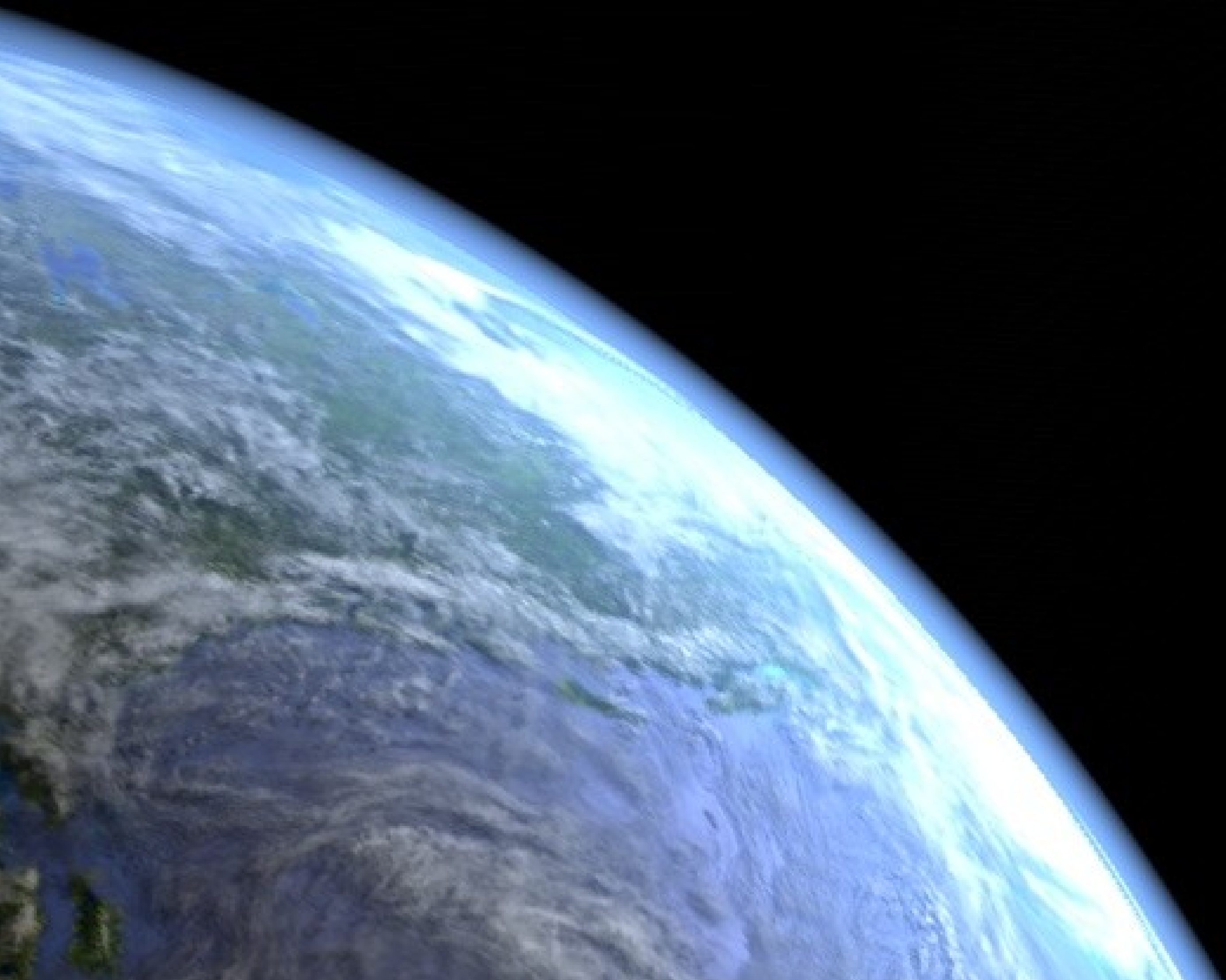
Modern Astronomical Optics - Observing Exoplanets

Summary of existing and future techniques, complementarity



Big questions

(1) How do planets form ?

(2) How many Earth-mass planets in habitable zones ? Around which stars ? Architecture and evolution of planetary systems.

(3) Do conditions suitable for the emergence of life exist on other words ? How frequently ? (Drake equation)

(4) Detect and characterize life on other planets.

As of 2012....
Questions (1) and (2) are directly addressed by current research
Questions (3) and (4) will take longer...

