Study of the ISM and CRs in the MBM 53-55 Clouds and the Pegasus Loop

Mar. 18th, 2017@JPS meeting in Osaka

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

(Mizuno+16, ApJ 833, 278)

フェルミ衛星によるMBM 53-55分子雲・Pegasus Loop領域における<u>星間ガスと宇宙線</u>の研究

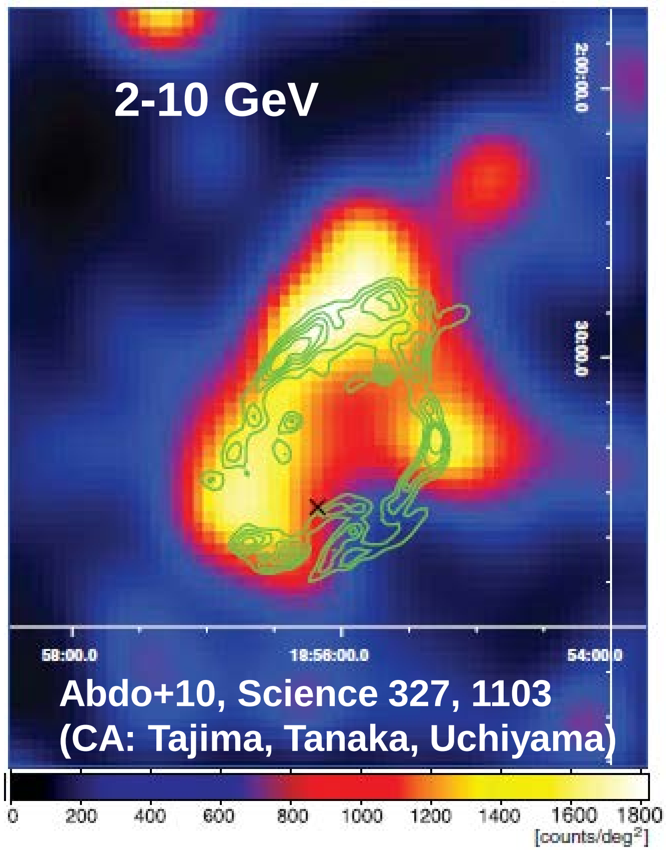
Mar. 18^th, 2017@大阪大学(日本物理学会)

水野恒史 (広島大学) on behalf of the Fermi-LAT Collaboration

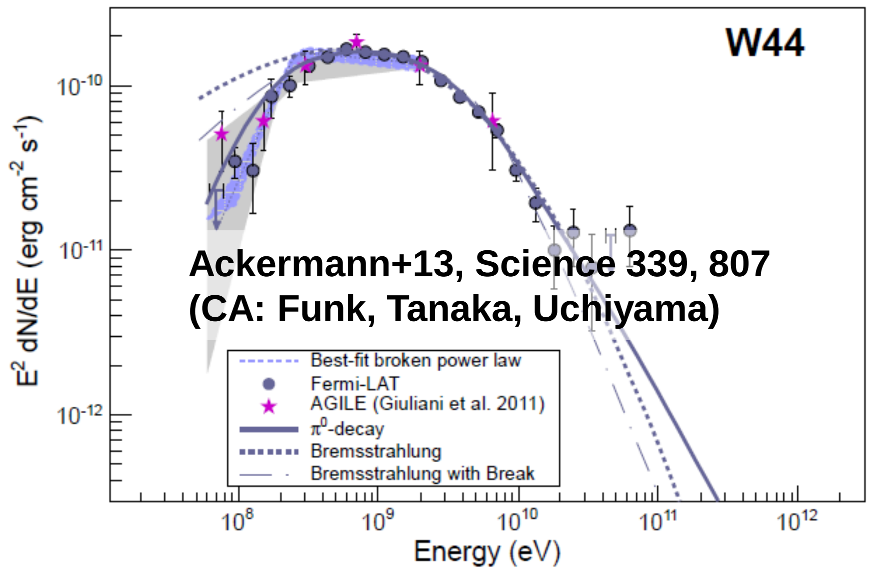
(Mizuno+16, ApJ 833, 278)

Motivation: ISM as a tracer of CRs

Deconvolved γ-ray image of W44 w/ Spitzer 4.5 μm contours (tracer of shocked H_2)



γ-ray spectrum shows a low-energy cutoff (signature of pi^0-decay)



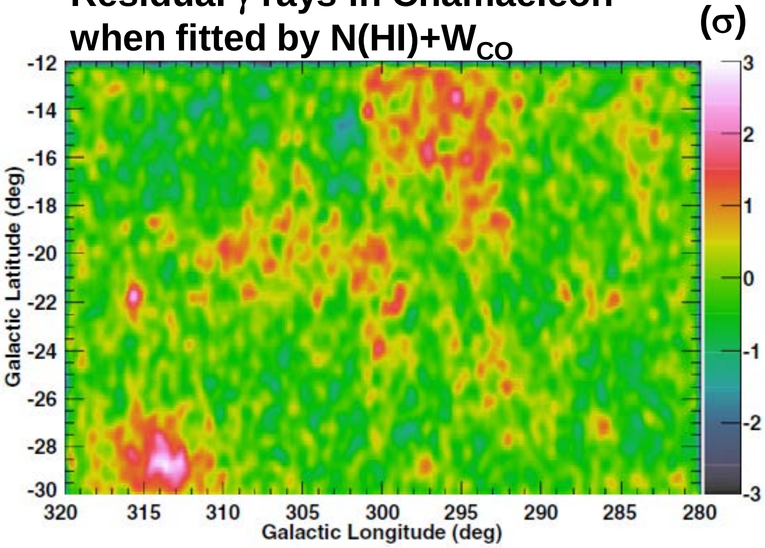
W_{SN}	5×10^{51} erg
W_{CR}	4×10^{49} (n/100cm^{-3})$^{-1}$erg

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

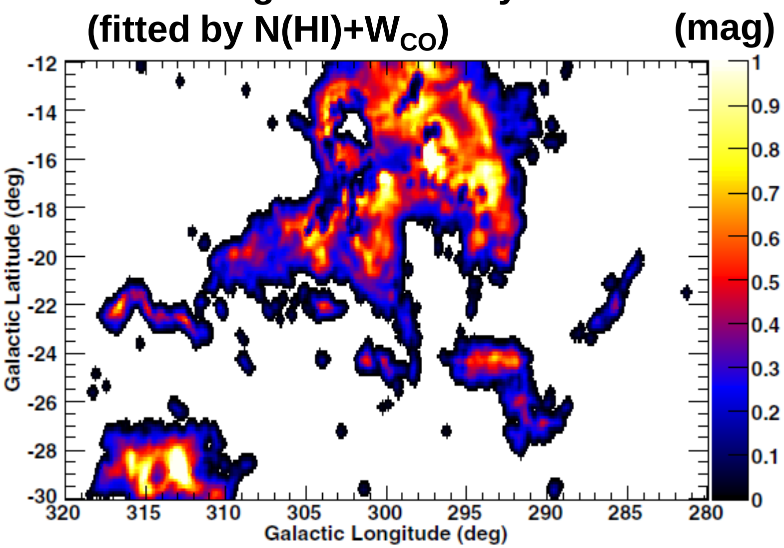
Uncertainty of ISM: Dark Gas

- **Fermi revealed a component of <u>ISM not measurable by standard tracers</u> (HI 21 cm, CO 2.6 mm), confirming an earlier claim by EGRET (Grenier+05)**

Residual γ rays in Chamaeleon when fitted by N(HI)+W_{CO}



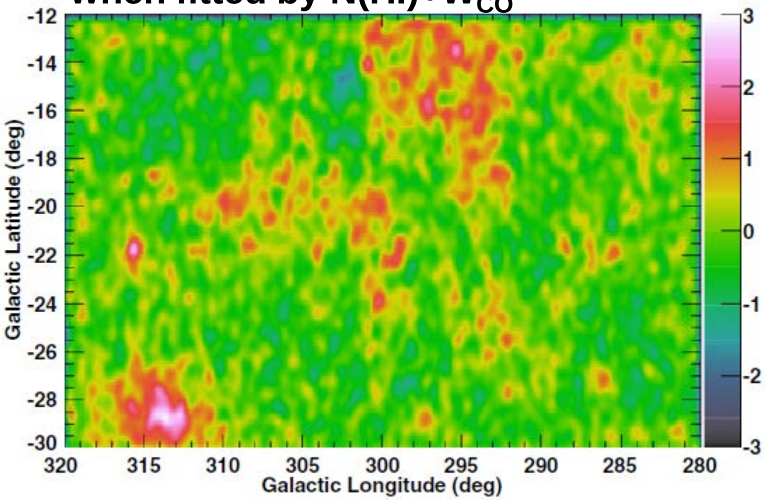
Residual gas inferred by dust (fitted by N(HI)+W_{CO})



Uncertainty of ISM: Dark Gas

- Fermi revealed a component of ISM not measurable by standard tracers (HI 21 cm, CO 2.6 mm), confirming an earlier claim by EGRET (Grenier+05)
- Mass of "dark gas" is <u>comparable to or greater than</u> that of H_2 traced by W_{CO}

Residual γ rays in Chamaeleon when fitted by N(HI)+W_{CO}

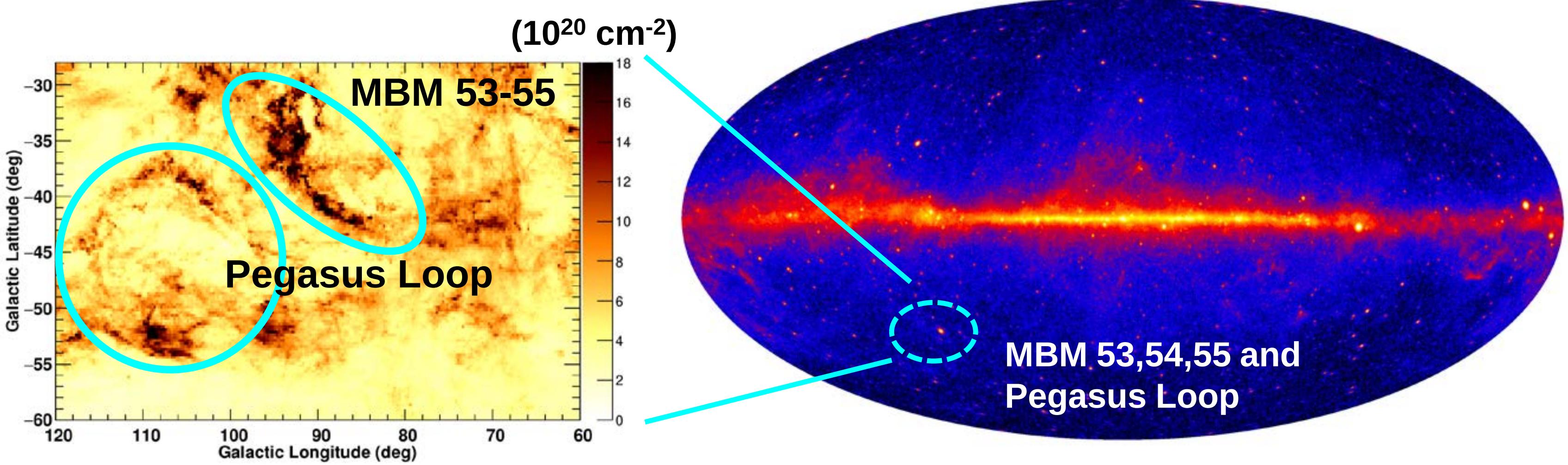


Molecular cloud	H_2 mass traced by W_{CO} (M_{solar})	"dark gas" (M_{solar})	$M_{DG}/M_{H2,CO}$
Chamaeleon	$\sim 5 \times 10^3$	$\sim 2.0 \times 10^4$	~4
R CrA	$\sim 10^3$	$\sim 10^3$	~1
Cepheus & Polaris	$\sim 3.3 \times 10^4$	$\sim 1.3 \times 10^4$	~0.4
Orion A	$\sim 5.5 \times 10^4$	$\sim 2.8 \times 10^4$	~0.5

Ackermann+12, ApJ 755, 22 (CA: Hayashi, TM); Ackermann+12, ApJ 756, 4 (CA: Okumura, Kamae)
See also Planck Collaboration 2015, A&A 582, 31 (CA: Grenier)

Study of ISM and CRs using Fermi-LAT

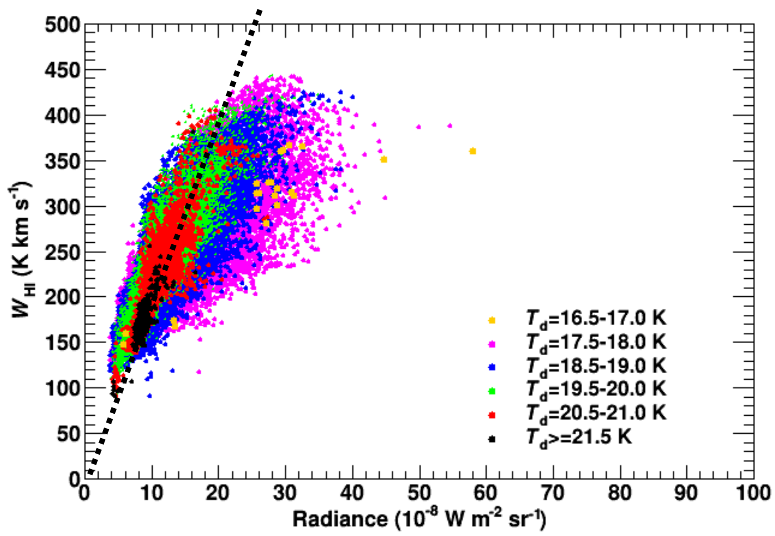
- **Study of ISM and CRs in high-latitude clouds using Fermi-LAT data has advanced significantly**
  - **We can assume that CR flux is uniform**
  - **We now have Planck dust thermal emission model which is useful to trace total gas column density ($N(H_{tot})$) in detail**
  - **(Procedure to convert dust distribution into $N(H_{tot})$ has not been established yet)**
- **Here we will present <u>the study of MBM53-55 and Pegasus Loop region</u> and implications for the ISM and CRs using Fermi-LAT**

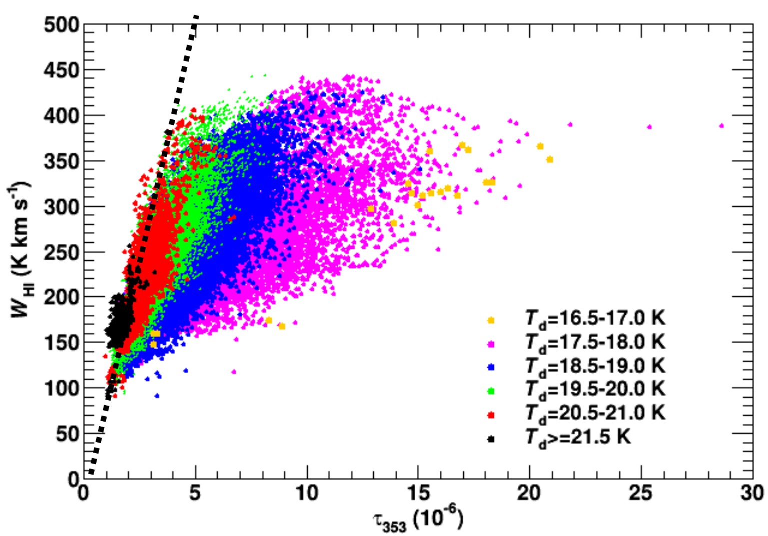


W_{HI}-Dust Relation (1)

