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

Apr. 13, 2021 @ 9th Fermi Symposium

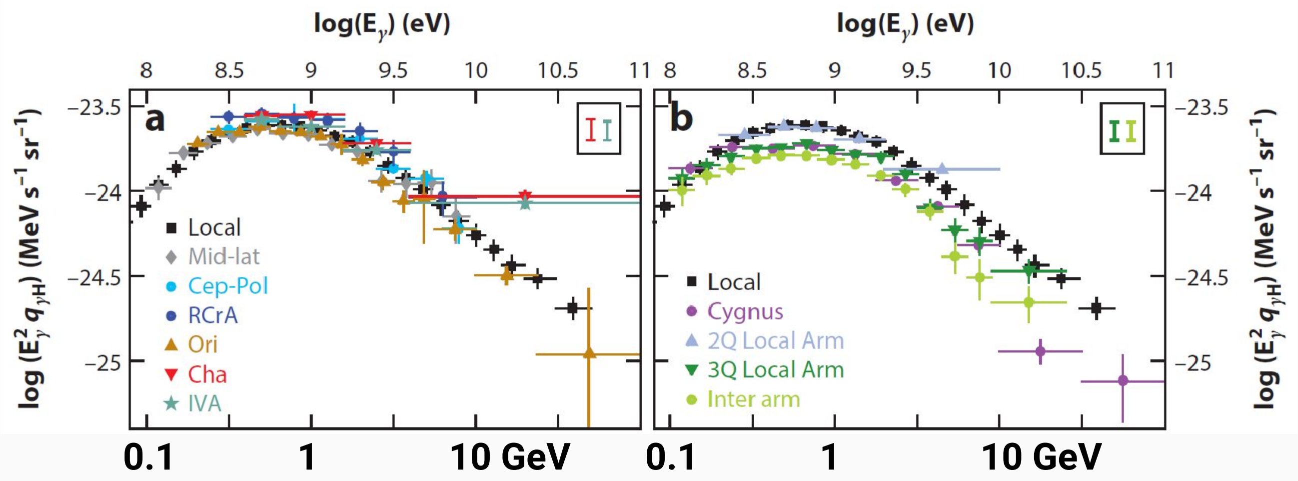
T. Mizuno (Hiroshima Univ.) on behalf of the Fermi-LAT Collaboration

Motivation: ISM & CRs

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

- In principle, we can measure CR intensity (I_{CR}) by γ-ray observation if we know interstellar medium (ISM) gas densities (N_H), since $I_\gamma \propto N_H I_{CR}$

Issue: Even in local environment, uncertainty is still large (a factor of ~1.5), mostly due to uncertainty of spin temperature T_S



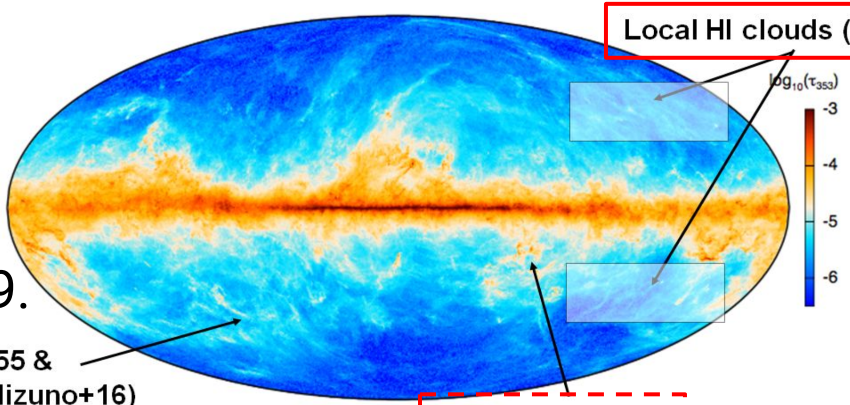
γ-ray emissivity of local clouds (Grenier, Black & Strong 2015)

Objective of this Study

To overcome difficulty, we proposed method no longer relies on uniform T_S (Mizuno+16). Instead, it adopts dust emission (D_{em}) and uses

- "low-density & high-T_d (dust temperature) area" as optically-thin HI
- γ-ray to correct T_d dependence of N_H/D_{em} under the plausible assumption of uniform CR intensity

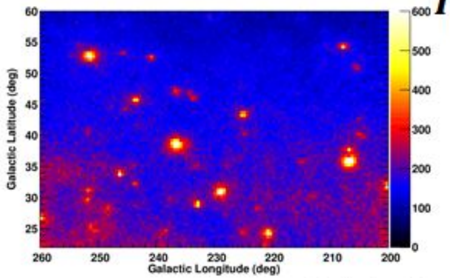
To study local ISM and CRs in details, we apply the method to high-lat. HI clouds in 3rd quad. (Mizuno+20, ApJ 890, 120). Also see relevant study by Hayashi+19.



Procedure of the Analysis

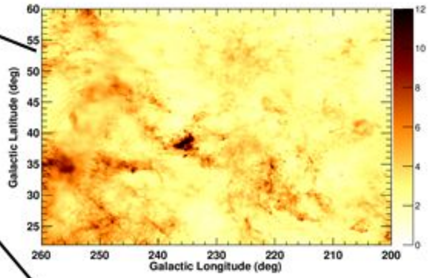
Uniform CR intensity (testable by energy dependence) -> we can model γ-ray intensity as a linear combination of templates

Fermi Data (8 yrs, 0.1-25.6 GeV)

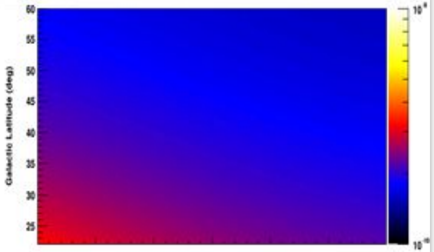


$$I_\gamma(l,b,E) = q_\gamma(E)\cdot N_{\mathrm{H}}(l,b) + I_{\mathrm{IC}}(l,b,E) + I_{\mathrm{iso}}(E) + \Sigma\, I_{\mathrm{source}}(l,b,E) + \cdots$$

Planck dust, W_{HI}, W_{CO}, etc.



IC model (e.g., galprop)



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

Fit quality tells us which tracer is better

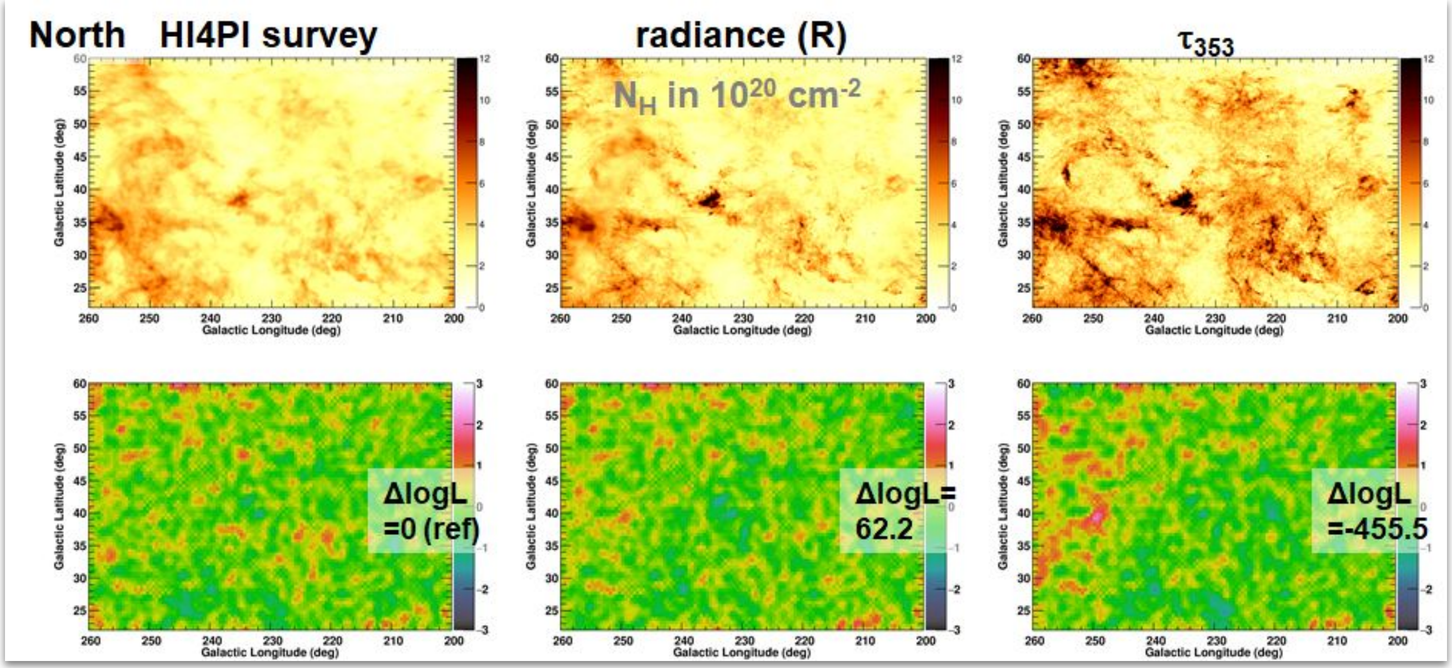
$$N_{\mathrm{H}} = \Sigma_i\, a_i \cdot N(\mathrm{H}_i)$$

