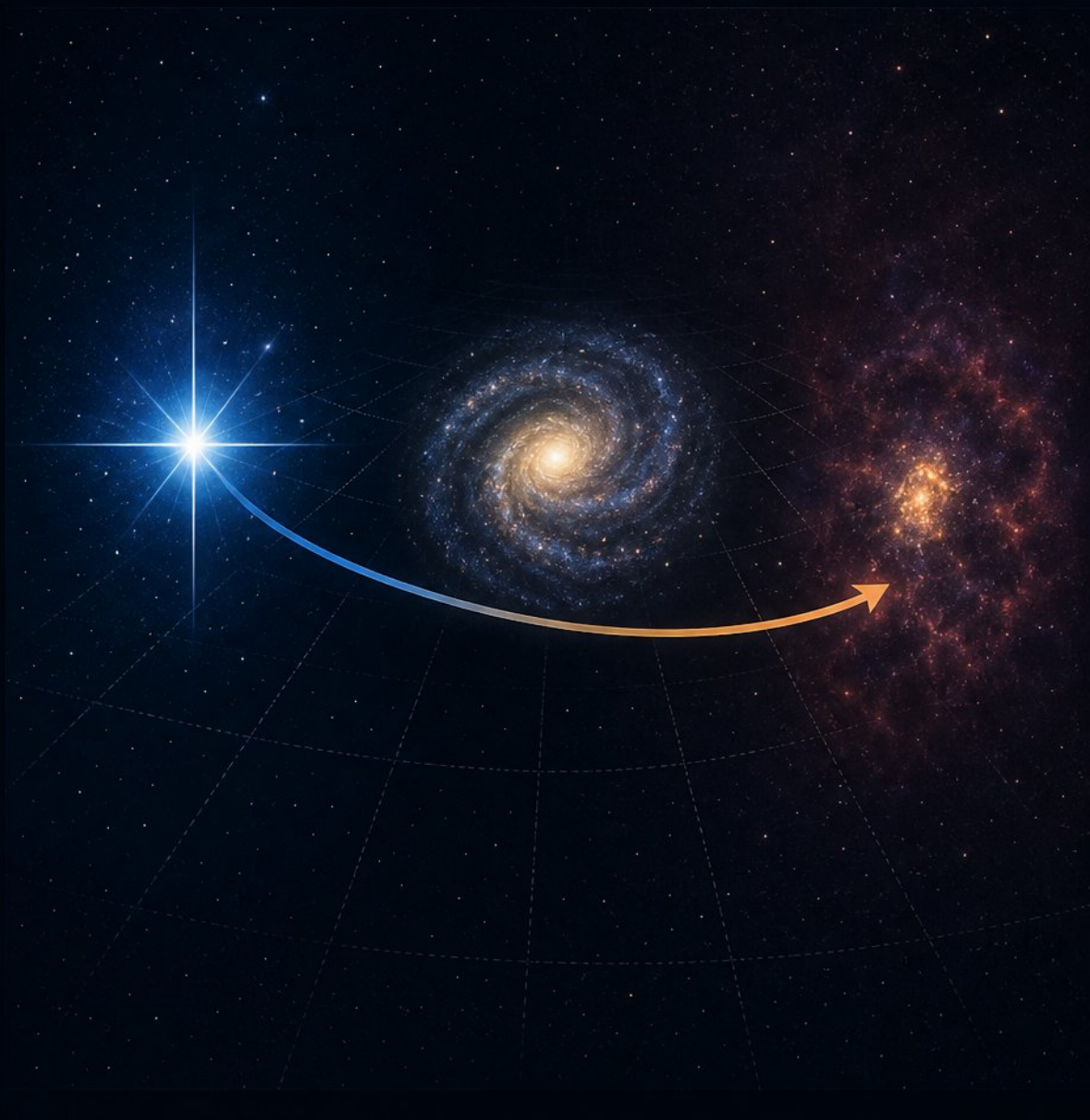
- How might upcoming surveys and detectors settle the Hubble tension?



- Suggested resources: recent studies on standard sirens and LSST simulations.



- Reflection: which method applies to a nearby star, nearby galaxy, or galaxy at $z \approx 10$?



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