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

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Tsunefumi Mizuno (Hiroshima Univ.)

S. Abdollahi, Y. Fukui, K. Hayashi, T. Koyama, A. Okumura, H. Tajima, and H. Yamamoto

On behalf of the Fermi-LAT collaboration

フェルミ衛星による太陽系近傍原子雲の宇宙線・星間ガスの研究(3)

2018年9月18日@日本物理学会(山形大学)

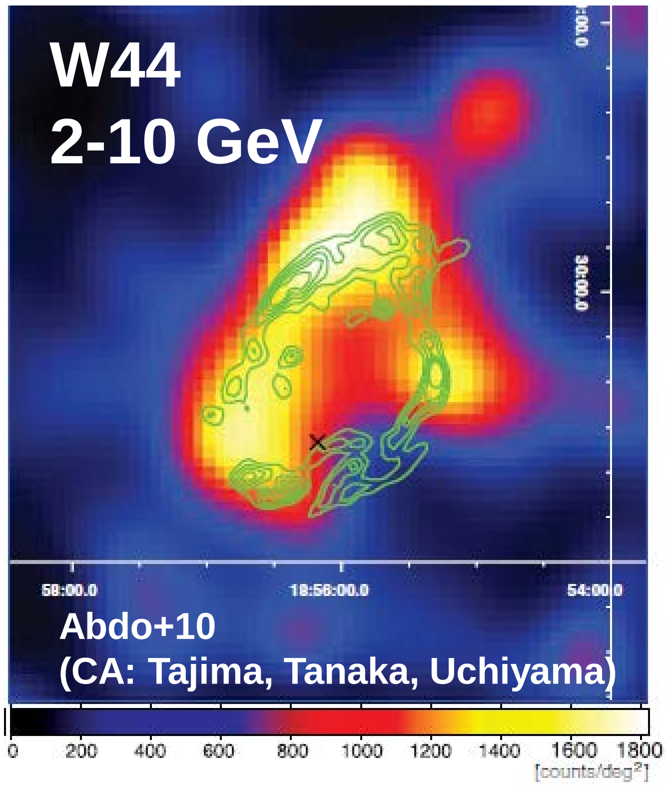
水野　恒史(広島大学)

S. Abdollahi, 福井康雄，林克洋，小山恭弘，奥村曉，田島宏康，山本宏昭

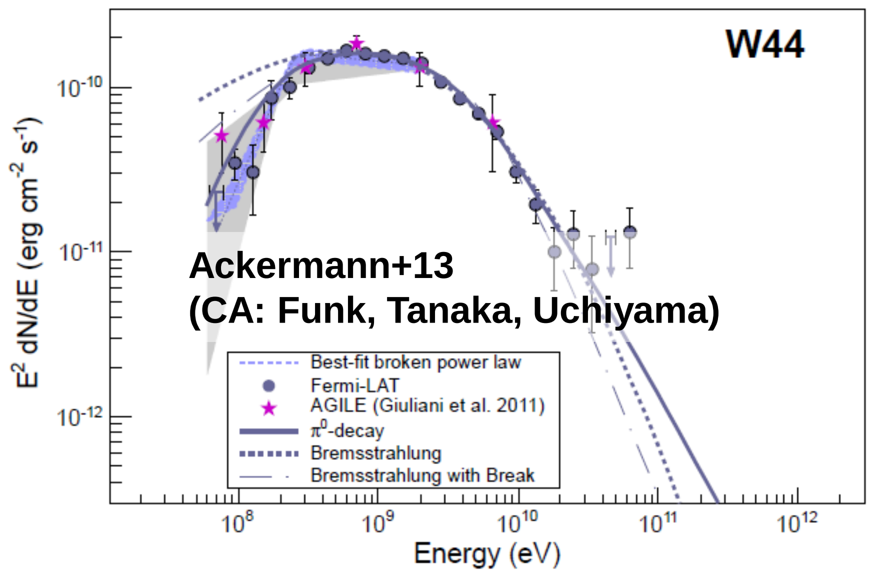
Fermi-LAT Collaboration

Motivation: ISM as a Tracer of CRs

γ-ray image
w/ 4.5 μm contours



low-energy cutoff
= signature of pi^0-decay

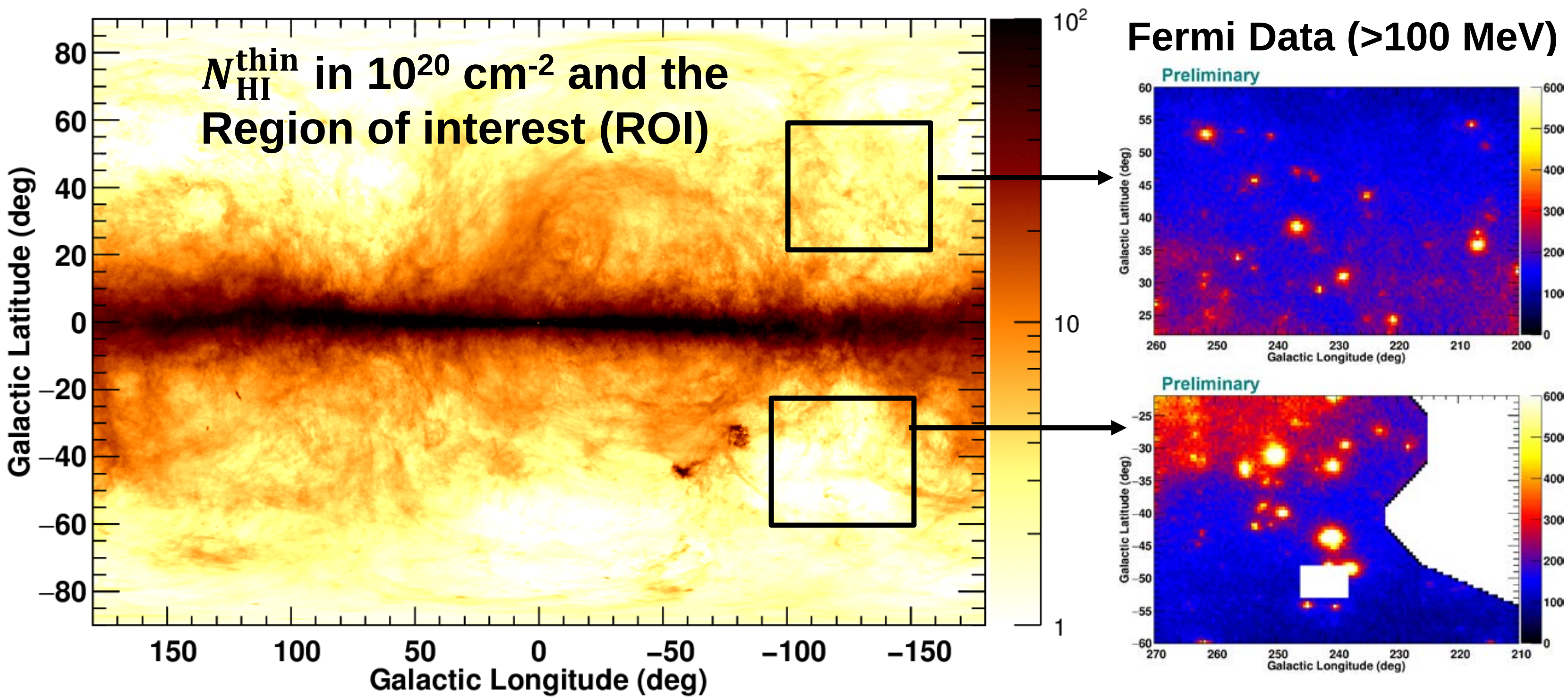


W_{SN}	5×10^{51} erg
W_{CR}	4×10^{49} $(n/100\ cm^{-3})^{-1}$ erg

<u>Accurate estimate of the interstellar medium (ISM) gas densities</u> is crucial to study Galactic cosmic rays (CRs), because $I_\gamma \propto N_{\rm H} U_{\rm CR}$

