GeV ガンマ線・21cm 輝線・ダスト放射による近傍分子雲領域の宇宙線・星間ガスの研究 (Study of Cosmic-ray and Interstellar medium gas in nearby molecular clouds using GeV gamma-rays, 21 cm line and dust emission)

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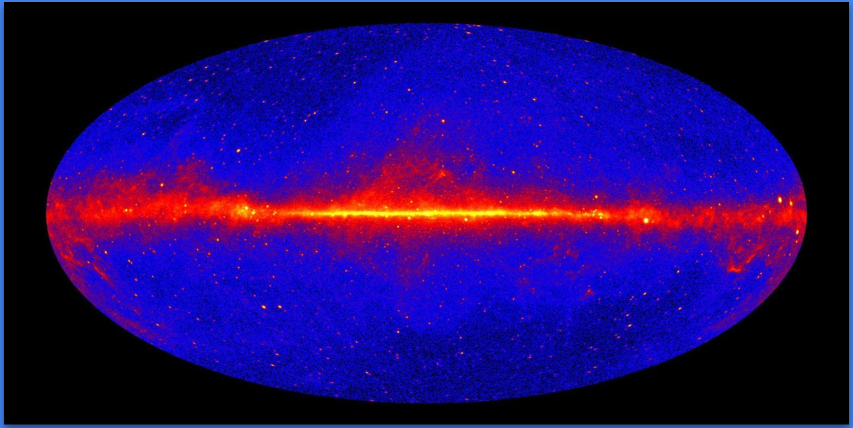
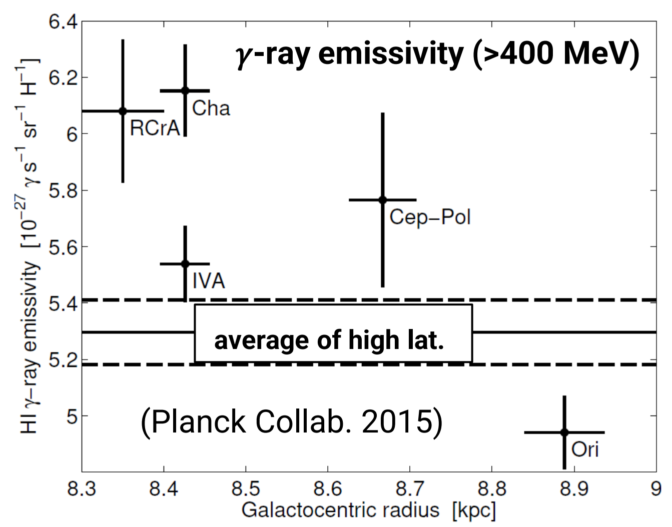
2025 Mar 18 @ ASJ meeting (Mito City Civic Center)



Motivation: Study of ISM Gas & CRs in the Solar Neighborhood

γ-ray provides vital information of interstellar medium (ISM) gas & cosmic rays (CRs) $I_\gamma \propto I_{CR} \cdot N_H$

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



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

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

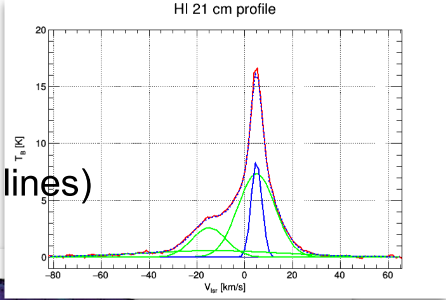
Study of Local Clouds with T_d and HI linewidth

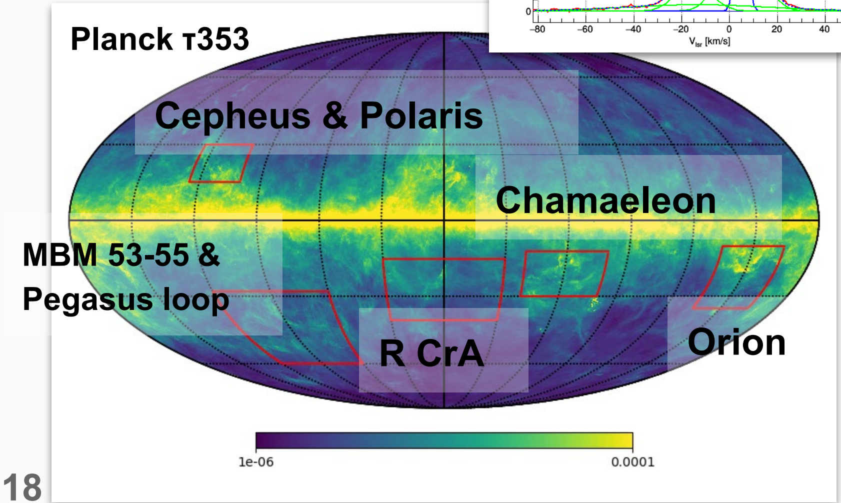
To investigate local CRs and ISM-gas, we studied five nearby molecular clouds using Td and HI linewidth. We first re-analyzed MBM 53-55 clouds and Pegasus loop (cf; Mizuno+22), then studied four other regions

