CHEX-MATE: X-ray absorption and molecular content of the Interstellar Medium toward galaxy clusters

H. Bourdin, on behalf of the CHEX-MATE collaboration

$$\boxed{I(e) = I_o(e)\exp(-N_H \sigma_{ISM}(e))}$$

$$N_H = N_{HI} + 2N_{H_2}$$

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{molecules} + \sigma_{dust}$$

σ_{gas} $\sigma_{molecules}$ photoionisation cross sections

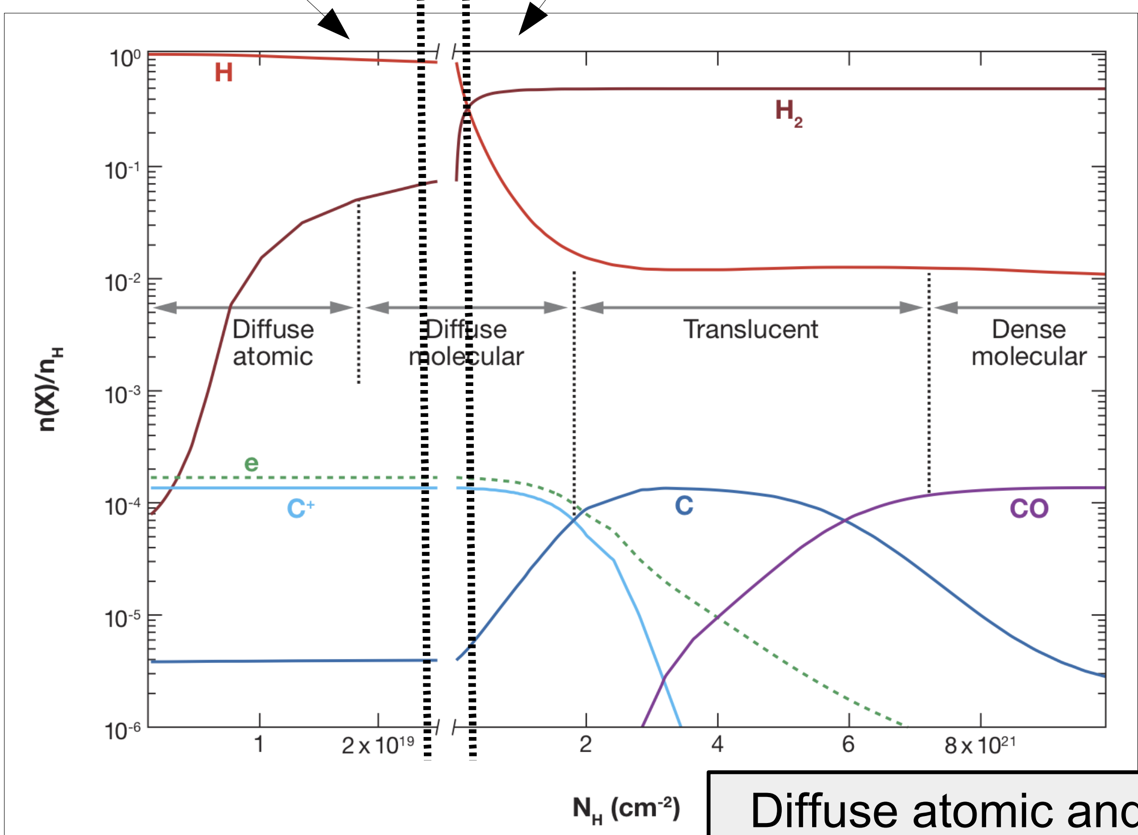
σ_{dust} photoabsorption cross sections

- A *Planck*+HI4PI view of hydrogen density column (N_H) toward CHEX-MATE clusters
- Modelling the ISM cross sections (σ_{ISM})

$$f = \frac{2N_{H_2}}{N_{HI} + 2N_{H_2}}$$

CHEX-MATE
lines of sight

f<0.1 f>0.1



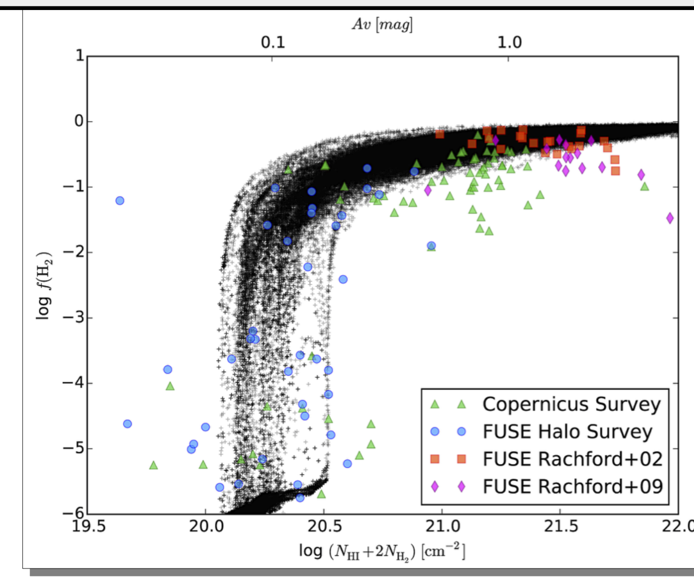
Diffuse atomic and molecular clouds (Snow & McCall, 06)

- Hydrogen transition in diffuse clouds:
  - H_2 formation: (Hollenbach, Werner & Salpeter, 71)

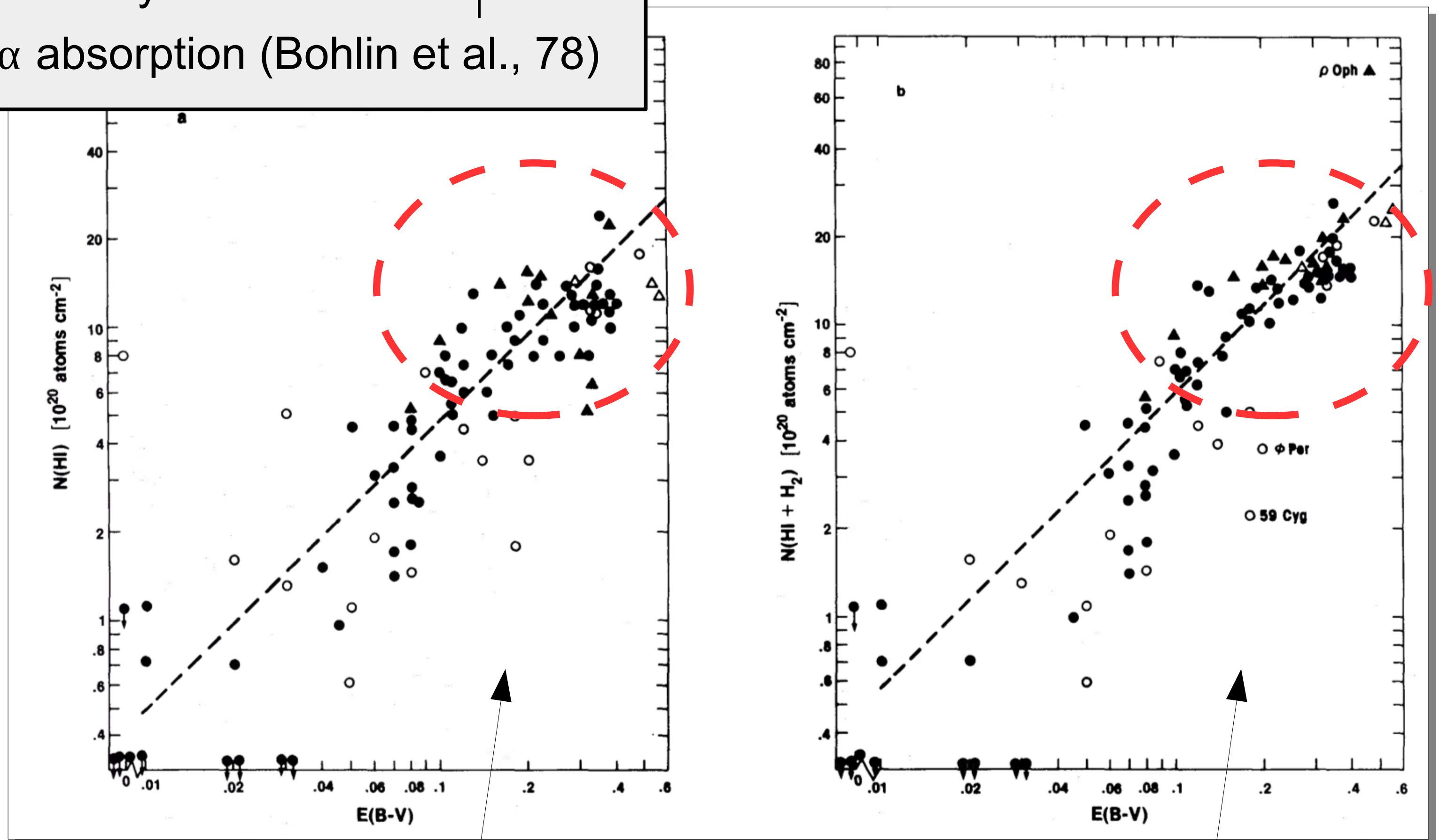
$$R_G = \frac{1}{2}\gamma \langle v_H \rangle n_g n_{HI} \langle \sigma_G \rangle$$
$$\propto n_H n_{HI}$$

