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

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Tsunefumi Mizuno (Hiroshima Univ.)

On behalf of the Fermi-LAT collaboration

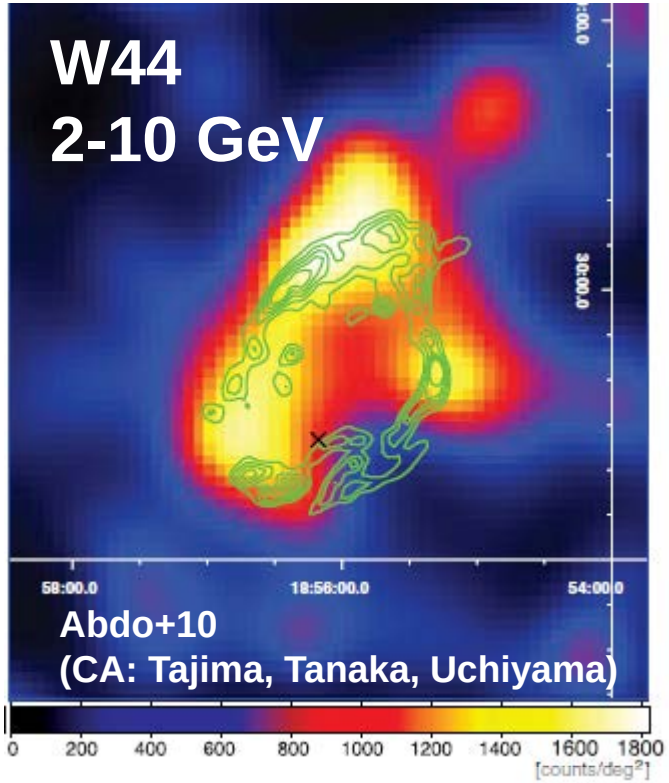
フェルミ衛星による太陽系近傍原子雲の宇宙線・星間ガスの研究

2018年3月22日@日本物理学会
(東京理科大学)

