Envelopes and natures of close-in exoplanets:

from hot-Jupiters to temperate Earths

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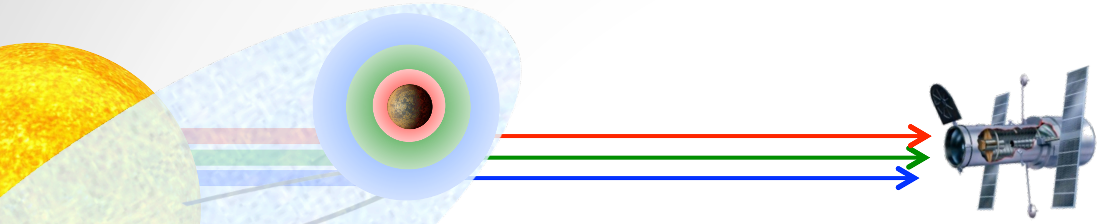
LUVOIR workshop – 11 January 2017

UNIVERSITÉ DE GENÈVE

Picture: Mark Garlick/University of Warwick

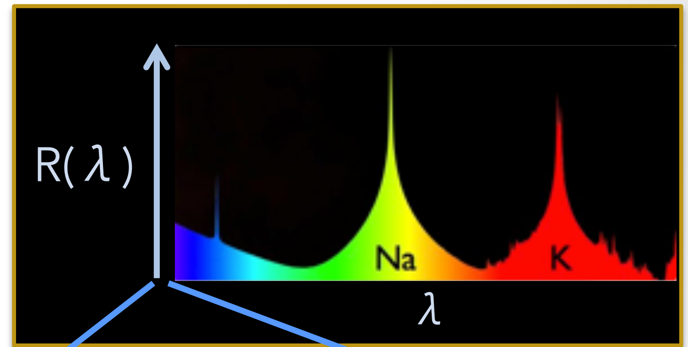
PlanetS

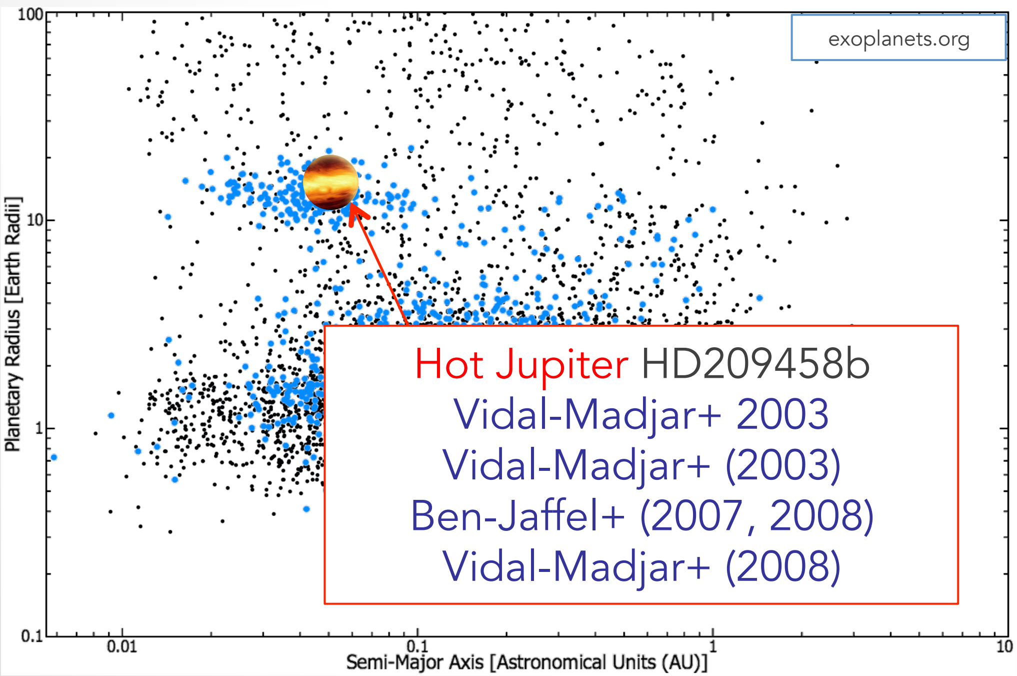
Probing exoplanets atmospheres



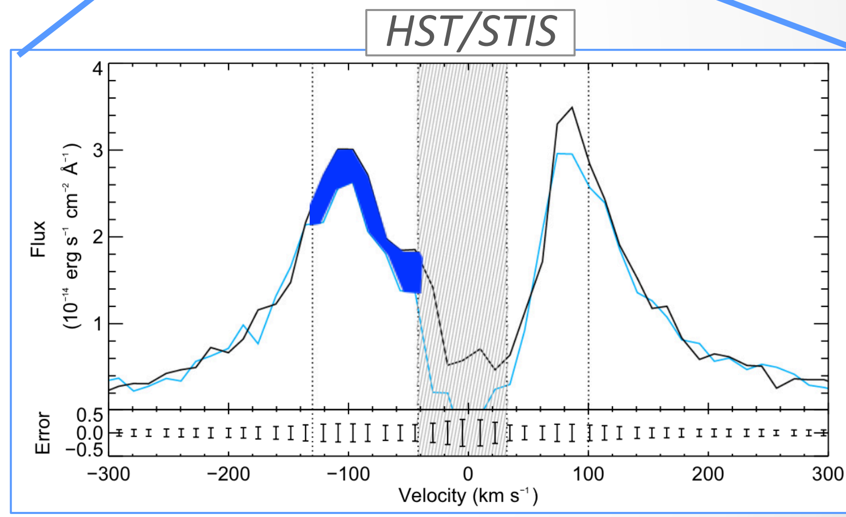
Infrared: CO, H_2O, …
Visible: Na, K, H_2O, …
Ultraviolet: H, ions, …

Transit spectroscopy





Hot Jupiter HD209458b
Vidal-Madjar+ 2003
Vidal-Madjar+ (2003)
Ben-Jaffel+ (2007, 2008)
Vidal-Madjar+ (2008)

