

It's not just a *phase*

The multi-phase ISM and the star-formation

Arshia Maria Jacob

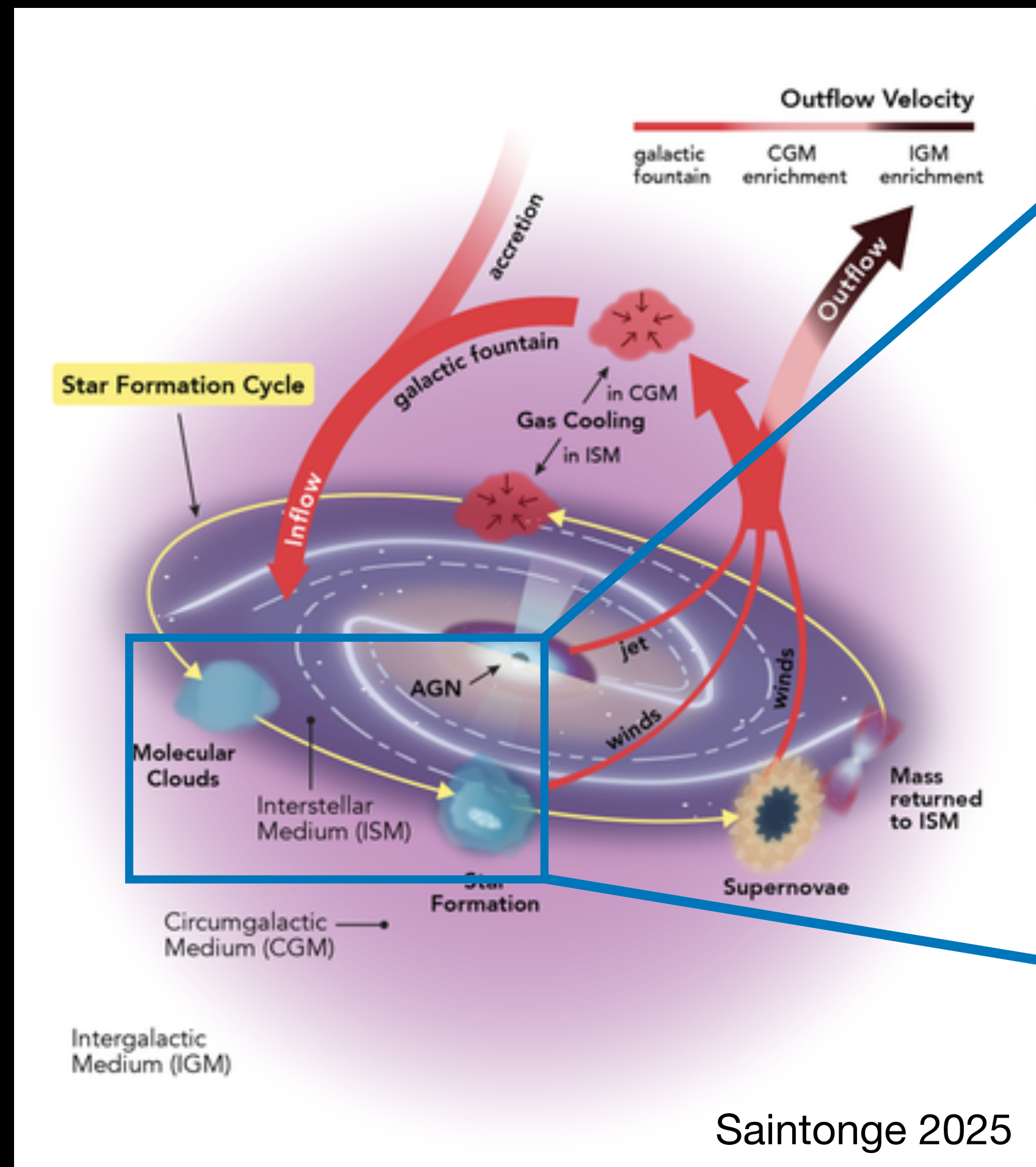
University of Cologne, Max Planck Institute for Radio Astronomy

Puzzles of Star Formation II, Schloss Ringberg, May 6, 2025

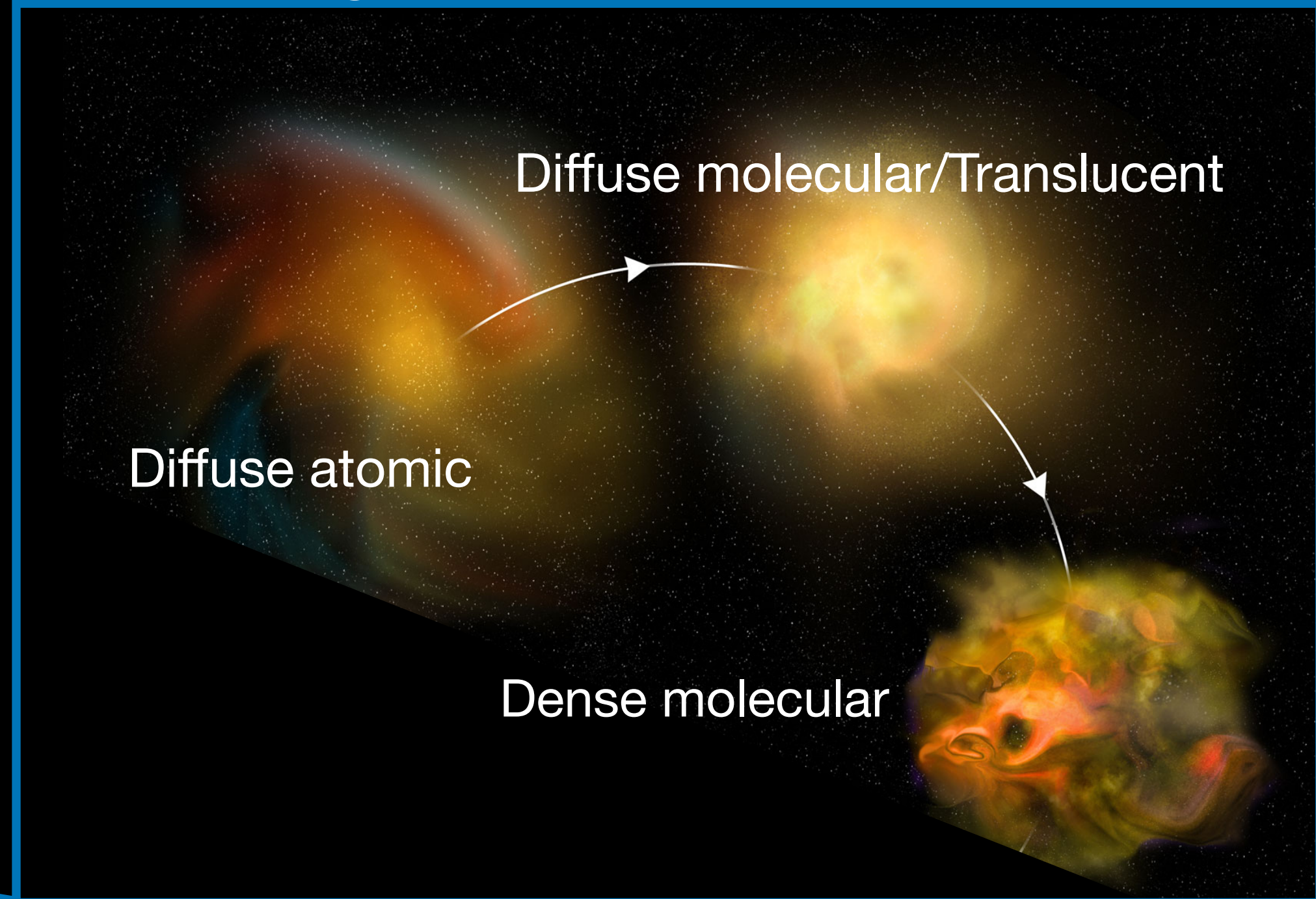


(Credit: S. Vogel/UMD)

Essence of galaxy evolution → processes that govern the baryonic cycle

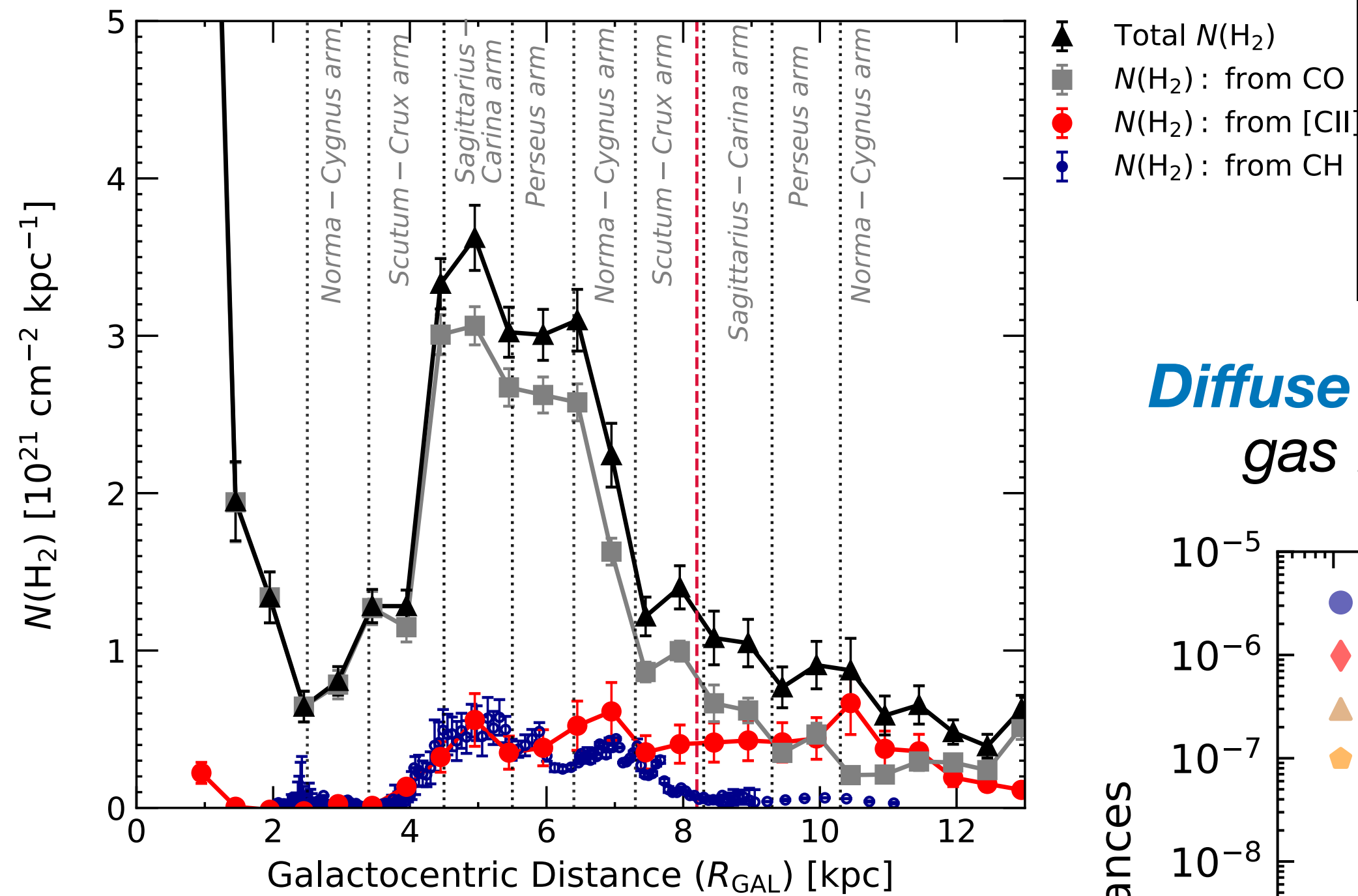


Transition from atomic (HI) to molecular (H₂) gas is a major bottleneck!