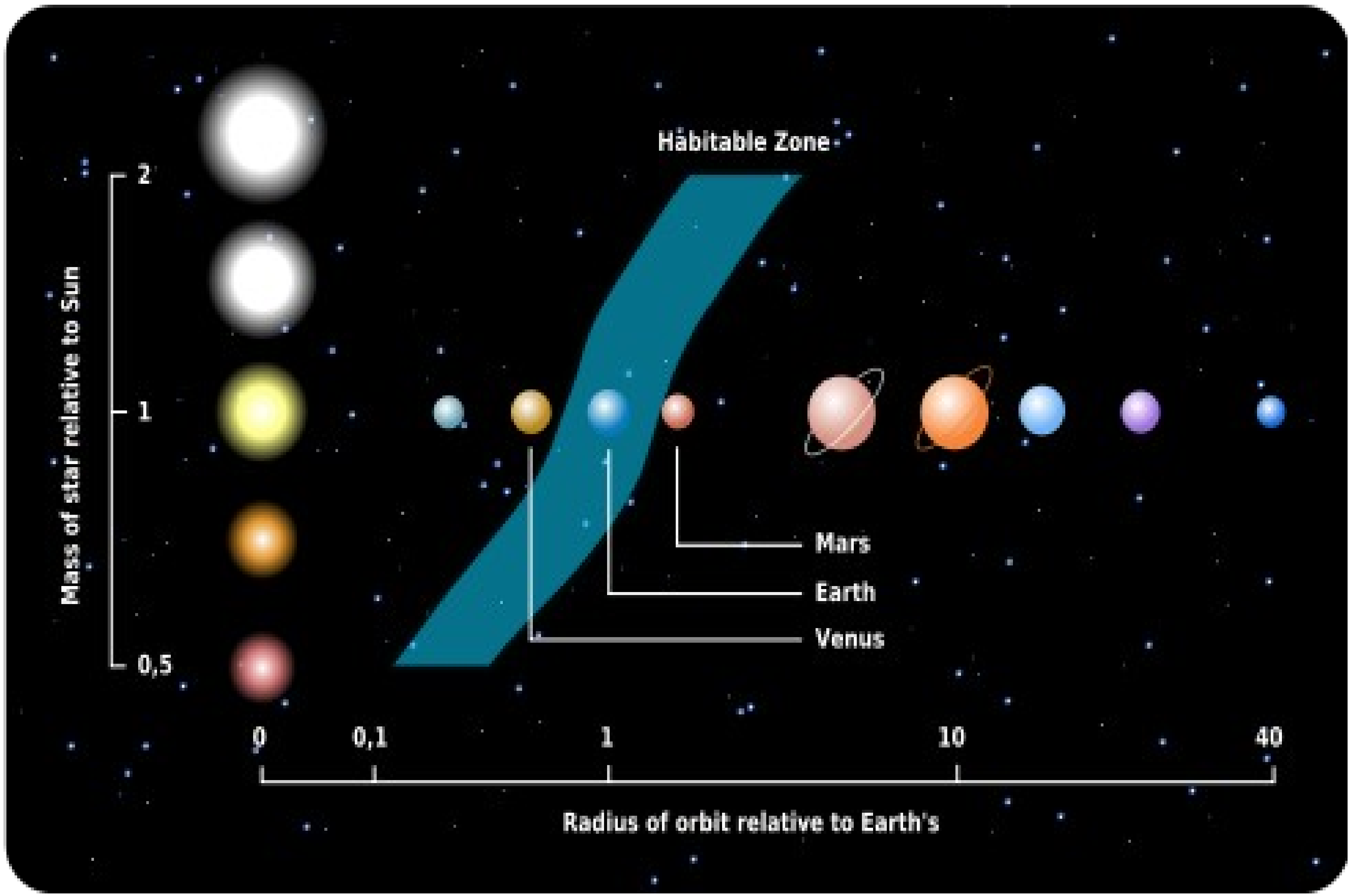
Answering these questions requires combination of techniques

Example: Planet mass measurement requires radial velocity or astrometry, chemical composition measurement requires direct detection

Habitable planets

WHERE ?

Habitable zone = range of distance around the host star for which liquid water can exist at the surface of a rocky planet



Techniques covered in this course

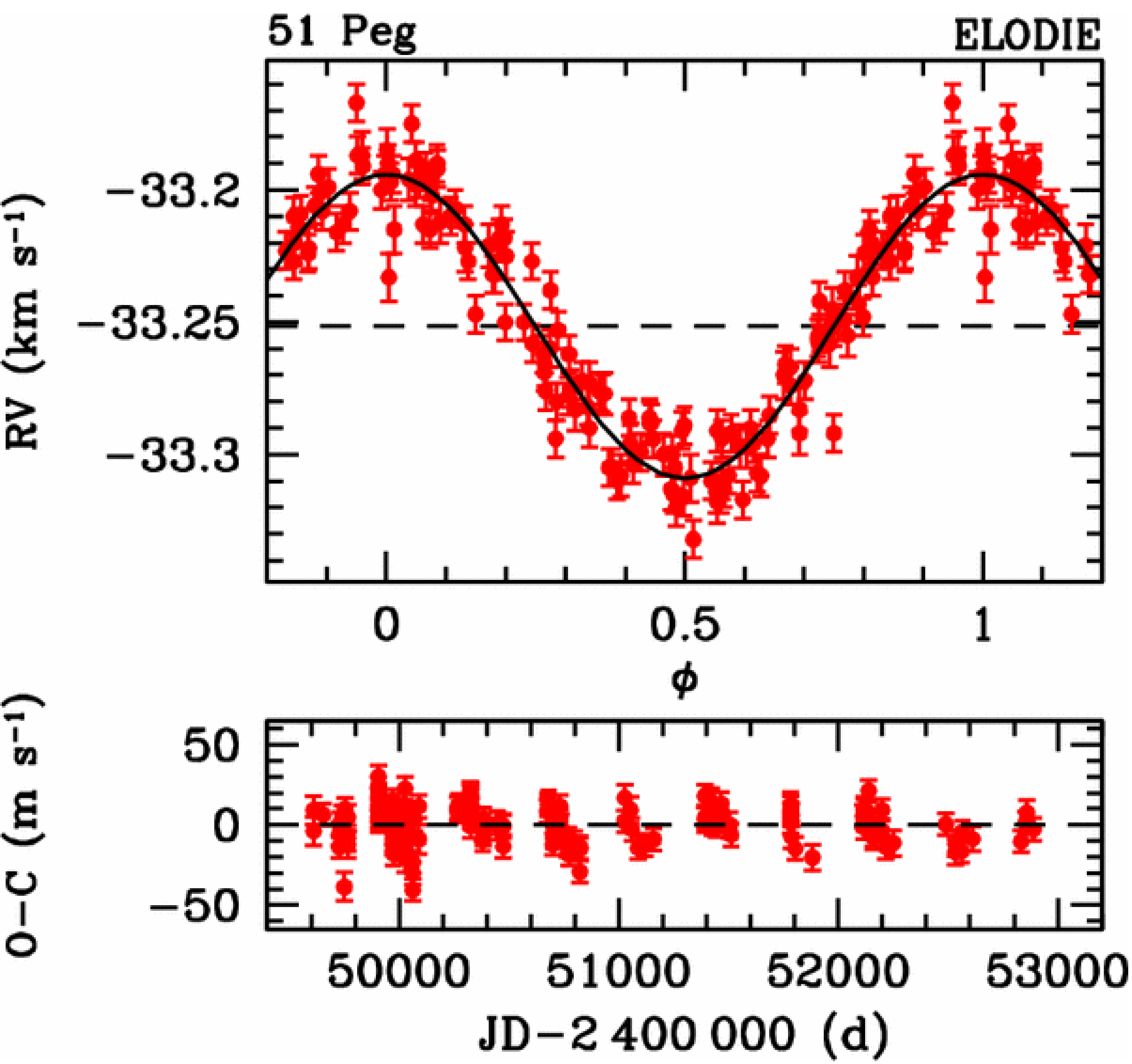
Spectroscopy – Radial velocity	
Transit photometry (detection and spectroscopy)	Indirect detection
Microlensing	
Astrometry	
Interferometric techniques	
Coronagraphy	Direct detection
Adaptive Optics (especially Extreme AO)	