Objectives of the Study

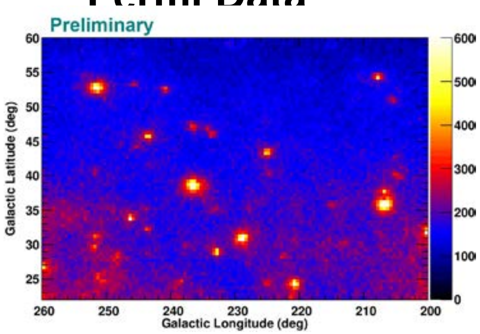
- **Accurate estimate of the ISM gas densities is crucial to understand the ISM and Galactic CRs**
- **Procedure to trace the "dark gas" (gas not properly traced by HI and CO line surveys** (Grenier+05)**) not established yet => detailed study of nearby clouds**



Analysis Strategy Procedure

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

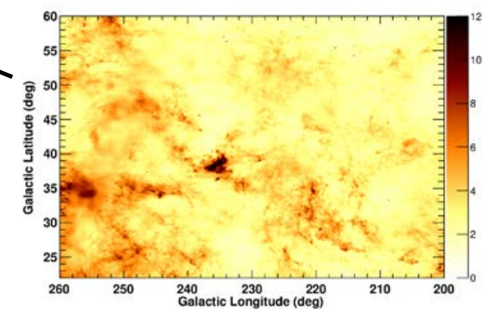
Fermi Data



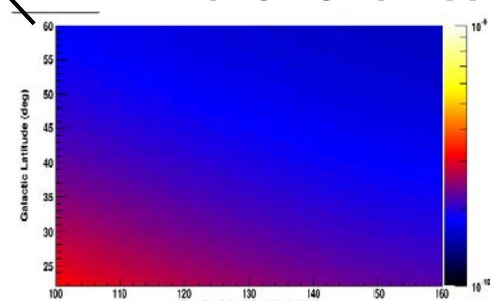
$$I_\gamma(l,b,E) = q_\gamma(E)\cdot N_{\mathrm{H}}(l,b)$$
$$+I_{\mathrm{IC}}(l,b,E)$$
$$+I_{\mathrm{iso}}(E)$$
$$+\Sigma\, I_{\mathrm{source}}(l,b,E)$$
$$+\cdots$$

$q_\gamma(E)$ **tells us CR density/spectrum**

Planck dust, LAB $\mathrm{H_I}$, $\mathrm{W_{CO}}$, etc.



IC model (e.g., galprop)



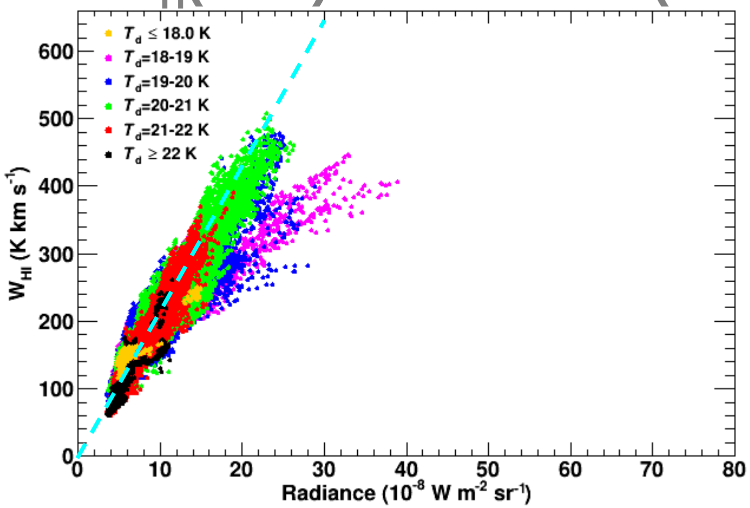
$$N_{\mathrm{H}} = \Sigma_i\ a_i\cdot N(\mathrm{H}_i)$$
$$(\mathrm{e.g.}, N(\mathrm{H_I}) + 2X_{\mathrm{CO}}\cdot W_{\mathrm{CO}} + X_{\mathrm{DG}}\cdot N(\mathrm{H_{DG}}))$$

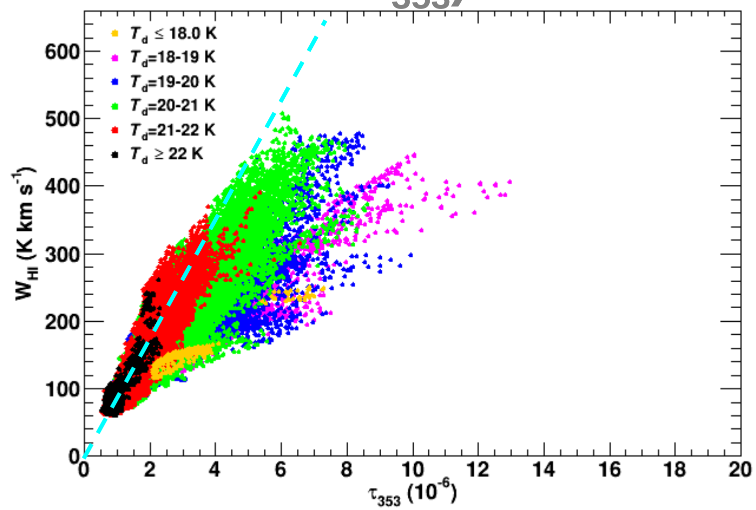
Fit quality tells us which tracer is better
Coefficients (a_i) tell us gas properties

W_{HI}-Dust Relation (North)

- Correlation btw. W_{HI} and dust emission D_{em} (R or τ_{353})
- Dust temperature (T_d) dependence is seen in W_{HI}-τ_{353} correlation
- Linear curves that follow trends in high T_d area used to construct initial N_H templates assuming $N_H \propto D_{em}$

$N_H(cm^{-2}) = 1.82\times10^{18} \times (21.1\times10^{8}\ R \text{ or } 87.2\times10^{6}\ \tau_{353})$

