HI 21cm線プロファイル・ダスト放射・ガンマ線を用いた, MBM 53-55分子雲・Pegasus loop領域における星間ガスと宇宙線の研究

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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 & CRs

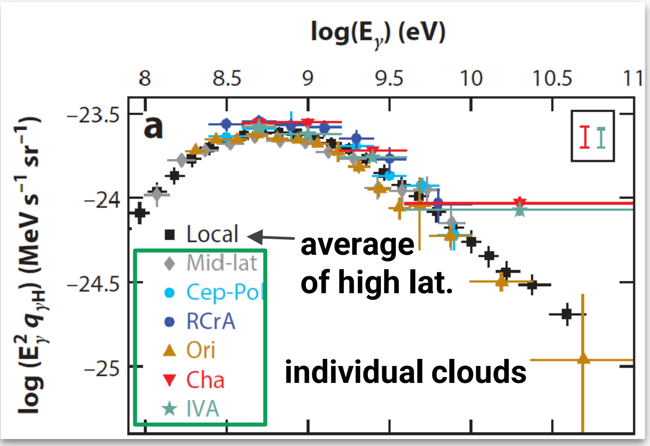
I_{CR} ($\propto I_\gamma / N_H$)

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

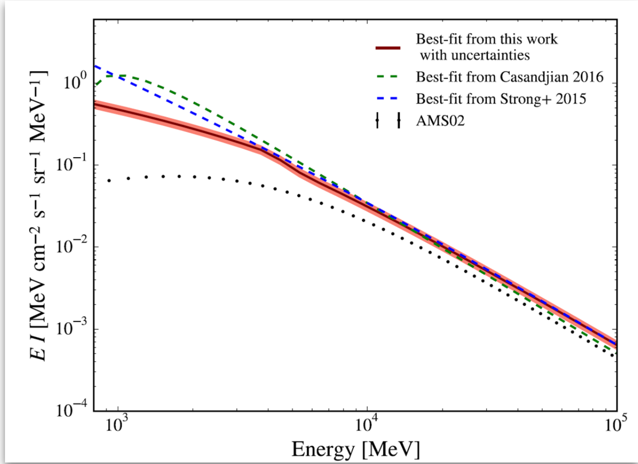
Issue: Uncertainty is still large (factor of ~1.5) even in local environment

Key: Identify optically thin HI ($N_{HI} \propto W_{HI}$)

γ-ray emissivity



Proton LIS (Local Interstellar Spectrum)



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

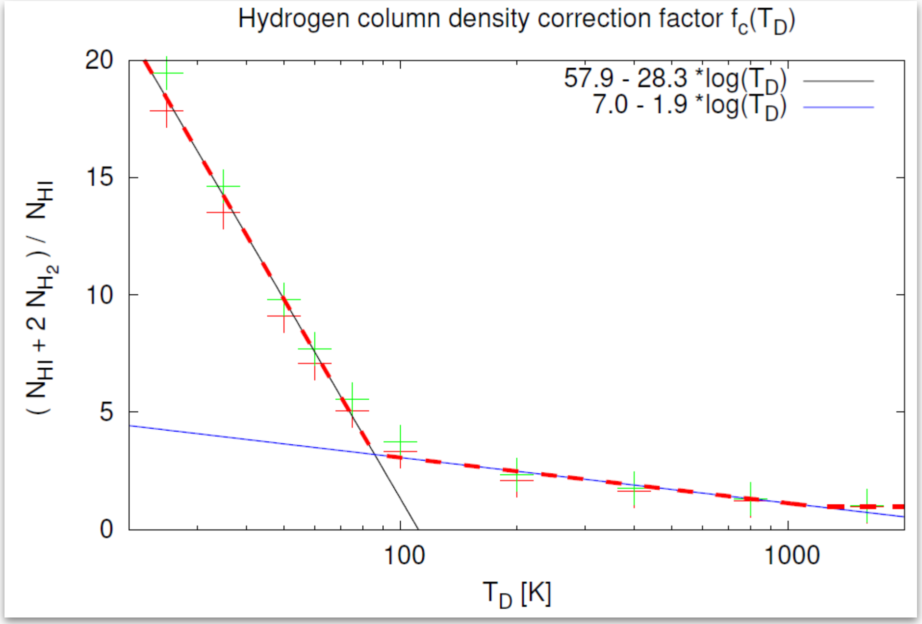
Local γ-ray emissivity is known to be ~30% larger than expected by CR measurements (Strong 2015, Orlando 2018)

Possible Solution: Using HI-line Profiles

(see also Heiless & Troland 03)

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

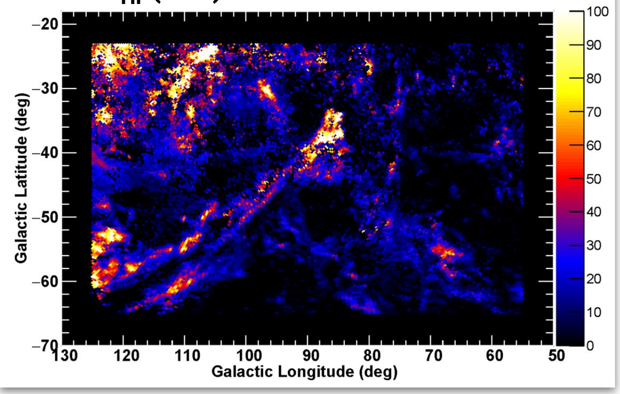
- T_D (Doppler temperature)=$22*\delta v^2$
- Vertical axis shows ratio of N_H^{tot} to N_{HI}^{thin} (estimated using dust emission)
- Areas of ratio>1 (dark-gas rich) are with narrow HI line



