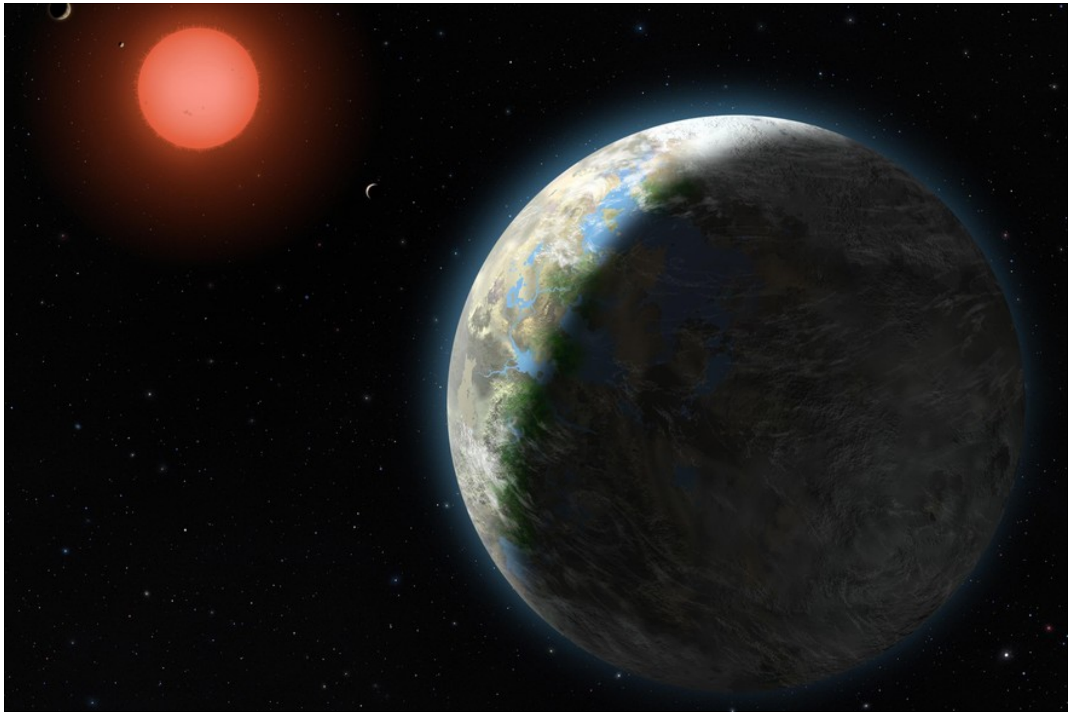
Characterization of exoplanets

➢ Definition

– An exoplanet is a planet that does not orbit around the Sun but around another star (well sort of…)



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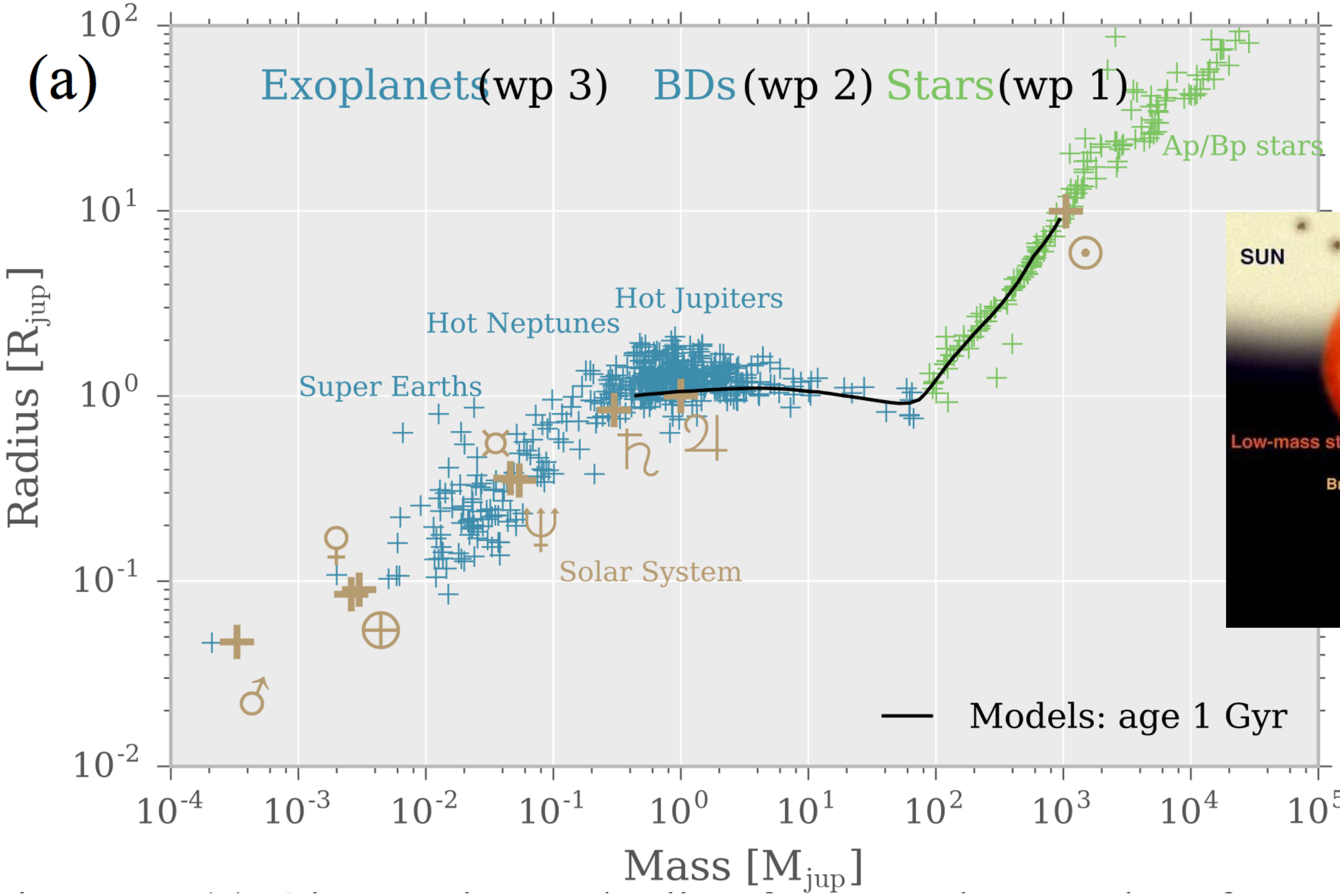

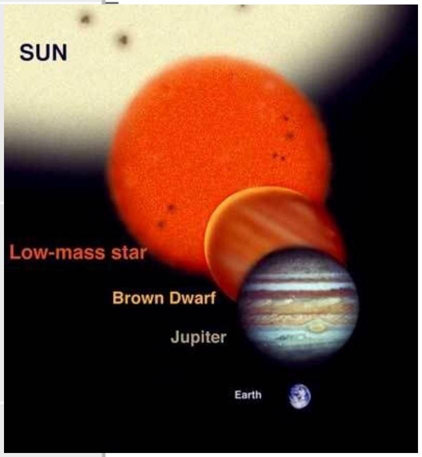

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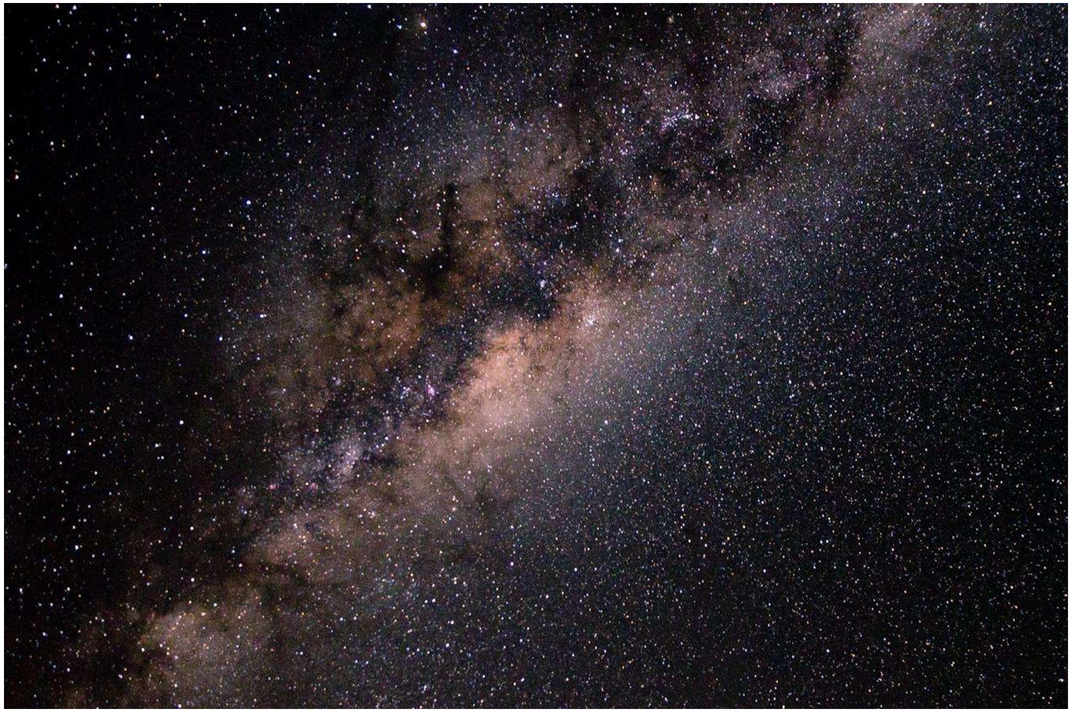
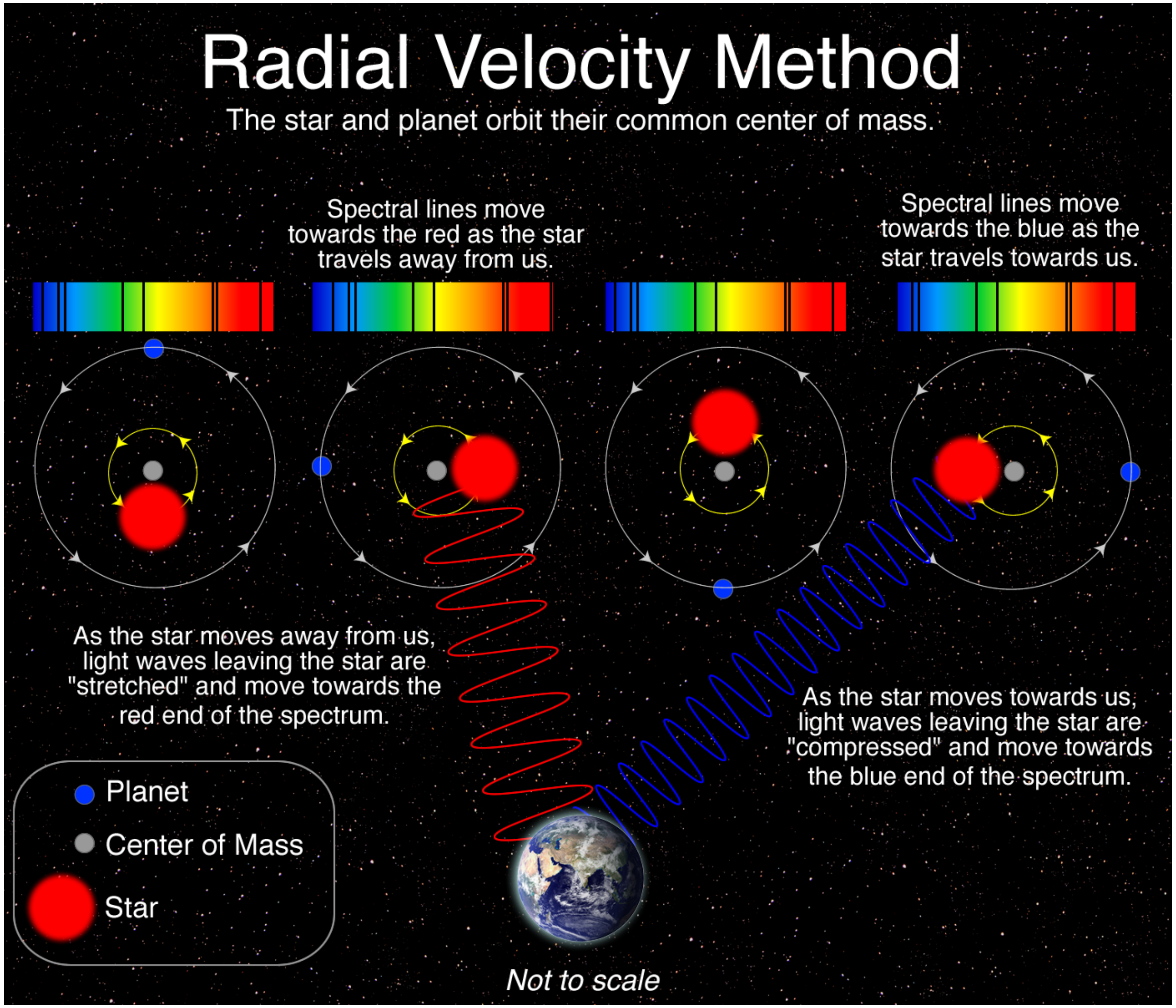


– Quite hard to find in the sky…

A bit of history…

- Astronomers have imagined an undirect detection method: the radial-velocity method



➢ A bit of history…

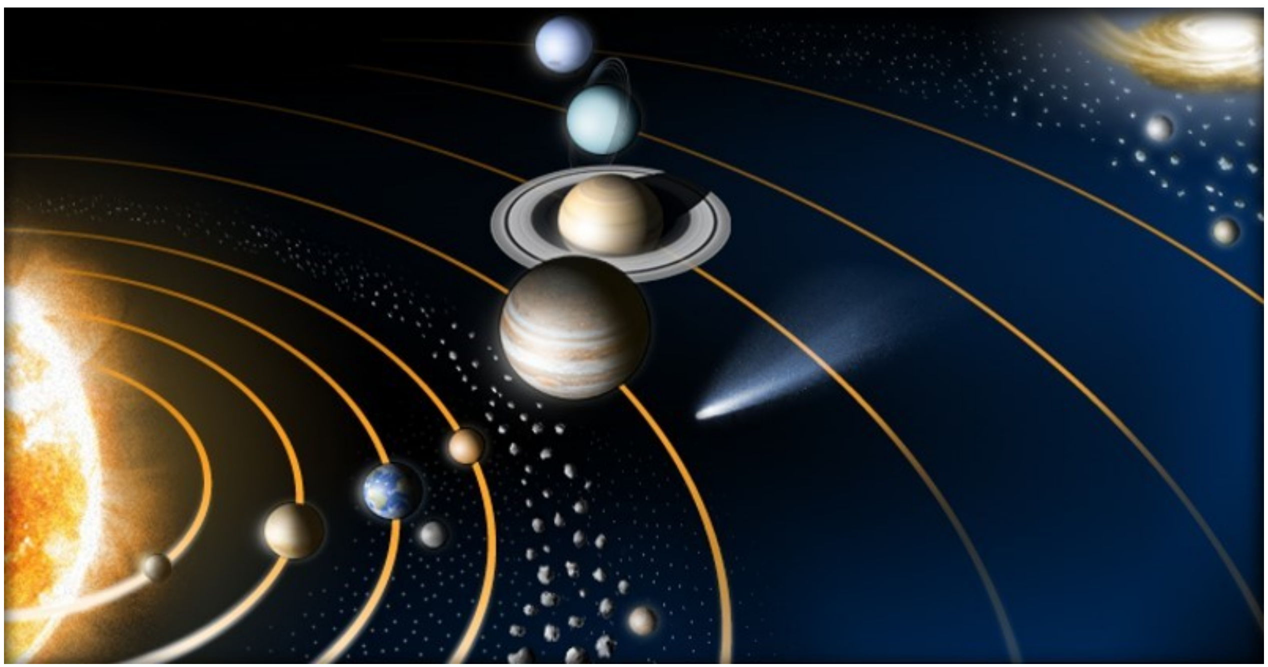
- In the end of 80's early 90's, astronomers knew that their detectors were sensitive enough to detect this kind of signal.
- Many teams around the world started to collect data and look for planets. But no robust detection has been made in the beginning…

- Why ?

➢ A bit of history…

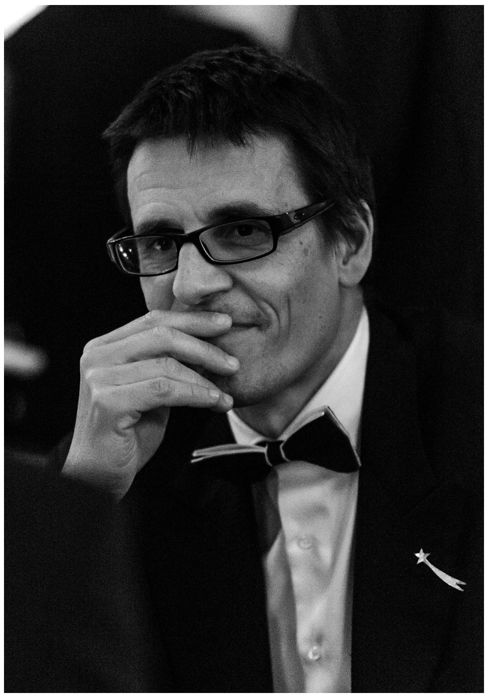
- In the end of 80's early 90's, astronomers knew that their detectors were sensitive enough to detect this kind of signal.
- Many teams around the world started to collect data and look for planets. But no robust detection has been in the beginning…

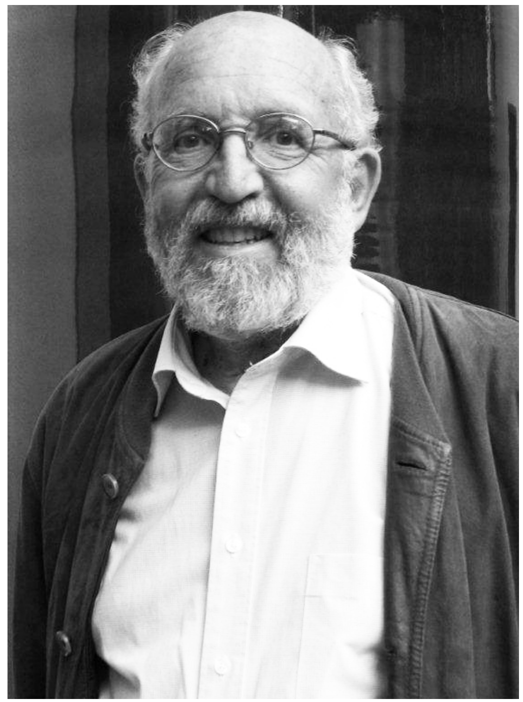
- Why ? You need the big guy, like Jupiter for the star to move



➢ A bit of history…

– In 94/95, Didier Queloz and Michel Mayor were actually analysing their data on the fly with the Elodie spectrograph at Observatoire de Haute Provence.