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

Coefficients (a_i) tell us gas properties

N_H Template Maps and Residuals (North)

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

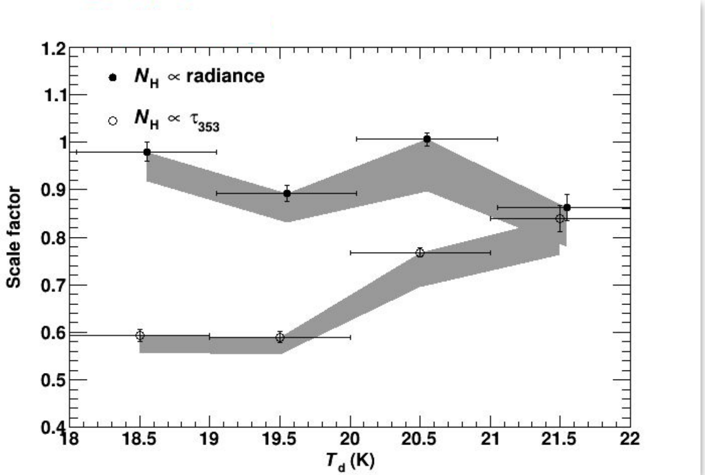


T_d Dependence and linearity (North)

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
- T_d dependence of N_H/R ratio is small. We also confirmed linear N_H-R relation; we conclude $N_H \propto R$ (same conclusion for the south region)

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

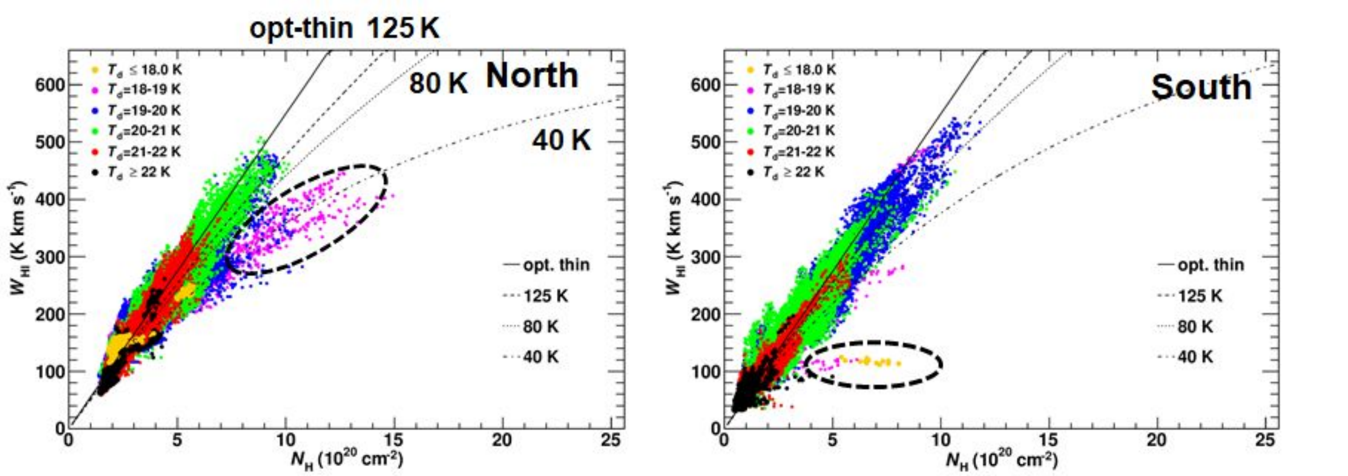


Discussion: ISM properties

W_{HI} vs. N_H ($\propto$R) with models for several values of T_S ; 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

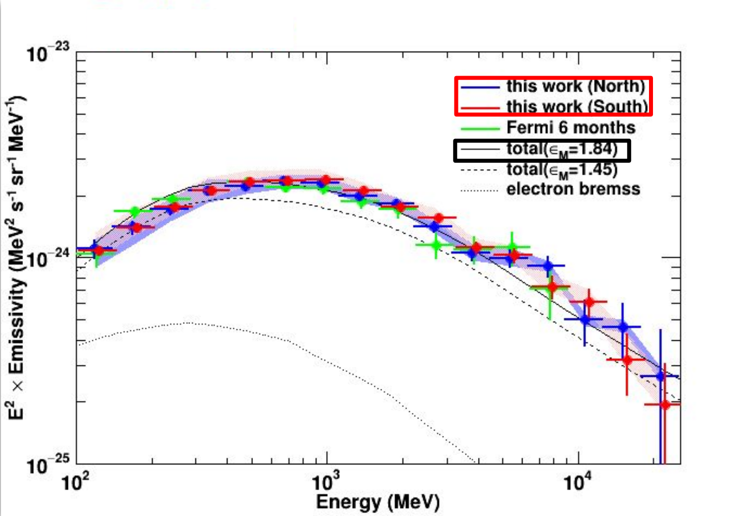
South: Flat profile with W_{HI}~100 K km/s corresponds to residuals at (l, b)~(230°, -28.5°); likely CO-dark H_2



Discussion: CR properties

HI emissivity spectra of north/south regions compared with a model for local interstellar spectrum (LIS)

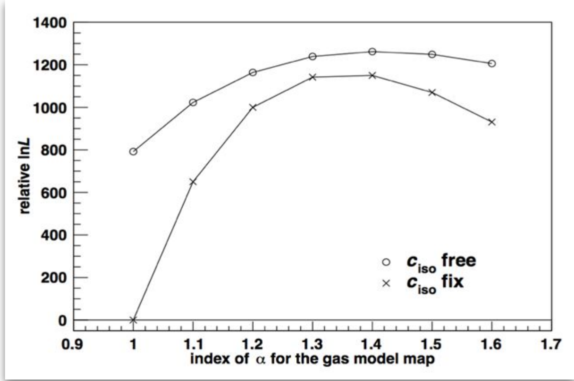
Two spectra agree within uncertainty, supporting uniform CR intensity. Small deviation from a model in low energy implies a possible spectral break (e.g. Strong15) and should be investigated

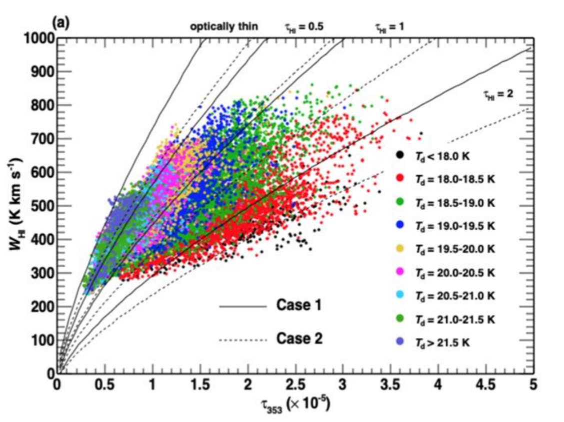


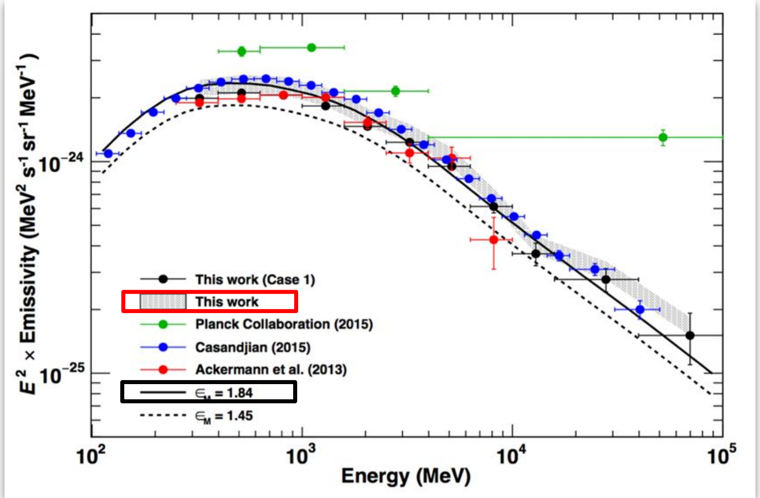
Discussion: Comparison with Relevant Study

We also studied Chamaeleon clouds using dust-based modeling (Hayashi+19)

- $\tau_{353} \propto N_H^{1.4}$ reproduces the data well; non-linear N_H-D_{em} relation due to dust grain evolution. τ_{HI}=0.5-1 suggested (for opt-thick scenario)
- γ-ray emissivity agree with this study, further supporting uniform CR intensity







Summary

We studied local HI clouds in 3rd quadrant using dust-based N_H model (no longer assumes uniform T_S)

