# The lightest hydrides, witnesses of cosmochemical evolution


**Helmut Wiesemeyer[1]**

**In collaboration with: A. Faure[2], R. Güsten[1], P. Hartogh[3], B. Klein[1], D. Neufeld[4], Y. Okada[5], O. Ricken[1], M. Sil[2], J.Stutzki[5]**

Max-Planck-Institut für Radioastronomie

[1] Max Planck Institute for Radio Astronomy, [2] Université Grenoble Alpes / CNRS, [3] MPI Solar System Research, [4] The Johns Hopkins University, [5] Universität zu Köln



**The first molecular bonds:** $HeH^+$, together with $He_2^+$, is predicted to form the first molecular bond in the primordial universe. While $H_2^+$ was quickly destroyed by dissociative recombination, the abundance of $HeH^+$ reached a first maximum at z ~ 2000 (0.1 Myr after the big bang), together with the rise of $H_2^+$, $H_2$, $H_3^+$, and their deuterated isotopologs (Fig. 1). After the recombination era (z ~ 1000), the steady increase of the abundances provided coolants for the collapse of halos forming population III stars (z ~ 30)*. When temperatures dropped to T ~200 K, rotational line cooling by HD and $HeH^+$ became important (Fig. 2). HD was subsequently depleted by astration (Fig. 3) and $HeH^+$ through dissociative recombination and proton transfer. *Klessen & Glover 2023, ARA&A

