Atmospheric Chemistry on Uranus and Neptune

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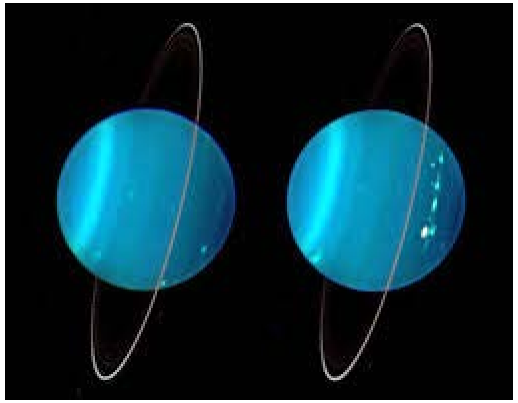
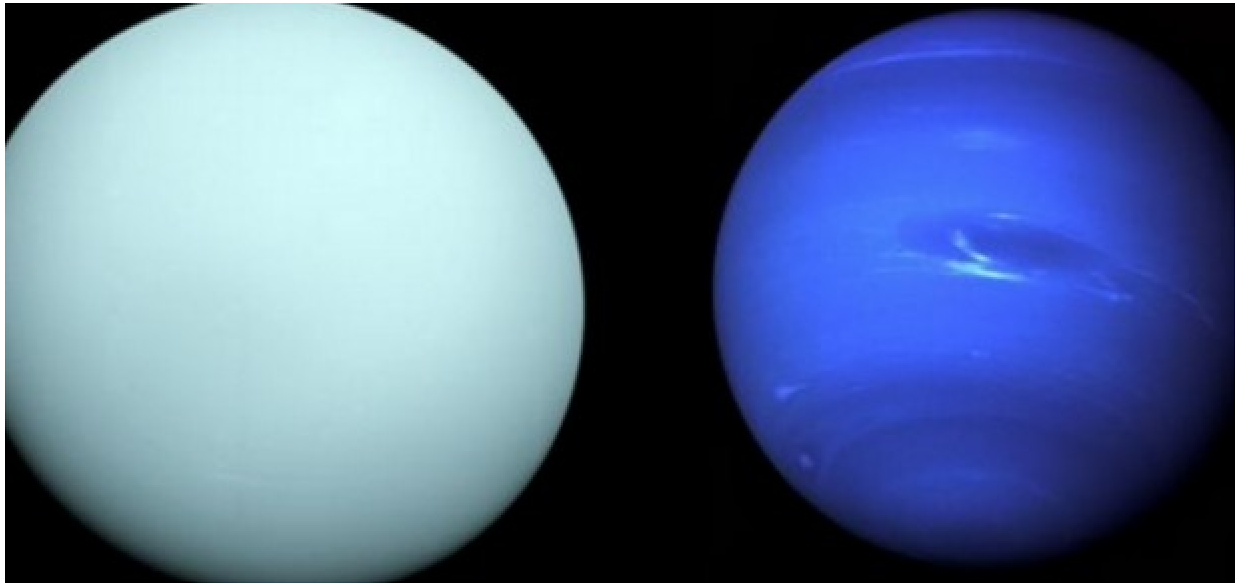
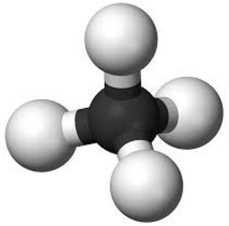
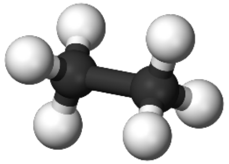
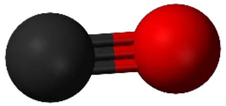


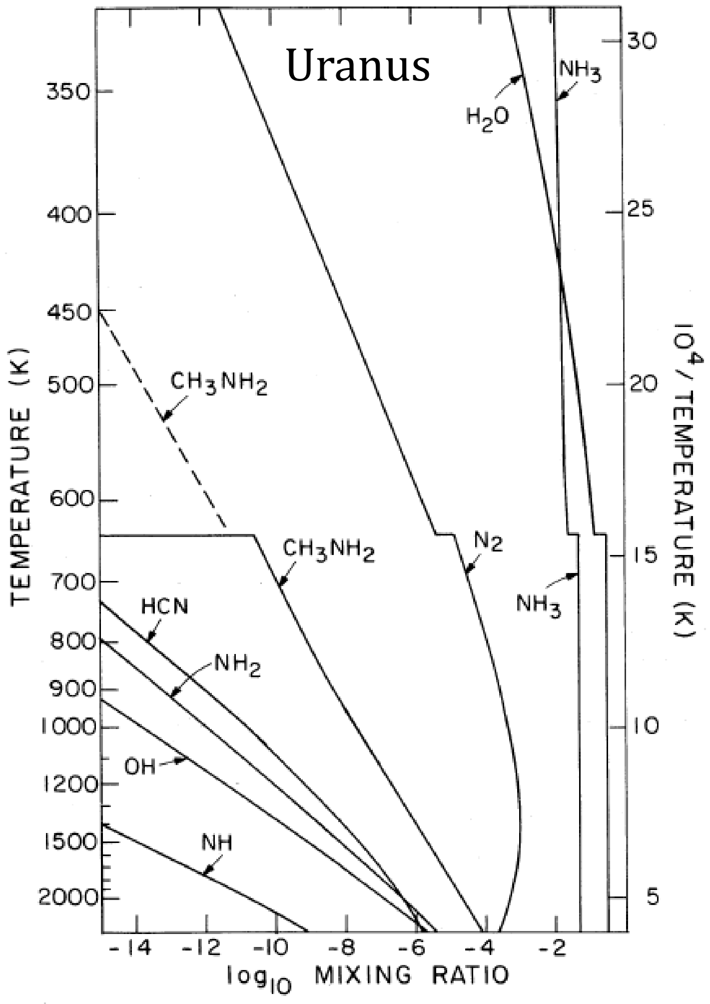






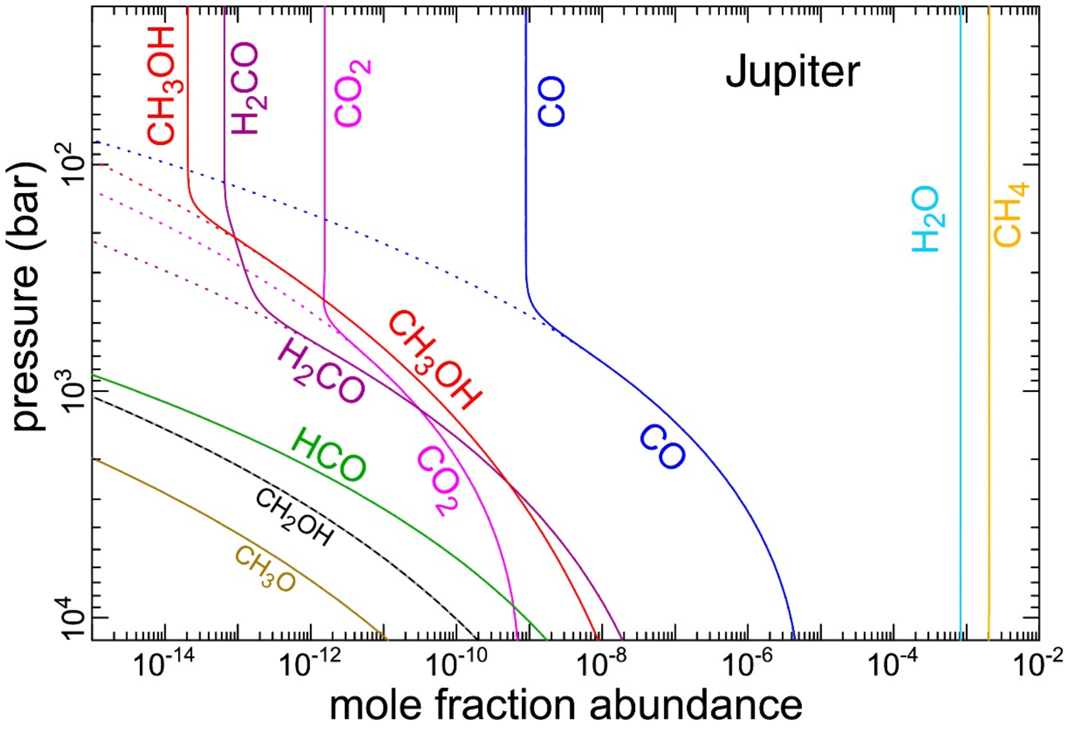


Thermochemical Equilibrium



from Fegley et al. (1986)