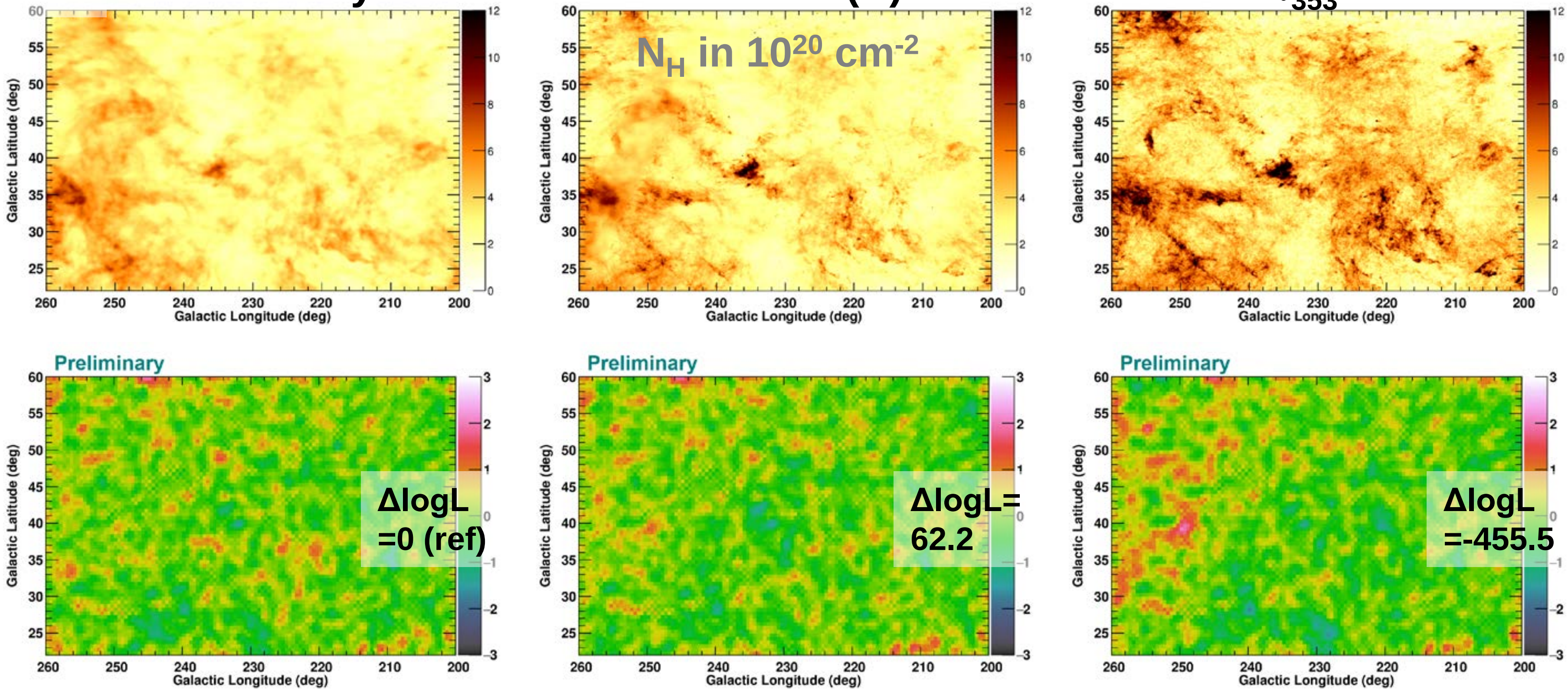




N_H Model Maps and Residuals (North)

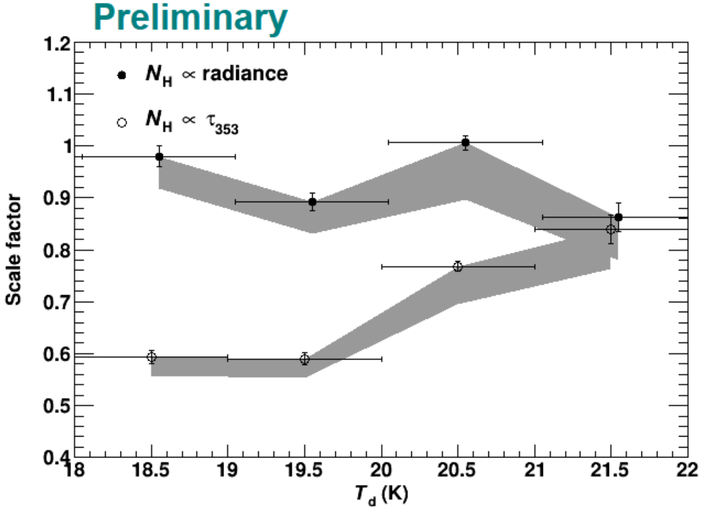
- **We prepared N_H model maps ($\propto W_{HI}$ or D_{em}) and used them in a fit of γ-ray data -> R gives the best fit** (same conclusion for the south)

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



T_d Dependence (North)

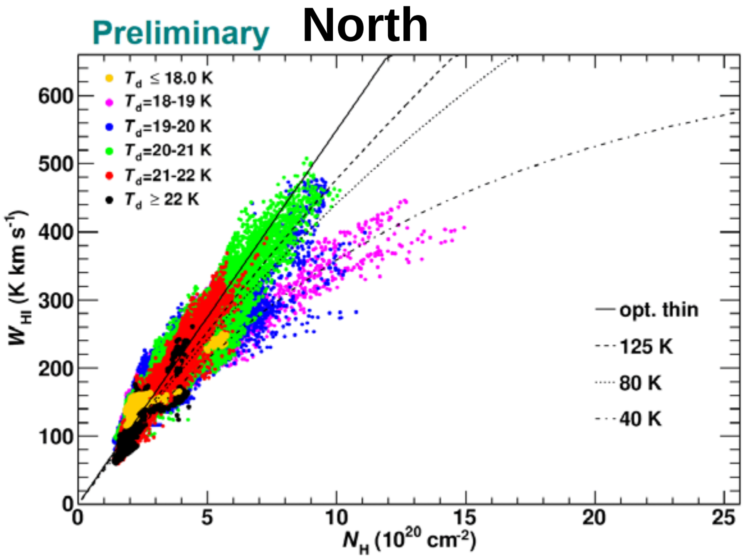
- If $N_H \propto D_{em}$, the fit coefficient should be constant for uniform CR intensity
- A fit with T_d-sorted N_H templates shows a significant T_d dependence for τ_{353}, implying an overestimate of N_H/τ_{353} in low T_d area
- Fit improvement not significant for R; we adopt a single R-based N_H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

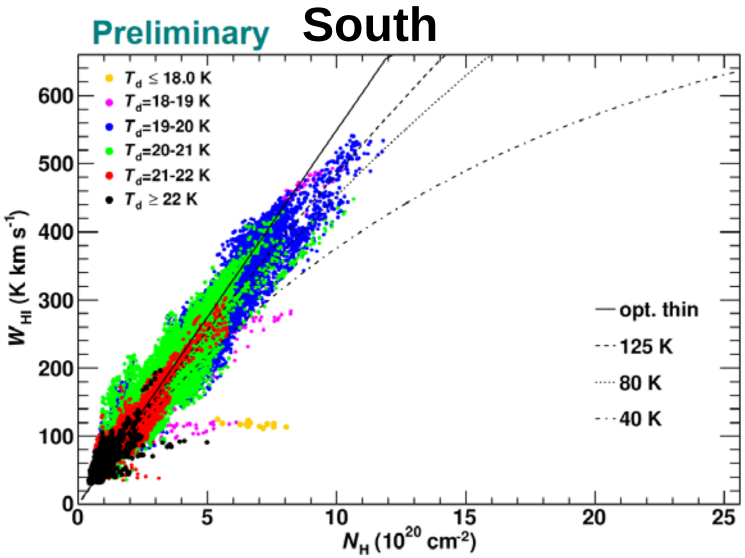


Emissivity scale factor ($\propto N_H/D_{em}$), averaged over 0.2-12.8 GeV

Properties of ISM gas

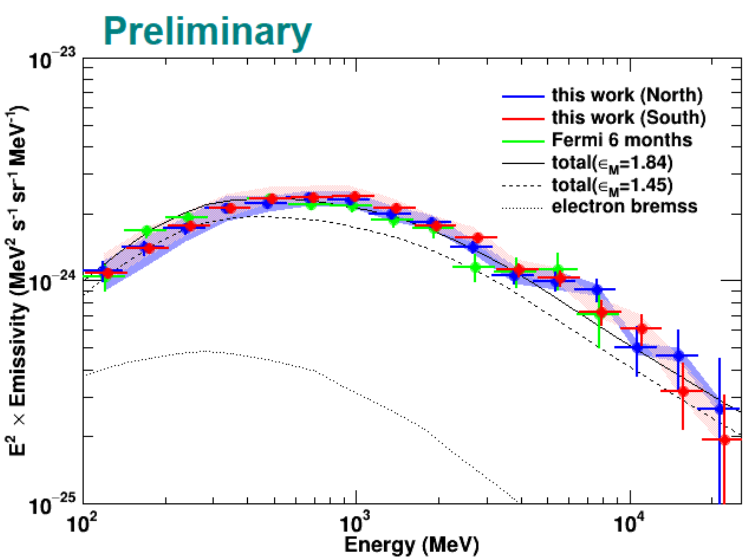
- W_{HI} vs. N_H ($\propto$ R) with models for several values of T_S
- In general, data agrees with T_S=125 K or higher
- (North) Large N_H/W_{HI} ratio in T_d=18-19 K corresponds to residual at around (l, b)~(236°, 37.5°) for W_{HI}-based model; likely optically-thick HI
- (South) Flat profile with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

