Constraining Methane Abundance and Cloud Properties from the Reflected Light Spectra of Directly Imaged Exoplanets

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We have assembled an atmospheric retrieval package for the reflected light spectra of gas- and ice- giants in order to inform the design and estimate the scientific return of future space-based coronagraph instruments. Such instruments will have a working bandpass of ~0.4-1 microns and a resolving power R~70, and will enable the characterization of tens of exoplanets in the Solar neighborhood. The targets will be chosen form known RV giants, with estimated effective temperatures of ~100-600 K and masses between 0.3 and 20 M_Jupiter. In this regime, both methane and clouds will have the largest effects on the observed spectra. Our retrieval code is the first to include cloud properties in the core set of parameters, along with methane abundance and surface gravity. We consider three possible cloud structure scenarios, with 0, 1 or 2 cloud layers, respectively. The best-fit parameters for a given model are determined using either a Monte Carlo Markov Chain ensemble sampler, or nested sampling. The most favored cloud structure is chosen by calculating the Bayes factors between different models. We present the performance of our retrieval technique applied to a set of representative model spectra, covering a SNR range form 5 to 20 and including possible noise correlations over a 25 or 100 nanometer scale. Further, we have applied the technique to more realistic cases, namely simulated observations of Jupiter, Saturn, Uranus, and the gas-giant HD99492c, out of which only Jupiter is shown. In each case, we determine the confidence levels associated with the methane and cloud detections, as a function of SNR and noise properties.

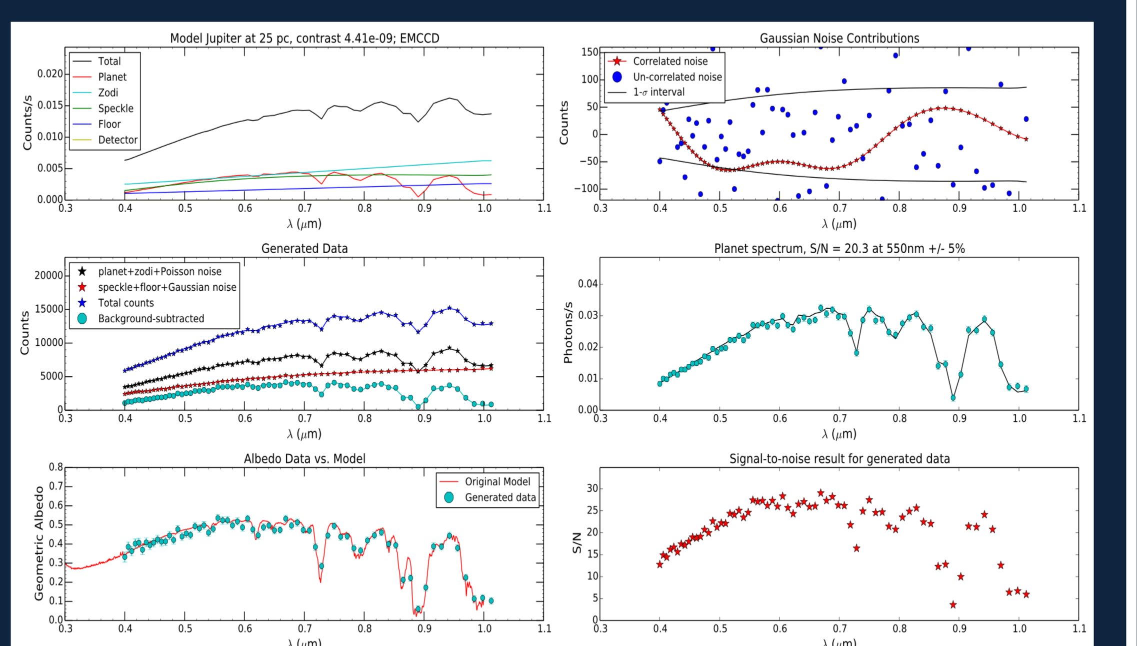
Simulated Data

We define the signal-to-noise as corresponding to the integrated count in a 10%-wide bandpass centered at 550 nm.

Planet + zodi = Poisson distribution

speckle + background noise = Gaussian distribution

The noise correlations are Gaussian, with a length scale of 25 or 100 nm.



