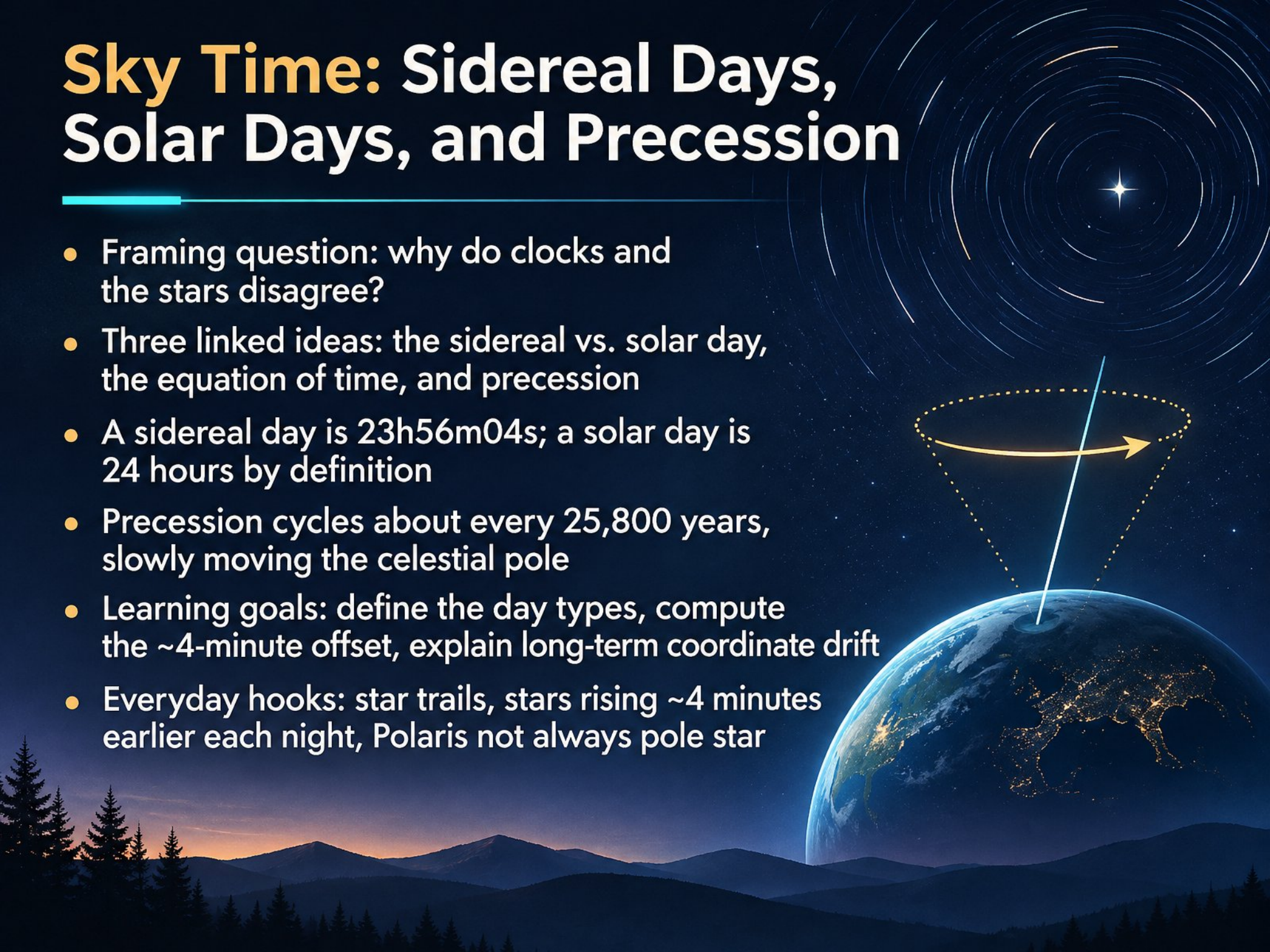
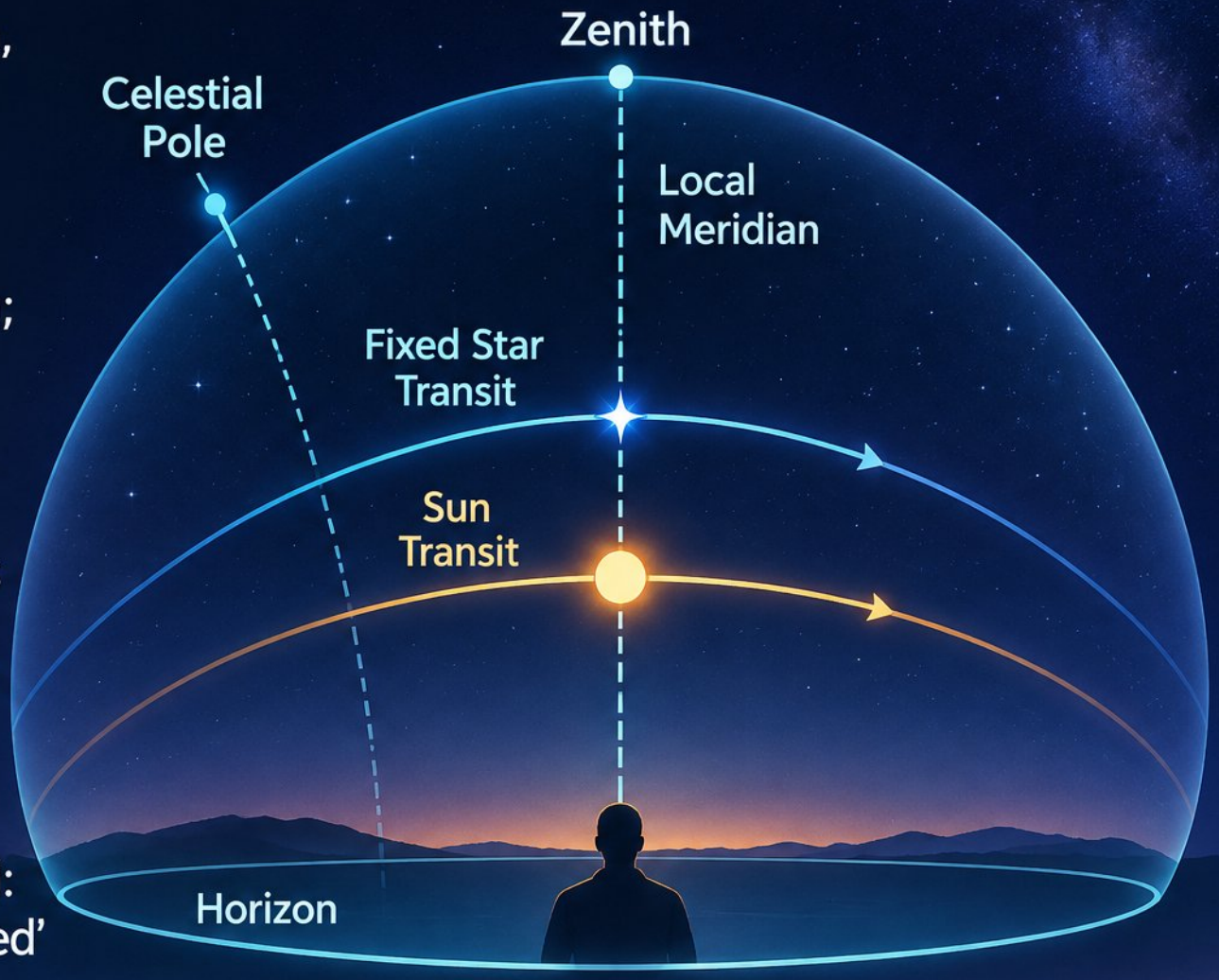
Sky Time: Sidereal Days, Solar Days, and Precession