- **Dust is mixed with gas and has been used as a tracer of $N(H_{tot})$**
  - **But what kind of quantity should we use?**
- **We examined correlations btw. W_{HI} and two dust tracers (radiance (R) and opacity at 353 GHz (τ_{353}))** **(see also Fukui+14,15, Planck Collab. 2014)**
  - **Two tracers show different, dust-temperature (T_d) dependent correlations with W_{HI}**

(Areas with W_{co}>1.1 K km/s are masked)





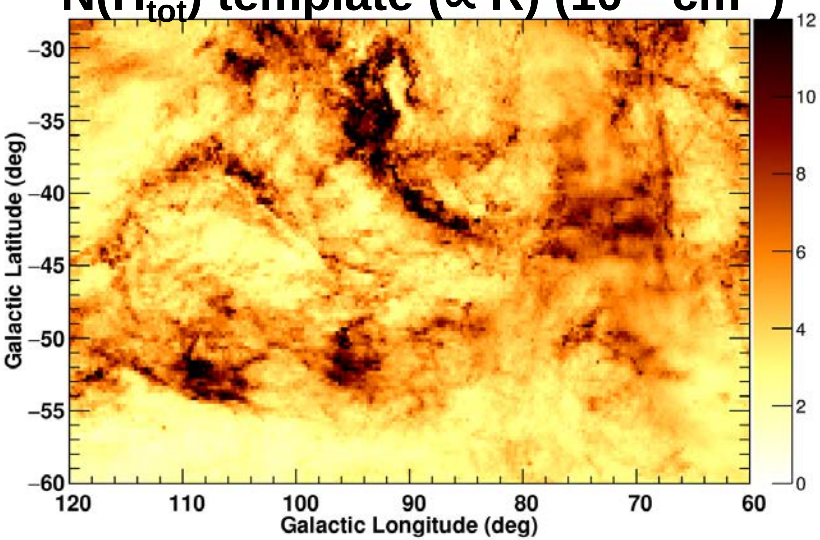
lines show best-fit linear relations in T_d>21.5K

W_{HI}-Dust Relation (2)

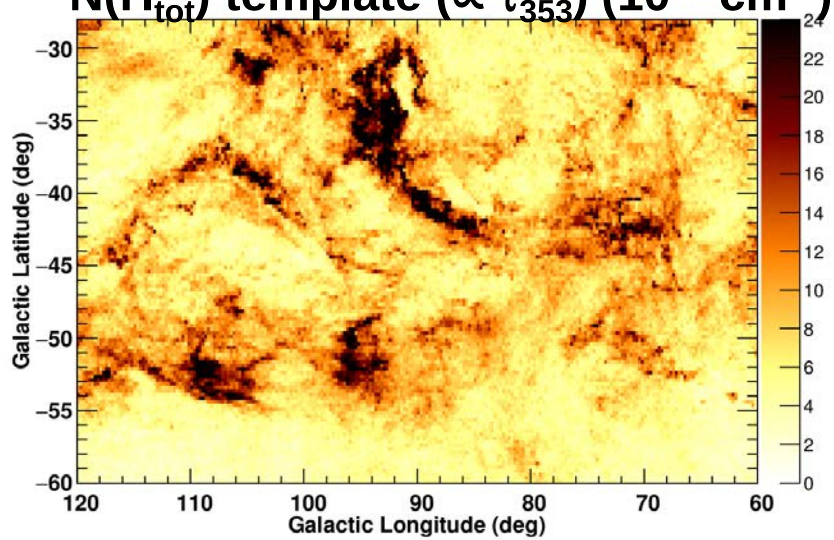
- **Dust is mixed with gas and has been used as a tracer of $N(H_{tot})$**
  - **But what kind of quantity should we use?**
- **We examined correlations btw. W_{HI} and two dust tracers (radiance (R) and opacity at 353 GHz (τ_{353}))** **(see also Fukui+14,15, Planck Collab. 2014)**
  - **Two tracers show different and T_d-dependent correlations with W_{HI}**
  - **We tested two tracers against γ-ray data. We also examined T_d dependence and found that $N(H_{tot,\gamma})/R$ (or τ_{353}) depends on T_d. (likely artificial)**

=> use γ-ray data to compensate for the dependence $(I_\gamma \propto N(H_{tot})U_{CR})$

$N(H_{tot})$ template ($\propto$ R) (10^{20} cm^{-2})



$N(H_{tot})$ template ($\propto \tau_{353}$) (10^{20} cm^{-2})



(Two tracers show different contrast in $N(H_{tot})$ template maps)

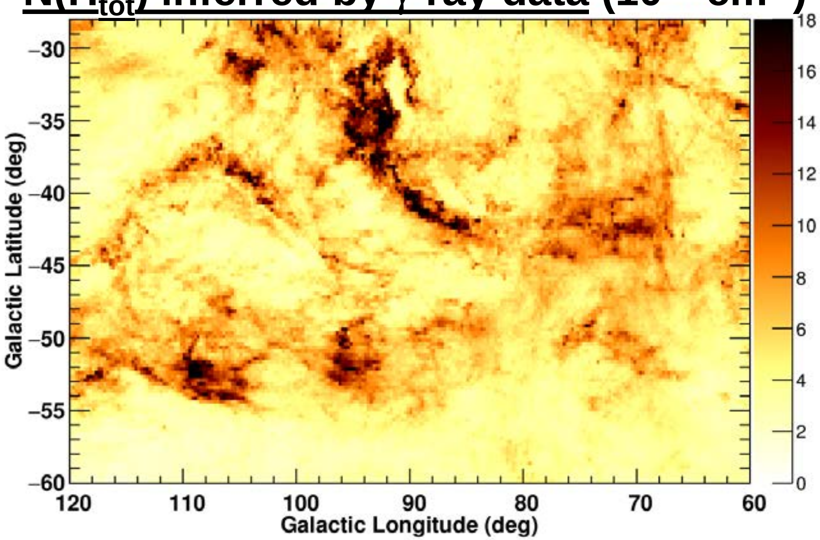
T_d-Corrected Modeling

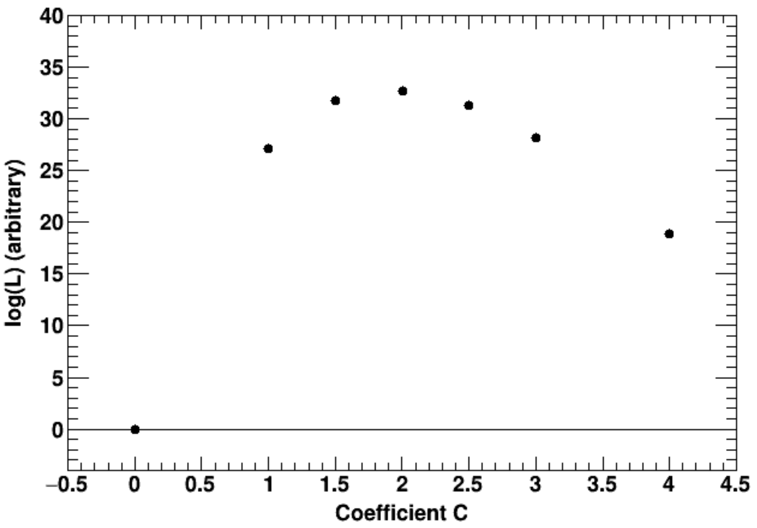
- We started with R-based $N(H_{tot})$ map and applied a correction on $N(H_{tot})$ by using an empirical function as below (modeling the increase of $N(H_{tot})$ in areas with low Td)

$$N(\mathrm{H_{tot,mod}}) = \begin{cases} N(\mathrm{H_{tot,R}})\ (T_\mathrm{d} > T_\mathrm{bk}) & , \\ (1 + 0.05 \cdot C \cdot \frac{T_\mathrm{bk} - T_\mathrm{d}}{1\ \mathrm{K}}) \cdot N(\mathrm{H_{tot,R}})\ (T_\mathrm{d} \le T_\mathrm{bk}) & , \end{cases}$$ (T_{bk}=20.5 K)

- Then we scanned coefficient C which best represents γ-ray data
  - Idea is to use γ-ray data as a robust tracer of $N(H_{tot})$ $(I_\gamma \propto N(H_{tot}) U_{CR})$
- T_{bk}=20.5 K and C=2 (10% required increase in $N(H_{tot})$ by 1K) provides highest fit likelihood. It gives $M_{DG}/M_{H2,CO} <= 5$.

$N(H_{tot})$ inferred by γ-ray data (10^{20} cm^{-2})



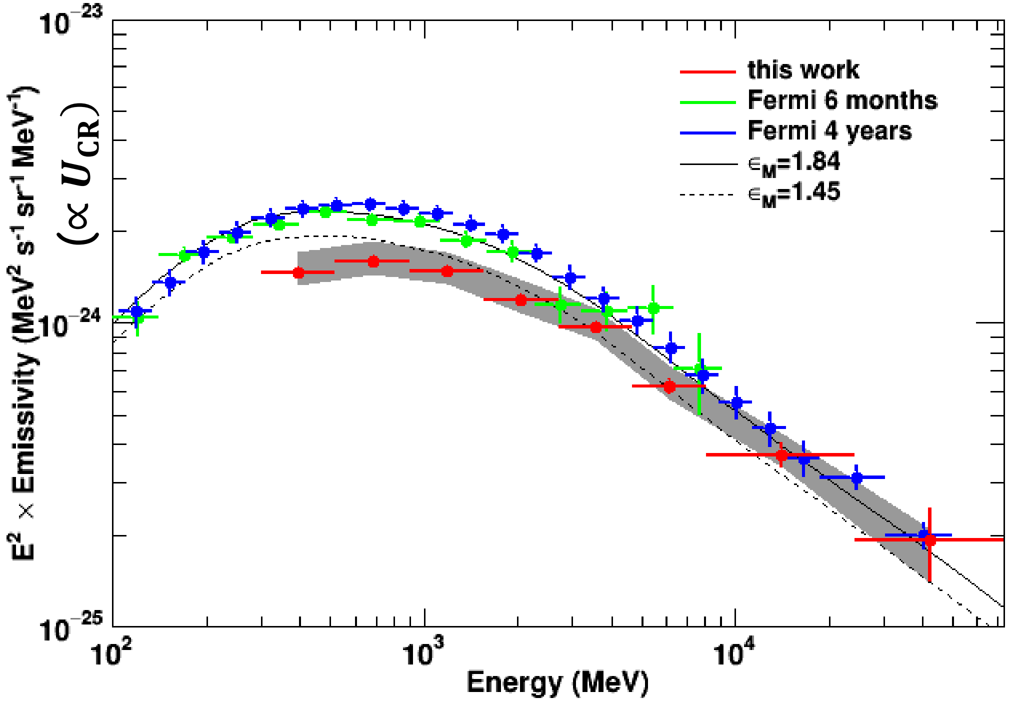


Discussion (HI emissivity or I_{CR})

- HI emissivity spectrum is compared with model curves based on the local interstellar spectrum (LIS) and results by relevant LAT studies employing a conventional template-fitting method
- Our spectrum agrees with the <u>model for LIS with ε_m (nuclear enhancement factor)=1.45</u>, while previous LAT studies favor ε_m=1.84

Most of difference can be understood due to the different $N(H_{tot})$ inferred in low T_d area (where our method has more flexibility to adjust $N(H_{tot})$)

<u>Systematic study of other high-latitude regions</u> is necessary to better understand the ISM and CRs



Summary

- <u>An accurate estimate of ISM densities is crucial</u> to study CRs
- Diffuse GeV γ rays are a powerful probe to study the ISM and CRs
- We present a joint Planck & Fermi-LAT study of MBM 53-55 clouds and the Pegasus Loop for the first time
  - We propose to use γ rays as a robust tracer of $N(H_{tot})$, and obtained the ISM (and CR) properties
  - We obtained physical quantities on ISM and CRs (e.g., mass of dark gas, HI emissivity)
  - <u>Systematic study of other high-latitude regions is necessary</u> to better understand the ISM and CRs

Thank you for your Attention

References (Fermi-LAT Studies of Diffuse Emission in MW)

- Abdo+09, ApJ 703, 1249 (CA: TM)
- Abdo+09, PRL 103, 251101 (CA: Johanneson, Porter, Strong)
- Abdo+10, ApJ 710, 133 (CA: Grenier, Tibaldo)
- Abdo+10, PRL 104, 101101 (CA: Ackermann, Porter, Sellerholm)
- Ackermann+11, ApJ 726, 81 (CA: Grenier, TM, Tibaldo)
- Ackermann+12, ApJ 750, 3 (CA: Johanneson, Porter, Strong)
- Ackermann+12, ApJ 755, 22 (CA: Hayashi, TM)
- Ackermann+12, ApJ 756, 4 (CA: Kamae, Okumura)
- Ackermann+12, A&A 538, 71 (CA: Grenier, Tibaldo)
- Ackermann+14, ApJ 793, 64 (CA: Franckowiak, Malyshev, Petrosian)
- Casandjian 2015, ApJ 806, 240
- Ackermann+15, ApJ 799, 86 (CA: Ackermann, Bechtol)
- Tibaldo+15, ApJ 807, 161 (CA: Digel, Tibaldo)
- Planck Collaboration 2015, A&A 582, 31 (CA: Grenier)
- Ajello+16, ApJ 819, 44 (CA: Porter, Murgia)
- Acero+16, ApJS 223, 26 (CA: Casandjian, Grenier)
- Mizuno+16, ApJ 833, 278
- Remy+17, A&A accepted (CA: Grenier, Remy)

