SF2A 2026

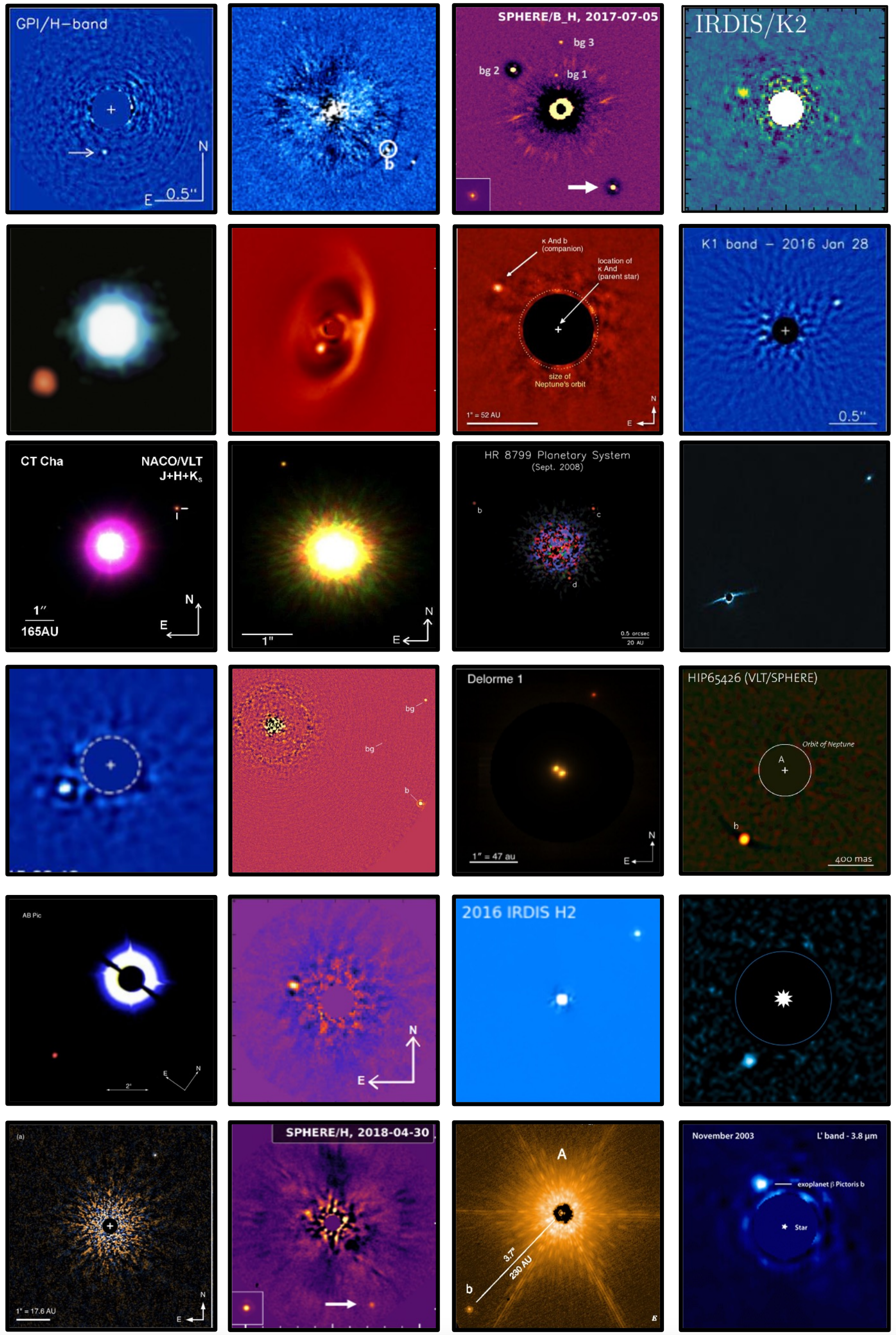
Image: ESA/WEBB

OPTEX

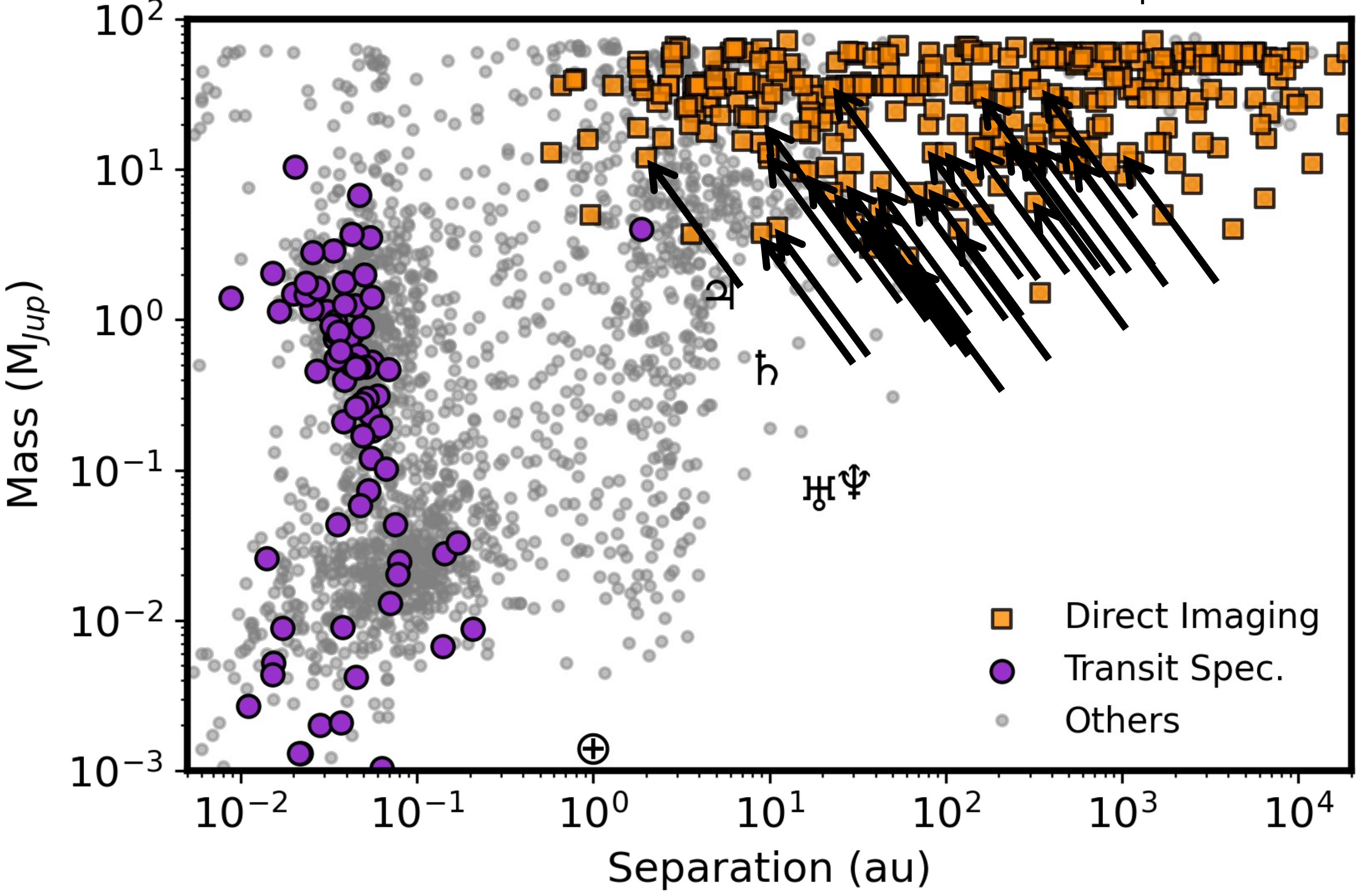
Atmospheric retrievals with optimal estimation

Paulina Palma-Bifani, Benjamin Charnay, Jeremy Leconte, Alice Radcliffe, Bruno Bezard, et al.

