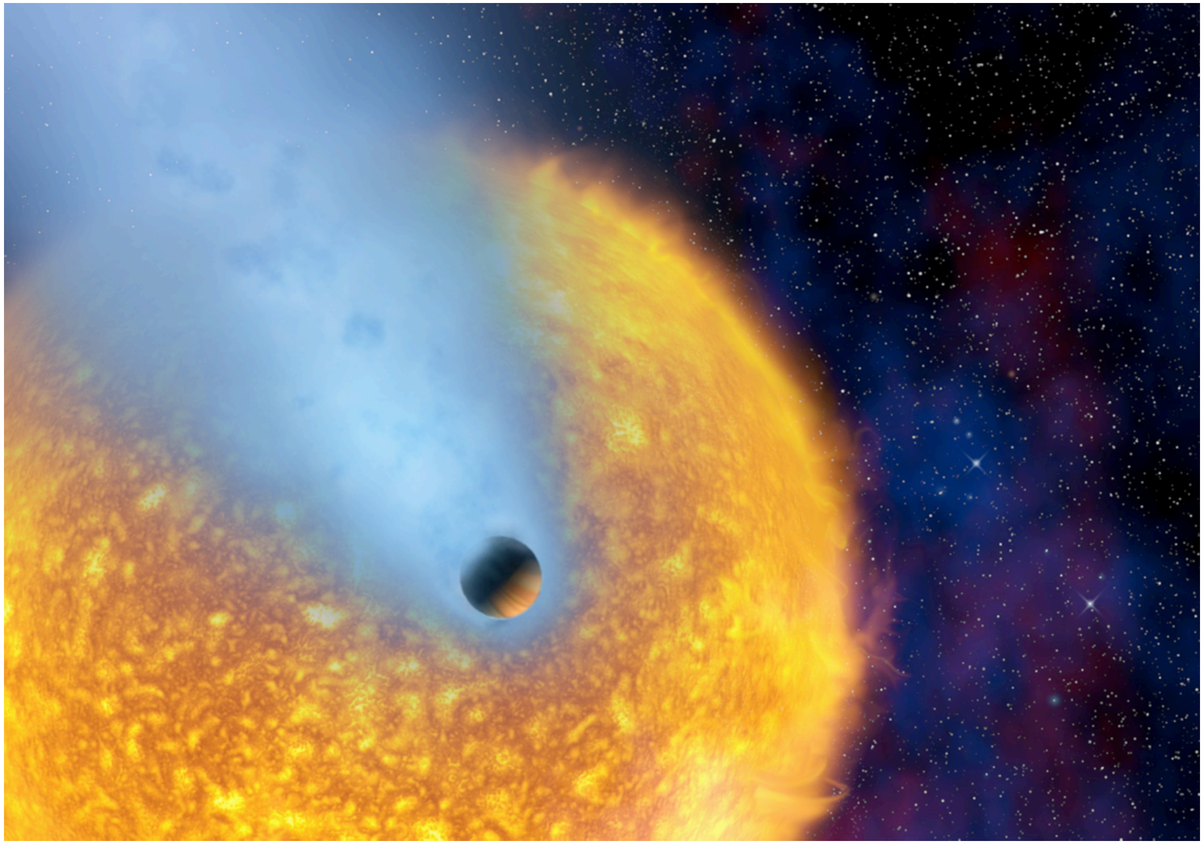
Observations of atmospheric escape of hot Jupiters



Jean-Michel Désert

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A. Vidal-Madjar (IAP)
A. Lecavelier (IAP)
G. E. Ballester (U. Arizona)
D. Ehrenreich (LAOG)
R. Ferlet (IAP)
G. Hébrard (IAP)
M. Mayor (Obs. Genève)
J. C. McConnell (York Univ.)
C. D. Parkinson (JPL)
D. Sing (IAP)

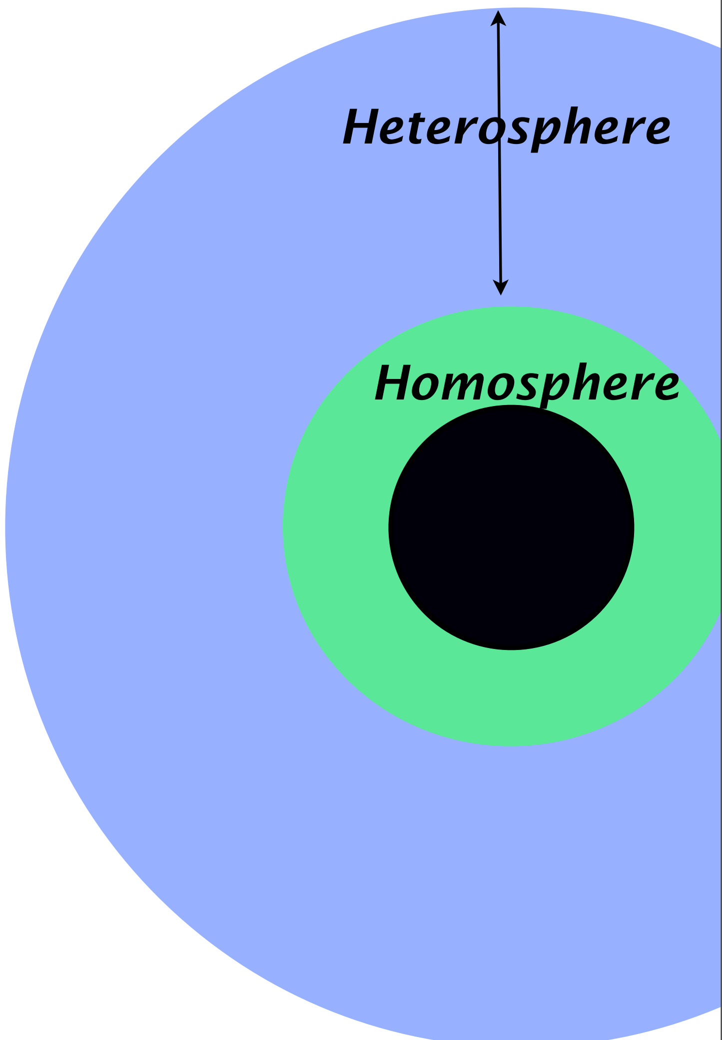
Outline

- Exosphere, escape processes

- Observations of evaporating hot jupiters

- Escape rate, lifetime and remnants

Vertical structure puzzle



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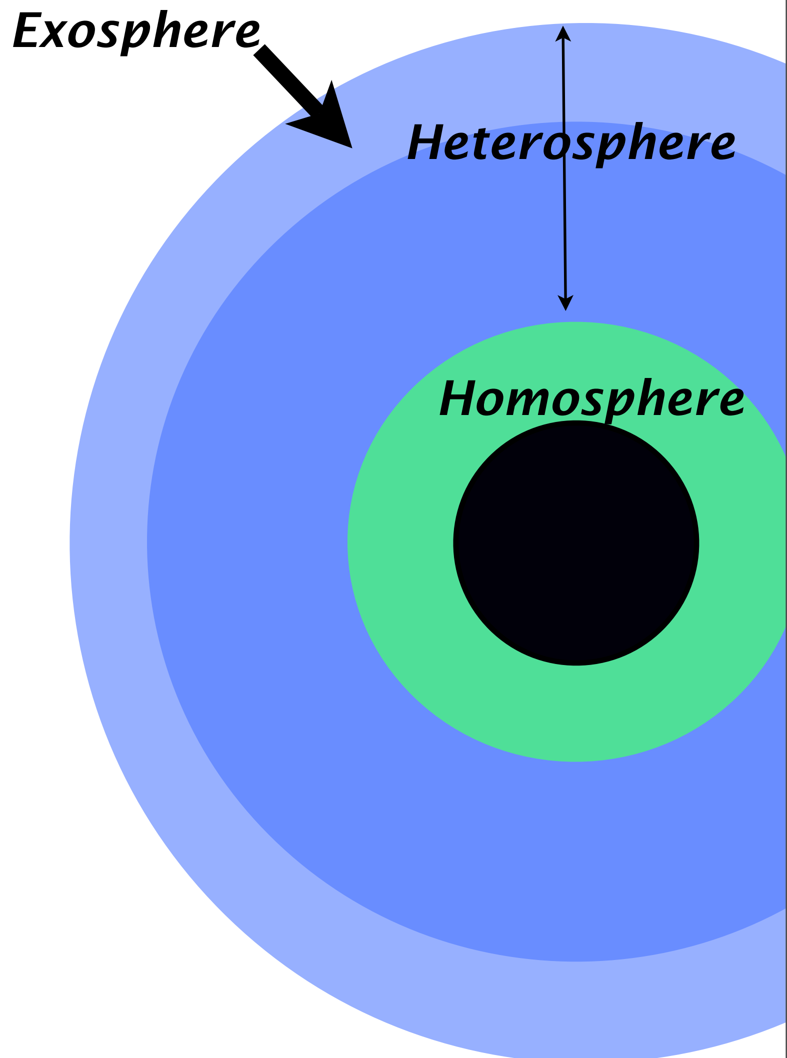

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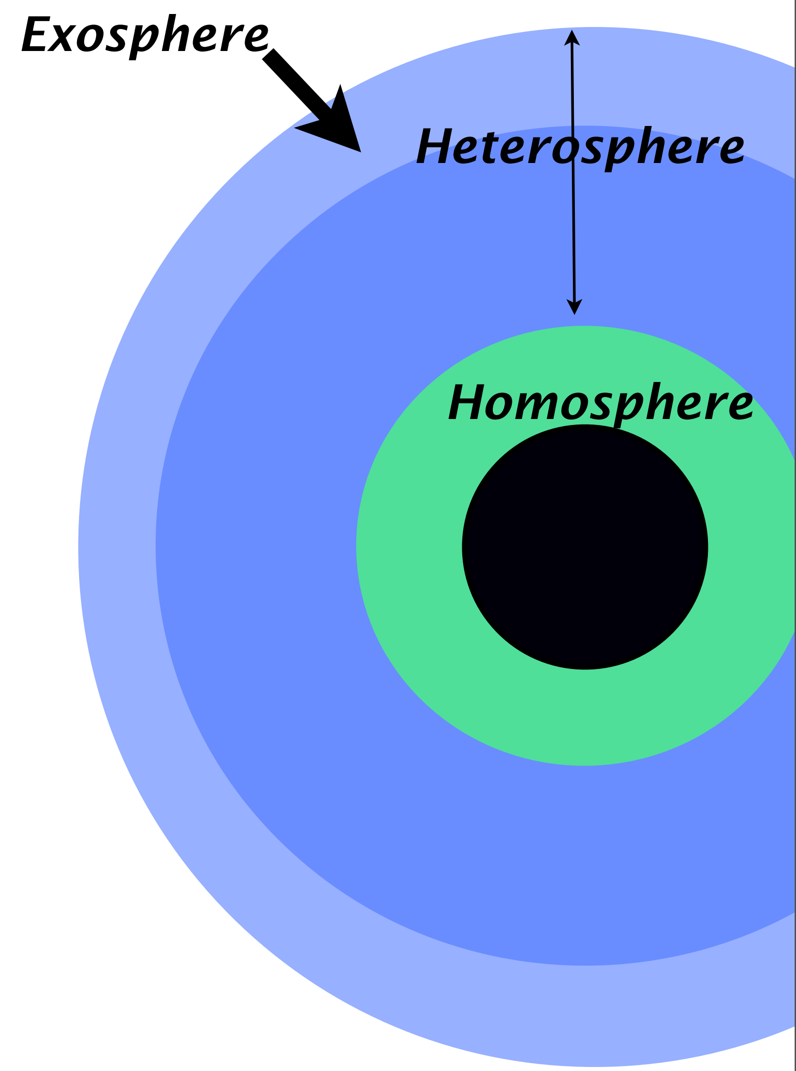
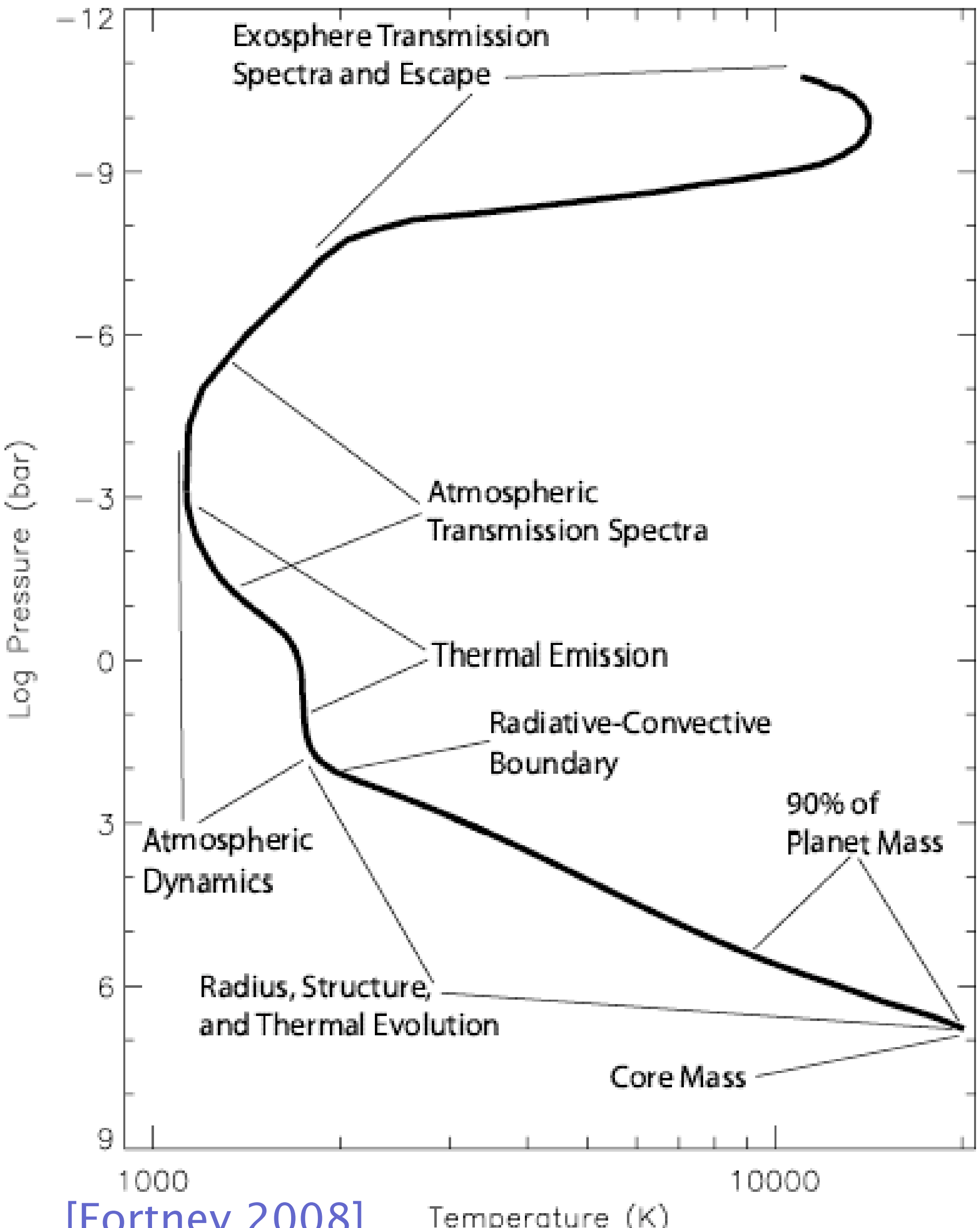


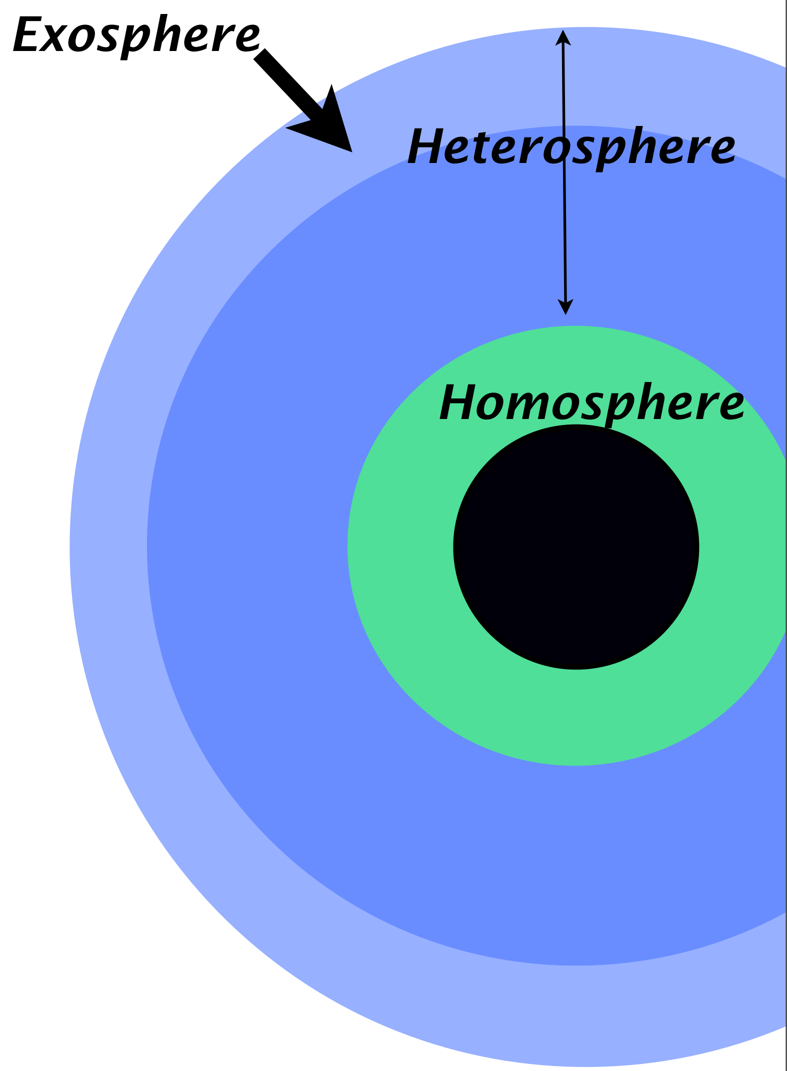
Planetary corona

Vertical structure puzzle

HD209458b



[Fortney 2008]



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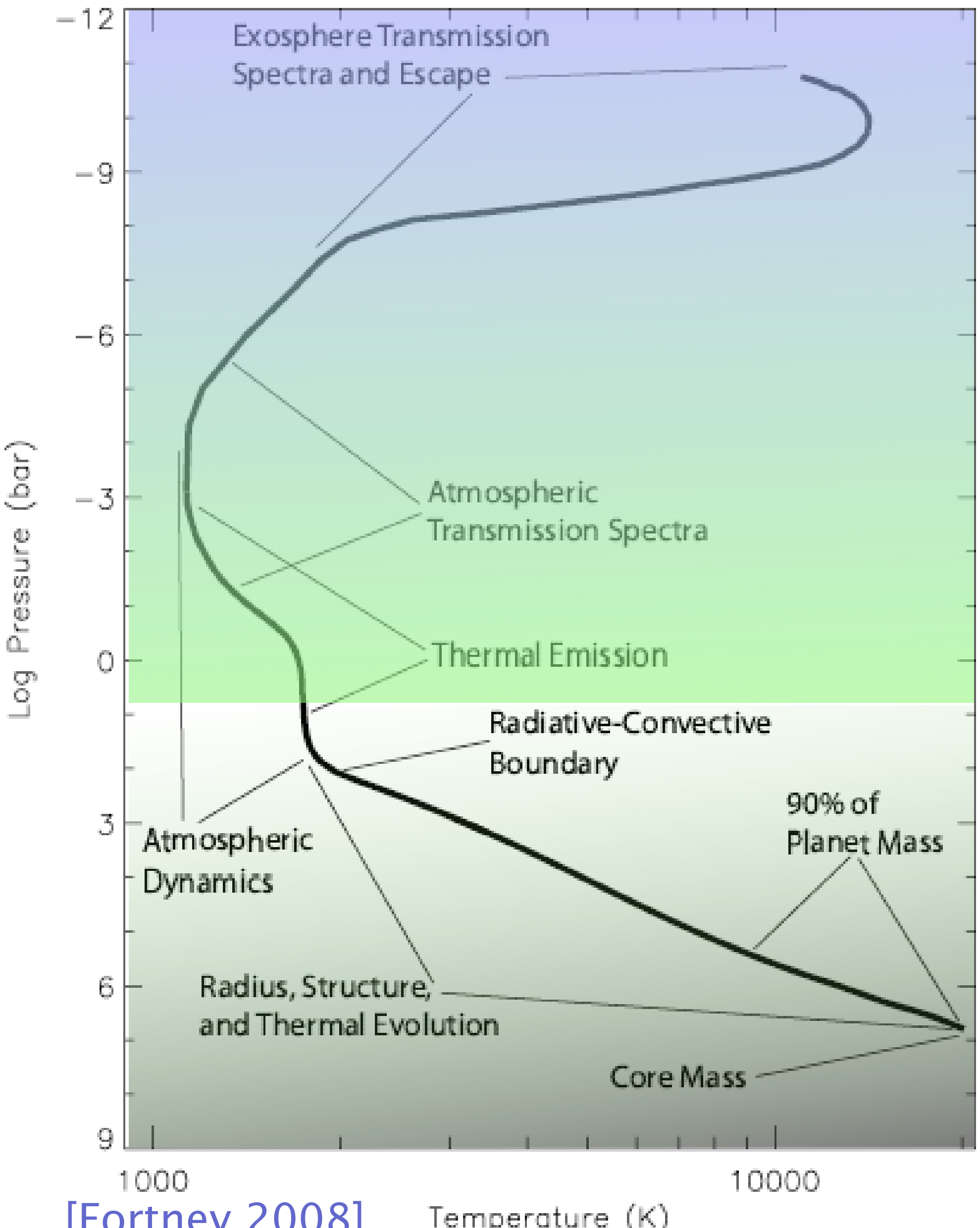

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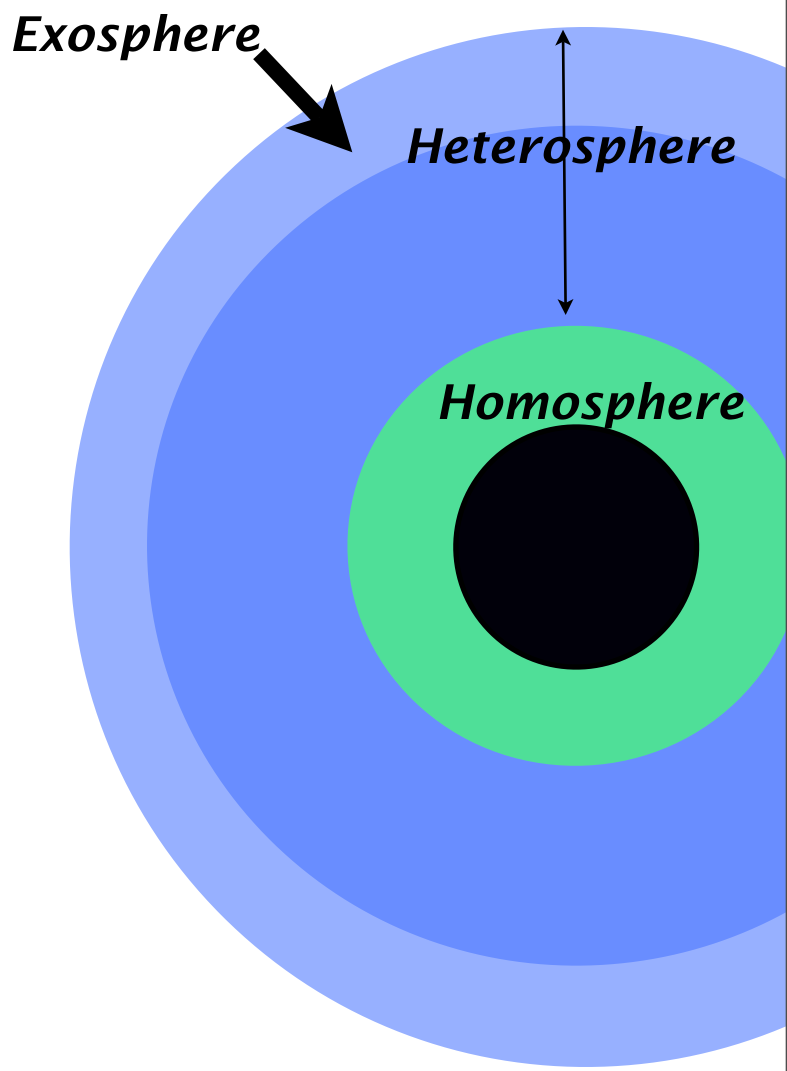


Planetary corona

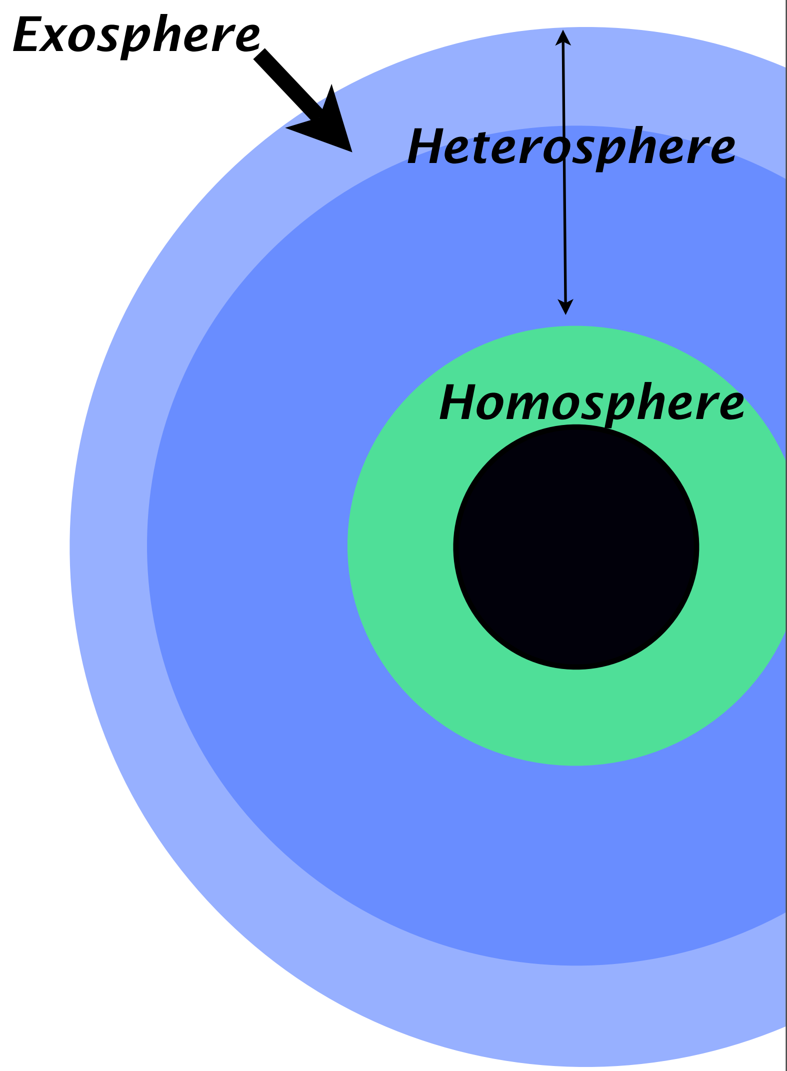
Exosphere

- Mainly H

- Constant high T_{exo} (10^4K) > T_{eff}

  $H_{exo} = kT_{exo}/\mu g = c^{te}$

- Low density ($N_{exo} < 10^5$ cm^{-3})



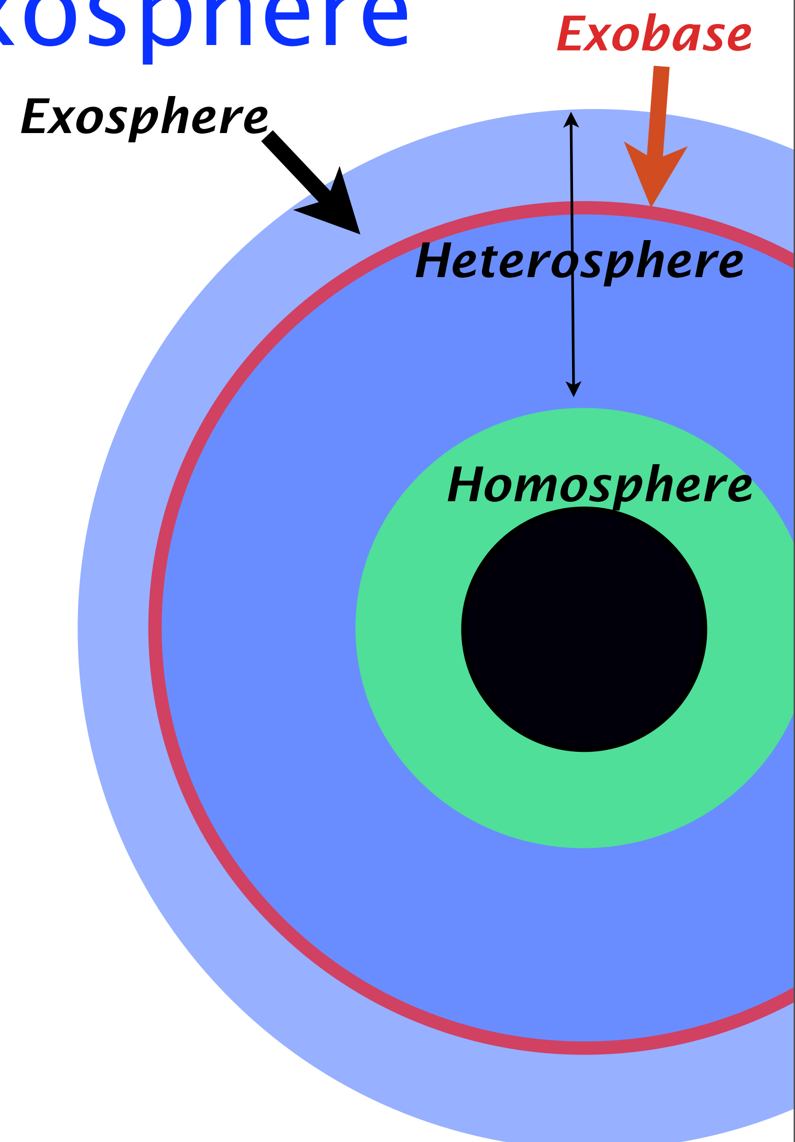
Collisionless exosphere

Critical level:
No collision above exobase

density — scale height

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

mean free path — collisional cross section (3×10^{-15} cm^2)

