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Fermi

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

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(Mizuno+22, ApJ 935, 97)

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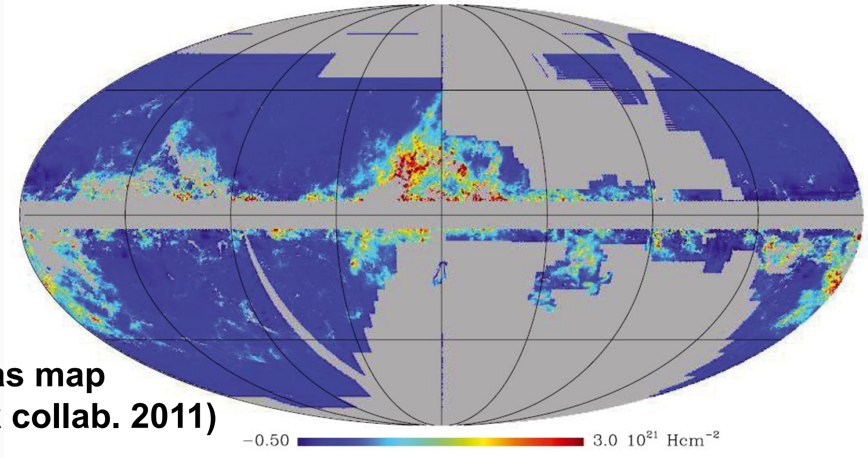
Motivation: Gas and CRs in Milky Way

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 gas phases (presumably optically thick HI and CO-dark H_2) => uncertainty of N_H

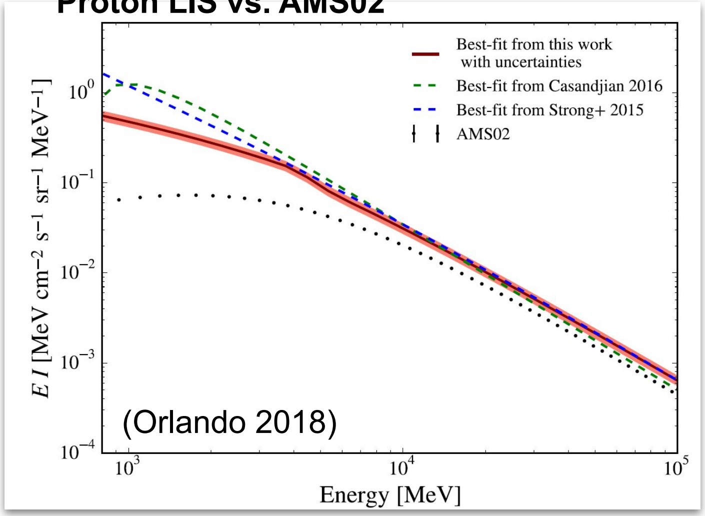
Motivation: Gas and CRs in Milky Way

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

Proton LIS vs. AMS02



LIS (Local Interstellar Spectrum) inferred by γ-ray emissivity is known to be ~30% larger than expected by CR measurements

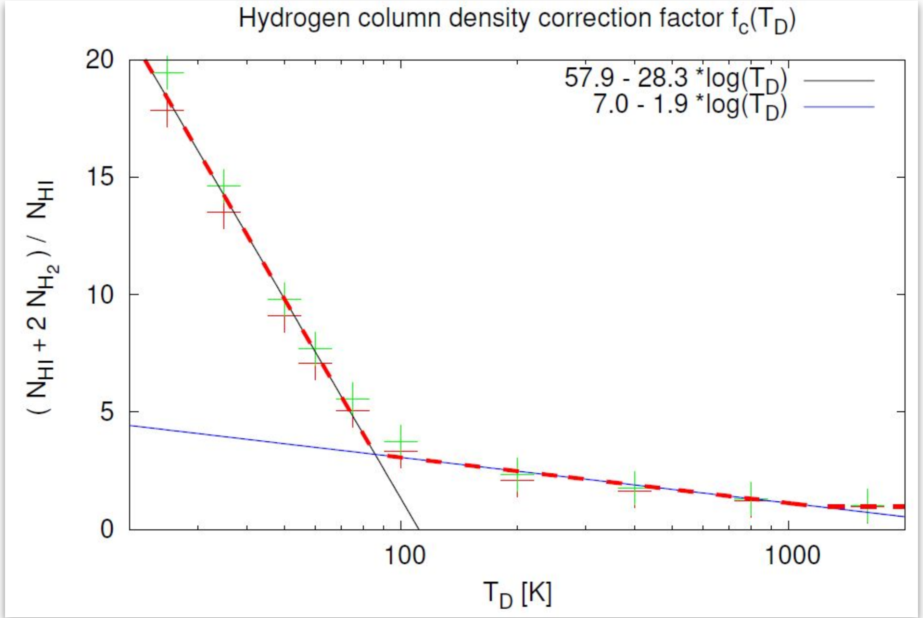
Key: Identify optically thin HI ($N_{HI} \propto W_{HI}$)

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

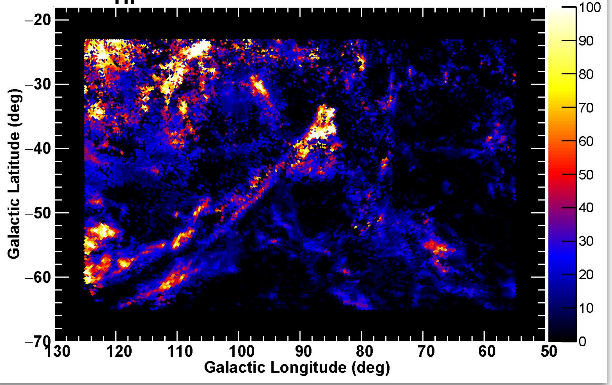
- T_D (Doppler temperature)=22*δv^2
- Vertical axis shows ratio of N_H^{tot} to N_{HI}^{thin} (estimated using dust emission)
- Areas of ratio>1 (dark-gas rich) are with narrow-line HI