  - H_2 destruction: photodissociation vs. self-shielding

H_2 distribution during molecular cloud formation (Valdivia et al., 16)



A survey of interstellar H_I from $L\alpha$ absorption (Bohlin et al., 78)

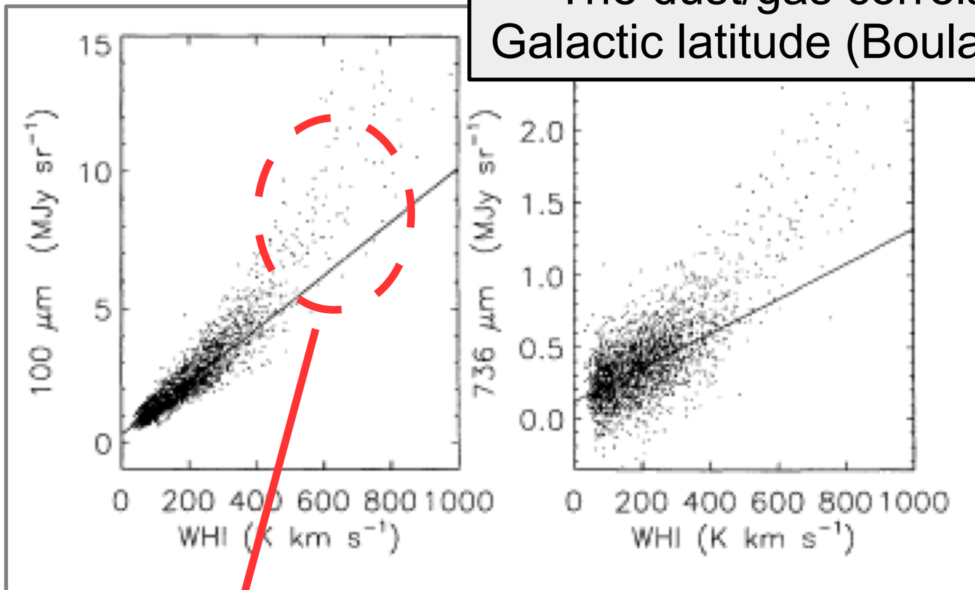


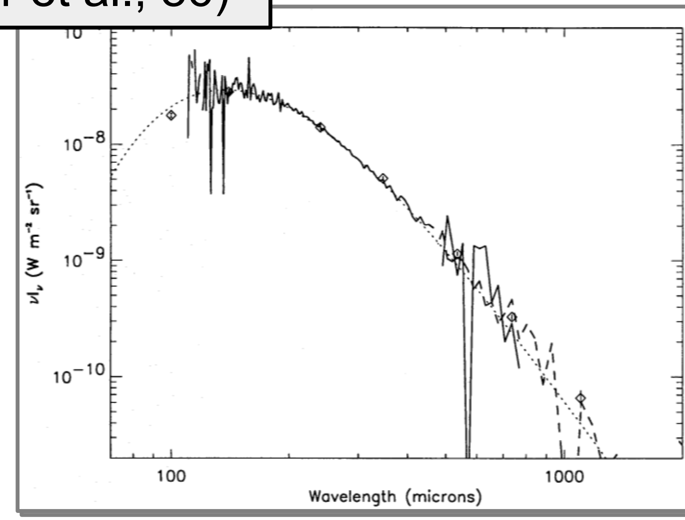
$N(H_I) = f(E(B\text{-}V))$

$N(H_I + H_2) = f(E(B\text{-}V))$

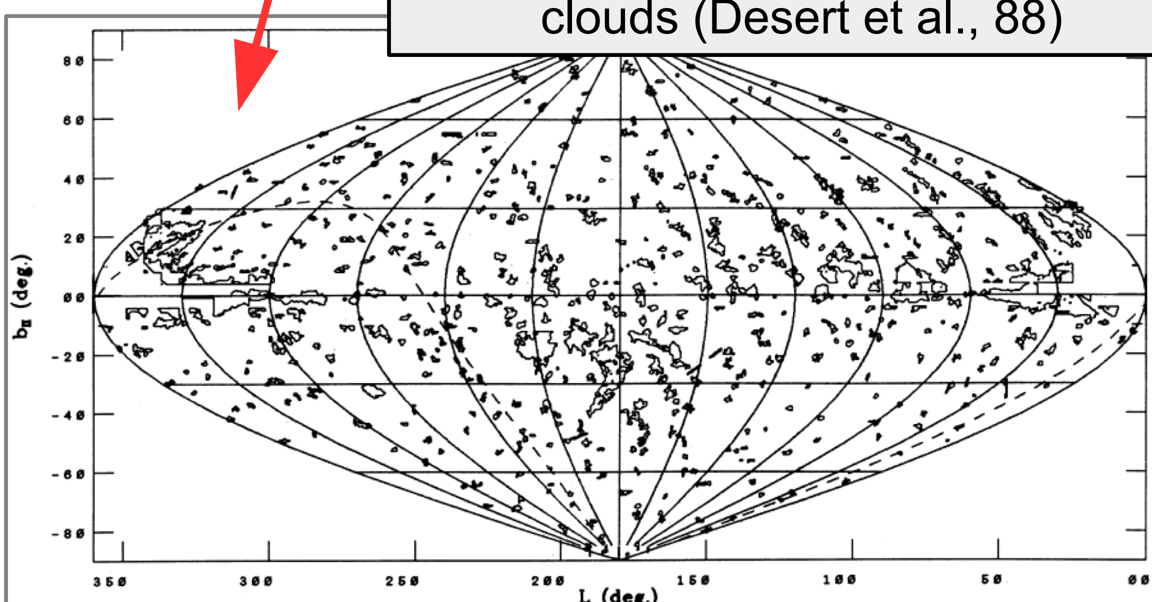
$\langle N(H_I + H_2)/E(B\text{-}V)\rangle = 5.8$ atoms cm^{-2} mag^{-1}

The dust/gas correlation at high Galactic latitude (Boulanger et al., 86)





An all sky search for molecular cirrus clouds (Desert et al., 88)



- HI-(dust emissivity) linear correlation at high Galactic latitude

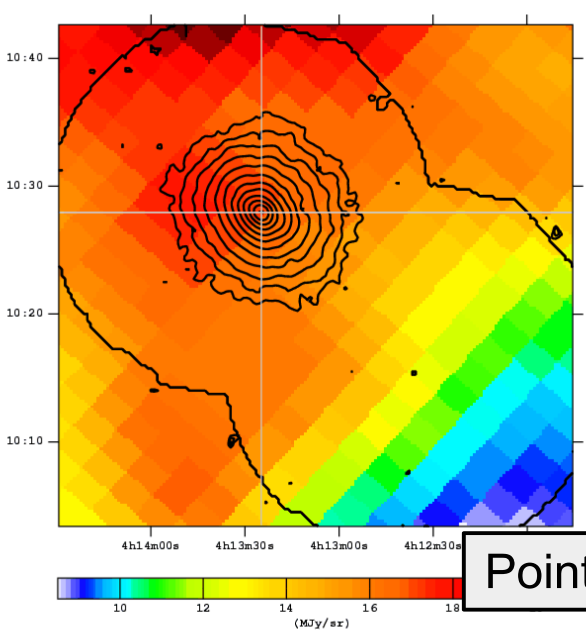
  (HI Leiden/Dwingeloo, DIRBE/FIRAS)

