Water vapor in PDRs: the *Herschel*/HIFI view

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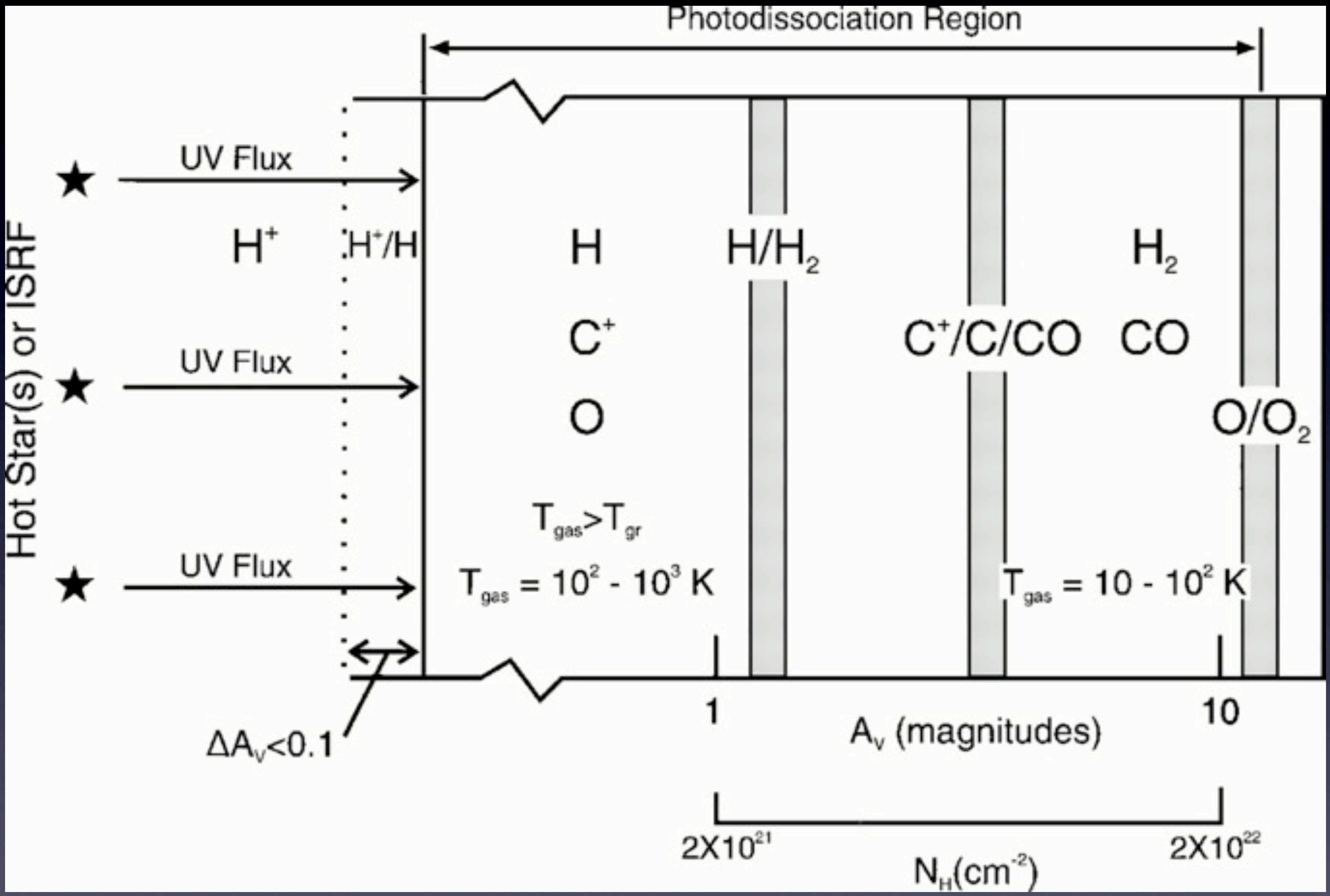
Classical Photodissociation Regions (PDRs)



Hollenbach & Tielens 1997

- A classical PDR includes large columns of warm O, C^+ (outer part), and CO and vibrationally excited H_2 (deeper into the cloud).