- N_H ($\propto$R) model reproduces the data for both north and south regions
- T_S>=125 K suggested. Areas with opt-thick HI and CO-dark H2 identified
- Uniform CR intensity supported

We also studied (denser) Chamaeleon clouds using the same method

- Non-linear N_H/D_{em} ratio suggested
- Uniform CR intensity further supported

Future tasks for accurately measuring gas and CRs in MW:

1. Solve possible degeneracy btw. non-linearity and T_d dependence
2. Identify opt-thin HI in Galactic plane

Thank you for your attention

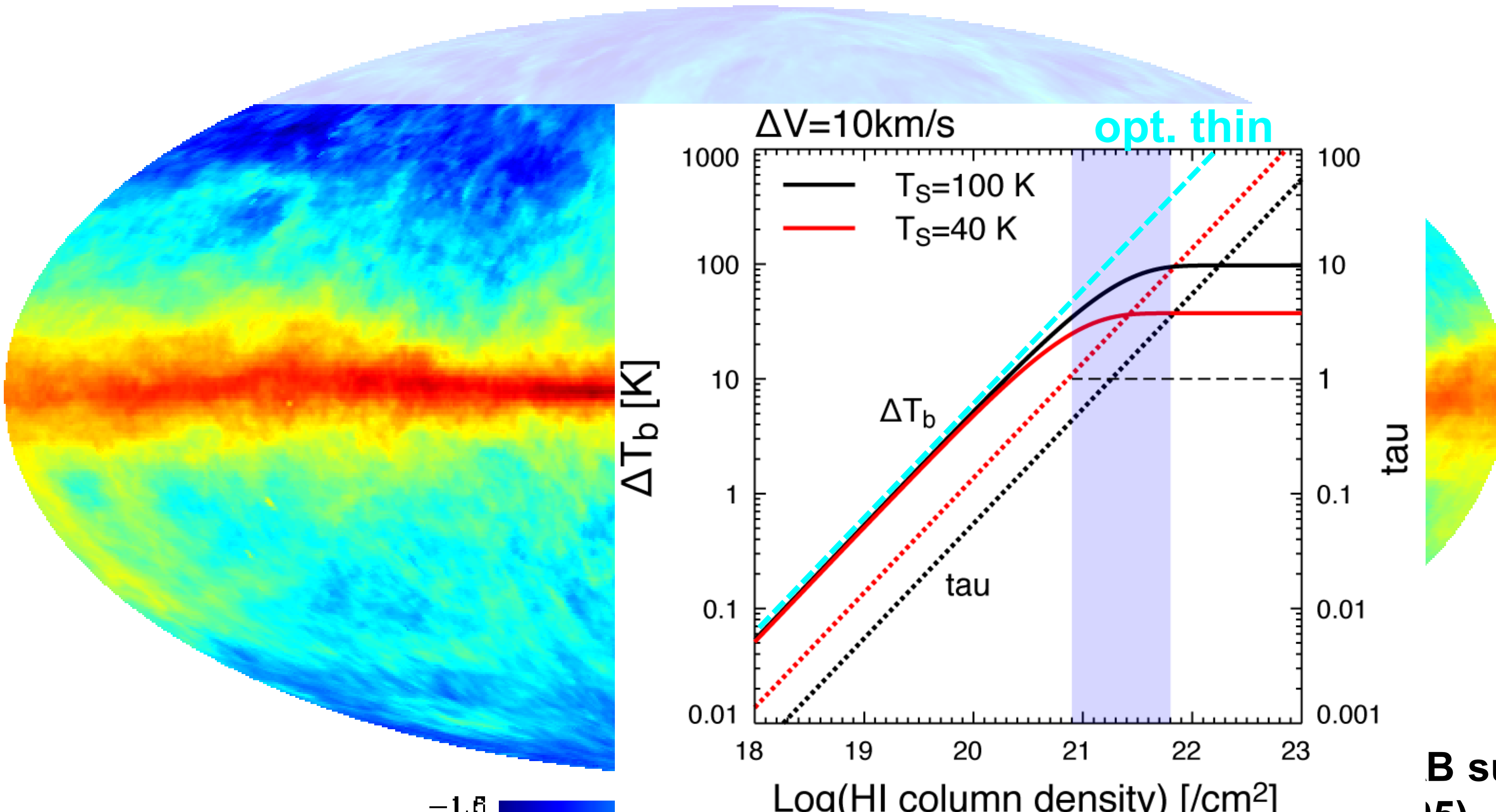
References

- Abdo+ 2009, ApJ 703, 1249
- Brown+ 1995, A&A 300, 903
- Grenier+ 2005, Science 307, 1292
- Grenier+ 2015, ARAA 53, 199
- Hayashi, TM+ 2019, ApJ 884, 130
- HI4PI Collaboration 2016, A&A 594, 116
- Karberla+ 2005, A&A 440, 775
- Ochsendorf+ 2015, ApJ 808, 111
- Planck Collaboration 2014, A&A 571, 13 (Planck 2013 Results XIII)
- Ptsukin+ 2006, ApJ 642, 902
- Strong 2015, Proc. ICRC 34, 506
- Mizuno+ 2016, ApJ 833, 278
- Mizuno+ 2020, ApJ 870, 120
- Mori 2009, 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**

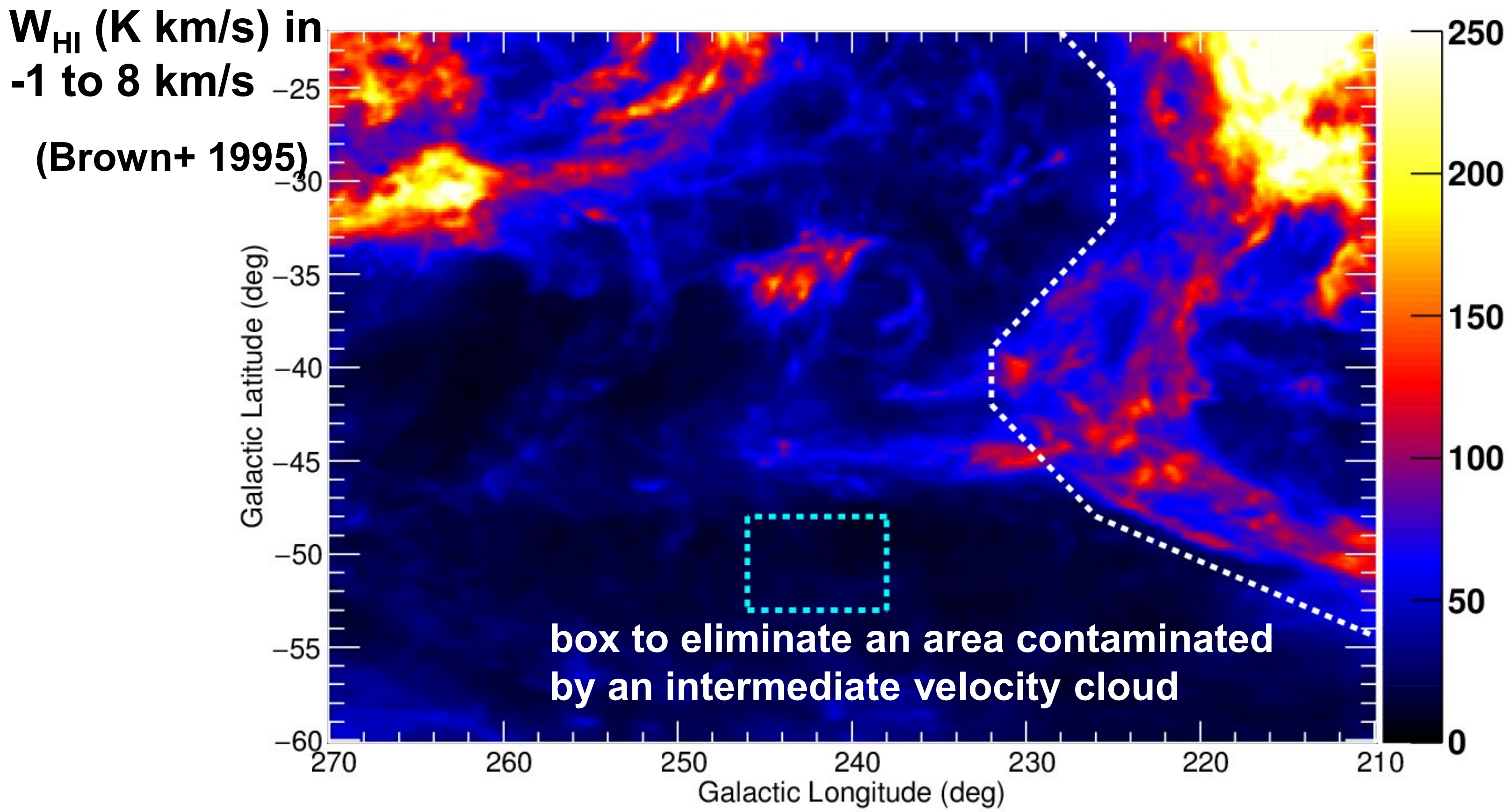


B survey;

