Gamma-ray emission from molecular clouds observed by the *Fermi* Large Area Telescope

Luigi Tibaldo

luigi.tibaldo@pd.infn.it

INFN – Sezione di Padova
Dip. di Fisica “G. Galilei”, Università di Padova
Laboratoire AIM, CEA Saclay

for the diffuse emission & molecular clouds group

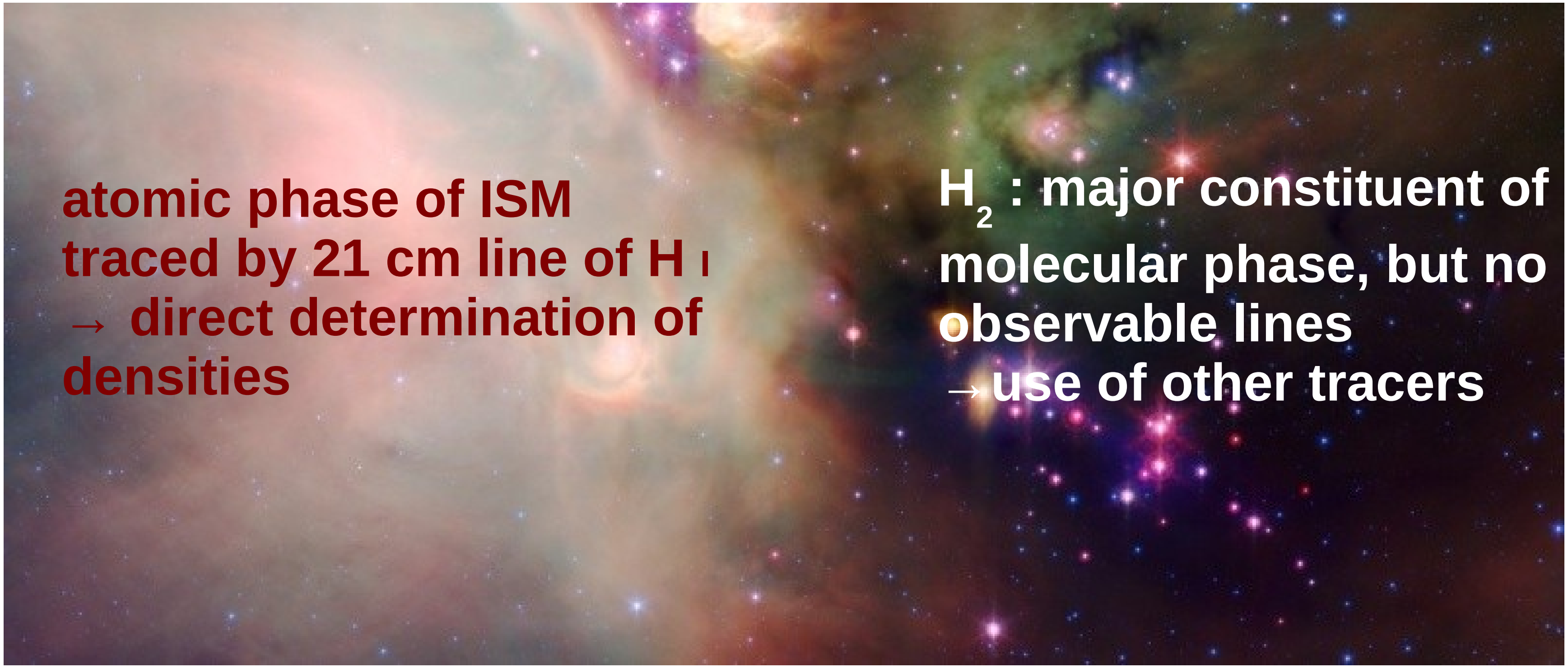
on behalf of the *Fermi* LAT Collaboration

9th September 2009

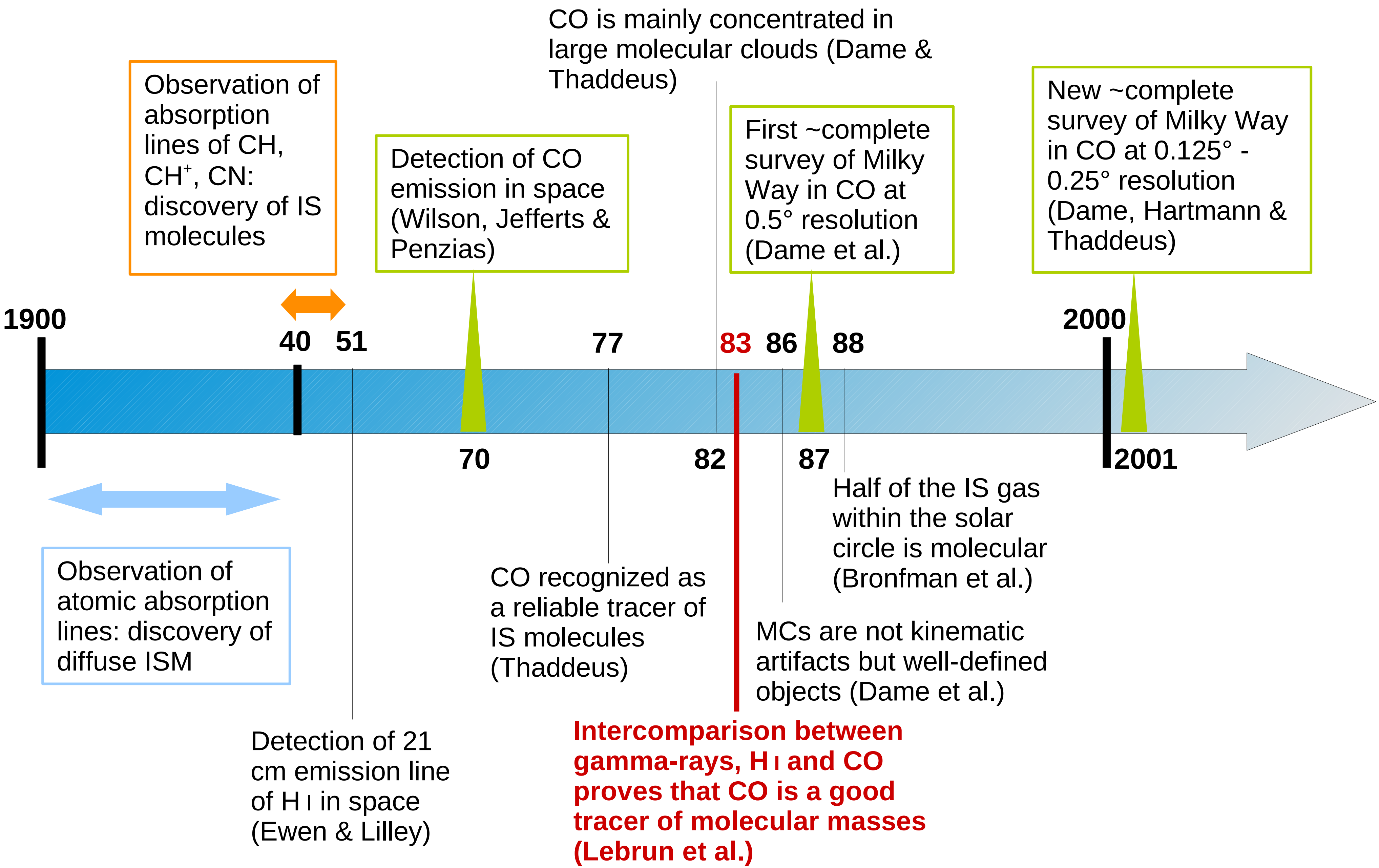
I – Introduction: molecular clouds, cosmic rays and gamma rays

Molecular clouds

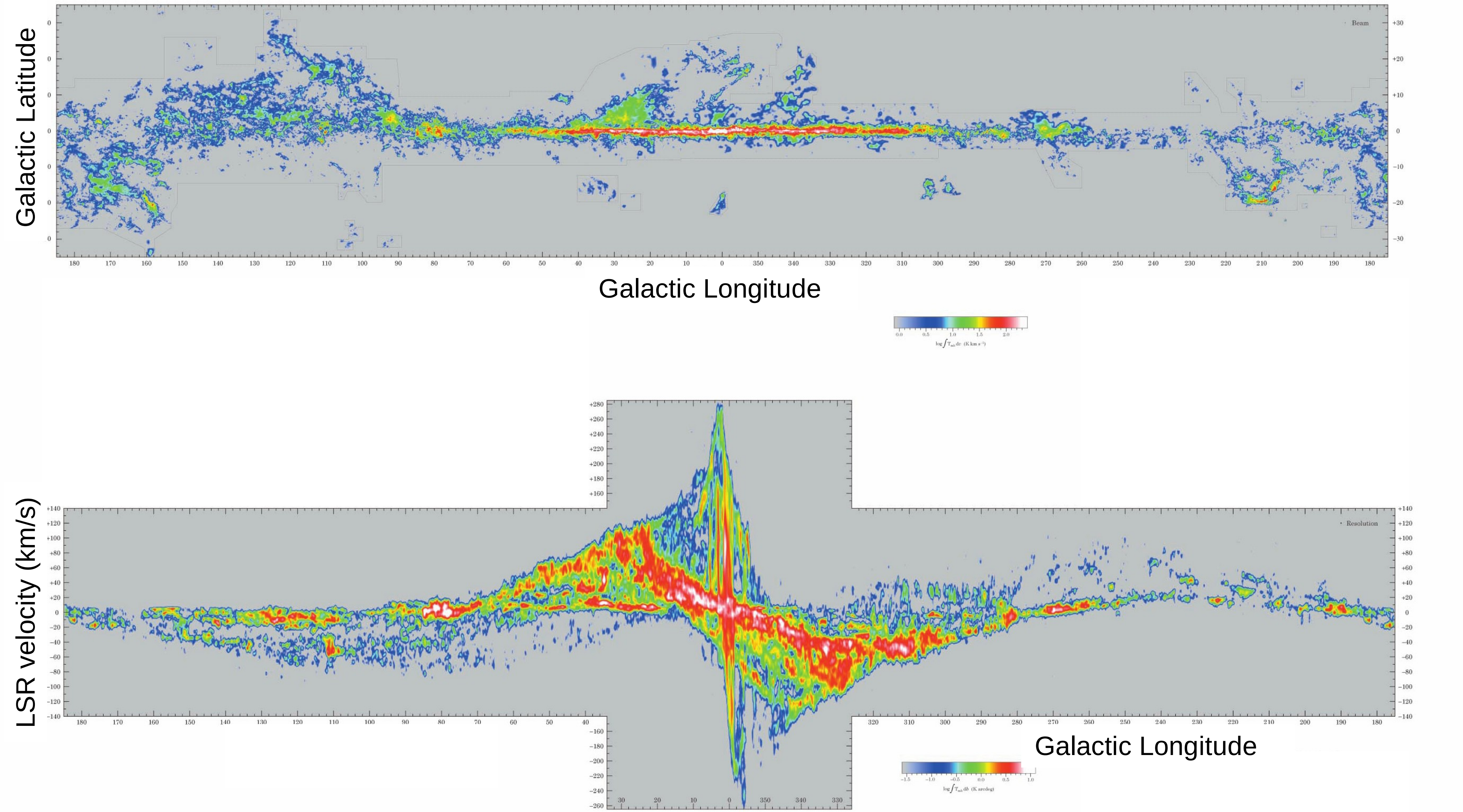
- Sites of star formation (stellar nurseries)
- Tracer of the Galactic structure
- **Tracer of cosmic rays in the Galaxy (gamma-ray emission)**



