

ARES VI:
**Are 1D retrieval models accurate enough to
characterize exo-atmospheres with transmission
spectroscopy in the era of JWST and Ariel?**

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Ariel France - February, 18th 2024





Goals and scientific questions?

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Goals and scientific questions?

How does the **3D atmospheric structure** affect the **transmission spectra** of exoplanets, from a cold planet to an ultra-hot Jupiter?



Goals and scientific questions?

How does the **3D atmospheric structure** affect the **transmission spectra** of exoplanets, from a cold planet to an ultra-hot Jupiter?

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?



Analysis pipeline

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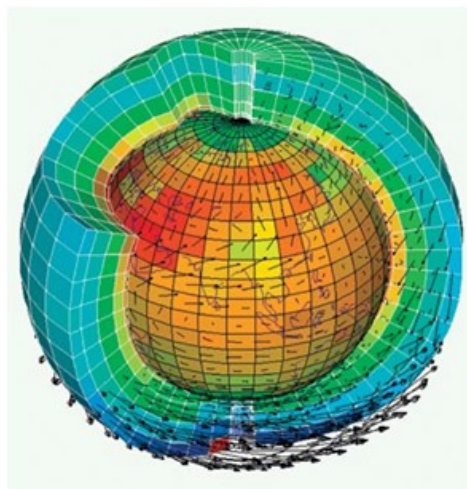
Analysis pipeline

Leconte (2021)



Deals with all different format of opacities

Global Climate Model
Generic 3D



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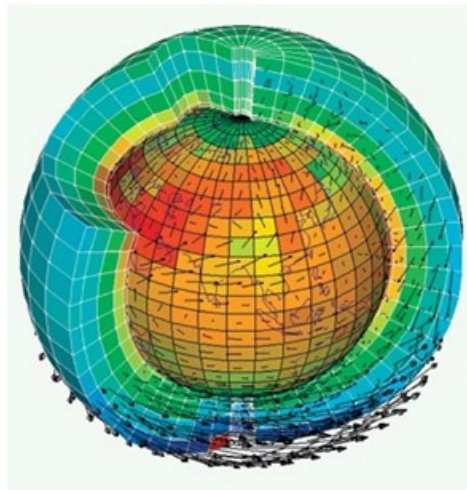
Analysis pipeline

Leconte (2021)



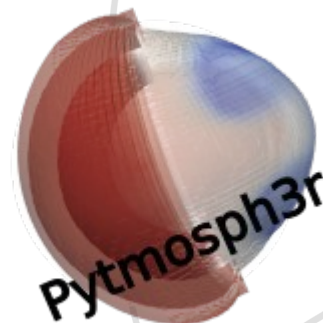
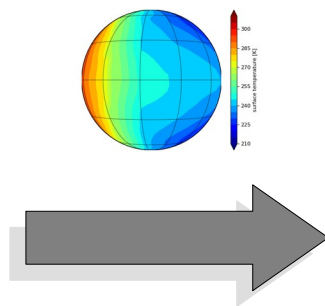
Deals with all different format of opacities

Global Climate Model
Generic 3D



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Pytmosph3r
Transit 3D



Falco et al. (2021)

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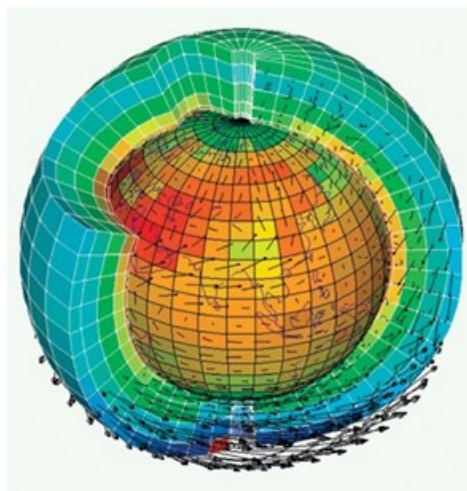
Analysis pipeline

Leconte (2021)



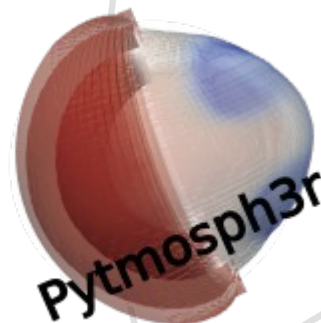
Deals with all different format of opacities

Global Climate Model
Generic 3D



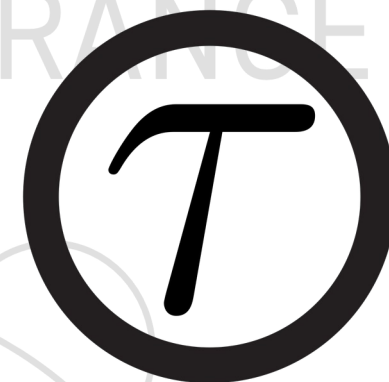
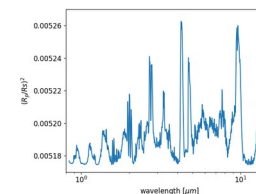
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Pytmosph3r
Transit 3D



Falco et al. (2021)

TauREx
Retrieval 1D



Al-Rafaie et al. (2019)



Modelling: Global Climate Model

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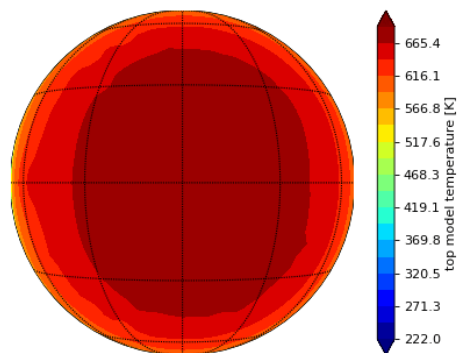


Modelling: Global Climate Model

GJ1214 b

Warm sub-Neptune

$$T_{\text{eq}} = 600 \text{ K}$$



Charnay et al. (2015)

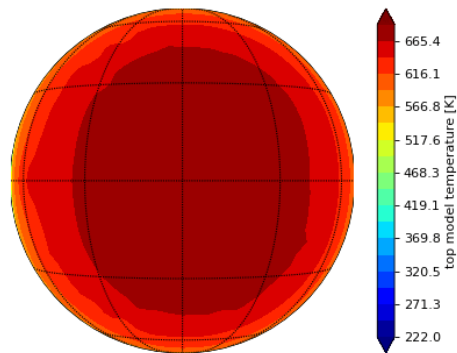
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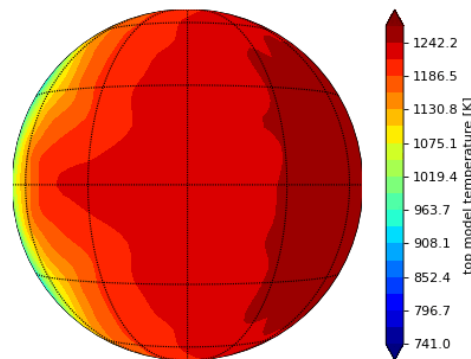
Modelling: Global Climate Model

| GJ1214 b | HD189733 b |
|--------------------------|---------------------------|
| Warm sub-Neptune | Hot Jupiter |
| $T_{eq} = 600 \text{ K}$ | $T_{eq} = 1200 \text{ K}$ |

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Charnay et al. (2015)

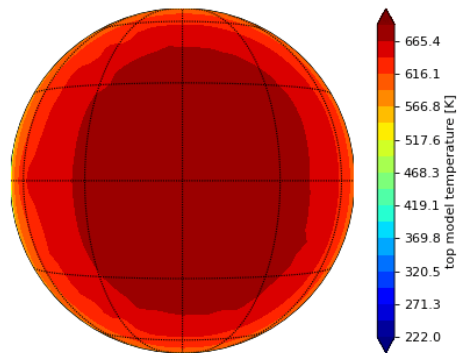


Drummond et al. (2018)

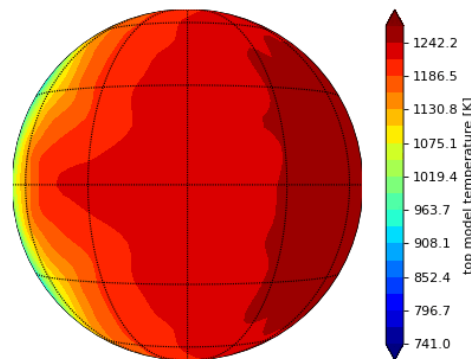


Modelling: Global Climate Model

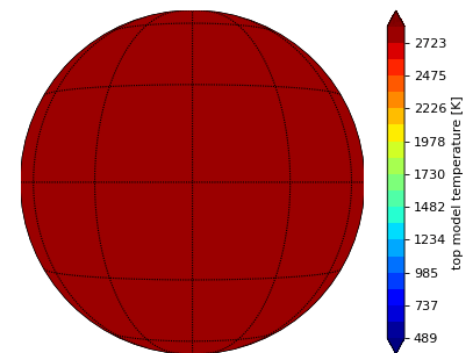
| GJ1214 b | HD189733 b | WASP-121 b |
|--------------------------|---------------------------|---------------------------|
| Warm sub-Neptune | Hot Jupiter | Ultra hot Jupiter |
| $T_{eq} = 600 \text{ K}$ | $T_{eq} = 1200 \text{ K}$ | $T_{eq} = 2400 \text{ K}$ |



Charnay et al. (2015)



Drummond et al. (2018)



Parmentier et al. (2018)



Modelling: Observations

Tools: pytmosph3R (*Falco et al. 2021*)

From 1D to 3D

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Modelling: Observations

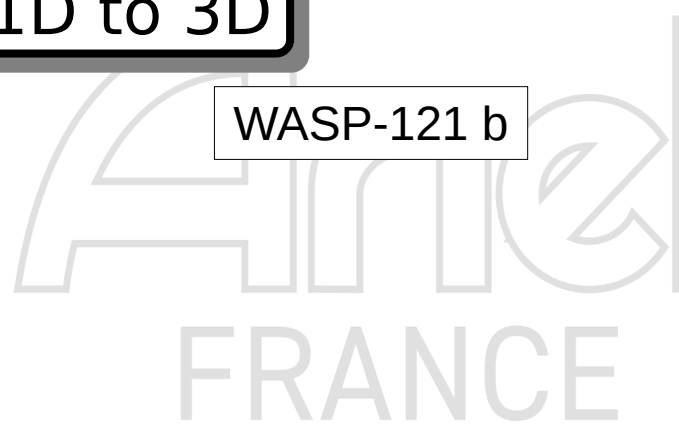
Tools: pytmosph3R (*Falco et al. 2021*)

From 1D to 3D

GJ1214 b

HD189733 b

WASP-121 b





Modelling: Observations

Tools: pytmosph3R (*Falco et al. 2021*)

From 1D to 3D

GJ1214 b

HD189733 b

WASP-121 b

Constant chemistry



Modelling: Observations

Tools: pytmosph3R (*Falco et al. 2021*)

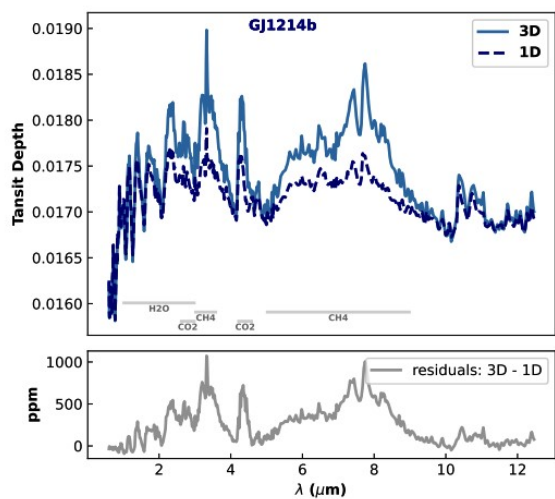
From 1D to 3D

GJ1214 b

HD189733 b

WASP-121 b

Constant chemistry





Modelling: Observations

Tools: pytmosph3R (*Falco et al. 2021*)

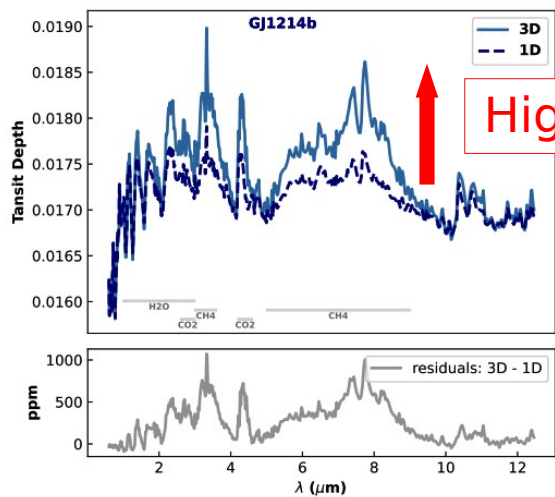
From 1D to 3D

GJ1214 b

HD189733 b

WASP-121 b

Constant chemistry



Higher probe scale height in 3D



Modelling: Observations

Tools: pytmosph3R (Falco et al. 2021)

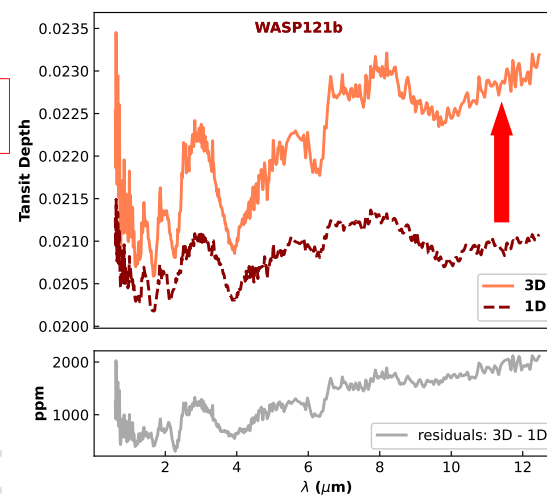
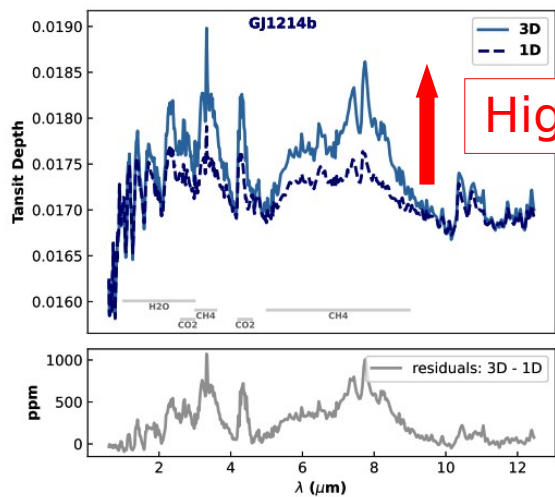
From 1D to 3D