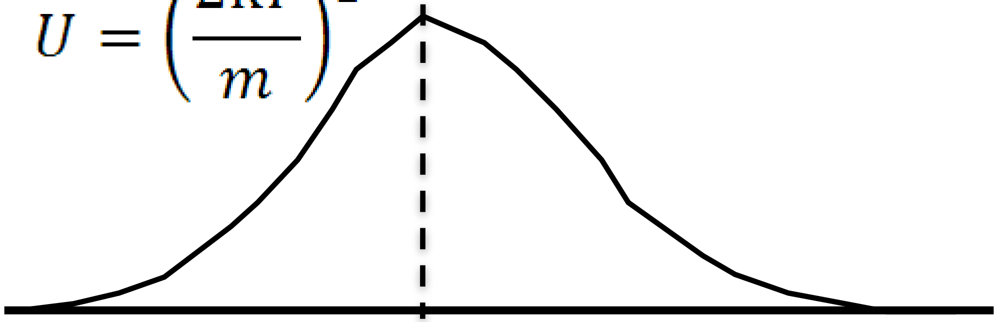


[Chamberlain 1978; Chamberlain & Hunten 1987]

Thermal escape (Jeans 1925)

- Maxwellian velocity distribution

$$U = \left(\frac{2kT}{m}\right)^{\frac{1}{2}}$$



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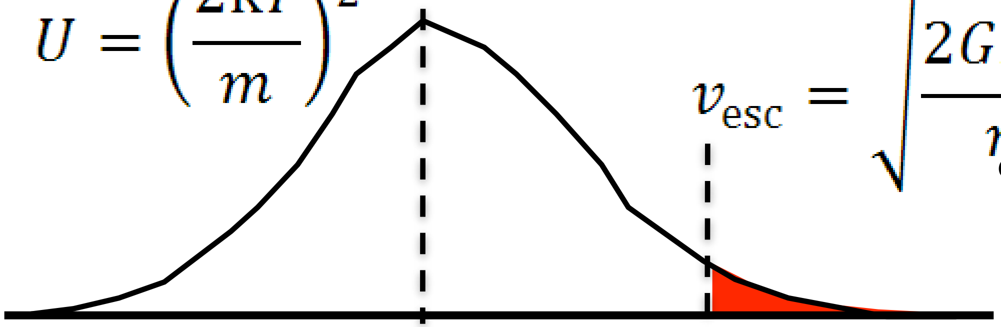

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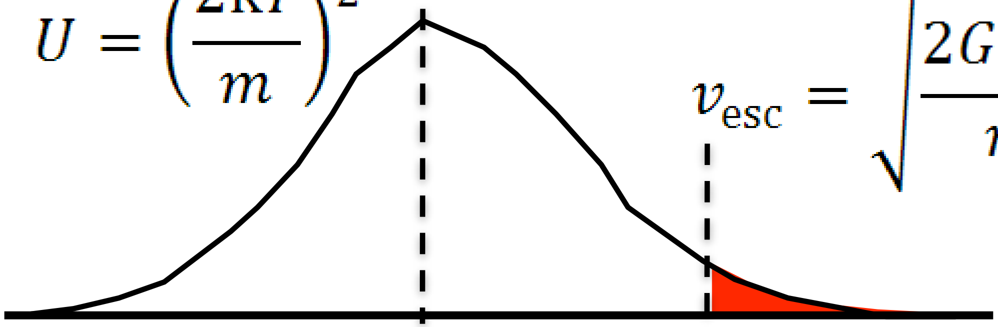

Escape parameter:

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

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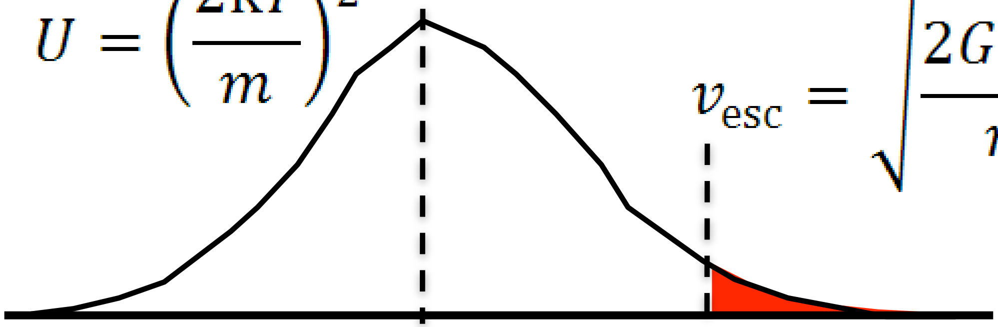


Escape parameter:

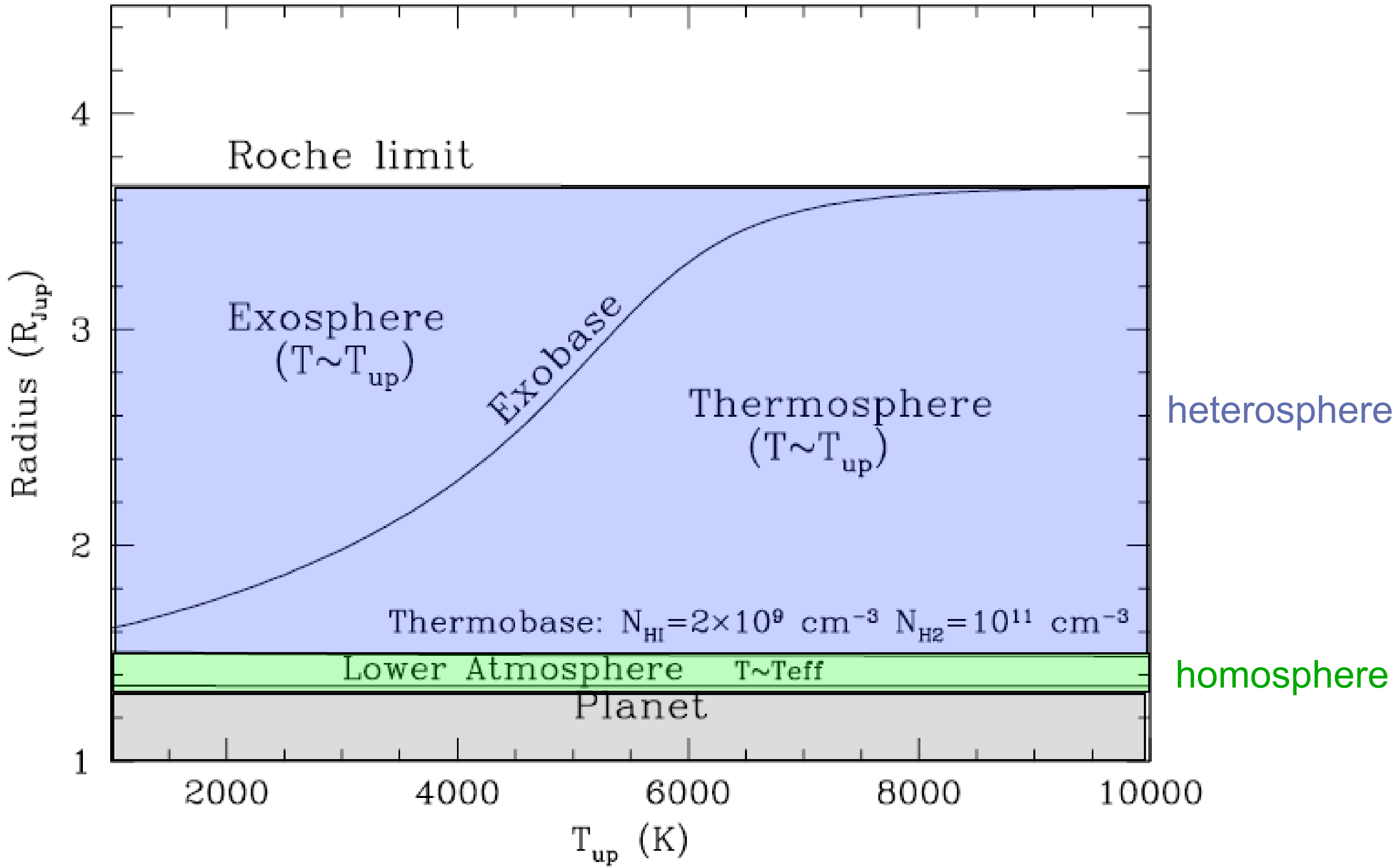
$\lambda = (V_{esc}/U)^2 = r_{exo}/H$

$\lambda > 30$ => Grav. binded
$\lambda < 5$ => hydrodynamic
$\lambda < 1.5$ => $T=T_c$ "Blow-off"

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

Atmospheric structure of hot Jupiters

[Lecavelier et al. 2004]



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- Tidal forces enhance escape rate

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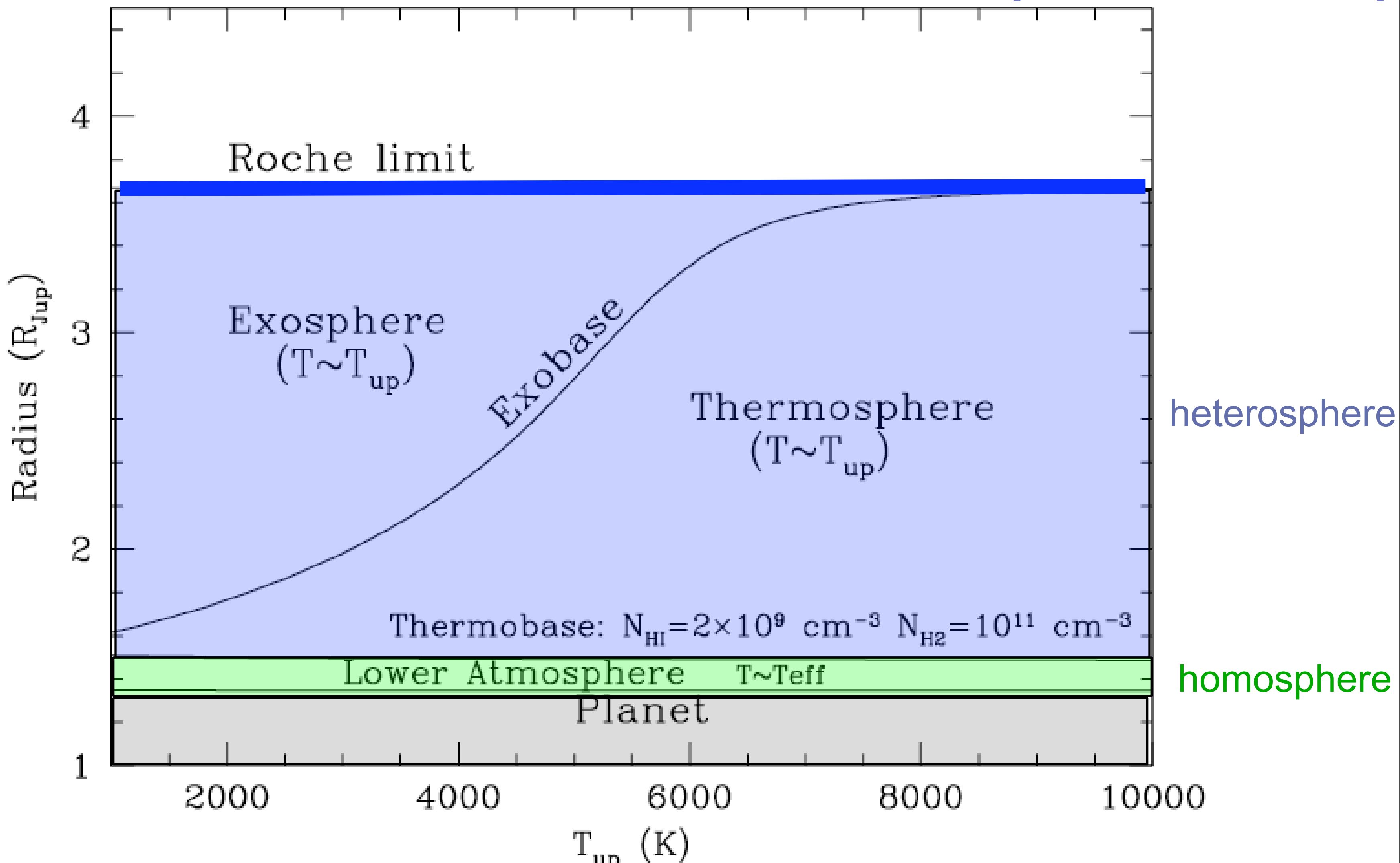

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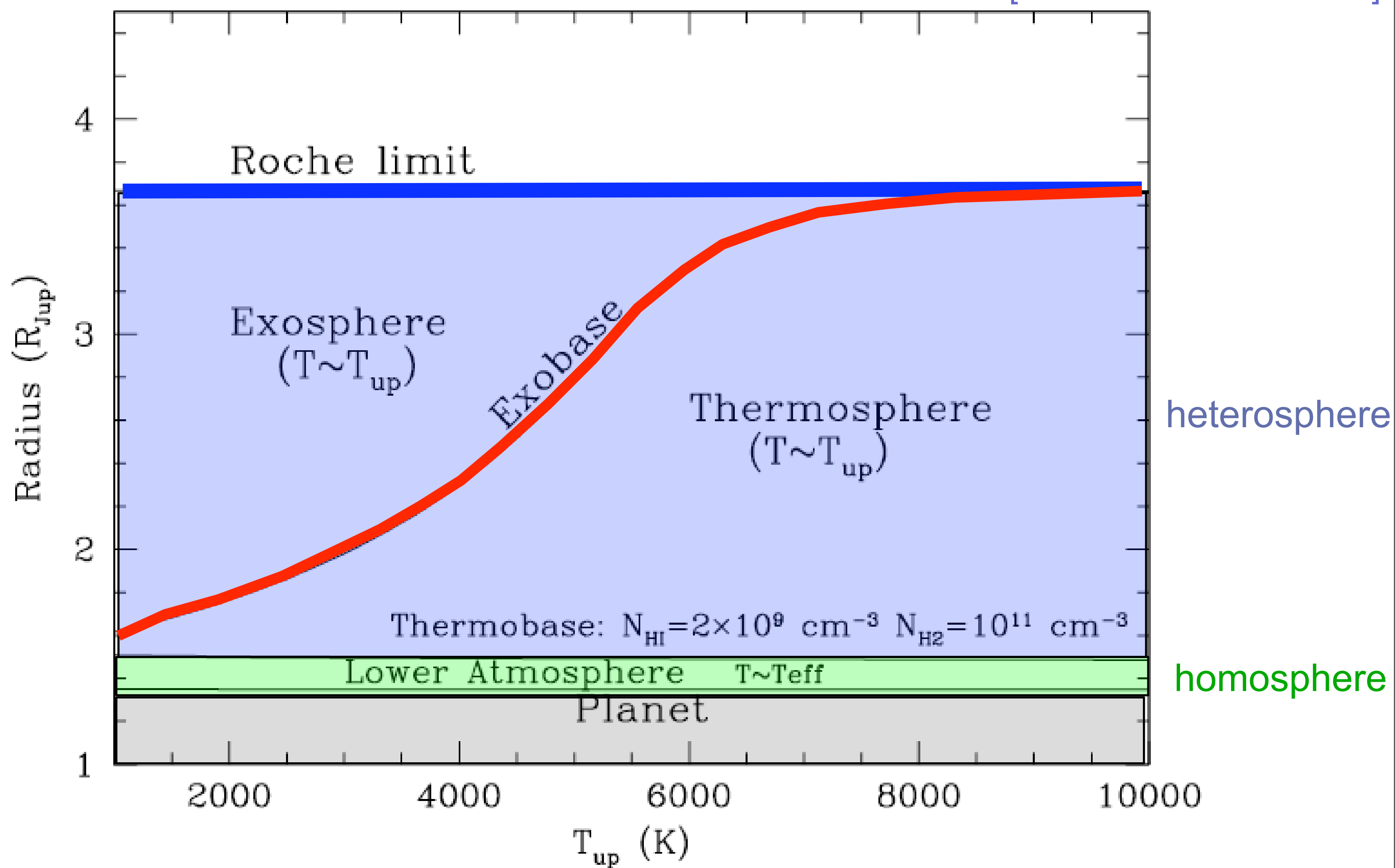

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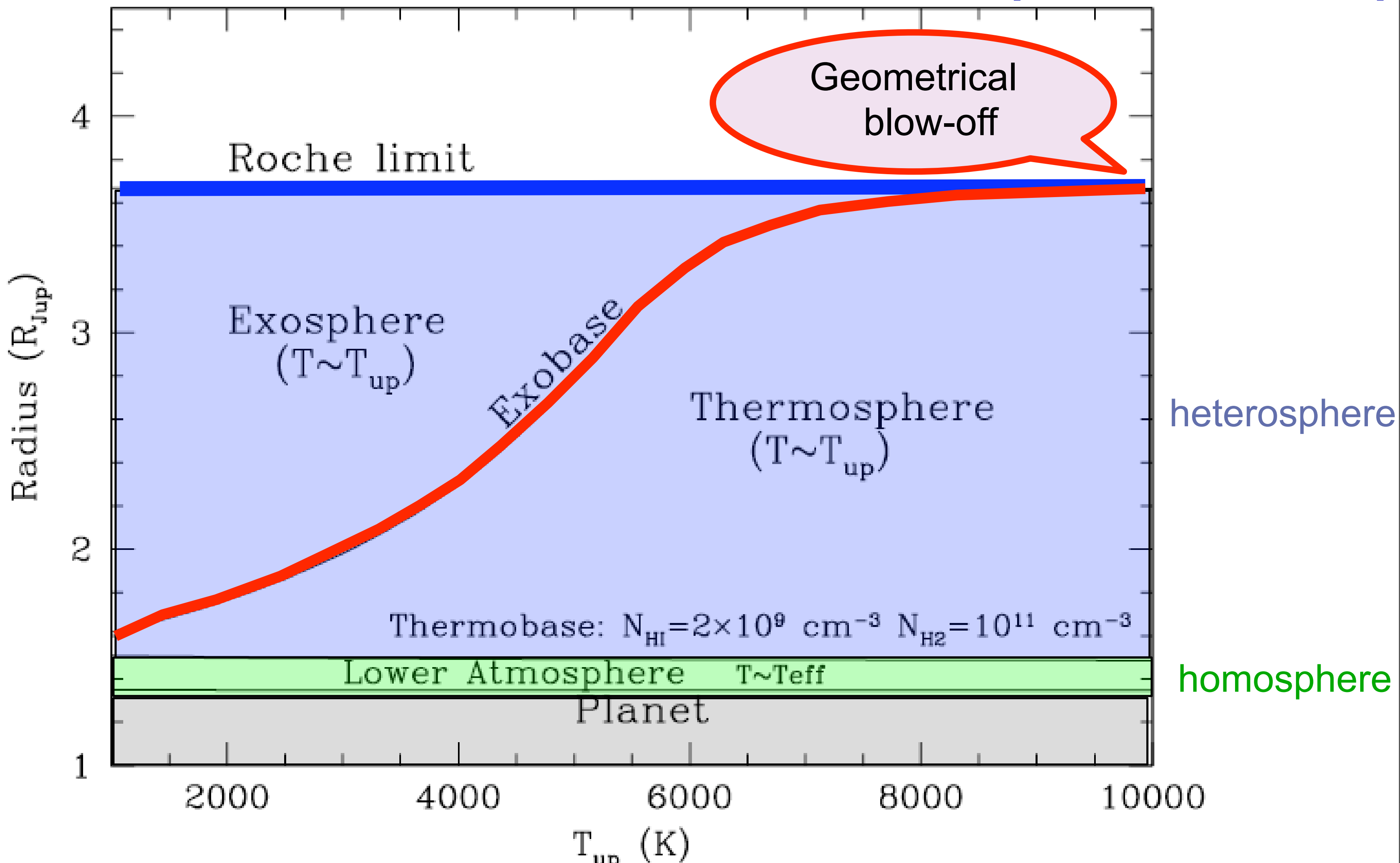

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Thermal escape (Jeans)

- Diffusion-limited process
- Lower limit to the actual escape flux

Nonthermal escaping processes

- Often dominate escape rate
- 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

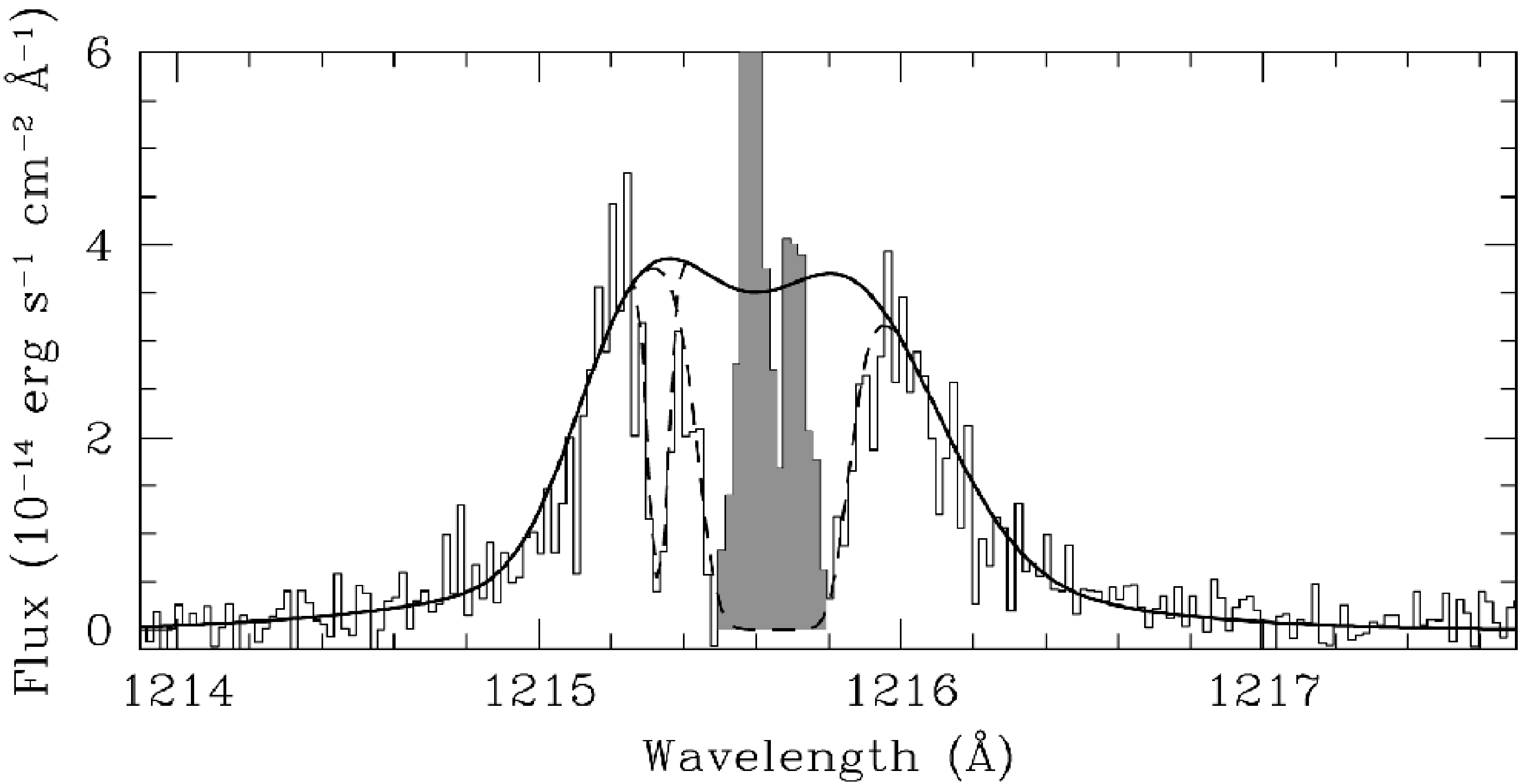
[Hunten 1982; Chamberlain & Hunten 1987]

Observations

HD 209458 at Lyman α

HST/STIS observations

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



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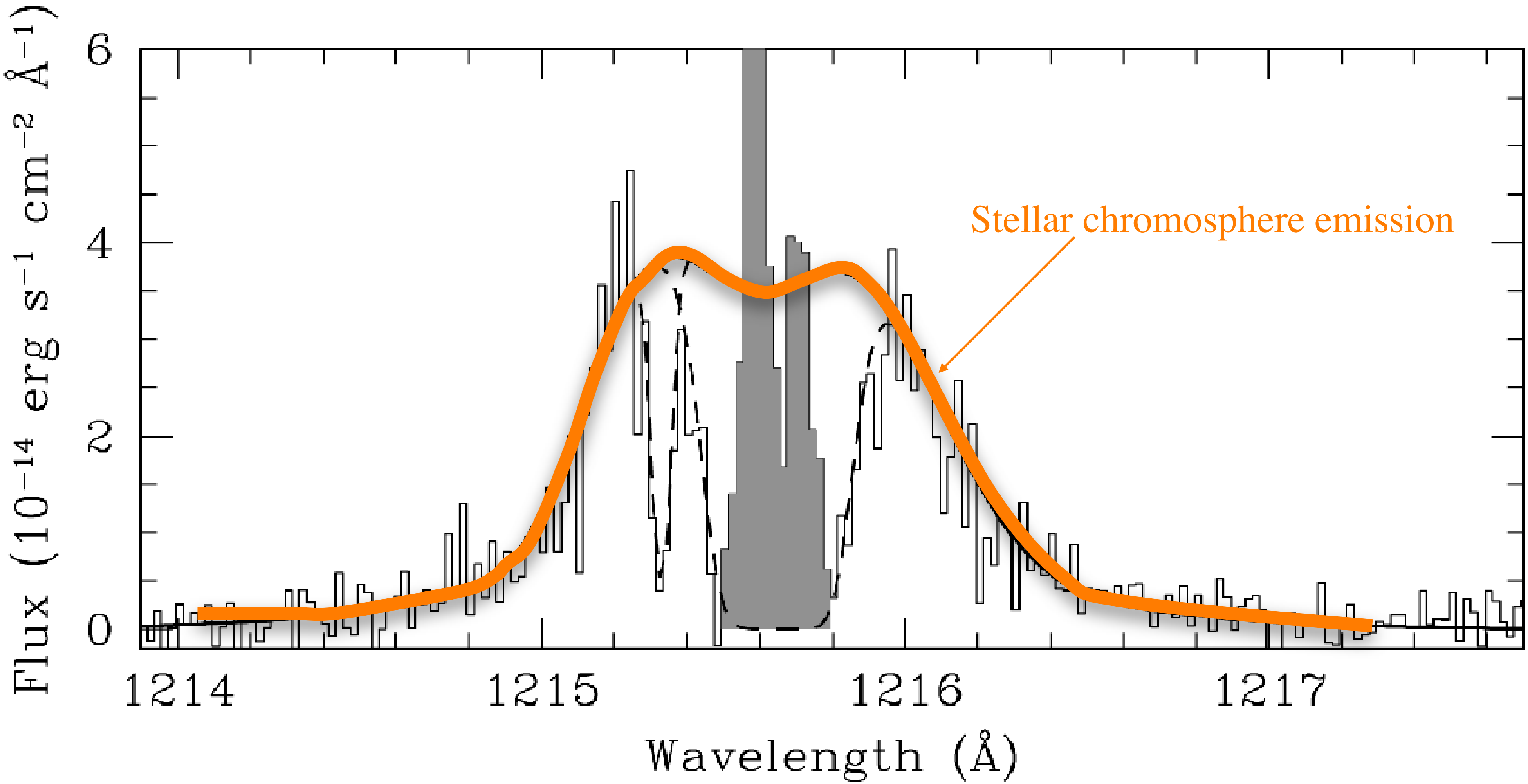

