Cosmic-Ray and Gas Properties in the MBM 53-55 Clouds and the Pegasus Loop as Revealed by HI Line Profiles, Dust, and Gamma-Ray Data

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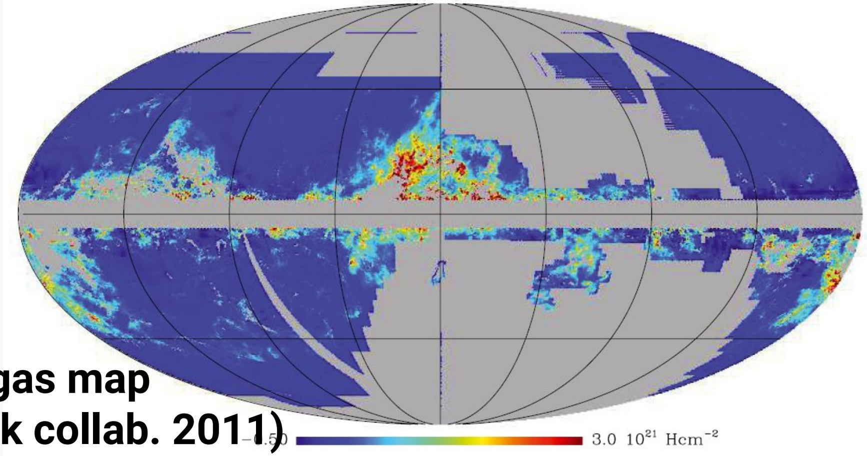
Motivation: Gas and CRs

Goal: Accurately measure gas and cosmic rays (CRs) in Milky Way

(Simplest) Way: Use HI and CO lines to trace HI and H_2 gas, then use γ-ray to obtain I_{CR} ($\propto I_\gamma/N_H$)

Issue: Significant amount of gas not properly traced by HI/CO lines

(e.g., Grenier+05, Planck collab. 2011)



Dark gas map
(Planck collab. 2011)

Dust and γ-ray have been used to trace "Dark gas", but they cannot distinguish

- optically thick HI and CO-dark H_2
- gas phases along the line of sight

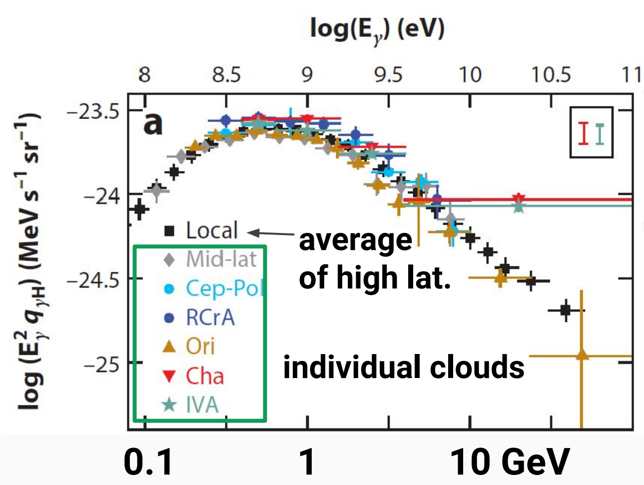
Motivation: Gas & CRs

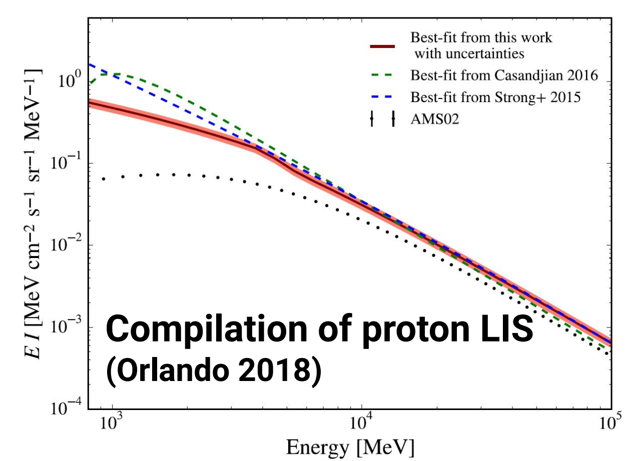
I_{CR} ($\propto I_\gamma / N_H$)

Goal: Accurately measure gas and cosmic rays (CRs) in Milky Way

Issue: Uncertainty still large (factor of ~1.5) even in local environment

Key: Identify optically thin HI (basis of measuring emissivity, dust-to-gas ratio)





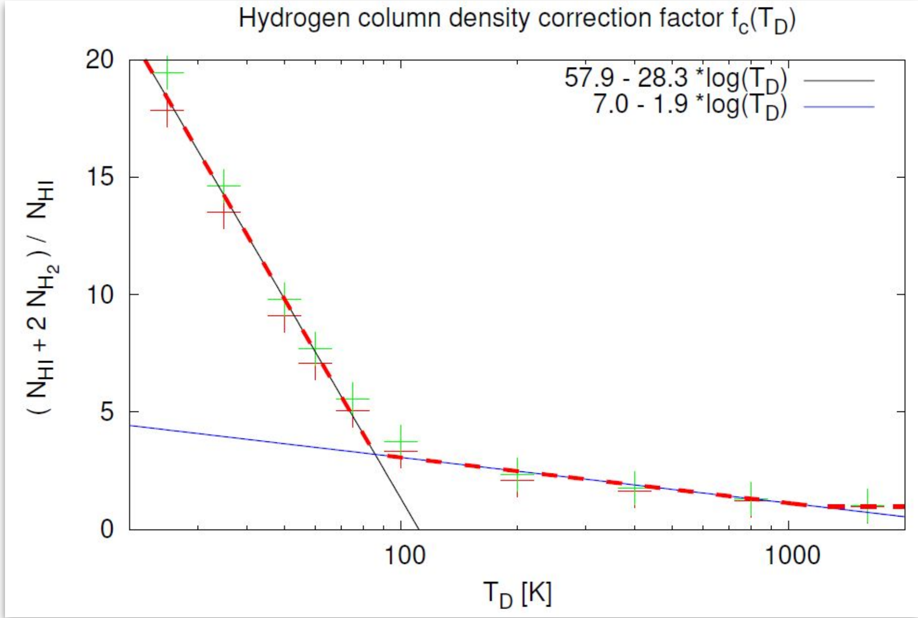
γ-ray emissivity ($\propto I_{CR}$) of local clouds (Grenier, Black & Strong 2015) scatter due to uncertainty of spin temperature T_s

