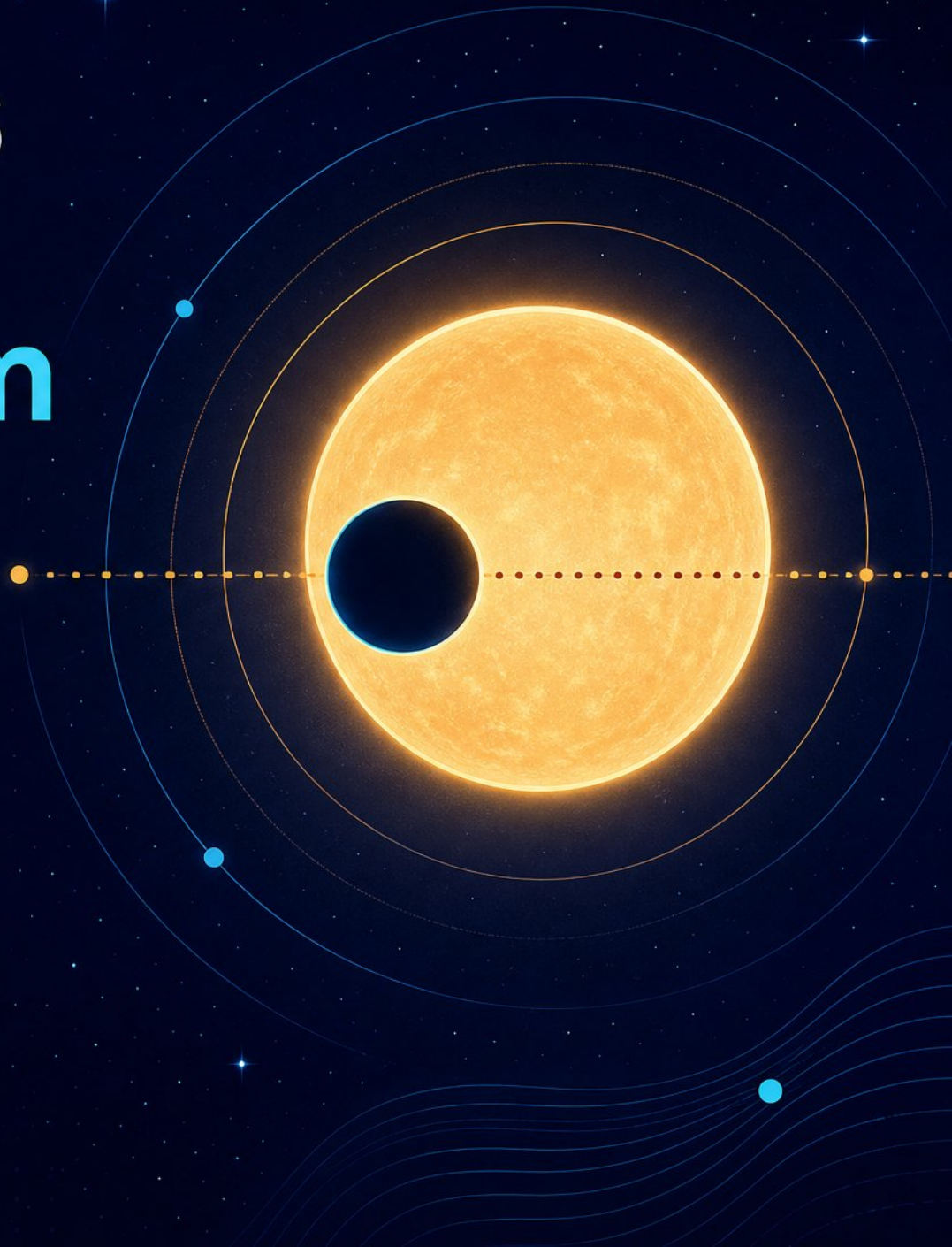


Exoplanets and How We Detect Them

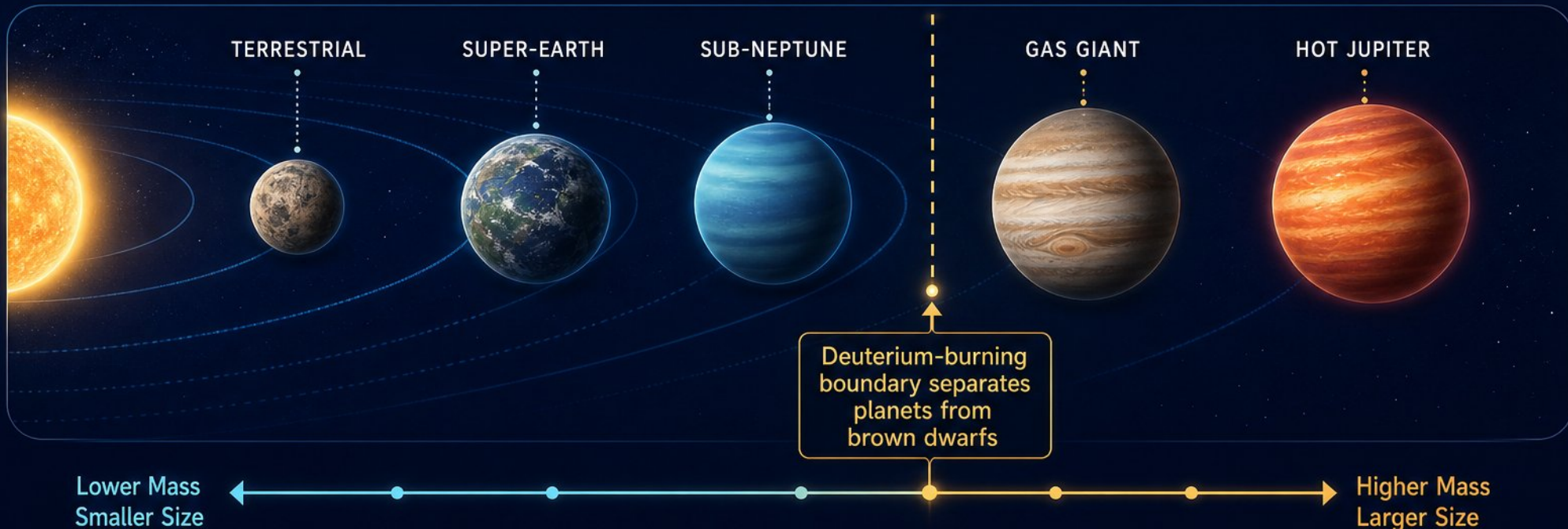
- Exoplanets: planets orbiting stars beyond our Sun
- Early claims gave way to rigorous confirmation
- Now: over 6,000 confirmed, thousands of candidates
- We will explore four main detection methods





