Study of Local Clouds using HI Line Profile

T. Mizuno (Hiroshima Univ.), K. Hayashi (ISAS/JAXA),
I. Moskalenko, E. Orlando (Stanford Univ.), A. Strong (MPE)
On behalf of the Fermi-LAT collaboration

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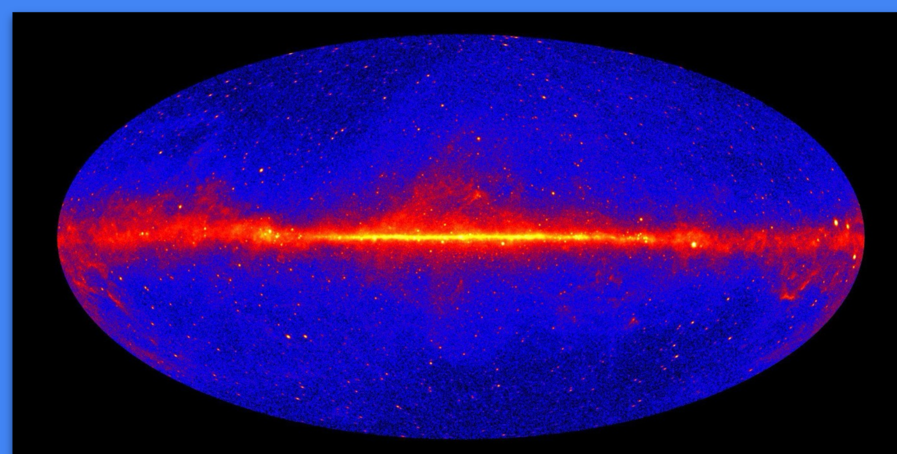


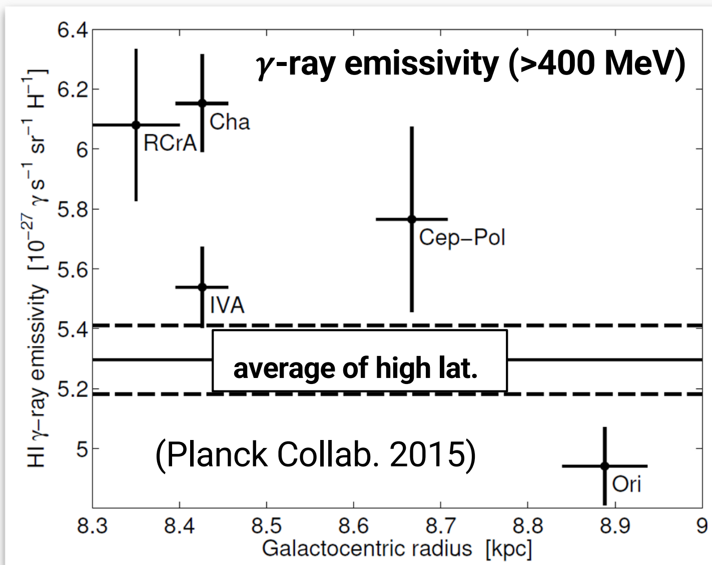
Motivation: Study of Local Gas & CRs

γ-ray provides vital information of interstellar gas & CRs $I_\gamma \propto I_{CR} \cdot N_H$

Issue: Uncertainty is still large (30-50% level) even in local environment

$q_\gamma = I_\gamma / N_H$ ($\propto I_{CR}$) varies considerably, higher than expected (directly-measured CR)

Key: Identify optically thin HI ($N_{HI} \propto W_{HI}$)



Broad (warm) HI is likely to be optically-thin (Kalberla+20), and we succeeded in modeling γ-rays of MBM 53-55 clouds and Pegasus loop using HI line width (Mizuno+22)

Now we will update the procedure and apply it to other local clouds (using 15 years data)

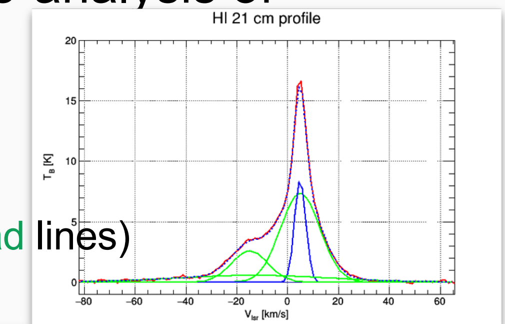
Targets of This Study

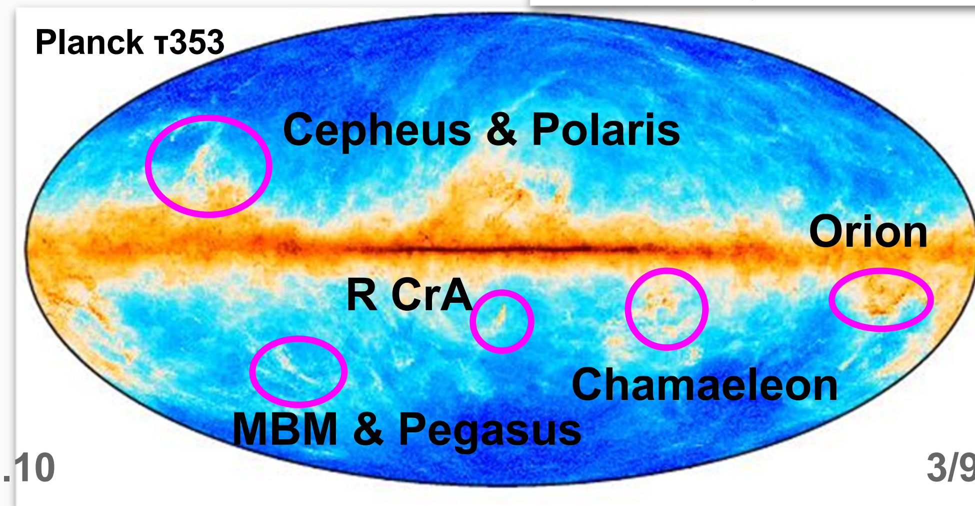
To study local gas and CRs, we analyzed <u>5 nearby molecular clouds</u> (see map) using HI-line profile. We first updated the procedure through re-analysis of MBM & Pegasus, then studied the other 4 regions

Properties of clouds (Dame+87, Yamamoto+06)

Cloud	Distance (pc)	M_{H2} (M_{Sun})
MBM&Pegasus	~150	~0.1×10^4
R CrA	~150	~0.3×10^4
Chamaeleon	~200	~1×10^4
Cep & Pol	~450	~2×10^5
Orion	~500	~3×10^5

Example of the line profile
(one narrow and three broad lines)



