ALESSANDRO LUPI

Università degli Studi dell'Insubria - Como

The impact of a consistent of cosmic ray propagation on the chemistry of pre-stellar cores

Cosmic Rays 3: the salt of the star-formation recipe

in collaboration with:

G. Latrille, S. Bovino, T. Grassi, G. Sabatini, and M. Padovani

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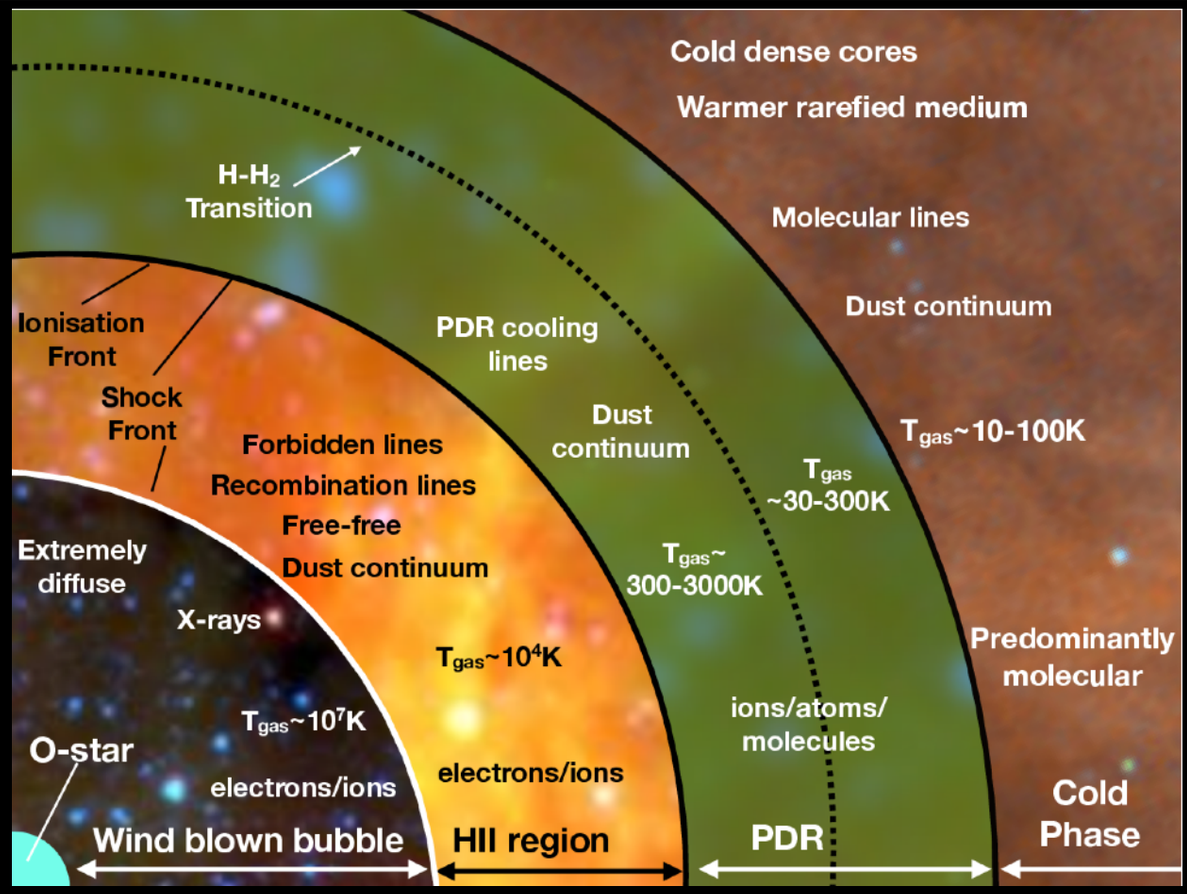
Introduction

Radiation is a fundamental component of the interstellar medium, as it affects the gas thermodynamics and the formation of stars and planets around them.

The densest regions of the interstellar medium are the so-called molecular clouds (MCs).



As we move deep into them, we observe filaments and clumps, which culminate in the pre-stellar cores, characterised by low temperatures (~10 K) and high densities ($>10^4$ cm^{-3}).

At these column densities, most of the radiation is absorbed, but for X-rays (potentially) and cosmic rays, the latter representing the main ionising agent in these conditions, triggering ion-neutral reactions

Introduction

Similarly to electromagnetic radiation, cosmic rays are also attenuated by the gas. Modelling such attenuation, and its impact on the gas thermochemistry, is therefore crucial to properly describe the evolution of MCs, filaments, and cores.

Modelling CR propagation and attenuation on-the-fly is complex, and is rarely applied on (sub-)MC scales, instead assuming:

1) a constant CR ionisation everywhere (sometimes exploring different values, see e.g. Bovino+19)

2) a semi-analytic attenuation prescription applied on-the-fly or in post-processing to numerical simulations (see, e.g., Lupi+21)

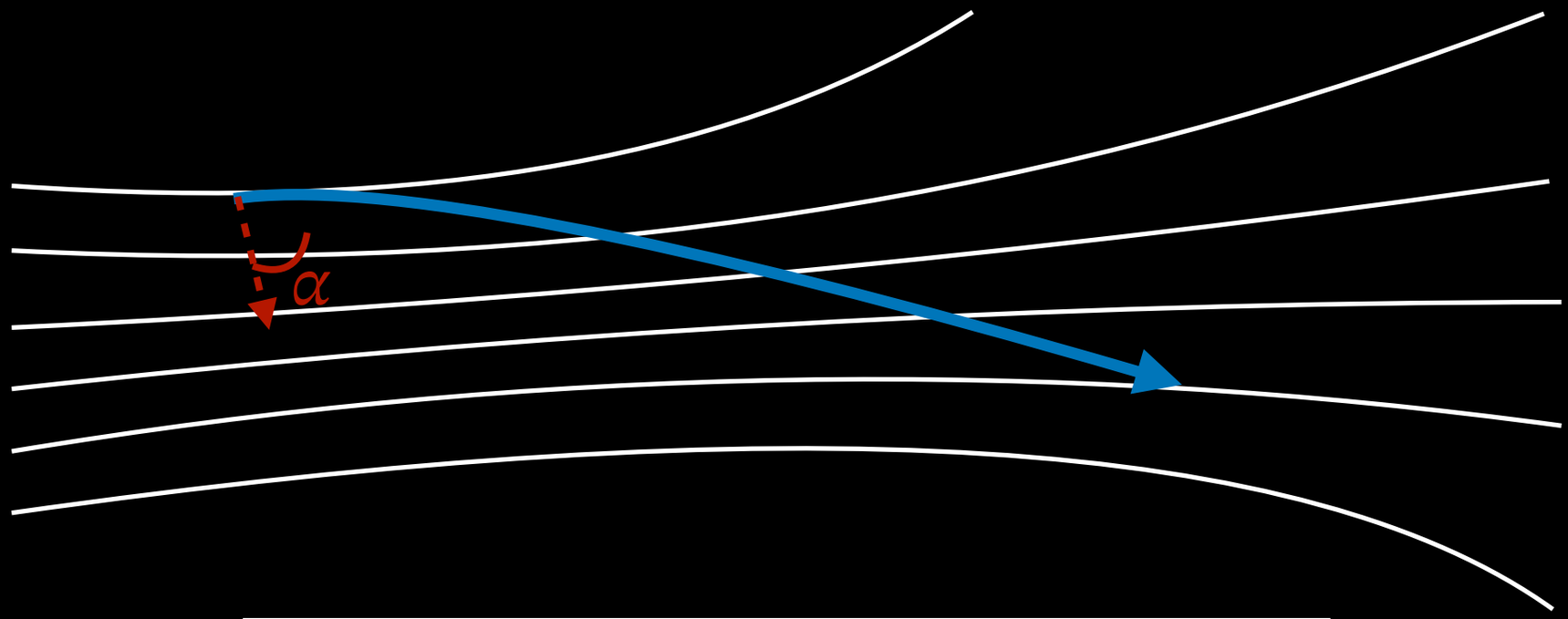
Recently, more accurate models have been developed, which assume CRs as a secondary fluid, but such approach is still expensive, as they require MHD+thermochemistry+CRs.