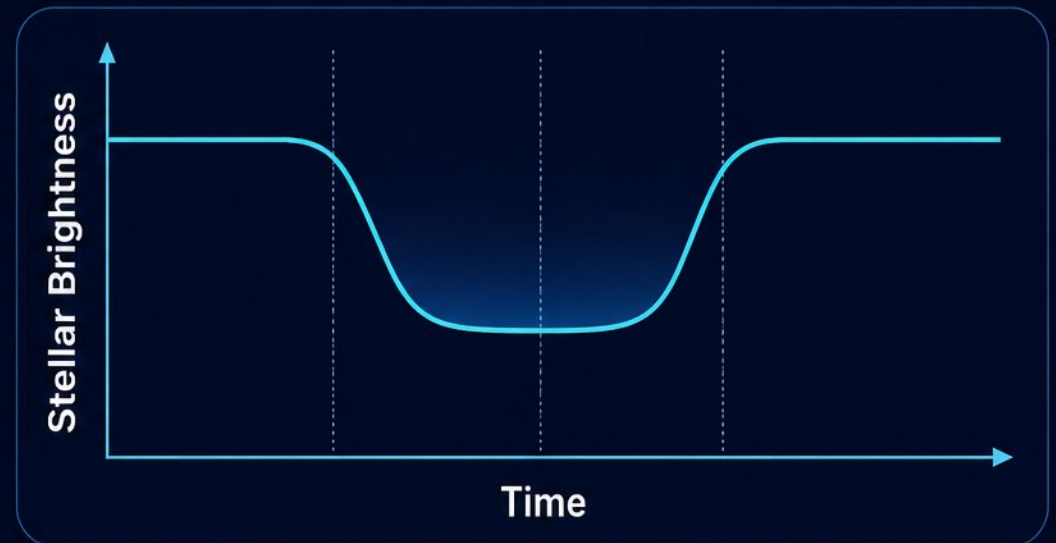
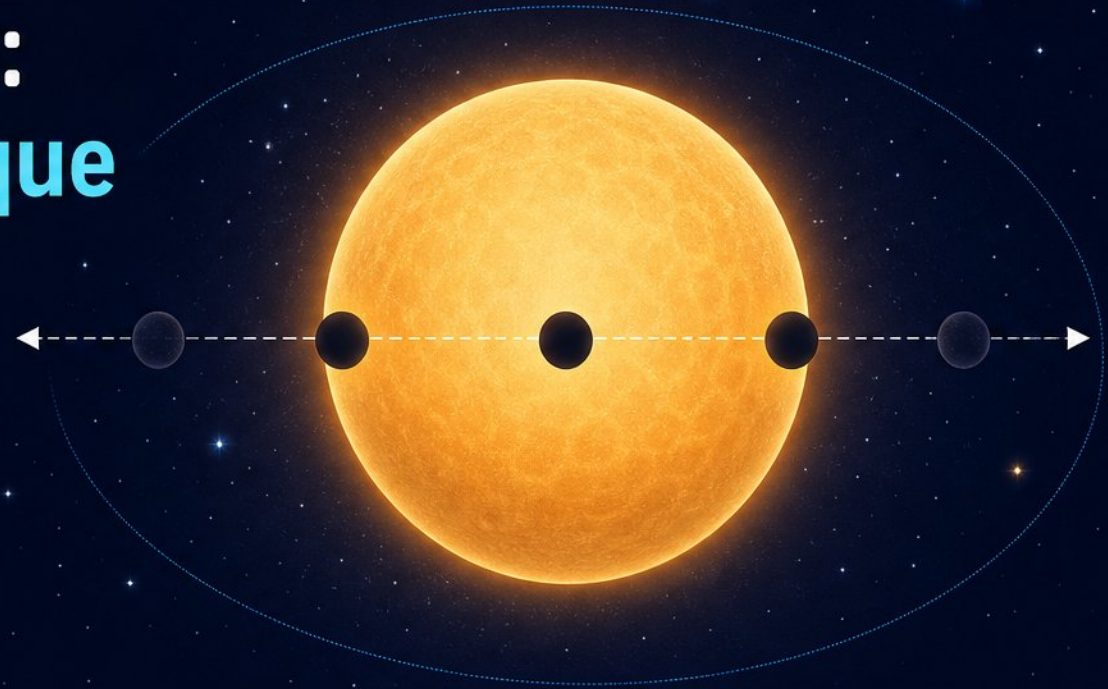
Core Concepts: Defining a Real Planet

-  IAU working definition: below ~13 Jupiter masses, orbiting a star or brown dwarf
-  Mass-ratio criterion: planet mass must be less than ~1/25 of the host's mass
-  Deuterium-burning boundary separates planets from brown dwarfs
-  Common categories: terrestrial, super-Earth, sub-Neptune, gas giant, hot Jupiter
-  Habitable zone: orbital distance allowing liquid surface water