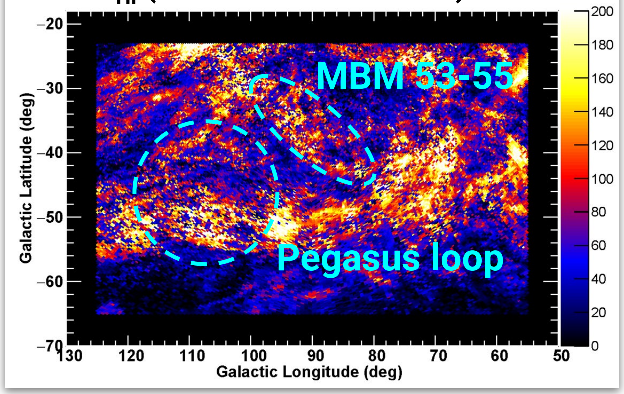
To (validate the work and) estimate CR & ISM gas accurately, we employed HI-line-profile based analysis to MBM 53-55 clouds and Pegasus loop (Mizuno+16)

ISM Gas Maps: HI, CO, dust (residual)

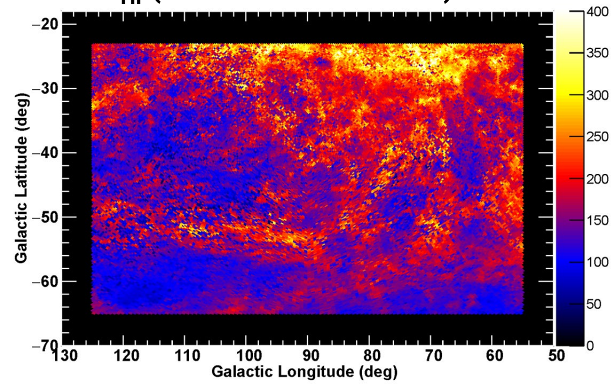
W_{HI} (IVC)



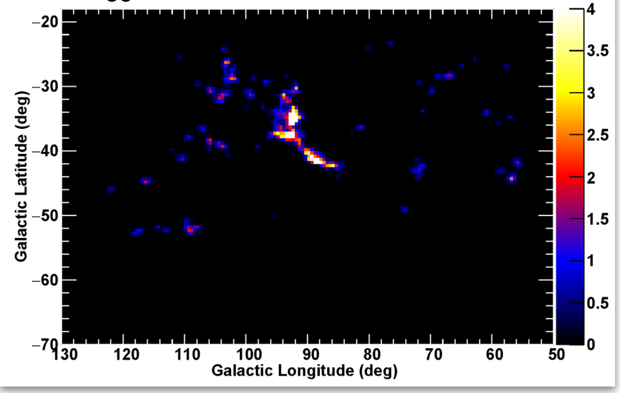
W_{HI} (w/ narrow linewidths)



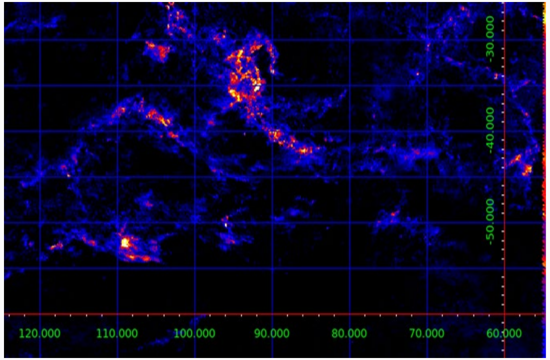
W_{HI} (w/ broad linewidths)



W_{CO}



Residual gas template (dust Radiance)

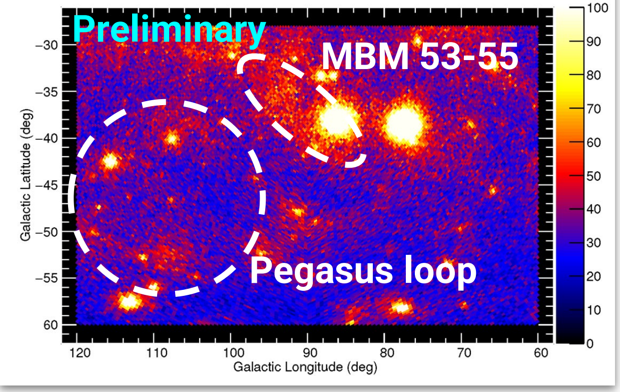


3W_{HI} and W_{CO} maps (K km/s)

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

Residual gas found and modeled using dust Radiance

Count map (0.1-73GeV)

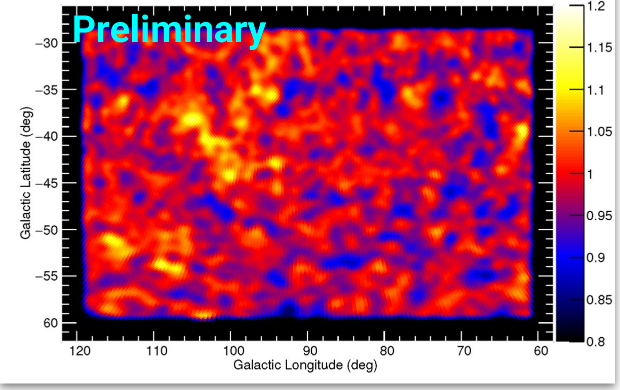


Residual gas found (btm. left) and modeled using dust Radiance

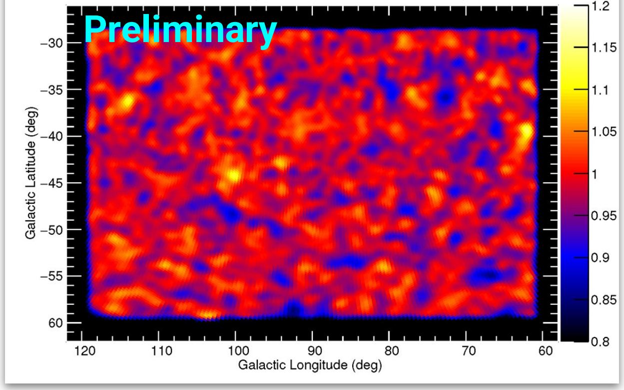
We succeeded in reproducing data with $3W_{HI}$(IVC, narrow HI, broad HI)+W_{CO}+D_{res}+Iso+IC+sources

