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（2）

(Study of Cosmic-ray and Interstellar medium gas in nearby molecular clouds using GeV gamma-rays, 21 cm line and dust emission (2))

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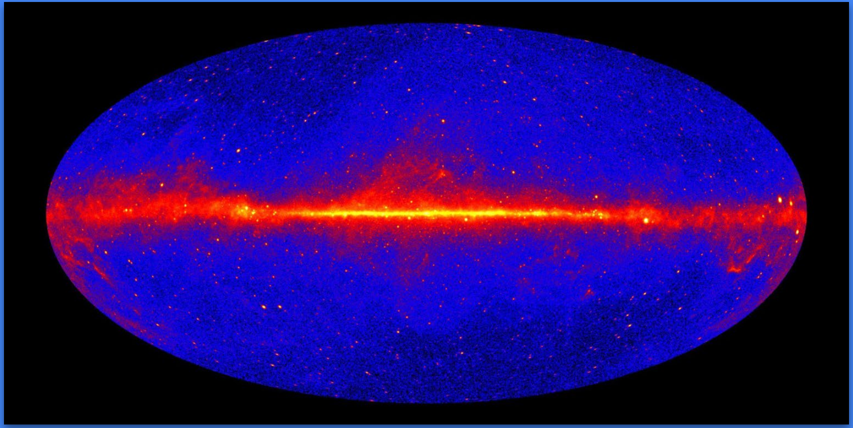
2025 Sep 10 @ ASJ meeting (Yamaguchi)

(See Mizuno+25 (10.1093/pasj/psaf069) for details)



Our Task: Accurately Measure ISM Gas and CRs

Interstellar medium (ISM) gas plays crucial role in Milky Way (MW)

- Star formation, interaction with SNR shock, etc.
- Also used as "passive target" to trace cosmic-rays (CRs)

Unfortunately, measuring ISM gas distribution is not a trivial task

- HI/CO line: (pros) highly sensitive and provide velocity information
  (cons) will miss thick HI and/or CO-dark H_2 (=dark gas)
- Dust: (pros) trace all phases of neutral gas with good angular resolution
  (cons) "dust emission"-to-gas ratio is not uniform
- **γ-ray**: (pros) <u>trace all gas phases with constant ratio</u> w/ uniform I_{CR} ($I_\gamma \propto I_{CR} \cdot N_H$)
  (cons) poor angular resolution

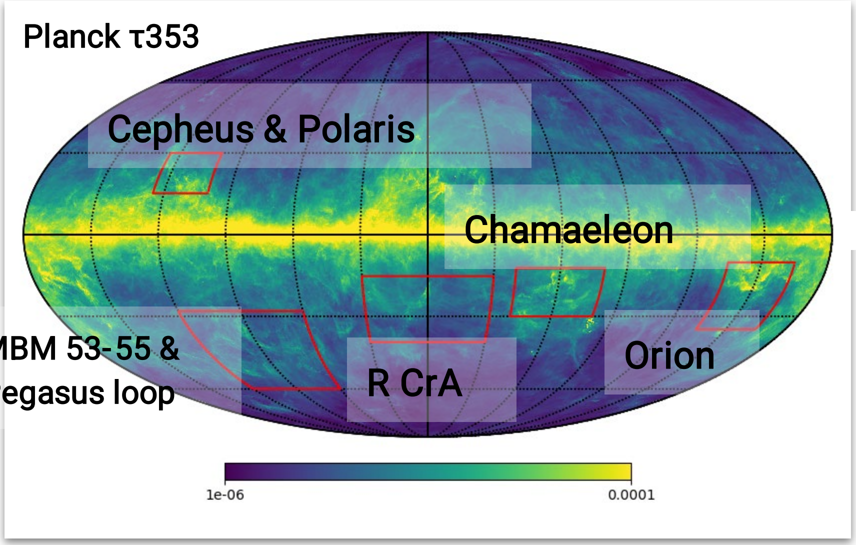
=> Examine their correlation and reveal ISM gas and CR distribution

Study of Local Clouds using T_d and HI linewidth

To investigate ISM-gas and CRs in Solar neighborhood, we studied **γ-ray data** of five nearby molecular clouds using Td and HI linewidth. Specifically, we interpret high-Td and broad-HI rich area to be optically-thin HI

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

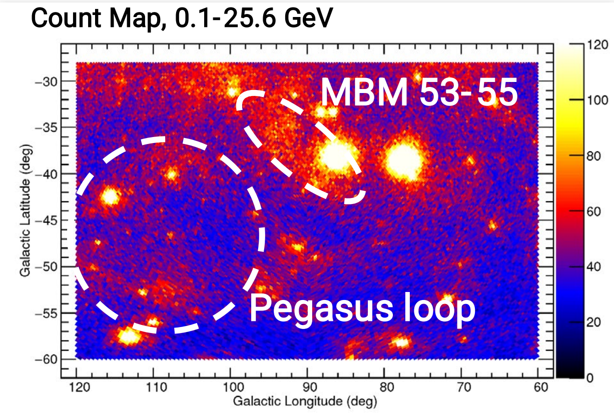


ISM Templates (MBM & Pegasus)

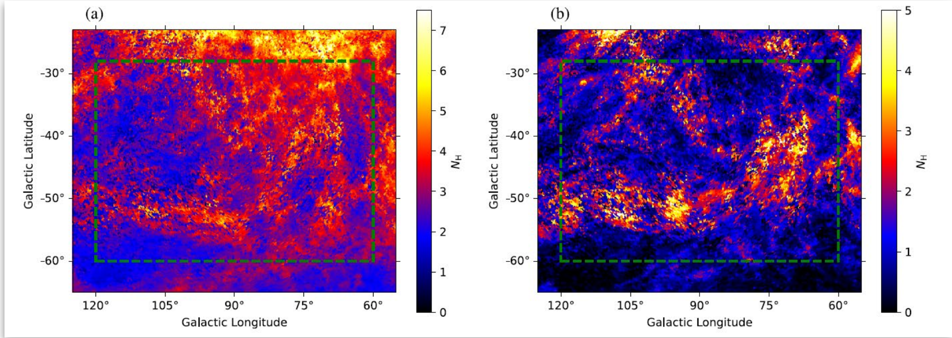
We prepared gas templates from radio line surveys; broad/narrow HI maps and W_{CO} map

- Different spatial distributions allow to distinguish different gas phases, and broad-HI map allows to accurately measure N_{HI} and HI emissivity $\equiv I_\gamma/N_{HI}$ ($\propto$CR intensity)

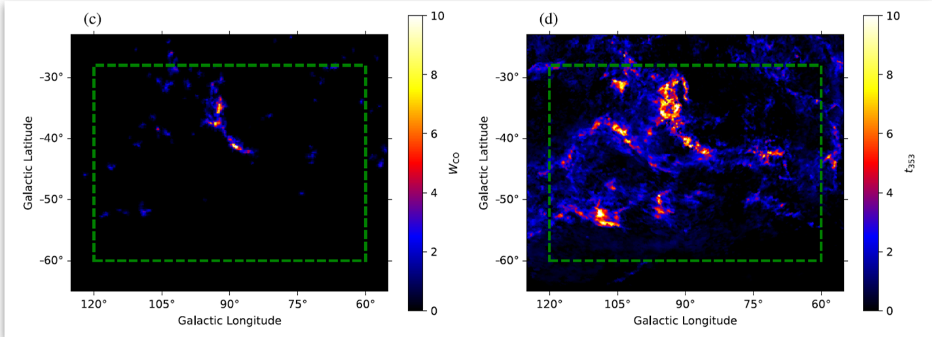
These surveys likely miss CO-dark H_2; we prepared residual gas (RG) template from Planck τ_{353} (as dust emission excess)