Also, local γ-ray emissivity is known to be ~30% larger than expected by CR measurements (Strong 2015, Orlando 2018)

Possible Solution: Using HI-line Profiles

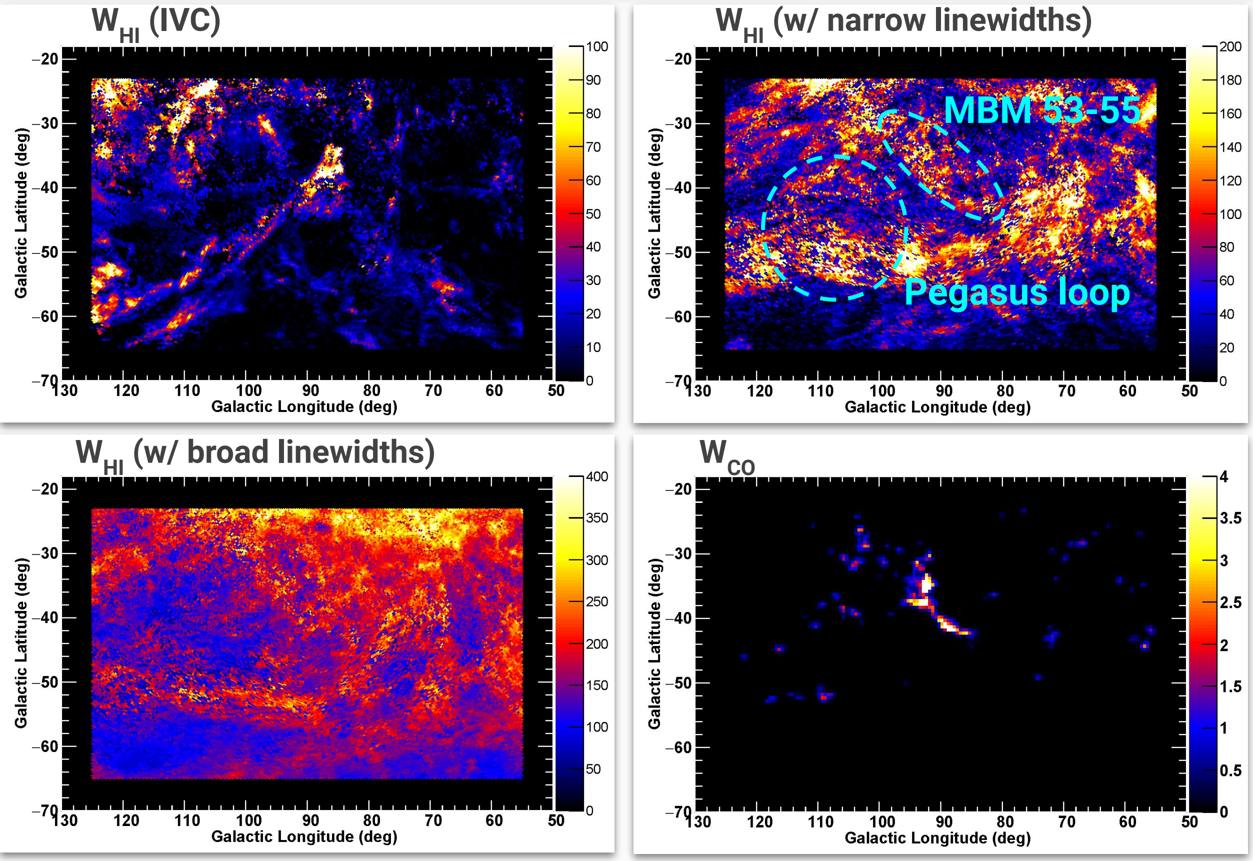
Kalberla+20 found narrow-line HI gas is associated with dark gas [gas not properly traced by HI and CO lines]

- T_D (Doppler temperature)=22*δv^2
- Vertical axis shows ratio of NH_{tot} to NH_{thin} (estimated using dust emission w/ CO-bright area masked)
- Areas of ratio>1 (dark-gas rich) are with narrow HI line



To validate the work and establish the method, we applied HI-line-profile based analysis to MBM 53-55 clouds and Pegasus loop (Mizuno+16)

ISM Gas Maps (HI & CO)



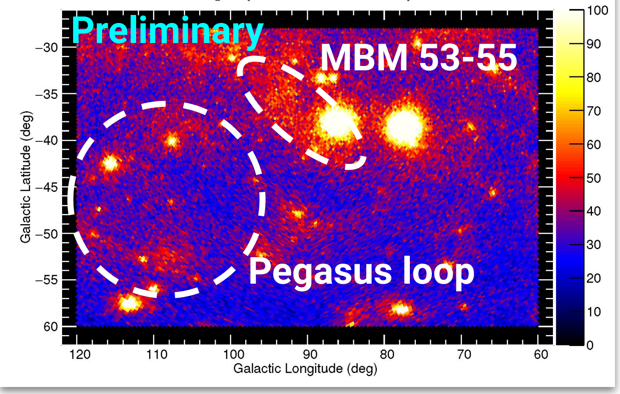
We prepared $3W_{HI}$ and W_{CO} maps (K km/s) as initial gas model

- intermediate velocity cloud
- narrow HI (T_D<1000K)
- broad HI (T_D>1000K)
- W_{CO} (to trace CO-bright H_2)

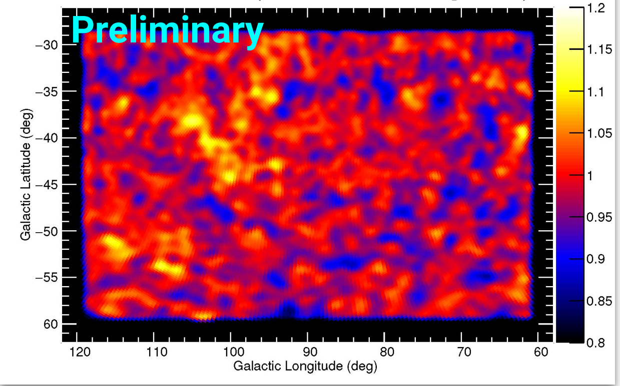
Narrow HI shows coherent structures that correspond to MBM 53-55 clouds and Pegasus loop (known to be dark-gas rich)