Narrow HI gives ~1.5 times larger γ-ray emissivities than broad HI => agree with expectations (“broad HI” = “thin HI”, “narrow HI” = “w/ dark gas”)

Data/model (w/o dust template)



Data/model (w/ final model)

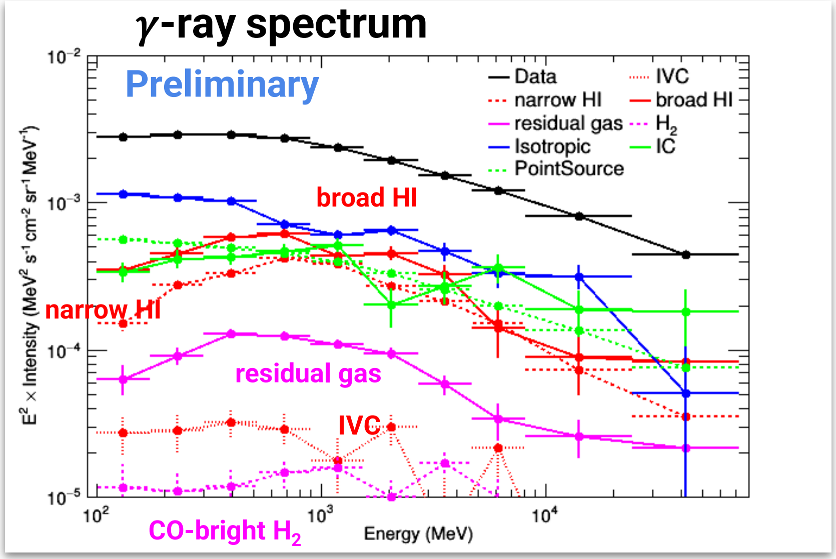


Results with Final Model

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

- IVC, narrow HI, broad HI, Wco, dust_res
- Isotropic, Inverse Compton, γ-ray sources

Spectrum of each component shows relative contribution of each gas phase



broad HI = thin HI

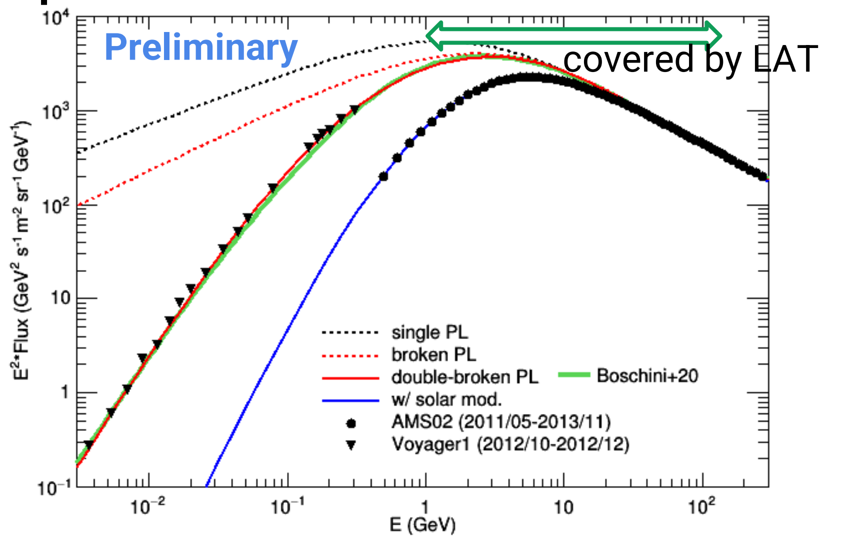
narrow HI = thick HI

residual gas = CO-dark H_2

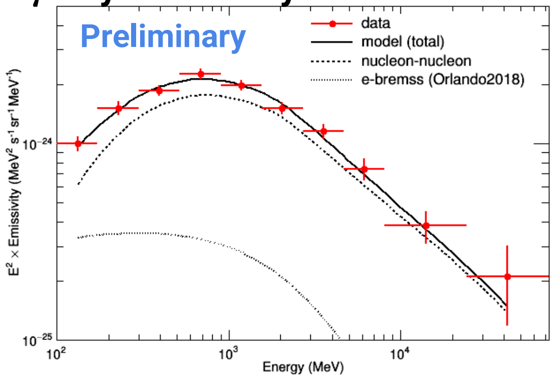
[mass of N_{HI}^{thick} (over thin HI case) ~ mass of CO-dark H_2]