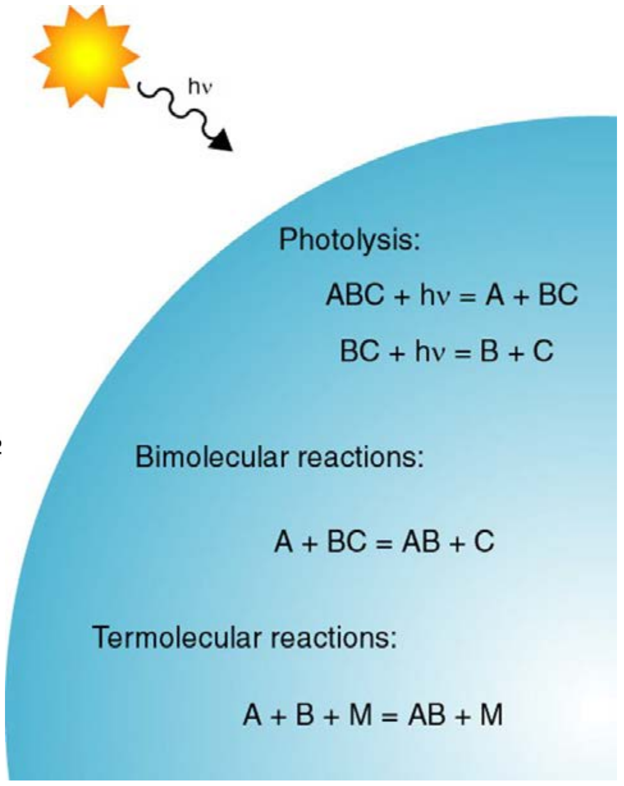
Transport-Induced Quenching



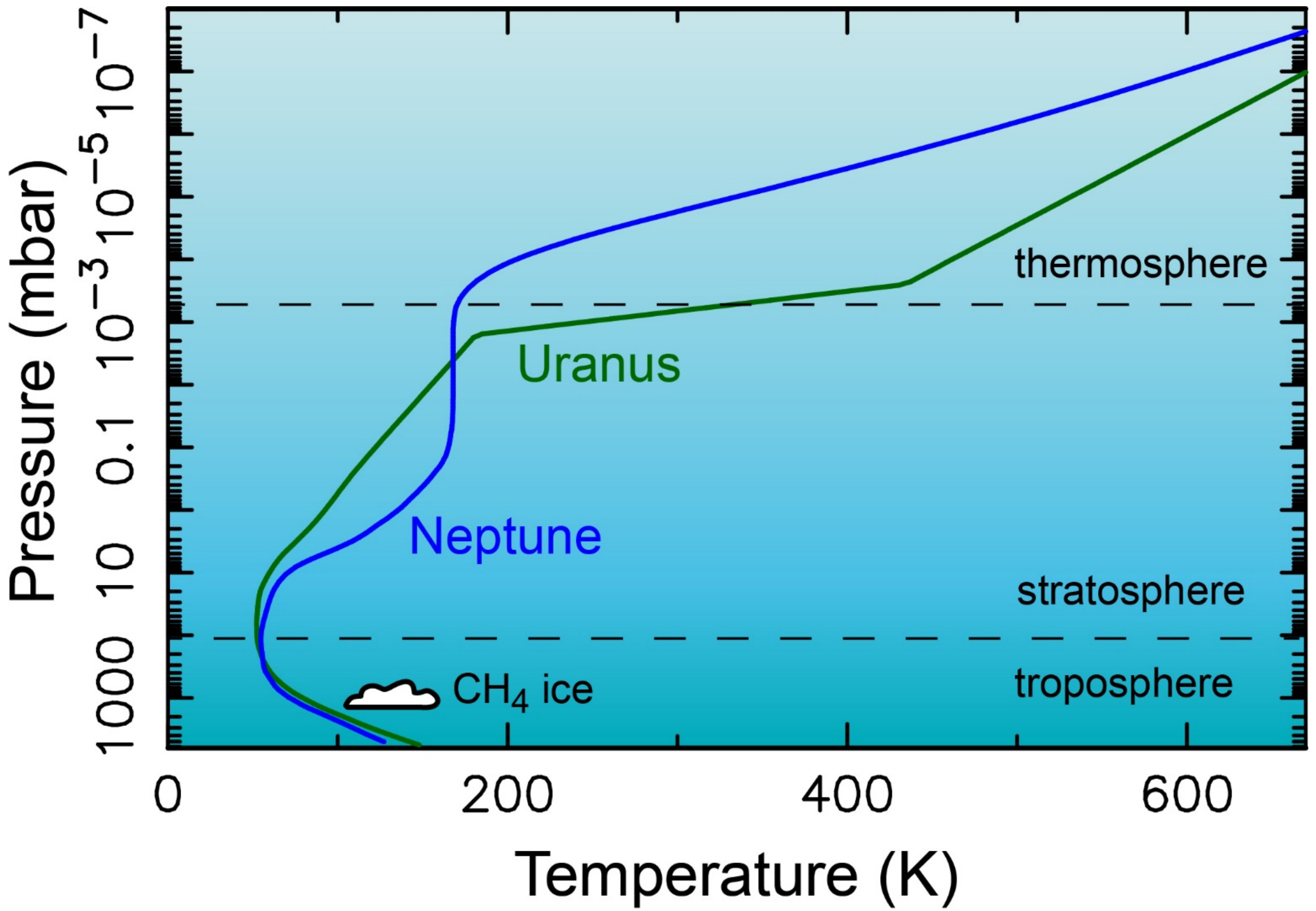
from Visscher et al. (2010)

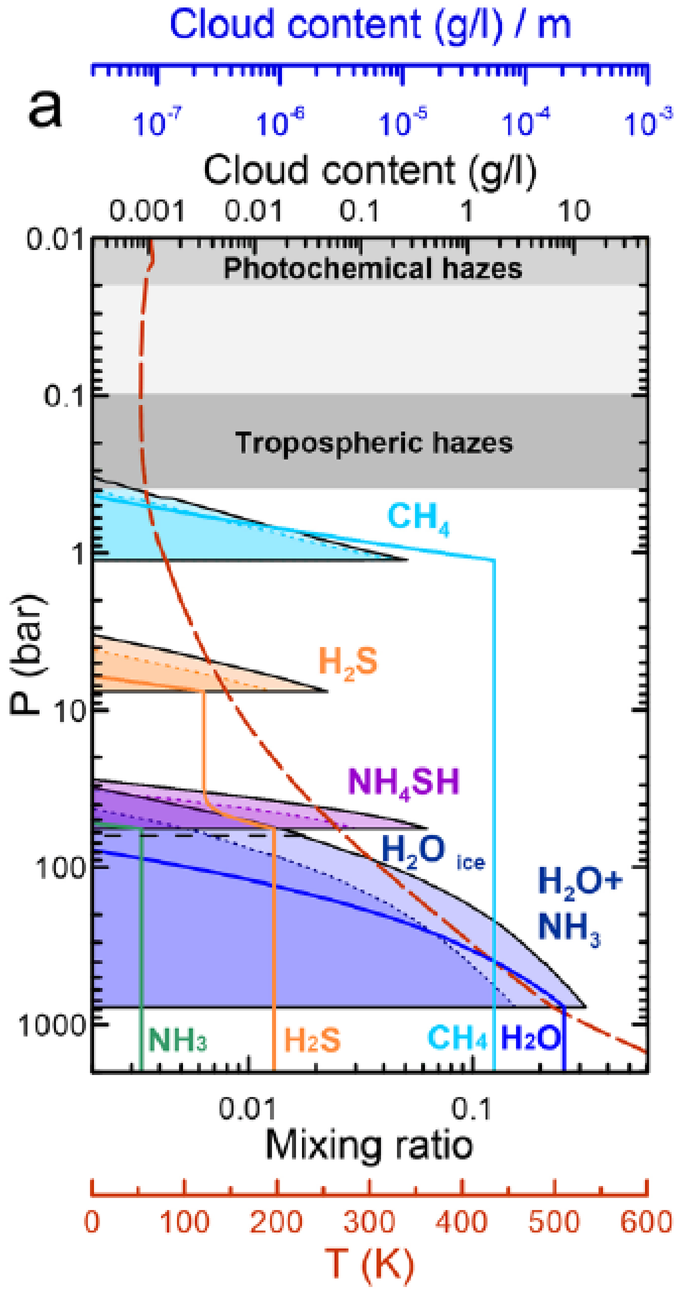
Three main chemical processes affect composition on the Ice Giants. Each of these processes dominate in different regions of the atmosphere

