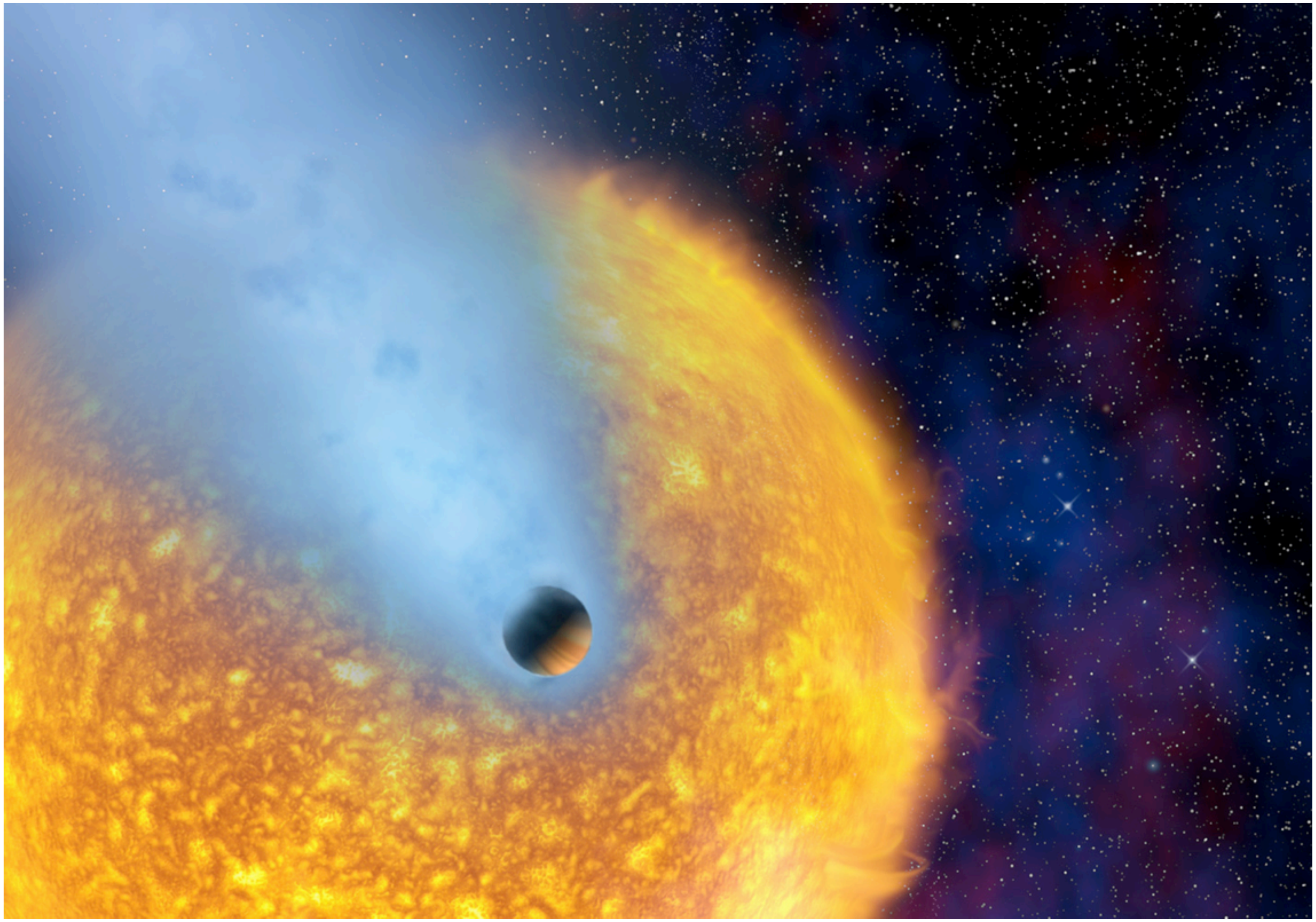
Observations of atmospheric escape of hot Jupiters



Jean-Michel Désert ***(CfA)***

Outline

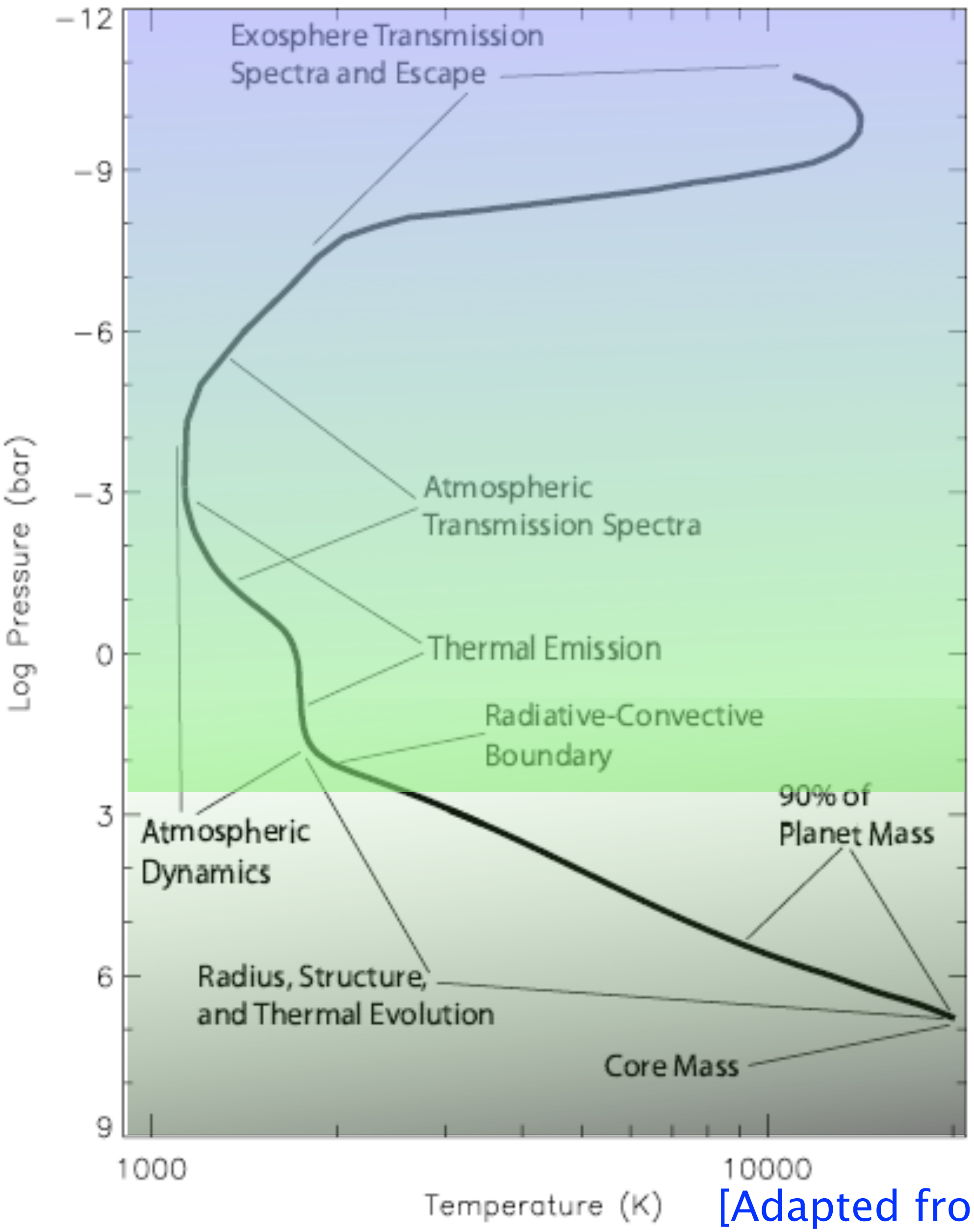
- Exosphere, escape processes

- Observations of evaporating hot jupiters:
  - HD209458b: Hydrodynamic escape
  - New detection of escaping atmosphere: HD189733b
  - Escape rate, lifetime and remnants

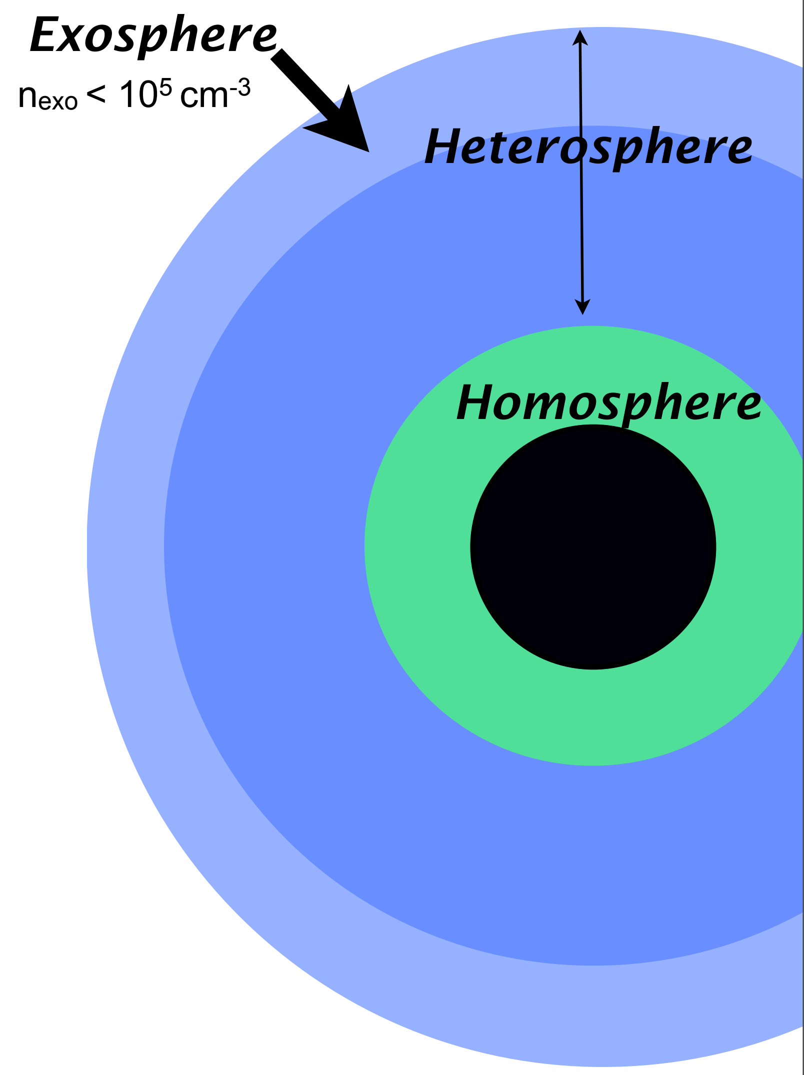
- Future observations

HD209458b

Vertical structure puzzle



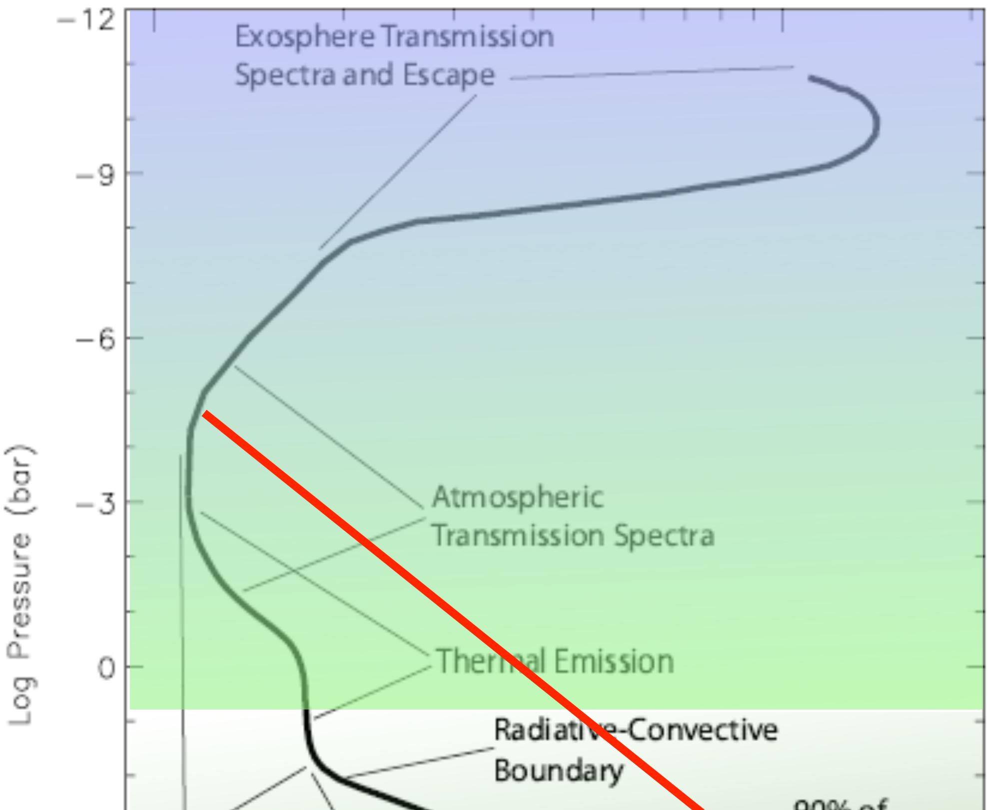
[Adapted from Fortney 2008]