GJ1214 b

HD189733 b

WASP-121 b

Constant chemistry





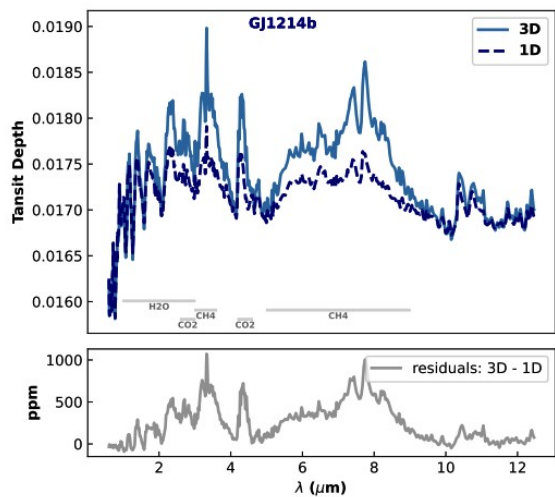
Modelling: Observations

Tools: pytmosph3R (Falco et al. 2021)

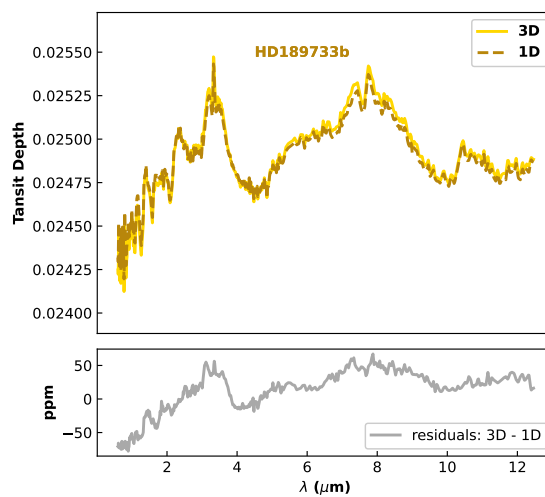
From 1D to 3D

Constant chemistry

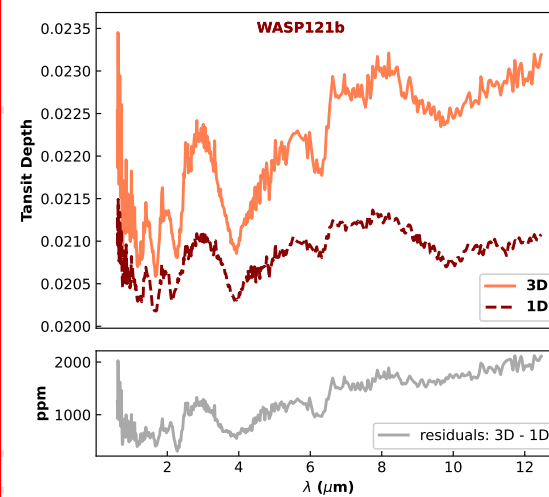
GJ1214 b



HD189733 b



WASP-121 b



High gravity → low change of scale height

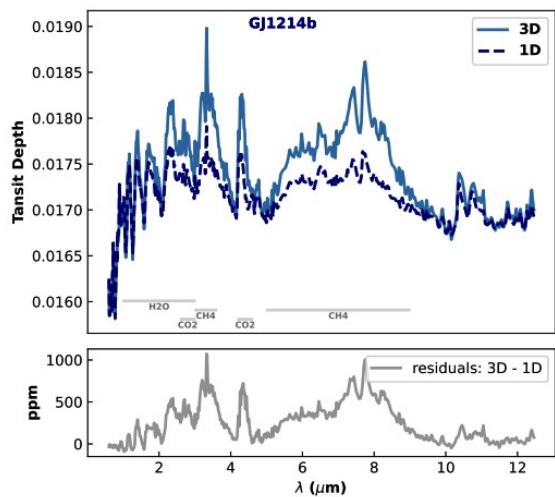


Modelling: Observations

Tools: pytmosph3R (*Falco et al. 2021*)

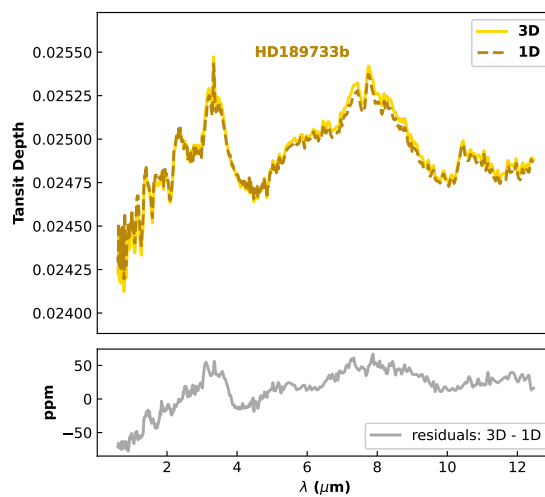
From 1D to 3D

GJ1214 b



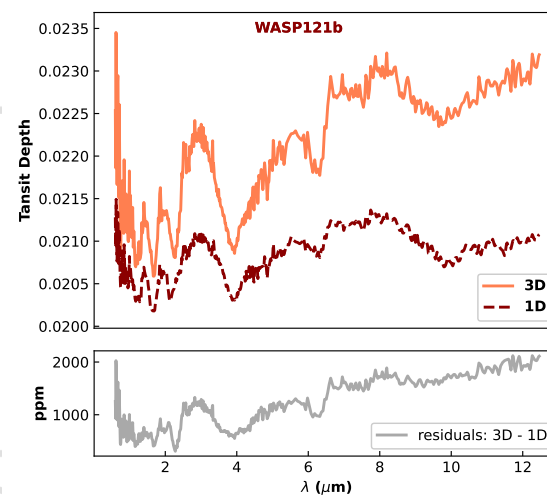
Constant chemistry

HD189733 b



Equilibrium chemistry

WASP-121 b





Modelling: Observations

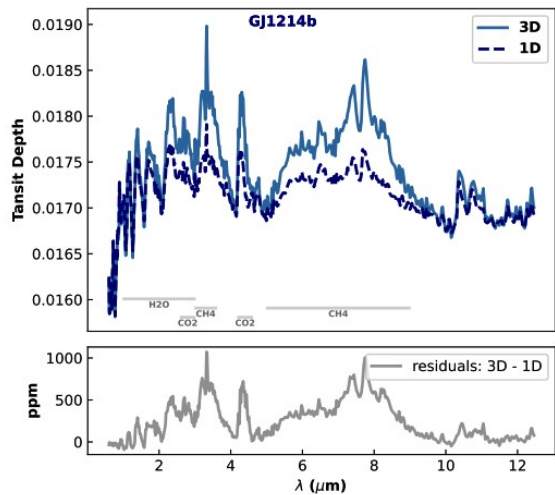
Tools: pytmosph3R (Falco et al. 2021)

From 1D to 3D

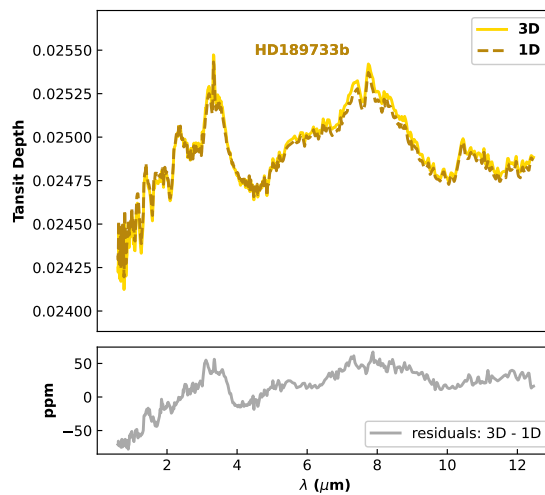
Constant chemistry

Equilibrium chemistry

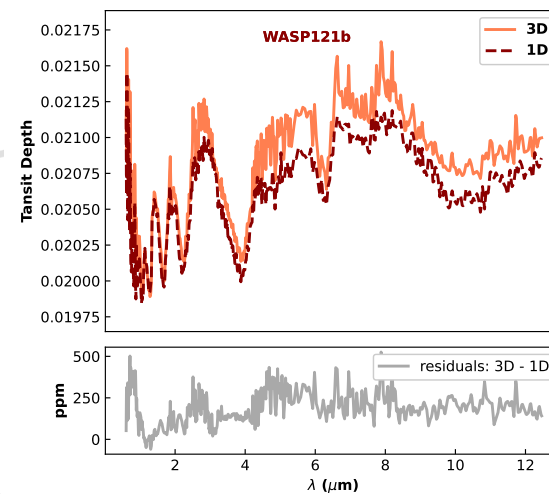
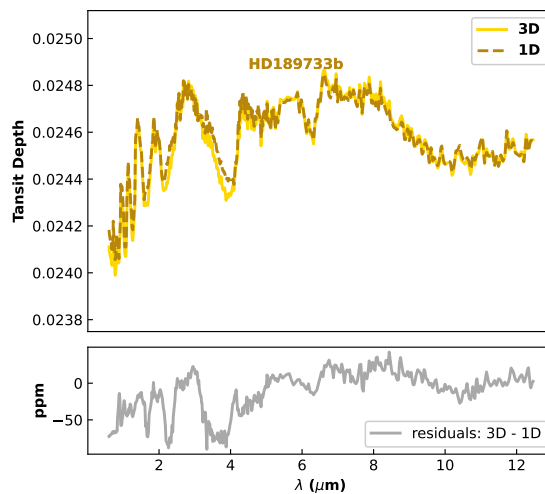
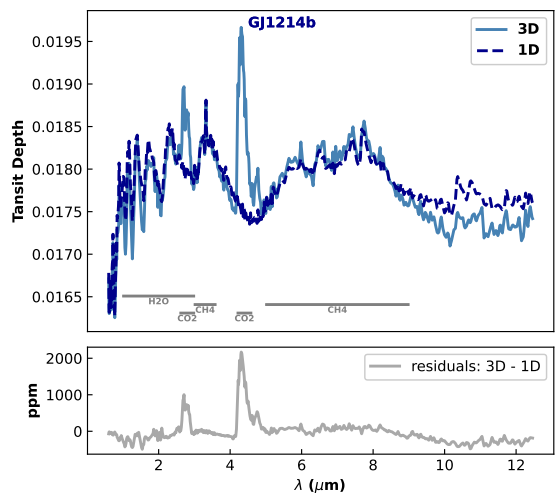
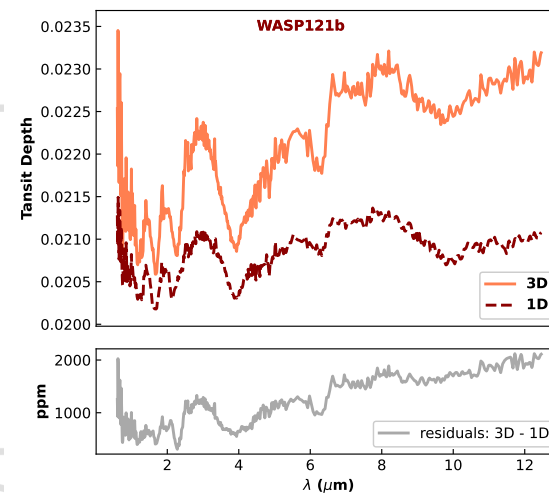
GJ1214 b



HD189733 b



WASP-121 b





Modelling: Observations

Tools: pytmosph3R (Falco et al. 2021)

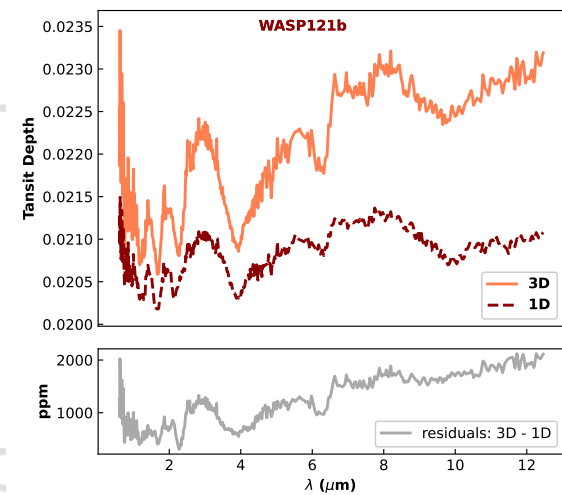
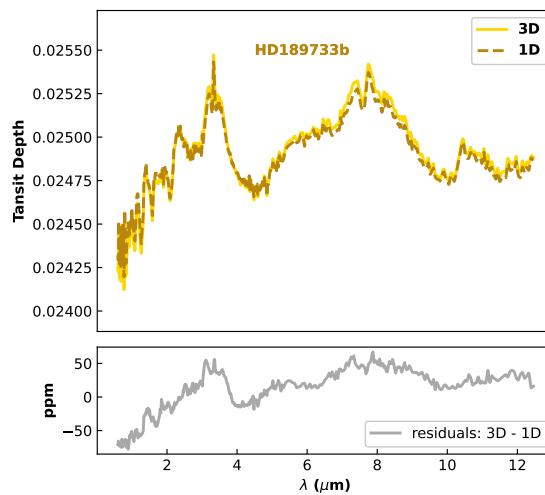
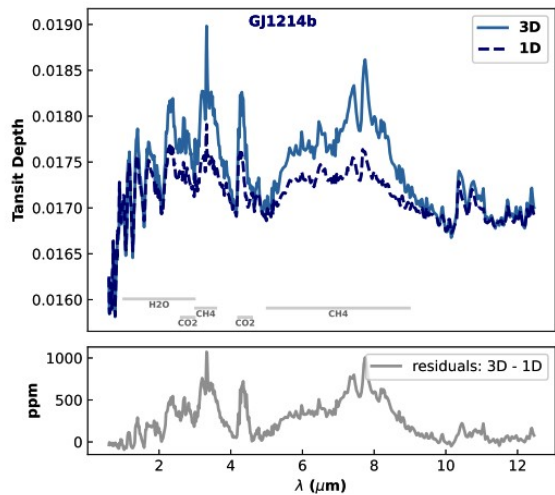
From 1D to 3D