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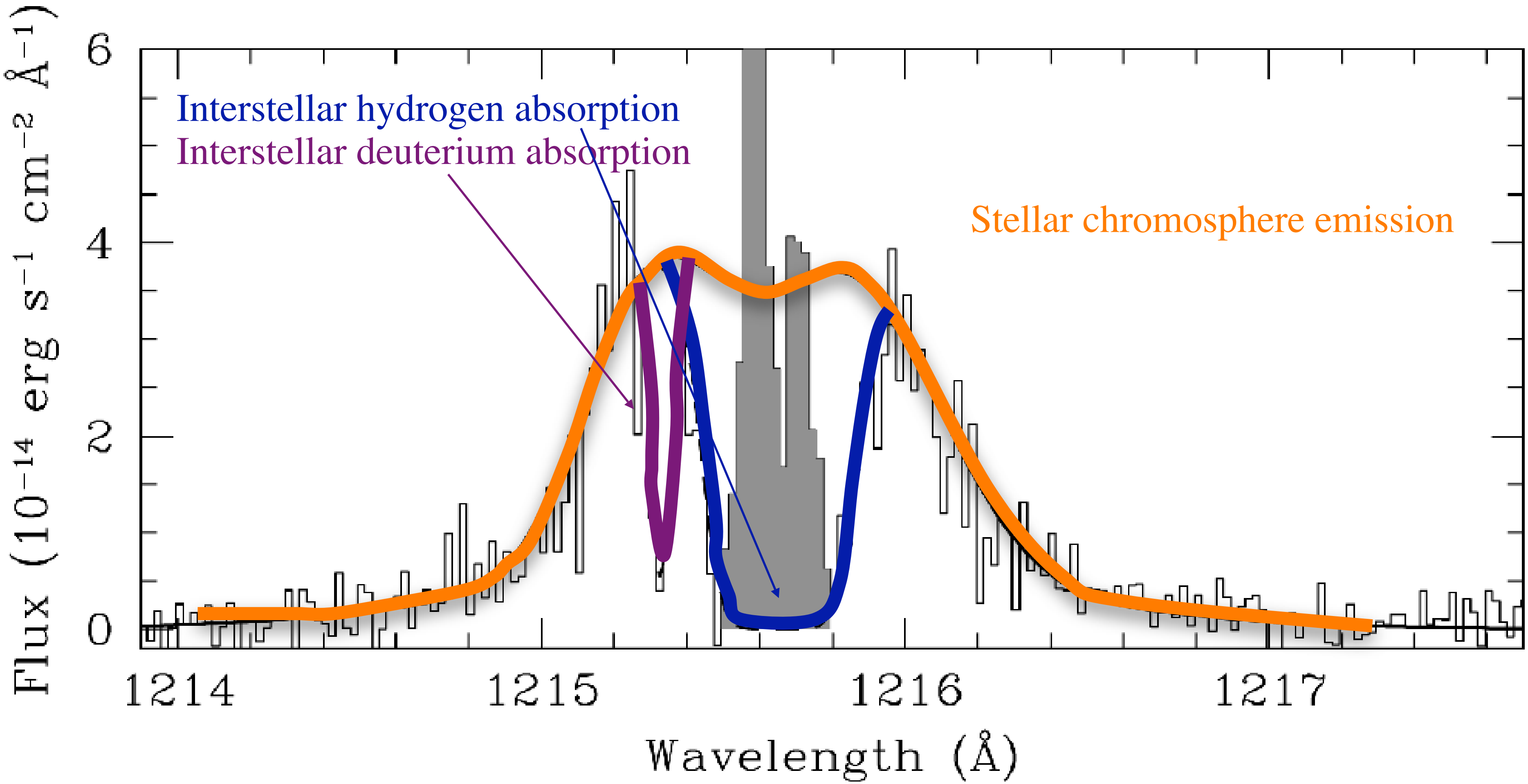

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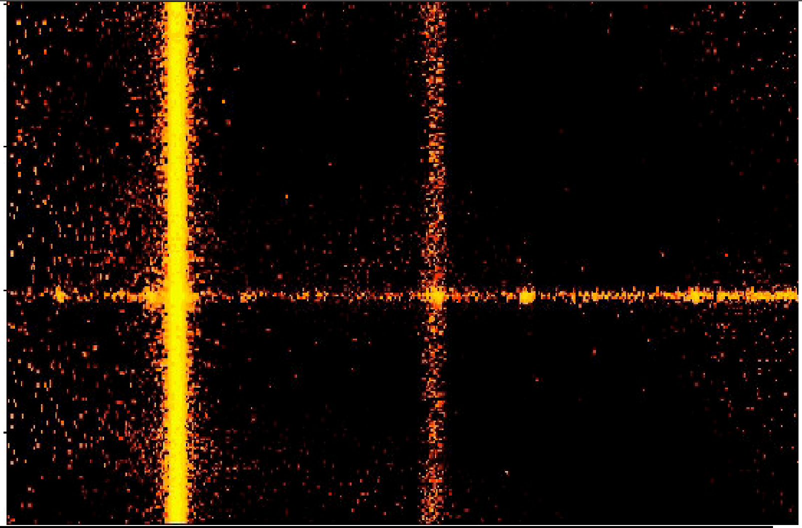
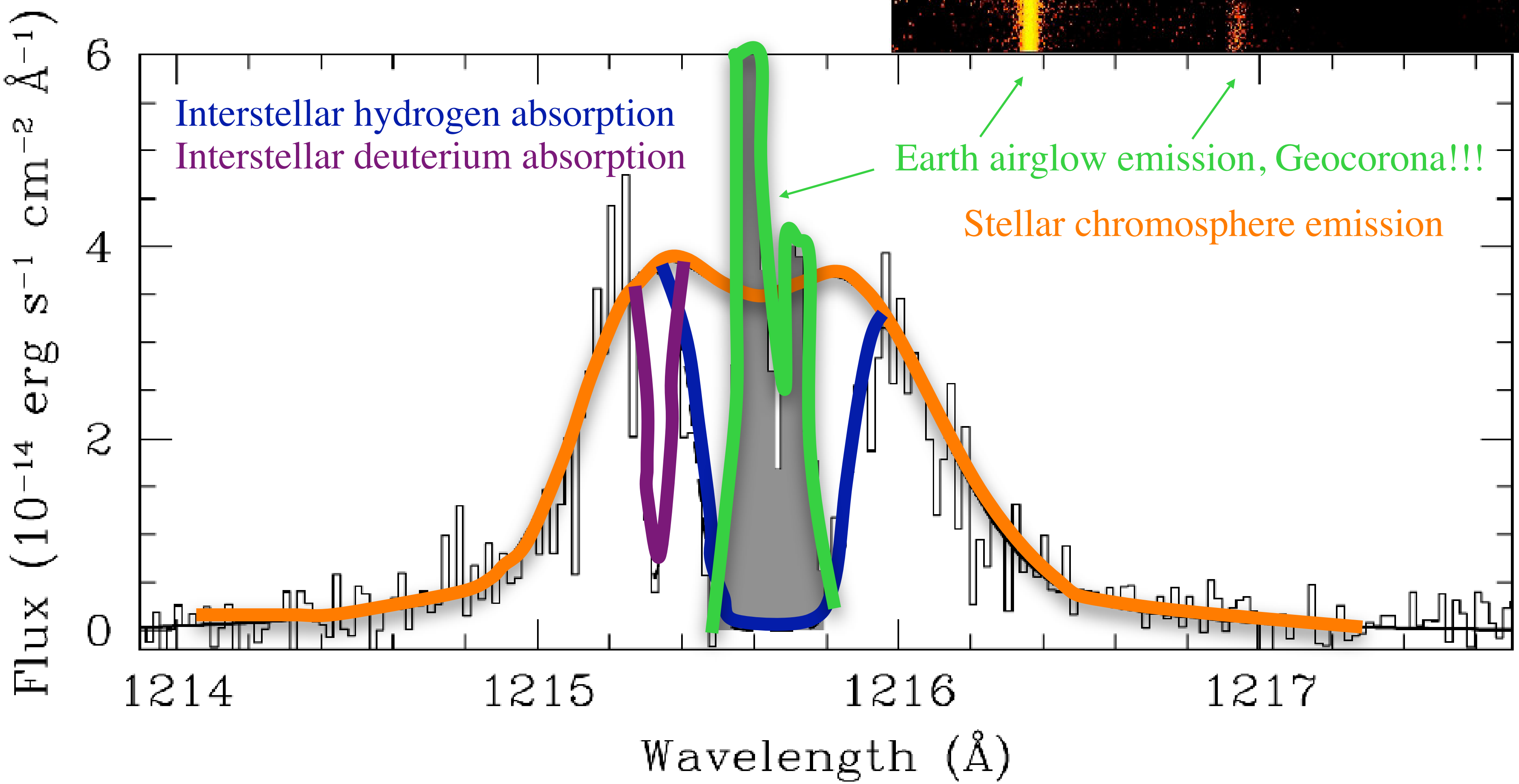
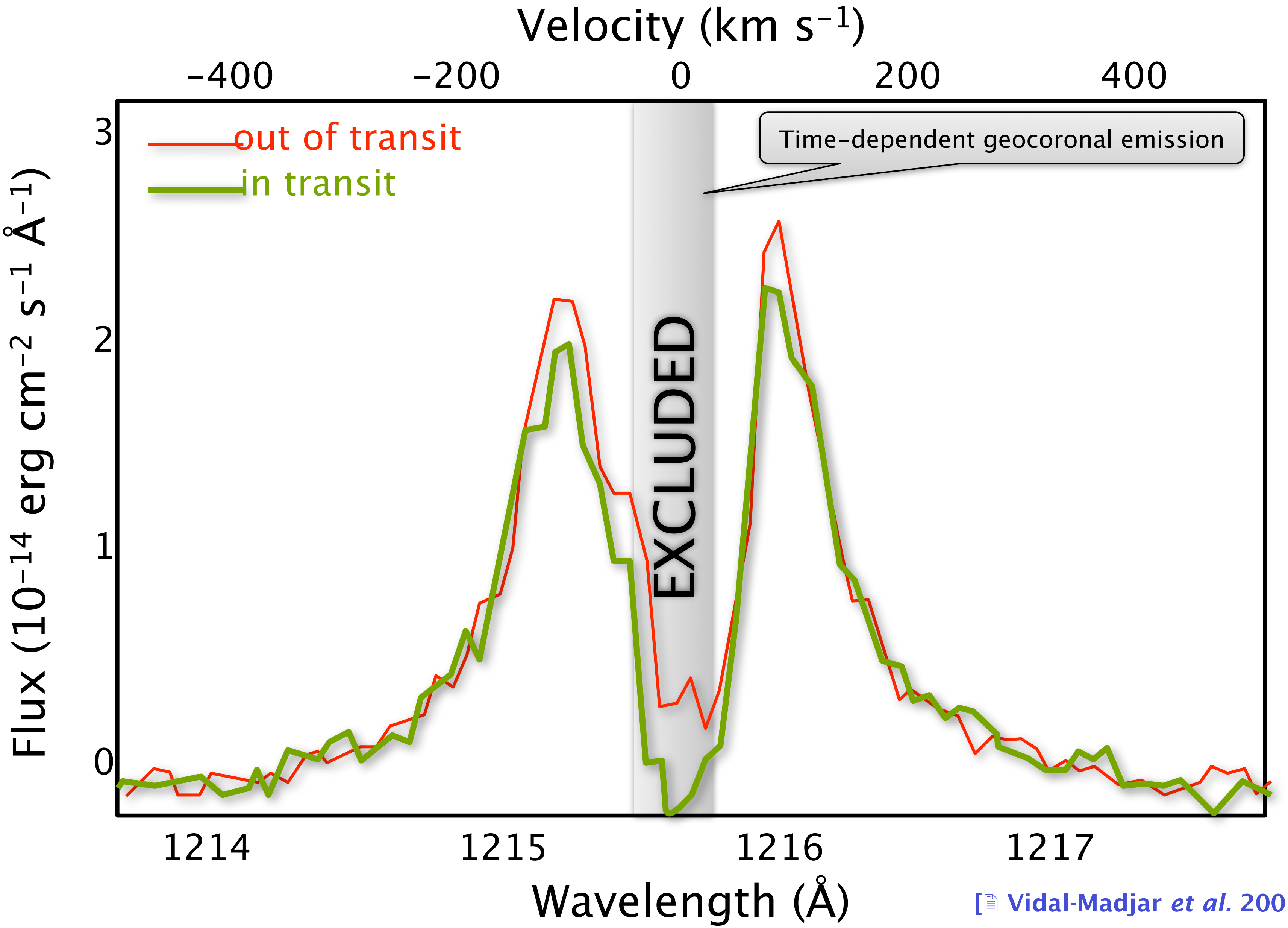




Observations of transits at Lyman α



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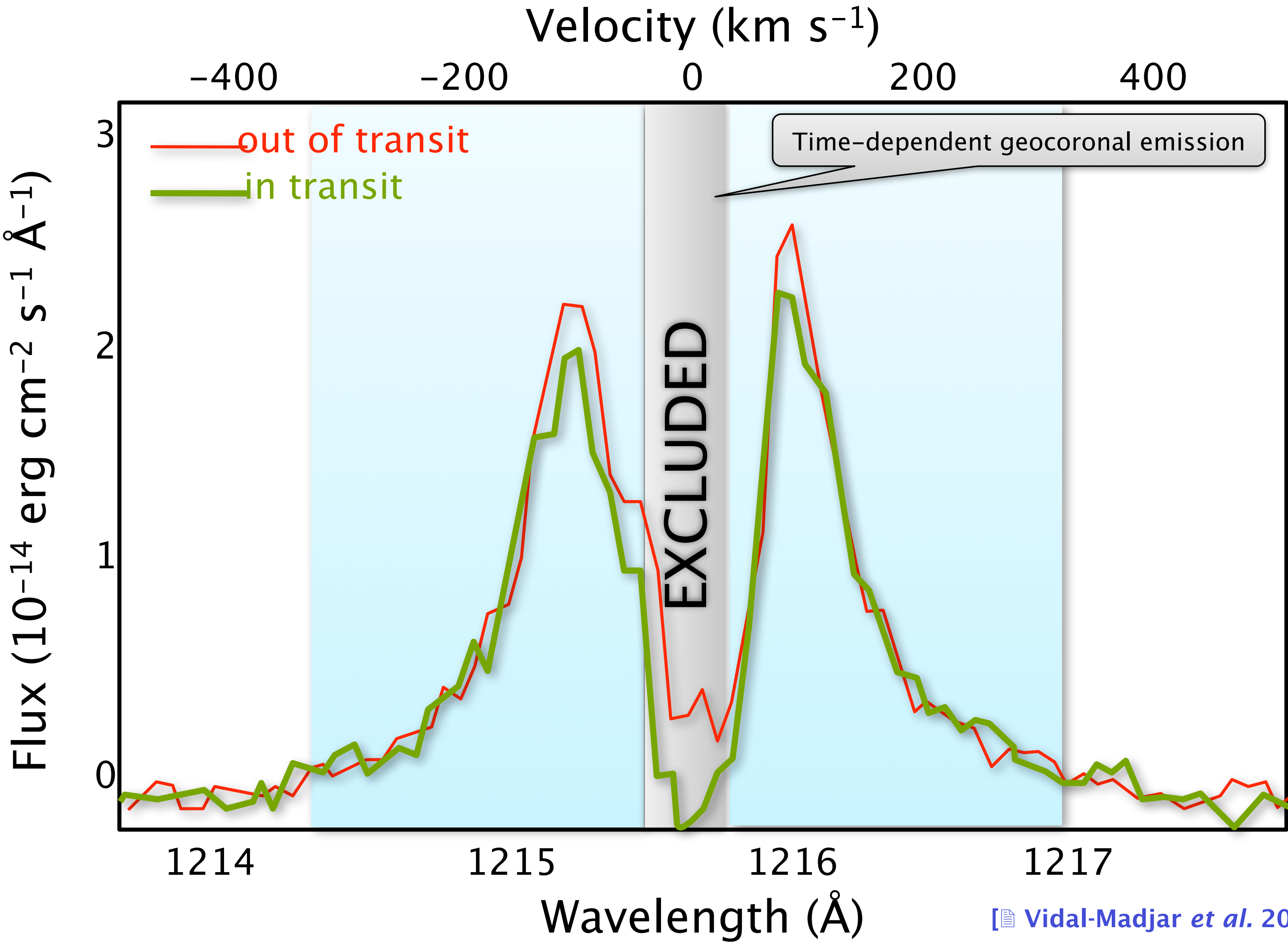

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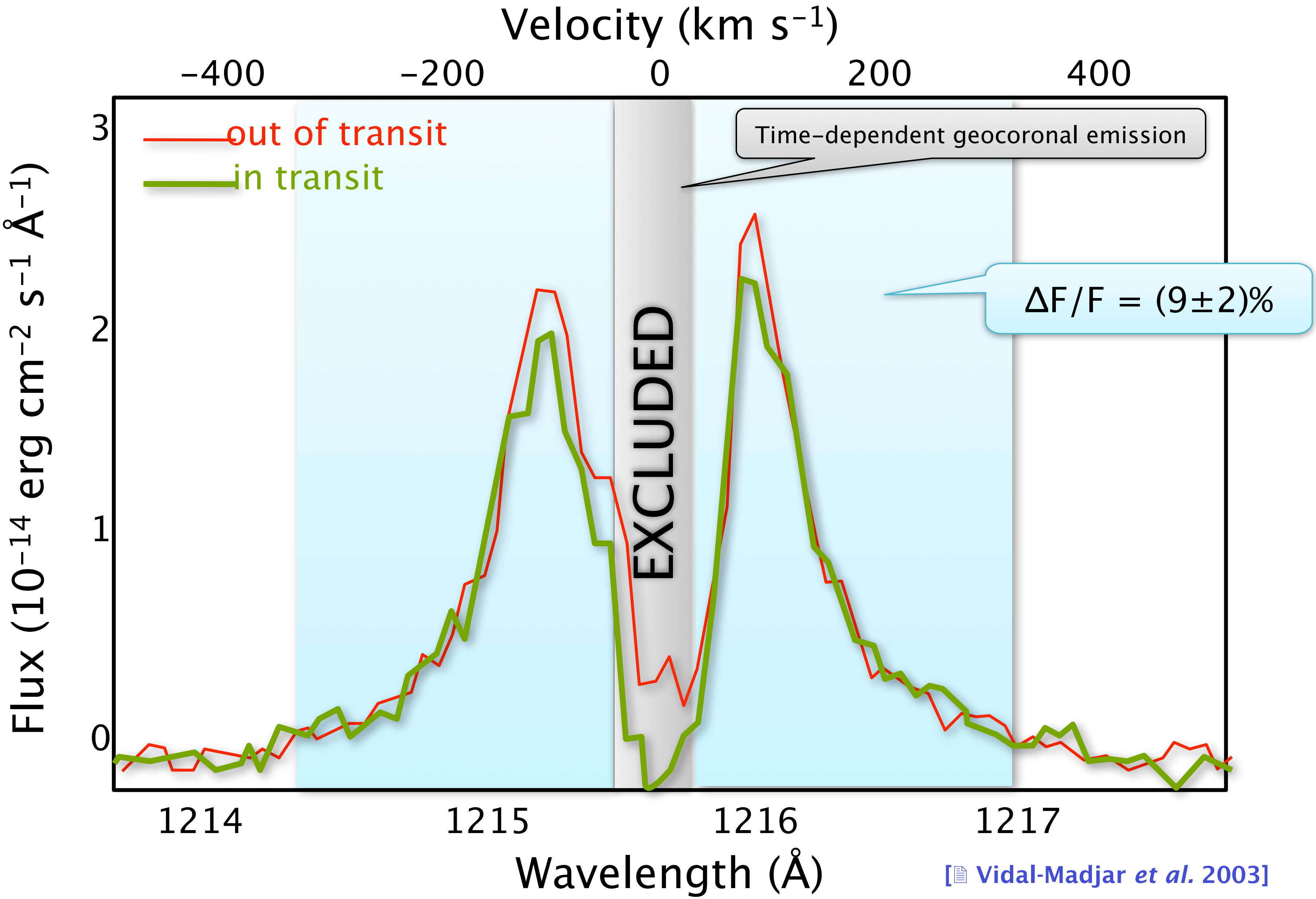

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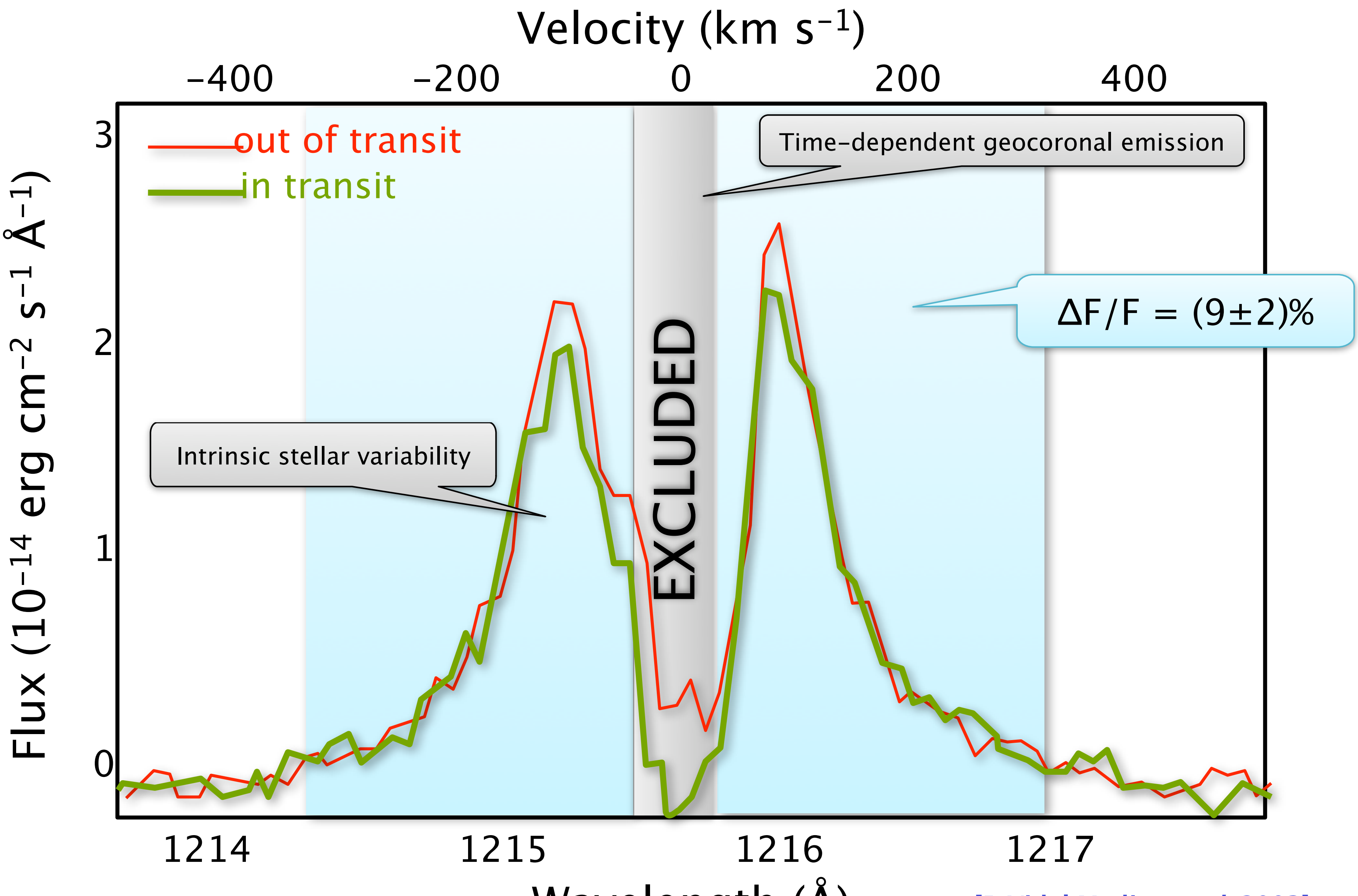

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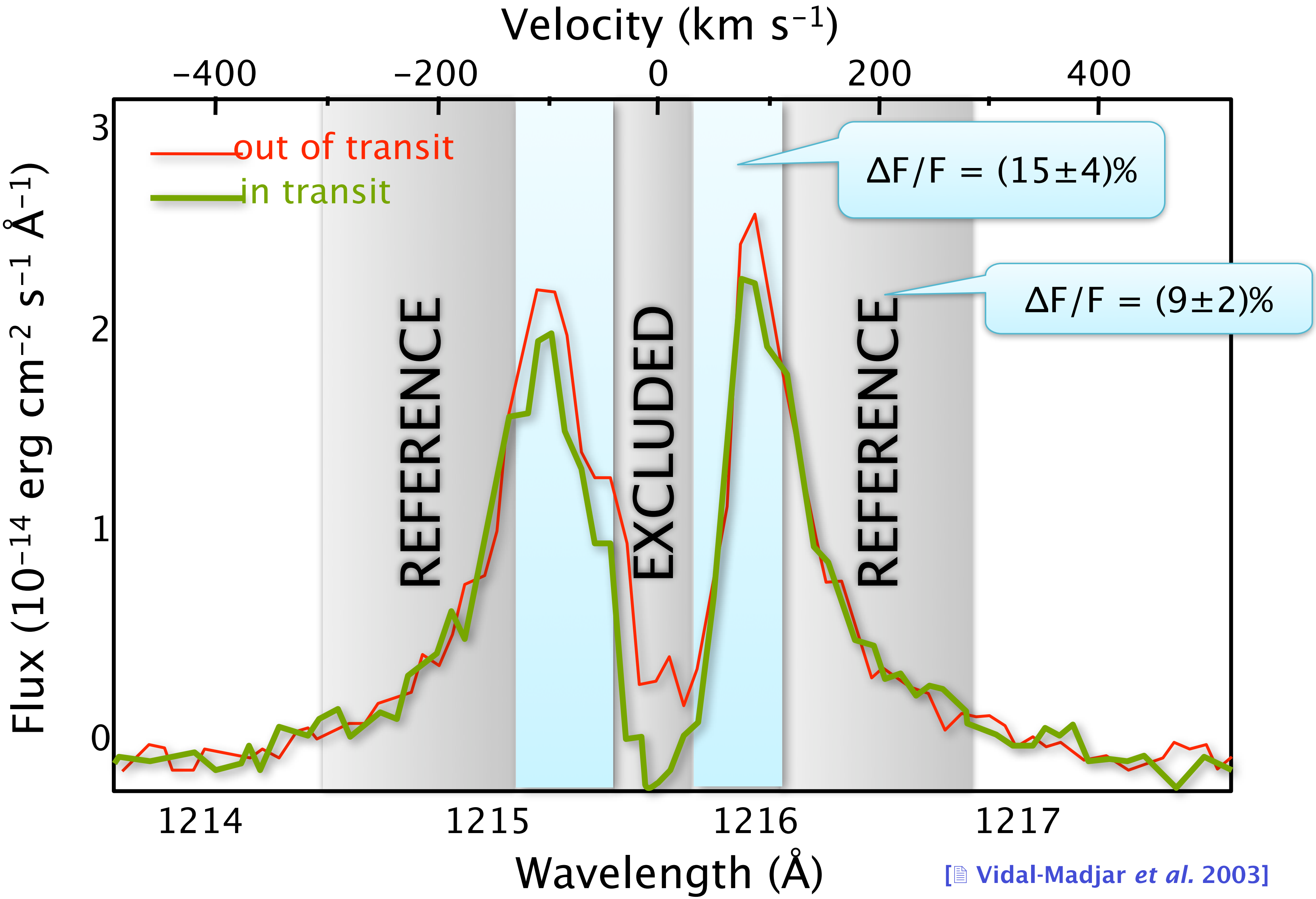
Detection of exospheric hydrogen



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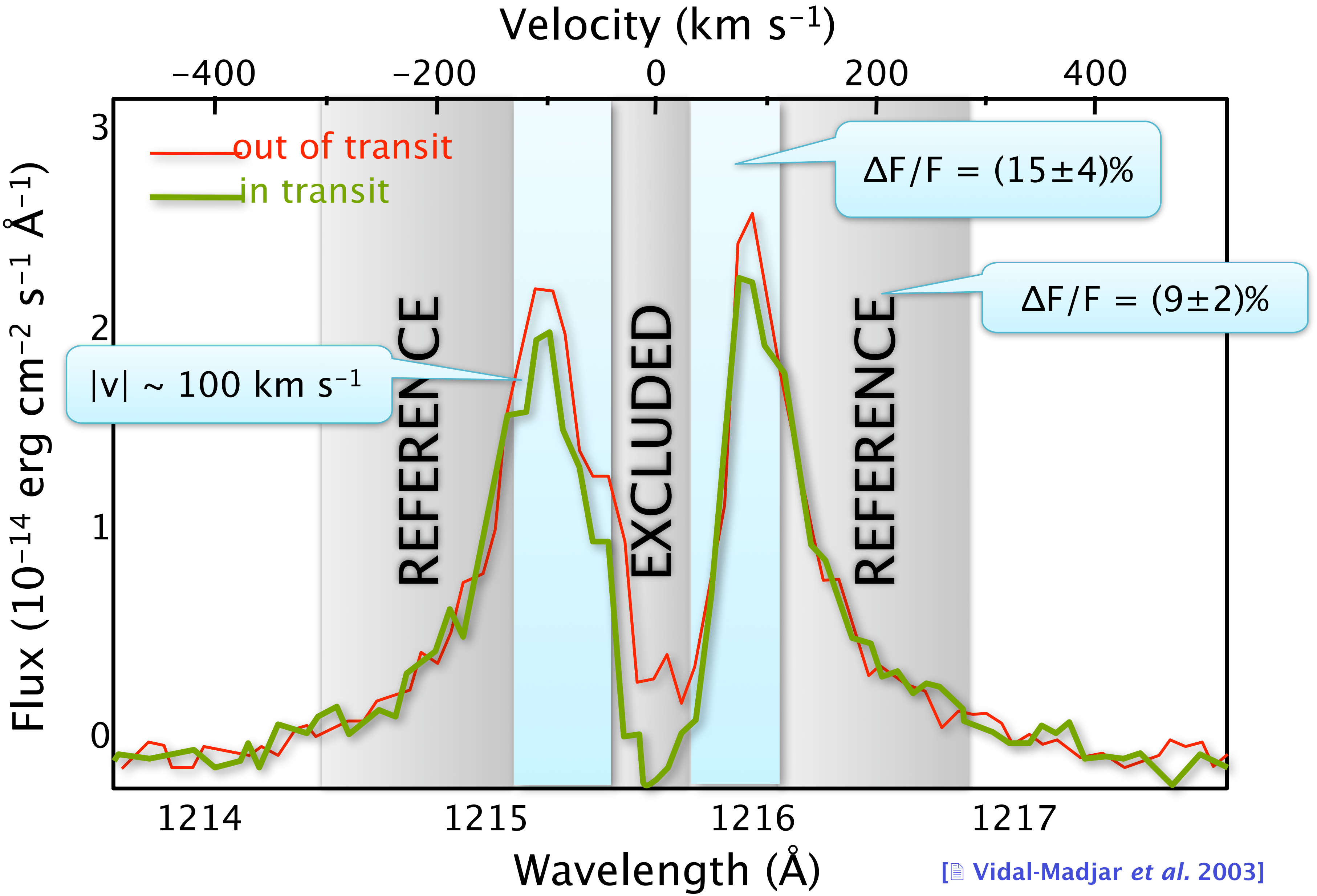

