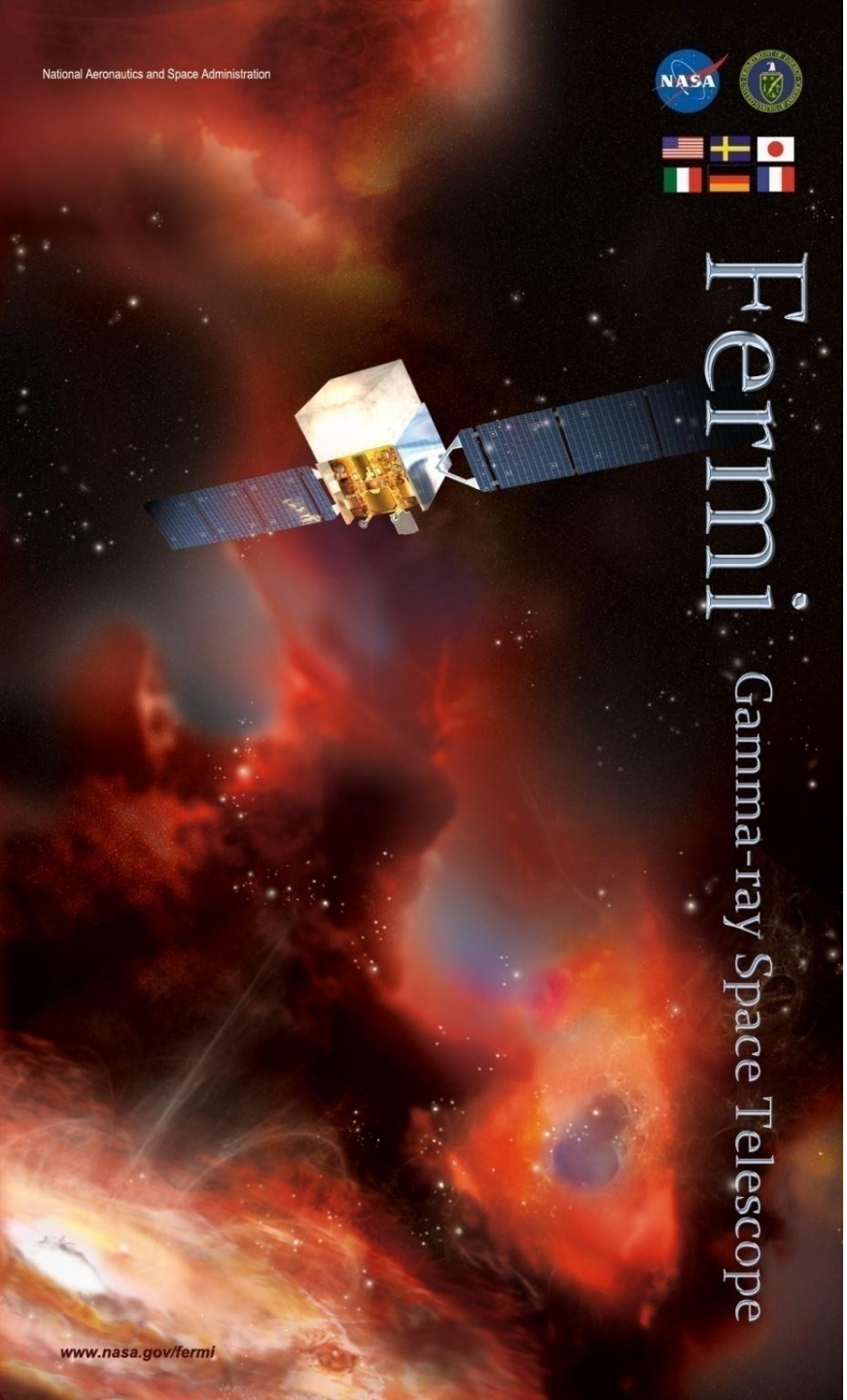

Fermi LAT study of cosmic-rays and the interstellar medium in nearby molecular clouds

