MAX-PLANCK-GESELLSCHAFT

Re-evaluation of the cosmic-ray ionization rate in diffuse clouds

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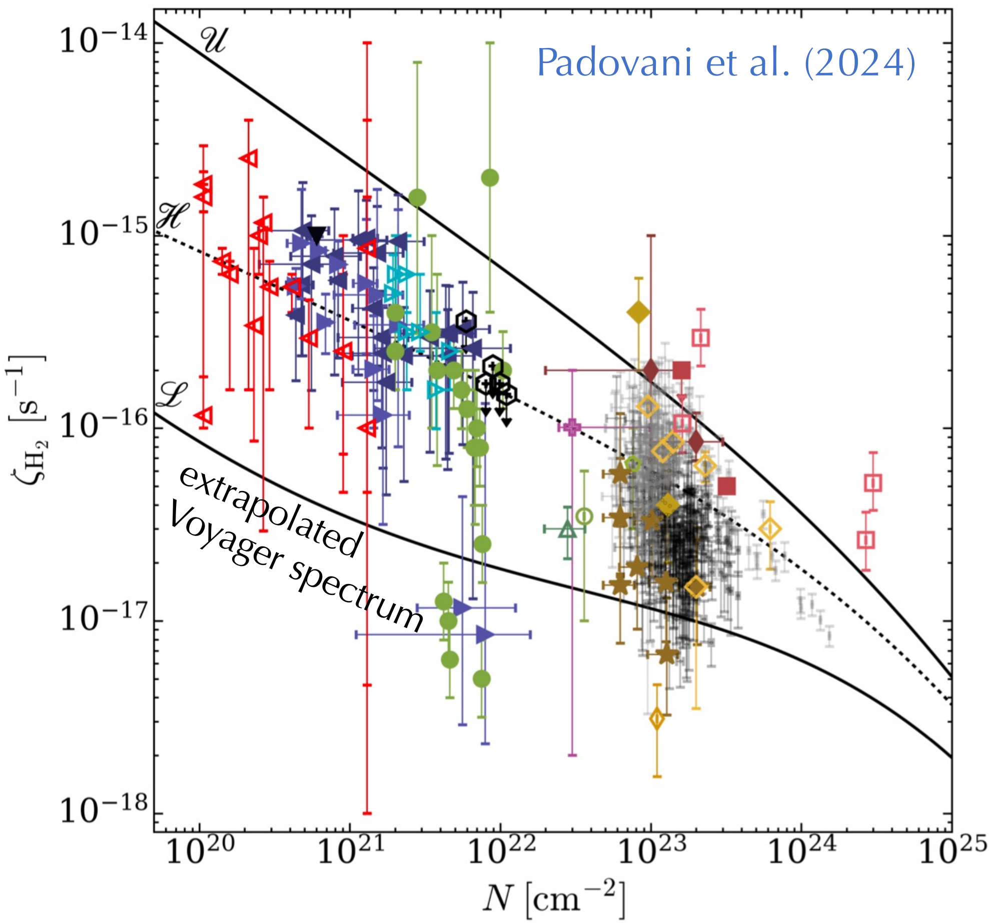
Variety of processes driven by low-energy CRs

- Gas ionization
  ⇒ coupling to magnetic field, properties of turbulence, …
- Gas heating
  ⇒ cloud dynamics, chemistry, …
- Dust evolution
  ⇒ dust coagulation, chemical processes on grain surface, …
- Processing of icy mantles
  ⇒ abundances of complex molecules, desorption of ices, …
- …

Measurements of CR ionization rate ζ



Specific ions generated by CRs are measured (in absorption or emission):

- Atomic gas, ζ_H : OH^+, H_2O^+, ArH^+, …
- Molecular gas, ζ_{H2} : H_3^+, HCO^+, H_2D^+, …

Irrespective of the tracer, the deduced parameter is always ζ / n_{tot} .

