Empirically Determining Substellar Cloud Compositions in the era of JWST

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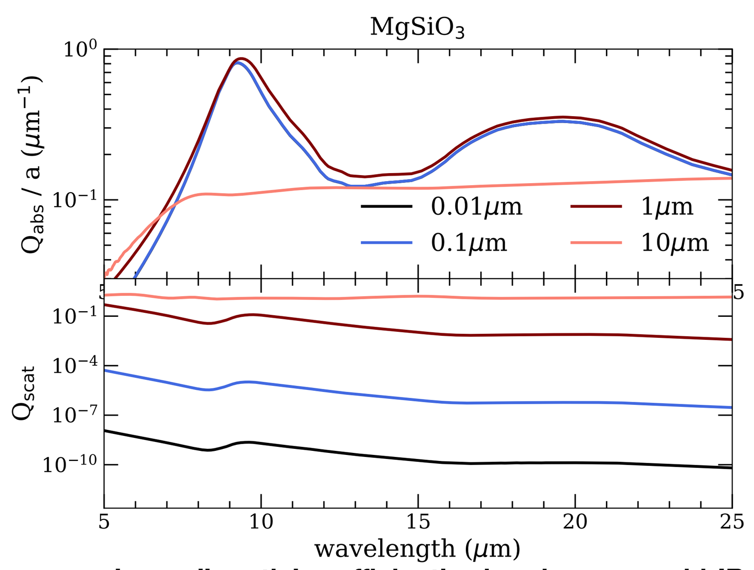
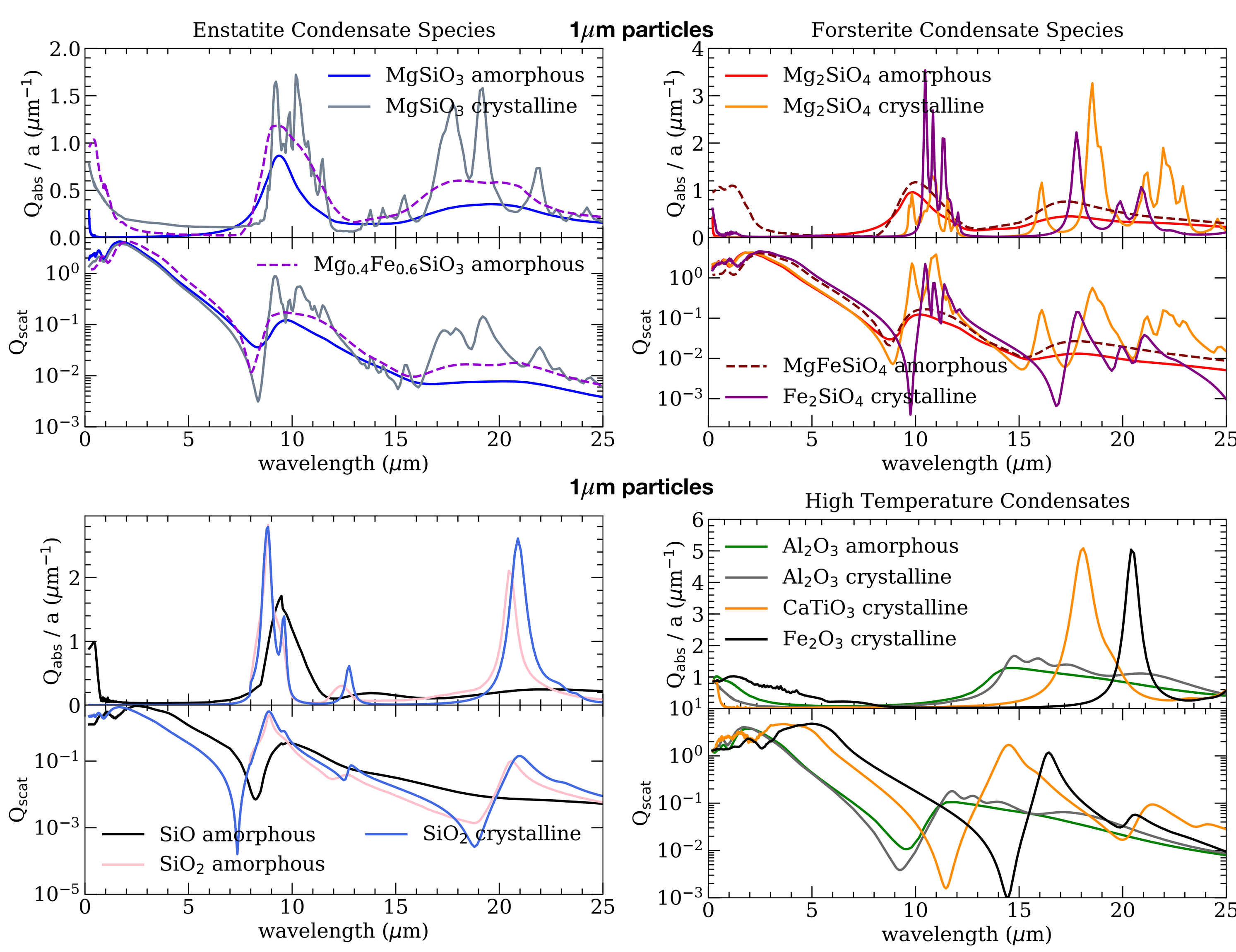
Abstract: There is growing observational evidence of heterogeneous clouds in substellar atmospheres. However the content of these clouds is not well constrained from theory, which is a major barrier in understanding exoplanet atmospheres. The next key step in understanding these clouds is to empirically determine which clouds form using mid-infrared spectroscopy to identify mineral species. **We present a new technique to identify the cloud species in substellar atmospheres using the MIRI instrument on JWST.**