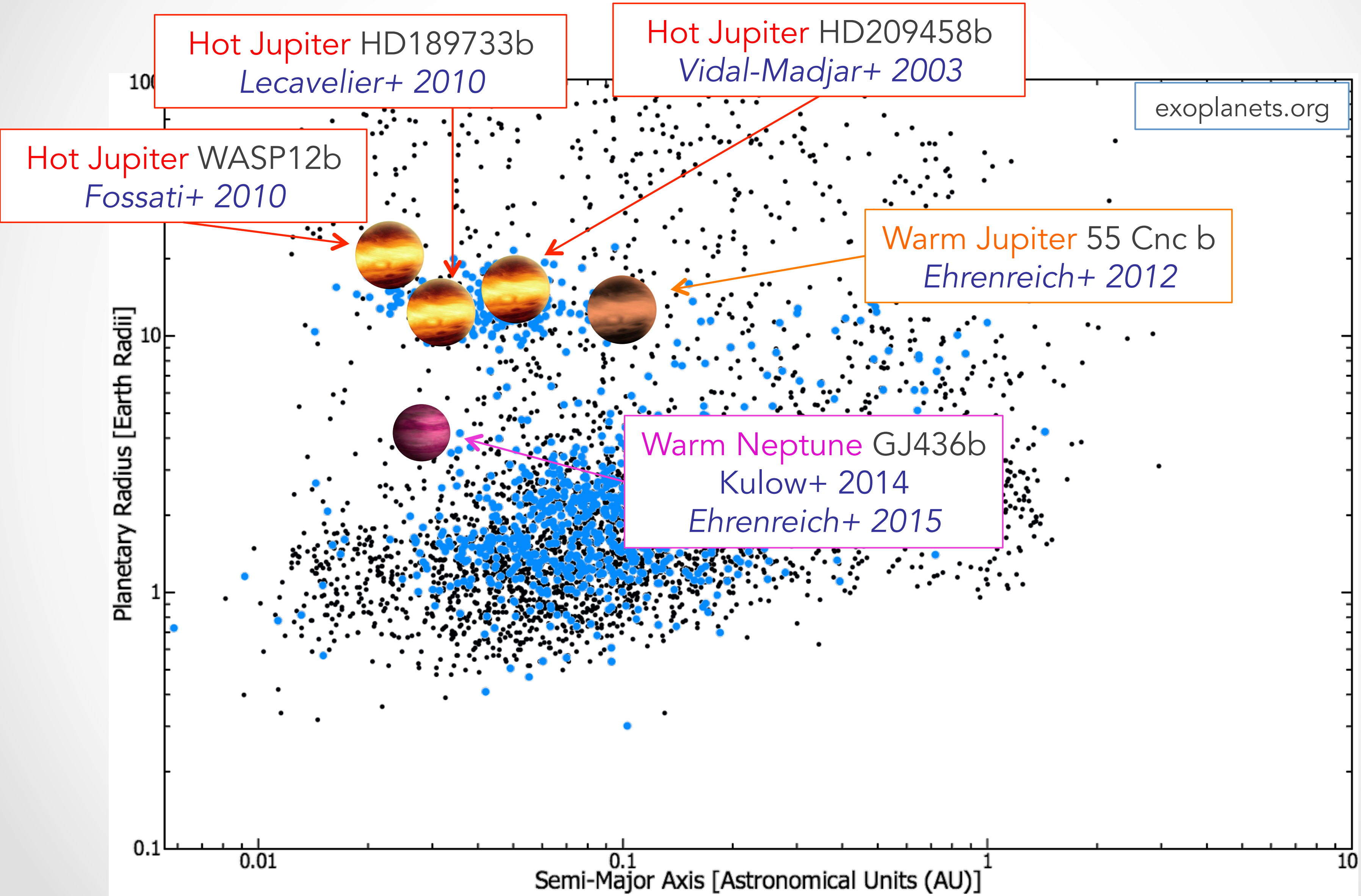


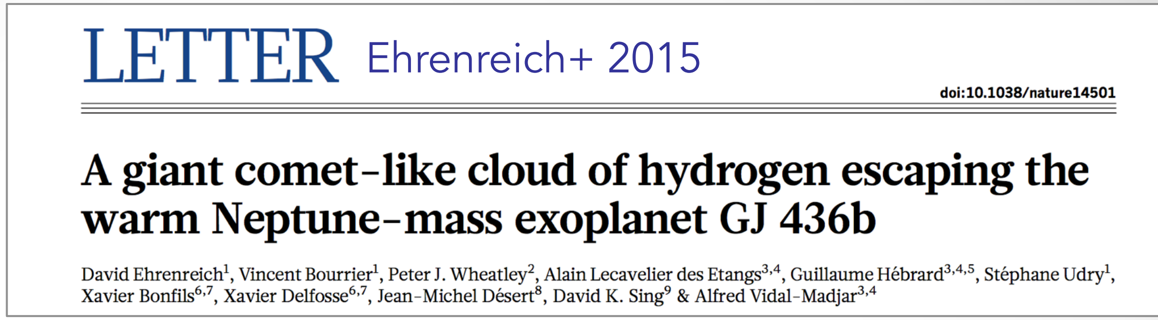
HI Lyman-α line:

