ESO in the 2020s

Exoplanets

Yann ALIBERT

many thanks to Sascha Quanz, David Ehrenreich, Christophe Lovis, Artie Hatzes

The National Centres of Competence in Research (NCCR)
are a research instrument of the Swiss National Science Foundation

Outlook

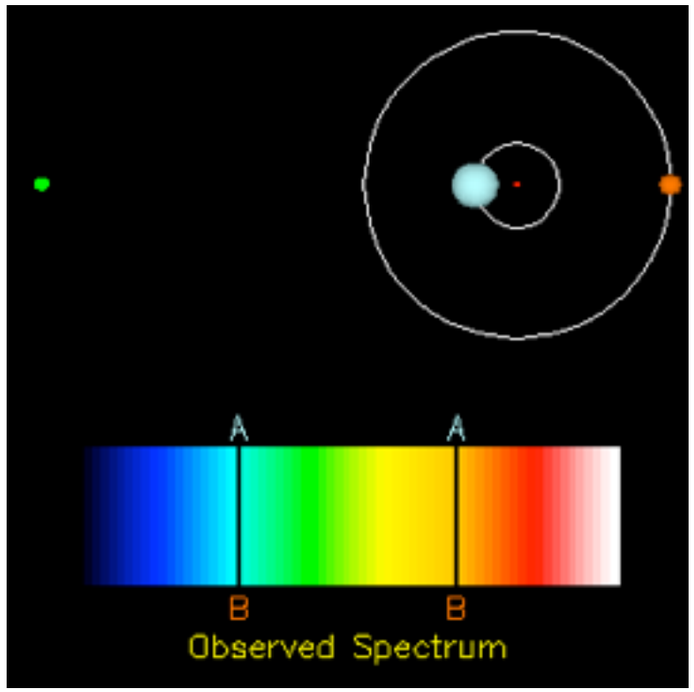
1- Exoplanets: what do we know?

2- Exoplanets: what do we want to know?

3- Recent progresses

4- The future (plans and extrapolations)

Exoplanets: major discovery/characterization methods



-> M sin(i)

-> orbit

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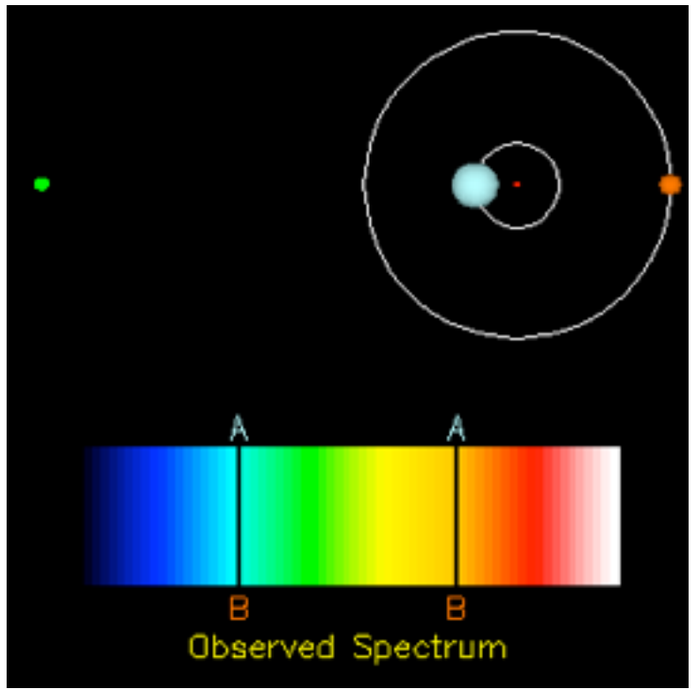

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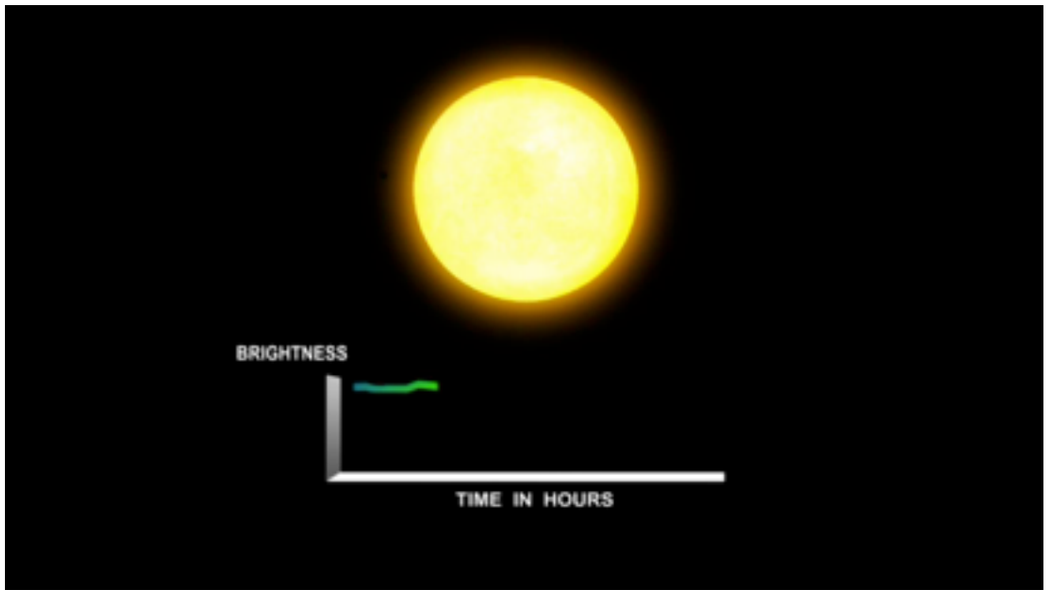

-> radius

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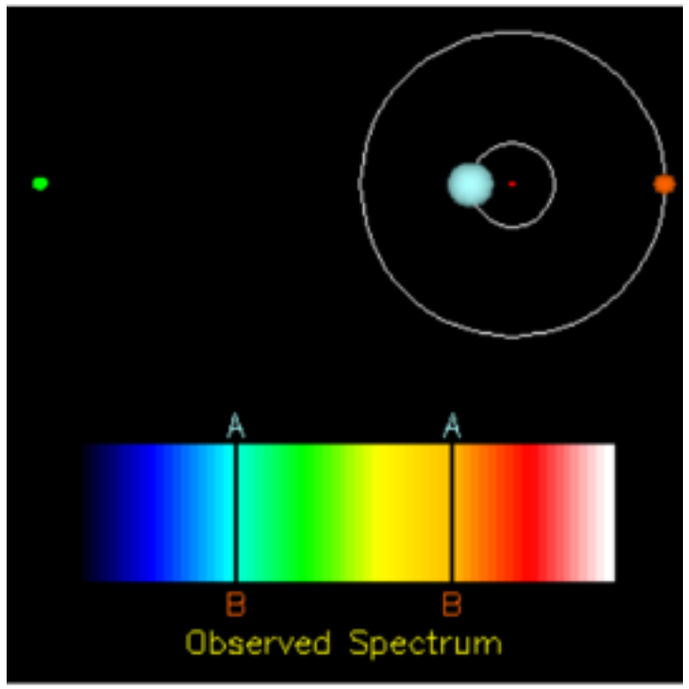

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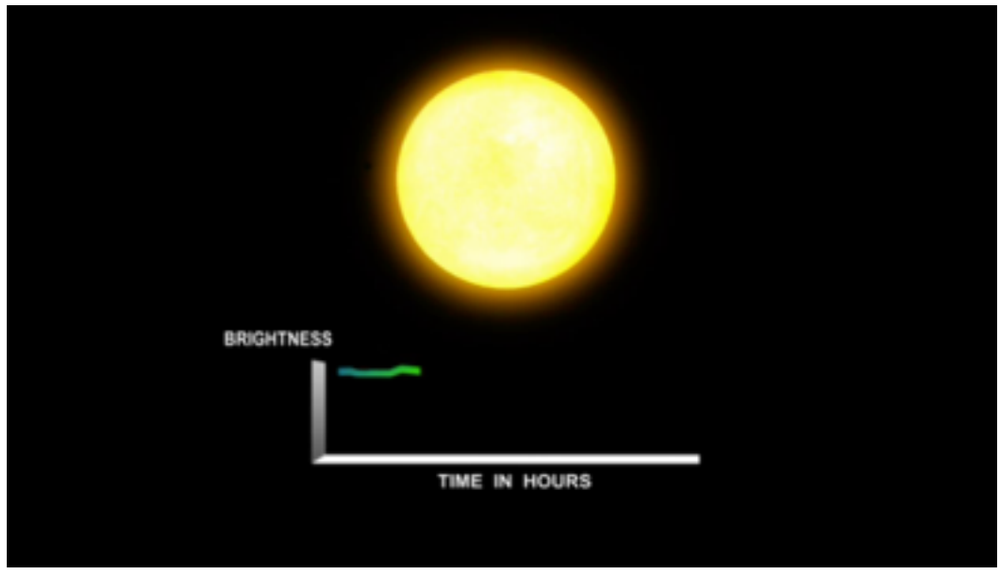

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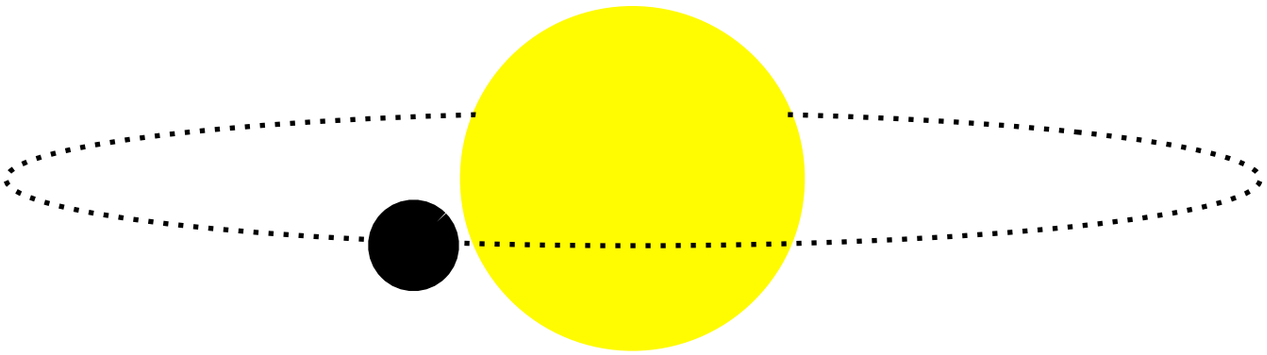

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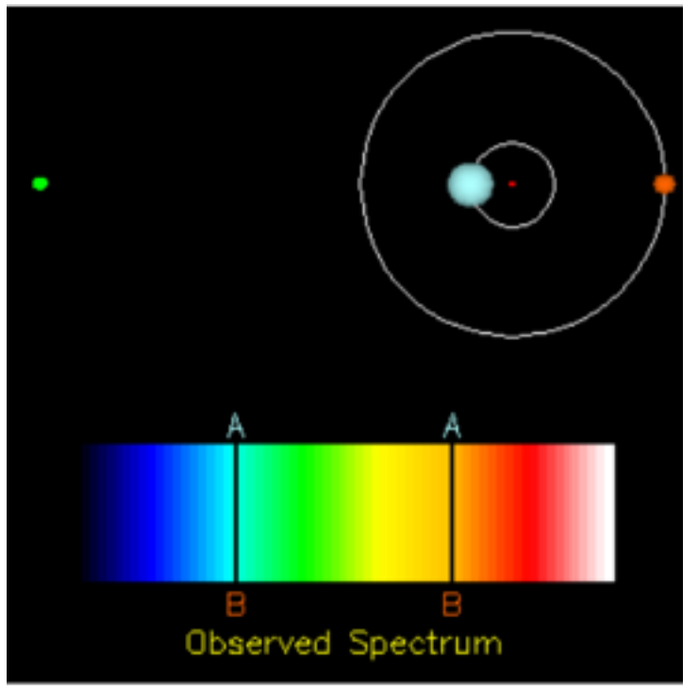

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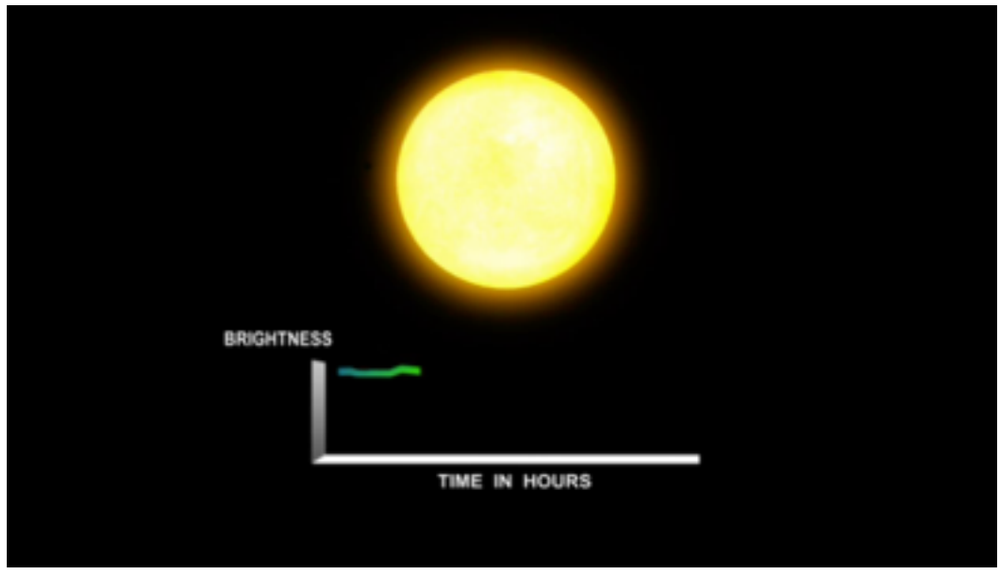

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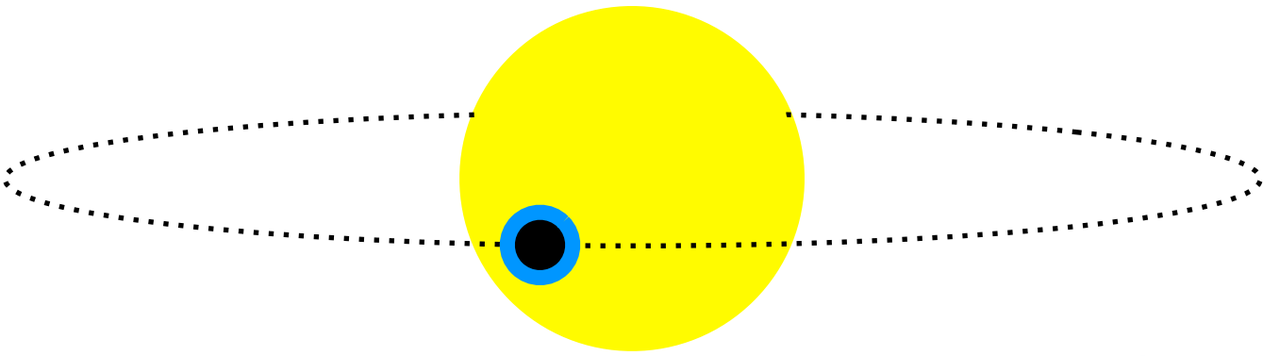
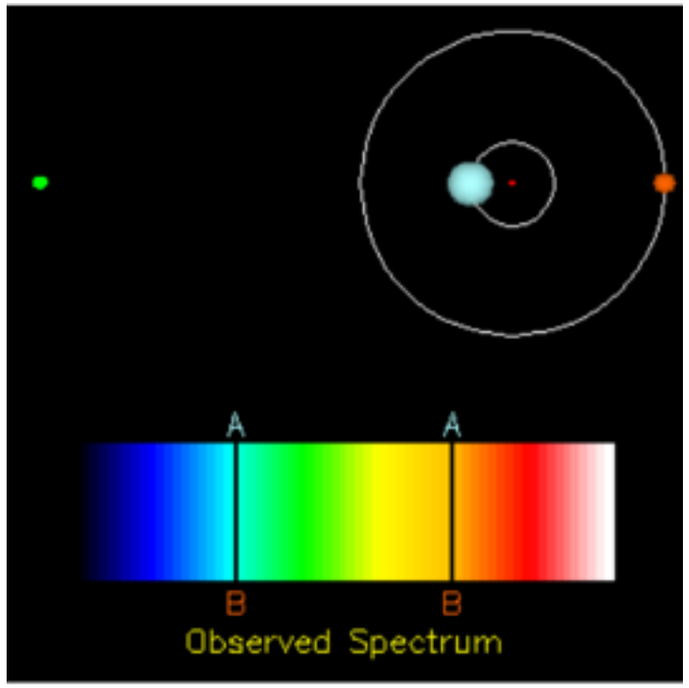


Transmission spectroscopy through the limb

Exoplanets: major discovery/characterization methods



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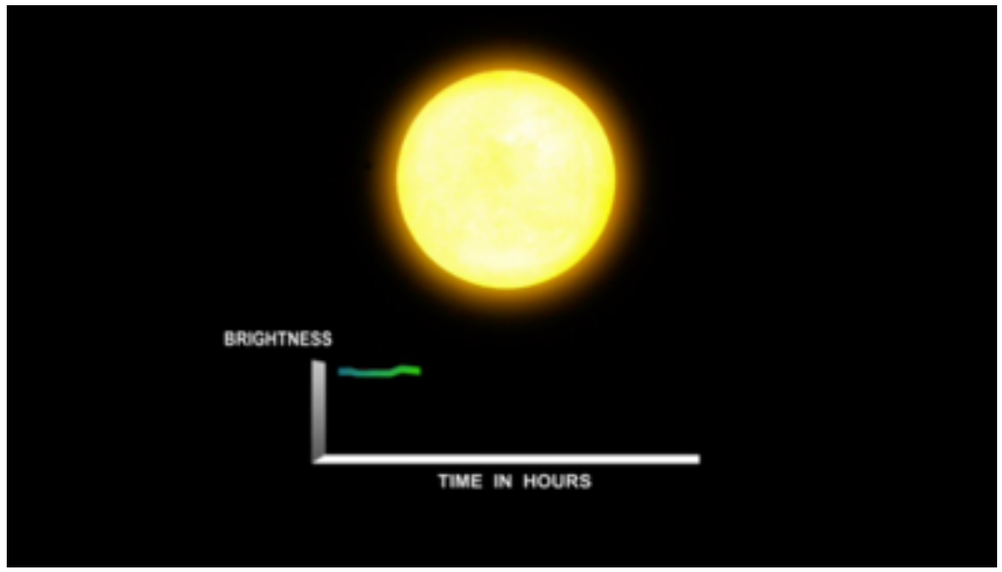