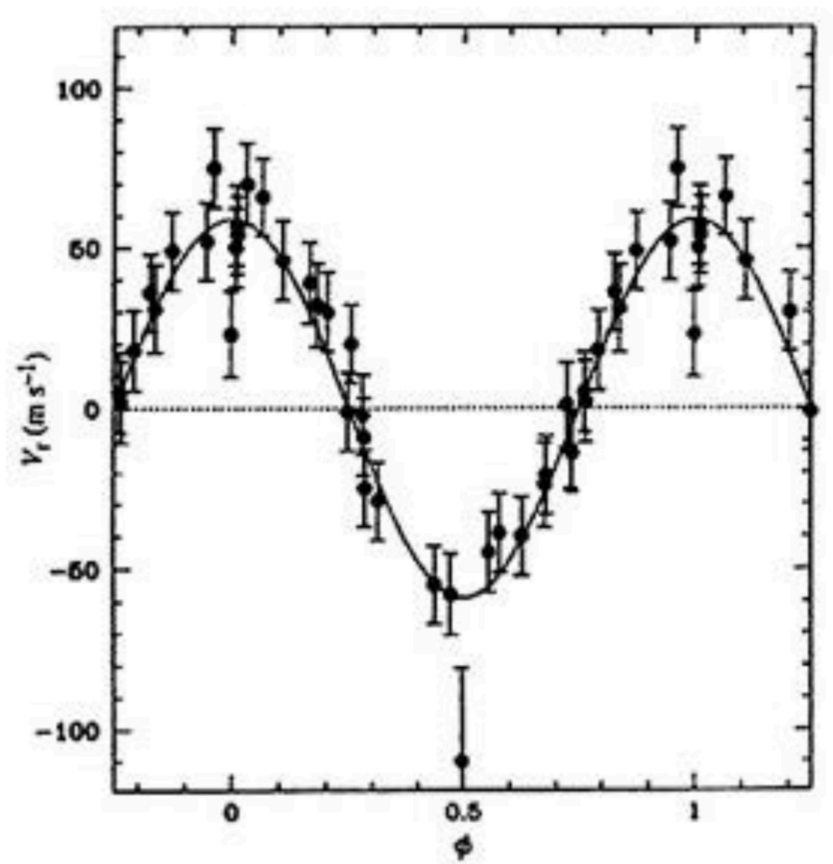




– … and found a tiny signal in their data…

➢ A bit of history…

- After almost one year checking their data, they extract this signal from the star 51 Pegasus



- … and found that an object (51 peg b) is orbiting with a period of only **4.2 days**

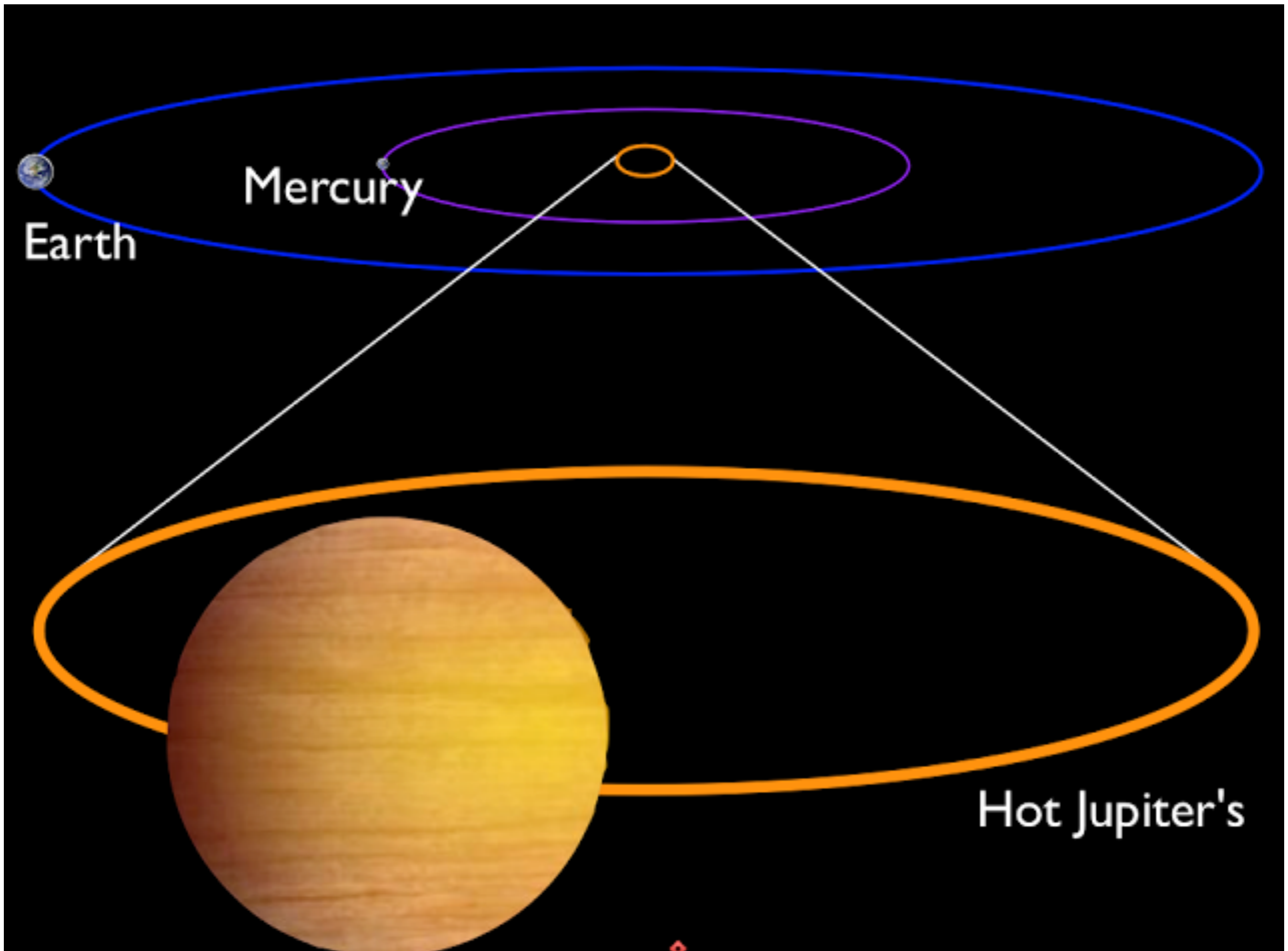
A bit of history…

- How do we get the orbit of the object?

- How do we get the mass of the object?

A bit of history…

- Minimum mass of 0.5 mass of Jupiter orbiting at 0.05 au of the star…
- Strongly irradiated by the star: **Hot Jupiter**



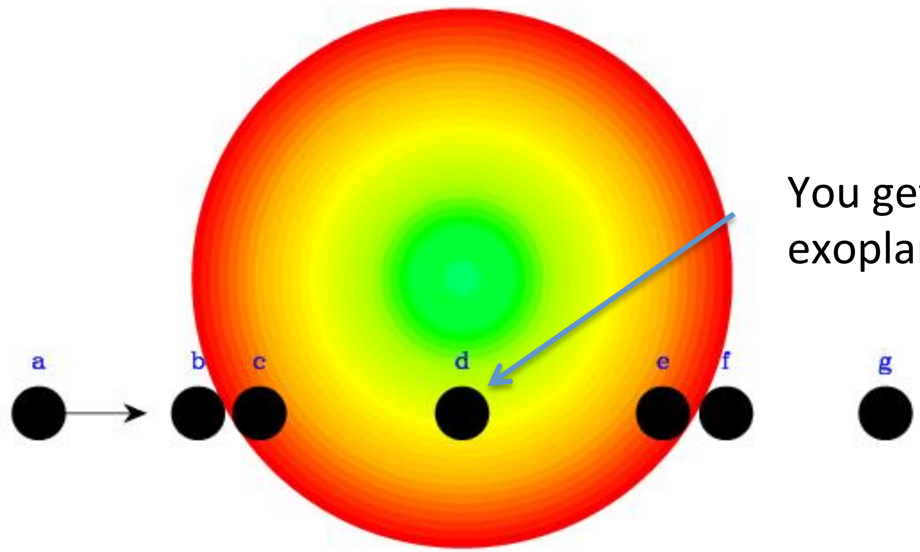
A bit of history…

- Nobody has ever predicted this kind of planets to exist: a huge part of the astrophysics community (and the press) was not ready to accept this detection:

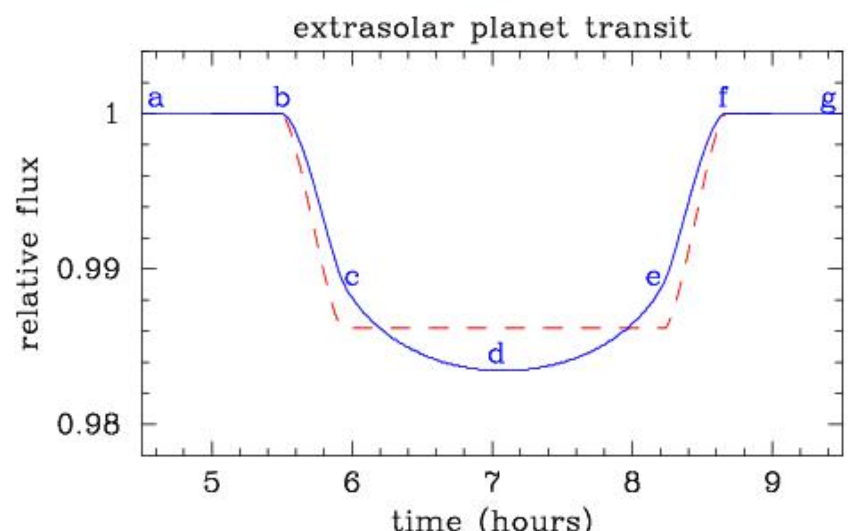
  - Instrumental error? (the signal around 51 peg was immediatly confirmed by competitors, Marcy's group)
  - Astrophysical artifact? E.g. from the atmosphere of the star? star spots ?
  - A binary star?

➢ A bit of history… part 2

– Astronmers have imagined a second undirect detection technique: the transit method

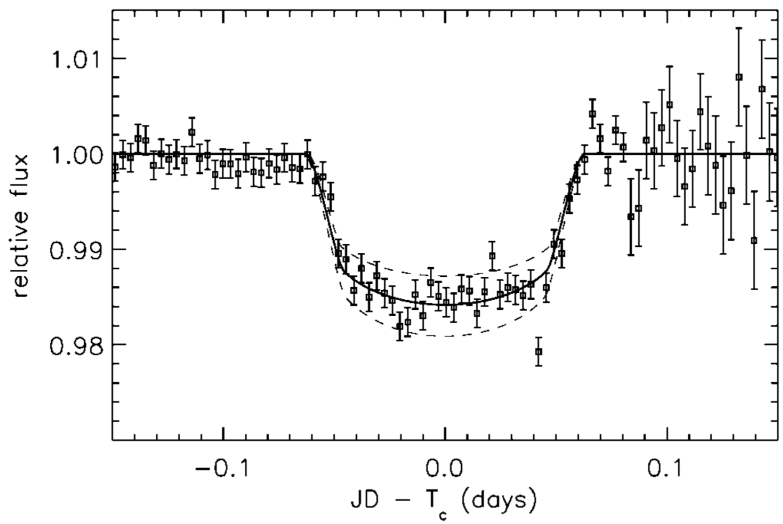


You get the radius of the exoplanet



➢ A bit of history… part 2

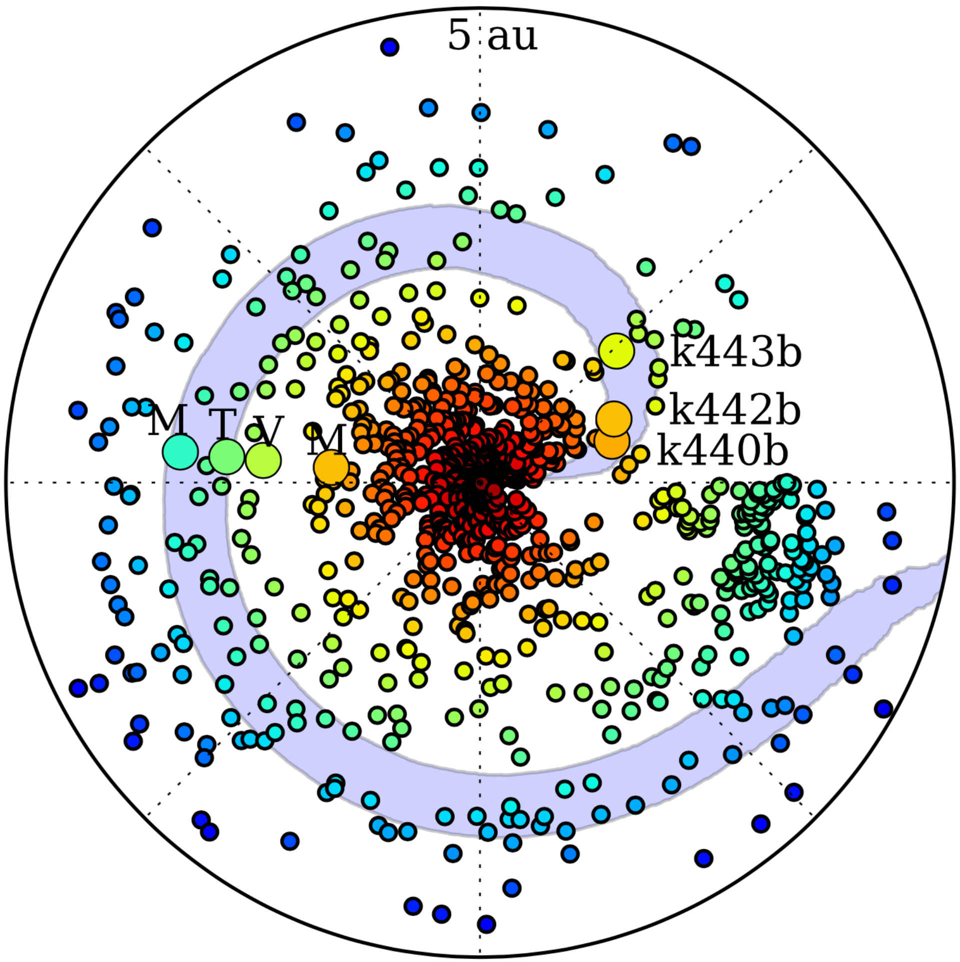
– Astronomers had to wait until 1999 for the first detection by this method, a 0.7 Jupiter-mass hot jupiter called HD209458b



– Finally confirming the existence of exoplanets !

➢ A bit of history… part 2

– Since then astronomers have observed up to **3500 exoplanets** with an important diversity in terms of mass, radius, orbits, etc… with a few rocky planets in the habitable zone of their parent stars:



- But a big challenge: the inflated radius of hot jupiter

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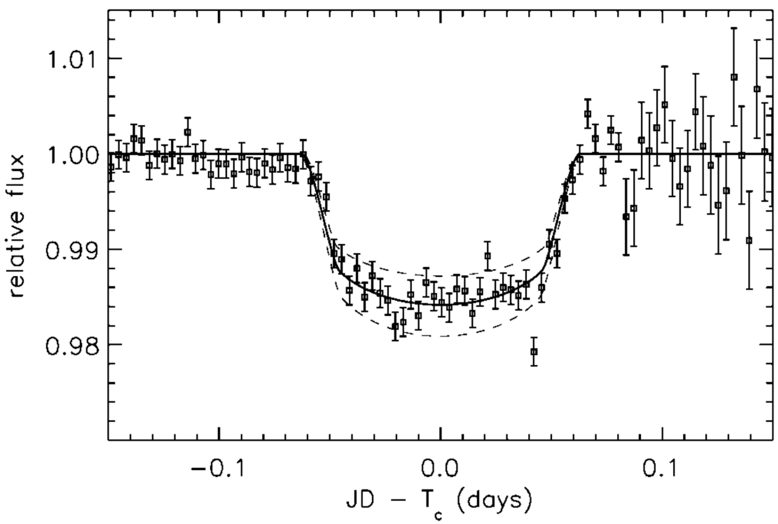
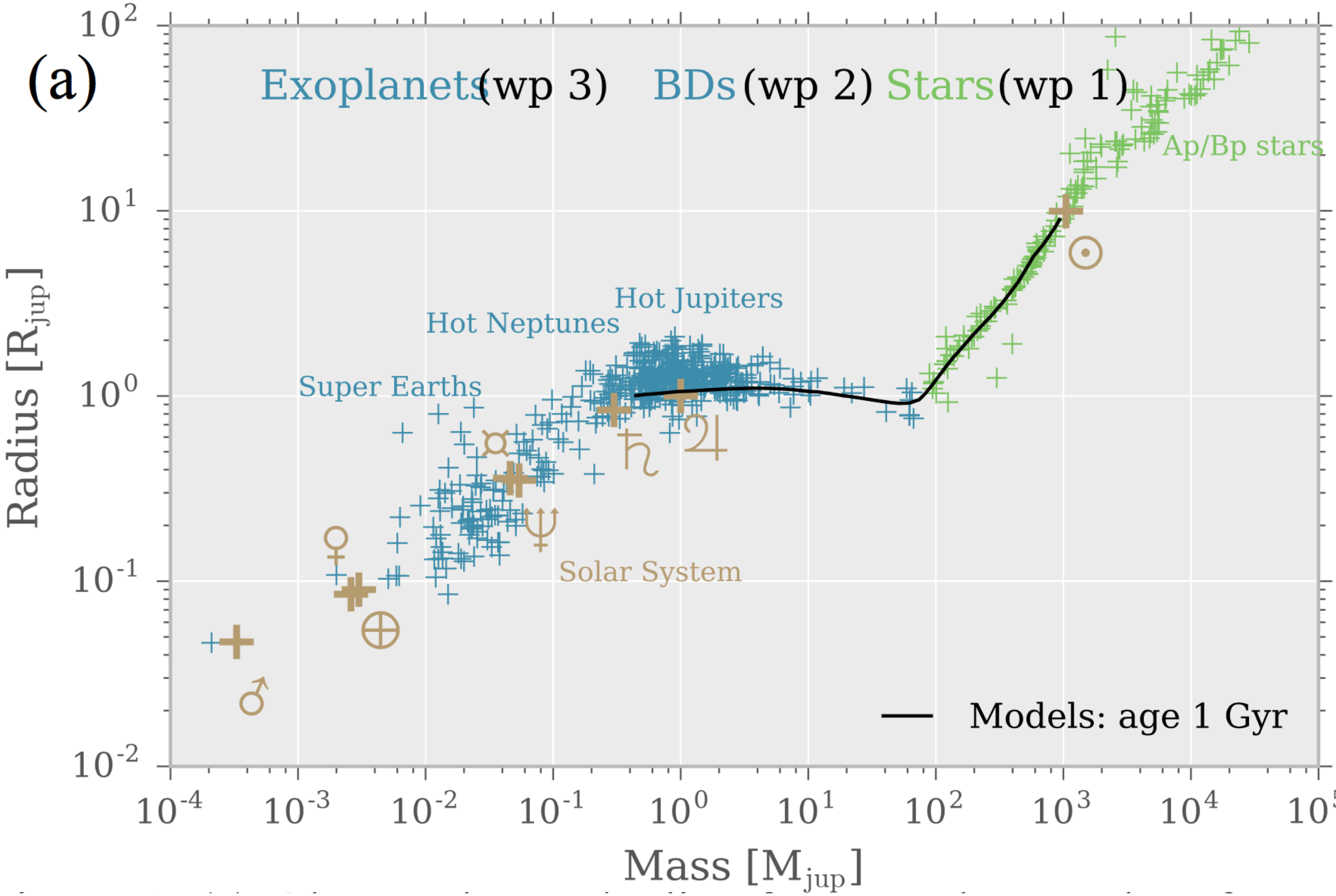


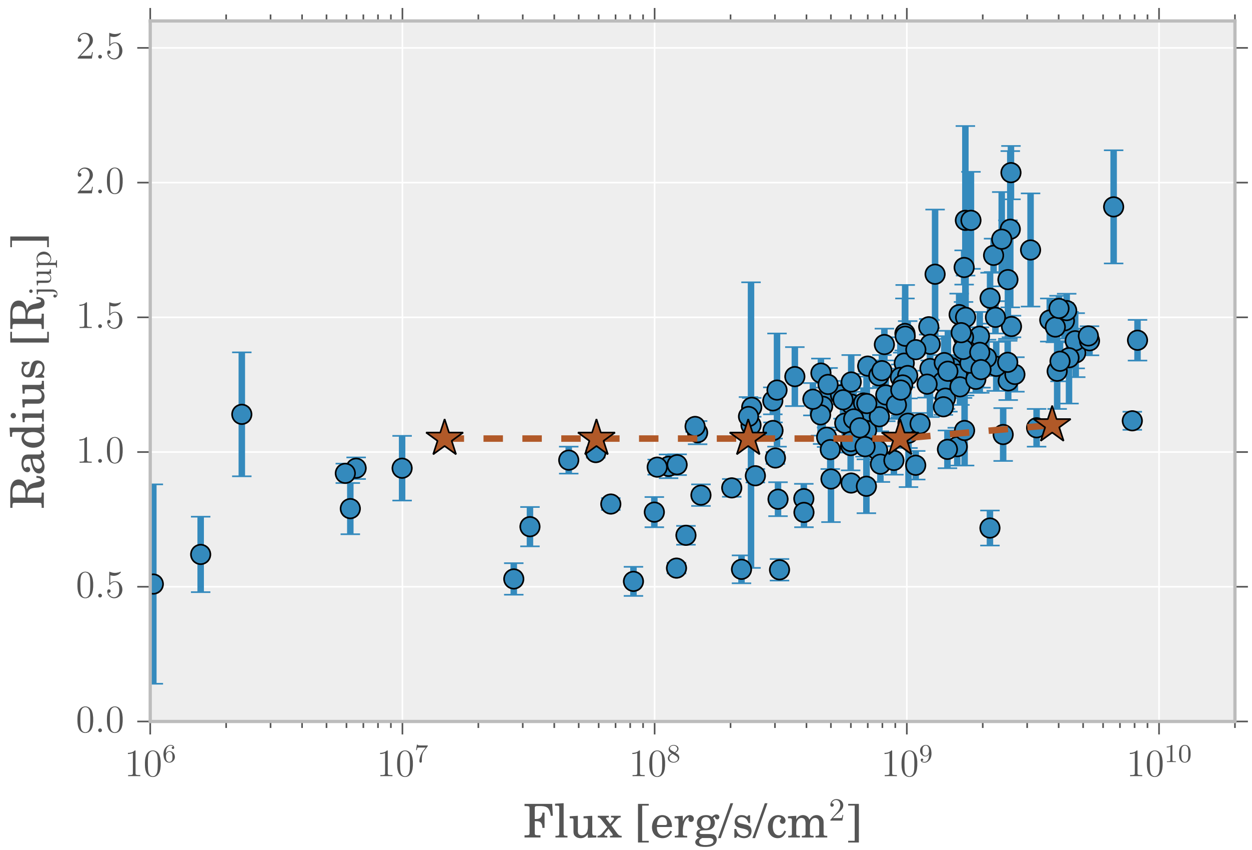
➢ Why is it a challenge?