CO as tracer of interstellar molecules



The Milky Way in CO



Credit: T. M. Dame, D. Hartmann, P. Thaddeus, 2001, ApJ **547** 792

CO-to-H_2 conversion

$$X_{CO} = \frac{N(H_2)}{W_{CO}}$$

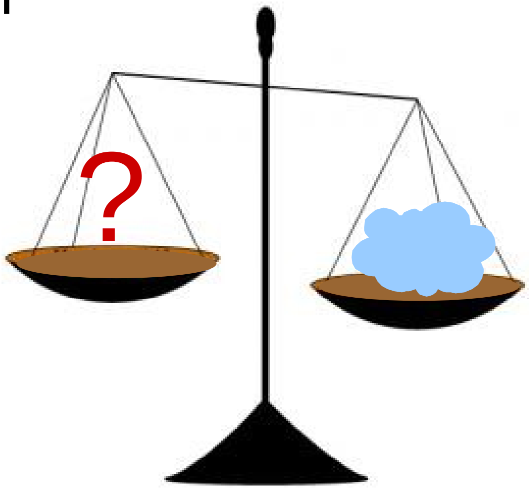
column density of H_2

$$W_{CO} = \int dv\, T_B(CO)$$

visual absorption through (nearby) clouds

velocity dispersion (clouds are virialized systems)

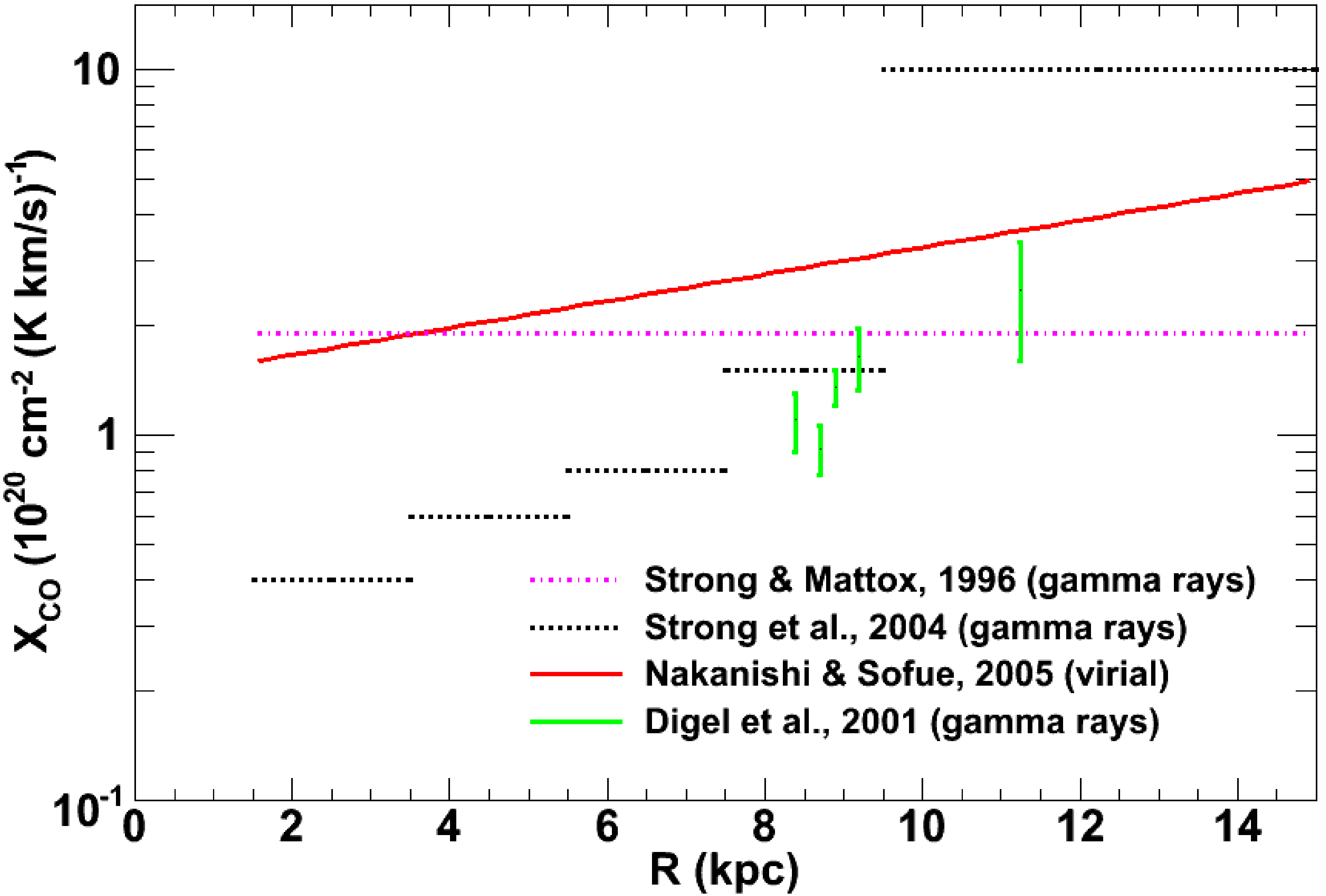
thermal emission from dust (constant dust-to-gas ratio, dust temperature and emissivity)



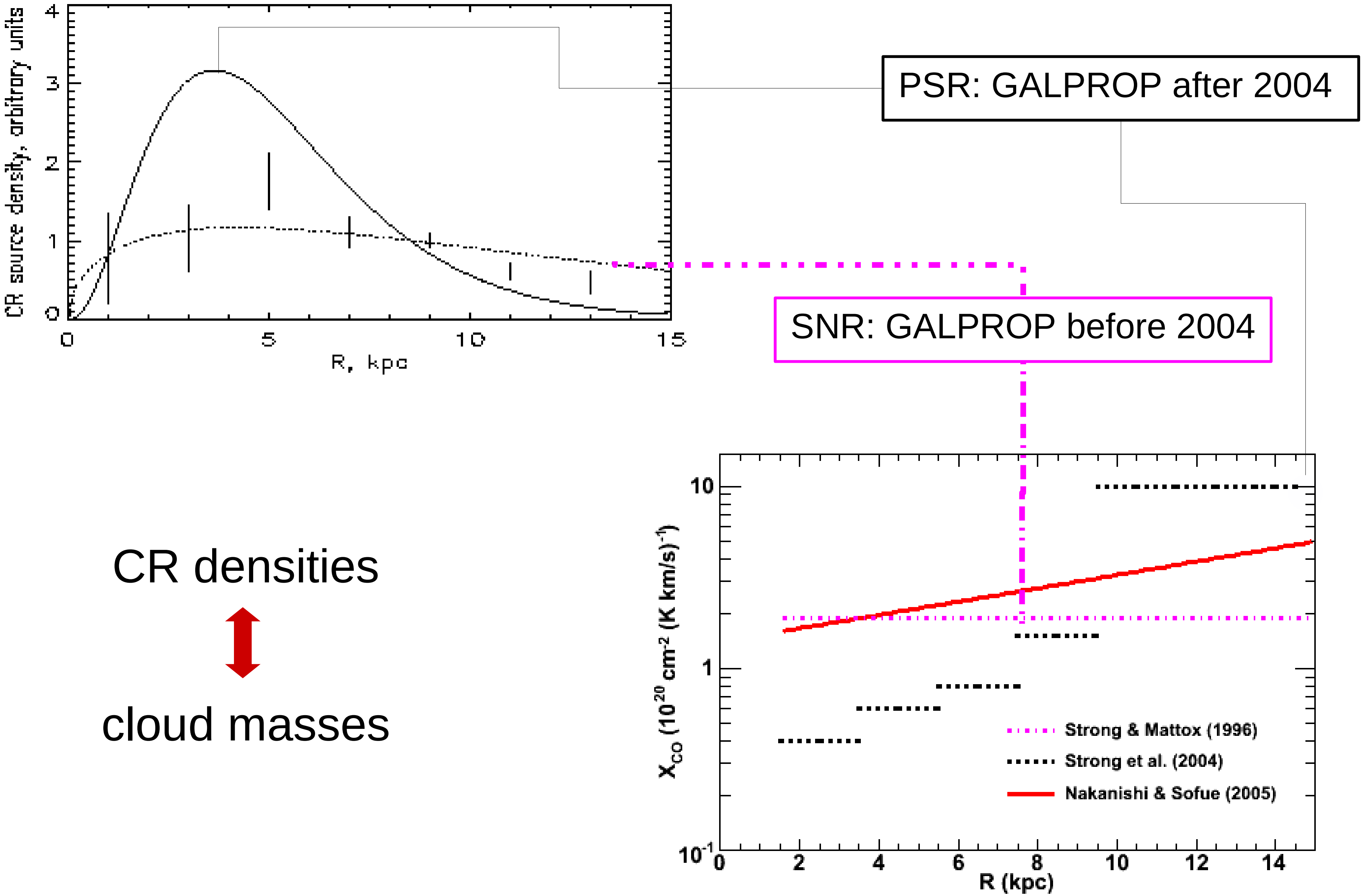
gamma-ray emission from clouds (need to know CR densities or to intercalibrate with H I emissivity)

