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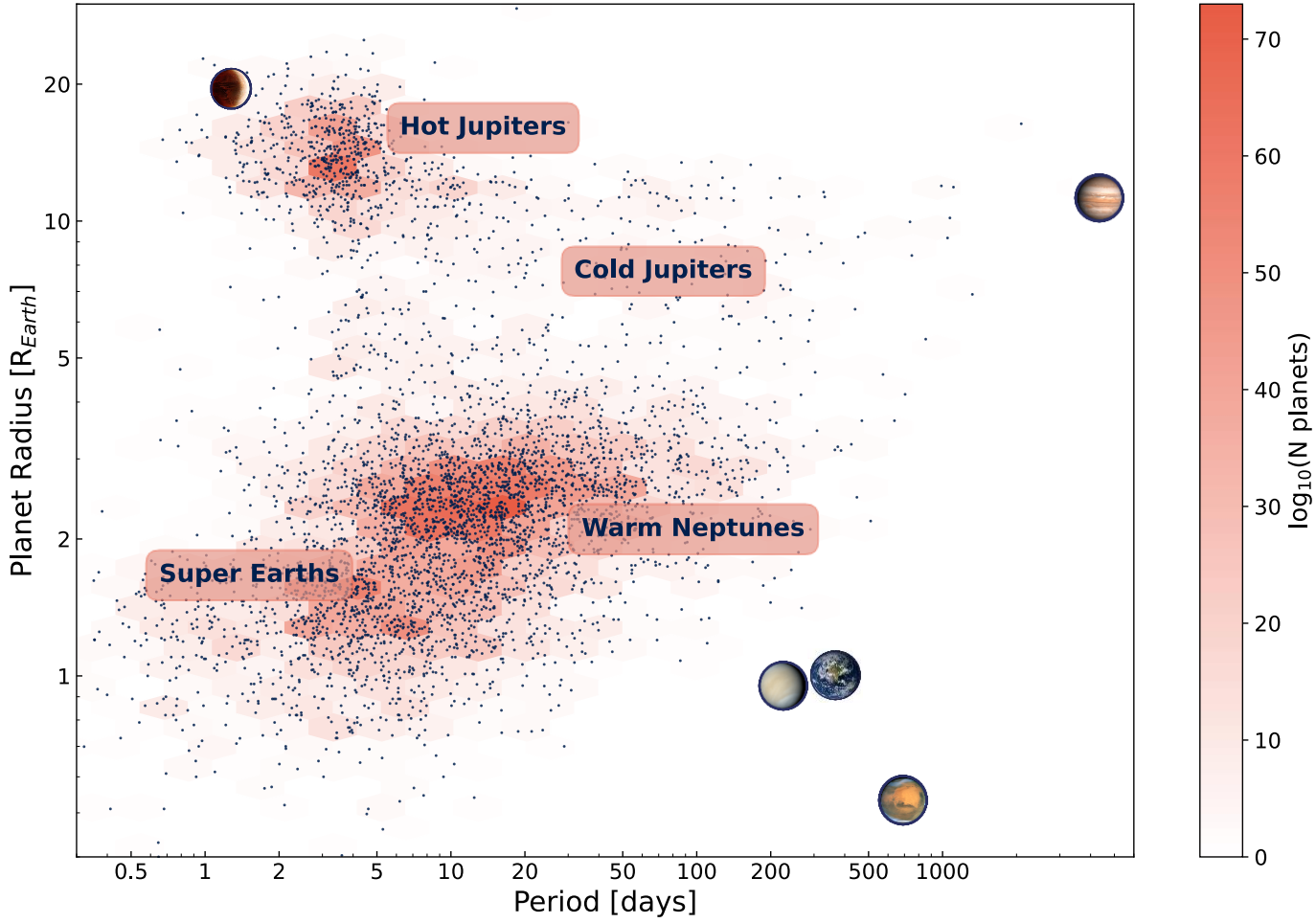
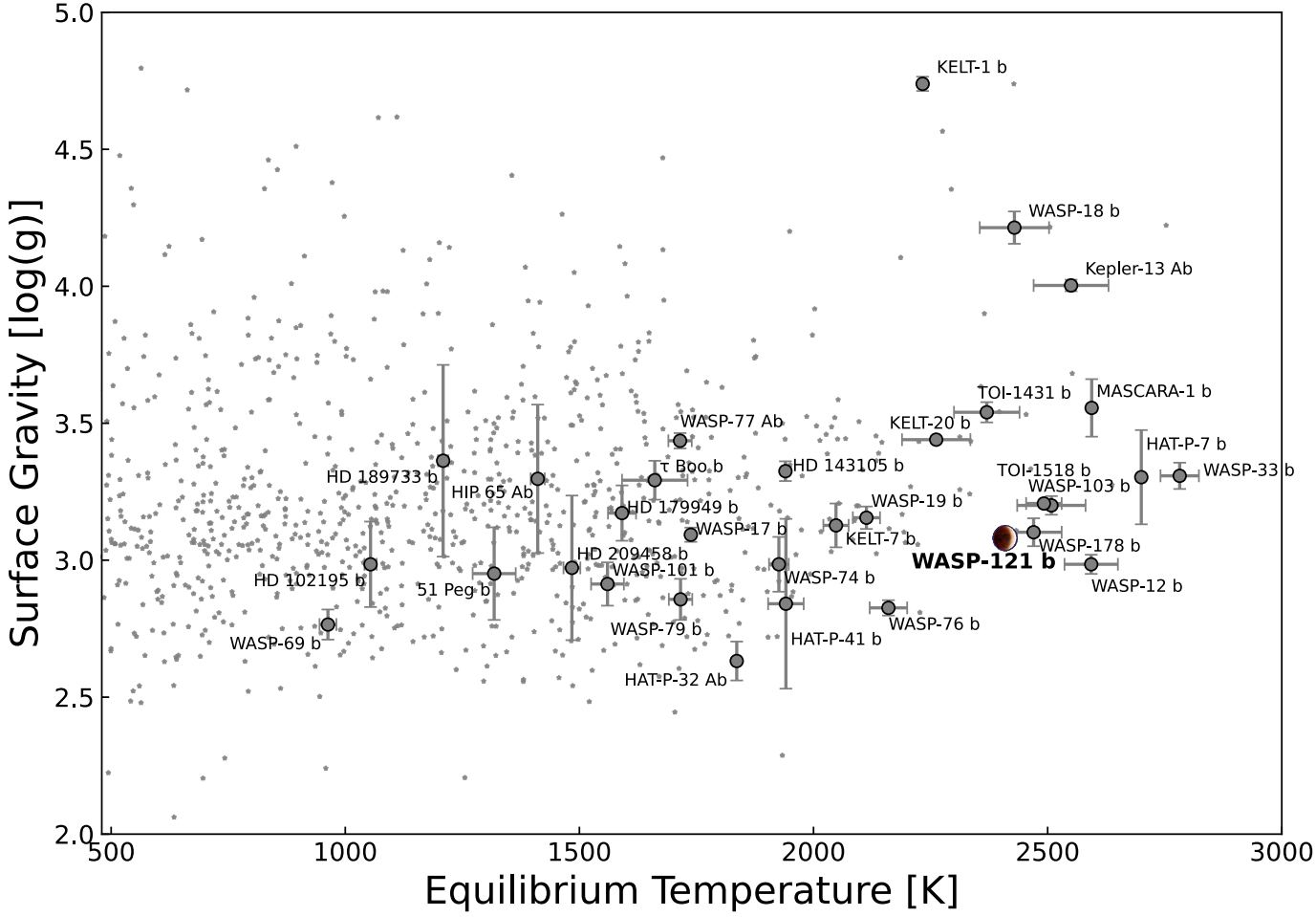
How optical absorbers shape the circulation and spectra of hot Jupiters: application to the JWST spectrum of WASP-121b

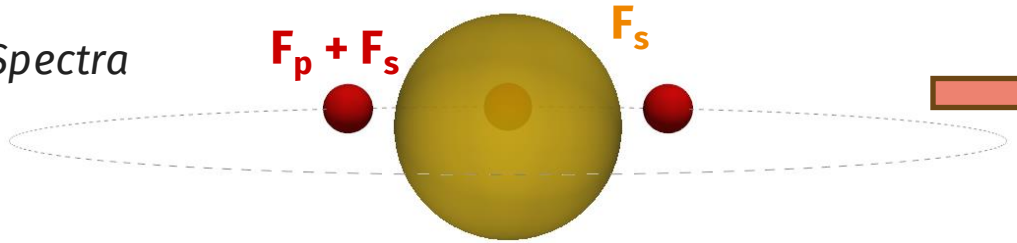
Pablo Drake Hernández

Dr. Vivien Parmentier (Observatoire de la Côte d'Azur)
with the instrumental help of **Nishil Mehta.**

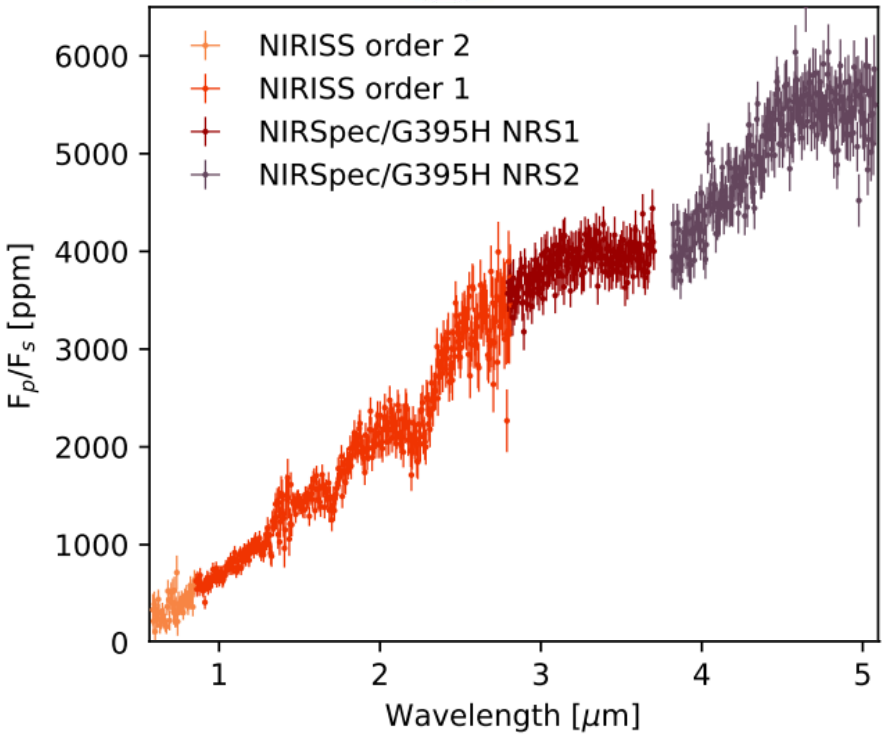

Hot Jupiters
Cold Jupiters
Warm Neptunes
Super Earths
Planet Radius [R$_{Earth}$]
Period [days]
log$_{10}$(N planets)
20
10
5
2
1
0.5
1
2
5
10
20
50
100
200
500
1000
70
60
50
40
30
20
10
0


Surface Gravity [log(g)]
Equilibrium Temperature [K]
5.0
4.5
4.0
3.5
3.0
2.5
2.0
500
1000
1500
2000
2500
3000
KELT-1 b
WASP-18 b
Kepler-13 Ab
TOI-1431 b
MASCARA-1 b
KELT-20 b
HAT-P-7 b
WASP-77 Ab
τ Boo b
HD 143105 b
TOI-1518 b
WASP-33 b
WASP-103 b
HD 189733 b
HIP 65 Ab
HD 179949 b
WASP-19 b
WASP-17 b
KELT-7 b
WASP-178 b
HD 209458 b
WASP-121 b
WASP-101 b
WASP-74 b
HD 102195 b
51 Peg b
WASP-12 b
WASP-79 b
WASP-76 b
HAT-P-41 b
WASP-69 b
HAT-P-32 Ab

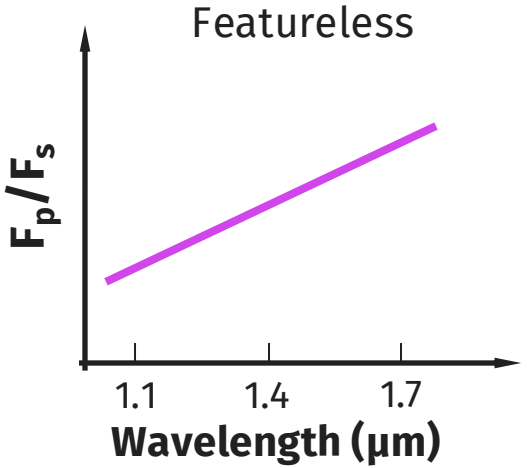
Thermal Emission Spectra

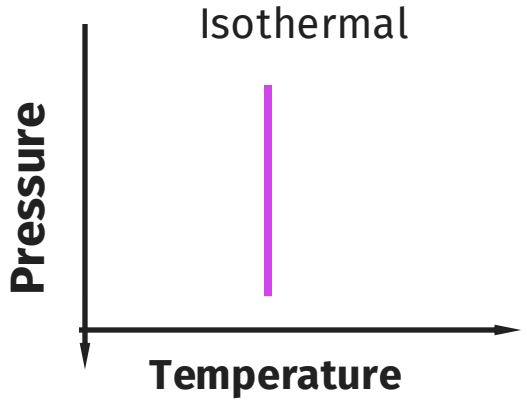


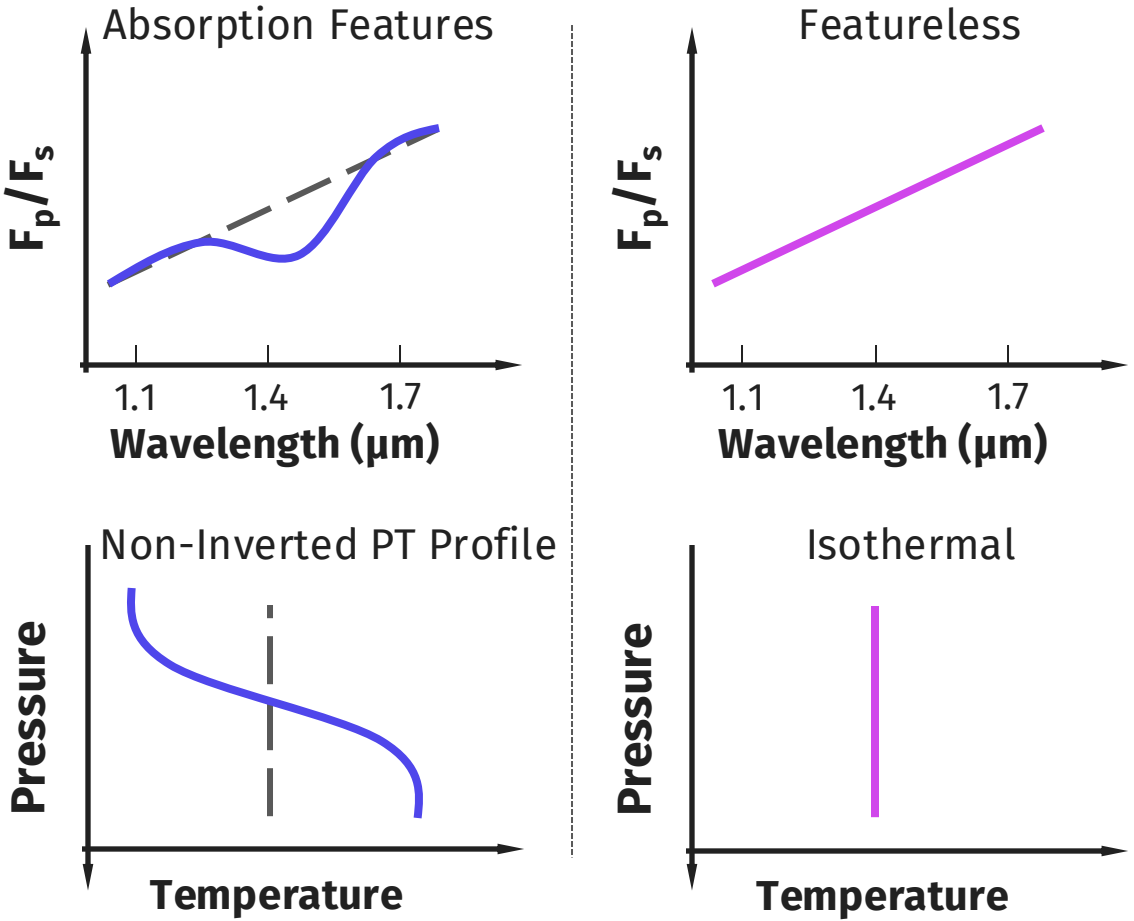
F_p/F_s (λ)