Retrieval

We have implemented both the affine-invariant Monte Carlo Markov Chain ensemble sampler (`emcee`) and the nested sampling algorithm `MultiNest` to sample the posterior distributions for parameter estimation and model selection.

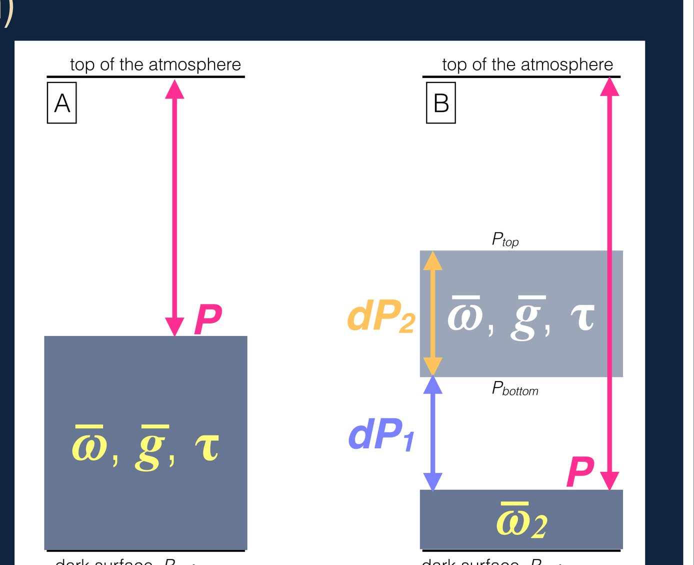
The planetary albedo is calculated assuming a simple cloud model and taking the methane abundance and the surface gravity as free parameters.

The significance of cloud and methane detection is determined by comparing models containing 0, 1, or 2 clouds, or lacking methane opacity.

Pressure-temperature profile = fixed

Phase angle = 0 (face on)

The top cloud is absent in the 1-cloud model. The remaining cloud is characterized by P , τ , ϖ , and ğ

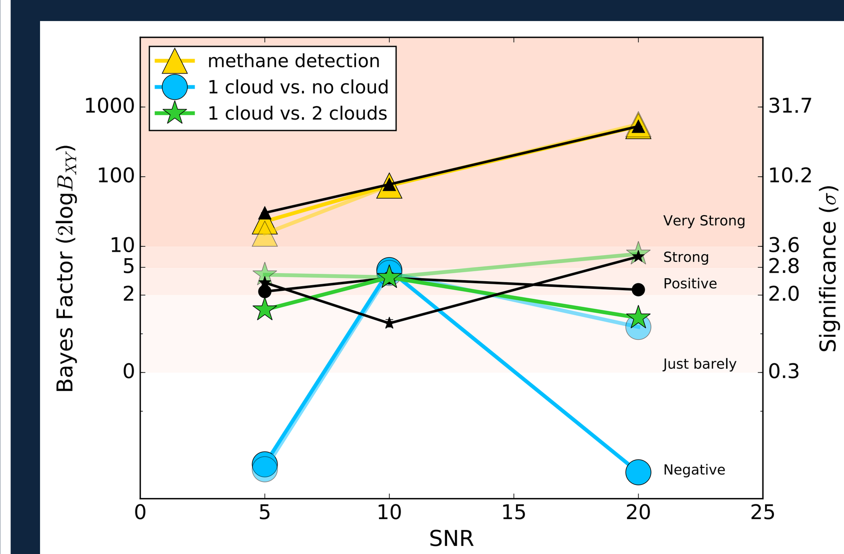


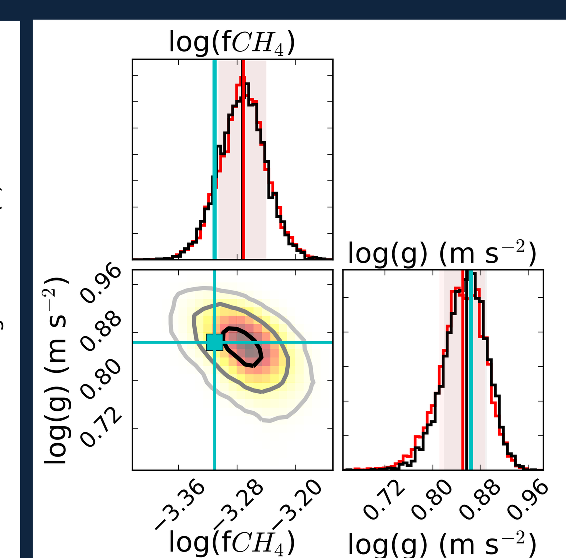
Parameters for the 2-cloud model:
$X(CH_4)$, g
dP_1, dP_2, τ , ϖ , ğ for the upper cloud
P , ϖ for the bottom cloud