Properties of clouds

Cloud	Distance (pc)	$M_{H2, CO}$ (M_{Sun})
MBM&Pegasus	~150	~800
R CrA	~150	~1600
Chamaeleon	~150	~6000
Cep & Pol	~450	~72000
Orion	~450	~180000

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



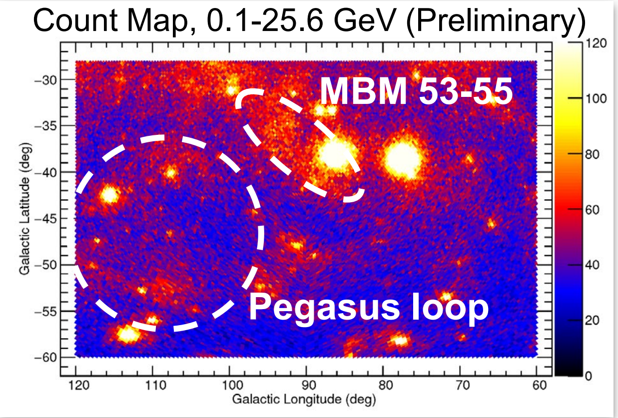


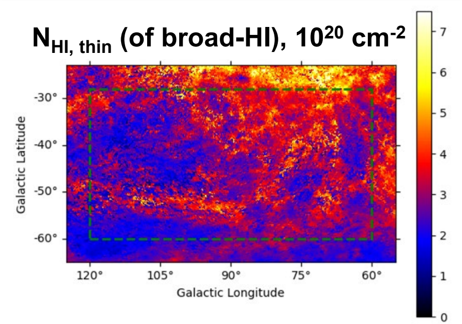
Data Analysis of MBM & Pegasus

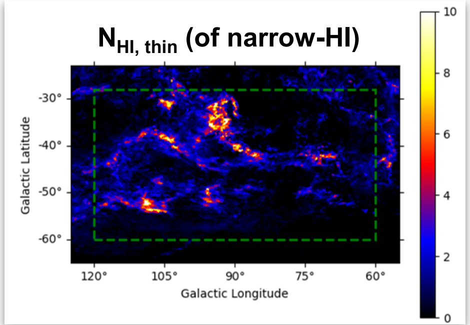
We prepared gas templates from radio line surveys; W_{CO} map and narrow/broad-HI maps

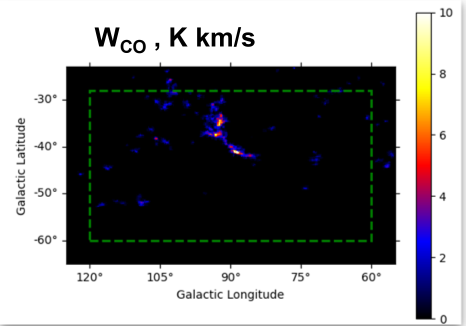
- Different spatial distributions allow to distinguish different gas phases, and broad-HI map allows to accurately measure HI emissivity (CR intensity)

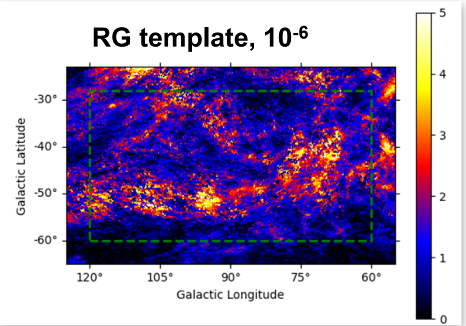
These line surveys likely miss CO-dark H_2; we prepared residual gas (RG) template from Planck τ_{353} (as dust excess with T_d and HI linewidth considered)