*Cold neutral medium (CNM) is an important part of the gas life cycle and a precondition for star formation BUT it's **distribution is not fully understood.***

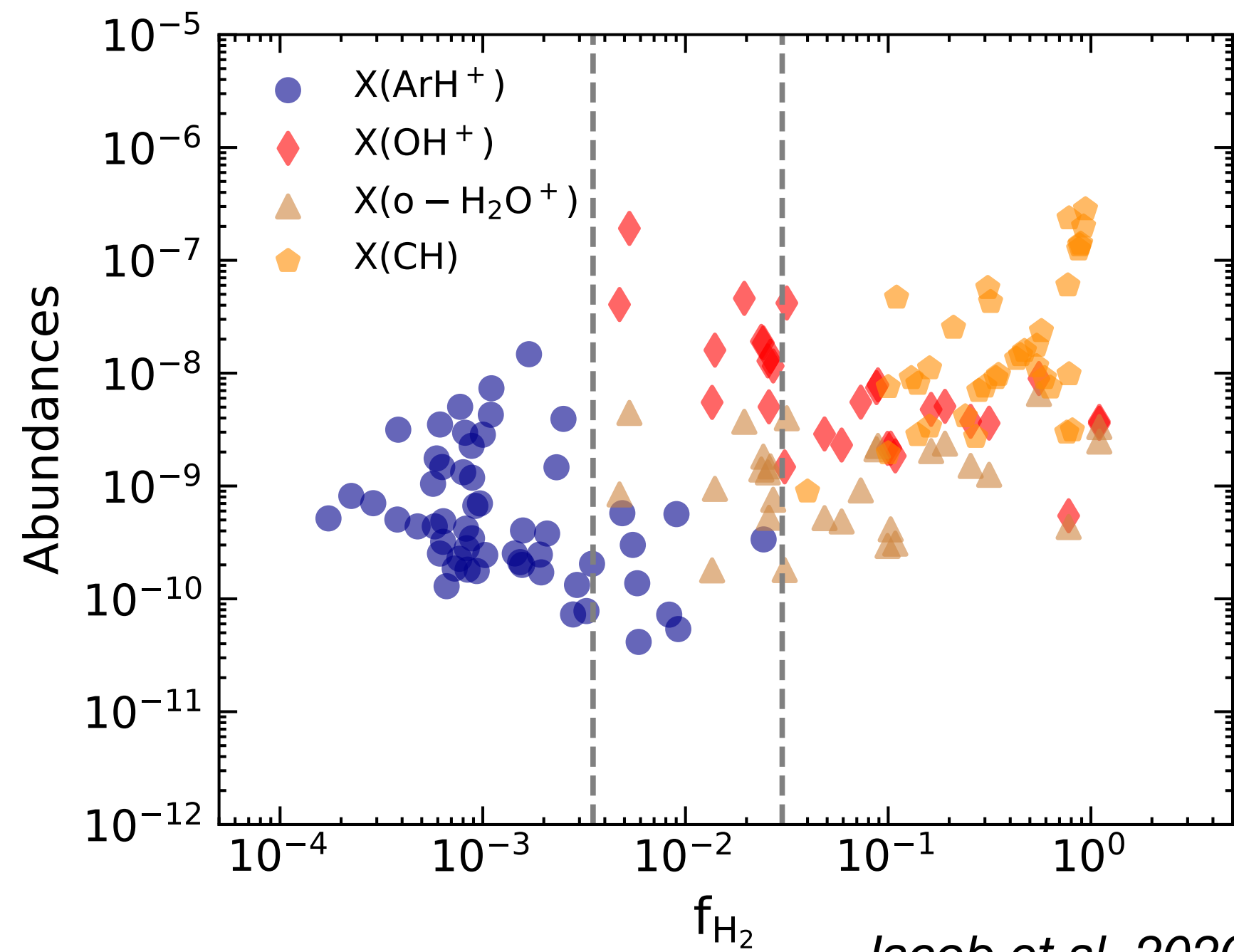
Tracing the distribution of diffuse-to-dense molecular gas



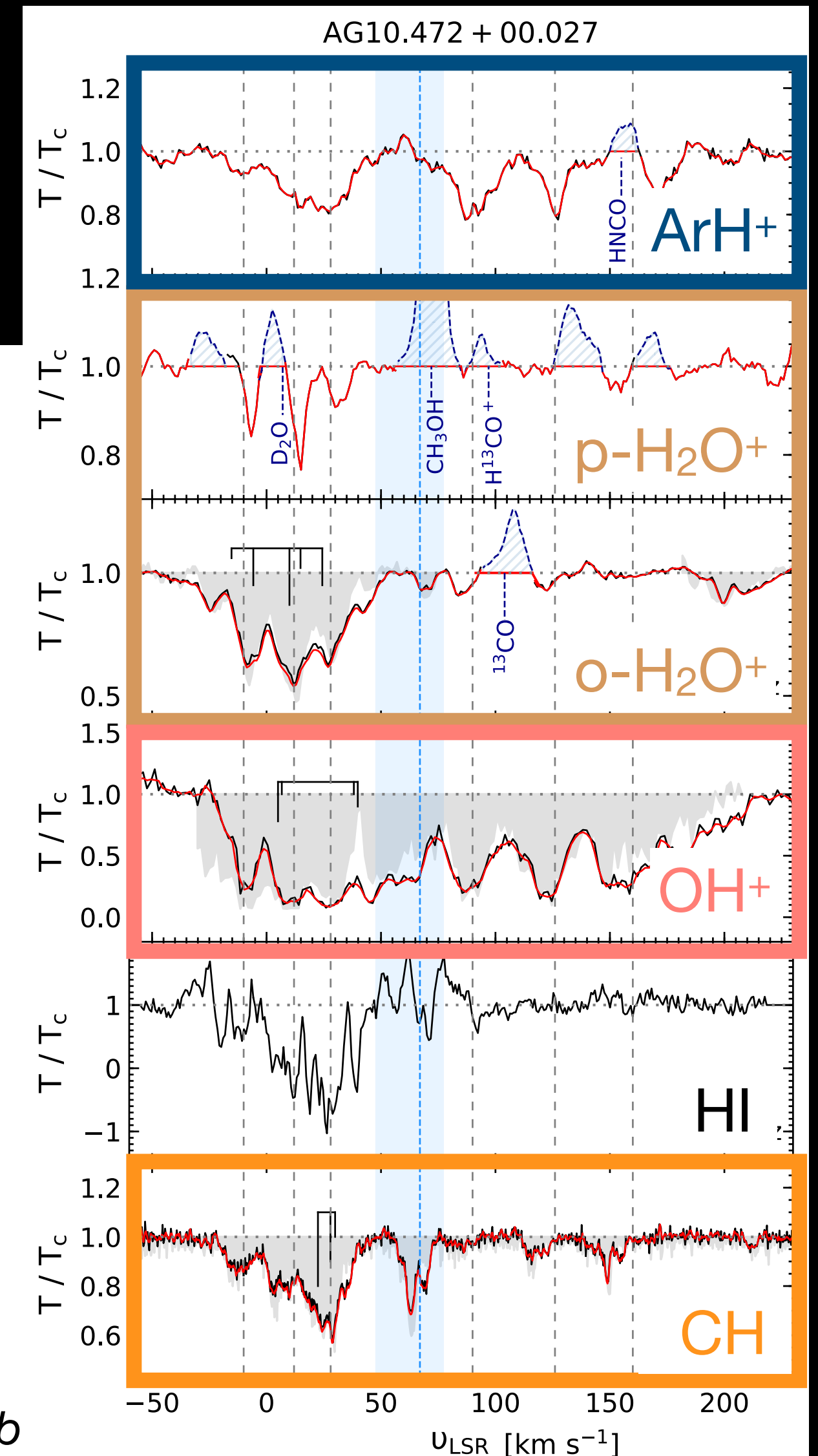
H₂ traced by multiple tracers.
CO-dark fraction can be as high as 50% in the outer galaxy

Pineda et al. 2013, Jacob et al. 2019, 2023b

Diffuse atomic-to-diffuse molecular
gas fraction traced by hydrides



Jacob et al. 2020b



Why does star-formation care about H₂?

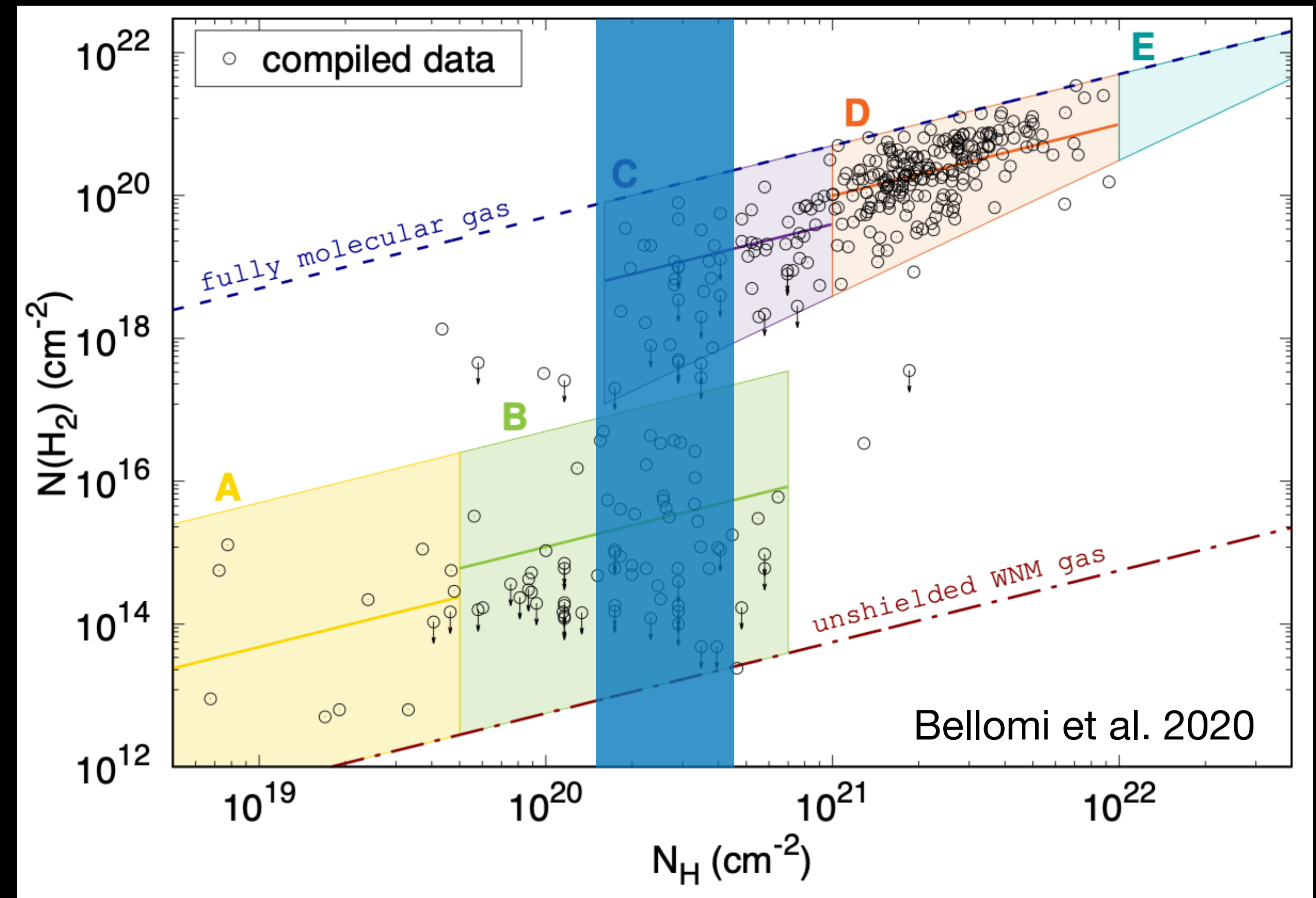
Molecular fraction

Chemical State

Balance between:

- 1. Formation of H₂ on dust $\propto nZ$
- 2. Photodissociation of H₂ by photons in the Lyman-Werner bands $\propto \chi_{UV}$

Models can now predict the distribution molecular fractions and recreate local Galactic sightlines



Numerical simulations of the **turbulent multi-phase diffuse ISM**, using the RAMSES code with **non-equilibrium H₂** abundance.