Detection Method 1: The Transit Technique

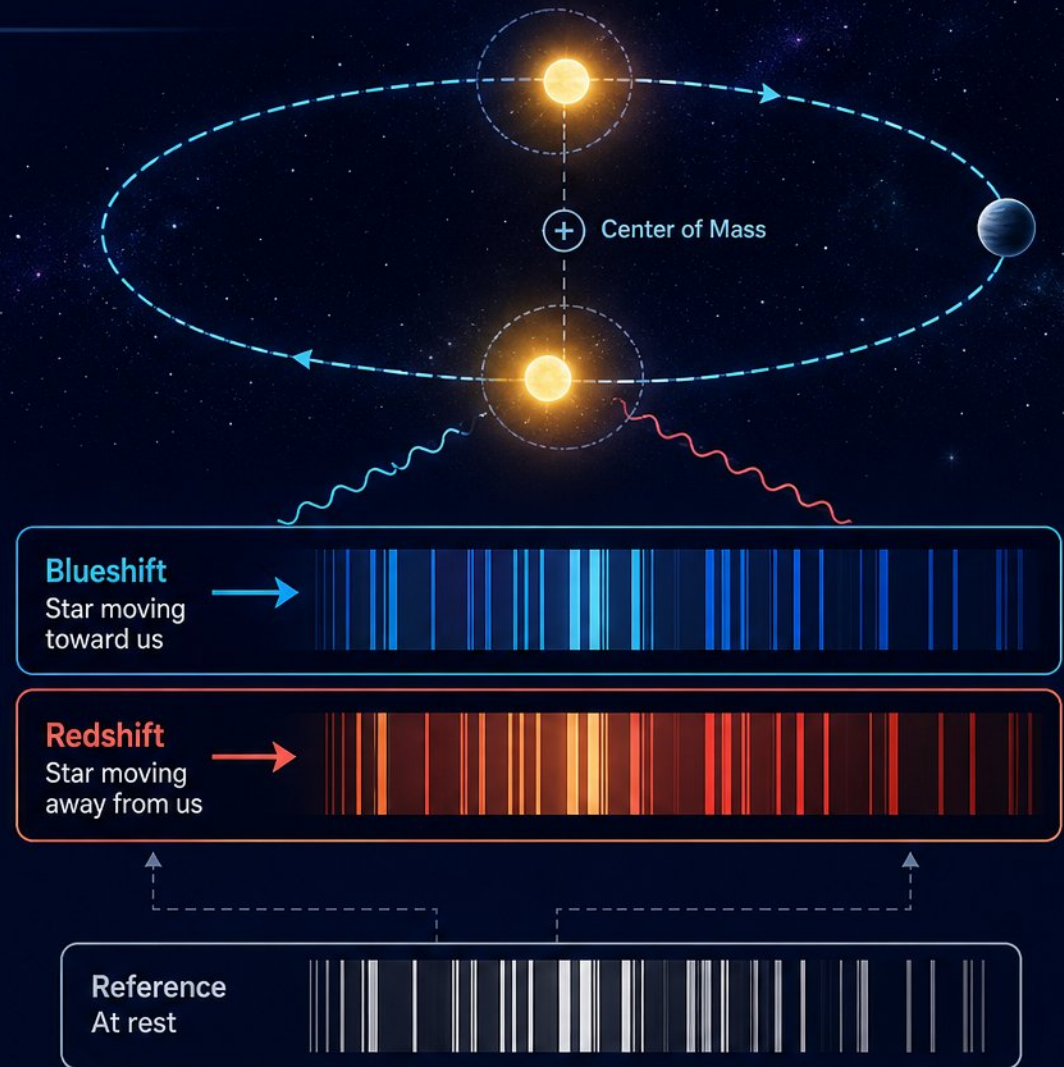
- Planet passing in front of its star dims the light
- The most productive exoplanet detection method so far
- Reveals planet size, orbit period, and atmospheric hints
- Key surveys: Kepler, TESS, and CHEOPS
- Biases: favors large planets close to their stars



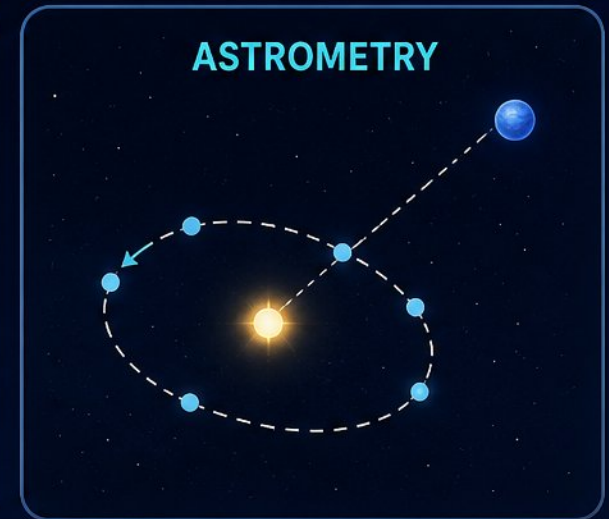
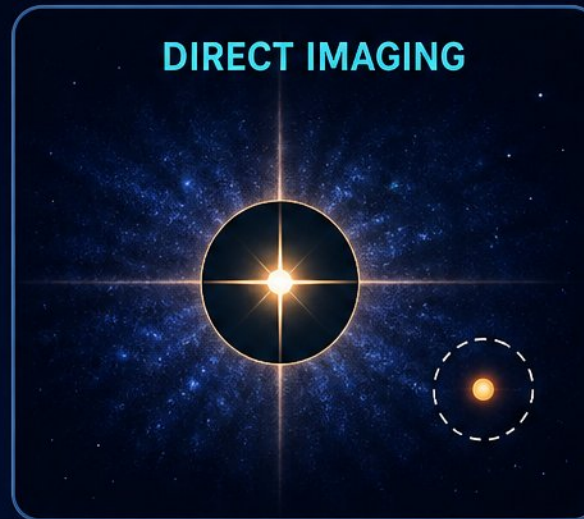
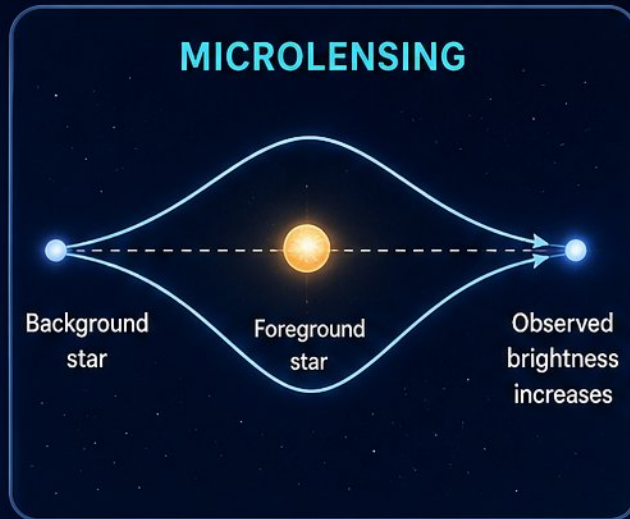
Detection Method 2:

Radial Velocity and Stellar Wobble

- Planet's gravity shifts star's spectral lines via the Doppler effect
- Reveals minimum mass and orbital shape
- Best as follow-up to transit detections
- Major instruments: HARPS and ESPRESSO
- Limited by stellar activity and needs high-resolution spectroscopy



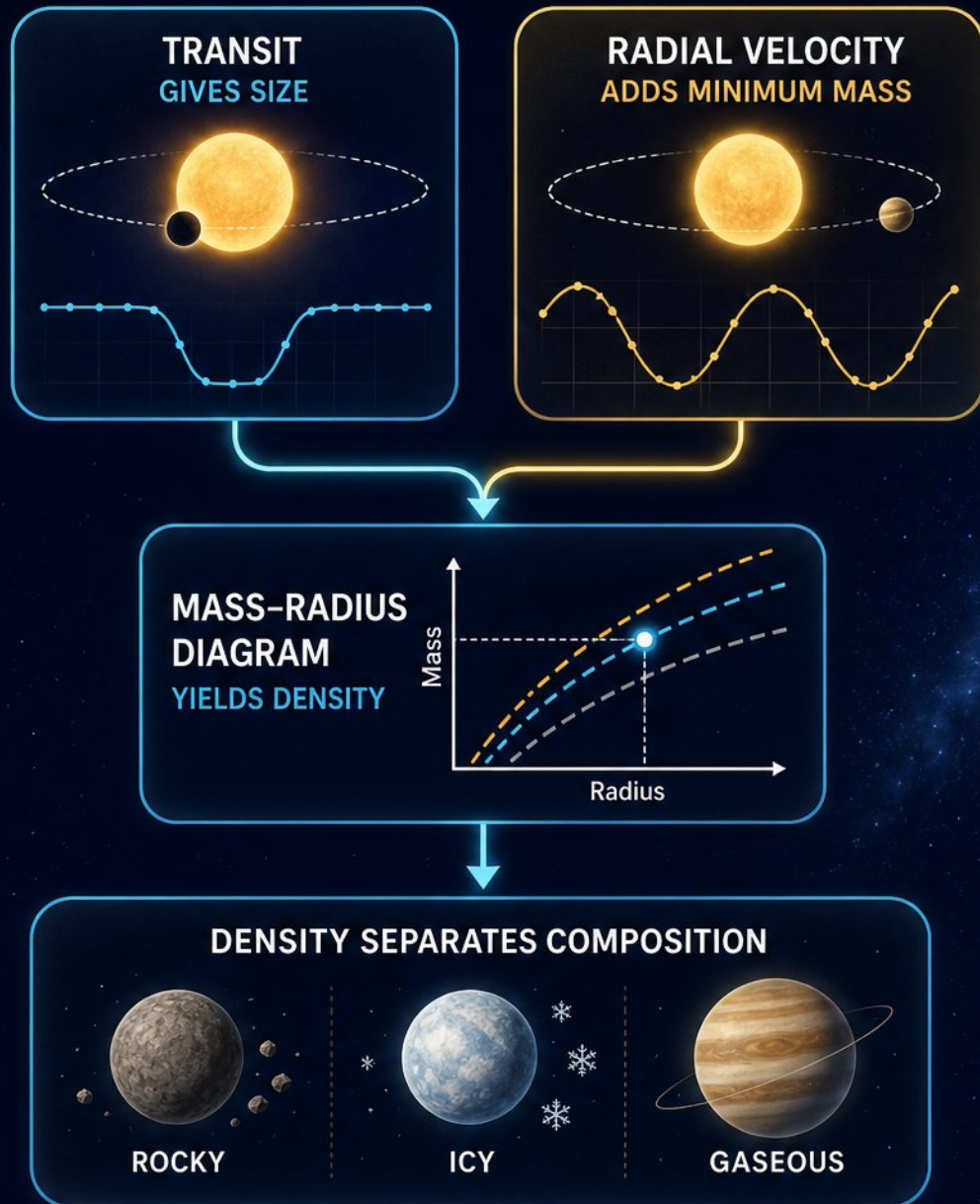
Other Methods: Microlensing, Direct Imaging, and Astrometry



- Microlensing: a foreground star's gravity magnifies a distant background star
- Direct imaging: captures young, hot giant planets in actual images
- Astrometry: precise positional shifts reveal companions over time
- Combined with Gaia, astrometry targets stars with unseen gravitational tugs
- HIP 54515 b and AF Lep b: superjovians found via imaging plus astrometry