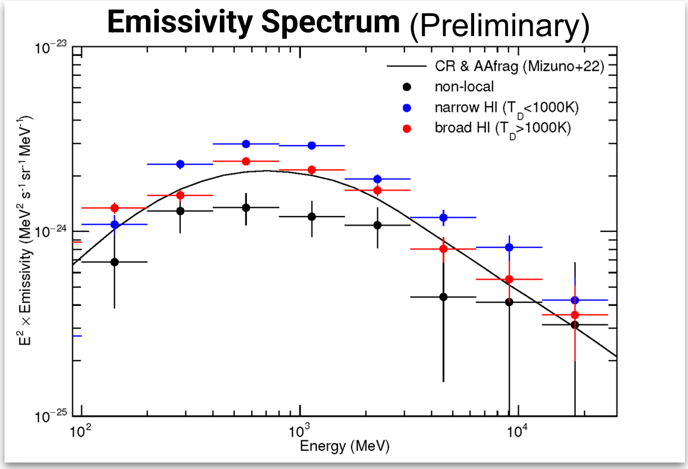


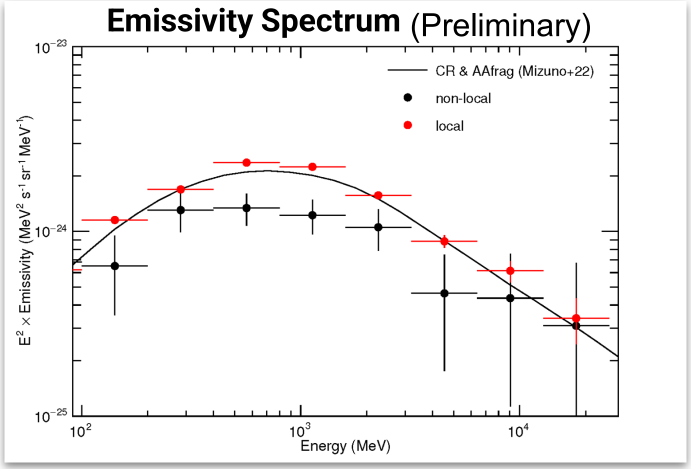


Results of MBM & Pegasus

We fit γ-ray data with W_{CO}, $N_{HI,narrow}$, $N_{HI,broad}$, RG (+sources, etc.); narrow-HI gives higher emissivity than broad-HI by 30%, confirming narrow-HI to be opt. thick ($N_{HI}>N_{HI,thin}$)

We multiplied the ratio (~1.3) to narrow-HI and constructed a single (local) $N_{HI,corr}$ map. Fit using the map gives emissivity spectrum compatible with a model based on directly-measured CR





Common Trends in ISM Templates and Results

We prepared ISM gas templates in the same way for other clouds

Through gamma-ray data analysis, we found that narrow-HI always gives larger emissivity than broad HI, confirming <u>narrow HI to be optically thick</u>

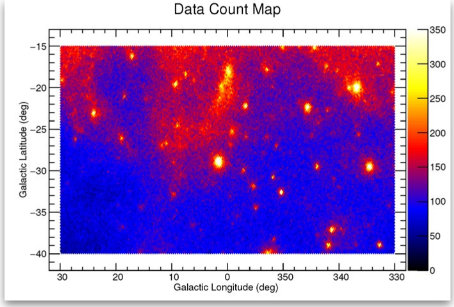
We also found that $N_{HI,corr}$ always gives <u>emissivity spectrum compatible with directly-measured CR</u>

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

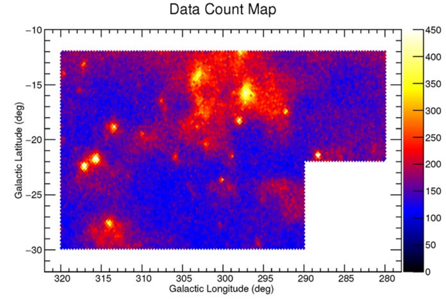
MBM&Pegasus	1.27+/-0.05
RCrA	1.12+/-0.03
Chamaeleon	1.21+/-0.04
Cep&Pol	1.61+/-0.07
Orion	1.41+/-0.03

Count maps, 0.1-25.6 GeV (Preliminary)

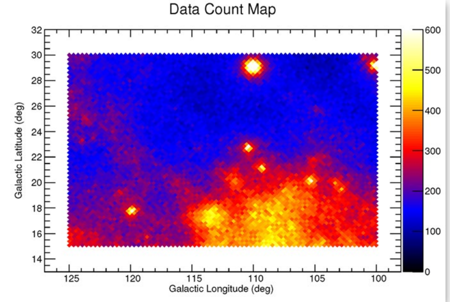
R CrA



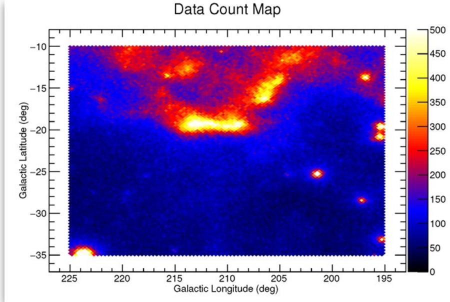
Chamaeleon



Cep&Pol



Orion



Gas Property in Solar Neighborhood

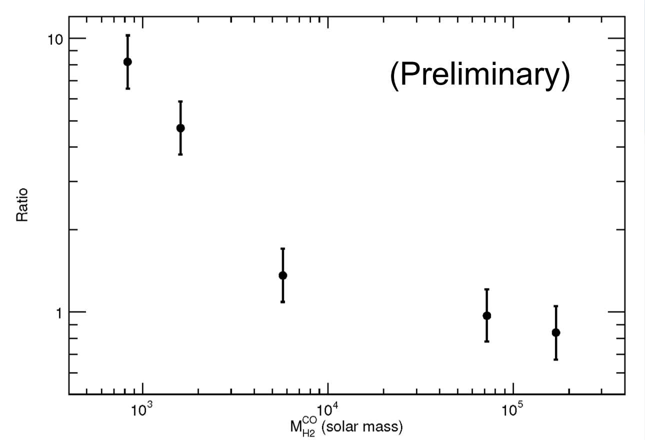
Assuming uniform CR intensity in each region, we evaluated integrated H column density (proportional to gas mass) of each gas phase in unit of 10^{22} cm^{-2} deg^2