15 ± 4 % in [-130 ; -40] km/s

Planetary occultation (optical) ~ 1%

Evaporating gaseous planets



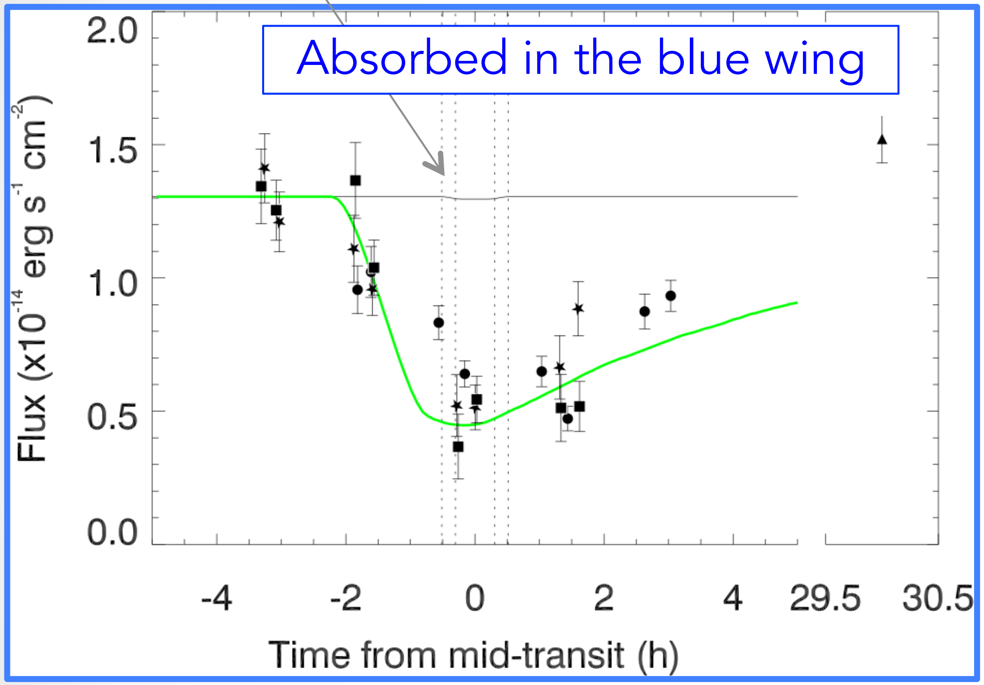

LETTER Ehrenreich+ 2015

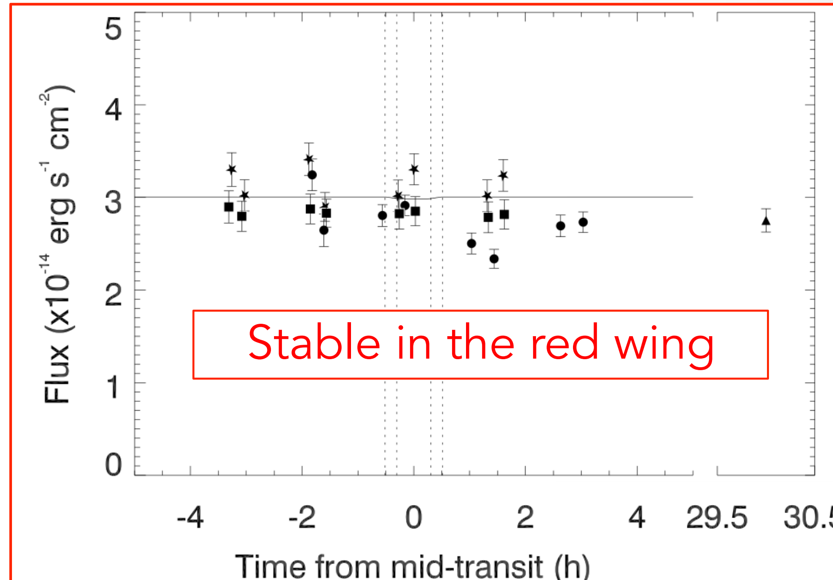
doi:10.1038/nature14501

A giant comet-like cloud of hydrogen escaping the warm Neptune-mass exoplanet GJ 436b

David Ehrenreich[1], Vincent Bourrier[1], Peter J. Wheatley[2], Alain Lecavelier des Etangs[3,4], Guillaume Hébrard[3,4,5], Stéphane Udry[1], Xavier Bonfils[6,7], Xavier Delfosse[6,7], Jean-Michel Désert[8], David K. Sing[9] & Alfred Vidal-Madjar[3,4]

Planetary disk= 0.7%





- 56.3±3.5% in [- 120 ; - 40] km/s
- Detection at 16 σ
- Transit 80 times deeper and > 10 times longer than in the optical

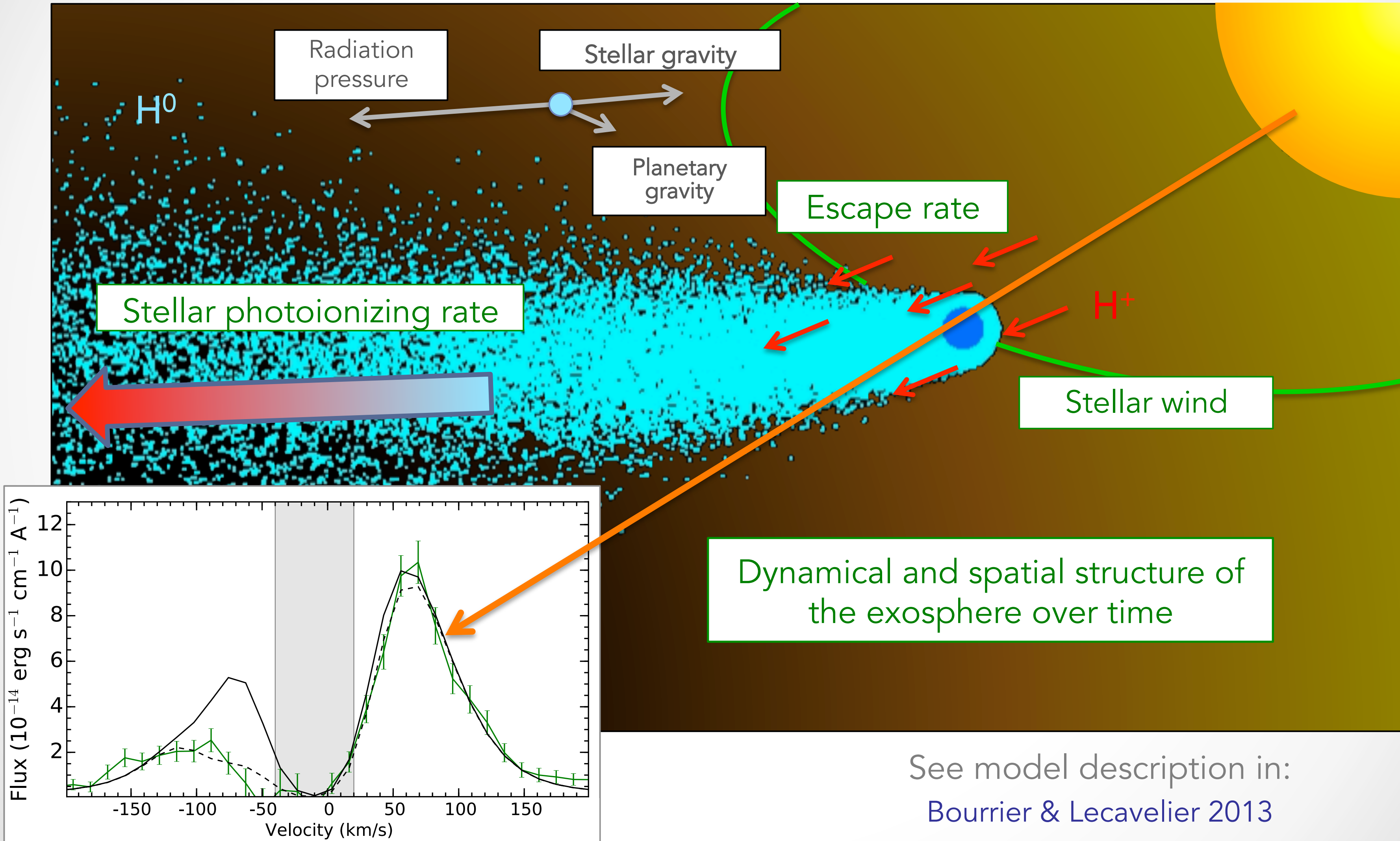
Repeatable over three epochs :

December 2012	●
June 2013	★
June 2014	■

EVE : the EVaporating Exoplanets code

Few 3D forward-retrieval models to interpret observations of exospheres

Schneiter+2007, Holstrom+2008, Ekenbäck+2010, Kislyakova+2014, Bourrier+ 2013,14,15,16; Schneiter+ 2016



Direct comparison between observed and theoretical spectra

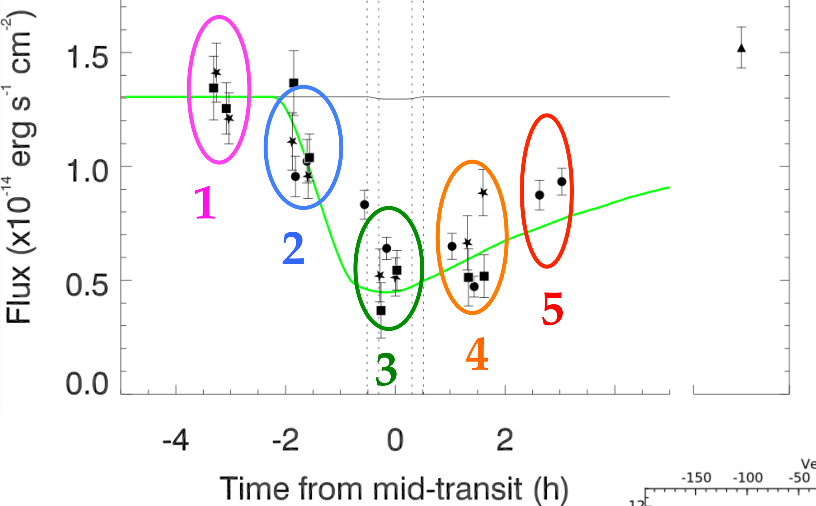
See model description in:

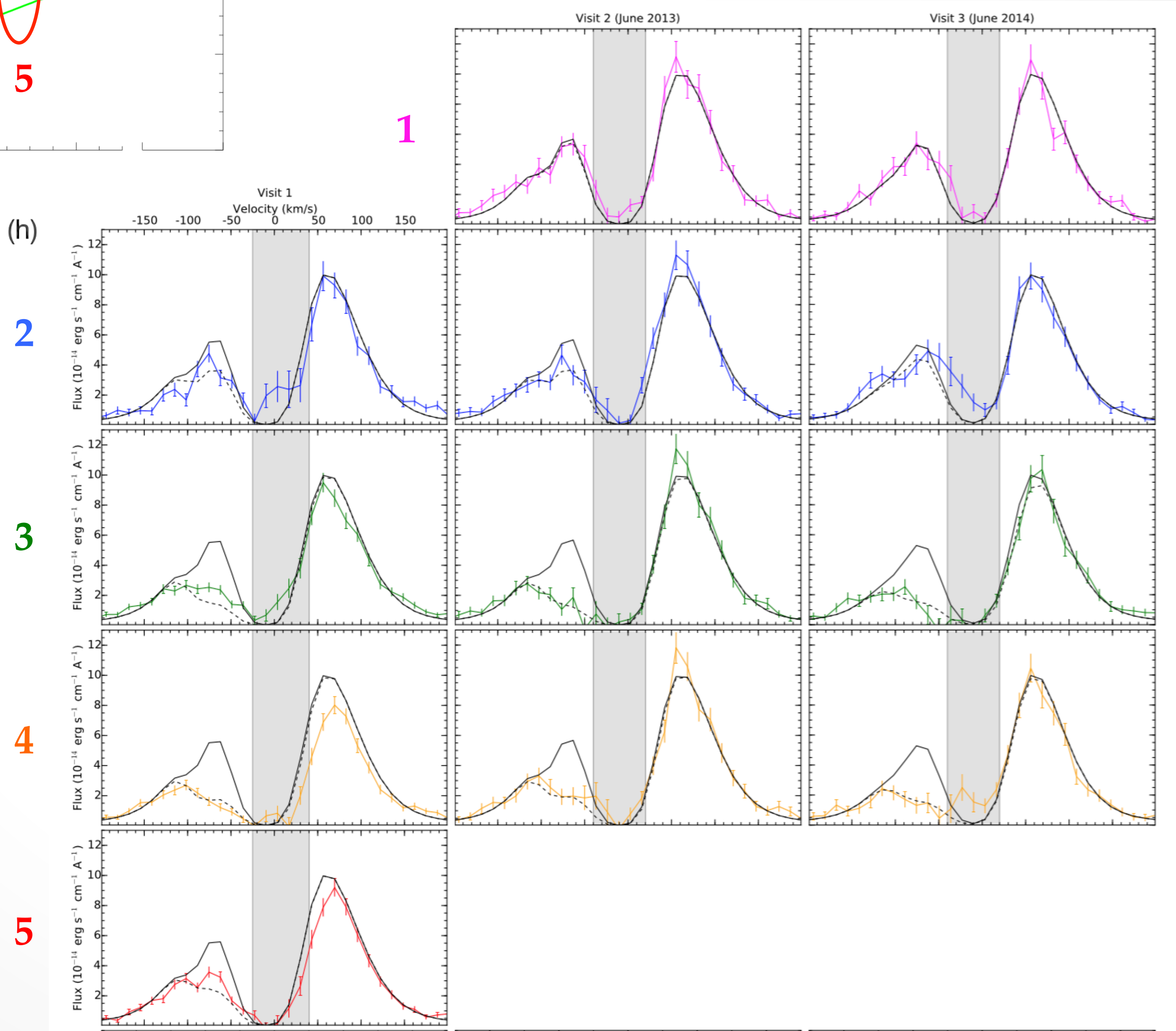
Bourrier & Lecavelier 2013

Bourrier+ 2014 a

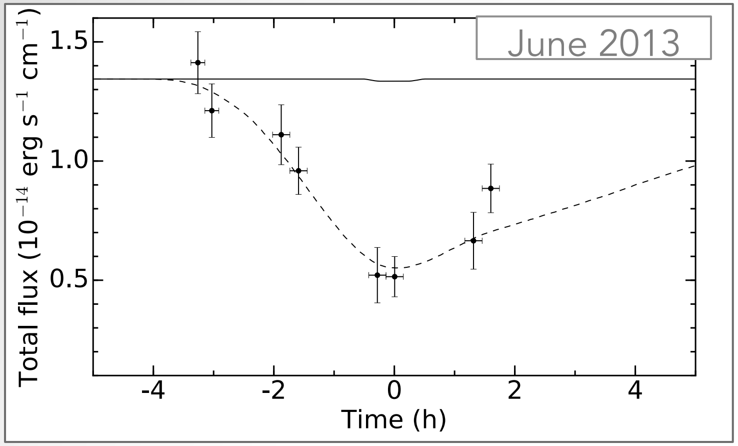
Bourrier+ 2015 b

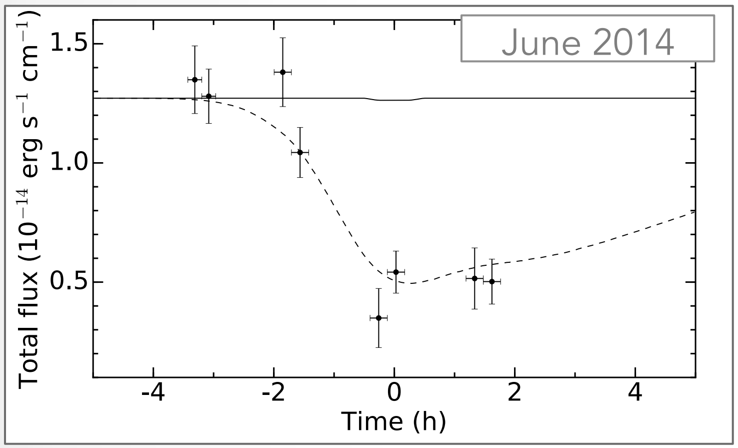
HST/STIS UV spectrograph: a wealth of constraints



