Where is the Water? Jupiter-like C/H ratio but strong H_2O depletion found on τ Boötis b using SPIRou

Stefan Pelletier, Björn Benneke, Antoine Darveau-Bernier, Anne Boucher, Neil Cook, Caroline Piaulet, Louis-Philippe Coulombe, Étienne Artigau , David Lafrenière, Simon Delisle, Romain Allart, René Doyon, Jean-François Donati, Pascal Fouqué, Claire Moutou, Charles Cadieux, Xavier Delfosse, Guillaume Hébrard, Jorge H. C. Martins, Eder Martioli, Thomas Vandal

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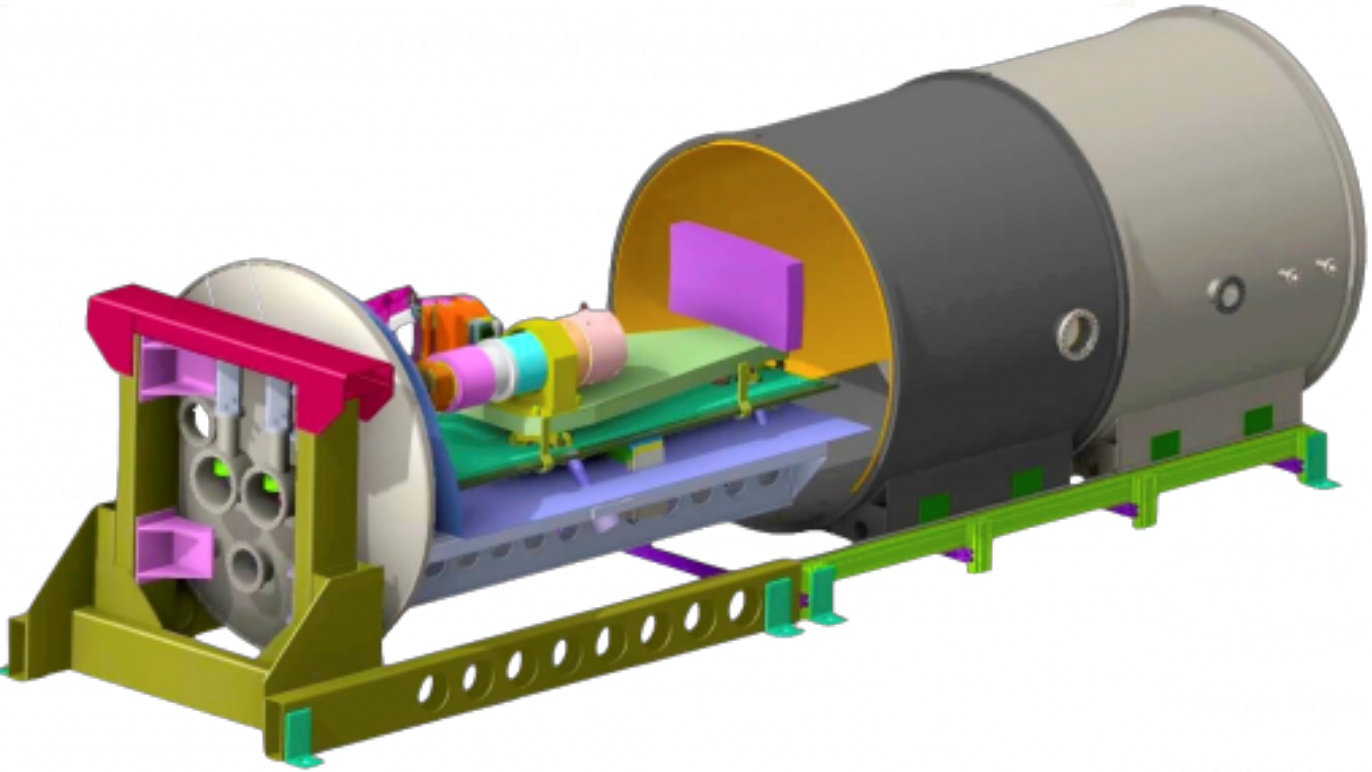
Atmo 2021, ESO

August 26th 2021

SPiRou



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SPIROU & FANTASIO 1

Where is the Water? Jupiter-like C/H but strong H_2O depletion found on τ Boo b

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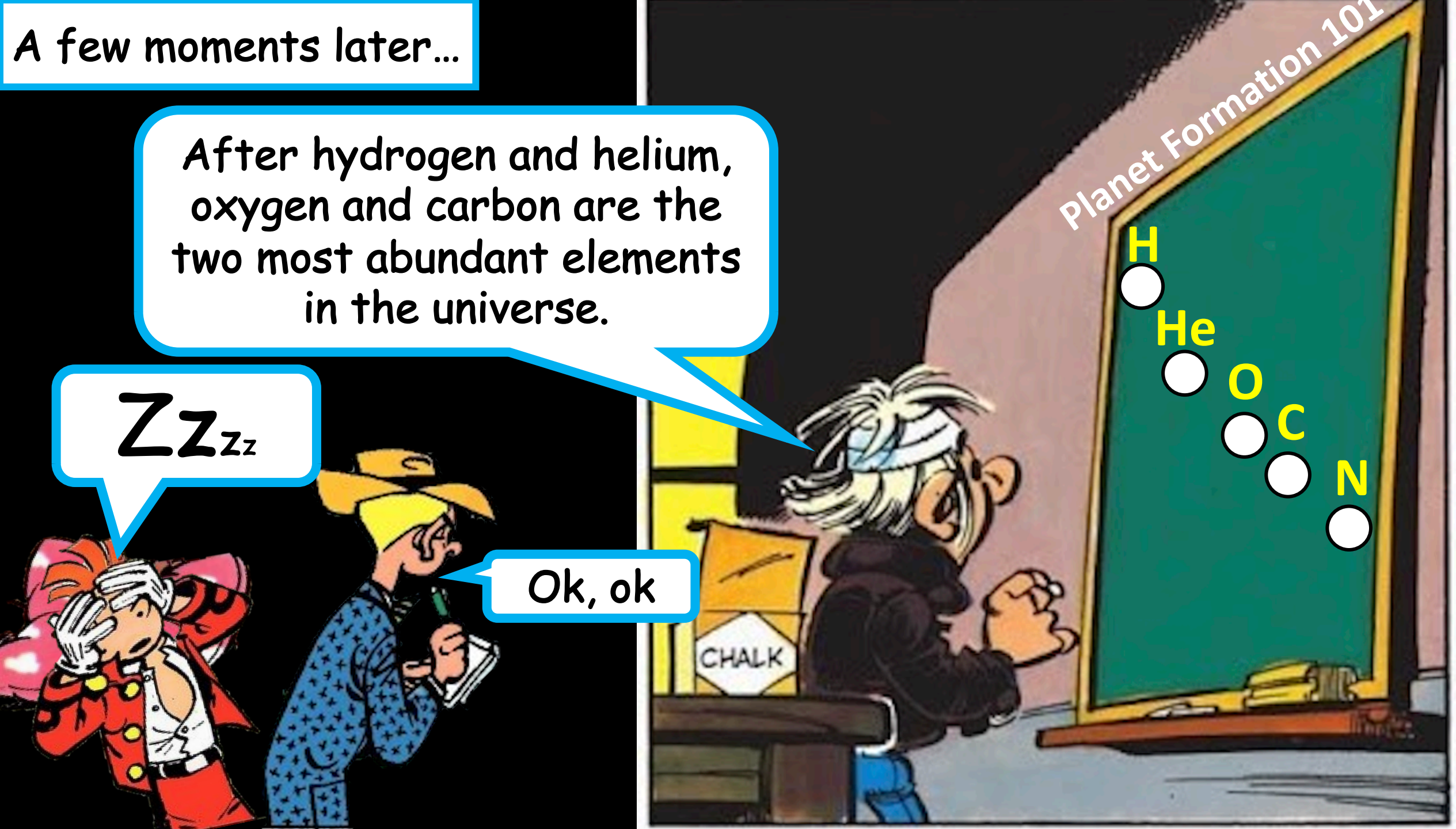
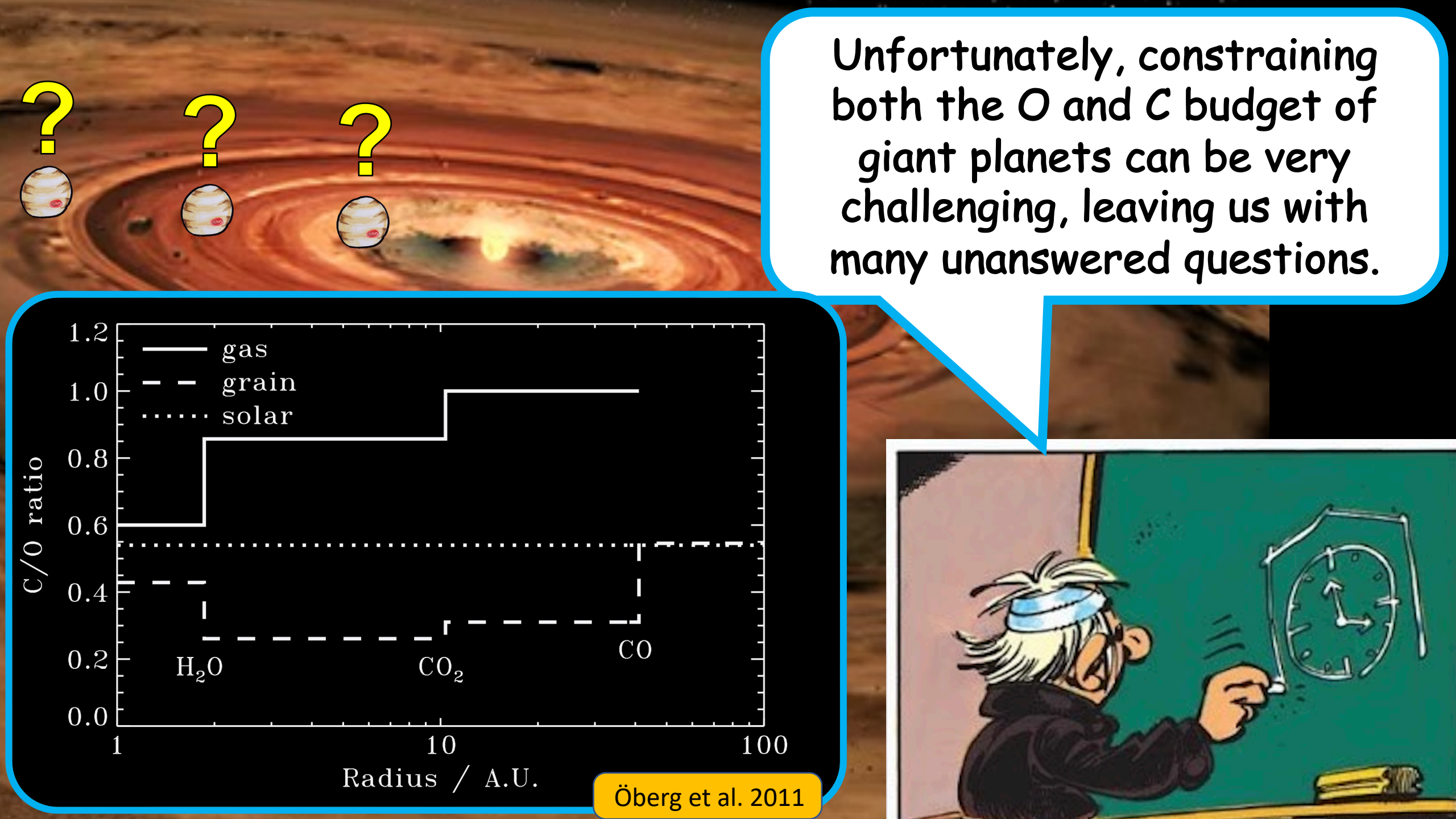
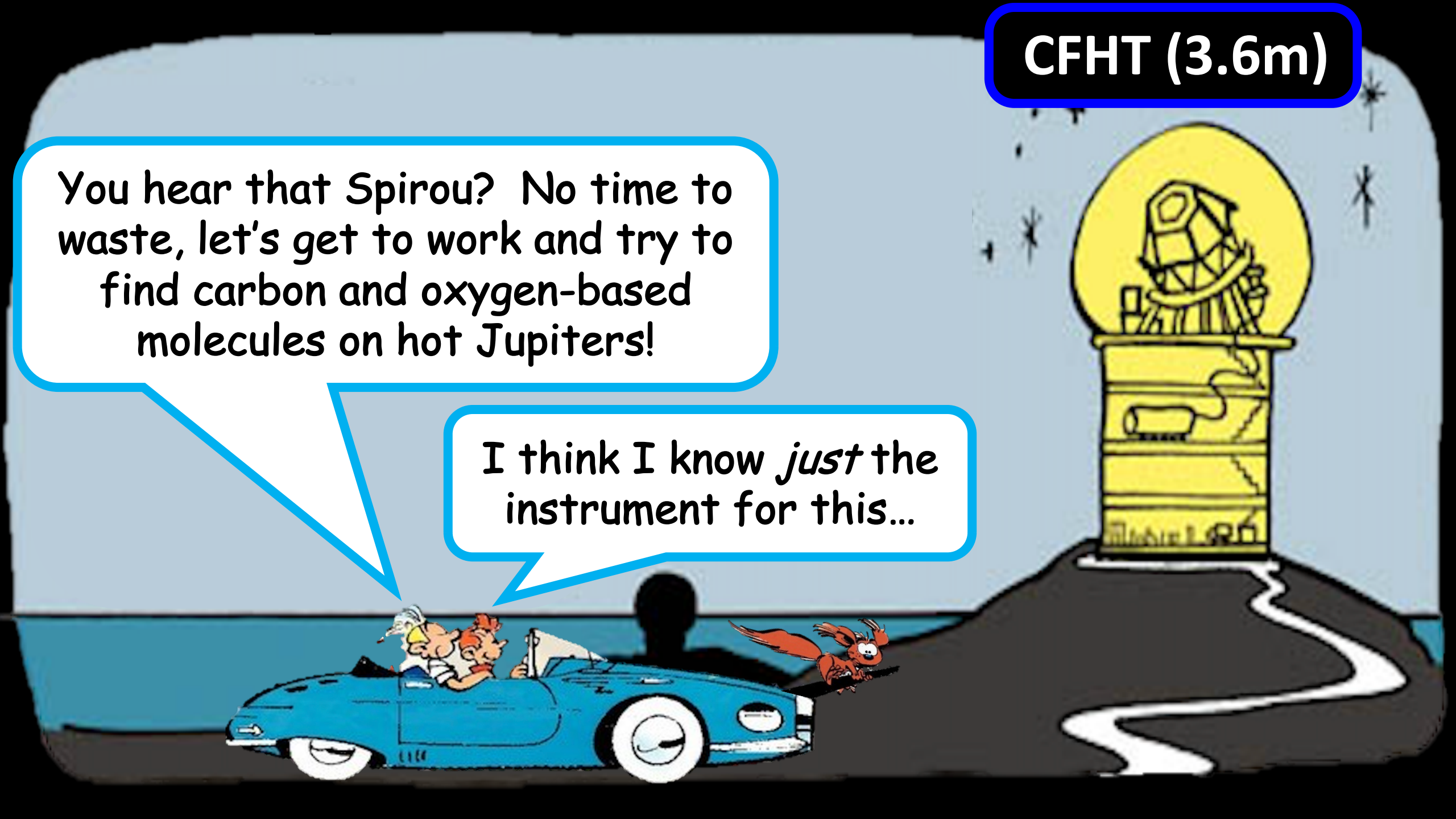
Stefan Pelletier