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Giant Molecular Cloud

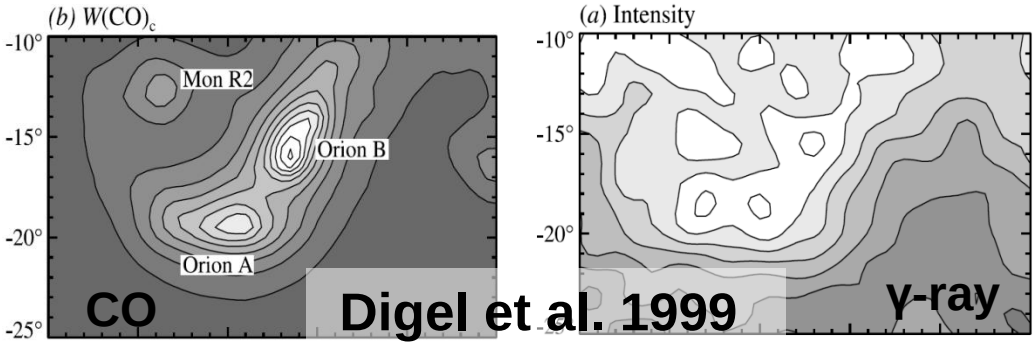
- Temperature ~10K, Mass ~$10^{4\text{-}6}M_{\odot}$, density ~10^{2}-10^{3} cm^{-3}
- Some GMCs close to the solar system (Orion, Taurus, etc)
- Emission/absorption mechanism
  - rotational transition of molecule → radio
  - extinction/emission by dust → optical, infra-red
  - interaction with CR → gamma-ray

H_2 (main component of molecular gas) is not detectable directly

$$p + p \longrightarrow \pi^{+},\pi^{-}$$
$$\pi^{0} \longrightarrow \gamma+\gamma$$

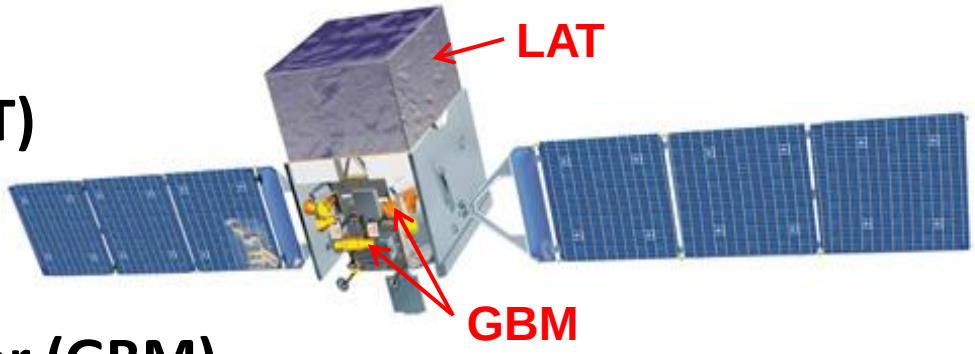
Gamma-ray emissivity does not depend on the gas temperature, phase, etc.
→ Study of CR spectrum and matter distribution by gamma-rays

Although EGRET observed several GMCs in 90', detailed study of CRs and matter distribution has not been performed due to the limited sensitivity.



Fermi Gamma-ray Space Telescope

- Launched on June 11, 2008
- Two instruments:
  - Large Area Telescope (LAT)
    e+/e- pair-conversion
    with silicon detectors
  - Gamma-ray Burst Monitor (GBM)



	CGRO-EGRET	Fermi-LAT
Energy range	20 MeV – 30 GeV	20 MeV – 300 GeV
Effective area	1500 cm^2	>8000 cm^2
Angular resolution @100 MeV @ 1GeV	5.8 deg 1.7 deg	3.5 deg 0.6 deg
Field of view	0.5 str	2.5 str
Detected sources (>5σ)	271 (10 years)	1873 (2 years)

Motivation

Fermi enables studying the diffuse gamma-ray emission with unprecedented sensitivity.

Detect gamma-ray from small GMCs ($M < 10^4 M_{sun}$)

→ We can study CRs and matter distribution in wide-ranging samples.

Reveal the CRs and matter distribution in the vicinity of the solar system (<~500pc).