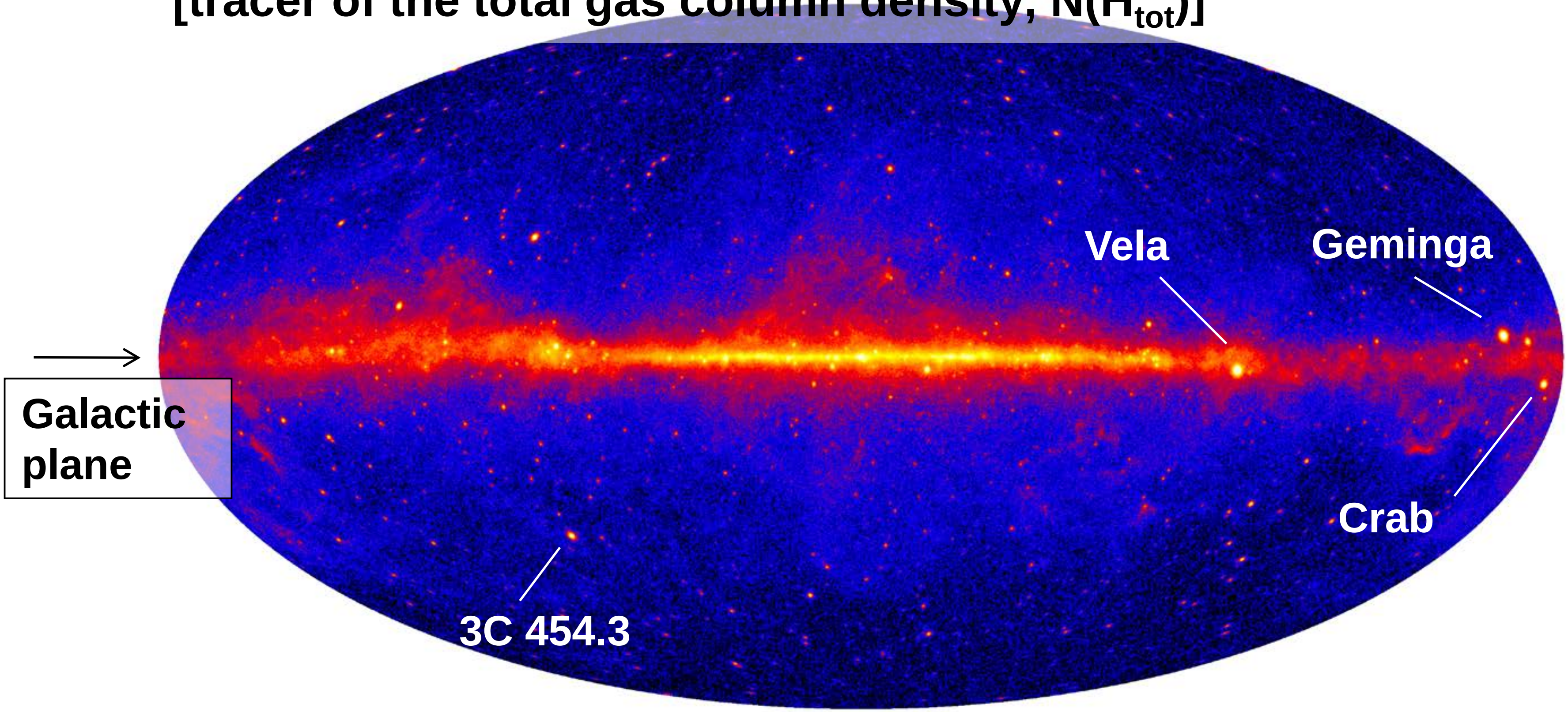
References (others)

- Atwood+09, ApJ 697, 1071
- Dame+01, ApJ 547, 792
- Fukui+14, ApJ 796, 59
- Fukui+15, ApJ 798, 6
- Grenier+05, Science 307, 1292
- Kalberla+05, A&A 440, 775
- Kiss+04, A&A 418, 131
- Planck Collaboration XI 2014, A&A 571, 11
- Strong & Moskalenko 98, ApJ 509, 212
- Welty+89, ApJ 346, 232
- Yamamoto+03, ApJ 592, 217
- Yamamoto+06, ApJ 642, 307
- Ysard+15, A&A 577, 110

Backup Slides

All-Sky Map in γ Rays

- Interstellar Medium (ISM) plays an important role in physical processes in the Milky Way
- <u>Diffuse GeV γ rays</u> are a powerful probe to study the ISM gas [tracer of the total gas column density, $N(H_{tot})$]

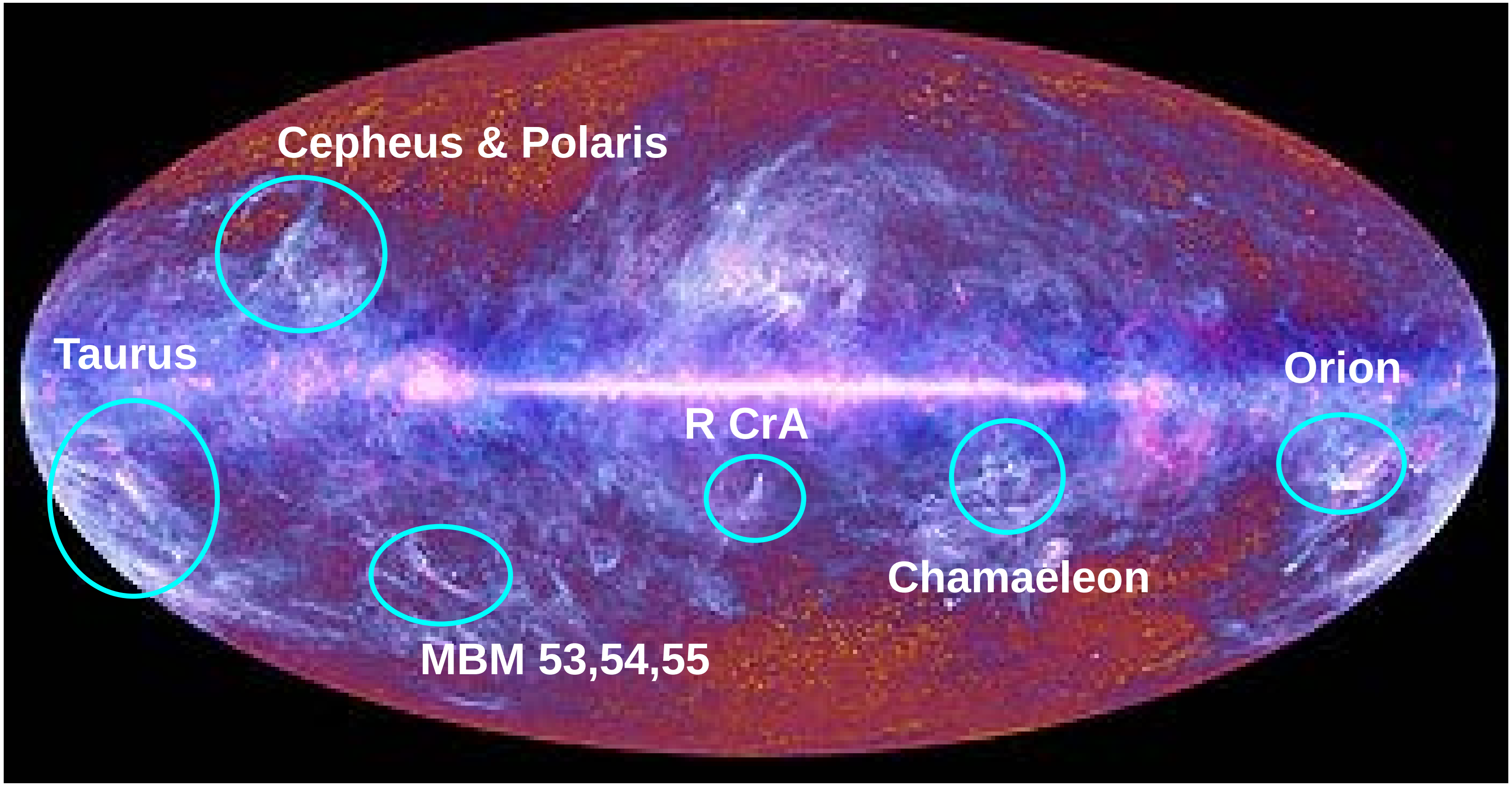


Fermi-LAT 4 year all-sky map = point sources + <u>diffuse γ rays</u>
~80% of γ rays

All-Sky Map in Submillimeter

- **Planck submillimeter map (30-857 GHz)**

= Dust thermal emission = ISM gas in the Milky Way (MW)

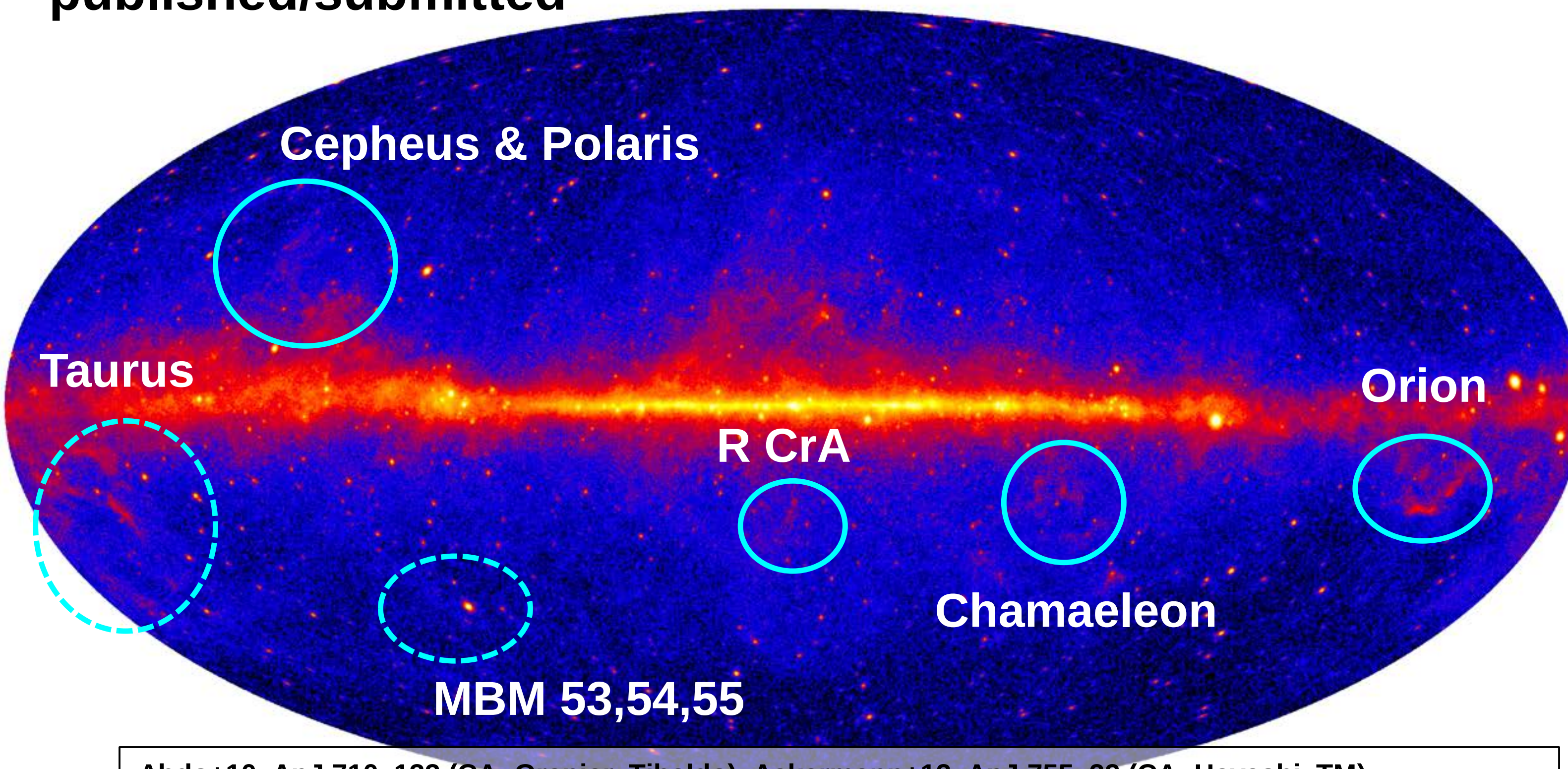


Nearby molecular clouds at high latitude

All-Sky Map in γ Rays

- **Diffuse GeV γ-rays ~ Cosmic Rays (CRs) x ISM**

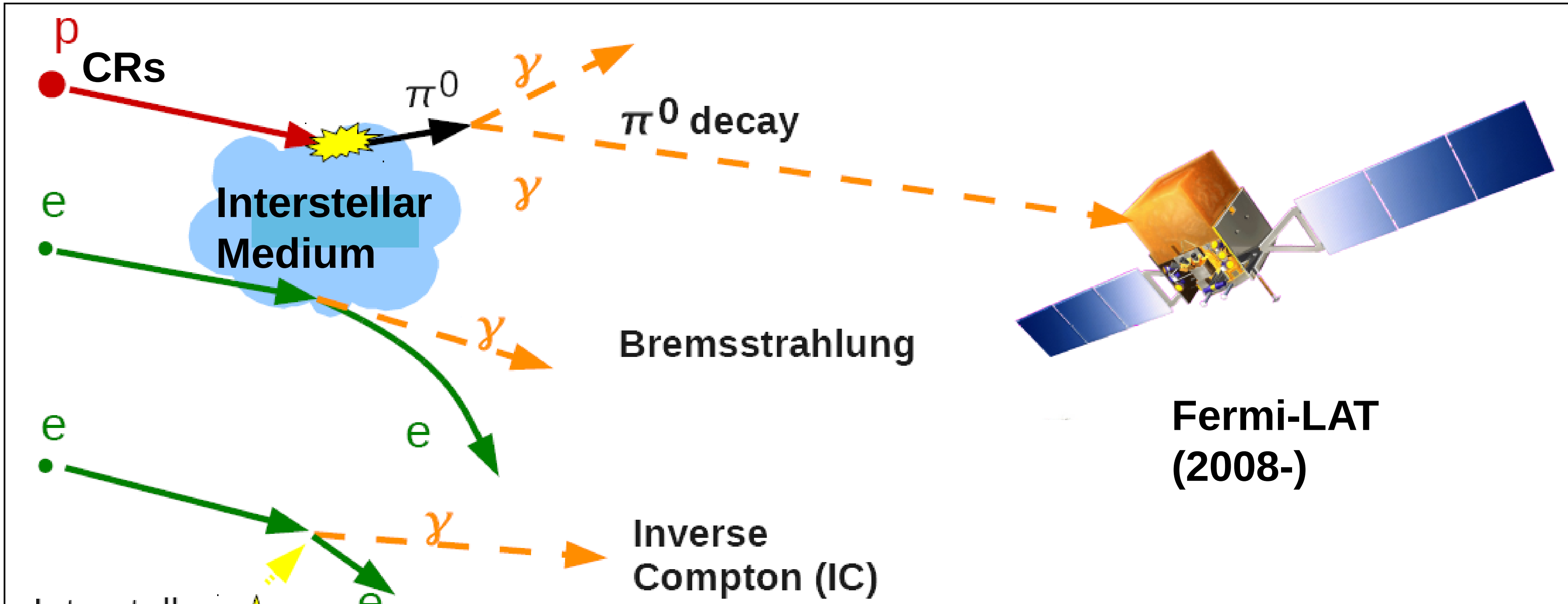
Detailed studies of individual clouds (+ISM in galactic plane) published/submitted



Abdo+10, ApJ 710, 133 (CA: Grenier, Tibaldo); Ackermann+12, ApJ 755, 22 (CA: Hayashi, TM); Ackermann+12, ApJ 756, 4 (CA: Okumura, Kamae); Planck Collaboration 2015, A&A 582, 31 (CA: Grenier); Mizuno+16, ApJ 833, 278 (CA: TM); Remy+17, A&A accepted (CA: Grenier, Remy)
(See also references)

Processes to Produce γ rays (1)

γ rays = CRs x ISM gas (or ISRF)



- Known ISM distribution => CR properties
- Those "measured" CRs => ISM distribution

A powerful probe to study ISM and CRs

(γ rays directly trace gas in all phases)