Exoplanet observations rely on precision measurements due to large mass ratio (planet signal is always small)

Techniques are highly complementary, probing different planet population/characteristics

Radial velocity – Signal amplitude

Jupiter → 12.7 m/s
Earth → 9 cm/s



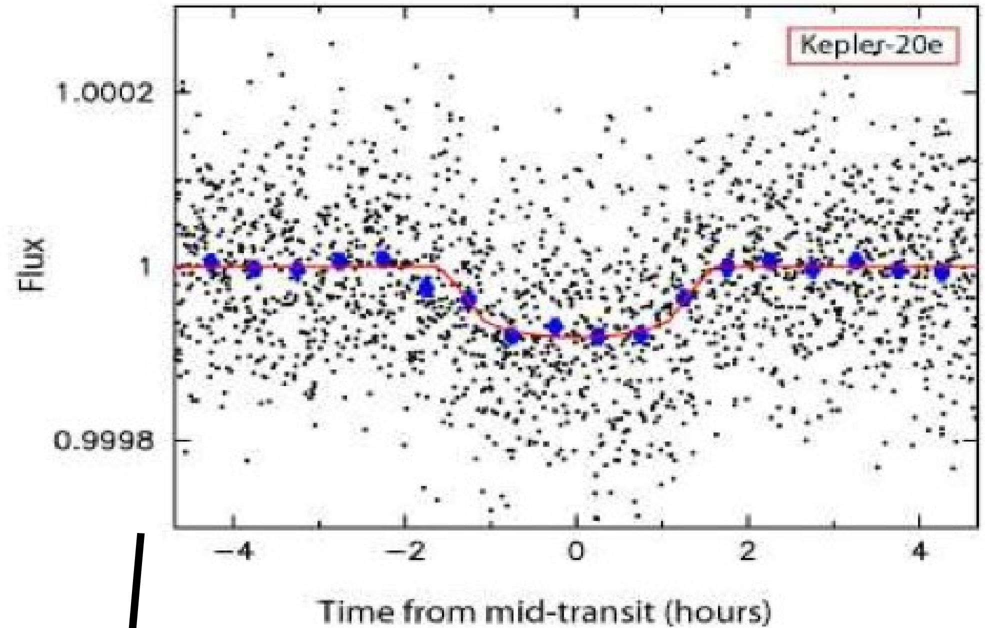
51 Peg b : first exoplanet identified around Sun-like star (1995)

Period = 4.23 day
Mass sin(i) = 0.47 MJ
Eccentricity = 0

RV ampl = 57 m/s

Transit depth

Kepler 20e: transit depth = 0.008 %
(similar to Earth transit depth)



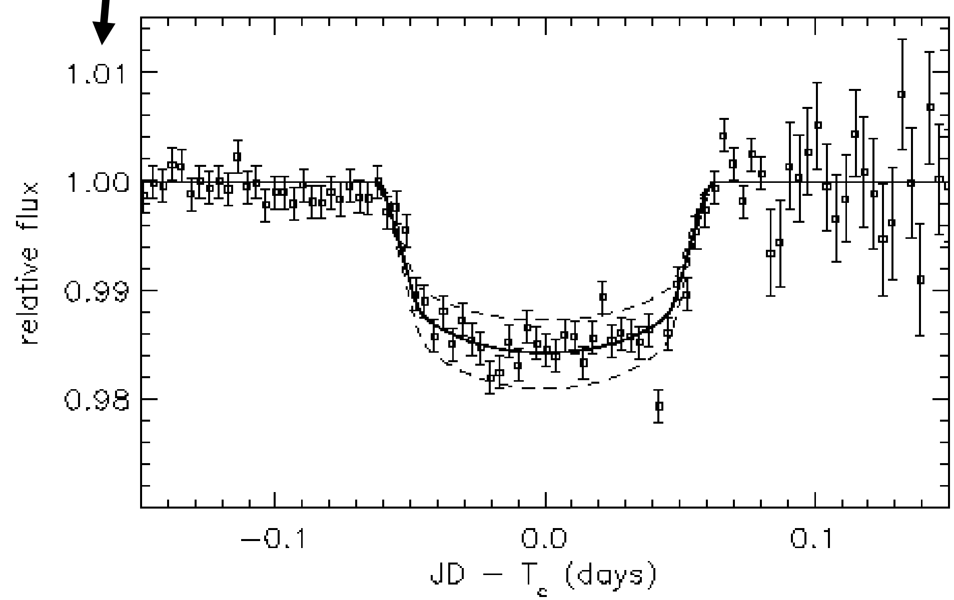
Transit depth = $(R_{planet} / R_{star})^2$