CR Properties

proton LIS



γ-ray emissivity



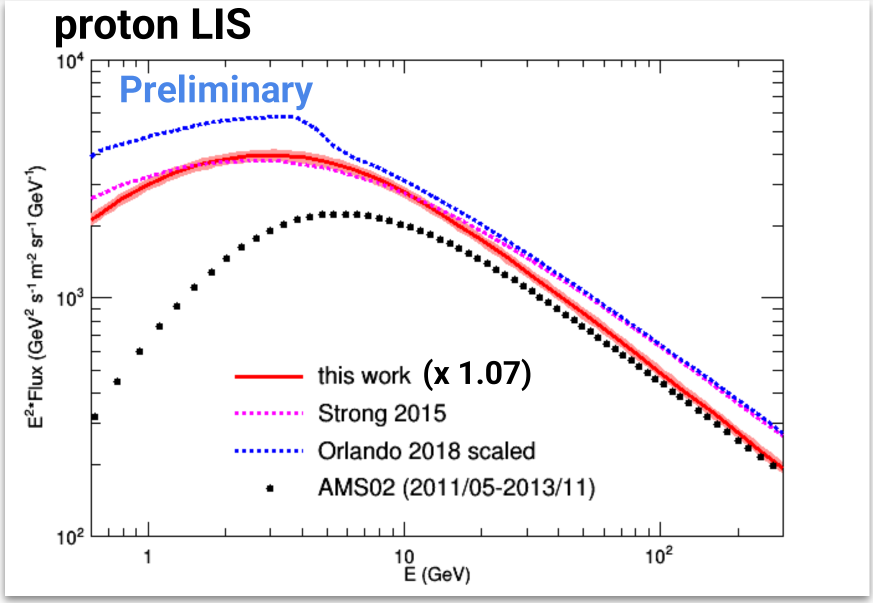
- 1st spectral break presumably due to a break in the interstellar diffusion coeff.
- 2nd break due to ionization loss
- CR α and ISM He are taken into account

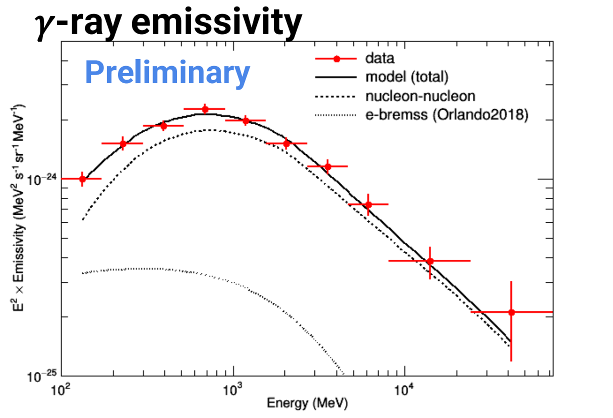
$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

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) and delta1=0.07+/-0.01 (B/C ratio, etc. give 3-5 GV)
- Scaling factor for γ-ray is 1.07+/-0.03

CR Properties (Contd.)





- 1st spectral break presumably due to a break in the interstellar diffusion coeff.
- 2nd break due to ionization loss
- CR α and ISM He are taken into account

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

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) and delta1=0.07+/-0.01 (B/C ratio, etc. give 3-5 GV)
- γ-ray emissivity agrees with CR measurements within 10% (solves ~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 CR properties

- Spectral break of LIS at R~7 GV (direct measurements give 3-5 GV)
- LIS agrees with AMS-02 spectrum within 10% (solves discrepancy in past studies)

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
- Heiless & Troland 03, ApJ 586, 1067
- 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

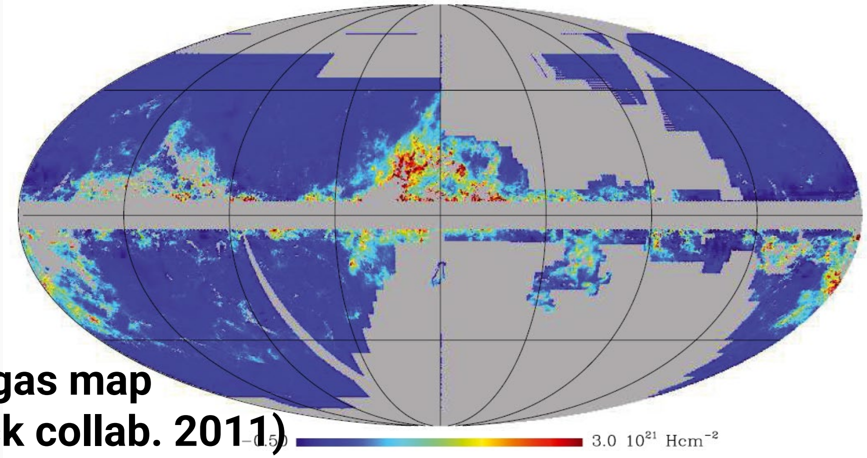
Backup Slide

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)



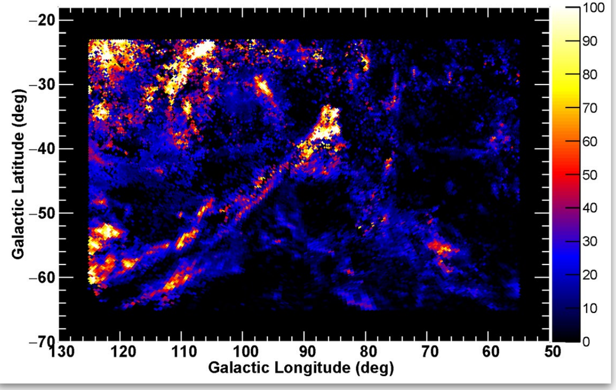
Dark gas map (Planck collab. 2011)

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

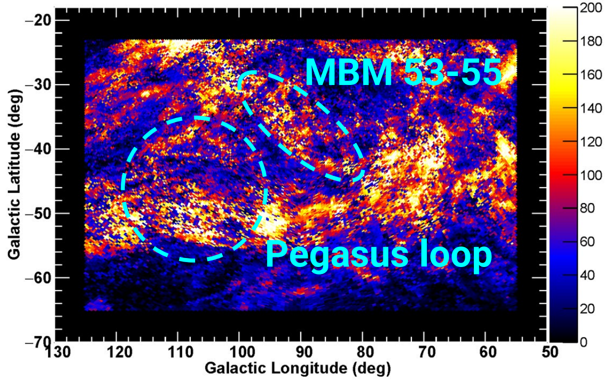
- optically thick HI and CO-dark H_2
- gas phases along the line of sight

ISM Gas Maps (HI & CO)