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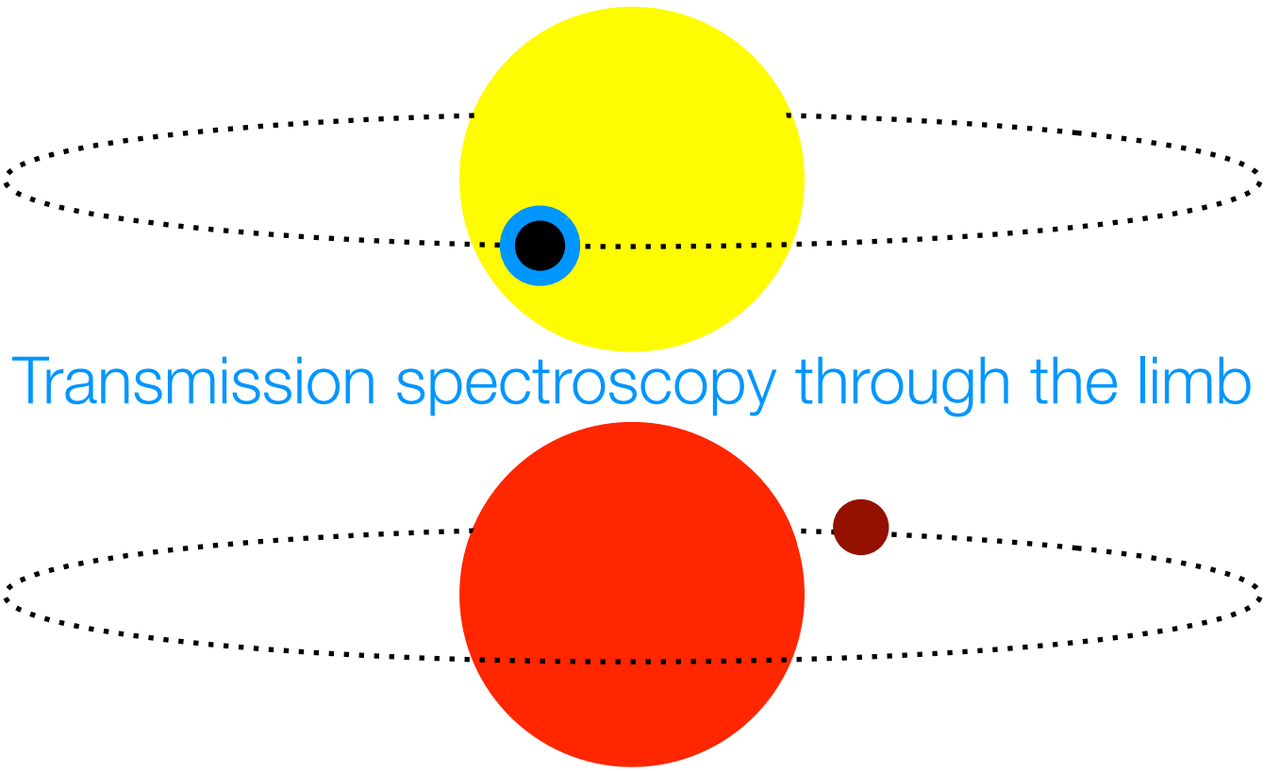
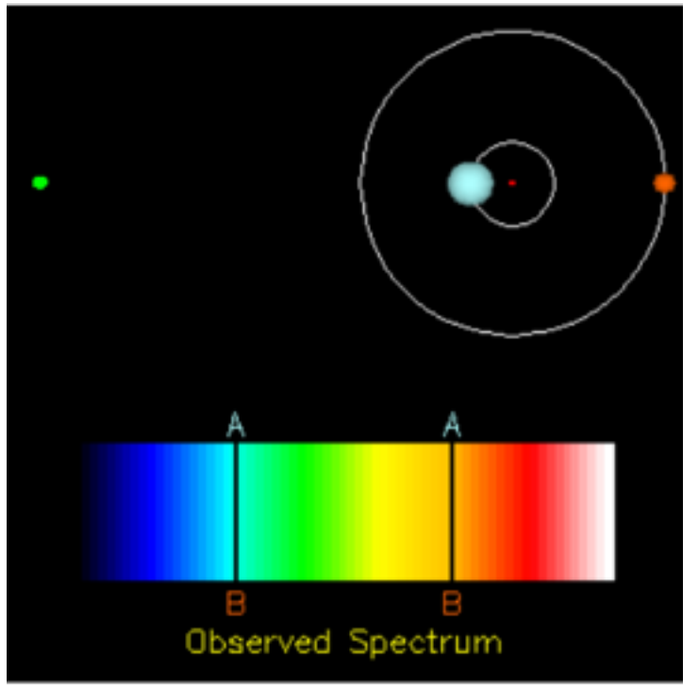


Transmission spectroscopy through the limb

Planetary emission

Exoplanets: major discovery/characterization methods



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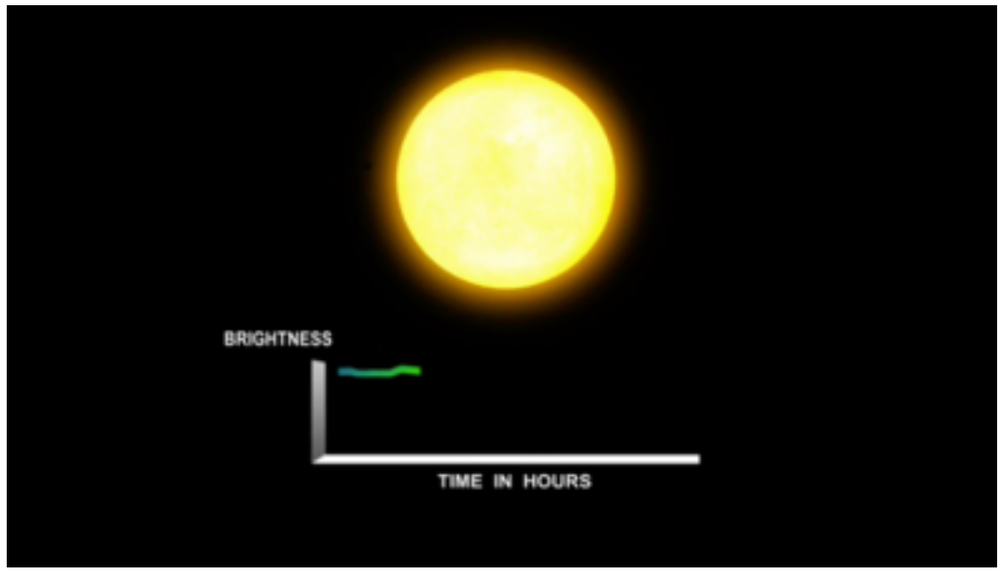

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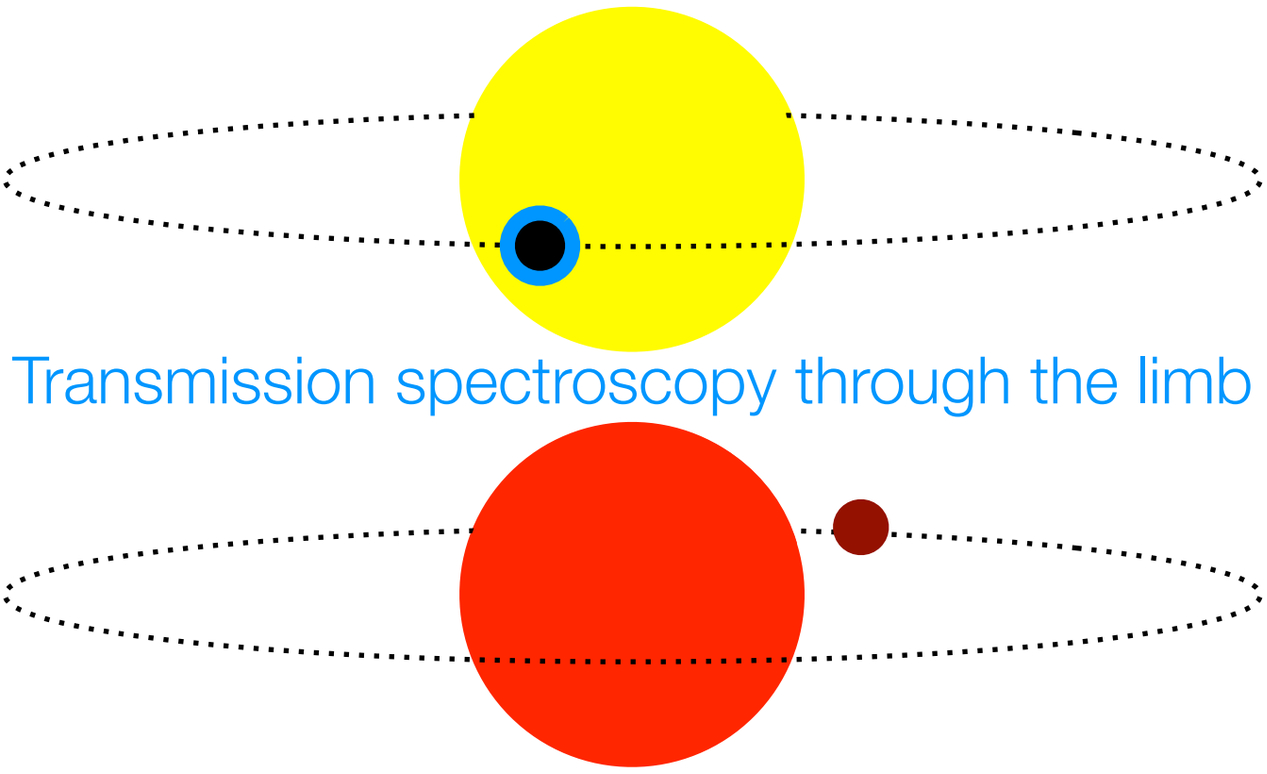
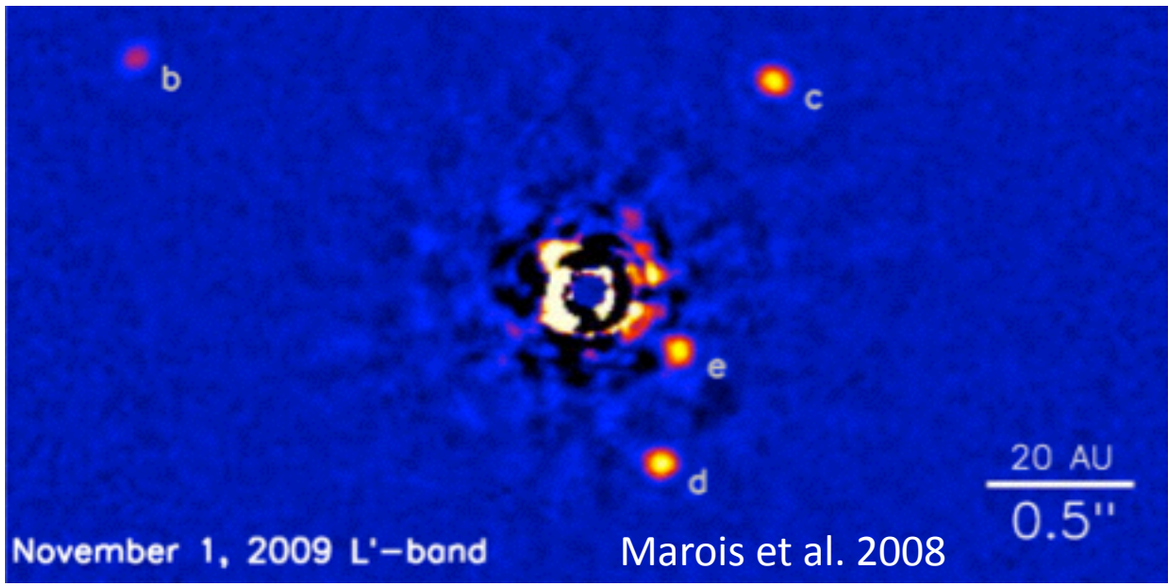


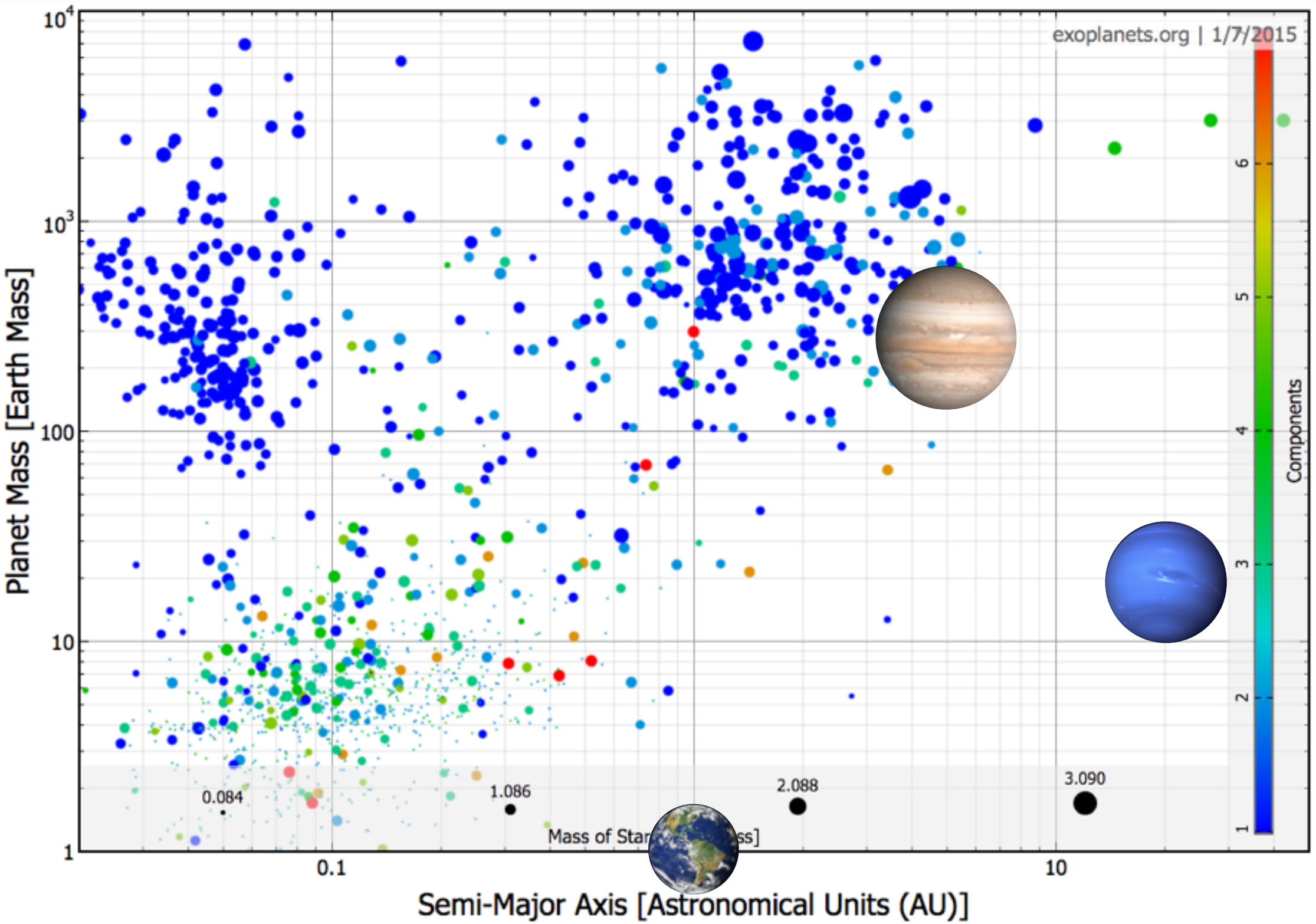
Transmission spectroscopy through the limb

Planetary emission



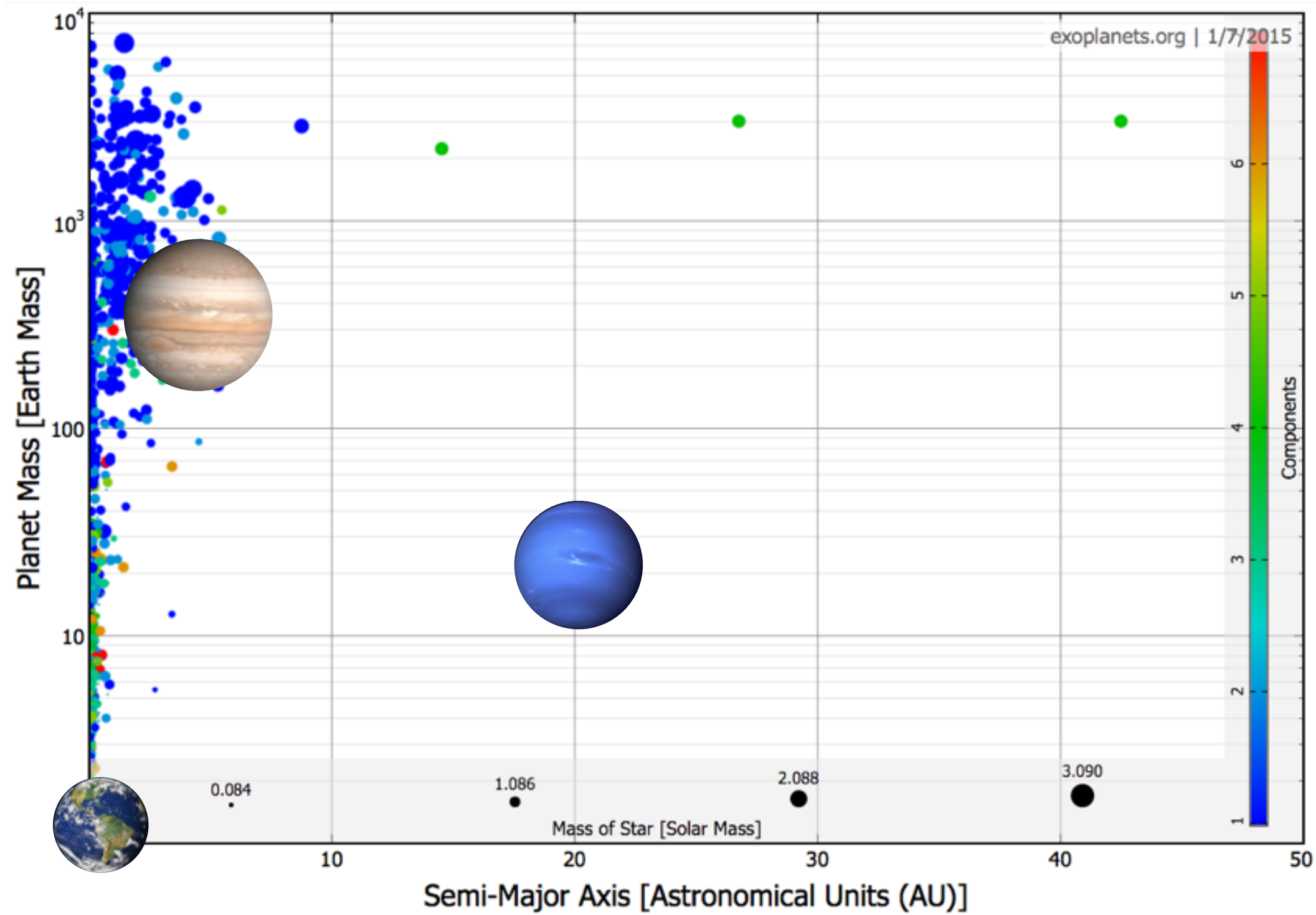
-> planetary emission

Exoplanets: what do we know? - the aM diagram



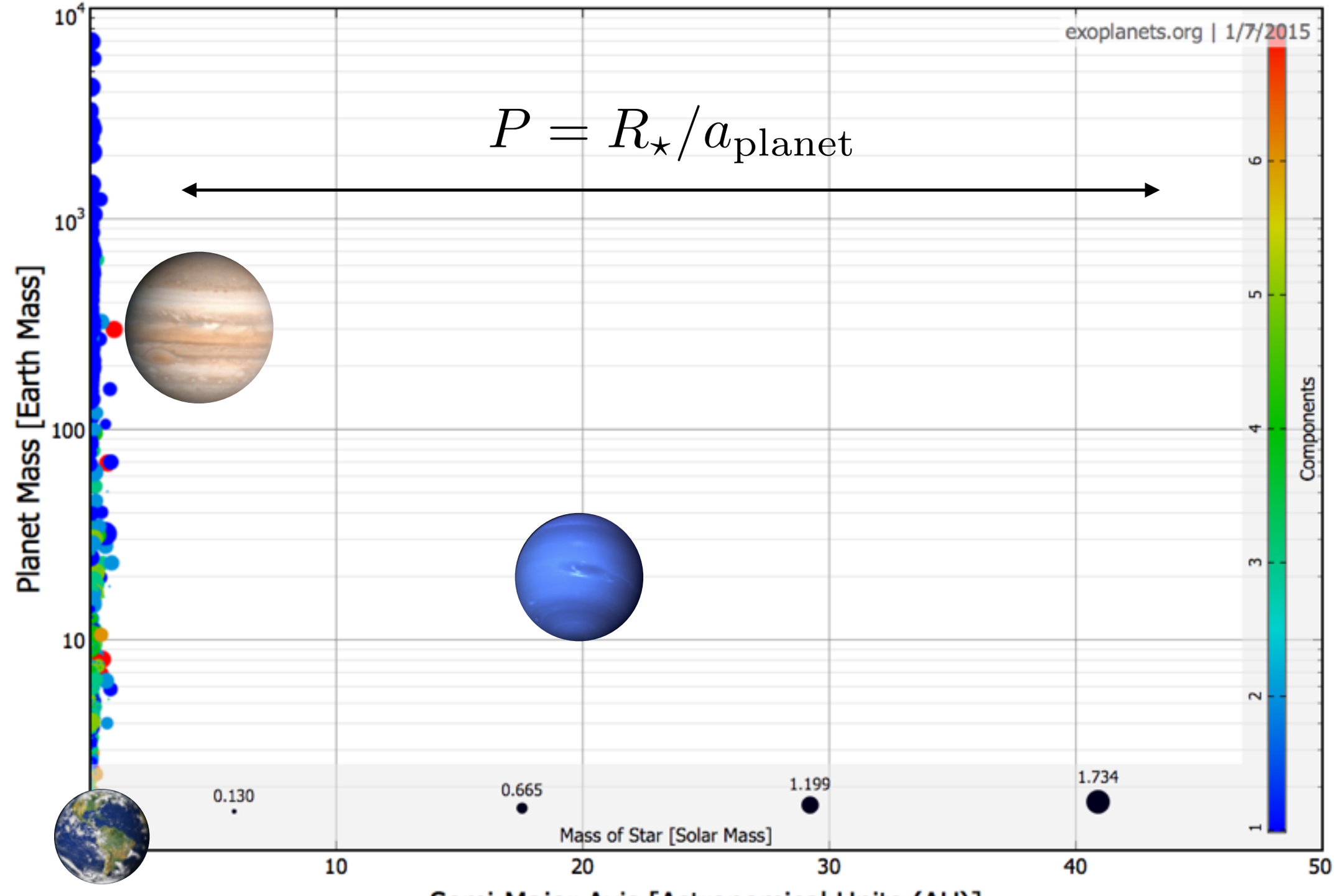
Exoplanets: what do we know? - the aM diagram for RV