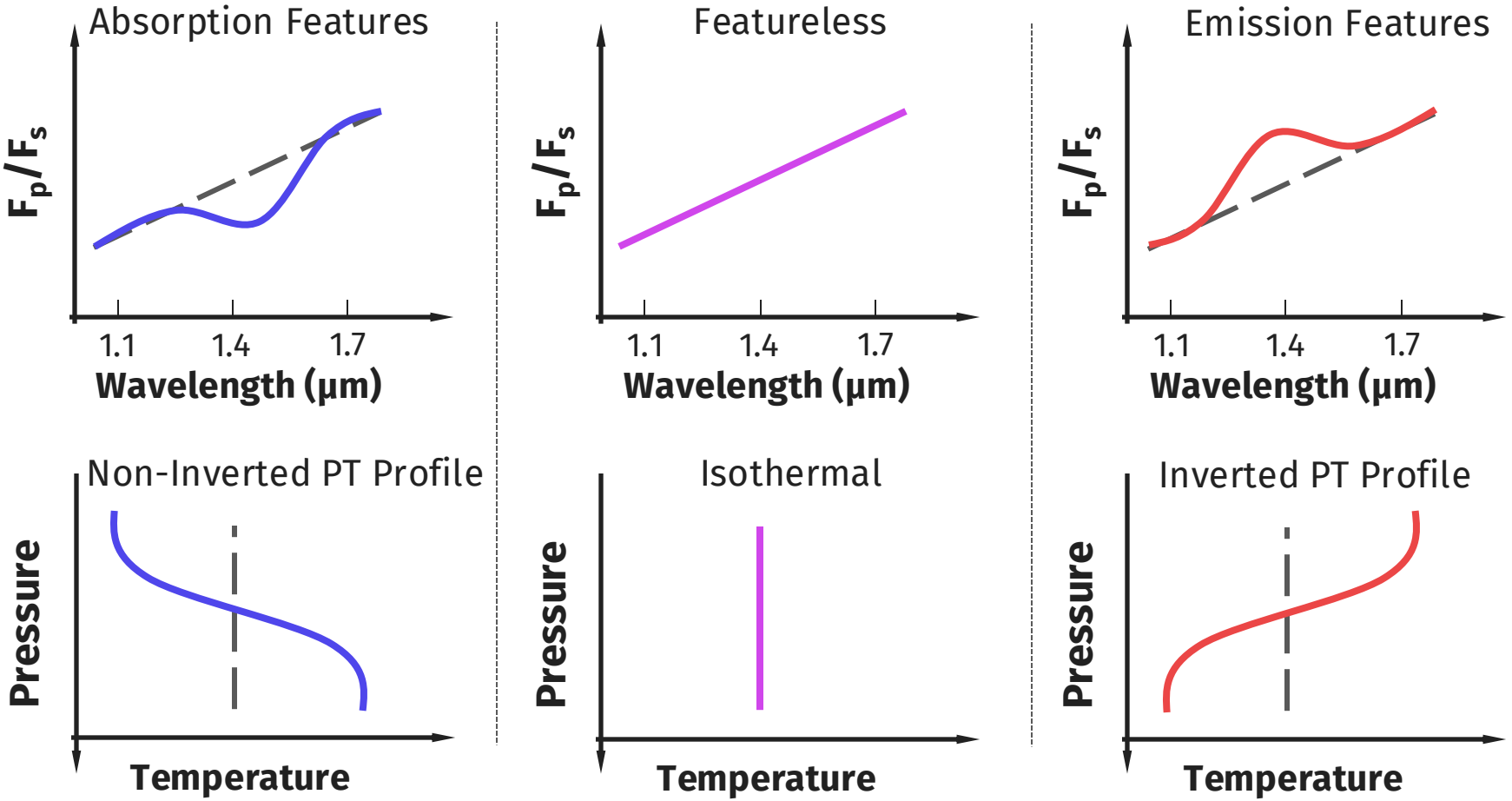


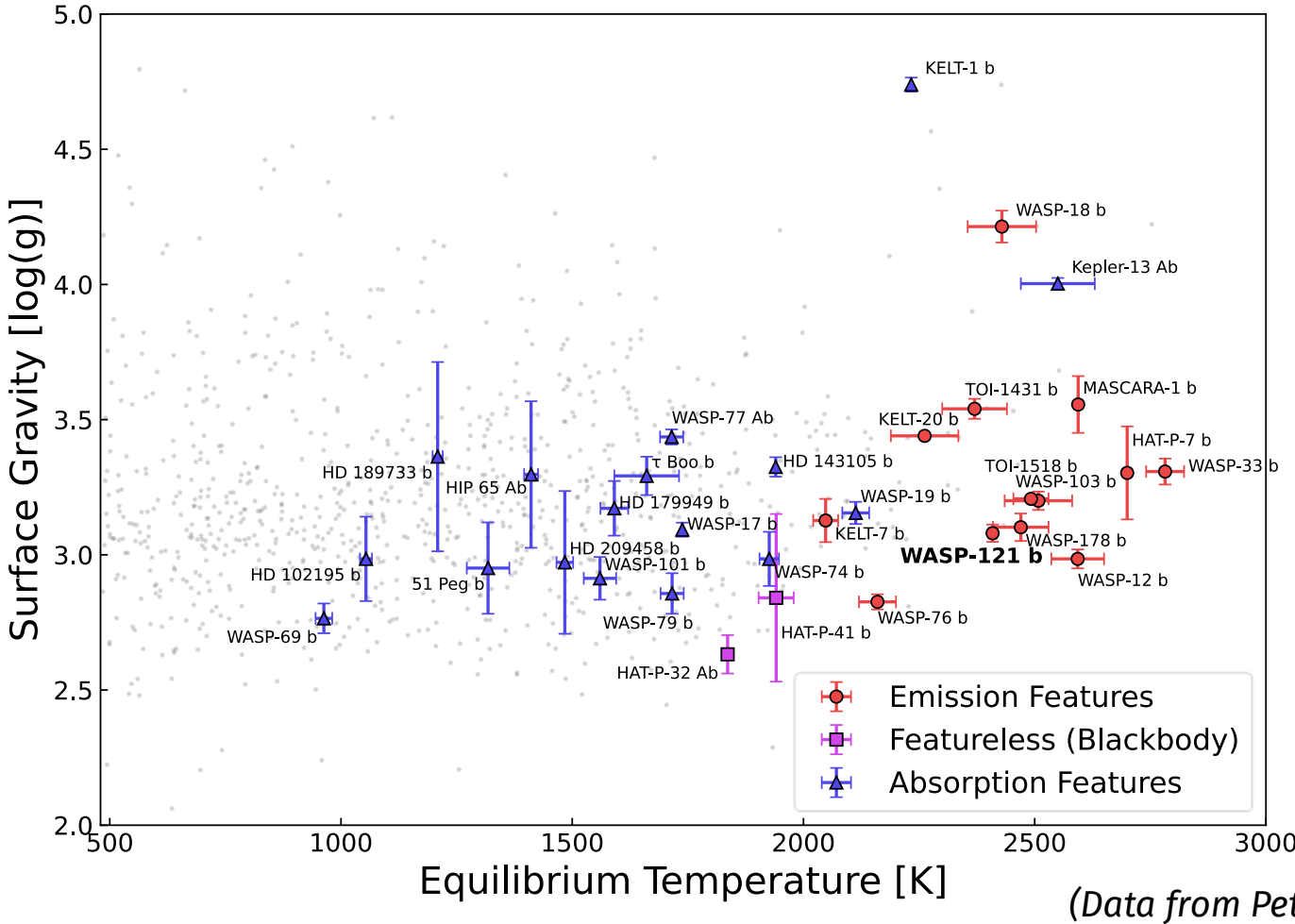
Data from *Pelletier+25*
Gapp+25


Featureless
F_p/F_s
1.1
1.4
1.7
Wavelength (μm)

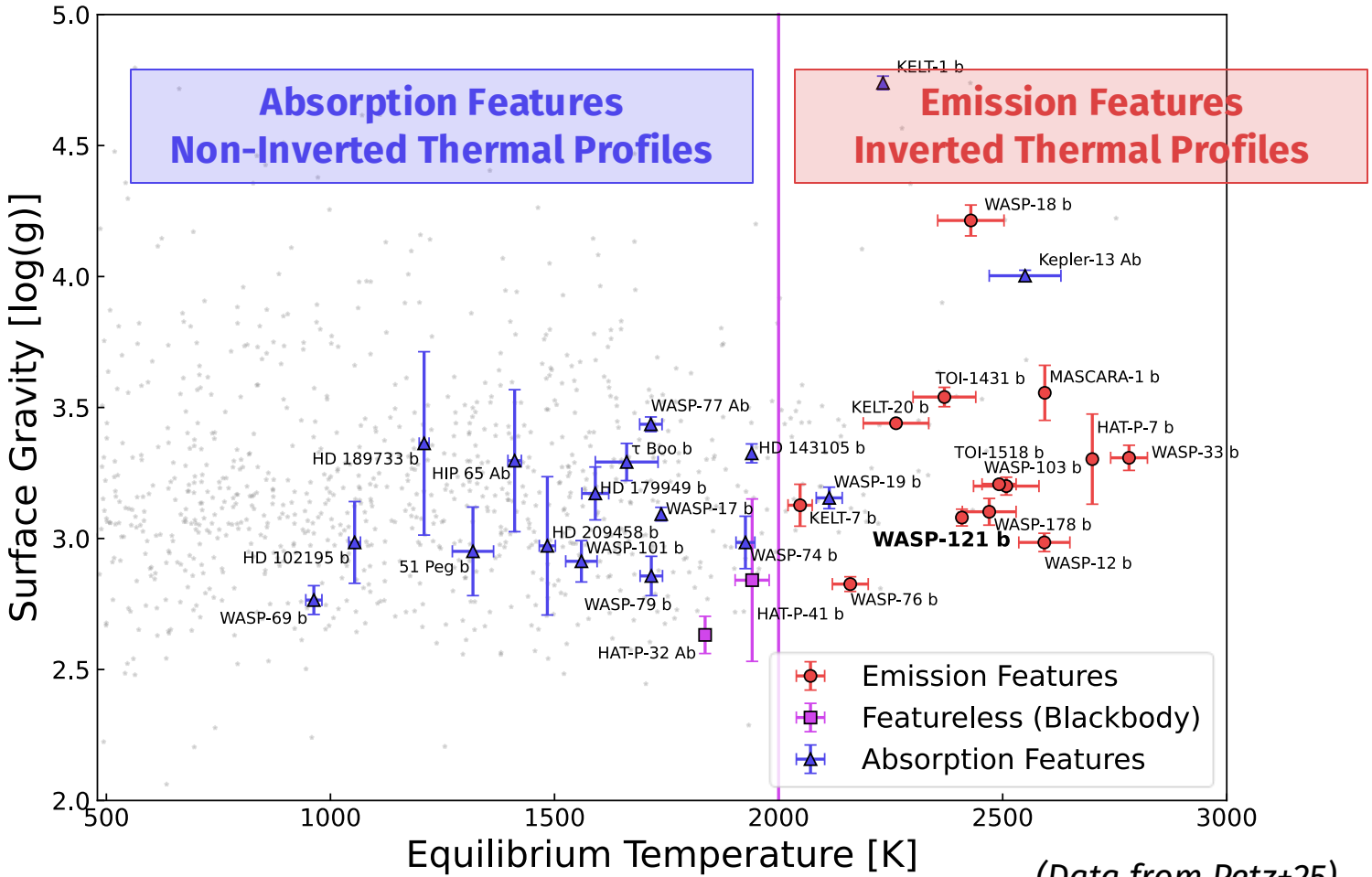

Isothermal
Pressure
Temperature


Absorption Features
F_p/F_s
1.1
1.4
1.7
Wavelength (μm)
Featureless
F_p/F_s
1.1
1.4
1.7
Wavelength (μm)
Non-Inverted PT Profile
Pressure
Temperature
Isothermal
Pressure
Temperature


Absorption Features
Featureless
Emission Features
F_p/F_s
1.1
1.4
1.7
Wavelength (μm)
Non-Inverted PT Profile
Isothermal
Inverted PT Profile
Pressure
Temperature

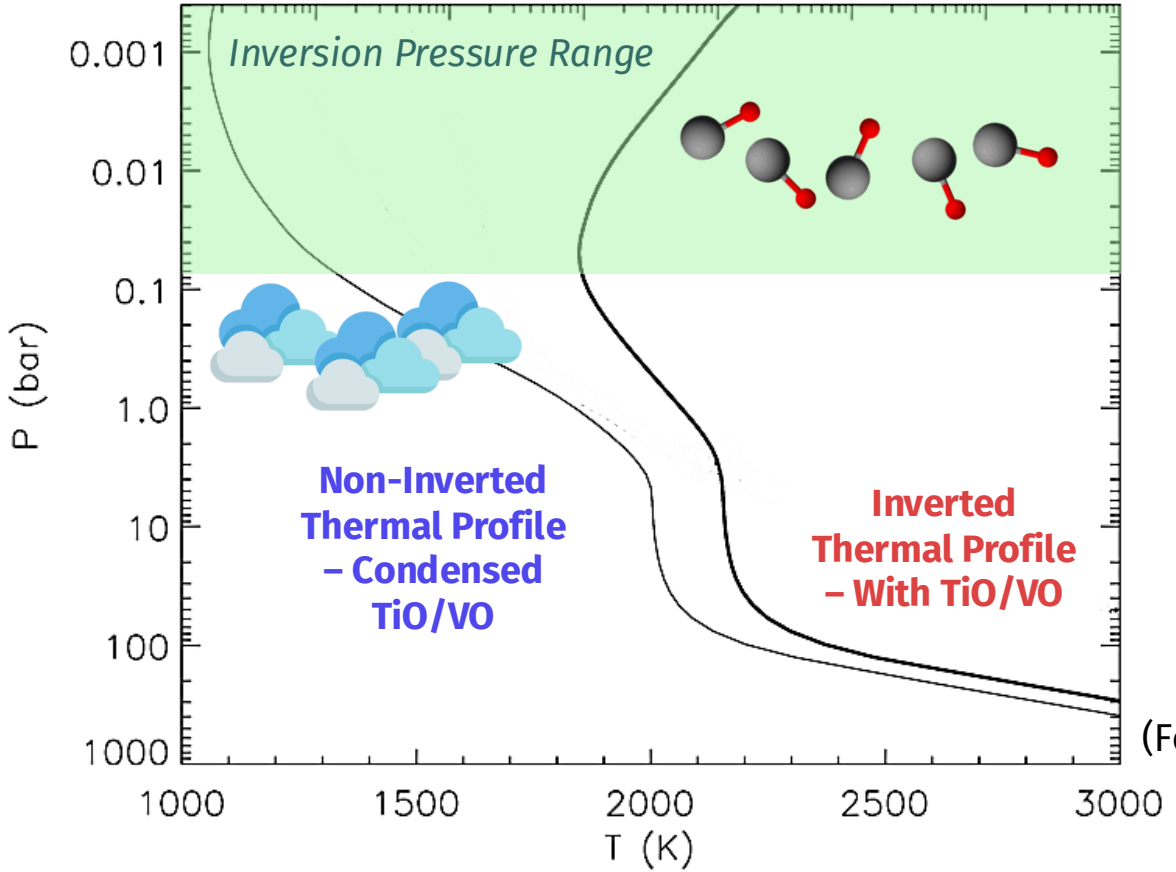


(Data from Petz+25)



