Towards Multidimensional Atmospheric Retrievals of Exoplanet Transmission Spectra

Cornell University

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Exo-Webbinar

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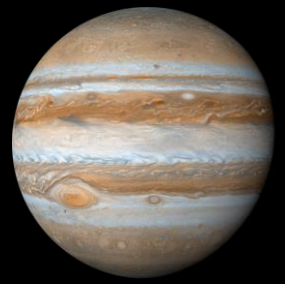
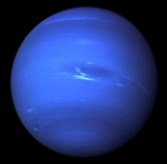
Image credit

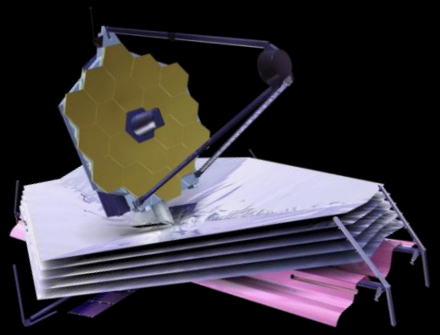
ESO/L. Benassi

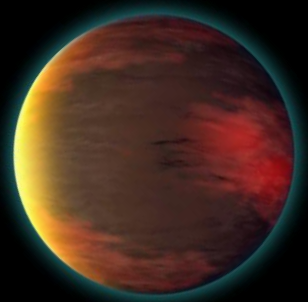
THE BIG PICTURE: EXOPLANETS VS. THE SOLAR SYSTEM



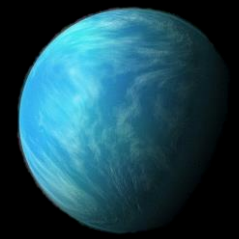


1. Which planets are most common?
2. How do planetary systems form?
3. Is our Solar System common or rare?
4. How Earth-like are rocky exoplanets?
5. Is there life in the Universe?

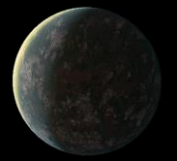




Hot Jupiter



Exo-Neptune

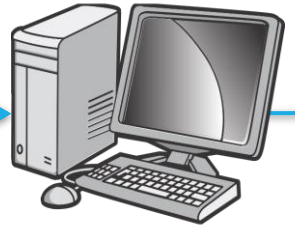


Super-Earth

Terrestrial

INFERRING PROPERTIES OF EXOPLANET ATMOSPHERES

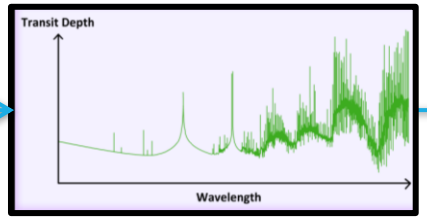
Forward modelling

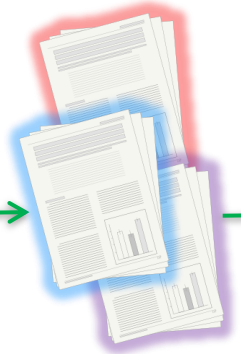


Physics, chemistry, GCMs

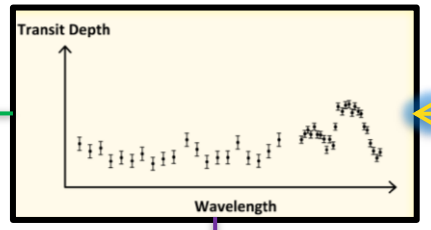
First principles calculations

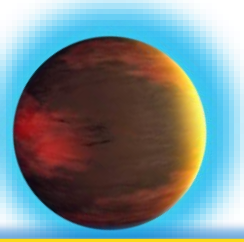
Predicted spectrum



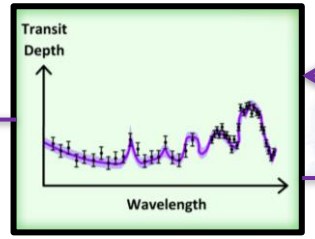


Observed spectrum





Inverse modelling



Bayesian statistics, MCMC etc.

Some kind of magic…

Atmospheric Retrieval

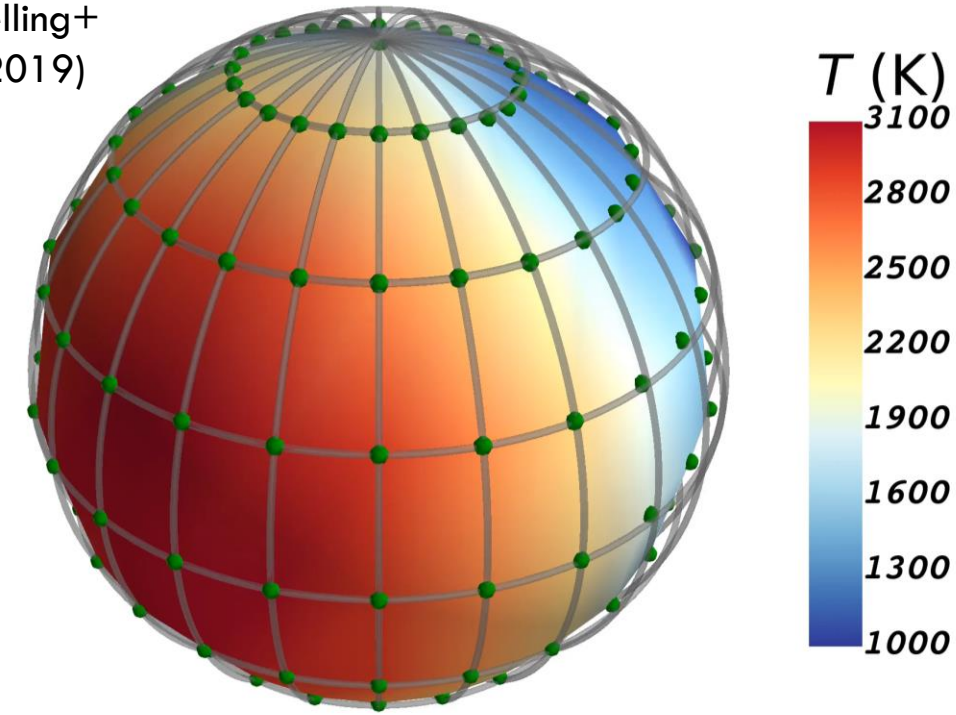
Retrieval code assumptions:

- Temperature profile function
- Abundance profile function
- Cloud / haze parametrisation
- Hydrostatic equilibrium
- **1D spherical atmosphere**

3D GENERAL CIRCULATION MODEL VS. RETRIEVAL MODEL

GCM temperature structure
(Ultra-hot Jupiter HAT-P-7b)

Helling+
(2019)



Strong variation (temperature, chemistry, clouds, etc.)
with **longitude, latitude, and altitude**

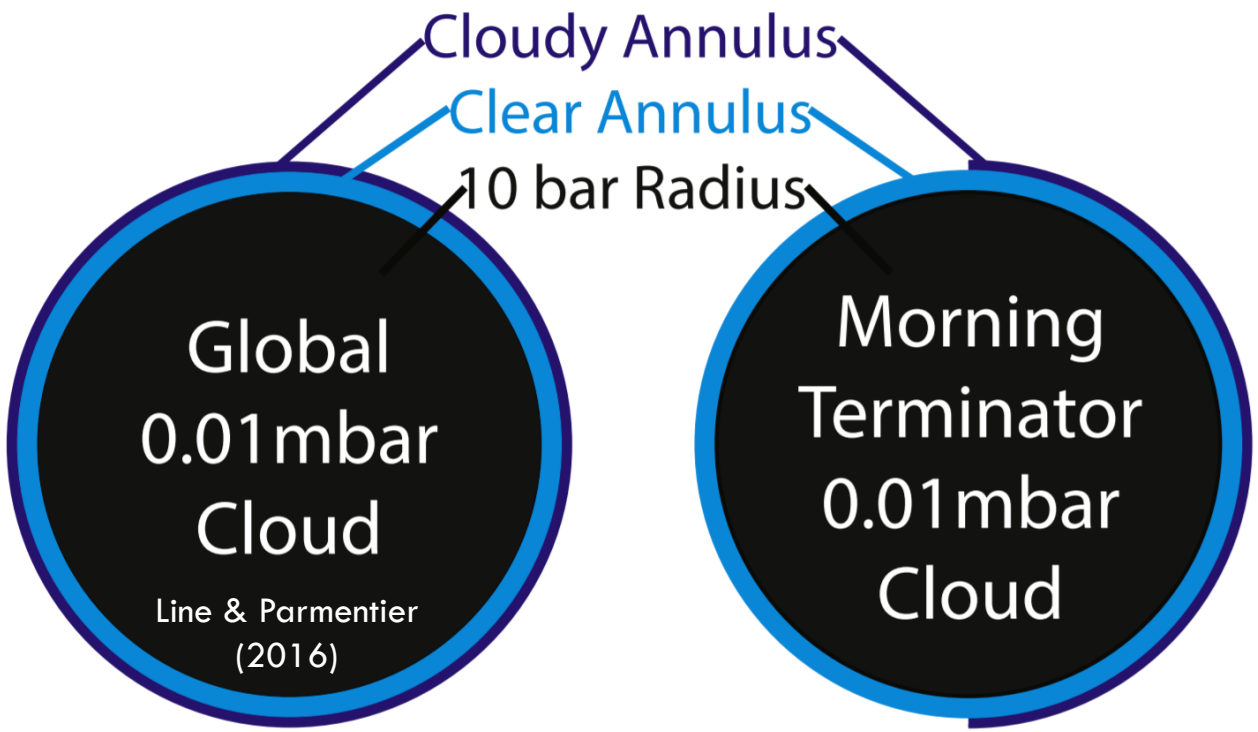
Standard retrieval
temperature structure

Uniform properties in longitude and latitude
Vertical variation sometimes included
(for computational speed)