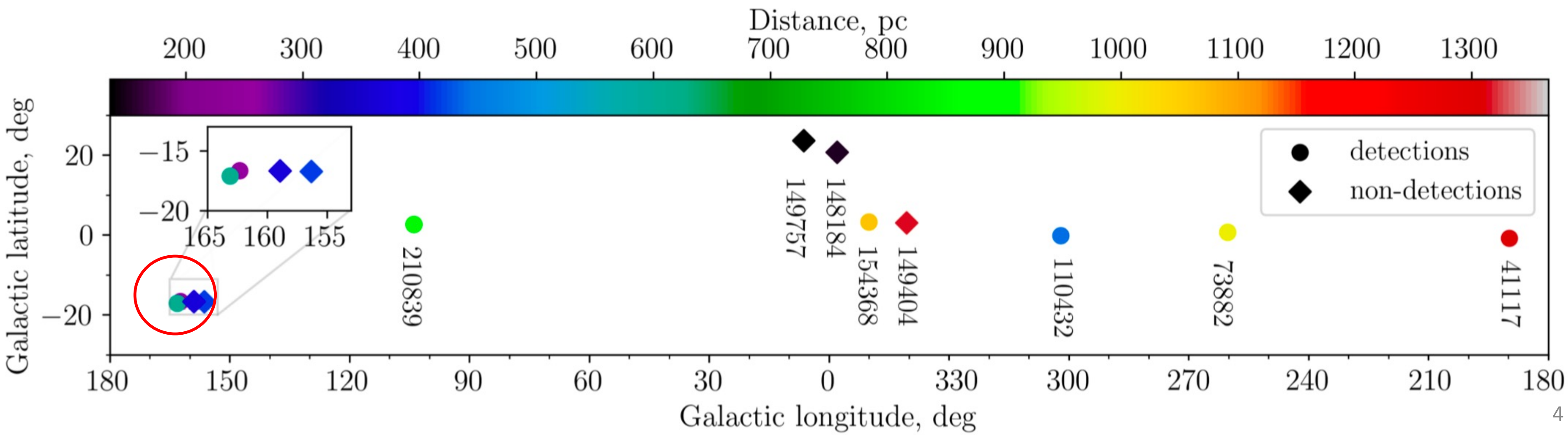
Total density n_{tot} in diffuse gas is evaluated from measuring rotational states of C_2 (Sonnentrucker et al. 2007).

Re-evaluated H_3^+ measurements: targets

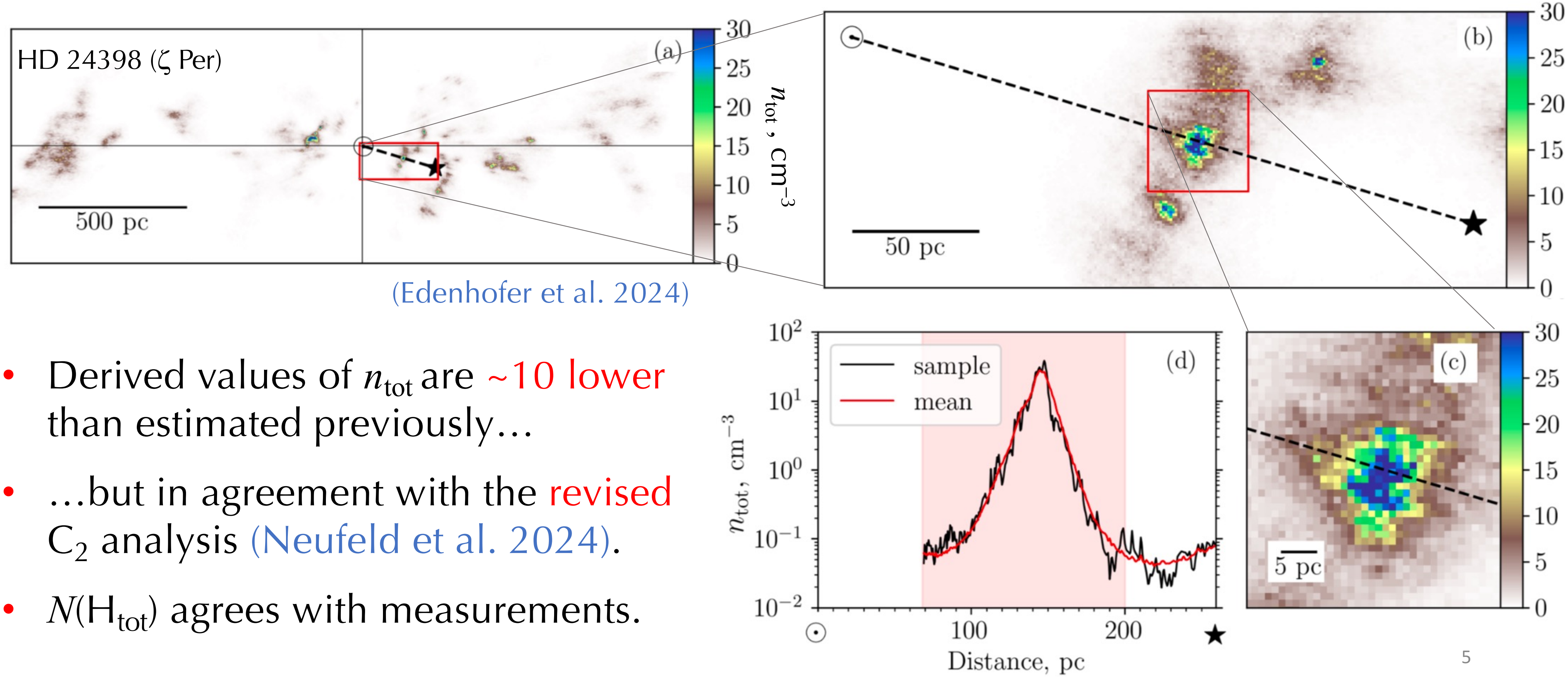
Observations of H_3^+ ions are considered as the most reliable method to measure the H_2 ionization rate in diffuse molecular clouds (Indriolo & McCall 2012).