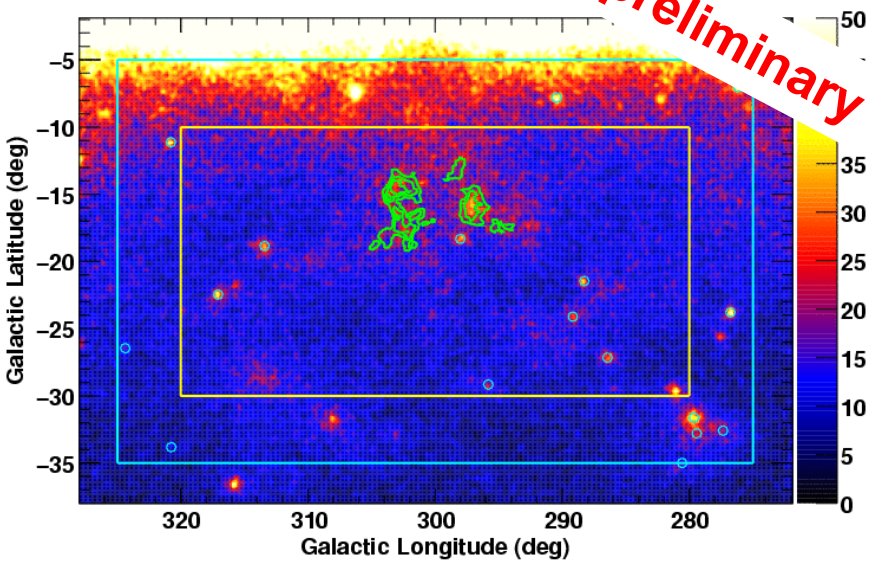
- **Cosmic-rays**
  - **What is the distribution of local CRs?**
- **Matter distribution**
  - **Molecular mass calibration ratio**
    - **$X_{co} = N(H_2)/W(CO) \sim (1\text{-}2) \times 10^{20}$ cm^{-2}/(K km/s) is highly uncertain.**
  - **How is the gas not traced by HI and CO surveys spread?**

Fermi-LAT is an ideal instrument to study these questions.

Targets; Chamaeleon & RCrA regions

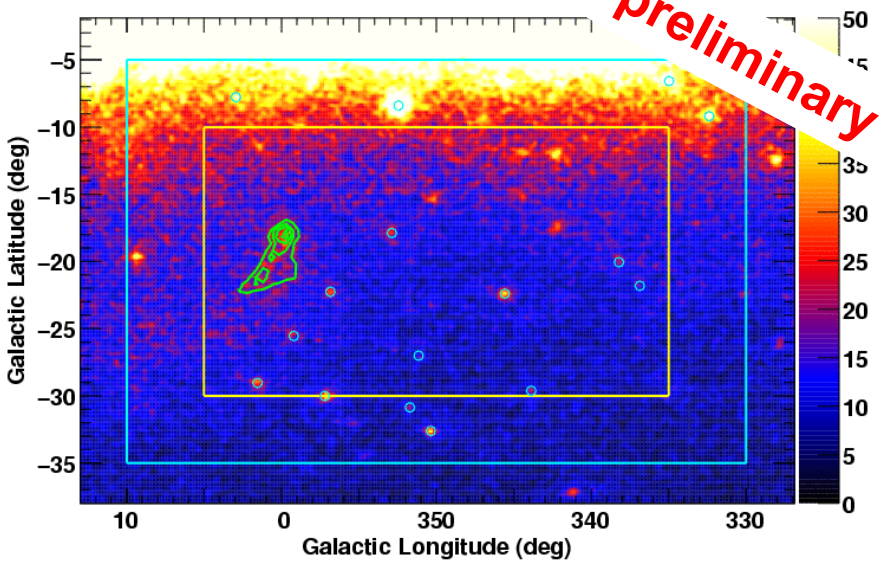
Chamaeleon molecular cloud

Distance ~215pc, Mass ~10000 M_sun
(Dame et al. 1987)



R CrA molecular cloud

Distance ~150 pc, Mass ~3000 M_sun
(Dame et al. 1987)



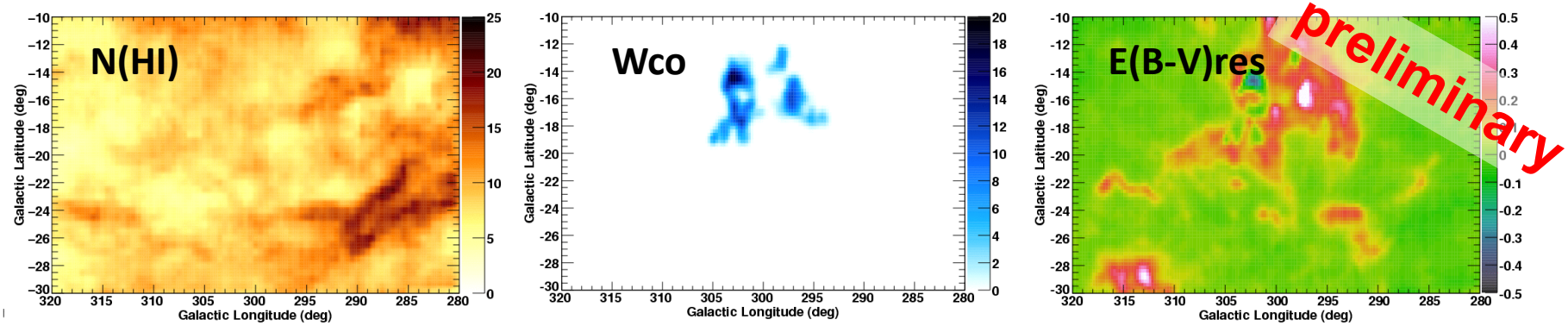
Data Count Map (E>250 MeV) smoothed with a gaussian of 0.5 deg