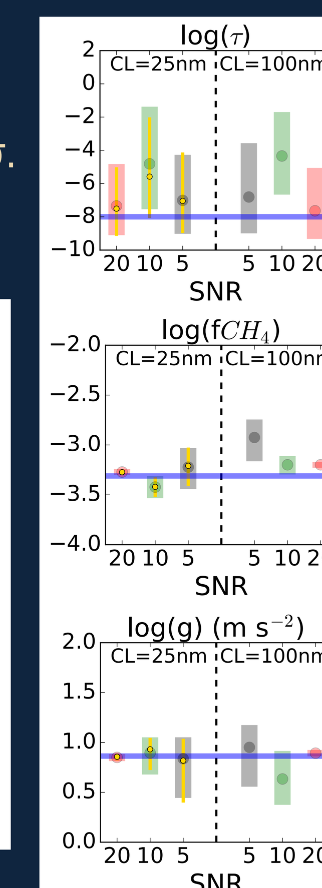
Validation and Testing

Planet without clouds:

Both *g* and methane abundance are well constrained. The methane detection is >4σ. The cloud detection is not significant, and its optical depth is low.

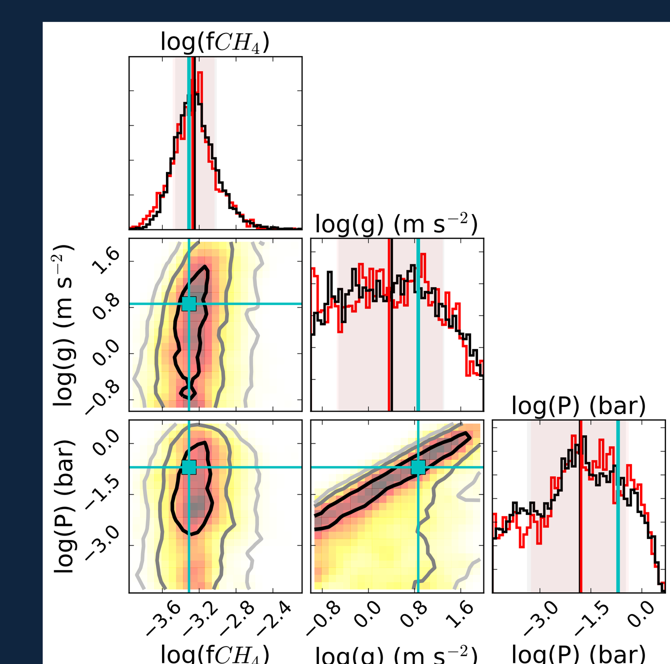


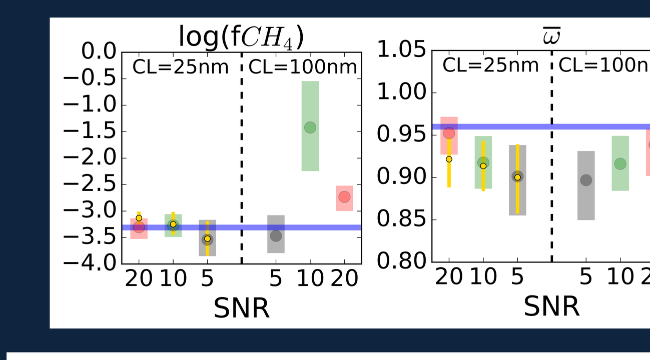