Ahhh, Spirou, wake up! We're going to be late to our class on giant planet formation!!
?!?!!!!


A few moments later...
After hydrogen and helium, oxygen and carbon are the two most abundant elements in the universe.
Zzzz
Ok, ok
Planet Formation 101
H
He
O
C
N
CHALK


?
?
?
Unfortunately, constraining both the O and C budget of giant planets can be very challenging, leaving us with many unanswered questions.
1.2
1.0
0.8
0.6
0.4
0.2
0.0
C/O ratio
gas
grain
solar
H_2O
CO_2
CO
1
10
100
Radius / A.U.
Öberg et al. 2011

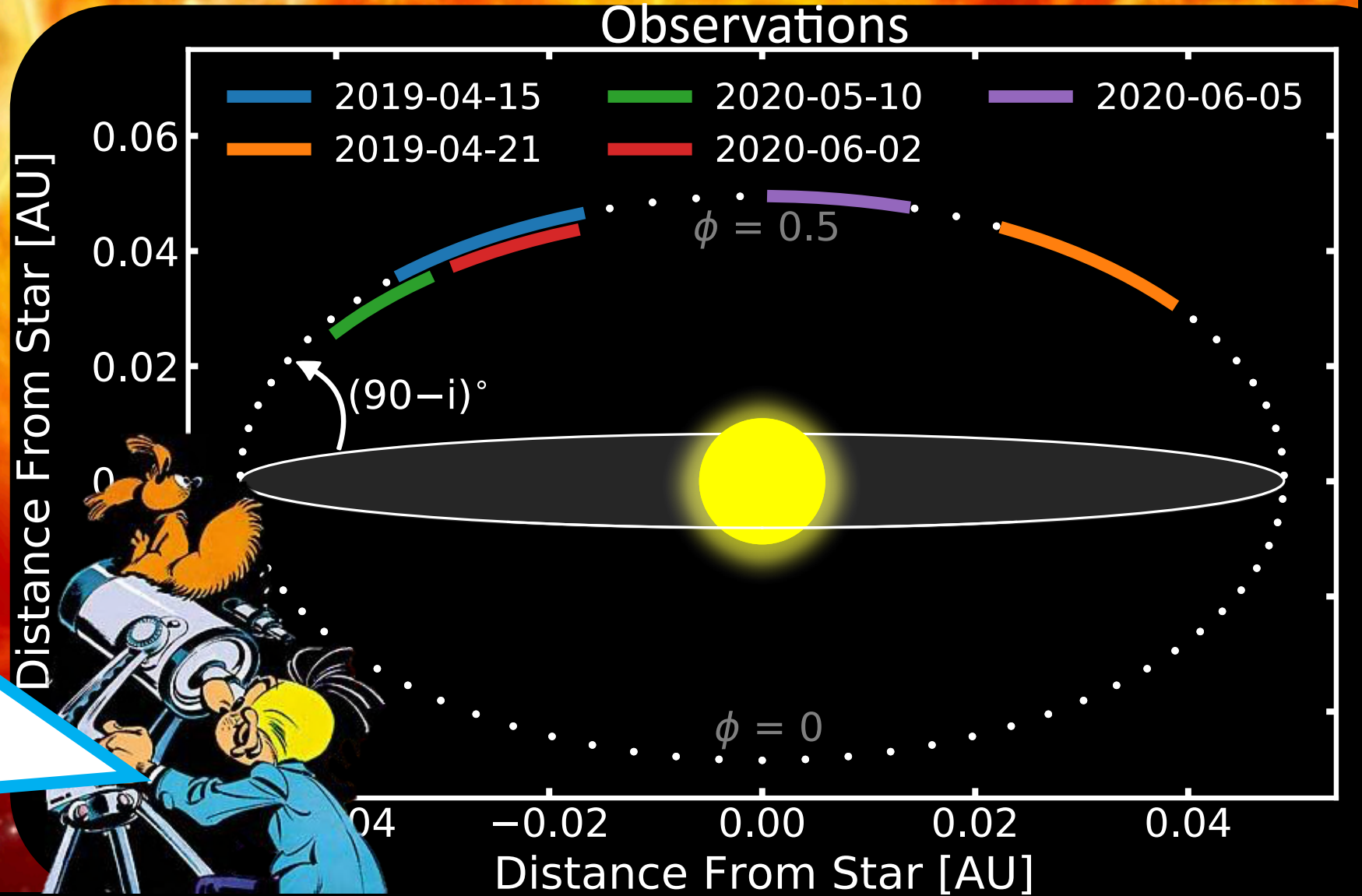

CFHT (3.6m)
You hear that Spirou? No time to waste, let's get to work and try to find carbon and oxygen-based molecules on hot Jupiters!
I think I know *just* the instrument for this...