PDRs including grain chemistry

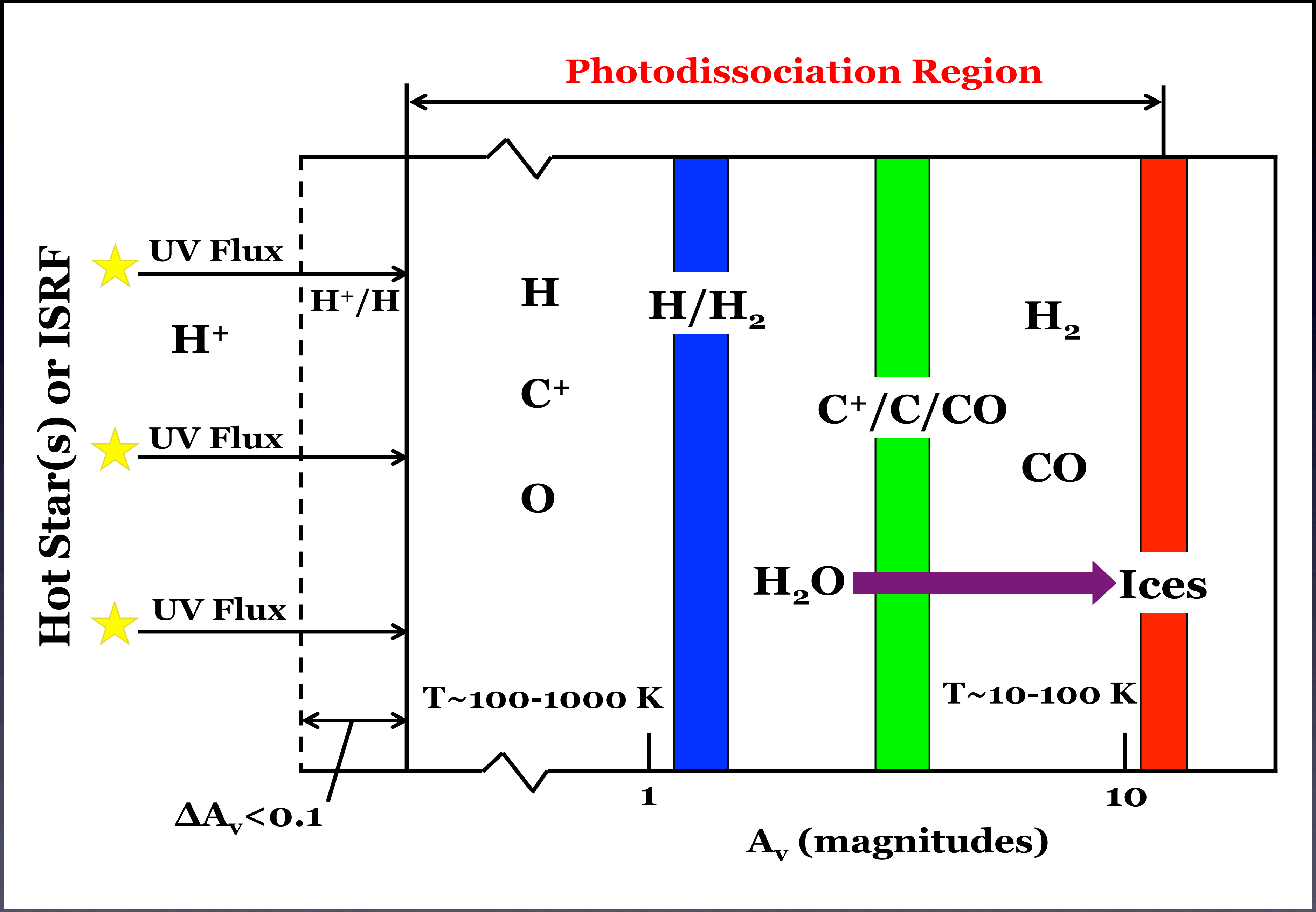
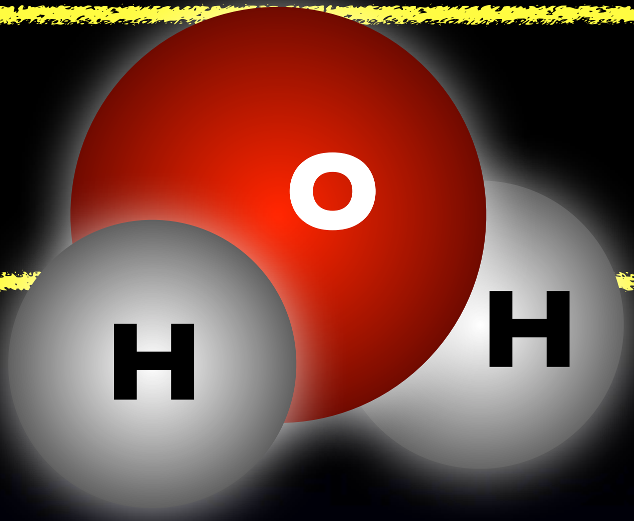


