Analysis of the mass uncertainties on retrieval accuracy

Work in progress…

Speaker

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2nd Meeting of the Ariel-It Science
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Goal of this project

Quantify the impact of mass uncertainty on spectral retrieval analyses for different kind of planets (in presence of clouds at different altitude), to evaluate whether these measurements are precise enough for the atmospheric characterisation.

Scale Height

$$H = \frac{k_b T (R_0 + z)^2}{\mu M_p G}$$

- R_0 is radius at which a clear-sky atmosphere becomes opaque at all wavelengths.
  - In the case of a cloudy atmosphere degeneracies may exist as R_0 cannot be detected accurately.
- For a gaseous planets, μ is usually equal to 2.3 (defined by the ratio H_2/He only). In secondary atmospheres, a wide range of main atmospheric components may exist.
  - μ is degenerate with M_p
- The temperature is expected to change with altitude
- The trace gases' number densities may change with altitude but could be independent from other parameters, including the mass.

About Taurex

TauREx Forward Model

Inputs:

- **Planet Characteristics**
    - (R_p, M_p, T_p)
- **Stellar Characteristics**
    - (R_s, M_s, T_s)
- **Main atmospheric composition**
    - H_2/He ratio (primordial atmosphere)
    - H_2/He and N_2/He ratio (secondary)
- **Trace atmospheric composition**
    - H_2O mix ratio
    - CH_4 mix ratio
    - CO mix ratio

→ High-resolution theoretical spectrum

↓

Convolution through the instrument model

↓

Spectrum as observed by ARIEL → **Retrieval!**

TauREx 3.1

A fully Bayesian retrieval framework.

What we already know?

TauREx 3.1

THE ASTROPHYSICAL JOURNAL, 896:107 (13pp), 2020 June 20
https://doi.org/10.3847/1538-4357/ab8f8t

CrossMark

Impact of Planetary Mass Uncertainties on Exoplanet Atmospheric Retrievals

Q. Changeat, L. Keyte, I. P. Waldmann, and G. Tinetti
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Received 2019 August 17; revised 2020 April 11; accepted 2020 May 1; published 2020 June 17

Primordial Atmosphere

Stellar Characteristics	
Spectral type	G0
$M_\star (M_\odot)$	1.04
$R_\star (R_\odot)$	1.19
$T_{\rm eff}$ (K)	6091
m_V	7.65

Planet Characteristics	
$M_p (M_J)$	0.73
$R_p (R_J)$	1.39
T_p (K)	1450

Secondary Atmosphere

Stellar Characteristics	
Spectral type	M
$M_\star (M_\odot)$	0.4
$R_\star (R_\odot)$	0.3
$T_{\rm eff}$ (K)	3671

Planet Characteristics	
$M_p (M_J)$	0.01
$R_p (R_J)$	0.2
T_p (K)	450

What we already know?

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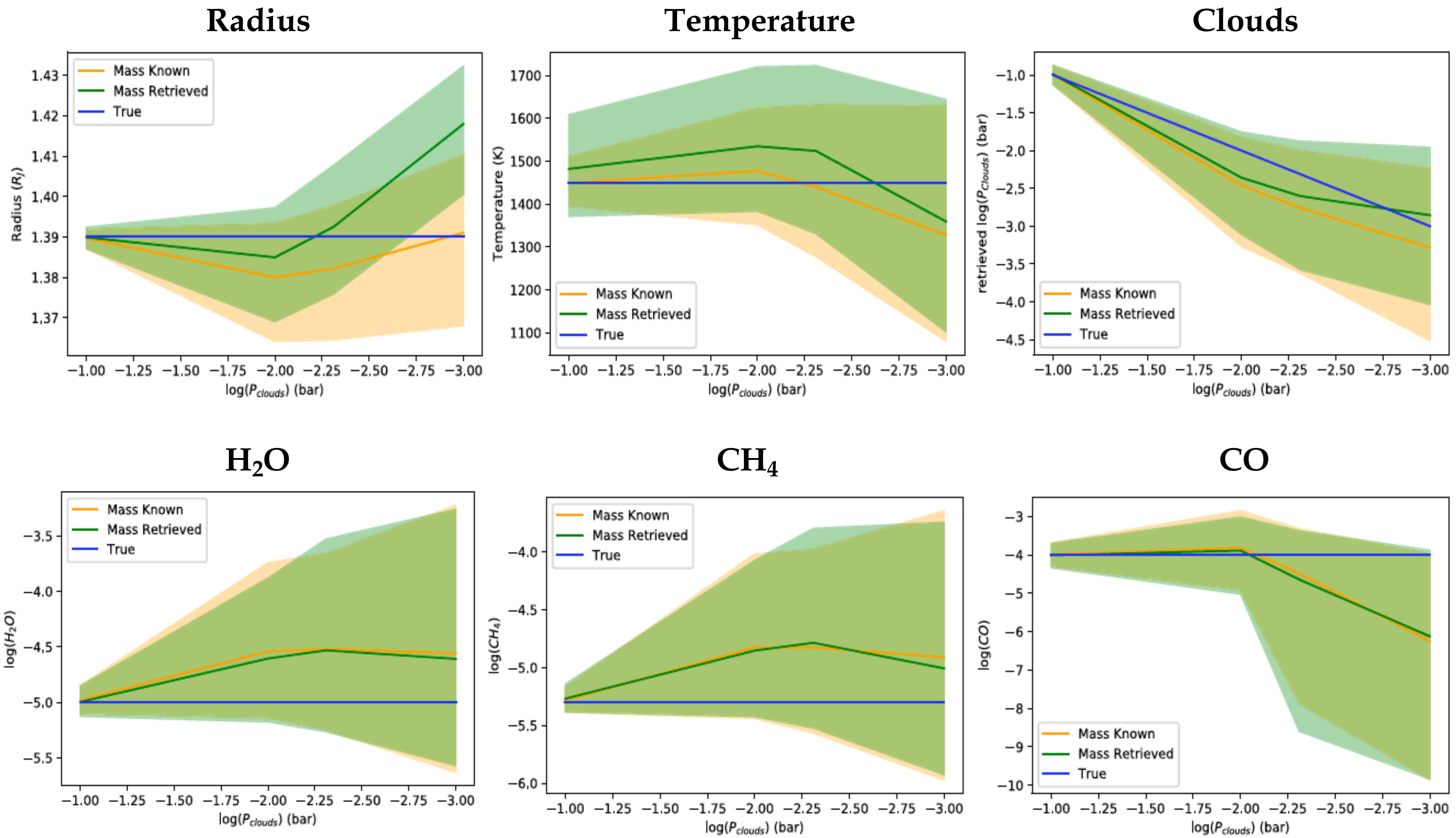

From Changeat et al. 2020

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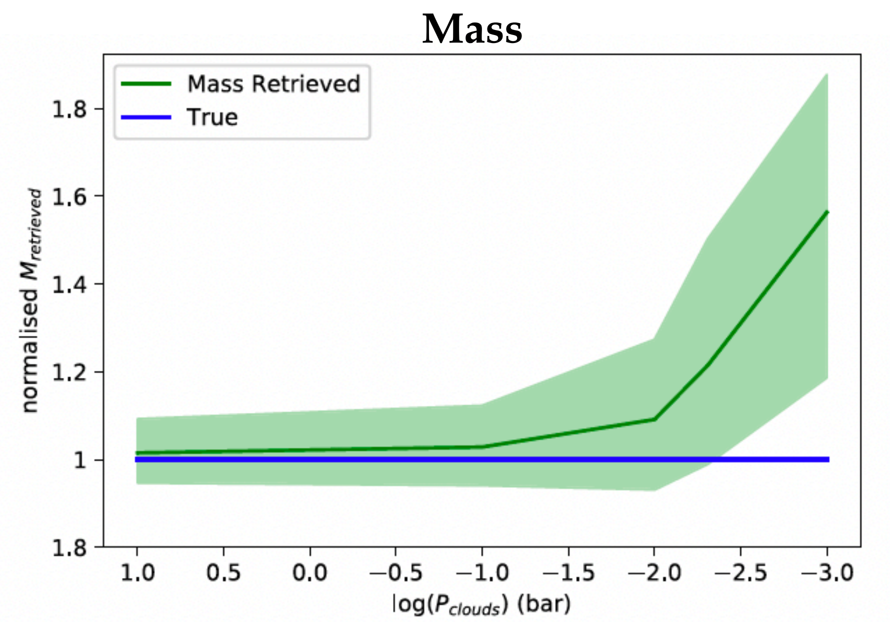
Clear Sky

Taurex retrieved correctly the atmospheric parameters

Clouds

The radius retrieval is less accurate when the cloud pressure gets closer to 10^{-3} bar

What we already know?



From Changeat et al. 2020

- Retrieved Mass became less accurate when the cloud pressure is lower than 10^{-2} bar.
- The inaccuracy of the retrieved mass for high altitude, opaque clouds appears to be correlated with the inaccuracy of the retrieved radius.

Retrieval degeneracy between planetary mass, planetary radius and cloud top pressure.

