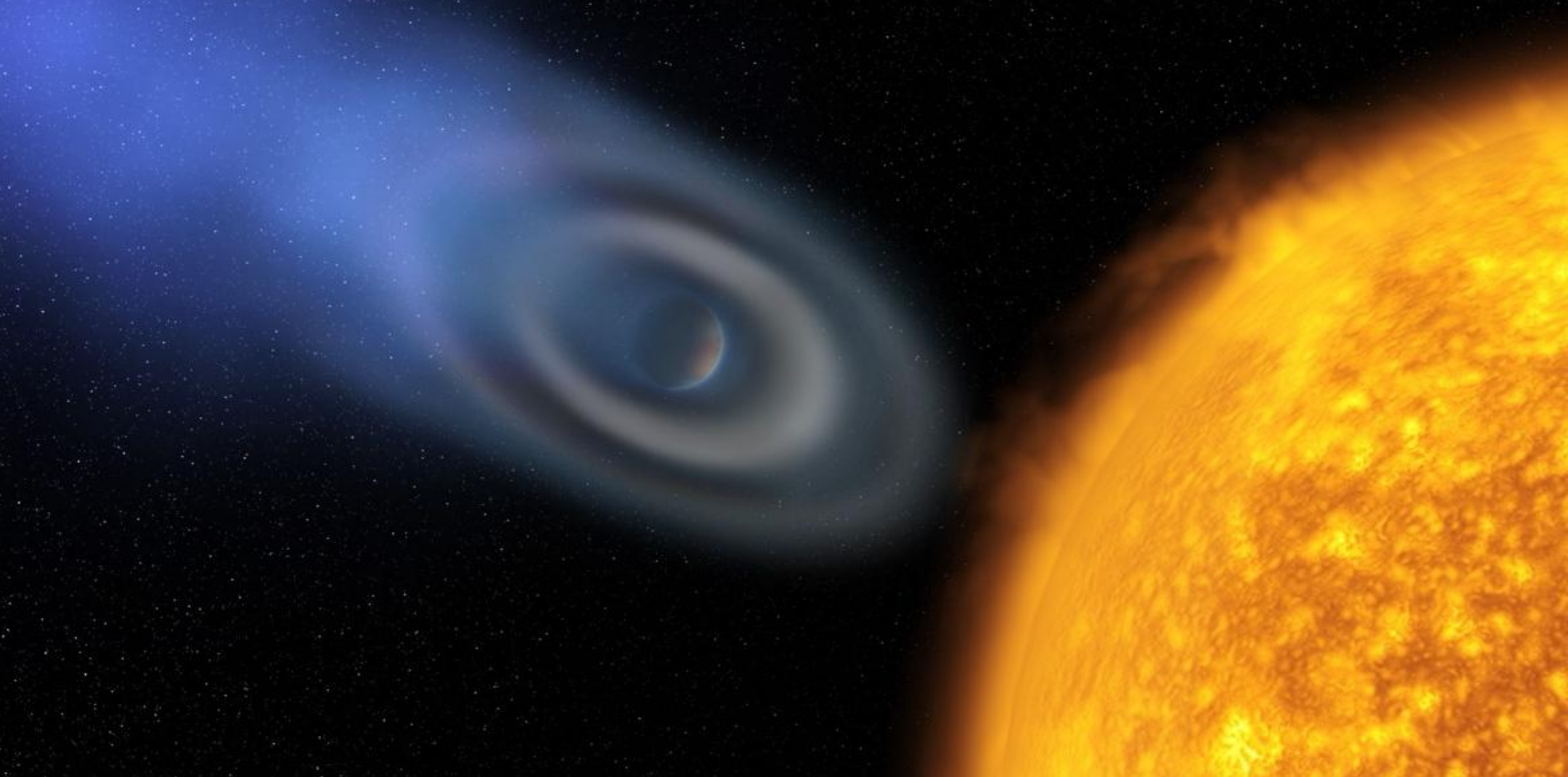
Evaporation of hot-Jupiters



Alain Lecavelier des Etangs

Institut d'Astrophysique de Paris

Evaporation of hot-Jupiters

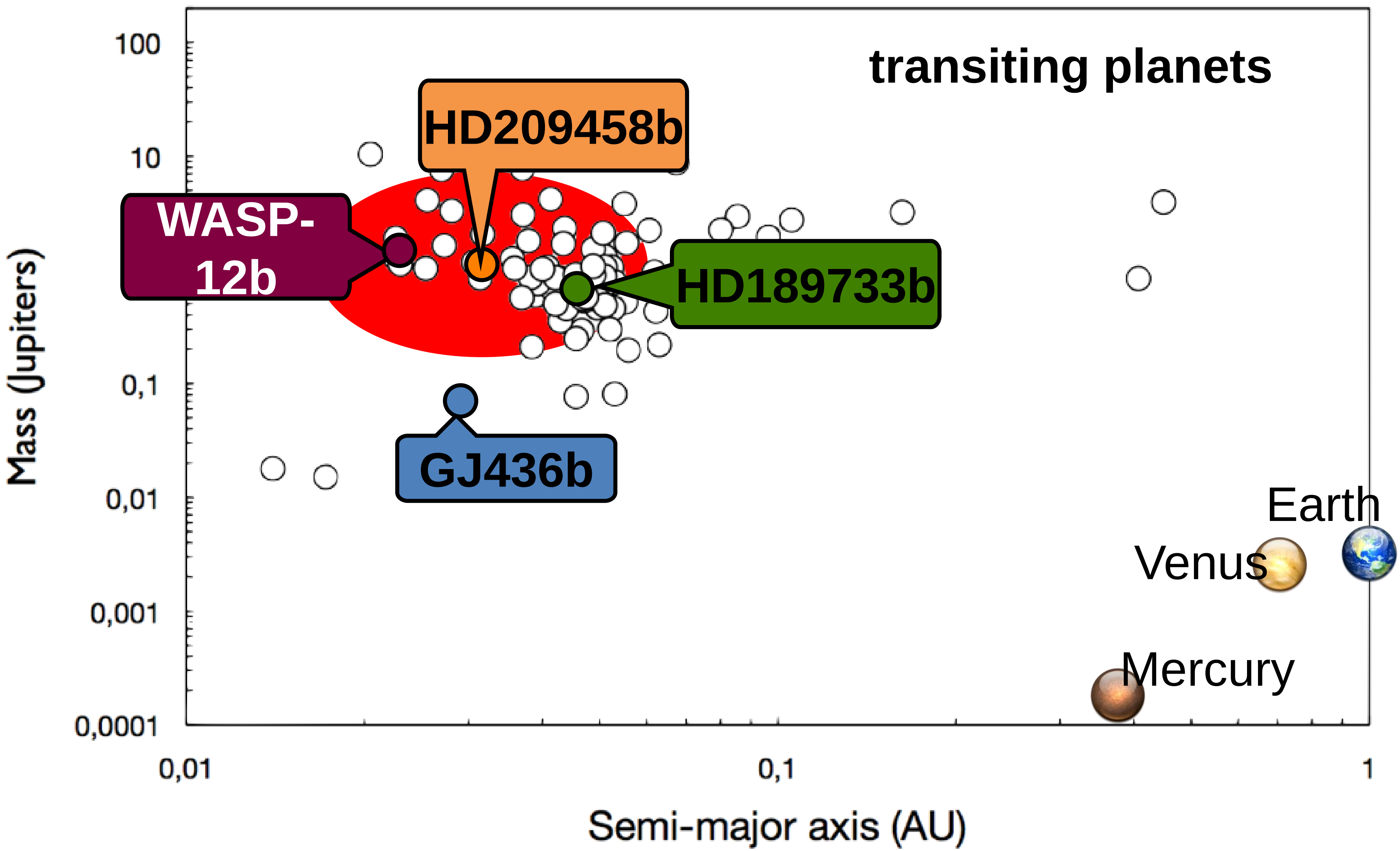
A. Vidal-Madjar (IAP)
F. Bouchy (OHP)
R. Diaz (IAP)
D. Ehrenreich (LAOG Grenoble)
R. Ferlet (IAP)
G. Hébrard (IAP)
A. Lecavelier des Étangs (IAP)

G. E. Ballester (U. Arizona)
J.-M. Désert (CfA Havard)
Gopal-Krishna (NCRA-TIFR)
M. Mayor (Obs. Genève)
J. C. McConnell (York Univ.)
F. Pont (Exeter, UK)
D. Sing (Exeter, UK)
S. K. Sirothia (NCRA-TIFR)

Outline

- Observations of transit in Lyman-α ➔ Evaporation
- From Lyman-α absorption to escape rate
- Models of upper atmosphere and evaporation
- Energy diagram and evaporation remnants
- HD 189733b / Wasp-12b other evaporating planets

Hot exoplanets in transit



An extended upper atmosphere around the extrasolar planet HD209458b

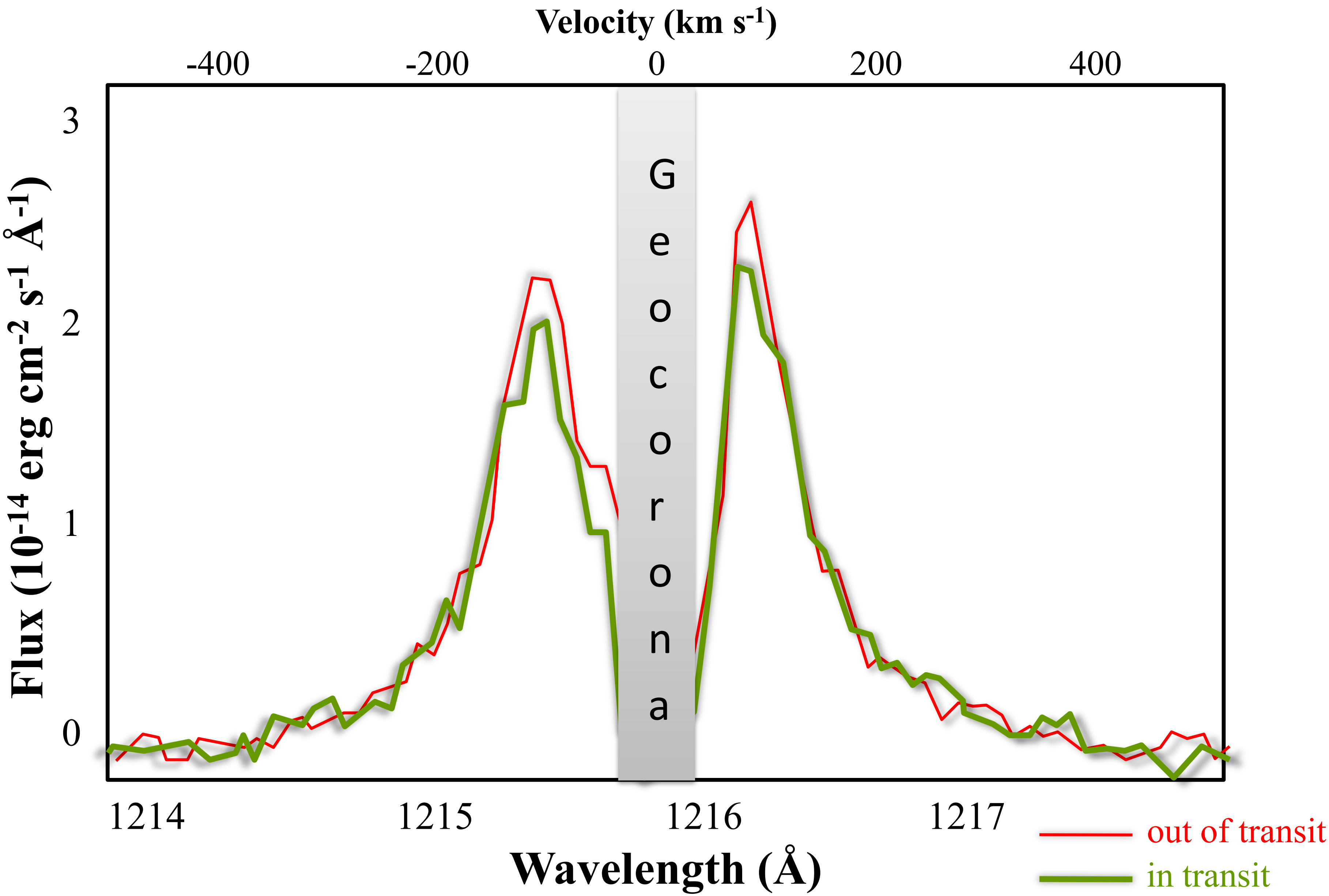
A. Vidal-Madjar*, A. Lecavelier des Etangs*, J.-M. Désert*, G. E. Ballester†, R. Ferlet*, G. Hébrard* & M. Mayor‡

** Institut d'Astrophysique de Paris, CNRS/UPMC, 98bis boulevard Arago, F-75014 Paris, France*
† Lunar and Planetary Laboratory, University of Arizona, 1040 E. 4th St., Rm 901, Tucson, Arizona 85721-0077, USA
‡ Observatoire de Genève, CH-1290 Sauverny, Switzerland