)5)

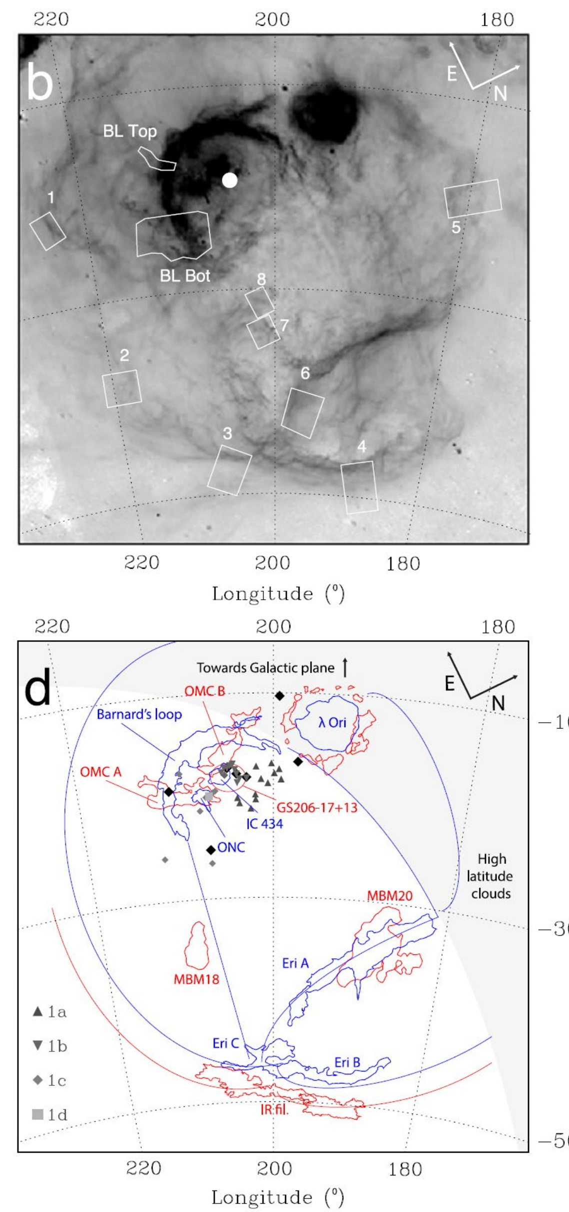
Region Mask: Velocity-Sorted HI Map

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



Hα Filaments (in Ref.)

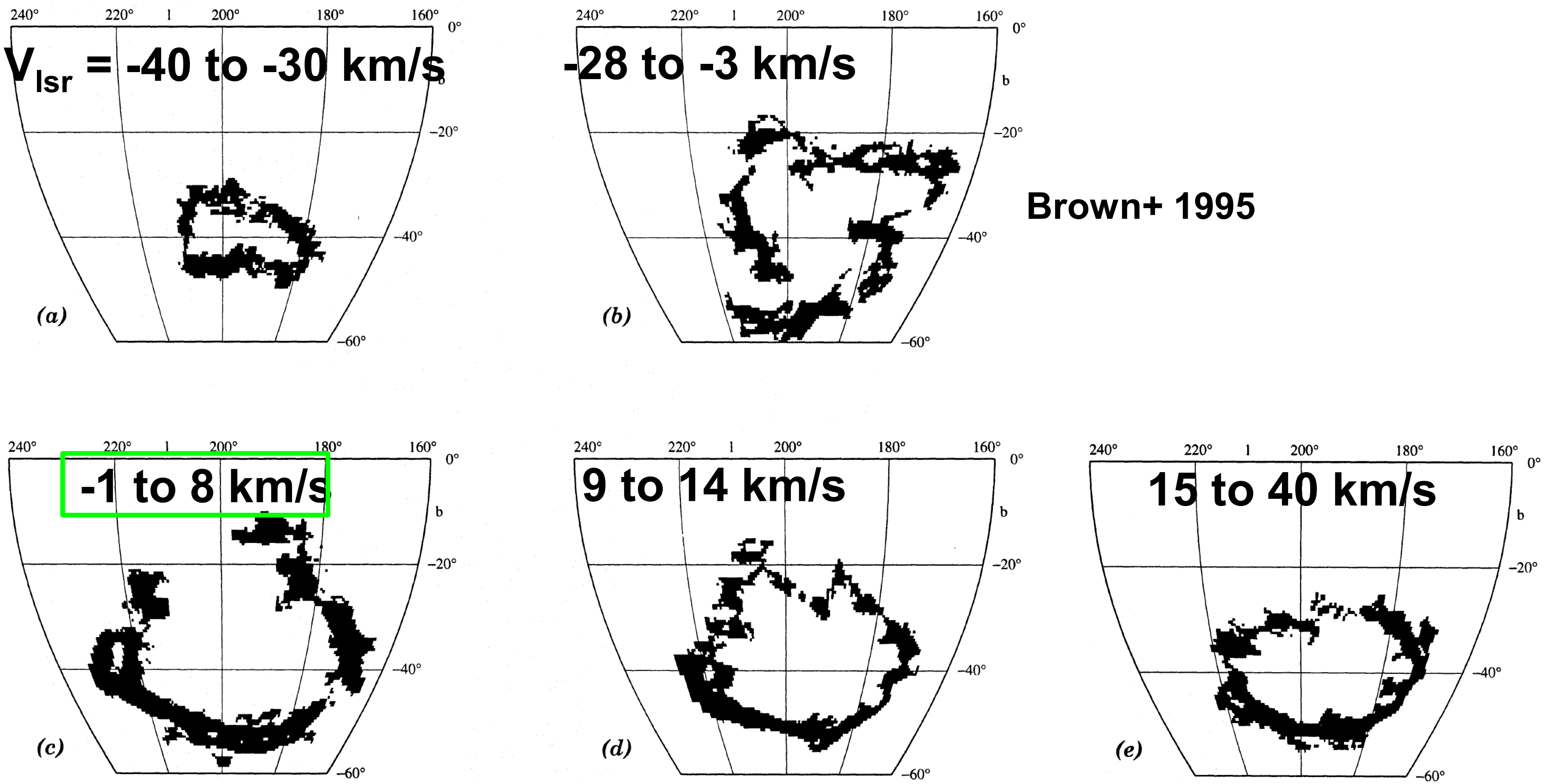
- (upper right) Several Hα filaments in the Orion-Eridanus superbubble
- (lower right) Outer parts of Hα filaments on the south and west are traced by a solid blue line to guide the eye. Toward the southwest, they are surrounded by a shell of neutral gas (traced by a red line).



Ochsendorf+ 2015

Neutral Gas (in Ref.)

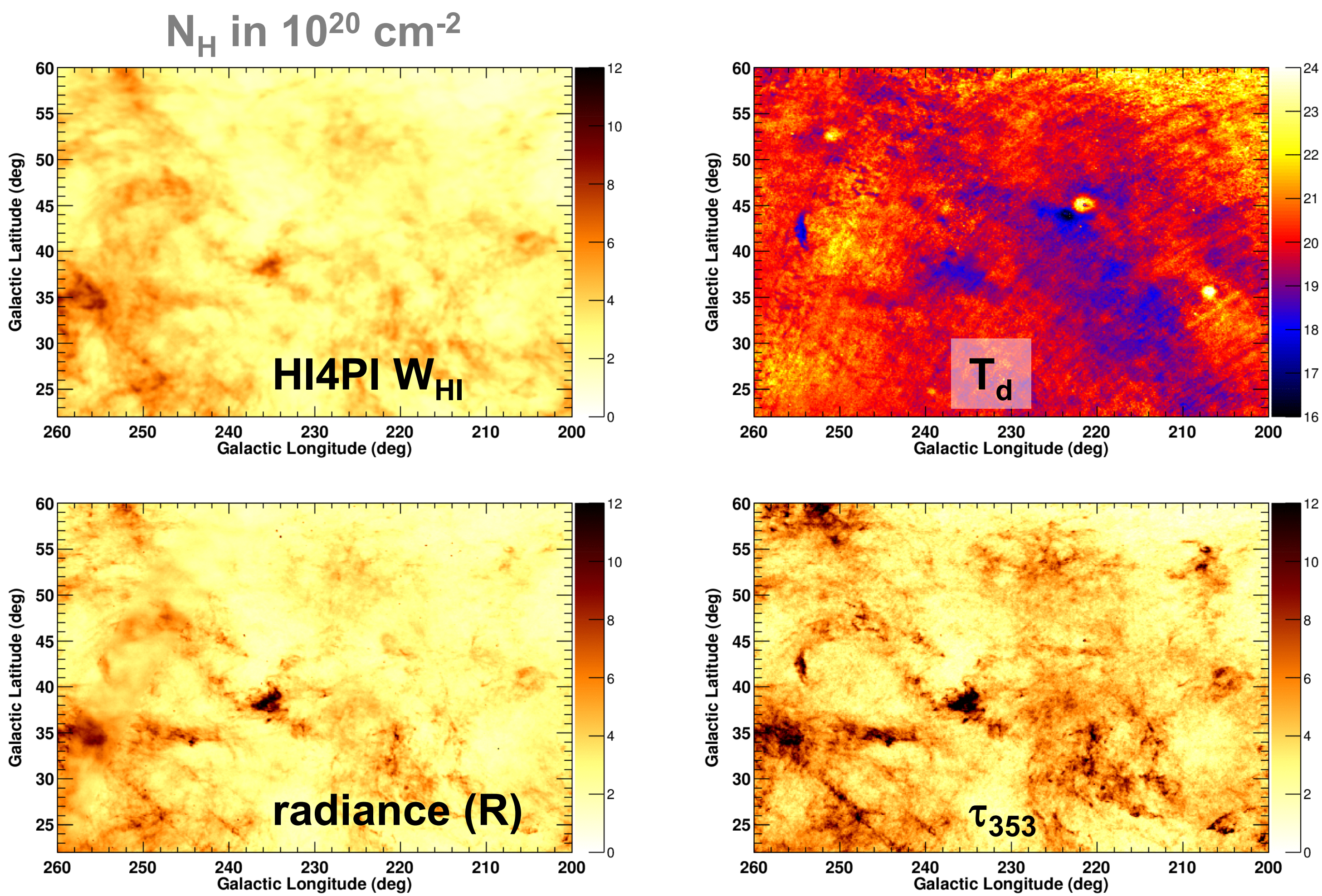
- Velocity-sorted HI maps reveal an expanding HI shell -> Use HI maps (and also Hα) to define the bubble area