(Data from Petz+25)

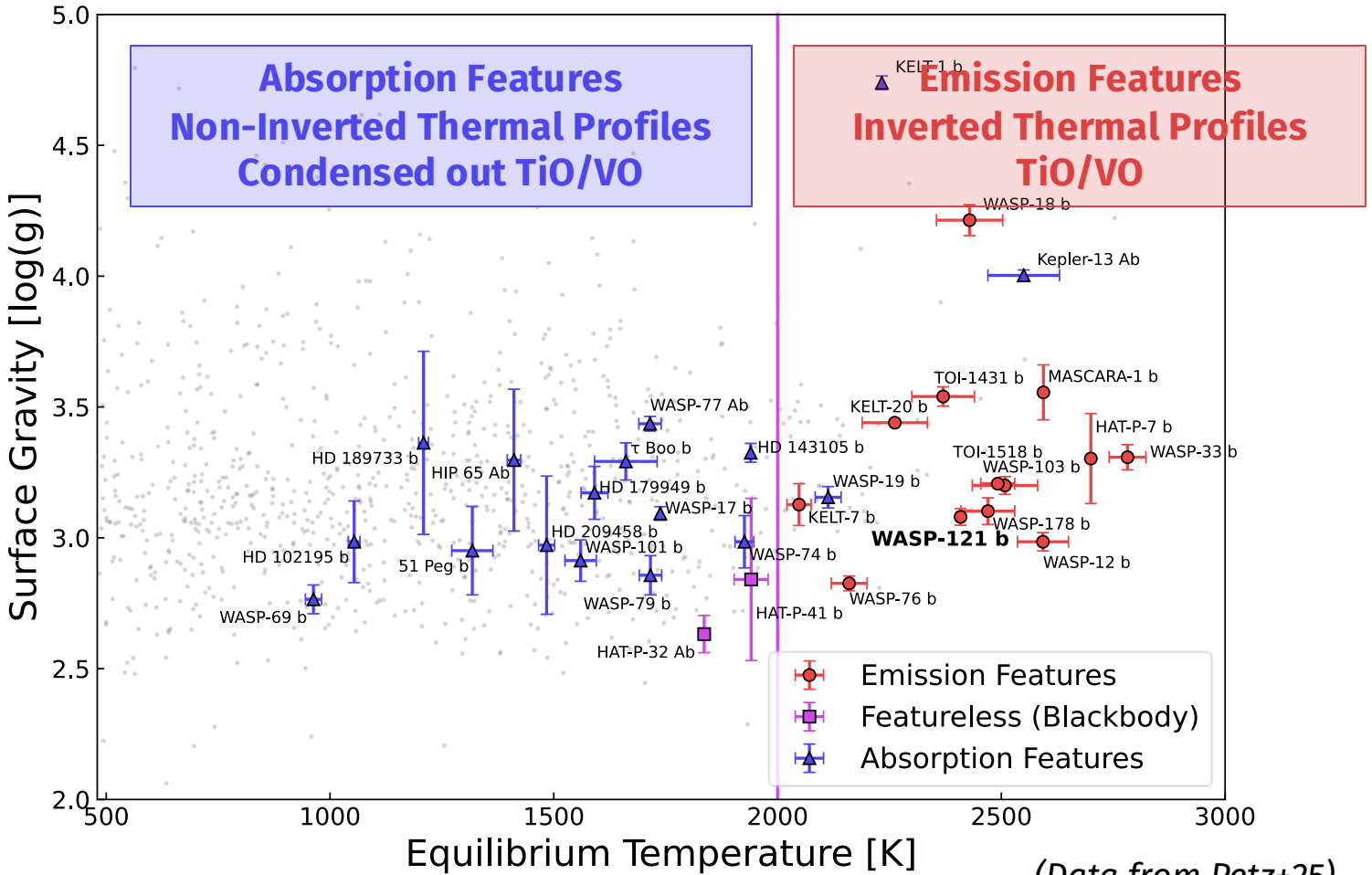
Presence of gaseous TiO/VO ⇨ inverted profiles



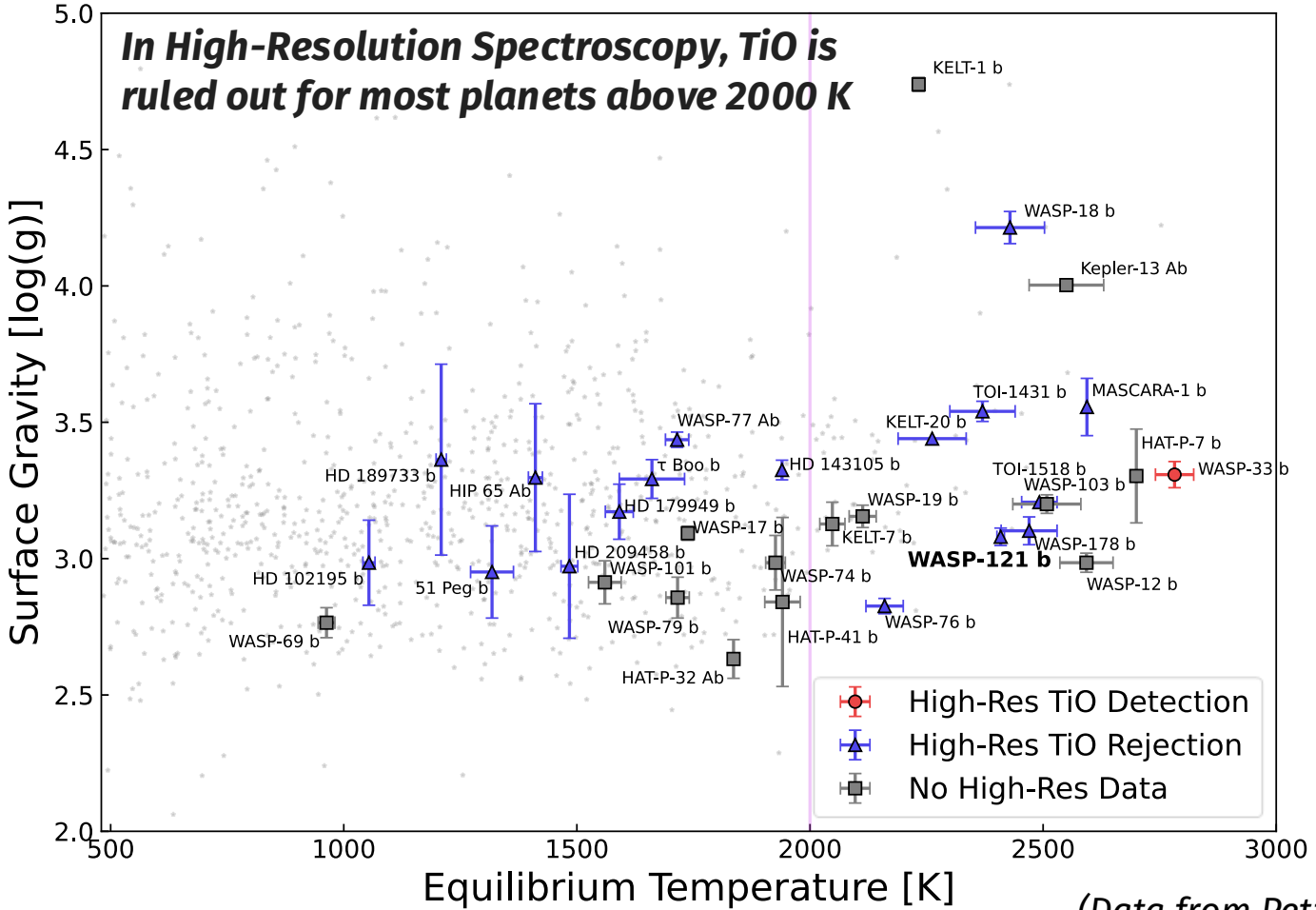
TiO/VO superabsorbers in the visible

(Fortney+08)

Transition between inverted & non-inverted at T_{eq}=2000K

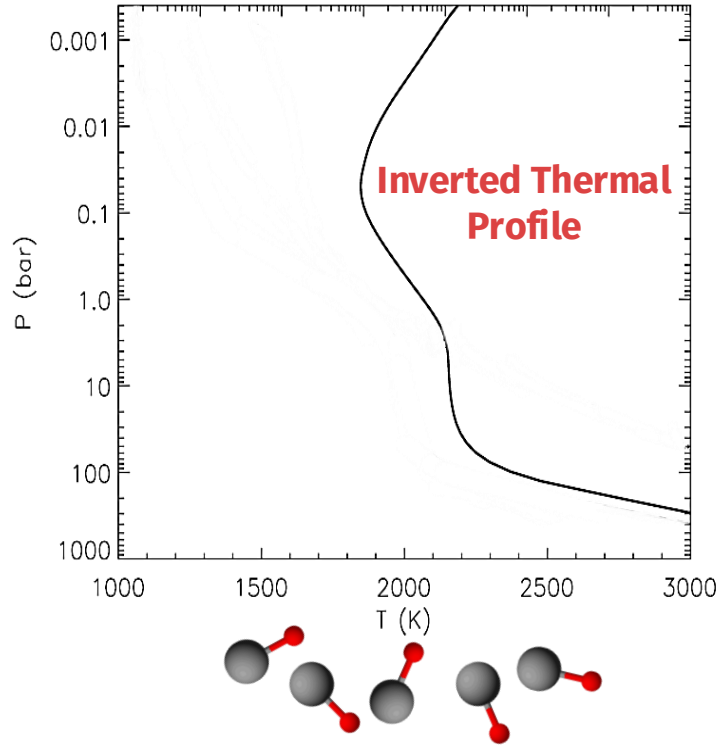


(Data from Petz+25)



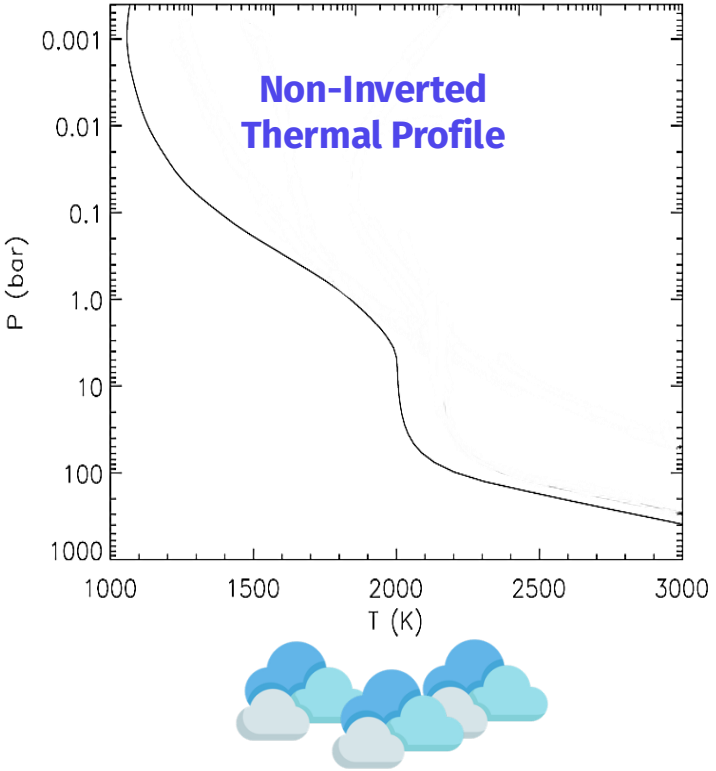
(Data from Petz+25)

Thermal Emission Spectra



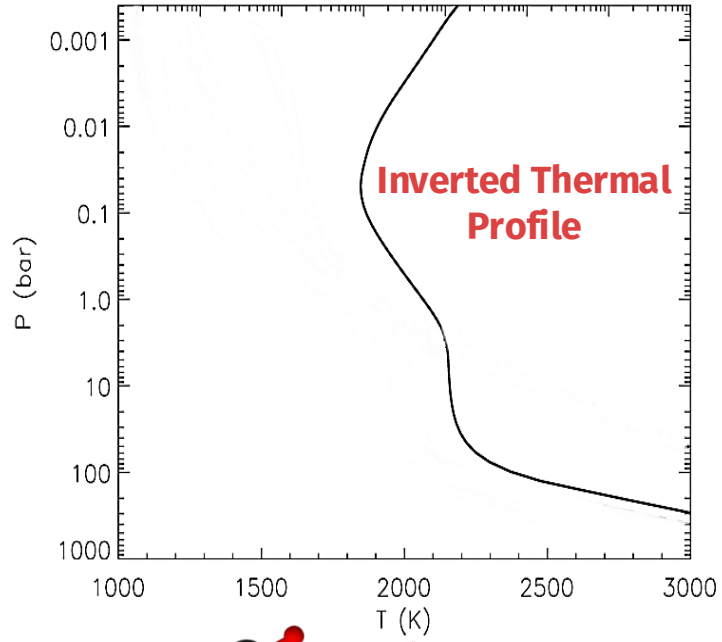
TiO/VO

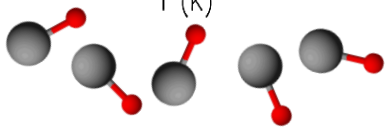
High-Res Spectroscopy



Condensed out TiO/VO

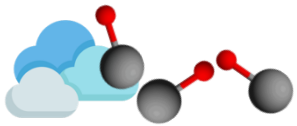
Thermal Emission Spectra





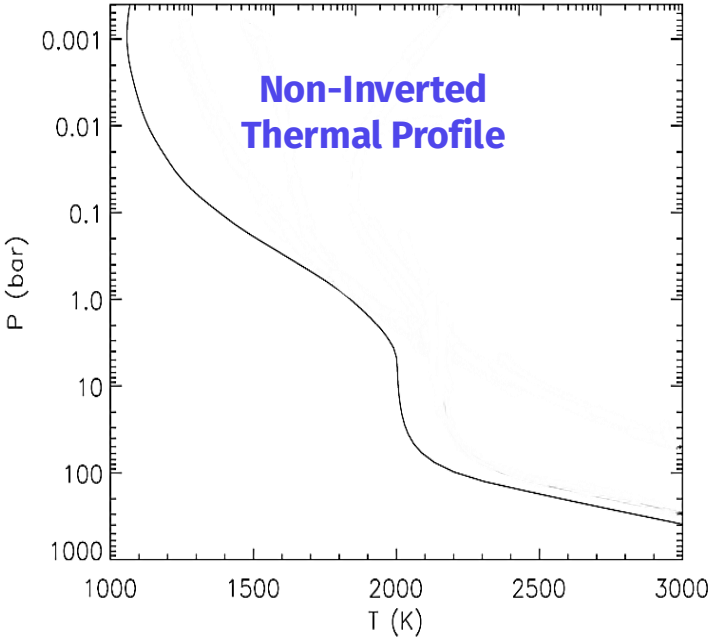
TiO/VO

?