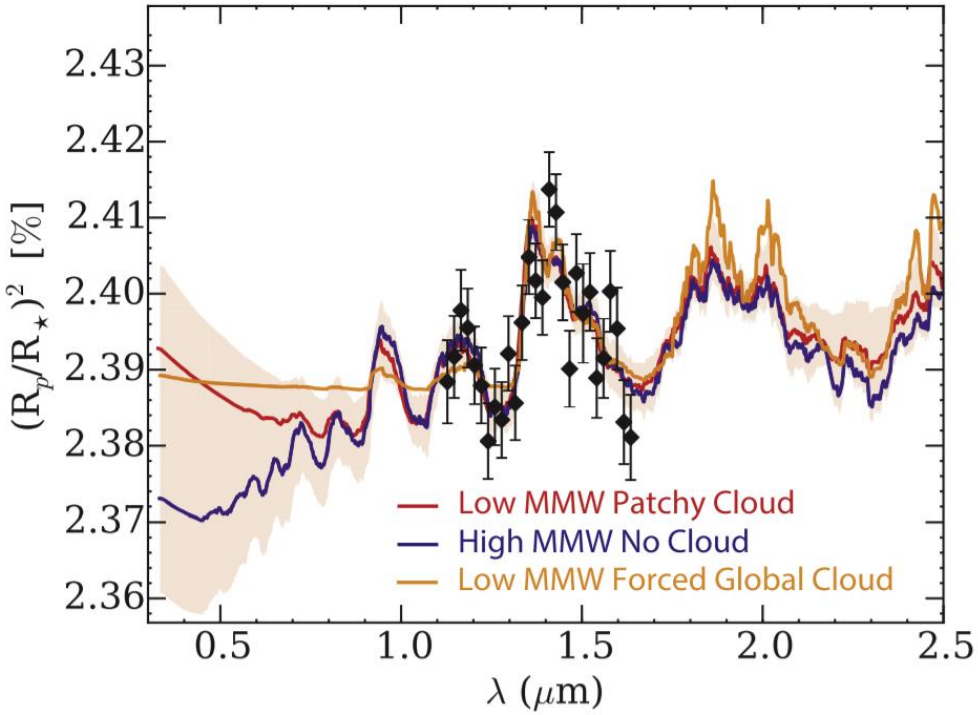
WHEN DO 1D RETRIEVALS GO WRONG?

INHOMOGENEOUS ('PATCHY') CLOUDS

Observer perspective



Transmission spectrum



Transmission spectra of planets with 2D patchy clouds can mimic a 1D clear high mean molecular weight atmosphere

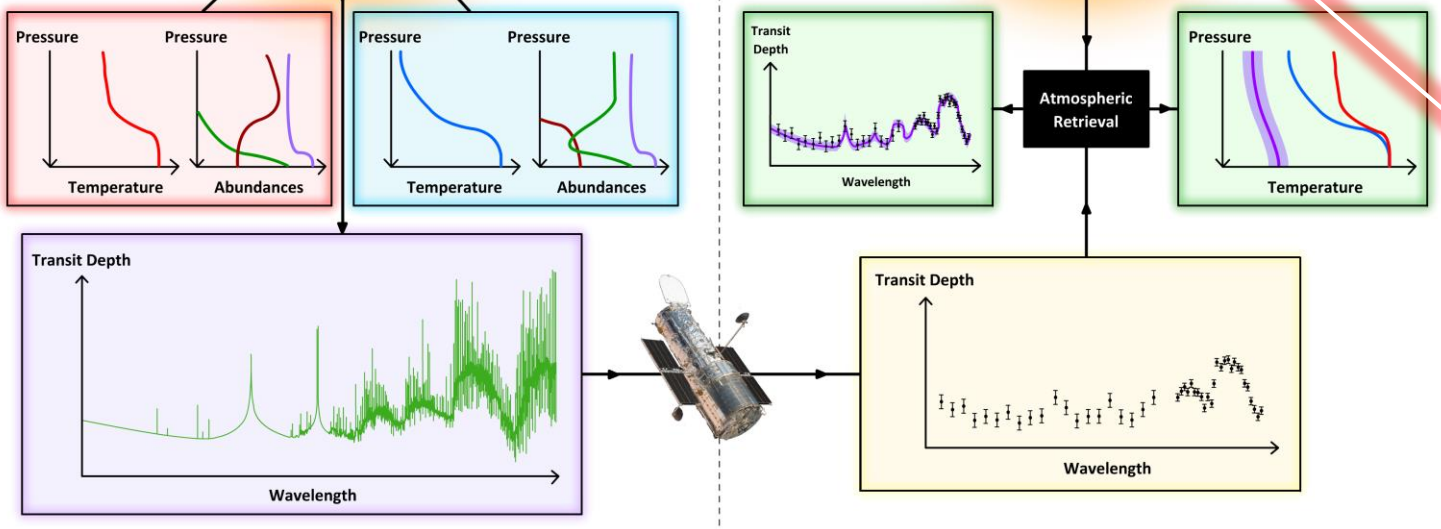
Mainly an issue for near-infrared wavelengths (e.g. HST WFC3); visible data resolves degeneracy