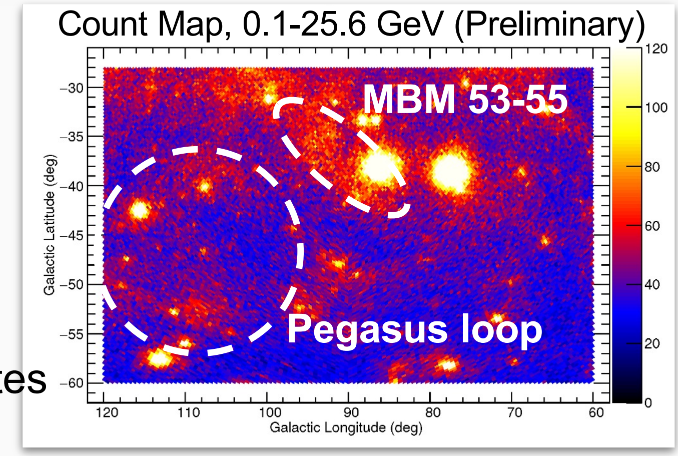


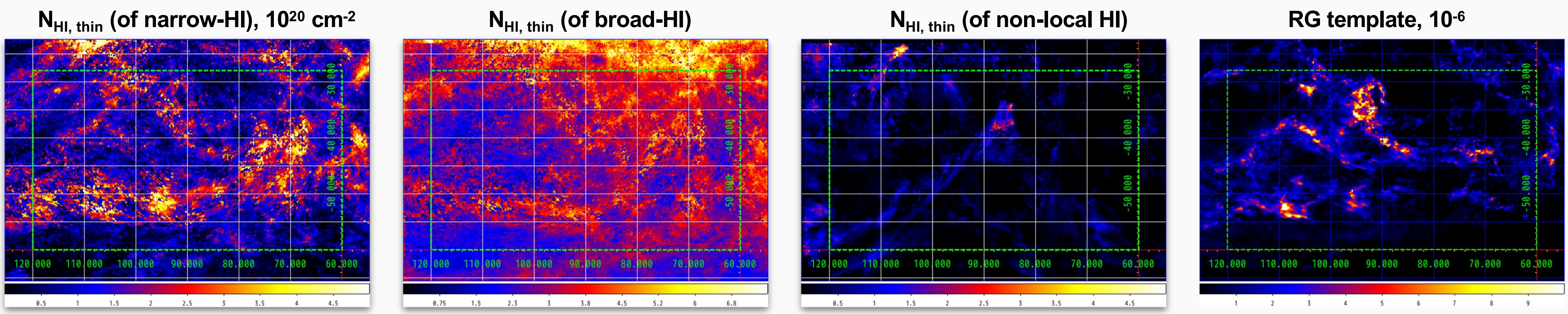
Procedure of γ-ray Data Analysis (1): MBM & Pegasus

We prepared 4 gas templates; W_{CO} map, non-local HI map (velocity based), and narrow/broad-HI maps (line width based)

- Different spatial distributions allow to distinguish different gas phases, and broad-HI map allows to accurately measure HI emissivity (CR intensity)

There remains residual gas (RG; presumably CO-dark H_2) and Inverse Compton (IC) contributions. We prepared several templates and tested them against γ-ray data (to cope with uncertainties)



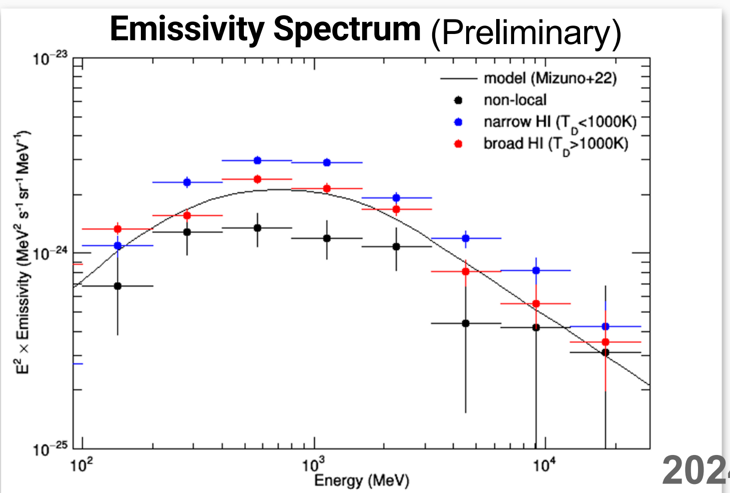


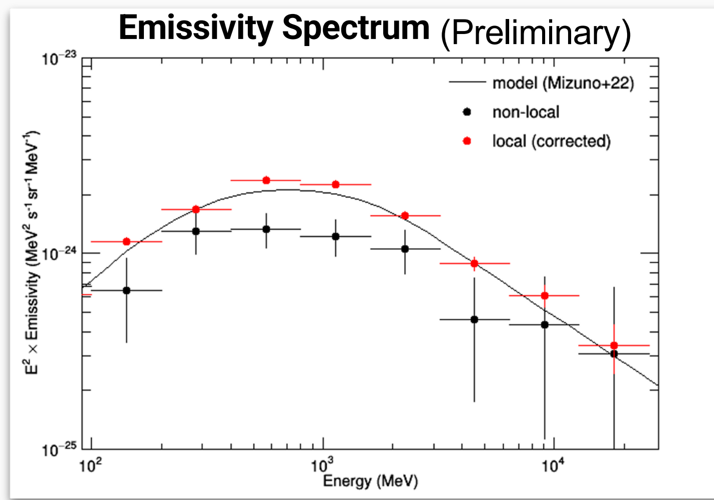
Procedure of γ-ray Data Analysis (2): MBM & Pegasus

We fit γ-ray data with W_{CO}, $3N_{HI,thin}$, RG, IC, isotropic and sources. We found that narrow-HI gives higher emissivity than broad-HI (left), confirming narrow HI to be opt. thick (N_{HI}>$N_{HI,thin}$)

We evaluated correction factor for narrow-HI by looking at emissivity ratio wrt broad-HI and constructed single local $N_{HI,corr}$ map

We selected best RG&IC combination based on logL. Fit using single local $N_{HI,corr}$ map gives emissivity spectrum compatible with a model based on directly-measured CR (right)





Common Trends in γ-ray Data Analysis

We found that narrow-HI always gives larger emissivity than broad HI, <u>confirming narrow HI to be optically thick</u>

We also found that $N_{HI,corr}$ gives <u>emissivity spectrum compatible with directly-measured CR</u>

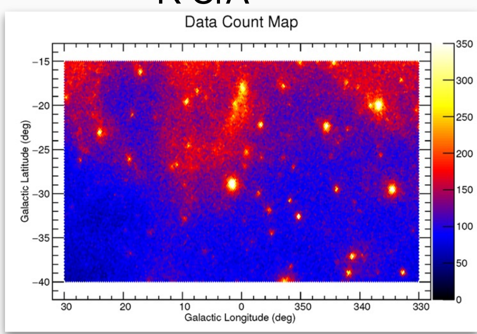
(RG template; τ353 gives better fit than radiance)

emissivity ratio of narrow-HI to broad-HI (preliminary)