- Contour: CO line intensity (Dame et al. 1987)
- Cyan circles: the position of point source (TS>=50, 1FGL Catalog)
- Yellow rectangle: the region used for the fitting
- Cyan rectangle: the region in which sources are taken into account in the fitting

Analysis Procedure (1)

Prepare template gas maps (HI, CO and E(B-V)res) for each region.

- N(HI): LAB survey by Kalberla et al. (2005)
  - HI optical depth correction; spin temperature (T_S) = 125 K
  - T_S = (100K～∞) → evaluate the systematic uncertainty
- Wco: composite survey by Dame et al. (2001)
- E(B-V)res: Gas not properly traced by HI and CO surveys.
  Estimated by E(B-V) reddening map (Schlegel et al. 1998)



Gas maps for the Chamaeleon region

Analysis Procedure (2)

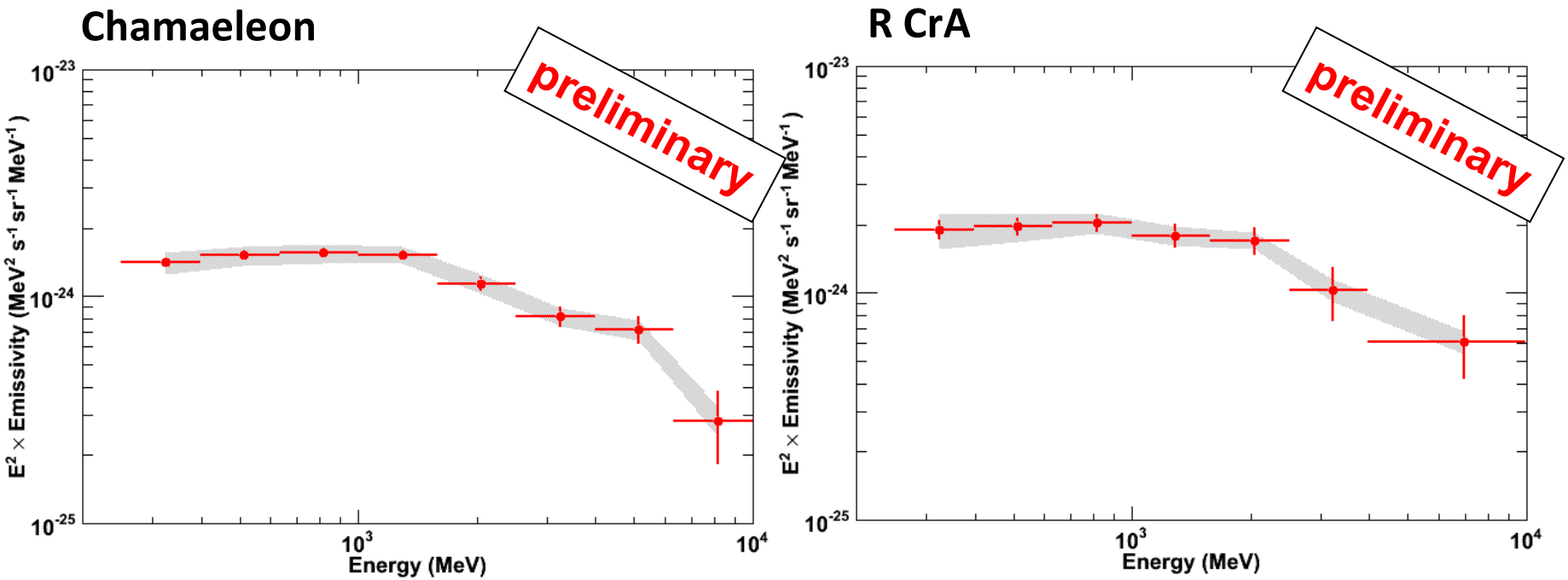
Fit the gamma-ray data and obtained each gas emissivity in 8 logarithmically spaced energy bins from 250MeV to 10GeV.