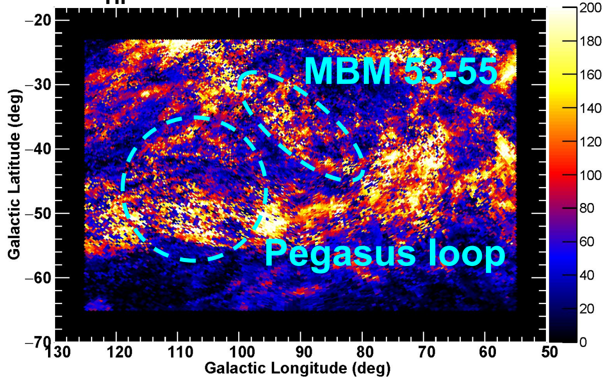
To estimate ISM gas & CRs accurately, we used HI-line-profile-based analysis on Fermi data of MBM 53-55 clouds and Pegasus loop (<u>γ-ray is a robust tracer</u> of N_H^{tot})

ISM Gas Maps: HI, CO, Dust (Residual)

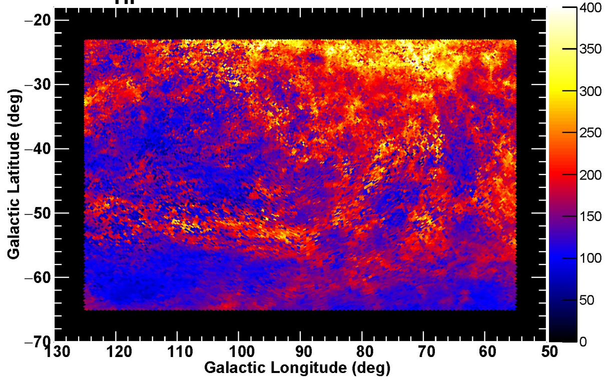
W_{HI} (IVC)



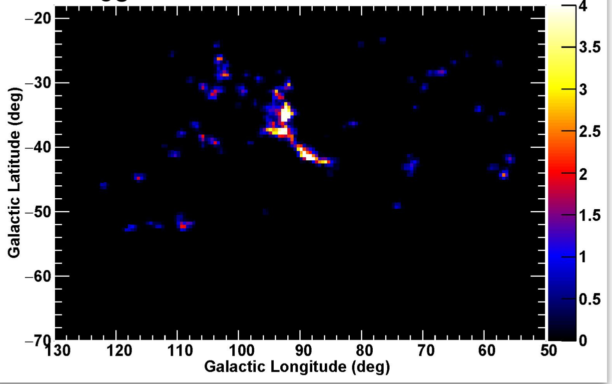
W_{HI} (w/ narrow linewidths)



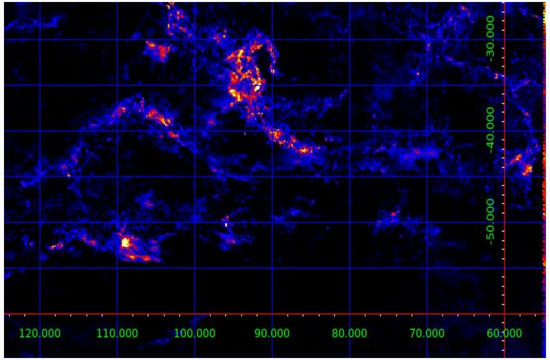
W_{HI} (w/ broad linewidths)



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)

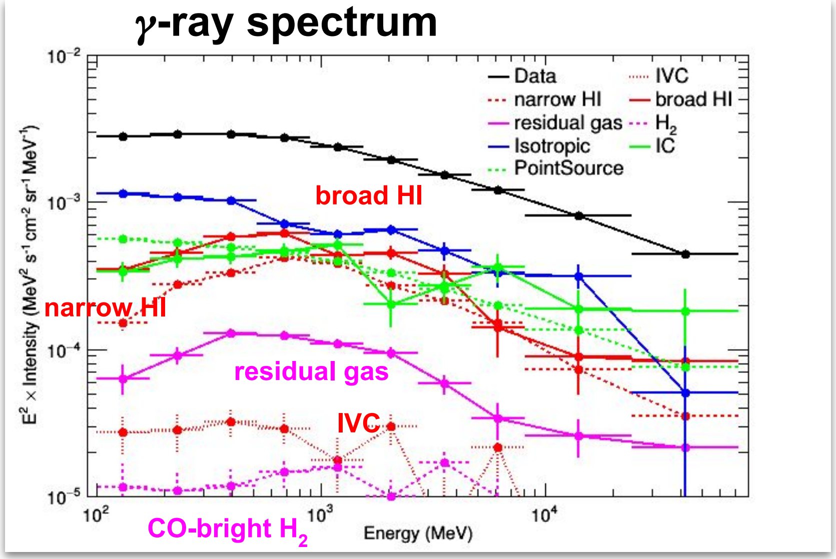
(+IC, iso, src)

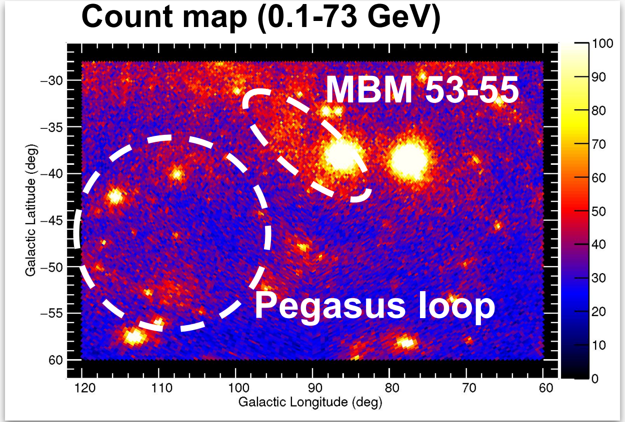
Residual found and modeled using dust Radiance

