Cosmic rays, gas, and dust in Local clouds

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on behalf of the *Fermi*-LAT Collaboration

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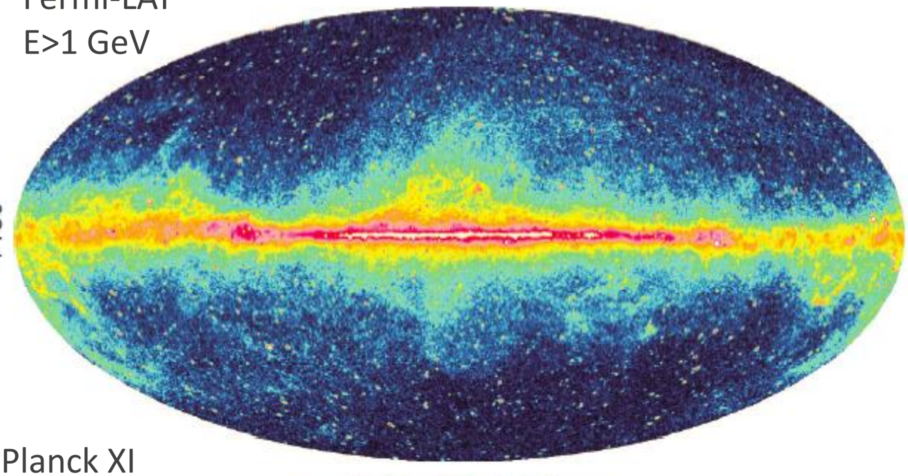
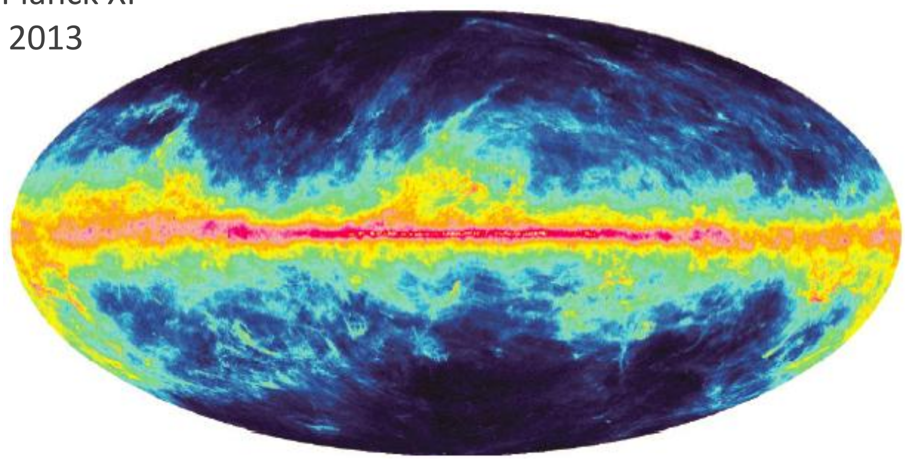
Total gas tracers

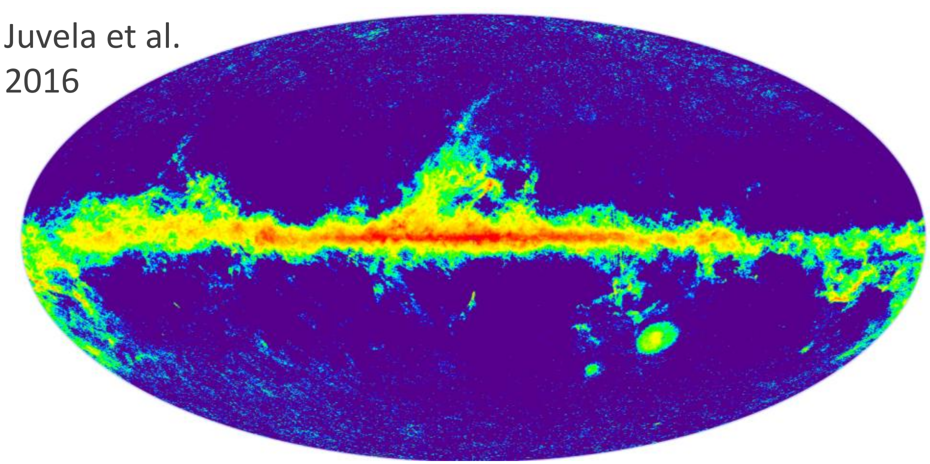
Fermi-LAT
E>1 GeV



Planck XI
2013



Juvela et al.
2016



- γ rays of interstellar origin

Cosmic-Ray interactions with gas

$$p_{CR} + p_H \rightarrow \pi_0 \rightarrow 2\,\gamma$$

$$I_\gamma \;\alpha \int n_{CR}\, n_H\, dl$$

- Dust thermal emission from

large dust grains mixed with gas

$$I_\nu = \tau_\nu B_\nu(T)$$

Dust optical depth $\tau_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta R_{\rm DG}\, \mu_{\rm H} N_{\rm H}$

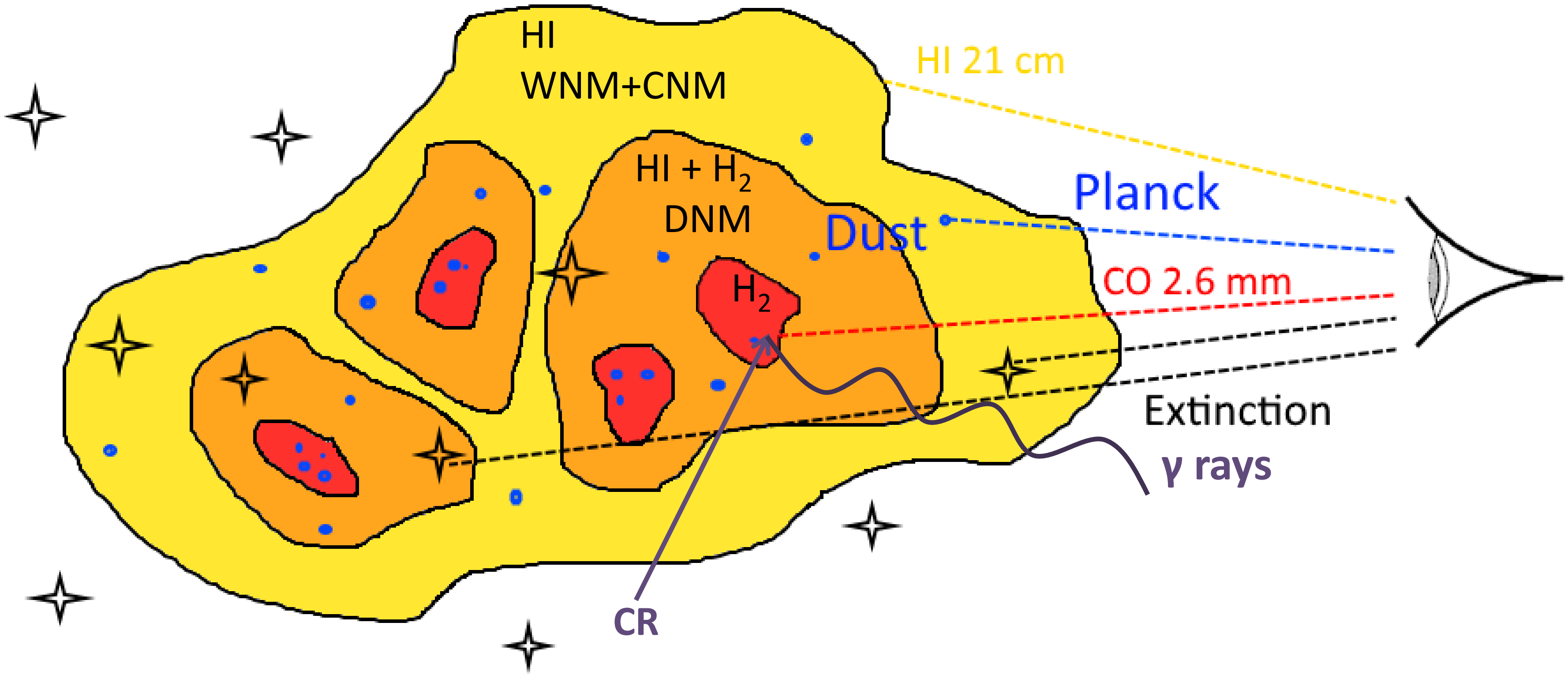
- Extinction caused by

large dust grains mixed with gas

$$A_\lambda = 1.086 \tau_\lambda^{\rm ext} = 1.086 \int n_{\rm dust} \sigma_\lambda^{\rm ext} {\rm d}s$$