- Framing question: why do clocks and the stars disagree?
- Three linked ideas: the sidereal vs. solar day, the equation of time, and precession
- A sidereal day is 23h56m04s; a solar day is 24 hours by definition
- Precession cycles about every 25,800 years, slowly moving the celestial pole
- Learning goals: define the day types, compute the ~4-minute offset, explain long-term coordinate drift
- Everyday hooks: star trails, stars rising ~4 minutes earlier each night, Polaris not always pole star



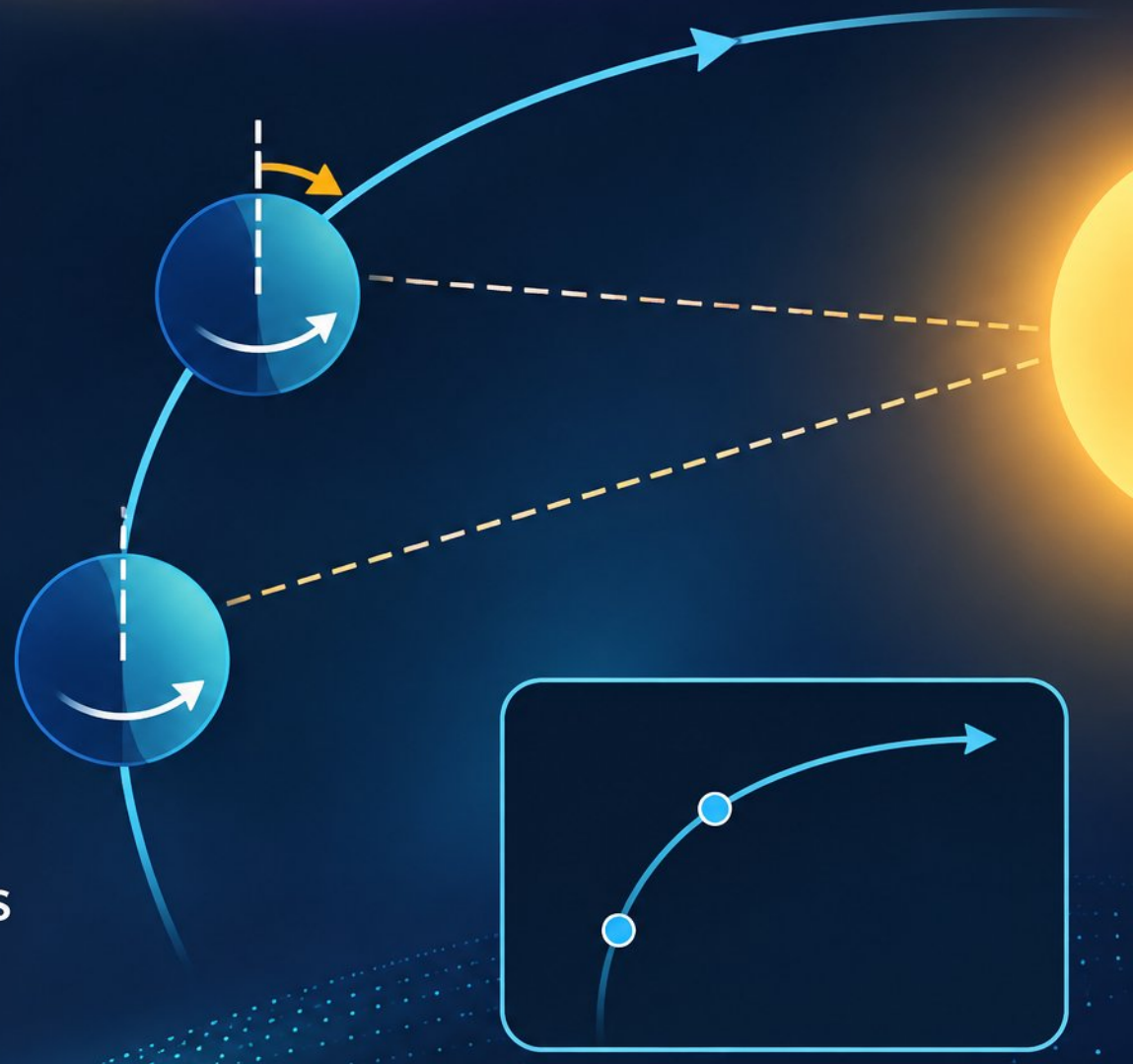
Two Kinds of Day: Observing the Sky from a Moving Earth