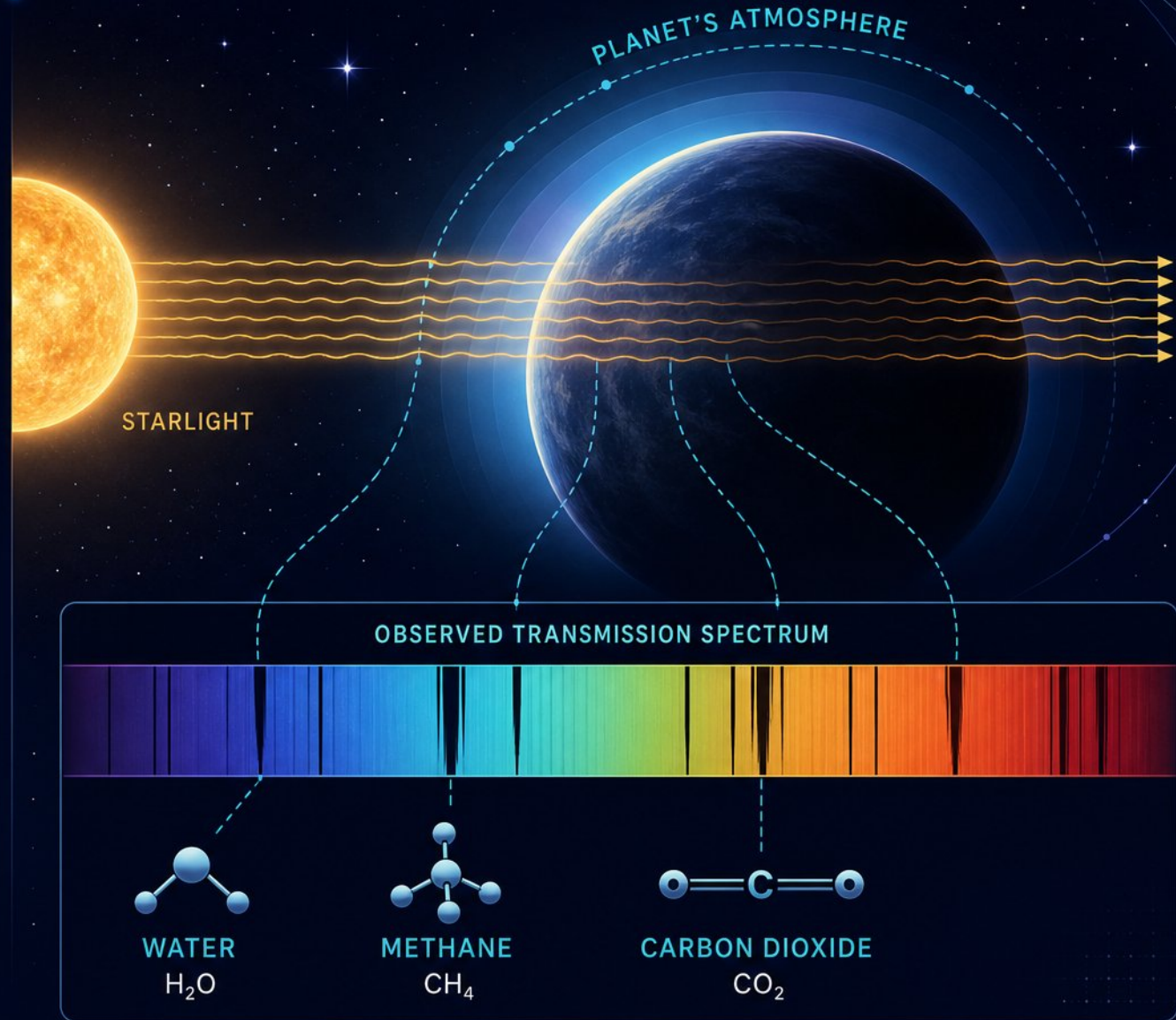
Combining Methods: From Candidate to Characterized World

- Transit gives size; radial velocity adds minimum mass
- Together they yield density, the key to composition
- Density separates rocky, icy, and gaseous planets
- Multiple methods confirm real planets and reject false positives
- Example: TRAPPIST-1 planets characterized through combined observations



Peeking into Exoplanet Atmospheres

- **Transmission spectroscopy:** starlight filtering through a planet's atmosphere reveals its composition
- **Key molecules detected:** water, methane, carbon dioxide, sulfur dioxide, and carbon monoxide
- **JWST** provides unprecedented infrared sensitivity for exoplanet spectra
- **Hubble** pioneered atmospheric studies; upcoming **Ariel** will expand the survey
- **Current challenges:** clouds, hazes, and stellar contamination complicate interpretation