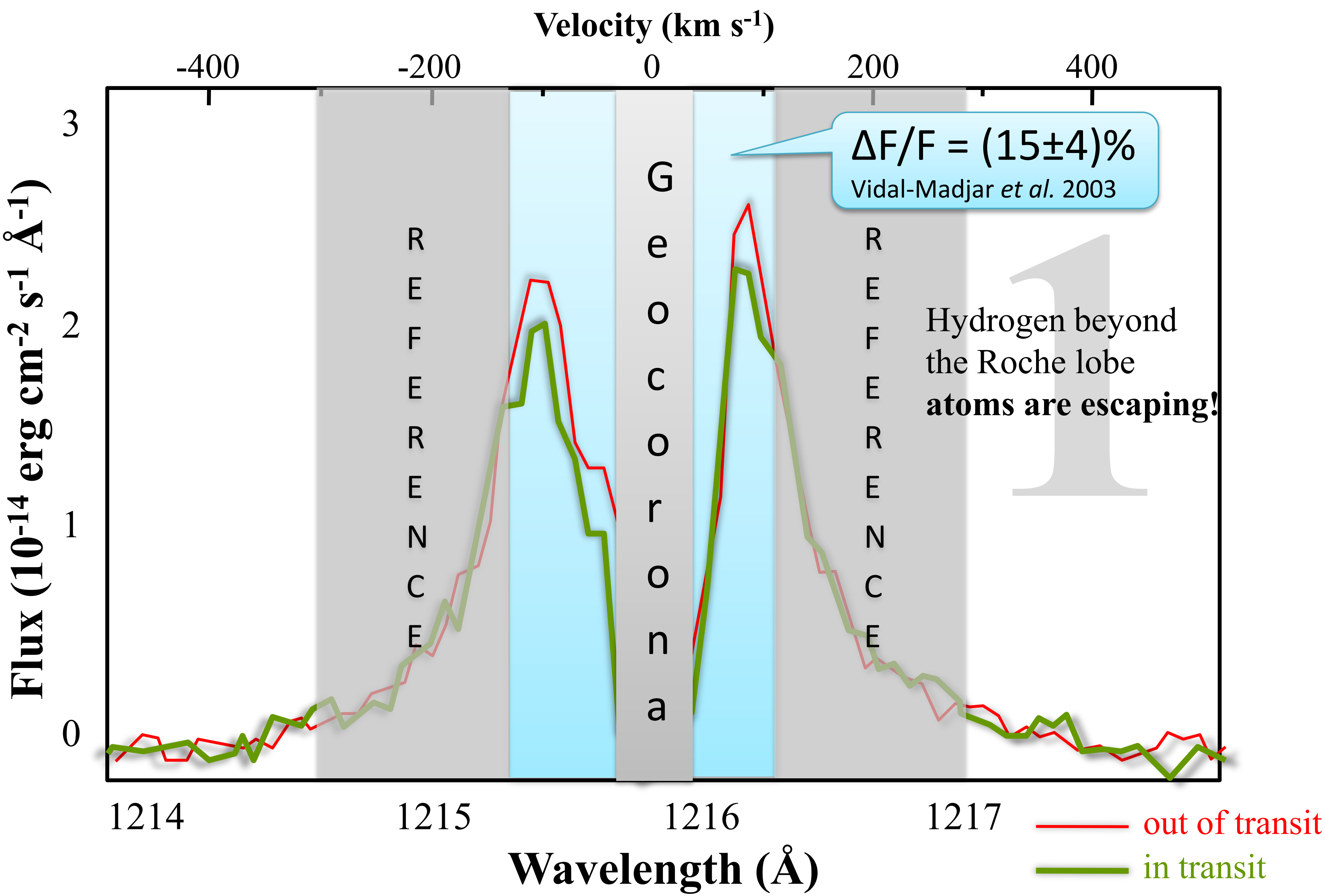
The planet in the system HD209458 is the first one for which repeated transits across the stellar disk have been observed[1,2]. Together with radial velocity measurements[3], this has led to a determination of the planet's radius and mass, confirming it to be a gas giant. But despite numerous searches for an atmospheric signature[4–6], only the dense lower atmosphere of HD209458b has been observed, through the detection of neutral sodium absorption[7]. Here we report the detection of atomic hydrogen absorption in the stellar Lyman α line during three transits of HD209458b. An absorption of $15 \pm 4\%$ (1σ) is observed. Comparison with models shows that this absorption should take place beyond the Roche limit and therefore can be understood in terms of escaping hydrogen atoms.

Far more abundant than any other species, hydrogen is well-suited for searching weak atmospheric absorptions during the

