NTHU AstroRead

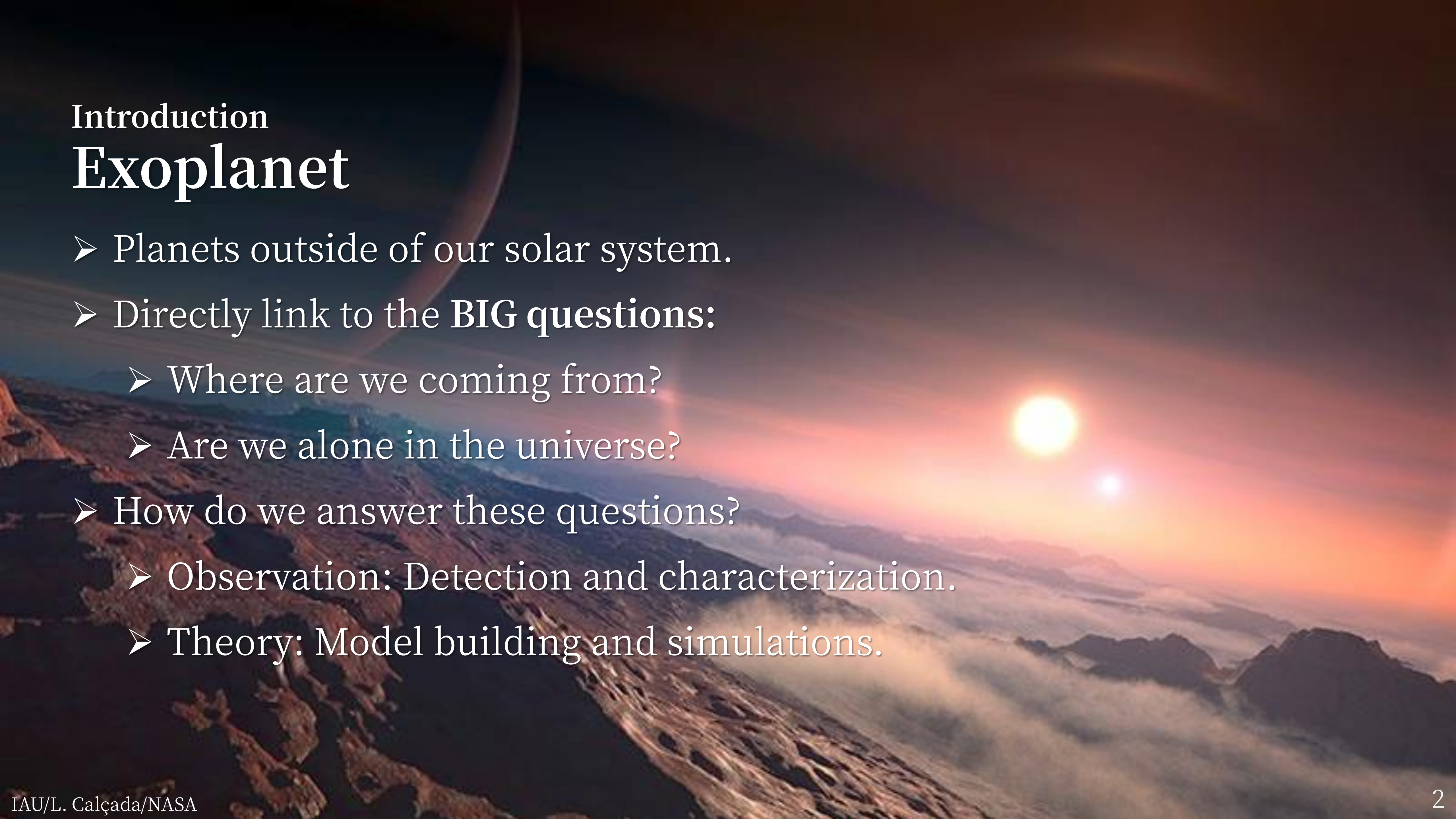
Exoplanets

Lin Yen-Hsing | 2023.05.23

NASA, ESA, Joseph Olmsted (STScI)

Exoplanet

- Planets outside of our solar system.
- Directly link to the **BIG questions:**
  - Where are we coming from?
  - Are we alone in the universe?
- How do we answer these questions?
  - Observation: Detection and characterization.
  - Theory: Model building and simulations.



IAU/L. Calçada/NASA

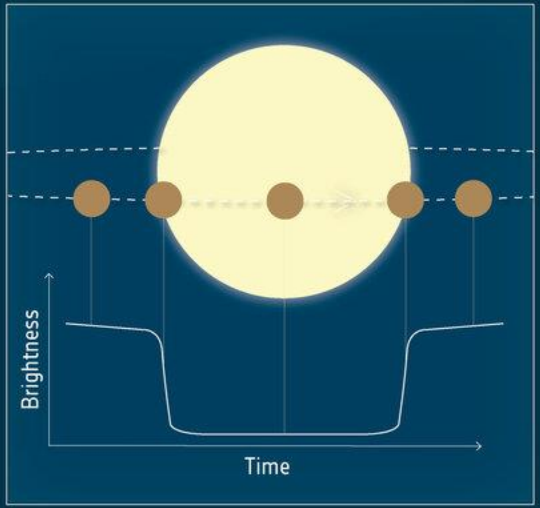
Exoplanet Detection

Fundamental difficulties

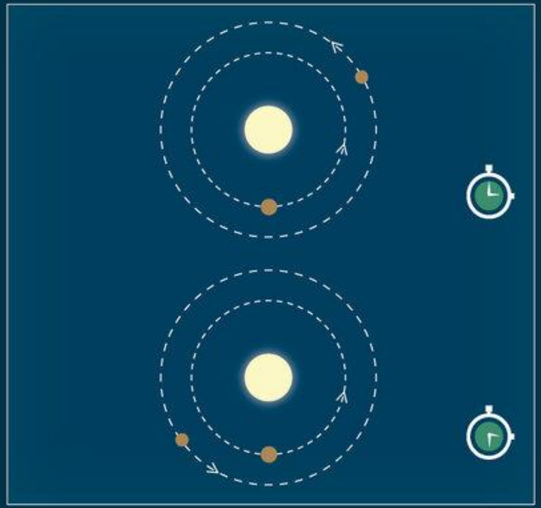
- Star – Planet brightness contrast.
  - E.g. Sun Earth contrast ~ 10^9.
- Star – Planet angular separation.
  - E.g. Sun – Jupiter at 50 pc for HST max. res.
- Trying to see a bug beside a light house.
- Most of the exoplanets are found using **indirect methods**.

→ EXOPLANET DETECTION METHODS

Transit photometry



Transit-timing variation

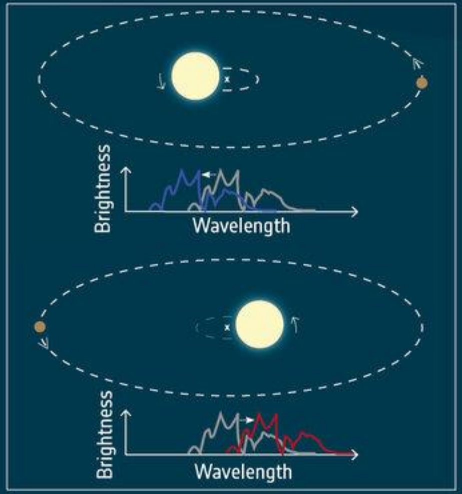


Transit photometry is one of the main techniques used to **discover** exoplanets. Cheops will use this technique to **measure the sizes** of known exoplanets and to start to **characterise** them.

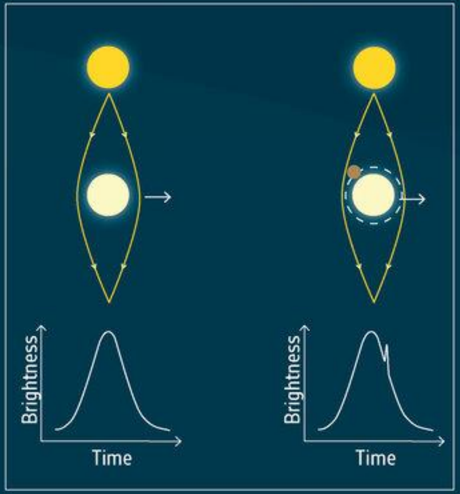
By using the **transit-timing variation** technique, Cheops will be able to **discover** additional, previously unknown planets around some stars, and also determine the planet **masses**.

Other techniques used to discover new exoplanets (not employed by Cheops) are: radial velocity, microlensing, astrometry and direct imaging.

