Why Brown Dwarfs Should Be Your Friends: Lessons Learned From Their Atmospheric Retrievals

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ExoExplorers Seminar Series June 11, 2021

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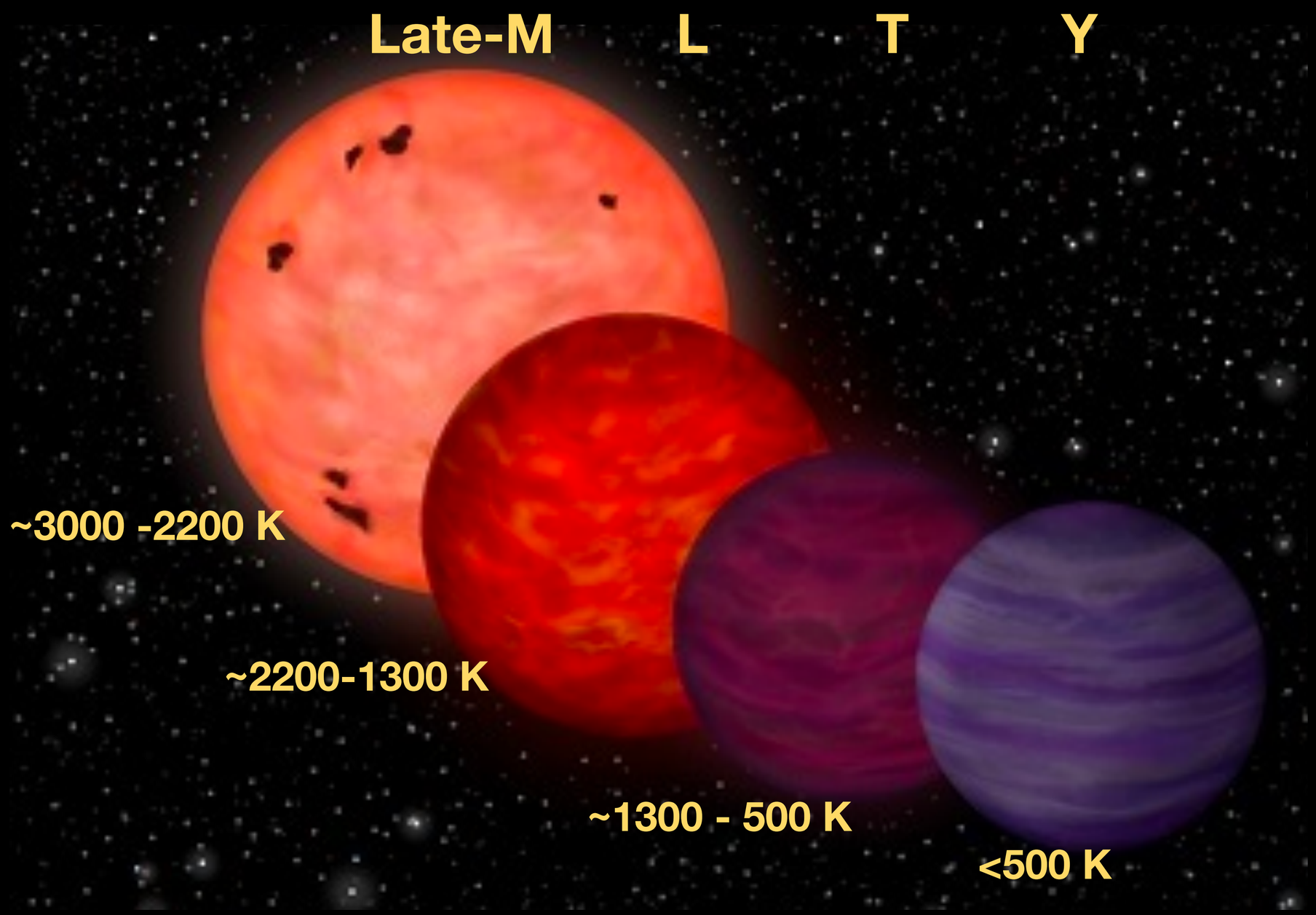
51 Pegasi b
Fellowship in Planetary Astronomy

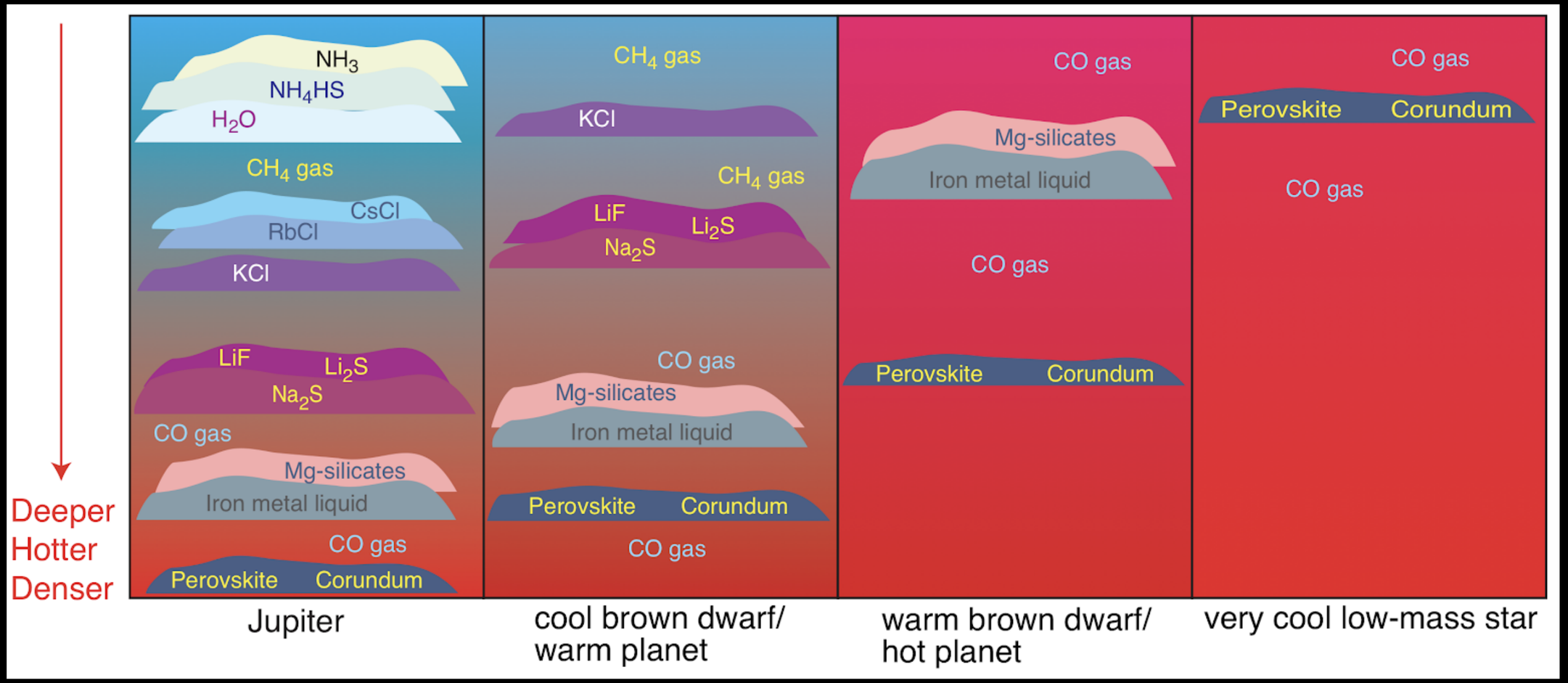
The Department of Astronomy

Brown Dwarfs



- Masses between those of stars and planets
- All have radii of ~1 R_{Jup}, but are more massive

Brown Dwarf Atmospheres

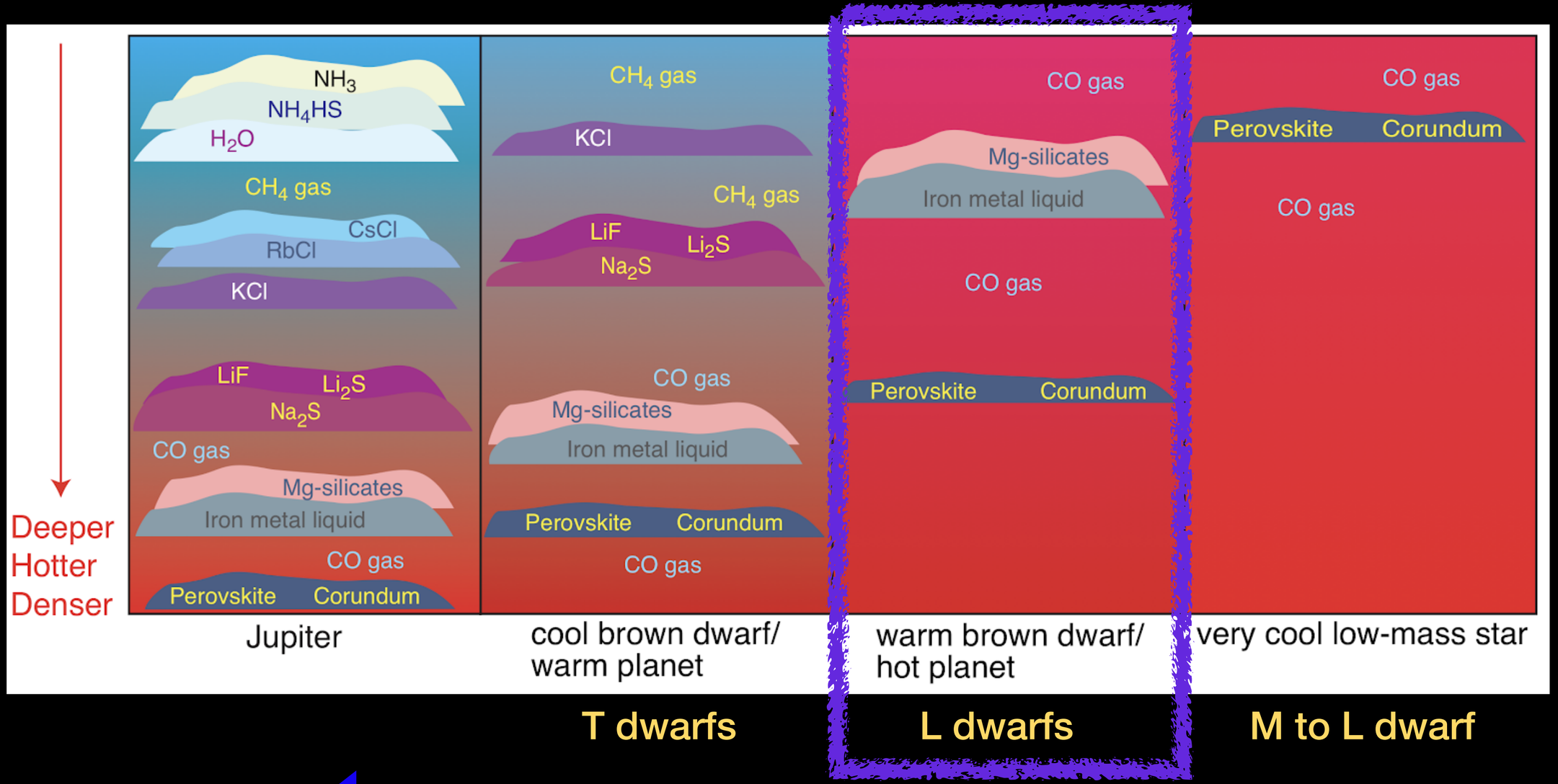


Modified from Lodders & Fegley (2006)

T dwarfs L dwarfs M to L dwarf

Cool ← Hot

Brown Dwarf Atmospheres



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A brief History of Atmospheric Retrievals

- Theoretical inverse spectral modeling technique that makes minimal assumptions about the physics involved

- Developed from remote sensing for Earth and solar system objects

- Many Exoplanet atmospheres examined
    - Transiting exoplanets
    - Directly imaged exoplanets

- Brown dwarf retrievals are relatively new
        - CHIMERA- T and Y dwarfs
        - *Brewster*- L and T dwarfs
        - Helios-r2- T dwarfs
        - Modified HyDRA- Single T dwarf
        - PETRA- 2 transiting brown dwarfs

How do Retrievals work?

Spectrum + Assumed Gases = Thermal profile + Gas Abundances

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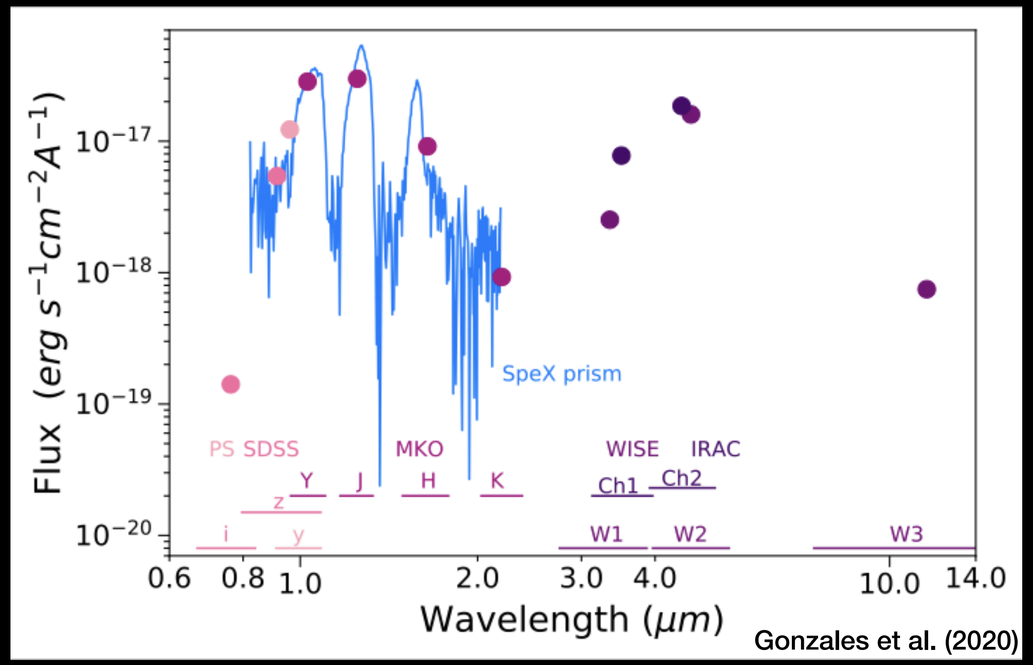

Gonzales et al. (2020)

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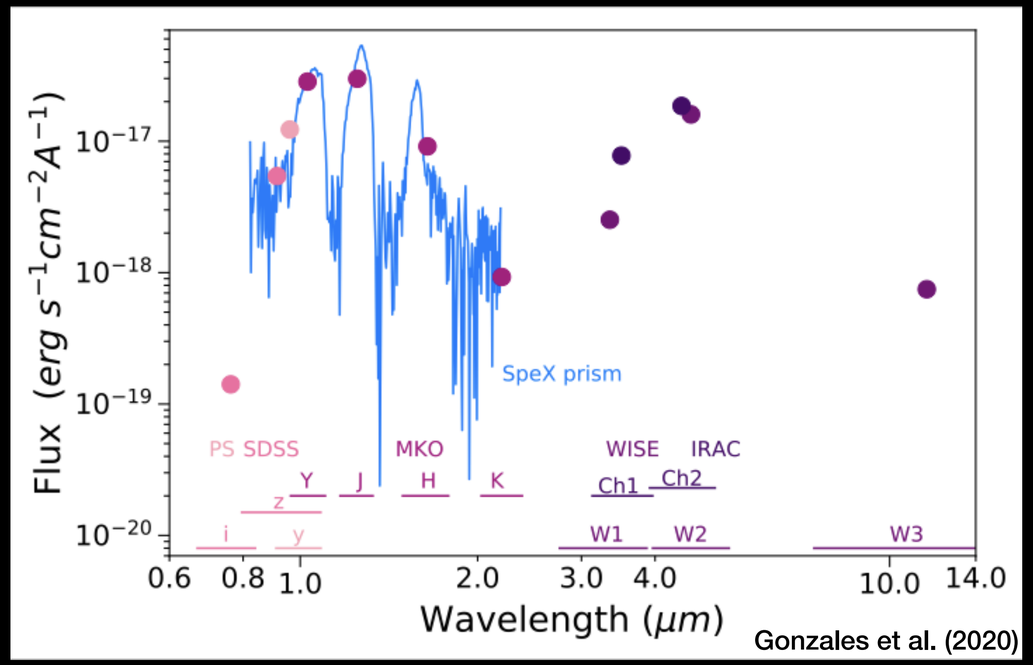

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NH_3 Na K

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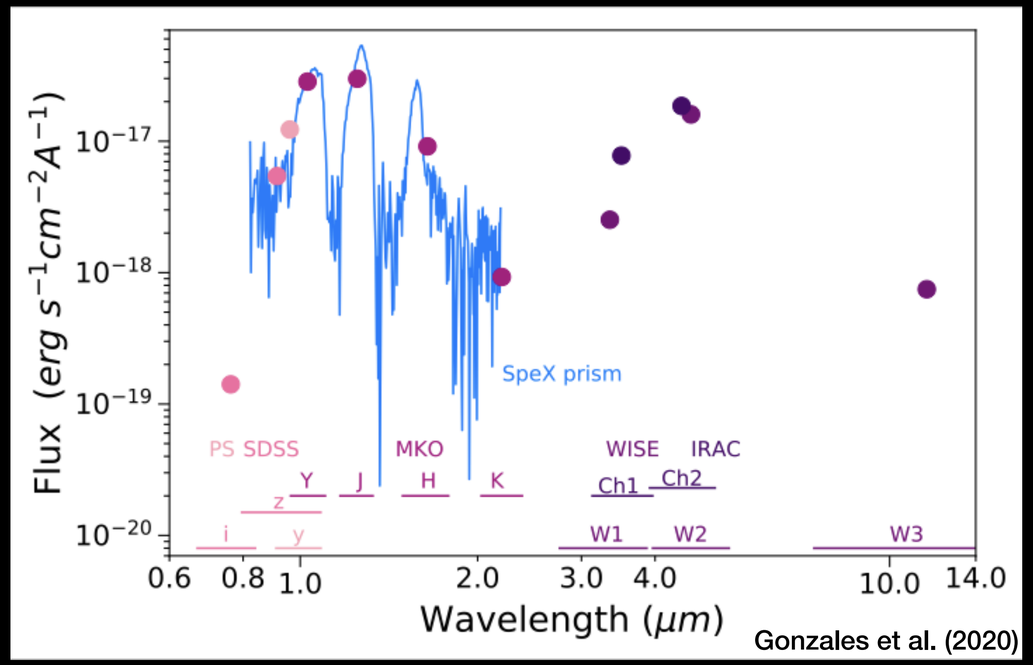

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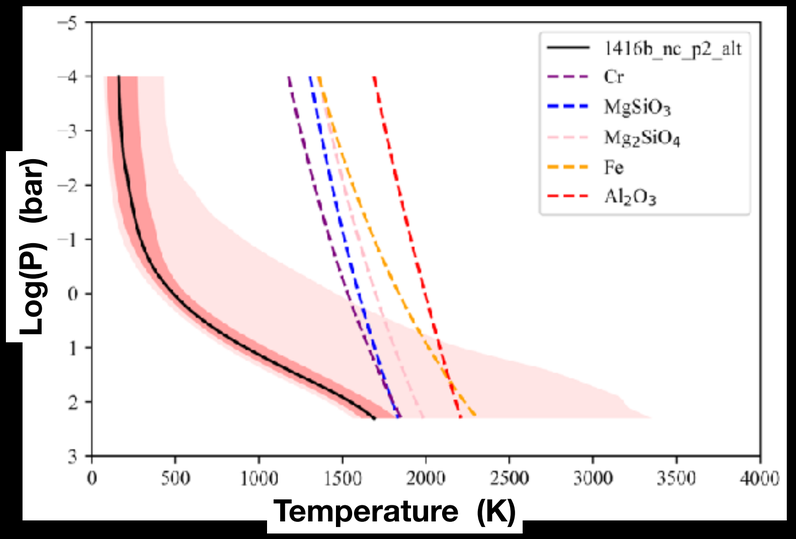

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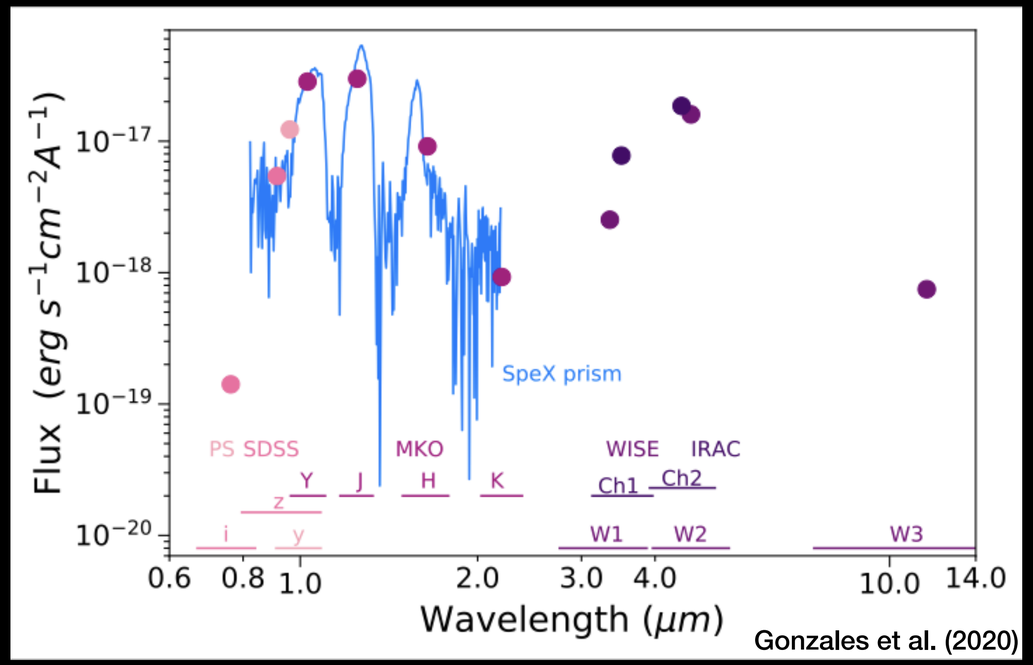

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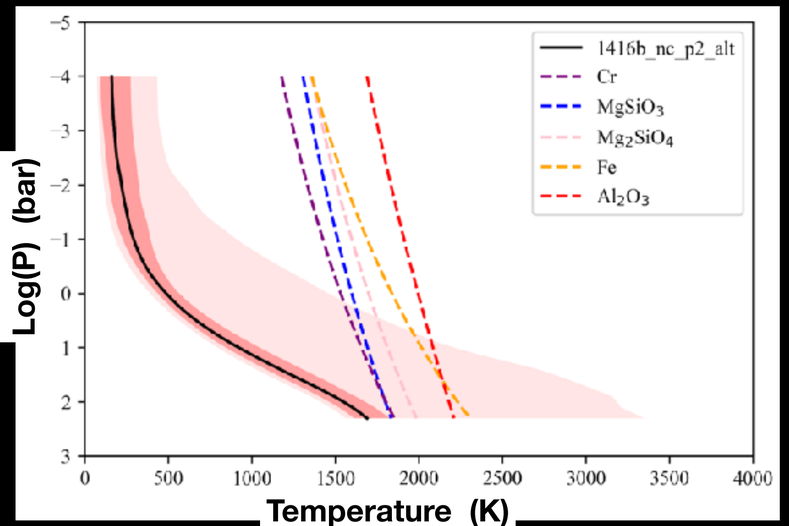

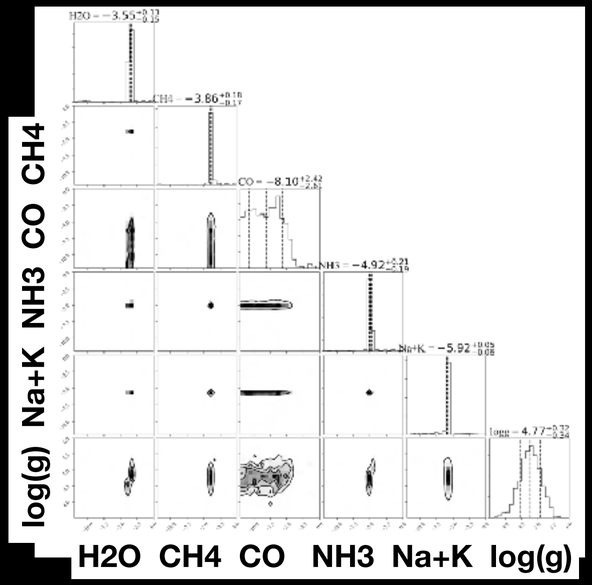

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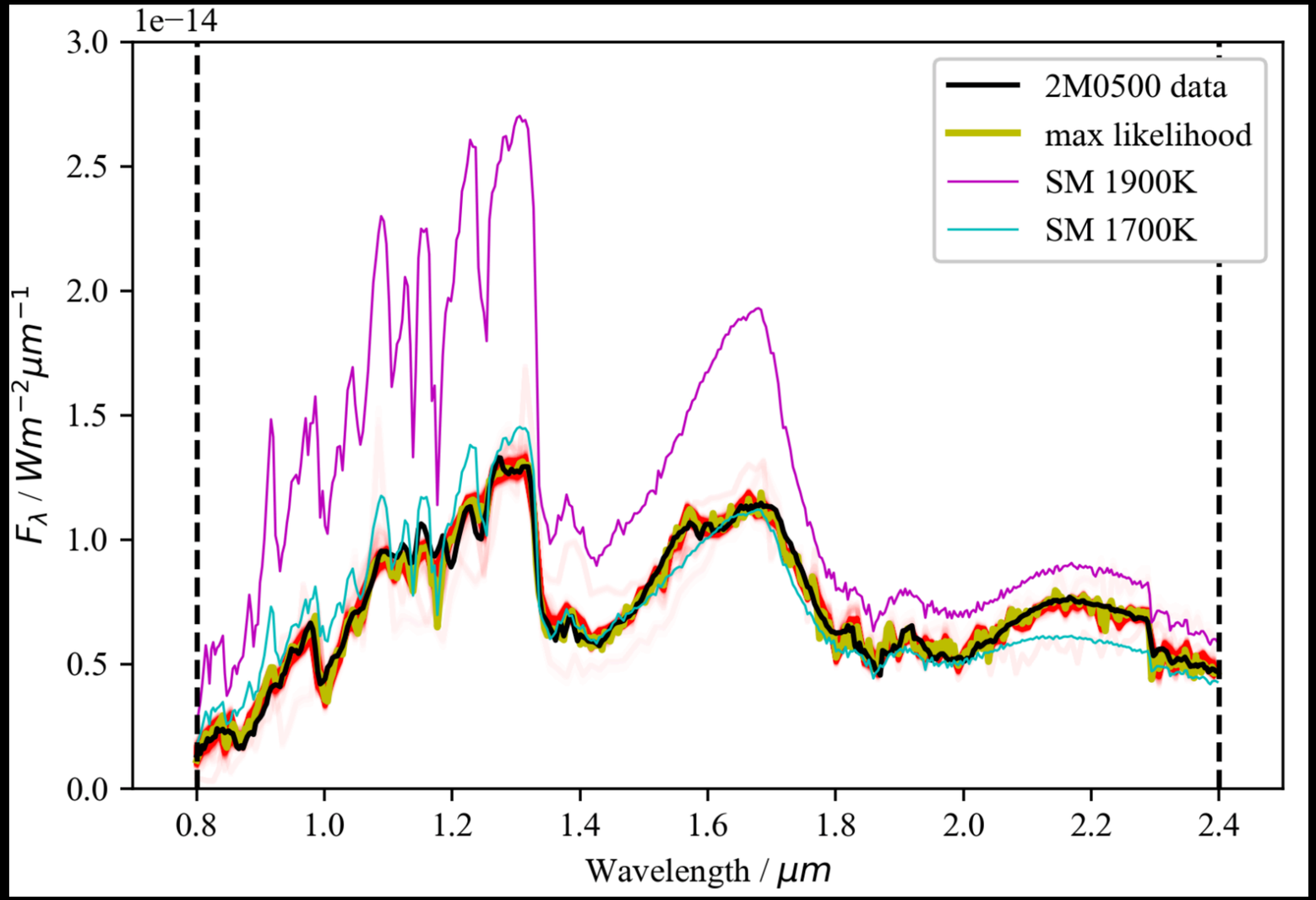

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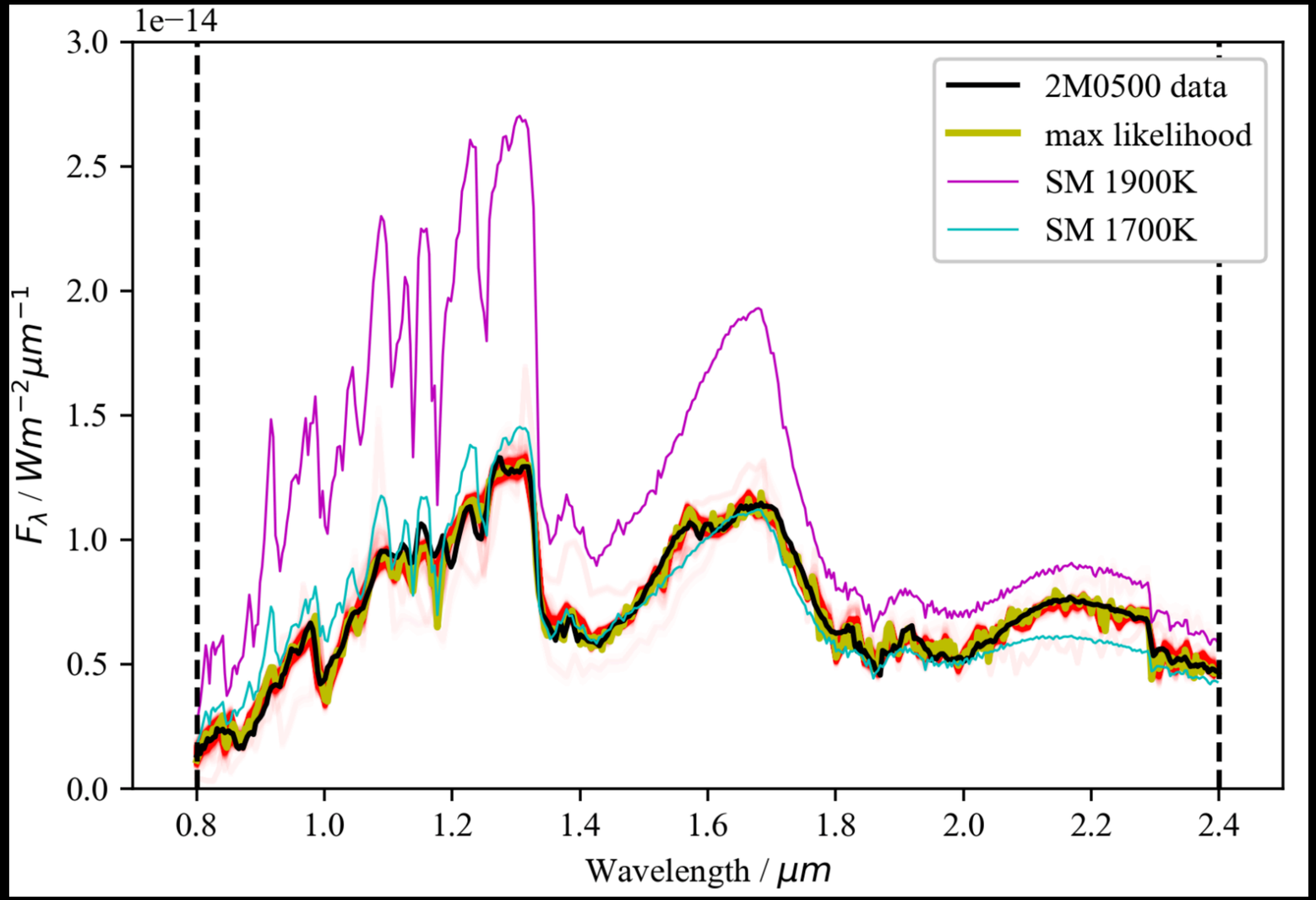

Retrieved spectrum fits better than model grid spectrum

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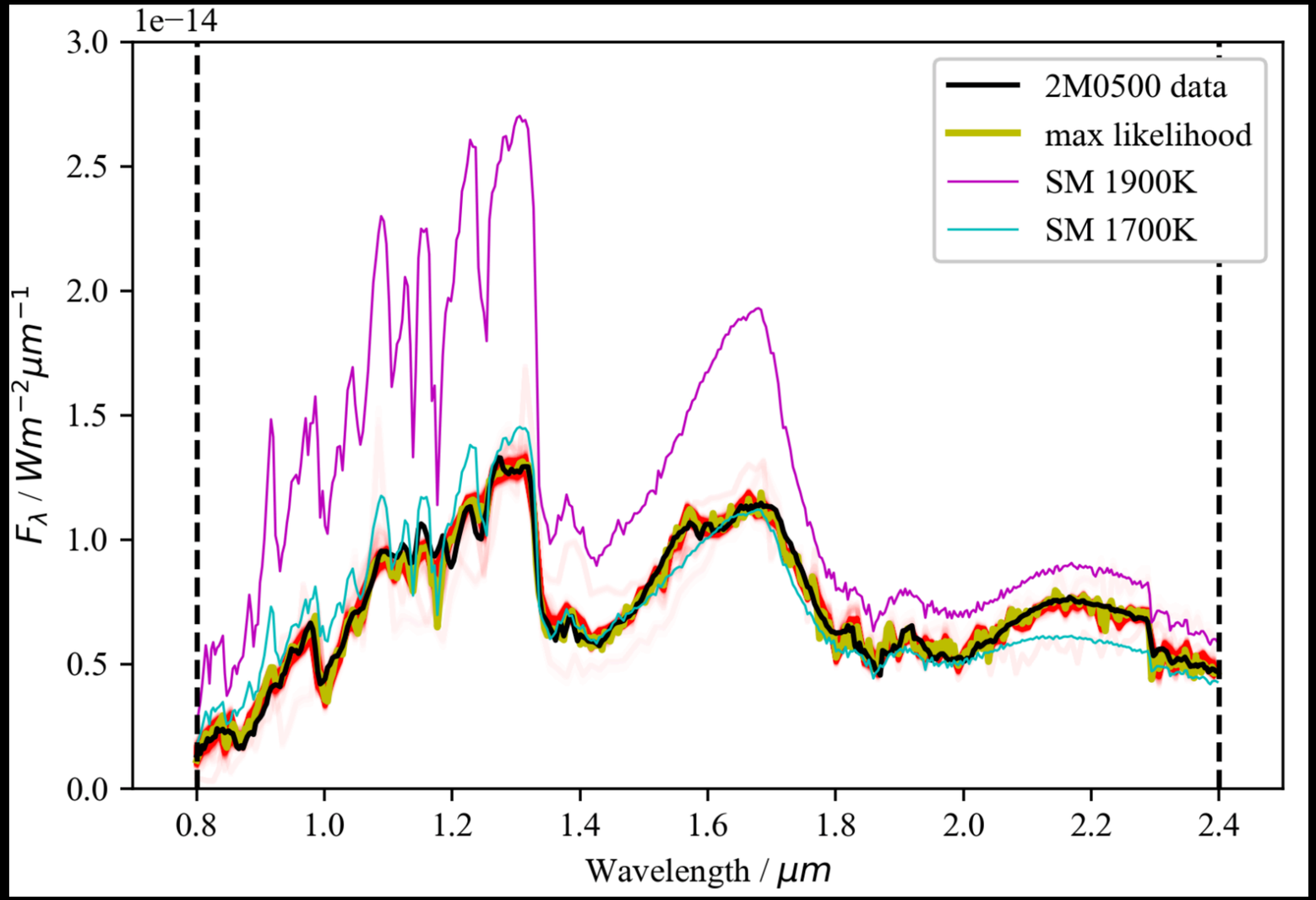

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Brewster was built with cloudy brown dwarf atmospheres in mind

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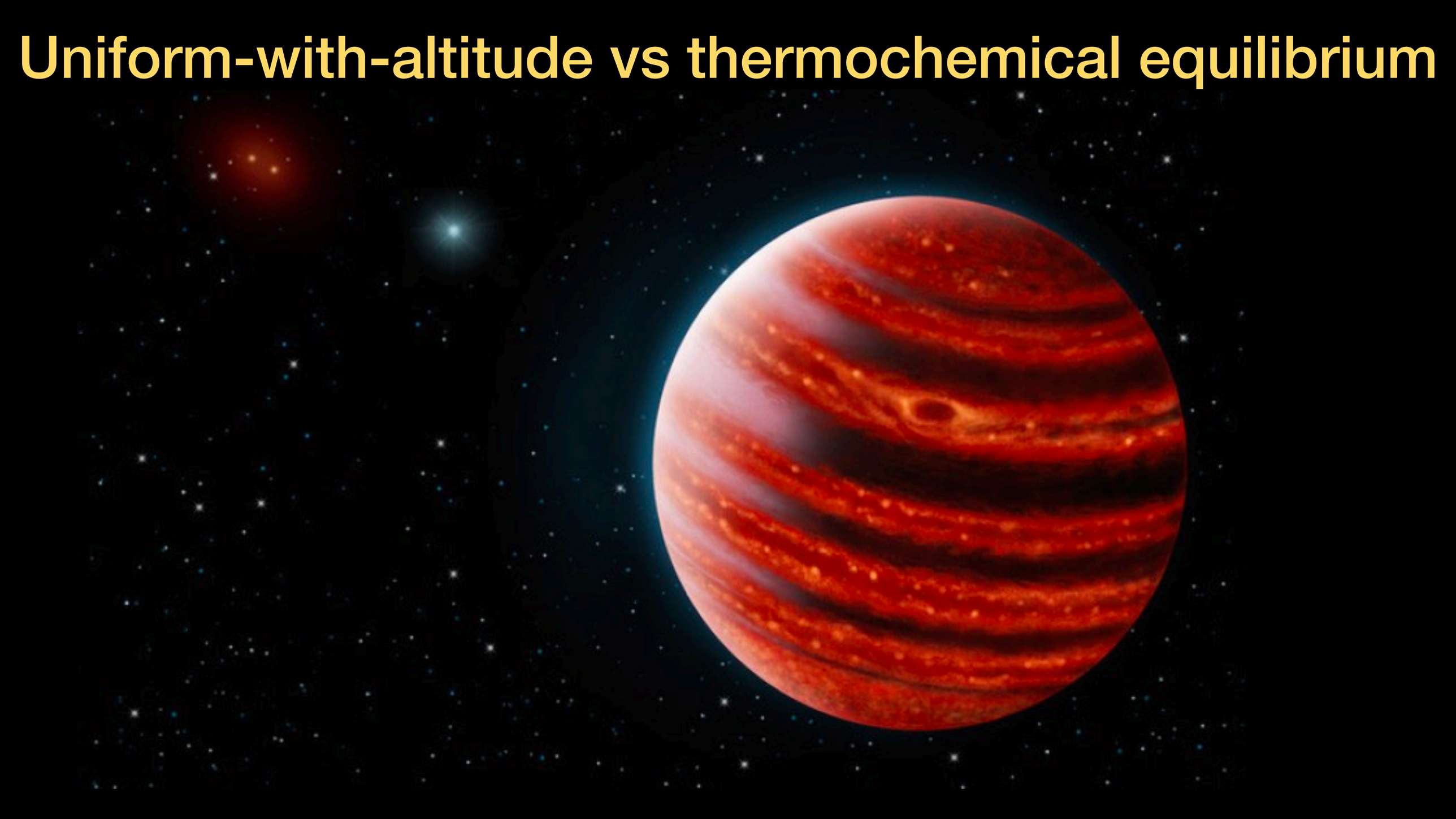
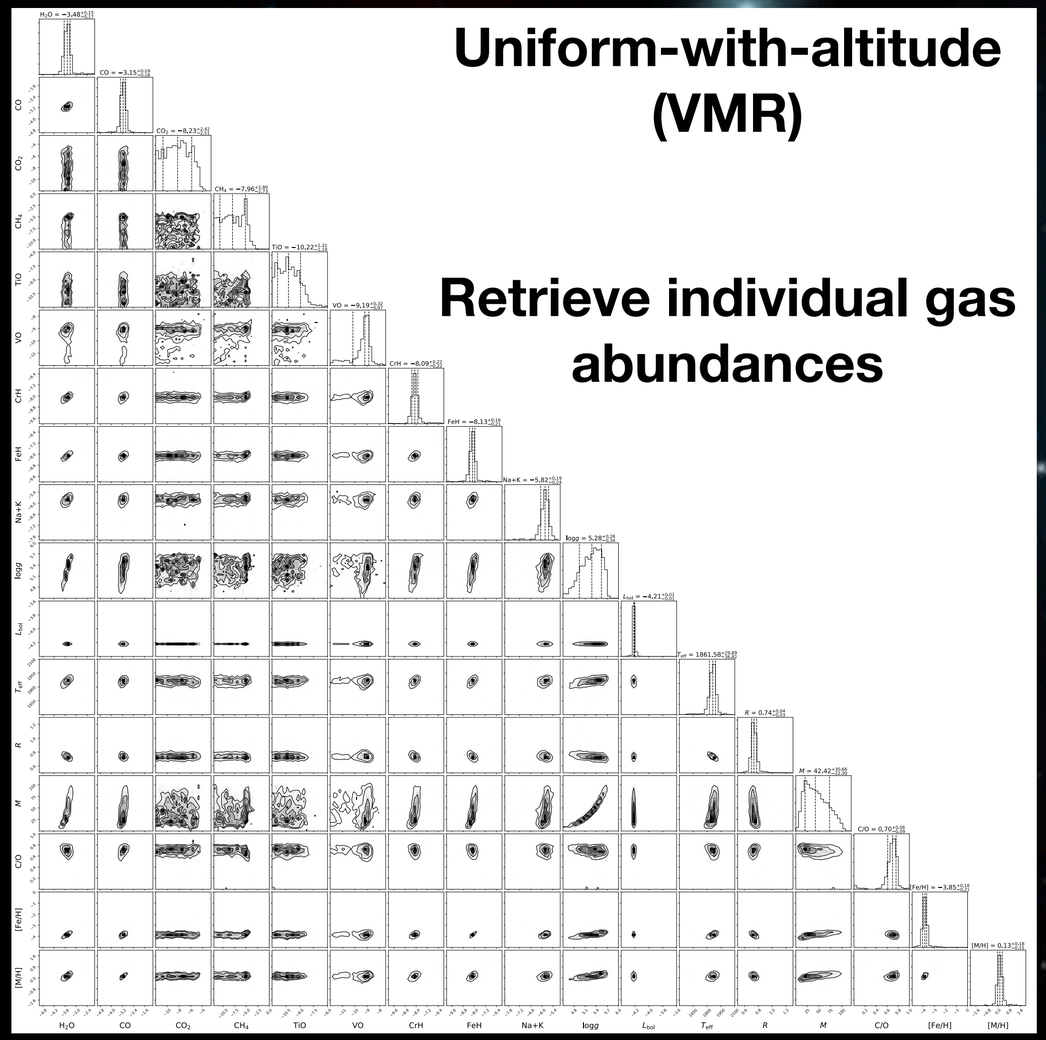
Uniform-with-altitude vs thermochemical equilibrium



Uniform-with-altitude vs thermochemical equilibrium

VMR

Assume gas abundance is the same no matter the altitude



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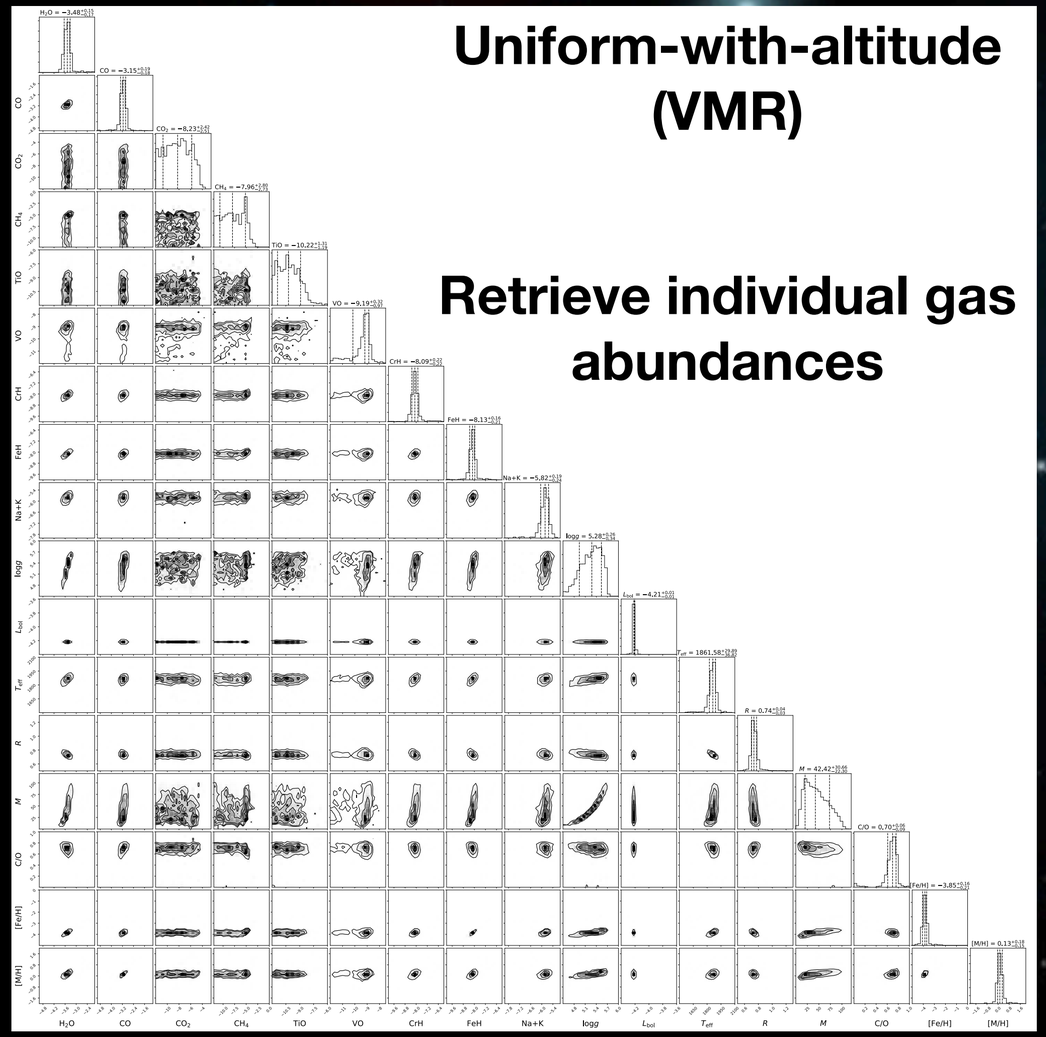
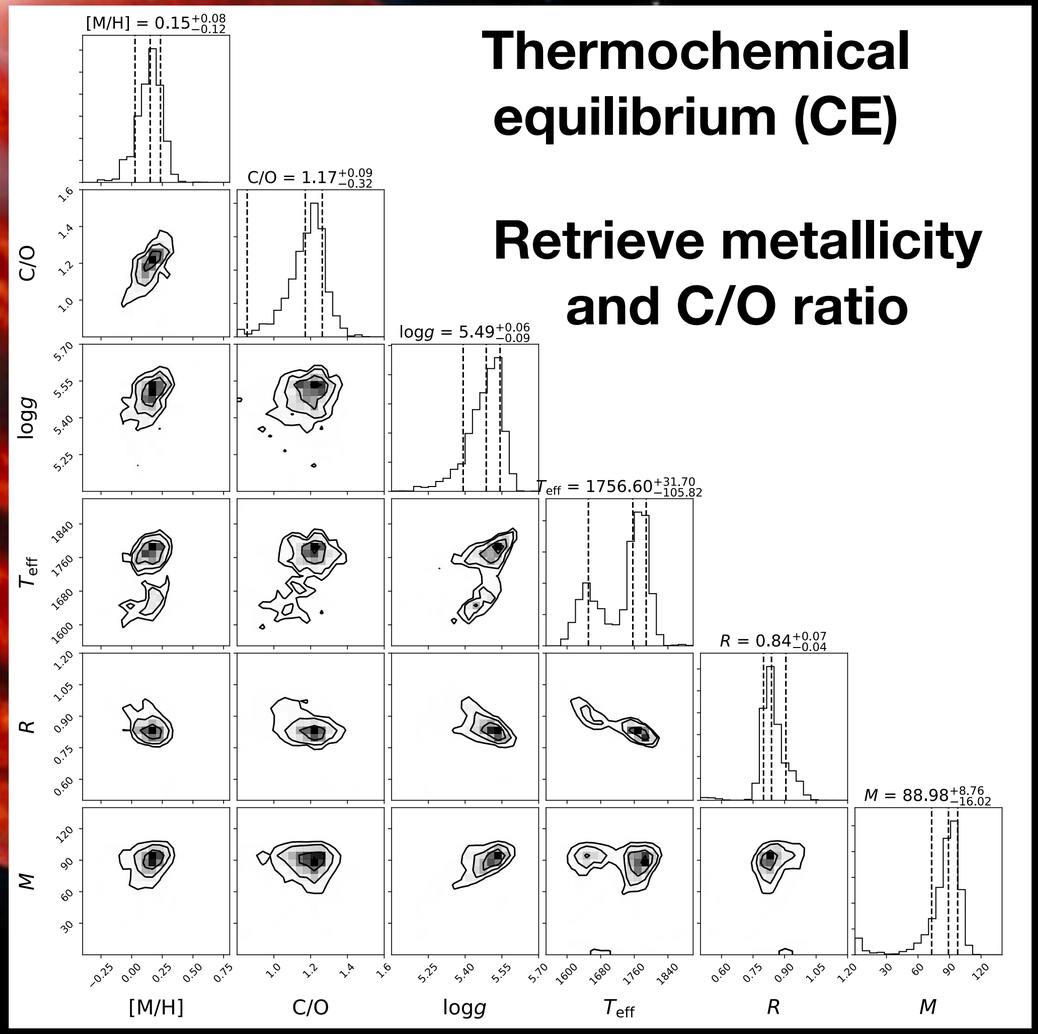


CE

Gas abundances from thermochemical grid



How does the Pressure-Temperature profiles of objects of similar effective temperature or spectral type compare to one another?

