

On-going gas-phase organic chemistry observed through the emission of CH^+ and CH_3^+ in the Orion Bar

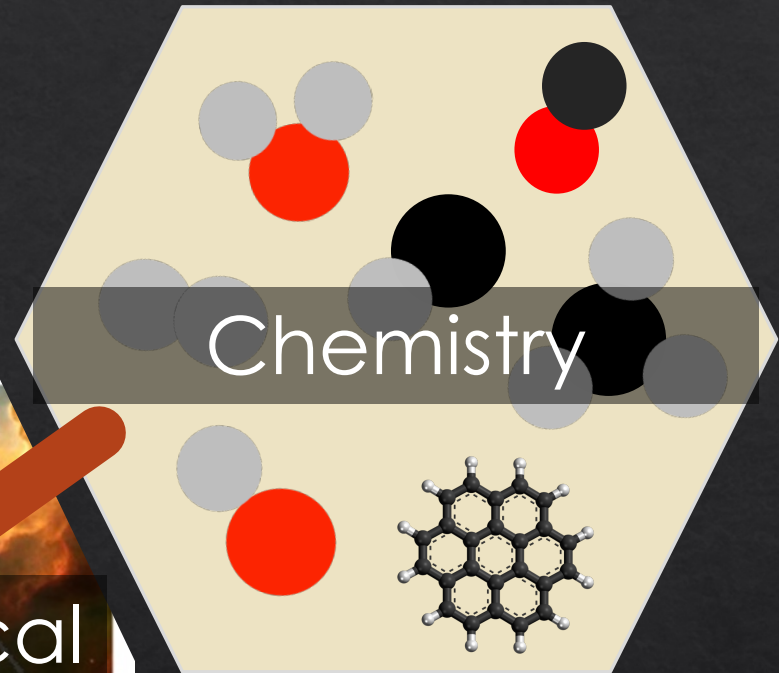
Marion Zannese

Émilie Habart, Benoît Tabone, PDRs4All

Institut d'Astrophysique Spatiale

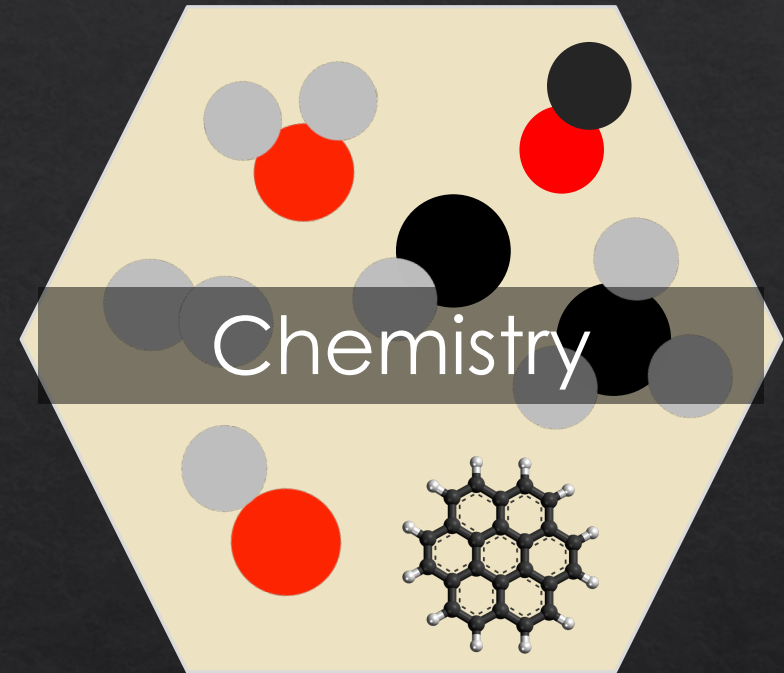


Probing astrochemistry directly from observations ?



Knowledge of chemistry and physics relies on thermochemical models that predict abundances based on a chemical network

Probing astrochemistry directly from observations ?



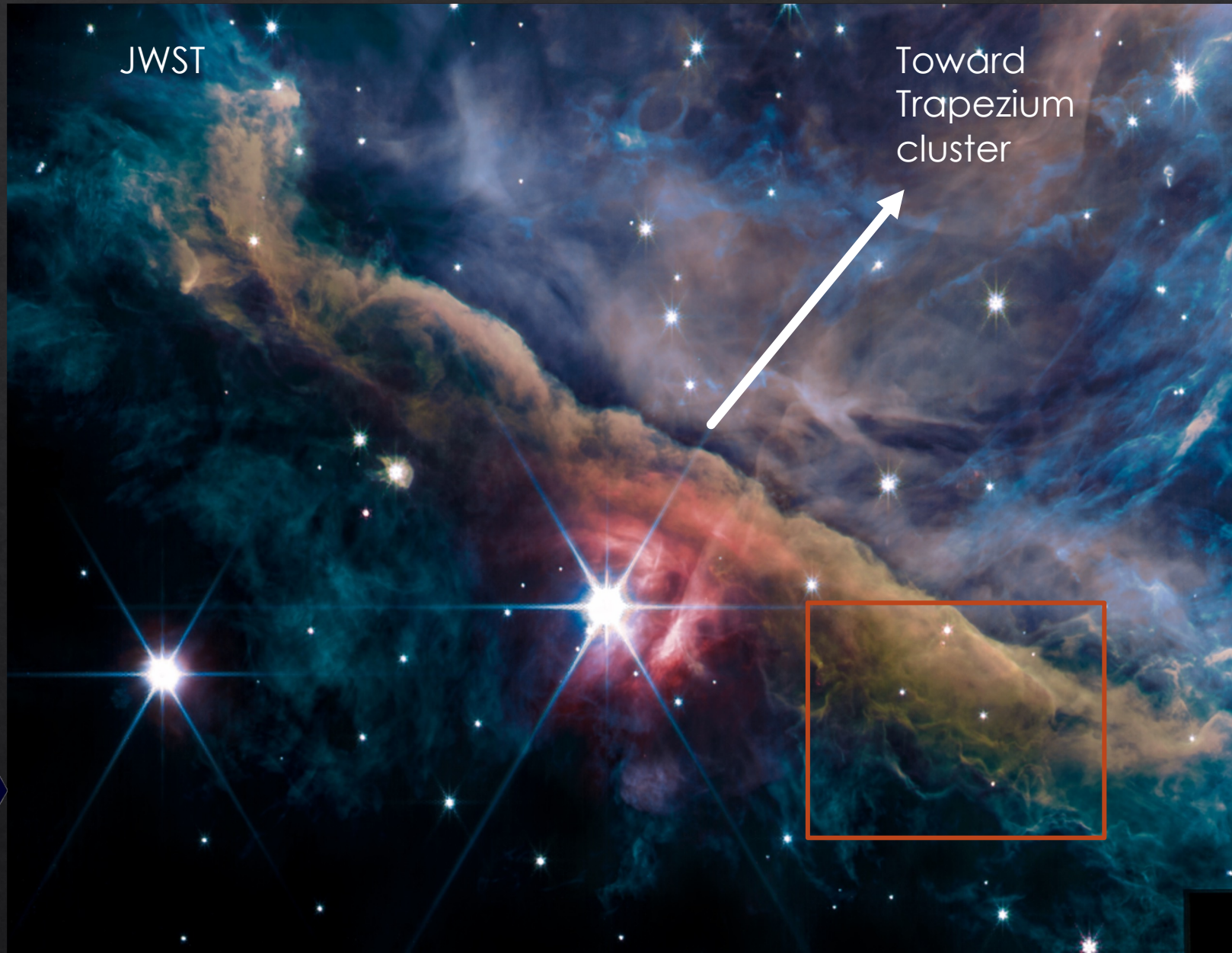
What if we could probe directly from observations the formation rate of the species?
→ Use of formation-pumping processes

