Characterization of imaged planetary atmospheres: The case of VHS 1256 b at the era of JWST

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5th September 2023

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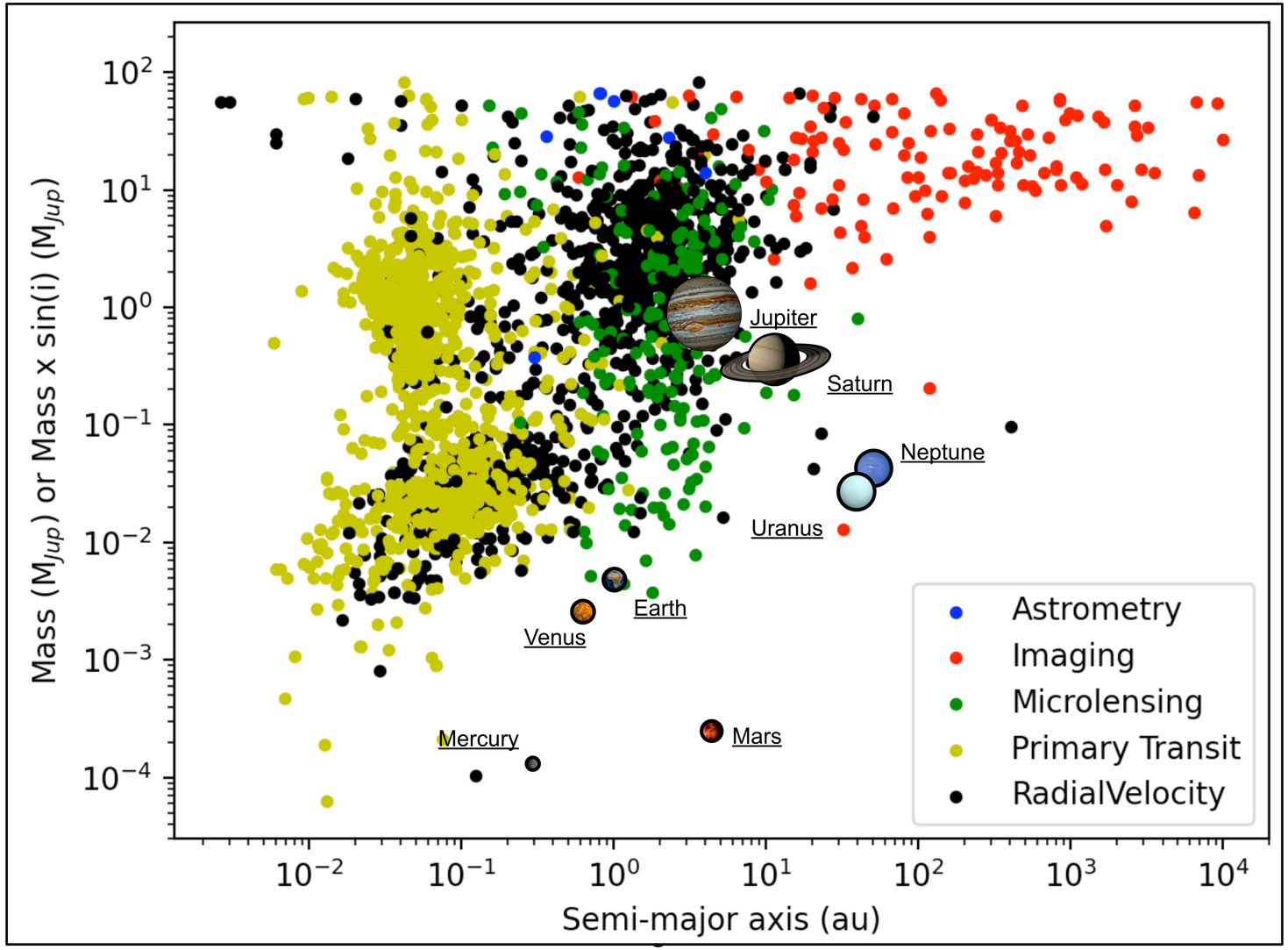
Part 1

Context

Context - *The diversity of exoplanets*

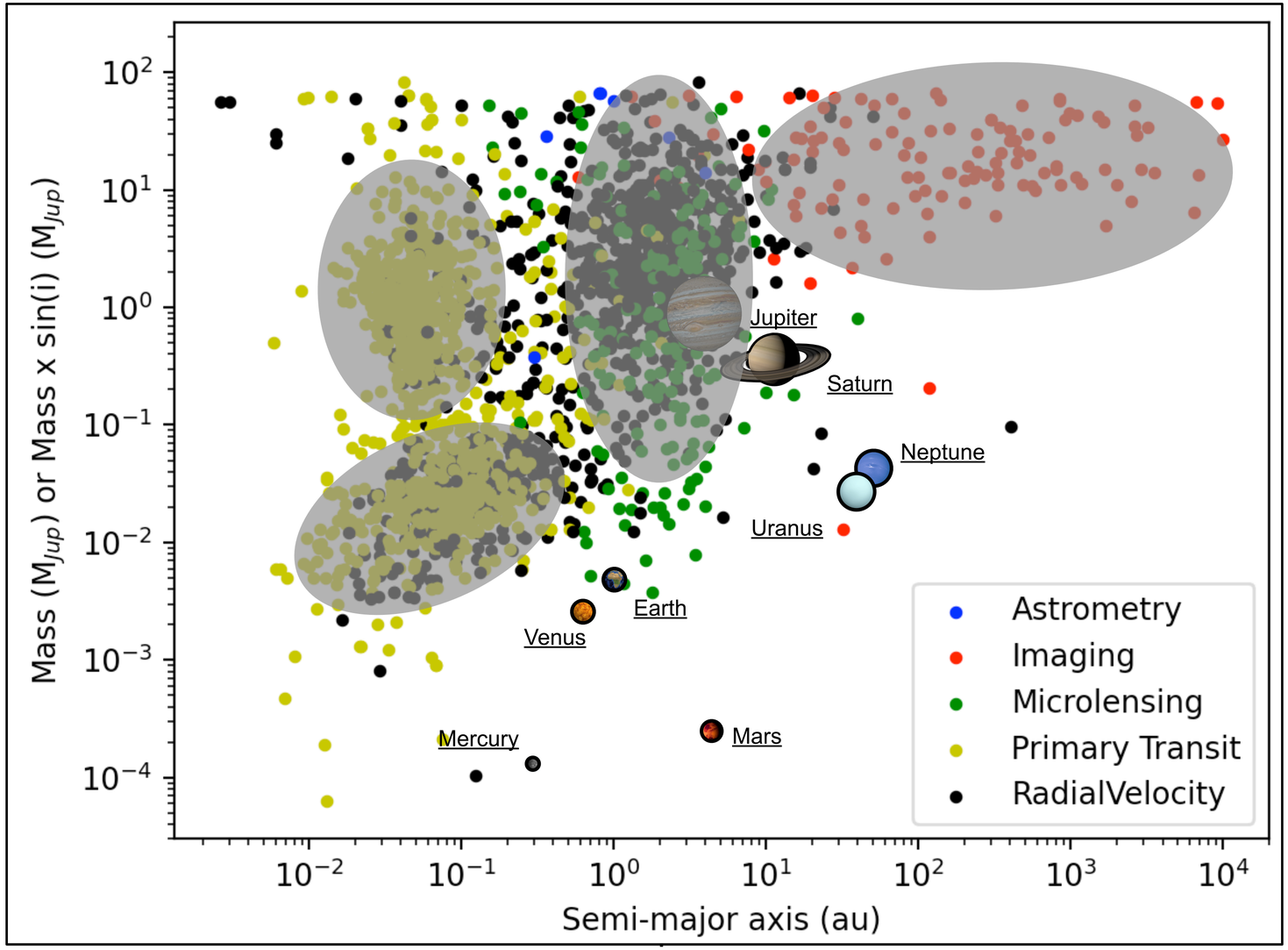


exoplanet.eu/

Context - *The diversity of exoplanets*

Sensibility of the detection methods

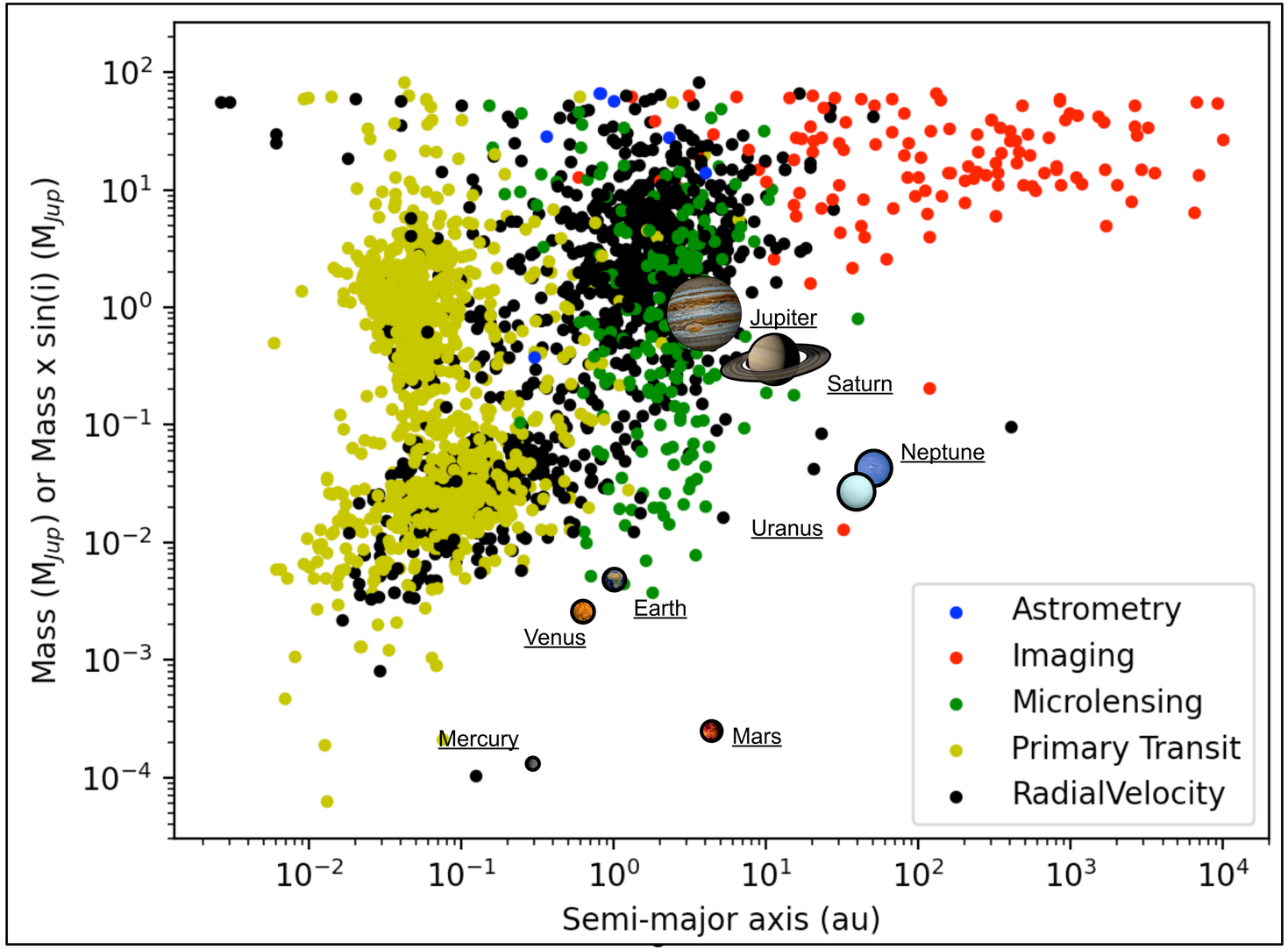
Possible different formation/evolution history ??



exoplanet.eu/

Context - *The diversity of exoplanets*

HOW THESE PLANETS HAVE BEEN FORMED ?
EVOLVED ?



exoplanet.eu/

Context - *Shopping list*

Models of formation — *What do we know about planetary formation?*

Objects of interest

Tracers of formation

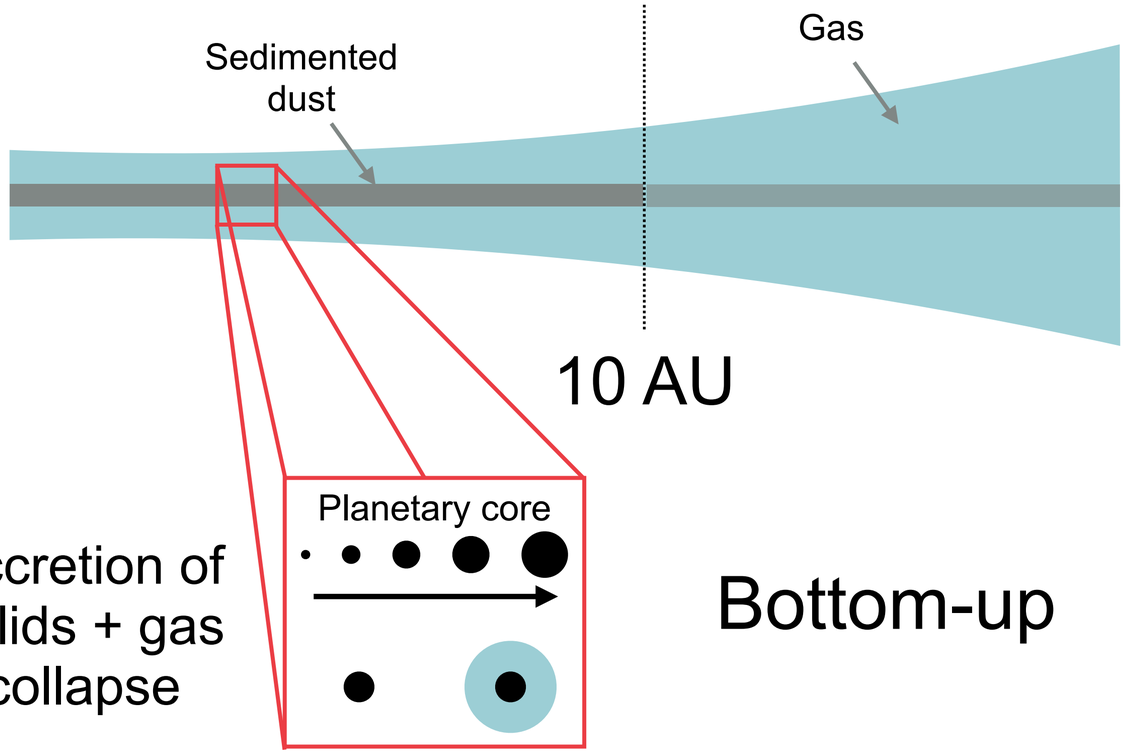
Spectral features

Data

Planet diversity

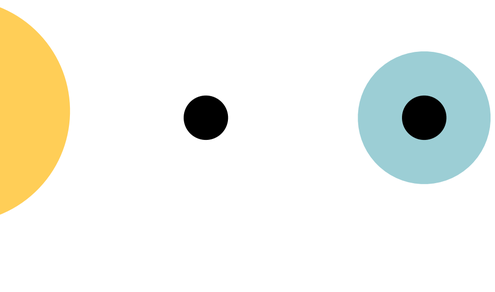
Context - *Shopping list - Models of formation*

CORE ACCRETION Pollack 1996

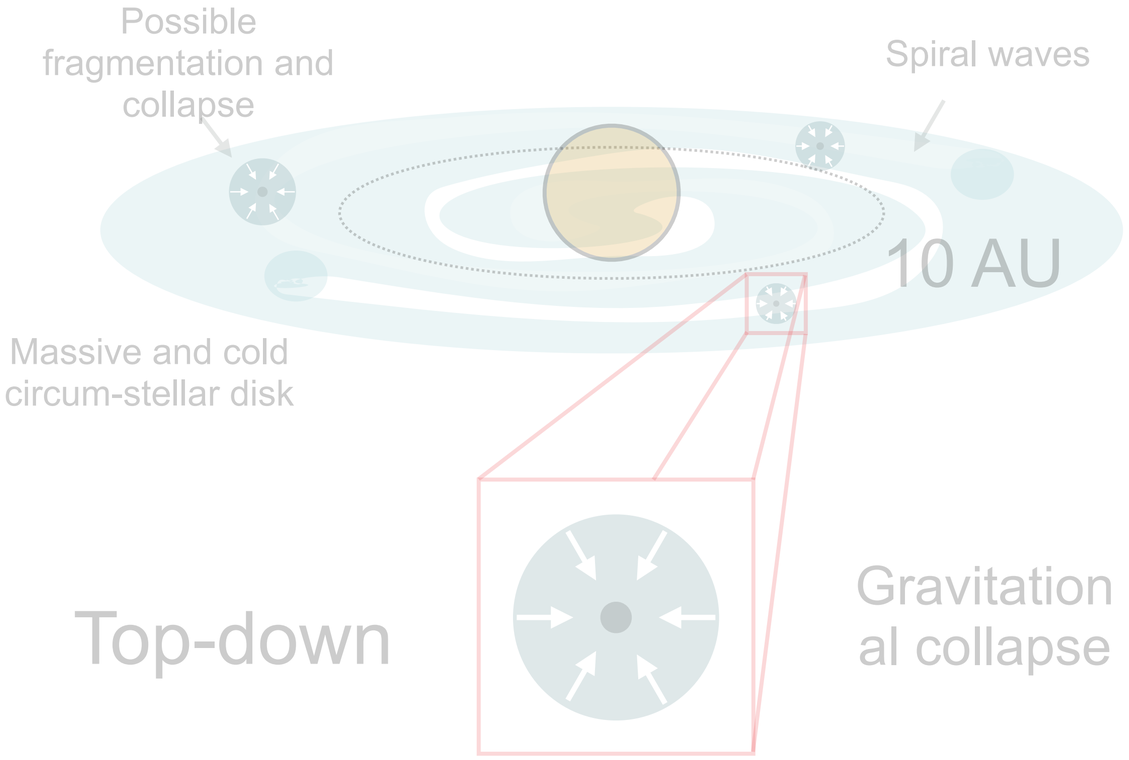


Accretion of solids + gas collapse

Bottom-up

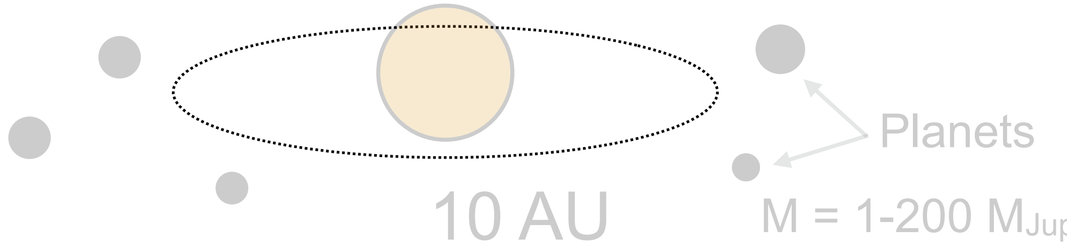


DISK INSTABILITY Boss 1997



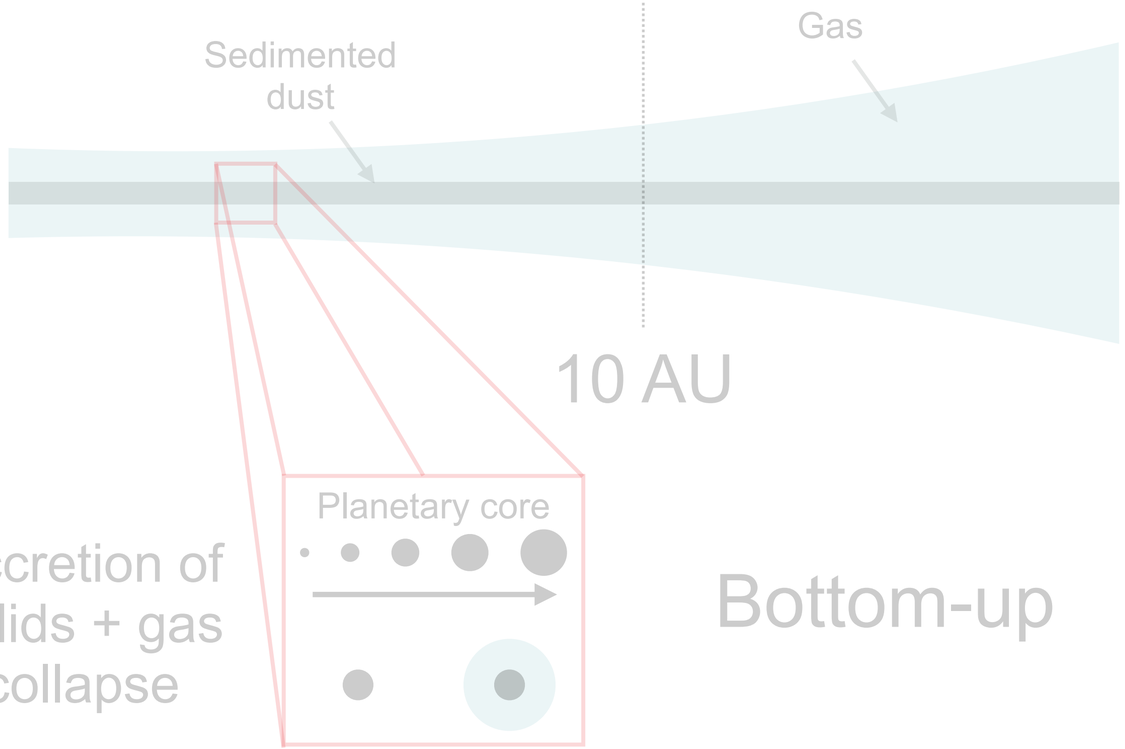
Top-down

Gravitational collapse

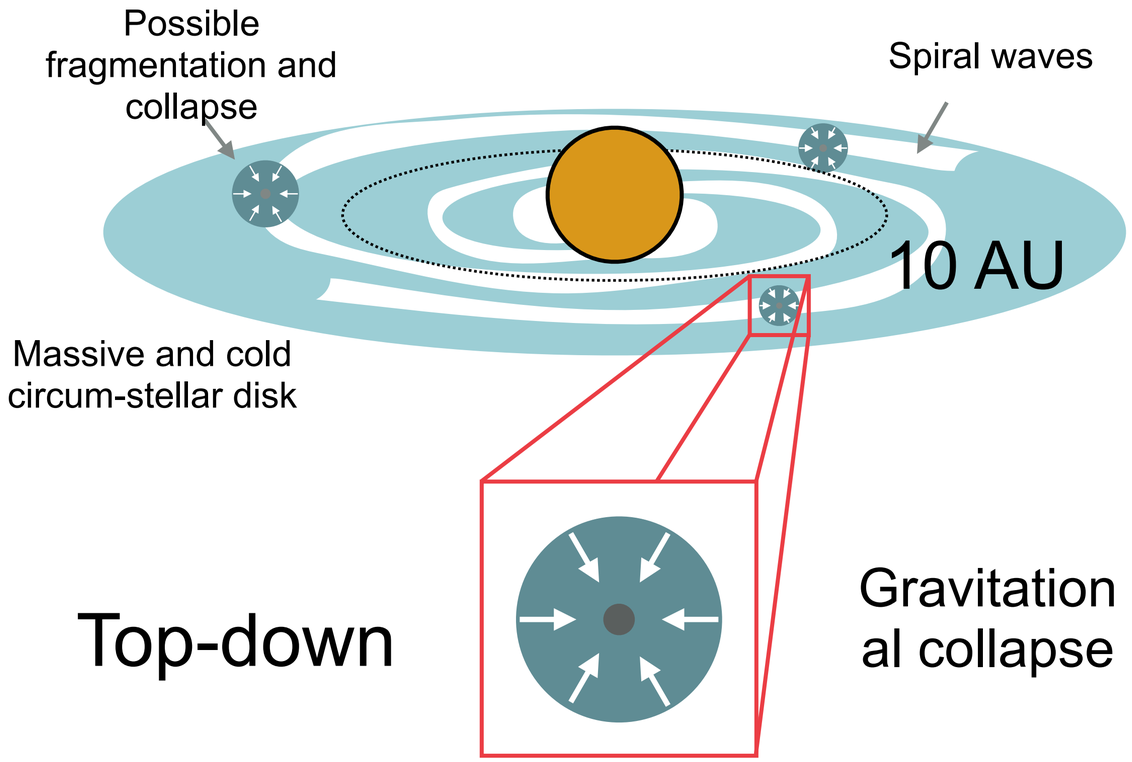


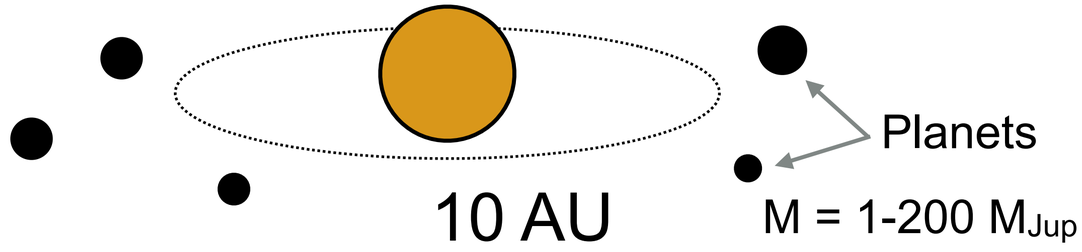
Context - *Shopping list - Models of formation*

CORE ACCRETION Pollack 1996



DISK INSTABILITY Boss 1997

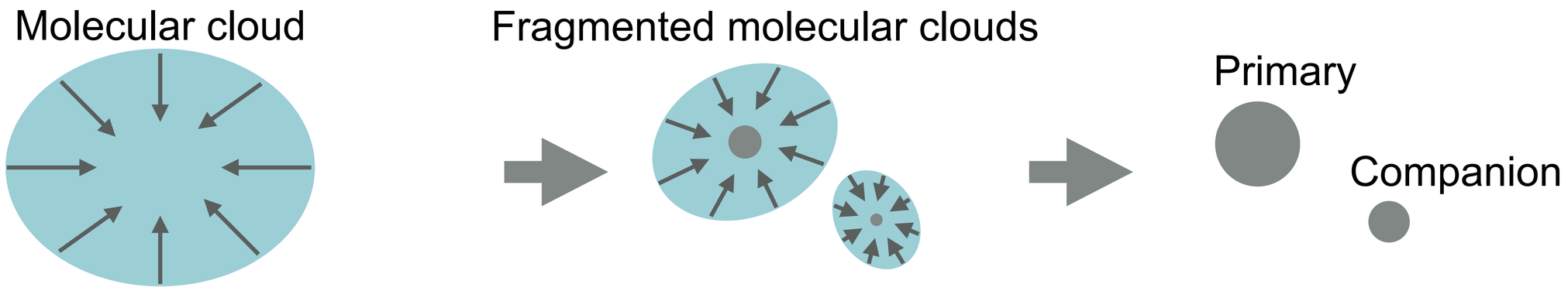


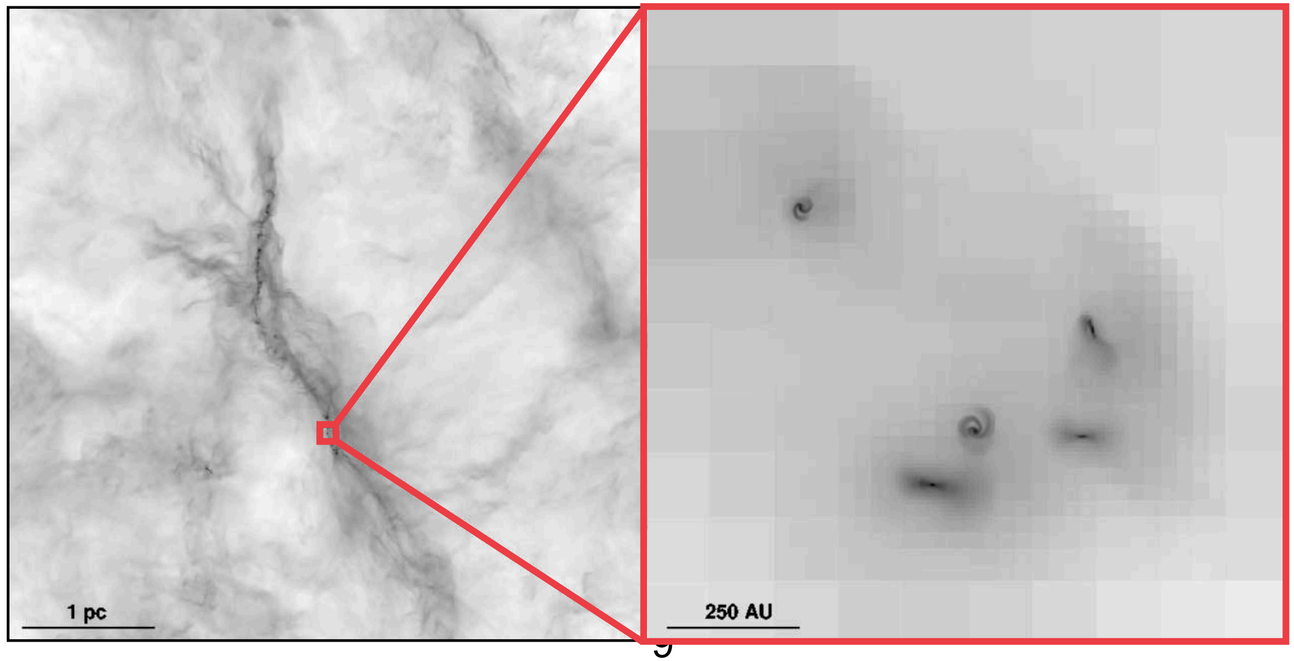


Context - *Shopping list - Models of formation*

TURBULENT FRAGMENTATION OF A MOLECULAR CLOUD

Padoan & Nordlund (2004)





Padoan & Nordlund (2005)