SPIRou Observations of τ Boo b

τ Boo b

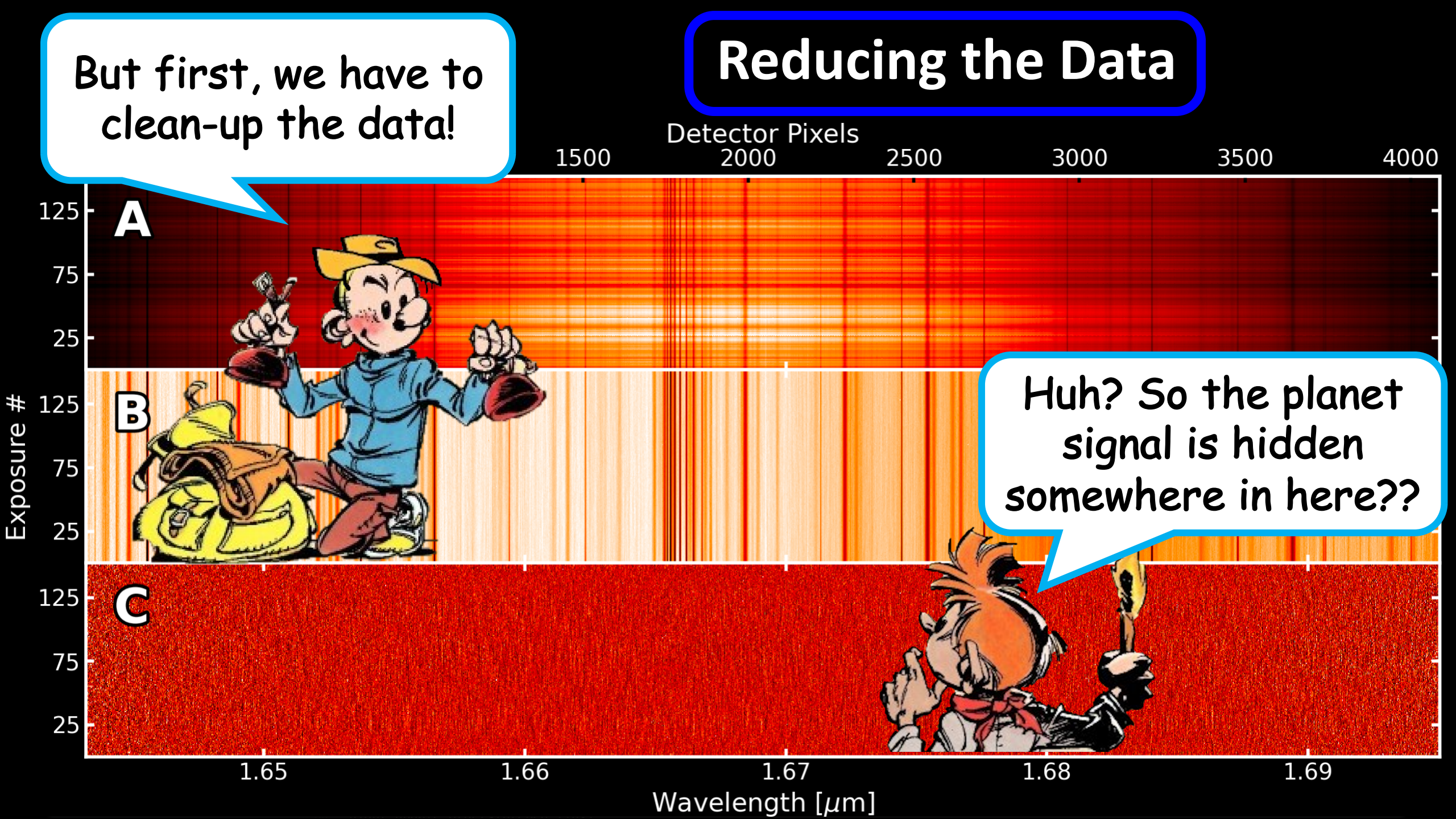
SPIRou

1 – 2.5μm
R = 70,000
Thermal emission
5 nights/20 hours



Reducing the Data

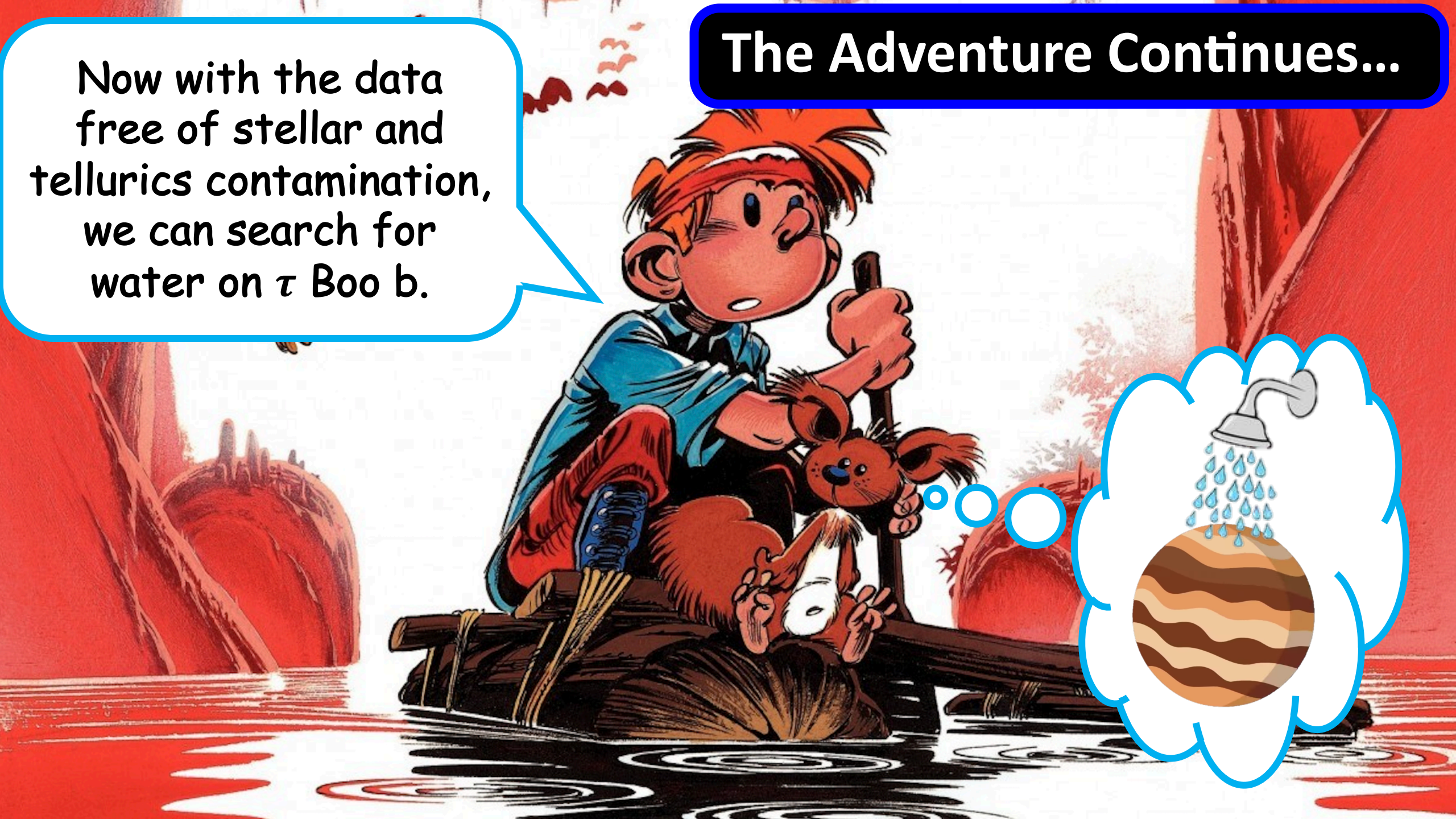
But first, we have to clean-up the data!



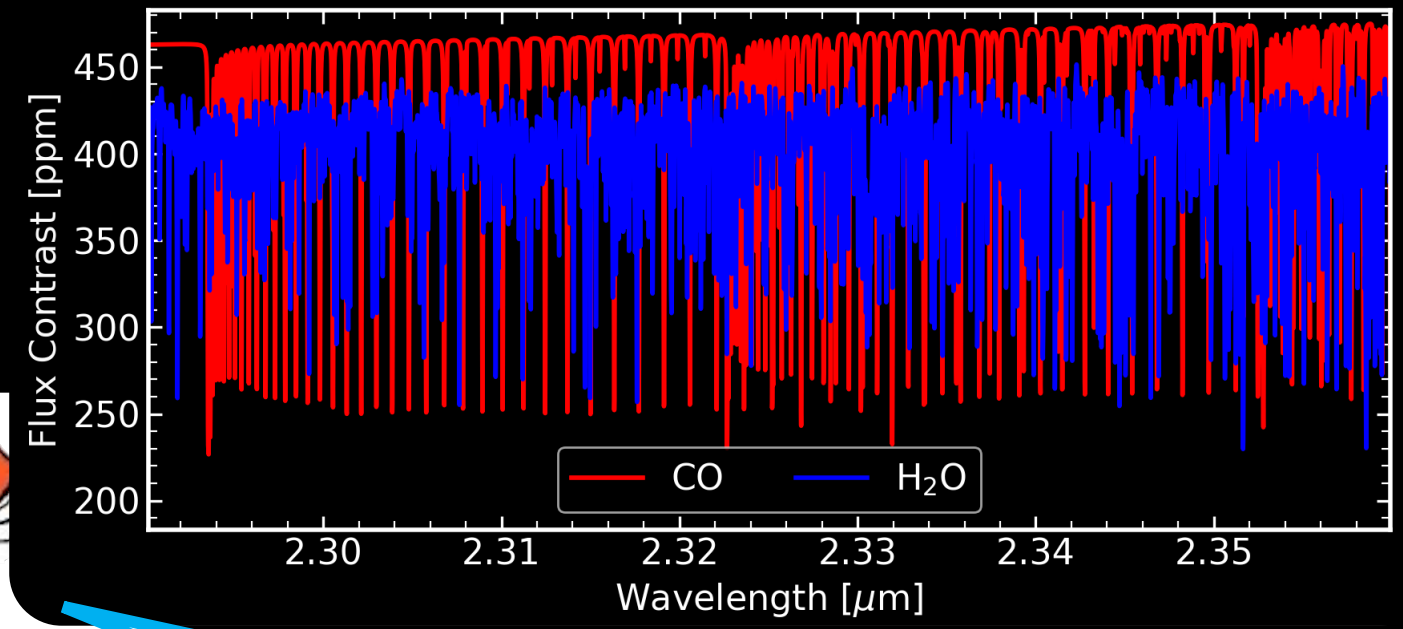
Huh? So the planet signal is hidden somewhere in here??