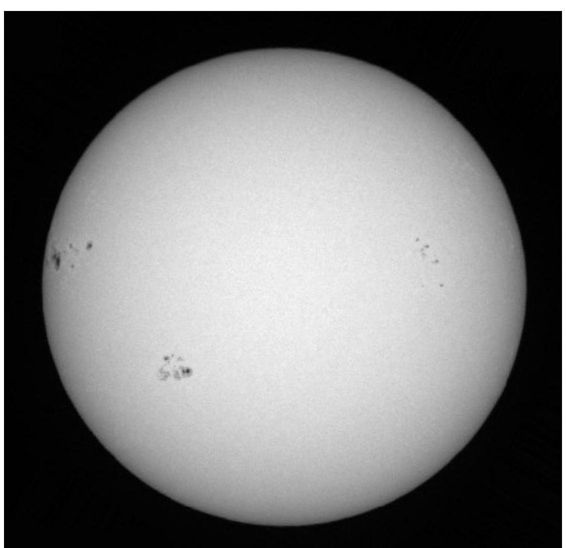
Earth radius = 6,371 km
Jupiter radius = 69,911 km
Sun radius = 696,000 km

→ Amplitude = 8e-5 (Earth)
→ Amplitude = 1% (Jupiter)

~100x factor in scale

HD 209458: 1.7% deep transit





Note that transit is deeper at mid-transit
(limb darkening)

Microlensing geometry : Flux amplification with planet

planet has its own microlensing event

Event is short due to smaller planet mass

Einstein radius is small → source angular size can affect lightcurve

Bennett & Hung Rhie 1996

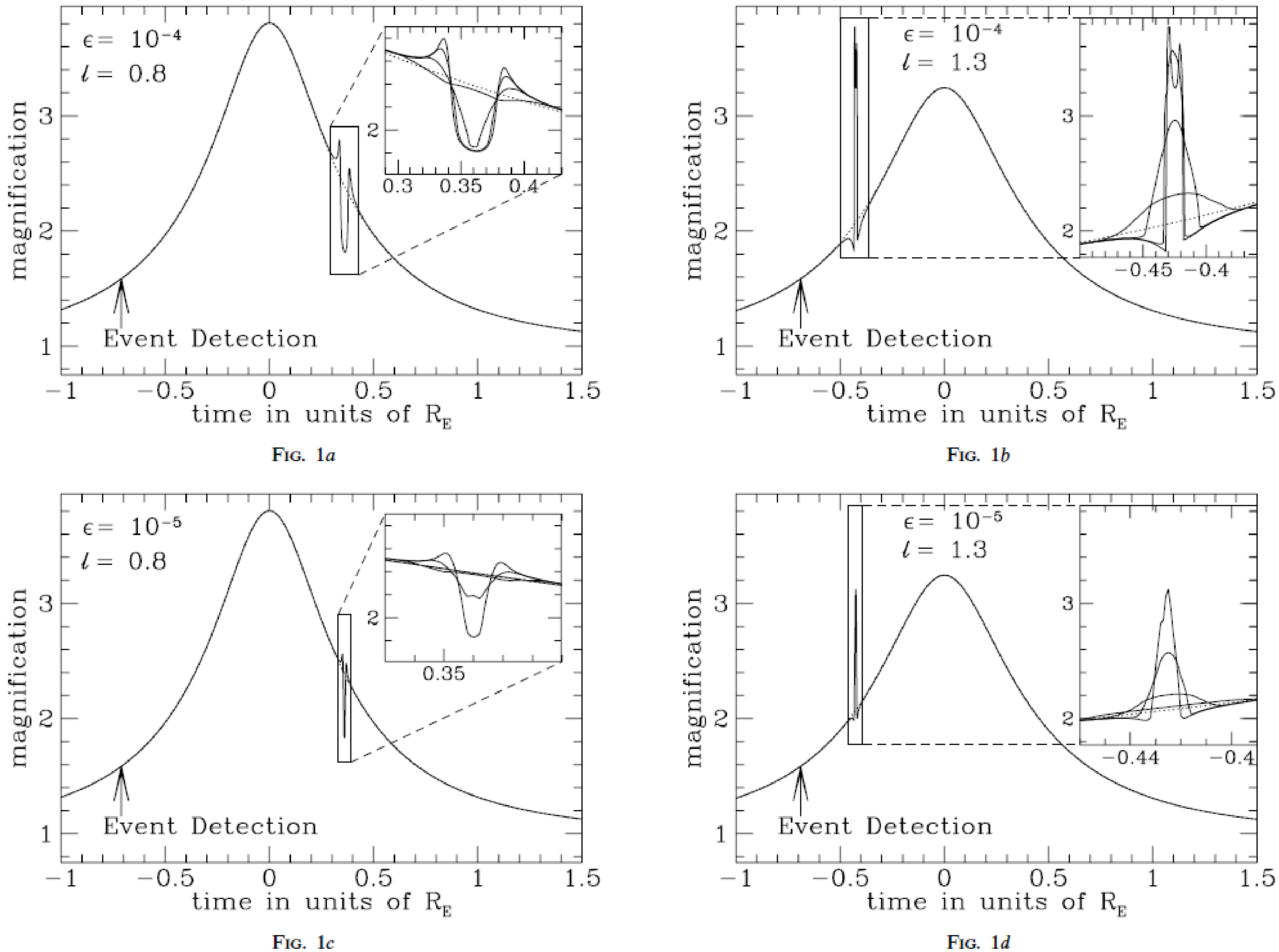


Fig. 1.—Microlensing light curves that show planetary deviations are plotted for mass ratios of $\epsilon = 10^{-4}$ and 10^{-5} and separations of $l = 0.8$ and 1.3. The main plots are for a stellar radius of $r_s = 0.003$ while the insets show light curves for radii of 0.006, 0.013, and 0.03 as well. (The amplitude of the maximum light curve deviation decreases with increasing r_s.) The dashed curves are the unperturbed single lens light curves, $A_0(t)$. For each of these light curves, the source trajectory is at an angle of $\sin^{-1} 0.6 = 36^\circ.9$ with respect to the star-planet axis. The impact parameter $u_{min} = 0.27$ for the $l = 0.8$ plots and $u_{min} = 0.32$ for the $l = 1.3$ plots.