Stellar reddening: $E(B\text{-}V) = A_V / R_V$

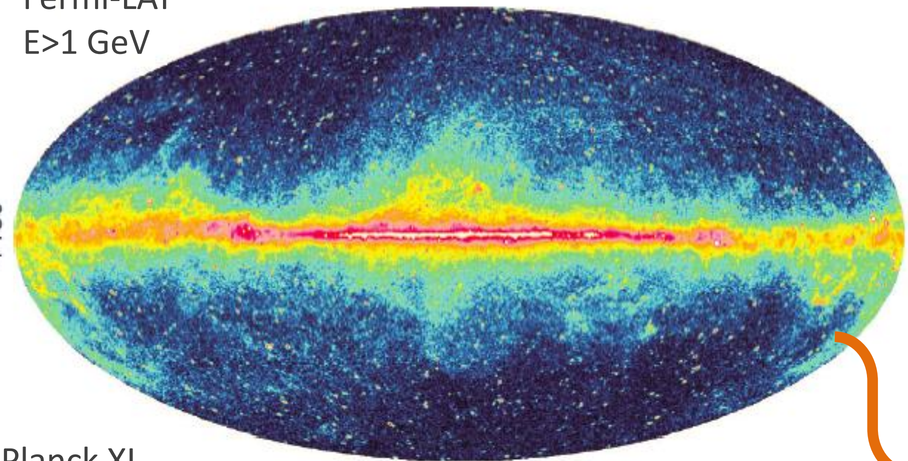
Tracing gas and dust in the interstellar medium

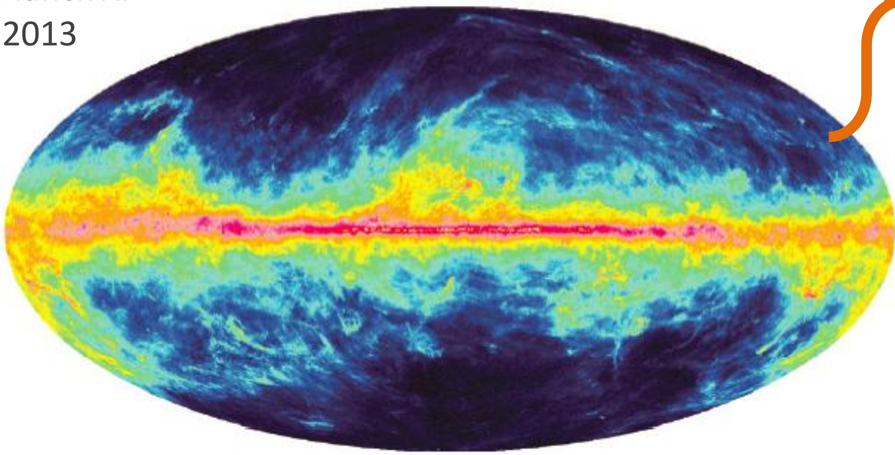


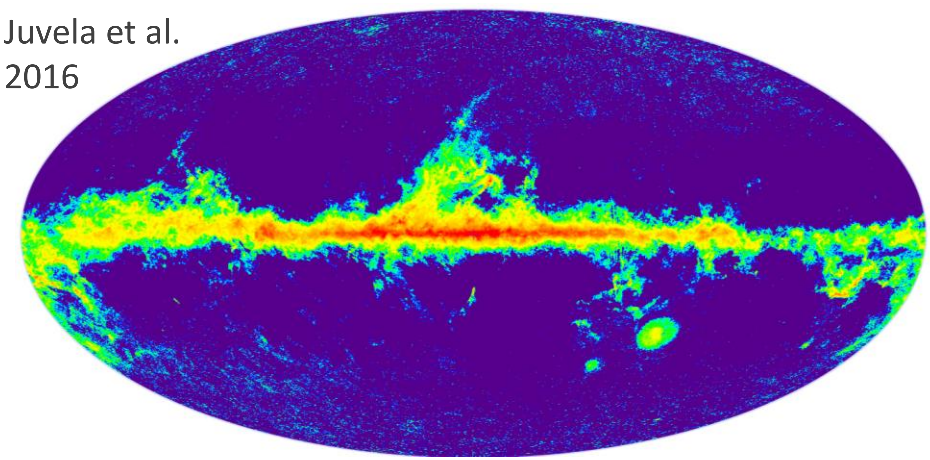
Objectives:

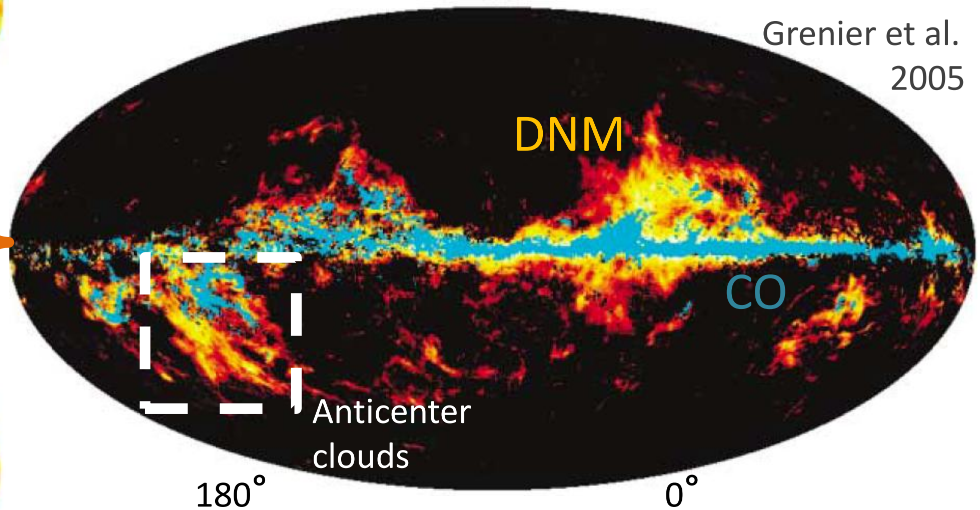
- Modelling diffuse γ-rays emission, dust optical depth, stellar reddening : linear commination of gas colum density in different phases (HI, CO, DNM)
- Test reliability of the tracers
- Constraints on the gas phases and dust properties