Surveys have probed 15% of the planetary system parameter space



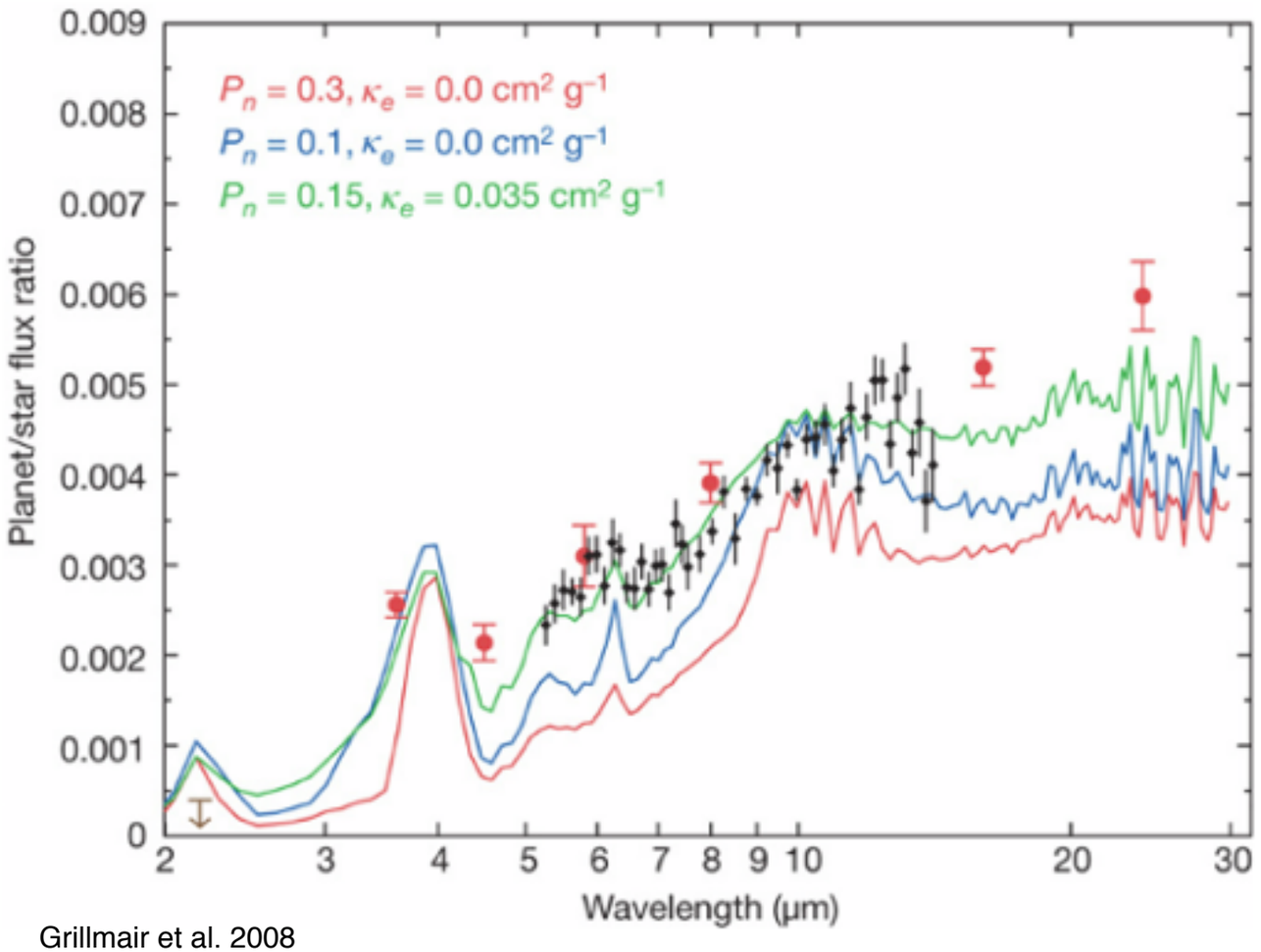
Exoplanets: what do we know? - the aM diagram for transits

Transit: only 2% of the planetary system parameter space



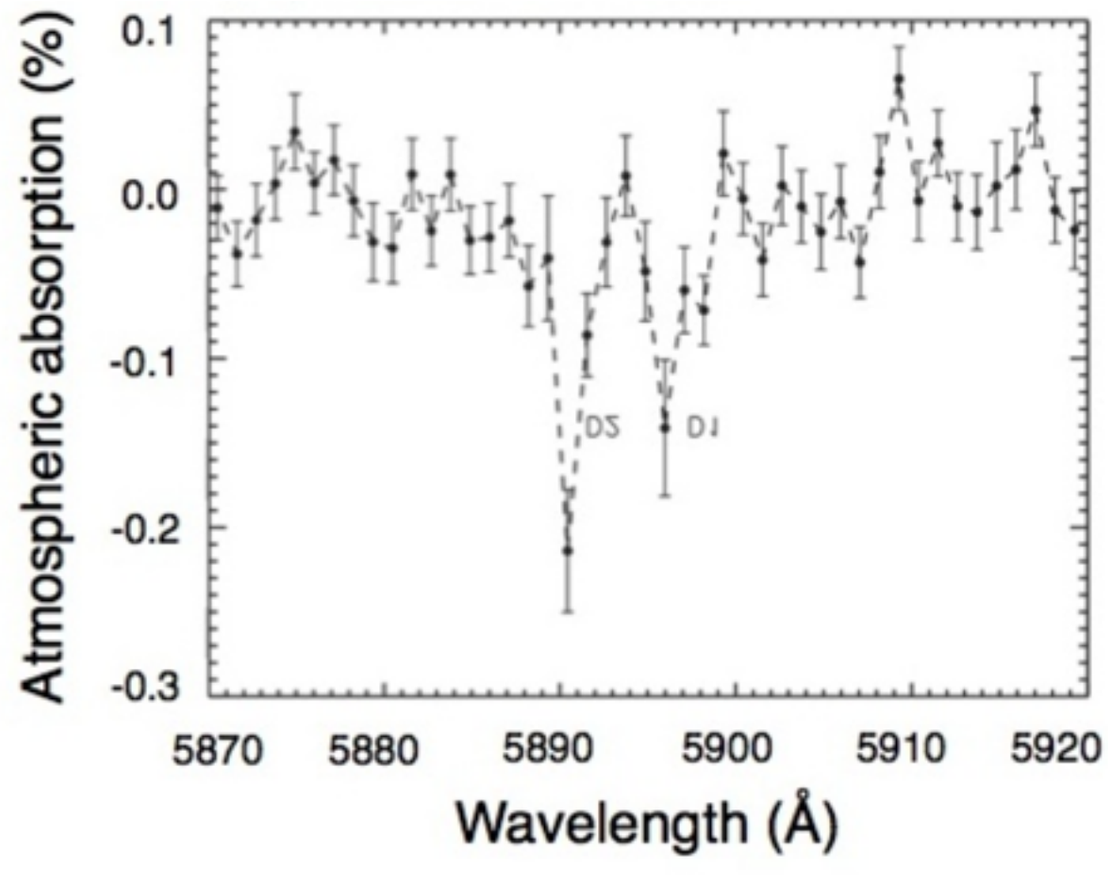
Exoplanets: what do we know? - atmosphere

HD189733b dayside spectrum



Grillmair et al. 2008

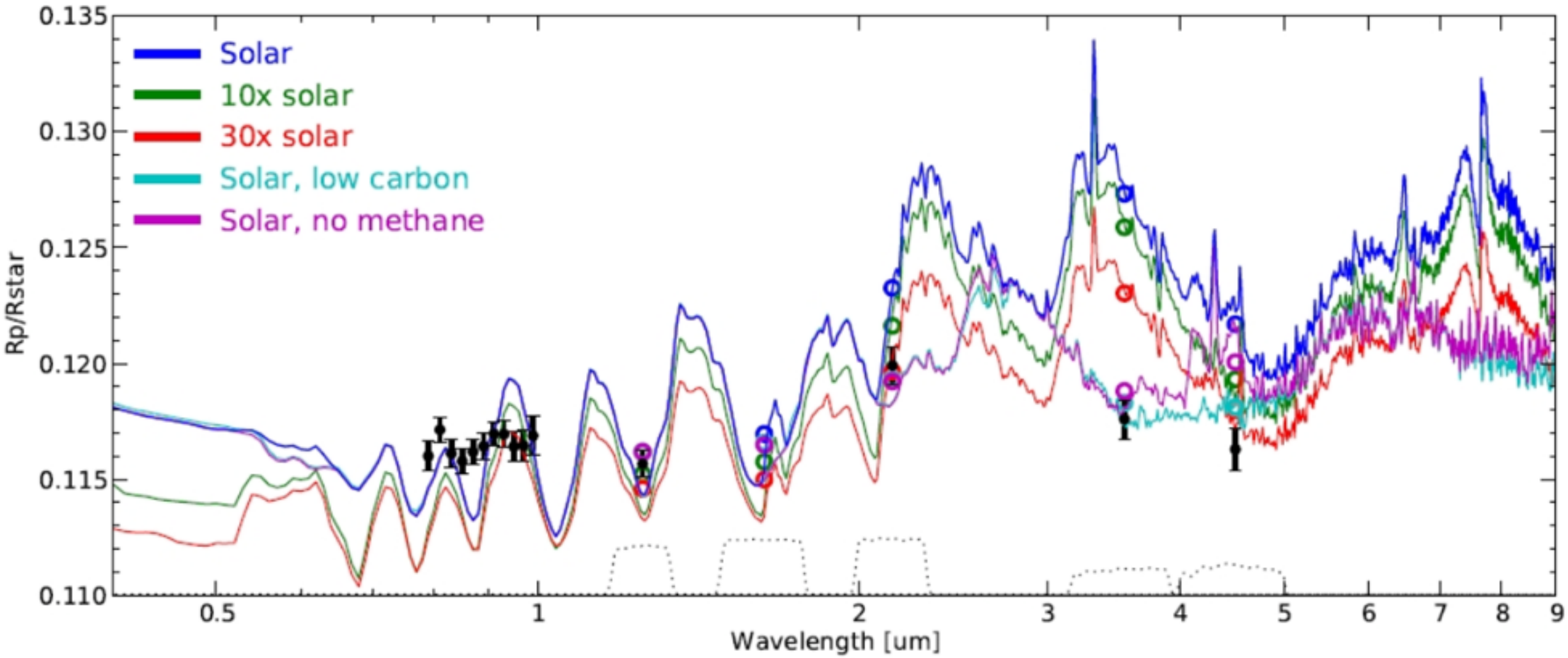
HD189733b transmission



Huitson etal 2012

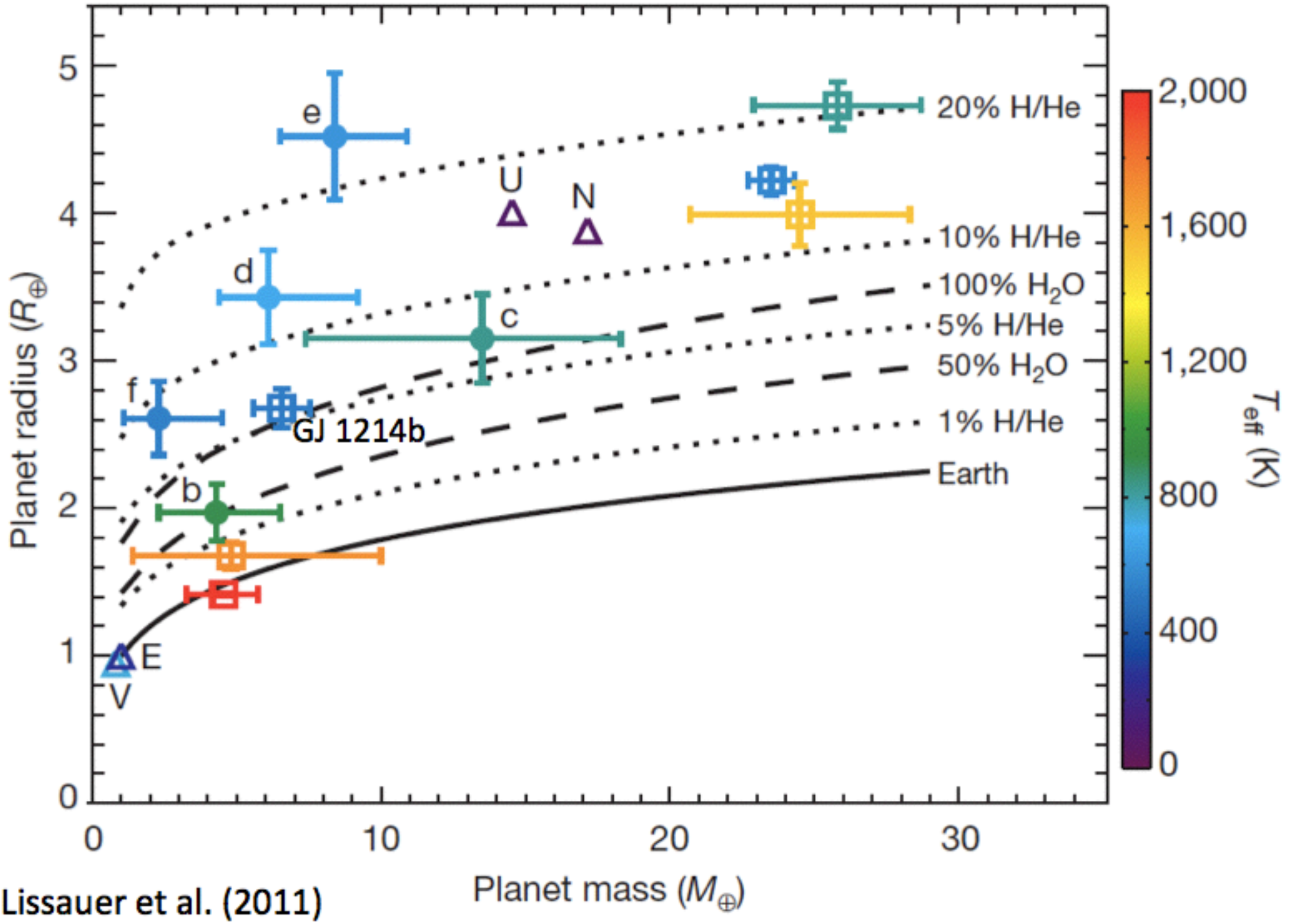
Exoplanets: what do we know? - atmospheric composition

GJ 1214b transmission



Crossfield et al. 2011

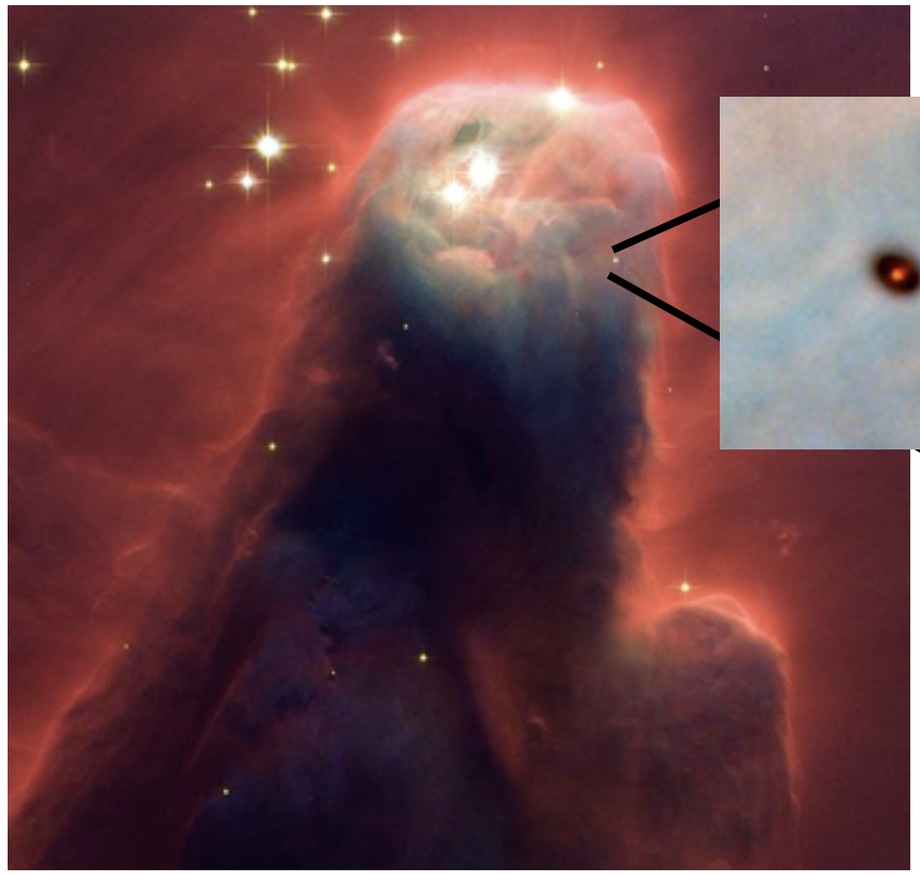
Exoplanets: what do we know? - planetary bulk composition