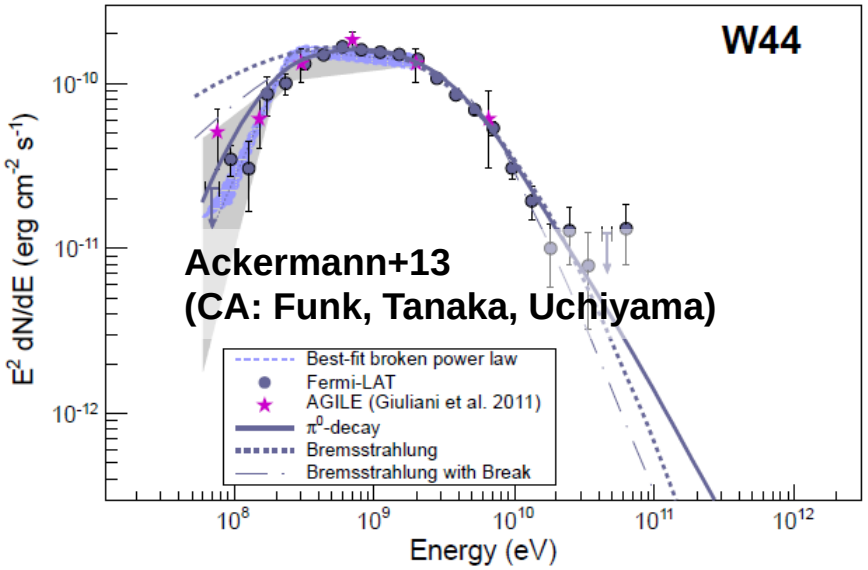
水野　恒史(広島大学)ほか
Fermi-LAT Collaboration

Motivation: ISM as a Tracer of CRs

γ-ray image
w/ 4.5 μm contours



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

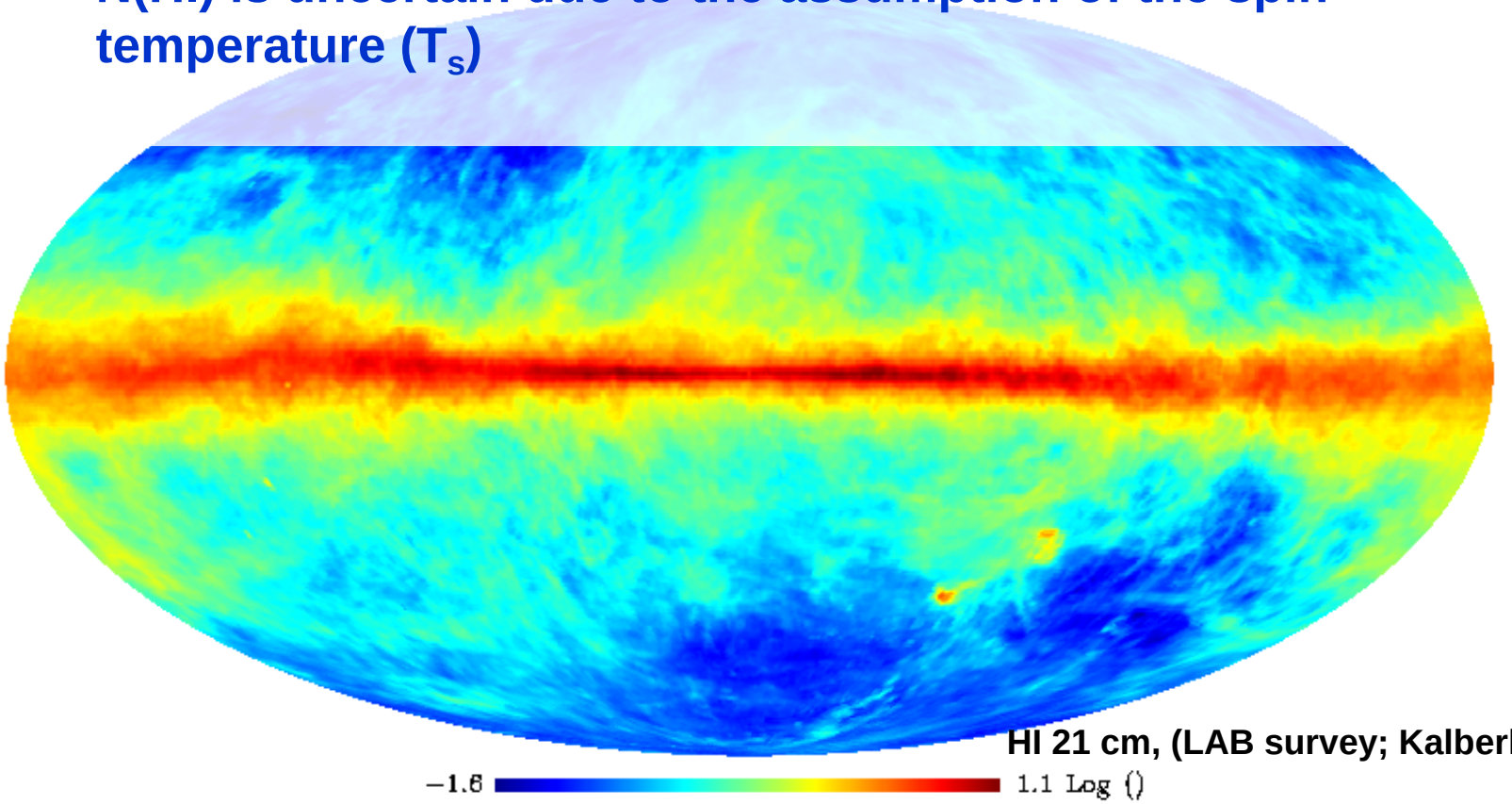


W_{SN}	5×10^{51} erg
W_{CR}	4×10^{49} $(n/100\ \mathrm{cm}^{-3})^{-1}$ erg

Accurate estimate of the interstellar medium (ISM) densities is crucial to study Galactic cosmic rays (CRs), since $I_\gamma \propto N(\mathrm{H_{tot}})U_{\mathrm{CR}}$

Atomic Gas

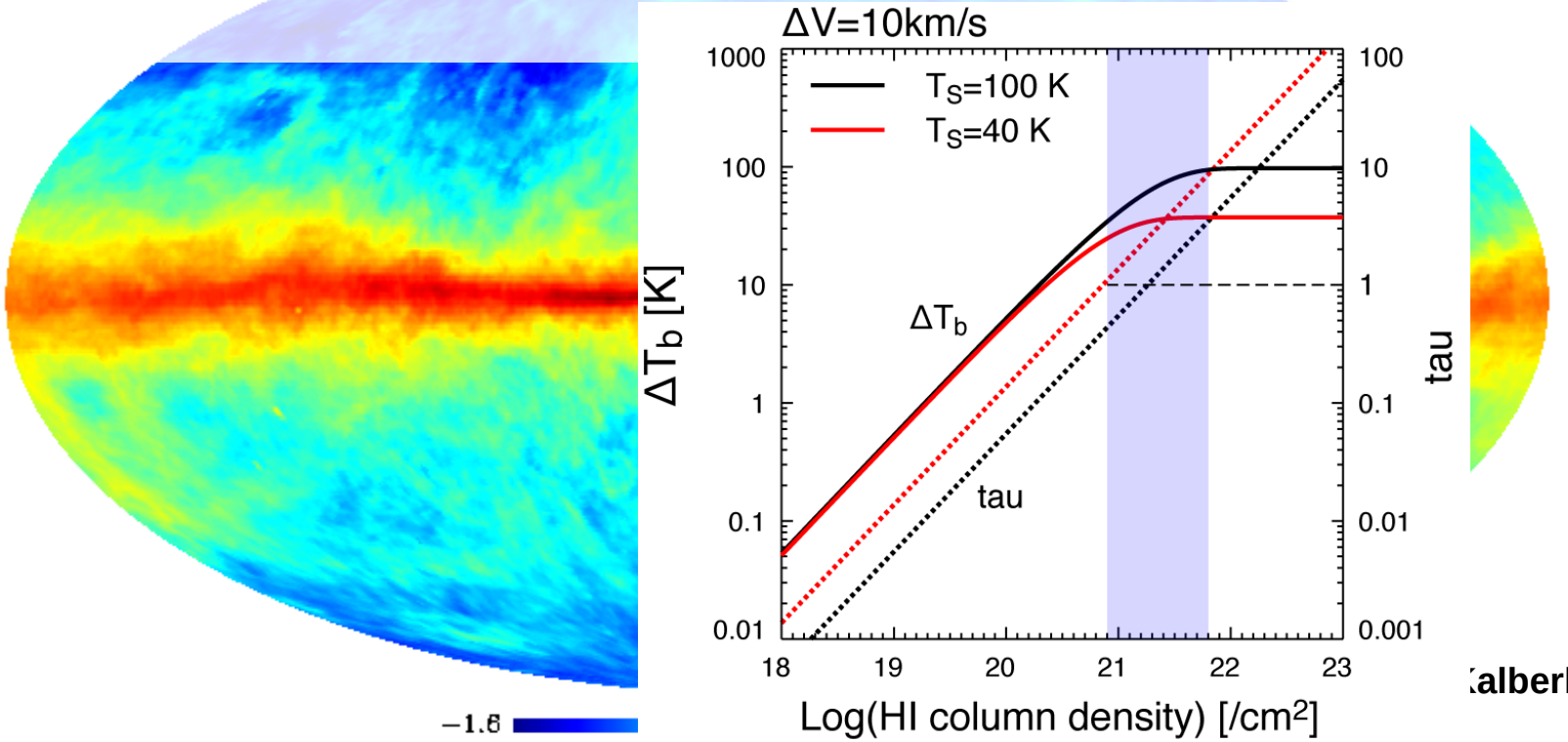
- **Main component of ISM, scale height ~ 200 pc**
- **Traced by 21 cm line**
  - **N(HI) is uncertain due to the assumption of the spin temperature (T_s)**