Photochemistry



Uranus and Neptune have similar atmospheric structure and bulk elemental composition, but notable differences in chemistry. ***Why?***

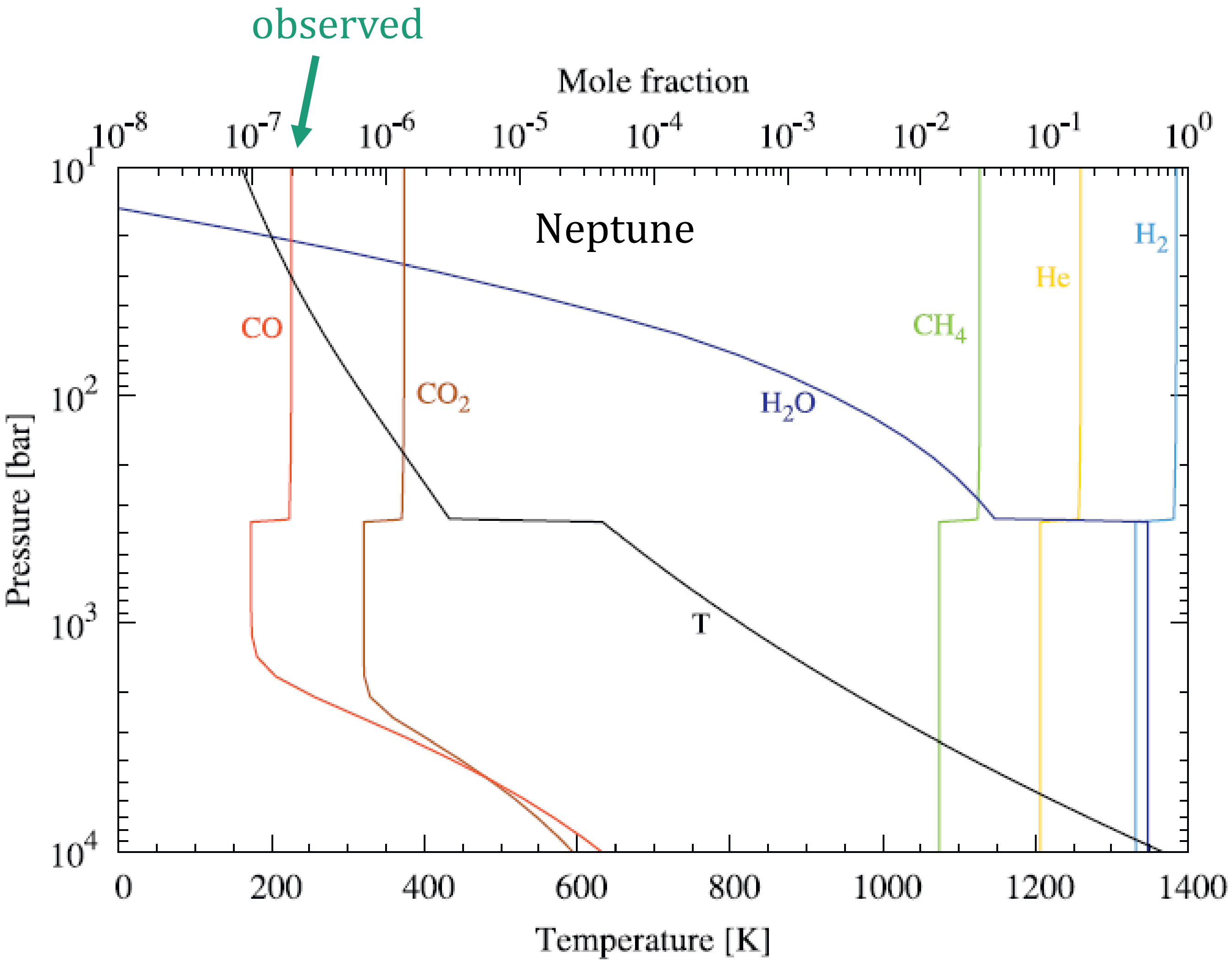




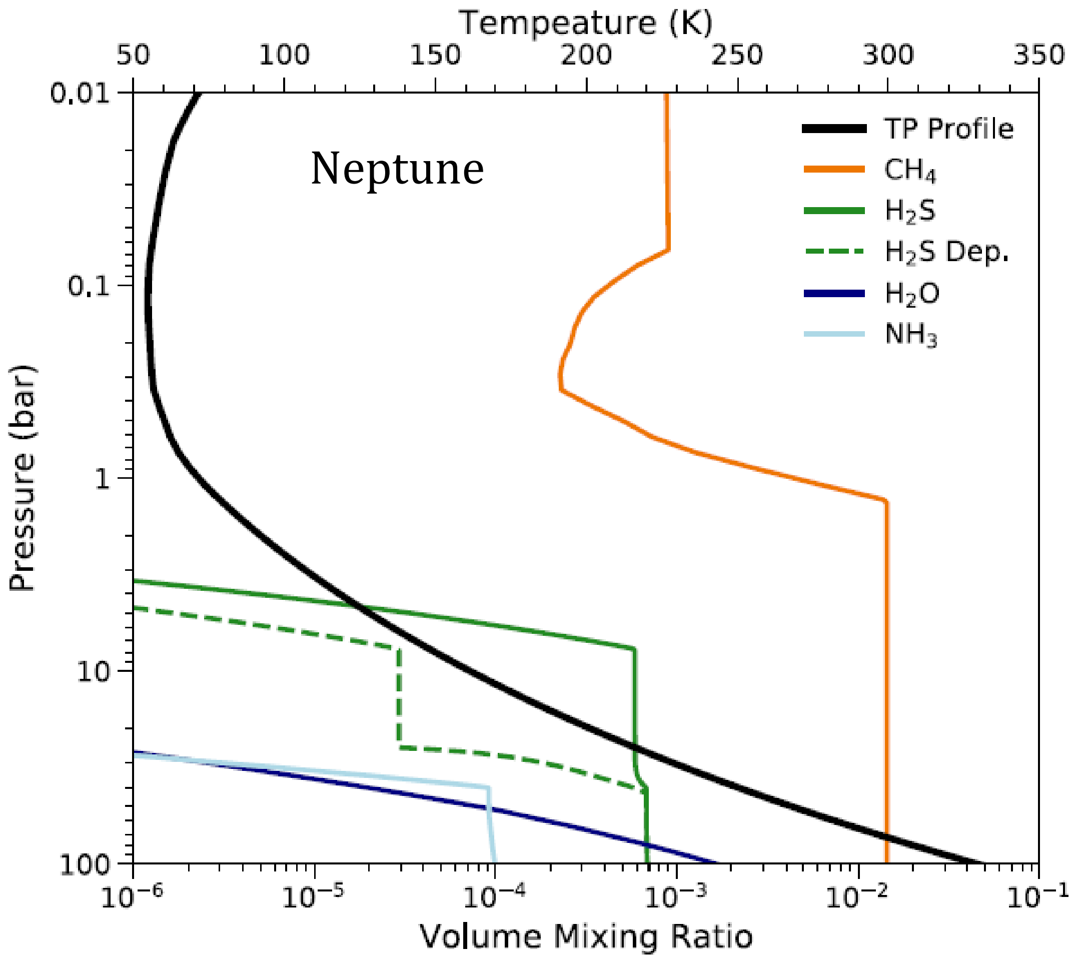
from Hueso and Sánchez-Lavega (2019)