$$\zeta_{H_2} n_{H_2} = k n_{H_3^+} n_e \quad \Rightarrow \quad \zeta_{H_2} = k\, x_e\, n_{tot} \frac{N(H_3^+)}{N(H_2)}$$

We selected all available target stars with directly measured $N(H_2)$ and $N(H)$:



Gas distribution from 3D dust extinction maps

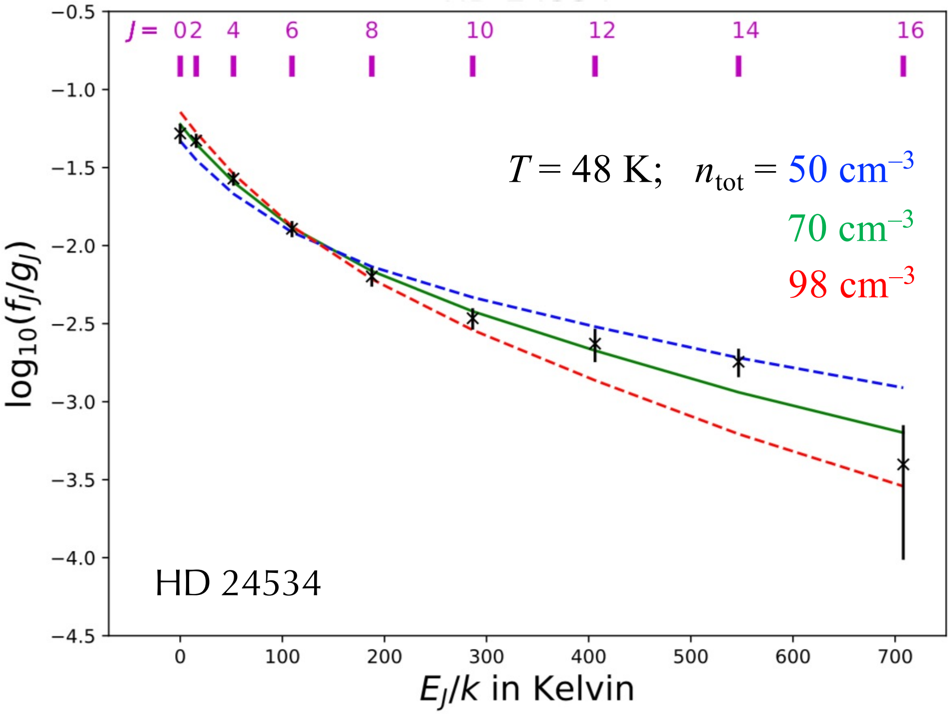


(Edenhofer et al. 2024)