All methods agree within a factor 2-3
$X_{CO} \sim 10^{20}$ molecules cm^{-2} (K km s^{-1})$^{-1}$

X_{CO} (before *Fermi*)



Molecular masses and CR sources



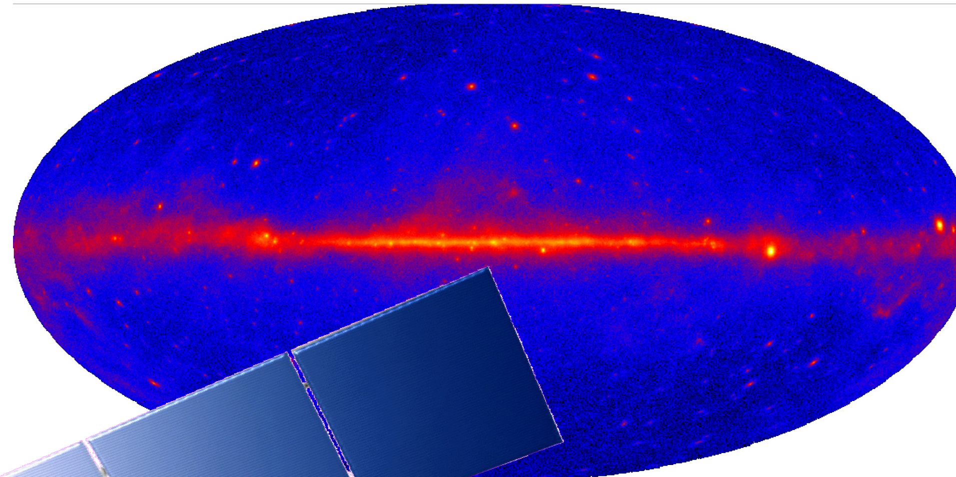
CR densities

⬍

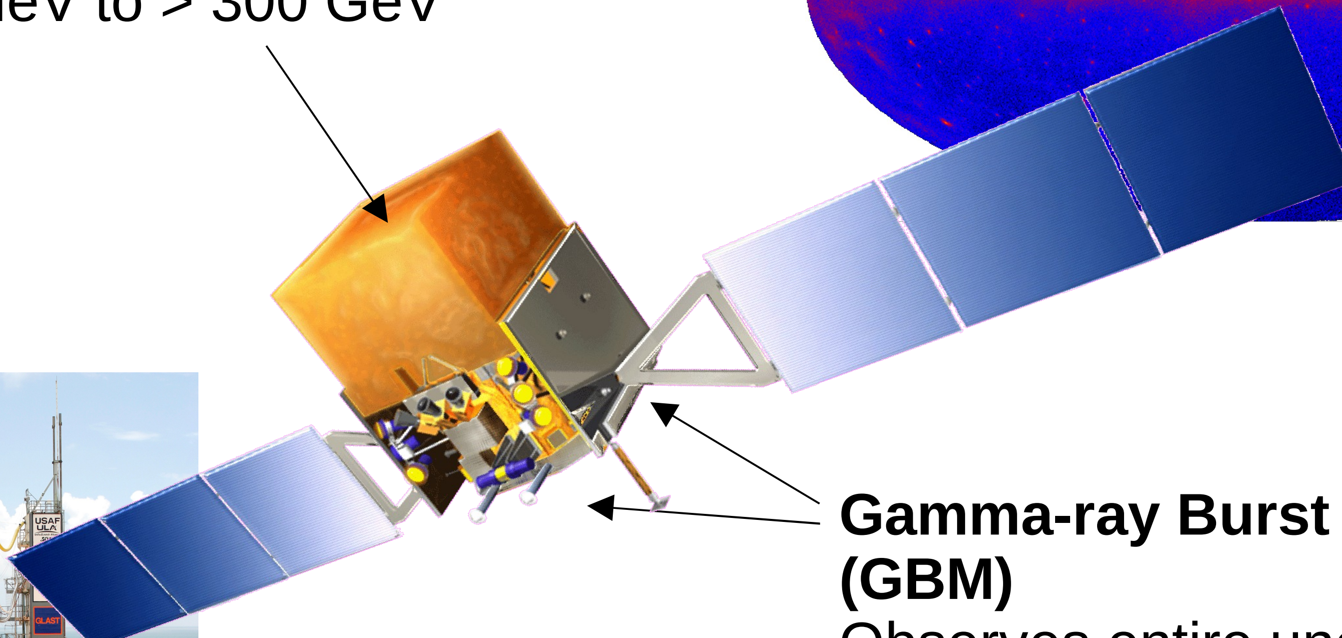
cloud masses

II – The *Fermi* Large Area Telescope and molecular clouds

The *Fermi* observatory



Large Area Telescope (LAT)
Observes 20% of the sky at any instant,
entire sky every 3 hours
from 20 MeV to > 300 GeV



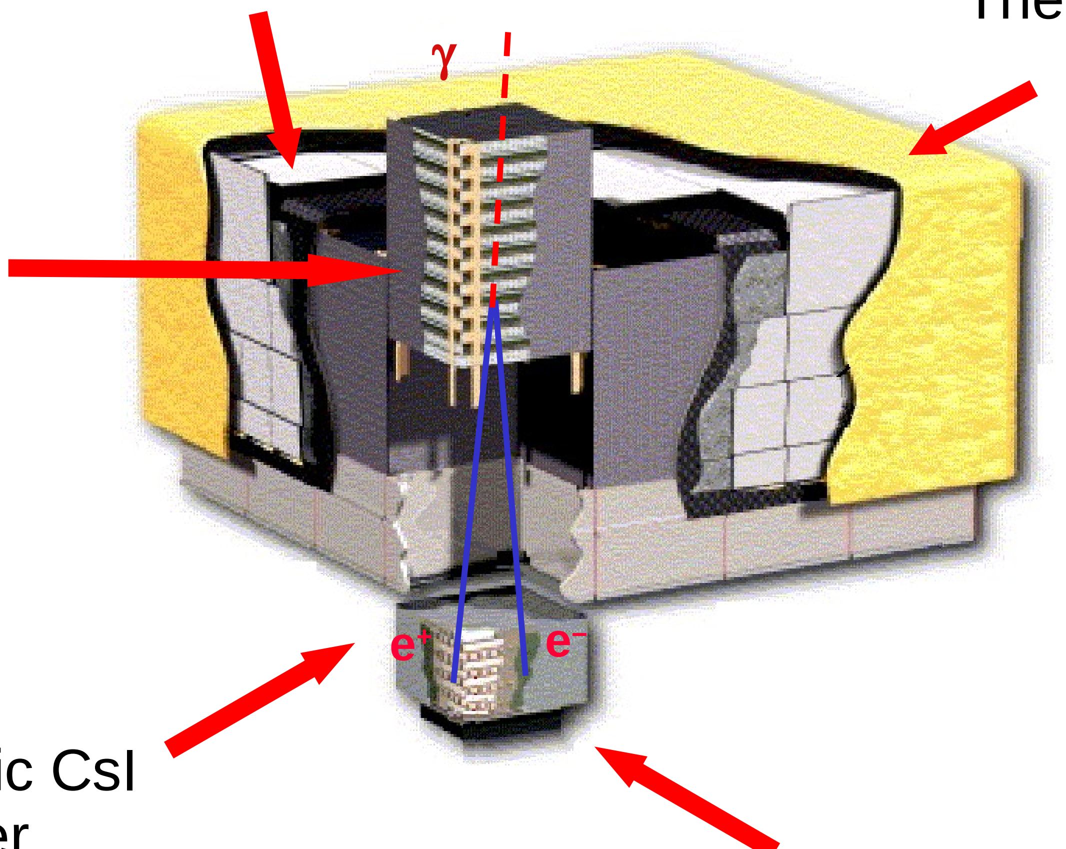
Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky transients from 8 keV to 40 MeV

Launched from Cape Canaveral Air Station on 11 June 2008.
Orbit: 565 km, 25.5°.

