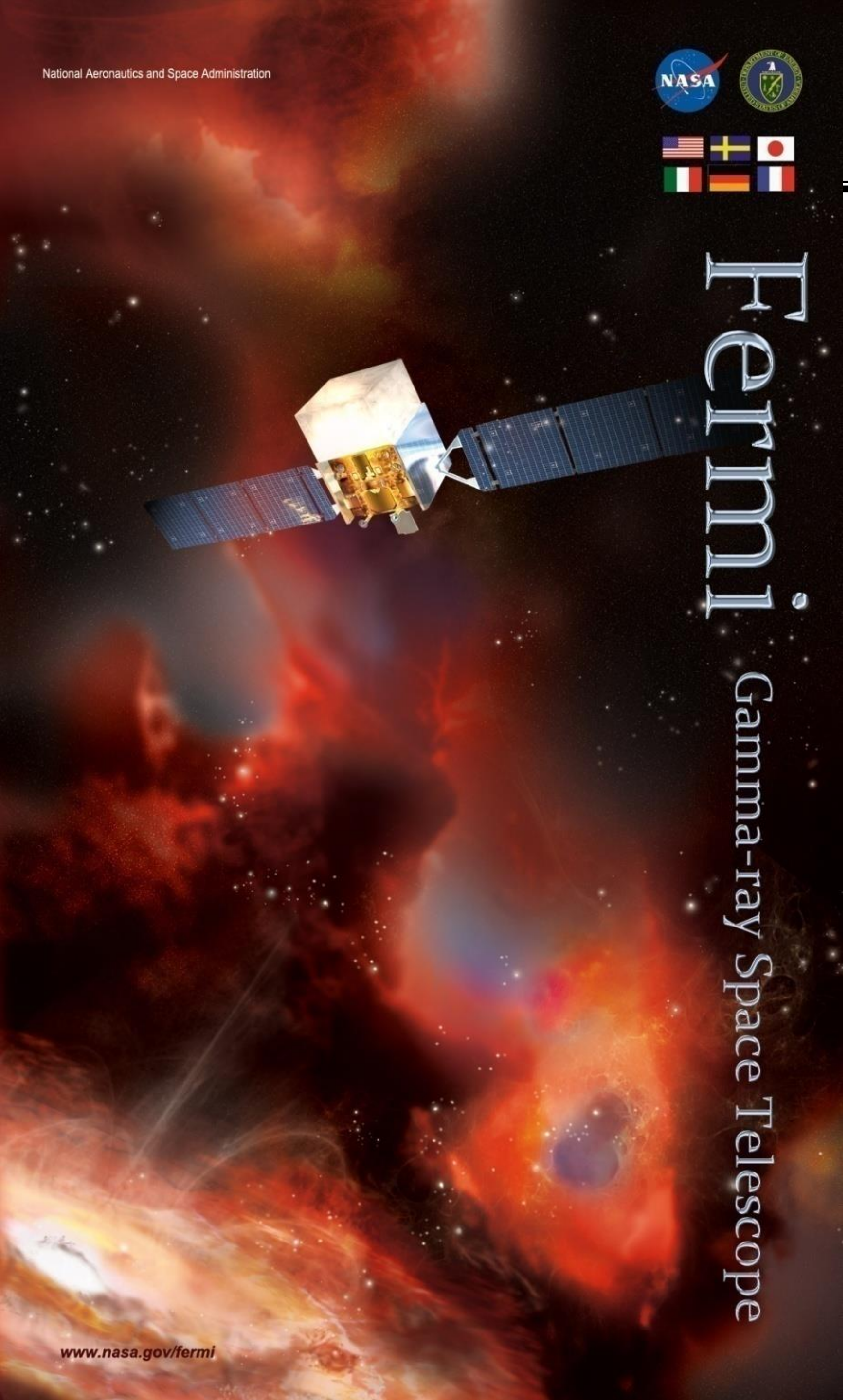

Study of the Cosmic Rays and Interstellar Medium in Local HI Clouds using Fermi-LAT Gamma-Ray Observations

Dec. 5, 2019 @ TeVPA 2019 in Sydney, Australia

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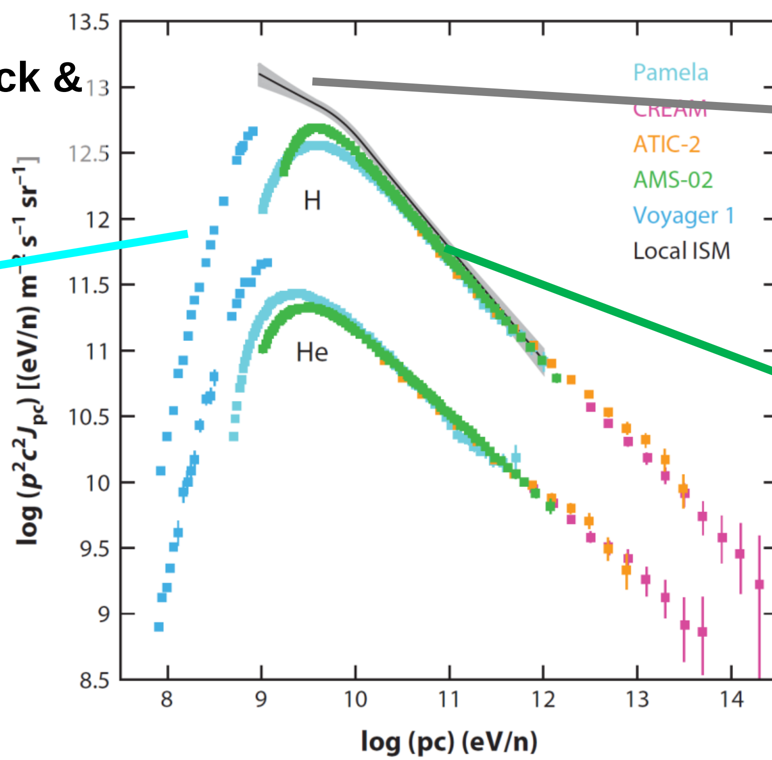
On behalf of the Fermi-LAT collaboration

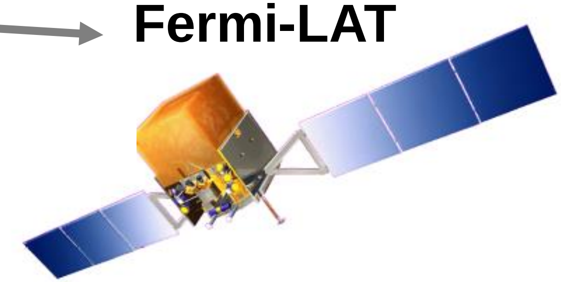
Motivation: Local Interstellar Spectra (LIS)

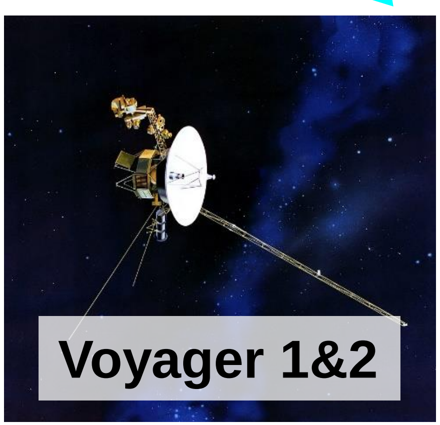
- **LIS of galactic cosmic-rays (CRs) provide vital information about their origin and propagation**
  - **Special variation? Spectral break? (e.g., Ptsukin +06)**
- **In addition to direct measurements, <u>γ-ray observation</u> is unique and crucial to constrain the LIS**

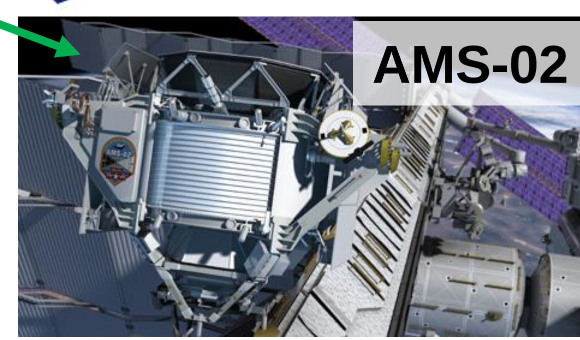
Grenier, Black & Strong 2015



Fermi-LAT





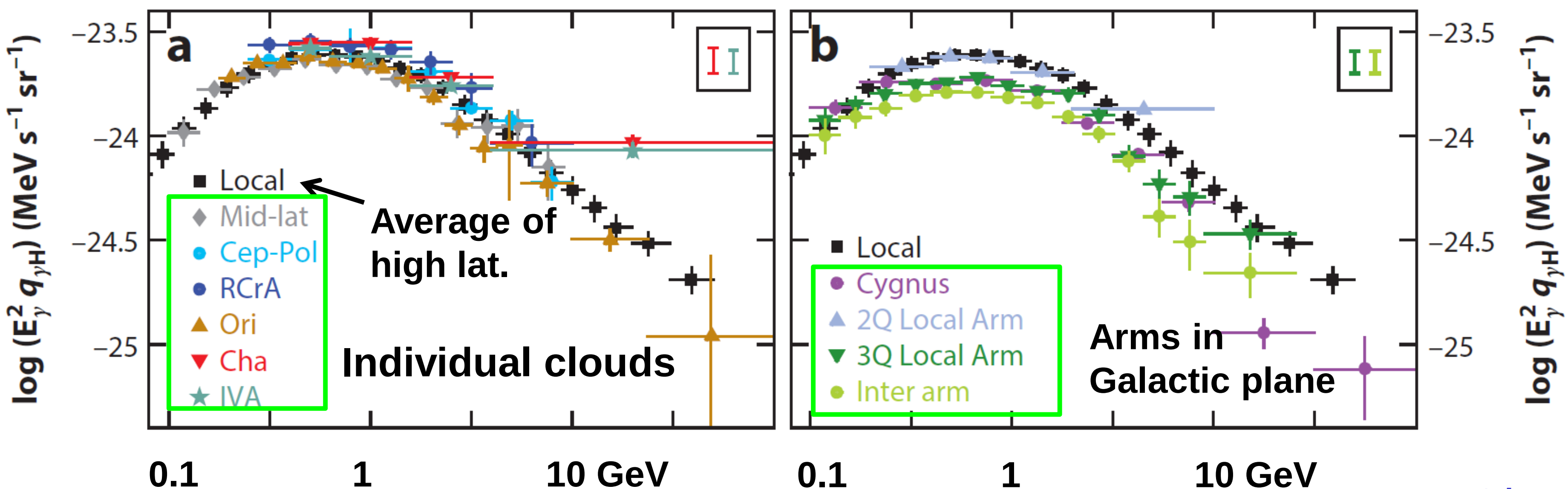


Caveat: Uncertainty of ISM & CR

- **In principle, we can measure CR intensities by γ-ray obs. if we know interstellar medium (ISM) gas densities, since $I_\gamma \propto N_\mathrm{H} I_\mathrm{CR}$**
- **Uncertainty of local CR intensities <u>still large</u> (a factor of ~1.5) because of the uncertainty of N_H (mostly due to the uncertainty of spin temperature T_S)**