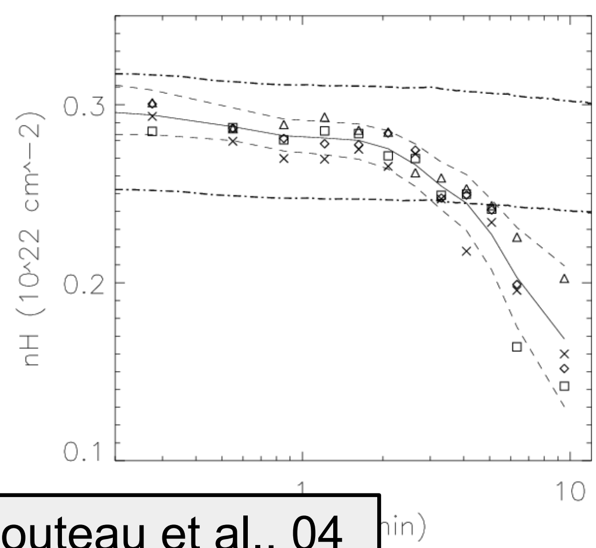
- Excess w.r.t. to the correlation traces molecular clouds

  (HI, IRAS)

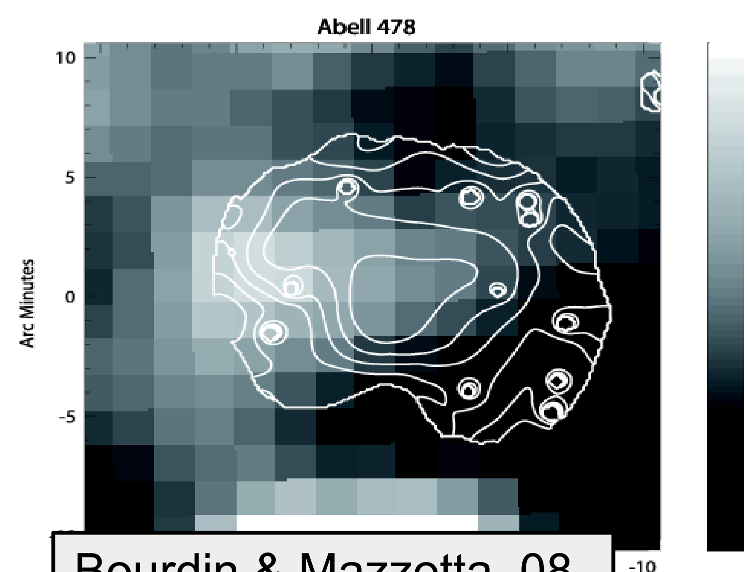
XMM-Newton observation of the relaxed cluster A478
Pointecouteau et al., 04

We considered the IRAS 100 m cleaned map of Schlegel et al. (1998). The Galactic hydrogen is correlated with the Galactic dust responsible for the IR emission, as shown by Boulanger et al. (1996) and Schlegel et al. (1998), who correlated COBE/DIRBE and IRAS data with the Leiden/Dwingeloo survey (Hartmann & Burton 1997). The correlation between the IR emission and the atomic hydrogen column density is determined from low N_H data (N_H <4.6 10^{20} cm^{-2}). Above this threshold an increasing dispersion is observed with higher IR/HI ratio on average. Boulanger et al. (1996) argued that this excess IR emission is due to dust associated with molecular hydrogen. The IR emission could thus actually be a tracer of the total hydrogen content. Assuming that the correlation determined at low values (where the H_2 fraction is expected to be small) is representative of this IR – total correlation, we converted the IR brightness map into a total map.