Large Area Telescope

Anticoincidence Detector

Thermal Blanket



Precision Si-strip Tracker:

18 x-y tracking planes + W converters

12 x 0.03 X_0 front-end

4 x 0.18 X_0 back-end

Hodoscopic CsI Calorimeter

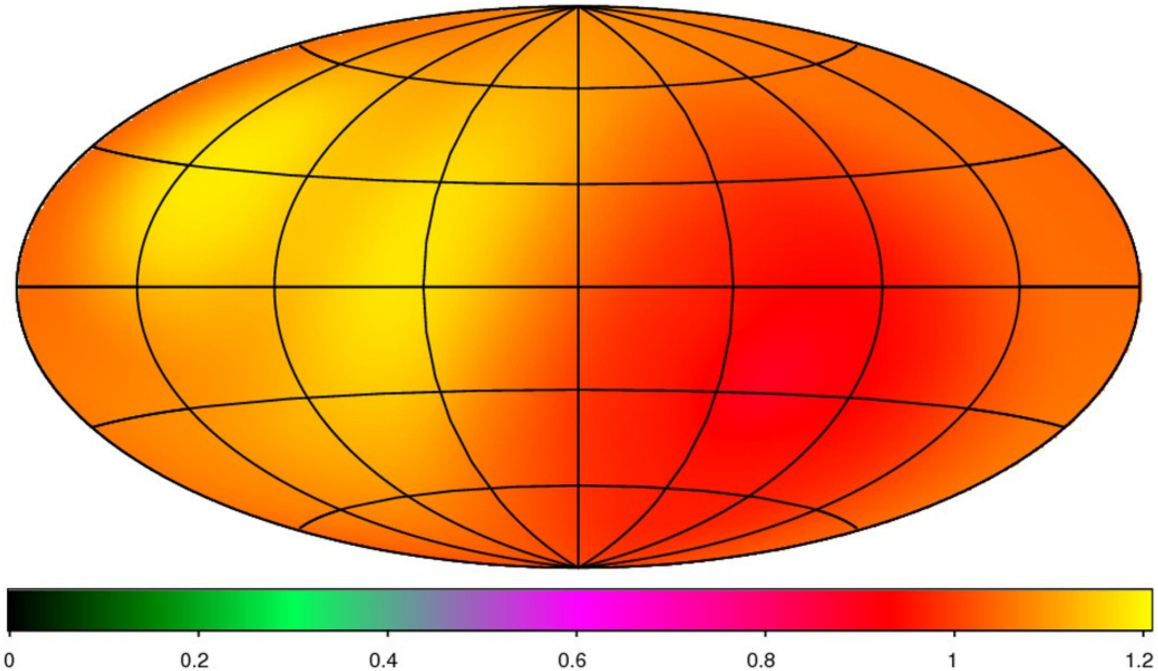
Electronics System

LAT observations

	energy range (GeV)	acceptance (cm^2 sr)	angular resolution (1 GeV)
LAT	0.02 – > 300	20000	0.6° (front)
EGRET	0.03 – 30	750	1.7°

continuous sky survey: whole sky every 3 hours, almost uniform exposure in a few months

Exposure (Ms equivalent on axis) during the first three months of the science phase

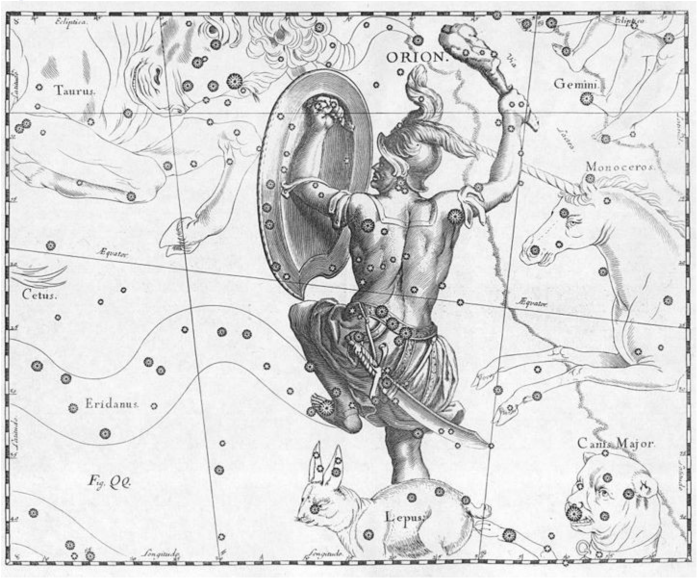


Top-six questions for the LAT

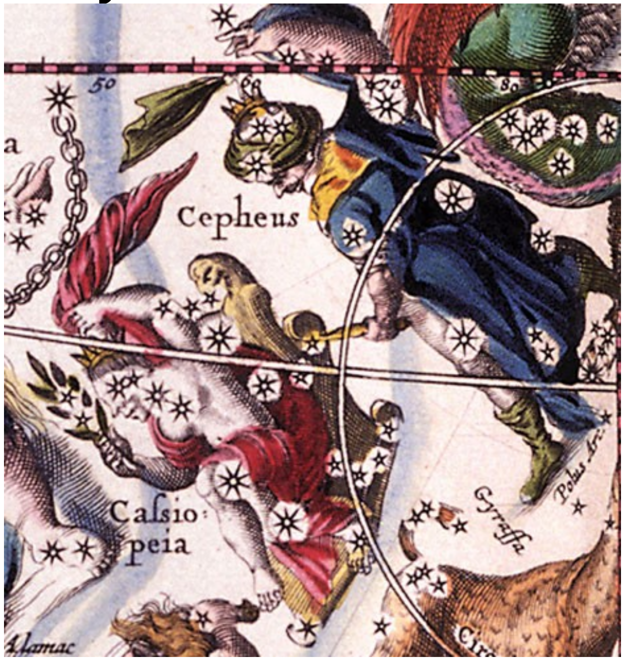
1) Is W_{CO} a good tracer of molecular masses?
2) How does X_{CO} vary in the Galaxy?
3) Is all the neutral interstellar gas traced by H I + CO?
4) What about other environmental variables (e.g. temperature ...) ?
5) How are CR sources distributed in the Galaxy?
6) Are there clouds escaped to CO surveys so far?

Highlight analyses

- Selected local clouds
  - **Orion A & B**
    A. Okumura et al., *Proc of 31st ICRC*



- Selected regions towards the outer Galaxy
  - **Cassiopeia and Cepheus**
    L. Tibaldo, I. A. Grenier et al., *Proc of 31st ICRC*
    arXiv:0907.0312