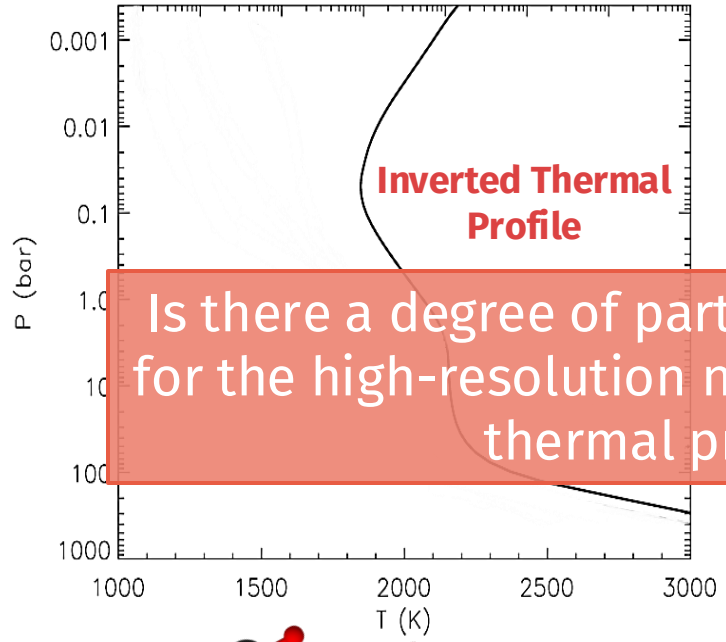
Partial TiO/VO Depletion

High-Res Spectroscopy

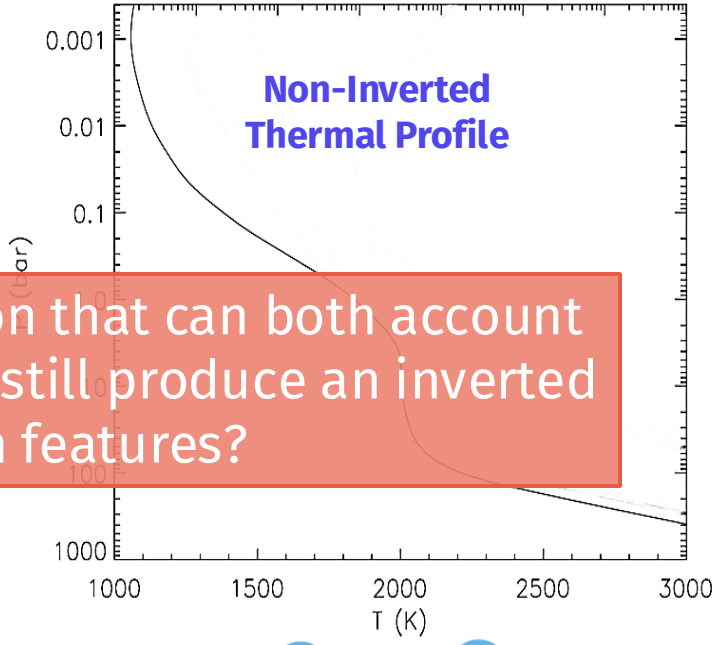


Condensed out TiO/VO

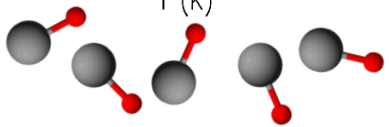
Thermal Emission Spectra



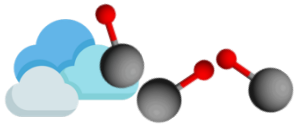
High-Res Spectroscopy



Is there a degree of partial TiO/VO depletion that can both account for the high-resolution non-detections and still produce an inverted thermal profile with emission features?



TiO/VO



Partial TiO/VO Depletion

Condensed out TiO/VO

We simulate disequilibrium chemistry in WASP-121b's atmosphere through **Global Circulation Models (GCMs)**: `MITgcm` (dynamics), Marley & McKay (radiative transfer) & `gCMCRT` (post-processing). Avoid biases inherent to 1D analyses (Feng+20)

How do we simulate TiO depletion? Input opacity tables with reduced TiO/VO (wrt chemical equilibrium)

	Solar Equilibrium	***Supersolar (10× $[Fe/H]_\odot$, 1.5× $C/O_\odot$) Equilibrium***
Deplete both TiO & VO	0%, 0.2%, 1%, 2%, 10%, 20%, 100% $[TiO]_{eq}$	0%, 0.2%, 1%, 2%, 10%, 20%, 100% $[TiO]_{eq}$
Only deplete TiO	0%, 0.2%, 1%, 2%, 10%, 20%, 100% $[TiO]_{eq}$	0%, 0.2%, 1%, 2%, 10%, 20%, 100% $[TiO]_{eq}$

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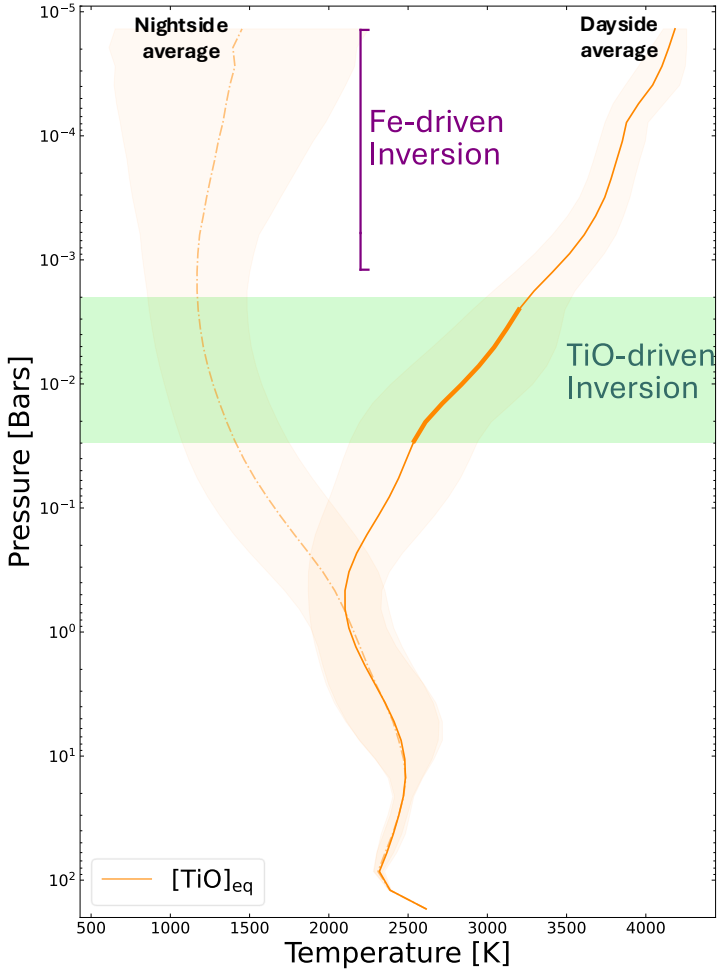
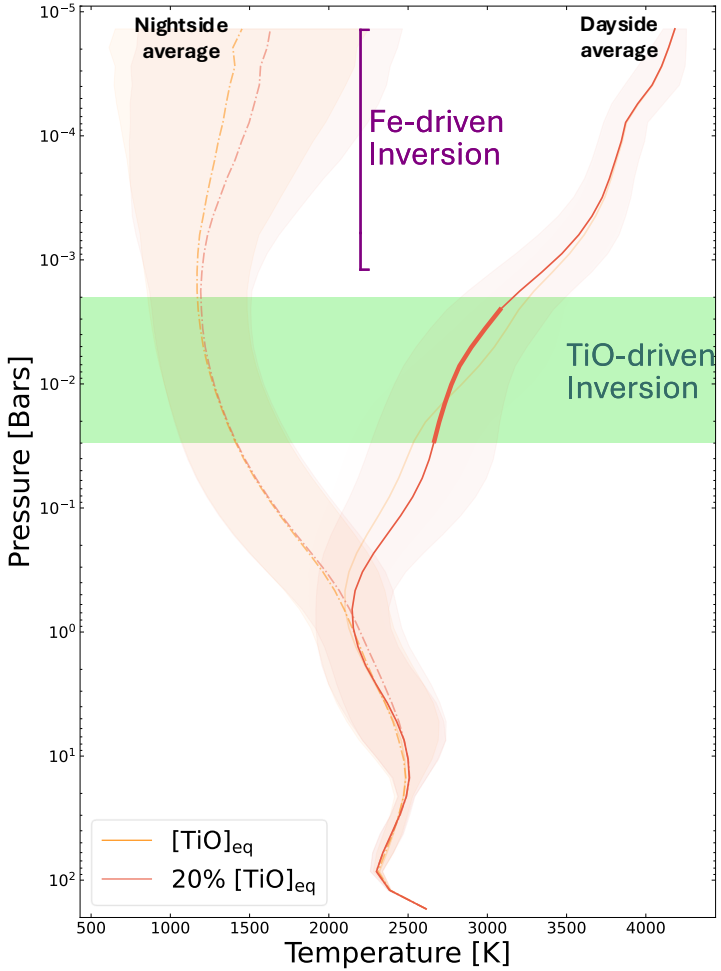
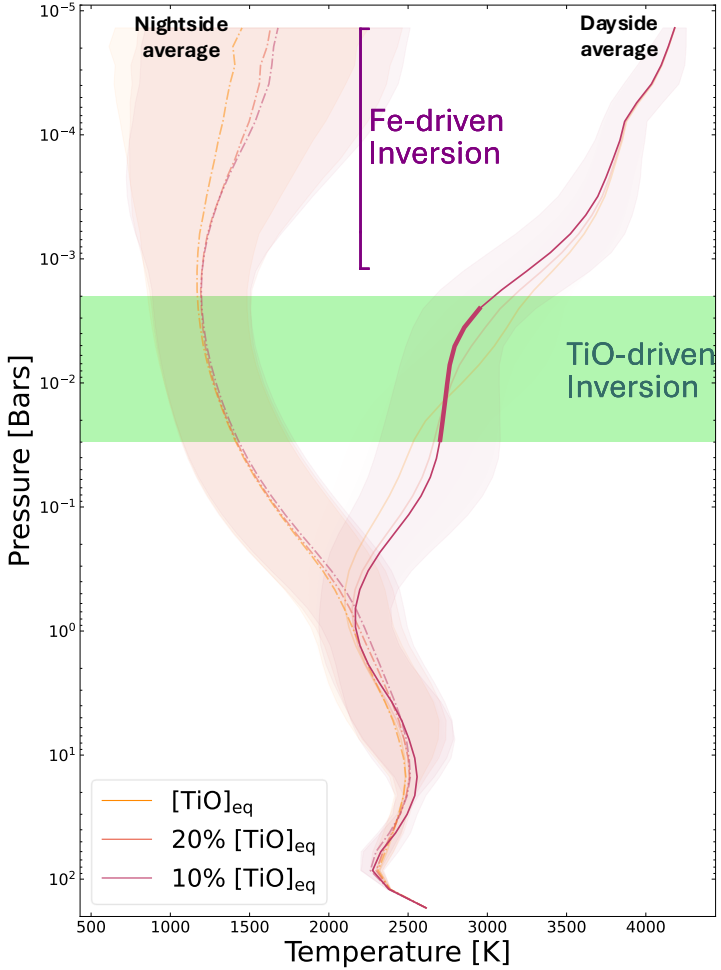
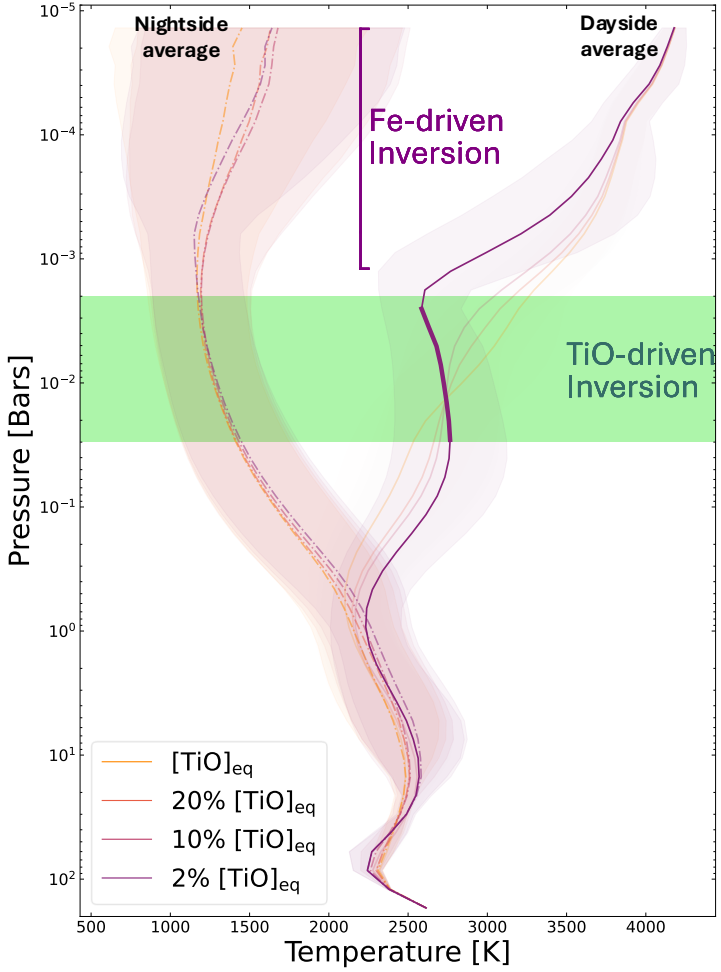
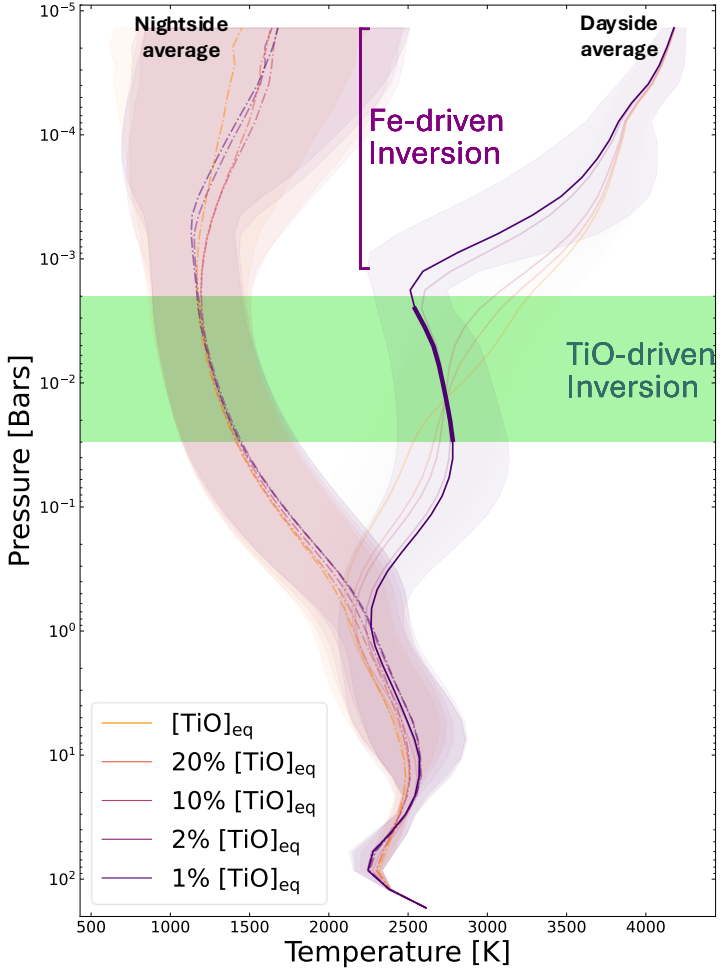
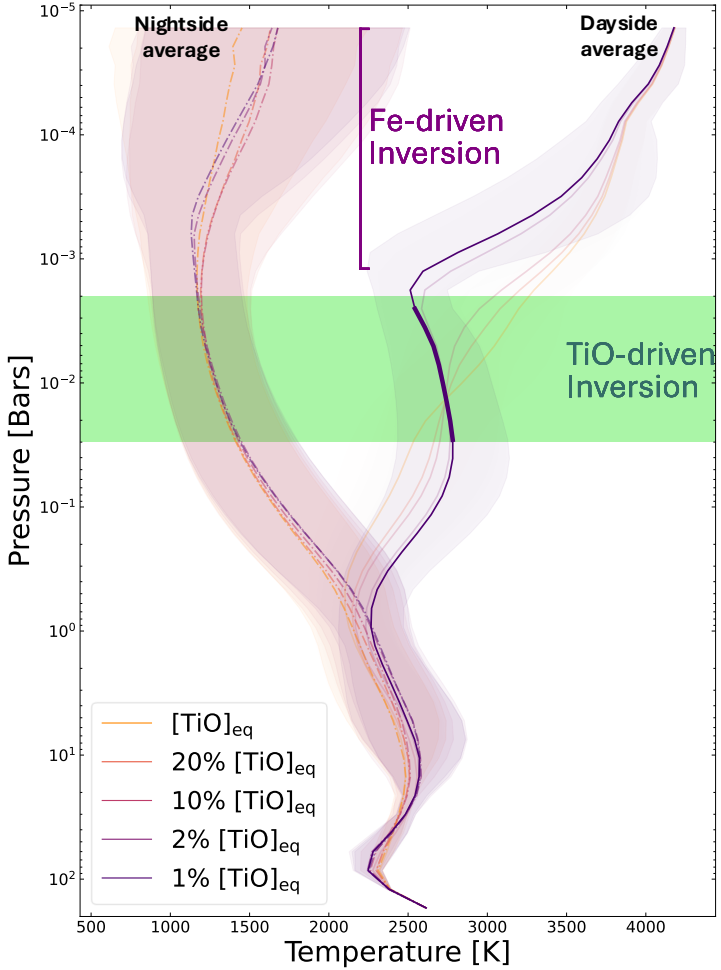