Impact of mass		
Parameter	ClearSky	Clouds
Mass	√	X
Temperature	√	√
Radius	√	X
Clouds	NAN	X
Trace Composition	√	√

Adapted from Changeat et al. 2020

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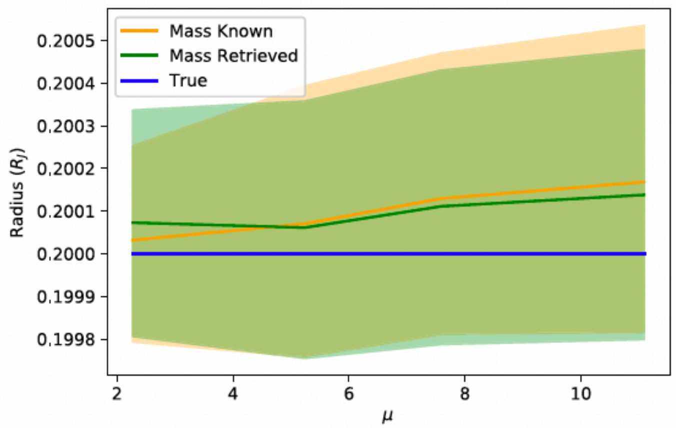
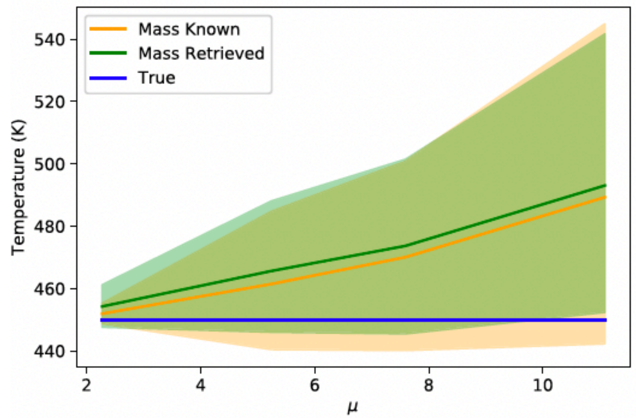
What we already know?

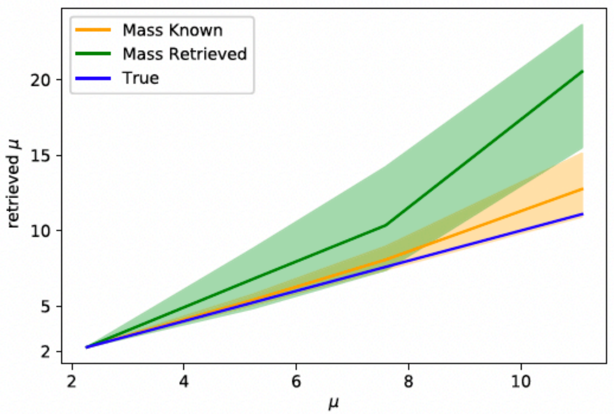
Radius

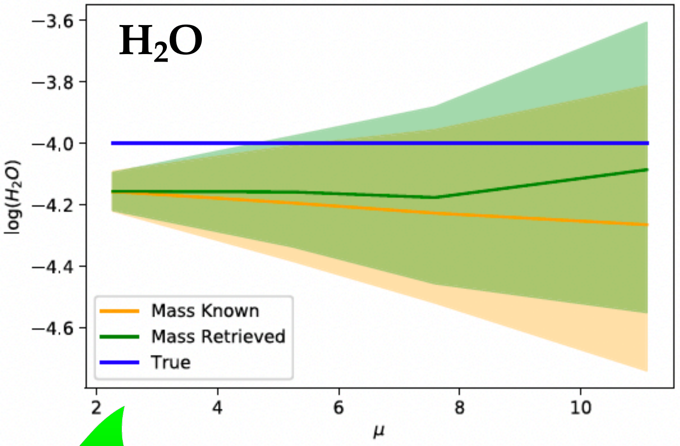


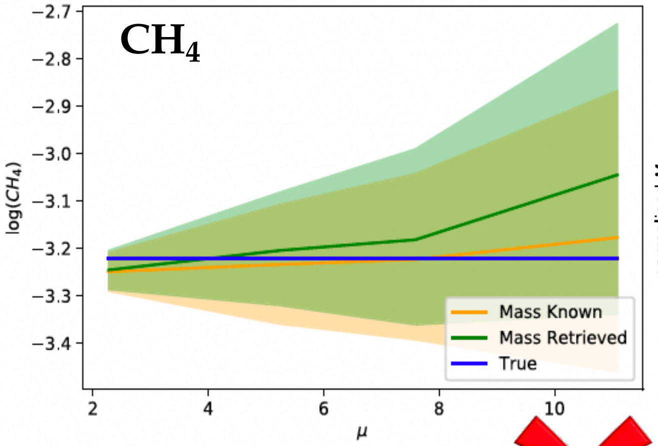
Temperature

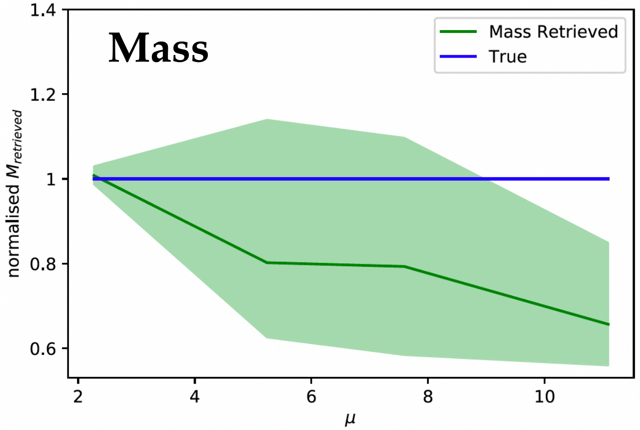


Retrieved μ









From Changeat et al. 2020

Trace gases, temperature and planetary radius are accurately retrieved for both the known and retrieved mass cases

The degeneracy mass/mean molecular weight becomes more important for increasing μ

For planets with a secondary atmosphere an independent determination of the mass can help to break the degeneracy

Secondary Atmosphere

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Planet Characteristics	
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T_p (K)	450

Clear Sky

Trace gases, temperature and planetary radius are accurately retrieved

Degeneracy mass/mean molecular weight

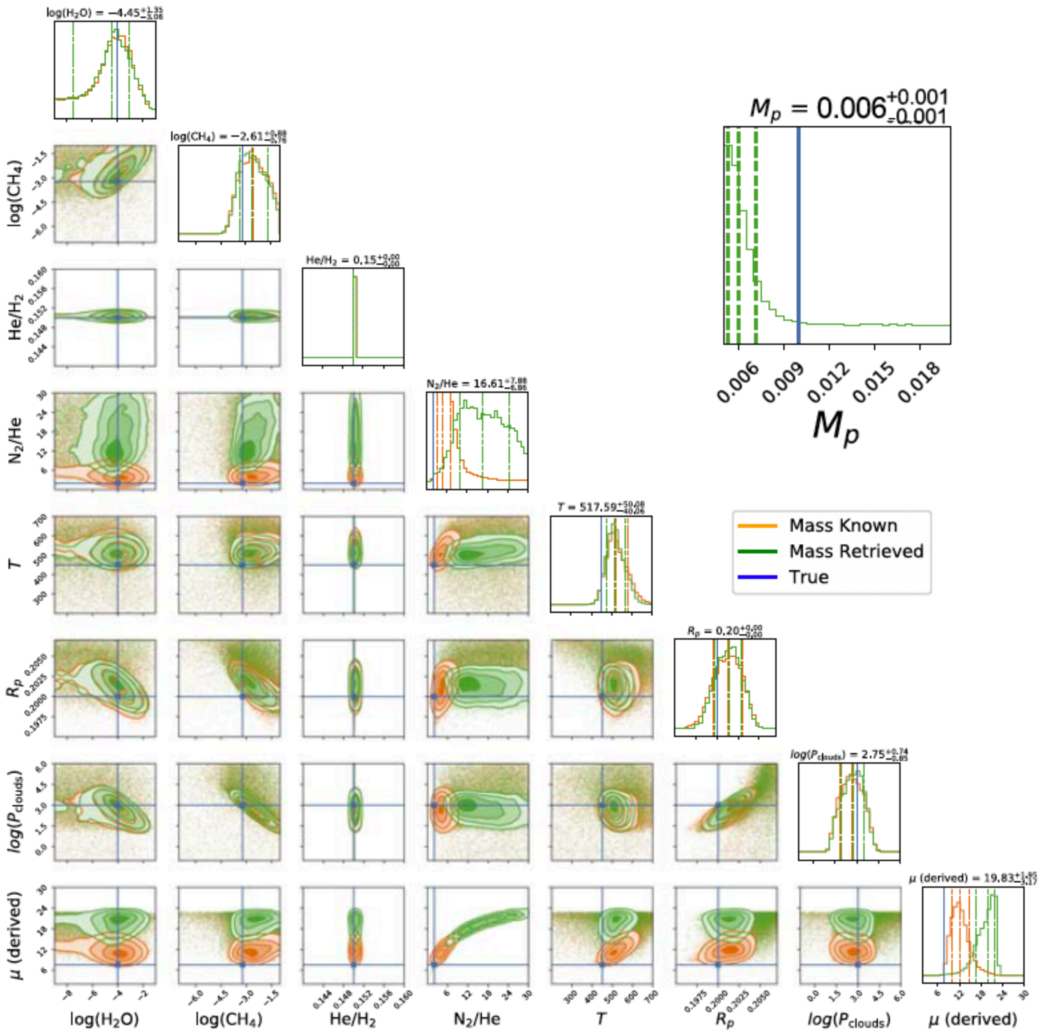
Clouds

Trace gas, temperature

Mean molecular weight

What we already know?