$N_{HI,\ thin}$ (of broad-HI), 10^{20} cm^{-2} — $N_{HI,\ thin}$ (of narrow-HI), 10^{20} cm^{-2}



W_{CO}, K km/s — D_{em_res}, 10^{-6}



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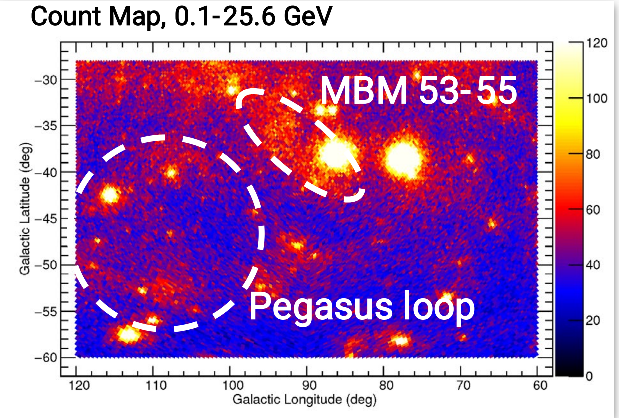
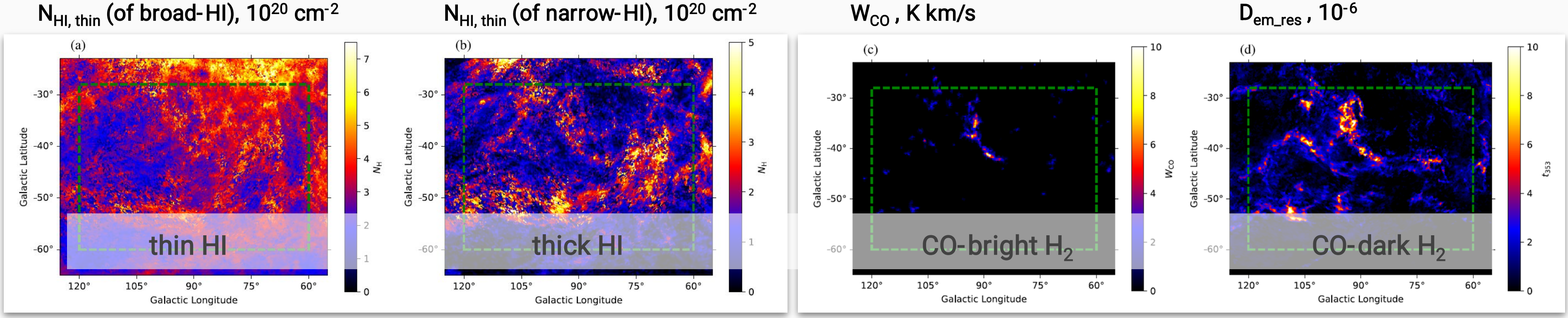


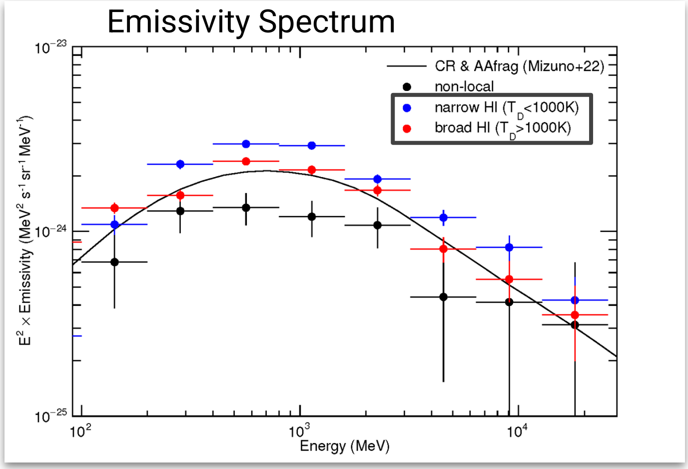


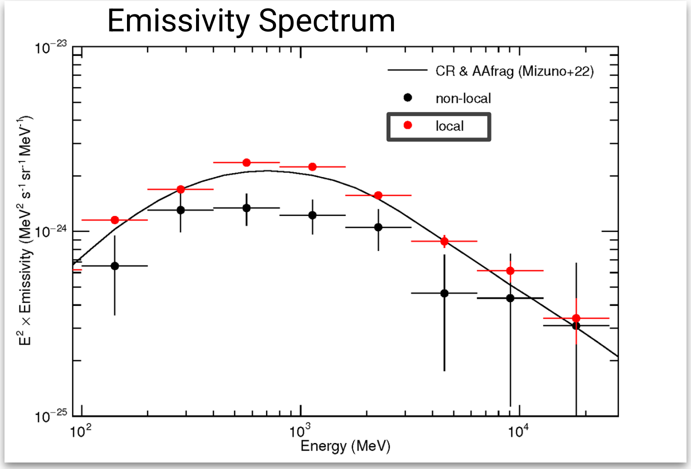
Analysis/Results (MBM & Pegasus)

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

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

Likewise, we analyzed other regions and evaluated gas mass and CR intensity/spectrum

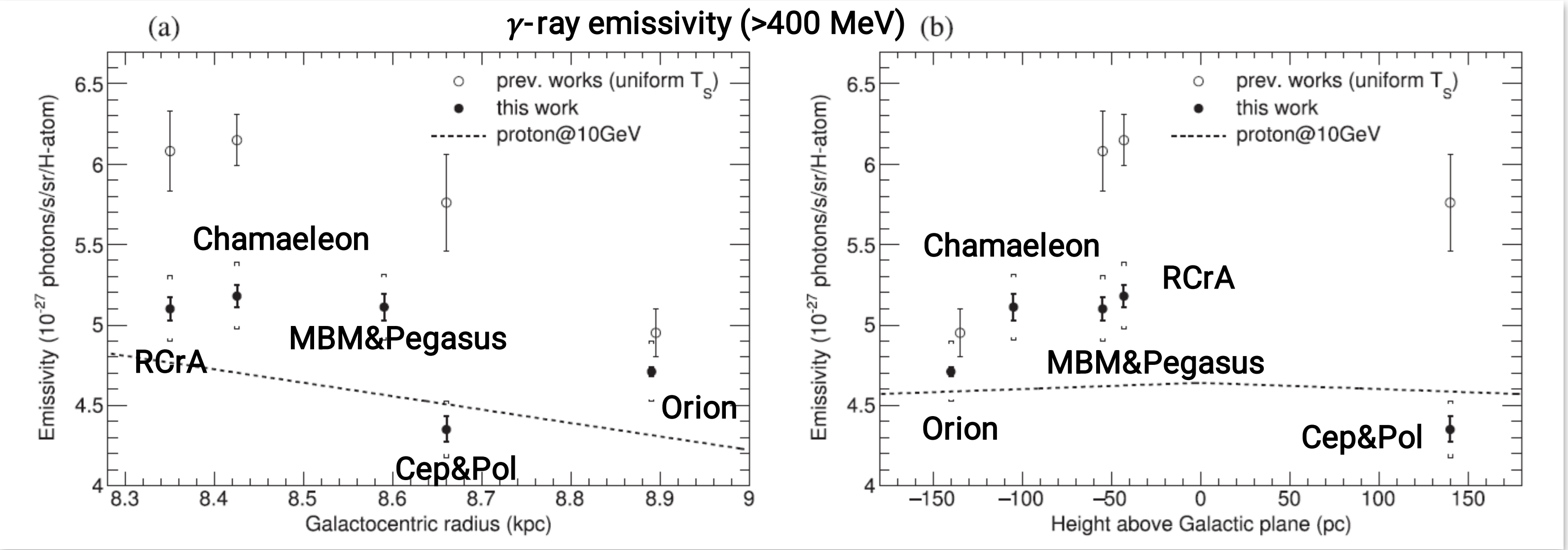




γ-ray Emissivity (CR Spectrum) in Solar Neighborhood

Most of previous works used single HI template with uniform spin temperature (T_S), and reported γ-ray emissivity larger than expectation from directly-measured CRs