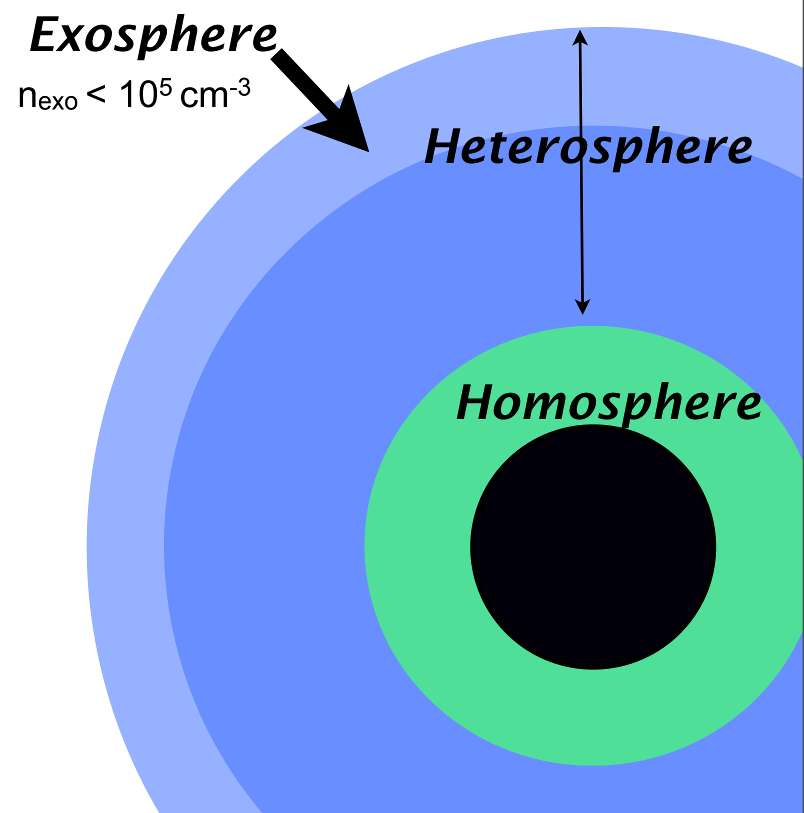


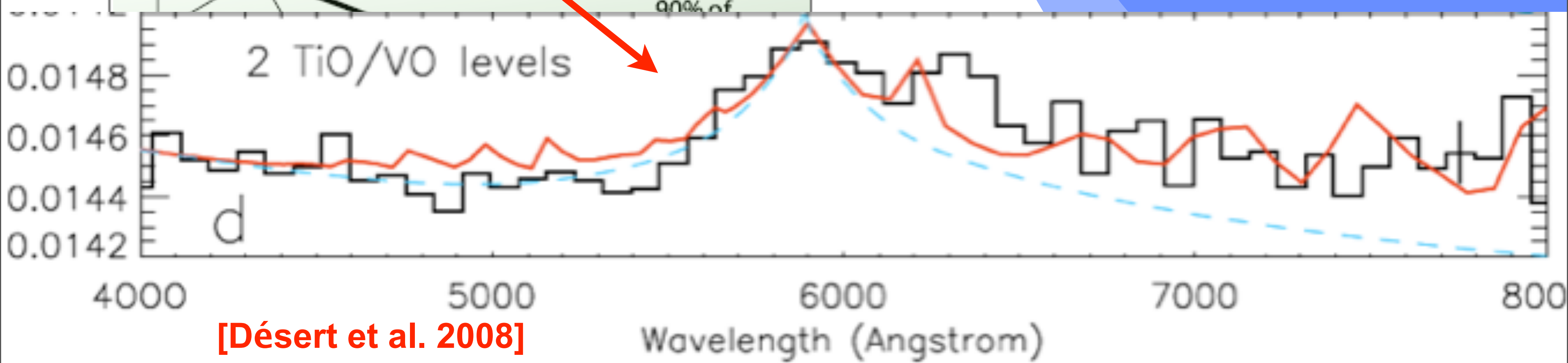
Planetary corona

HD209458b

Vertical structure puzzle



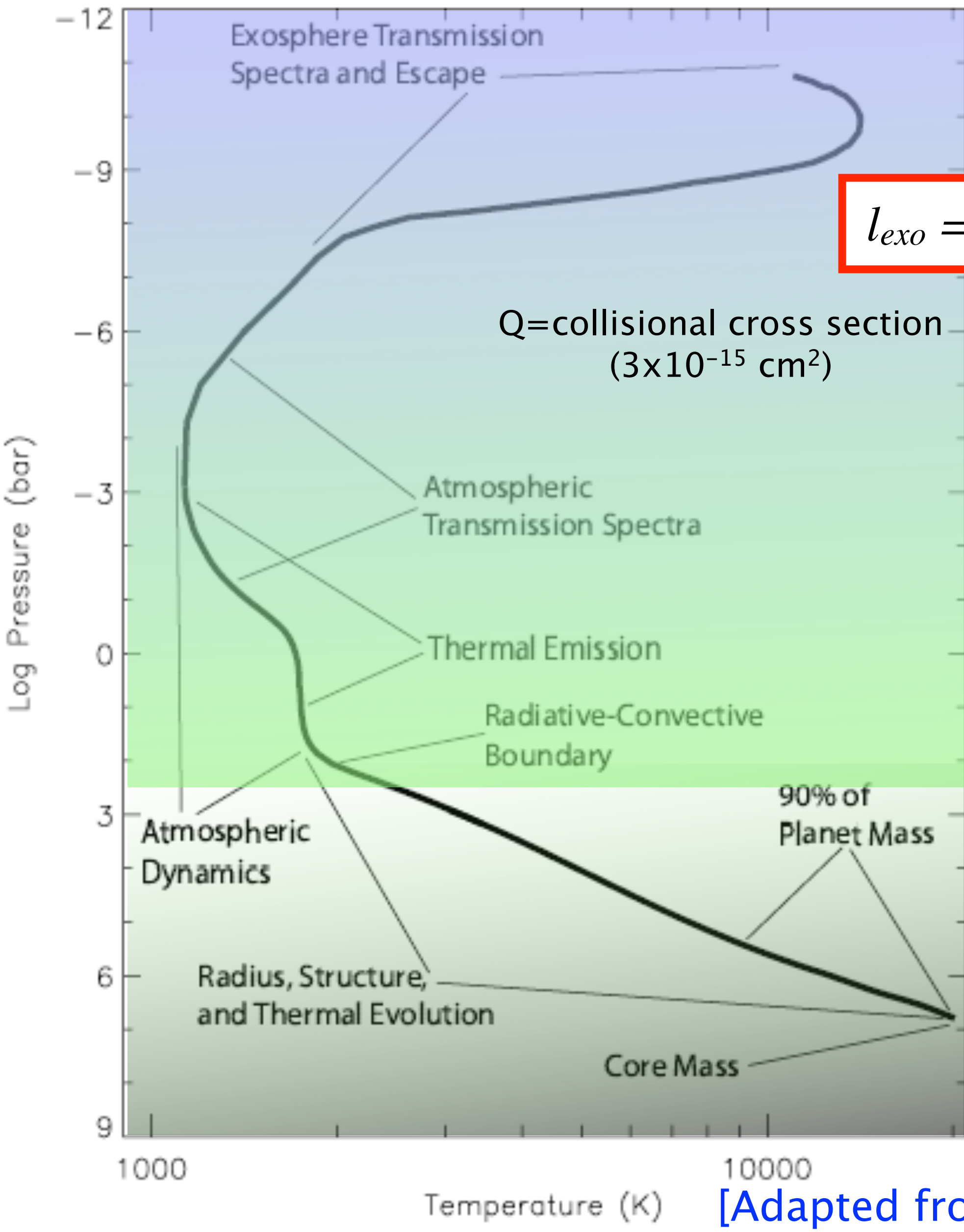




[Désert et al. 2008]

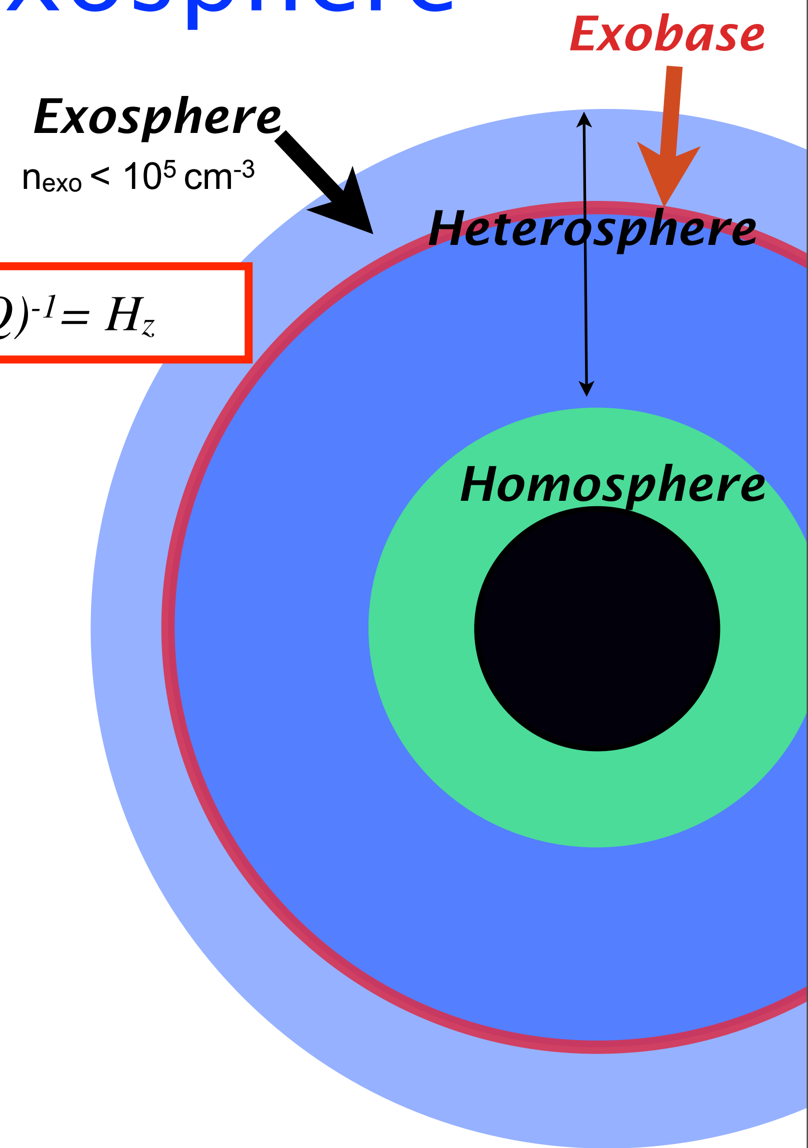
HD209458b

Collisionless exosphere



$$l_{exo} = (n_{exo} Q)^{-1} = H_z$$

Q=collisional cross section (3×10^{-15} cm^2)



[Adapted from Fortney 2008]

Escaping processes

- **Thermal:** Jeans (1925)

$\lambda = (V_{esc}/U)^2 = r_{exo}/H$

  - $E_{Kinetic} > E_G$ + No Collision => ballistic, satellite, escaping
  - Exospheric T => controls escape
  - Diffusion-limited process

- **Nonthermal:** Neutral particules gain E (Most of them involve charged particles) :
  - UV photodissociation => products may gain sufficient E
  - sputtering: a fast ion/atom meets atmospheric atom
  - no magnetic field: solar wind sweeping
  - charge exchange: a fast ion meets neutral
  - ion/neutral reaction => fast atom created
  - accelerated by electric field

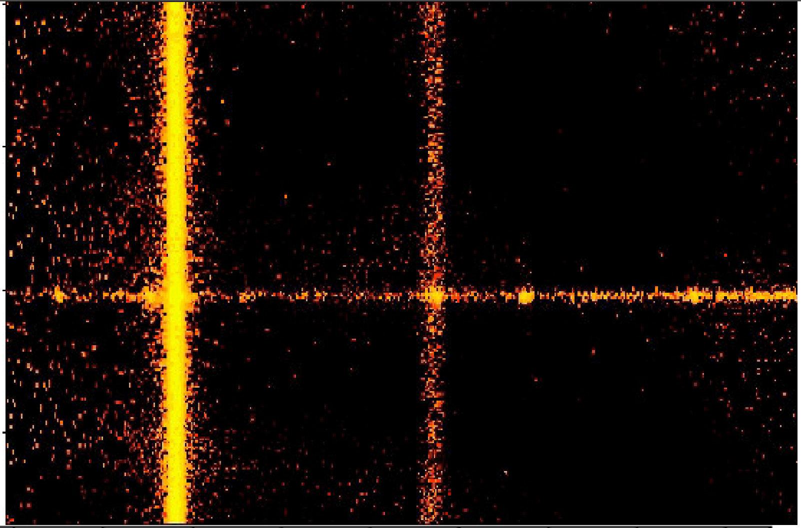
[Hunten 1982; Chamberlain & Hunten 1987]