Models of formation ✓

Objects of interest — *Which objects can we investigate?*

Tracers of formation

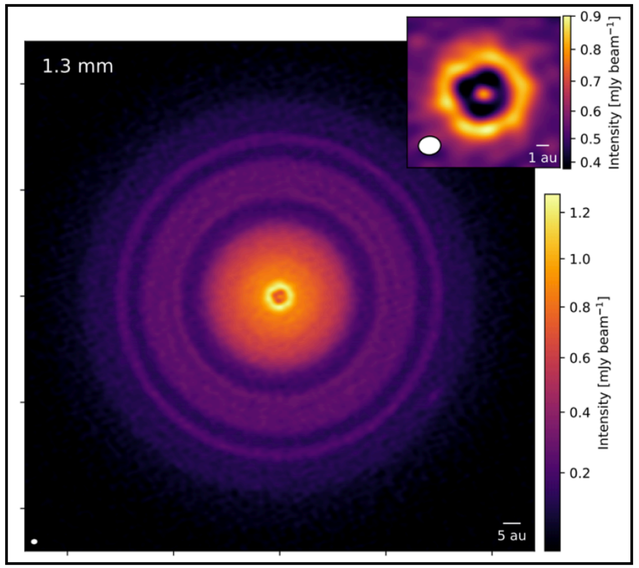
Spectral features

Data

Planet diversity

Context - *Shopping list - Fields of investigations*

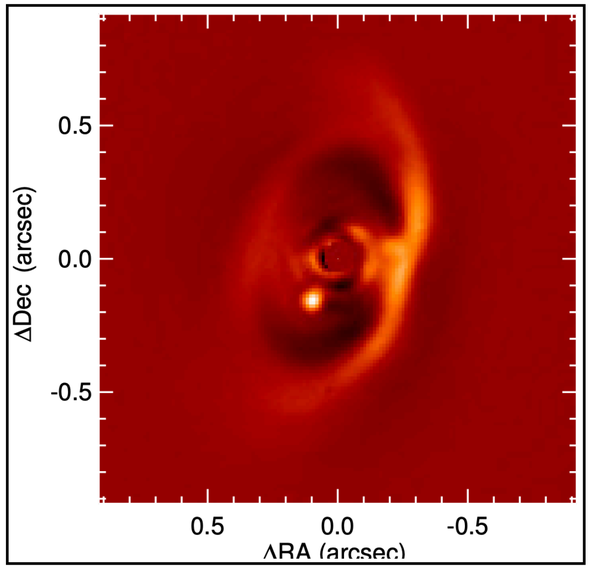
Initial conditions



ALMA - Macías et al. 2021

Disk morphology, composition & evolution (TW Hydrae)

In formation

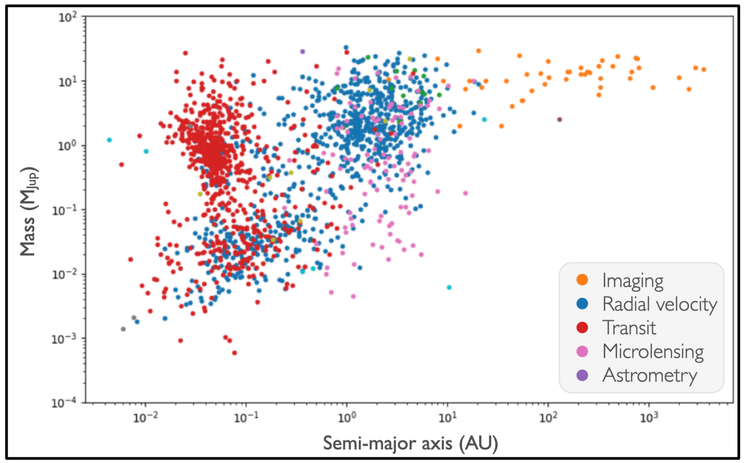


SPHERE - Muller et al. 2018

Observed planets in formation (system PDS 70)

10 Myr

Final product



Characterization of the sample of known exoplanets (architecture, orbital & mass distribution, atmosphere's properties)

The purpose of ForMoSA

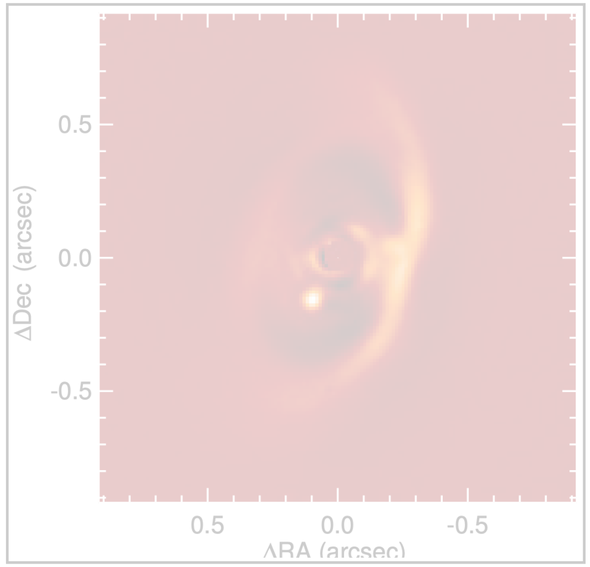
MY WORK

Initial conditions

ALMA - Macías et al. 2021

Disk morphology, composition & evolution (TW Hydrae)

In formation

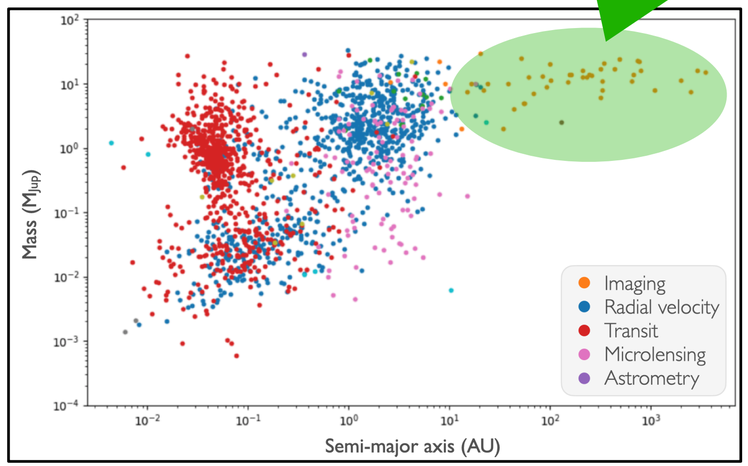


SPHERE - Muller et al. 2018

Observed planets in formation (system PDS 70)

10 Myr

Final product



Characterization of the sample of known exoplanets (architecture, orbital & mass distribution, atmosphere's properties)

Context - *Shopping list*

Models of formation ✓

Objects of interest ✓

Tracers of formation — *How can we determine the formation history?*

Spectral features

Data

Planet diversity

Context - *Shopping list - Tracers of formation*

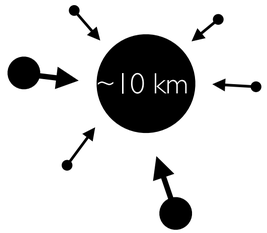
The metallicity [M/H]

TURBU. FRAG.

$[M/H]_{Primary} = [M/H]_{Companion}$

CORE ACCRETION

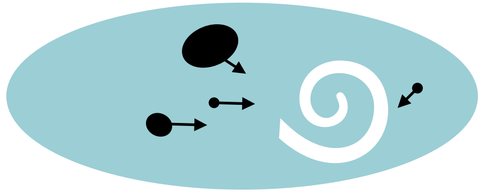
Accretion of solids



$[M/H]_{Primary} < [M/H]_{Companion}$

DISK INSTABILITY

Can accrete solids (asteroids, planetesimals)



$[M/H]_{Primary} \leq [M/H]_{Companion}$

Context - *Shopping list - Tracers of formation*

The metallicity [M/H]

Can be hard to estimate

TURBU. FRAG.

$[M/H]_{Primary} = [M/H]_{Companion}$

LIMITATIONS

Accretion of solids

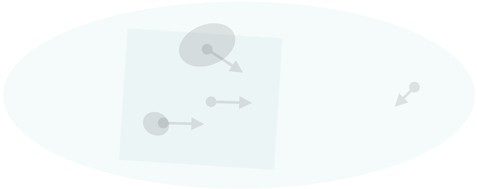
CORE ACCRETION

$[M/H]_{Primary} < [M/H]_{Companion}$

$\neq ?$

Can accrete solids (asteroids, planetesimals)

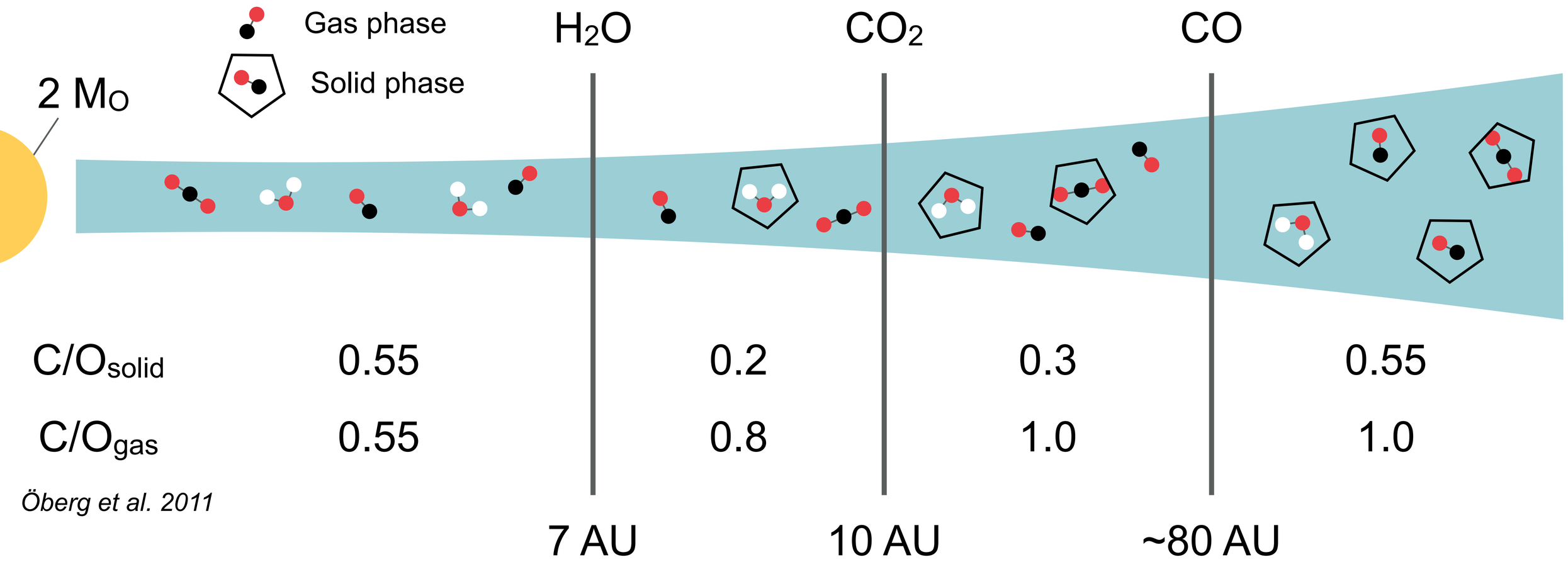
DISK INSTABILITY



$[M/H]_{Primary} \leq [M/H]_{Companion}$

Context - *Shopping list - Tracers of formation*

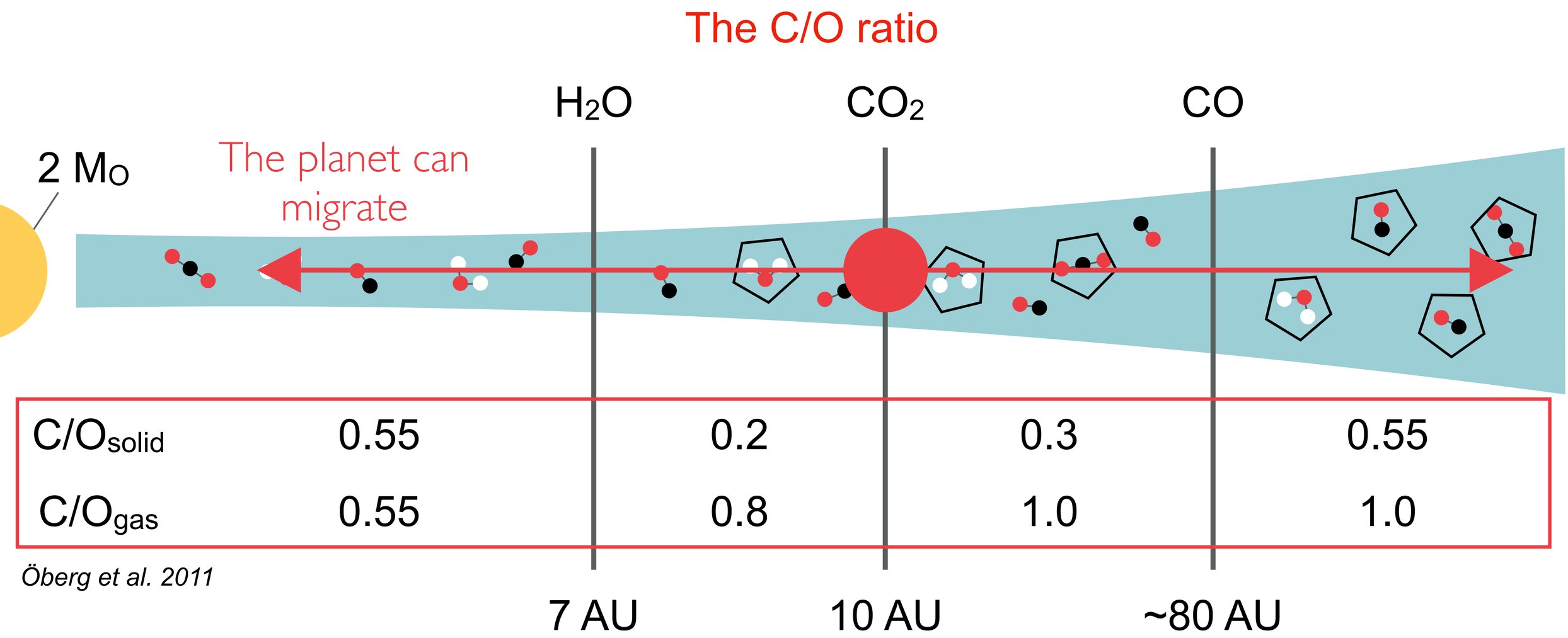
The C/O ratio



Öberg et al. 2011

Compare these values to the C/O in a planet's atmosphere can bring clues about the amount of solid accreted and its birth location

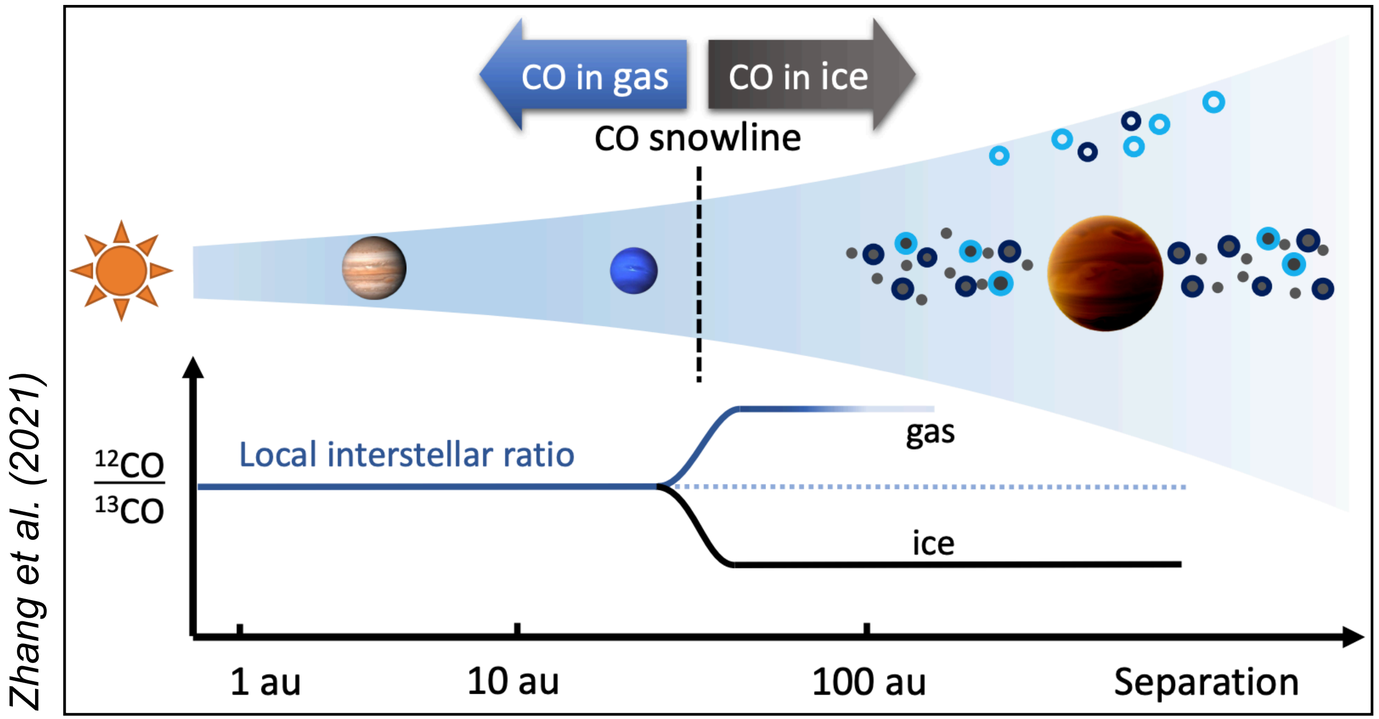
Context - *Shopping list - Tracers of formation*



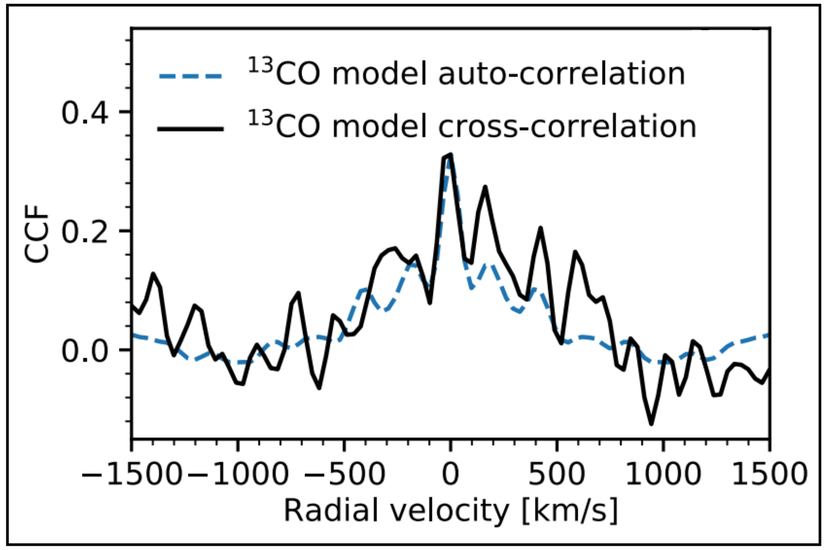
Öberg et al. 2011

LIMITATIONS

$^{12}CO/^{13}CO$



Ices are supposed to be rich in ^{13}CO



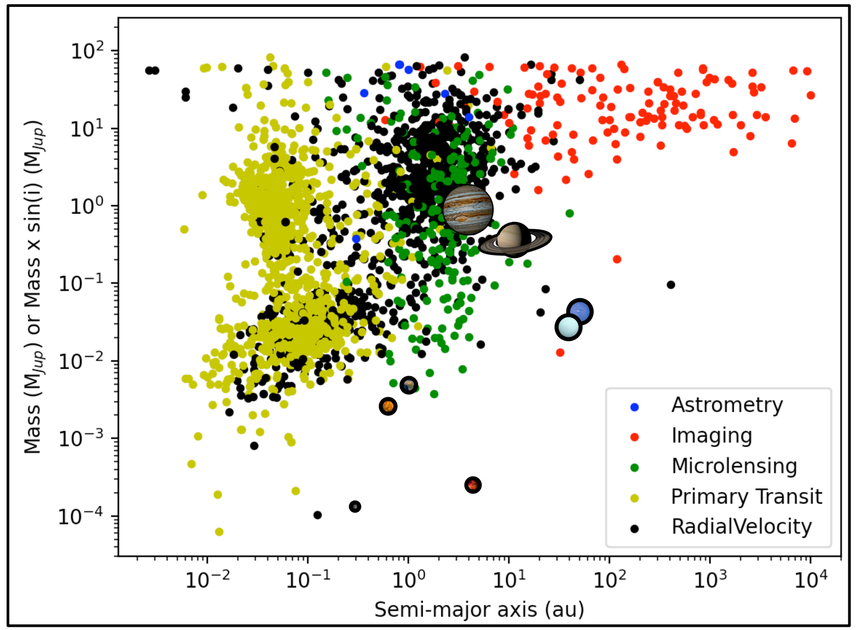
First detection of ^{13}CO in TYC 8998-760-1 b

Context - *Shopping list - Tracers of formation*

There is currently no absolute method to constrain a planet's formation history

Identification ⟶ Quantification ⟶ Comparison

NEED FOR DIVERSITY AND A HUGE SAMPLE OF PLANETARY OBJECTS



Context - *Shopping list*

Models of formation ✓

Objects of interest ✓

Tracers of formation ✓

Spectral features — *How can we estimate these properties?*

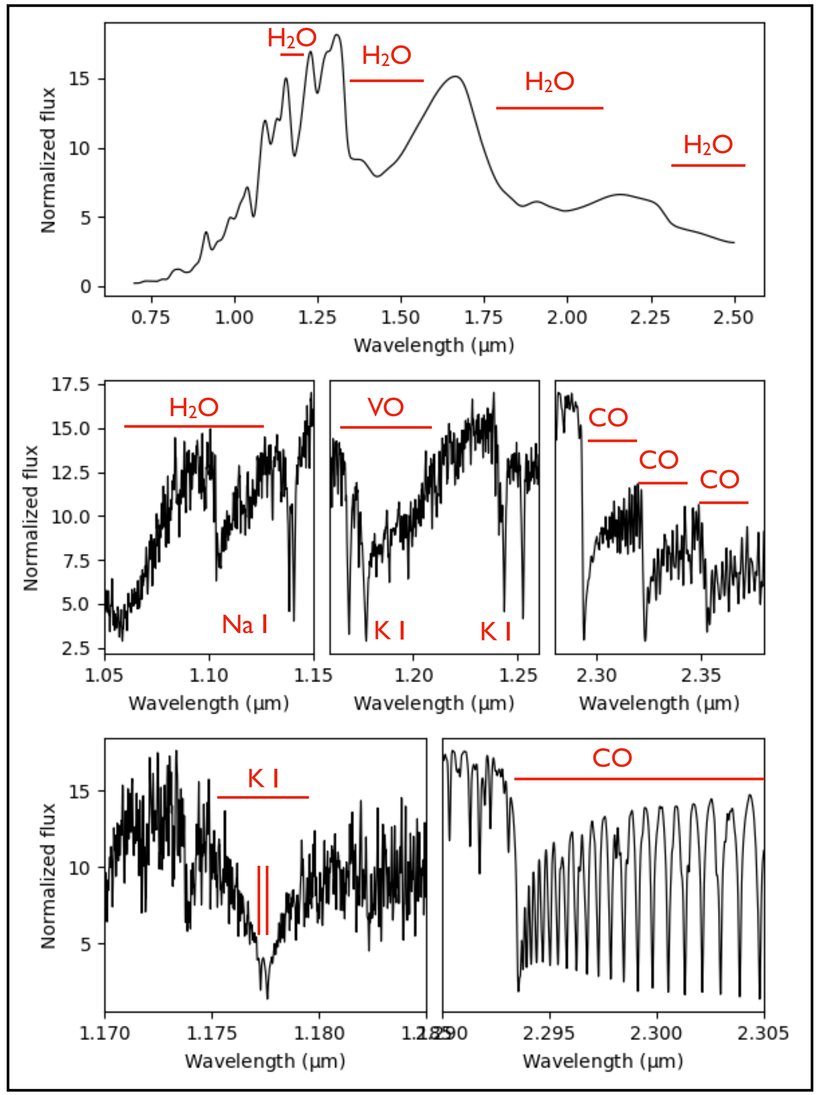
Data

Planet diversity

Context - *Shopping list - Spectral properties*

T_{eff} = 2000 K ; log(g) = 4.0 dex ; C/O = 0.6

BT-SETTL



R_λ ~ 100

Large absorption bands
(H_2O, CH_4, etc.)

→ T_{eff}, clouds properties

R_λ ~ 5000

Atomic and molecular absorptions
(Na I, K I, CO, VO, FeH, TiO, etc.)

→ Molecular abundances, RV (inaccurate)

R_λ ~ 50000

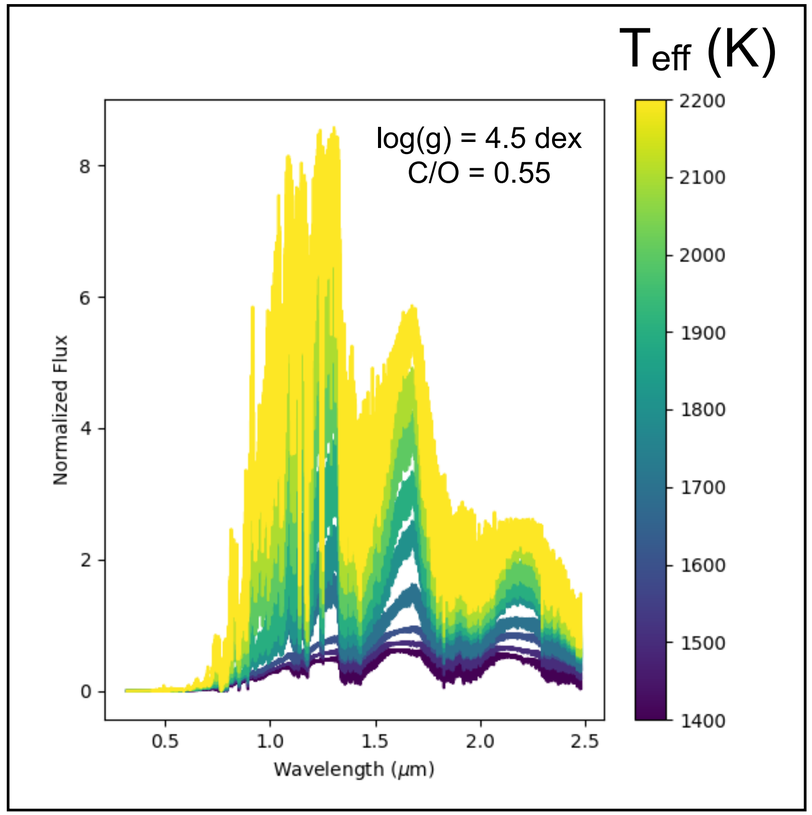
Tiny doublets resolved, line profile, comb of lines
(K I, CO, FeH, etc.)