Top cloud pressure 10^{-2} bar
$\mu = 7.6$



From Changeat et al. 2020

Without prior information about the mass the model retrieves the **trace gas abundances** and the **temperature** with equal accuracy but it is not able to constrain the **mean molecular weight**

Impact of mass

Parameter	ClearSky	Clouds
Mass	√	X
Temperature	√	√
Radius	√	X
Clouds	NAN	X
Trace Composition	√	√
Main Composition	X	X

Adapted from Changeat et al. 2020

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Clear Sky

Trace gases, temperature and planetary radius are accurately retrieved
Degeneracy mass/mean molecular weight

Clouds

Trace gas, temperature
Mean molecular weight

Tested Cases

Primordial Atmosphere

- **G star vs M star (same Jovian planet)**
  - Mass totally unknown vs Mass uncertainty 40%
- **T_p = 1450 K vs T_p = 800 K around a G star**
- **m_v = 8 vs m_v = 10.5**
  - G star with a Jovian Planet
  - G star with a Neptunian Planet
  - M star with a Jovian Planet
  - M star with a Neptunian Planet

Stellar Characteristics		
Spectral type	G	M
$M_\star(M_\odot)$	1.23	0.57
$R_\star(R_\odot)$	1.19	0.59
$T_{\rm eff}$ (K)	6091	3900

Planet Characteristics	
$M_p(M_J)$	0.73
$R_p(R_J)$	1.39
T_p (K)	1450

Secondary Atmosphere

- **M star m_v = 8 with a Super Earth (without clouds)**
  - Different main composition (μ = 2.3, 5.2, 7.6, 11.1)
  - Different Mass uncertainties (δM_p = 10%, 30%, 50%)
- **M star m_v = 10.5 with a Super Earth (without clouds)**
  - Different main composition (μ = 2.3, 5.2, 7.6, 11.1)
  - Different Mass uncertainties (δM_p = 10%, 30%, 50%)

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Primordial Atmosphere

G star vs M star (Mass totally unknown vs δM=40%)

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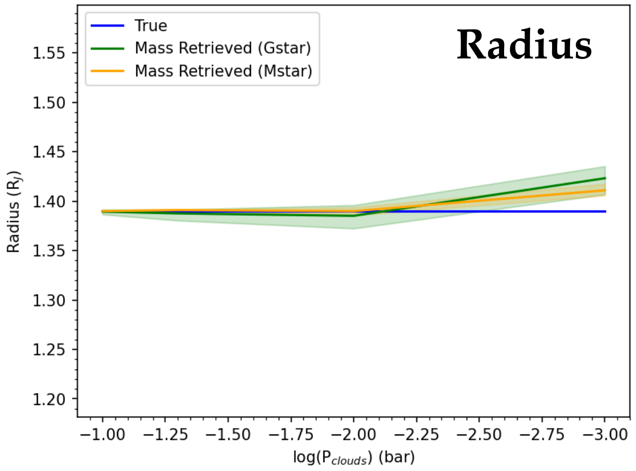
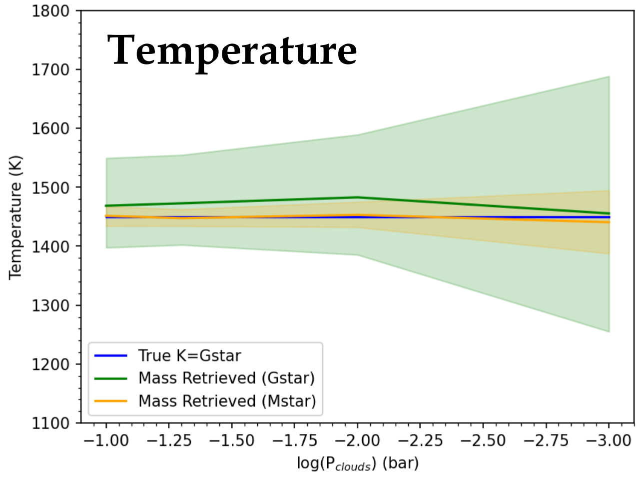
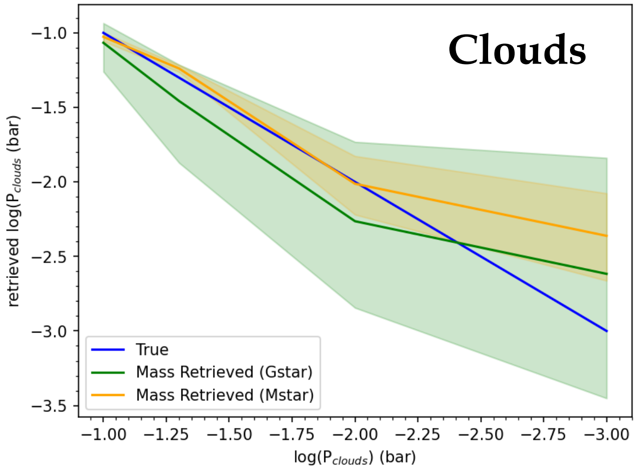
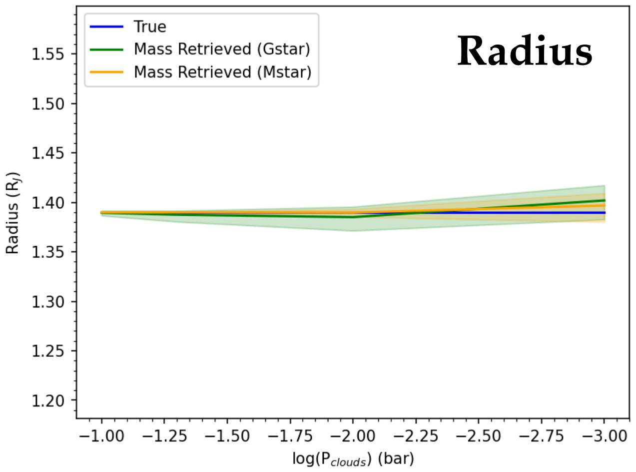
Mass totally unknown (Changeat 2020)

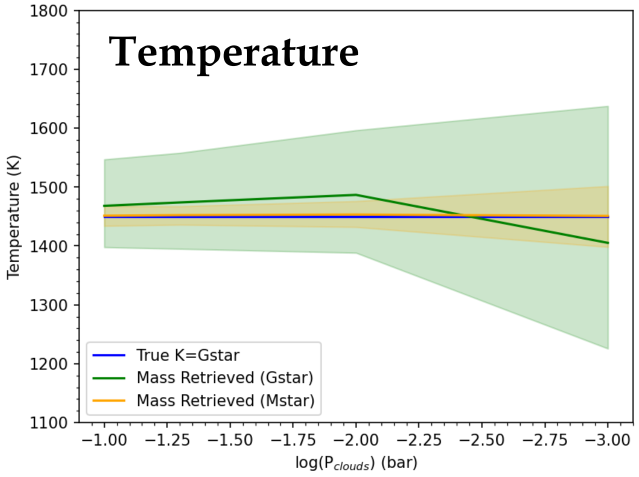


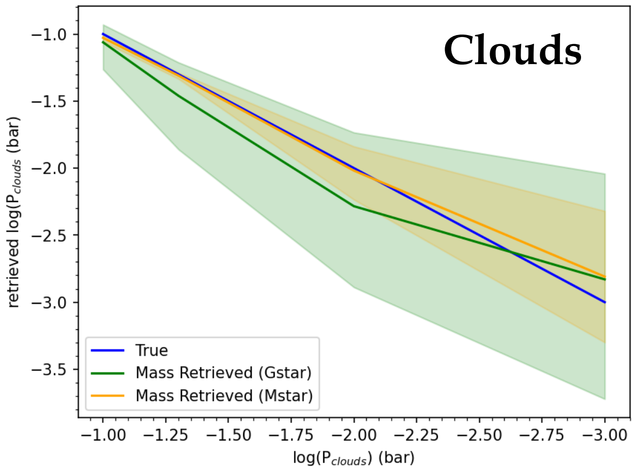




Mass uncertaninty 40 %







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Clear Sky

Taurex retrieved correctly the atmospheric and planetary parameters

Clouds

Trace gases are retrieved with less accuracy for the M star. Retrieved Mass is compatible at 1σ with the input value for high altitude clouds

Claudia Di Maio

Analysis of the mass uncertainties on retrieval accuracy

G star vs M star (Mass totally unknown vs δM=40%)

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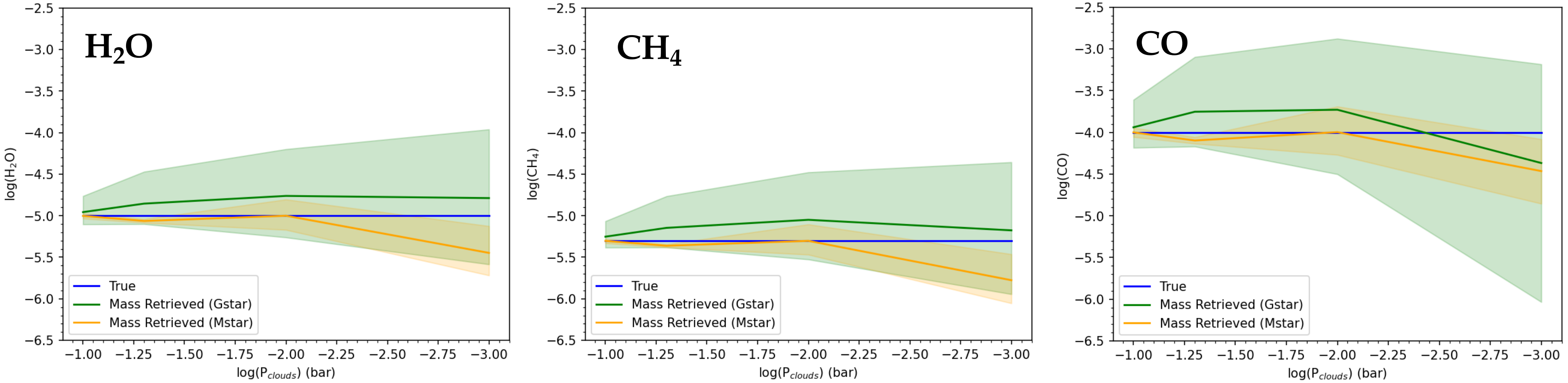
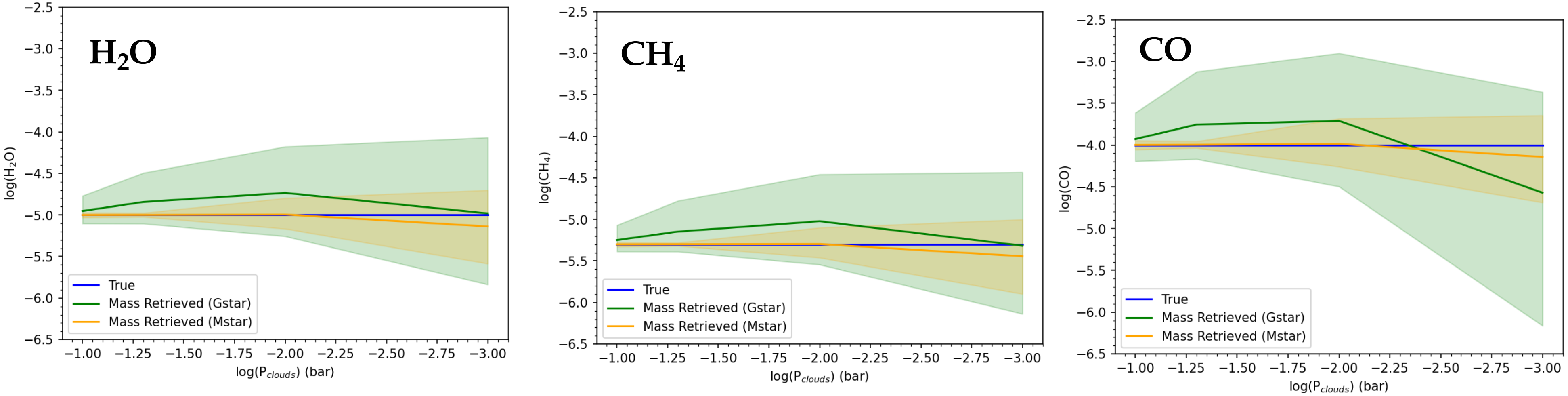
Mass totally unknown (Changeat 2020)