Habitable Worlds and the Search for Biosignatures



- Habitability depends on atmosphere, not just distance from the star



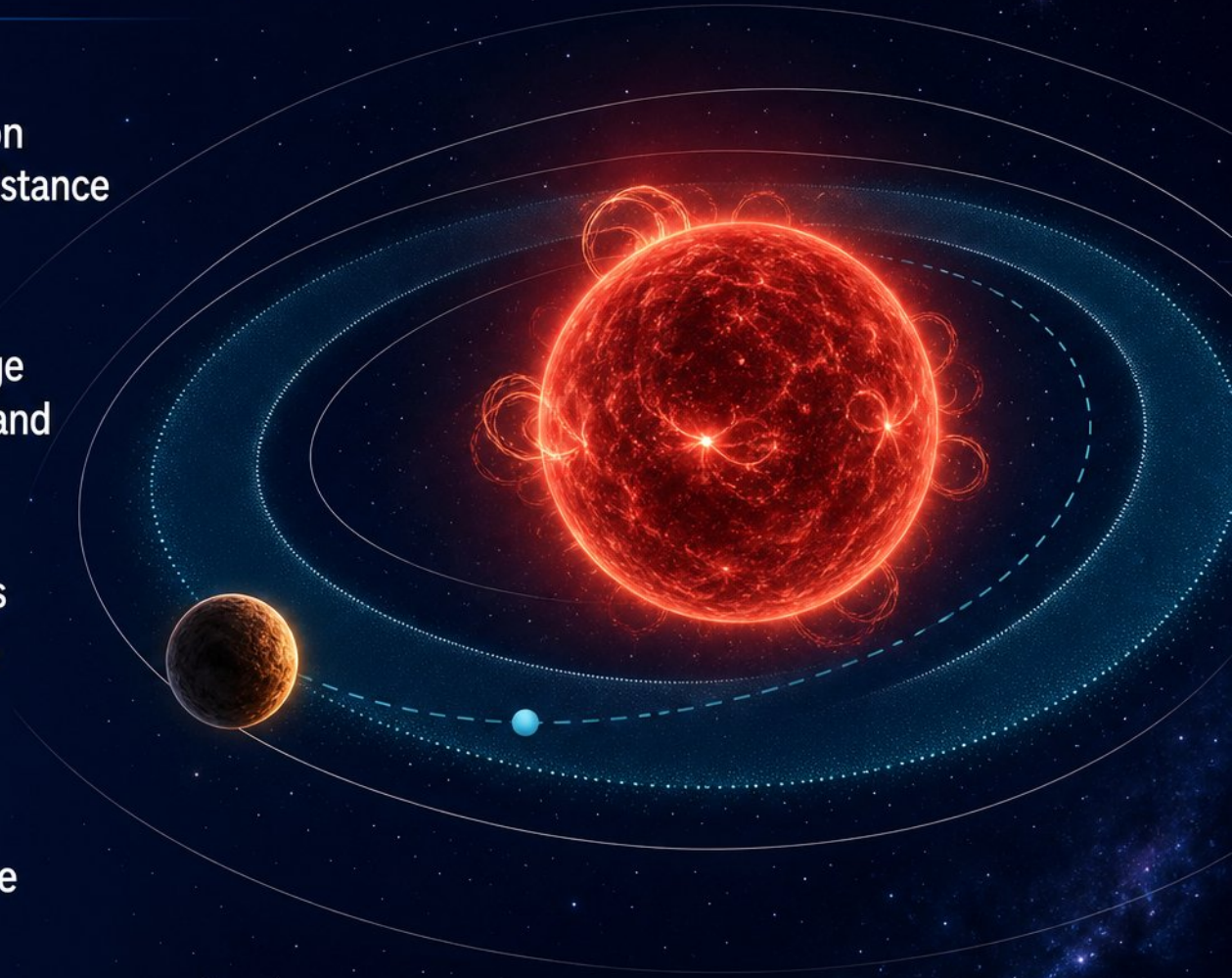
- M-dwarf stars challenge habitability with flares and tidal locking



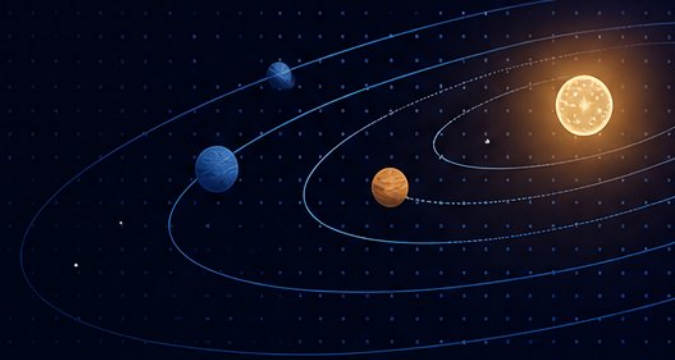
- Biosignatures are gases like O_2 , CH_4 , and CO_2 from life



- TRAPPIST-1 e and Proxima Centauri b are key test cases



Demographics: Patterns in the Exoplanet Population



- Radius valley: a gap between super-Earths and sub-Neptunes



- Formation models differ for rocky vs. volatile-rich planets



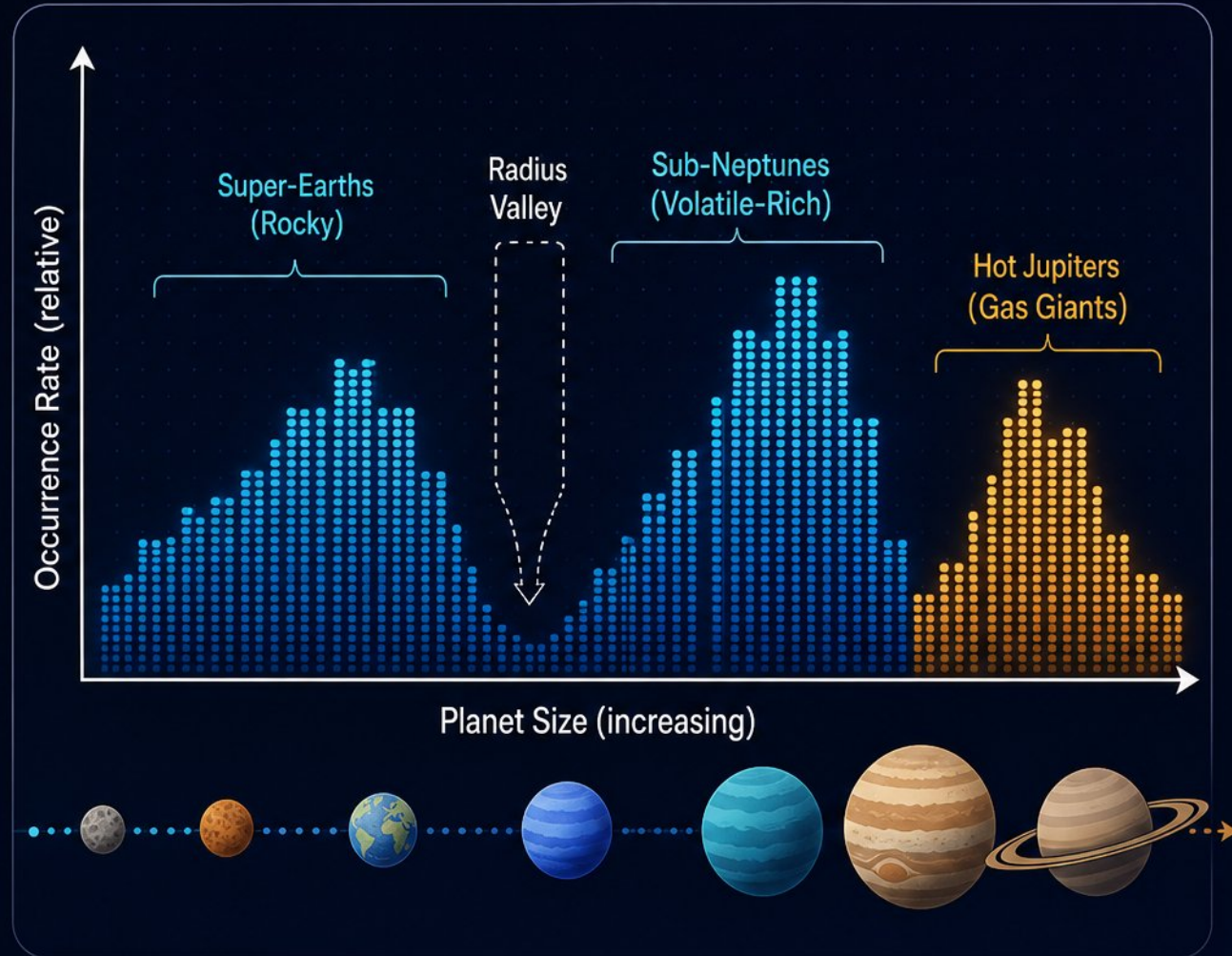
- Hot Jupiters likely migrate inward after forming farther out