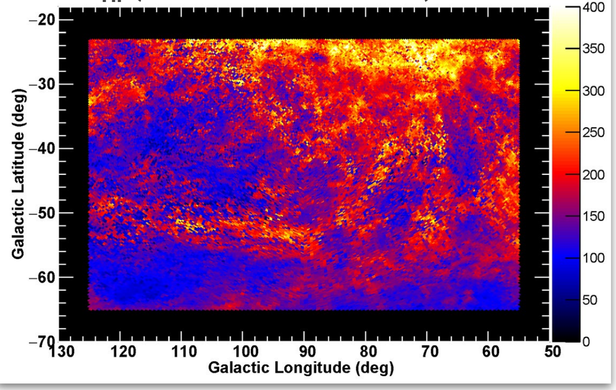
W_{HI} (IVC)



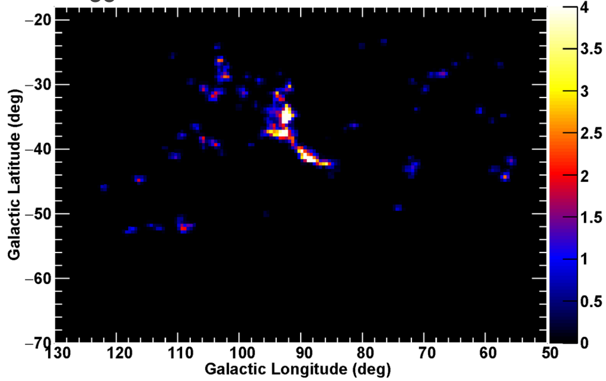
W_{HI} (w/ narrow linewidths)



W_{HI} (w/ broad linewidths)



W_{CO}



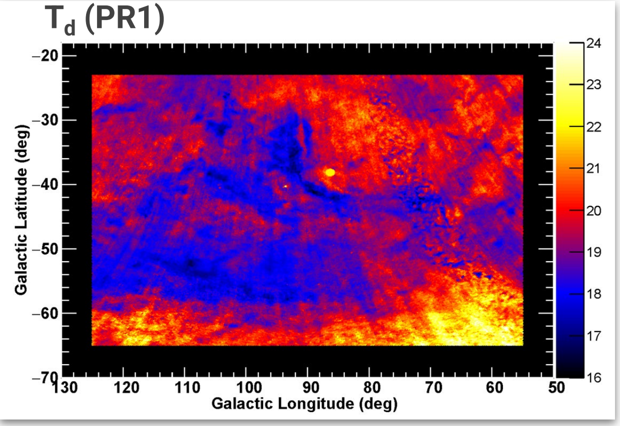
We prepared 3W_{HI} and W_{CO} maps (K km/s) as initial gas model

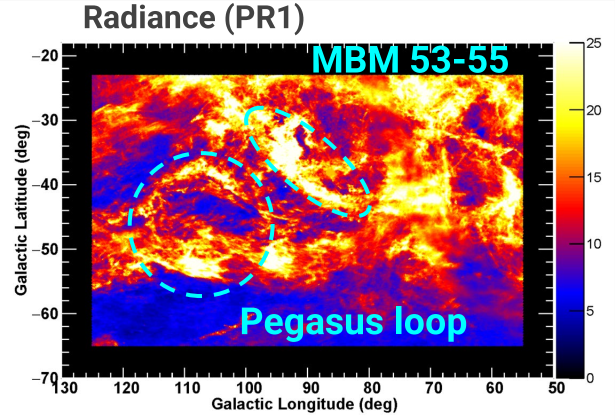
intermediate velocity cloud

- 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)

Dust Maps

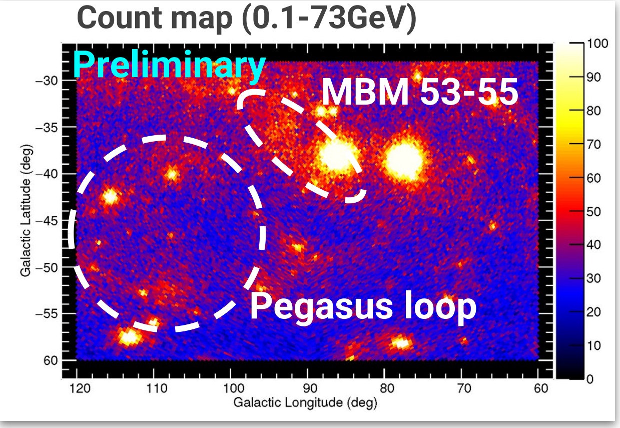




(narrow HI is associated with MBM53-55 and Pegasus loop seen in dust map)

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

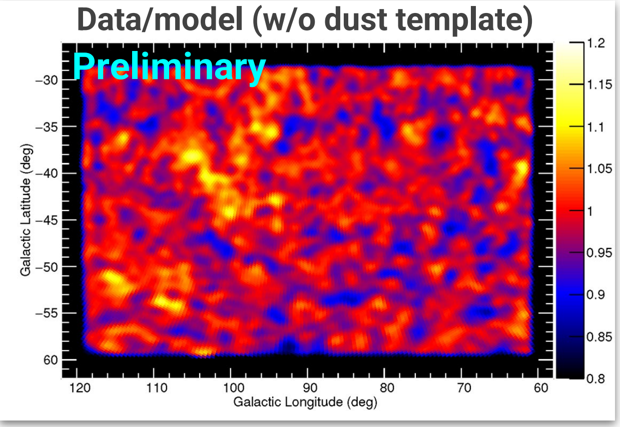
Model and Analysis

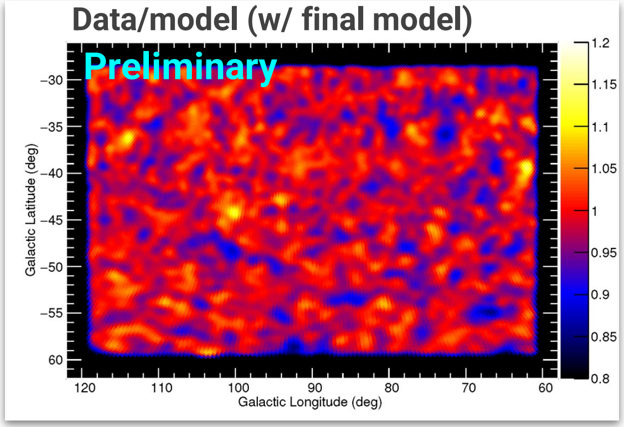


First modeled data with $3W_{HI}+W_{CO}$+Iso+IC+sources and observed residuals in MBM53-55 and Pegasus loop (btm. left)