Model and Analysis

Count map (0.1-73GeV)



Data/model (w/o dust template)

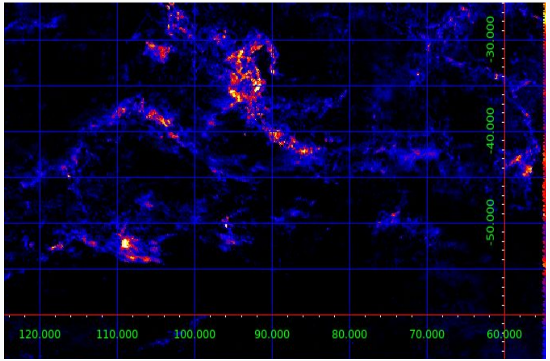


First modeled data with $3W_{HI}+W_{CO}$+Iso+IC+sources and observed residuals in MBM53-55 and Pegasus loop (btm. left)

Then applied a correction proposed by Kalbarla+20 (p4), but residual remains => HI not fully trace gas (even w/ linewidth info.)

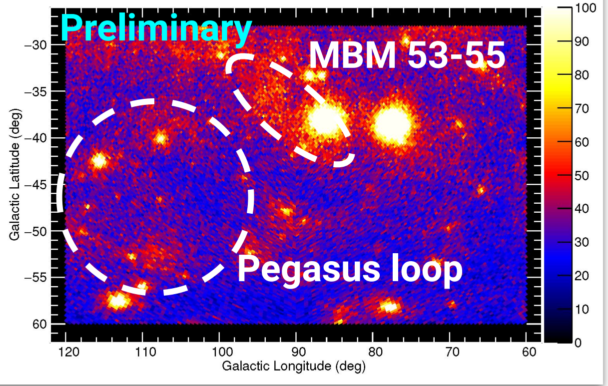
So we employed dust maps to model residual gas (subtract IVC, narrow HI, etc. one by one)

Residual gas template (dust Radiance)



Model and Analysis (Cntd.)

Count map (0.1-73GeV)



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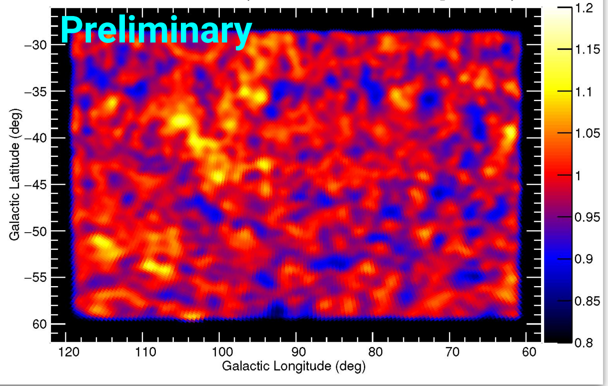
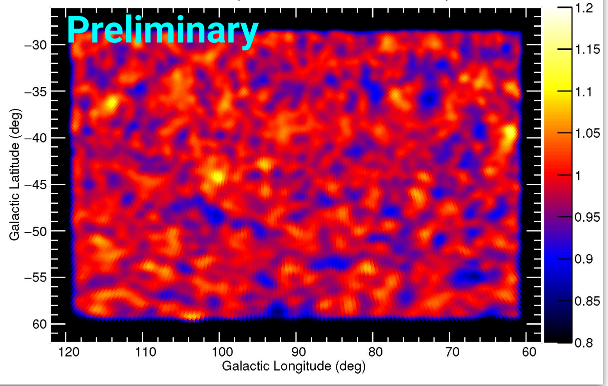
Data/model (w/o dust template)



Data/model (w/ final model)



Narrow HI gives ~1.5 times larger γ-ray emissivities than broad HI => We applied a T_s correction (of 40K) to it and obtained a final model (btm. right)

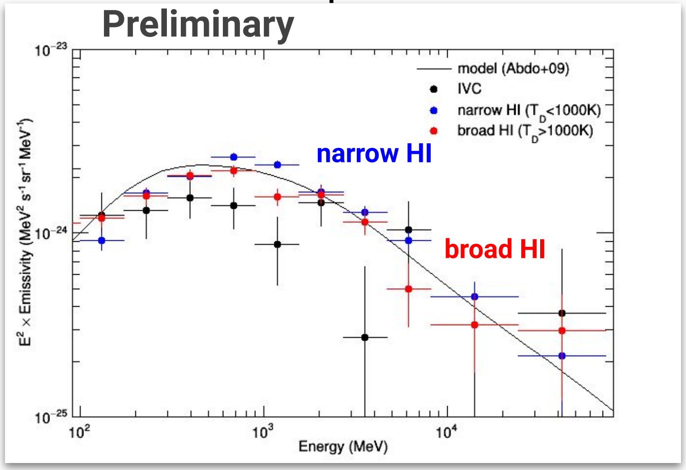
Results with Final Model

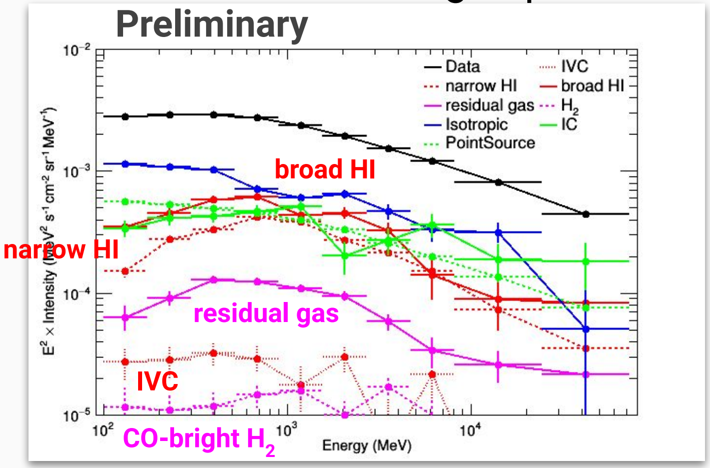
Final model reproduces the data well (see prev. slide)