Mass uncertainty 40 %



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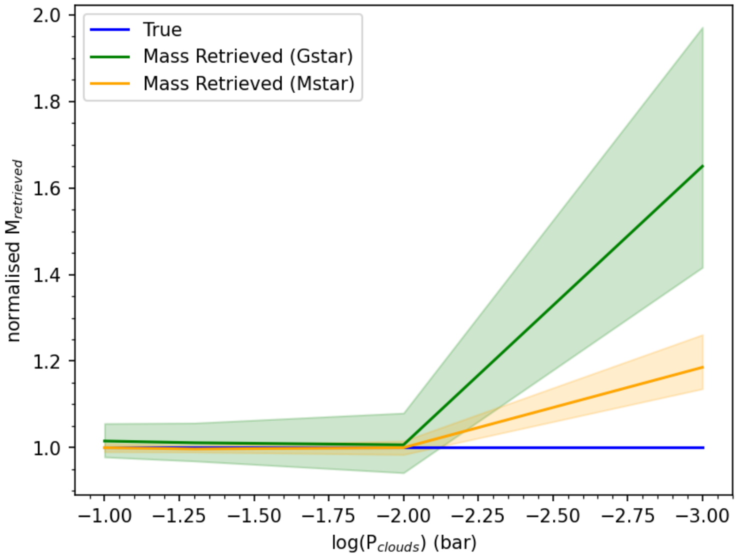
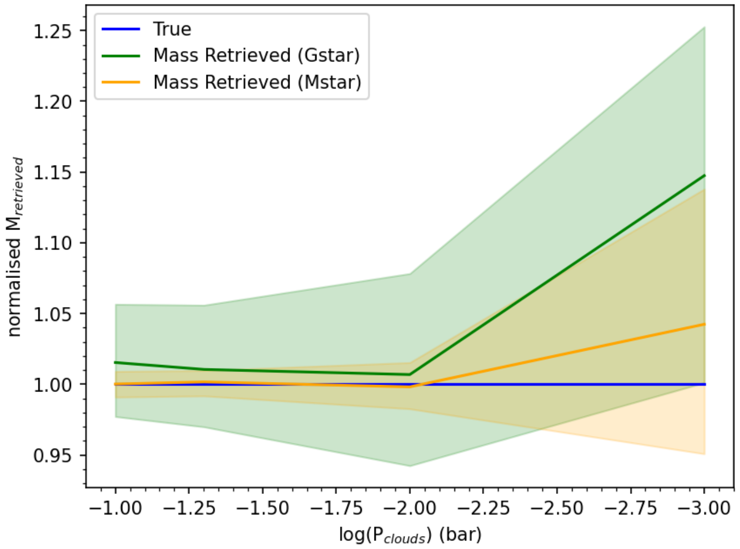


Mass uncertainty 40 %



- **Radius, temperature** and **clouds** parameters are **compatible at 1σ for high altitude clouds** for mass **uncertainties of about 40%**
- The **retrieved mass is compatible at 1σ** when we considered a **mass uncertainty of 40%.**
- In this case we could be able to retrieve the mass with more accuracy.

- Retrieved mass became less accurate when the cloud pressure is lower than 10^{-2} bar.
- Retrieved mass obtained for the M star is more accurate with respect to the retrieved mass of the planet around the G star

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Retrieved Mass is compatible at 1σ with the input value for high altitude clouds

T_p = 1450 K vs T_p = 800 K around a G star

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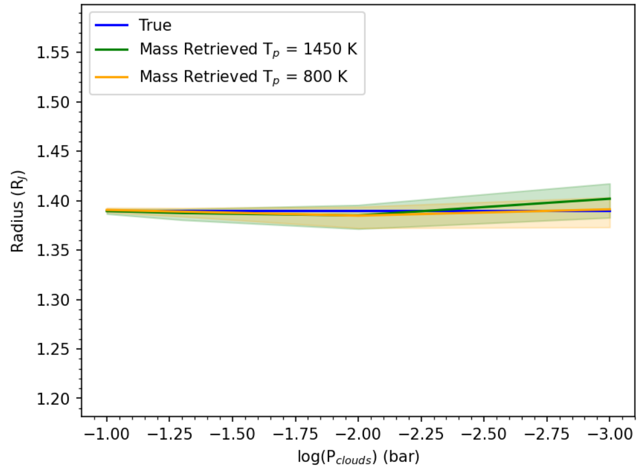
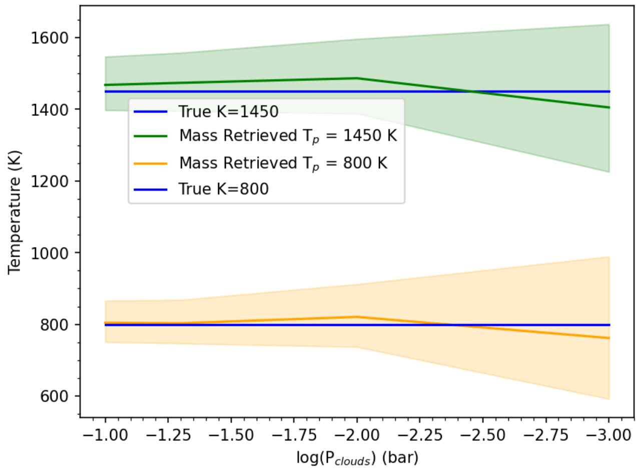
Radius



Temperature



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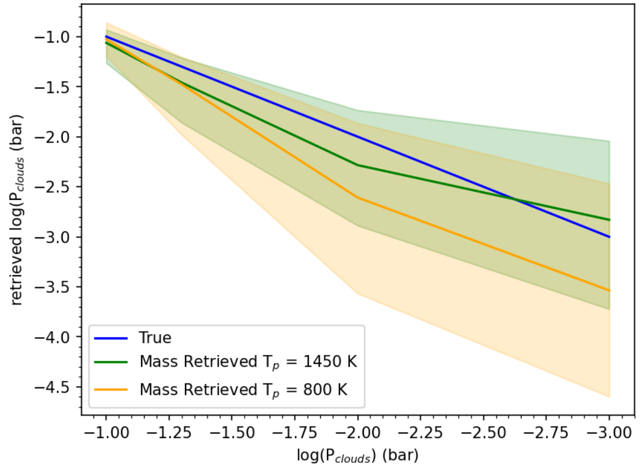
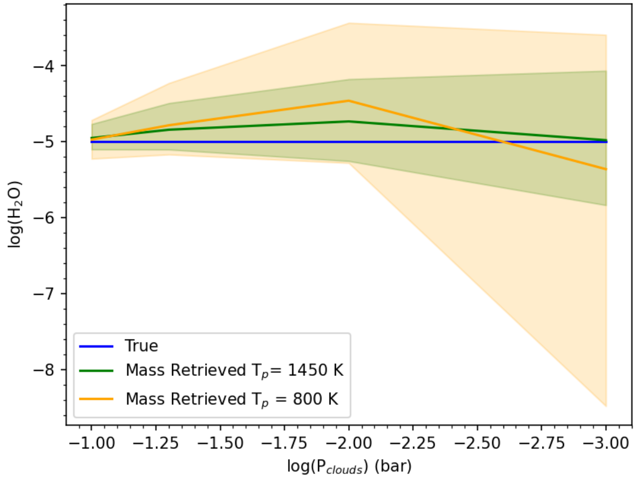
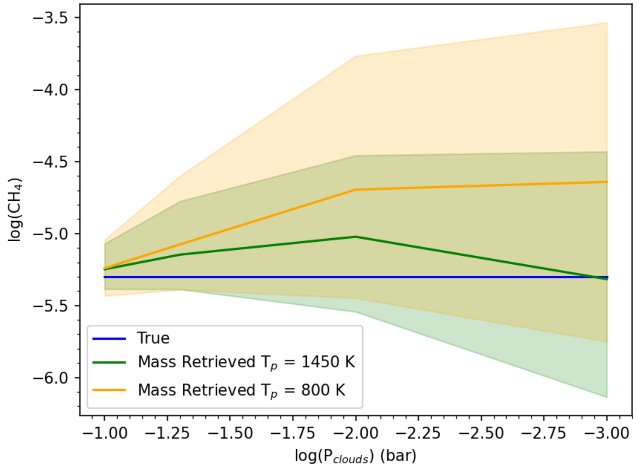