LIRA Observatoire de Paris | PSL

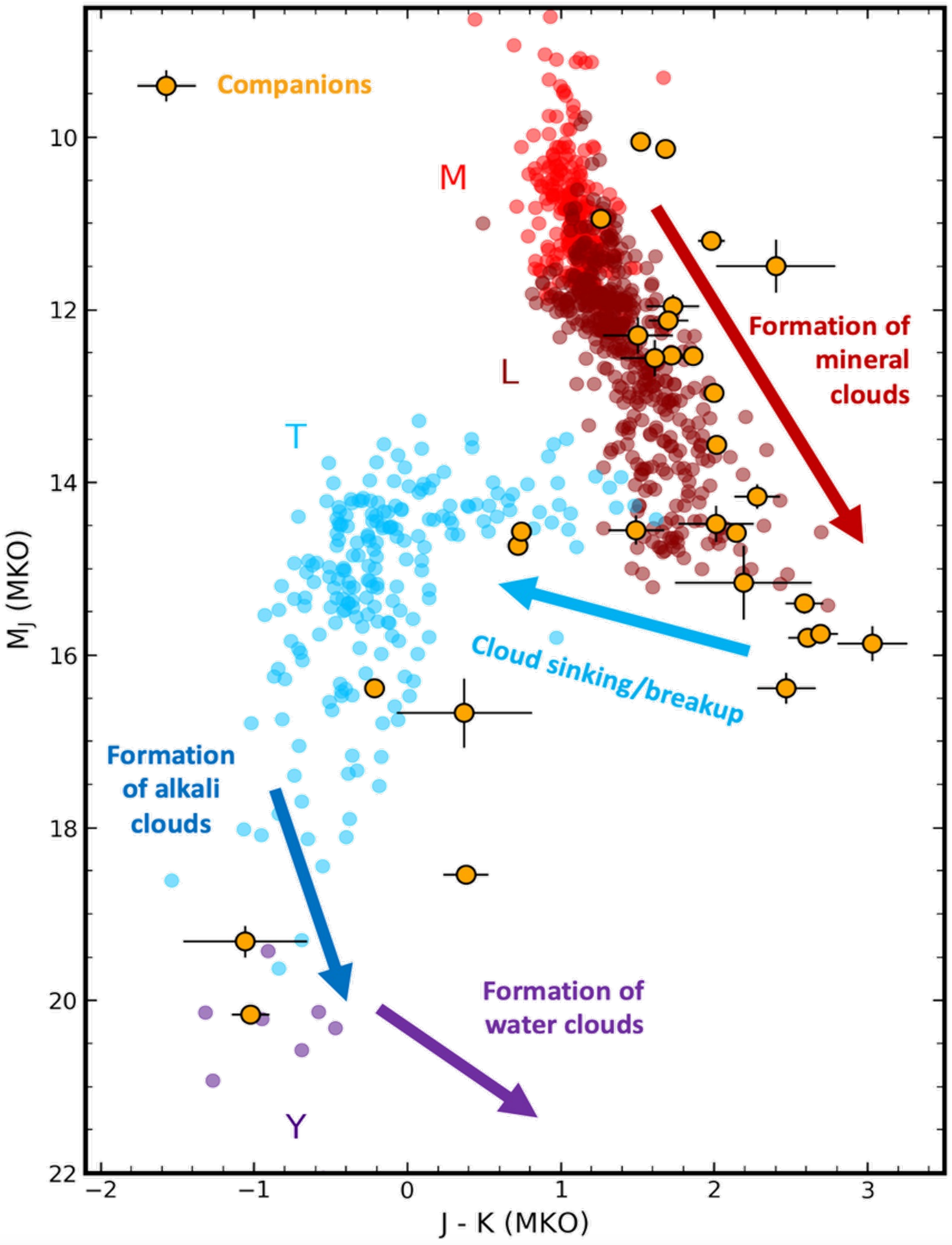


Credit: Data from exoplanets.eu

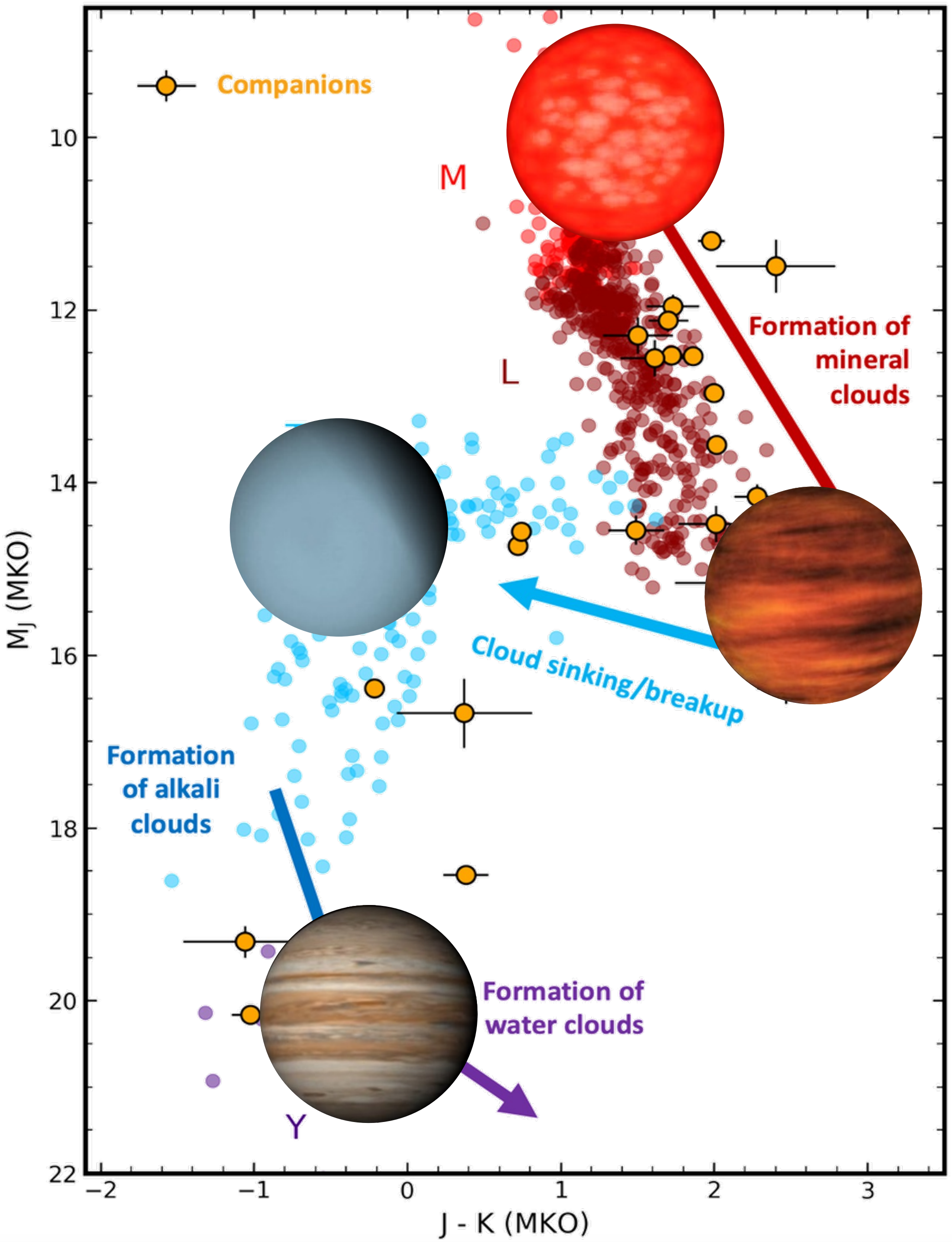


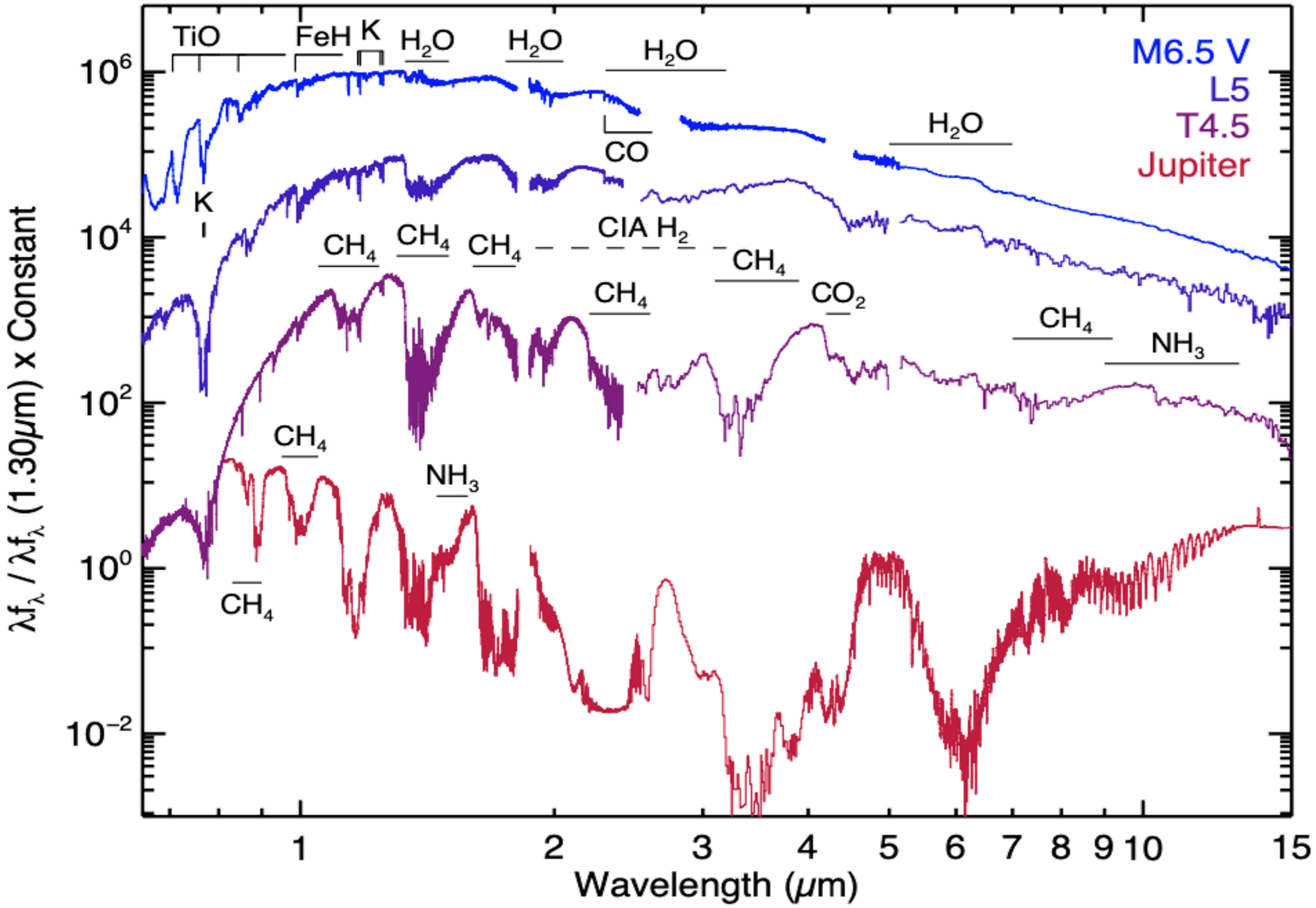
Chauvin et al. (2004, 2005, 2017),
Lafrenière et al. (2008),
Marois et al. (2008, 2010),
Lagrange et al. (2019),
Nowak et al. (2019),
Rameau et al. (2013),
Kurzawa et al. (2013),
Delorme et al. (2012),
Bailey et al. (2012),
Macintosh et al. (2015),
Keppler et al. (2018),
Cheetham et al. (2018),
Milli et al. (2017),
Wagner et al. (2021),
Squicciarini et al. (2022),
Janson et al. (2019, 2021),
Bohn et al. (2020, 2021a, 2021b),
de Rosa et al. (2023)

Credit: Gao et al. (2021)



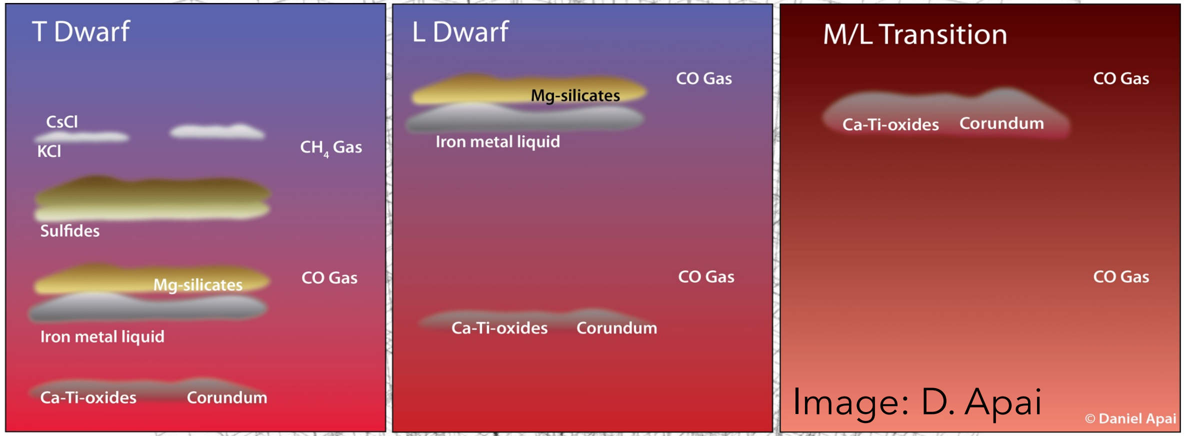
Credit: Gao et al. (2021)





Credit: J. Fortney (2018)