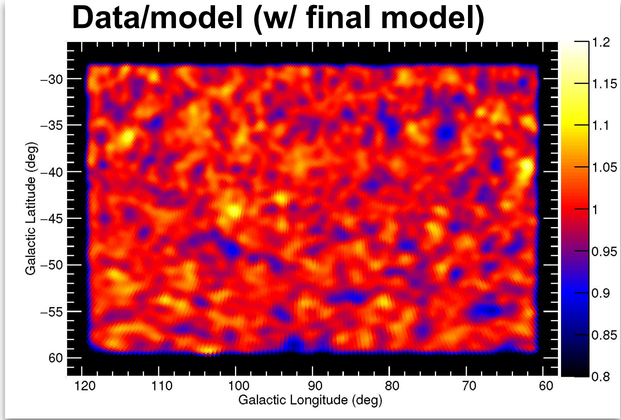
Results with Final Model

Final model reproduces the data well

- ISM Gas: IVC, narrow HI, broad HI, Wco, dust_res







Norm of each component tells relative contribution of each gas phase

Emissivity (I_γ/N_H) of broad HI tells CR spectrum

Discussion 1: ISM Gas Properties

We interpret broad HI=thin HI, narrow HI=thick HI, residual gas=CO-dark H_2

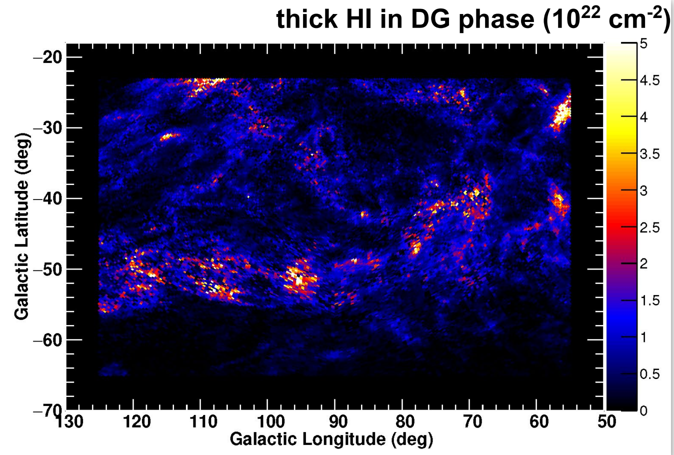
Assuming uniform CR intensity, we evaluated N_H (∝ mass) of each gas phase

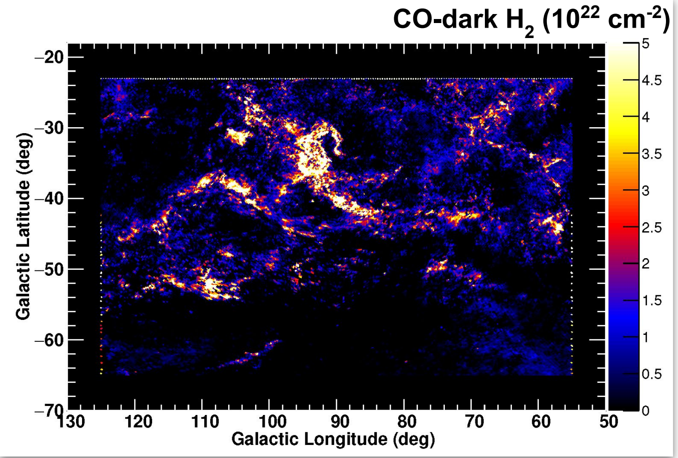
- Ratio of thick HI (in dark gas phase) and CO-dark H_2 is ~1:1
- Fraction of thick HI and CO-dark H_2 (="dark gas") to total is ~20%

phase	∫N(H)dΩ (10^{22} cm^{-2} deg^2) (∝ Mass)
broad HI (thin HI)	39.9
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

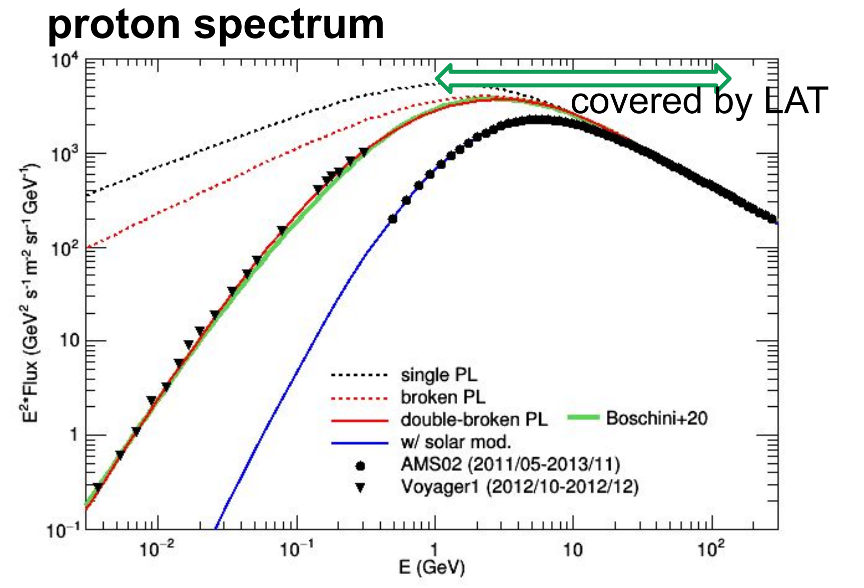
We succeed in distinguishing between thick HI and CO-dark H_2

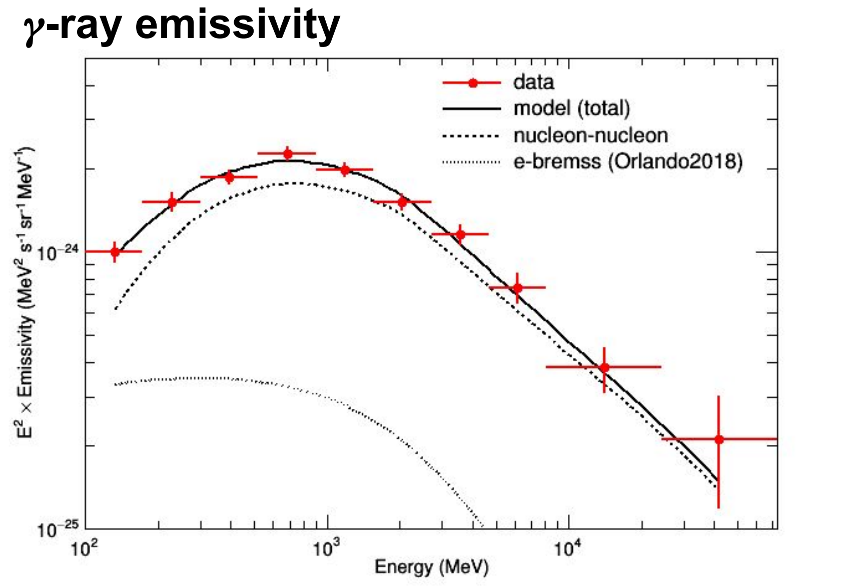
Their spatial distributions may help us understand gas evolution