– We know very well what the radius of ball of gas should be:



➢ Why is it a challenge?

- We know very well what the radius of ball of gas should be
- And we do not know why irradiated hot jupiters are bigger with increasing irradiation

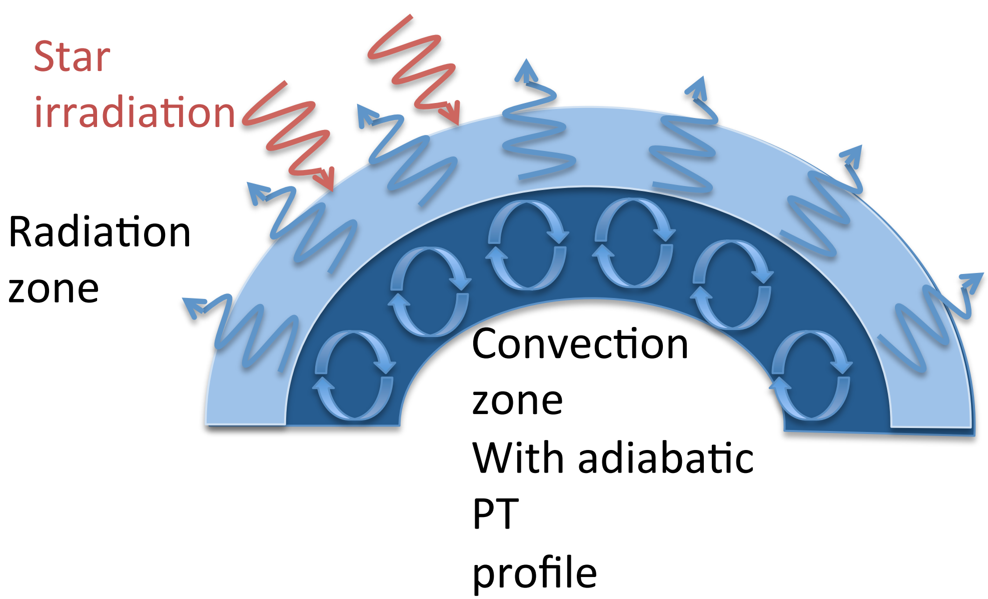


➢ Why is it a challenge?

- We do not know why irradiated hot jupiters are bigger with increasing irradiation
- 1D atmospheric models

What you want to get:
- Pressure P
- Temperature T

What you need to solve (steady state):
- Hydrostatic balance
- Energy conservation



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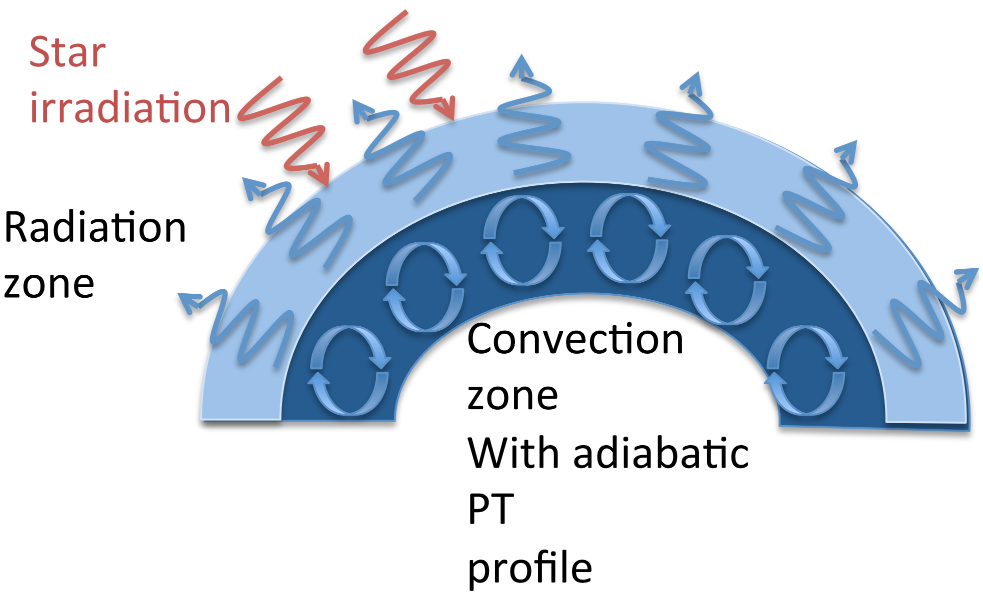
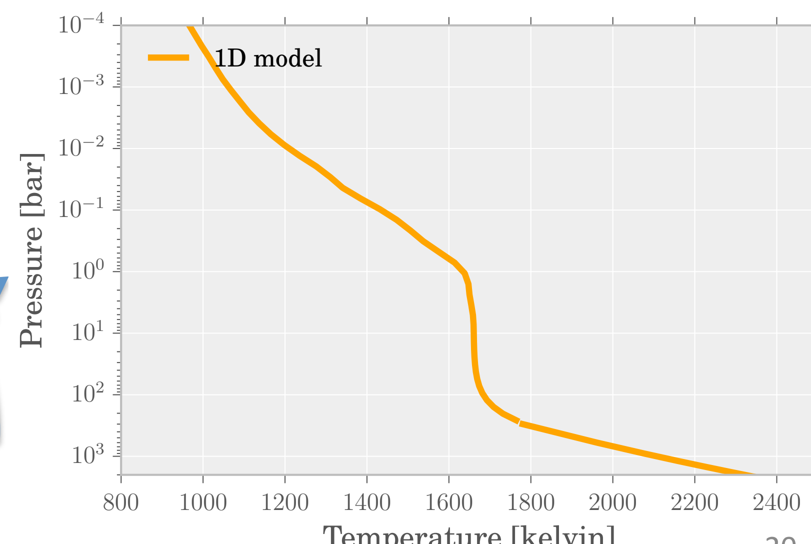
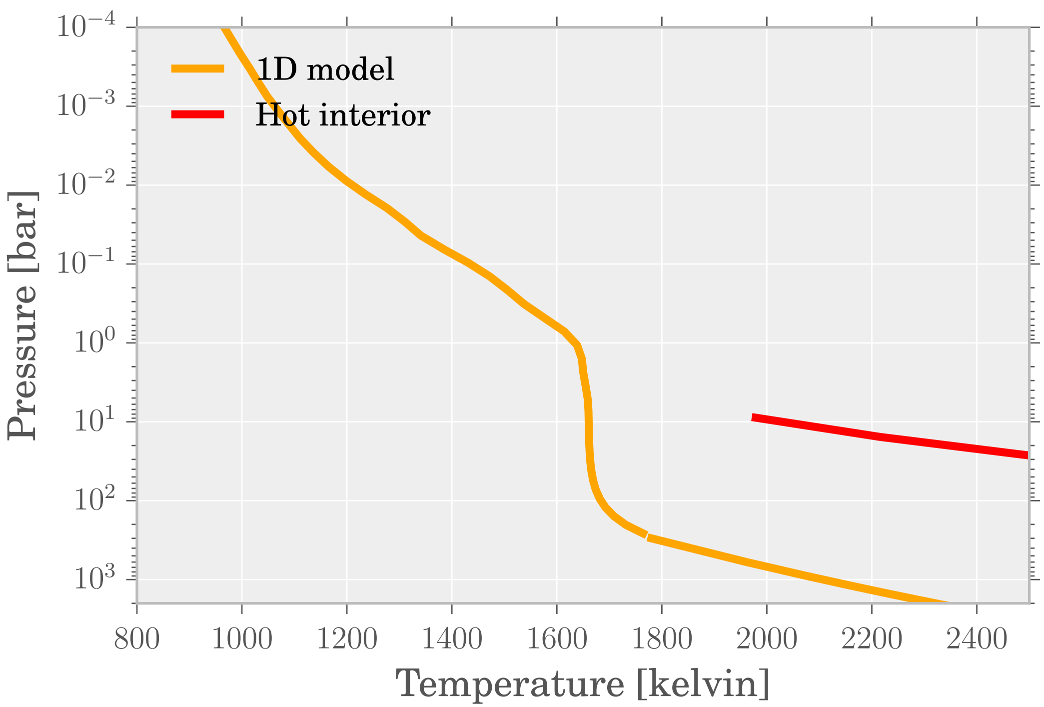
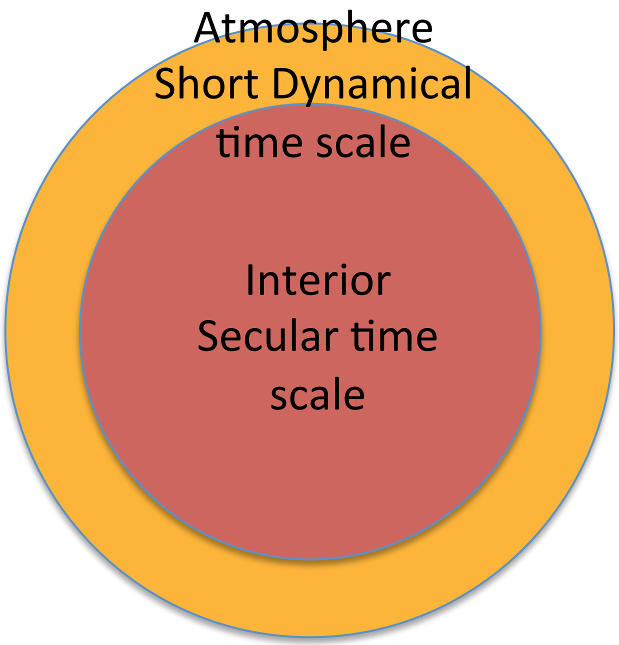




➢ Why is it a challenge?

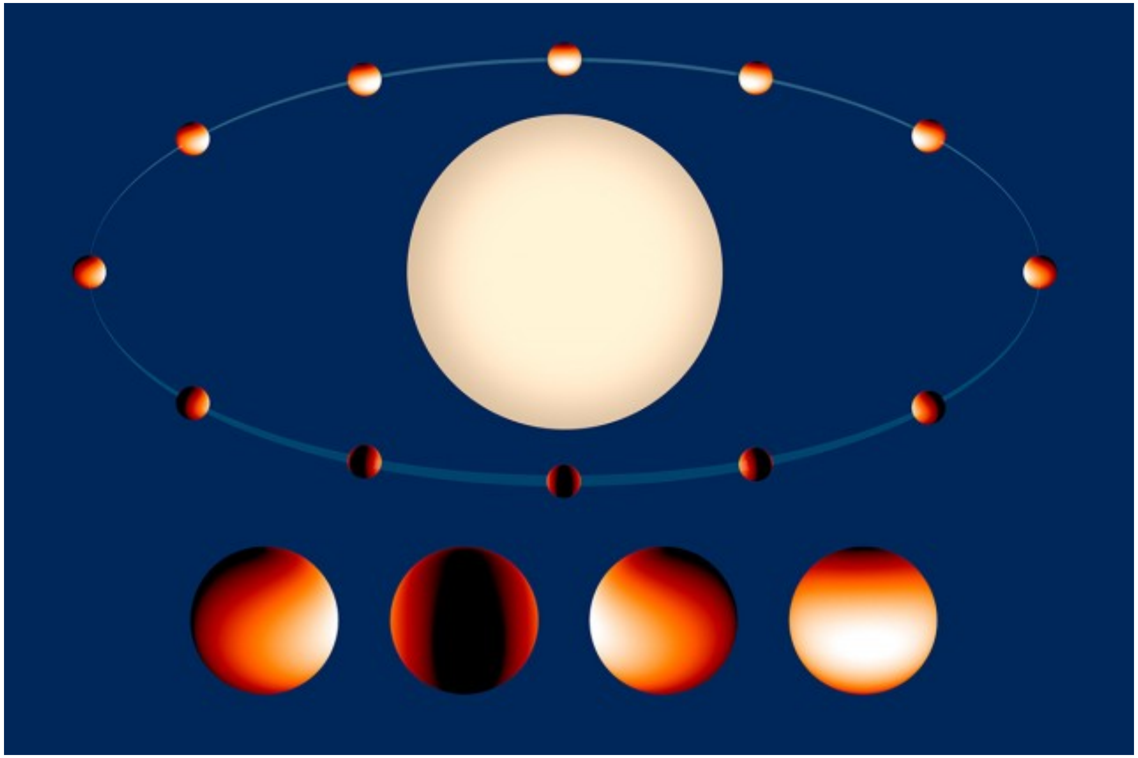
- We do not know why irradiated hot jupiters are bigger with increasing irradiation
- 1D atmospheric models do not work, too cold in the deep atmosphere





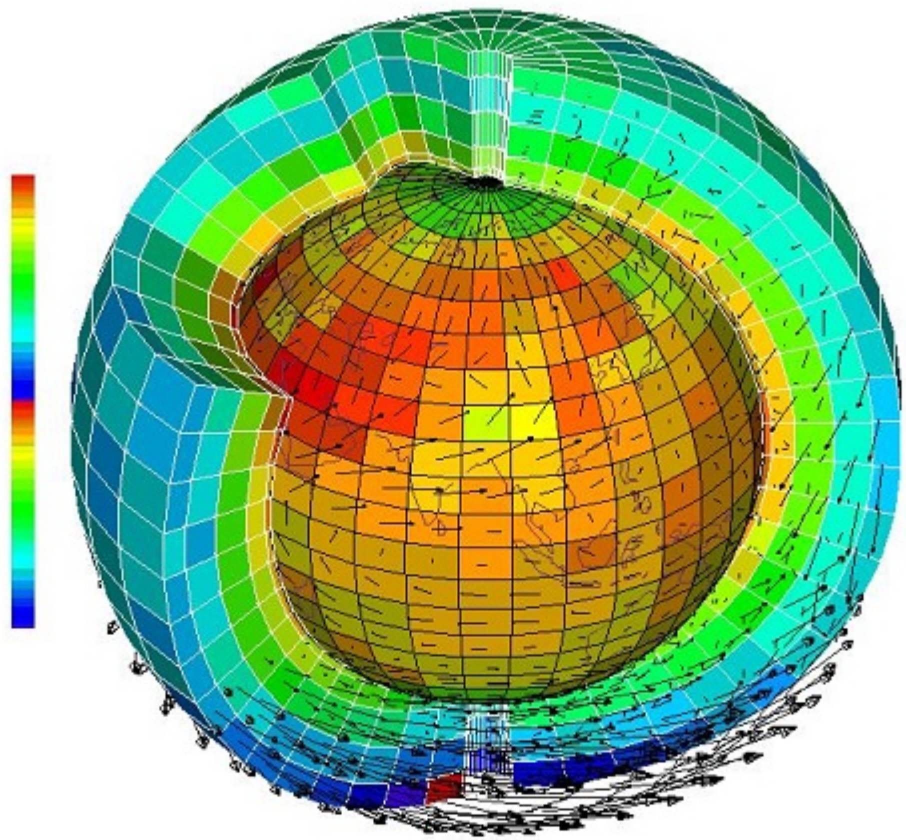
➢ Asymetric irradiation of tidally locked hot jupiter

- A hot dayside and a cold nightside implies pressure gradients and winds
- 3D atmospheric models to study the circulation

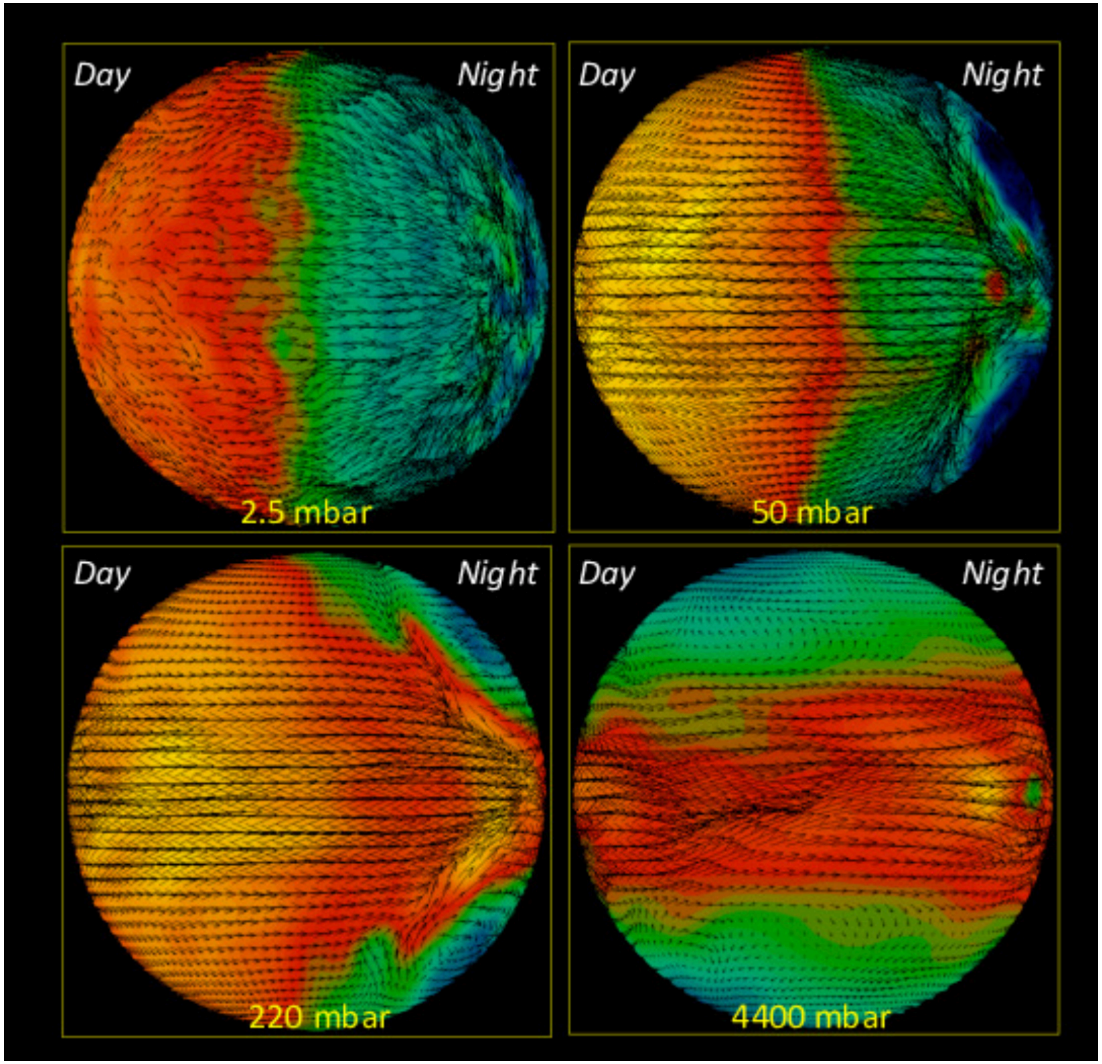


➢ Asymetric irradiation of tidally locked hot jupiter

- A hot dayside and a cold nightside implies pressure gradients and winds
- 3D atmospheric models to study the circulation: time-dependent Euler equations in spherical coordinates)