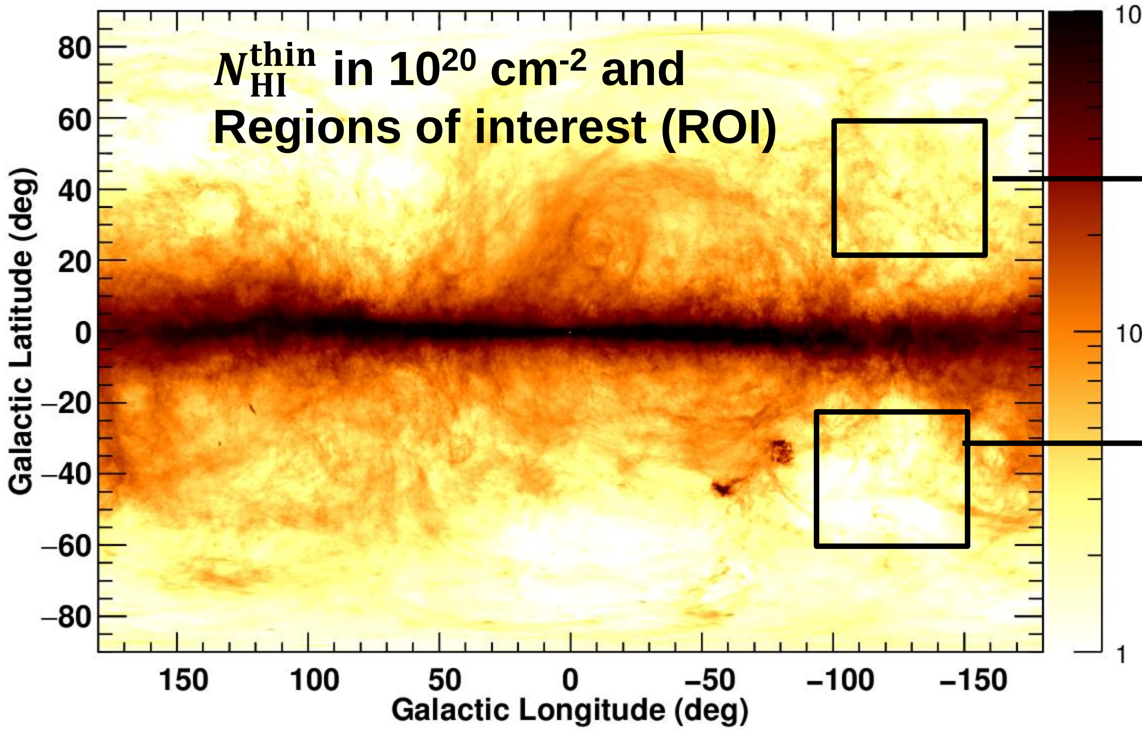
Grenier, Black & Strong 2015

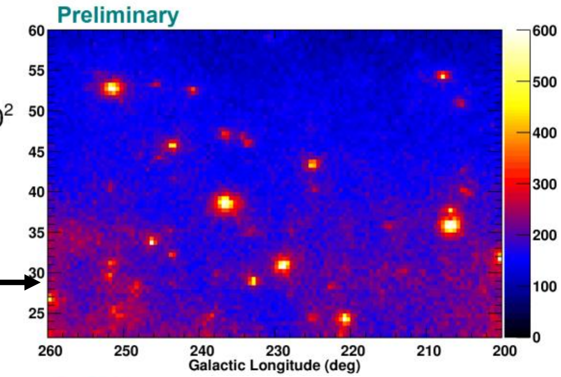
γ-ray emissivity of local clouds ($\propto I_\mathrm{CR}$) ($E_\gamma \sim \frac{1}{10} E_\mathrm{p}$)

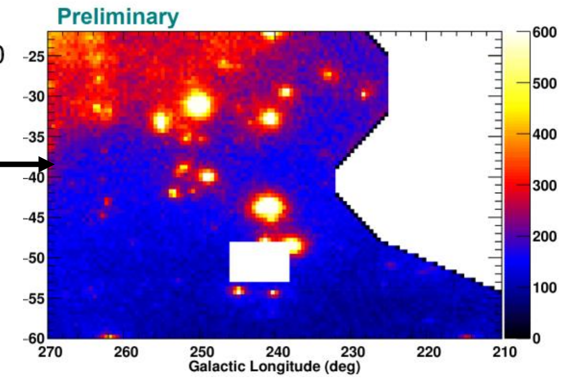


Objectives of the Study

- **Accurate estimate of ISM gas densities is crucial to constrain Galactic CR intensities**
- **Procedure to trace "dark gas" (gas not properly traced by HI and CO line surveys** (Grenier+05)**) not established yet => <u>detailed study of nearby clouds</u>**





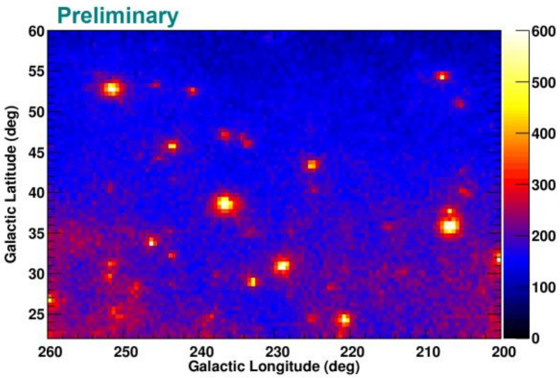


Fermi Data (>100 MeV)

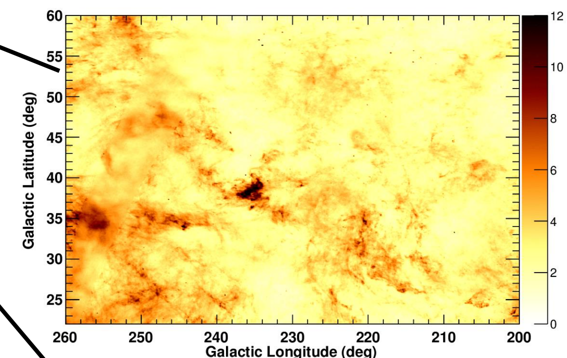
Procedure of the Analysis

- **Uniform CR intensity (assumption testable by energy dependence) -> we can model γ-ray intensity as <u>a linear combination of templates</u>**

Fermi Data (8 yrs, 0.1-25.6 GeV)

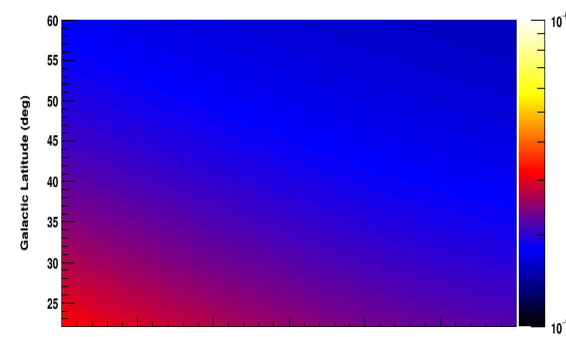


Planck dust, LAB H_I, W_{CO}, etc.



$$I_\gamma(l,b,E) = q_\gamma(E)\cdot N_\mathrm{H}(l,b) + I_\mathrm{IC}(l,b,E) + I_\mathrm{iso}(E) + \Sigma\, I_\mathrm{source}(l,b,E) + \cdots$$

IC model (e.g., galprop)



$q_\gamma(E)$ tells us CR spectrum

Fit quality tells us which tracer is better

$$N_\mathrm{H} = \Sigma_i\ a_i\cdot N(\mathrm{H}_i)$$

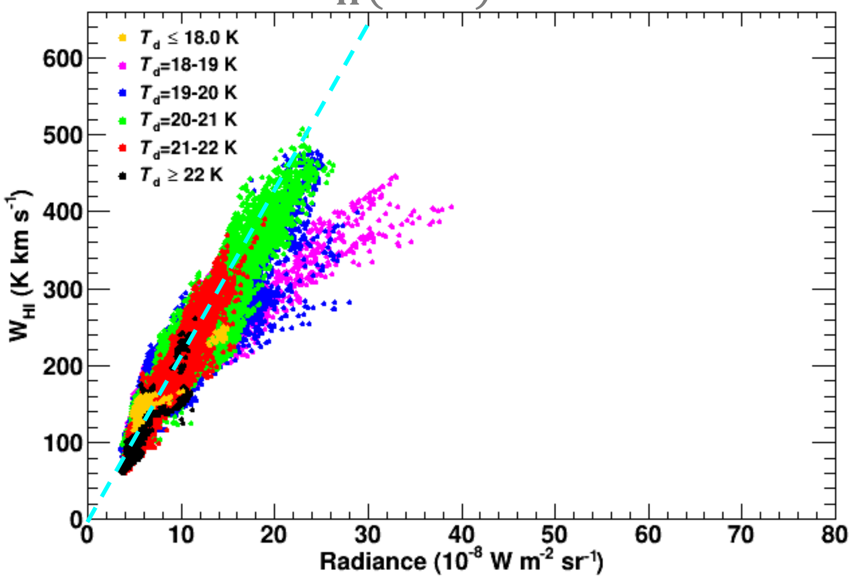
$$(\mathrm{e.g.},\ N(\mathrm{H_I}) + 2X_\mathrm{CO}\cdot W_\mathrm{CO} + X_\mathrm{DG}\cdot N(\mathrm{H_{DG}}))$$

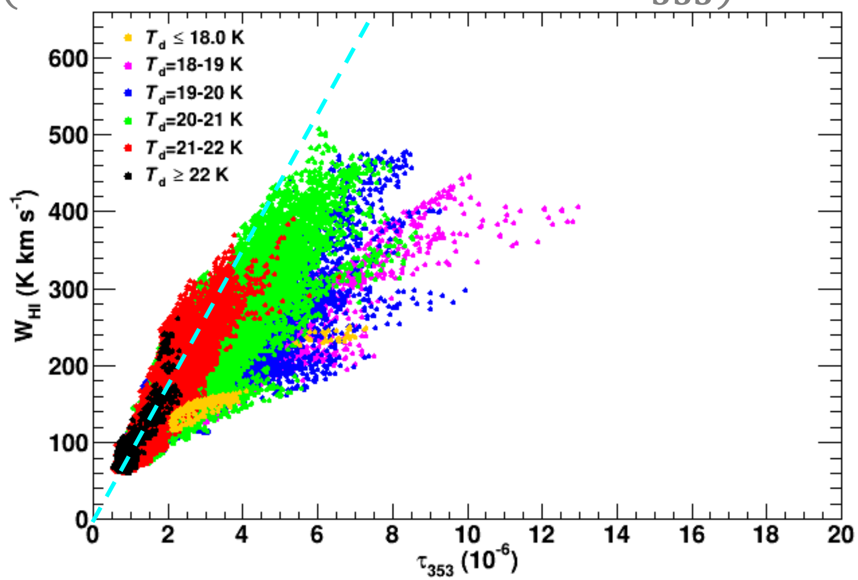
Coefficients (a_i) tell us gas properties

W_{HI}-Dust Relation (North)

- Correlation btw. W_{HI} and dust emission D_{em} (R or τ_{353})
  - Dust temperature (T_d) dependence seen in the W_{HI}-τ_{353} correlation
- Linear curves that follow trends in high T_d areas are used to construct initial N_H templates assuming $N_H \propto D_{em}$
- We will use γ-rays (robust tracer of ISM gas) to constrain N_H
  - R vs. τ_{353}, possible T_d-dependence/non-linearity

$$N_H(\mathrm{cm}^2) = 1.82 \times 10^{18} \times \left(21.1 \times 10^8\, R \text{ or } 87.2 \times 10^6\, \tau_{353}\right)$$