J. Moses, Ice Giants 2020

Deep Troposphere: Thermochemistry, Quenching, Condensation

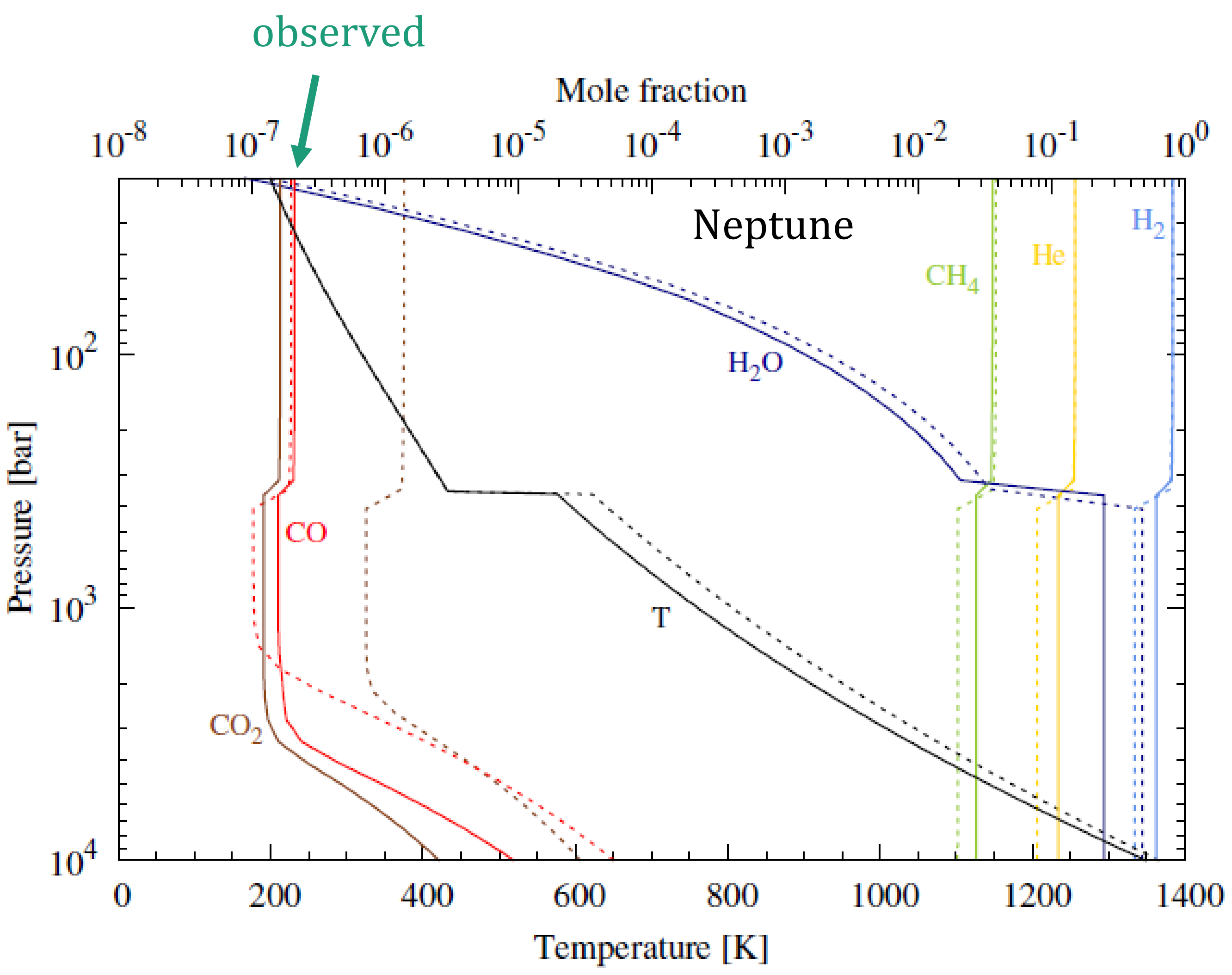


model from Cavalié et al. (2017), assumes 540x solar O/H



from Tollefson et al. (2019)

Quenching models can help indirectly determine deep elemental abundances



model update from Venot et al. (2019), assumes 250x solar O/H

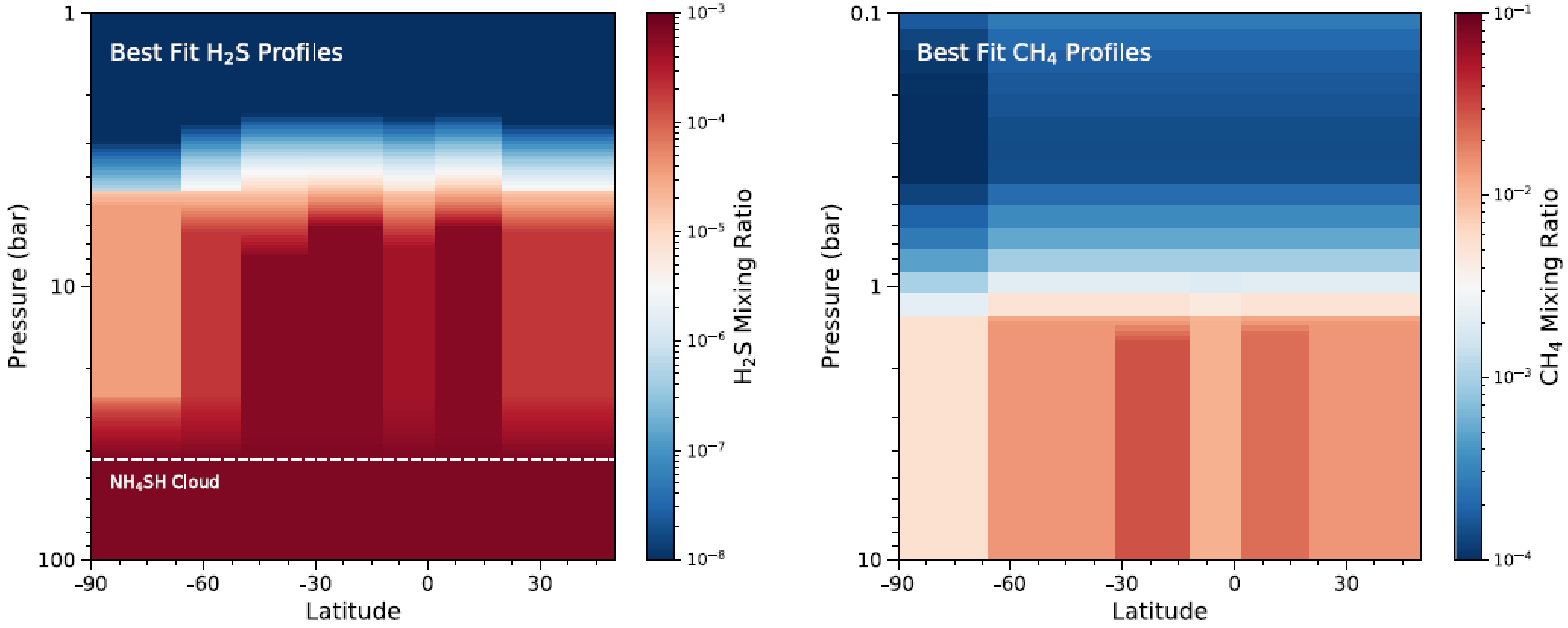
Using a thermochemical kinetics model, the observed upper tropospheric CO (and CO_2) can help constrain the deep H_2O abundance

But… results depend on

- Thermal structure
- Vertical transport rates
- Chemical reaction rates
- Horizontal homogeneity