GJ1214 b

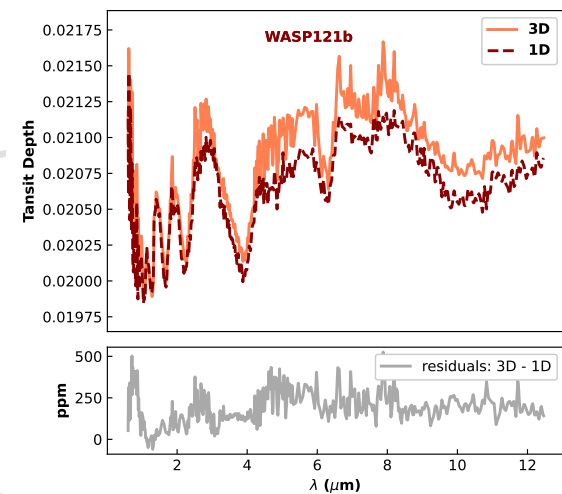
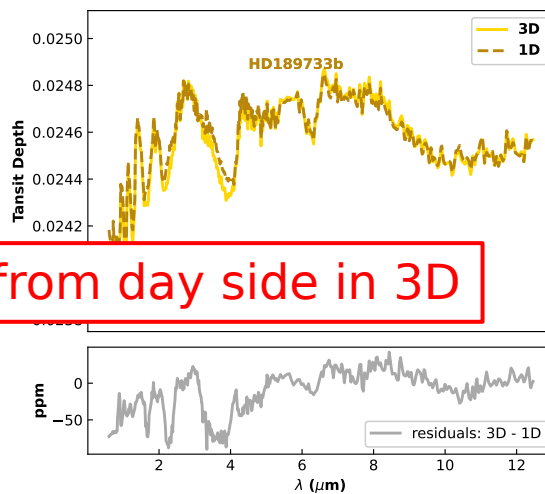
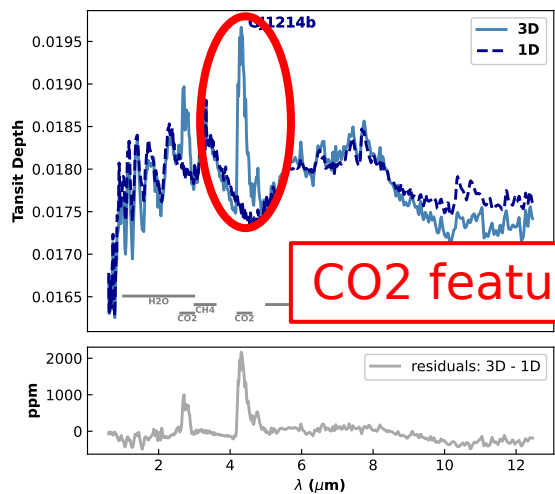
HD189733 b

WASP-121 b

Constant chemistry



Equilibrium chemistry



CO2 feature from day side in 3D



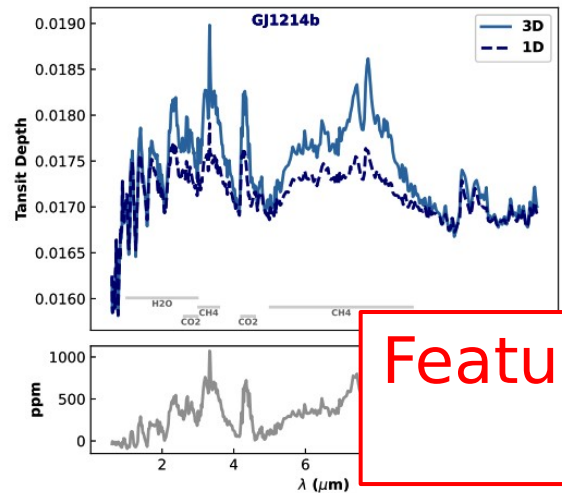
Modelling: Observations

Tools: pytmosph3R (Falco et al. 2021)

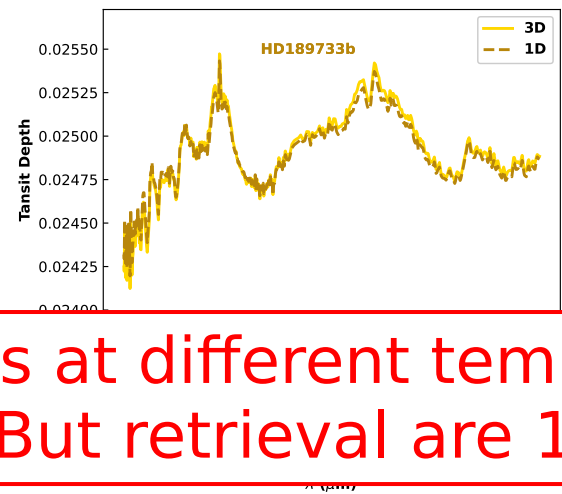
From 1D to 3D

Constant chemistry

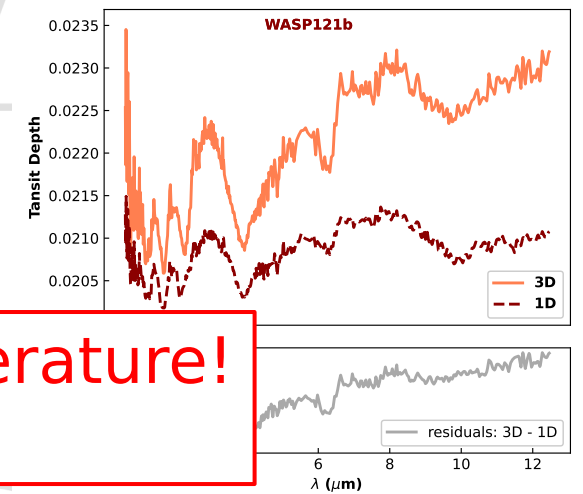
GJ1214 b



HD189733 b

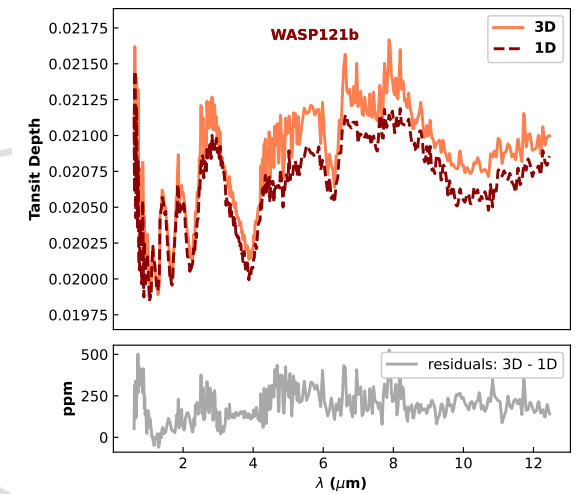
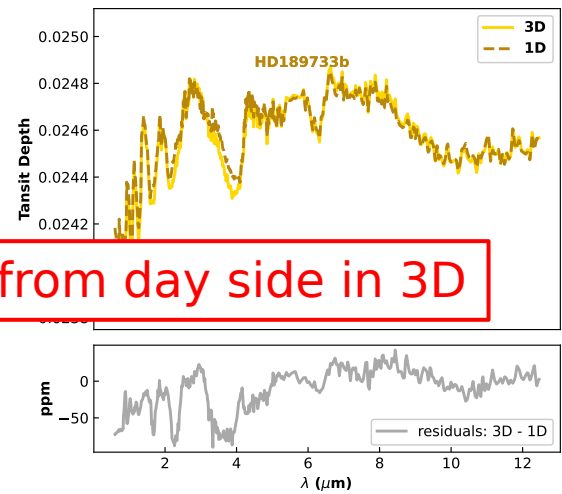
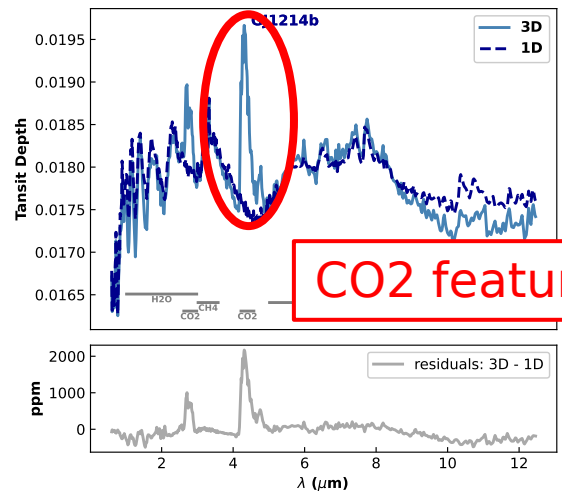


WASP-121 b



Features at different temperature!
But retrieval are 1D

Equilibrium chemistry



CO2 feature from day side in 3D



Summary

How does the **3D atmospheric structure** affect the **transmission spectra** of exoplanets, from a cold planet to an ultra-hot Jupiter?



Summary

How does the **3D atmospheric structure** affect the **transmission spectra** of exoplanets, from a cold planet to an ultra-hot Jupiter?

- Features from different part of the atmosphere and so different temperature



Summary

How does the **3D atmospheric structure** affect the **transmission spectra** of exoplanets, from a cold planet to an ultra-hot Jupiter?

- Features from different part of the atmosphere and so different temperature
- No linear effect from cold to hot planets: depends on the gravity



Retrieval: Log Evidence

Tools: pytmosph3R (*Falco et al. 2021*) + ArielRad (*Mugnai et al. 2020*) + TauREX (*Al-Refaie et al. 2019*)

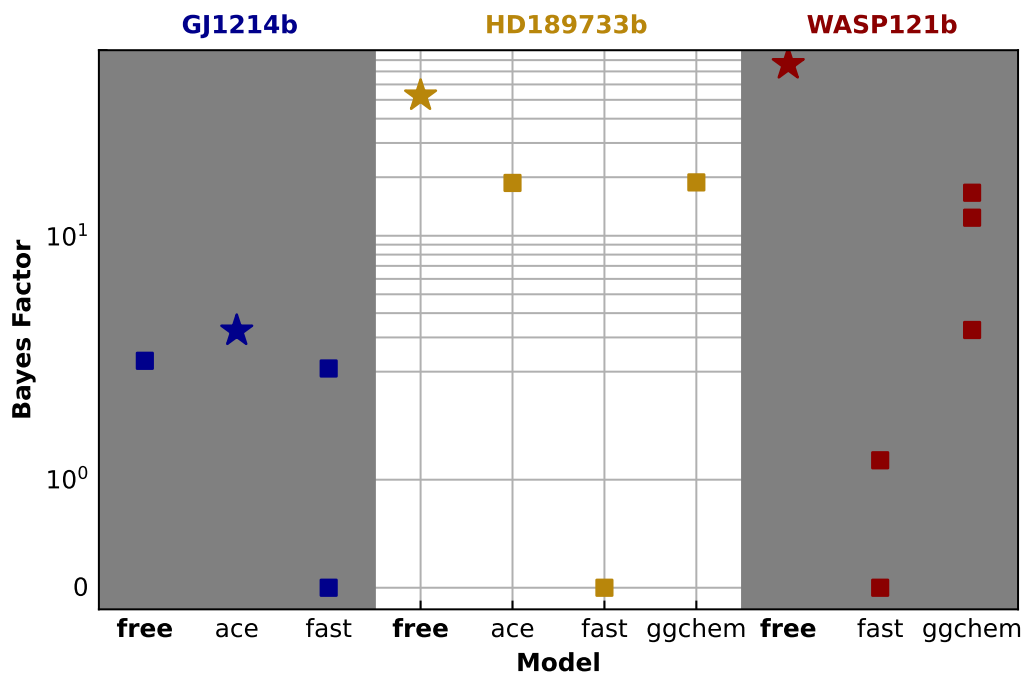
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Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry

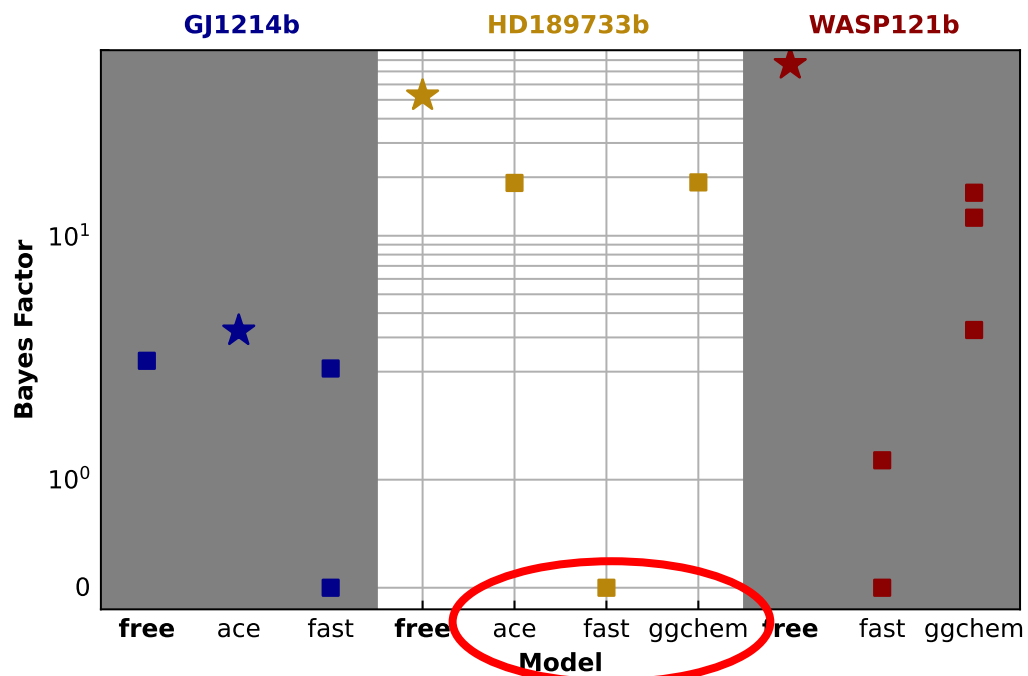




Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry



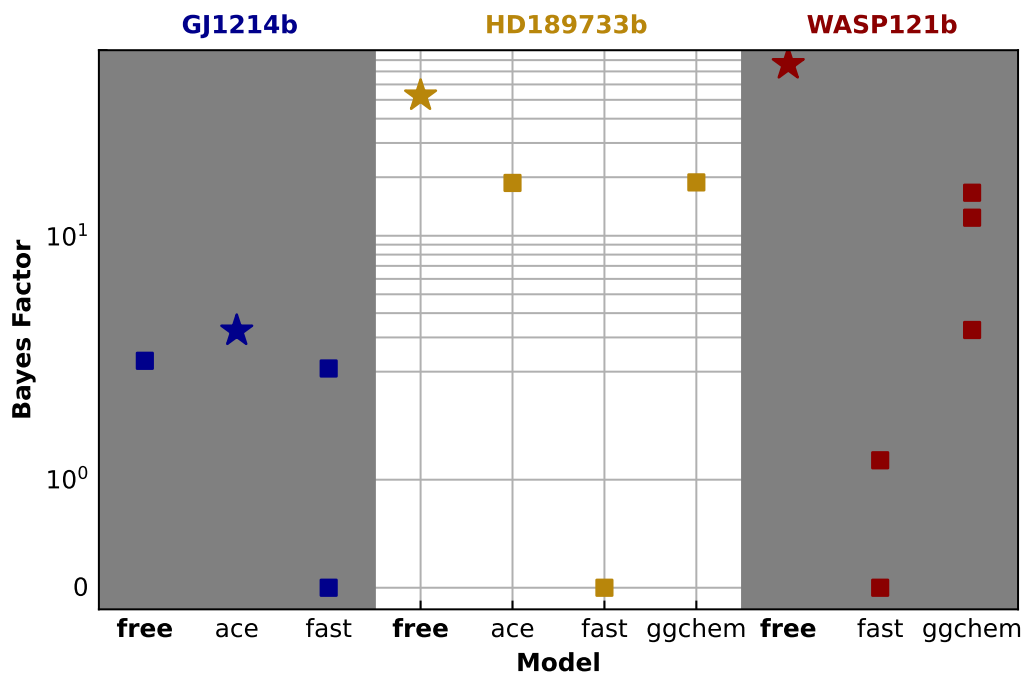
3 different equilibrium chemical models for retrieval



Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry



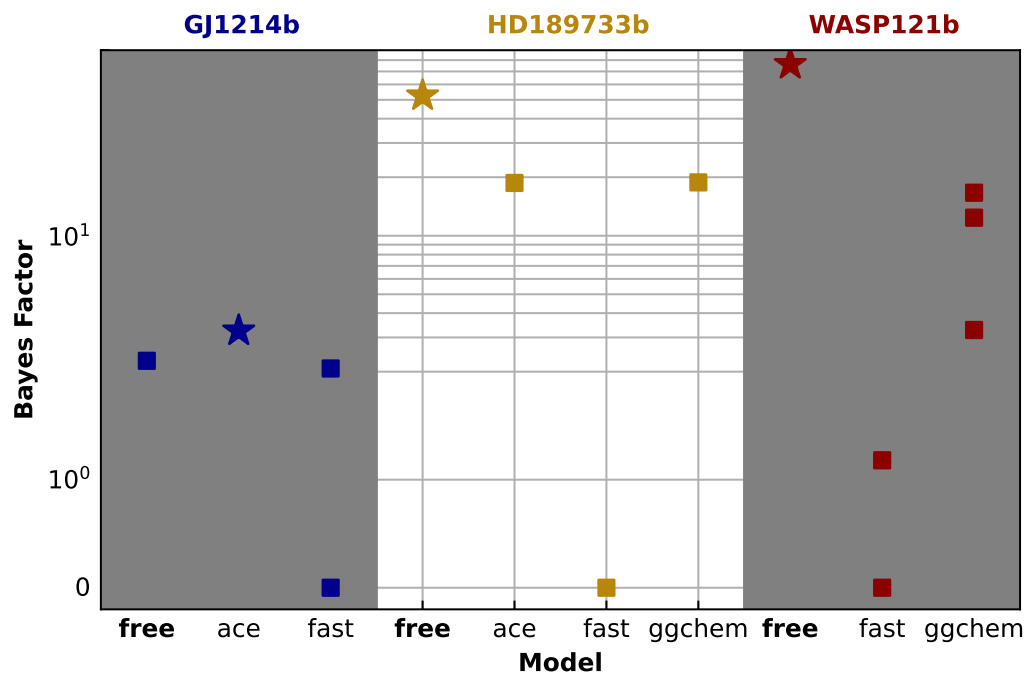
BAD



Retrieval: Log Evidence

Tools: pytmosph3R (*Falco et al. 2021*) + ArielRad (*Mugnai et al. 2020*) + TauREX (*Al-Refaie et al. 2019*)