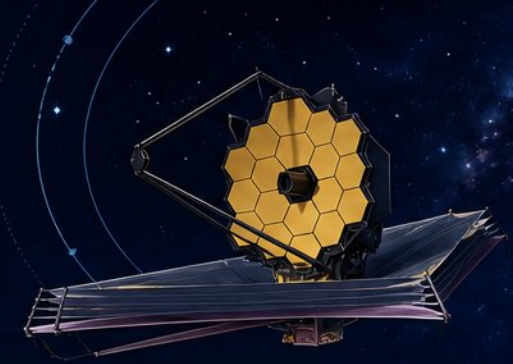
- Occurrence rates depend on stellar type and metallicity



- Current census is biased toward short-period, large planets



The James Webb Space Telescope Era: Key Results and Open Questions



- JWST revolutionized exoplanet atmosphere characterization with unprecedented sensitivity



- Detections of CO, H₂O, OH, and SO₂ in giant planet atmospheres



- Stellar contamination complicates weak transmission spectra



- Cross-correlation techniques extract molecular signals at native instrument resolution



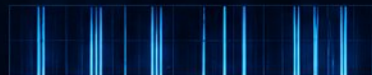
- Open questions: atmospheric composition, dynamics, and disequilibrium chemistry

JWST TRANSMISSION SPECTRA: MOLECULAR DETECTIONS



MOLECULAR SIGNATURES DETECTED

CO



H₂O



OH

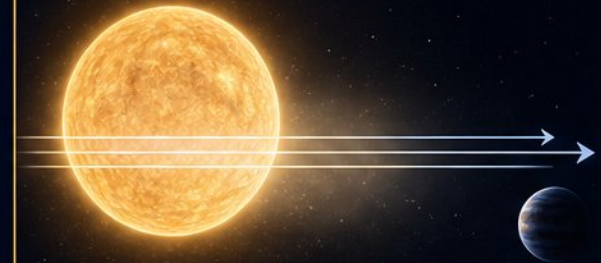


SO₂



SPECTRAL "BARCODE"

STELLAR CONTAMINATION: A CHALLENGE



WEAK, CONTAMINATED SIGNAL



AFTER CROSS-CORRELATION EXTRACTION



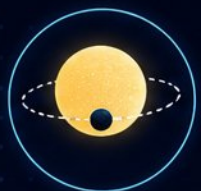
RECOVERED MOLECULAR SIGNAL

The Road Ahead: New Missions and Technologies



- **PLATO:** 26-camera transit surveyor of Sun-like stars, launching late 2026
- **Ariel:** dedicated atmospheric surveyor of 1000+ exoplanets, launching 2029
- **Roman Space Telescope Coronagraph:** advancing direct imaging capabilities
- **ELT and ANDES:** ground-based characterization of small planet atmospheres
- **Future focus:** climates, chemistry, and potential biosignatures

Practice: Interpreting a Transit Light Curve



- Depth reveals planet size relative to its star



- Duration and spacing show orbital period and geometry



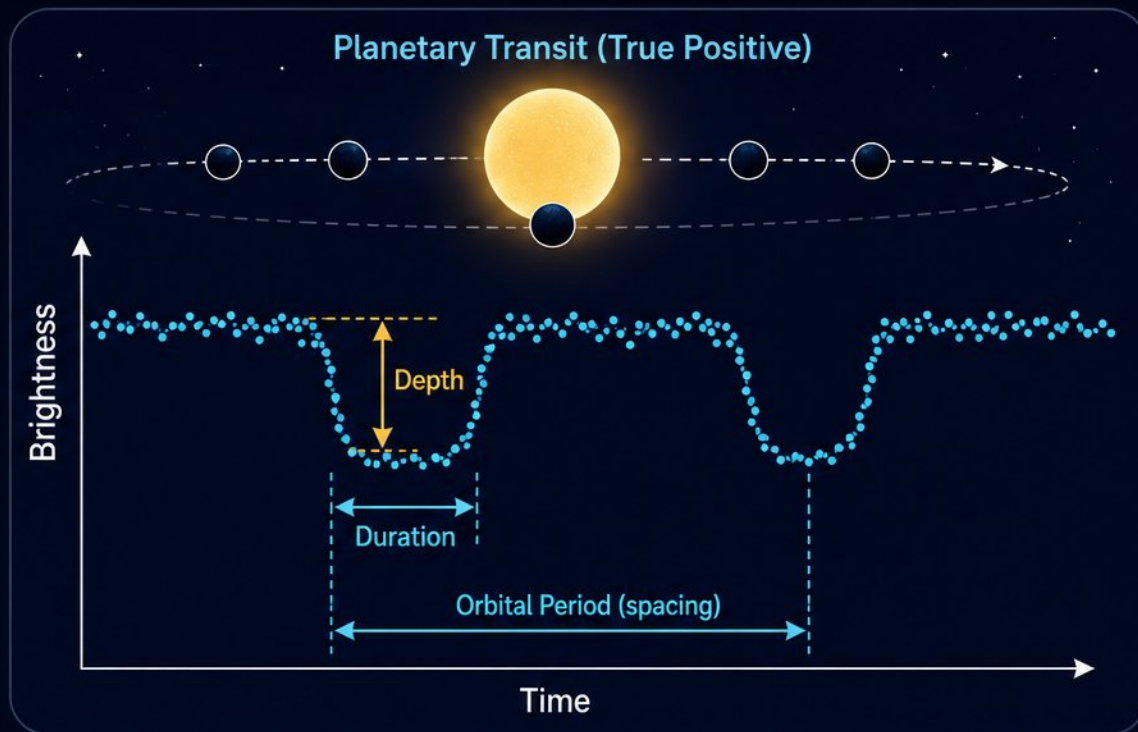
- U-shaped versus V-shaped dips help flag false positives