HI 21 cm, (LAB survey; Kalberla+05)

Atomic Gas

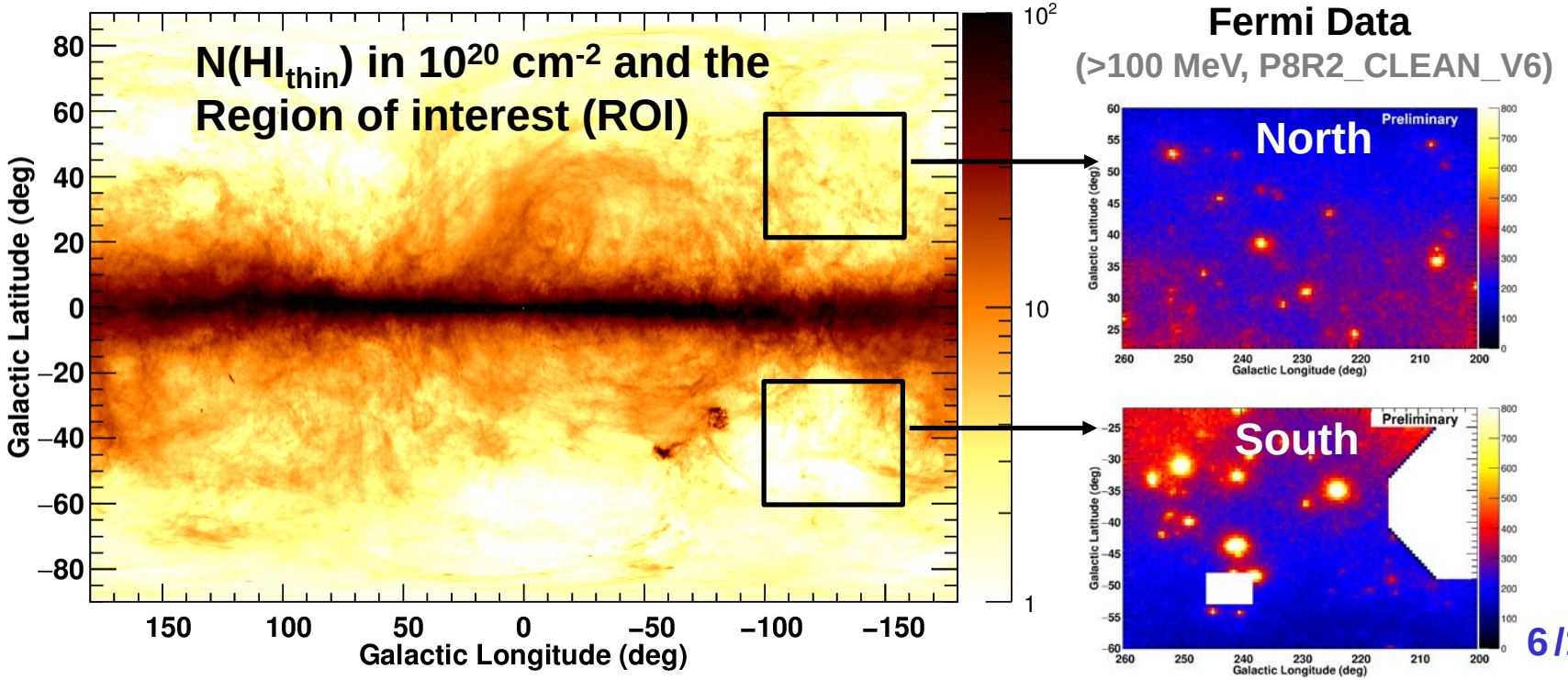
- **Main component of ISM, scale height ~ 200 pc**
- **Traced by 21 cm line**
  - **Conversion from the observed T_b to N(HI) is uncertain due to the assumption of the spin temperature (T_s)**



(Kalberla+05)

Objectives of the Study

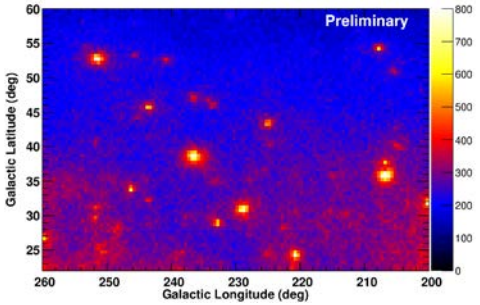
- **Accurate estimate of the ISM gas densities is crucial to understand the ISM and Galactic CRs**
- **Procedure to trace the "dark gas" [gas not properly traced by HI and CO line surveys (Grenier+05)] not established yet => detailed study of nearby clouds**