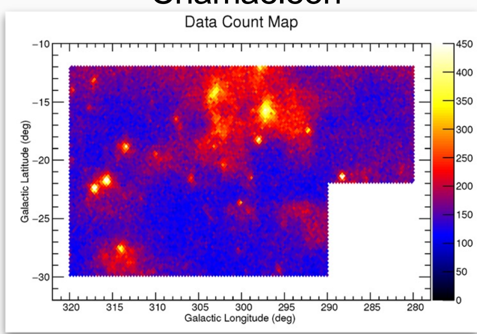
MBM&Pegasus	1.27+/-0.05
RCrA	1.12+/-0.03
Chamaeleon	1.21+/-0.04
Cep&Pol	1.61+/-0.07
Orion	1.39+/-0.03

Count maps, 0.1-25.6 GeV (Preliminary)

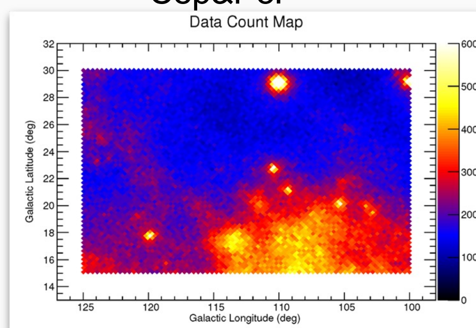
R CrA



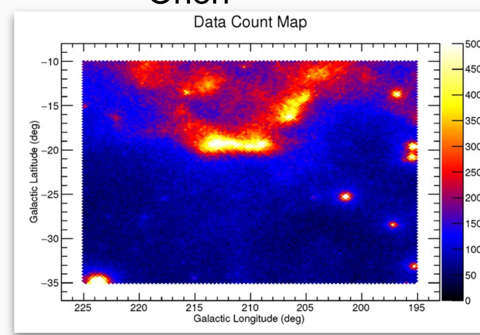
Chamaeleon



Cep&Pol



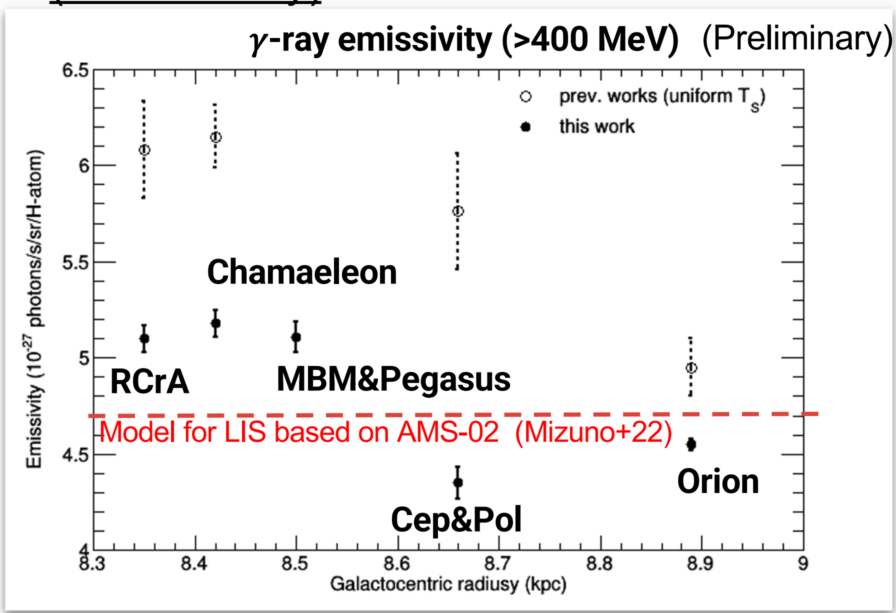
Orion

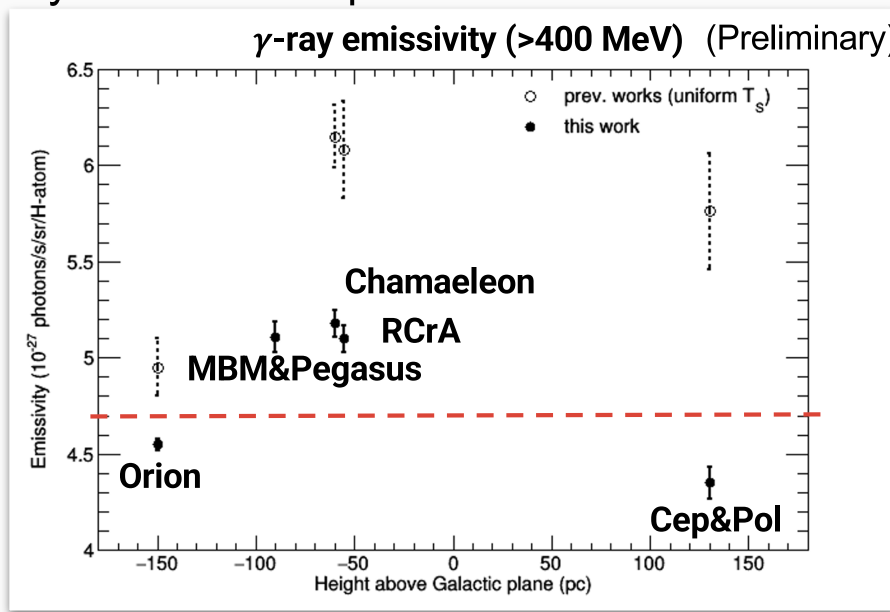


γ-ray Emissivity (CR Spectrum) in Local Environment

Most of previous works used HI templates with uniform spin temperature (T_S), and reported γ-ray emissivity larger than that expected from directly-measured CR spectra

Analysis using HI line width gives emissivities compatible with LIS. Hint of higher emissivity (CR intensity) in areas closer to the inner Galaxy and Galactic plane





Gas Property in Local Environment

Assuming uniform CR intensity in each region, we evaluated integrated H column density (proportional to gas mass) of each gas phase in unit of 10^{22} cm^{-2} deg^2

- Assuming that RG template traces CO-dark H_2, ratio of CO-dark H_2 to optical depth correction is 2-7, indicating that dark gas is mainly CO-dark H2

(Preliminary)

	MBM&Pegasus	RCrA	Chamaeleon	Cep&Pol	Orion
Broad HI	39.9	59.2	37.3	19.1	57.2
Narrow HI (opt. thin case + correction)	18.0 + 5.0	18.5 + 2.2	16.0 + 3.4	7.8 + 4.7	19.9 + 7.7
Non-local HI	2.8		0.7	4.2	1.8
Residual gas	9.0	15.7	9.4	10.5	21.4
CO-bright H2	1.1	2.6	7.7	10.8	26.6

(opt. thin assumed for non-local HI)

Summary and Future Prospect

We applied HI-line-profile based analysis to nearby clouds to accurately measure CR and gas properties

- Narrow HI always gives larger emissivity, confirming it to be optically-thick
- Broad HI gives emissivity (CR intensity) compatible with a model for LIS. Hint of higher emissivity in areas closer to inner Galaxy and Gal. plane is observed
- We found that ratio of CO-dark H2 (traced by residual gas template) to optical depth correction is >1, indicating that dark gas is mainly CO-dark H2
- Application of HI-line-profile based analysis to other nearby clouds and Galactic plane is worth doing