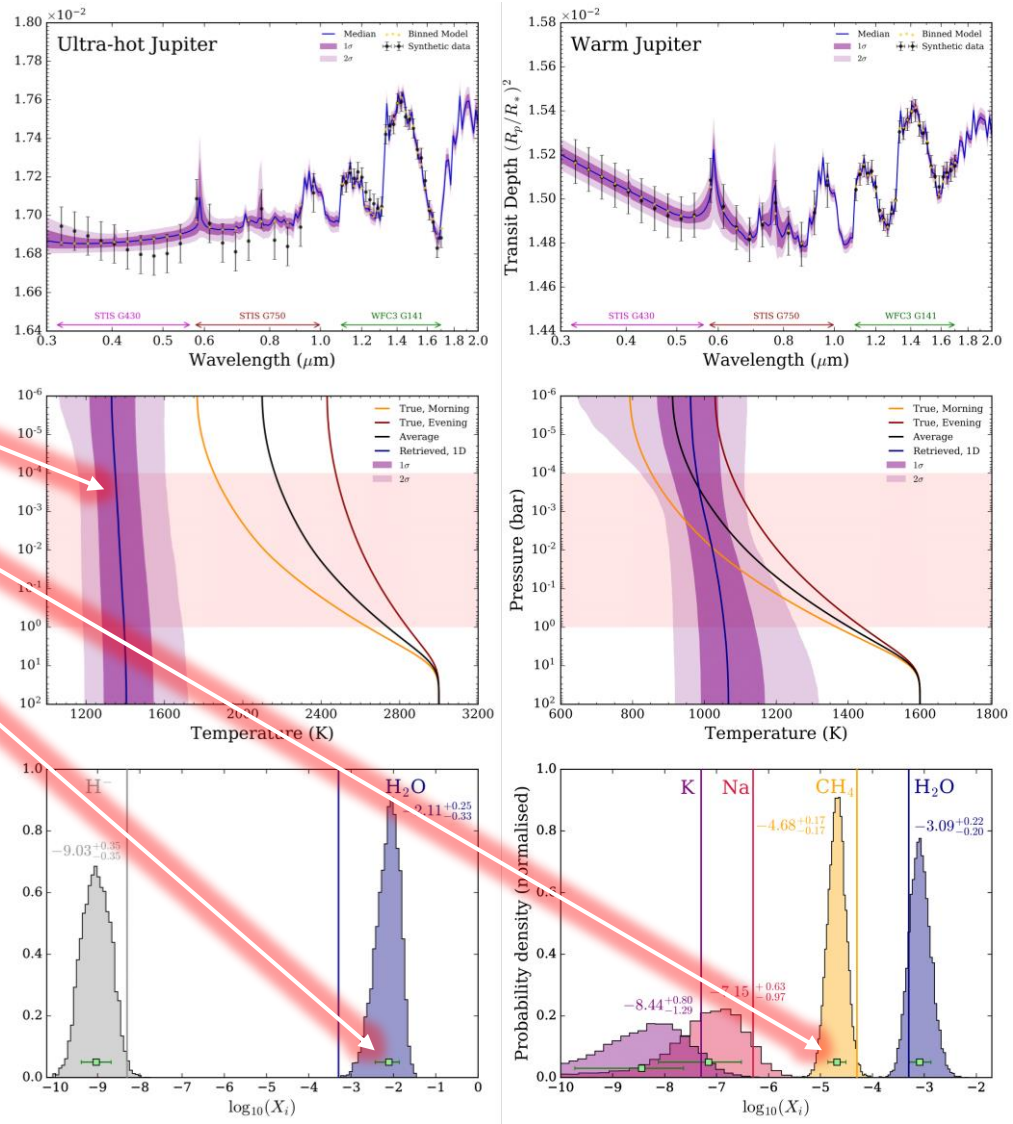
ASYMMETRIC TERMINATOR BIASES

Reality
(2D Atmosphere)

Assumed
(1D Atmosphere)

- **Temperature** profiles are **too cold**
- **Abundances** can be **biased** by $> 3\sigma$
- Biases **worst for ultra-hot Jupiters**