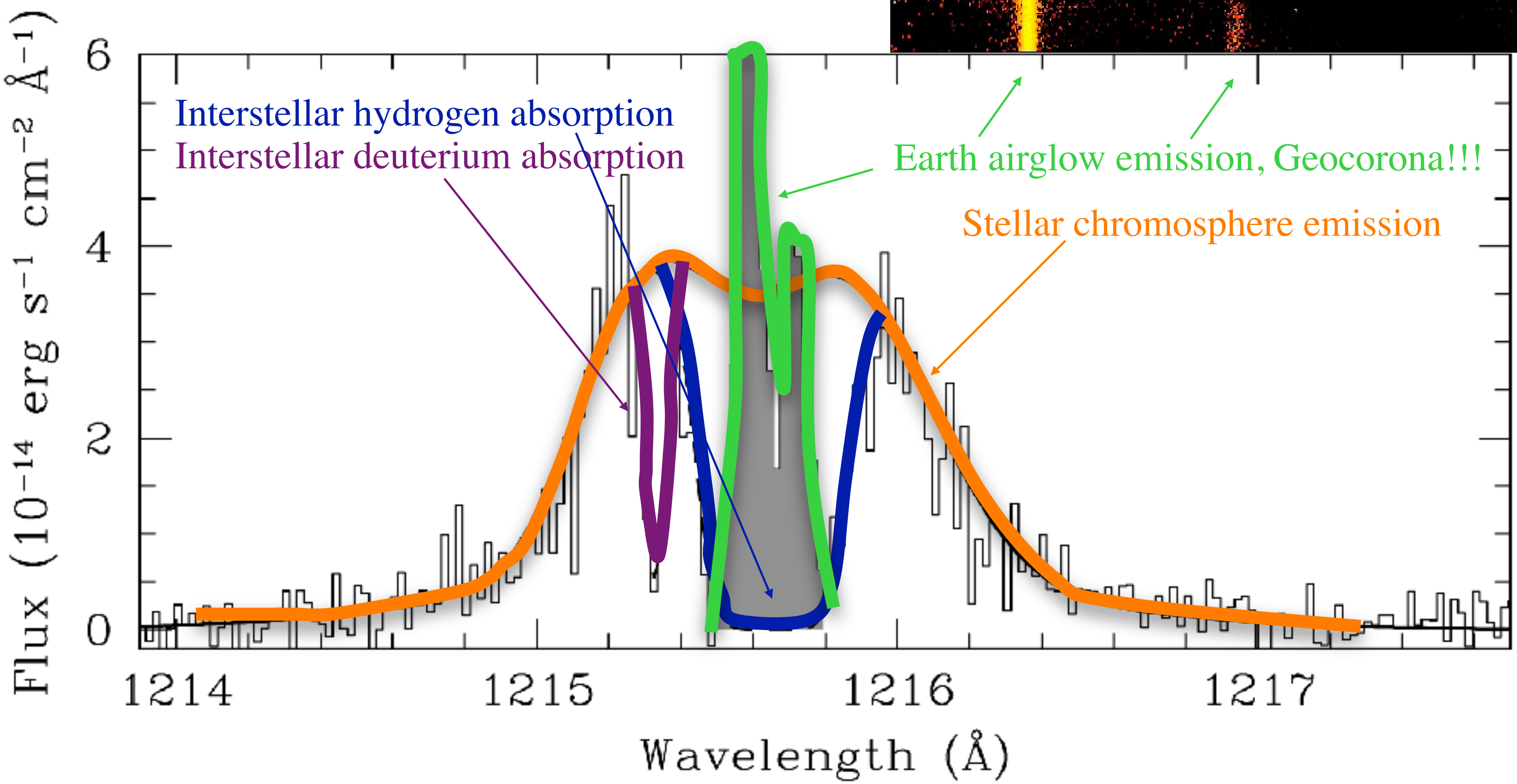
Observations of hot-Jupiters' upper atmospheres

HD 209458 at Lyman α

HST/STIS observations

[Vidal-Madjar *et al.* 2003]
[Désert et al. 2004]





HD 209458 at Lyman α

HST/STIS observations

[Vidal-Madjar *et al.* 2003]
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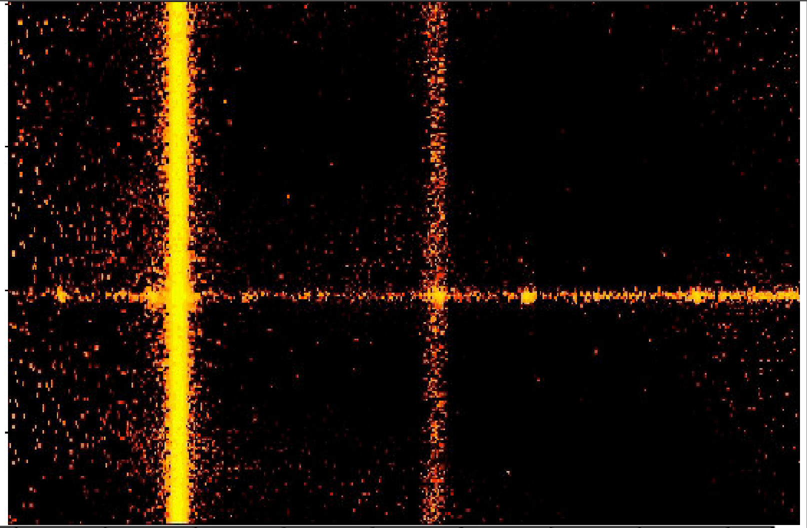
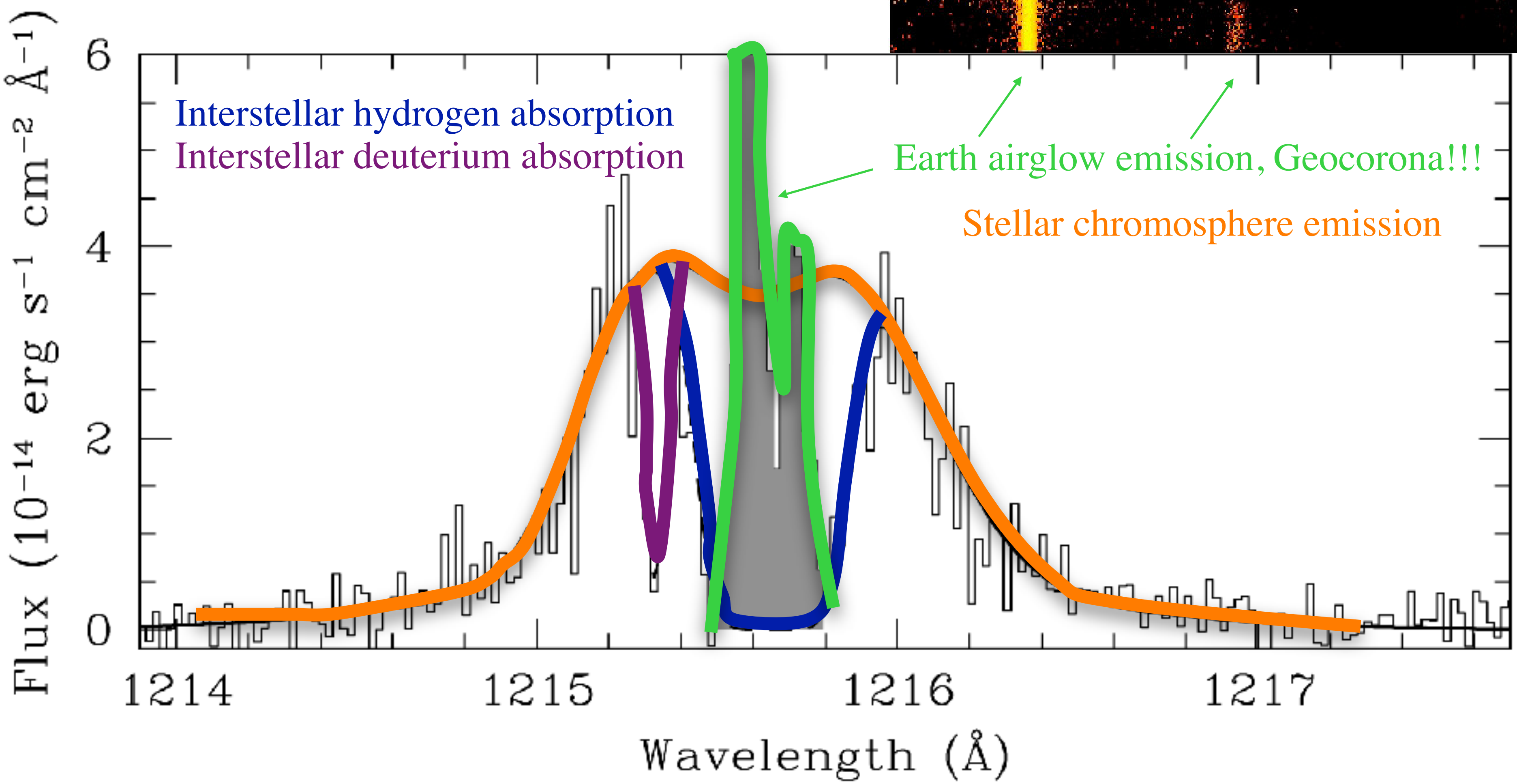
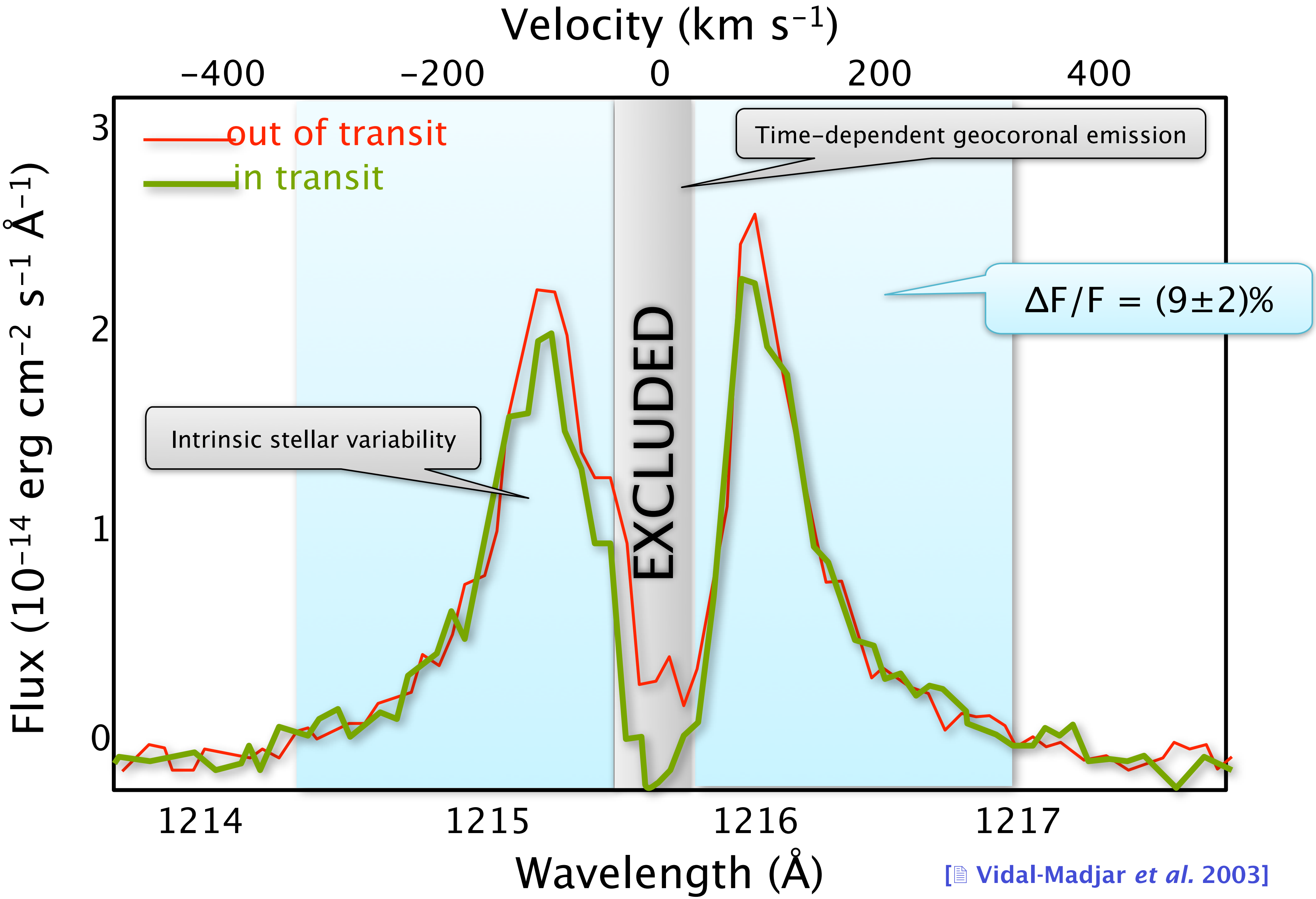


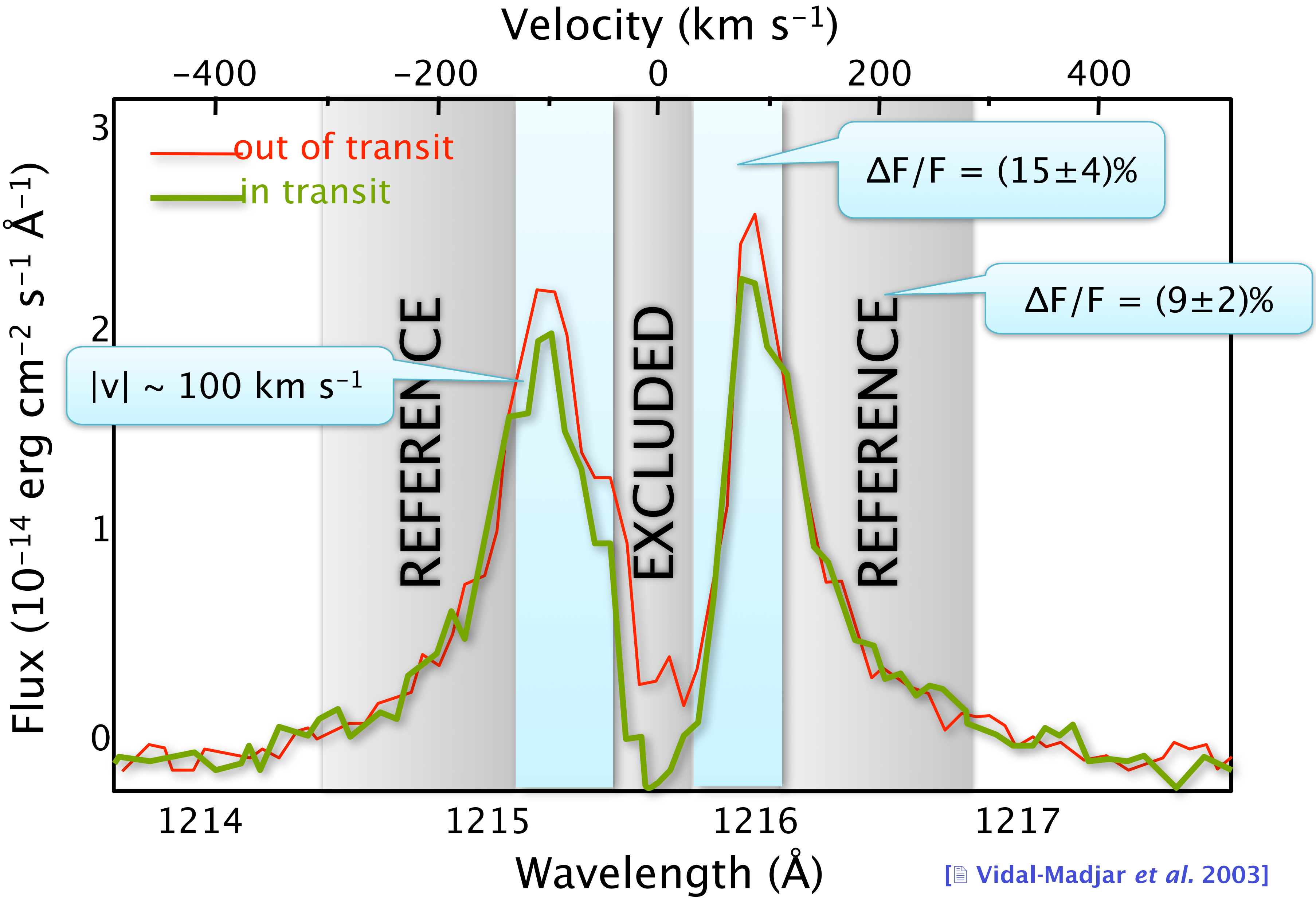


Observations of transits at Lyman α



[Vidal-Madjar *et al.* 2003]