Discussion 2: CR Properties

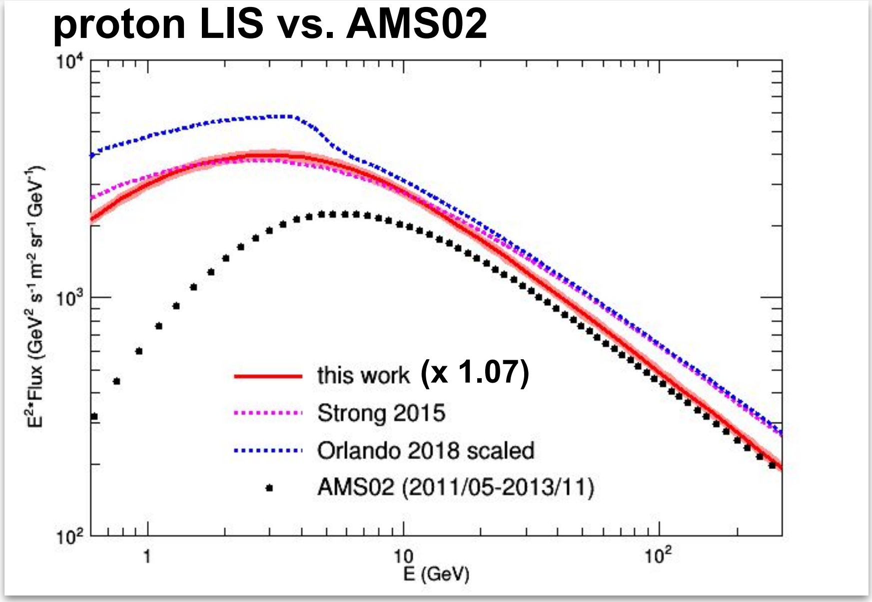




We modeled LIS by PL of momentum w/ two breaks (to represent a break in interstellar D and ionization loss), and fit CR (AMS02, Voyager1) and γ-ray data simultaneously

- Scaling factor for γ-ray is 1.07+/-0.03
- R_{br1}=7.1+/-0.3 (GV)

Discussion 2: CR Properties (Cont'd)



- Scaling factor for γ-ray is 1.07+/-0.03 (solves ~30 % discrepancy in past studies)
  - Can use direct meas. as a reference for LIS
- R_{br1}=7.1+/-0.3 (GV) (agrees with a break in D indicated by B/C ratio)
  - Provide independent proof of a break

Our study also opens possibilities for future studies:

- Investigate a possible local variation of the CR spectrum (by systematic study of local regions)
- Investigate a possible (additional) break in CR injection spectrum (by detailed study of γ-ray spectrum)
- Investigate CR intensity distribution in the MW (by studying γ-ray emission of Galactic plane)

Summary & Future Prospect

We used HI-line-profile-based analysis on MBM 53-55 clouds and Pegasus loop to investigate ISM gas and CR properties

ISM gas: Succeed in distinguishing among thin HI, thick HI and CO-dark H_2

- Their spatial distributions may help us understand gas evolution

CR: Succeed in simultaneously reproducing CR and gamma-ray data

- LIS agrees with AMS-02 spectrum within 10% (solves discrepancy in past studies)
- Spectral break of LIS at R~7 GV (independent measurement of a break in LIS)

Systematic study of local regions is crucial to investigate gas & CRs in detail, and application to Galactic plane is interesting and worth doing

Thank you for your attention

References

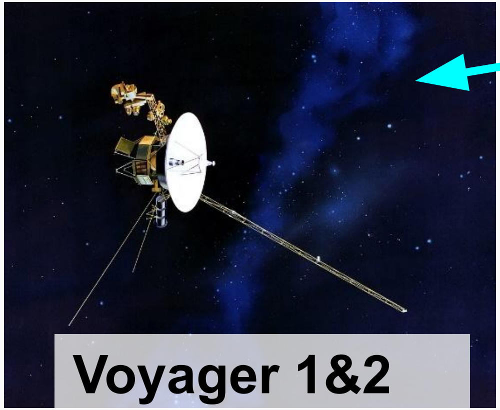
- Abdo+09, ApJ 703, 1249
- Boschini+20, ApJS 250, 27
- Casandjian 2015, ApJ 806, 240
- Cummings+16, ApJ 831, 18
- Fukui+14, ApJ 796, 59
- Grenier+ 2015, ARAA 53, 199
- Hayashi+19, ApJ 884, 130
- Heiless & Troland 03, ApJ 586, 1067
- Kalberla+20, A&A 639, 26
- Mizuno+16, ApJ 833, 278
- Mizuno+20, ApJ 890, 120
- Mizuno+22, ApJ 935, 97
- 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

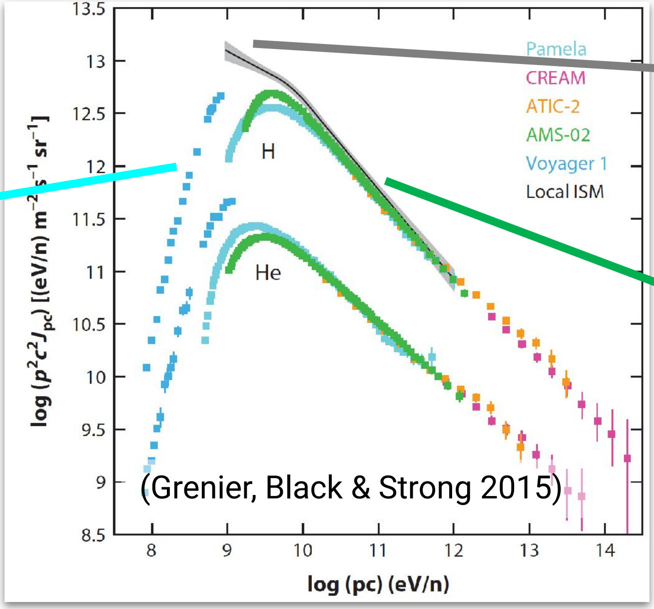
Motivation: Gas and CRs in Milky Way

Goal: Accurately measure CRs in Milky Way (local and Galactic scale) to understand their origin and propagation

Method: AMS-02, Voyager and Fermi-LAT provide vital and complementary information

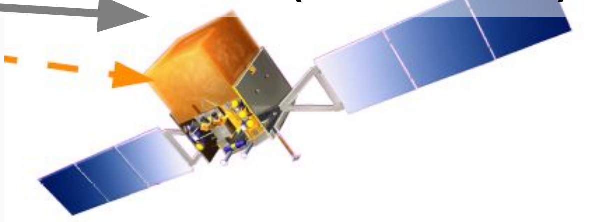


Voyager 1&2
(in Situ meas.)