Astrometric signature of planets

Star AND planet orbit the center of mass of the system

planet mass

star mass

orbit radius

distance to system

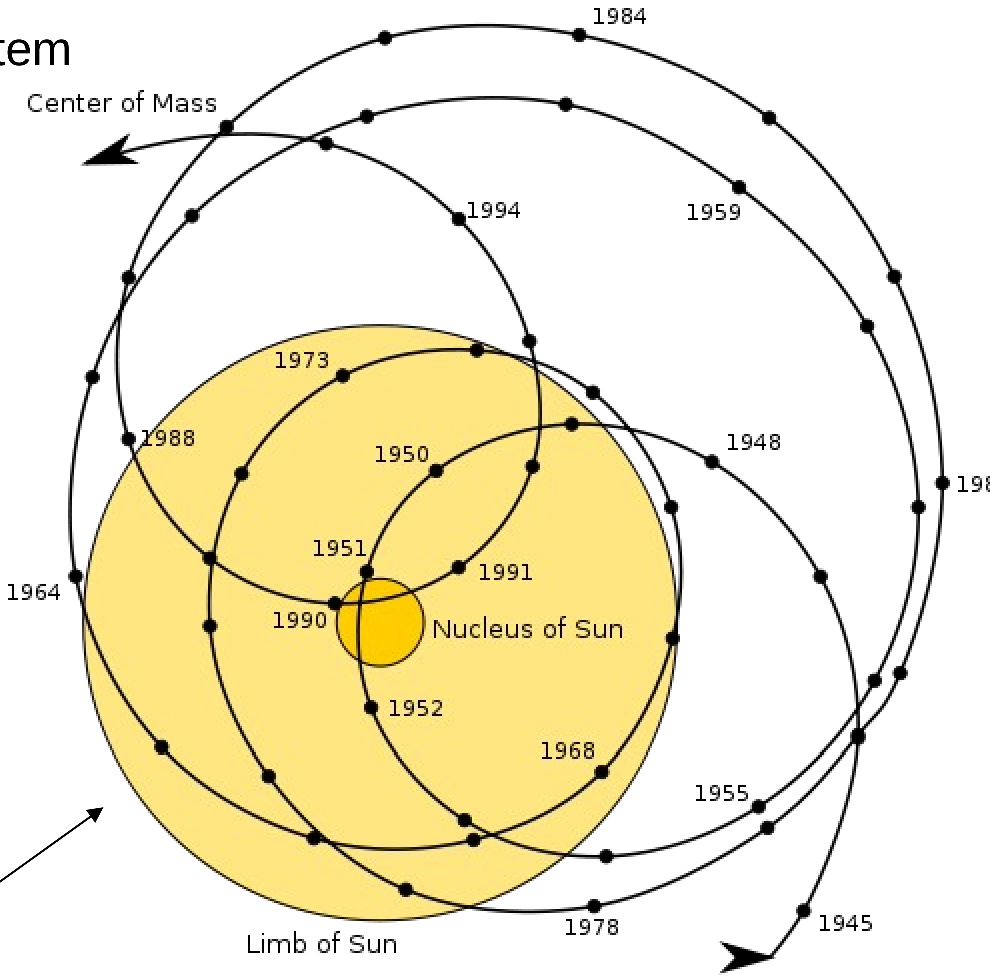
$$\textbf{signal} = (m_{planet}/m_{star})\,(a/d)$$

0.3 uas for Earth around Sun at 10 pc
0.5 mas for Jupiter around Sun at 10 pc

signal period = orbital period

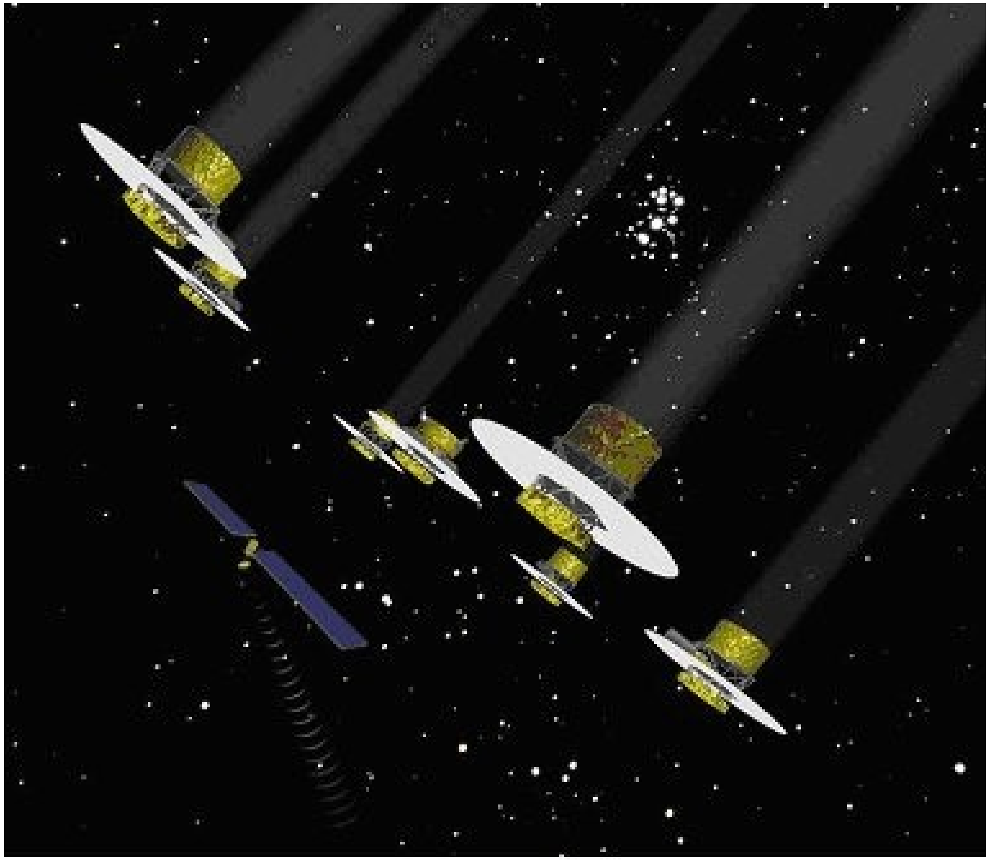
For circular orbit, an ellipse is observed
(circle only if viewed face-on)