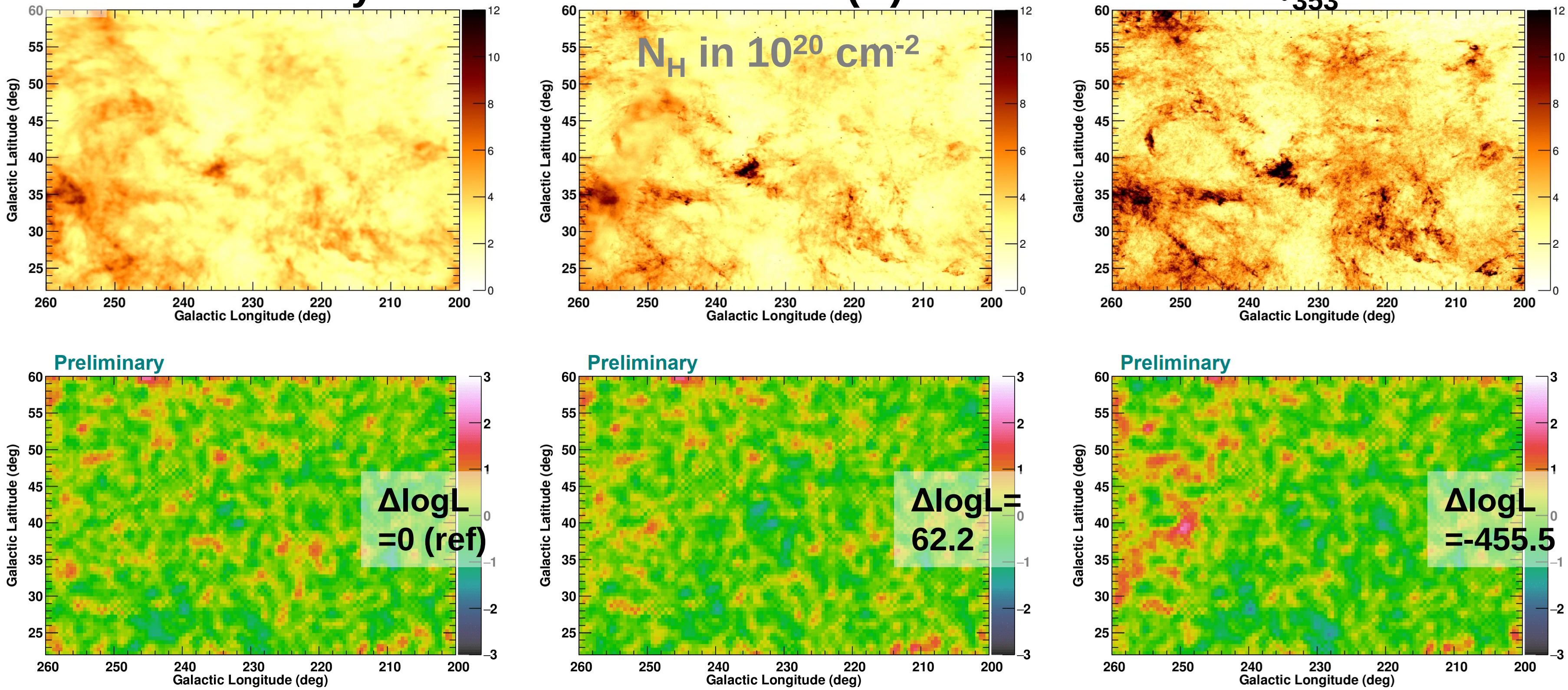




N_H Model Maps and Residuals (North)

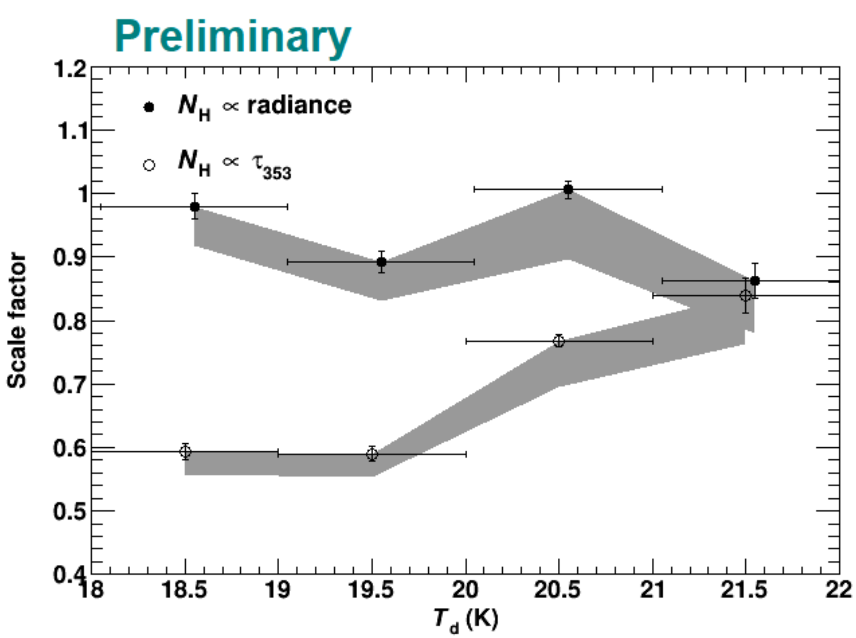
- We prepared N_H model maps ($\propto W_{HI}$ or D_{em}) and used them in the fit of γ-ray data -> R gives the best fit (same conclusion for the south region)

North HI4PI survey | radiance (R) | τ_{353}



T_d Dependence (North)

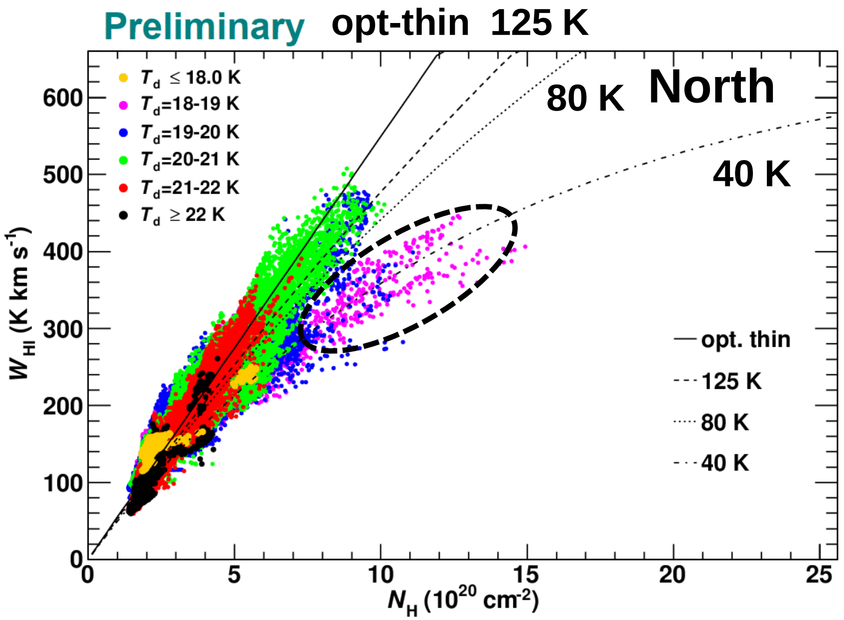
- If $N_H \propto D_{em}$, fit coefficient is constant for a uniform CR intensity
- Fit with T_d-sorted N_H templates shows a significant T_d dependence for τ_{353}, implying an overestimate of N_H/τ_{353} in low T_d areas
- Fit improvement not significant for R; we adopt a single R-based template as our best estimate of N_H (same conclusion for the south region)

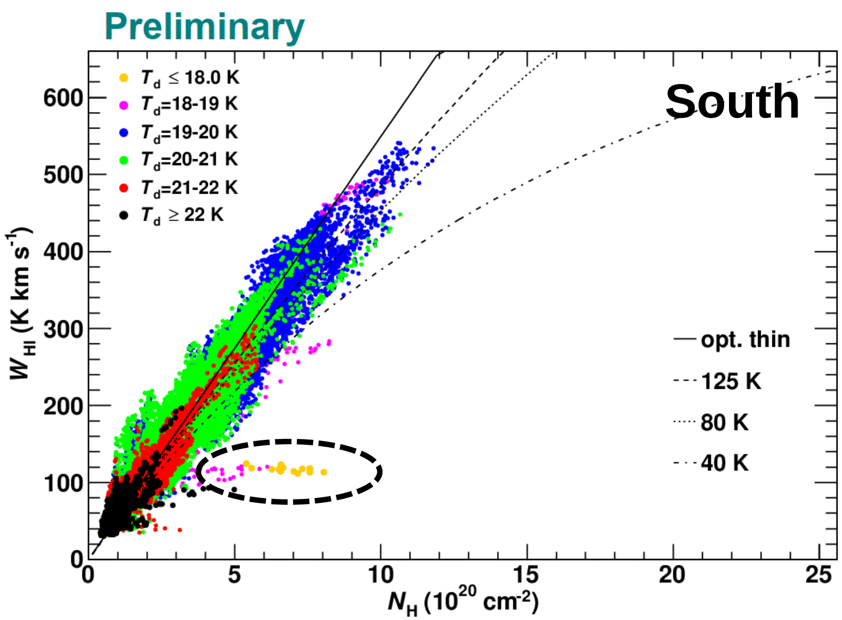


Emissivity scale factor ($\propto (N_H/D_{em})^{-1}$), averaged over 0.2-12.8 GeV

Properties of ISM Gas

- W_{HI} vs. N_H ($\propto$ R) with models for several values of T_S
  - In general, data agrees with T_S=125 K or higher
- (North) Large N_H/W_{HI} ratio in T_d=18-19 K corresponds to residuals at around (l, b)~(236°, 37.5°) for the W_{HI}-based model; likely optically-thick HI
- (South) Flat profile with W_{HI}~100 K km/s corresponds to residuals at (l, b)~(230°, -28.5°); likely CO-dark H_2