Detection of exospheric hydrogen



[Vidal-Madjar *et al.* 2003]

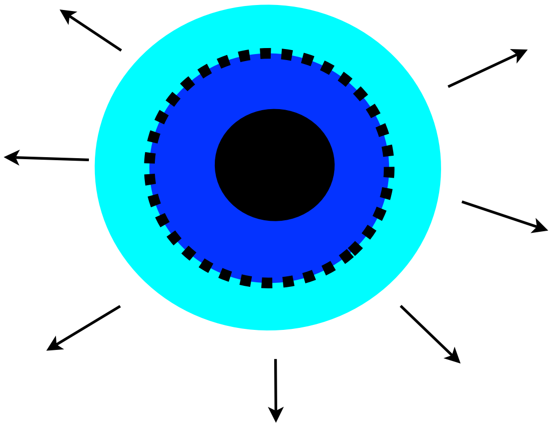
Escape : two observational evidence

- HD209458b continuum (1.35 $R_{Jupiter}$ = 96,500 km) → 1.6 % absorption

[Charbonneau *et al.* 2000]

[Henry *et al.* 2000]

- Roche Lobe (2.7 R_{planet} = 3.6 $R_{Jupiter}$) → 10 % absorption
- Hydrogen: 15 % absorption → 3.2 R_{planet} = 4.3 $R_{Jupiter}$ = 300 000 km



→ Beyond the Roche Lobe

➔ **Hydrogen is escaping**

- Absorption width: $V_{blue} \leq -100$ km/s (V_{esc} = 54 km/s)

→ Beyond escape velocity

➔ **Hydrogen is escaping**

Estimation of the escape rate

$$\phi_{esc} = N\ V\ S$$

- Estimation of the density:

15% => optically depth above Roche lobe $\tau = N\ \sigma\ L \sim N\ 10^{-14}\ R_{Roche\ lobe}$

➔ $N_{Roche\ lobe} \sim 10^{3}$ atoms.cm^{-3}

- Escape velocity => exospheric T

2 000 K < T < 20 000 K

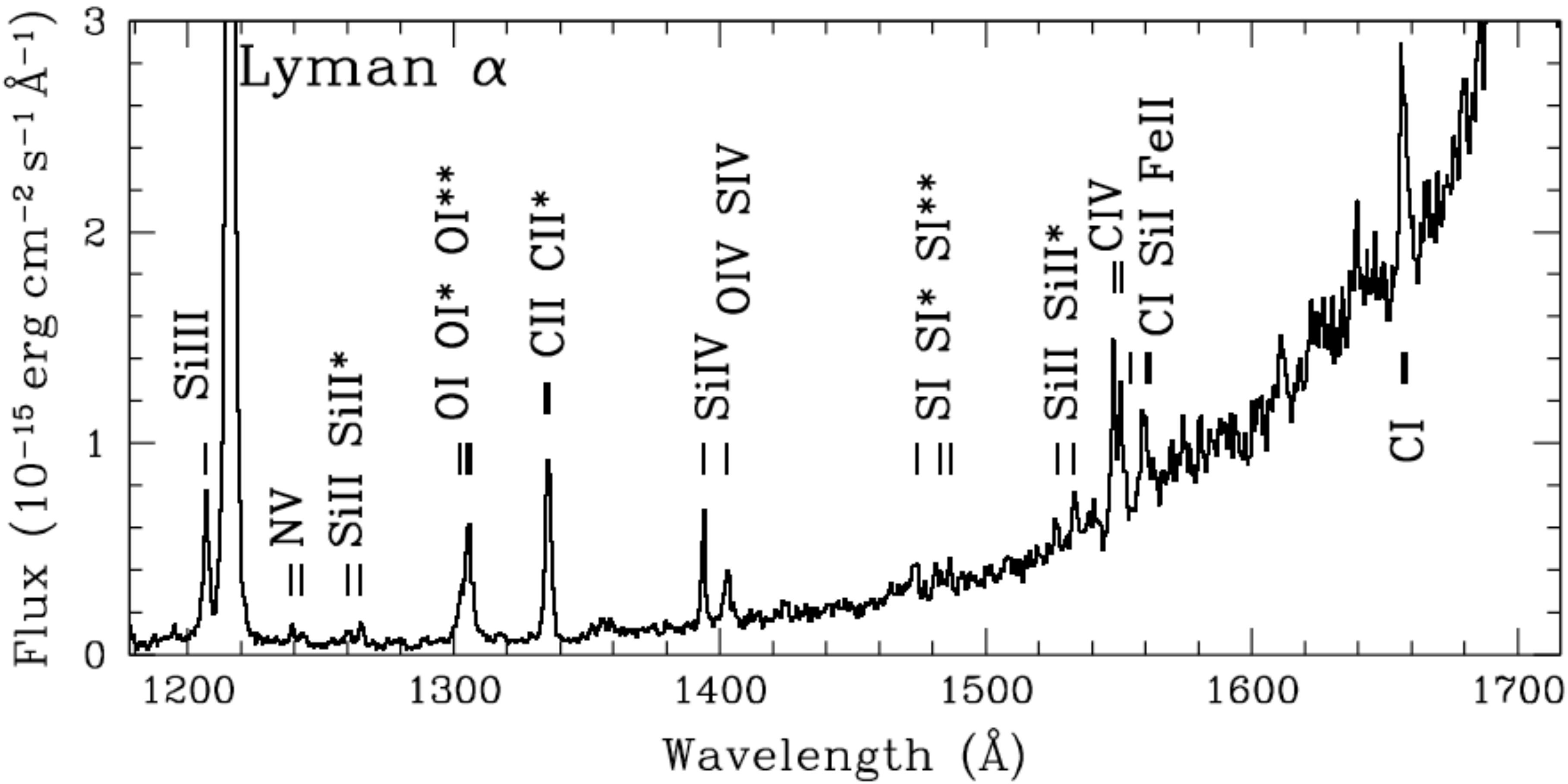
➔ 5 kms^{-1} < V < 15 kms^{-1}

➔ $\phi_{esc} \sim 10^{10}$ g s^{-1} => < 1% mass / lifetime

Which escape mechanism ?
(observations)

FUV with HST/STIS/G140L

HD209458b

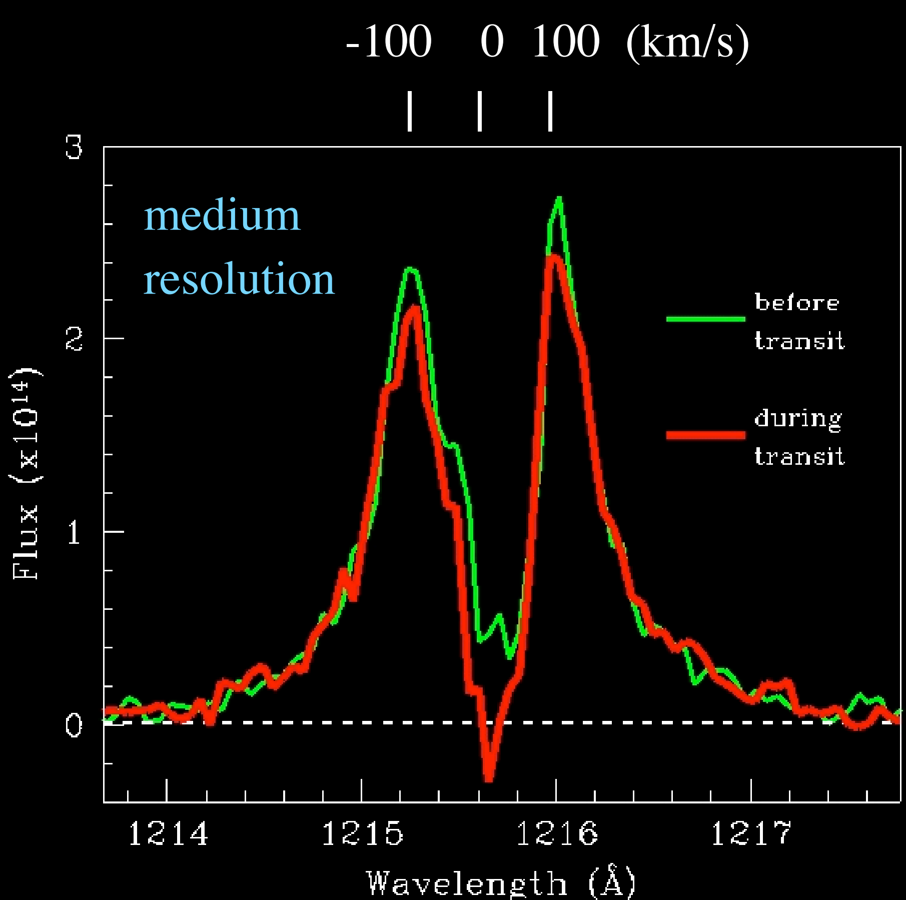


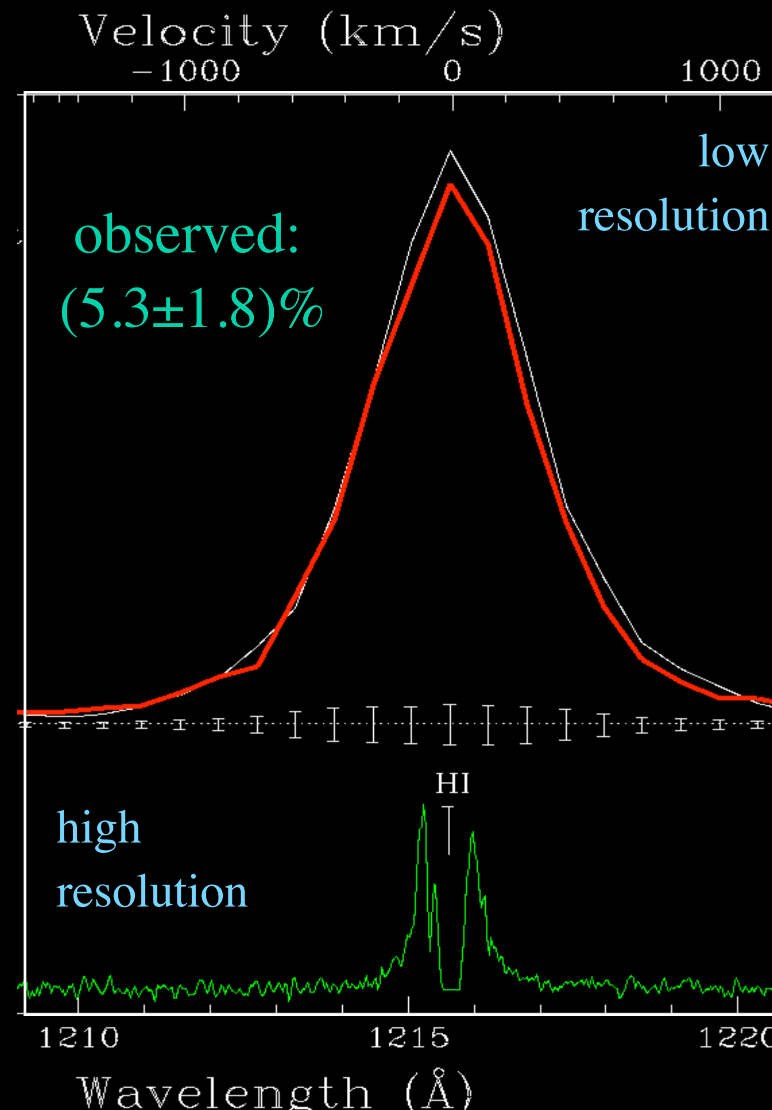
[Vidal-Madjar, Désert *et al.* 2004]

Confirmation of the HI absorption (1)

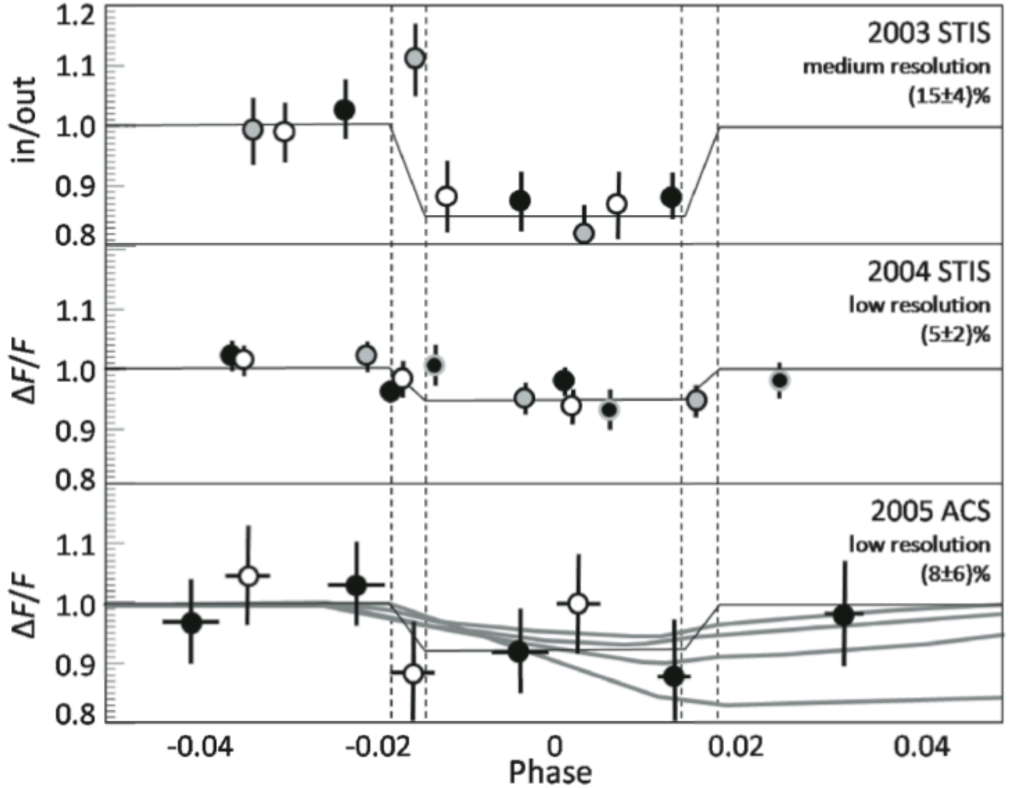
[🗎 Vidal-Madjar, Désert *et al.* 2004]