For pre-stellar cores, we can instead rely on a simpler approach, which propagates CRs in post-processing and then applies the attenuated distribution to a consistent chemical evolution.

A consistent CR propagation scheme

(Latrille, AL, et al. submitted)

Given the much higher propagation speed of CRs compared to the fluid (v~c), we assume their propagation on a core scales occurs almost instantaneously, and build a propagation scheme that can be applied on single simulation outputs in post-processing



$$N_{\rm eff}(\mathbf{x}', \alpha) = N_{\rm eff}(\mathbf{x}, \alpha) + \frac{n(\mathbf{x}')\Delta\ell_k}{\sqrt{1 - B_k(\mathbf{x}')\sin^2(\alpha)/B_{k,0}}}$$

$$\zeta_2(\mathbf{x}') = \delta(\mathbf{x}') \int_0^{\pi/2} f\left[N_{\rm eff}(\mathbf{x}', \alpha)\right] \sin\alpha \, \mathrm{d}\alpha$$

A consistent CR propagation scheme

(Latrille, AL, et al. submitted)

Structure of the scheme:

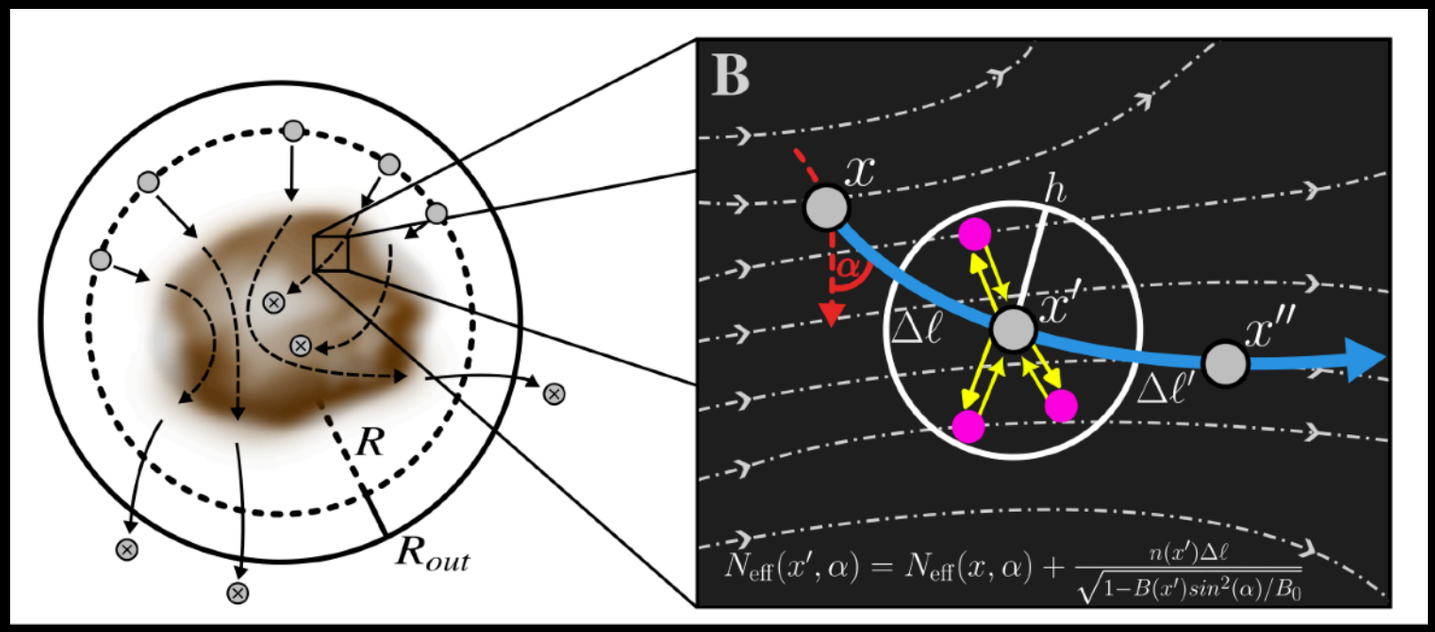
- TP generation (outside the region of interest) =>
  initial trajectory, gas column density, and pitch angle distribution

- TP propagation across the domain for each pitch angle (until $N>N_{max}$ or $R>R_{out}$)

  - "grid" interpolation at x' (kernel smoothing)

  - Update N_{eff} (and ζ_2) for each pitch angle

  - Sum of ζ_2 over all pitch angles and deposition onto the "grid"