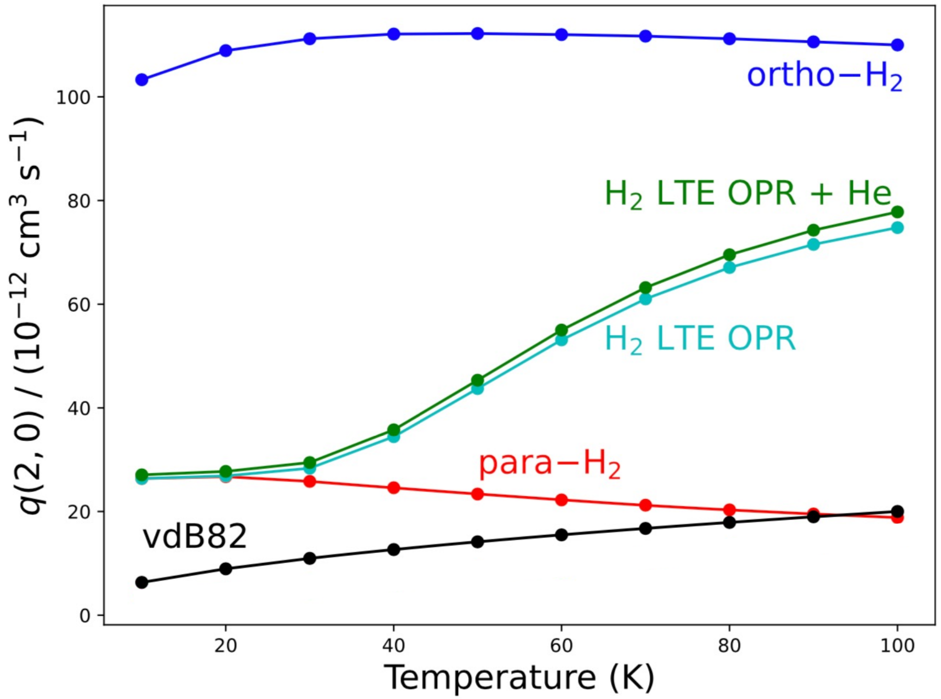
- Derived values of n_{tot} are ~10 lower than estimated previously…
- …but in agreement with the revised C_2 analysis (Neufeld et al. 2024).
- $N(H_{tot})$ agrees with measurements.

Re-evaluation of gas density (Neufeld et al. 2024)

