Summary of the lesson

Cosmic Rays

CRs in Galaxies

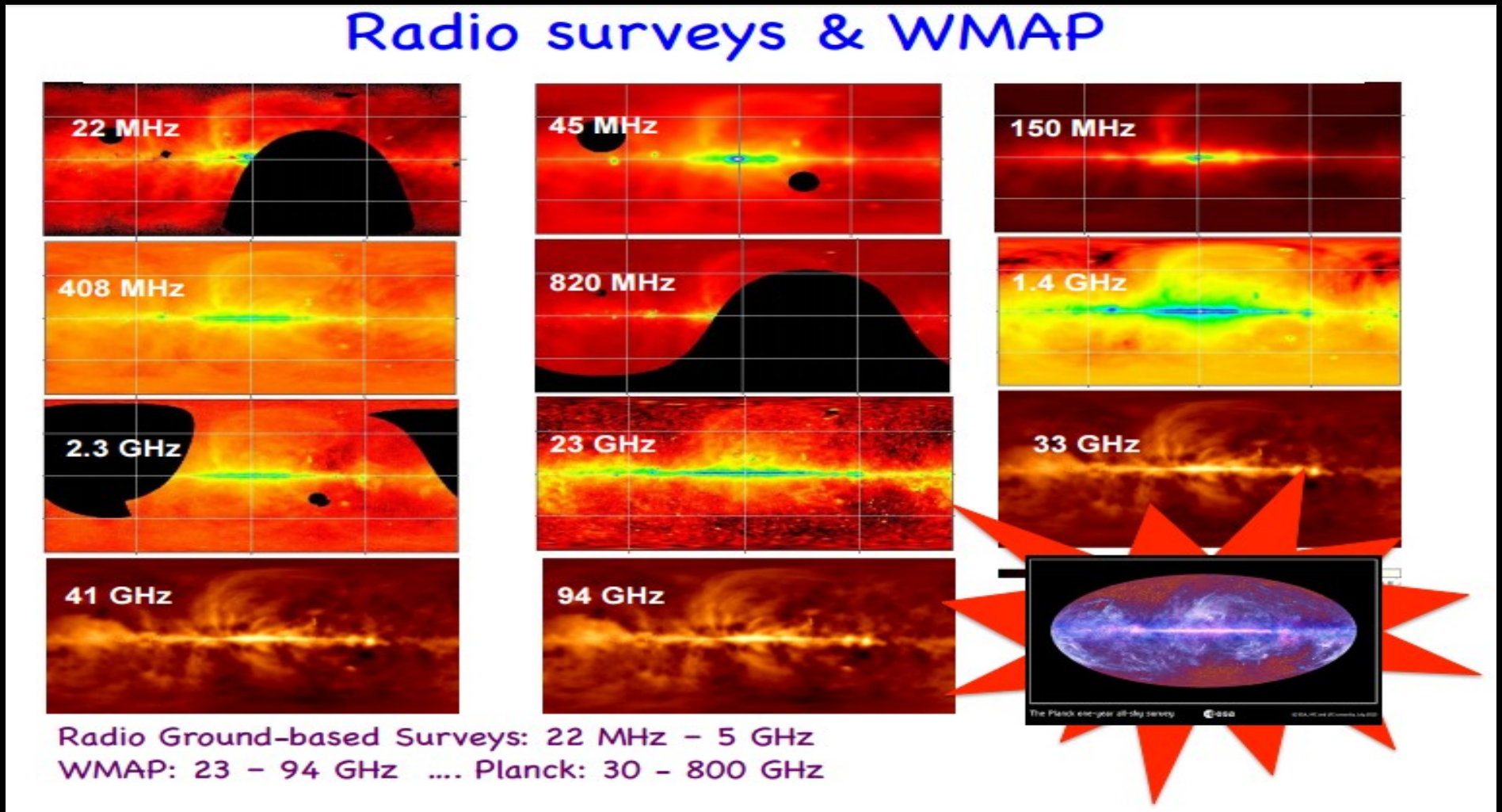
- **The MilkyWay in ɣ Rays**
  - Diffuse emission
  - Molecular Clouds
- **ɣ Rays from other galaxies**