Lissauer et al. (2011)

Exoplanets: what do we know? - theory

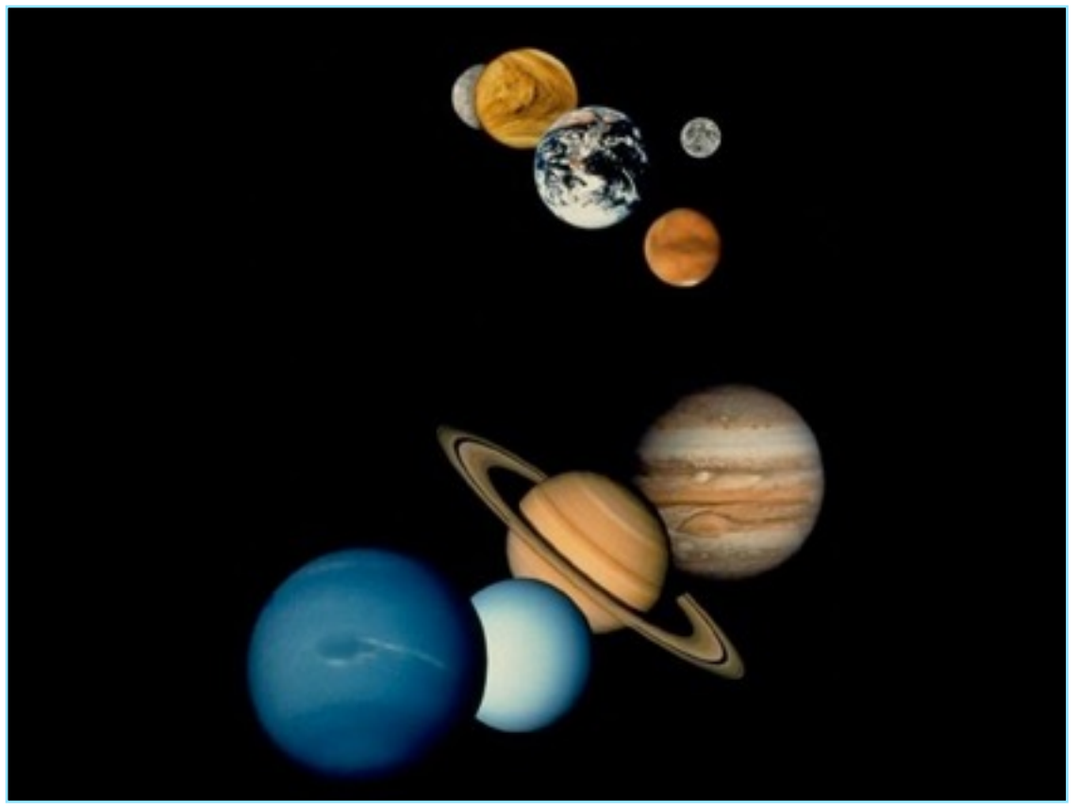
NGC2264



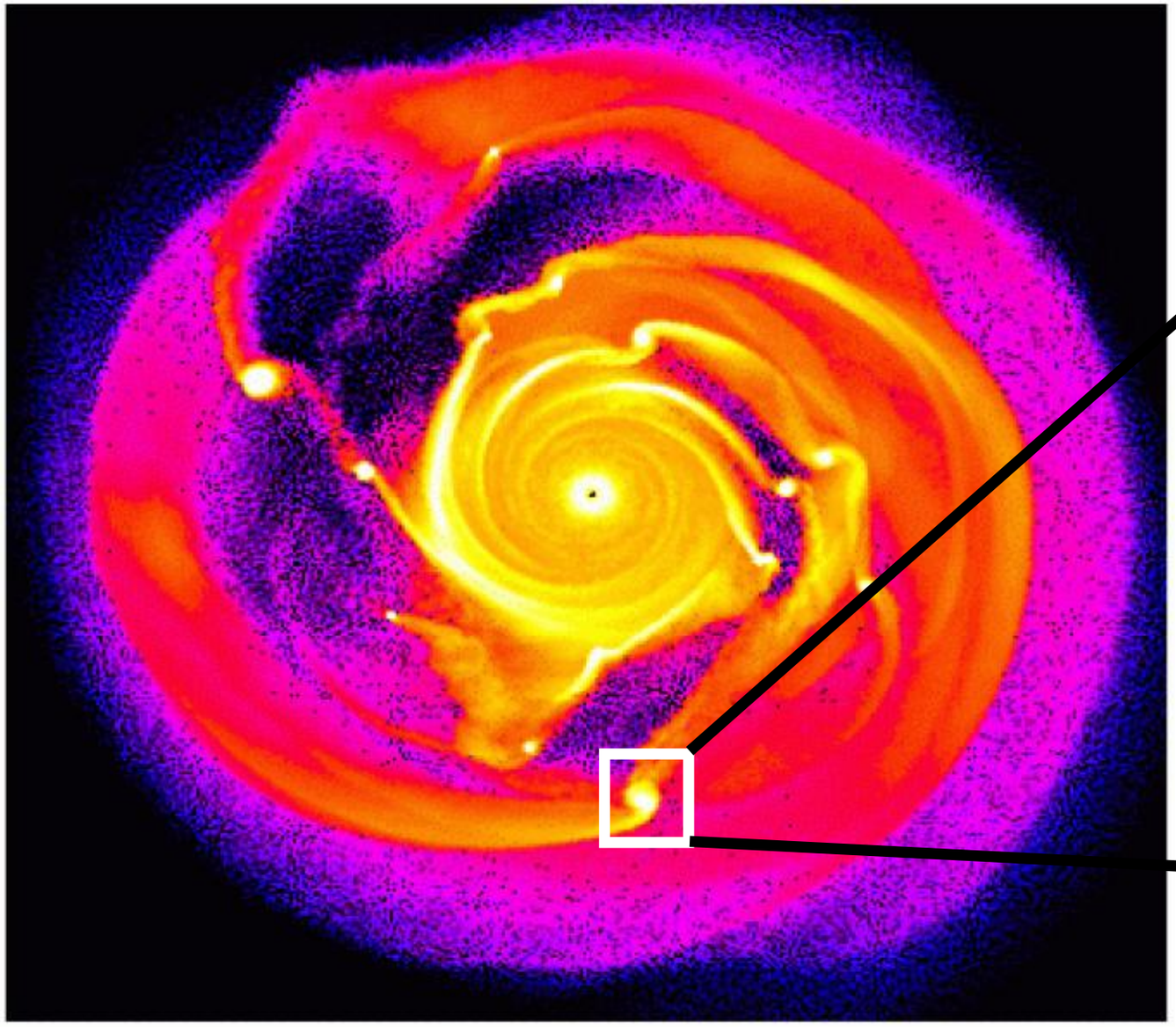
2.5 Light years ~160000 AU

~100s AU

⇓ Planet formation



Exoplanets: what do we know? - Disk instability paradigm



Mayer et al. 2004

Clump formation depends critically on disk cooling

⇒ formation of massive planets

⇒ formation in outer parts of the disk

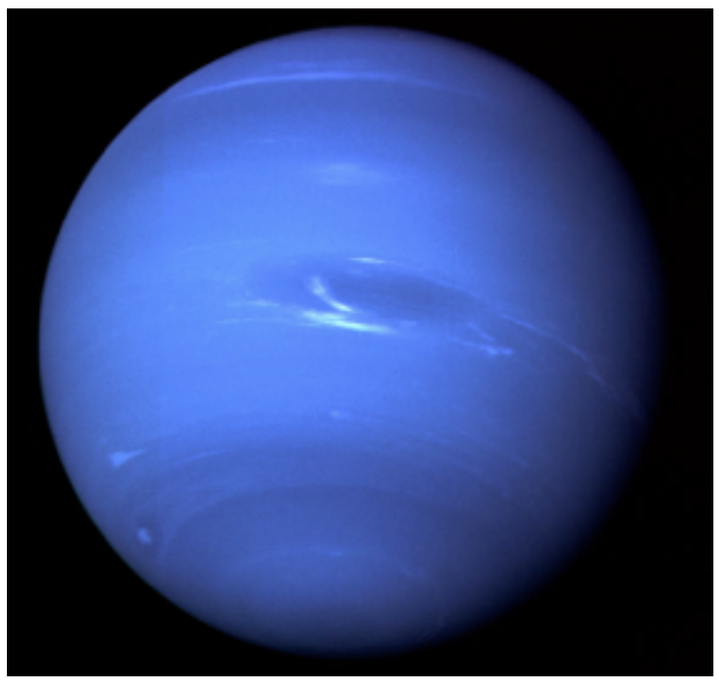
Origin of enrichment in heavy elements/formation of low mass (Earth,Neptune) planets?

Exoplanets: what do we know? - Core accretion paradigm

terrestrial planet

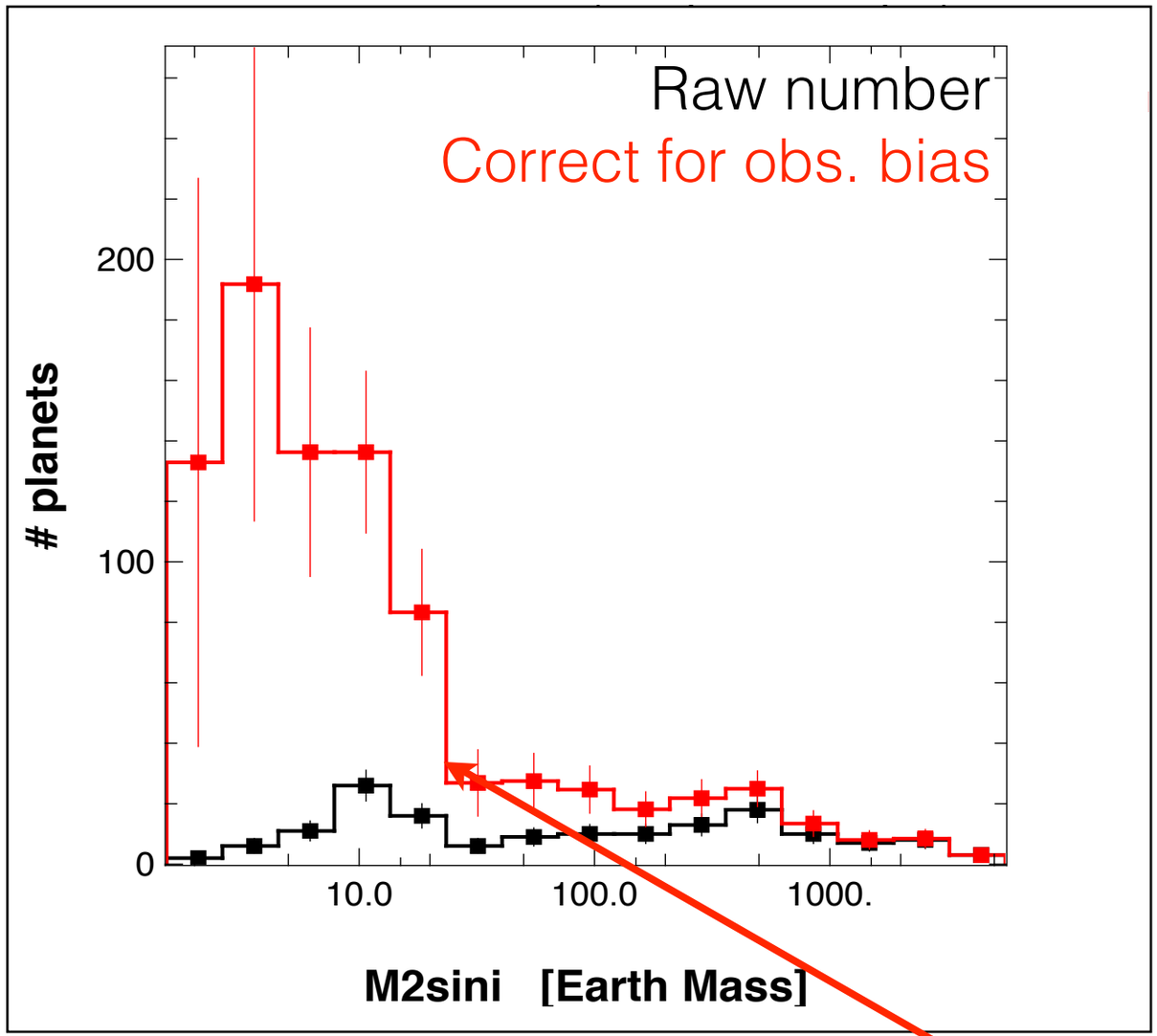
gas giant
M > Mcrit

core dominated giant



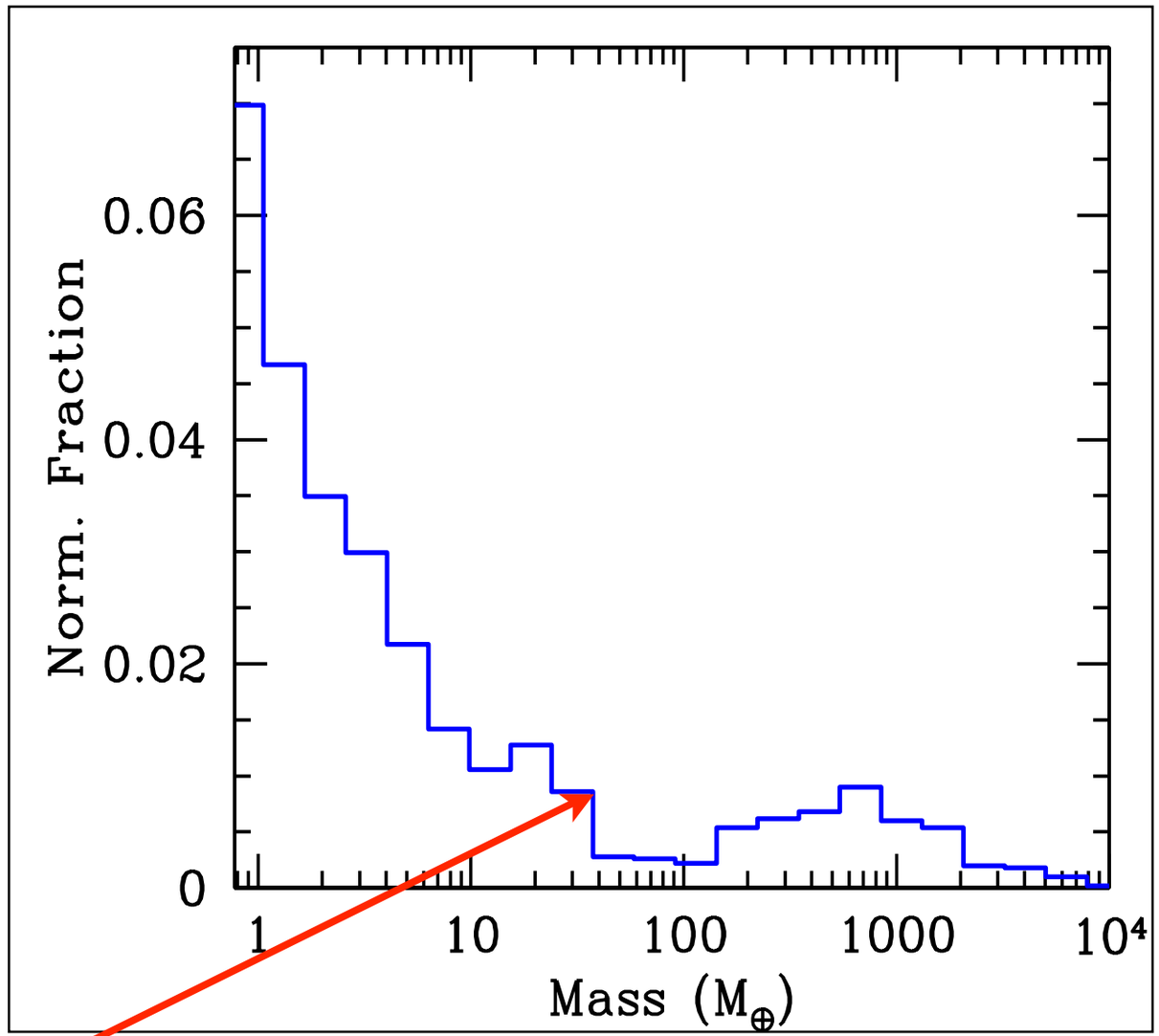
Exoplanets: what do we know? - PIMF

Observations



Mayor et al. 2011

Synthetic



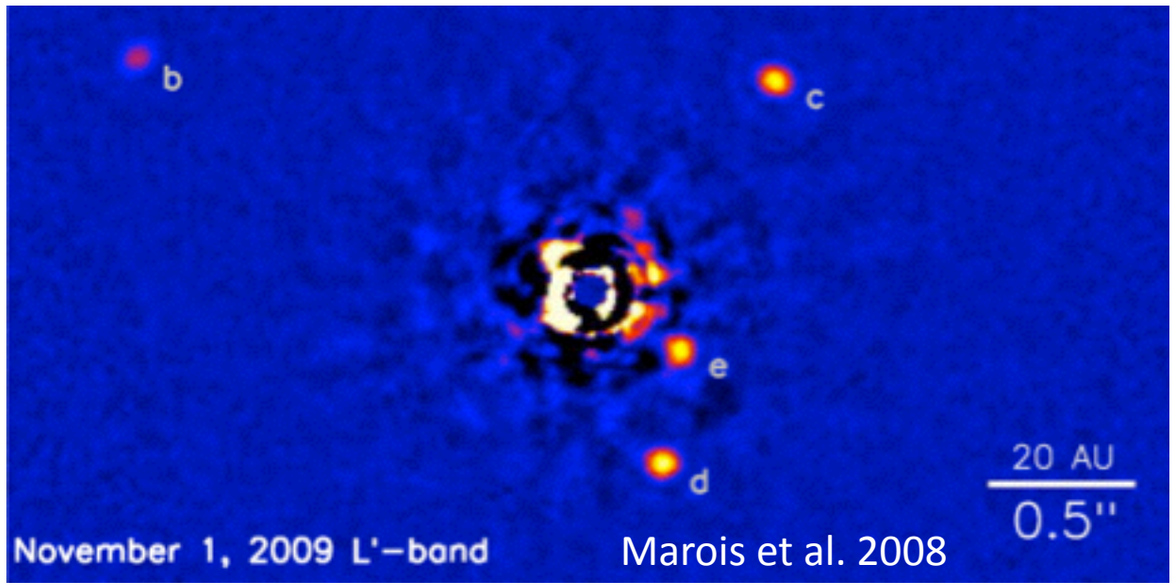
Benz et al. 2014

Sudden increase

Typical for core accretion: rapid gas accretion above critical mass

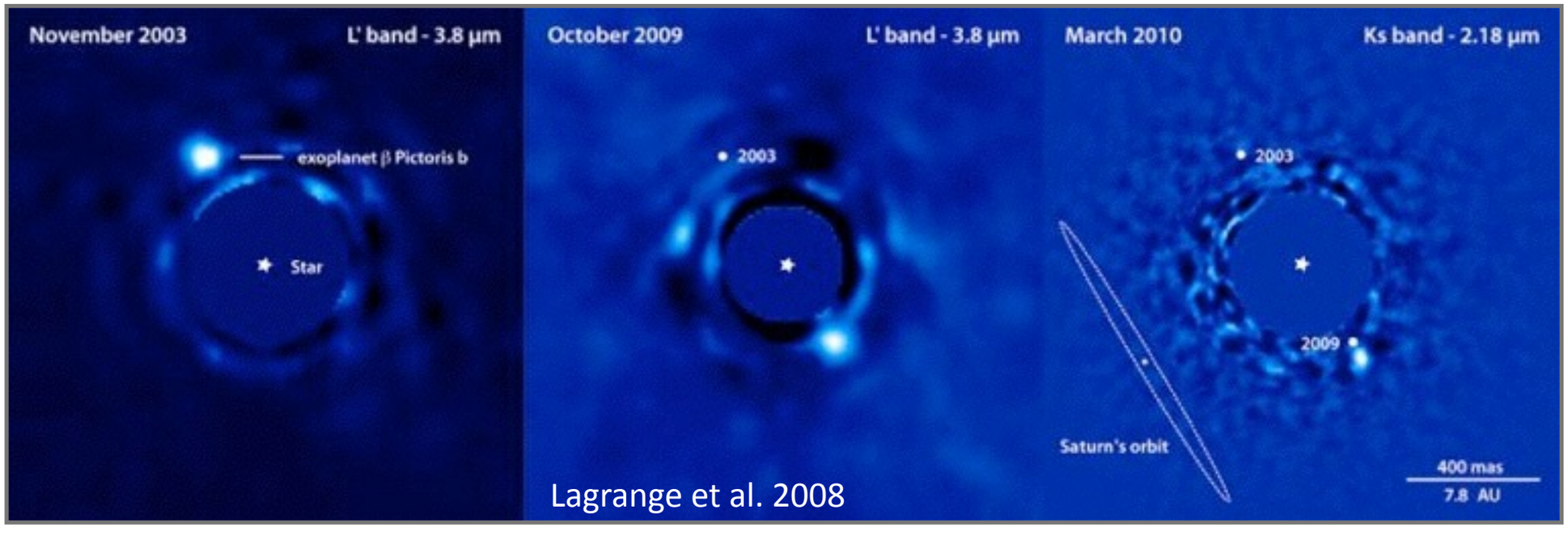
Exoplanets: what do we know? - directly imaged planets

Core-accretion mechanism has also some difficulties



Marois et al. 2008

HR 8799 b,c,d,e:
M≈ 5-13 JM
d= 15-70 AE



Lagrange et al. 2008

Beta Pictoris b
M≈ 6-12 MJ
d= 8 AU

Exoplanets: what do we know?