- Observer frame: horizon, zenith, and the local meridian
- Solar day: successive upper transits of the Sun; mean solar day = 24 h
- Sidereal day: successive upper transits of a fixed star; 23 h 56 min 04.0905 s
- Stars are effectively fixed; the Sun drifts eastward ~1° per day
- Synodic (solar) vs. sidereal: ‘meeting’ vs. ‘star-referenced’ cycles



Why the Solar Day Is Longer: The Geometry of One Extra Turn

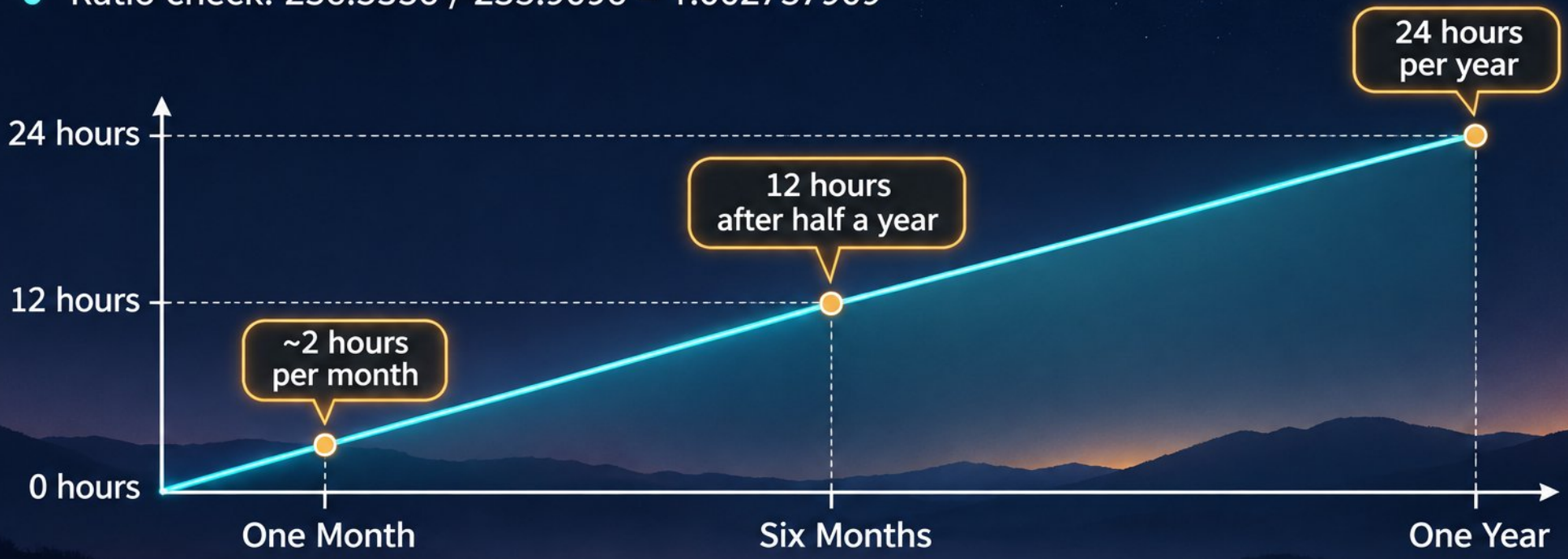
- After one 360° star-to-star turn, Earth has moved ~1° in orbit
- The Sun is not yet on the meridian — Earth must turn ~1° more
- That extra ~1/365 of a turn takes about 4 minutes
- Reciprocal rule: $1/T_{sid} = 1/T_{solar} + 1/T_{year}$
- Tropical year: 365.2422 solar days = 366.2422 sidereal days
- Sign test: retrograde spin (Venus) makes the sidereal day longer