Rotational diagram from C_2 absorption observations



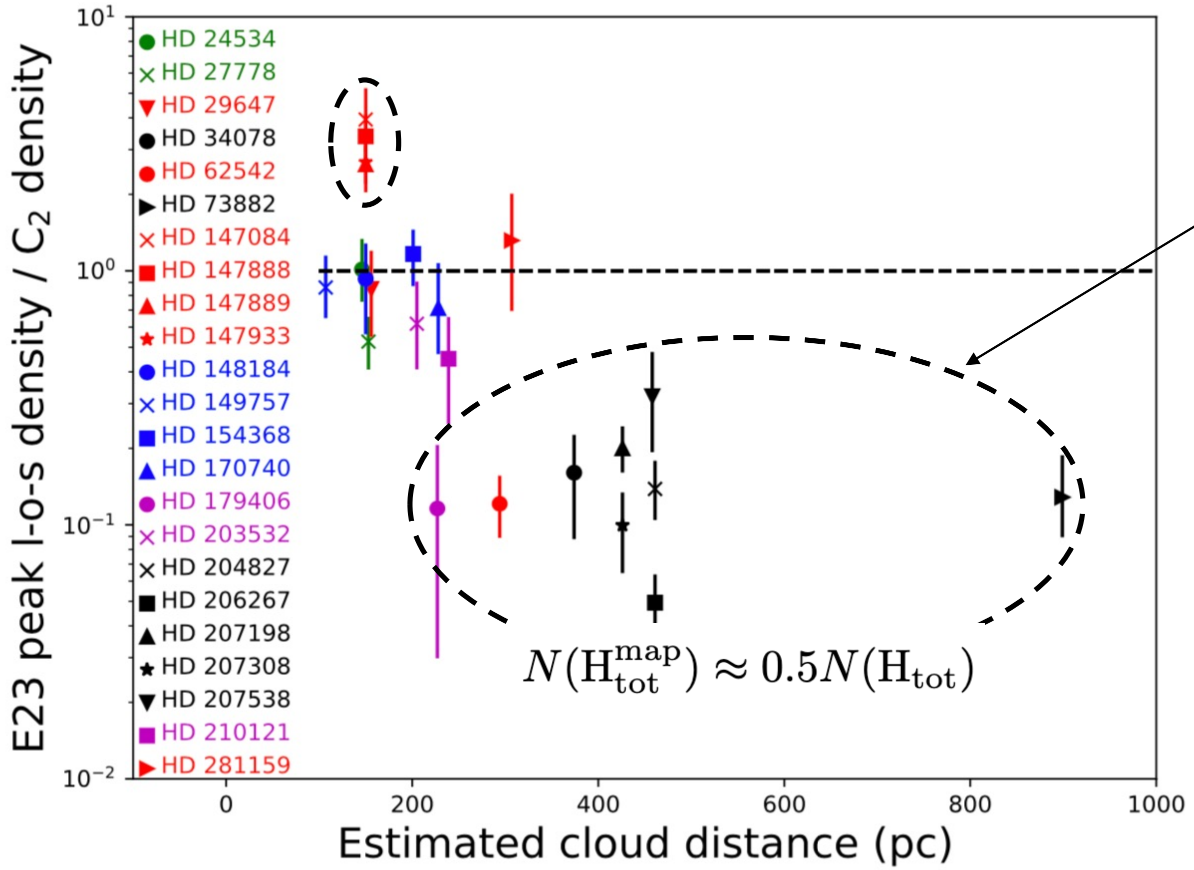
Updated collisional de-excitation rates



The collisional coefficients were strongly **underestimated**

⇒ the estimated density was **too high**!

Gas density: Dust map versus C_2 data

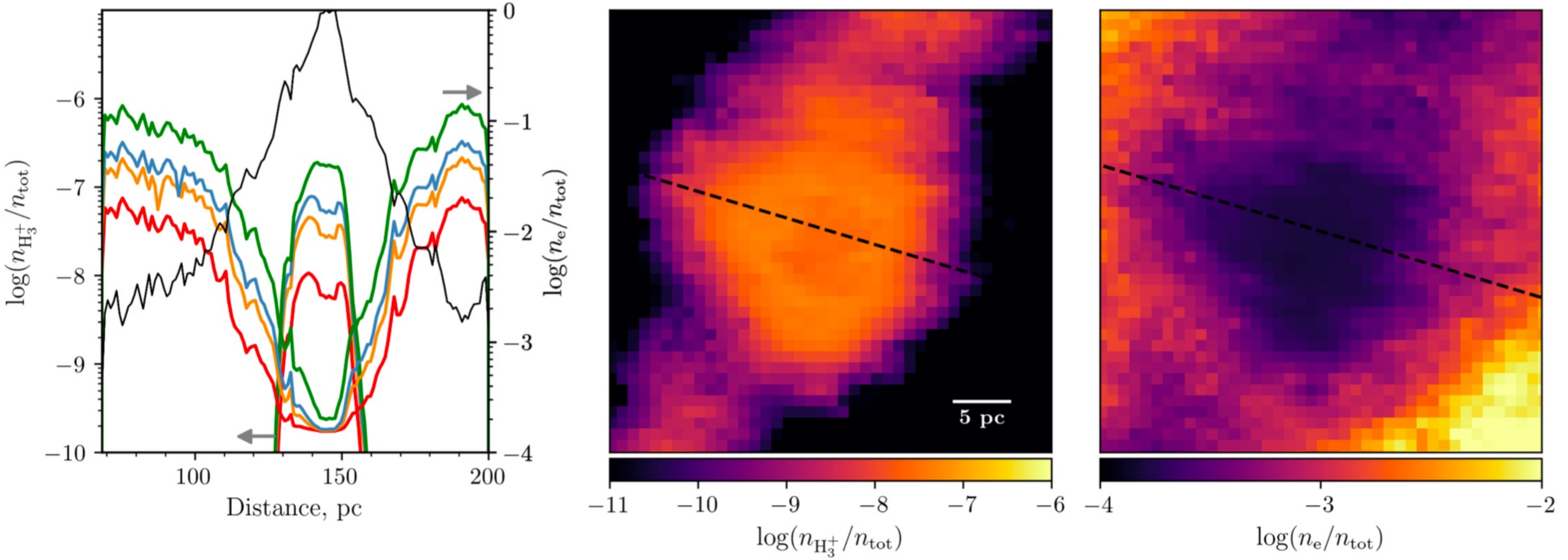


Possible origins are…

- The map becomes inaccurate at lower n_{tot} …?
- … or at higher distances?
- Dust is less evolved ⇒ $N(\mathrm{H}_{\mathrm{tot}}^{\mathrm{map}})/A_V$ must be higher?
- G/D mass ratio varies?
- Variations in the NIR field?
- H_2 O/P ratio deviates from LTE?
- …