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SDSS J1416A

SpT: d/sdL7, Unusually Blue, primary in wide binary

SED T_{eff} ~1700K, Retrieved T_{eff} ~1900K

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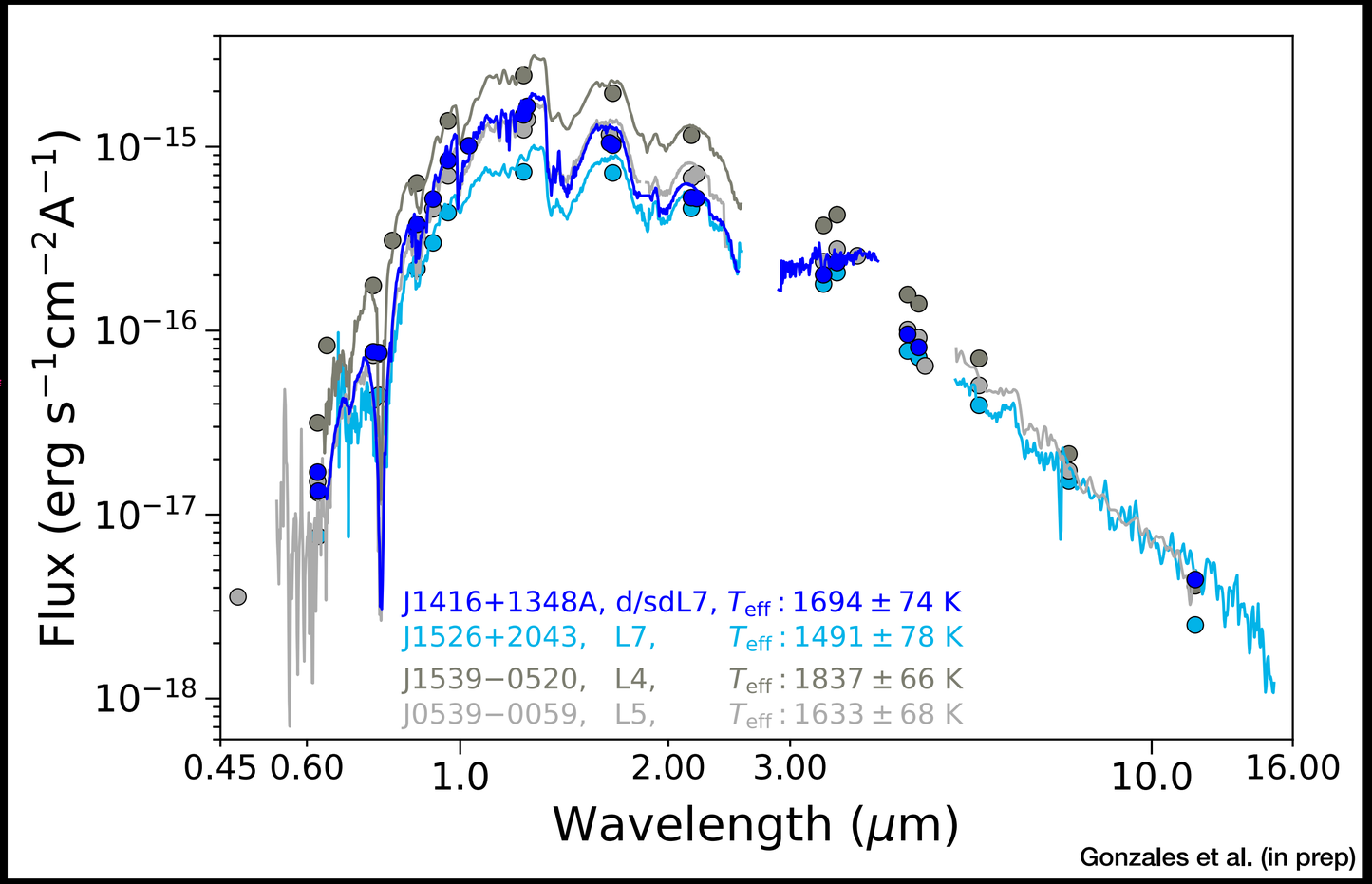

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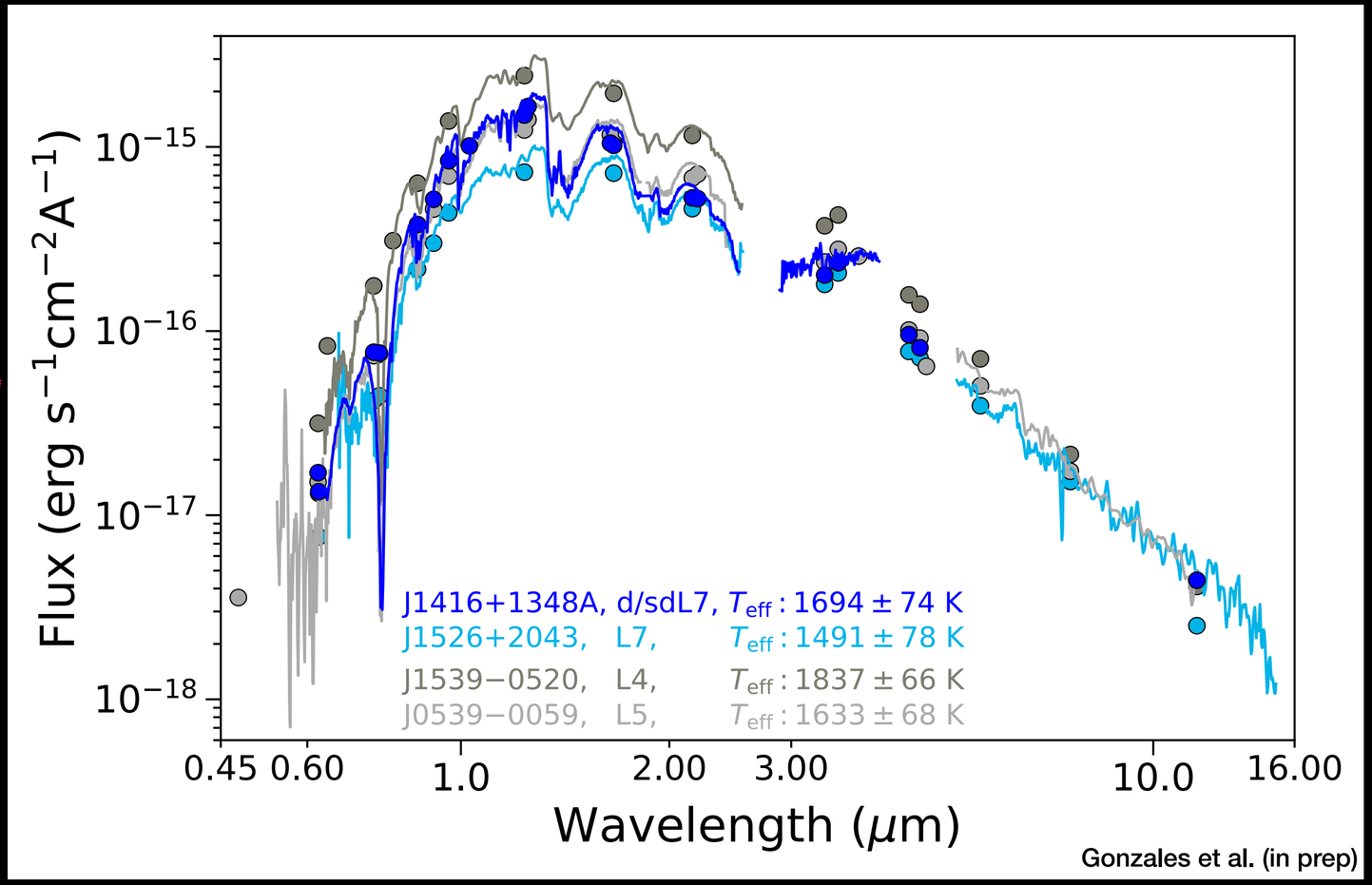

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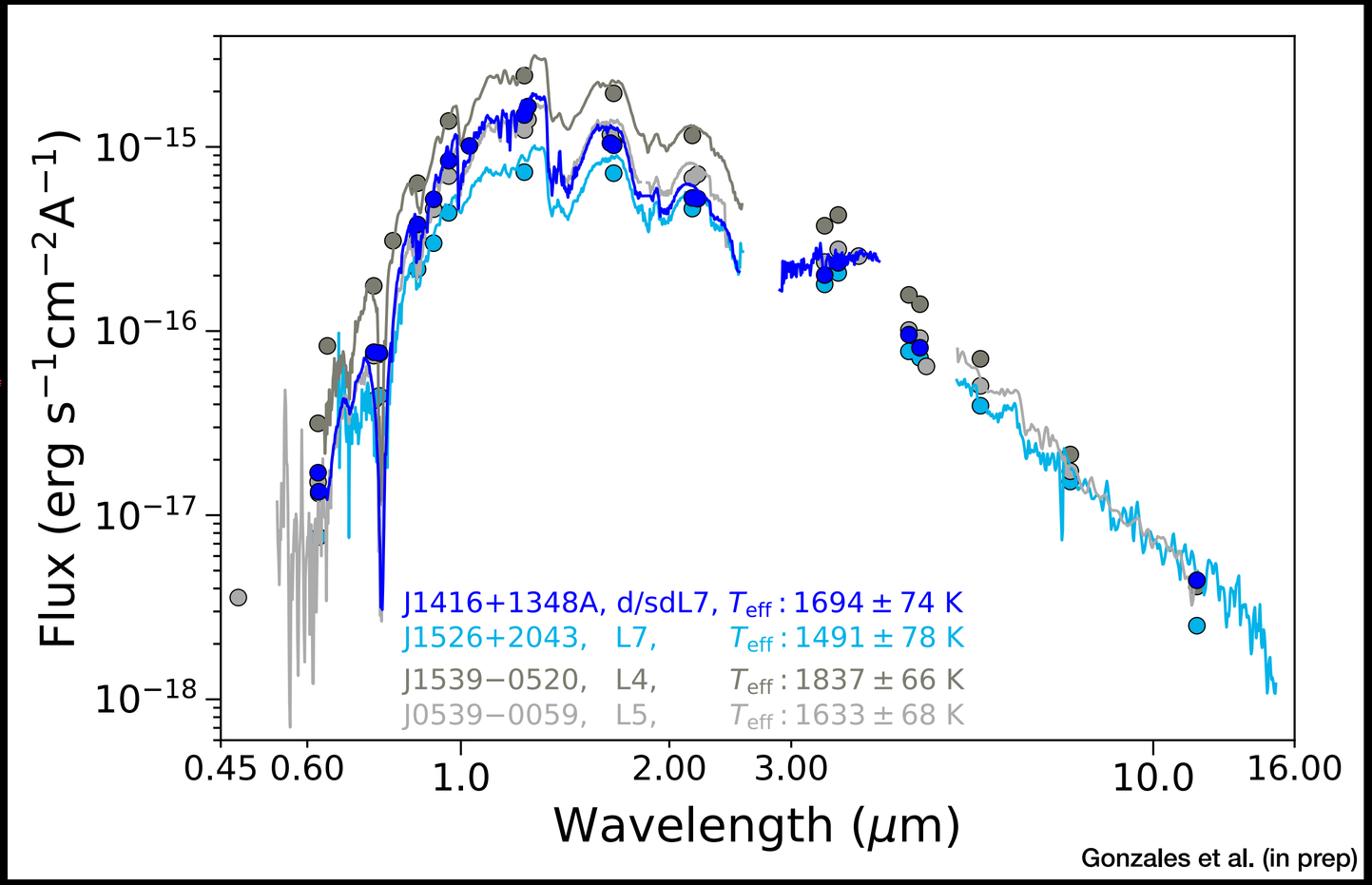
Variable!



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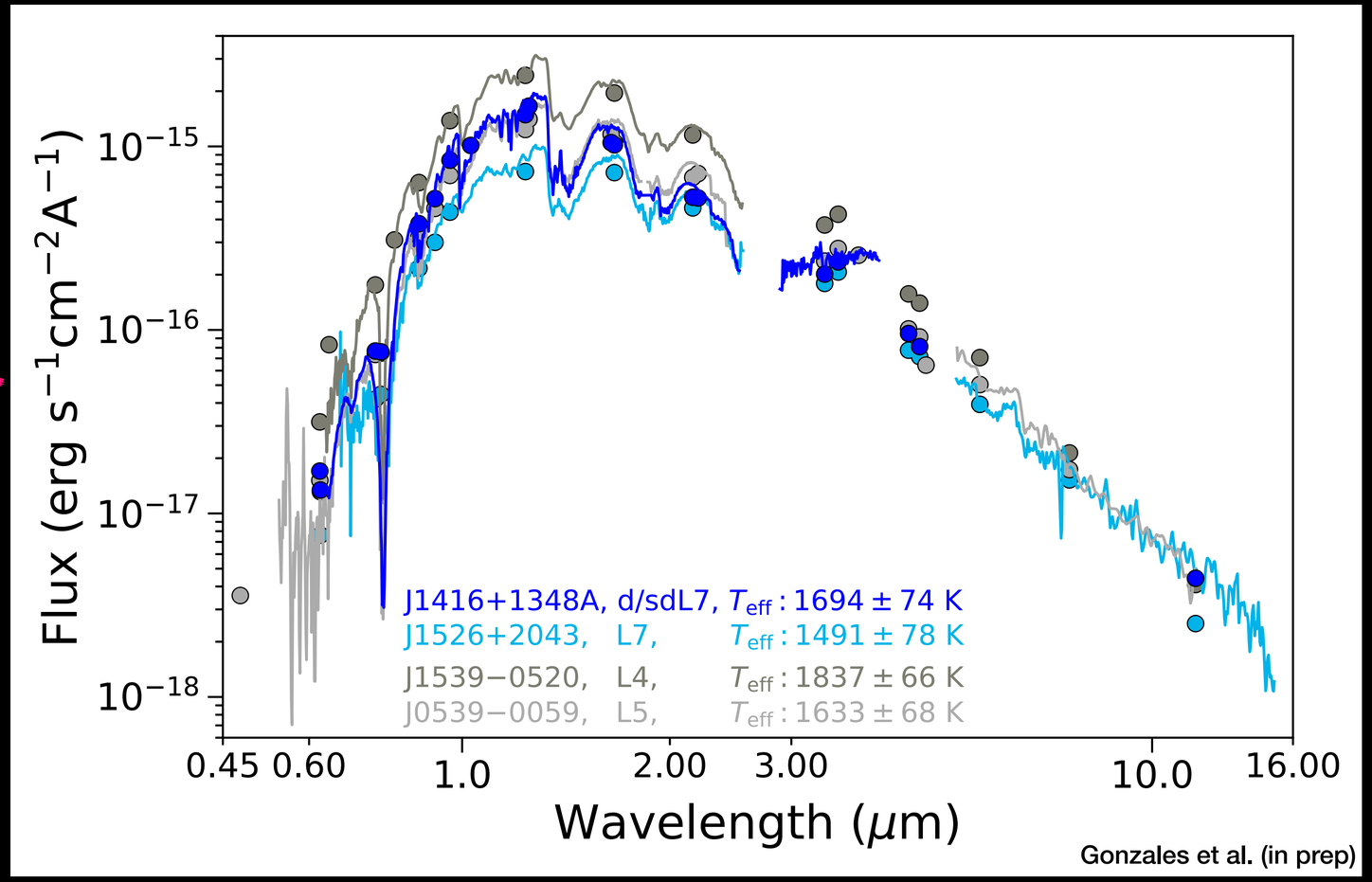

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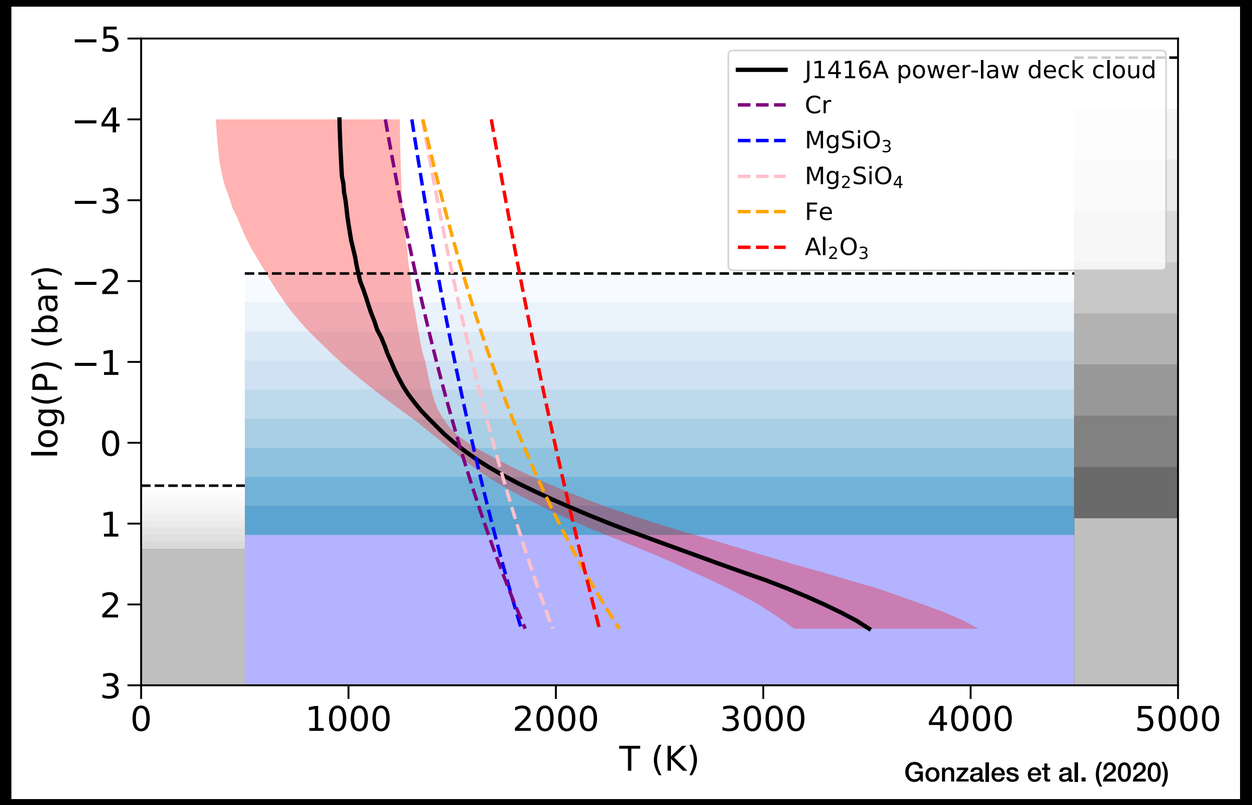
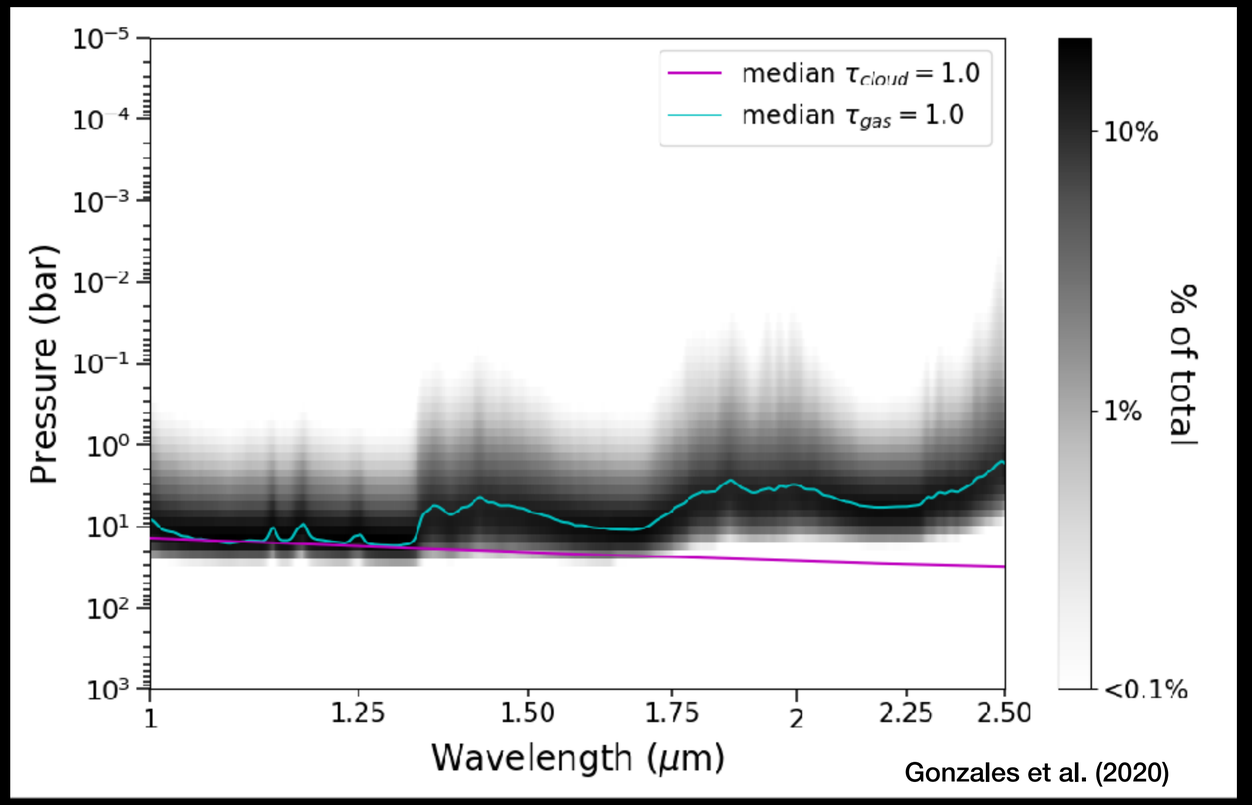
A Deck Cloud for 1416A!





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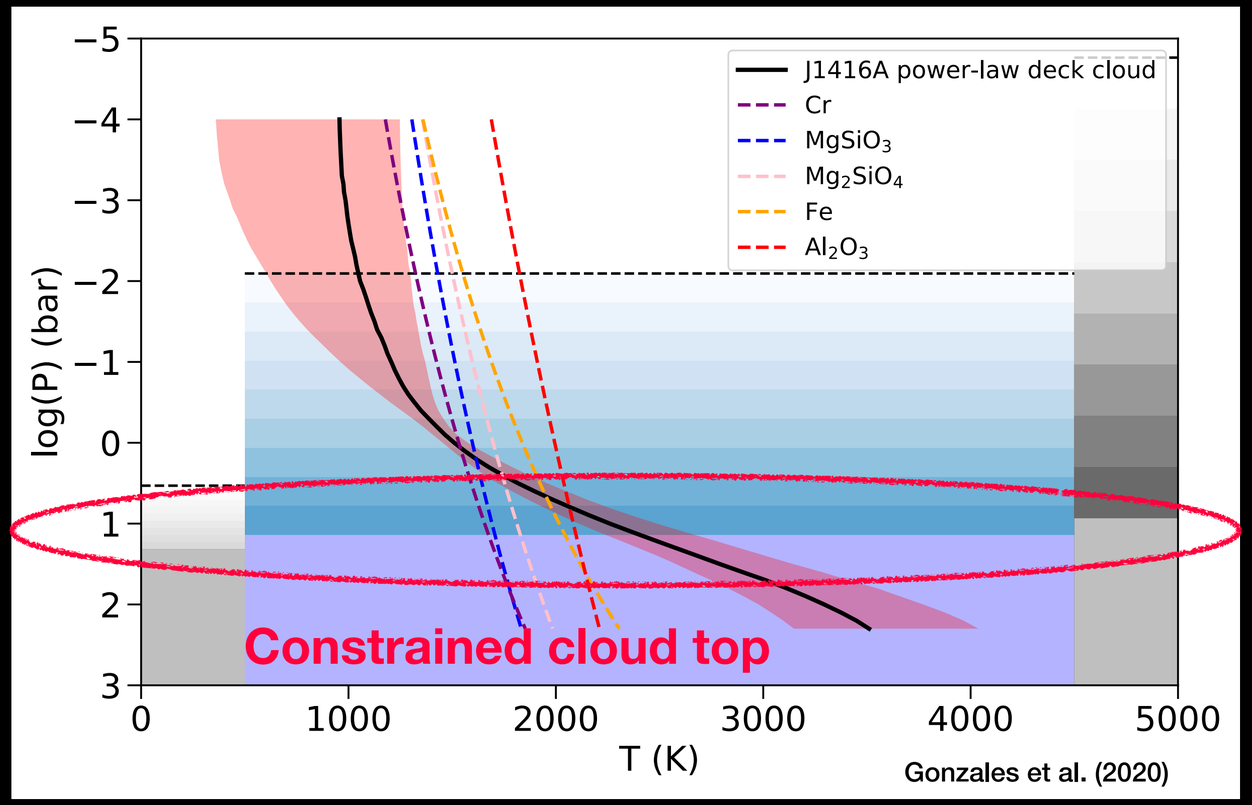

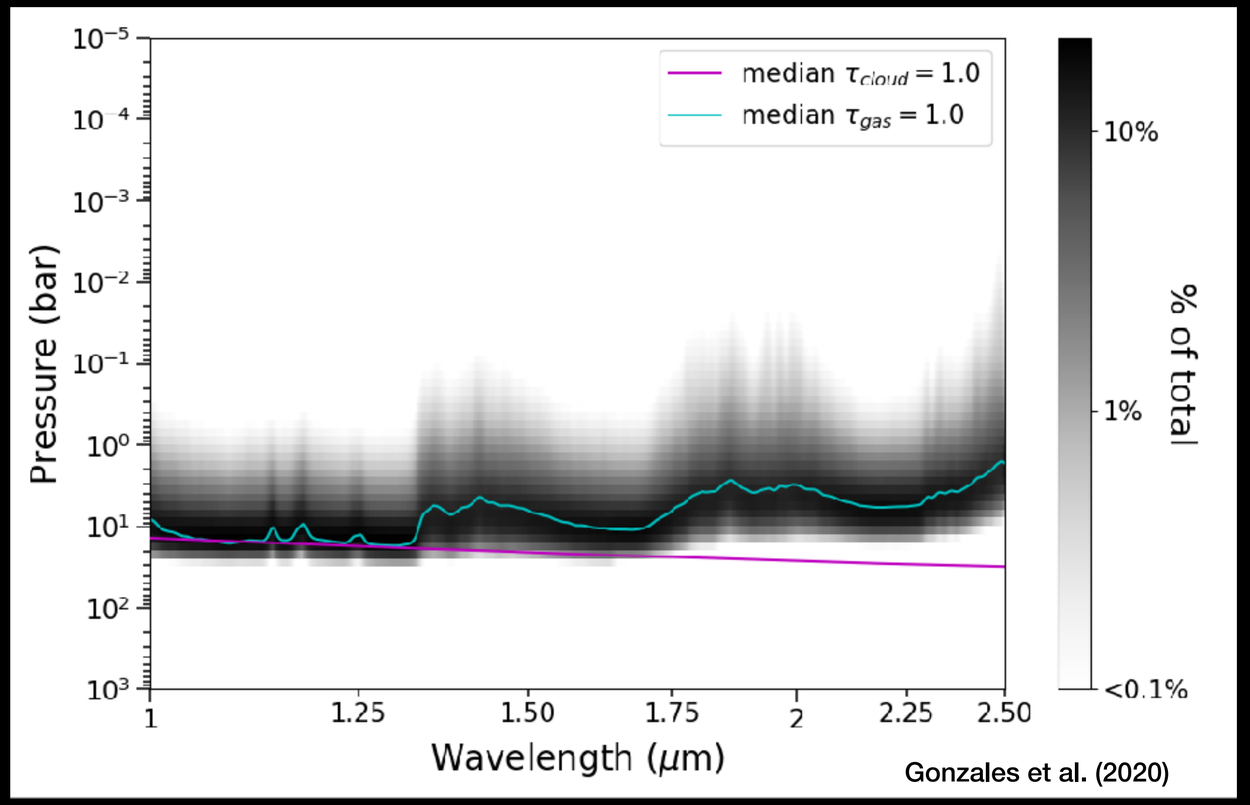

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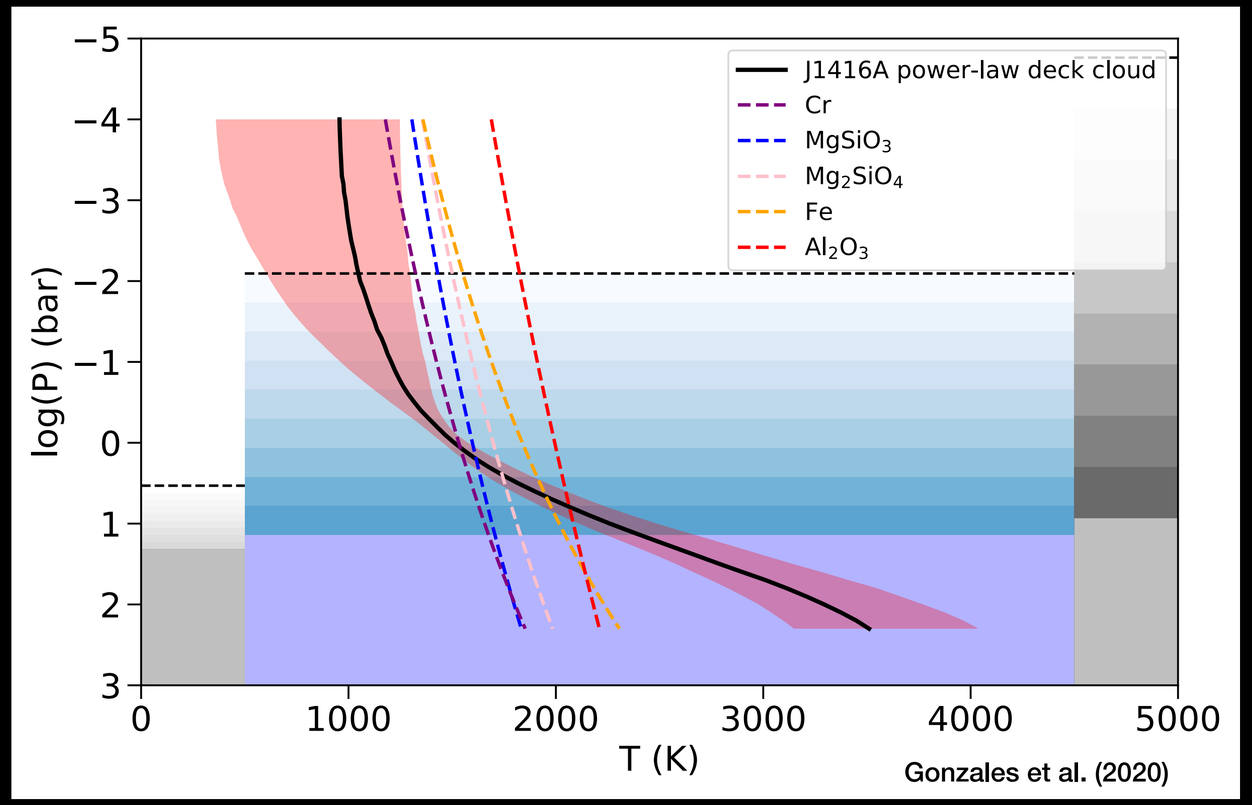

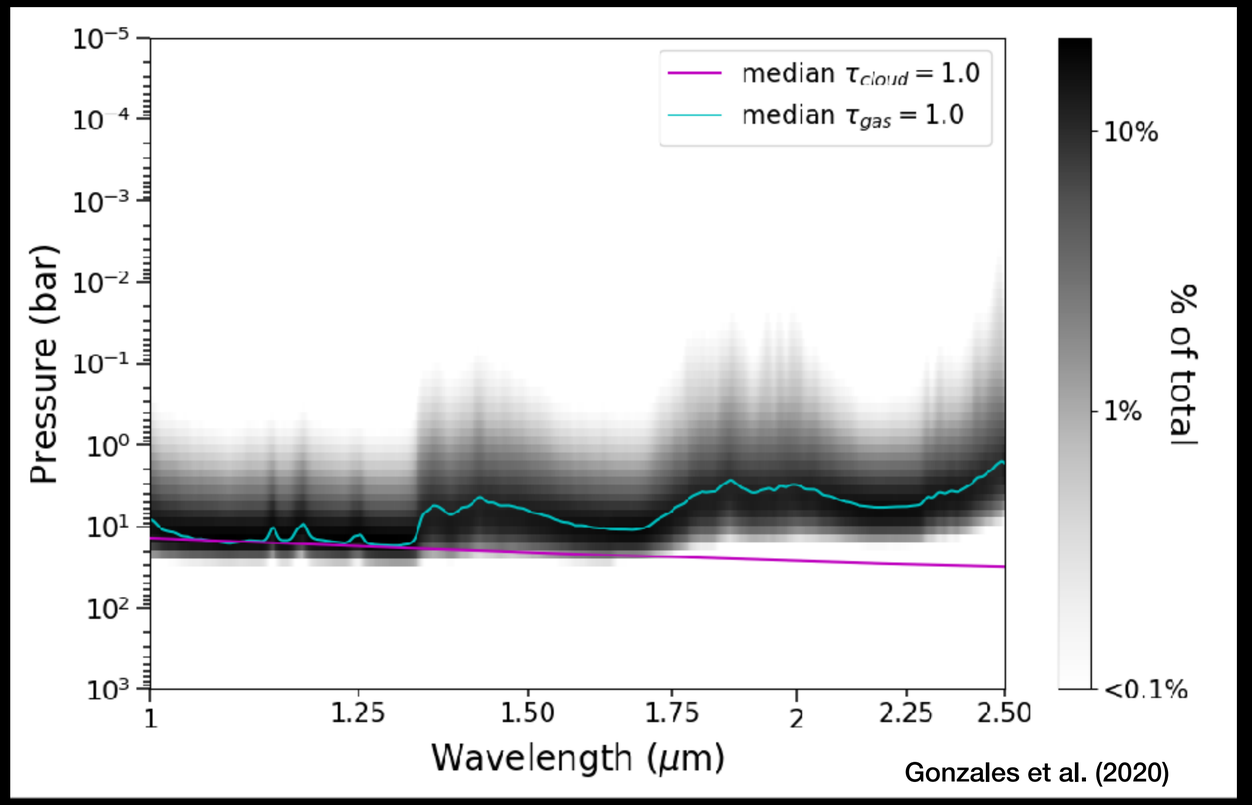

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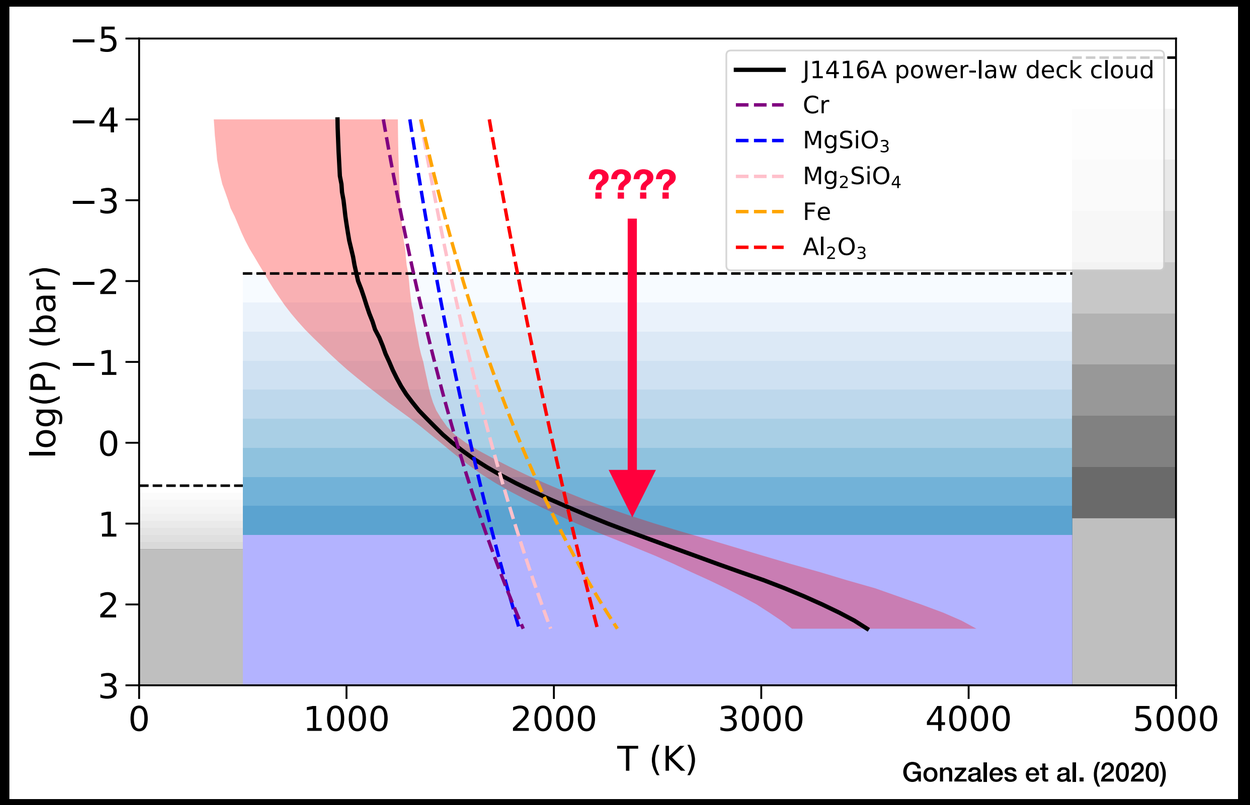

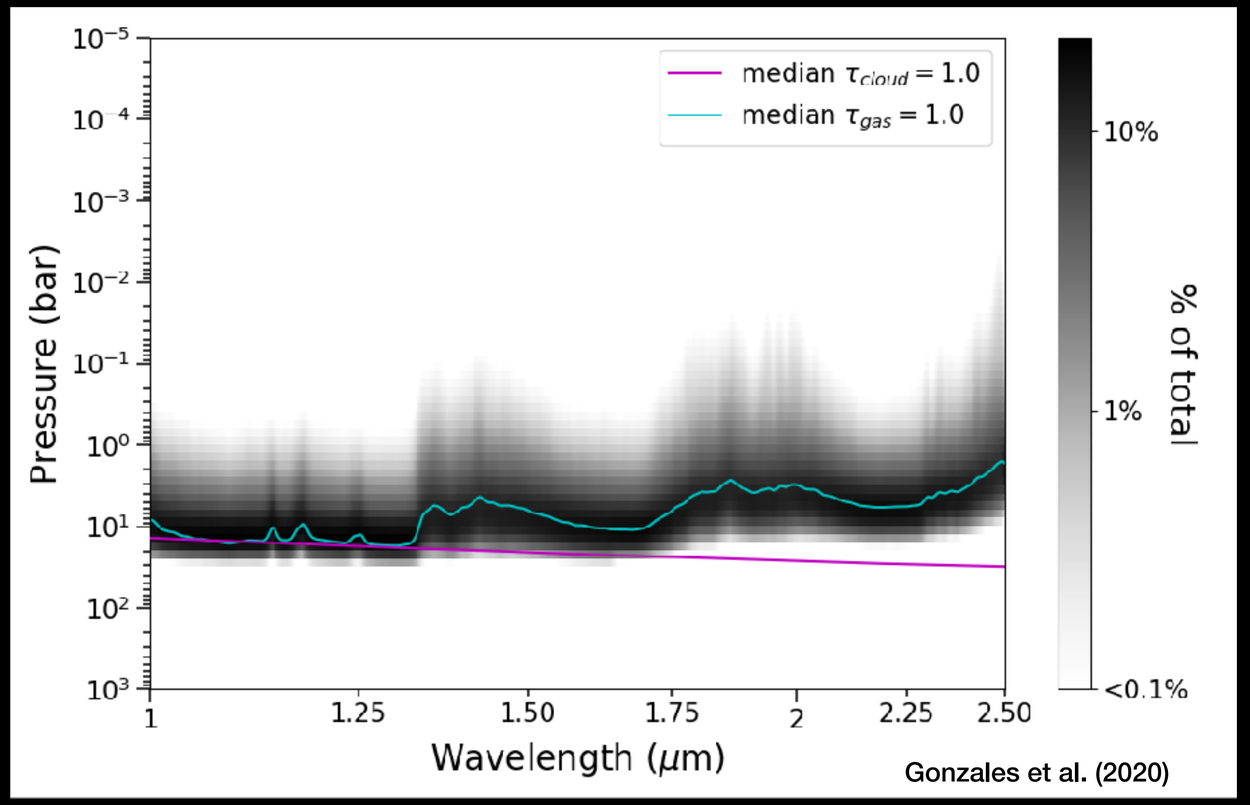

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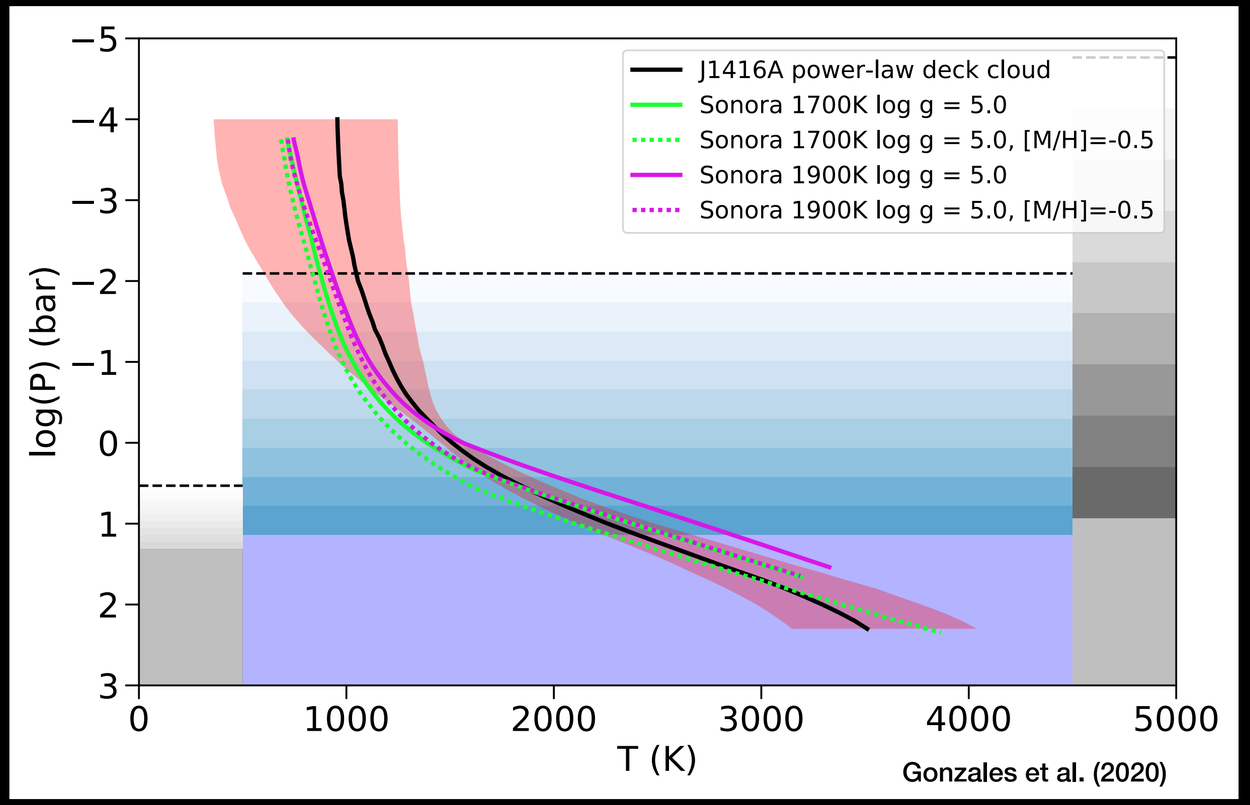