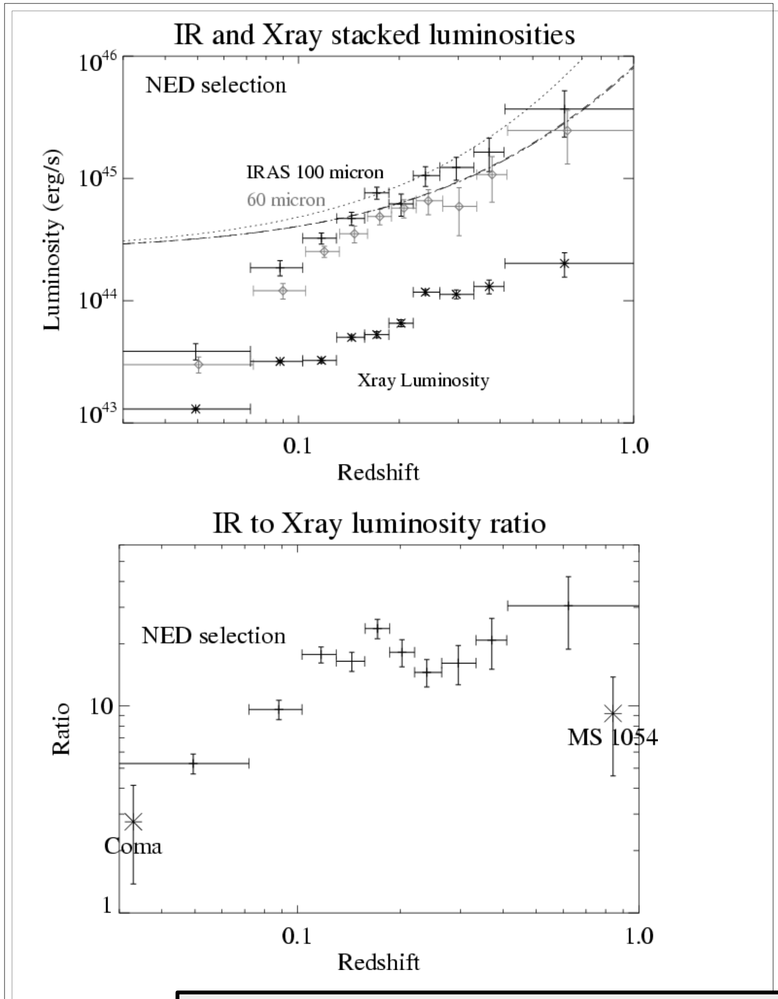


Pointecouteau et al., 04

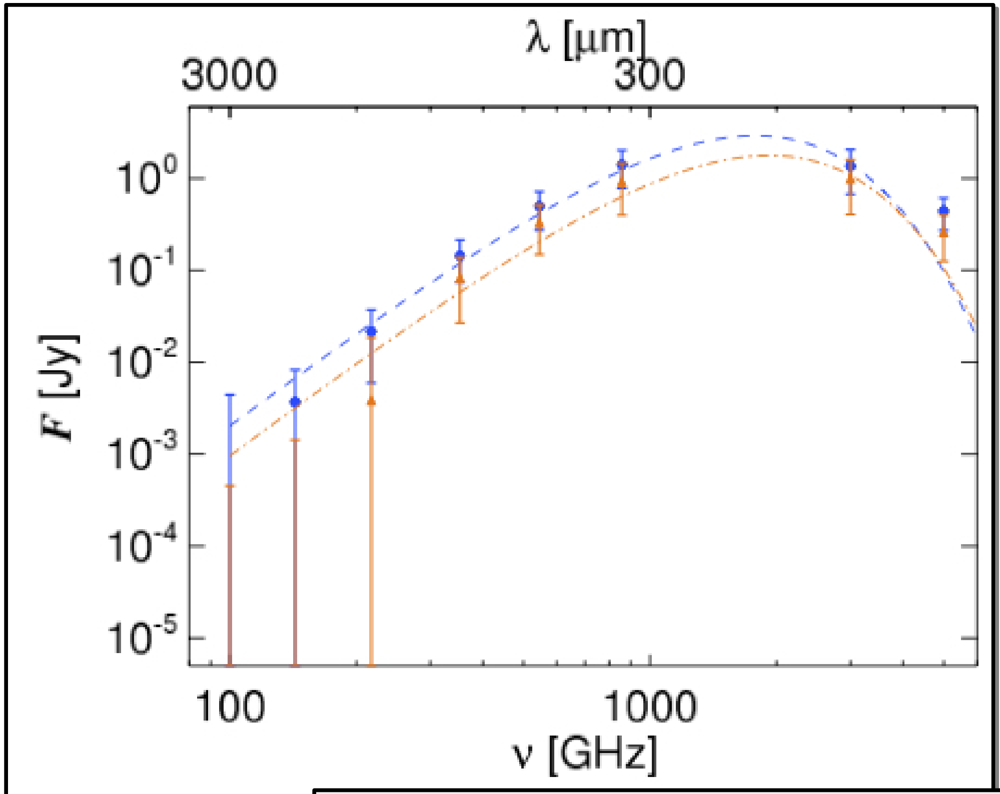


Bourdin & Mazzotta, 08

Stacked intra-cluster dust luminosity and SED as seen by IRAS and *Planck*

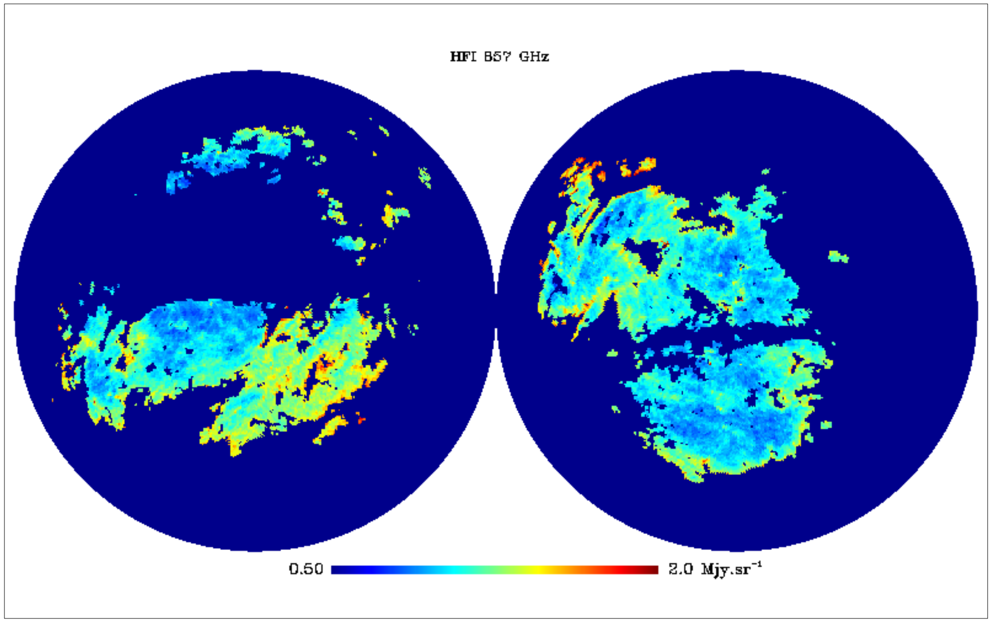


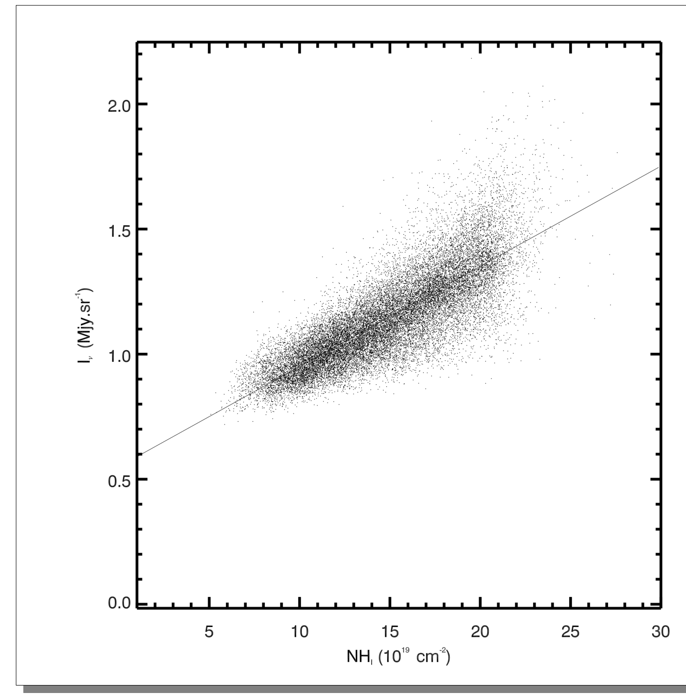
X-ray and IR luminosities of NED clusters stacked into redshift bins (Giard et al., 08)



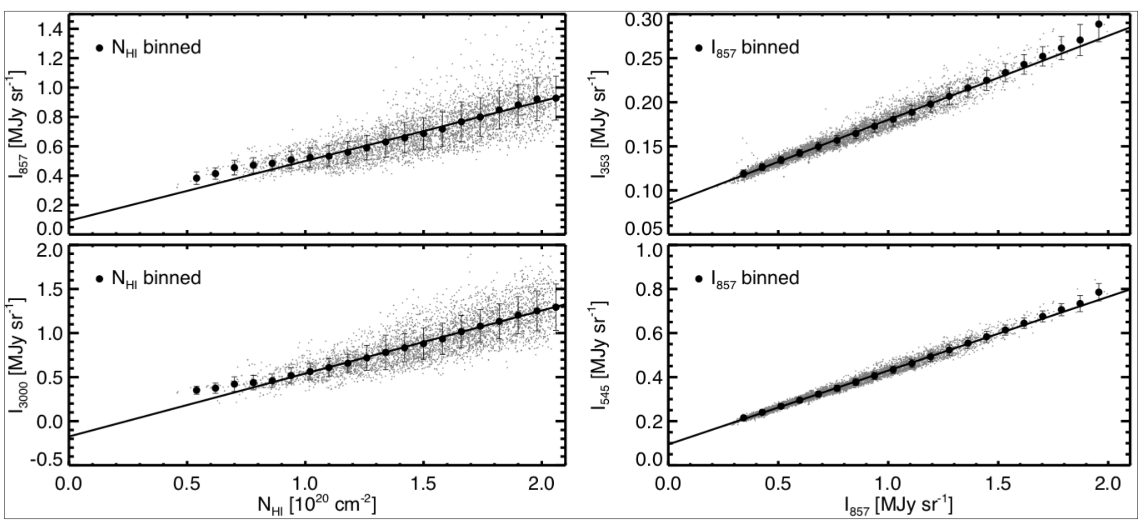
Stacked intra-cluster dust SED (Planck collaboration, 16)