The Orion Bar – Interstellar laboratory

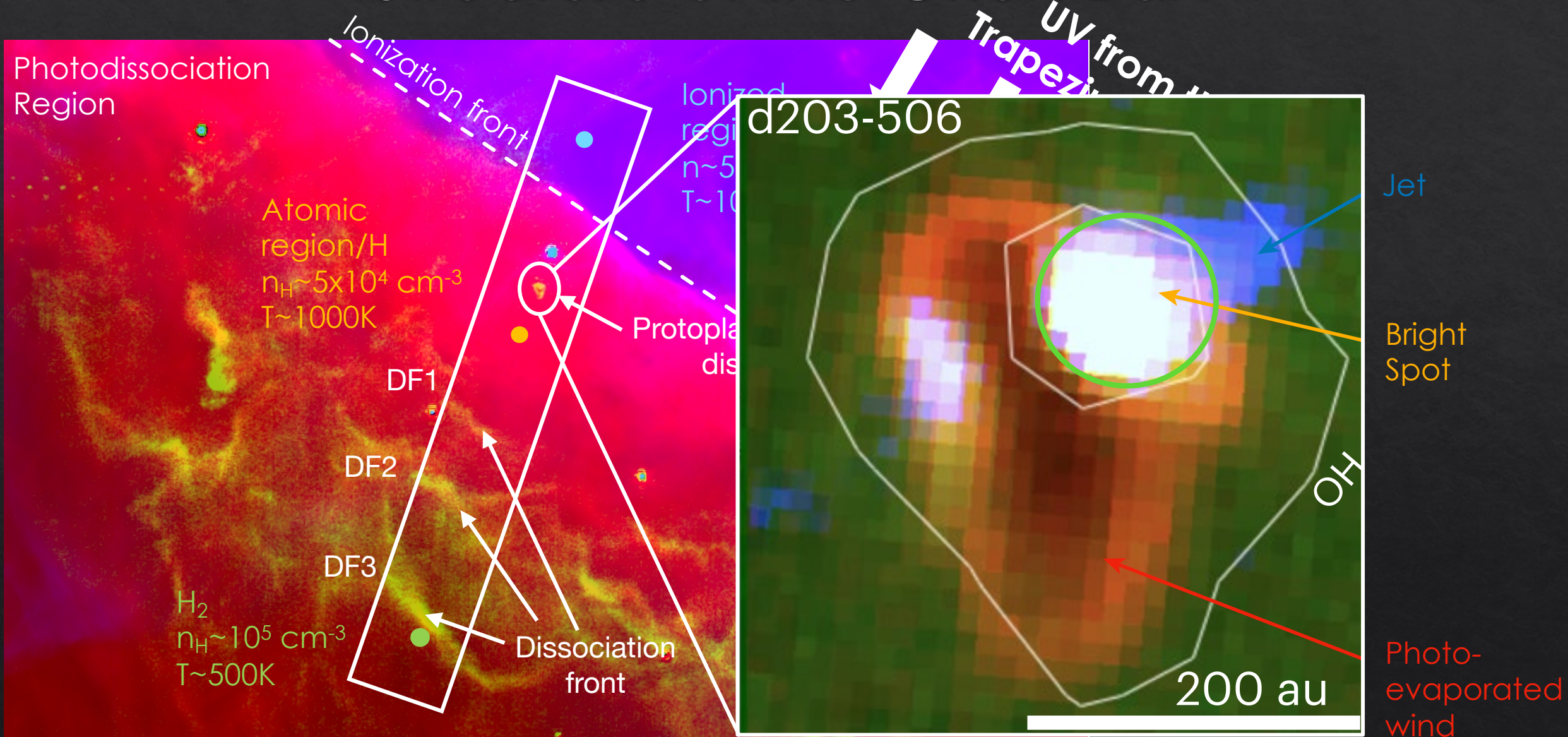


Orion Nebula

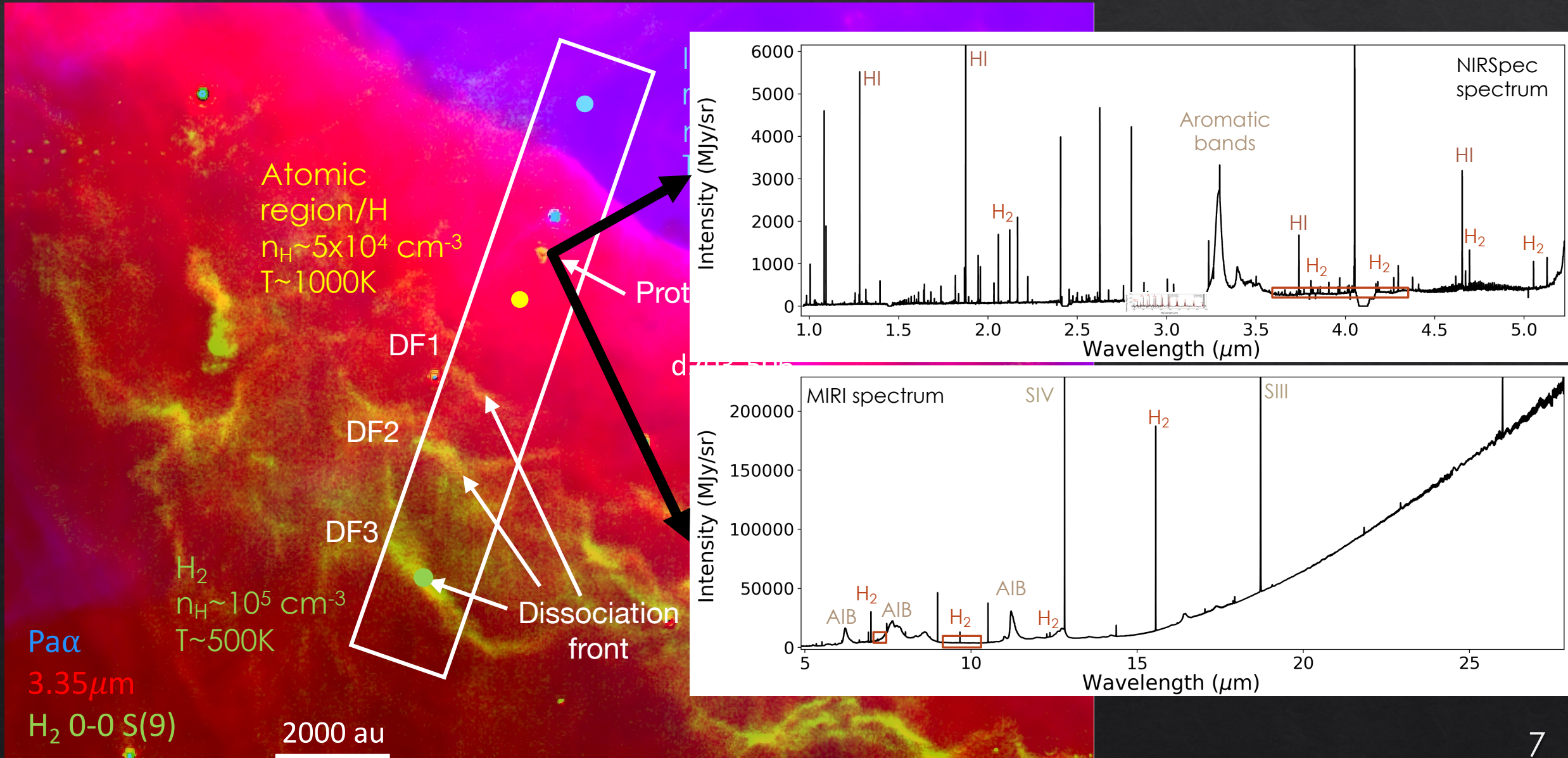
The Orion Bar seen by the JWST



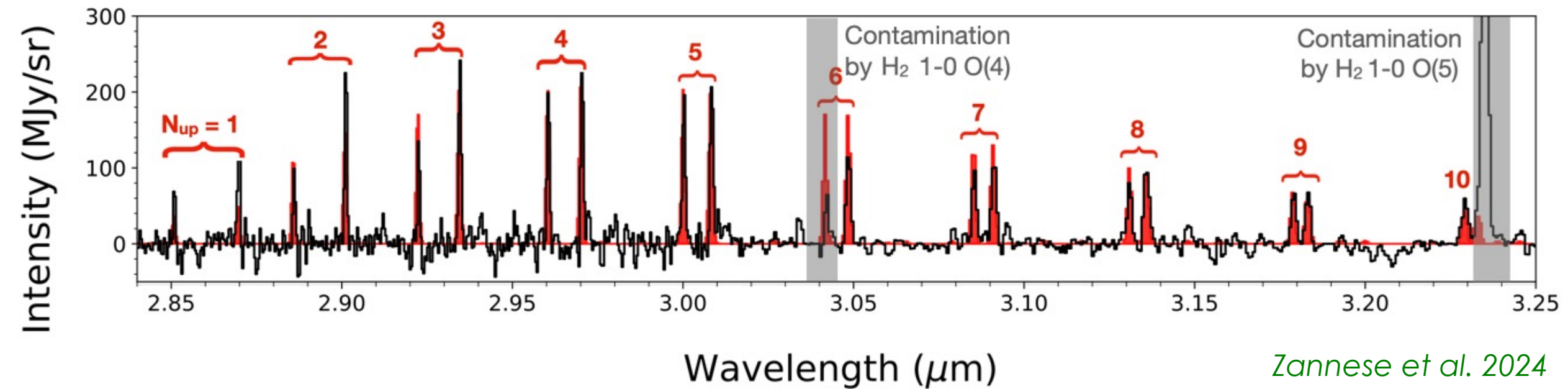
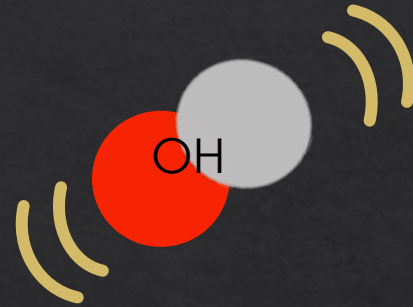
Structure of the Orion Bar



Very rich spectra observed in the Orion Bar

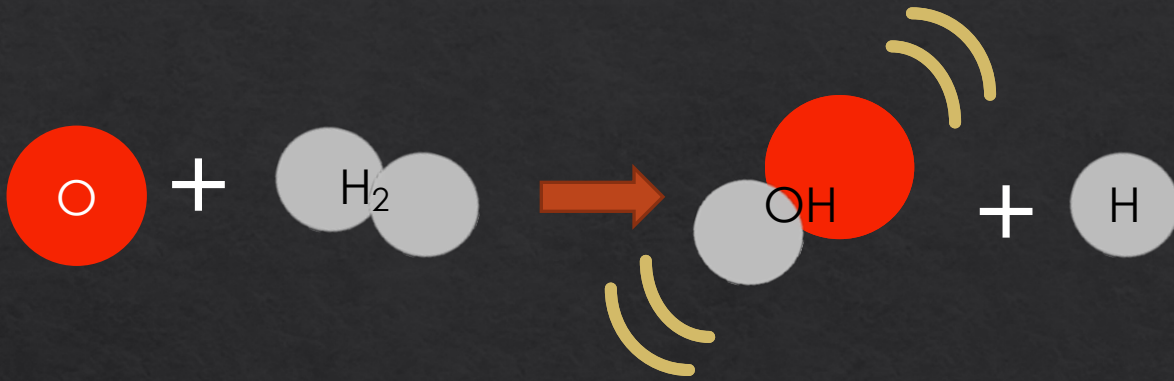


Rovibrational emission of OH detected in d203-506

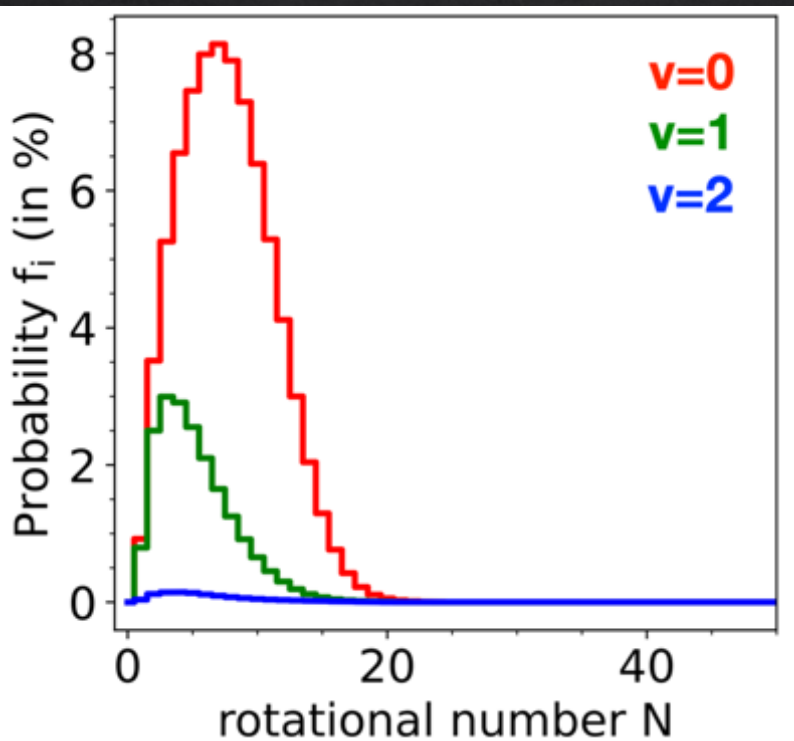


Chemical pumping?