The Adventure Continues...

Now with the data free of stellar and tellurics contamination, we can search for water on τ Boo b.



Atmospheric Models

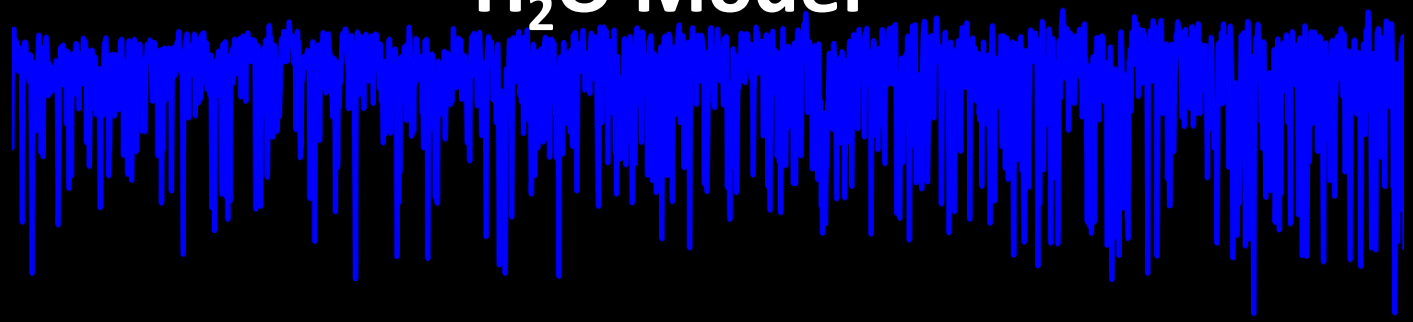


We use the SCARLET framework to generate atmospheric models of τ Boo b.

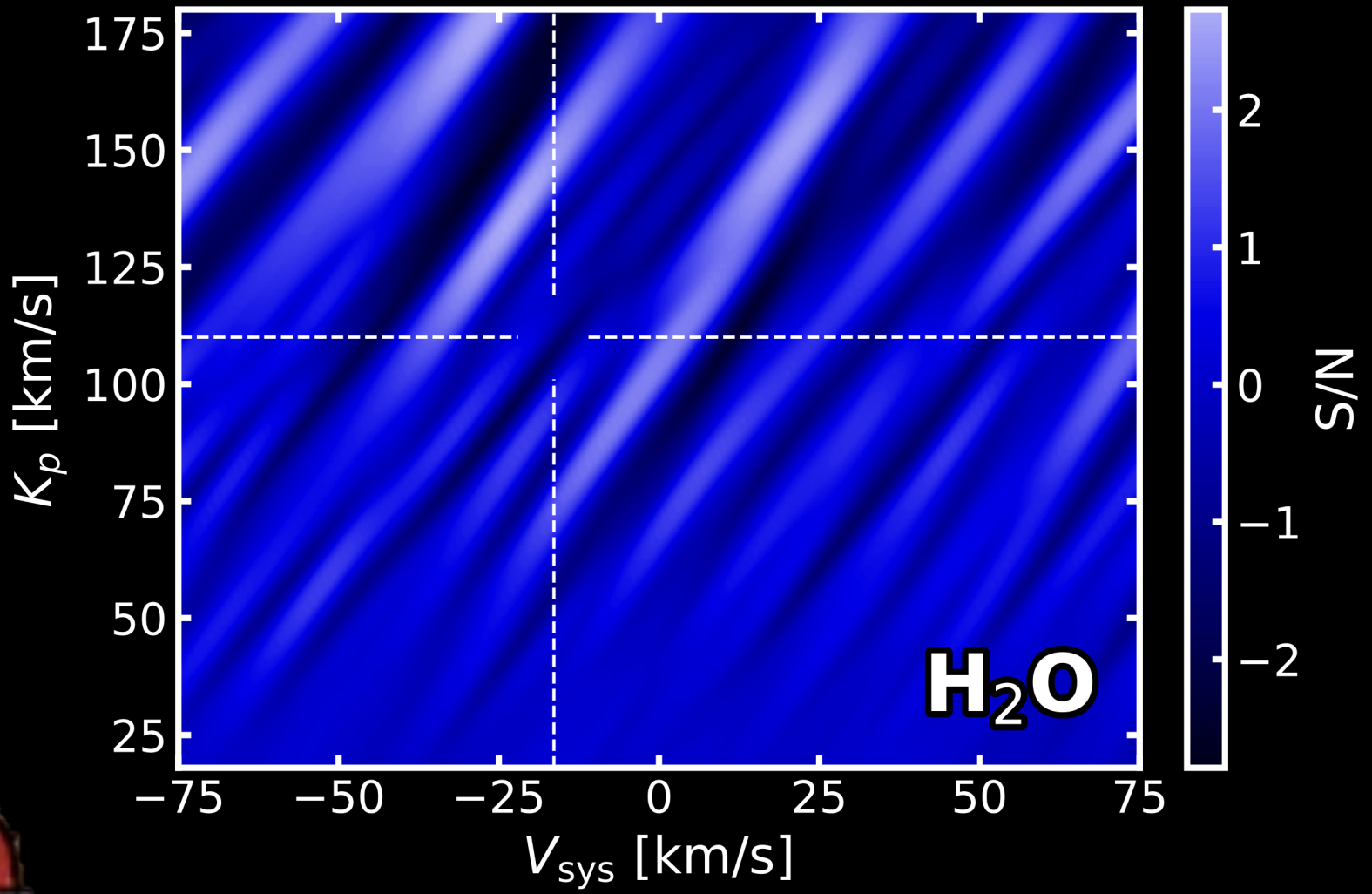
```
for i in range(1000000):
    print('Atmospheres, Atmospheres! Do I look...')
```