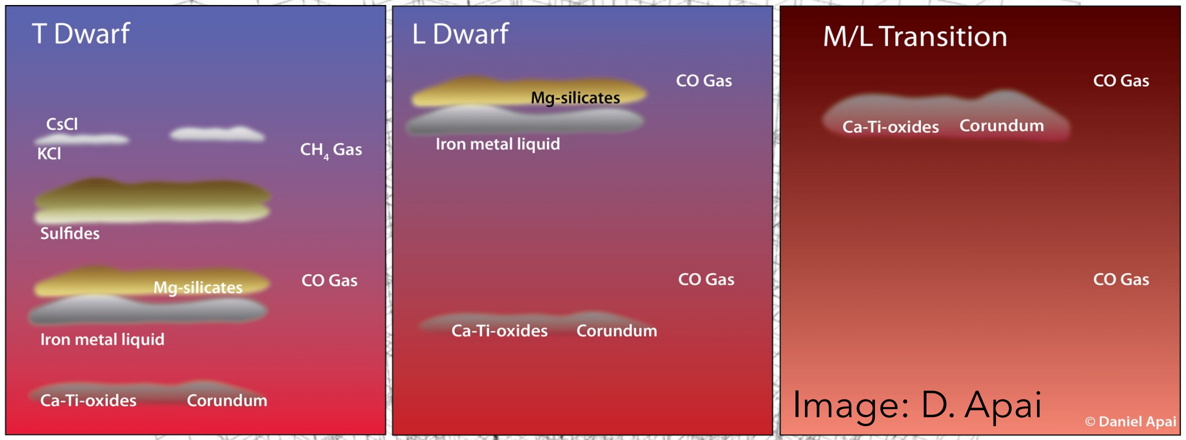
Atmospheric parametrizations of self consistent models:



Temperature
Surface gravity
Metallicity ([M/H])
Abundances (X_A/X_B)
Clouds, …

Grids: Exo-REM, Sonora, BT-Settl, ATMO, …

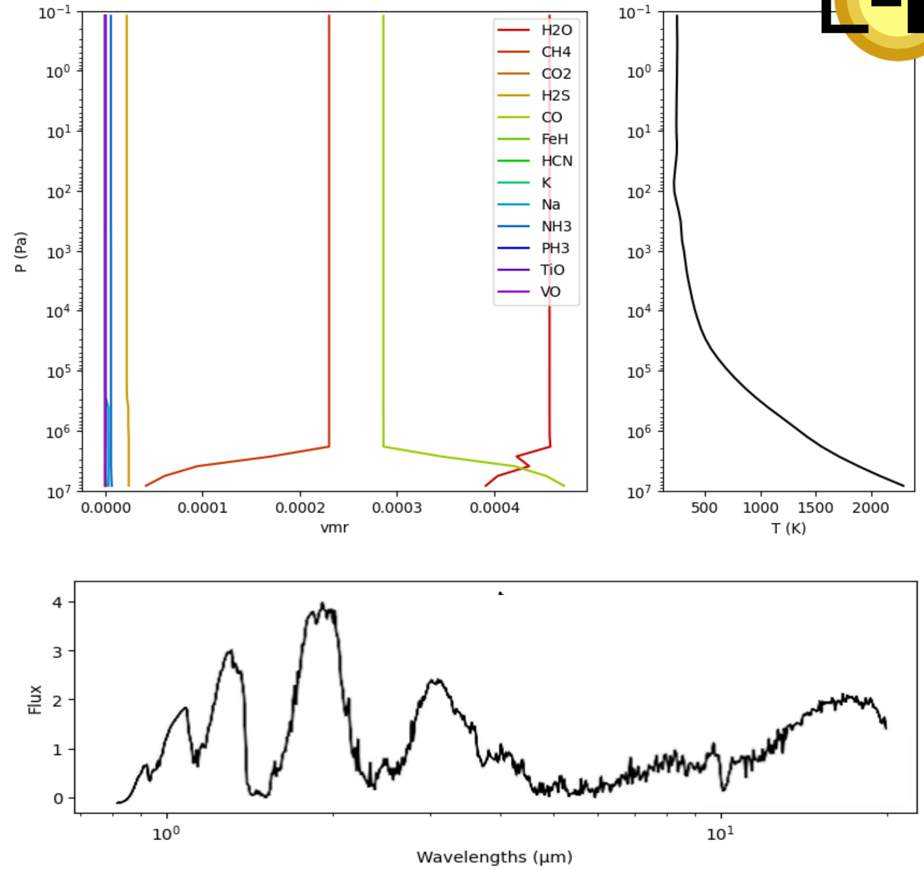
Atmospheric parametrizations of self consistent models:



Temperature
Surface gravity
Metallicity ([M/H])
Abundances (X_A/X_B)
Clouds, …

Exo-REM k26

(Radcliffe et al. 2026)



Grids: Exo-REM, Sonora, BT-Settl, ATMO, …

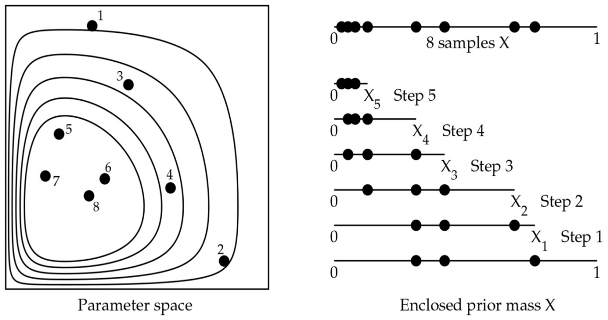
How to use these models to analyze observations?

$$Bayesian\ framework$$

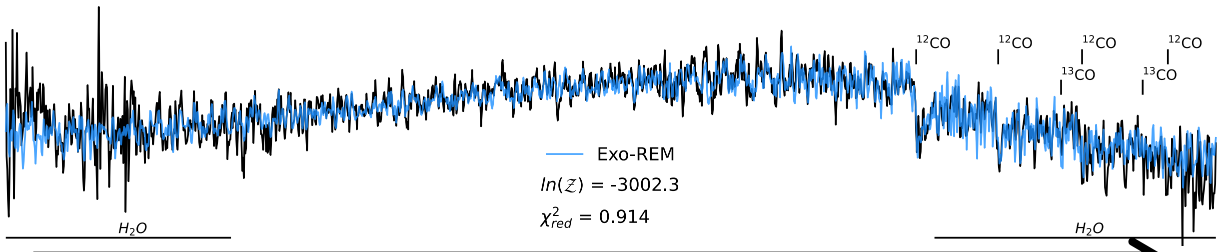
$$P(y|x)P(x) = P(x|y)P(y)$$

Forward modeling with ForMoSA:

Nested Sampling:



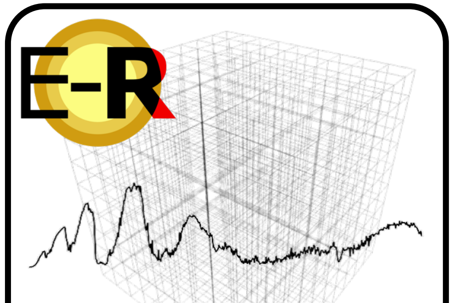
Exo-REM model of β Pic b VLTI/GRAVITY+ observations
Ravet et al. (2025)



Free parameters include:

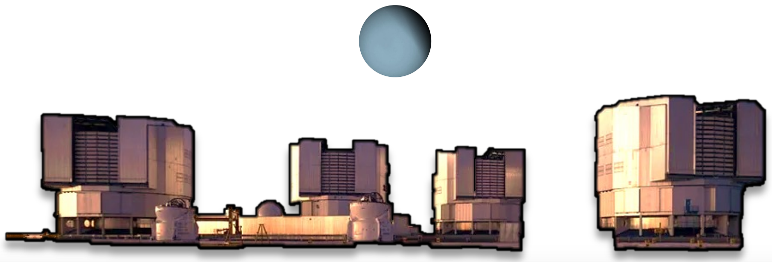
$T_{eff}, \log(g), [^M/_H], {^C/_O}, f_{sed}, R, d, RV, vsin(i), \ldots$

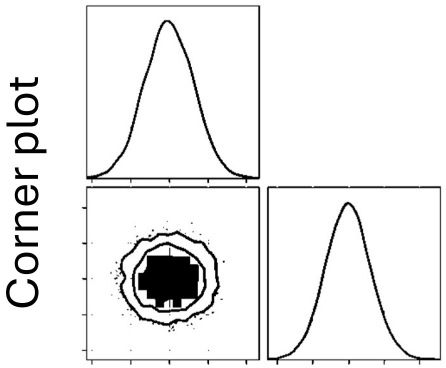
Self-consistent atmospheric model:

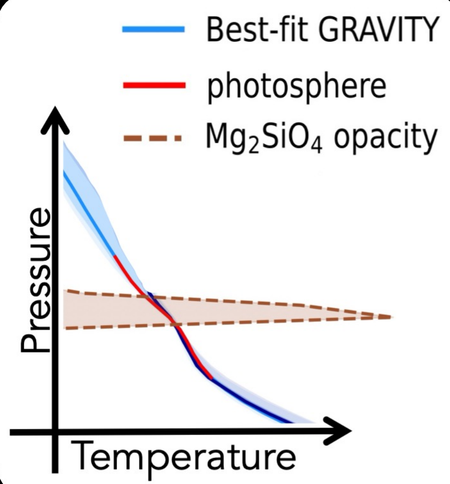


Exo-REM
(Charnay et al. 2018)

Observation:
β Pic b with VLTI/GRAVITY+







Forward modeling with ForMoSA:

- **Robust framework:** Grids based on self-consistent models
- **Statistical flexibility:** Multi-metric likelihoods tailored to the dataset
- **Comprehensive parameters:** Grid properties, d, R, vsin(i), RV, scaling, and CPDs
- **Wide exploration:** Efficient global mapping across extensive parameter ranges

W1935

Exo-REM k26
(Radcliffe et al. 2026)