At 10pc, sun diam = 1mas



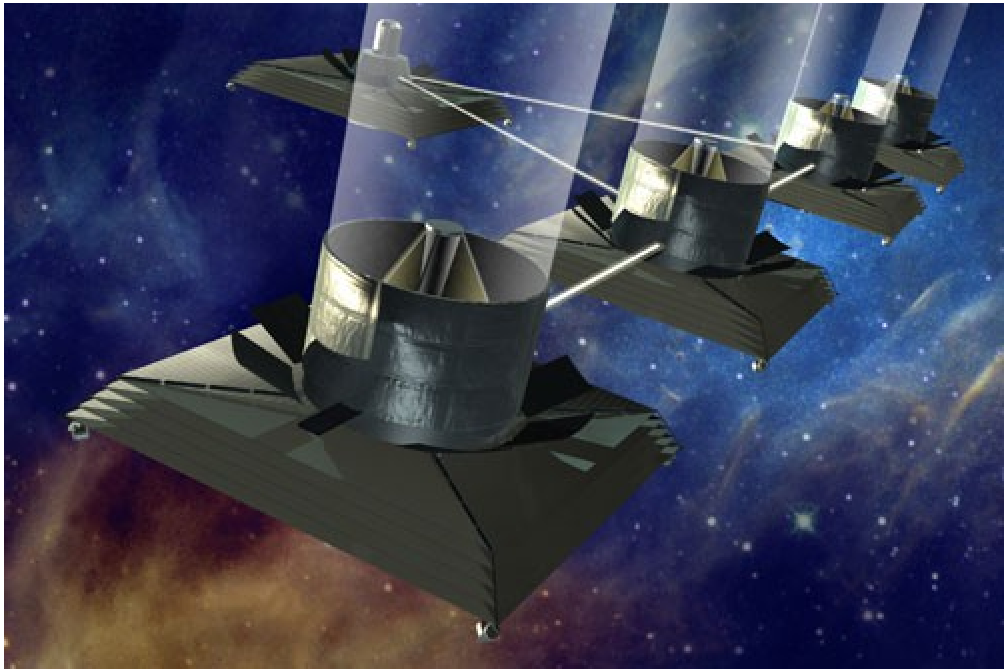
Combined astrometric signal of solar system planets

Imaging exoplanets with interferometers – Earth-like planets



DARWIN mission concept (ESA)

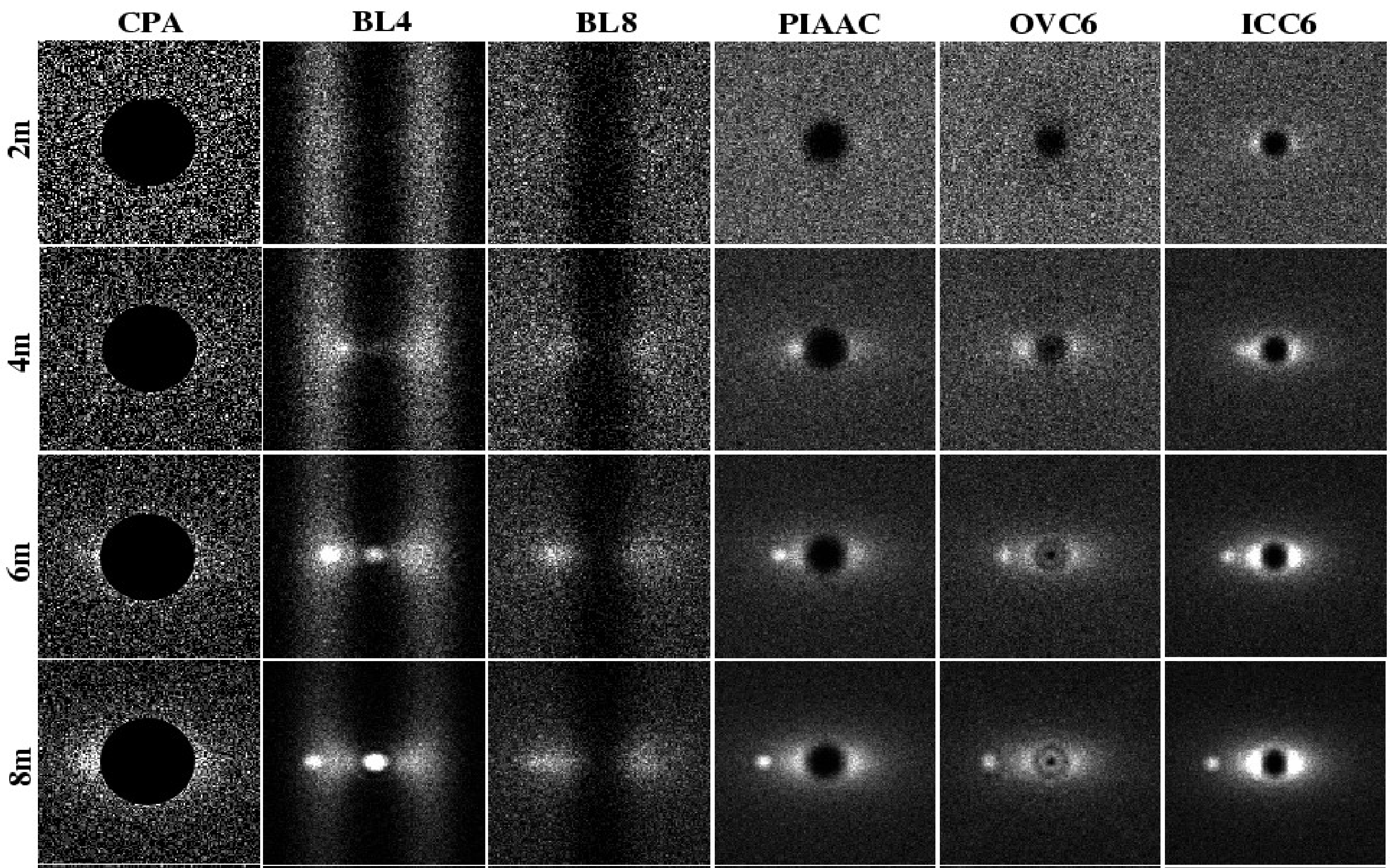
Earh is relatively bright at 10um (peak of thermal emission, ~1e7 contrast instead of ~1e10 in visible light), but diffraction limit of a single telescope at 10um is insufficient
→ interferometer well-suited