Cross-Correlation Search for Water ☹

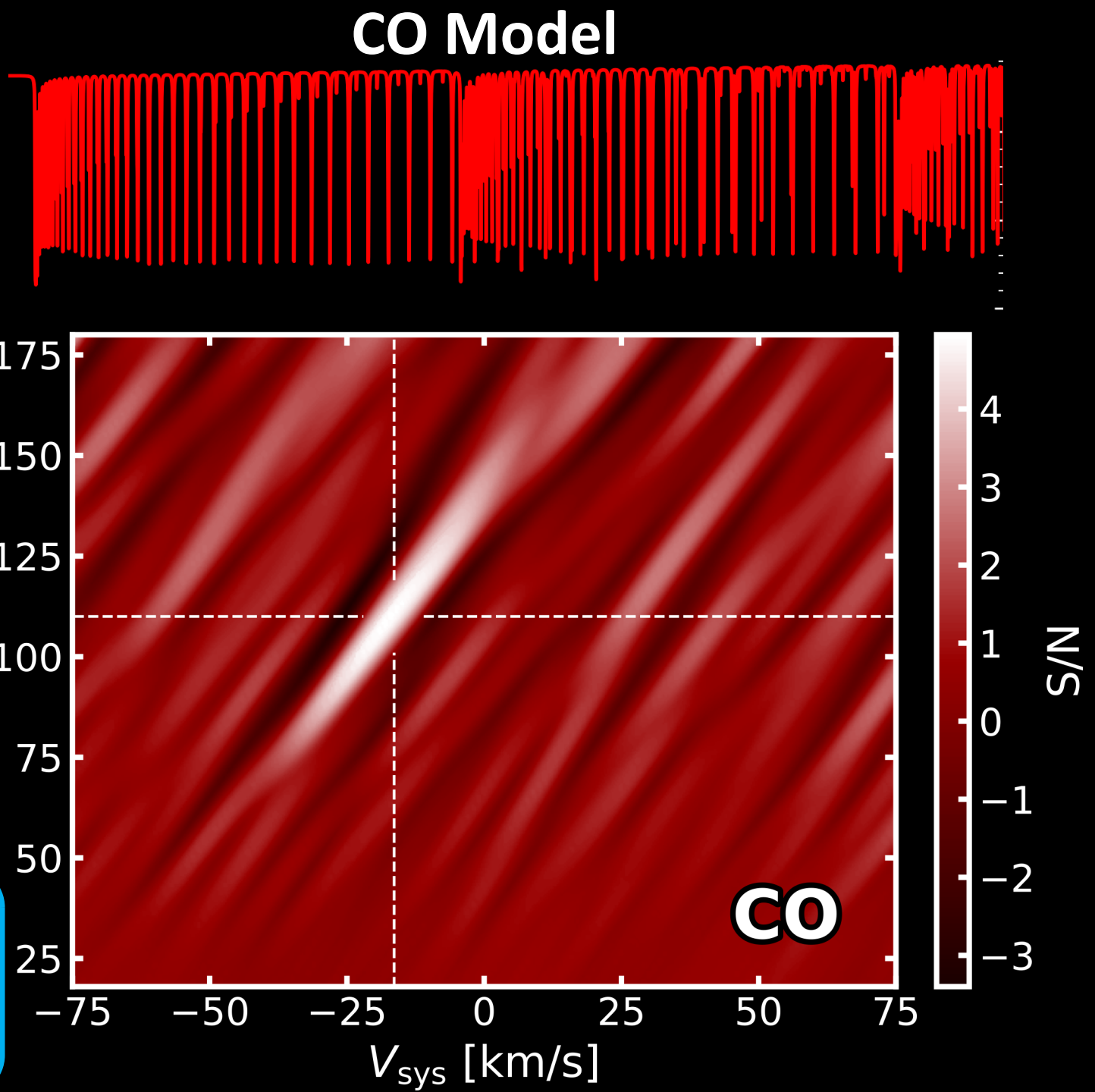
H_2O Model



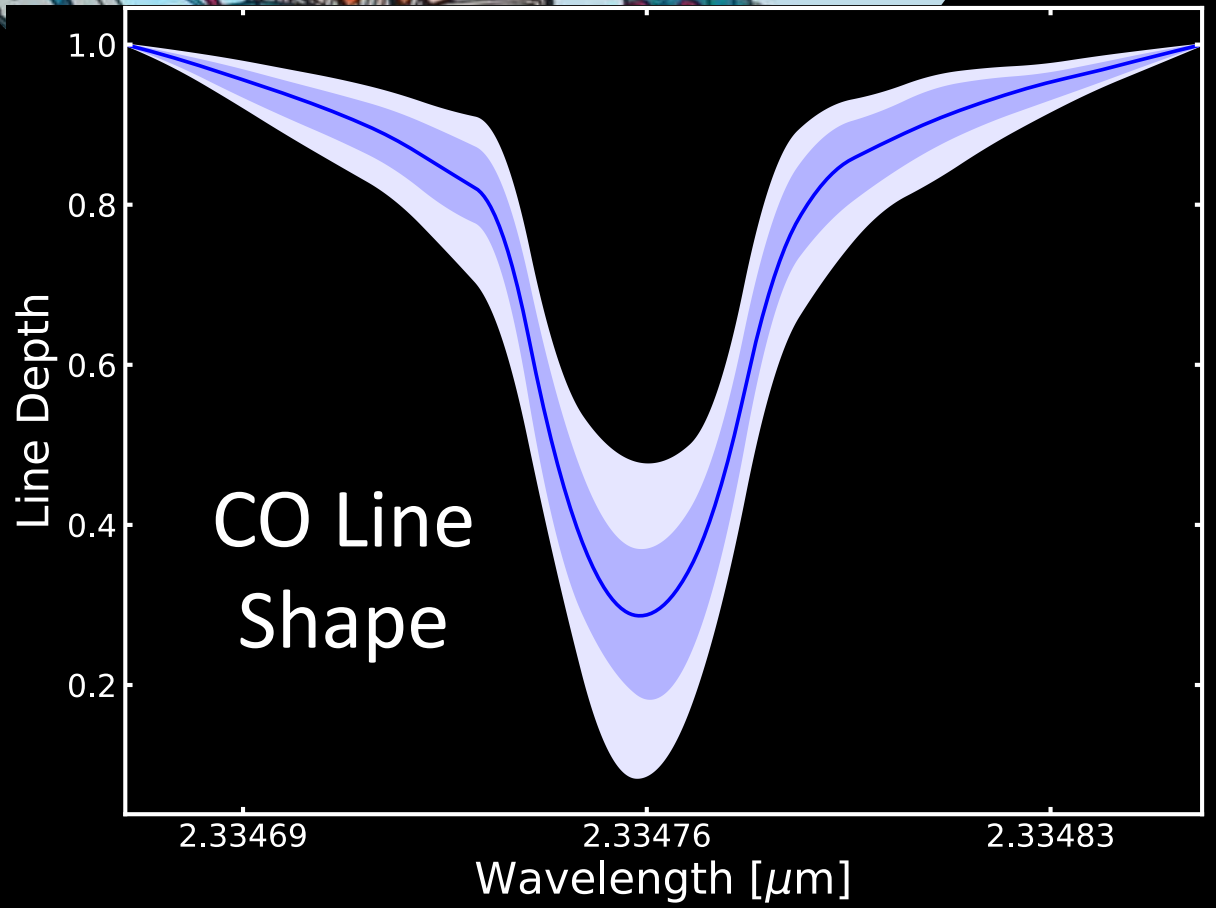
Huh??? No water at the known planet location?!? That's unexpected!