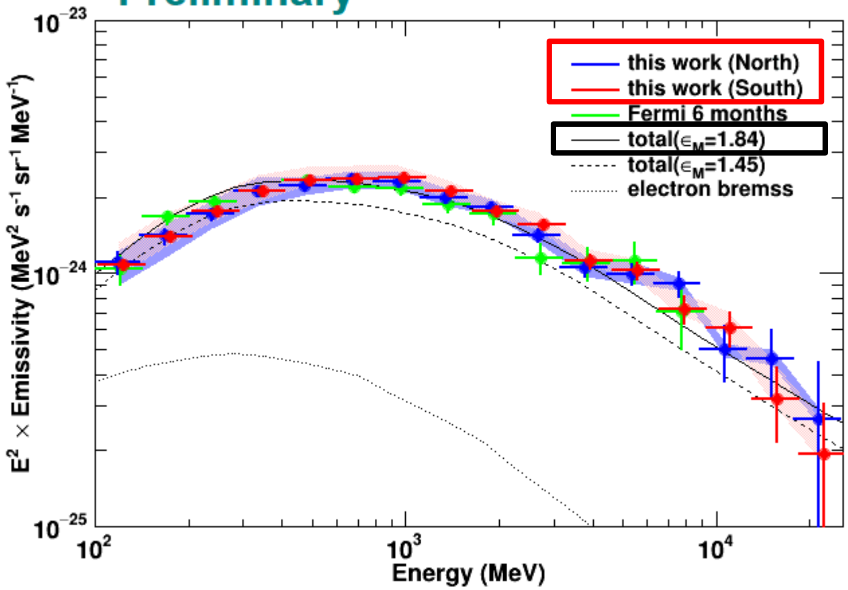




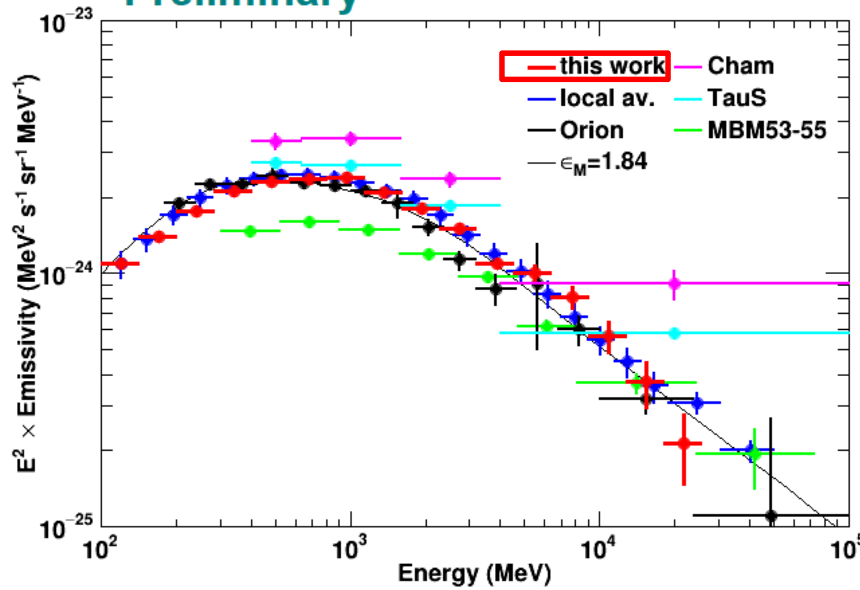
Properties of CRs

- (left) HI emissivity spectra of two regions and model curves (right) average compared with results of other areas
- (left) Two regions agree within uncertainty, supporting <u>uniform CR intensity</u>. Small deviation from a model implies <u>a possible spectral break</u> and should be investigated
- (right) Comparison with other studies shows pk-pk variation by a factor of ~2 due to the uncertainty of N_H models (this study does not assume the value/uniformity of T_S)

Preliminary



Preliminary



Summary

- **We studied local HI clouds in detail to constrain LIS**
  - **Use γ-ray data as a robust tracer of the ISM gas with an aid by HI4PI survey data and Planck dust emission model**
- **Outcomes/Findings**
  - **We developed/showed the analysis procedure without the assumption of uniform T_S**
  - **While most of the gas can be interpreted as being HI of T_S=125 K or higher, possible optically-thick HI and CO-dark H_2 identified**
  - **Uniform CR intensity confirmed. The emissivity roughly consistent with a model for the LIS based on direct measurements. Possible spectral break should be investigated**

Thank you for your Attention

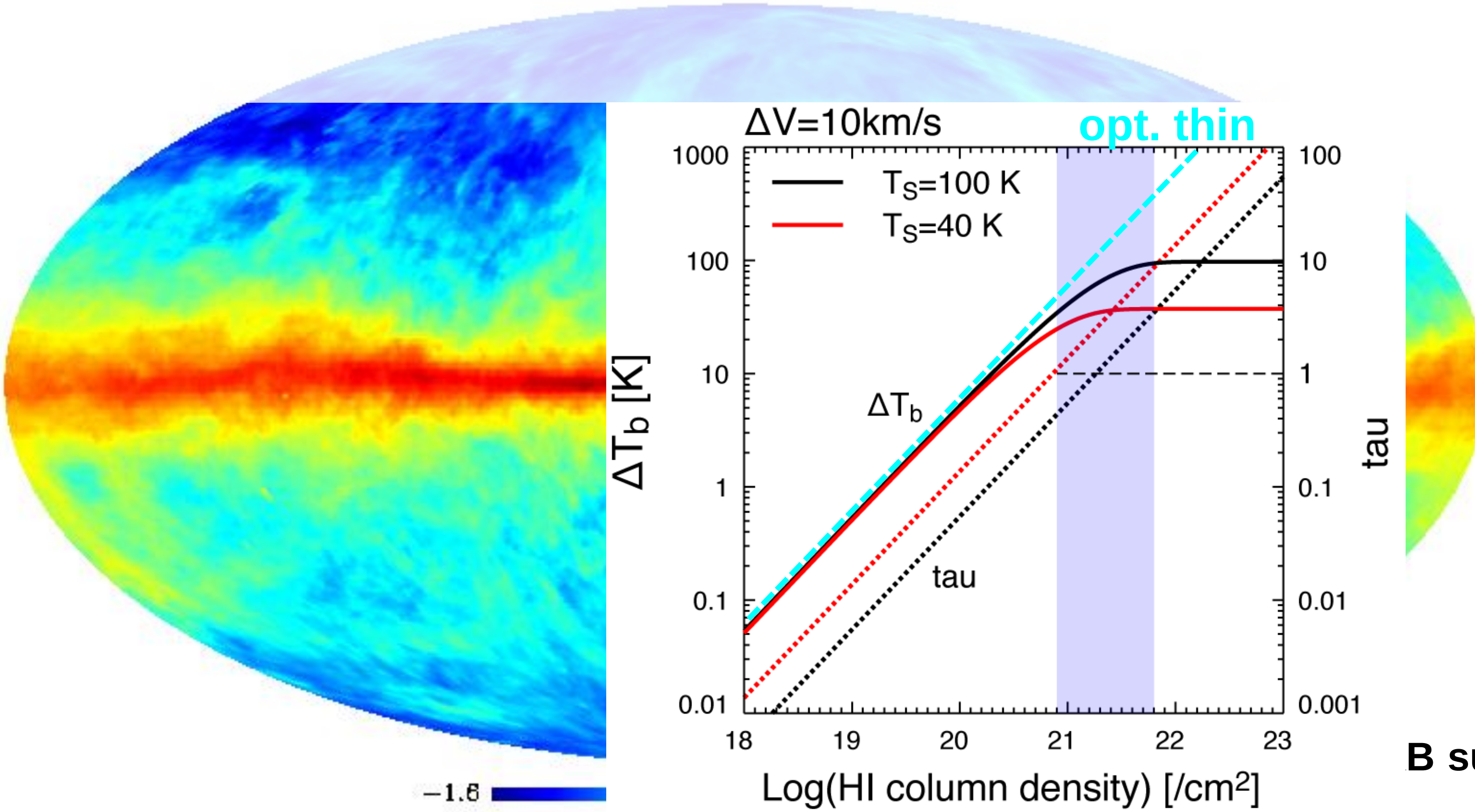
Reference

- Abdo +09, ApJ 703, 1249
- Brown +95, A&A 300, 903
- Grenier +05, Science 307, 1292
- Grenier +15, ARAA 53, 199
- Hayashi, TM +19, ApJ 884, 130
- HI4PI Collaboration 2016, A&A 594, 116
- Karberla +05, A&A 440, 775
- Ochsendorf +15, ApJ 808, 111
- Planck Collaboration 2014, A&A 571, 13 (Planck 2013 Results XIII)
- Ptsukin +06, ApJ 642, 902
- Mizuno +16, ApJ 833, 278
- Mori 09, Astropart. Phys. 31, 341

Backup Slides

Atomic Gas

- **Main component of ISM, scale height ~ 200 pc**
- **Traced by 21 cm line (W_{HI})**
  - **True N_{HI} is uncertain due to the uncertainty of the spin temperature T_S**



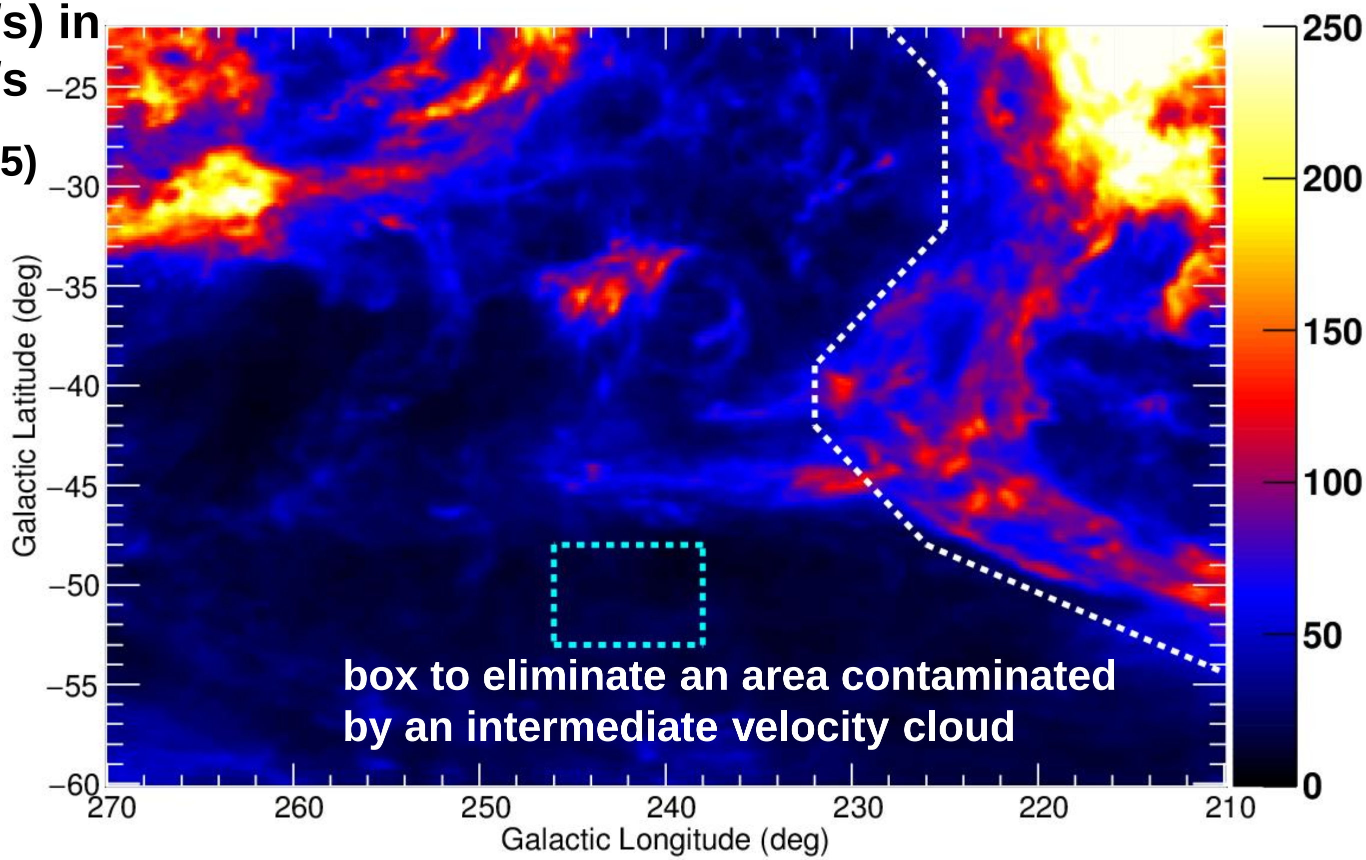
B survey;

Region Mask: Velocity-Sorted HI Map

- **A white polygon is defined to exclude Orion-Eridanus superbubble traced by outer Hα filaments and the expanding HI shell**