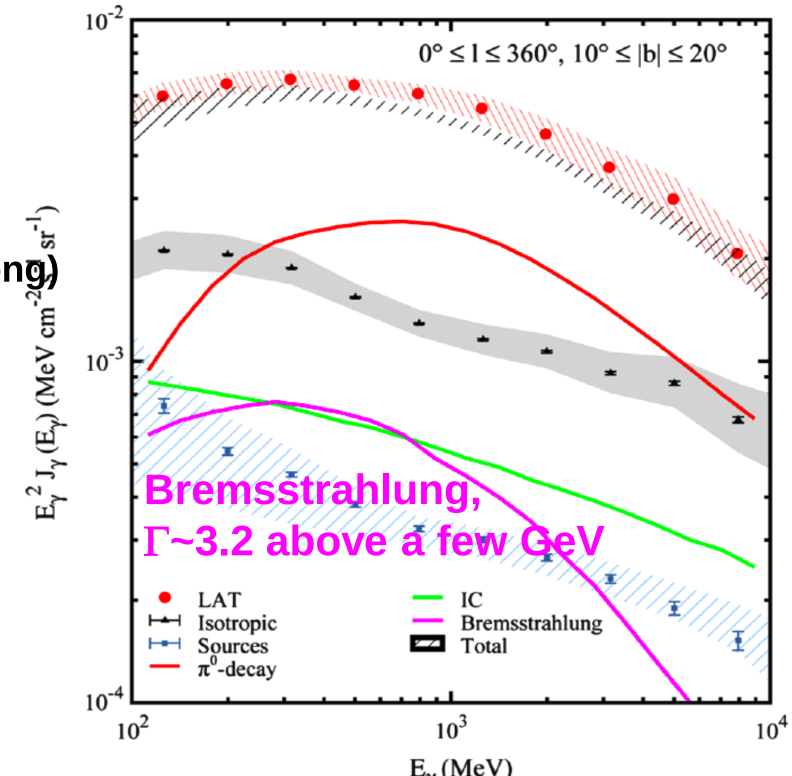
Processes to Produce γ rays (2)

γ rays = CRs x ISM gas (or ISRF)

γ-ray data and model (mid-lat. region)

Abdo+09, PRL 103, 251101
(CA: Porter, Johanneson, Strong)

We can distinguish gas-related γ rays from others based on the spectrum (right plot) and morphology (see the following slides)



π^0 decay, Γ~2.7 above a few GeV

(Isotropic)

Inverse Compton, Γ~2.1

a powerful probe to study <u>ISM</u> and CRs

Pro: optically-thin, “direct” tracer of all gas phases
Con: low-statistics, contamination (isotropic, IC), depend on CR density
=> need to be complemented with other gas tracers

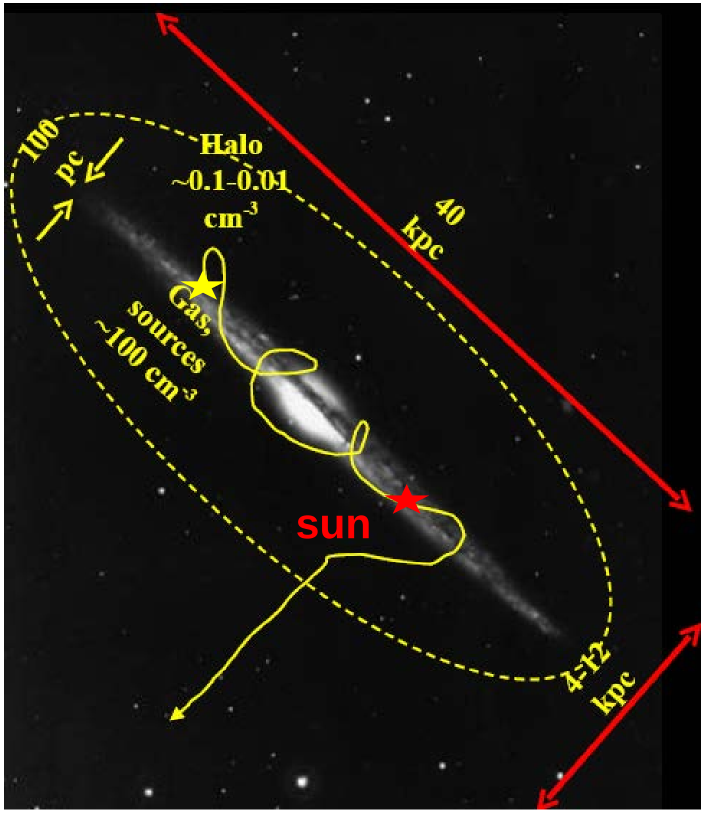
Origin and Propagation of Galactic CRs

- u_{CR}~1 eV/cm^3 at the solar system
- V_{gal}=10$^{67\text{-}68}$ cm^3, τ_{esc}~10^7 yr

$$P_{CR} \sim 10^{41}\ \mathrm{erg/s}$$

- E_{SN}~10^{51} erg, F_{SN}~1/30 yr
- If η~0.1

$$P_{inj} \sim 10^{41}\ \mathrm{erg/s}$$



To test this SNR paradigm of CRs, we need to observe

- CRs accelerated at SNRs and star-forming regions
- CR distribution in Milky Way (MW)

GeV γ ray as a tracer of CRs and ISM

- **For local CR, the γ-ray emissivity is**

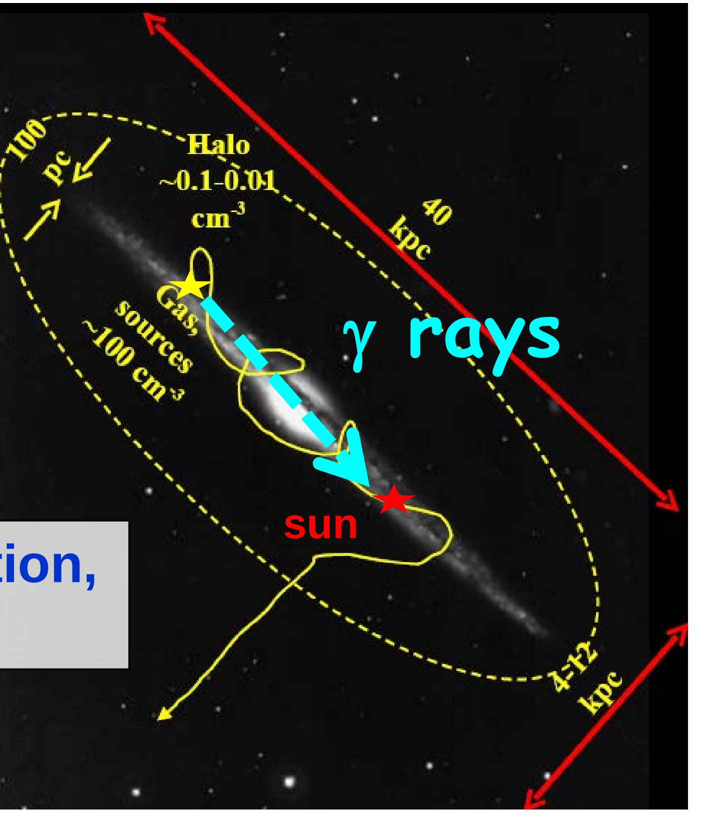
  $$Q_\gamma(>100\mathrm{MeV}) \sim 1.6\mathrm{x}10^{-26}\ \mathrm{ph/s/sr/H\text{-}atom}$$
  $$\sim 1.5\mathrm{x}10^{-28}\ \mathrm{erg/s/H\text{-}atom}$$

- **Then, the γ-ray luminosity is**

  $$L_\gamma(>100\mathrm{MeV}) \sim (M_{gas}/m_p)*Q_\gamma$$
  $$\sim 10^{39}\ \mathrm{erg/s}$$

(compatible to Galactic Ridge X-ray Emission)

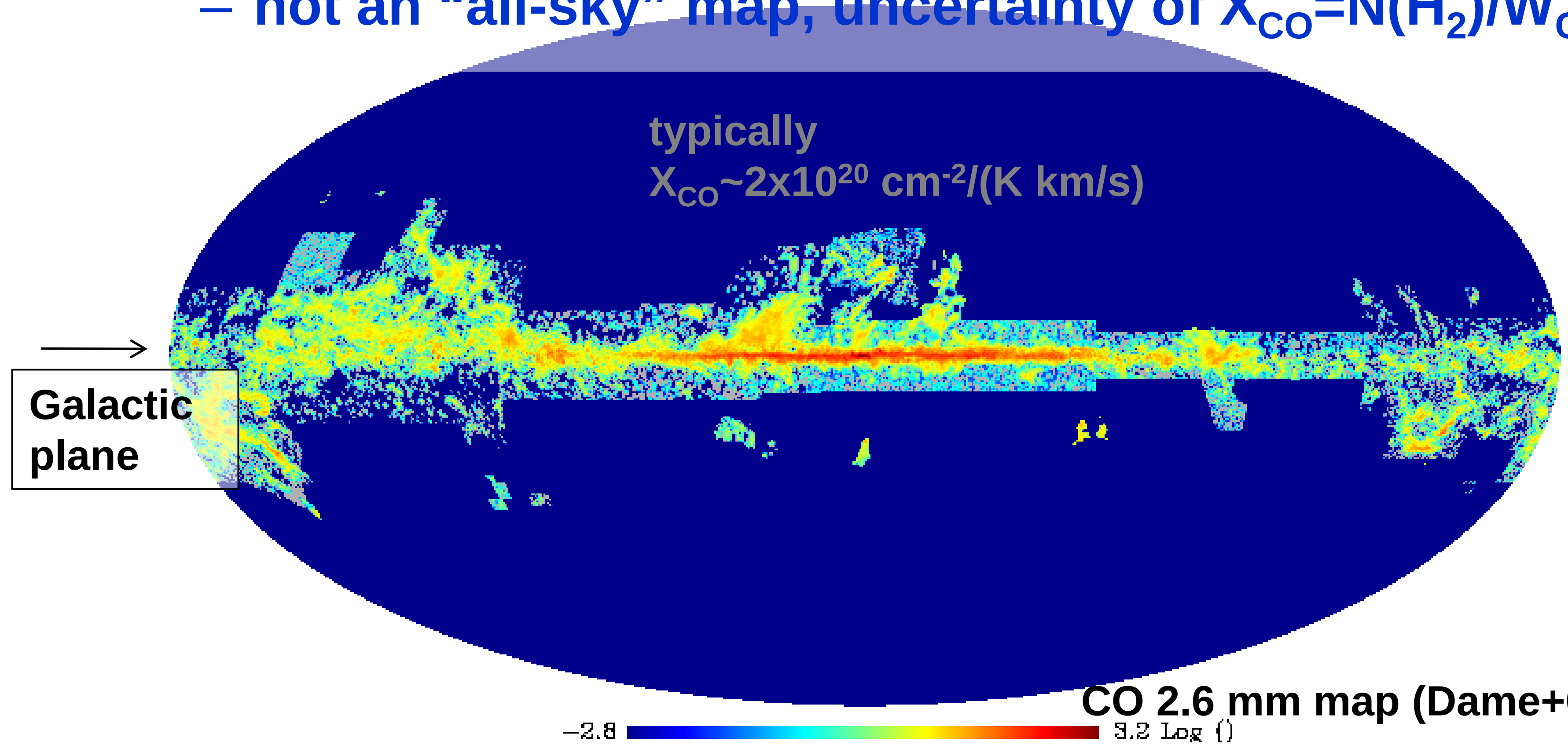
MW is bright in γ rays



A probe to study CR origin & propagation, ISM distribution

Molecular Gas

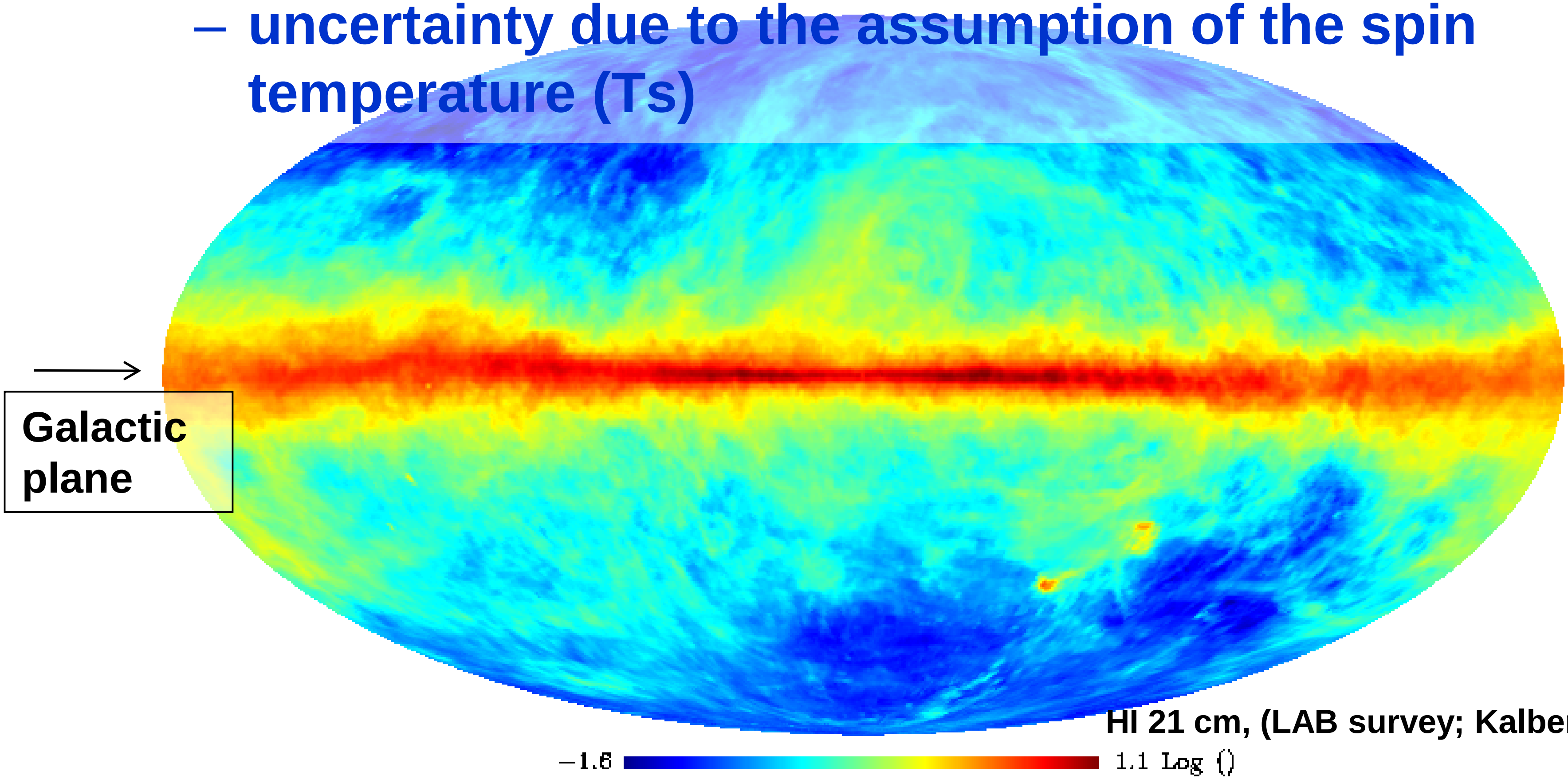
- **Scale height ~70 pc. Site of star formation**
- **Usually traced by CO lines in radio**
  - **not an "all-sky" map, uncertainty of $X_{CO}=N(H_2)/W_{CO}$**