Then applied a correction proposed by Kalbarla+20 (p3), but residual remains => HI not fully trace gas (even w/ linewidth info.)

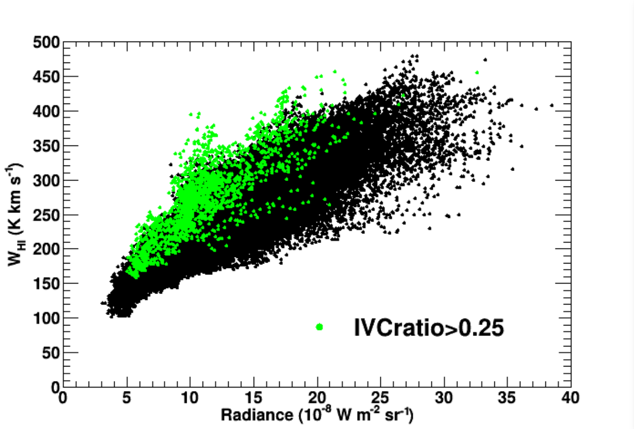
So we employed dust maps to model residual gas

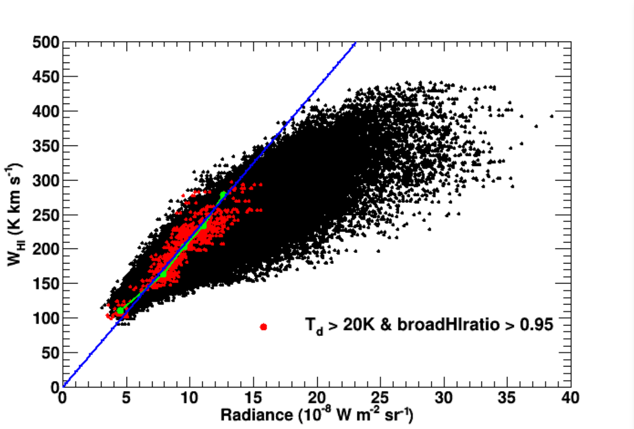


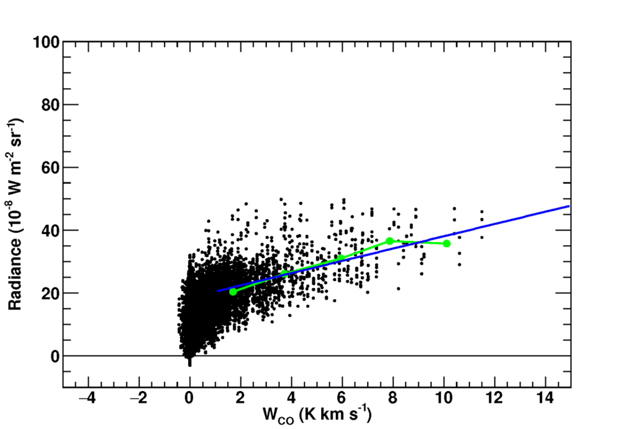


Narrow HI gives ~1.5 times larger γ-ray emissivities than broad HI => We applied a T_s correction to it and obtained a final model (btm. right)

Construction of Residual Gas Template

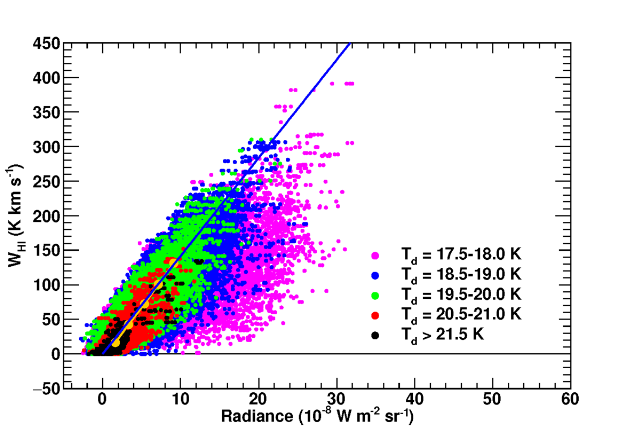


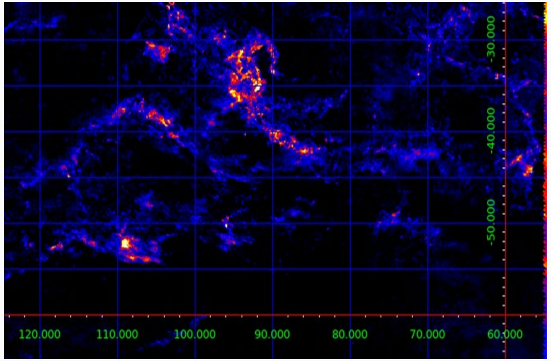




1) We found outliers in W_{HI}(tot)-Rad are affected by IVC. We removed them from W_{HI} assuming they have no dust. Now we have W_{HI}(narrow+broad HI)
2) We selected “warm-HI rich” (warmHIfrac>0.95) and “high-Tdust” (>20K) area and obtained W_{HI}(broad HI)-Rad ratio. We removed “broad HI gas” from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

Construction of Residual Gas Template (Contd.)