Chemical pumping of OH



Distribution of OH following chemical pumping



Depends on:

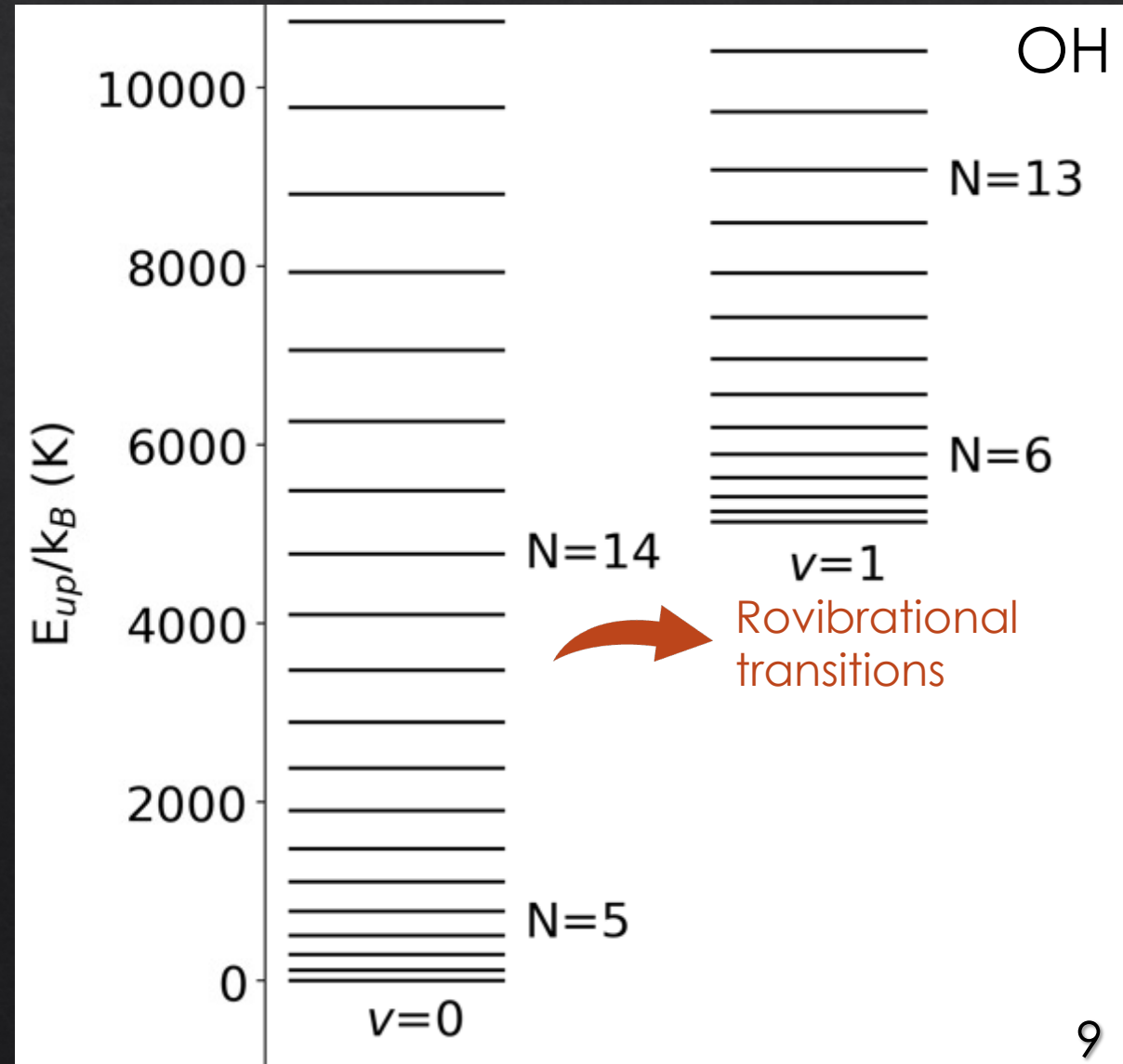
→ State-to-state rate $k_{i \rightarrow j}(T)$

→ *Veselinova et al. 2021*

→ Temperature

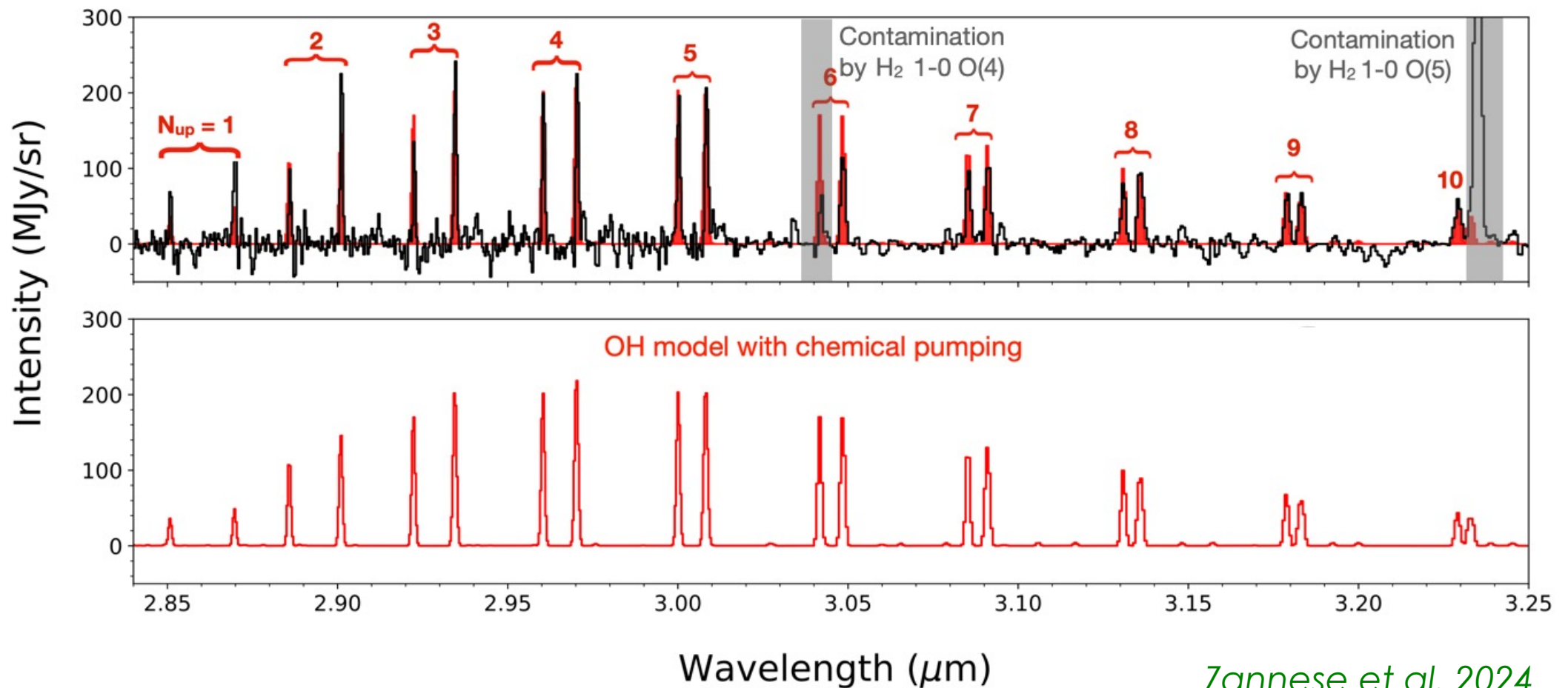
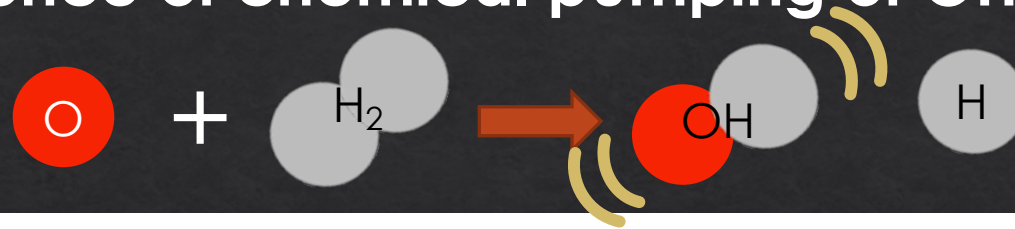
→ H_2 distribution

→ Parameters measured with H_2 lines in MIRI-MRS and NIRSPEC



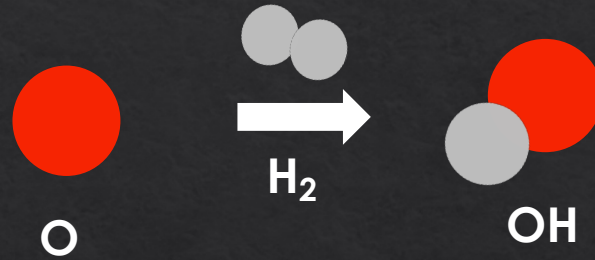
Unveiling O-chemistry in action in d203-506