(15±4)% from -130 to 100 km/s → (5.7±1.5)% on the whole line (predicted)





3 observations in agreement with escape



[🗎 Vidal-Madjar *et al.* 2003]

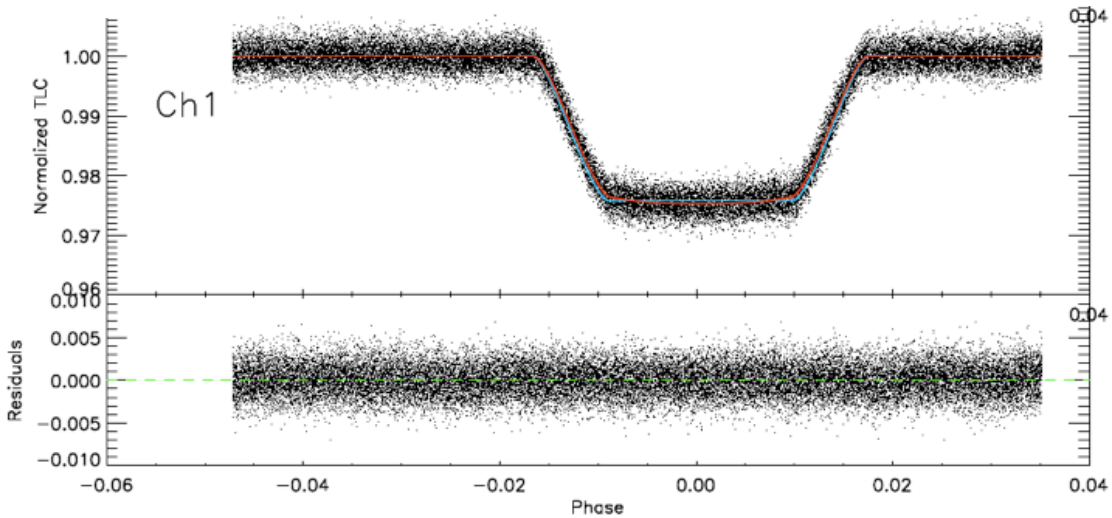
15 +/- 4%

[🗎 Vidal-Madjar *et al.* 2004]

5 +/- 2%

[🗎 Ehrenreich et al. 2008]

8 +/- 6%



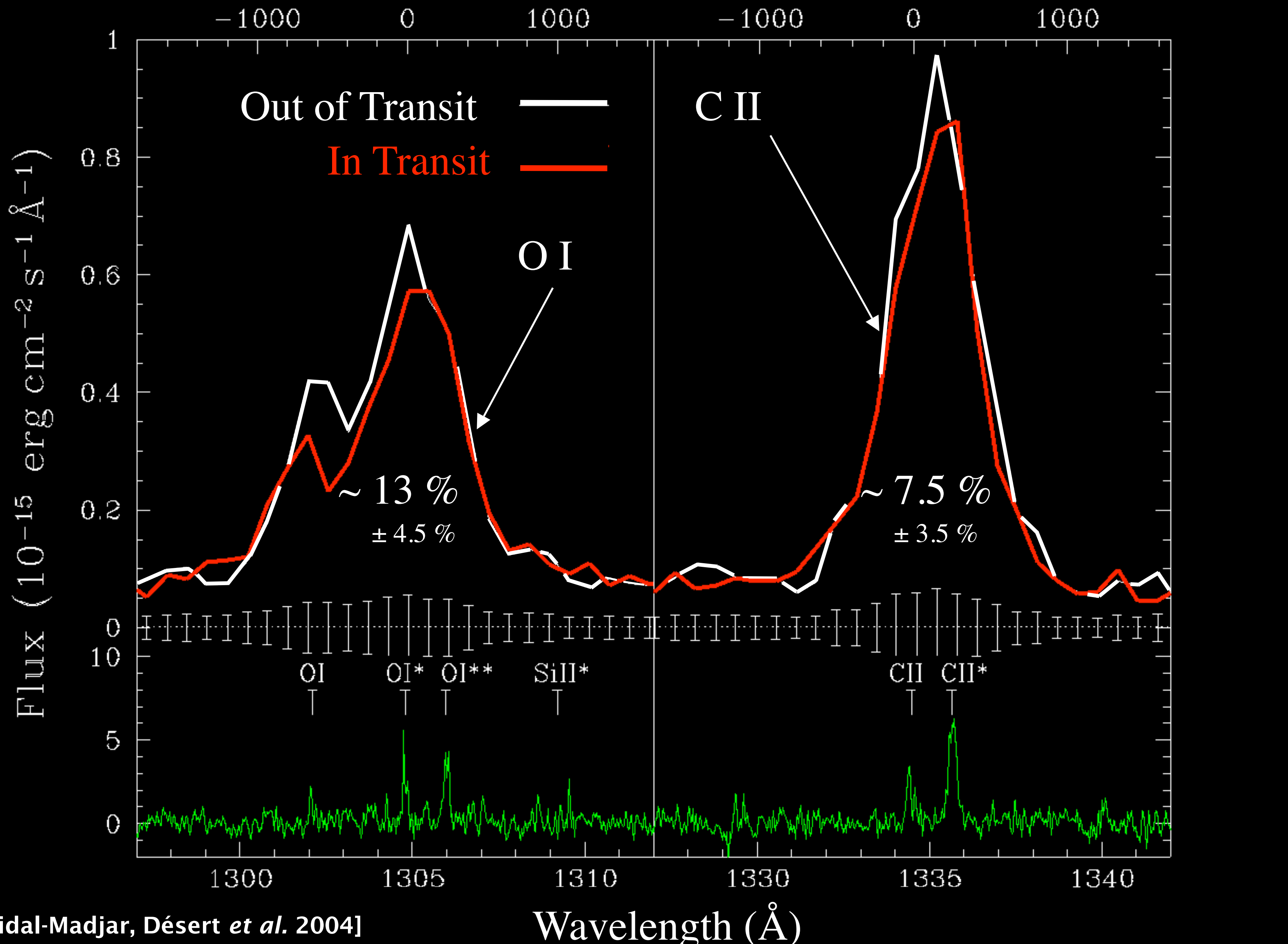
HD 189733 b

Spitzer/IRAC @ 3.6

122 000 expos. (0.1s)

[🗎 Désert *et al.* submitted]

Evidence of carbon and oxygen



[Vidal-Madjar, Désert *et al.* 2004]

Consequences of exospheric O & C

- O and C up to the Roche lobe
- Carried by H flow V > 10 km/s (~ sound speed)

➡ **Hydrodynamic escape (« Blow-Off »)**

- Presence of OI*, OI**, CII* ➔ $\mathbf{N \approx 10^6\ cm^{-3}}$ at R_{Roche}
- Escape rate: $\sim \mathbf{N}.\, S_{Roche\ lobe} \bullet V_{Roche\ lobe}$

$R_{Roche\ lobe} = 3.6\ R_{Jup}$ & $V_{Roche\ lobe} > 10$ km/s

➡ **Escape rate > 10^{10} g/s**

Escape rate ?

4 models to interpret the observations and estimate the escape rate

[🗎 **Vidal-Madjar *et al.* 2003] :**

Radiation pressure, F_{EUV} ionization

➔ $10^{9.5}$ g/s (F_{EUV}=1 solar) - $10^{11.5}$ g/s (F_{EUV}=4 solar)

[🗎 **Schneiter 2007] :**

Interaction between escaping gas and stellar wind

➔ $(1.1 \pm 0.3)\ 10^{10}$ g/s

[🗎 **Holmstrom et al. 2008] :**

$H + H^{+*} \rightarrow H^{+} + H^{*}$

Energetic Neutral Atoms (ENA) from stellar wind

➔ $\sim 10^{9}$ g/s

[🗎 **Murray-Clay et al. 2009] :**

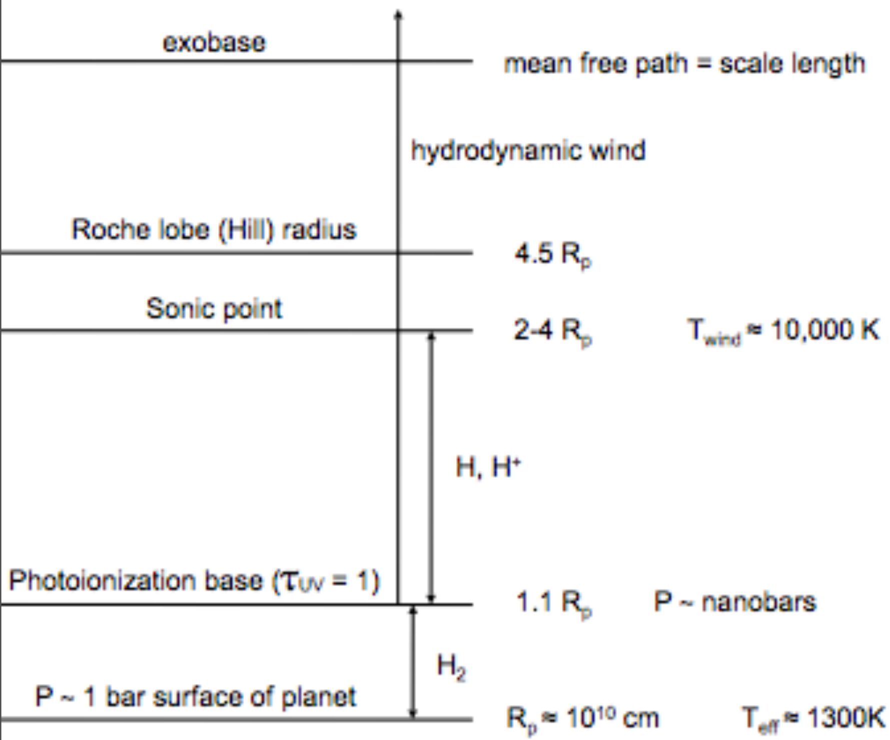
Bulk hydrodynamic outflow ➔ $\sim 10^{10}$ g/s

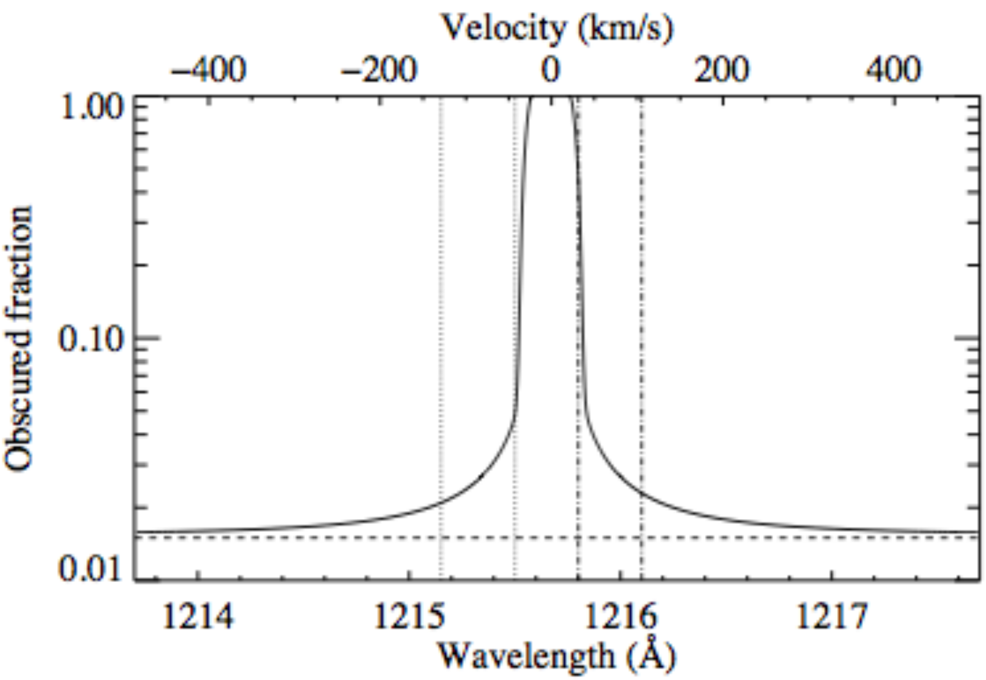
HD209458b

Hydrodynamic (Parker) wind

[Murray-Clay et al. 2009]

Heating and cooling, ionization balance, tidal gravity, pressure confinement by the host star wind