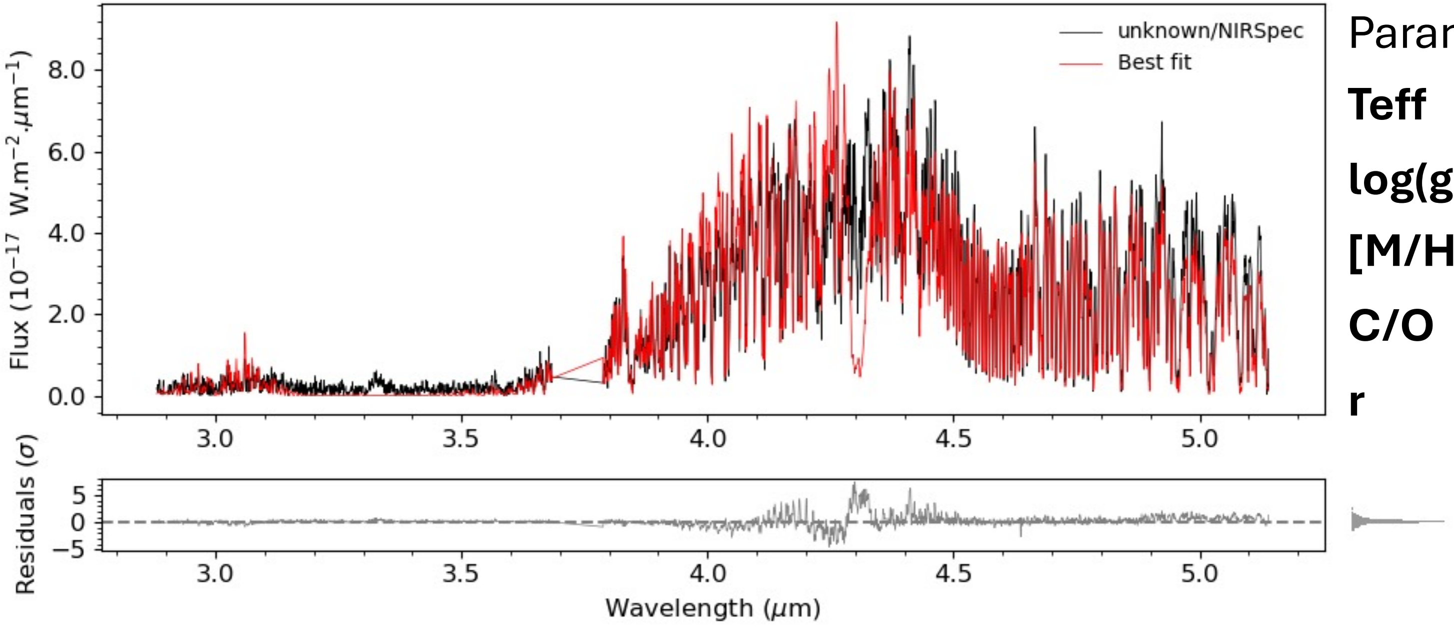
+

W1935

Faherty et al. 2024

Exo-REM k26
(Radcliffe et al. 2026)

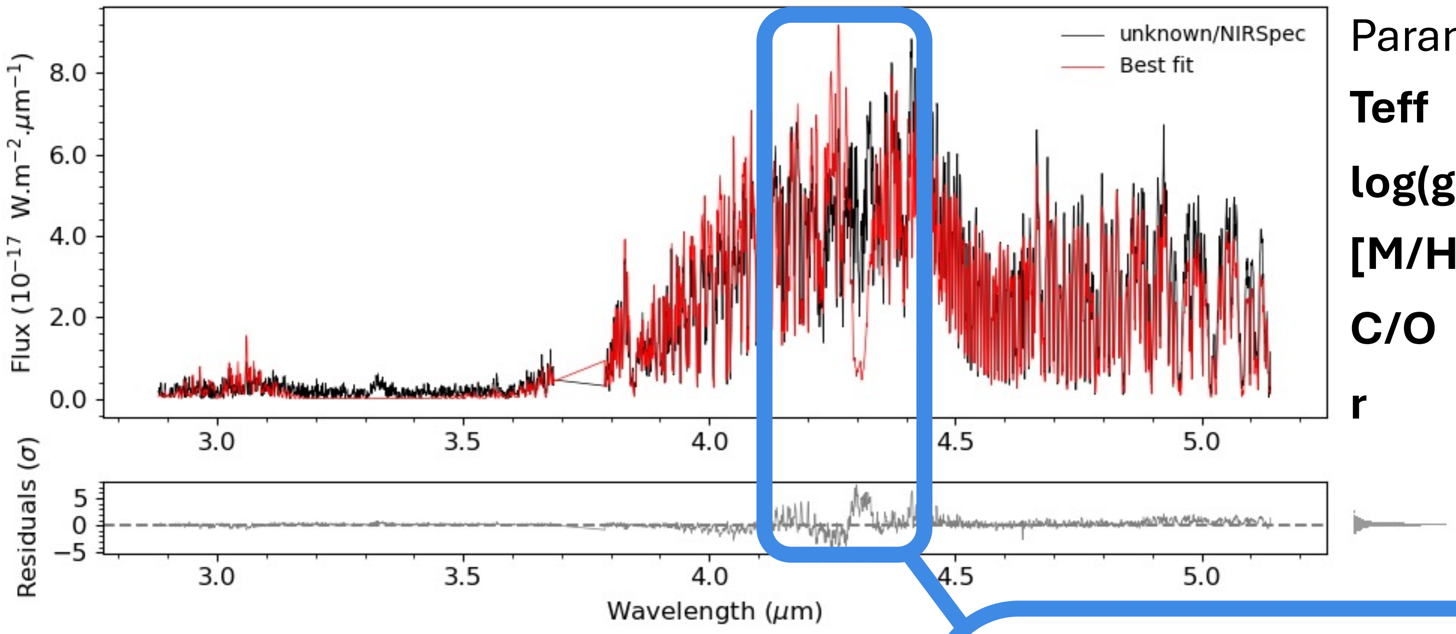
+



Parameters ± 1σ

Teff	= 407.6 ± 0.7
log(g)	= 4.60 ± 0.01
[M/H]	= -0.33 ± 0.01
C/O	= 0.8 ± 0.0003
r	= 1.37 ± 0.01

W1935



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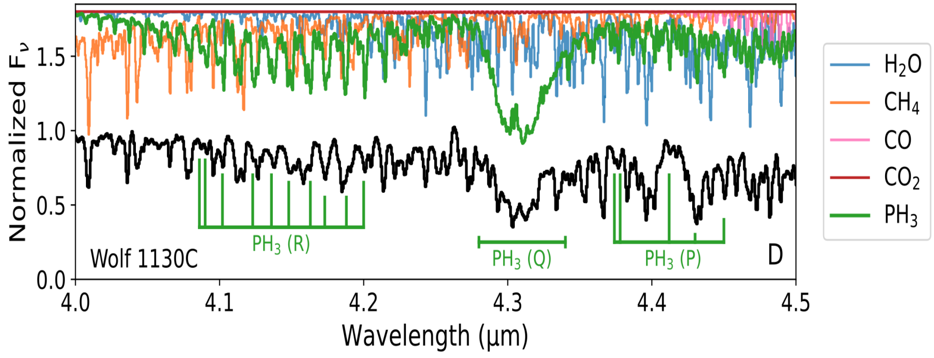
Exo-REM k26
(Radcliffe et al. 2026)

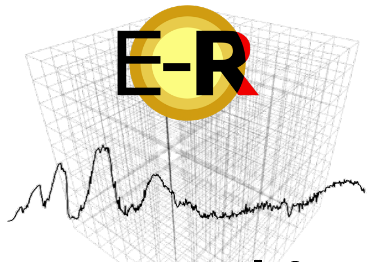
+

Excess of PH3 in the model



Burgasser et al. 2025

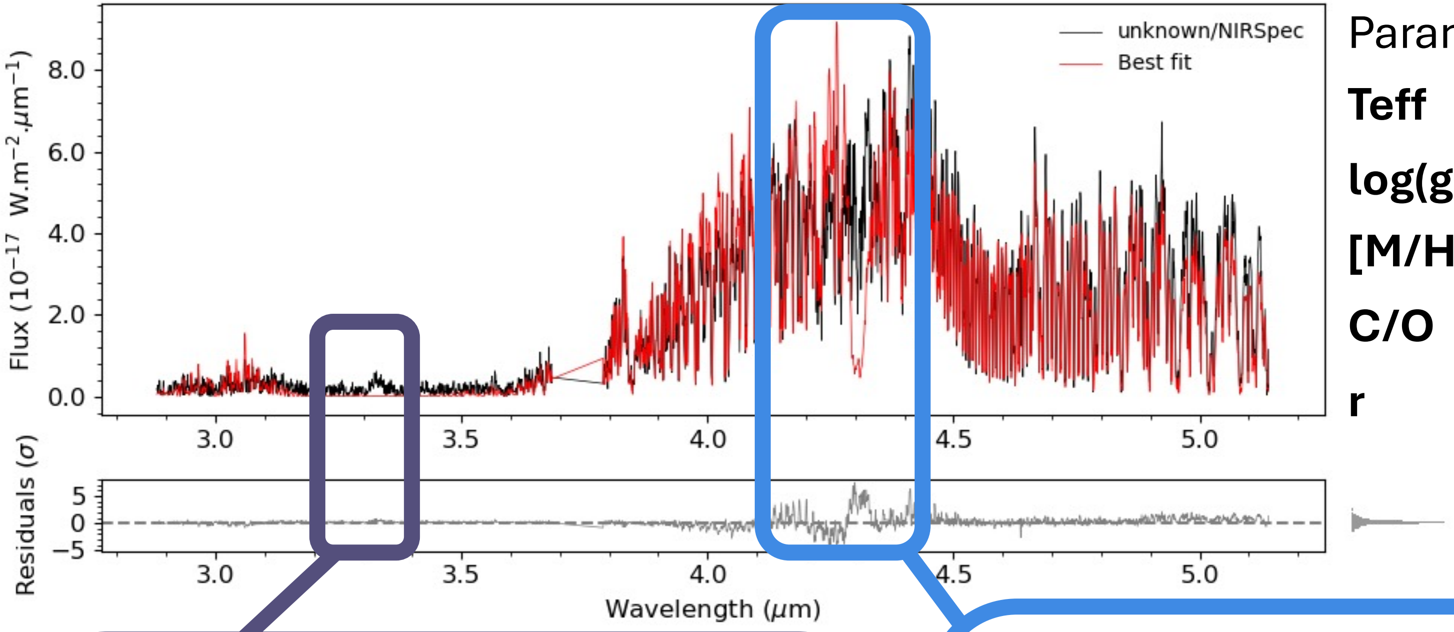
W1935



(Radcliffe et al. 2026)