- IVC, narrow HI (w/ correction for T_s=40K), broad HI, Wco, dust_res
- Isotropic, Inverse Compton, γ-raysources

Emissivity ($\propto I_{CR}$) of narrow HI agrees with that of broad HI and a model at 10% level

Spectrum of each component shows relative contribution of each gas phase





Discussion 1: ISM Gas Properties

We interpret broadHI=thinHI, narrowHI=thickHI, residual gas=CO-dark H_2

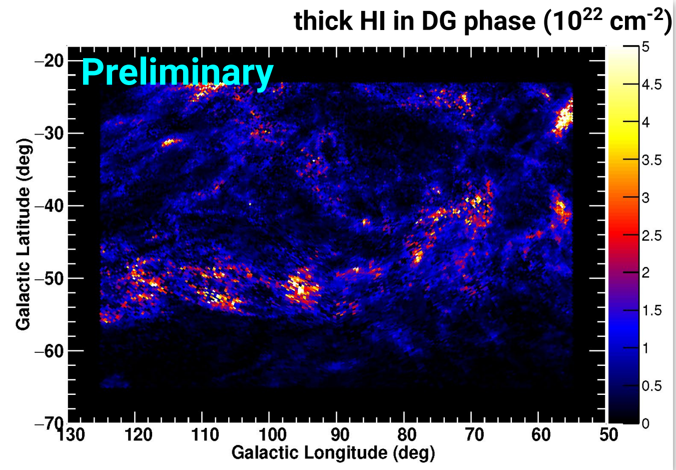
Assuming uniform CR intensity, we evaluated N_H of each gas phase

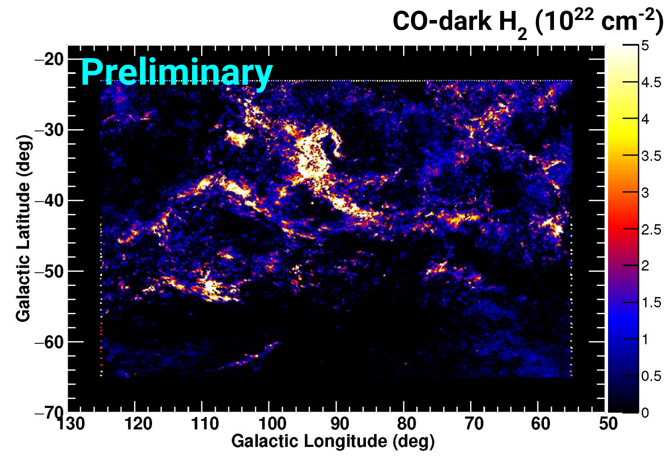
- Ratio of thick HI (in dark gas phase) and CO-dark H_2 is ~1:1
- Fraction of thick HI and CO-dark H_2 (="dark gas") to total is ~20%

phase	$\int N(H)d\Omega$ (10^{22} cm^{-2} deg^2) ($\propto$Mass)
broad HI (thin HI)	39.9 (~3×10^4 Msun for d=150pc)
narrow HI (thick HI)	26.1 (8.0 over the thin HI case)
residual gas (CO-dark H_2)	7.9
CO-bright H_2	1.1
IVC	2.8

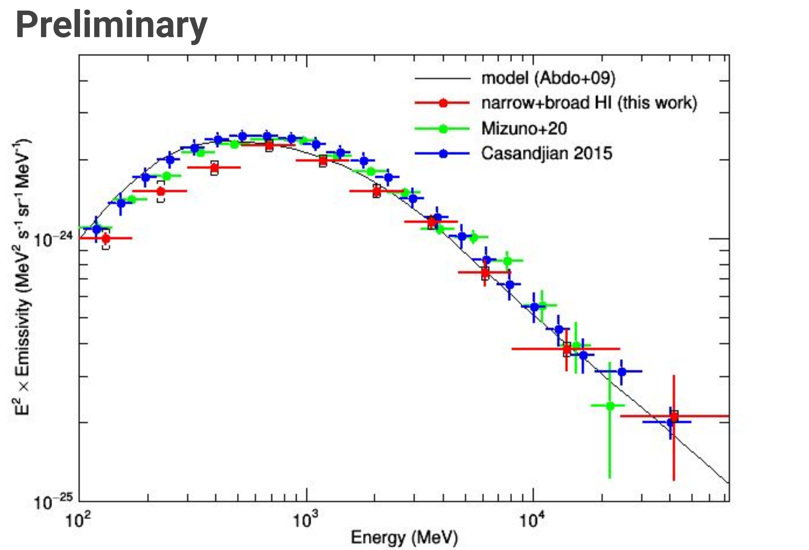
We succeed in distinguishing thick HI and CO-dark H_2

Their spatial distribution may help us understand gas evolution





Discussion 2: CR Properties



CR properties can be evaluated in detail with fewer gas templates

- We added narrow HI and broad HI templates

Emissivity (roughly) agrees with those of other studies and a model, but

- Our spectrum is <u>10-15% lower</u> than other Fermi-LAT results
- <u>Small deviation</u> from a model in low energy

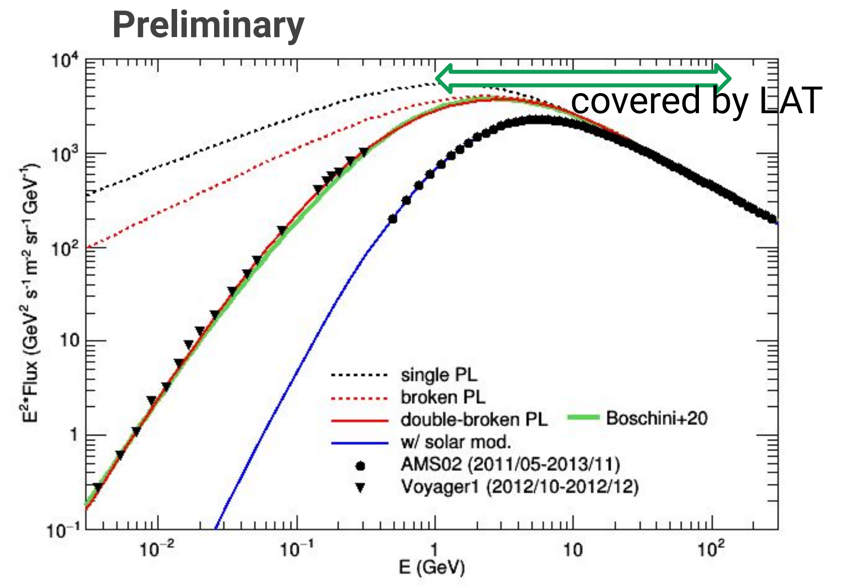
CR Properties (Contd.)