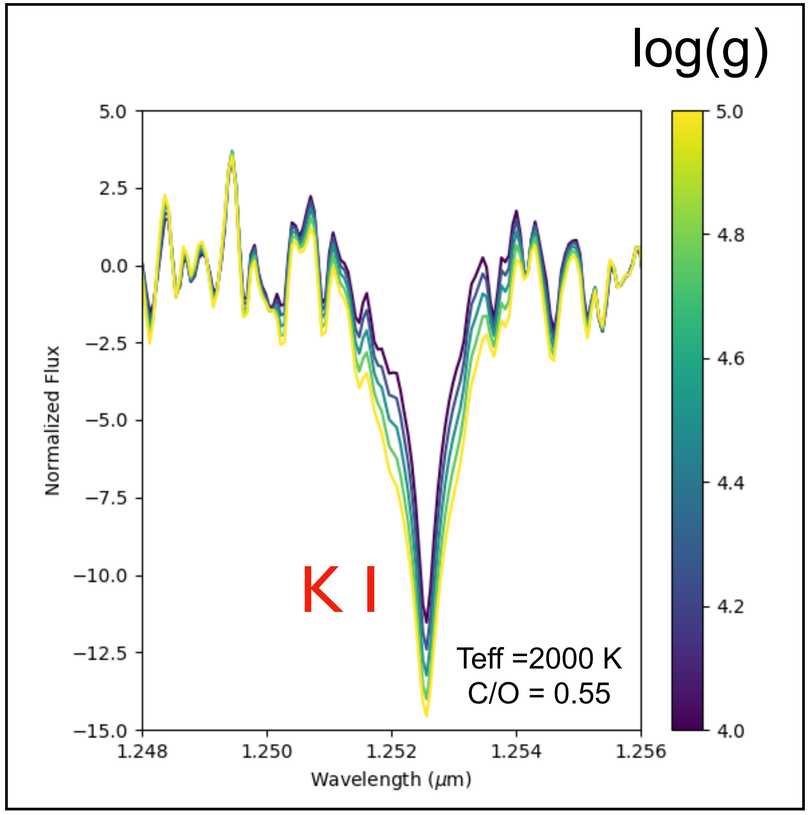
→ Accurate RV, v.sin(i), structures of the atmosphere, surface inhomogeneities (doppler imaging)

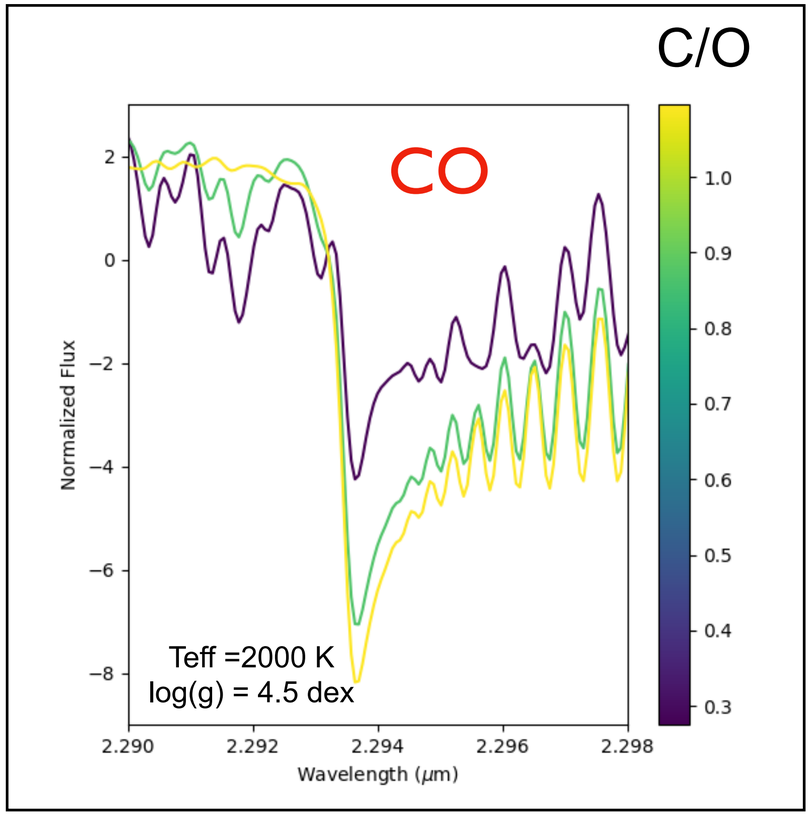
Context - *Shopping list - Spectral properties*

BT-SETTL models ($R_\lambda \sim 8000$)

Continuum subtracted







When T_{eff} increases :
Luminosity increases
Flux moves to the blue

When log(g) increases :
Absorption lines are deeper and broader (degeneracy with [M/H])

When C/O increases :
CO overtones are deeper

Context - *Shopping list*

Models of formation ✓

Objects of interest ✓

Tracers of formation ✓

Spectral features ✓

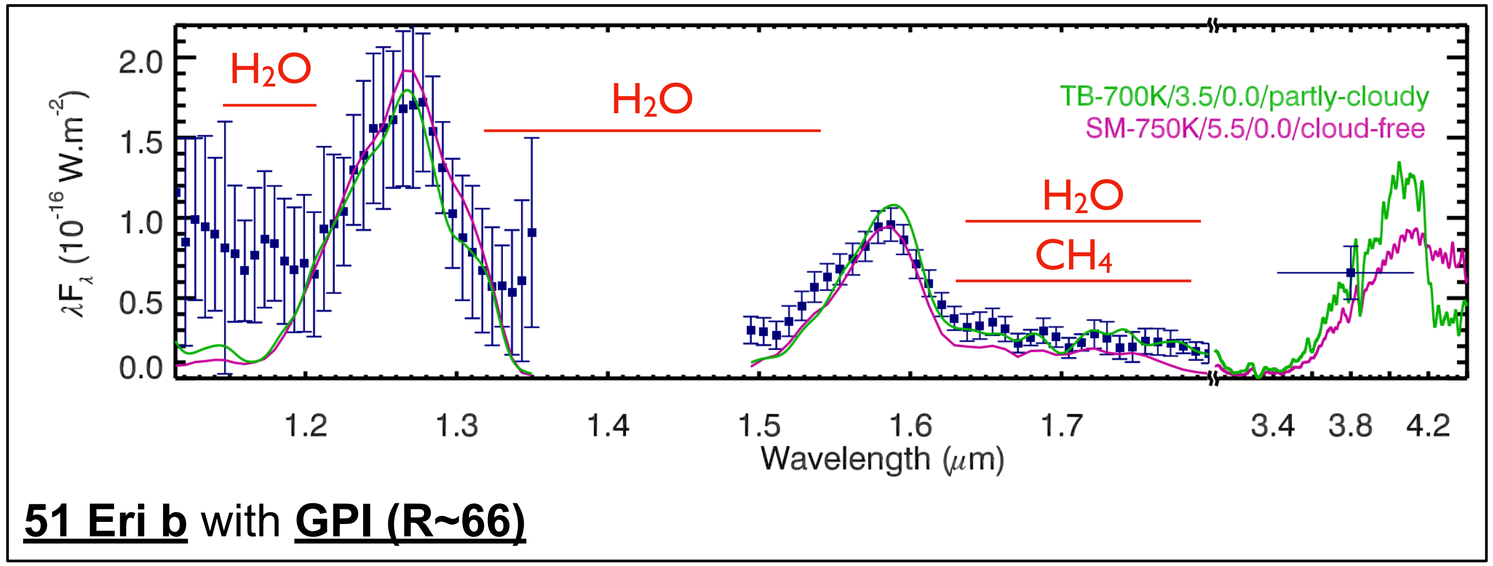
Data — *What kind of data can we acquire?*

Planet diversity

Context - *Spectroscopic data*

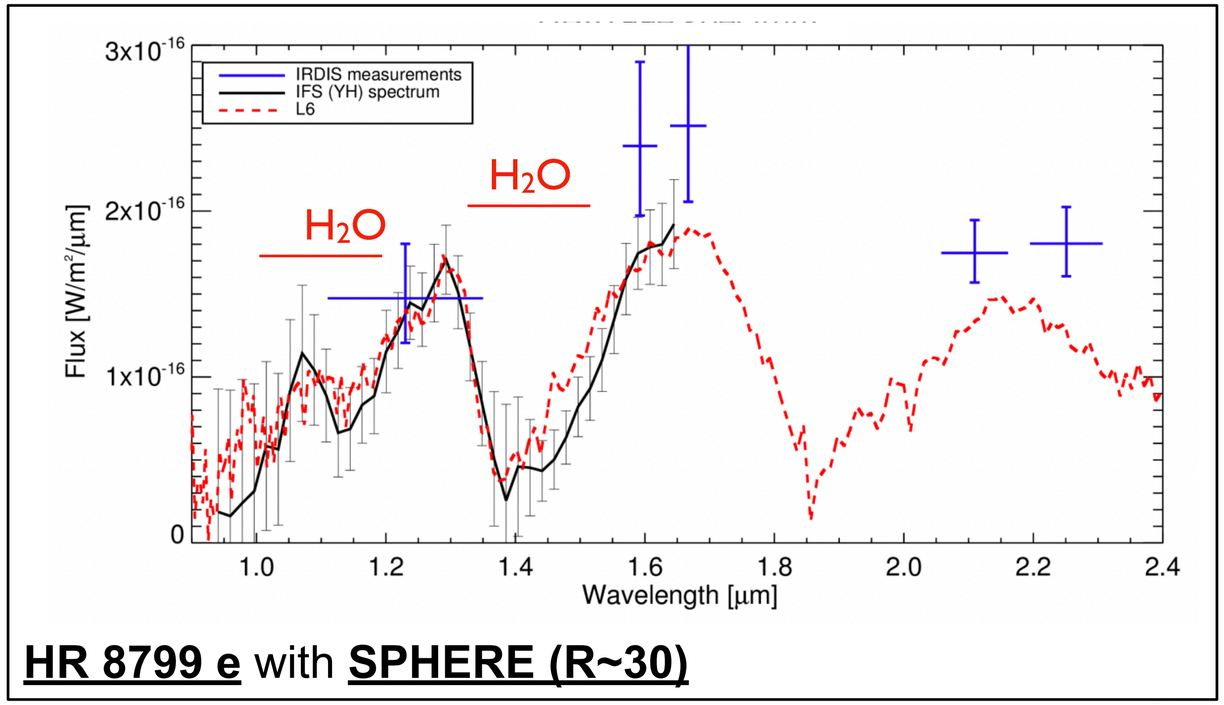
R_λ small
$\Delta\lambda$ wide

Macintosh et al. (2015)



51 Eri b with **GPI (R~66)**

Zurlo et al. (2016)



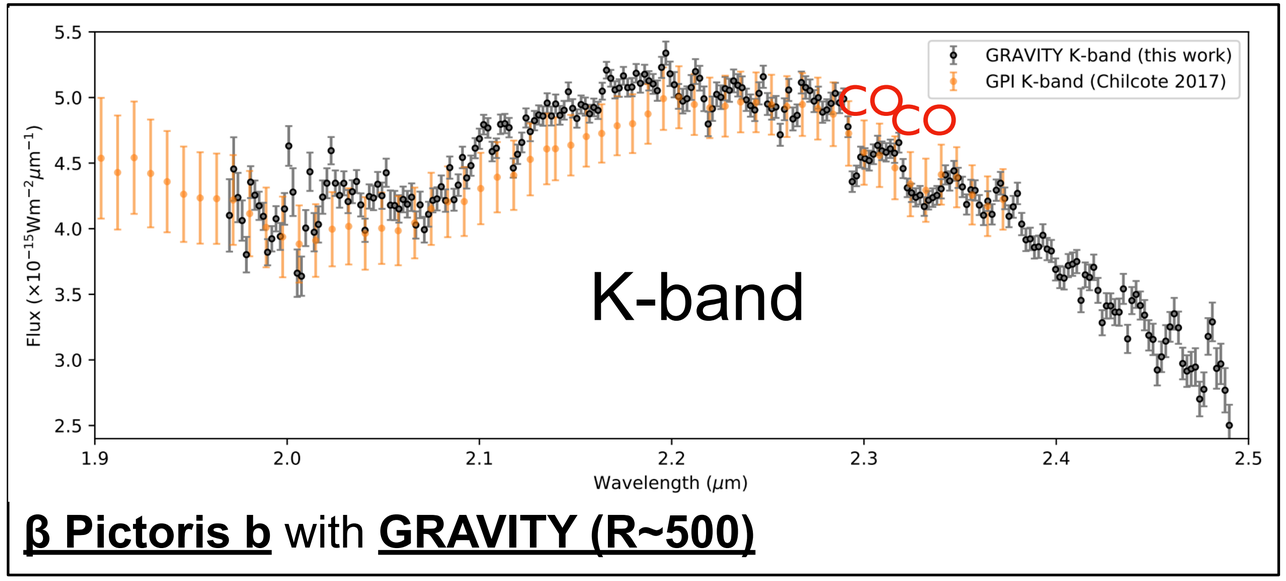
HR 8799 e with **SPHERE (R~30)**

Large absorption bands (H_2O, CH_4)

→ T_{eff}, clouds properties

Context - *Spectroscopic data*

Gravity Collaboration et al. (2019)



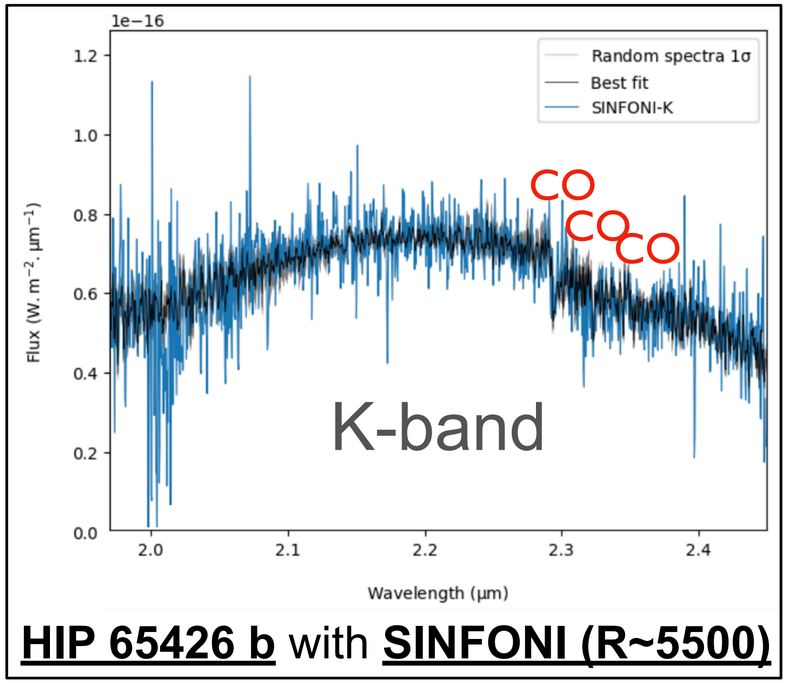
β Pictoris b with **GRAVITY (R~500)**

R_λ med
$\Delta\lambda$ med

Atomic and molecular absorptions (Na I, K I, CO, VO, FeH, TiO, etc.)

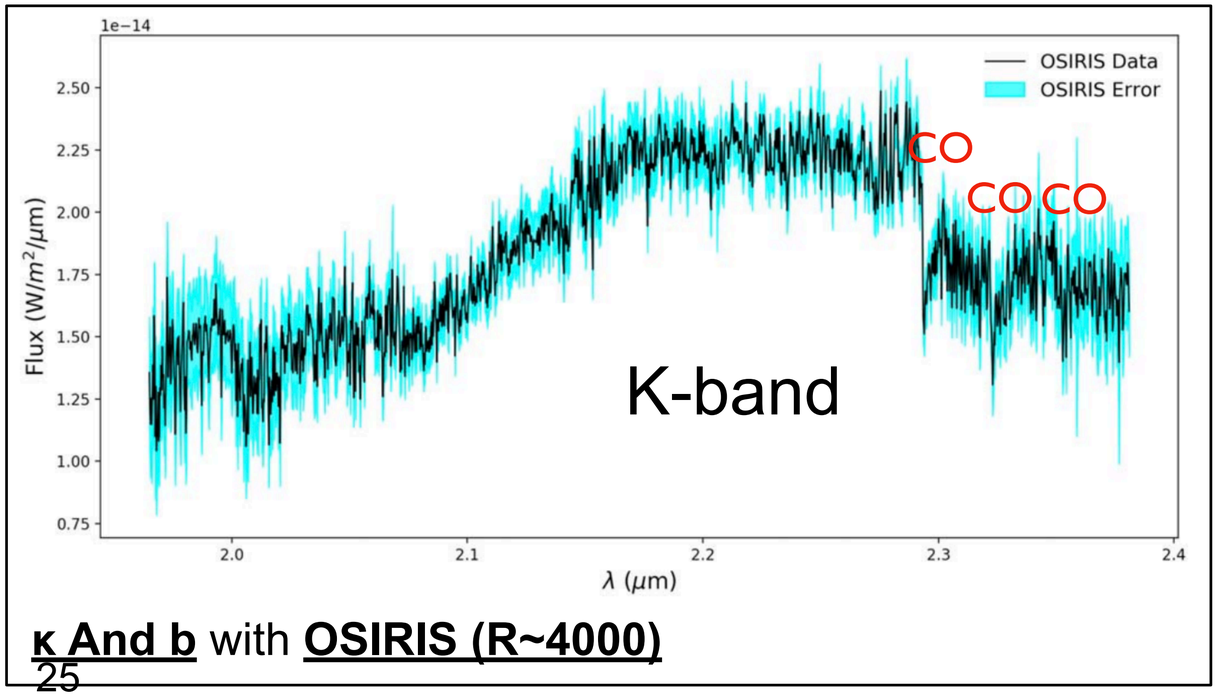
→ Molecular abundances, RV (inaccurate)

Petrus et al. (2021)



HIP 65426 b with **SINFONI (R~5500)**

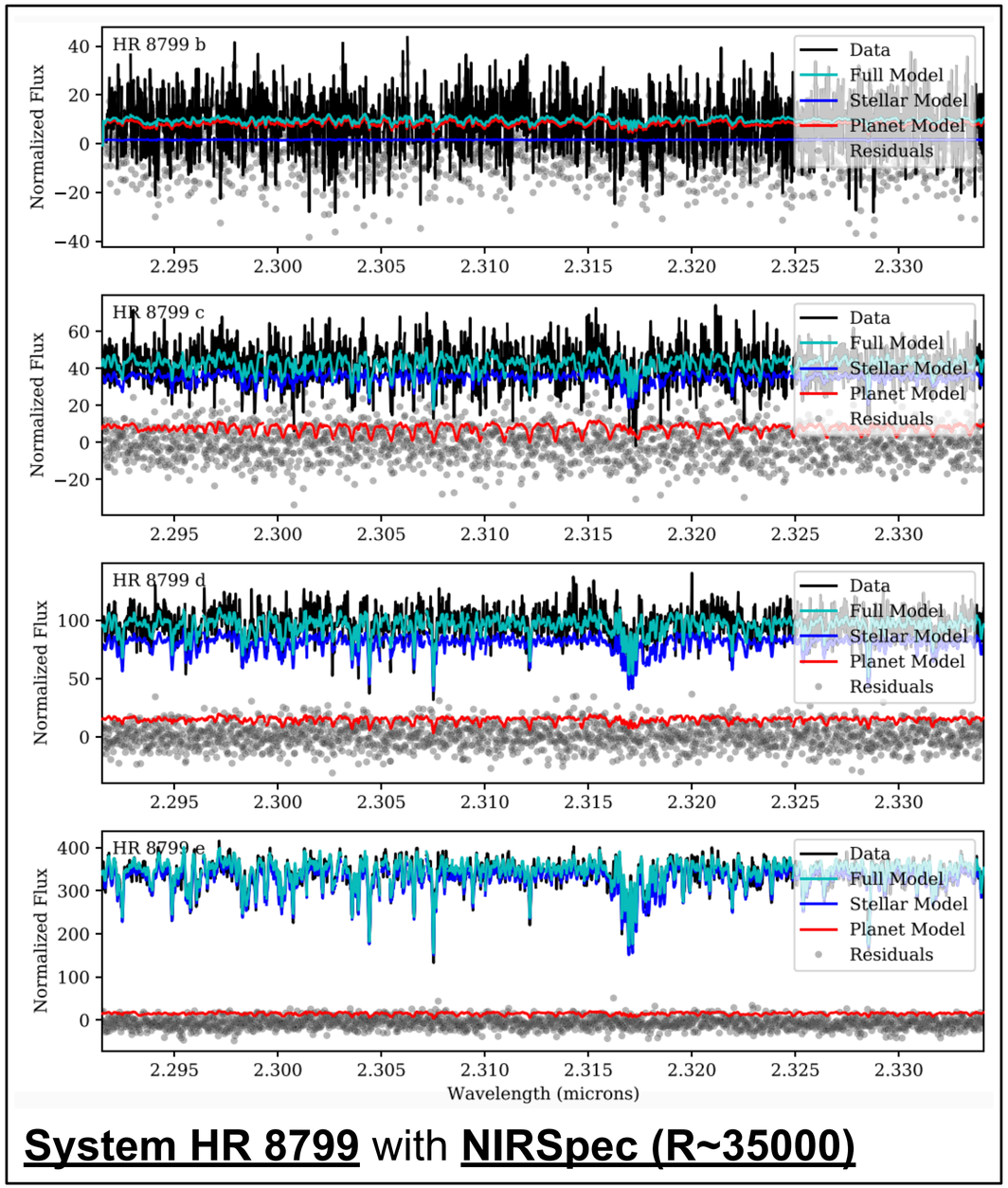
Wilcomb et al. (2020)



κ And b with **OSIRIS (R~4000)**

Context - *Spectroscopic data*

R_λ high
$\Delta\lambda$ small



Wang et al. (2021a)

System HR 8799 with **NIRSpec (R~35000)**

Tiny doublets resolved, line profile, comb of lines
(K I, CO, FeH, etc.)

→ Acurate RV, v.sin(i), structures of the atmosphere, surface inhomogeneities (doppler imaging)