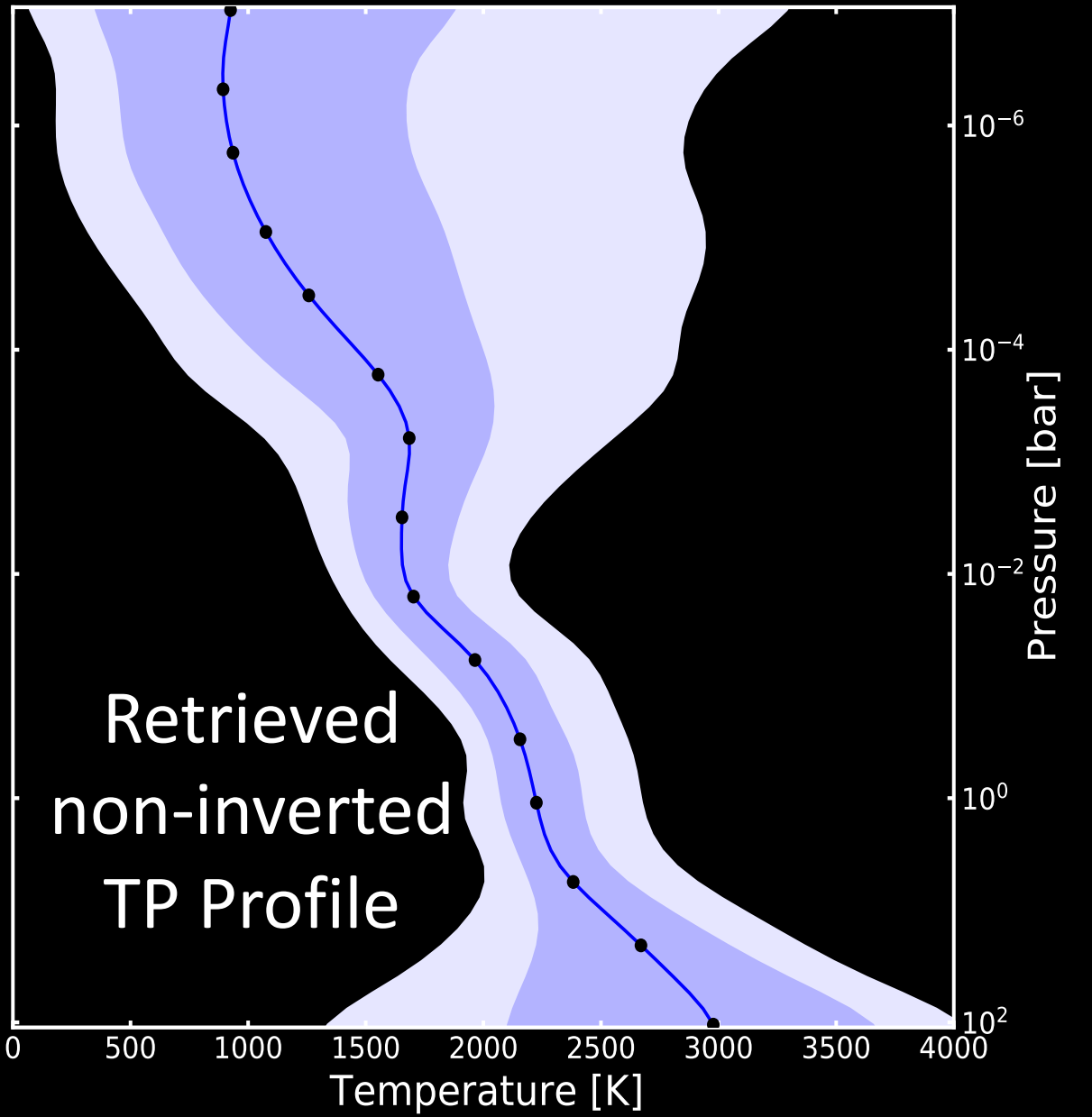


Cross-Correlation Search for CO 🙂

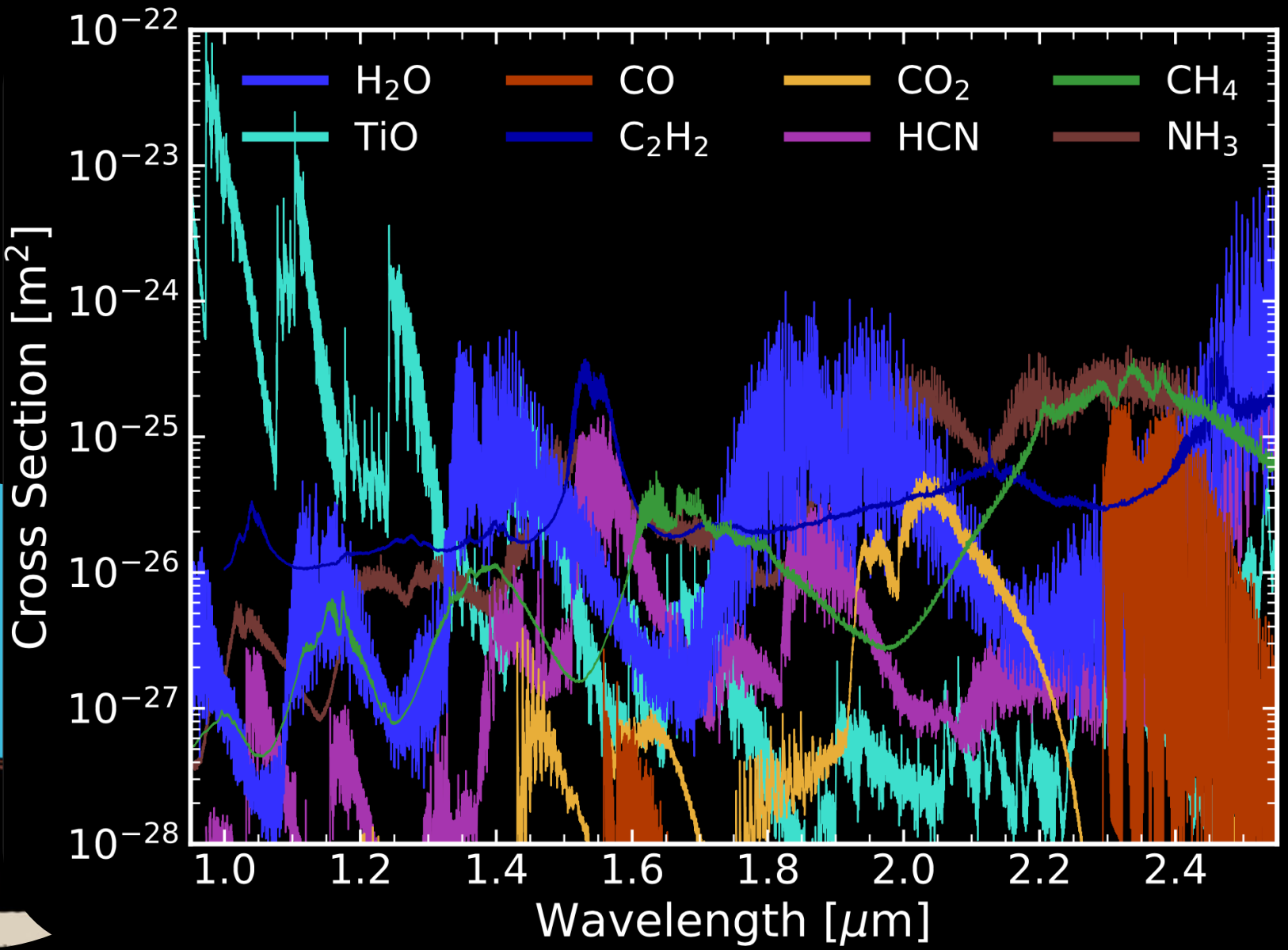


CO line shape --> TP profile



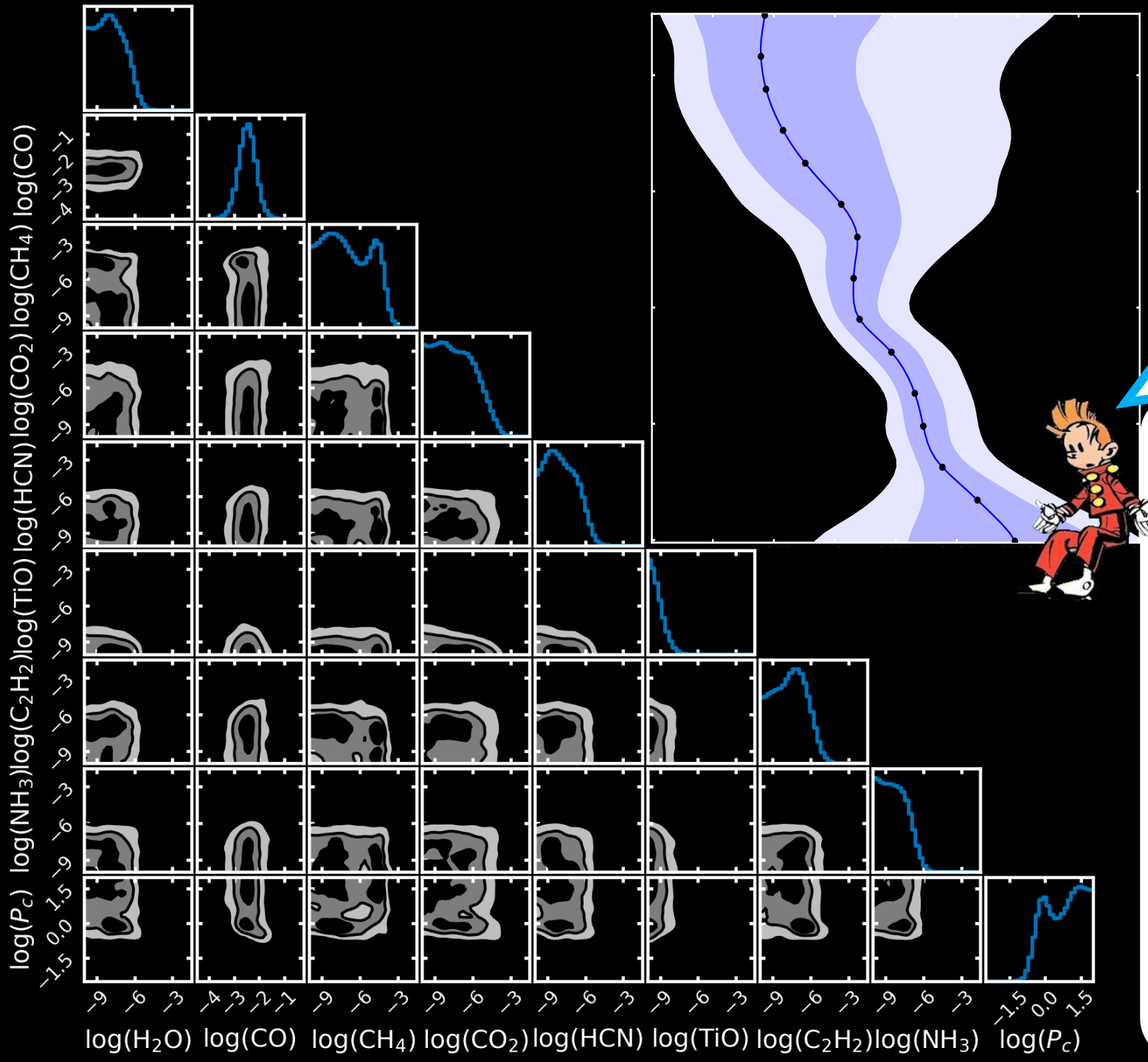


What about other Molecules?



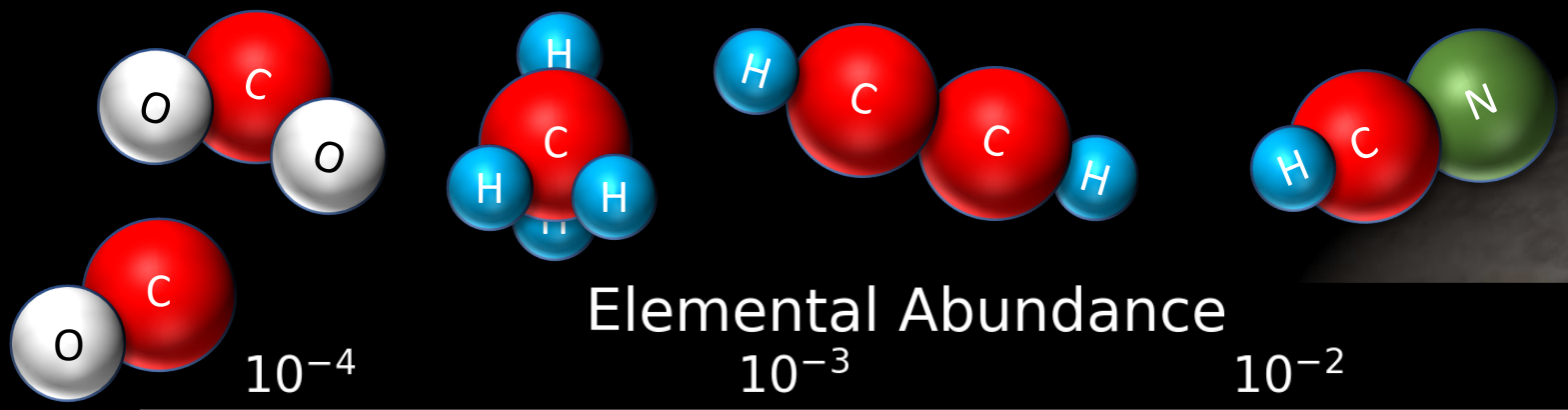
Full Retrieval Results

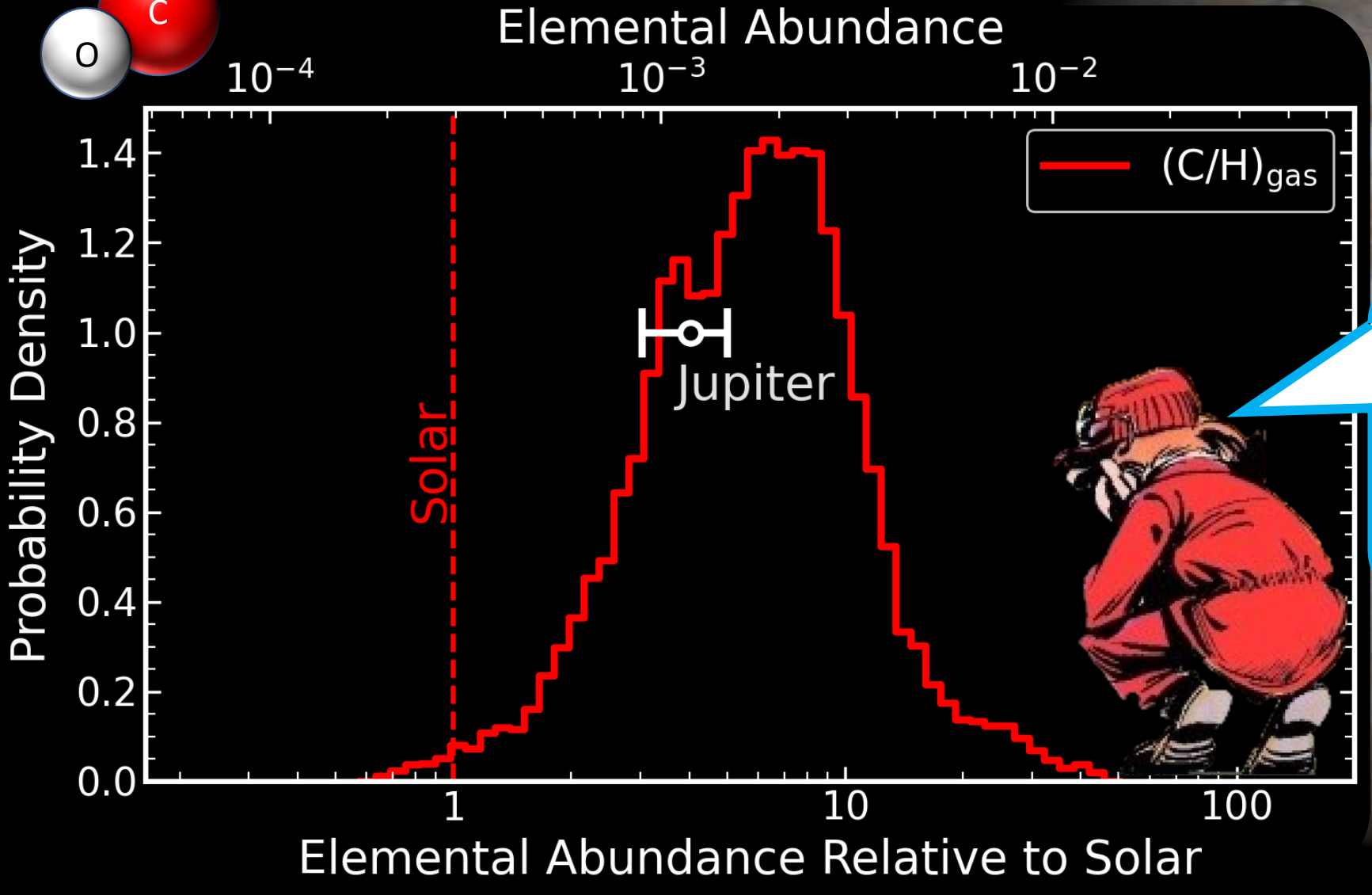
CO ~5 times solar
H_2O <0.007 times solar
No other molecules
Relatively cloud-free