+

ForMoSA



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Teff = 407.6 ± 0.7

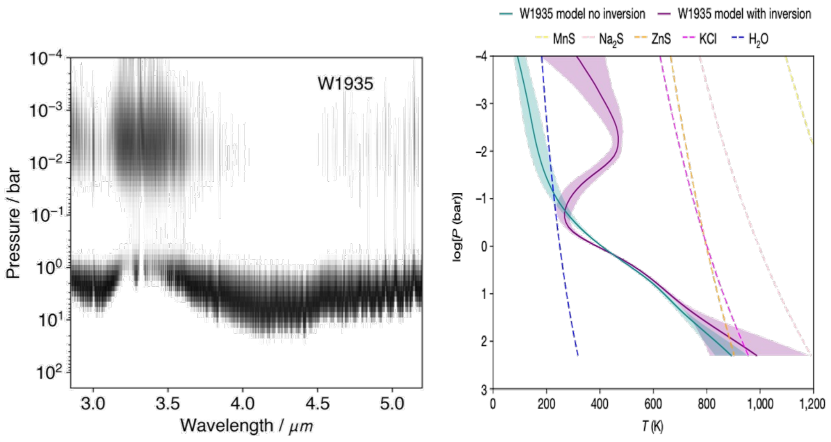
log(g) = 4.60 ± 0.01

[M/H] = -0.33 ± 0.01

C/O = 0.8 ± 0.0003

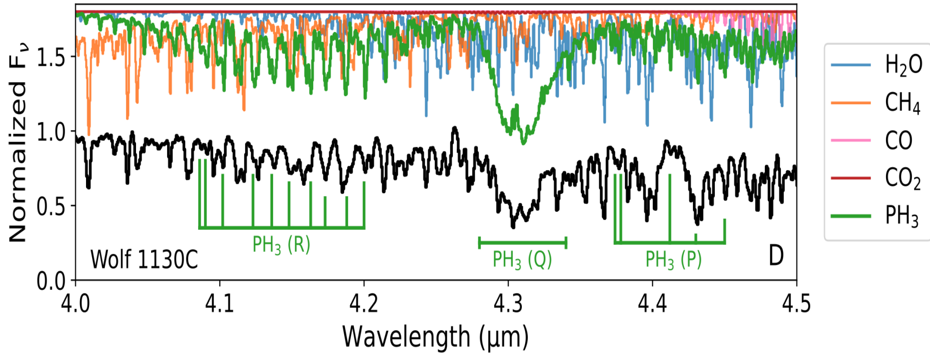
r = 1.37 ± 0.01

Missing a thermal inversion



Faherty et al. 2024

Excess of PH3 in the model



Burgasser et al. 2025

Forward modeling with ForMoSA:

- **Robust framework:** Grids based on self-consistent models
- **Statistical flexibility:** Multi-metric likelihoods tailored to the dataset
- **Comprehensive parameters:** Grid properties, d, R, vsin(i), RV, scaling, and CPDs
- **Wide exploration:** Efficient global mapping across extensive parameter ranges

- **Rigid chemistry:** Tied to pre-computed grids (inflexible)
- **Limited dynamics:** Cannot model complex/localized physics (e.g., aurora-induced thermal inversions)

Retrievals with optimal estimation:

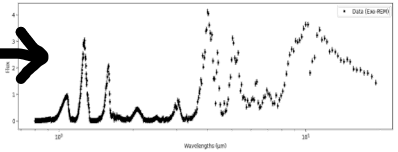
$$\widehat{x_k} = x_a + G(y - F(x_a))$$

"A classical Earth and solar system method,
~100× faster than nested sampling free retrievals."

Based on Rodgers (2000)

Retrievals with optimal estimation:

$$\widehat{x_k} = x_a + G(y - F(x_a))$$

$y \rightarrow$ 

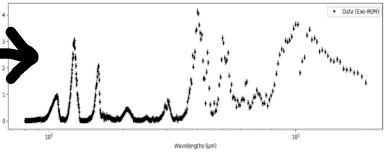
$$x_k \longrightarrow \begin{bmatrix} T_1 \\ T_2 \\ \dots \\ T_{15} \\ \log(g) \\ H_2O \\ CH_4 \\ CO \\ \dots \end{bmatrix}_k$$

$F(x_k) \rightarrow$ Exo.K

Leconte 2021

Retrievals with optimal estimation:

$$\widehat{x_k} = x_a + G(y - F(x_a))$$

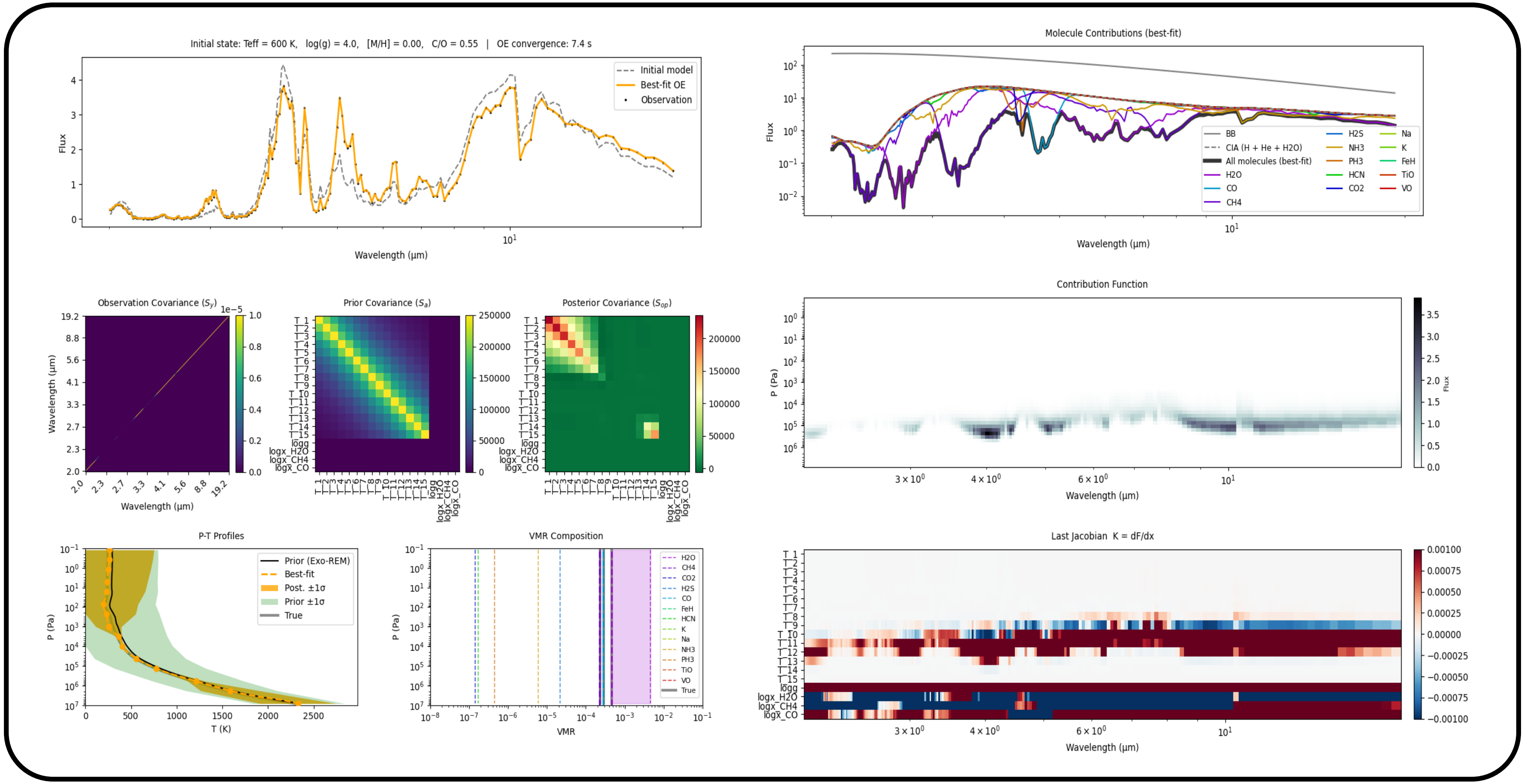
$y \rightarrow$ 

$$x_k \rightarrow \begin{pmatrix} T_1 \\ T_2 \\ \dots \\ T_{15} \\ \log(g) \\ H_2O \\ CH_4 \\ CO \\ \dots \end{pmatrix}_k$$

$F(x_k) \rightarrow$ Exo.K

Leconte 2021

Validation demo results:



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Preliminary results :

Retrieving a thermal inversion …

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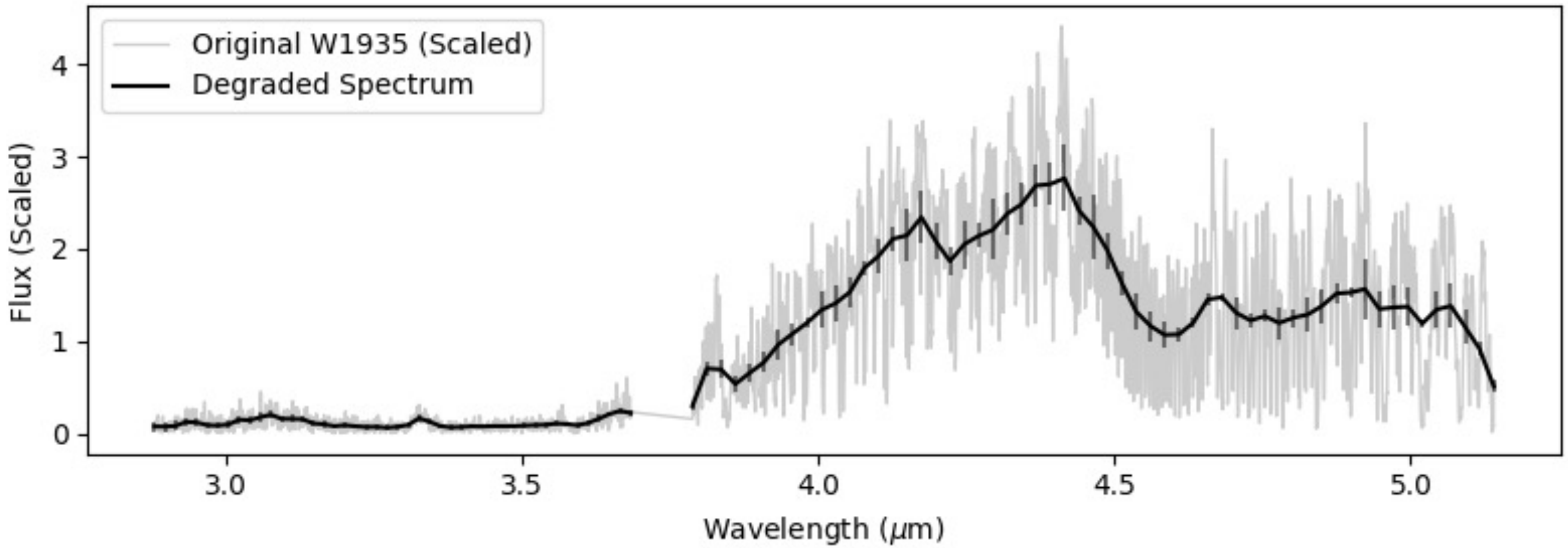
Preliminary results :