Fitting Procedure

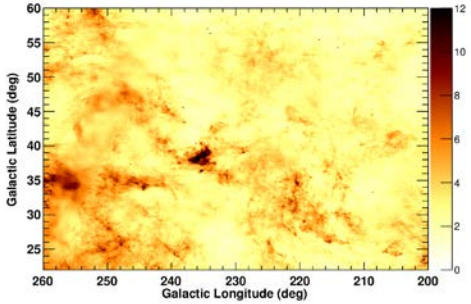
- **Uniform CR density (valid in high latitude regions) => the γ-ray intensity can be modeled as a <u>linear combination of templates</u>**

Fermi Data

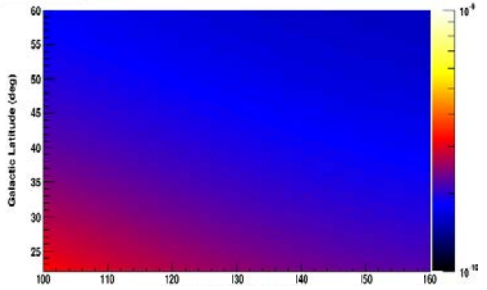


$$I_\gamma(l,b,E) = q_{\mathrm{HI}}(E)\cdot N(\mathrm{H_{tot}}) + I_{\mathrm{IC}}(l,b,E) + I_{\mathrm{iso}}(E) + \Sigma\, I_{\mathrm{source}}(l,b,E) + \cdots$$

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



IC model (e.g., galprop)



$q_{\mathrm{HI}}(E)$ **tells us CR density/spectrum**

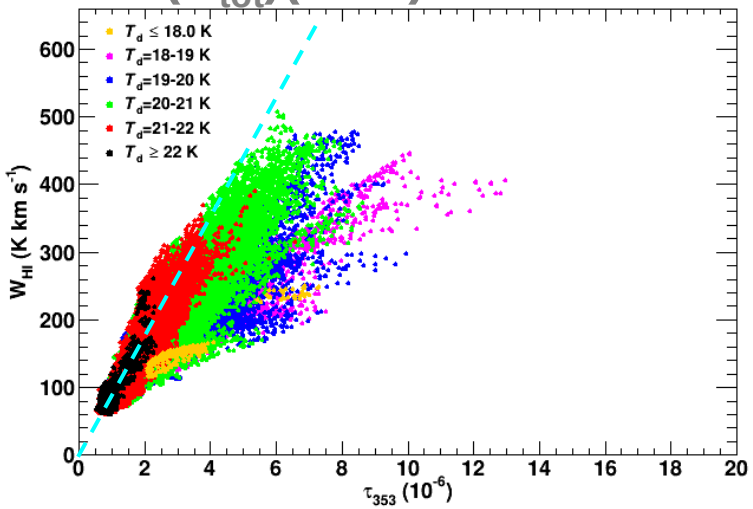
$$N(\mathrm{H_{tot}}) = \Sigma_i\ a_i \cdot N(\mathrm{H}_i)$$
$$(\mathrm{e.g.}, N(\mathrm{H_I}) + 2X_{\mathrm{CO}}\cdot W_{\mathrm{CO}} + X_{\mathrm{DG}} N(\mathrm{H_{DG}}))$$

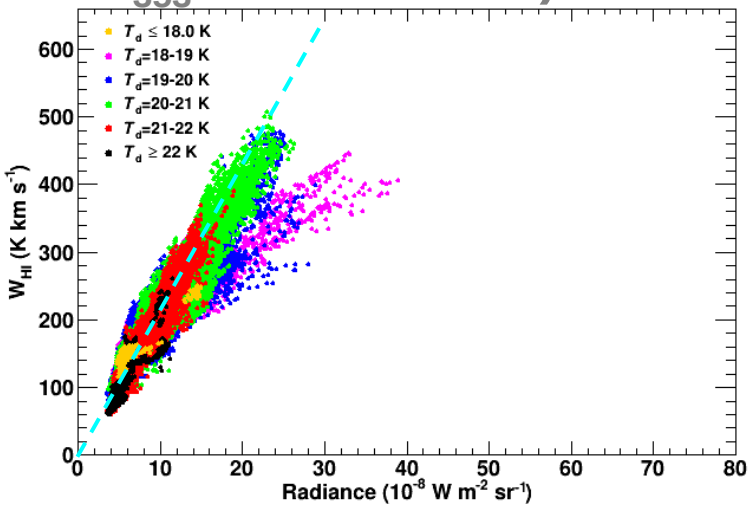
Fit quality tells us which tracer is better
Coefficients (a_i) tell us gas properties

W_{HI}-Dust Relation (North)