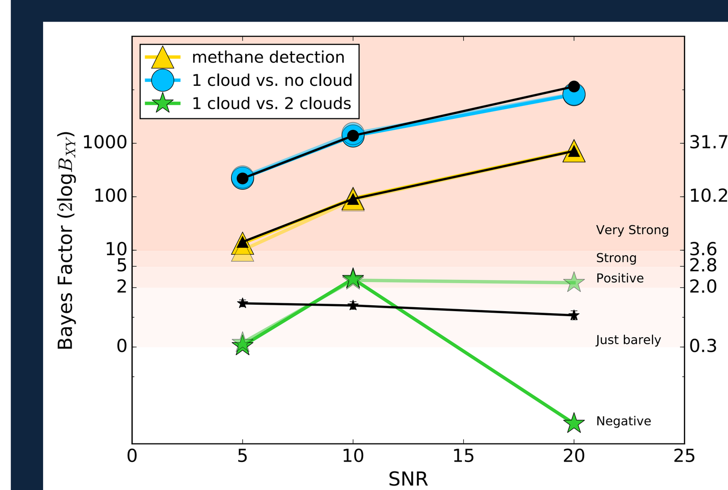


Planet with 1 cloud layer:

The methane detection is >4σ, and its abundance is well constrained.

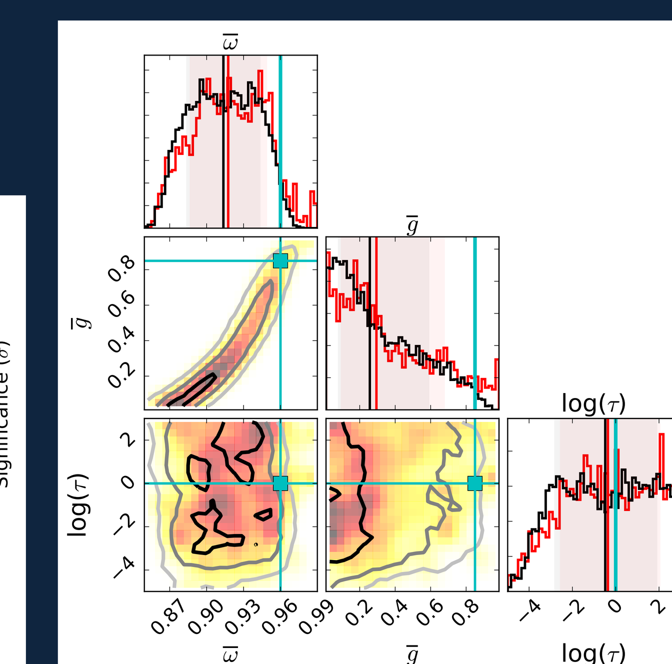






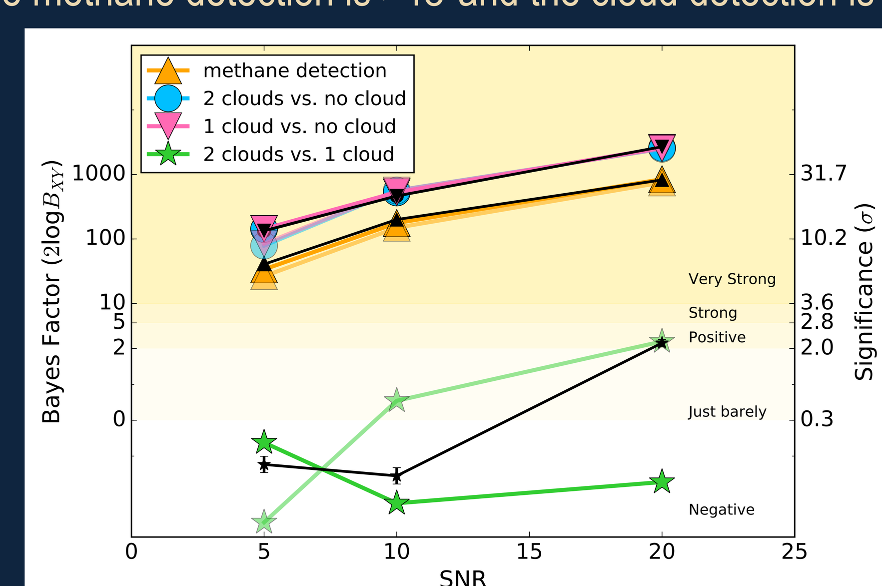
The cloud detection is >10σ.

(*g* , *P*) and (ϖ , ğ) are degenerate.