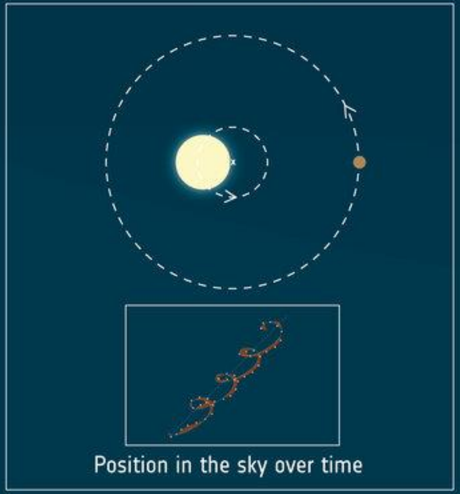
Radial velocity



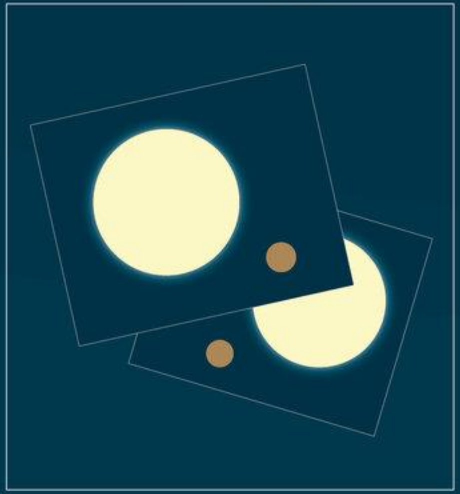
Microlensing



Astrometry



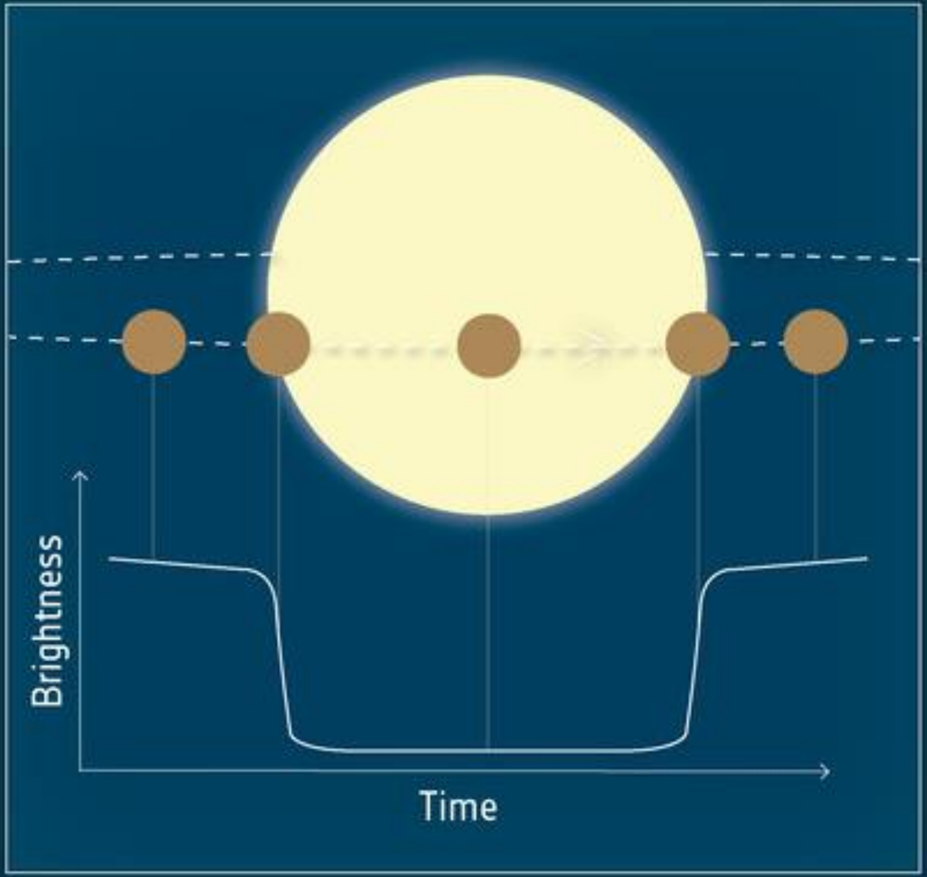
Direct imaging



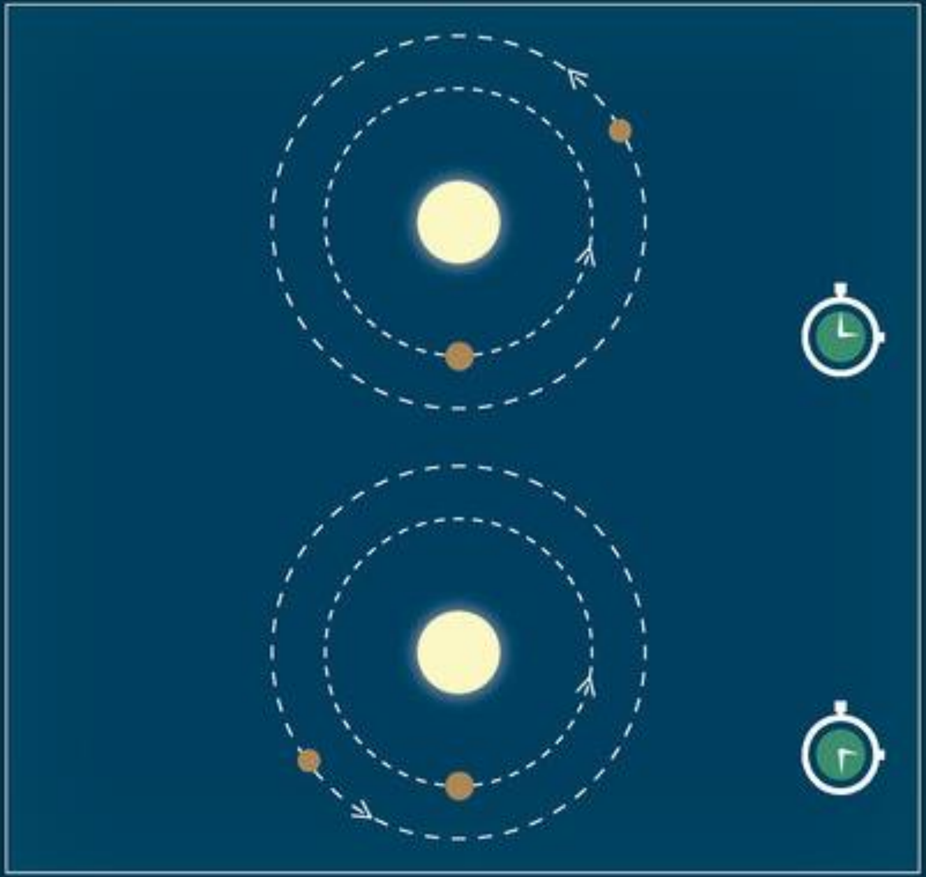
#cheops

OPLANET DETECTION METHODS

Transit photometry



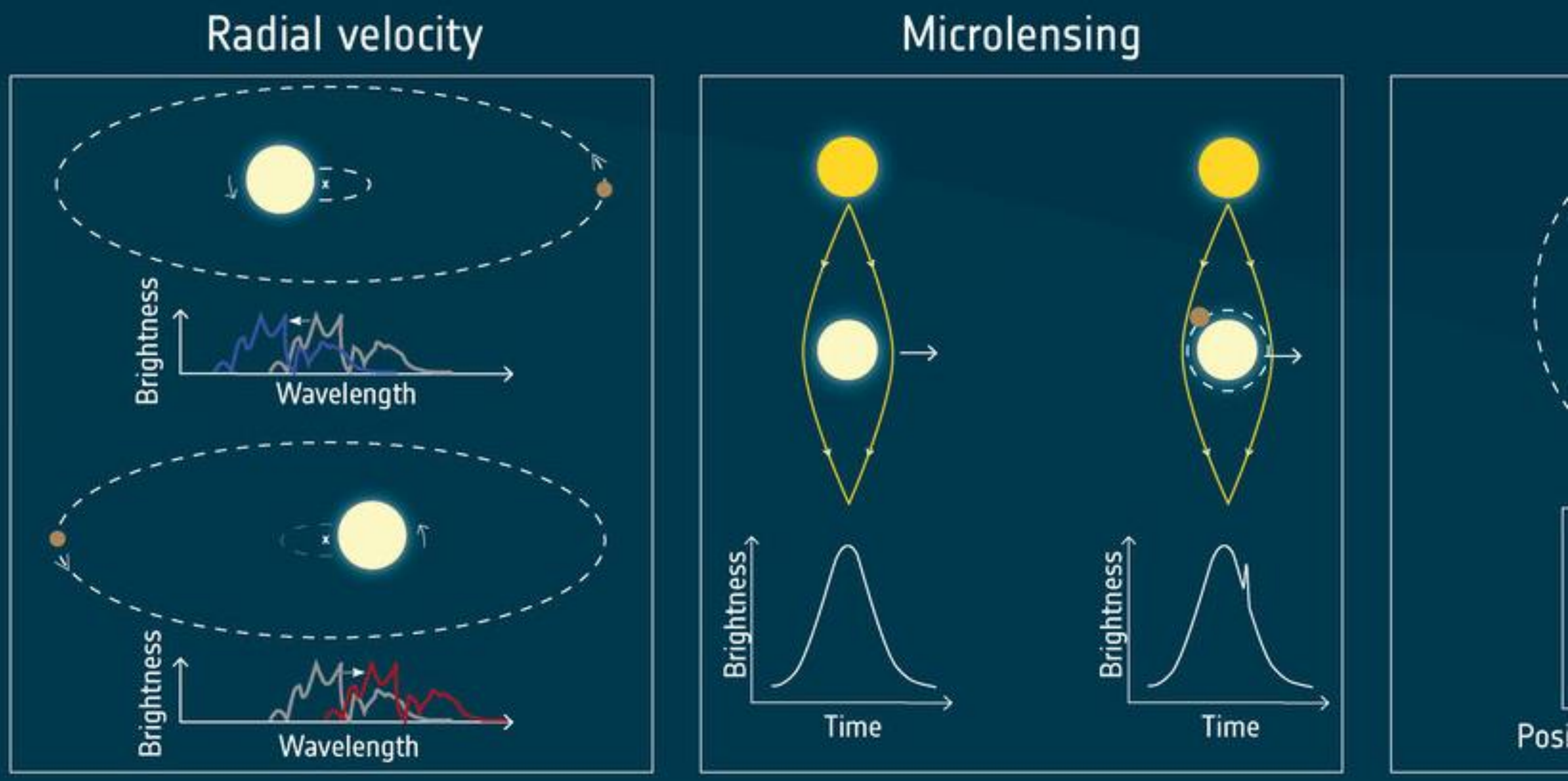
Transit-timing variation



Radial velocity

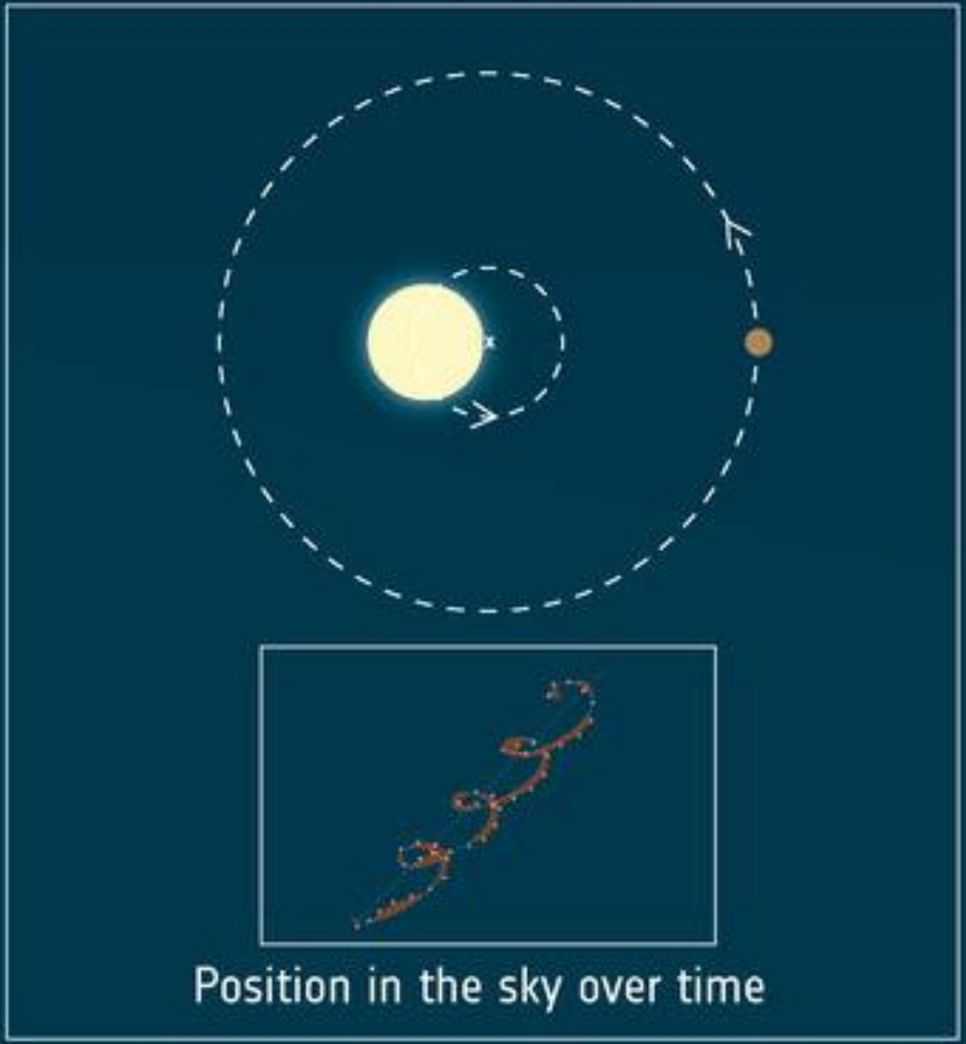
Microlensing

Astrometry

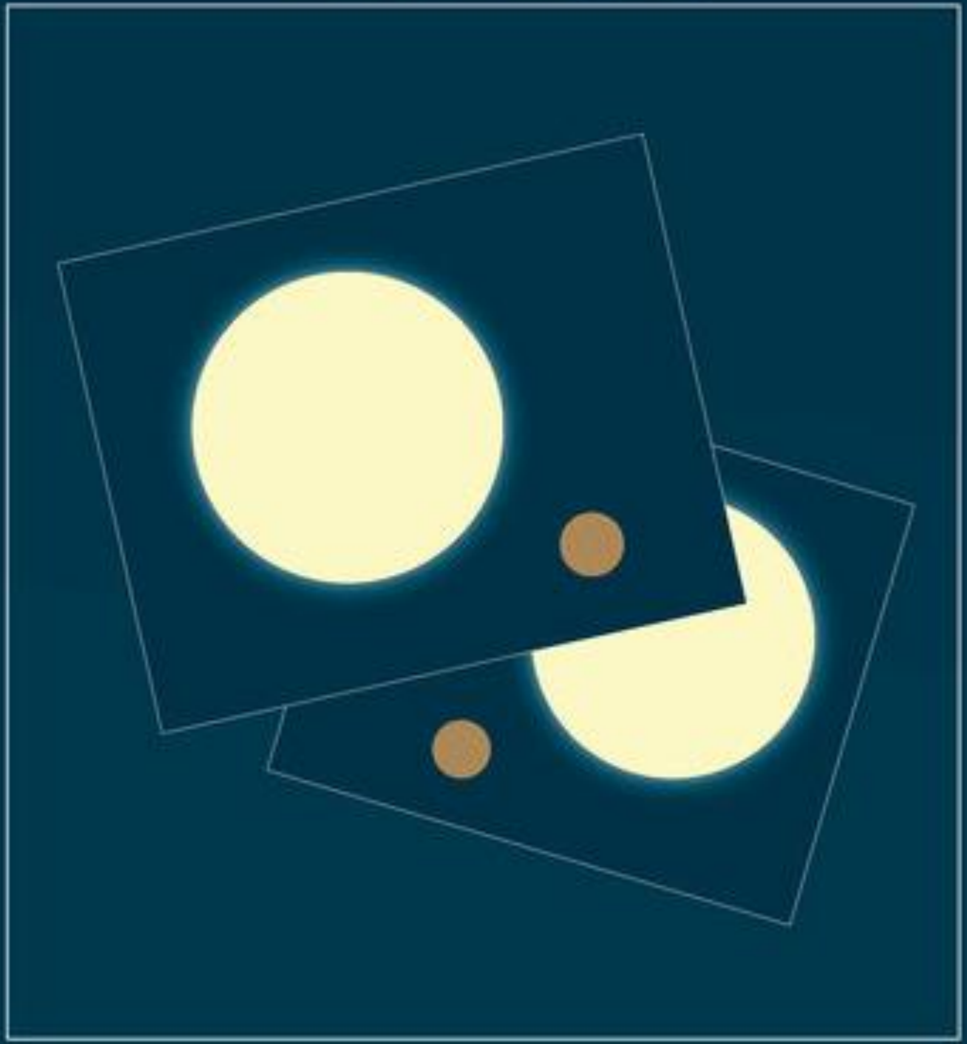


Radial velocity
Brightness
Wavelength
Brightness
Wavelength
Microlensing
Brightness
Time
Brightness
Time

Astrometry



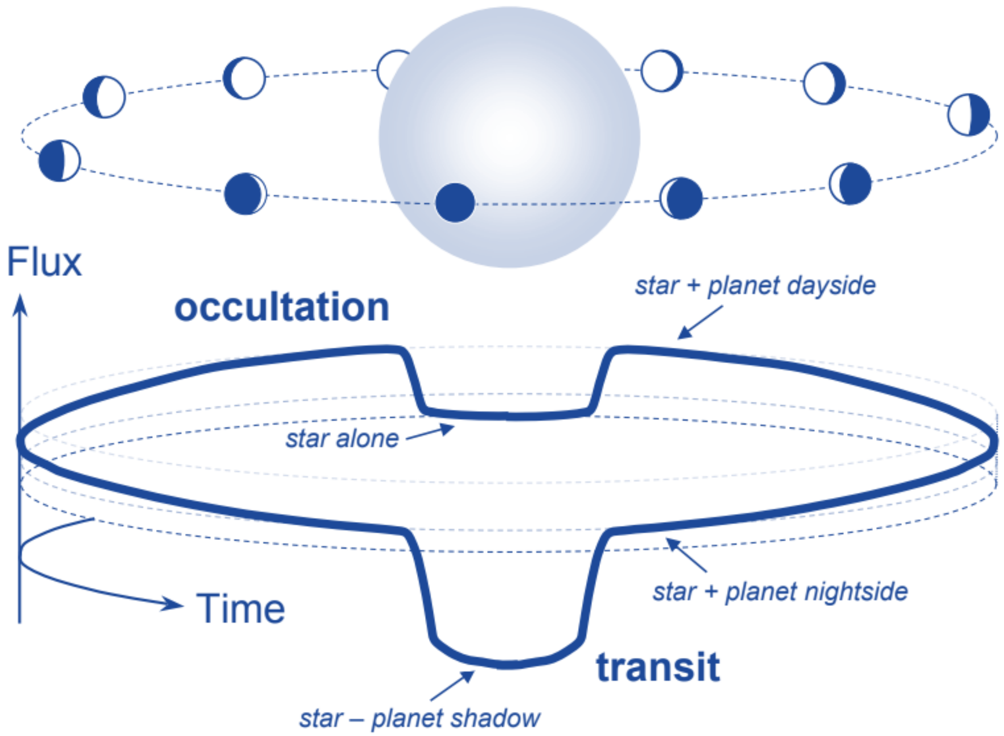
Direct imaging

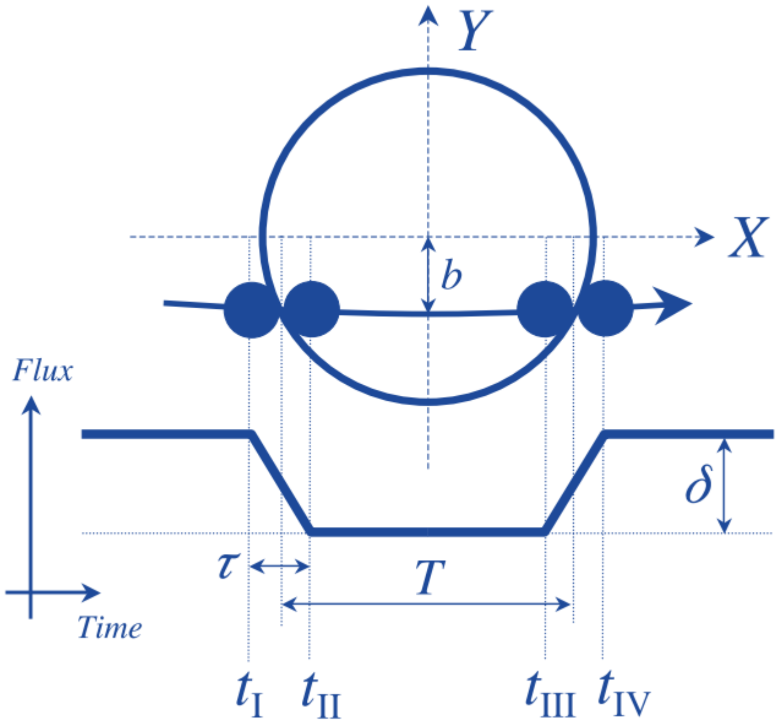


Exoplanet Detection

Transit method

- Most powerful method for searching (Discovered > 70% confirmed planets).
- Sun – Earth transit: 10^{-4} brightness change.