Model benchmark: a typical pre-stellar core

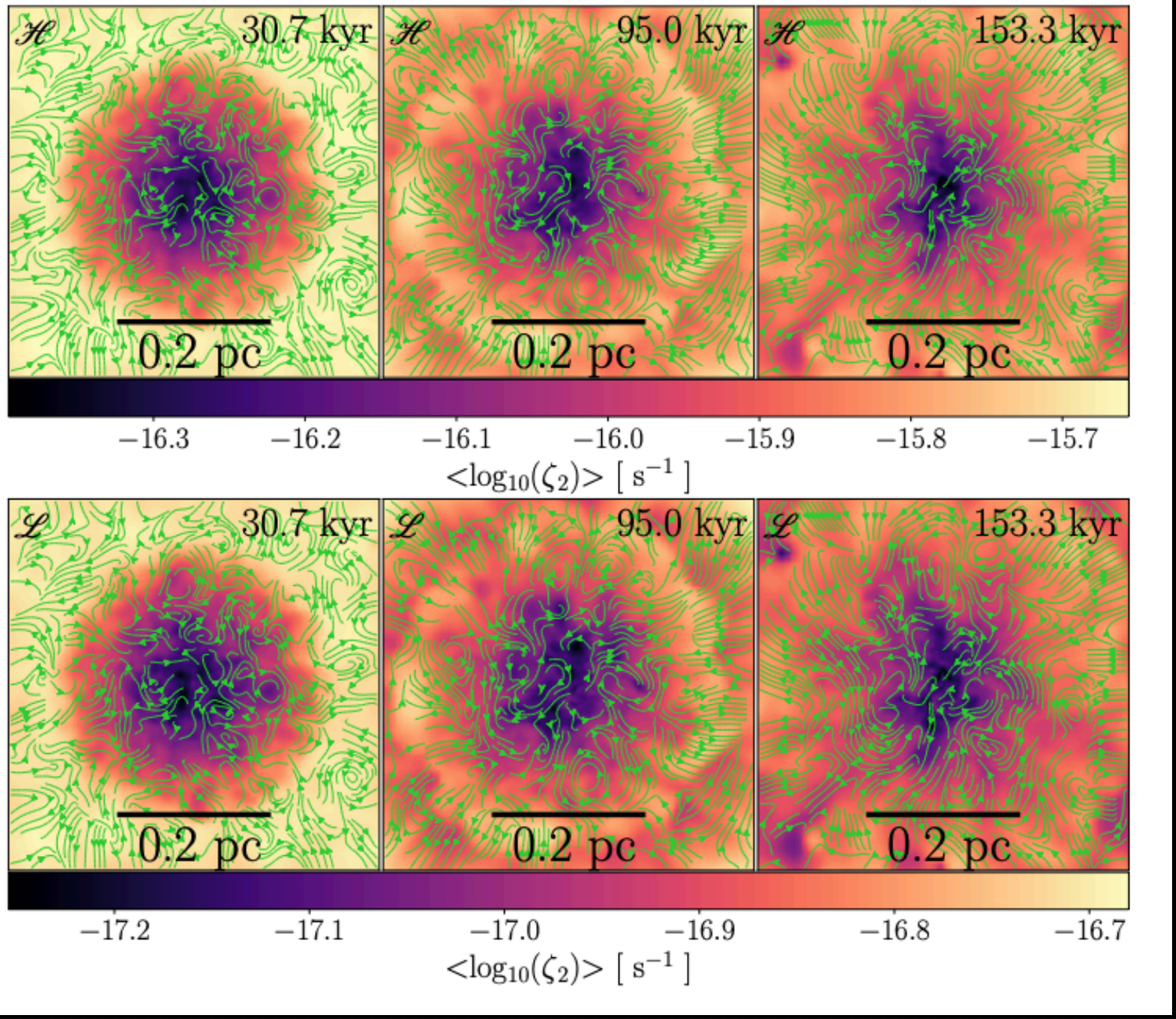
(Latrille, AL, et al. submitted)

We considered the M1 pre-stellar cores simulated in Bovino+19 (including **AL**).

	M_{BE} ($M_\odot$)	R_{BE} (pc)	α_{vir}	$\mathcal{M}$	$\langle B \rangle$ (μG)	M_J	t_{ff} (kyr)	n_0 (cm^{-3})	$\langle n \rangle$ (cm^{-3})
M1	20	0.17	4.32	3	46	5	260	1.81×10^5	2.21×10^4

Two CR attenuation models:

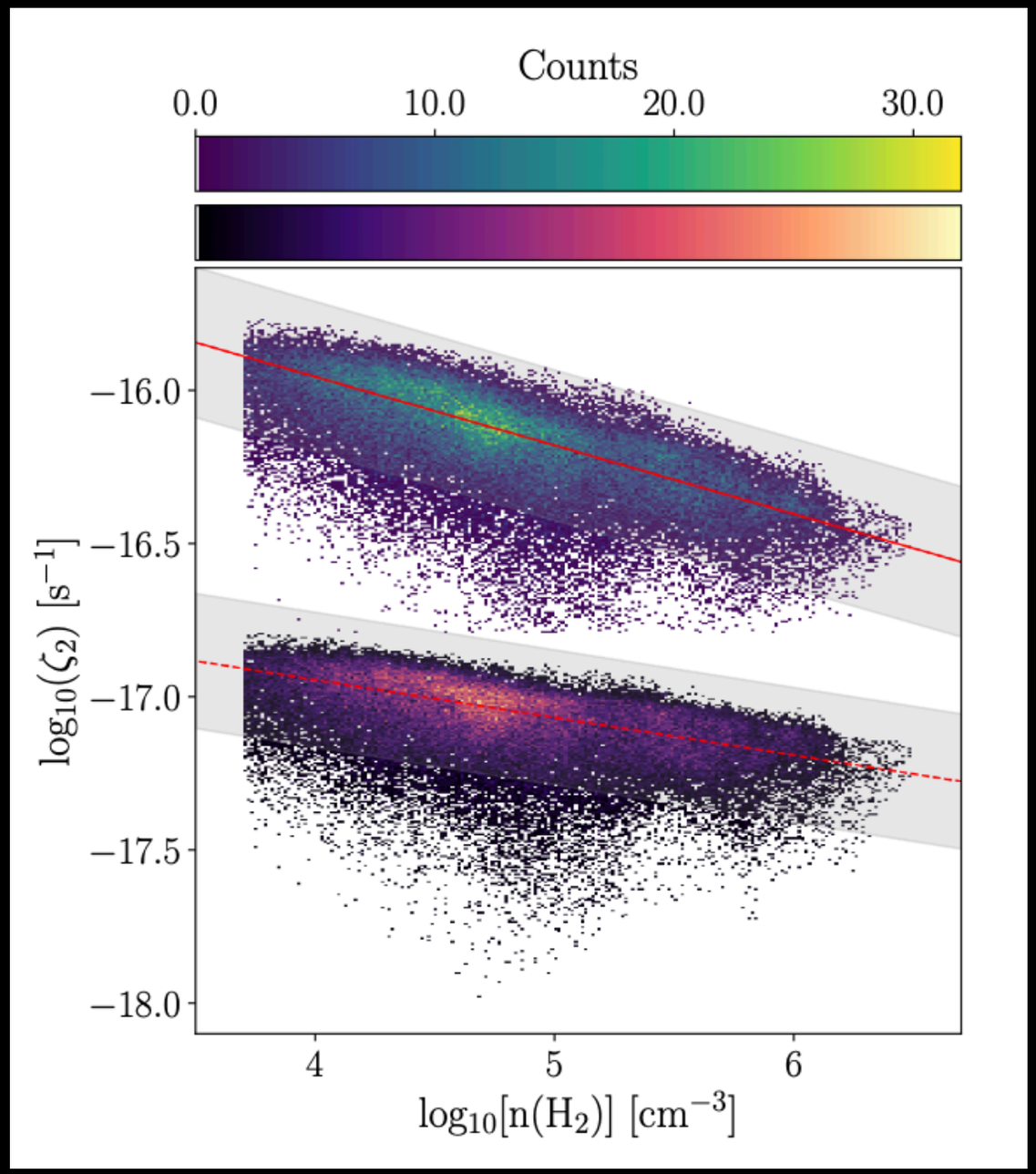
$\mathscr{H}$ and $\mathscr{L}$ (Padovani+ 2022)



Chemical post-processing: the CRIR-nH2 relation

(Latrille, AL, et al. submitted)

Given the isothermal conditions of the core, chemical evolution can be performed in post-processing. By using the scheme in Ferrada-Chamorro, **AL**+21, we determined the impact of CR propagation on the chemical evolution of the core across time.