Parameter	Value
VMR log(CO)	$-2.46^{+0.25}_{-0.29}$
VMR log(H_2O)	< -5.66 (3σ upper limit)
VMR log(CH_4)	< -3.78 (3σ upper limit)
VMR log(CO_2)	< -3.99 (3σ upper limit)
VMR log(HCN)	< -5.37 (3σ upper limit)
VMR log(TiO)	< -7.54 (3σ upper limit)
VMR log(C_2H_2)	< -4.88 (3σ upper limit)
VMR log(NH_3)	< -6.10 (3σ upper limit)
Cloud-Top Pressure (P_c)	> 0.26 bar (3σ lower limit)
Scaling Parameter (a)	1.04 ± 0.03
Keplerian Velocity (K_p)	$109.2 \pm 0.4\,\mathrm{km\,s^{-1}}$
Systemic Velocity ($V_{\rm sys}$)	$-15.4 \pm 0.2\,\mathrm{km\,s^{-1}}$

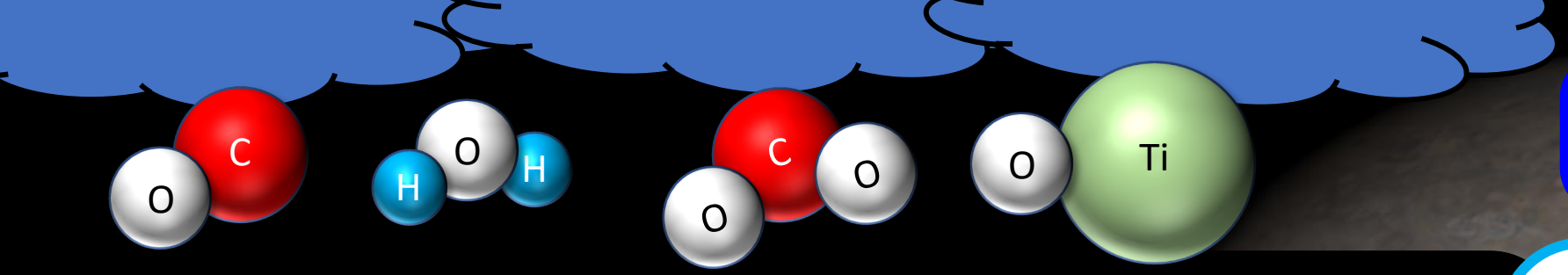
C/H Inference

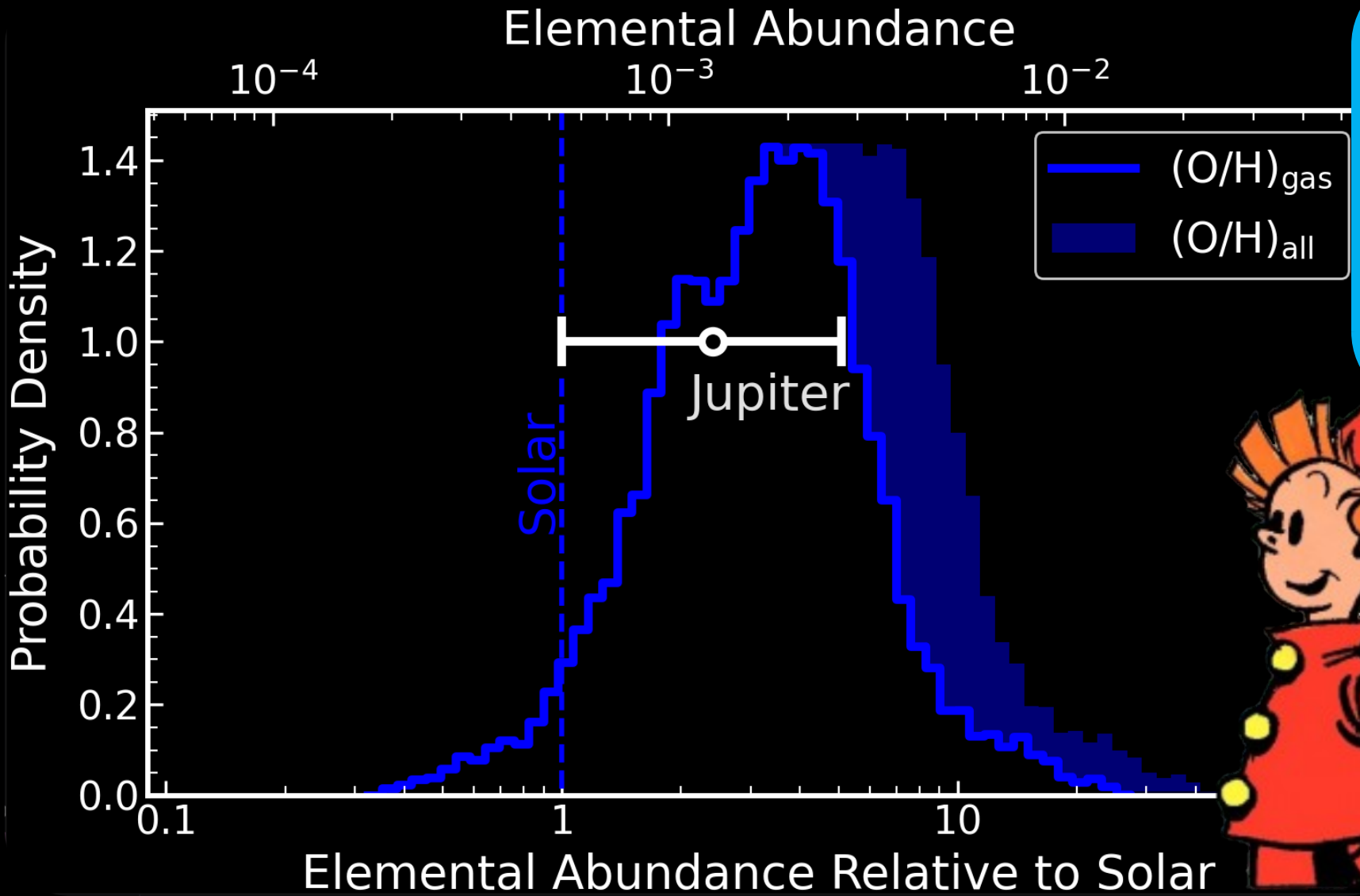




τ Boo b's C/H ratio is ~3-10 times solar and consistent with the value of Jupiter.