$$I(l,b,E) = \sum_{i=1}^{2} q_{HI,i}(E) \times N(HI)(l,b)_i + q_{CO}(E) \times W(CO)(l,b)$$
$$+ q_{EBV}(E) \times E(B-V)_{res}(l,b)$$
$$+ c_{IC}(E) \times I_{IC}(l,b) + I_{iso}(l,b) + \sum_j PS_j$$

Galactocentric radius
R = 0-8 kpc
R = 8-8.5 kpc

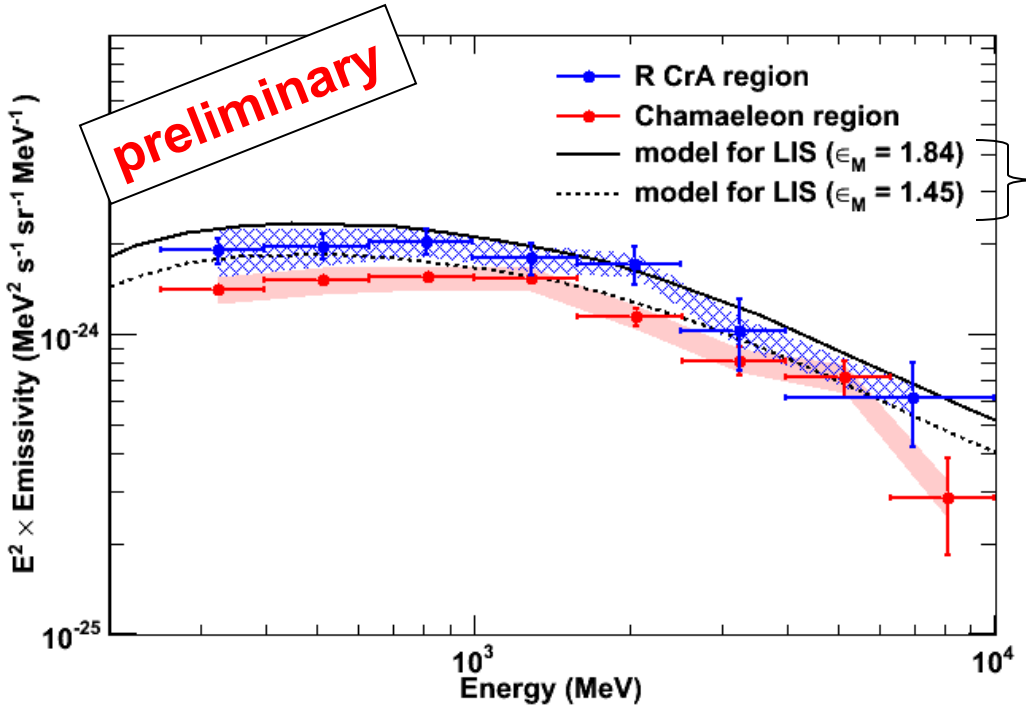
- Fit the normalization of the IC model (GALPROP model).
- Isotropic component (Extra galactic diffuse + BGD) is fixed but its systematic uncertainty is examined.
- Point sources: 1FGL catalog (TS>50)

HI emissivity Spectrum



- HI emissivity spectra in the Cham. and the R CrA regions (T_S = 125K).
- Shaded areas indicate the <u>systematic uncertainties</u> due to
  - Optical depth correction (T_S = 100K～∞)
  - Isotropic component by changing the intensity +/-10%
- Impact of point source was found to be smaller.

CR Spectrum in Local Region



(Abdo et al. 2009)

- Compared obtained HI emissivity spectra with model for LIS.
  Model uncertainty ;~20% (due to the uncertainty of the nuclear enhancement factor (ε_M) and proton flux)
- Spectral shapes of the Cham. & R CrA regions agree with LIS.
- The spectra of two regions and the model are consistent within the systematic uncertainties.

Conclusion

- We have studied gamma-ray emission from the Chamaeleon and the R CrA molecular clouds regions.
- We have obtained the gas emissivity spectra with unprecedented sensitivity.
- Systematic uncertainties are carefully evaluated.
- Spectral shapes agree well with the model for LIS and the absolute emissivities (CR densities) are consistent within the systematic uncertainty.

To Do:

- Compare the obtained emissivities with those of other local regions.
- Calculate the Xco values and molecular masses.