1- mass - radius - orbital elements (but not for the same planets)

2- only for a small part of the parameter space

3- few molecules/atoms detected in the atmosphere

4- some indication on the interior composition

5- many theoretical ideas

Exoplanets: what do we want to know?

Planet formation and evolution

Planets as objects

Habitability and life (Earth-like planets)

Exoplanets: what do we want to know?

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1- formation paradigm? top down or bottom up?

2- where do planets form?

3- how do planet evolve (loss of primitive envelope)?

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2- what is their composition (interior/atmosphere)

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Exoplanets: recent progresses

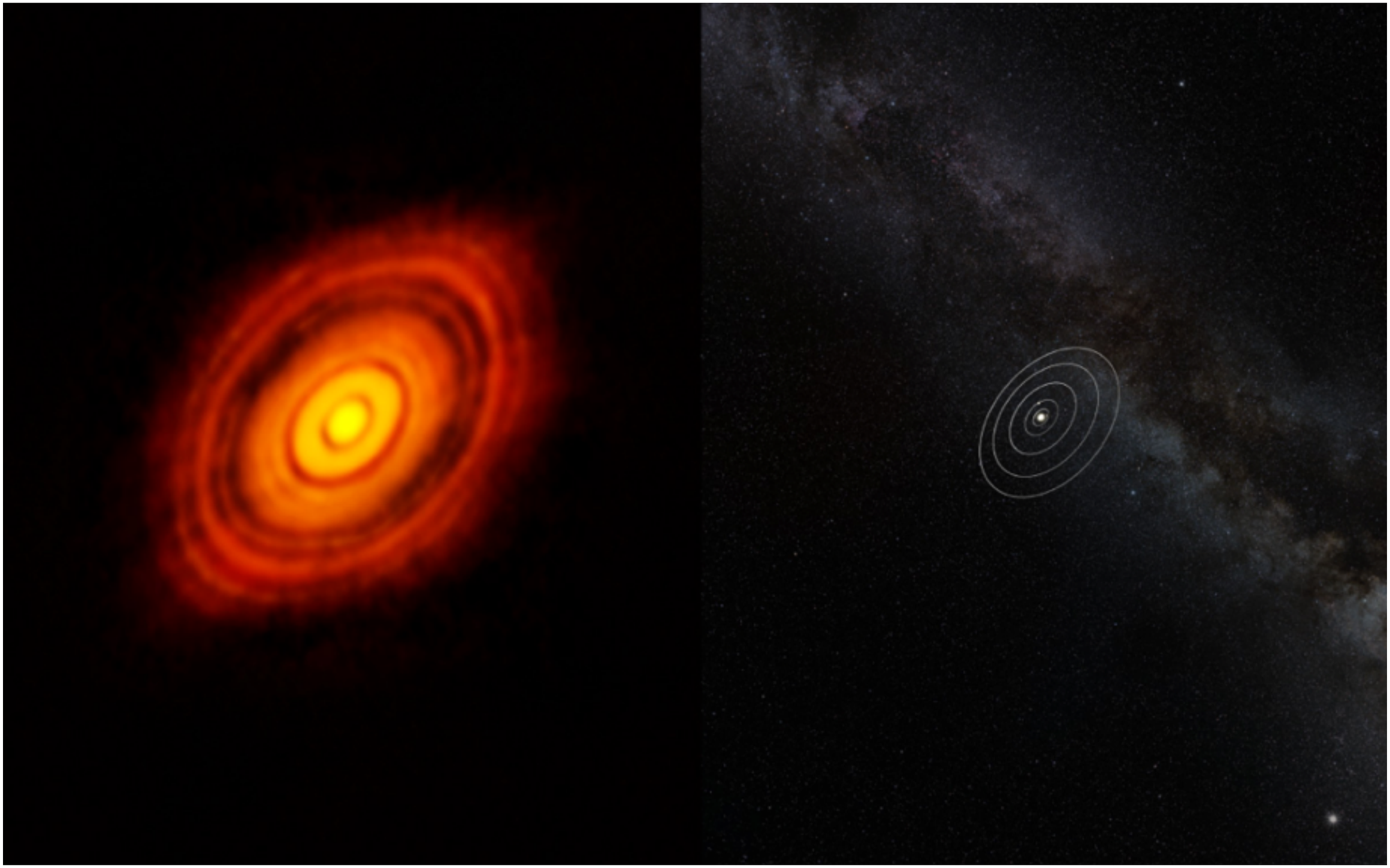
1- protoplanetary disks and planets in the process of formation

2- directly imaged planets

3- composition of planets

4- high resolution spectroscopy

Exoplanets: recent progresses - protoplanetary disks

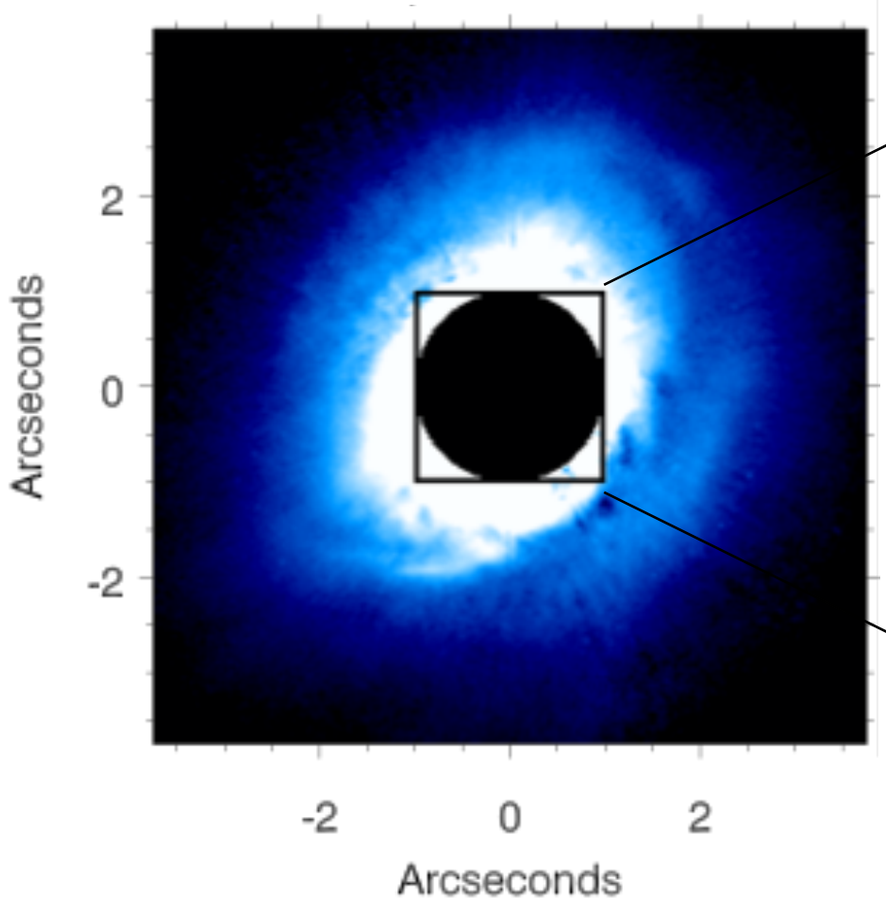


ALMA - HLTau

Credit: ESO

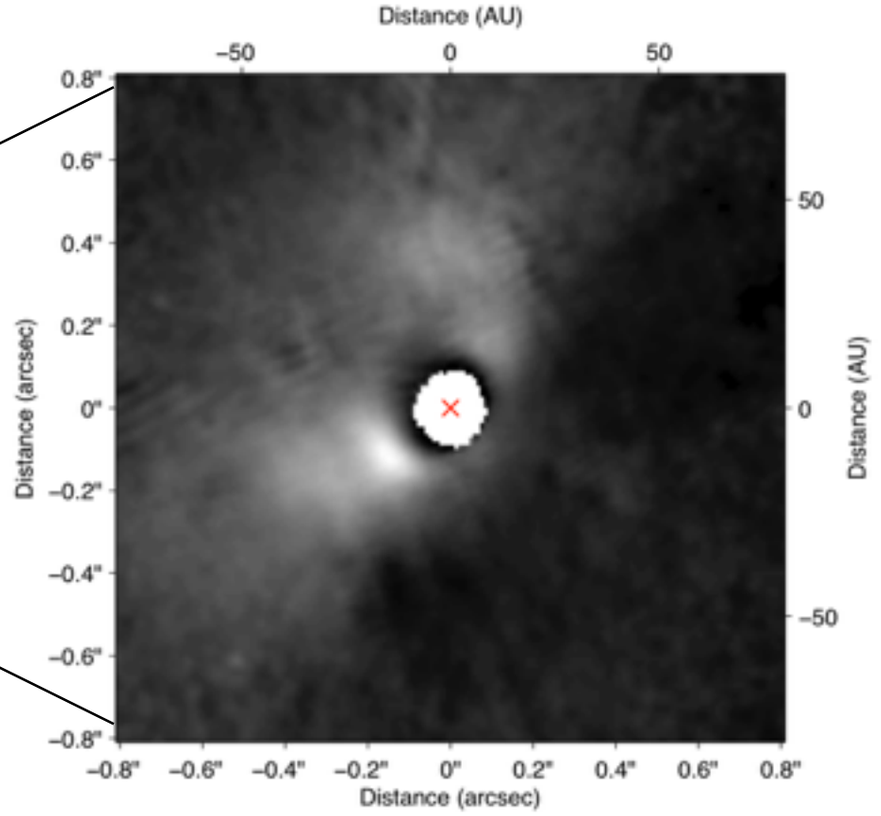
Disk around the Herbig Ae/Be star HD100546

HST ACS (optical)



Ardila et al. 2007

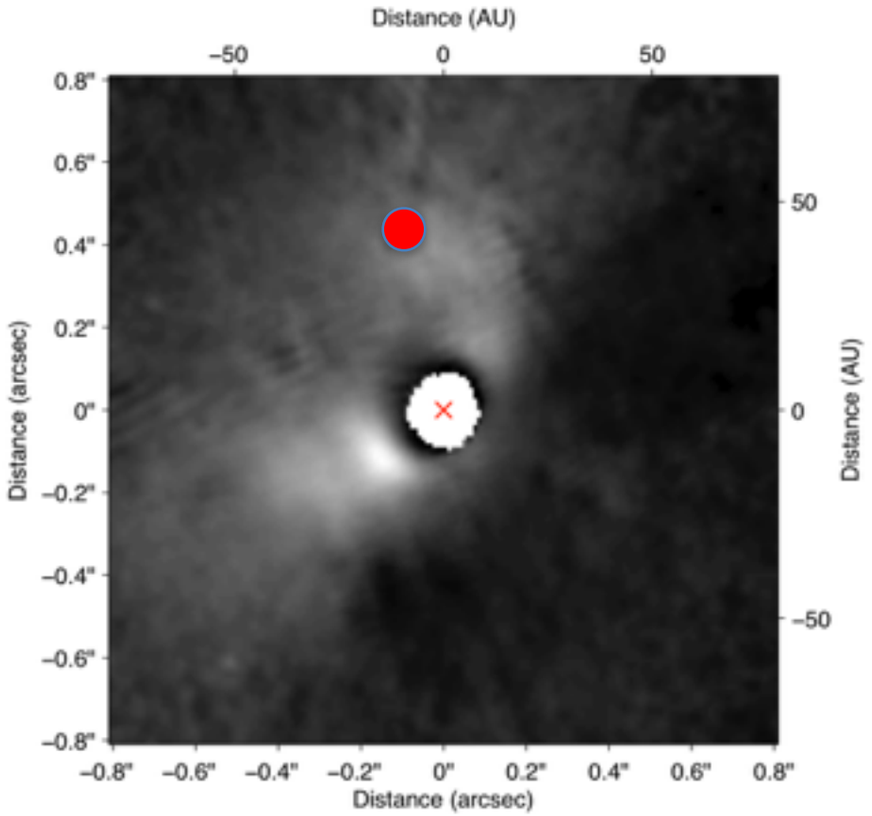
VLT/NACO
Polarimetric Imaging H band



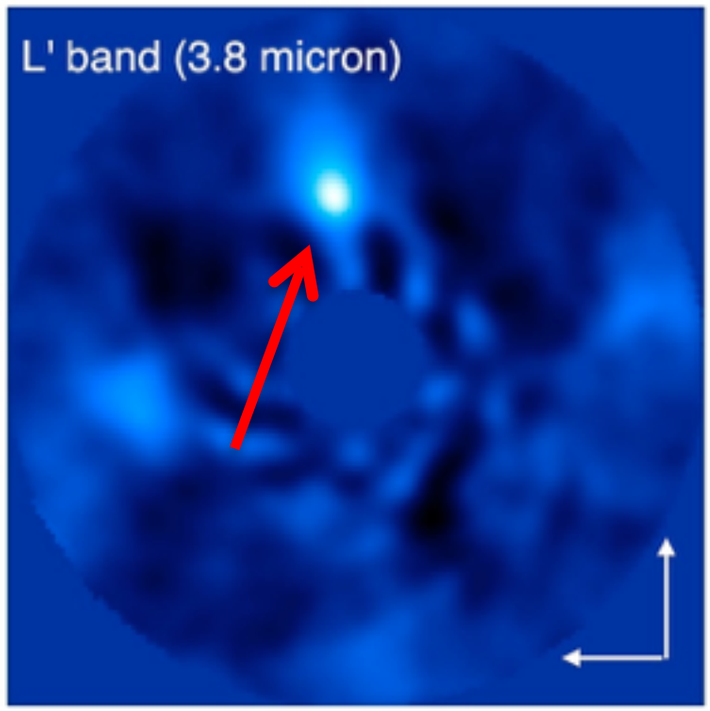
Avenhaus et al. 2014

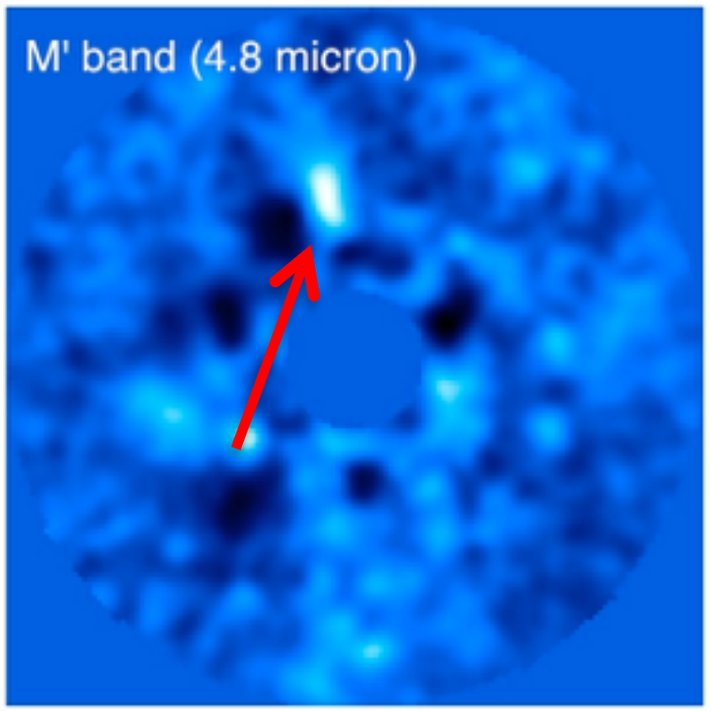
- Large scale spiral structures detected with HST and from ground
- NACO polarimetric observations reveal disk regions from ~10-150 au not accessible to HST
- Inner cavity with outer radius of ~15 au from modeling and observations

Exoplanets: recent progresses - disks and planets in formation



Avenhaus et al. 2014

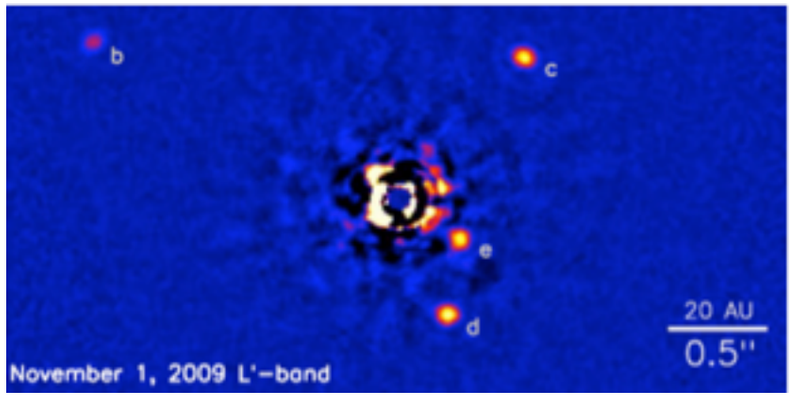




Quanz et al. 2013 / 2015 (under review)

- ~52 au separation and co-moving with the star (based on 2 epochs)
- Source = superposition of planet and circumplanetary disk ?