Retrieving a thermal inversion …



PTEX

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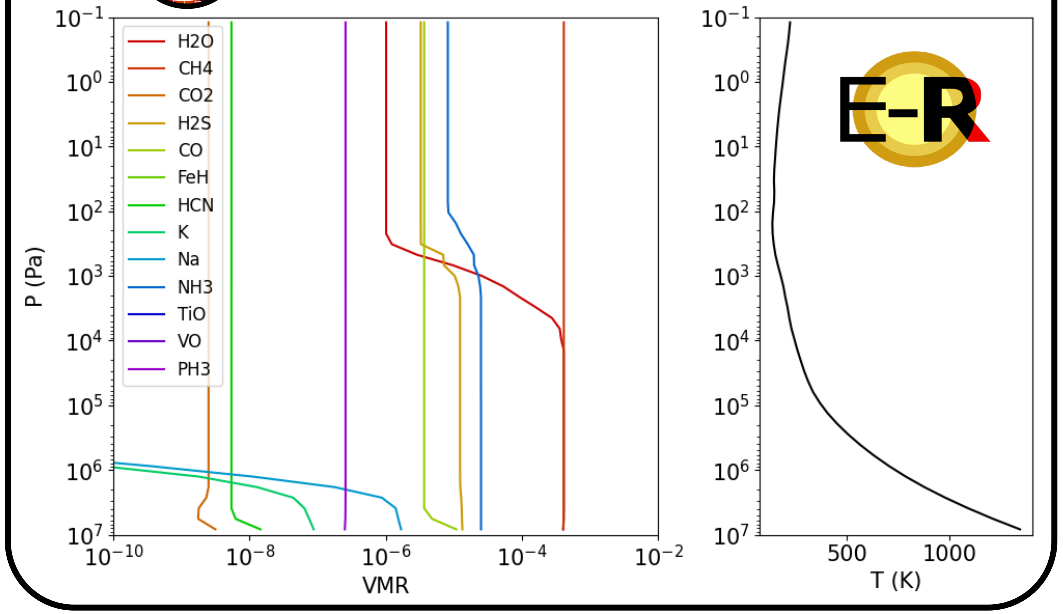
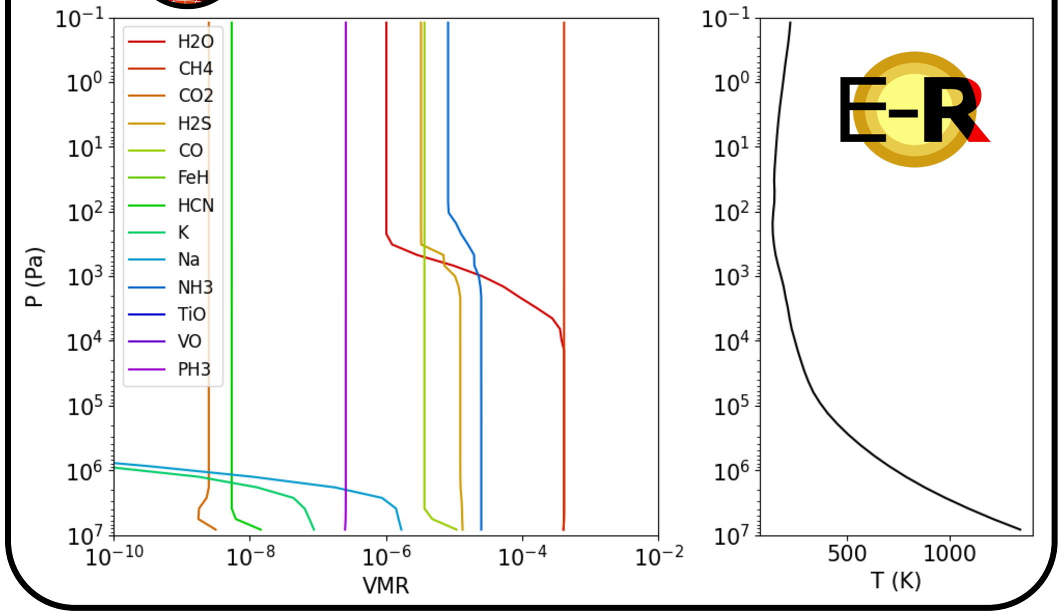
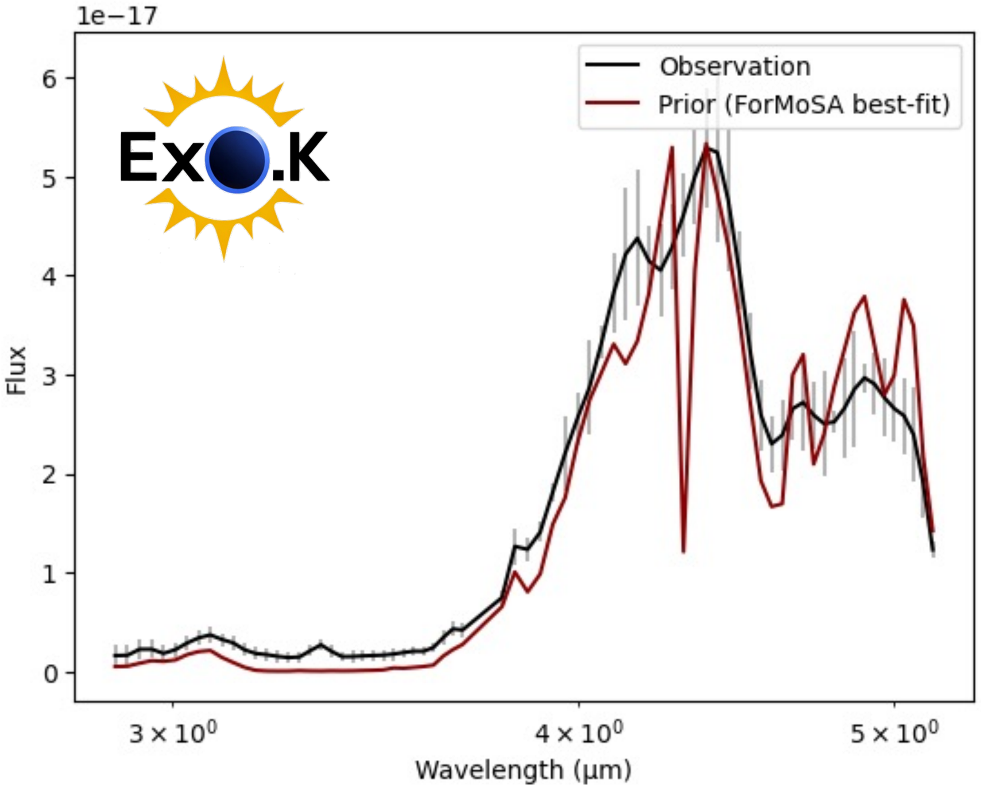
Best fit state retrieved as prior:



OPTEX W1935

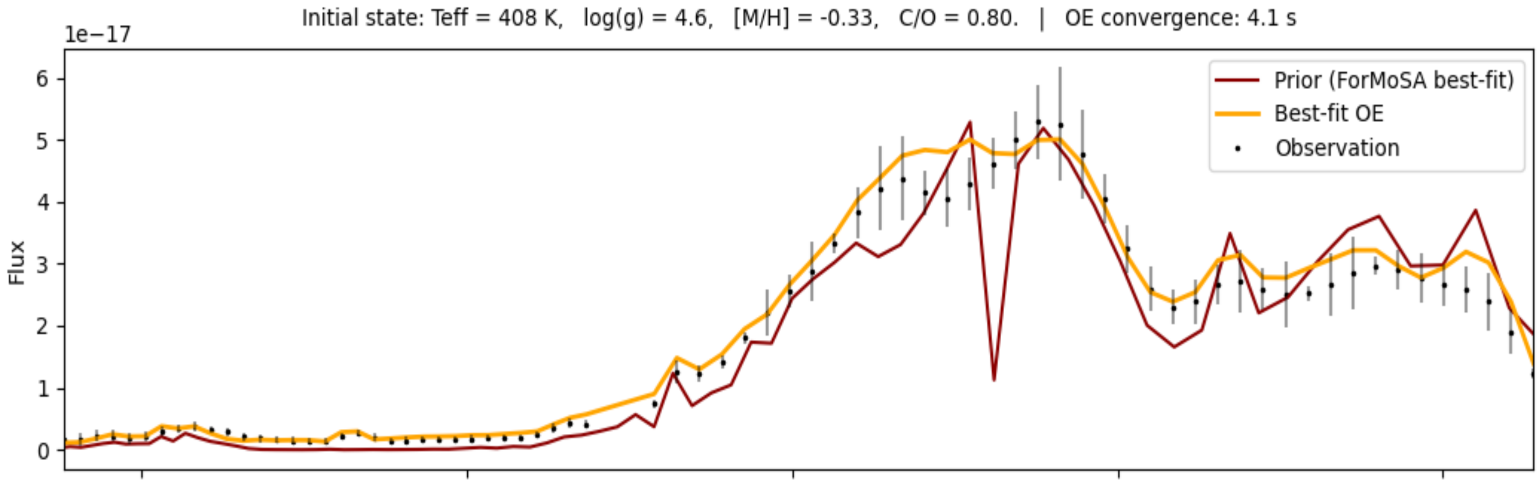
Best fit state retrieved as prior:





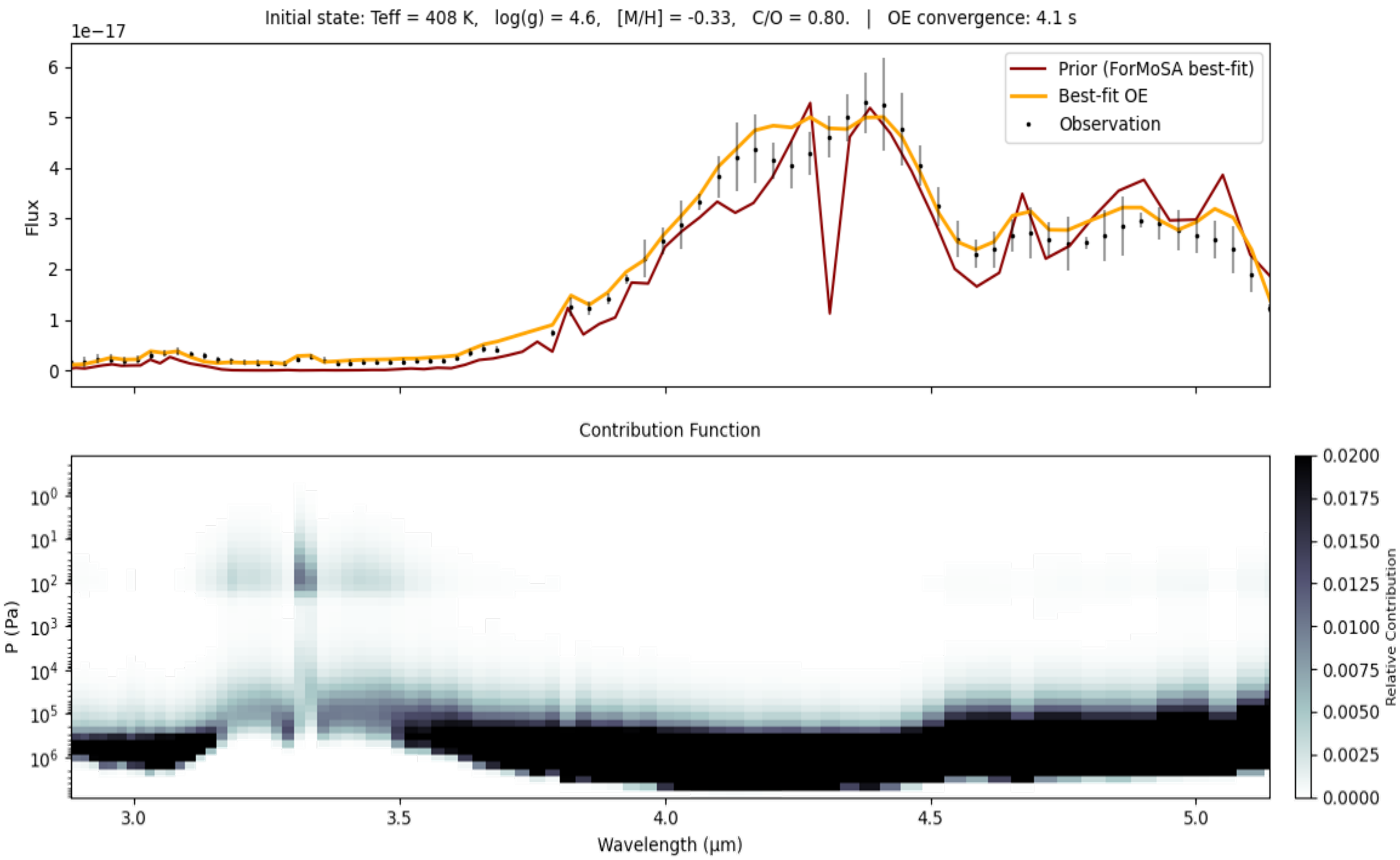
$$\begin{pmatrix} T_1 \\ T_2 \\ \dots \\ T_{15} \\ \log(g) \\ H_2O \\ CH_4 \\ CO \\ \dots \end{pmatrix}_k$$