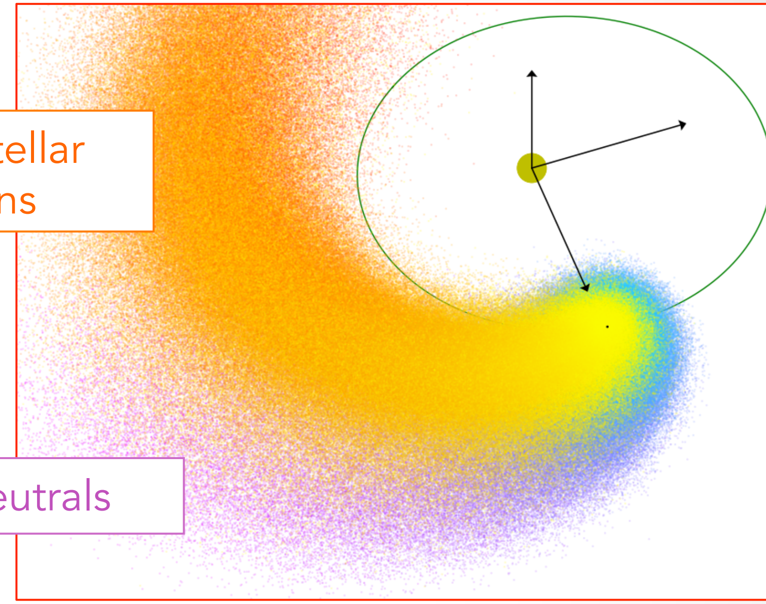


GJ436b: An evaporating planet in the wind





Radiative braking + Stellar wind interactions



Bourrier+ 2016 a

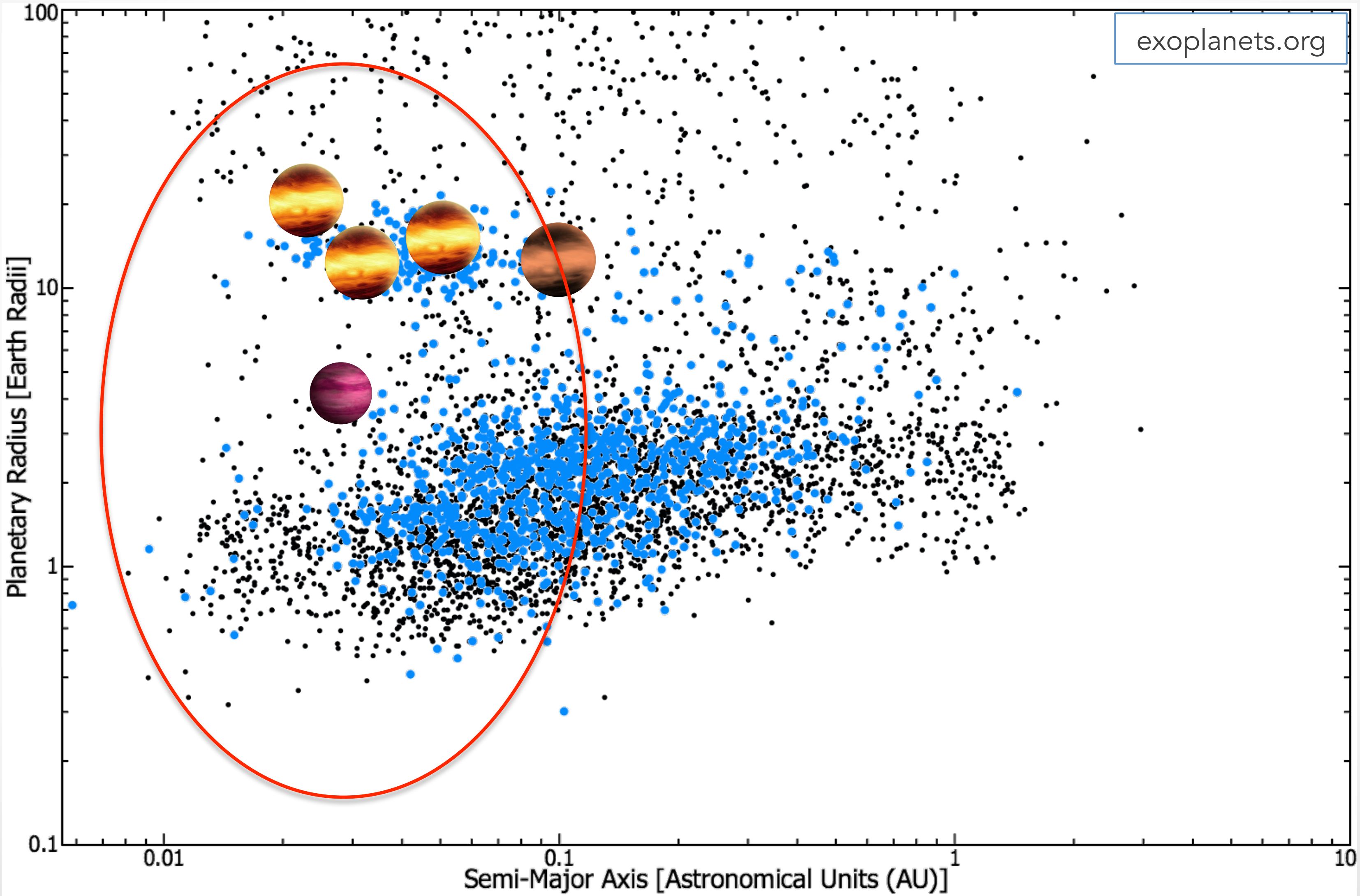
Parameter	Visit 2	Visit 3	Unit
$\dot{M}_{H^0}$	$2.5^{+1.1}_{-0.8} \times 10^8$	$2.5^{+0.8}_{-0.6} \times 10^8$	g s^{-1}
Γ_{ion}	$2.2^{+0.9}_{-0.8} \times 10^{-5}$	$2.4^{+1.0}_{-1.6} \times 10^{-5}$	s^{-1}
v^{p}_{wind}	50^{+5}_{-5}	60^{+6}_{-6}	km s^{-1}
$V^{st}_{bulk-wind}$	85^{+6}_{-12}	85^{+6}_{-16}	km s^{-1}
T^{st}_{wind}	$1.2 \pm 1.2 \times 10^4$	$1.2 \pm 1.2 \times 10^4$	K
$v^{st\dagger}_{therm-wind}$	10 ± 10	10 ± 10	km s^{-1}
n^{st}_{wind}	$1.3^{+0.5}_{-0.4} \times 10^3$	$3.3^{+1.5}_{-1.0} \times 10^3$	cm^{-3}