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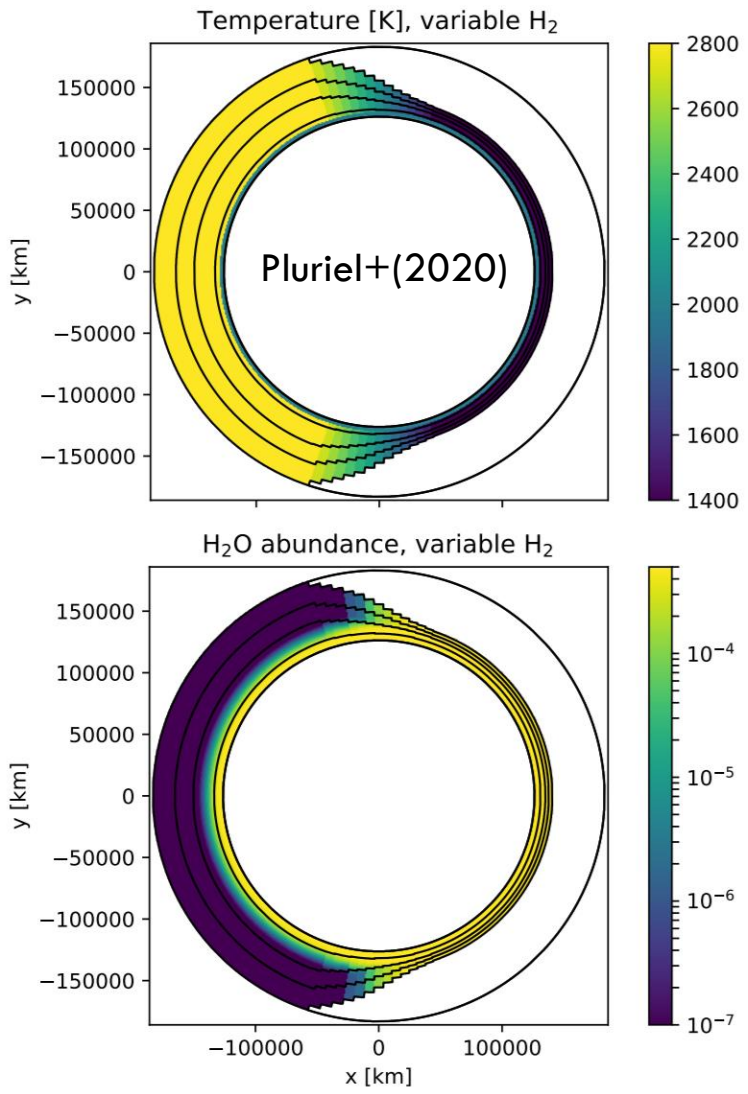
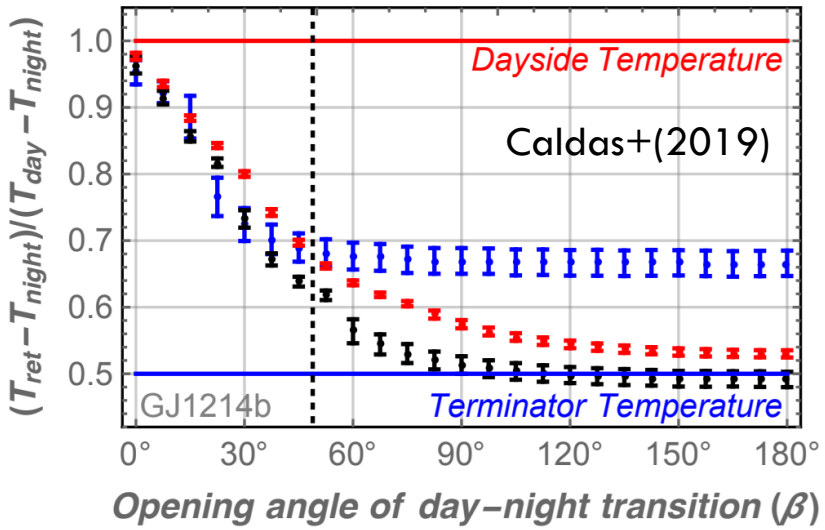
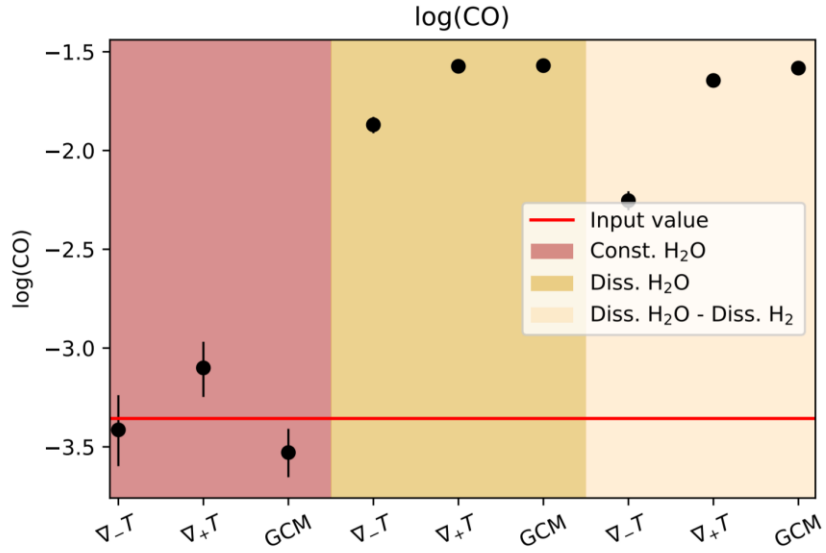
DAY-NIGHT ATMOSPHERIC PROPERTY GRADIENTS







Retrieved temperatures are biased towards the dayside temperature (greater extent, stronger features)