The dust/gas correlation as seen by *Planck,* LAB and HI4PI sky surveys



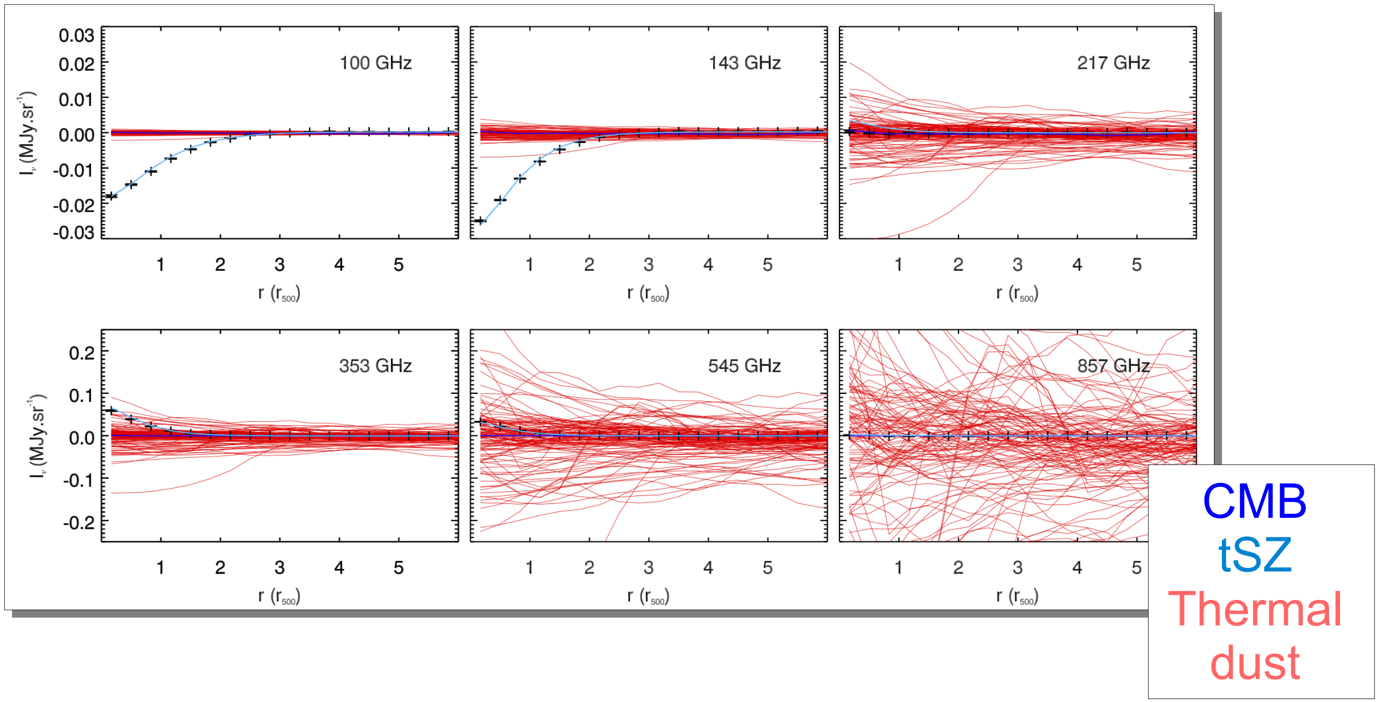


$$I_{857} = \phi^{-1}(N_{HI}) = a \times N_{HI} + b$$



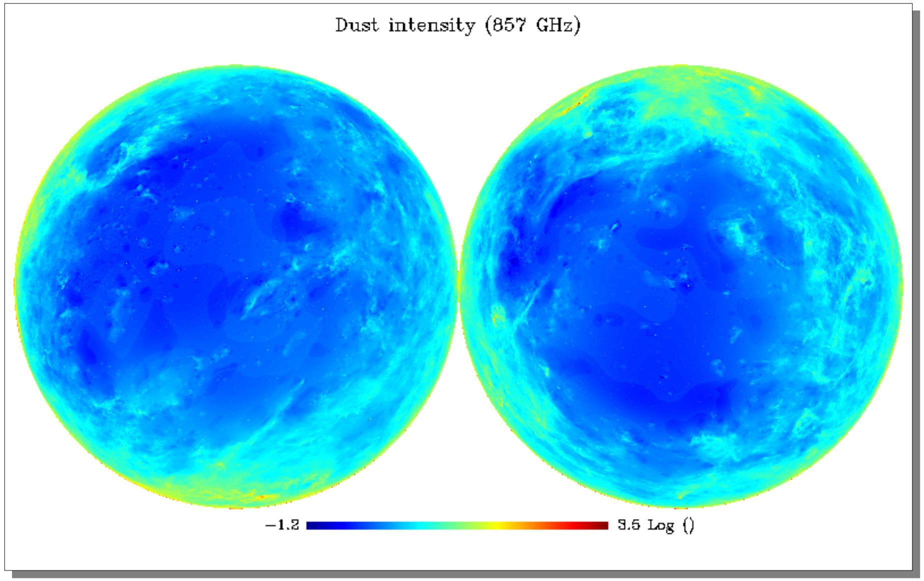
All-sky model of thermal dust (*Planck* collaboration, 14)

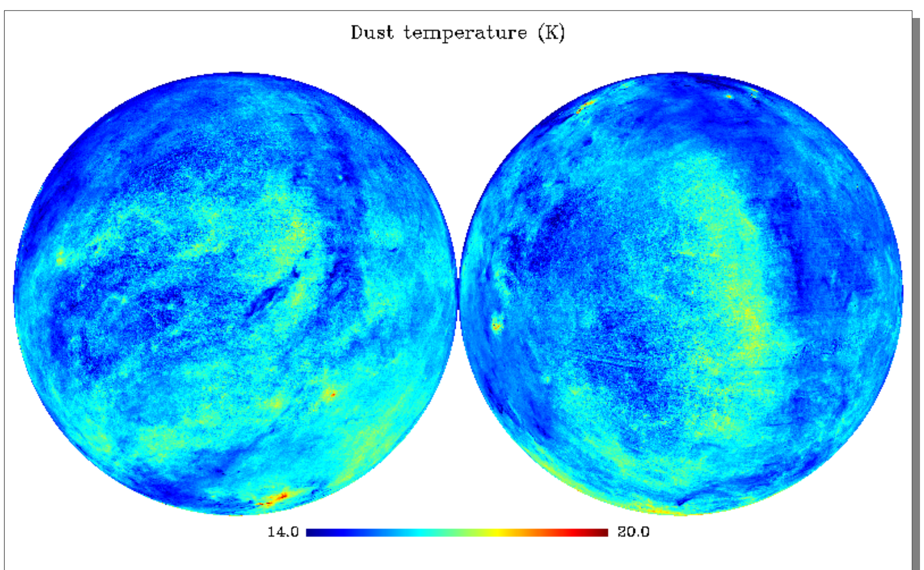
CHEX-MATE clusters (Planck HFI)

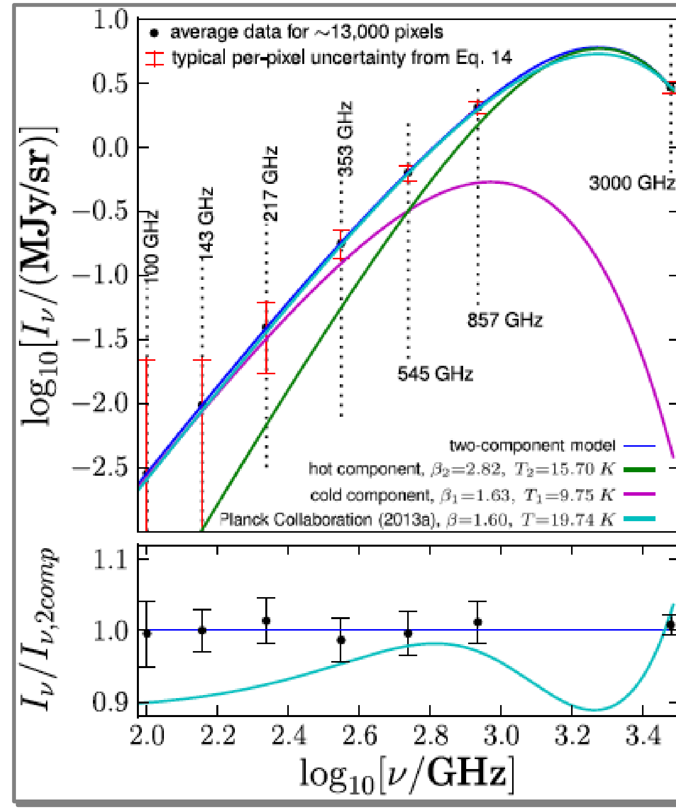


- Two-component thermal dust template:
  - Dust spatial template given from wavelet filtering of HFI 857 GHz map;
  - CMB spatial template given from wavelet filtering of HFI 217 GHz map;
  - ∂_{857}, τ_{857} jointly fitted with other spectroscopic thermal dust parameters and CMB intensity on the 6 HFI frequency maps;

Two component thermal dust template
(Meisner & Finkbeiner, 15)







- Two-component thermal dust template:
  - Dust optical depth and temperature mapped from a joint-fit of *Planck*+DIRBE+IRAS data

Dust/gas 'colour correction':
N_H proxies inferred from dust
intensity (I_{857})+optical depth (τ_{857})