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

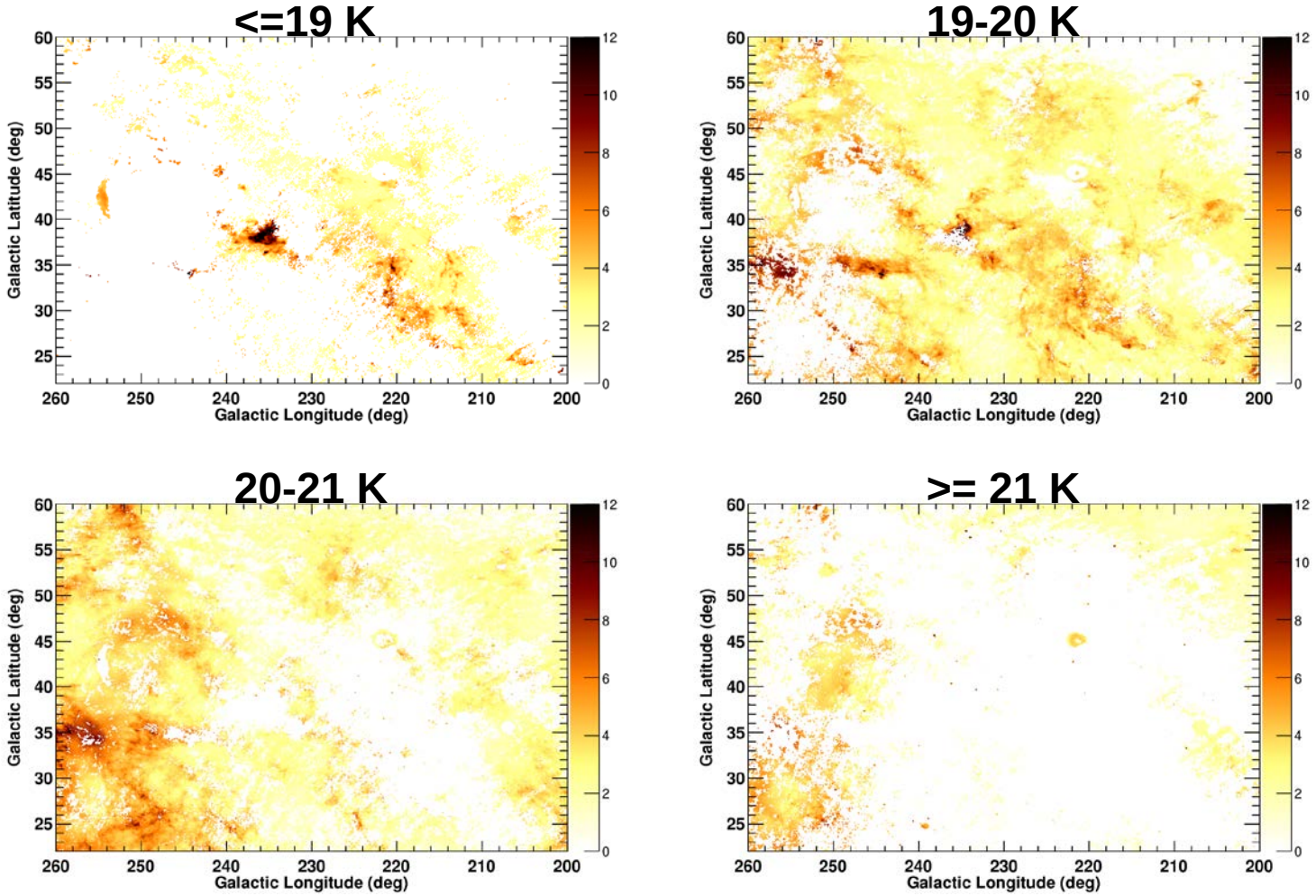
$N(H_{tot})(cm^{-2})=1.82x10^{18}$ x ($87.2x10^{6}$ τ_{353} or $21.1x10^{8}$ R)





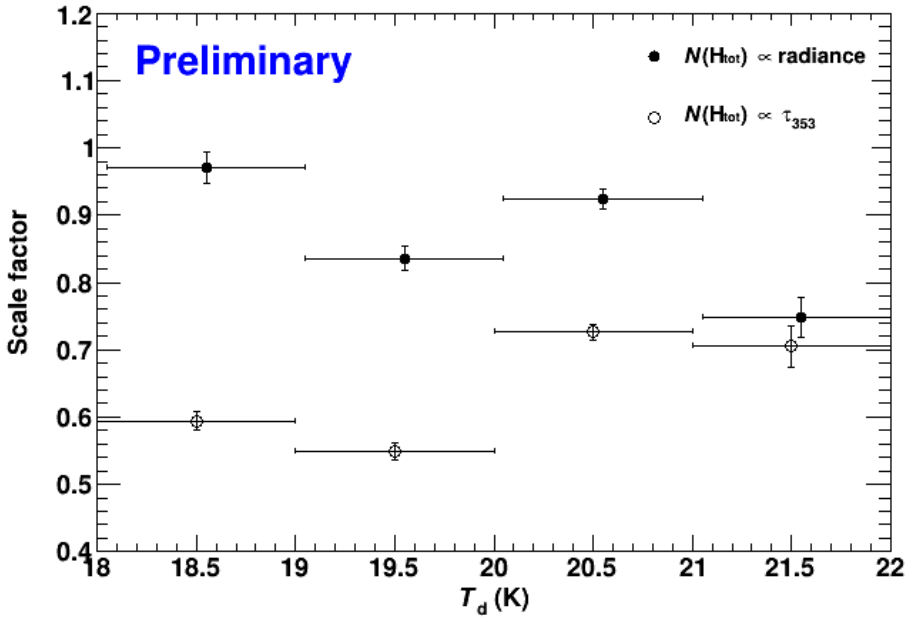
T_d-sorted N(H_{tot}) Model Maps (North)

- **R-based, T_d-sorted N(H_{tot}) model maps**



T_d Dependence (North)

- **Uniform CR density => Emissivity ($I_\gamma/N(H_{tot})$) should not depend on T_d**
- **Fit of γ-ray data with T_d-sorted maps gives a positive T_d dependence for τ_{353}, implying smaller $N(H_{tot})/\tau_{353}$ ratio in low T_d area** (Mizuno+16)