H_2O



CH_4



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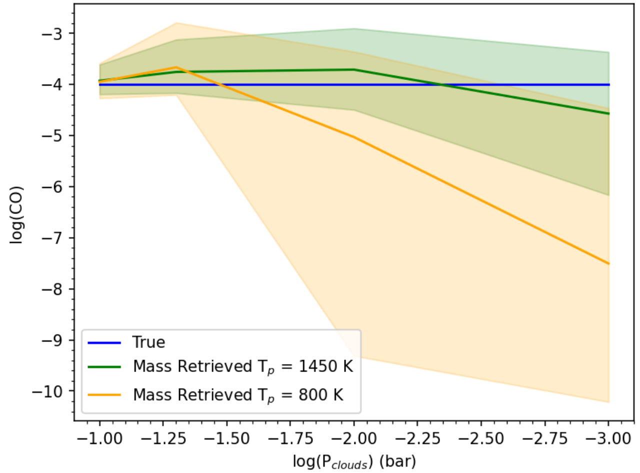

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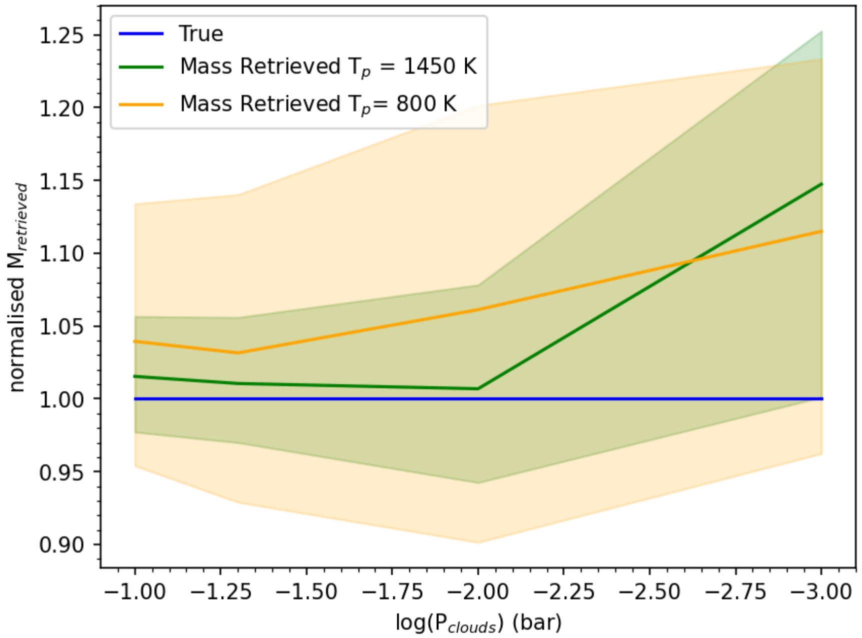
T_p = 1450 K vs T_p = 800 K around a G star



- Retrieved mass became less accurate when the cloud pressure is lower than 10^{-2} bar.
- The accuracy decrease for a planet with a lower temperature.

T_p = 1450 K vs T_p = 800 K around a G star (mass uncertainty 40%)

Parameter	T_p = 1450 K		T_p = 800 K	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$\simeq$ 2%	$\simeq$ 15%	< 5%	$\simeq$ 10%
Radius	√	√	√	√
Temperature	√	√	√	√
Trace Composition	√	√	√	X
Clouds	√	√	√	X

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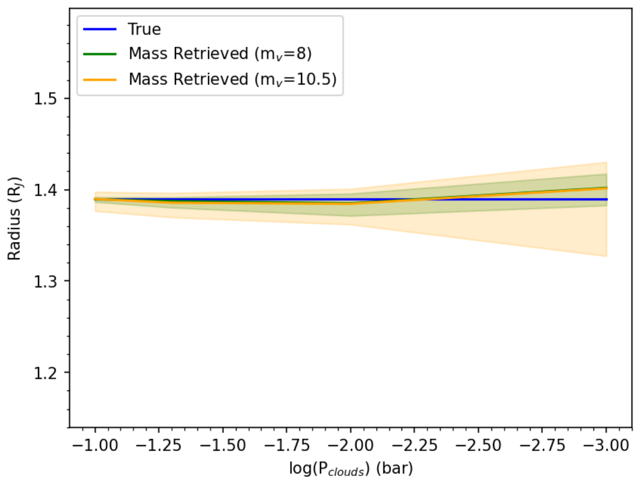
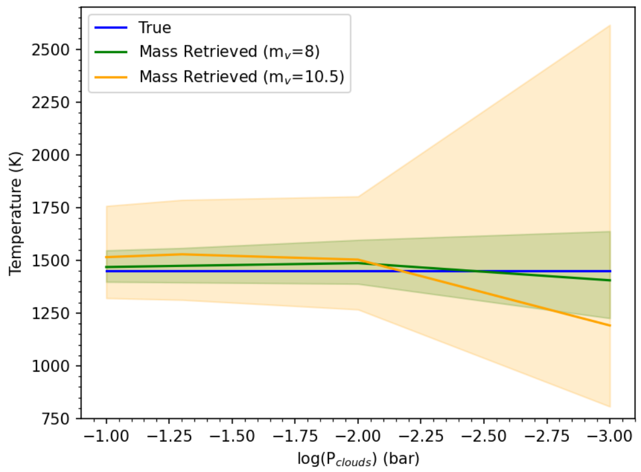
G star – Jovian Planet m_V = 8 vs m_V = 10.5