Figure by M. Kaufman

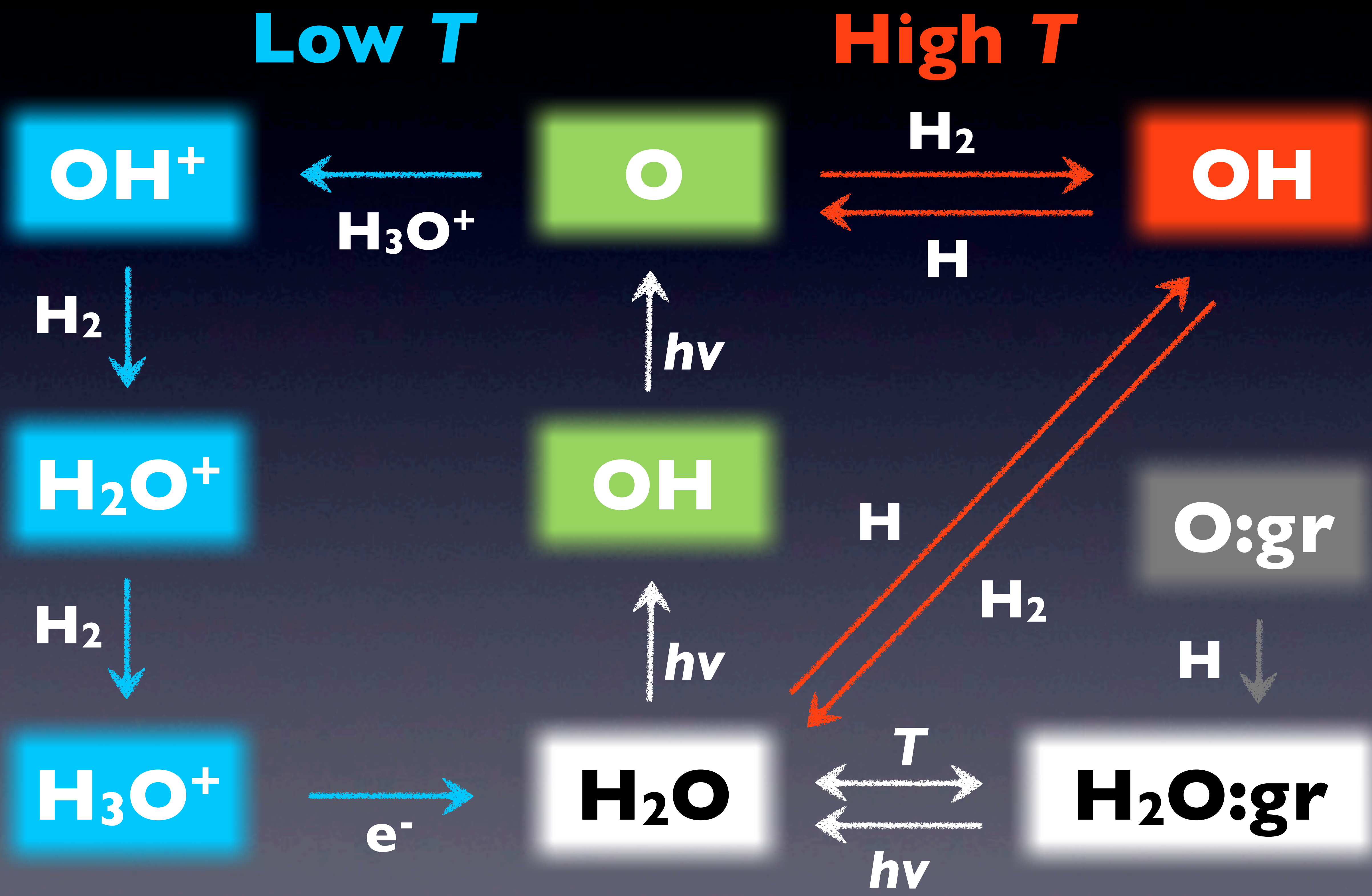
- The PDR structure has changed, including grain chemistry (freeze-out and desorption; Hollenbach et al. 2009).