Brown+ 1995

Initial N_H Template Maps (North)

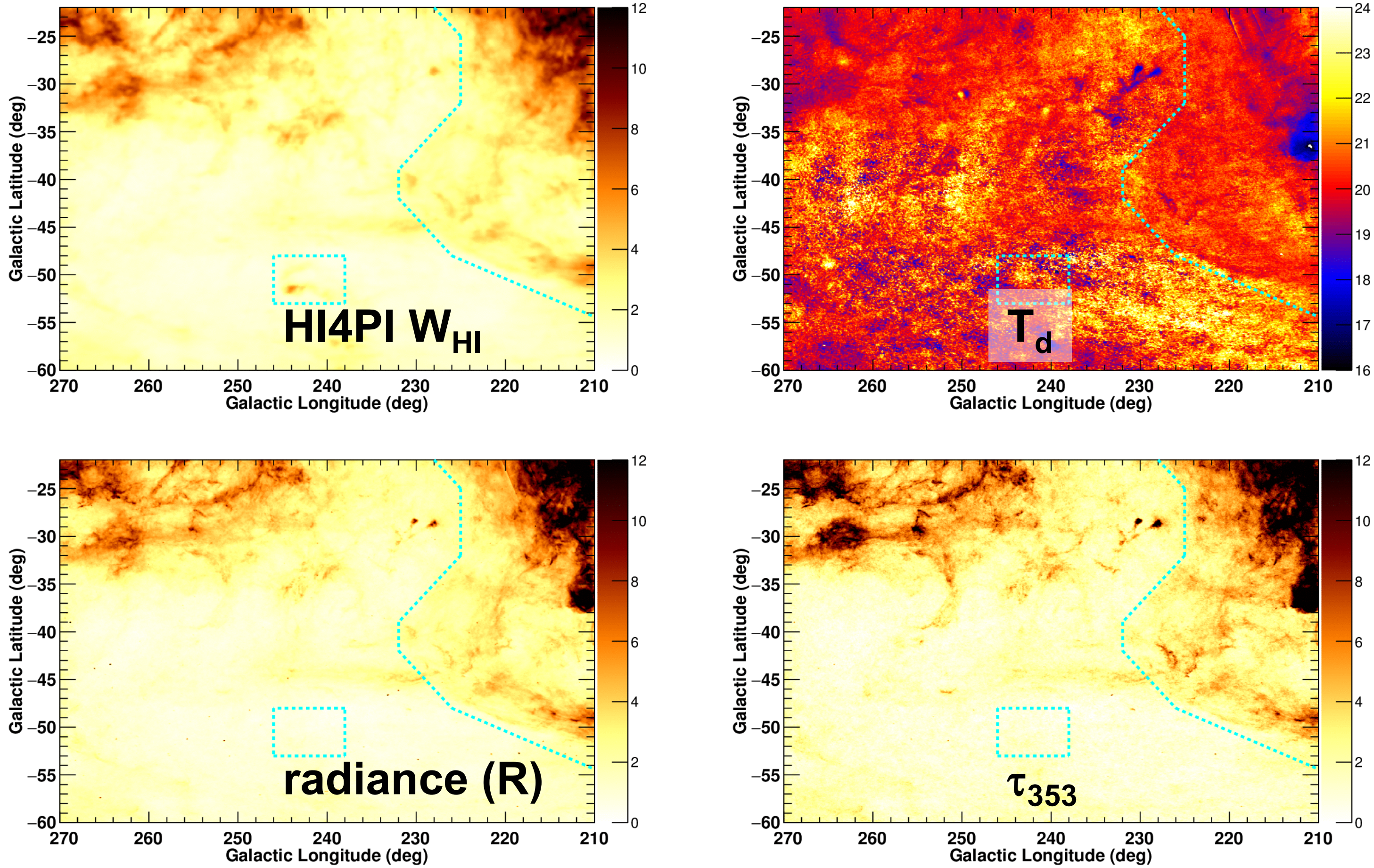
- **We prepared N_H template maps ($\propto W_{HI}$, R, or τ_{353}) and used them in a fit of γ-ray data** (different contrast in 3 models)



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)

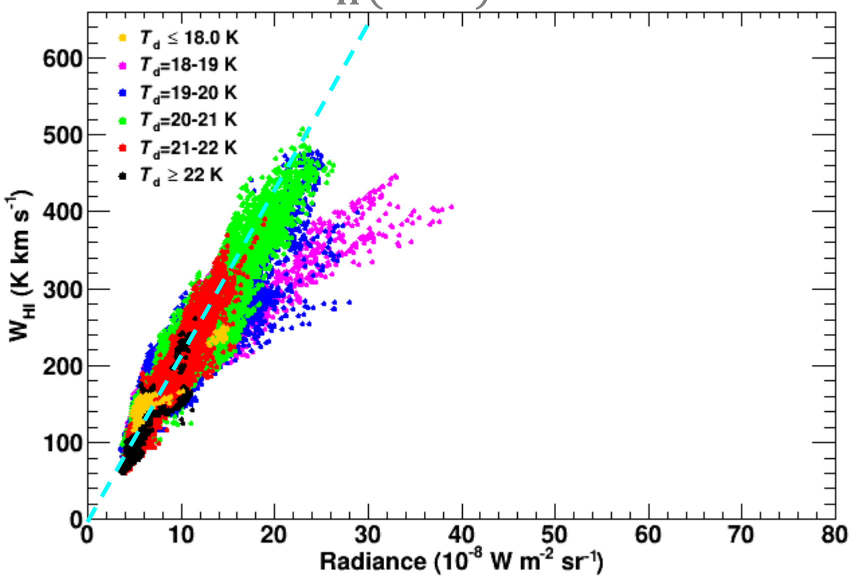
N_H in 10^{20} cm^{-2}

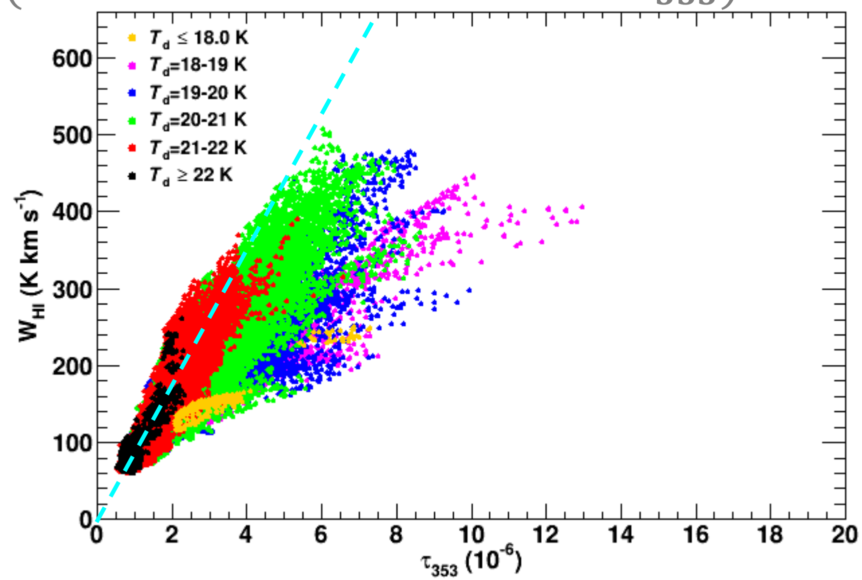


W_{HI}-Dust Relation (North)