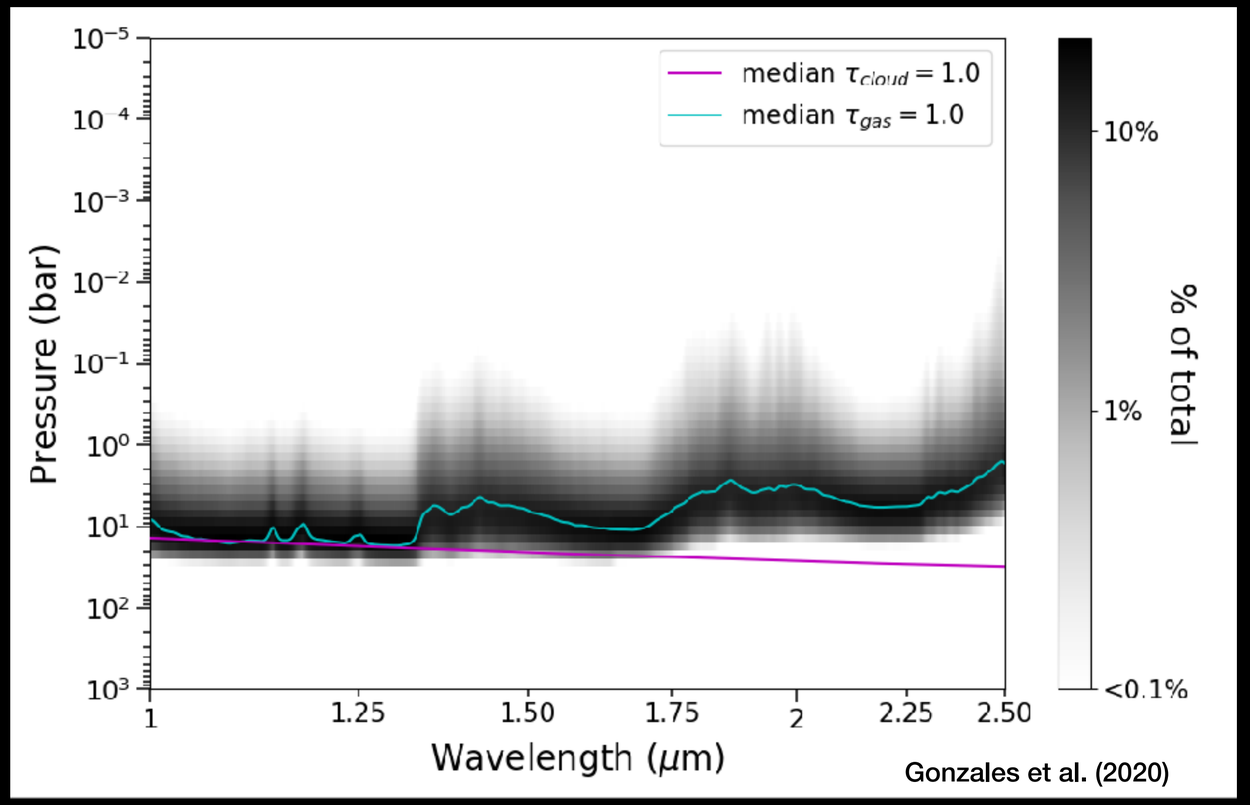

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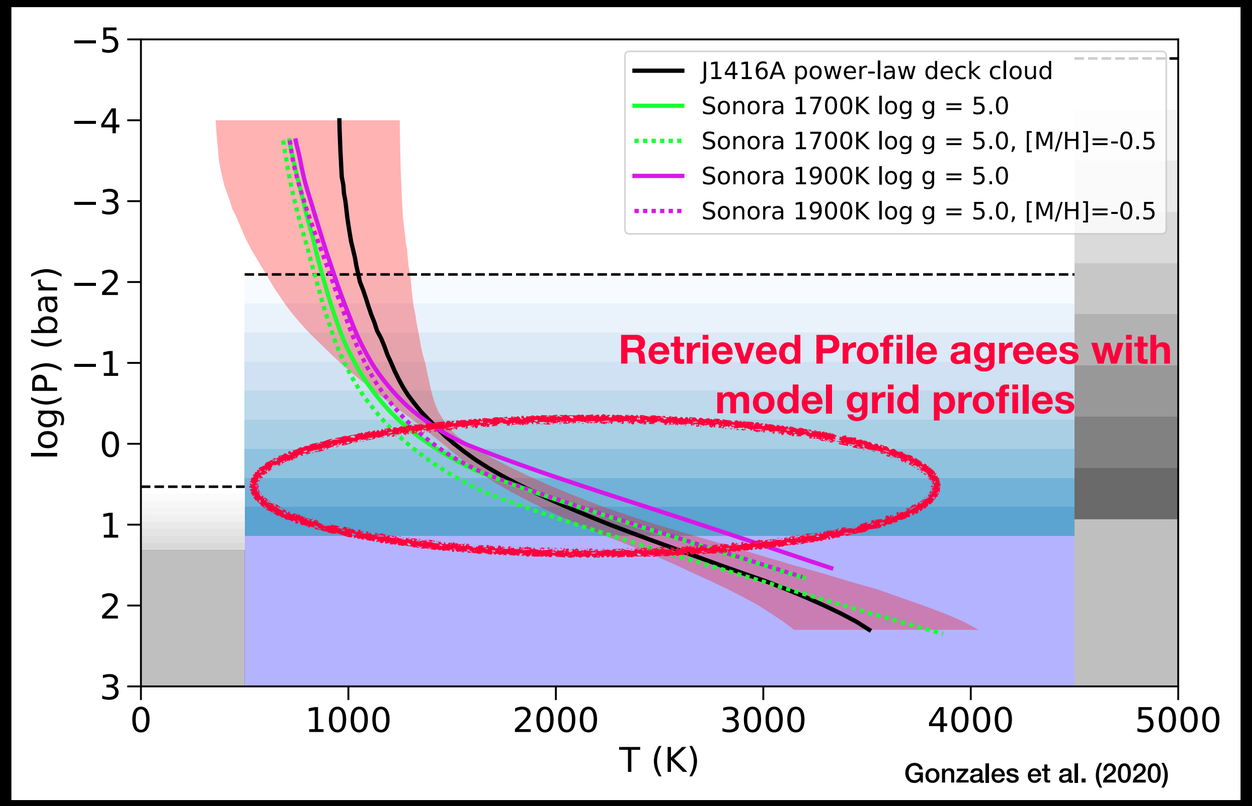

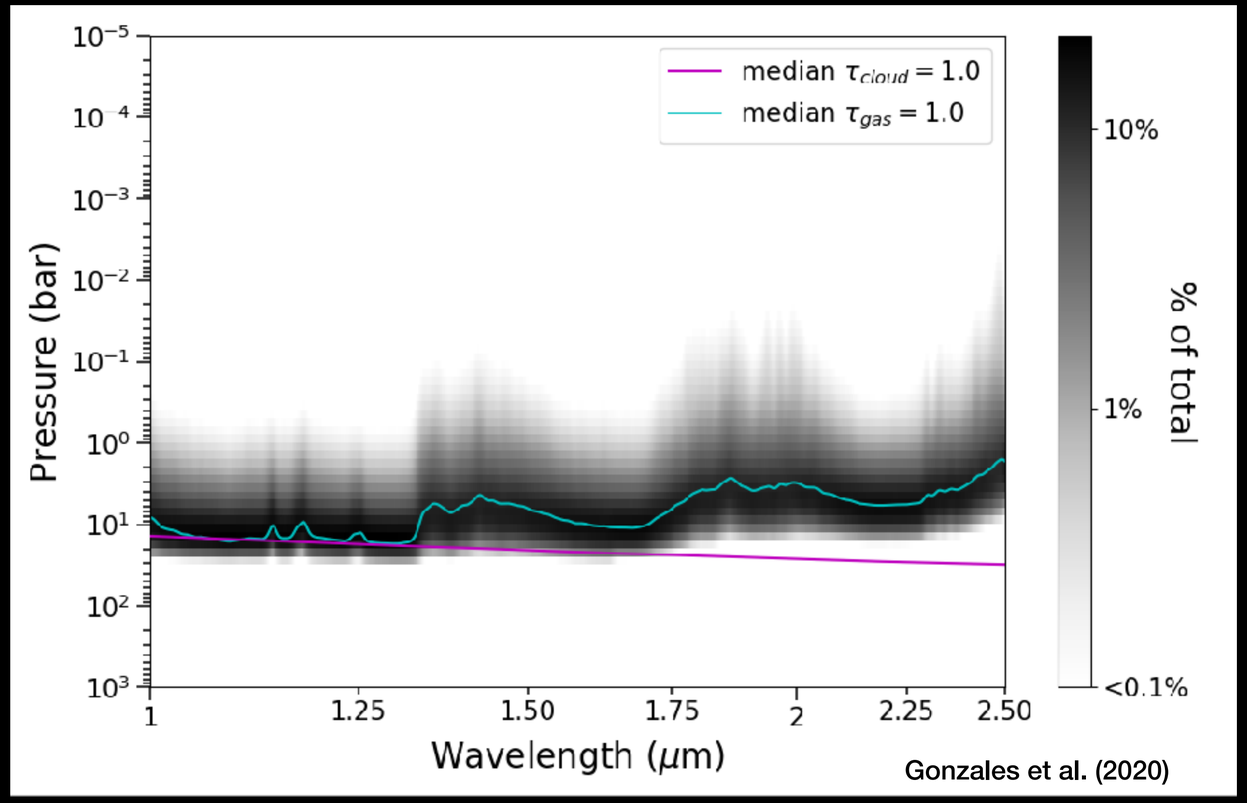

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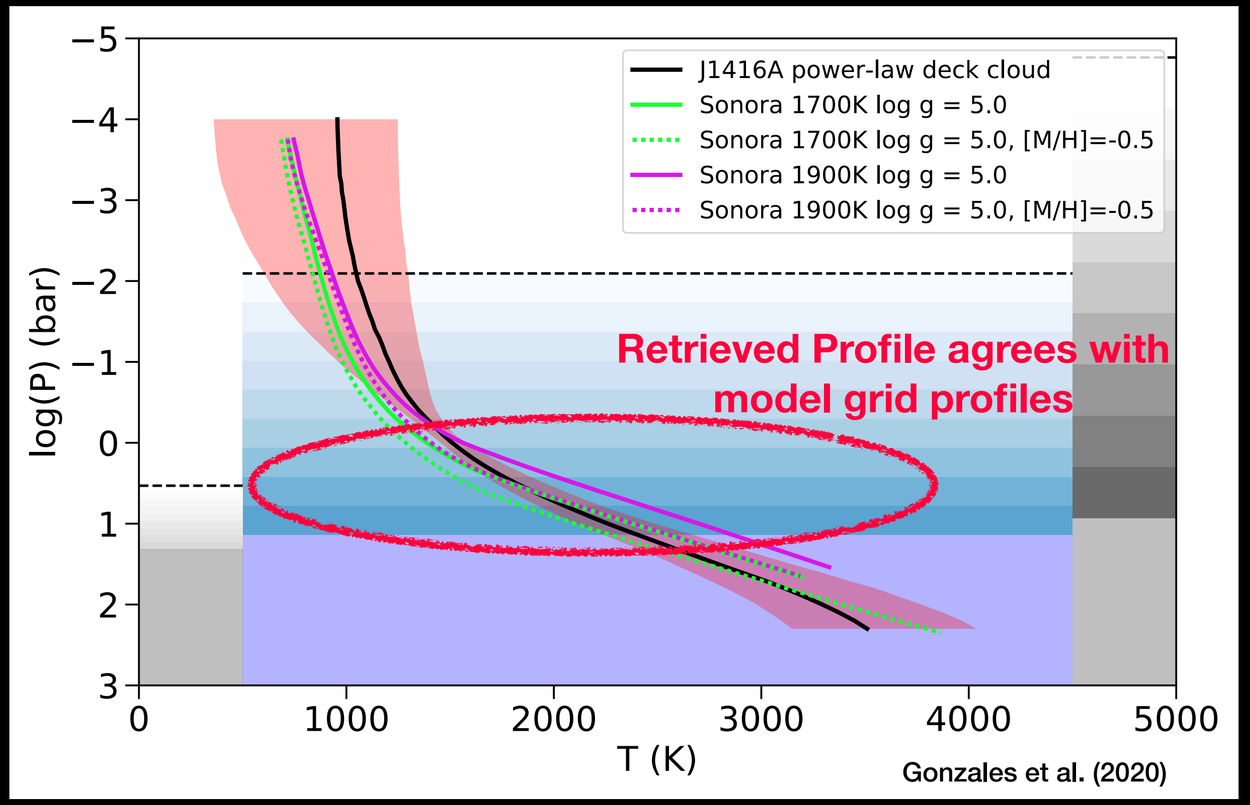
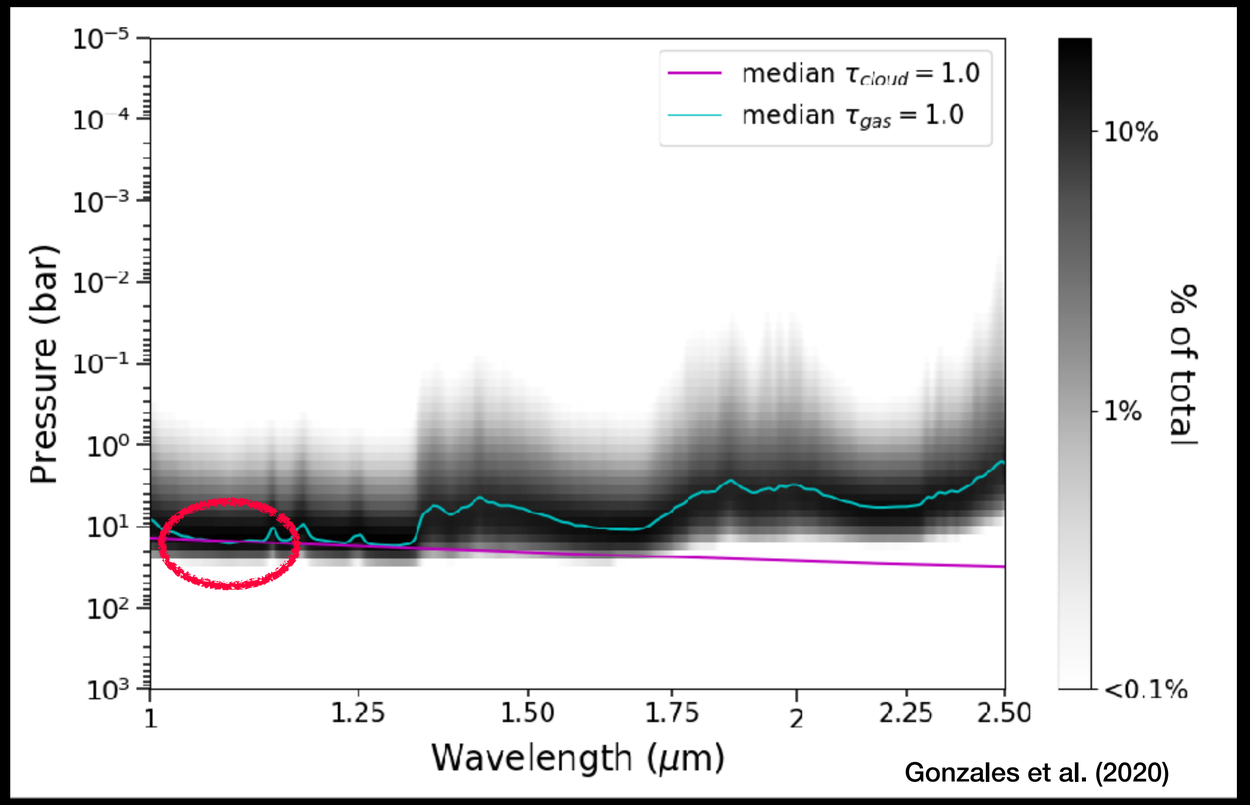
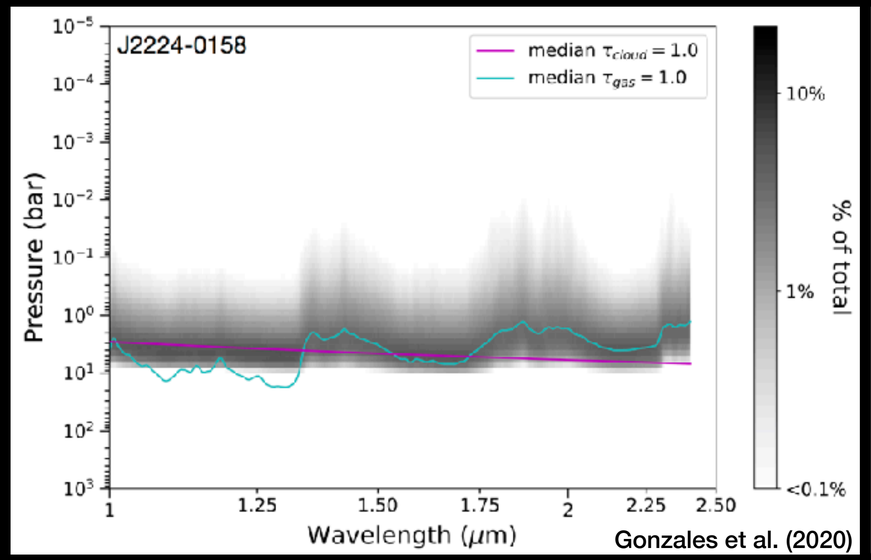
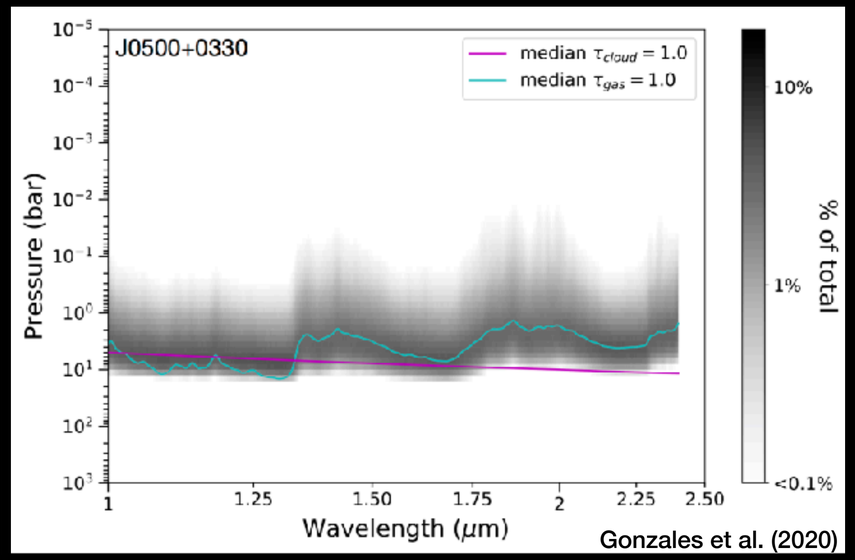
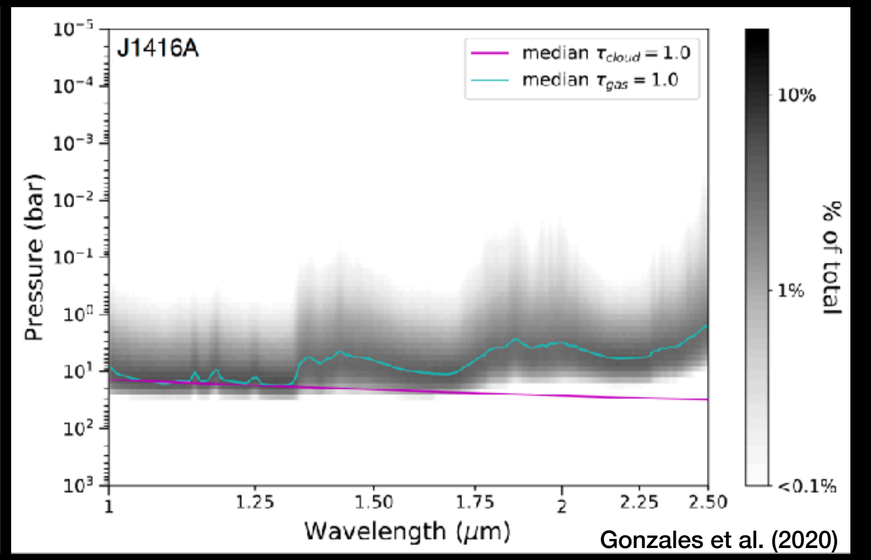




Location of cloud opacity could be related to *J-K* color



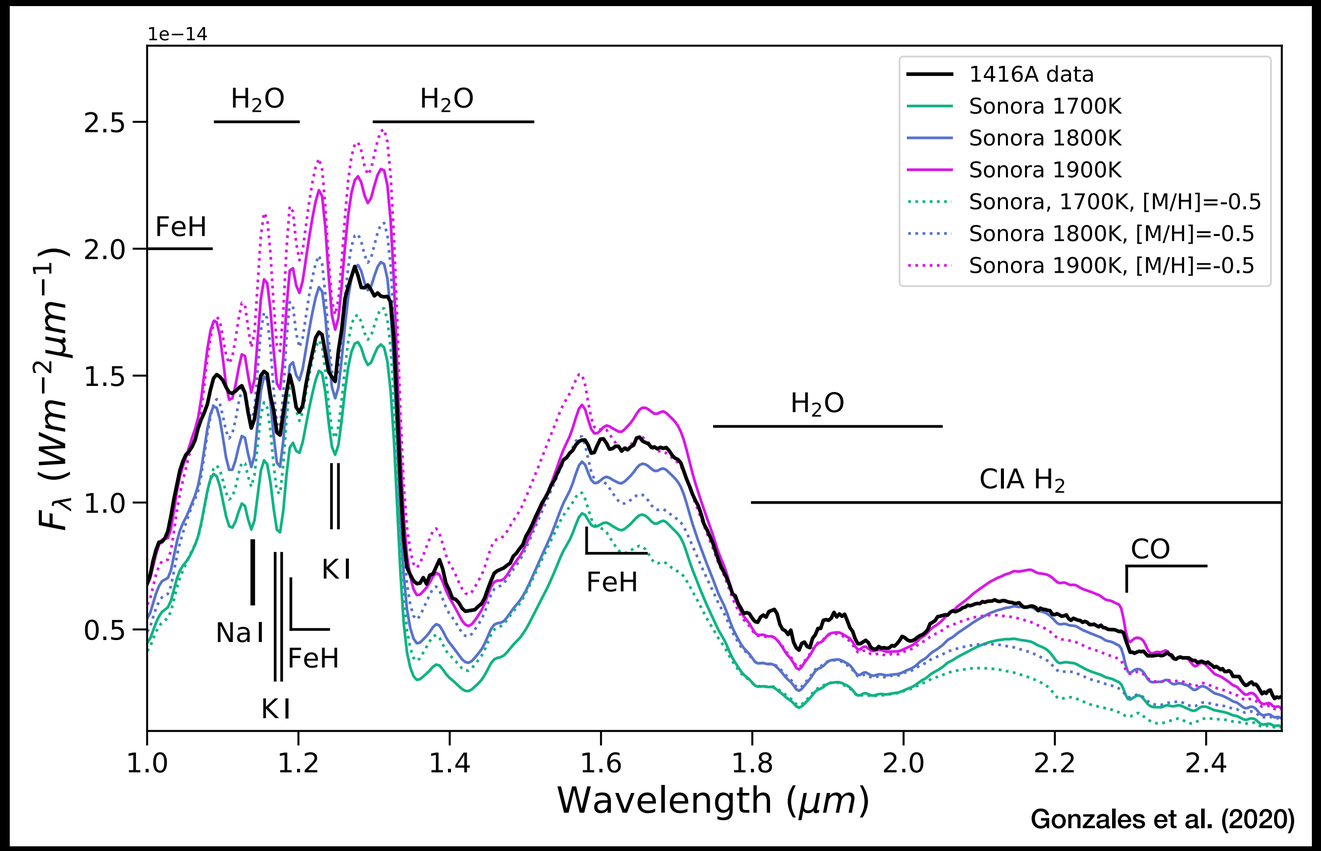


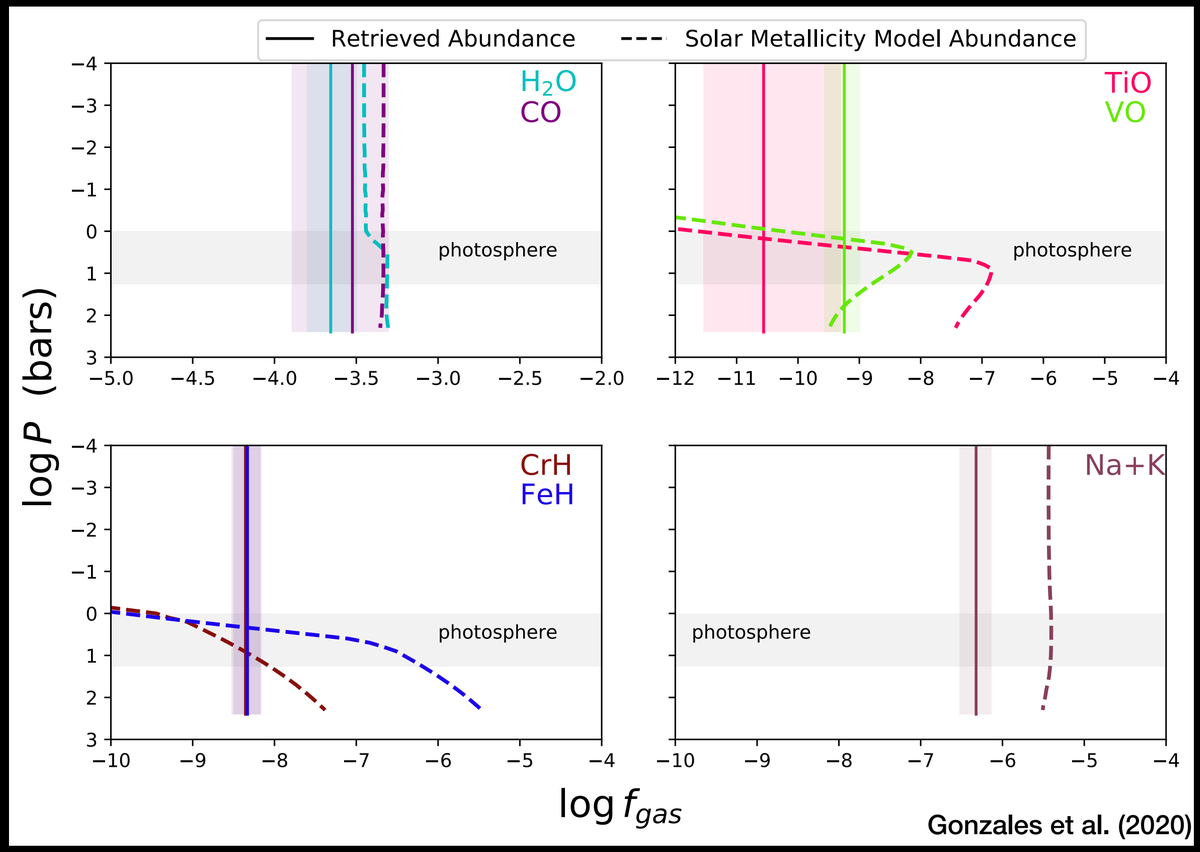


Red ⟶ ***J-K* color** ⟶ **Blue**

Comparison to the Models

J H K





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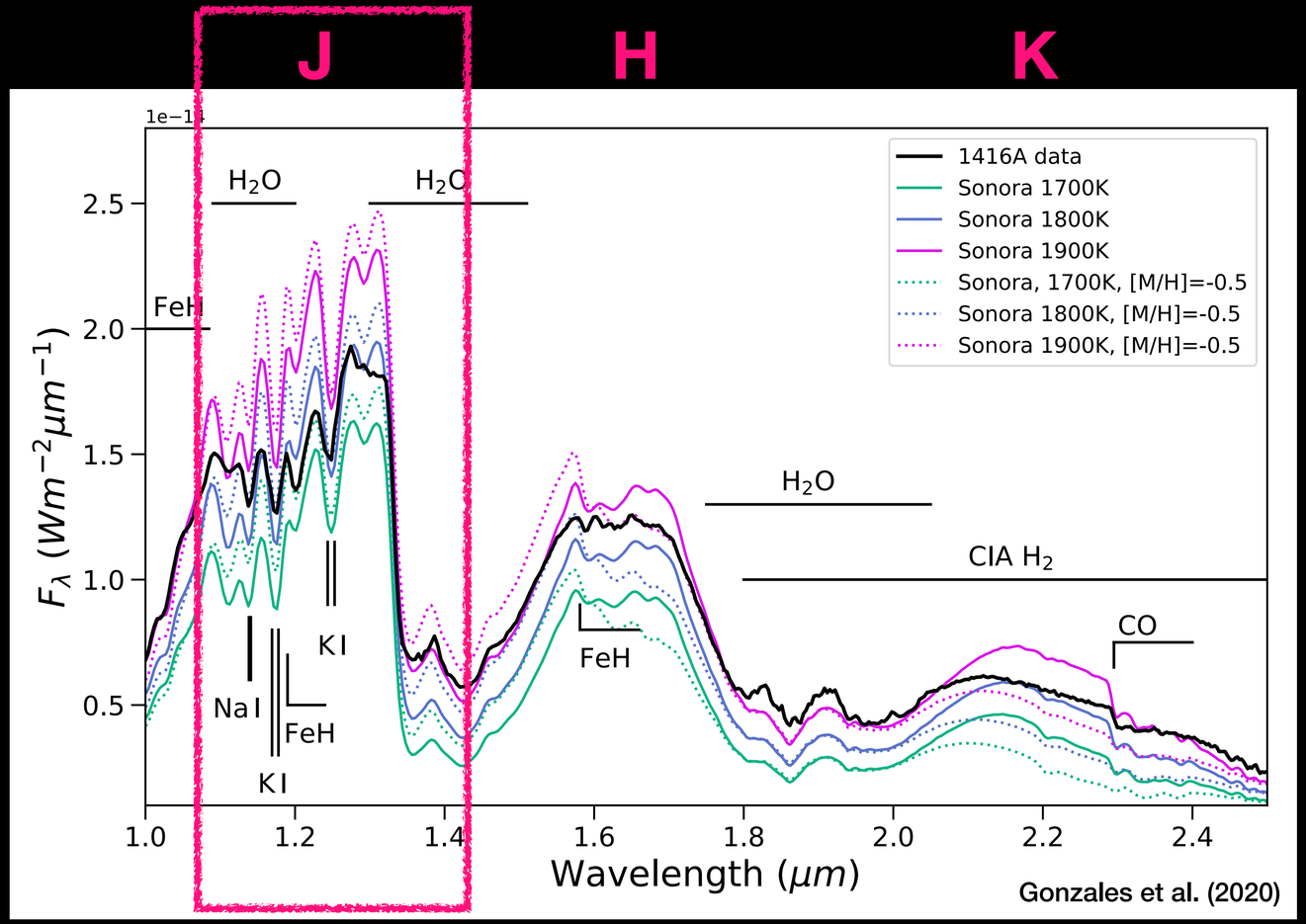

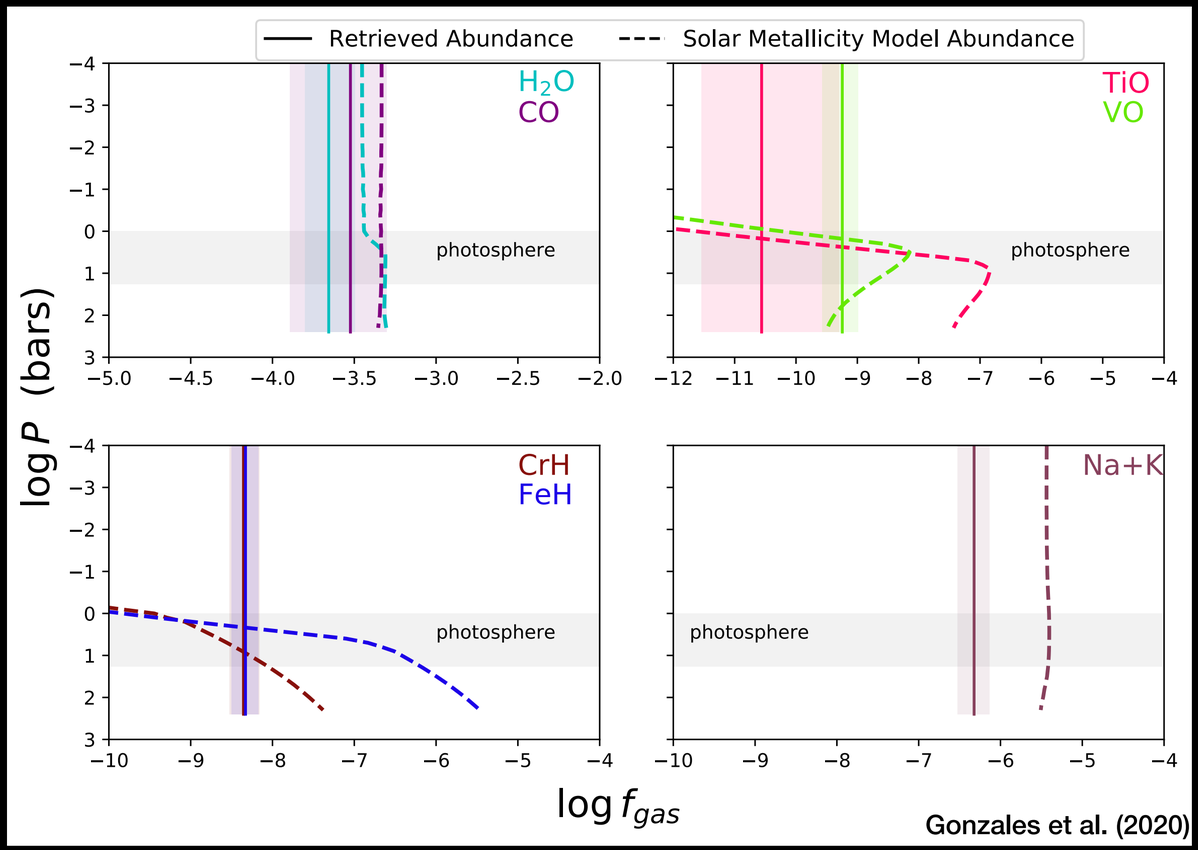

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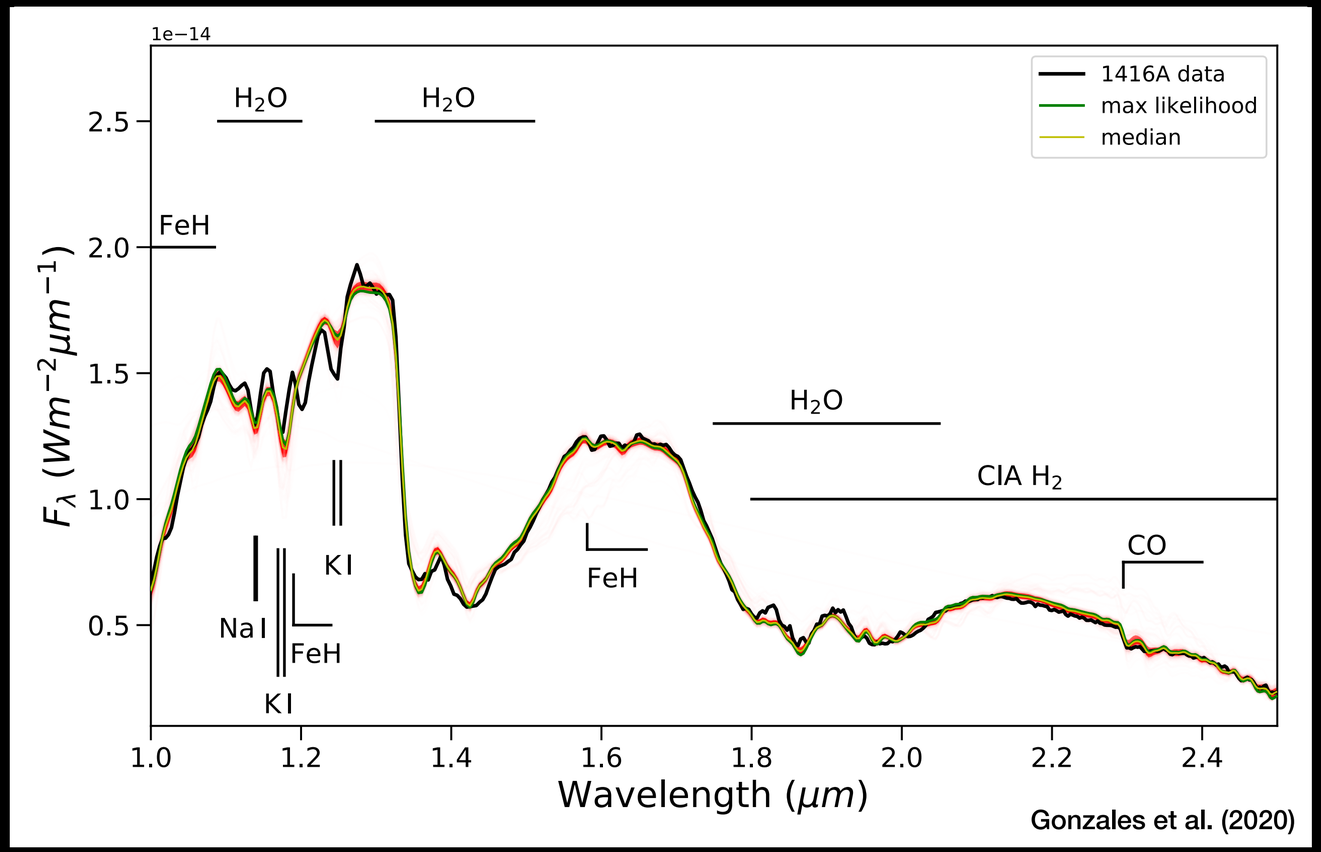

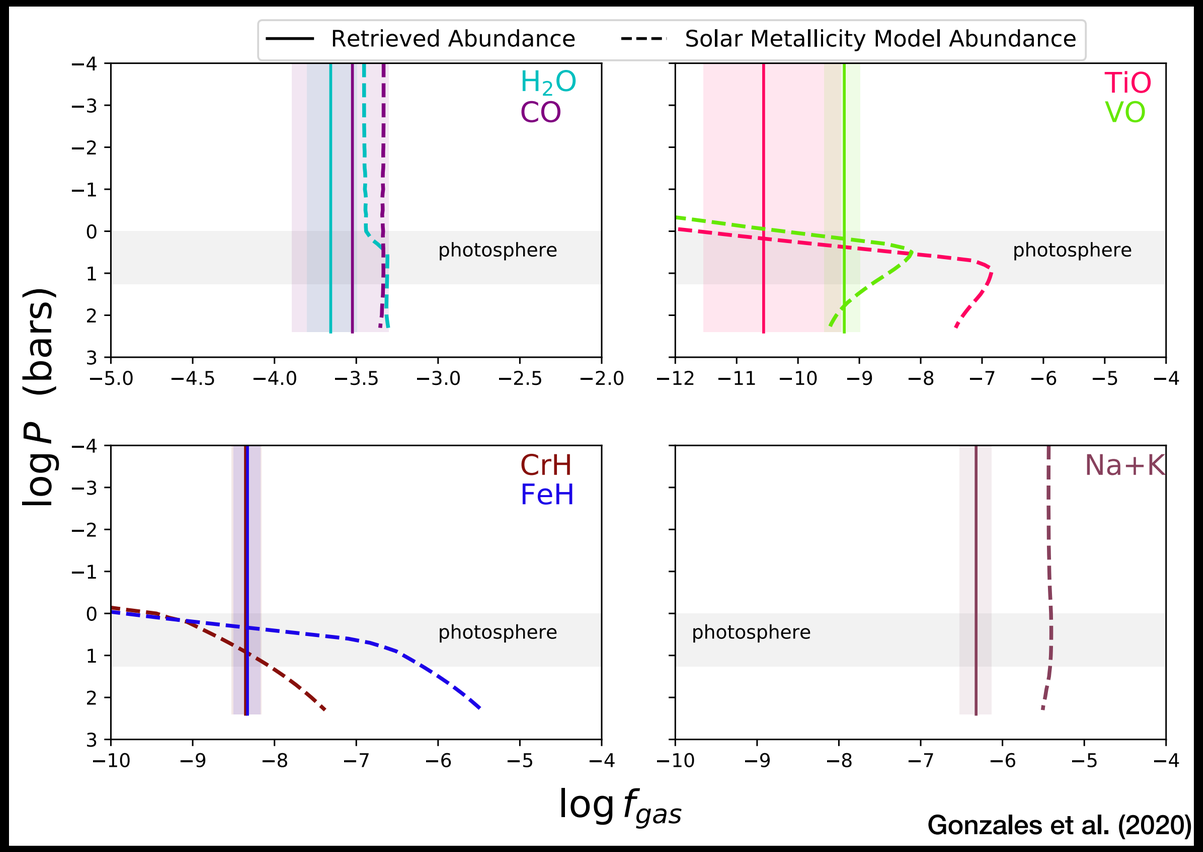

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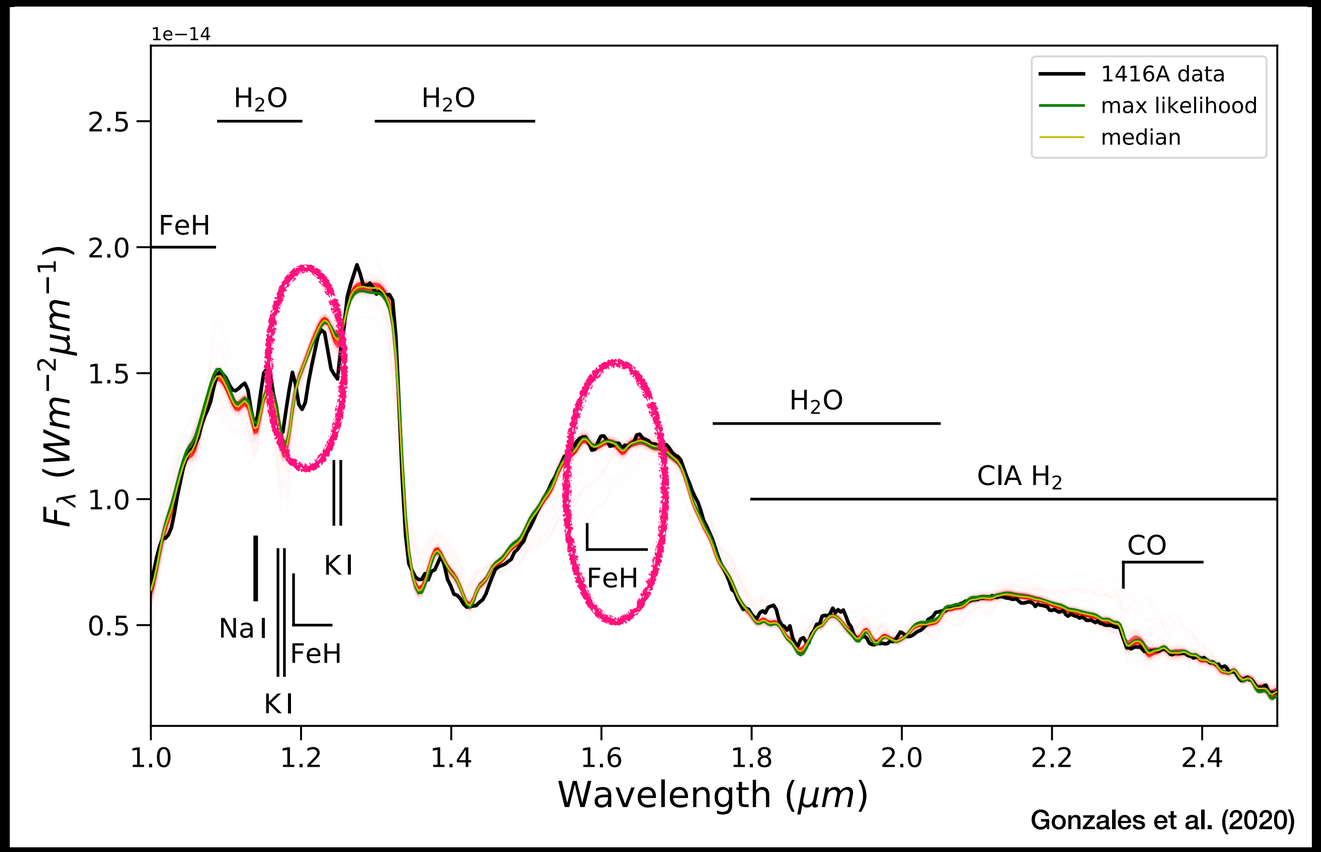

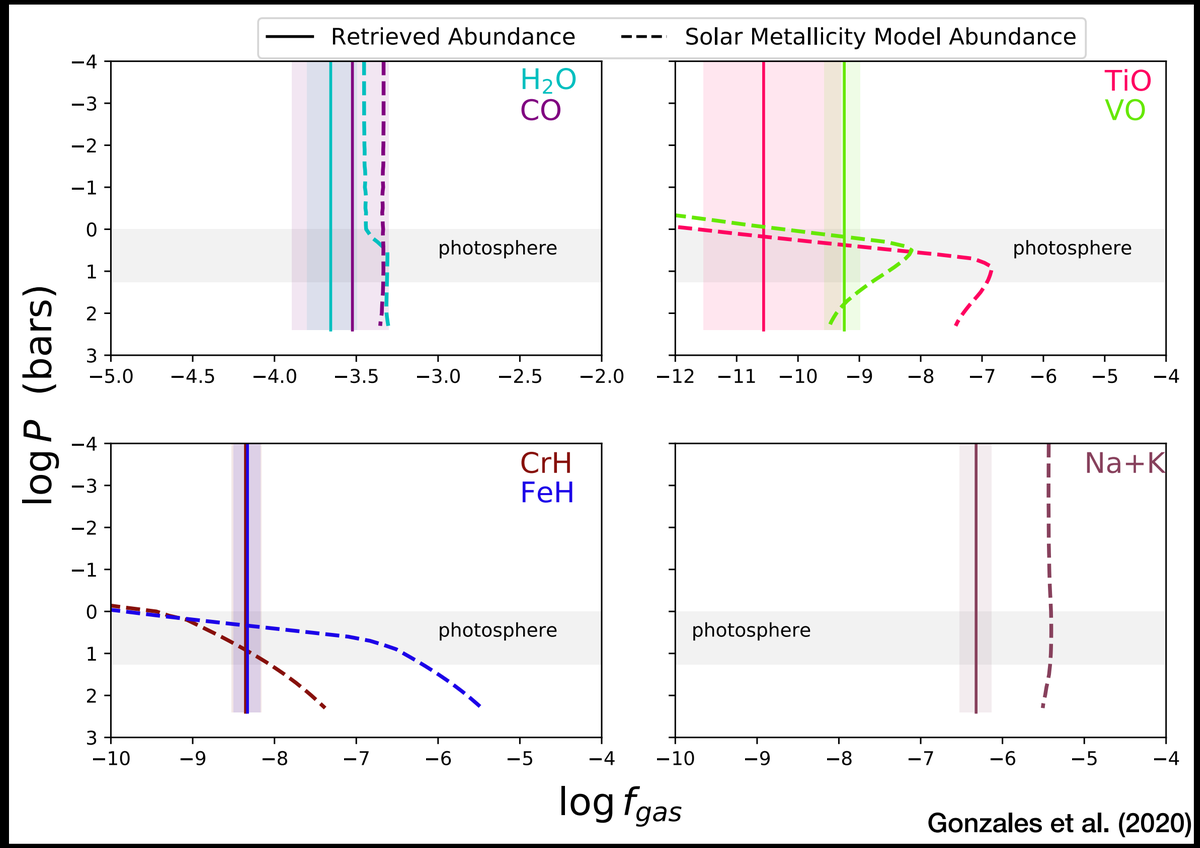

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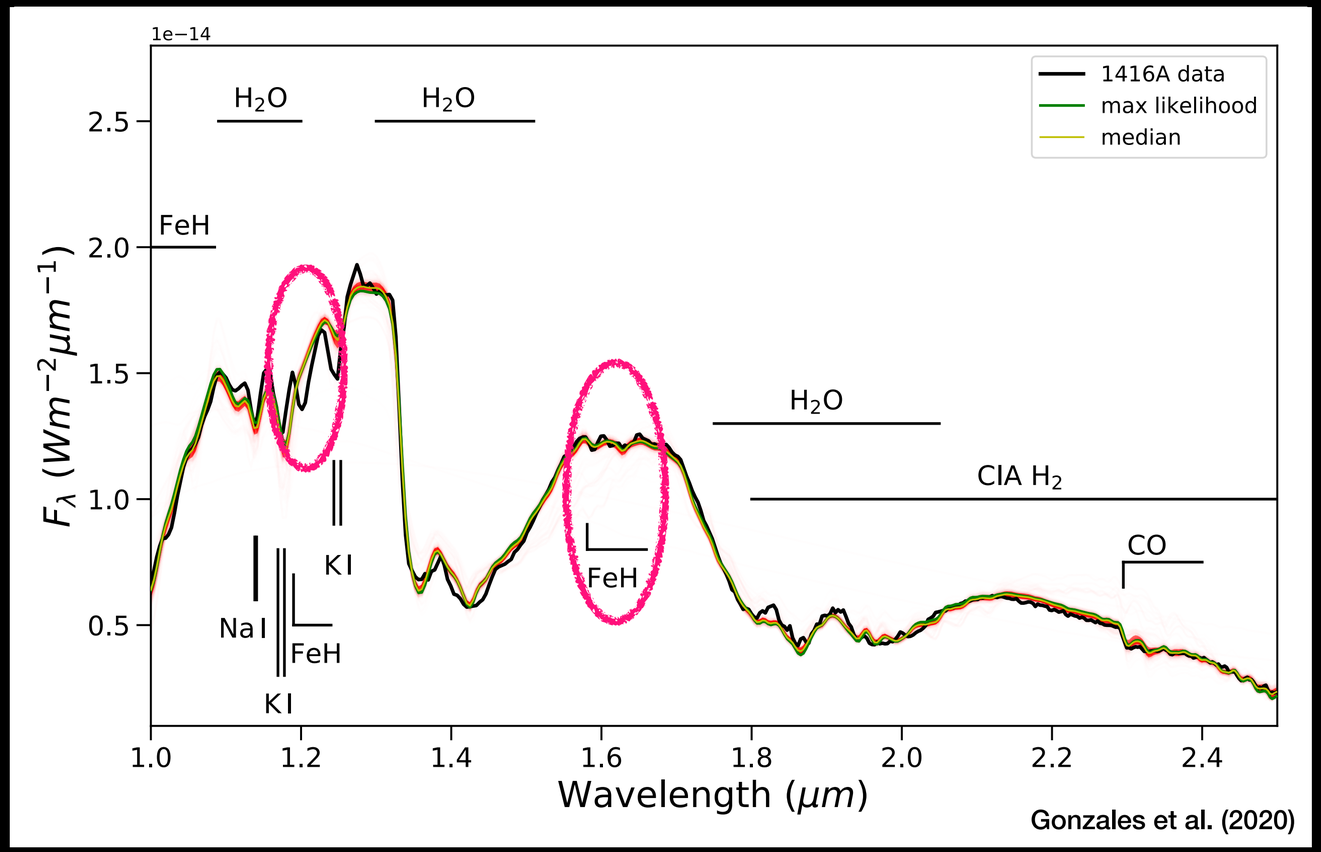