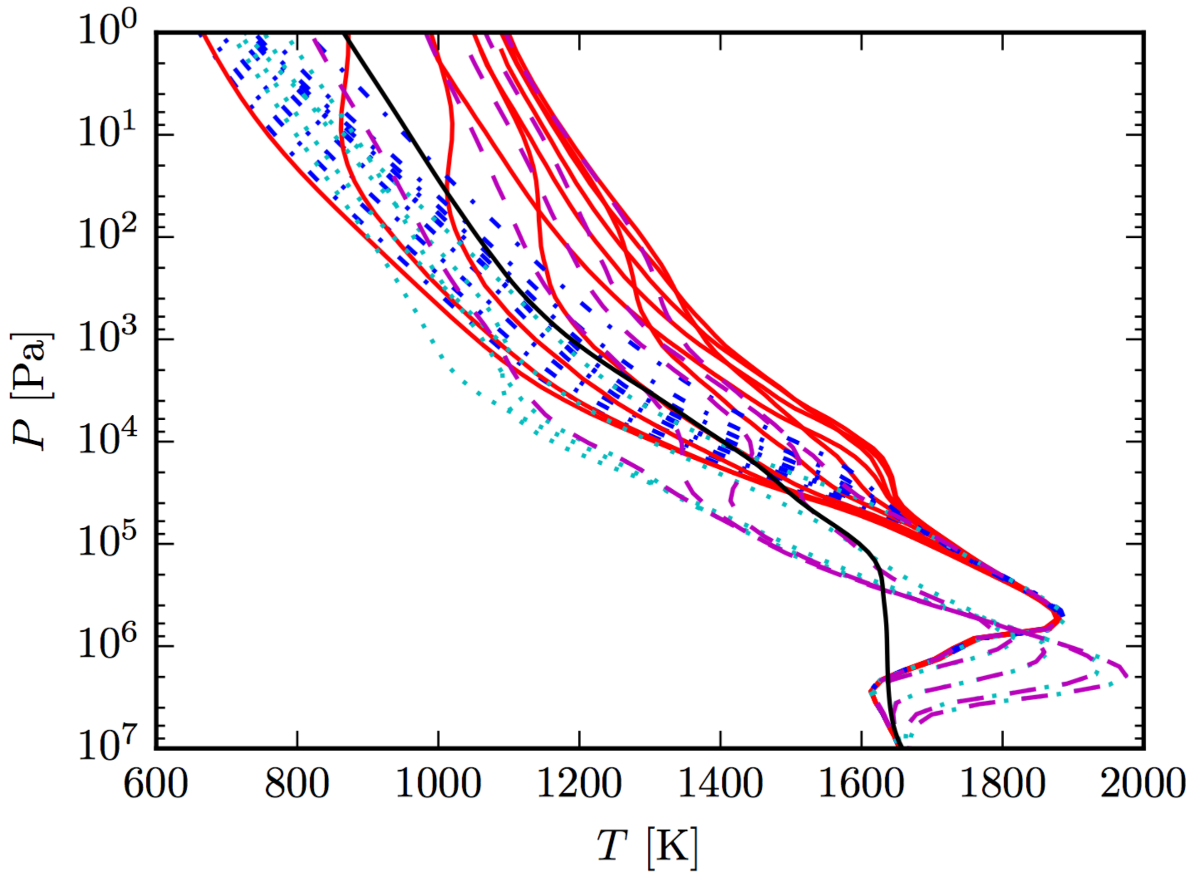


- Asymetric irradiation of tidally locked hot jupiter
  - 3D atmospheric models to study the circulation, evolution in time to get the steady state



➢ Asymetric irradiation of tidally locked hot jupiter

– Does it work ? No…



– Can you guess why ?

➢ Why is it a challenge?

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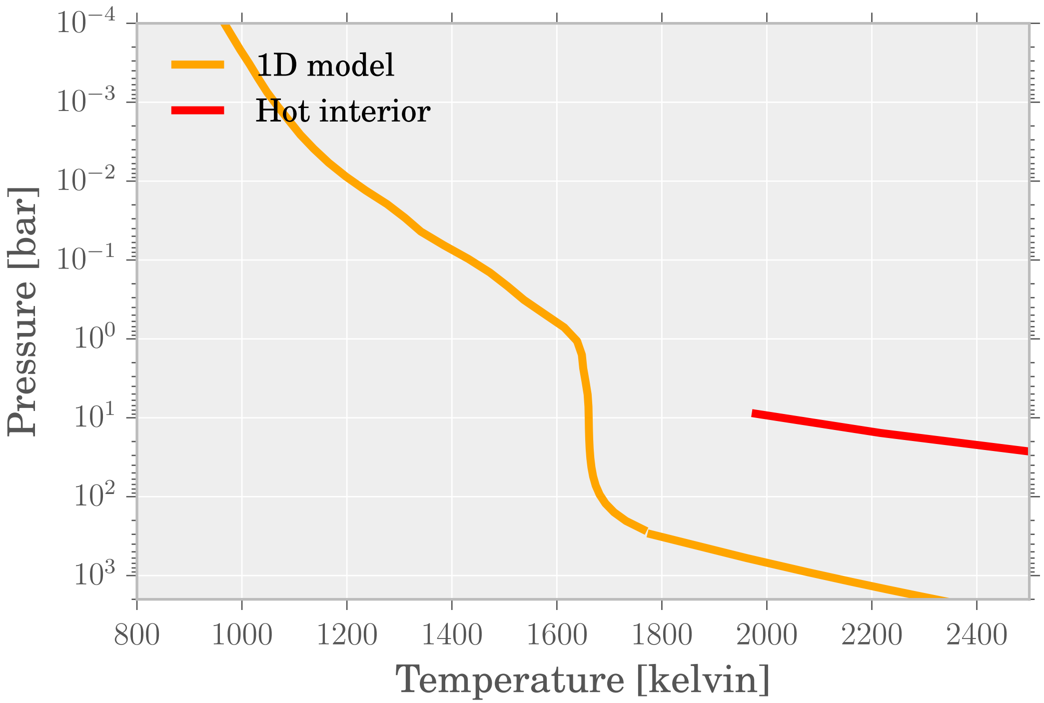
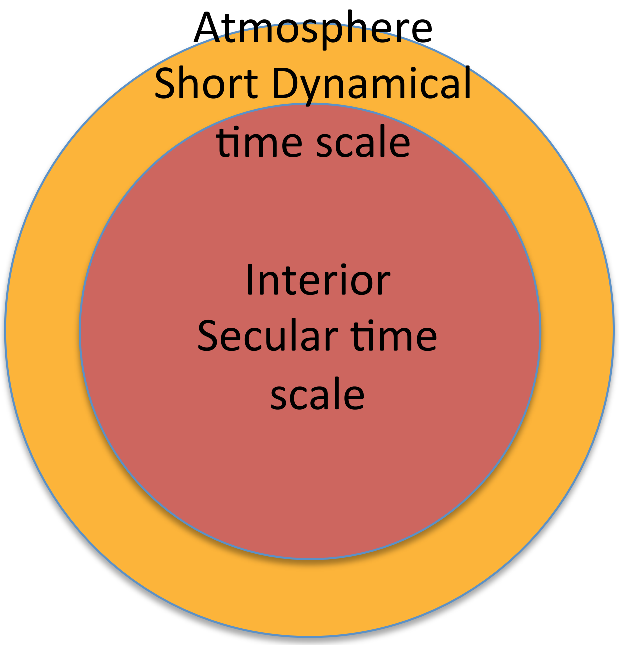
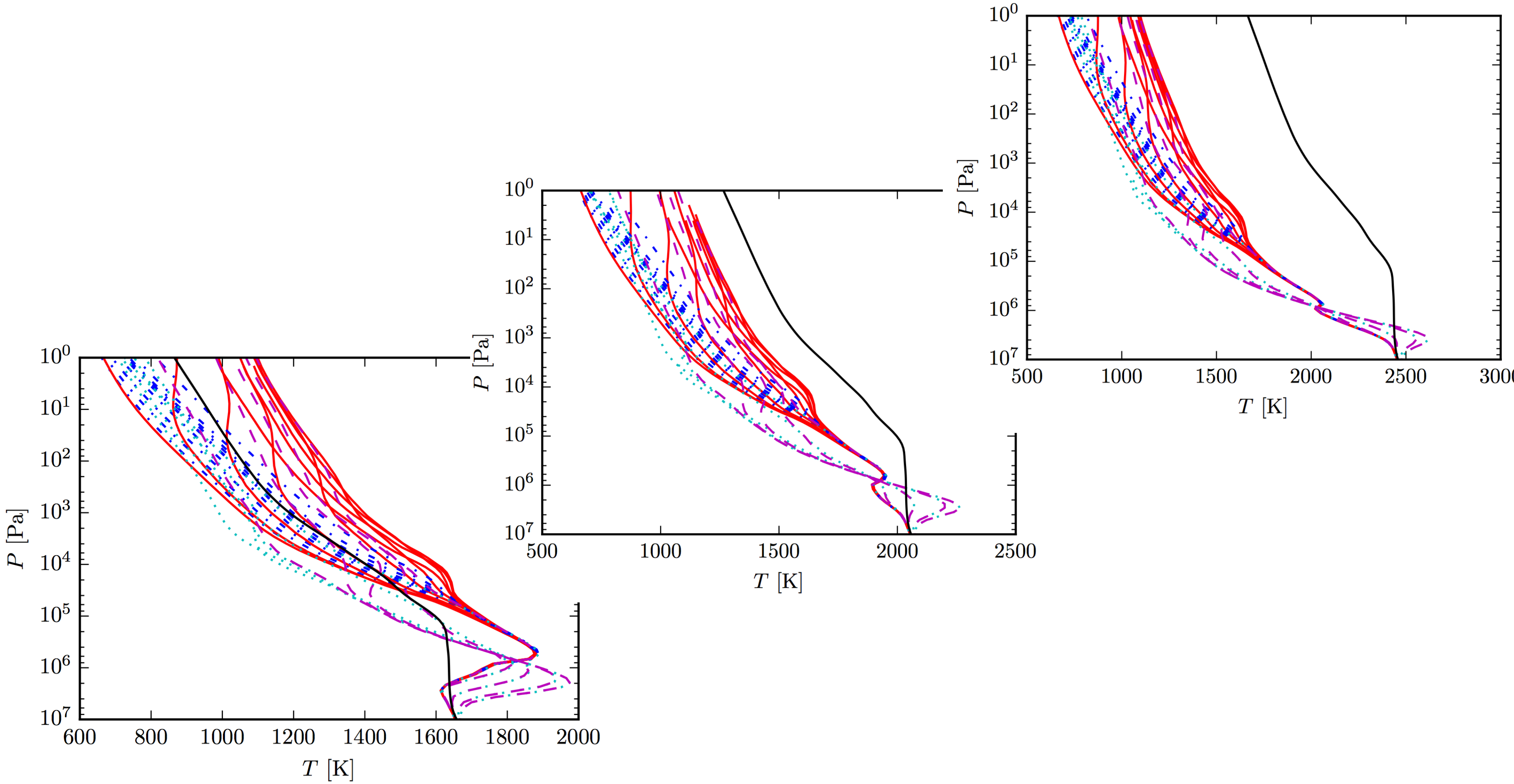




➢ Asymetric irradiation of tidally locked hot jupiter

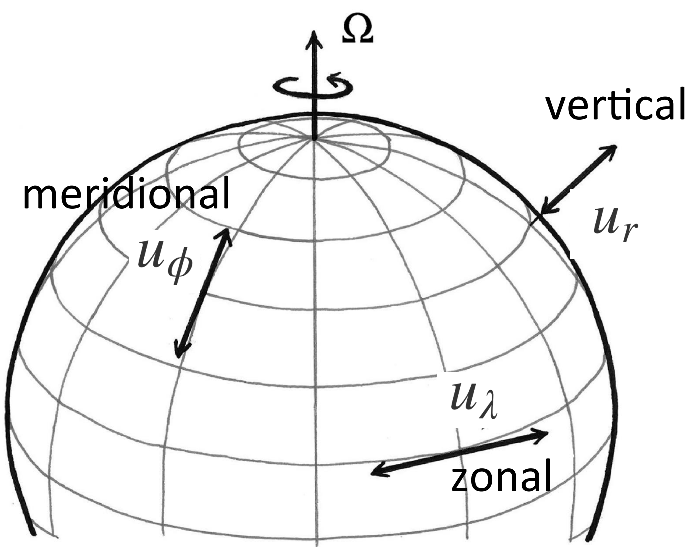
– The deep atmosphere is not converged in time because of computation limitation



Asymetric irradiation of tidally locked hot jupiter

- Need to construct a 2D steady state circulation model at the equator
  - Keep the steady state nature of the 1D model
  - Can take into account the asymetric irradiation as a 3D model

- Problems:
  - The meridional wind u_ϕ is zero at the equator by north/south symetry but not its derivative $\partial u_\phi / \partial \phi$
  - The meridional momentum equation vanishes at the equator and we lack one equation to close the system…



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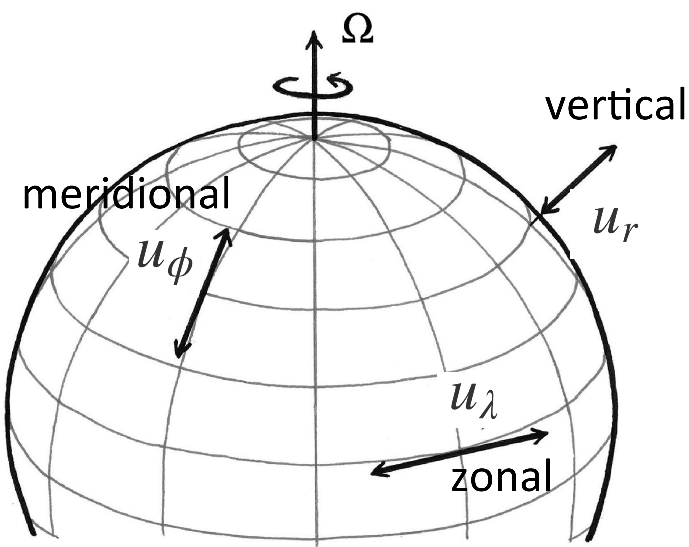


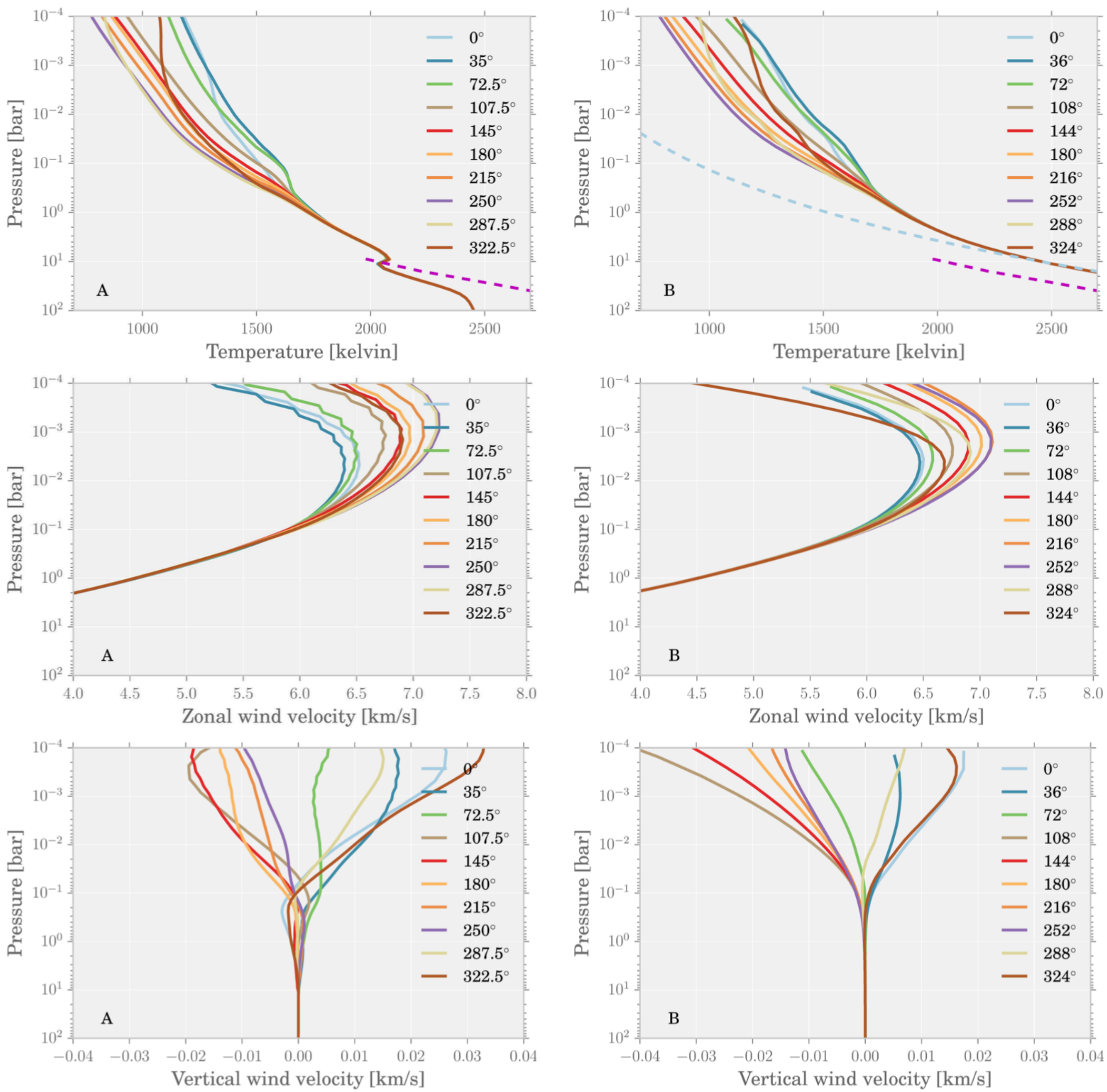
Just assume that transverse mass fluxes are proportional with a constant

$$\frac{1}{r^2}\frac{\partial r^2 \rho u_r}{\partial r} = \frac{1}{r\alpha}\frac{\partial \rho u_\phi}{\partial \phi}$$