Constant chemistry



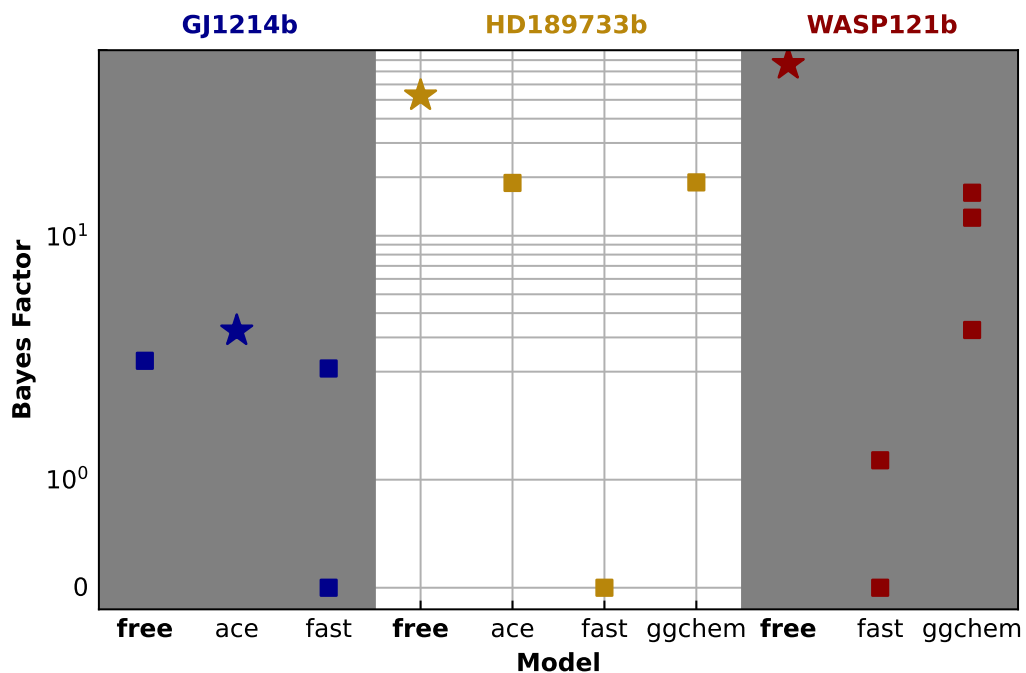
BAD ↑



Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry



Better

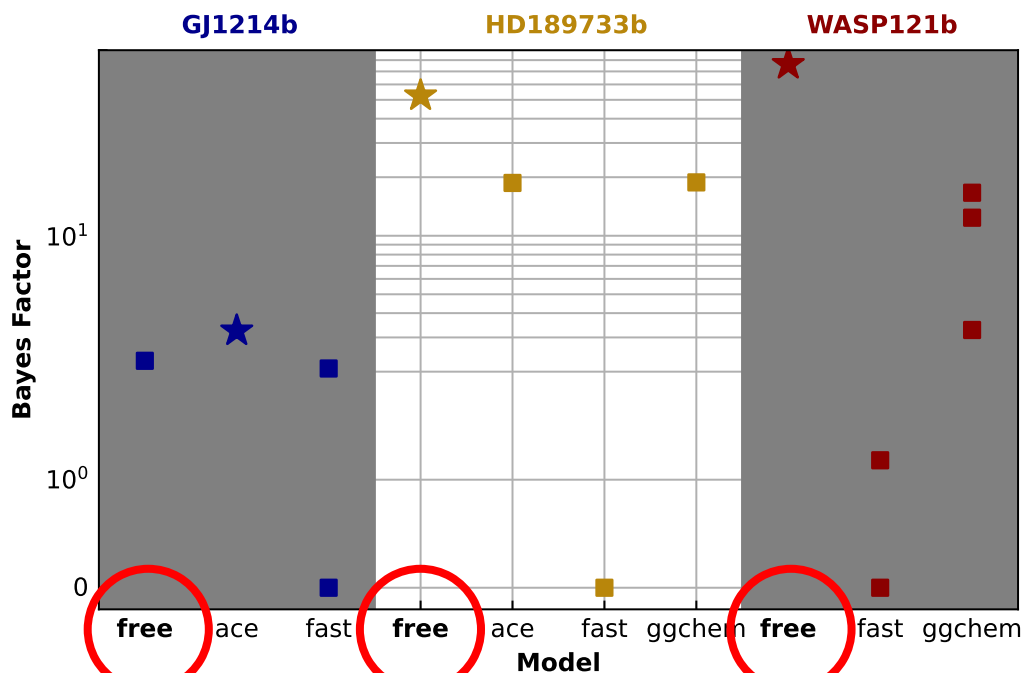
BAD



Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry



Better

BAD

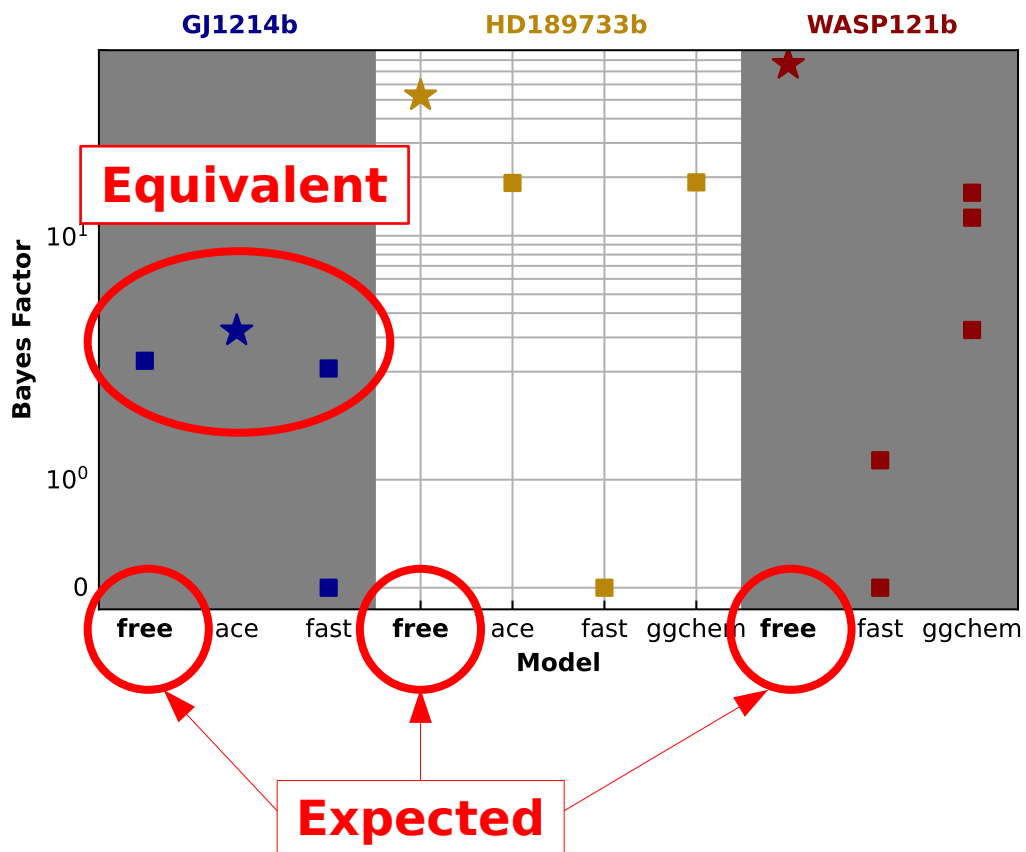
Expected



Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry



Better

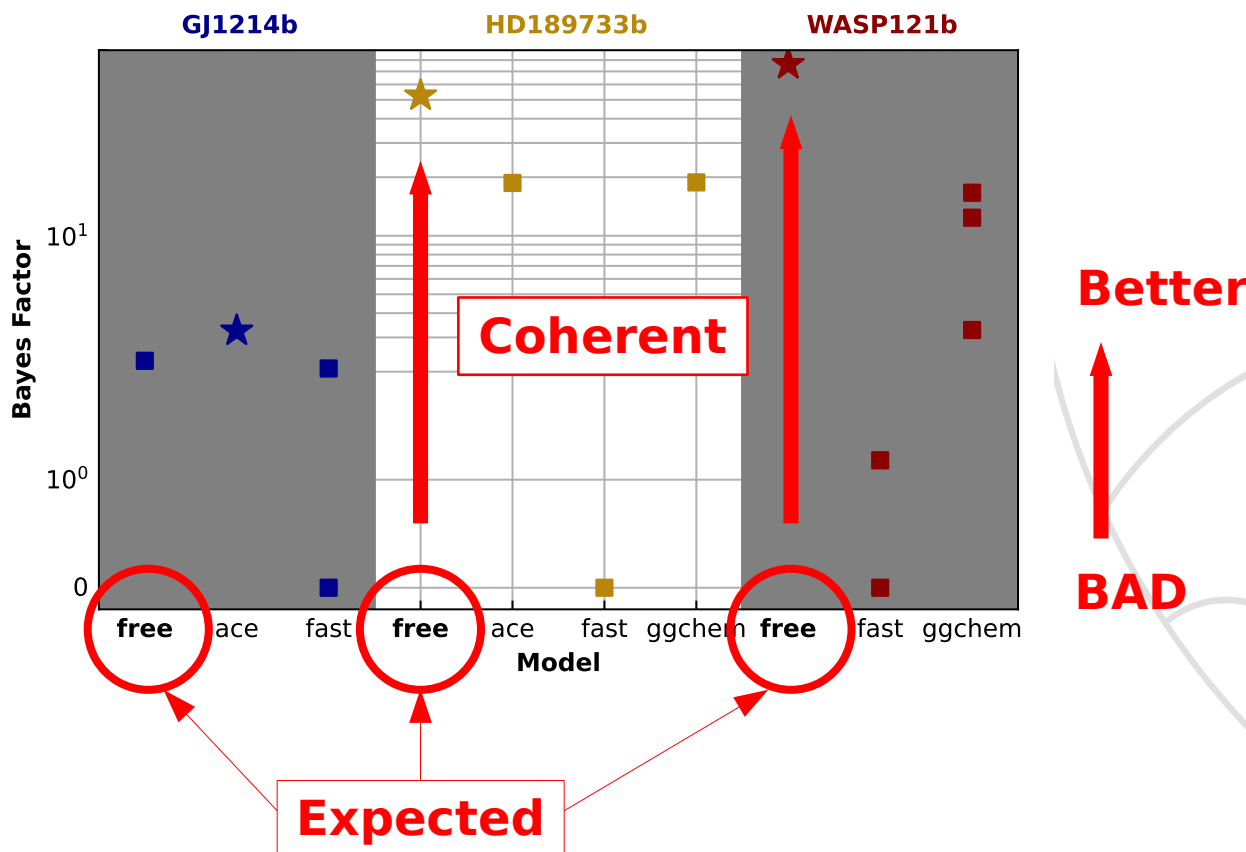
BAD



Retrieval: Log Evidence

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Constant chemistry



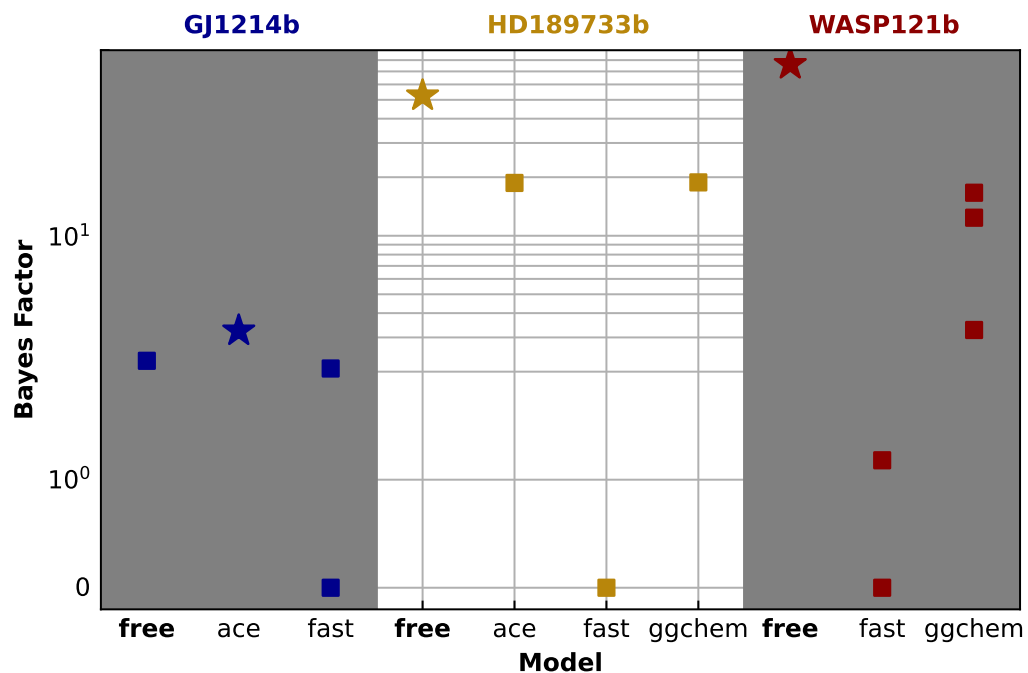


Retrieval: Log Evidence

Tools: pytmosp3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry

Equilibrium chemistry



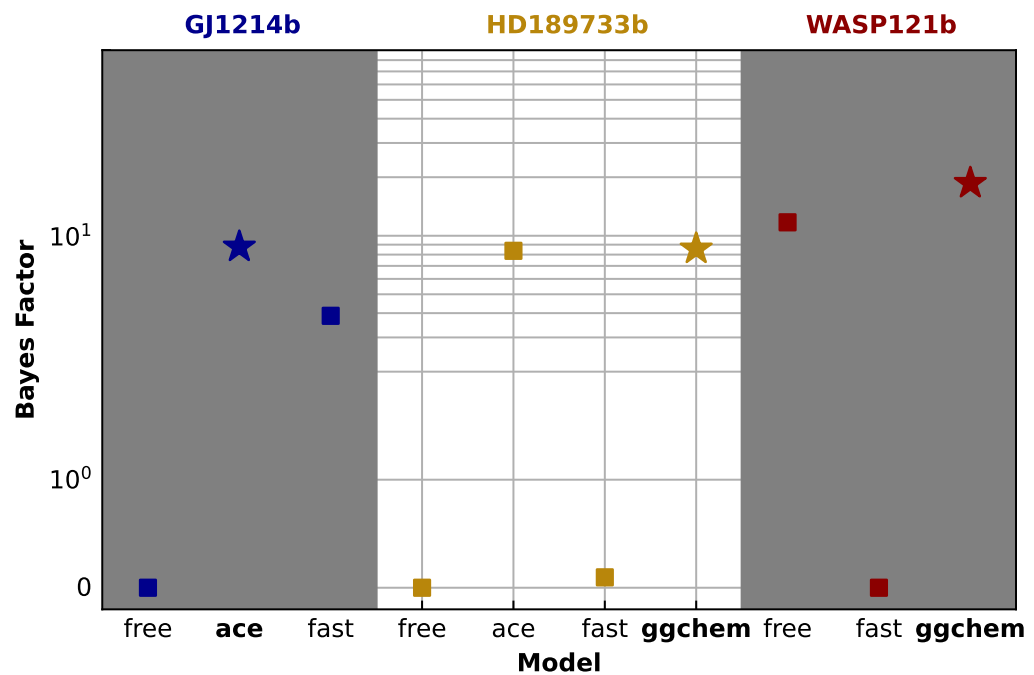
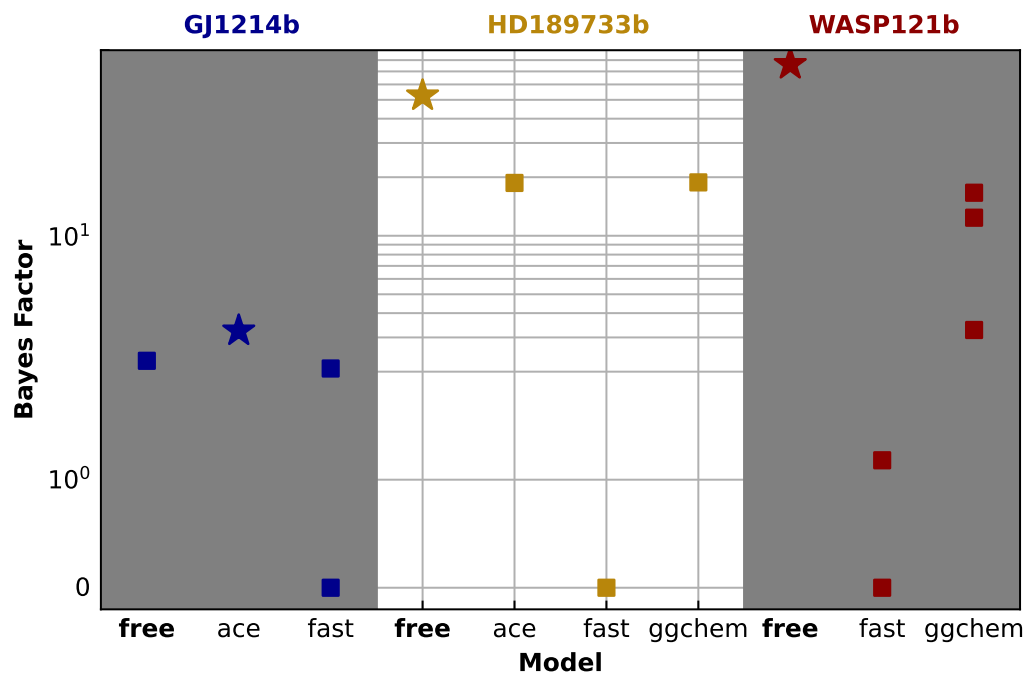


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Constant chemistry

Equilibrium chemistry



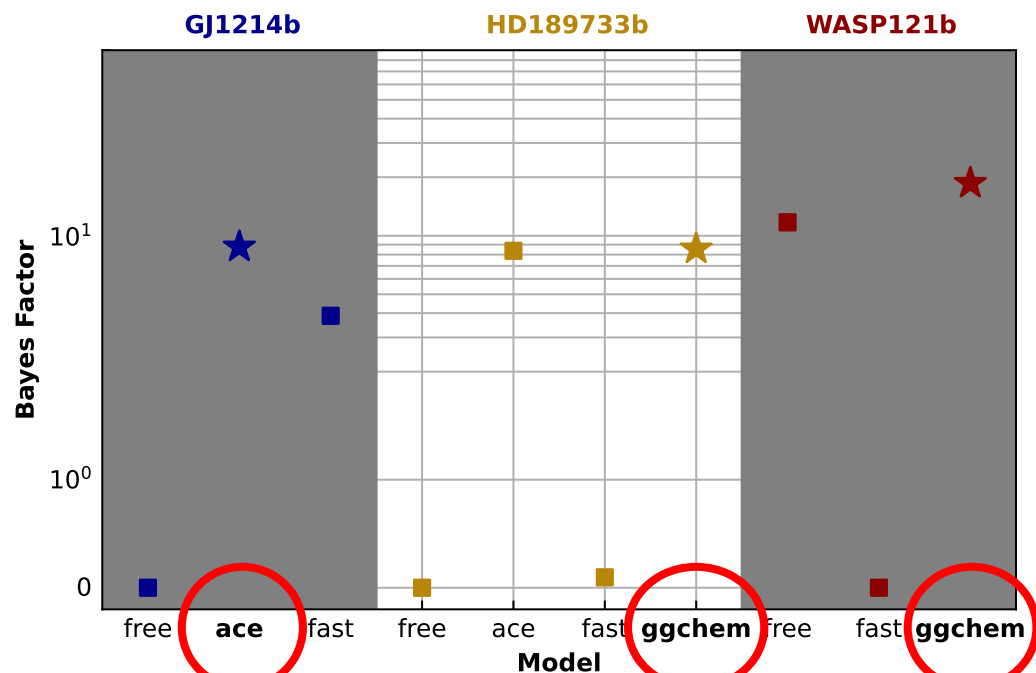
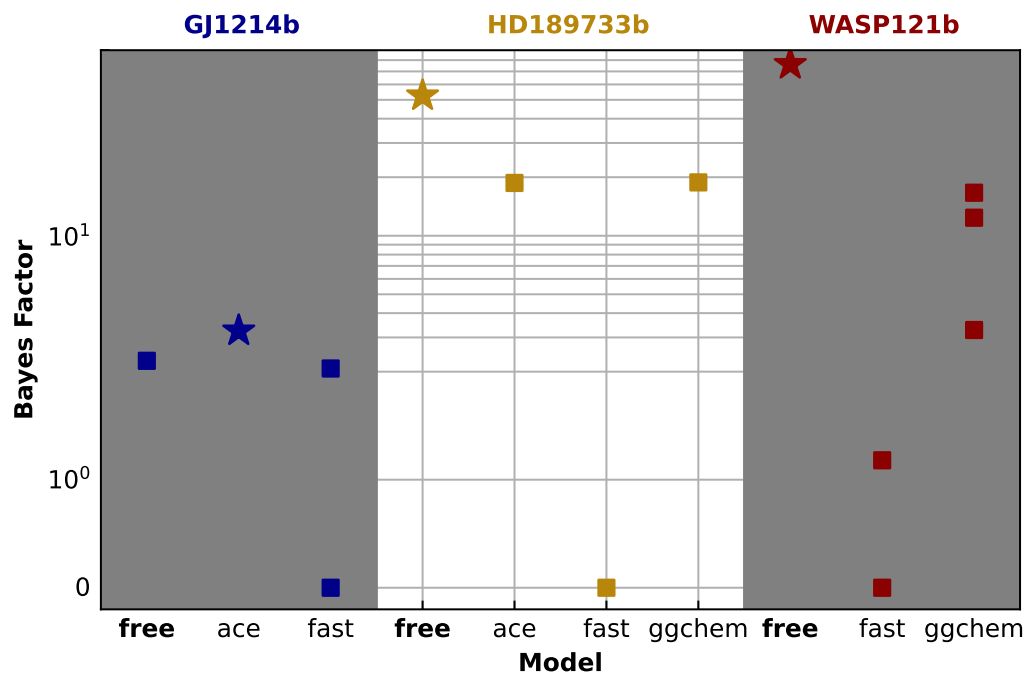


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Constant chemistry

Equilibrium chemistry



Expected

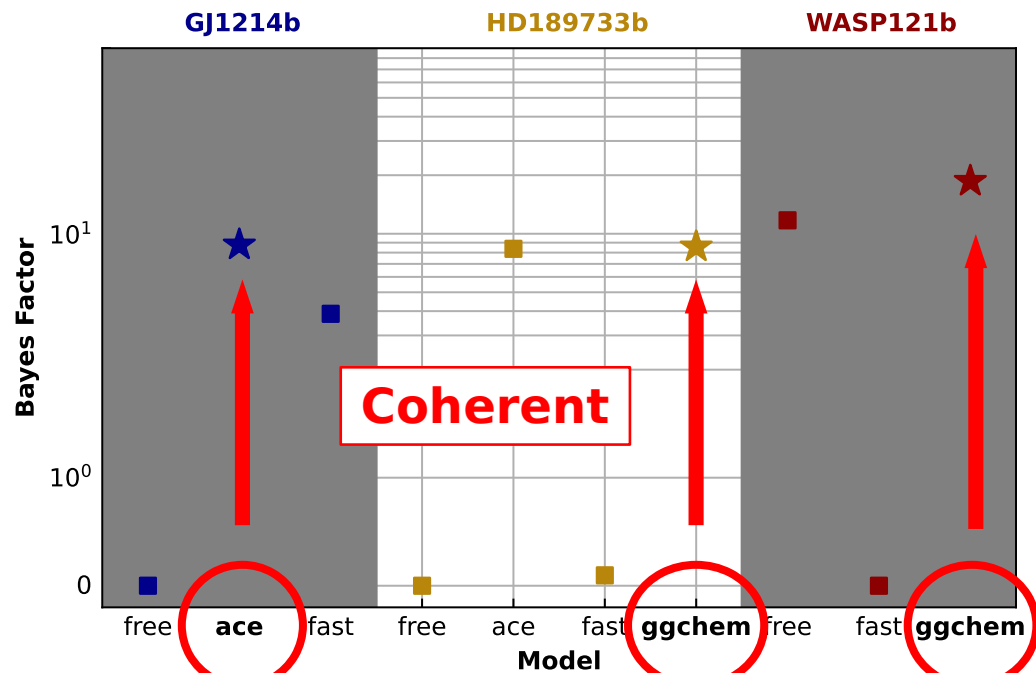
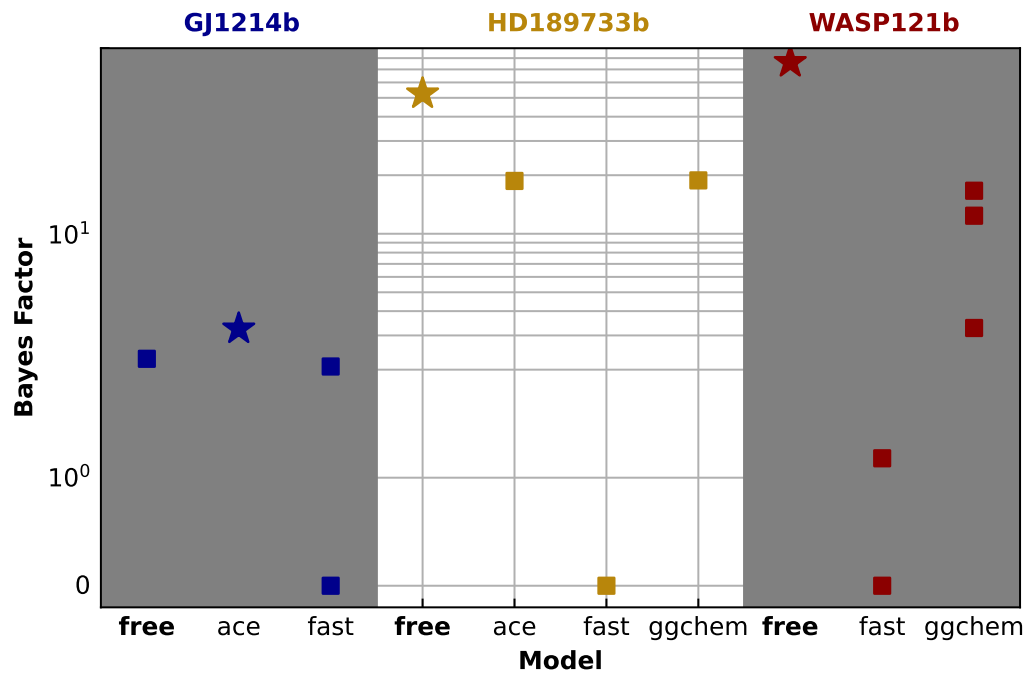