Water - H_2O

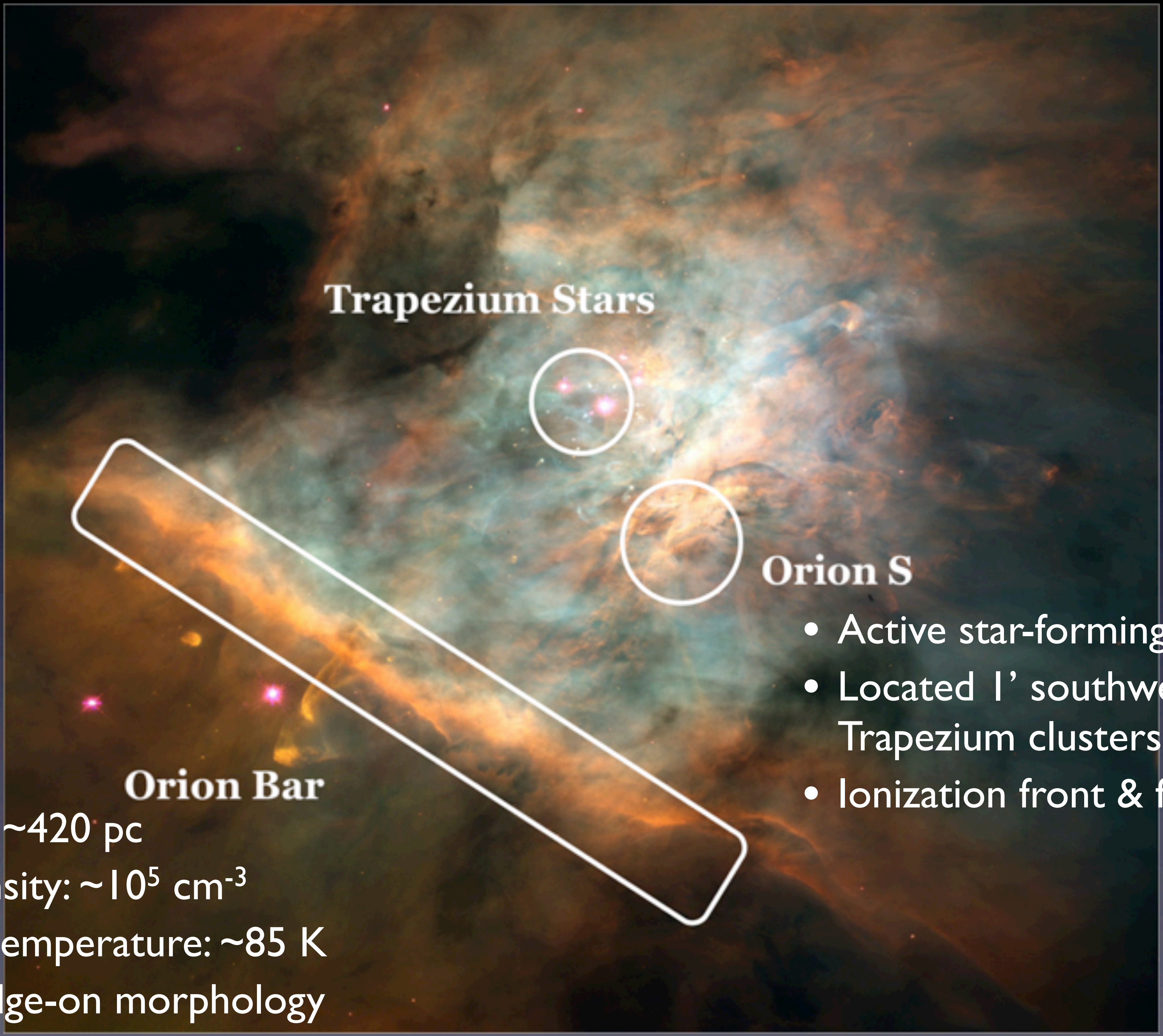


- Plays an important role in star-forming regions and protoplanetary disk.
  - a natural chemical filter
    - large abundance variation between cold dust (freeze-out) and warm gas (enhancement)
  - a crucial reservoir of oxygen
    - control the chemistry of oxygen-bearing molecules
  - a useful astrophysical tool
    - asymmetric molecule: rich line spectrum
    - line ratios for probing temperature and density
- Ortho-to-para ratio (OPR) of H_2O
  - the OPR of H_2O is expected to be ~3 at high temperature (> 40 K) and lower at low temperature.

H_2O Chemistry



Orion PDRs



- Active star-forming region
- Located 1' southwest from Trapezium clusters
- Ionization front & face-on PDR

- Distance: ~420 pc
- Mean density: ~10^5 cm^{-3}
- Average temperature: ~85 K
- Nearly edge-on morphology
- Clumpy structure

Image Credit: NASA/HST

Questions

- What is the ortho-to-para ratio (OPR) of H_2O in the Orion PDRs and how is it related to the formation of water?
- What drives the oxygen chemistry in PDRs - thermal or radiative processes?