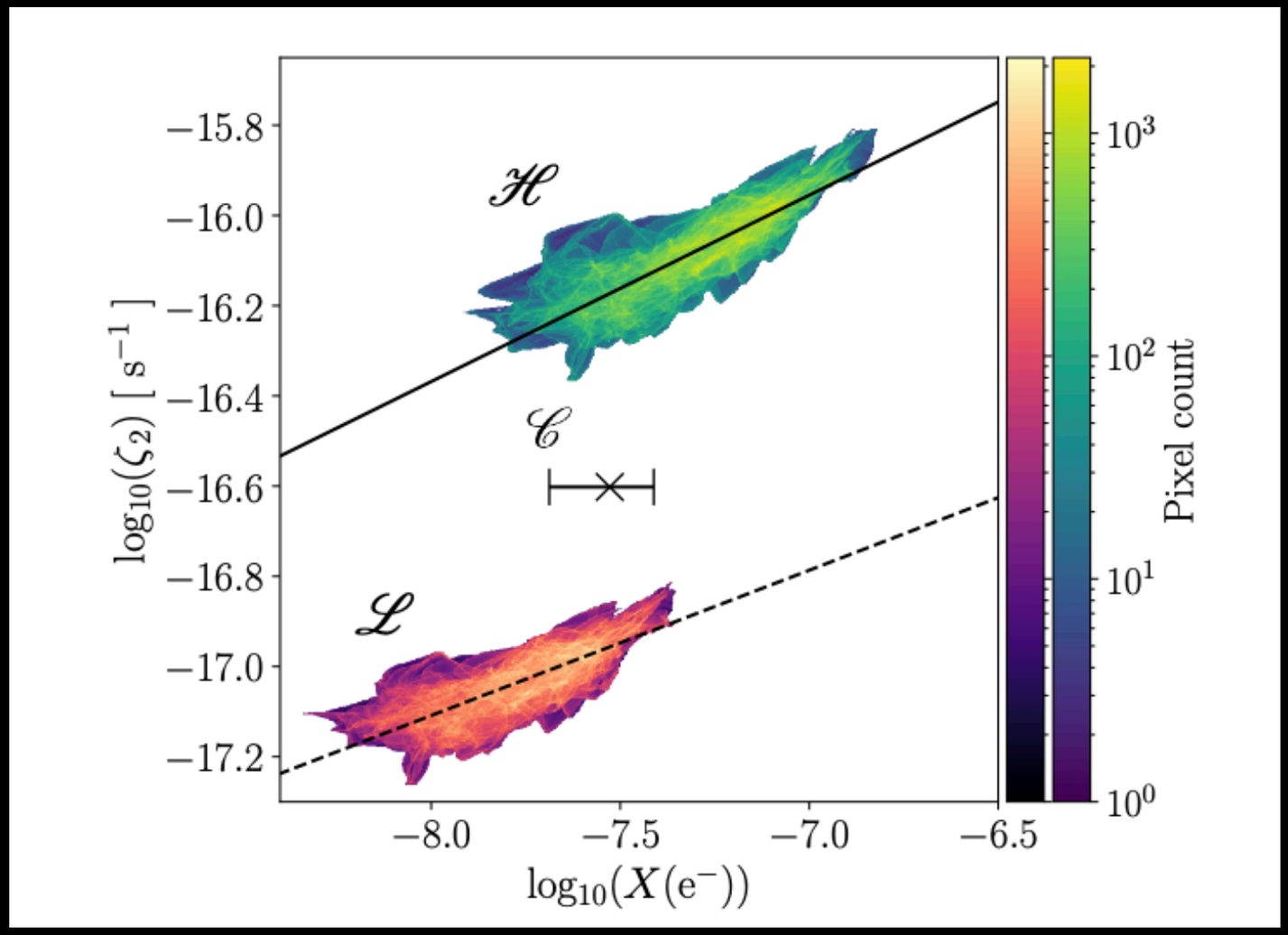


$\log_{10}\zeta_2^{\mathscr{H}} = -0.22\log_{10}n(H_2) - 15.06$	$\sigma^{\mathscr{H}} = 0.25$
$\log_{10}\zeta_2^{\mathscr{L}} = -0.12\log_{10}n(H_2) - 16.45$	$\sigma^{\mathscr{L}} = 0.22$

Chemical post-processing

(Latrille, AL, et al. submitted)

We can also relate the CRIR to the electron abundance. This has important implications for observations, as it can be used in combination with indirect methods used to infer the CRIR



$$\log_{10}\zeta_2^{\mathscr{H}} = 0.41\log_{10}X(\mathrm{e}^-) - 13.06$$

$$\log_{10}\zeta_2^{\mathscr{L}} = 0.32\log_{10}X(\mathrm{e}^-) - 14.53$$

Simulation vs indirect measure of chemical abundance

(Latrille, AL, et al. submitted)

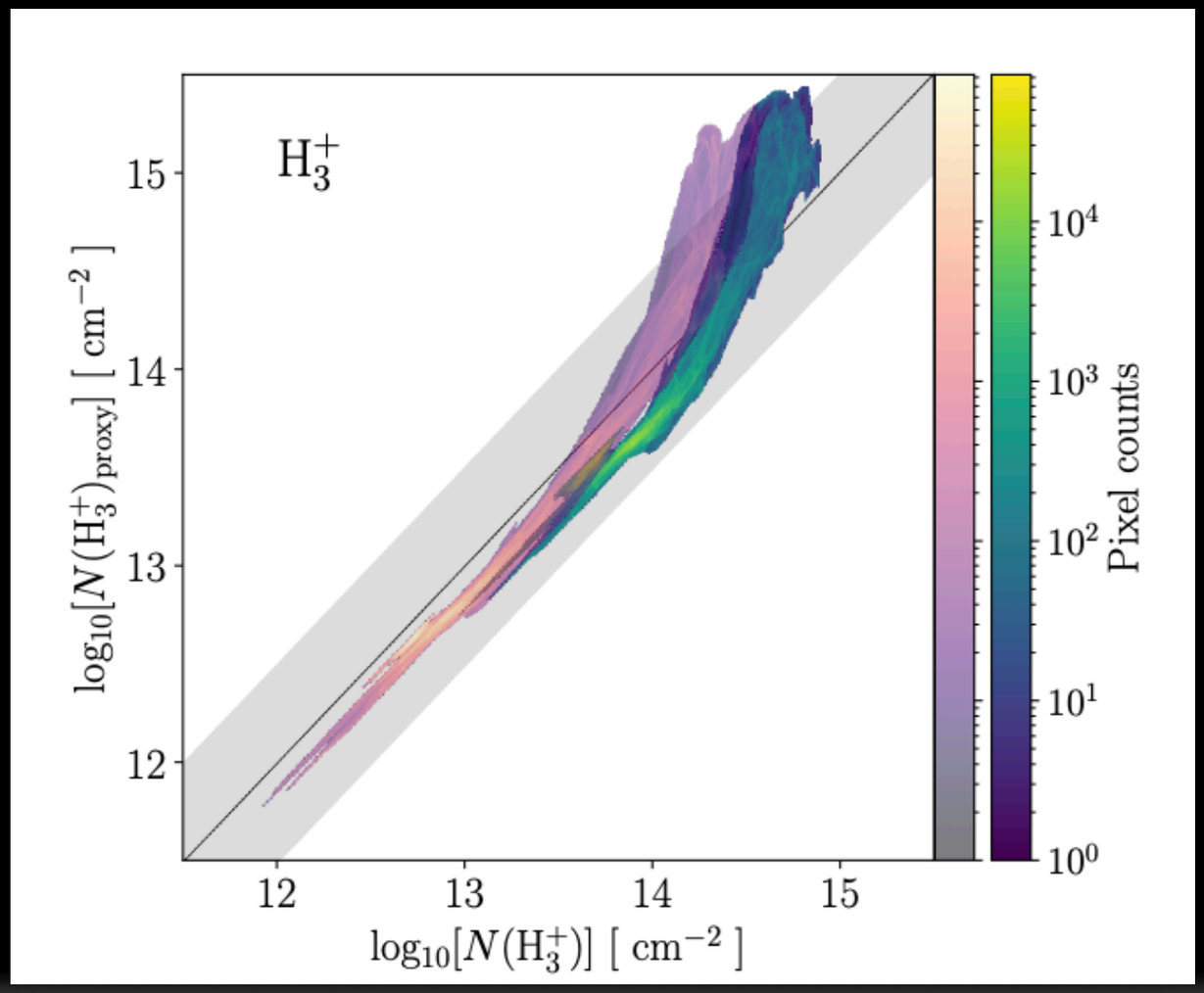
For instance, we are now in the position to compare the accuracy of the Bovino+20 (including **AL**) method with our results.