Our analysis (using broad HI as reference) gives <u>emissivities compatible with directly-measured CRs</u>. <u>Higher emissivity (CR intensity)</u> in areas closer to the inner Galaxy

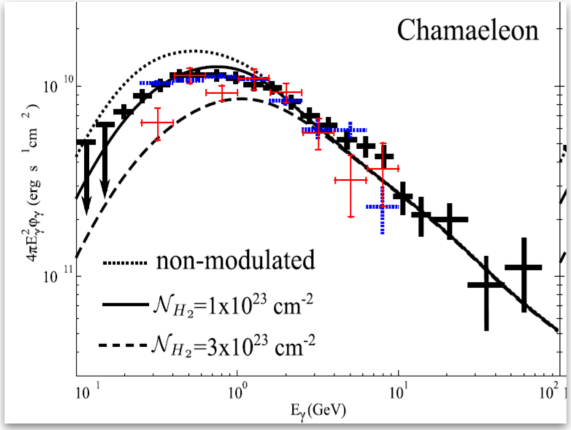


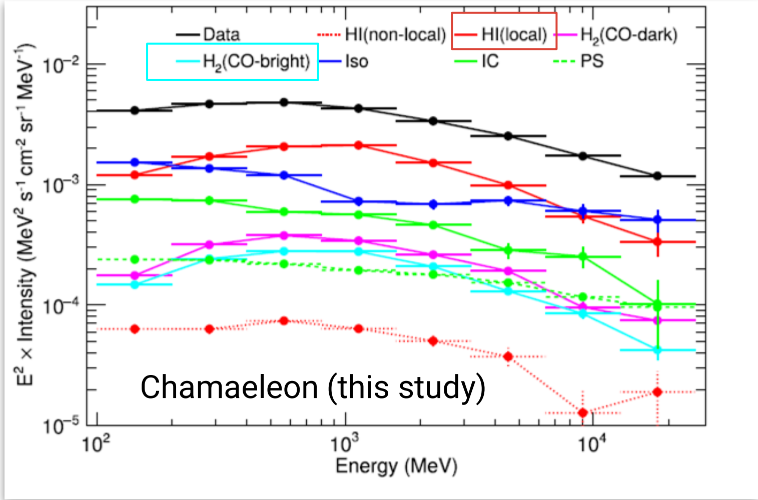
Penetration of Interstellar (IS) CRs in Dense Clouds

Past studies of local clouds reported possible spectral hardening (deficit) in low energies (e.g., Yang+14, Noronov+17); this can be interpreted as "depletion of IS CRs" due to self-excited MHD turbulence if effective N_H is sufficiently high

We have measured γ-ray spectrum of each gas phase accurately; we can conclusively test CR penetration scenario

Dogiel+18





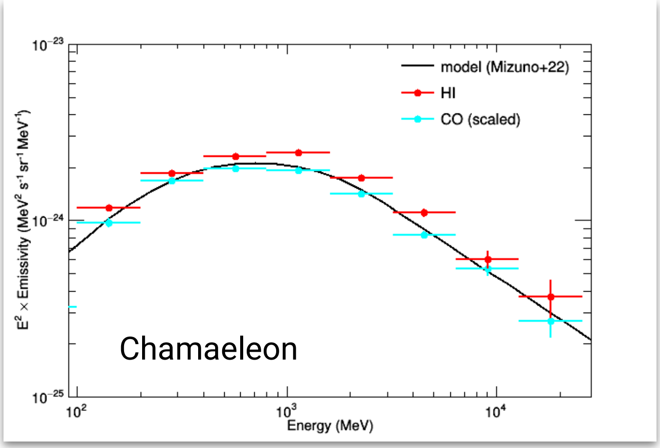
Penetration of IS CRs in Dense Clouds (Cont’d)

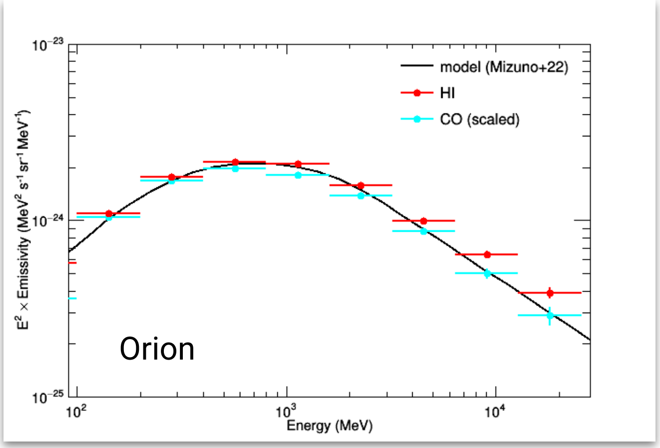
Possible “depletion of IS CRs” in dense clouds is predicted & reported (e.g., Dogiel+18)

- We would see different spectrum btw. CO and HI in dense clouds

We do not see such deficit; IS CRs of >=1GeV penetrate in core of molecular clouds

- Any deficit (if observed) can be interpreted to be due to CRs accelerated recently/nearby
- Deficit below 100 MeV is possible and of interest (e.g., GRAINE, AMEGO-X)





Summary

We applied HI-line-profile based analysis to gamma-ray data of five nearby clouds to accurately measure ISM gas and CR properties

- Narrow HI gives larger emissivity, confirming it to be optically-thick. Broad HI gives emissivity compatible with directly-measured CRs (broad HI = thin HI)
- (ISM) Ratio of CO-dark H2 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 $M_{H2,CO}$; small clouds are more CO-dark
- (CR) CR intensity gradient (higher in areas closer to inner Galaxy) is observed. IS CRs (>1 GeV) penetrate in core of molecular clouds

Thank you for your attention

References

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- Heiless & Troland 03, ApJ 586, 1067
- Kalberla et al. 2018, A&A 619, 58; Kalberla et al. 2020, A&A 639, 26
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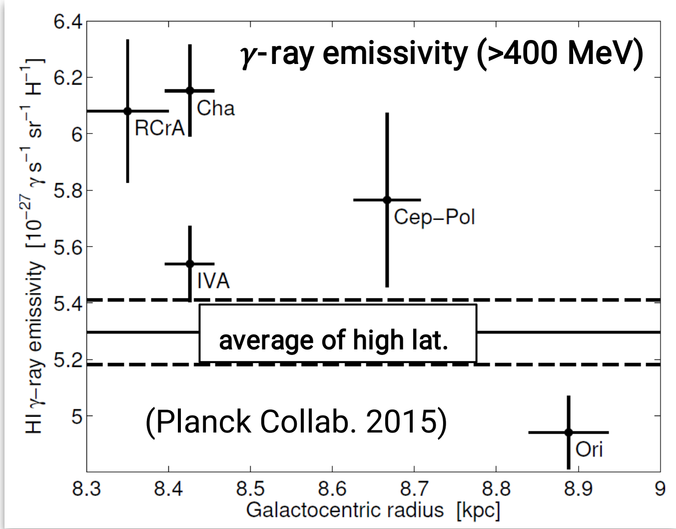
Motivation: Study of ISM Gas & CRs in the Solar Neighborhood