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
Pressure [Bars]
Temperature [K]
10−5
10−4
10−3
10−2
10−1
100
101
102
500
1000
1500
2000
2500
3000
3500
4000

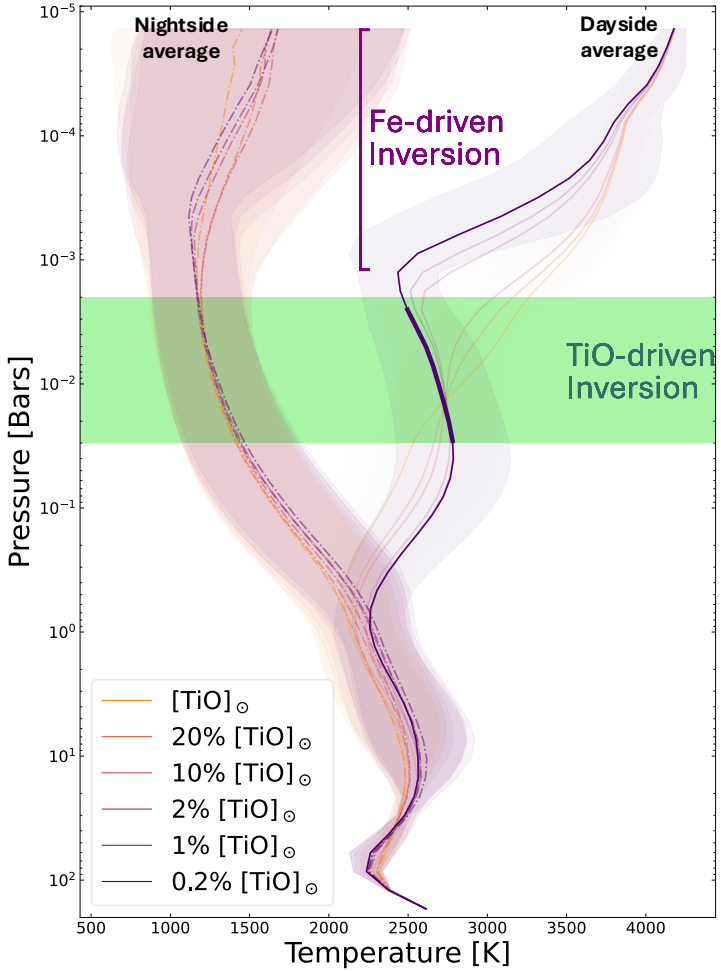

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
20% [TiO]eq
Pressure [Bars]
Temperature [K]
10−5
10−4
10−3
10−2
10−1
100
101
102
500
1000
1500
2000
2500
3000
3500
4000

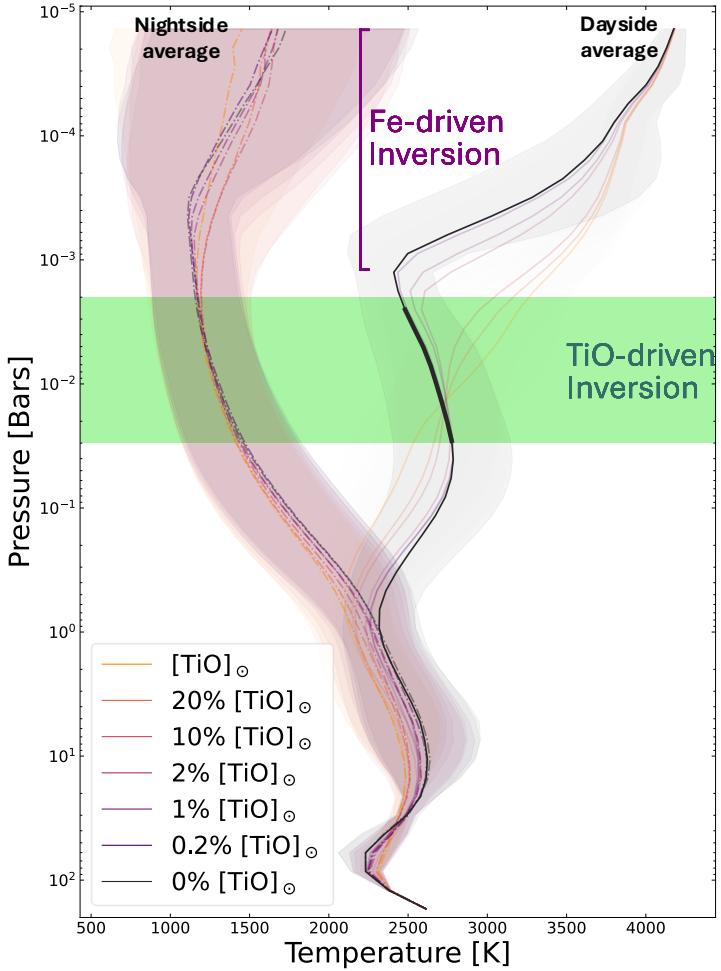

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
20% [TiO]eq
10% [TiO]eq
Pressure [Bars]
Temperature [K]
10−5
10−4
10−3
10−2
10−1
100
101
102
500
1000
1500
2000
2500
3000
3500
4000

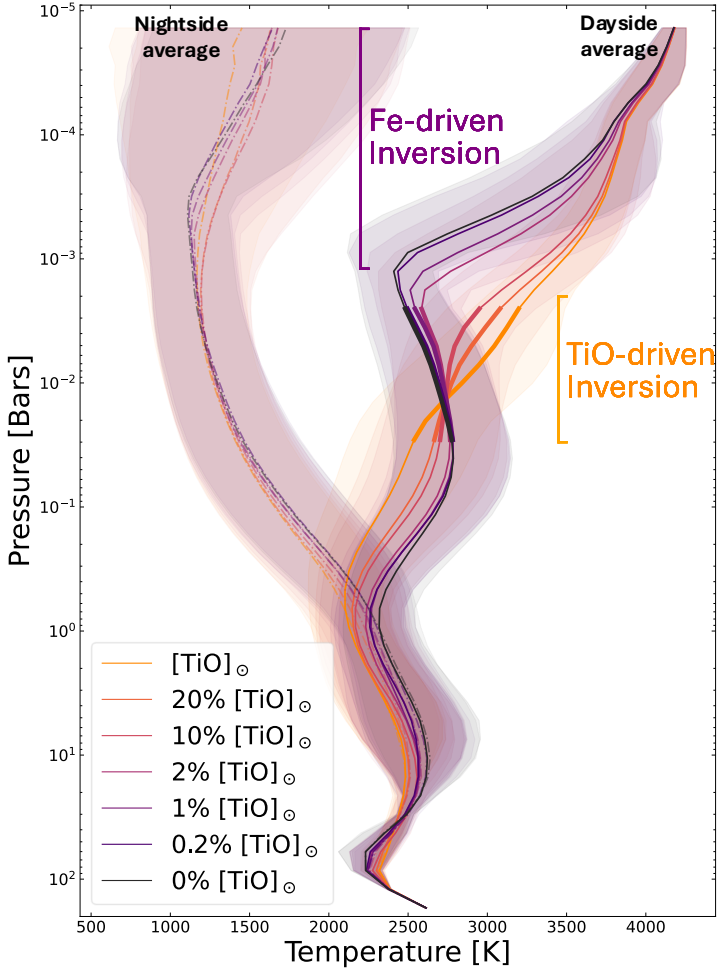

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
20% [TiO]eq
10% [TiO]eq
2% [TiO]eq
Pressure [Bars]
Temperature [K]


Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
20% [TiO]eq
10% [TiO]eq
2% [TiO]eq
1% [TiO]eq
Pressure [Bars]
Temperature [K]


Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
[TiO]eq
20% [TiO]eq
10% [TiO]eq
2% [TiO]eq
1% [TiO]eq
Pressure [Bars]
Temperature [K]

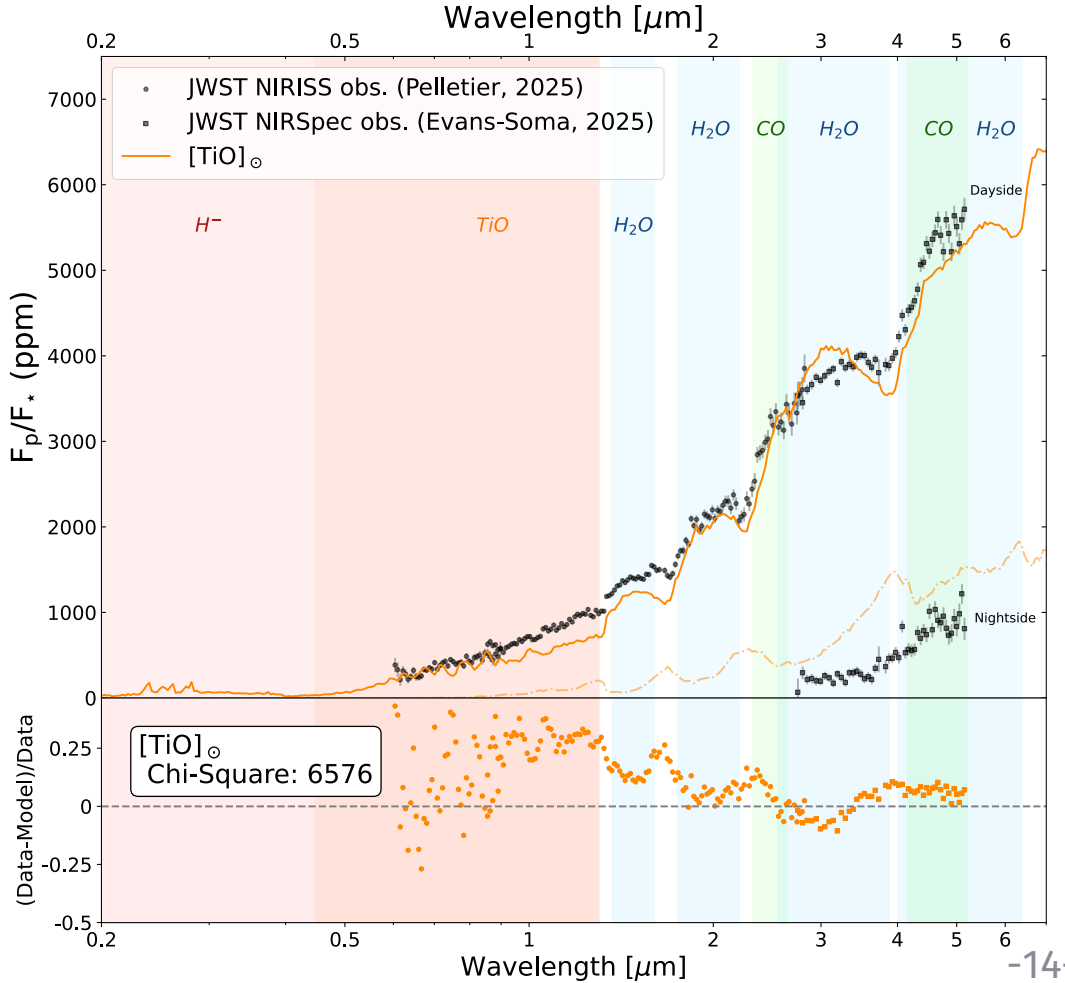

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
Pressure [Bars]
Temperature [K]
[TiO]⊙
20% [TiO]⊙
10% [TiO]⊙
2% [TiO]⊙
1% [TiO]⊙
0.2% [TiO]⊙

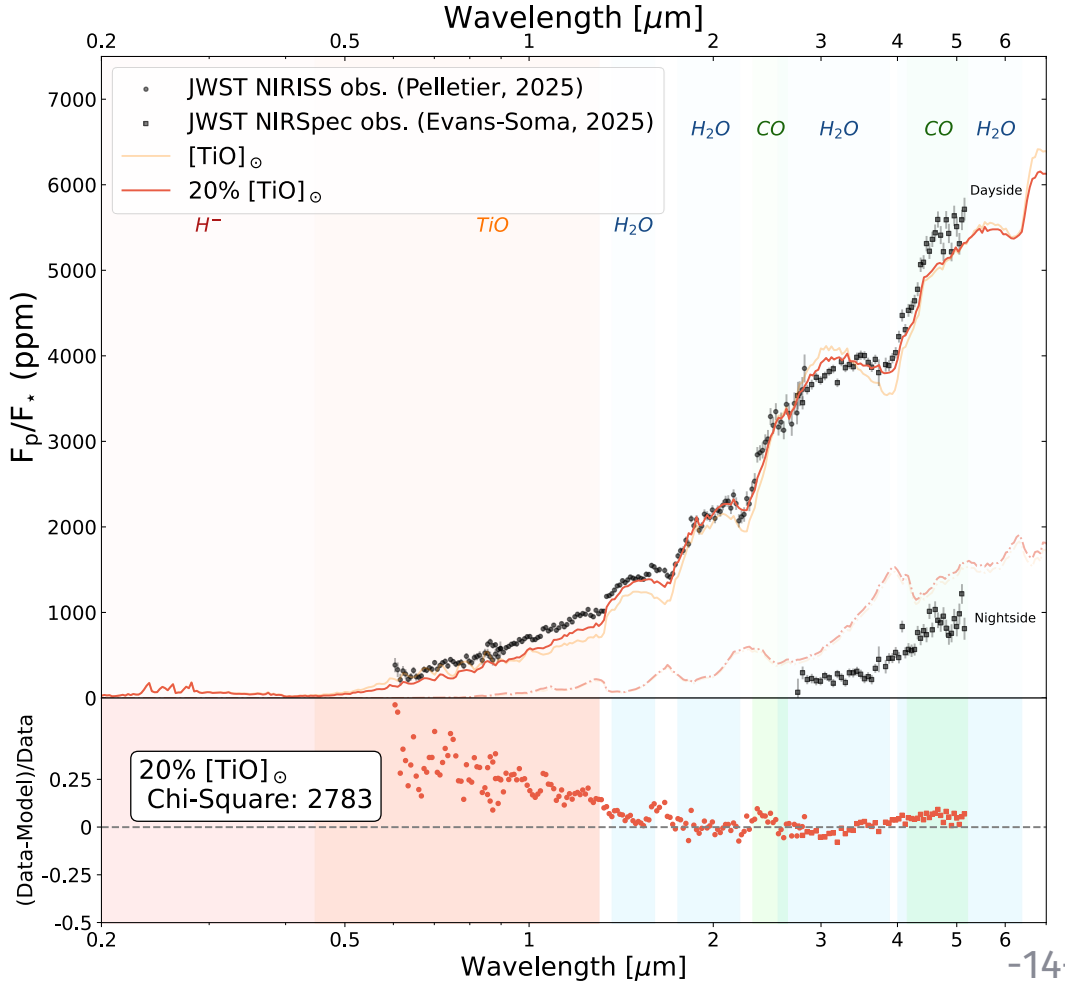

Nightside average
Dayside average
Fe-driven Inversion
TiO-driven Inversion
Pressure [Bars]
Temperature [K]
[TiO]⊙
20% [TiO]⊙
10% [TiO]⊙
2% [TiO]⊙
1% [TiO]⊙
0.2% [TiO]⊙
0% [TiO]⊙