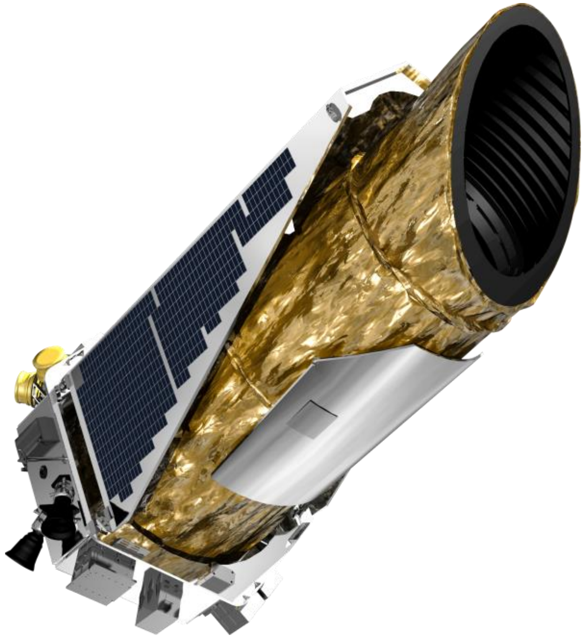


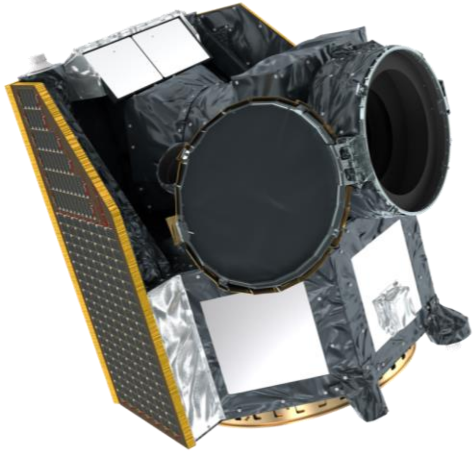
Winn et al. (2010)

Exoplanet Detection

Space telescopes for transit

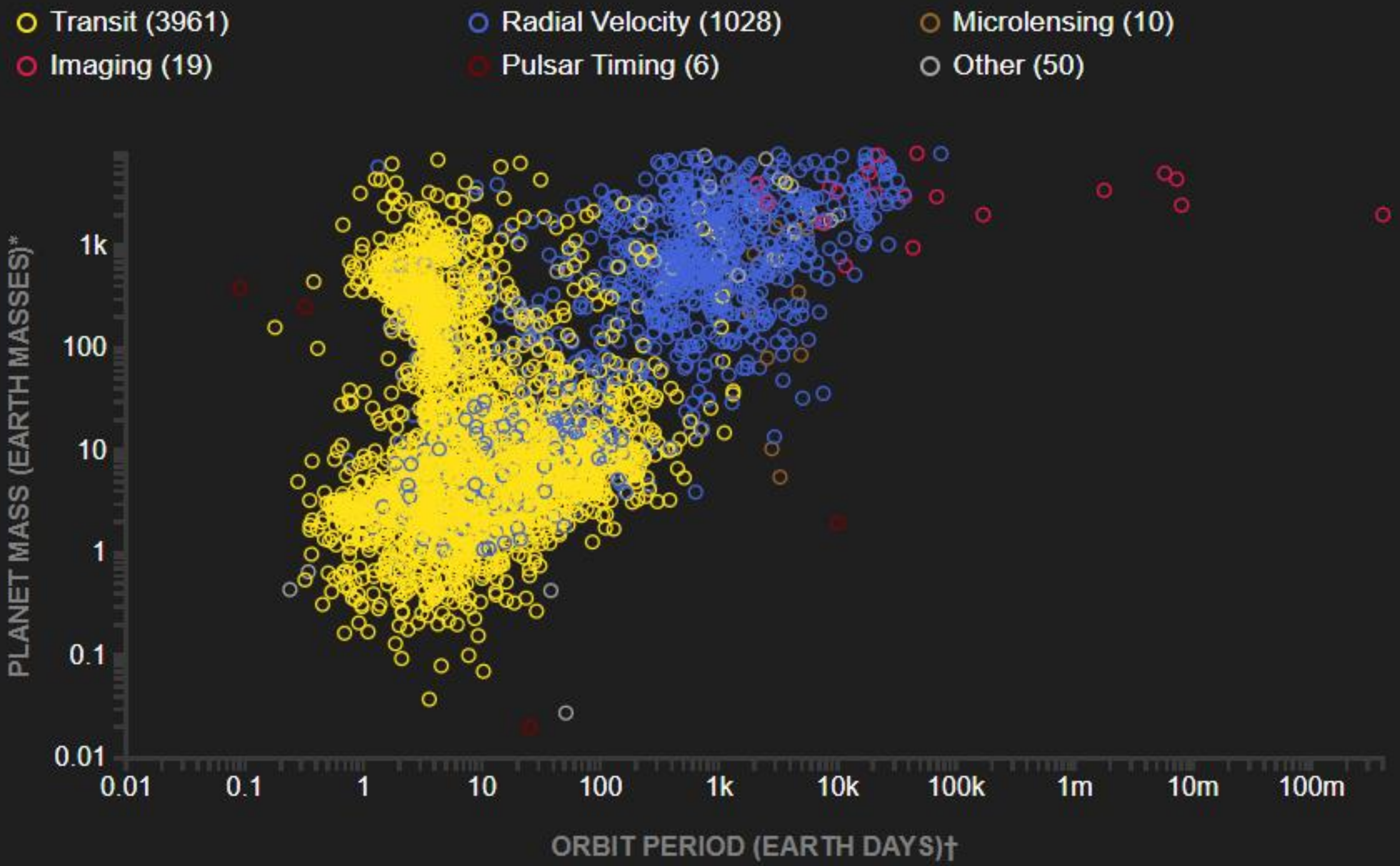
- Doing transit observation in space is much more efficient.
- Kepler (2009 ~ 2018), TESS (2018 ~ Now), Cheops (2019 ~ Now).





NASA | ESA/ATG medialab

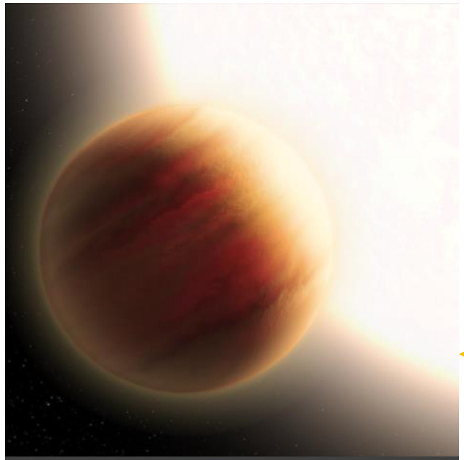

Radial Velocity 0
Transit 0
Imaging 0
Microlensing 0
Year: 1991
Exoplanets: 0
0 Timing Variations
0 Orbital Brightness Modulation
0 Astrometry
0 Disk Kinematics


Transit (3961)
Radial Velocity (1028)
Microlensing (10)
Imaging (19)
Pulsar Timing (6)
Other (50)
PLANET MASS (EARTH MASSES)*
1k
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1k
10k
100k
1m
10m
100m
ORBIT PERIOD (EARTH DAYS)†

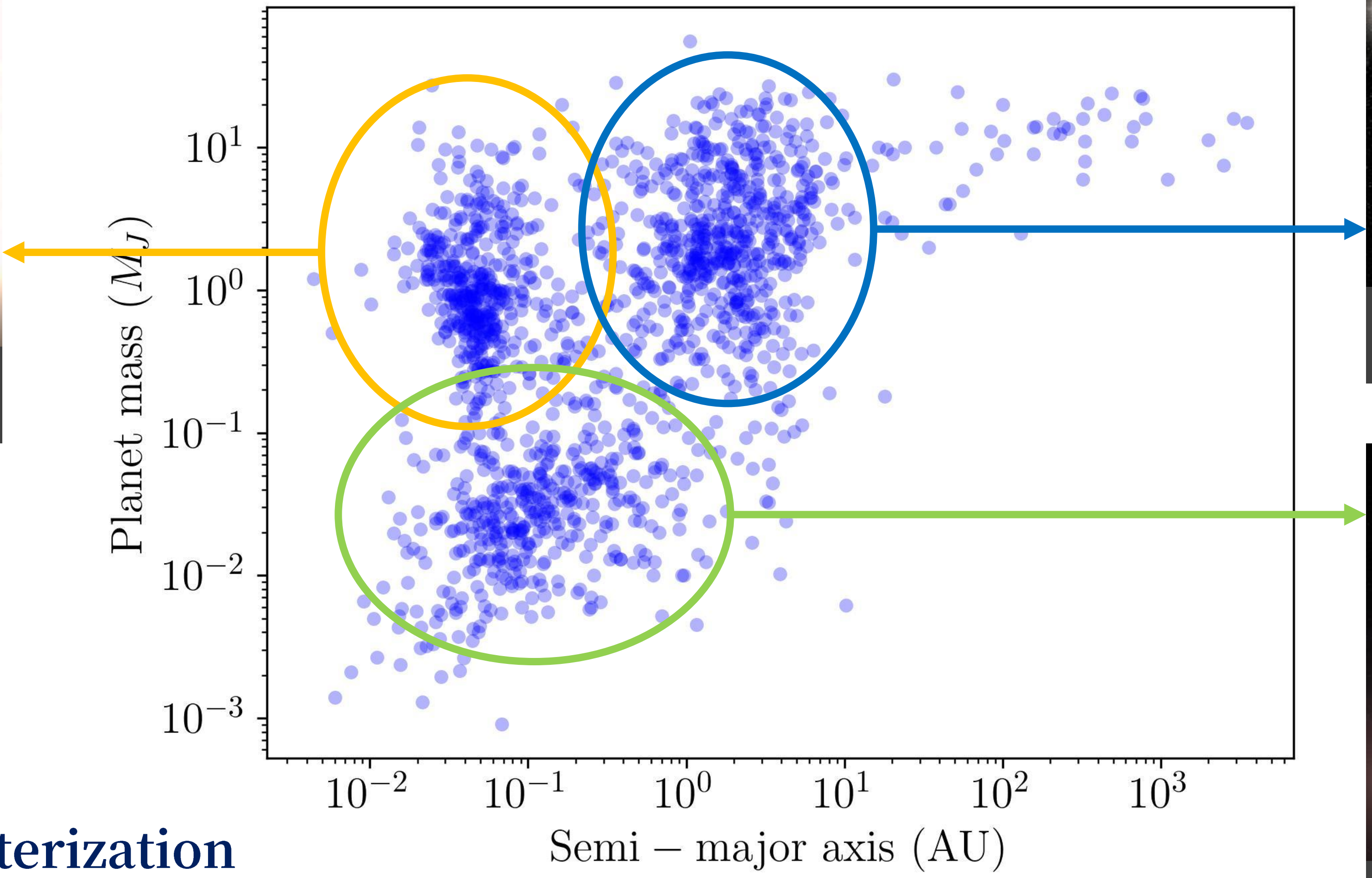
Exoplanet Characterization

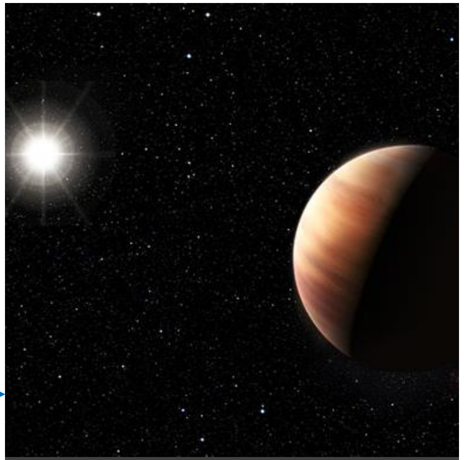
What can we learn from transits and radial velocity?

- Host star: stellar mass, stellar radius, etc.
- Transit: Planet radius, orbital period.
- Radial velocity: Planet mass, orbital period.
- Combined:
  - Semi-major axis: how far away from the host star? (Kepler 3rd law)
  - Density: is it a terrestrial planet or gas giant?
  - Temperature: Possible surface status, e.g. phase of water.