The ortho-to-para ratio (OPR) of H_2O in the Orion PDRs

Methods

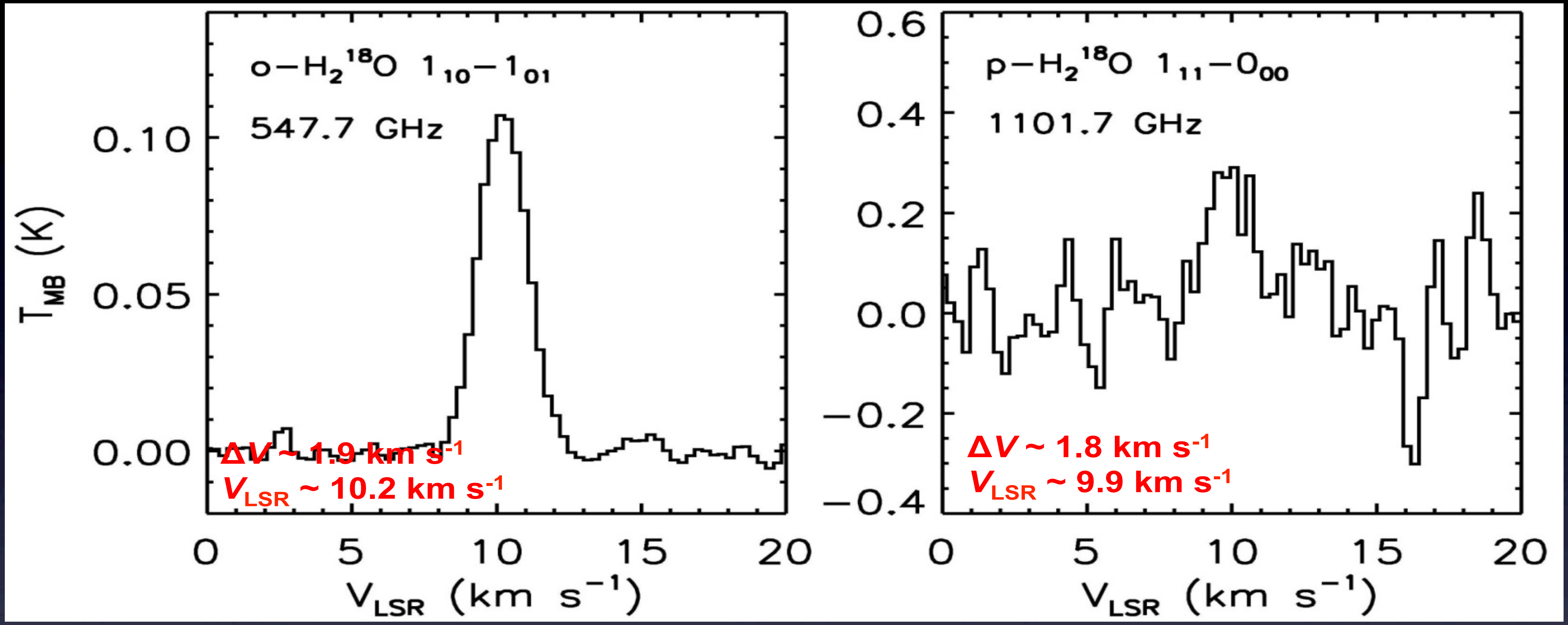
LTE Calculations

- We assume that
  - the lines are optically thin (non-detection of $H_2{}^{17}O$ lines).
  - the gas is not warm (< 100 K, non-detection of excited state lines of $H_2{}^{18}O$).
- We derive the column densities for different excitation temperature (T_{ex} = 50-100 K)

Non-LTE Calculations

- The RADEX code (van der Tak et al. 2007)
- A grid of models with values of T_{kin} = 20, 60, and 100 K, values of $n(H_2) = 10^4, 10^6$, and 10^8 cm^{-3}