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



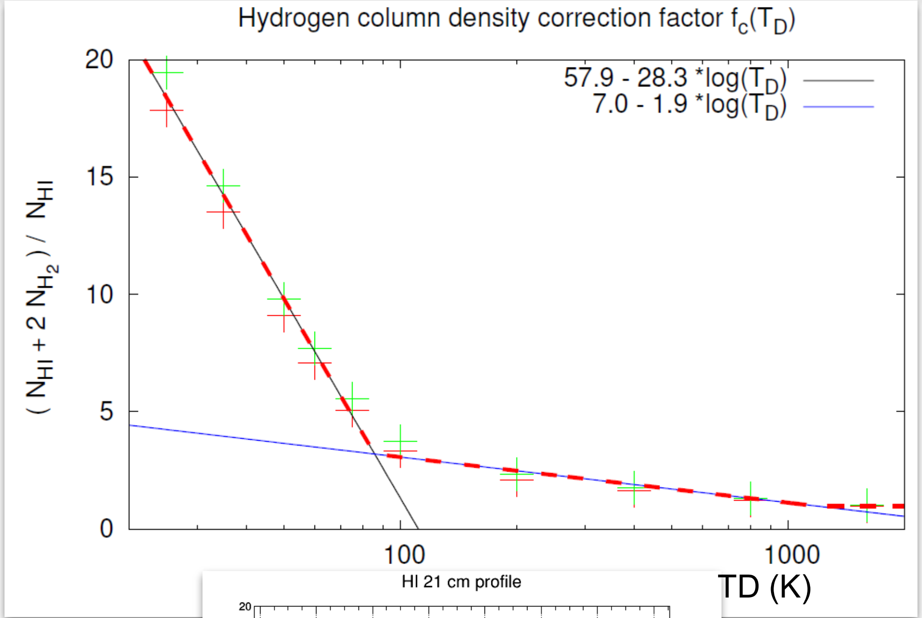
$q_\gamma = I_\gamma / N_H$ ($\propto I_{CR}$) varies considerably, and is also higher than expected (directly-measured CRs)

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)

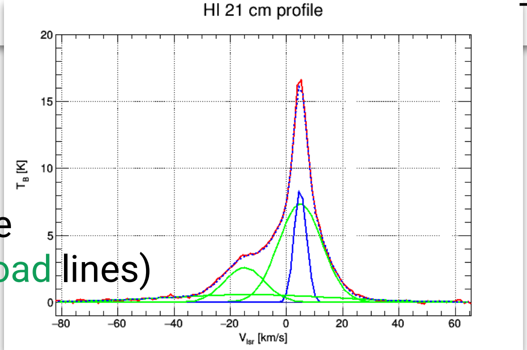
(see also Heiless & Troland 03)

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, $\tau \sim N_{HI}/10^{22}$ cm^{-2})



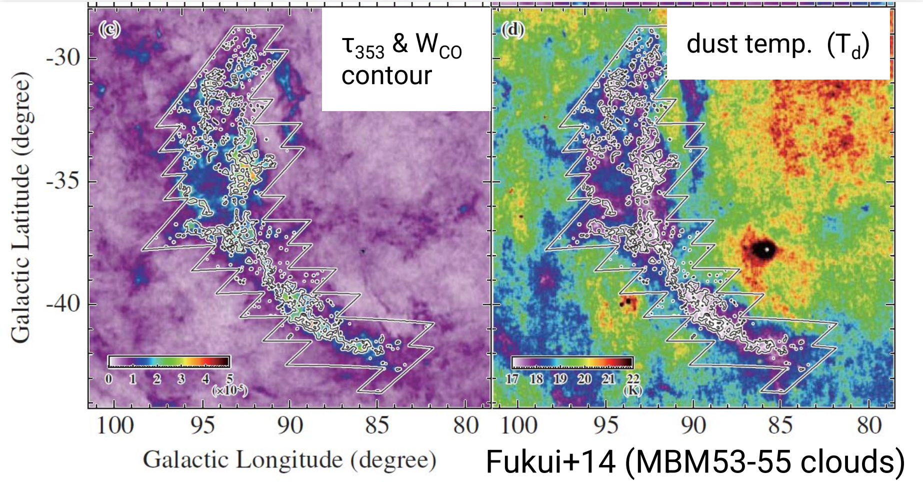
Example of the line profile (one narrow and three broad lines)

How to Measure ISM Gas Accurately?

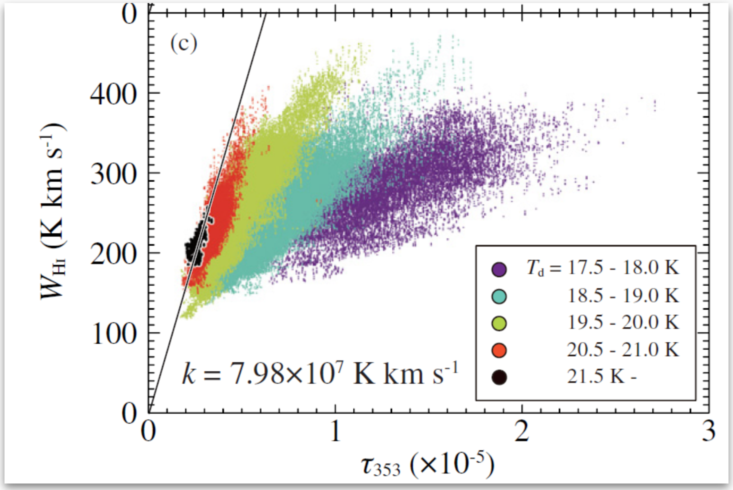
We aim to reveal ISM gas distribution accurately through correlation among tracers

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

- Fukui+14 and Kalberla+18&20 provided possible solutions
  - Low T_d areas are associated with CO-bright H_2 (W_{CO}) and high density (high τ_{353}) areas
  - High T_d areas show high W_{HI}/τ_{353} ratio (thin HI)



Fukui+14 (MBM53-55 clouds)



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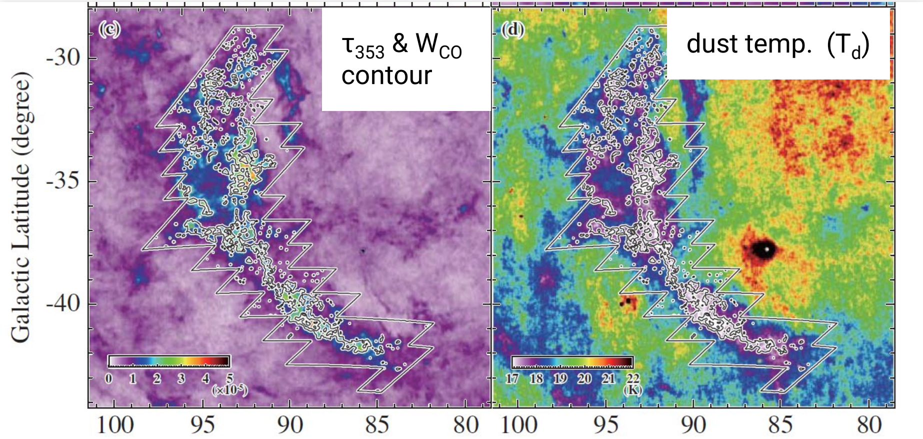
"You should look at high-T_d areas to find optically thin HI"