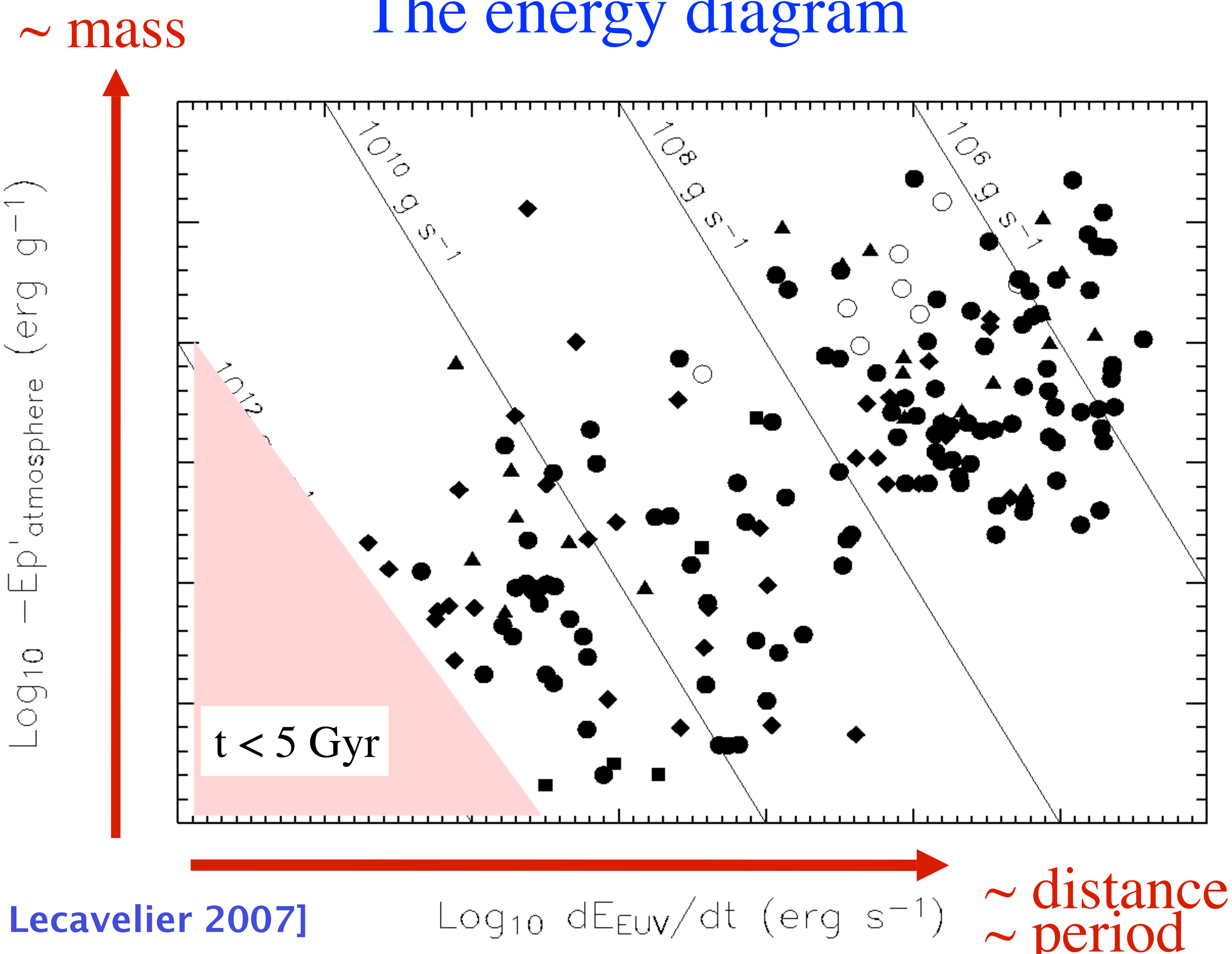
Mass loss is energy limited $dM/dt \sim (F_{uv}^{0.9} - F_{uv}^{0.6})$

Models to understand the escape rate

- Burrows et al. 1995
- Lammer et al. 2003
- Lecavelier des Etangs et al. 2004, 2007
- Baraffe et al. 2004, 2005, 2006
- Yelle 2004, 2006
- Jaritz et al. 2004
- Tian et al. 2005
- Hubbard et al. 2006
- Garcia-Muñoz 2007
- Erkaev et al. 2007
- Penz et al. 2007, 2008
- Murray-Clay et al. 2009
- Stone 2009
- Tian 2009

Use X-UV for escape

The energy diagram

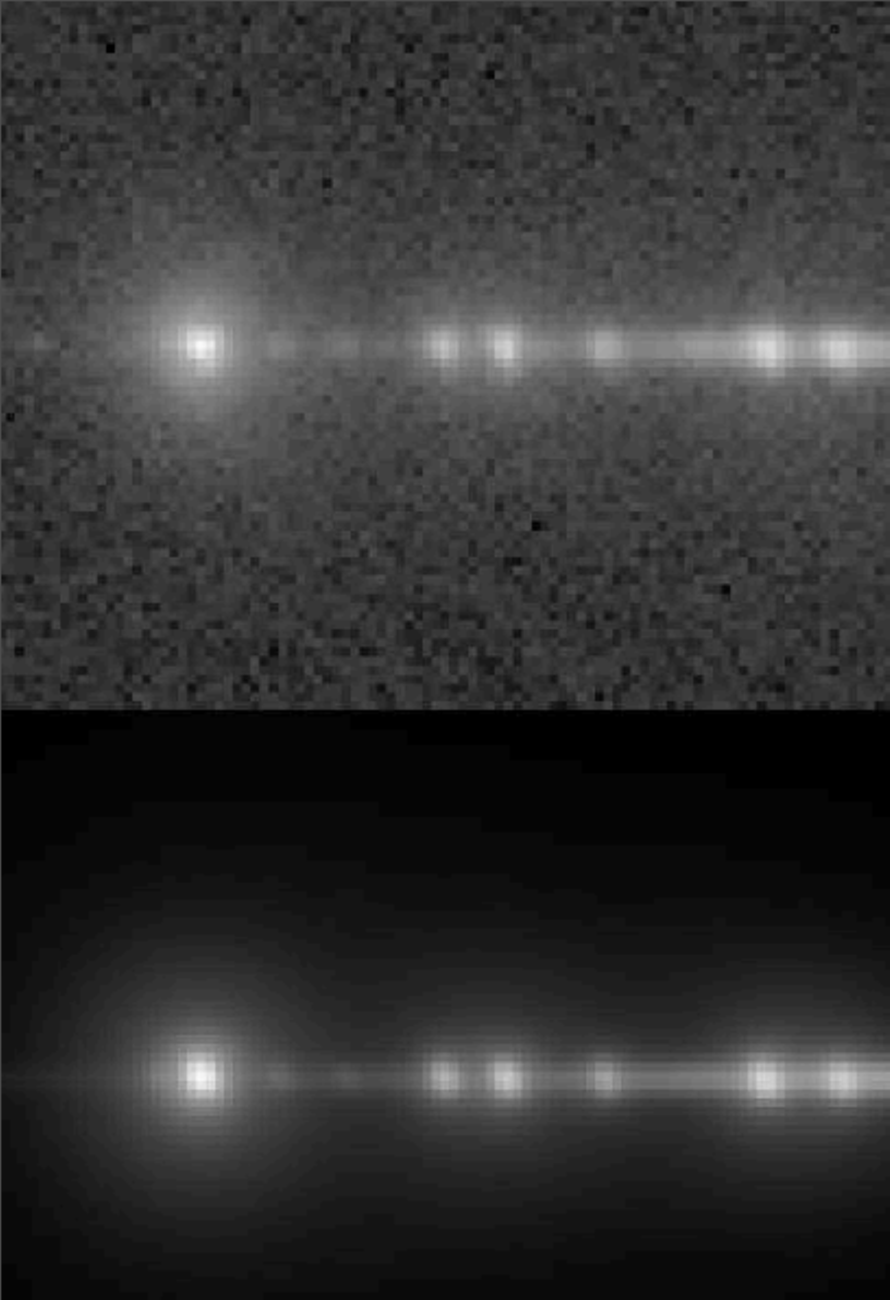


[Lecavelier 2007]

Other evaporating hot Jupiters ?

HD189733b

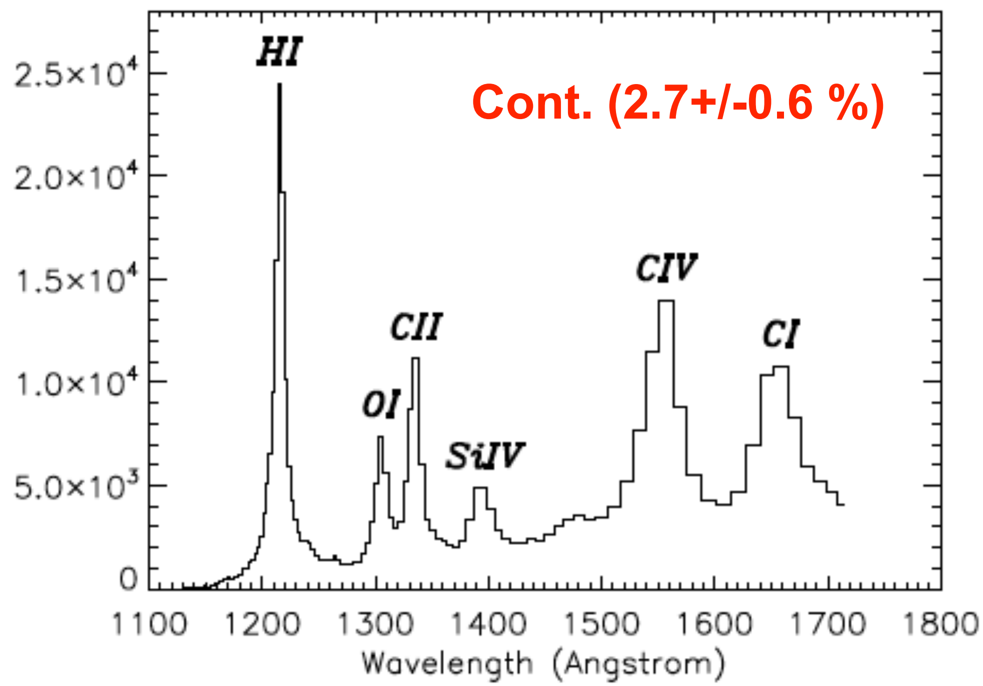
HST/ACS/SBC/PR110L



[Lecavelier et al., 2010 in press]

K1.5 M_V=7.65
R_*=0.8 R_{sun}
M_*=0.8+/-0.4 M_{sun}
d=20 pc

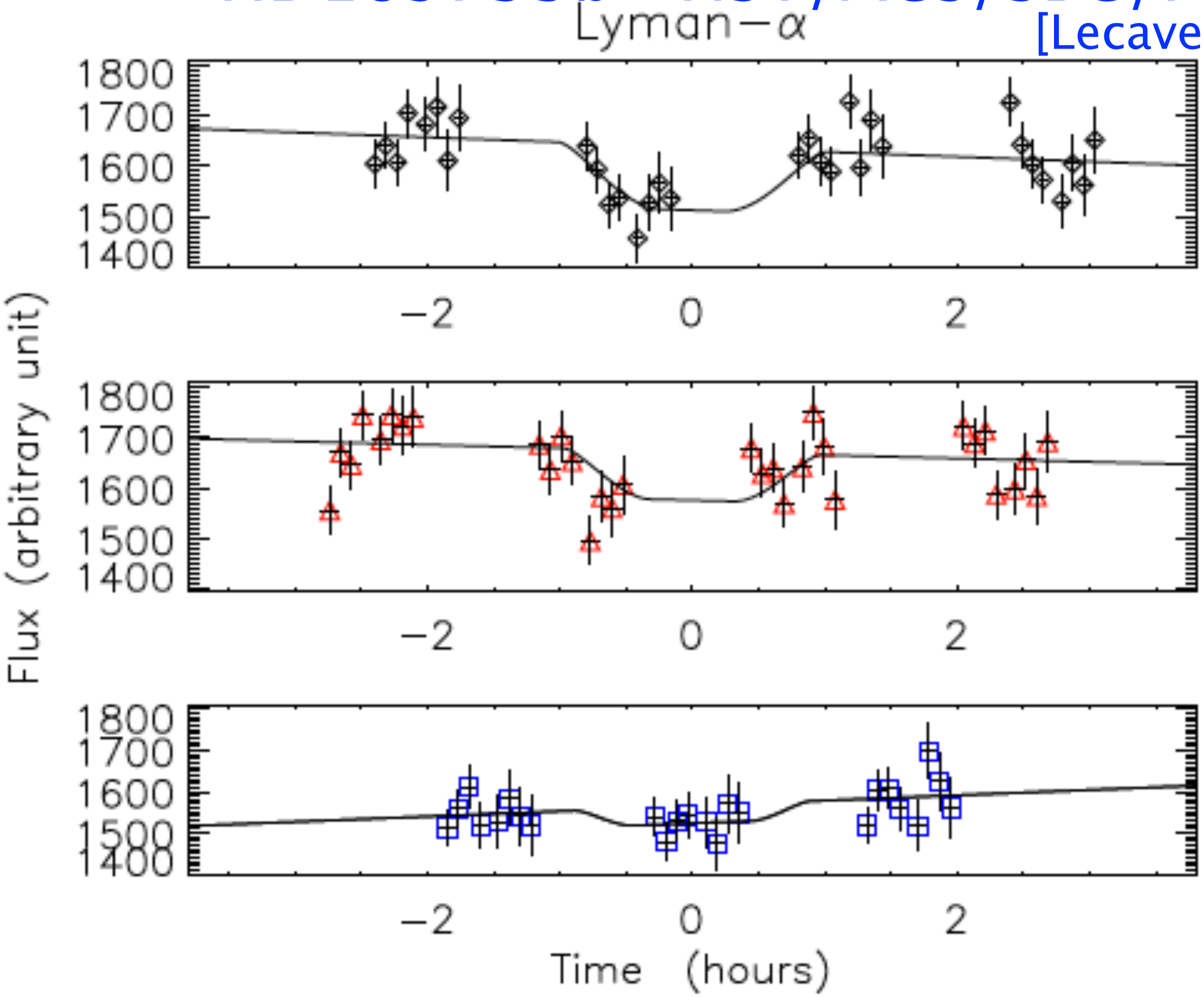
R_p=1.38R_{jup} (2.4 %)



R~300 @ 1200 Ang. (1.65A/pixel)

HD189733b HST/ACS/SBC/PR110L

[Lecavelier et al., 2010 in press]