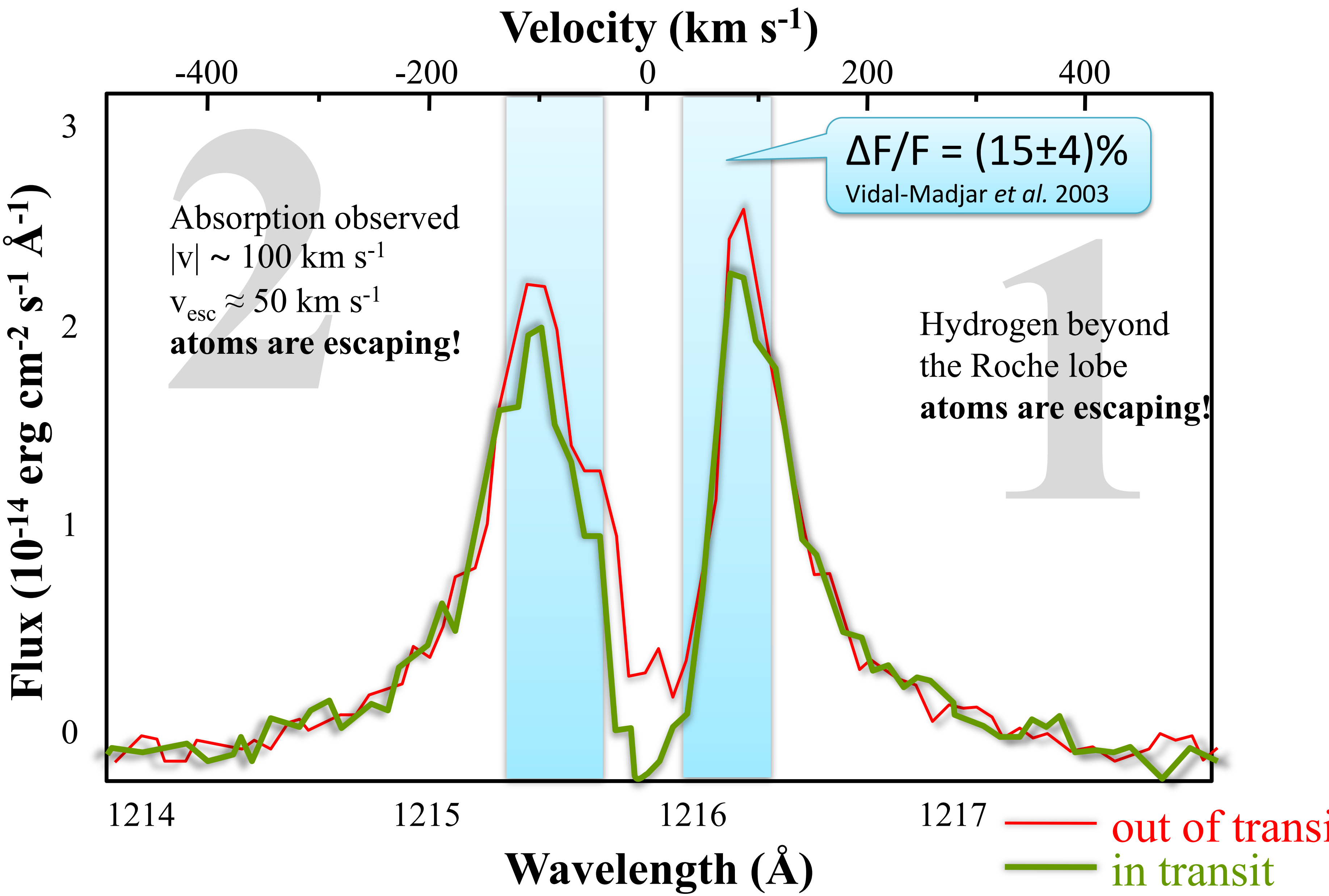
Observations of transits at Lyman α



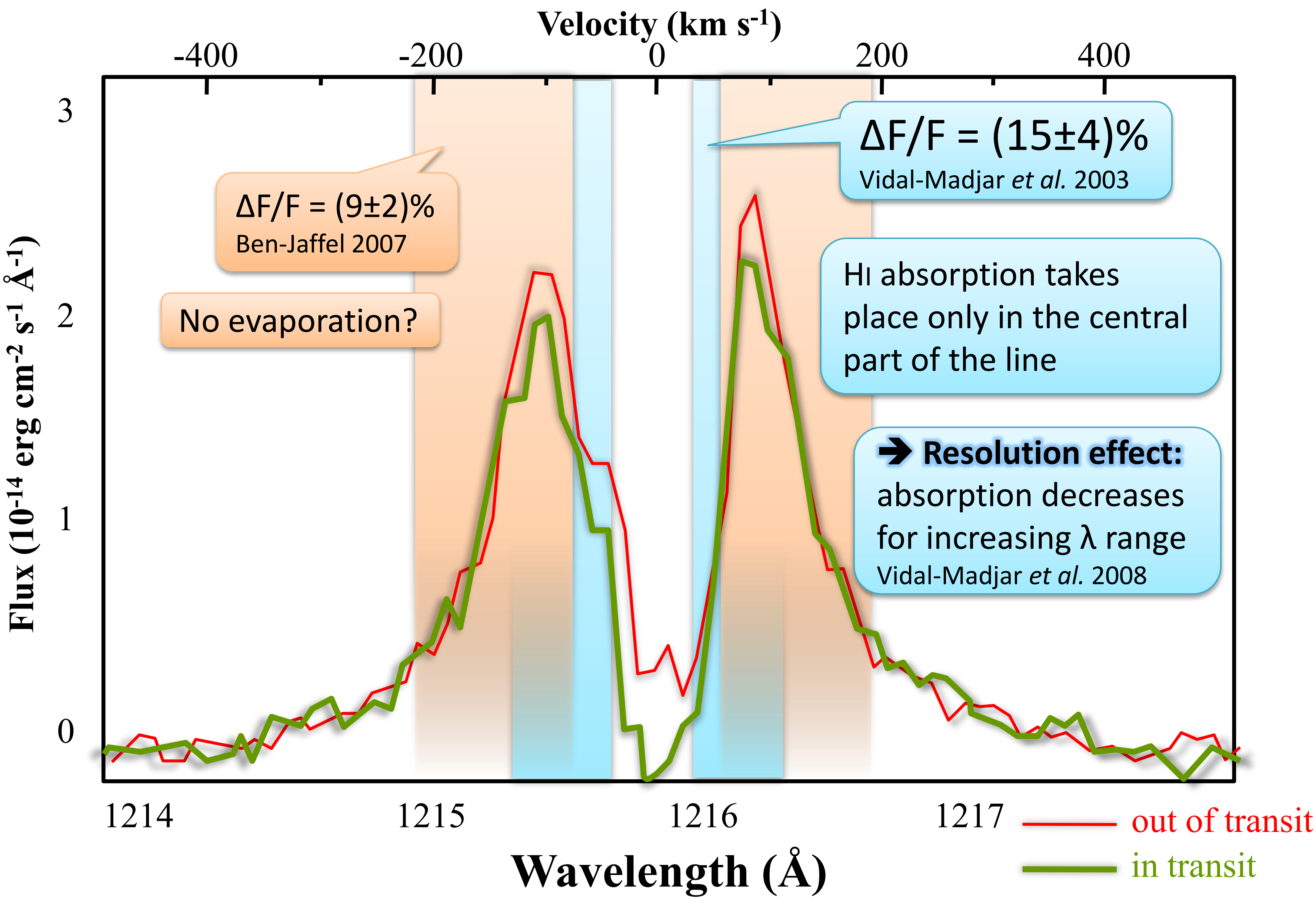
Detection of exospheric hydrogen



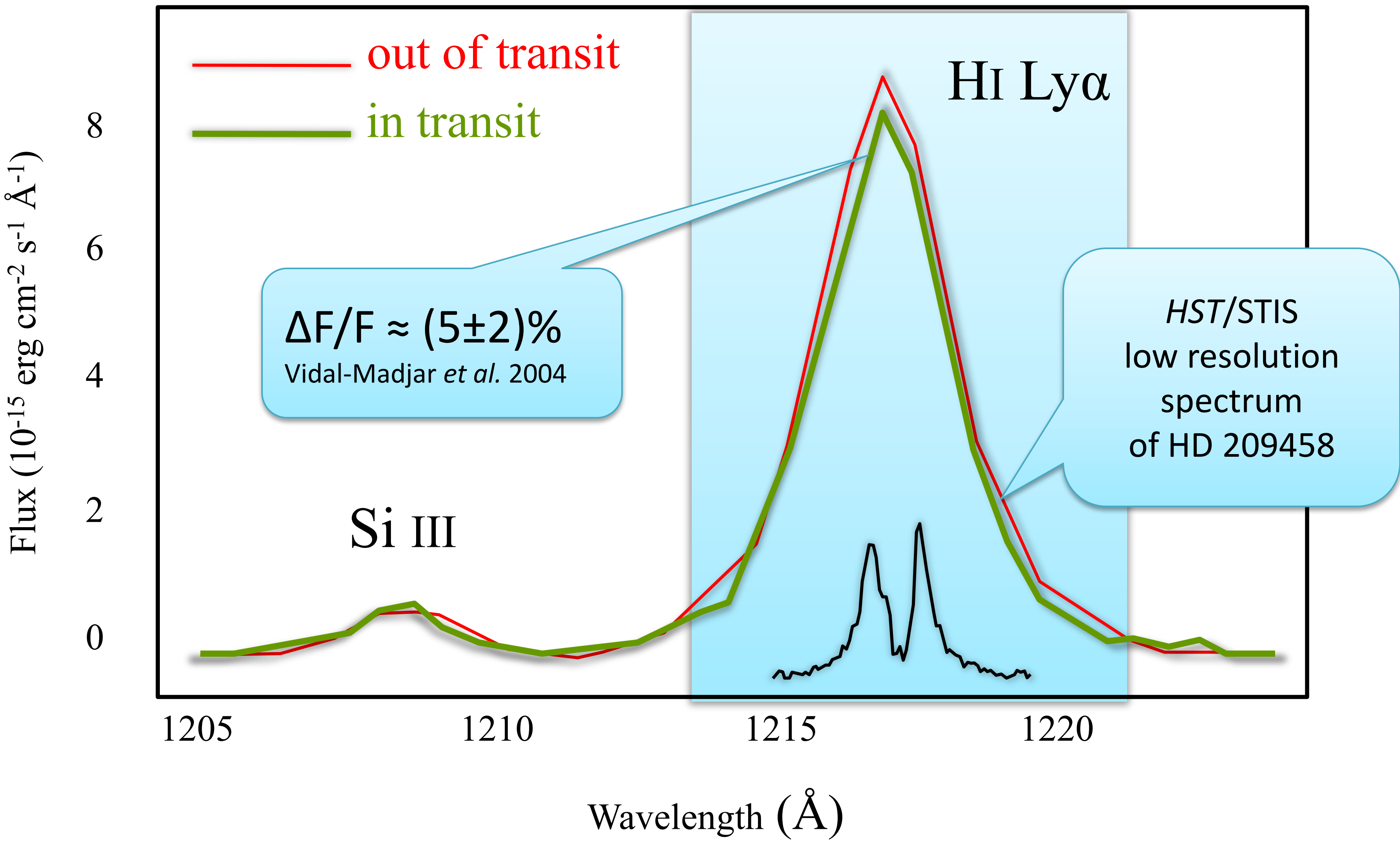
Detection of exospheric hydrogen



Detection of exospheric hydrogen



Absorption over unresolved Ly-α line



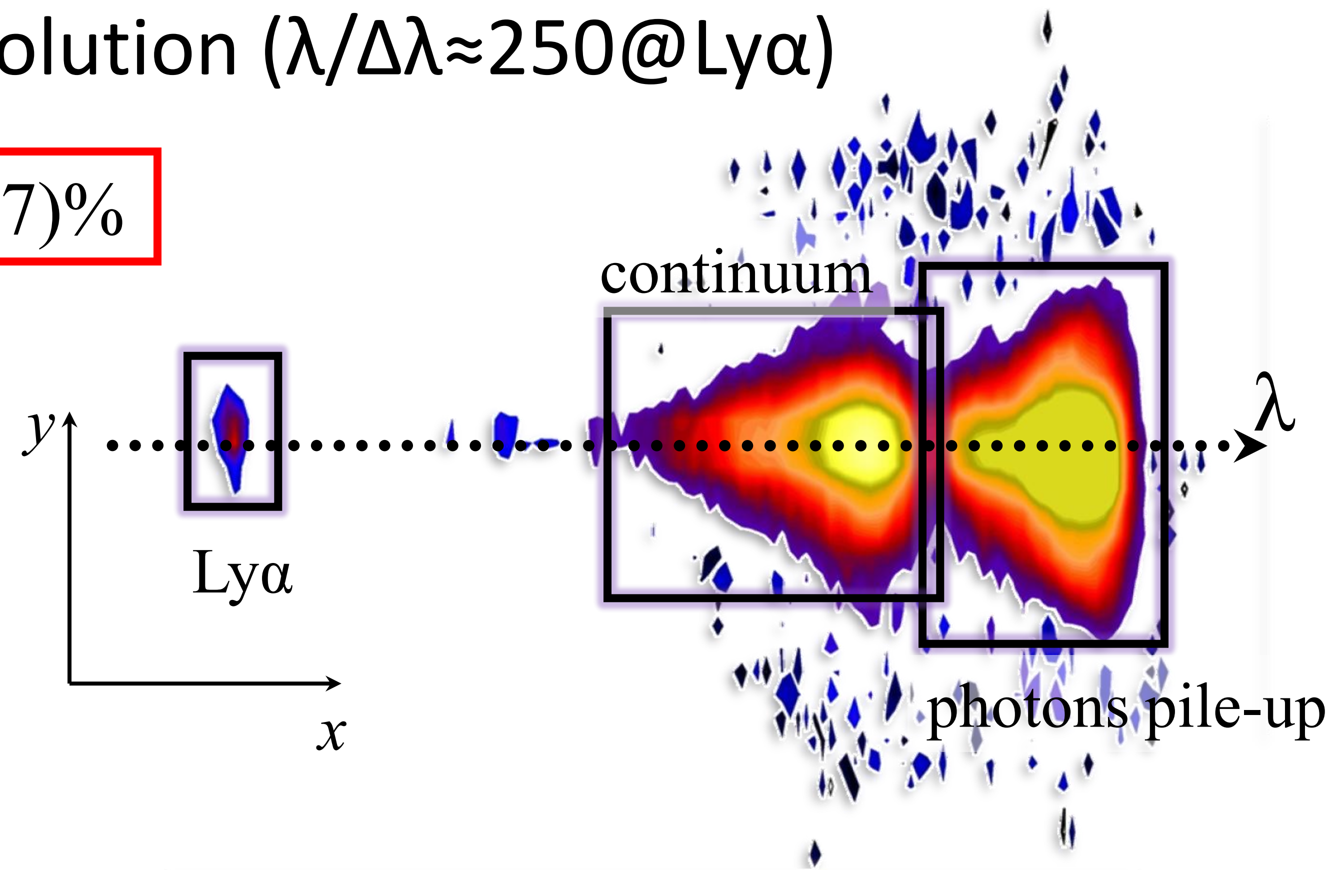
(Vidal-Madjar et al. 2004)

Lyman-α HST/ACS observations of HD 209458b

(Ehrenreich et al. 2008)

- Slitless spectroscopy with ACS
  → Low resolution (λ/Δλ≈250@Lyα)

ΔF/F= (8.0±5.7)%



Summary of the HI detection of HD209458b exosphere

- (15±4)% From -130 to 100 km/s (Med-res data; Vidal-Madjar et al. 2003)
- (5.7±1.5)% On the whole line (Low-res data; Vidal-Madjar et al. 2004)
- (8.9±2.1)% From -200 to 200 km/s (Med-res data; Ben-Jaffel 2007)
- (8.0±5.7)% On the whole line (ACS data; Ehrenreich et al. 2008)

3 models to interpret the observations and estimate the escape rate

- *Vidal-Madjar 2003; Lecavelier des Etangs et al. :*
  Radiation pressure, F_{EUV} ionization

- *Schneiter et al. 2007 :*
  Interaction between escaping gas and stellar wind

- *Holstrom et al. 2008, Ekenbäck et al. 2010:*
  Energetic Neutral Atoms (ENA) from stellar wind

Estimation of the escape rate

(Vidal-Madjar et al. 2003; Lecavelier des Etangs et al.)

N-body Particle simulation:

- Both planetary and stellar gravity taken into account
- Hydrogen atoms sensitive to stellar radiation pressure:

  - radiation pressure as a function of the radial velocity
  - extinction of Ly-α within the escaping hydrogen cloud

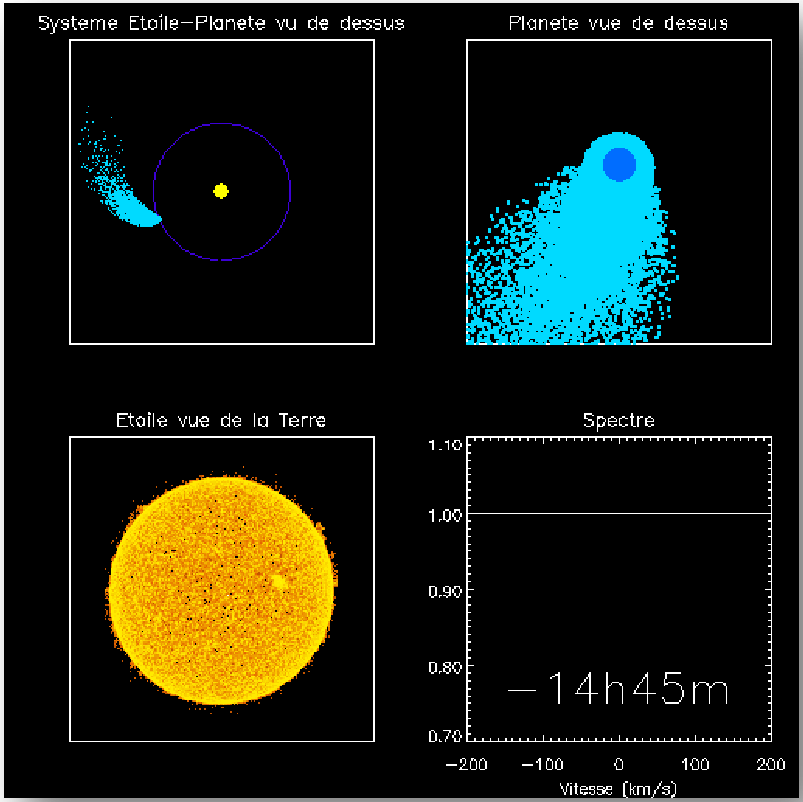
- Neutral hydrogen ionized by EUV photons
  (lifetime ~ few hours)

  - extinction of ionizing photons within the hydrogen cloud

Estimation of the escape rate

(Vidal-Madjar et al. 2003; Lecavelier des Etangs et al.)

N-body Particle simulation:



$\Delta F/F = 15\%$:

F_{EUV} =1 solar: **dM/dt~$10^{9.5}$ g/s**

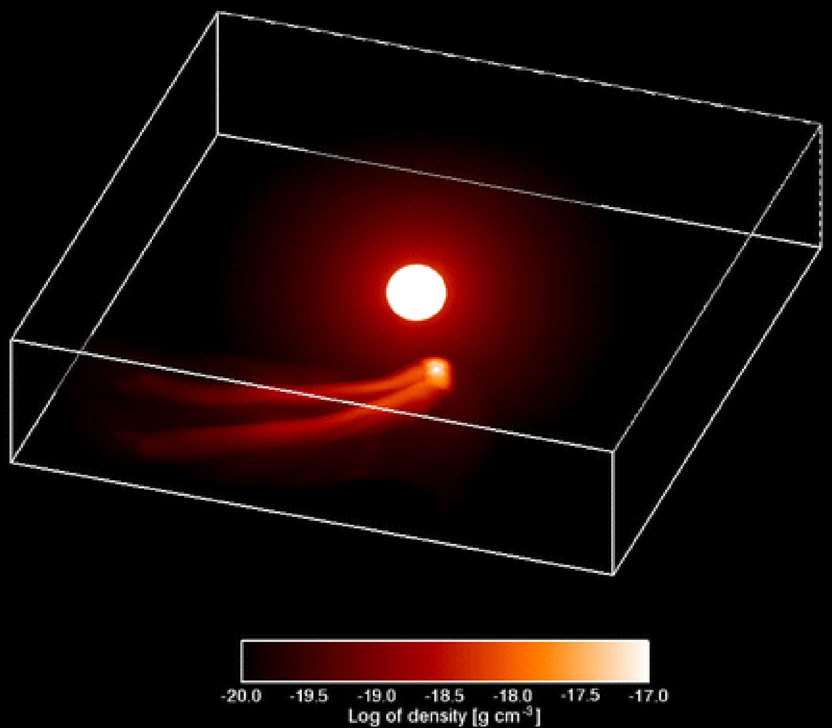
F_{EUV} =2 solar: **dM/dt~$10^{10.5}$ g/s**