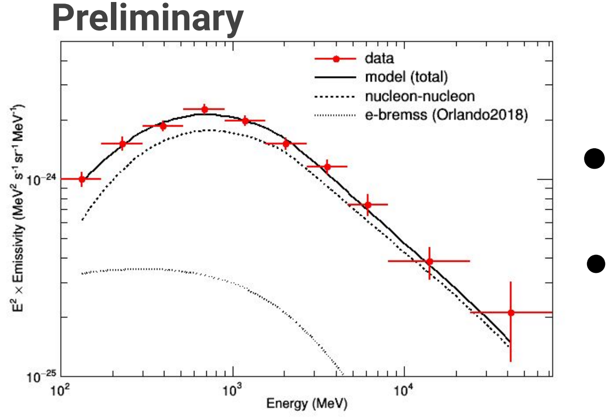
We used CR & γ-ray data constrain the LIS

- LIS is modeled as a power-law (PL) of momentum(p) with two breaks
  - α_1 and α_2 show indices in high and medium energy ranges
  - p_{br1} and δ_1 control the 1st spectral break presumably due to a break in the interstellar diffusion coefficient inferred by B/C ratio (e.g., Ptuskin+06)
  - p_{b2} and δ_2 control the 2nd break due to ionization loss (e.g., Cummings+16)
  - α_3 show the index below this break
  - force-field approximation for solar modulation
- γ-ray emissivity; p-p (Kamae+06 and AAfrag) + e-bremss (Orlando2018)
- Fit CR & γ-ray data simultaneously

$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

CR Properties (Contd.)





- 1st break due to break in D
- 2nd break due to ionization loss

$$J(p) \propto \left[\left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\mathrm{br2}}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

- LIS model reproduces data & agrees with Boschini+20 (w/ detailed CR transport in heliosphere)
- Rbr1=7.1+/-0.3 (GV) and δ1=0.07+/-0.01 (direct CR measurements give 3-5 GV)
- Scaling factor for γ-ray is 1.07+/-0.03 (relaxes ~30% discrepancy in past studies)

Summary & Future Prospect

We applied HI-line-profile based analysis to MBM53-55 clouds and Pegasus loop to investigate CR and gas properties

We succeed in distinguishing thin HI, thick HI and CO-dark H_2, and obtained the following gas/CR properties

(ISM) * thick HI: CO-dark H_2 ~ 1:1 (support the value usually assumed)
* [thick HI + CO-dark H_2]/tot ~ 20%

(CR) * Spectral break of LIS at R~7GV (direct measurements give 3-5 GV)
* LIS agrees with AMS-02 spectrum within 10% (relaxes discrepancy previously reported)

Systematic study of local regions is crucial to investigate LIS, and application to Galactic plane data is also interesting and worth doing

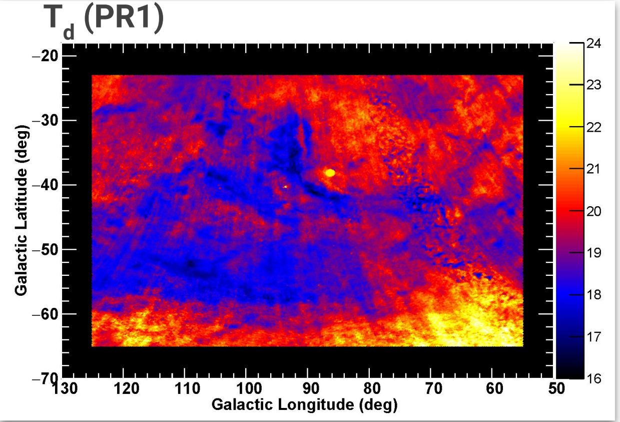
Thank you for your attention

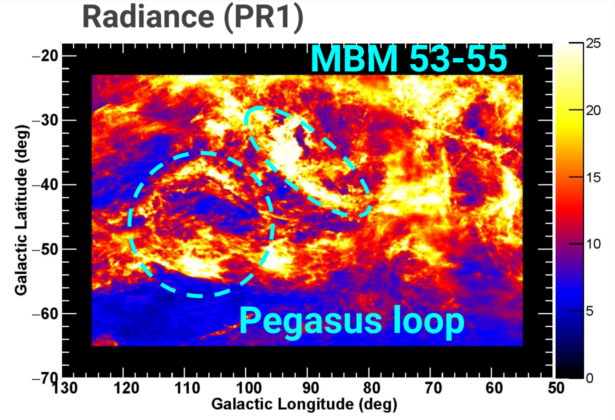
References

- Abdo+09, ApJ 703, 1249
- Boschini+20, ApJS 250, 27
- Casandjian 2015, ApJ 806, 240
- Cummings+16, ApJ 831, 18
- Fukui+14, ApJ 796, 59
- Hayashi+19, ApJ 884, 130
- Kalberla+20, A&A 639, 26
- Mizuno+16, ApJ 833, 278
- Mizuno+20, ApJ 890, 120
- Orlando 2018, MNRAS 475, 2724
- Planck Collaboration XXIV (2011), A&A 536, 24
- Porter+17, ApJ 846, 23
- Smith+2014, MNRAS 441, 1628
- Strong 2015, Proc. ICRC 34, 506
- Wolfire+2010, ApJ 716, 1191
- Yamamoto+06, ApJ 642, 307