Context - *Shopping list*

Models of formation ✓

Objects of interest ✓

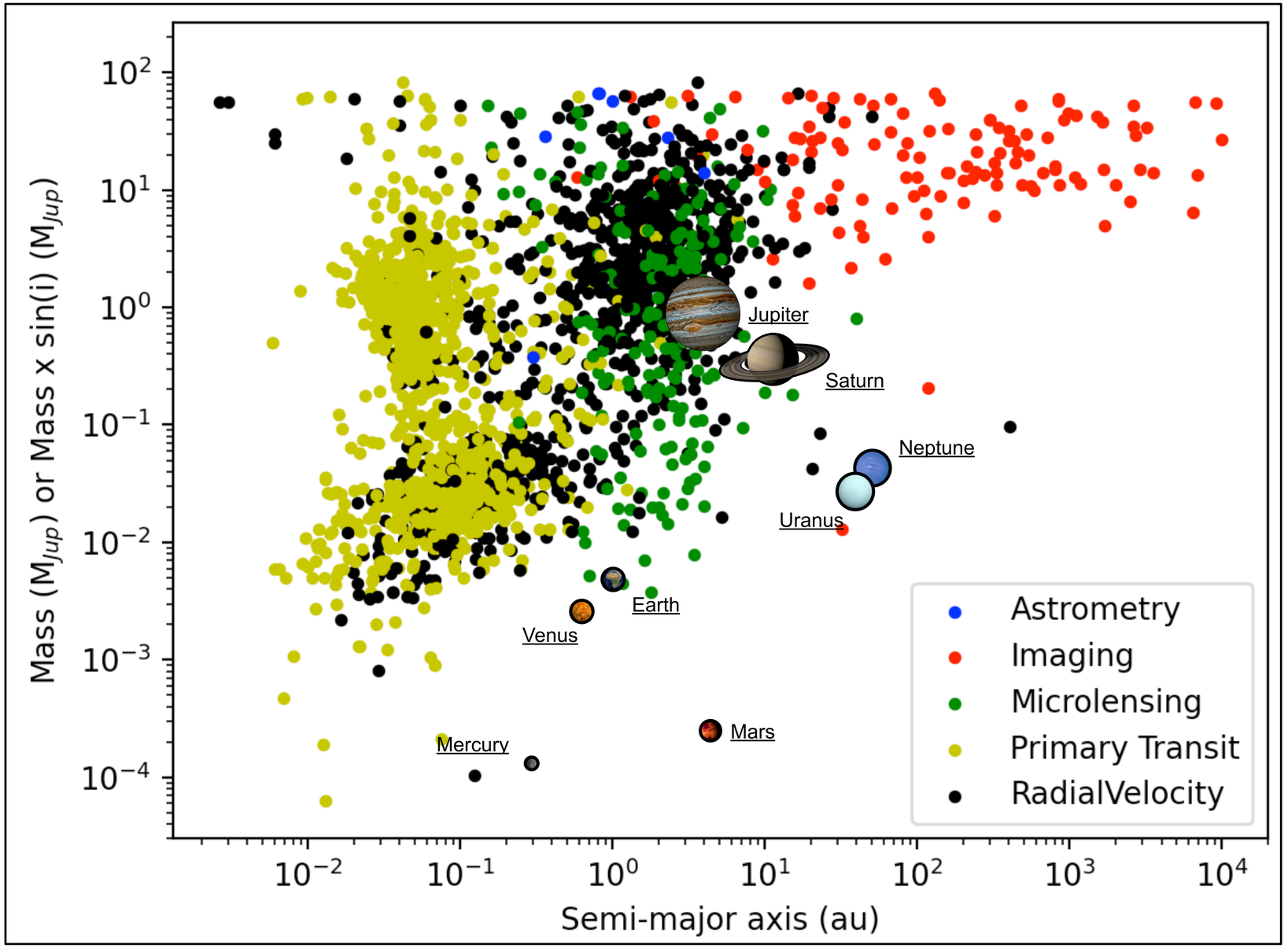
Tracers of formation ✓

Spectral features ✓

Data ✓

Planet diversity — *Are we able to perform object comparison?*

Context - *Shopping list - Planets analogs*

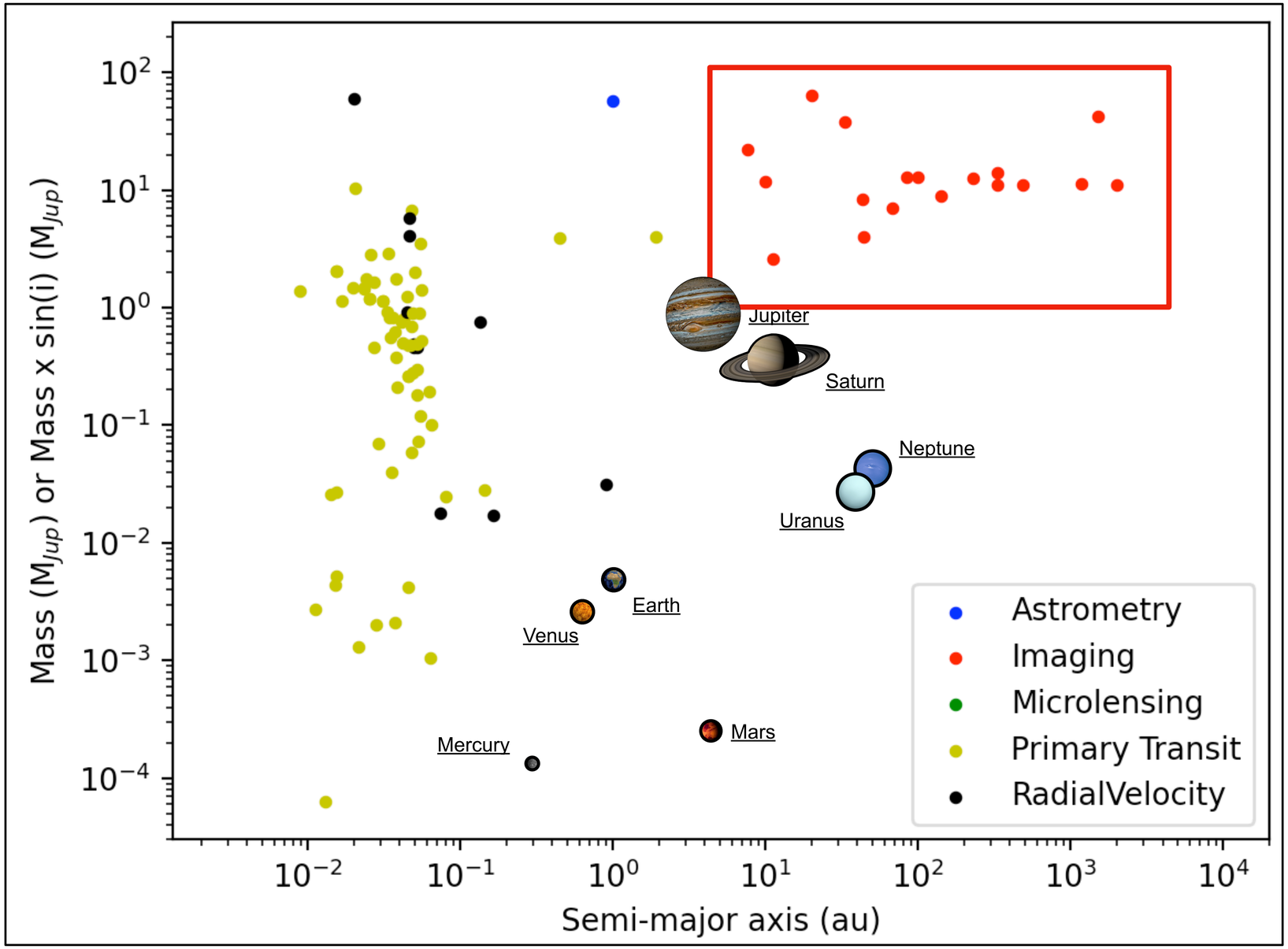


exoplanet.eu/

>5000

exoplanets
discovered so far

Context - *Shopping list - Planets analogs*

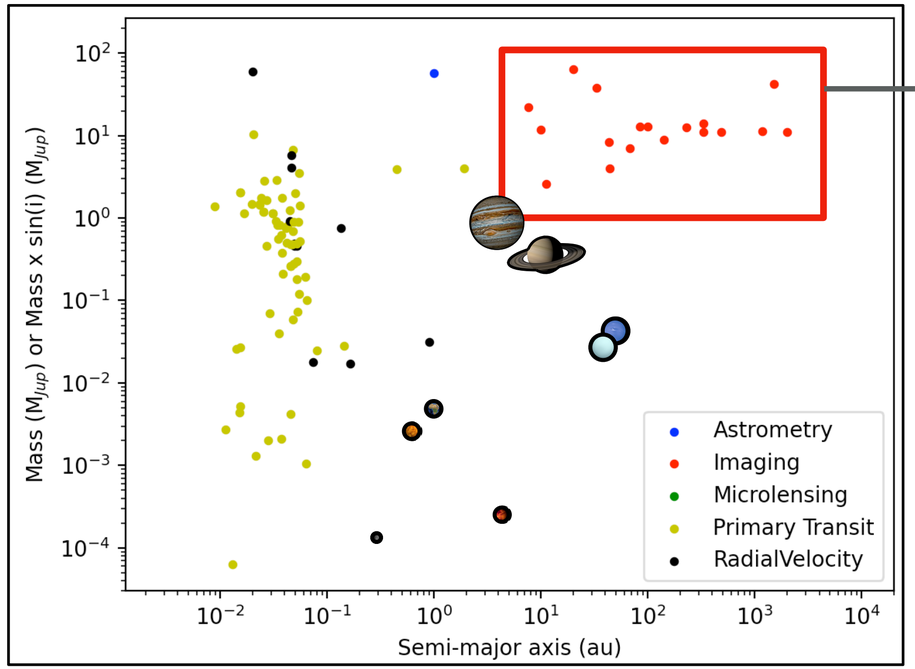


exoplanet.eu/

< 30

imaged exoplanets
with spectral data

Context - *Shopping list - Planets analogs*



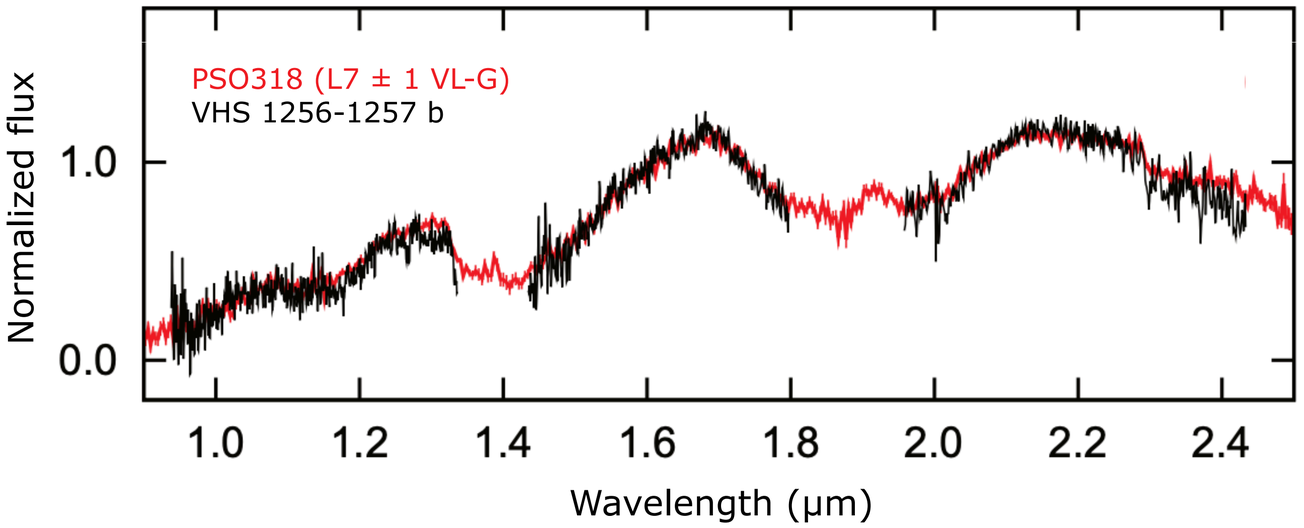
Not sufficient to constrain models…

… OF FORMATION

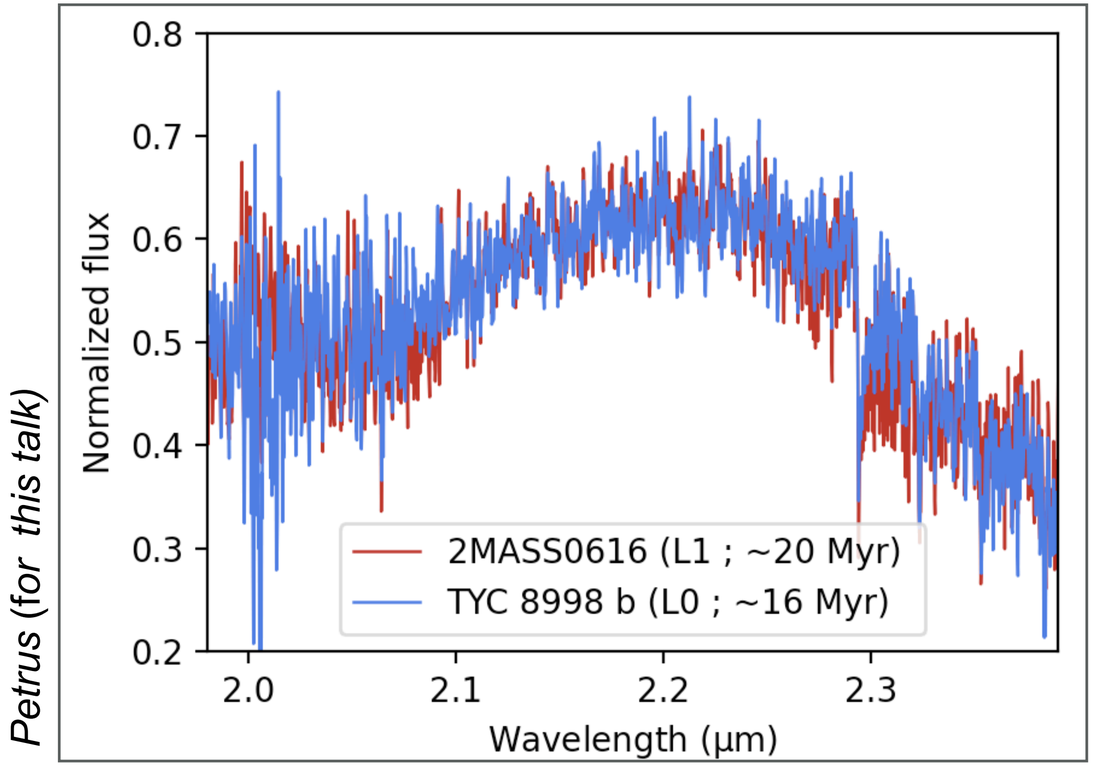
… OF EVOLUTION

… OF ATMOSPHERE

Context - *Shopping list - Planets analogs*



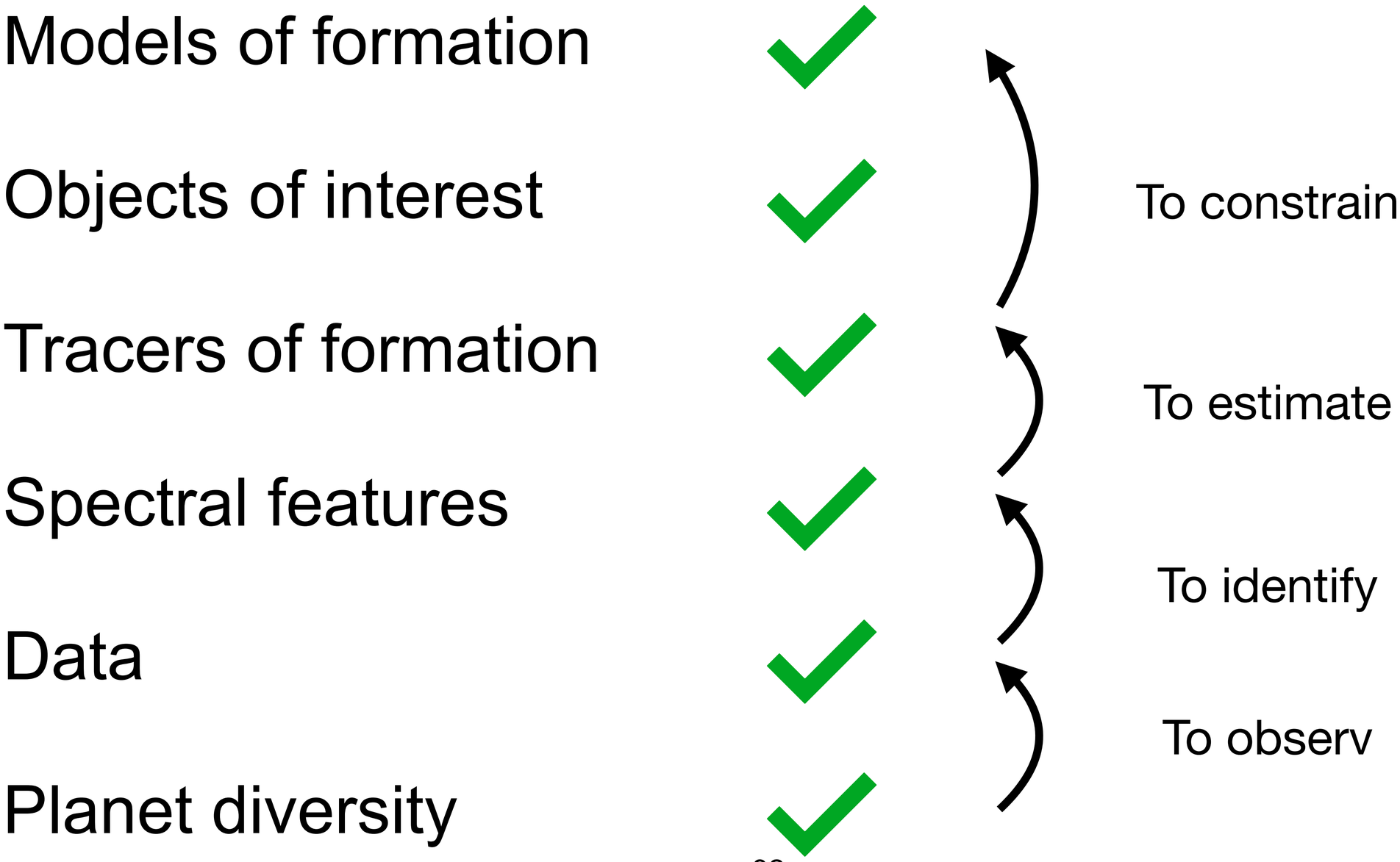
Gauza et al. (2015)



It exists a population of **young**, **planetary-mass** objects, **isolated (large separation)** in the sky, that have **similar spectral properties** than exoplanets

PLANETARY ANALOGS

Context - *Shopping list*

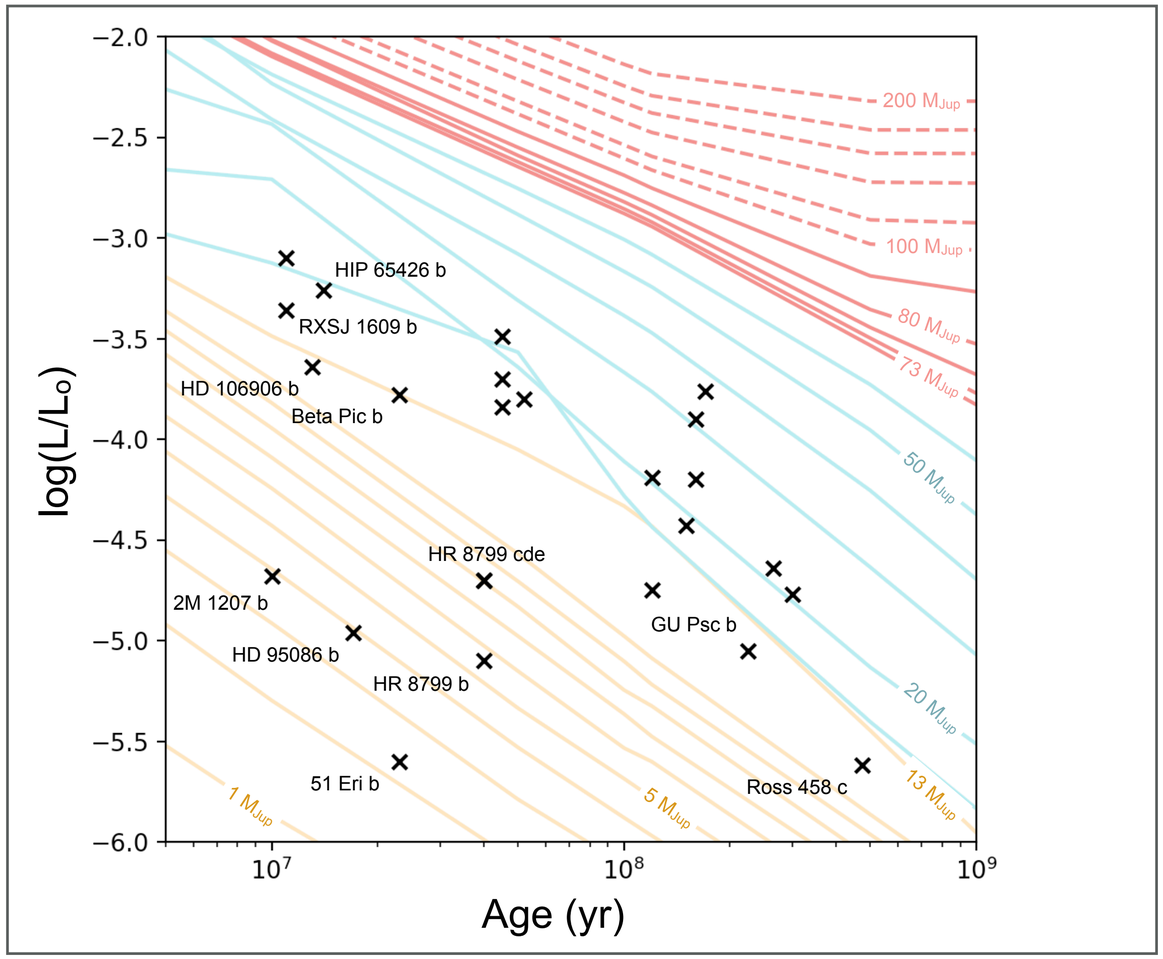


Part 2

The X-Shyne library

Petrus et al. (2023/24/25)
IN PREP

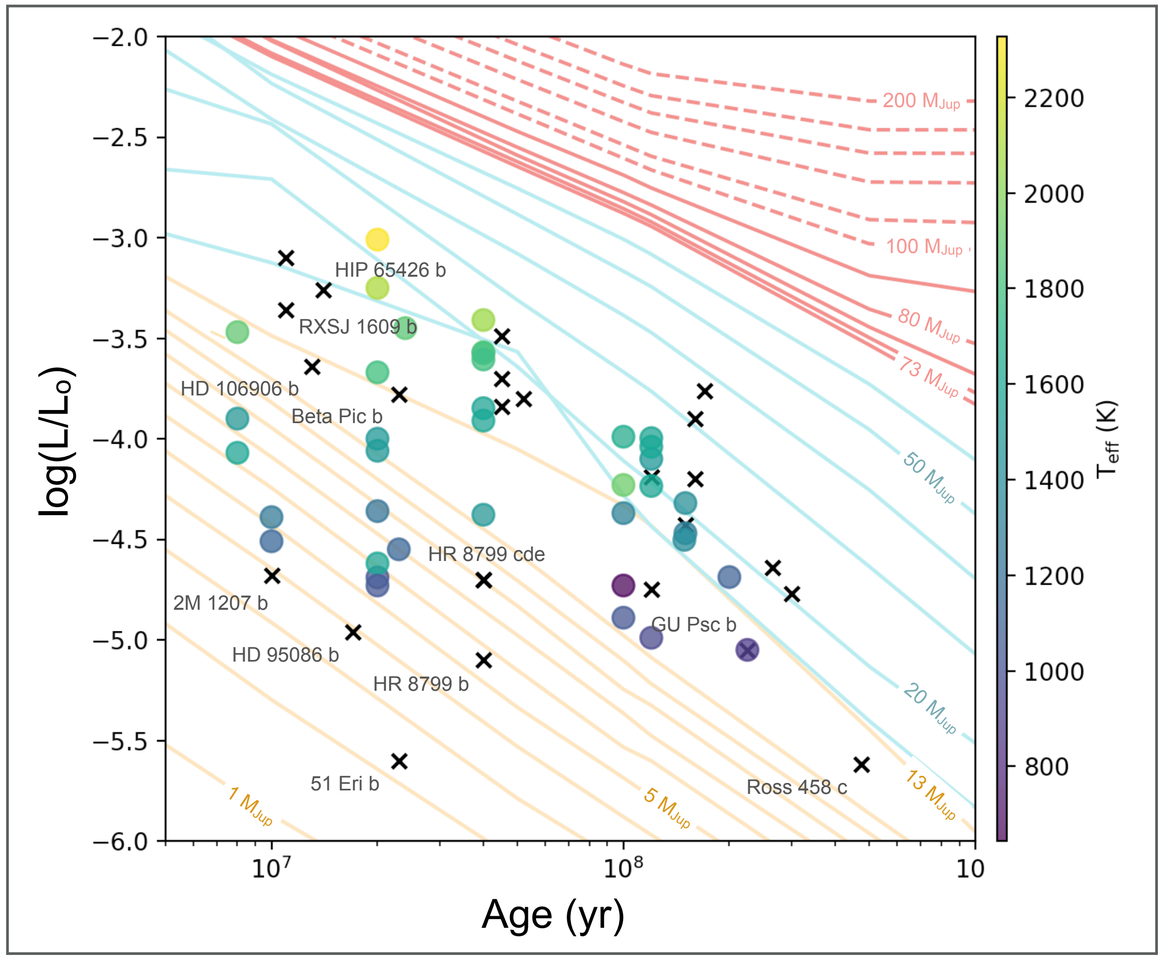
Part 2 - The X-Shyne library



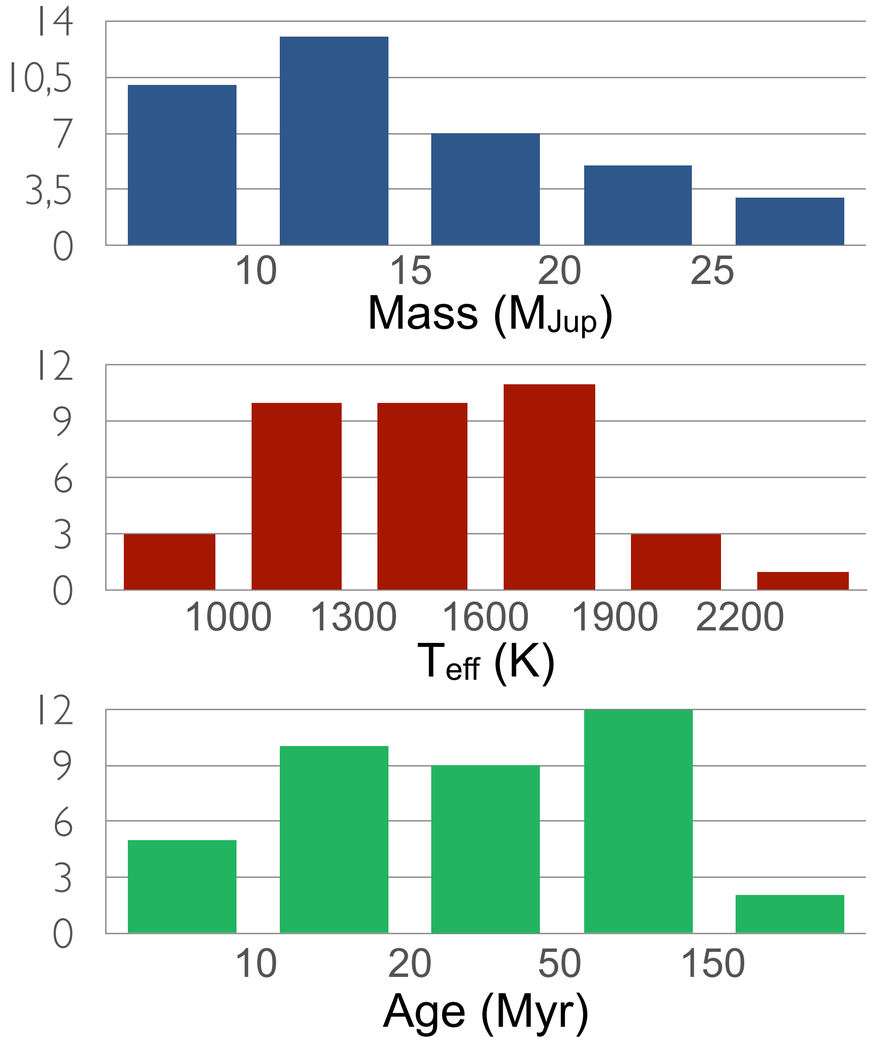
Part 2 - The X-Shyne library

XShooter
λ = 0.6μm – 2.5μm
R ~ 8000

38 young objects

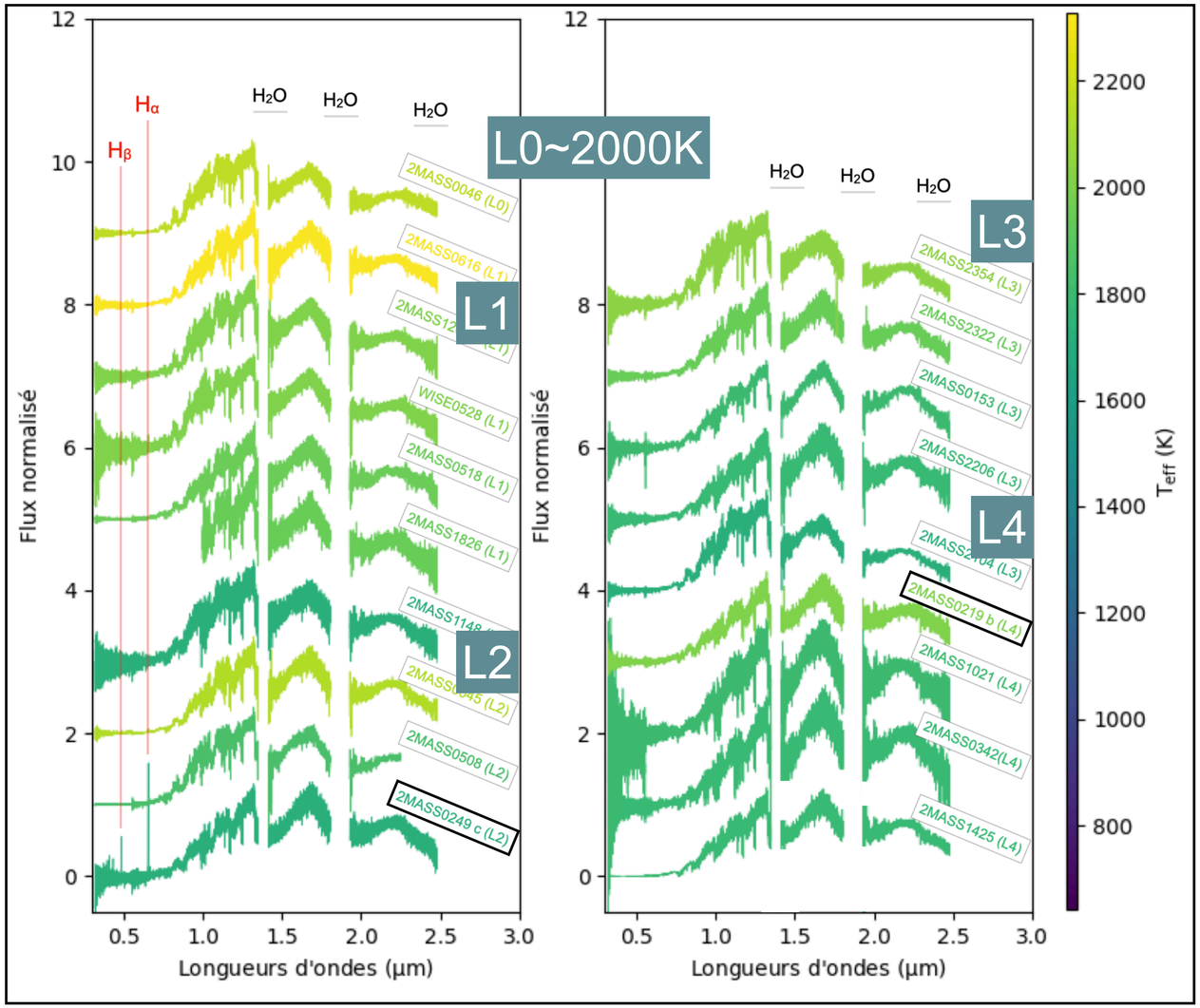


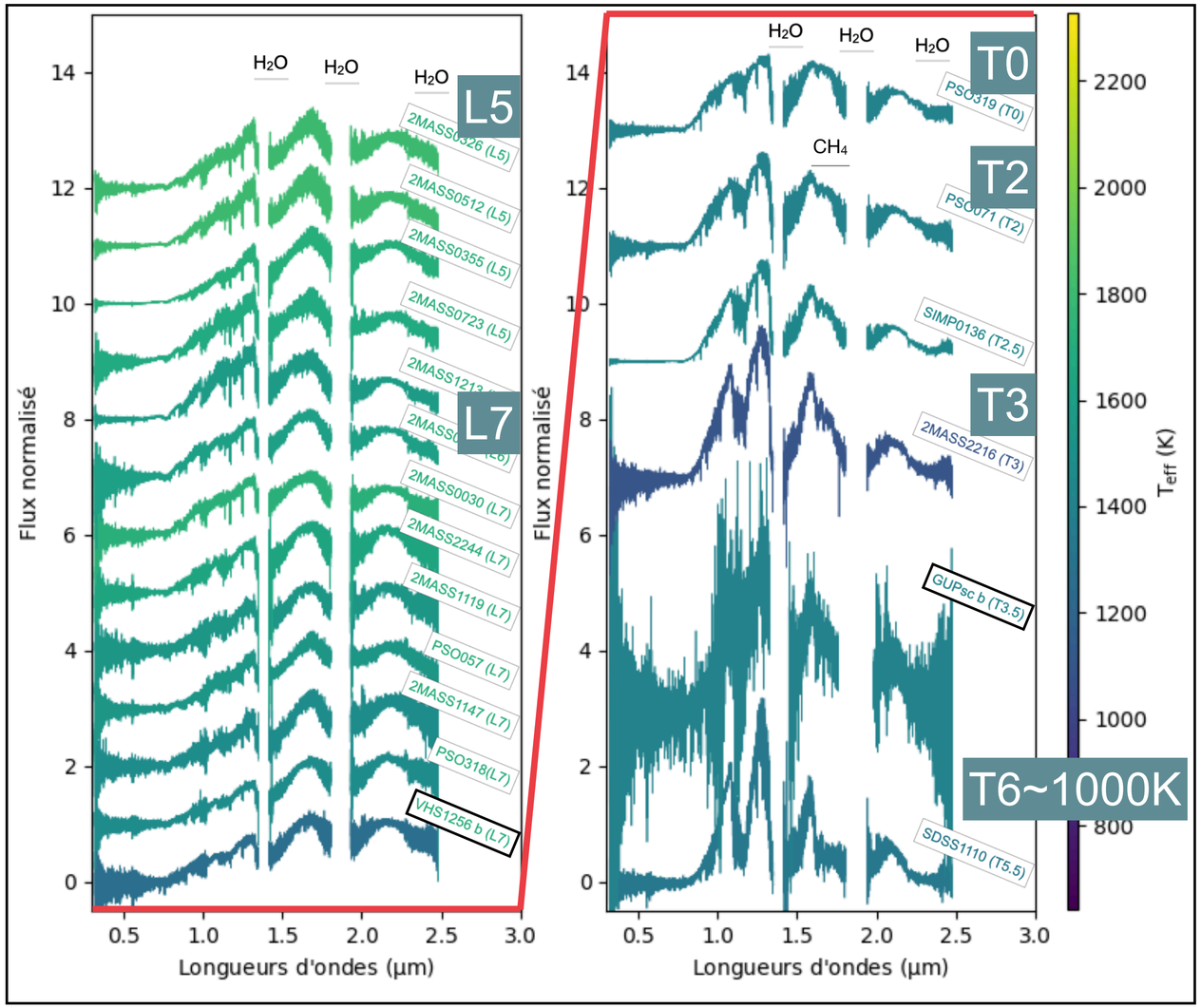
Unique library at this spectral resolution



Part 2 - The X-Shyne library

Spectra obtained in one shot with few hours of telescope time



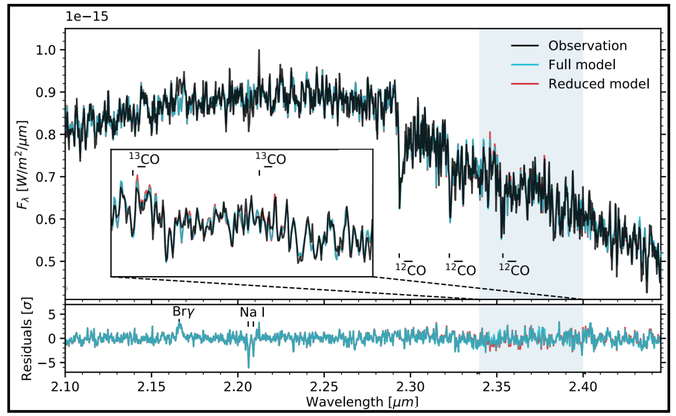


Companions (large separation)

L-T transition

Cloud cover sediments and breaks-up

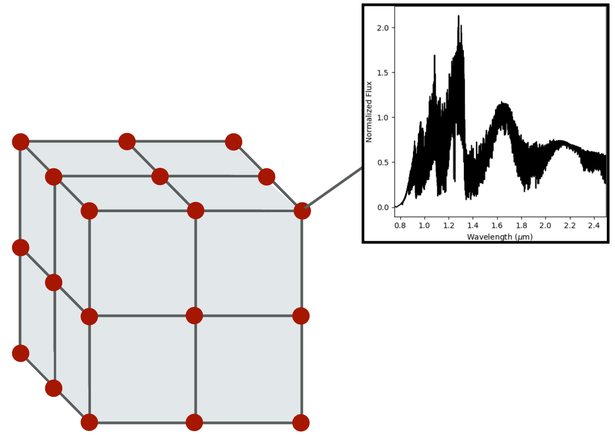
Part 2 - The X-Shyne library



OBSERVED SPECTRA

Bayesian algorithm
(Nested sampling)

FORMOSA



GRIDS OF SYNTHETIC SPECTRA

SYNTHETIC ANALYSIS

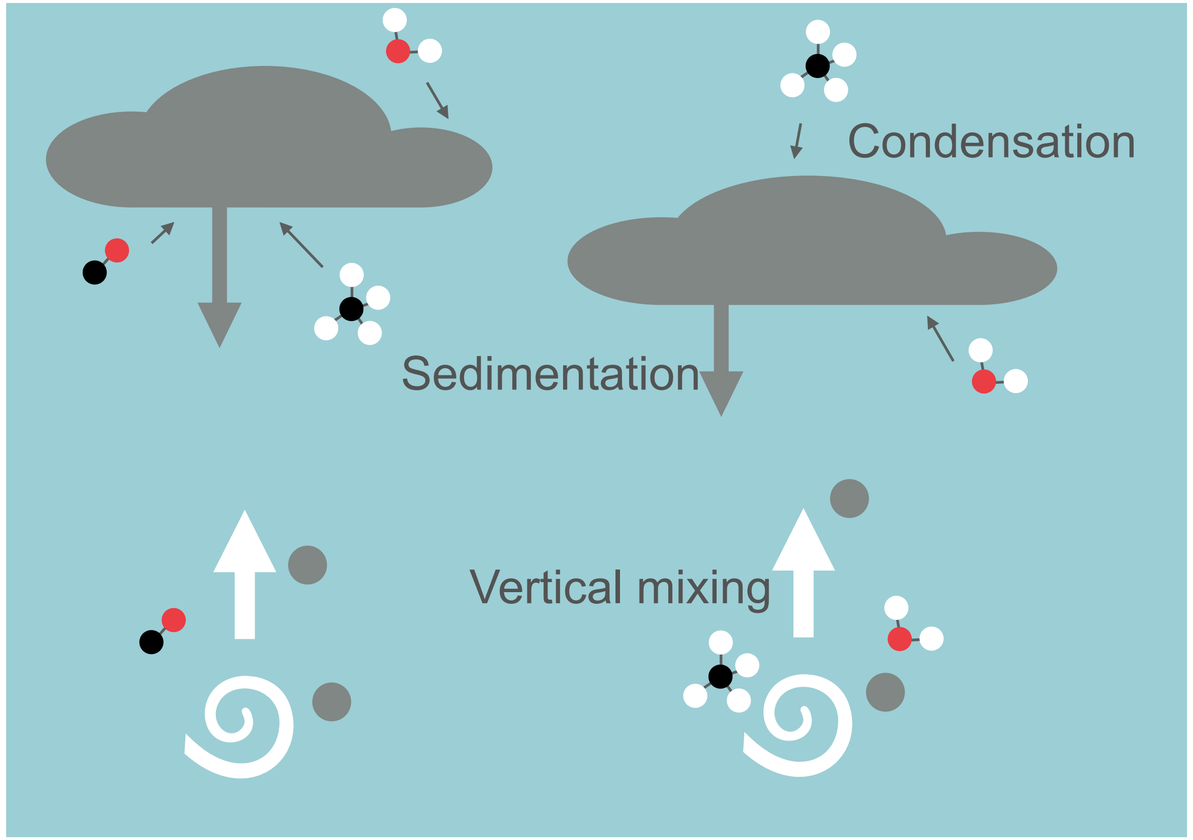
Atmospheric properties

T_{eff} log(g) C/O [M/H]

python

What kind of models?