First evidence of chemical pumping of OH by O+H₂



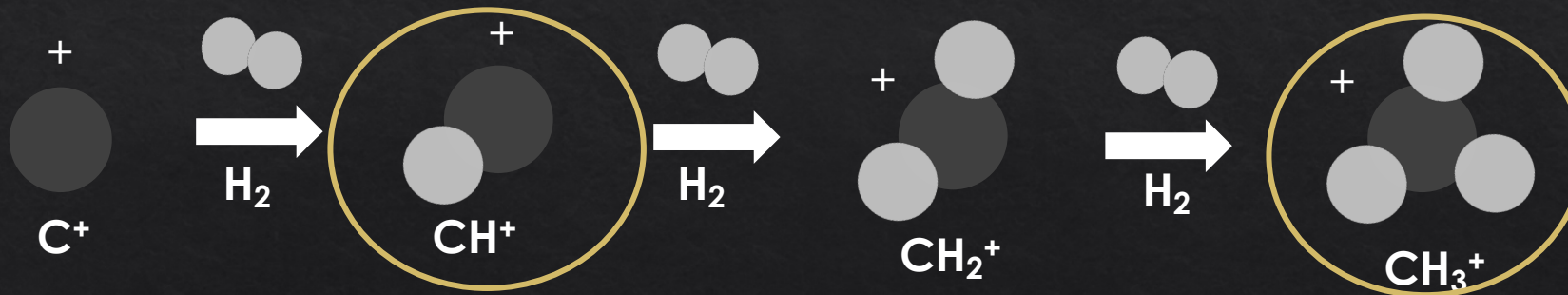
Similarity between O-chemistry and C-chemistry

Gas phase oxygen chemistry



Zannese et al. 2024

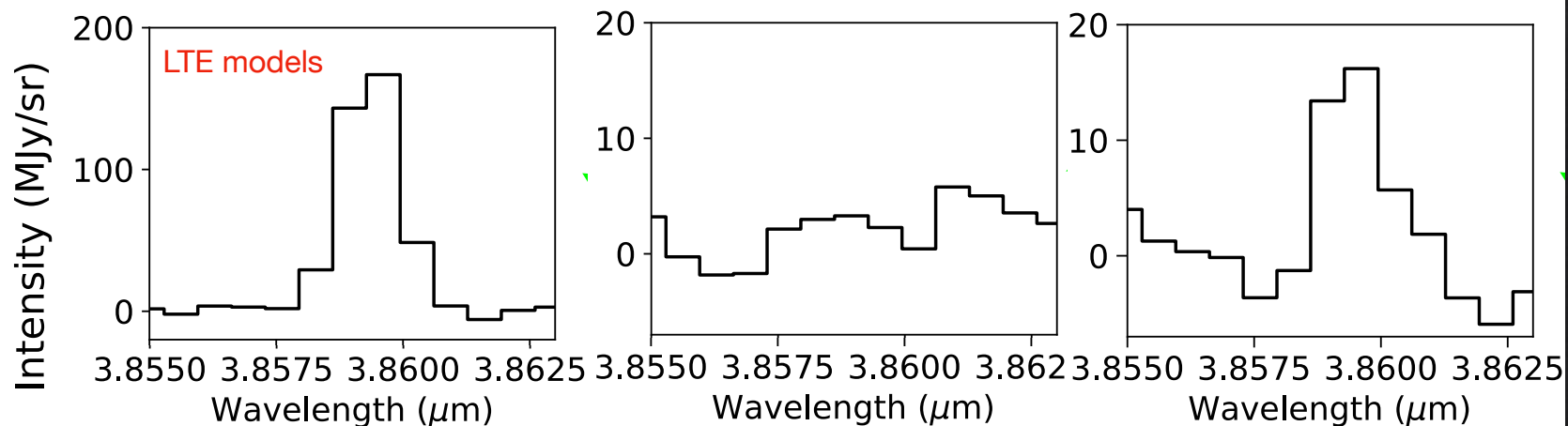
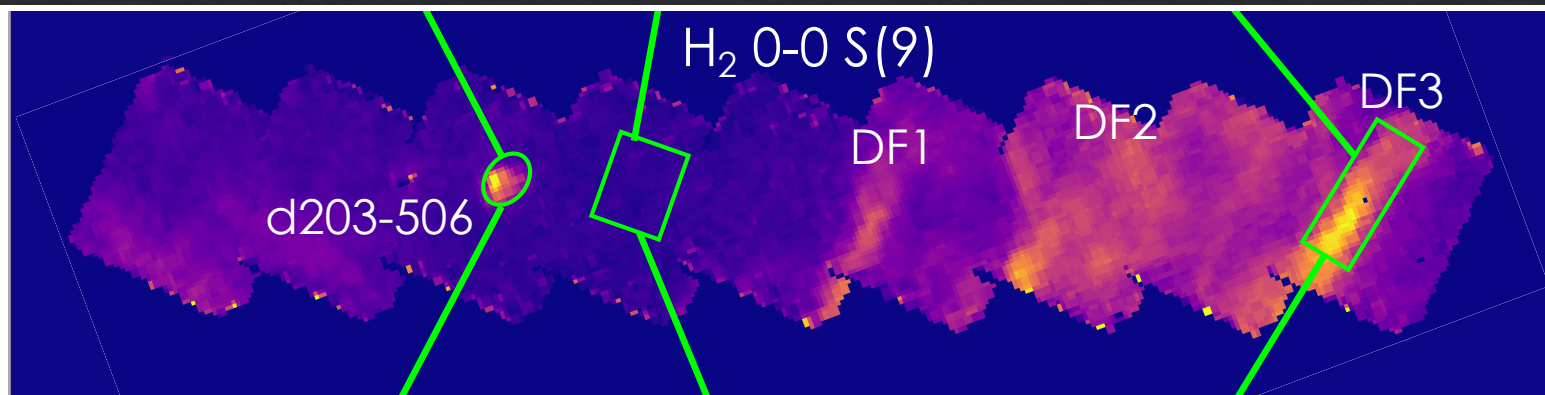
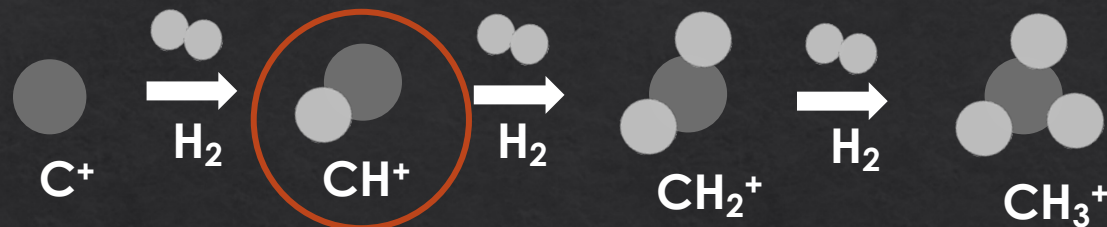
Gas phase carbon chemistry



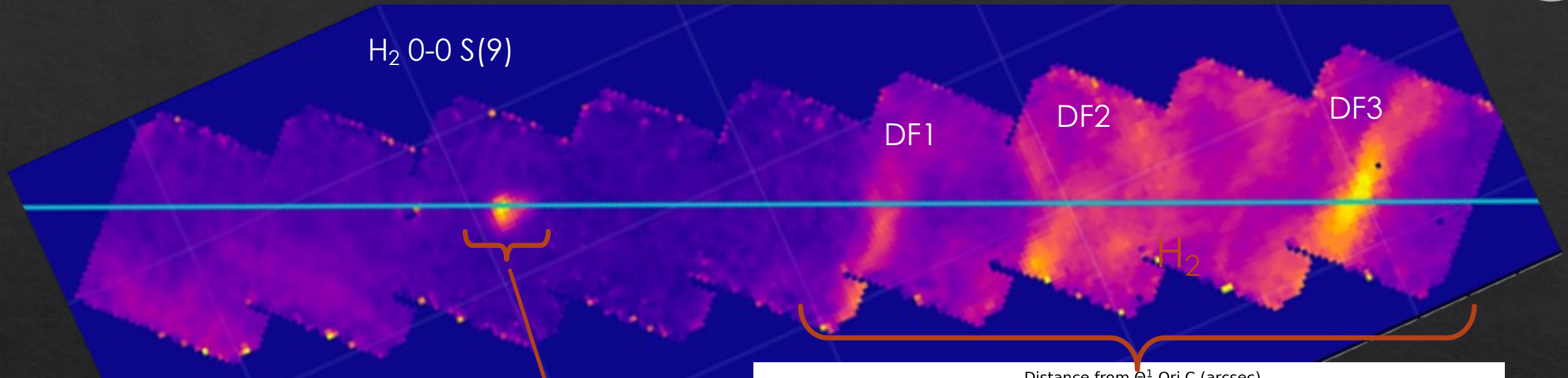
*Zannese et al.
in prep*

Chemical pumping in the carbon chemistry ?