Hot Jupiter





Cold Jupiter

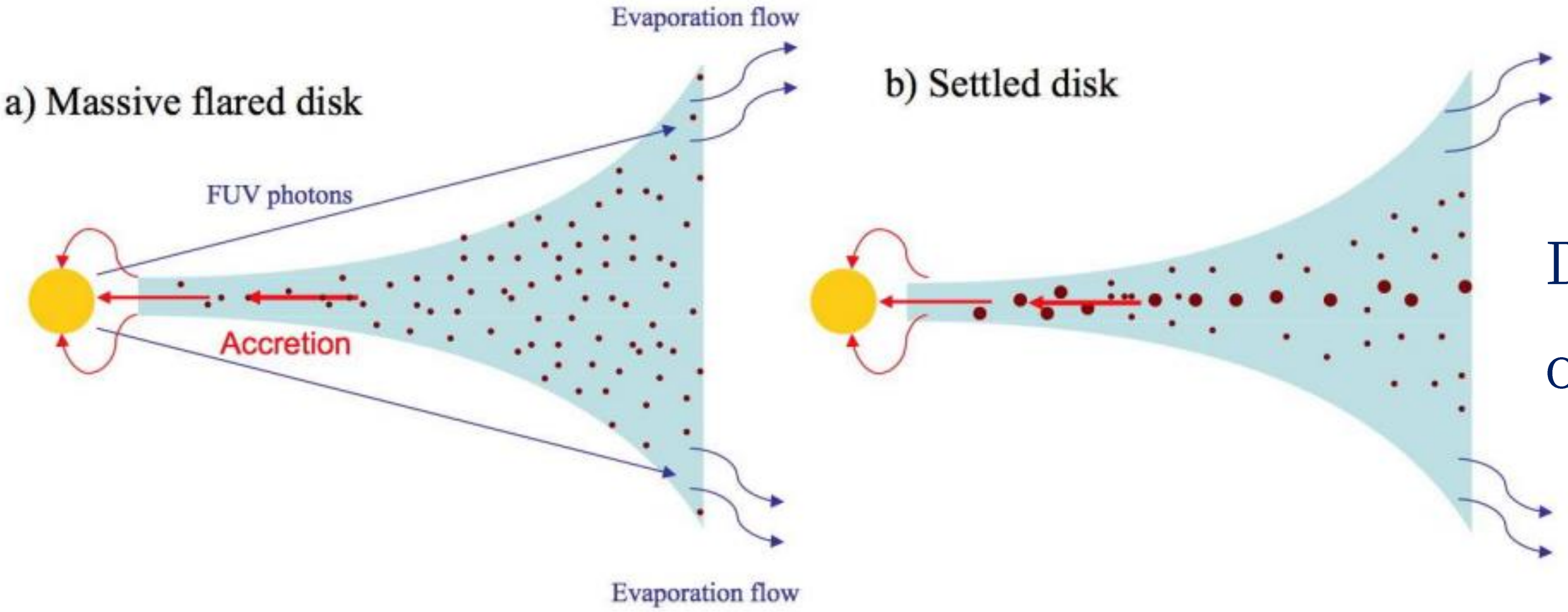
Super Earth

Exoplanet Characterization

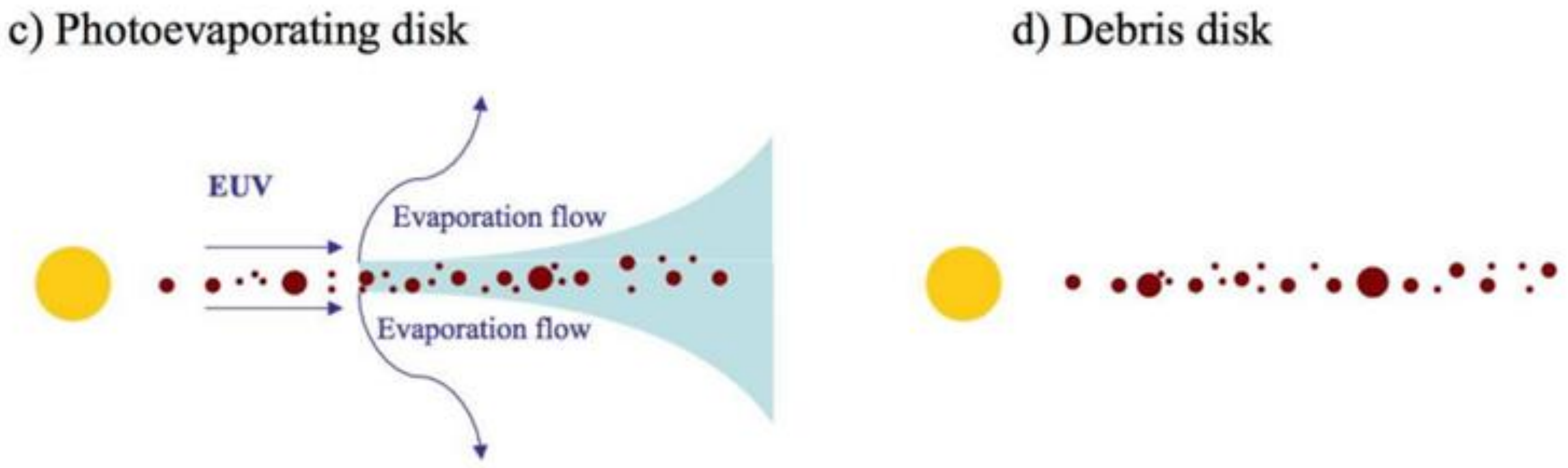
Types of Exoplanets

How was the exoplanet population formed?

Exoplanets form along with the star formation process and is coupled with protoplanetary disk evolution.

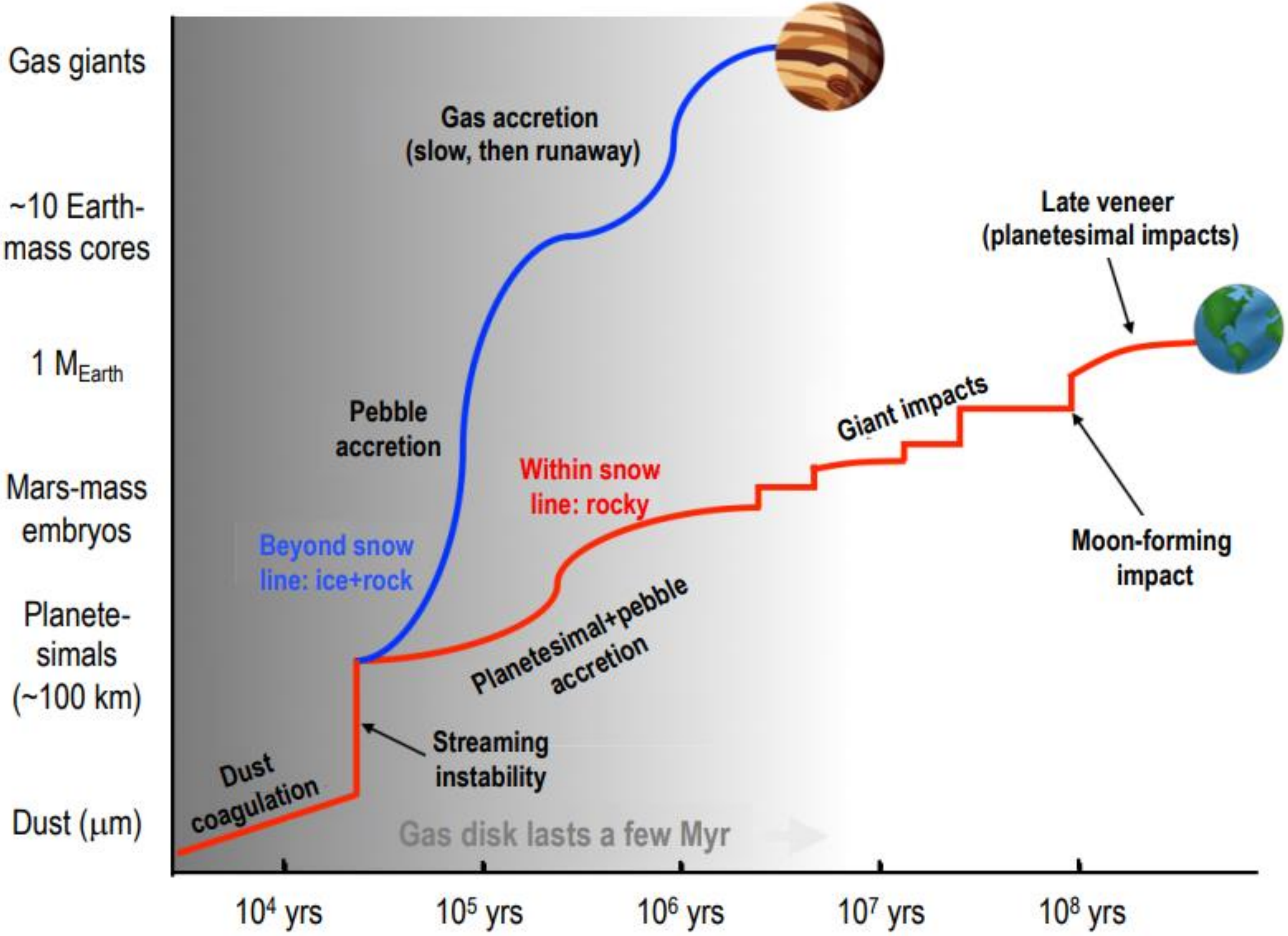


Dust grow and settle onto the midplane

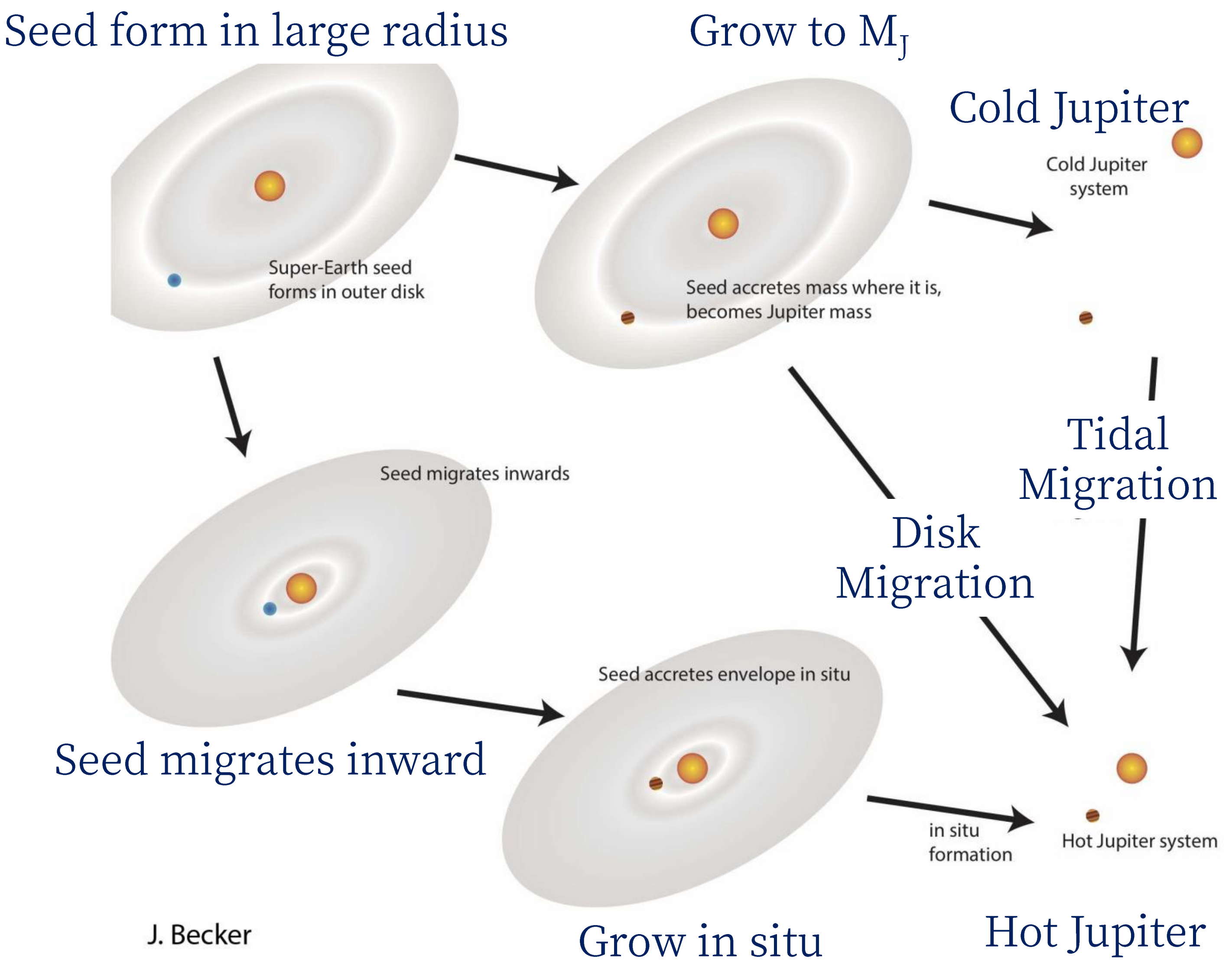


PPDs have limited life time

Planets must grab their mass before the disk is gone.