- Assuming that RG template traces CO-dark H_2, ratios of CO-dark H_2 to optical depth correction are 2-8, indicating that dark gas is mainly CO-dark H2
- Ratio of CO-dark H_2 to CO-bright H_2 is 1-10; small clouds are more CO-dark

(should be considered when analyzing individual sources)

(Preliminary)	MBM&Pegasus	RCrA (|l|<20deg)	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	2.5
Residual gas	9.0	17.3 (10.3)	10.5	10.5	21.4
CO-bright H2	1.1	2.5 (2.2)	7.7	10.8	25.4

Gas Property in Solar Neighborhood



Assuming uniform CR intensity in each region, we eva density (proportional to gas mass) of each gas phase

- Assuming that RG template traces CO-dark H_2, ratios c correction are 2-8, indicating that dark gas is mainly CO
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Summary

We applied HI-line-profile based analysis to five 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. Higher emissivity (CR intensity) in areas closer to inner Galaxy 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
- Ratio of CO-dark H2 to CO-bright H2 anti-correlates with $M_{H2,CO}$; this should be considered when discussing individual accelerators

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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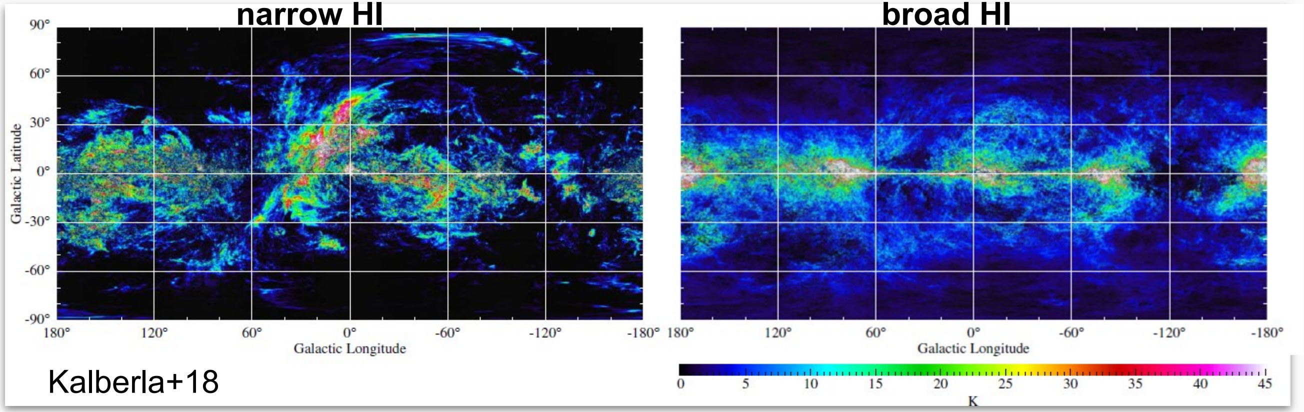
Issues and Solutions in Studying ISM Gas & CRs

Uncertainties of ISM gas & CRs are large even in the local environment

Key: Identify optically thin HI ($N_{HI} \propto W_{HI}$) and distinguish thick HI and CO-dark H_2

- Kalberla+18&20 provided possible solution
  - They decomposed HI lines in several gaussians, and found narrow HI is associated with dust excess (dark gas = thick HI or CO-dark H_2)



Kalberla+18

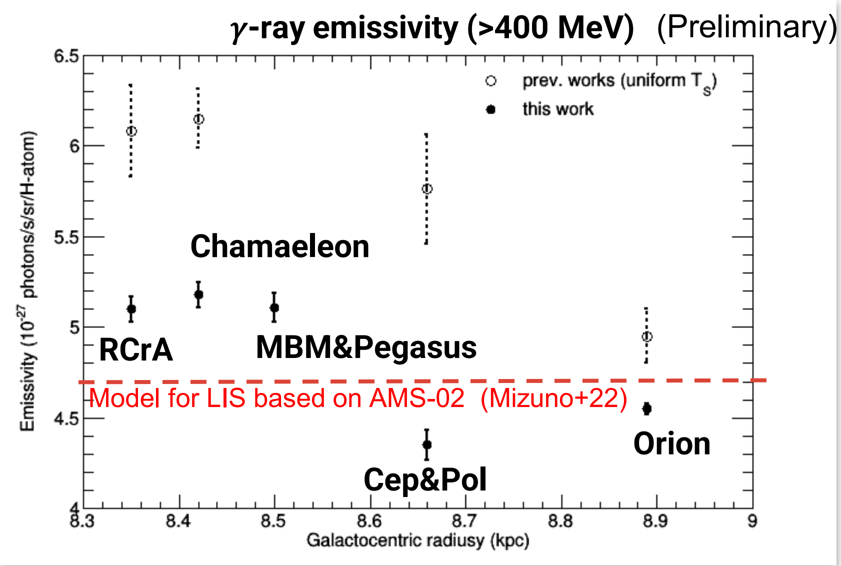
"We should look at broad HI to find optically thin HI"