Dark Neutral Medium





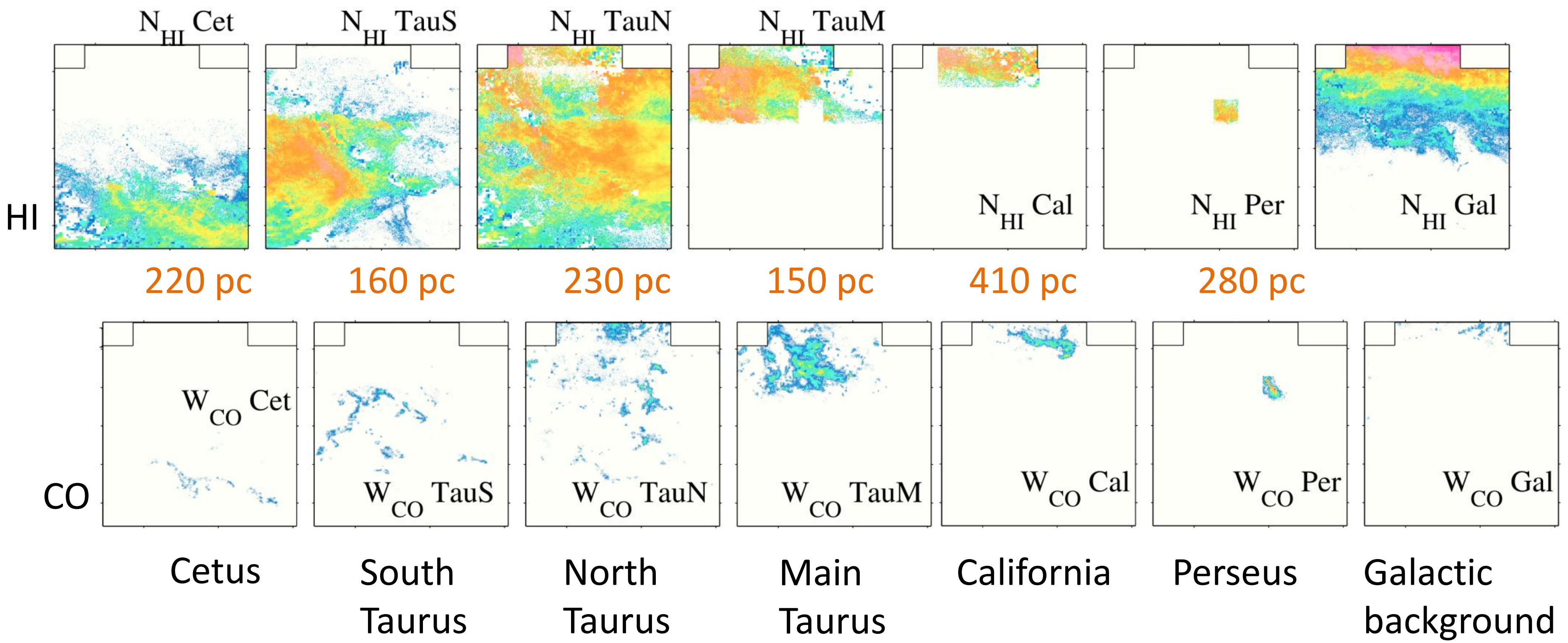




- Dust and γ-ray data jointly reveal significant amounts of gas in addition to that seen in HI and ^{12}CO emissions
- Dark Neutral Medium (or dark gas) DNM = dense HI + diffuse H_2

Anticenter region : 6 local clouds

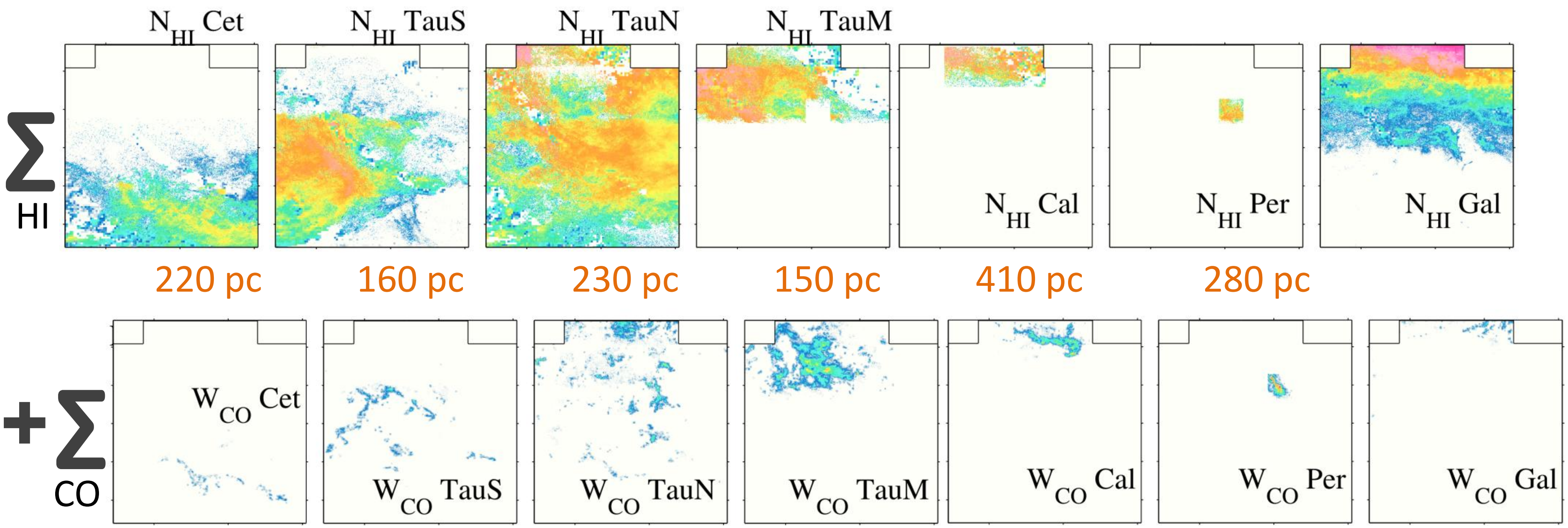
6 Local clouds separated in position-velocity + Galactic background gas

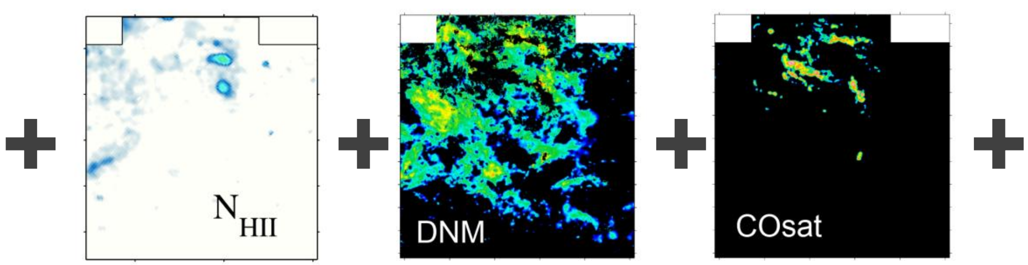


γ-ray and dust models

Uniform Cosmic Rays density n_{CR}, dust-to-gas ratio, grain emissivity κ_{ν}, extinction cross section σ_{λ}^{ext}