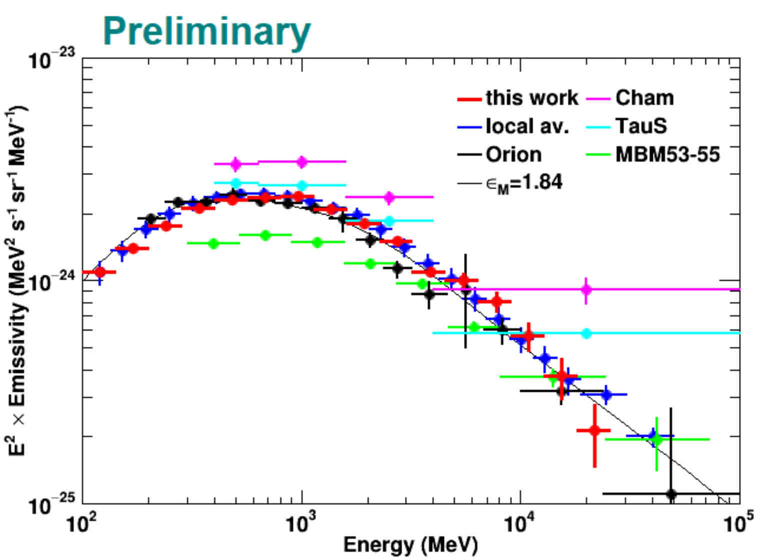




Properties of CRs

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





Summary

- **We study local HI clouds in detail**
  - **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, areas that can be interpreted as optically-thick HI and CO-dark H_2 identified**
  - **Uniform CR intensity confirmed. The emissivity roughly consistent with the model for the LIS based on direct measurements. Possible spectral break should be investigated**

Thank you for your Attention

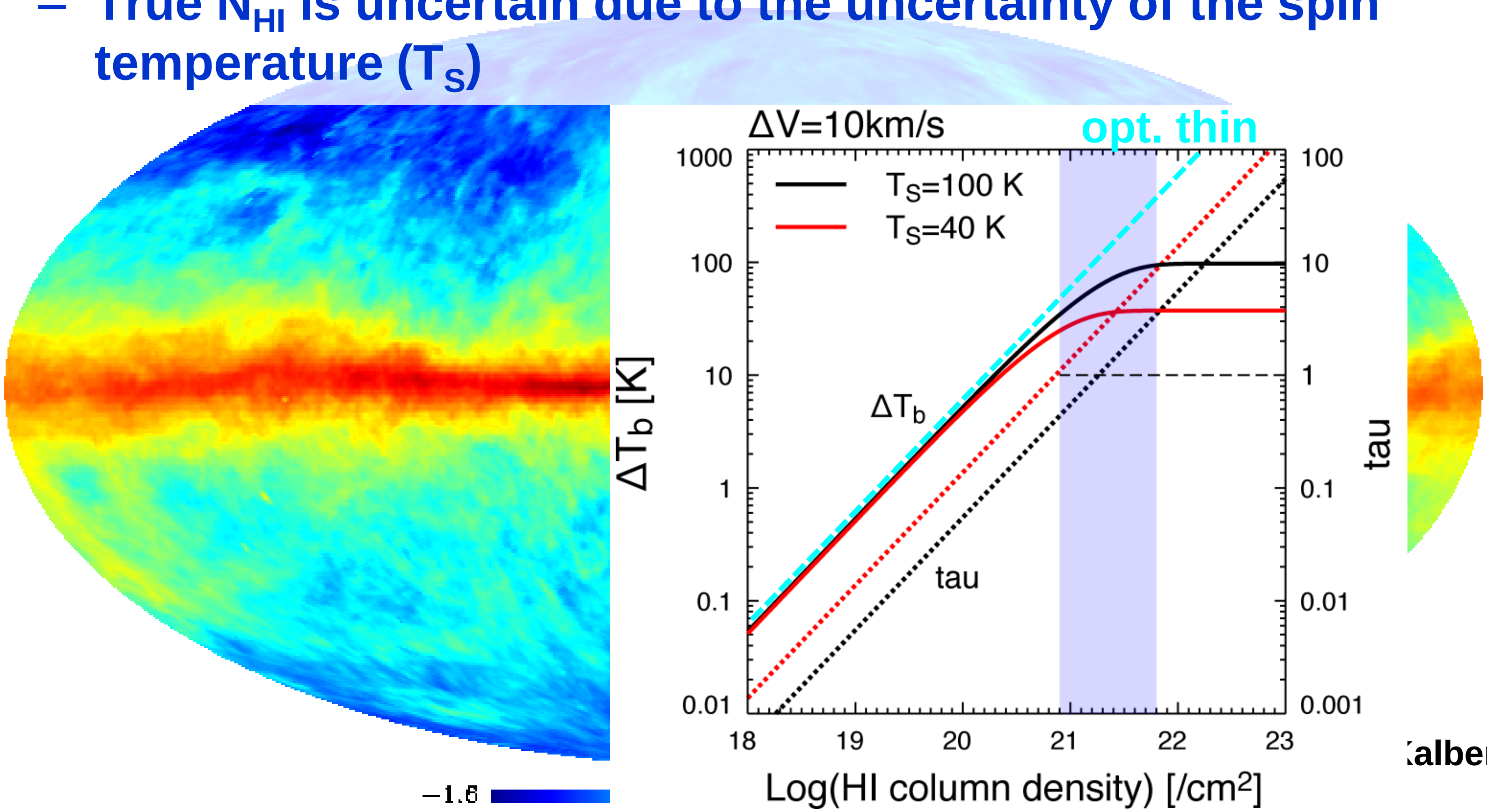
Reference

- Abdo+09, ApJ 703, 1249
- Abdo+10, Science 327, 1103
- Ackermann+13, Science 339, 807
- Grenier+05, Science 307, 1292
- Karberla+05, A&A 440, 775
- HI4PI Collaboration 2016, A&A 594, 116
- Mizuno+16, ApJ 833, 278
- Mori09, Astropart. Phys. 31, 341
- Planck Collaboration 2014, A&A 571, 13 (Planck 2013 Results XIII)