Planet Formation


Seed form in large radius
Grow to M_J
Cold Jupiter
Super-Earth seed forms in outer disk
Seed accretes mass where it is, becomes Jupiter mass
Cold Jupiter system
Tidal Migration
Disk Migration
Seed migrates inwards
Seed accretes envelope in situ
Seed migrates inward
in situ formation
Hot Jupiter system
J. Becker
Grow in situ
Hot Jupiter

Exoplanet Detection

Limitation for indirect methods

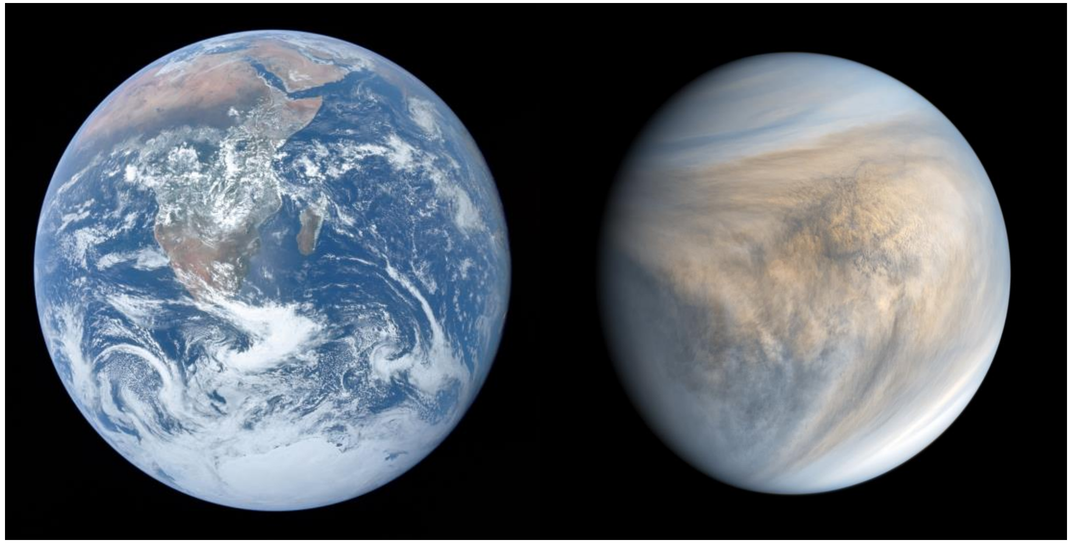
- Orbits and density are not enough:

  Earth and Venus would look similar with indirect methods.
- Observing planet atmosphere is the crucial next step.

15°C

Liquid water

N_2, O_2, H_2O



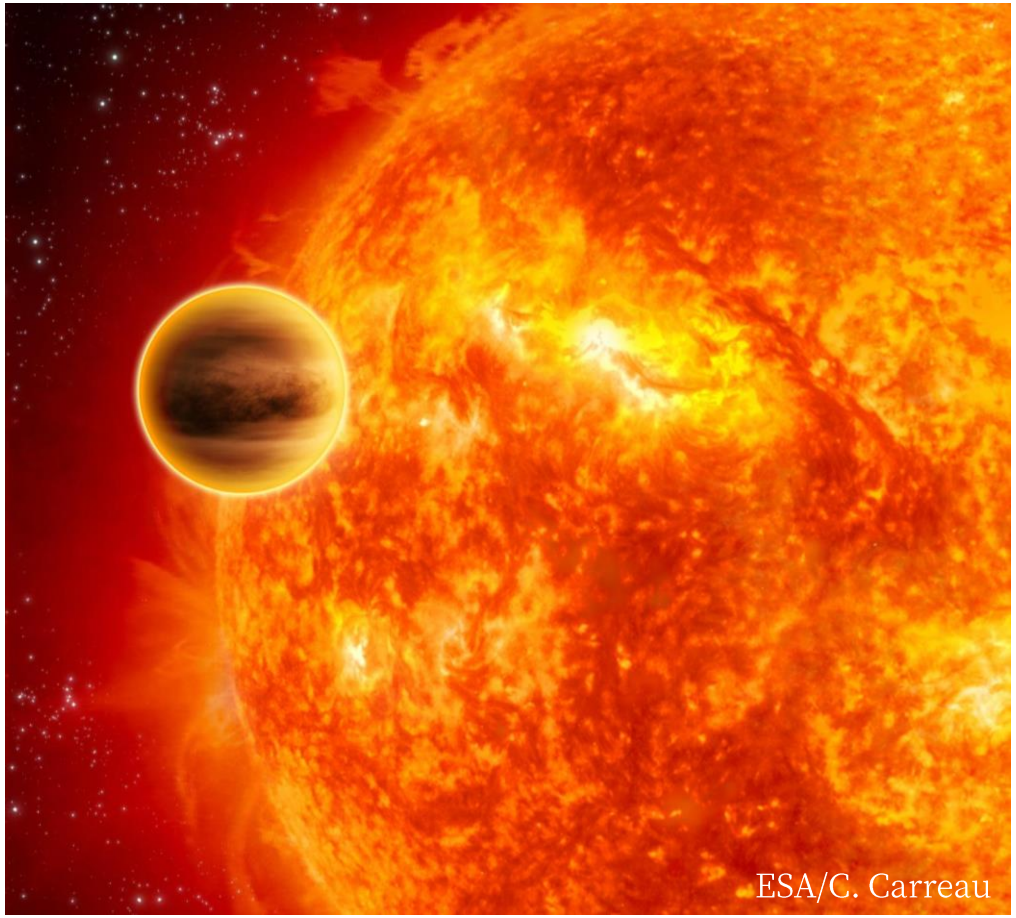
460°C

Liquid water

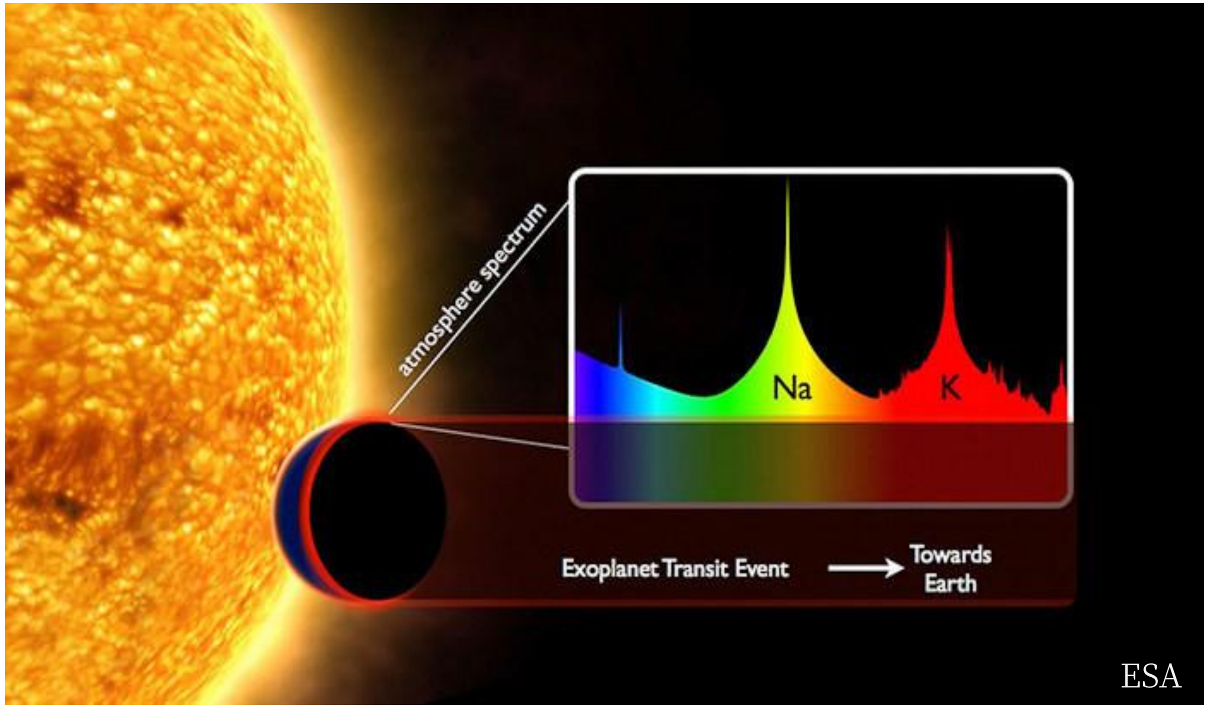
CO_2, N_2, SO_2

Issues with observing exoplanet atmosphere

- Brightness contrast between stars and planets is way to large.
- Current efforts mainly focus on **Hot Jupiters** that provides much stronger signal (large and close).
- Line is still dominated by stellar light and sky/instrument foreground even for hot Jupiters.