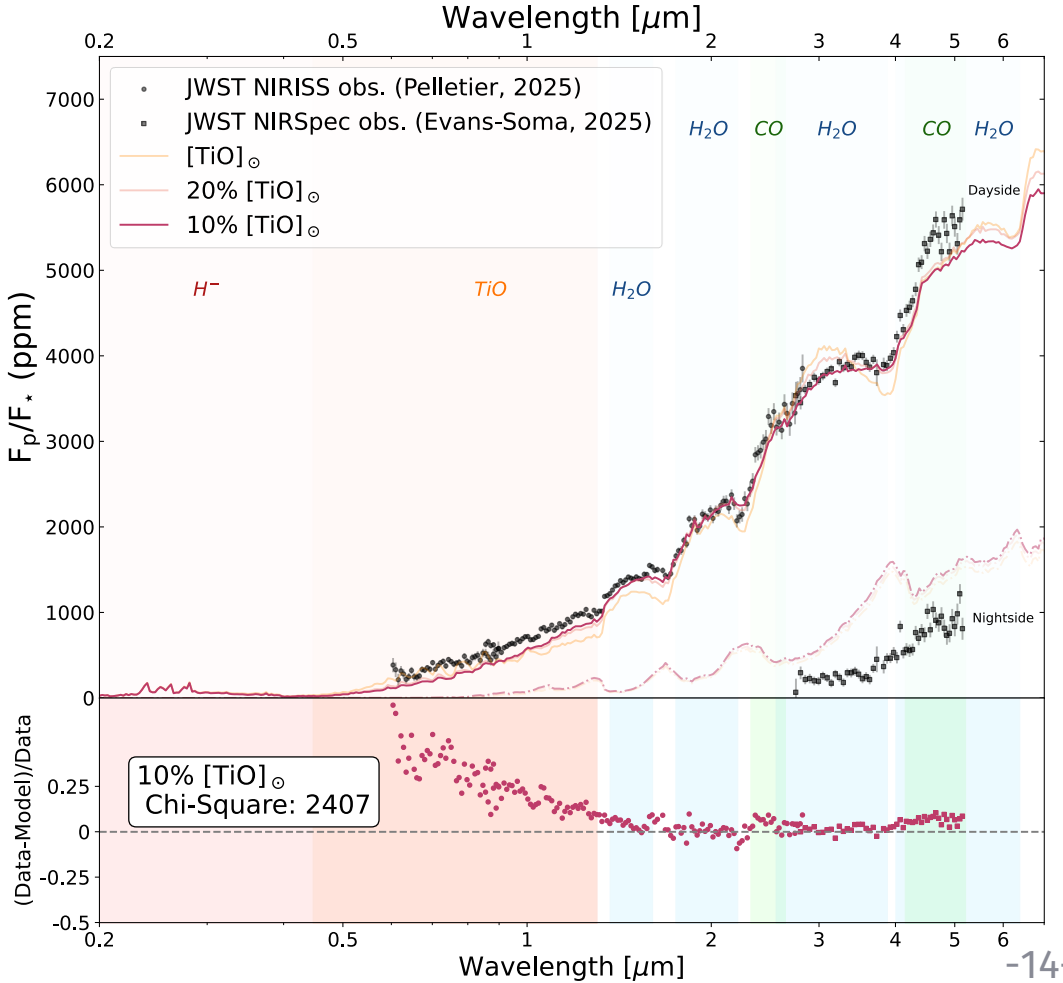
Dayside solar models confirm theoretical predictions:

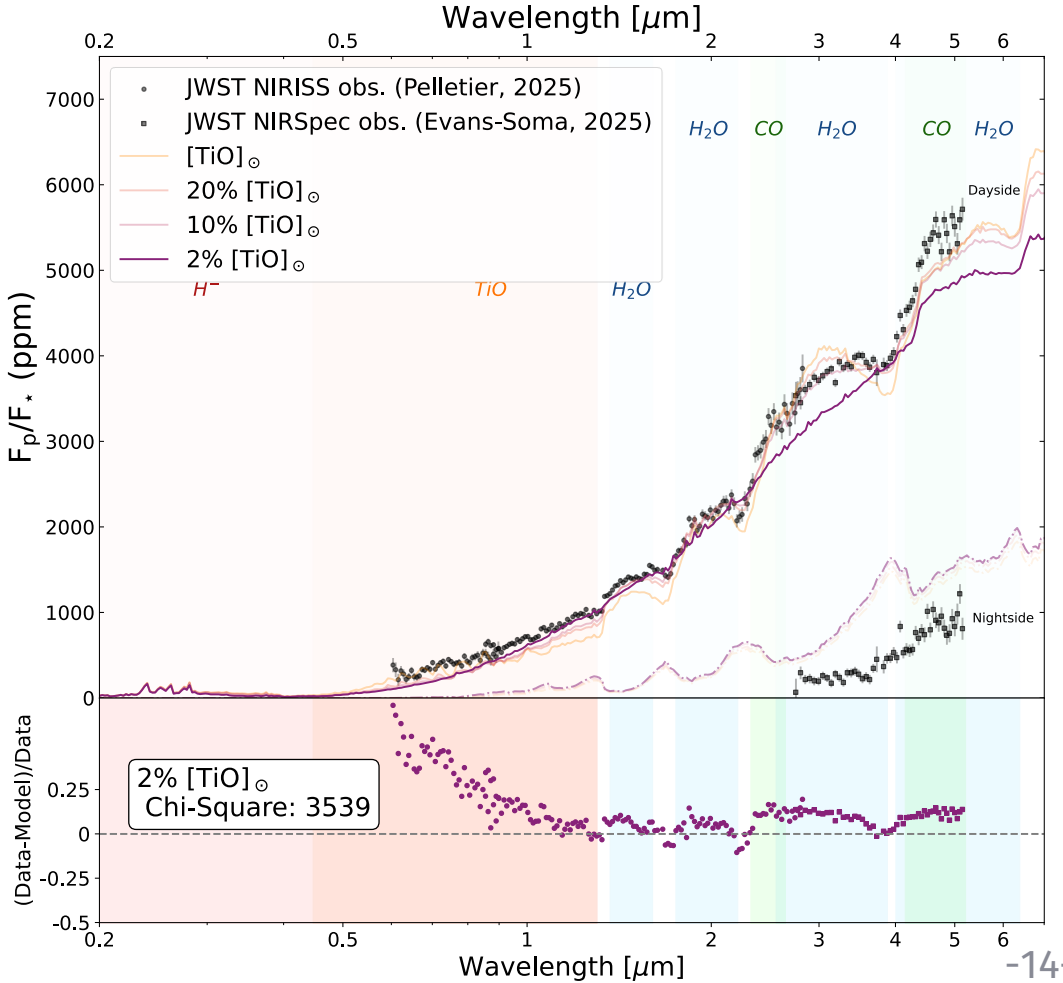
- As [TiO] decreases from equilibrium, thermal profiles get progressively non-inverted (between 1-100 mbar)
- **An inversion threshold occurs at ~3.5% $[TiO]_{eq}$**

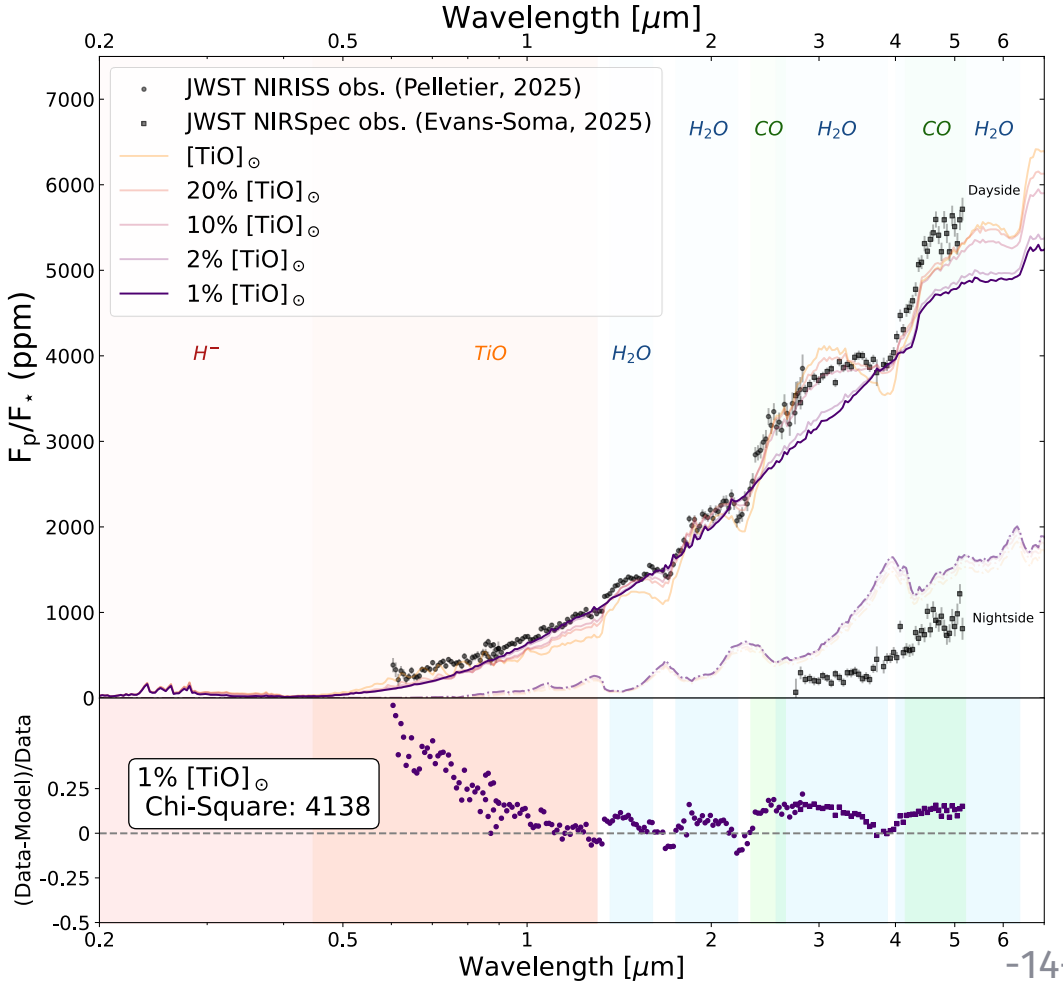

Wavelength [μm]
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]$_\odot$
H^-
TiO
H_2O
H_2O
CO
H_2O
CO
H_2O
Dayside
Nightside
F_p/F_* (ppm)
(Data-Model)/Data
[TiO]$_\odot$
Chi-Square: 6576
Wavelength [μm]

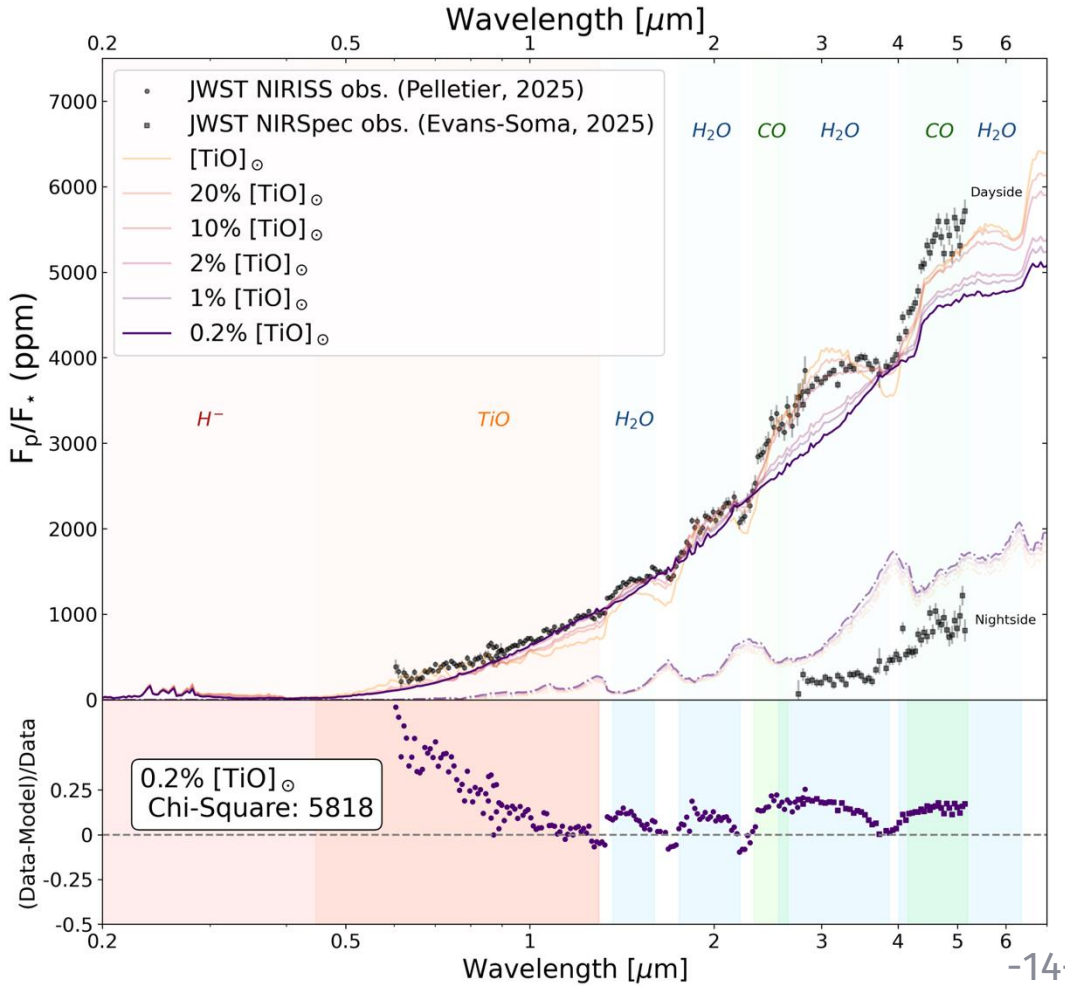

Wavelength [μm]
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]$_\odot$
20% [TiO]$_\odot$
H^-
TiO
H_2O
H_2O
CO
H_2O
CO
H_2O
Dayside
Nightside
F_p/F_* (ppm)
(Data-Model)/Data
20% [TiO]$_\odot$
Chi-Square: 2783
Wavelength [μm]