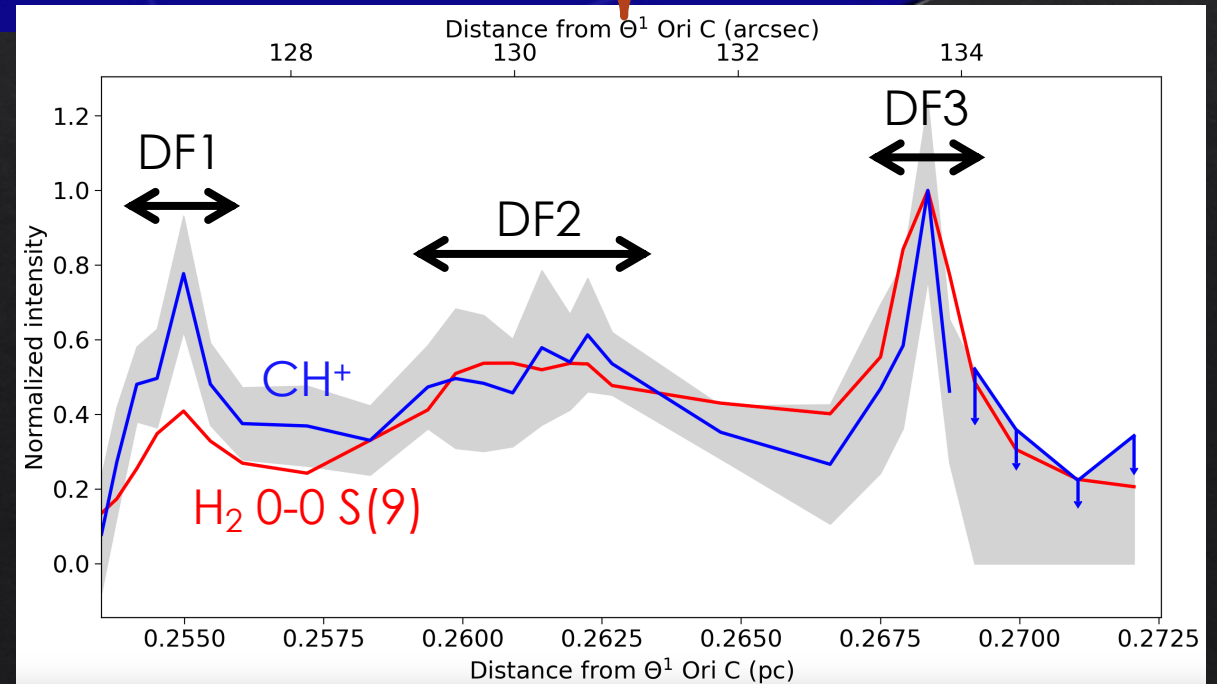
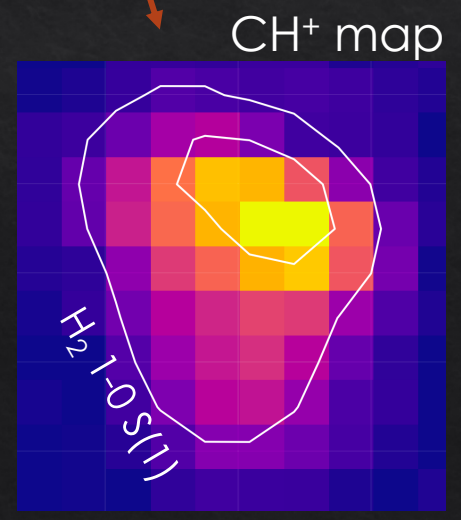
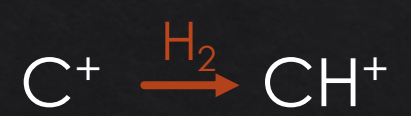
Detection of CH⁺ rovibrational emission in d203-506 and the Orion Bar



Spatial distribution of CH⁺

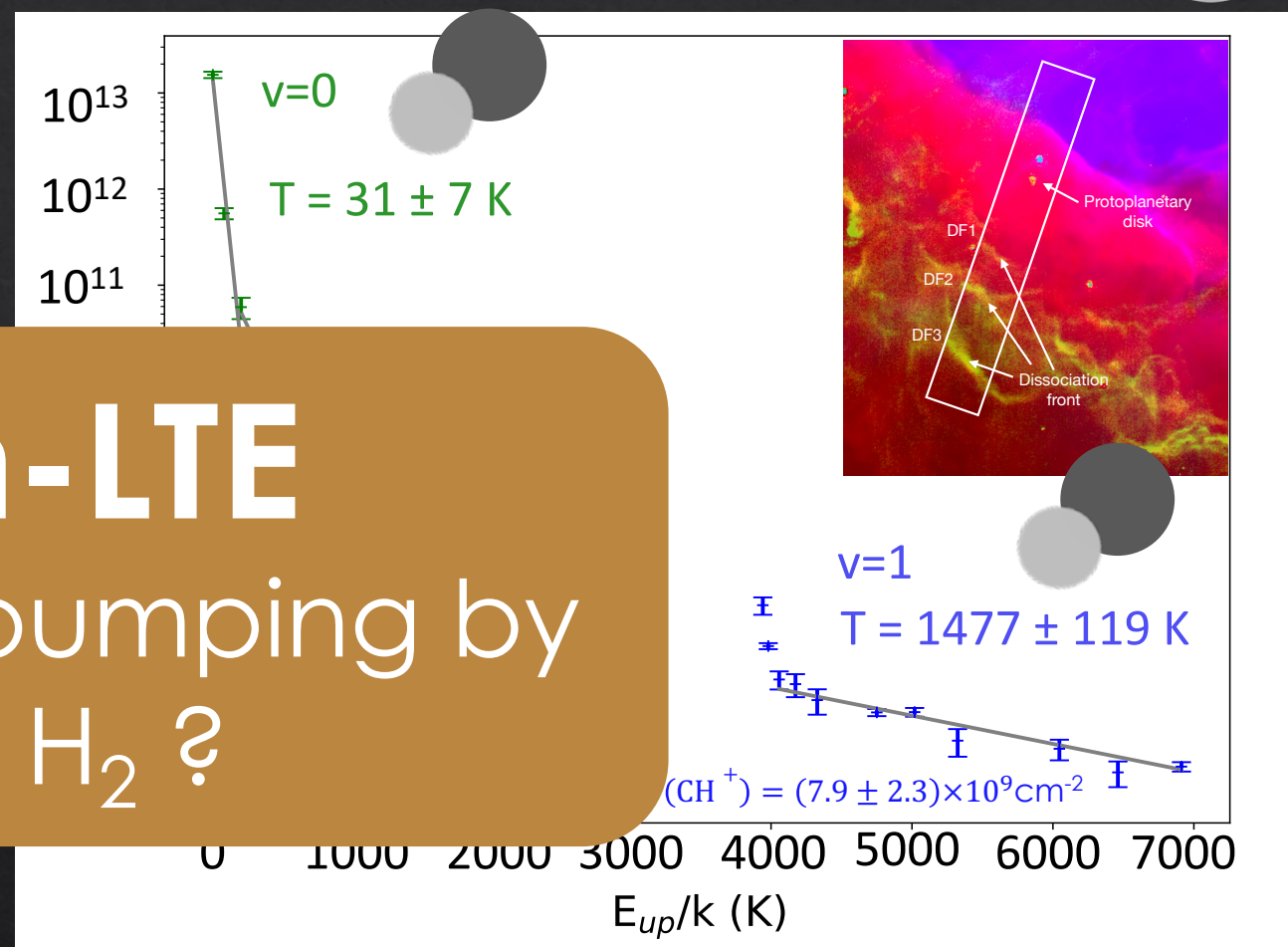
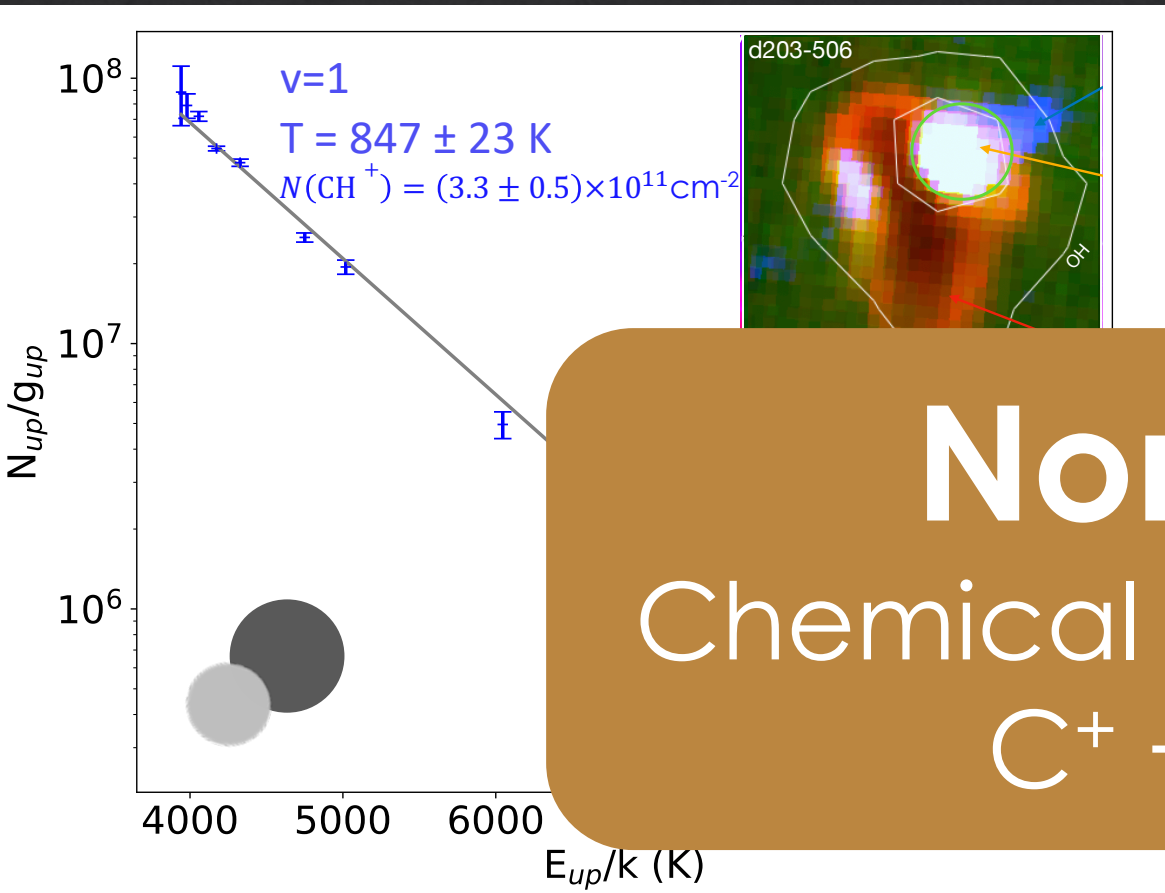


- CH⁺ follows excited H₂
- Formed (and excited?) by





Excitation of CH⁺



Non-LTE
 Chemical pumping by
 $\text{C}^+ + \text{H}_2 ?$

- $T_{\text{ex}}(v=1, v=2) \sim T_{\text{gas}} \sim 900 \text{ K}$
- Offset between $v=1$ and $v=2$

→ $T_{\text{ex}}(v=1) \gg T_{\text{gas}} \sim 600 \text{ K}$ and $T_{\text{ex}}(v=0)$