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)**



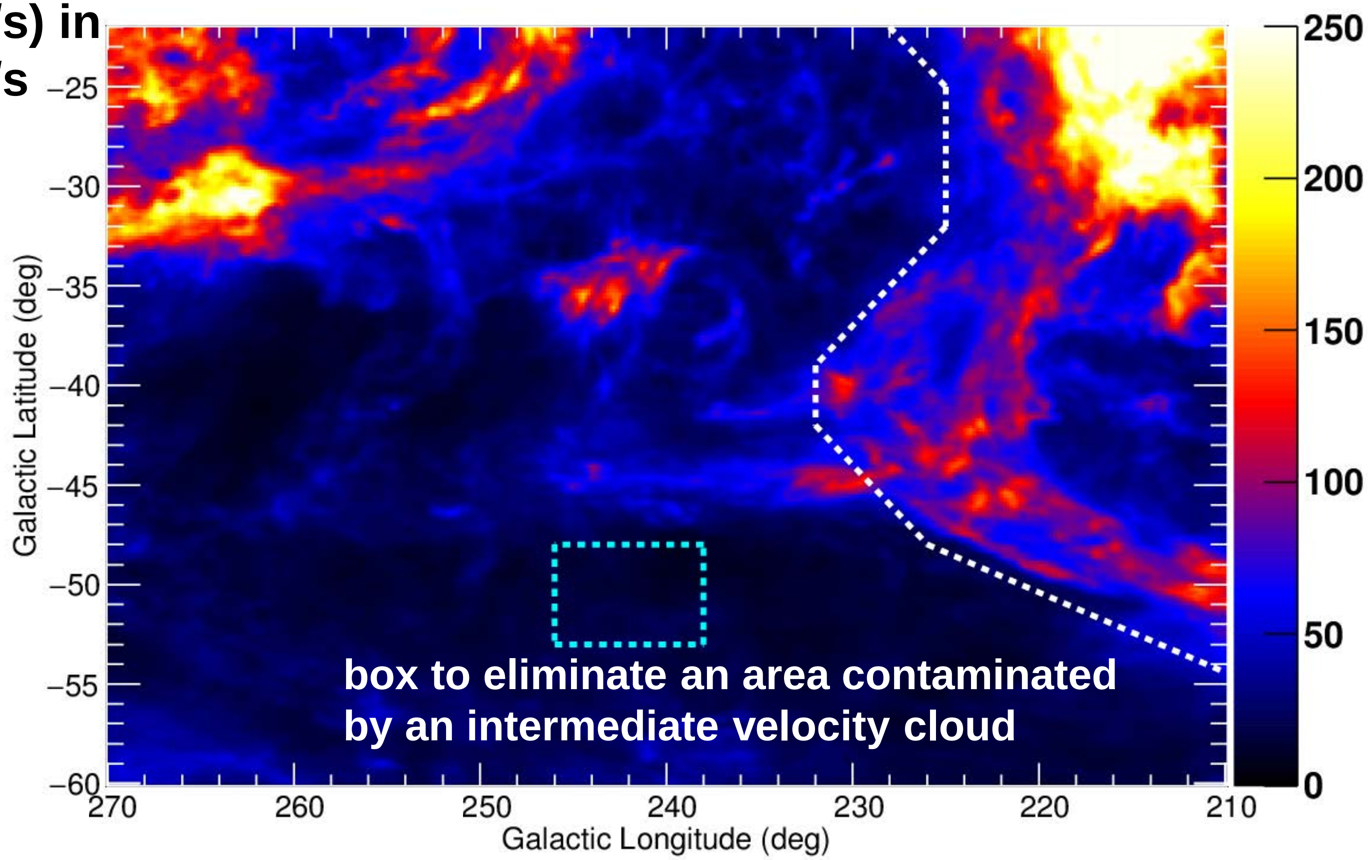
alberla+05)

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**

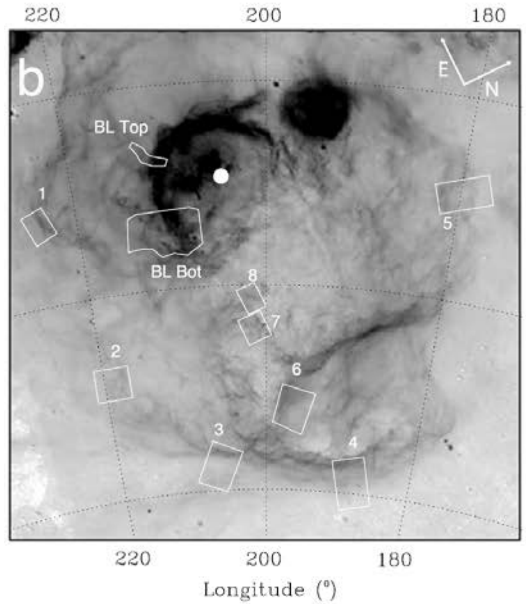
W_{HI} (K km/s) in -1 to 8 km/s

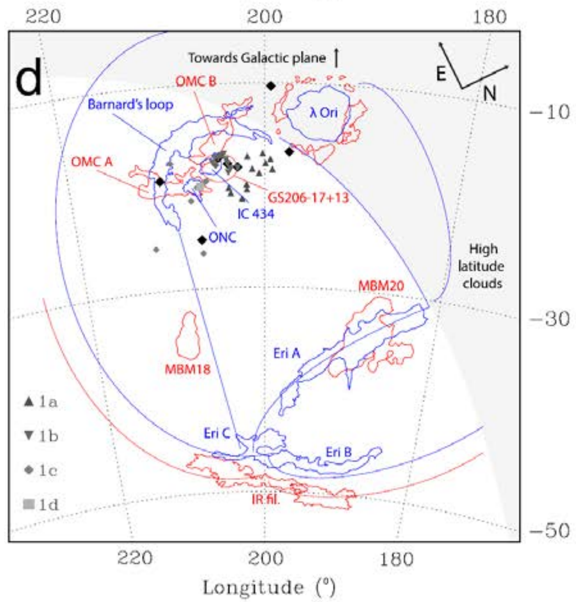
(Brown+95)



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).