- **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**

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

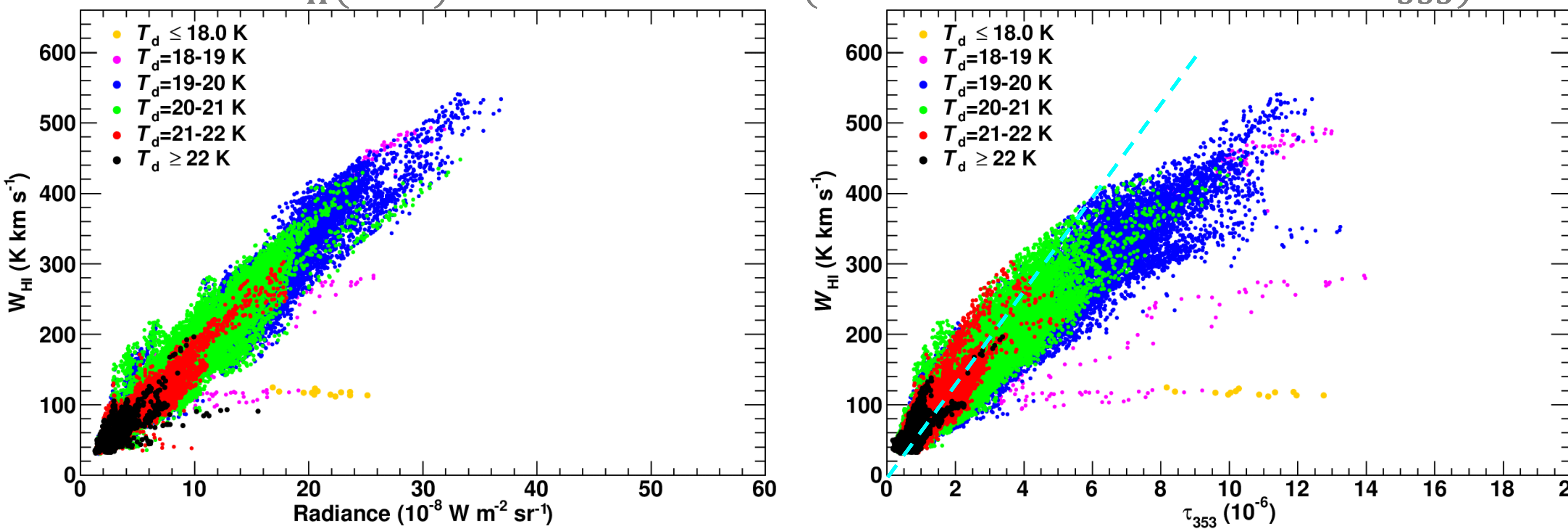




W_{HI}-Dust Relation (South)

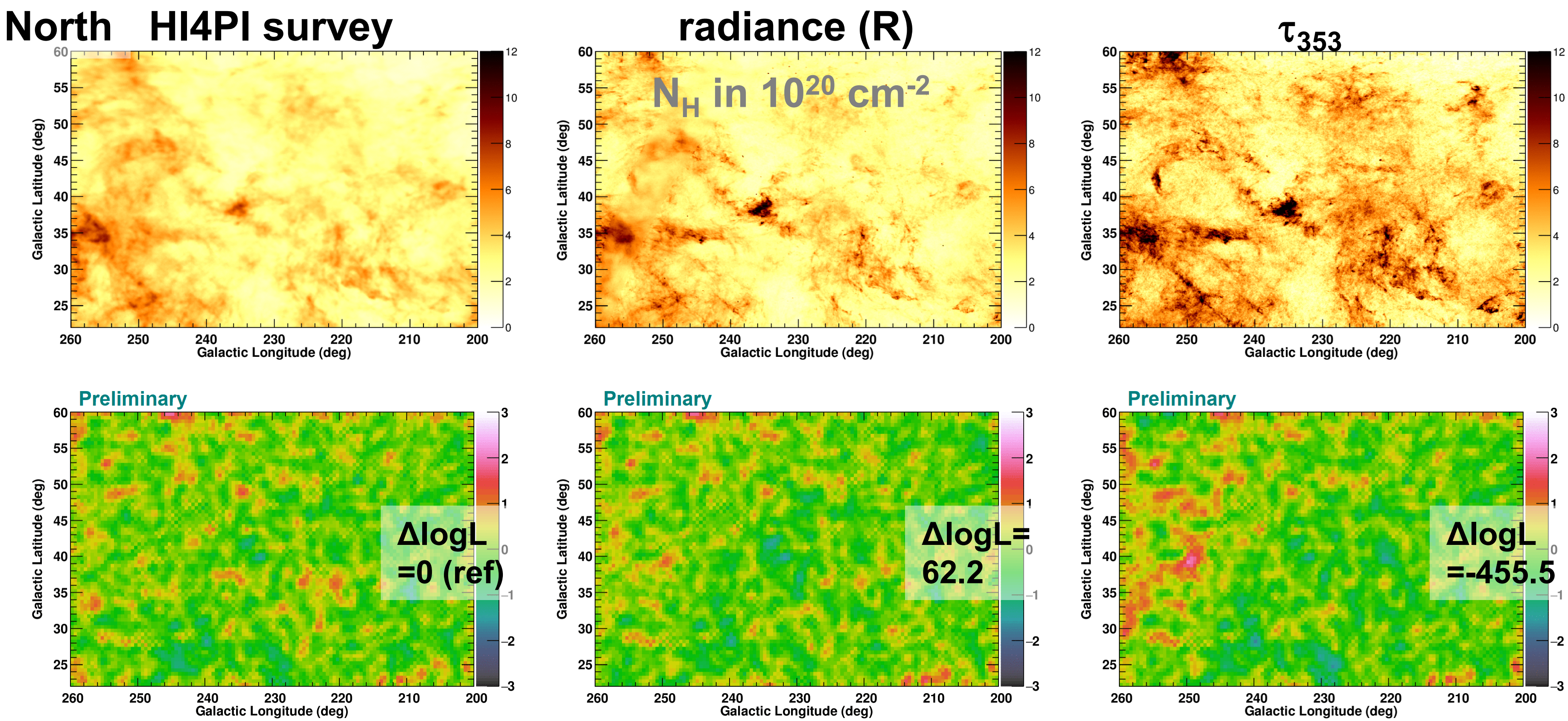
- **Correlation between W_{HI} and D_{em}**
  - **Weak T_d dependence, non-linear W_{HI}-D_{em} relations**
- **Linear curves that follow trends in high T_d areas are used to construct initial N_H templates assuming $N_H \propto D_{em}$**
- **We will use γ-rays (robust tracer of ISM gas) to constrain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

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



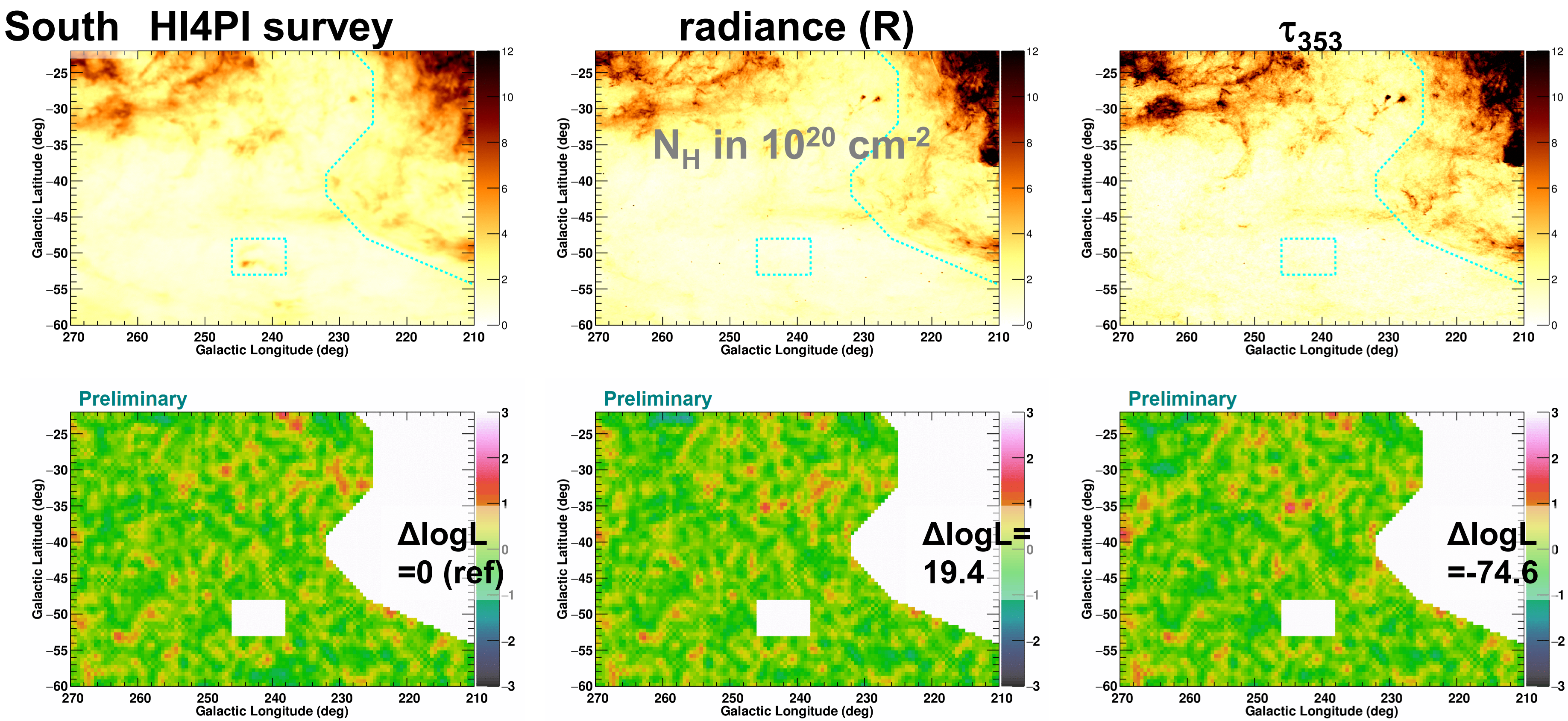
N_H Model Maps and Residuals (North)