Data set	χ^2	Degree of Freedom	Absorption (%)	$\sqrt{\Delta\chi^2}$ from 0% abs.	$\sqrt{\Delta\chi^2}$ from 2.4% abs.
Transit #1	29.4	29	7.6 ± 1.5	$5.7\ \sigma$	$3.8\ \sigma$
Transit #2	48.8	29	5.6 ± 1.7	$3.3\ \sigma$	$2.0\ \sigma$
Transit #3	12.7	21	2.7 ± 1.2	$2.2\ \sigma$	$0.2\ \sigma$
All	97.9	81	5.05 ± 0.75	$6.4\ \sigma$	$3.5\ \sigma$

HD189733b : a second evaporating hot-Jupiter

[Lecavelier et al., 2010 in press]

$R_p = 1.138 R_{jup}$ (2.4 %)
$R_{Roche\ Lobe} = 3.3 R_{jup} = 2.28\ R_p$

2 scenarii:

(1) 5% @ 150 km/s => $1.65 R_{jup}$ (>> V_{escape}=49 km/s)

(2) absorption < 49 km/s (line center) => 30% absorption cloud @ 4 R_{jup} (> 3.3 R_{jup})

Data set	χ^2	Degree of Freedom	Absorption (%)	$\sqrt{\Delta\chi^2}$ from 0% abs.	$\sqrt{\Delta\chi^2}$ from 2.4% abs.
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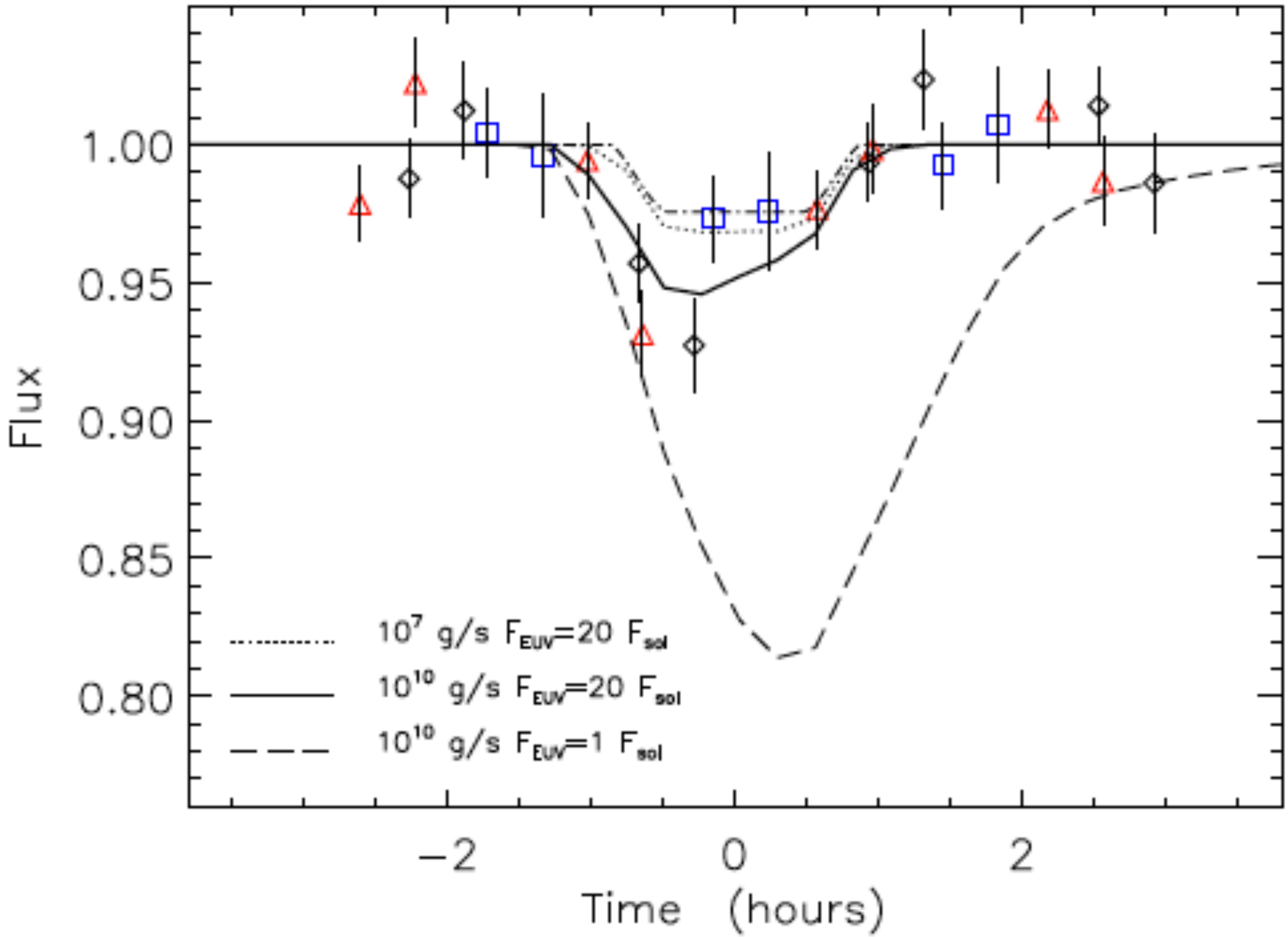
All	97.9	81	5.05 ± 0.75	$6.4\ \sigma$	$3.5\ \sigma$

HD189733b : Escape rate

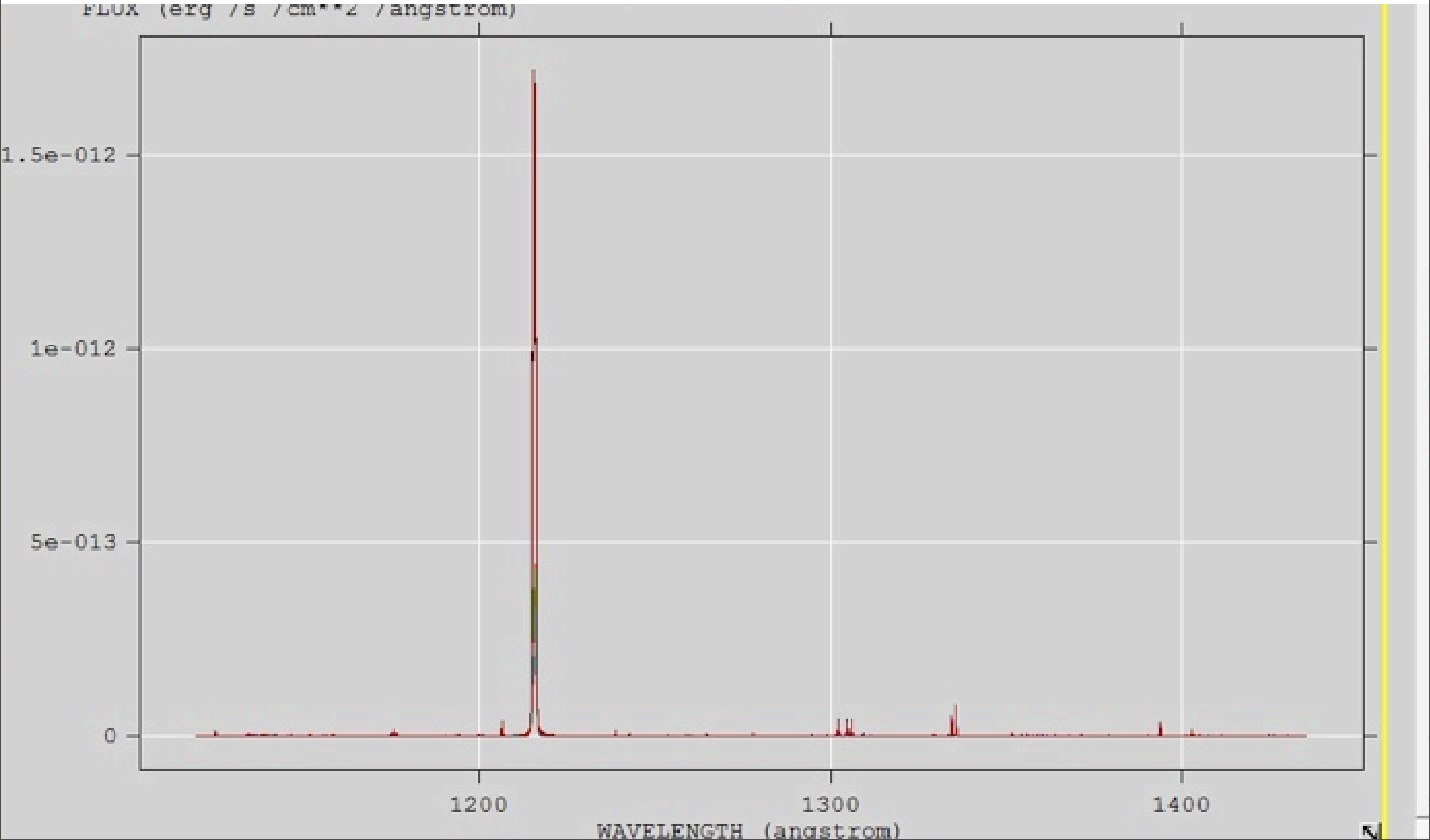
[Lecavelier et al., 2010 in press]



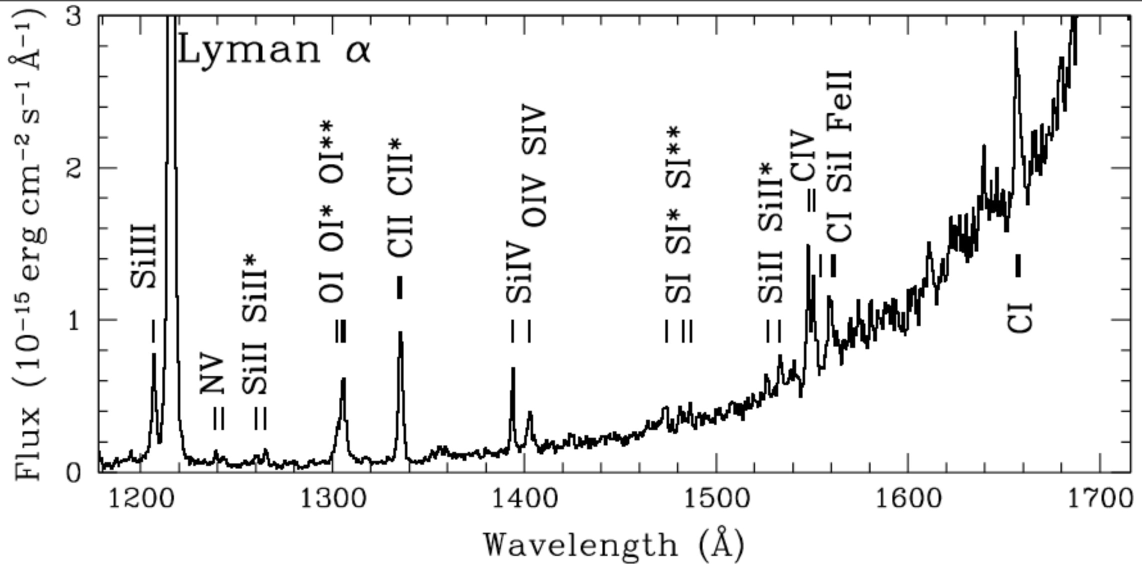
Other/better instruments?