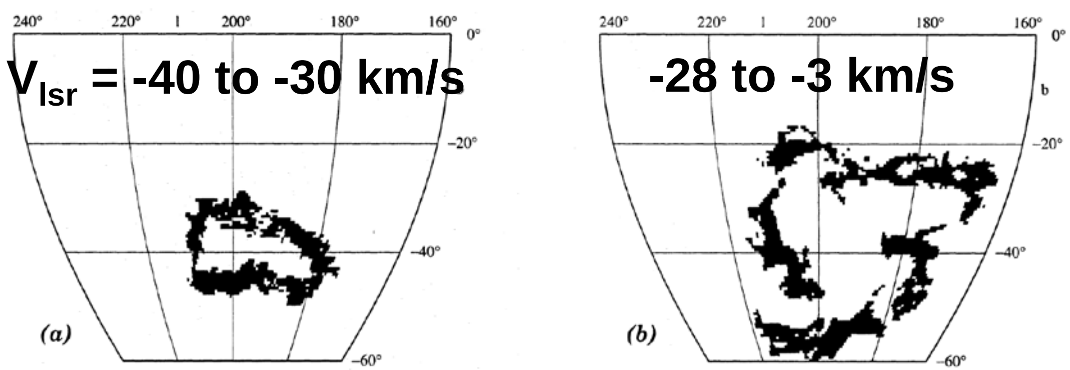




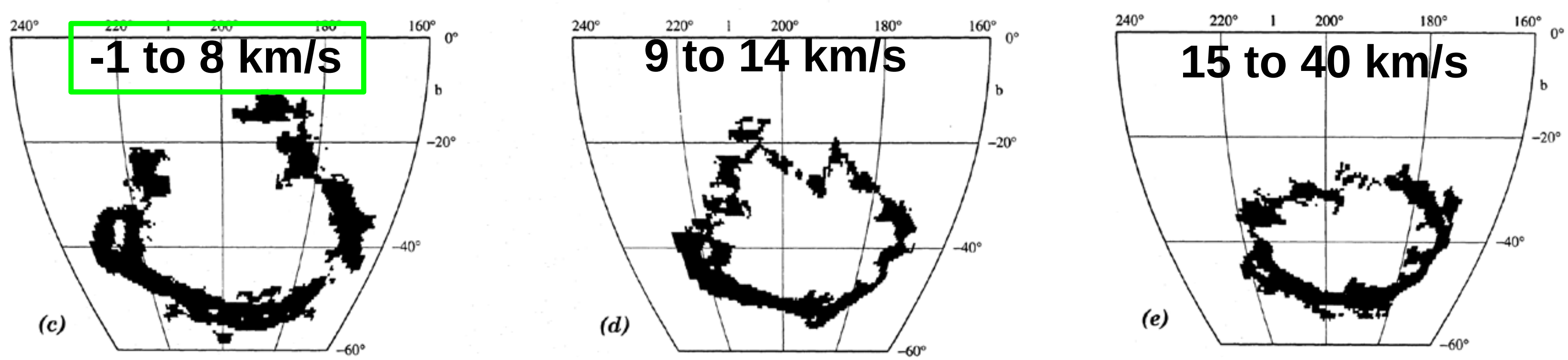
Ochsendorf+15, ApJ 808, 111

Neutral Gas (in Ref.)

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



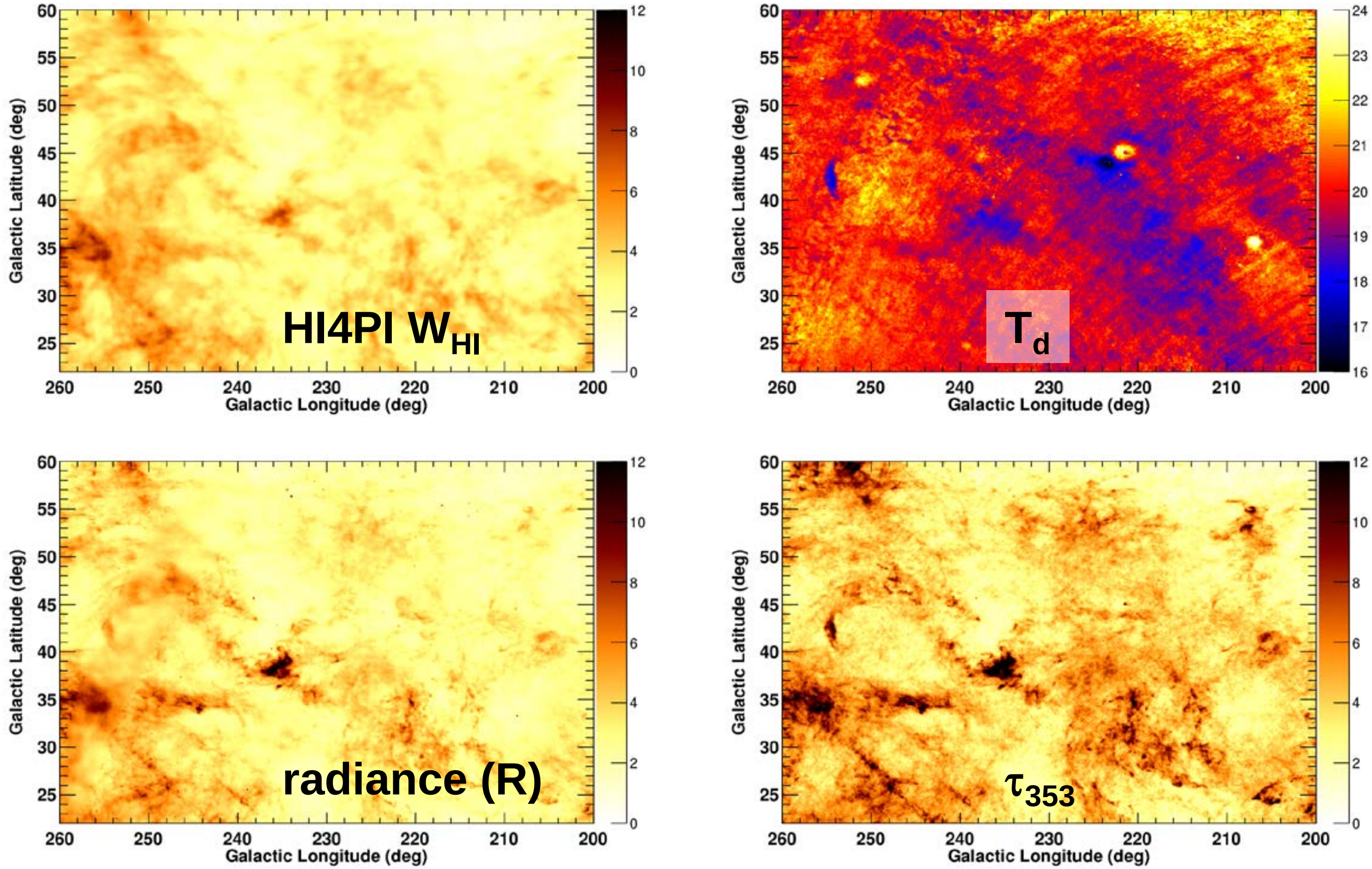
Brown+95, A&A 300, 903



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)