CO 2.6 mm map (Dame+01)

Atomic Gas

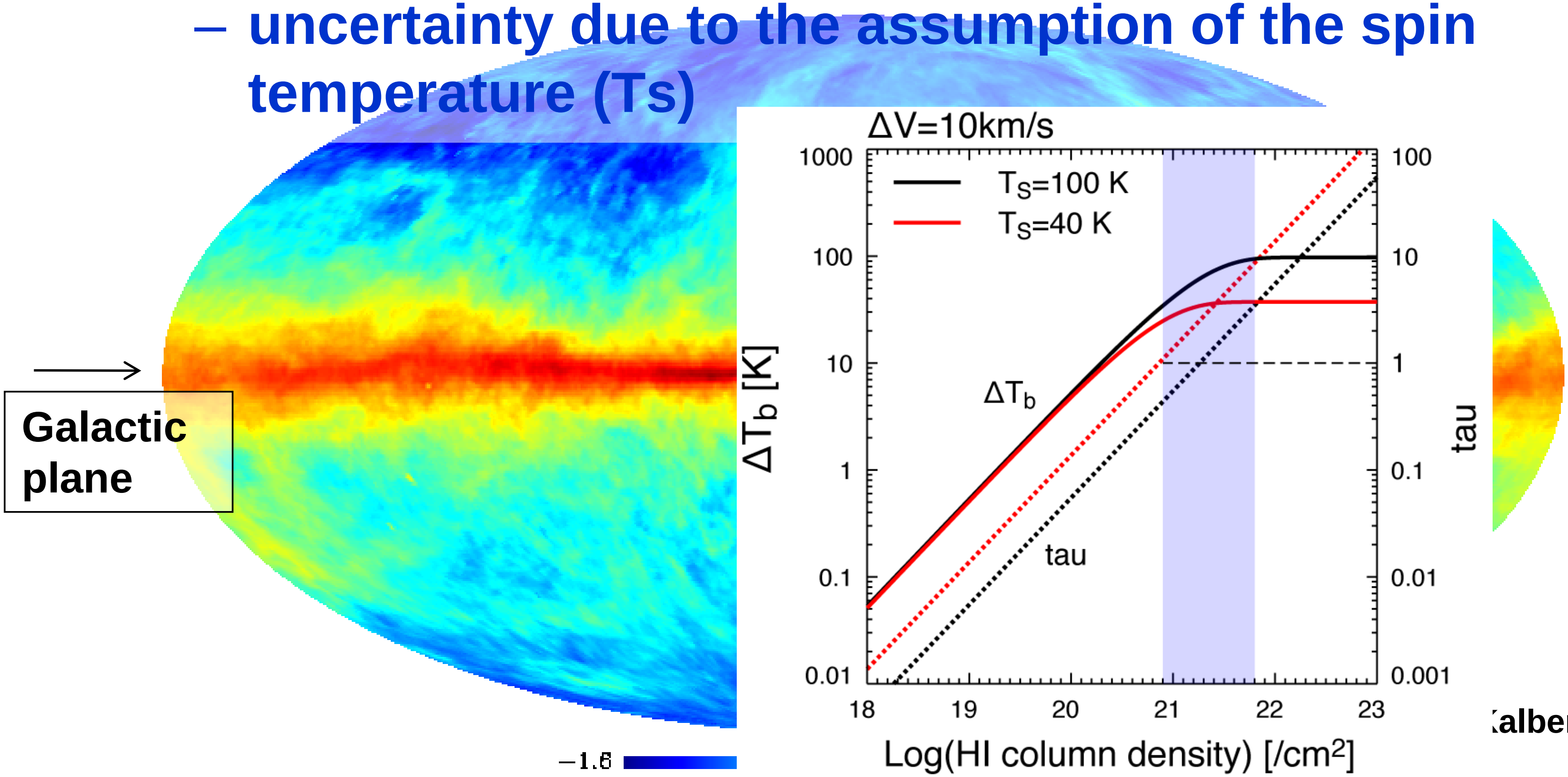
- **Scale height ~200 pc. Main component of ISM**
- **Usually traced by 21 cm line**
  - **uncertainty due to the assumption of the spin temperature (Ts)**



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

Atomic Gas

- **Scale height ~200 pc. Main component of ISM**
- **Usually traced by 21 cm line**
  - **uncertainty due to the assumption of the spin temperature (Ts)**

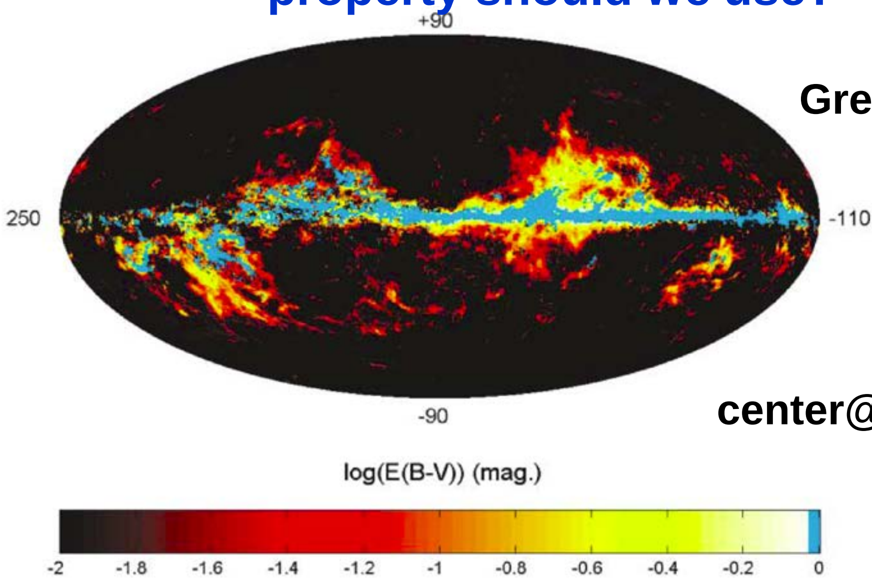


Dark Gas

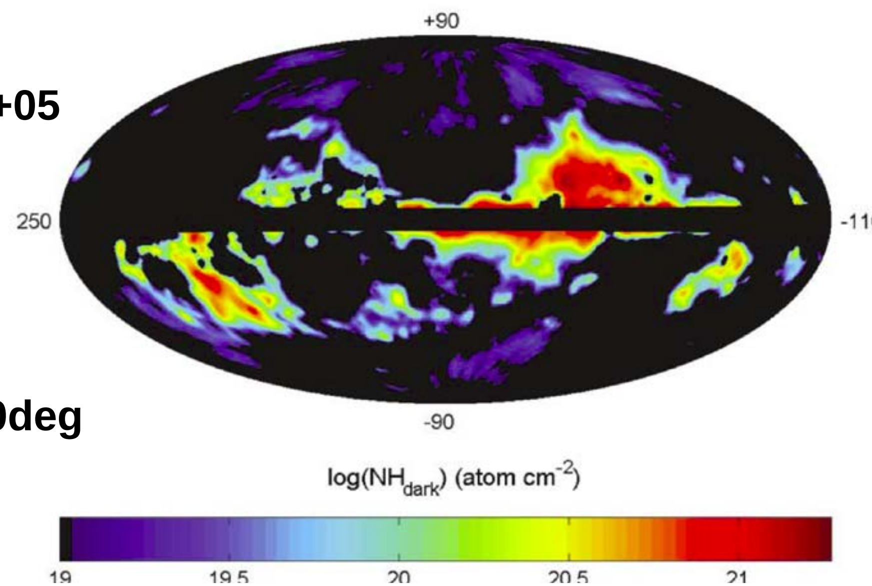
- **Usually ISM gas has been traced by radio surveys (HI by 21 cm, H_2 by 2.6 mm CO)**
- **Grenier+05 claimed considerable amount of <u>“dark gas”</u> surrounding nearby CO clouds**
  - **Cold HI or CO-dark H_2? M_{DG}?**
  - **It can be inferred from the distribution of dust, but what kind of dust property should we use?**

Grenier+05

center@l=70deg



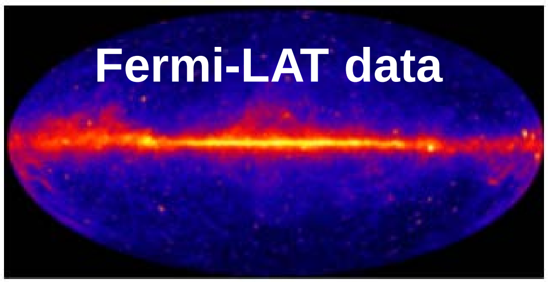
$E(B-V)_{excess}$ (residual gas inferred by dust) and W_{co}



“dark gas” inferred by γ rays (EGRET)

Modeling of γ-ray Data

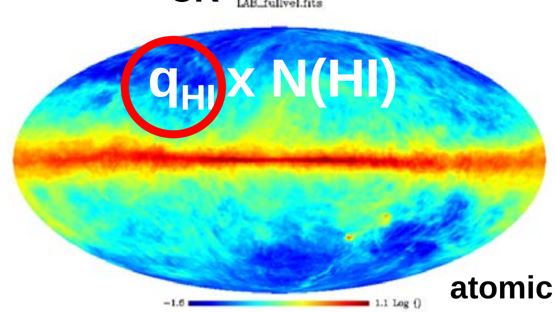
- **Under the assumption of a uniform CR density in the region studied, diffuse γ rays can be modeled by a linear combination of template maps**



(2008-)

=

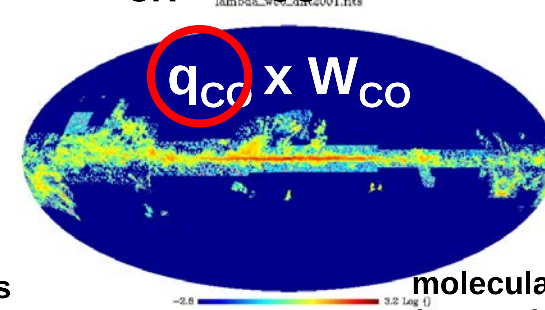
$\propto I_{CR}$



atomic gas (21 cm)

+

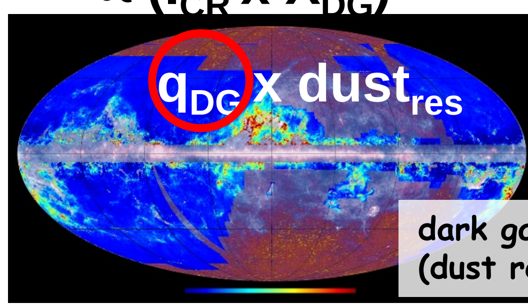
$\propto (I_{CR} \times X_{CO})$



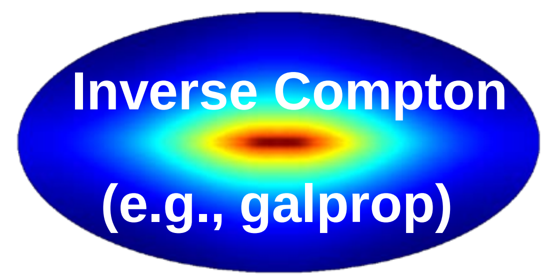
molecular gas (2.6 mm)

+

$\propto (I_{CR} \times X_{DG})$



+



interstellar radiation

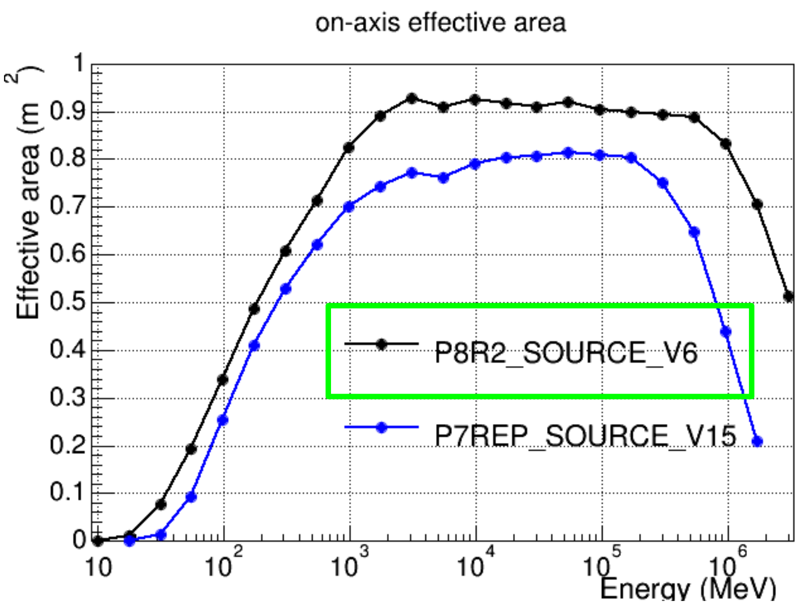
(+ Isotropic + point sources)

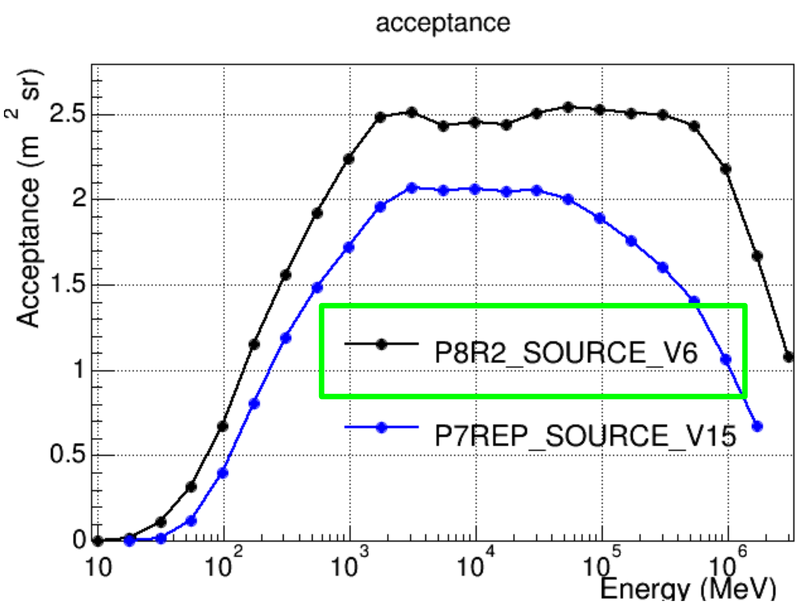
Source of uncertainties:

- **HI is usually estimated by assuming a uniform spin temperature (T_s)**
- **W_{CO} is not an all-sky map, may miss some fraction of H_2**
- **It is not clear what kind of dust property we should use to trace dark gas**

Fermi-LAT Performance (Pass8)

- **Launch in 2008, nearly uniform survey of the γ-ray sky**
- **Performance of Fermi-LAT was improved significantly with Pass8**
  - **large effective area (~1 m^2) and field-of-view (>=2 sr)**