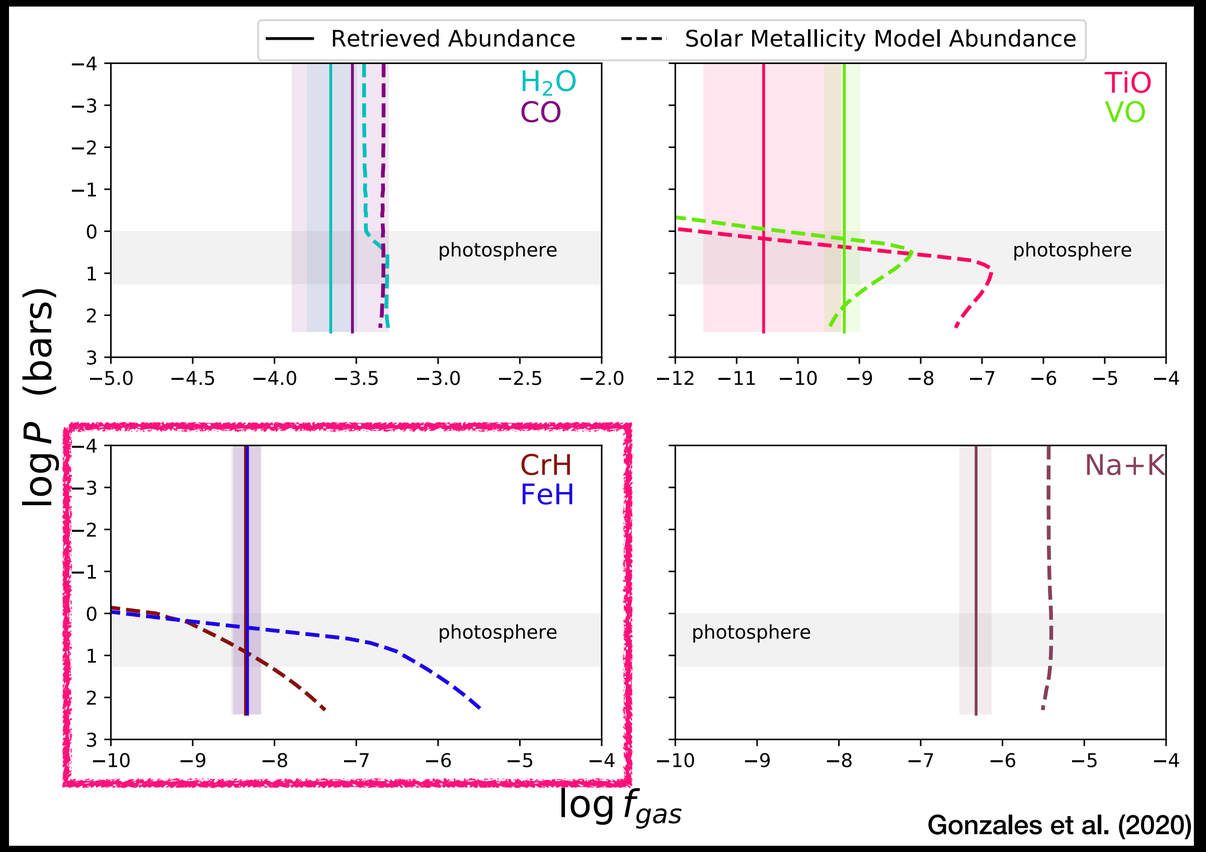

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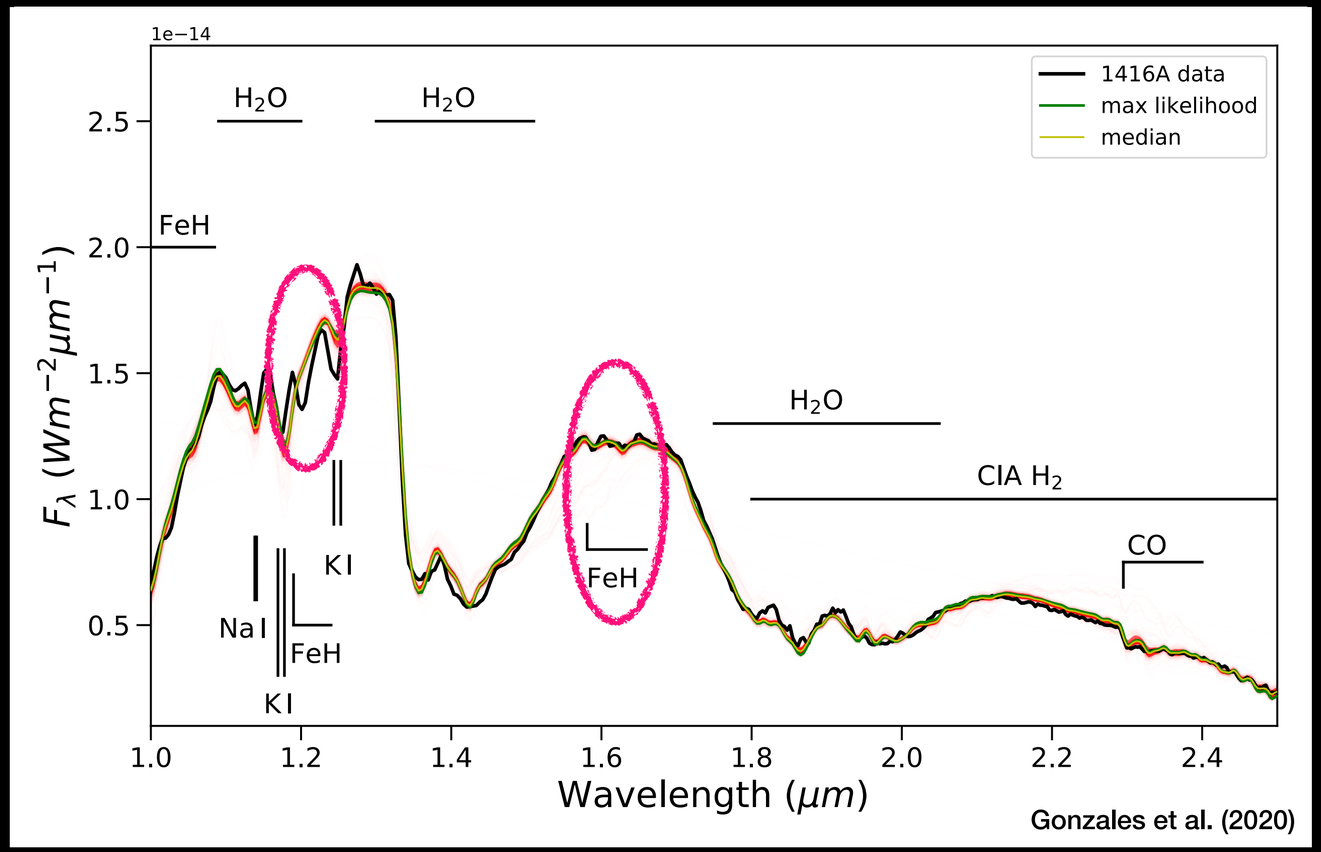
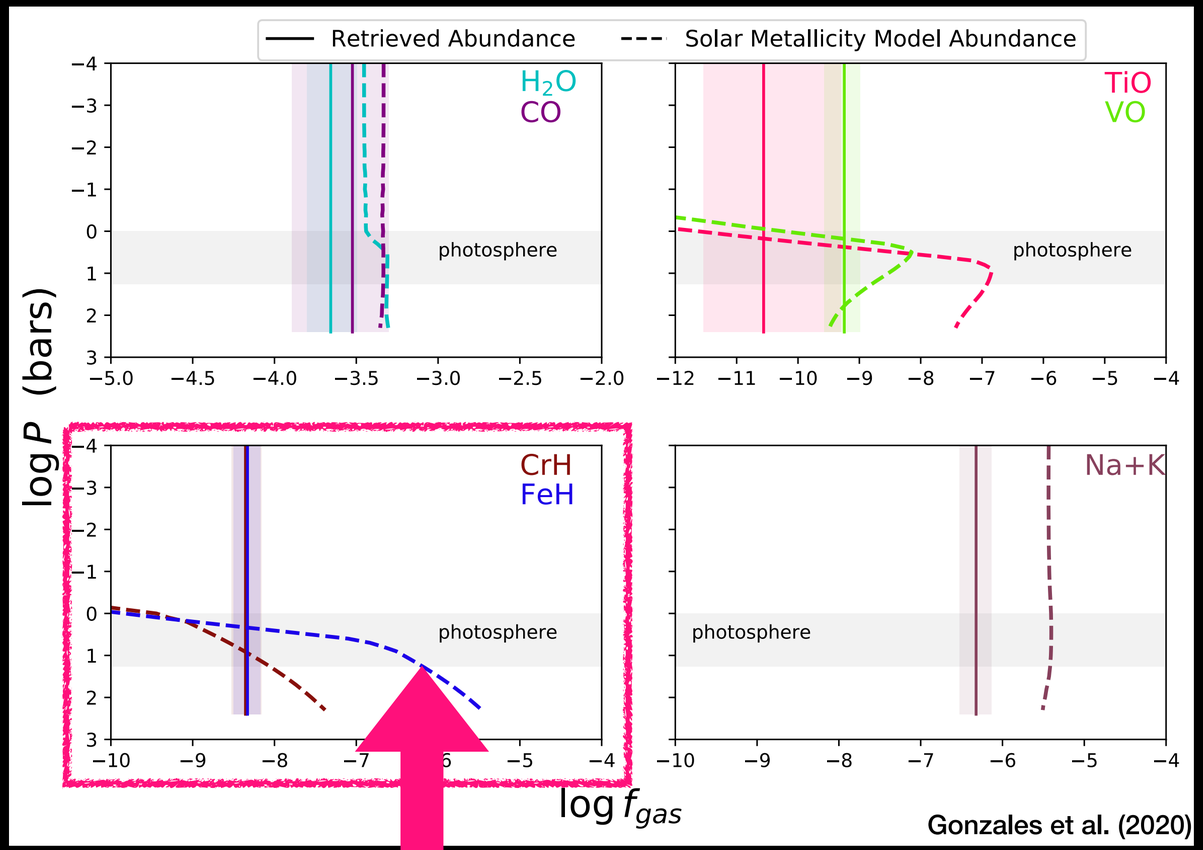
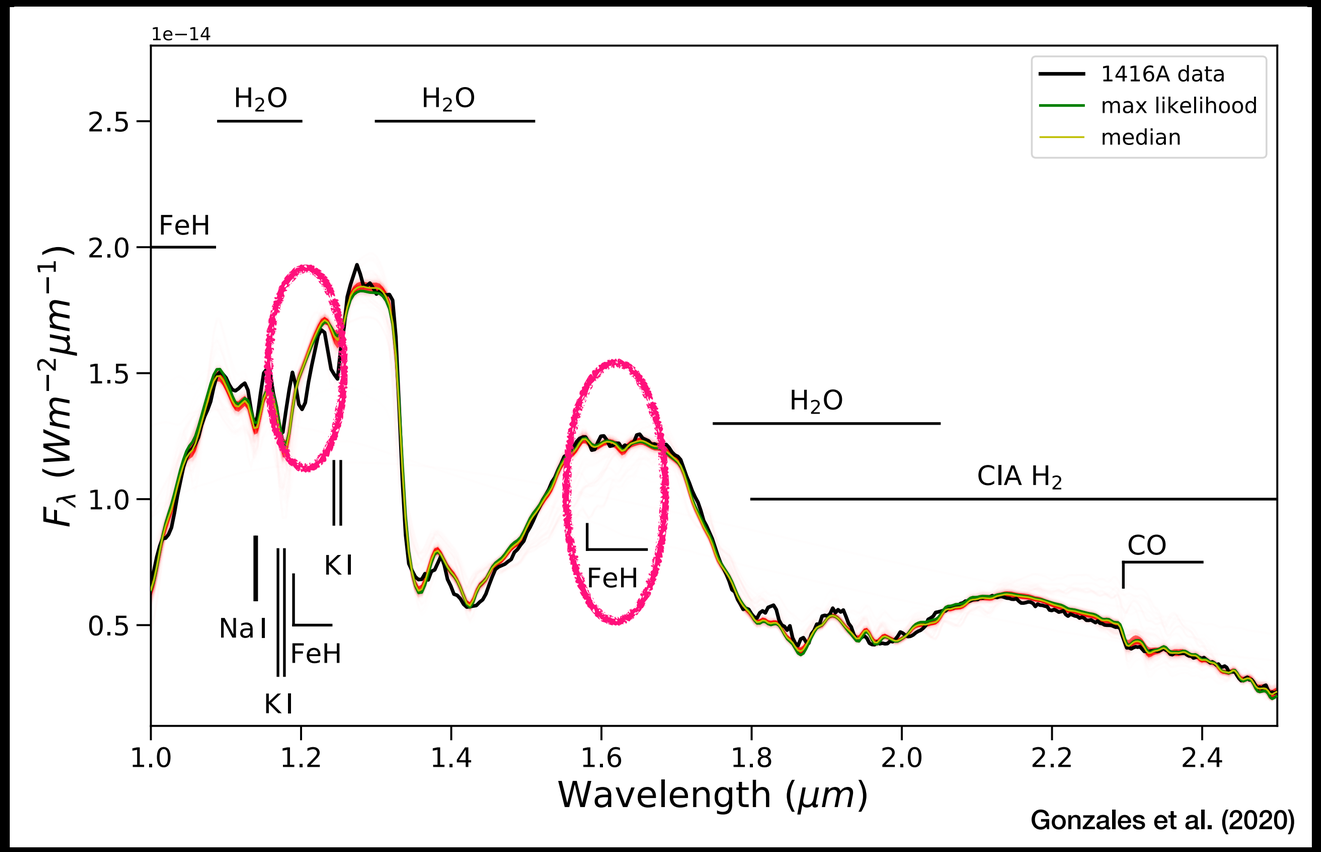


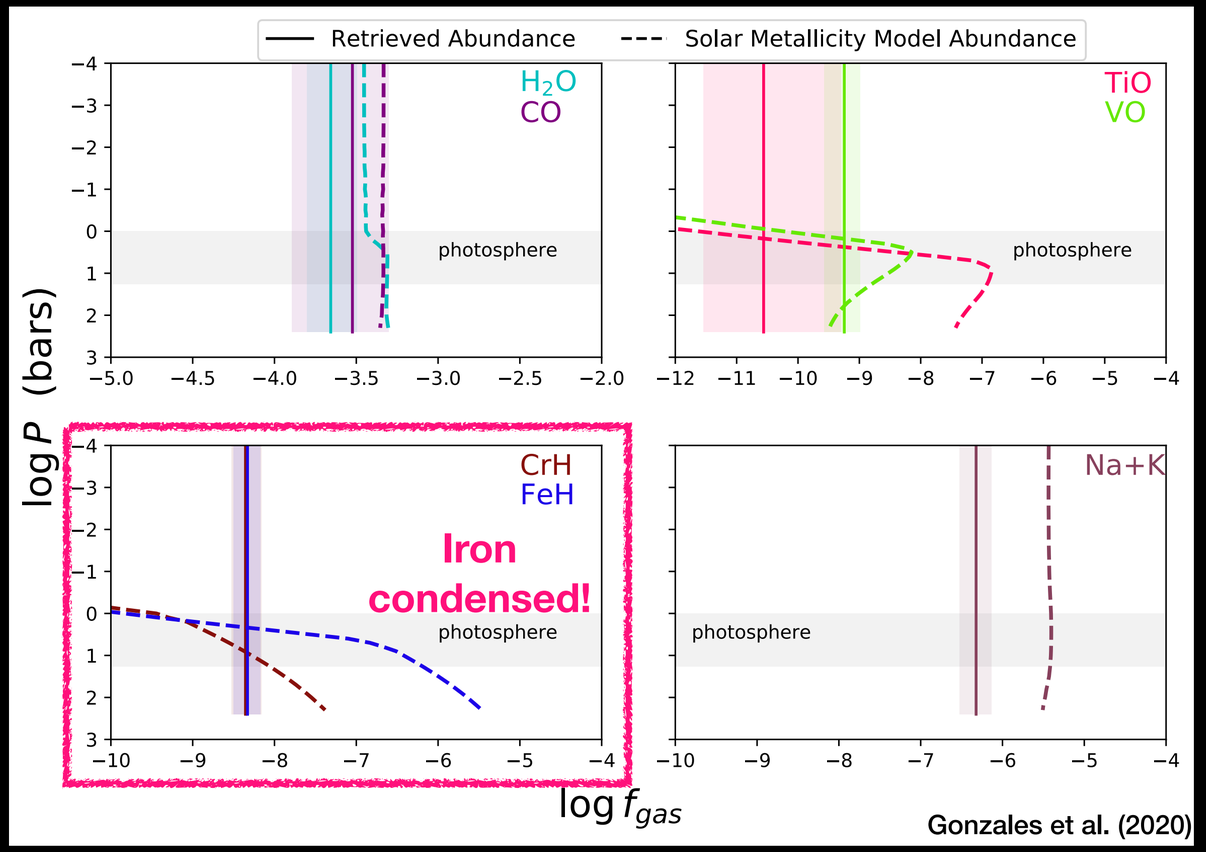


Maximum possible

Comparison to the Models

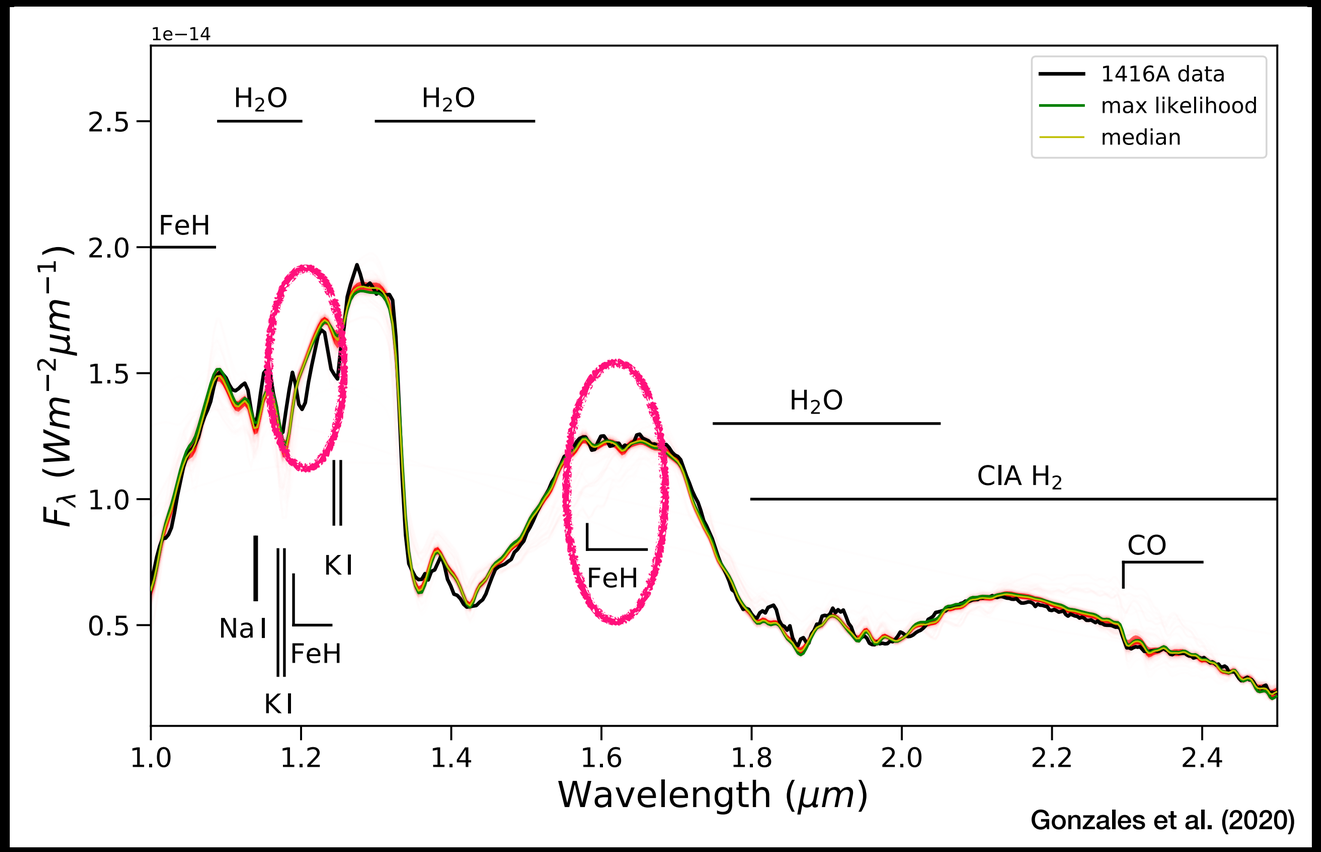
J H K

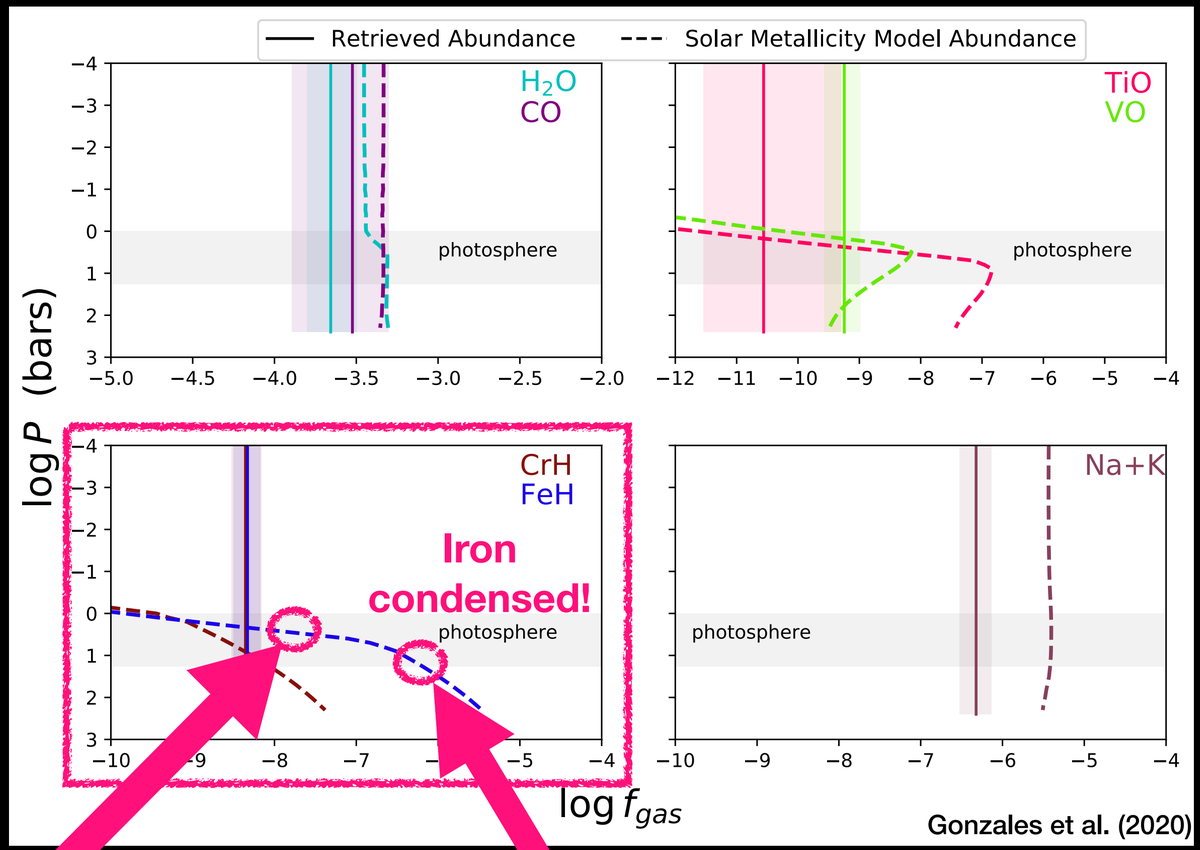




Comparison to the Models

J H K





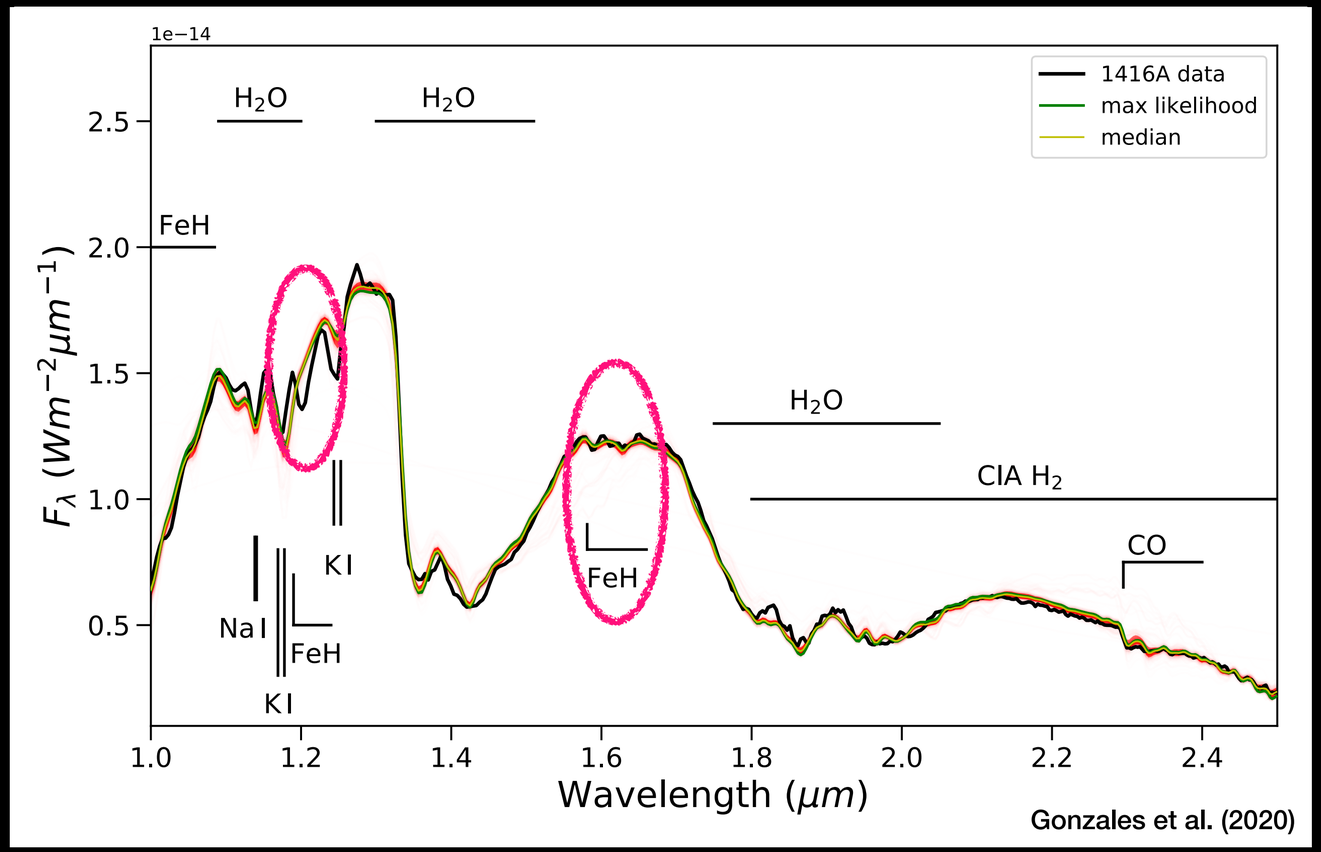
Issues with uniform-with-altitude assumption

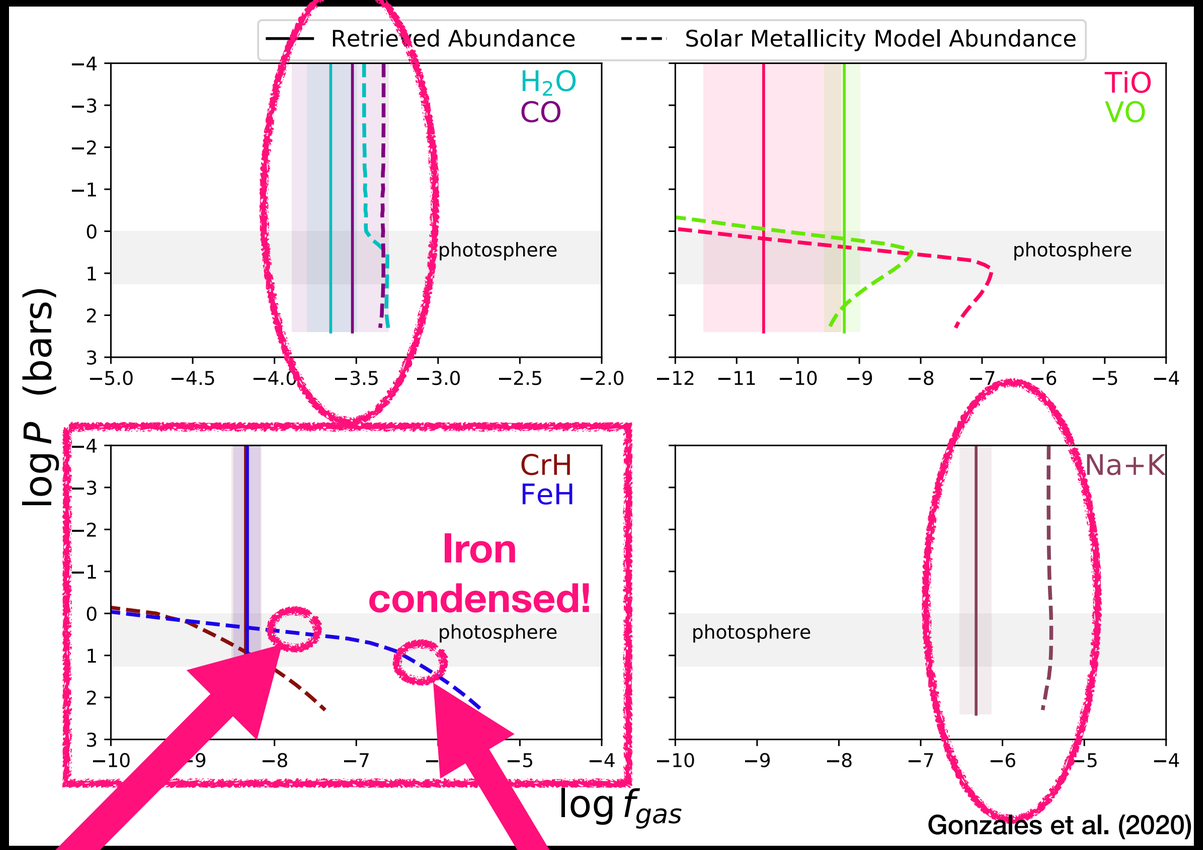
H band

J band

Comparison to the Models

J H K





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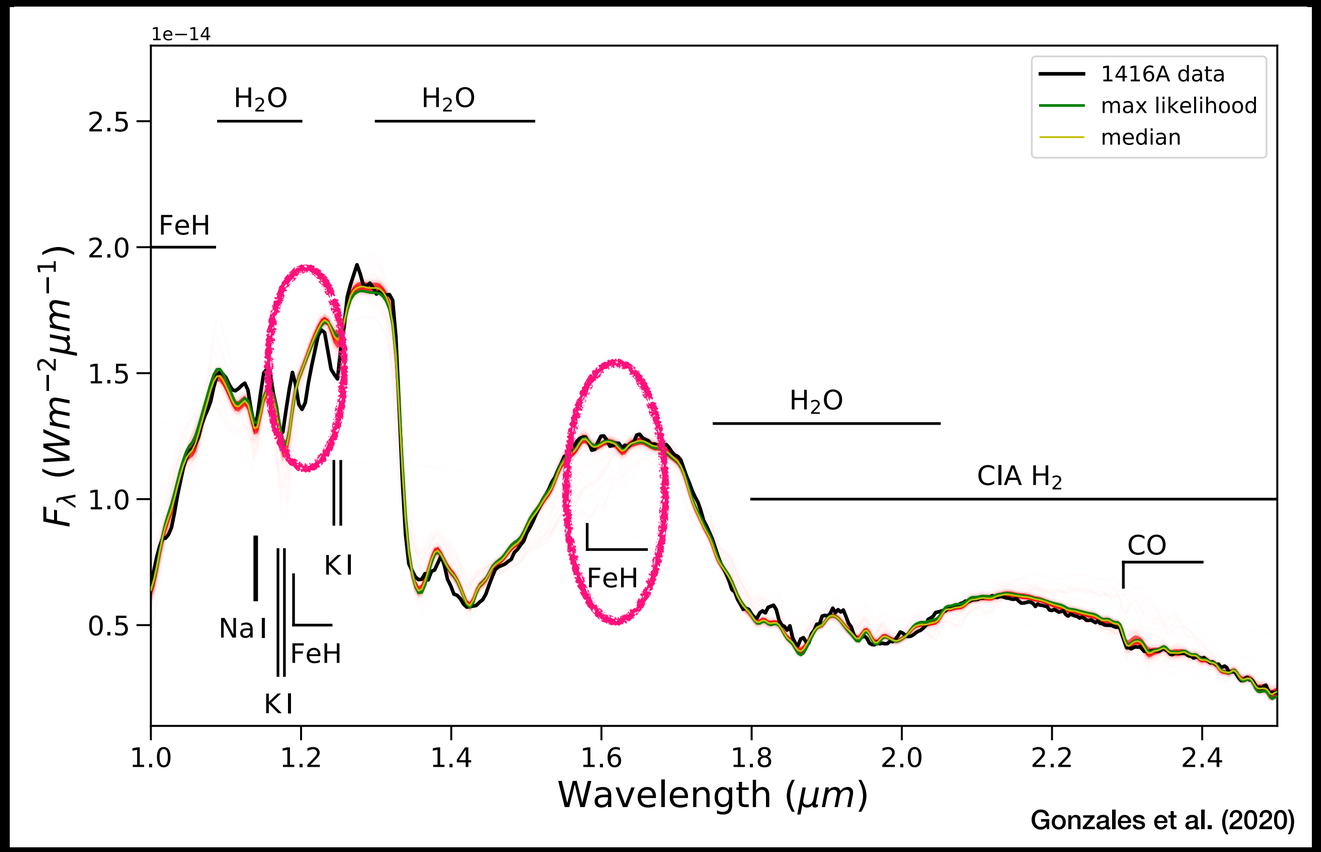
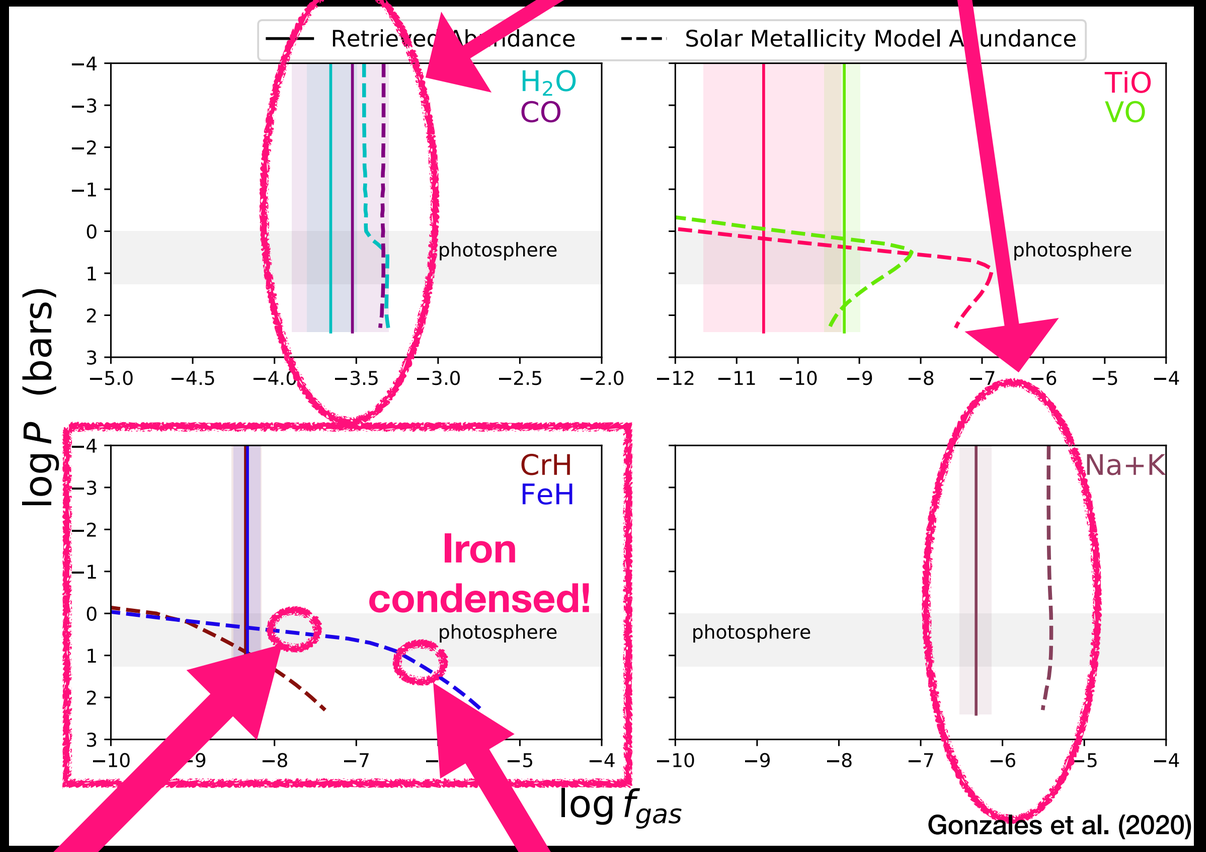


Low metallicity atmosphere



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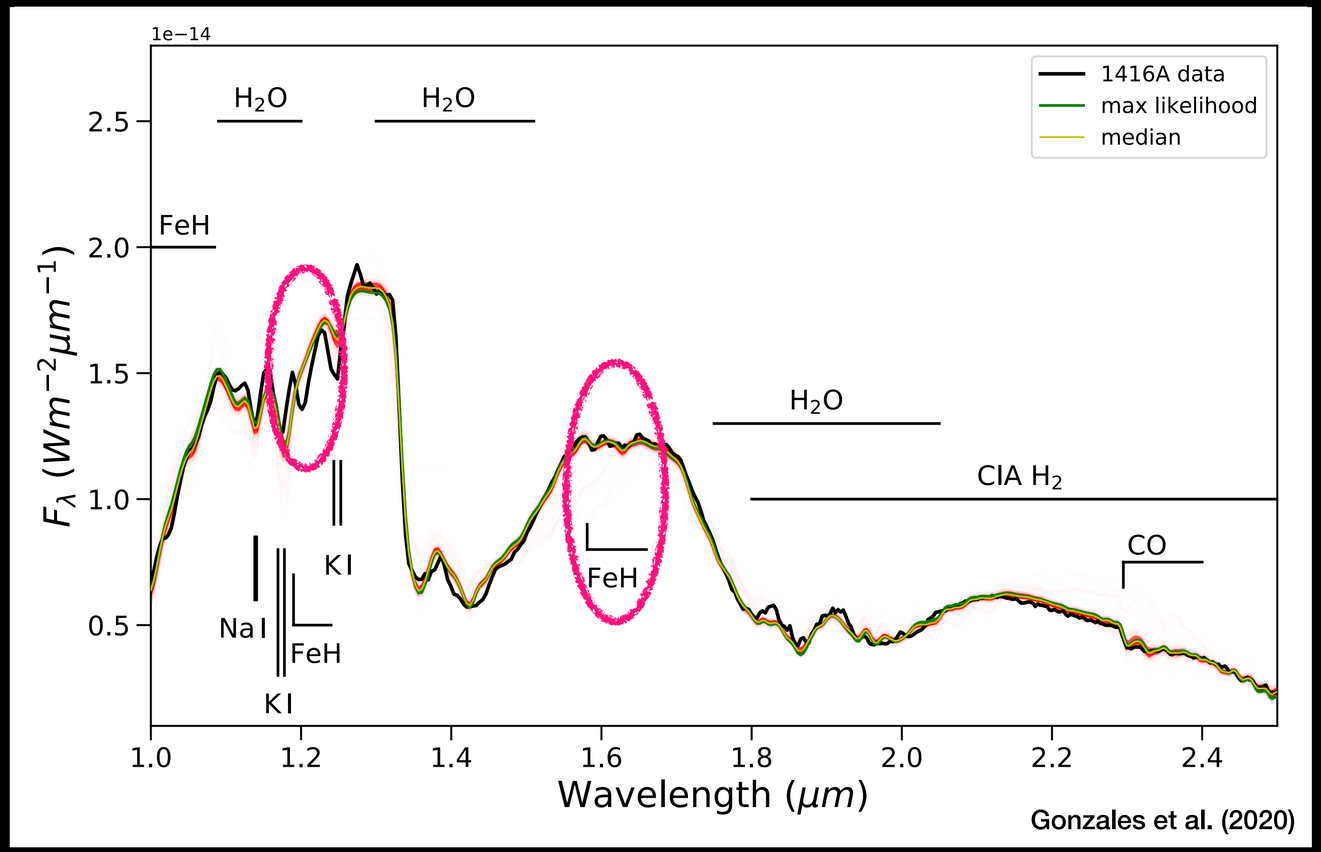

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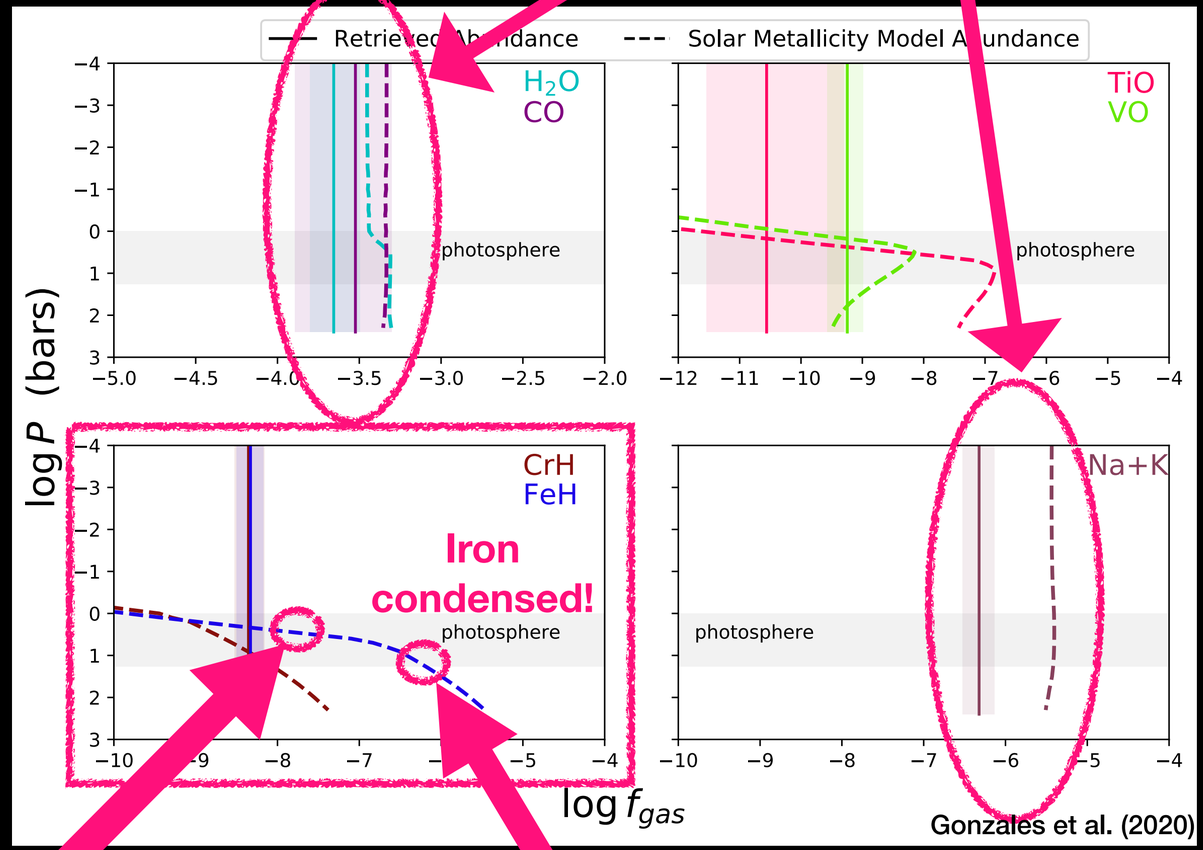

Issues with uniform-with-altitude assumption

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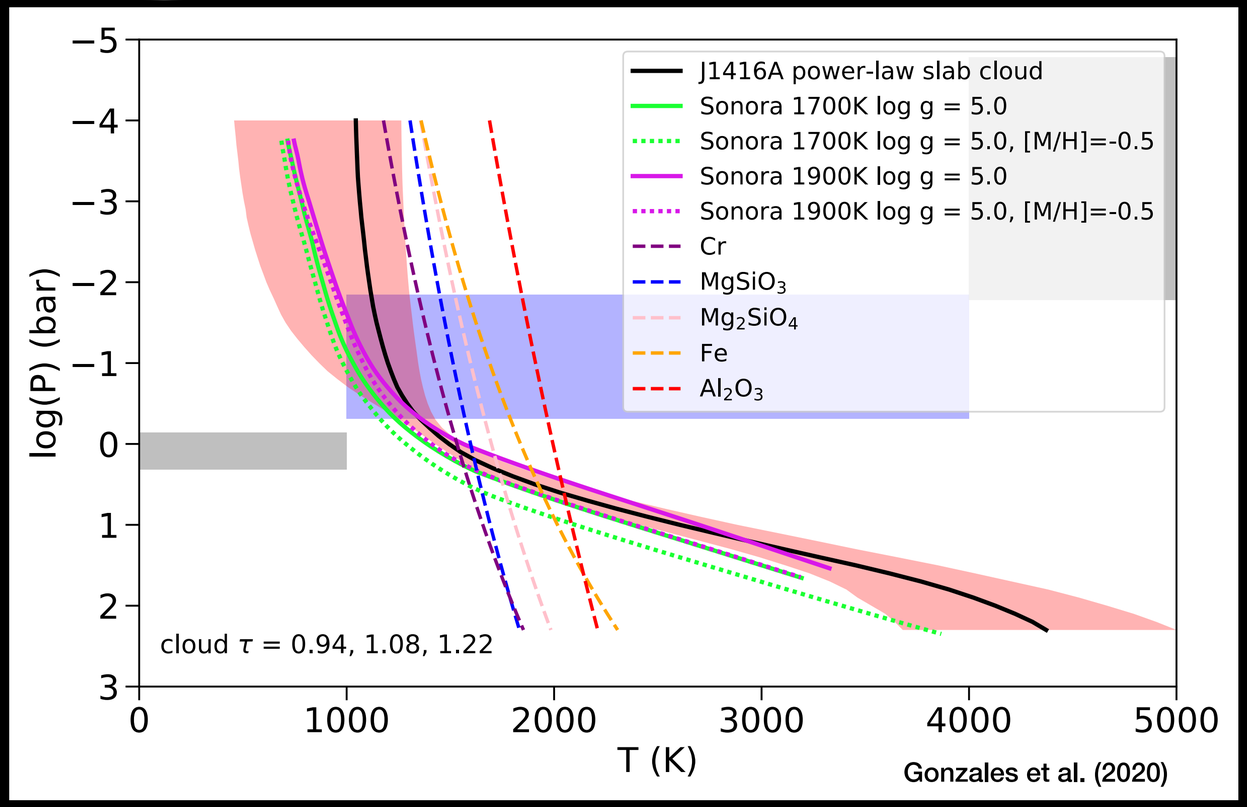
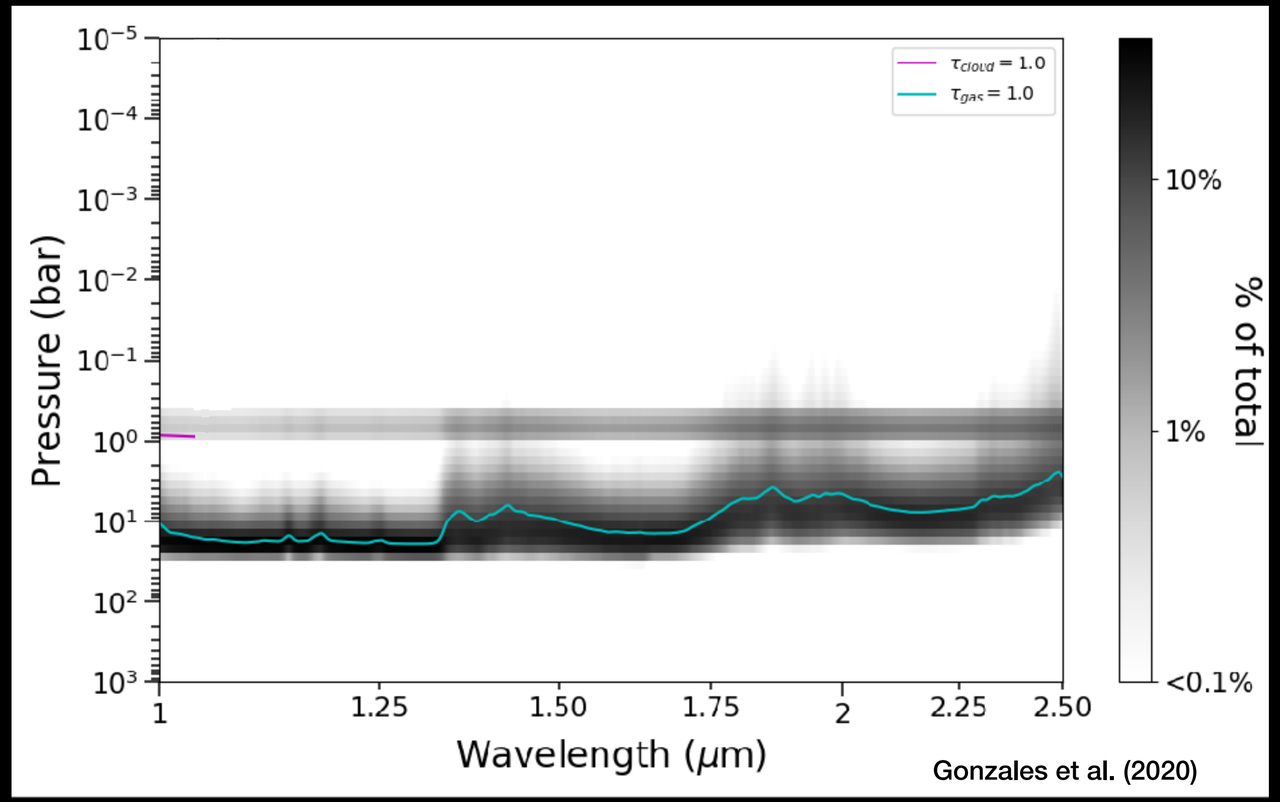
J band

Power-Law Deck Cloud is the winning model, but another cloud is indistinguishable…..