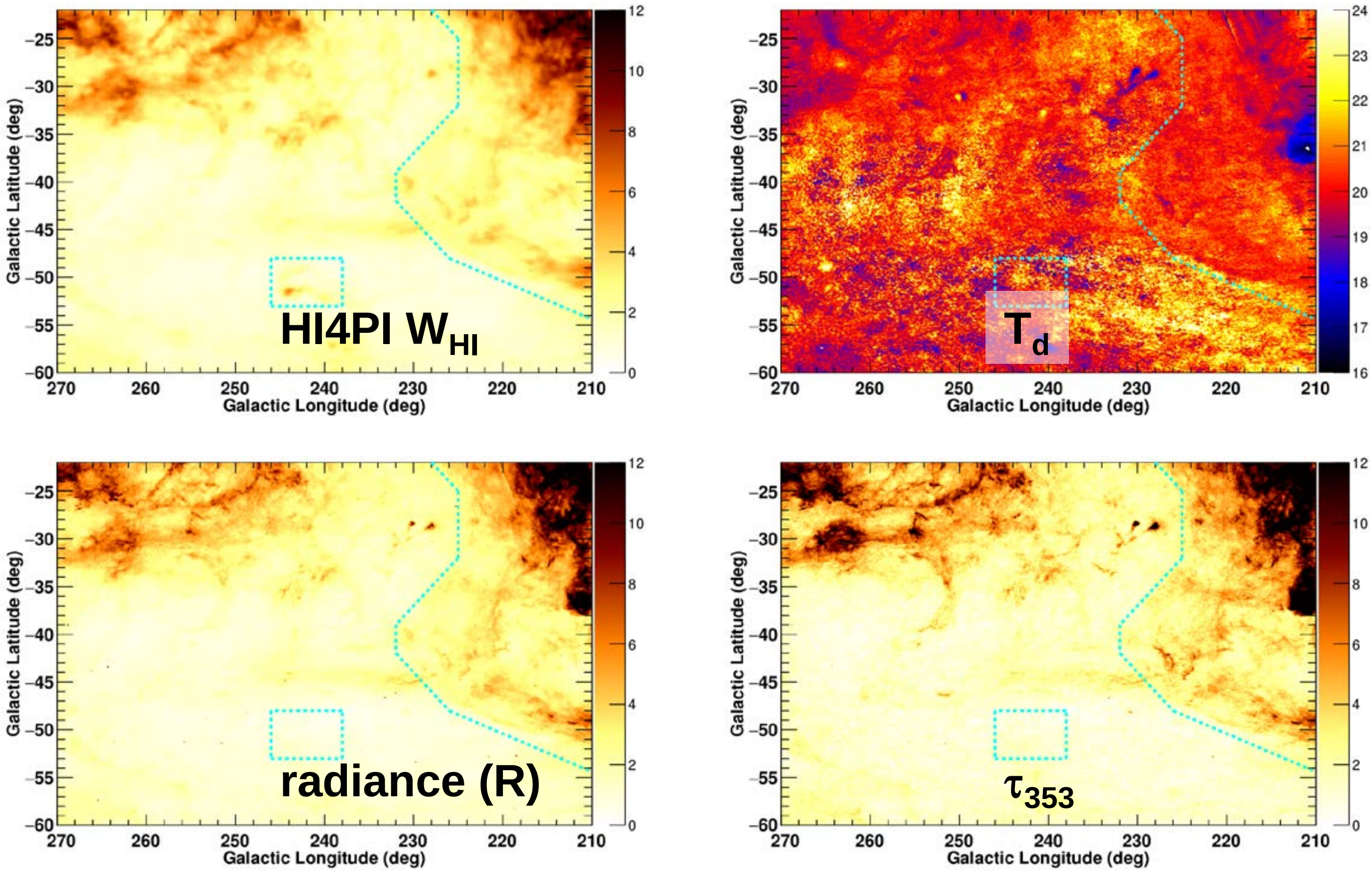
N_H in 10^{20} cm^{-2}



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)**

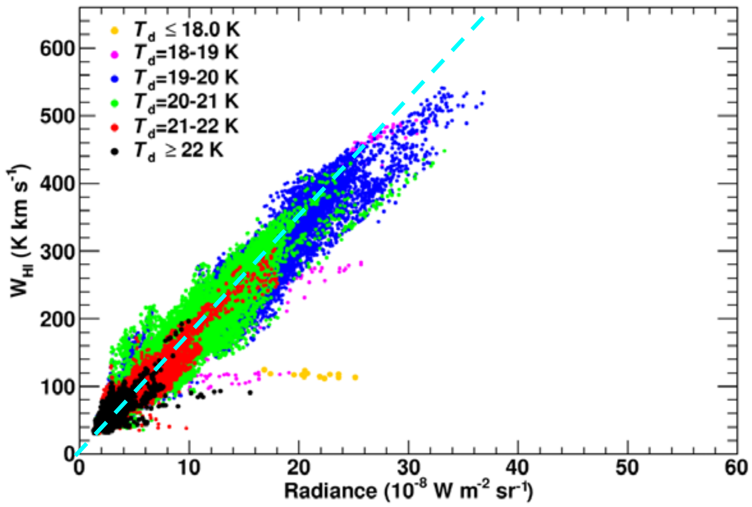
N_H in 10^{20} cm^{-2}

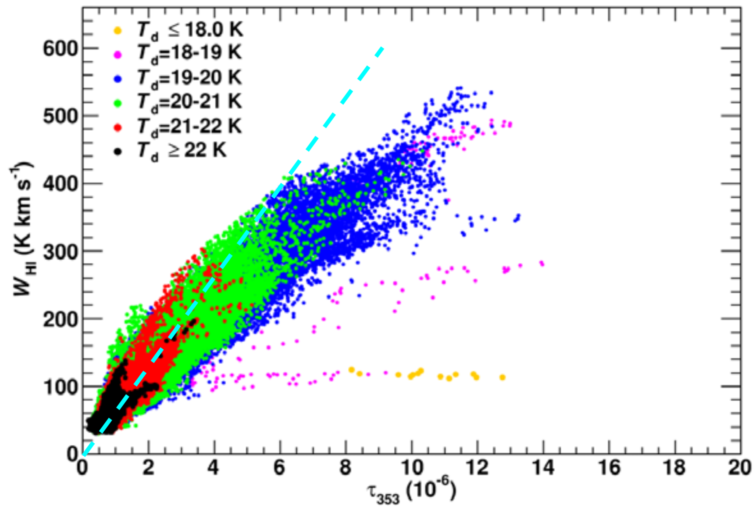


W_{HI}-Dust Relation (South)

- 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 area used to construct initial N_H templates assuming $N_H \propto D_{em}$

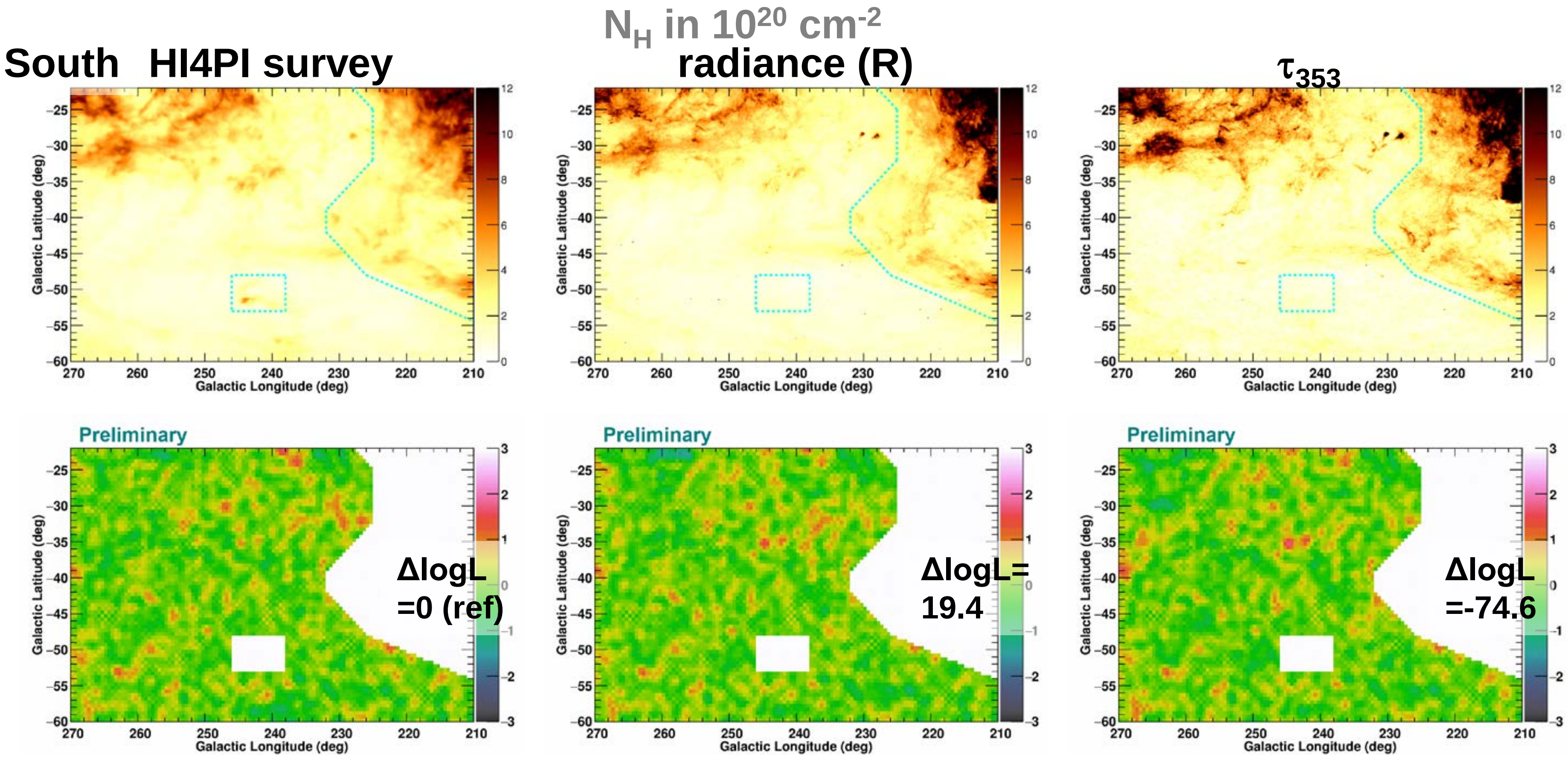
$$N_{\rm H}\left(\rm cm^2\right) = 1.82 \times 10^{18} \times \left(17.6 \times 10^8\ R \text{ or } 66.9 \times 10^6\ \tau_{353}\right)$$