→ γ, τ, E(B-V) =

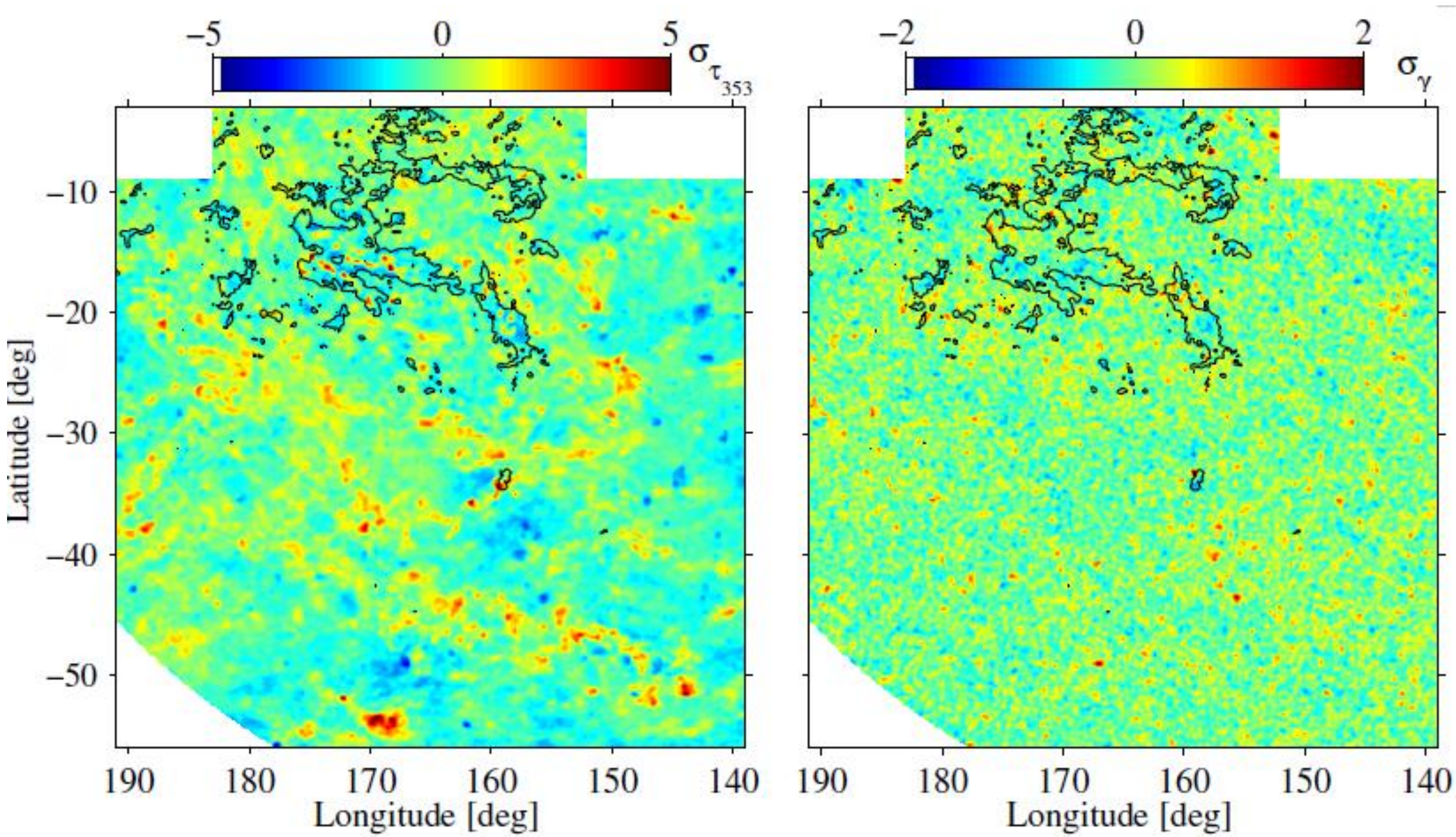




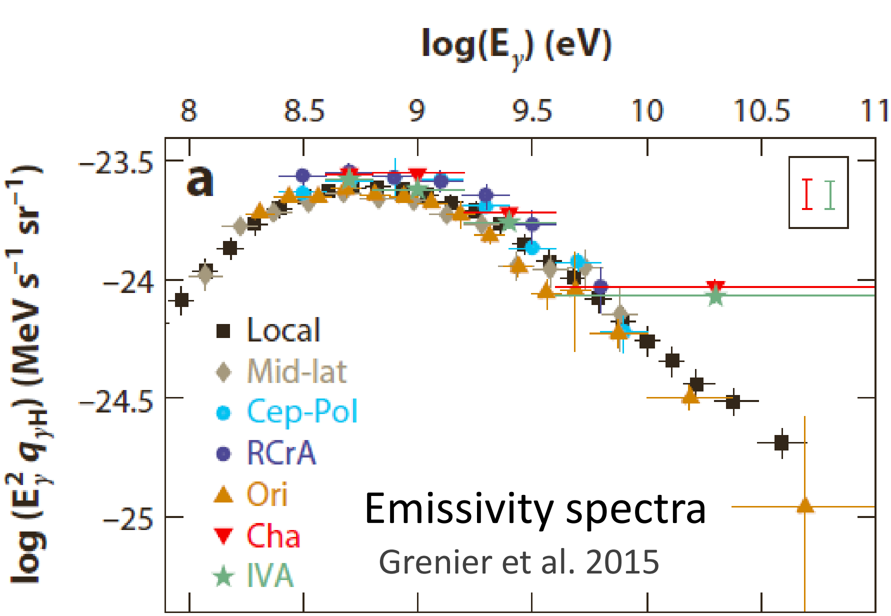
+ non-ISM ancillary data

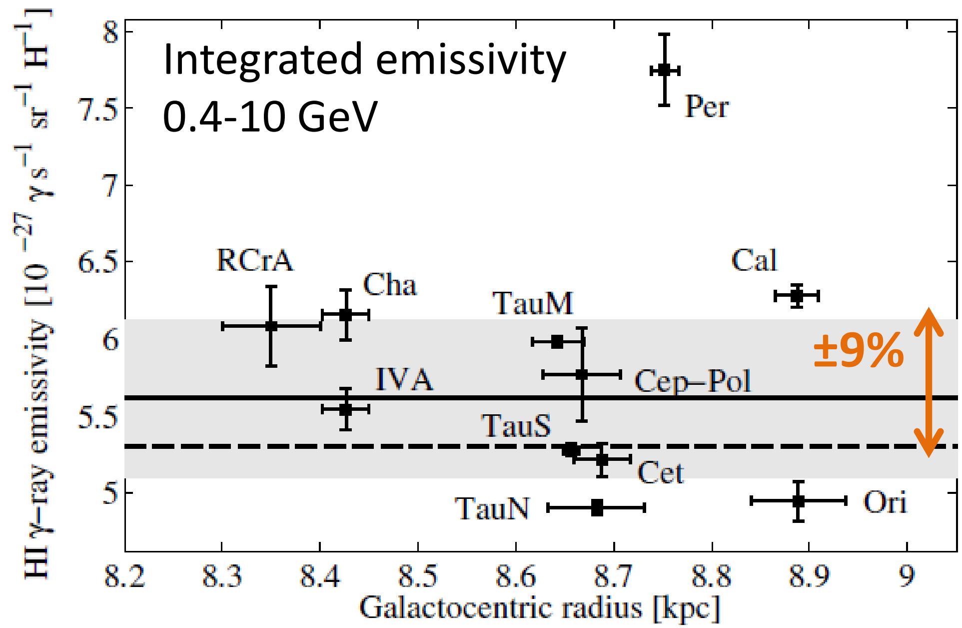
Final dust and γ-ray models residuals

- Data - model in sigma unit:



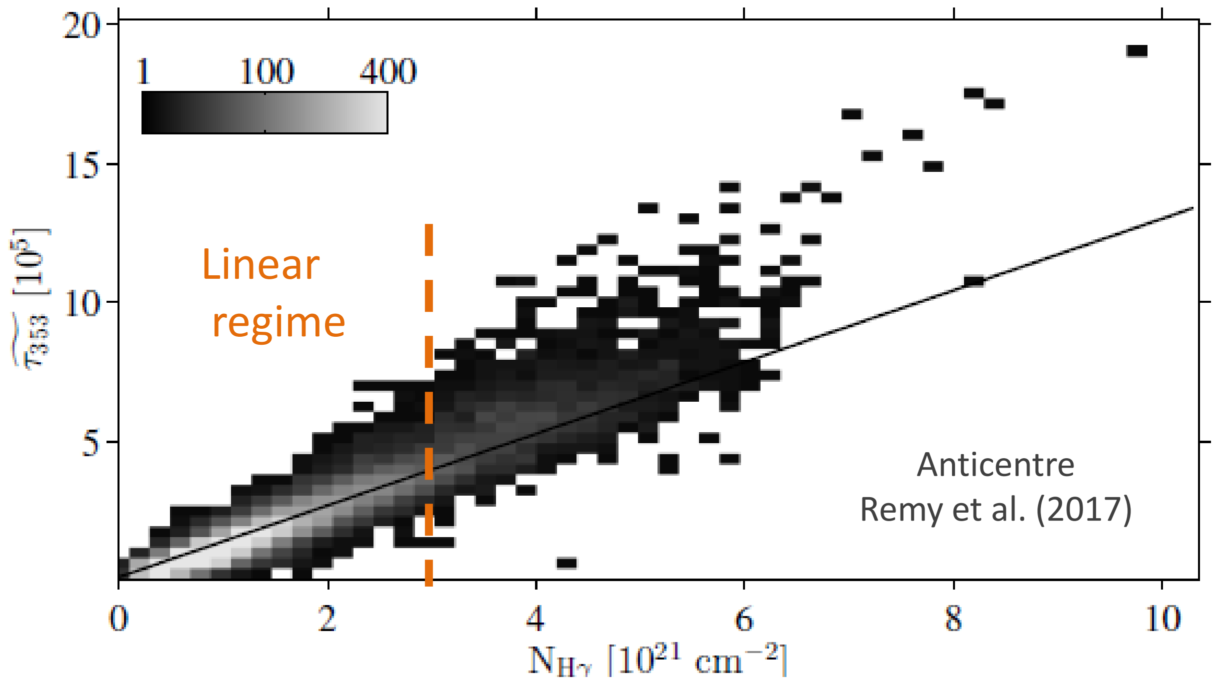
Local HI γ-ray emissivity

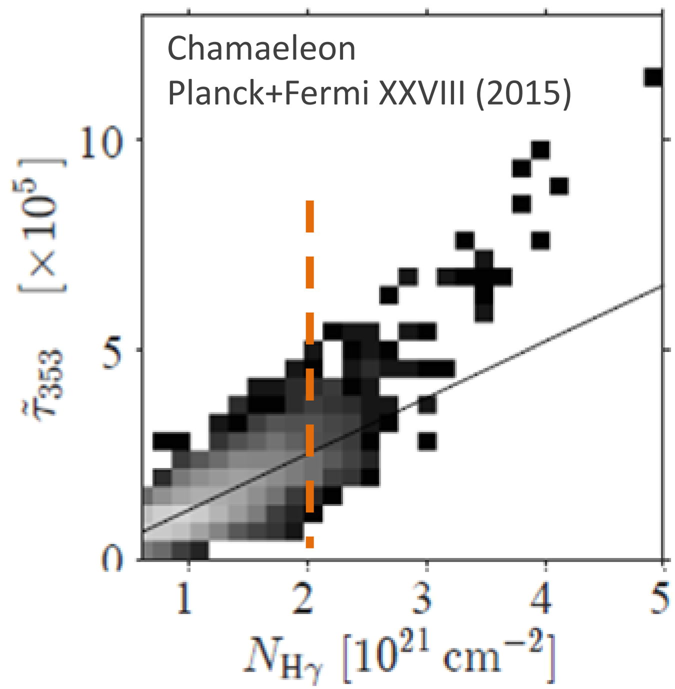


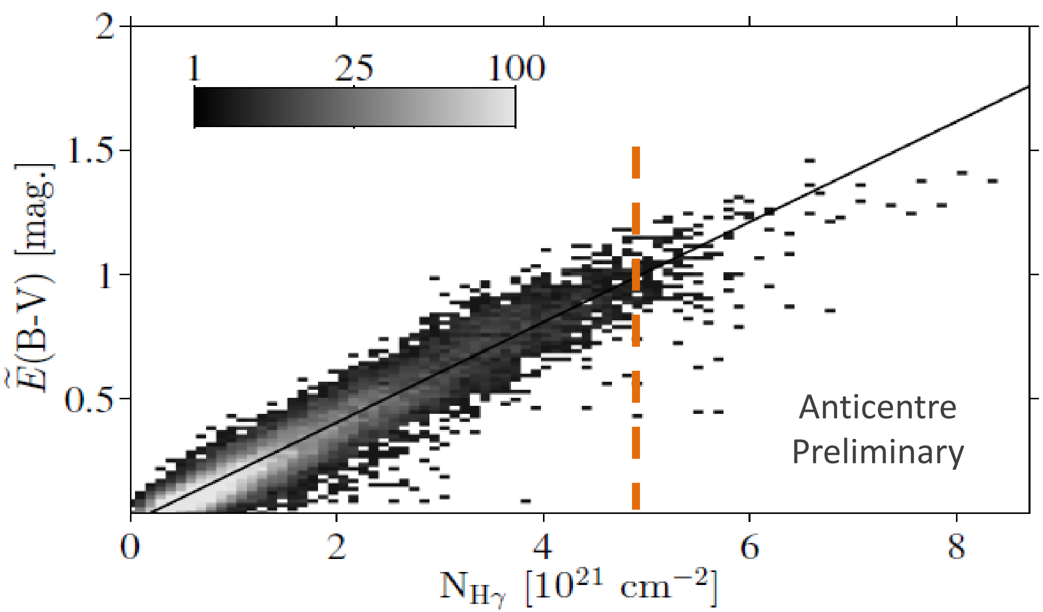


- Emissivity spectra of local clouds consistent with the local interstellar spectrum (Casandjian 15)
- Local dispersion ±9% : consistent with uncertainties in N_{HI} column densities
- Perseus value : no CR enhancement, cross-talk between HI and CO distributions
- No energetic evolution relative to the local interstellar spectrum accros cloud phases
  => good CR penetration into the cloud => γ-rays OK to trace N_H