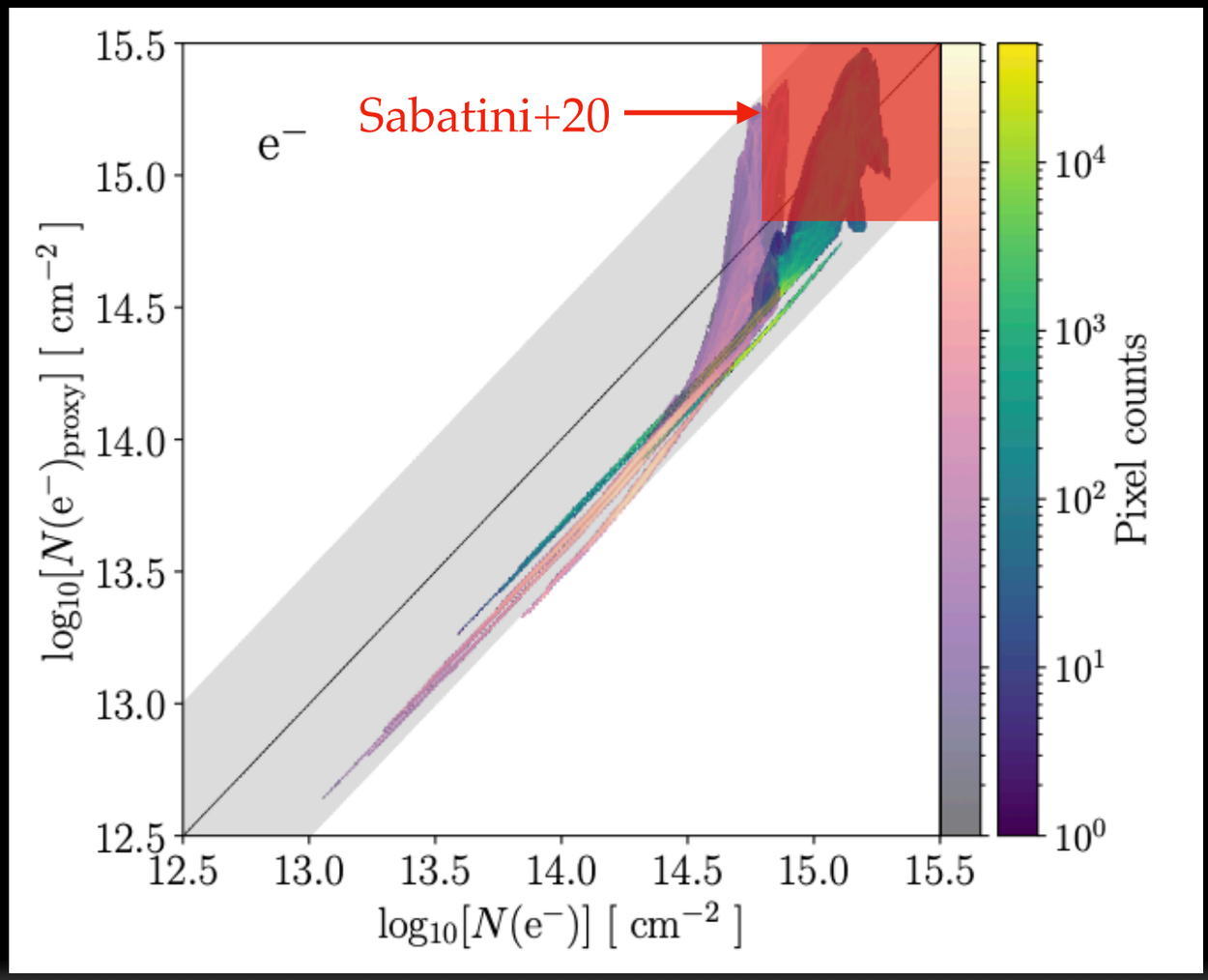
We start by comparing N($H3^+$) and N(e^-) in our simulated data with the proxies employed in observations:

$$N(\mathrm{H_3^+})_{\mathrm{proxy}} = \frac{1}{3}\frac{N(\text{o-}\mathrm{H_2D^+})}{R_{\mathrm{D}}} \quad \text{with} \quad R_{\mathrm{D}} = \frac{N(\mathrm{DCO^+})}{N(\mathrm{HCO^+})}$$

AND

$$N(\mathrm{e^-})_{\mathrm{proxy}} = N(\mathrm{DCO^+}) + N(\mathrm{HCO^+}) + N(\mathrm{N_2D^+}) + N(\mathrm{N_2H^+}) + N(\mathrm{H_3^+})_{\mathrm{proxy}}.$$