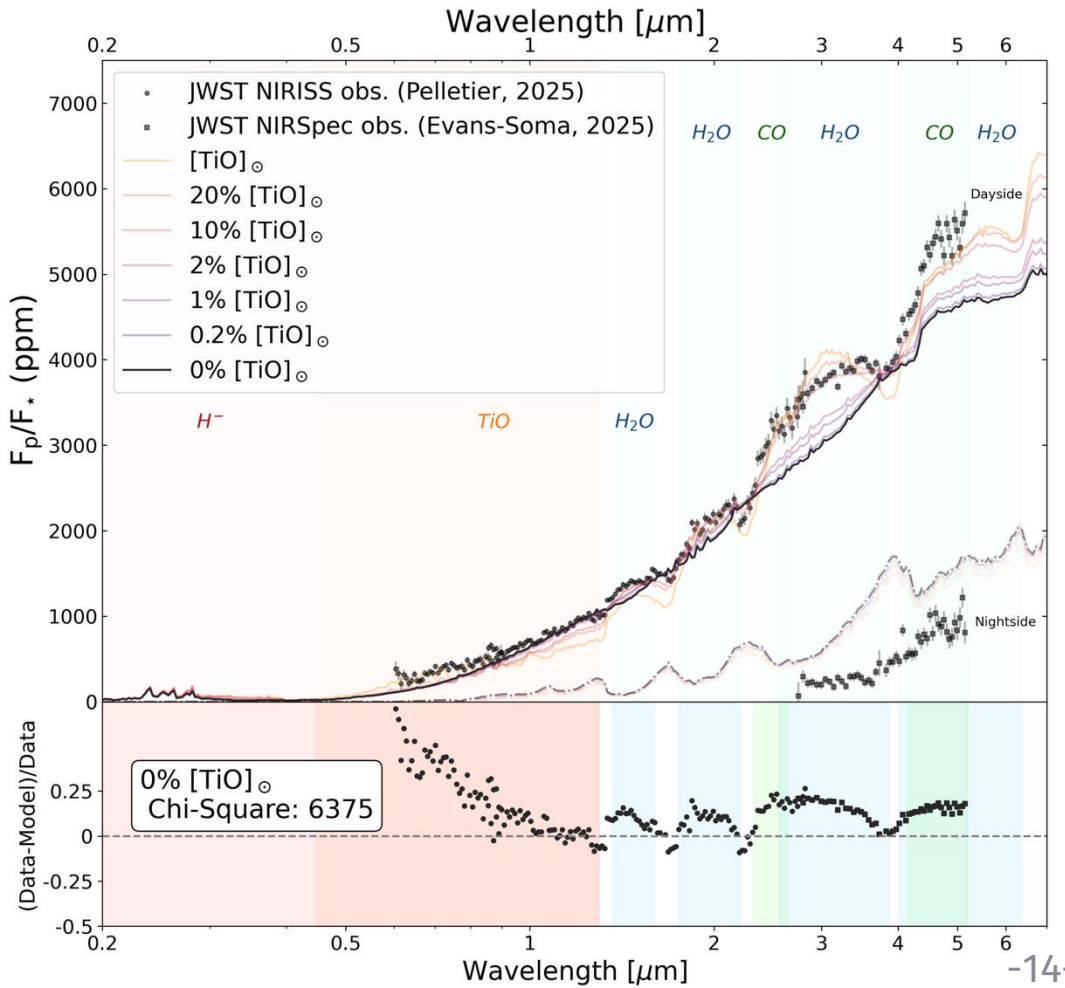
Minimum chi-square value for solar models ⇨




Wavelength [μm]
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]$_\odot$
20% [TiO]$_\odot$
10% [TiO]$_\odot$
2% [TiO]$_\odot$
H^-
TiO
H_2O
H_2O
CO
H_2O
CO
H_2O
Dayside
Nightside
F_p/F_* (ppm)
(Data-Model)/Data
2% [TiO]$_\odot$
Chi-Square: 3539
Wavelength [μm]

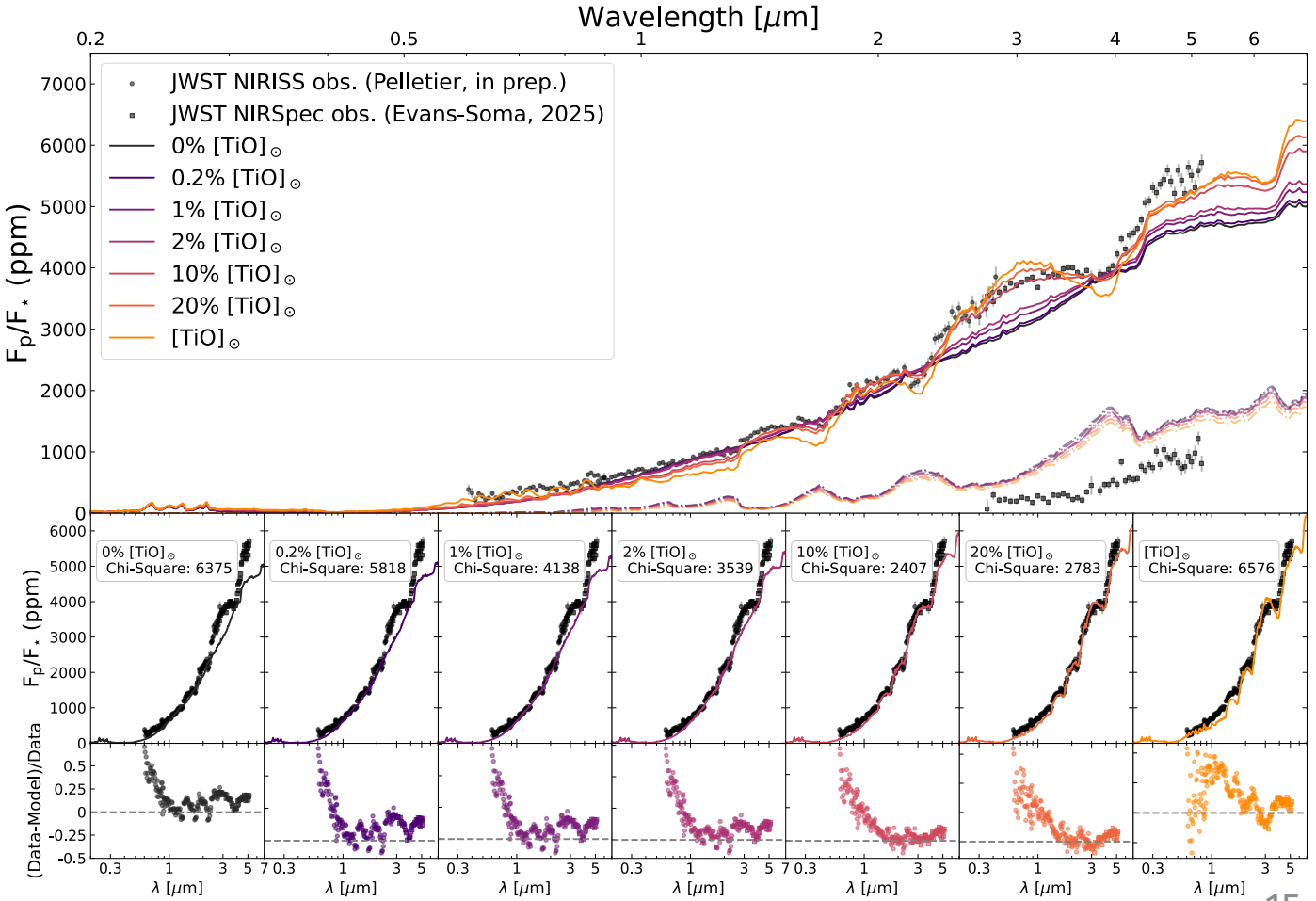

Wavelength [μm]
0.2
0.5
1
2
3
4
5
6
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]$_\odot$
20% [TiO]$_\odot$
10% [TiO]$_\odot$
2% [TiO]$_\odot$
1% [TiO]$_\odot$
H_2O
CO
H_2O
CO
H_2O
Dayside
Nightside
H^-
TiO
H_2O
$F_p/F_\star$ (ppm)
7000
6000
5000
4000
3000
2000
1000
0
(Data-Model)/Data
0.25
0
-0.25
-0.5
1% [TiO]$_\odot$
Chi-Square: 4138
Wavelength [μm]


Wavelength [μm]
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]⊙
20% [TiO]⊙
10% [TiO]⊙
2% [TiO]⊙
1% [TiO]⊙
0.2% [TiO]⊙
H⁻
TiO
H2O
H2O
CO
H2O
CO
H2O
Dayside
Nightside
Fp/F⋆ (ppm)
(Data-Model)/Data
0.2% [TiO]⊙
Chi-Square: 5818
Wavelength [μm]


Wavelength [μm]
JWST NIRISS obs. (Pelletier, 2025)
JWST NIRSpec obs. (Evans-Soma, 2025)
[TiO]⊙
20% [TiO]⊙
10% [TiO]⊙
2% [TiO]⊙
1% [TiO]⊙
0.2% [TiO]⊙
0% [TiO]⊙
H⁻
TiO
H2O
H2O
CO
H2O
CO
H2O
Dayside
Nightside
Fp/F⋆ (ppm)
(Data-Model)/Data
0% [TiO]⊙
Chi-Square: 6375
Wavelength [μm]

Solar Models:

- **Best-fit (χ^2): 10% $[TiO]_\odot$ ⇨ Partial depletion is preferred**
- Possible short-λ correction: increase H- and/or VO opacity
- Between H2O bands correction: maybe cloud opacity (?)



We present a suite of 3D GCMs studying TiO/VO depletion effects in WASP-121b:

- TiO/VO depletion turns thermal profiles non-inverted, with transition at 3% $[TiO]_{eq}$ for solar equilibrium chemistry
- **TiO partial depletion is preferred for all chemical equilibria** (VO depletion a secondary factor)
- Metallicity and C/O equilibrium alter substantially the [TiO]-inversion strength relation ⇨ Highly depleted supersolar case favored

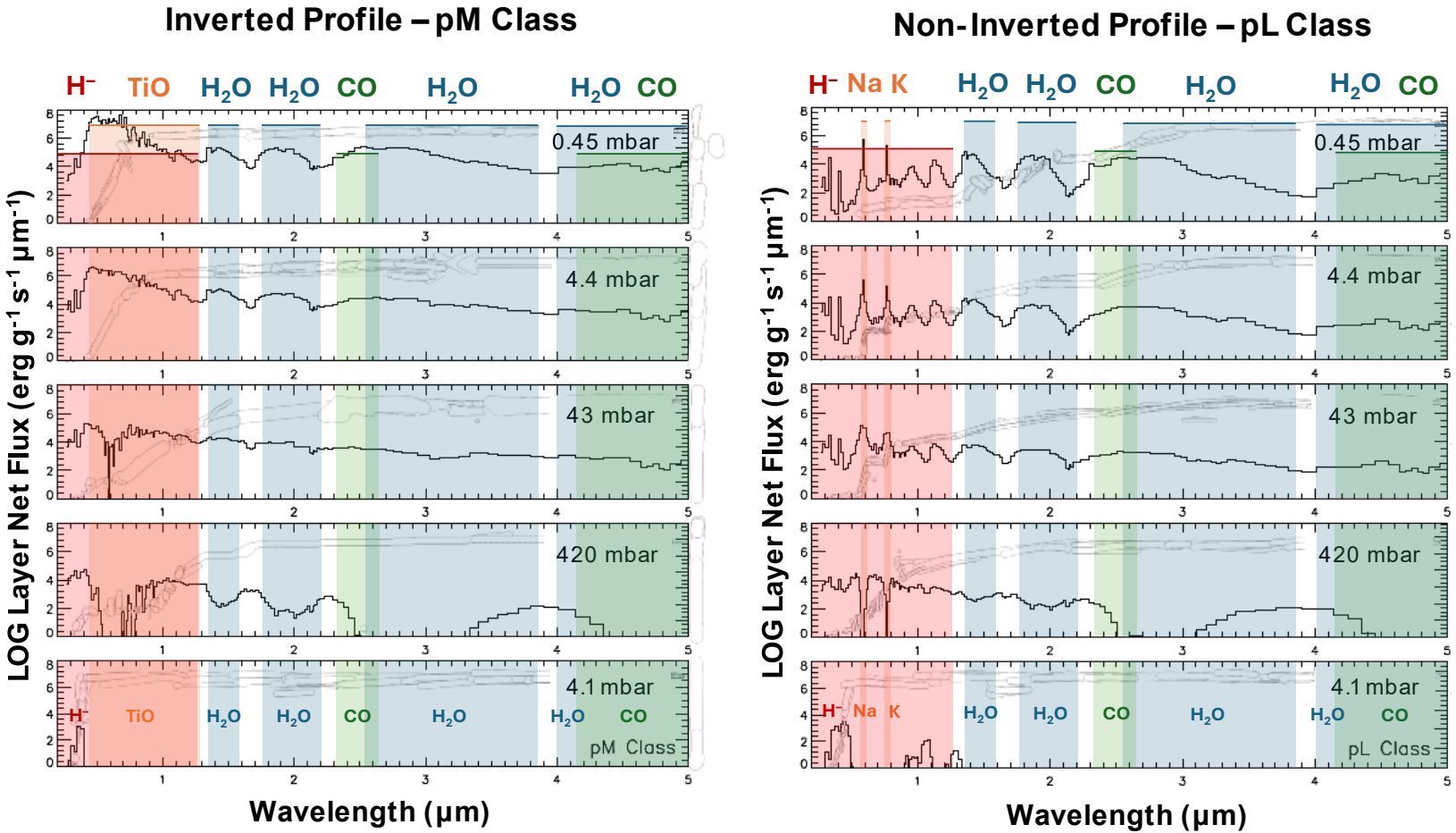
Future work:

- Active dynamic modeling of [TiO] abundances through tracers
- Further exploration of metallicity and C/O parameter space
- Modeling of clouds!

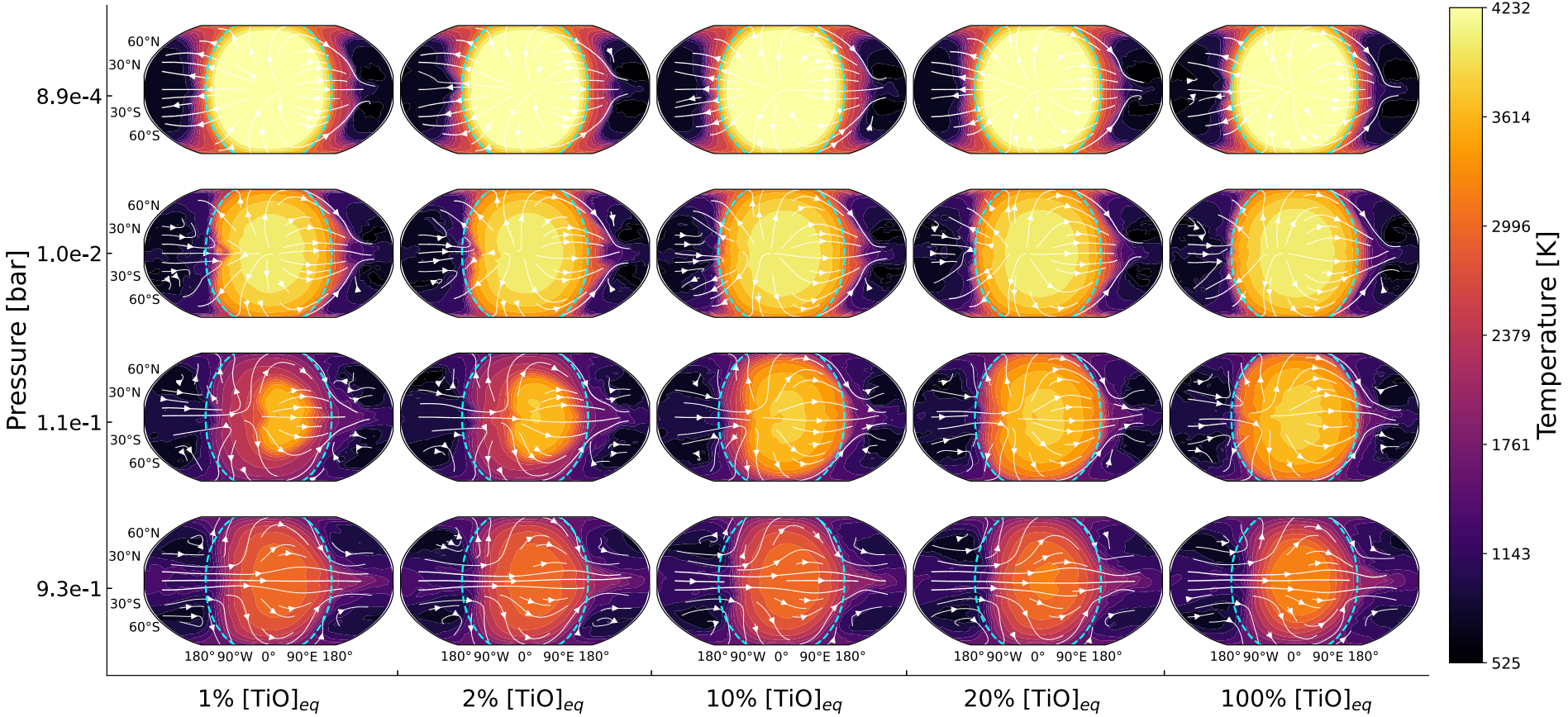
Thank you for your attention!
Any questions?