(Grenier, Black & Strong 2015)

Fermi-LAT (distant loc.)



AMS-02
(precise meas.)

Motivation: Gas and CRs in Milky Way

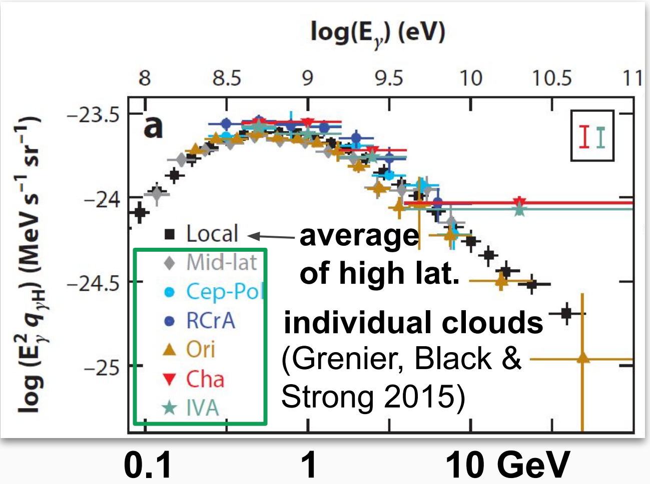
I_{CR} ($\propto I_\gamma/N_H$)

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

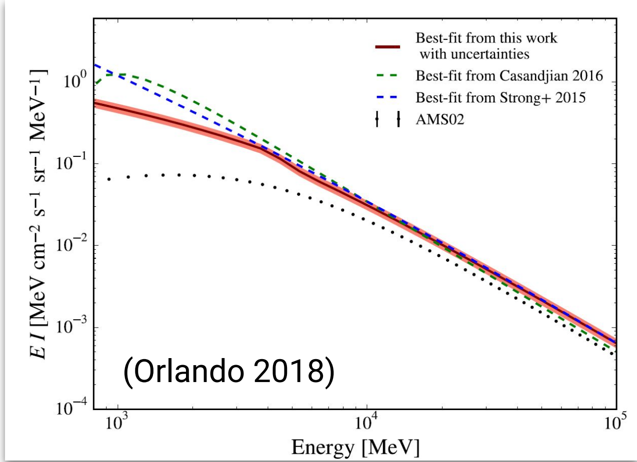
Issue: Uncertainty is still large (factor of ~1.5) even in local environment

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 scatter due to (presumably) uncertainty of optical depth correction

Local γ-ray emissivity is known to be ~30% larger than expected by CR measurements

Model and Analysis

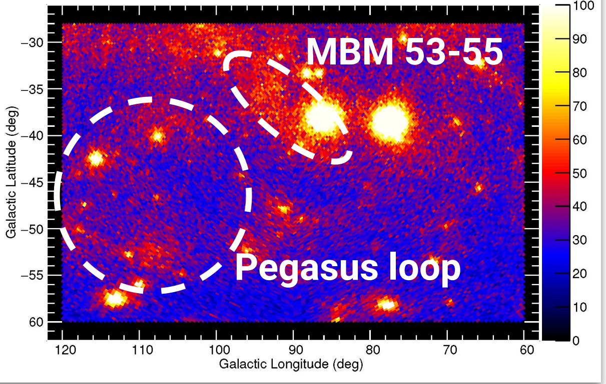
Residual gas found (middle) and modeled using dust Radiance

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

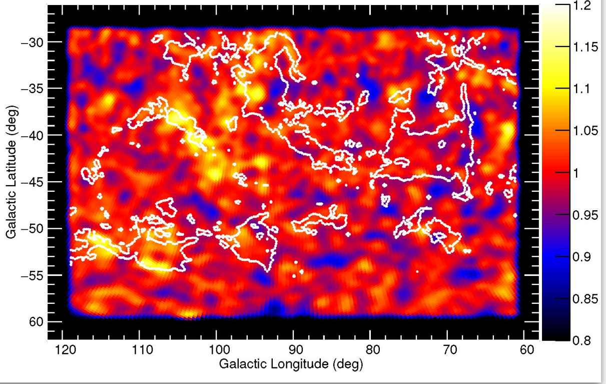
Narrow HI gives ~1.5 times larger γ-ray emissivities than broad HI

- agree with expectations (“broad HI” = “thin HI”, “narrow HI” = “w/ dark gas”)

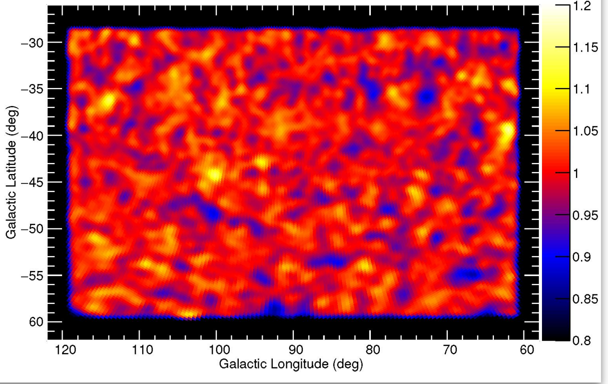
Count map (0.1-73GeV)



Data/model (w/o dust data)