$\alpha \rightarrow 0$ Zonal, vertical wind

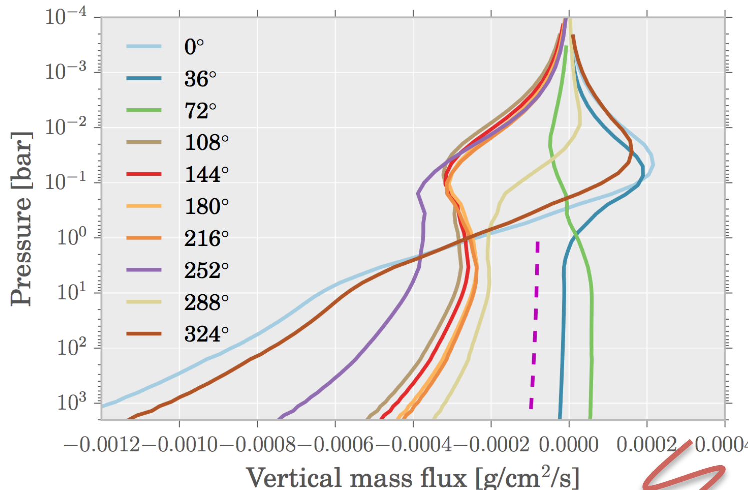
$\alpha \rightarrow \infty$ Zonal, meridional wind

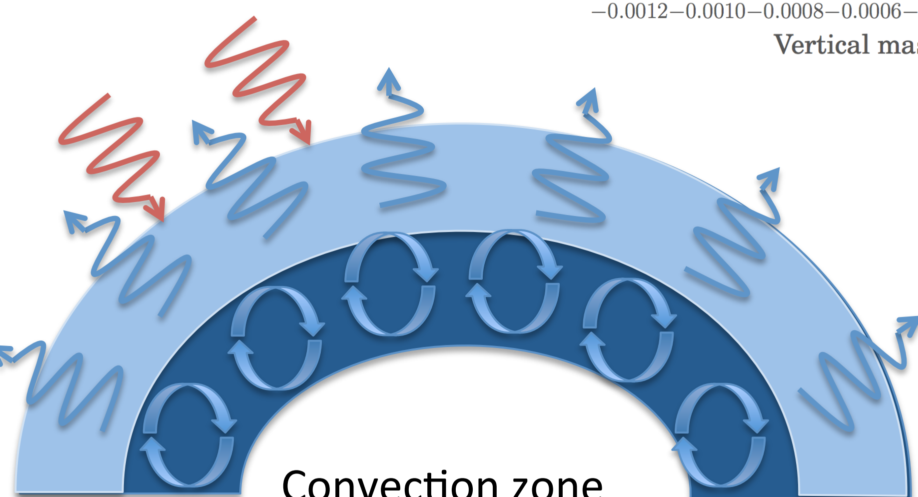
➢ Asymetric irradiation of tidally locked hot jupiter

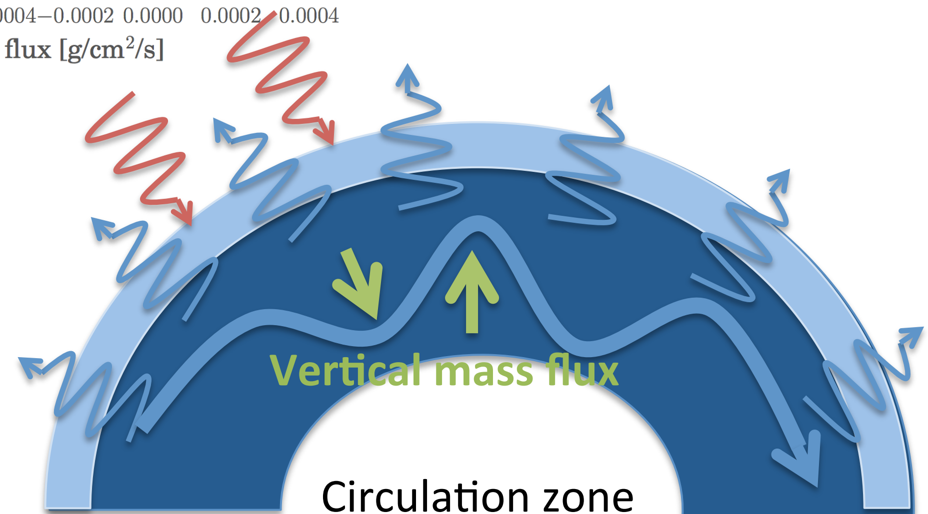


➢ Asymetric irradiation of tidally locked hot jupiter

– Get a hot deep interior because of vertical mass flows !



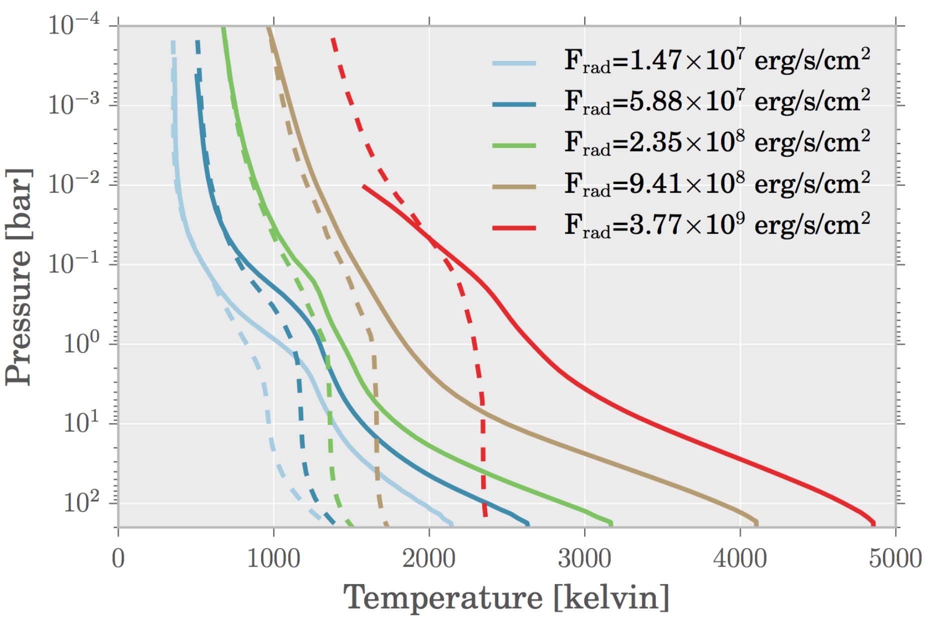


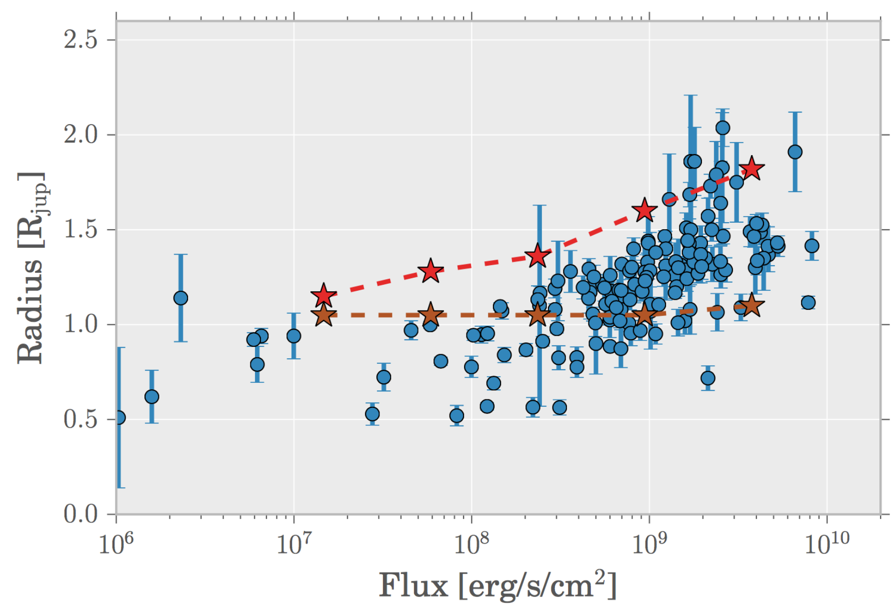


Convection zone
With small-scale motions
adiabatic PT profile

Circulation zone
With large-scale motions
adiabatic PTprofile

- Asymetric irradiation of tidally locked hot jupiter
  - Get a hot deep interior because of vertical mass flows !

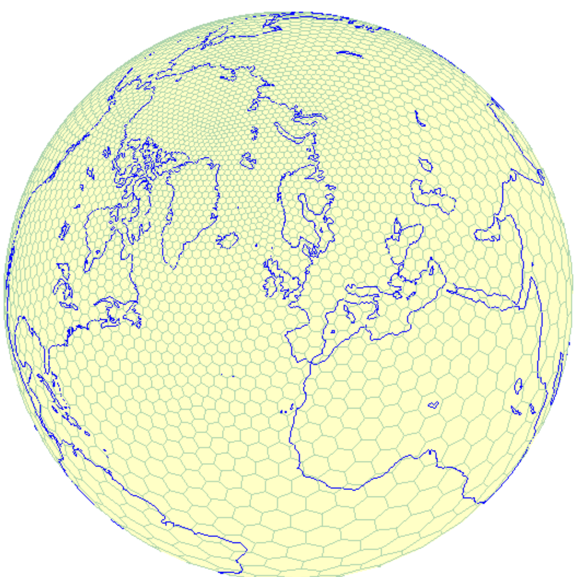


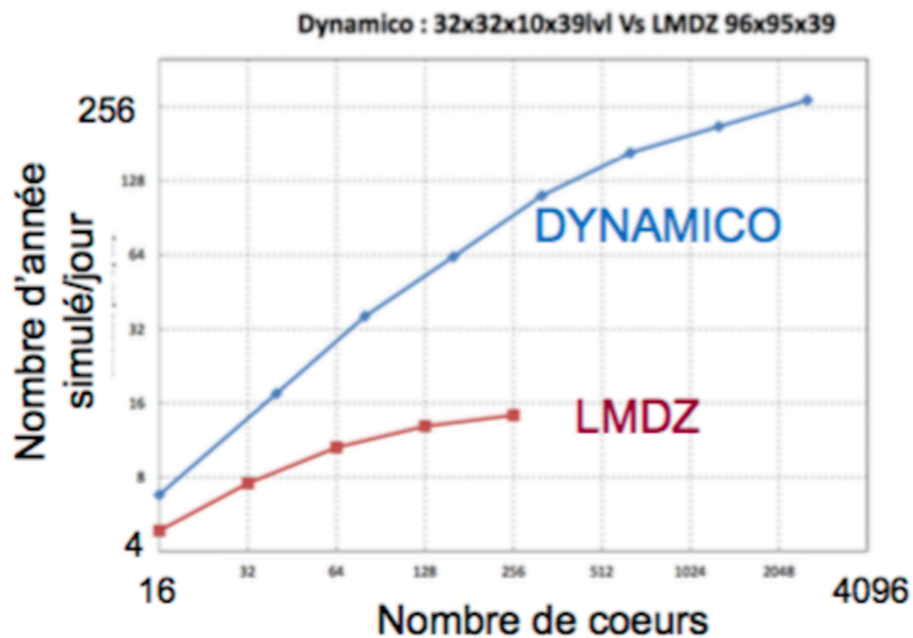


➢ Asymetric irradiation of tidally locked hot jupiter

- But the solution is only 2D at the equator… what happen at other latitudes ?? Still need 3D simulations but need efficient HPC to reach the steady state

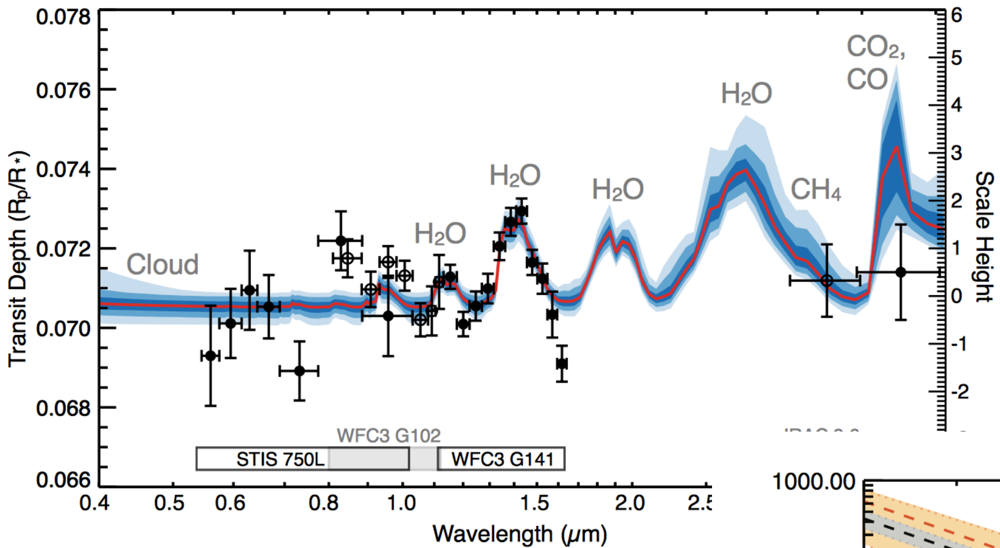
- Efficient new dynamical core for atmospheric circulation: Dynamico
  - Developped at LMD and LSCE by T. Dubos and Y. Meurtdesoif
  - Icosahedral grid instead of spherical grid to avoid small polar cells
  - Efficient MPI/open MP parallelization and vectorisation

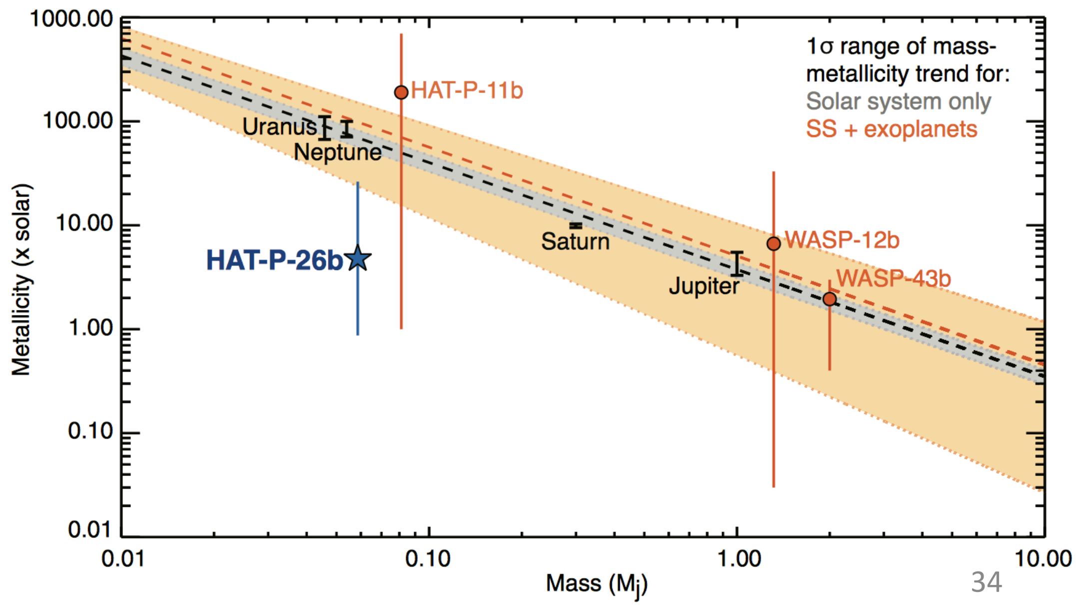




Characterization of molecular abundances

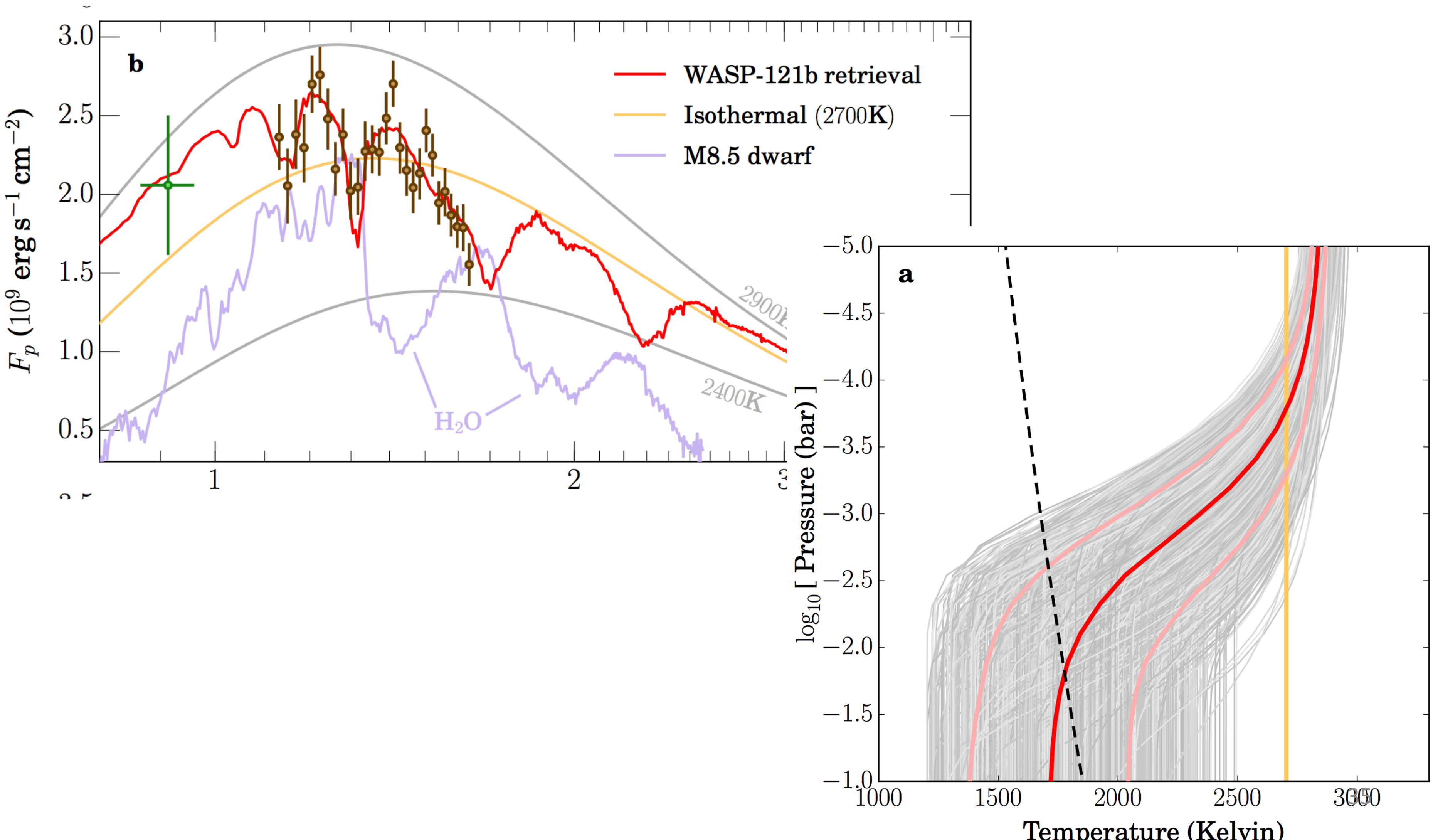
- Use 1D model to get the abundances of molecules in transmission spectra
- Wakeford et al. 2017: low-metallicity hot neptune