W1935



Initial state: Teff = 408 K, log(g) = 4.6, [M/H] = -0.33, C/O = 0.80. | OE convergence: 4.1 s
1e−17
Flux
0
1
2
3
4
5
6
Prior (ForMoSA best-fit)
Best-fit OE
Observation

W1935



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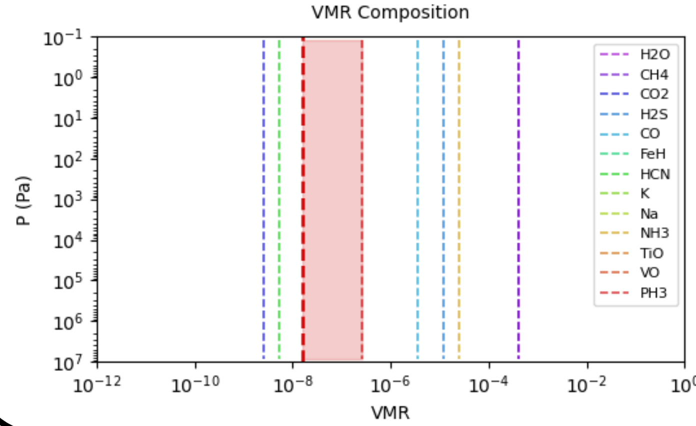
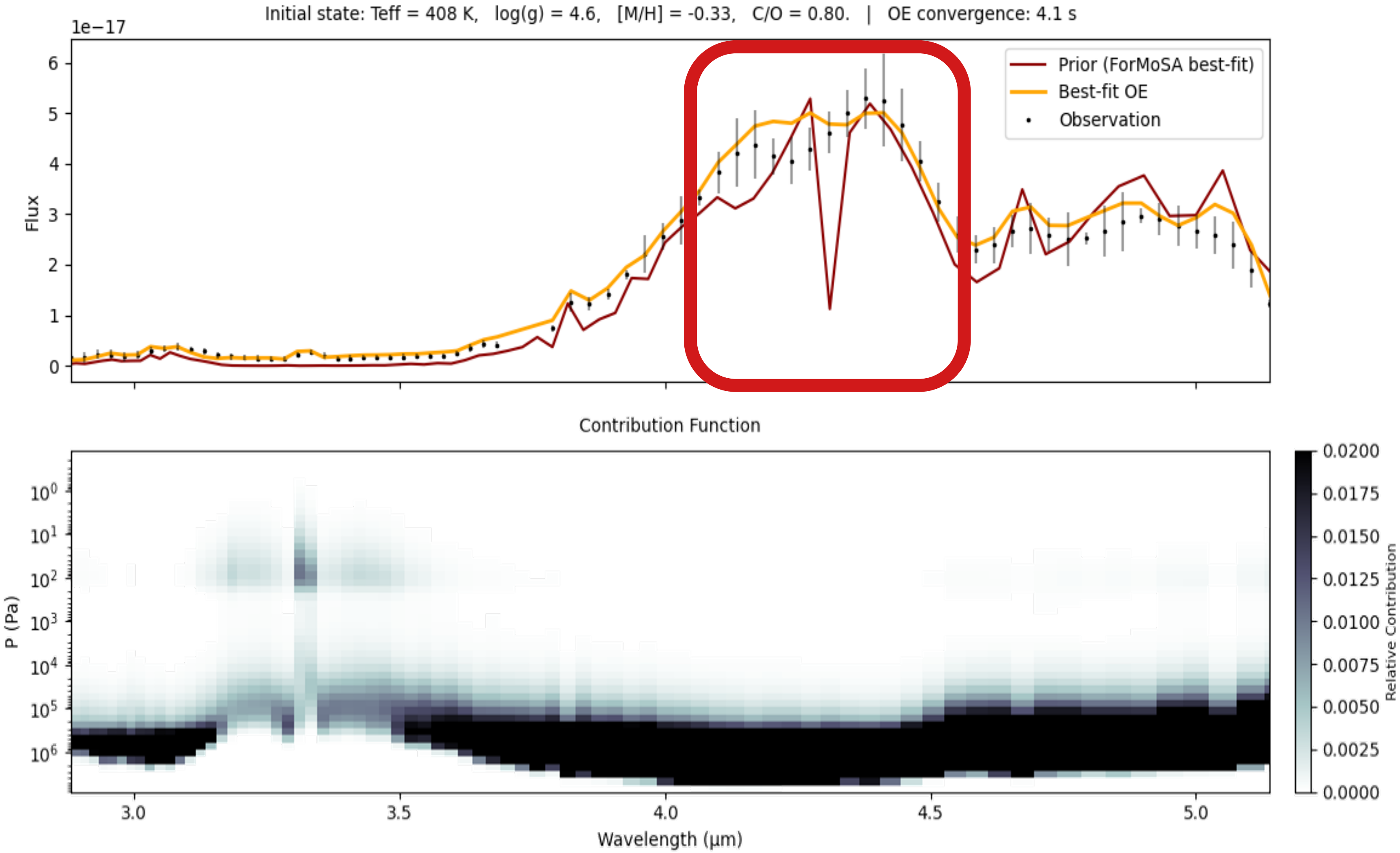
1e−17
Flux
Prior (ForMoSA best-fit)
Best-fit OE
Observation
Contribution Function
P (Pa)
Wavelength (μm)
Relative Contribution

W1935



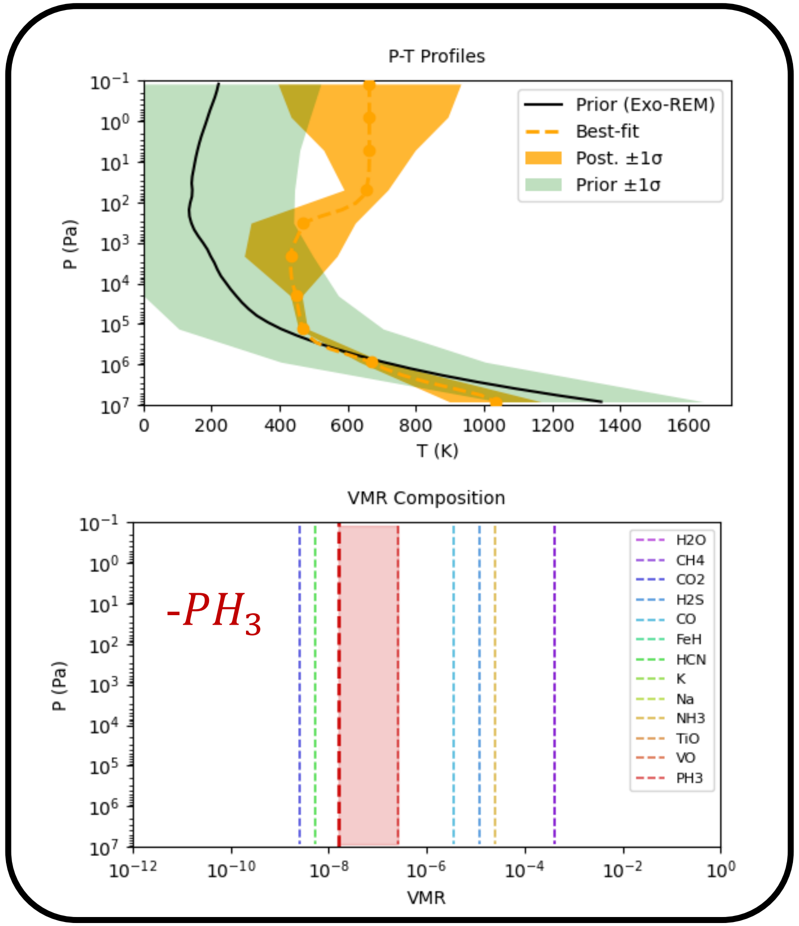
VMR Composition
P (Pa)
VMR
H2O
CH4
CO2
H2S
CO
FeH
HCN
K
Na
NH3
TiO
VO
PH3