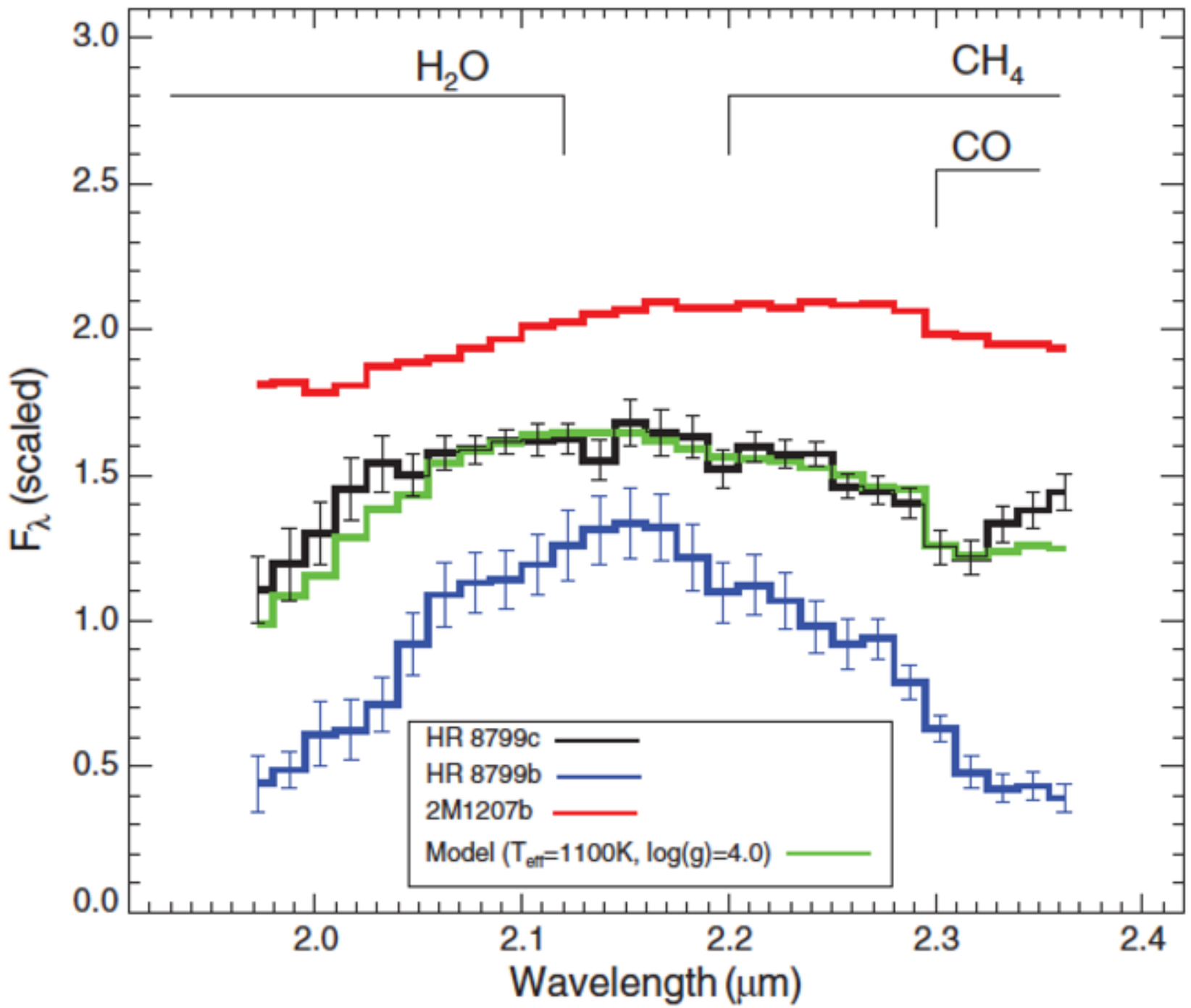
Exoplanets: recent progresses - directly imaged planets



$C/O_{planet} > C/O_{star}$

⇓

constraint on formation

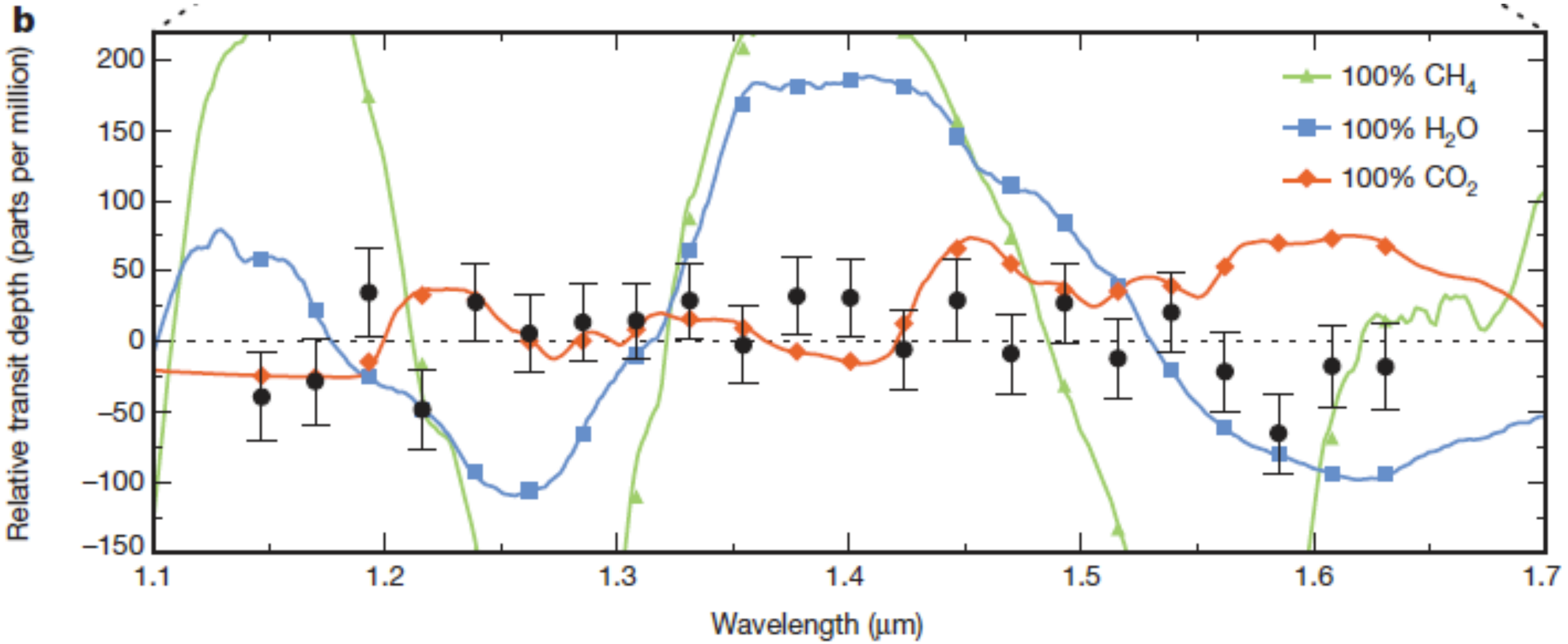


Konopacky et al. 2013

Exoplanets: recent progresses - composition

GJ1214

Transmission



what about higher resolution?

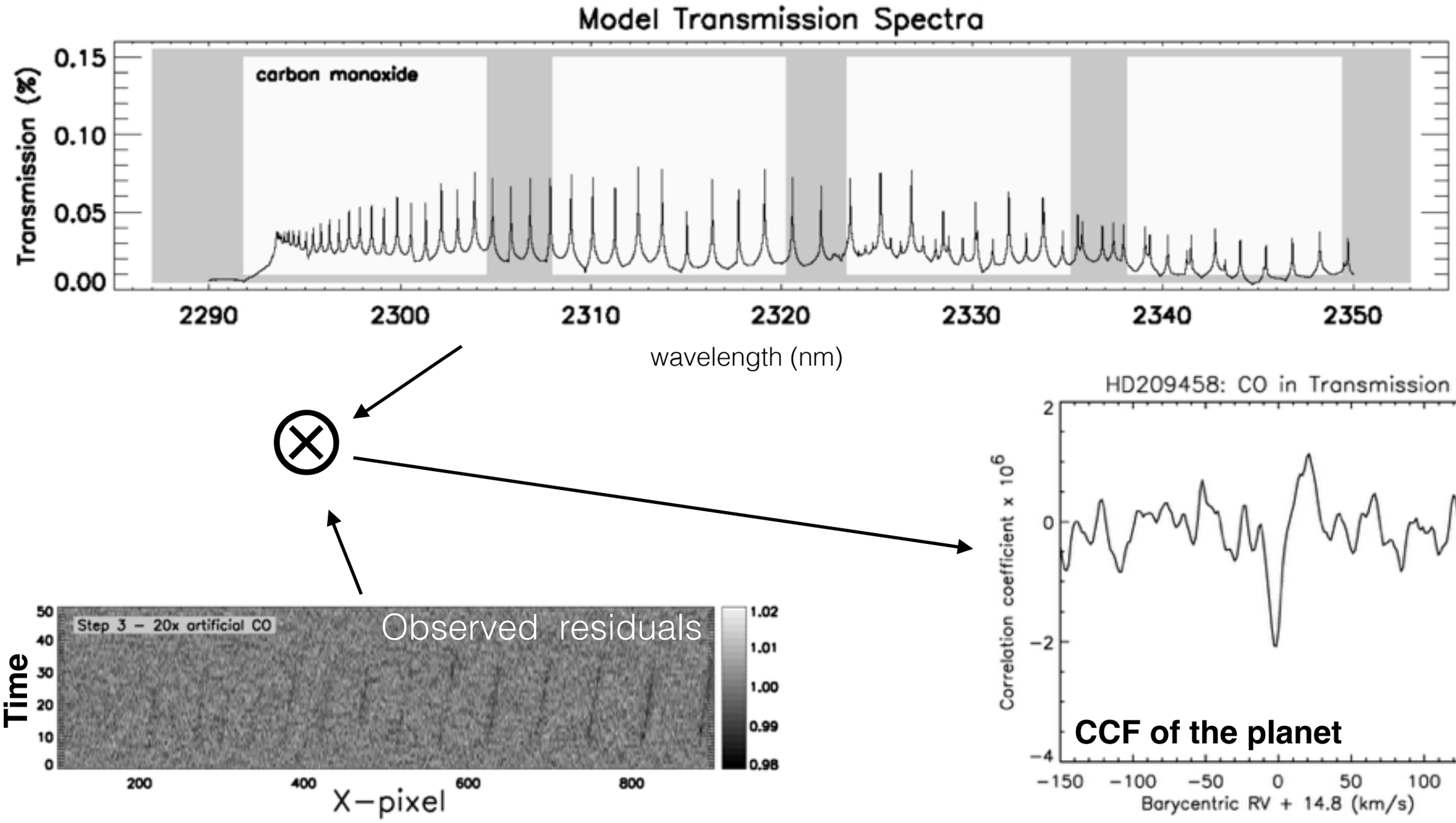
center of the lines $\Longrightarrow$ high absorption $\Longrightarrow$ above the clouds

Kreidberg et al. 2014

Exoplanets: recent progresses - characterization from Hi.-Res.

NIR transmission spectroscopy at high resolution

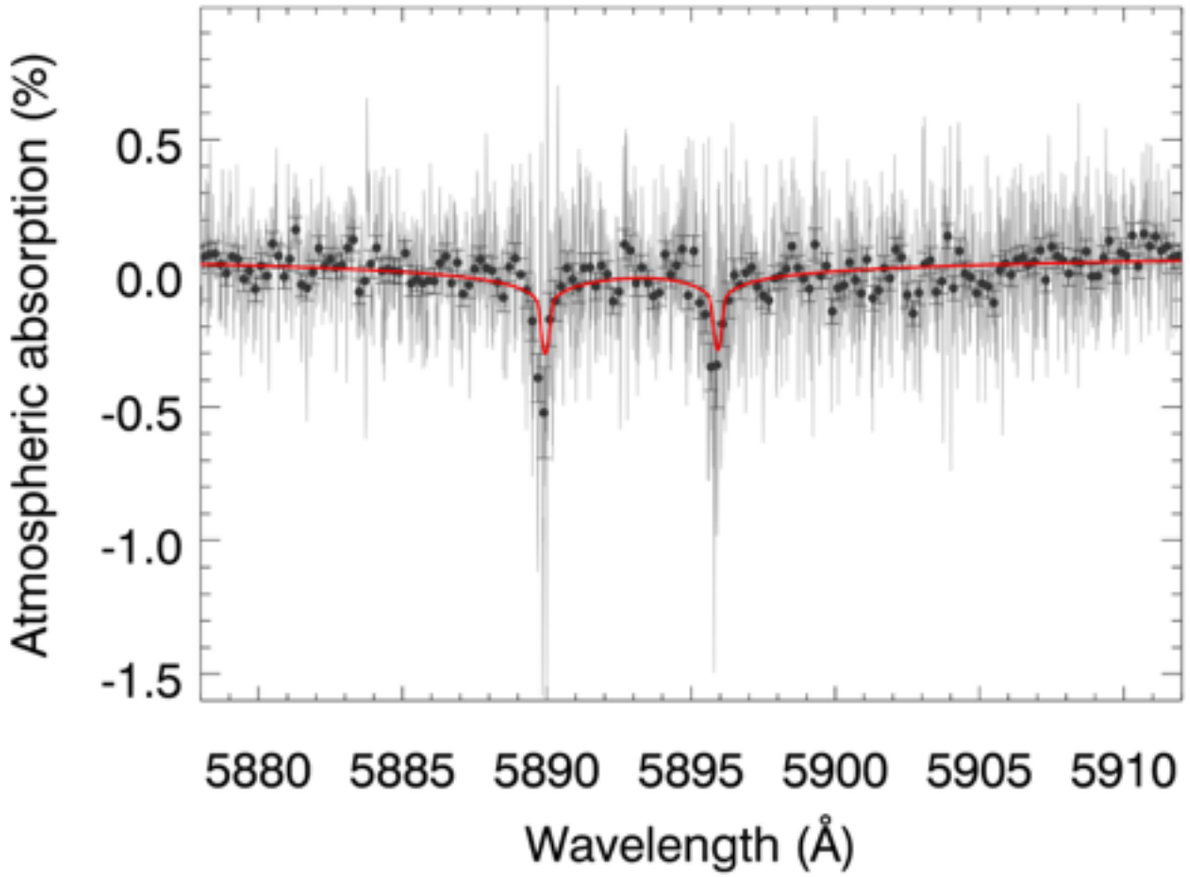
VLT (8m)/CRIRES transmission spectrum of HD 209458b (Snellen+2010)



Exoplanets: recent progresses - characterization from Hi.-Res.

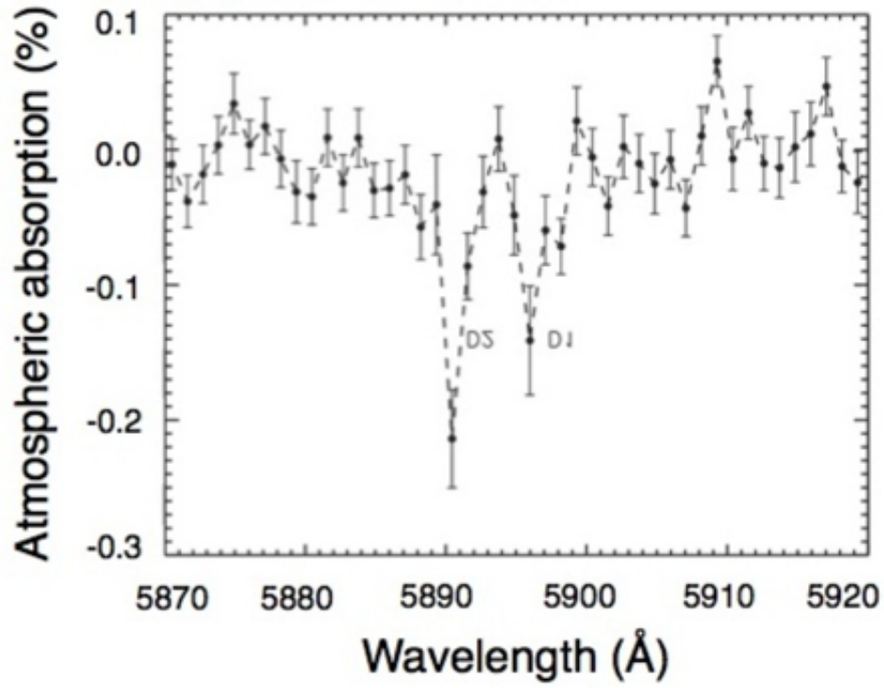
Transmission spectrum of HD 189733b

ESO 3.6m/HARPS, *R*~115,000 (Wyttenbach+, submitted)



HST(⌀2.4m)/STIS, 3 transits

R~5,000 (Huitson+ 2012)

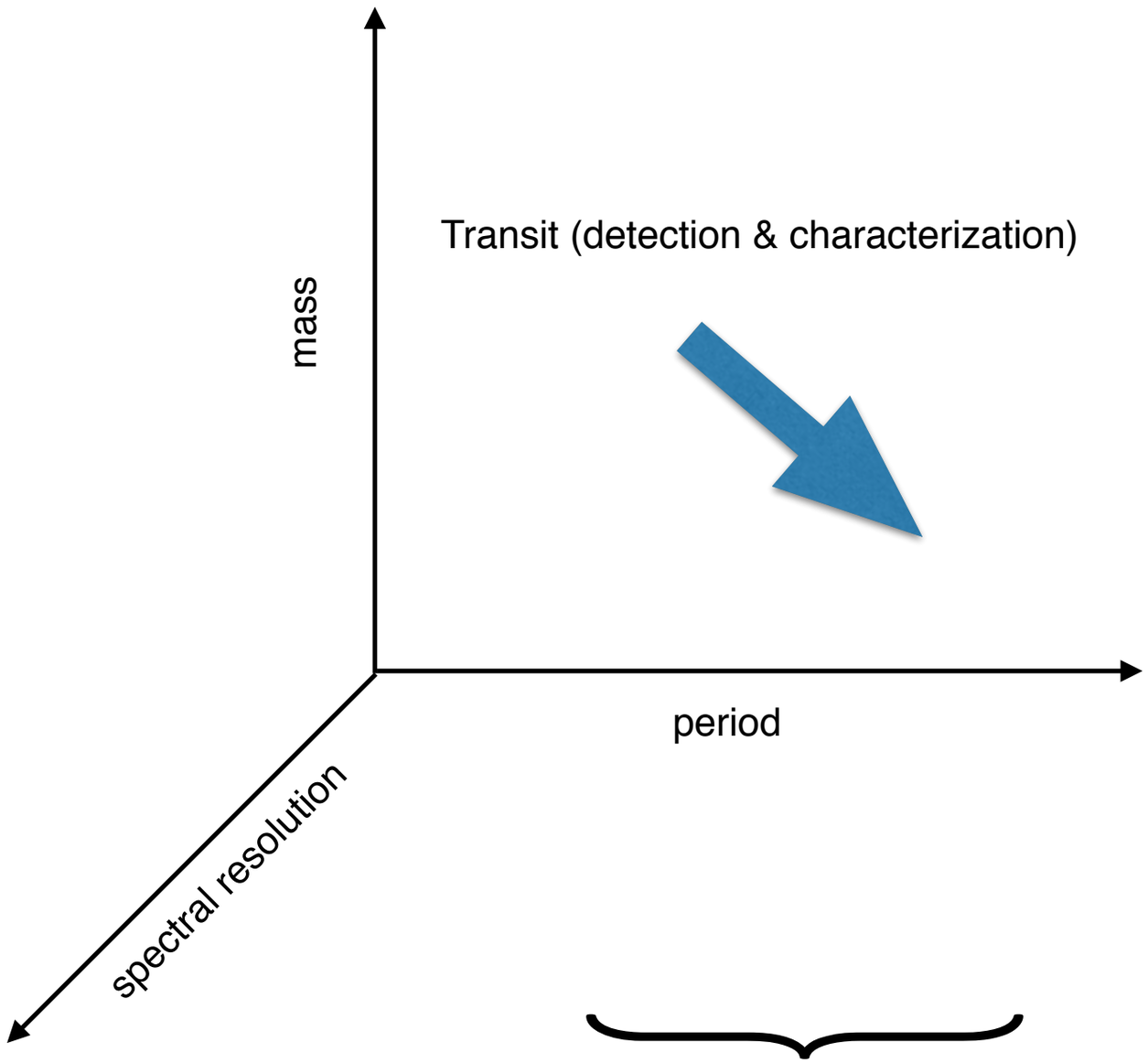


1- ground based instruments can achieve results similar to HST

2- High-resolution spectroscopy moves from a discovery to a characterization tool

3- present day ESO instruments can be used as pathfinder to prepare for ELT

Exoplanets: recent progresses and extrapolation



Transit (detection & characterization)

Resolved observations (disks and planets)

should converge one day
towards the ‘golden spot’

1- colder planets

2- smaller planets

3- higher spatial resolution

4- higher spectral resolution

Exoplanets: what quantity do we want to get?