It's A Different Cloud for 1416A





Power law Slab cloud is the next best fit ΔBIC 1.4

Bayesian Information Criterion
A way to compare models

0<BIC< 2 no preference
2<BIC< 6 positive
6<BIC<10 strong
BIC>10 very strong

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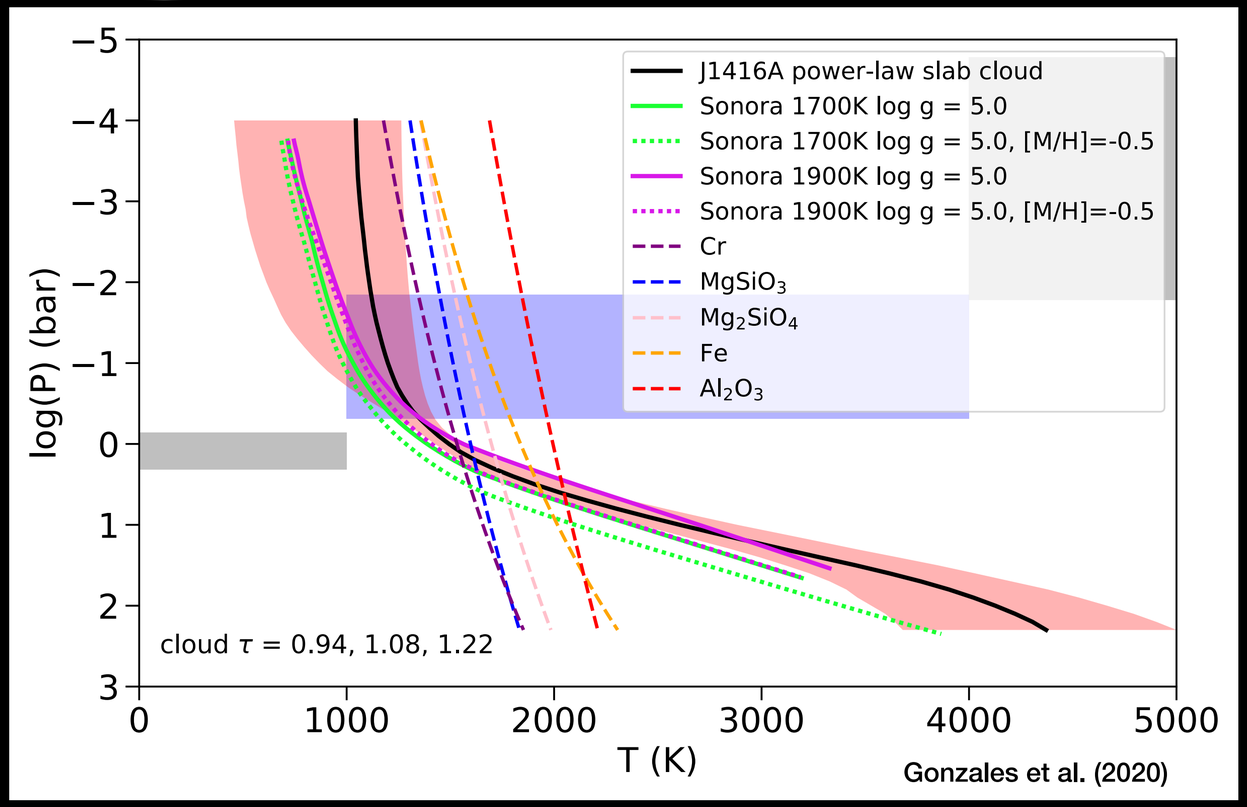

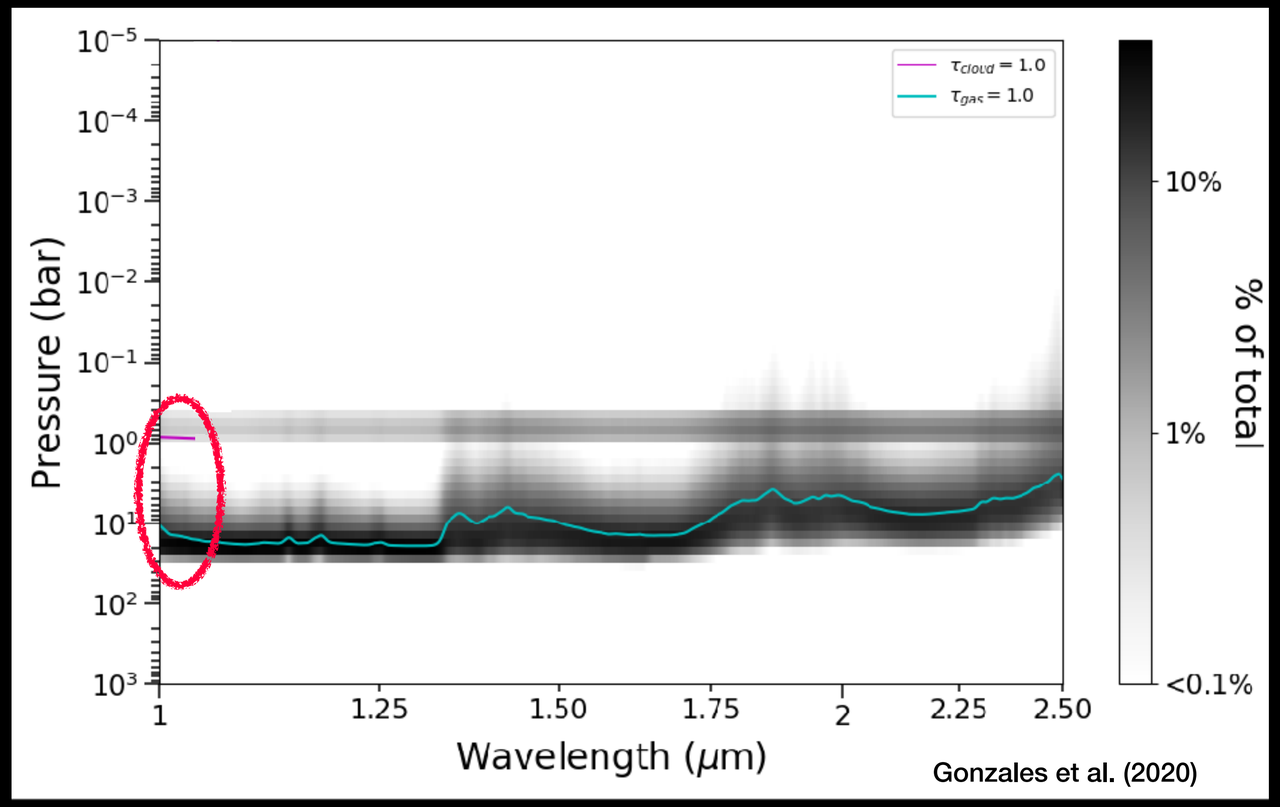

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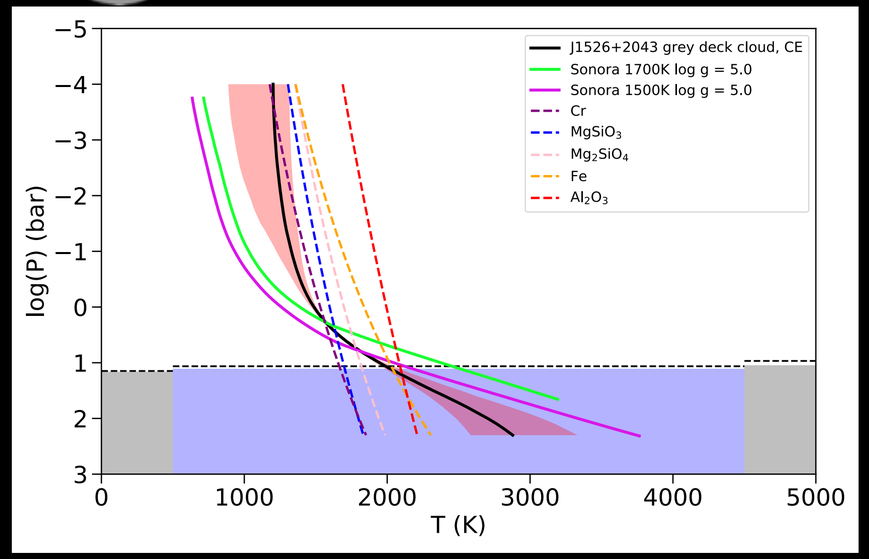
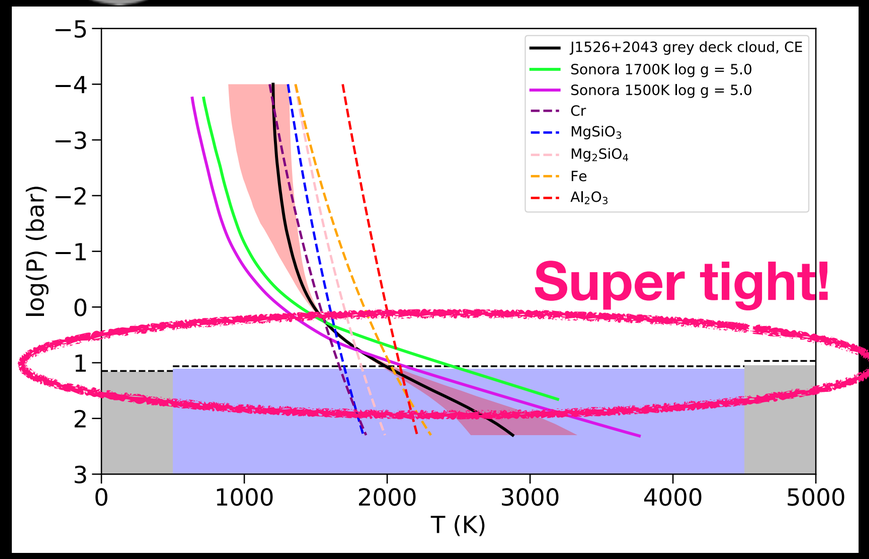
J1526+2043: Grey Deck Cloud, CE



Spectral Type Comparison

J1526+2043: Grey Deck Cloud, CE



- Tightly constrained cloud top and height

Spectral Type Comparison

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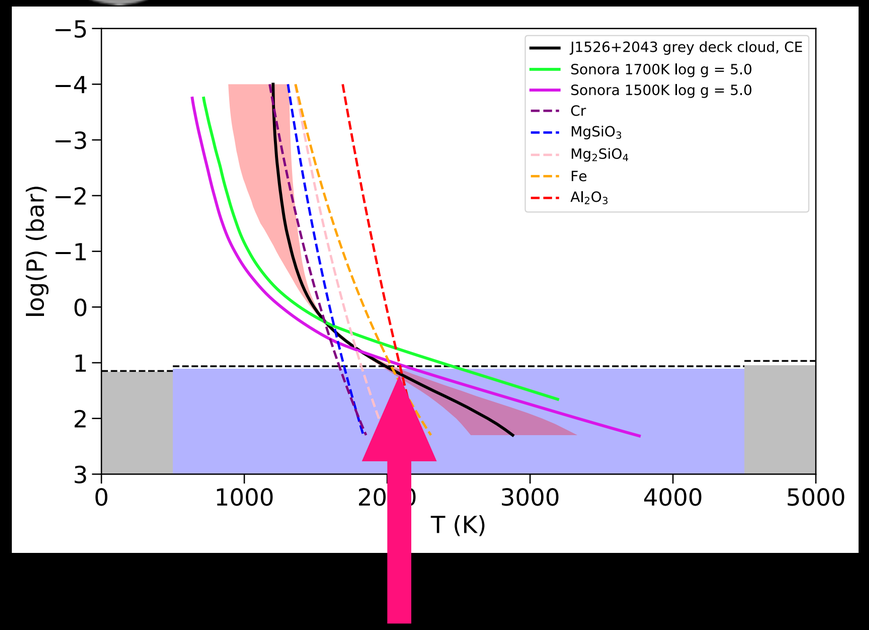

- Tightly constrained cloud top and height
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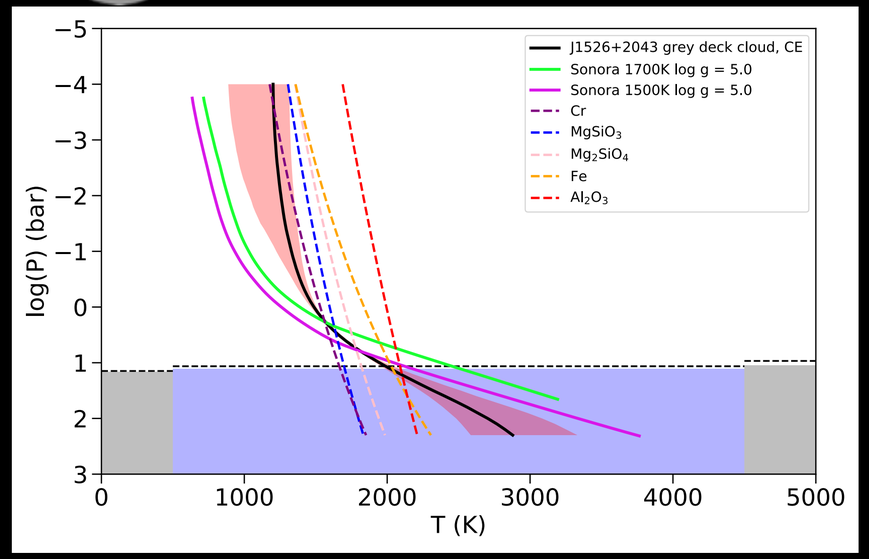
J1526+2043: Grey Deck Cloud, CE



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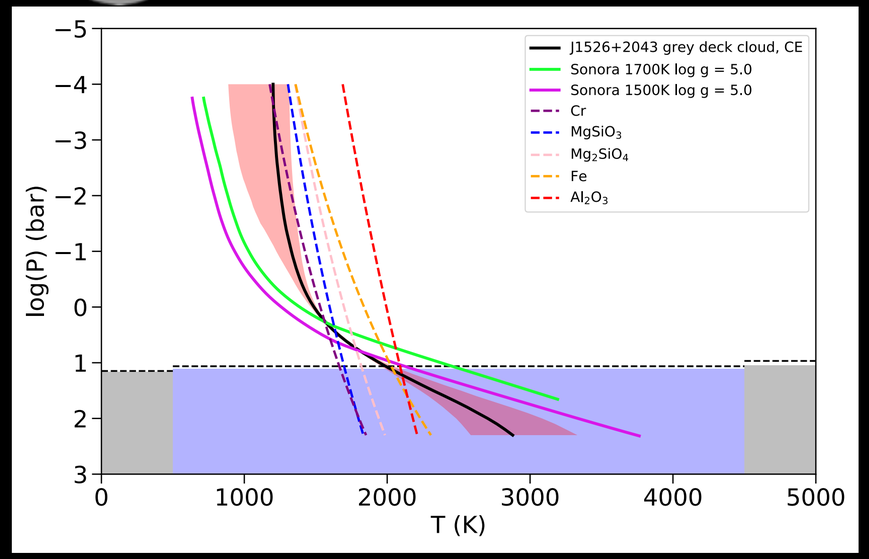

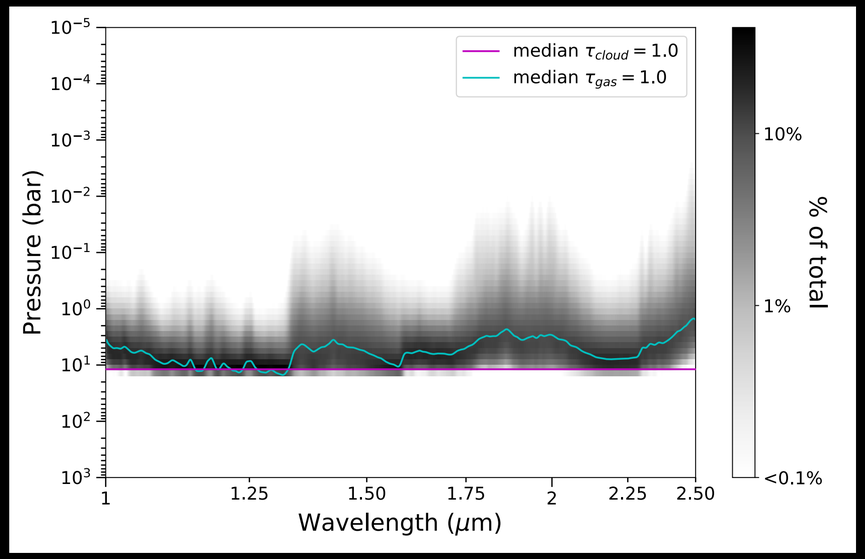

Gonzales et al. (in prep)

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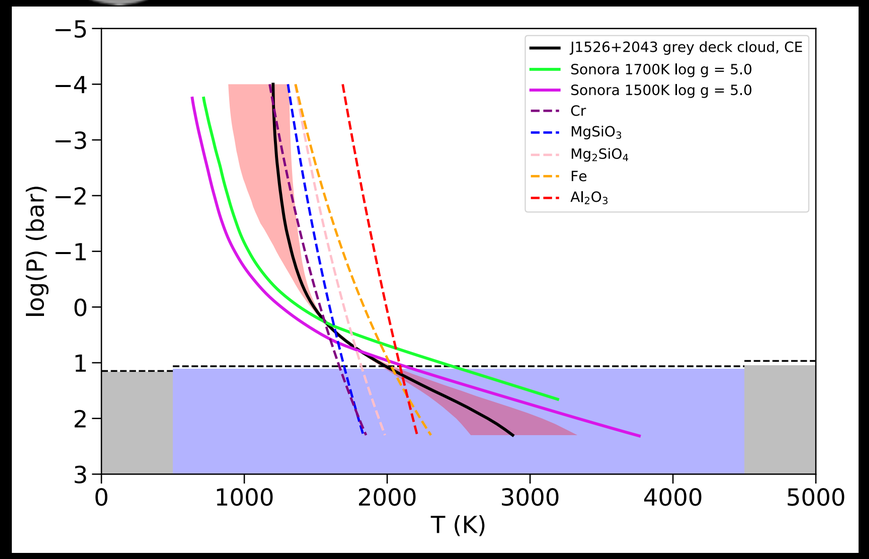

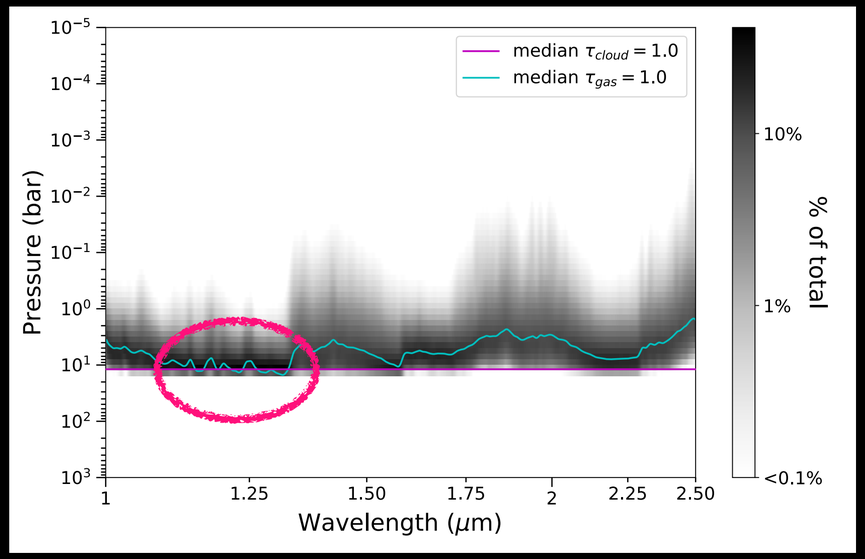

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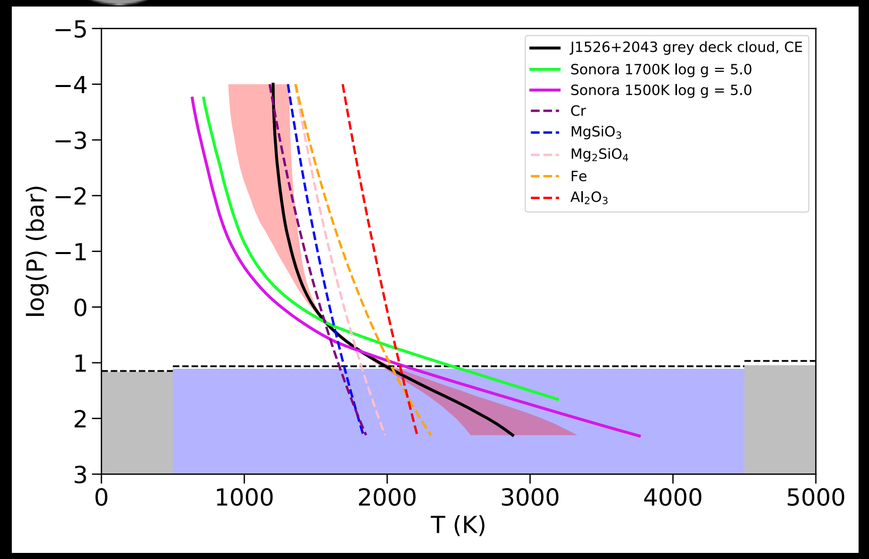
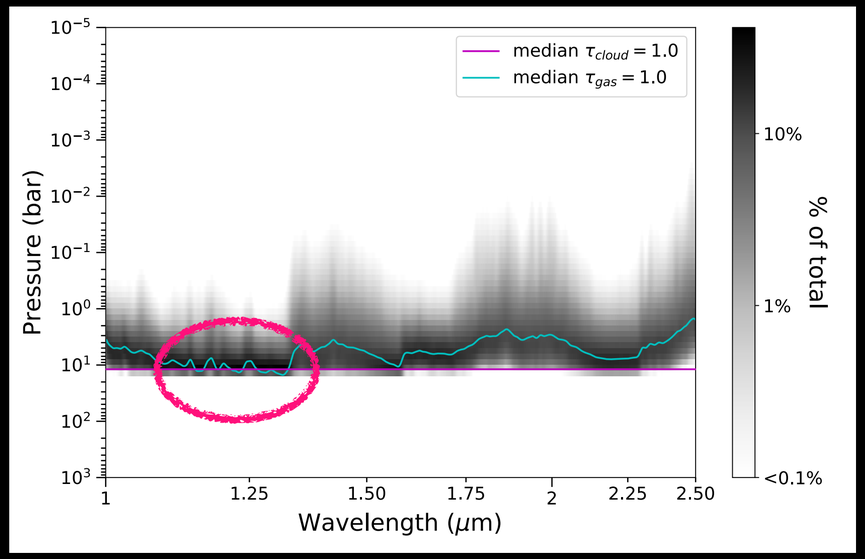
Spectral Type Comparison

J1526+2043: Grey Deck Cloud, CE





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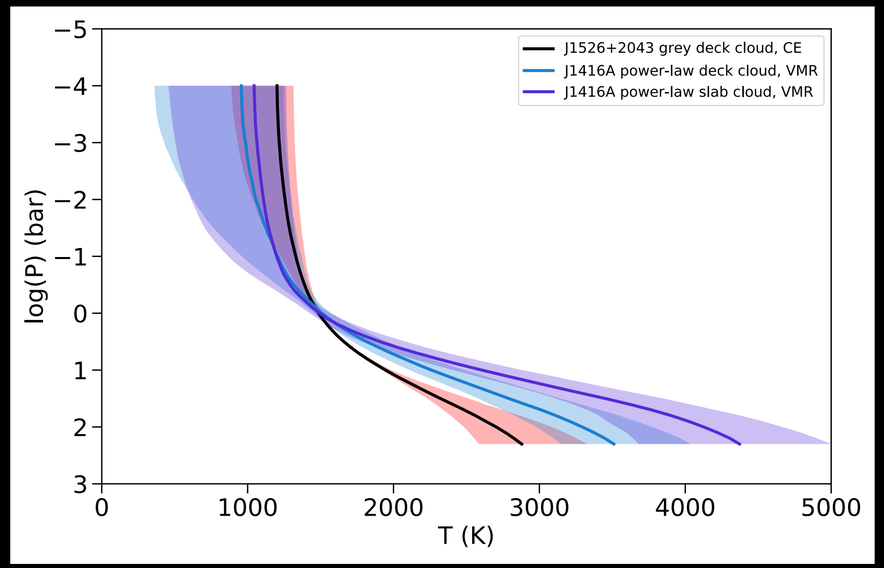

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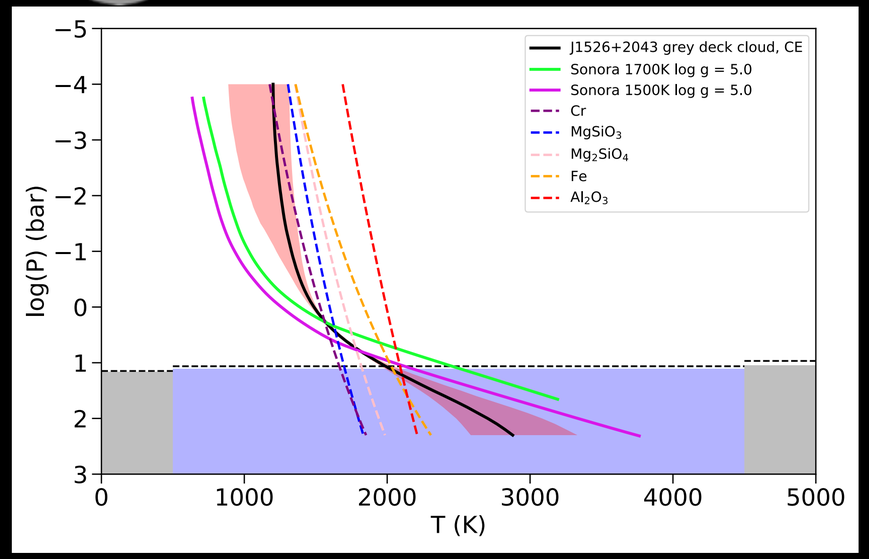

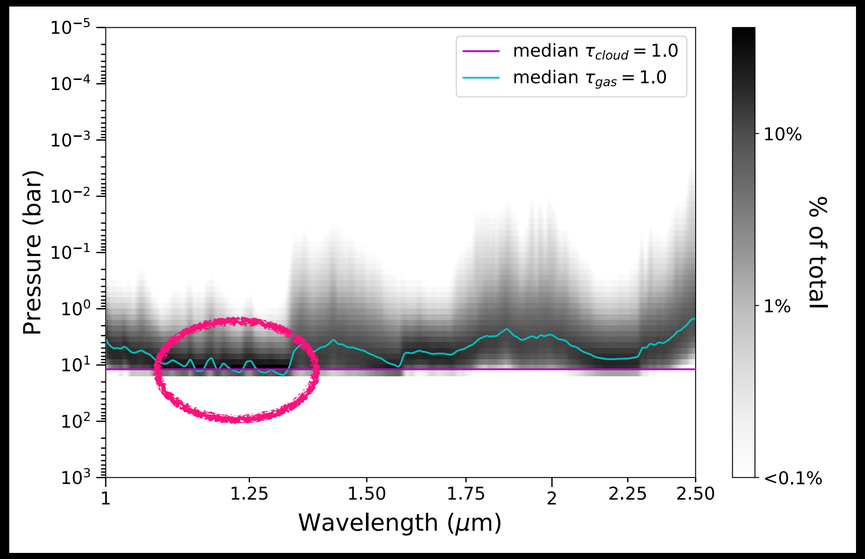

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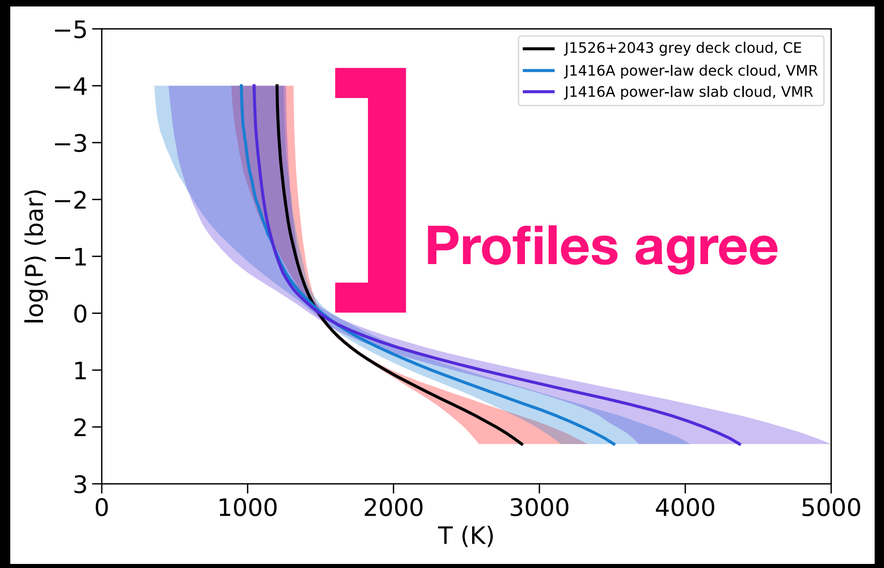
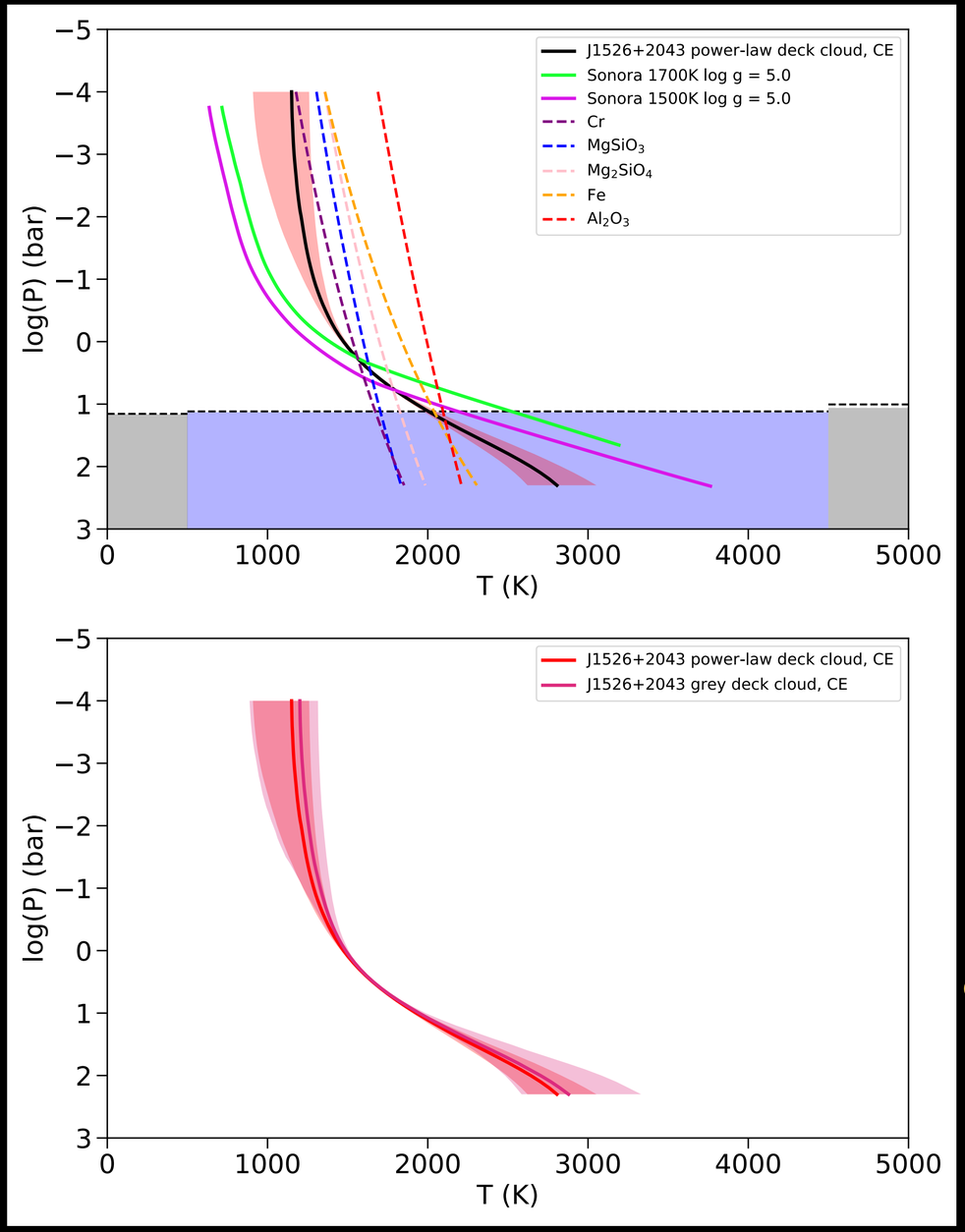


- Tightly constrained cloud top and height
- Iron or corundum cloud
- PT profile does not agree with models
- Cloud opacity affects small amount of the *J* band
- PT profile agrees with J1416A in upper atmosphere

Spectral Type Comparison

Runner Up: Power law Deck Cloud

ΔBIC=2.4



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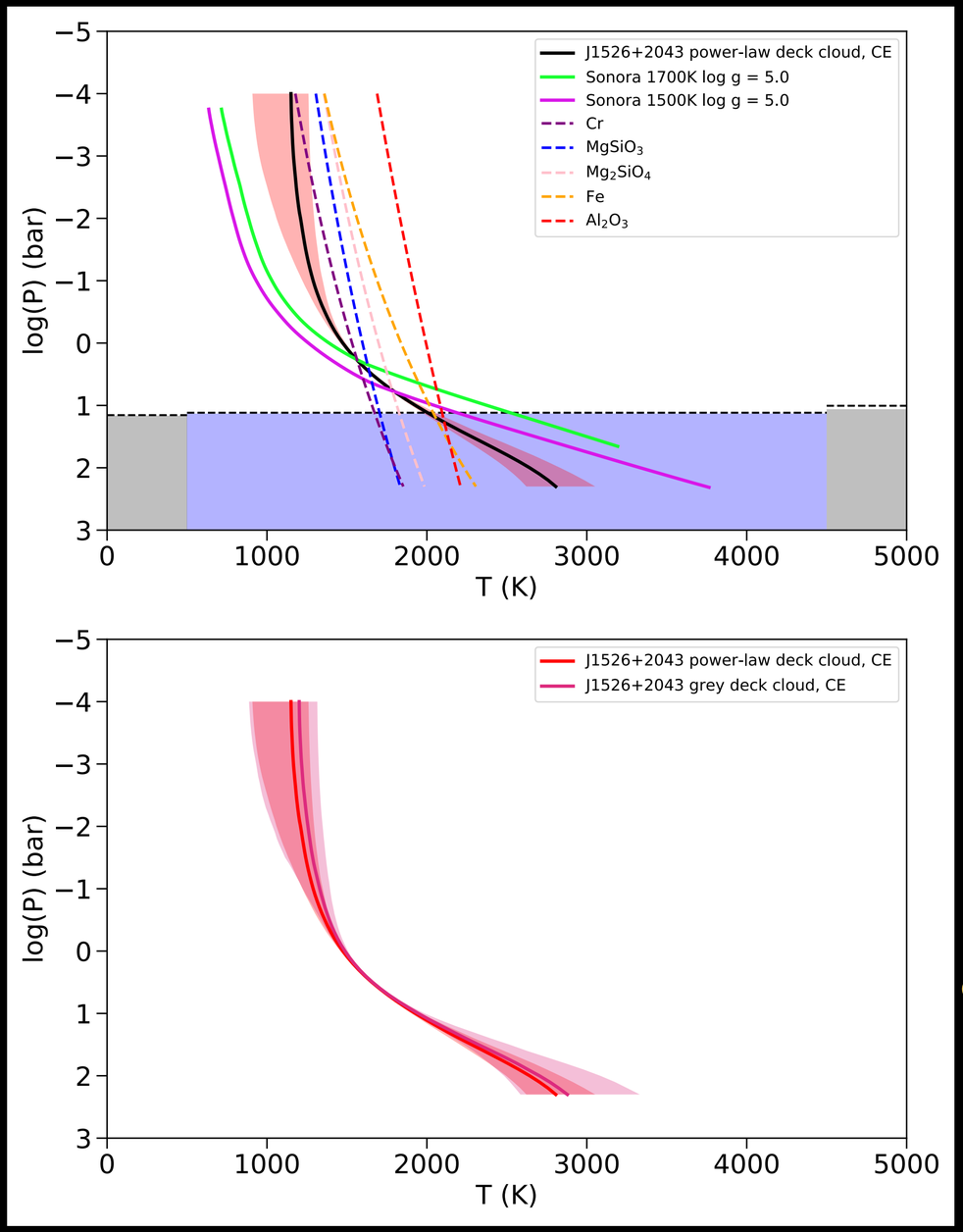

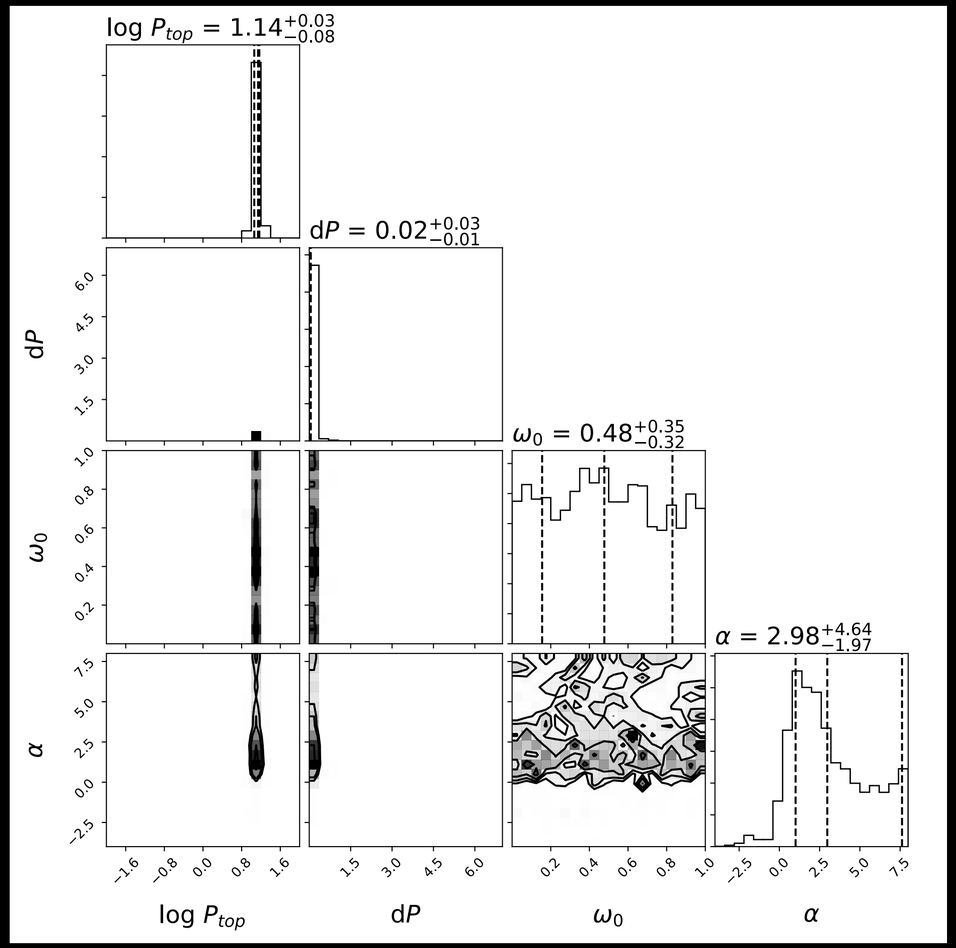

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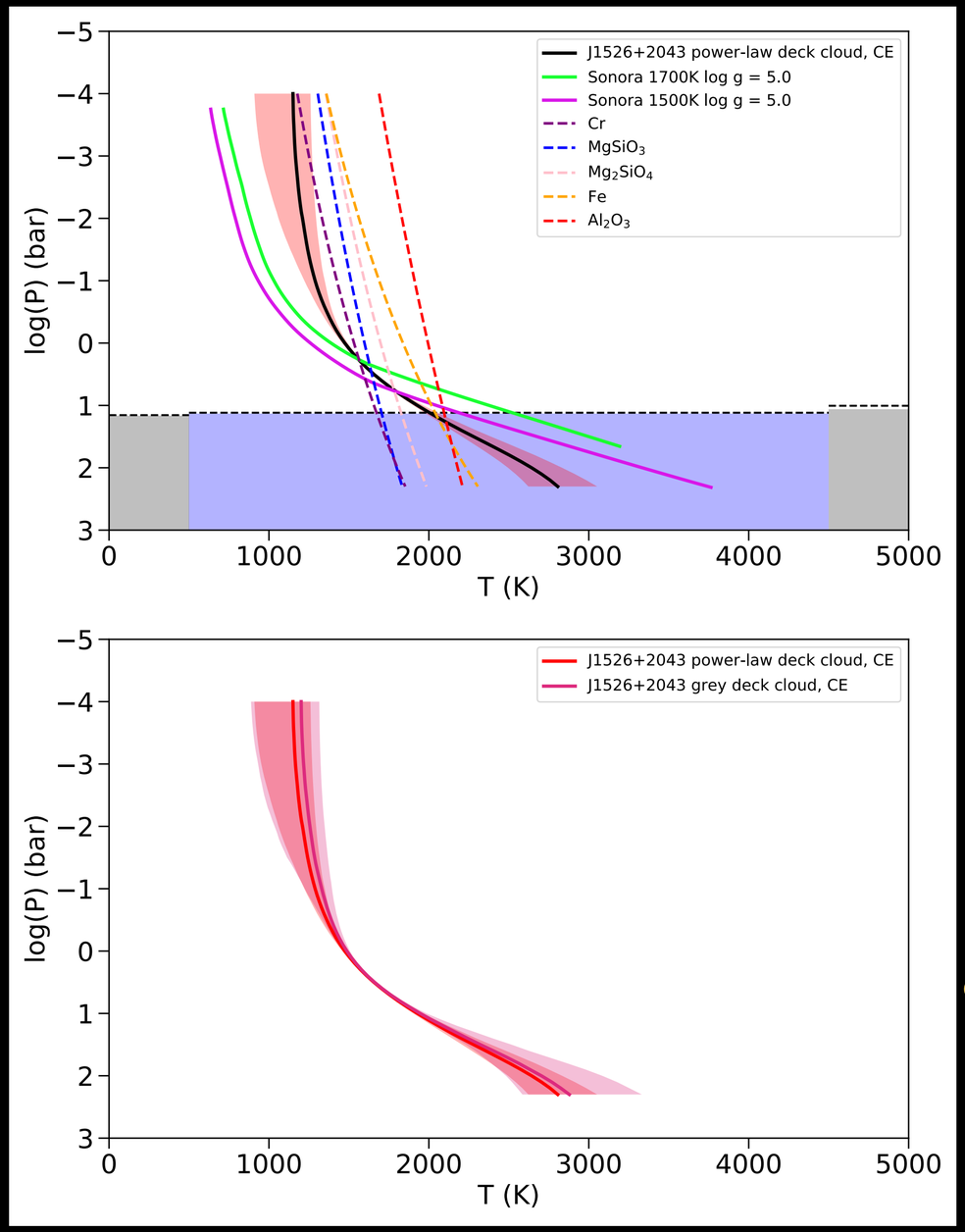