- Eclipsing binaries and starspots can mimic planetary transits

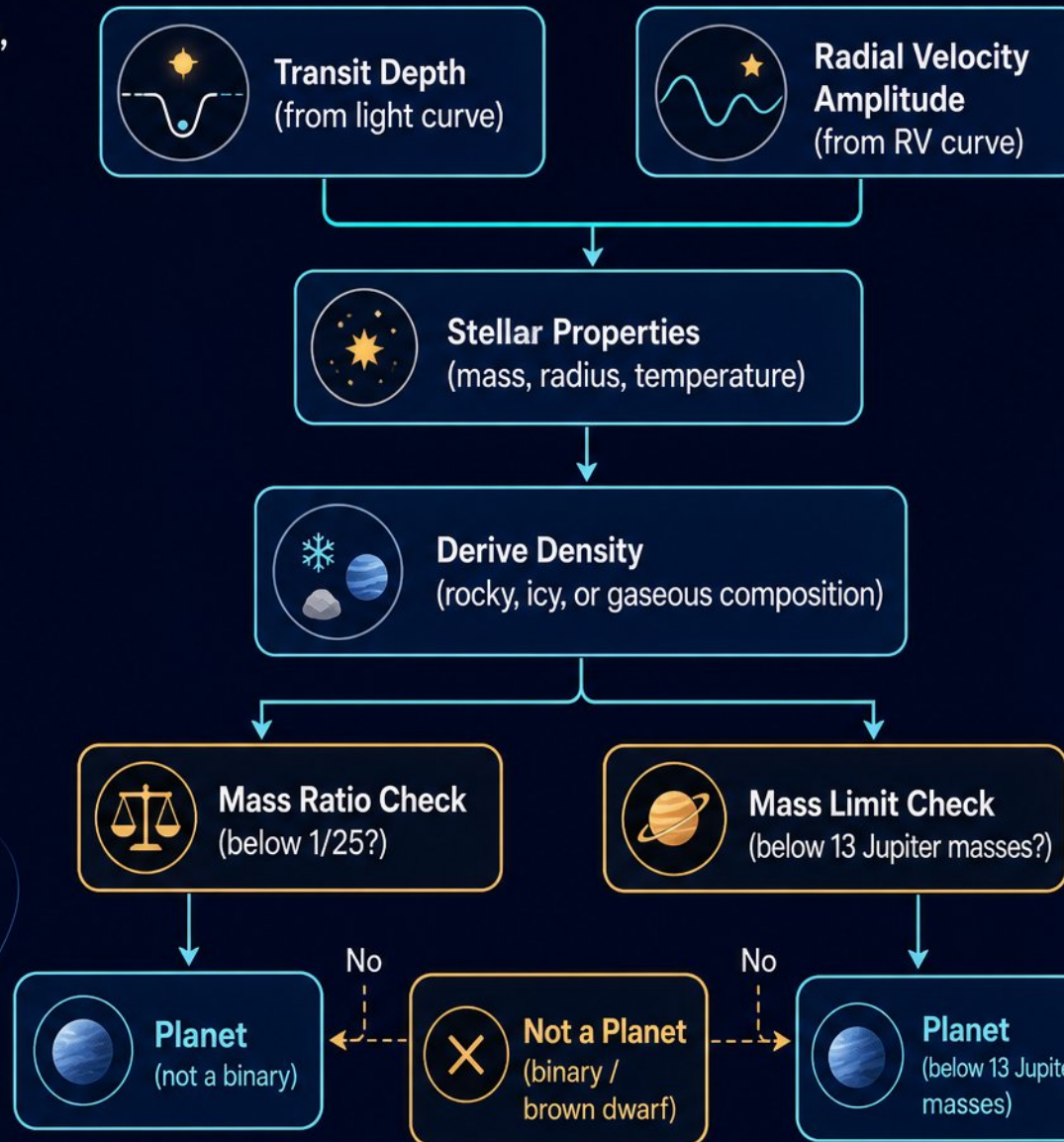


- Repeat transits and a second method build confidence



Practice: Deciding if a Signal Is a Real Planet

- Combine transit depth, radial velocity, and stellar properties
- Derive density: rocky, icy, or gaseous composition
- Mass ratio below 1/25 distinguishes planets from binaries
- Apply the 13 Jupiter mass limit vs. brown dwarfs



IAU Working Definition

Planet: a body that orbits a star, has sufficient mass for self-gravity to produce a nearly round shape, and has cleared the neighborhood around its orbit.

From Data to Discovery: Scientific Thinking in Exoplanet Research

- - Detection requires skepticism and independent verification
- - False positives refine methods and strengthen conclusions
- - Reproducibility is central to candidate confirmation
- - Open data and citizen science invite broader participation



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