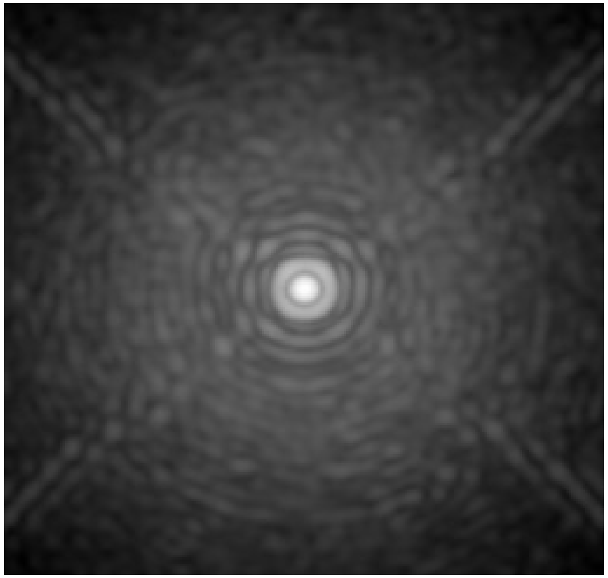
Terrestrial Planet Finder Interferometer (NASA)

Coronagraphy

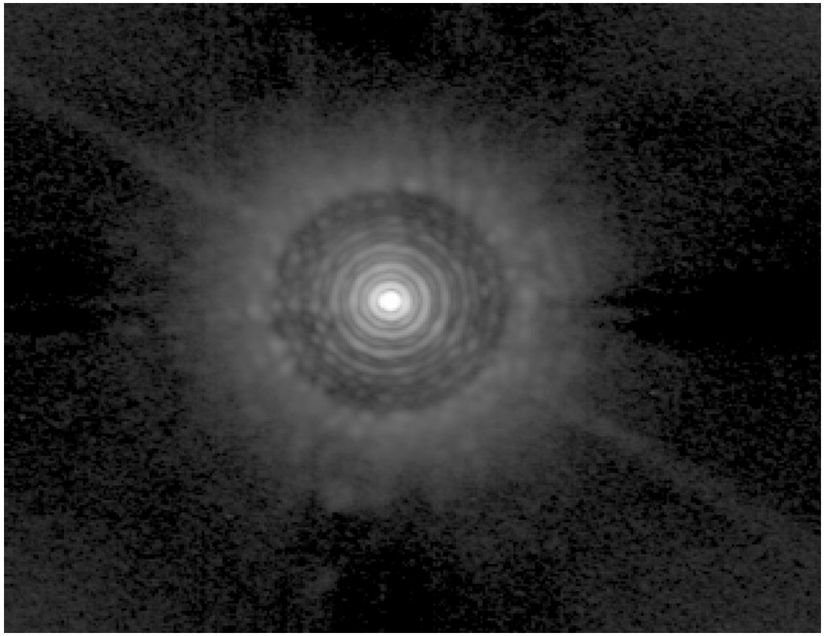
Coronagraphs with different throughput, IWA, contrast, discovery space, angular resolution
Simulated observations of a Sun/Earth system without wavefront errors
Telescope diameter shown on the left



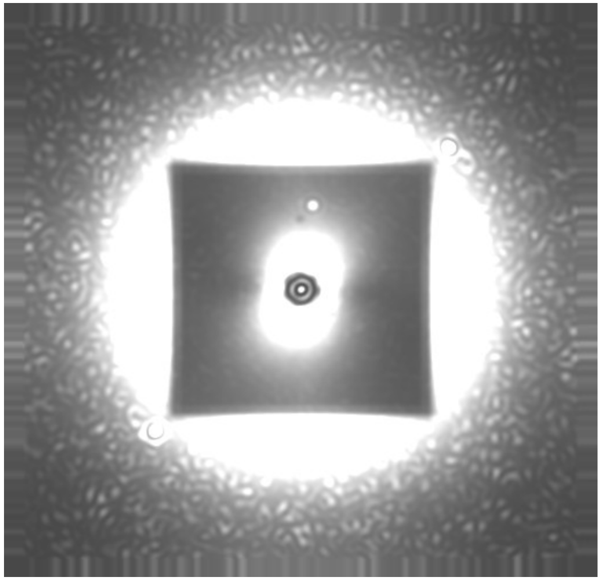
From conventional AO to Extreme-AO



Conventional AO system



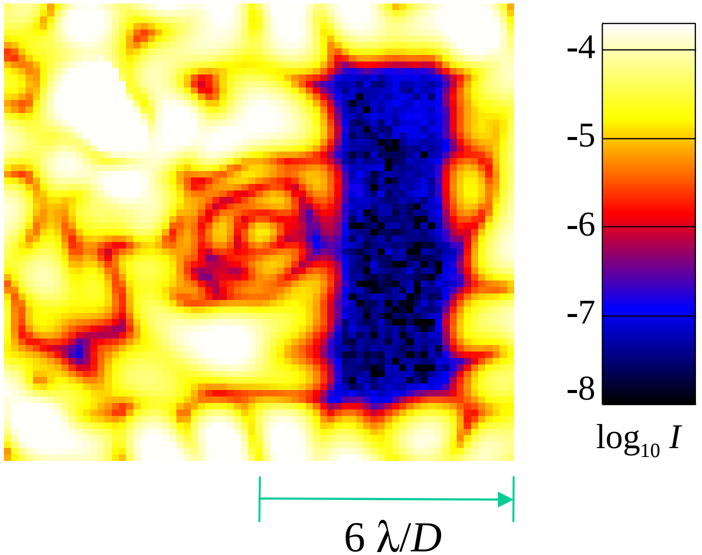
Very good conventional AO system (LBT)