Thank you for your attention

References

- Ackermann et al. 2012, ApJ 755, 22
- Ackermann et al. 2012, ApJ 756, 4
- Ackermann et al. 2017, ApJ 840, 43
- Casandjian et al. 2022, ApJ 940, 116
- Dame et al. 1987, ApJ 322, 706
- Grenier et al. 2005, Science 307, 1292
- Hayashi et al. 2019, ApJ 884, 130
- Heiless & Troland 03, ApJ 586, 1067
- Kalberla et al. 2020, A&A 639, 26
- Orlando 2018, MNRAS 475, 2742
- Planck Collab. 2015, A&A 582, 31
- Porter et al. 2017, ApJ 846, 23
- Mizuno et al. 2022, ApJ 935, 97
- Yamamoto et al. 2006, ApJ 642, 307

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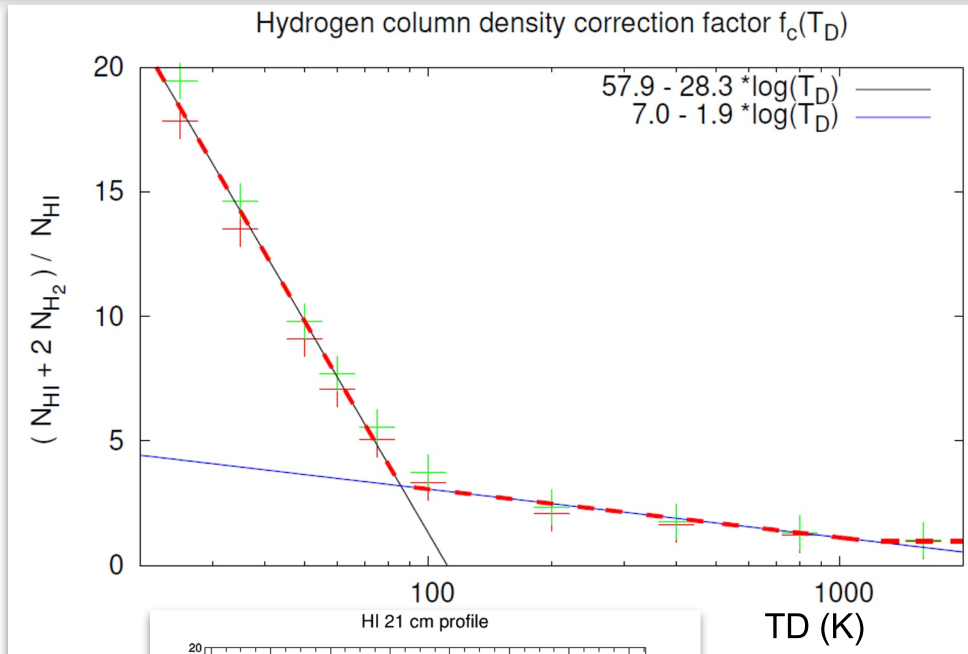
HI-line Profiles

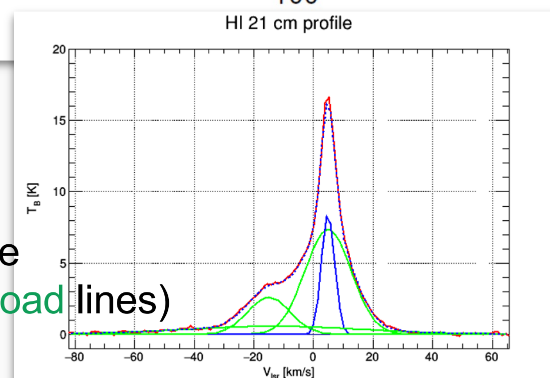
(see also Heiless & Troland 03)

Kalberla+20 found narrow-line HI gas is associated with dark gas [gas not properly traced by HI and CO lines] and broad-line HI gas with optically thin HI

- T_D (Doppler temperature)=$22*\delta v^2$
- Vertical axis shows ratio of N_H^{tot} to N_{HI}^{thin} (estimated using dust emission)
- Areas of ratio>>1 (dark-gas rich) are with narrow-line HI

We attribute gas with T_D<1000 K as narrow HI and that with T_D>1000 K as broad HI





Example of the line profile
(one narrow and three broad lines)

Construction of Residual Gas Template

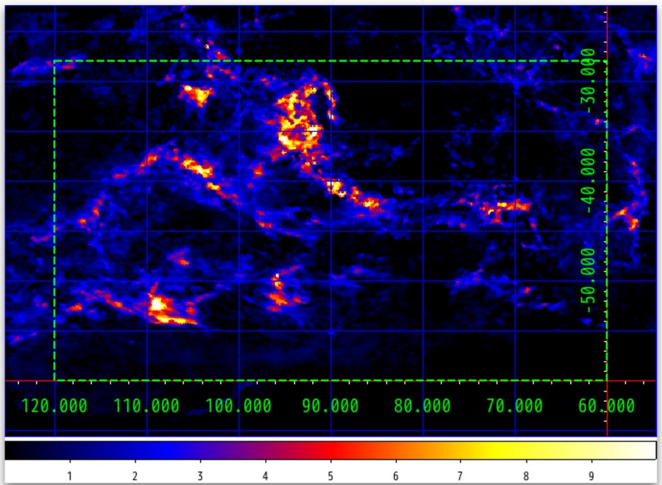
Some fraction of ISM gas is optically thick HI or CO-dark H_2, and is not properly traced by HI and CO lines (Grenier+05). While optically thick HI may be traced by narrow-line HI, CO-dark H_2 cannot. To construct this residual gas (RG) template for gamma-ray data analysis, we developed an iterative procedure. We use Planck dust emission (D_{em}) maps, specifically R2 radiance map, (original) τ353 map, and τ353 map by Casandjian+22

(1a) Select areas of low W_{CO} ($W_{CO}<W_{CO\_th}$), high T_d($T_d>T_{d\_th}$), and are broad-HI rich (frac of $W_{HI,\ broad}>f_{th}$) throughout step #1
(1b) (skip in the 1st iteration) Examine residual and select pixels within peak +/- 3*rms.
(1c) Fit D_{em} map with $W_{HI,\ narrow}$, $W_{HI,\ broad}$, and offset. If coefficients do not change significantly, quit the loop. Otherwise move back to (1b)

(2) Use obtained fit coefficients and calculate residuals of D_{em} in high W_{CO} areas for the entire ROI. Fit the residual with W_{CO}

(3) Use three coefficients and an offset (obtained in steps #1 and #2) and construct the RG template with median-filter (sigma=10') applied

Residual of D_{em}
(based on τ353 byCasandjian+22, in 10^{-6})