Planetary outflow ← $\dot{M}_{H^0}$, v^{p}_{wind}

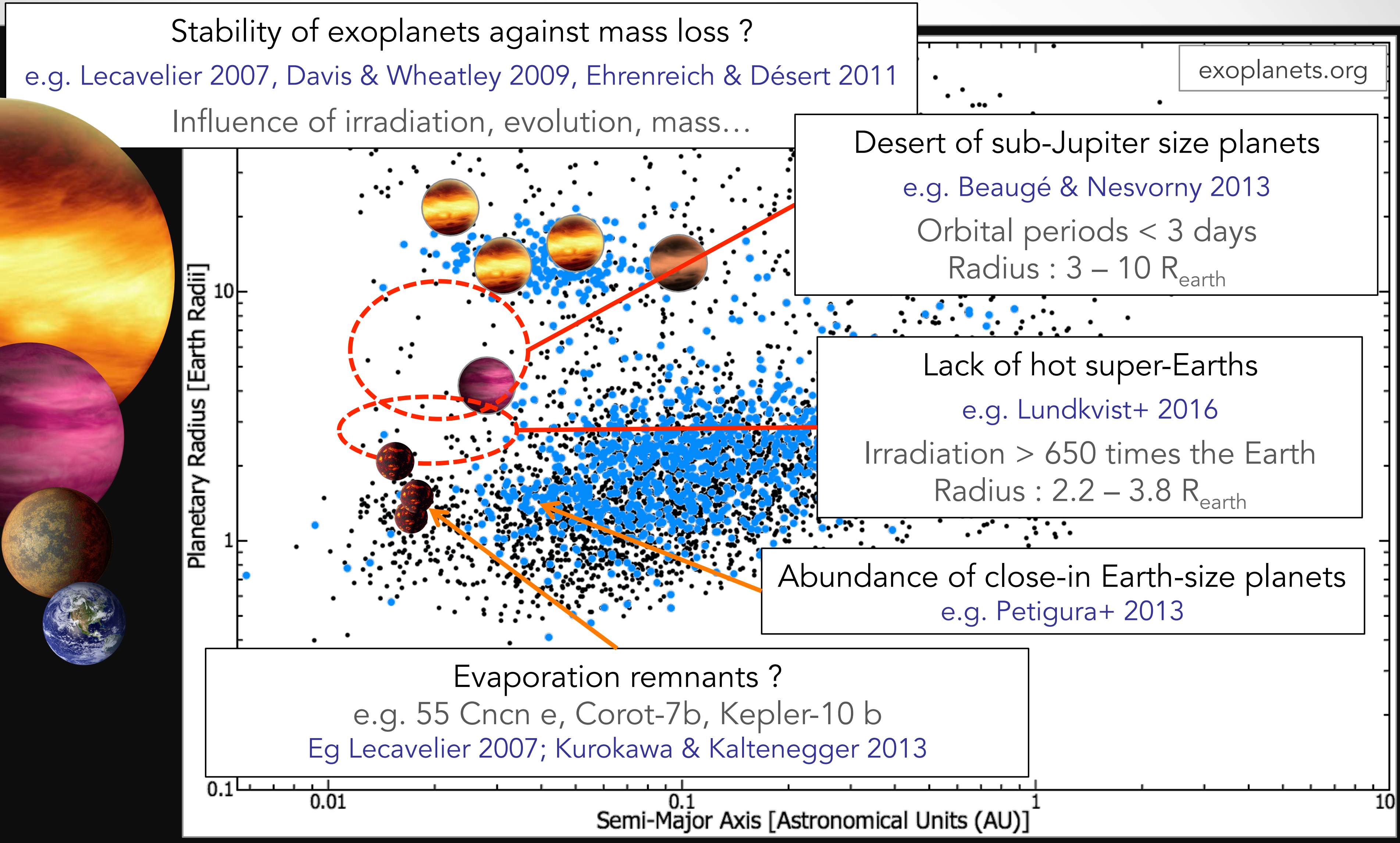
Stellar irradiation ← Γ_{ion}

Stellar wind ← $V^{st}_{bulk-wind}$, T^{st}_{wind}, $v^{st\dagger}_{therm-wind}$, n^{st}_{wind}

Evolution of close-in planets



Evolution of close-in planets



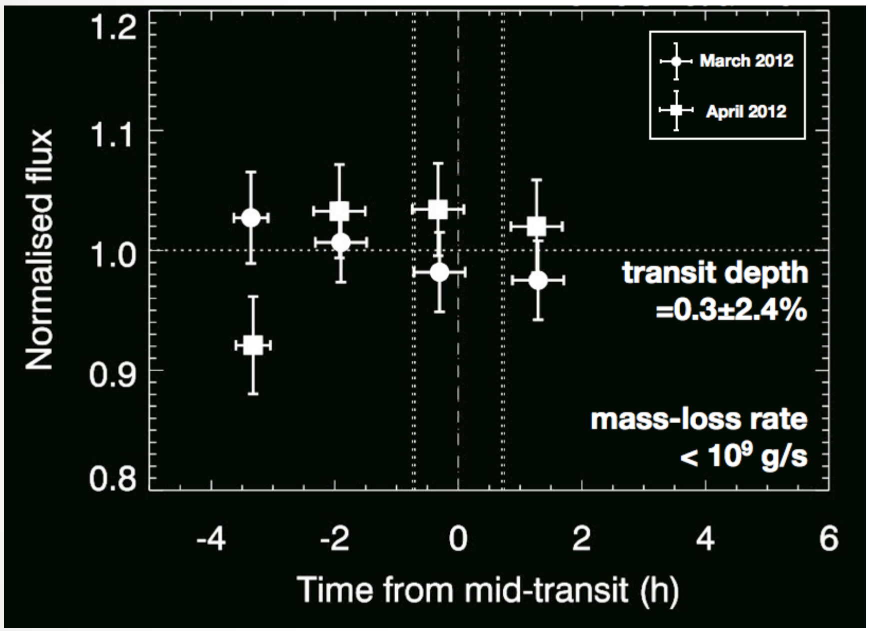
Supported by theoretical studies of the planet population (eg Jin et al. 2014, Kurokawa & Nakamoto 2014) and of specific systems (eg Lopez et al. 2012, Lopez & Fortney 2013)

Observing small planets at Lyman-alpha

55 Cnc e (Ehrenreich+2012)

In 2012: density ρ ~ 4 g cm-3

- Possible water envelope (~20% in mass)
- Teq > 2000 K : evaporating oceans ?

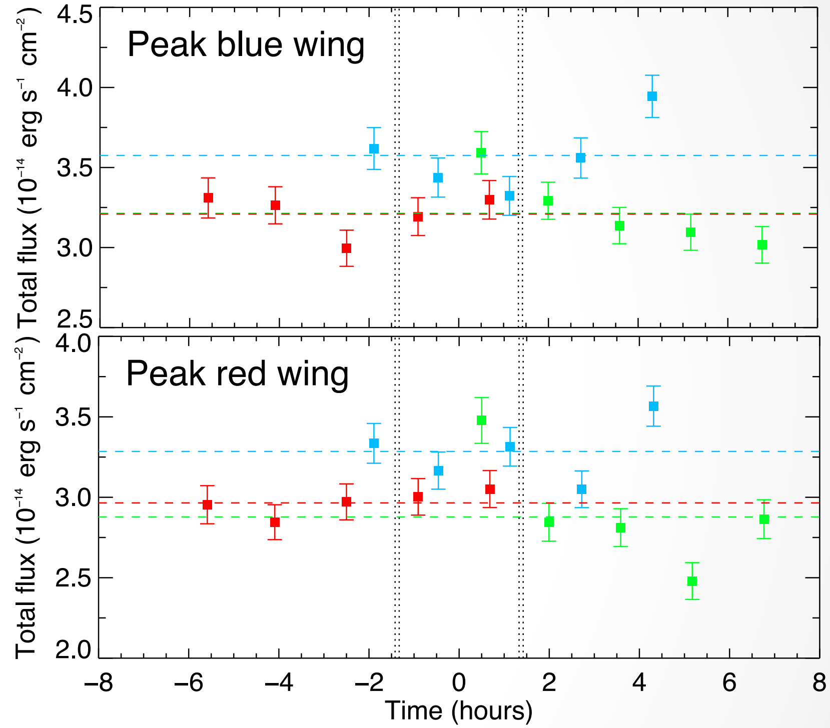


- Non-detection of hydrogen escape
  - Limited mass loss ?
  - Super-Venus ?