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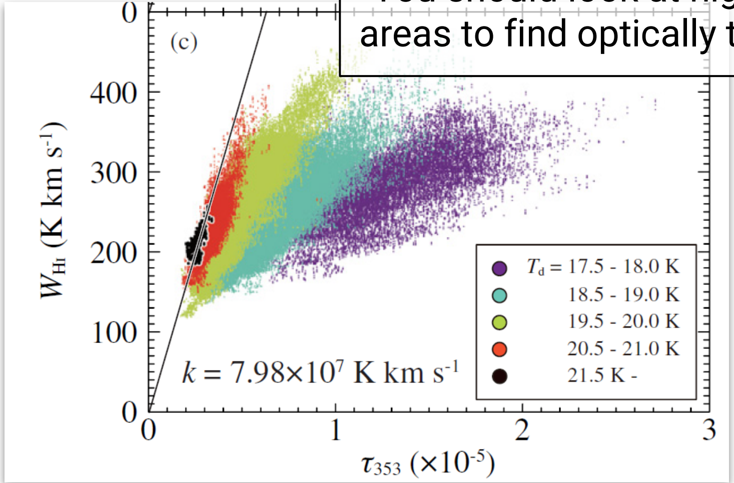

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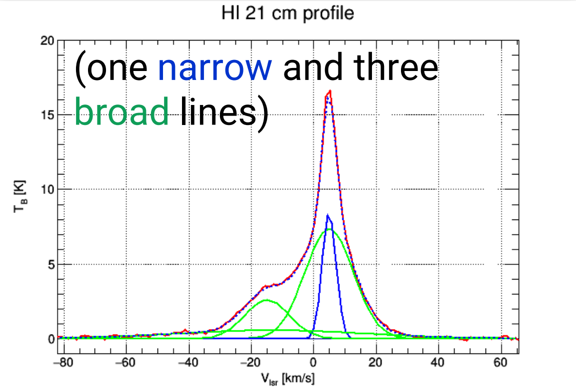

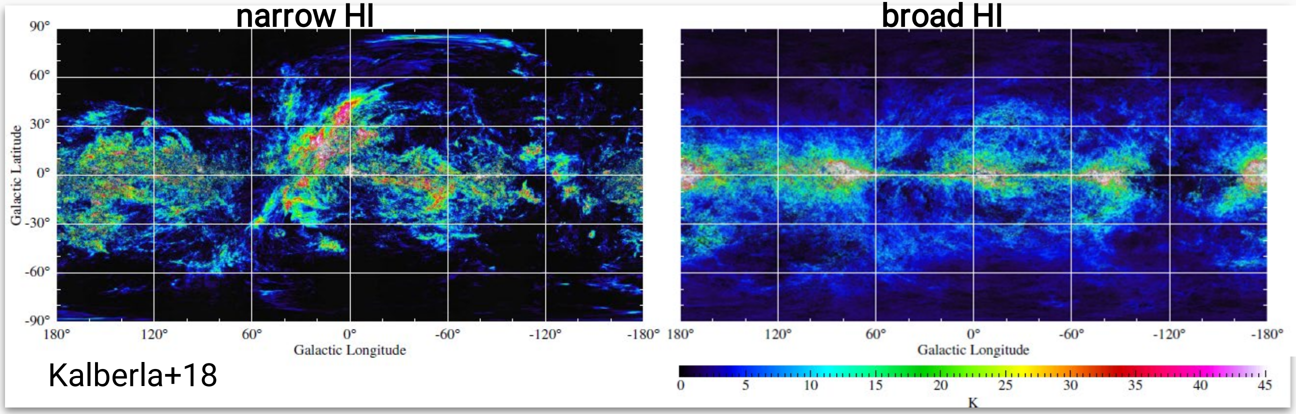

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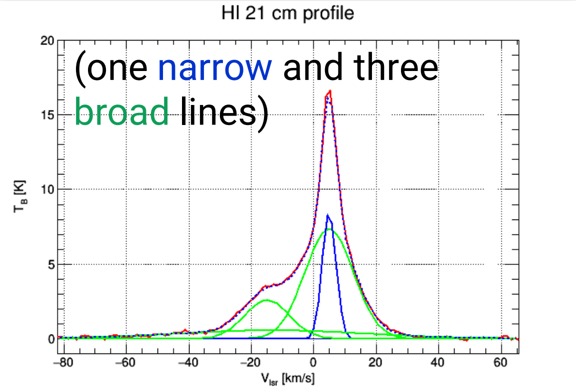
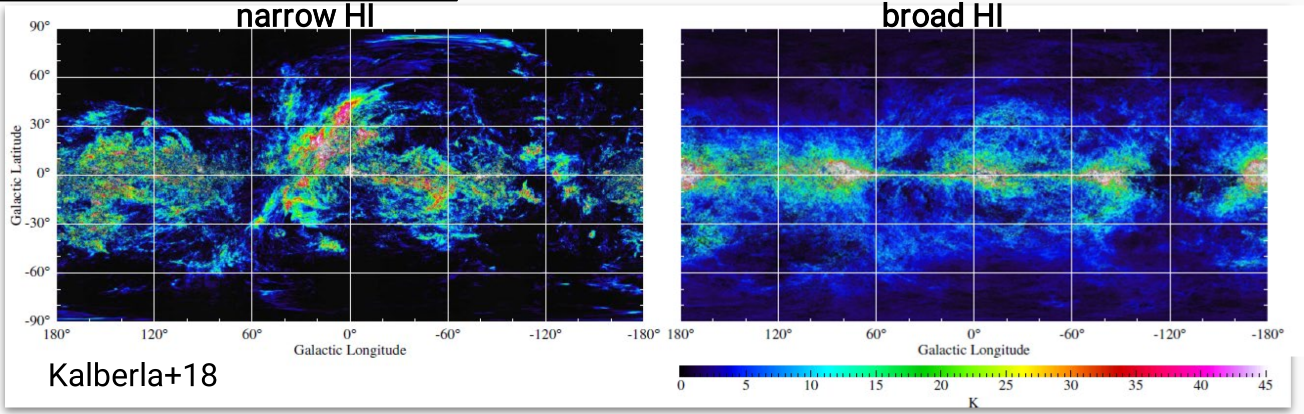
"You should look at broad HI to find optically thin HI"