None of which are very well constrained for the Ice Giants

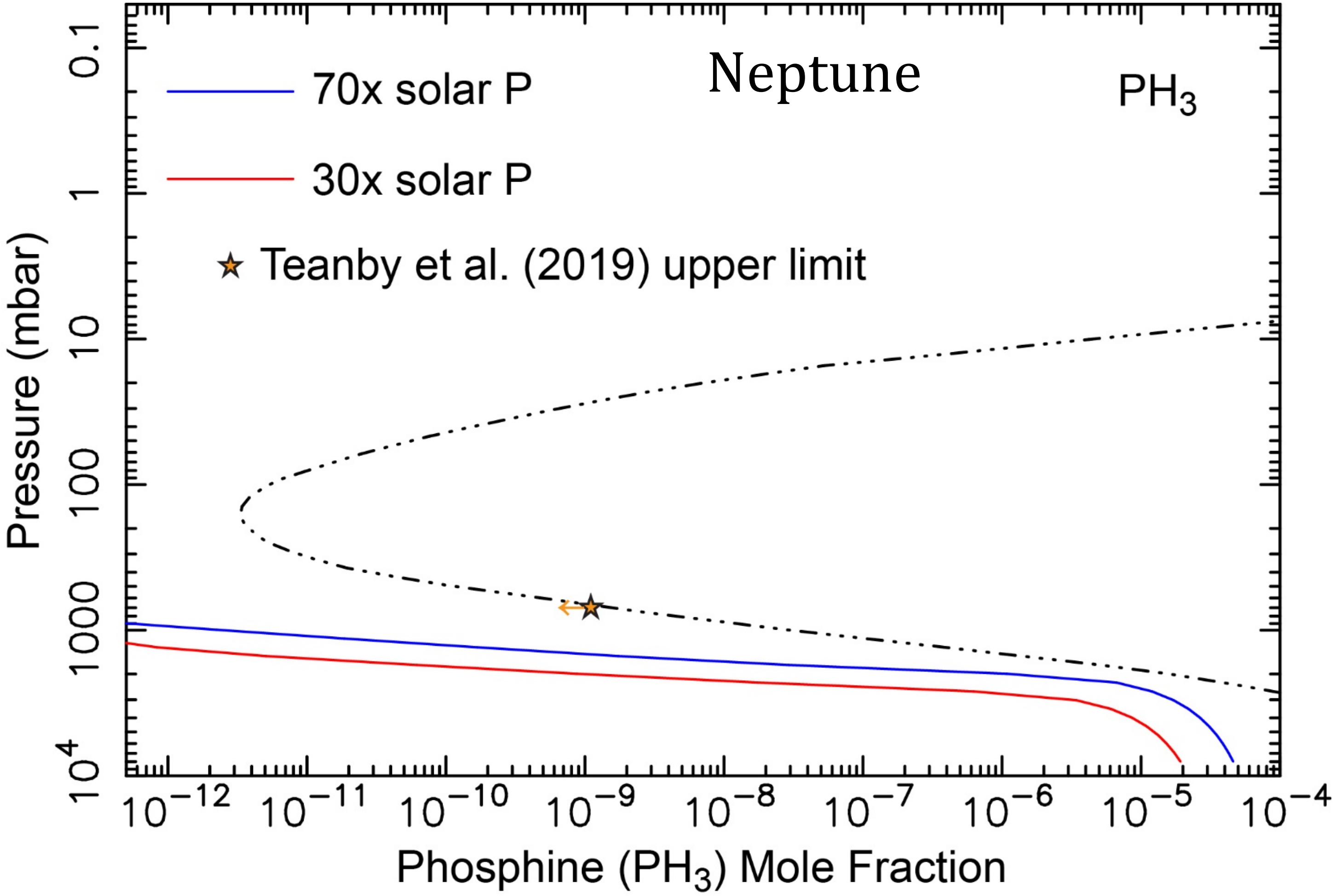
Tropospheric abundances vary with latitude, complicating remote-sensing analyses and deep-probe plans



from Tollefson et al. (2019)

As was first identified by Karkoschka & Tomasko (2009, 2011), the abundance of methane in the troposphere is greater at low latitudes than high latitudes, presumably due to atmospheric dynamics. ***Chemistry and dynamics are intimately linked.***

Tropospheric photochemistry limits the abundance of PH_3 and probably H_2S



from Teanby et al. (2019)

$PH_3 + h\nu \rightarrow PH_2 + H$
$H + PH_3 \rightarrow PH_2 + H_2$
$2PH_2 \rightarrow P_2H_4$

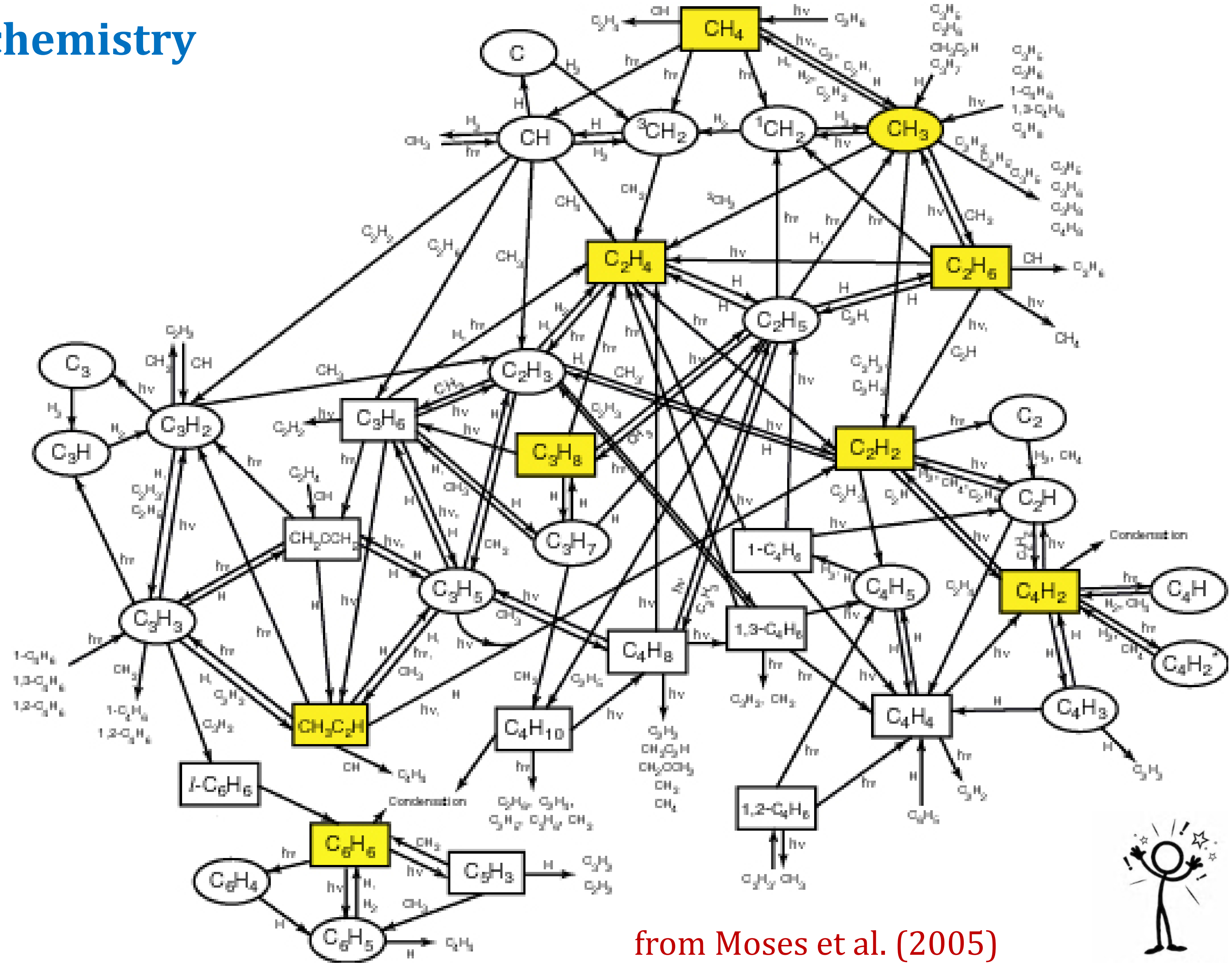
Net: $2PH_3 \rightarrow P_2H_4 + H_2$

Phosphine doesn't even make it to it's condensation level (but will produce diphosphine hazes), and hydrogen sulfide will be strongly depleted above the H_2S cloud top, probably producing elemental sulfur (?). We will not see these species at altitudes above 2-3 bars