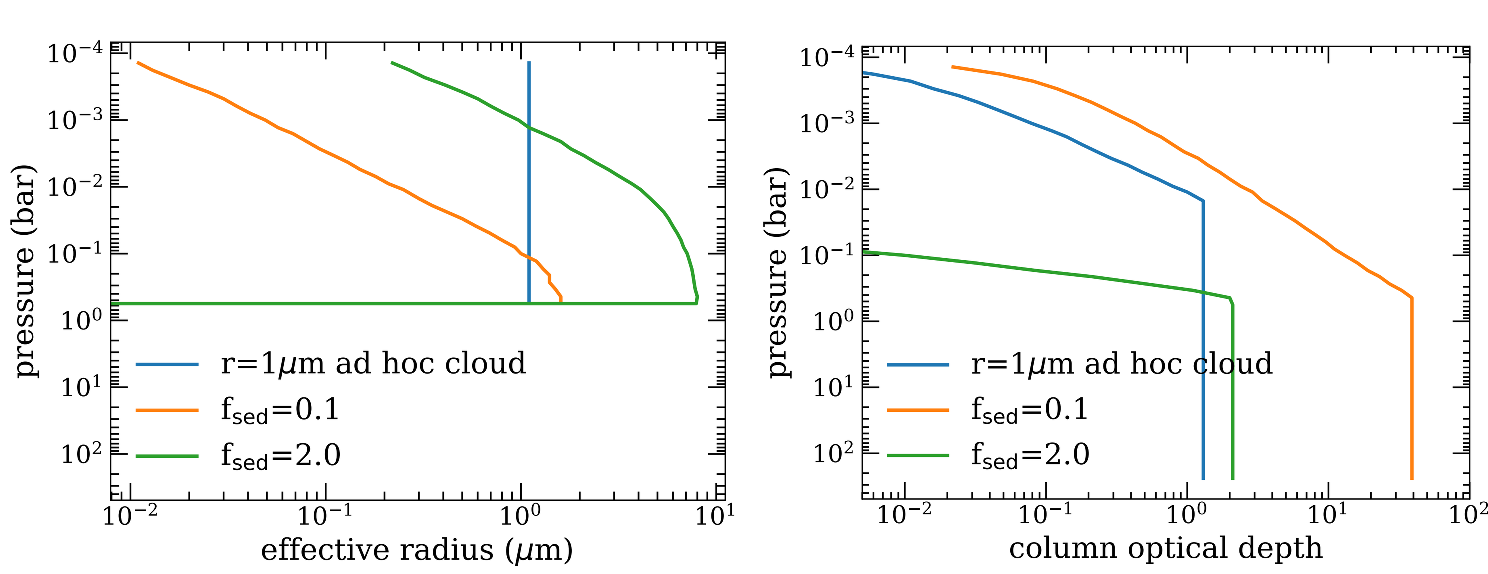
We use Mie scattering theory to calculate the absorption and scattering efficiencies for different particle sizes and species and the peak efficiency tells us at what wavelengths each species will exhibit these Mie scattering effects