One Day, Two Numbers:
The 3m56s Offset and How It Accumulates

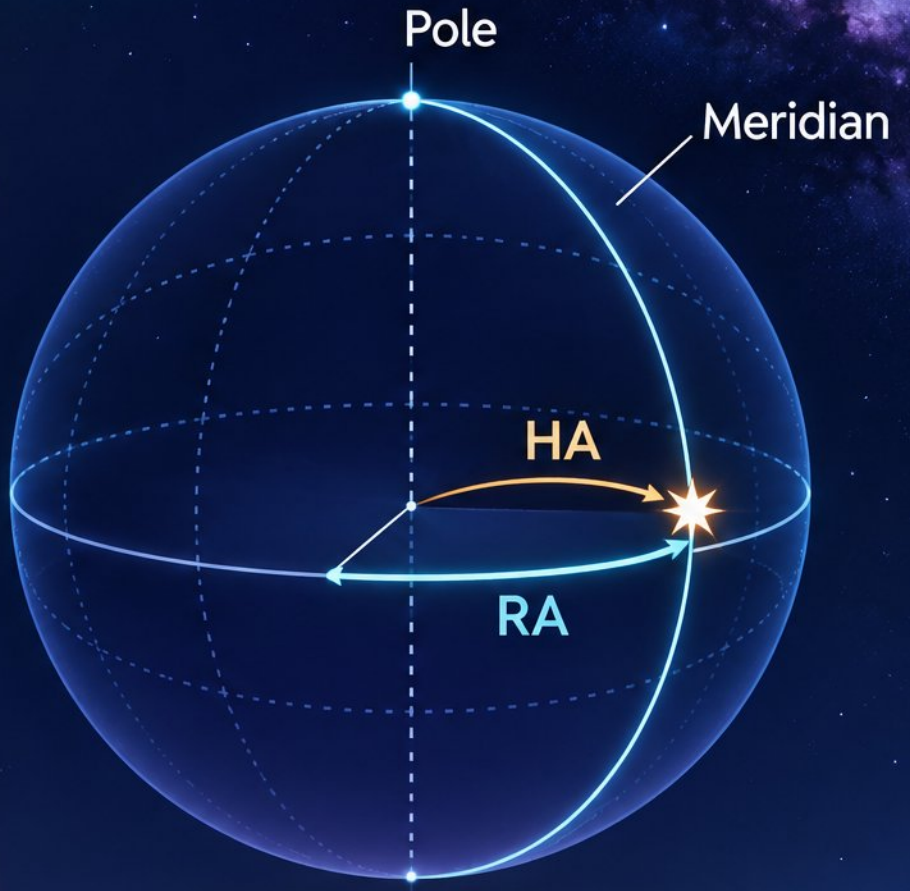
- Two ~4-minute offsets: 3m56.56s per solar day, 3m55.91s per sidereal transit
- Mean sidereal day 86,164.09054 s vs. 86,400 s solar day
- Stars rise ~4 minutes earlier nightly: ~2 hours per month, 24 hours per year
- After half a year, a star transits 12 hours from where it started
- Ratio check: 236.5556 / 235.9096 = 1.002737909





Sidereal Time in Practice: LST, Hour Angle, and Right Ascension

- LST = hour angle of the vernal equinox = RA on the meridian
- Master relation: LST = RA + HA; at transit HA = 0, so LST = RA
- Local vs. Greenwich: LST = GST + east longitude (subtract for west)
- Mean vs. apparent: difference (equation of the equinoxes) never exceeds 1.2 s
- Observatories run a sidereal clock ~4 min fast per day beside UT