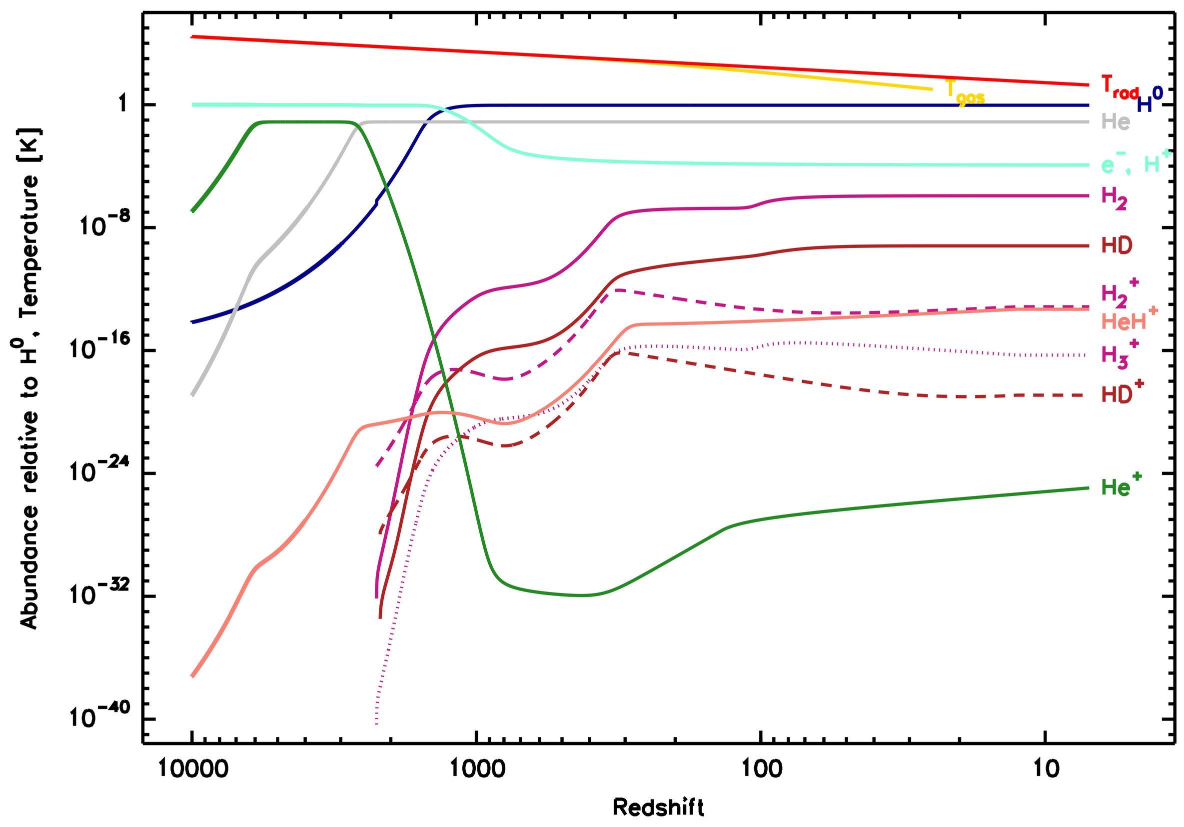


**Fig. 1:** *Chemical and thermal evolution of the young universe, including $H_2$ cooling (Galli & Palla 1998). Processed with KROME package v14.08 (Grassi et al. 2014) and rates therein (except for the proton transfer of $HeH^+$, Faure et al. 2024) under ΛCDM cosmology (final Planck data parameters, Tristram et al. 2024).*

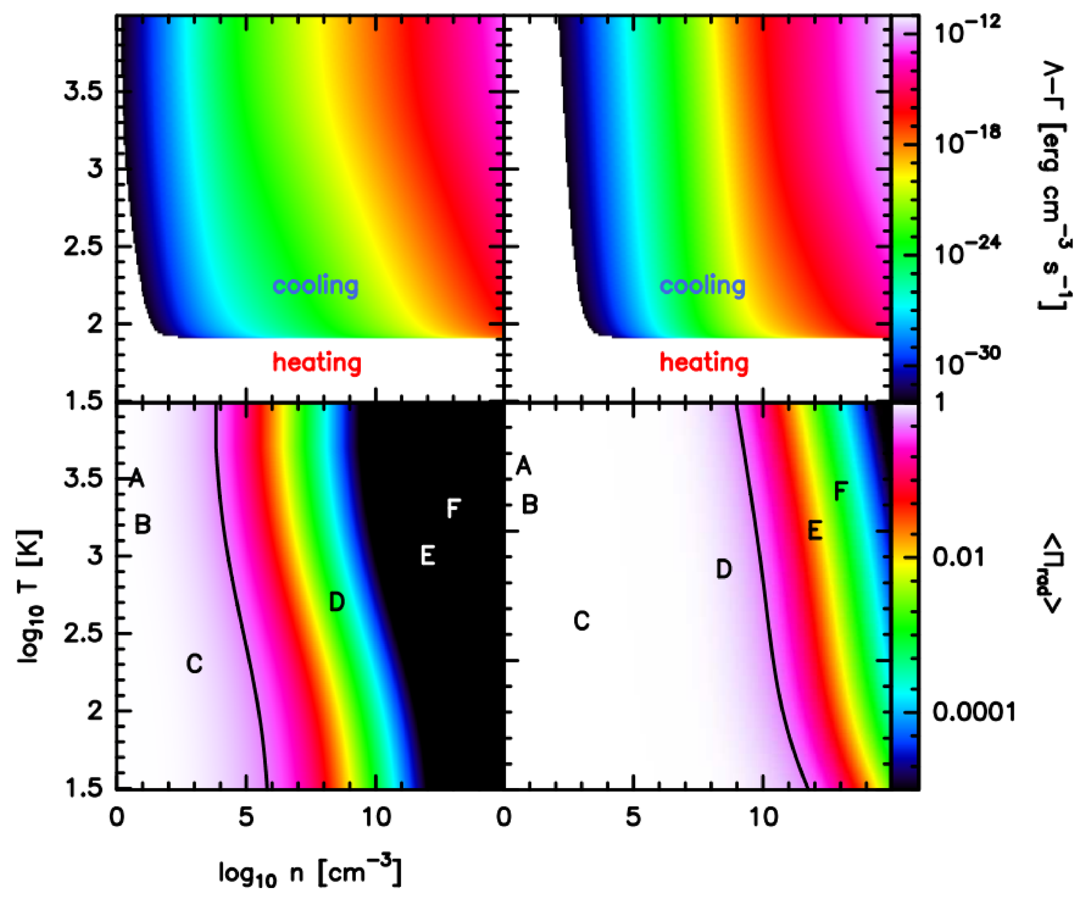


**Fig. 2:** *Top - Cooling of a collapsing halo by HD (left) and $HeH^+$ (right), for z = 30 and 10% escape probability. Bottom - Corresponding probabilities for radiative de-excitation. Evolutionary stages are labeled A (compression-heated flow into dark-matter halo), B – C (runaway $H_2$ cooling), C – D (PdV heating), E (gas fully molecular).*