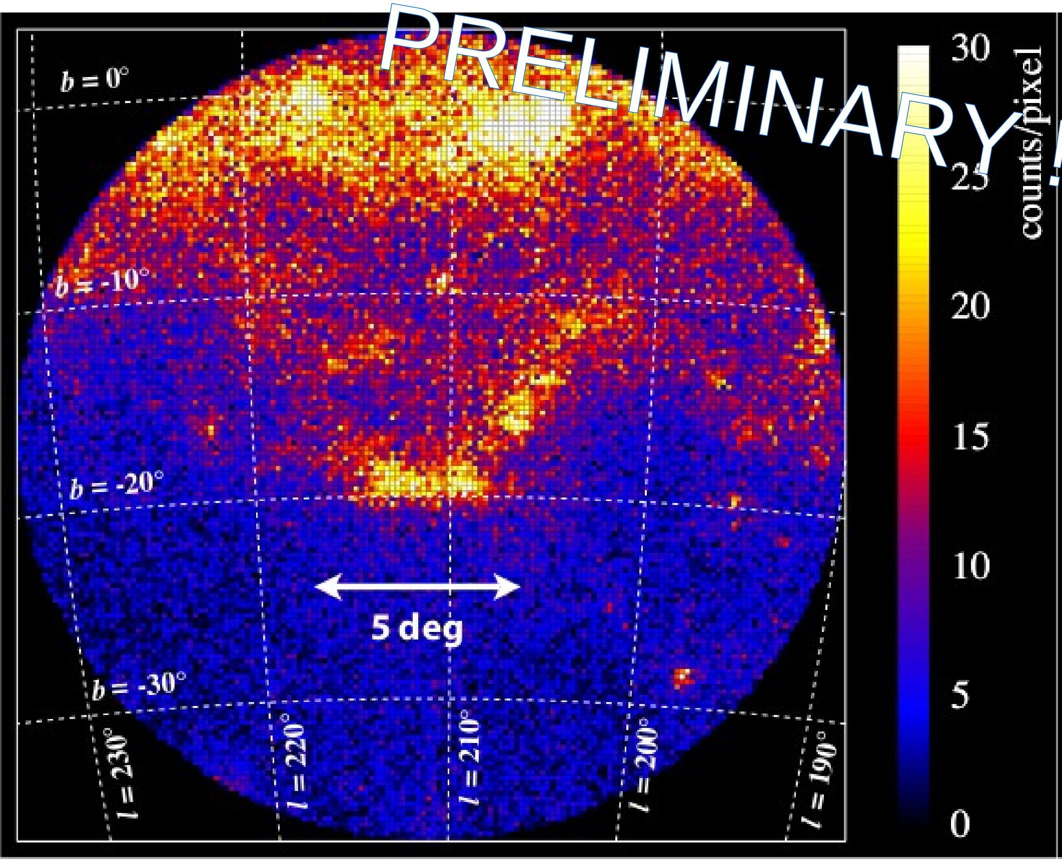


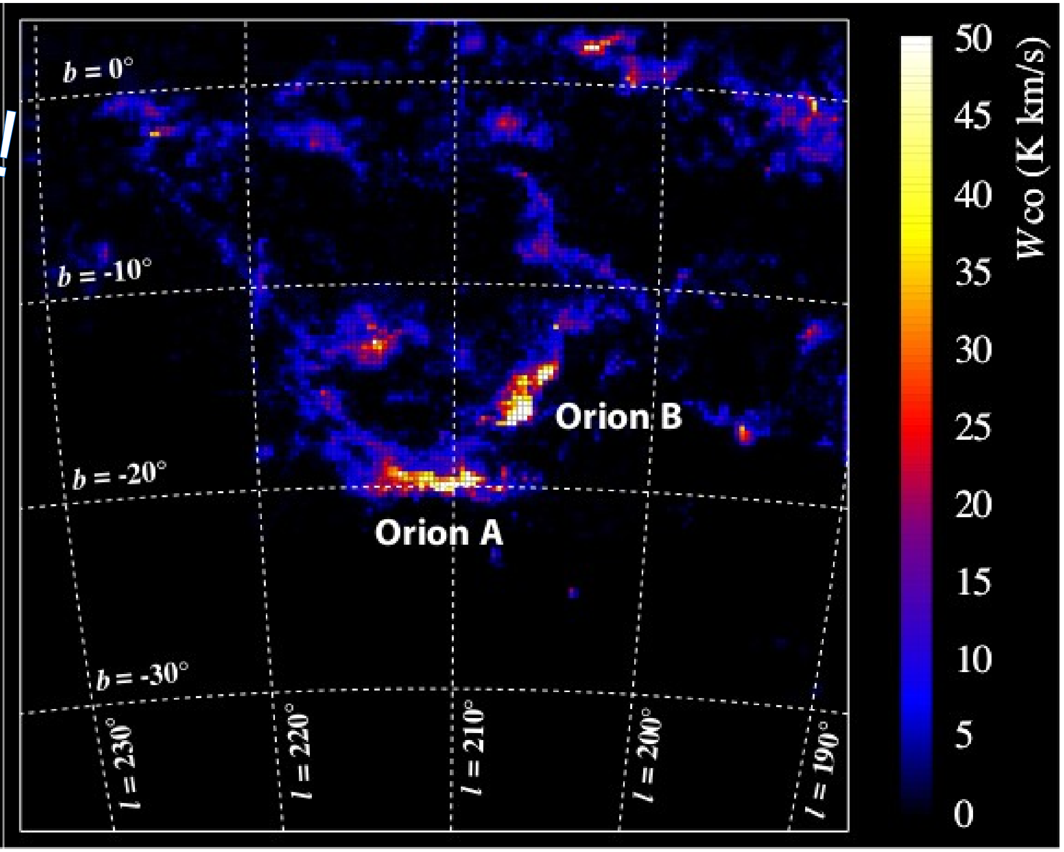
III – The giant molecular clouds in Orion

The Orion molecular clouds

LAT 9 months (200 MeV – 20 GeV)

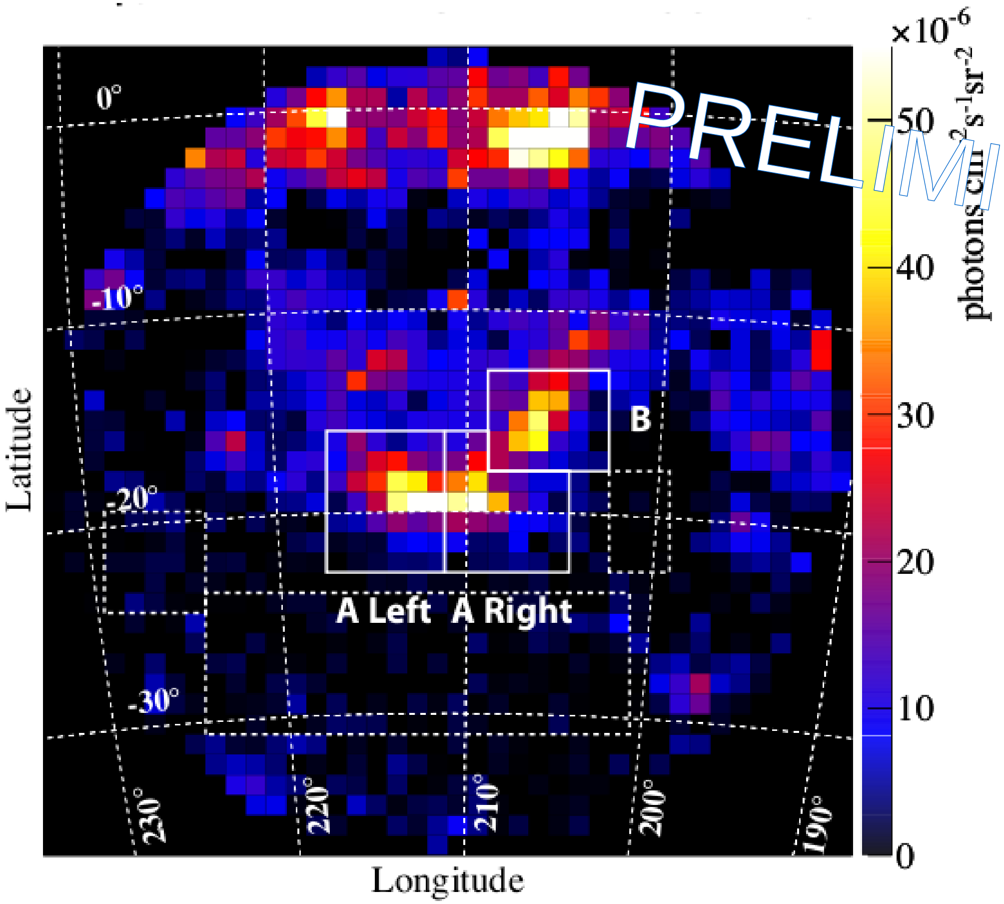
CO (Dame et al. 2001)

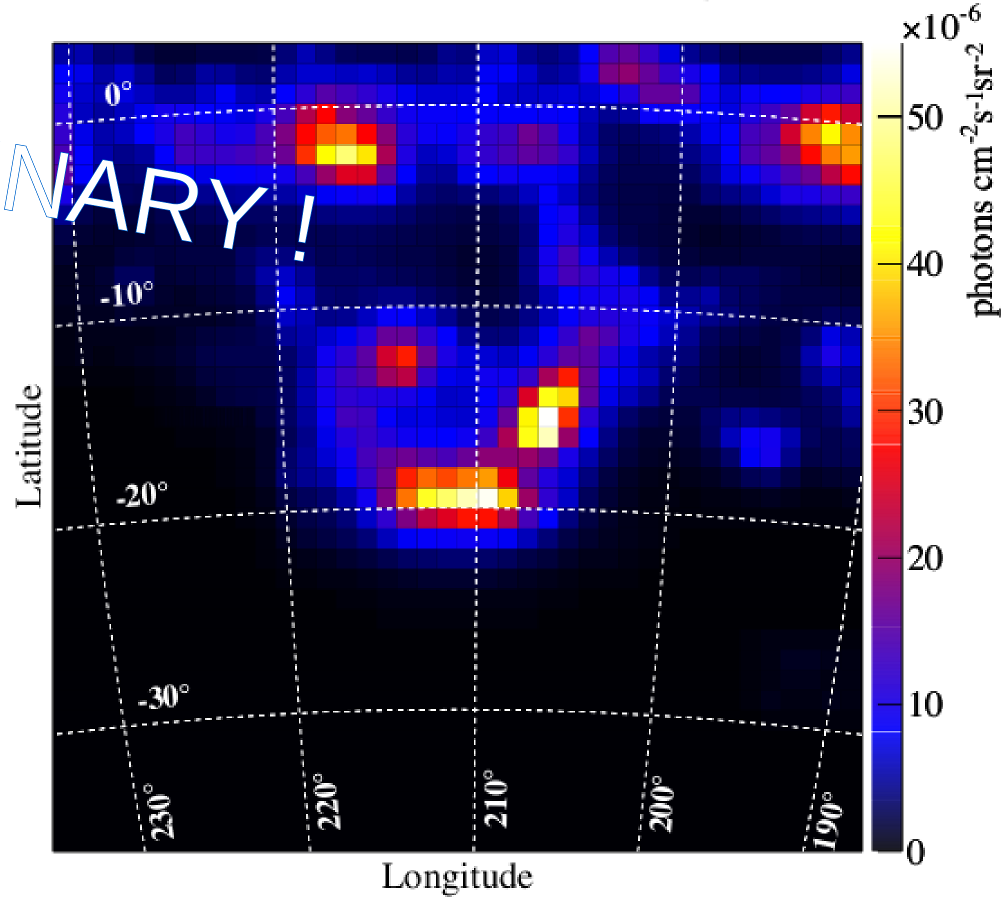




- brightest clouds off plane
- no bright gamma-ray sources known
- ~ 400 pc from Earth (similar CR environment)

Gamma-ray emission from molecular gas





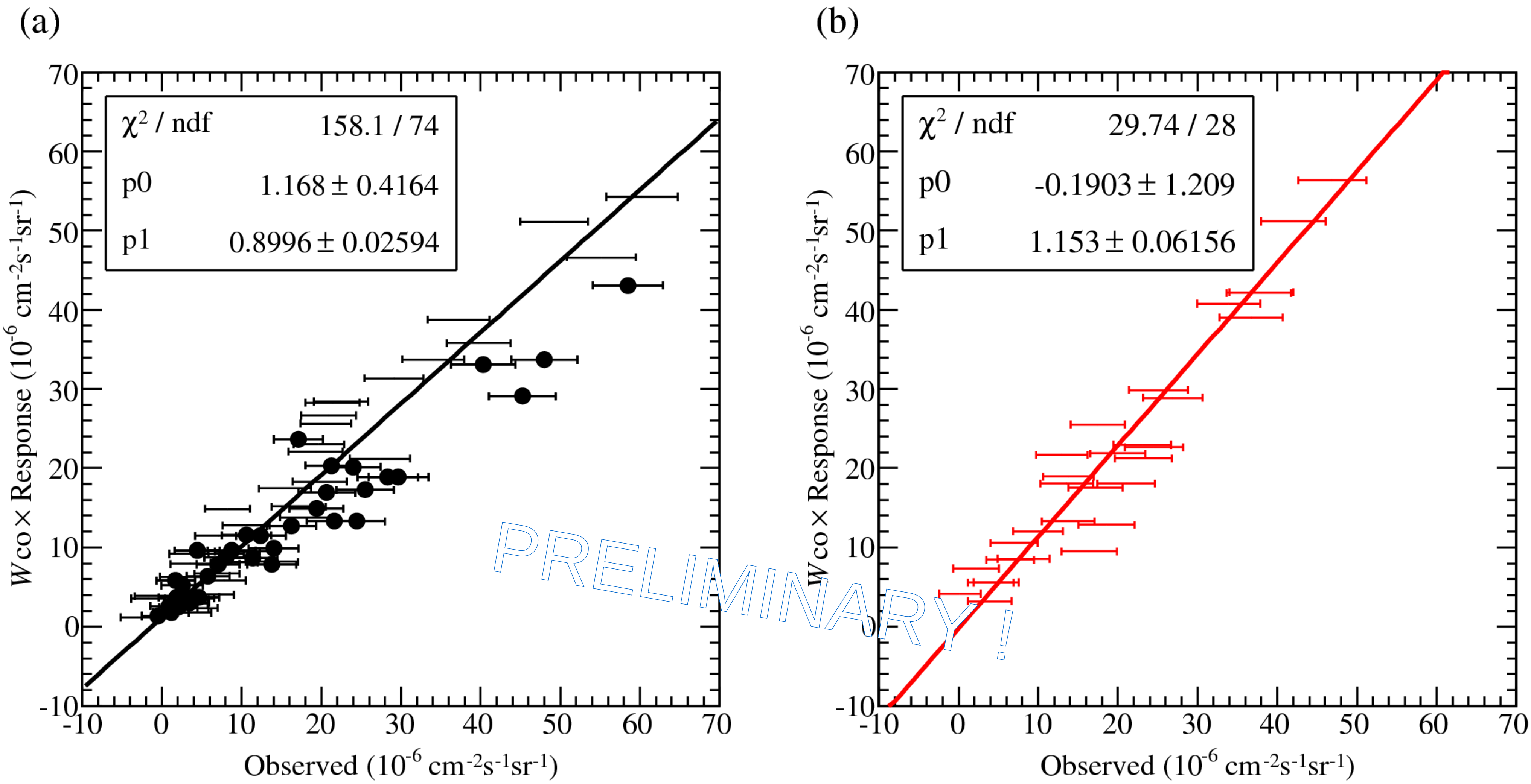
Extracted from LAT data:

- H I and IC emission subtracted using GALPROP tuned to LAT
- isotropic subtracted

Predicted from CO map:

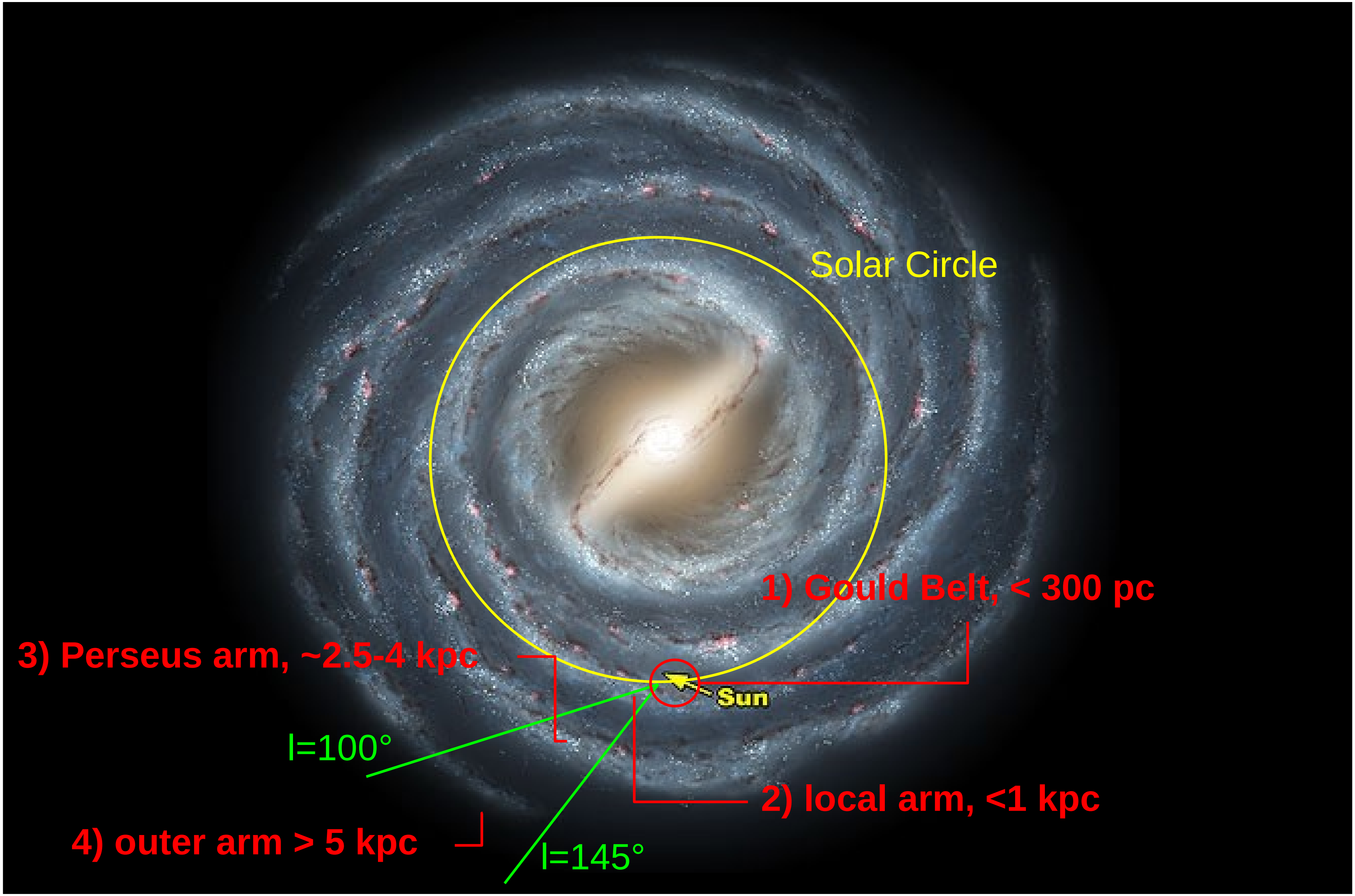
- flux by GALPROP [uniform X_{CO} for the two clouds]
- convolution with LAT PSF and exposure

Gamma-to-CO correlation



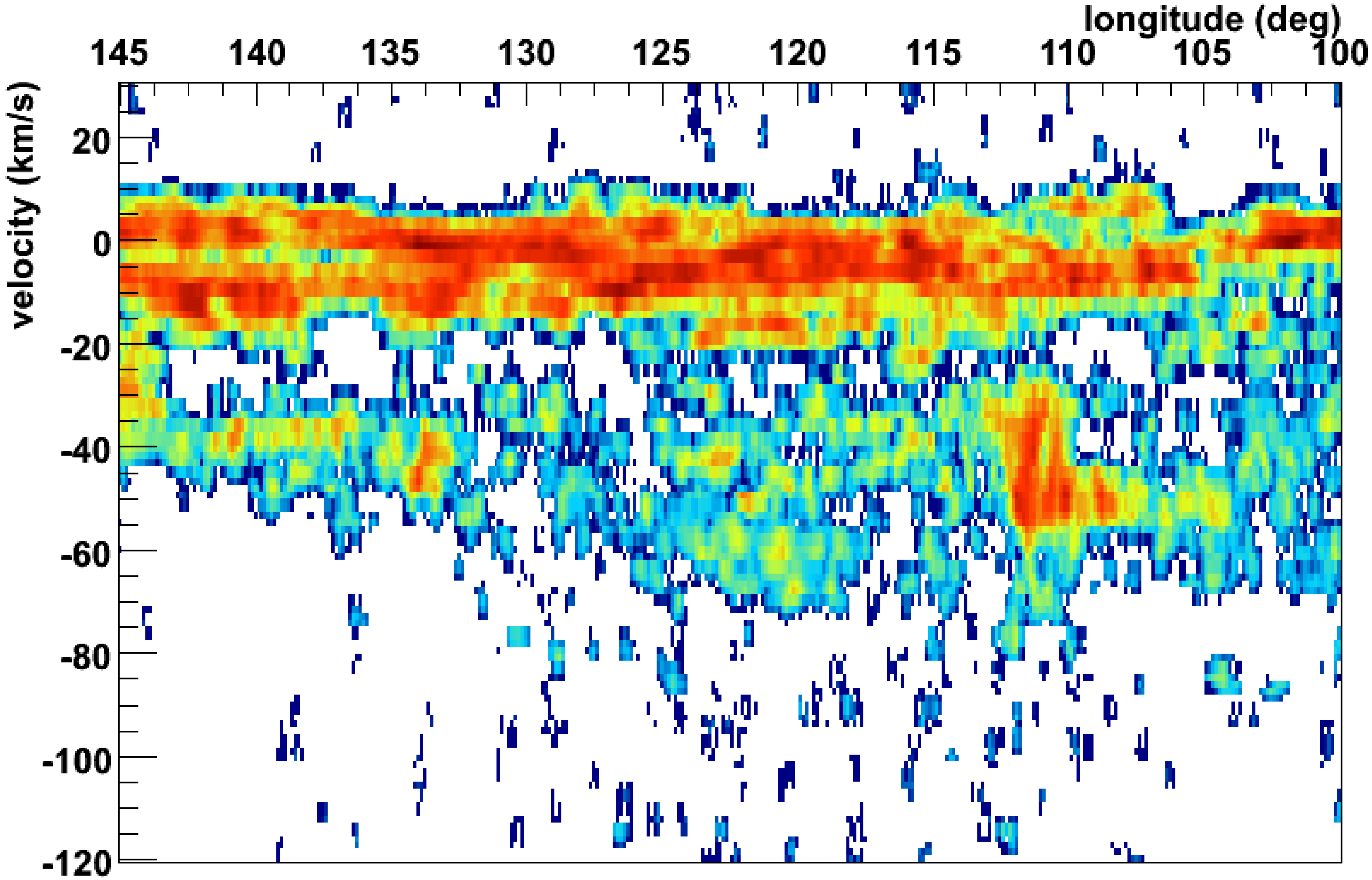
IV – Diffuse emission in Cassiopeia and Cepheus region