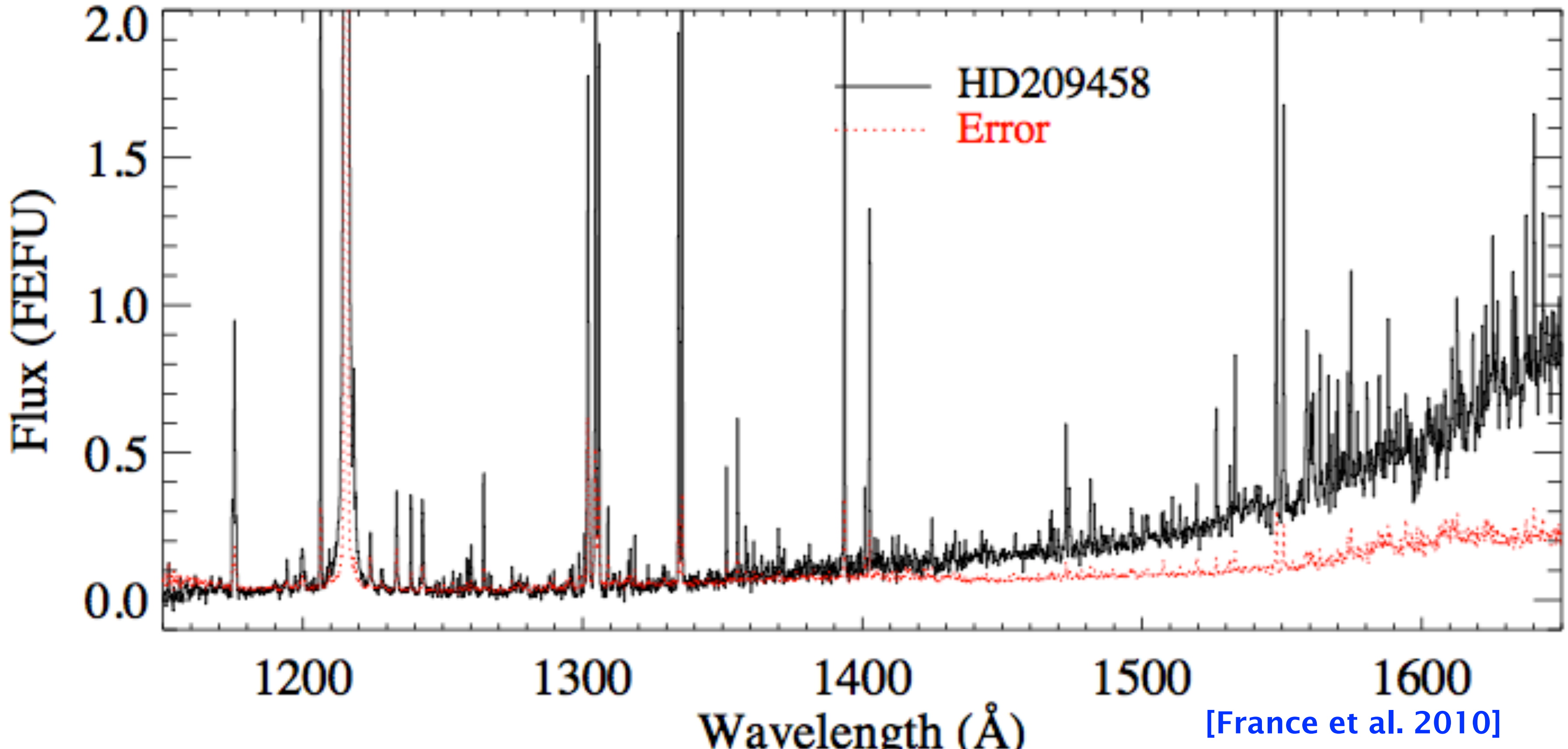
HD189733b

HST: STIS vs COS



HST/COS vs STIS

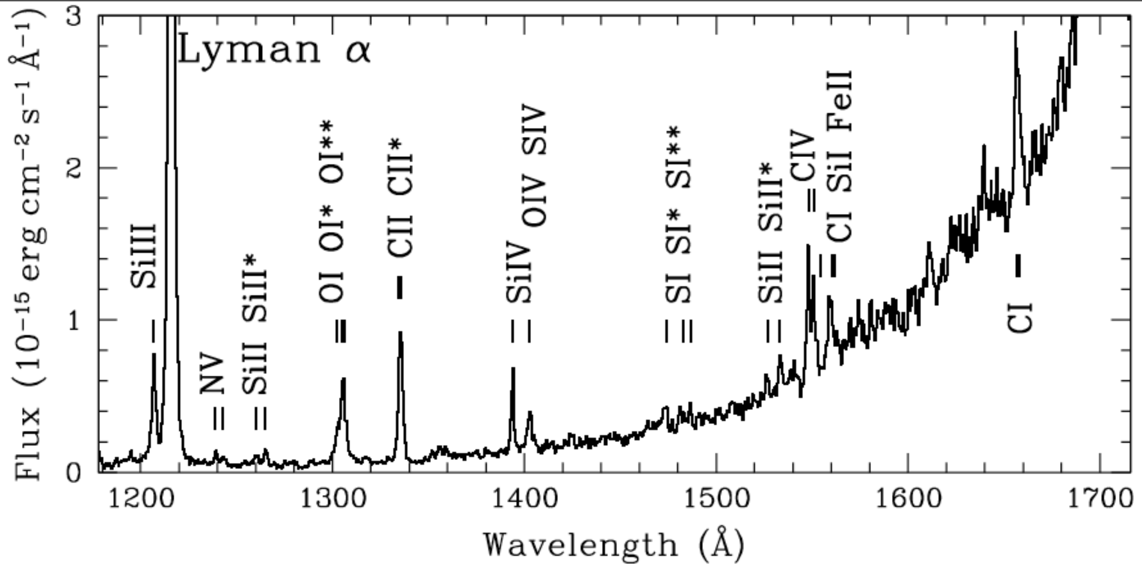


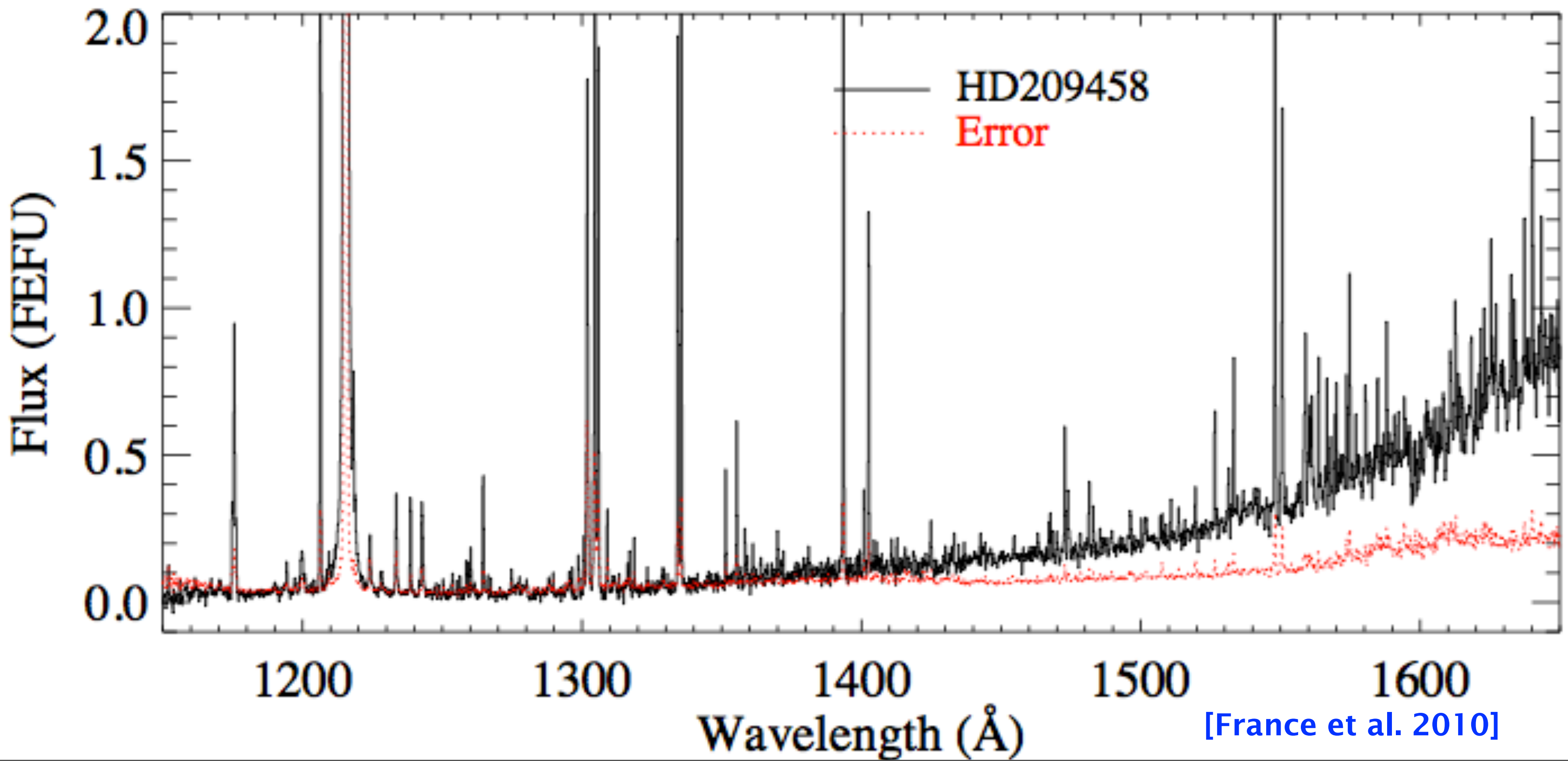


[France et al. 2010]

HD209458b

HST/COS vs STIS





[France et al. 2010]

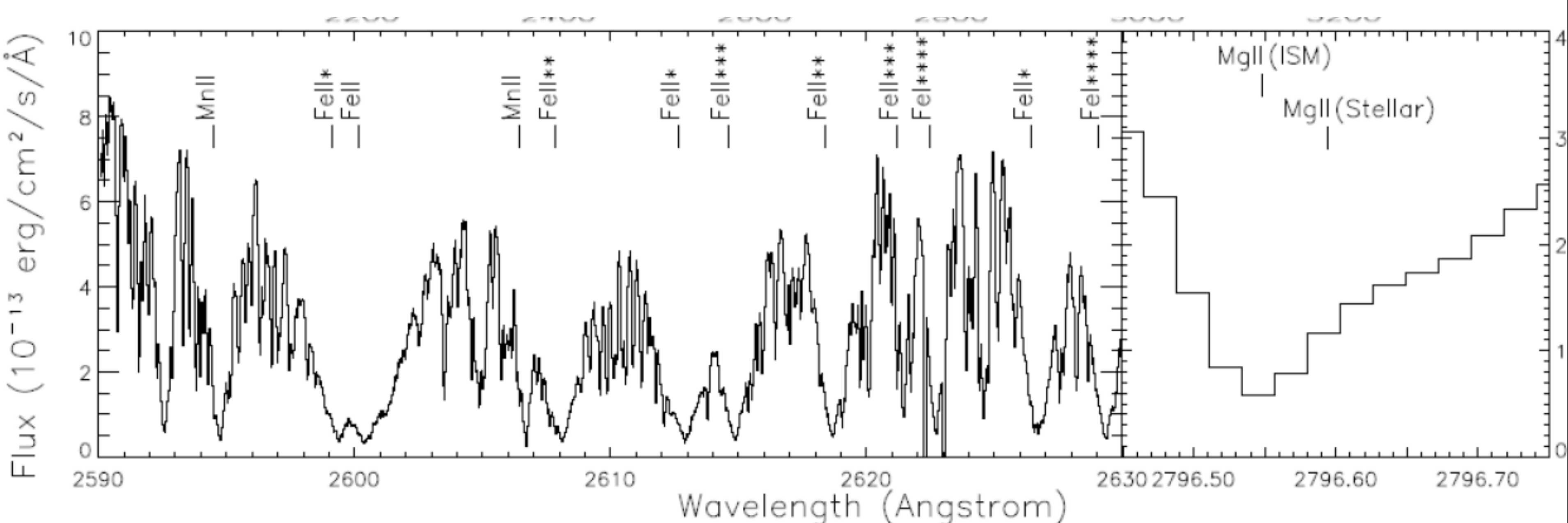
What’s next ?

High resolution observation (HST/STIS)

(PI: Désert)

- Blow-off ?
- Temperature ?
- Vertical density distribution ?

- Escape of heavier elements (FeI, MgII)
- Vertical density distribution
- Temperature at high altitude



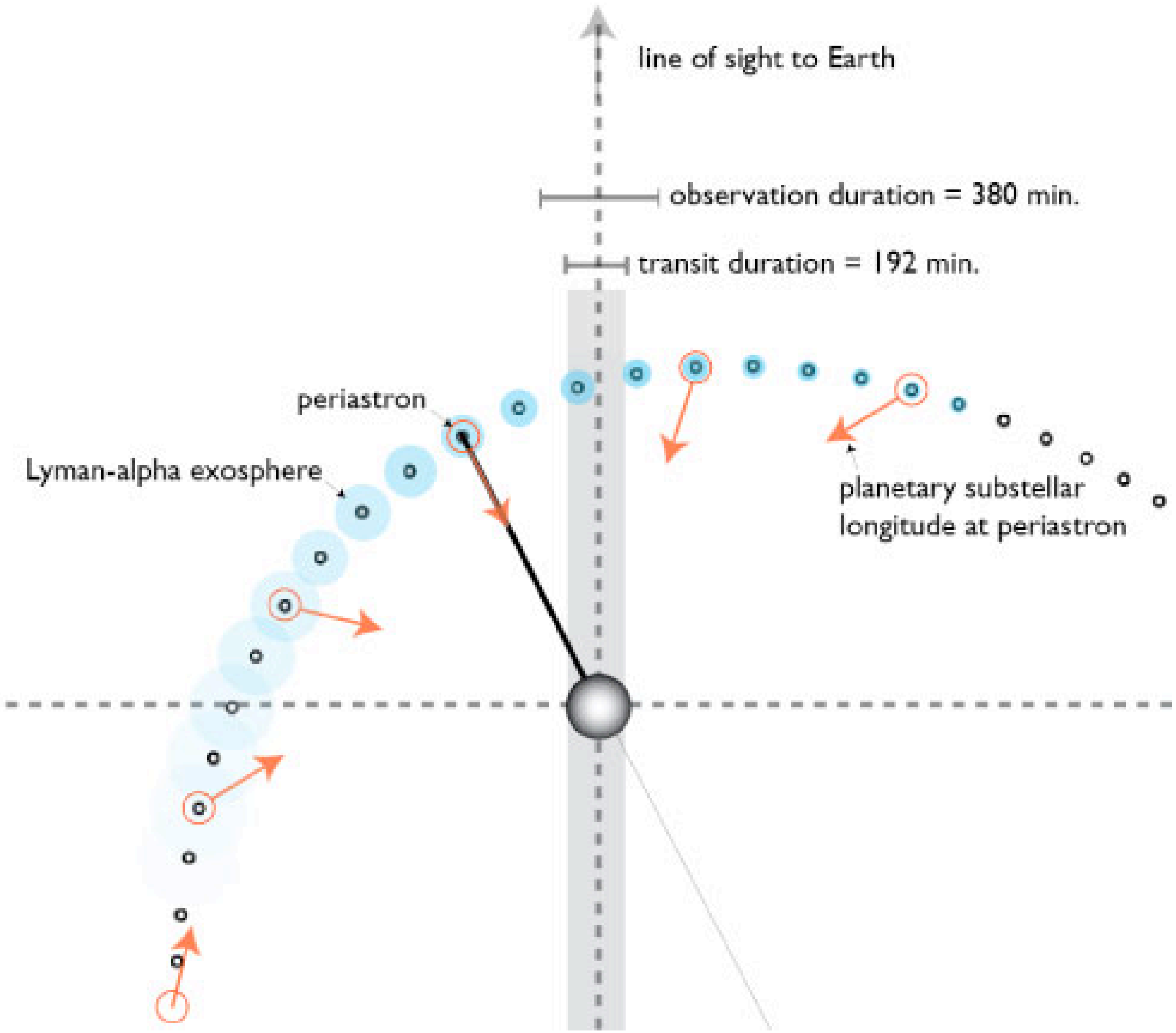
Towards smaller planets

HST/STIS proposal Cycle-18:

- GJ436b (PI : Ehrenreich)

- GJ1214b (PI : Désert)

HD 17156 b (from Greg Laughlin Systemic blog)



Remnants of evaporation?

- « Hot Neptunes »
  (hot hydrogen-poor Neptune-mass planets)

- « Massive Earths »
  (solid core)

Are some of the Neptune-mass planets evaporation-remnants?

➔ Corot & Kepler should be able to detect evaporation remnant at short orbital period.


Thank you !