LST = RA + HA



Sidereal Clock



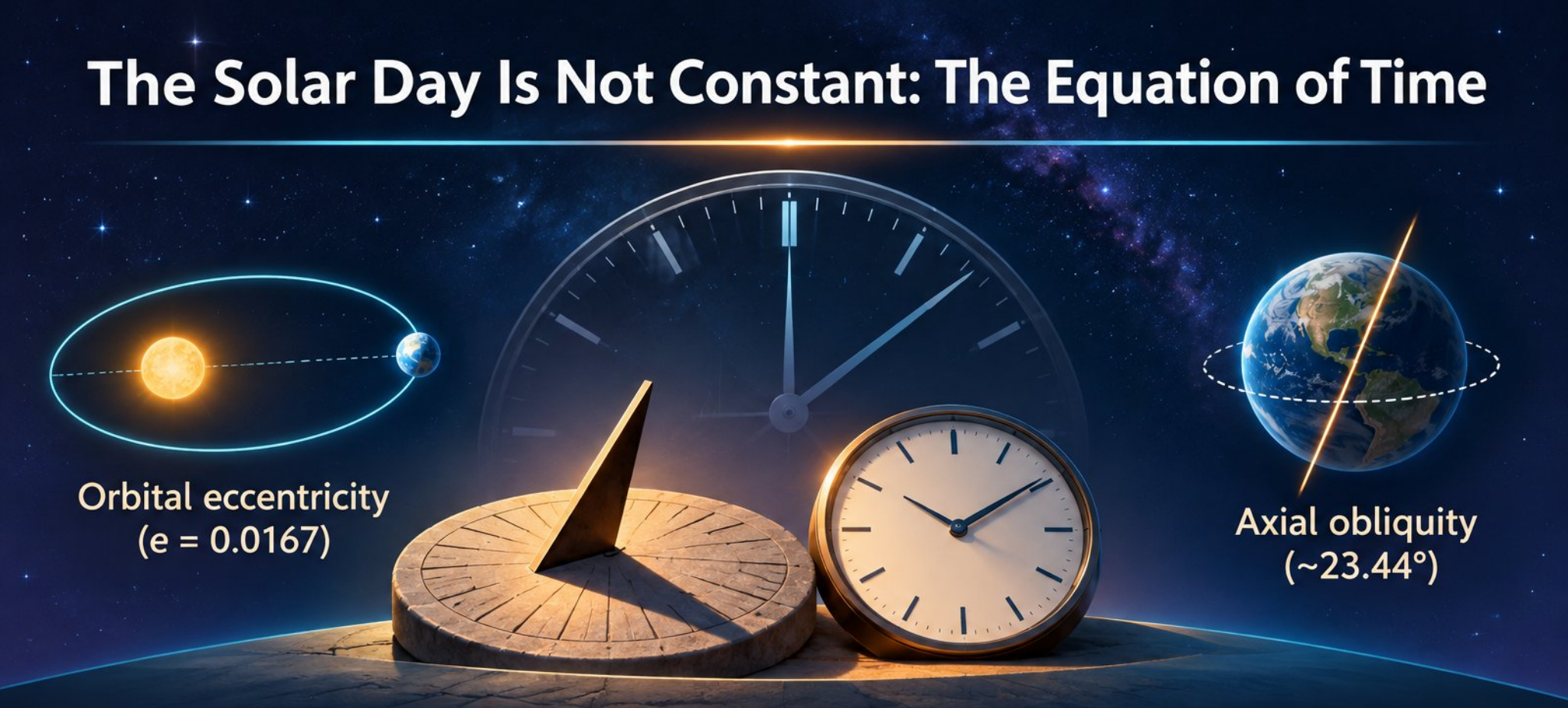
Civil UT Clock

From Night to Night:
Seasonal Star Visibility and the Calendar



- A star rising at 21:00 tonight rises about 20:56 tomorrow; ~2 hours earlier after a month.
- Why: stars rise, transit and set ~4 minutes earlier each solar day.
- Sidereal year (star-to-star, 365.2564 d) vs tropical year (equinox-to-equinox, 365.2422 d).
- The ~20-minute year difference comes from precession of the equinoxes.
- Calendars follow the tropical year; leap days fix the 0.2422-day fraction — not the 4-minute offset.
- Classroom project: time a star's nightly transit to recover ~23h56m.

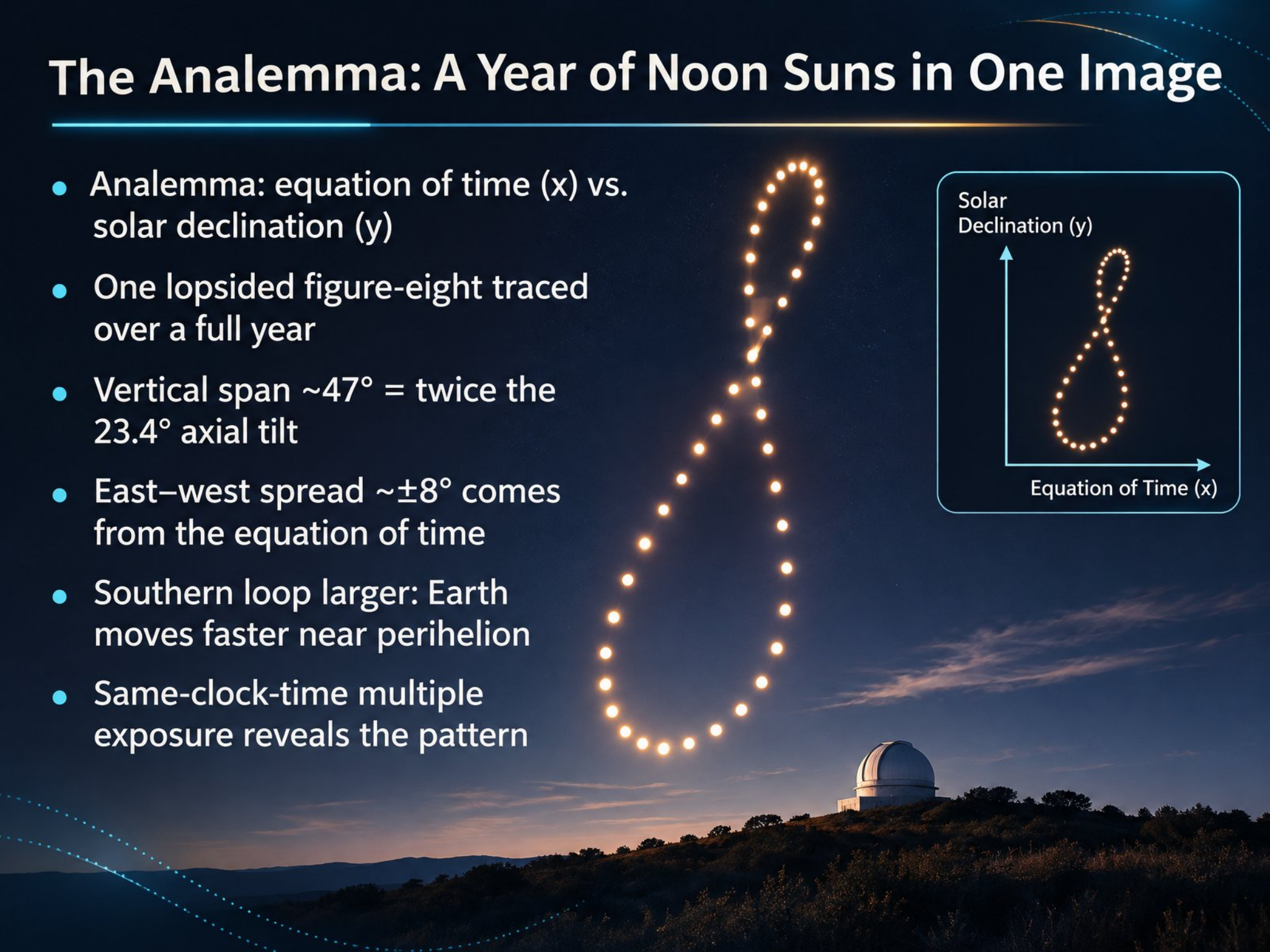
The Solar Day Is Not Constant: The Equation of Time