Probe would need to go > 10 bar to get deep P abundance

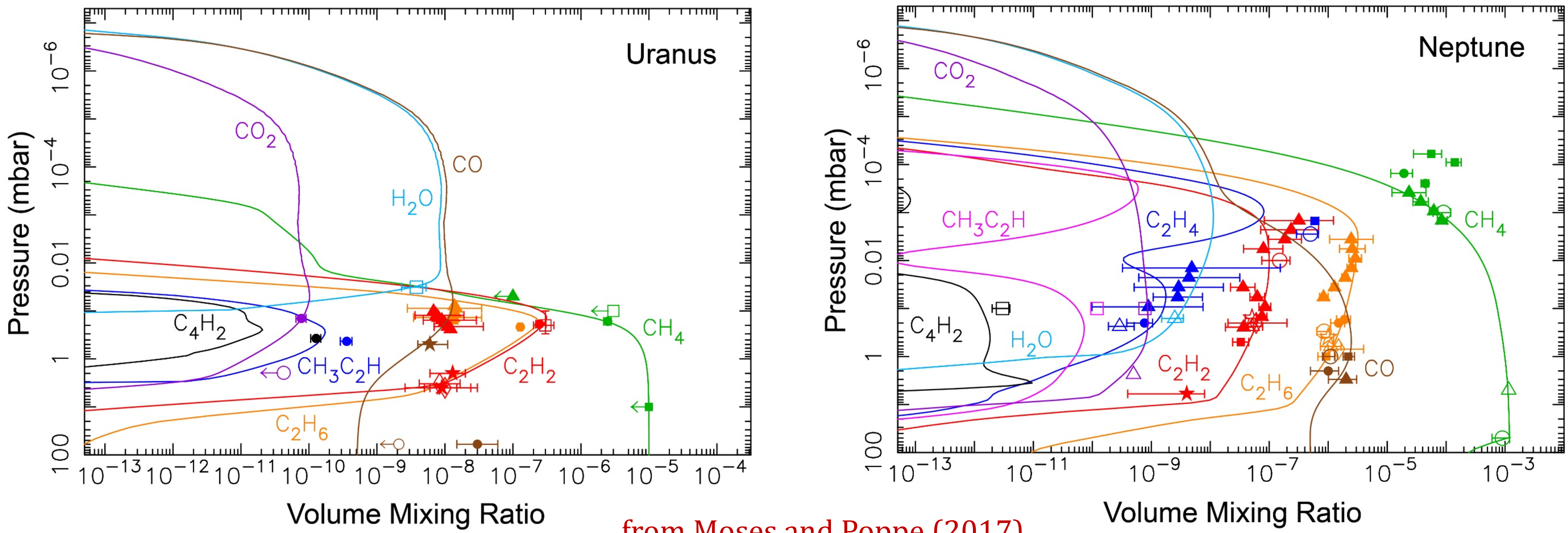
Stratospheric photochemistry

Despite the great distance of Uranus and Neptune from the Sun, solar UV photolysis of methane in the upper stratosphere produces a rich and interesting hydrocarbon photochemistry. Many of the major products will condense to form stratospheric hazes.



from Moses et al. (2005)

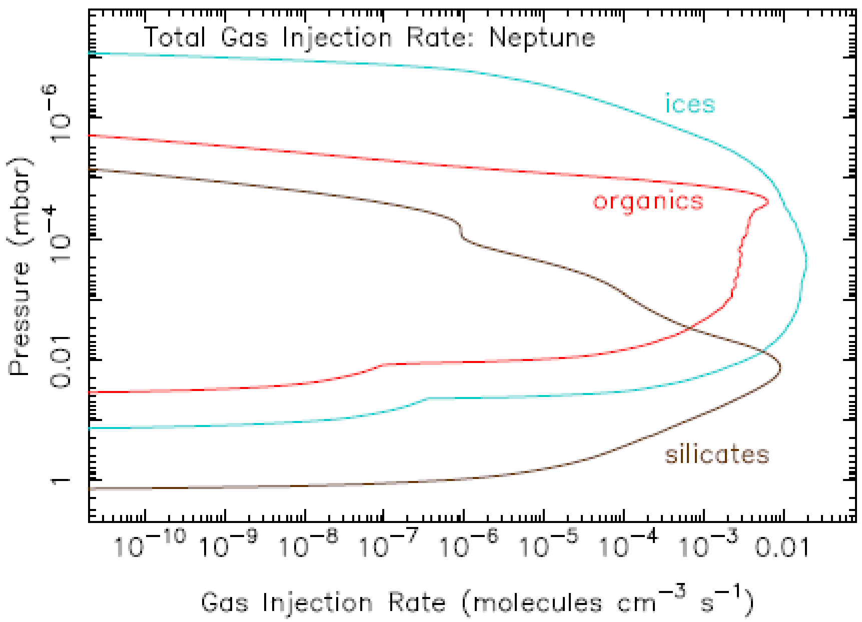
Stratospheric photochemistry: Uranus and Neptune are different!

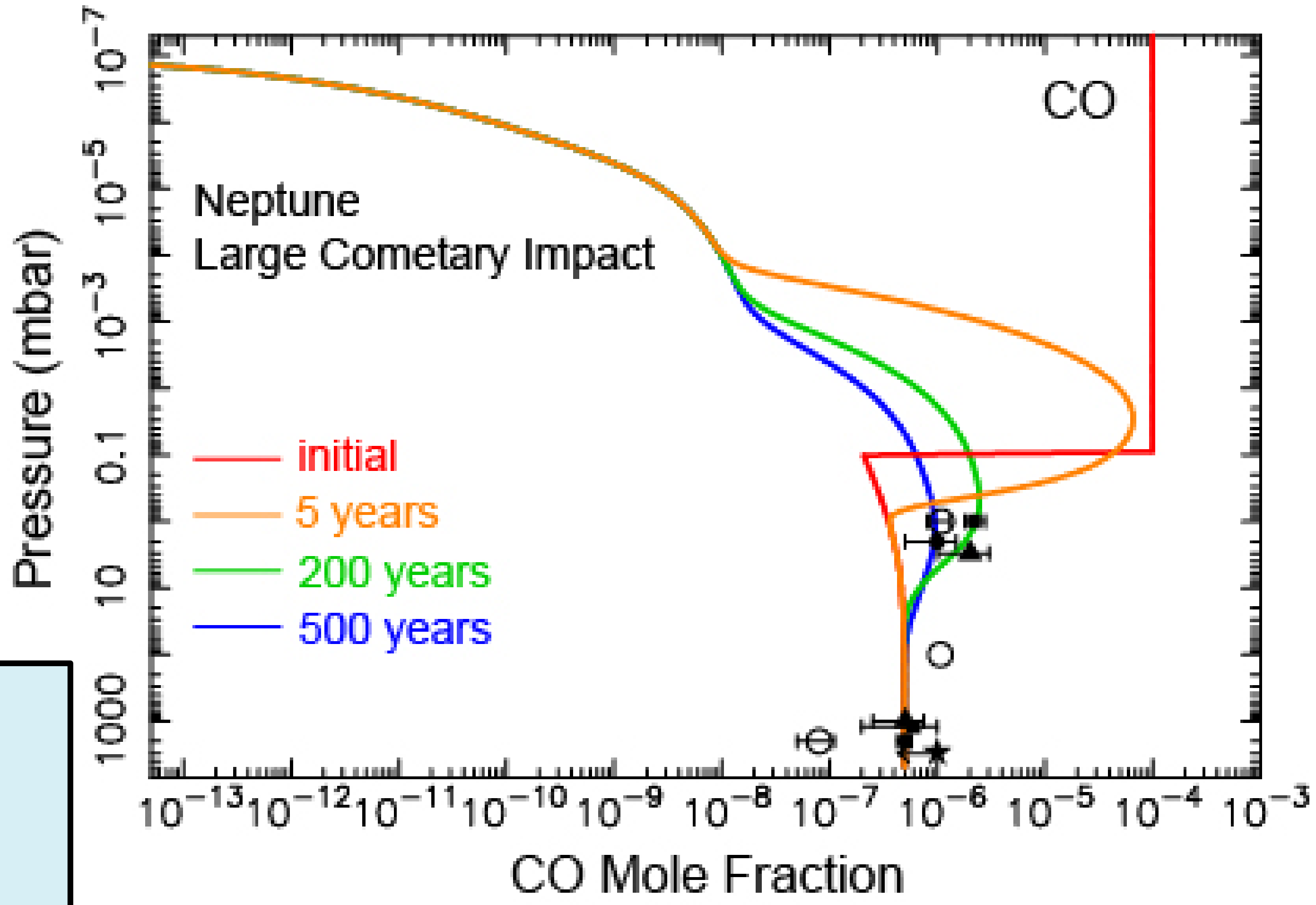


from Moses and Poppe (2017)

The main differences here are caused by differences in the strength of atmospheric “mixing”. Vertical motions in the Uranus atmosphere are apparently very sluggish. Methane does not get very high. Note also the influence of external material (oxygen) coming into the atmosphere. ***We need to better understand the reasons for and consequences of these differences.***

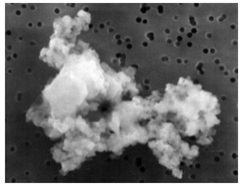
Stratospheric photochemistry: Influence of external material