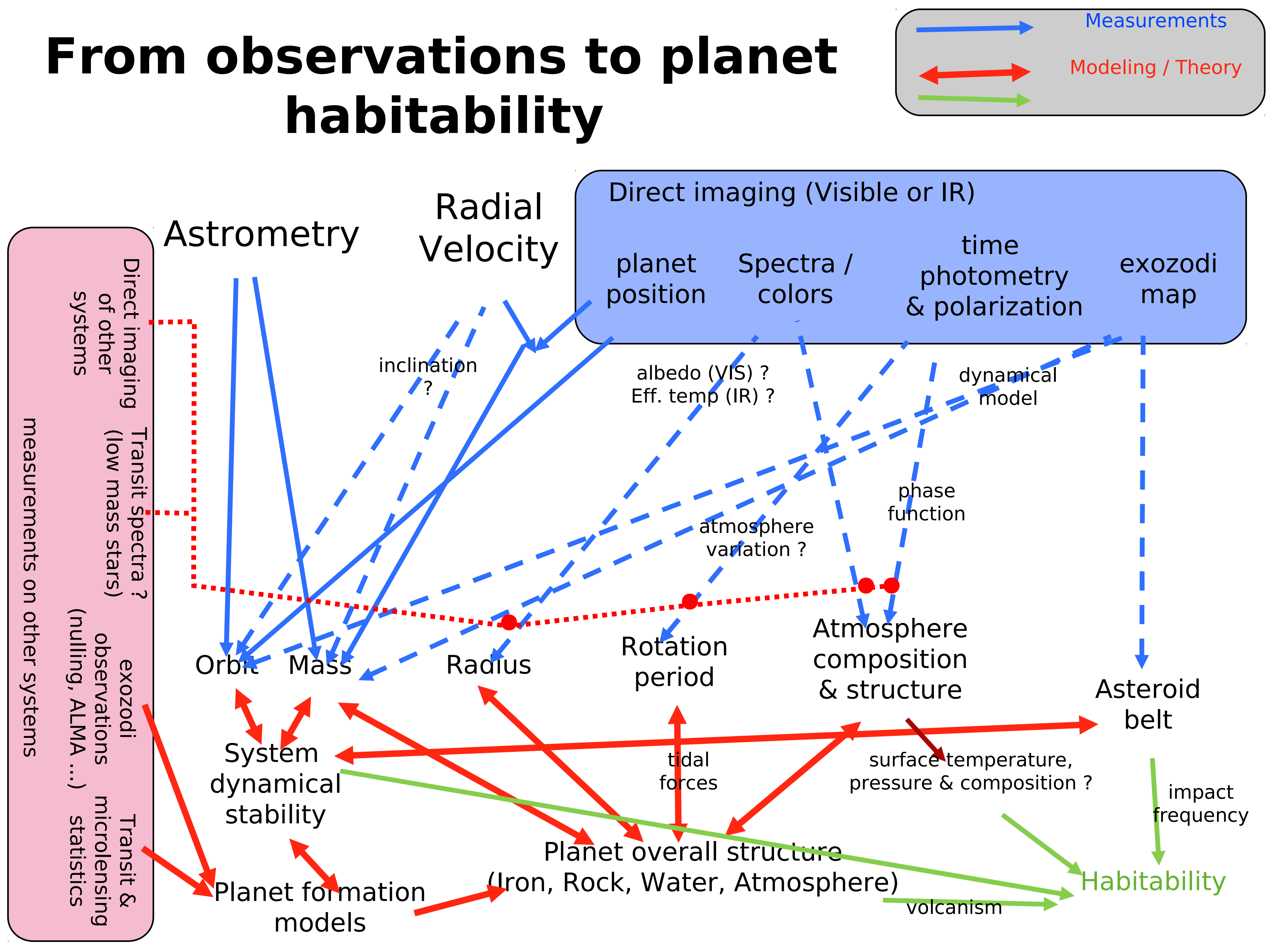
Ground-based Extreme-AO system (GPI - simulation)

High contrast imaging systems are specifically designed to produce dark areas in the image
Use:

- **coronagraphy**
- **contrast-optimized wavefront control**
- **calibration / differential imaging**



Space-based high contrast imaging system (lab)


From observations to planet habitability
Measurements
Modeling / Theory
Direct imaging of other systems
Transit spectra ? (low mass stars)
measurements on other systems
exozodi observations (nulling, ALMA ...)
Transit & microlensing statistics
Astrometry
Radial Velocity
Direct imaging (Visible or IR)
planet position
Spectra / colors
time photometry & polarization
exozodi map
inclination ?
albedo (VIS) ? Eff. temp (IR) ?
dynamical model
atmosphere variation ?
phase function
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure & composition ?
impact frequency
Planet overall structure (Iron, Rock, Water, Atmosphere)
Habitability
Planet formation models
volcanism

Future opportunities

Ground-based facilities:

- arrays of small robotic telescopes (transit, microlensing)
- better instruments on 8-m class telescopes (direct imaging, transit spectroscopy, RV)
- new instruments on extremely large telescopes (ELTs) for direct imaging (Extreme-AO) and RV

Space missions:

- better transit surveys (TESS, PLATO) with more completeness → better understanding of exoplanet statistics
- microlensing survey (WFIRST)
- transit spectroscopy (JWST, FINESSE) with highly stable observations
- possible astrometry mission ? → measure planet masses
- direct imaging and spectroscopy mission → characterization, habitability