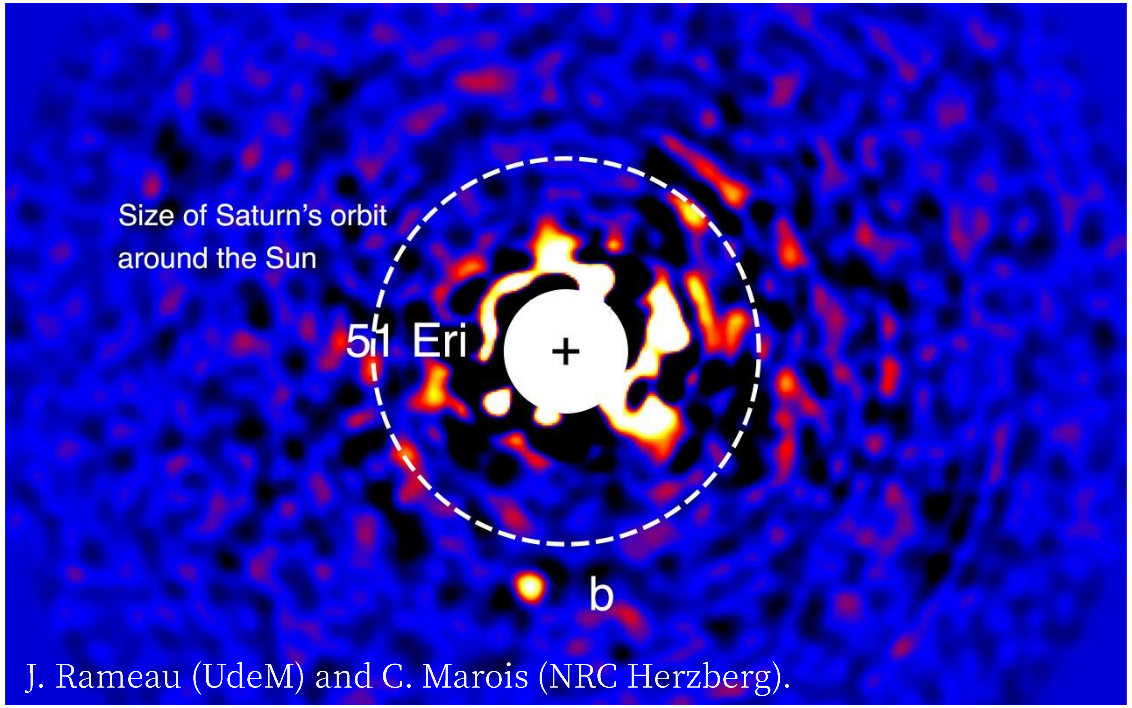

ESA/C. Carreau

Types of observations



ESA

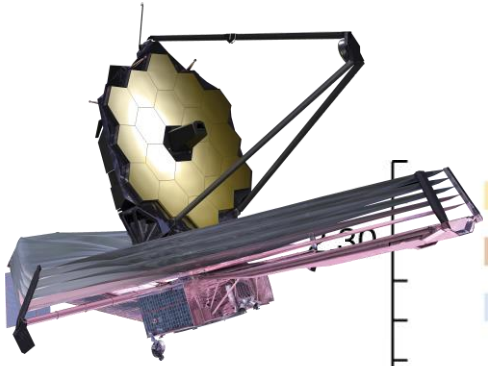
Transmission Spectroscopy

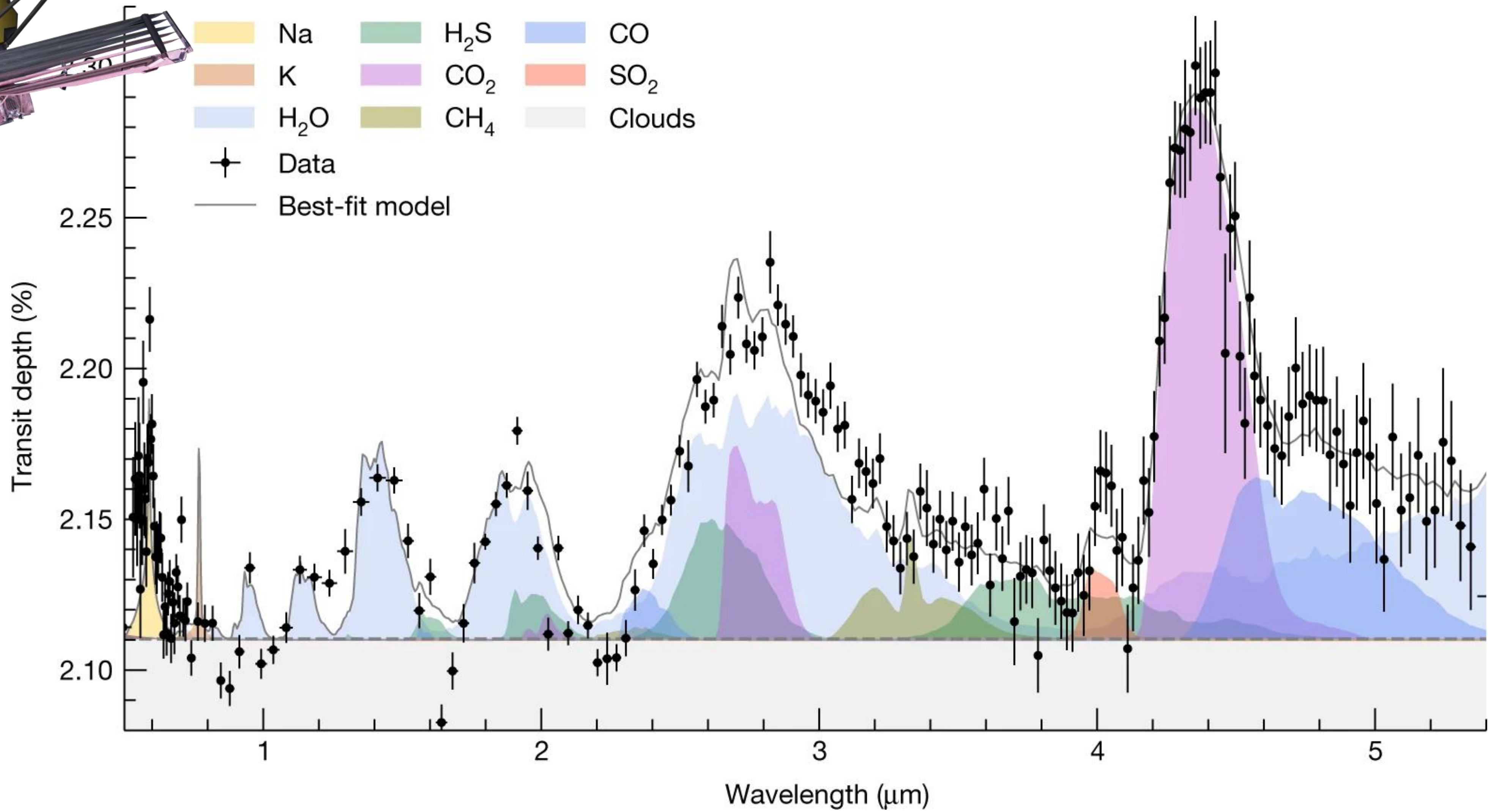


J. Rameau (UdeM) and C. Marois (NRC Herzberg).

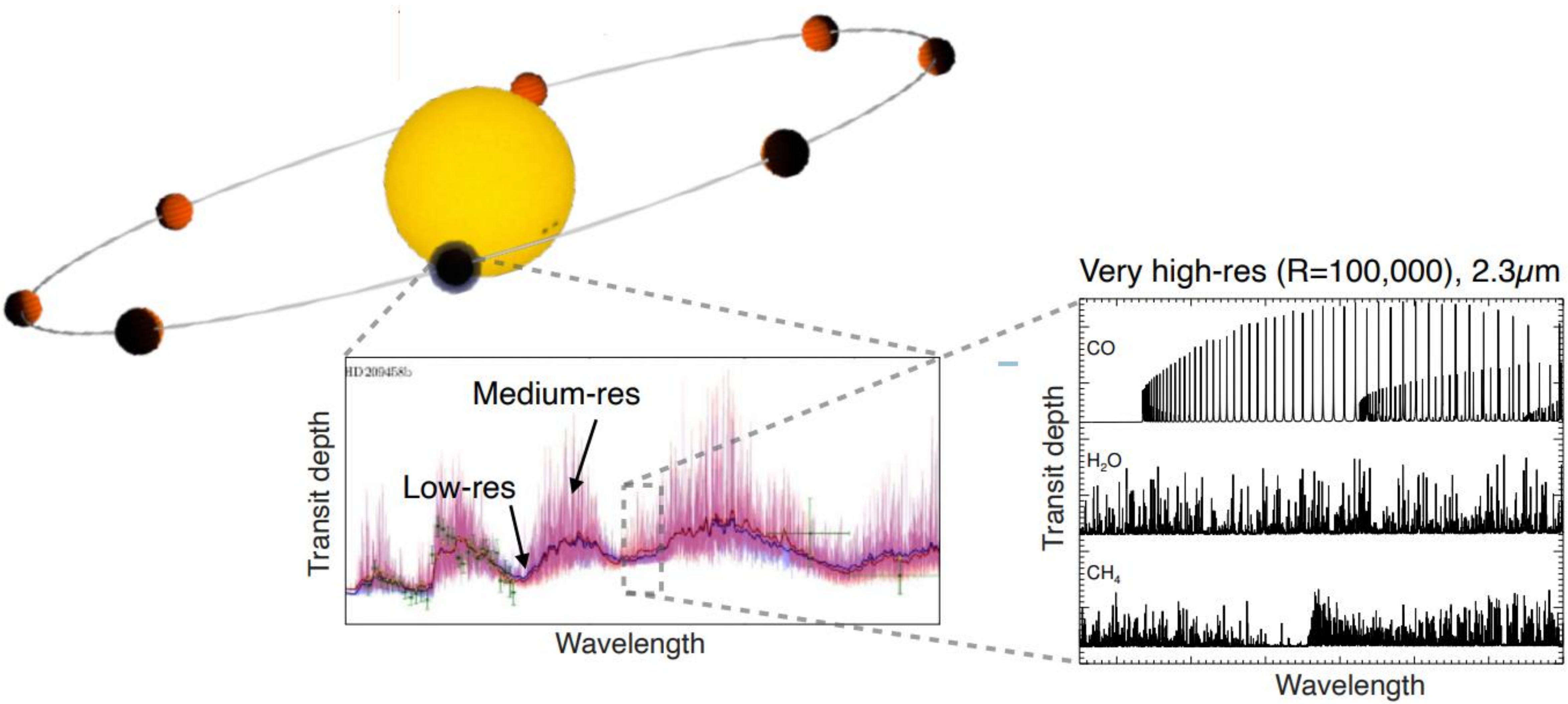
Reflectance Spectroscopy

JWST NIRSpec WASP-39b (R ~ 300)





Rustamkulov et al. (2023)



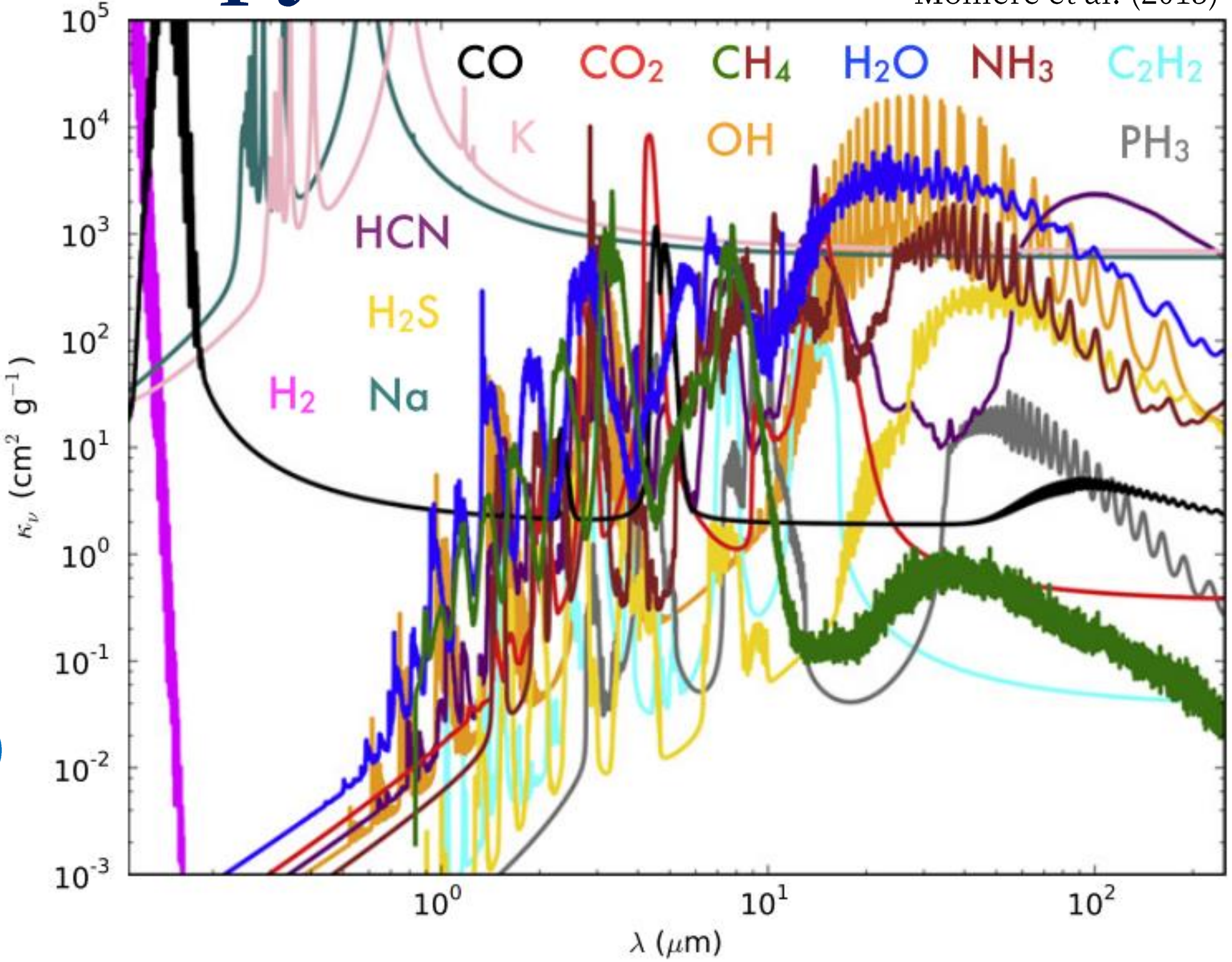
How about ground based observatories?
High resolution cross-correlation spectroscopy (HRCCS).

Exoplanet atmosphere

High resolution spectroscopy

- NIR is filled with spectral lines from molecules (vibration + rotation).
- State-of-the-art ground-based observatory (e.g. VLT ESPRESSO) has spectra resolution R ~ 190K. (JWST NIRSpec R~2.7K for comparison)
- How can we make use of them?

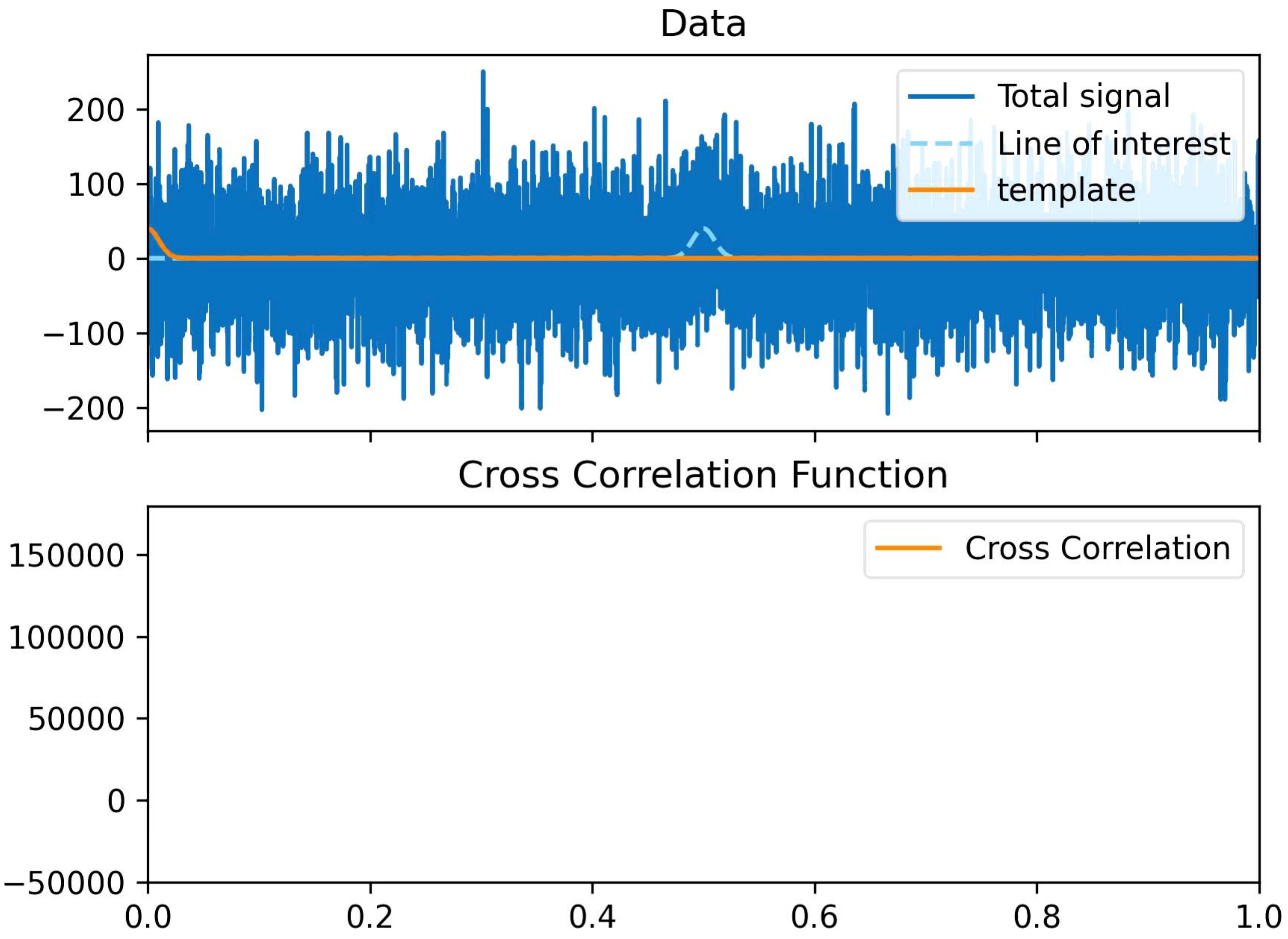
Mollière et al. (2015)



Exoplanet atmosphere

Cross Correlation

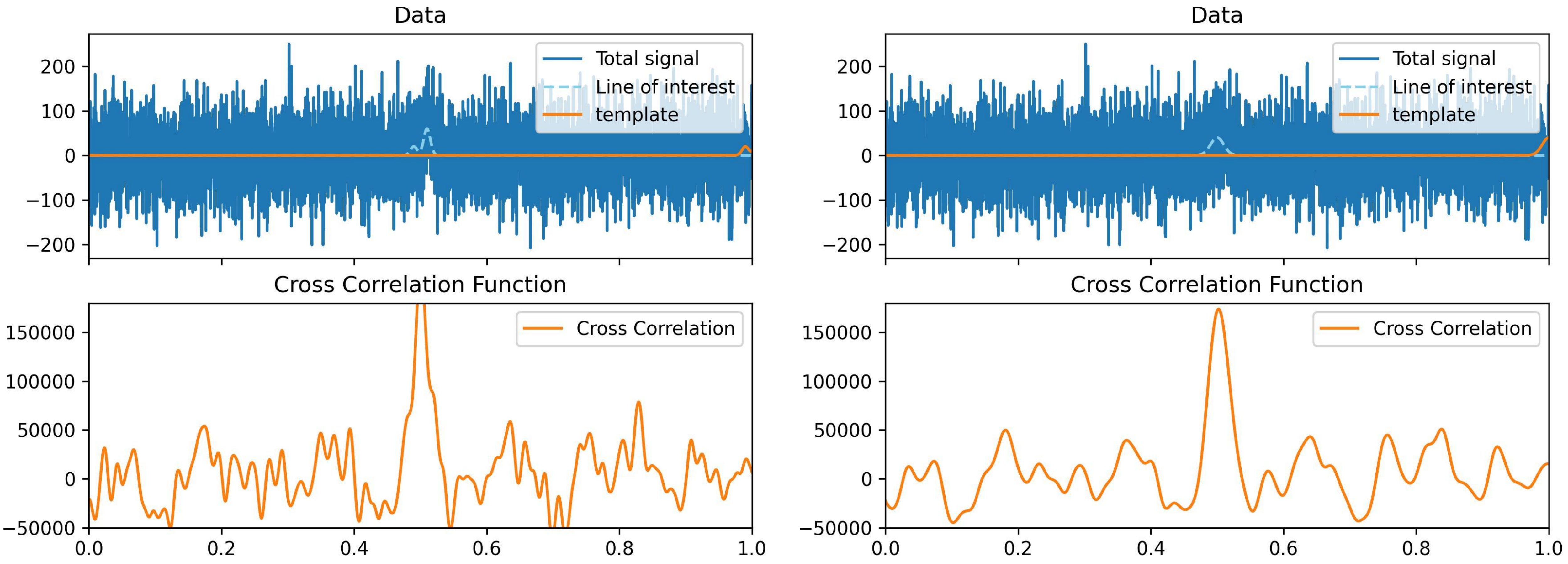
- Often used in finding **signals with specific feature** that is buried in noise.
- Cross correlation peaks when the template and the feature matches.