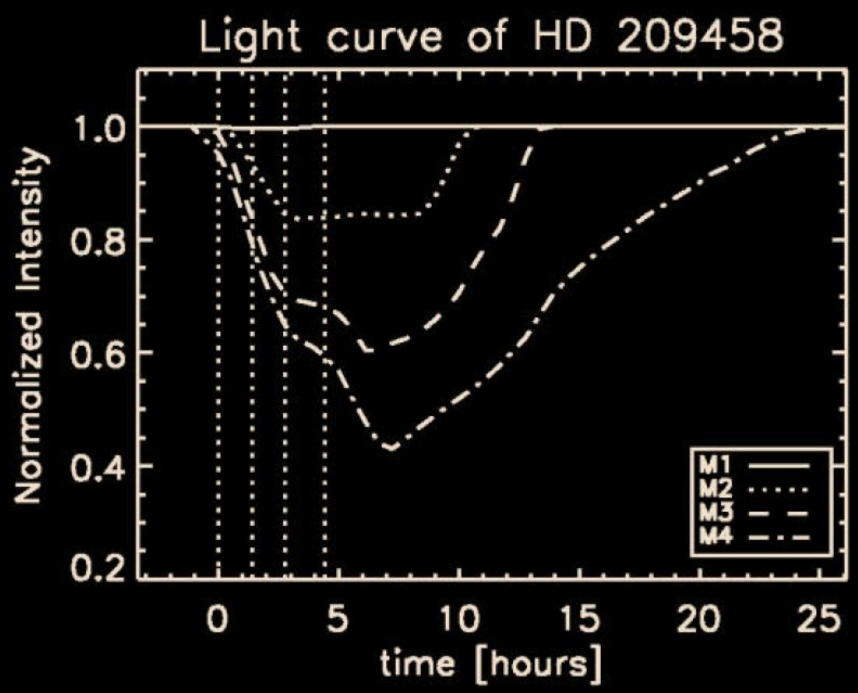
F_{EUV} =4 solar: **dM/dt~$10^{11.5}$ g/s**

Interaction between escaping gas and stellar wind

(Schneiter et al. 2007)

➔ $dM/dt = 1.1 +/- 0.3\ 10^{10}$ g/s

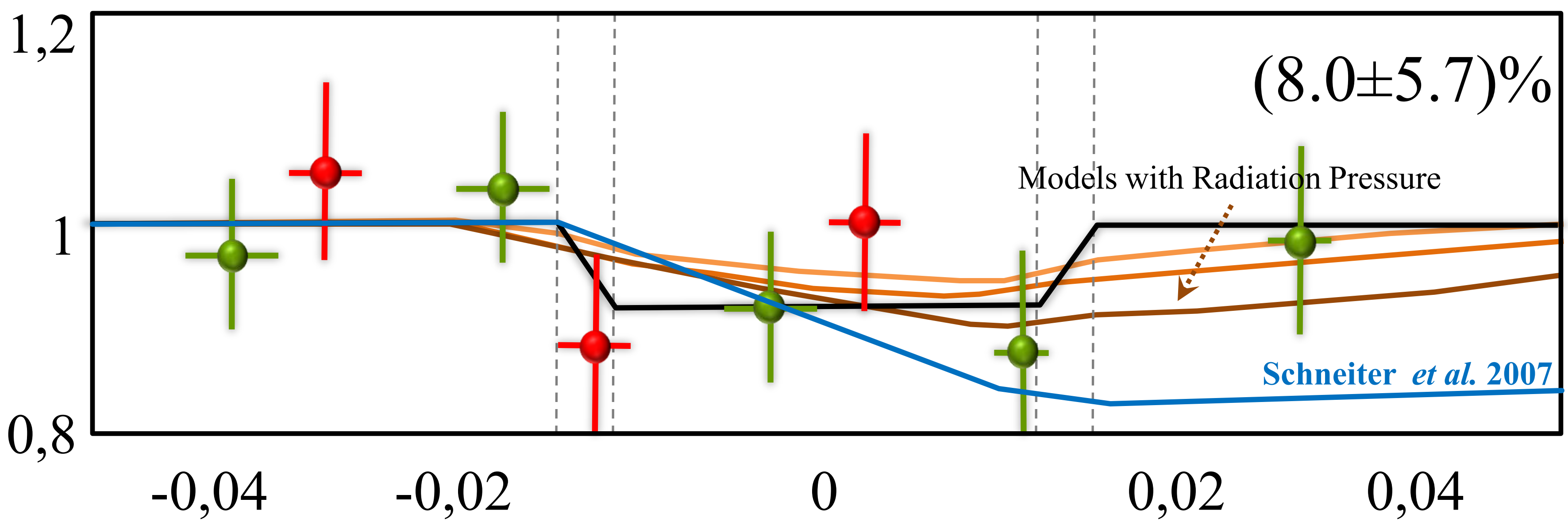




Lyman-α ACS observations of HD209458b

(Ehrenreich et al. 2008)

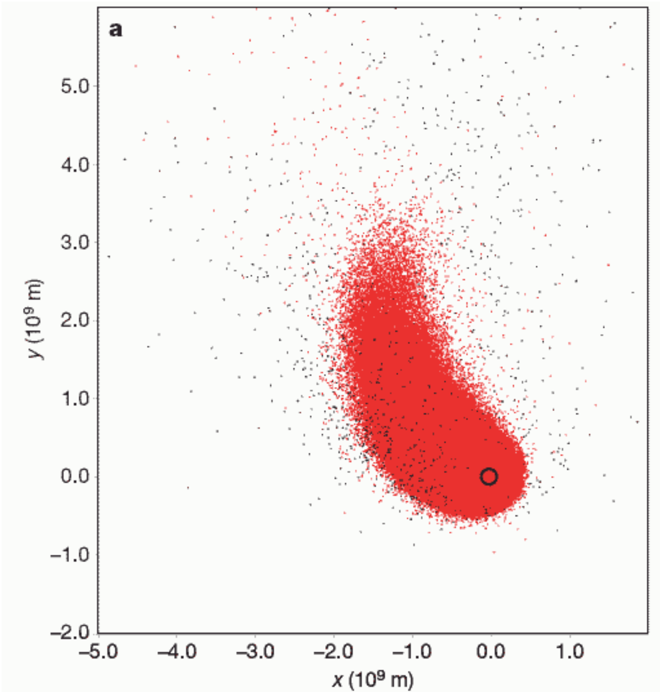
→ Measurement after the transit



Energetic Neutral Atoms (ENA) from stellar wind

(Holmstrom et al. 2008, Ekenbäck et al. 2010)

- Charge exchange between stellar wind protons and planetary exosphere atoms
- Holstrom et al. (2008) needed extraordinary condition for the stellar wind: $T=10^6$ K, 50 km/s
  ➔ Ekenbäck et al. 2010 solve this issue and use a solar-type wind
- Radiation pressure has been decreased to 2-5 times lower than solar value
- Escape from the planet is required



3 models to interpret the observations

- *Vidal-Madjar 2003; Lecavelier et al. :*
  ➔ $10^{9.5}$ g/s (F_{EUV}=1 solar) – $10^{11.5}$ g/s (F_{EUV}=4 solar)

- *Schneiter et al. 2007 :*
  ➔ $(1.1 \pm 0.3)\ 10^{10}$ g/s

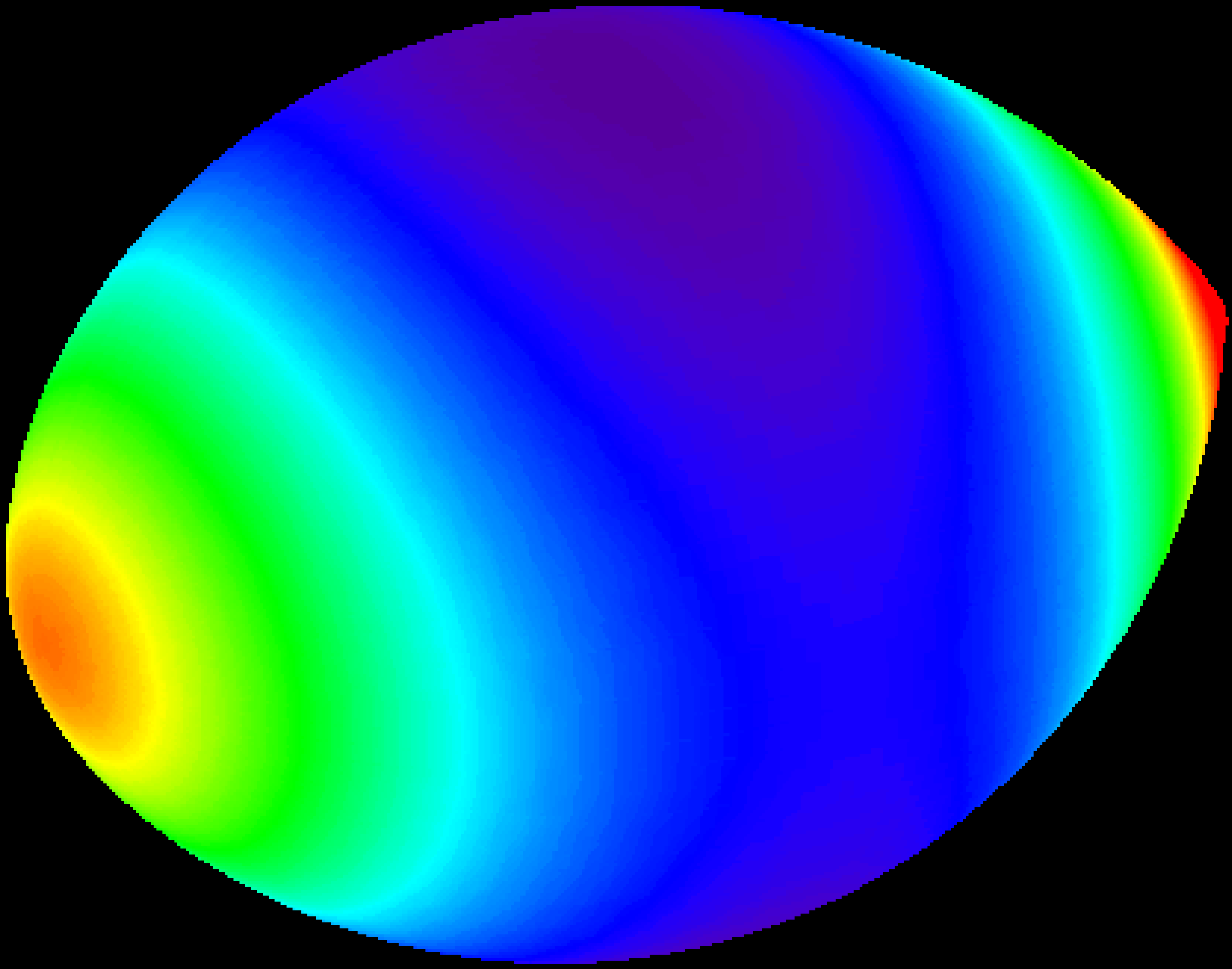
- *Holstrom et al. 2008:*
  ➔ ~ 10^{9} g/s

Numerous models to understand the escape rate

- 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
- Stone & Proga 2009
- Murray-Clay et al. 2009
- Ekenbäck et al. 2010
- Koskinen et al. 2010