Higher excitation in the PDR than in the disk

Evidence of chemical pumping of CH⁺ in d203-506 and in the Orion Bar

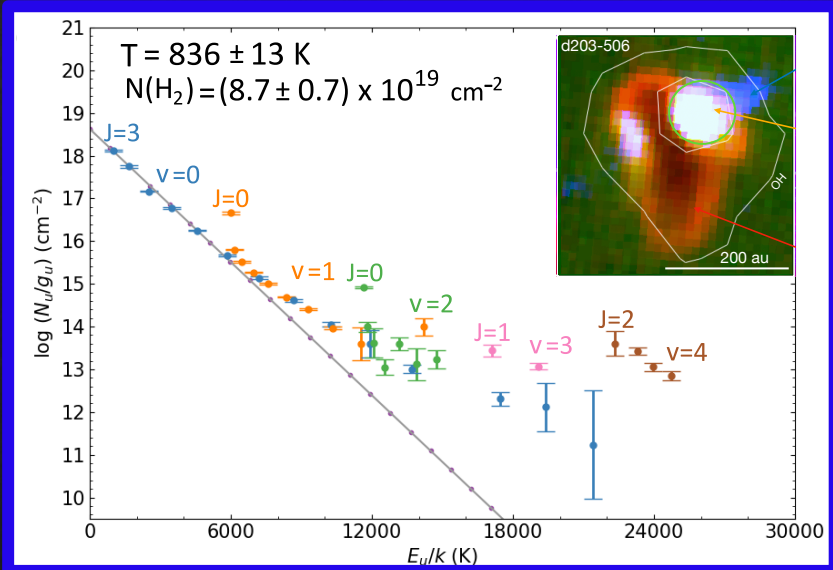
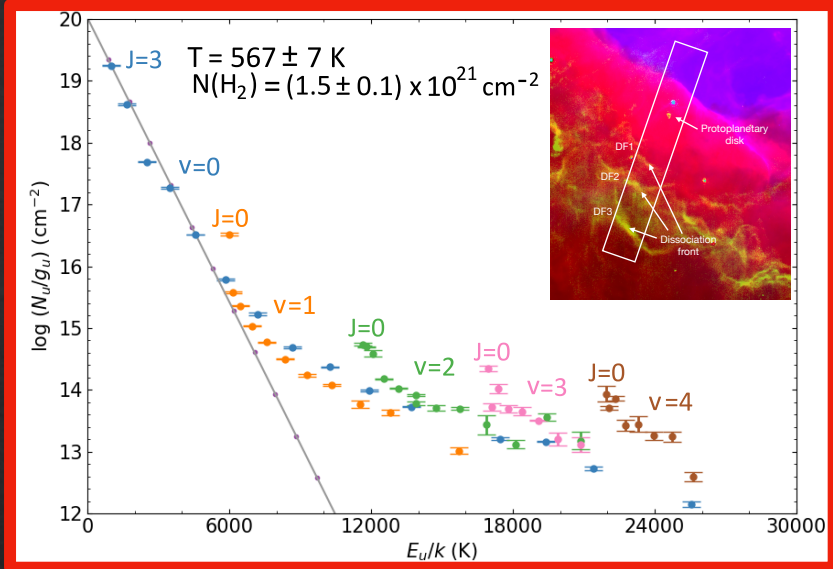


Distribution following chemical pumping depends on:

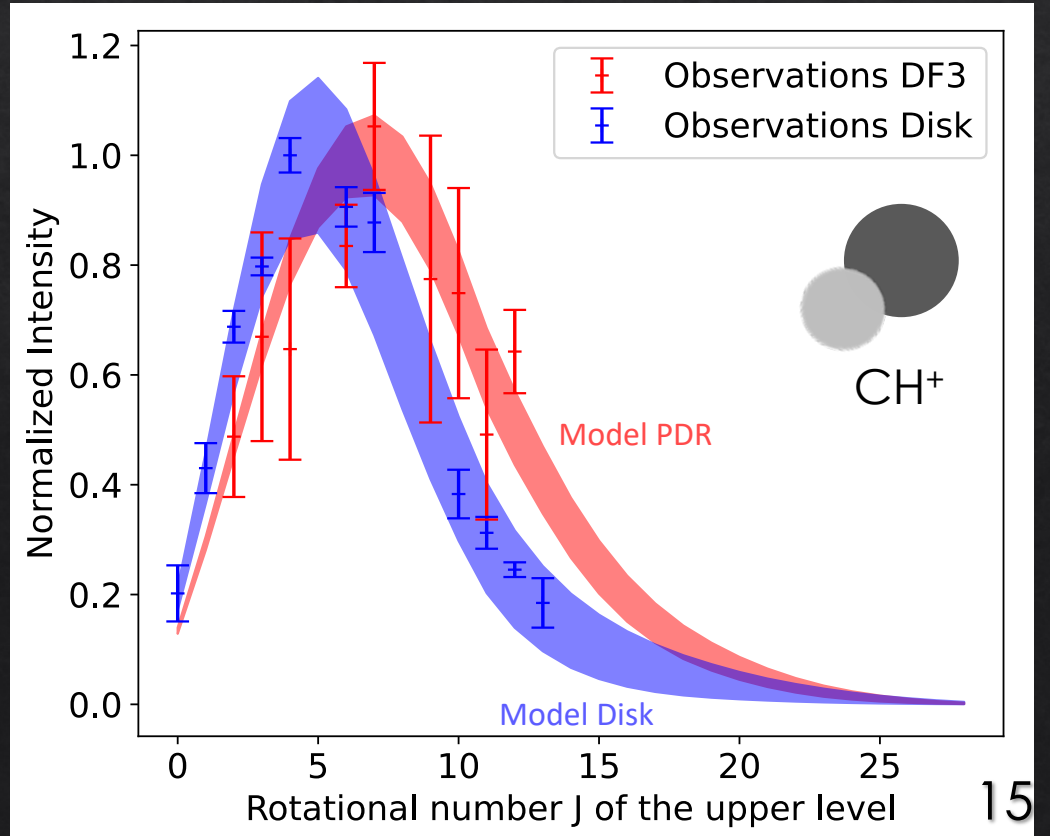
- Temperature
- H₂ distribution
- State-to-state rate $k_{i \rightarrow j}(T)$

$$f_i(\text{CH}^+) \propto \sum_j k_{j \rightarrow i} x_j(\text{H}_2)$$

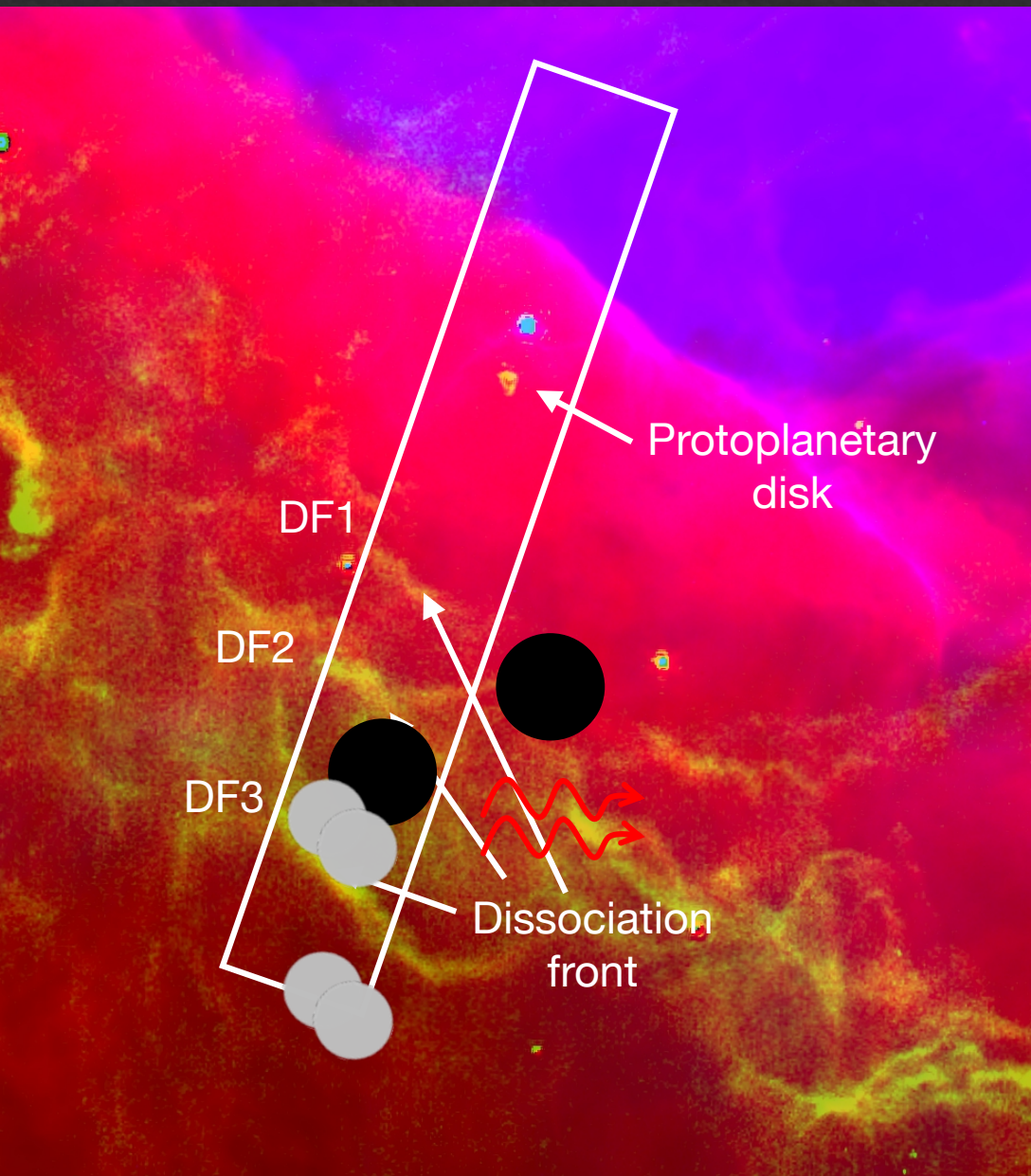
Zanchet et al. 2013
 Faure et al. 2017
 Neufeld et al. 2021



- Analytic model of chemical pumping reproduces nicely the observations of CH⁺ in both regions
- Higher excitation of CH⁺ in cooler gas due to efficient UV pumping of H₂ in the PDR