↓

Temperature profiles are **too hot**

Retrieved abundances also biased towards the dayside composition

↓

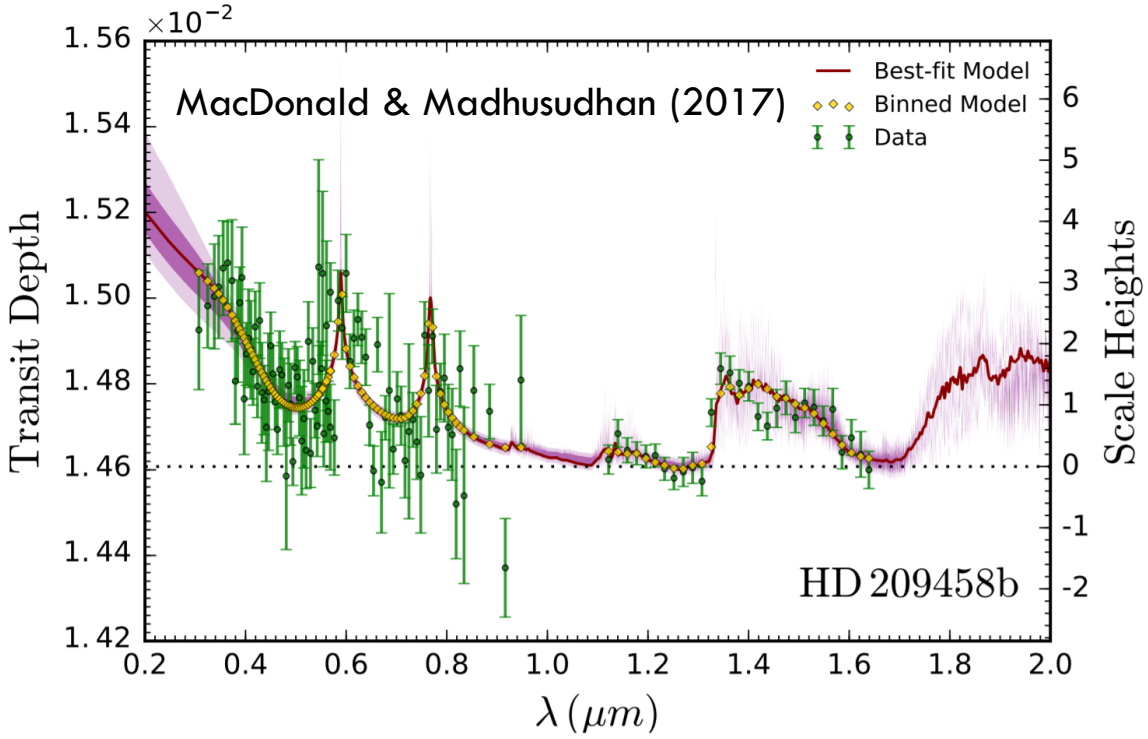
C/O can be biased by orders of magnitude

THE SOLUTION:

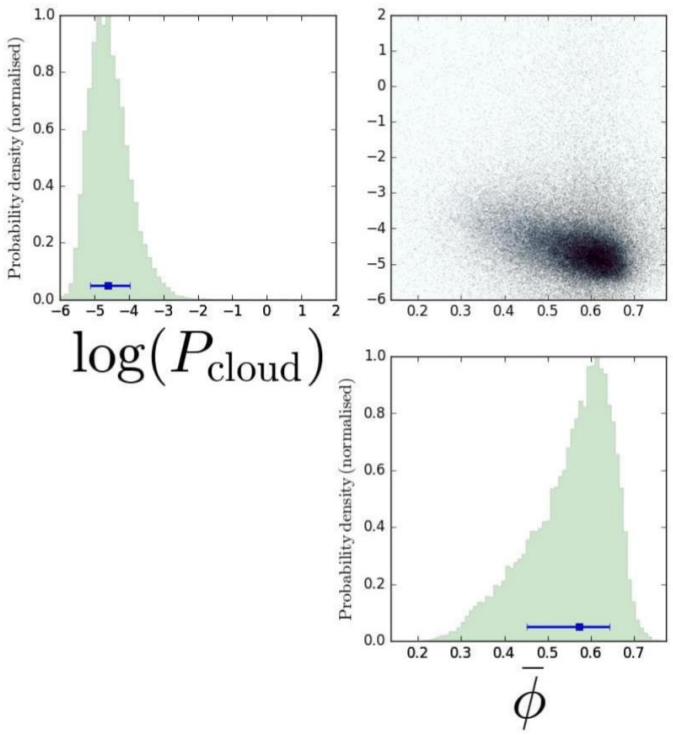
MULTIDIMENSIONAL RETRIEVALS

1+1D RETRIEVAL: PATCHY CLOUD APPLICATION

Retrieved Hubble spectrum of HD 209458b



Retrieved cloud properties



Linear superposition of two 1D transmission spectra models (clear and cloudy) allows **successful patchy cloud retrieval:**

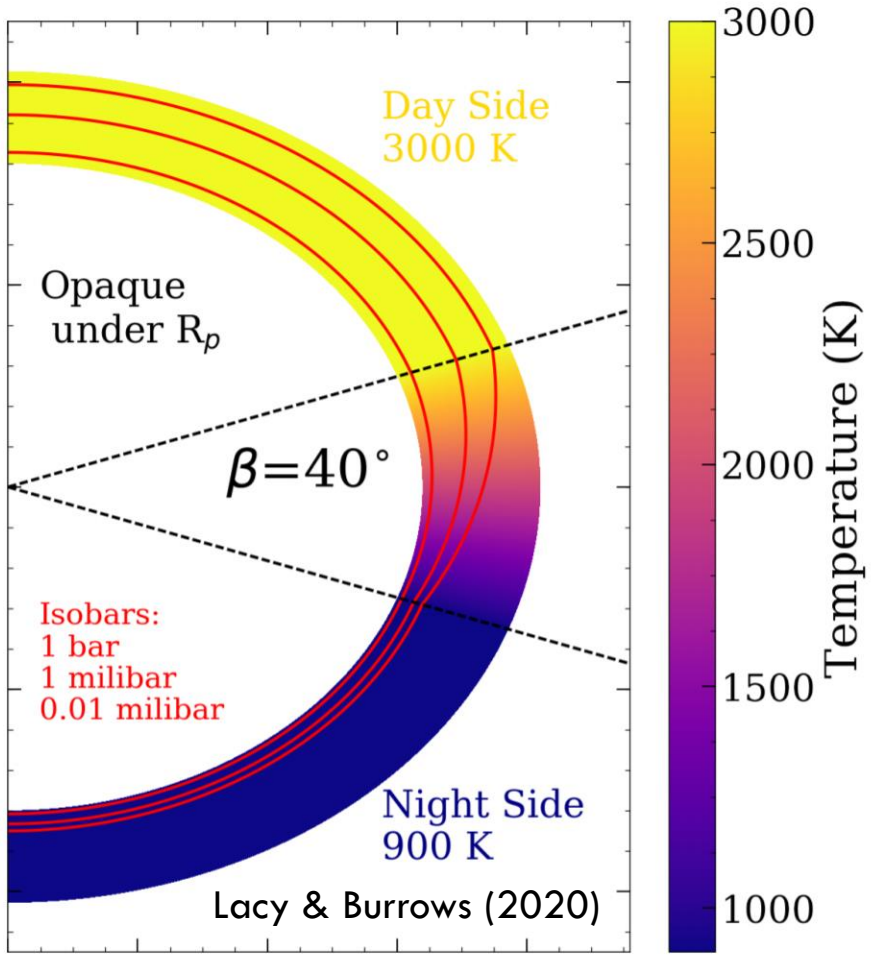
$$\Delta_\lambda = \bar{\phi}\,\delta_{\lambda,\,cloudy} + (1-\bar{\phi})\,\delta_{\lambda,\,clear}$$