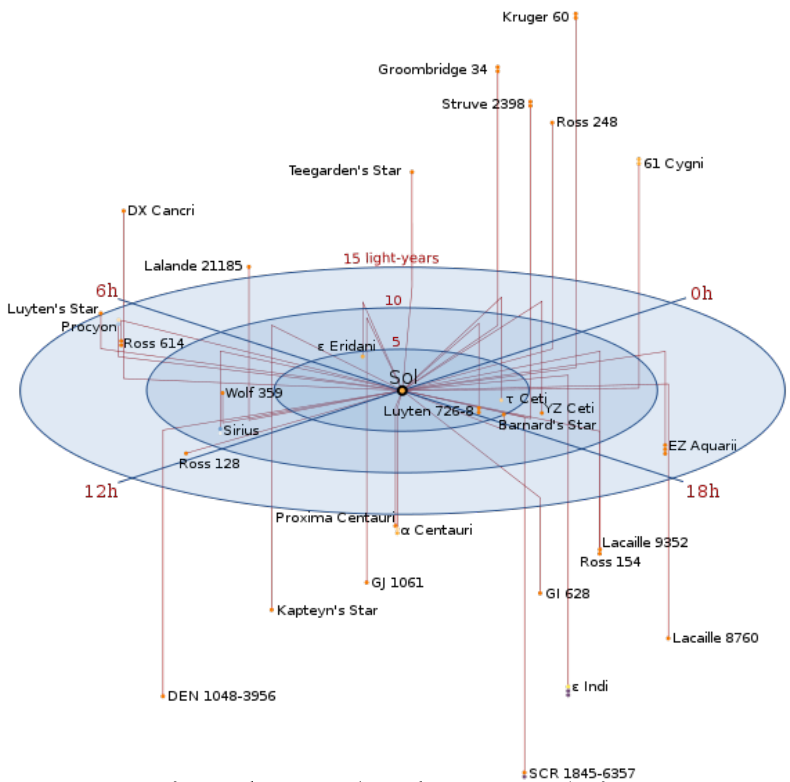


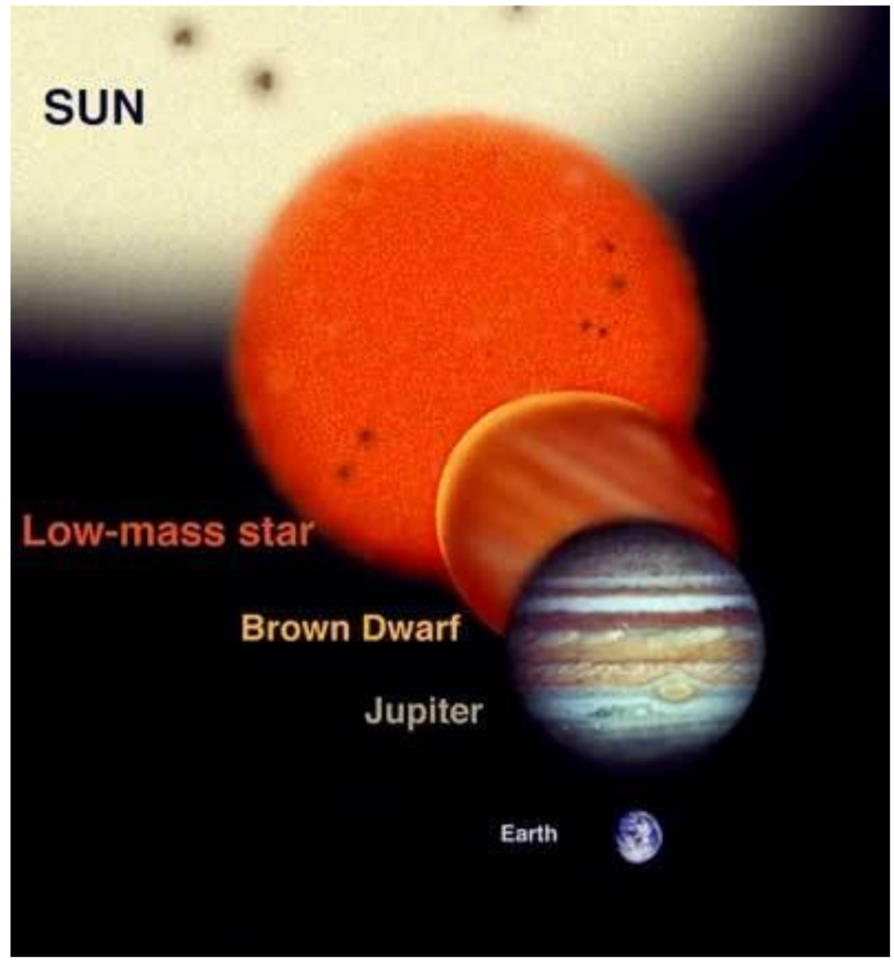
➢ Characterization of molecular abundances

– Use 1D model to get the abundances of molecules in Emission spectra
– Evans et al. 2017 (in press): detection of a stratosphere in a hot Jupiter

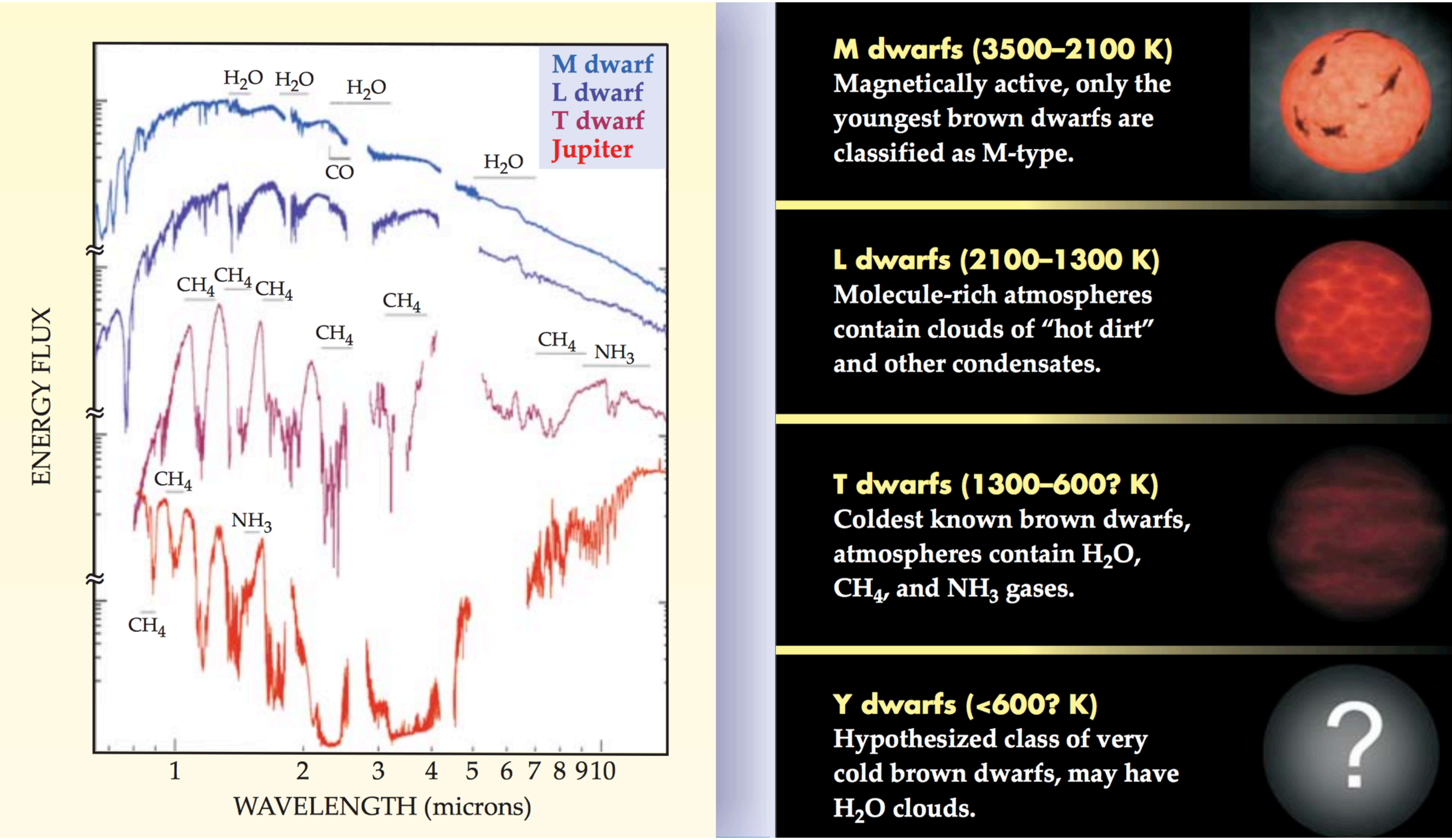


➢ Brown dwarfs: many observations with good-quality spectra



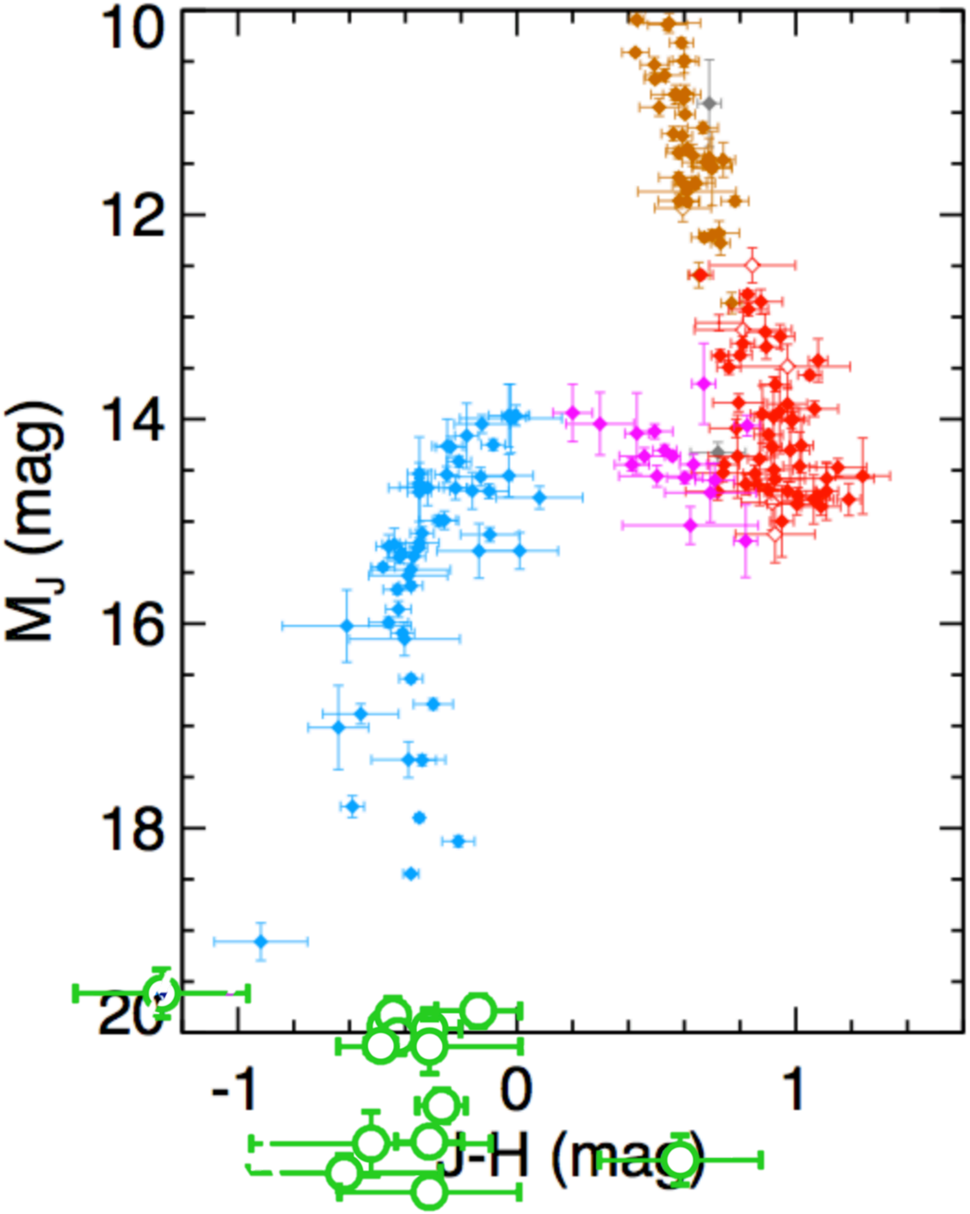


Many isolated close objects: good data ! Can test atmospheres from T=3000K down to T=300K


M dwarf
L dwarf
T dwarf
Jupiter
H2O
CO
CH4
NH3
ENERGY FLUX
WAVELENGTH (microns)
1 2 3 4 5 6 7 8 910
M dwarfs (3500–2100 K)
Magnetically active, only the youngest brown dwarfs are classified as M-type.
L dwarfs (2100–1300 K)
Molecule-rich atmospheres contain clouds of "hot dirt" and other condensates.
T dwarfs (1300–600? K)
Coldest known brown dwarfs, atmospheres contain H2O, CH4, and NH3 gases.
Y dwarfs (<600? K)
Hypothesized class of very cold brown dwarfs, may have H2O clouds.
?

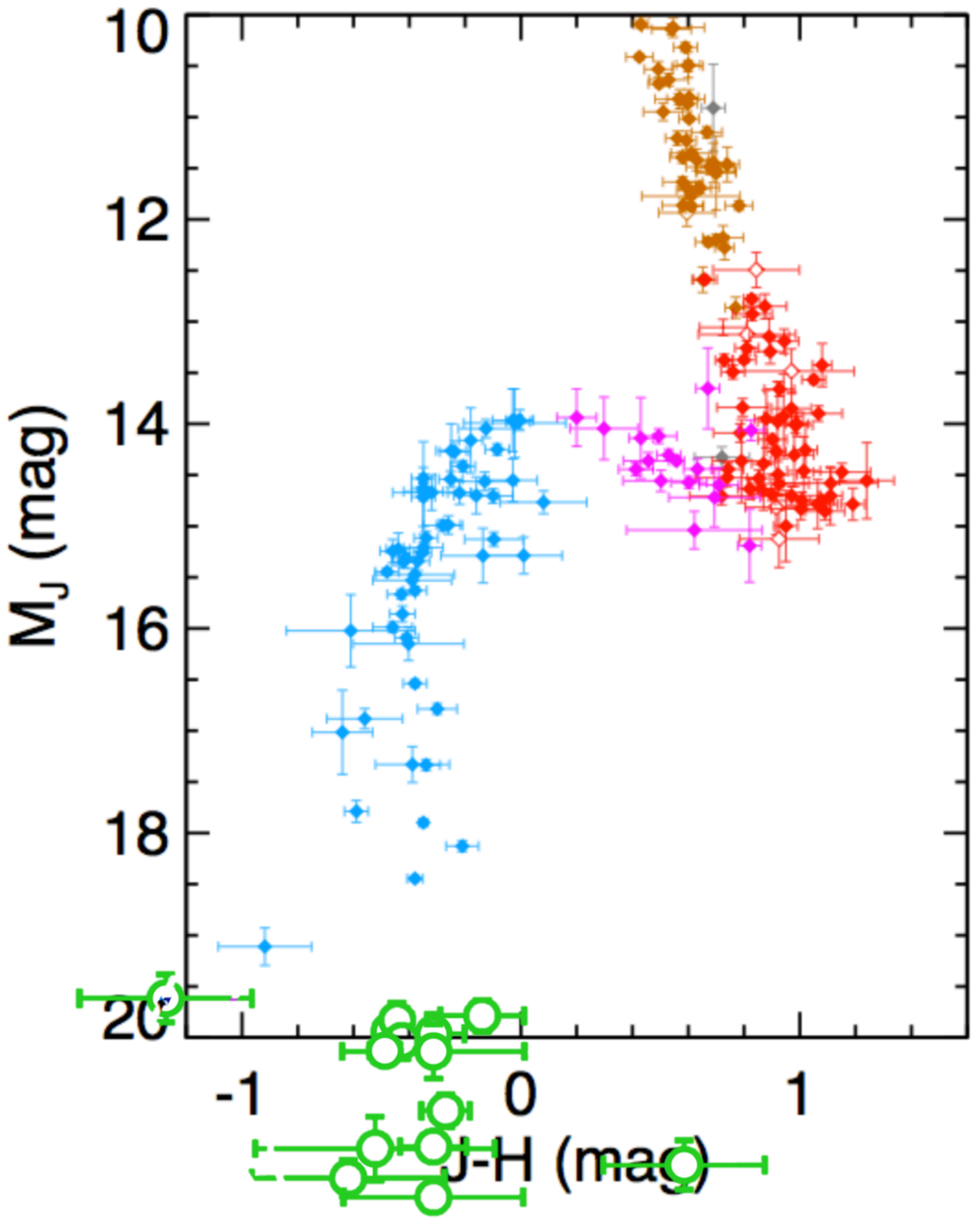
➢ Reddening -> clouds ?

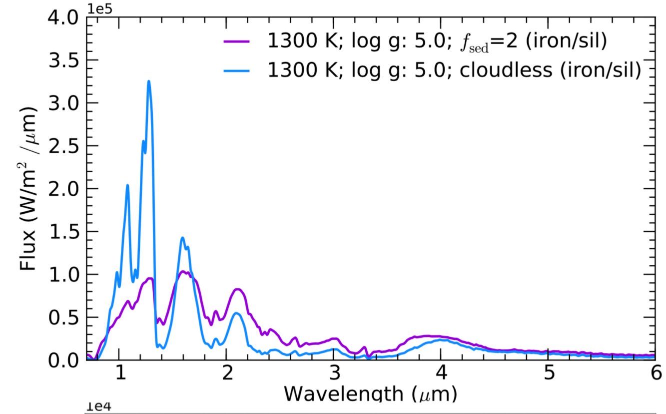
Dupuy et al. (2012) + Faherty et al. (2012)

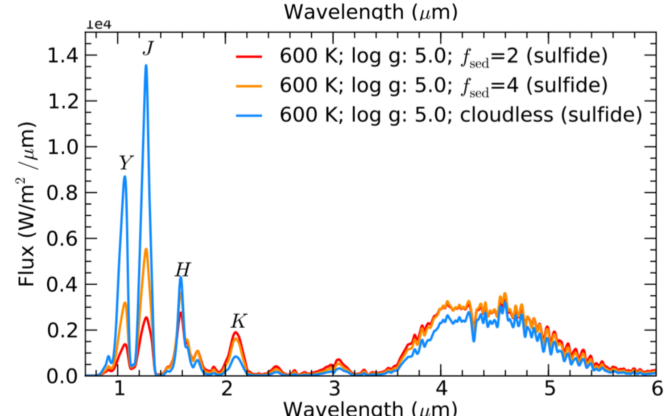


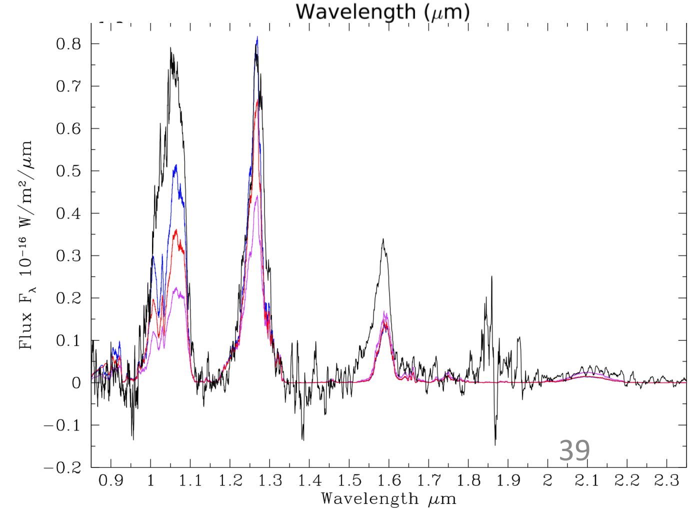
➢ Reddening -> clouds ?