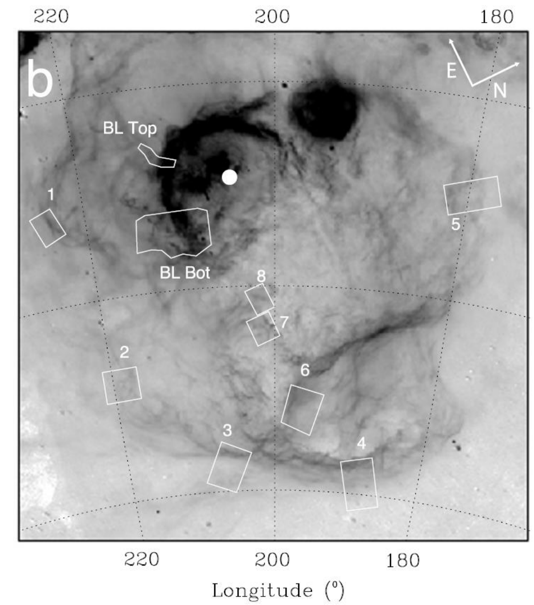
W_{HI} (K km/s) in -1 to 8 km/s

(Brown +95)

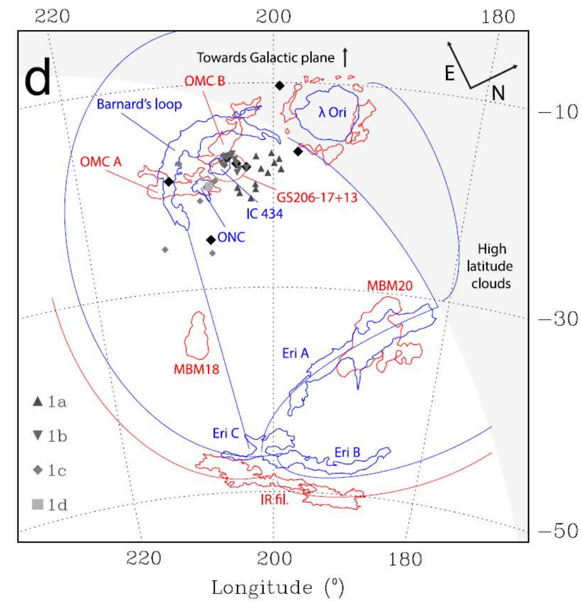


Hα Filaments (in Ref.)

- **(upper right) Several Hα filaments in the Orion-Eridanus superbubble**
- **(lower right) Outer parts of Hα filaments on the south and west are traced by a solid blue line to guide the eye. Toward the southwest, they are surrounded by a shell of neutral gas (traced by a red line).**

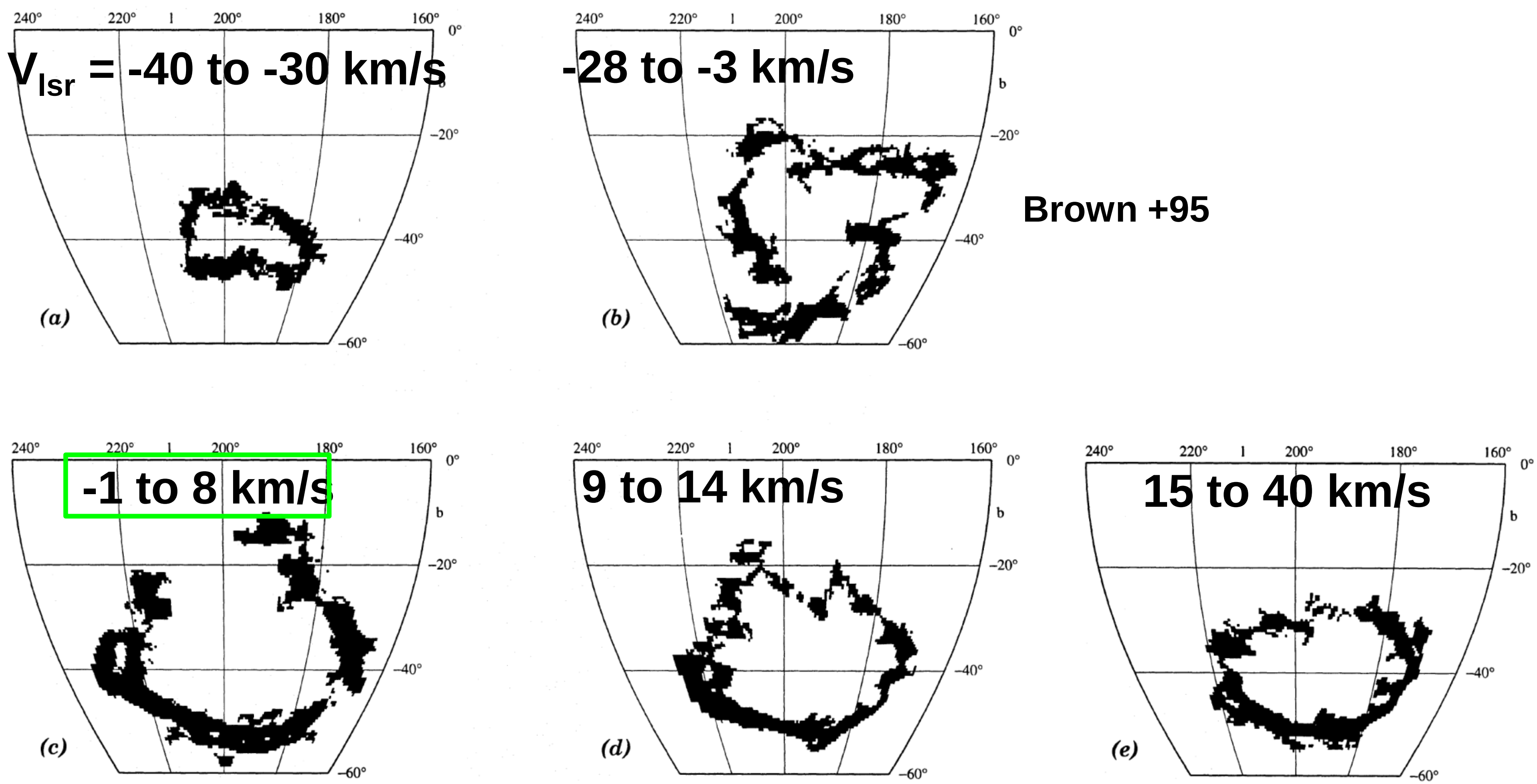


Ochsendorf +15



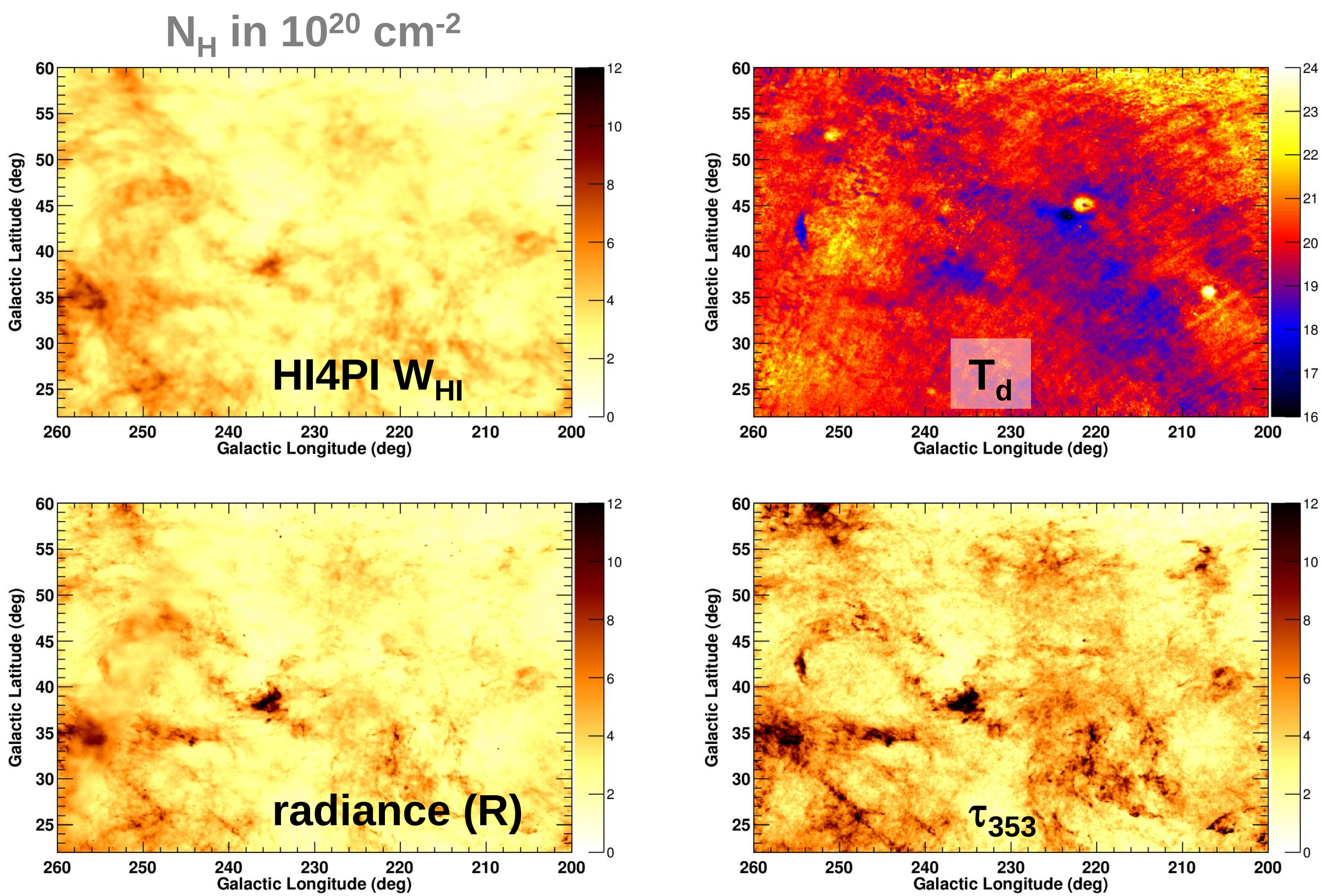
Neutral Gas (in Ref.)