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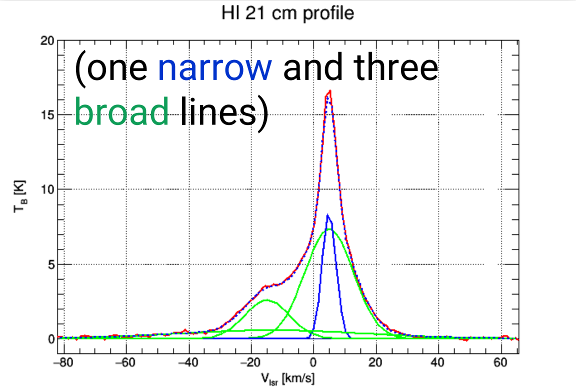
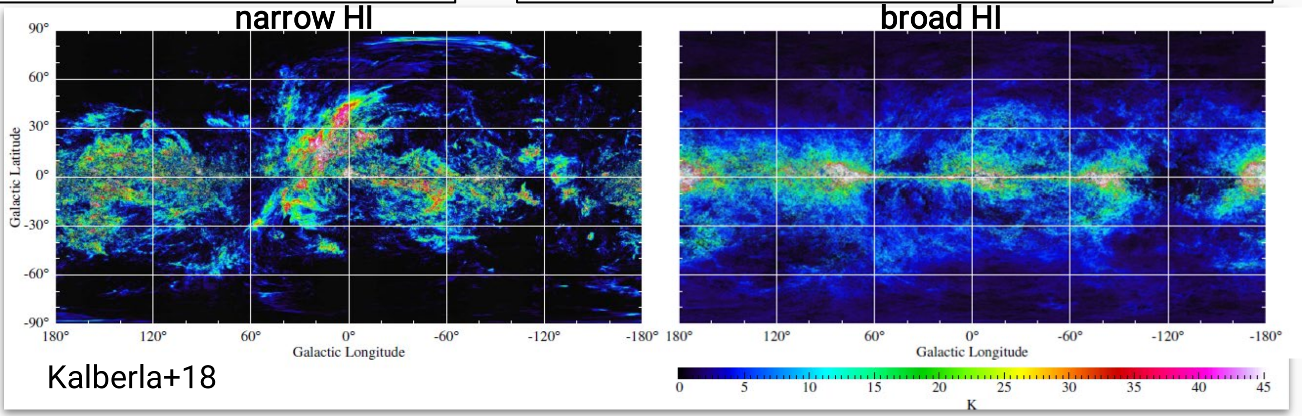
“You should look at broad HI to find optically thin HI”

(We interpret that narrow HI is “thick HI”)





Kalberla+18

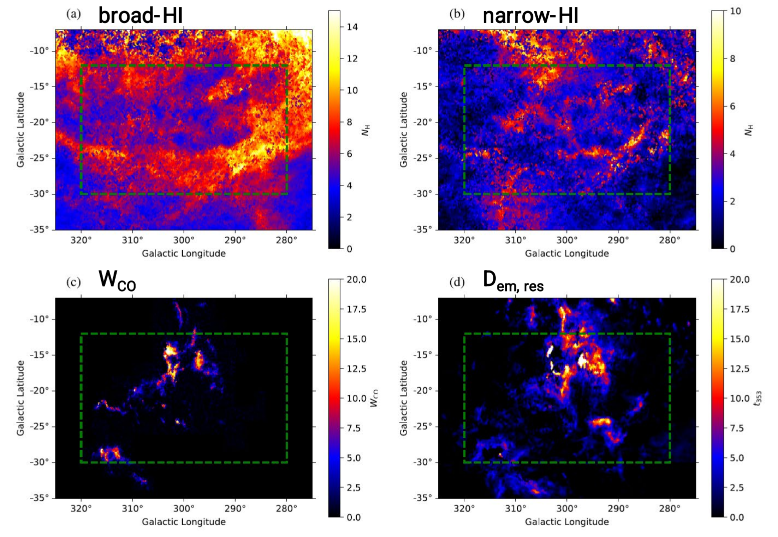
Common Trends in ISM Gas Templates

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

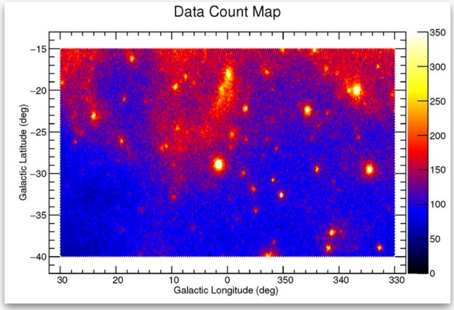
Through correlation with gamma-rays, we evaluated **γ-ray spectrum** of each gas phase

example (Chamaeleon) - - →

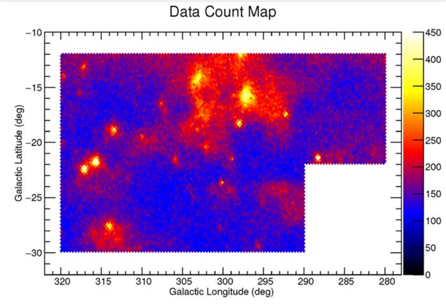


Count maps, 0.1-25.6 GeV

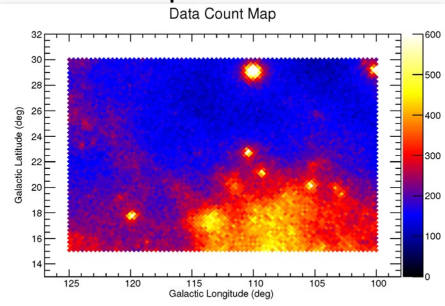
R CrA



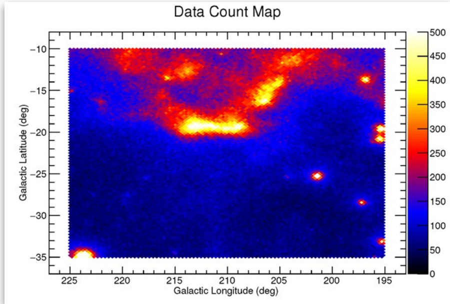
Chamaeleon



Cep&Pol



Orion



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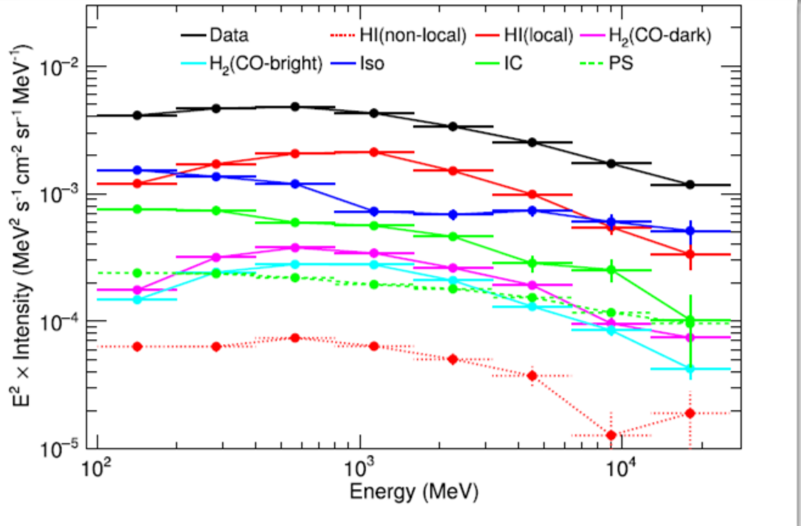