Patchy clouds detected ($> 4.5\sigma$)
Cloud fraction constrained ($\bar{\phi} \approx 55\%$)

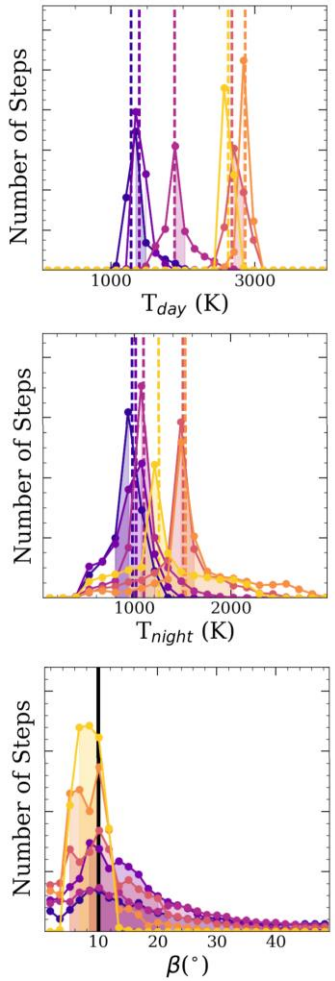
2D **Patchy clouds can be detected** with existing telescopes (e.g. **Hubble**)

2D RETRIEVAL: DAY-NIGHT GRADIENTS

2D geometry within retrieval model



Retrieved properties



Accounting for **changing geometry** along **slant path** allows retrieval of **day-night gradients**

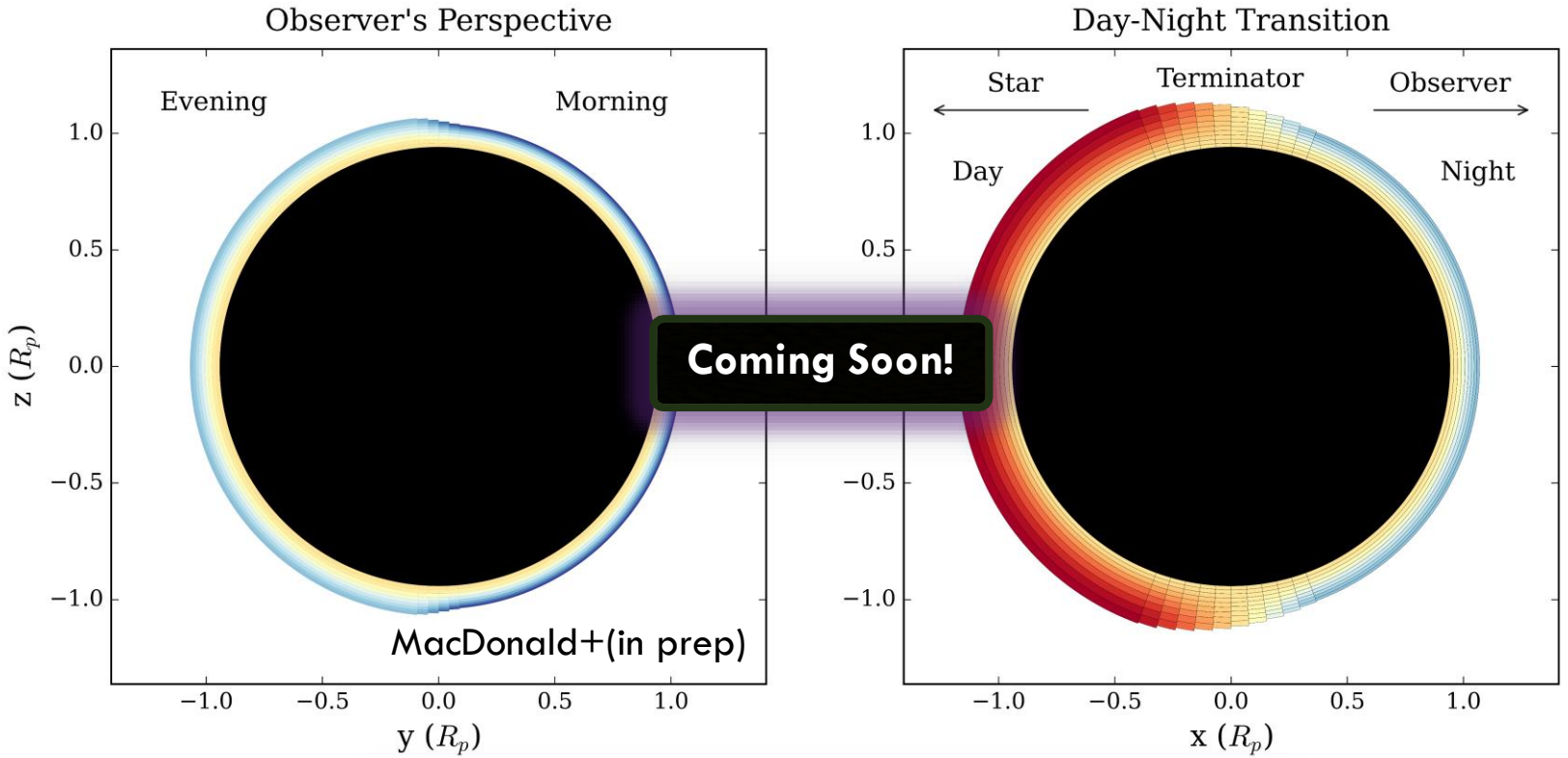
Dayside, nightside temperatures + terminator **opening angle** can be constrained with **JWST**