Why does star-formation care about H₂?

To be or not to be in equilibrium

Thermal State of the ISM

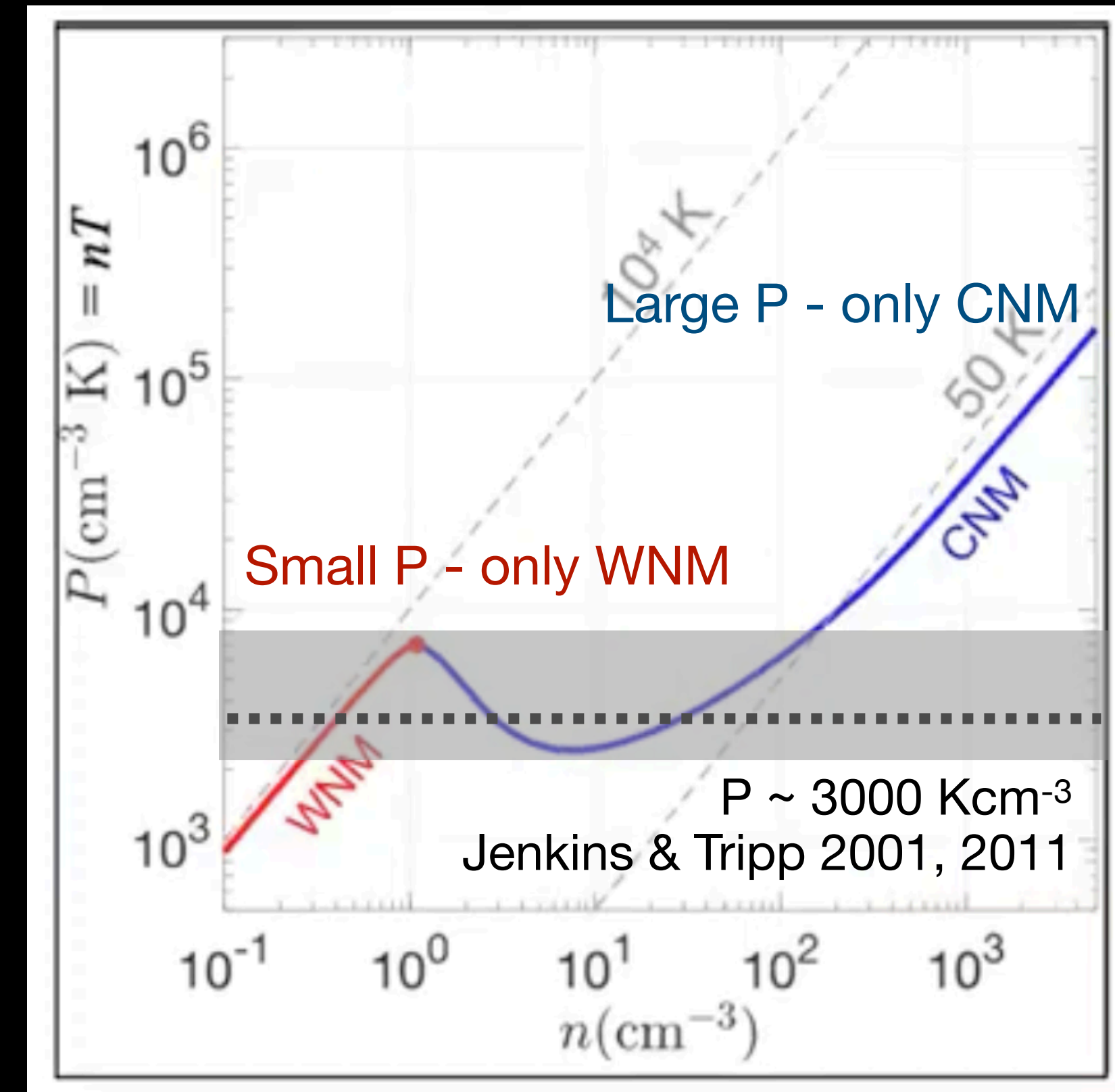
Balance between:

- **1. Heating:** photoelectric heating (dust, FUV), X-ray and cosmic-ray ionisation, H₂ heating

$$\propto n\chi_{\text{UV}}$$

- **2. Cooling:** Collisionally excited line emission, radiative decay (line emission), C⁺, O fine structure lines, Lyman alpha, H₂ ro-vibrational lines

$$\propto n^2Z$$



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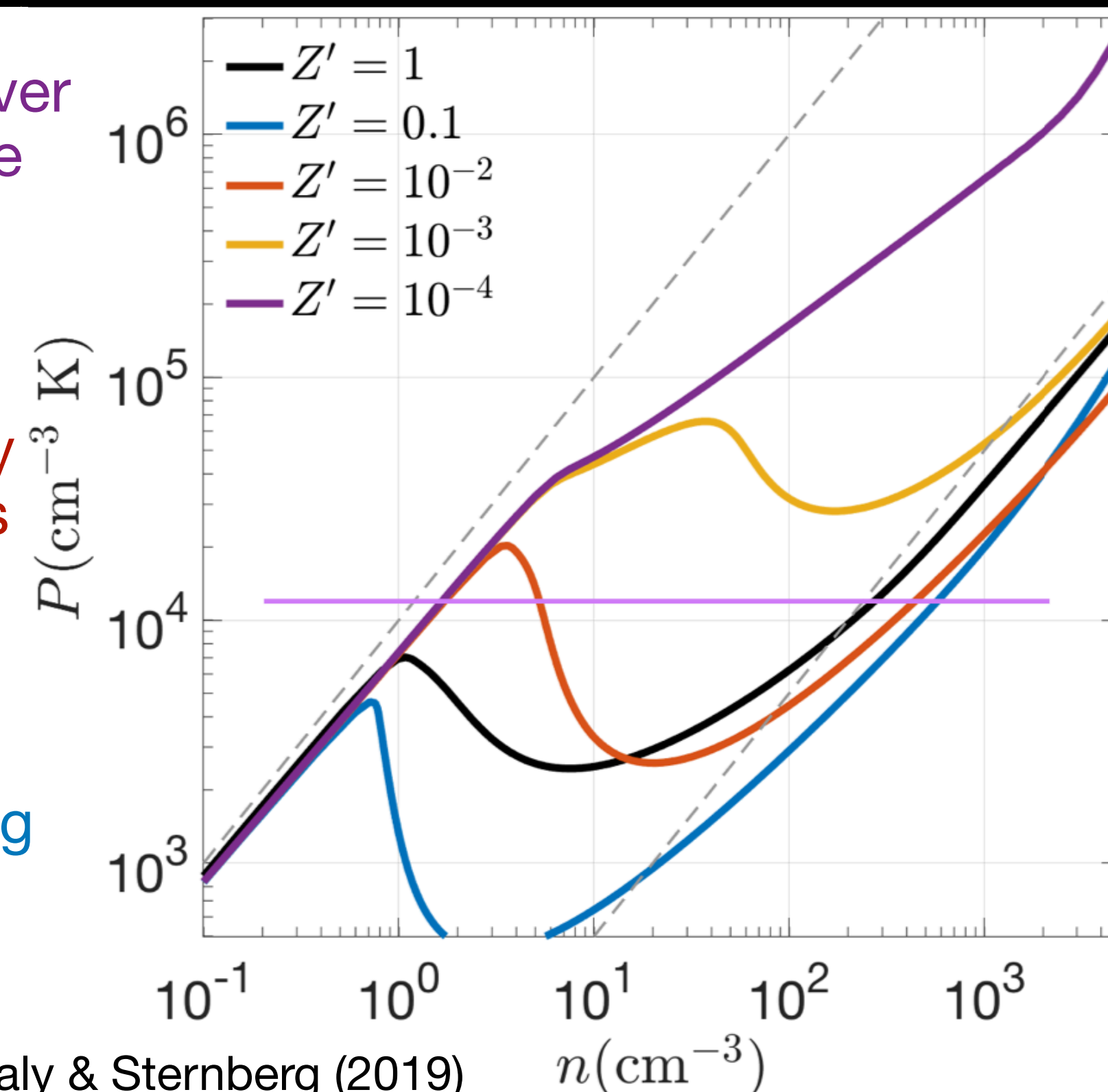
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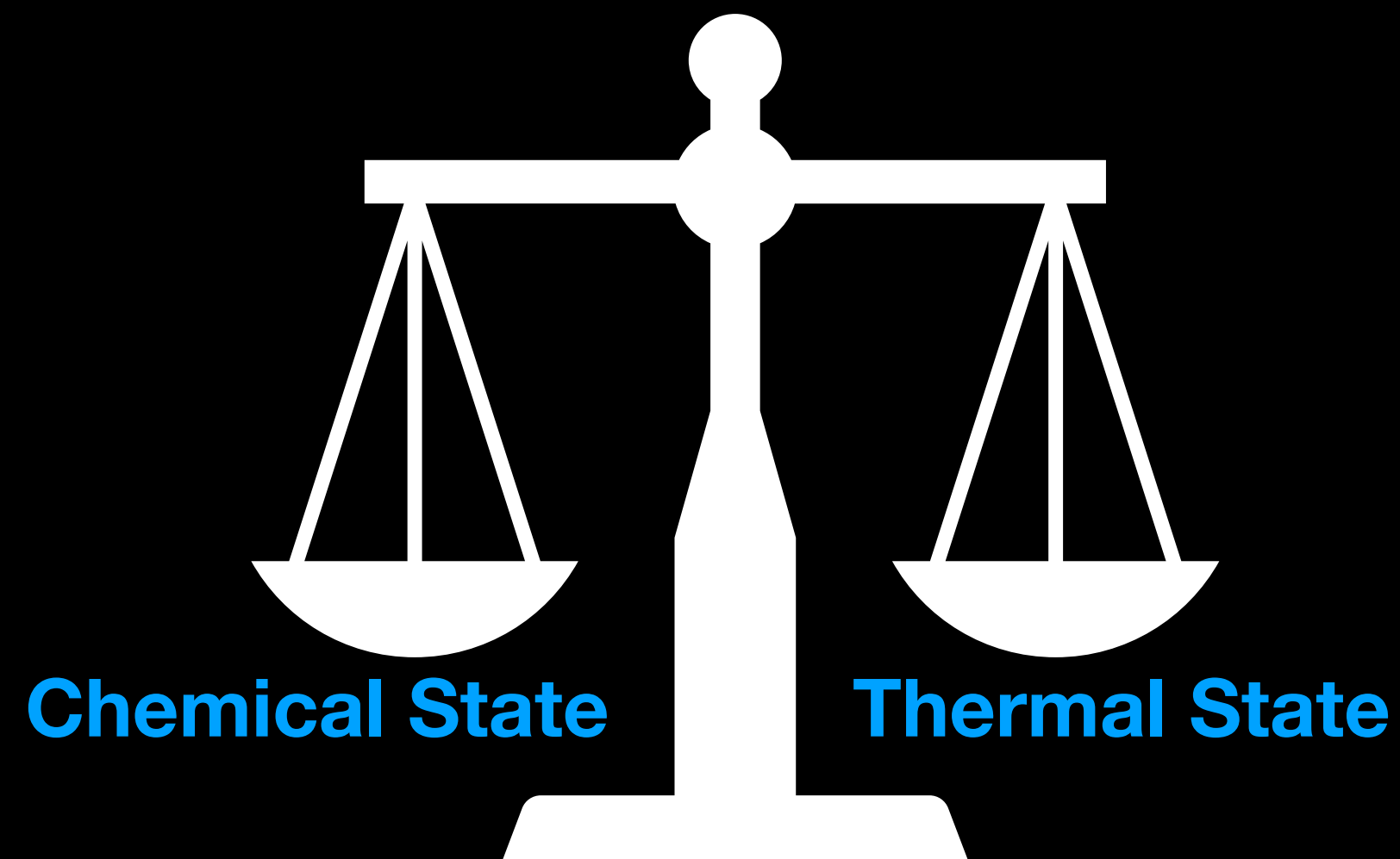
H₂ cooling dominates over metals, monotonic curve