In 2016: *magma oceans? Heavyweight atmosphere?* (Demory+2015,2016)

HD 97658b (Bourrier+2016b)

- Low density (4 g cm-3)
- Teq = 725 K



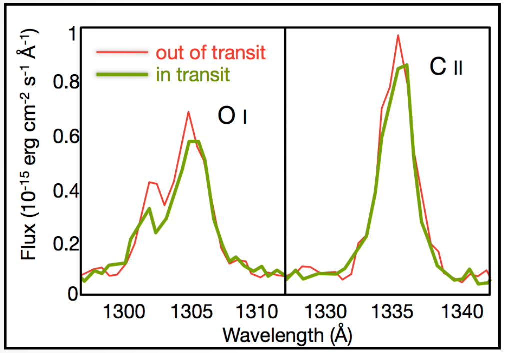
- Non-detection of hydrogen escape
  - No evaporation (mild irradiation) ?
  - Low hydrogen content ?

- Strong variability at short timescale (up to 25%) and long timescale (up to 10%)
  - Importance of multi-epochs observations

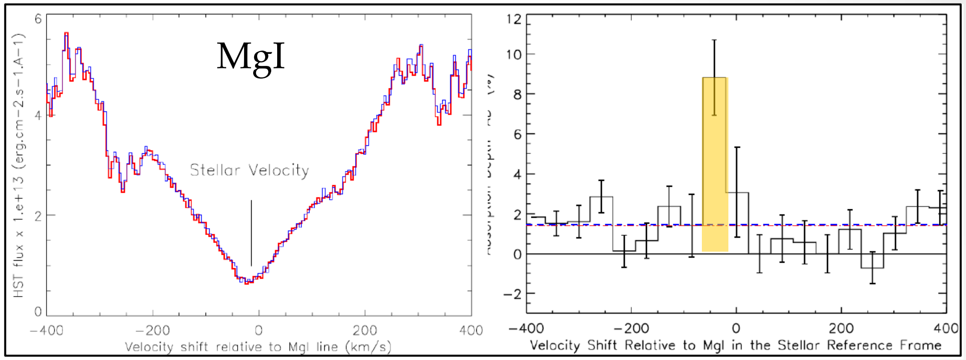
Observing small planets in the UV

Learning from gas giants: *HD209458b, HD189733b, WASP12b*

Detection of O^0 and C^+ (Vidal-Madjar+2004, Ben-Jaffel & Hosseini 2010, Benjaffel & Ballester 2013, 2014), possibly Si^{2+} (Linsky+2010, Ben-Jaffel & Ballester 2015), Mg^0 (Vidal-Madjar+2013), other metals (Fossati +2010 , Haswell+2012, Nichols+2015)



HST/STIS



Observational constraints on the planetary outflow properties (Bourrier+2014), stellar wind (Ben-Jaffel & Ballester 2013) …

Moving to Neptune-mass planets : *GJ436b* (Loyd+2016)

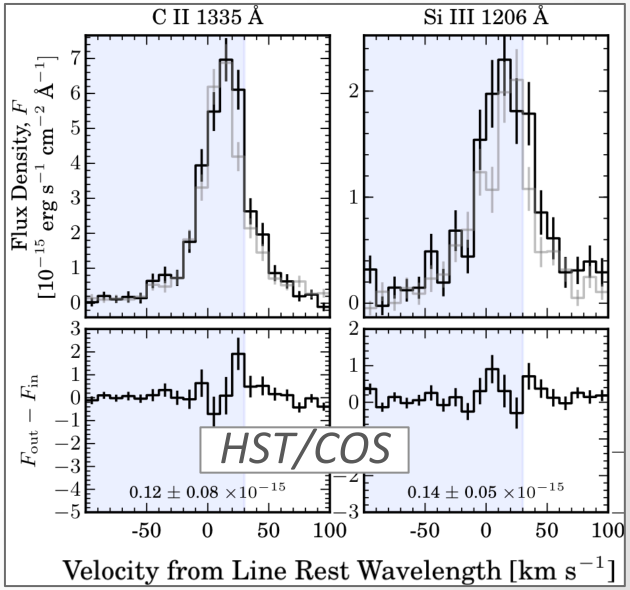
Search for C^+ and Si^{2+} during the extended H exosphere transit

No transit absorption over [-100, 100] km s^{-1}

➢ 95% (2 σ) upper limit of 14% for C^+

Prediction of 2% absorption

➢ Unique role of LUVOIR to characterize small planets



Perspectives: UV spectroscopy with the LUVOIR

- Upper atmospheres are probes of the entire planetary system
  - *Physical structure and chemical composition of the planet*
  - *Stellar EUV emission (-> photochemistry of the atmopshere) & stellar wind*
  - *Planet and star magnetic field (via spectropolarimetry and transiting bow-shocks)*

  …

- Evaporation sculpts the planet population
  - *Upper atmospheres are also probes of planetary nature and evolution*
    - *Hot gas giants: large mass loss but stable*
    - *Lower-mass, mildly irradiated planets : smaller mass loss, yet potentially giant 'sluggish' exospheres, yielding very deep UV signatures*

      -> targets of choice for LUVOIR
    - *Earth-size planets: still to explore, but huge potential for UV characterization (composition, nature, …) compared to IR observations*