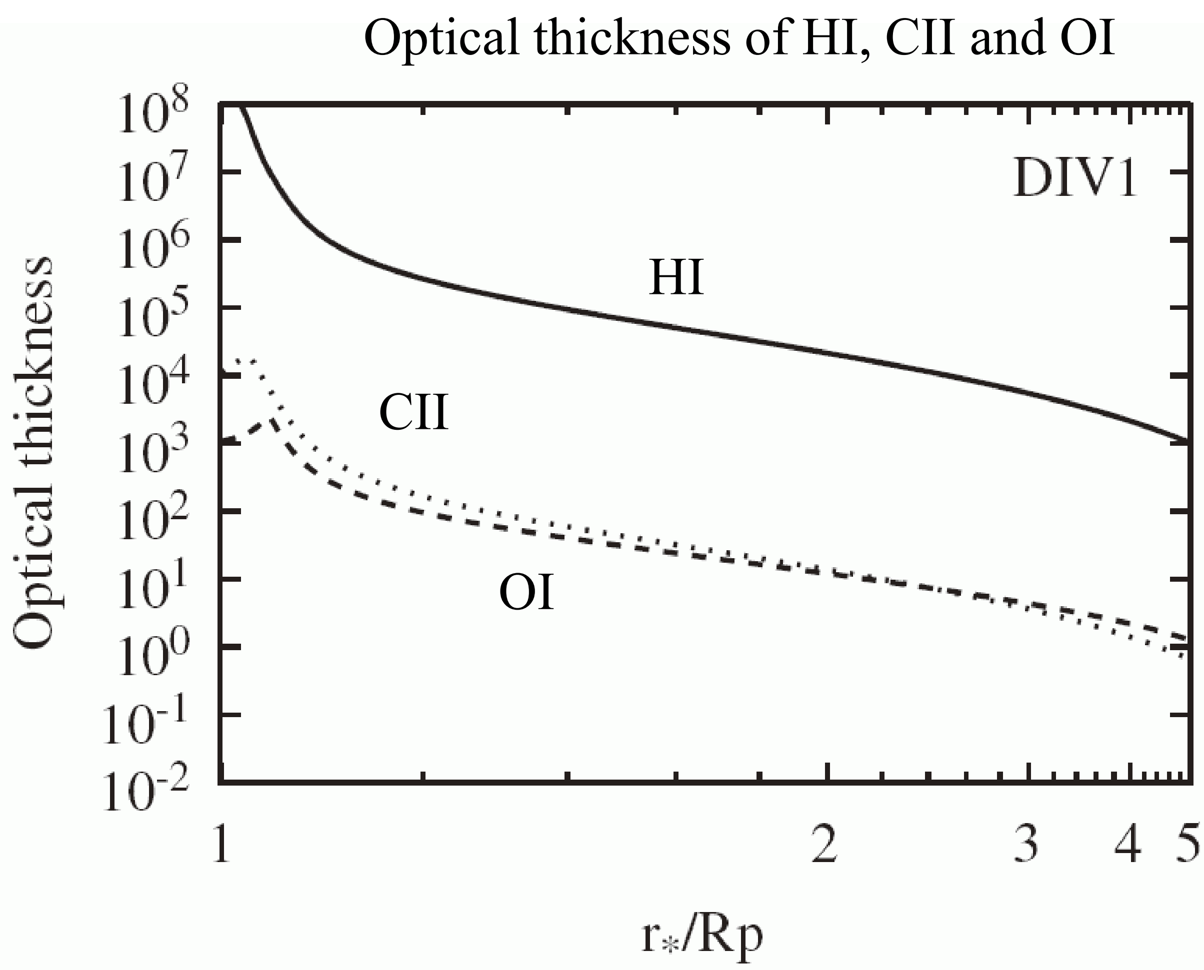
Thermosphere has a rugby-ball shape !

(Lecavelier des Etangs et al. 2004)



Physical and chemical aeronomy of HD209458b
(García Muñoz 2007)

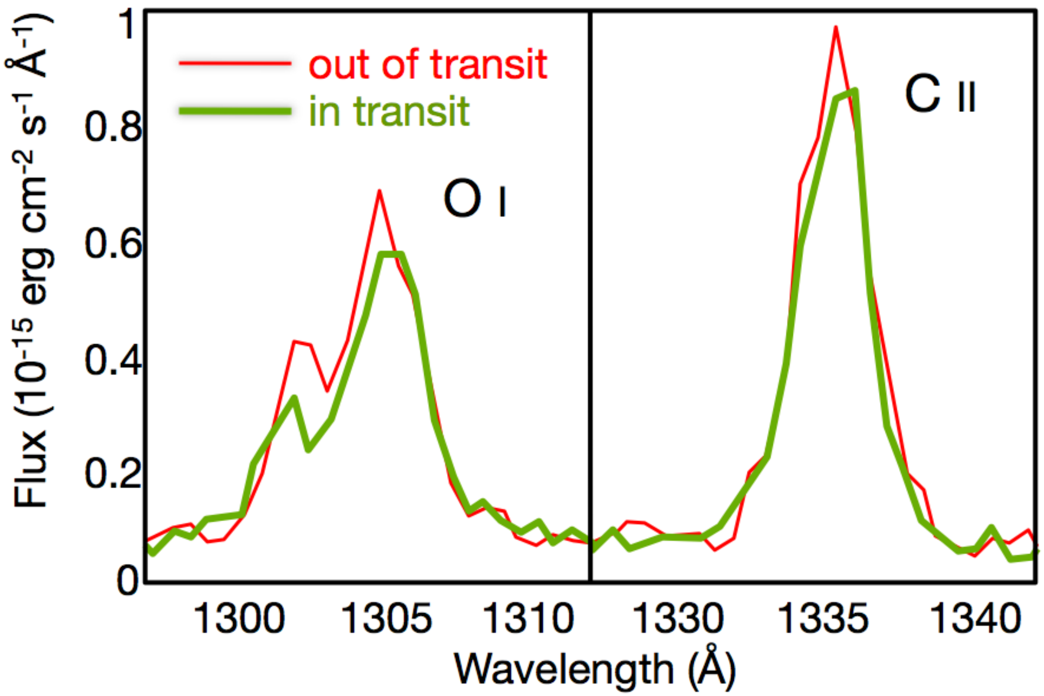
This model includes:
- Hydrodynamics
- Chemistry
- Tidal forces



Heavy elements escaping from HD209458b

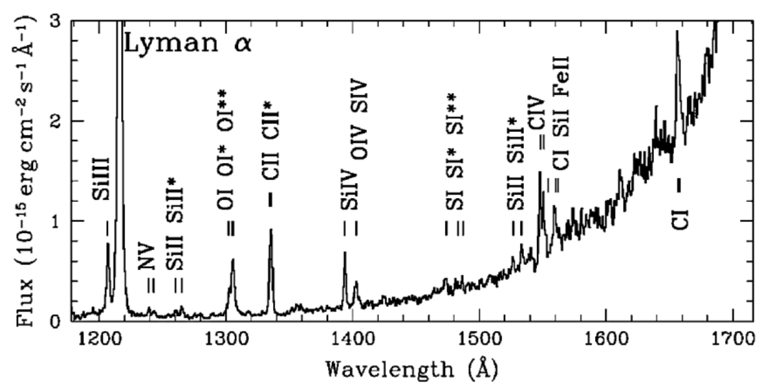
(Vidal-Madjar et al. 2004)

12.8±4.5% **7.5±3.6%**



➤ **O and C carried up by H flow**

➤ **hydrodynamic escape**

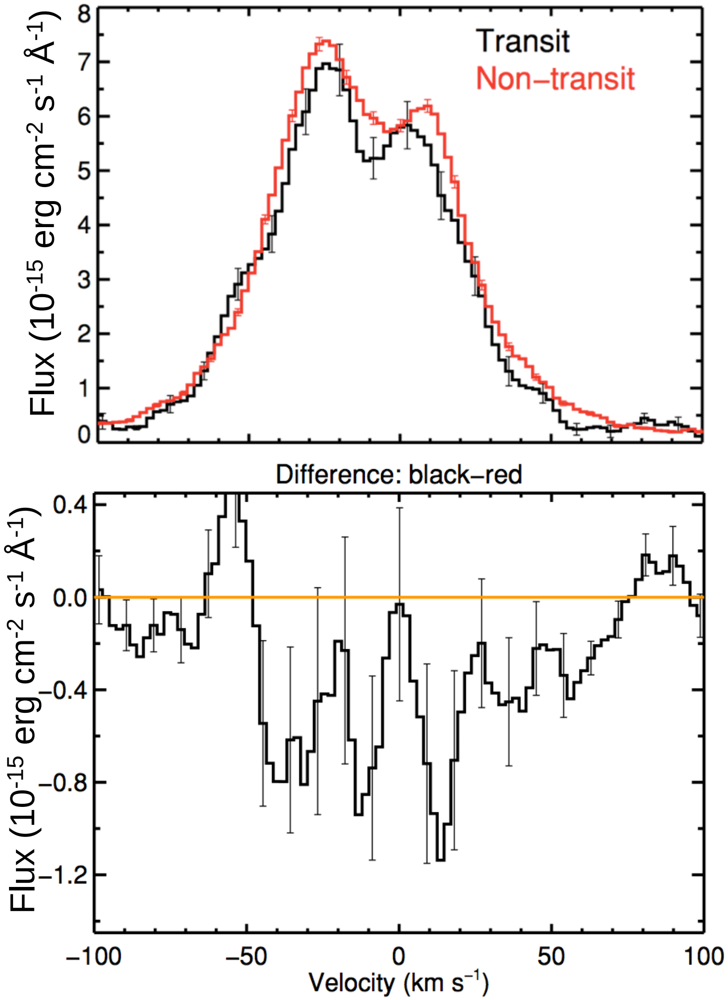


***HST*/STIS low resolution**

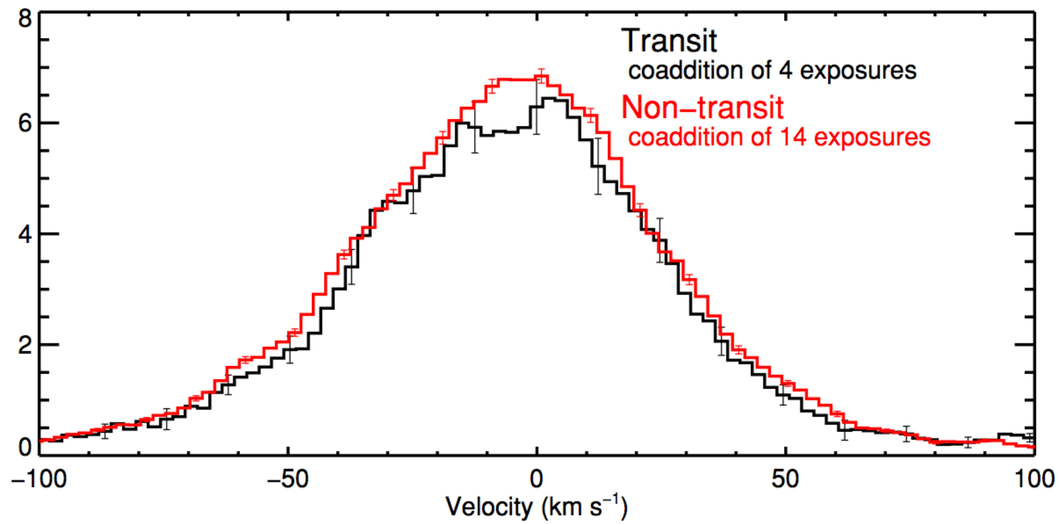
Heavy elements escaping from HD209458b

(Linsky et al. 2010)

C II : 7.8±1.3%



Si III : 8.2±1.4%



- ➢ **velocity structure**
- ➢ **cloud geometry?**

***HST*/COS high resolution**

Numerous models to understand the escape rate

- Lammer et al. 2003

→ $10^8 - 10^{12}$ g s^{-1}

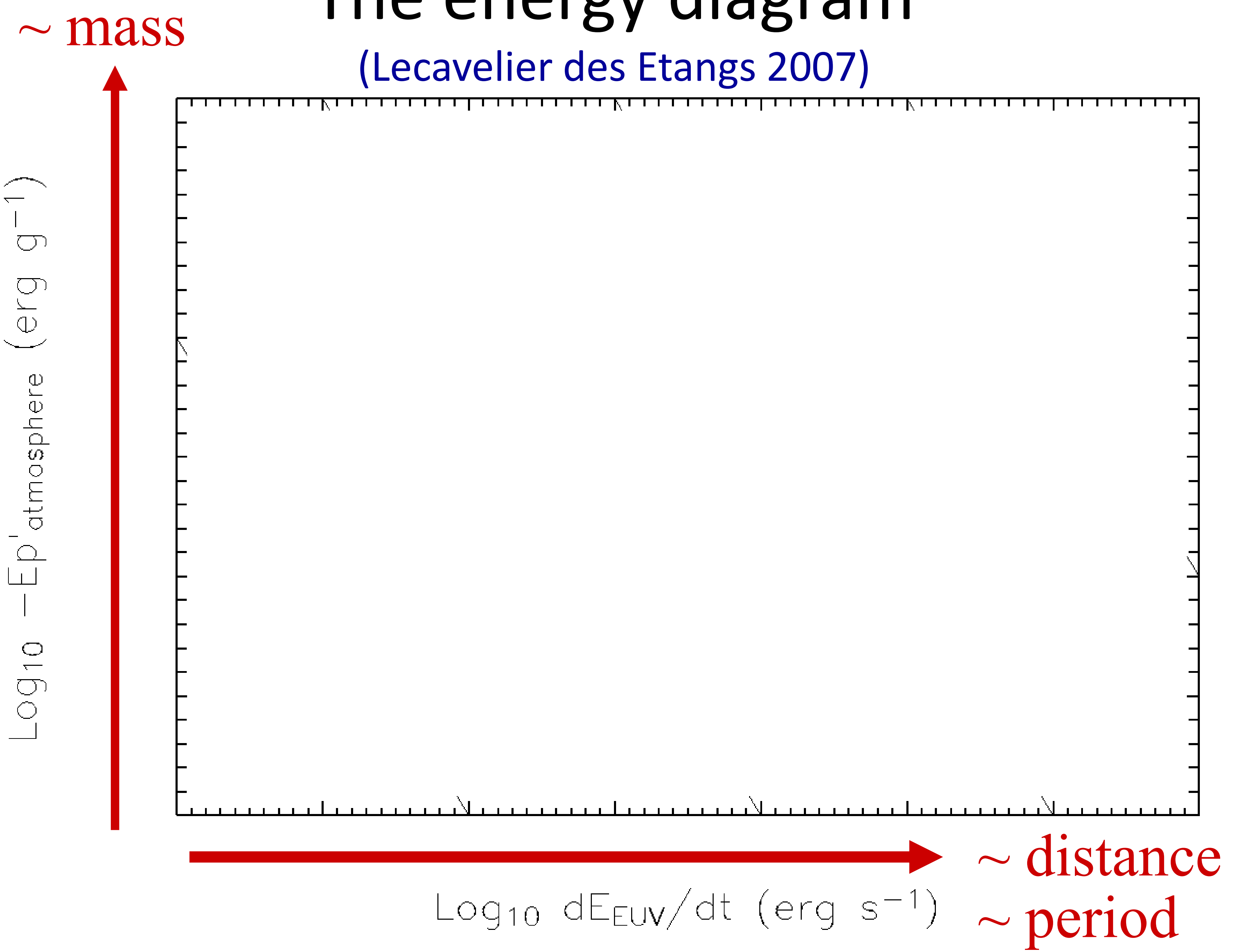
→ ~100% efficiency to convert EUV – X flux into escape