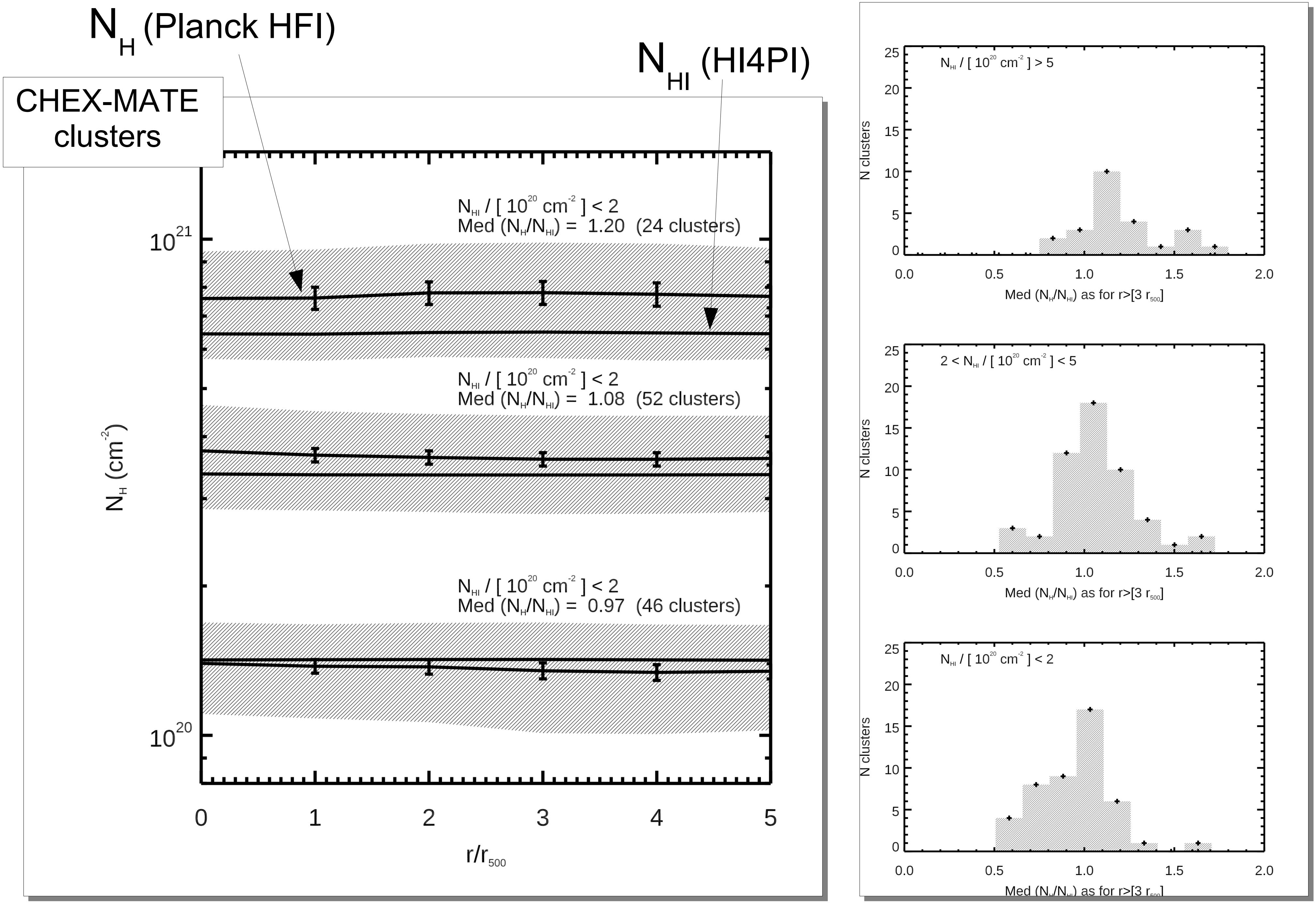
$$\boxed{I_\nu = \tau_\nu s(\nu)}$$

$$s(\nu) = \left[f_1 q_1 / q_2 (\nu/\nu_o)^{\beta_1} B_\nu(T_1) + (1 - f_1)(\nu/\nu_o)^{\beta_2} B_\nu(T_2) \right]$$

$$\boxed{N_H \equiv \phi(\tau_{857}) \times \langle s(857) \rangle = I_{857} / s(857) \times \langle s(857) \rangle}$$

local dust SED

Sky averaged dust SED



N_H (Planck HFI)
N_HI (HI4PI)
CHEX-MATE clusters
N_HI / [10^20 cm^-2] < 2
Med (N_H/N_HI) = 1.20 (24 clusters)
N_HI / [10^20 cm^-2] < 2
Med (N_H/N_HI) = 1.08 (52 clusters)
N_HI / [10^20 cm^-2] < 2
Med (N_H/N_HI) = 0.97 (46 clusters)
N_H (cm^-2)
r/r_500
N_HI / [10^20 cm^-2] > 5
2 < N_HI / [10^20 cm^-2] < 5
N_HI / [10^20 cm^-2] < 2
N clusters
Med (N_H/N_HI) as for r>[3 r_500]

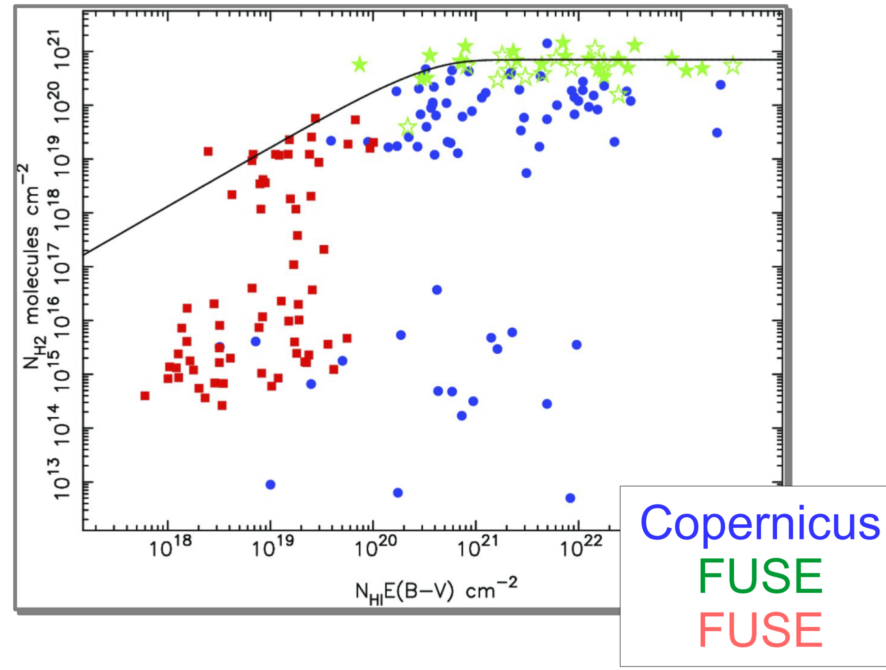
“We derive a simple function,
Dependent on the product of the atomic hydrogen column density, NHI , and dust extinction,E(B − V), which describes the variation of the molecular hydrogen column density, NH2, of our Galaxy, over the sky”

….