Heating is dominated by CRs $\propto Z$, cooling drops

Both heating and cooling has changed $\propto Z$

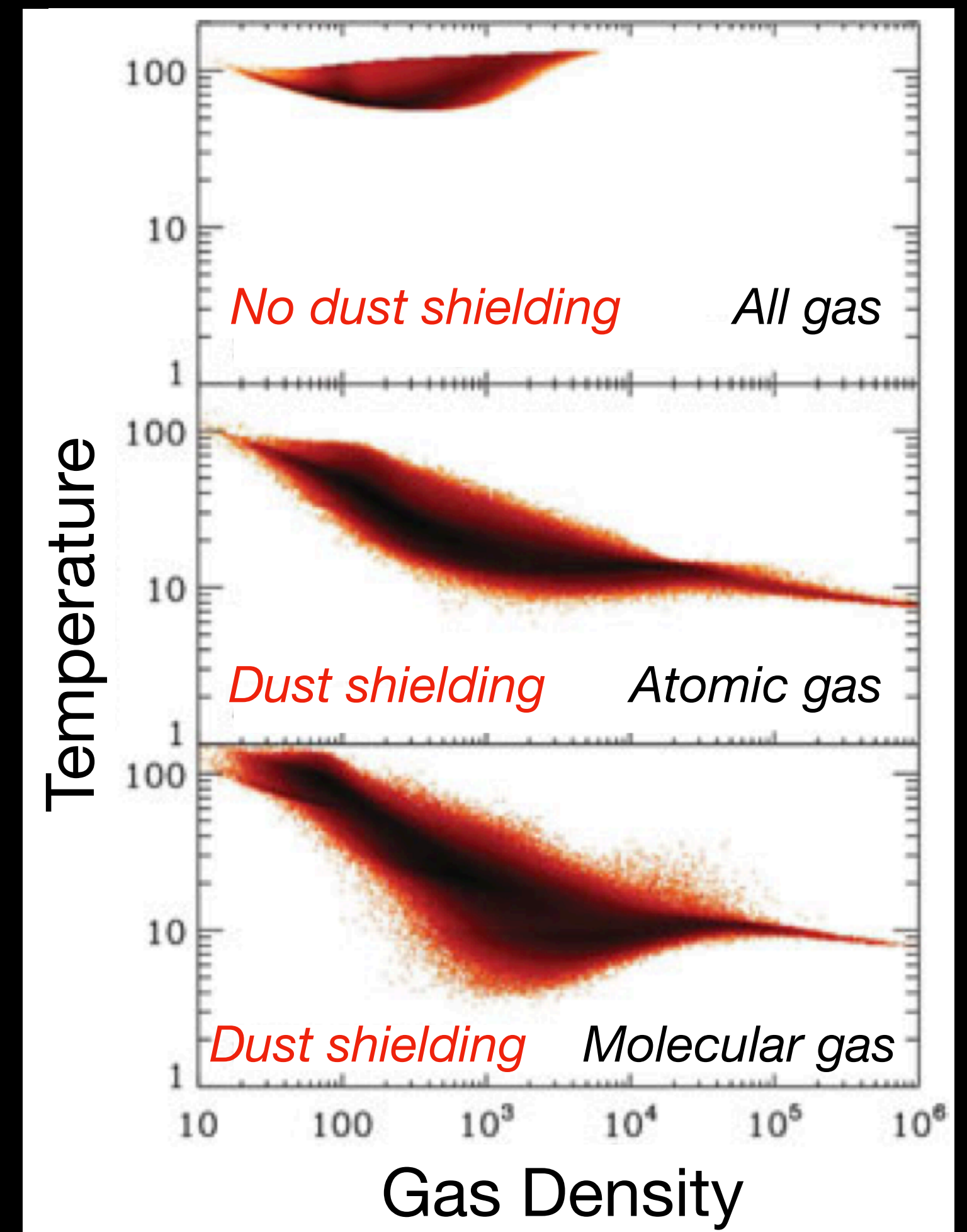


Why does star-formation care about H_2 ?



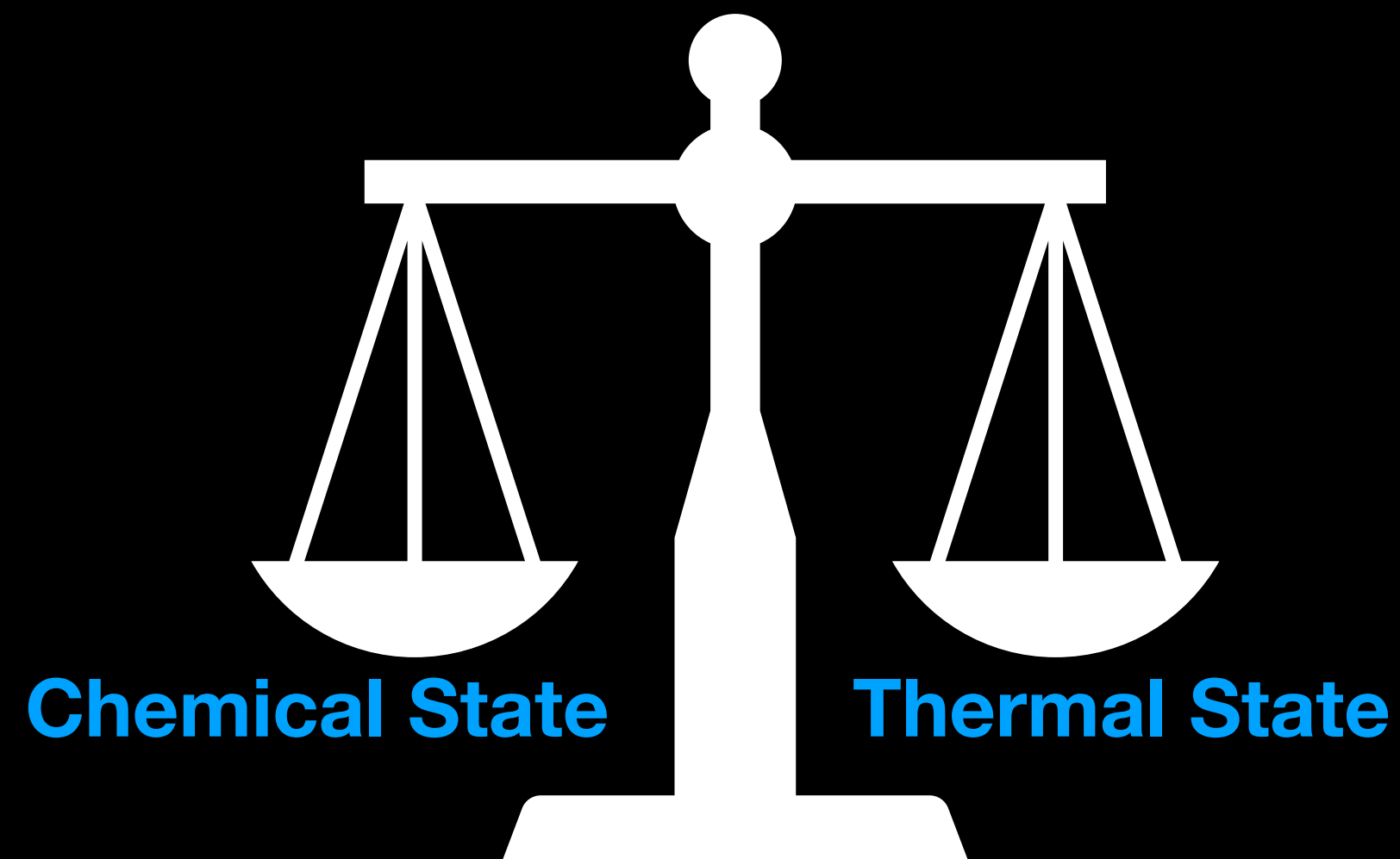
*Well correlated over a range of gas densities,
dust extinctions, and metallicities*

HI-to- H_2 phase transition is accompanied by a **drop in gas temperatures** due to dust shielding



Glover & Clark (2012a)

Why does star-formation care about H₂?



*Well correlated over a range of gas densities,
dust extinctions, and metallicities*

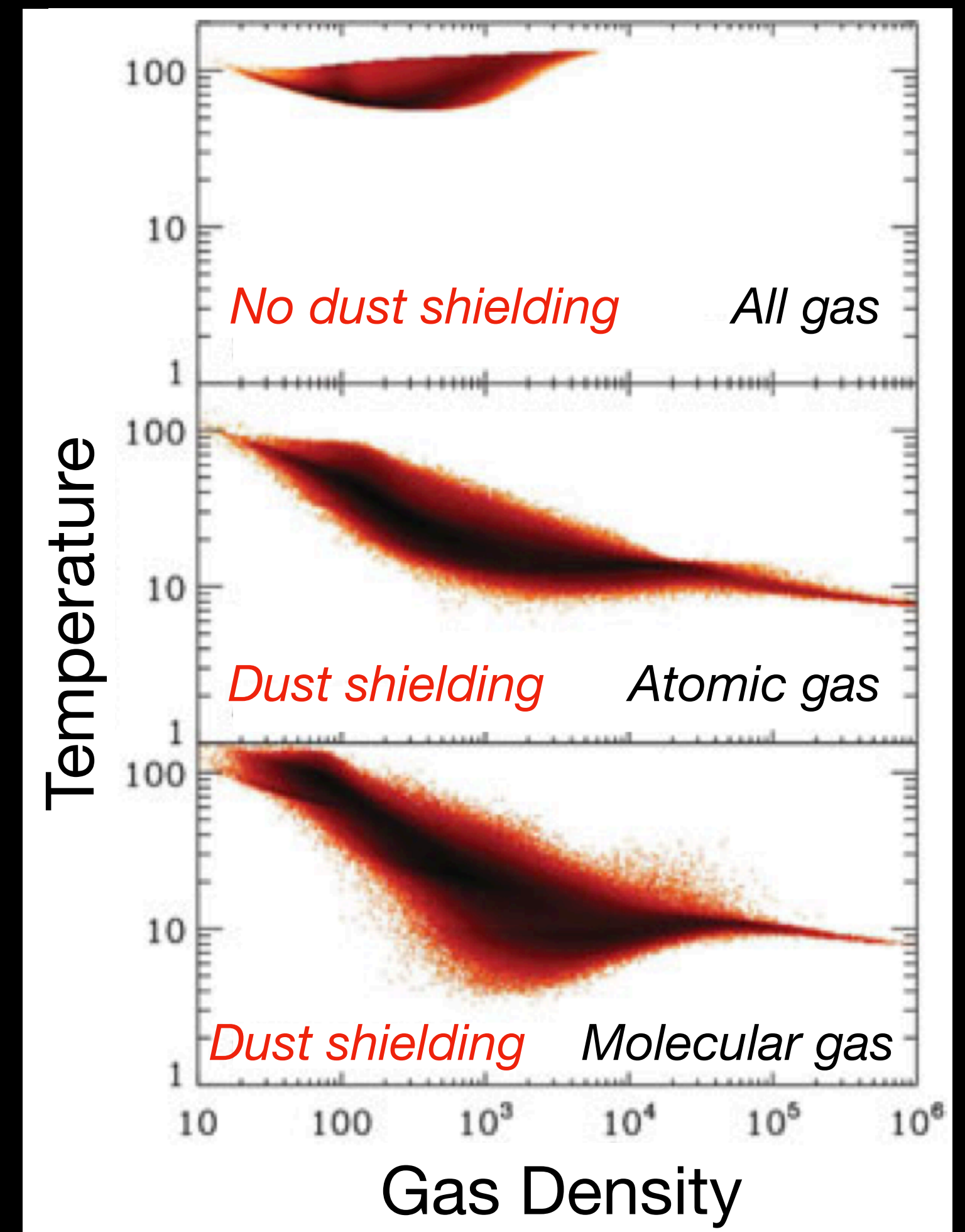
At low Z: the time scale for gas to become molecular can be very long