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Escape : two observational evidences

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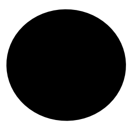

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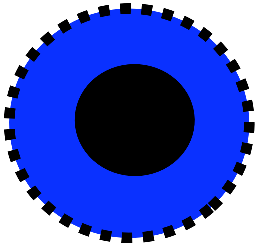

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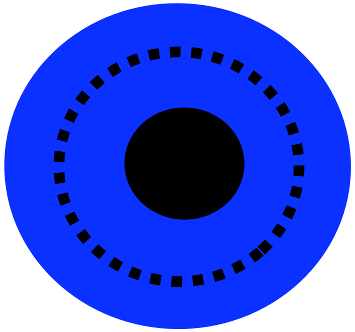

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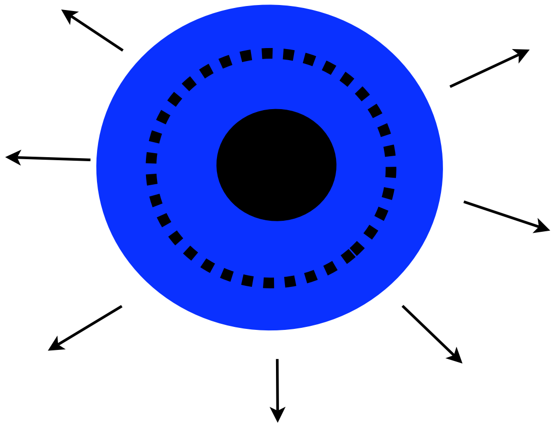

→ Beyond the Roche Lobe

➔ **Hydrogen is escaping**

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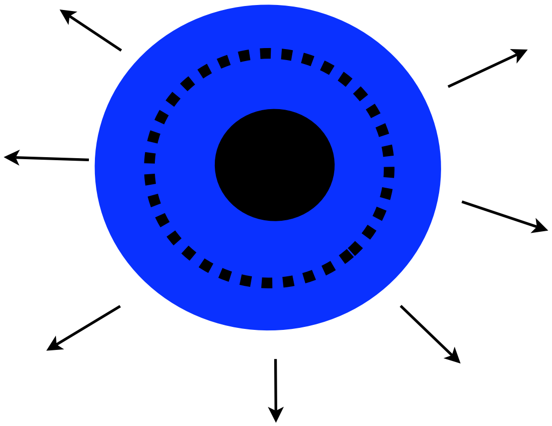


→ Beyond the Roche Lobe

➔ **Hydrogen is escaping**

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

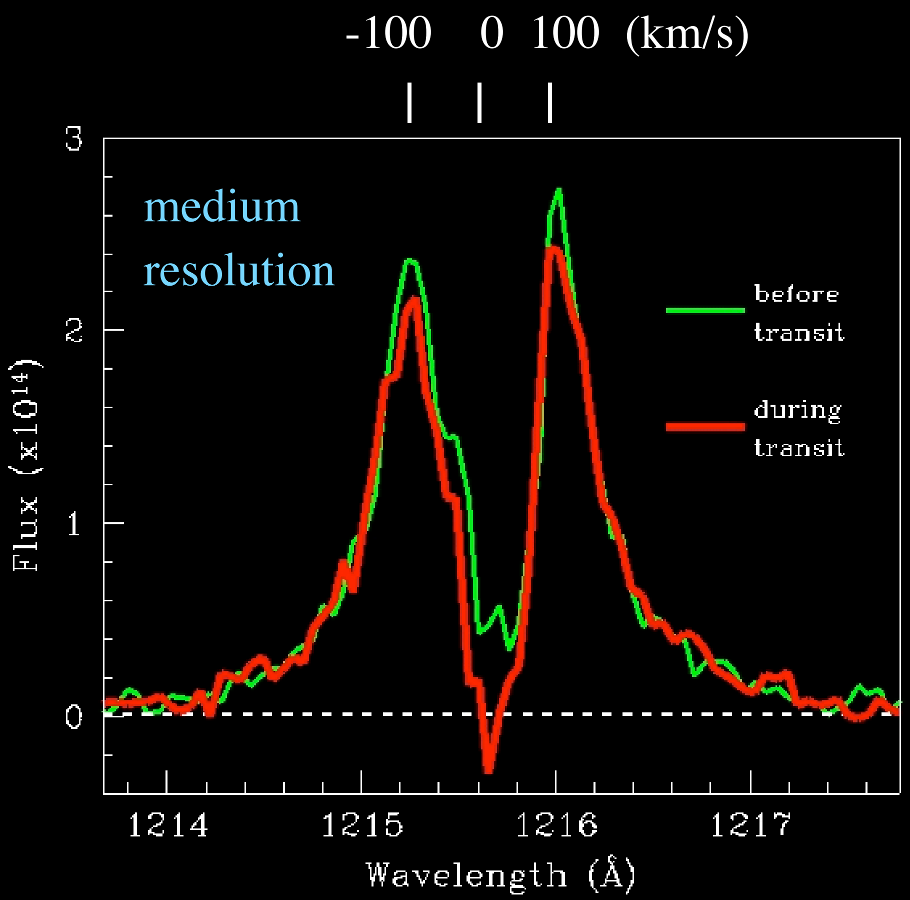
→ Beyond escape velocity

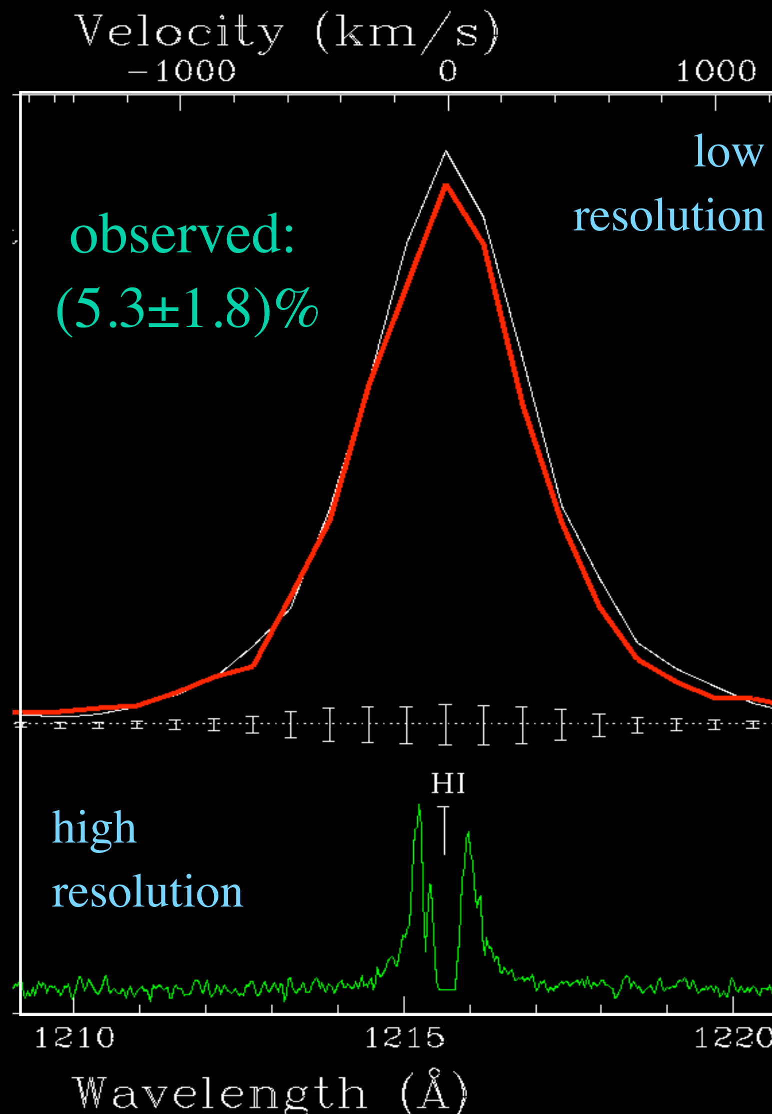
➔ **Hydrogen is escaping**

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)





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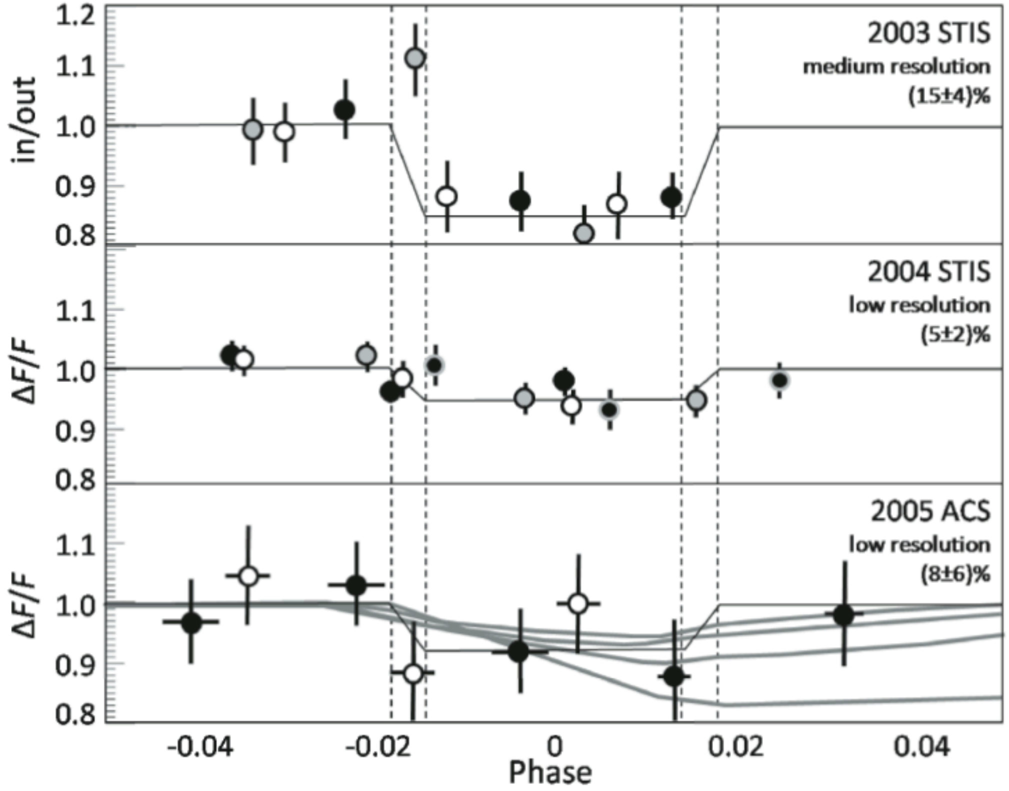

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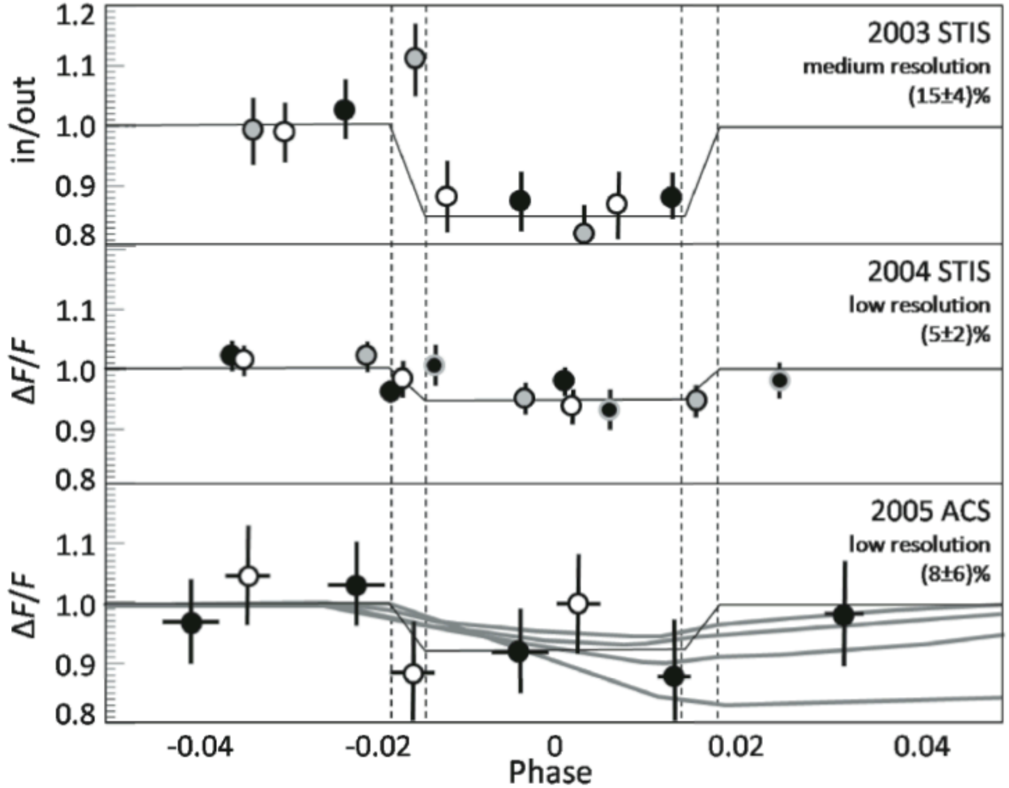

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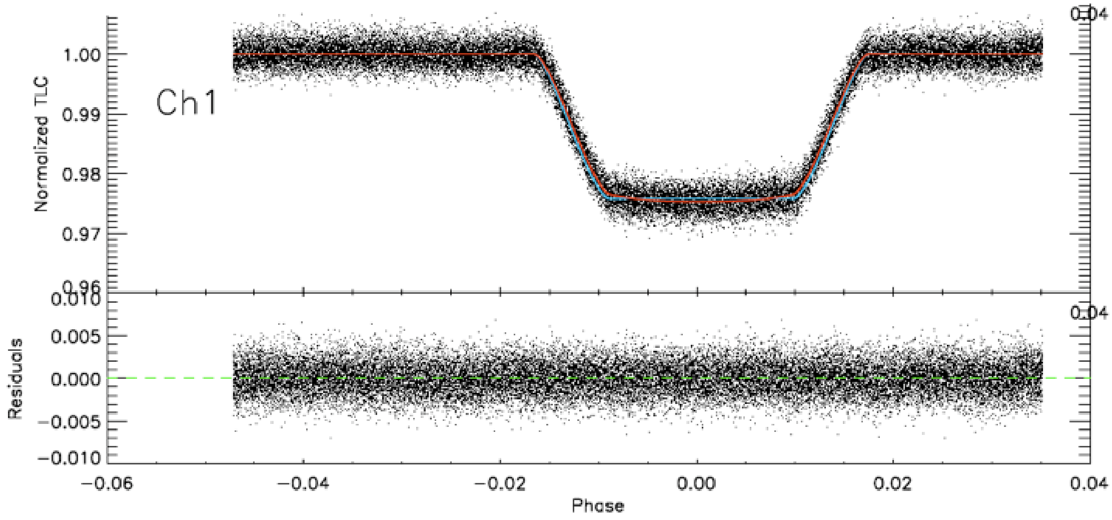

HD 189733 b
Spitzer/IRAC @ 3.6
122 000 expos. (0.1s)

[🗎 Désert *et al.* submitted]

Escape rate ?

Estimation of the escape rate

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

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$l = (N\,\pi\,a^2)^{-1} \sim 10^{16}\,N^{-1}$ cm $\sim R_{planet} \sim 100\,000$ km

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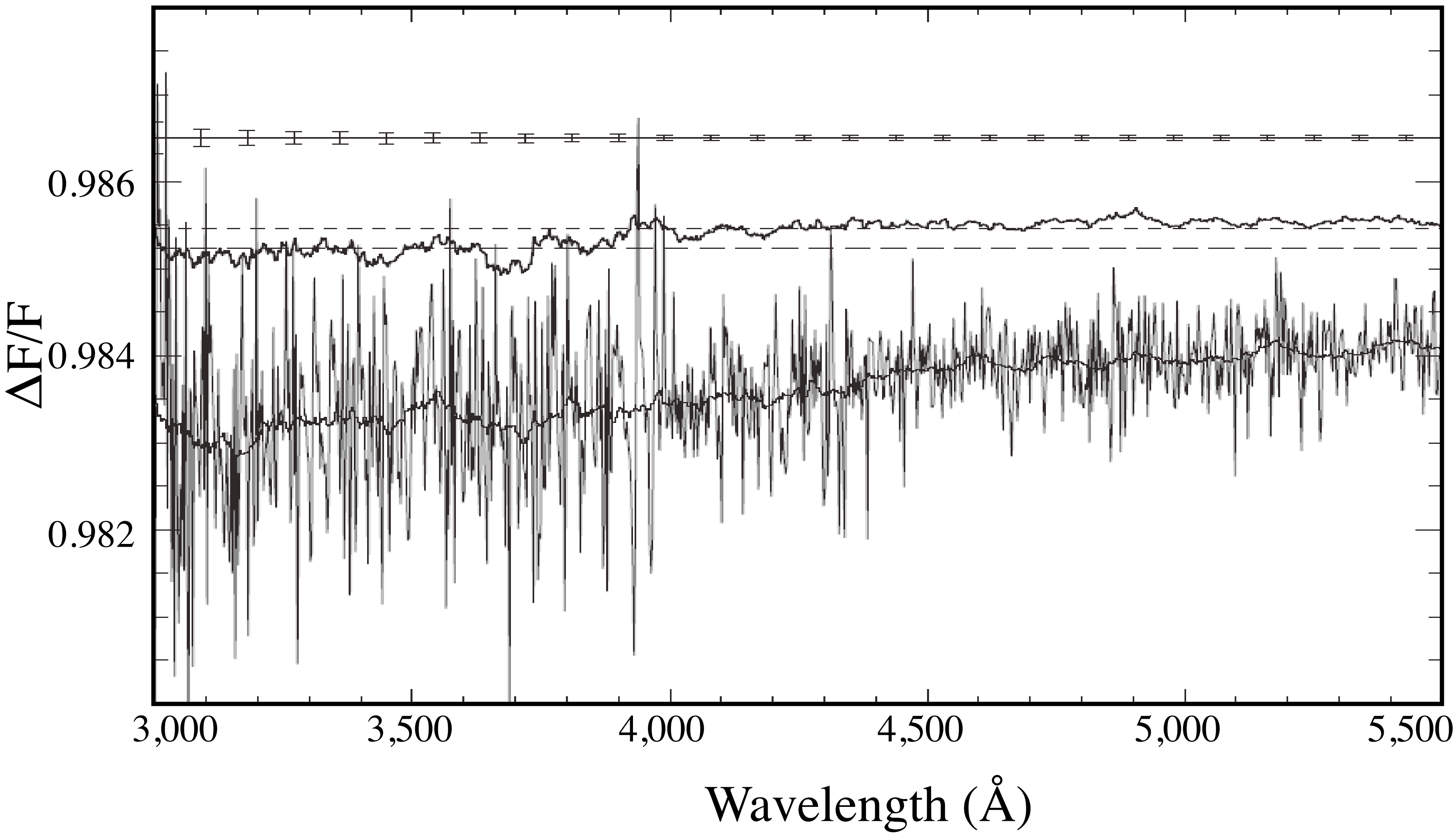
- Escape velocity => exospheric T ?

Hot hydrogen in HD 209458b

[Ballester *et al.* 2007]



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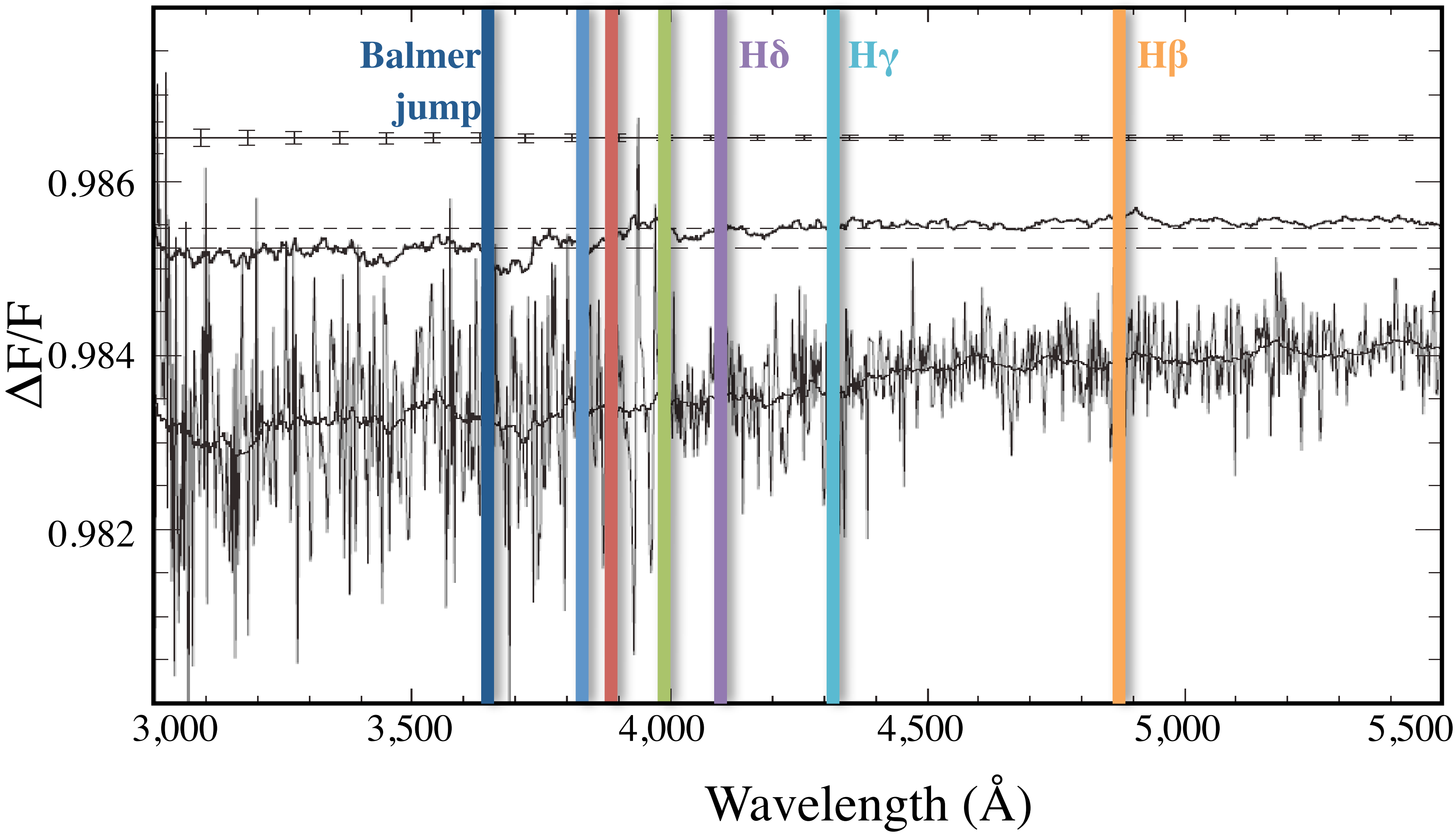

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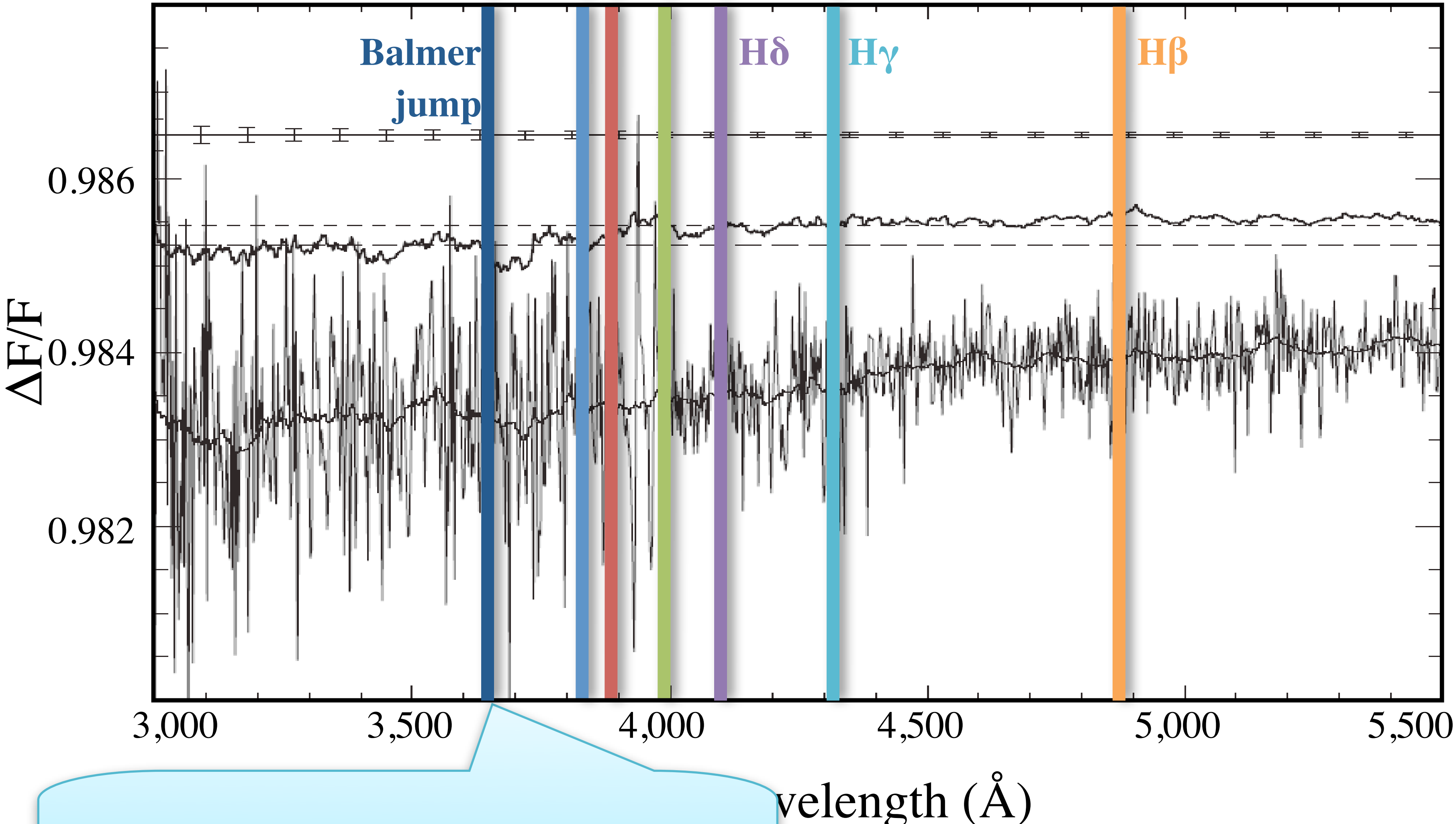

ΔF/F ~ 0.03% at ~ 3700 Å ➔ Balmer Jump

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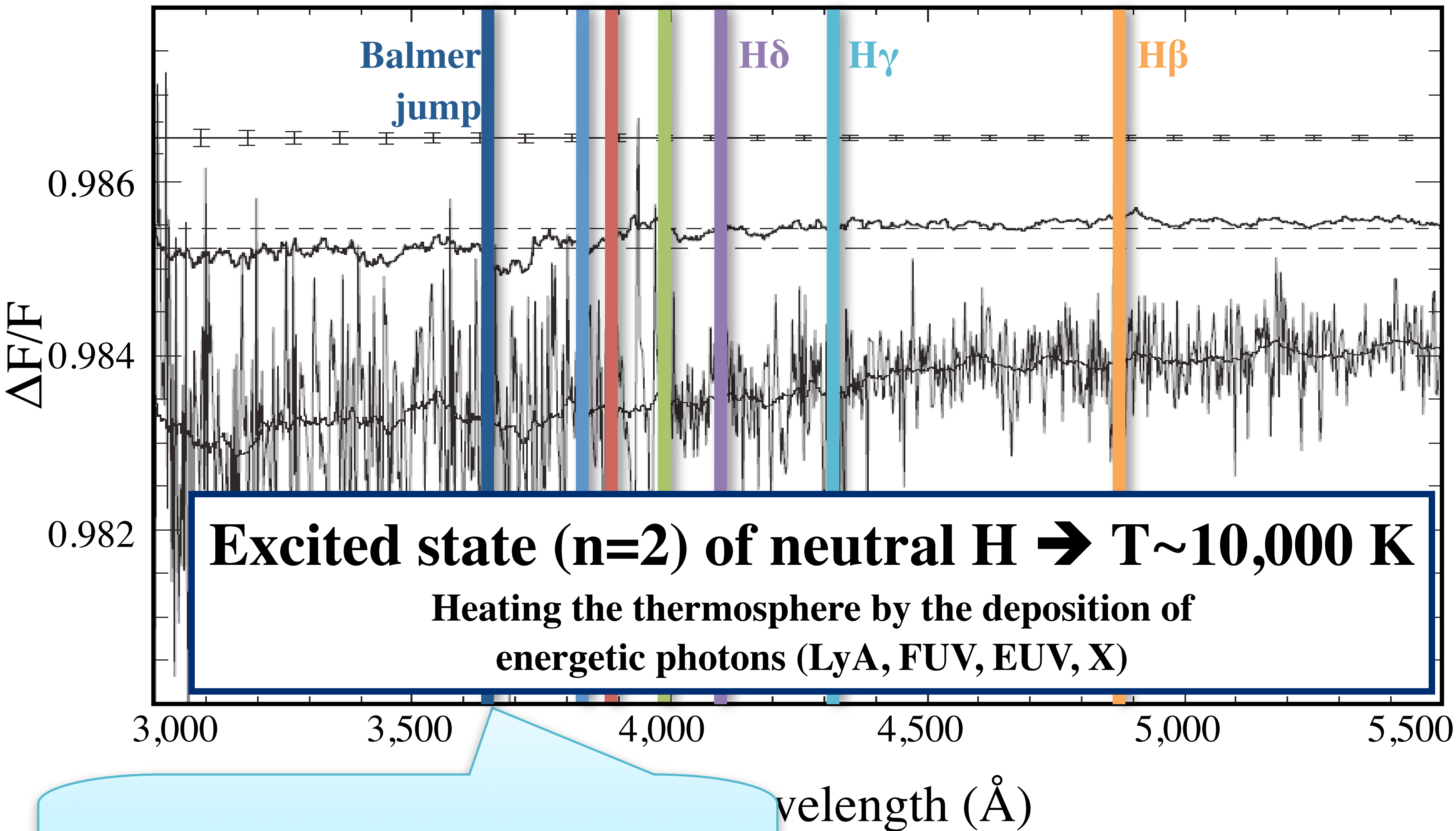