Estimation of the chemical and physical parameters



Intensity of the lines proportional to the formation rate R :

$$R = k(T)N(\text{H}_2)x(\text{C}^+)n_{\text{H}}$$

Zanchet et al. 2013
Faure et al. 2017
Neufeld et al. 2021

Measured parameters

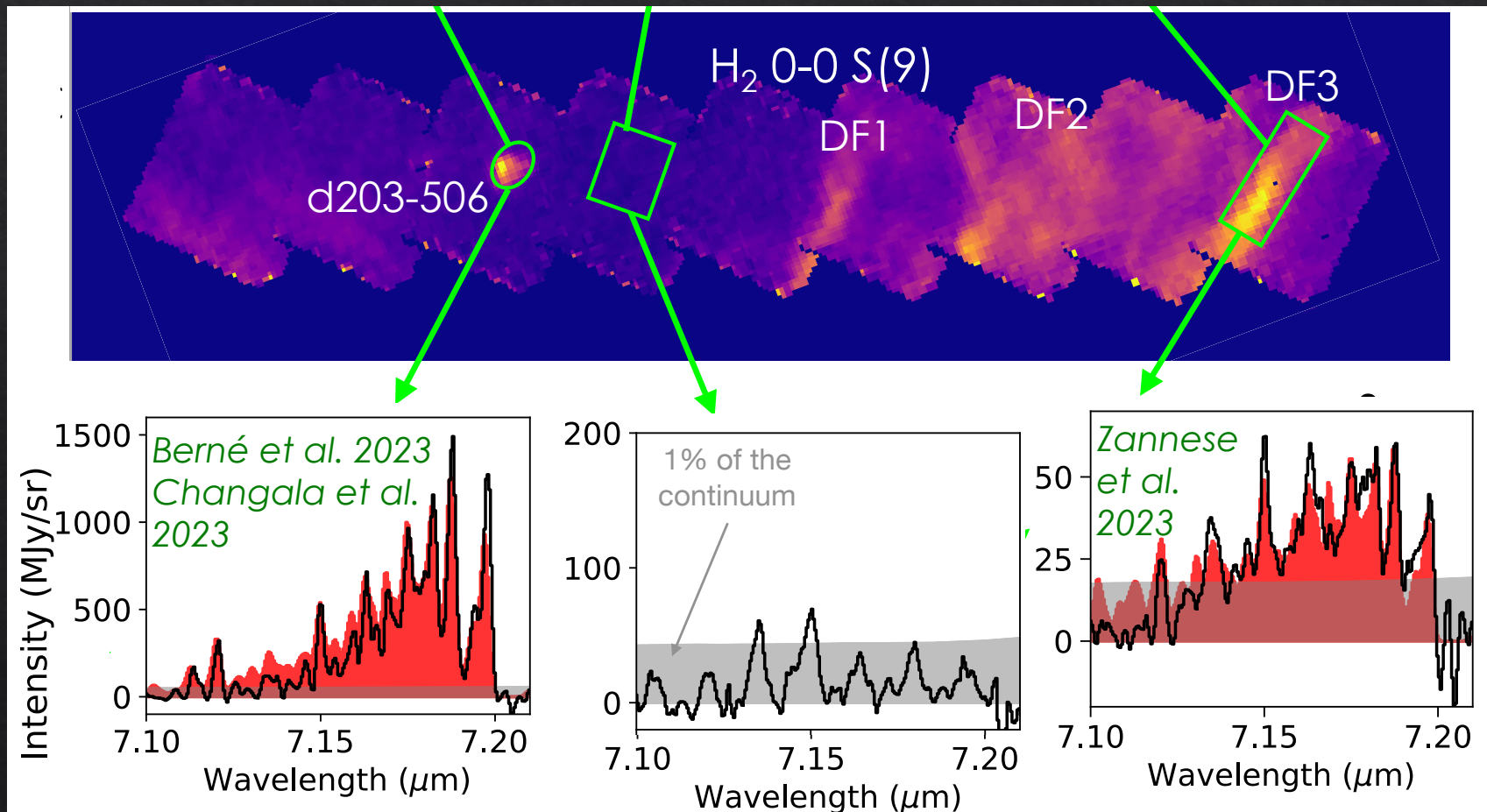
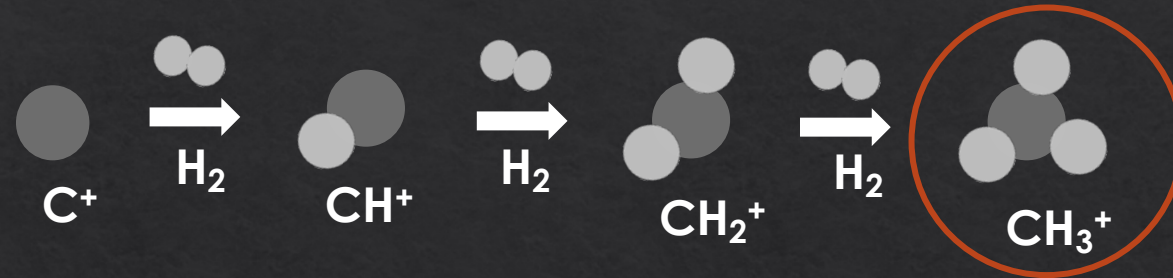
d203-506:

- $R = 3 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$
- $n_{\text{H}} = (1.0 \pm 0.5) \times 10^7 \text{ cm}^{-3}$
- Same results for OH, CH⁺ and H₂

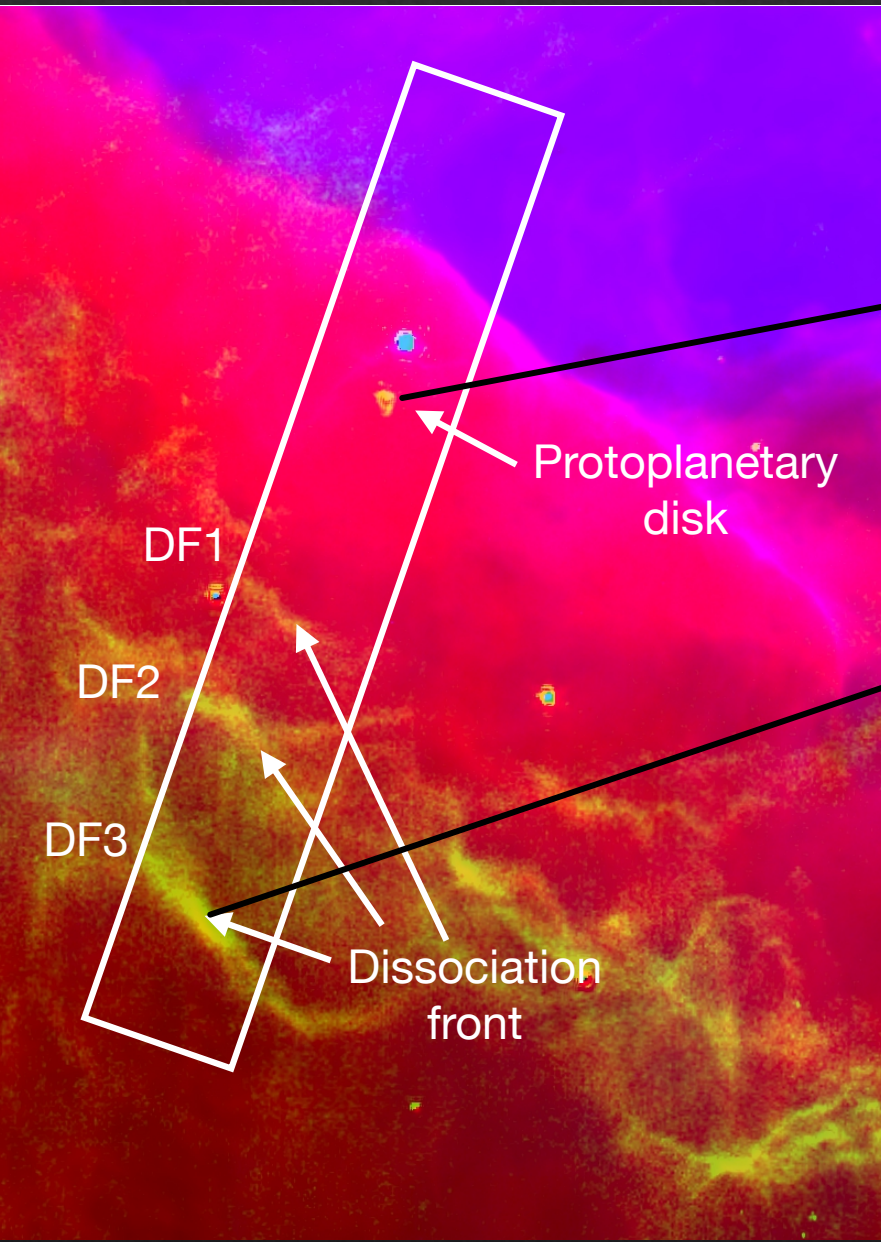
The Orion Bar:

- $R = 4 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$
- $n_{\text{H}} = (8 \pm 3) \times 10^5 \text{ cm}^{-3}$