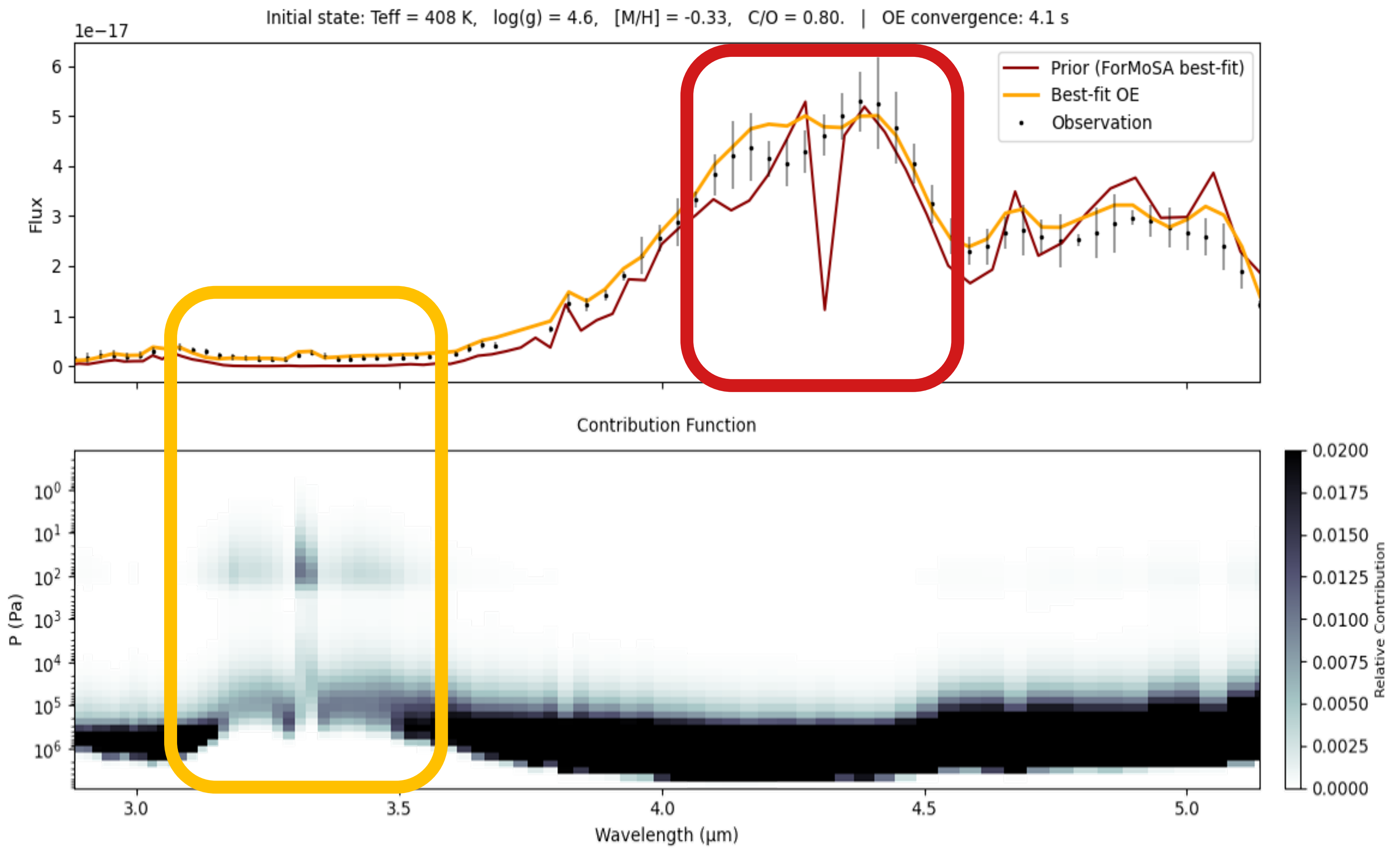


Initial state: Teff = 408 K, log(g) = 4.6, [M/H] = -0.33, C/O = 0.80. | OE convergence: 4.1 s
1e−17
Flux
Prior (ForMoSA best-fit)
Best-fit OE
Observation
Contribution Function
P (Pa)
Wavelength (μm)
Relative Contribution

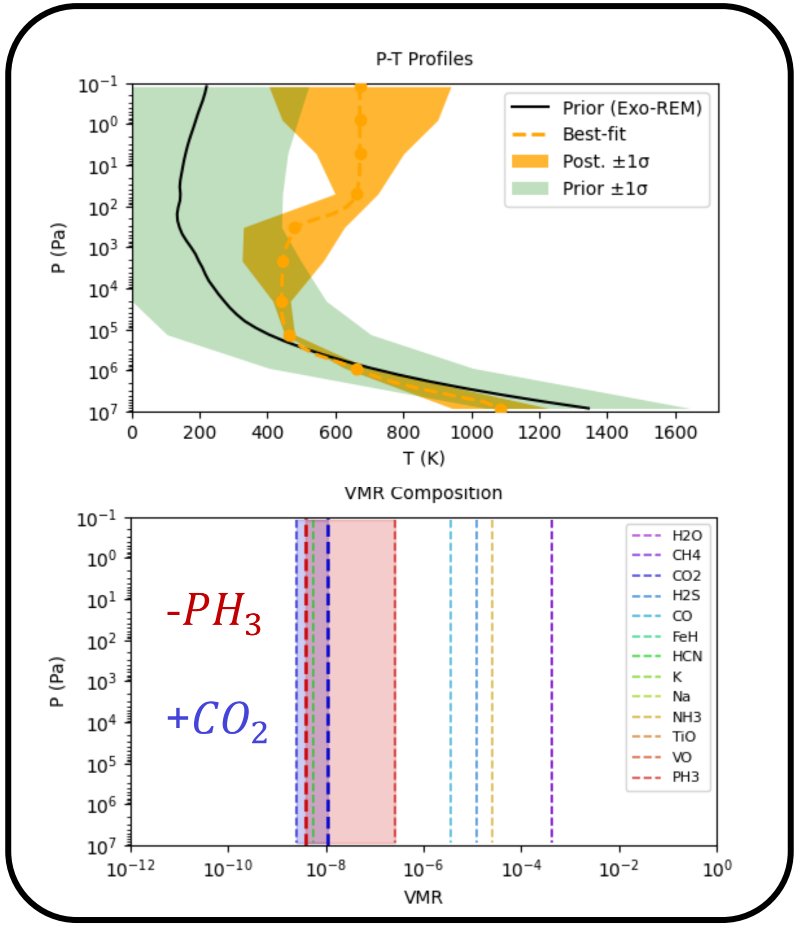
OPTEX

W1935

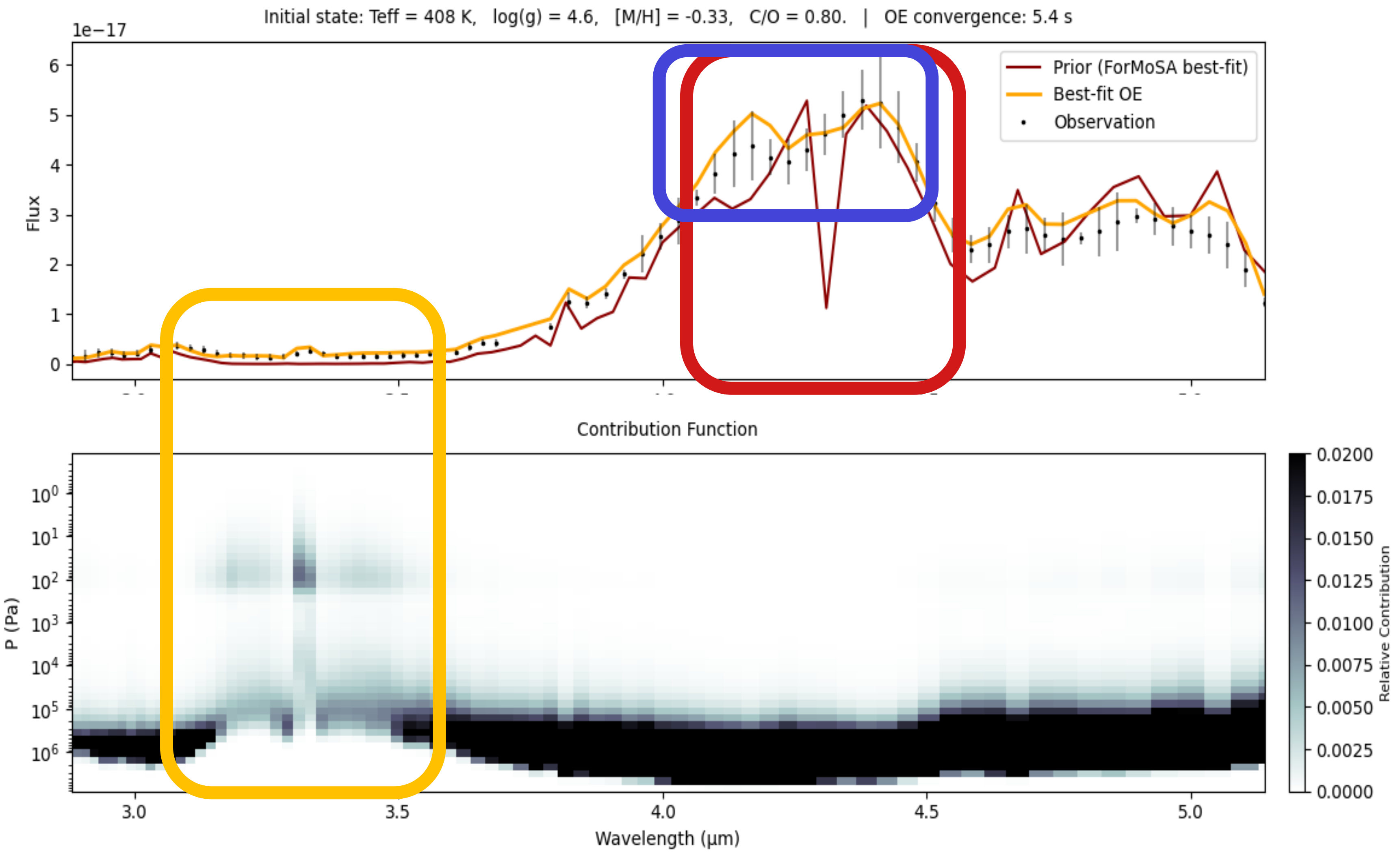

P-T Profiles
Prior (Exo-REM)
Best-fit
Post. ±1σ
Prior ±1σ
P (Pa)
T (K)
VMR Composition
$-PH_3$
H2O
CH4
CO2
H2S
CO
FeH
HCN
K
Na
NH3
TiO
VO
PH3
P (Pa)
VMR


Initial state: Teff = 408 K, log(g) = 4.6, [M/H] = -0.33, C/O = 0.80. | OE convergence: 4.1 s
1e−17
Flux
Prior (ForMoSA best-fit)
Best-fit OE
Observation
Contribution Function
P (Pa)
Wavelength (µm)
Relative Contribution

W1935



P-T Profiles
Prior (Exo-REM)
Best-fit
Post. ±1σ
Prior ±1σ
P (Pa)
T (K)
VMR Composition
H2O
CH4
CO2
H2S
CO
FeH
HCN
K
Na
NH3
TiO
VO
PH3
$-PH_3$
$+CO_2$
P (Pa)
VMR



Initial state: Teff = 408 K, log(g) = 4.6, [M/H] = -0.33, C/O = 0.80. | OE convergence: 5.4 s
1e−17
Flux
Prior (ForMoSA best-fit)
Best-fit OE
Observation
Contribution Function
P (Pa)
Wavelength (μm)
Relative Contribution

W1935

Work in progress...

Current status:

Validated: Successful initial end-to-end testing

W1935: Selected as the ideal benchmark target

Prospects & preparation for future telescopes:

Fast and flexible retrieval: Built for increasingly complex datasets

Advanced physics: Incorporating clouds, variability, reflected light, and CPDs

New modules: HR spectroscopy, multi-observations, and transit modules