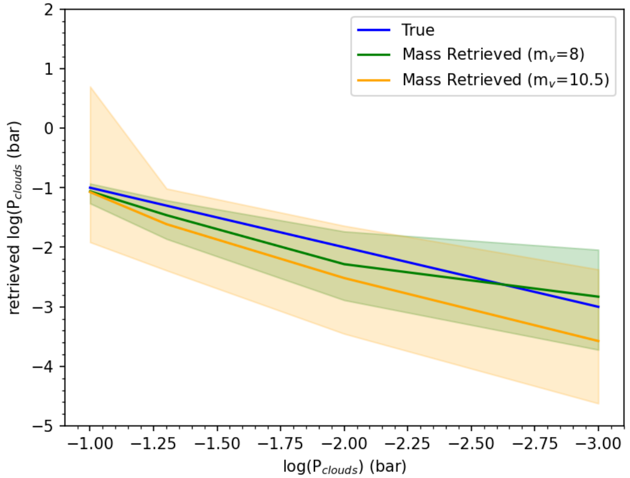
Radius



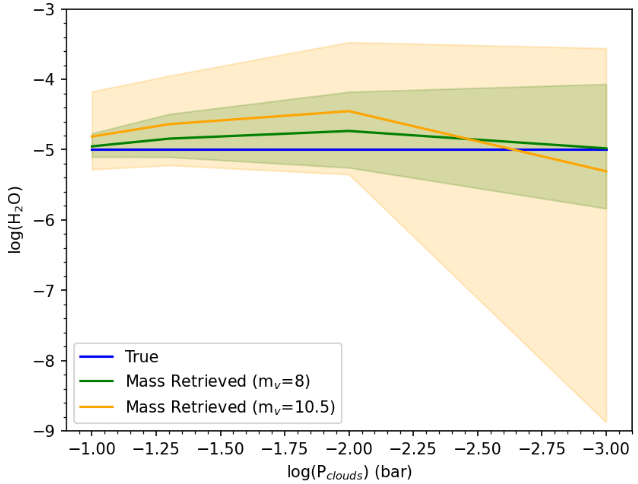
Temperature



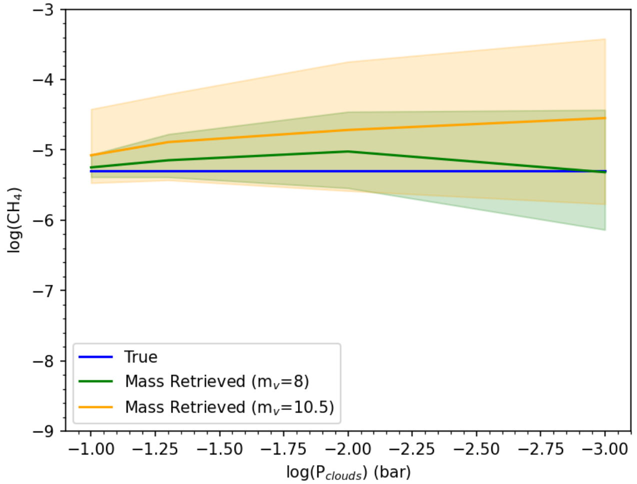
Clouds



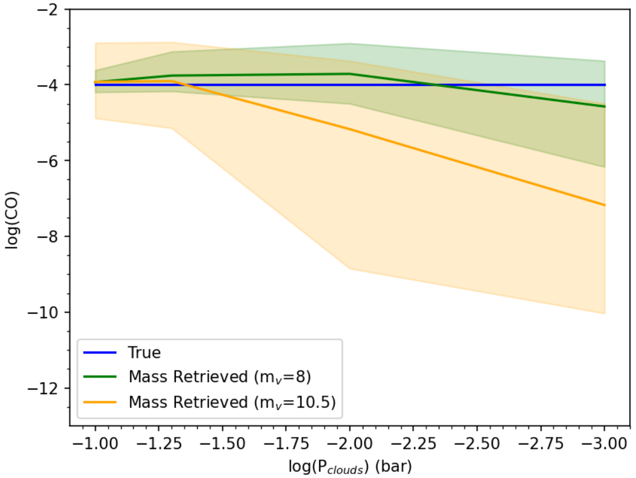
H_2O



CH_4



CO



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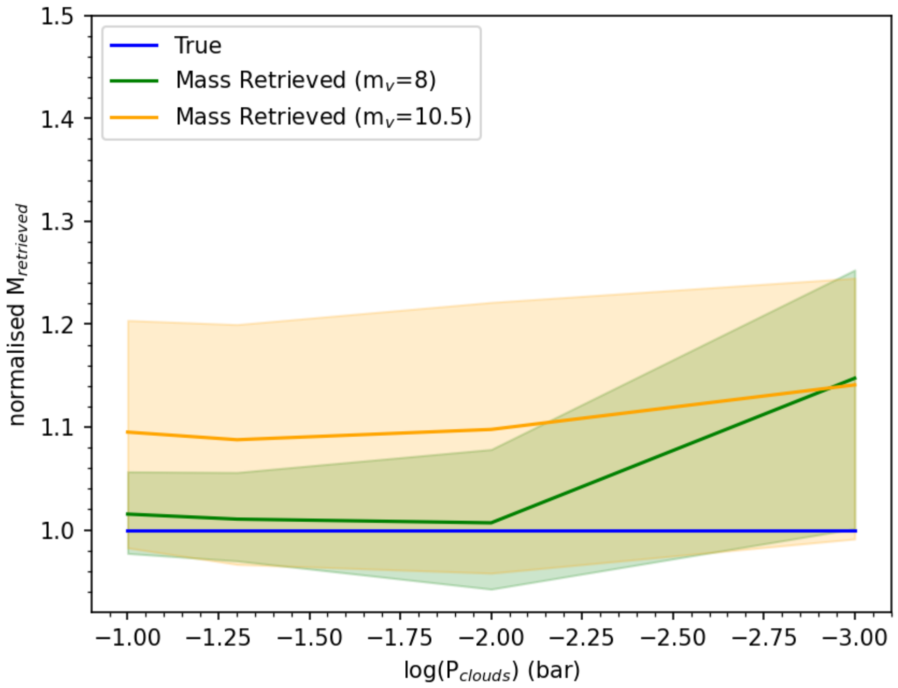
Clouds

Trace gases are retrieved with values compatible at 1σ for a star with a higher magnitude.

G star – Jovian Planet $m_V = 8$ vs $m_V = 10.5$



- Retrieved Mass is compatible at 1σ when we considered a G star with a higher magnitude (lower S/N).

An adequate S/N could increase the accuracy in the mass retrieval

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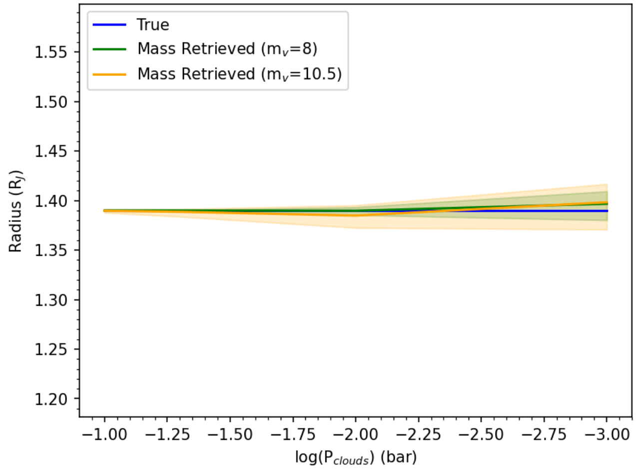
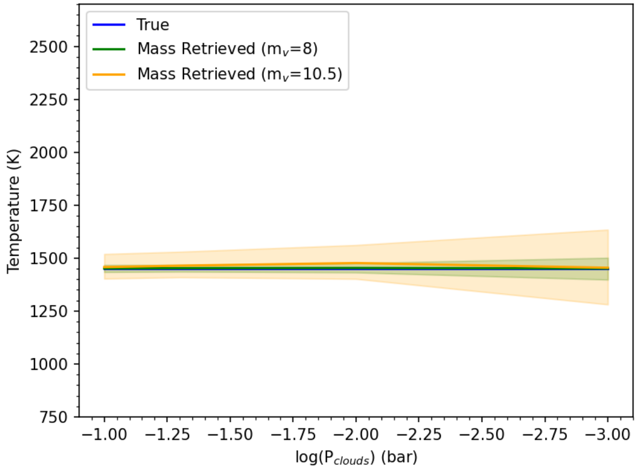
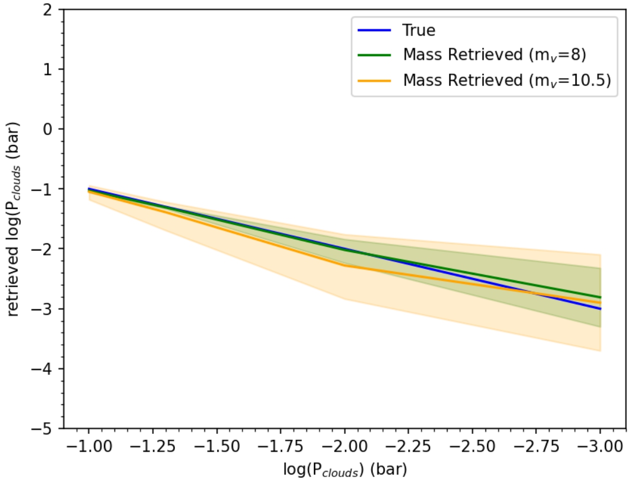
Radius



Temperature



Clouds



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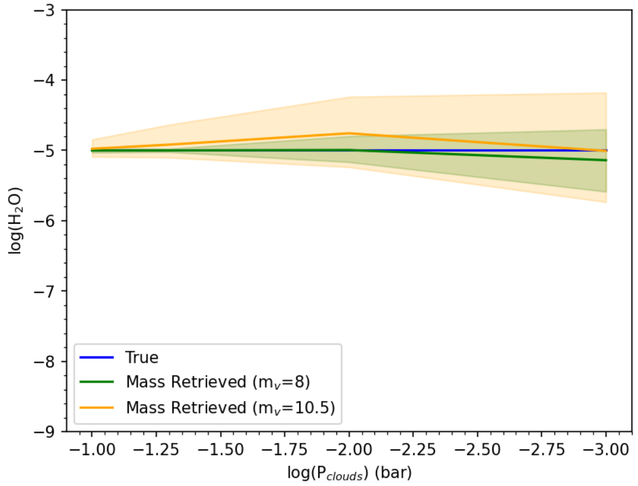
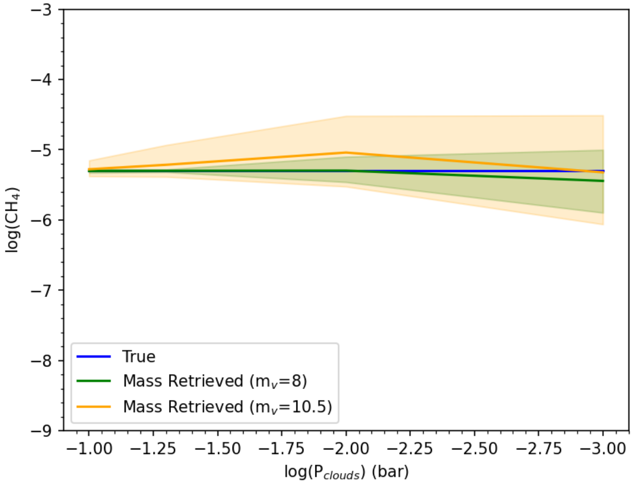
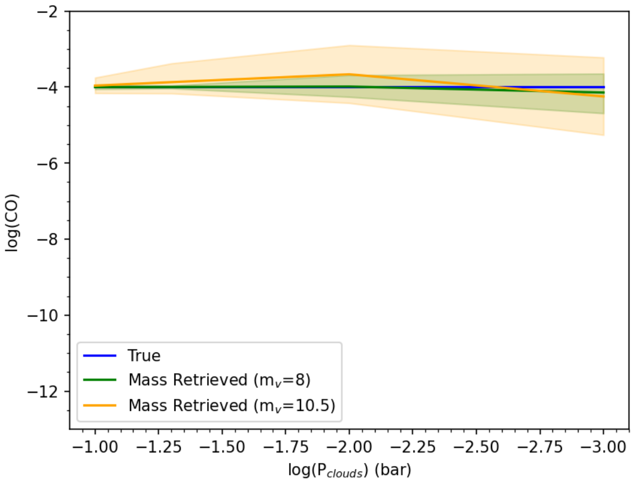


CH_4



CO



Primordial Atmosphere

Stellar Characteristics	
Spectral type	M
$M_\star (M_\odot)$	0.4
$R_\star (R_\odot)$	0.3
$T_{\rm eff}$ (K)	3671

Planet Characteristics	
$M_p (M_J)$	0.73
$R_p (R_J)$	1.39
T_p (K)	1450

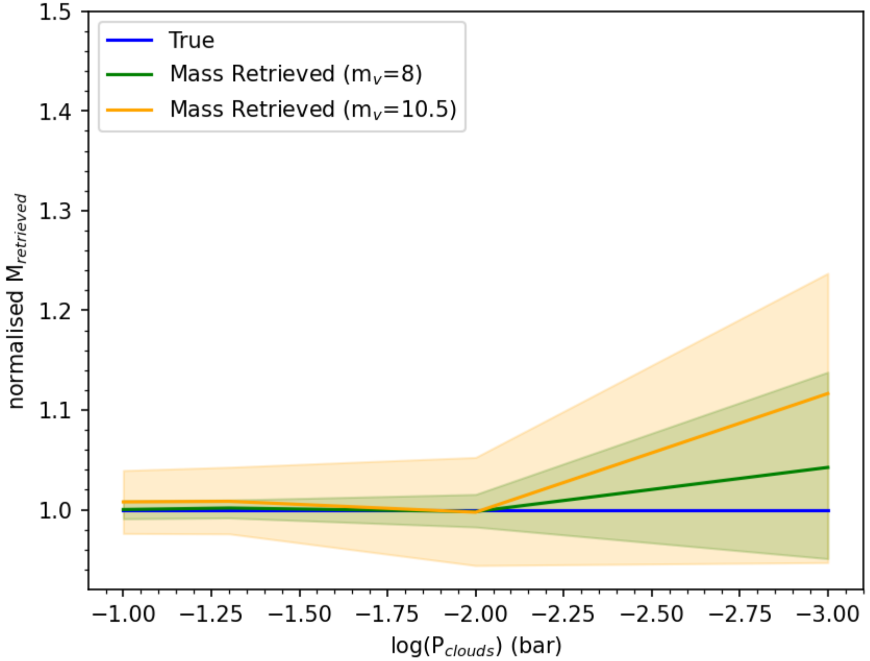
Clear Sky

Taurex retrieved correctly the atmospheric and planetary parameters

Clouds

By increasing the magnitude of the star we decrease the accuracy of all retrieved parameters still reproducing the configuration of the forward model

M star – Jovian Planet $m_v = 8$ vs $m_v = 10.5$



- Retrieved Mass became more accurate when we considered a M star with a higher magnitude (lower S/N) with respect to the G star case.