Cloudy models



DRIFT PHOENIX Helling et al. (2008)

Tsuji et al. (2002)

BT-Settl Allard et al. (2012)

Ackerman & Marley (2001)

Exo-REM Charnay et al. (2018)

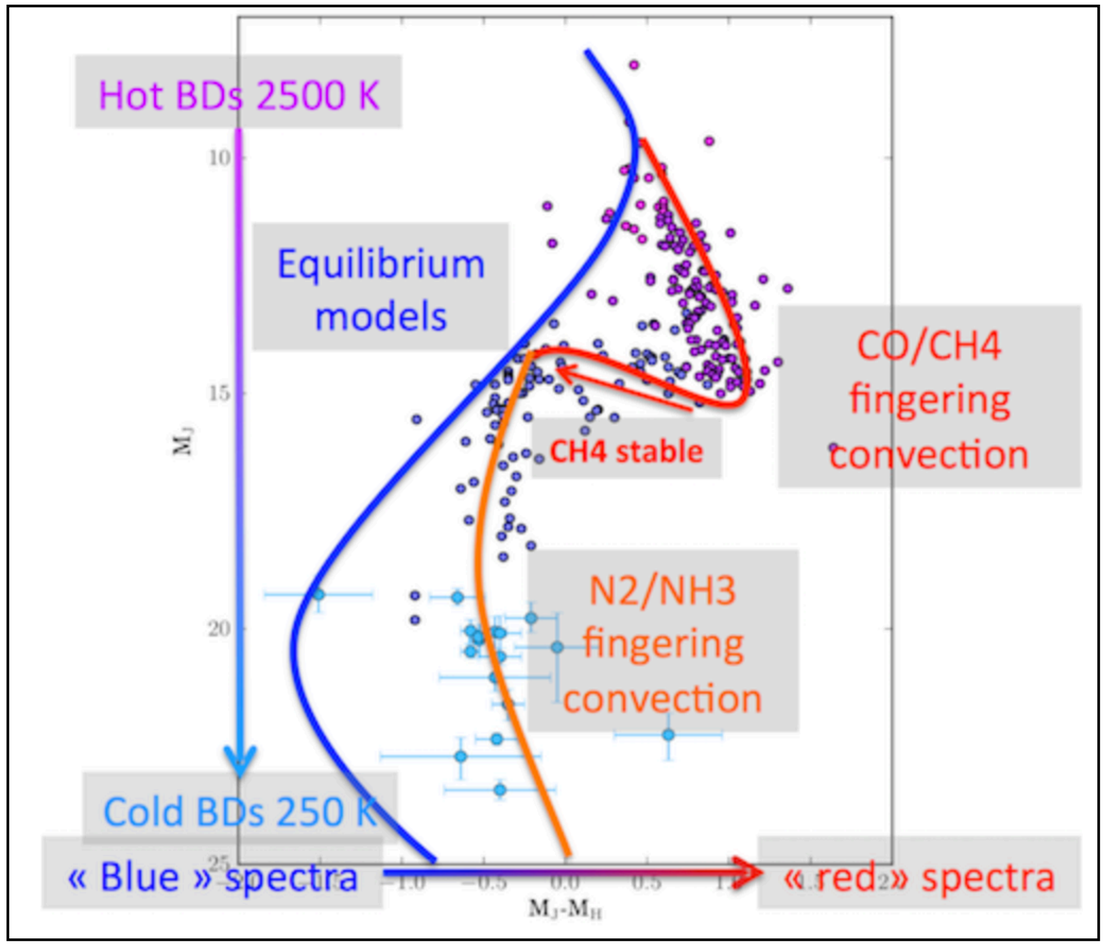
SONORA Marley et al. (2021)

With different complexity, molecules, grains size, clouds formation, etc.

What kind of models?

Cloud-less models

ATMO

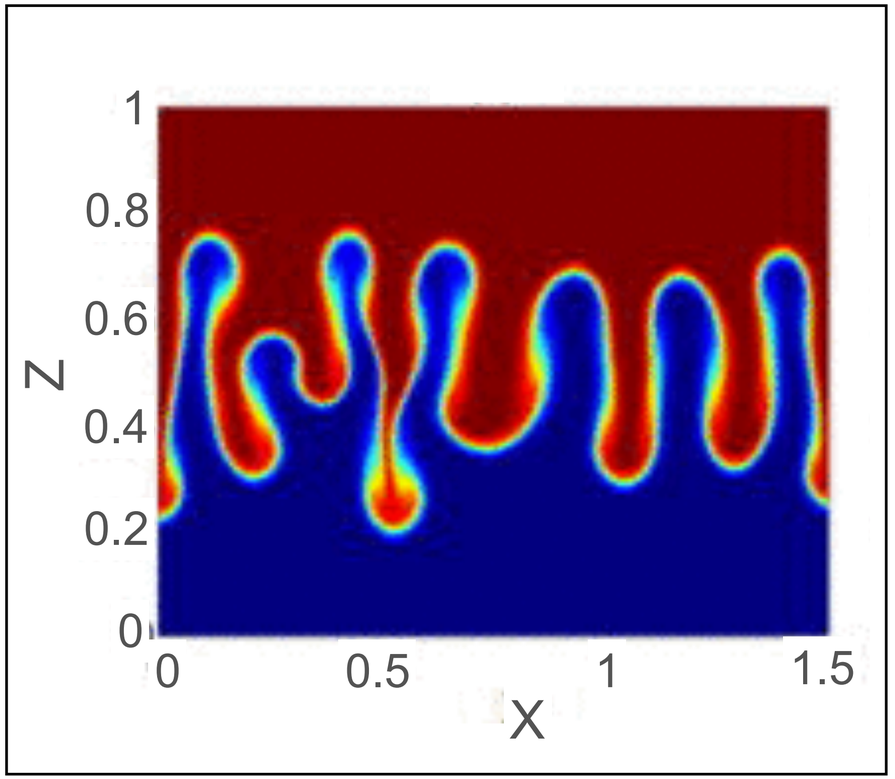


Tremblin et al. 2016

2 thermo-chemical instabilities

The energy transport reduces the temperature gradient in the atmosphere

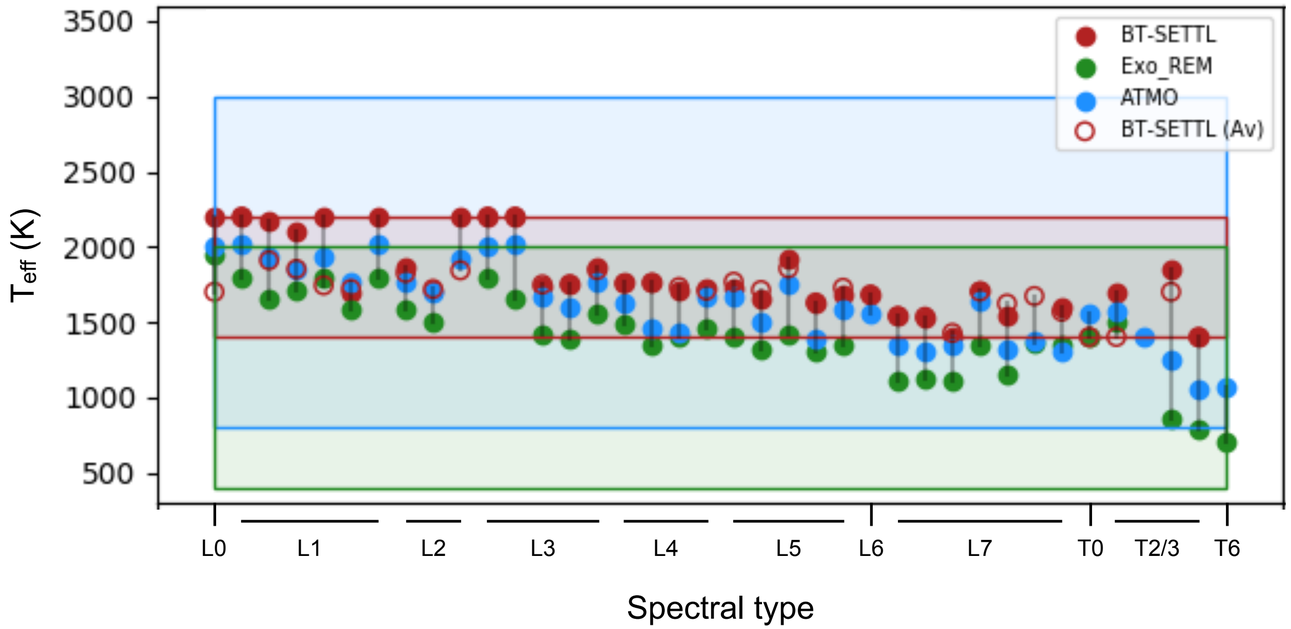
Fingering convection



Sreenivas et al. 2009

Modification of the P-T profile: mimic the clouds effect

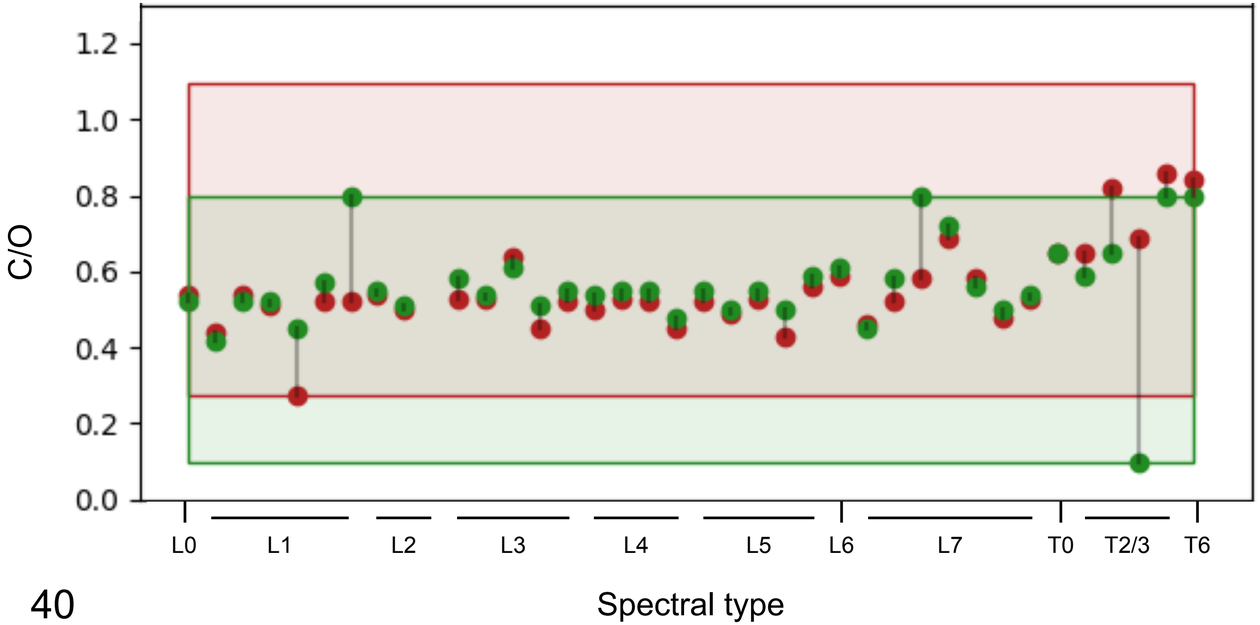
Part 2 - The X-Shyne library



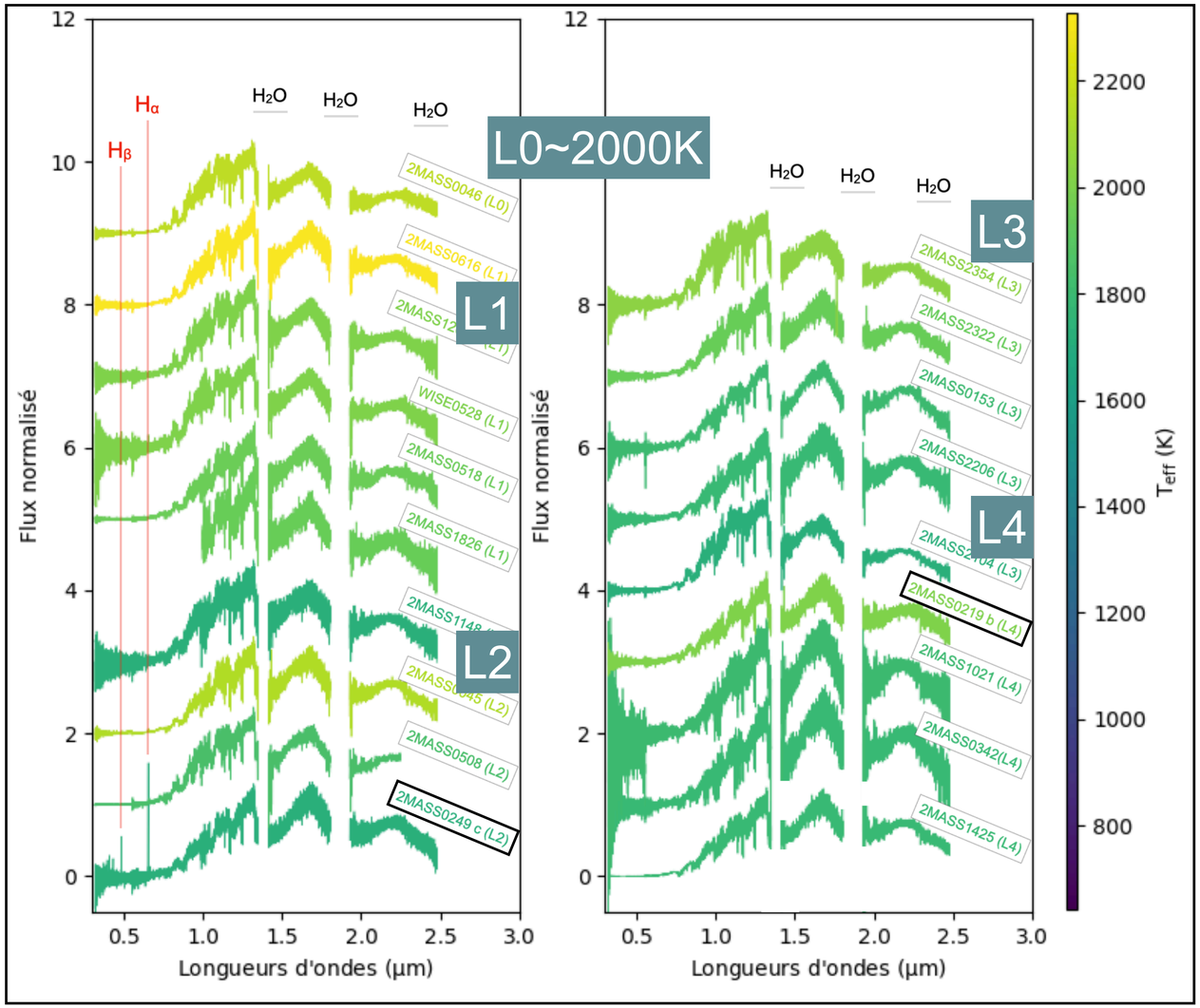
Relation T_{eff} - SpT is expected

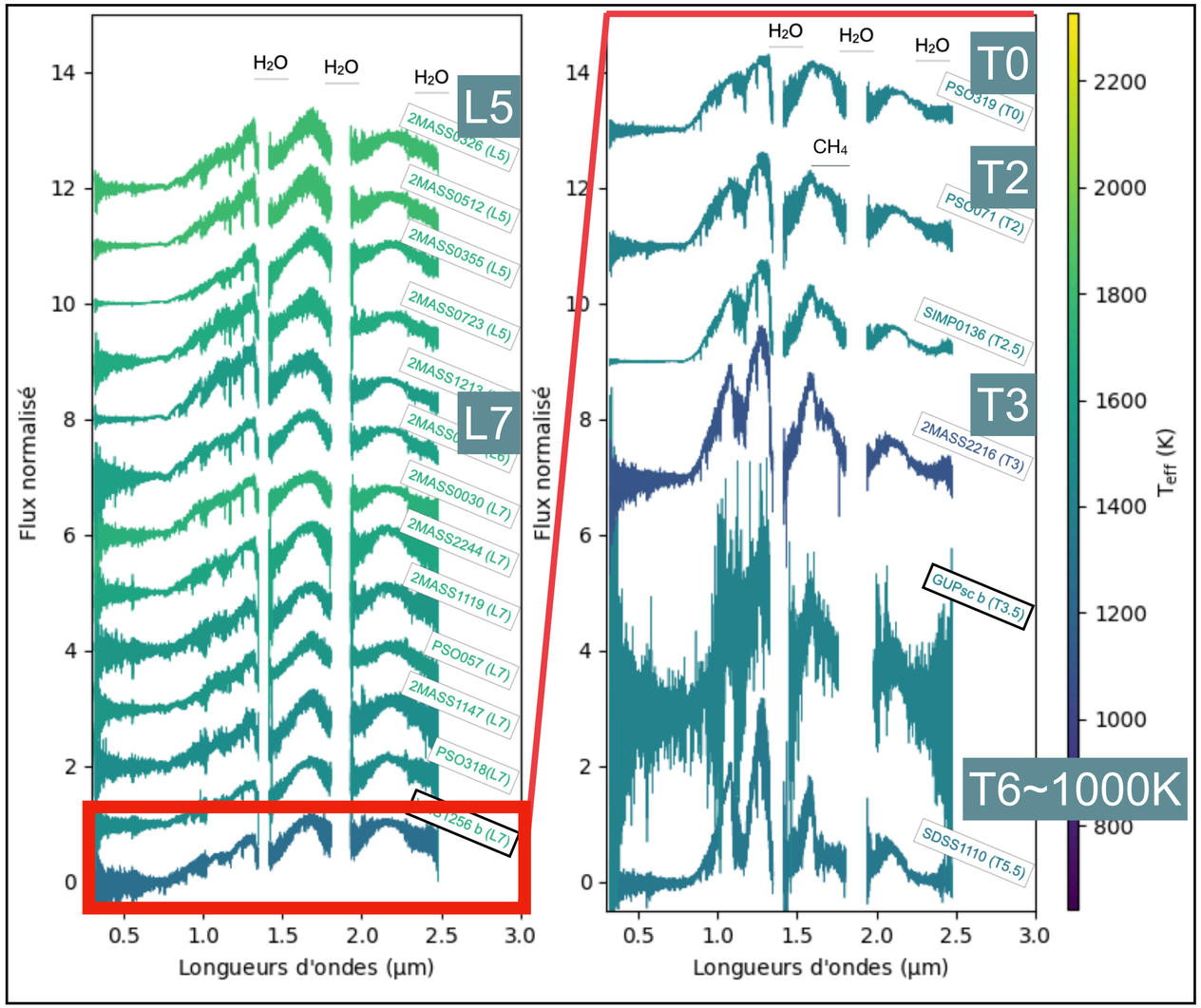
Relation C/O - SpT is **NOT** expected

- Due to models?
- Due to atmospheric structure after the L/T ?



Part 2 - The X-Shyne library





Companions (large separation)

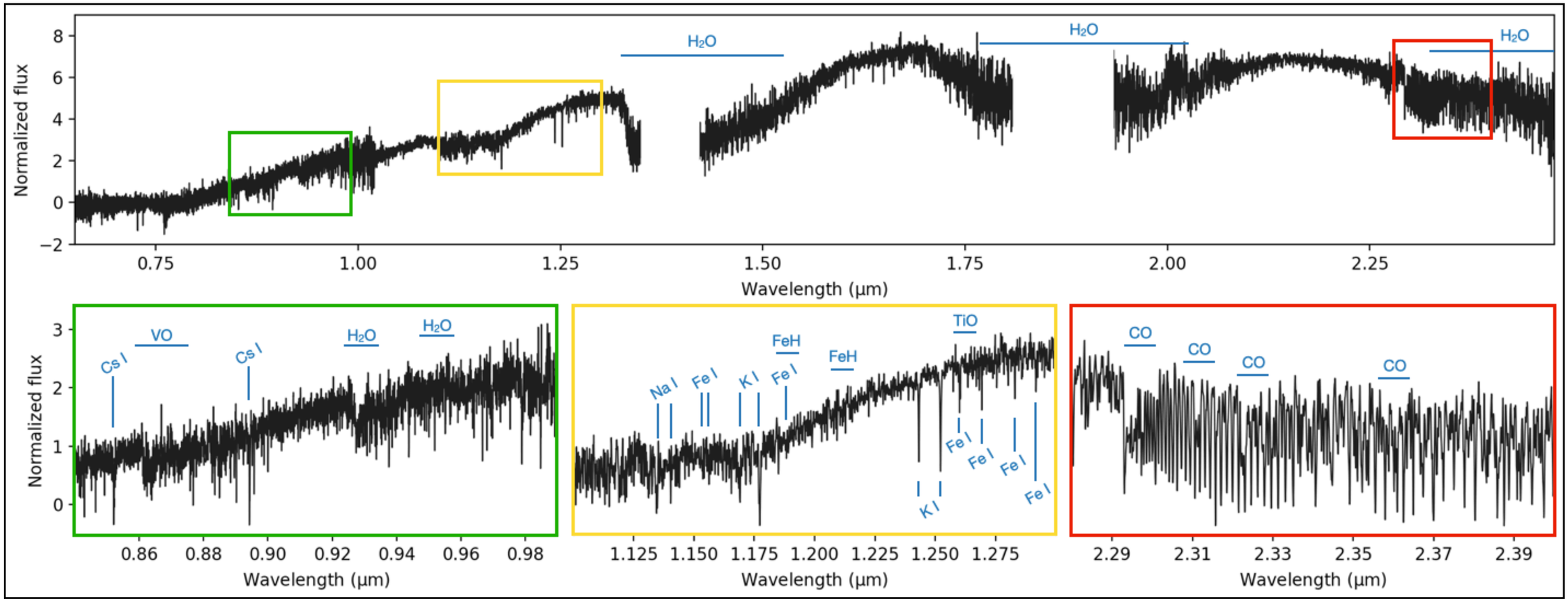
VHS 1256 b a JWST ERS target

Part 3

The case of VHS 1256 b

Petrus et al. (2023)
Petrus et al. (2024) submitted

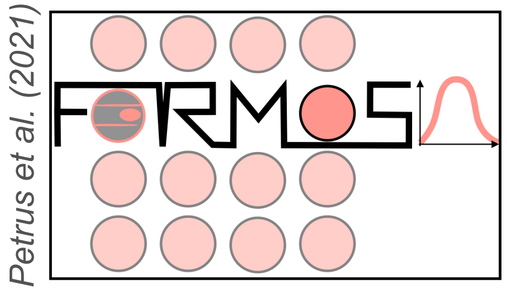
Part 3 - The case of VHS 1256 b



Petrus et al. (2023)

K I absorption lines sensible to the **surface gravity** and the **metallicity**
CO overtones sensible to the **C/O**

Part 3 - The case of VHS 1256 b



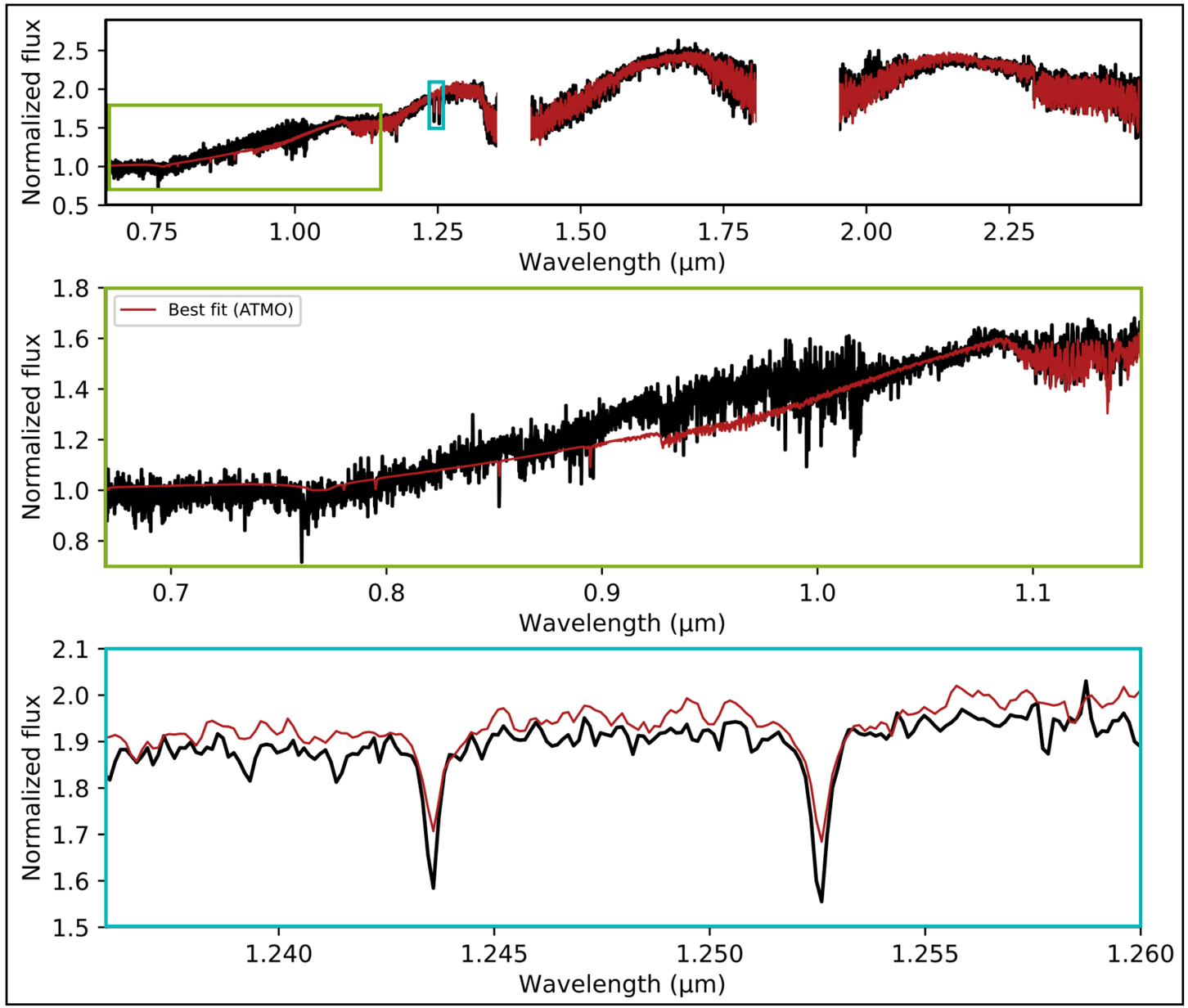
Fit on the <u>FULL SED</u>

Exo-REM (clouds)

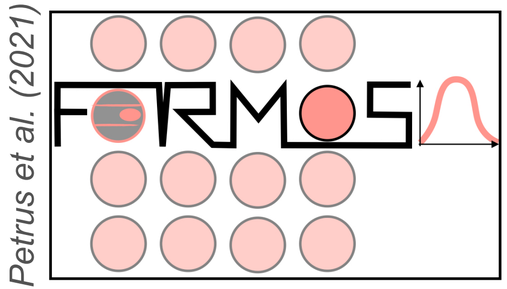
Charnay et al. (2018)

ATMO (cloud free)

Tremblin et al. (2018)



Part 3 - The case of VHS 1256 b



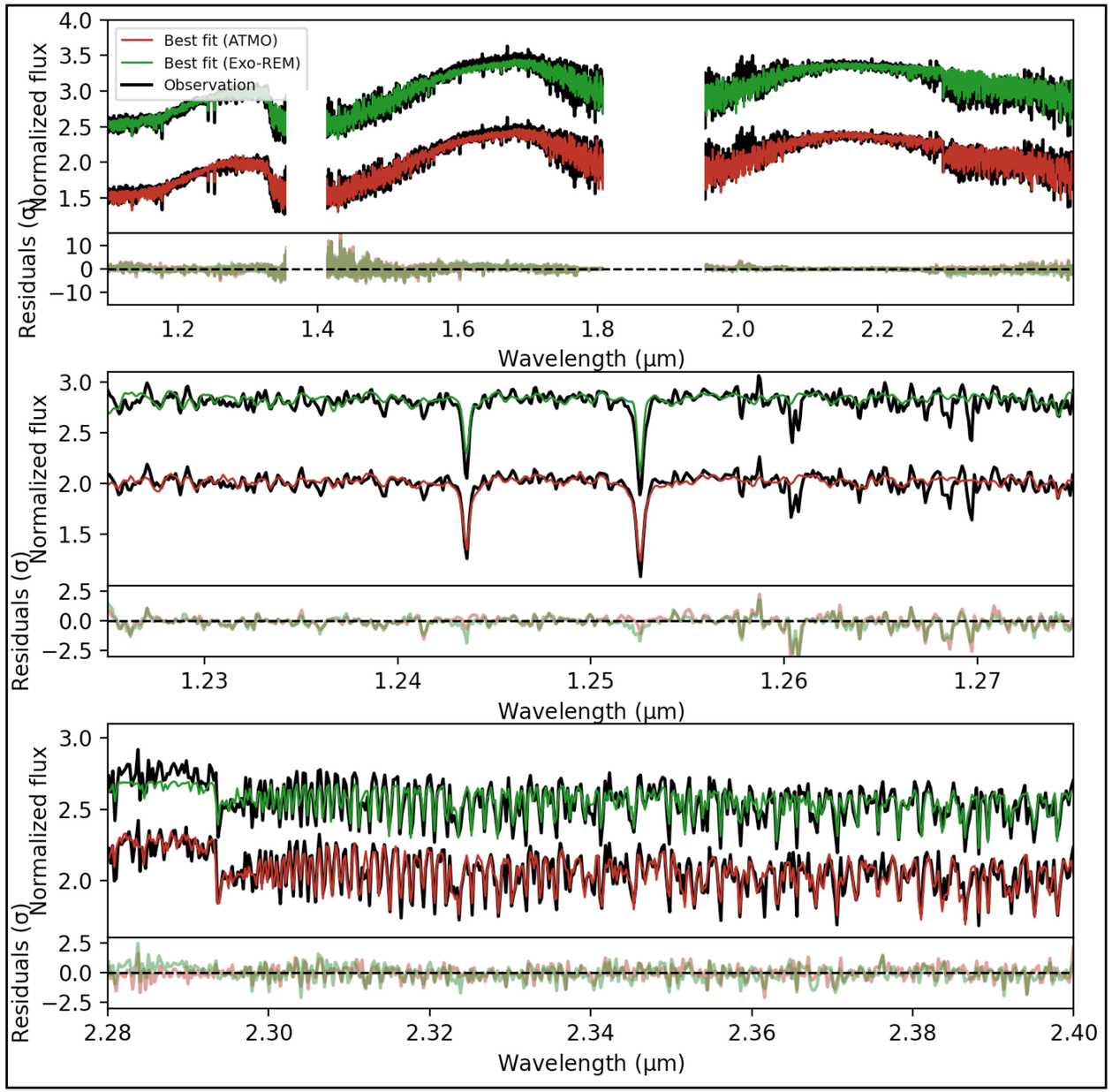
Fit on the spectral windows

Exo-REM (clouds)

Charnay et al. (2018)

ATMO (cloud free)

Tremblin et al. (2018)