Cas & Cep region



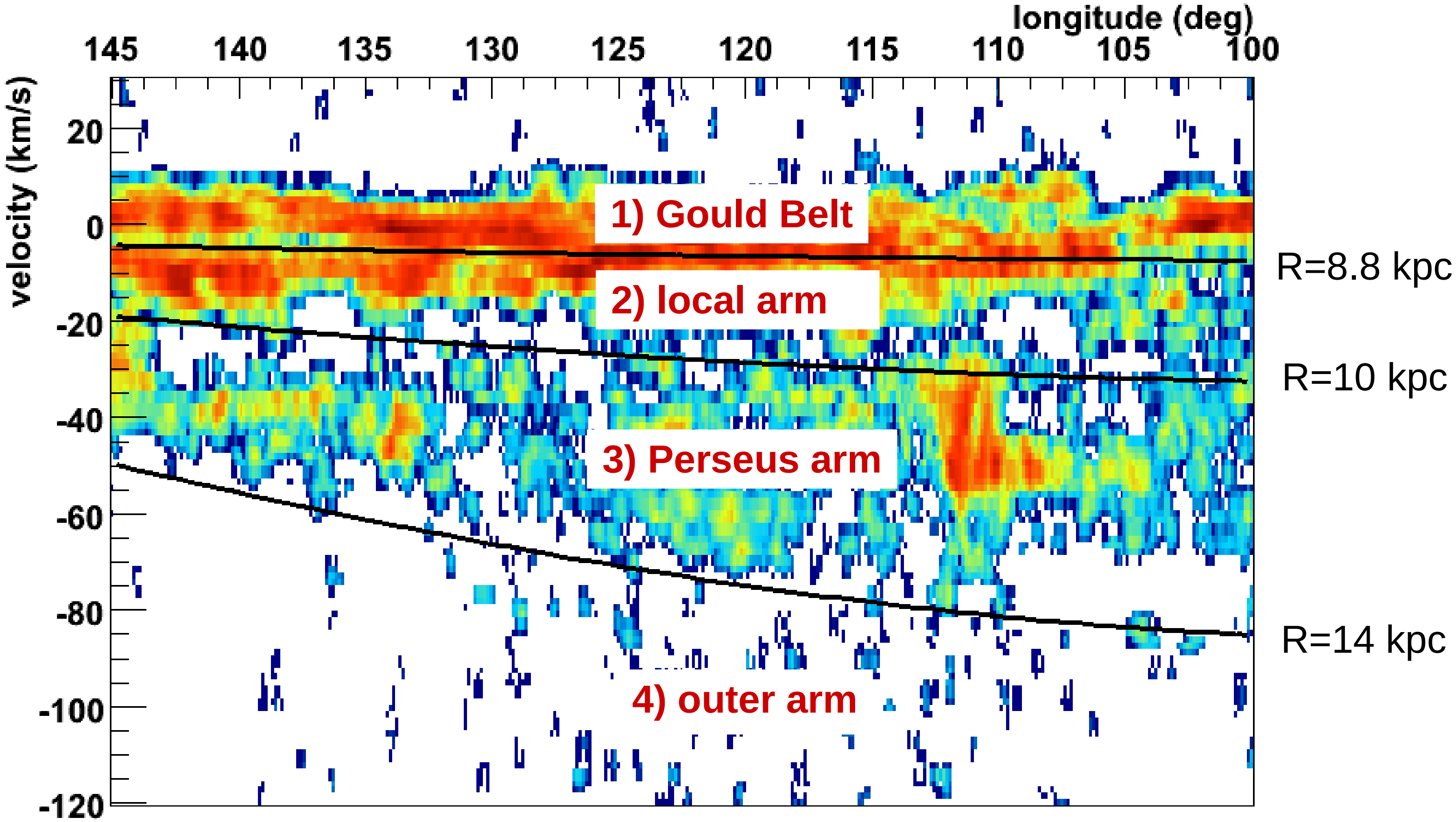
Kinematic separation of gas

$T_B(CO)$ integrated over -10° < b < 10°

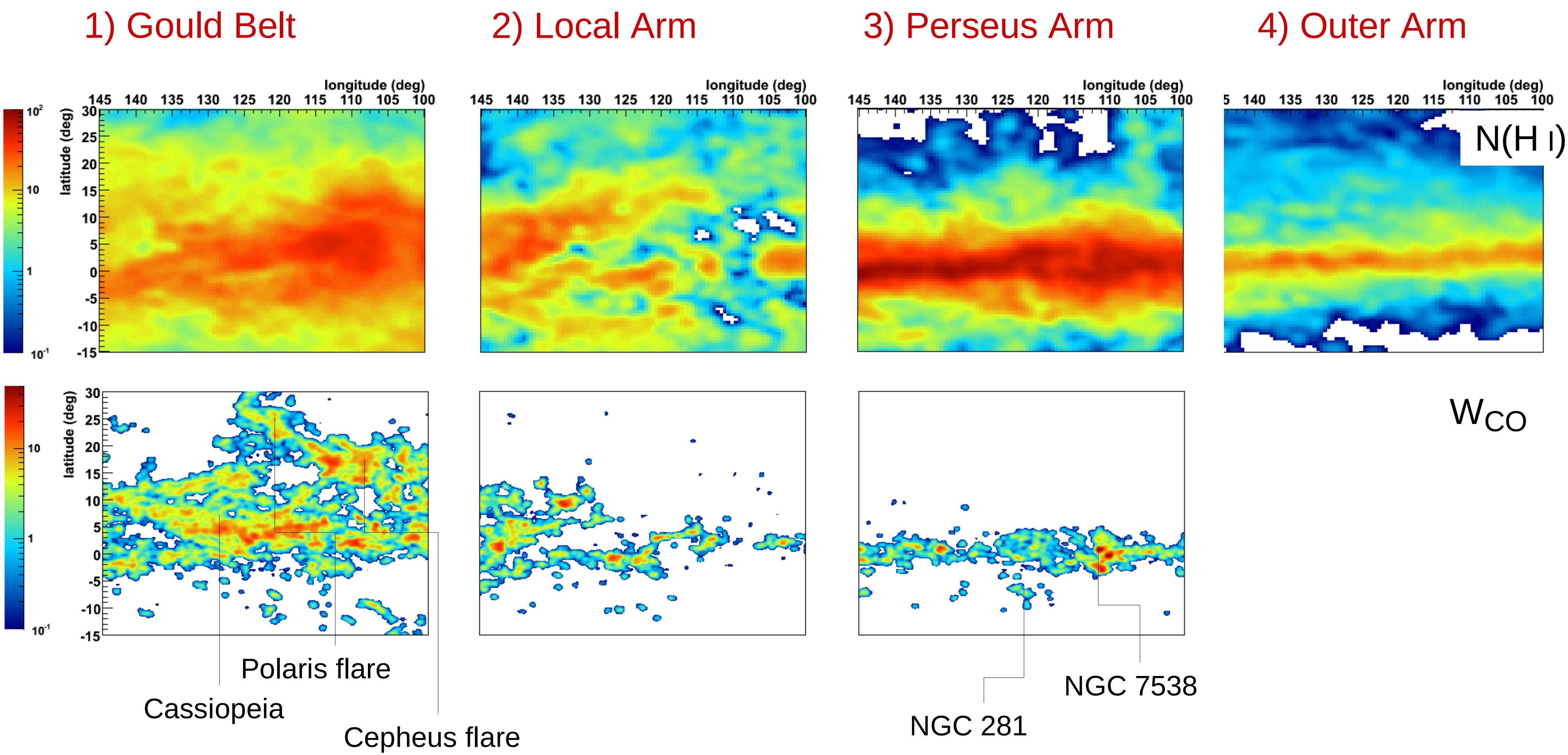


Kinematic separation of gas

T_B(CO) integrated over -10° < b < 10°



H I and CO maps



- H I from LAB survey (Kalberla et al. 2005)
- CO from Dame et al. 2001, moment-masked

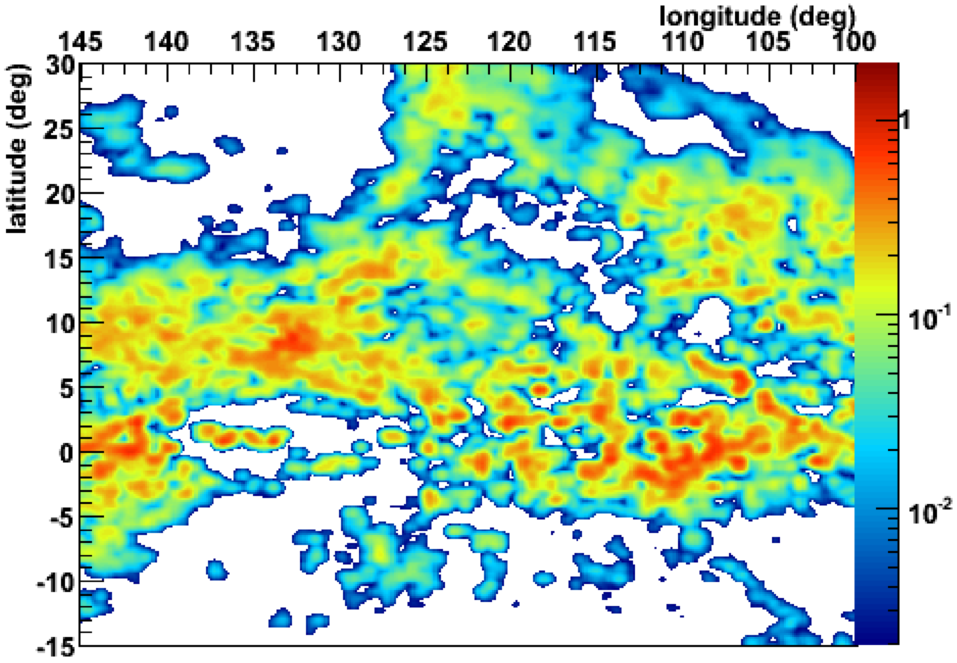
Local dark gas

EGRET gammas + H I + CO + total dust column density

→ Dark neutral gas not shining in radio/other wavelengths

Grenier et al. (2005)

E(B-V) map (Schlegel et al. 1998)
subtracted parts linearly correlated with N(H I) and W_{CO}
$E(B-V)_{res}$ tracer of dark gas.