Primordial Atmosphere

Stellar Characteristics	
Spectral type	M
$M_\star (M_\odot)$	0.4
$R_\star (R_\odot)$	0.3
$T_{\rm eff}$ (K)	3671

Planet Characteristics	
$M_p (M_J)$	0.73
$R_p (R_J)$	1.39
T_p (K)	1450

Clear Sky

Taurex retrieved correctly the atmospheric and planetary parameters

Clouds

By increasing the magnitude of the star we decrease the accuracy of all retrieved parameters still reproducing the configuration of the forward model

Main results for a Primordial Atmosphere

G star vs M star (mass totally unknown)

Parameter	G star		M star	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$< 5\%$	$\simeq 70\%$	$< 5\%$	$< 20\%$
Radius	√	X	√	X
Temperature	√	√	√	√
Trace Composition	√	√	√	X
Clouds	√	X	√	X

G star vs M star (mass uncertainty 40%)

Parameter	G star		M star	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$\simeq 2\%$	$\simeq 15\%$	$< 1\%$	$< 5\%$
Radius	√	√	√	√
Temperature	√	√	√	√
Trace Composition	√	√	√	√
Clouds	√	√	√	√

G star with a Jovian Planet (mass uncertainty 40%)

Parameter	$m_v = 8$		$m_v = 10.5$	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$< 2\%$	$\simeq 15\%$	$\simeq 10\%$	$\simeq 10\%$
Radius	√	√	√	√
Temperature	√	√	√	$< 20\%$
Trace Composition	√	√	√	X
Clouds	√	√	√	X

M star with a Jovian Planet (mass uncertainty 40%)

Parameter	$m_v = 8$		$m_v = 10.5$	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$< 0.1\%$	$< 5\%$	$< 0.1\%$	$\simeq 10\%$
Radius	√	√	√	√
Temperature	√	√	√	√
Trace Composition	√	√	√	√
Clouds	√	√	√	√

G star with a Neptunian Planet (mass uncertainty 40%)

Parameter	$m_v = 8$		$m_v = 10.5$	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$< 0.2\%$	$\simeq 20\%$	$< 0.4\%$	$\simeq 50\%$
Radius	√	√	√	√
Temperature	√	√	√	√
Trace Composition	√	X	√	X
Clouds	√	X	√	X

M star with a Neptunian Planet (mass uncertainty 40%)

Parameter	$m_v = 8$		$m_v = 10.5$	
	Clear Sky	Clouds	Clear Sky	Clouds
Mass	$< 0.1\%$	$< 0.1\%$	$< 5\%$	$\simeq 10\%$
Radius	√	√	√	√
Temperature	√	√	√	√
Trace Composition	√	√	√	√
Clouds	√	√	√	X

Primordial Atmosphere

1. We could **use Taurex to retrieve the mass** with an accuracy ~ 10% for a clear sky planet.
2. We need a estimation of the **mass with an uncertainty of ~ 40%** to very accurate retrieve the trace composition of the atmosphere (in particular for the CO)
3. We need a more precise estimation of the mass and higher S/N to correctly retrieve the trace composition of the atmosphere for a Neptunian planet around a G star in the cloudy case.

Secondary Atmosphere

M star – Super Earth Planet $m_V = 8$

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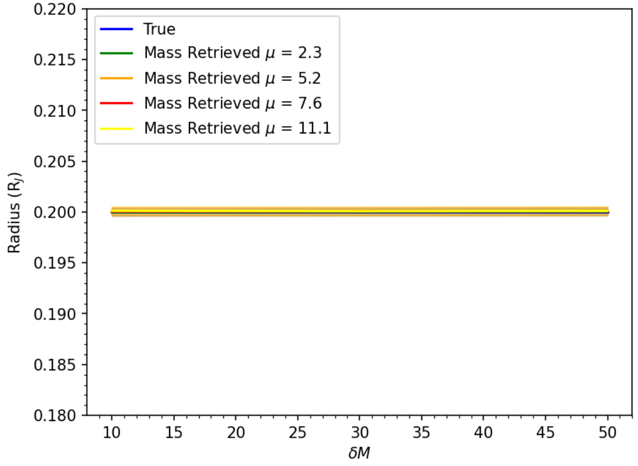
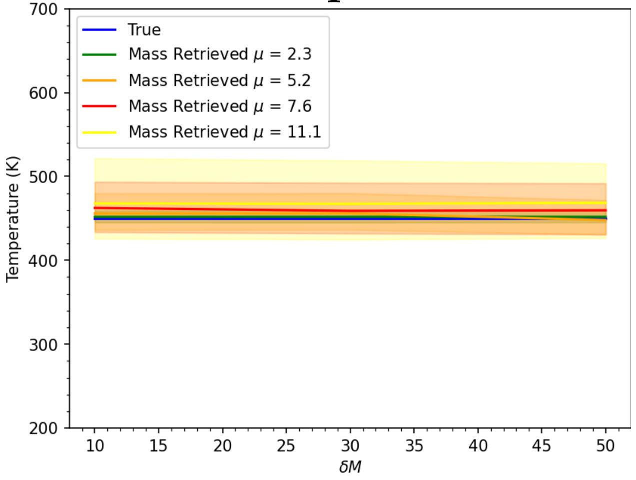
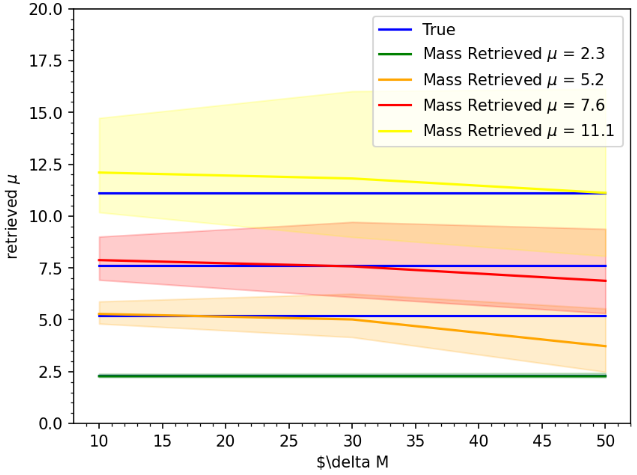
Radius



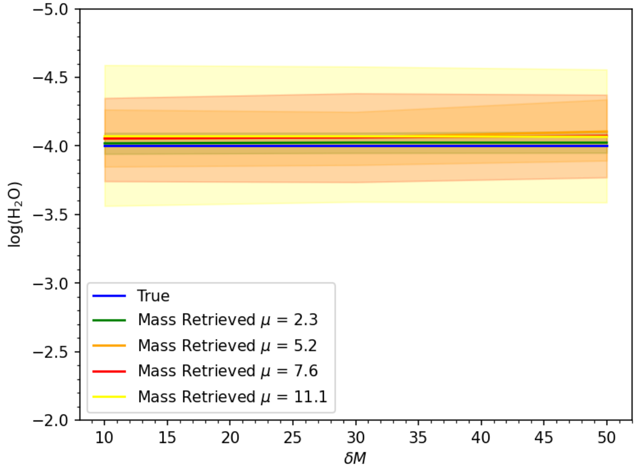
Temperature



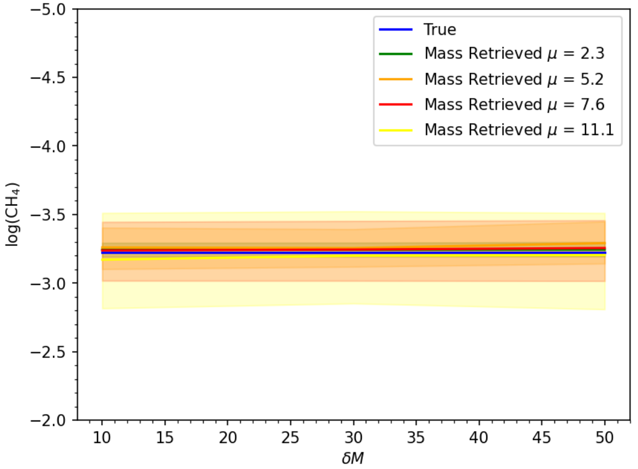
Retrieved μ



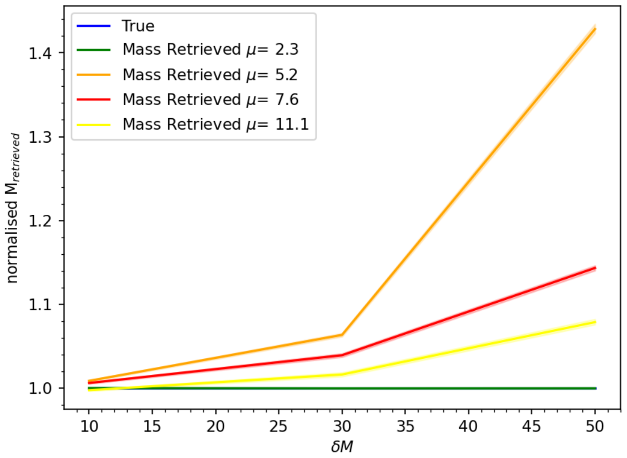
H_2O



CH_4



Retrieved Mass



Secondary Atmosphere

Stellar Characteristics	
Spectral type	M
$M_\star(M_\odot)$	0.4
$R_\star(R_\odot)$	0.3
T_{eff} (K)	3671

Planet Characteristics	
$M_p(M_J)$	0.01
$R_p(R_J)$	0.2
T_p (K)	450

Correct retrieval of the trace composition of the atmosphere.