Excited state (n=2) of neutral H ➔ T~10,000 K

Heating the thermosphere by the deposition of energetic photons (LyA, FUV, EUV, X)

ΔF/F ~ 0.03% at ~ 3700 Å ➔ Balmer Jump

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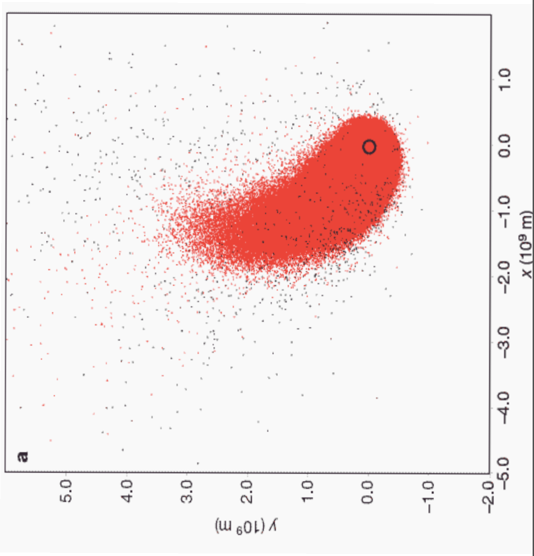
2 000 K < T < 20 000 K

→ 5 kms^{-1} < V < 15 kms^{-1}

→ $\Phi_{esc} \sim 10^{10}$ g s^{-1} => 1% mass / lifetime

3 models to interpret the observations and estimate the escape rate



[Vidal-Madjar *et al.* 2003] :

Radiation pressure, F_{EUV} ionization

[Schneiter 2007] :

Interaction between escaping gas and stellar wind

[Holmstrom et al. 2008] :

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

Energetic Neutral Atoms (ENA) from stellar wind

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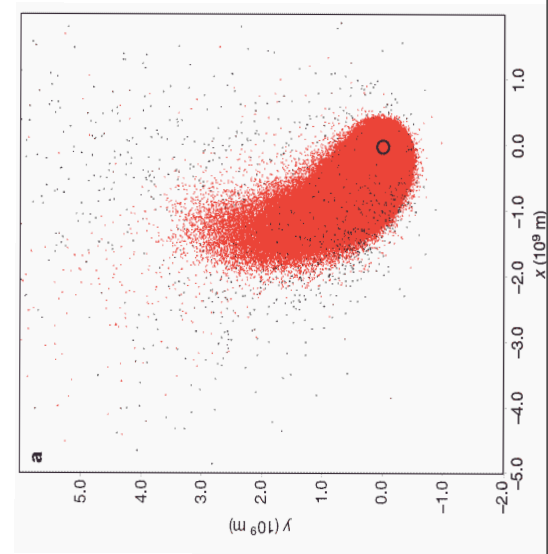


[Vidal-Madjar *et al.* 2003] :

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

Models to understand the escape rate

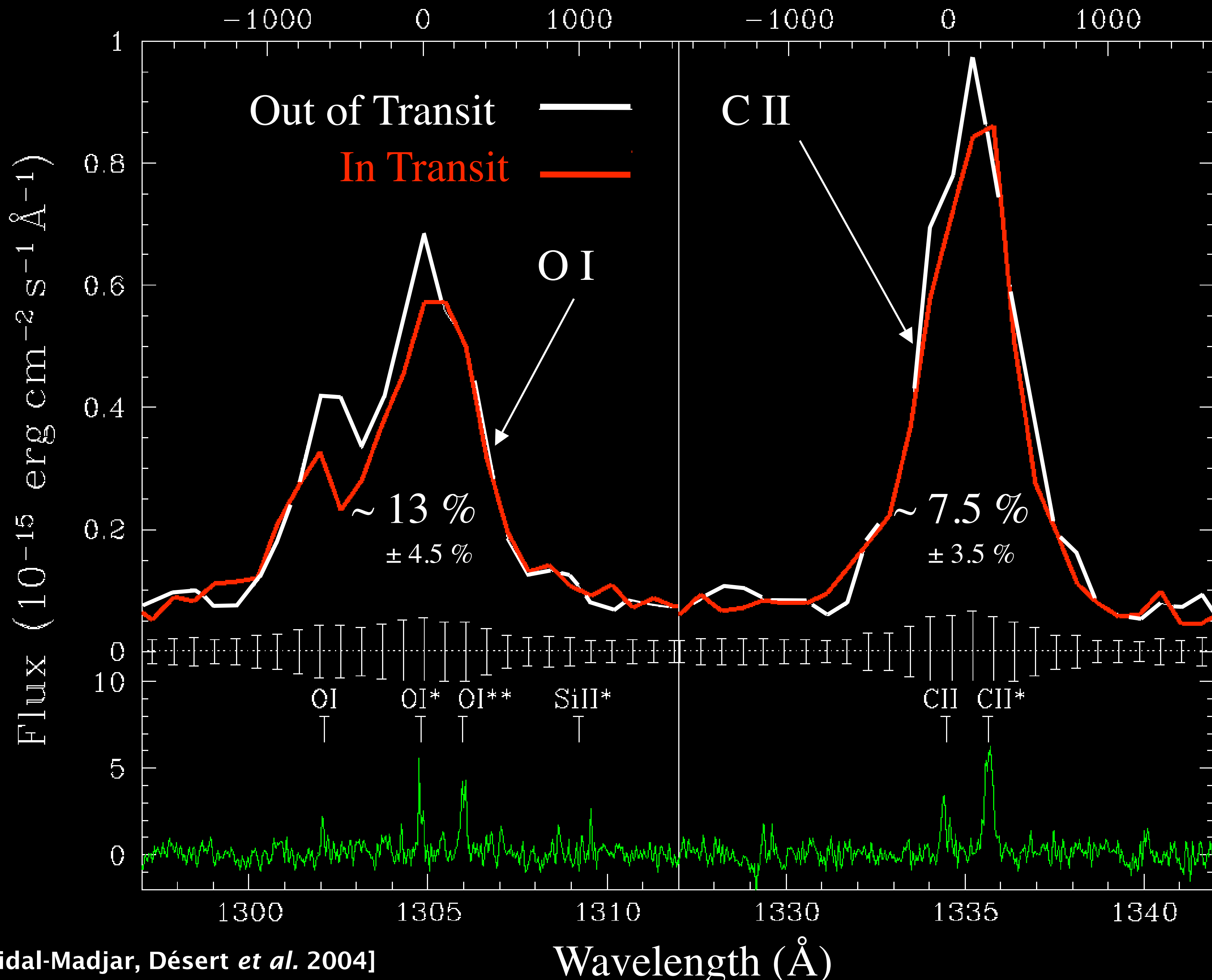
- Burrows et al. 1995
- Lammer et al. 2003
- Lecavelier des Etangs et al. 2004, 2007
- Baraffe et al. 2004, 2005, 2006
- Yelle 2004, 2006
- Jaritz et al. 2004
- Tian et al. 2005
- Hubbard et al. 2006
- Garcia-Muñoz 2007
- Erkaev et al. 2007
- Penz et al. 2007, 2008
- Murray-Clay 2008
- Stone 2009

Use X-UV for escape

Which escape mechanism ?

Jeans escape or “blow-off” ?

Evidences 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)

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Consequences of exospheric O & C

- O and C up to the Roche lobe
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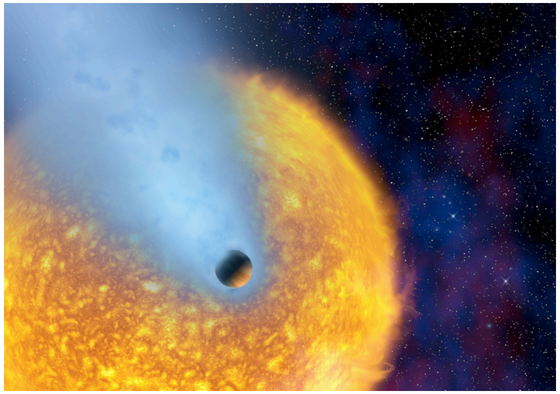
➡ **Hydrodynamic escape (« Blow-Off »)**

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

What's next?



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

What's next?

- Blow-off ?
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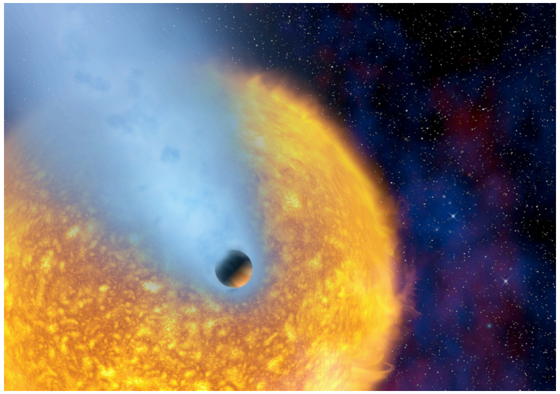

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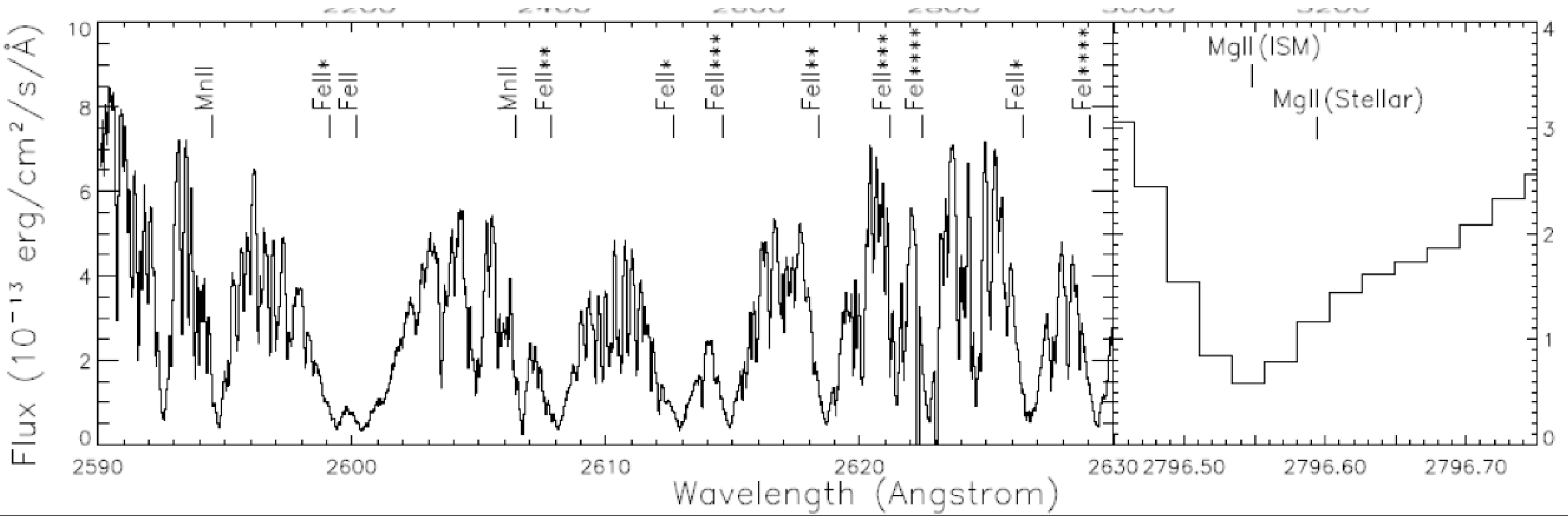
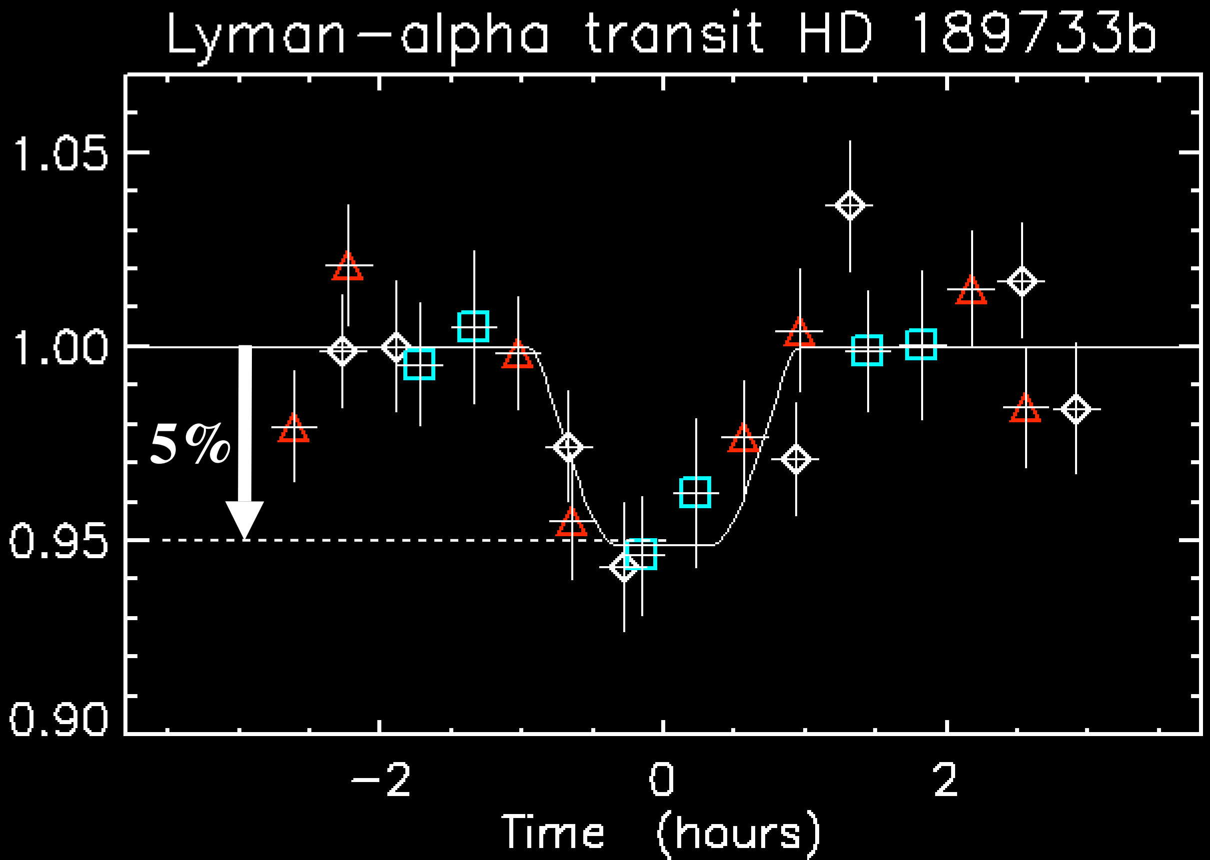


Other evaporating hot Jupiters ?

A second case of evaporation: HD189733b

HST/ACS Lyman-α observation



- Depth ~ 5.1 ± 0.7 %
  dM/dt ~ few 10^8 g/s

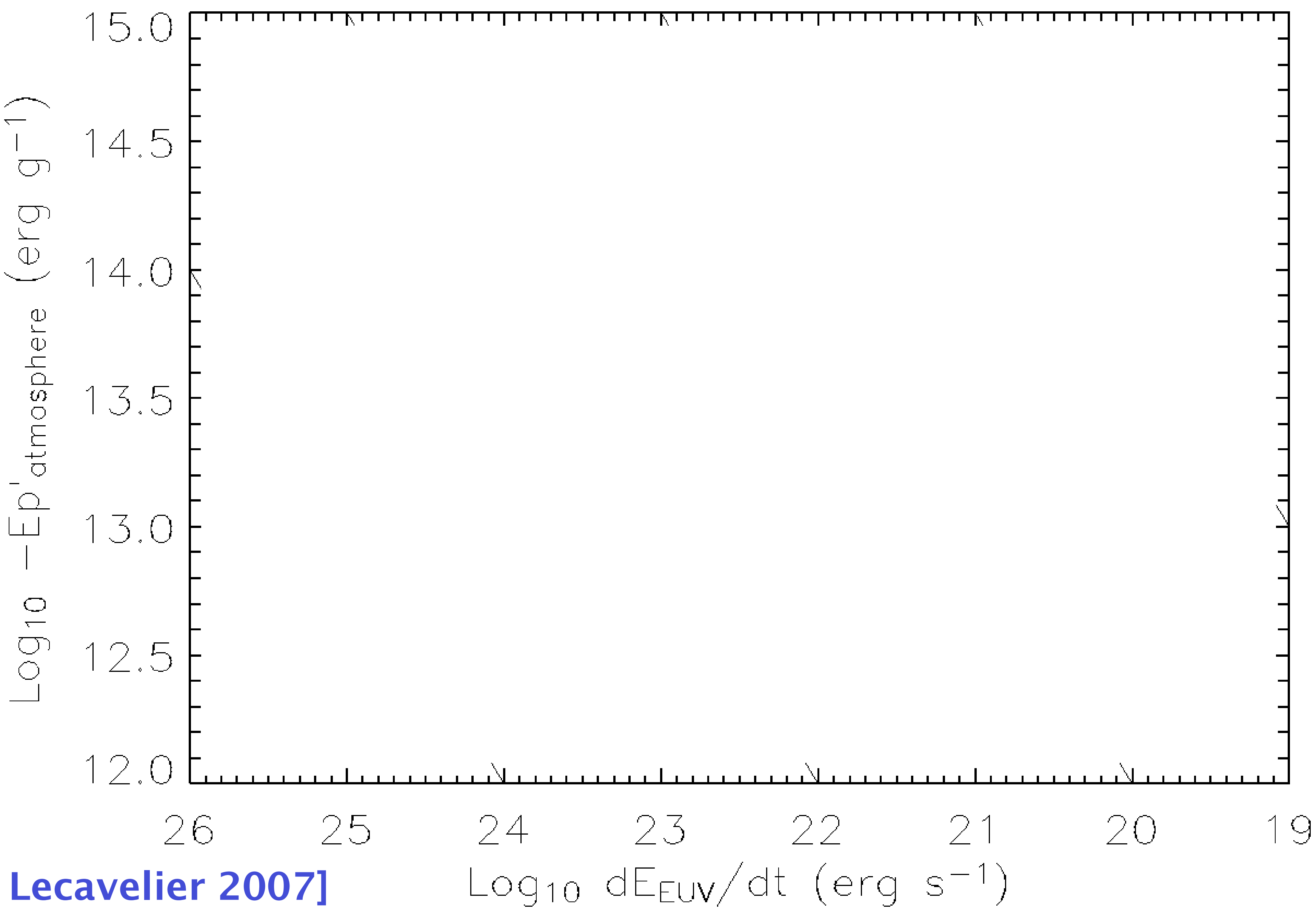
- No tail of occulting HI

large ionizing EUV
from the central K star

[Lecavelier et al. in prep.]

Evaporation status of extrasolar planets ?

The energy diagram



[Lecavelier 2007]

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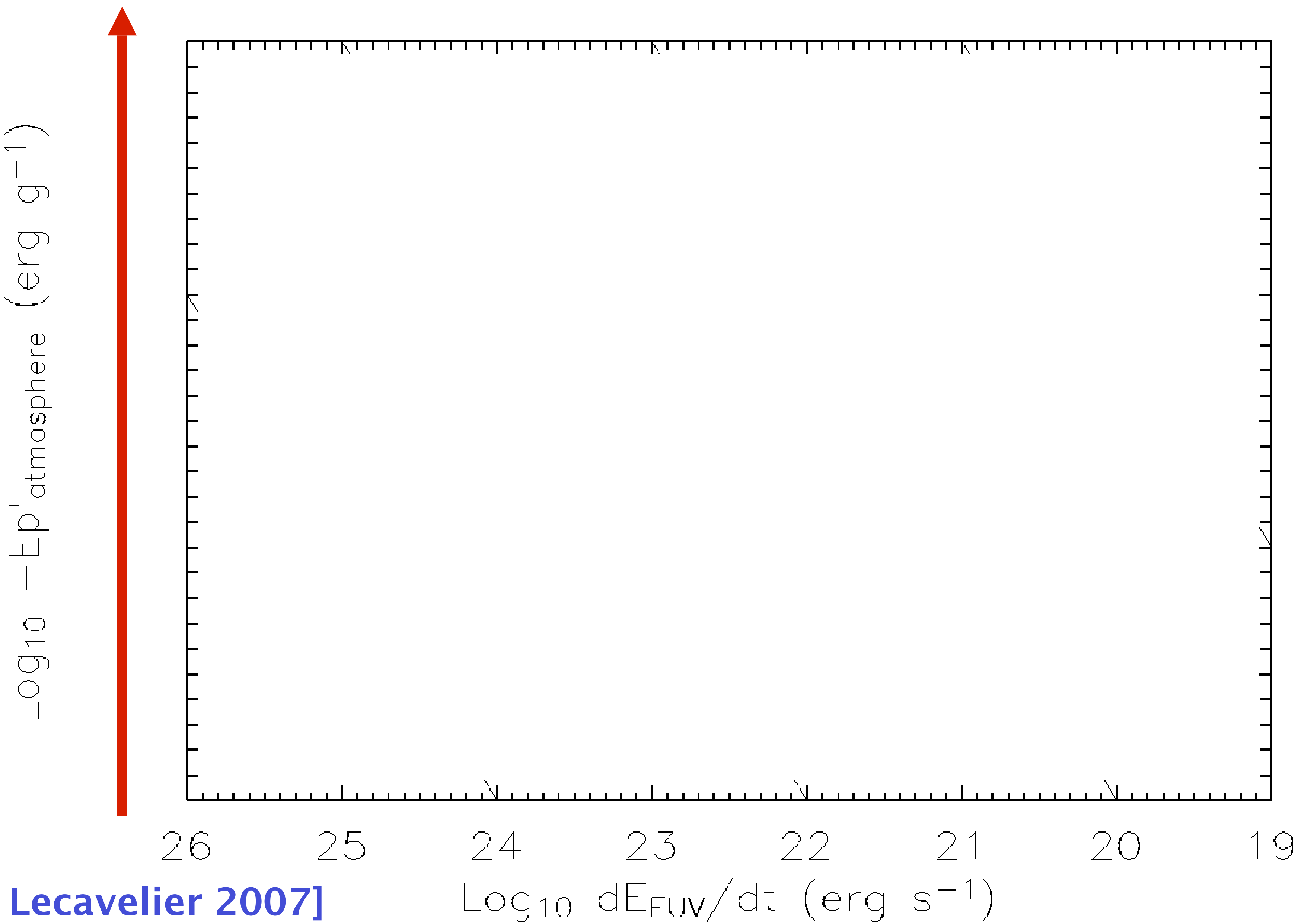

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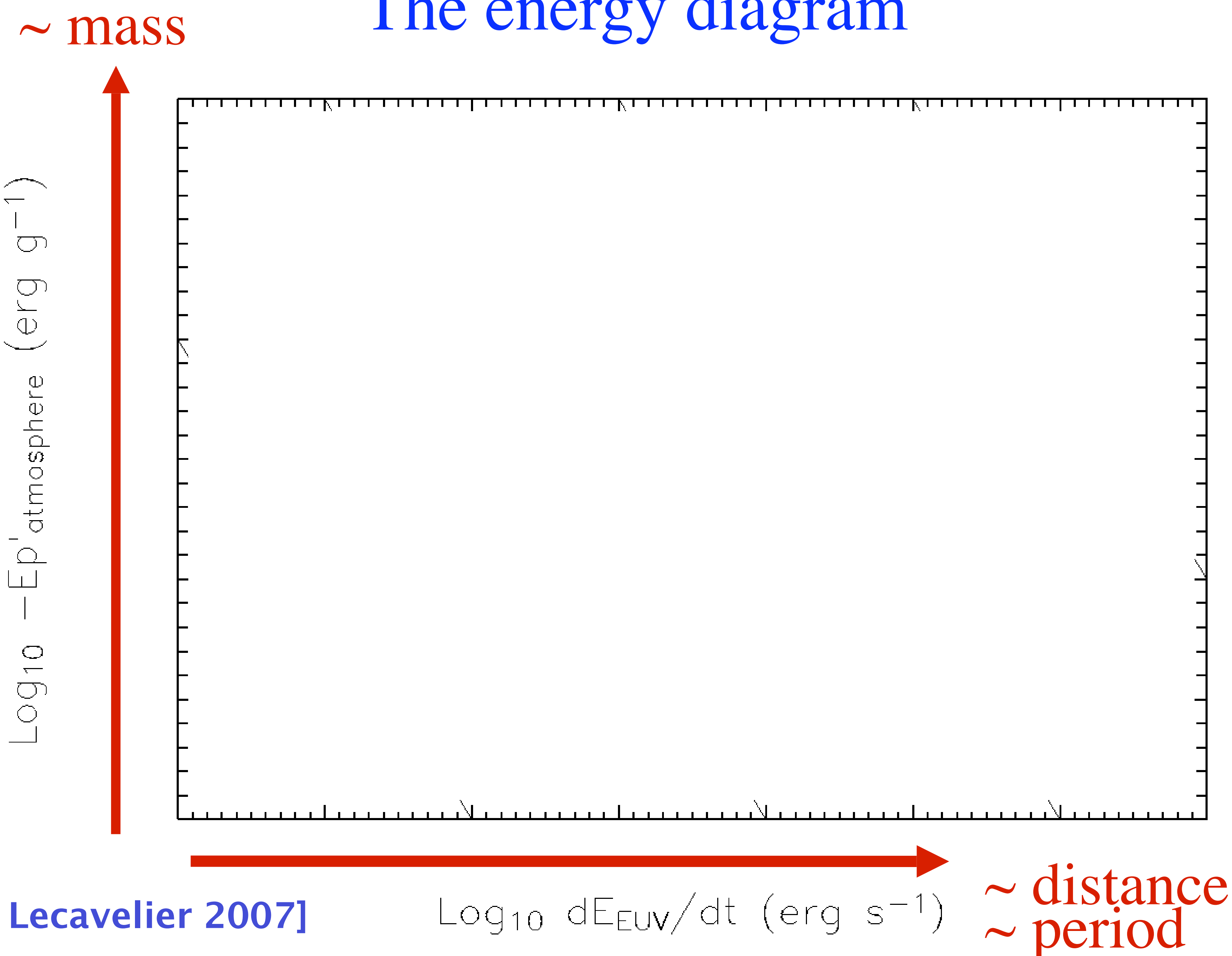