$$t_{\text{thermal}} < t_{\text{dyn}} < t_{\text{chem}}$$

star formation *might* proceed before the gas is able to turn molecular

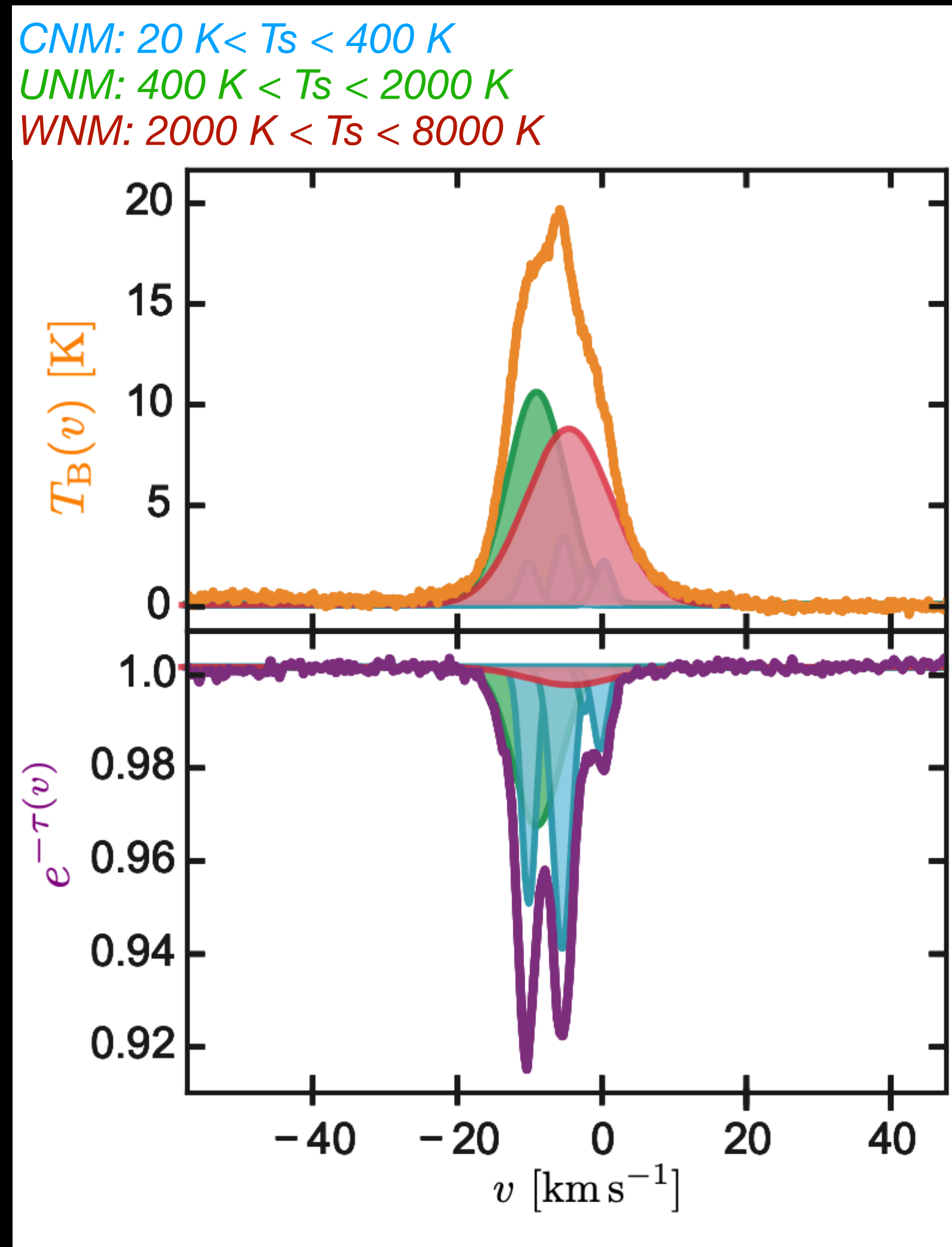
So what is the contribution of atomic gas to the CNM?

HI-to-H₂ phase transition is accompanied by a **drop in gas temperatures** due to dust shielding

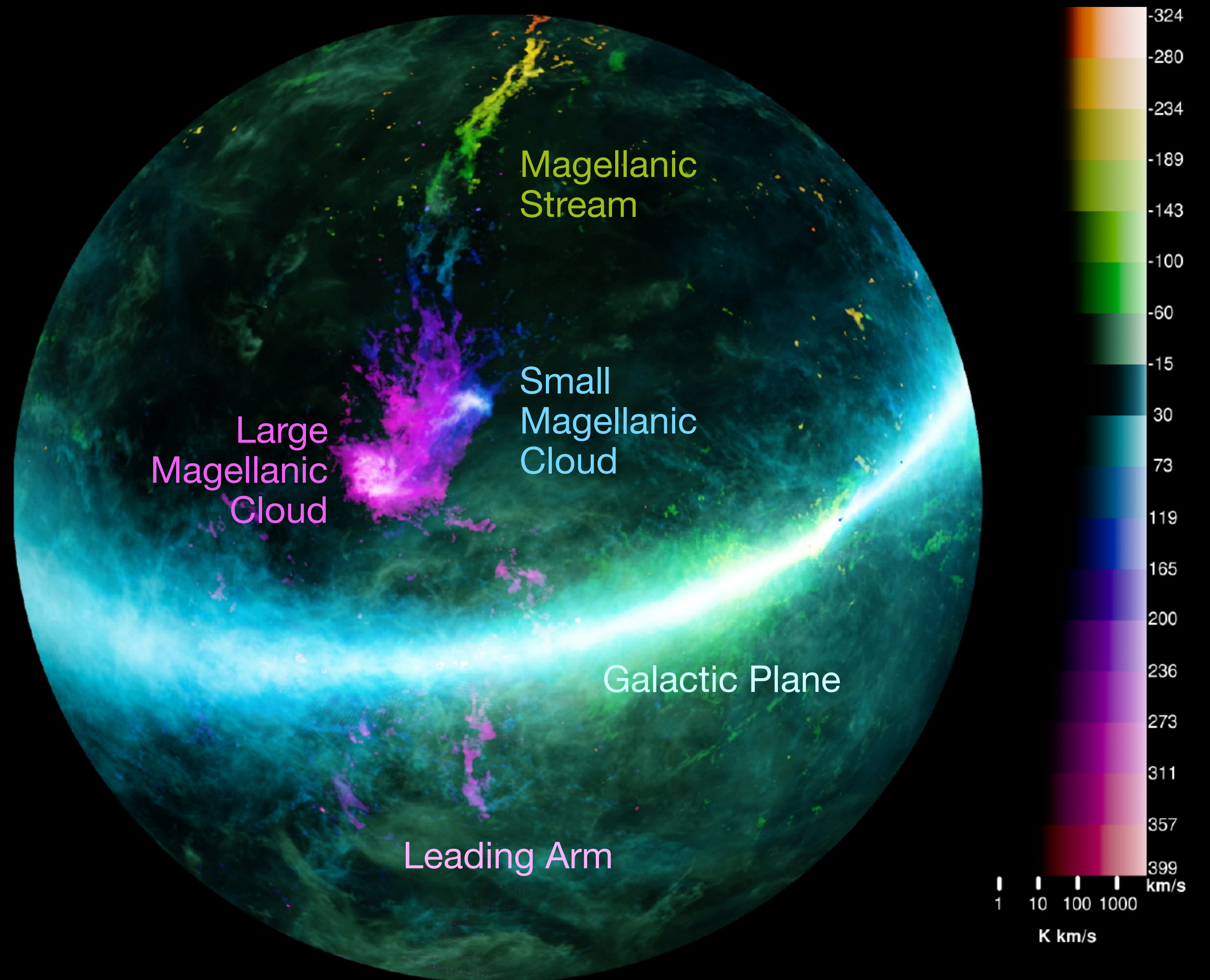


Glover & Clark (2012a)

What is the distribution of HI?



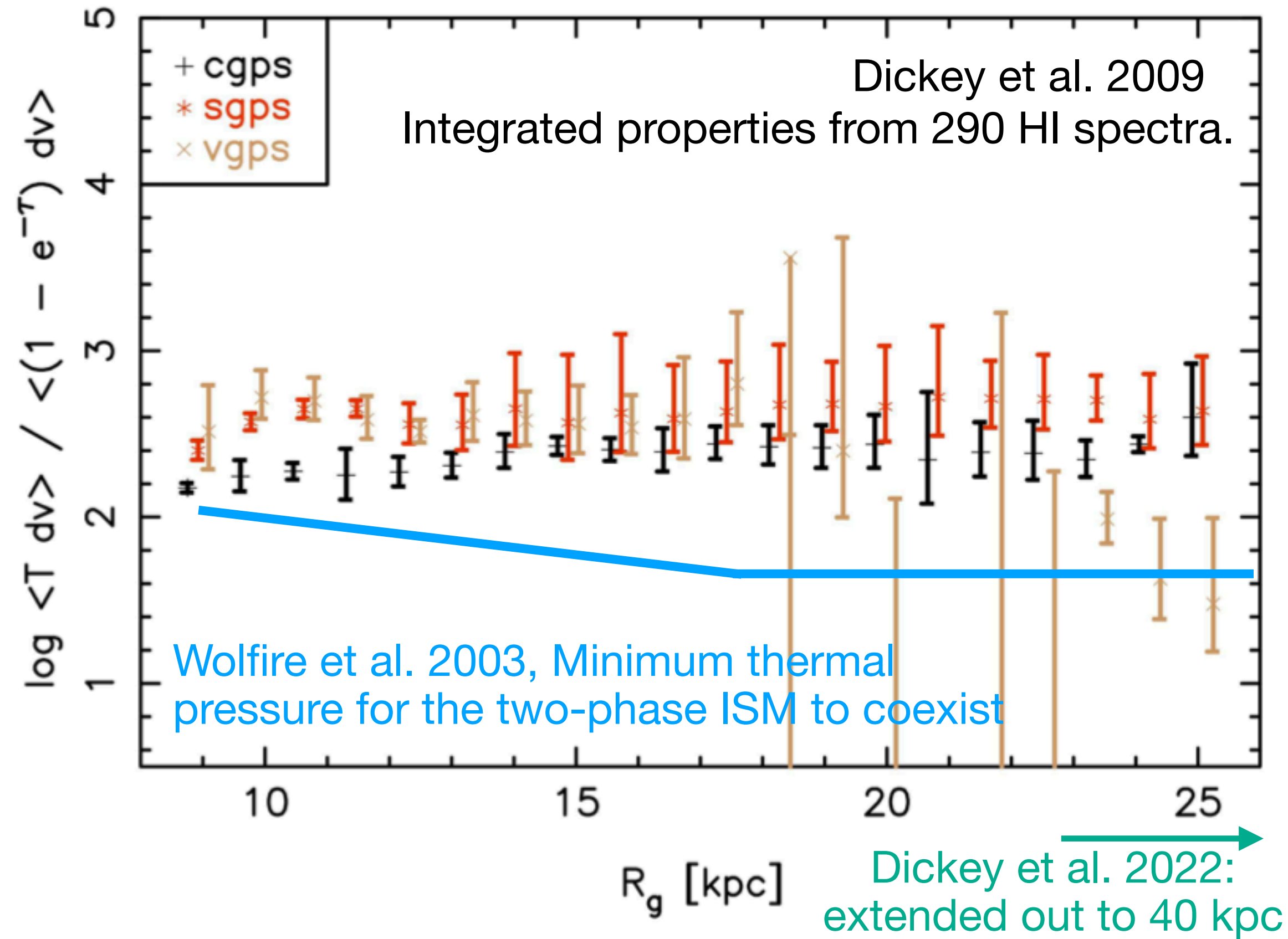
Murray et al. 2018b



Parkes Galactic All Sky Survey (GASS), HI
McClure-Griffiths et al. 2009

What is the *cold* HI fraction?