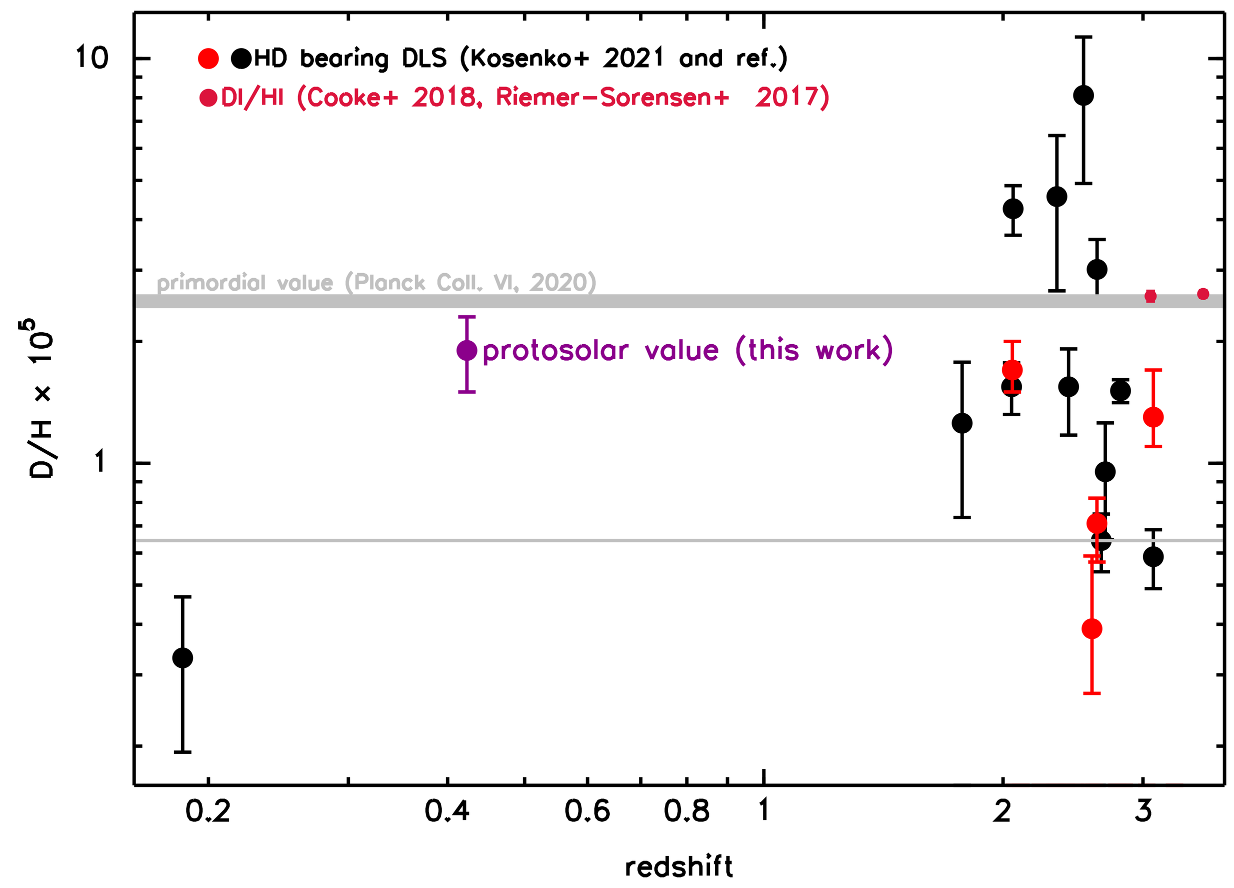


**Fig. 3:** *Synopsis of cosmic deuterium fractions. Shown are the primordial value, D/H and HD/$H_2$ in damped Lyman α systems, and the protosolar value against redshift.*