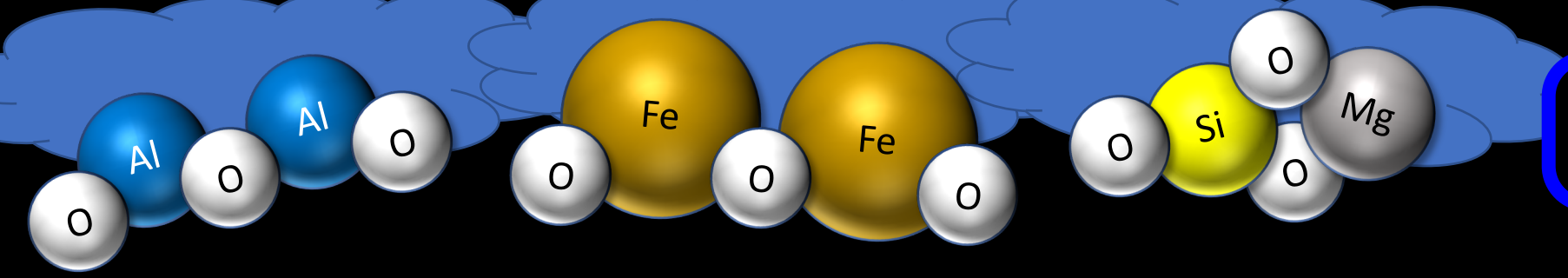
O/H Inference

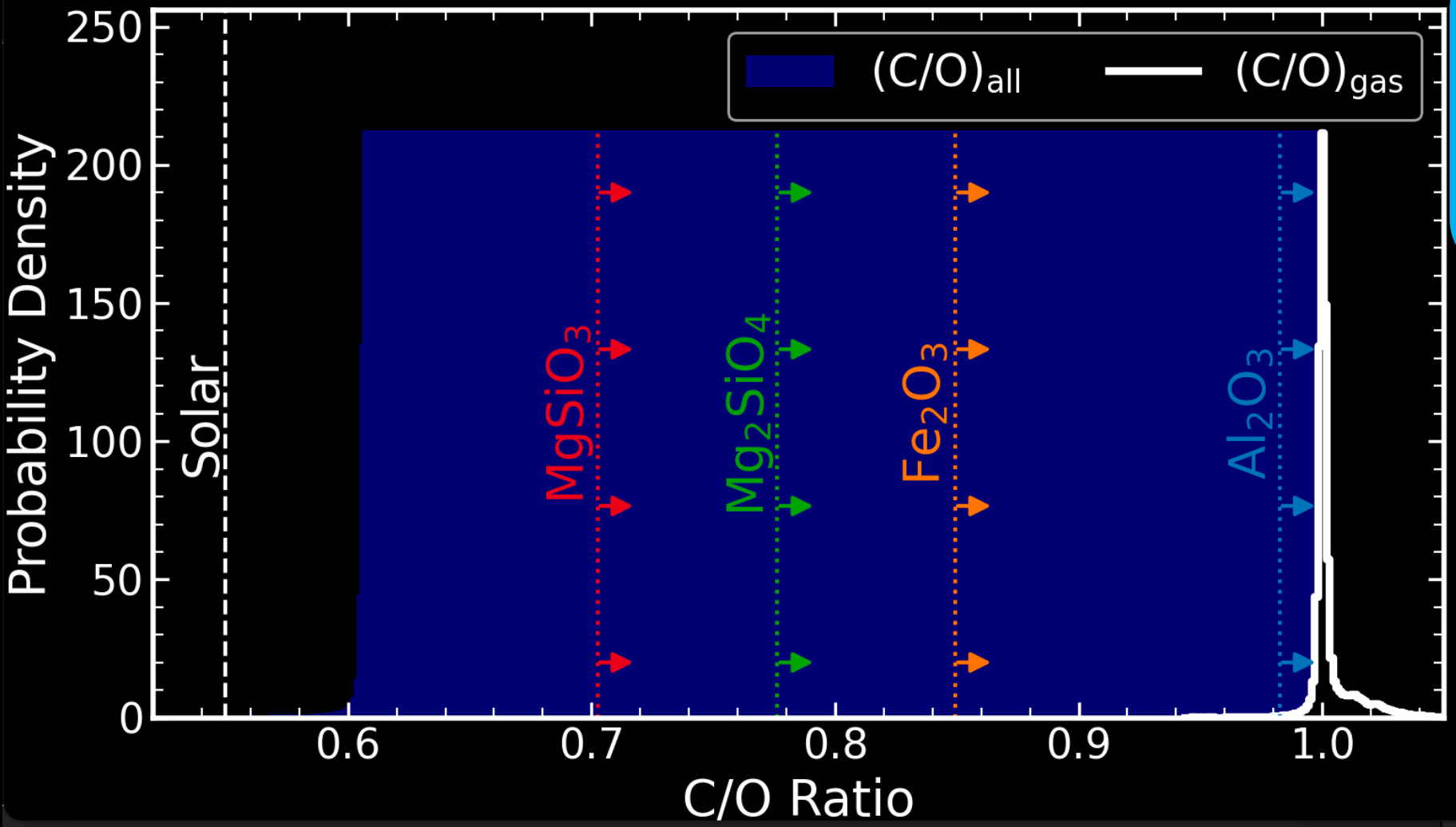




Similarly, we find a O/H ratio 2-12 times solar, consistent with the recent JUNO results for Jupiter.

C/O Inference





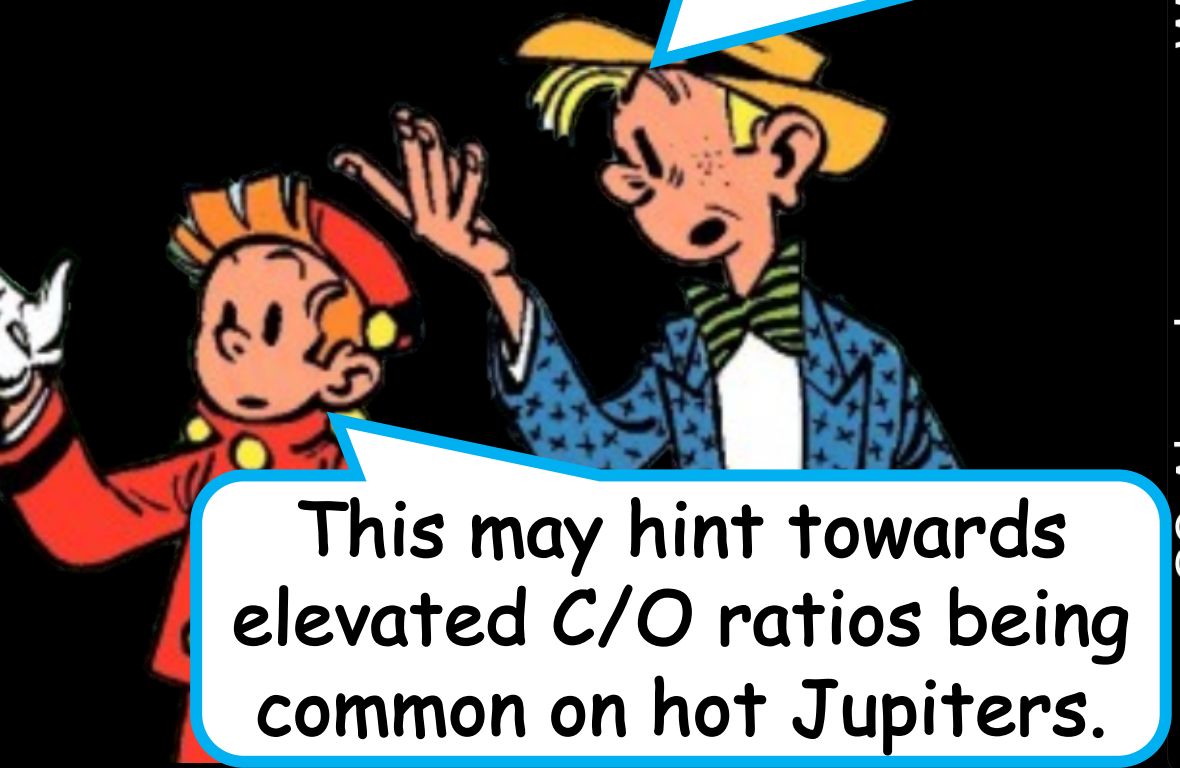
τ Boo b C/O ratio

Gas-phase: ~1

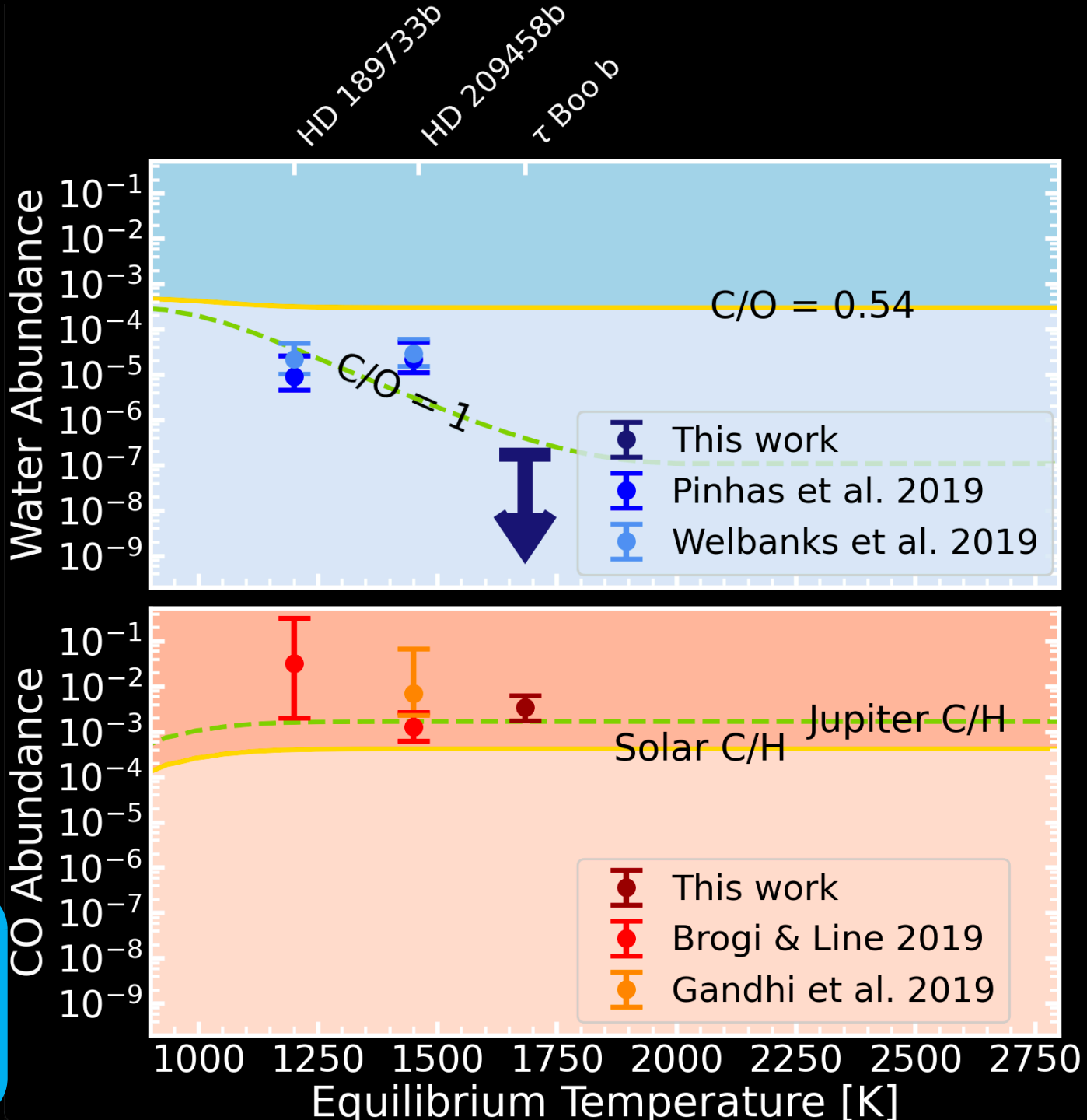
Envelope: $\geq$0.6

τ Boo b in Context

HD 189733b, HD 209458b, and τ Boo b all seem to follow a trend of elevated CO and depleted H_2O abundances.



This may hint towards elevated C/O ratios being common on hot Jupiters.



Link to Planet Formation

The combination of a super-solar C/O ratio AND a super-solar metallicity most likely indicates a formation scenario further out in the disk, possibly due to pebble drift, followed by disk-free migration.

Summary

- Super-solar abundance of CO found on τ Boo b using SPIRou
- Depletion of H_2O, the consequence of a super-solar C/O ratio (NOT a low metallicity)
- Favored formation mechanism: gas accretion beyond the iceline + disk-free migration

Image Credits: Spirou Comics