- 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)



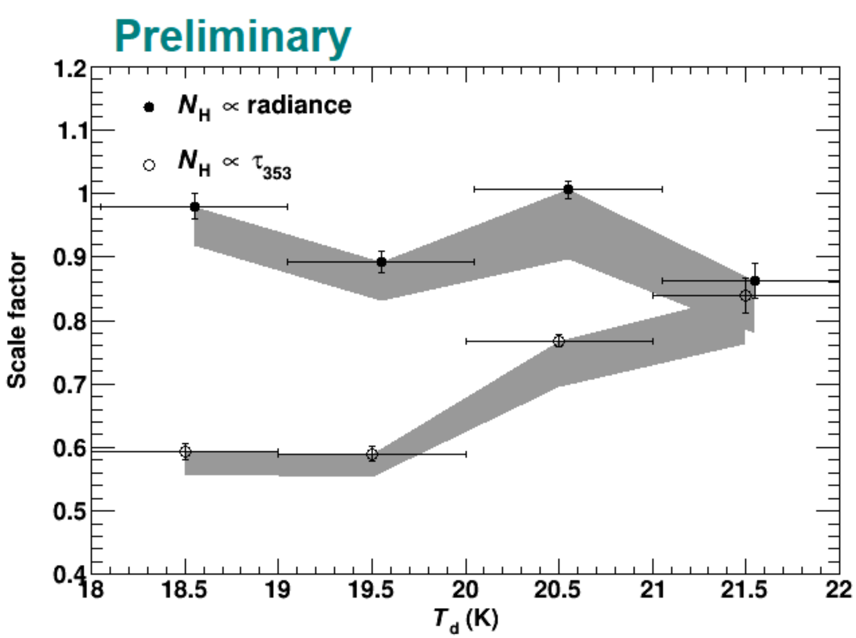
N_H Model Maps and Residuals (South)

- 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.



T_d Dependence (North)

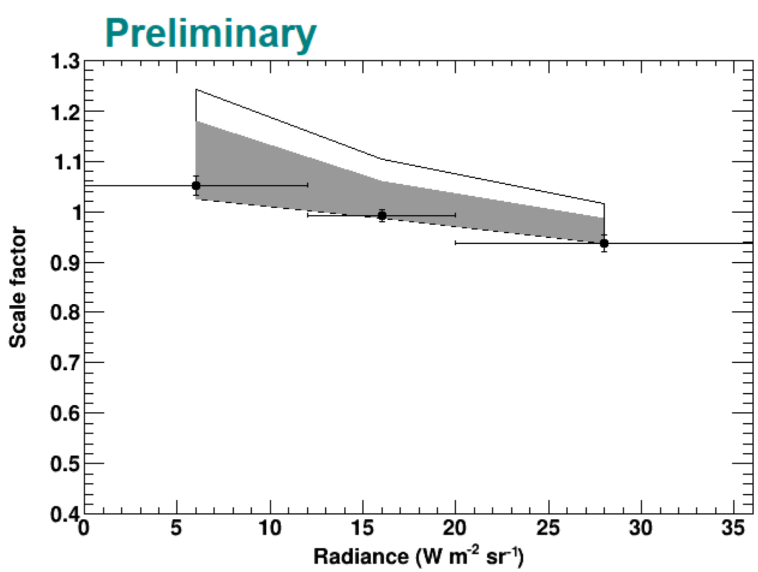
- If $N_H \propto D_{em}$, fit coefficient is constant for a uniform CR intensity
- Fit with T_d-sorted N_H templates shows a significant T_d dependence for τ_{353}, implying an overestimate of N_H/τ_{353} in low T_d areas
- Fit improvement not significant for R; we adopt a single R-based template as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

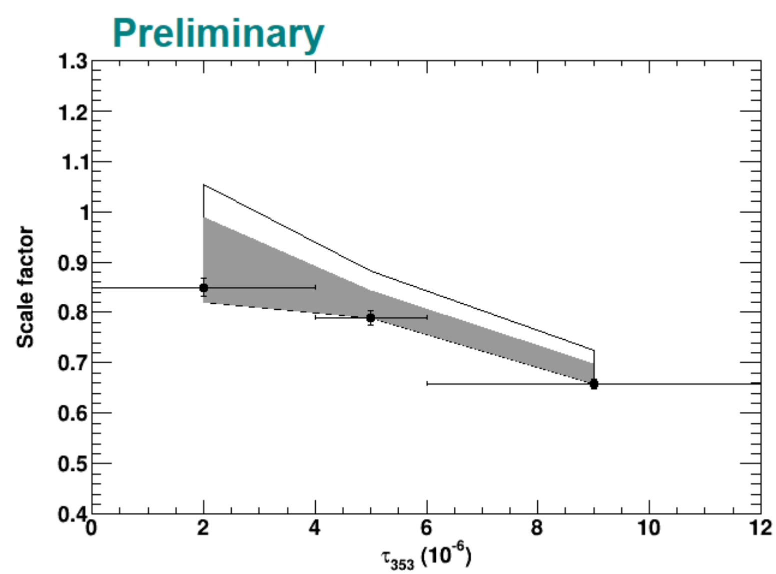


Emissivity scale factor ($\propto(N_H/D_{em})^{-1}$), averaged over 0.2-12.8 GeV

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, TM+ 2019)
- 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