Evolution of grain emission properties





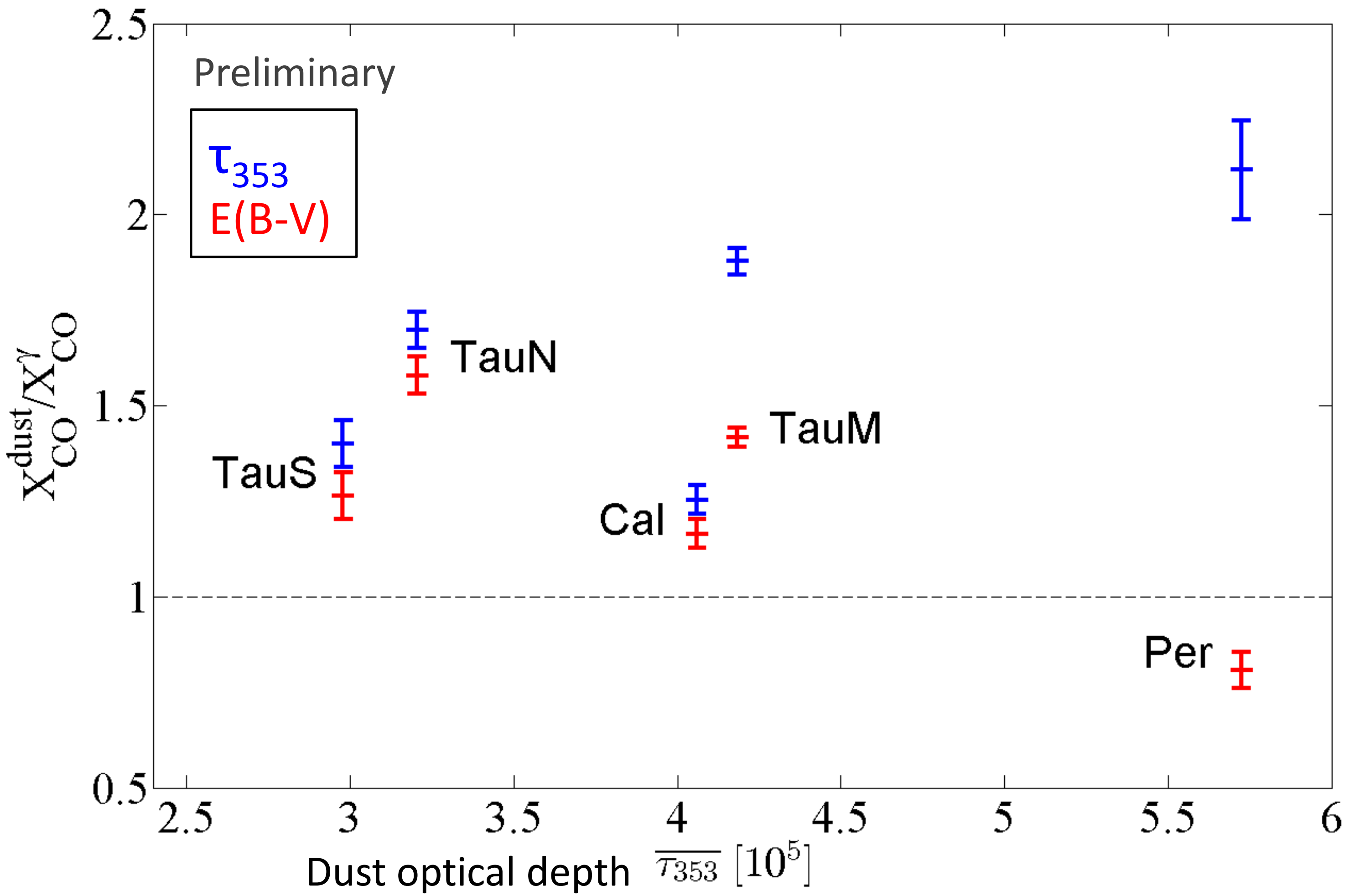


- Non-linear increase in τ_{353} with gas column density, N_H, likely due to grain evolution (coating, aggregation…)

- Better correlation of the stellar reddening caused by dust, E(B-V), with gas column density, N_H

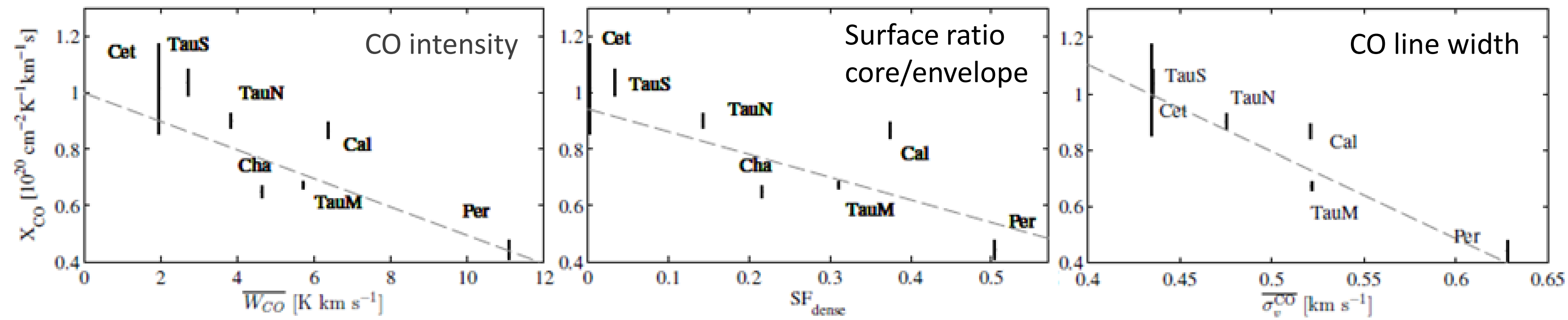
X_{CO} measurements with dust and γ rays

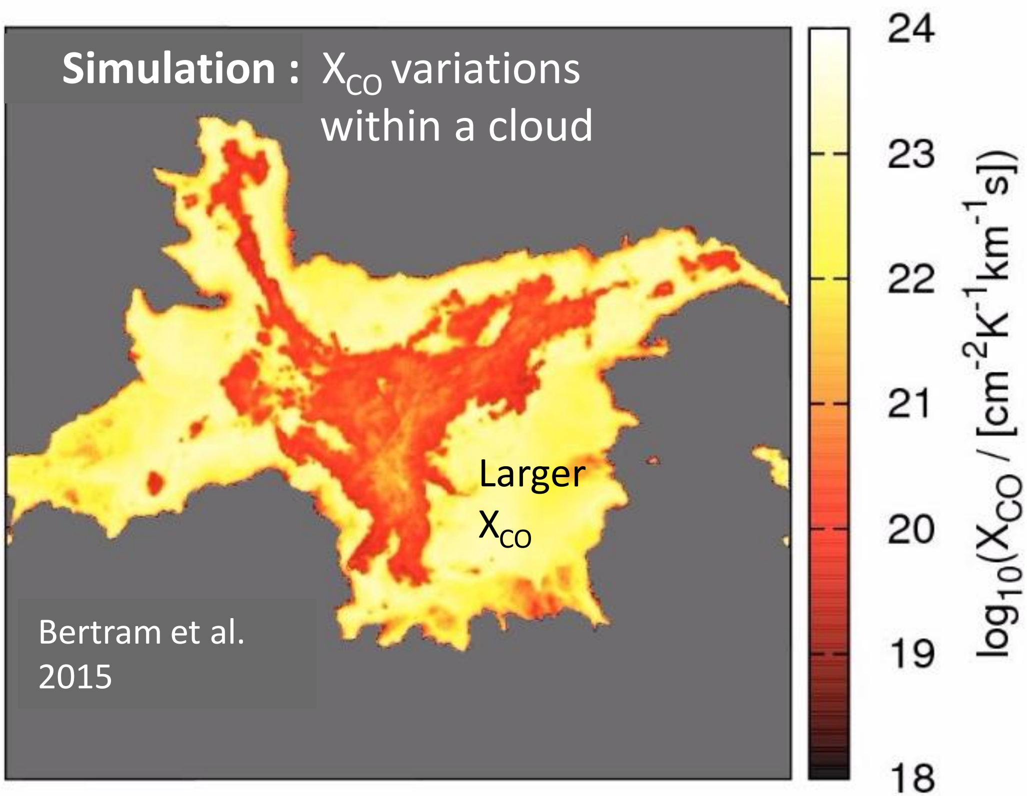
- X_{CO} estimates from τ_{353} systematically larger than γ-ray and E(B-V) ones
  Better to rely on X_{CO} measurements from γ rays



X_{CO} environnemental changes

γ-ray measurements : $X_{CO} = q^{\gamma}(CO) / 2q^{\gamma}(HI)$ Average X_{CO} of a cloud





Simulations :
X_{CO} decreases from cloud edge (photo-dissociated) to core (well shielded)

γ-ray measurements :
Average X_{CO} decrease from diffuse to bright and compact clouds

Consistent with X_{CO} decreases from edges to denser cores

Take away messages

- No energetic evolution relative to the local interstellar spectrum accros cloud phases
  => good CR penetration into the cloud => γ-rays OK to trace N_H
- Dust optical depth τ_{353} do not linearly correlate with gas column density, N_H due to a chemical and/or structural change in the dust grains.
- γ-ray and dust data jointly reveal significant amounts of DNM gas in addition to that seen in HI, free-free, and ^{12}CO emissions.
- Evidence for X_{CO} variations in different environnement
  => importance of clouds separation

See more :

Chamaeleon clouds : *Planck* & *Fermi*-LAT Collaborations XXVIII (2015), A&A ... 82A..31A
Nearby Anticenter clouds: Remy et al. (2017), A&A...601A..78R

Questions or bonus slides ?