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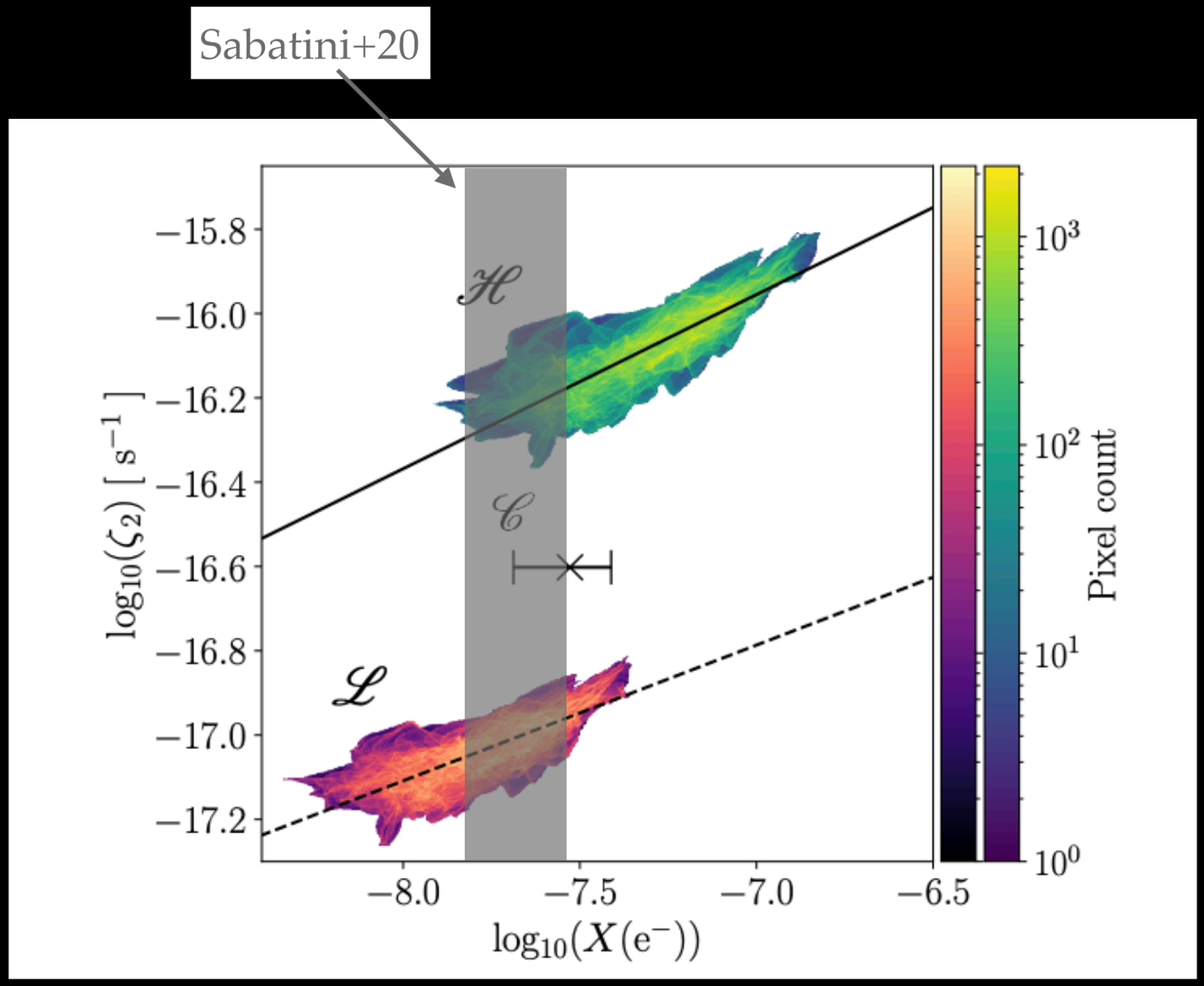

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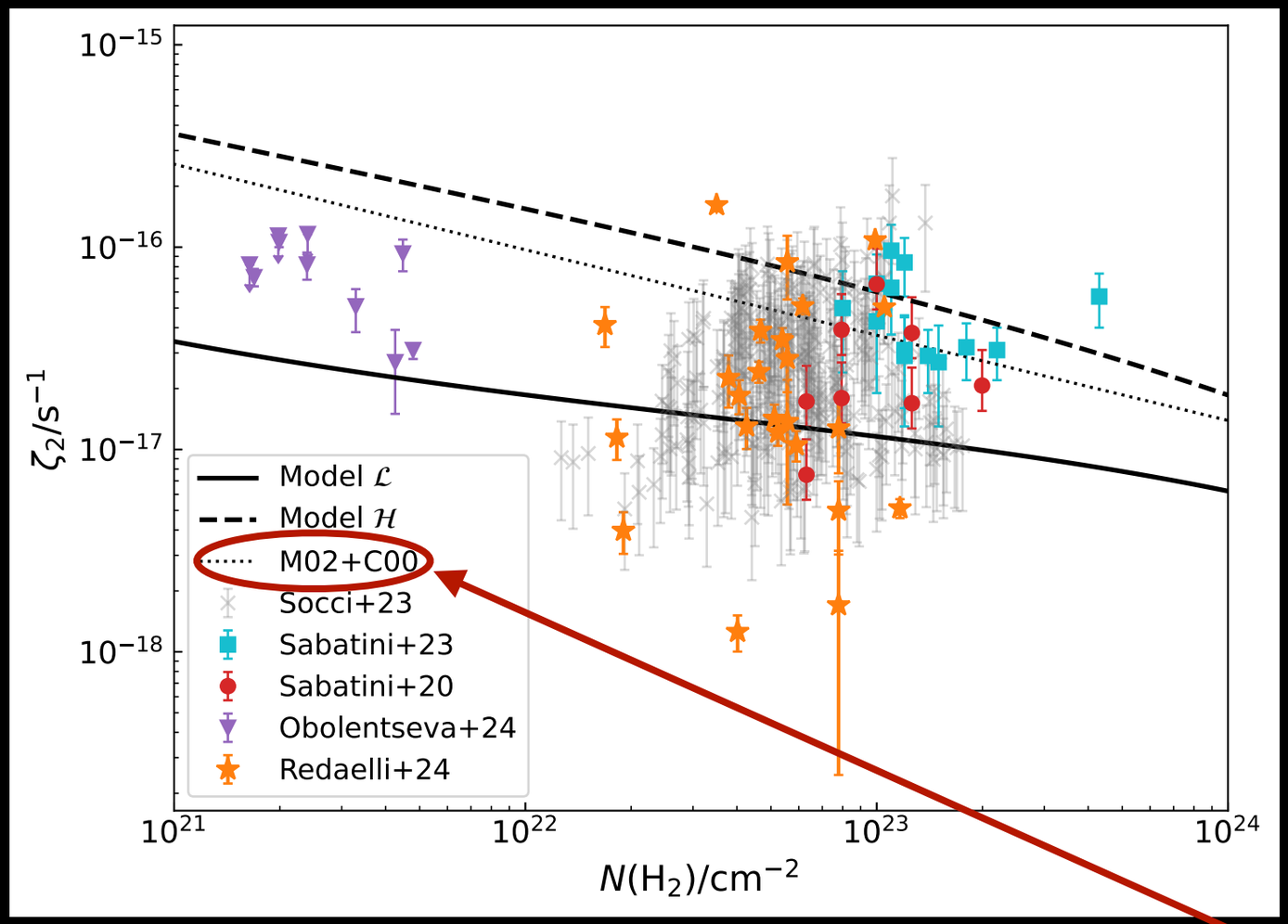
See Gonzalo Latrille's poster for more results