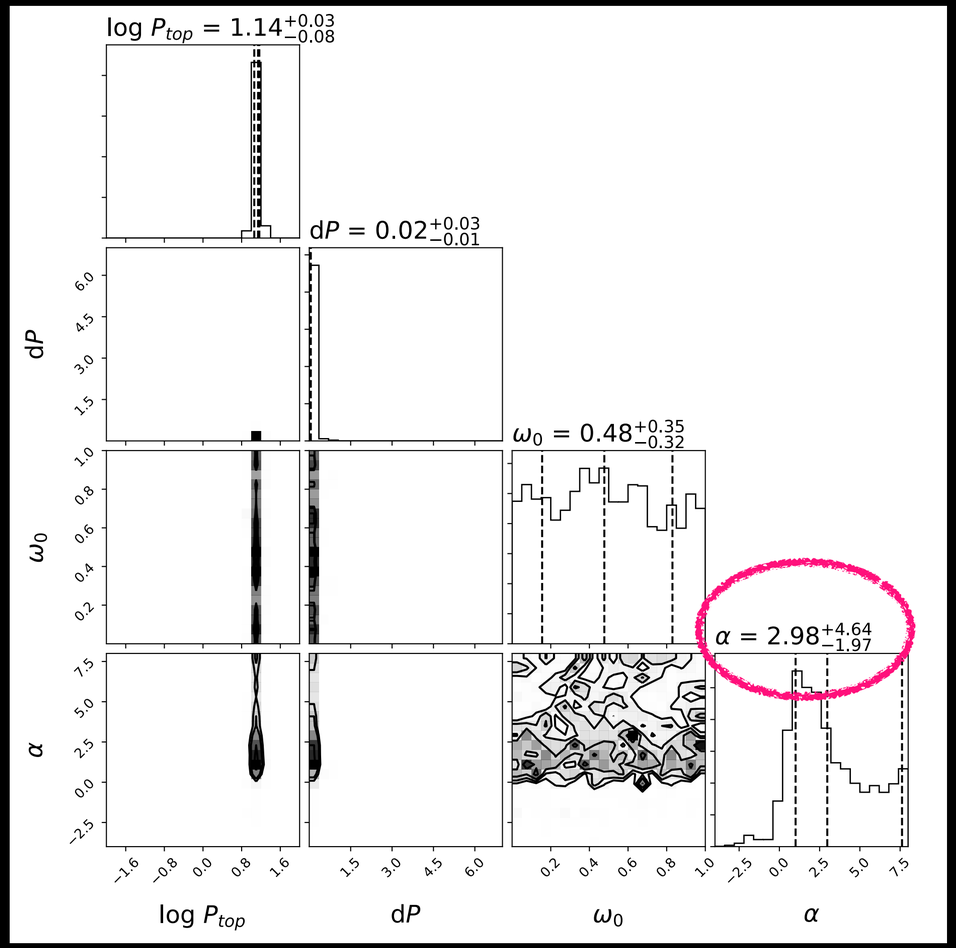

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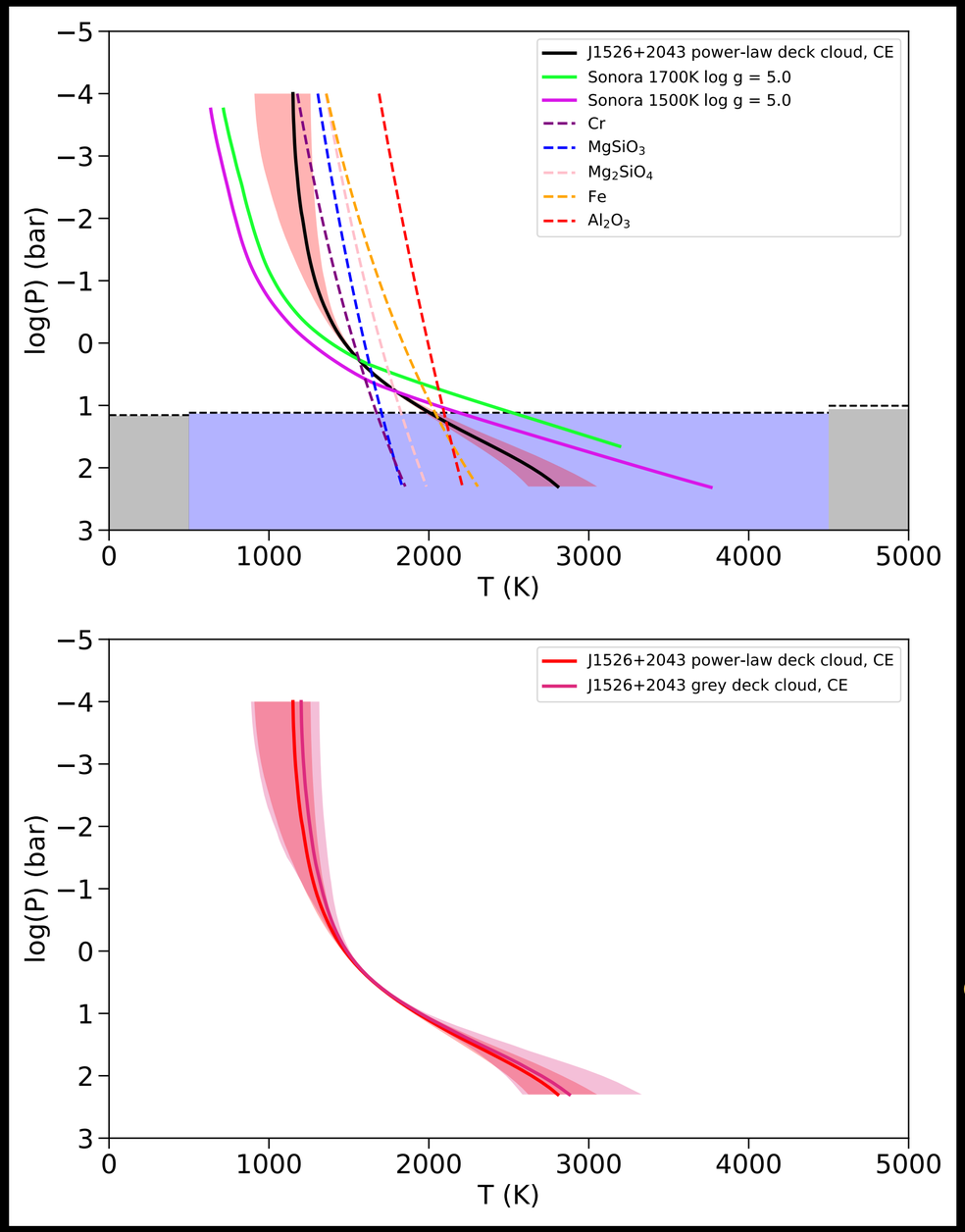
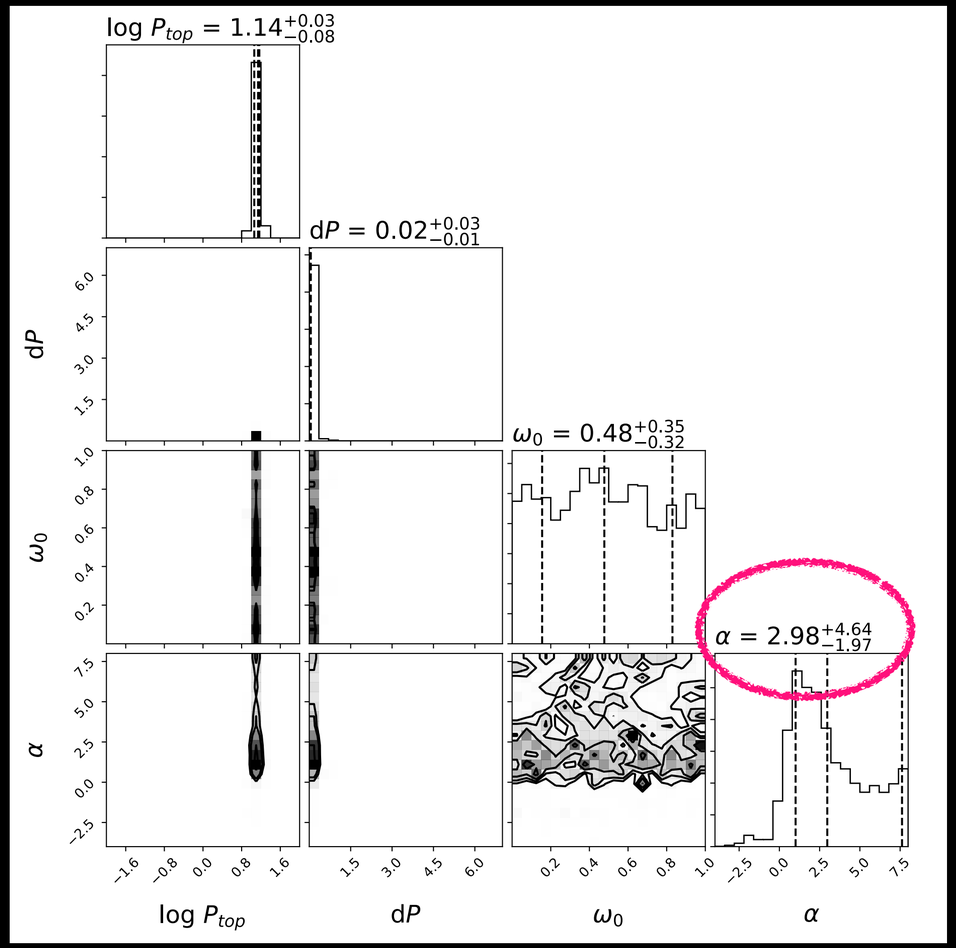


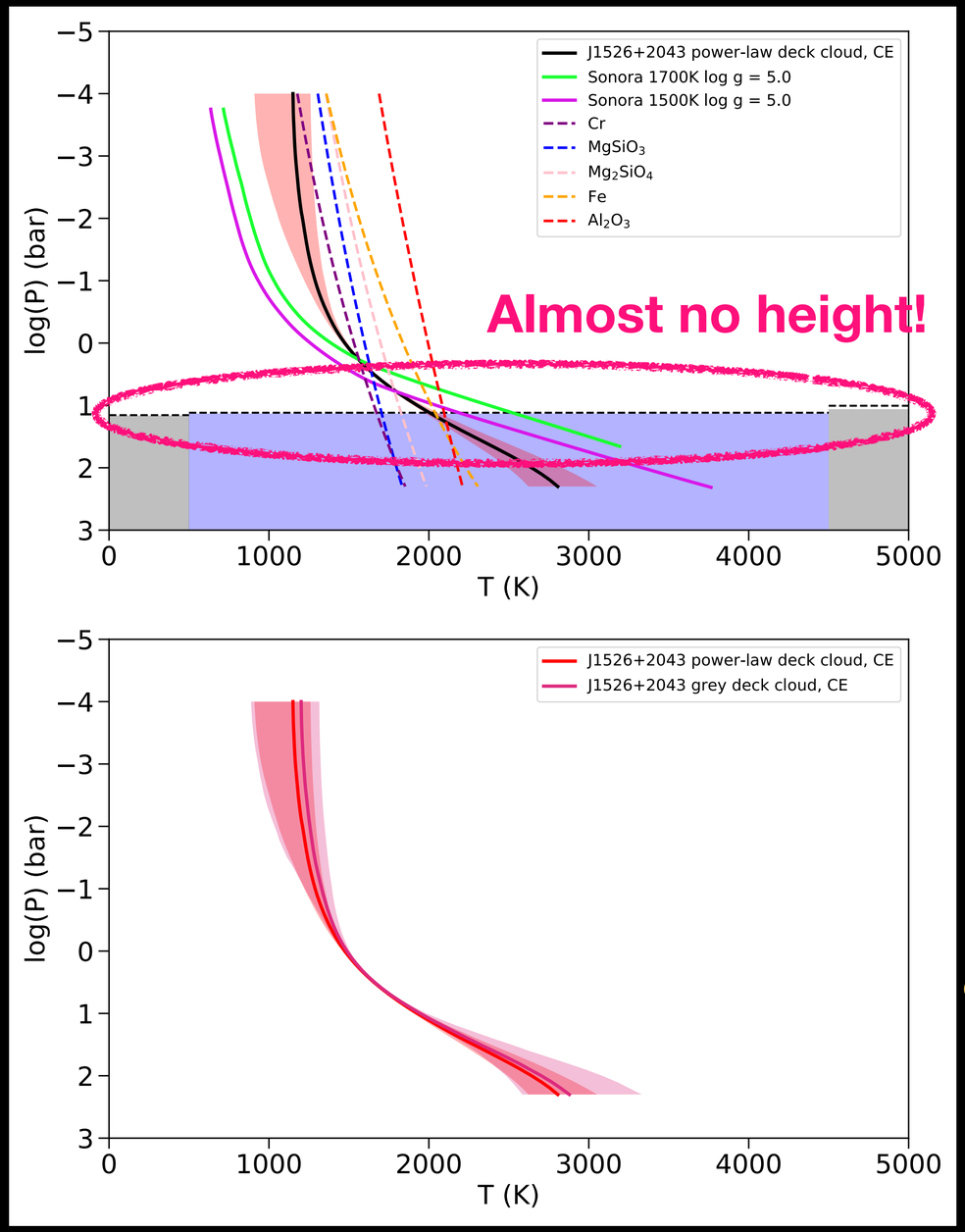


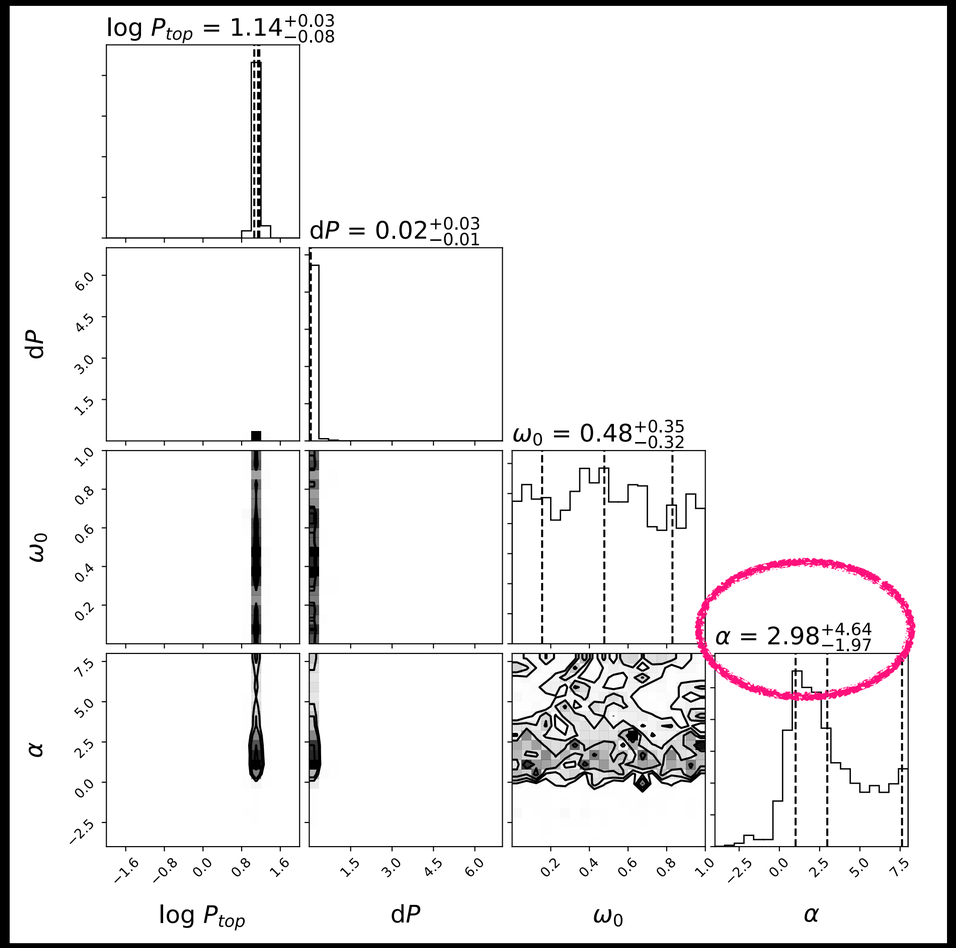
Gonzales et al. (in prep)

$$\tau = \tau_0 \lambda^{\alpha}$$

where α tells you how "non-grey" the cloud is

Runner Up: Power law Deck Cloud





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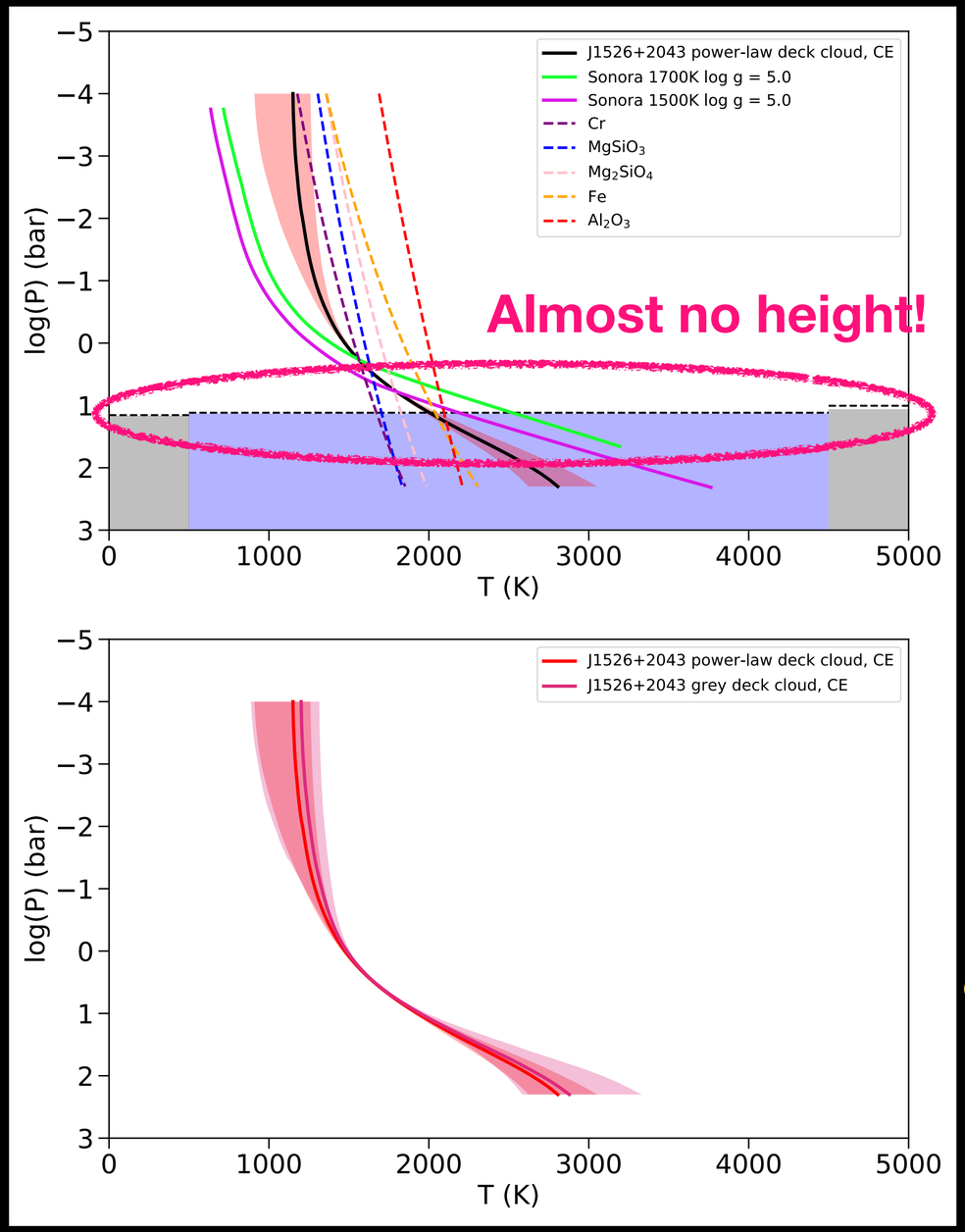

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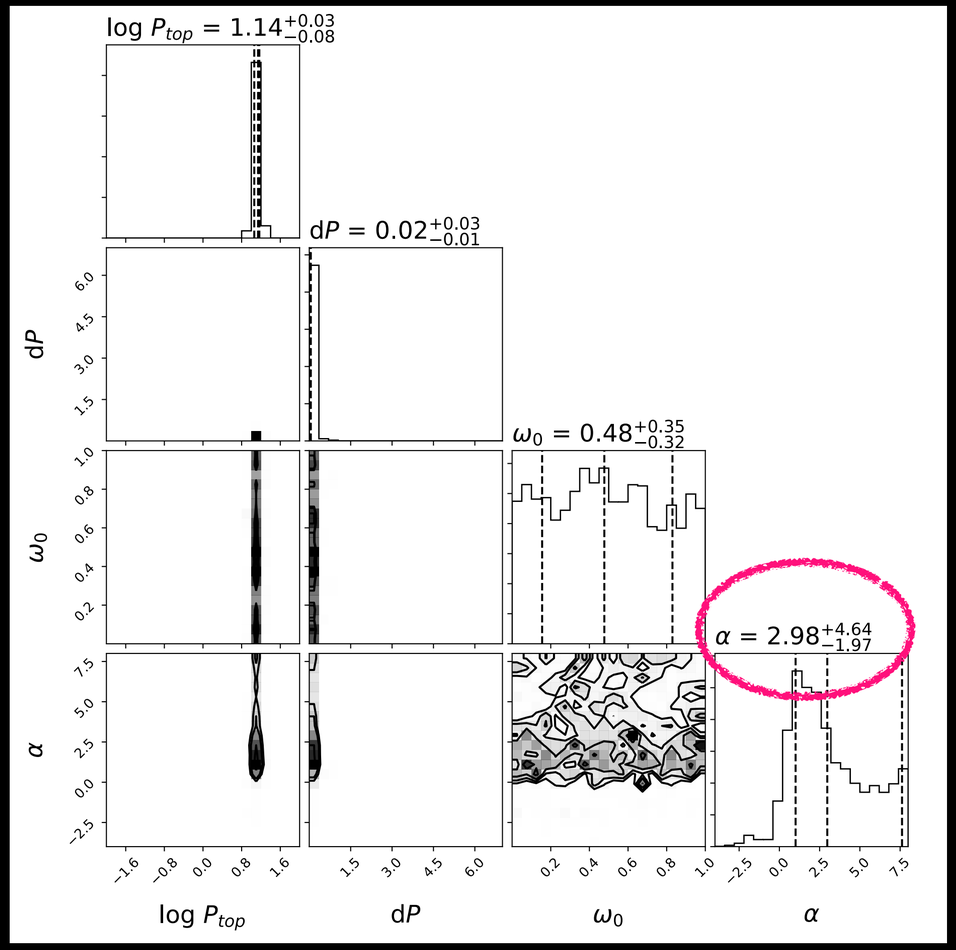


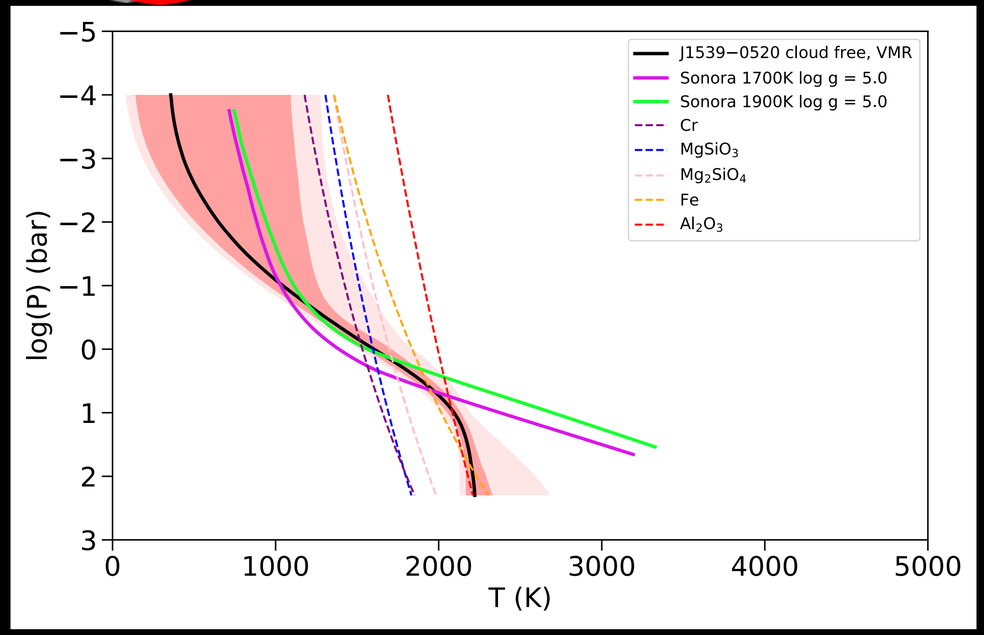
Gonzales et al. (in prep)

$\tau = \tau_0 \lambda^{\alpha}$

where α tells you how "non-grey" the cloud is

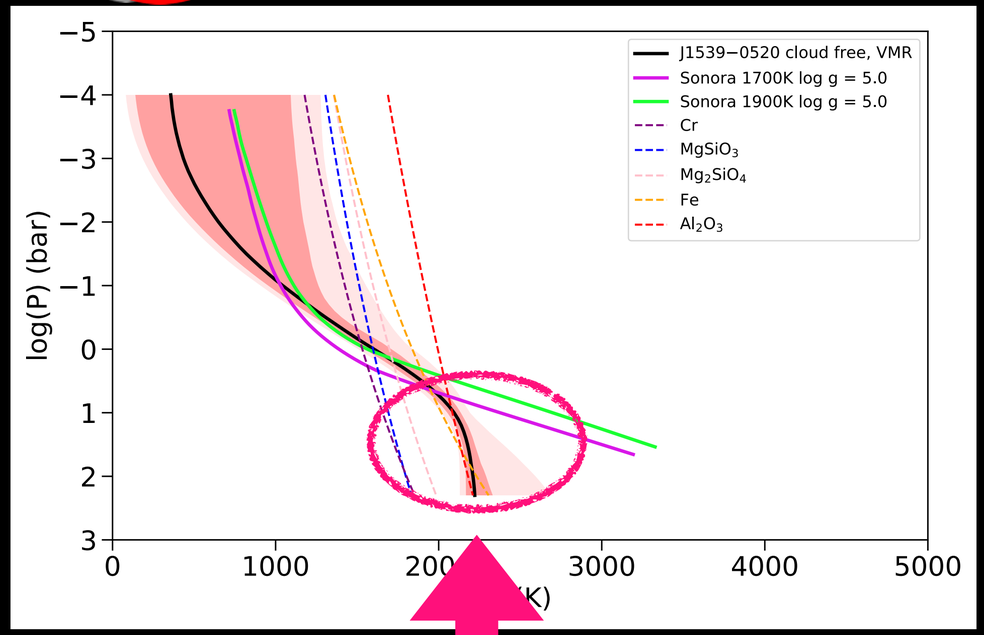
α is degenerate with cloud height and can mimic the effect of a grey cloud

J1539-0520: Cloud free?!,VMR



Temperature Comparison

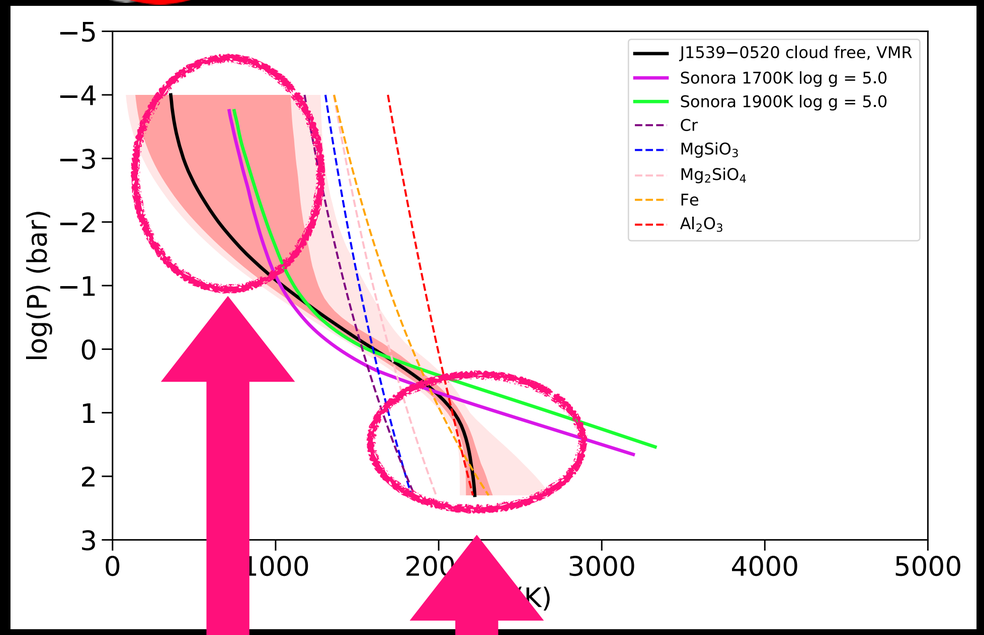
J1539-0520: Cloud free?!,VMR



Typically indicates a cloud

Temperature Comparison

J1539-0520: Cloud free?!,VMR



Median profile cooler than models

Typically indicates a cloud

Temperature Comparison

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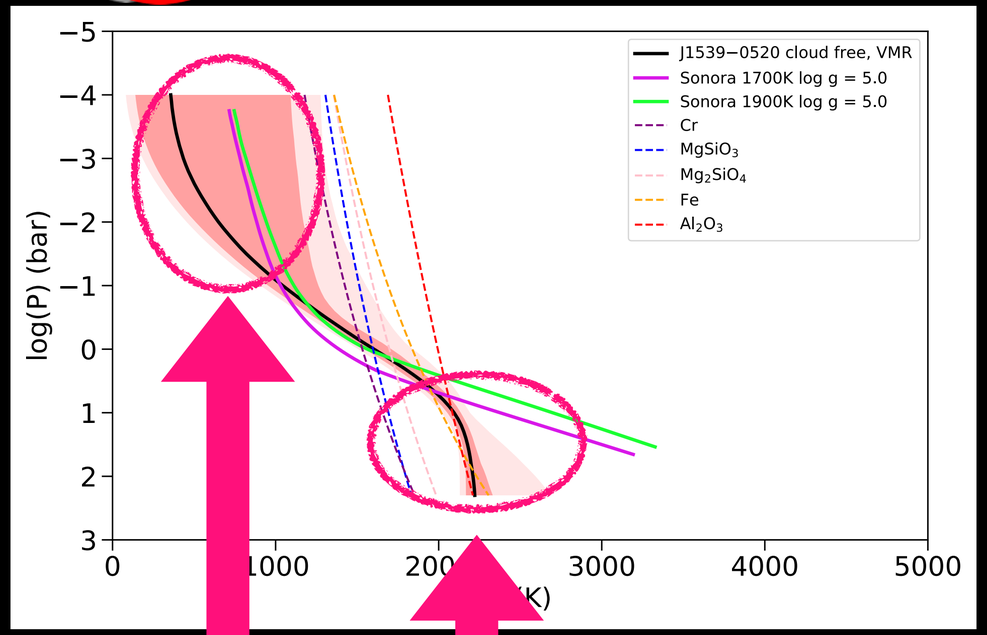

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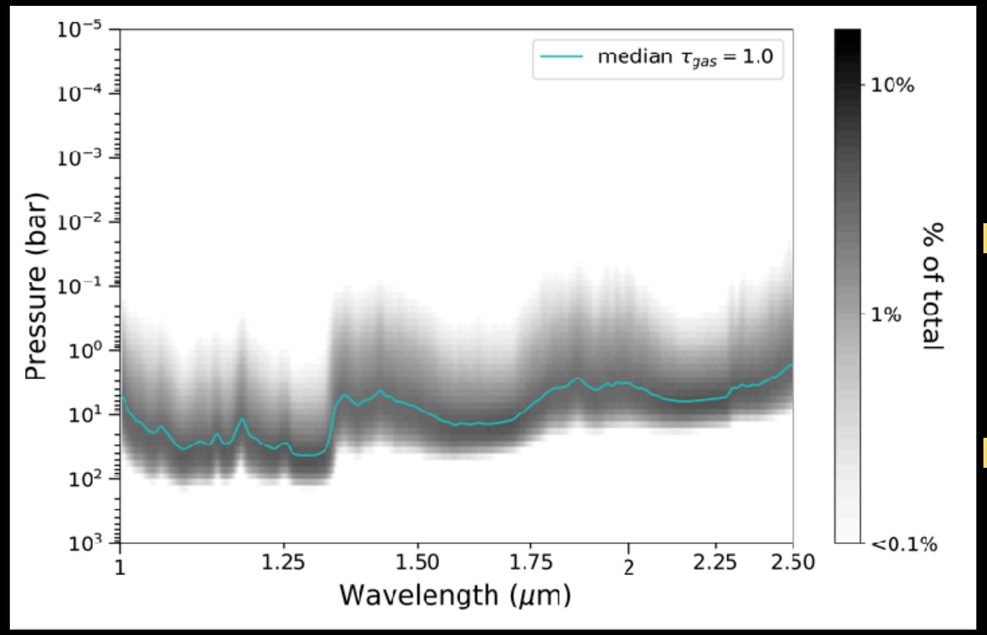

Wider photosphere than J1416A

Gonzales et al. (in prep)

Temperature Comparison

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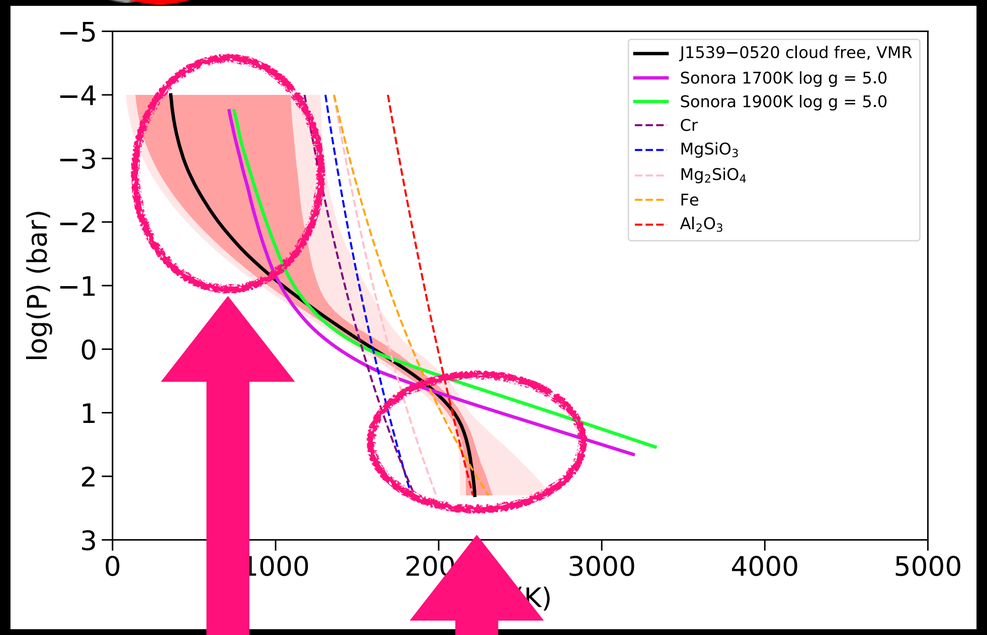

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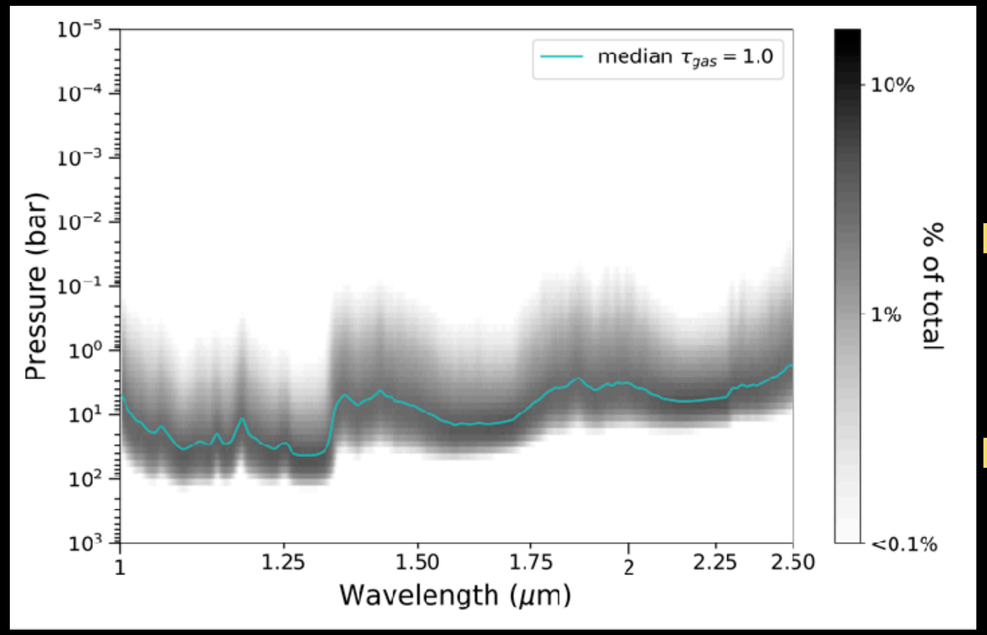

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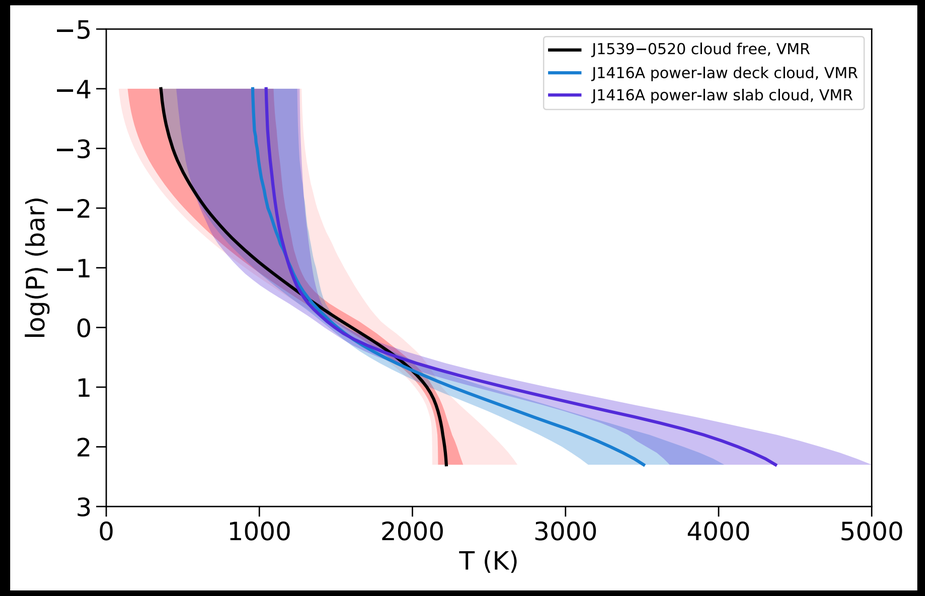

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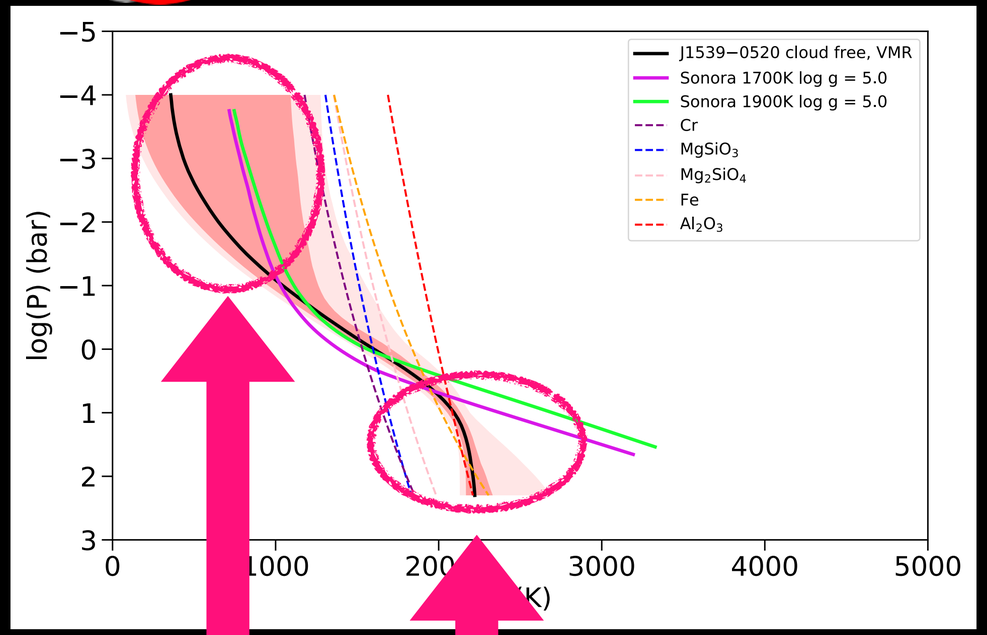

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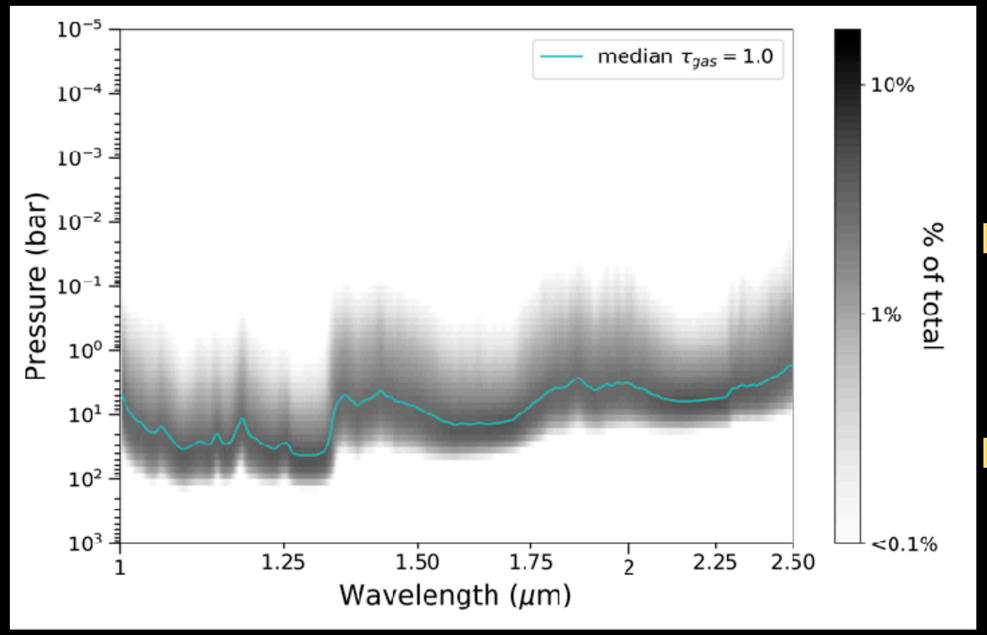

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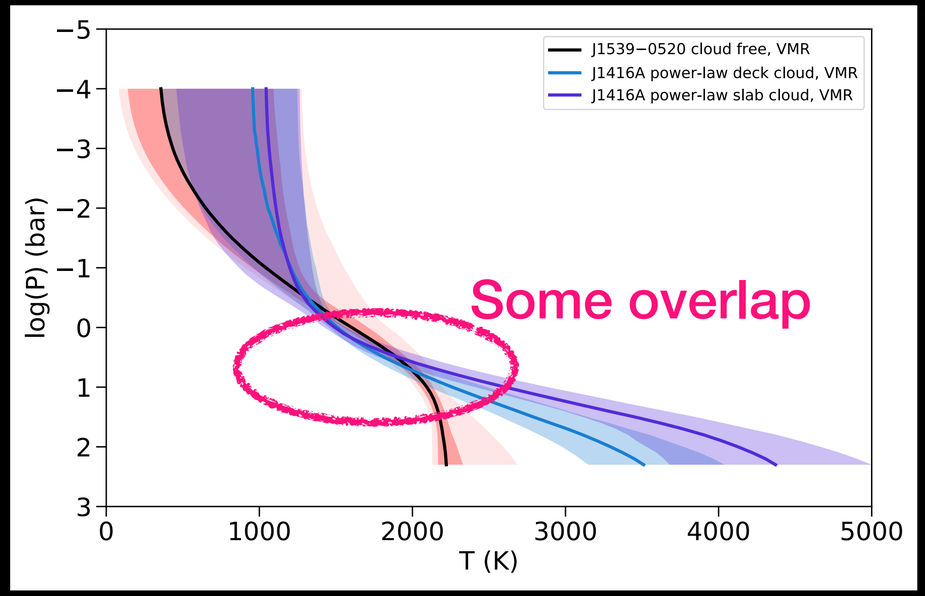
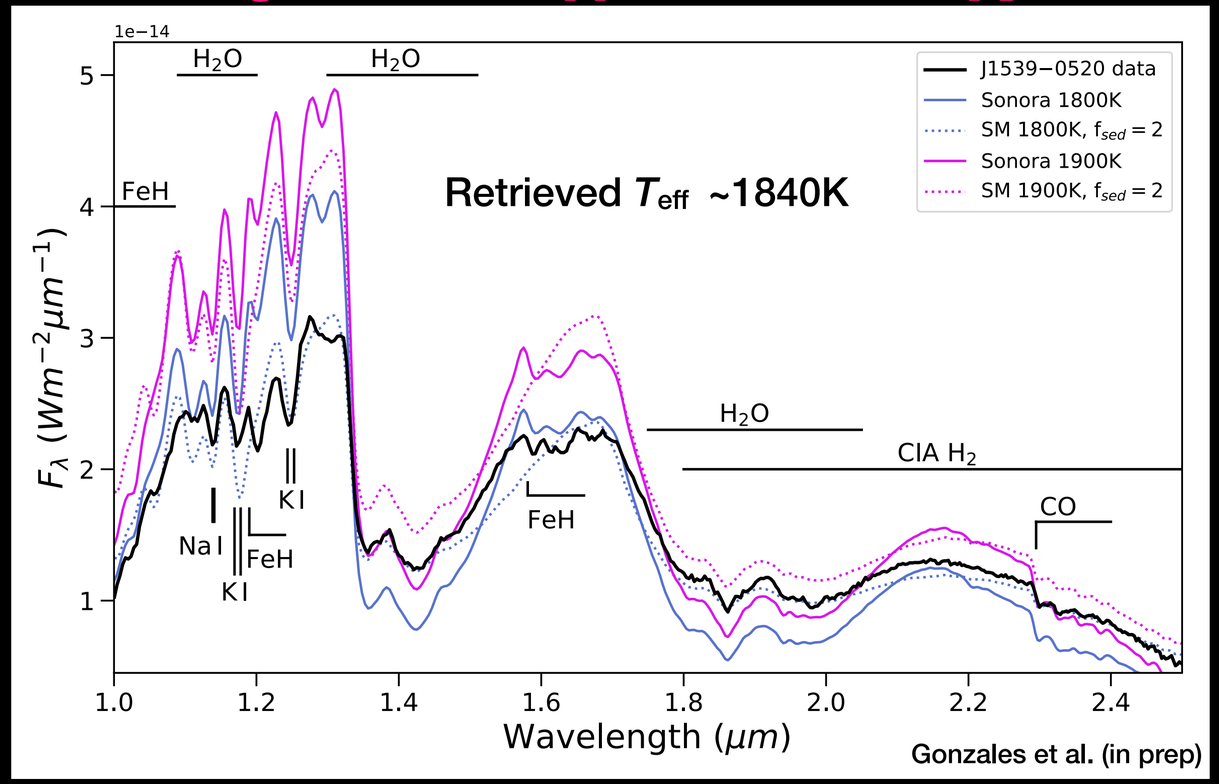


Temperature Comparison

J1539-0520: Comparison to the models

J H K



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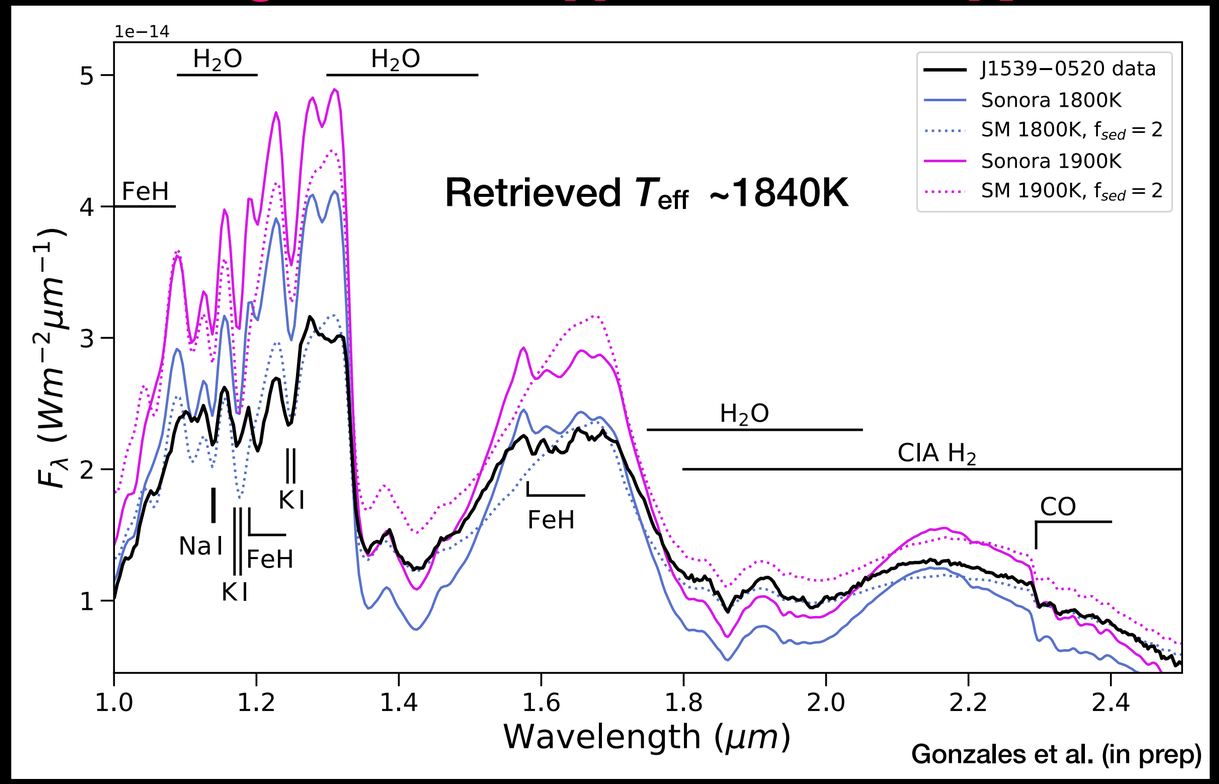

Cloudy grid model fits better than the cloud-free!