Allard et al. (2001) Saumon et al. (2008) Marley et al. (2010)
Morley et al. (2012,2014) Leggett et al. (2015)



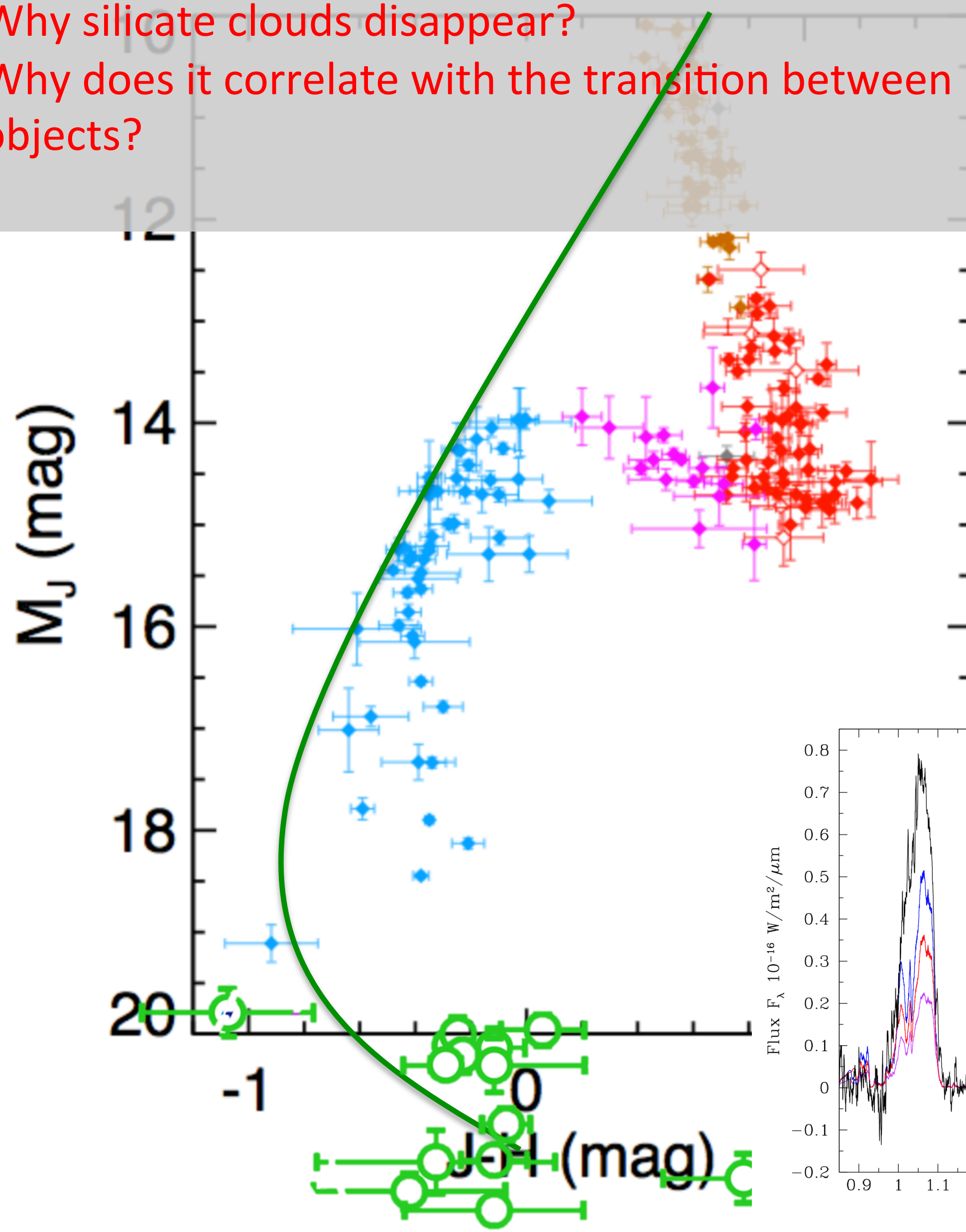


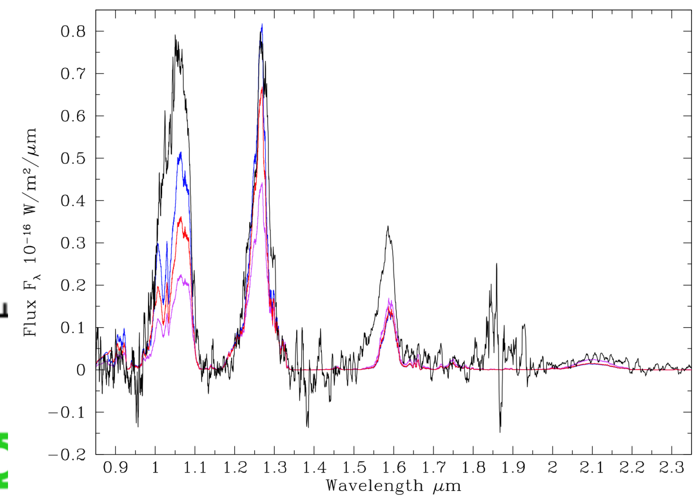




- Why water clouds do not work well?
- Why silicate clouds disappear?
- Why does it correlate with the transition between CO and CH_4 in the objects?

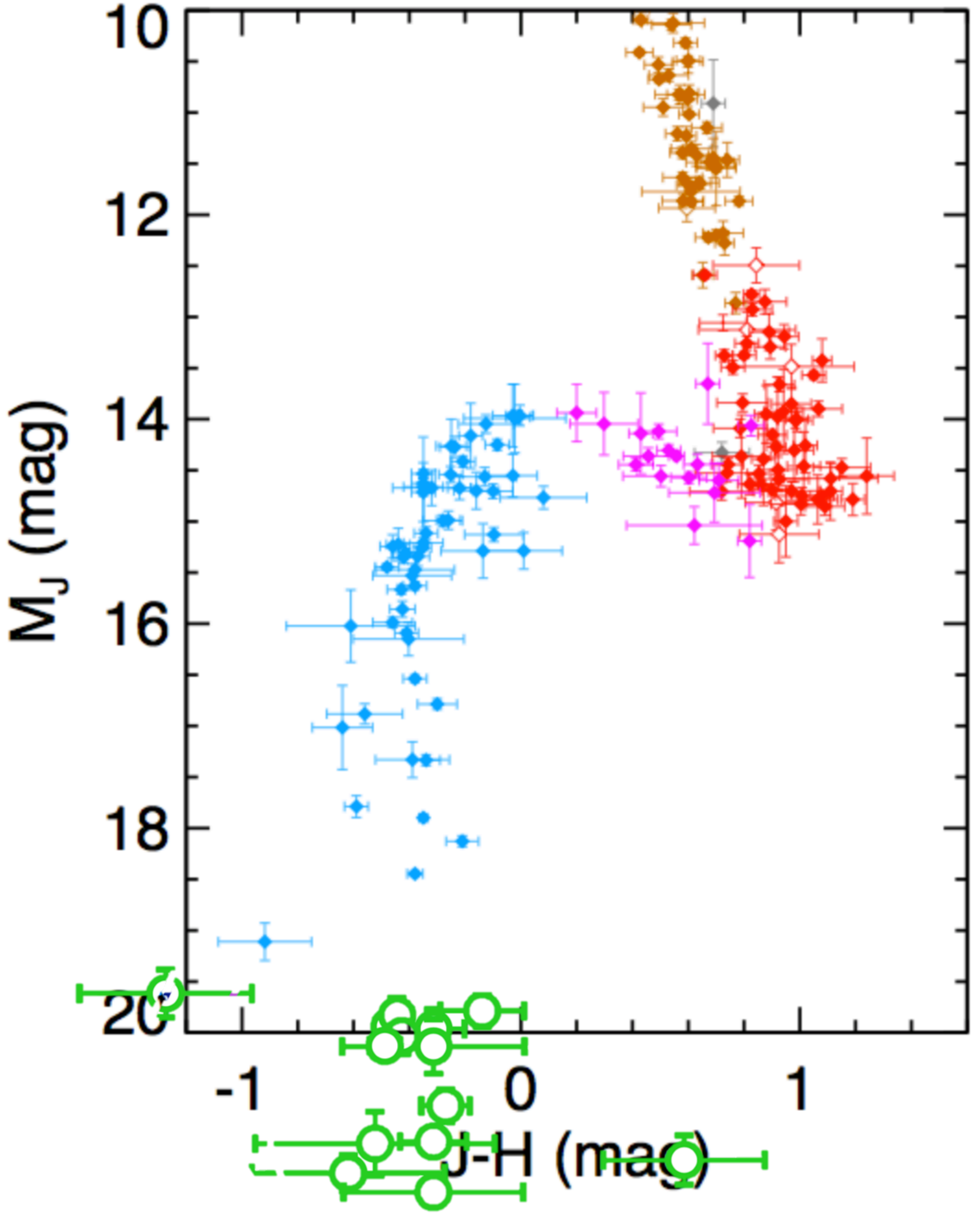
Dupuy et al. (2012) + Faherty et al. (2012)

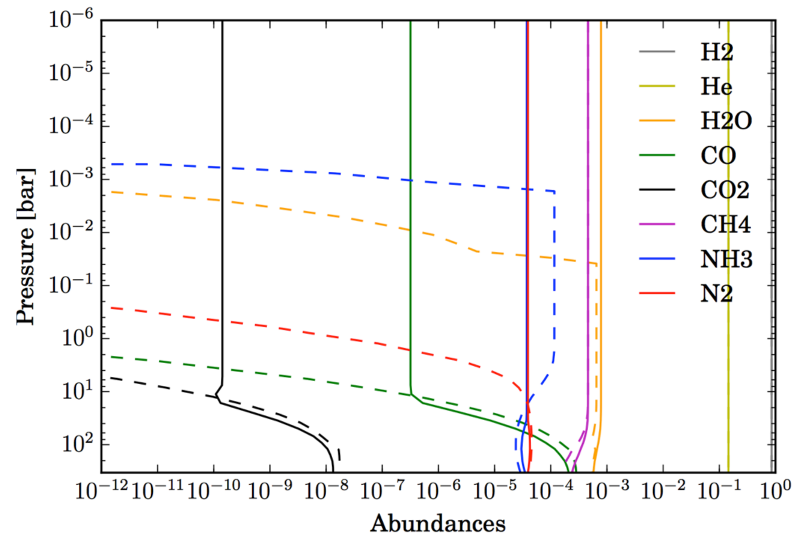


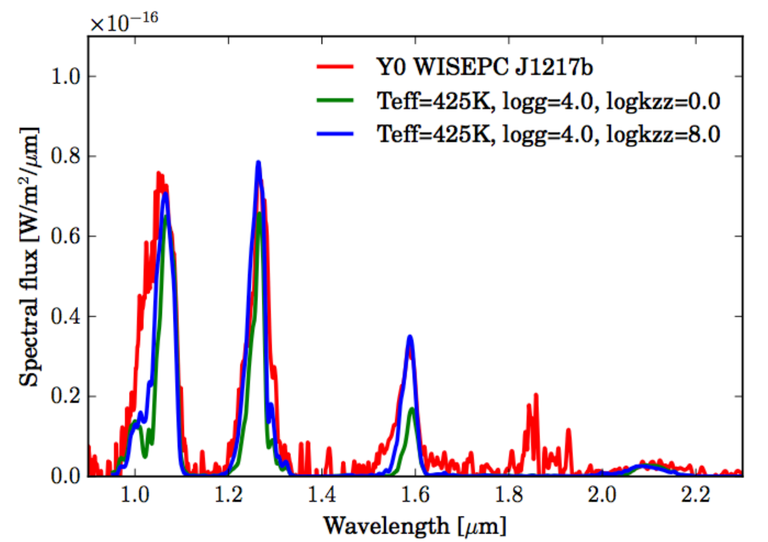


➢ Y dwarfs, no need for clouds -> out-of-equilibrium chemistry

Tremblin et al. (2015)

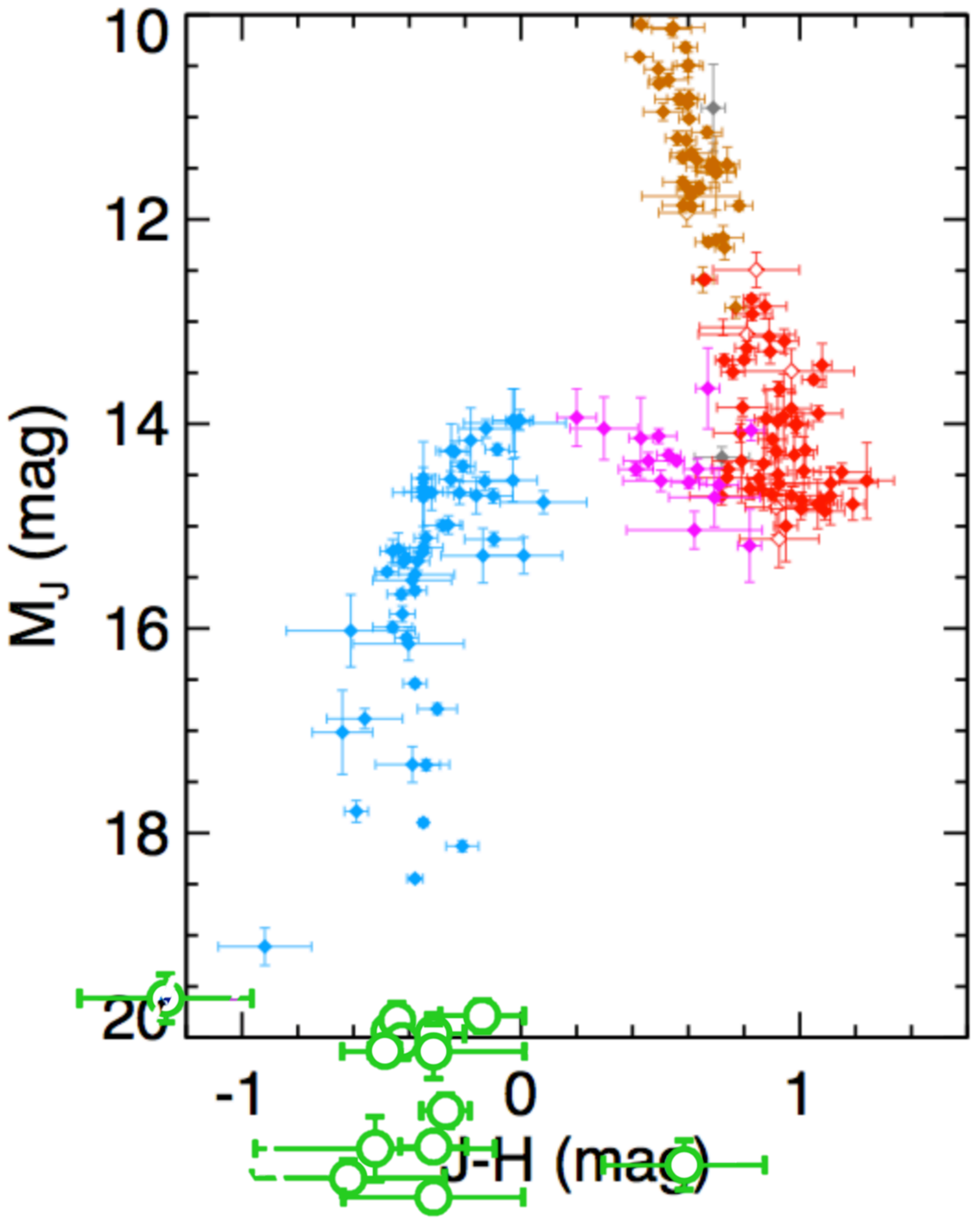


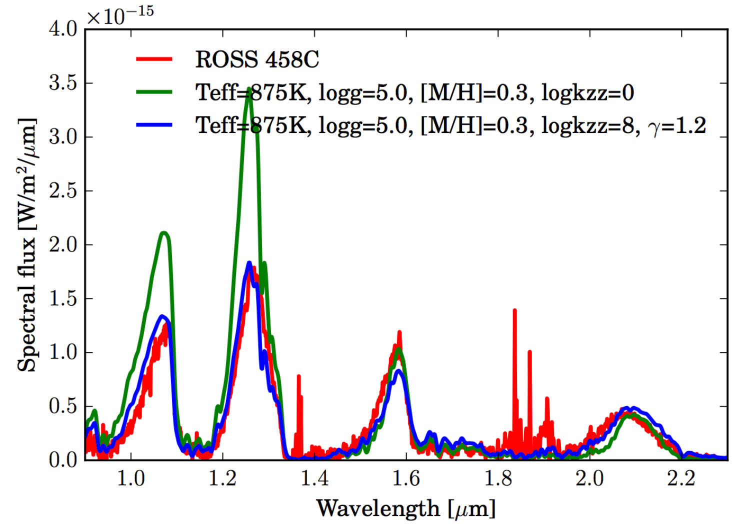


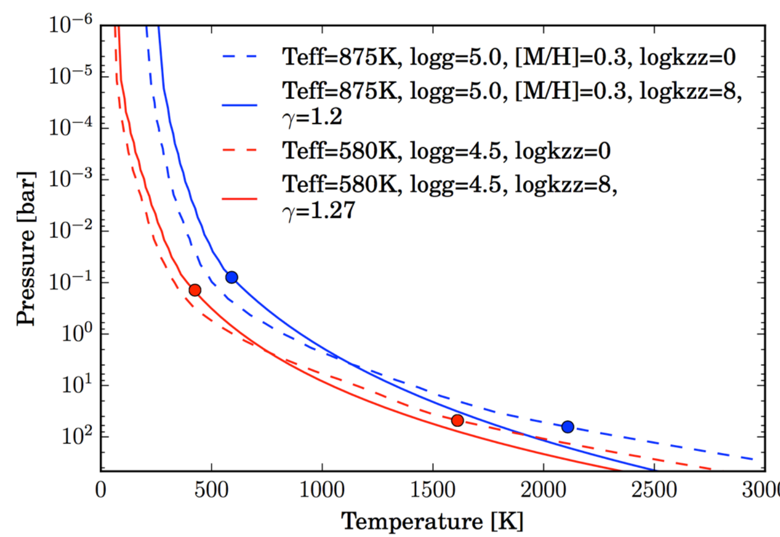


- T dwarfs, no need for clouds -> cooler deep layers

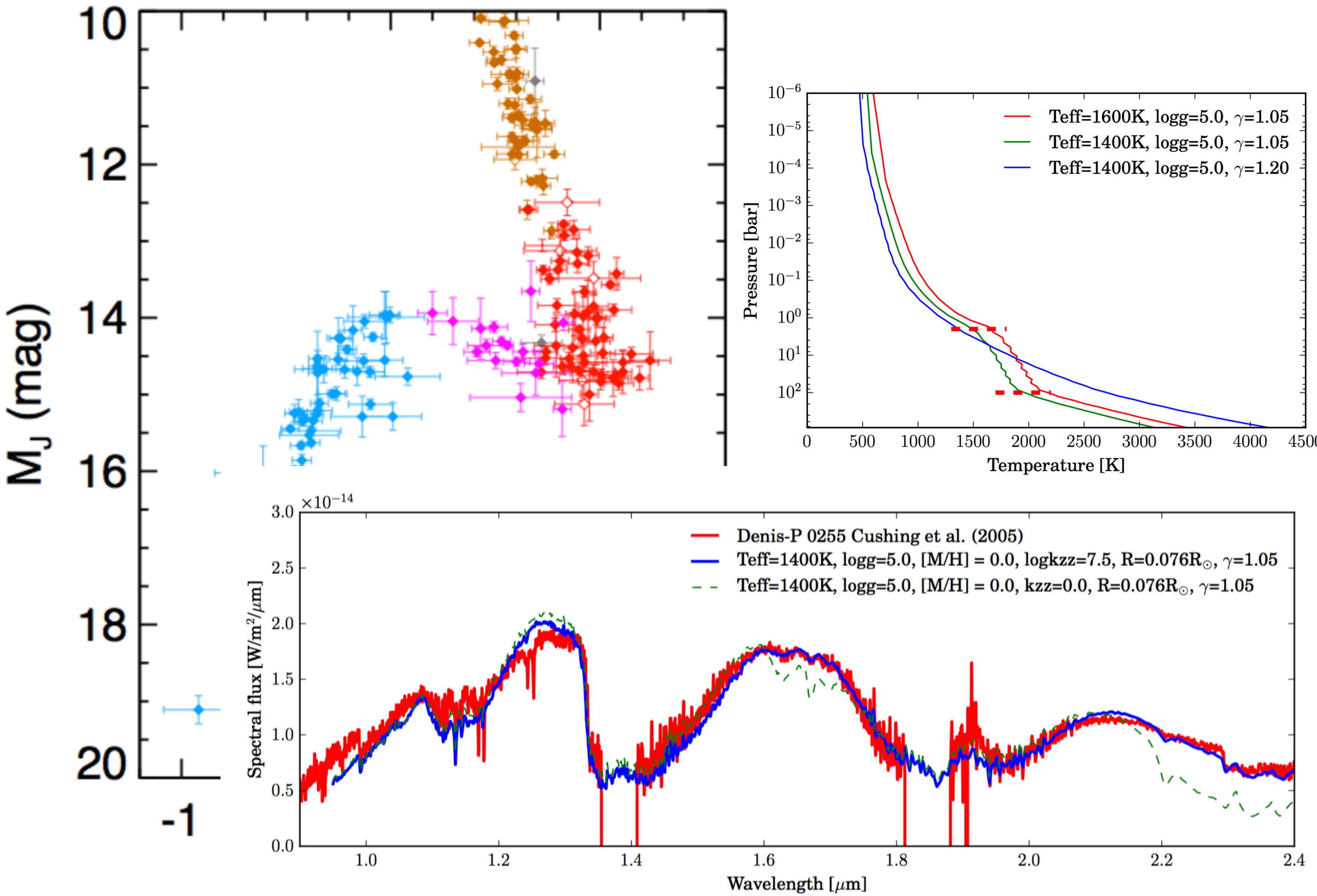
Tremblin et al. (2015)