Simulated 3D physical structure of gas clumps

`3D PDR` code (Bisbas et al. 2012)



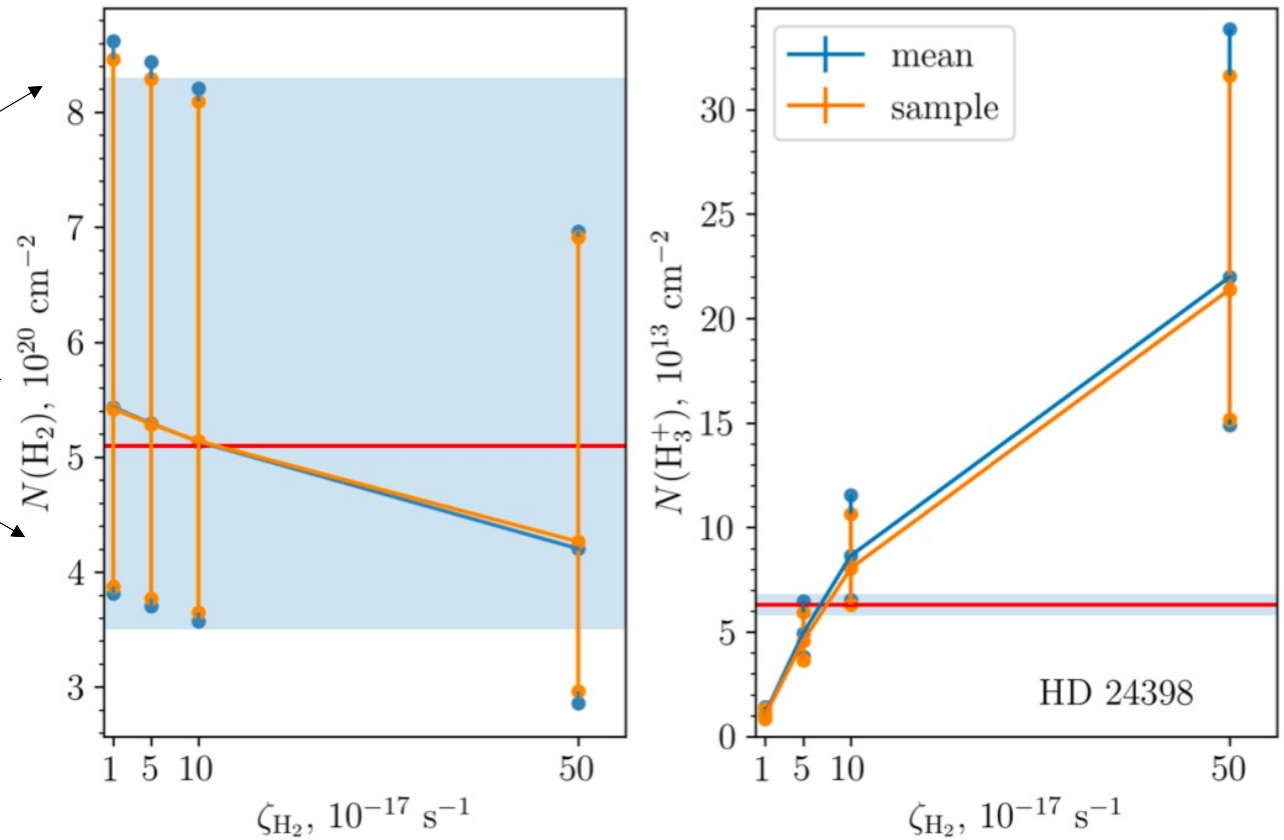
ζ_{H2} is the only unconstrained parameter

Simulations versus observations

Simulations for the mean measured $N(\mathrm{H_{tot}})$ and for 68% confidence limits