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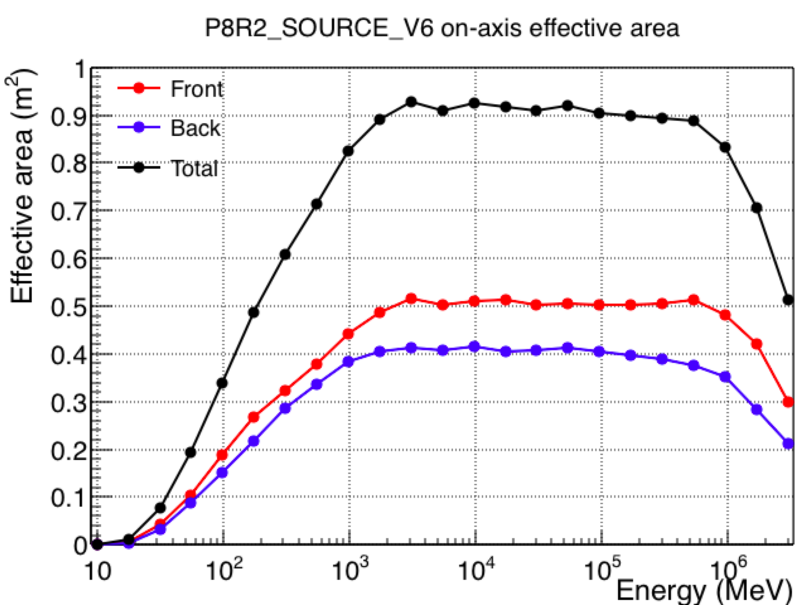
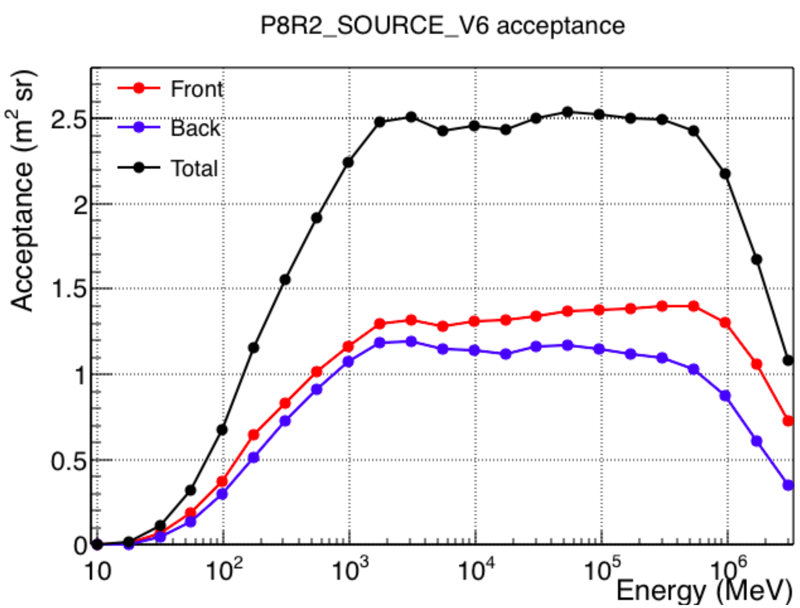
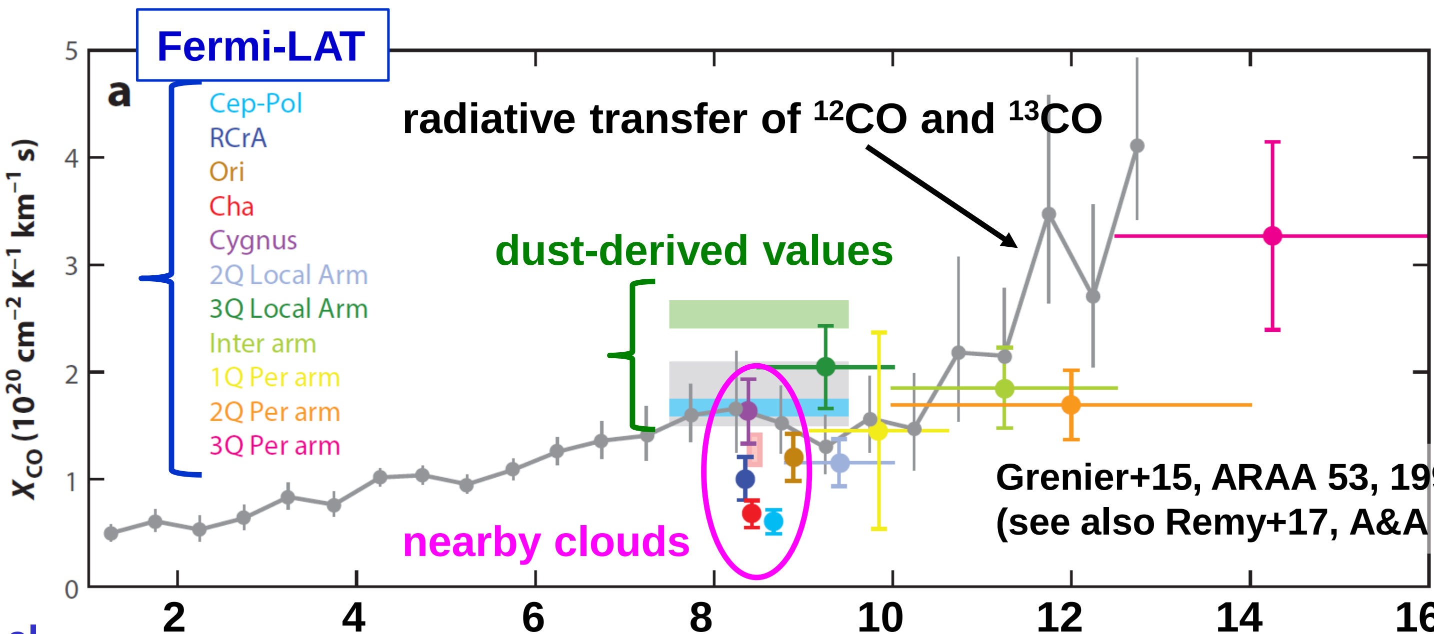




Uncertainty of ISM: X_{CO}

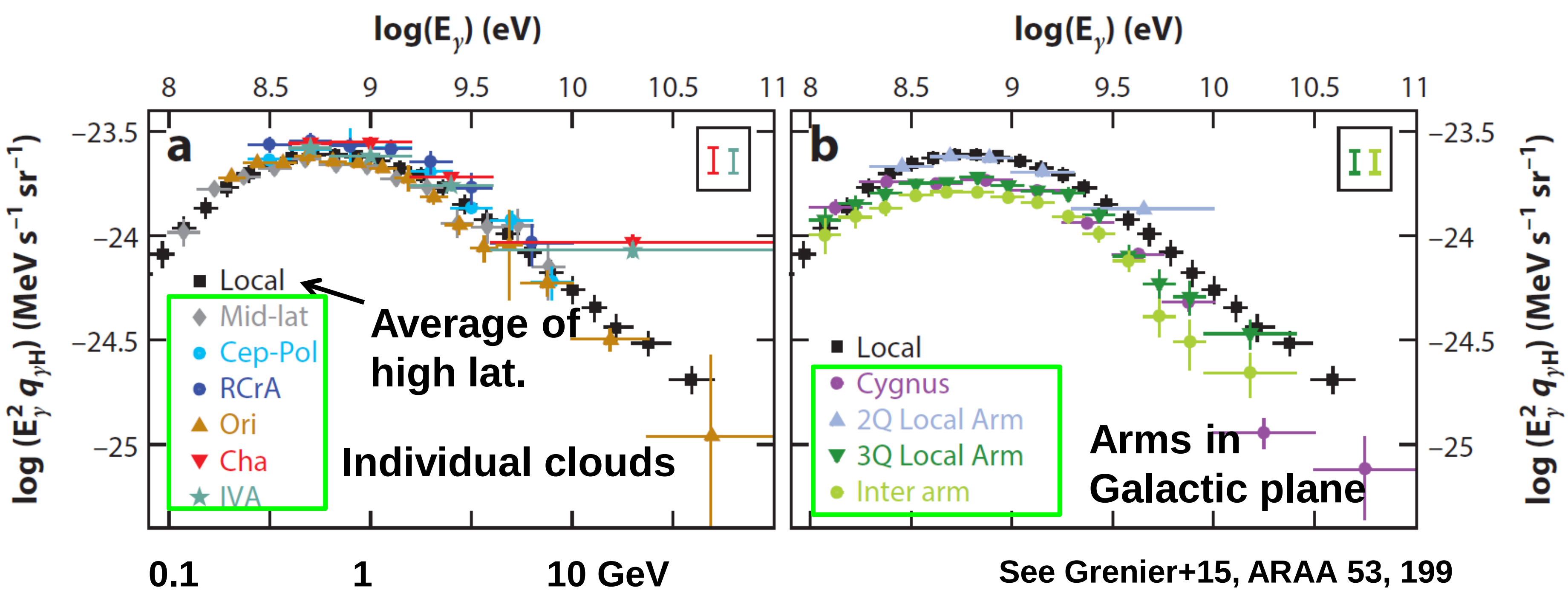
- **Usually H_2 gas is traced by CO 2.6 mm line observations. A canonical value of $X_{\mathrm{CO}}(\equiv N(\mathrm{H_2})/W_{\mathrm{CO}})$ is $\sim 2\times10^{20}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\ s^{-1}})^{-1}$**
- **γ rays are a useful probe to study X_{CO}**
  - **CRs penetrate to the core of H_2 clouds**
  - **CR density can be estimated from nearby HI clouds**
  - **$X_{CO,\gamma}$ does not depend on assumptions on the dynamical state of the gas**
- **Even in nearby clouds/local arm, uncertainty is by a factor of ~2**



Grenier+15, ARAA 53, 199
(see also Remy+17, A&A accepted)

Fermi-LAT Results (3): Local Emissivity (I_{CR})

- "local" CR densities among regions agree by a factor of 1.5, within systematic uncertainty
- Uncertainties are shown by inserts and are mostly due to the assumption of T_s

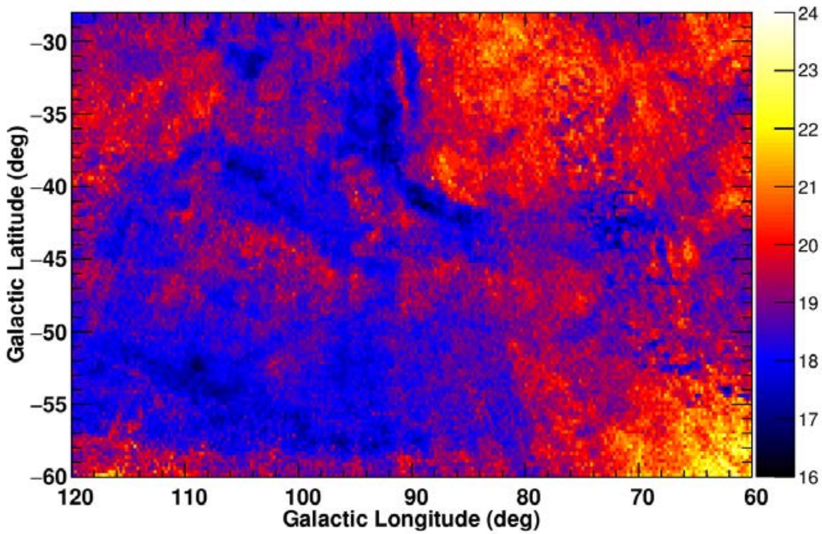


See Grenier+15, ARAA 53, 199 and reference therein

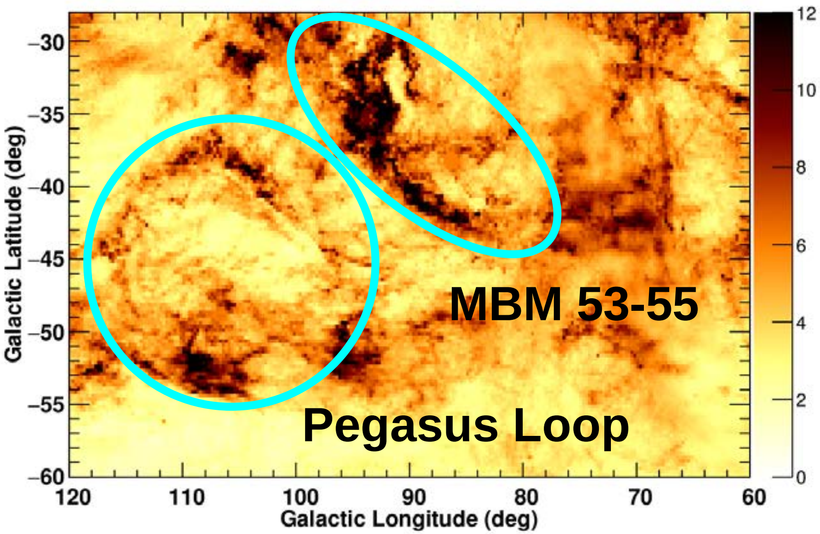
MBM 53,54,55 & Pegasus Loop

- **Nearby, high-latitude clouds <u>suitable to study the ISM</u> and cosmic rays (CRs) in the solar neighborhood** (Welty+89, Kiss+04, Yamamoto+03,06)
  - d ~ 150 and 100 pc for MBM 53-55 and Pegasus Loop, respectively
  - Most of HI in the region is local (from HI velocities in appendix)

Planck dust temperature (T_d) map



Planck radiance (R) map converted in $N(H_{tot})$ template map

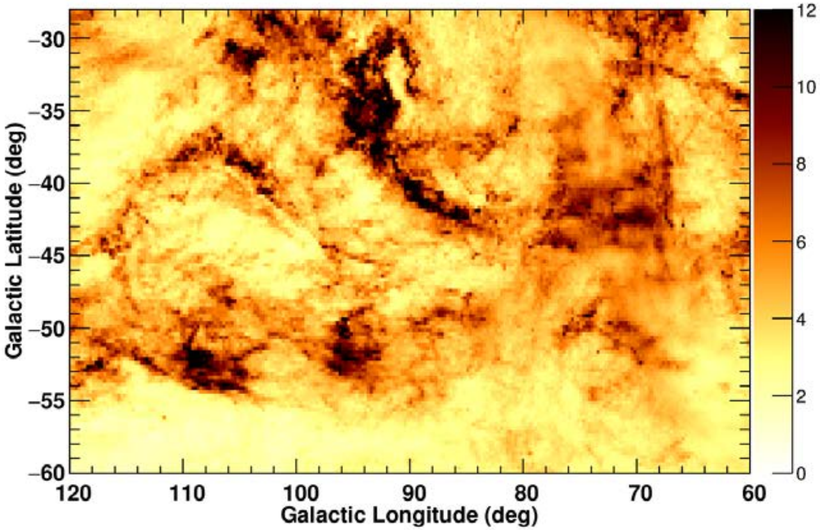


Initial Modeling with a Single $N(H_{tot})$ Map

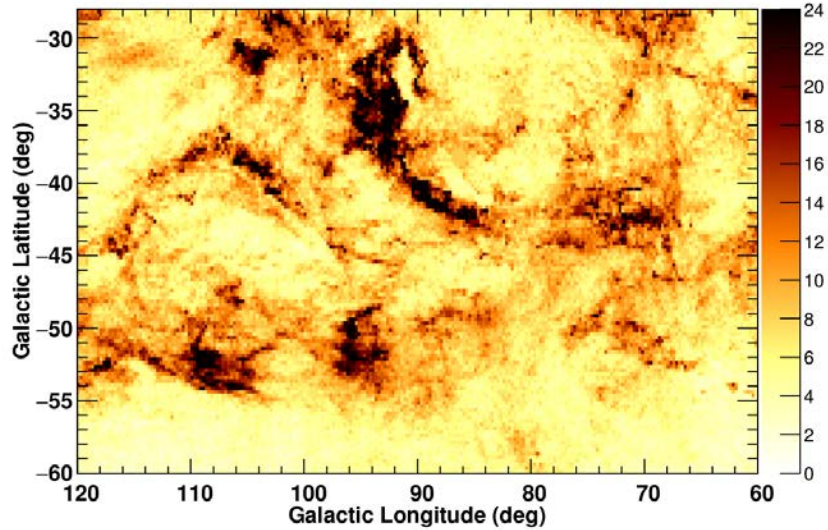
- We assumed $N(H_{tot}) \propto R$ (or τ_{353}) and constructed $N(H_{tot})$ maps
  - Coefficients were determined by assuming that HI is optically thin and well represents $N(H_{tot})$ in T_d>21.5 K (dotted lines in slide #15)
- We used 7 years P8R2 data and modeled γ-ray intensity as below
  - q_γ is the emissivity model adopted. Subscript i is for separating $N(H_{tot})$. Single map is used in initial analysis

$$I_\gamma(l,b,E) = \sum_i c_{1,i}(E) \cdot q_\gamma(E) \cdot N(\mathrm{H_{tot}})_i(l,b) + c_2(E) \cdot I_{\mathrm{IC}}(l,b,E) + I_{\mathrm{iso}}(E) + \sum_j \mathrm{PS}_j(l,b,E)$$