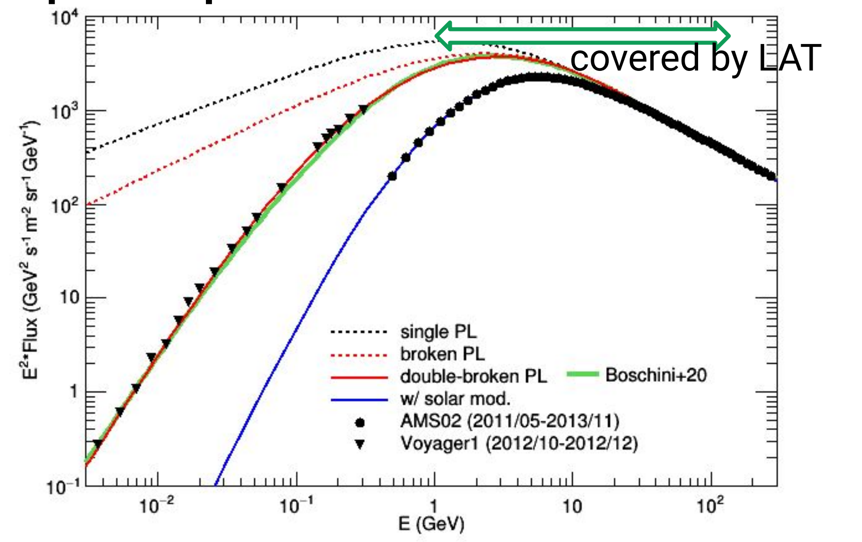
Data/model (w/ final model)



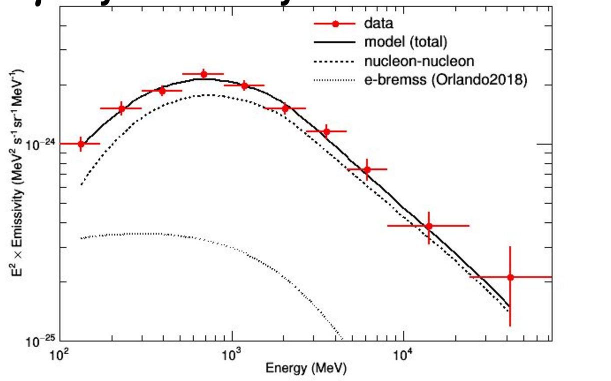
(contour: Radiance to indicate ISM structures)

CR & Gamma-Ray Fit Results

proton spectrum



γ-ray emissivity

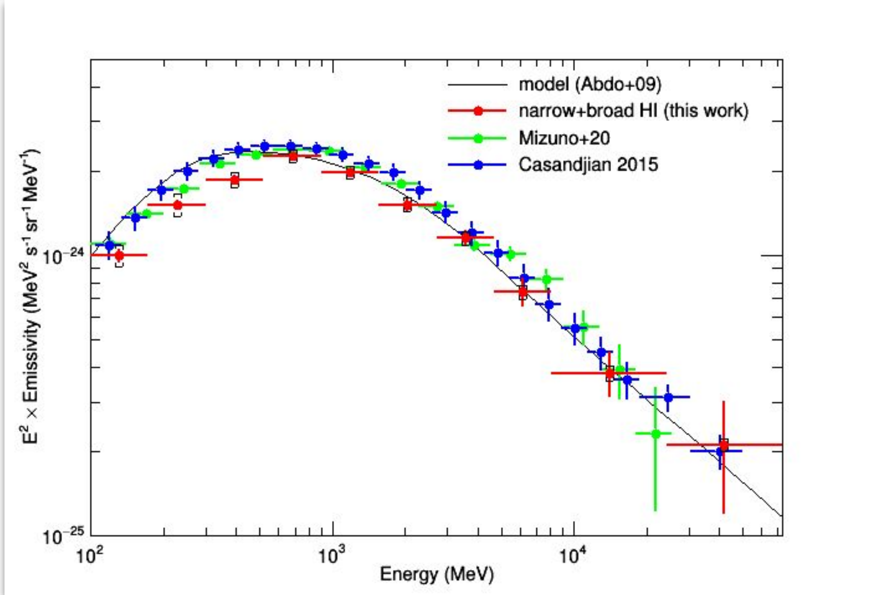


$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

- 1st spectral break due to a break in D
- 2nd break due to ionization loss
- CR α and ISM He are taken into account

- Our LIS model reproduces data & agrees with Boschini+20
- Scaling factor for γ-ray is 1.07+/-0.03
- R_{br1}=7.1+/-0.3 (GV) and δ_1=0.07+/-0.01

Result: Gamma-ray Emissivity Spectrum



(We added narrow HI and broad HI templates w/ normalization taken into account)

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
- We can see <u>a small deviation</u> from a model in low energy

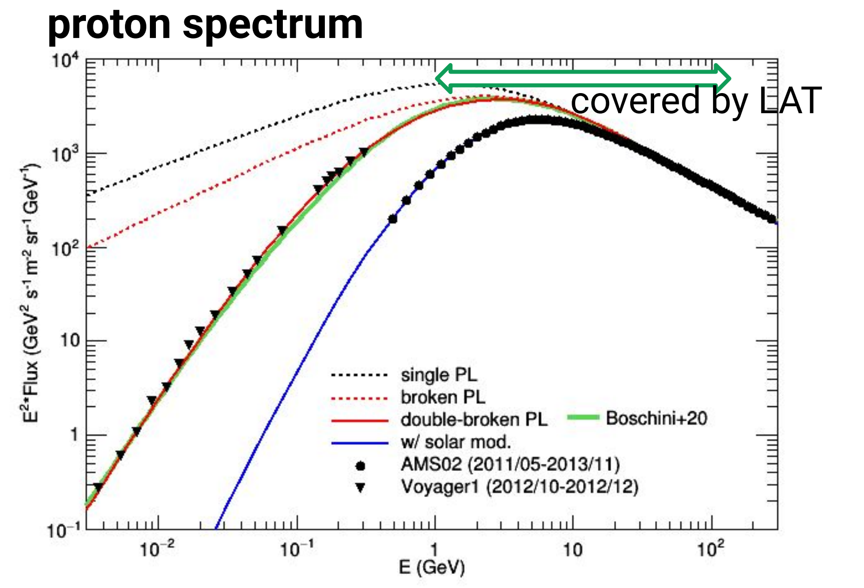
CR & Gamma-Ray Fit to Constrain LIS

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 represent the 1st spectral break presumably due to a break in the interstellar diffusion coefficient inferred by B/C ratio (e.g., Ptuskin+06)
  - p_{br2} and δ_2 represent 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)
- We take into account CR α and ISM He, and fit CR & γ-ray data simultaneously