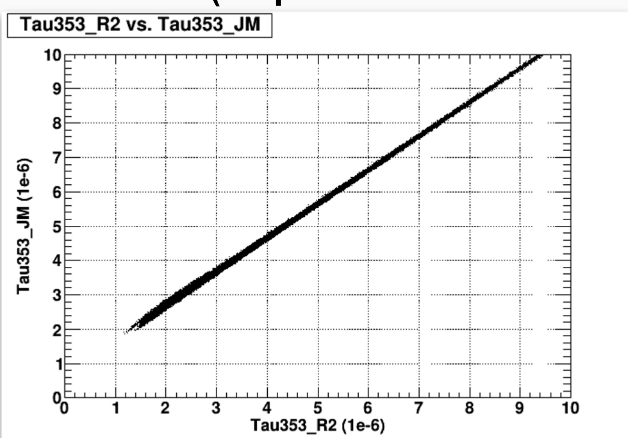


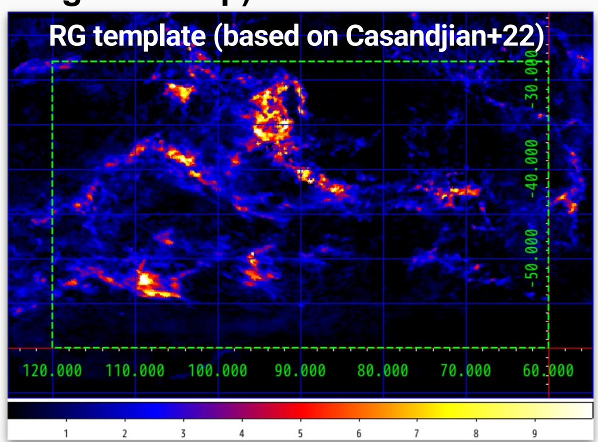
τ353 Maps: Original vs. Casandjian+22

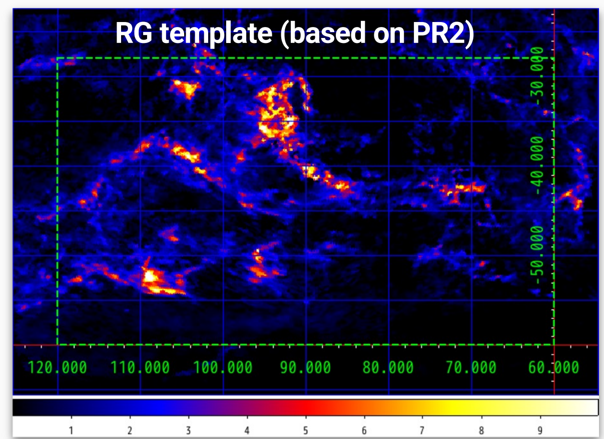
We confirmed difference of τ353 by ~0.7e-6 in MBM 53-55 clouds (left) and other regions

Two RG templates are similar as expected (middle and right) and give similar logL in gamma-ray data analysis

(All plots are of MBM 53-55 & Pegasus loop)



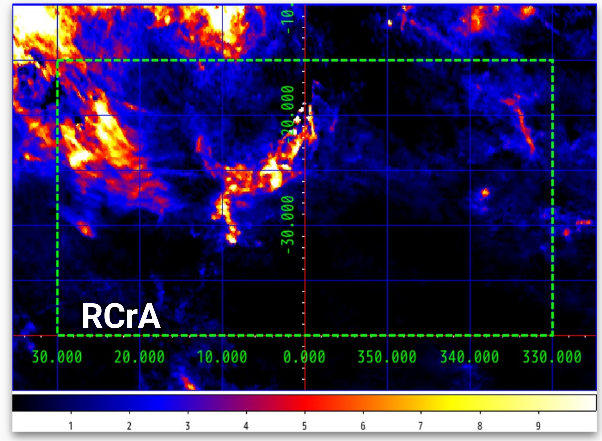


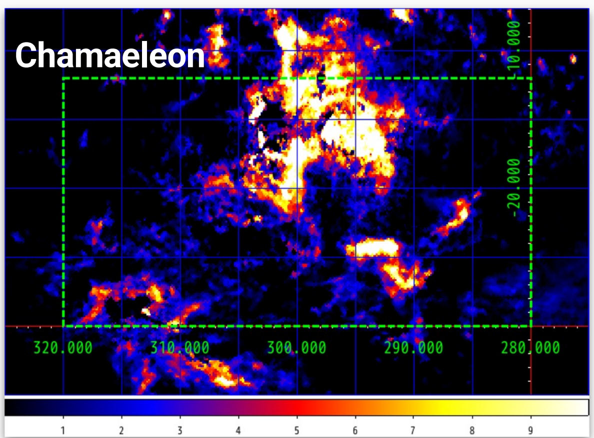


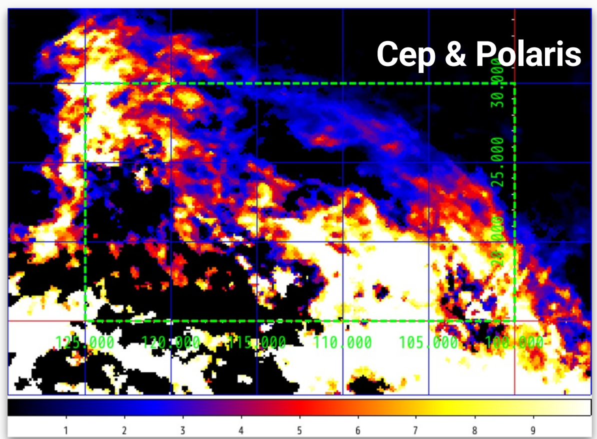
RG Templates (based on Casandjian+22)

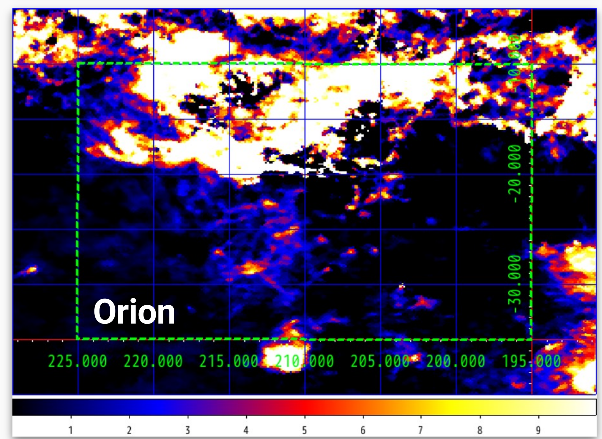
RG templates of 4 other region; fit coefficient ratios (narrow-HI to broad-HI) are 1.47 (MBM53-55), 1.43 (RCrA), 1.47 (Cham), 1.67 (Cep&Polaris), and 1.19 (Orion)

Opacity (σ_{e353}) for broad HI is 0.84 (MBM53-55), 0.67 (RCrA), 0.91 (Cham), 0.73 (Cep&Pol), and 0.79 (Orion) in 10^{-26} cm^2, <u>similar to that of Casandjian+22</u> (0.89)