Backup Slide

Dust Maps

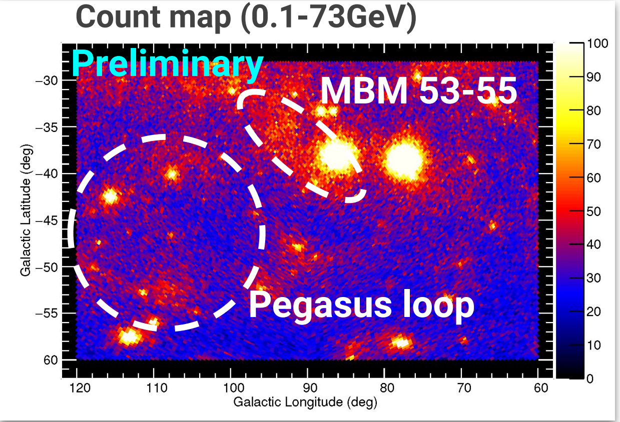




(narrow HI is associated with MBM53-55 and Pegasus loop seen in dust map)

We also employed Planck (R1 and R2) dust Radiance and tau353 maps as NH_{tot} model

Model and Analysis



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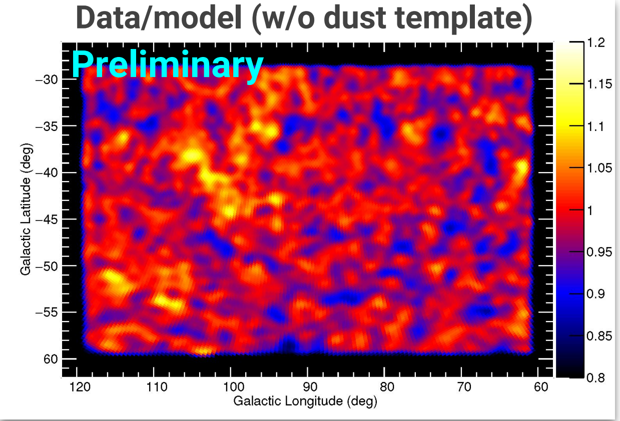
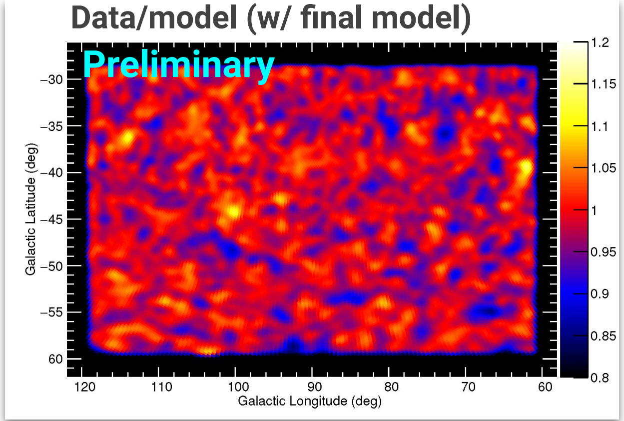
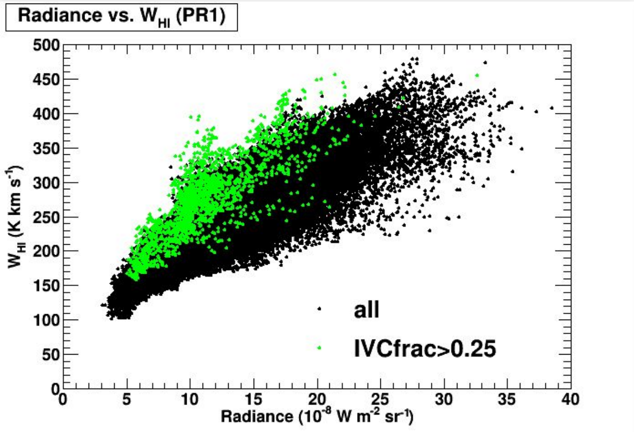
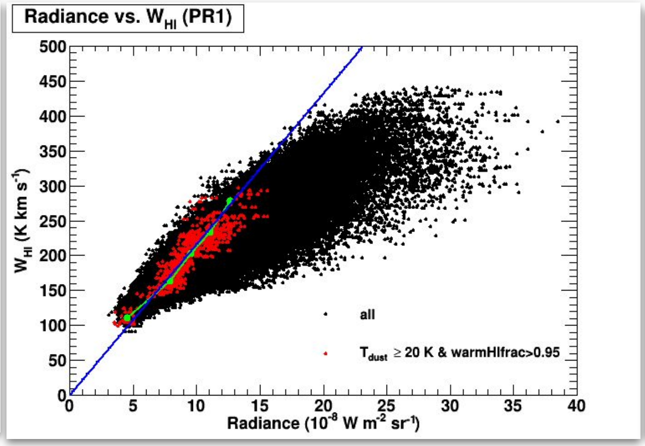


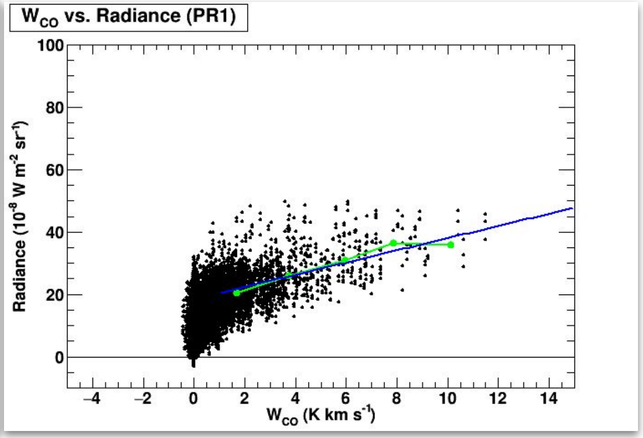


Narrow HI gives ~1.5 times larger γ-ray emissivities than broad HI => We applied a T_s correction to it and obtained a final model (btm. right)