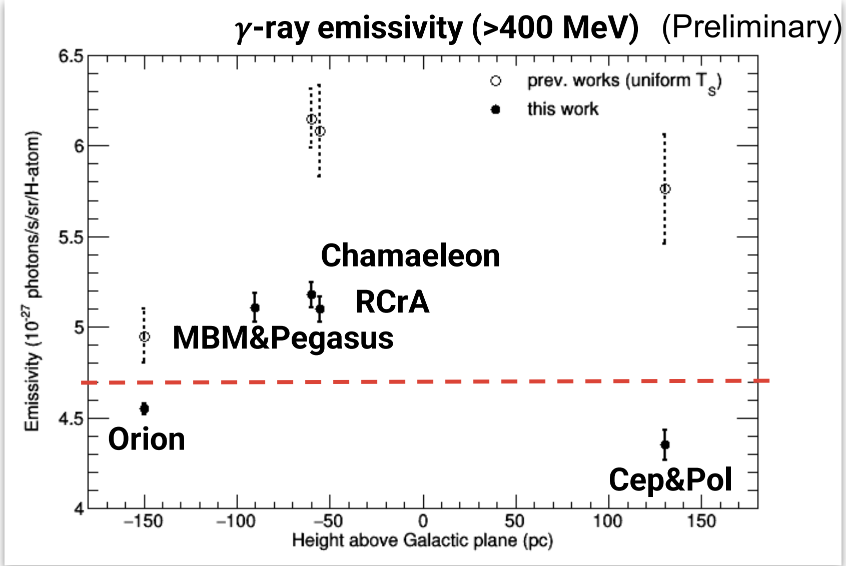
(Kalberla+ interpreted narrow HI to be CO-dark H_2, but we interpret it to be "thick HI")

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





Common Trends in ISM Templates and Results

We prepared ISM gas templates in the same way for other clouds

- Residual gas always surrounds CO-bright H2
- Narrow HI always shows more filamentary structure than broad HI

(templates for Chamaeleon) - - →

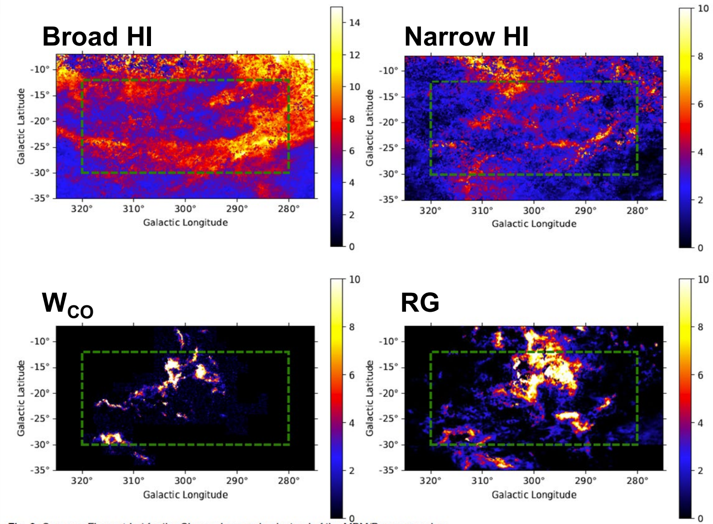
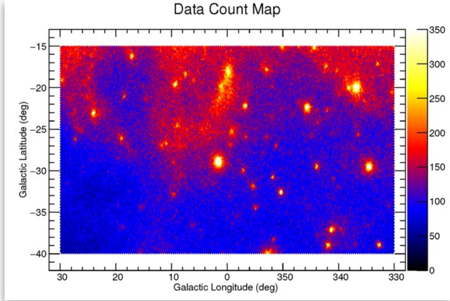


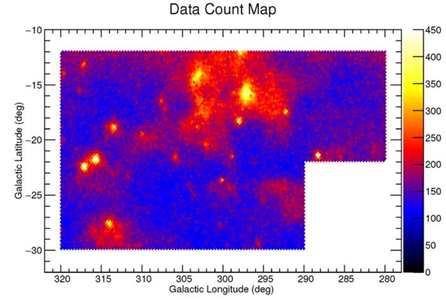
Fig. 3. Same as Figure 1 but for the Chamaeleon region instead of the MBM/Pegasus region.