→ Energy diagram

- Koskinen et al. 2010

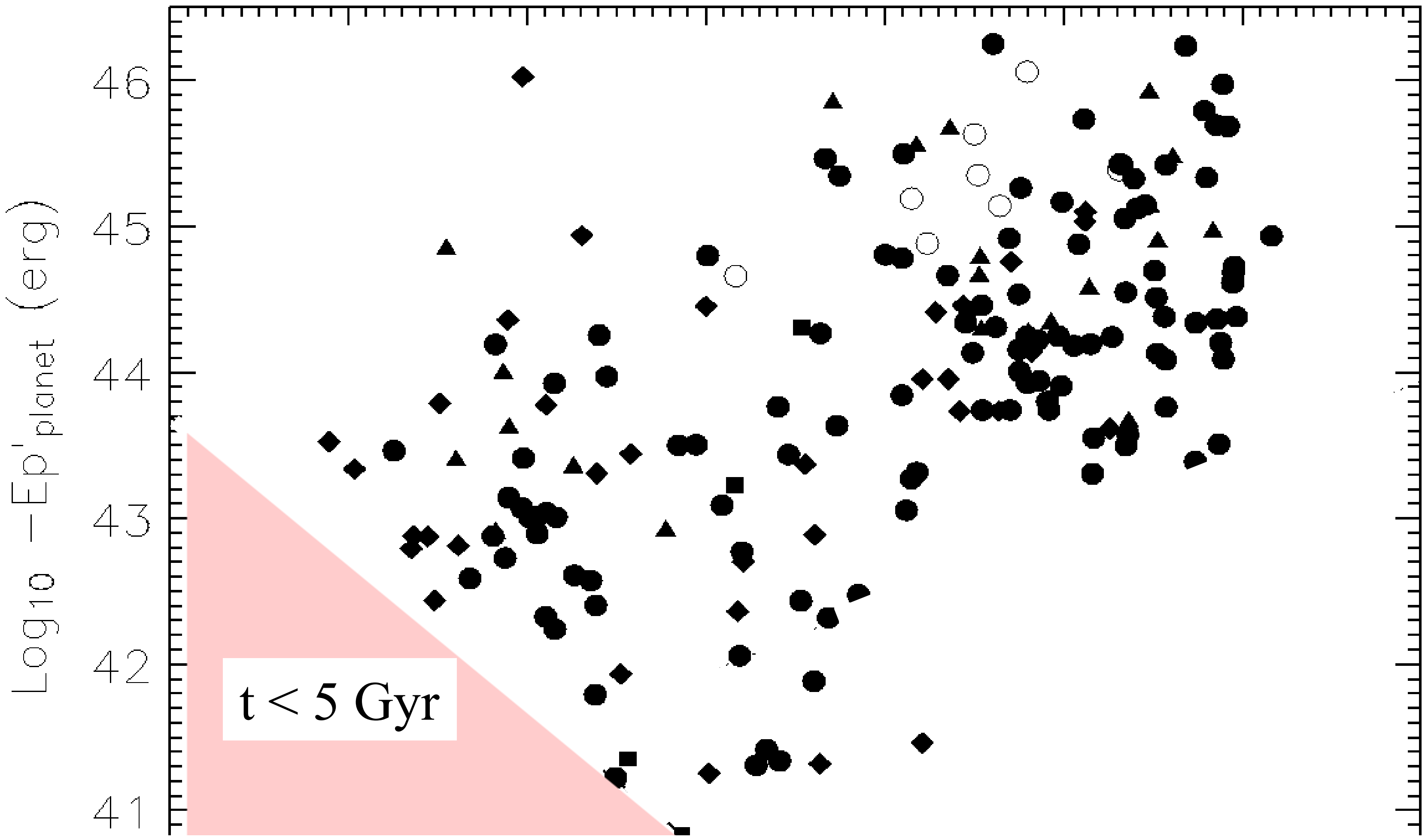
The energy diagram

(Lecavelier des Etangs 2007)



Life-time in the energy diagram

(Lecavelier des Etangs 2007)



Davis & Wheatley (2009) reach similar conclusions

Remnants of evaporation?

- « Hot Neptunes »

  (hot hydrogen-poor Neptune-mass planets)

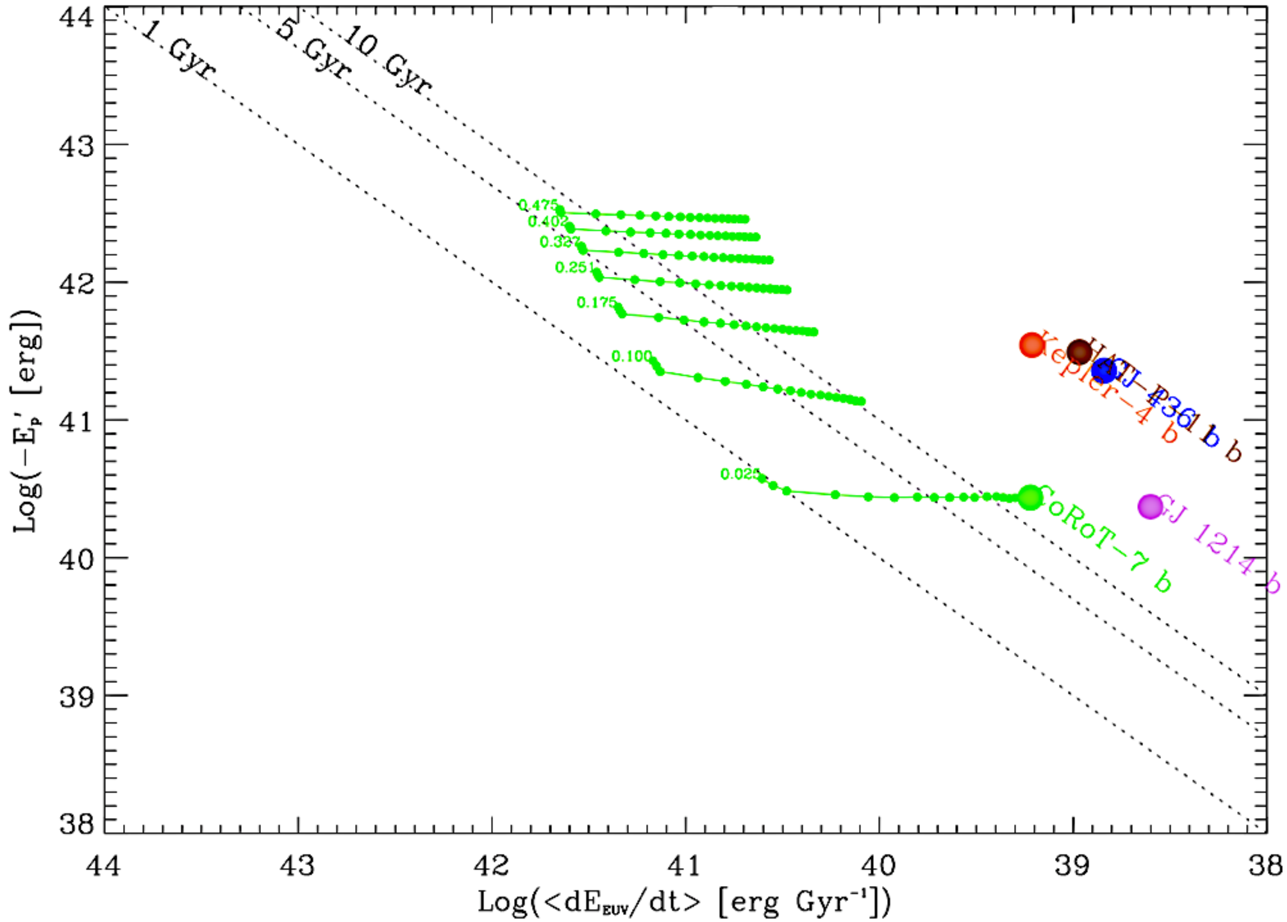
- « Massive Earths »

  (solid core)

Are some of the Neptune-mass or hot-super Earths evaporation-remnant ?

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

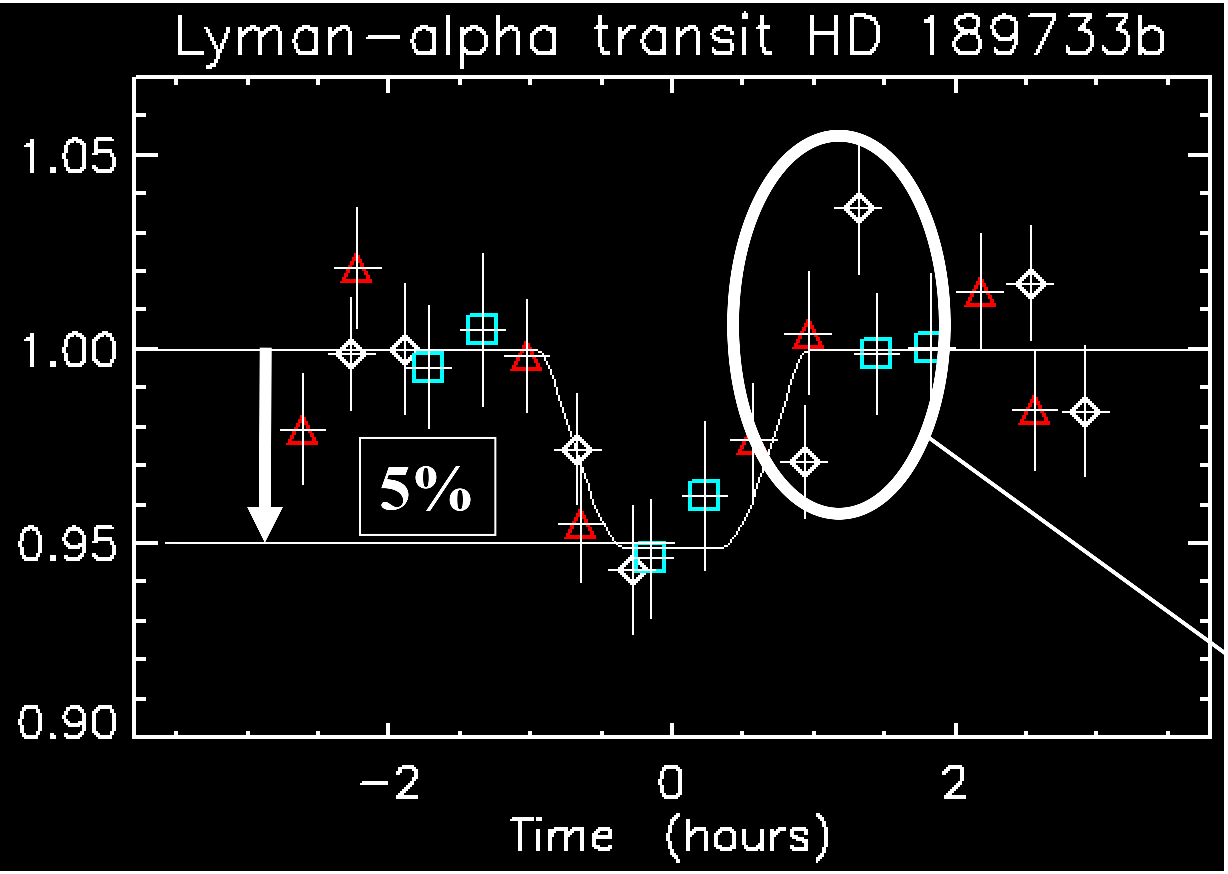
Ehrenreich & Désert, in prep.