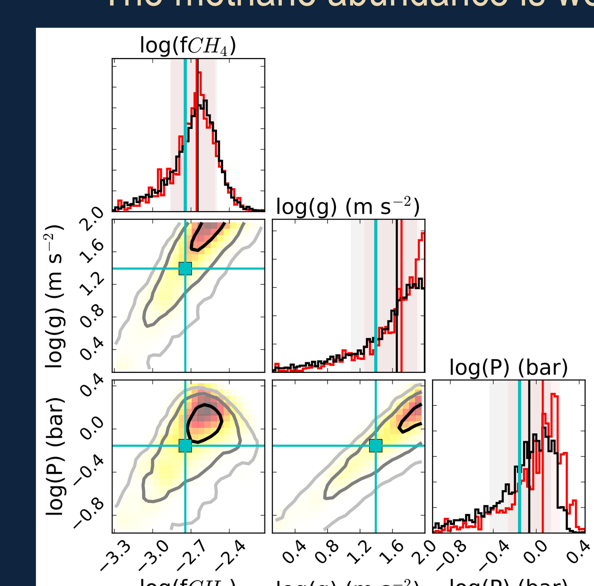


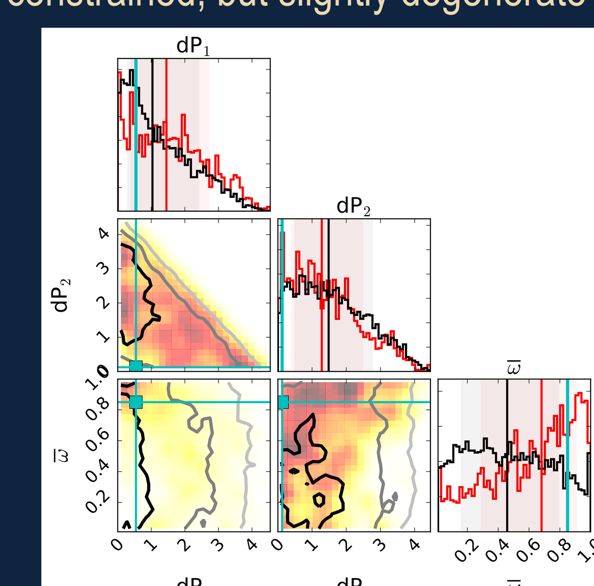
Planet with 2 cloud layers:

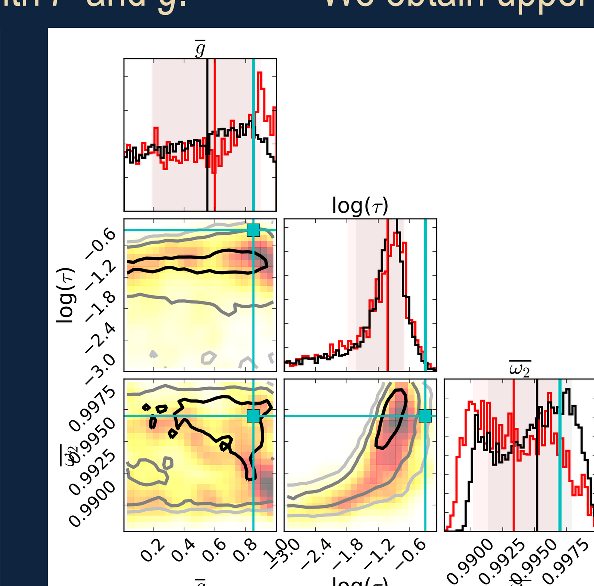
The methane detection is >4σ and the cloud detection is >10σ.



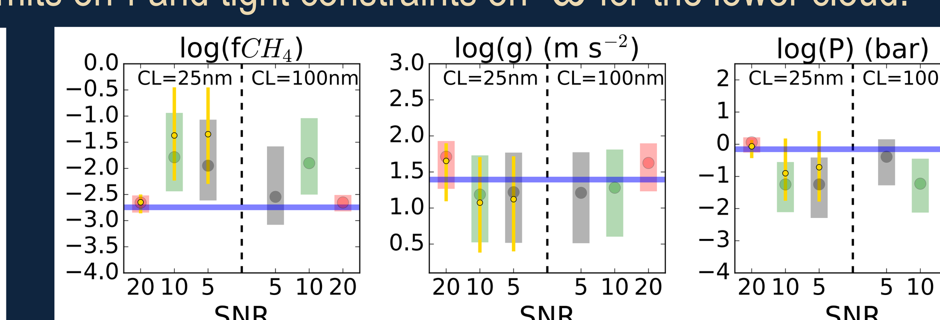
The methane abundance is well constrained, but slightly degenerate with *P* and *g*.