Planet formation and evolution

1- formation paradigm? top down or bottom up? **Direct imaging**

2- where do planets form? **ALMA / Direct imaging / Hi.-Res.**

3- how do planet evolve (loss of primitive envelope)? **Hi.-Res. spectro in UV/visible**

Planets as objects

1- what is $\eta_{\oplus}$? (Planetary IMF)

2- what is their composition (interior/atmosphere)

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Habitability and life (Earth-like planets)

1- what is η_{Hab} (necessary/sufficient conditions for habitability)?

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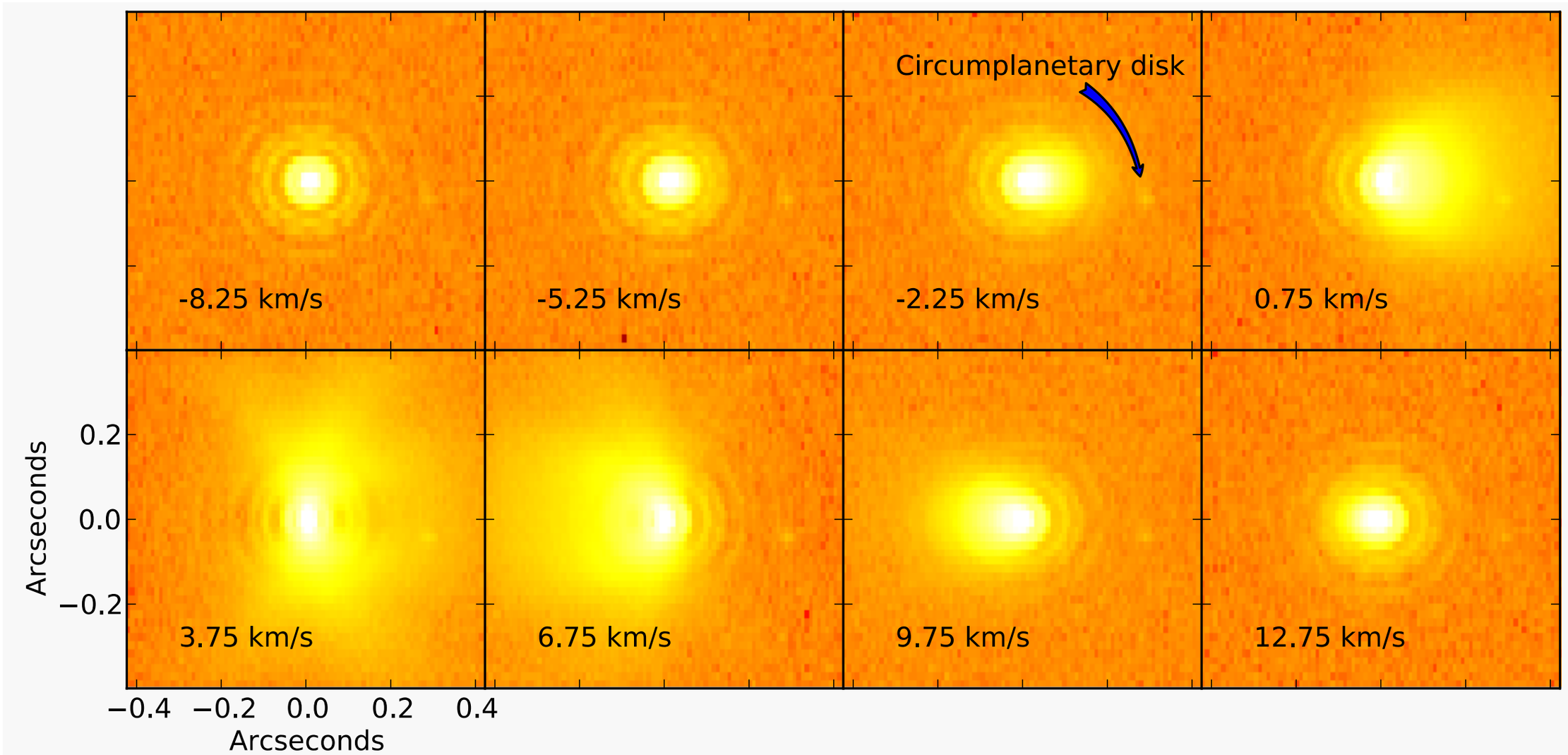
Exoplanets: imaging planet formation?

Simulated METIS observation at 4.7 microns of a gas-rich PPD with a 10 Mjup planet



Brandl et al. 2014

Exoplanets: what quantity do we want to get?

Planet formation and evolution

1- formation paradigm? top down or bottom up? **Direct imaging**

2- where do planets form? **ALMA / Direct imaging / Hi.-Res.**

3- how do planet evolve (loss of primitive envelope)? **Hi.-Res. spectro in UV/visible**

Planets as objects

1- what is $\eta_\oplus$? (Planetary IMF) **RV surveys / PLATO Follow up**

2- what is their composition (interior/atmosphere) **PLATO / Hi.-Res. spectro / Direct imaging**

3- is there a correlation between planets and system properties? **GAIA/RV/transit**

Habitability and life (Earth-like planets)

1- what is η_{Hab} (necessary/sufficient conditions for habitability)? **theory solar system**

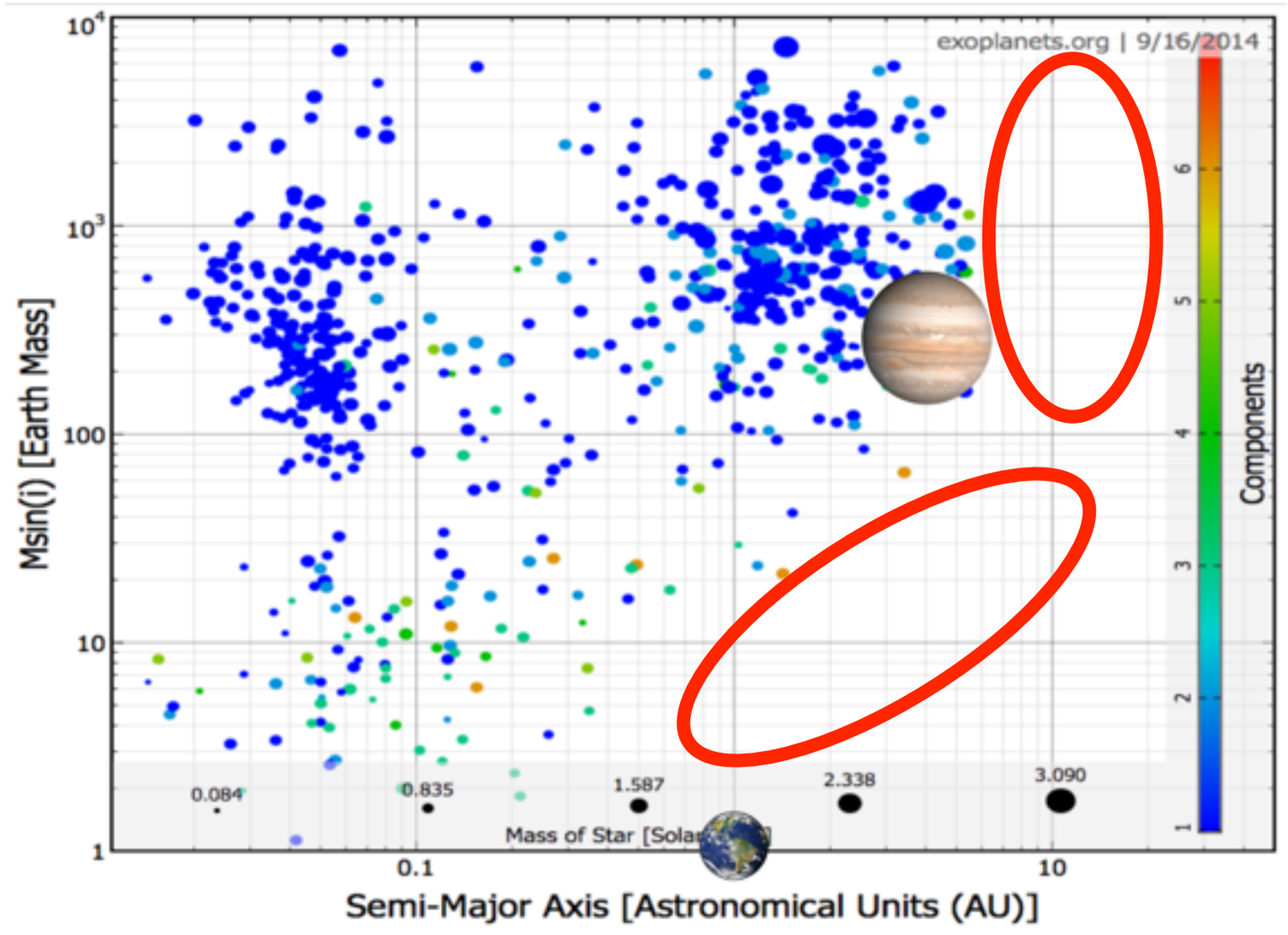
2- what are the planetary surface conditions (Earth-like planets) **??**

3- what is their geology (plate tectonic)? **theory / ??**

Exoplanets: which targets will be known in the 2020s?

1- all targets we already know

2- all targets we will discover by the 2020s



who will be the target providers by/in the 2020s?

Space

TESS

Gaia

K2

CHEOPS

Warm Spitzer

HST

WSO-UV(??)

JWST

PLATO

ESA S2,S3(?)

ESA M4(?)

2014 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36

Ground

ALMA

ELT

E-ELT/**?**

GMT/G-CLEF, TMT/HROS

8m

VLT/**ESPRESSO**

VLT/**CRIRES+**

Direct imaging: VLT/**SPHERE**, GEMINI/**GPI**

4m

CFHT/**SPIRou**

NTT/**NIRPS**(?), INT/**THE**(?)

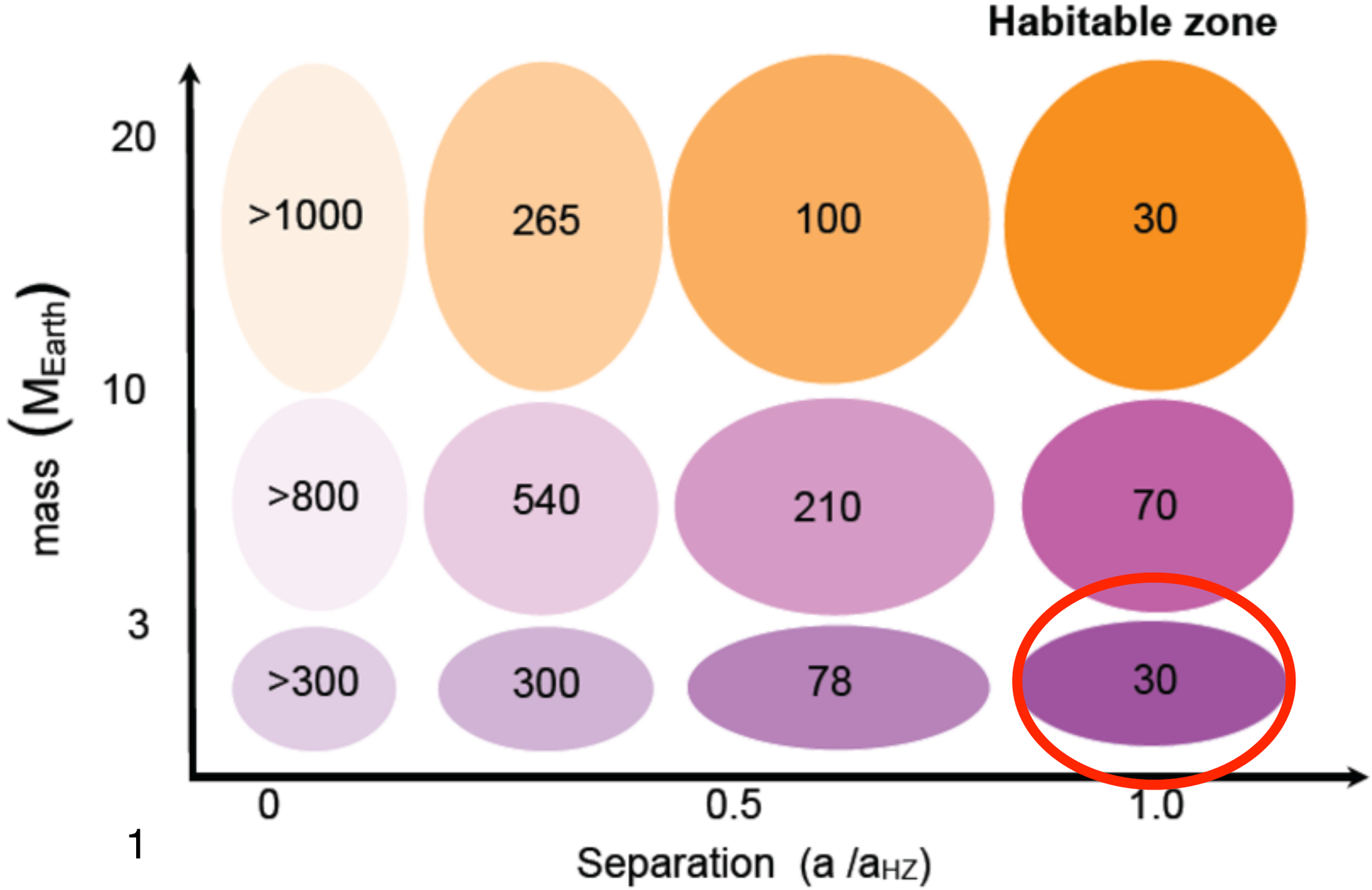
CAHA/**CARMENES**

TNG/**HARPS-N**

ESO 3.6m/**HARPS**

Exoplanets: new targets in the 2020s

PLATO yield: planets detected and characterized (including effect of stellar activity)



atmospheric characterization of Earth-like planets?

Exoplanets: characterization of PLATO targets

PLATO targets will be transiting planets!!!

-> transmission spectroscopy through the limb

1- in the visible

-> alkali, water, oxygen
-> methane, ammonia
-> Rayleigh scattering (mean molecular weight)

2- in the NIR

-> water
-> CH4, NH3
-> CO, CO2, O2

However:

1- transits are short events -> size of mirror is critical!!!

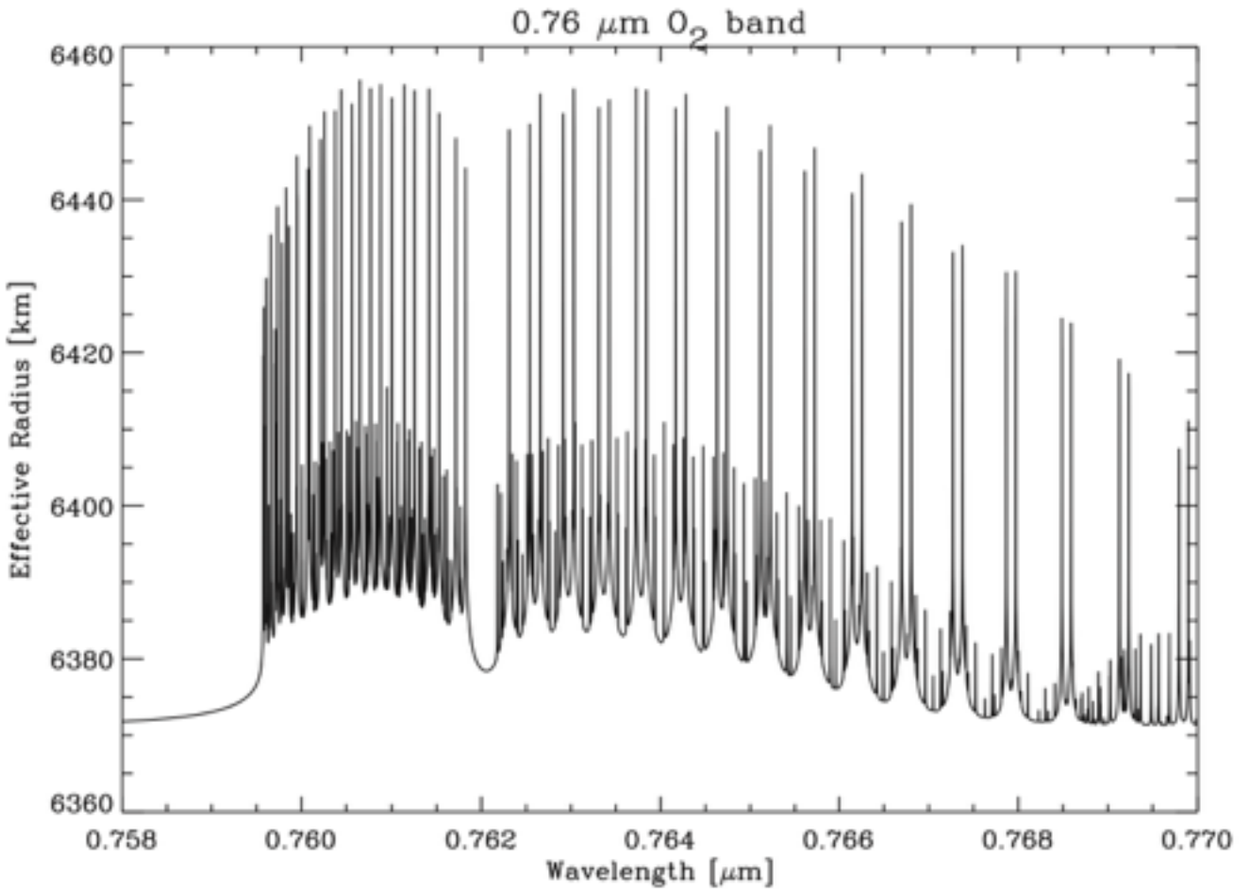
2- needs Hi.-Res. (separation from telluric lines, above the clouds)

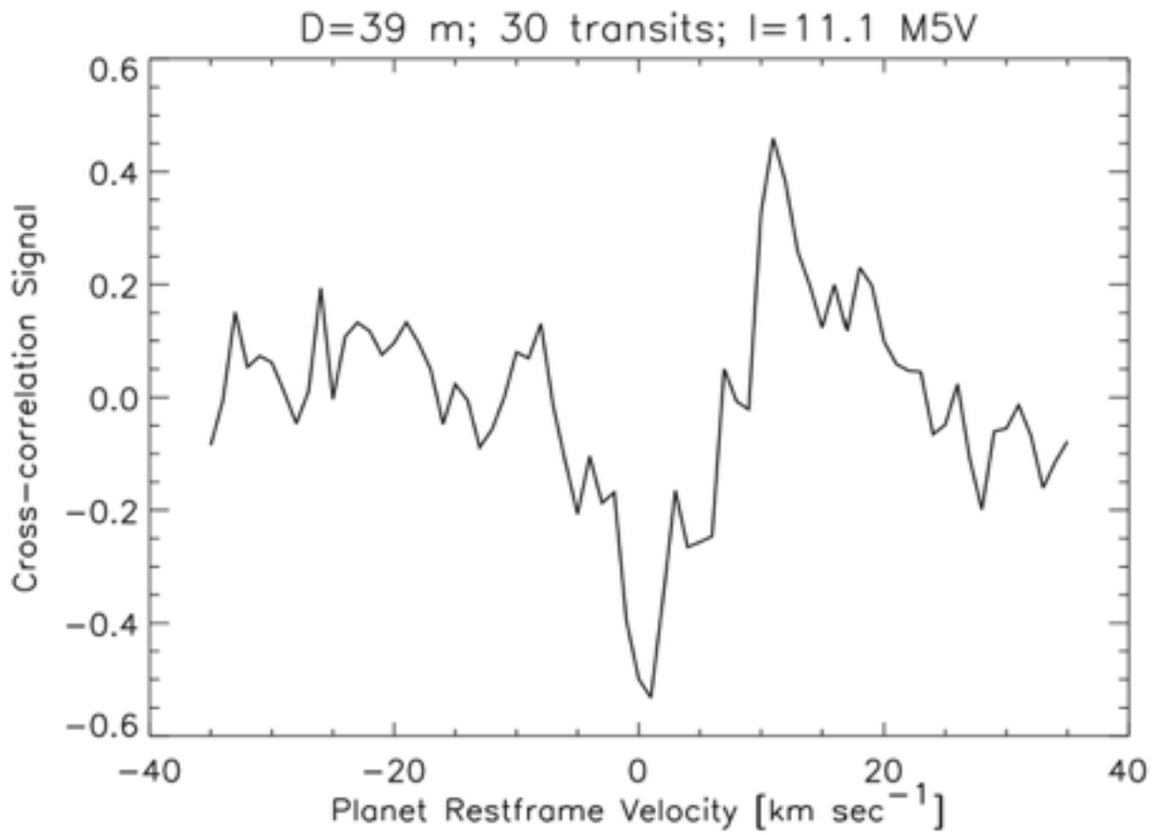
Is it doable with JWST (stability, availability)?