See also : Jackson et al. 2010, Valencia et al. 2010

HST/ACS Lyman-α observation of HD 189733b

(Lecavelier des Etangs et al. 2010)



Results:

• Depth ~ 5.1 ± 0.7 %

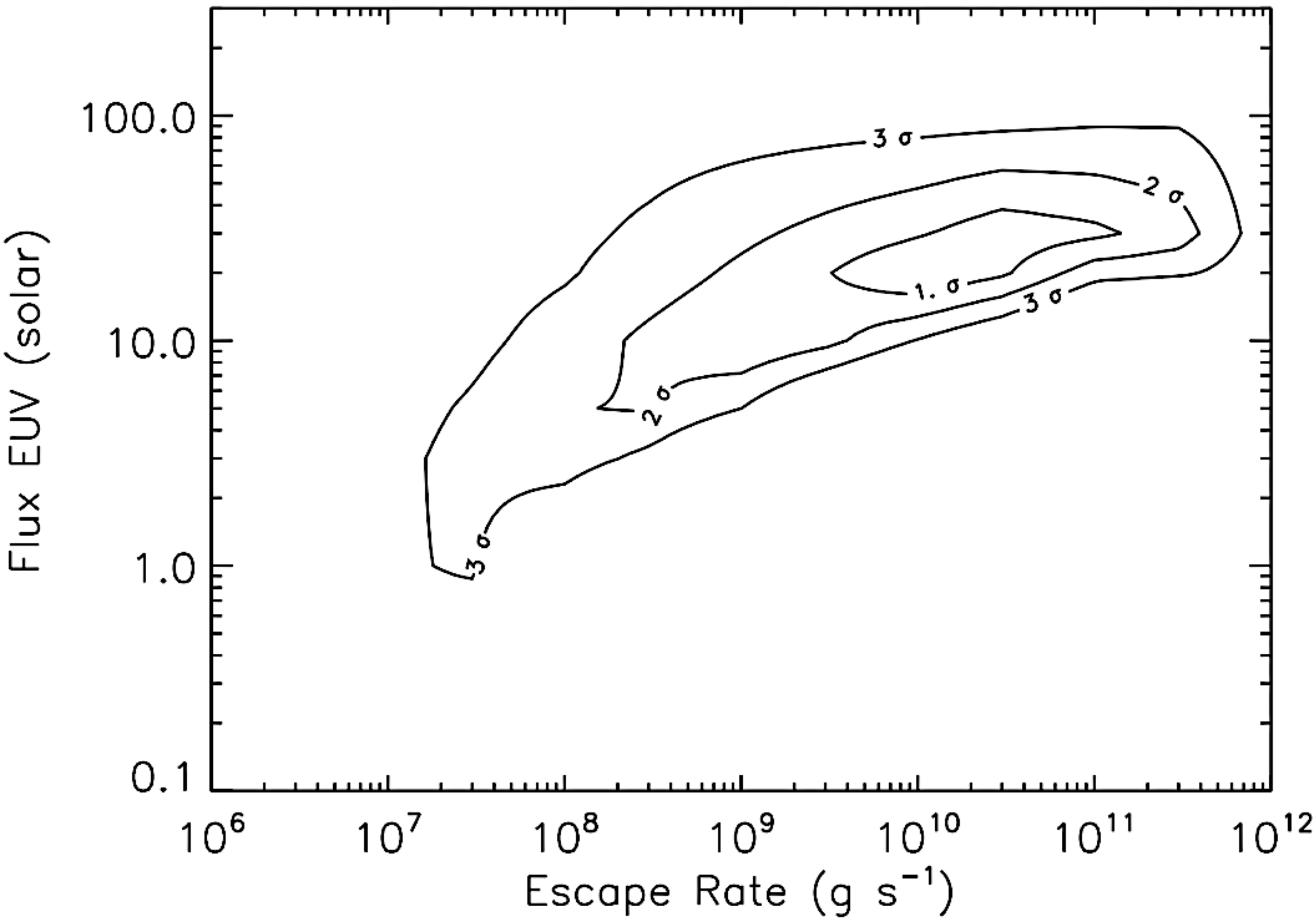
⇒ dM/dt ~ 10^9 -10^{11} g/s

• No tail of occulting HI

⇒ large ionizing EUV from the central K star

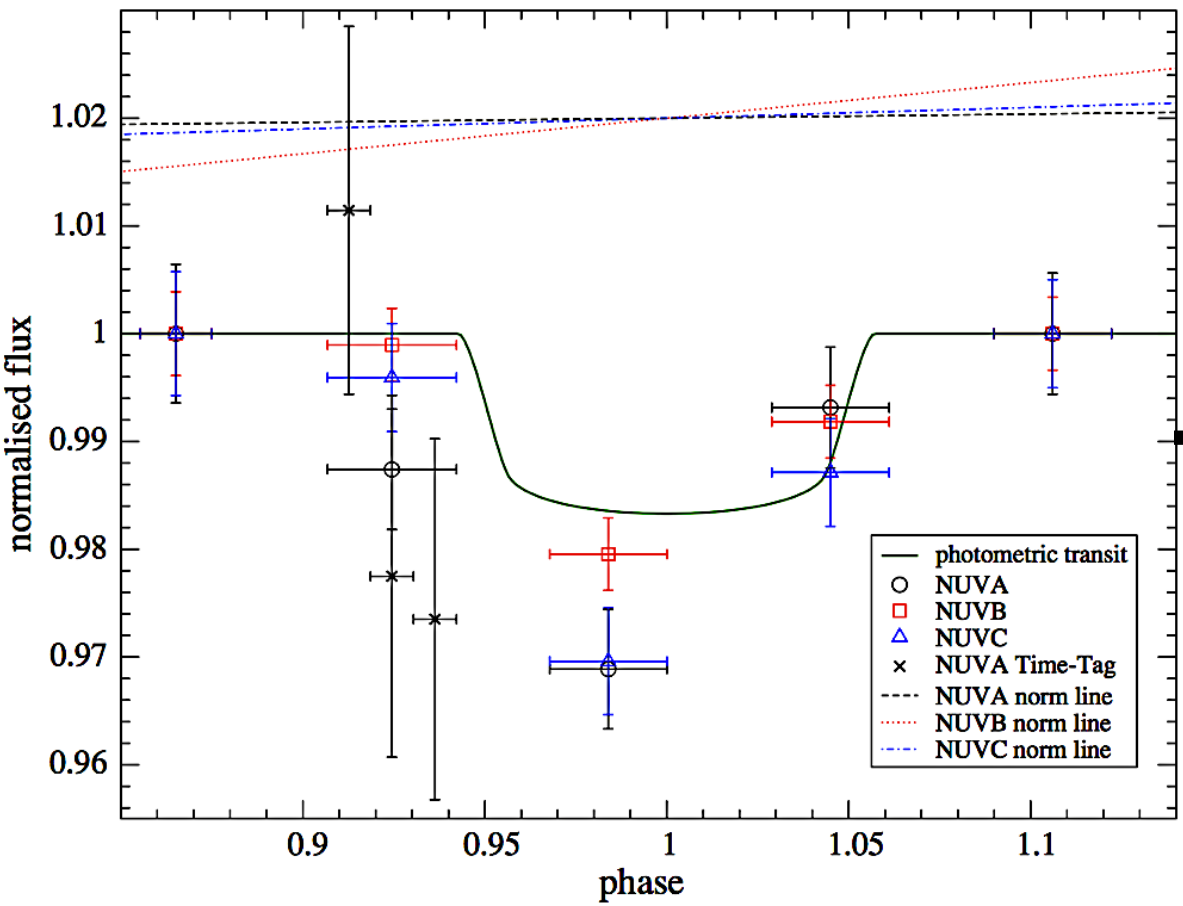
HST/ACS Lyman-α observation of HD 189733b

(Lecavelier des Etangs et al. 2010)



HST/COS UV observations of Wasp-12 b

(Fossati et al. 2010)

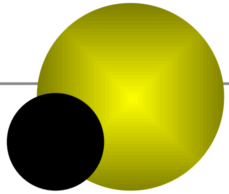


➔ **MgII lines : ~3±0.5%**

See **Poster 2.9 by Fossati et al.**

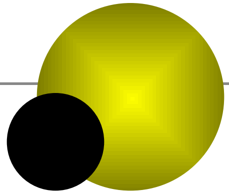
***HST*/COS high resolution**

Summary of observations of exospheres



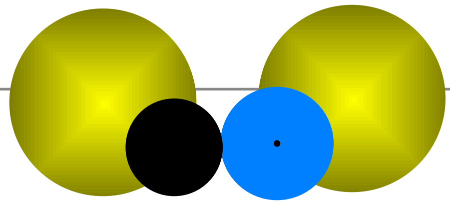
		resolved?	ΔF/F (%)	transit detection significance
HD209458b	H I	✔	15±4	3.8σ
	O I	✘	12.8±4.5	2.8σ
	C II	✔	7.8±1.3	6.0σ
	Si III	✔	8.2±1.4	5.9σ
	Si IV	✘	12±5	2.4σ
HD189733b	H I	✘	5.1±0.8	6.4σ
WASP-12b	Mg II	✘	3±0.5%	6σ

Summary of observations of exospheres



		resolved?	ΔF/F (%)	transit detection significance	
HD209458b	H I	✔	15±4	3.8σ	
	O I	✘	12.8±4.5	2.8σ	
	C II	✔	7.8±1.3	6.0σ	
	Si III	✔	8.2±1.4	5.9σ	
	Si IV	✘	12±5	2.4σ	*Schlawin et al. 2010*
HD189733b	H I	✘	5.1±0.8	6.4σ	
WASP-12b	Mg II	✘	3±0.5%	6σ	

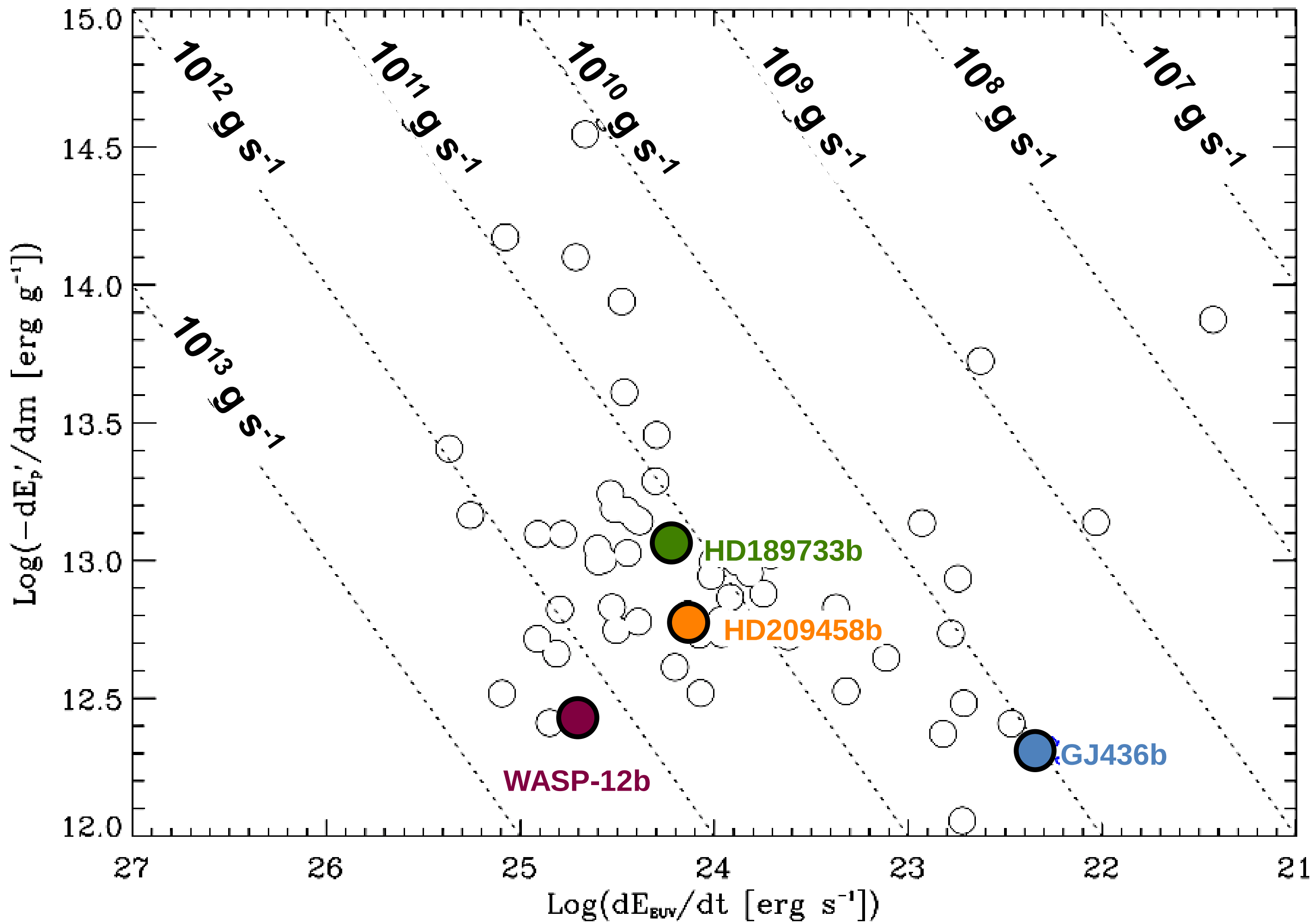
Summary of observations of exospheres



		resolved?	ΔF/F (%)	transit detection significance	atmospheric detection significance
HD209458b	H I	✔	15±4	3.8σ	**3.4σ**
	O I	✘	12.8±4.5	2.8σ	2.5σ
	C II	✔	7.8±1.3	6.0σ	**4.8σ**
	Si III	✔	8.2±1.4	5.9σ	**4.7σ**
	Si IV	✘	12±5	2.4σ	2.1σ
HD189733b	H I	✘	5.1±0.8	6.4σ	**3.4σ**
WASP-12b	Mg II	✘	3±0.5%	6σ	2.5σ