      -> unique role of LUVOIR

Credit: NASA/JPL-Caltech/R. Hurt

(Why?) observe super Earths at Lyman-alpha

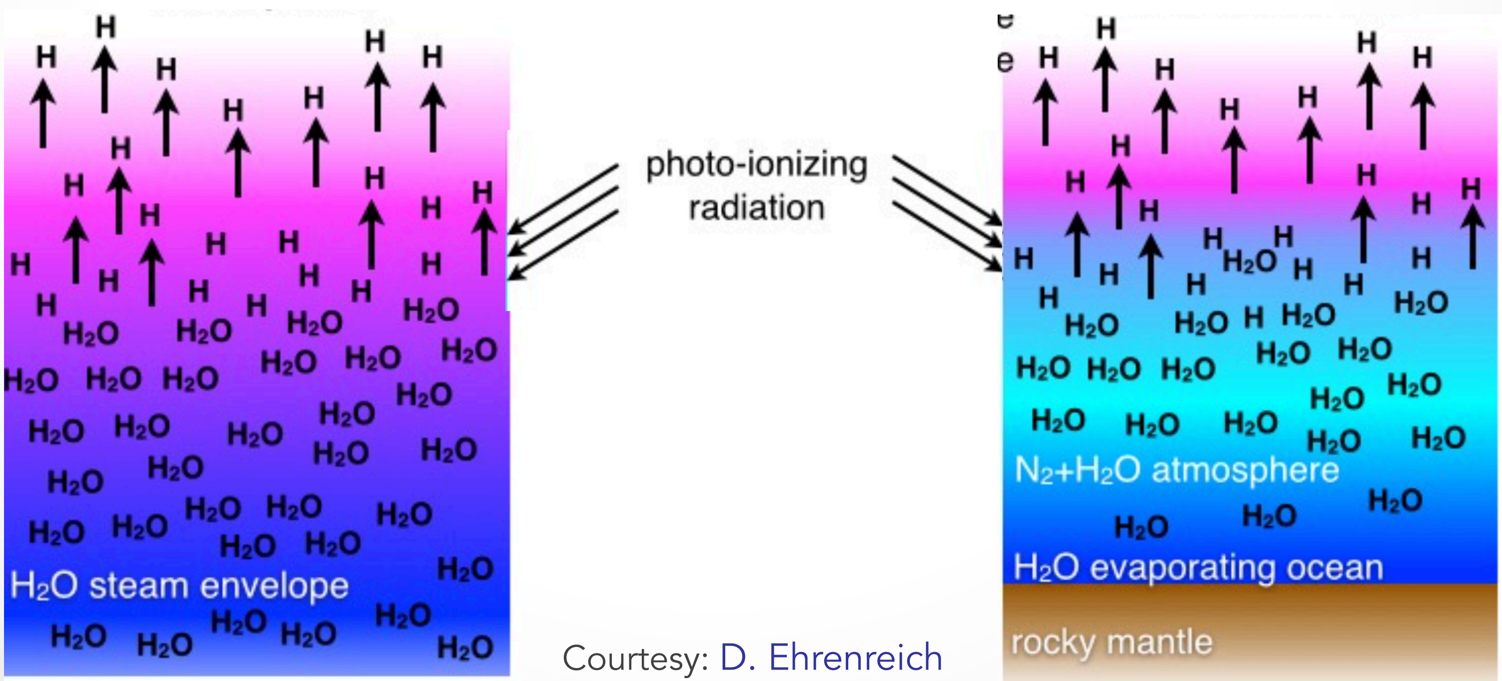
Ocean planets (Leger et al. 2004)

- In between rocky terrestrial planets and mini-Neptunes, formed in external regions of protoplanetary disk with large amount of ices
- Inward migration

Evolved oceans on terrestrial planets (Jura 2004)

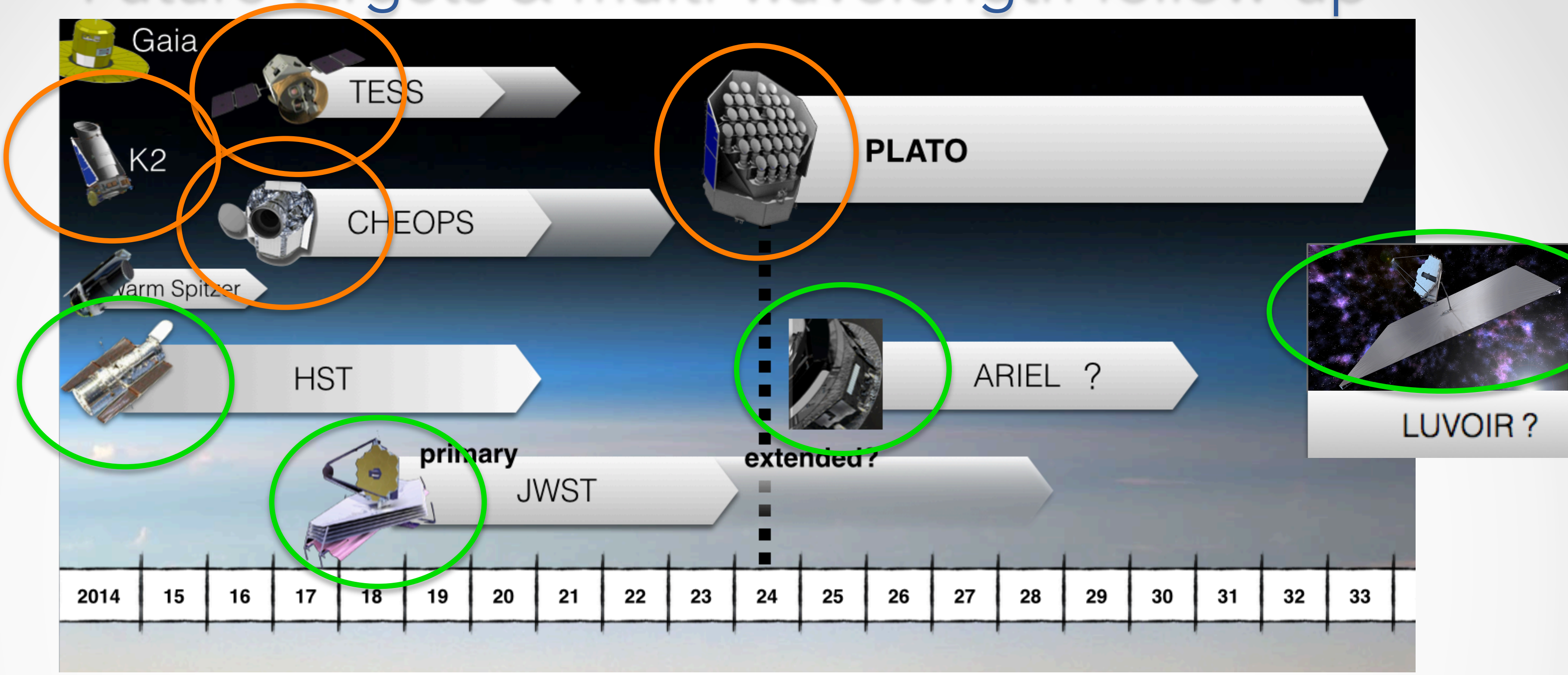
- Earth-like planet formed in-situ with surface water oceans
- Increase of stellar luminosity with time

- Formation of a steam envelope
- Photo-dissociation at high altitudes
- Hydrogen escape



Courtesy: D. Ehrenreich

Future targets & multi-wavelength follow-up



Detection of many small planets around bright stars:
golden targets for transit spectroscopy of their atmospheres

Follow-up of the upper atmospheres of low-mass exoplanets

- Importance of the UV : Arago, LUVOIR
  (see "Characterising exoplanets and their environment in the UV ", Fossati+ 2015)
- Potential for observations in the optical
  (e.g. sodium in the thermosphere with HARPS, Wyttenbach+ 2015)