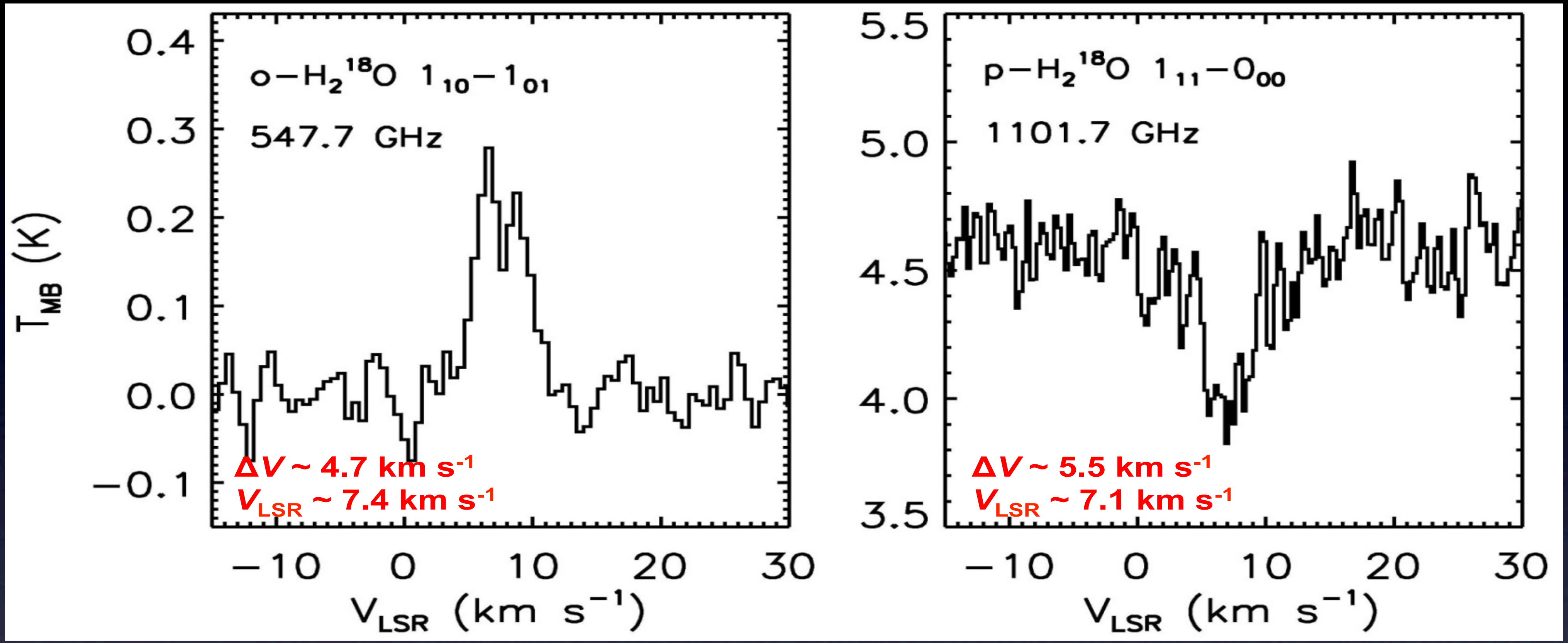
Results: the Orion Bar



- Assuming LTE, an OPR of ~0.3
- For non-LTE calculations, an OPR of ~0.1-0.5

- The derived OPR of ~0.1-0.5
- Unexpectedly low given gas temperature of ~85 K
- Much lower than the dust temperature of ~49 K