Back up

Sample of GMCs

Dame et al. 1987
(see also Dame et al. 2005)

TABLE 2

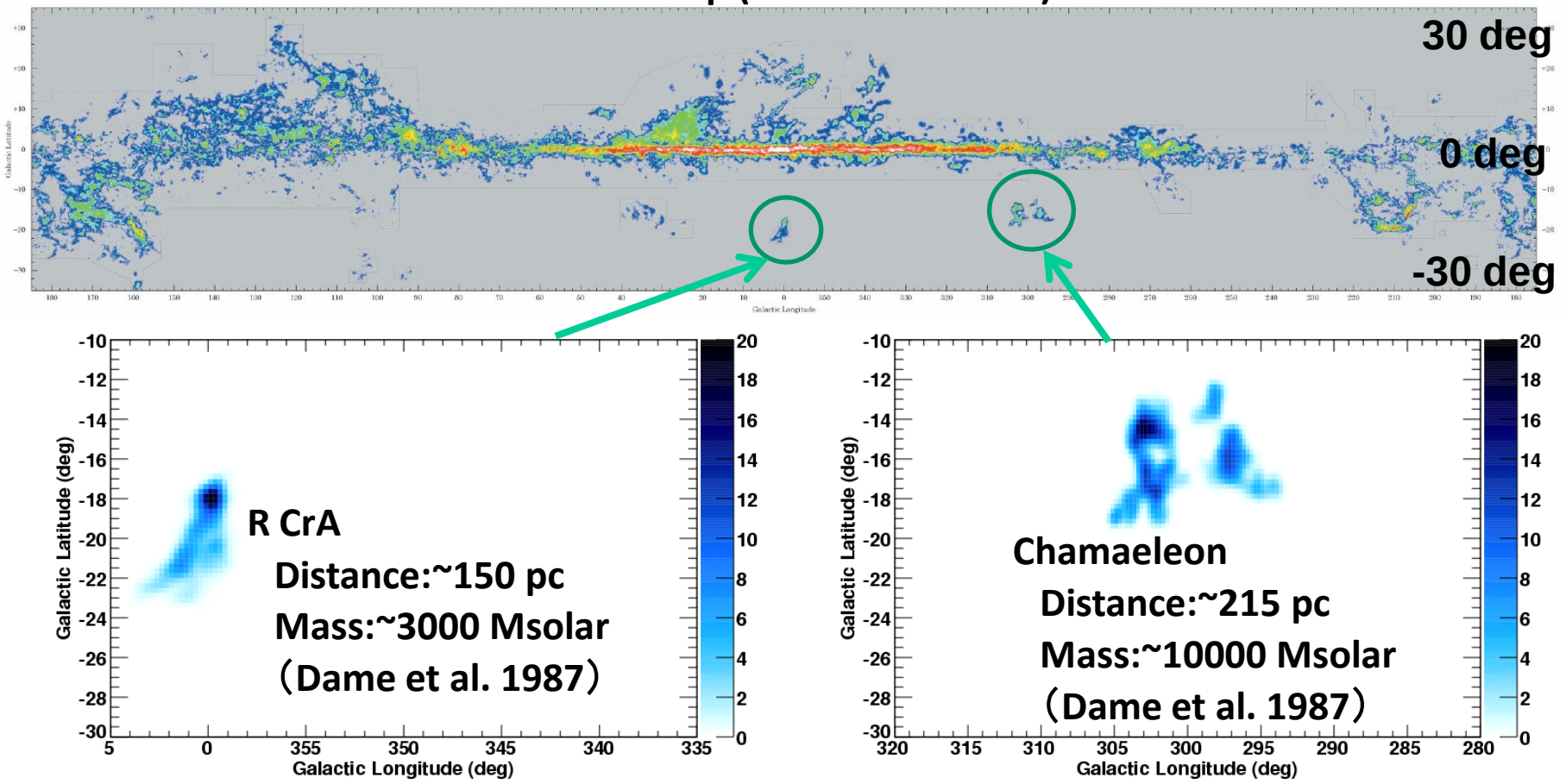
MOLECULAR GAS WITHIN 1 KILOPARSEC OF SUN