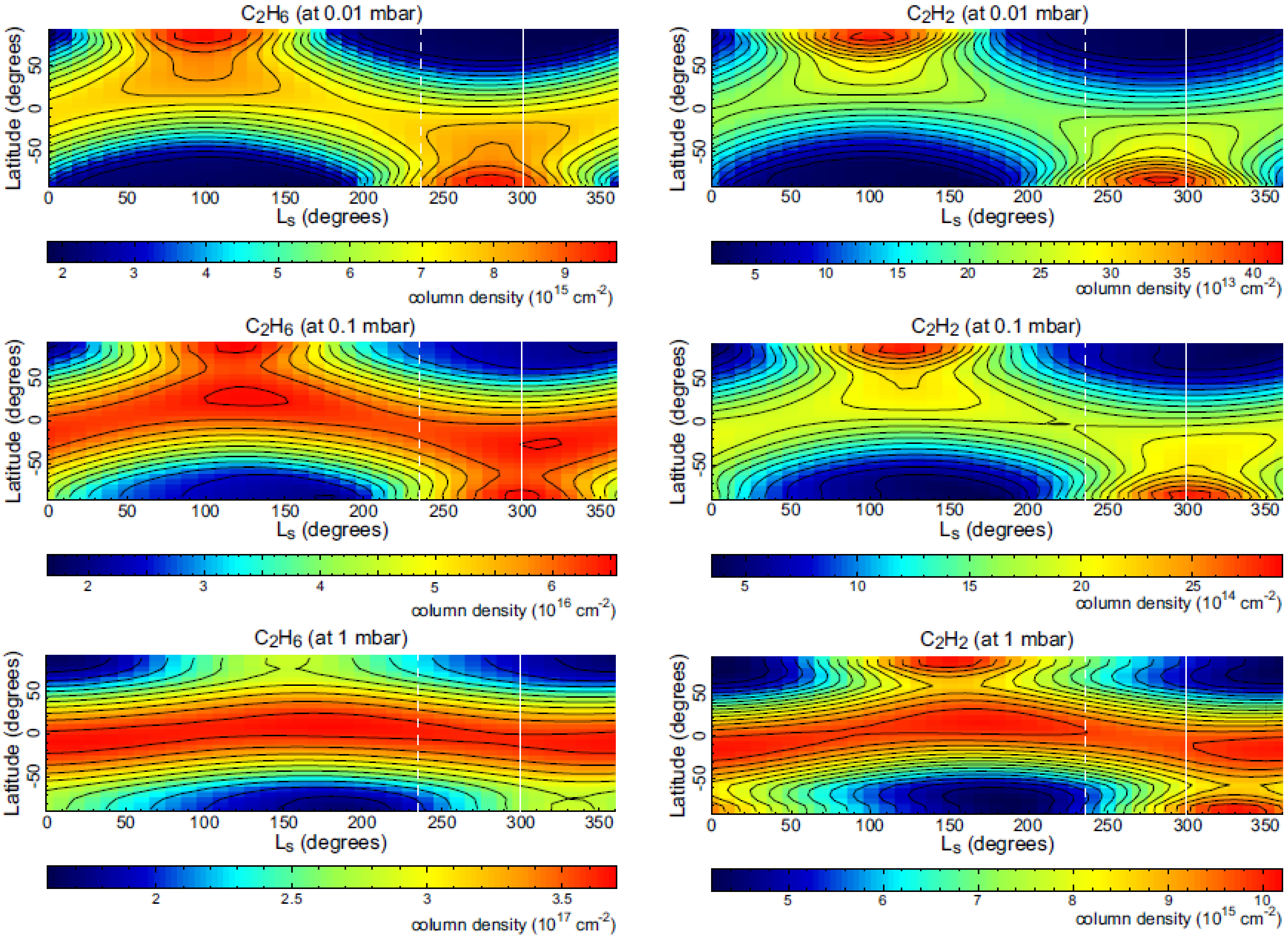
Ice Giant atmospheres are affected by external material from interplanetary dust particles, comets, satellite debris, magnetospheric particles. This external material can affect ionospheric, stratospheric, and potentially tropospheric chemistry.

from Moses & Poppe (2017)



Stratospheric photochemistry: Seasonal forcing matters!

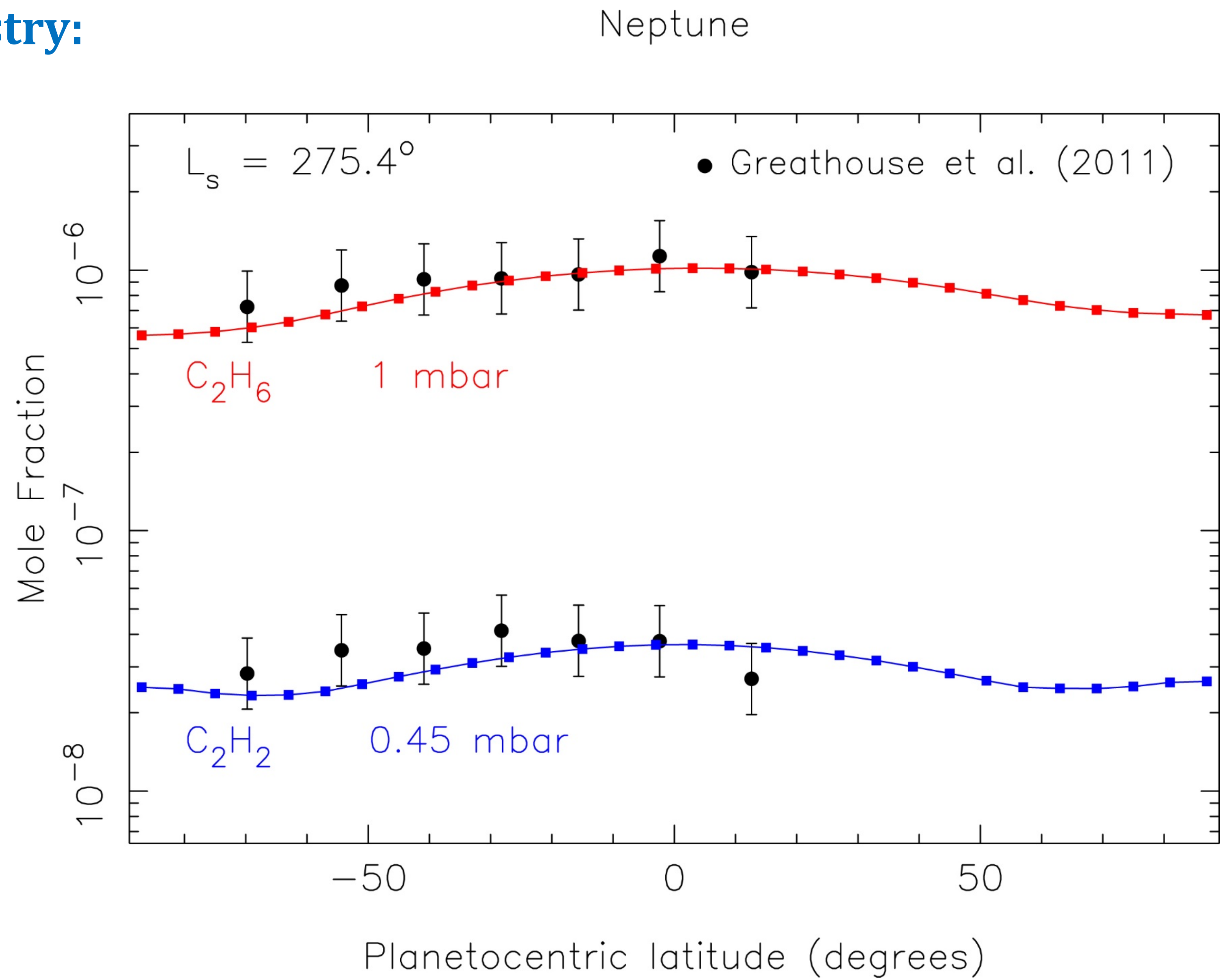
Models predict that photochemical product abundances can vary significantly with latitude and season due to changes in solar forcing. Counterintuitively, Uranus should exhibit less seasonal variation because of the larger time constants at the greater pressures where CH_4 is photolyzed.



from Moses et al. (2018)