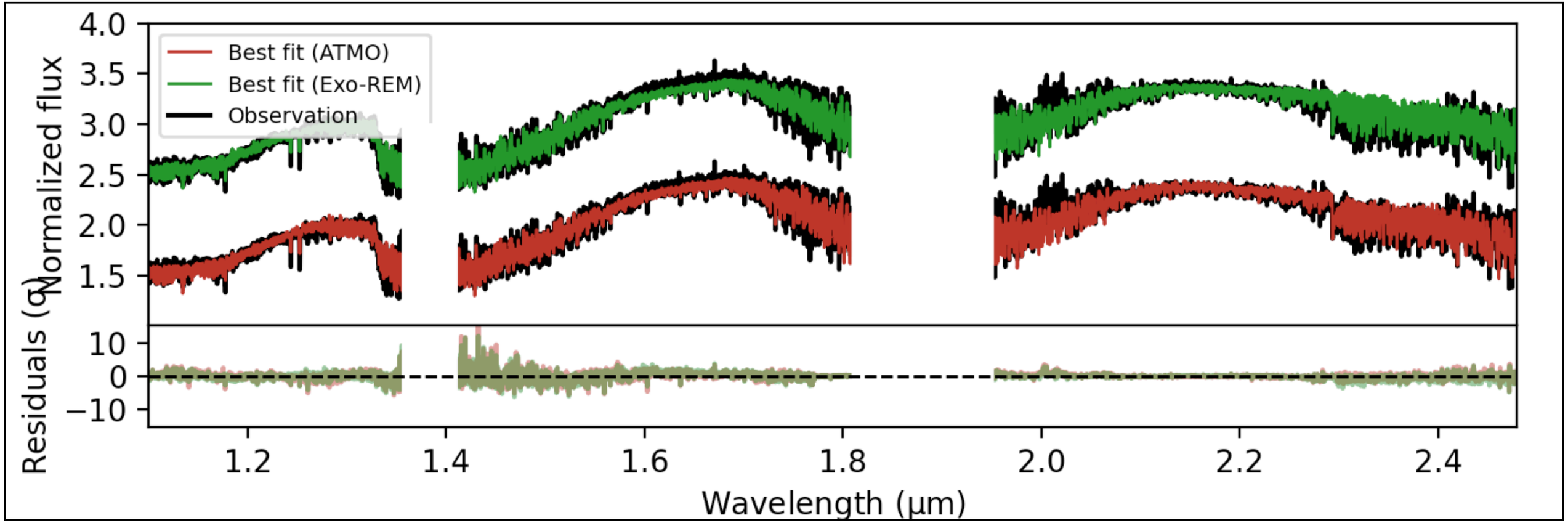


→ T_{eff}

→ log(g) [M/H]

→ C/O

Part 3 - The case of VHS 1256 b



Exo-REM T_{eff} ~ 1250 ± 50 K

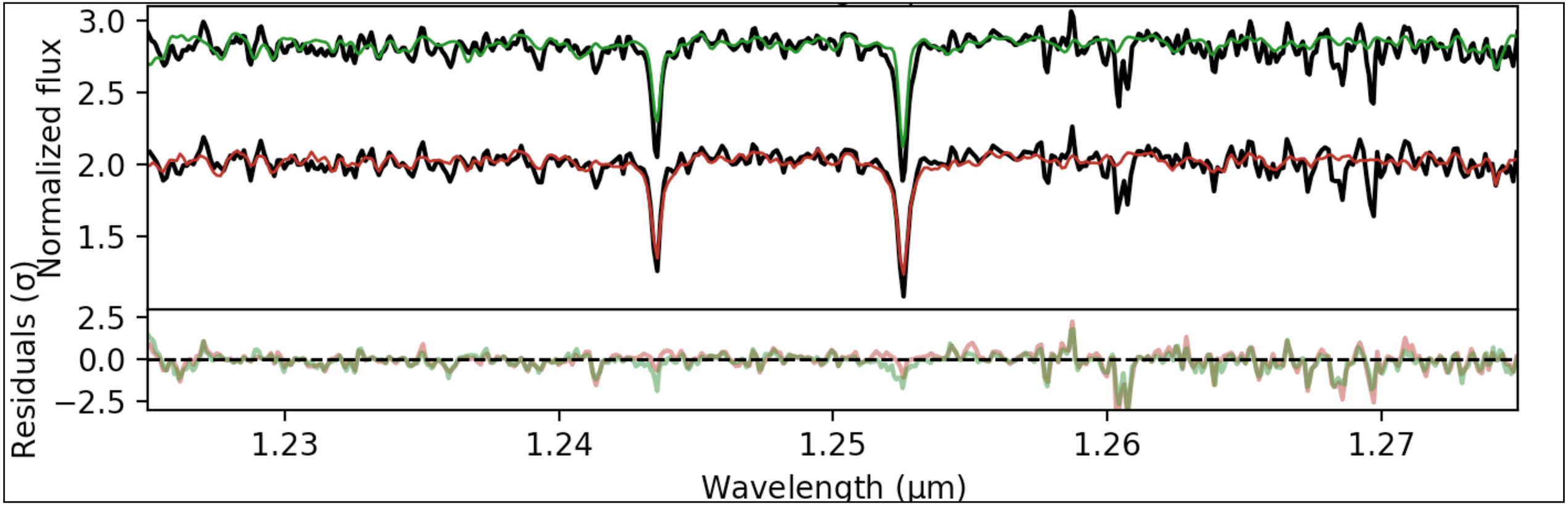
ATMO T_{eff} ~ 1326 ± 2 K

Dupuy et al. (2020) : T_{eff} = 1240 $^{+50}_{-50}$ K

Compatible with an L7

There is a difference between both models
(Different physics)

Part 3 - The case of VHS 1256 b



Exo-REM log(g) : not determined
[M/H] > 0.2

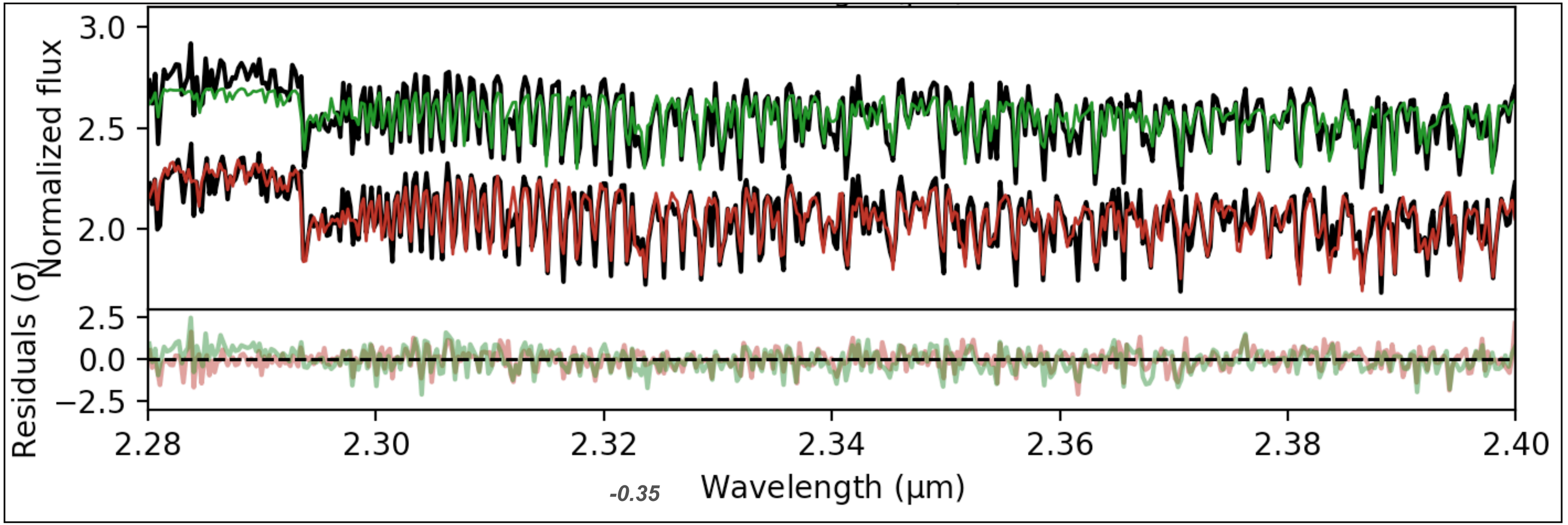
ATMO log(g) ~ 4.25 ± 0.20 dex
[M/H] > 0.32

Dupuy et al. (2020) : log(g) =4.55 $^{+0.15}_{-0.11}$

log(g) compatible with a young object (150-300 Myr)

[M/H] compatible with solar value but we are in the grid's edge

Part 3 - The case of VHS 1256 b



Exo-REM C/O > 0.62

ATMO C/O > 0.63

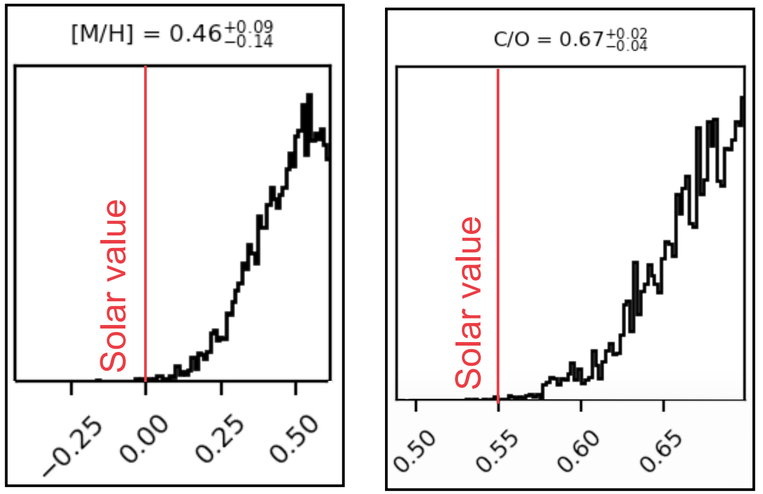
Solar value = 0.55

C/O compatible with solar value but we are in the grid's edge

Part 3 - The case of VHS 1256 b

$[M/H]_{VHS\ 1256\ b} > [M/H]_{Solar}\ (= 0.0)$

$C/O_{VHS\ 1256\ b} > C/O_{Solar}\ (= 0.55)$



ATMO posteriors

How does JWST help?

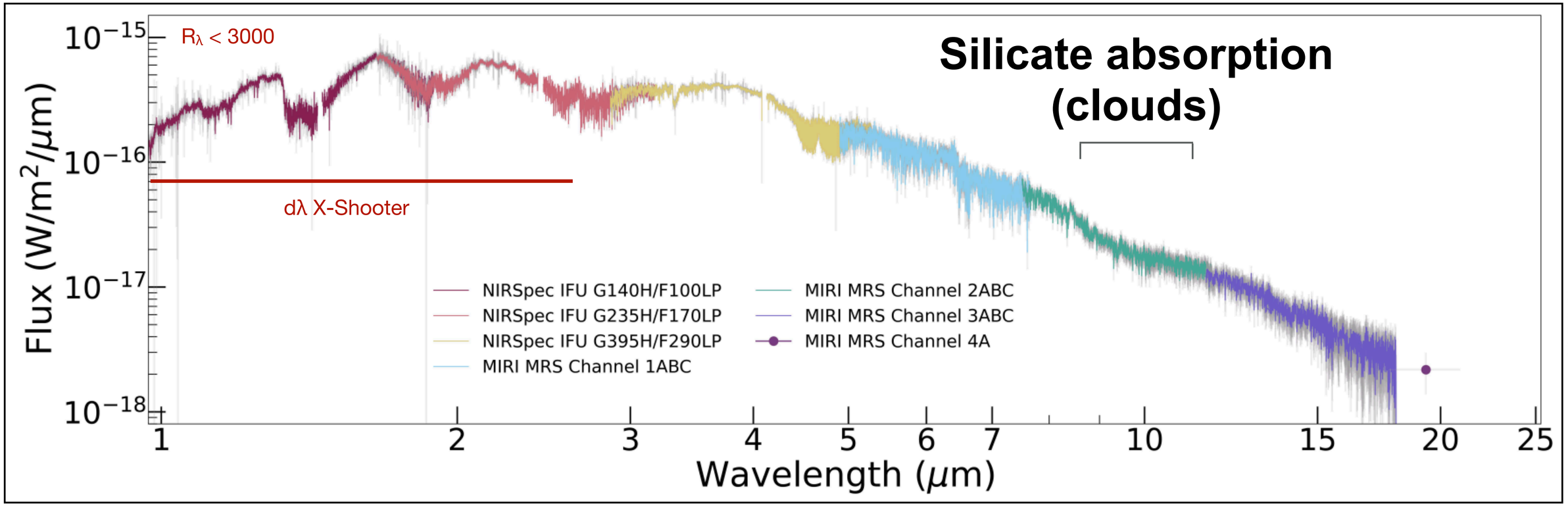
Medium spectral resolution

Large wavelength coverage

Part 3 - The case of VHS 1256 b

The most complete spectrum ever obtained for an exoplanet

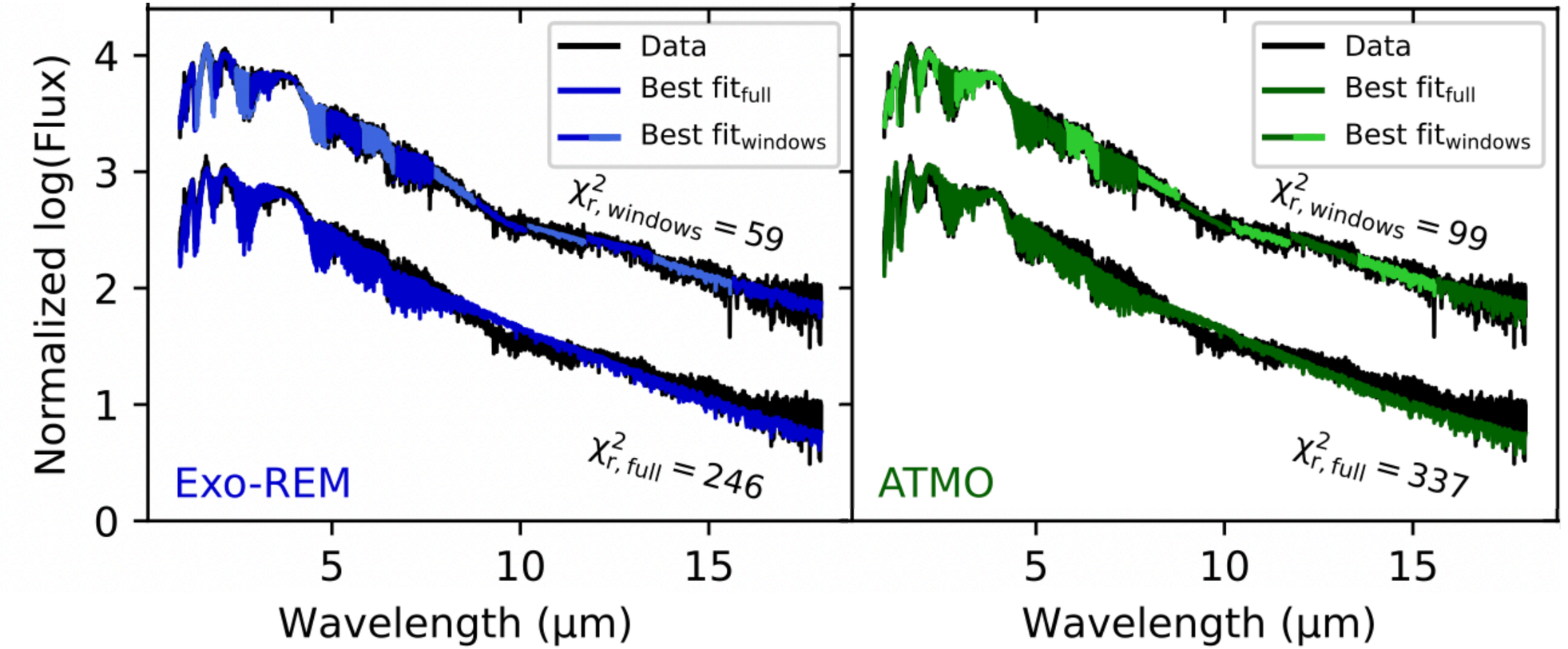
JWST / NIRSpec + MIRI



Miles et al. (2023)

Part 3 - The case of VHS 1256 b

15 independent spectral windows

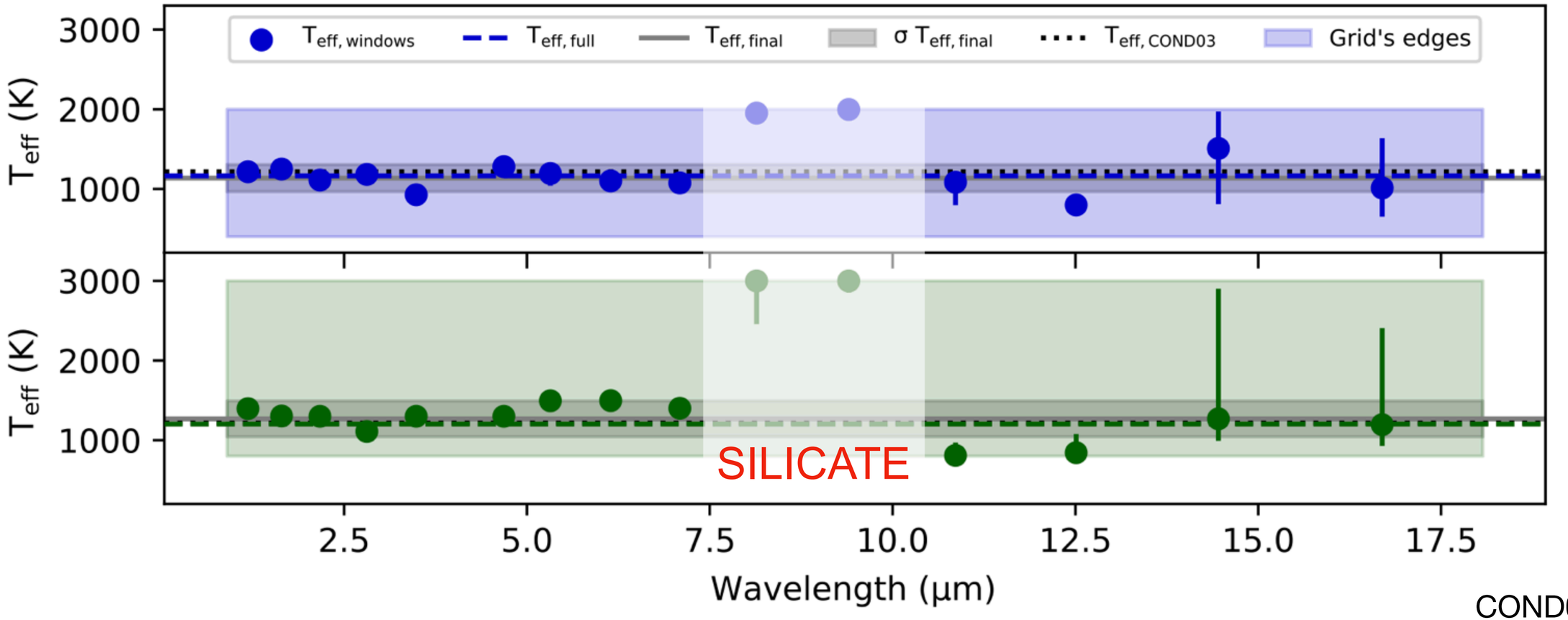


Petrus et al. (2023, in prep.)

Increase the quality of the fits

(Not surprising because it is ~ $n_{free\ parameters}$ x 15)

Part 3 - The case of VHS 1256 b



Petrus et al. (2023, in prep.)

Different fits means different posteriors

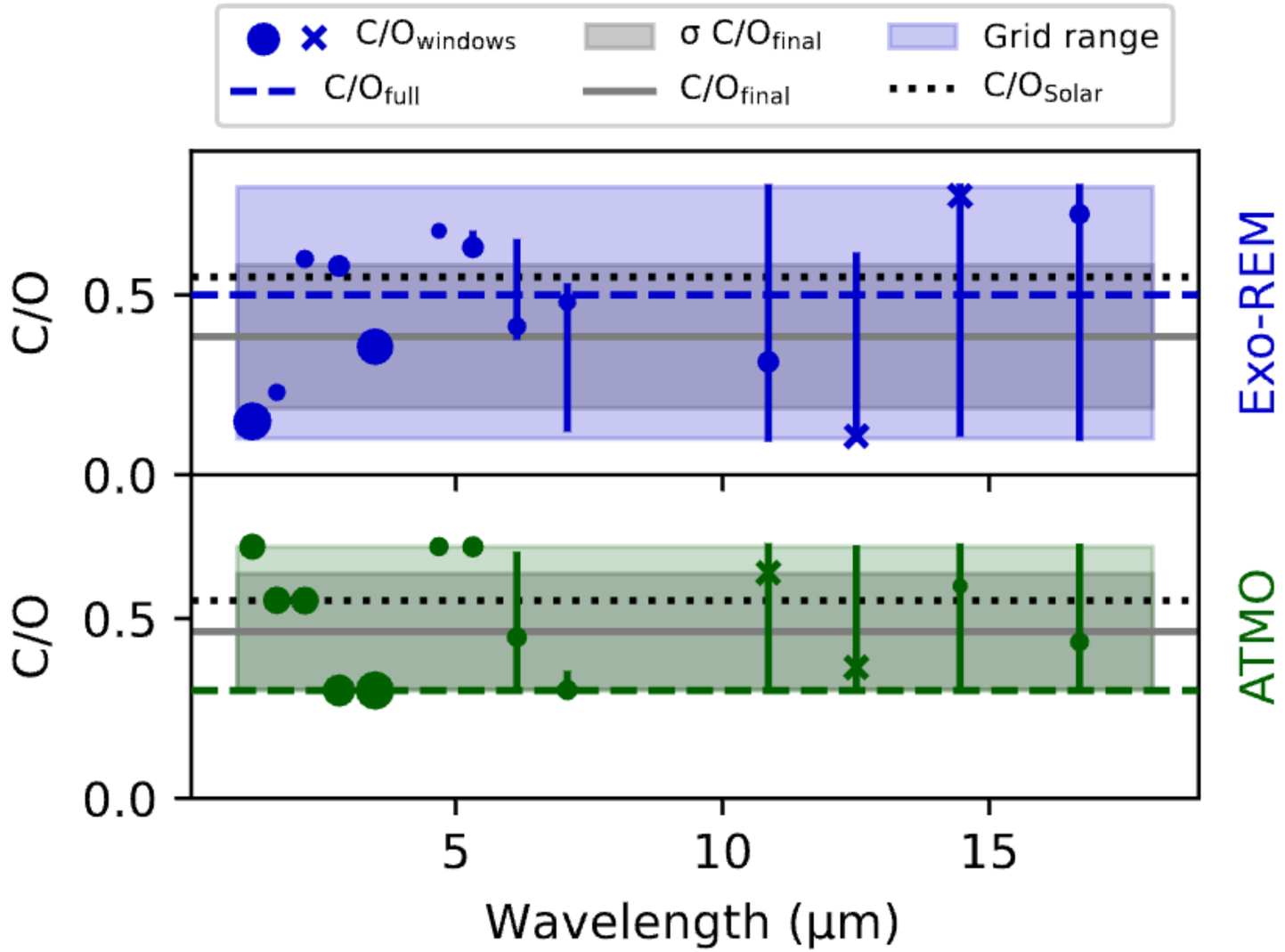
The final estimate takes into account the variation

COND03
1234 ± 6 K

EXOREM
1135 ± 169 K
OK

ATMO
1265 ± 221 K
OK

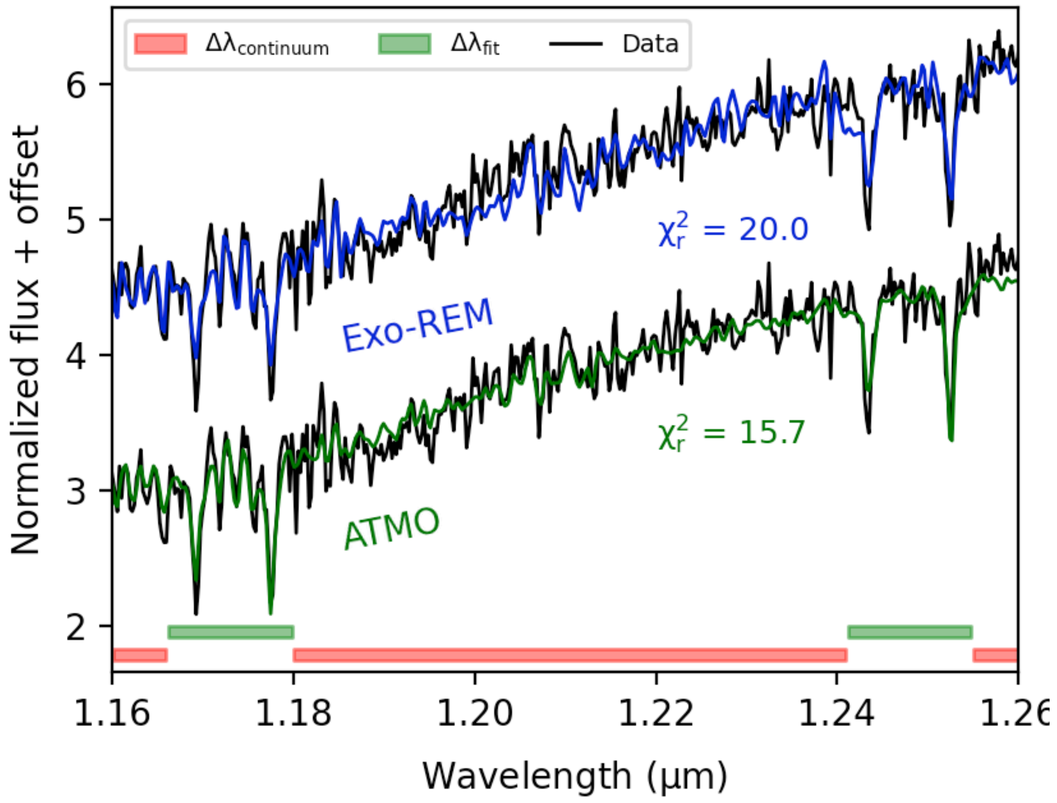
Part 3 - The case of VHS 1256 b

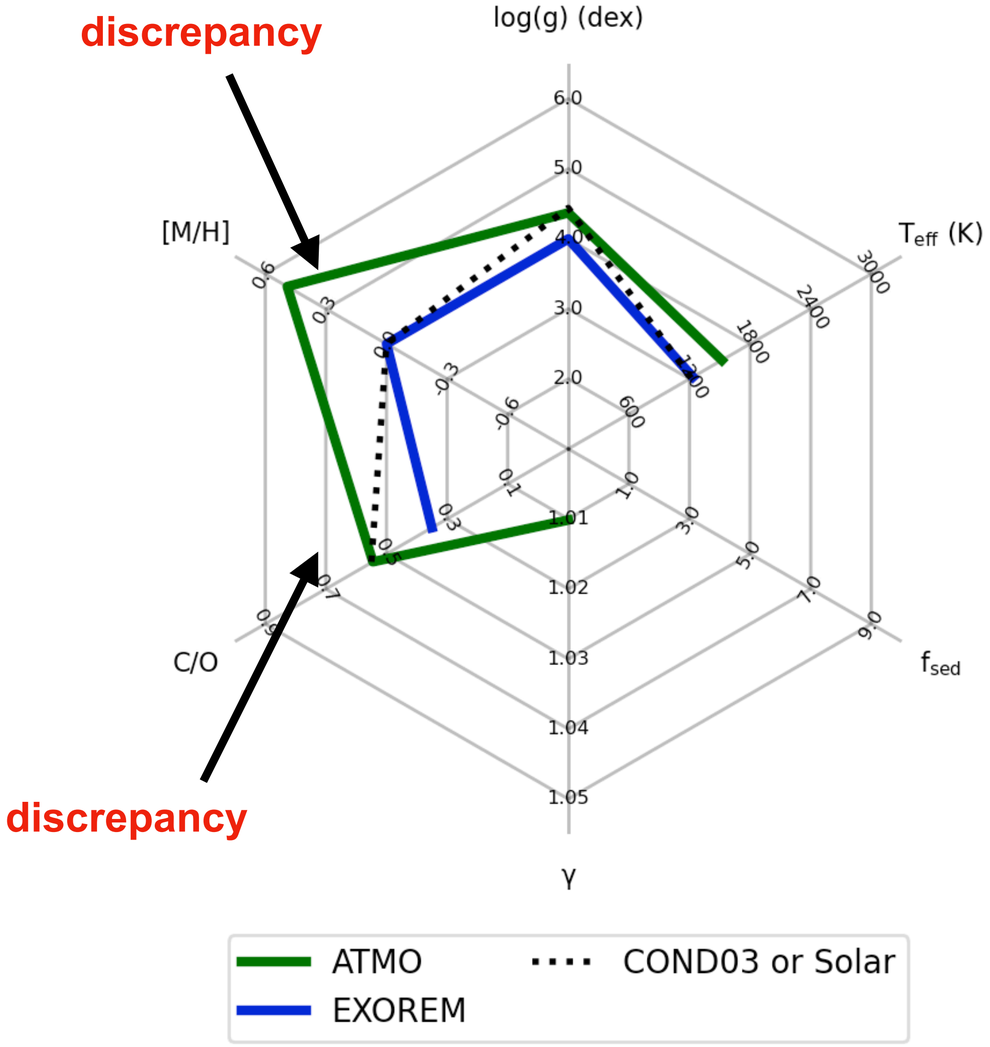


Petrus et al. (2023, in prep.)