Count maps, 0.1-25.6 GeV

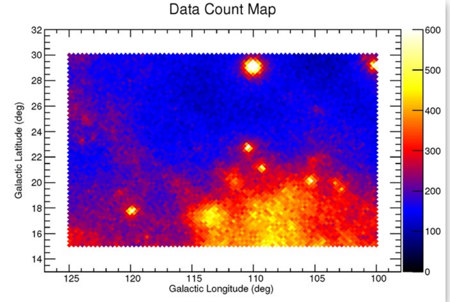
R CrA



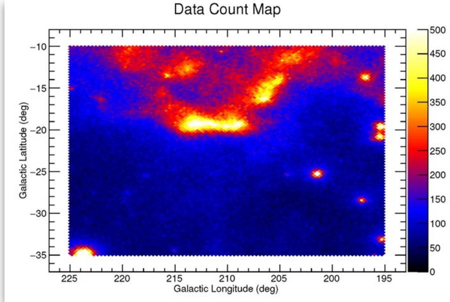
Chamaeleon



Cep&Pol



Orion

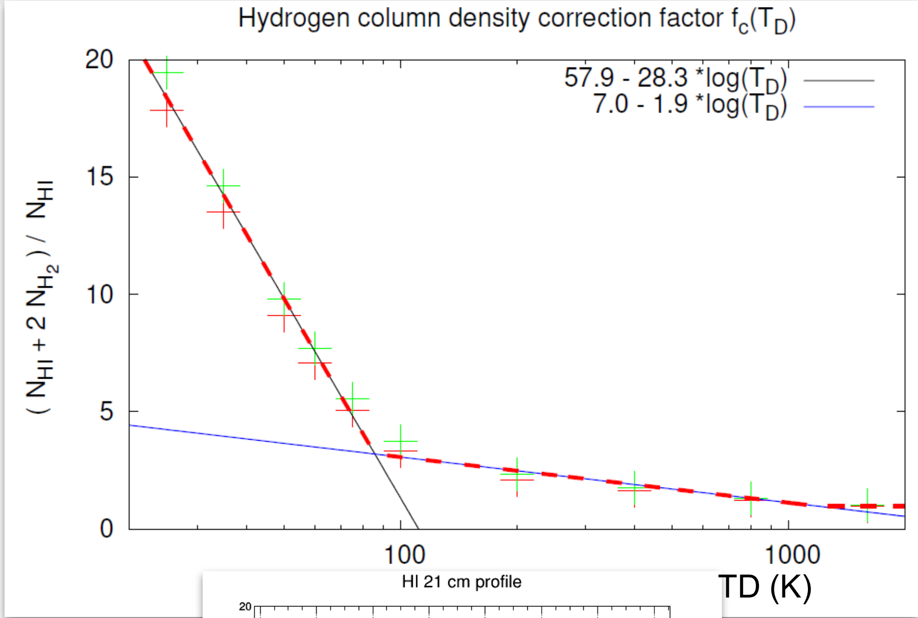


HI-line Profiles

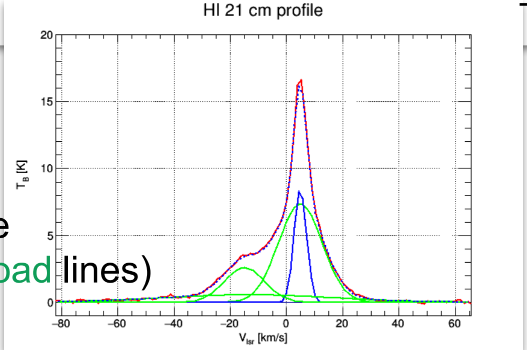
(see also Heiless & Troland 03)

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 (Δv~6.8 km/s, τ~$N_{HI}/10^{22}$ cm^{-2})



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

Construction of Residual Gas Template

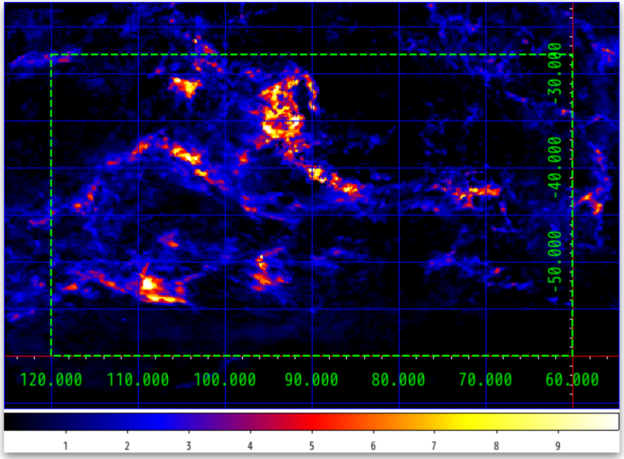
Some fraction of ISM gas is optically thick HI or CO-dark H_2, and is not properly traced by HI and CO lines (Grenier+05). While optically thick HI may be traced by narrow-line HI, CO-dark H_2 cannot. To construct this <u>residual gas (RG) template</u> for gamma-ray data analysis, we developed an iterative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