Stratospheric photochemistry: Seasonal/latitudinal differences

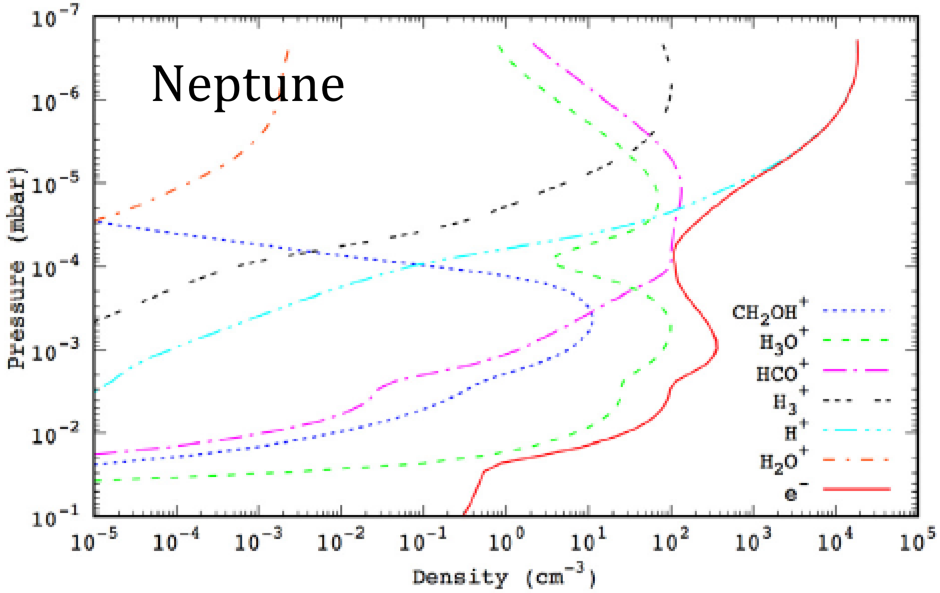
We need more spatially resolved observations to test current theories and to better understand the complex coupling between chemistry, dynamics, and radiative transport in Ice-Giant atmospheres. Does the latitude variation in CH_4 play any role in the spatial distribution of stratospheric hydrocarbon abundances? Are photochemical products good tracers of stratospheric circulation?

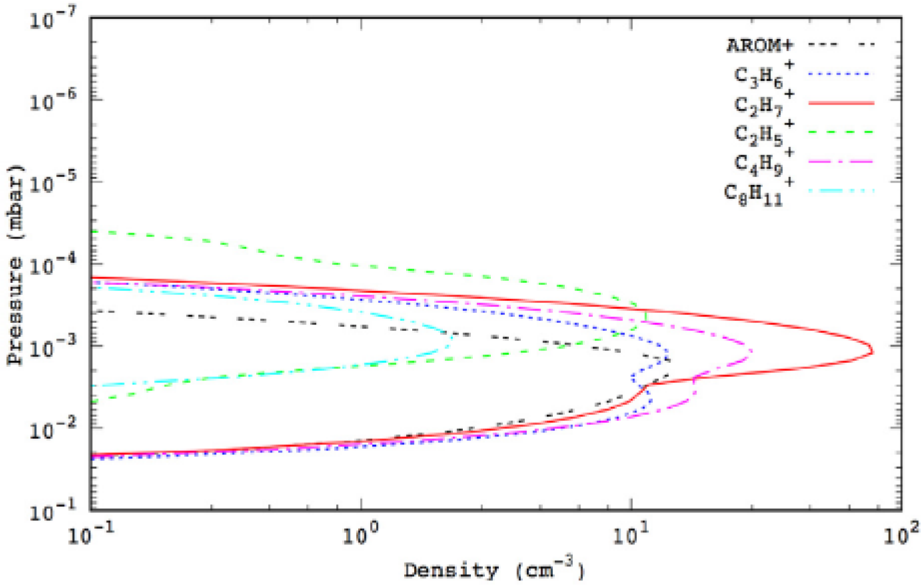


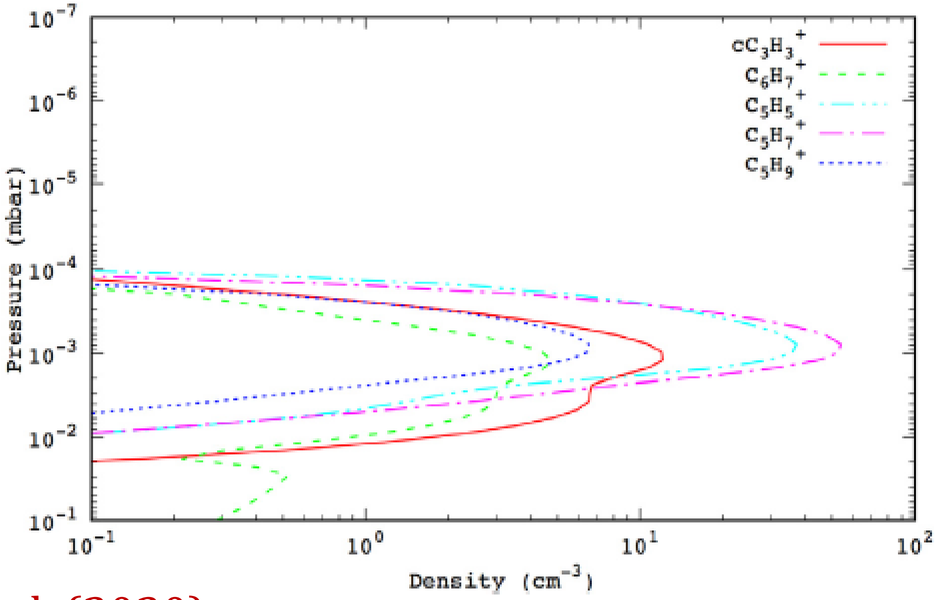
from Moses et al. (2018)

Ionospheric chemistry

Ice Giant ionospheres are dominated by H^+ and H_3^+ at higher altitudes, with external oxygen from dust ablation contributing H_3O^+ and HCO^+ at mid altitudes, and interactions with stratospheric hydrocarbons producing a secondary peak at lower altitudes. Metal ions may also be important, as a result of the delivery of external material. Uranus and Neptune will have very different ionospheres.







from Dobrijevic et al. (2020)

Key Science Questions for Mission Planning

- **What is the elemental composition in the deep atmosphere of Uranus and Neptune, and what does that tell us about planetary formation processes?** (via probe measurements of He, Ne, Ar, Kr, Xe, CH_4, H_2S, NH_3, PH_3, D/H and other isotopic ratios, etc.).
- **How does the tropospheric composition vary across the planet, and what does that tell us about deep atmospheric dynamics and circulation; what are the implications for determining deep abundances?** (remote sensing/probe measurements of CH_4, H_2S, NH_3, PH_3, CO, noble gases, etc.).
- **Can disequilibrium tracers such as CO, CO_2, H_2CO, C_2H_6, HCN, N_2, PH_3 provide *robust* indirect indicators of the deep abundance of O, N, and other elements?** (remote/probe measurements of these species, combined with accompanying lab/theoretical supporting efforts).
- **How does the stratospheric composition vary in three dimensions across the planet, and what does that tell us about atmospheric circulation, moist convection, atmospheric structure, chemistry, response to seasonal forcing, cometary impacts, etc.?** (remote-sensing mapping of CH_4 (!), hydrocarbons, HCN, CS, oxygen species; UV occultations).

Key Science Questions for Mission Planning

- **To what extent is cometary or other external debris affecting the composition of the troposphere, stratosphere, and thermosphere/ionosphere of Uranus and Neptune, and what are the implications for impact rates, atmospheric structure and chemistry, and measuring deep abundances?** (determine 3D distribution of CO, CO_2, H_2O, HCN, CS; resolve CO line profiles).
- **What is the composition and structure of the ionosphere of Uranus and Neptune, and what does that tell us about thermospheric processes, magnetospheric processes, external influence?** (radio occultations, UV occ/imaging, IR obs).
- **Why is the observable atmospheric composition of Uranus and Neptune so different, and is this difference time variable or static?** (remote/probe measurements of atmospheric species, combined with accompanying lab/theory/obs supporting efforts).
- **What process(es) is(are) responsible for the excess methane in Neptune's stratosphere (and to a lesser extent Uranus'), and what are the implications for transiting exoplanets?** (probe/remote CH_4 measurements, thermal mapping)

Probes would provide an important benchmark to help break degeneracies in remote-sensing observations; orbiter is needed for good mapping & studies of dynamics/chemistry.