Region	l_{min}	l_{max}	b_{min}	b_{max}	v (km s^{-1})	D (pc)	Ref.	M (10^5 $M_\odot$)	$\bar{z}^a$ (pc)	$\sigma_z{}^b$ (pc)
Aquila Rift	18°.5 34	34° 44	−6° −4	10° 4	8	200	1	1.5	9	15
Cloud A	44	49.5	−4	2	27	500	1	0.4[c]	−7	14
Cloud B	44	54	−4	5	7	300	1	0.4[c]	0	11
Cloud C	50	55	−1	3.5	24	500	1	0.3	5	12
Vul Rift	54	63	−3	5	10	400	1	0.8	5	12
Cyg Rift	63	86.5	−4	4	7	700	1	8.6[d]	−4	24
Cyg OB7	87	99	−3	8	−1	800	1	7.5	41	52
Lindblad Ring	100	164	−4	10	1	300	2	1.6	22	28
"−12 km/s"	102	161	−4	10	−12	800	3	8.7	44	59
Cepheus	100	120	11	22	−5	450	4	1.9	131	133
Taurus	163	178	−22	−9.5	5	140	5	0.3	−37	38
Per OB2	154 163	162.5 171	−25 −9	−7 −6	5 −3	350	5	1.3	−84	92
Mon OB1	197.5	205	−1	4	7	800	7	1.6	17	22
Orion A	208.5	218	−21	−14.5	5	500	6	1.6	−163	164
Orion B	202.5	208	−21	−6	5	500	6	1.7	−129	132
Mon R2	210	218	−14	−10	7	830	6	1.2	−182	183
Vela Sheet	272	279	−3	8	0	425	8	0.8	9	19
Cham	295	305	−20	−12	4	215	9	0.1	−60	60
Coalsack	300	307	−4	3	−4	175	10	0.04	−2	5
G317 − 4	315	320	−6	−2	−6	170	11	0.03	−11	11
Lupus	333	346	4	22	5	170	8	0.3	32	35
ρ Oph	350 356	2 5	13 3	24 12.5	3	165	12	0.3	35	39
R CrA	357	4	−22	−14	6	150	13	0.03	−55	55

Detailed analysis by EGRET (e.g; Digel et al. 1999)

Chamaeleon & RCrA regions

2.6 mm CO map (Dame et al. 2001)

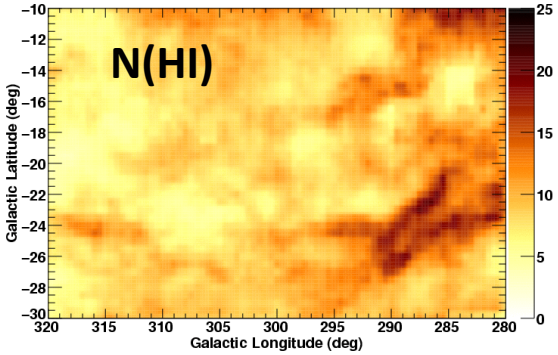


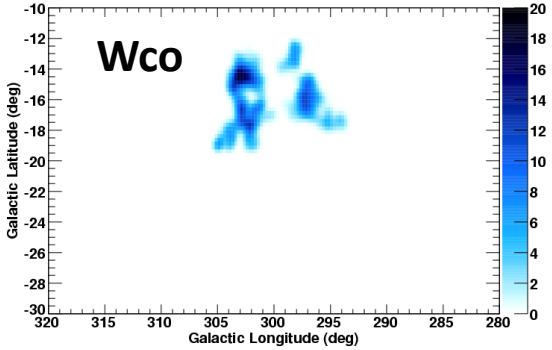
• high latitude position (-19<b<-12deg; 45 pc<|z|<70 pc) → avoid confusion with the strong emission from the Galactic plane.