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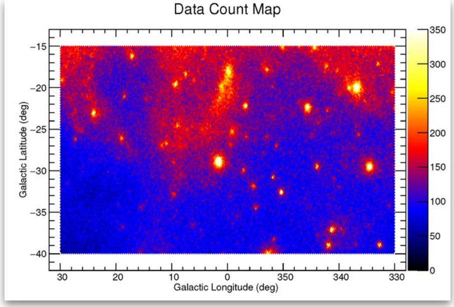
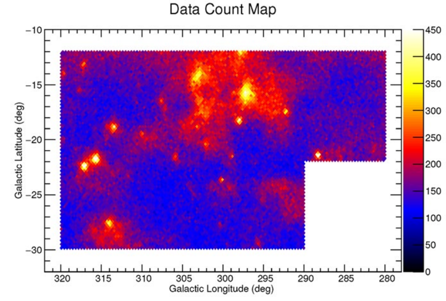


Chamaeleon



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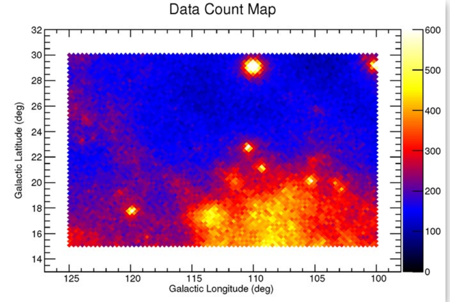
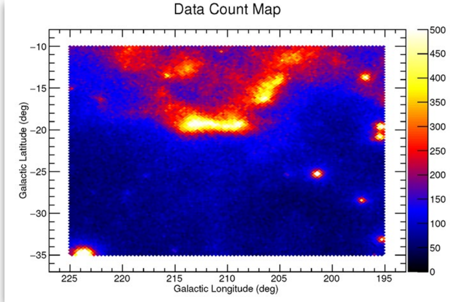


Orion



Common Trends and Results

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

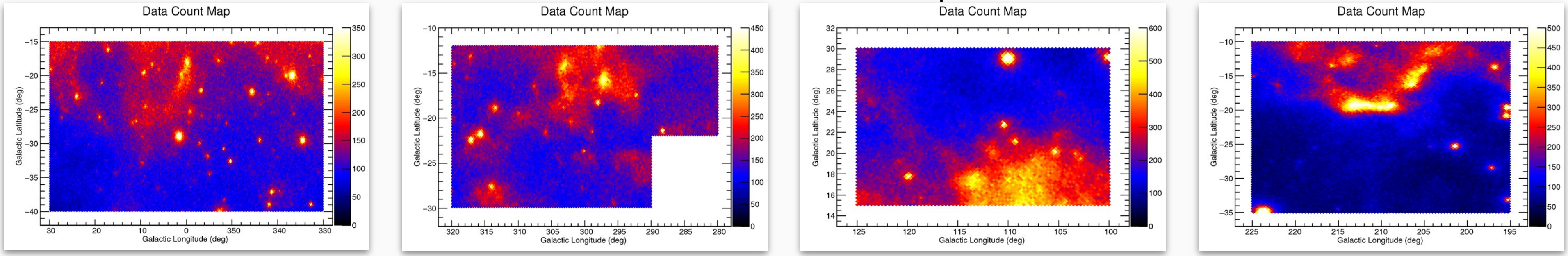
We also found that $N_{HI,corr}$ always gives emissivity spectrum compatible with directly-measured CR (broad HI = thin HI)

emissivity ratio of narrow-HI to broad-HI

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

R CrA　Chamaeleon　Cep&Pol　Orion



ISM Gas Properties 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

- Ratios of CO-dark H_2 to optical depth correction are >=2, indicating that dark gas is mainly CO-dark H2
- Ratio of CO-dark H_2 to CO-bright H_2 >=1; CO-dark H2 is ubiquitous

(Phase)	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 (CO-dark H2)	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

ISM Gas Properties in Solar Neighborhood (Cont'd)

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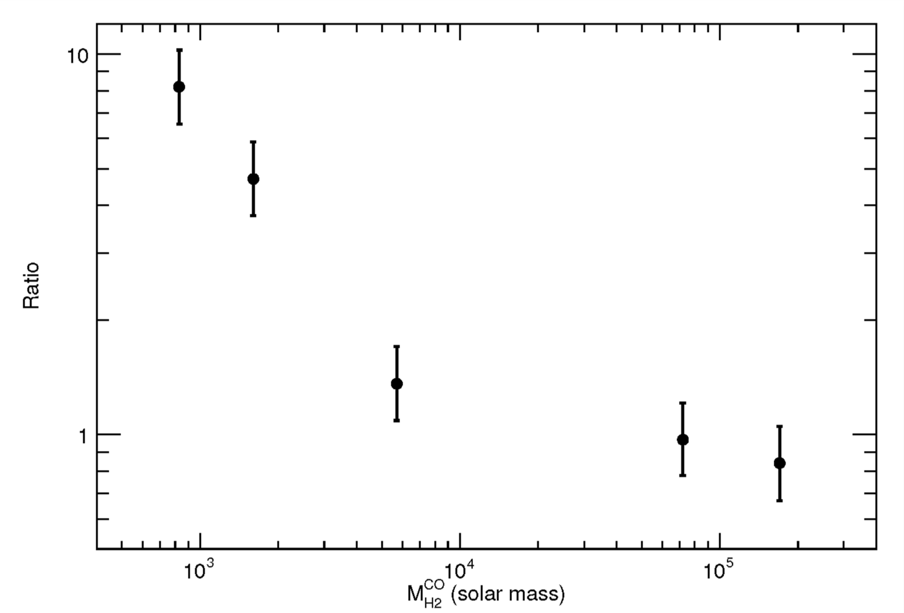
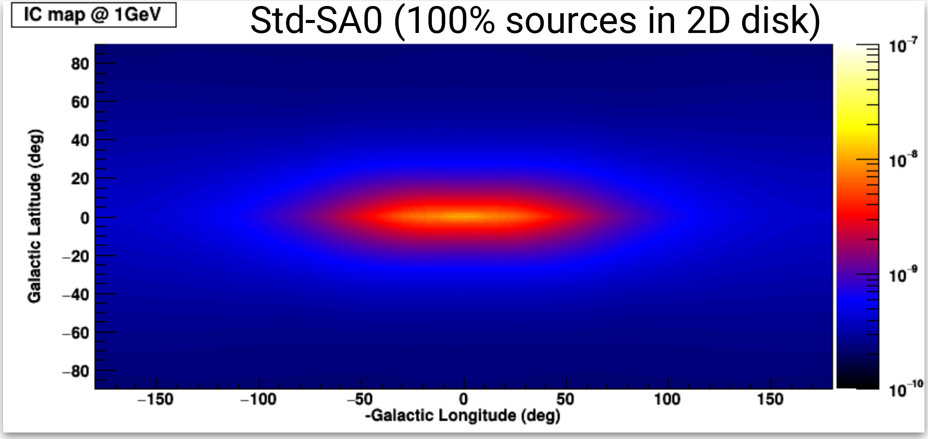
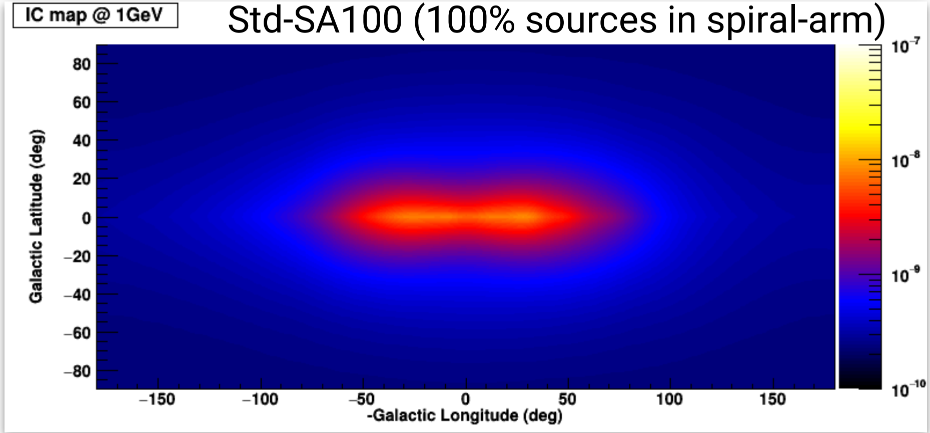