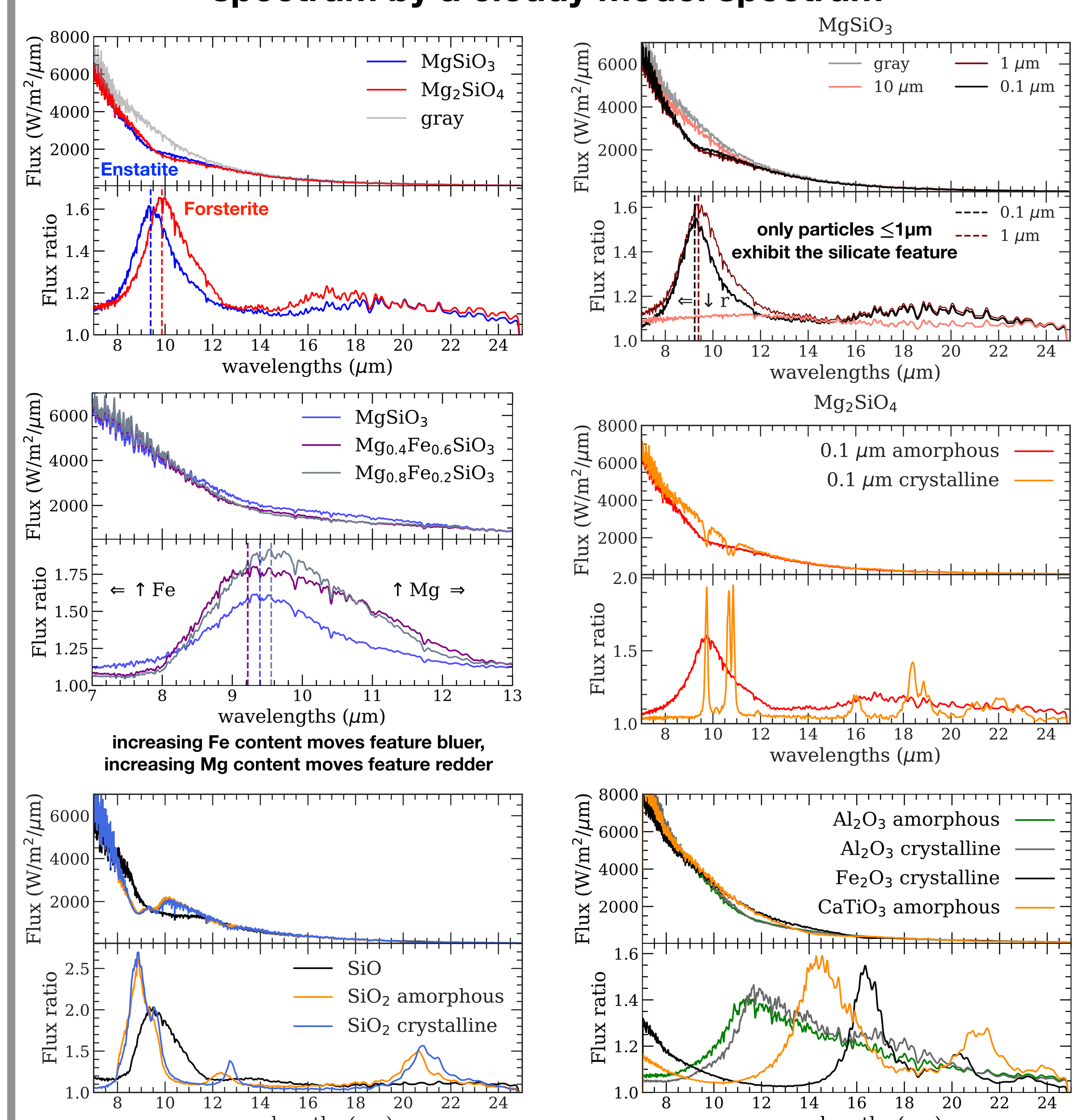
only small particles efficiently absorb across mid-IR