J1539-0520: Comparison to the models

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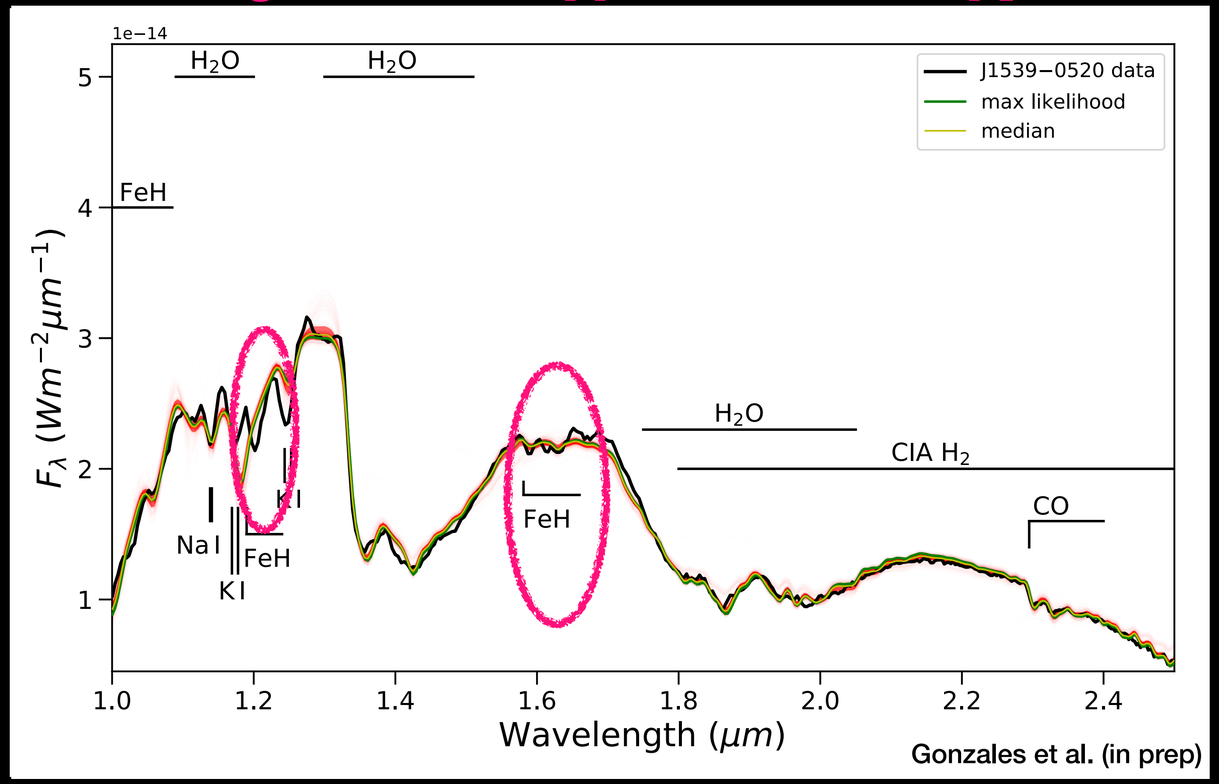

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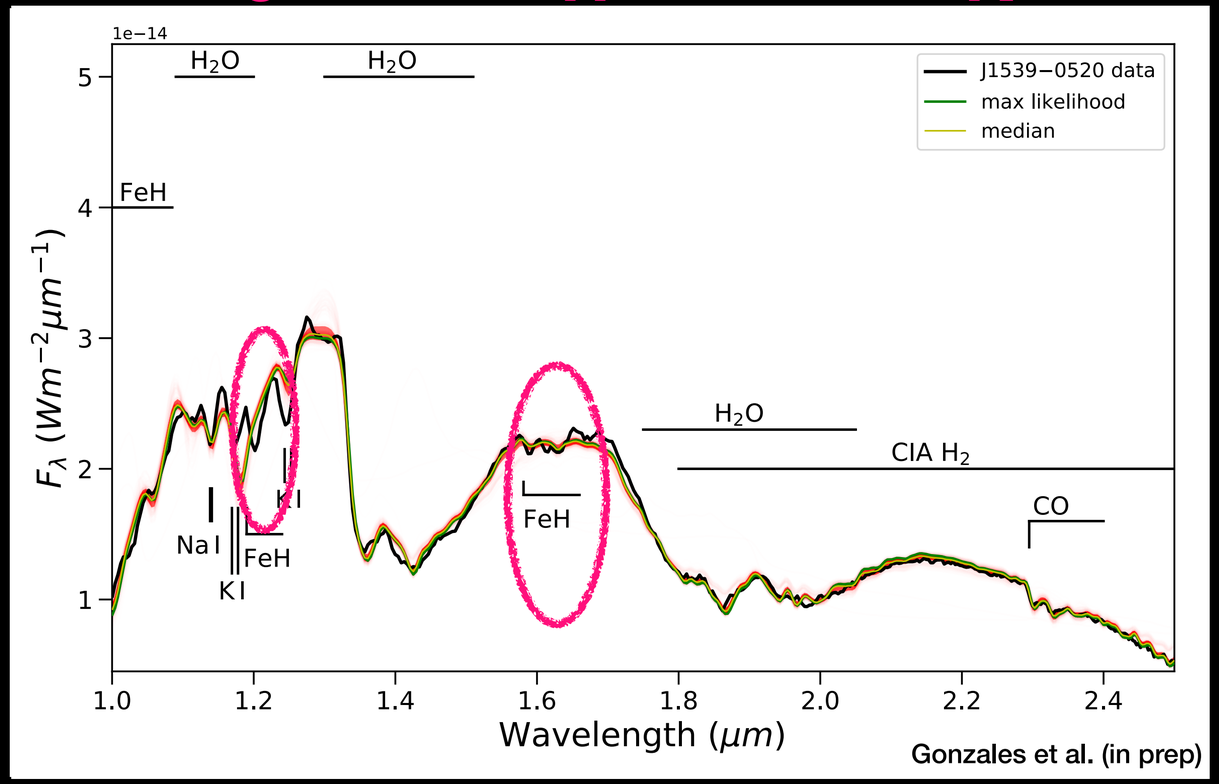
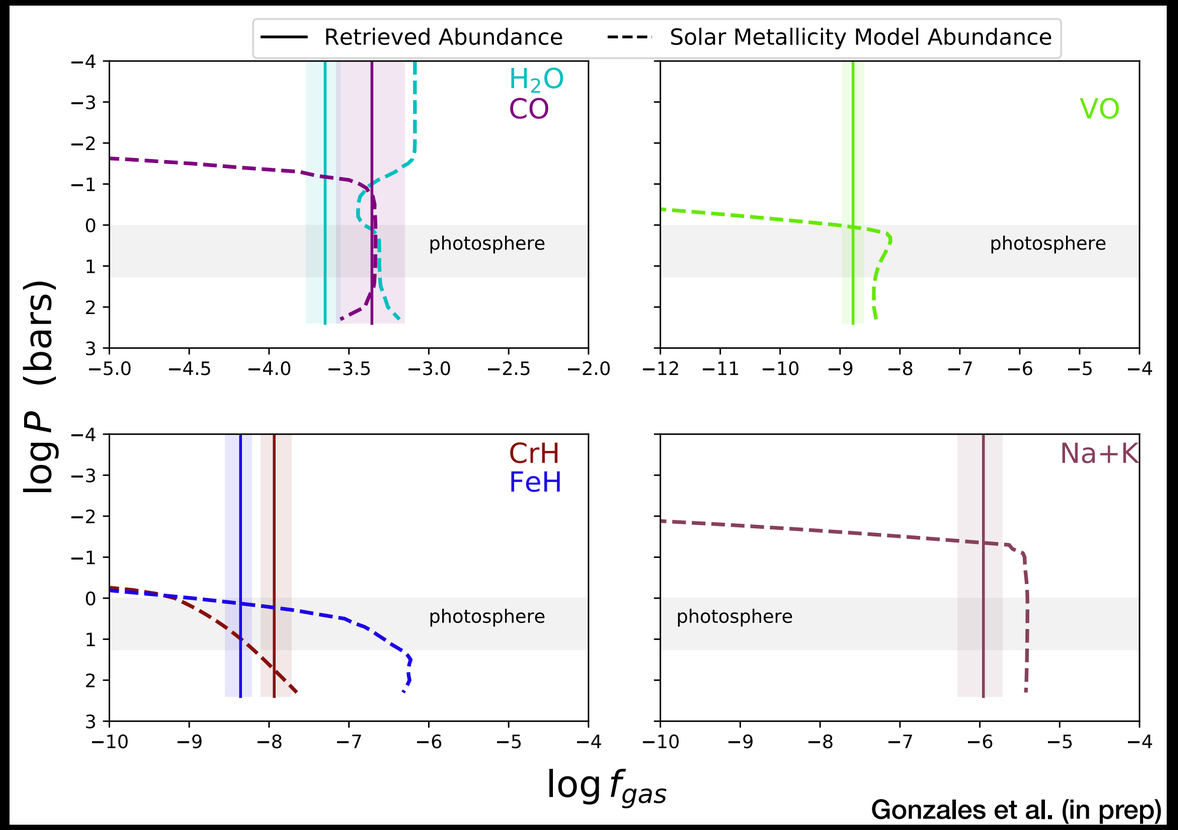
J H K

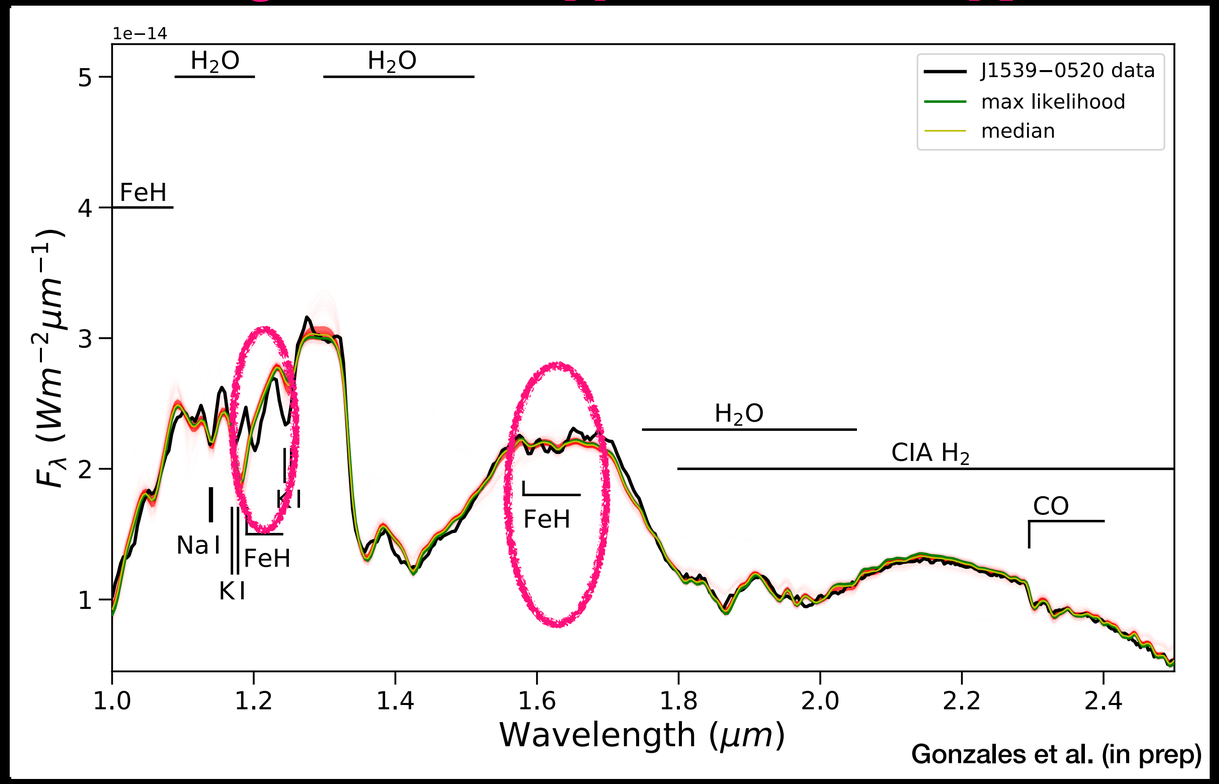


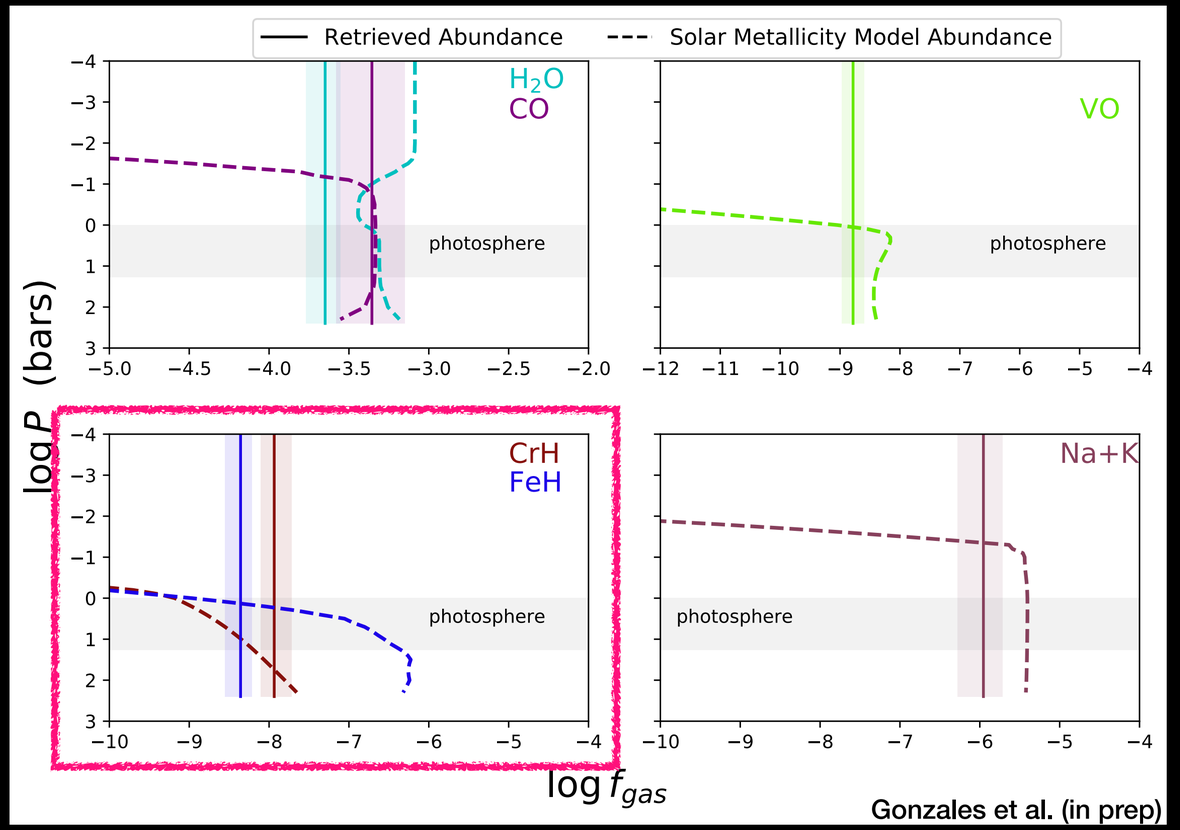


Cloudy grid model fits better than the cloud-free!

J1539-0520: Comparison to the models

J H K





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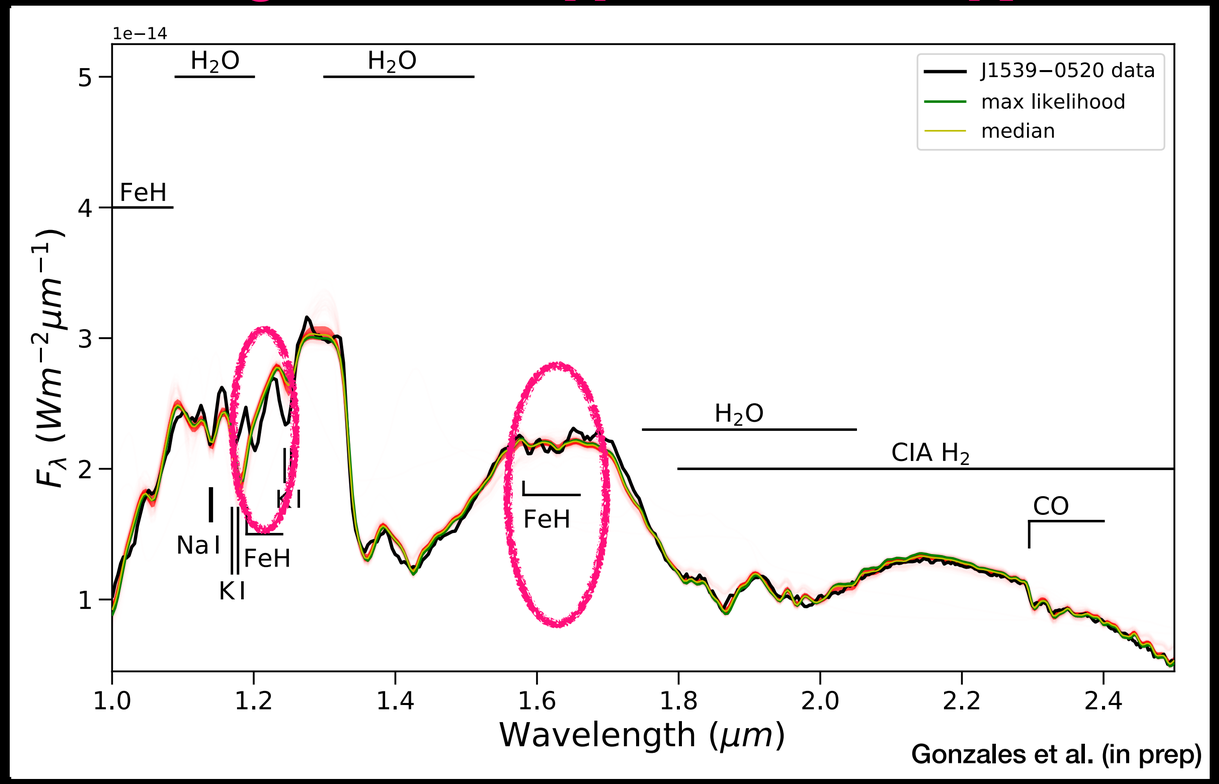

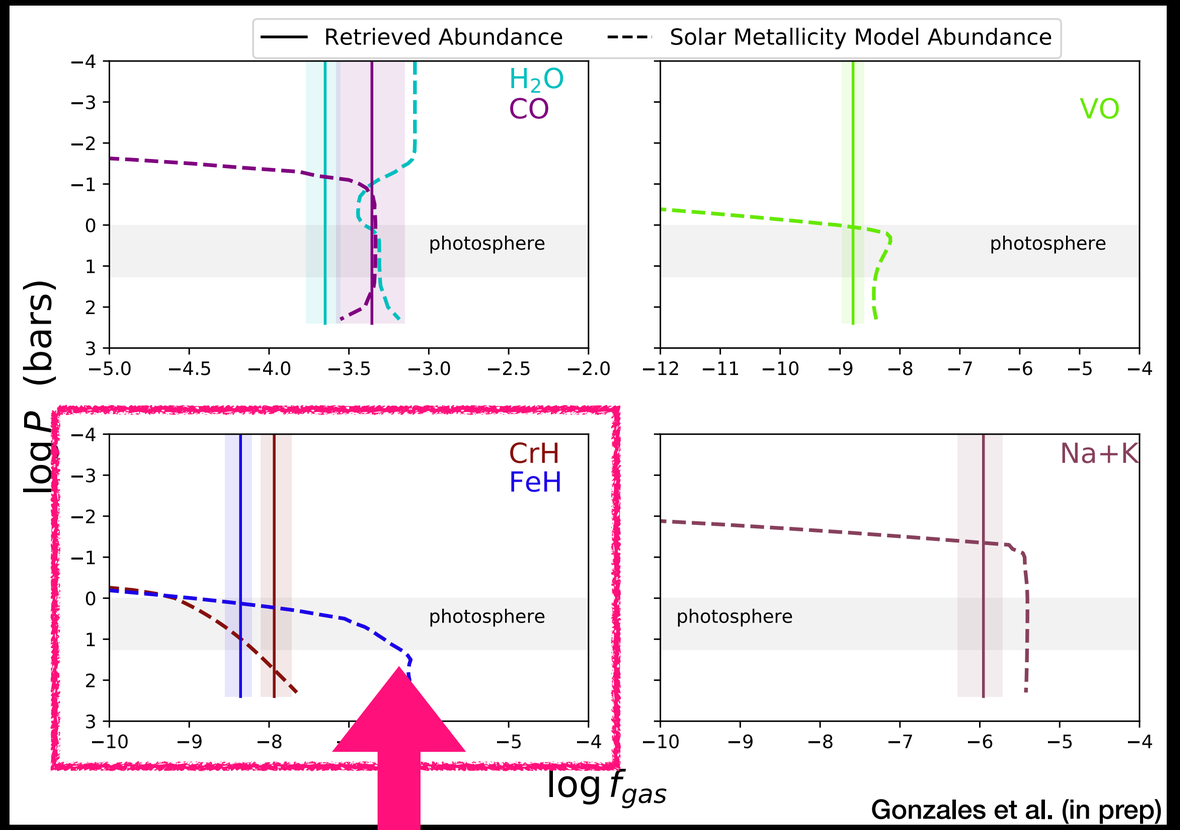

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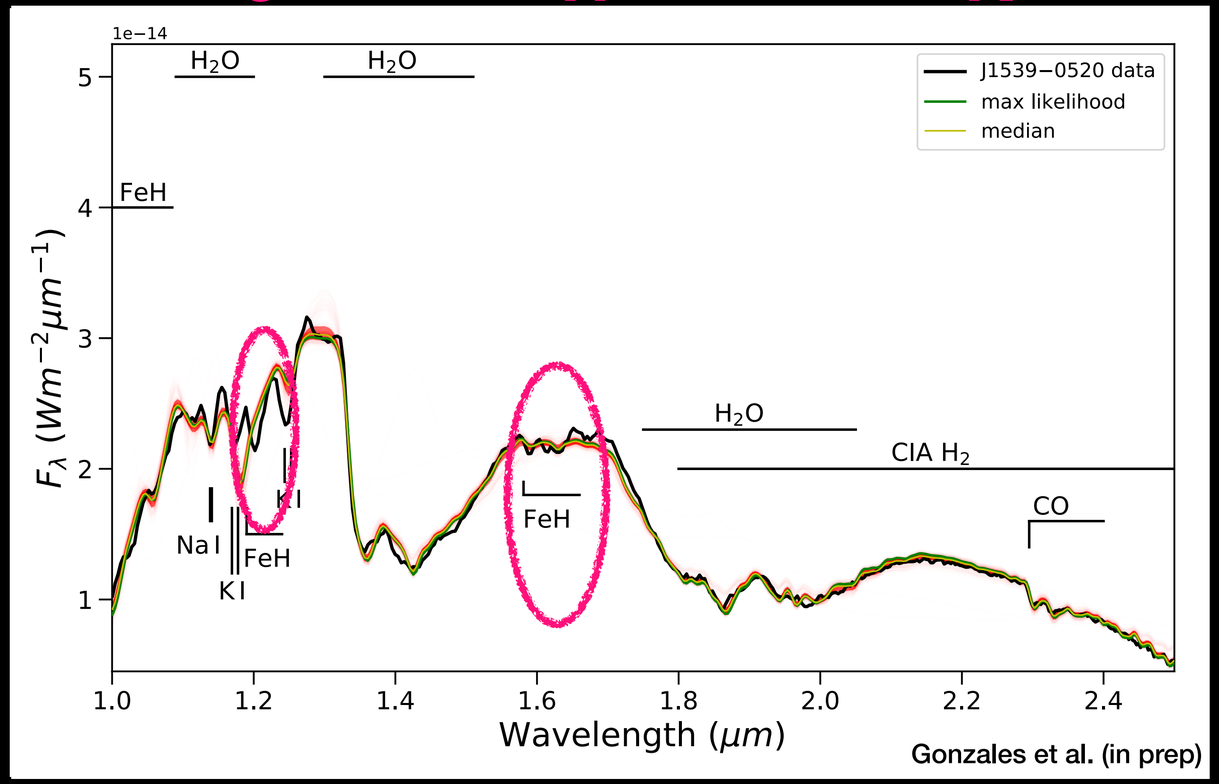
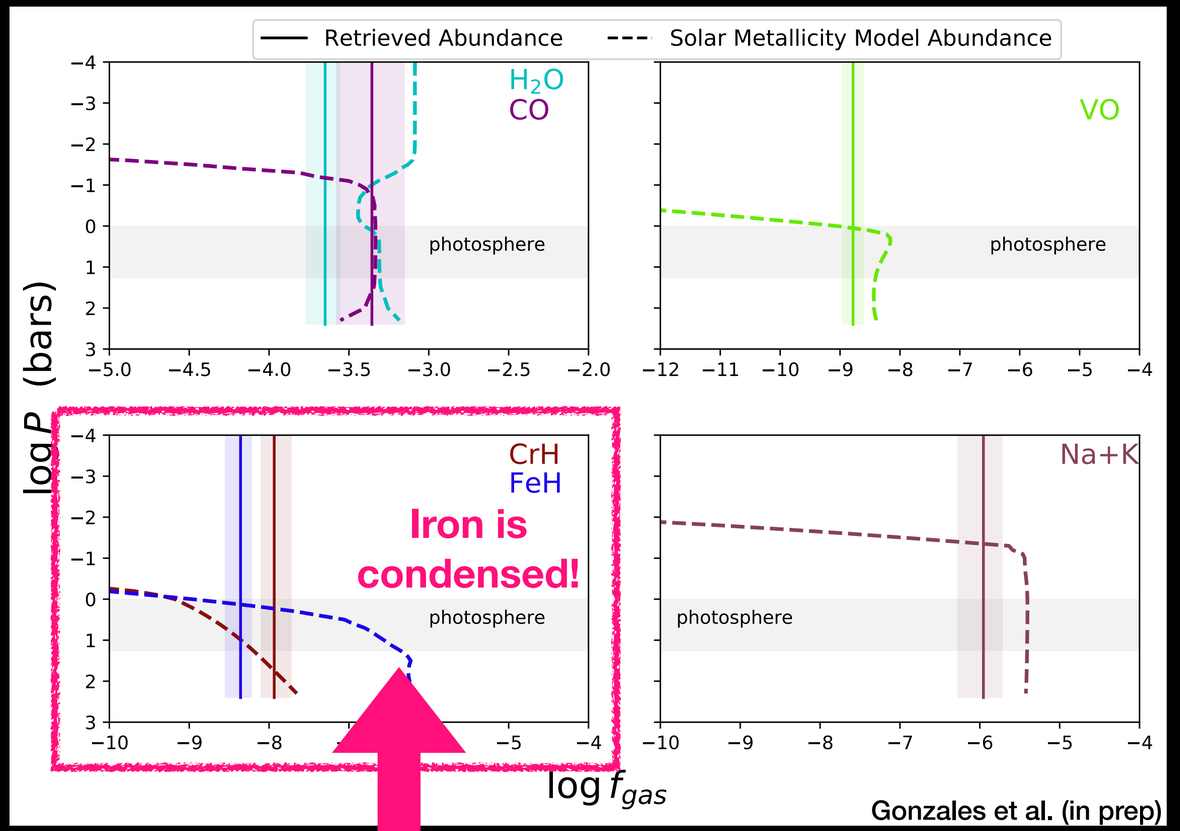
Maximum possible

J1539-0520: Comparison to the models

J H K





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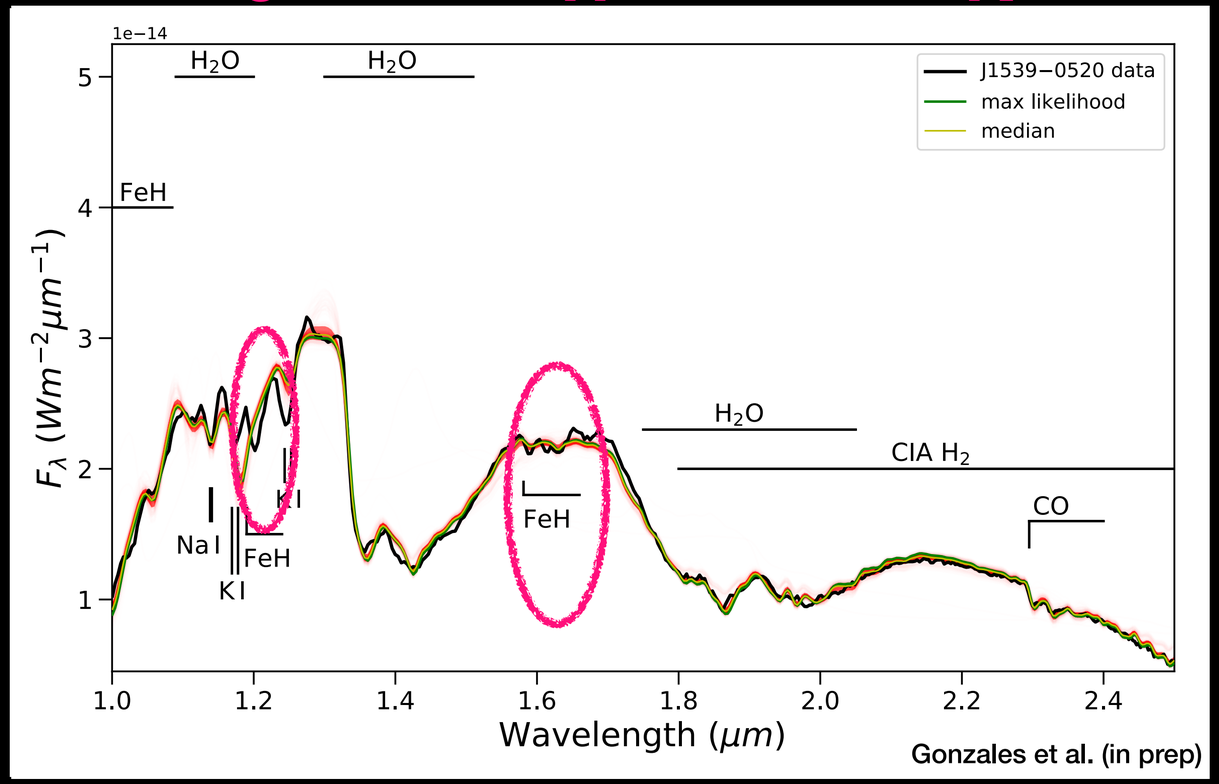
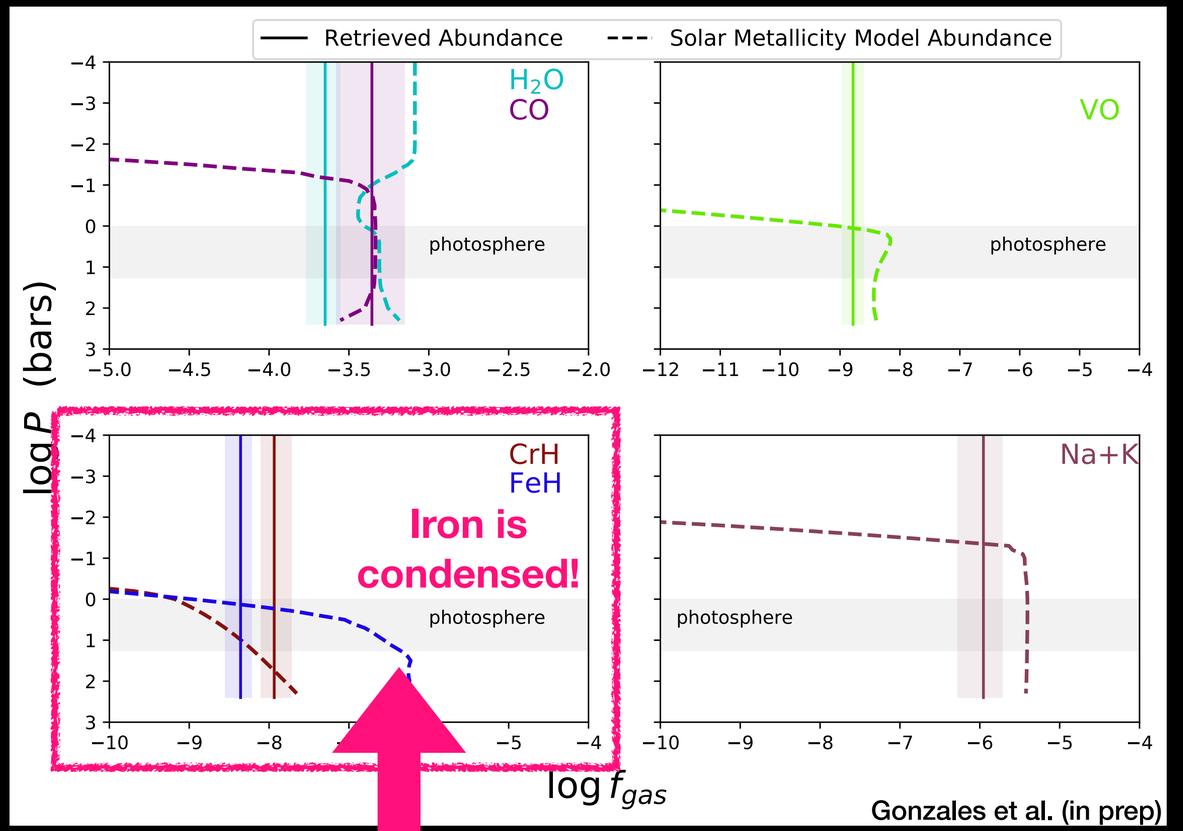




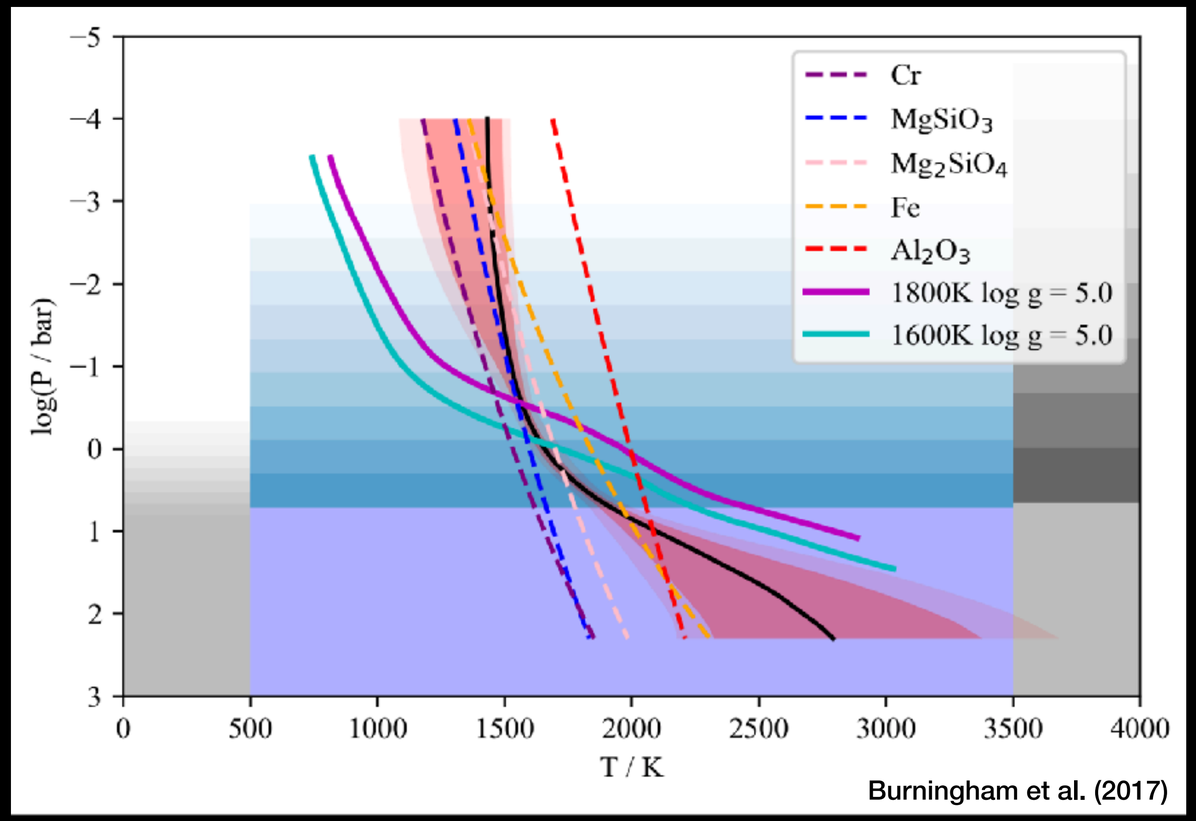
Cloudy grid model fits better than the cloud-free!

Maximum possible

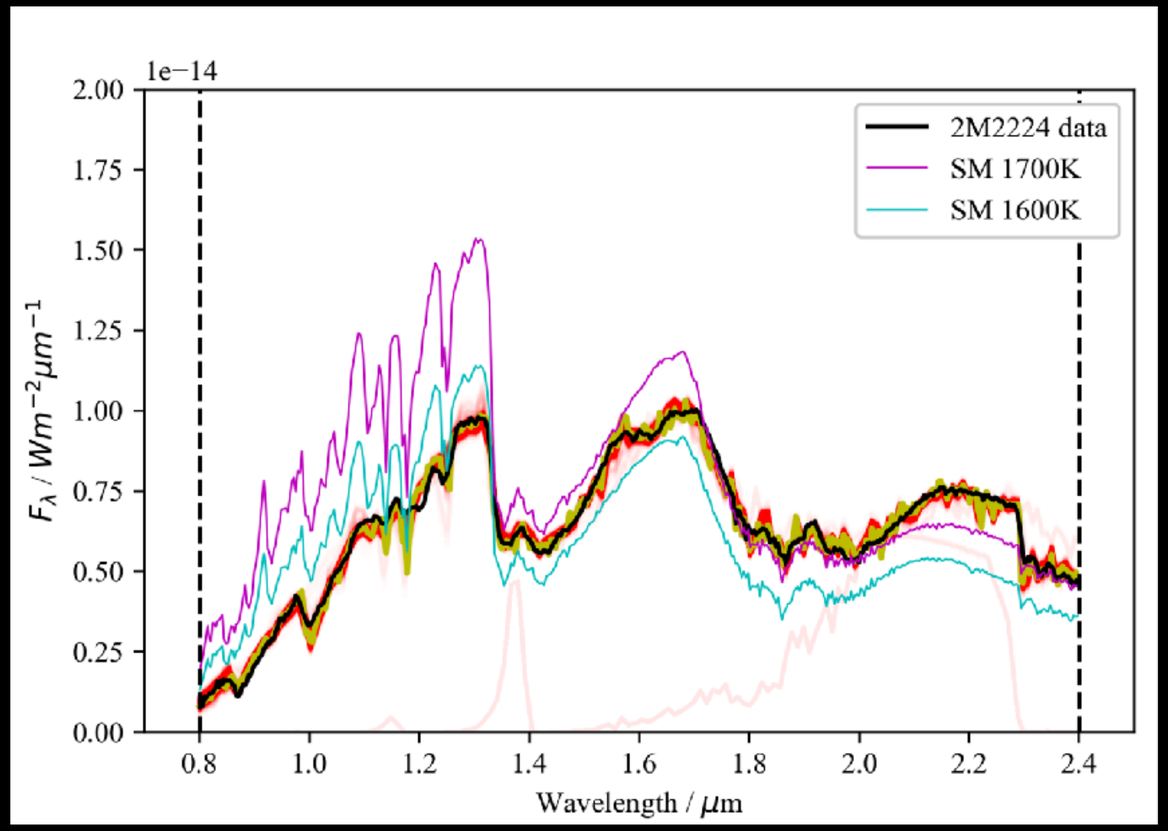
NIR data alone is unable to fully constrain the cloud properties

The Power of Data: 2M2224

Unusually Red, Field age, H alpha emission



Burningham et al. (2017)



Burningham et al. (2017)

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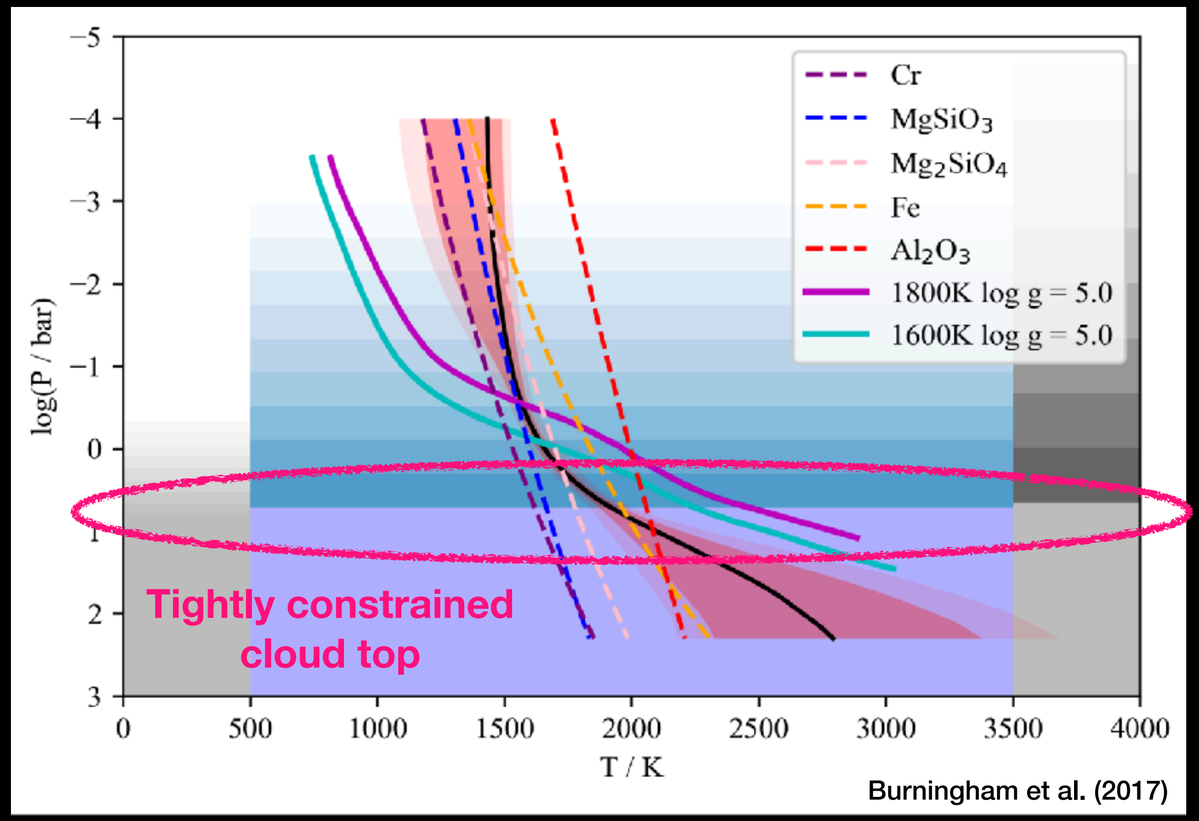

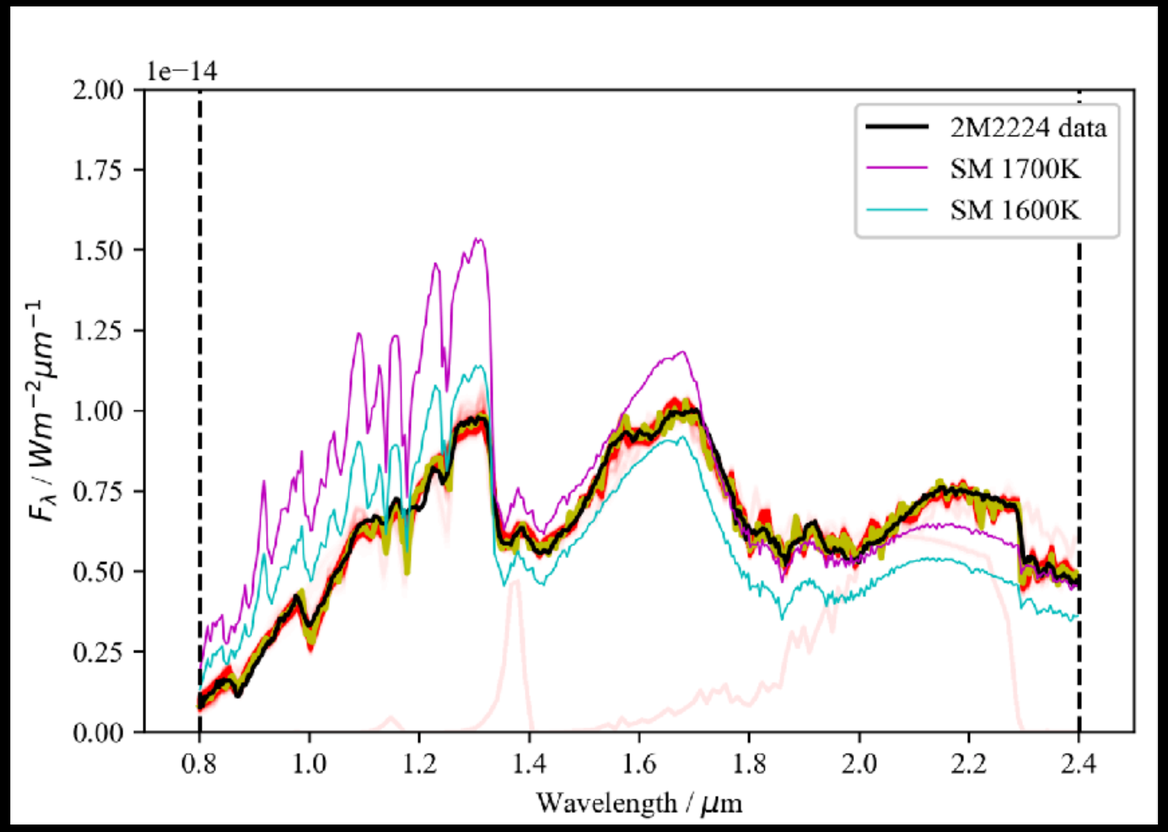

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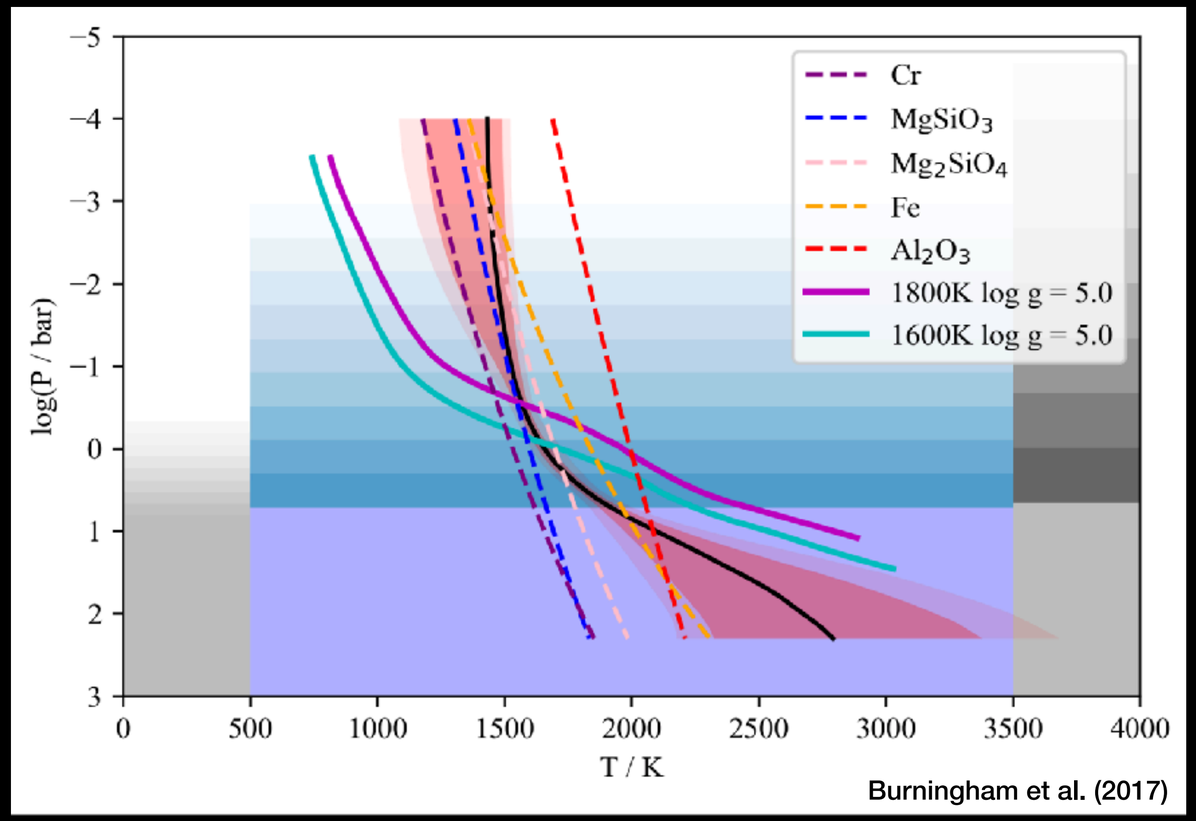