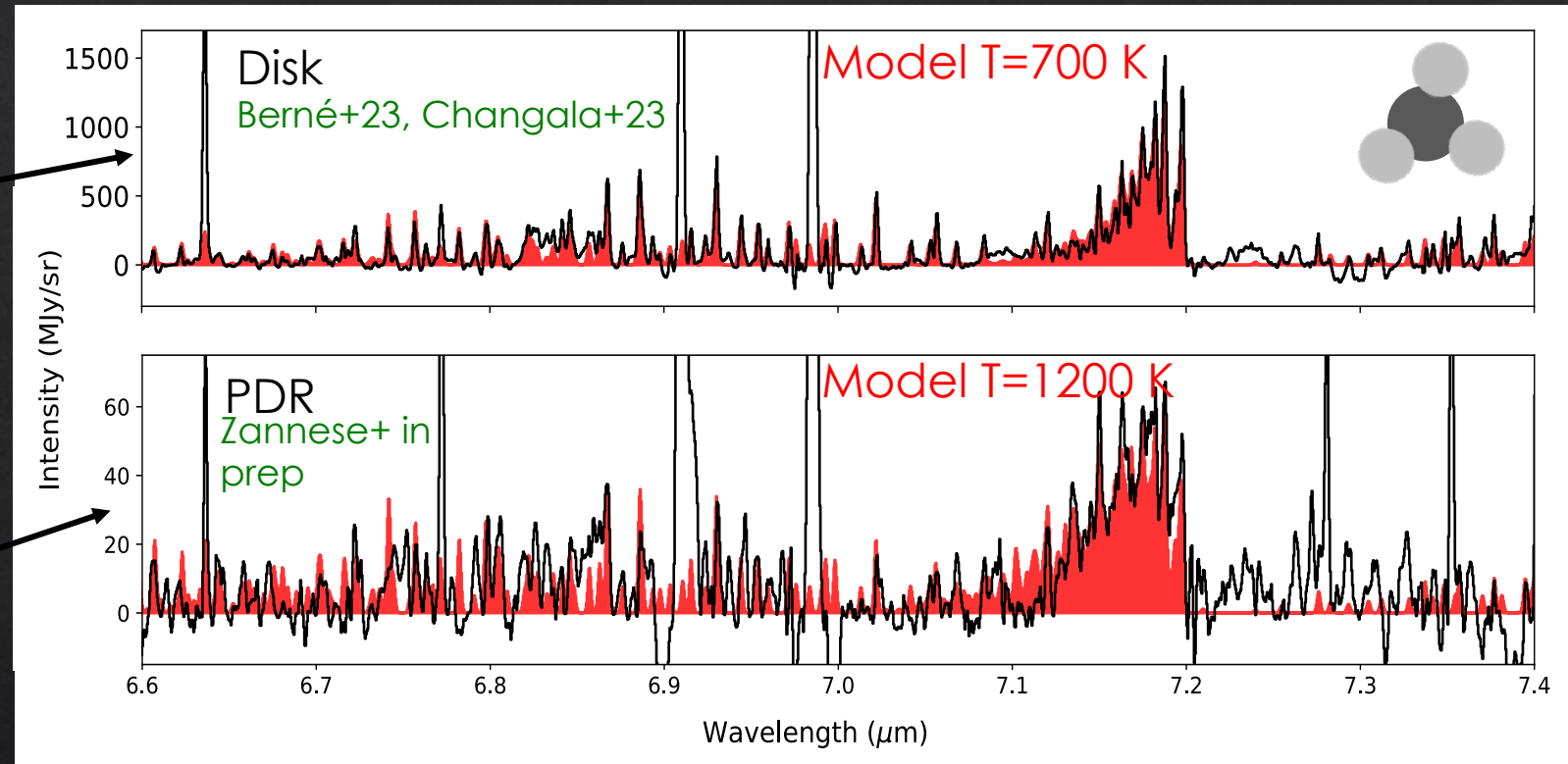
Detection of CH_3^+ rovibrational emission in d203-506 and the Orion Bar



Chemical pumping for CH_3^+ ?



- Follows the emission of H_2 and CH^+

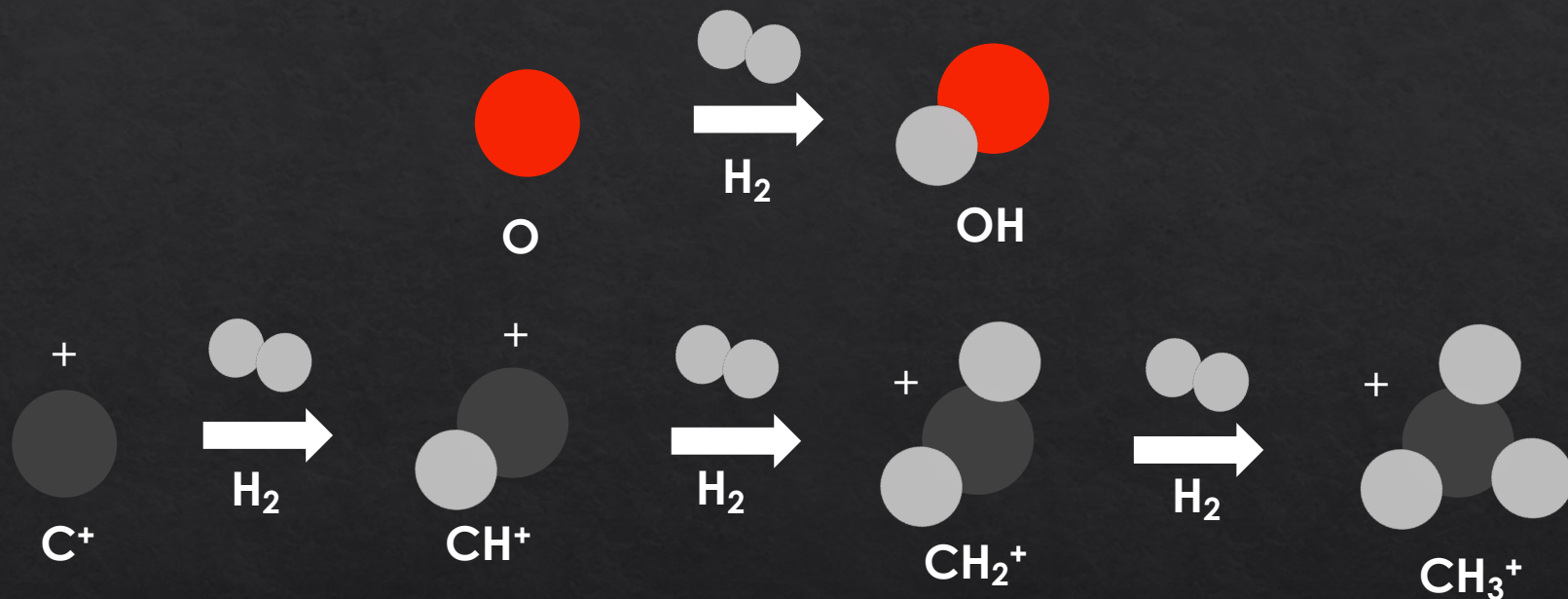


- Same as for CH^+ : higher excitation of CH_3^+ in cooler gas
Chemical pumping $\text{CH}_2^+ + \text{H}_2$?

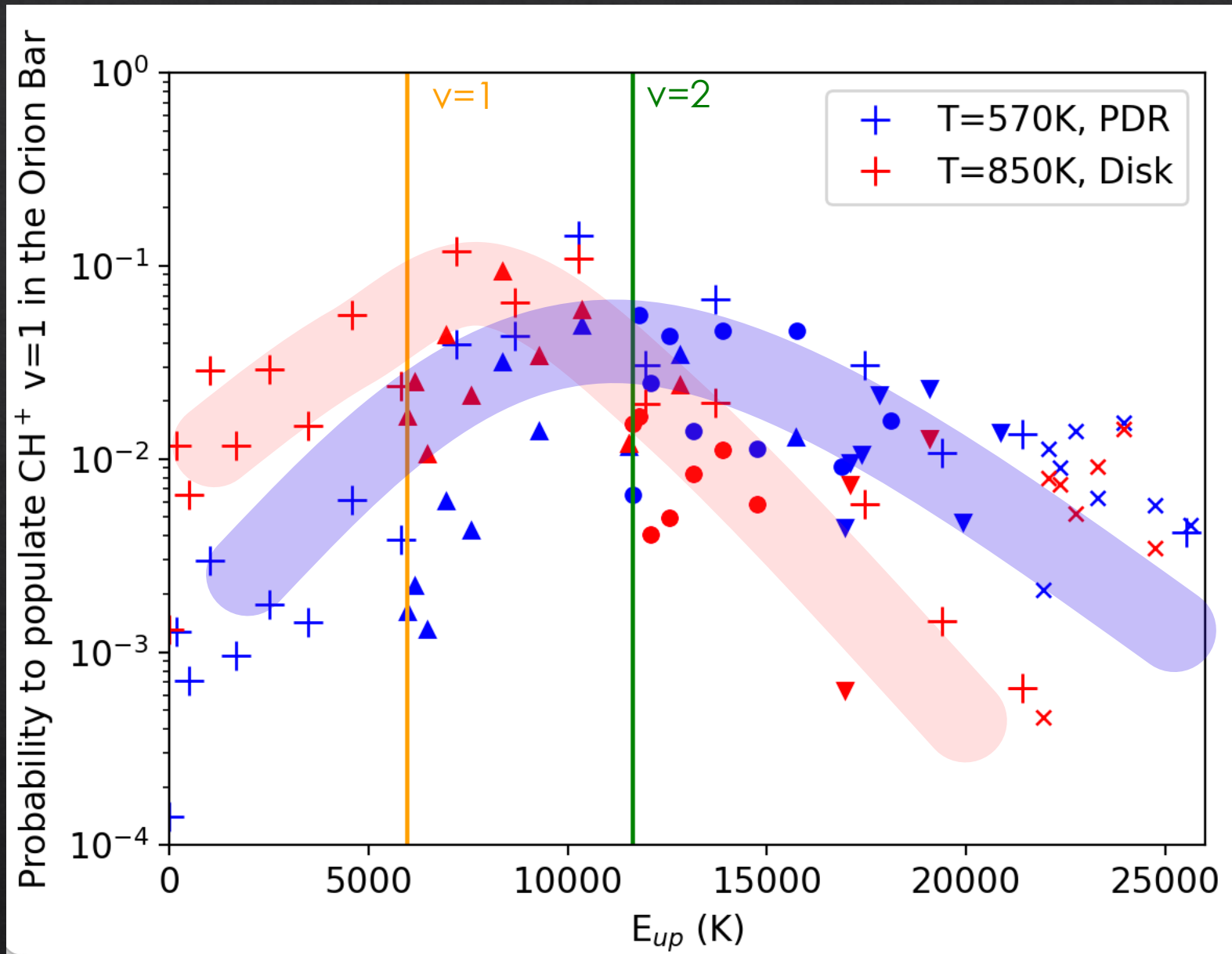
➔ A new system to study by molecular physicists

Take-home message

Formation pumping processes used to probe astrochemistry in action



- Diagnostics: formation rate, local density...
- More detections of excited hydride to come in other interstellar and circumstellar regions
- Collaboration with molecular physicists vital in JWST era



CH⁺ v=1 excited by H₂ with higher v in the PDR than in the disk