Exoplanet atmosphere

Cross Correlation

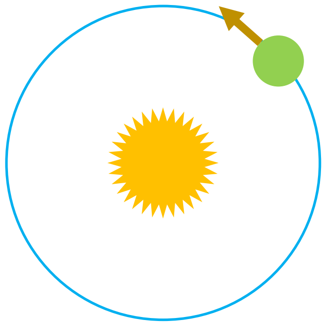
More feature gives better results!

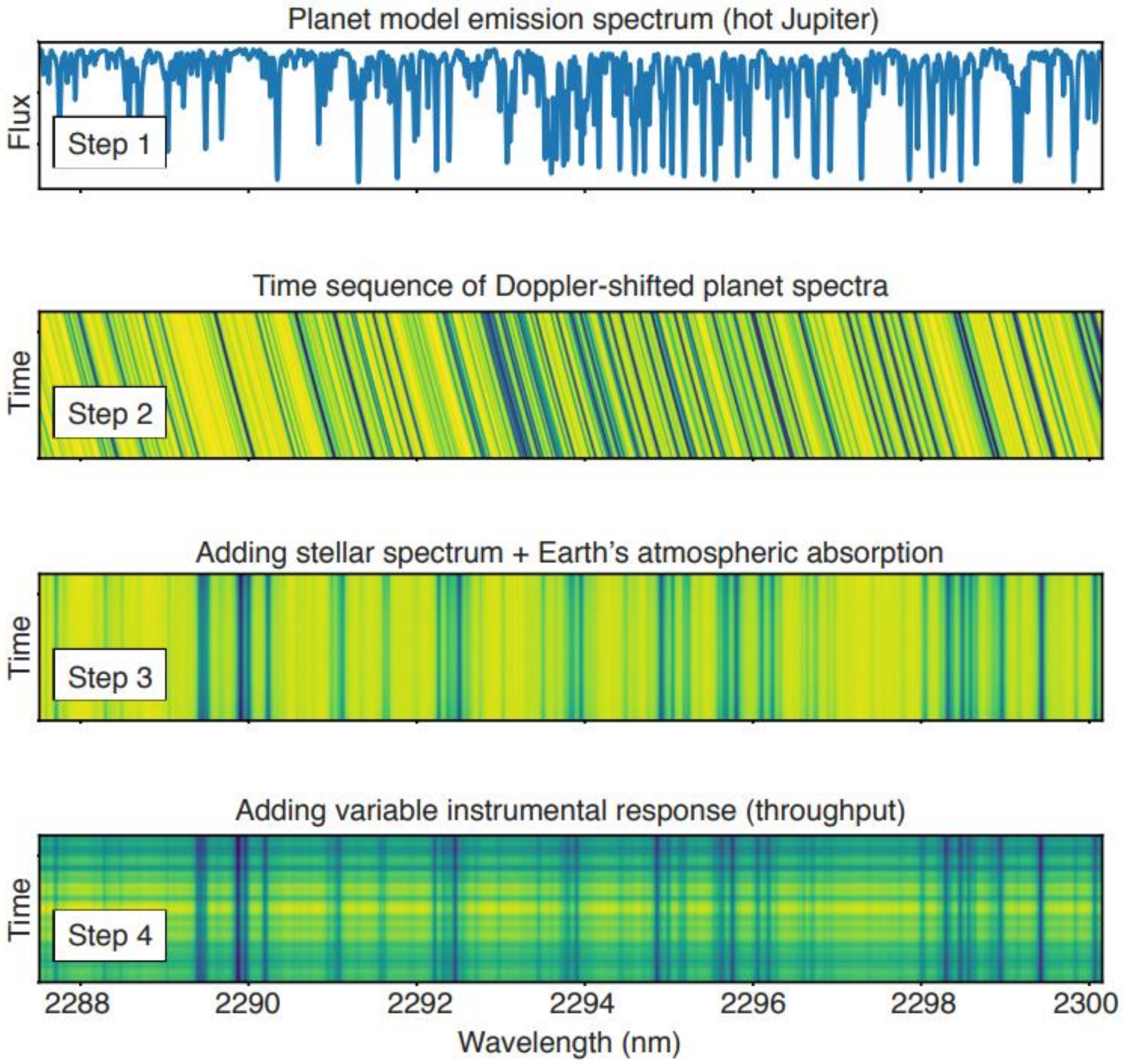


Exoplanet atmosphere

Doppler shift

- ➢ Orbital velocity of hot Jupiters produce doppler shifts.
- ➢ Doppler shift from the sky, star, and planets are decoupled. Helping avoid systematic errors.