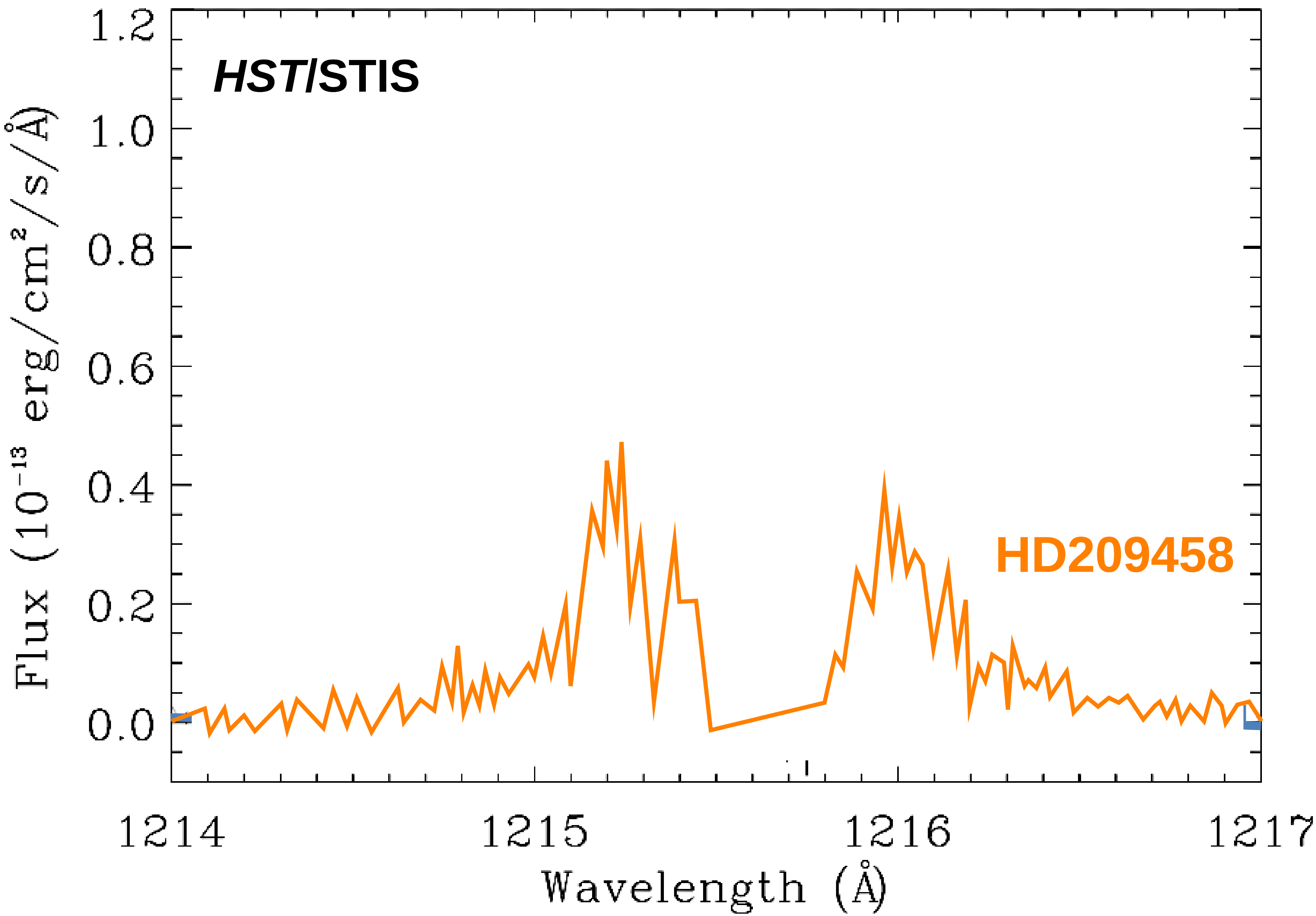
What is the evaporation status of the hot Neptune GJ 436b?

Estimation of the escape rate



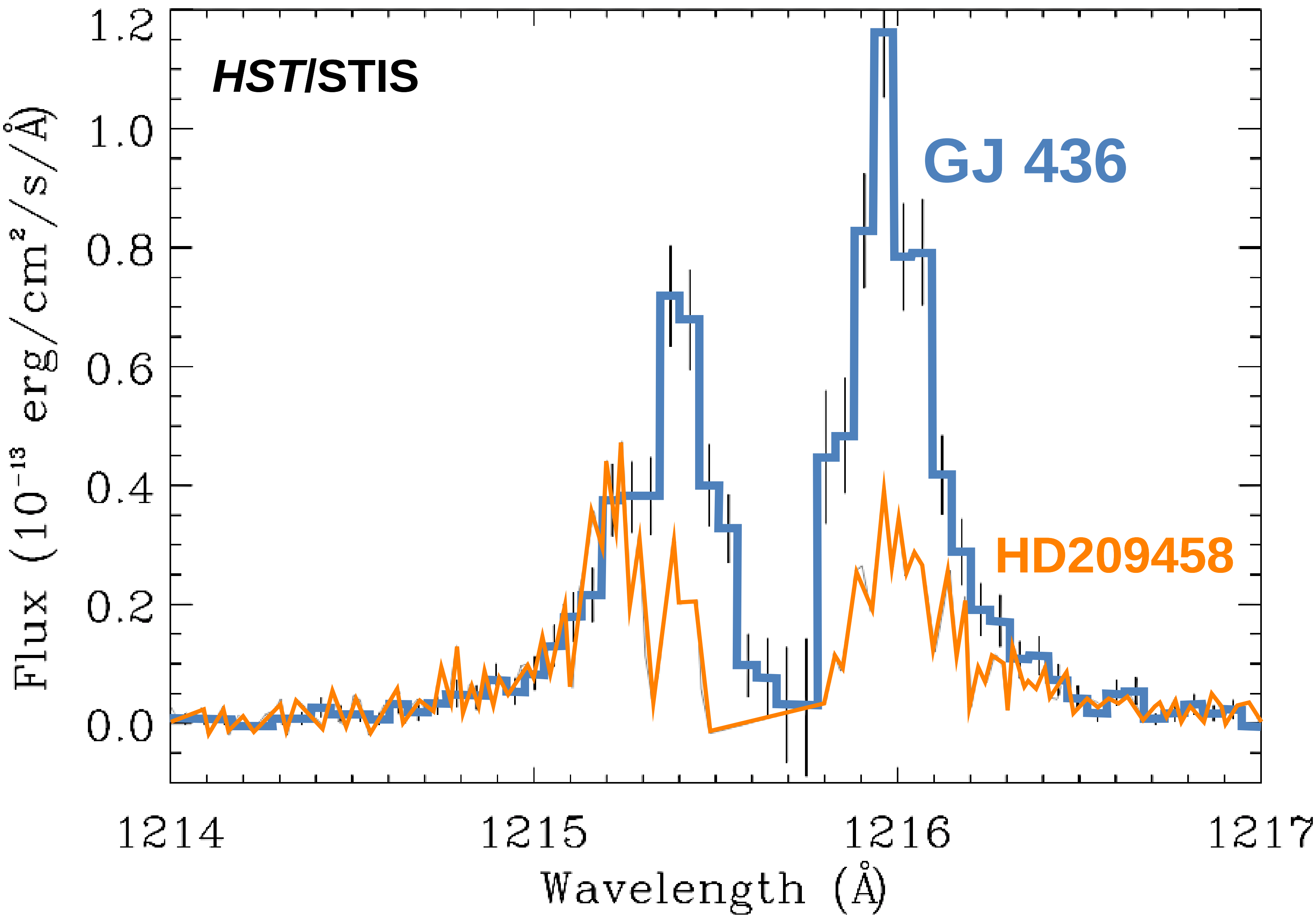
Ehrenreich & Désert, in prep.
see also **Davis & Wheatley 2009**

Is there enough flux at **Lyman α**?



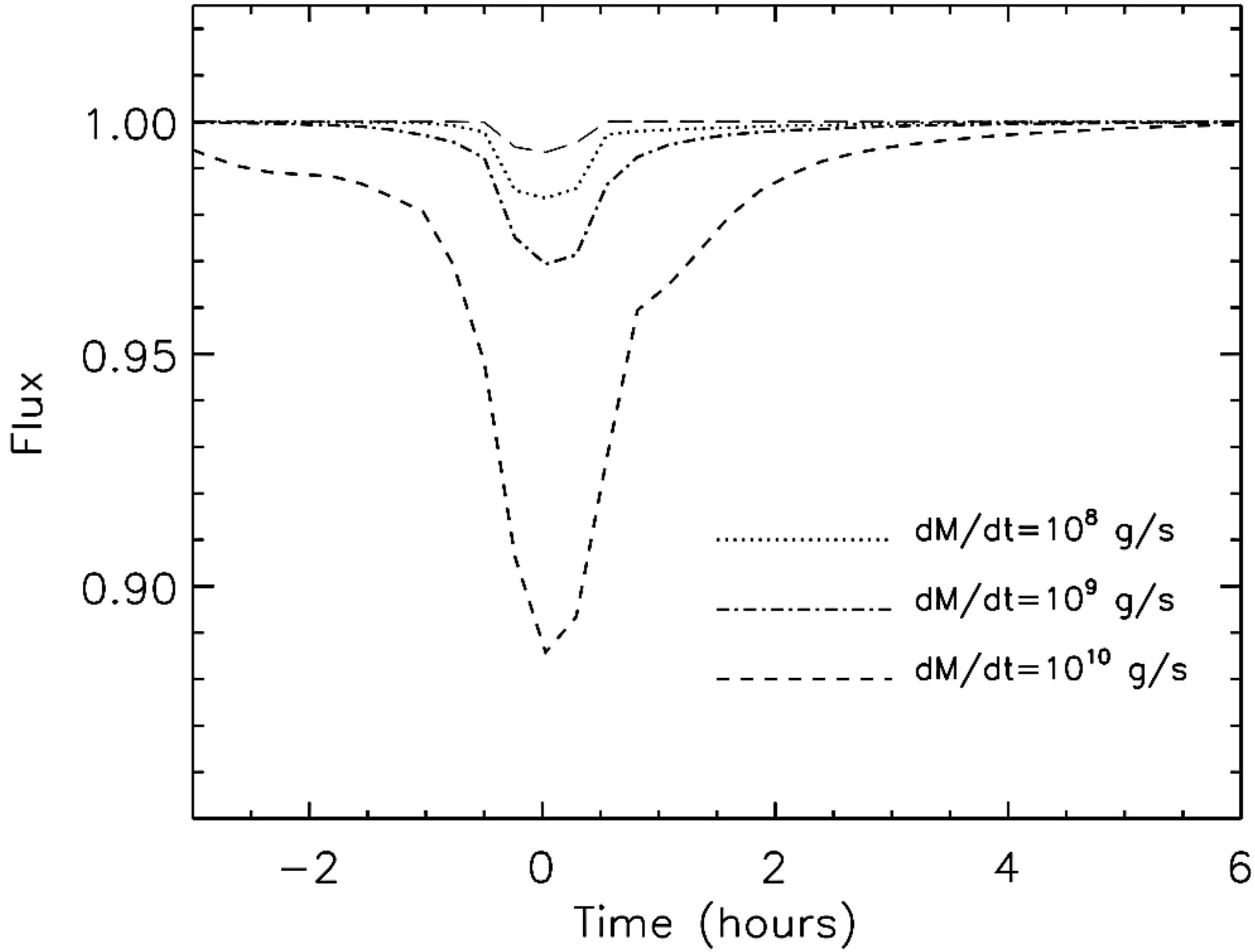
Ehrenreich *et al.*, to be subm.

Is there enough flux at Lyman α?



Ehrenreich *et al.*, to be subm.

Lyman-α light curve



Ehrenreich *et al.*, to be subm.

Conclusion

- Observations of HI Ly-α in HD209458b show an escaping atmosphere.

- Escape rate estimated through modeling of the transit light curve.

- Energy diagram to constrain the evaporation status of planets

- New detections of the evaporation of extrasolar planets :
  HD189733b and Wasp-12b