What's next

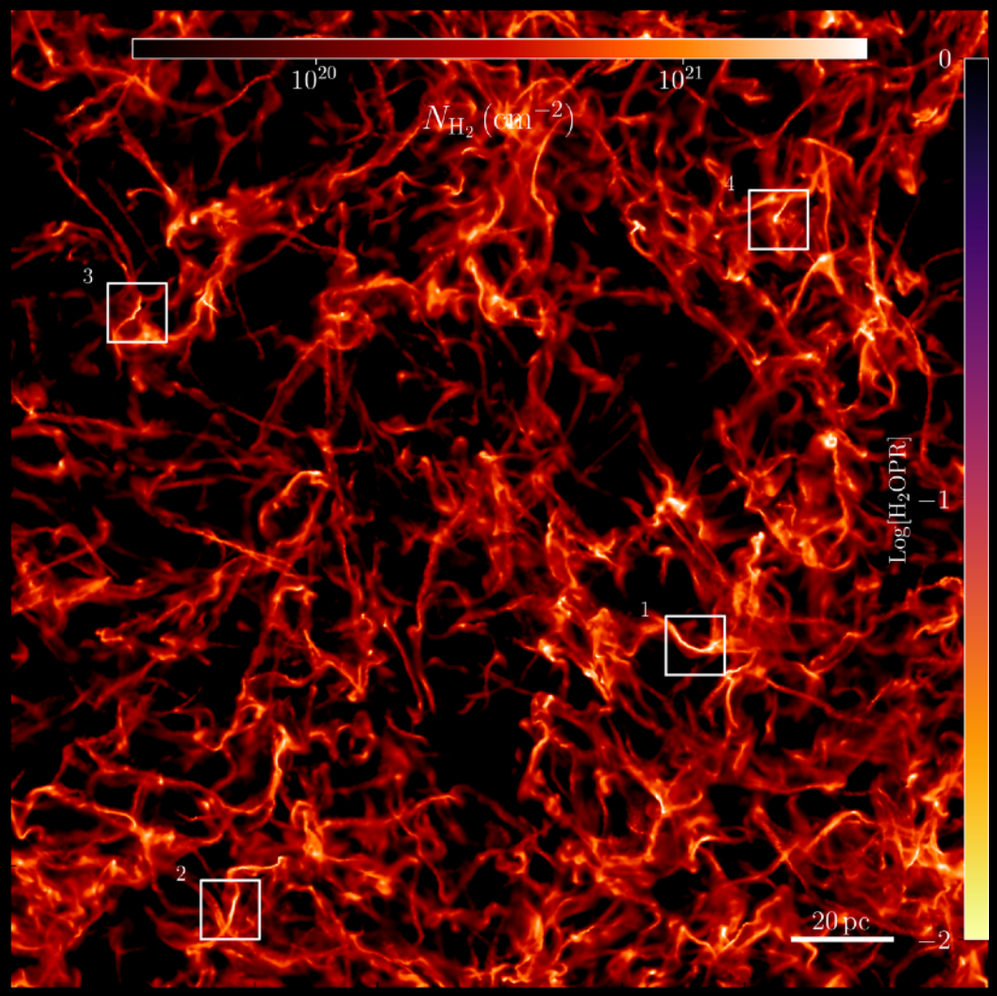
New observations have highlighted a bias in the previous estimate of $n(H_2)$ of diffuse clouds (Neufield+24).

$n(H_2)_{new} < n(H_2)_{old}$ => lower CRIR (in between models $\mathscr{H}$ and $\mathscr{L}$)

This result has been also reported by Obolentseva+24.



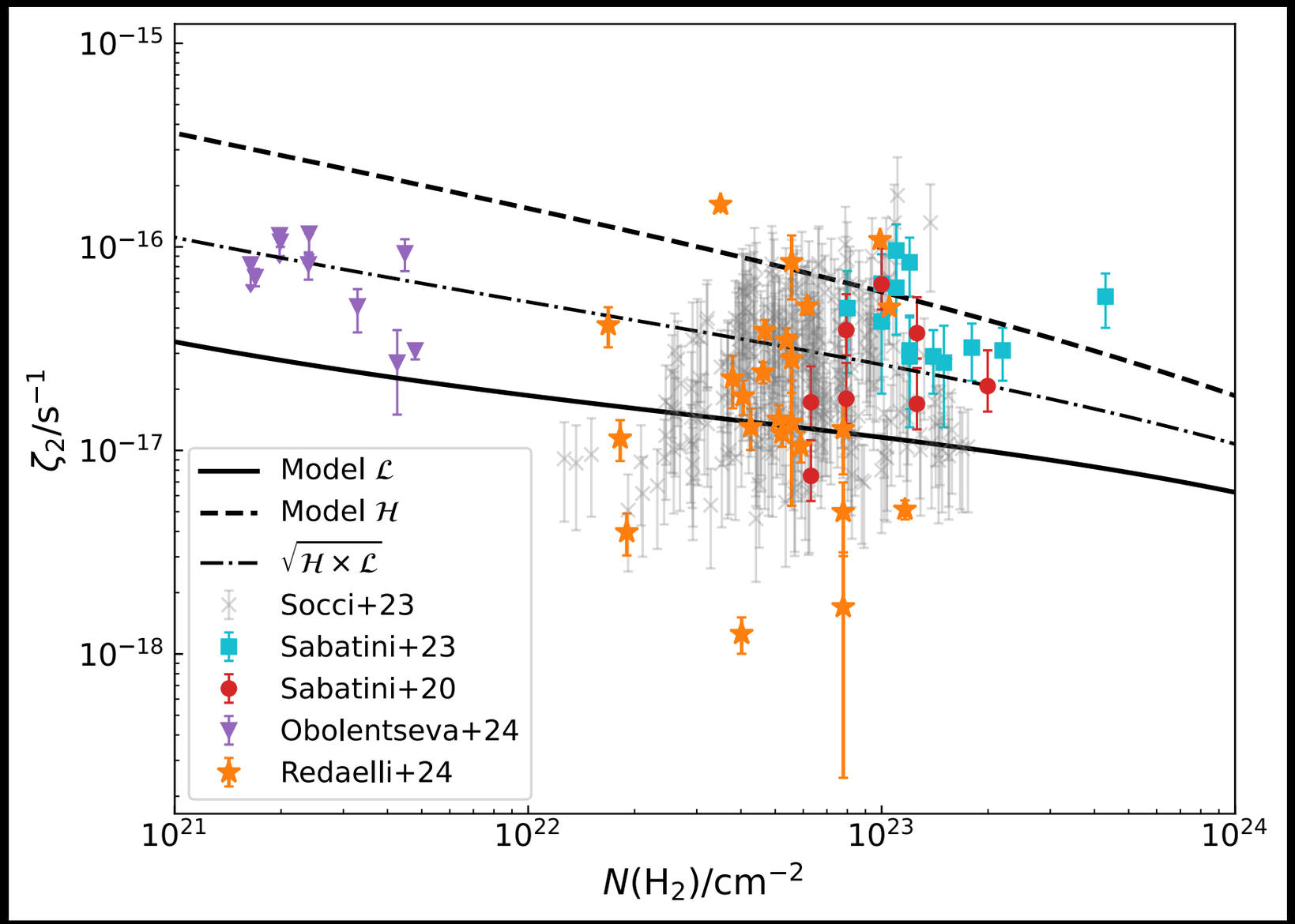
Courtesy of E. Redaelli



Intermediate curve employed in Lupi+21

What's next (preliminary)