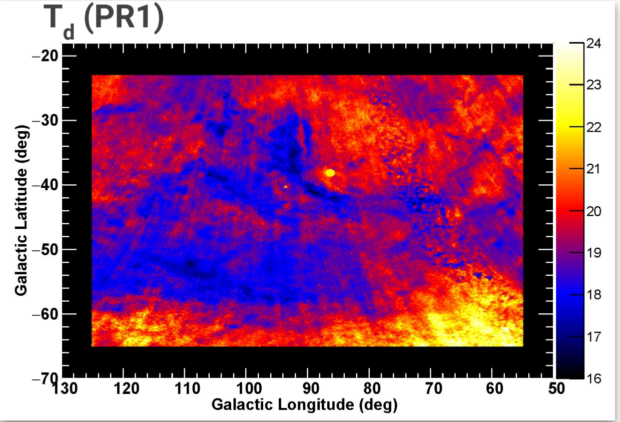
$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

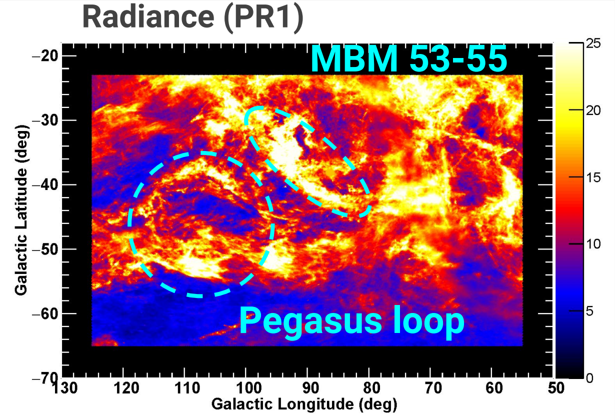
CR Properties



- Our LIS model reproduces data & agrees with Boschini+20 (w/ detailed CR transport in heliosphere)
  - Developed a formula that represents CR transport
- Scaling factor for γ-ray is 1.07+/-0.03 (solves ~30 % discrepancy in past studies)
  - Can use direct meas. as a reference for LIS
- R_{br1}=7.1+/-0.3 (GV) and δ_1=0.07+/-0.01 (B/C ratio etc. indicate break at similar Rigidity)
  - Provided independent proof of a break in D

Dust Maps

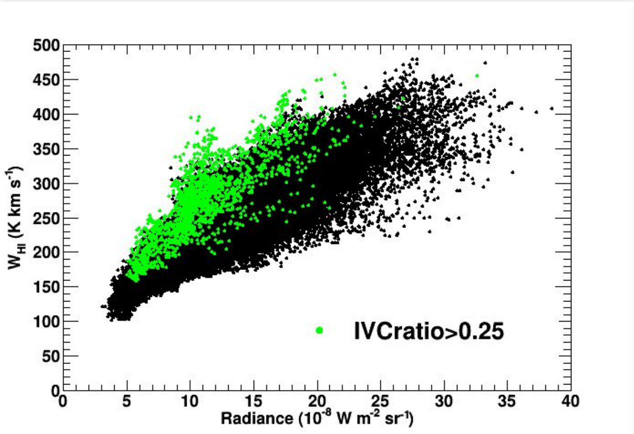


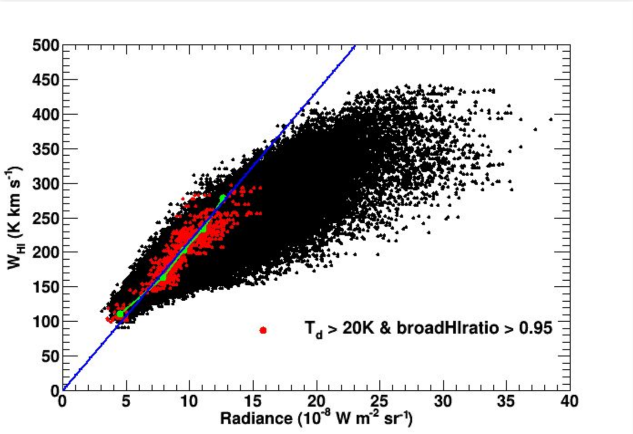


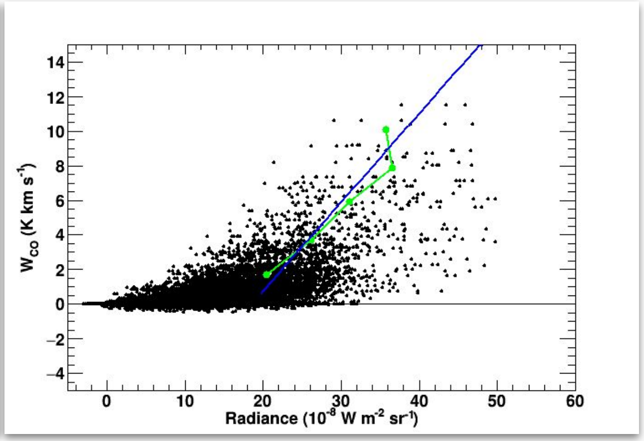
(narrow HI is associated with MBM53-55 and Pegasus loop seen in dust map)

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

Construction of Residual Gas Template

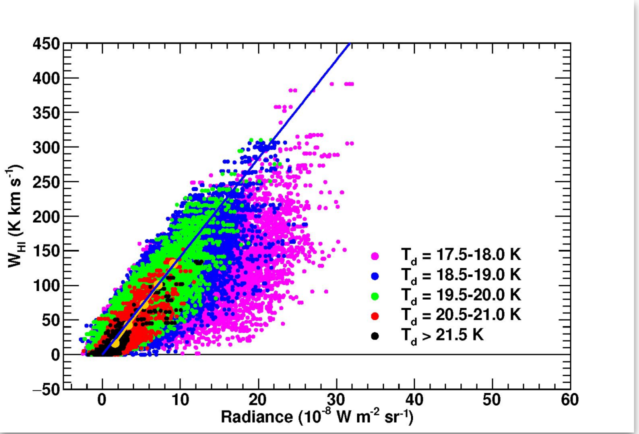


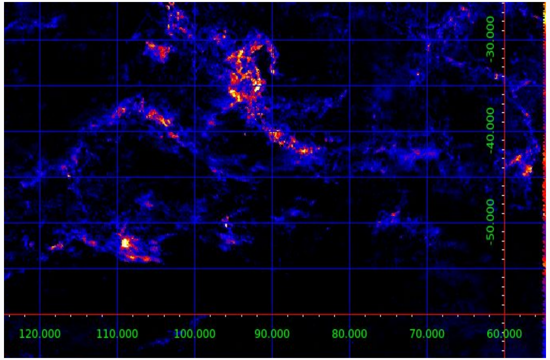




1) We found outliers in W_{HI}(tot)-Rad are affected by IVC. We removed them from W_{HI} assuming they have no dust. Now we have W_{HI}(narrow+broad HI)
2) We selected “warm-HI rich” (warmHIfrac>0.95) and “high-Tdust” (>20K) area and obtained W_{HI}(broad HI)-Rad ratio. We removed “broad HI gas” from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