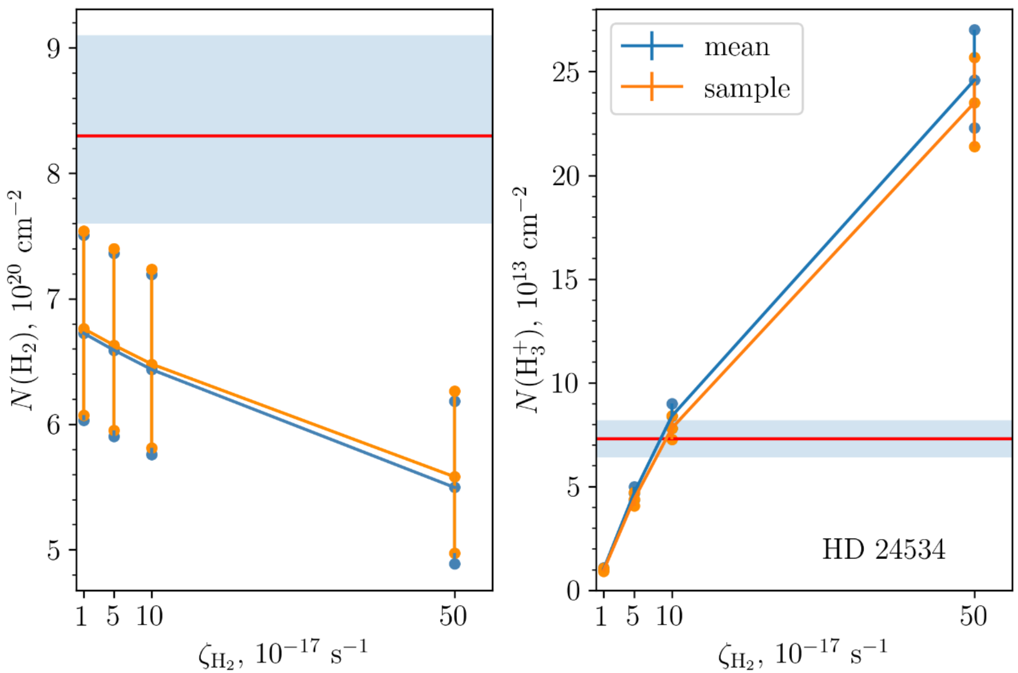
⇓

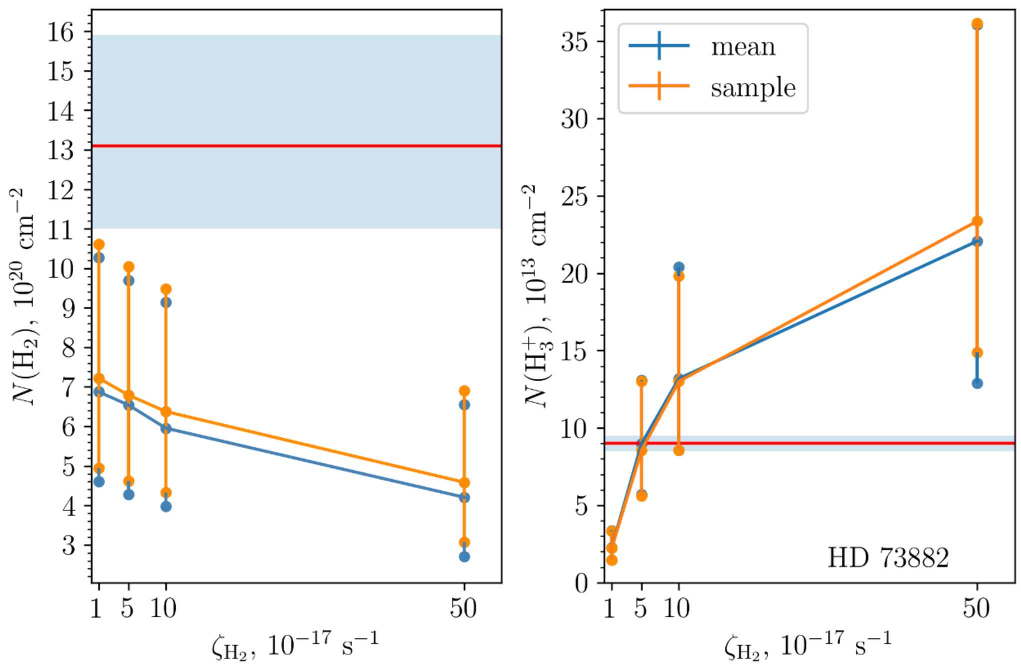
Optimum ζ_{H2} and $N(\mathrm{H_{tot}})$



Simulations versus observations (cont'd)