  - We found R-based $N(H_{tot})$ better represents γ-ray data in terms of lnL



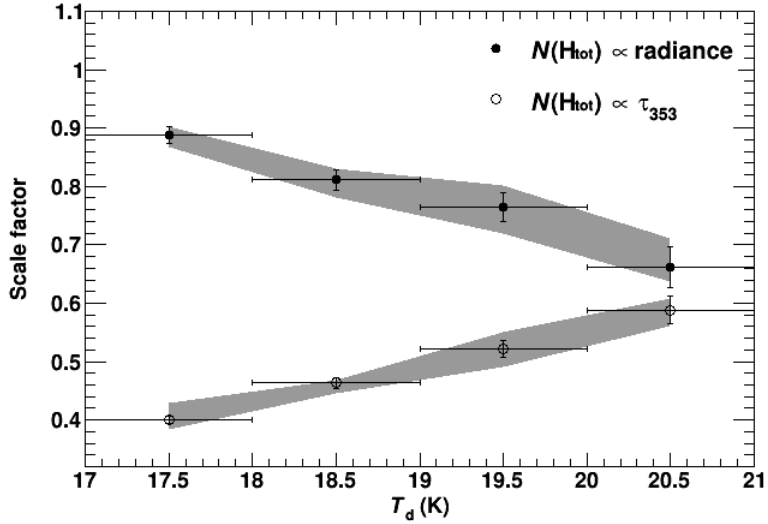
$N(H_{tot})$ template ($\propto$ R) (10^{20} cm^{-2})



$N(H_{tot})$ template ($\propto \tau_{353}$) (10^{20} cm^{-2})

T_d-Sorted Modeling

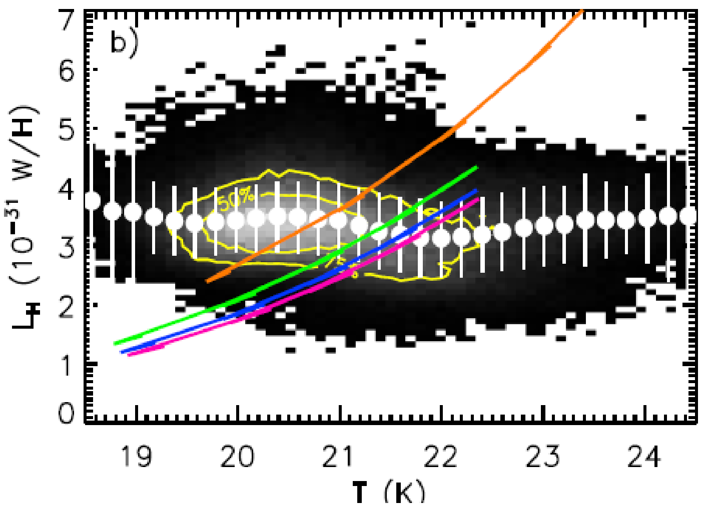
- Even though R-based $N(H_{tot})$ is preferred by γ-ray data, true $N(H_{tot})$ could be appreciably different
- Therefore we split $N(H_{tot})$ template map into four based on T_d and fit γ-ray data with scaling factors freely varying individually
  - Scaling factors should not depend on T_d if $N(H_{tot}) \propto D$ (R or τ_{353})
- Fit improves significantly and shows clear T_d dependence of scaling factors
  - The trend is robust against various tests of systematic uncertainty



We propose to use γ-ray data to compensate for the dependence

Possible Explanation of T_d Dependence (1)

- **We found, from γ-ray data analysis, neither the radiance nor τ_{353} are good tracers of $N(H_{tot})$**
  - **Even though the interstellar radiation field (ISRF) is uniform in the vicinity of the solar system, <u>the radiance (per H) could decrease as the gas (and dust) density increases</u>, because the ISRF is more strongly absorbed by dust. This will cause a correlated decrease in the T_d and the radiance (per H).**

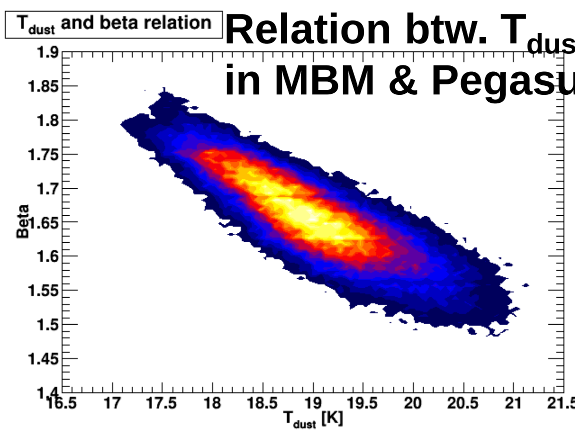


Ysard+15, Fig.2
(Radiance per H vs. T_d for several choices of ISRF hardness. <u>Both radiance and T_d decrease as the ISRF is abosrbed</u>)

Possible Explanation of T_d Dependence (2)

- **We found, from γ-ray data analysis, neither the radiance nor τ_{353} are good tracers of $N(H_{tot})$**
  - **In the optically-thin limit, $I_\nu = \tau_\nu B_\nu(T_d) = \sigma_\nu N(H_{tot}) B_\nu(T_d)$, where τ_ν and σ_ν are the optical depth and the dust opacity (cross section) per H, respectively. σ_ν depends on the frequency and is often describes as a power law, giving $I_\nu = \tau_{\nu 0} (\nu/\nu_0)^\beta B_\nu(T_d)$ (modified blackbody, β~1.5-2).**
  - **Therefore, <u>IF the dust cross section is uniform</u>, $\tau_\nu \propto N(H_{tot})$ and we can measure the total gas column density by measuring the dust optical depth at any frequency (e.g., τ_{353}).**
  - **However, <u>dust opacity is not uniform</u> but rather anti-correlates with T_d as reported by Planck Collaboration (2014).**

Relation btw. T_{dust} and β in MBM & Pegasus



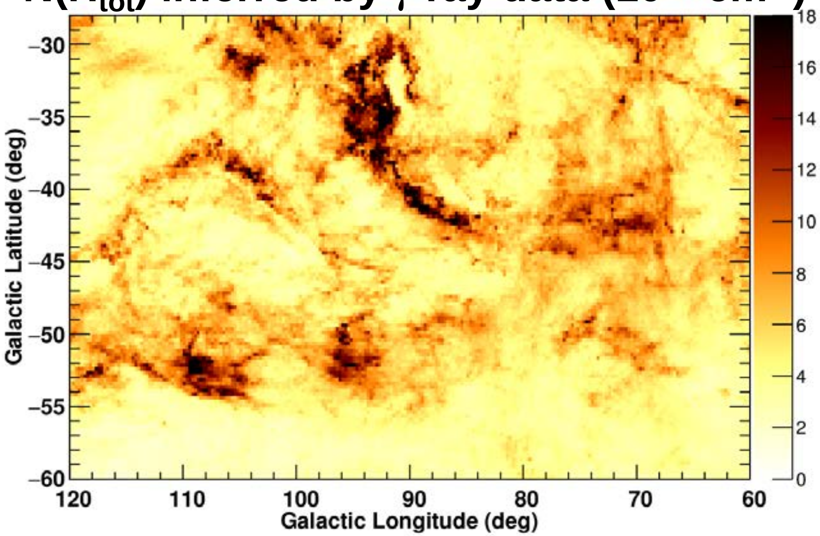
T_d-Corrected Modeling (2)

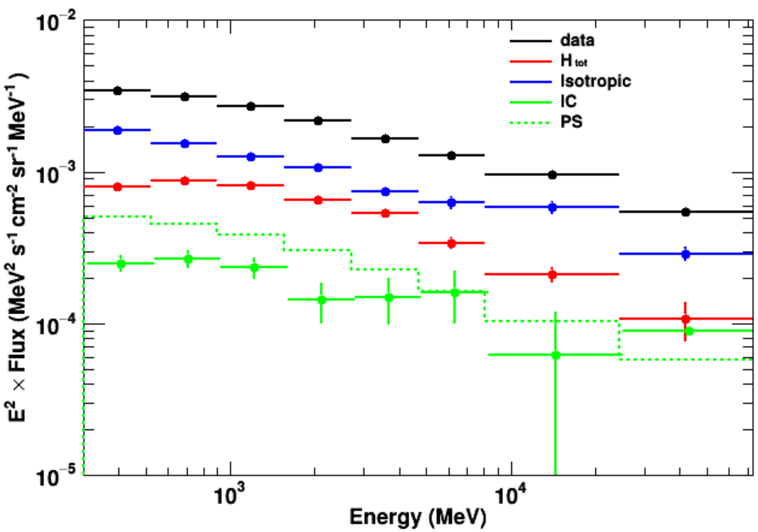
- We started with R-based $N(H_{tot})$ map and employed an empirical function as below [modeling the increase of $N(H_{tot})$ in areas with low Td]

$$N(\mathrm{H_{tot,mod}}) = \begin{cases} N(\mathrm{H_{tot,R}})\ (T_\mathrm{d} > T_\mathrm{bk}) & , \\ (1 + 0.05 \cdot C \cdot \frac{T_\mathrm{bk} - T_\mathrm{d}}{1\ \mathrm{K}}) \cdot N(\mathrm{H_{tot,R}})\ (T_\mathrm{d} \le T_\mathrm{bk}) & , \end{cases}$$

- T_{bk}=20.5 K and C=2 [10% required increase in $N(H_{tot})$ by 1K] gives highest fit likelihood, and obtained $N(H_{tot,mod})$ and the spectrum are shown below

$N(H_{tot})$ inferred by γ-ray data (10^{20} cm^{-2})

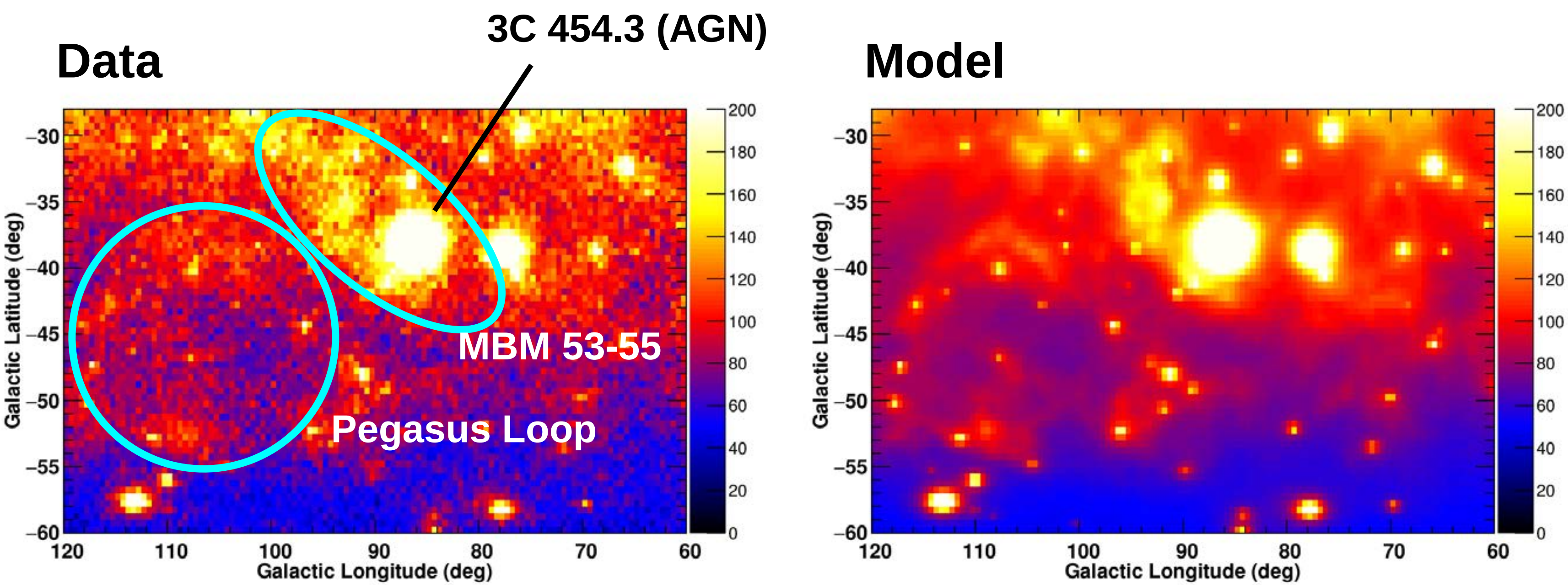




T. Mizuno et al.

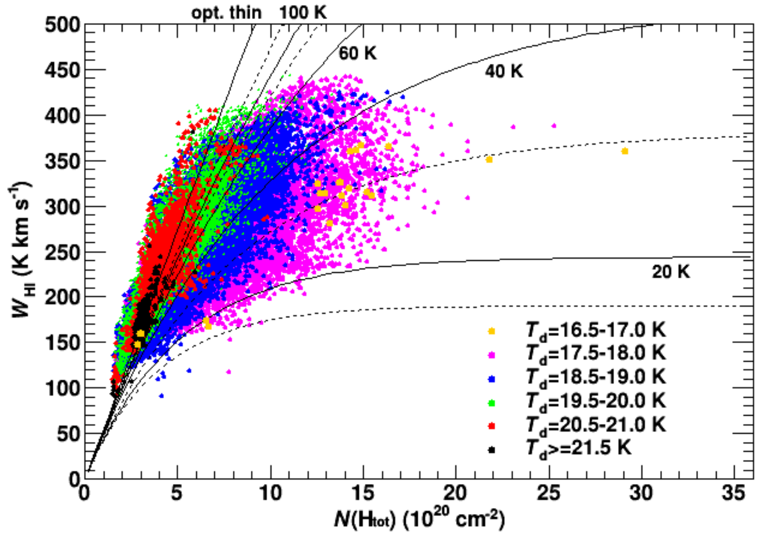
T_d-Corrected Modeling (3)