Construction of Residual Gas Template

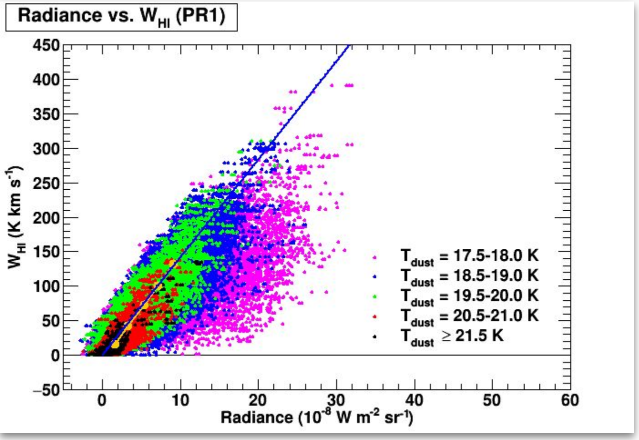


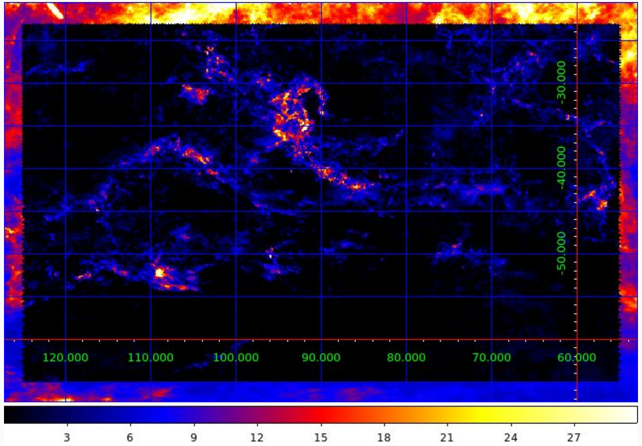




1) We found outliers in W_{HI}(tot)-Rad are affected by IVC. We removed them from W_{HI} assuming they have no dust. Now we have W_{HI}(cold+warm HI)
2) We selected "warm-HI rich" (warmHIfrac>0.95) and "high-Tdust" (>20K) area and obtained W_{HI}(warm HI)-Rad ratio. We removed "warm-HI gas" from W_{HI} and Rad using this ratio. Now we have W_{HI}(cold HI) and Rad (cold HI, CO-brightH_2 and residual gas)
3) We obtained W_{CO}-Rad ratio. We removed CO-bright H_2 from Rad using this ratio. Now we have Rad (cold HI, residual gas)

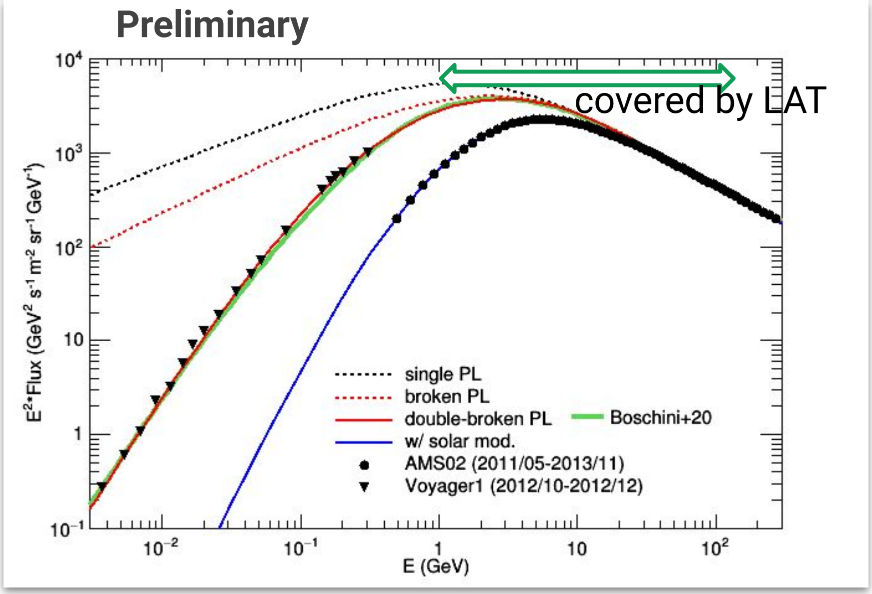
Construction of Residual Gas Template (Contd.)

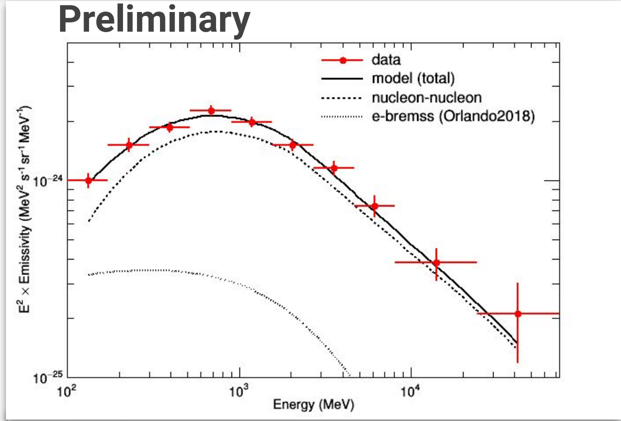




4) We selected high Tdust (>20K) area to reduce contamination from possible CO-dark H_2 and obtained W_{HI}(coldHI)-Rad ratio. We removed cold HI from W_{HI} and Rad using this ratio. Now we have Rad_res (likely associated with CO-dark H_2) and use it as residual gas template.

CR Properties (Contd.)