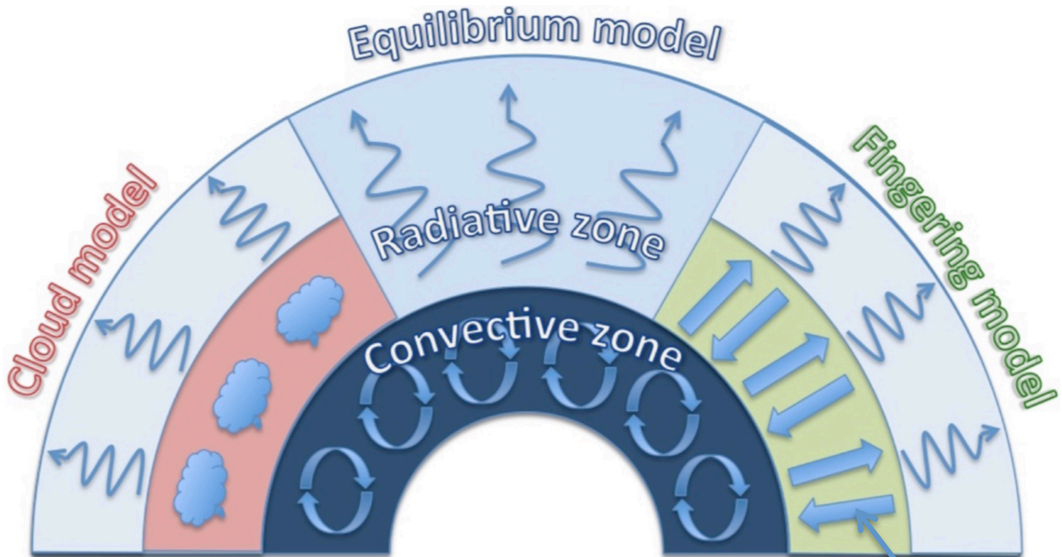


➢ L dwarfs, no need for clouds ! -> cooler deep layers with CH4 quenching Tremblin et al. (2016)



- Cooler deep layers + out-of-eq chemistry -> fingering convection ?

Tremblin et al. (2016) Rosenblum et al. (2011)

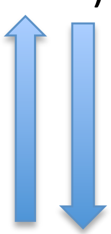


Created by gradients of mean molecular weight

Thermohaline convection
In Earth oceans
(Stern 1960)

Salt-poor water

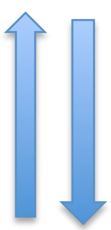
Salt-rich water



Fingering convection
in Stars atmosphere
(Théado et al. 2009)

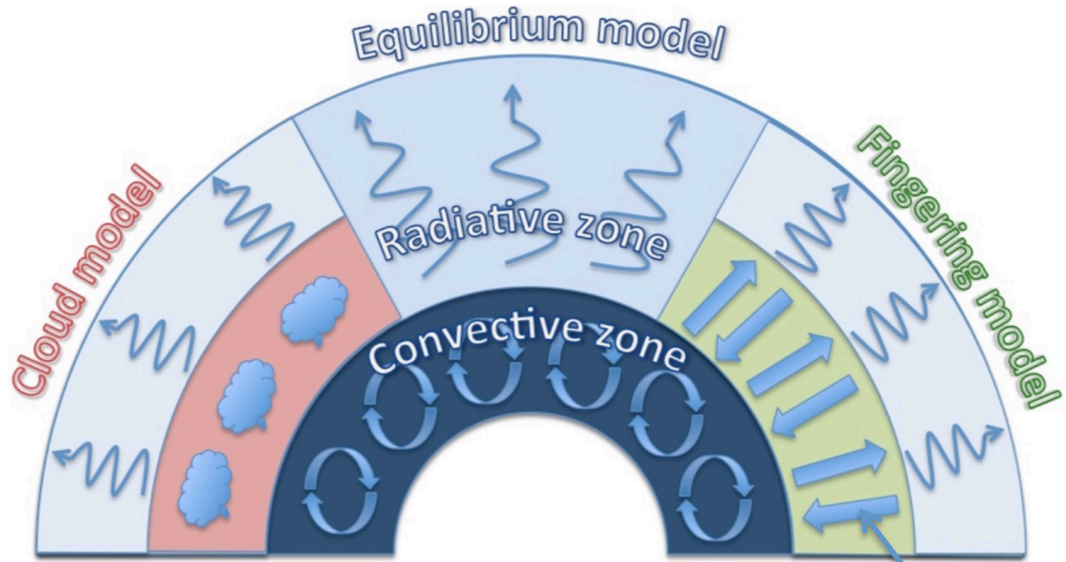
Iron-poor gas

Iron-rich gas



- Cooler deep layers + out-of-eq chemistry -> fingering convection ?

Tremblin et al. (2016) Rosenblum et al. (2011)



Created by gradients of mean molecular weight

Phase transition of molecules !

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$N_2 + 3H_2 \rightarrow 2NH_3$$

Fingering convection
in Exoplanets Brown dwarfs
(Tremblin et al. 2015,2016)

CO+3H2 gas

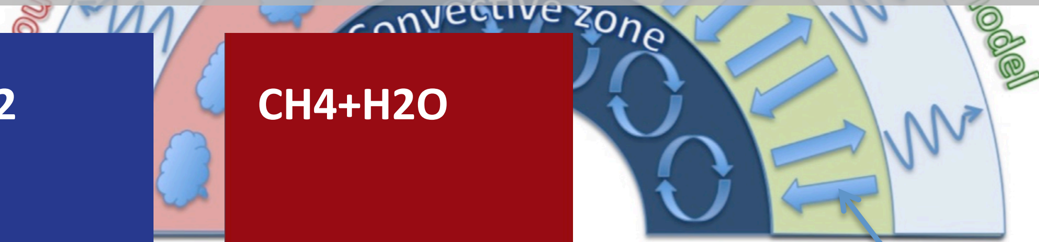
CH4+H2O gas

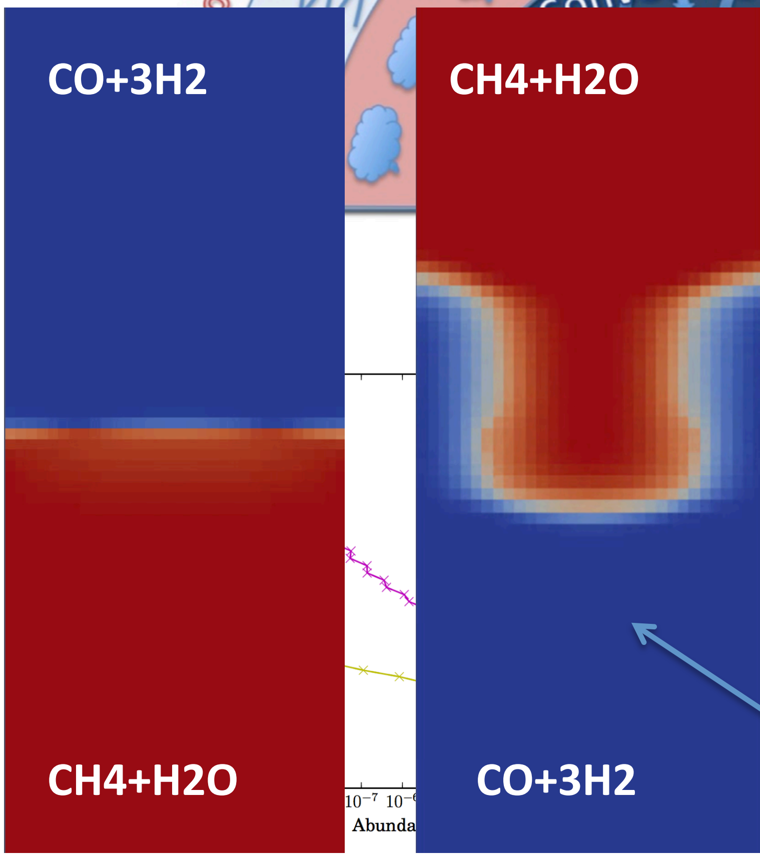
➢ Cooler deep layers + out-of-eq chemistry -> fingering convection ?

Tremblin et al. (2016) Rosenblum et al. (2011)

The CO/CH4 transition and N2/NH3 transition introduce destabilizing mean-molecular-weight gradients in the atmosphere that triggers fingering convection and turbulence

When the transition is deep enough the chemical timescale is fast and the instability disappear -> sharp transition to a full CH4 stable state of NH3 stable state explaining the L/T transition





Created by gradients of mean molecular weight

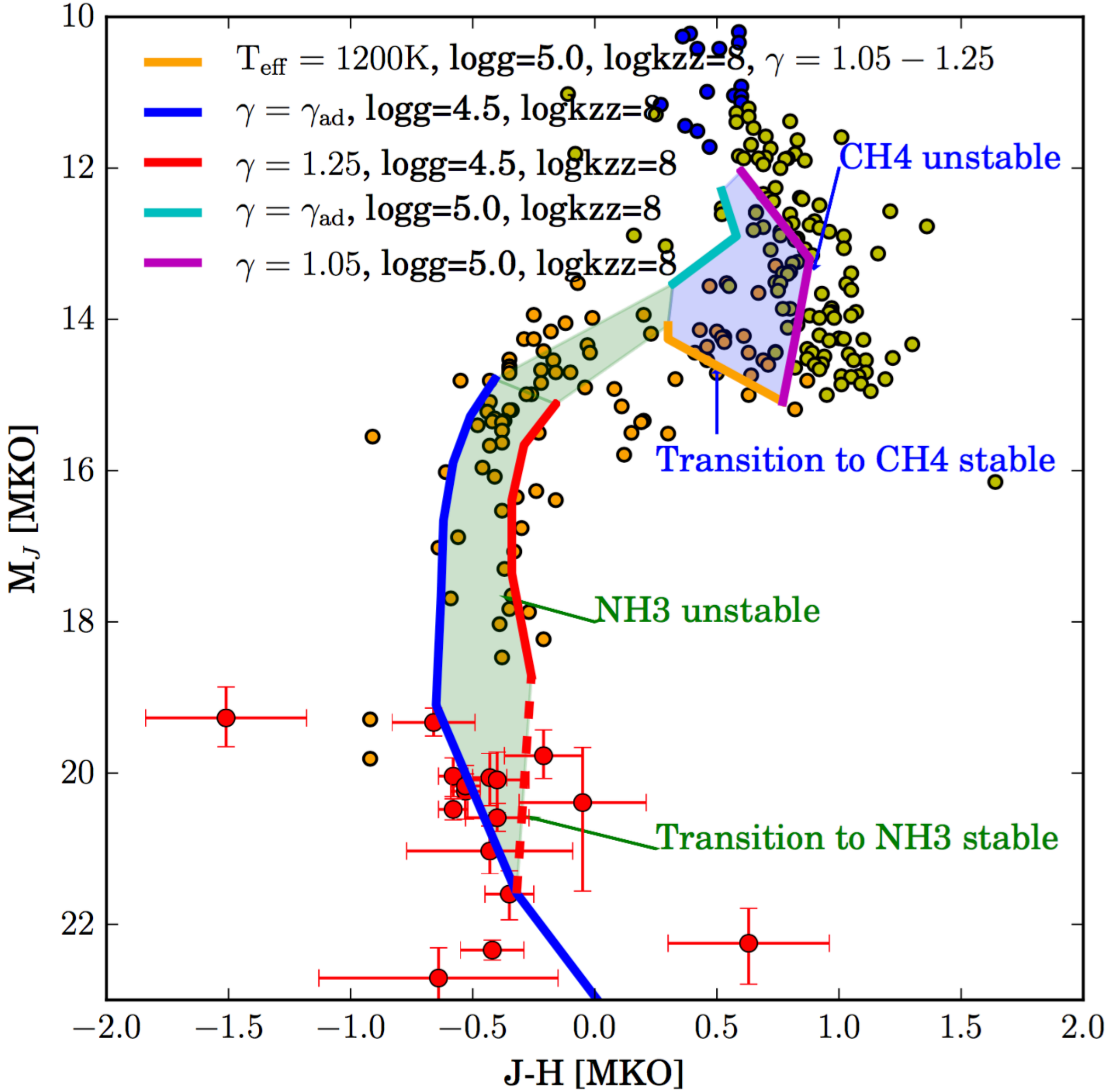
Phase transition of molecules !

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$N_2 + 3H_2 \rightarrow 2NH_3$$

Predicted by equilibrium chemistry in brown dwarfs and isolated exoplanets

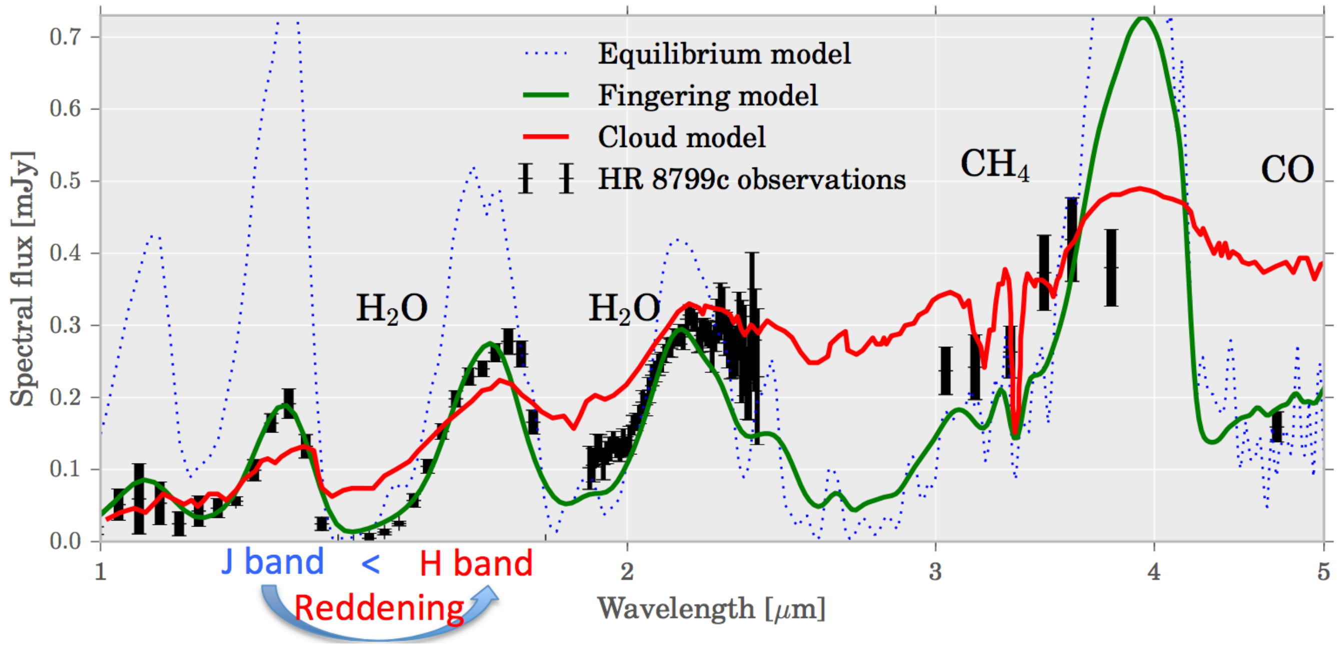
➢ A whole new picture based on turbulence

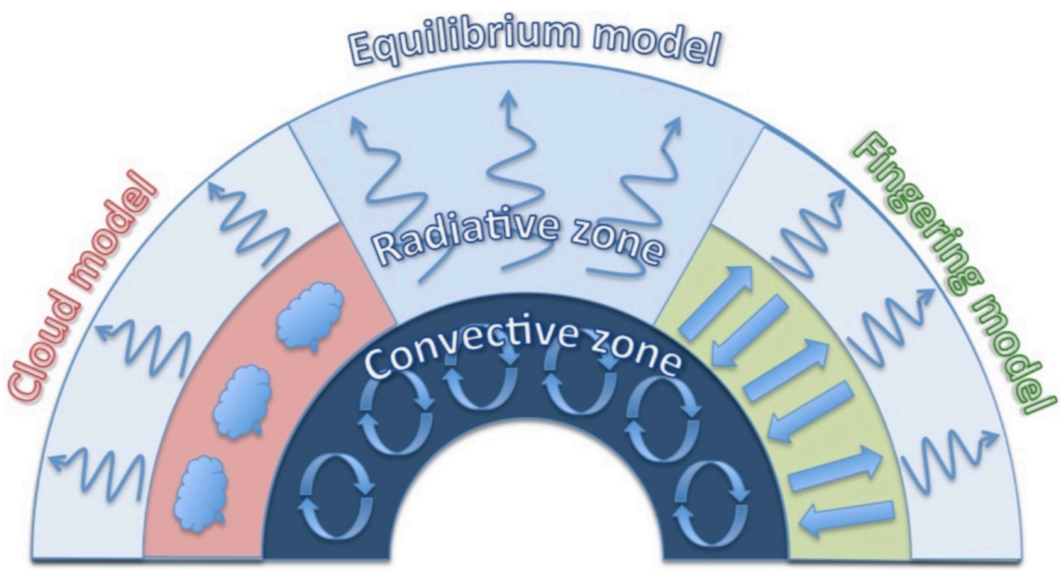
Tremblin et al. (2016)



➢ Do we care for exoplanets?

Tremblin et al. (2016)





Thanks!
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