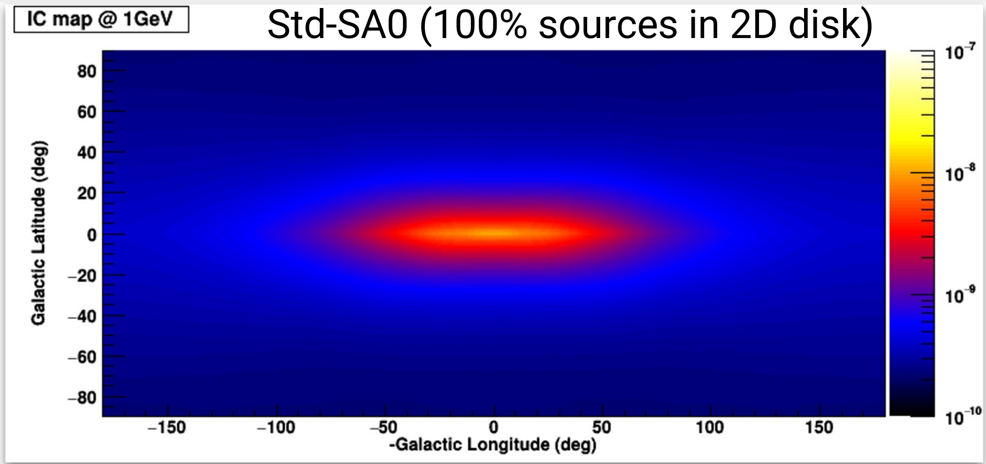


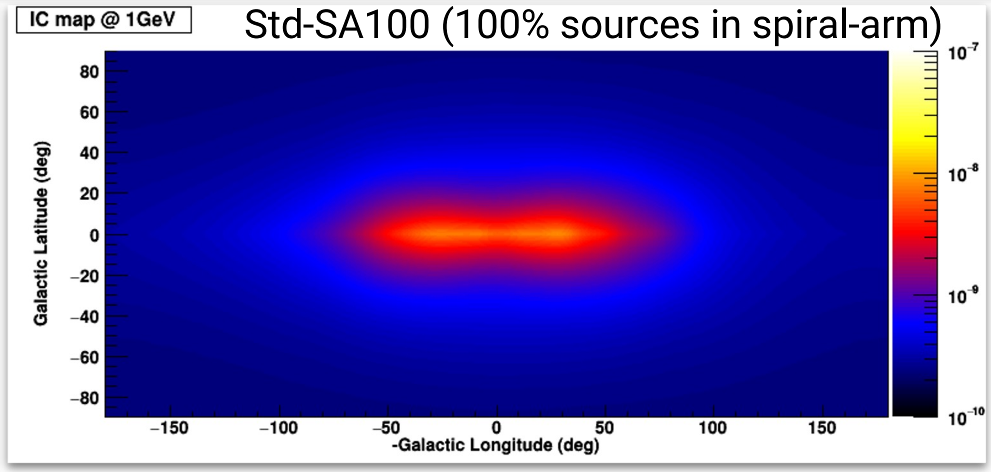






Testing IC Models

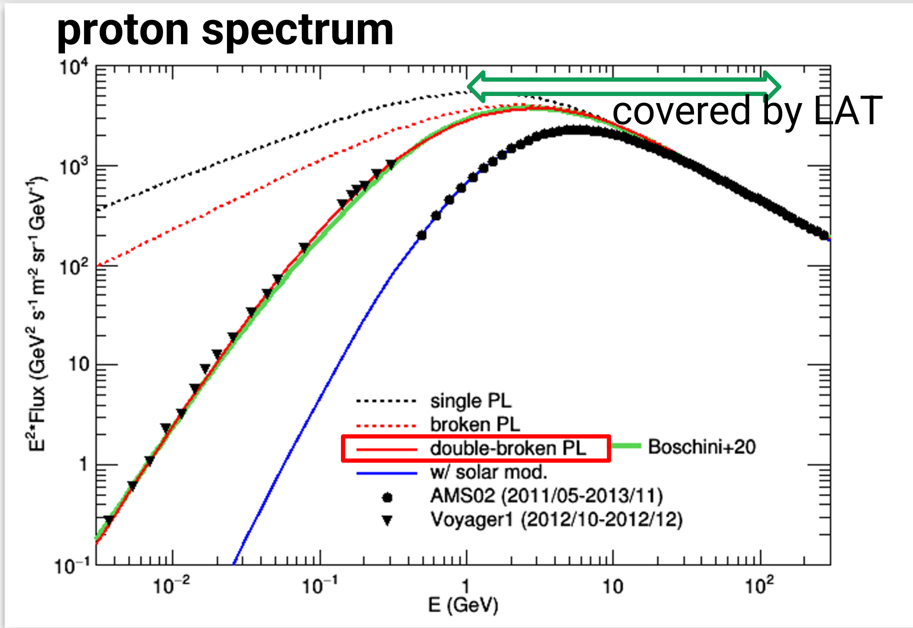


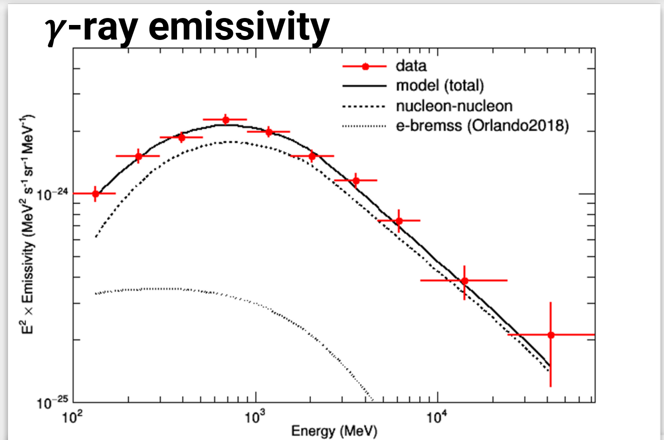


Porter+17 provides 9 IC models (3 ISRFs, 3 CR distributions)

While 3 ISRFs give similar IC maps, 3 CR source distributions give different spatial distribution; we prepare 3 IC maps of different CR source distributions (with “standard” ISRF) and adopt the model that gives best fit in gamma-ray data analysis

CR & Gamma-Ray Fit Results (Mizuno+22)





- 1st spectral break due to a break in D
- 2nd break due to ionization loss
- CR α and ISM He are taken into account

$$J(p) \propto \left[\left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\mathrm{br2}}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

- Our LIS model reproduces data & agrees with Boschini+20
- Scaling factor for γ-ray is 1.07+/-0.03
- R_{br1}=7.1+/-0.3 (GV) and δ_1=0.07+/-0.01

CR & Gamma-Ray Fit to Constrain LIS (Mizuno+22)

We used CR & γ-ray data constrain the LIS

- LIS is modeled as a power-law (PL) of momentum(p) with two breaks
  - α_1 and α_2 show indices in high and medium energy ranges
  - p_{br1} and δ_1 represent the 1st spectral break presumably due to a break in the interstellar diffusion coefficient inferred by B/C ratio (e.g., Ptuskin+06)
  - p_{br2} and δ_2 represent the 2nd break due to ionization loss (e.g., Cummings+16)
  - α_3 show the index below this break
  - force-field approximation for solar modulation
- γ-ray emissivity; p-p (Kamae+06 and AAfrag) + e-bremss (Orlando2018)
- We take into account CR α and ISM He, and fit CR & γ-ray data simultaneously