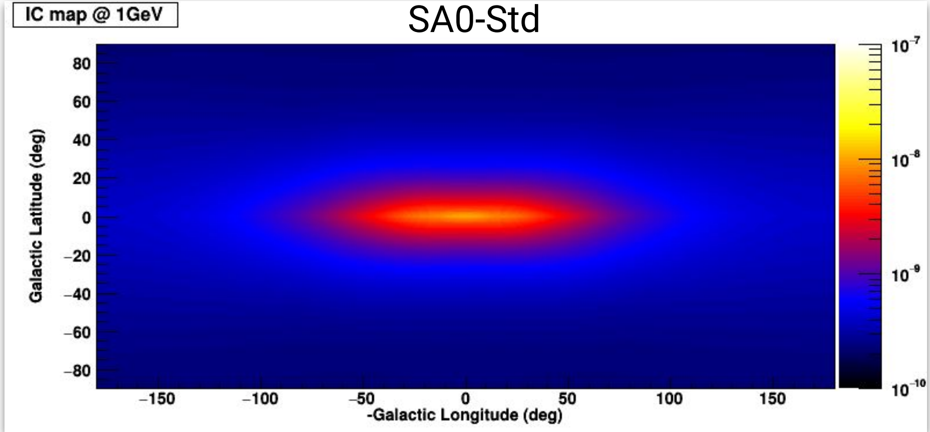
Construction of Residual Gas Template (Contd.)

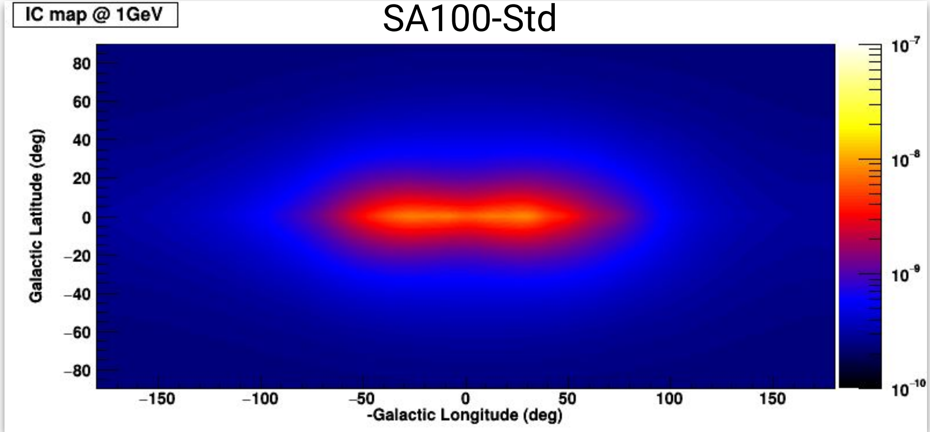




4) We selected high Tdust (>20K) area to reduce contamination from residual gas and obtained W_{HI}(narrow HI)-Rad ratio. We removed narrow HI from W_{HI} and Rad using this ratio. Now we have Rad_res and use it as residual gas template.

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

Results with Final Model

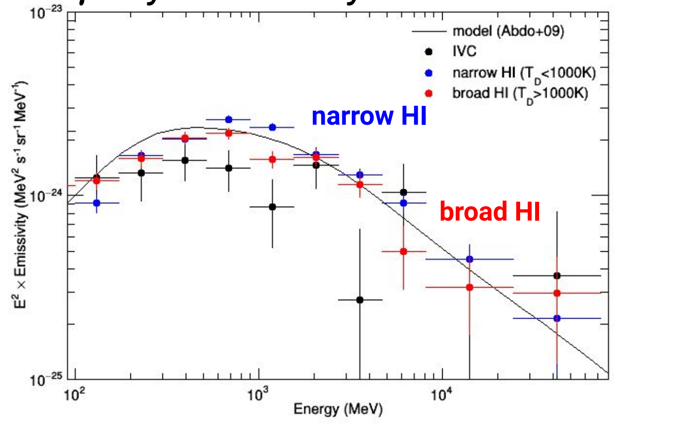
Final model reproduces the data well (see prev. slide)

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

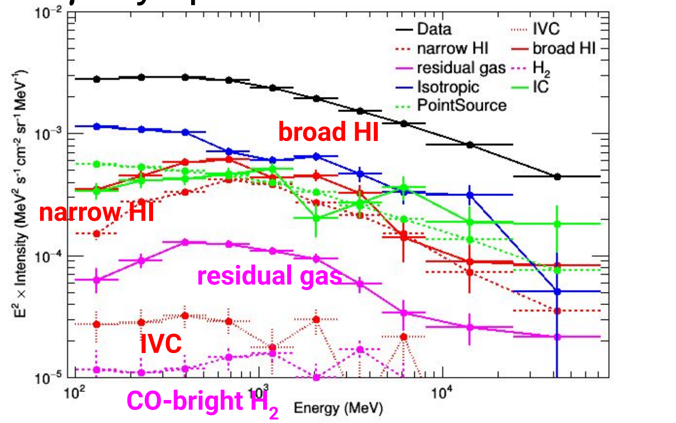
Emissivity ($\propto I_{CR}$) of narrow HI agrees with that of broad HI and a model at 10% level

Spectrum of each component shows relative contribution of each gas phase

γ-ray emissivity



γ-ray spectrum



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]

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)

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

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

Then, we have total column density as

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