Strong dispersion for the chemical abundances

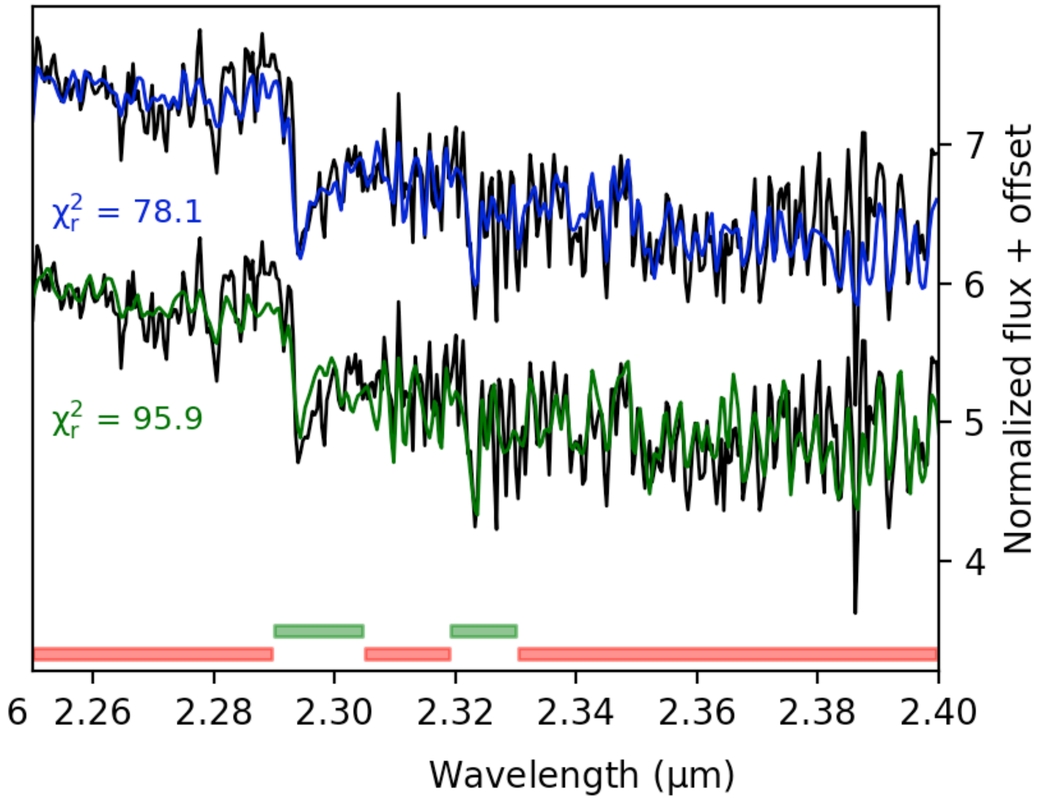
Part 3 - The case of VHS 1256 b

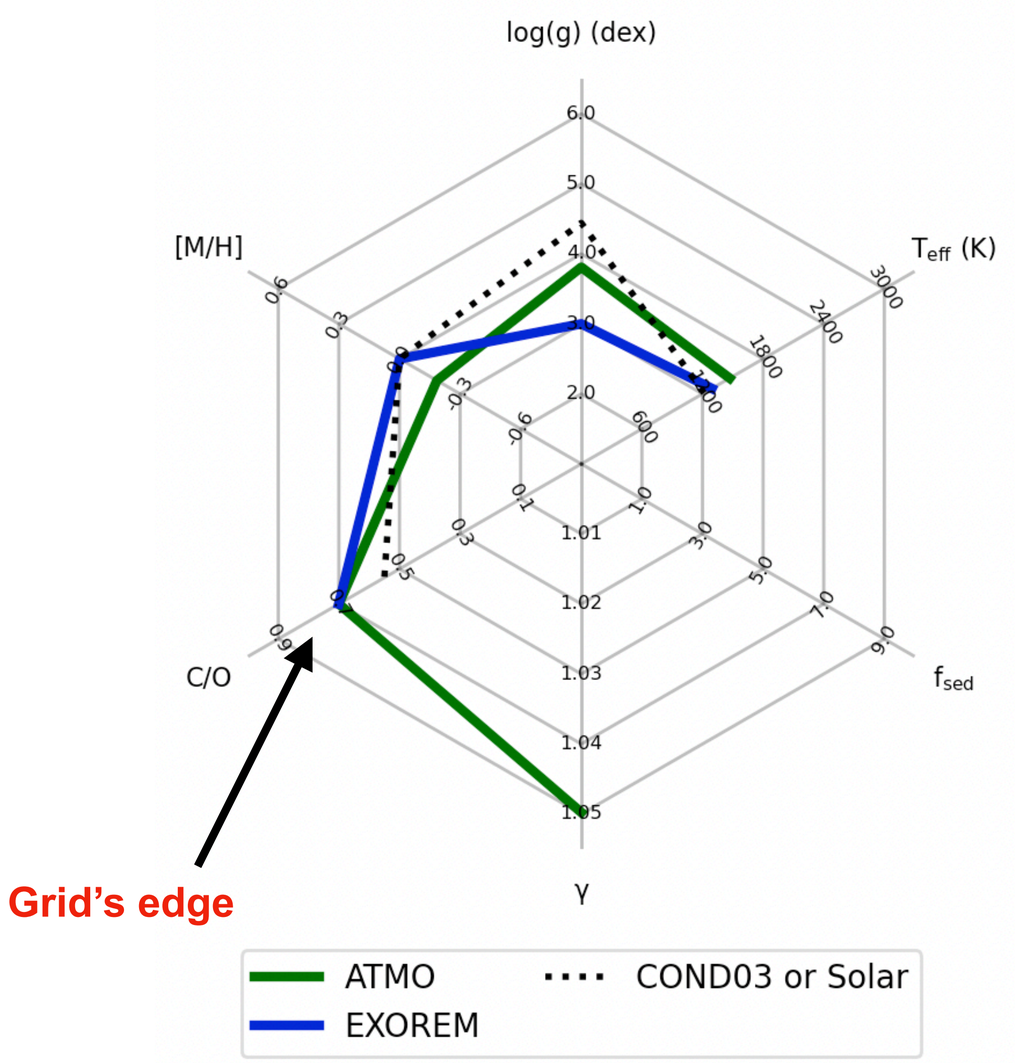




Fits on specific spectral features

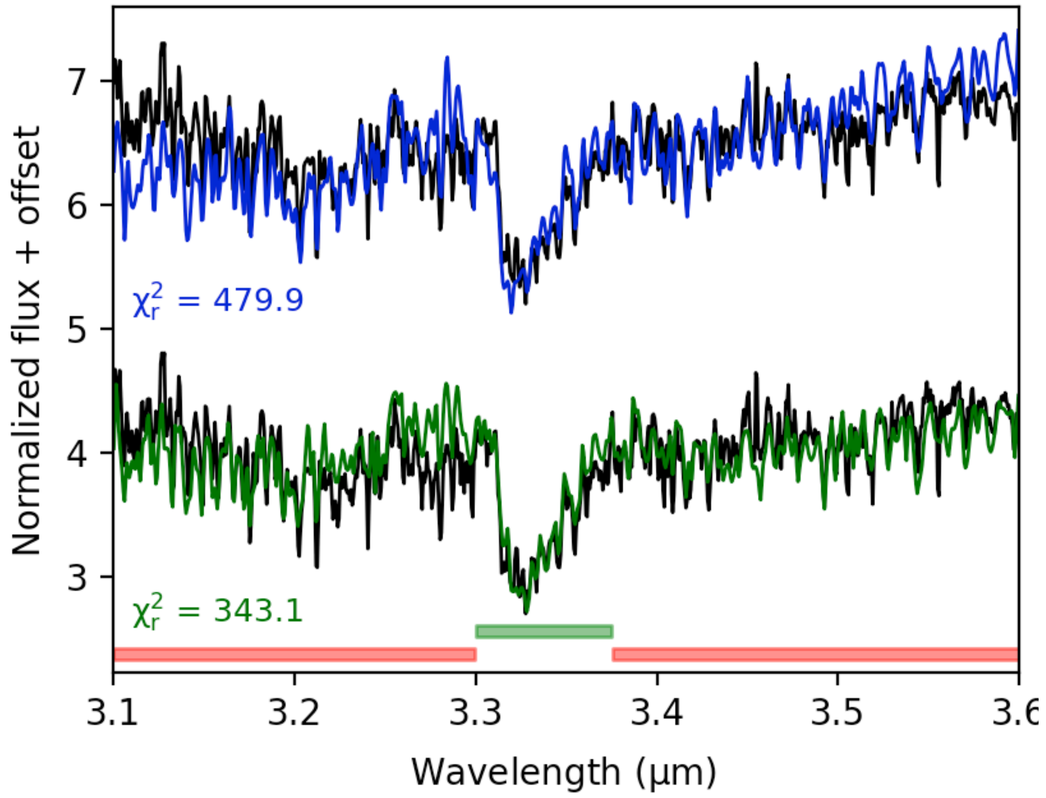
Part 3 - The case of VHS 1256 b

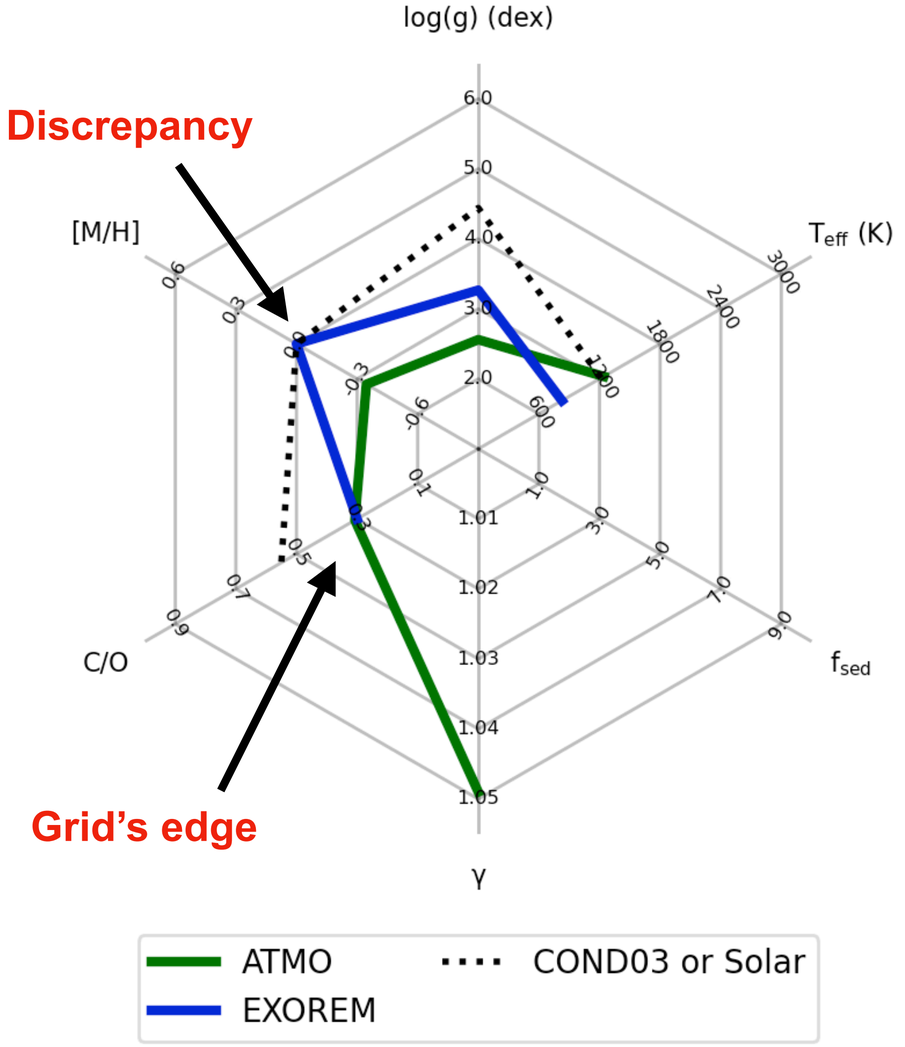




Fits on specific spectral features

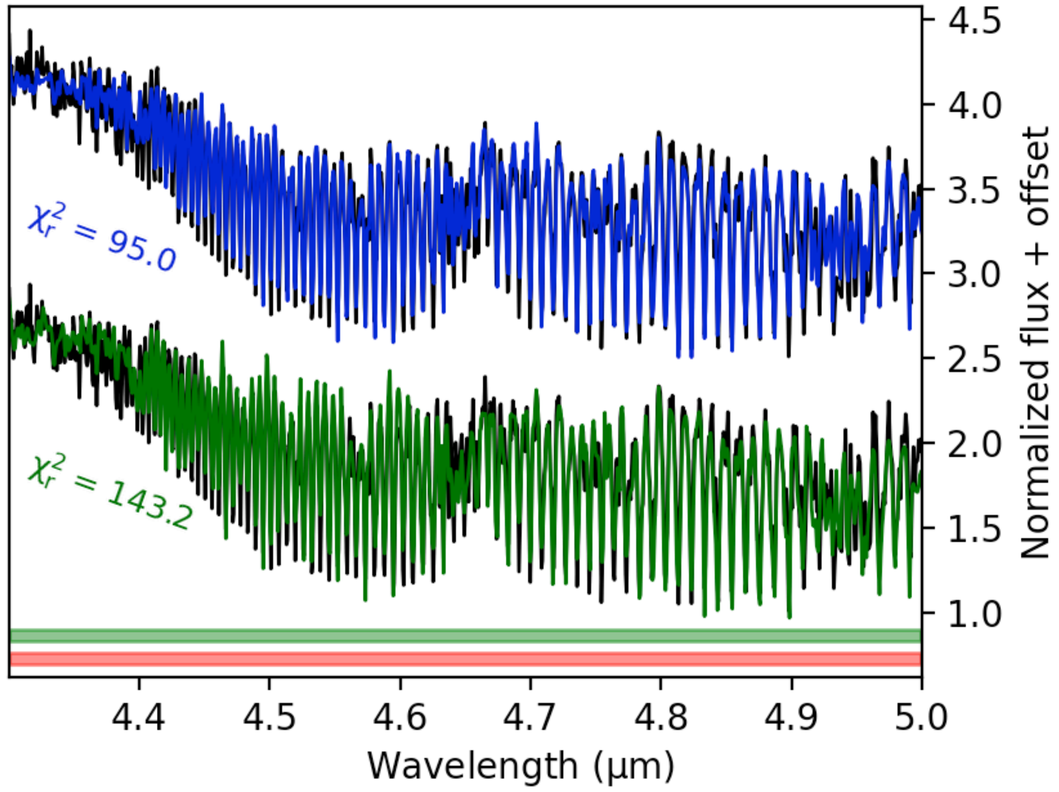
Part 3 - The case of VHS 1256 b

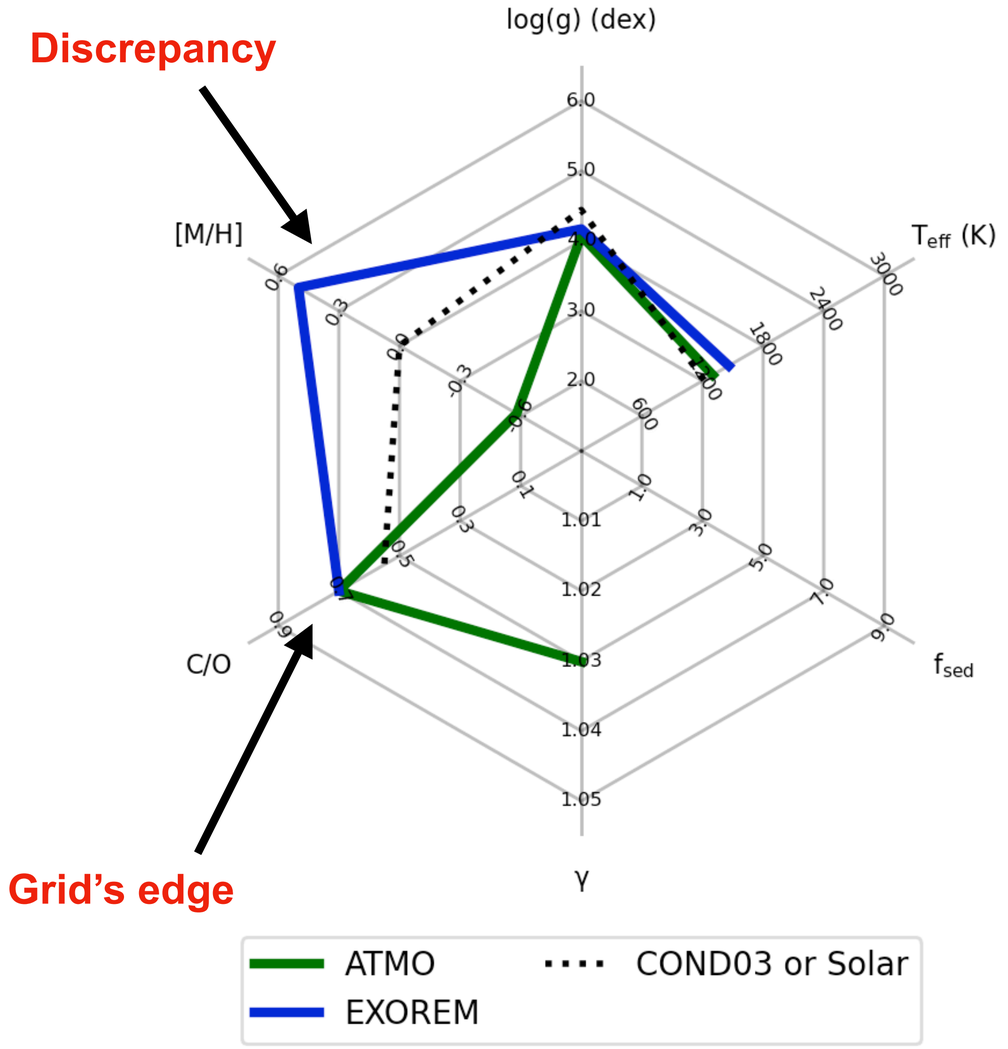




Fits on specific spectral features

Part 3 - The case of VHS 1256 b

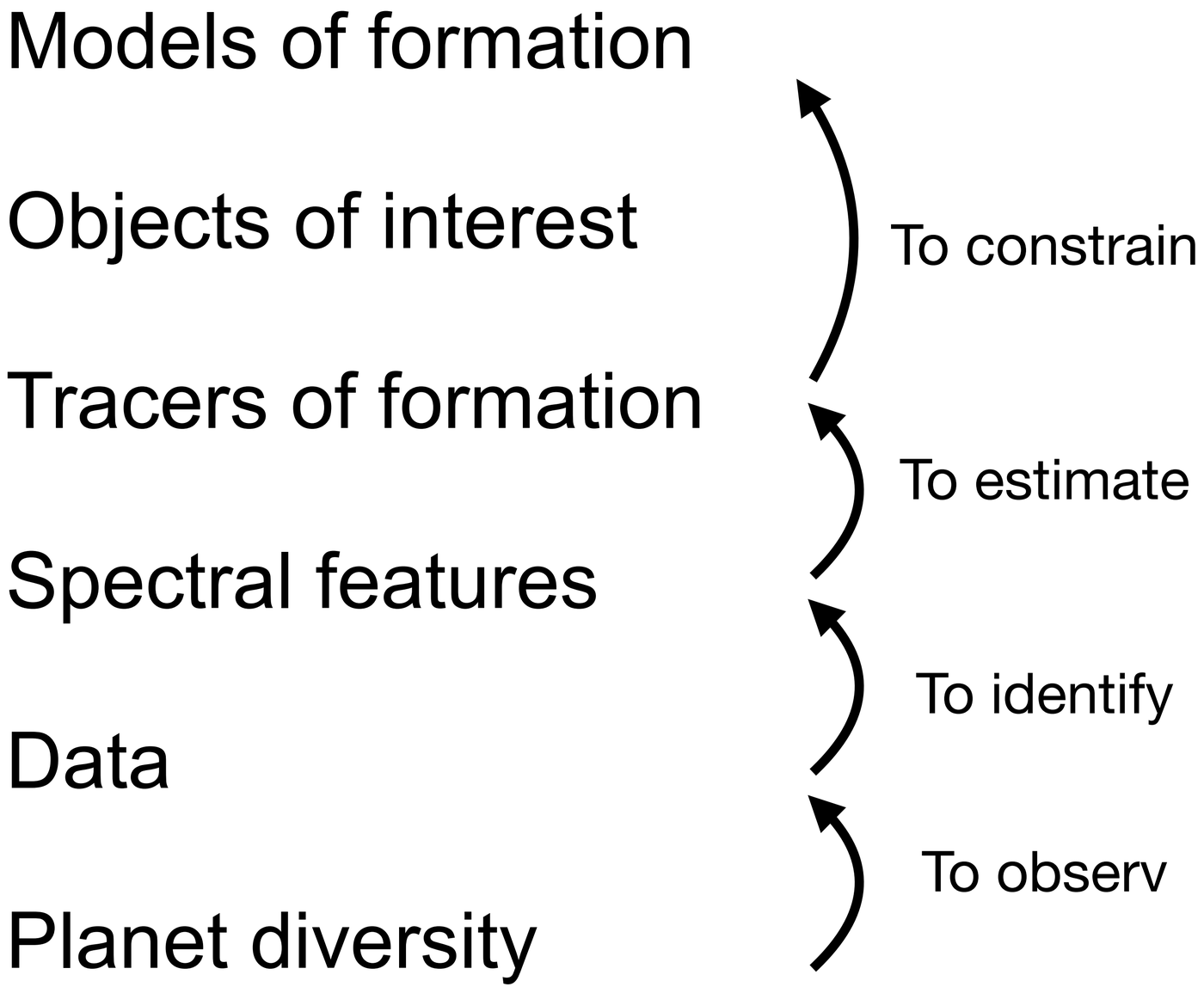




Fits on specific spectral features

Conclusion

Conclusion

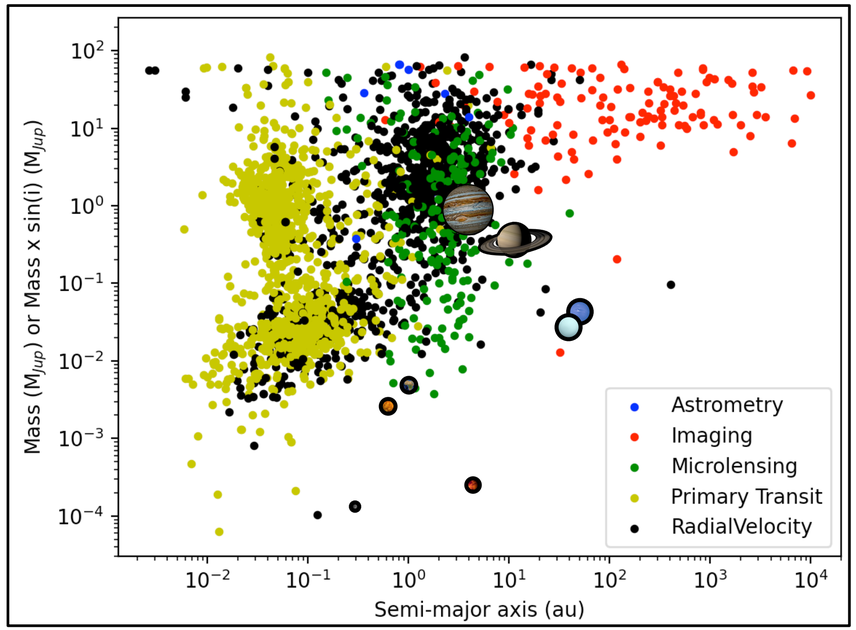

Models of formation
Objects of interest
Tracers of formation
Spectral features
Data
Planet diversity
To constrain
To estimate
To identify
To observ
We cannot estimate robustly the tracers of formation
We identify spectral features
We have data

Conclusion

There is currently no absolute method to constrain a planet's formation history

Identification ⟶ Quantification ⟶ Comparison

NEED FOR DIVERSITY AND A HUGE SAMPLE OF PLANETARY OBJECTS



Conclusion

There is currently no absolute method to constrain a planet's formation history

Identification → Quantification → Comparison

NEED FOR DIVERSITY AND A HUGE SAMPLE OF PLANETARY OBJECTS

This work needs to be done for each exoplanets observed with JWST

Part 3 - The case of VHS 1256 b

- Young planetary-mass brown dwarfs are ideal exoplanetary analogs:
  - To explore their physical & atmospheric properties (together with imaged planets)
  - To push the limitations of atmospheric models

- X-Shyne:
  - An R=8000 VIS/NIR X-Shooter survey of 38 L to mid-T planetary-mass objects
  - Systematic Forward-Modelling analysis using ExoREM & ATMO models
  - Exploration bulk properties, clouds, chemical abundances, isotopologues, radial & rotational velocities,
  - Soon, available for the community - library & code

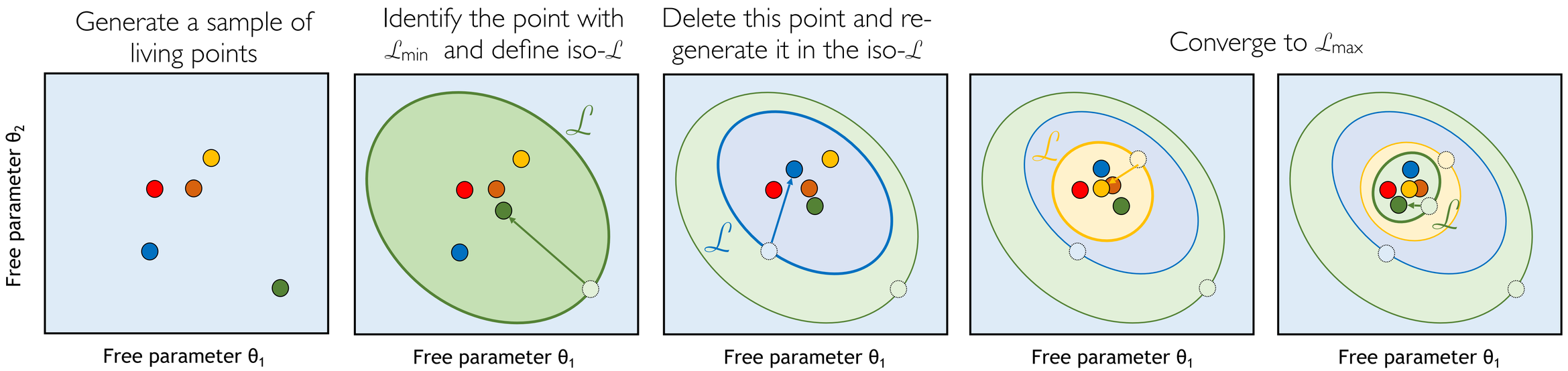
- Application to VHS1256 b
  - Hierarchical architecture: probably formed via stellar-like mechanism,
  - Relatively well reproduced by cloud (ExoREM) & cloud-free (ATMO) models
  - T_{eff} & log(g) compatible with L7 SpT & age,
  - M/H & C/O, solar to super-solar, but pointing the current limitations of the models
  - The JWST provided new spectral information inaccessible so far
  - We can define new methods to provide robust estimate of the atmospheric parameters
  - Perspectives: variability study, new/extended models, 1D to 3D

Thank you !

Appendices

The Nested sampling (alternative to MCMC)

Skilling 2006



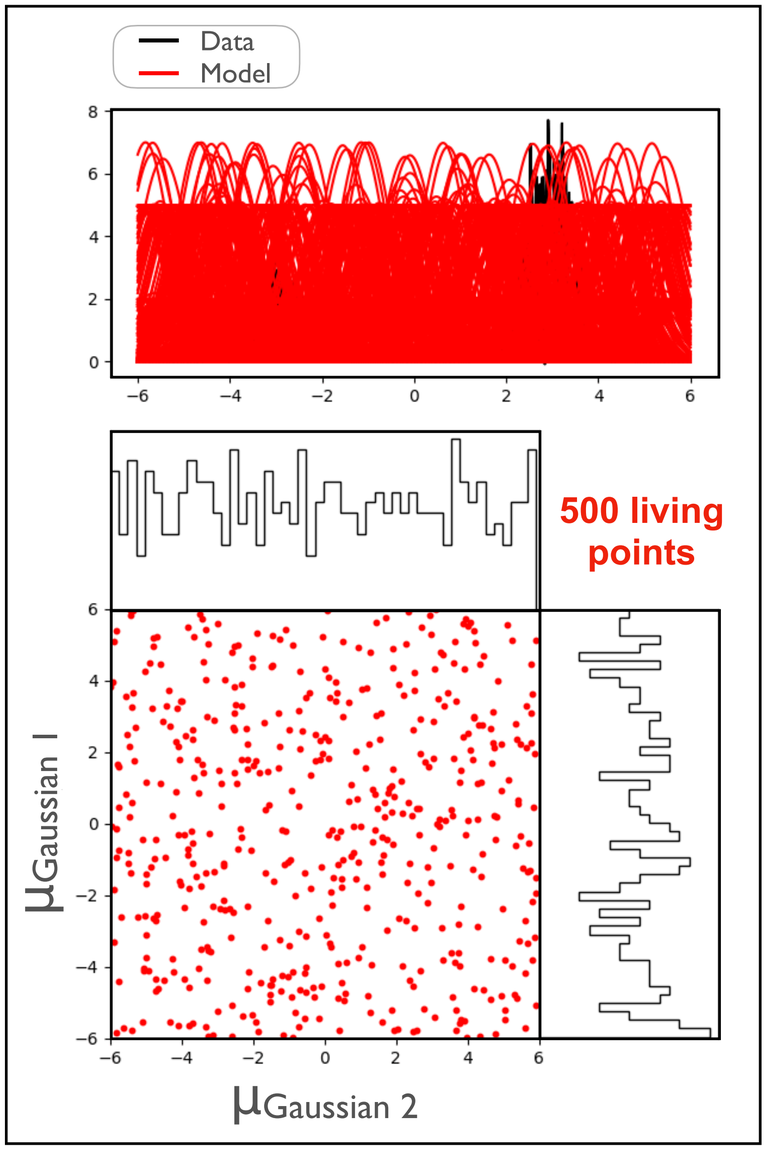
Iterative process

The Nested sampling (alternative to MCMC)

Fit the positions of two Gaussian laws
with A_1, A_2, σ_1 and σ_2 constant

Nested sampling advantages

- Global exploration of the parameter space
- Immediate identification of local maxima
- Immediate identification of correlations
- Immediate estimation of the statistical evidence
  (Useful to perform model comparison, not detailed here)