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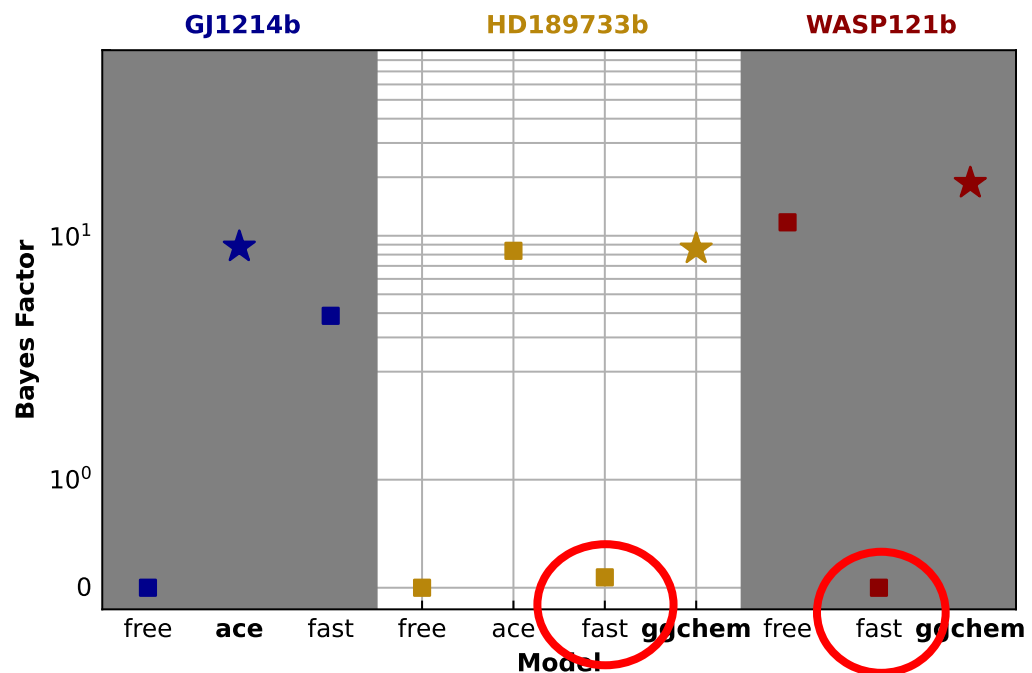
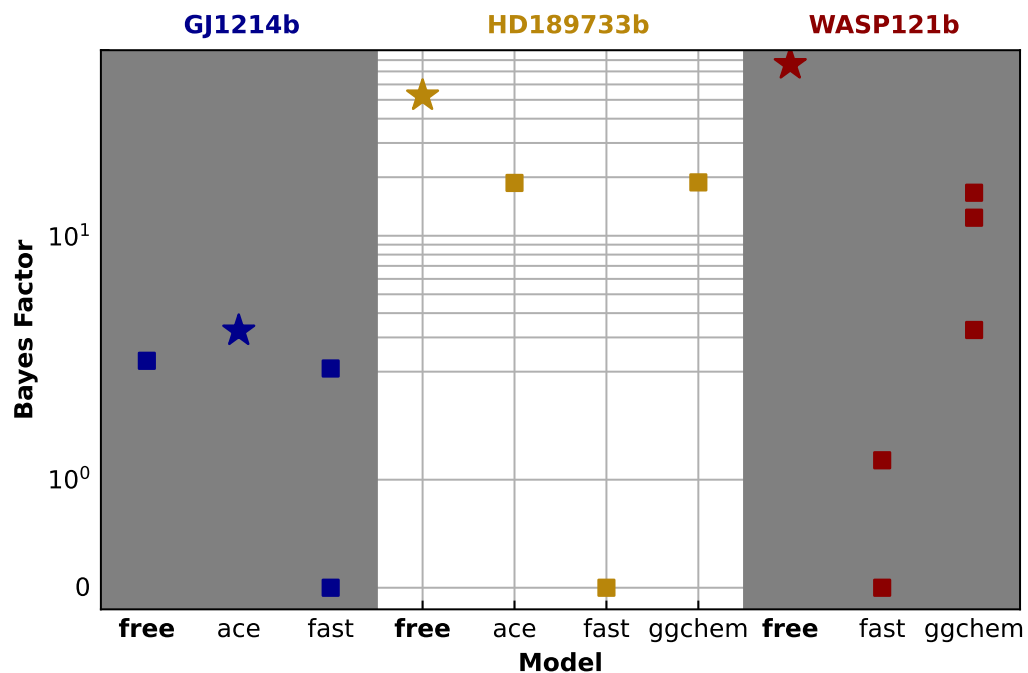


Retrieval: Log Evidence

Tools: pytmosph3R (Falco et al. 2021) + ArielRad (Mugnai et al. 2020) + TauREX (Al-Refaie et al. 2019)

Constant chemistry

Equilibrium chemistry



Bad equilibrium models



Retrieval: Temperature

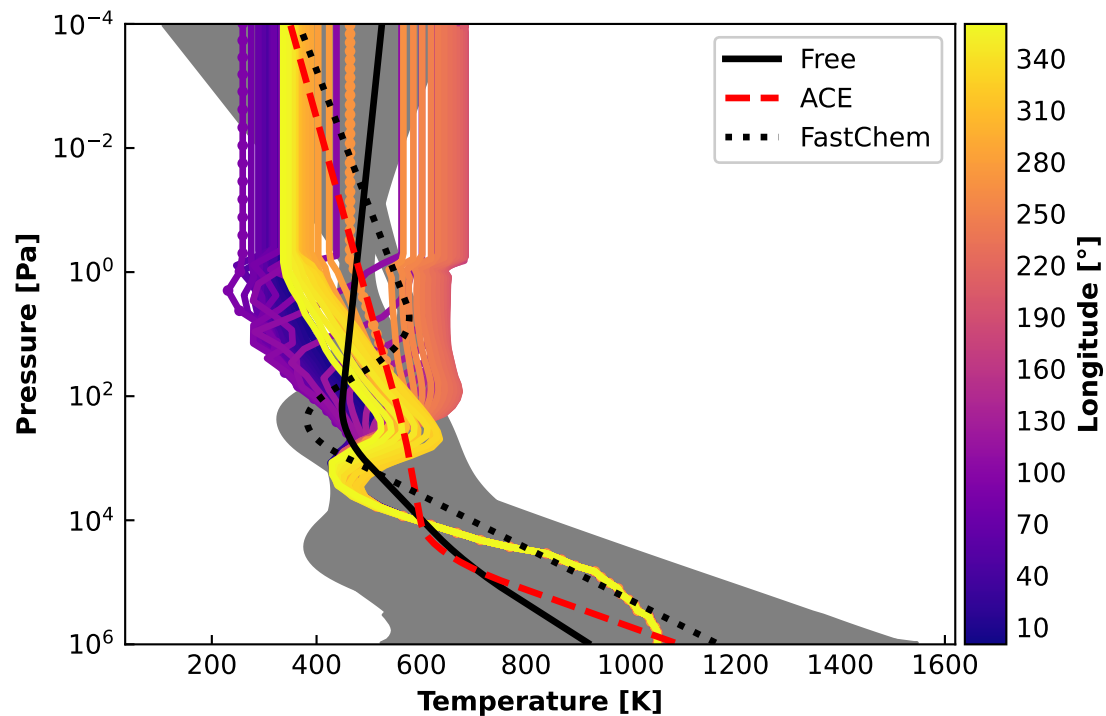
Ariel
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Retrieval: Temperature