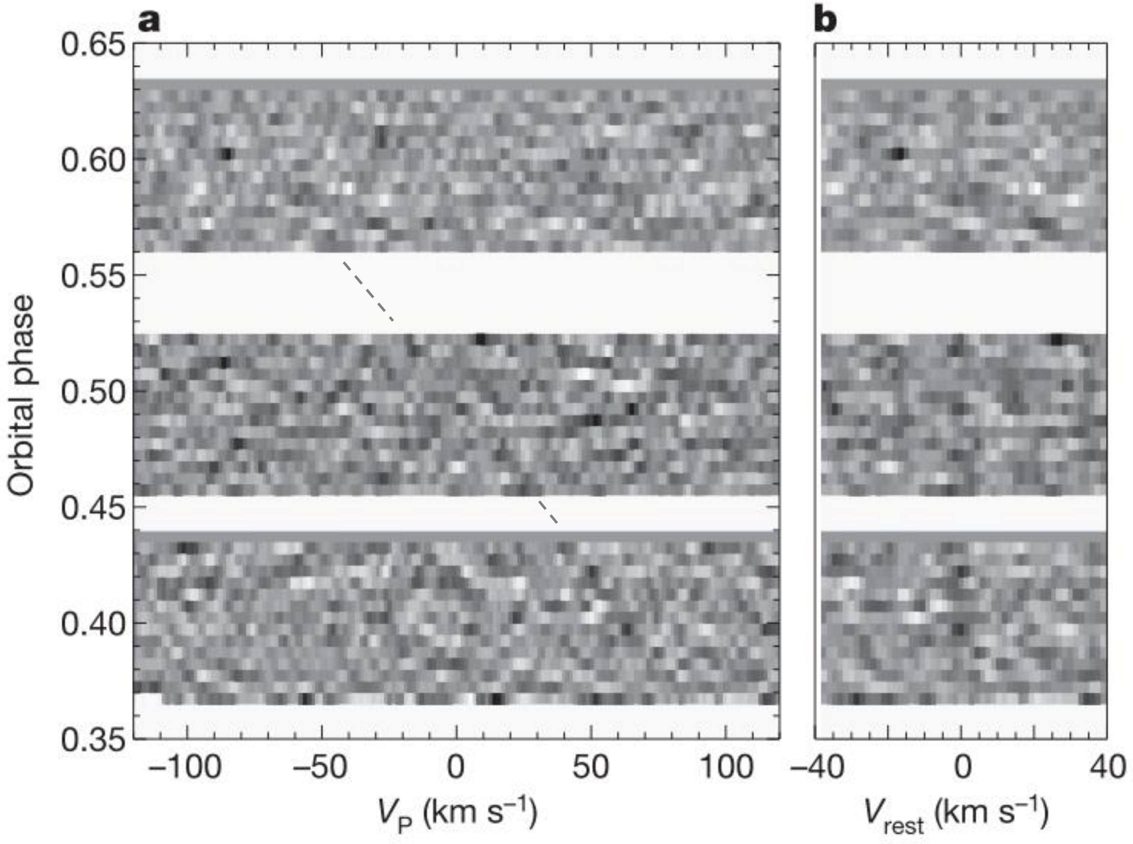


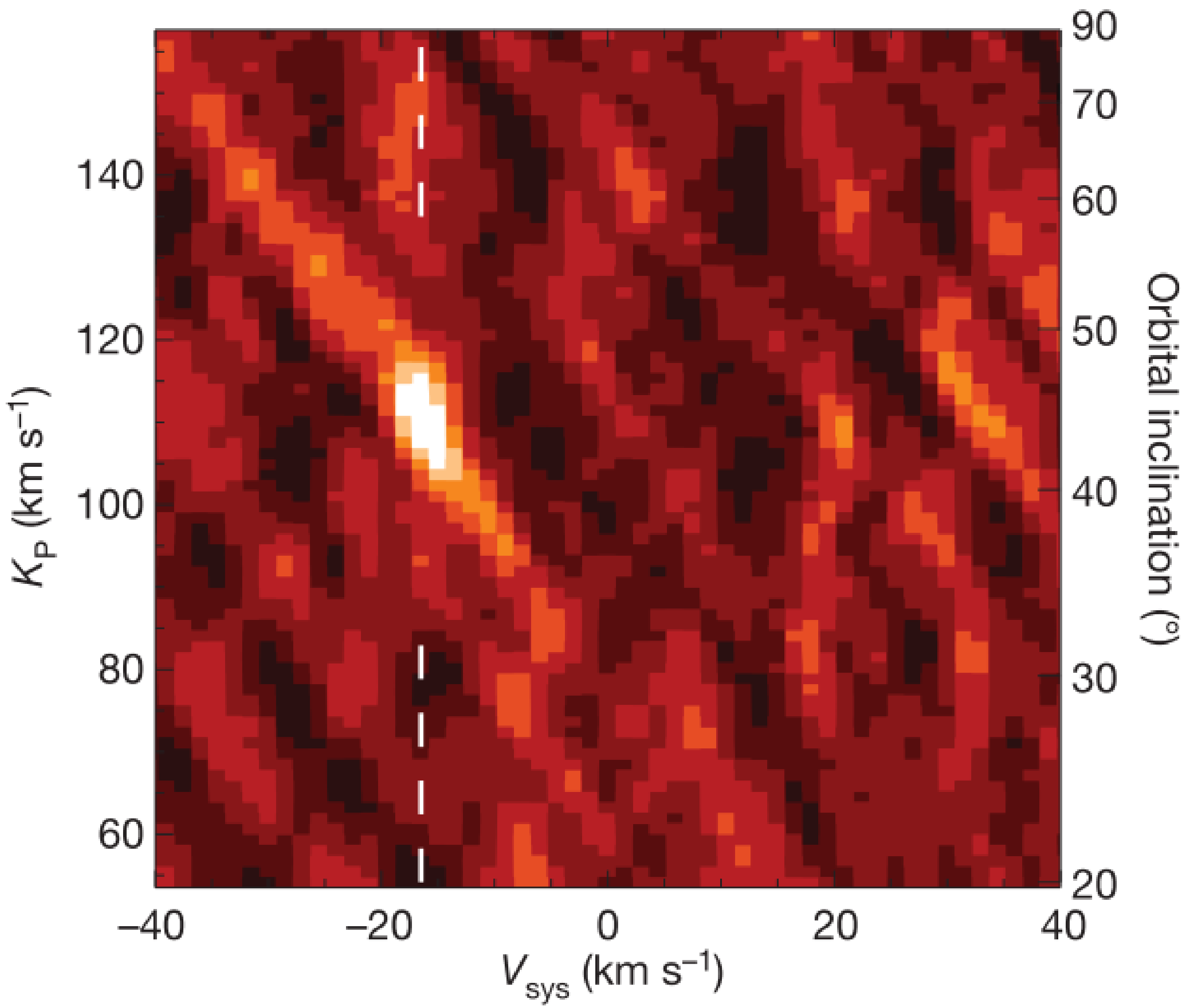
Brogi et al. 2019

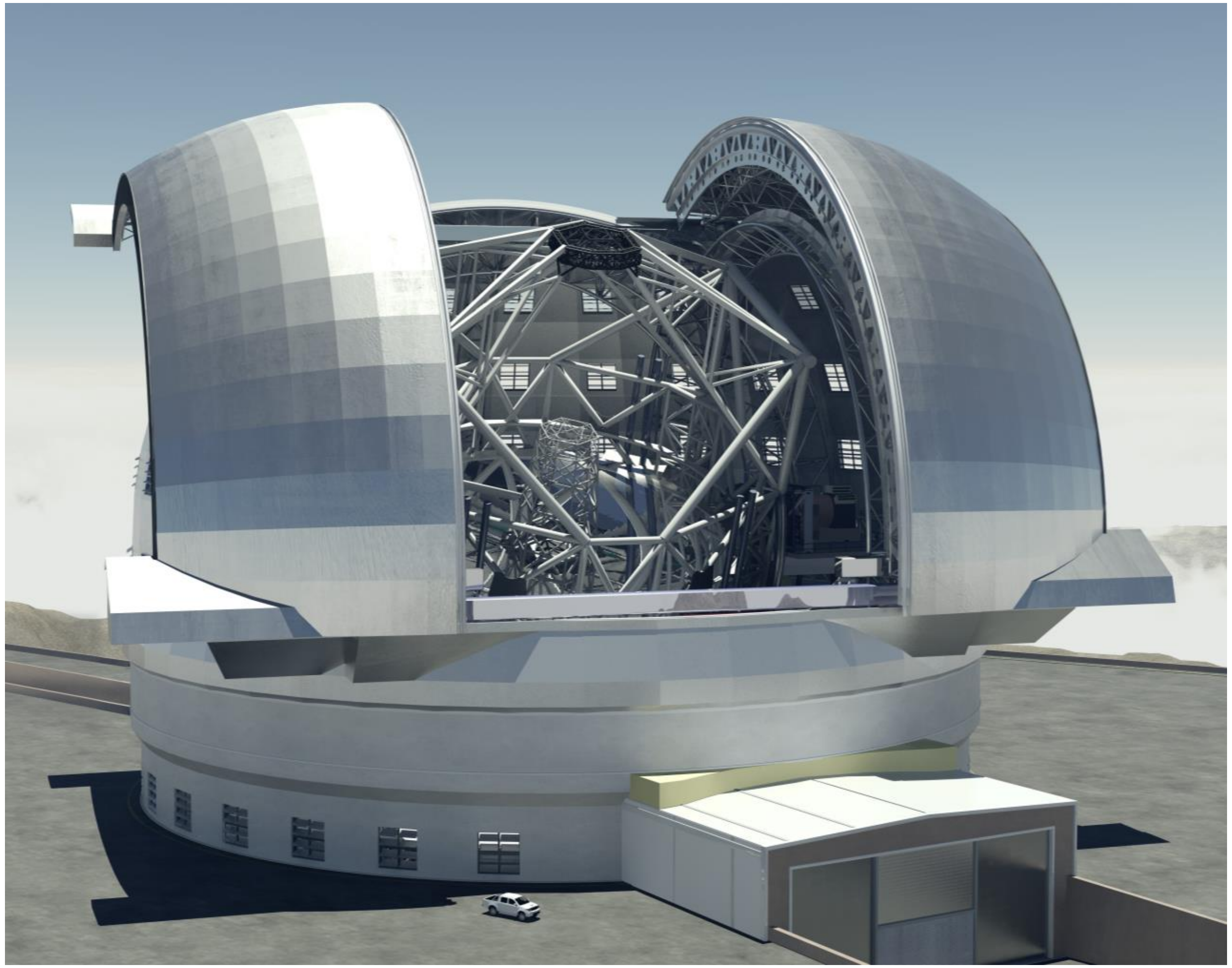
Example: pioneer work

Brogi et al. (2012)

- ➢ CO in hot Jupiter τ Bootis b.







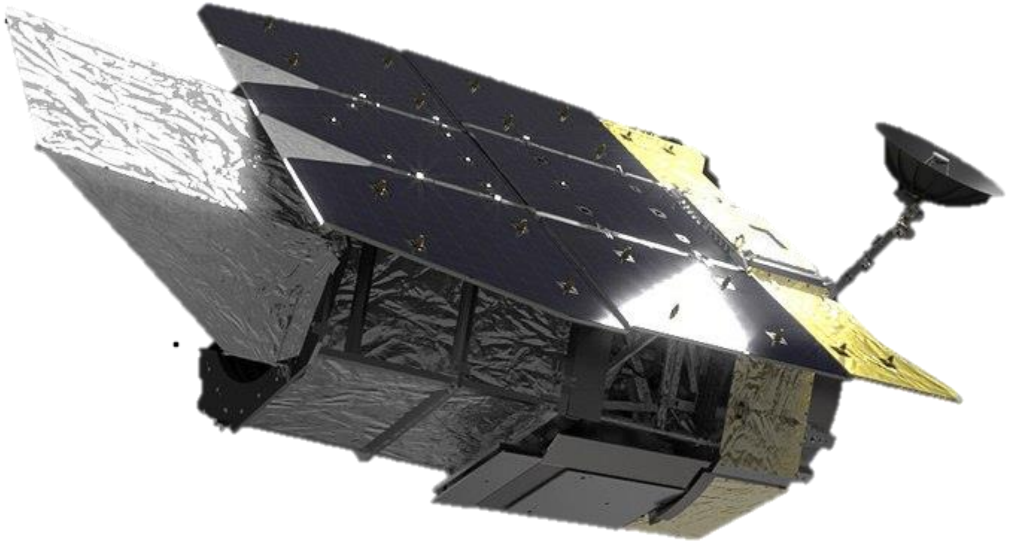
Future
ELTs

- Extremely large collecting area
- 30 – 40 m.
- EELT, GMT, TMT

Future

PLATO mission

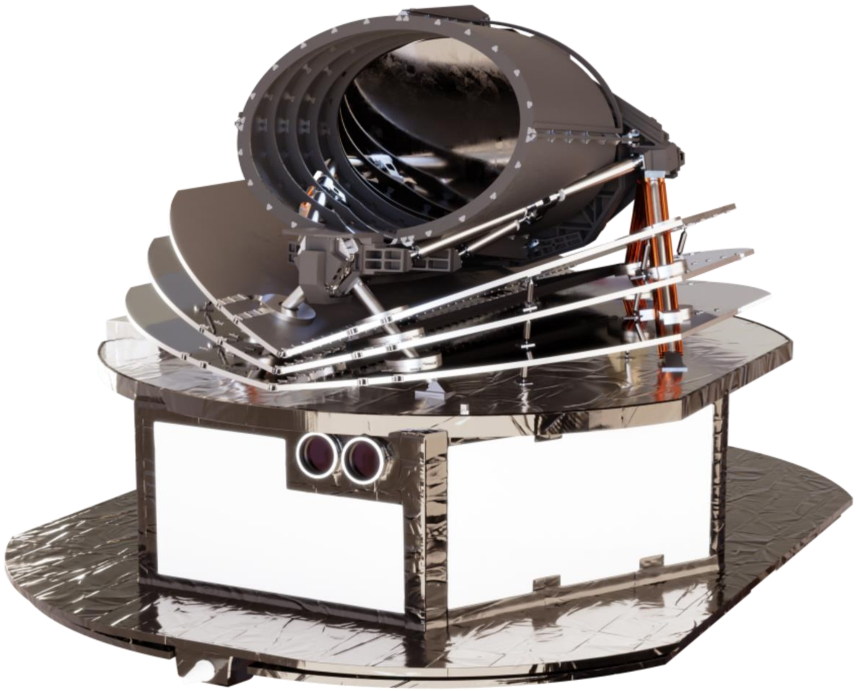
- A larger and more powerful TESS-like mission
- Launch: ~ 2026



Future

Roman telescope

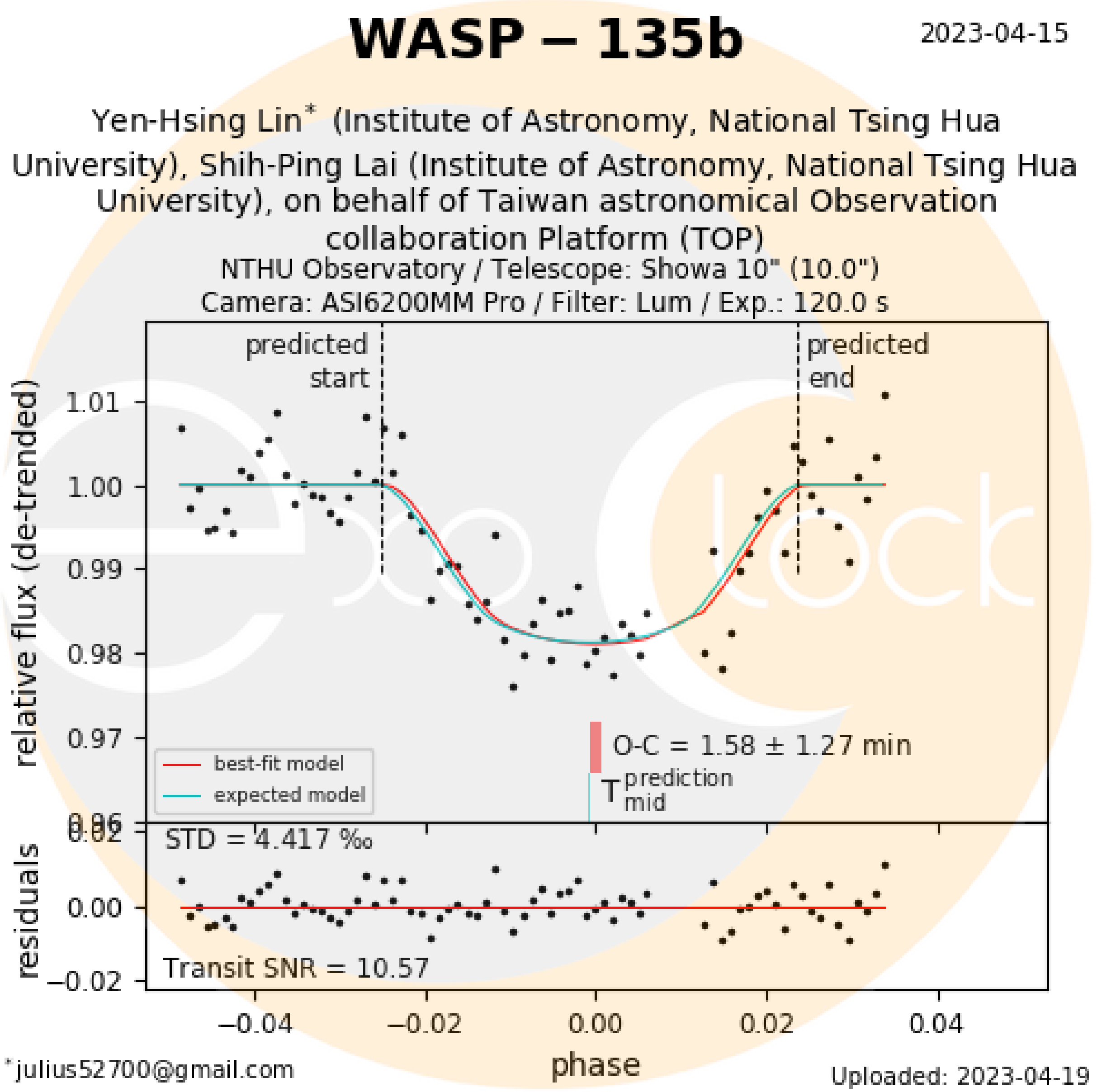
- Focus on cosmology but would see exoplanets using microlensing and coronagraph.
- Launch: ~ 2027



Future

Ariel mission

- A JWST-class mission that focus on exoplanets.
- Launch: Early 2030s.

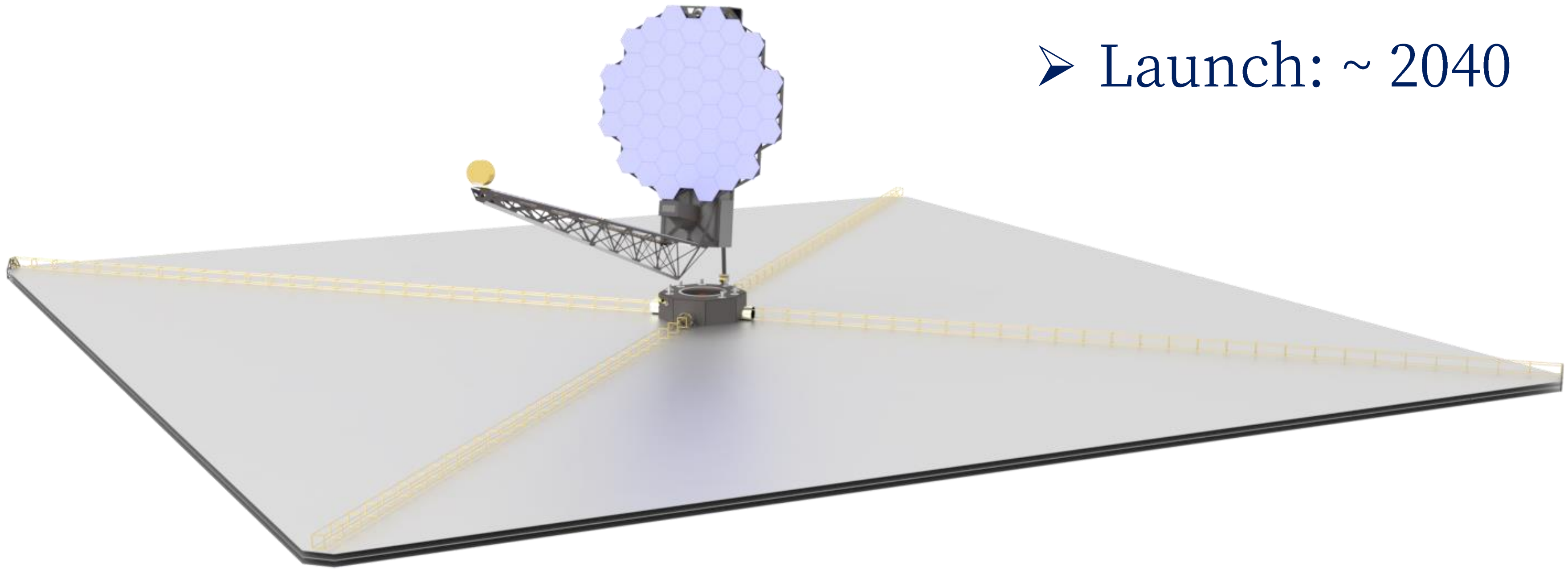


Ariel

Exoclock Project

Monitor transits for better schedule optimization.

Future
LUVOIR



- Extremely strong coronagraph.
- Launch: ~ 2040

Summary

Exoplanetology

- Directly links to the BIG questions:

  Where are we coming from & Are we alone in the universe.
- More than 5000 exoplanets have been detected and confirmed.

  Mostly using transit photometry of space telescopes (Kepler, TESS).
- Atmospheric spectroscopy is the crucial next step for deeper understanding exoplanets.
- Future mission: Plato, Roman, Ariel, ELTs, LUVOIR.