This work was carried out in partial fulfillment of the requirements for the degree Master Physique Fondamental et Applications, parcours MASS, as part of a multiple degree awarded in the framework of the Erasmus Mundus Joint Master in Astrophysics and Space Science -- MASS jointly delivered by a Consortium of four Universities: Tor Vergata University of Rome, University of Belgrade, University of Bremen, and Université Cote d'Azur, regulated by the MASS Consortium Agreement and Co-funded by the EU under the call ERASMUS-EDU-2021-PEX-EMJM-MOB.

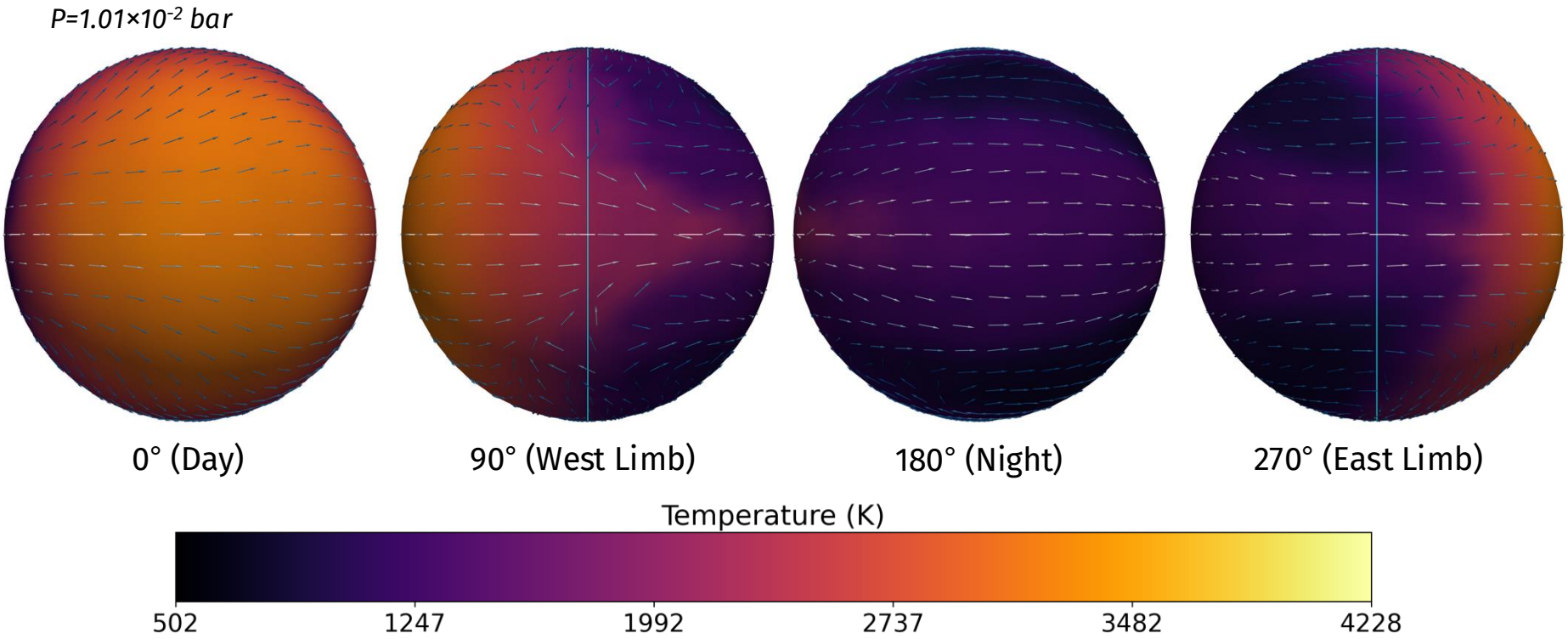
BONUS: Fortney Absorption Spectra



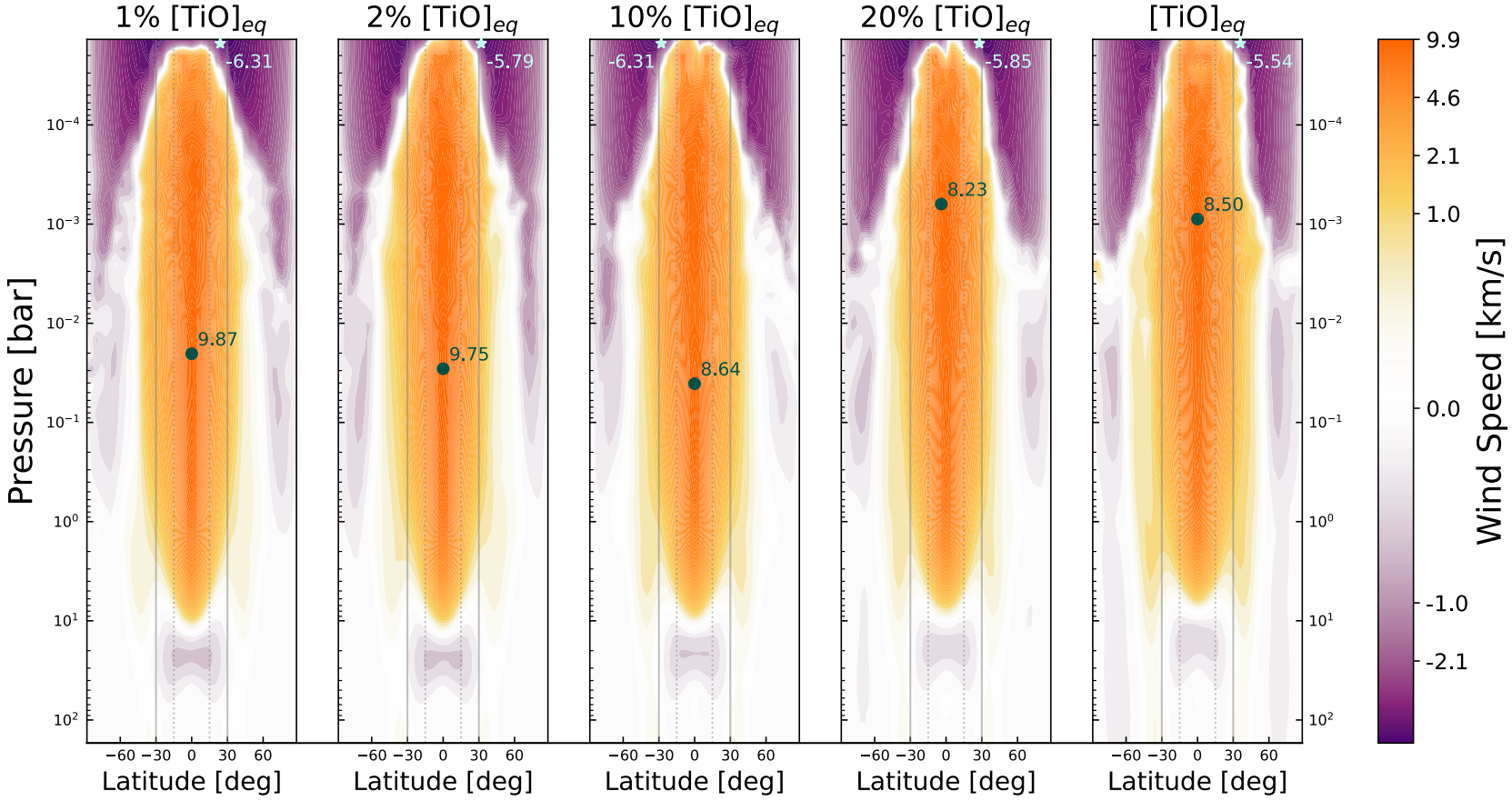
BONUS: Solar T-Maps



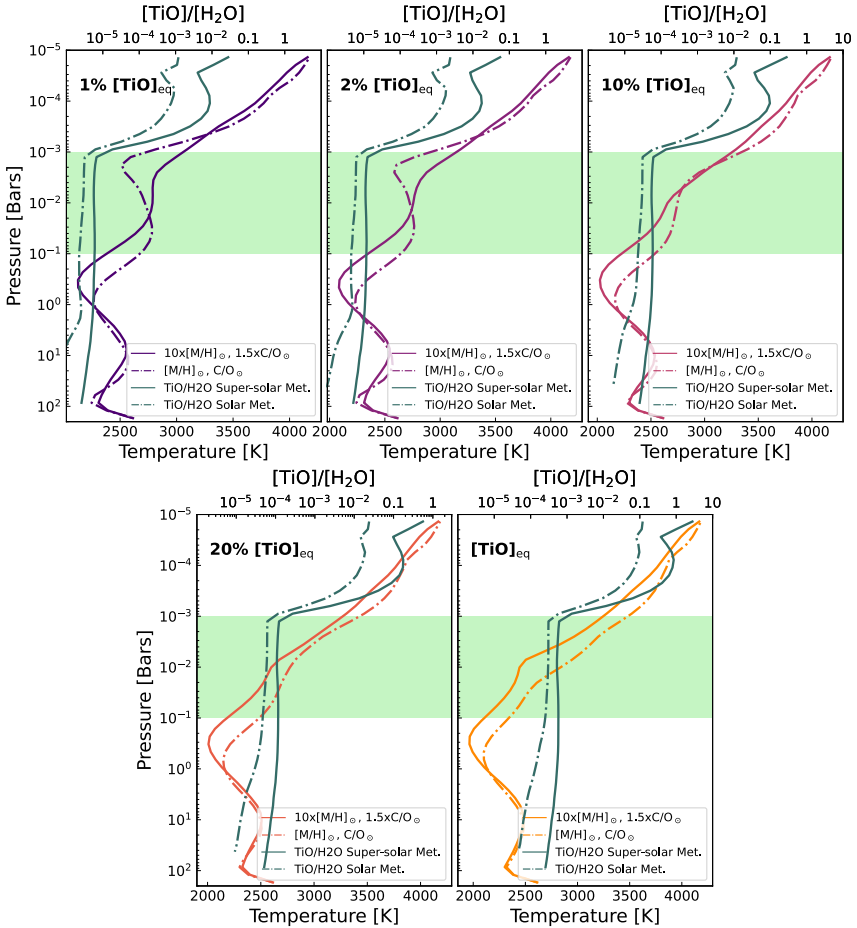
BONUS: 3D Projected layer



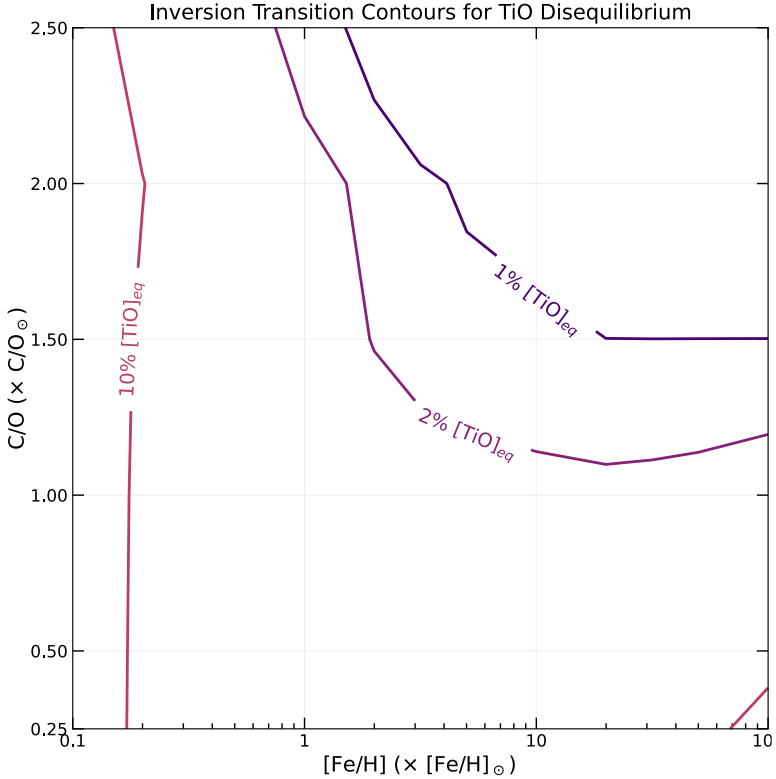
BONUS: Solar Mean Zonal Winds

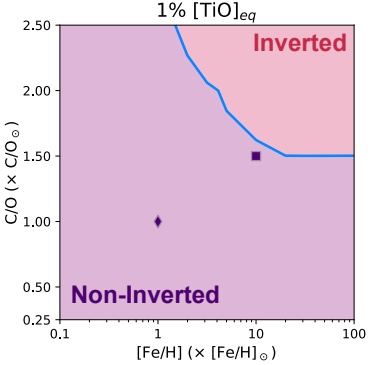


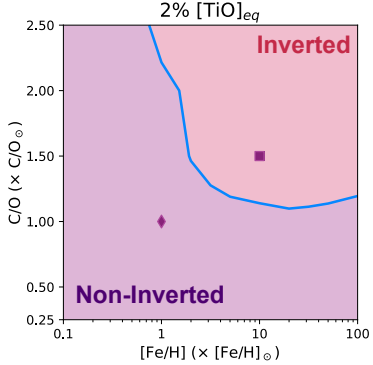
BONUS: TiO/H2O Metric (1)

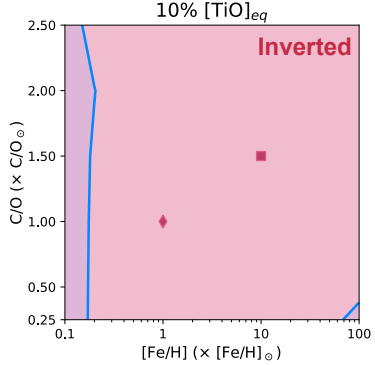


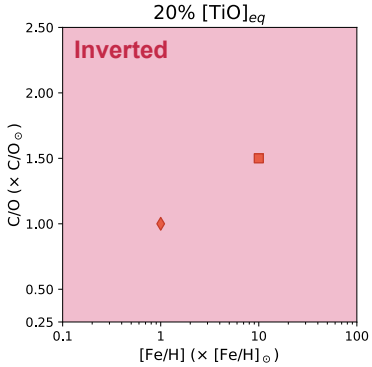
BONUS: TiO/H2O Metric (2)

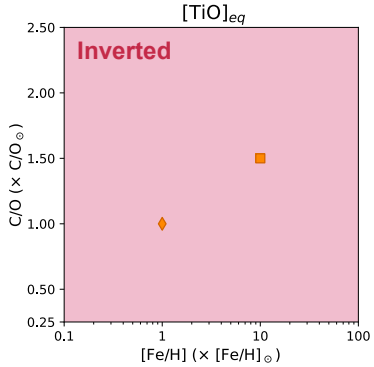












BONUS: Water Feature Strength