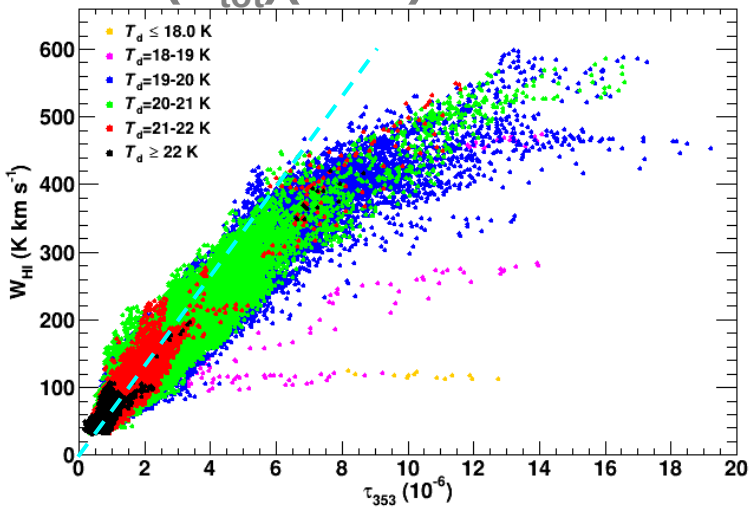


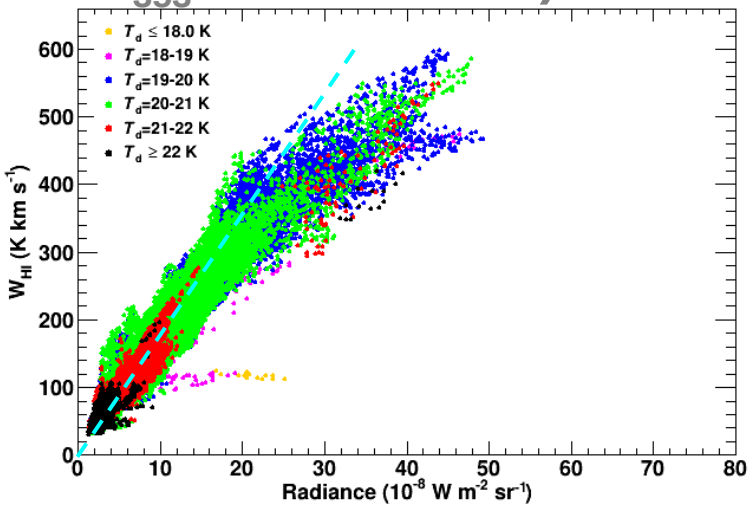
emissivity scale factors to the model for local interstellar spectrum (LIS) with ε_M=1.84 (Mori09, Abdo+09)

W_{HI}-Dust Relation (South)

- Correlation between W_{HI} and D_{em} (τ_{353} or R)
- Weak T_d dependence, non-linear W_{HI}-D_{em} relations ($N(H_{tot})/D_{em}$ and/or $N(H_{tot})/N(HI)$ not uniform)
- Linear curves that follow trends in (high T_d & low W_{HI}) area are used to construct $N(H_{tot})$ model maps assuming $N(H_{tot}) \propto \tau_{353}$ (or R)

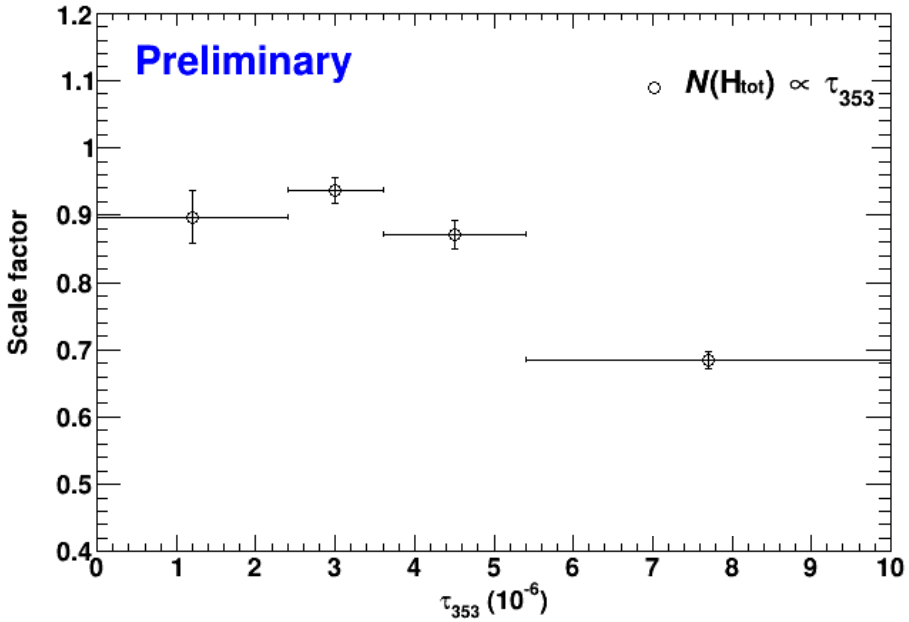
$N(H_{tot})(cm^{-2})=1.82x10^{18}$ x ($66.9x10^{6}$ τ_{353} or $17.6x10^{8}$ R)





τ_{353} Dependence (South)