4) We selected high Tdust (>20K) area to reduce contamination from residual gas and obtained W_{HI}(narrow HI)-Rad ratio. We removed narrow HI from W_{HI} and Rad using this ratio. Now we have Rad_res and use it as residual gas template.

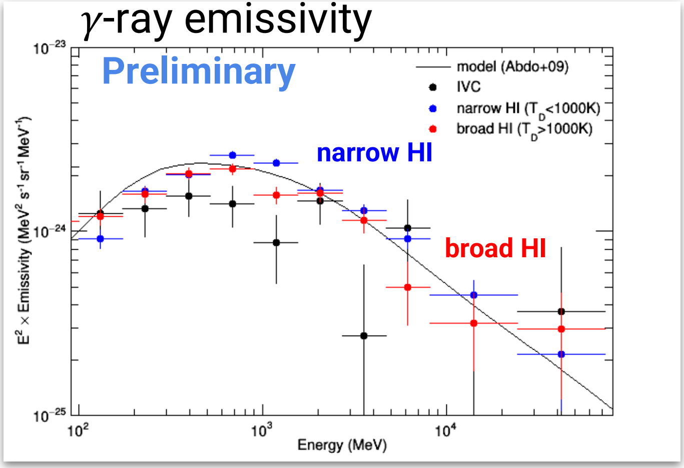
Results with Final Model

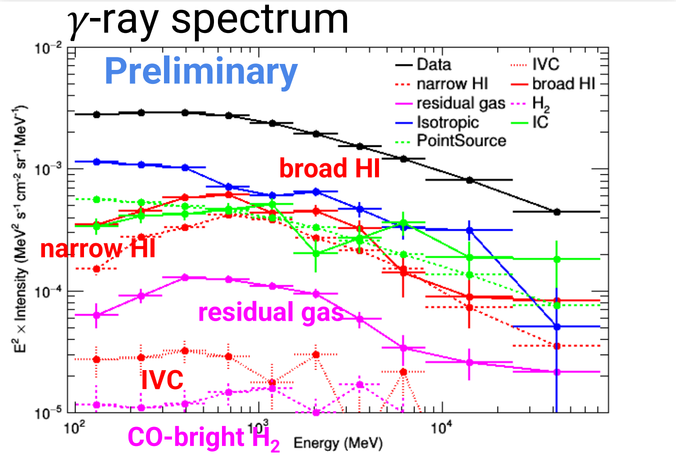
Final model reproduces the data well (see prev. slide)

- IVC, narrow HI (w/ optical depth correction), broad HI, Wco, dust_res
- Isotropic, Inverse Compton, γ-ray sources

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





broad HI = thin HI

narrow HI = thick HI

residual gas = CO-dark H_2

[mass of N_H^{thick} (over thin HI case) ~ mass of CO-dark H_2]

Discussion 1: ISM Gas Properties

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

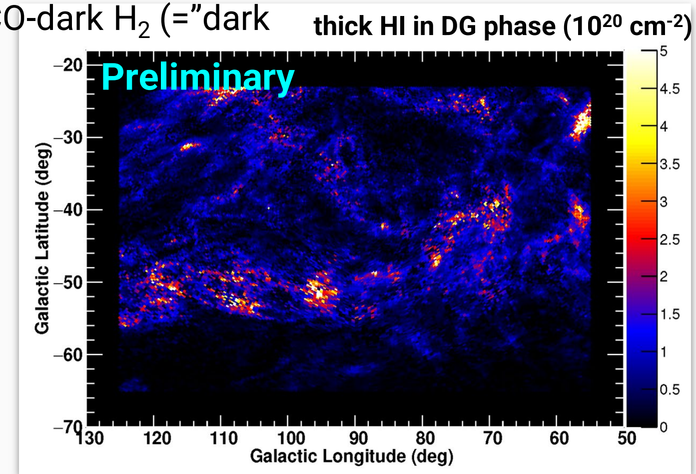
Assuming uniform CR intensity, we evaluated N_H of each gas phase

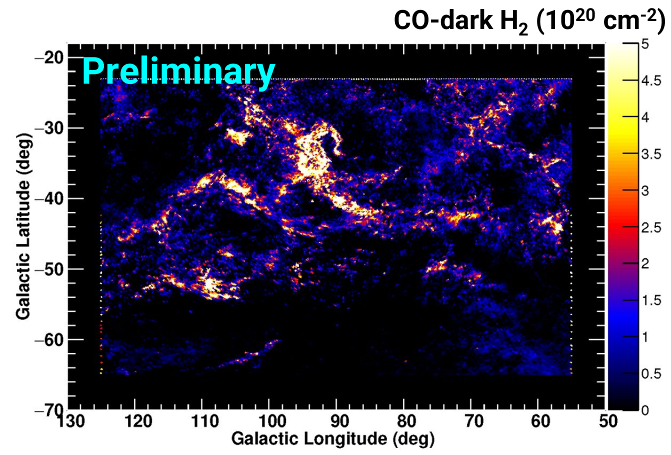
- Ratio of thick HI (in dark gas phase) and CO-dark H_2 is ~1:1
- Fraction of thick HI and CO-dark H_2 (=”dark gas”) to total is ~20%