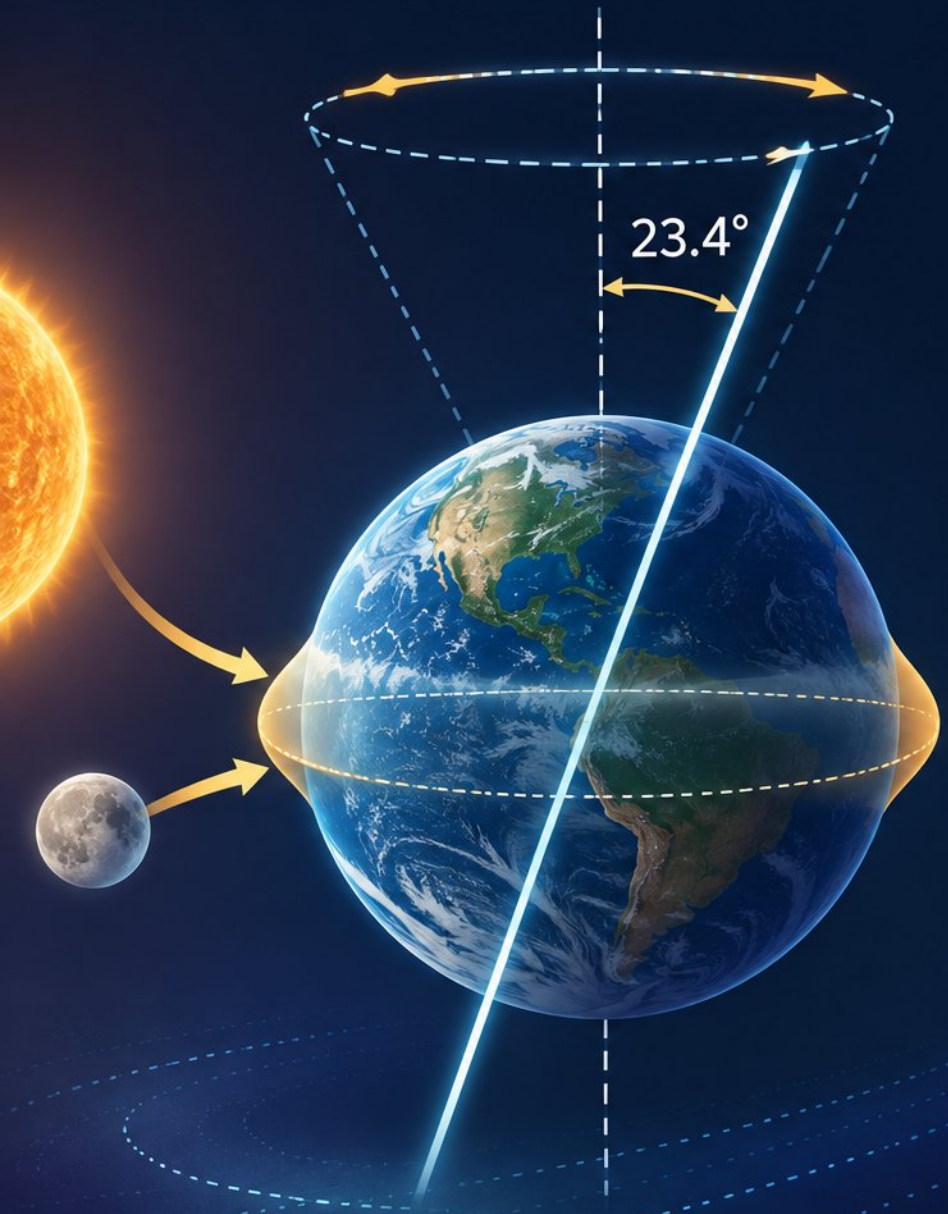
- Sundial (apparent) vs. clock (mean) time: equation of time = apparent − mean
- Two causes of similar size: orbital eccentricity (e = 0.0167) and axial obliquity (~23.44°)
- Extremes: about +16 min in early November, −14 min in mid-February
- The fictitious mean sun defines uniform time; the true Sun stays within ~4° of it
- Net effect: the Sun runs fast or slow by minutes, never more than ~16 minutes