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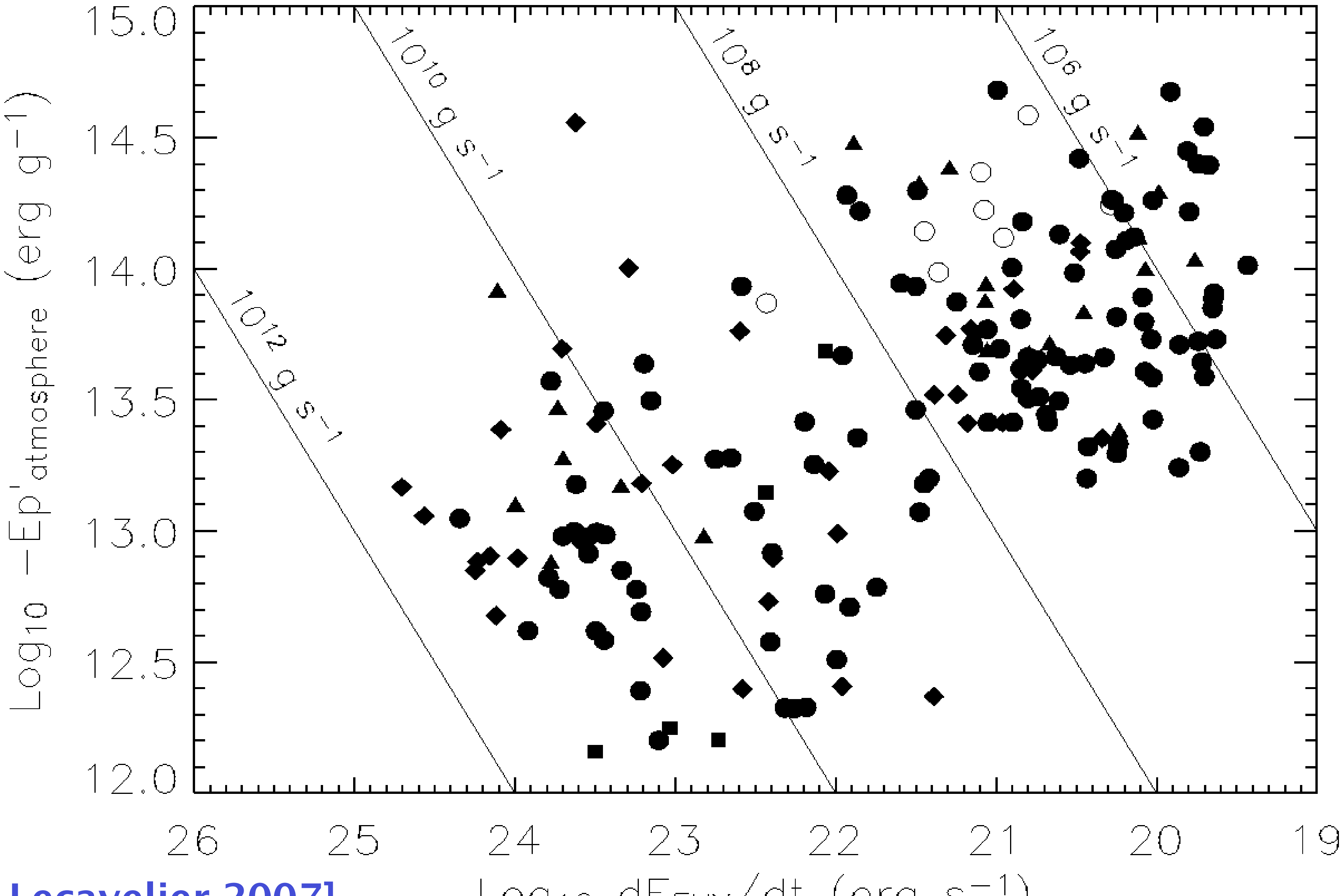

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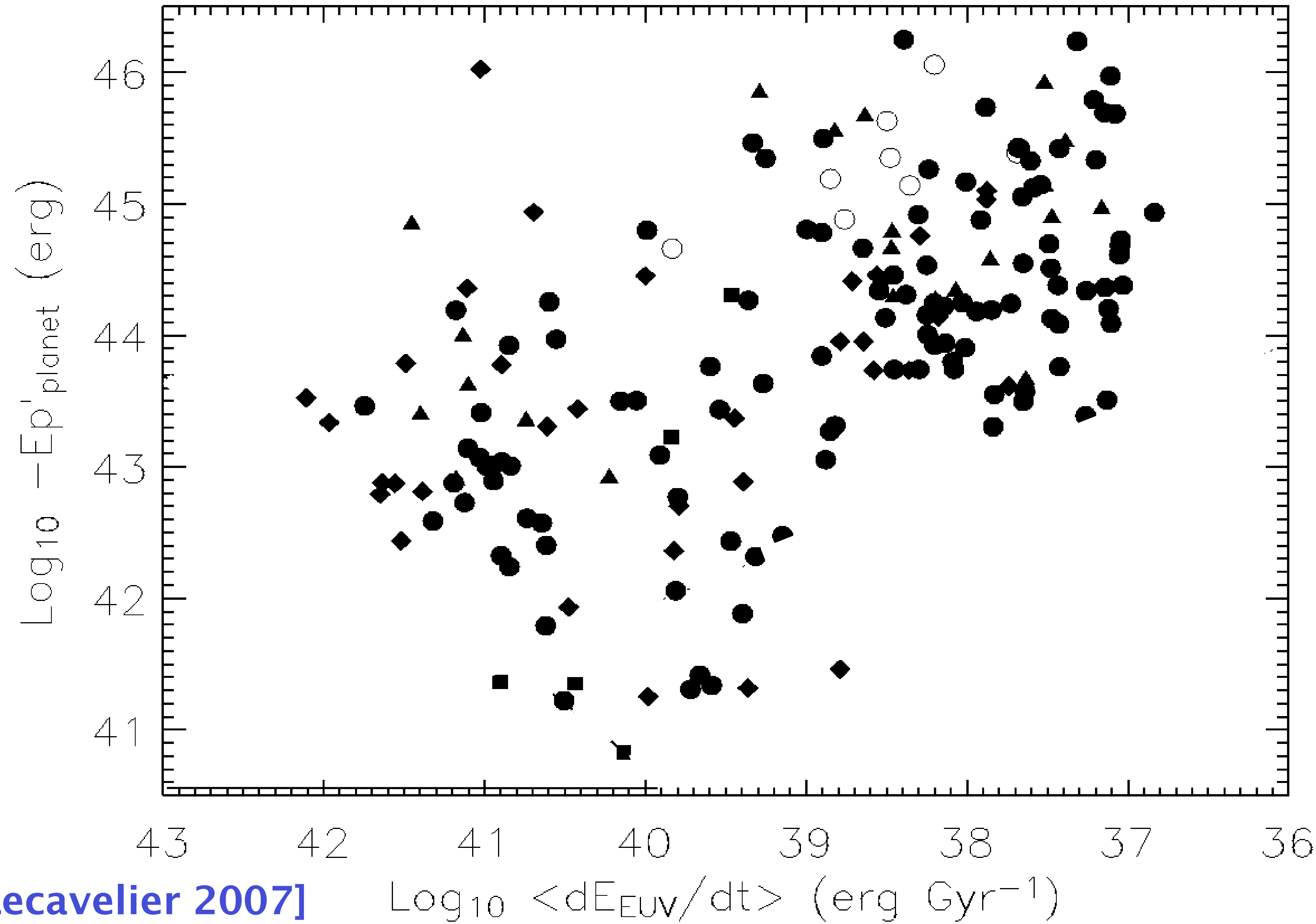

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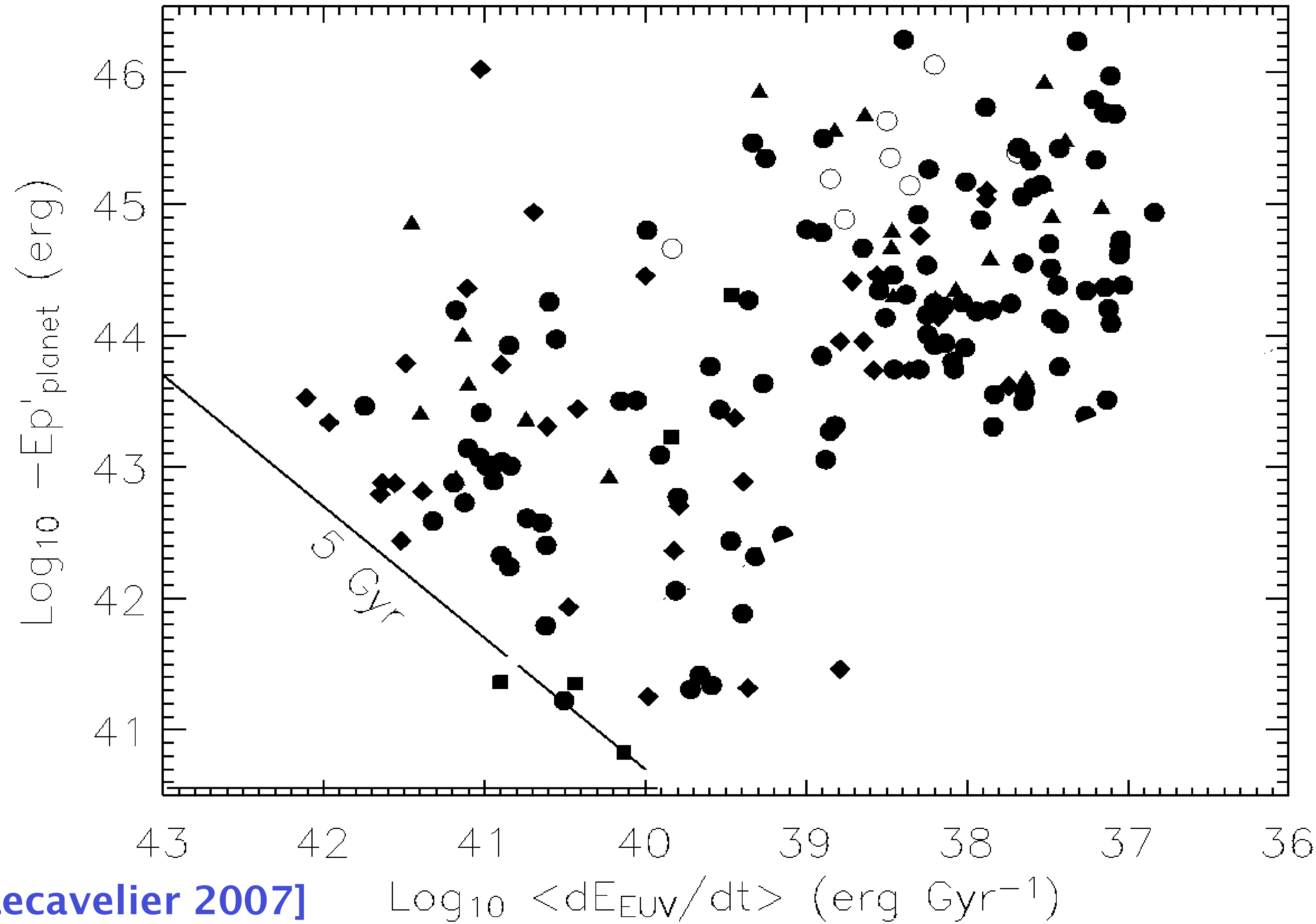

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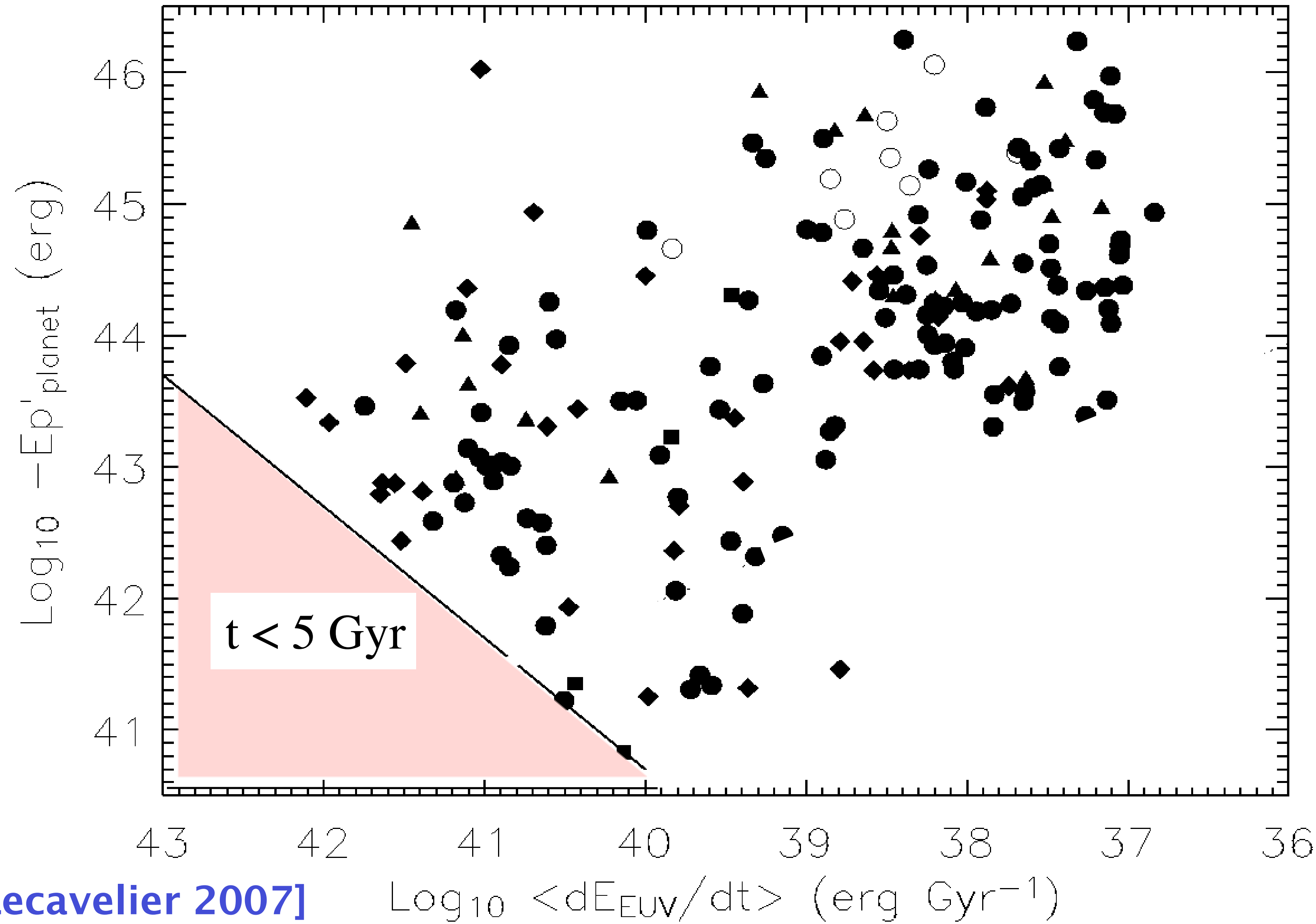


[Lecavelier 2007]

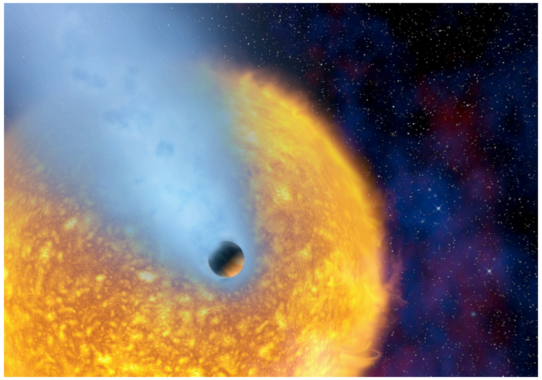
Remnants of evaporation?

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

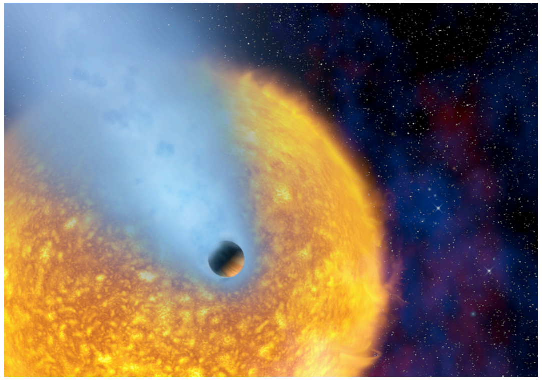
- « Massive Earths »
  (solid core)

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

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



Conclusion and next



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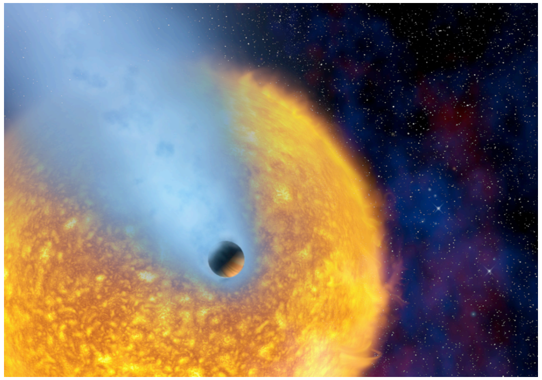

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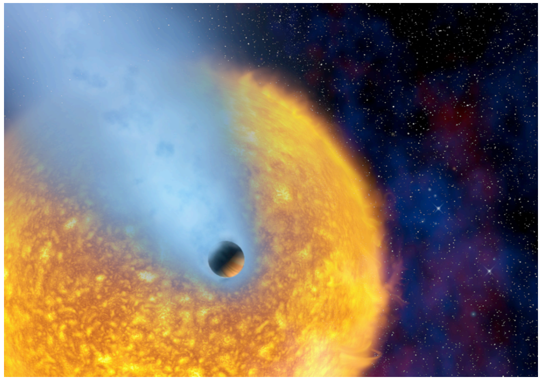
- Survey : HD189733b, Wasp-1b ,12b, HAT-P-1b, 6b etc..



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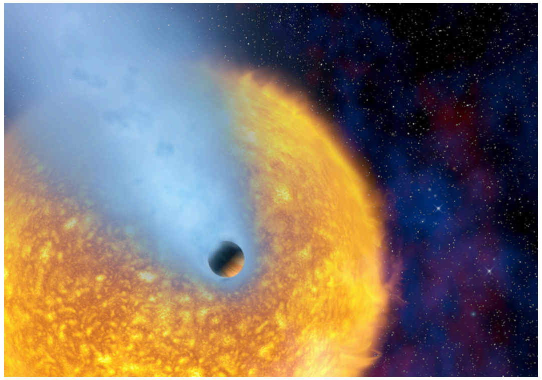

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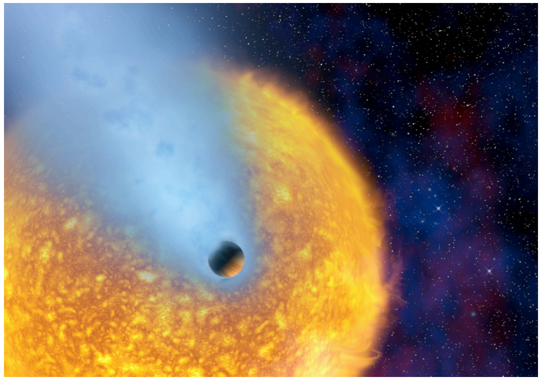

Conclusion and next

➡ **2 evaporating hot-jupiters** (hd209458b & HD189733b)

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Thank you !


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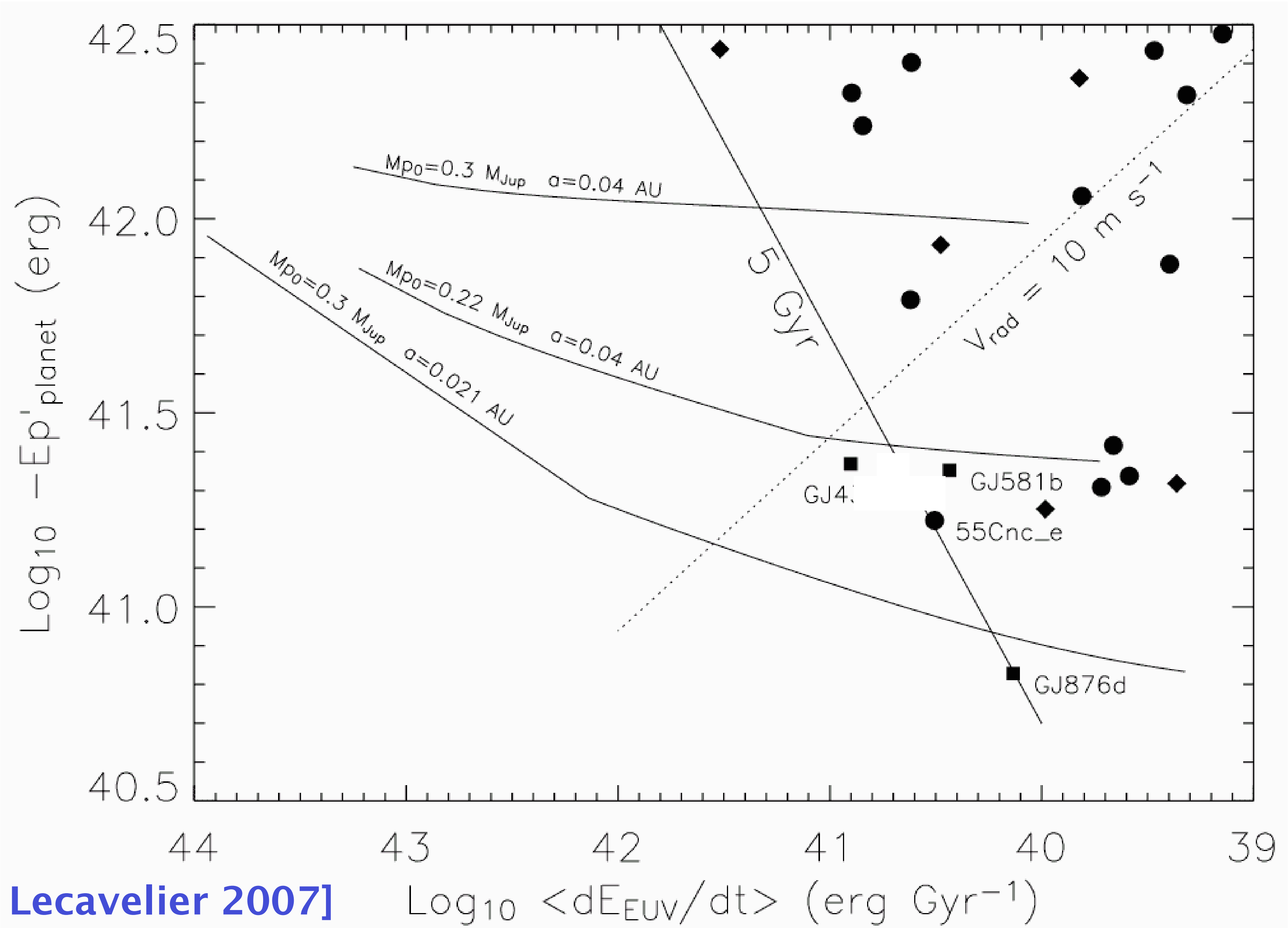
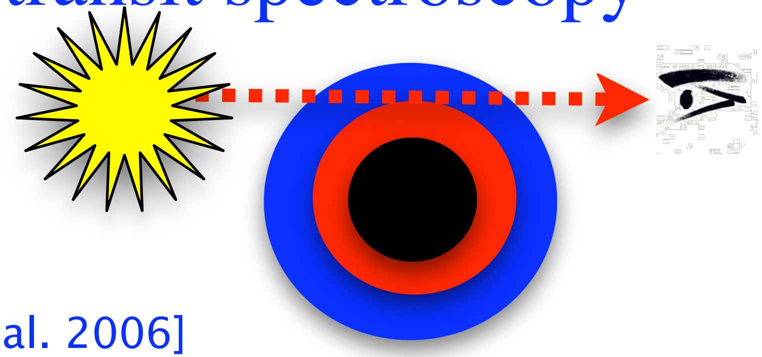
Evolution track in the energy diagram



[🗎 Lecavelier 2007]

Atmospheric temperature with transit spectroscopy



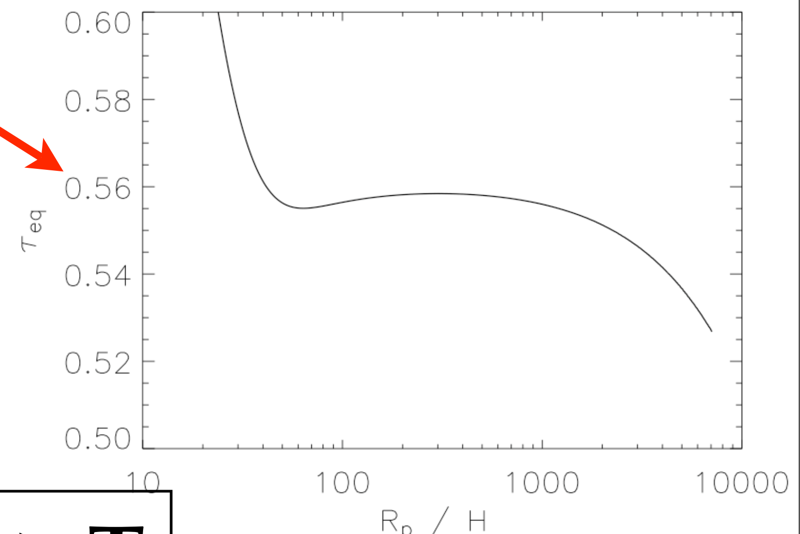
$$R_p(\lambda) = R_{planet} + z(\tau = \tau_{eq}) \quad (1)$$

$$\tau(\lambda, z) \approx \sigma(\lambda) n(z) \sqrt{2\pi R_{planet} H} \quad (2)$$

[Fortney et al. 2006]

$$n(z) = n_{(z=0)} exp(-z/H) \quad (3)$$

(1)+(3)



$$\Delta_{Rp} = \mathbf{H}\ \Delta \boldsymbol{ln}(\sigma_\lambda)$$

$$\sigma = \sigma_0 (\lambda/\lambda_0)^\alpha$$

Rayleigh Scattering α =-4 => Δ_{Rp} => T

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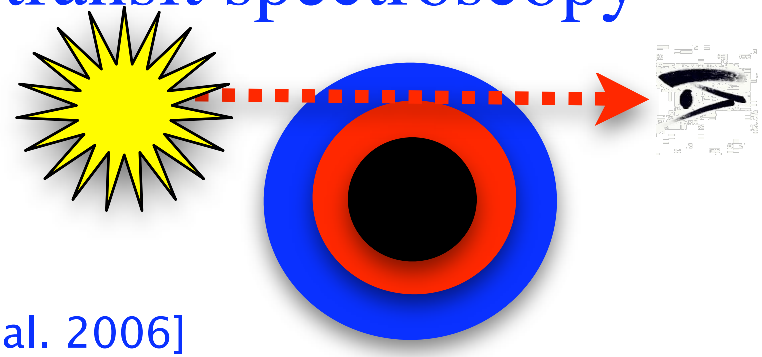

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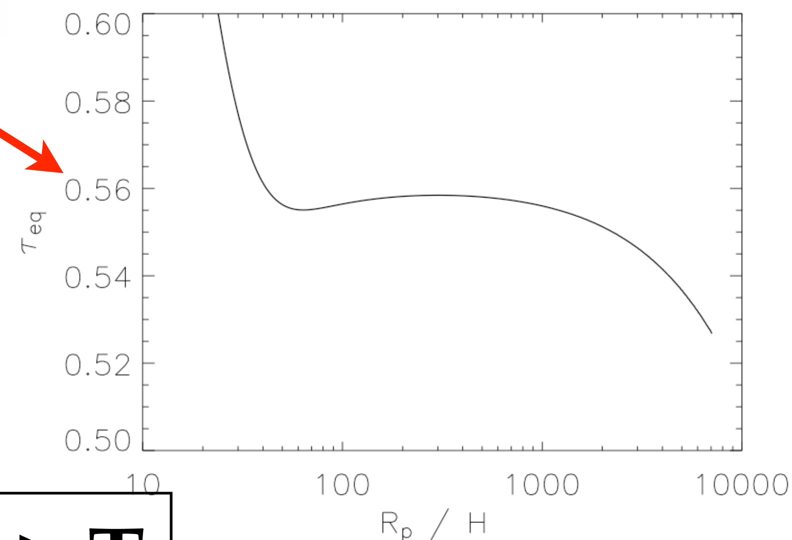

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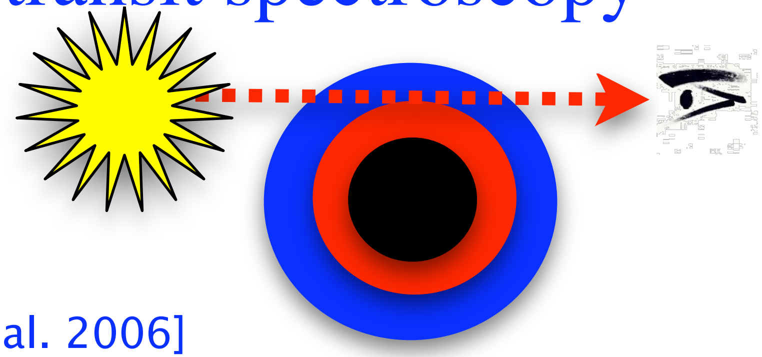

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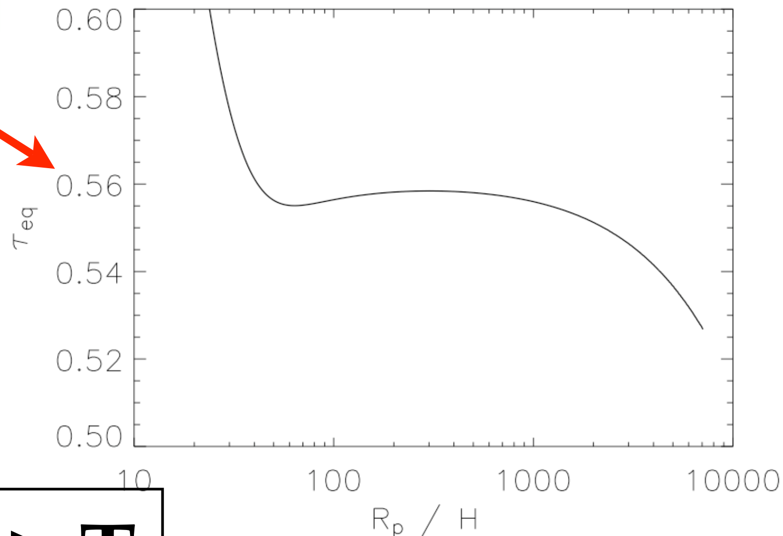