Mean spin temperature $\langle T_s \rangle$



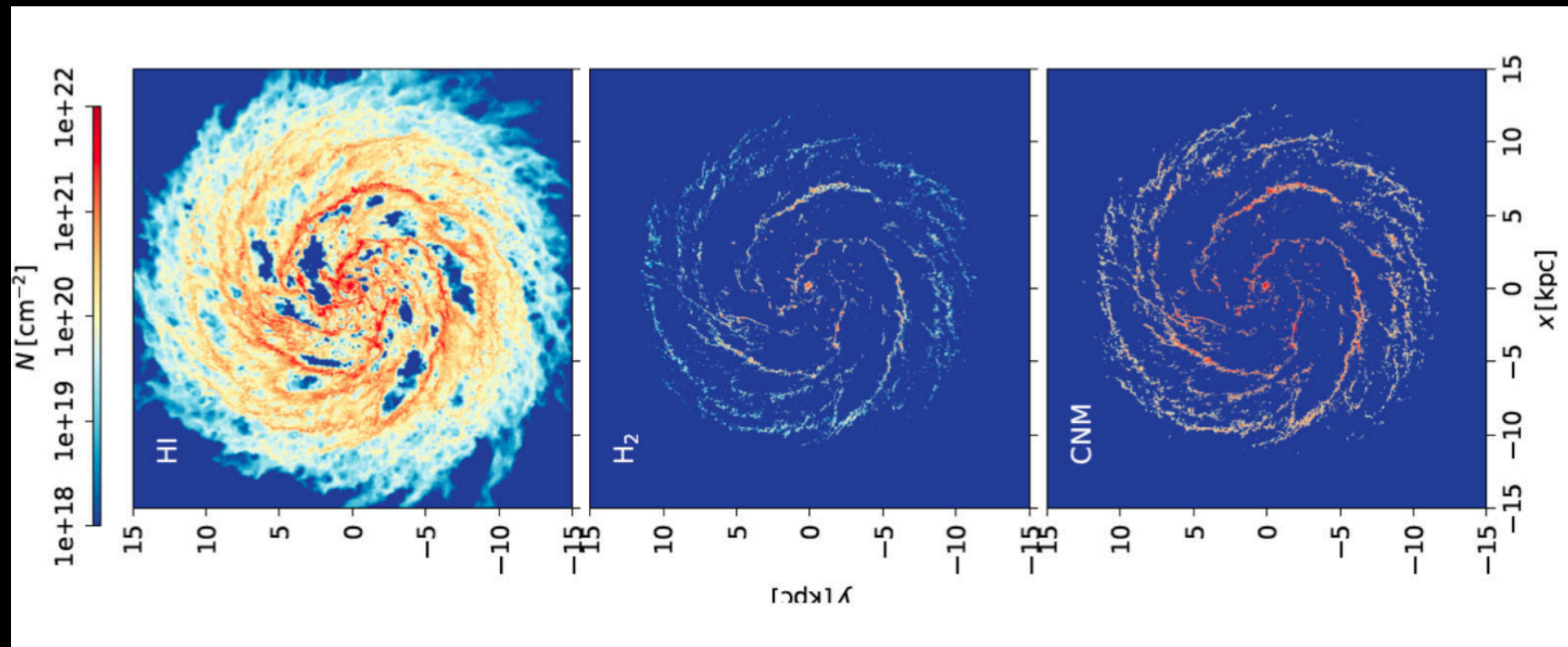
In the outer galaxy, the photoelectric heating is less effective, less cooling and less shielding \rightarrow lower CNM fraction

A mixture of cool and warm HI is observed in MW out to distances of 25 kpc (now extended to 40 kpc with GASKAP)

$$f_{\text{CNM}} = T_s / \langle T_s \rangle$$

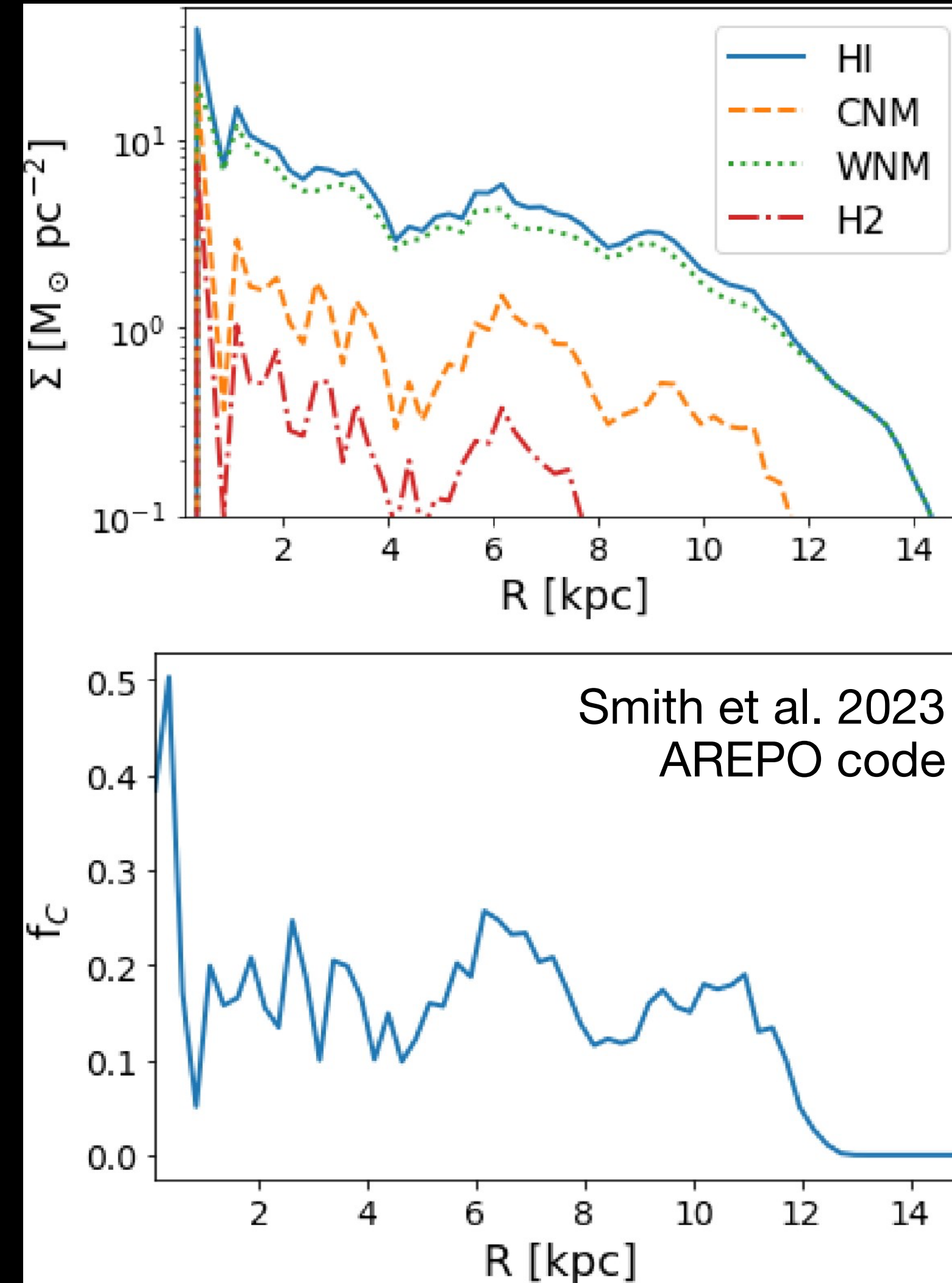
If $T_s \sim \text{constant}$, then the CNM fraction $\sim \text{constant} \rightarrow 15\text{-}20\%$ of HI in cold at $R \sim 22$ kpc.

What is the *cold* HI fraction?



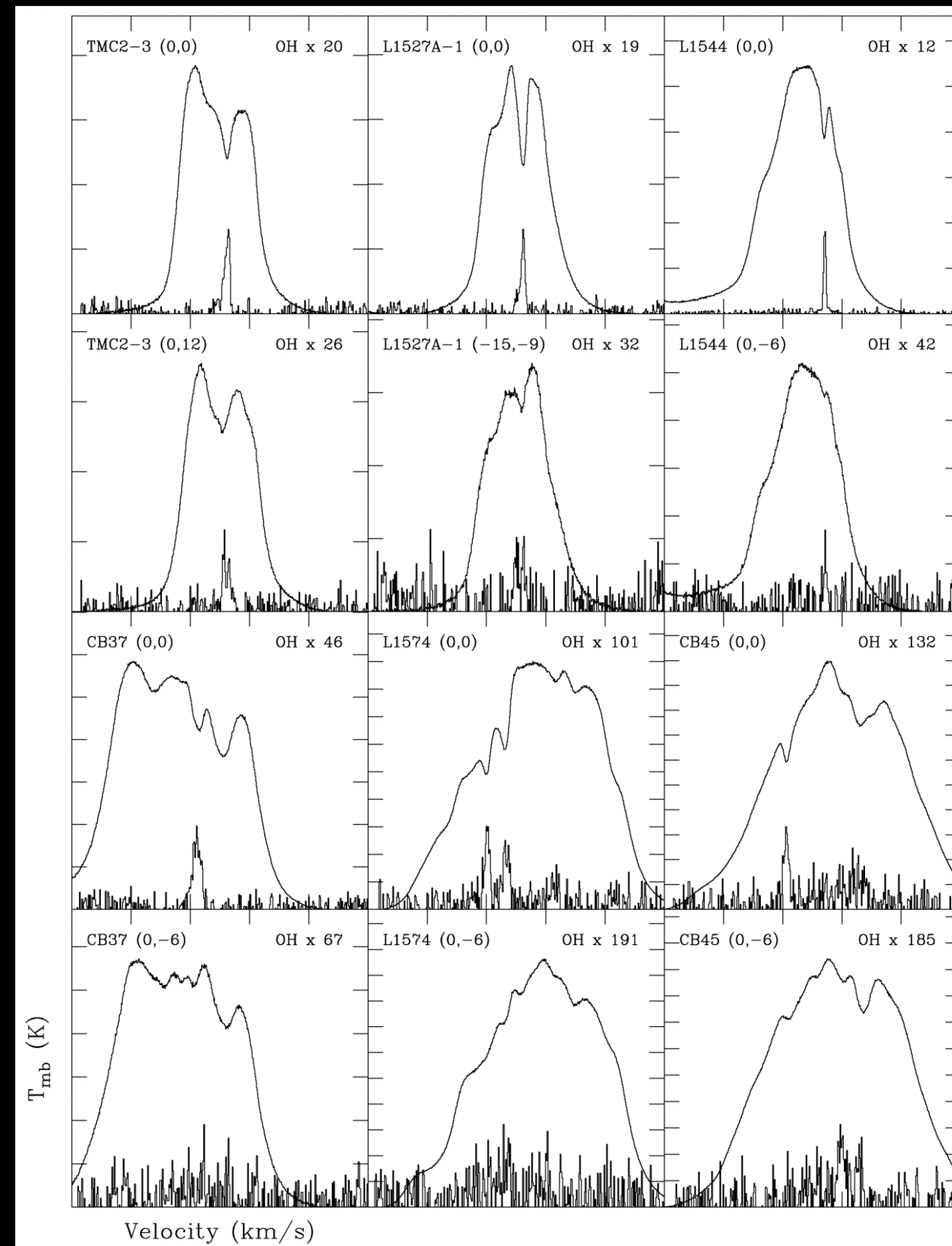
CNM extends to the outer galaxy but not as far as the HI.

The CNM fraction \sim constant. This is due to falling ISRF and with decreasing column density in the outer galaxy.