The Analemma: A Year of Noon Suns in One Image

- Analemma: equation of time (x) vs. solar declination (y)
- One lopsided figure-eight traced over a full year
- Vertical span ~47° = twice the 23.4° axial tilt
- East–west spread ~±8° comes from the equation of time
- Southern loop larger: Earth moves faster near perihelion
- Same-clock-time multiple exposure reveals the pattern



Precession: The Slow Wobble of Earth's Axis

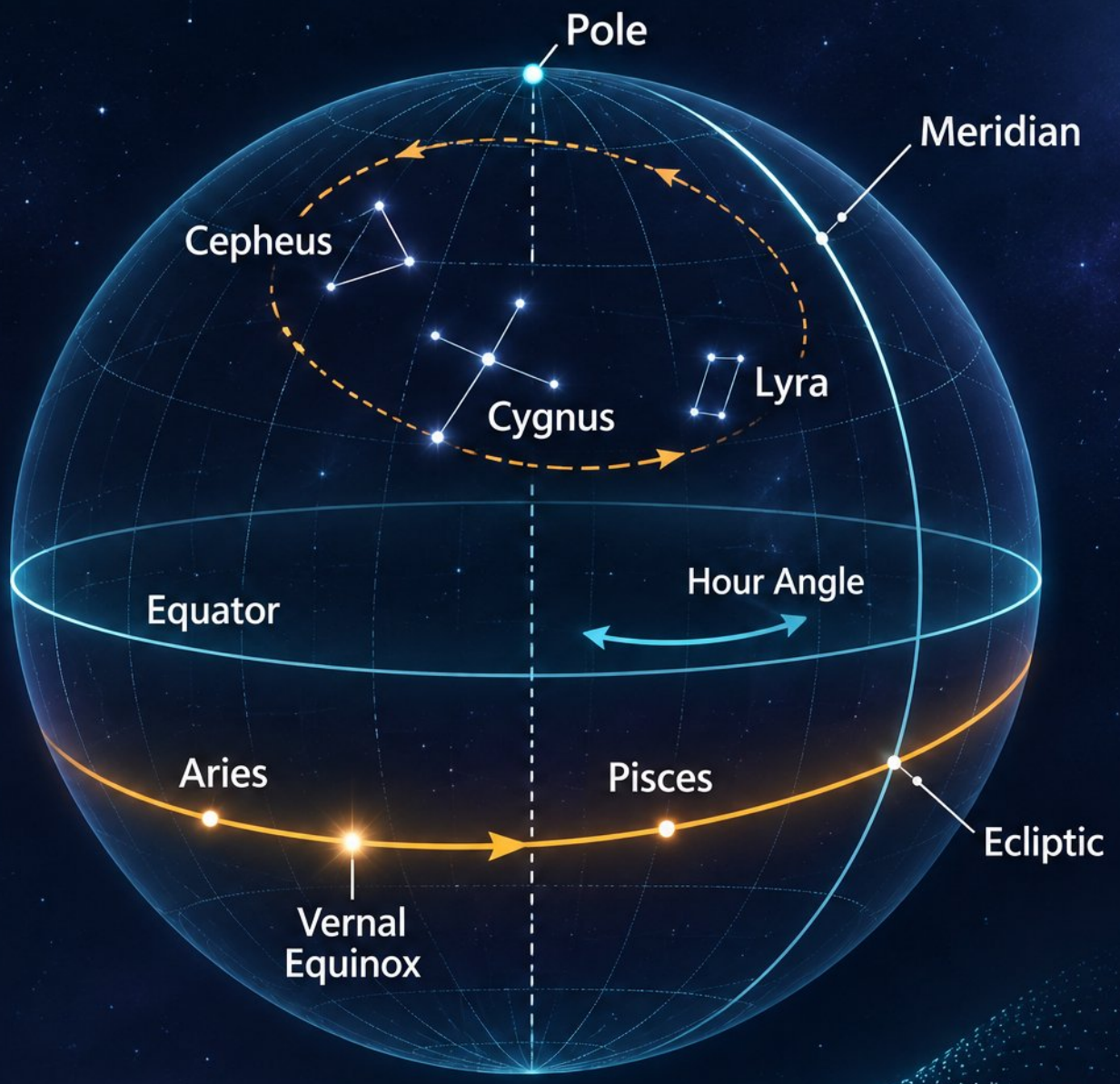


- Sun and Moon tug on Earth's equatorial bulge → axis traces a cone
- Cone half-angle ≈ 23.4° (the obliquity); one circuit ≈ 25,772 years
- Drift ≈ 50.288 arcsec/year westward along the ecliptic; about 1° per 71.6 years
- Rate is not exactly constant — it slowly increases (IAU 2006 polynomial has a positive T term)
- Nutation: a small ~9 arcsec wobble superimposed, with an ~18.6-year lunar-node period



Precession of the Equinoxes: The Moving Coordinate Grid

- Vernal equinox drifts westward ~50.288″/yr; in Pisces since 68 BCE, Aquarius by 2597 CE
- Celestial pole wanders: Polaris now, Errai ~4000 CE, Vega ~13,700 CE
- RA and Dec shift with position: up to ~20″/yr in Dec; RA diverges near poles
- Ecliptic latitudes stay fixed — precession is an equatorial-frame effect
- Hipparchus (~130 BCE) detected the shift by comparing eclipse records