Ratio of CO-dark H_2 to CO-bright H_2 is 1-10 and anti correlates with $M_{H2, CO}$; small clouds are more CO-dark
(we should consider this when studying individual CR accelerators)

Testing IC Models

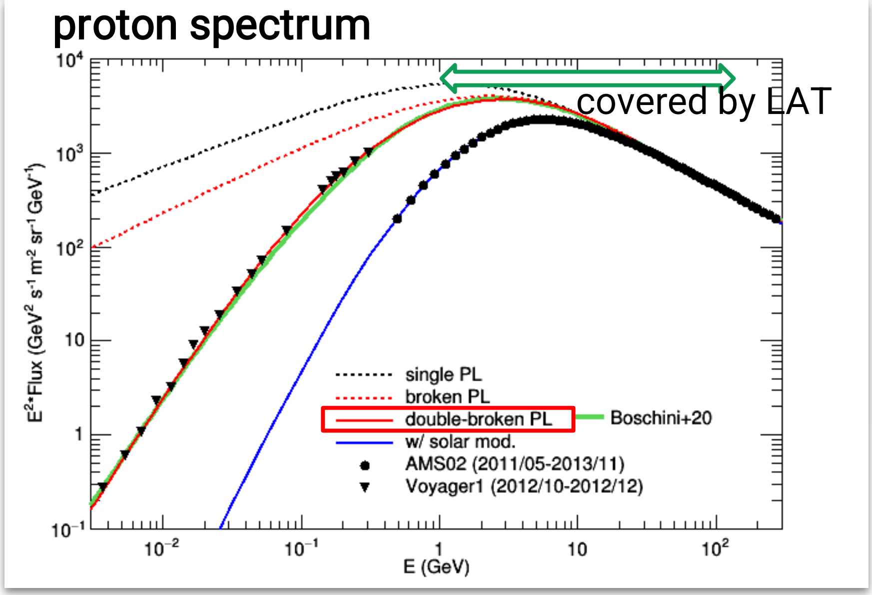


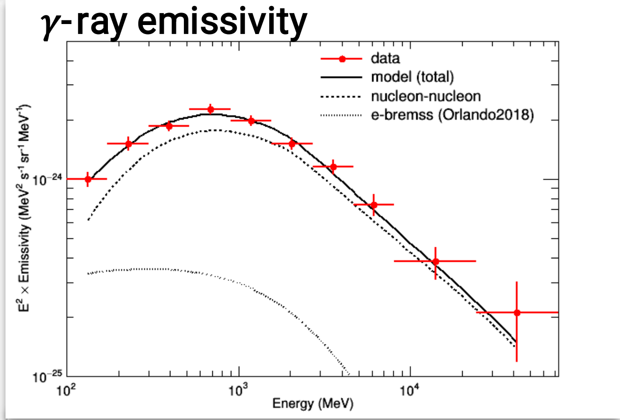


Porter+17 provides 9 IC models (3 ISRFs, 3 CR distributions)

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 (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

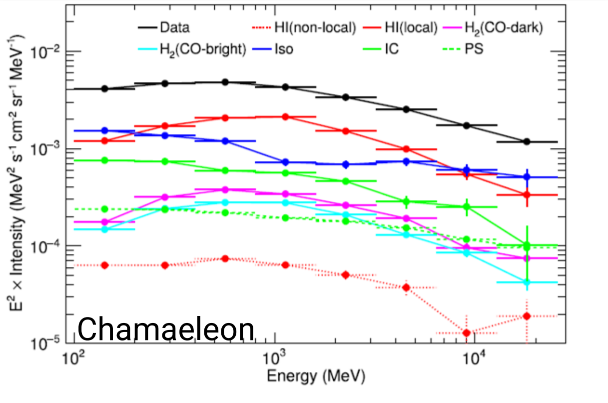
$$J(p) \propto \left[\left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_1/\delta_1} + \left(\frac{p}{p_{\mathrm{br1}}}\right)^{\alpha_2/\delta_1}\right]^{-\delta_1} \times \left[1+\left(\frac{p}{p_{\mathrm{br2}}}\right)^{\alpha_3/\delta_2}\right]^{-\delta_2}$$

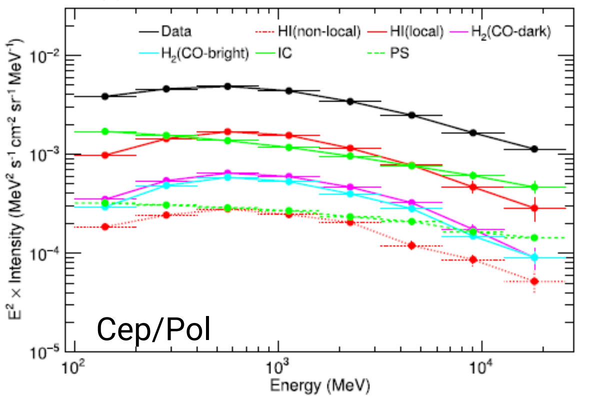
- Our LIS model reproduces data & agrees with Boschini+20
- γ-ray emissivity; p-p (Kamae+06 and AAfrag) + e-bremss (Orlando2018)
  - We also take into account CR α and ISM He explicitly and consider heavier nuclei based on the formalism of Kachelriess et al. (2014)

Summary of X_{CO}

We evaluated gamma-ray spectrum of each gas phase and calculated Xco as ratio of fit coefficients for W_{CO} and broad-HI

- X_{CO}~1×10^{20} cm^{-2} $(K\ km/s)^{-1}$ for giant molecular clouds (>10^4 M_{SUN})





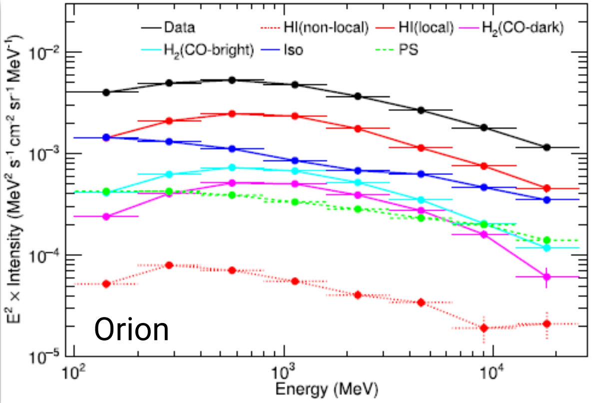


Table 9. Summary of X_{CO} in units of 10^{20} cm^{-2} $(K\ km\ s^{-1})^{-1}$.

MBM/Pegasus	R CrA	Chamaeleon	Cep/Pol	Orion
0.559 ± 0.038	1.668 ± 0.034	0.932 ± 0.016	0.912 ± 0.017	1.296 ± 0.010