We generate 1D model atmospheres in radiative-convective equilibrium and add an ad hoc cloud at the top layers of the atmosphere. We set the add hoc cloud optical depth to be optically thin (τ < 2/3) and the particle radius to be small (r ≤ 1μm) whereas the Ackerman and Marley (2001) f_{sed} = 0.1 gives vertically tall clouds with smaller particles and f_{sed} = 2 gives an optically thin cloud with larger particles



Model thermal emission spectra and flux ratios for each cloud species by dividing a gray model thermal emission spectrum by a cloudy model spectrum



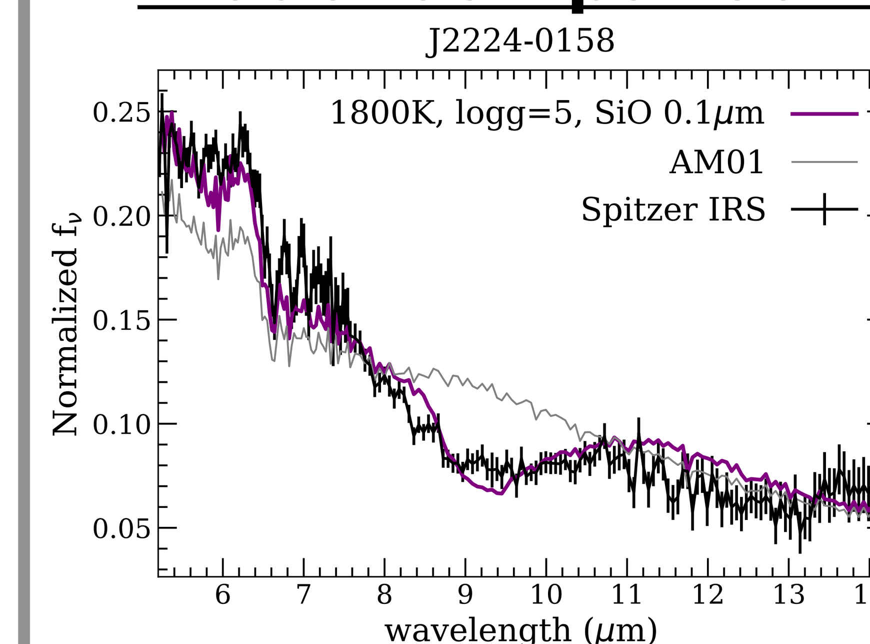
increasing Fe content moves feature bluer, increasing Mg content moves feature redder

Each cloud species absorbs at specific wavelengths and cloud particles ≤1μm strongly exhibit Mie scattering effects that produce mineral features (ie. silicate feature), allowing us to constrain the crystalline structure and composition