- **Obtained data count map (left) and model count map (right) in E > 300 MeV**



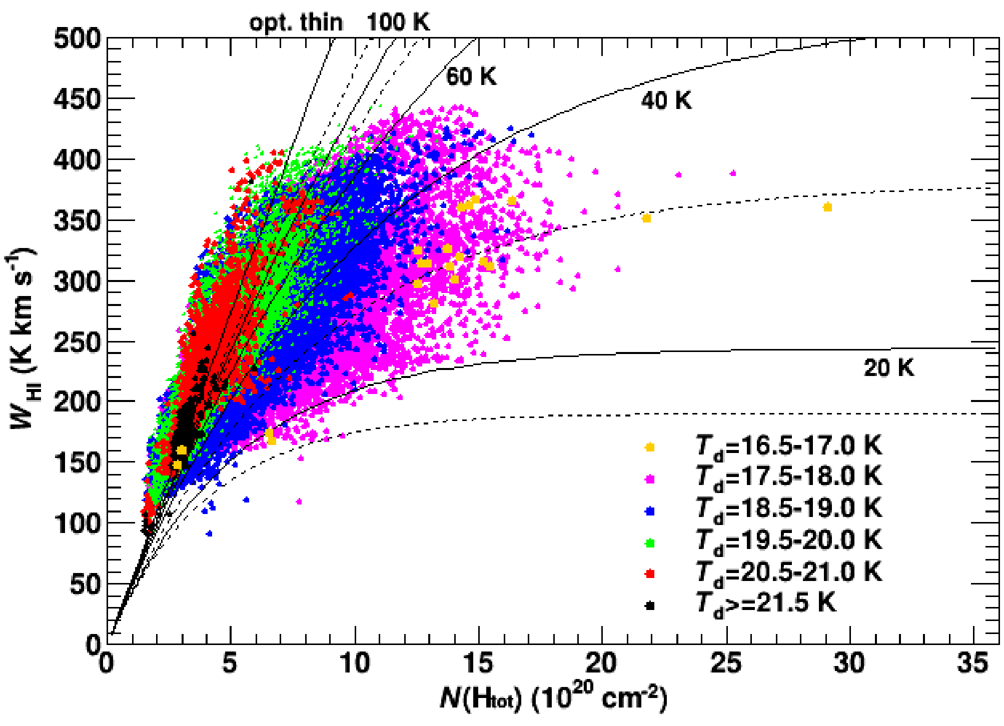
Discussion (ISM)

- **The correlation between W_{HI} and the "corrected" $N(H_{tot})$ map**
  - **Scatter due to dark gas (DG)**



Discussion (ISM)

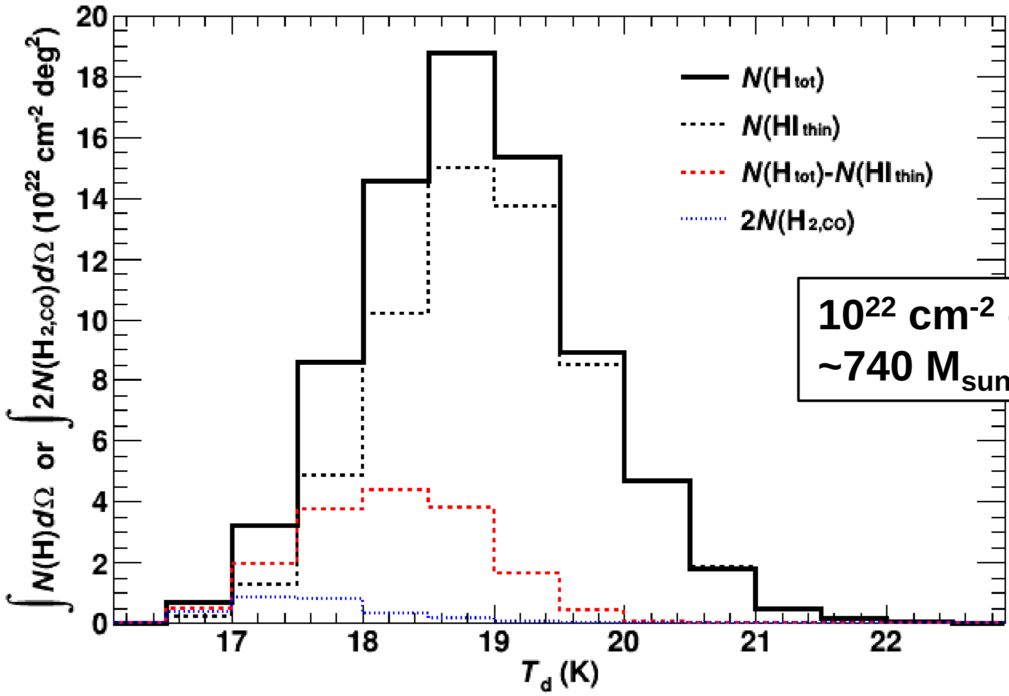
- The correlation between W_{HI} and the "corrected" $N(H_{tot})$ map
  - Scatter due to dark gas (DG). T_s<100 K is inferred in the scenario that optically thick HI dominates



Discussion (ISM)

- **Integral of gas column density ($\propto M_{gas}$) as a function of T_d for $N(H_{tot})$, $N(HI_{thin})$, $N(H_{tot})$-$N(HI_{thin})$(~N(H) for dark gas) and $2N(H_{2,CO})$**
  - **M_{DG} is ~25% of $M_{HI,thin}$ and ~ 5 x $M_{H2,CO}$ (the factor of 5 is large compared to those in other regions)**
  - **M_{DG} differs by a factor of ~4 if we use only R (or τ_{353}); <u>The correction based on γ-ray data is crucial</u>**

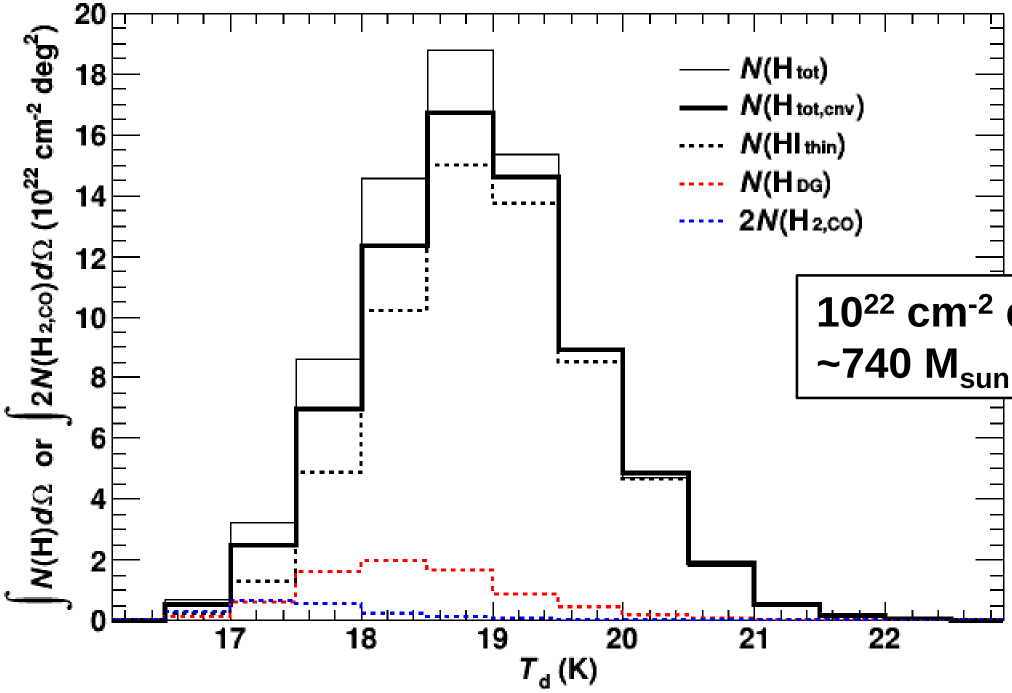
$M(DG,\gamma)$ = ~ 4 x M(DG, R)
~1/4 x $M(DG, \tau_{353})$



10^{22} cm^{-2} deg^2 corresponds to ~740 M_{sun} for d=150 pc

Results by a Conventional Template-Fitting Method

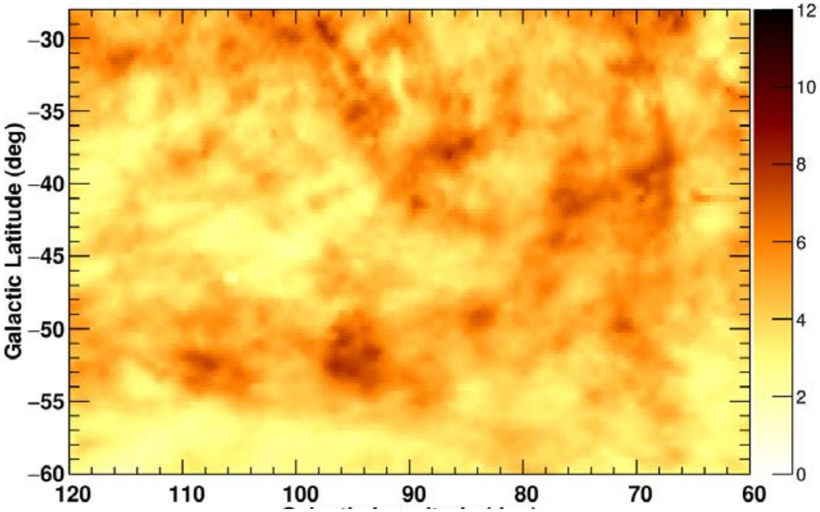
- **We also employed a conventional template-fitting method**
  - **Fit gamma-ray data with $N(\mathrm{HI_{thin}})$ map, W_{CO} map, R_{res} map (template of dark gas) with isotropic, Inverse Compton and point sources**
  - **M_{DG} (shown by red dotted histogram) is ~50% smaller than that we obtained through T_d-corrected modeling**

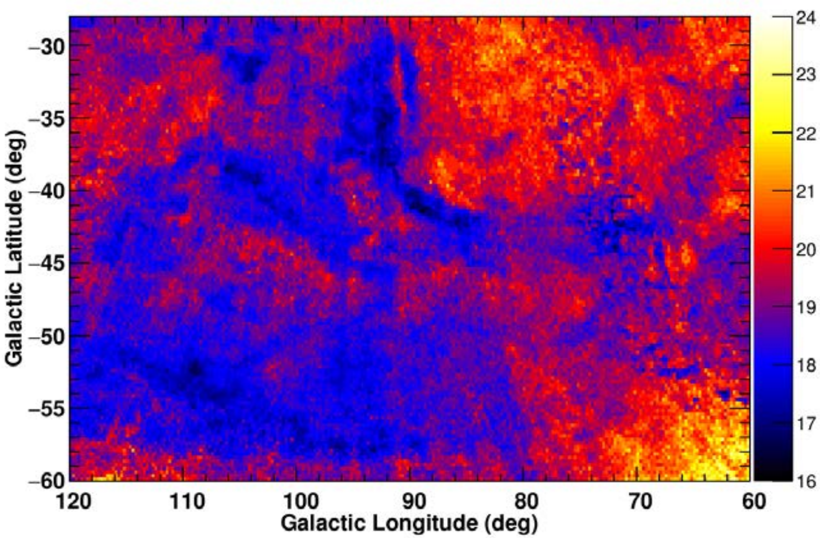


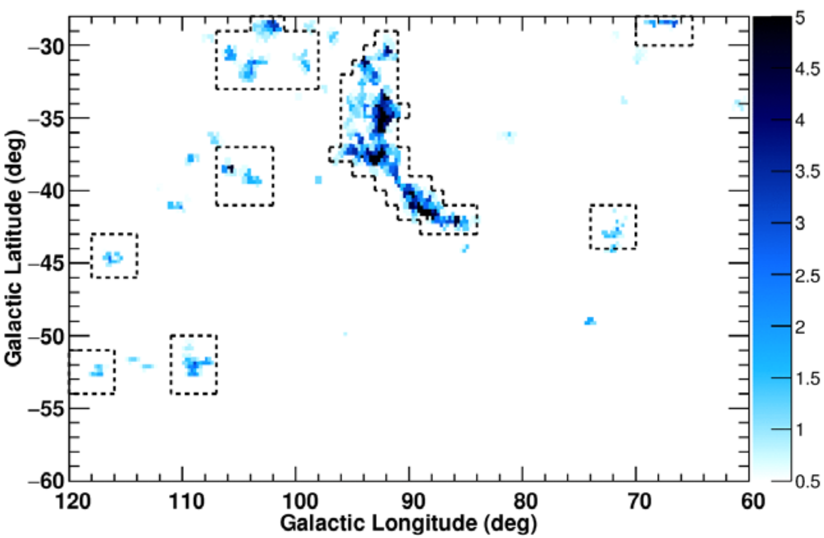
10^{22} cm^{-2} deg^2 corresponds to ~740 M_{sun} for d=150 pc

ISM Maps of the Region Studied

- $N(HI_{thin})$ in 10^{20} cm^{-2}
- W_{co} in K km/s
- T_d in K



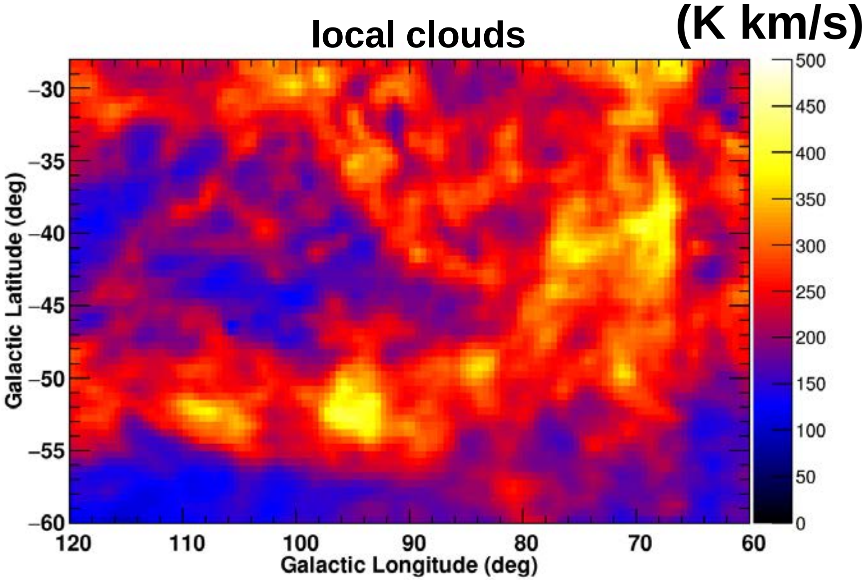




Intermediate Velocity Clouds

- We are studying high-latitude region, therefore most of gas is in local. Still, there are some clouds with different velocities [intermediate velocity clouds (IVCs)]
- (Left) W_{HI} of local clouds. (Right) W_{HI} of IVCs
  - Contribution of IVCs is at the ~5% level

$-30 < V_{lsr}$ (km/s) < 20



$-80 < V_{lsr}$(km/s) -30