- Investigate possible non-linear $N(H_{tot})$-D_{em} relations through a fit with τ_{353}(or R)-sorted $N(H_{tot})$ maps
- Negative τ_{353} dependence is seen, implying smaller $N(H_{tot})/\tau_{353}$ ratio in high density area



emissivity scale factors to the model for LIS with ε_M=1.84

Summary & Future Prospect

- **We have been studying CRs and ISM in mid-latitude region of the 3rd quadrant**
- **Fit γ-ray data with T_d-sorted $N(H_{tot})$ maps in North**
  - **Positive T_d dependence of emissivity for τ_{353}, implying smaller $N(H_{tot})/\tau_{353}$ ratio in high T_d area**
- **Fit γ-ray data with τ_{353}-sorted $N(H_{tot})$ maps in South**
  - **Negative τ_{353} dependence, implying smaller $N(H_{tot})/\tau_{353}$ ratio in high density area**

- **We will examine systematic uncertainties (background, IC model, etc.) and discuss CR/ISM properties quantitatively**

Thank you for your Attention

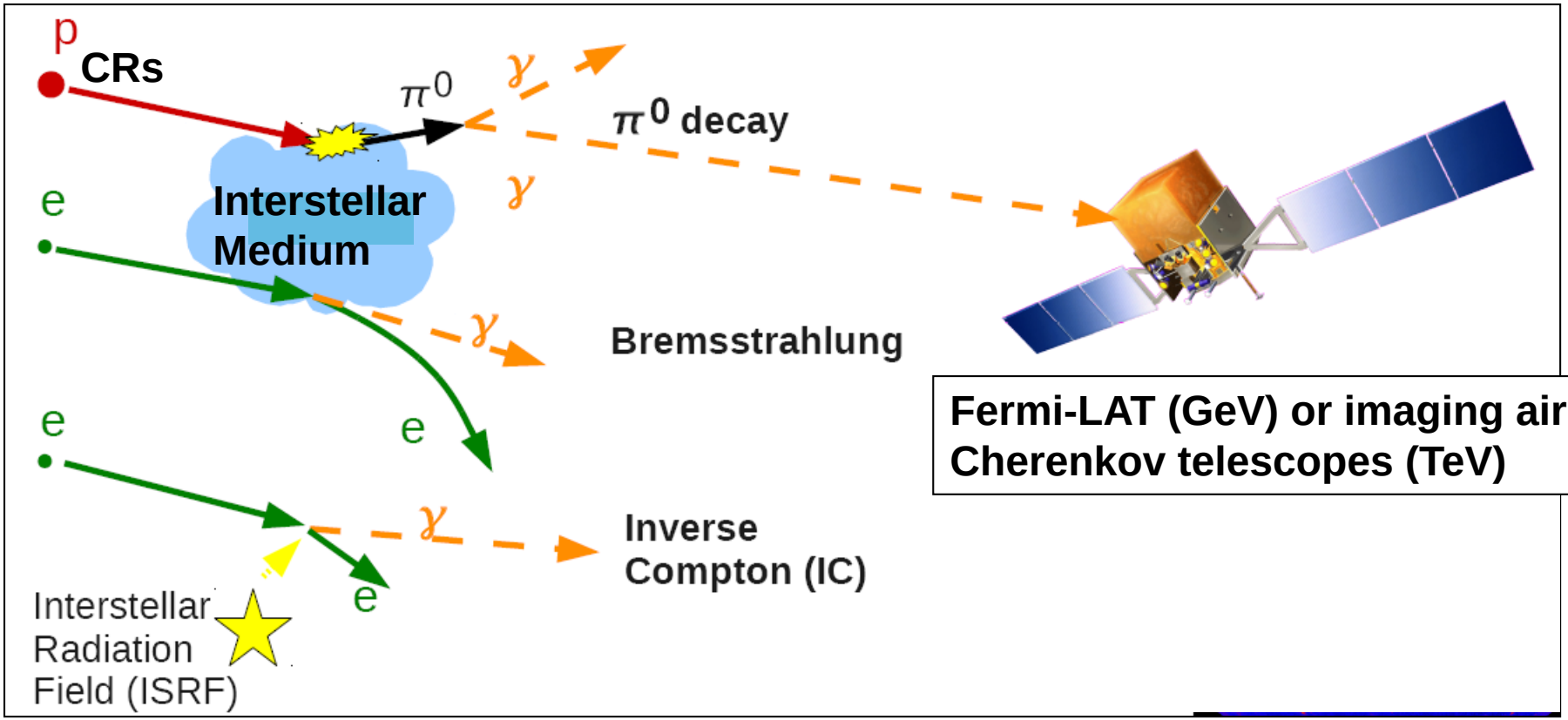
Reference

- 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

GeV γ rays as a CRs/ISM Tracer

γ rays = CRs x ISM gas (or ISRF)