GJ1214 b

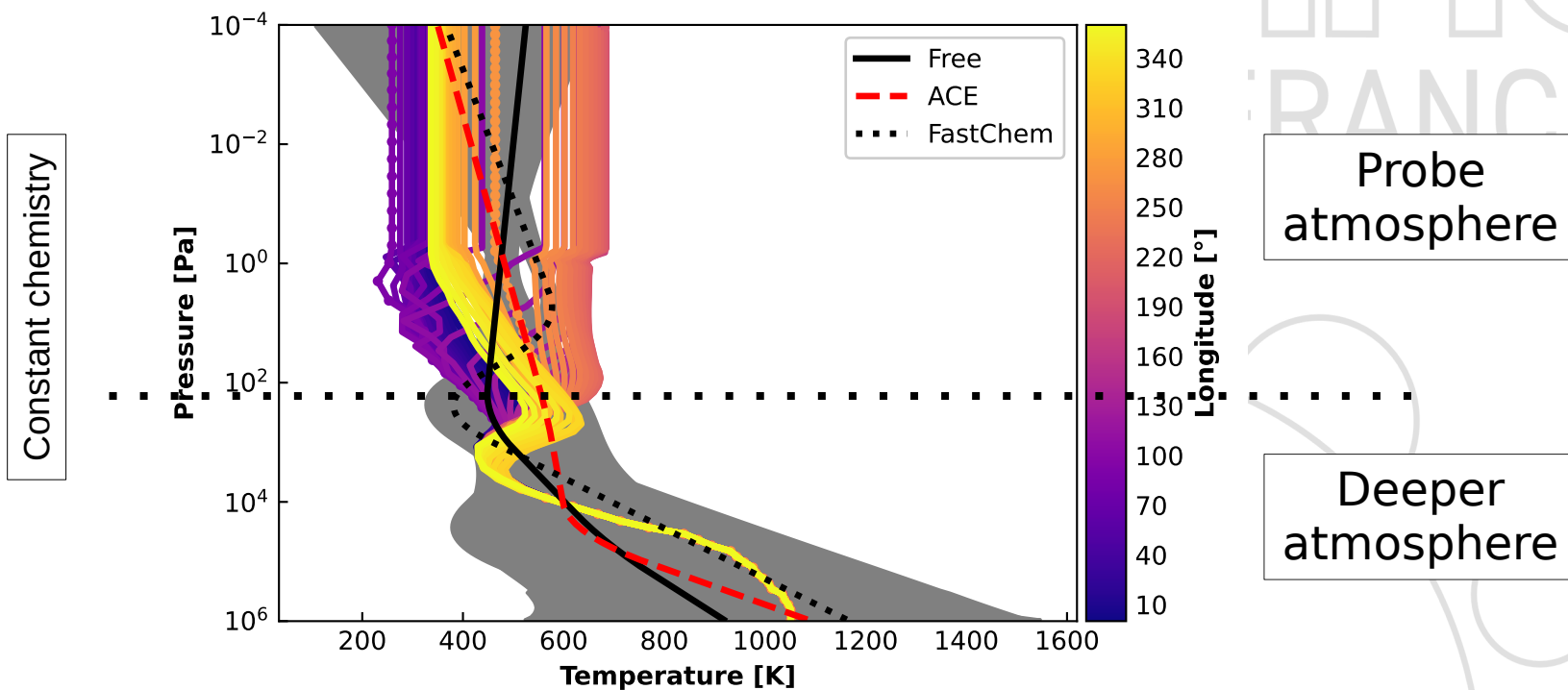
Constant chemistry





Retrieval: Temperature

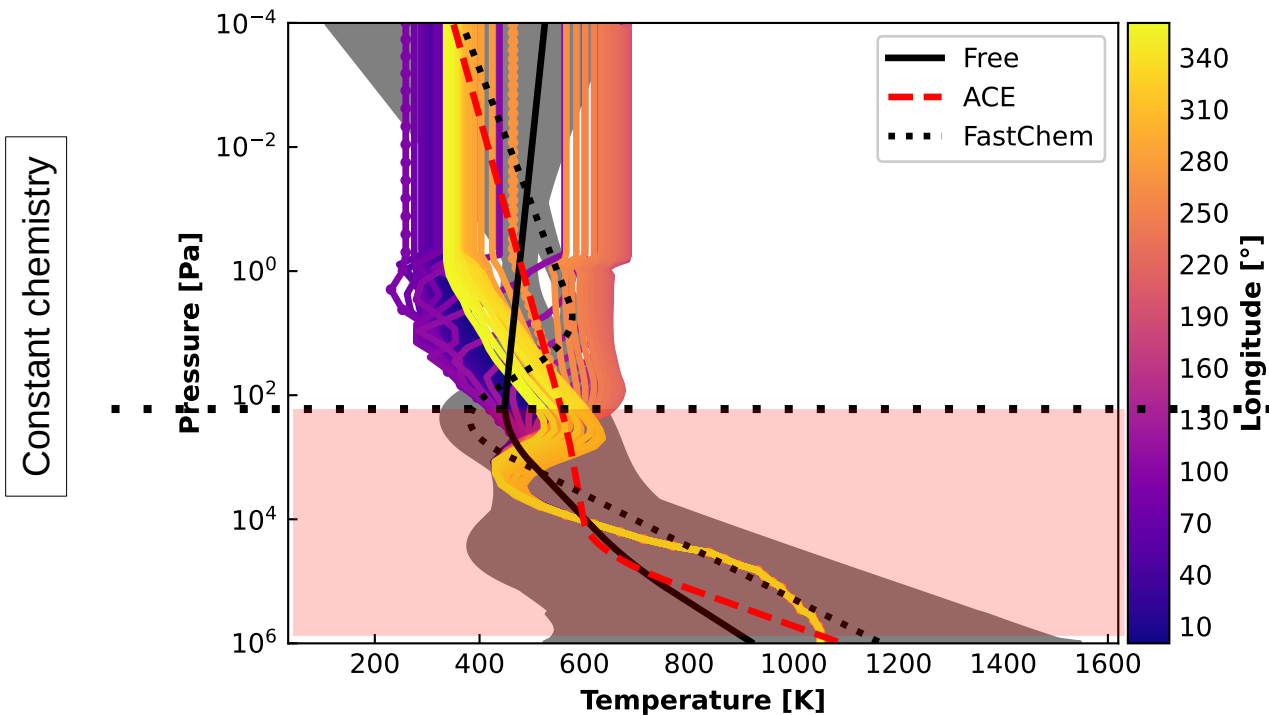
GJ1214 b





Retrieval: Temperature

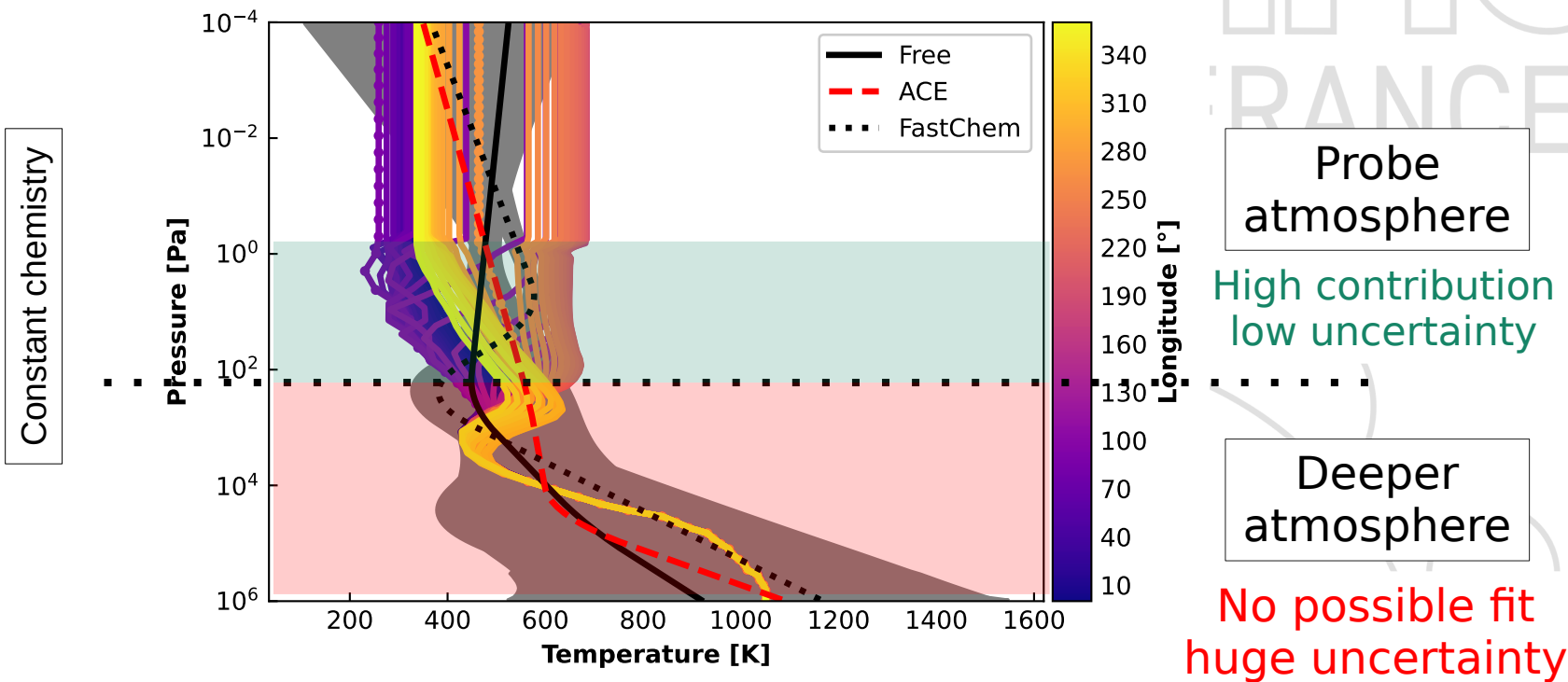
GJ1214 b





Retrieval: Temperature

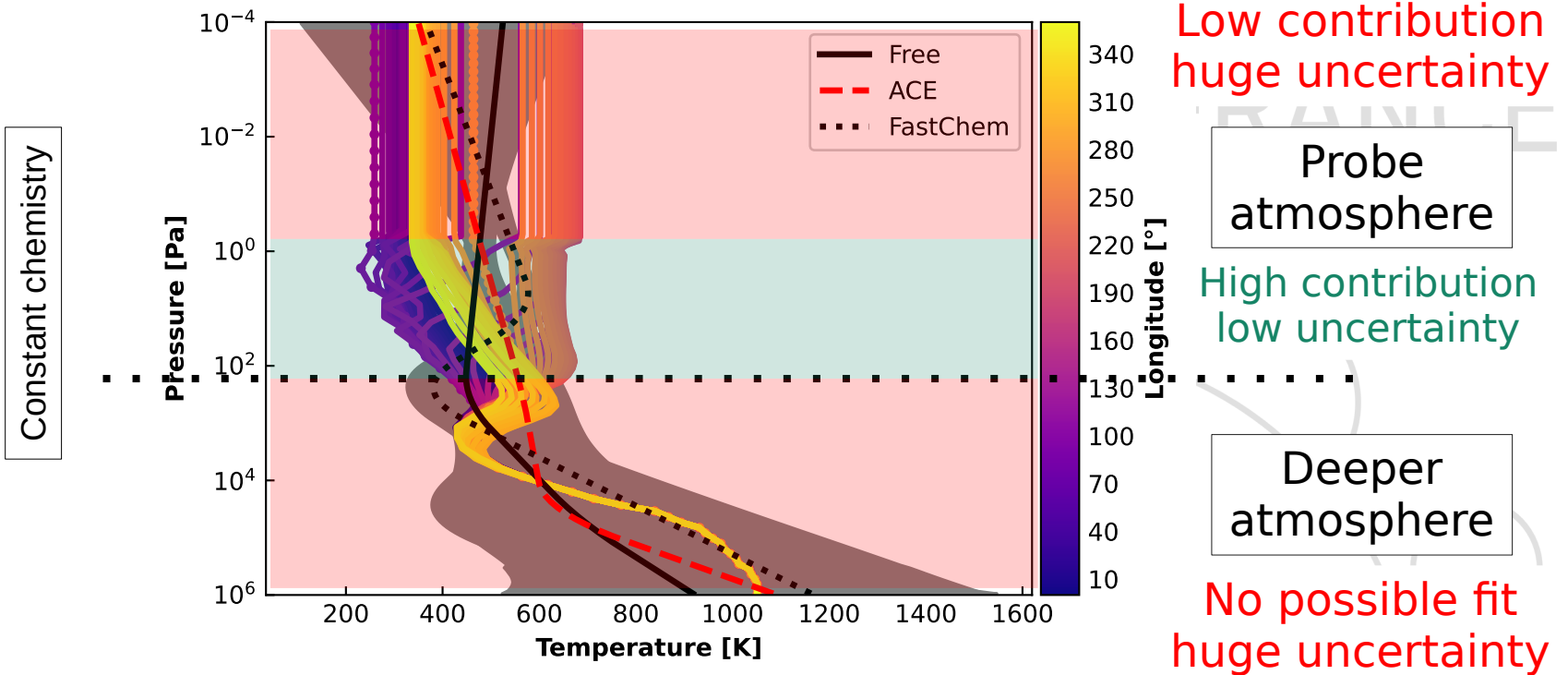
GJ1214 b





Retrieval: Temperature

GJ1214 b





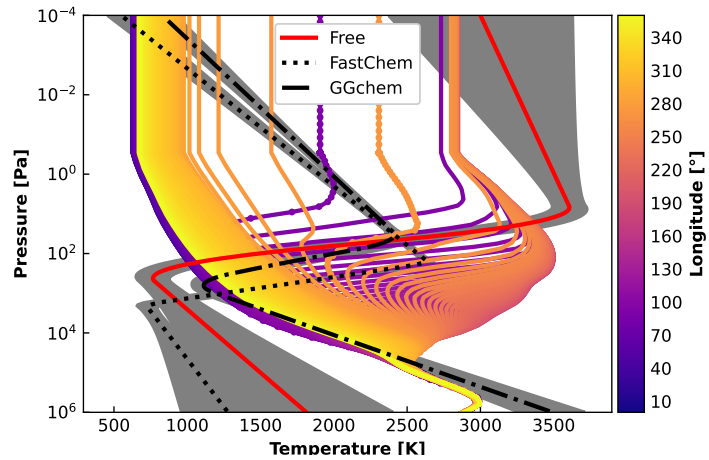
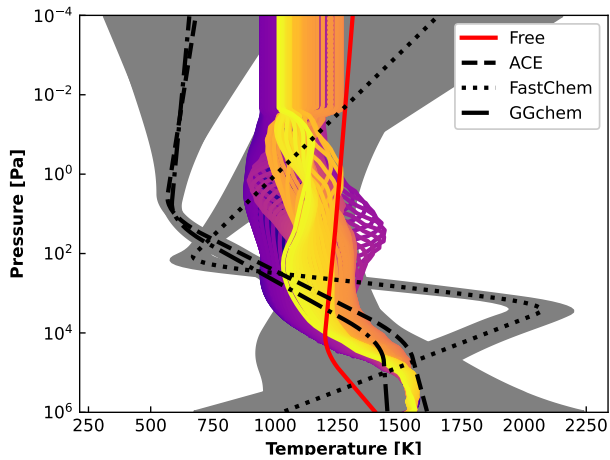
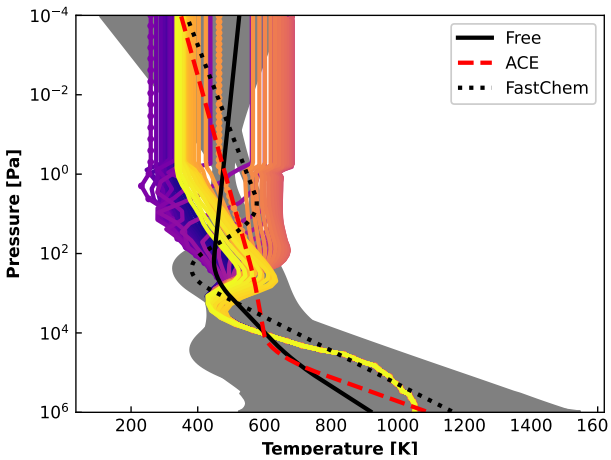
Retrieval: Temperature

GJ1214 b

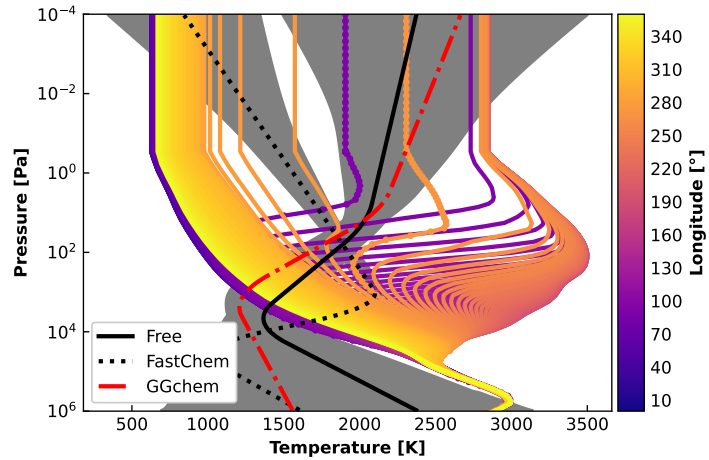
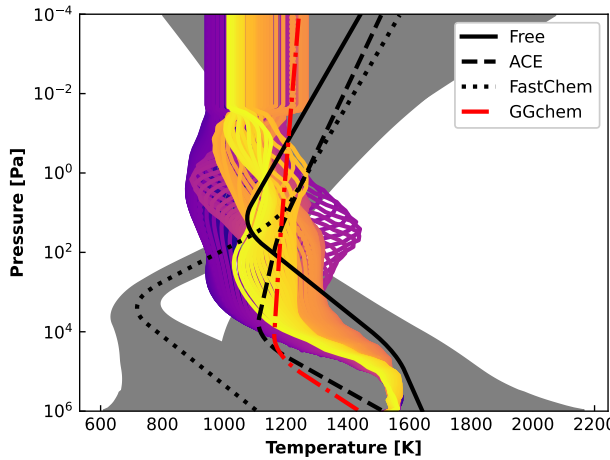
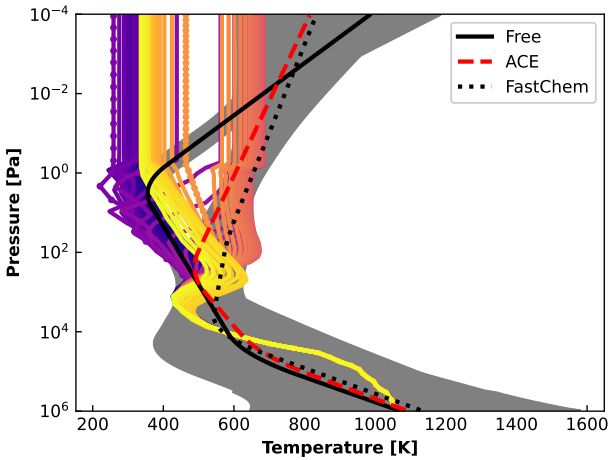
HD189733 b