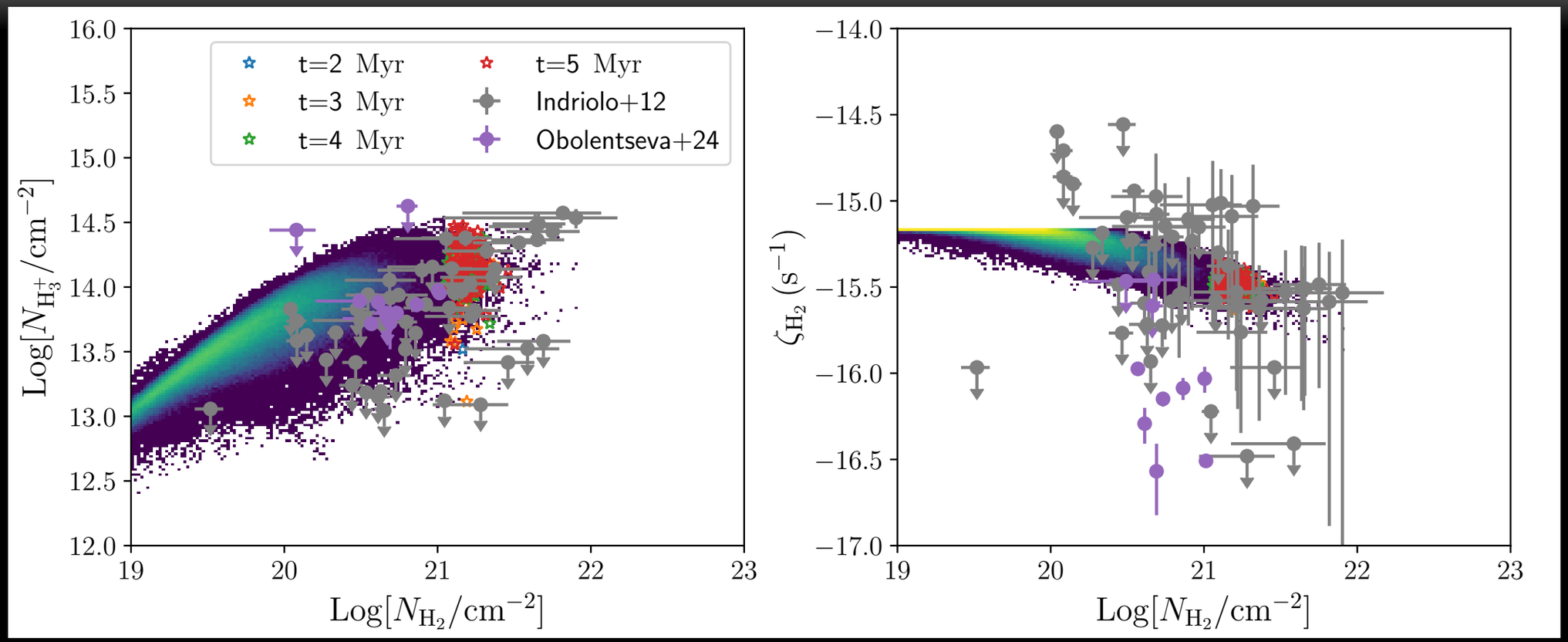
Interestingly, the geometric average of the $\mathscr{H}$ and $\mathscr{L}$ models (Padovani+22) seems consistent with the data. We have thus rerun the simulation from Lupi+21 with this new CRIR function, finding a better agreement with the new data.



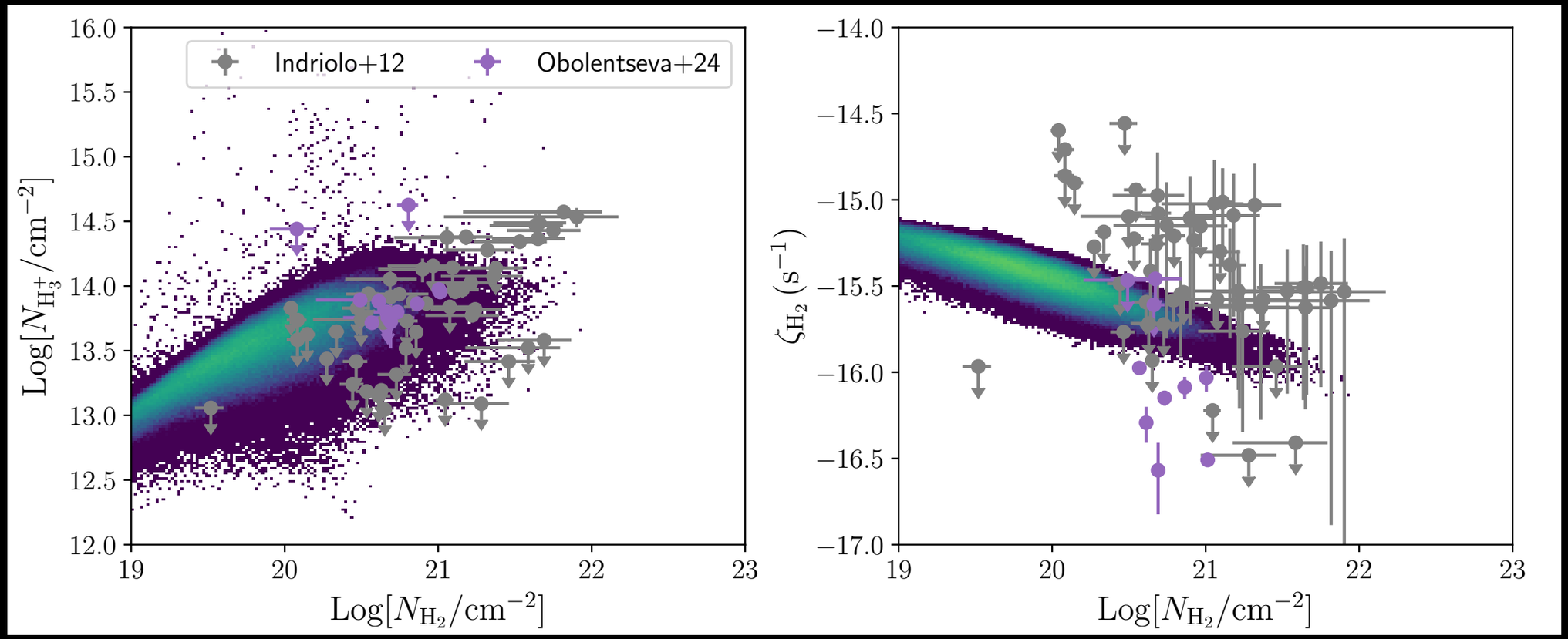
Courtesy of E. Redaelli

See Stefano Bovino's talk

What's next (preliminary)



Lupi+21



New run

Conclusions

We have developed a post-processing propagation scheme for CRs that can be used in combination with chemical post-processing to better model the chemical evolution of simulated pre-stellar cores.

By applying this scheme to the M1 case in Bovino+19:

1) we have verified again the validity of the Bovino+20 model to infer the CRIR from observations.

2) we have fitted a simple relation between the CRIR and the electron fraction that can be directly applied to observations to estimate the electron abundance, which is not directly probed by the Bovino+20 formula

3) in the light of recent results pointing to a lower H2 density (and CRIR) in diffuse clouds, we have rerun the Lupi+21 simulation, finding very good agreement with new observations.

In the near future, we will explore the CR propagation on molecular cloud scales, and we will calibrate corrected formulae to include CR attenuation in numerical simulations.