Results: Orion S

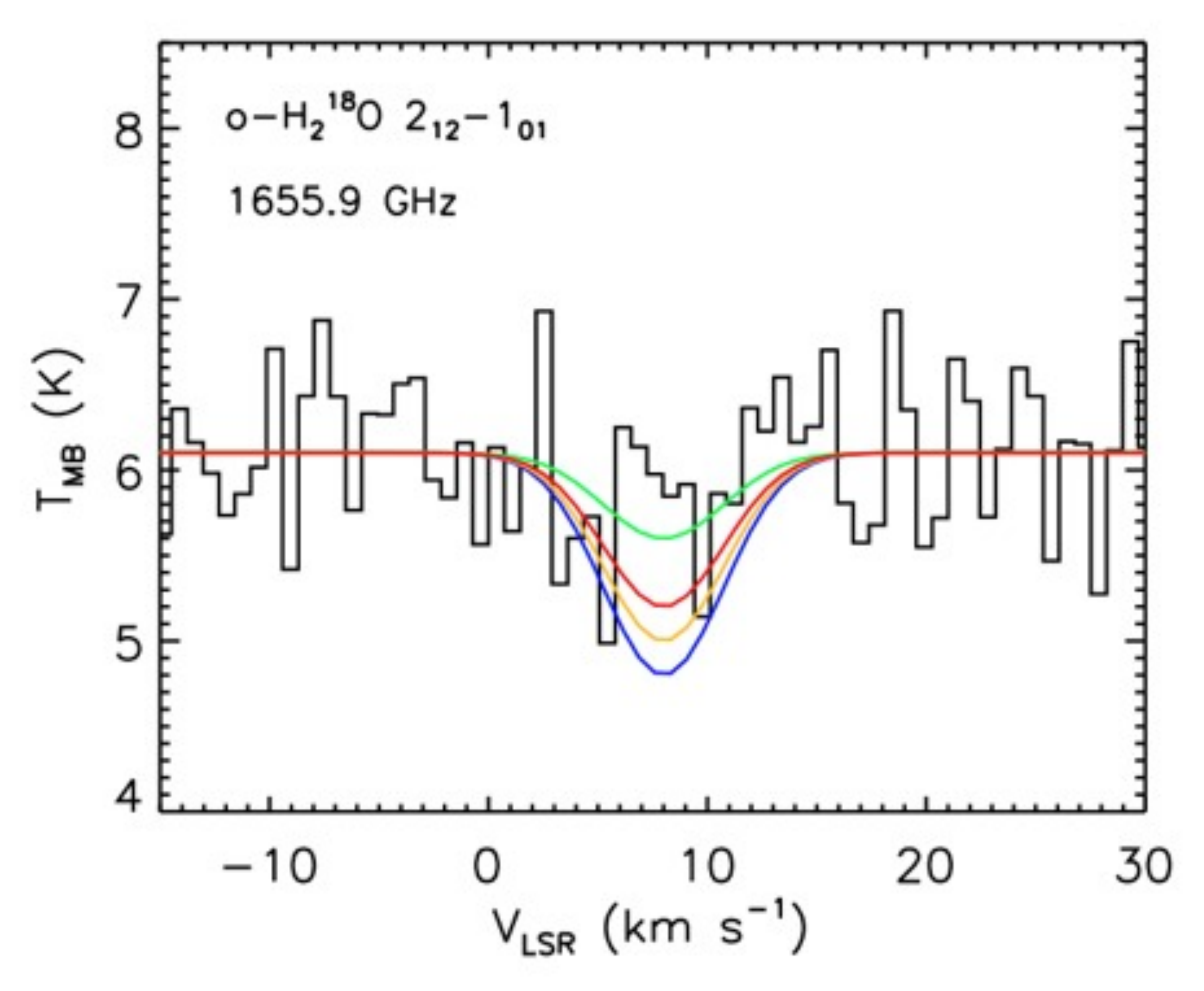


- We derived the column density for the absorption component of p-$H_2{}^{18}O$ 1_{11}-0_{00} using the optical depth.
- Assuming LTE, an OPR of ~0.1
- For non-LTE calculations, an OPR~0.3-3

- The derived OPR is strongly sensitive to the assumed physical conditions.

Further Analysis: Orion S

- For further constrains on the OPR in Orion S, we estimate the intensity (T_{peak}) of o-$H_2{}^{18}O$ 2_{12}-1_{01} line (1656 GHz) assuming that this line appears in absorption.



If OPR=1 → T_{peak}= -0.5 K
If OPR=2 → T_{peak}= -0.9 K
If OPR=2.5 → T_{peak}= -1.1 K
If OPR=3 → T_{peak}= -1.3 K

- The observation data are consistent with OPR = 1 and 2, but not with OPR = 2.5 and 3.
- The OPR of H_2O in Orion S is below 2.

OPR of H_2O in the Orion PDRs

- The OPR of H_2O is subthermal in the Orion PDRs.
- Cannot be explained by gas-phase formation of water.
  - H_3O^+ dissociative recombination is exothermic (OPR~3).
- Water formation on the grains, recent evaporation?
  - dust temperature is too low (< 100 K).
- Effect of photodesorption?
  - recombination of H + OH $\Rightarrow$ H_2O (OPR~3)
  - kick-out mechanism
  - the relative importance: ice thickness & ice temperature
  - The original ice OPR is partially preserved into the gas phase through the kick-out mechanism (Arasa et al. 2015).
  - Some laboratory experiments are ongoing (e.g., Hama, Kouchi, & Watanabe 2016).

Summary

- What is the ortho-to-para ratio (OPR) of H_2O in the Orion PDRs and how is it related to the formation of water?

➡ The ortho-to-para ratios of H_2O is ~1 in the Orion PDRs (photodesorption).

- What drives the oxygen chemistry in PDRs - thermal or radiative processes?

➡ H_2O chemistry is dominated by photodesorption in the Orion Bar.