What is the *cold* HI fraction?

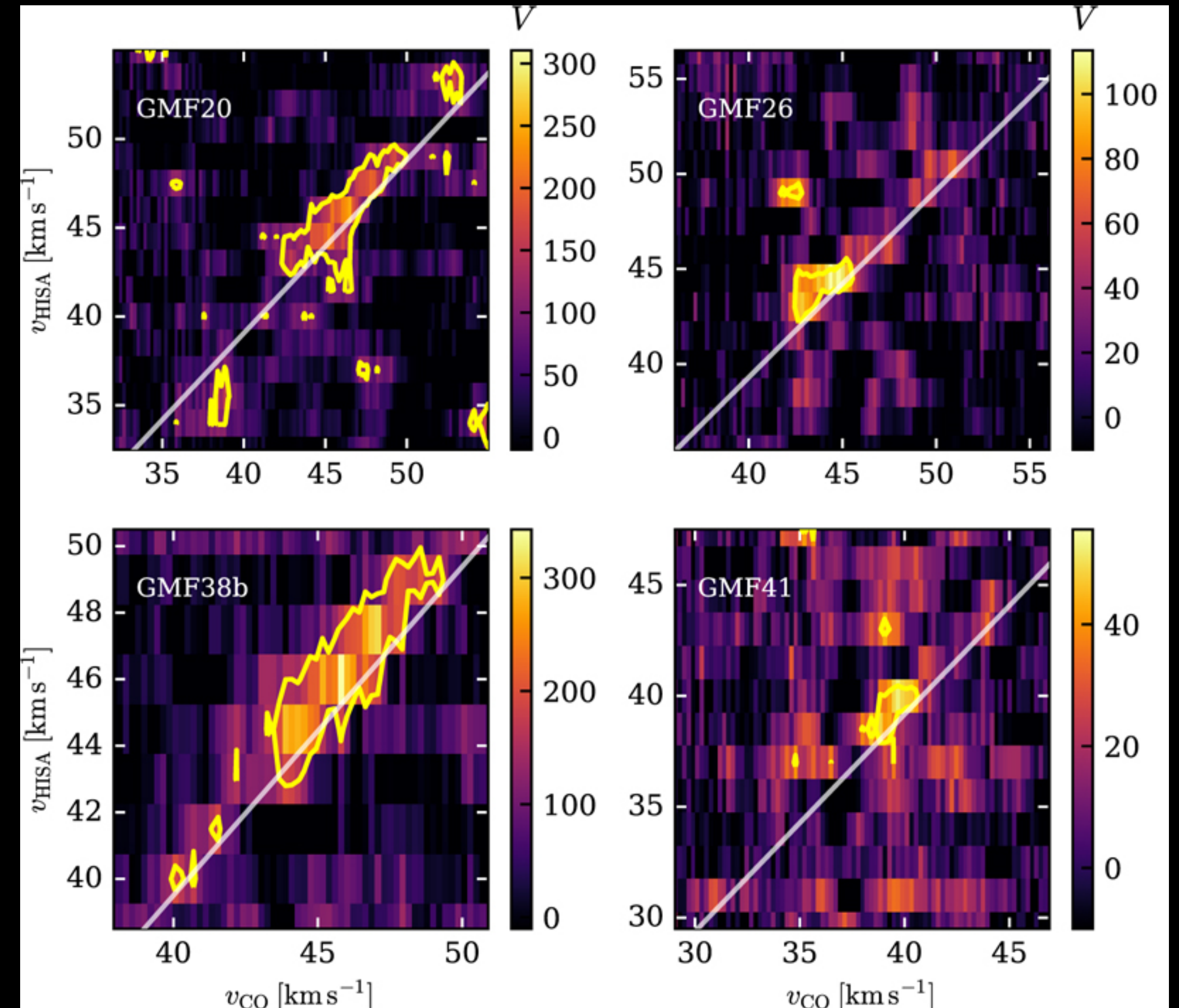
HI (narrow) self-absorption : cold H I cloud is located in front of a warmer H I emitting cloud



Li & Goldsmith 2003

Cold HI is spatially correlated with the molecular gas on a global scale

Variations in each filament arise from local star formation events.



Syed et al. 2023, THOR

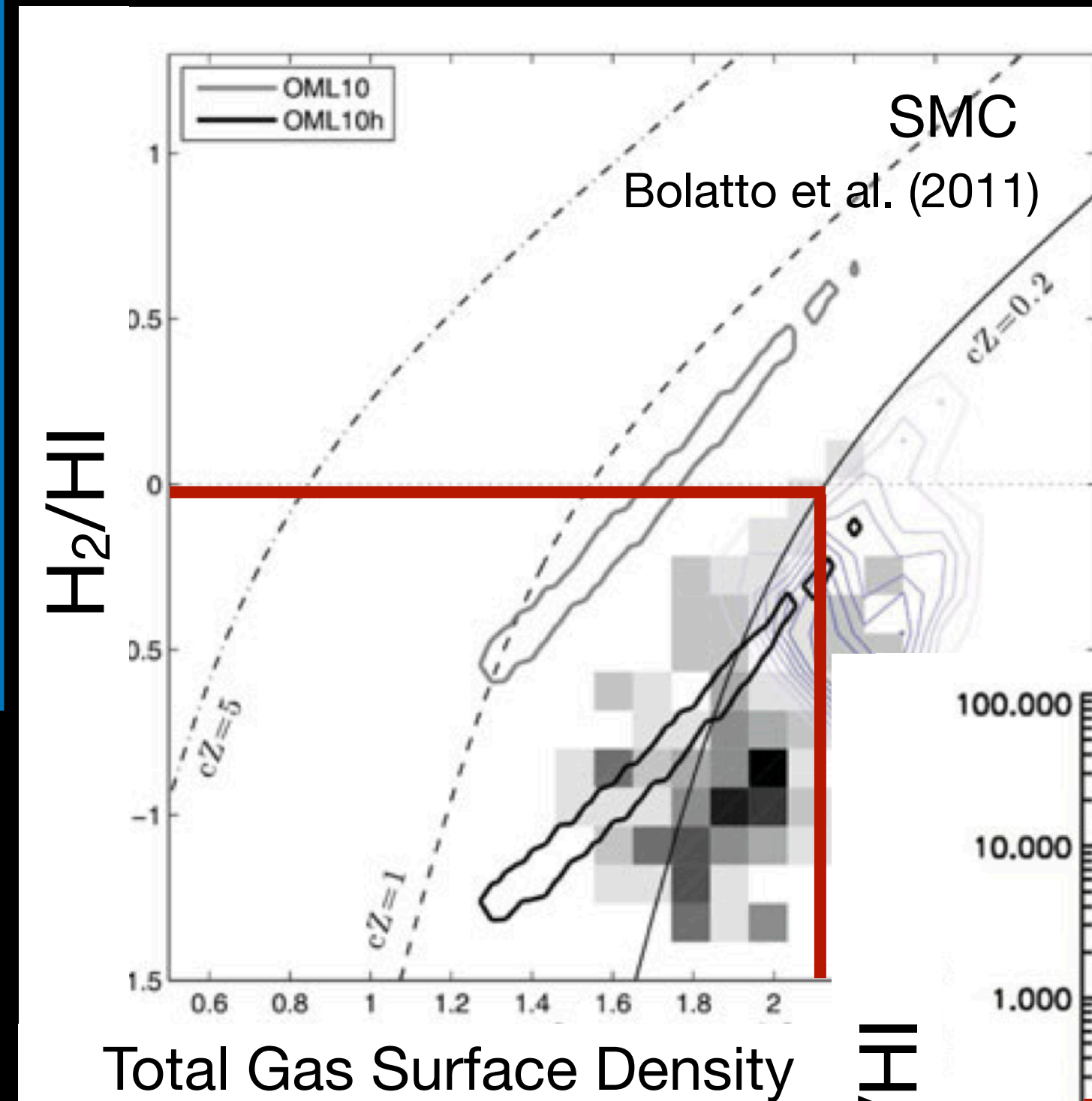
Why does star-formation care about H₂?

Molecular fraction

Chemical State

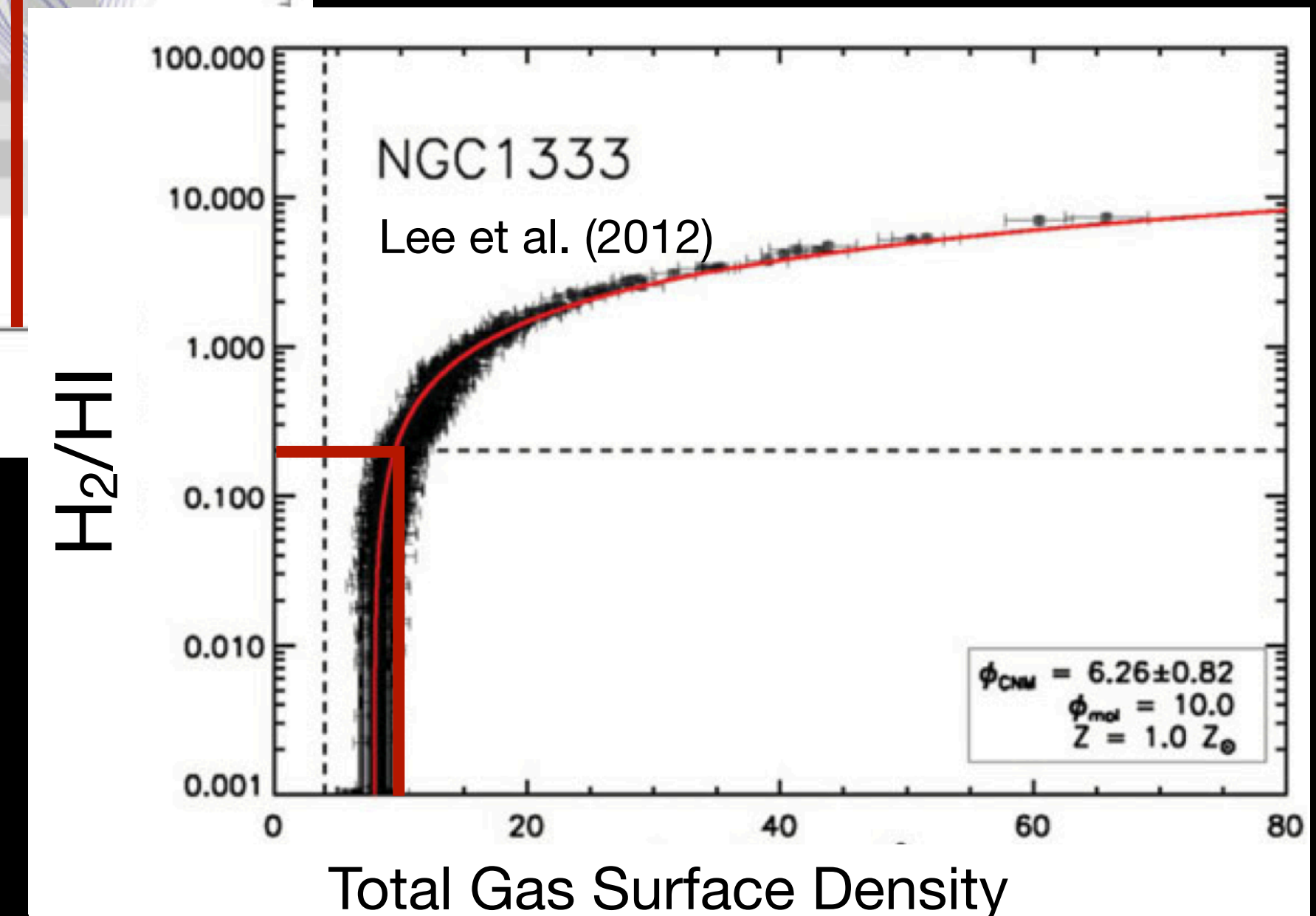
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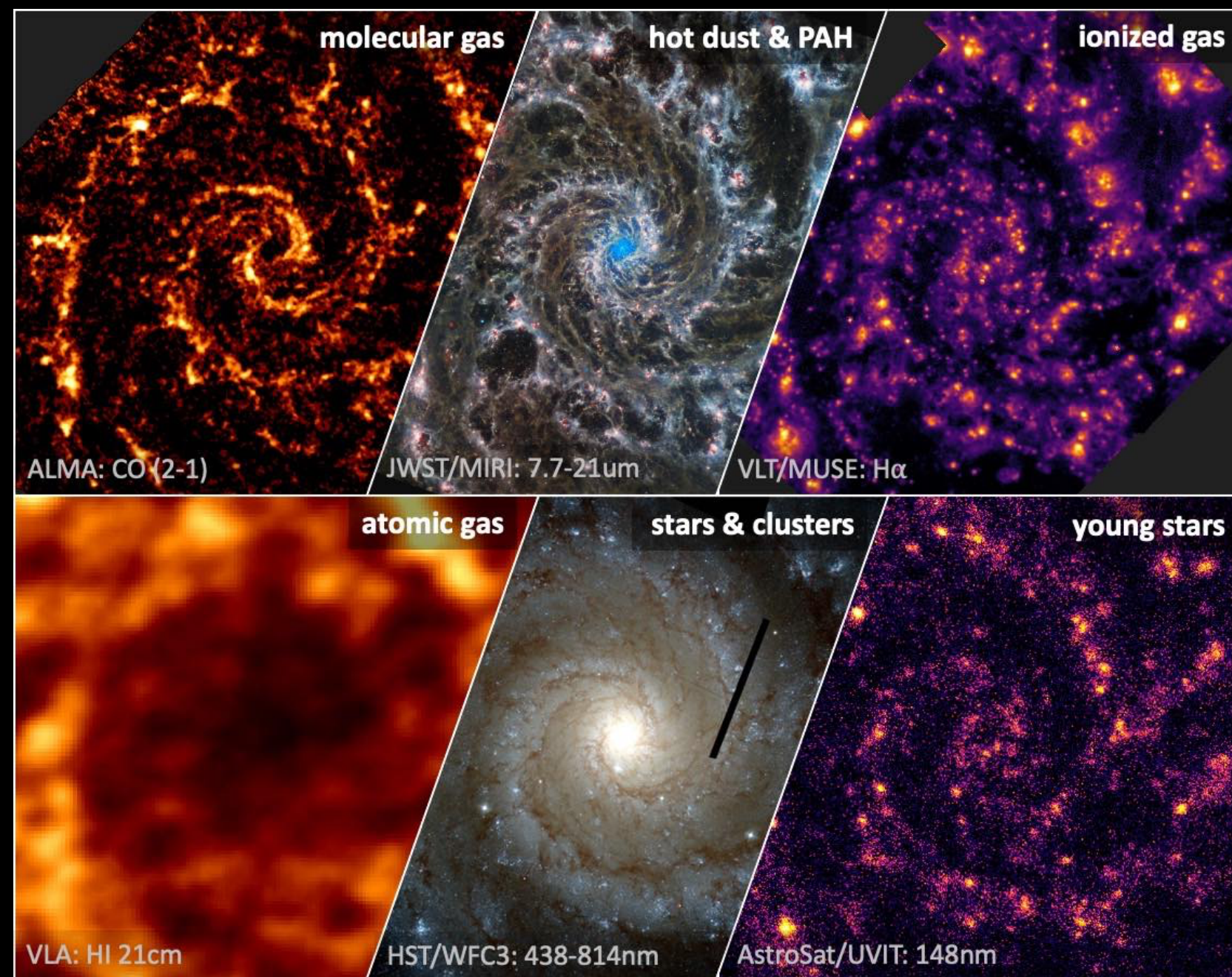
Assuming **chemical and thermal equilibrium** a characteristic HI column density required to shield H₂ can be derived.