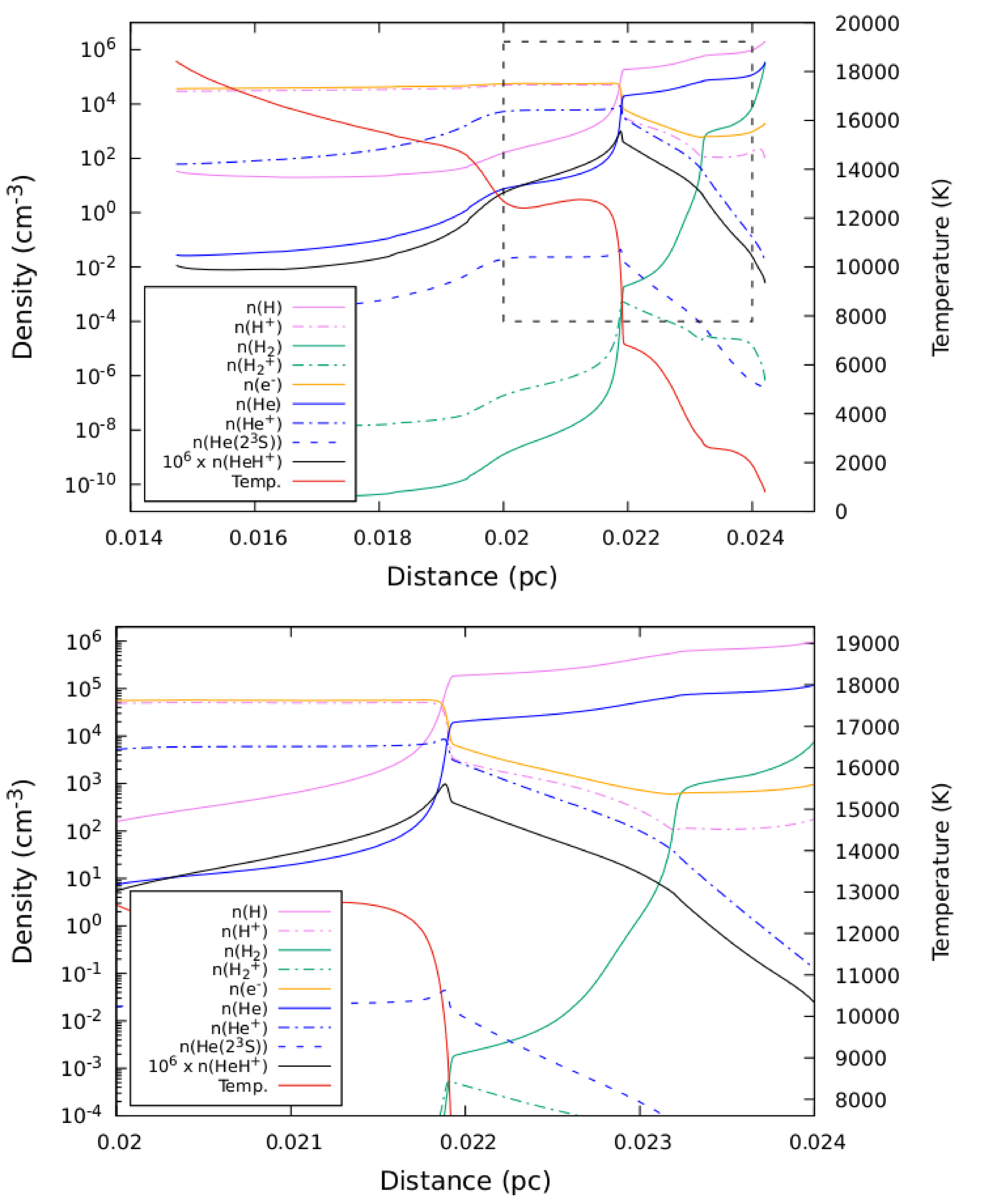


**Fig. 4:** *Top - Equilibrium temperature and densities for an isobaric Cloudy* model of NGC 7027 as a function of distance from the 1.98 × $10^5$ K hot central star, starting at the illuminated face of the nebula. Bottom - Zoom into the dashed area above (Sil+ 2025, A&A in press).* *v23.01, Gunasekara+ 2023