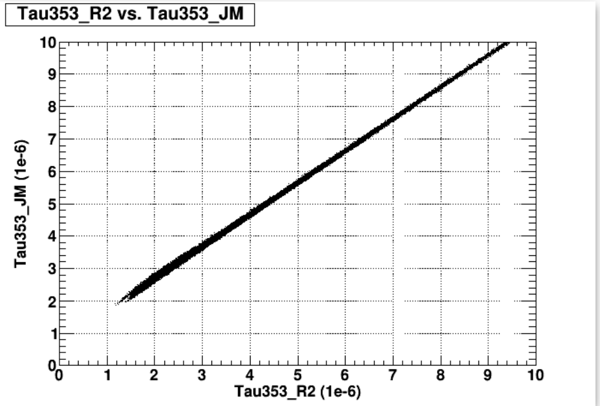


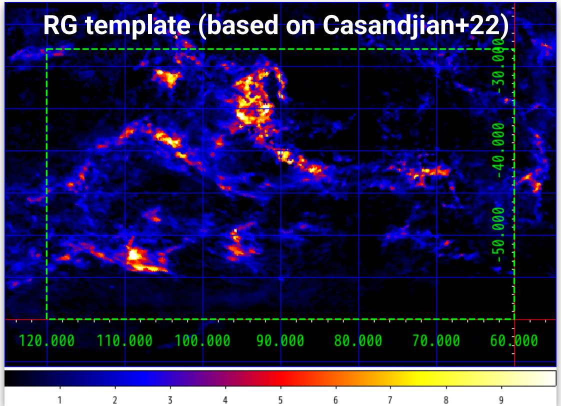
τ353 Maps: Original vs. Casandjian+22

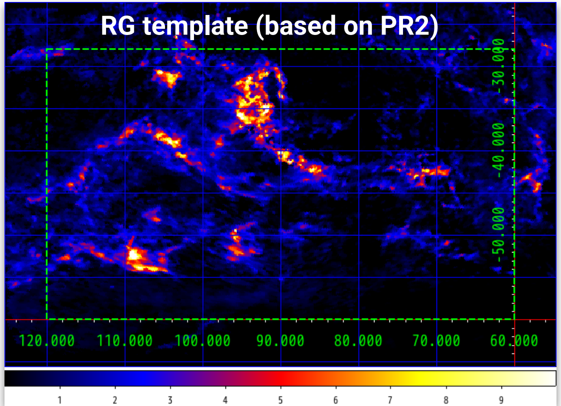
We confirmed difference of τ353 by ~0.7e-6 in MBM 53-55 clouds (left) and other regions

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

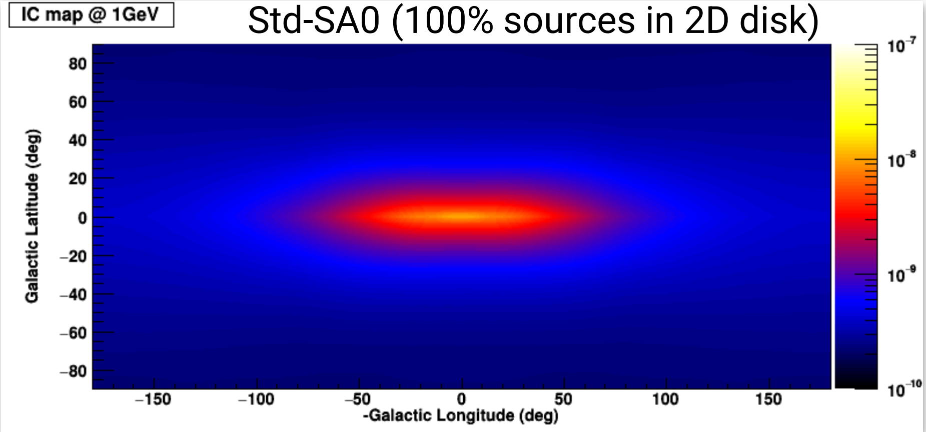
(All plots are of MBM 53-55 & Pegasus loop)