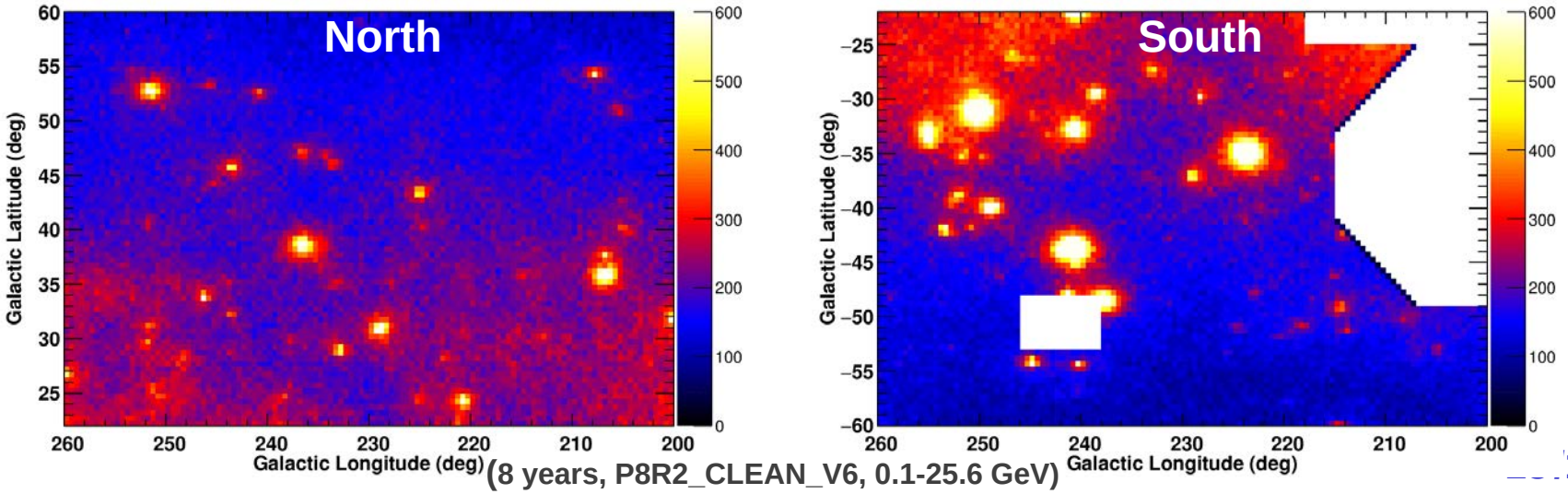
- **CR proton density is expected to be uniform in a few 100s pc scale, making GeV γ-rays a powerful probe of the ISM ($I_\gamma \propto N(\mathrm{H_{tot}})U_{\mathrm{CR}}$)**

LAT Data Analysis

- 8 years data, P8R2_CLEAN_V6, zmax=100 deg
- We fit γ-ray data with N(H_{tot}) model map [based on HI4PI data or Planck τ_{353} or Planck radiance (R)]+ isotropic + inverse Compton (IC) + ionized gas model map + Sun/Moon template + point sources in 0.1-25.6 GeV (logarithmically-sliced 8 bins)
  - IC model of GALPROP run 54_Yusifov_z4kpc_R30kpc_Ts150K_EBV2mag
  - 3FGL sources detected at >=6σ in ROI and bright 3FGL sources in peripheral area
  - WMAP Free-free emission map for H^+ template (wmap_K_mem_freefree_9yr_v5.fits)
  - Template of Sun/Moon of 6 years observation (template_SunMoon_6years_zmax100.fits used for Catalog study)
- All components were taken as free parameters in each band
  - Local HI emissivity template spectrum for N(H_{tot}) and ionized gas components. PL with free index for isotropic. Γ=2.2 for point sources.
  - Normalization of Sun/Moon template was fixed to 1 in South region
- North and South regions were fitted individually.

Objective of This Study

- **We studied local ISM and CRs in mid-lat. region of the 3rd quadrant (Abdo+09)**
- **We revisit the region using recent γ-ray (Fermi-LAT), HI (HI4PI) and dust (Planck) data to examine:**
  - **T_d dependence of dust-emission to gas ratio (Mizuno+16)**
  - **Non-linear dust-emission to gas ratio (Roy+13, Planck Collaboration 2015)**



Initial $N(H_{tot})$ Model Maps

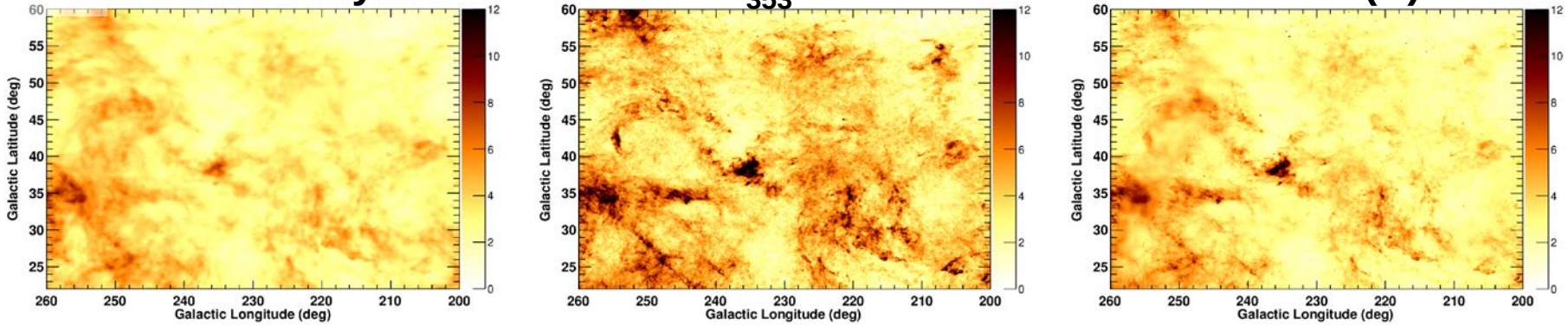
- We prepared $N(H_{tot})$ model maps ($\propto \tau_{353}$ or R) and used them in a fit of γ-ray data

$N(H_{tot})$ in 10^{20} cm^{-2}

North HI4PI survey

τ_{353}

radiance (R)



South