Some outstanding questions:

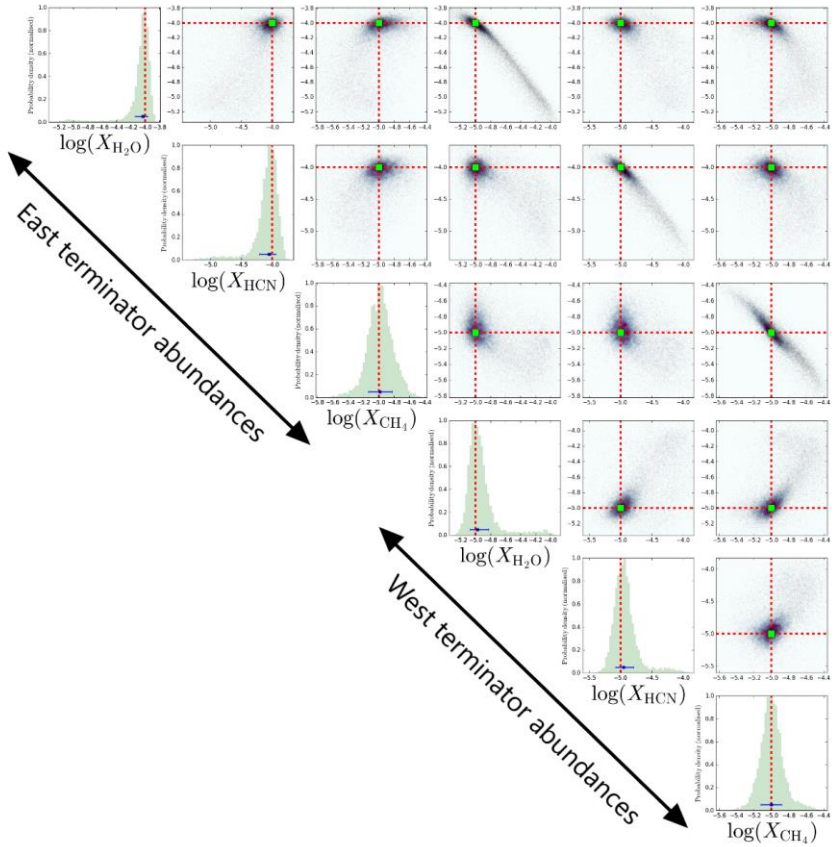
1. Free chemical gradients vs. equilibrium chemistry
2. Free cloud parametrisation vs. equilibrium clouds
3. Non-isothermal vertical temperature structures
4. Non-linear day-night transition region
5. **Axial asymmetry (morning / evening, poles etc.)**

3D RETRIEVAL OF EXOPLANET TRANSMISSION SPECTRA

We are developing a general
3D atmospheric retrieval technique



Retrieved properties

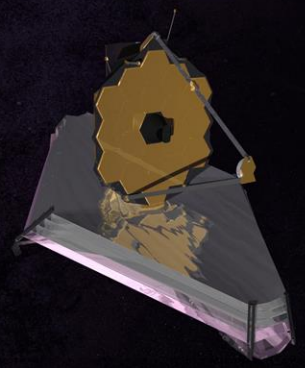


3D atmospheric properties can be extracted from transmission spectra **without biases**

KEY TAKEAWAYS

1. 1D atmospheric retrievals suffer many biases
2. Some existing transmission spectra suggest 2D effects
3. 3D properties of exoplanet atmospheres can be retrieved from transmission spectra without biases

The **3D nature** of exoplanet atmospheres is an **opportunity for retrievals**



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