- **Velocity-sorted HI maps reveal an expanding HI shell -> Use HI maps (and also Hα) to define the bubble area**



Initial N_H Template Maps (North)

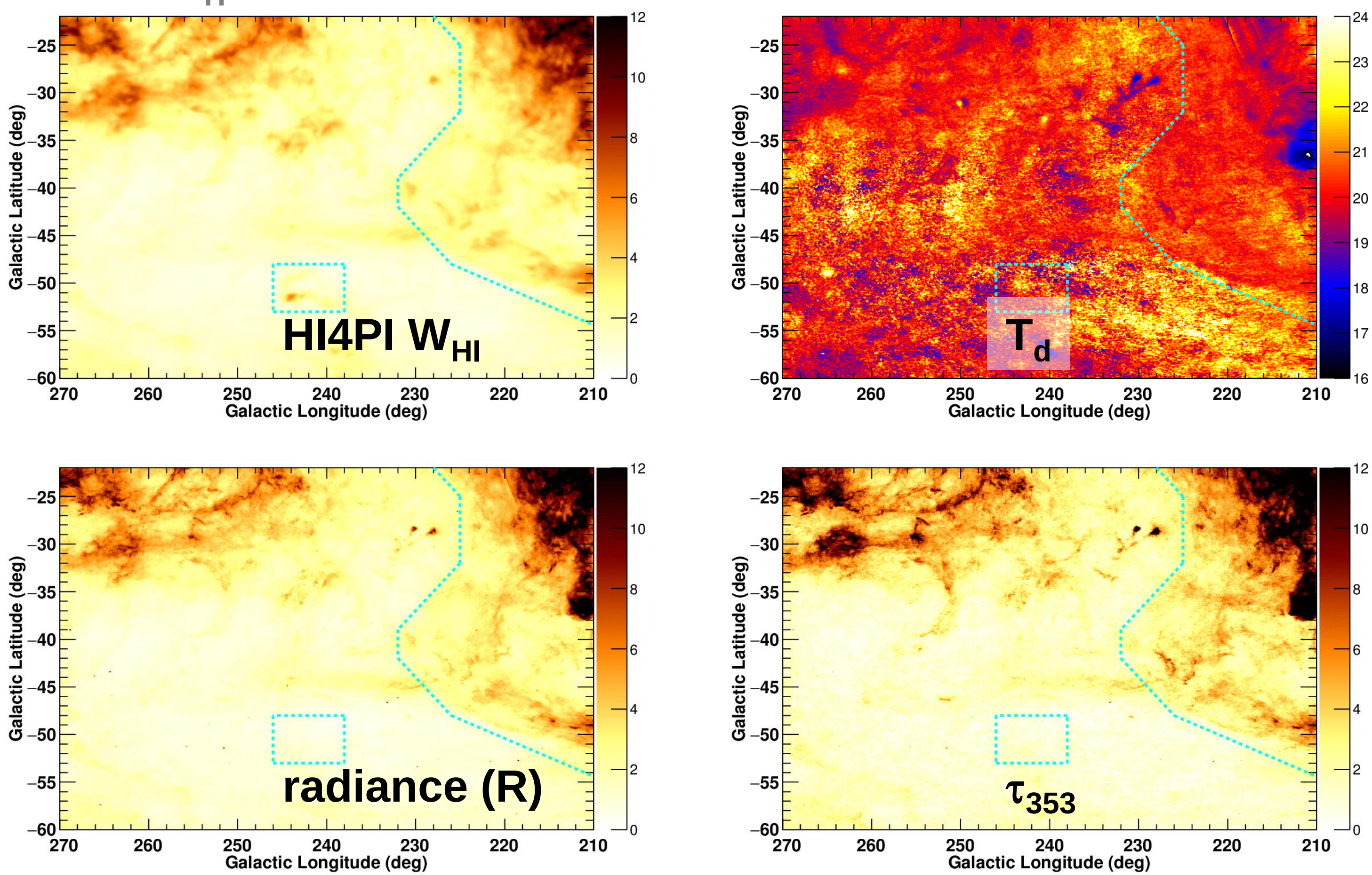
- **We prepared N_H template maps ($\propto W_{HI}$, R, or τ_{353}) and used them in a fit of γ-ray data (different contrast in 3 models)**



Initial N_H Template Maps (South)

- **We prepared N_H template maps ($\propto W_{HI}$, R, or τ_{353}) and used them in a fit of γ-ray data** (different contrast in 3 models)

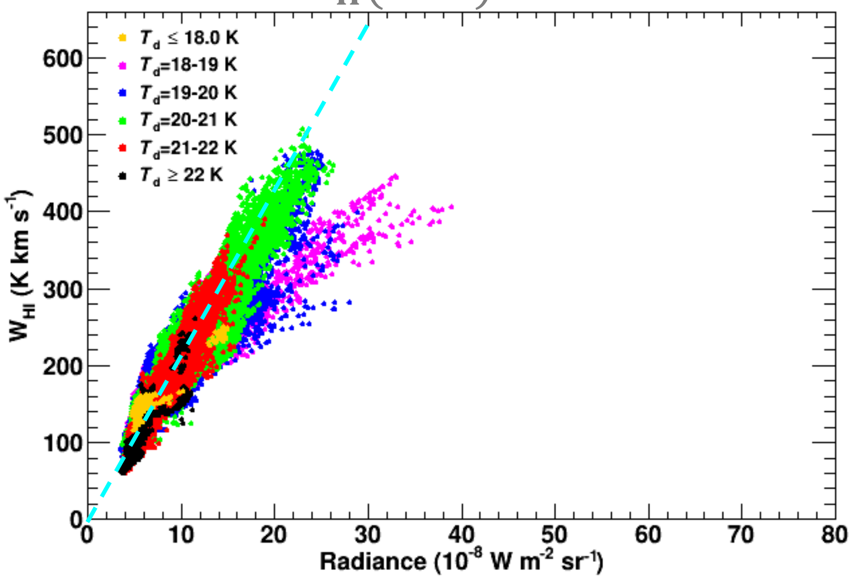
N_H in 10^{20} cm^{-2}

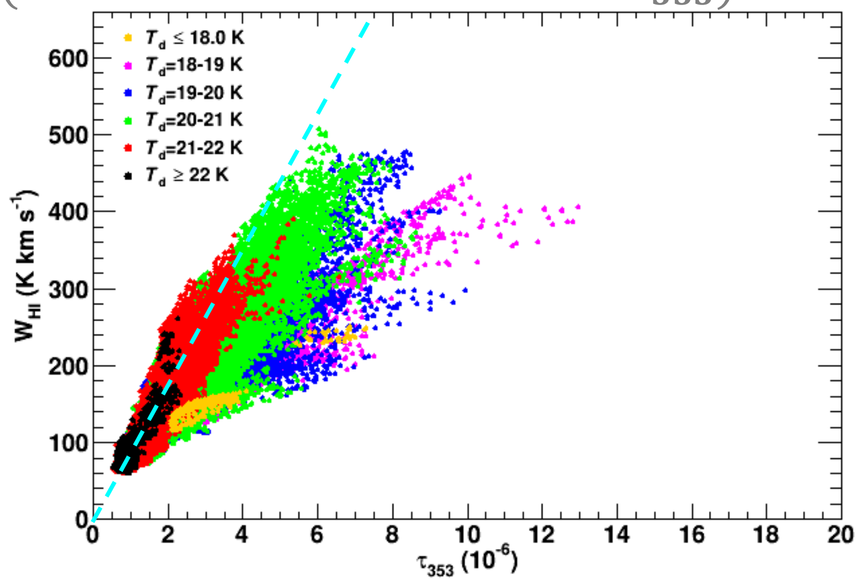


W_{HI}-Dust Relation (North)

- **Correlation btw. W_{HI} and dust emission D_{em} (R or τ_{353})**
  - **Dust temperature (T_d) dependence seen in the W_{HI}-τ_{353} correlation**
- **Linear curves that follow trends in high T_d areas are used to construct initial N_H templates assuming $N_H \propto D_{em}$**
- **We will use γ-rays (robust tracer of ISM gas) to constrain N_H**
  - **R vs. τ_{353}, possible T_d-dependence/non-linearity**

$$N_{\mathrm{H}}(\mathrm{cm}^2) = 1.82 \times 10^{18} \times (21.1 \times 10^8\, R \text{ or } 87.2 \times 10^6\, \tau_{353})$$

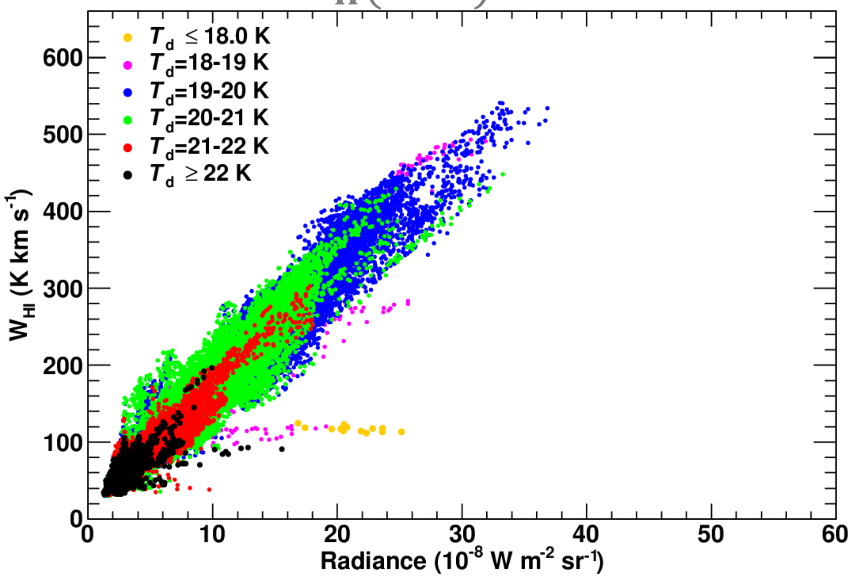


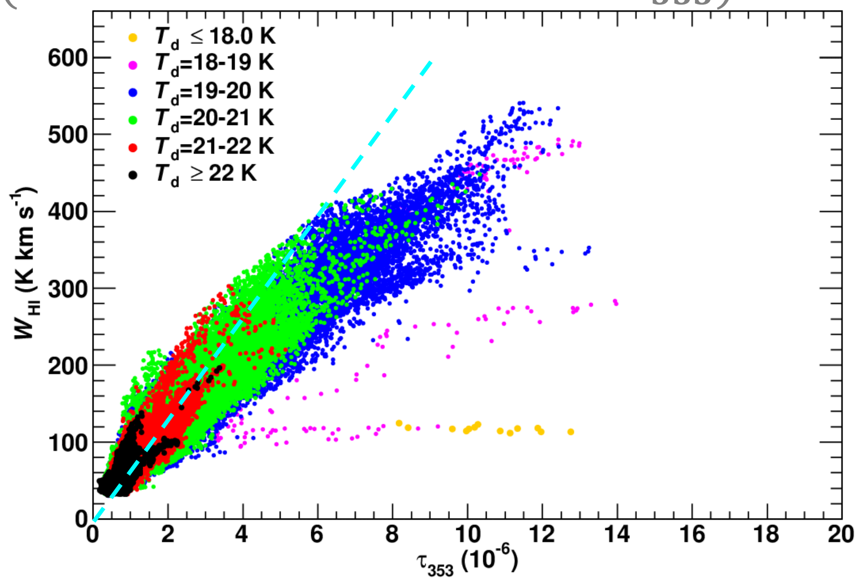


W_{HI}-Dust Relation (South)

- **Correlation between W_{HI} and D_{em}**
  - **Weak T_d dependence, non-linear W_{HI}-D_{em} relations**
- **Linear curves that follow trends in high T_d areas are used to construct initial N_H templates assuming $N_H \propto D_{em}$**
- **We will use γ-rays (robust tracer of ISM gas) to constrain N_H**
  - **R vs. τ_{353}, possible T_d-dependence/non-linearity**

$$N_{\mathrm{H}}(\mathrm{cm}^2) = 1.82 \times 10^{18} \times \left(17.6 \times 10^{8}\, R \text{ or } 66.9 \times 10^{6}\, \tau_{353}\right)$$