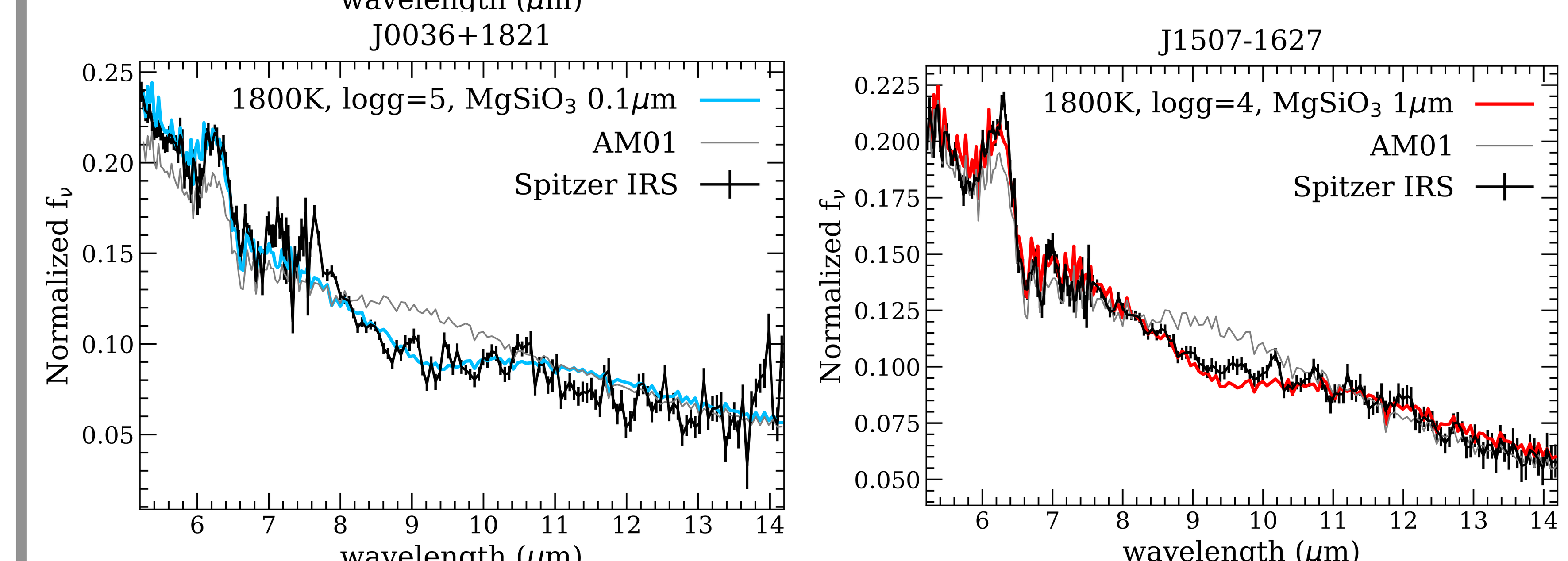
Key takeaways

- **Upcoming JWST/MIRI observations of both non-variable and variable brown dwarfs will allow us to easily identify substellar cloud compositions to gain insight that directly pertains to exoplanet atmospheres**
- **Only small silicate and refractory cloud particles ≤ 1μm produce a cloud mineral feature at specific wavelengths**
- **For the first time, MIRI on JWST will allow us to identify**
  - **cloud composition using spectra, if cloud particles are small ≤ 1μm**
  - **patchy clouds as the cause of brightness variations, removing previous ambiguity**