Models based on Krumholz et al. 2008, 2009b; McKee & Krumholz 2010

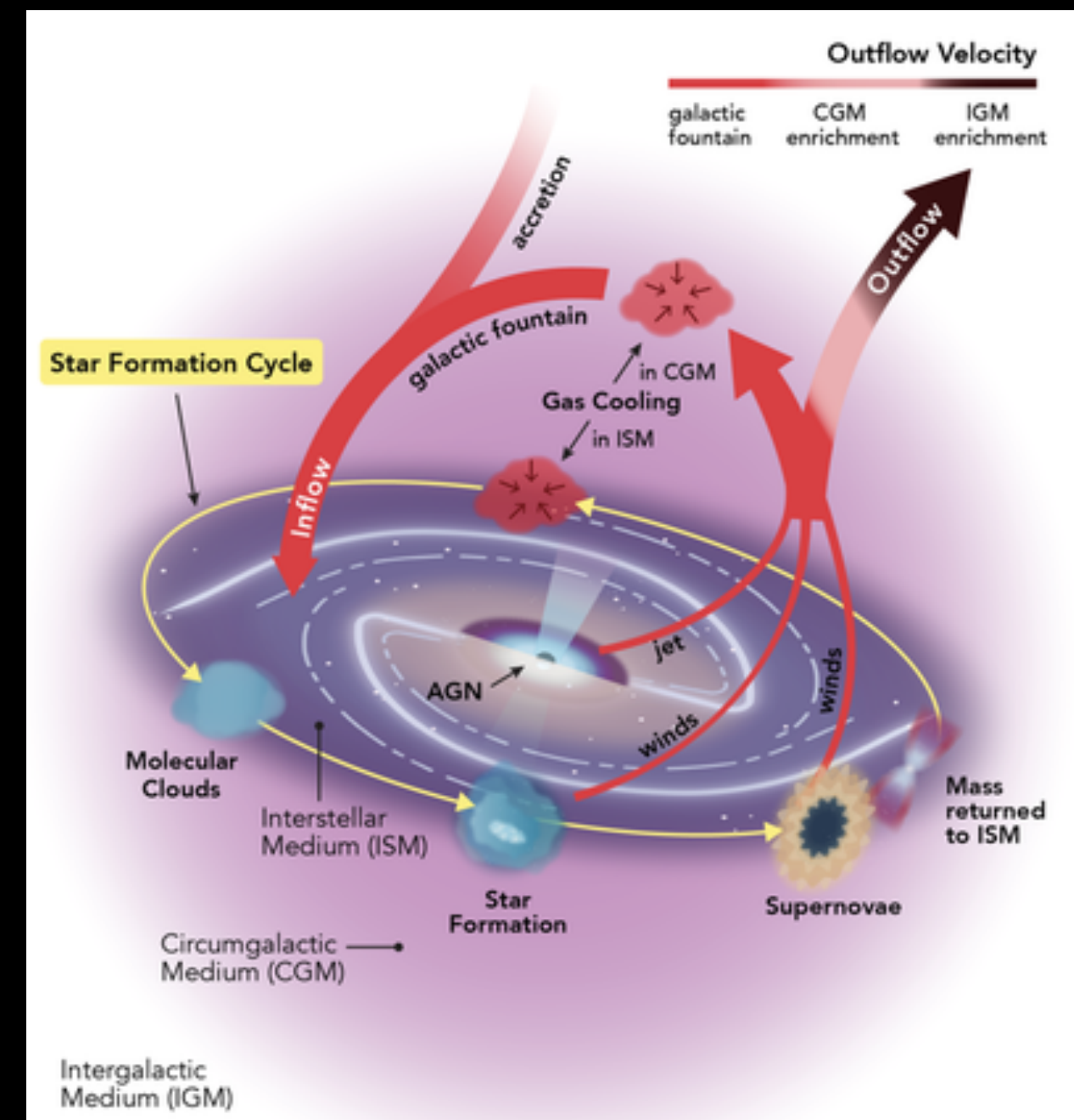


What does the extended fraction of CNM in the outer galaxy mean for star formation?

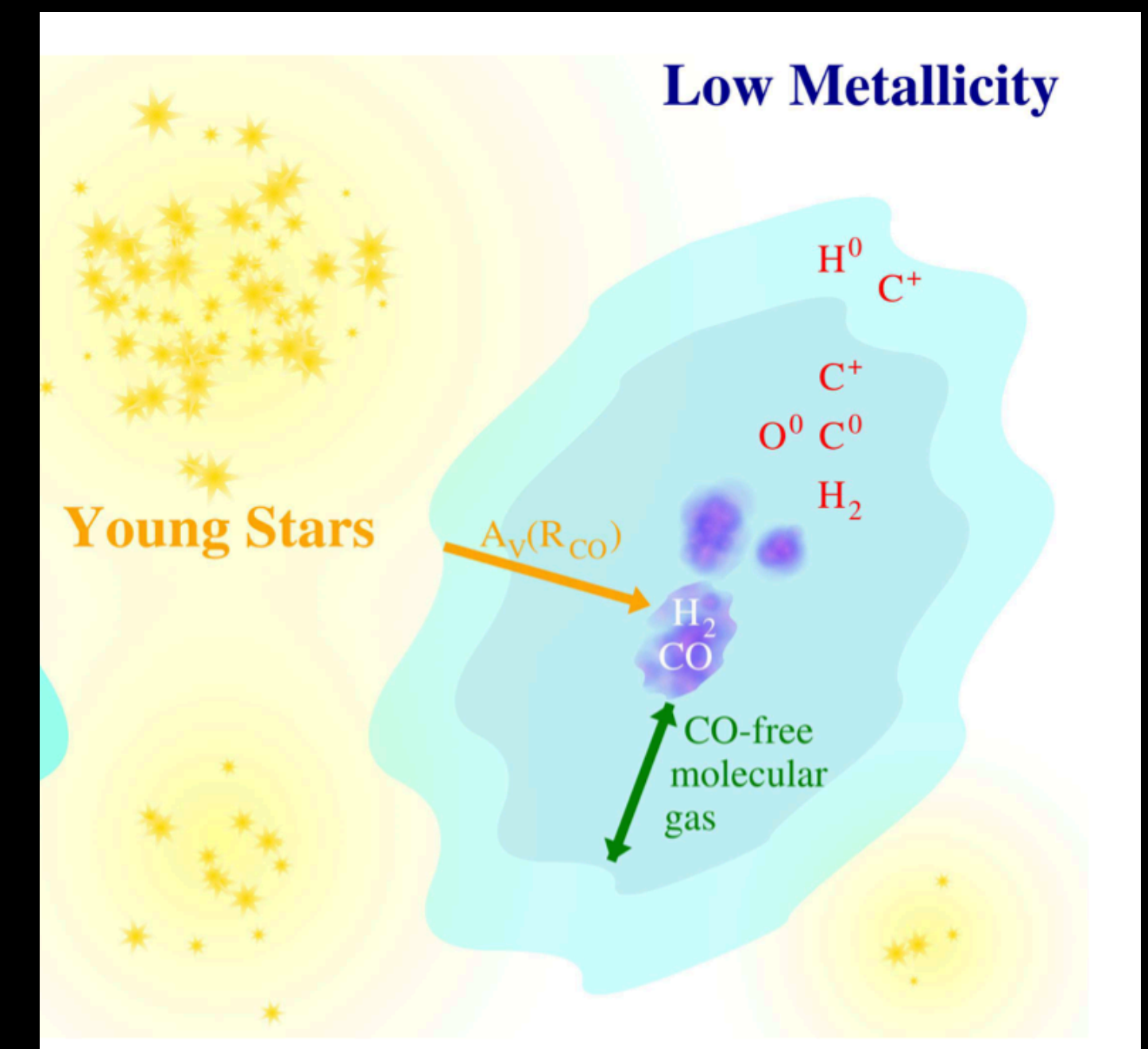
Linked questions:



What is the distribution of the CNM across galaxies?



What are the distribution and fraction of the thermally unstable HI?



How does star-formation proceed in low metallicity, dwarf galaxies with large amounts of CO-dark gas and HI?

“... the bottom line is that the ideas are useful, the geometry is wrong, and the details trouble me ...”

- Cox, 2005