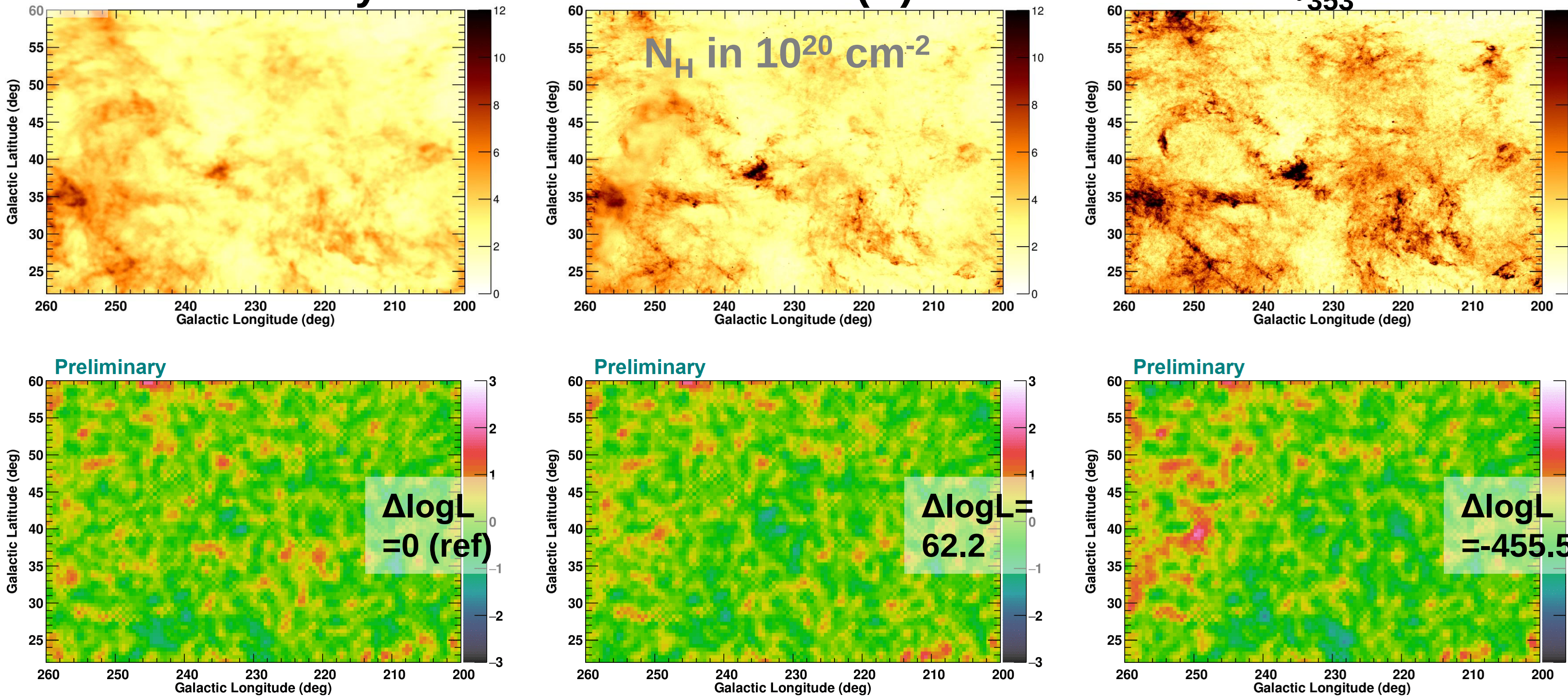




N_H Model Maps and Residuals (<u>North</u>)

- **We prepared N_H model maps ($\propto W_{HI}$ or D_{em}) and used them in the fit of γ-ray data -> R gives the best fit** (same conclusion for the south region)

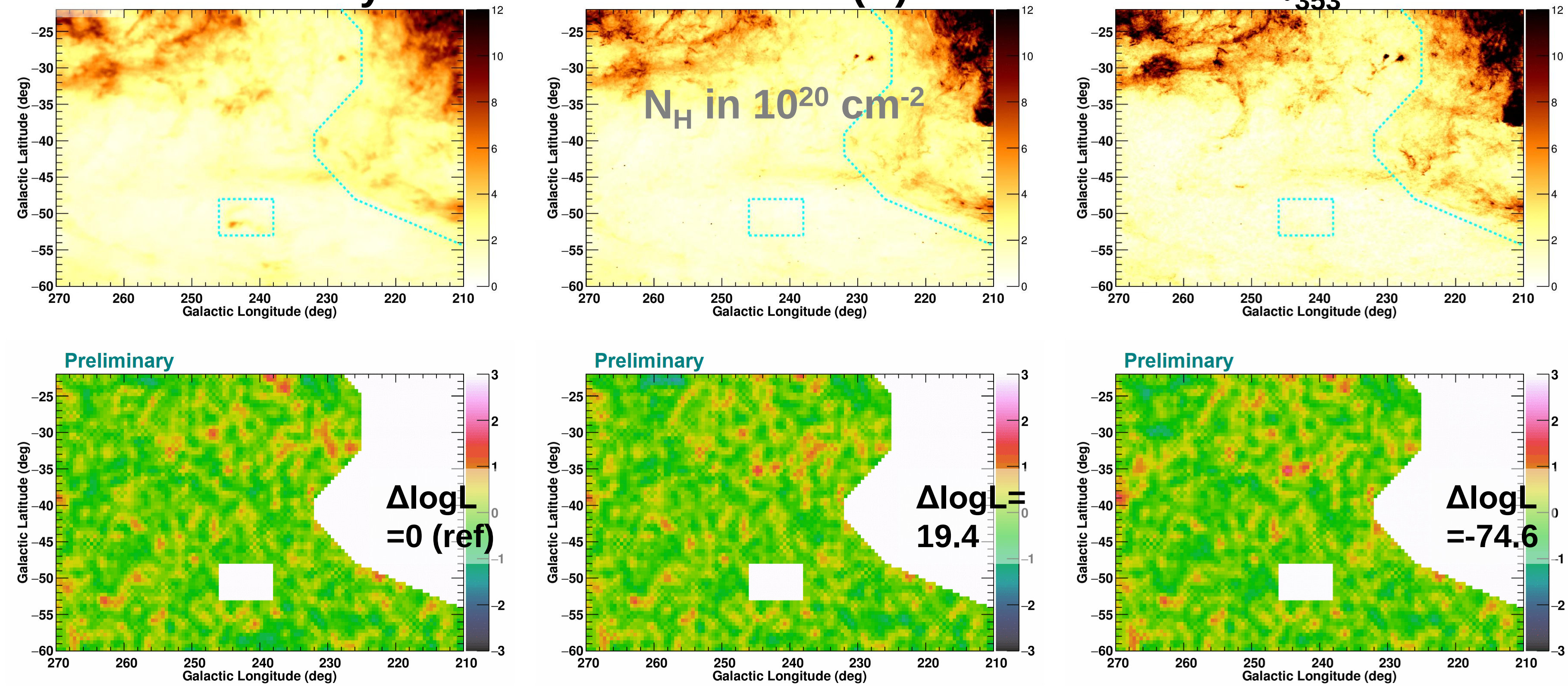
North HI4PI survey **radiance (R)** **τ_{353}**



N_H Model Maps and Residuals (South)

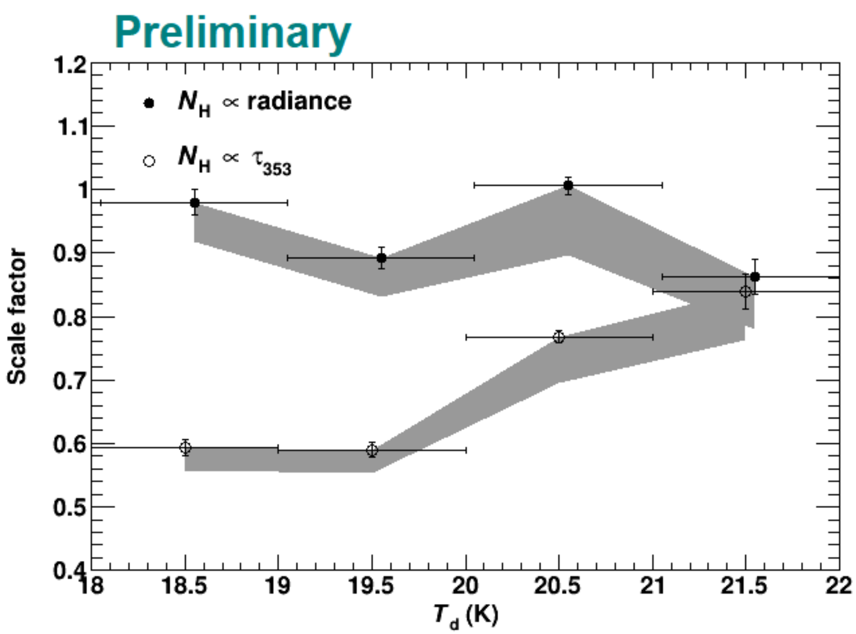
- We prepared N_H model maps ($\propto W_{HI}$ or D_{em}) and used them in the fit of γ-ray data -> R gives the best fit.

South HI4PI survey | radiance (R) | τ_{353}



T_d Dependence (North)

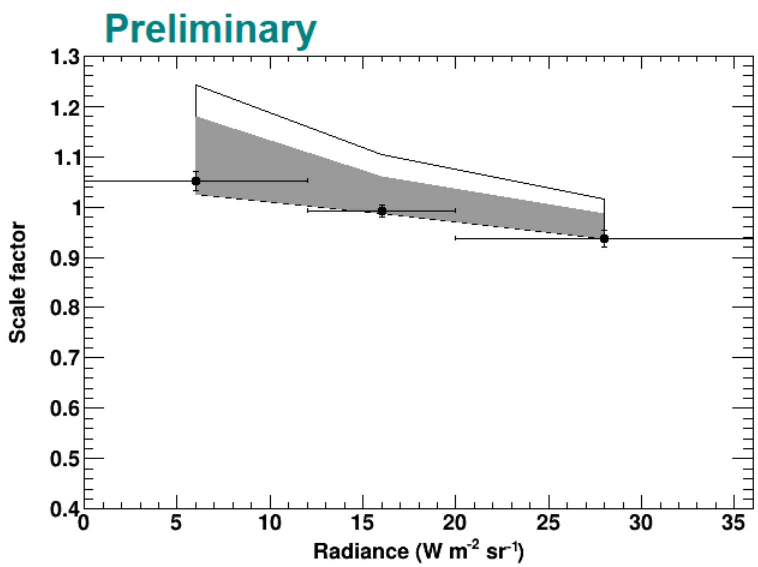
- If $N_H \propto D_{em}$, fit coefficient is constant for a uniform CR intensity
- Fit with T_d-sorted N_H templates shows a significant T_d dependence for τ_{353}, implying an overestimate of N_H/τ_{353} in low T_d areas
- Fit improvement not significant for R; we adopt a single R-based template as our best estimate of N_H (same conclusion for the south region)

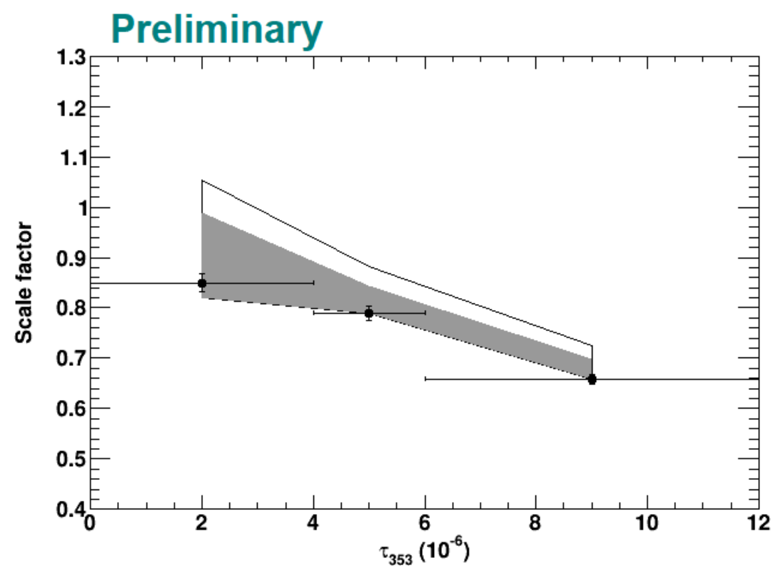


Emissivity scale factor ($\propto (N_H/D_{em})^{-1}$), averaged over 0.2-12.8 GeV