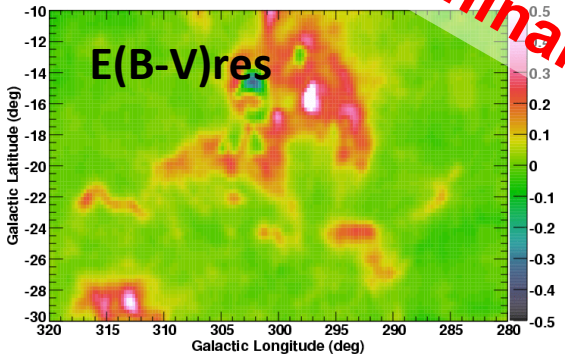
Template Gas Maps

Chamaeleon region

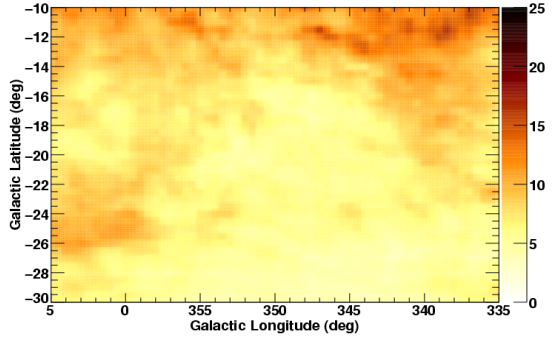
preliminary

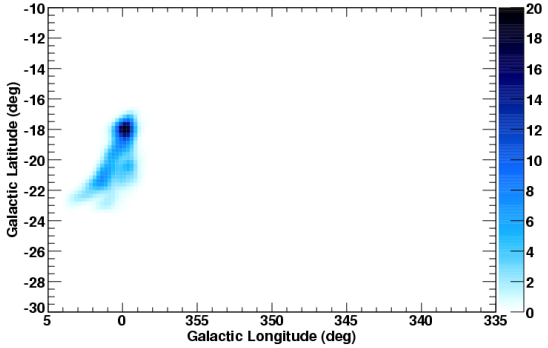


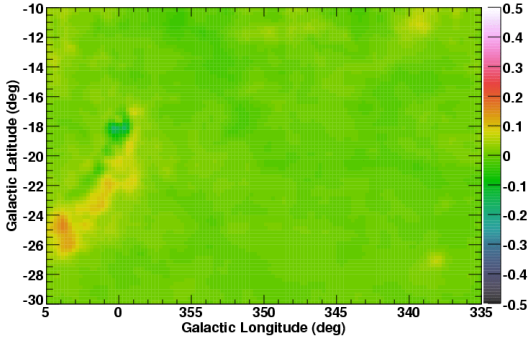




RCrA region



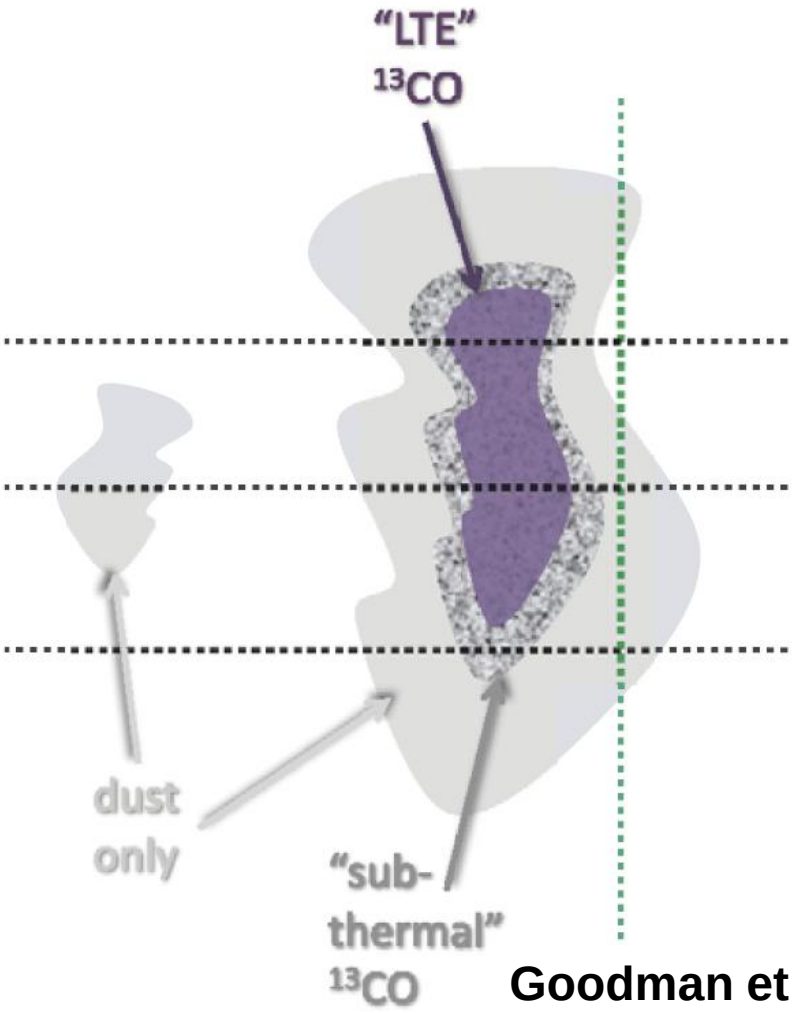




Gas of traced by excess of E(B-V)

- Some fraction of gas is not detectable by 21 cm line (atomic hydrogen) and CO line (e,g; Grenier et al. 2005, Goodman et al. 2009)

- We estimated their contribution from the emission of dust.



Goodman et al. 2009