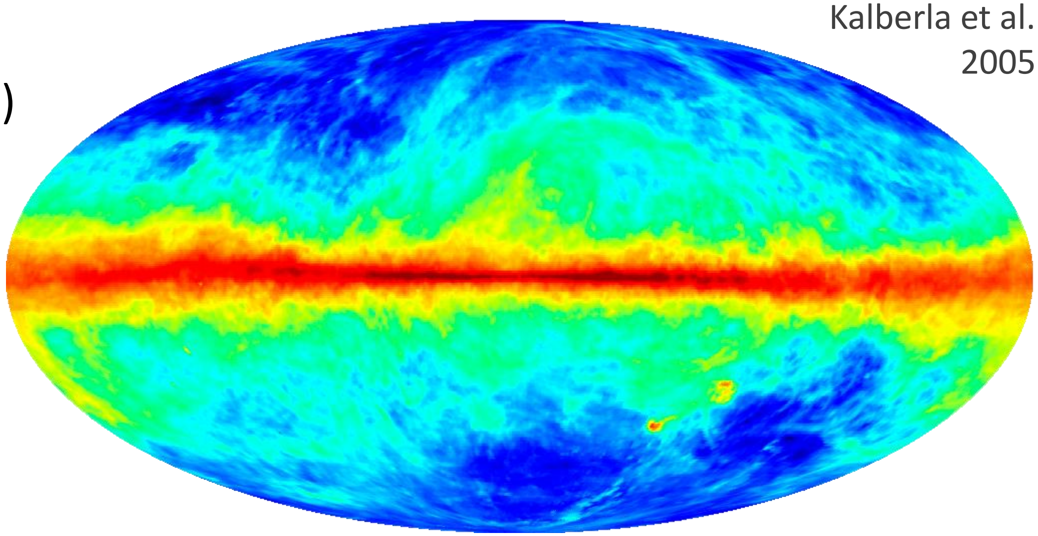
Gas emission lines

❖ Atomic gas : HI 21cm emission line (LAB, GASS, EBHIS, HI4PI, GALFA surveys)

$$N_H = 1.83 \times 10^{18}\ \mathrm{cm^{-2}}\ \mathrm{T_S} \int \ln\left(\frac{\mathrm{T_S}}{\mathrm{T_S} - \mathrm{T_b}}\right) \mathrm{dv}$$

Spin temperature T_S unknown without absorption line measurement (uncertainty in dense HI)

LAB survey
Kalberla et al.
2005



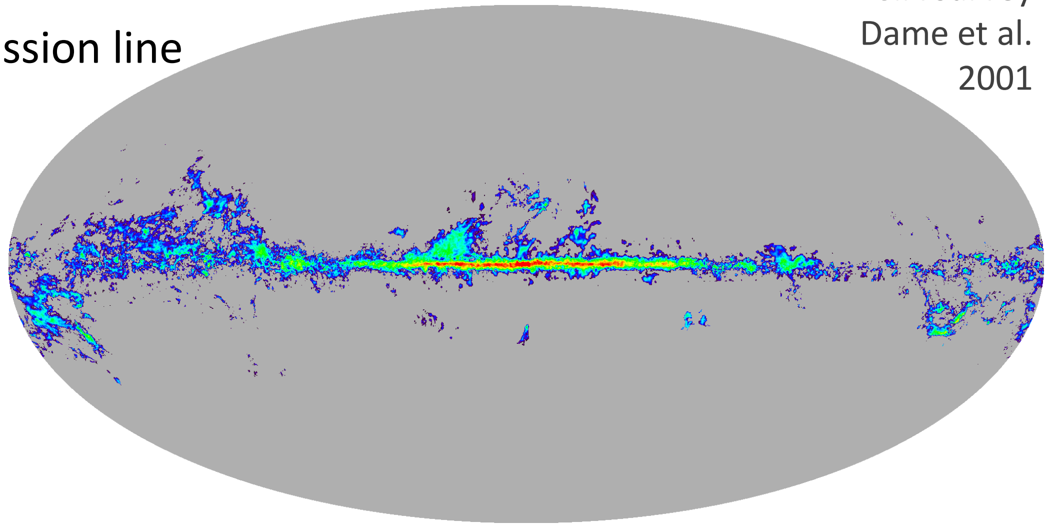
❖ Molecular gas : CO (J 1-0) 2.6 mm emission line (CfA, Nanten surveys)

$$W_{CO} = \int T_b\, dv$$

CO to H_2 conversion factor :

$$X_{CO} = \frac{N_{H_2}}{W_{CO}}$$

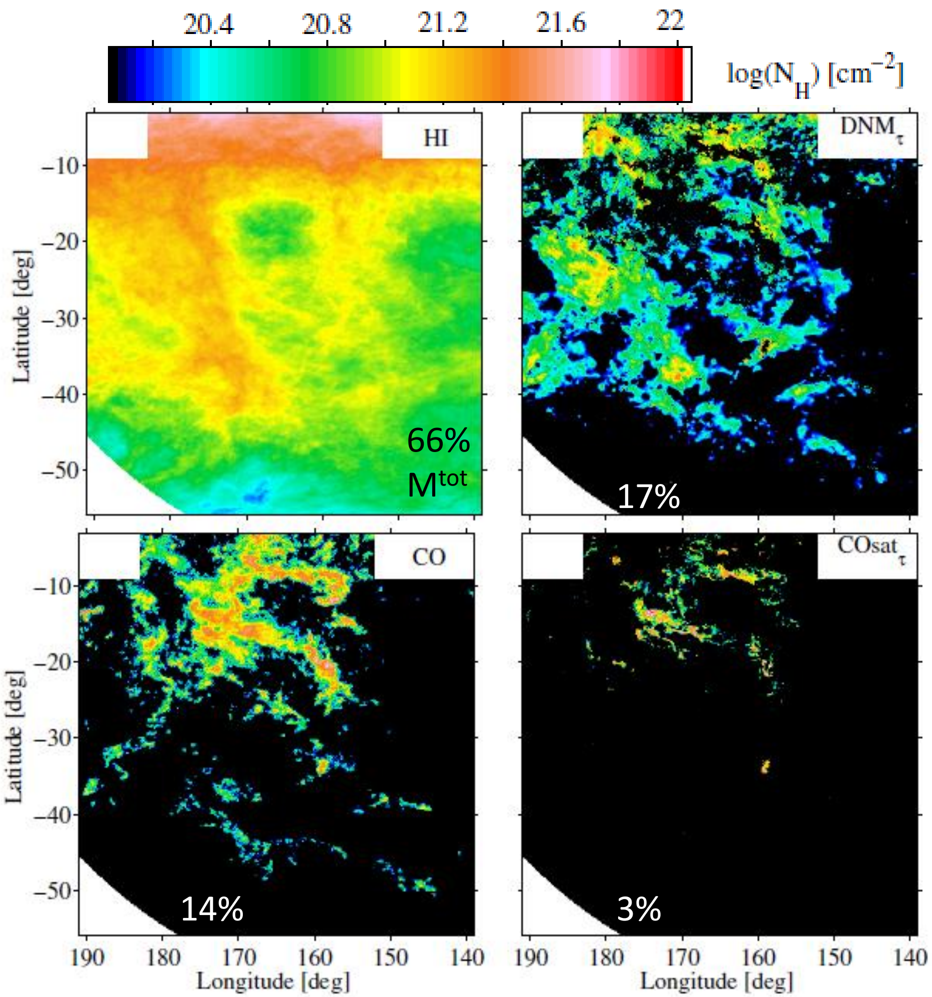
CfA survey
Dame et al.
2001



Neutral gas phases

Anticentre region

Remy et al. (2017)