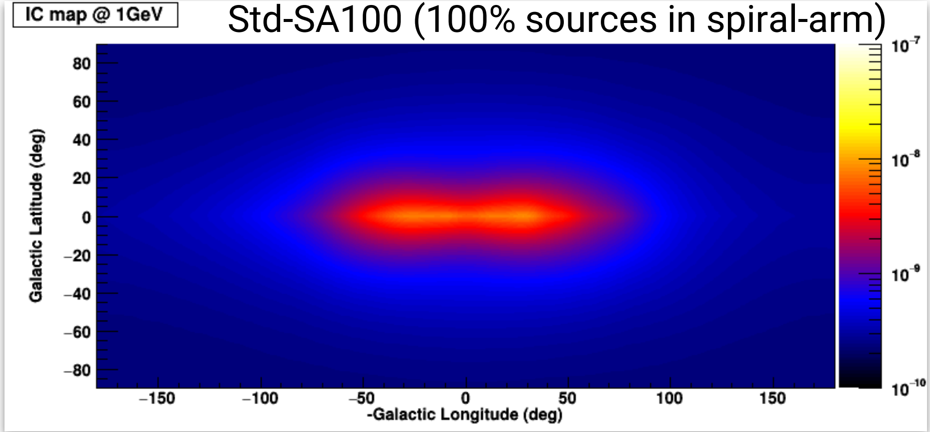






Testing IC Models





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

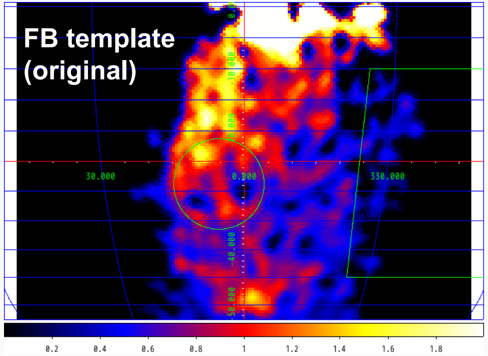
While 3 ISRFs give similar IC maps, 3 CR source distributions give different spatial distribution; we prepare 3 IC maps of different CR source distributions (with “standard” ISRF) and adopt the model that gives best fit in gamma-ray data analysis

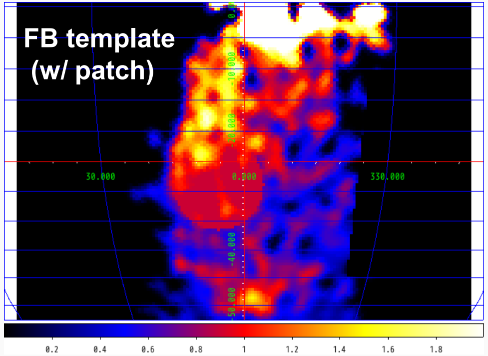
RCrA Molecular Cloud (Fermi Bubble)

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)

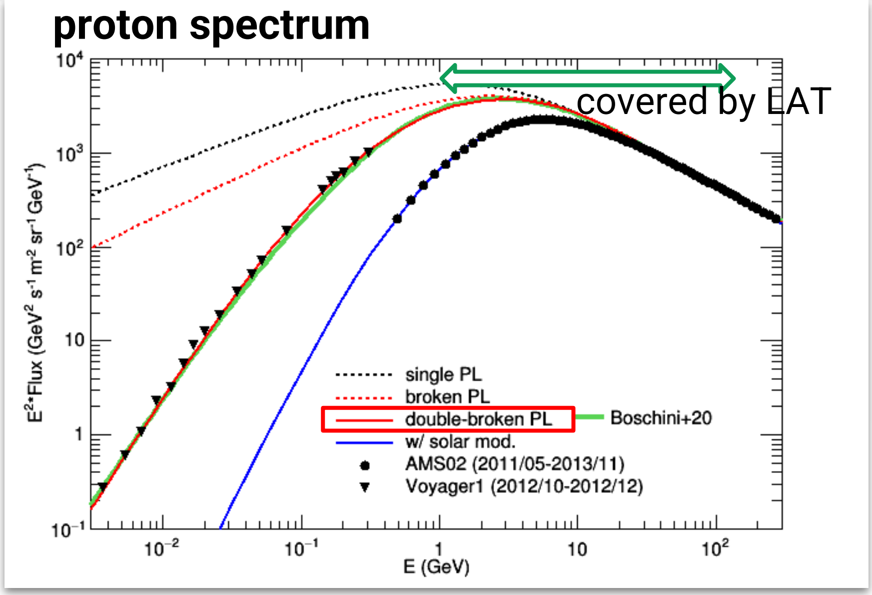
- Those positive residuals correspond to holes in the template map that positionally coincide with brobs in soft component (Ackermann+17), and negative residuals are at peripherals of the FB template

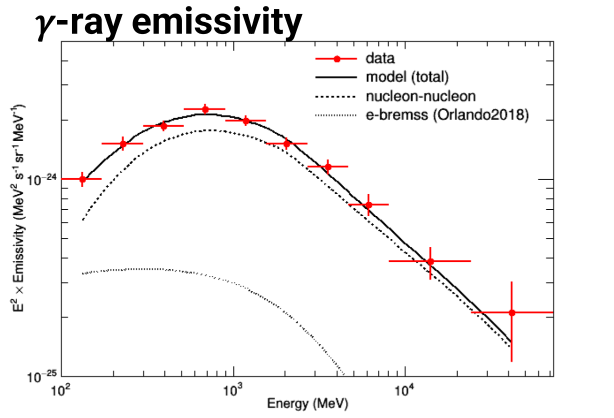
We filled holes in the template and removed peripherals; new template gives improved fit to γ-ray data





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
- γ-ray emissivity; p-p (Kamae+06 and AAfrag) + e-bremss (Orlando2018)
    - We also take into account CR α and ISM He explicitly and consider heavier nuclei based on the formalism of Kachelriess et al. (2014)