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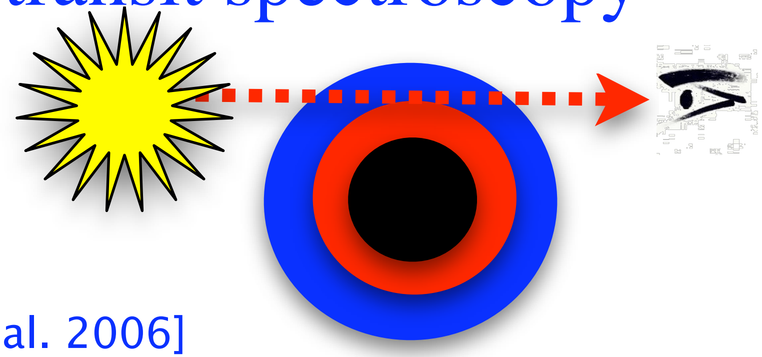

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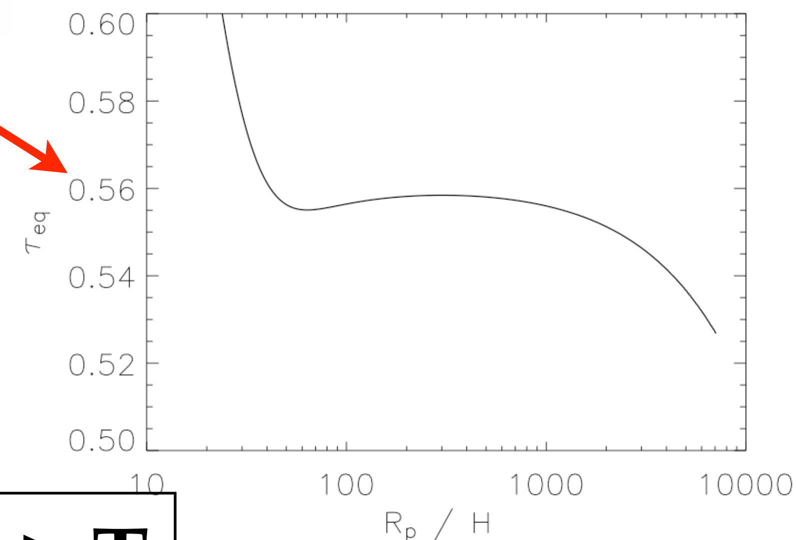
H = KT/μg



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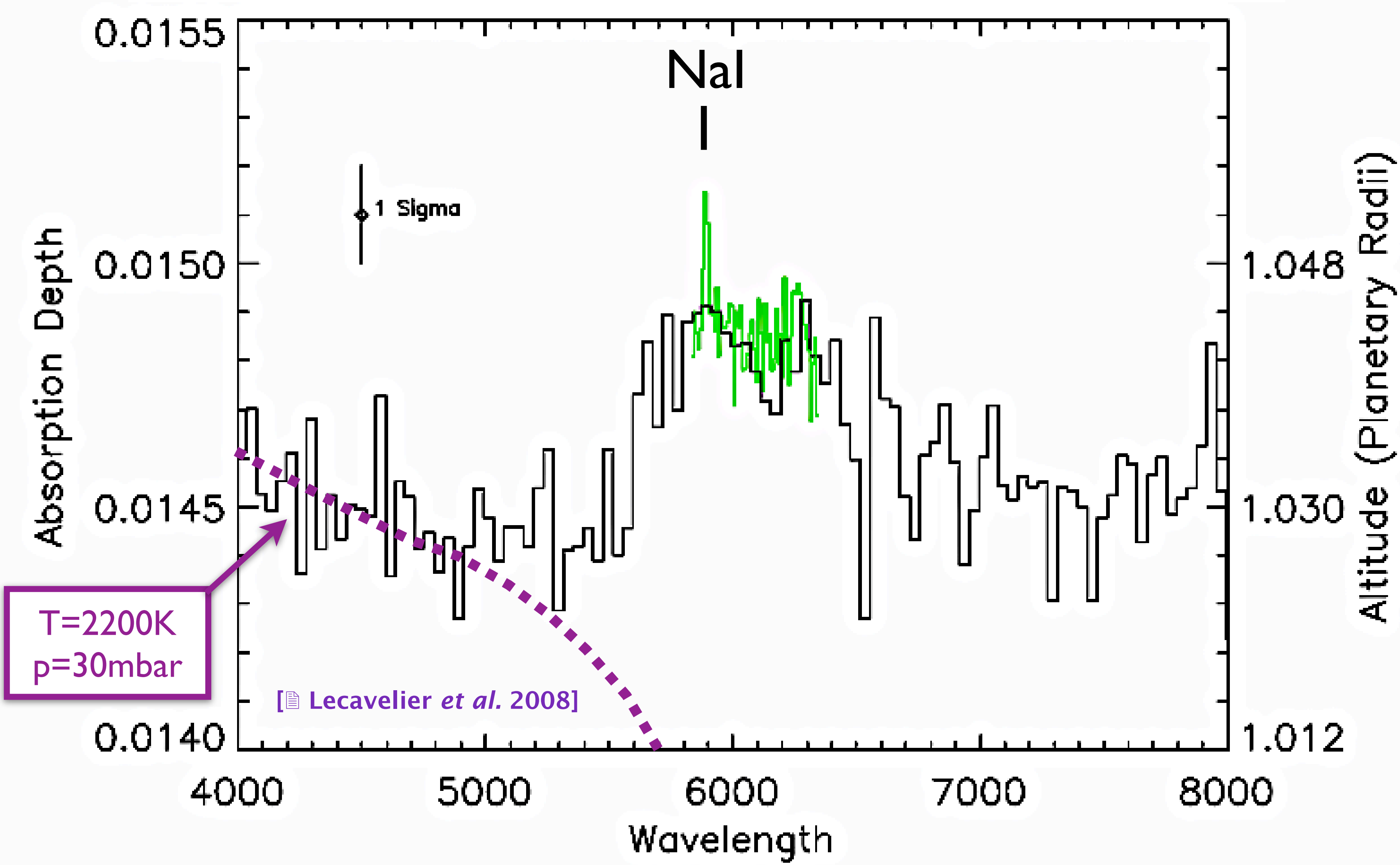
HST/STIS HD209458b



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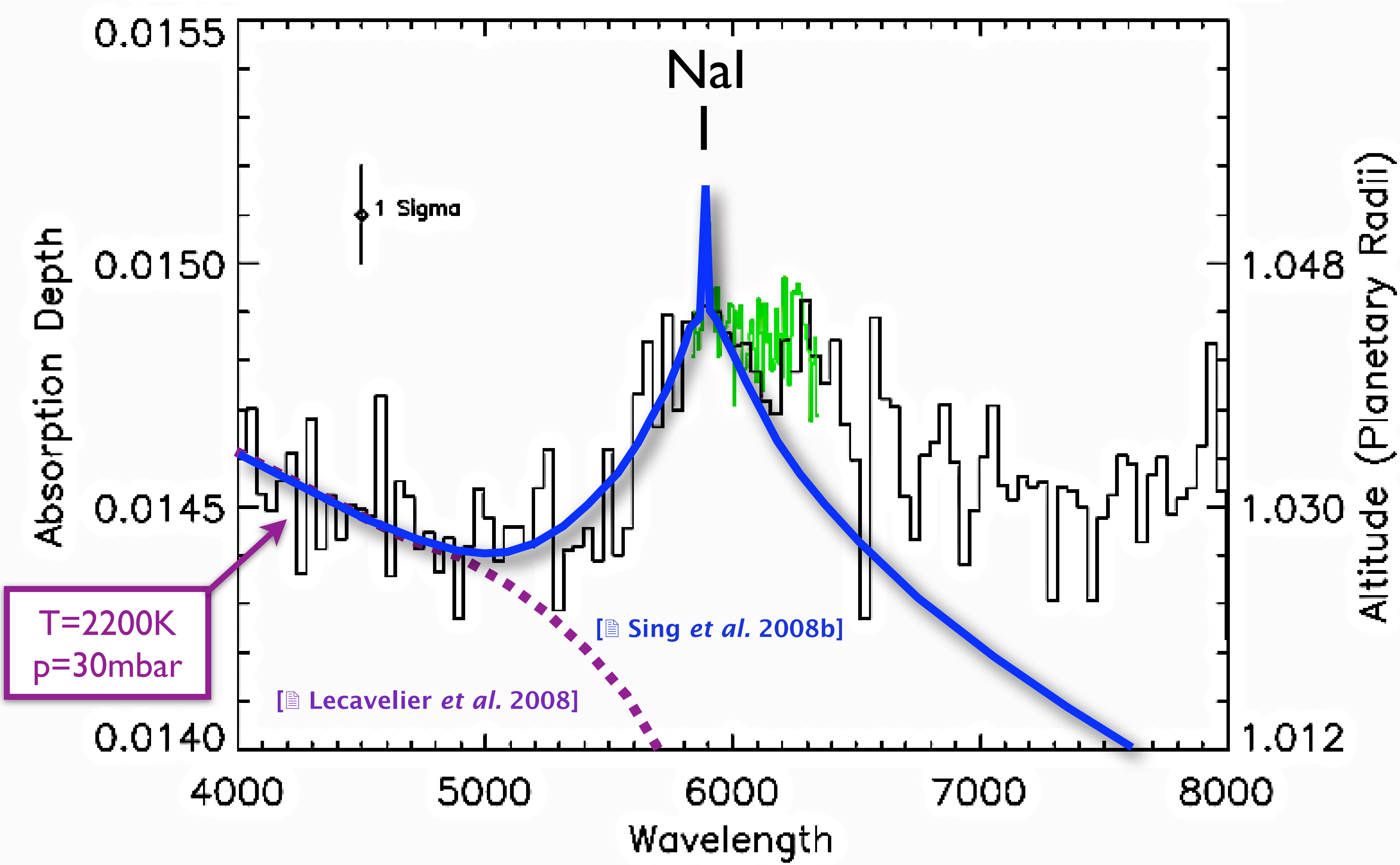

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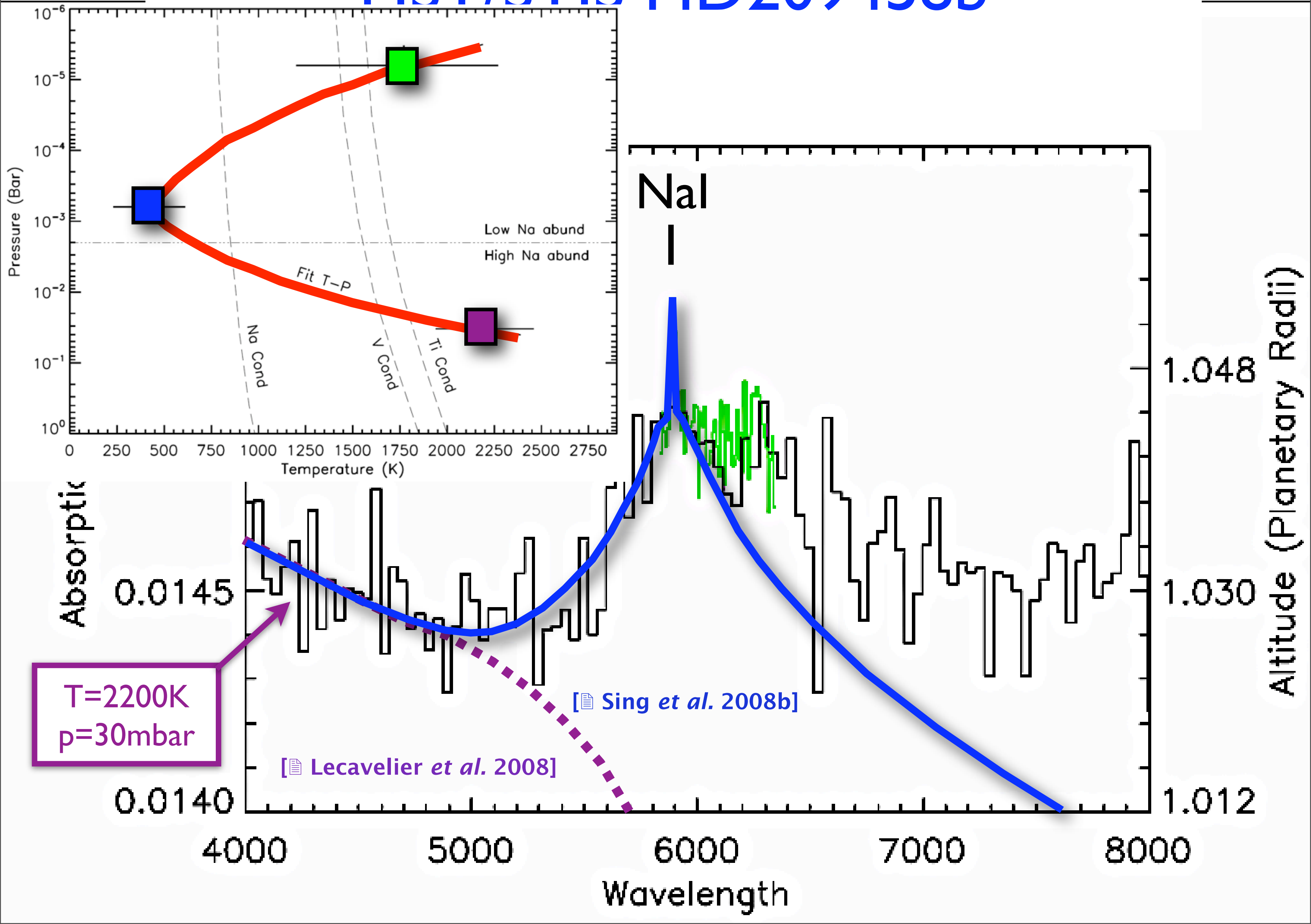

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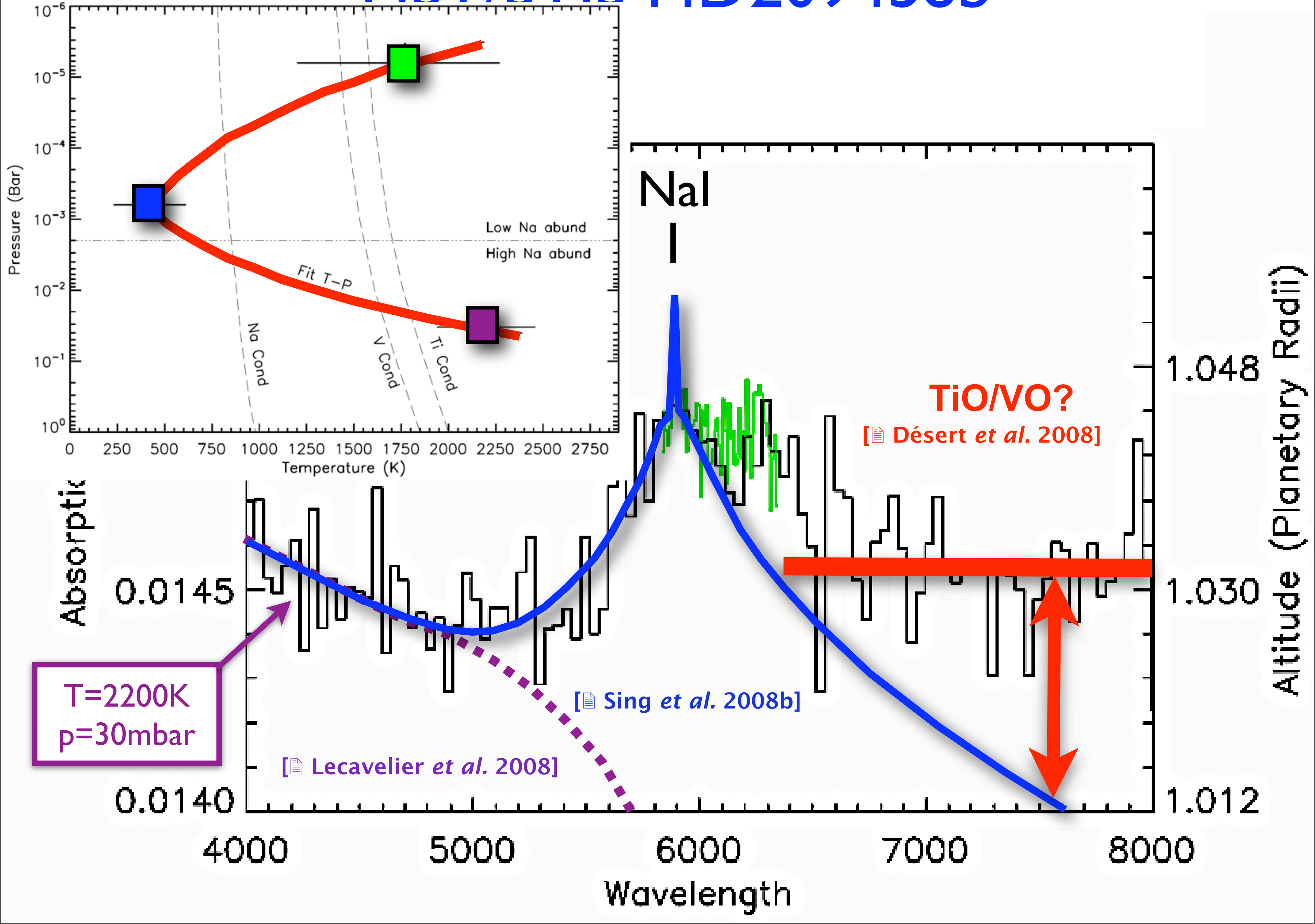

Temperature at high altitude

(from transit spectroscopy)

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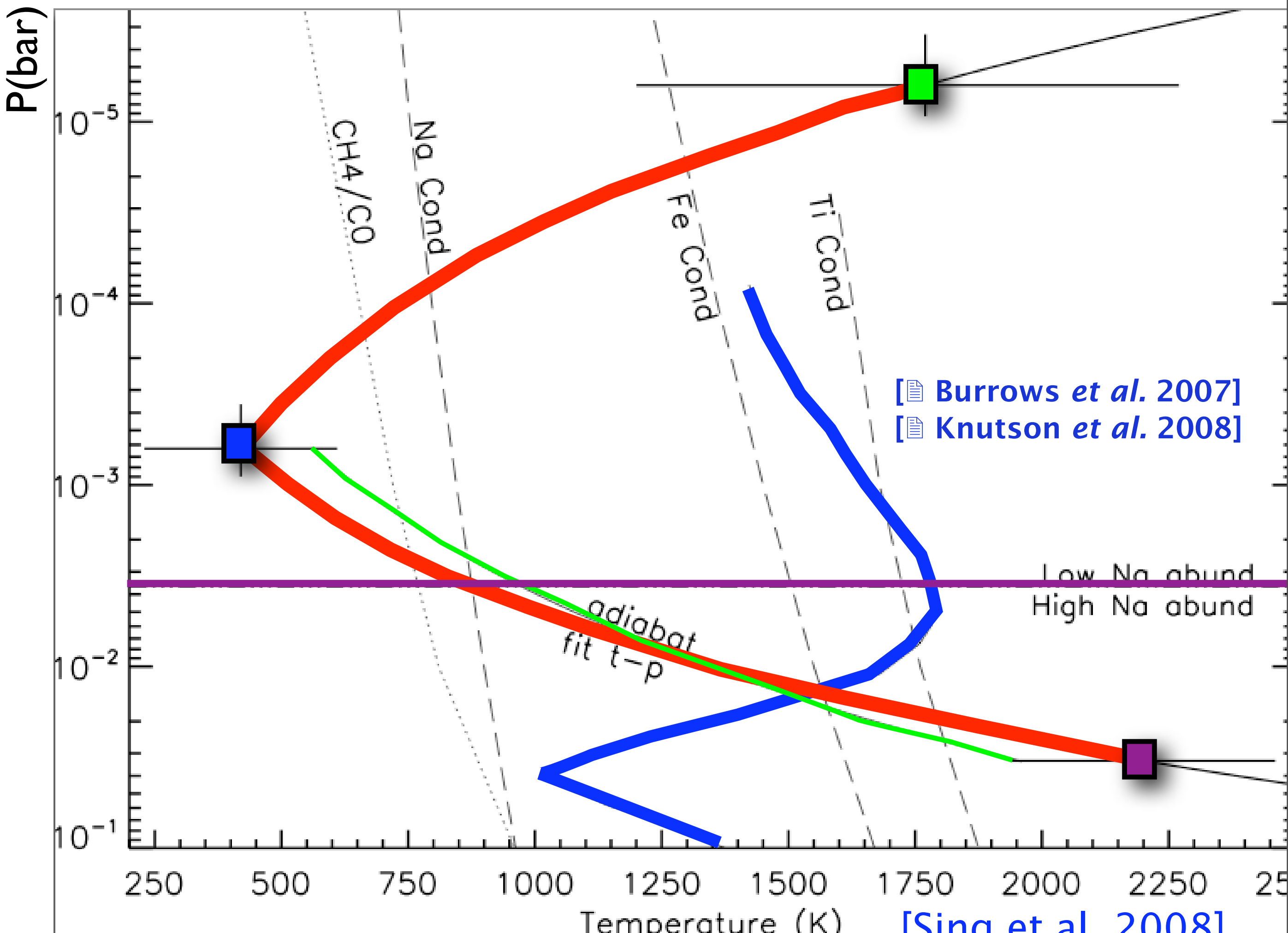

[Sing et al. 2008]

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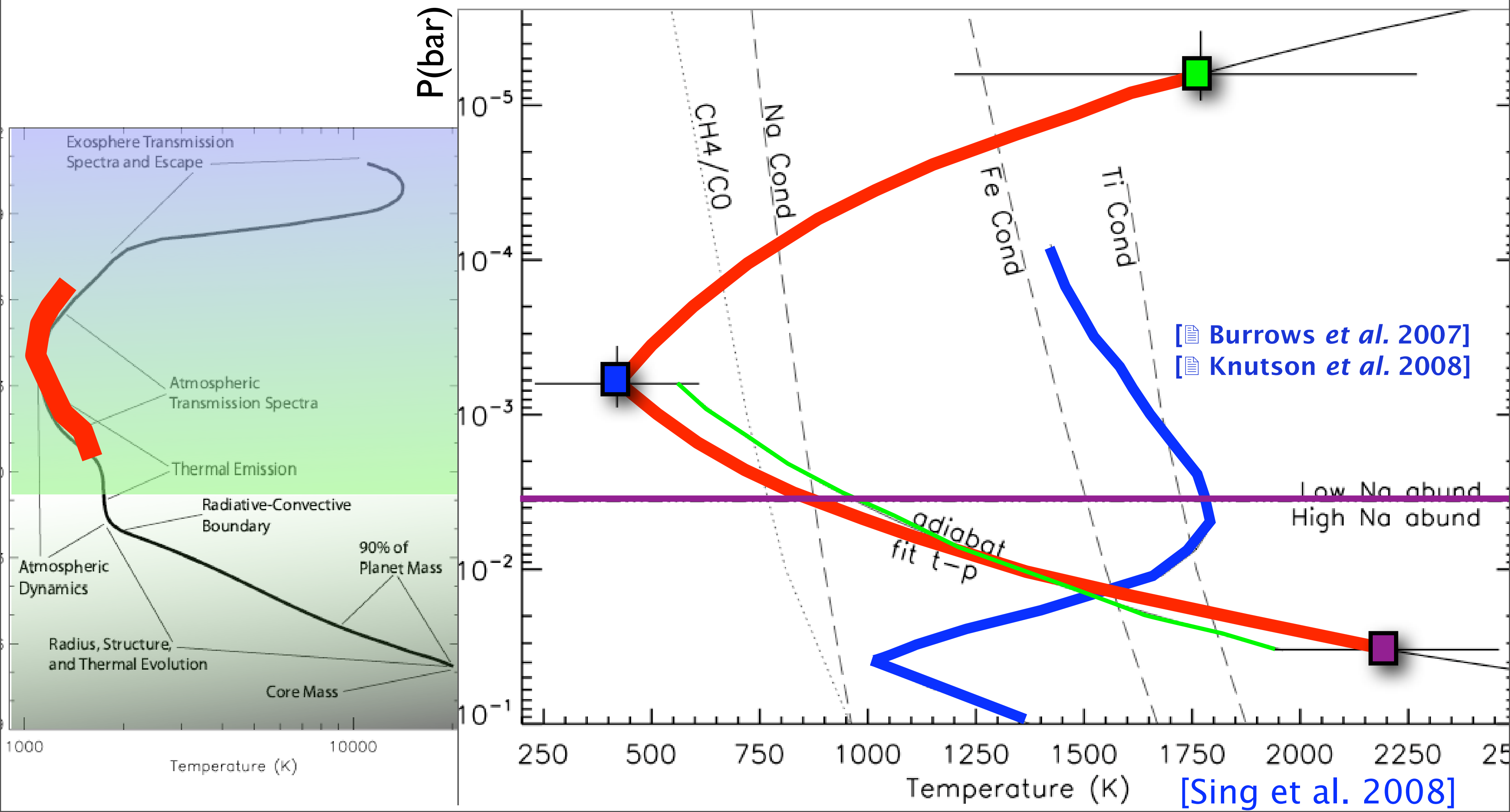
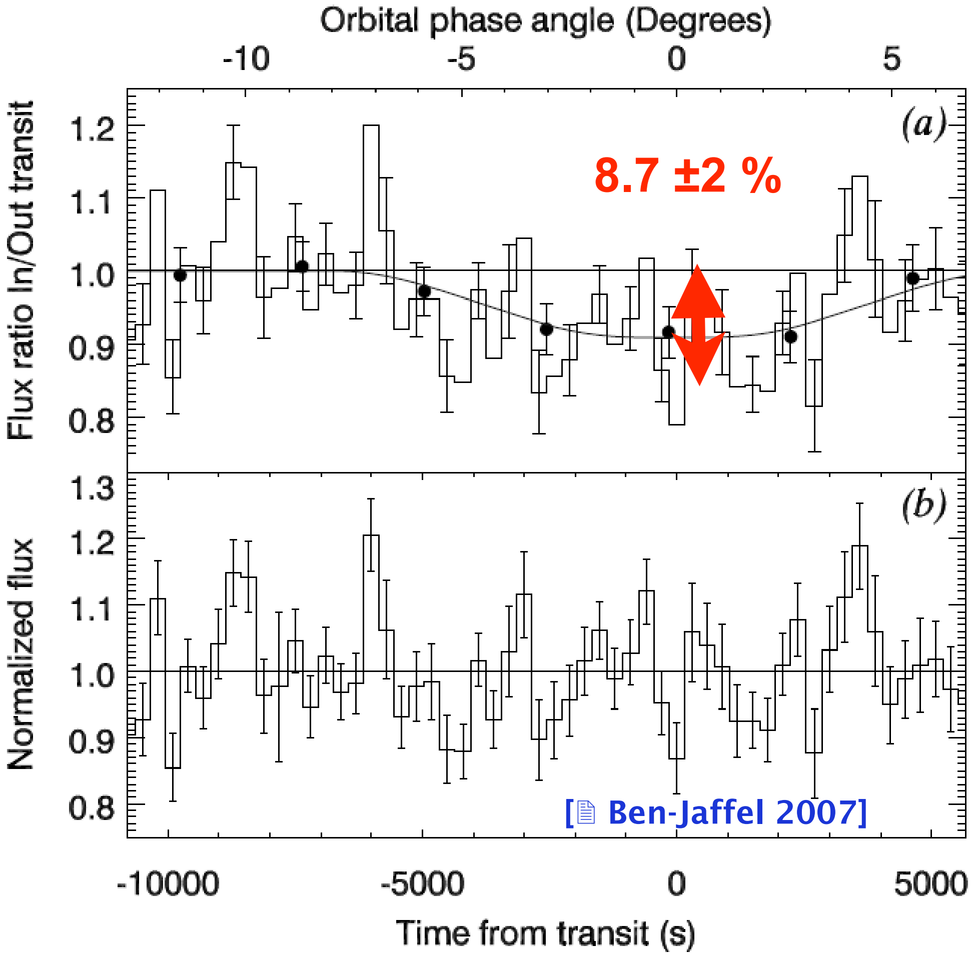
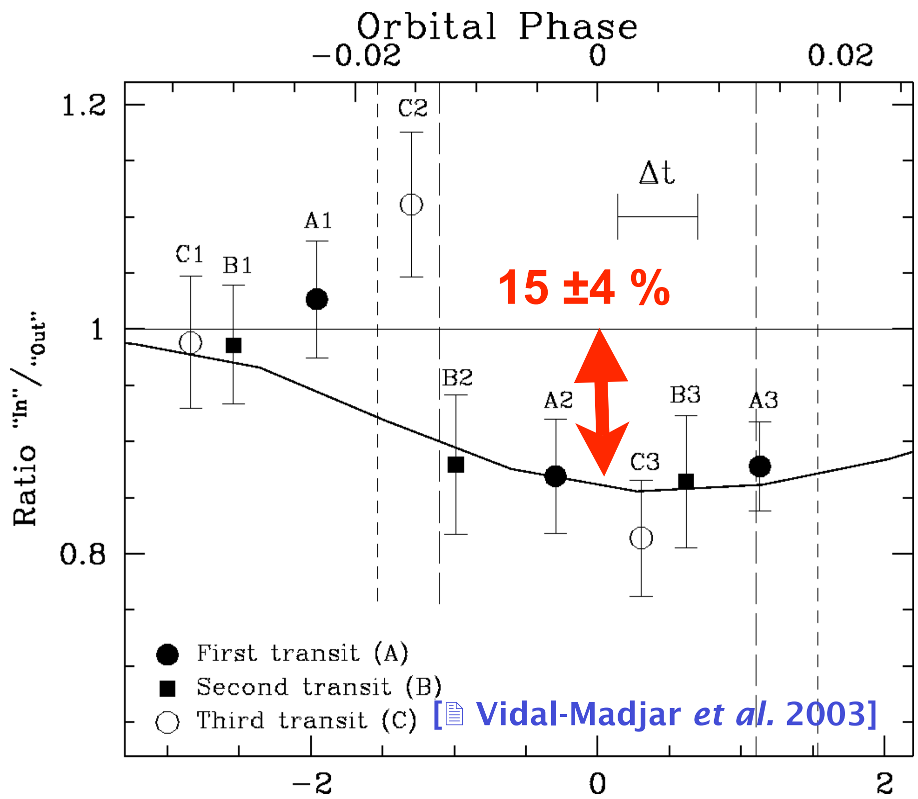


Two approaches...