WASP-121 b

Constant chemistry



Equilibrium chemistry





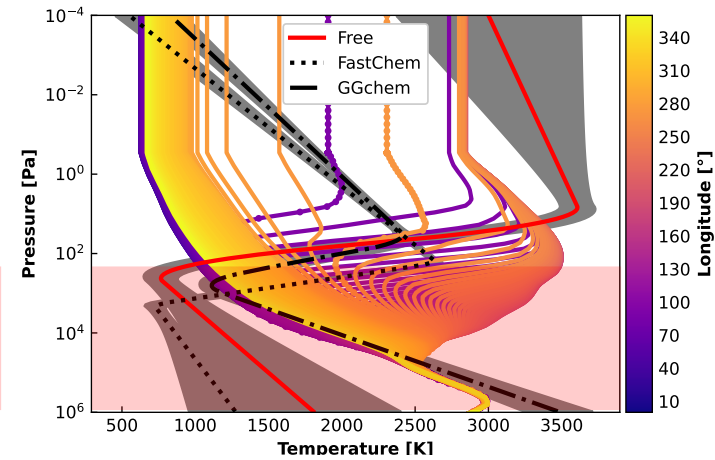
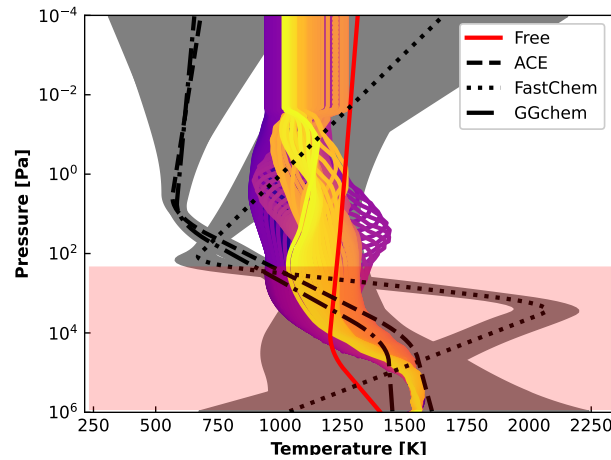
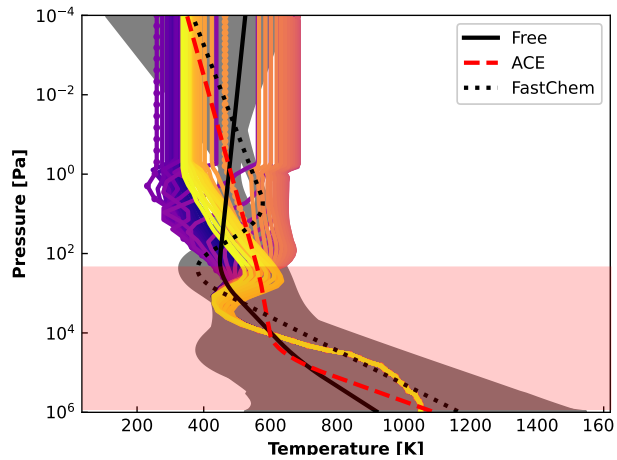
Retrieval: Temperature

GJ1214 b

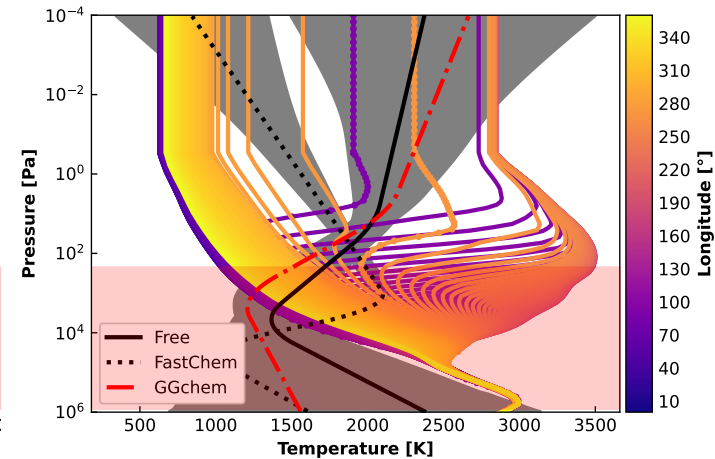
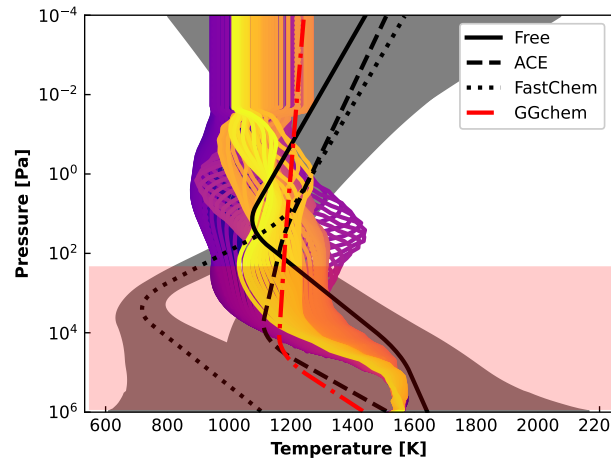
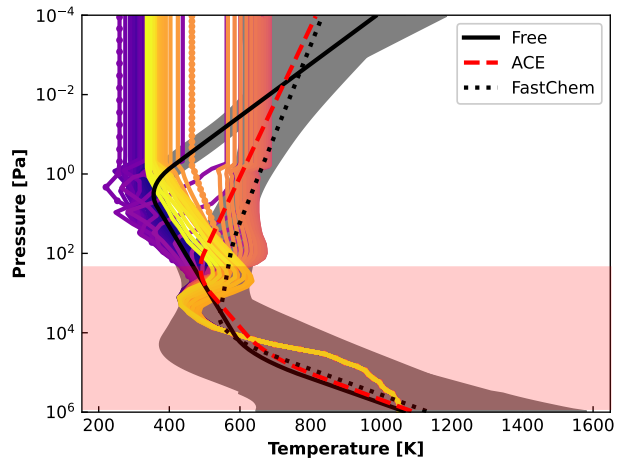
HD189733 b

WASP-121 b

Constant chemistry



Equilibrium chemistry





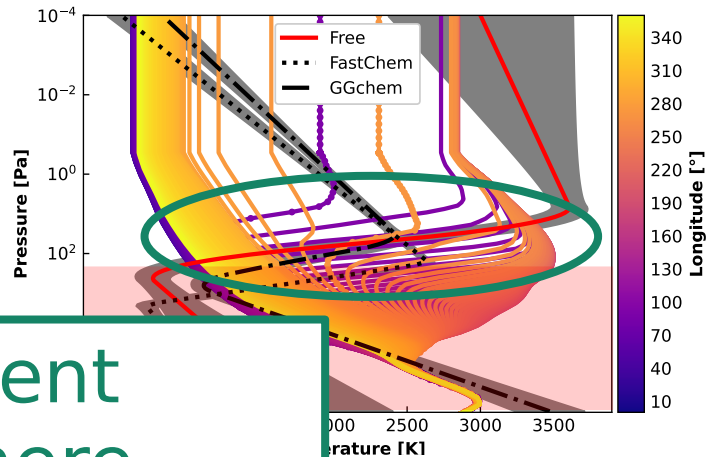
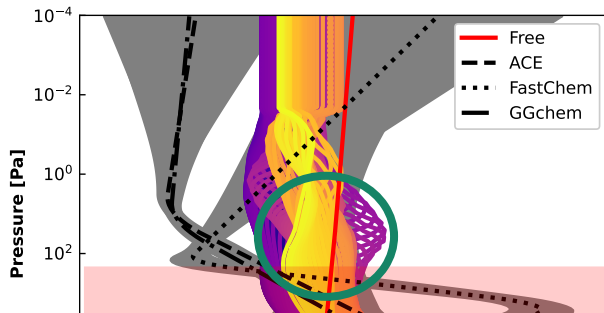
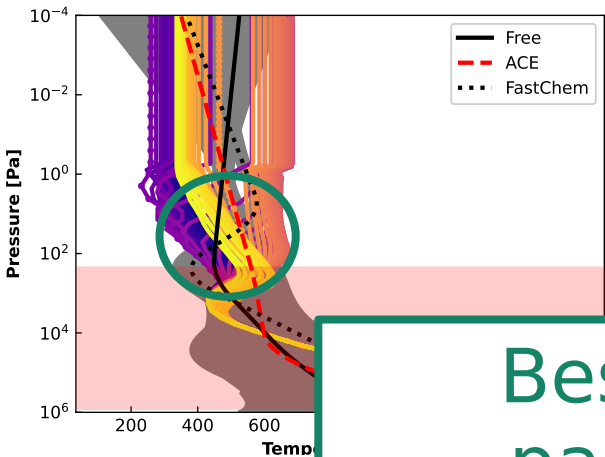
Retrieval: Temperature

GJ1214 b

HD189733 b

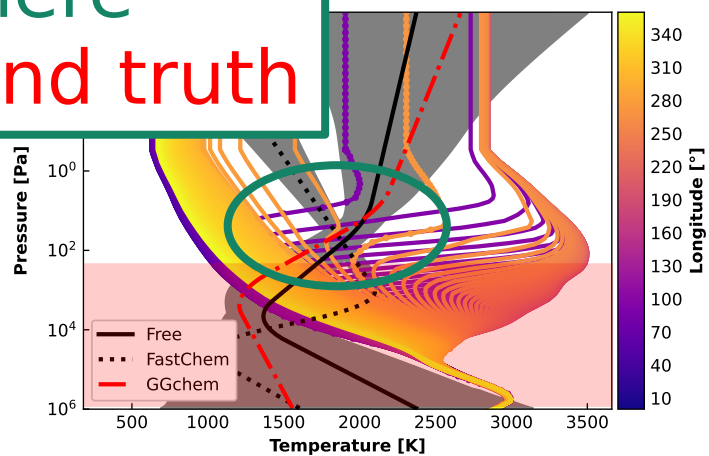
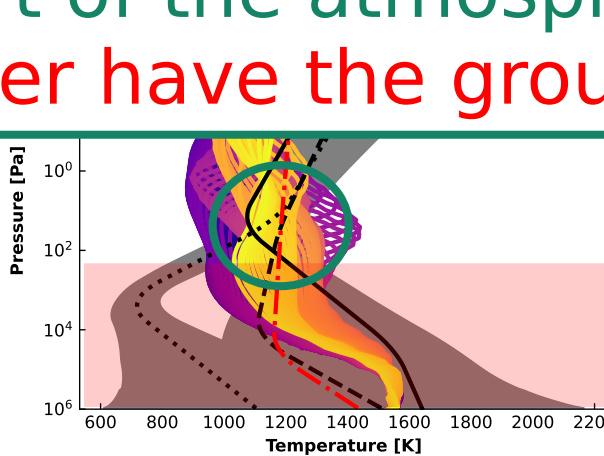
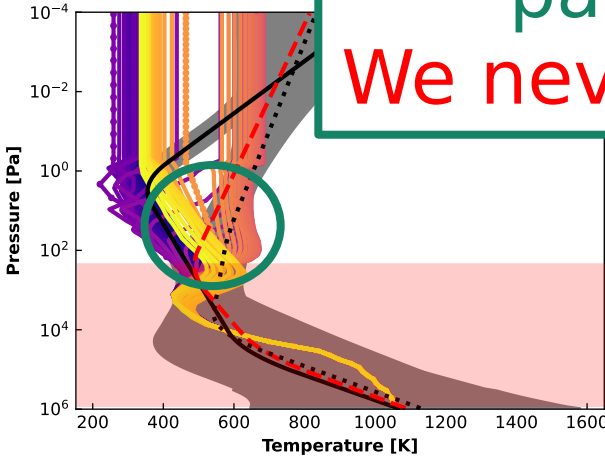
WASP-121 b

Constant chemistry



Best model fit different part of the atmosphere
We never have the ground truth

Equilibrium chemistry





Summary

Can **1D retrievals** find **consistent parameters**
(T-P profile, abundances, C/O ratio, metallicity, and clouds)?

Ariel
FRANCE



Summary

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?

| Ariel | | | | | |
|----------|----|------|-------------|----|------|
|) | | | | | |
| constant | | | equilibrium | | |
| GJ | HD | WASP | GJ | HD | WASP |



Summary

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| Ariel | | | | | |
|----------|----|------|-------------|----|------|
|) | | | | | |
| constant | | | equilibrium | | |
| GJ | HD | WASP | GJ | HD | WASP |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Species detection



Summary

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?

| Ariel | | | | | |
|----------|----|------|-------------|----|------|
|) | | | | | |
| constant | | | equilibrium | | |
| GJ | HD | WASP | GJ | HD | WASP |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | | ✓ | ✓ | ✓ |
| | | | ✓ | ✓ | ✗ |

| |
|-------------------|
| Species detection |
| C/O |
| Metallicity (Z) |



Summary

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?

| Ariel | | | | | |
|----------|----|------|-------------|----|------|
| constant | | | equilibrium | | |
| GJ | HD | WASP | GJ | HD | WASP |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | | ✓ | ✓ | ✓ |
| | | | ✓ | ✓ | ✗ |

Species detection
C/O
Metallicity (Z)

Middle of the atmosphere [$\sim 10^2$ Pa - $\sim 10^0$ Pa]

| Limb | Day | Limb | Limb | Limb | Limb |
|------|-----|------|------|------|------|
| ✓ | ~ | ~ | Limb | Limb | ✗ |

Temperature profile
Chemical profile



Summary

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?

| JWST | | | | | | Ariel | | | | | |
|----------|----|------|-------------|----|------|----------|----|------|-------------|----|------|
| 3D | | | | | | | | | | | |
| constant | | | equilibrium | | | constant | | | equilibrium | | |
| GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | | ✓ | ~ | × | | | | ✓ | ✓ | ✓ |
| | | | ✓ | ~ | × | | | | ✓ | ✓ | × |

Species detection
C/O
Metallicity (Z)

Middle of the atmosphere [$\sim 10^2$ Pa - $\sim 10^0$ Pa]

| Limb | Day | Limb | Limb | Limb | Limb | Limb | Day | Limb | Limb | Limb | Limb |
|------|-----|------|------|------|------|------|-----|------|------|------|------|
| ✓ | ~ | ~ | Limb | Limb | × | ✓ | ~ | ~ | Limb | Limb | × |

Temperature profile
Chemical profile



Summary

Can **1D retrievals** find **consistent parameters** (T-P profile, abundances, C/O ratio, metallicity, and clouds)?

| | JWST | | | | | | | | | Ariel | | | | | | | | |
|-------------------|----------|----|------|-------------|----|------|----------|----|------|-------------|----|------|----------|----|------|-------------|----|------|
| | 1D | | | | | | 3D | | | | | | | | | | | |
| | constant | | | equilibrium | | | constant | | | equilibrium | | | constant | | | equilibrium | | |
| | GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP | GJ | HD | WASP |
| Species detection | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| C/O | | | | ✗ | ~ | ✗ | | | | ✓ | ~ | ✗ | | | | ✓ | ✓ | ✓ |
| Metallicity (Z) | | | | ✓ | ✓ | ✗ | | | | ✓ | ~ | ✗ | | | | ✓ | ✓ | ✗ |

Middle of the atmosphere [$\sim 10^2$ Pa - $\sim 10^0$ Pa]

| | | | | | | | | | | | | | | | | | | |
|---------------------|---|---|---|---|---|---|------|-----|------|------|------|------|------|-----|------|------|------|------|
| Temperature profile | ✓ | ✓ | ~ | ✓ | ✓ | ✓ | Limb | Day | Limb | Limb | Limb | Limb | Limb | Day | Limb | Limb | Limb | Limb |
| Chemical profile | ✓ | ~ | ~ | ✓ | ✓ | ~ | ✓ | ~ | ~ | Limb | Limb | ✗ | ✓ | ~ | ~ | Limb | Limb | ✗ |



Concusion

Ariel
FRANCE



Concusion

Retrievals are model dependent



Conclusion

Retrievals are model dependent

Models need to be improved to face new observational accuracy



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