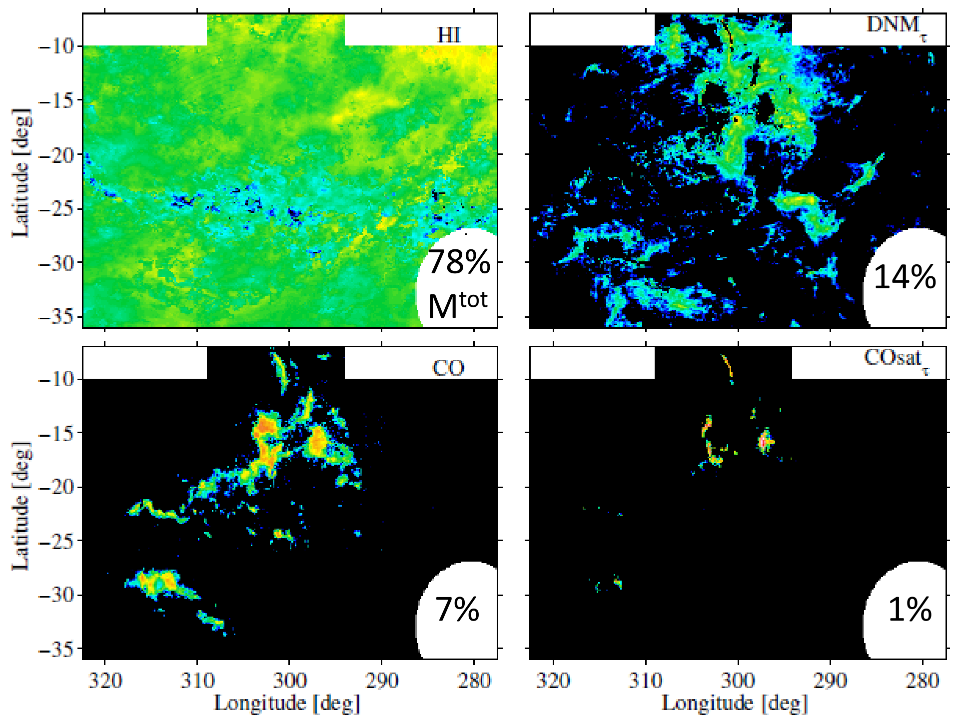


Chamaeleon region

Planck+Fermi XXVIII (2015)

Bright HI

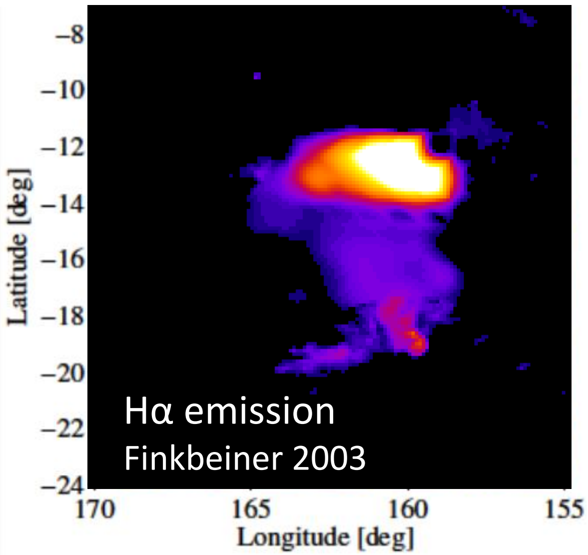
Dark Neutral Medium : Opaque HI + diffuse H_2

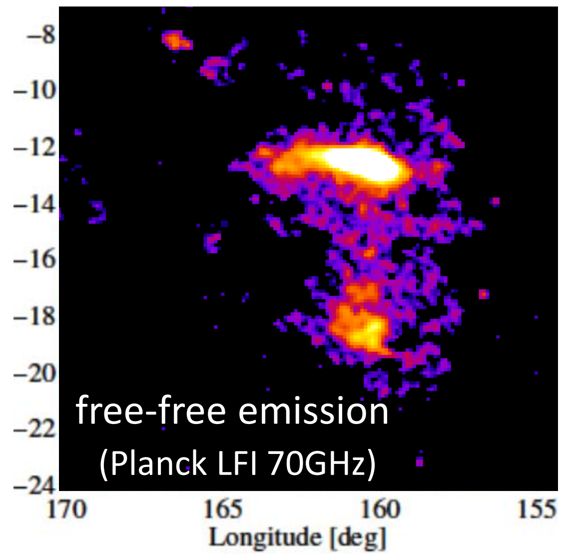


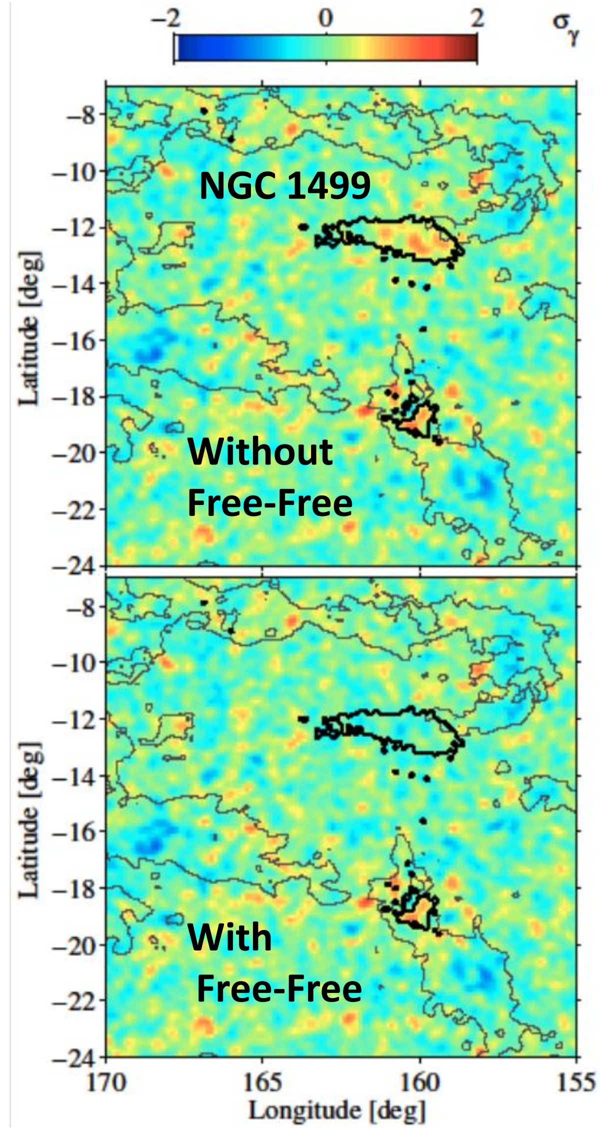
CO-traced H_2

CO-saturated H_2

γ-ray detection of ionized gas







- γ-ray detection 10 σ, hadronic origin, not Inverse Compton
- Hα and free-free emissions model in NGC1499:

  Mean electron density: $N_e = 5.0 \pm 1.1\ cm^{-3}$

  Electron temperature: $T_e = 7700 \pm 1700$ K

γ-ray measurement for T_e = 8000 K :

$N_e = 4.3 \pm 0.6\ cm^{-3}$