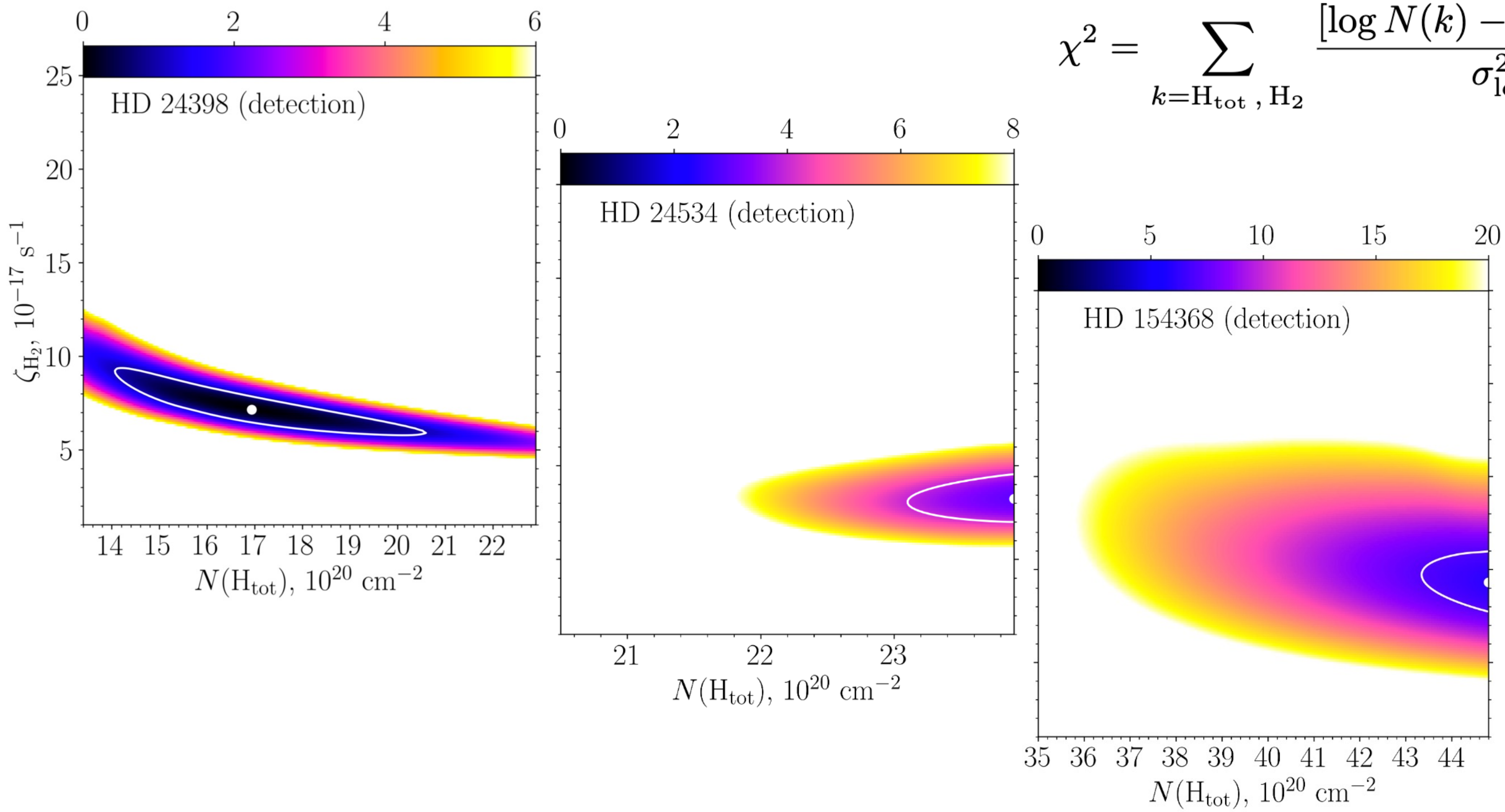
Our simulations systematically underestimate $N(\mathrm{H_2})$, by 30%–50% on average…





… but Bialy et al. (2019) showed that $N(\mathrm{H_2})$ increases due to compressive turbulence!

Assessment of uncertainties



$$\chi^2 = \sum_{k=\mathrm{H_{tot}},\,\mathrm{H_2}} \frac{[\log N(k) - \langle \log N(k) \rangle]^2}{\sigma^2_{\log,k}} + \frac{[N(\mathrm{H_3^+}) - \langle N(\mathrm{H_3^+}) \rangle]^2}{\sigma^2_{\mathrm{H_3^+}}}$$

Re-evaluated ionization rate