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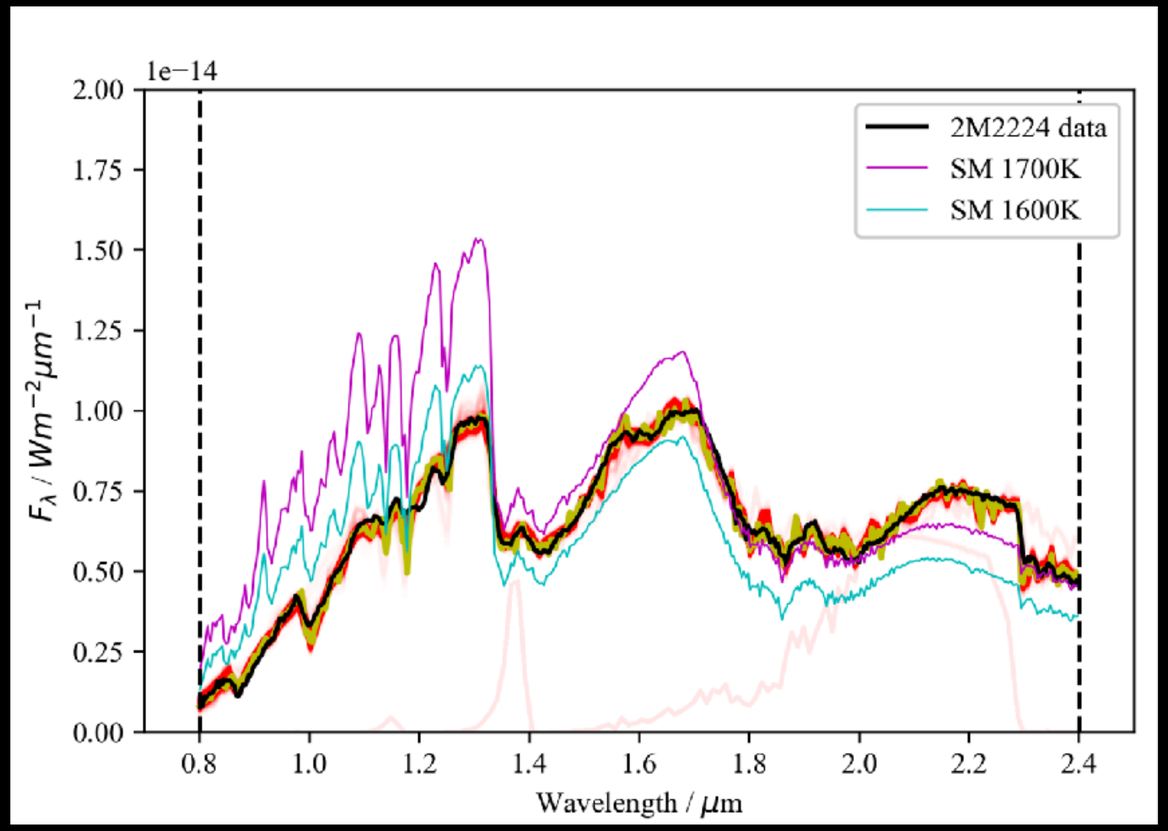

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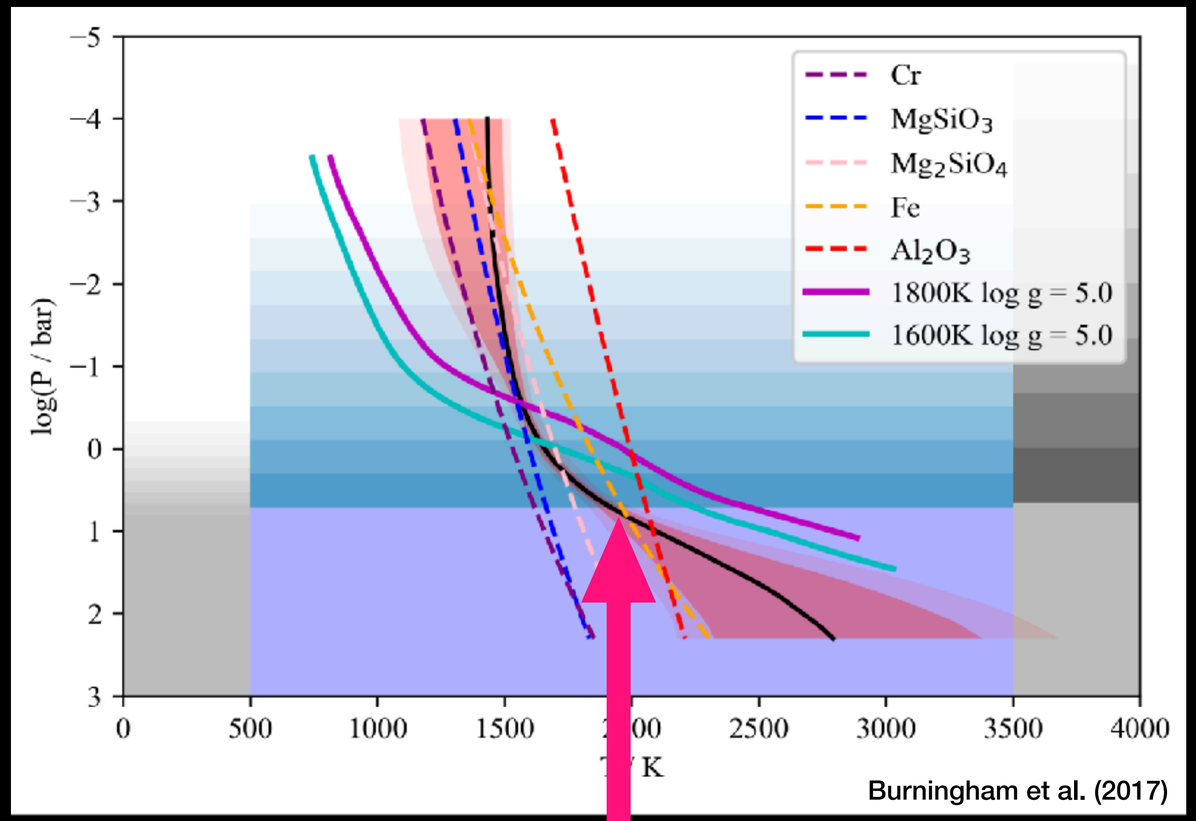
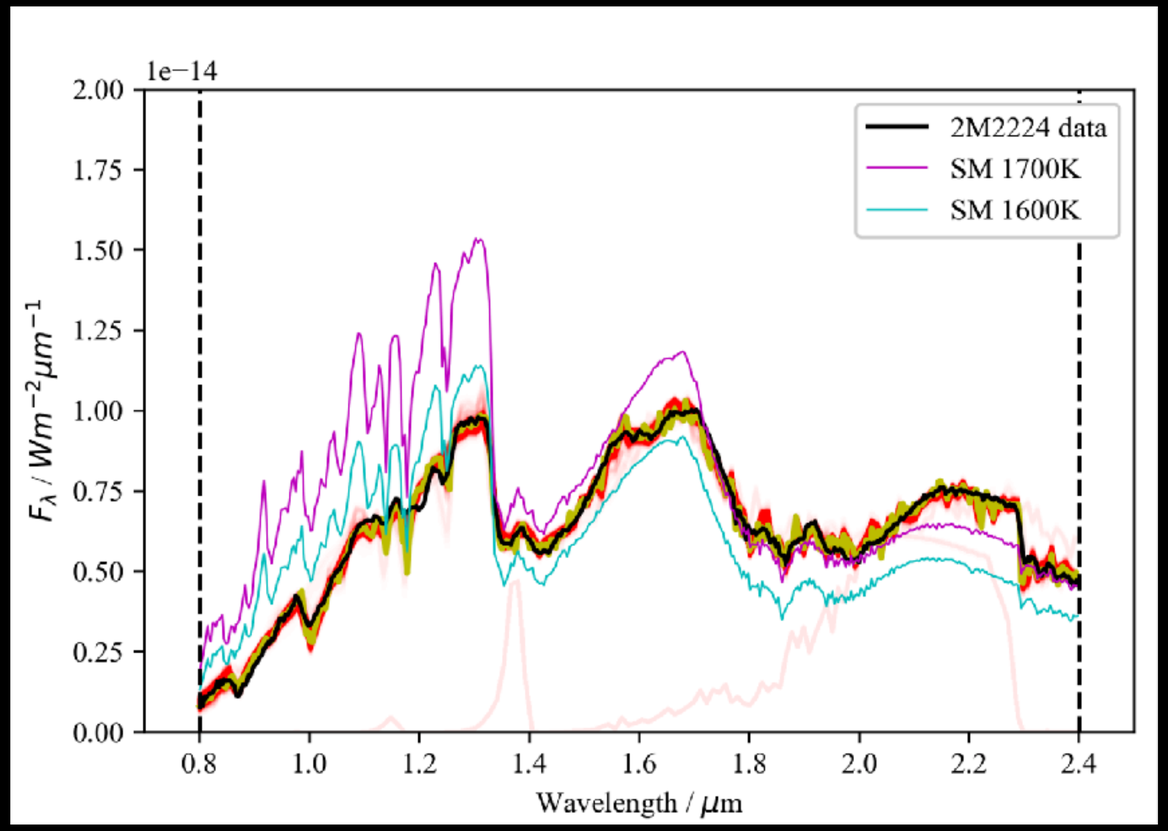


Burningham et al. (2017)

Opacity likely due to iron or corundum cloud



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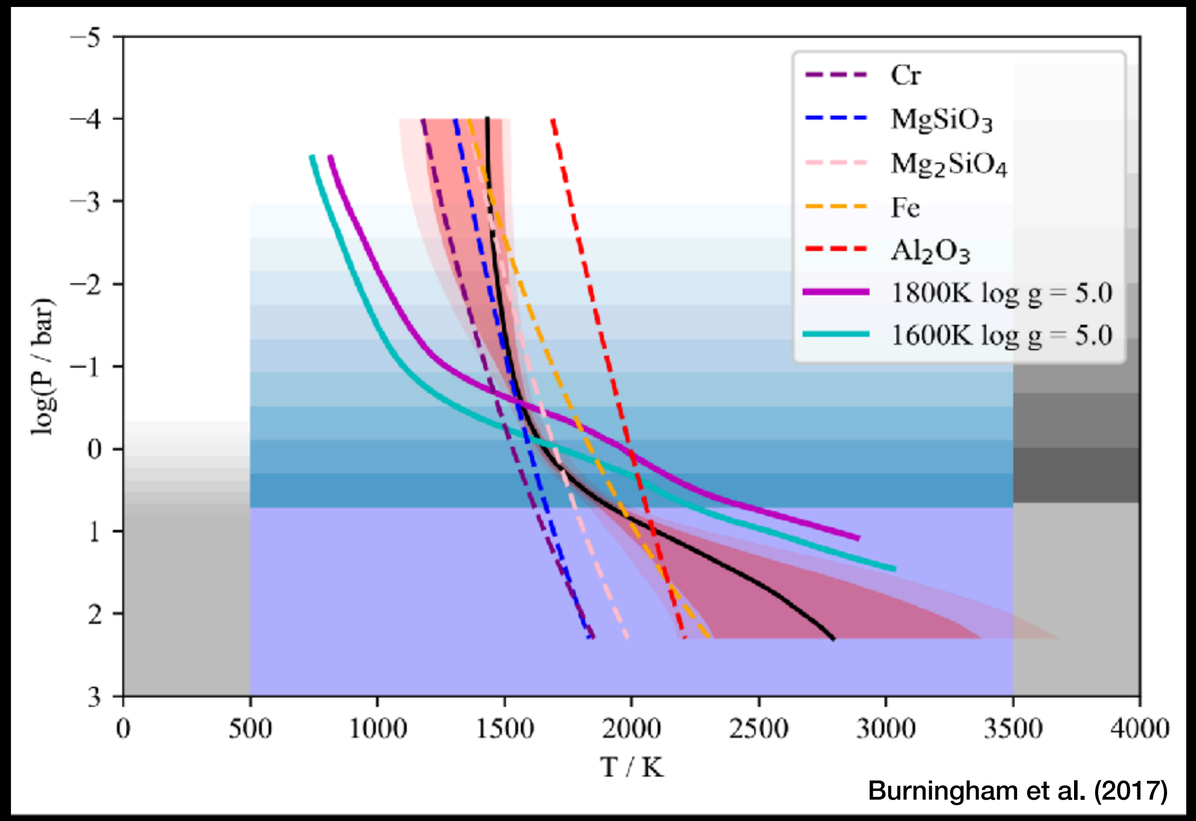

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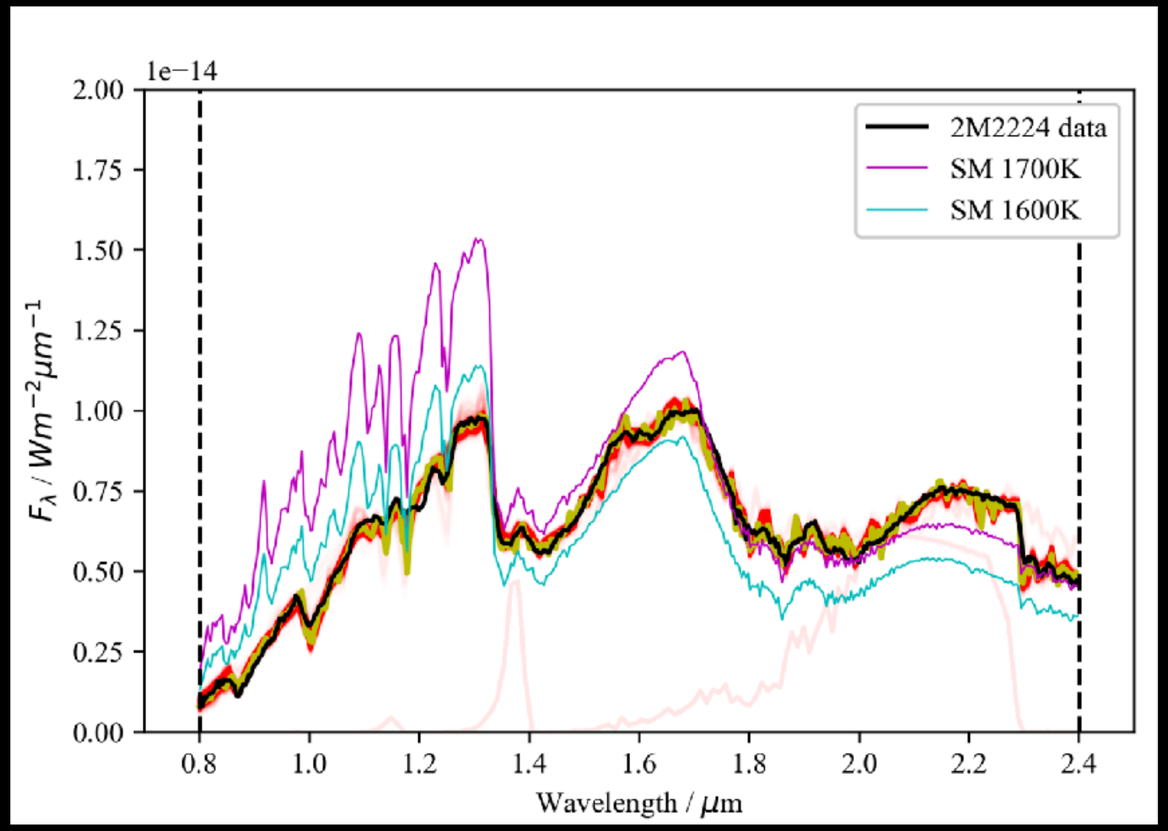
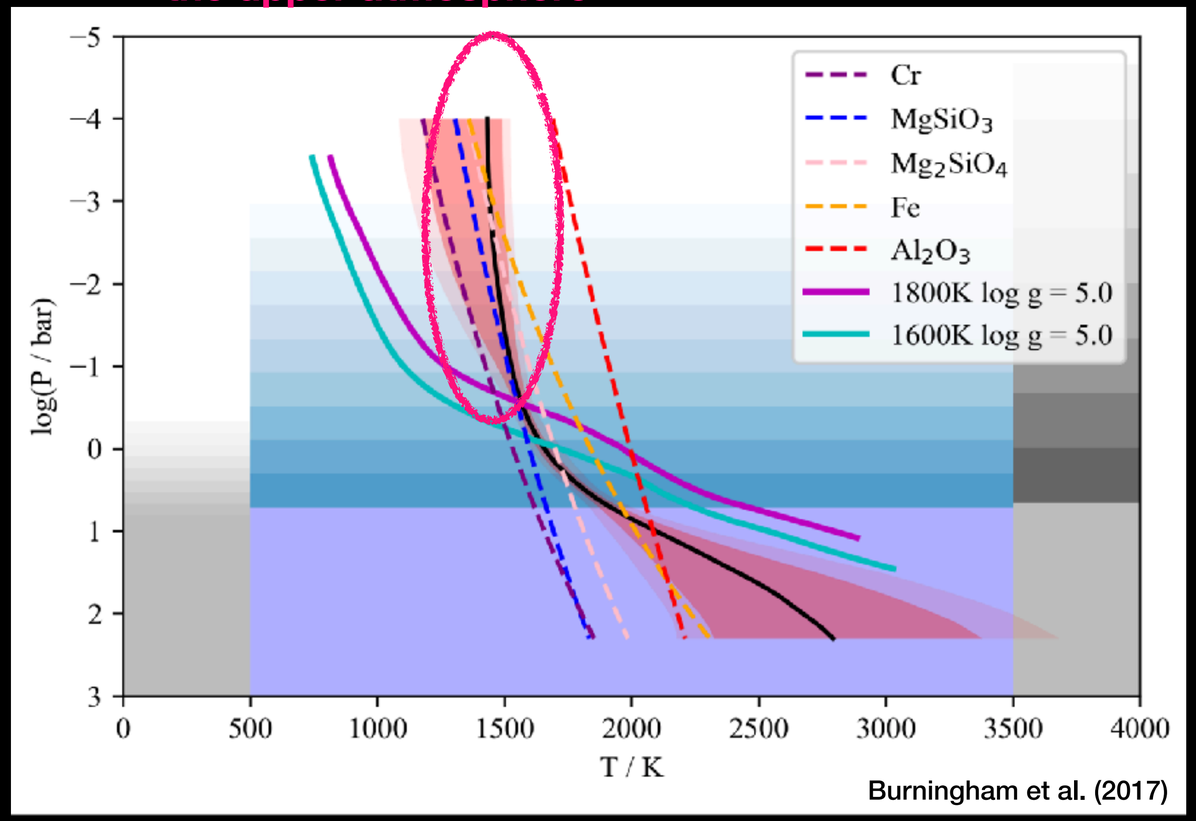


Burningham et al. (2017)

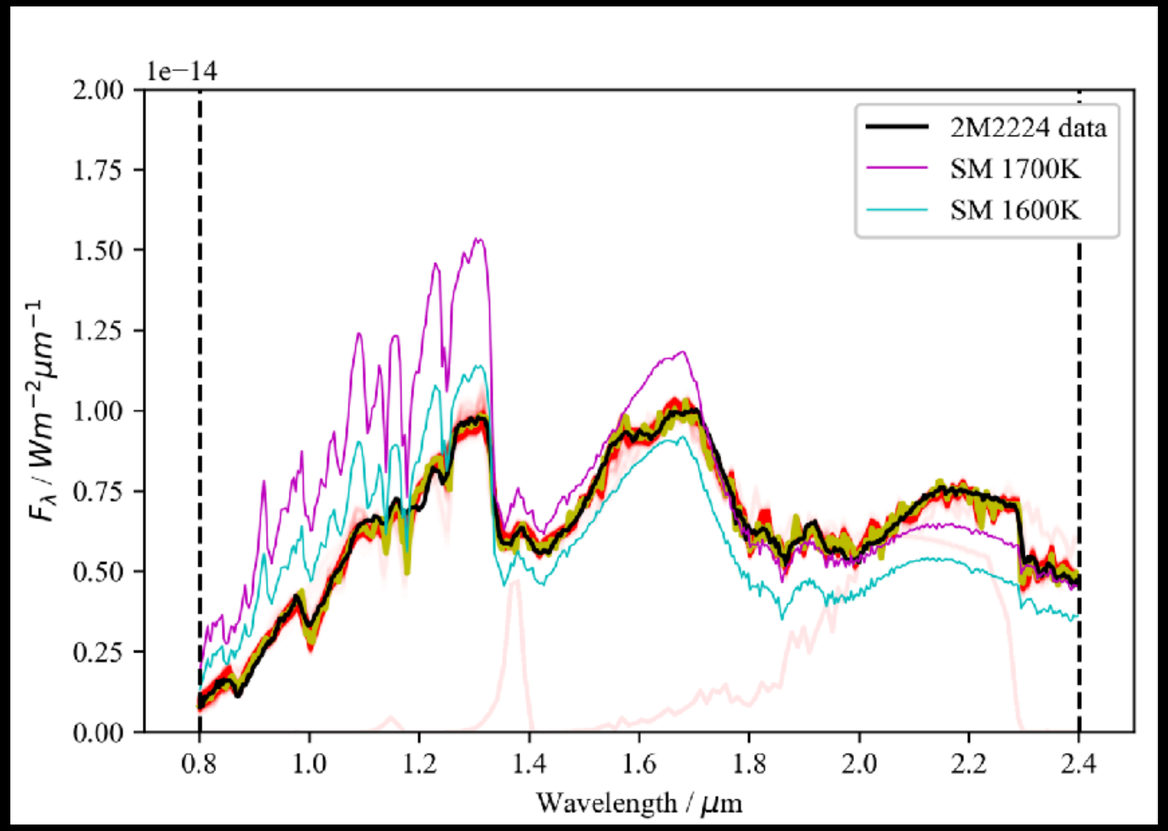
The Power of Data: 2M2224

Nearly isothermal in the upper atmosphere

Unusually Red, Field age, H alpha emission



Burningham et al. (2017)



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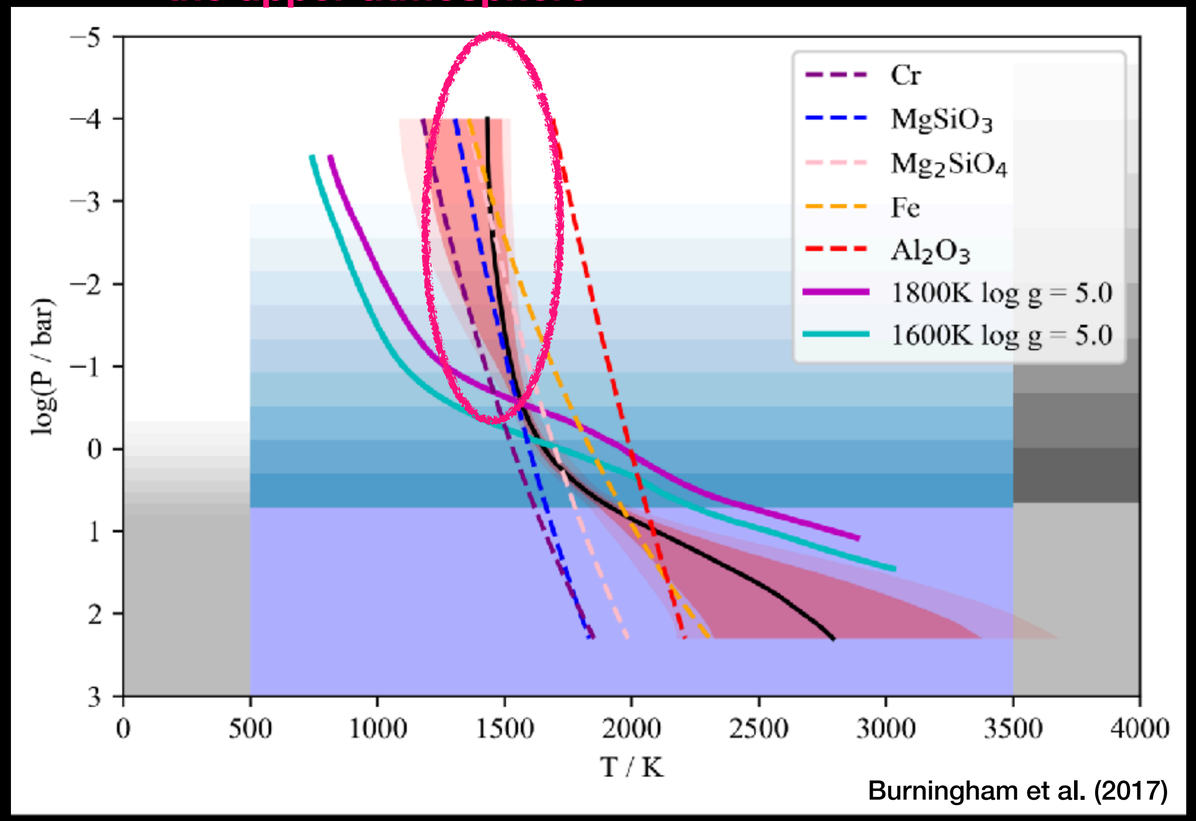

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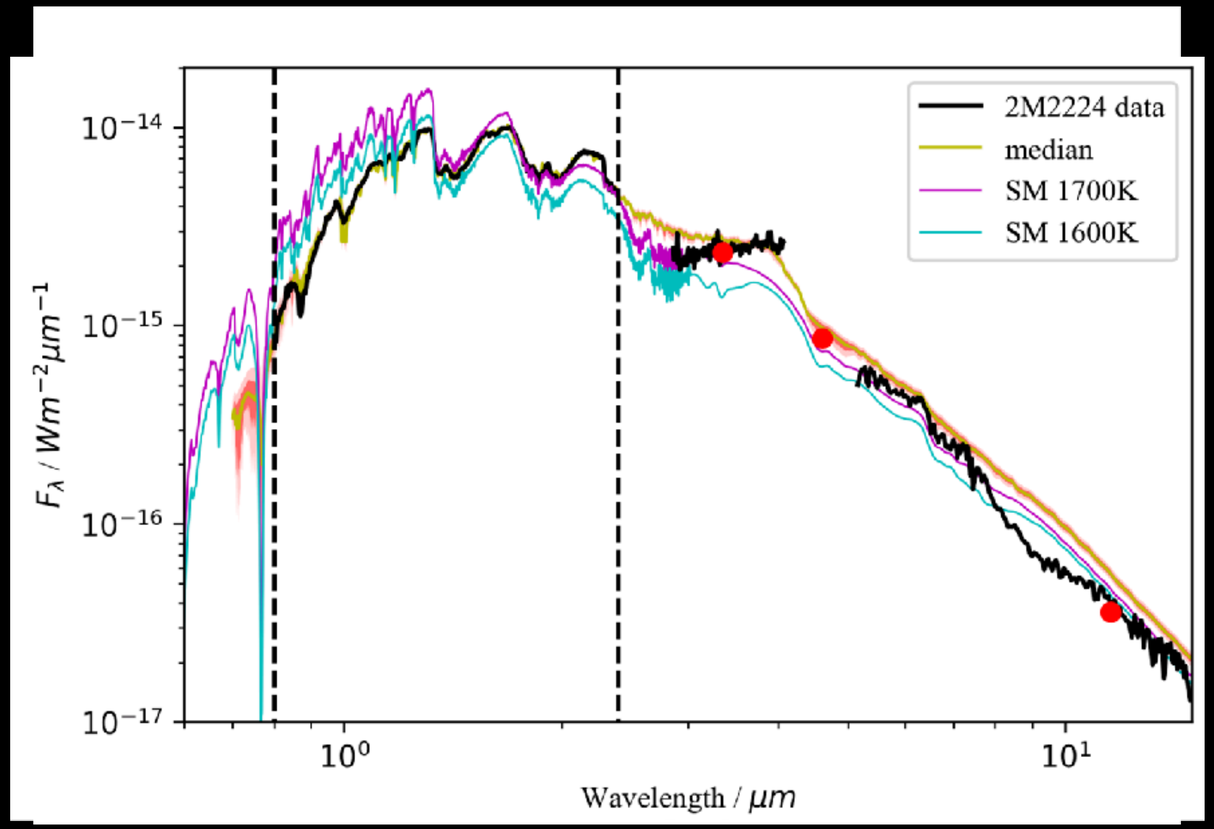
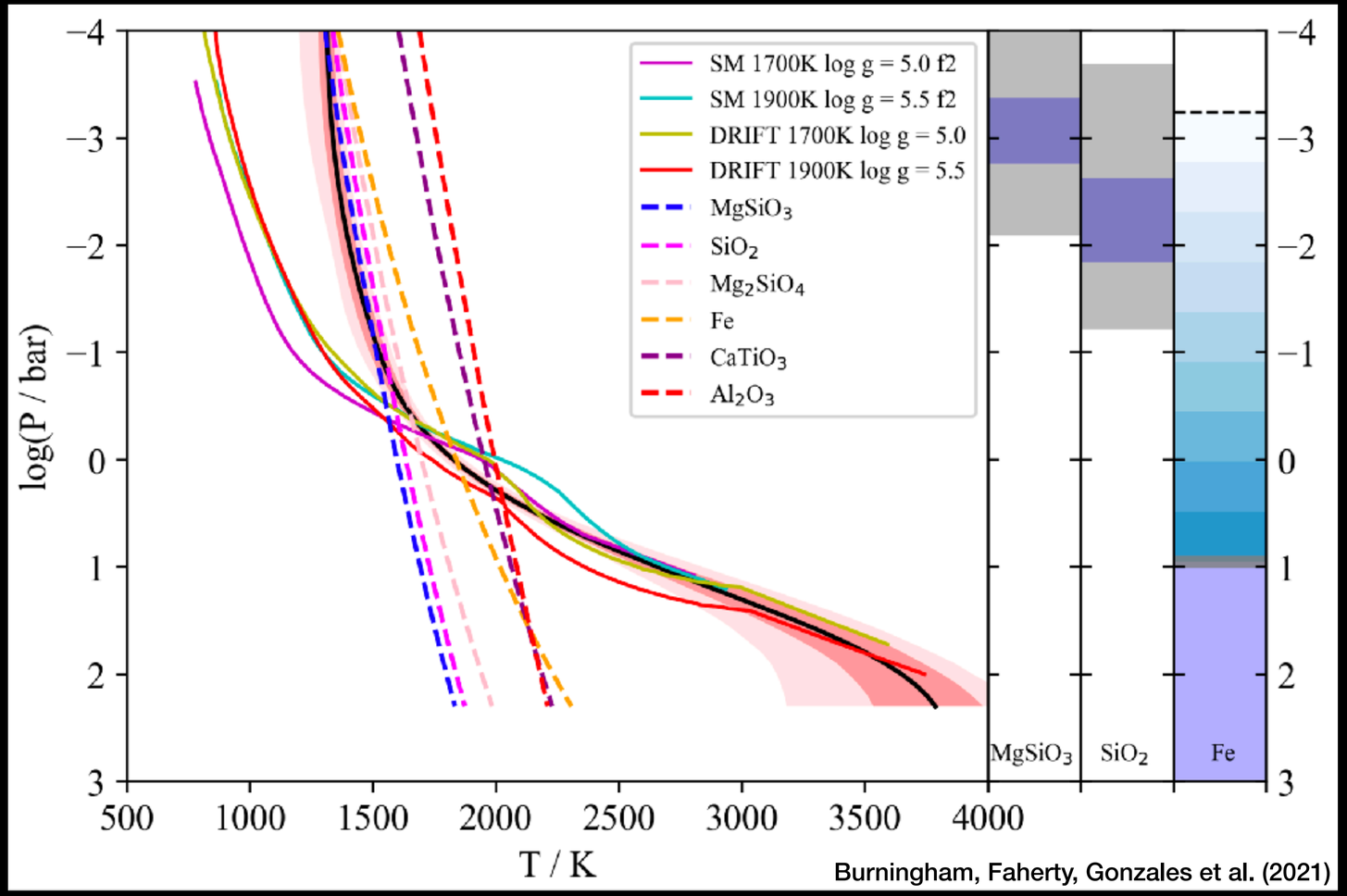


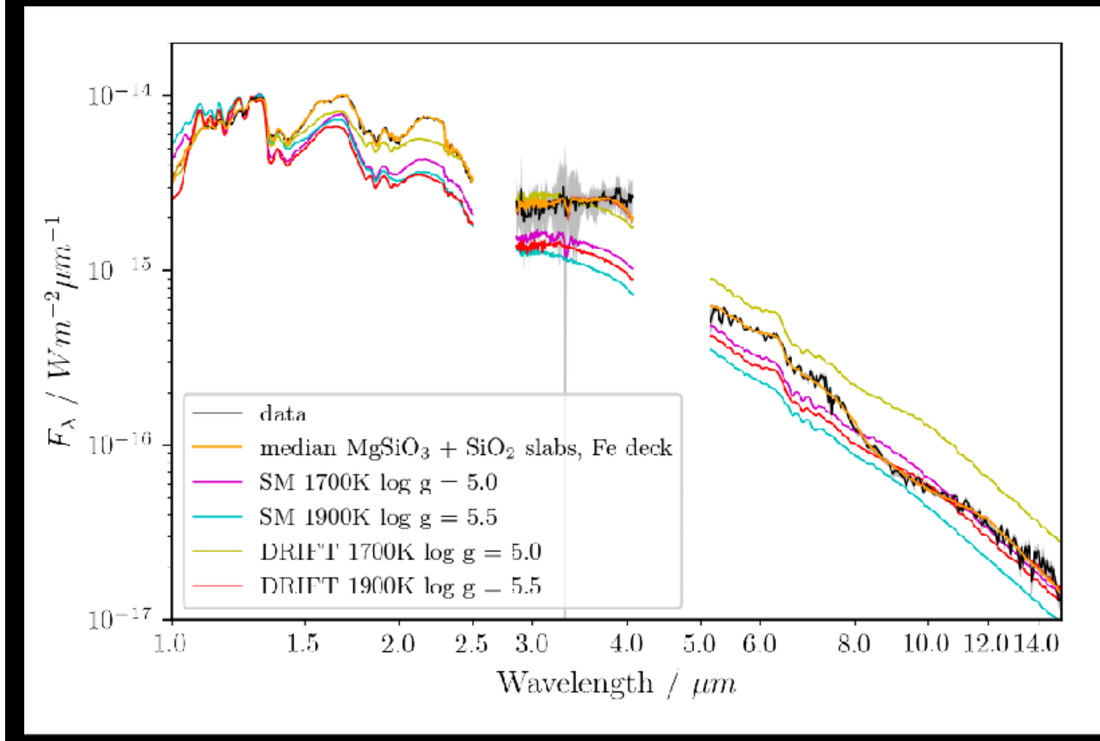
Burningham et al. (2017)

MIR Wavelength coverage can distinguish cloud species



Burningham, Faherty, Gonzales et al. (2021)

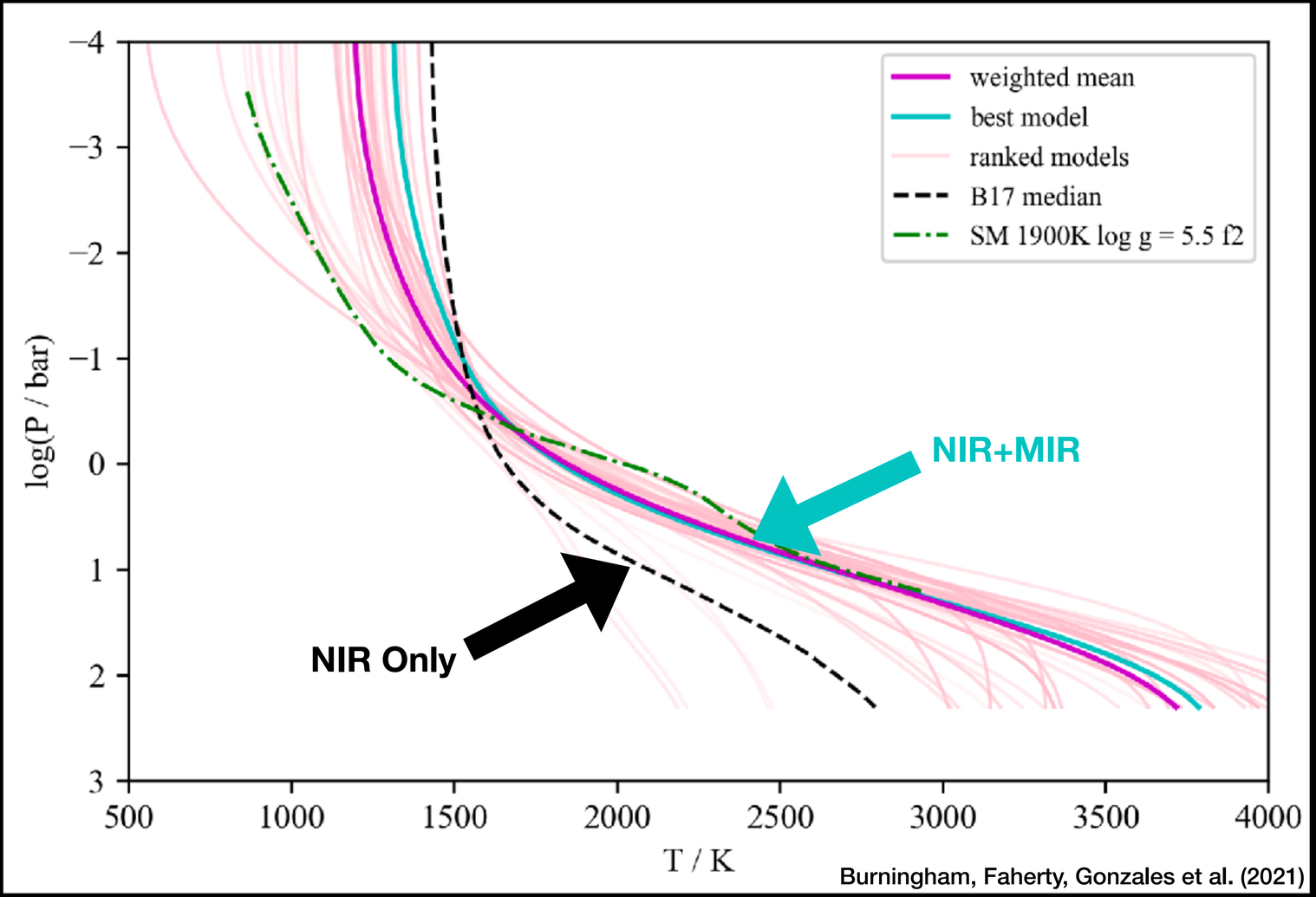
61 models tested!!



Burningham, Faherty, Gonzales et al. (2021)

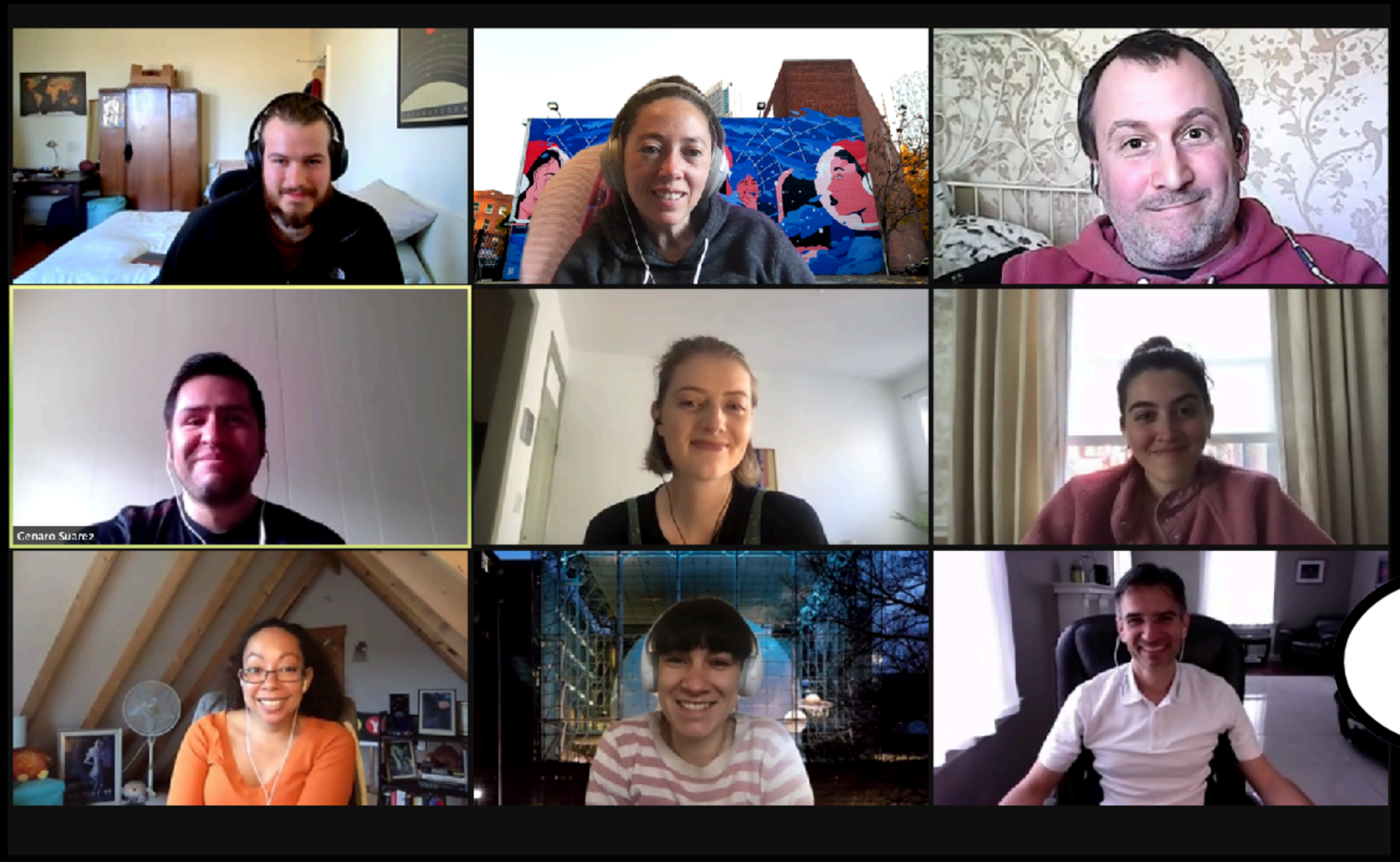
Profile matches grid model predictions much better

Wavelength coverage can drastically change the shape of the PT profile



Burningham, Faherty, Gonzales et al. (2021)

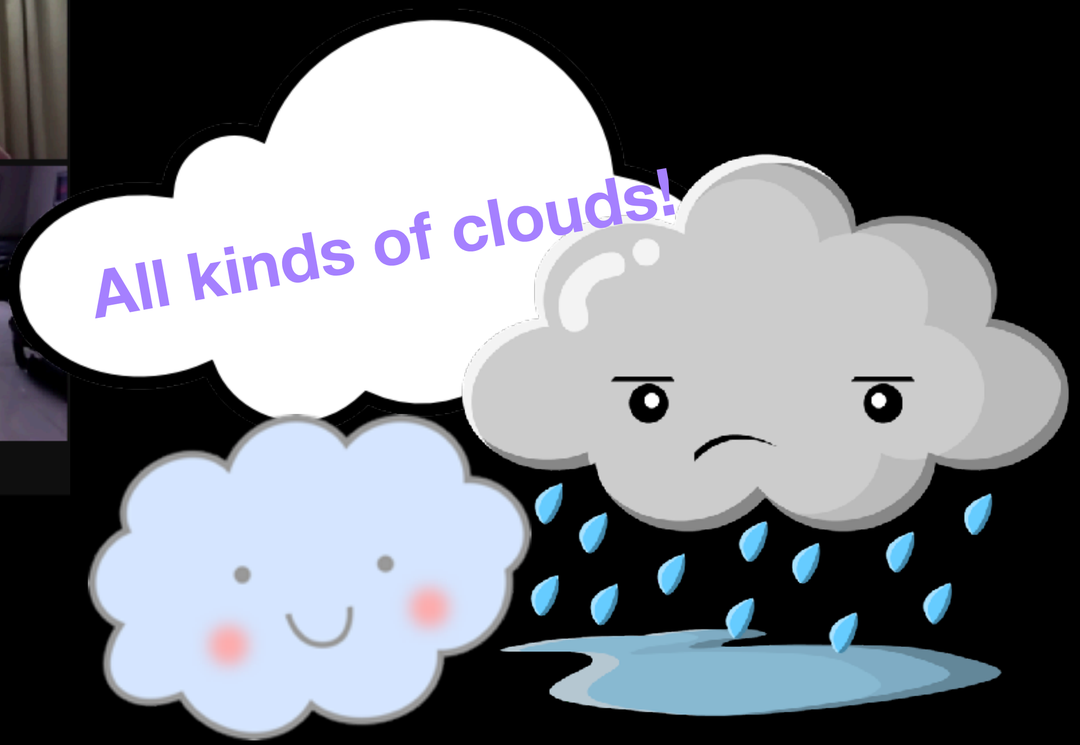
Retrievals Gang!



Retrieving:

- **Variable brown dwarfs**
- **Planetary mass Objects**
- **Subdwarfs**
- **Young brown dwarfs**

AND More!



Conclusions

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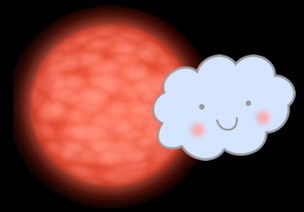
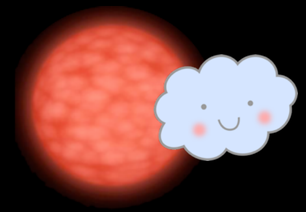


2MASS J1416A prefers a cloud model, but indistinguishable between a deck or slab cloud parameterization

Conclusions



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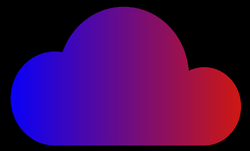
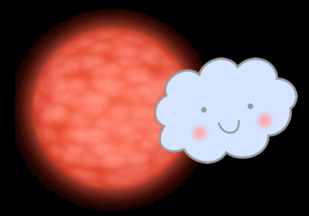


The location of the τ=1 cloud opacity relative to the gas opacity could be related to an object's *J-K* color

Conclusions



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Degeneracy between power law value (α) and cloud decay height

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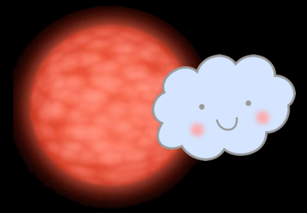

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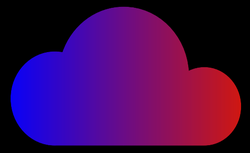

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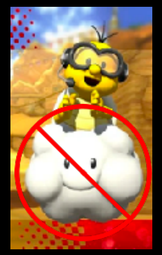

MIR data is necessary to best constrain cloud properties