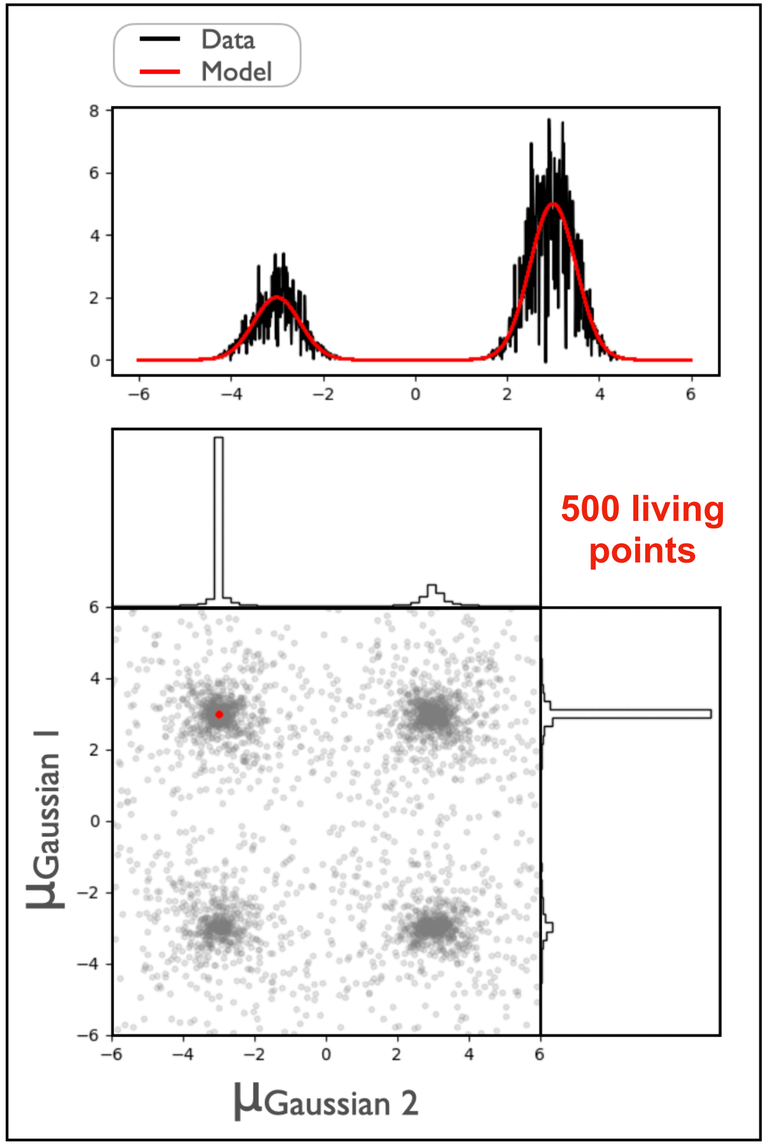
Animation

The Nested sampling (alternative to MCMC)

Fit the <u>positions</u> of two Gaussian laws
with A_1, A_2, σ_1 and σ_2 constant

<u>Nested sampling advantages</u>

- Global exploration of the parameter space
- Immediate identification of local maxima
- Immediate identification of correlations
- Immediate estimation of the statistical evidence
  (Useful to perform model comparison, not detailed here)



Part 2 - The X-Shyne library

FORWARD MODELING

The models drive the fit

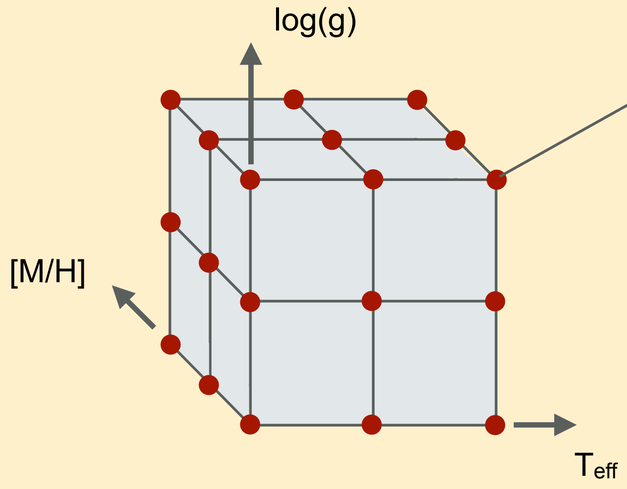
T_{eff} | log(g) | [M/H] | …

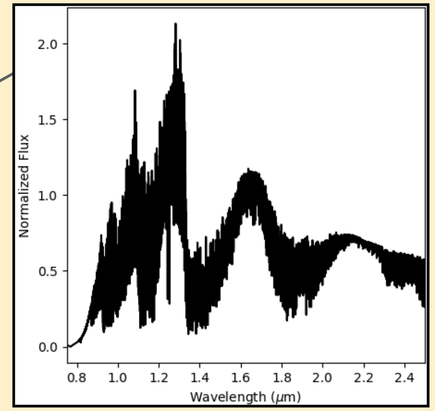
Fundamental parameters of the atmosphere (< 5 today)

P-T profile | Chemical species | Mixing | Cloud formation

Chemical equilibrium | Complex physics … | Sedimentation

Self-consistent models

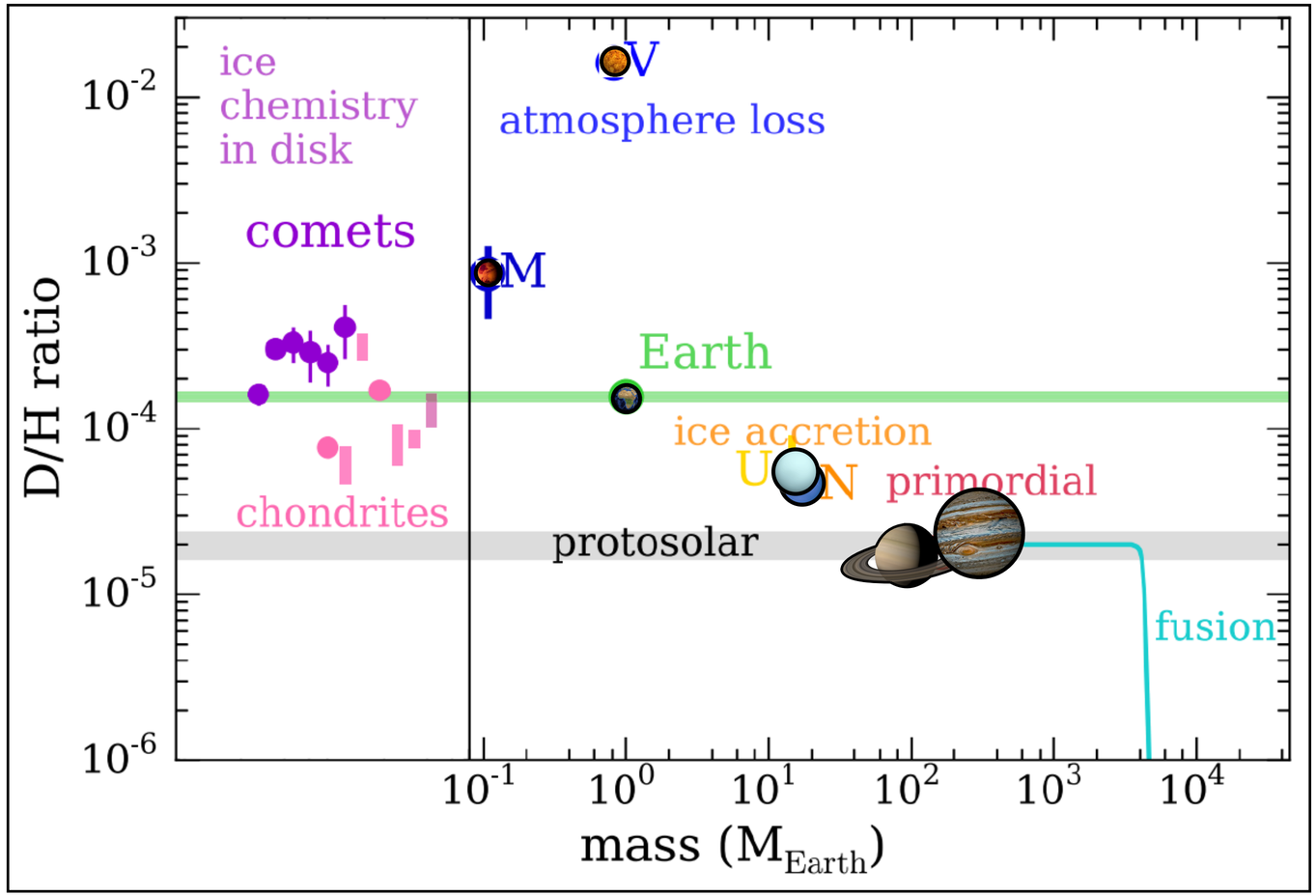




Pre-computed synthetic spectrum
Exo-REM (Charnay et al. 2018)

≥ 10 minutes of computing time to generate one synthetic spectrum with thousands points

D/H



Morley et al. (2019)

CH_3D between 4 and 5 µm

HDO at 3.7 µm

→ JWST

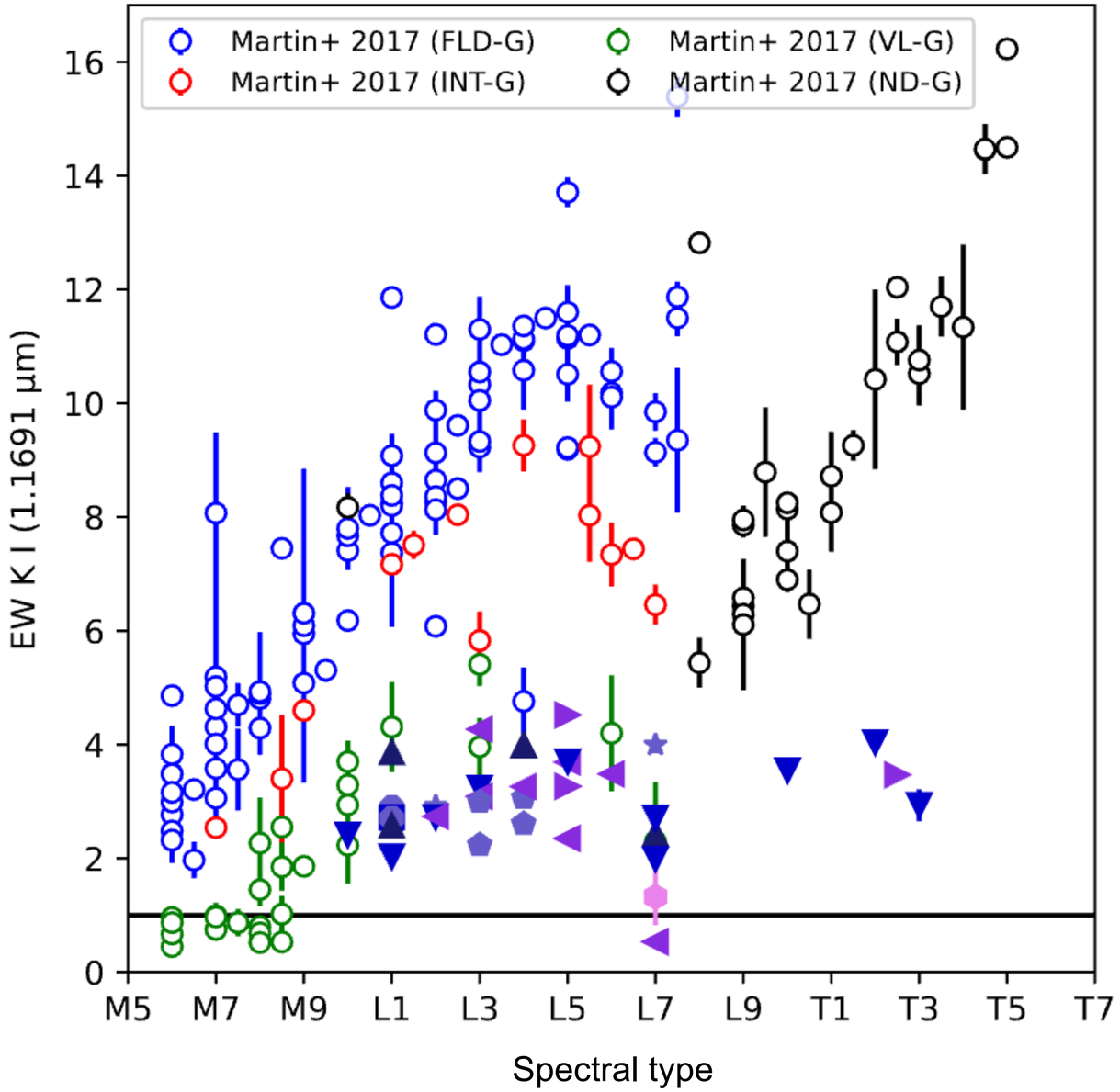
"For objects from 200 to 800 K closer than 10 pc, a protosolar D/H ratio would be readily observable in 2.5 hr"

Morley et al. (2019)

EMPIRICAL ANALYSIS

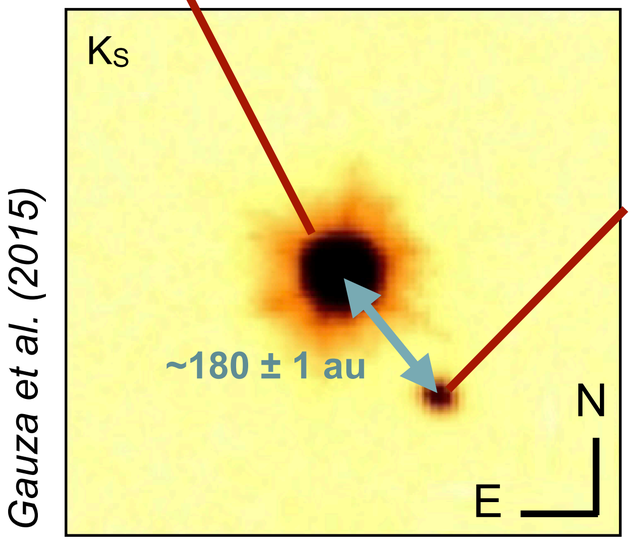
It exists a trend of the EWs and the spectral type

Young objects have not the same spectral properties than old objects



Part 3 - The case of VHS 1256 b

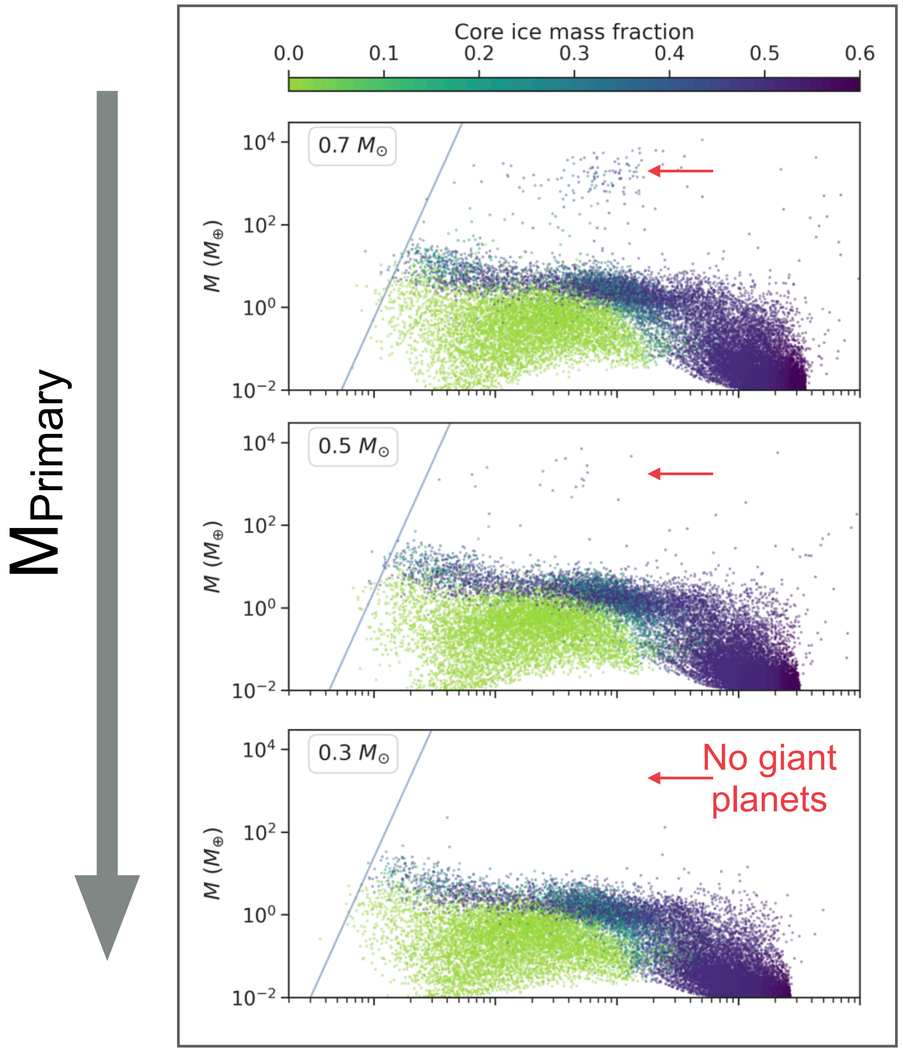
VHS 1256 (AB)
SpT ~ M7.5 ± 0.5
M_{tot} ~ 114 ± 7 M_{Jup}



Gauza et al. (2015)

VHS 1256 b
SpT ~ L7 ± 1.5
M ~ 19 ± 5 M_{Jup}

System
Age ~ 150-300 Myr
Distance ~ 22 ± 1 pc Dupuy et al. (2020)



$M_{Primary}$

NGPPS, Burn et al. (2021)

Synthetic planets
Core accretion

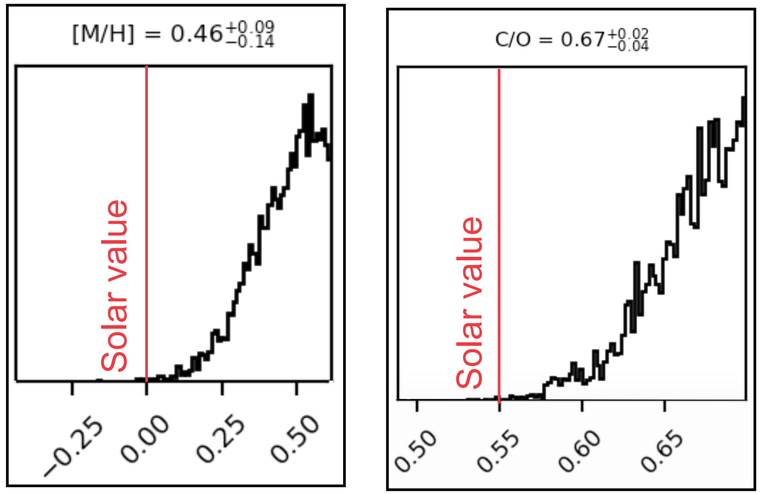
Excludes a formation in a disk
Hierarchical system formed by stellar mechanism? Solar chemical properties ???

Part 3 - The case of VHS 1256 b

$[M/H]_{VHS\ 1256\ b} > [M/H]_{Solar}\ (= 0.0)$

$C/O_{VHS\ 1256\ b} > C/O_{Solar}\ (= 0.55)$

But still compatible with solar at 3 sigma

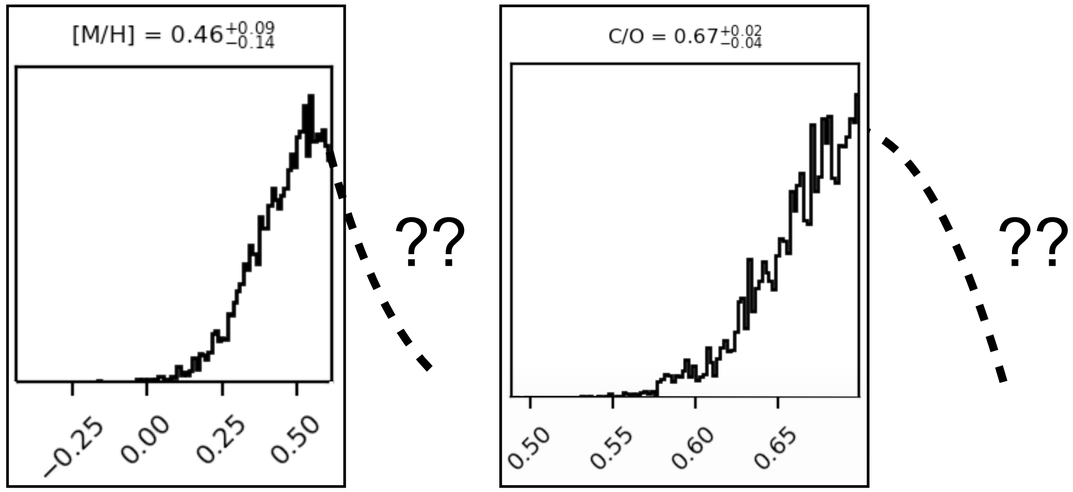


ATMO posteriors

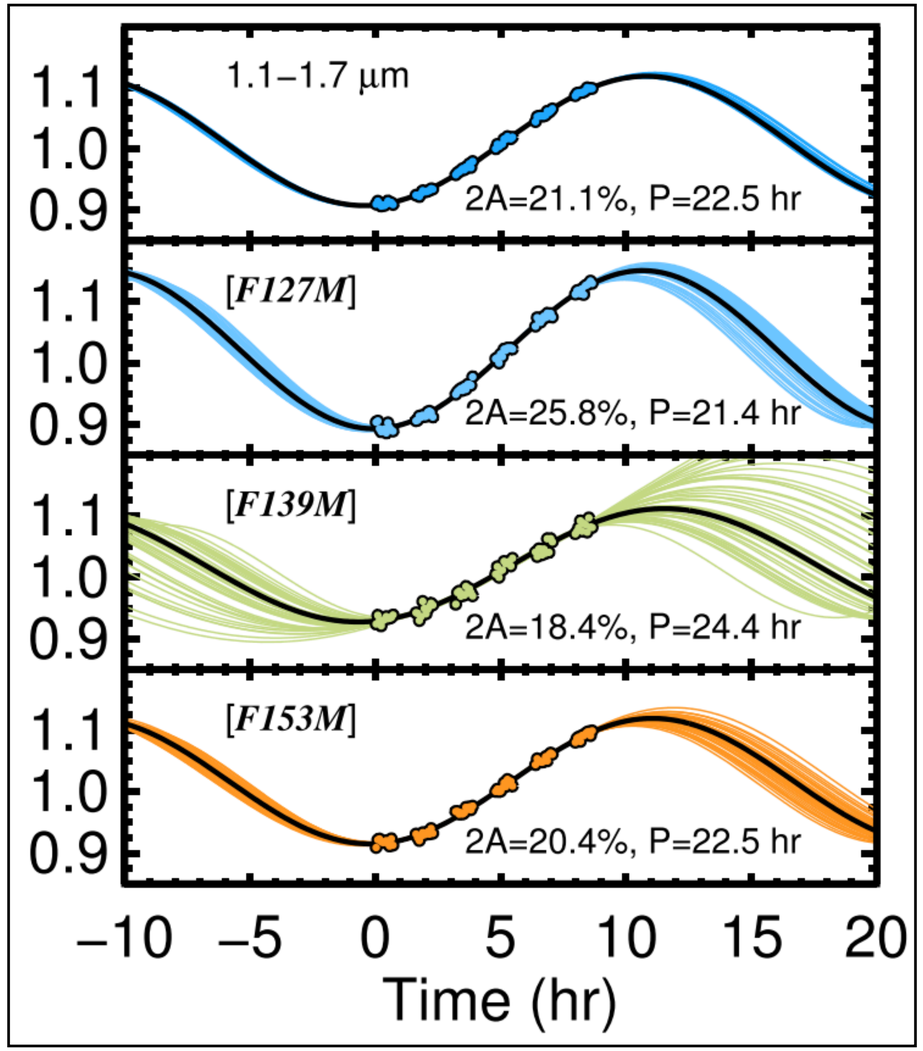
LIMITATION FROM **MODELS**

We need **extensions** of current grids to conclude

We need to **compare** these properties with the primary



Part 3 - The case of VHS 1256 b



Bowler et al. (2020)

LIMITATION FROM **DATA**

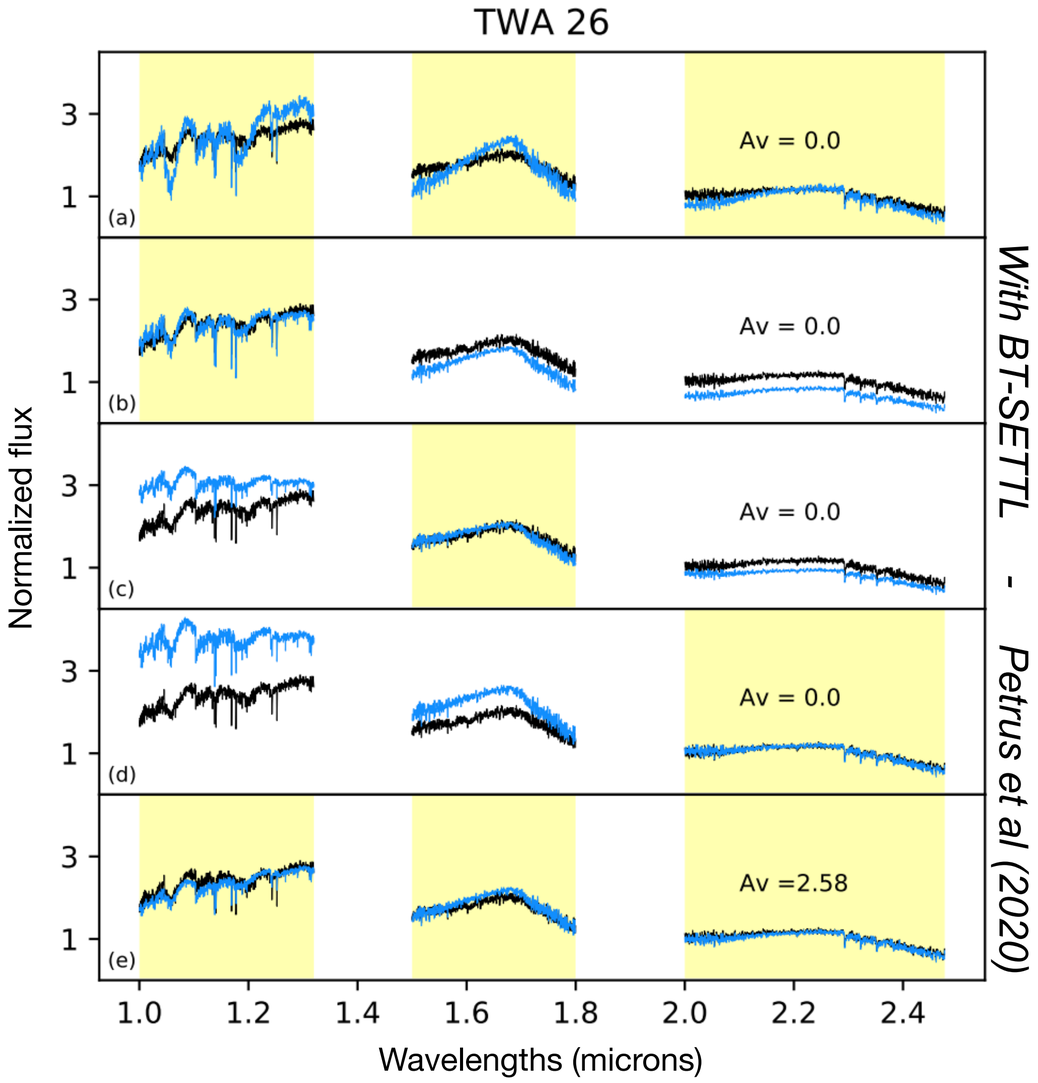
Variability

Complex atmosphere
(inhomogeneous cloud cover, local chemical disequilibrium, etc.)

Parameters estimate representative of the atmosphere?

Part 3 - The case of VHS 1256 b

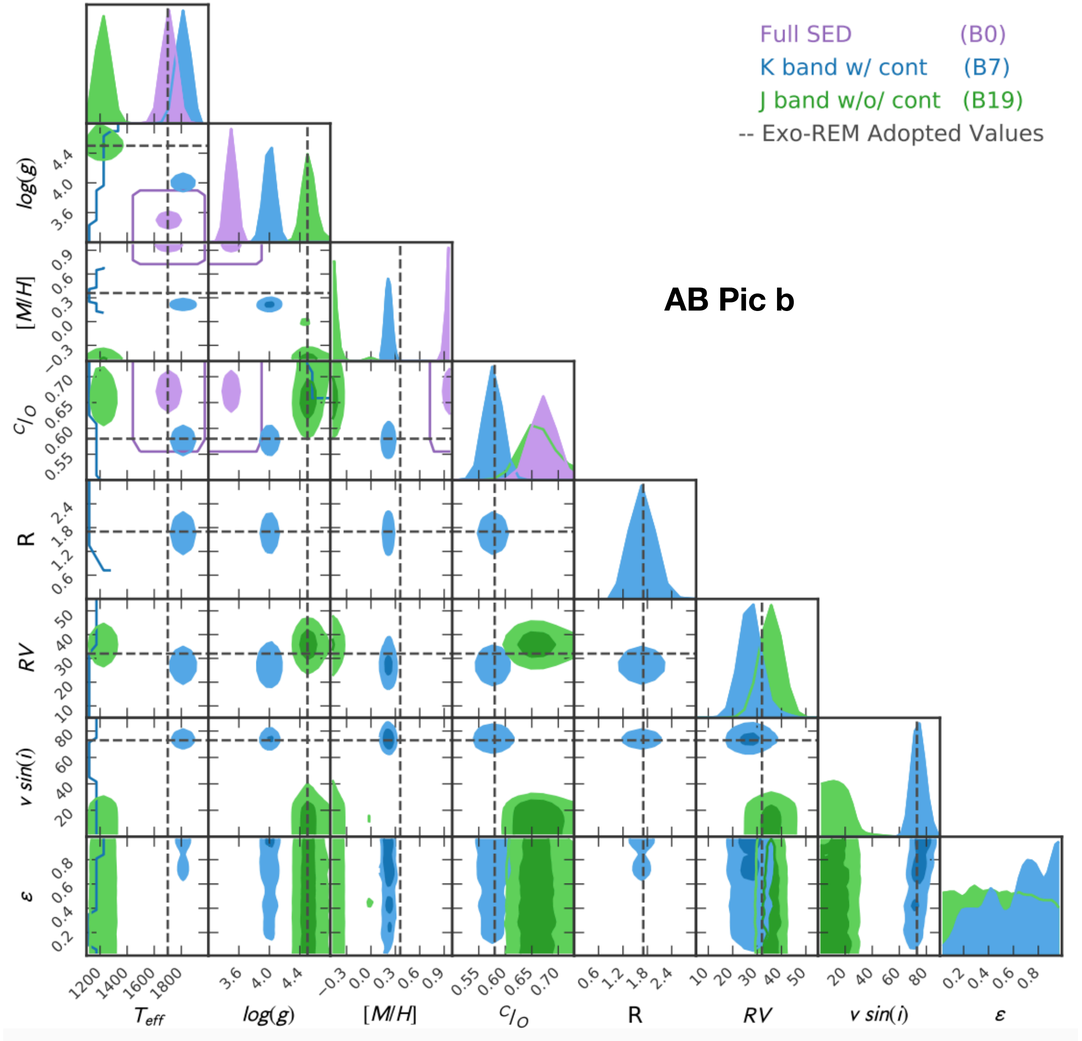
There are systematics in models



With BT-SETTL - Petrus et al (2020)

LIMITATION FROM **MODELS**

These systematics impact the estimate of the atmospheric properties and then their interpretations



With Exo-REM - Palma-Bifani et al (2022)