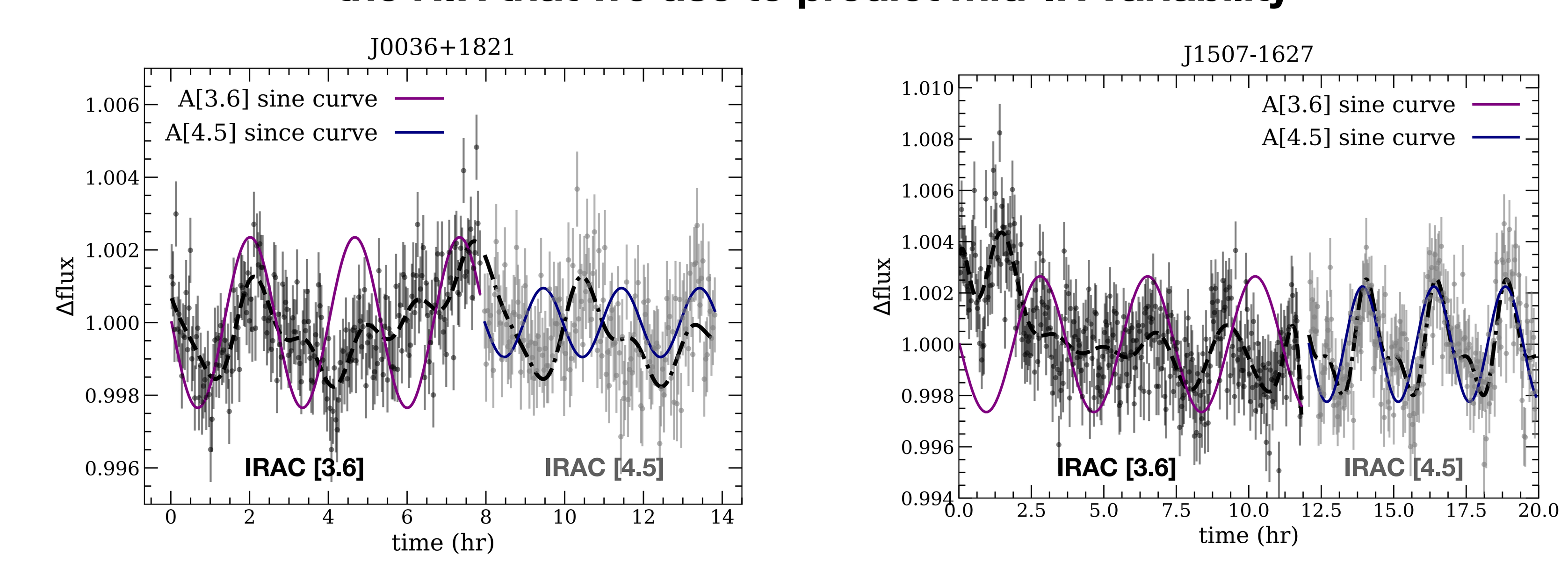
Model comparison with Spitzer IRS data



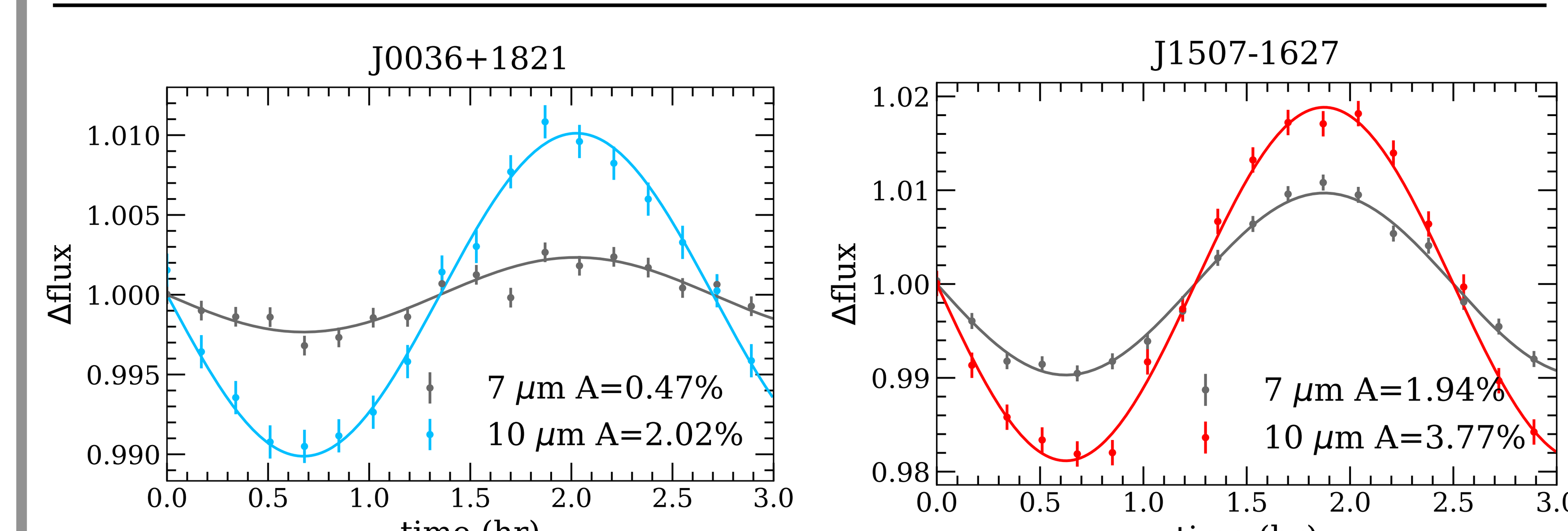
Our ad hoc silicate and refractory cloud models better capture the silicate feature that is seen in some brown dwarfs than the Ackerman & Marley (2001) cloud model



Some Brown dwarfs with tentative Spitzer Silicate detections are also variable. Metchev et al. (2015) used Spitzer IRAC [3.6] + [4.5] to estimate variability in the NIR that we use to predict mid-IR variability



Simulated time-series data with MIRI JWST



By measuring the spectroscopic variability inside and outside a mineral feature, we can uniquely identify a range of cloud species in substellar atmospheres using the MIRI instrument on the future JWST