Gamma-ray analysis

- 9 months of LAT data (diffuse selection + zenith angle < 100°)
- Exposure + LAT PSF
- Binned Likelihood 0.5°x0.5°
- 4 energy ranges
  - 0.3 GeV – 0.6 GeV
  - 0.6 GeV – 1 GeV
  - 1 GeV – 2 GeV
  - 2 – 10 GeV

emissivity per W_{CO} unit (emissivity per H_2 is twice emissivity per H I) -> X_{CO} value

$$X_{CO\,i} = \frac{B_i}{2 A_i}$$

H I emissivity
-> CR density
-> **distribution of CR sources**

$$I(l,b) = \sum_i \left[A_i N(H_I)(l,b)_i + B_i W_{CO}(l,b)_i \right]$$

$$+ C \cdot E(B-V)_{res}(l,b) + D$$

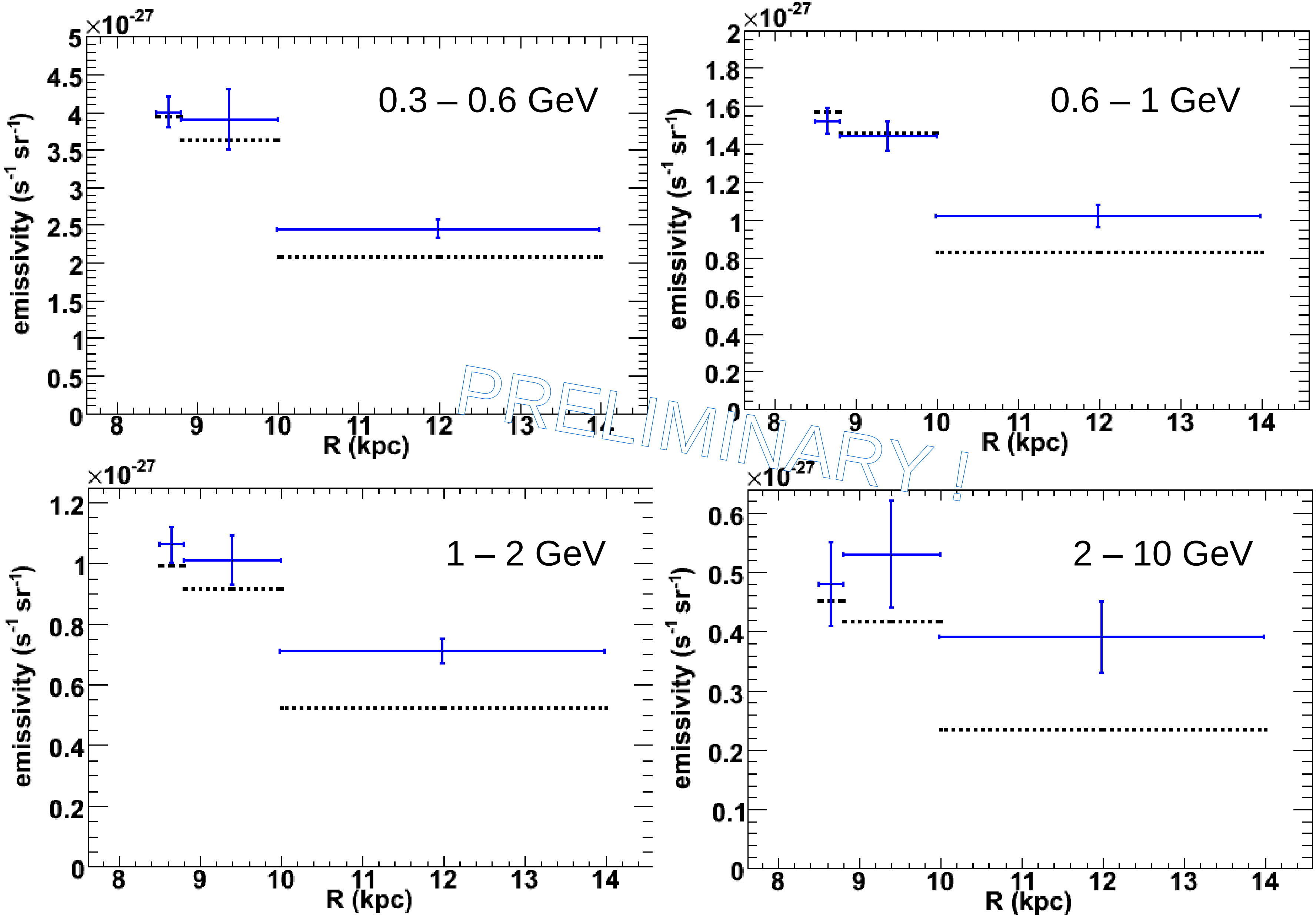
$$+ \sum_j S_j \cdot \delta^{(2)}(l-l_j, b-b_j)$$

gamma-ray flux

LAT Bright Source List

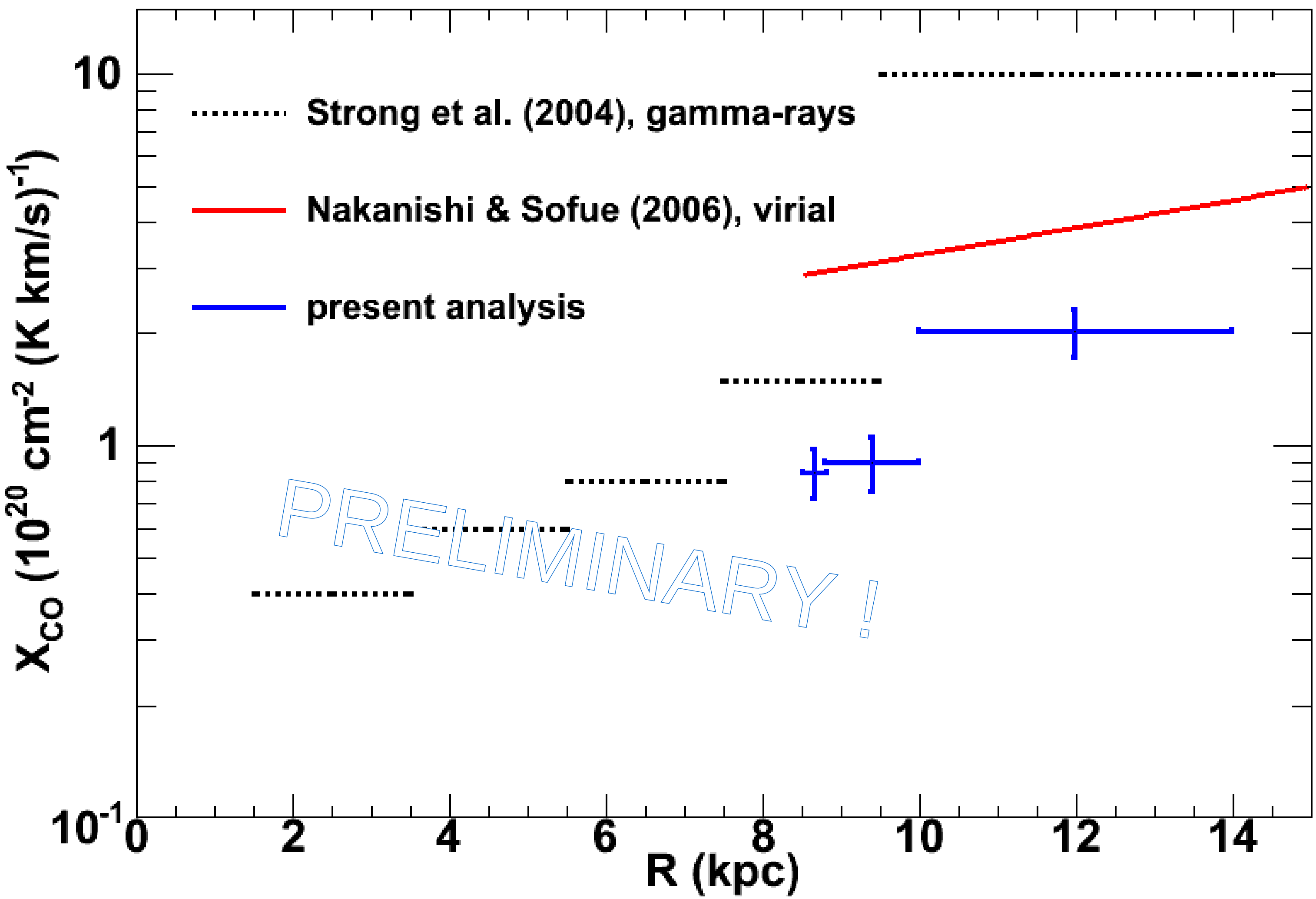
EGB
+ charged bkg
+ IC

Gradient of H I emissivities



Comparison with Galprop using CR source distribution like SNRs as traced by PSRs.

X_{CO}: local and outer Galaxy



V – Concluding remarks

- Improved constraints for X_{CO} in the local/outer Galaxy, confirmed increase with Galactic radius

- Large variability of X_{CO} between local clouds?

- Gradient of gamma-ray emissivities in the outer Galaxy flatter than for supernova remnant sources (as traced by pulsars)

VI – Backup slides

H I emissivity