We succeed in distinguishing thick HI and CO-dark H_2

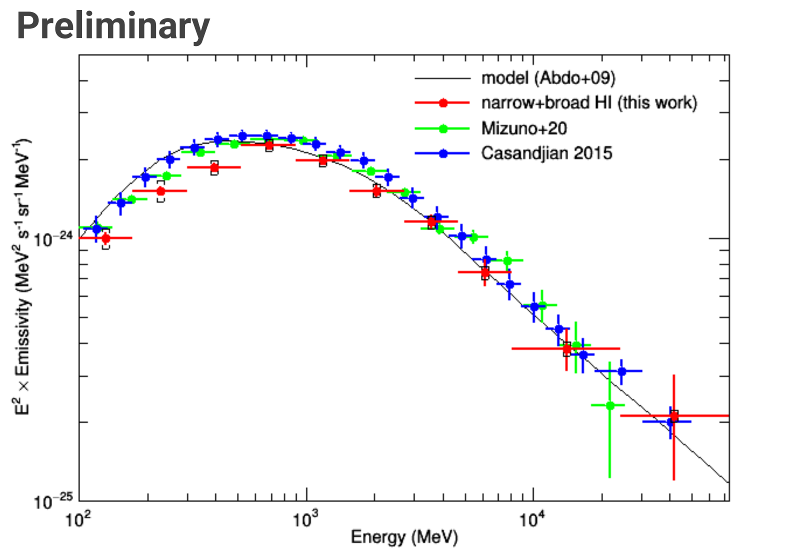
Their spatial distribution may help us understand gas evolution

phase	∫N(H)dΩ (10^{22} cm^{-2} deg^2) (∝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





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 10-15% lower than other Fermi-LAT results
- Small deviation 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 (p, He) & γ-ray data simultaneously

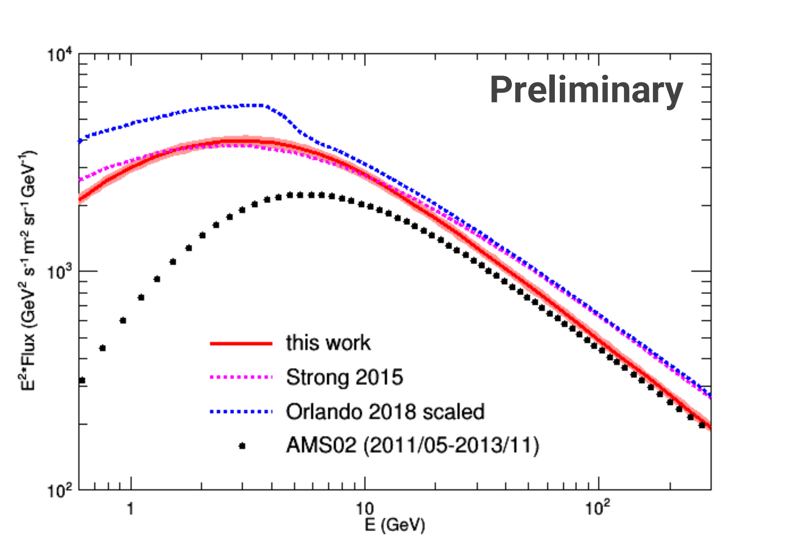
$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

Proton LIS based on γ-ray Emissivities

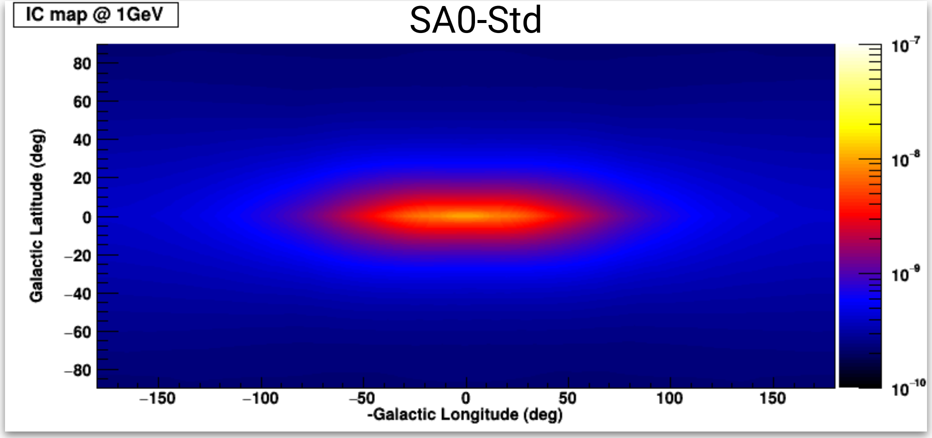
Several studies (Strong 2015, Orlando 2018) used γ-ray emissivity (Casandjian 2015) and reported ~30% larger proton LIS than that expected by measurements at the Earth

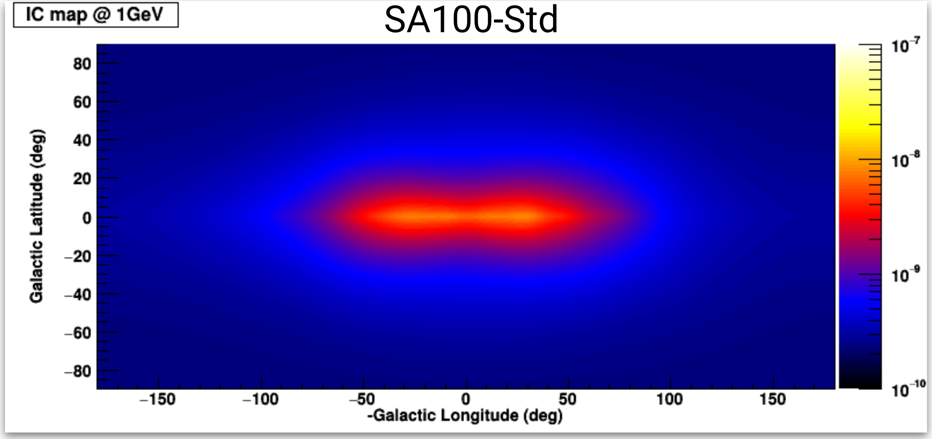
Our new emissivity is 10-15% lower, giving LIS consistent with AMS-02 spectrum within 10%

- 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)

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

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

Then, we have total column density as

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