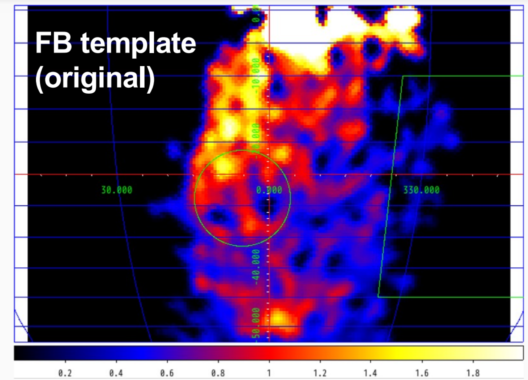
$$J(p) \propto \left[\left(\frac{p}{p_{\rm br1}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\rm br1}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1 + \left(\frac{p}{p_{\rm br2}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

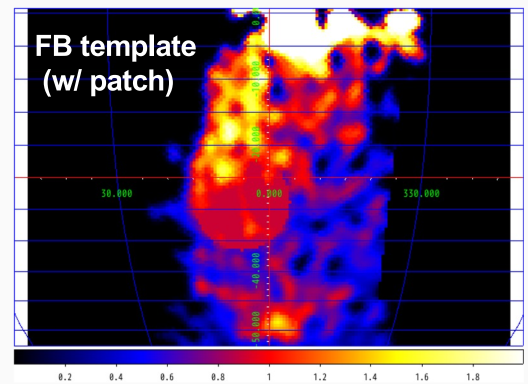
RCrA Molecular Cloud (Fermi Bubble)

We employed the FB template in Ackermann+17 (upper right), but there remain coherent positive residuals in (l,b)~(0,-30) and (-10,-32) and coherent negative residuals in l=330-334 (bottom)

- Those positive residuals correspond to holes in the template map that positionally coincide with brobs in soft component (Ackermann+17), and negative residuals are at peripherals of the FB template

We filled holes in the template and removed peripherals; new template gives improved fit to γ-ray data



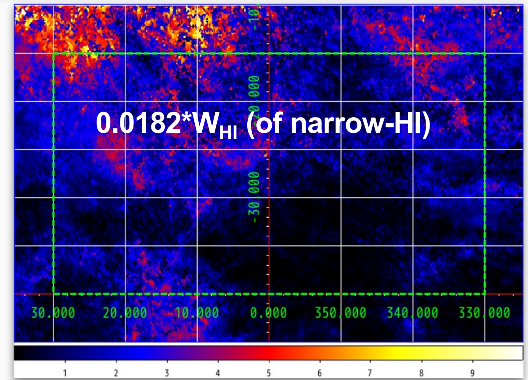


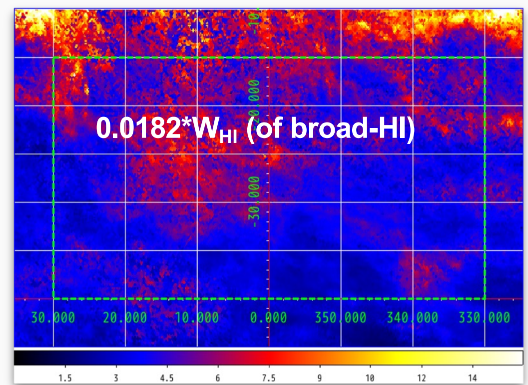
RCrA Molecular Cloud

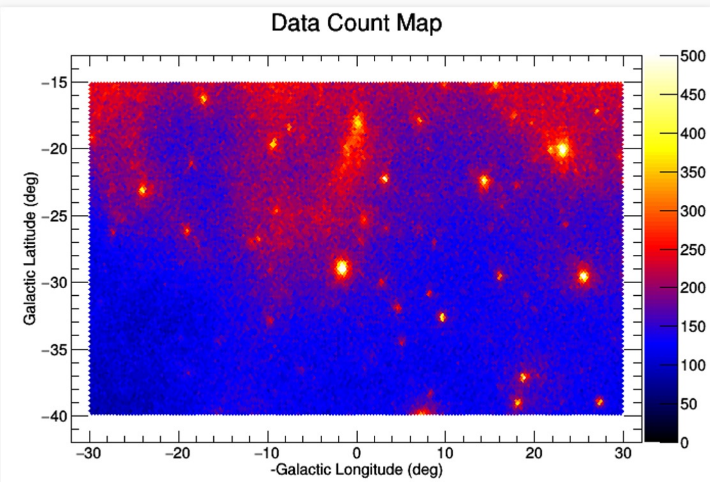
Different spatial distributions of narrow and broad HI will allow distinguishing different gas phases (right panels)

We fit γ-ray data (btm left) with narrow-/broad-HI templates and others (RG, W_{CO}, etc.). We employed FB template of Ackermann+17

Narrow HI gives larger emissivity, indicating it to be optically-thick HI, and broad HI gives emissivity similar to the model for LIS in >400 MeV





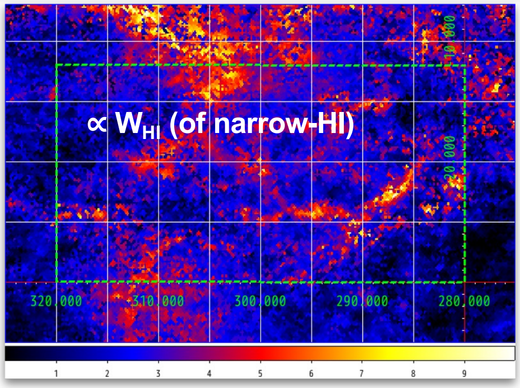


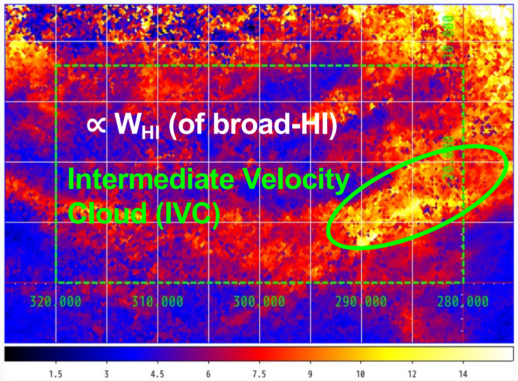
Chamaeleon Molecular Cloud

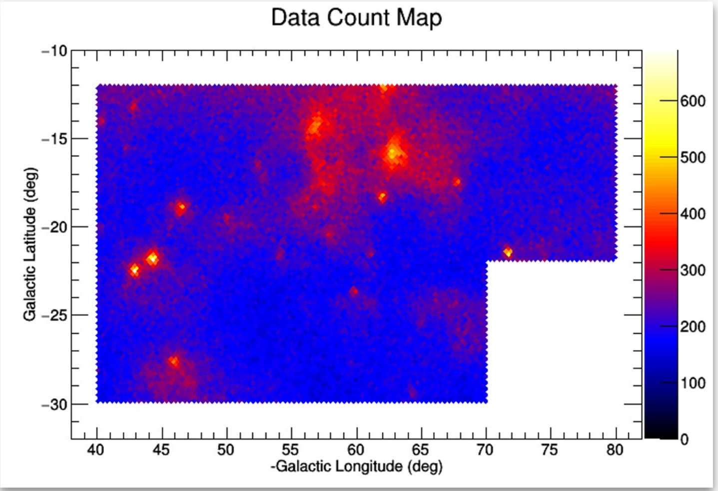
Different spatial distributions of narrow and broad HI will allow distinguishing different gas phases (right panels)