- 1st spectral break presumably due to a break in the interstellar diffusion coeff.
- 2nd break due to ionization loss

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We fitted CR & γ-ray data with analytical function simultaneously to constrain the LIS

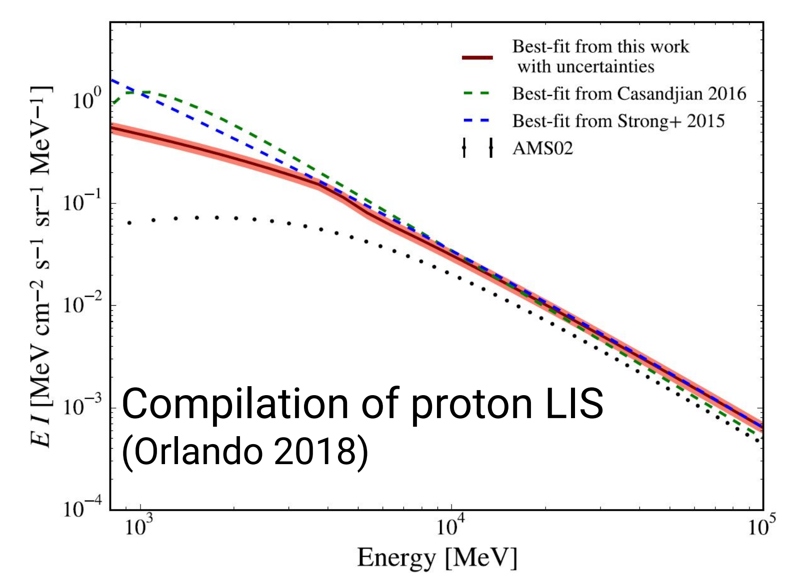
- Our model reproduces the data well, agrees with Boschini+20 (w/ detailed CR transport in heliosphere)
- Rbr1=7.1+/-0.3 (GV) andd delta1=0.07+/-0.01 (direct CR measurements give 3-5 GV)
- Scaling factor for γ-ray is 1.07+/-0.03 (relaxes ~30% discrepancy in past studies)

Proton LIS based on γ-ray Emissivities

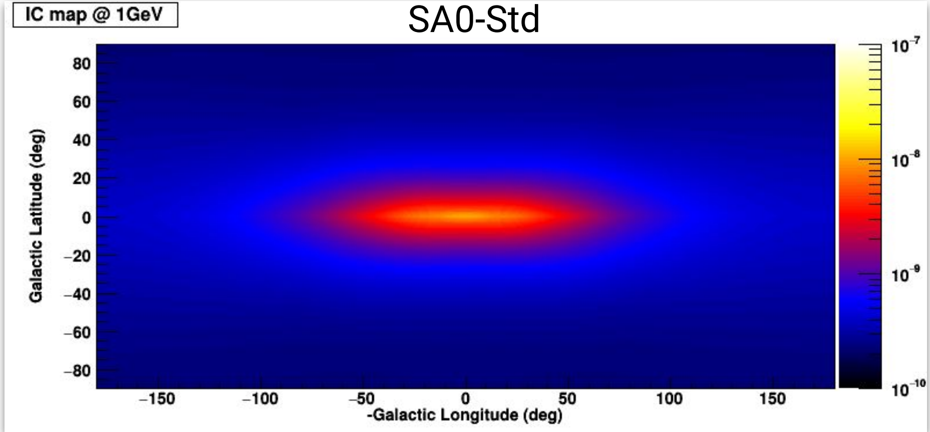
Several studies (Strong 2015, Orlando 2018) used γ-ray emissivity (Casandjian 2015) and reported ~30% larger proton LIS than that expected by measurements at the Earth

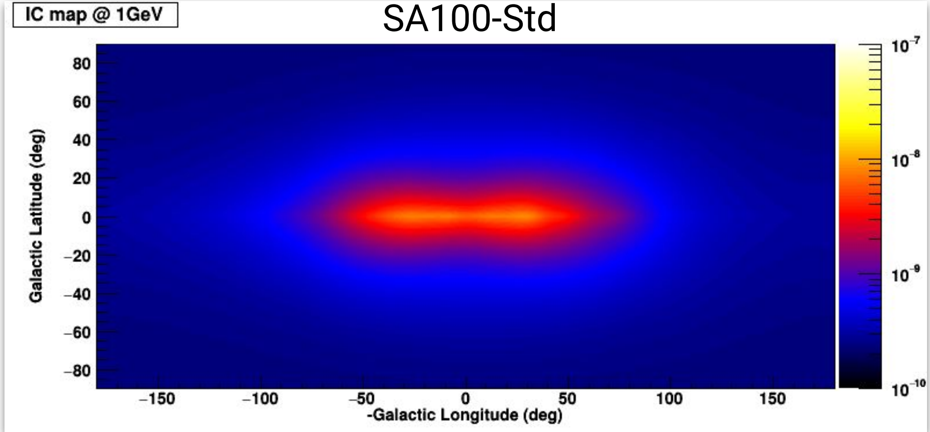
Our new emissivity is 10-15% lower, giving LIS consistent with AMS-02 spectrum within 10%

- It is based on a particular area in the sky; systematic study of local regions is crucial to settle the issue and investigate possible local variation of CR spectrum



Testing IC Models





We tested 9 IC models (3 CR distributions, 3 ISRFs) and a model used in Mizuno+16 (54_77Xvarh7S) against gamma-ray data using 3Hi+CO gas template

SA0 gives the best fit and difference among 3 ISRF minor. So we will use SA0-Std in this study

T_S Correction

Assuming a single brightness temperature (Tp) for simplicity, radiative transfer gives W_{HI} and optical depth of HI (Tau_{HI}) as a function of ΔV_{HI} ($=W_{HI}/Tp$) (Fukui+14)

$$W_{\rm H\,I}(\text{main})\,(\text{K km s}^{-1}) = [T_s\,(\text{K}) - T_{\rm bg}\,(\text{K})] \cdot \Delta V_{\rm H\,I}\,(\text{km s}^{-1}) \cdot [1 - \exp(-\tau_{\rm H\,I}(\text{main}))], \quad (3)$$

$$\tau_{\rm H\,I}(\text{main}) = \frac{N_{\rm H\,I}(\text{main})\,(\text{cm}^{-2})}{1.823 \times 10^{18}} \cdot \frac{1}{T_s\,(\text{K})} \cdot \frac{1}{\Delta V_{\rm H\,I}\,(\text{km s}^{-1})}, \quad (4)$$

Then, we have total column density as

$$N_{\rm H} = -1.82 \times 10^{18} \cdot T_S \cdot \Delta V_{\rm HI} \cdot \log\left[1 - \frac{W_{\rm HI}}{(T_S - T_{\rm bg})\Delta V_{\rm HI}}\right]$$