Epochs, ICRS, and the Tropical vs. Sidereal Zodiac

- Every coordinate needs an equinox: B1950, J2000, or of-date
- ICRS is quasar-anchored and frozen, aligned with J2000 to ~23 mas
- Precess catalog coordinates to the equinox of date before pointing
- Tropical zodiac: 30° signs from the moving equinox; sidereal fixes signs to stars
- Offset (ayanamsa) means the Sun's real constellation no longer matches your sign





Quantitative Walkthrough: Three Worked Calculations

- **Daily offset:** 86,400 s ÷ 365.2422
  ≈ **236.56 s** — one extra turn per year



- LST = GST + east longitude:
  GST 10h18m + 2h04m → LST ≈ **12h22m**



- Precession: 50.288″/yr × 100 yr = 5,029″
  ≈ **1.397°;** 1,000 yr ≈ **14°**



- Polaris sits ~0.65° from the pole today — and the pole keeps moving
- Watch pitfalls: longitude sign, time zones, mean vs. apparent, B1950 vs. J2000

Classroom Demonstrations: Making the Invisible Visible

- Sundial vs. clock: chart equation-of-time offsets; plot a year-long analemma
- Nightly transit timing: a star crosses a fixed sight line; recover ~23h56m
- Plot crossing times: the negative slope shows ~4 minutes lost per day
- Star trails and planetarium overlays: ~1° daily drift against the stars
- Spinning top or gyroscope, tilted globe: trace the pole's 23.5° cone
- Animated orbital geometry measurably beats prose alone



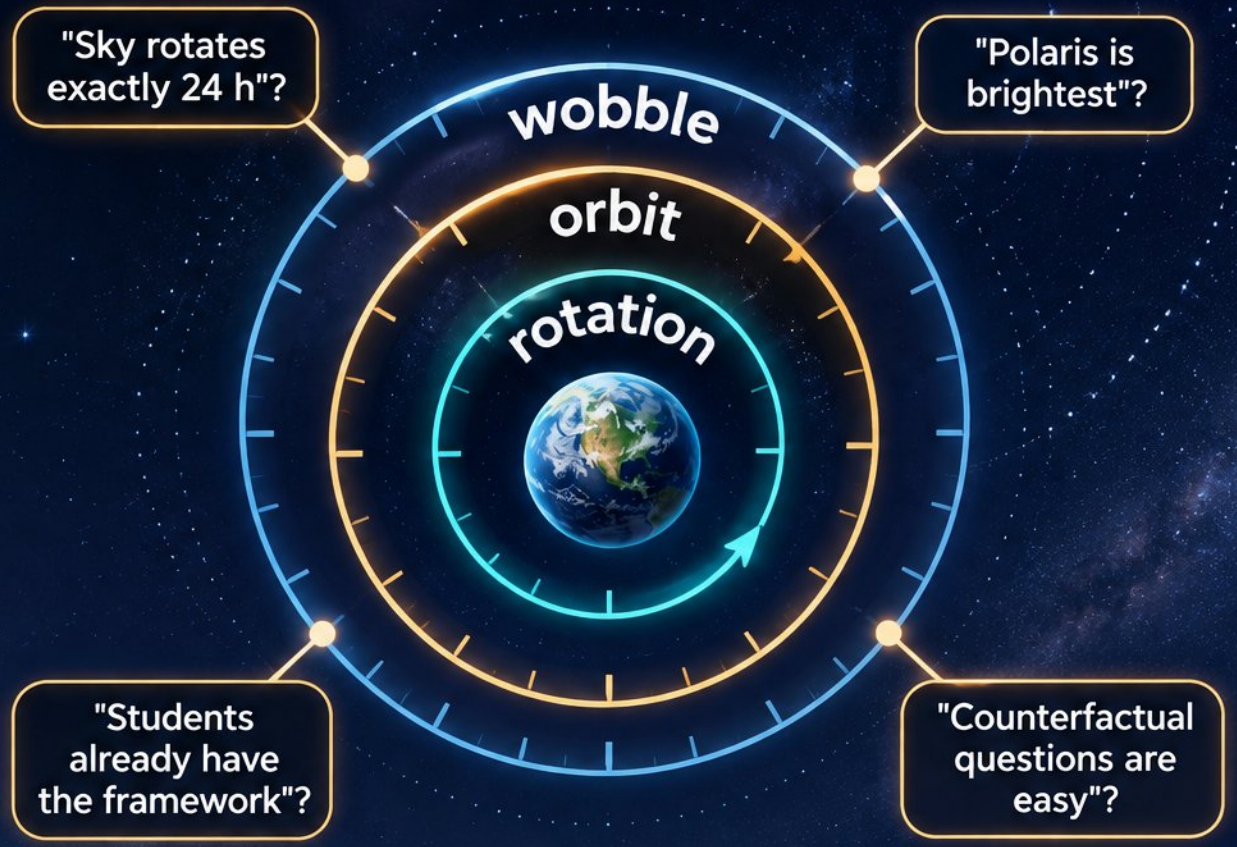






Misconceptions, Assessment, and Wrap-Up

- "Sky rotates exactly 24 h"? It's 23h56m; Polaris isn't brightest
- Students often lack prior framework — teach as new knowledge
- Assessment: compute offsets, predict rise times, explain analemma
- Counterfactual questions need scaffolded practice
- One rotation, one orbit, one wobble — three clocks of sky time





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