We fit γ-ray data (btm left) with narrow-/broad-HI templates and others (RG, W_{CO}, etc.). Areas dominated by IVC masked (cf. Hayashi+19)

Narrow HI gives larger emissivity, indicating it to be optically-thick HI, and broad HI gives emissivity similar to the model for LIS in >400 MeV





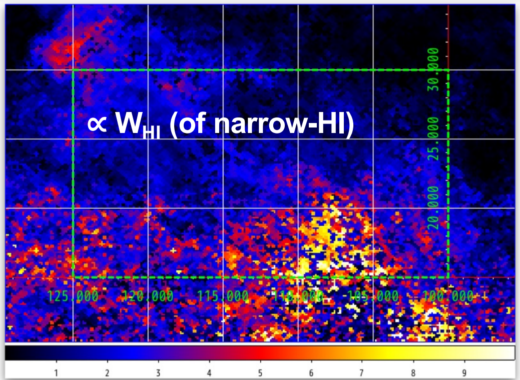


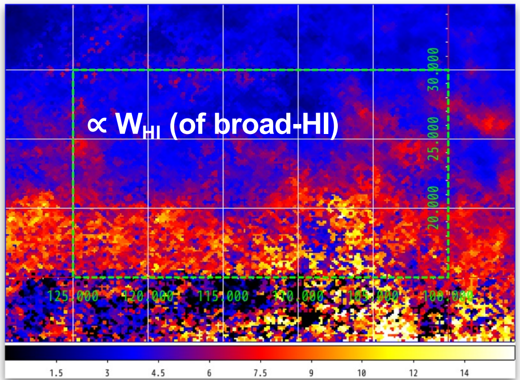
Cep&Polaris Flare

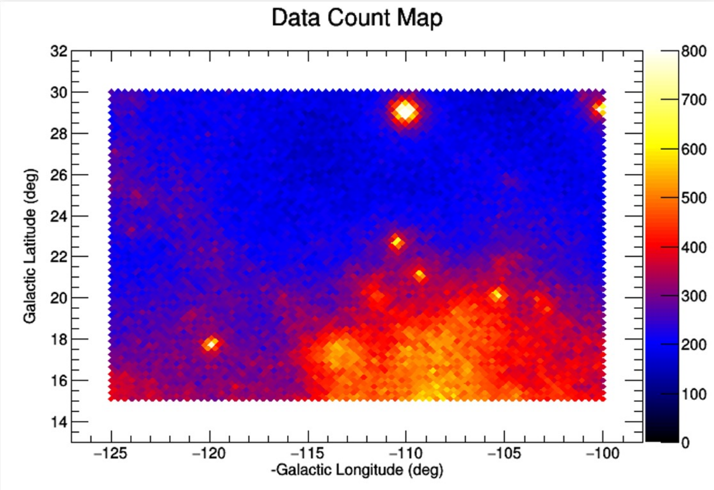
Different spatial distributions of narrow and broad HI will allow distinguishing different gas phases (right panels)

We fit γ-ray data (btm left) with narrow-/broad-HI templates and others (RG, W_{CO}, etc.). We constructed “merged” RG template

Narrow HI gives larger emissivity, indicating it to be optically-thick HI, and broad HI gives emissivity similar to the model for LIS in >400 MeV





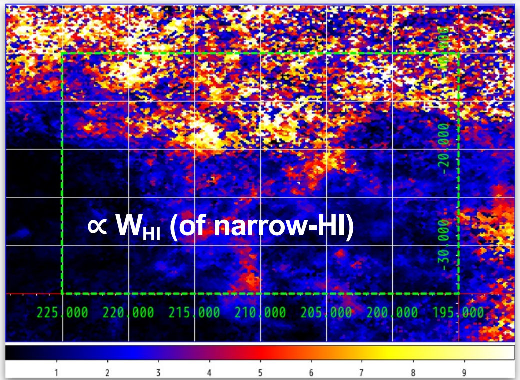


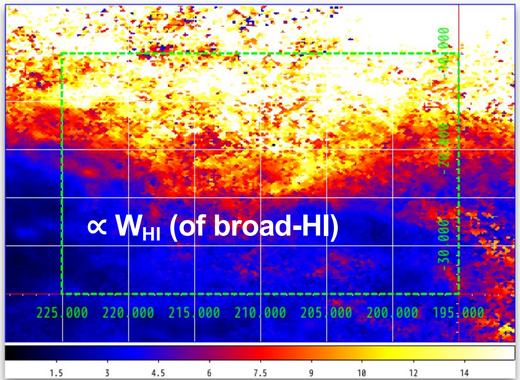
Orion Molecular Cloud

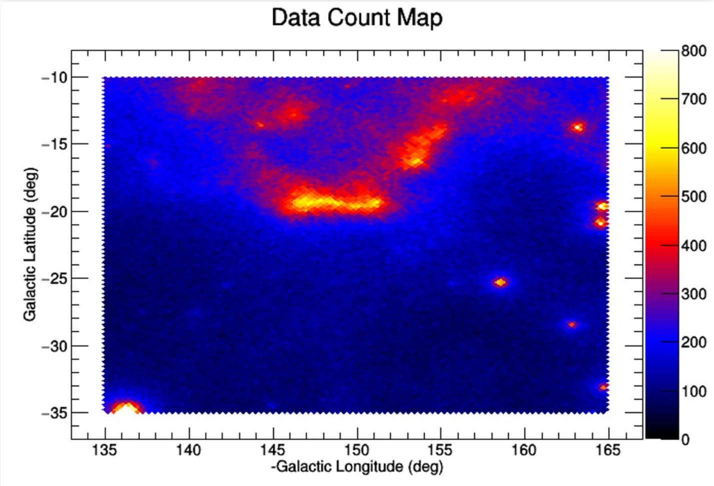
Different spatial distributions of narrow and broad HI will allow distinguishing different gas phases (right panels)

We fit γ-ray data (btm left) with narrow-/broad-HI templates and others (RG, W_{CO}, etc.). RG map was constructed with bright IR sources masked

Narrow HI gives larger emissivity, indicating it to be optically-thick HI, and broad HI gives emissivity similar to the model for LIS in >400 MeV







Wco Map and X_{CO}

Region	X_{CO} (10_{20} cm_{-}^{2} (K km/s)$^{-1}$)
MBM&Pegasus	0.55
RCrA	1.67
Chamaeleon	0.94
Cep&Polaris	0.90
Orion	1.36

(Preliminary)