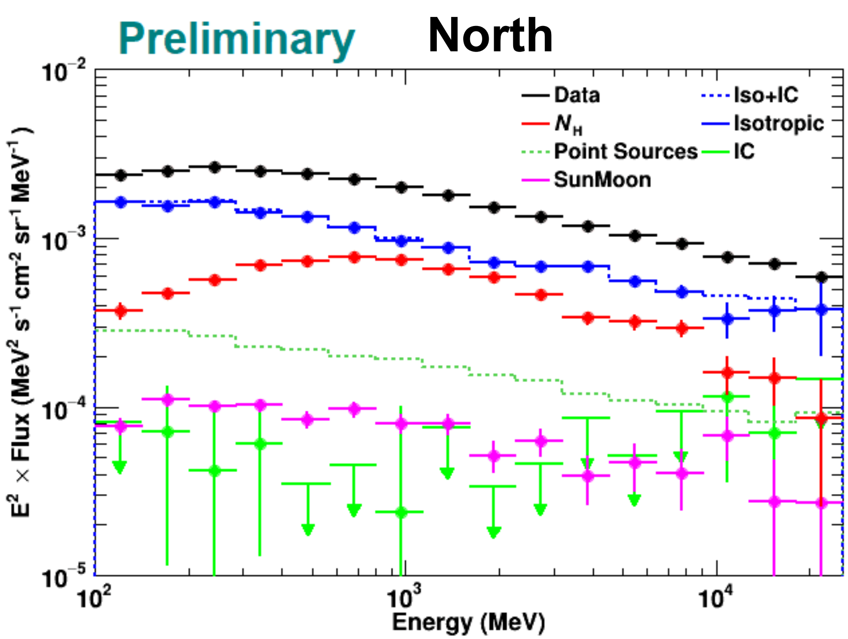


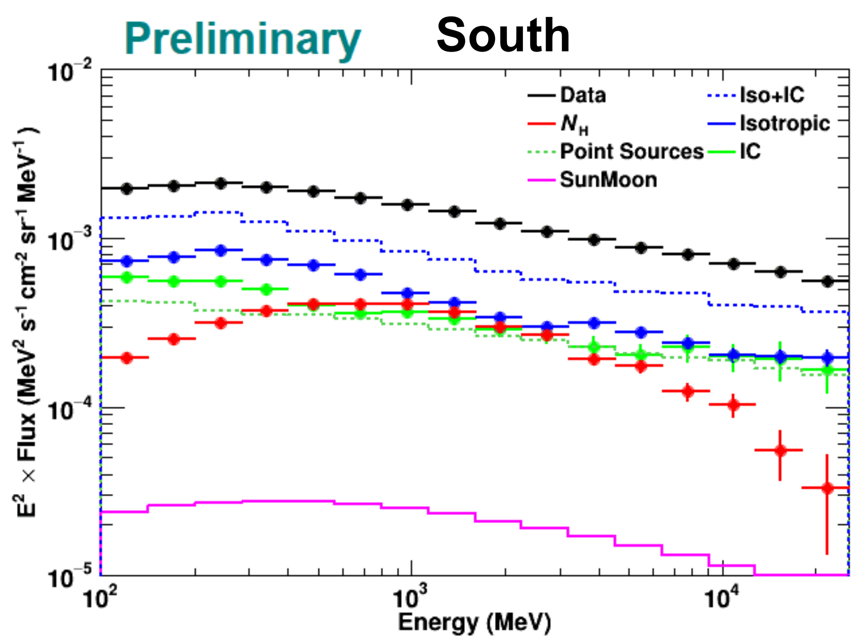


Emissivity scale factor ($\propto(N_H/D_{em})^{-1}$), averaged over 0.2-12.8 GeV

Spectrum of Each Component

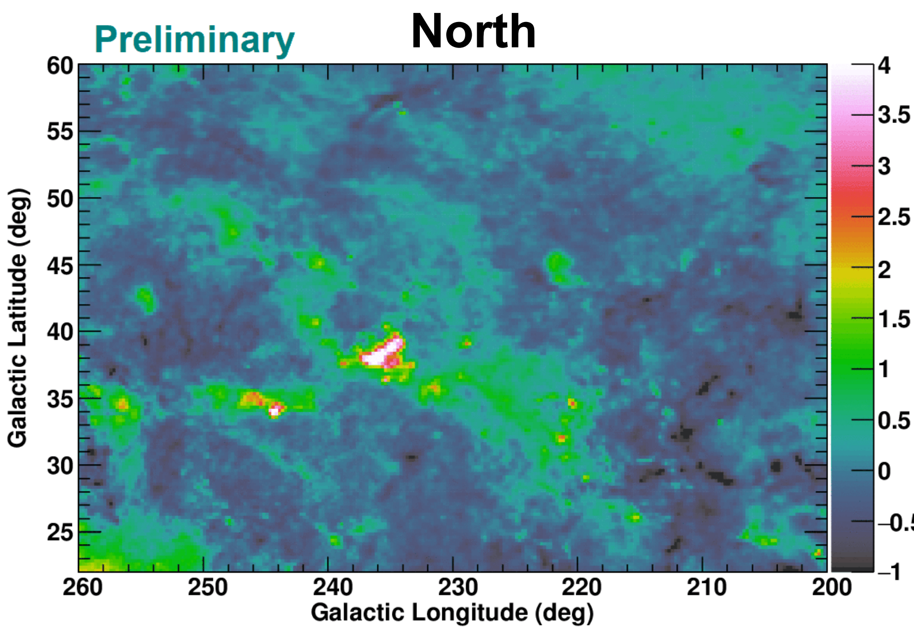
- In both North and South regions we conclude that <u>single N_H template based on R reproduces the data</u> well and fit the data with finer energy bins
- Spectrum of each component summarized below

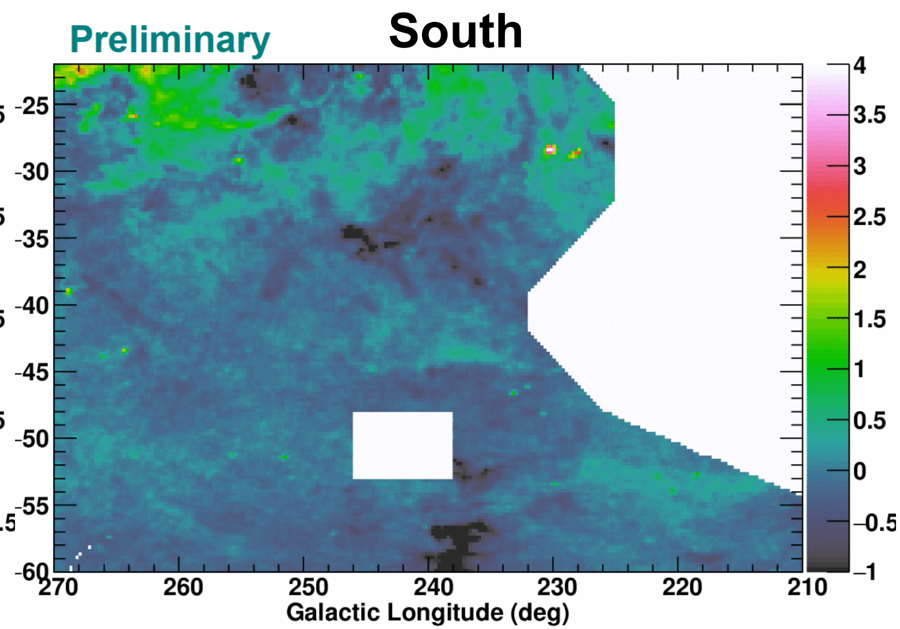




Properties of ISM gas

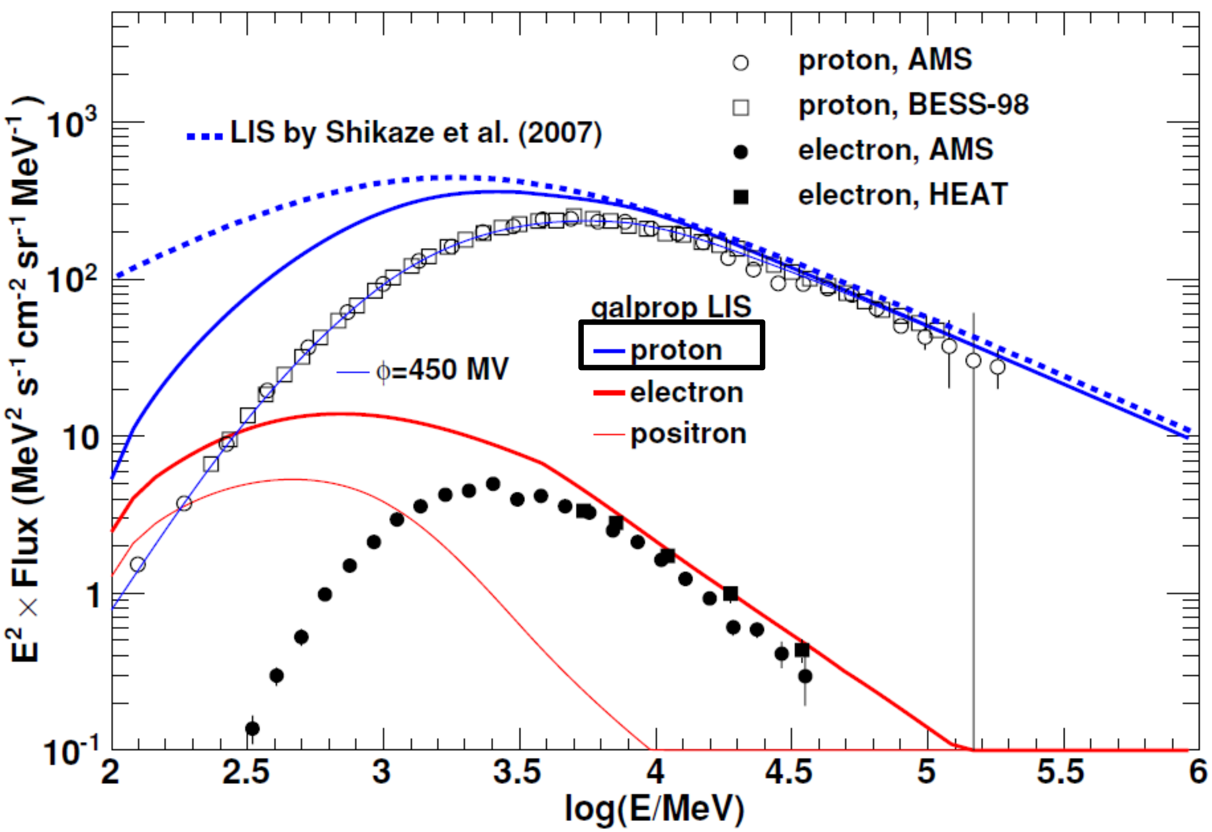
- Excess gas densities (N_H-N_{HI}^{thin}) in 10^{20} cm^{-2}
- (North) Large N_H/W_{HI} ratio in T_d=18-19 K corresponds to residuals at around (l, b)~(236°, 37.5°) for the W_{HI}-based model; likely <u>optically-thick HI</u>
- (South) Flat profile with W_{HI}~100 K km/s corresponds to residuals at (l, b)~(230°, -28.5°); 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+ 2007; dotted blue)
- Both models can reproduce CR spectrum directly measured (with different ϕ); γ-ray data is crucial to constrain the LIS



Abdo+ 2009