Schedule is critical for PLATO follow-up!!!!!

Exoplanets: Hi-Res. spectroscopy at E-ELT

detection of O_2 in the atmosphere of a planet around a late M dwarf





Snellen +2013

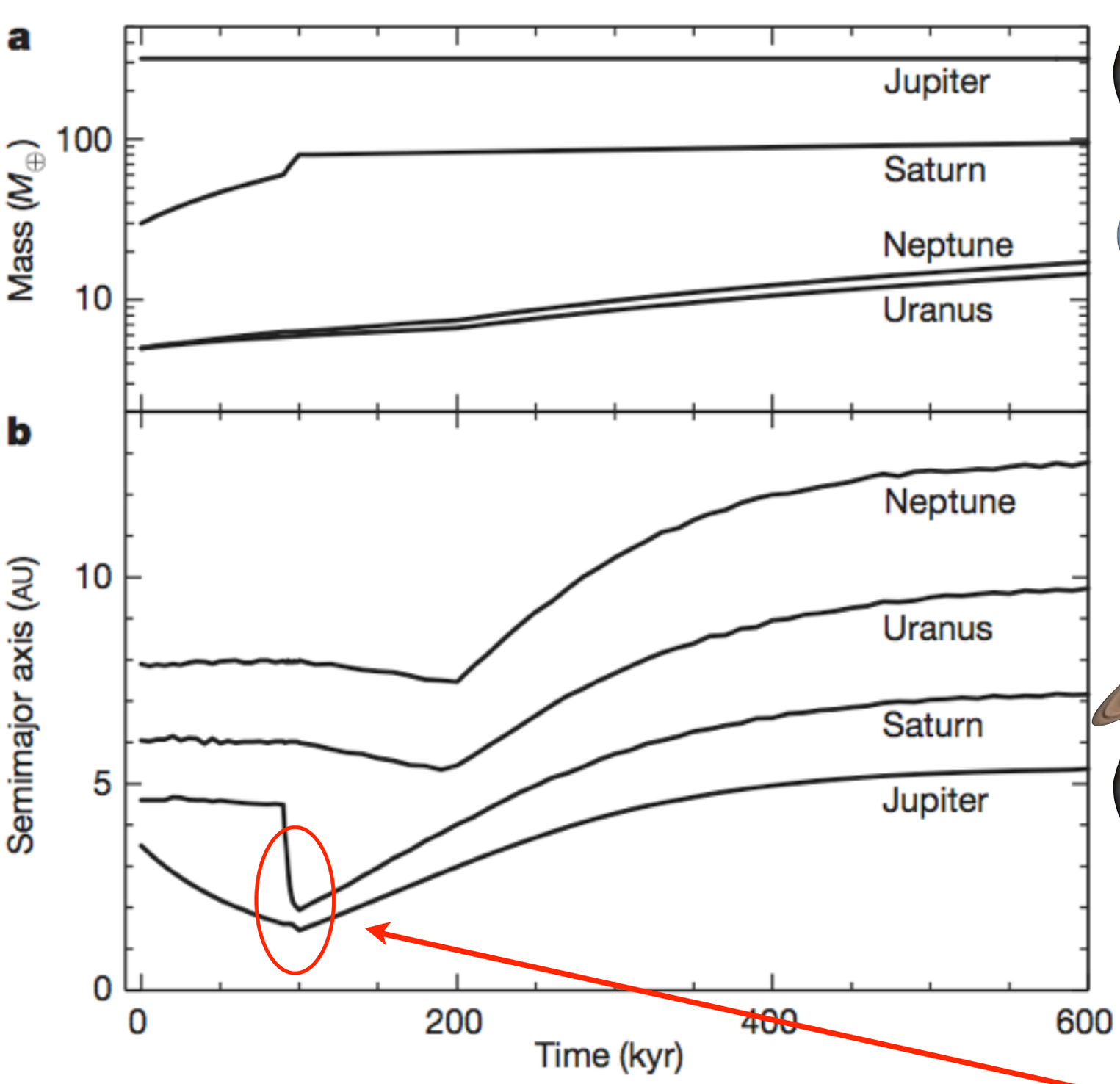
See also Rodler & Lopez-Morales 2014

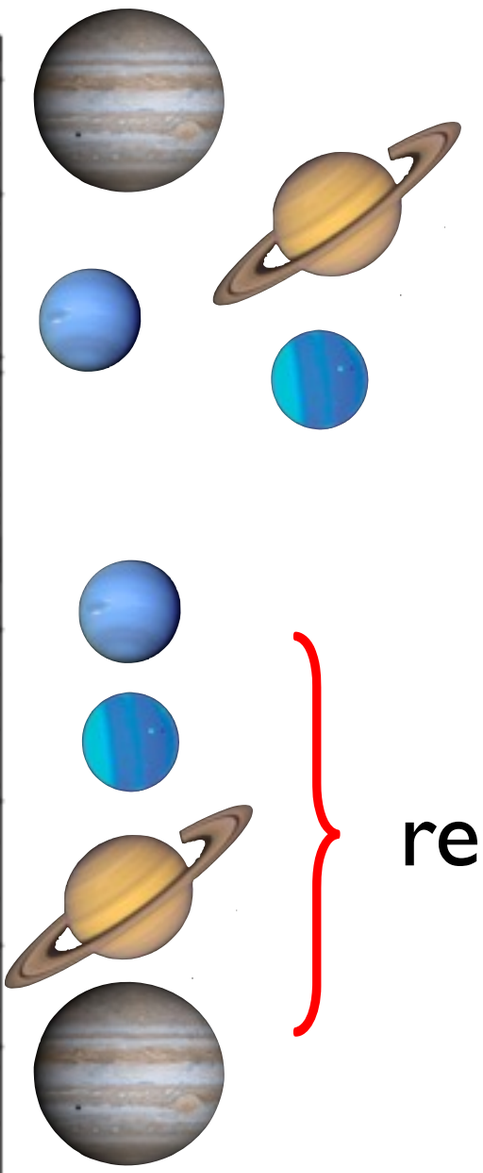
Exoplanets: characterization of the planetary system

Is the characterization of Earth-like planets the ultimate goal?

no.

Exoplanets: the rest of the system





resonant system

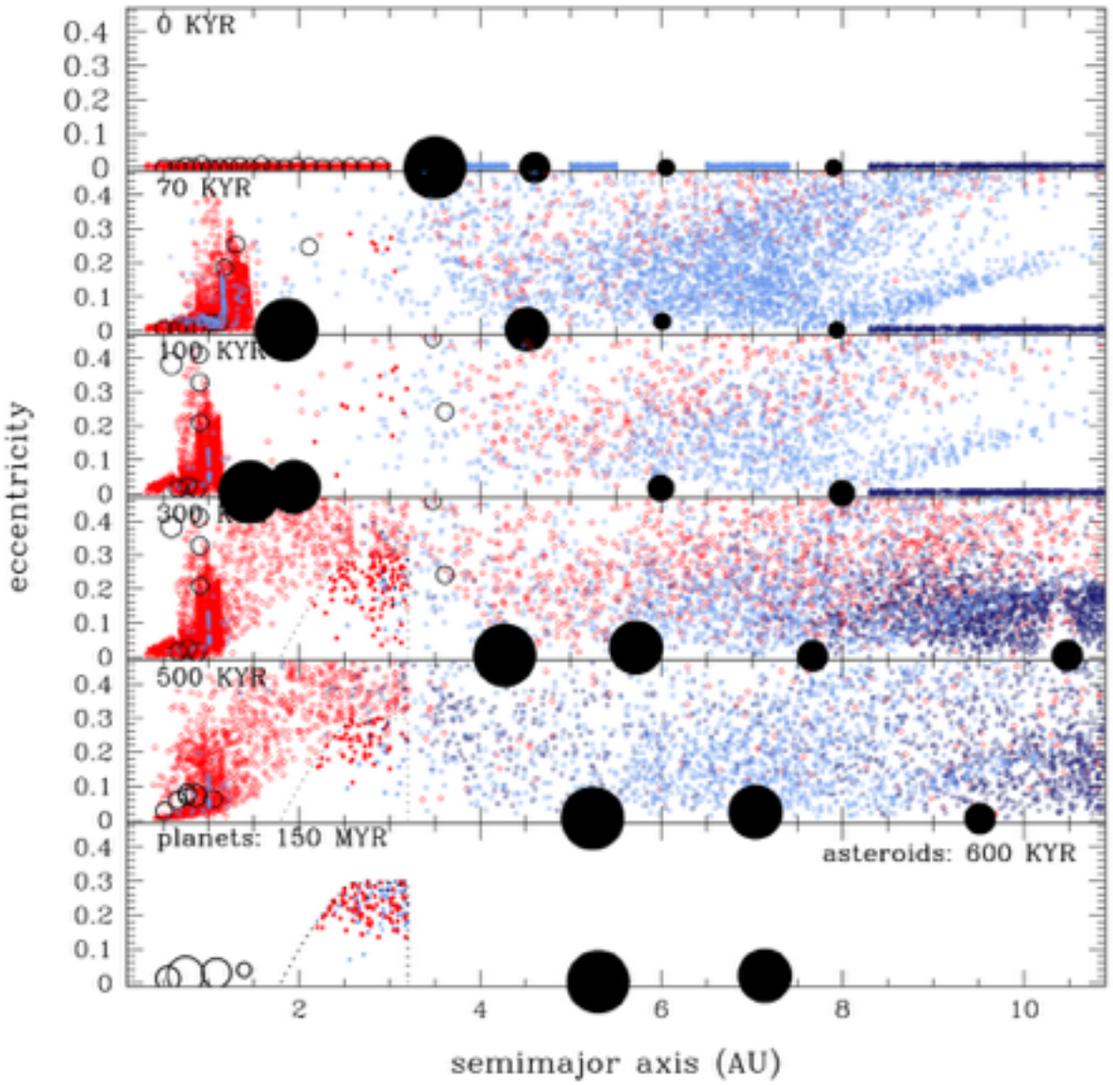
gap merging

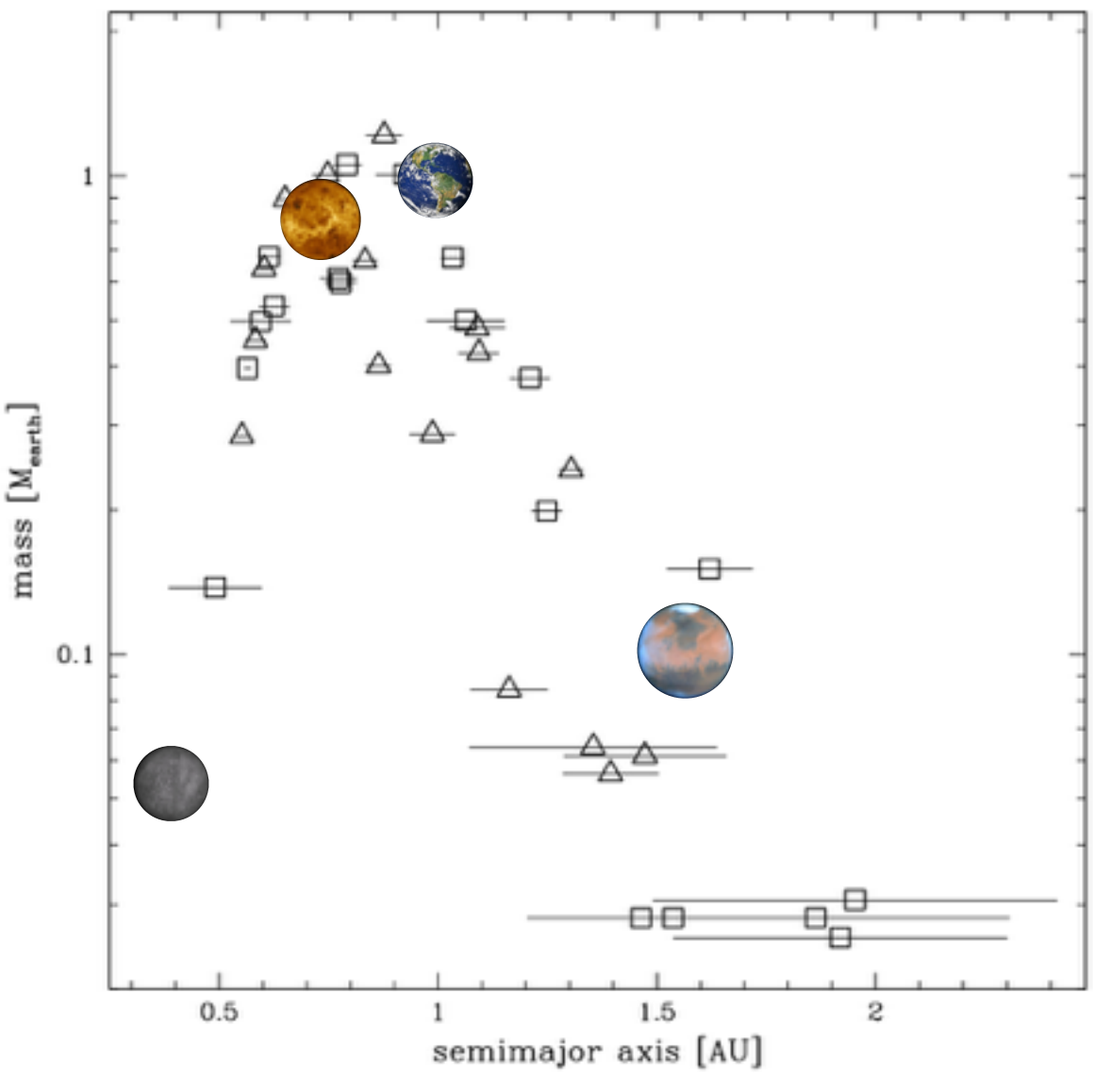
outward migration

Walsh et al. 2011

Exoplanets: the rest of the system

Walsh et al. 2011



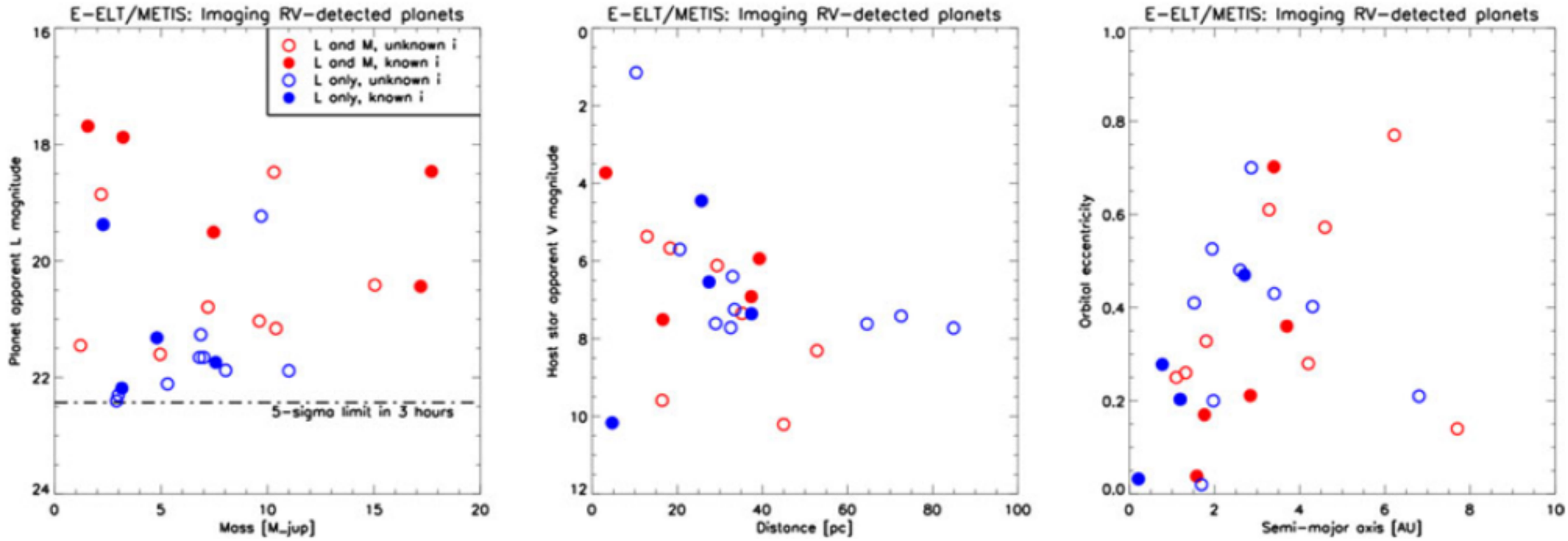


Mixing of asteroids

Formation of terrestrial planets

We need to understand the formation of systems (including giant planets) to understand the properties of Earth-like planets in the HZ

Exoplanets: the rest of the system



Quanz et al. 2014

characterization of outer planets of the system with METIS and PCS

(> 1 Rj, > 150K,
> 3 AU, <10 pc)

Hi.-Res. *and* imaging of planets in the 'golden spot' in favourable conditions

!! characterization from visible to thermal IR !!

Exoplanets: Conclusions

Exoplanets in 2015

1- key questions: from formation to planets to habitability

2- Hi.Res. observations move from detection to characterization

3- Earth-like planets in the HZ are not the full story

4- do not forget theory and laboratory experiments (EOS/lines)

Exoplanets until 2020

1- need to achieve the best IWA possible (observe the same targets with different instruments - cannot fight against transit probability)

2- need to find future targets

3- present day ESO instruments can be used as pathfinder (challenging obs. better to train on 4m telescopes than on 8m)

4- do not forget theory and laboratory experiments (EOS/lines)

Exoplanets in the 2020s

1- complementarity HIRES/METIS (and PCS) instruments

2- schedule is important for PLATO targets!!!

3- do not forget theory and laboratory experiments (EOS/lines)

Thank you !