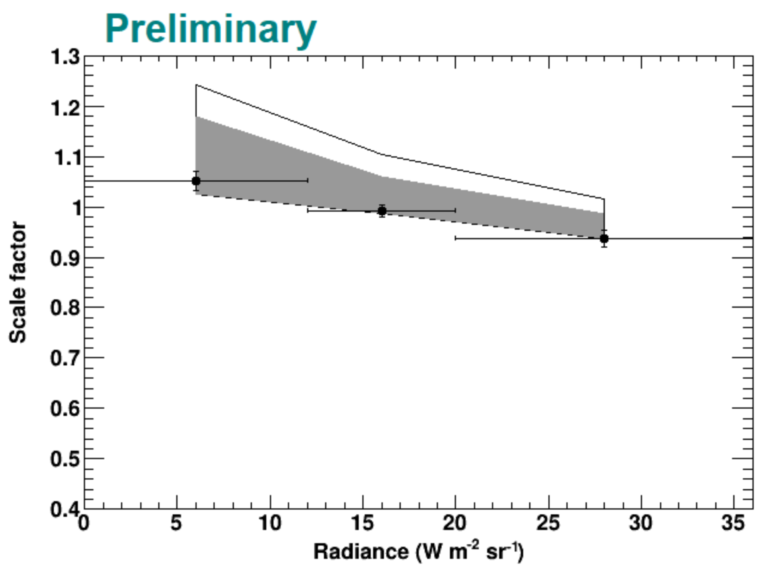
N_H Model Maps and Residuals (South)

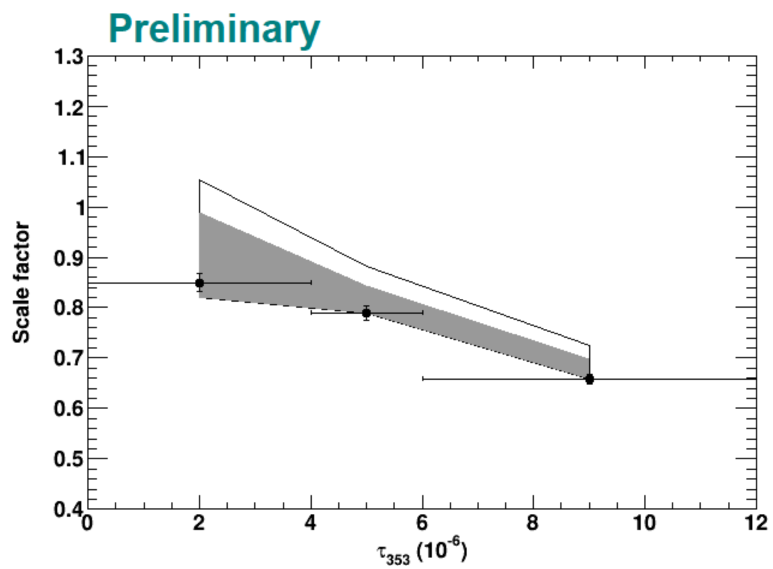
- We prepared N_H model maps ($\propto W_{HI}$ or D_{em}) and used them in a fit of γ-ray data -> R gives the best fit.



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
- Large (~25%) negative τ_{353} dependence, implying an overestimate of N_H/τ_{353} in high density area.
- R dependence not significant (1.2σ) and small (~10%); we adopt a single R-based N_H template as our best estimate

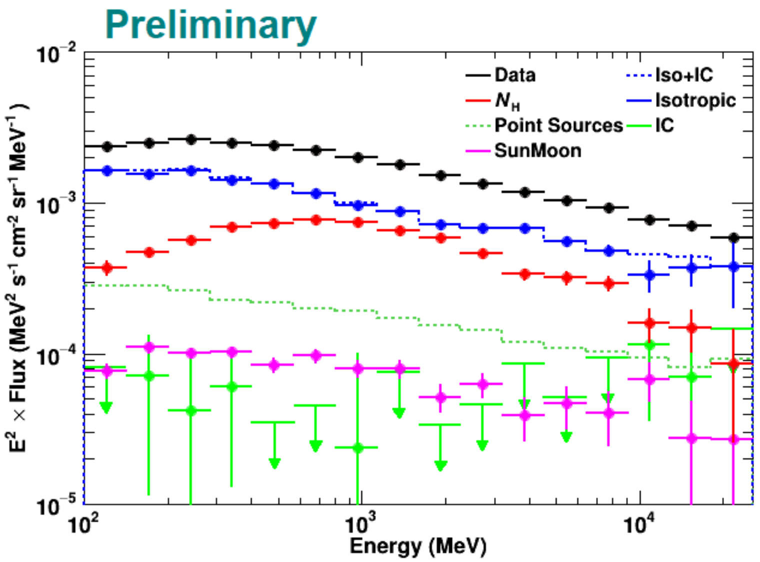


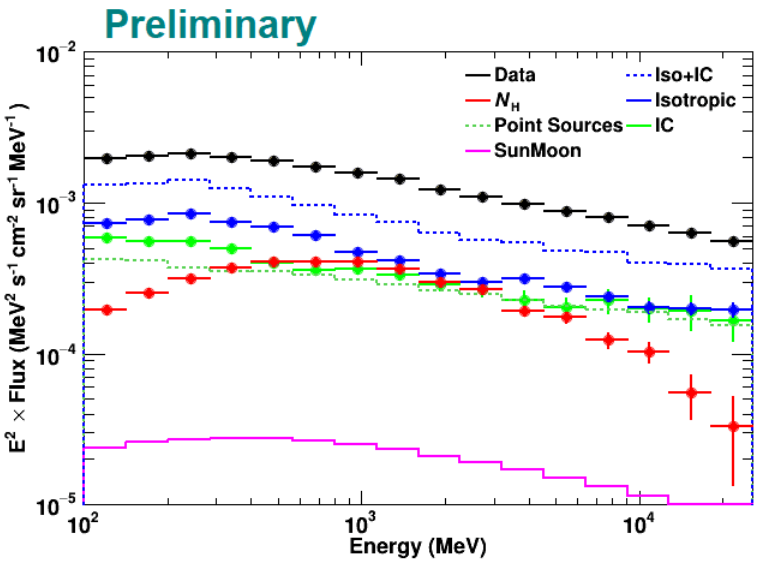


Emissivity scale factor ($\propto N_H/D_{em}$), averaged over 0.2-12.8 GeV

Spectrum of Each Component

- In both North and South regions we conclude that __single N_H template based on R reproduces the data__ 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 excess gas around (l, b)~(236°, 37.5°); likely optically-thick HI**
- **(South) Flat profile with W_{HI}~100 K km/s corresponds to excess gas at (l, b)~(230°, -28.5°); likely CO-dark H_2**