**Table 1:** *The chemistry of $HeH^+$*

**Dominant production pathways (radiative association):**

| | | | | | |
|---|---|---|---|---|---|
| Present day Universe (k1): | $He^+$ | + H | → | $HeH^+$ | + photon |
| | $He(2^3S)$ | + H | → | $HeH^+$ | + photon |
| Primordial Universe (k2): | He | + $H^+$ | → | $HeH^+$ | + photon |

**Dominant destruction pathways (z < 200 and NGC 7027):**

| | | | | | |
|---|---|---|---|---|---|
| Dissociative recombination: | $HeH^+$ | + $e^-$ | → | He | + H |
| Proton transfer: | $HeH^+$ | + H | → | He | + $H_2^+$ |

**Table 2:** *NGC 7027* vs. primordial Universe[1]*

| | | NGC 7027[2] | z = 2600 |
|---|---|---|---|
| T | [K] | 5100 | 7100 |
| $n_H$ | [cm$^{-3}$] | 2.6 × $10^5$ | 7400 |
| $n_e$ | [cm$^{-3}$] | 5960 | 7080 |
| P/k | [K cm$^{-3}$] | 1.6 × $10^9$ | 5.3 × $10^7$ |
| $\int_{\nu_{Ly}}^{\infty} I_\nu \, d\nu$ | [erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$] | 160 | 20 |
| $n(He^+)n(H^0)k_1$ | [cm$^{-3}$ s$^{-1}$] | 2.9 × $10^{-8}$ | 3.6 × $10^{-18}$ |
| $n(He^0)n(H^+)k_2$ | [cm$^{-3}$ s$^{-1}$] | 2.0 × $10^{-12}$ | 1.6 × $10^{-14}$ |

| $HeH^+$ | J=1-0 | P(1) | P(2) |
|---|---|---|---|
| measured / a-posteriori flux ratios[3] | 0.95(19) | 0.86(9) | 1.08(16) |

[1] krome model, [2] Cloudy17.02 model for $HeH^+$ yielding layer, [3] Sil et al. 2025, MCMC