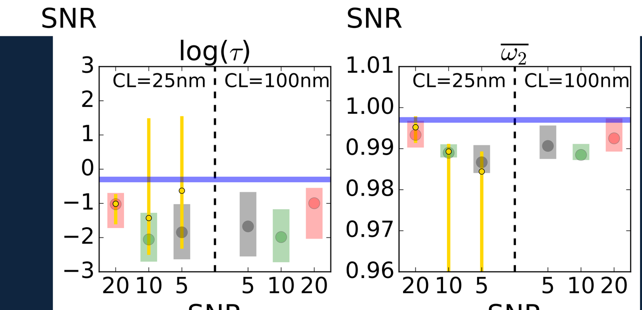






We obtain upper limits on τ and tight constraints on ϖ for the lower cloud.



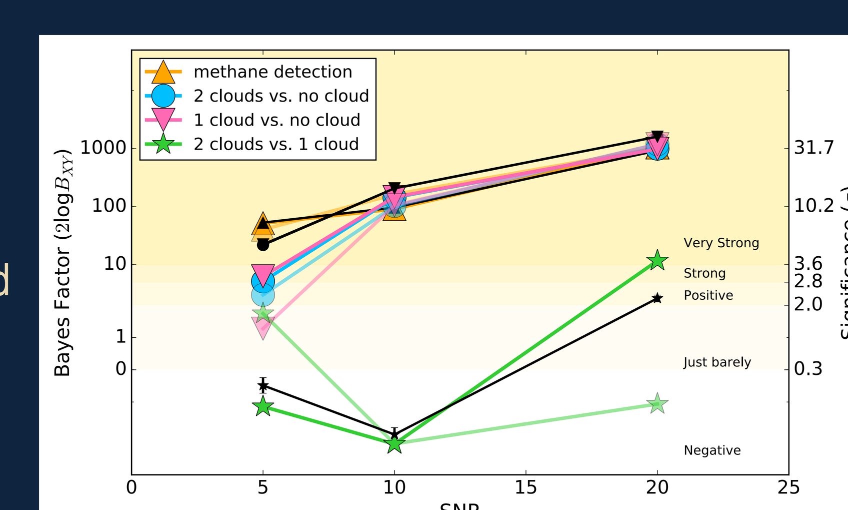


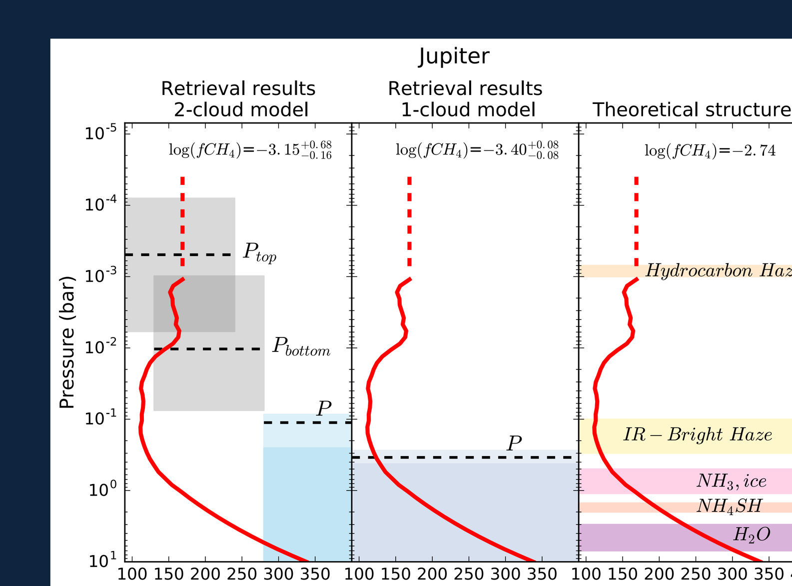
Real-World Scenario: Jupiter

The methane detection is >6σ and the cloud detection is >3σ.