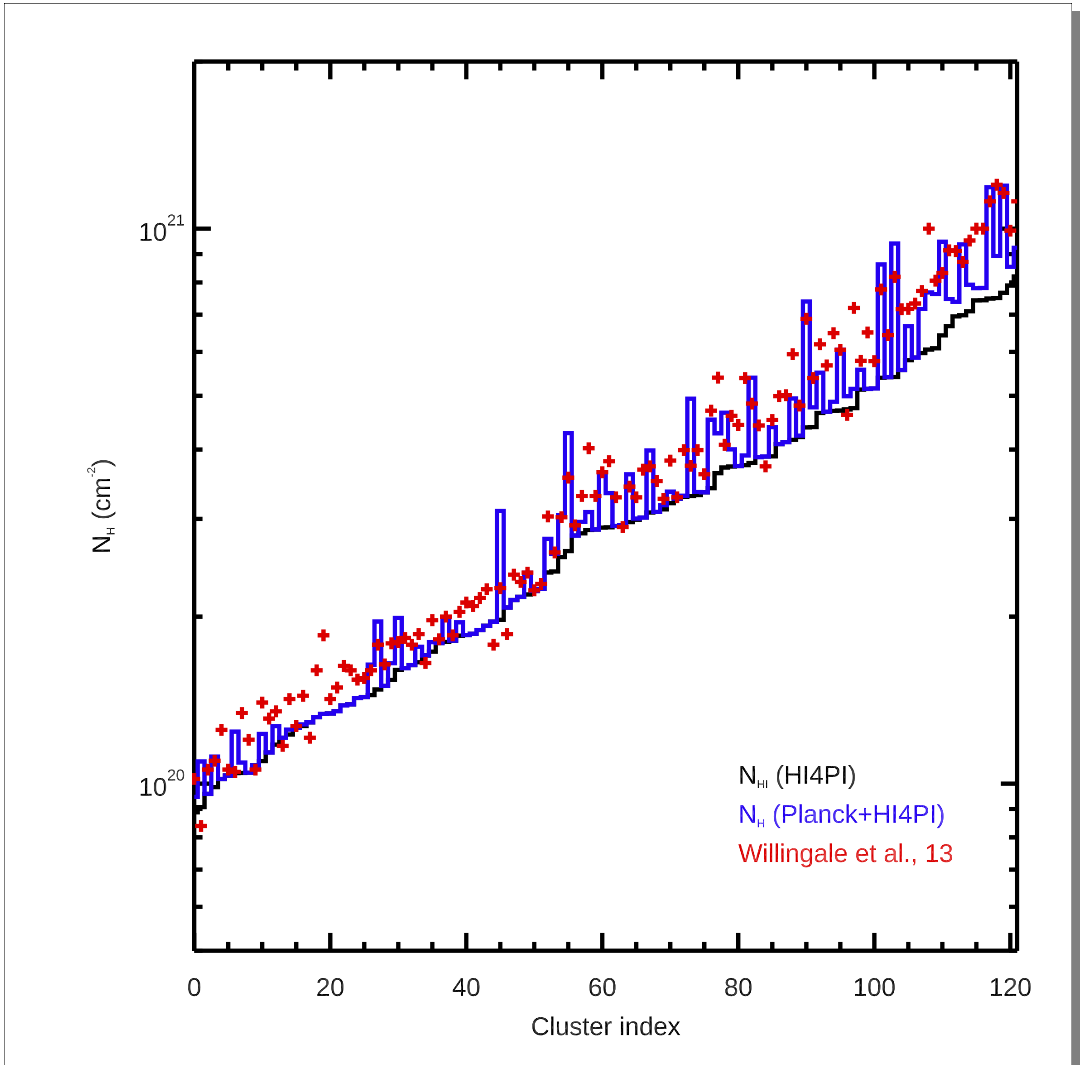
“Our resulting recipe represents a significant revision in Galactic absorption compared to previous standard methods, particularly at low Galactic latitudes.”

Calibration of X-ray absorption in our Galaxy (Willingale et al., 13)

$$N_{H_2} = N_{H_2,max}\left[1-\exp\left(\frac{-N_{HI}\,E(B-V)}{N_c}\right)\right]^{\alpha}$$

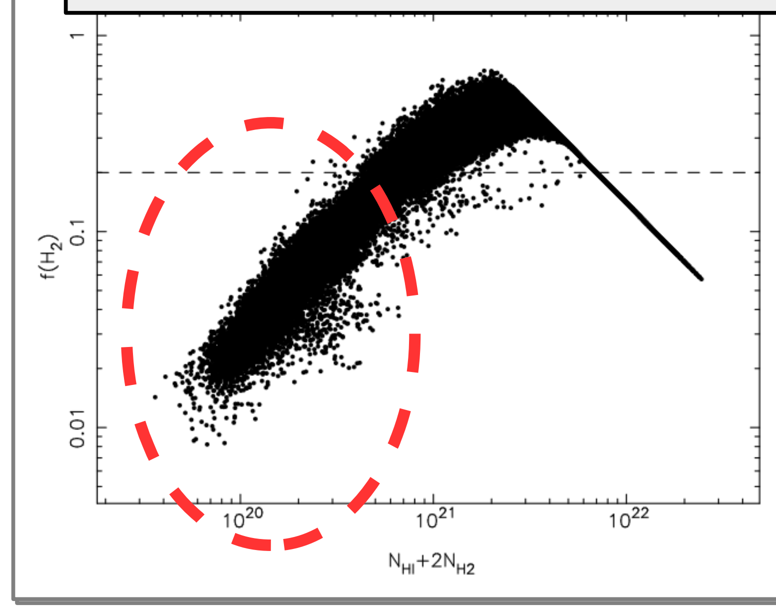


- Willingale et al. 13: fit of 500 SWIFT GRB re-binned in 13 N_H bins by empirical law, $N_{H2} = f(N_{HI}, E(B\text{-}V))$;
- f(NH2): N_{H2} saturates at high N_H and exhibits a cutoff as for intermediate N_H values (as expected from ISM studies); upper limit of UV absorption measurements;
- Limited to the angular resolution of HI-LAB (0.6 degrees), and to the COBE-DIRBE calibration of thermal dust temperature (0.7 degrees)



- Median N_H ratios toward the CHEX-MATE clusters:
  - N_H exceeds N_{HI} by 4%
  - W13 exceeds N_{HI} by 20%
- Biggest discrepancy as for $N_H<3.10^{20}$ cm^{-2}

Calibration of X-ray absorption in our Galaxy (Willingale et al., 13)

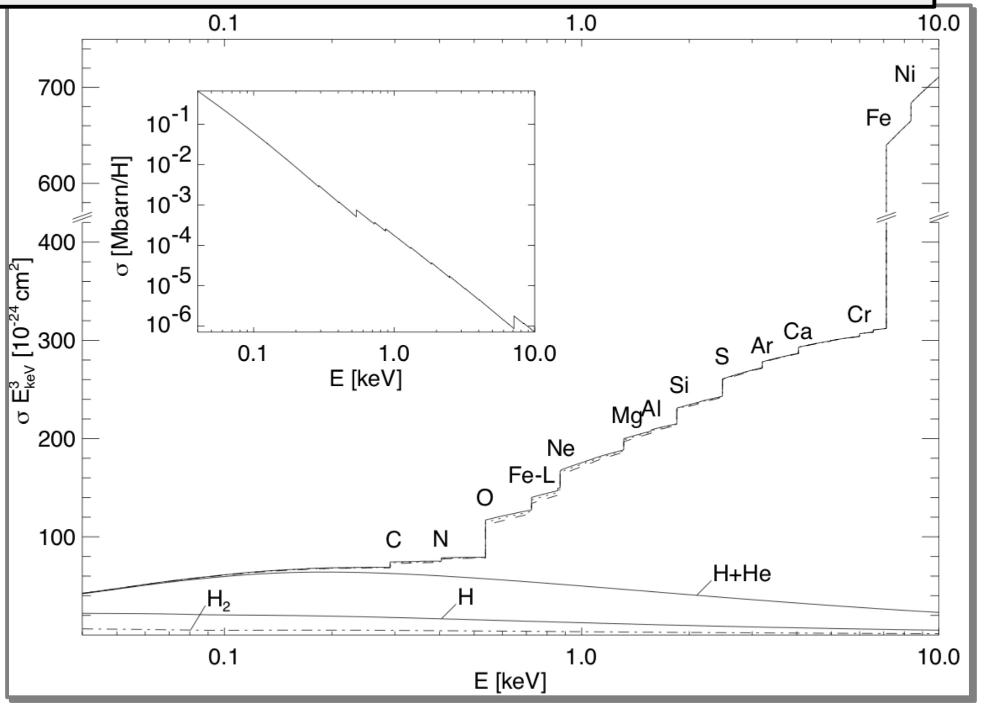


$$f=\frac{2N_{H_2}}{N_{HI}+2N_{H_2}}$$

$$I(e)=I_o(e)\exp(-N_H\,\sigma_{ISM}(e))$$

- Molecular fraction of hydrogen density column, *f,* can be estimated from dust excesses over H_I using HI4PI + *Planck* HFI data;
- As expected from the catalogue selection (high *Planck* SNR, high Galactic latitude), *f* is close to zero for most CHEX-MATE clusters;
- Few clusters located in high dust extinction regions show *f* values as high as 50%;