All the line
No Lyman α correction



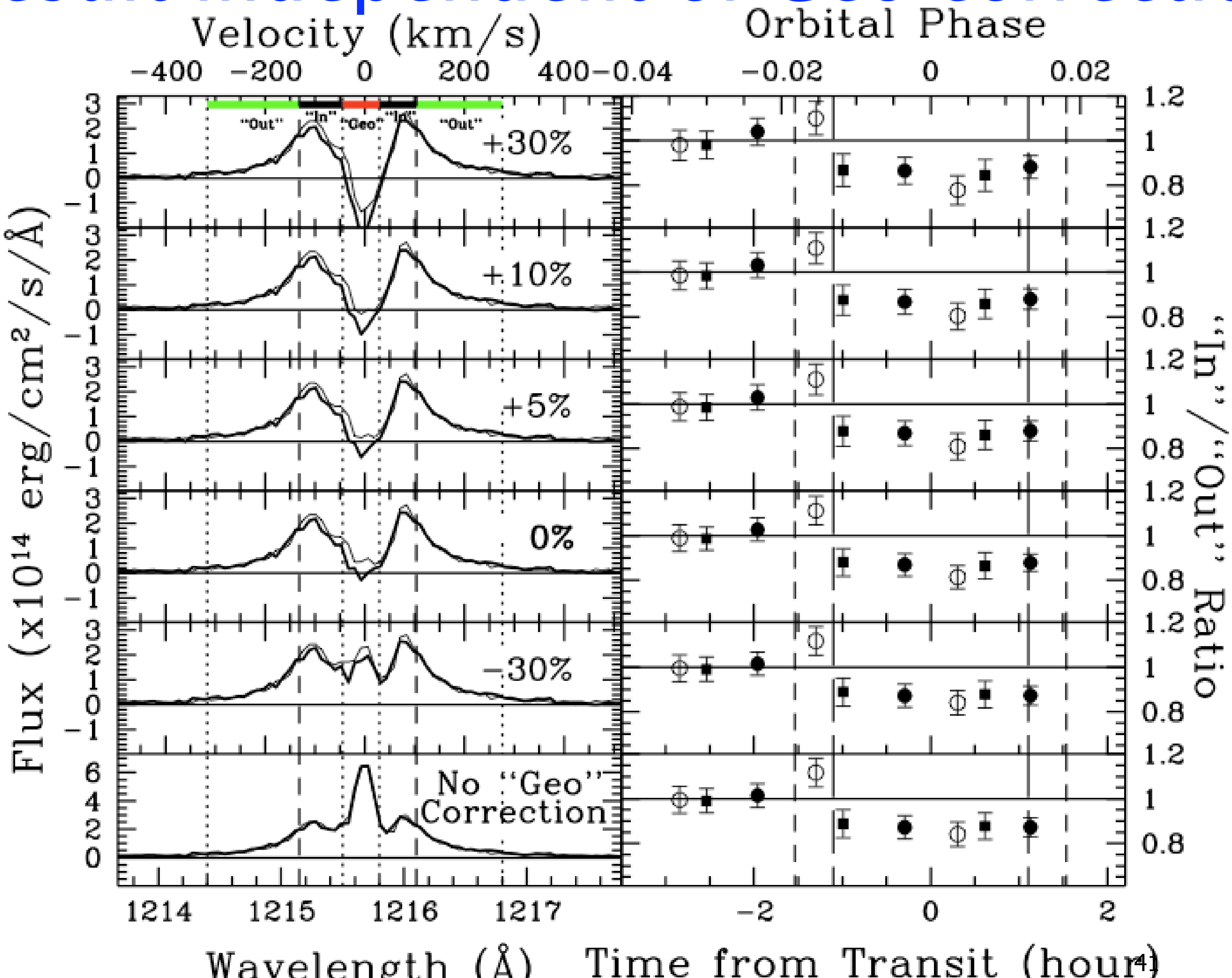
Center of the line
With Lyman-α correction



...the same conclusion

[🗎 Vidal-Madjar *et al.* 2008]

Result independent of Geo correction



Estimation of the escape rate

[Vidal-Madjar *et al.* 2003]

N-body Particle simulation:

Estimation of the escape rate

[🗎 **Vidal-Madjar *et al.* 2003**]

N-body Particle simulation:

- Both planetary and stellar gravity taken into account

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- 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

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[Vidal-Madjar *et al.* 2003]

N-body Particle simulation:

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

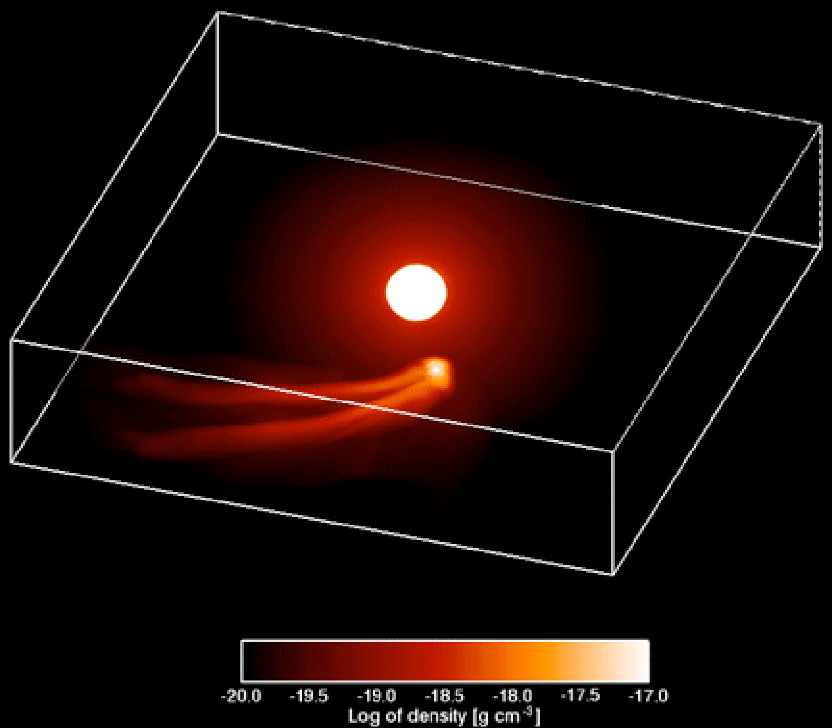
- Neutral hydrogen ionized by EUV photons
  (lifetime ~ few hours)

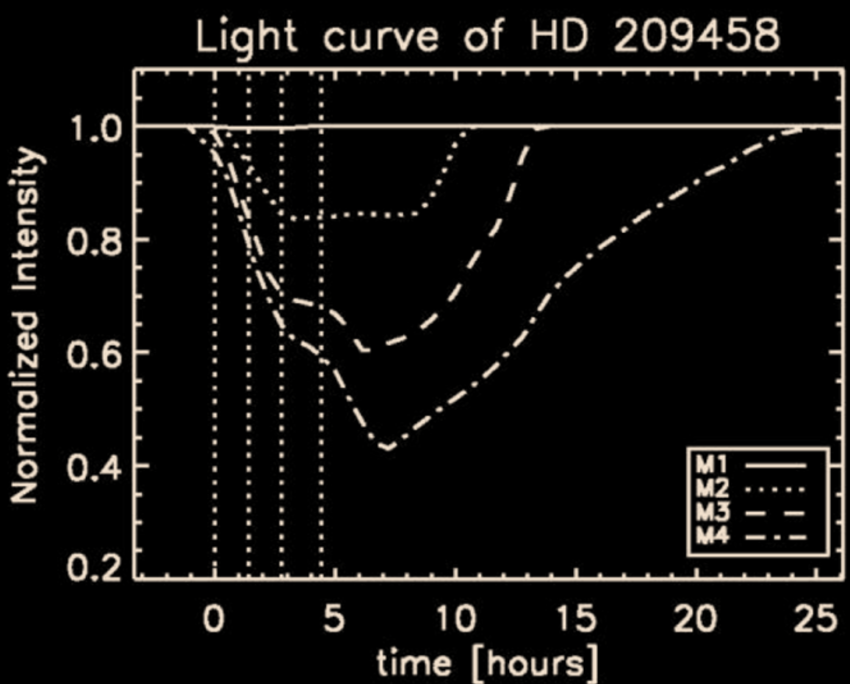
  – extinction of ionizing photons within the hydrogen cloud

Interaction between escaping gas and stellar wind

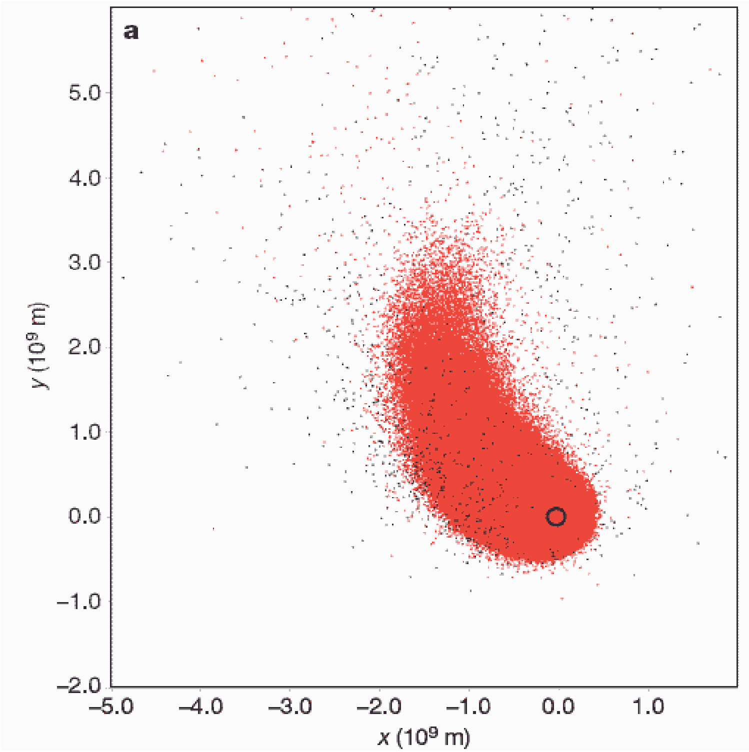
(Schneiter et al. 2007)

➔ dM/dt = 1.1 +/- 0.3 10^{10} g/s





Energetic Neutral Atoms (ENA) from stellar wind



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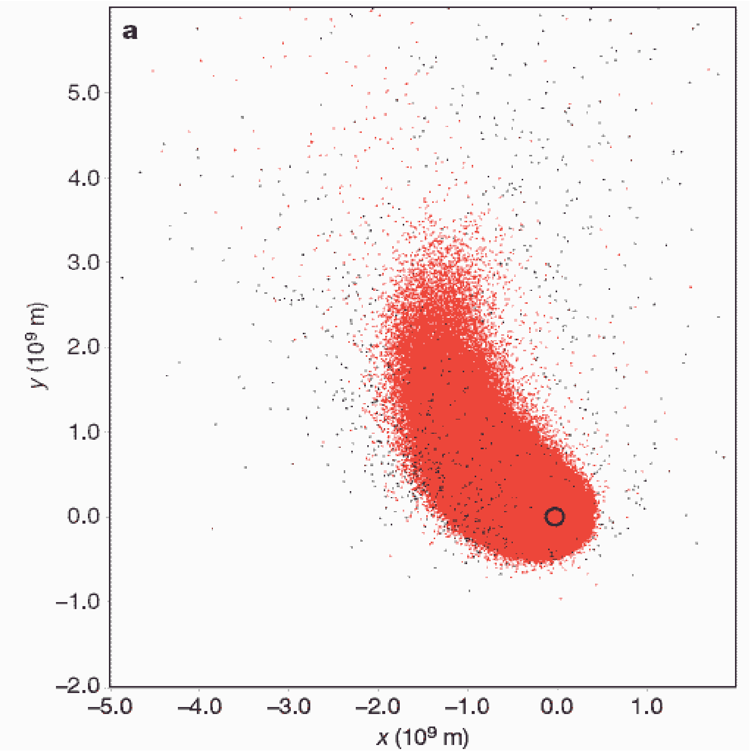

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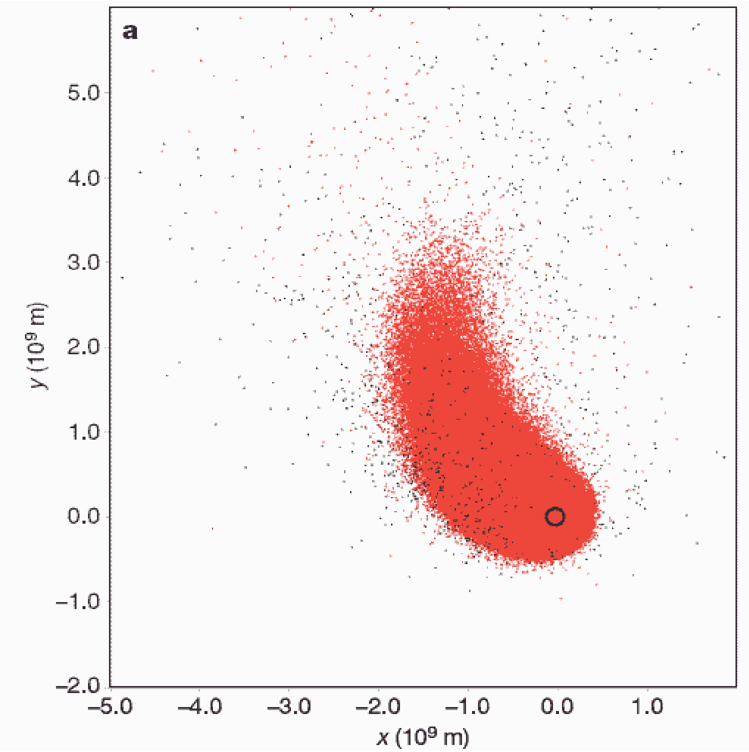

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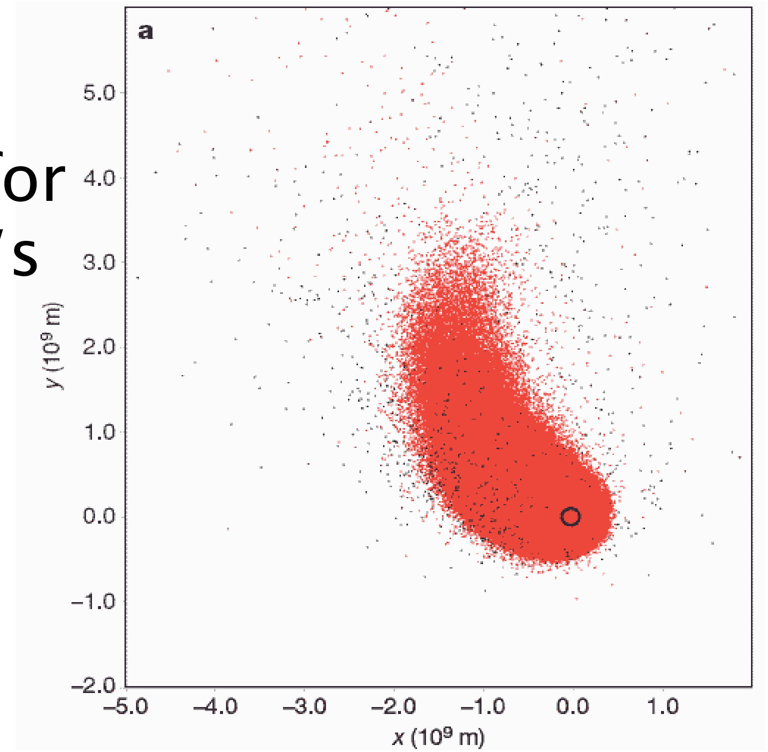

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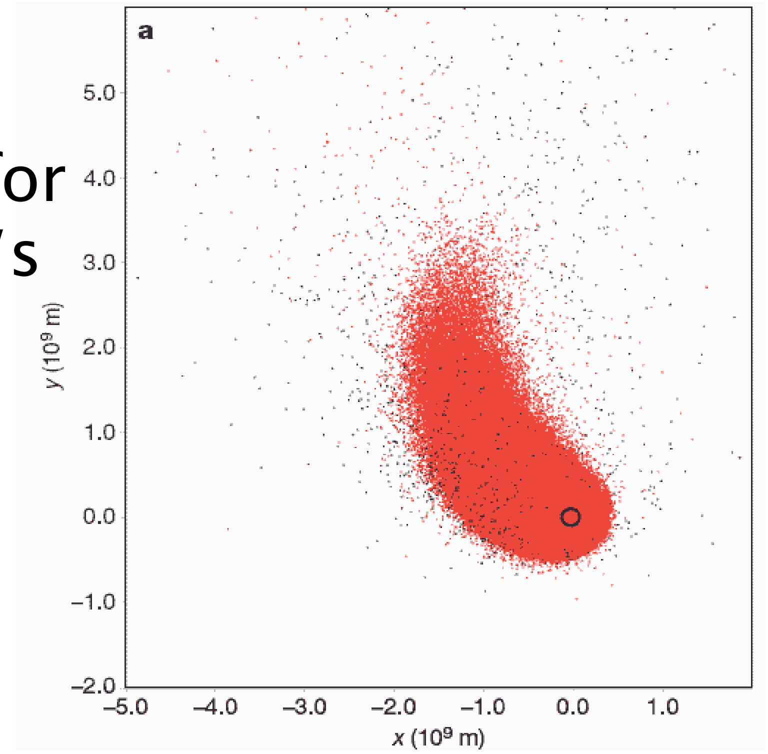

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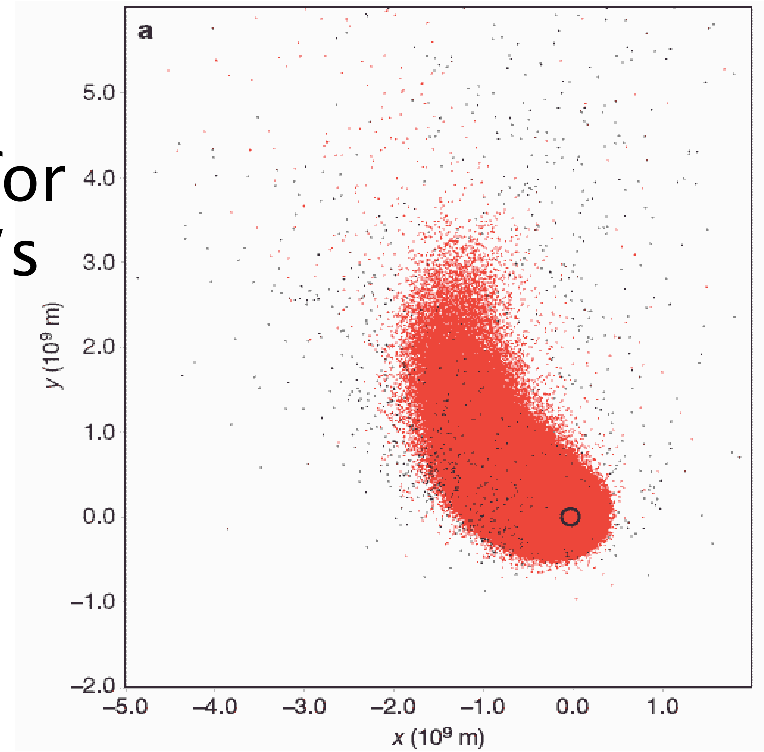

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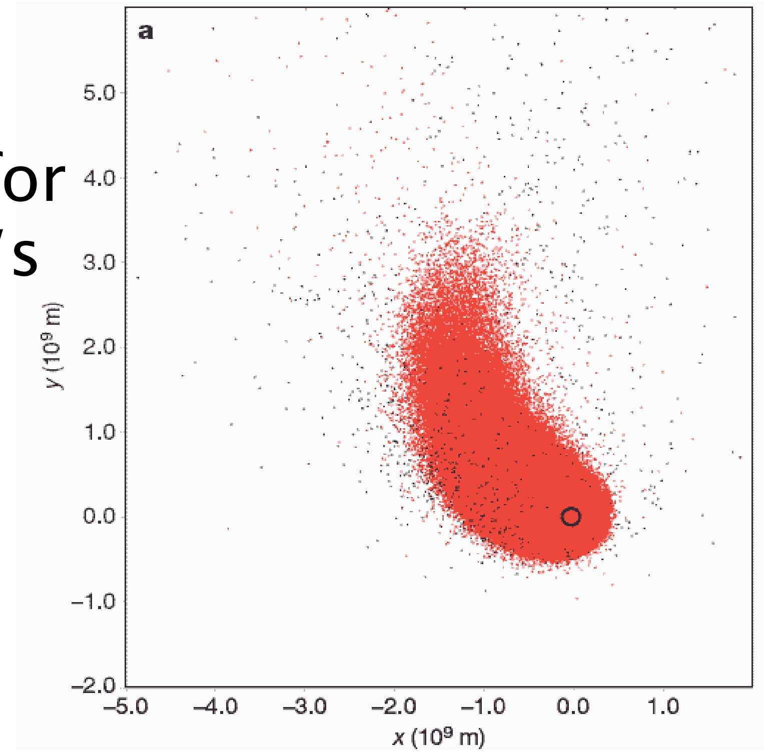
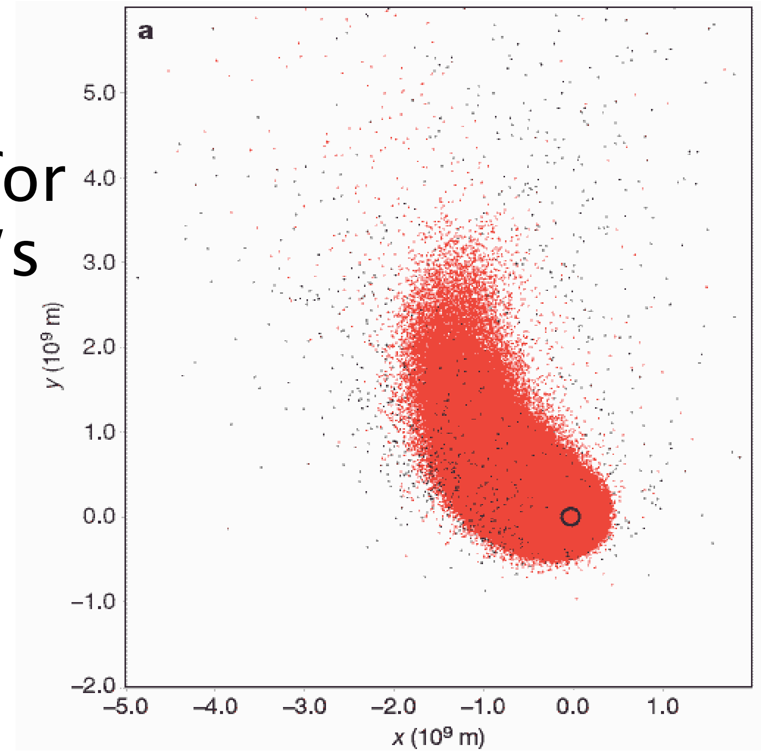
- Requires extraordinary condition for the stellar wind: $T=10^6$ K, 50 km/s
- Radiation pressure has been decreased to 2-5 times lower than solar value

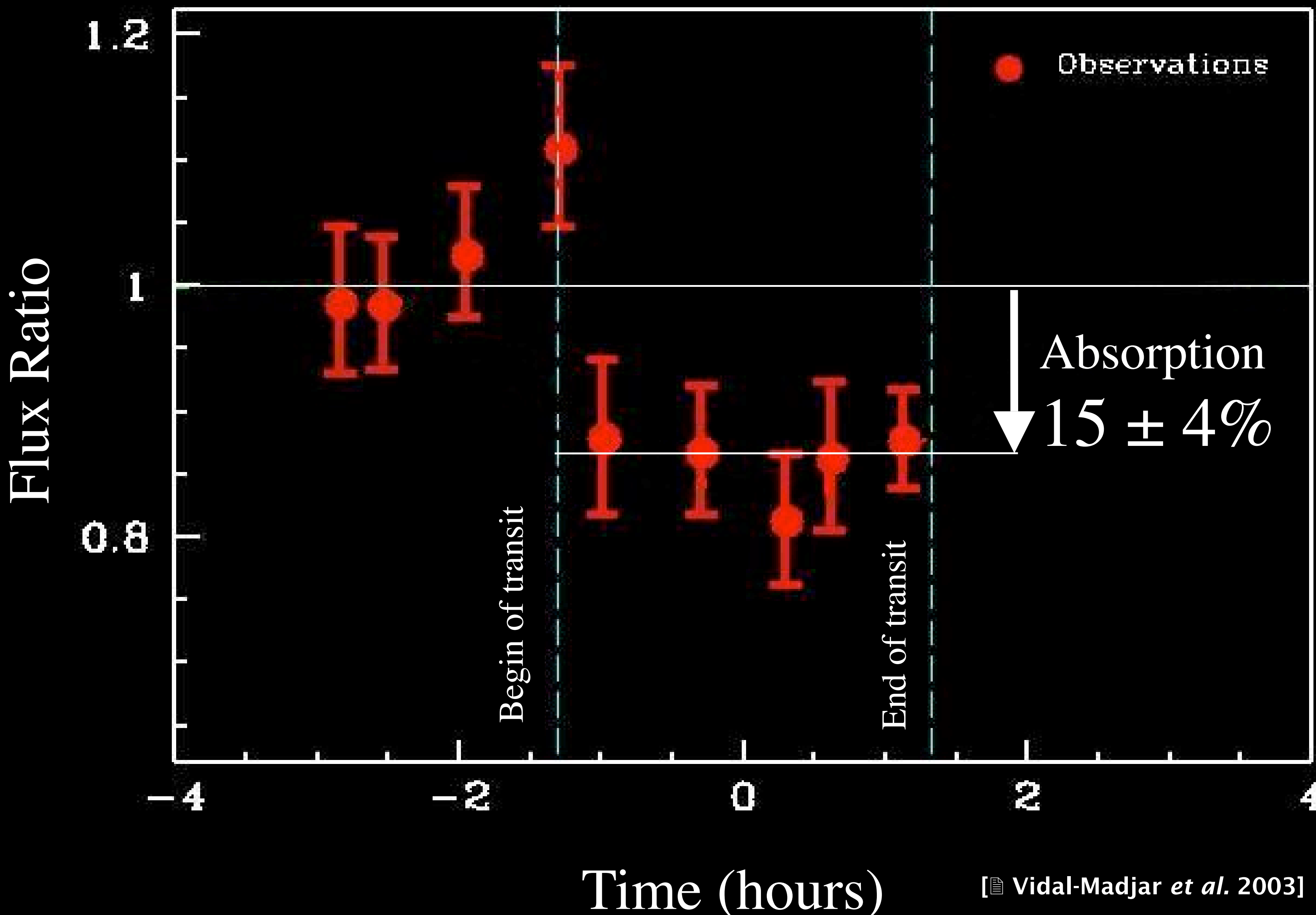


Energetic Neutral Atoms (ENA) from stellar wind

- Observed HI atoms from stellar wind but escape from the planet is still required
- Requires extraordinary condition for the stellar wind: $T=10^6$ K, 50 km/s
- Radiation pressure has been decreased to 2-5 times lower than solar value
- Interpretation of the shape of absorption line does not allow favoring this model.



TLC at Lyman α



[🗎 Vidal-Madjar *et al.* 2003]

No correlations with stellar nor geocoronal fluxes

Figure D

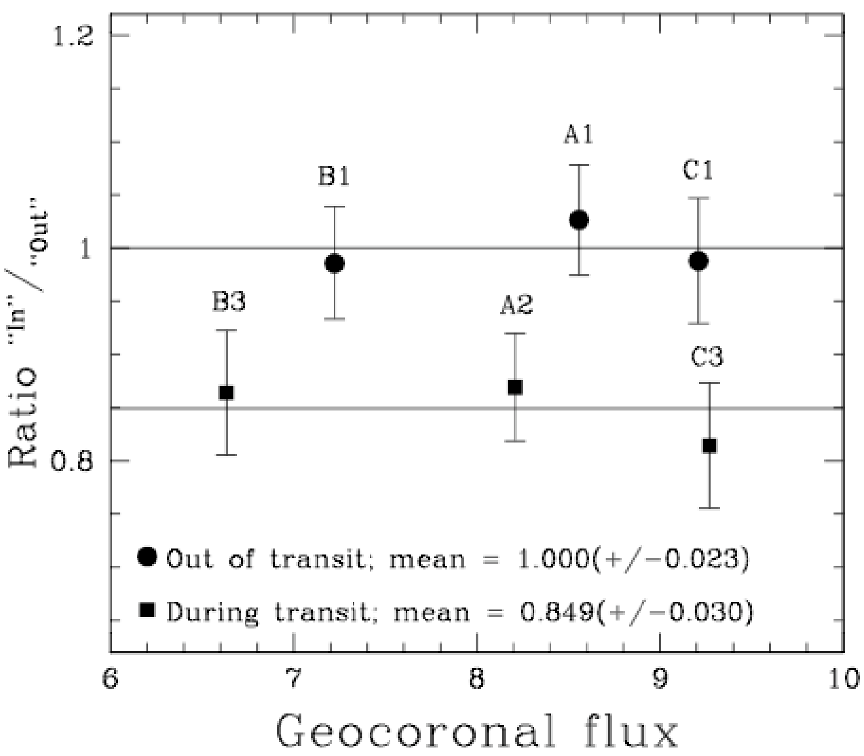


Figure F