There is no compelling evidence for a second cloud.

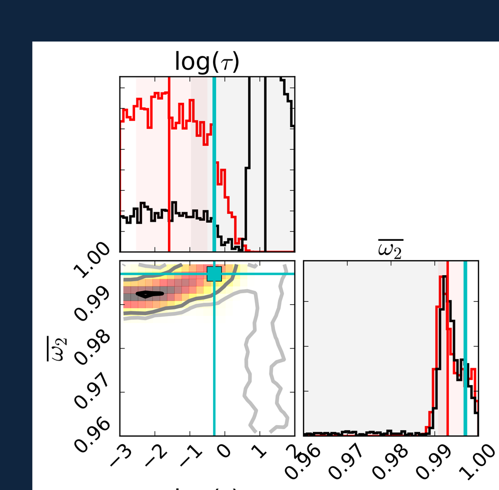
Constrained: single scattering albedo of the lower cloud.

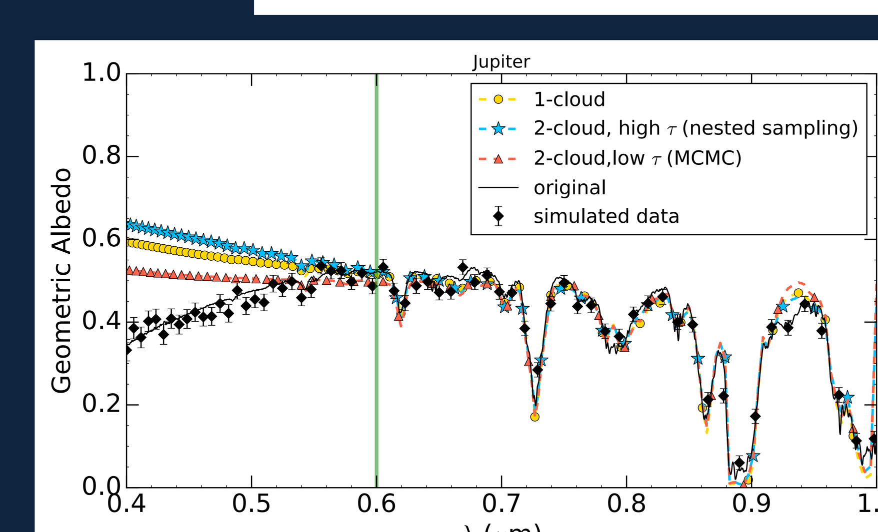




Degenerate: low- and high-optical depth solutions.

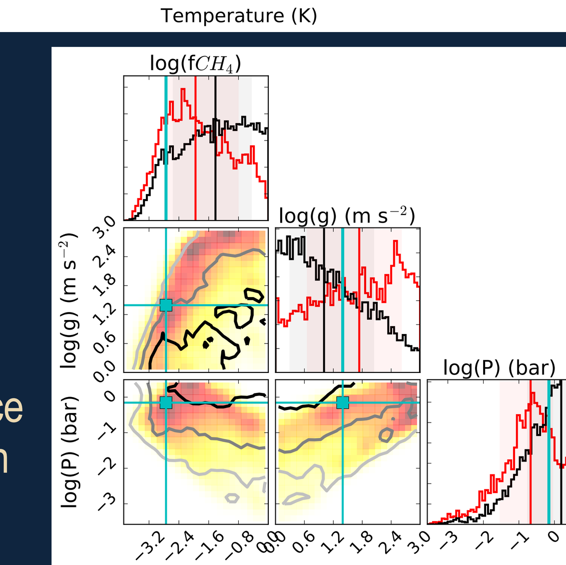
MultiNest and MCMC may lock onto different, degenerate modes.





Correlated: methane abundance, surface gravity, pressure at the top of the bottom cloud.

The methane abundance is consistent with known measurements.



REMARKS:

- The limitations of the models can be more important than the uncertainties in the data.
- Independent constraints on surface gravity and cloud properties will improve the measurement of methane abundance.
- The gravity can be independently determined via the mass-radius relationship for imaged RV planets, and this constraint will tighten the constraints on the other parameters.
- Water and alkali opacities will be important for other types of planets.
- A scaling factor is needed to take into account radius uncertainties.