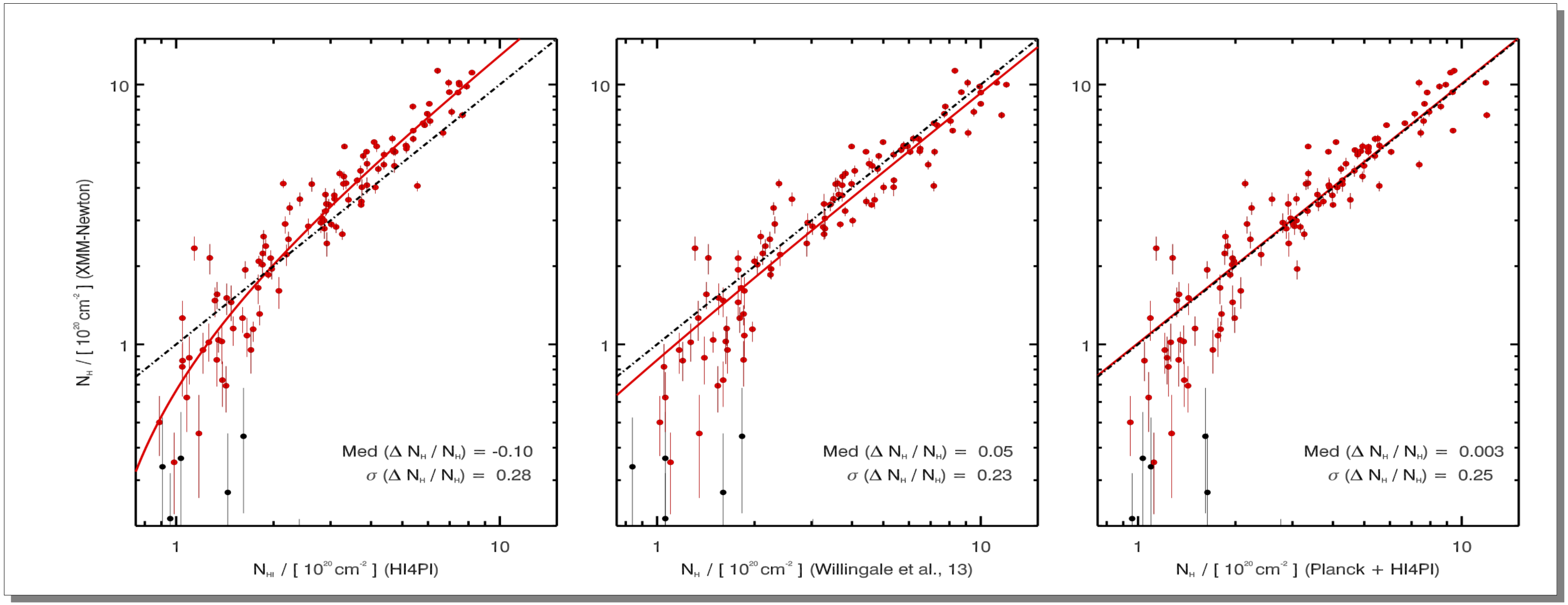
On the absorption of X-rays in the interstellar medium (Wilms et al., 00)



- Relevant photoabsorption edges (e< 1keV): O, Fe-L
- Relevant photoionisation elements and molecules: He, H ($HI+H_2$)

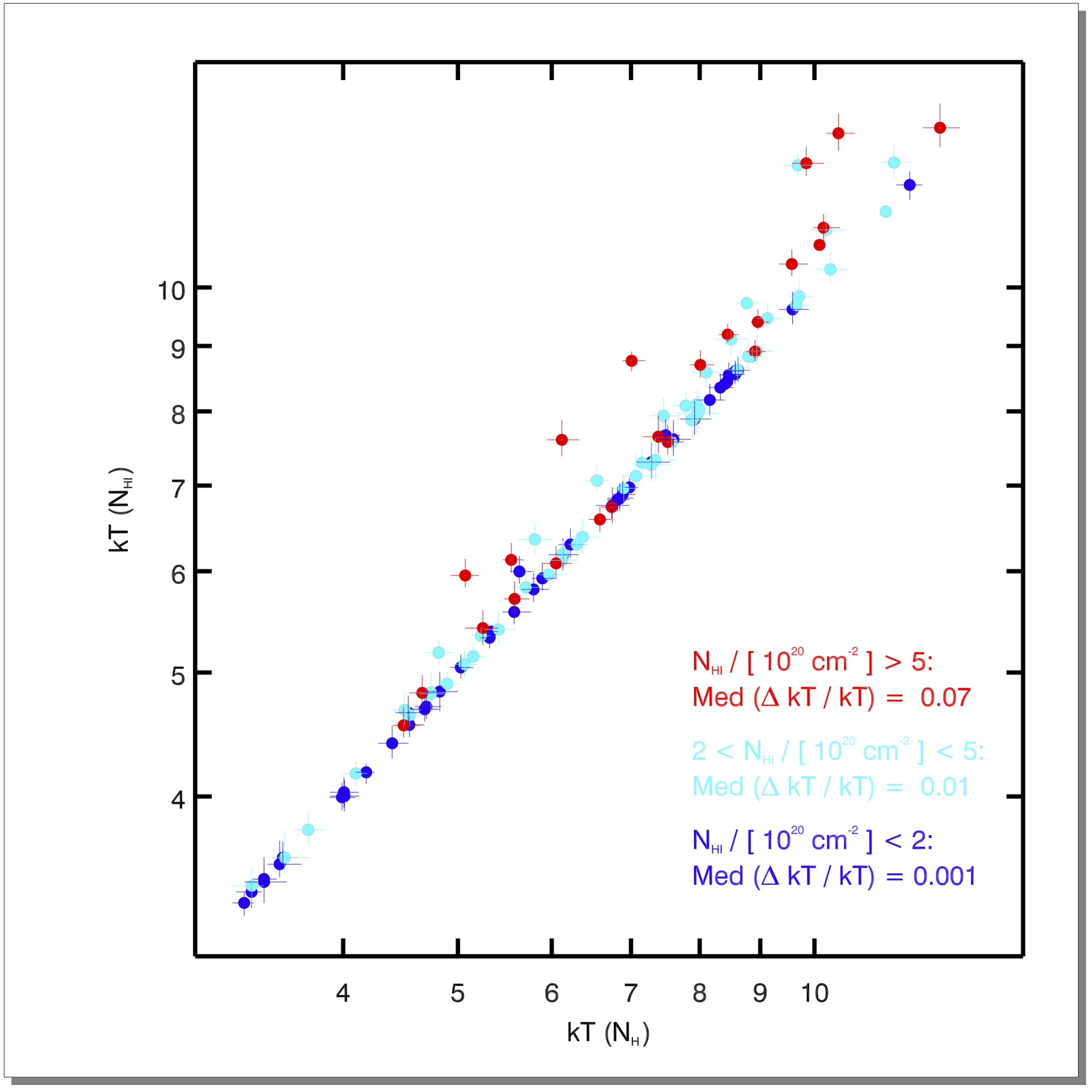
- Given that the Heritage catalogue selection corresponds to high Galactic latitudes (i.e. to the solar neighbourhood ISM) and that *f* is close to zero, a simple modelling of ISM cross sections could rely on:
  - *Solar* He (+O, Fe) abundances from Asplund M., Grevesse N., Sauval A.J. & Scott P. (2009, ARAA, 47, 481)
    - Warning: solar photospheric abundances of noble gas are *indirect* estimates (1% systematics), yielding higher He abundances than CMB
  - $\sigma_{molecules}=0$

X-ray absorption vs. N_H estimates



- ISM absorption averagely exceeds N_{HI} toward CHEX-MATE clusters
- Excess compatible with molecular fraction derived from *Planck*+ HI4PI

Molecular fraction of N_H impact on CHEX-MATE cluster temperatures



- Significant impact on temperature measurements as for 20% of the CHEX-MATE sample

Conclusions

$$f = \frac{2N_{H_2}}{N_{HI} + 2N_{H_2}}$$

- Molecular fraction of hydrogen density column, *f*, can be estimated from dust excesses over H_I using HI4PI + *Planck* HFI data (compatible with X-ray absorption excess above H_I)
- As expected from the catalogue selection (high *Planck* SNR, high Galactic latitude), *f* is close to zero for most CHEX-MATE clusters;
- Molecular fractions significantly impact temperature measurements as for 20% of the CHEX-MATE sample