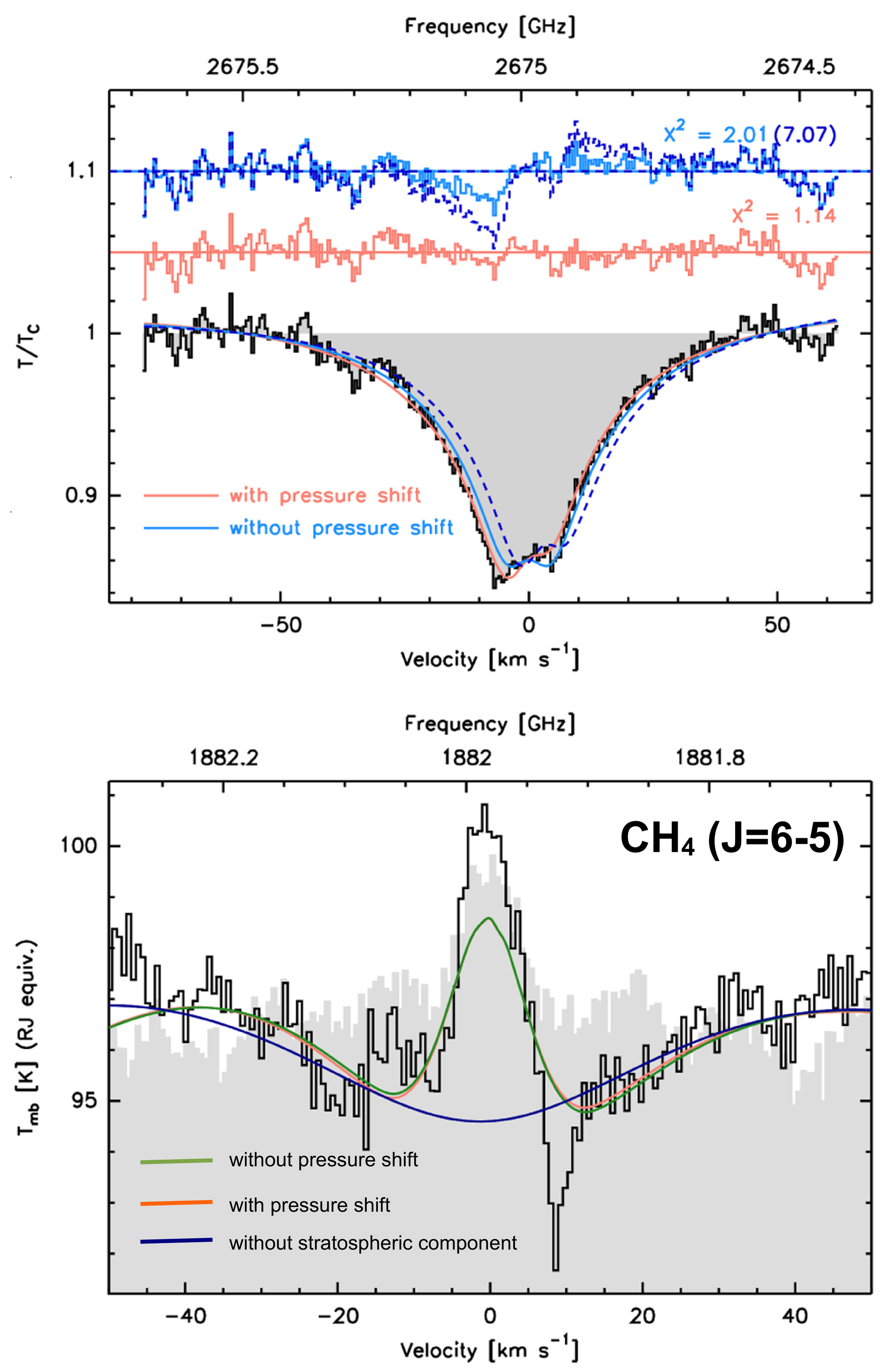


**Fig. 3:** *Top - HD (J=1-0) line (4GREAT) of Jupiter and Voigt profile fits (best with inclusion of the pressure shift). Bottom - $CH_4$ (J=6-5) line (upGreat, equivalent from HIFI underneath) and fit for same model.*

**Results:** The spectroscopy of rotational (FIR) and vibrational (NIR) lines of $HeH^+$ in NGC 7027 confirms a chemistry controlled by ion-neutral reactions and photo-ionization (Güsten+ 2019; Neufeld+ 2020; Sil+ 2025). The Strömgren sphere of this young planetary nebula and the primordial universe form $HeH^+$ on different pathways (radiative association of He + $H^+$ and $He^+$ + H, respectively) but share (for z < 200) the same destruction channels (dissociative recombination & proton transfer). Inclusion of He ($2\,^3S$), the longest-lived metastable atomic state, reproduces the observed $HeH^+$ abundance thanks to its 19.8 eV energy input. While reaction rates are measured in ion storage rings, removal of ambiguities between temperature and density requires further IR spectroscopy and high resolution to avoid blends (e.g., of $HeH^+$ and CH). **— Why it matters:** The cooler stages in the formation of population III stars, when $HeH^+$ and HD contend for the role of the major coolant, call for quantum-state selective reaction networks. Evidence for HD is as well limited to the local universe (except for a few z ≤ 3 samples), where it traces, thanks to its weak fractionation, native D/H ratios. GREAT (R > 5×$10^5$ !) confirms the protosolar origin of Jupiter's deuterium fraction (Wiesemeyer+ 2024), significantly falling below the primordial value, by separating tropospheric absorption from stratospheric emission.