D_{em} Dependence (South)

- Examine a possible non-linear N_H-D_{em} relation through a fit with R(or τ_{353})-sorted N_H templates (cf. Hayashi +19)
- Large (~25%) negative τ_{353} dependence, implying an overestimate of N_H/τ_{353} in high density areas
- R dependence not significant (1.2σ) and small (~10%); we adopt a single R-based N_H template as our best estimate of N_H

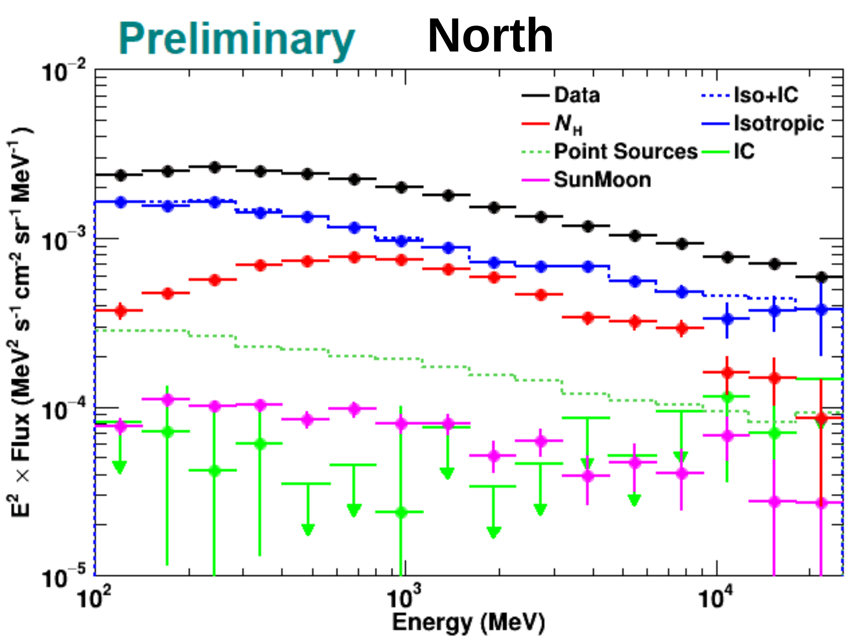


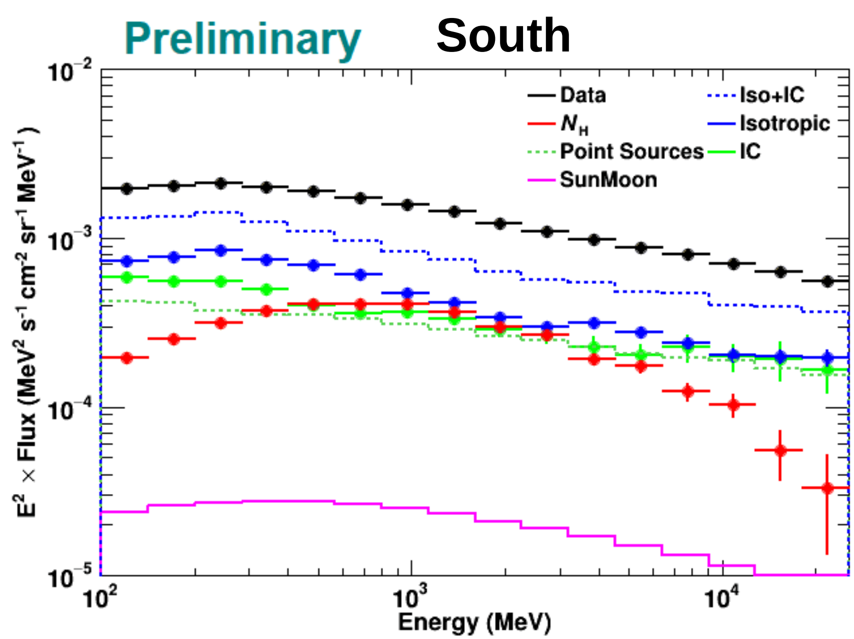


Emissivity scale factor ($\propto(N_H/D_{em})^{-1}$), averaged over 0.2-12.8 GeV

Spectrum of Each Component

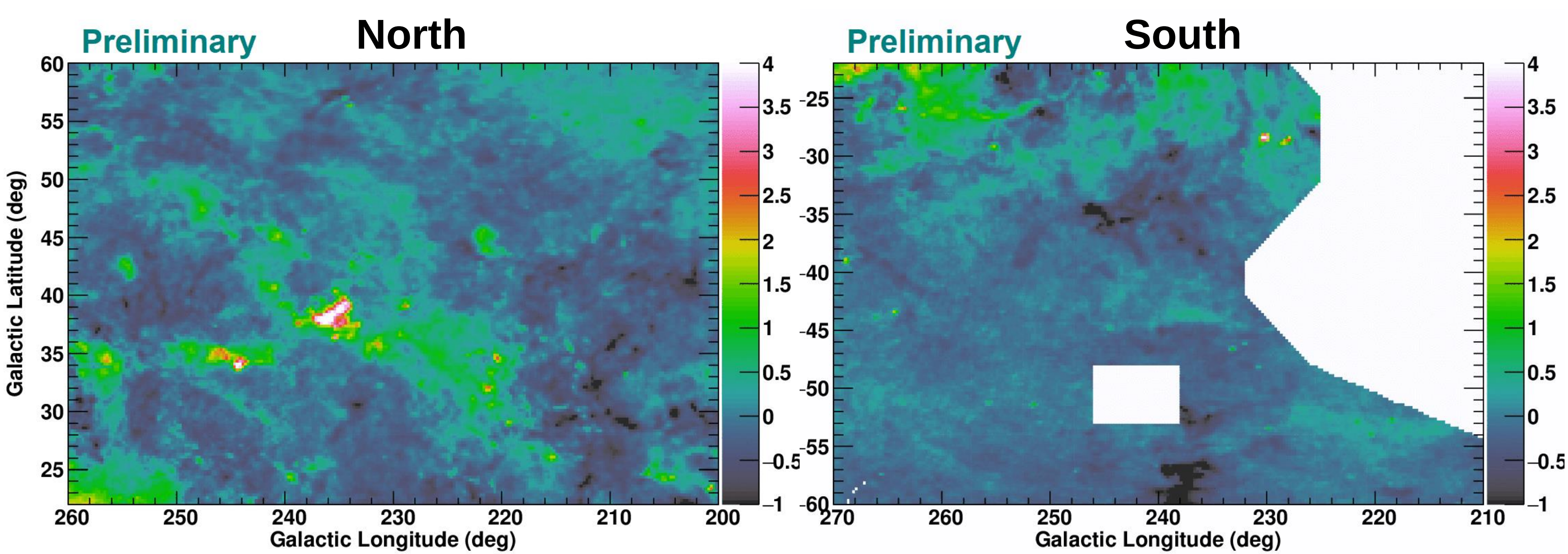
- In both North and South regions we conclude that <u>single N_H template based on R reproduces the data</u> well and fit the data with finer energy bins
- Spectrum of each component summarized below





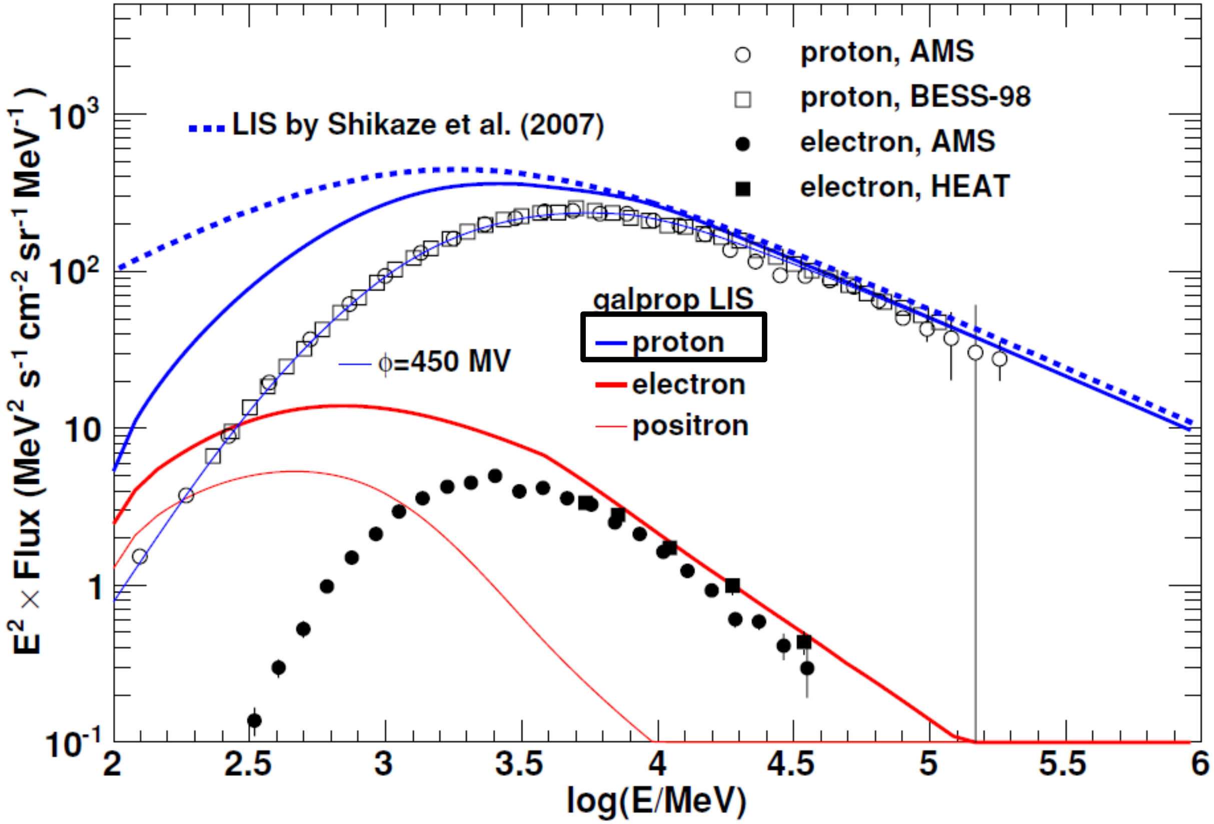
Properties of ISM gas

- Excess gas densities (N_H-N_{HI}^{thin}) in 10^{20} cm^{-2}
- (North) Large N_H/W_{HI} ratio in T_d=18-19 K corresponds to residuals at around (l, b)~(236^o, 37.5^o) for the W_{HI}-based model; likely <u>optically-thick HI</u>
- (South) Flat profile with W_{HI}∼100 K km/s corresponds to residuals at (l, b)~(230^o, -28.5^o); likely <u>CO-dark H_2</u>



Assumed LIS Model

- **Assumed proton LIS model (solid blue) has marginal break in momentum (cf. LIS model by Shikaze +07; dotted blue)**
- **Both models can reproduce CR spectrum directly measured (with different ϕ); γ-ray data is crucial to constrain the LIS**



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