We could retrieve the mass with more accuracy

The retrieval of the main composition and the mean molecular weight is compatible at 1σ when the mass uncertainties increase.

M star – Super Earth Planet $m_V = 10.5$

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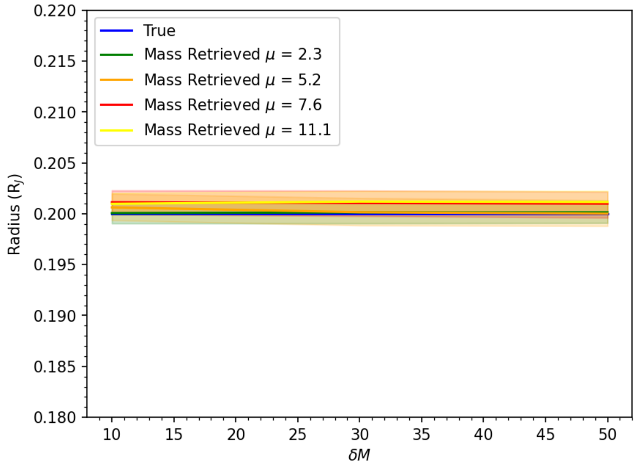
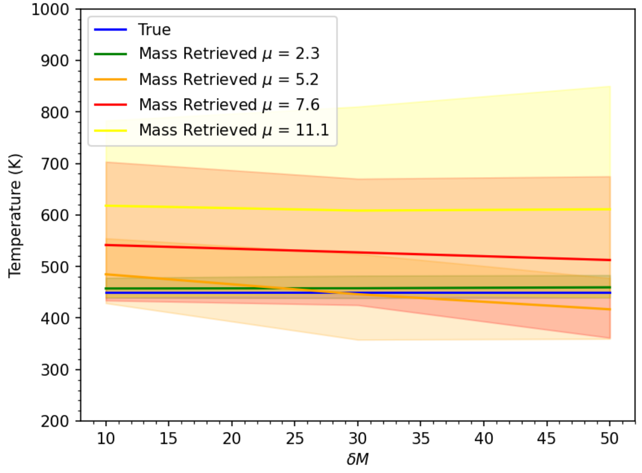
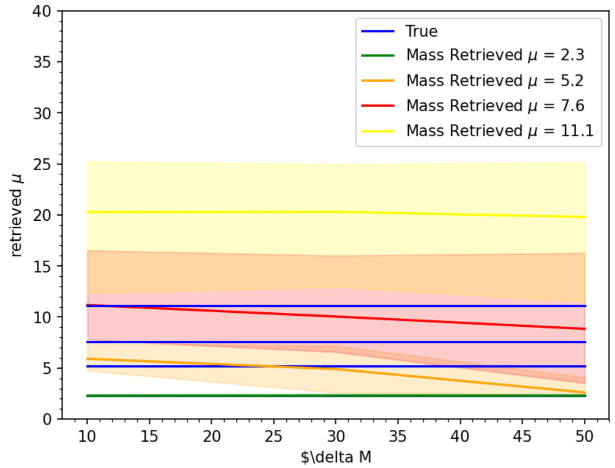
Radius



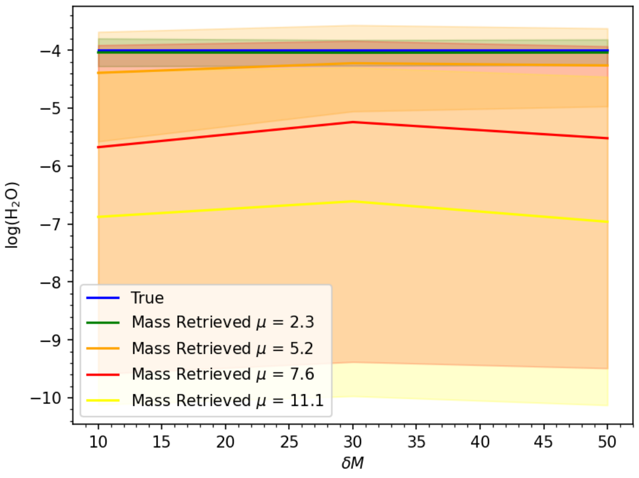
Temperature



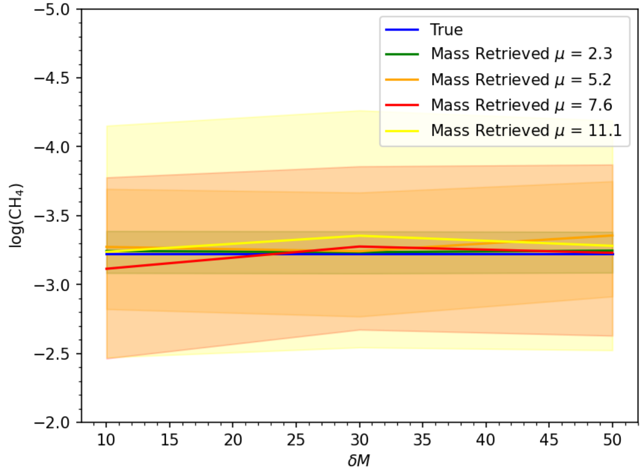
Retrieved μ



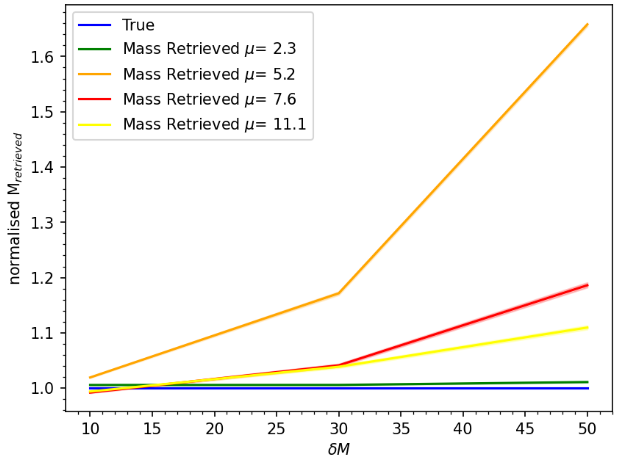
H_2O



CH_4



Retrieved Mass



Secondary Atmosphere

Stellar Characteristics	
Spectral type	M
$M_\star(M_\odot)$	0.4
$R_\star(R_\odot)$	0.3
$T_{\rm eff}$ (K)	3671

Planet Characteristics	
$M_p(M_J)$	0.01
$R_p(R_J)$	0.2
T_p (K)	450

We could retrieve the mass with more accuracy

The retrieval of the trace gases is compatible at 1σ accurate for a star with higher magnitude.

Correlation between mass and mean molecular weight.
In this cases we need a higher S/N.

Main results for a Secondary Atmosphere

M star Super-Earth Planet $m_v = 8$

Parameter	$\mu = 2.3$			$\mu = 5.2$			$\mu = 7.6$			$\mu = 11.1$		
δM	10%	30%	50%	10%	30%	50%	10%	30%	50%	10%	30%	50%
Mass	$< 1\%$	$< 1\%$	$< 1\%$	$< 2\%$	$< 6\%$	$< 45\%$	$< 2\%$	$< 4\%$	$< 15\%$	$< 1\%$	$< 2\%$	$< 10\%$
Radius	√	√	√	√	√	√	√	√	√	√	√	√
Temperature	√	√	√	√	√	√	√	√	√	√	√	√
Trace Comp	√	√	√	√	√	√	√	√	√	√	√	√
Main Comp	√	√	√	√	√	X	X	X	X	X	X	X

M star Super-Earth Planet $m_v = 10.5$

Parameter	$\mu = 2.3$			$\mu = 5.2$			$\mu = 7.6$			$\mu = 11.1$		
δM	10%	30%	50%	10%	30%	50%	10%	30%	50%	10%	30%	50%
Mass	$< 1\%$	$< 1\%$	$< 1\%$	$\simeq 2\%$	$\simeq 18\%$	$\simeq 65\%$	$< 2\%$	$< 6\%$	$\simeq 18\%$	$< 2\%$	$< 6\%$	$\simeq 10\%$
Radius	√	√	√	√	√	√	√	√	√	√	√	√
Temperature	√	√	√	√	√	√	√	√	√	√	√	√
Trace Comp	√	√	√	√	√	√	X	X	X	X	X	X
Main Comp	√	√	√	√	√	X	X	X	X	X	X	X

Conclusions

Primordial Atmosphere

1. We could use **Taurex to retrieve the mass with more accuracy** than that estimate with other methods (accuracy ~ 10% for a clear sky planet).
2. A estimation of the **mass with an uncertainty ~ 40%** could allow us to more accurate retrieve the trace composition of the atmosphere (in particular for the CO mix ratio)
3. We need a **more precise estimation of the mass and/or higher S/N** to correctly retrieve the trace composition of the atmosphere for a **Neptunian planet around a G star in the cloudy cases**.

Secondary Atmosphere

1. We could be able to **use Taurex to retrieve the mass with a more accuracy** than that known.
2. In the cases with lower S/N a more accurate estimation of the mass could not be useful to a correct retrieval of the atmospheric composition. In this cases only an increase of the S/N ratio could bring us to a correctly atmospheric retrieval.

Next steps

- Retrieval of the main components of a primary atmosphere in presence of clouds with less accurate estimation of the mass (from 40% to 20%)
- Try to correct the mass estimation in presence of high altitude clouds to improve the accuracy of the atmospheric retrieval
- Secondary Atmosphere cases with different altitude of clouds