Supernova Remnants

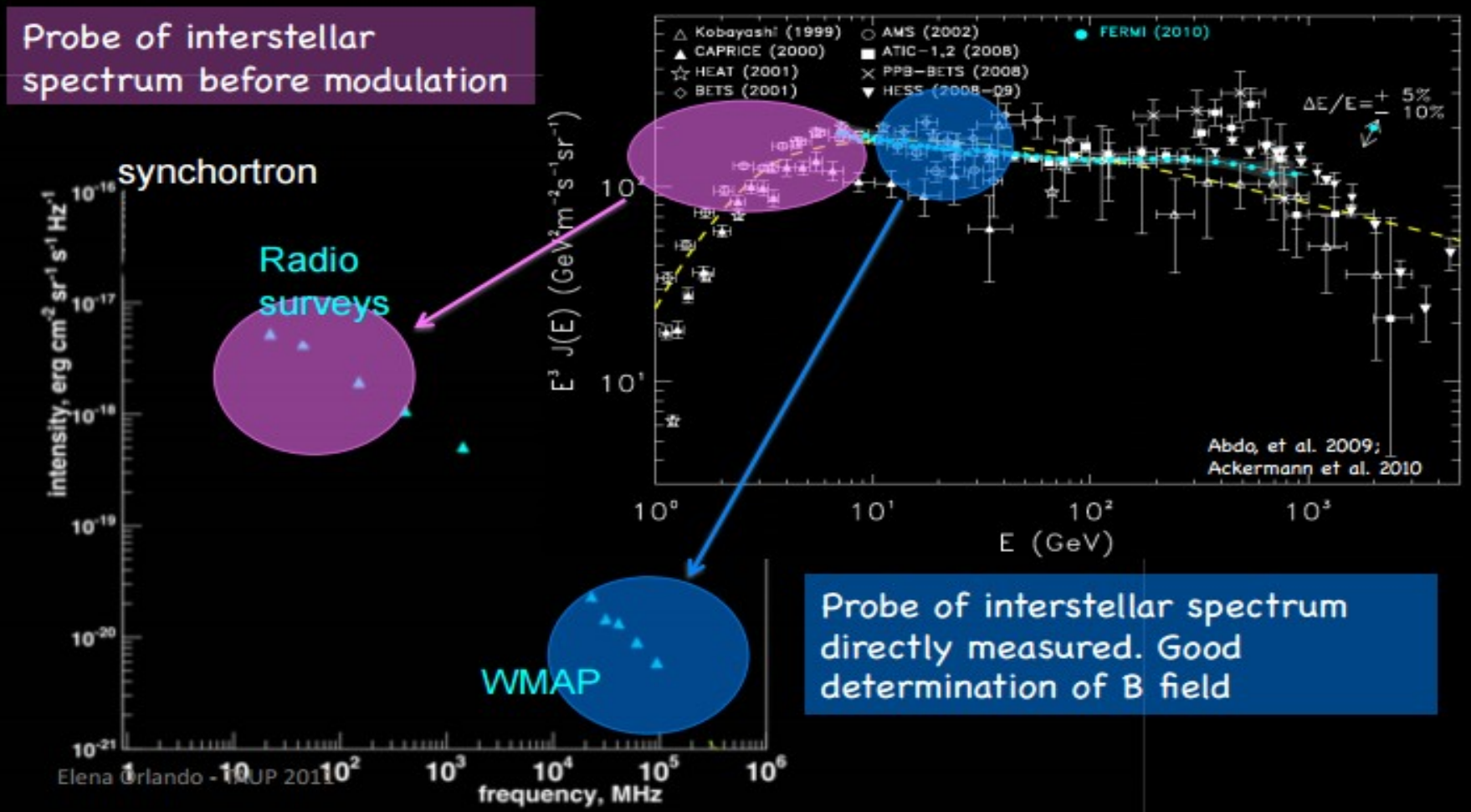
- Evolution
- MC associations
- Gamma-ray from SNR

Others possible CRs sources

Radio emission of the Galaxy

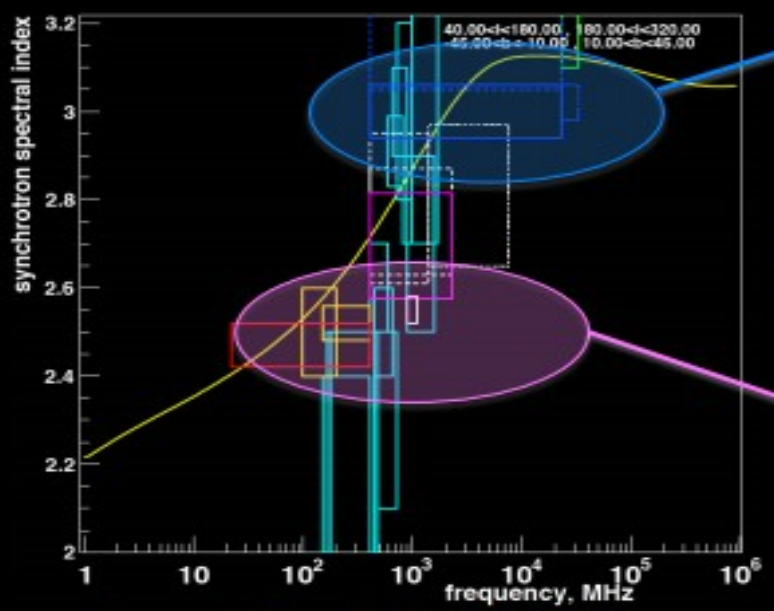


Radio emission of the Galaxy



Radio emission of the Galaxy

Synchrotron spectral index measurements ...



Strong, Orlando & Jaffe A&A accepted (arXiv:1108.4822)

β~3.0 → P~3.0

β=2+(p-1)/2
(p=ambient e- spectrum)

β~2.5 → p~2.0

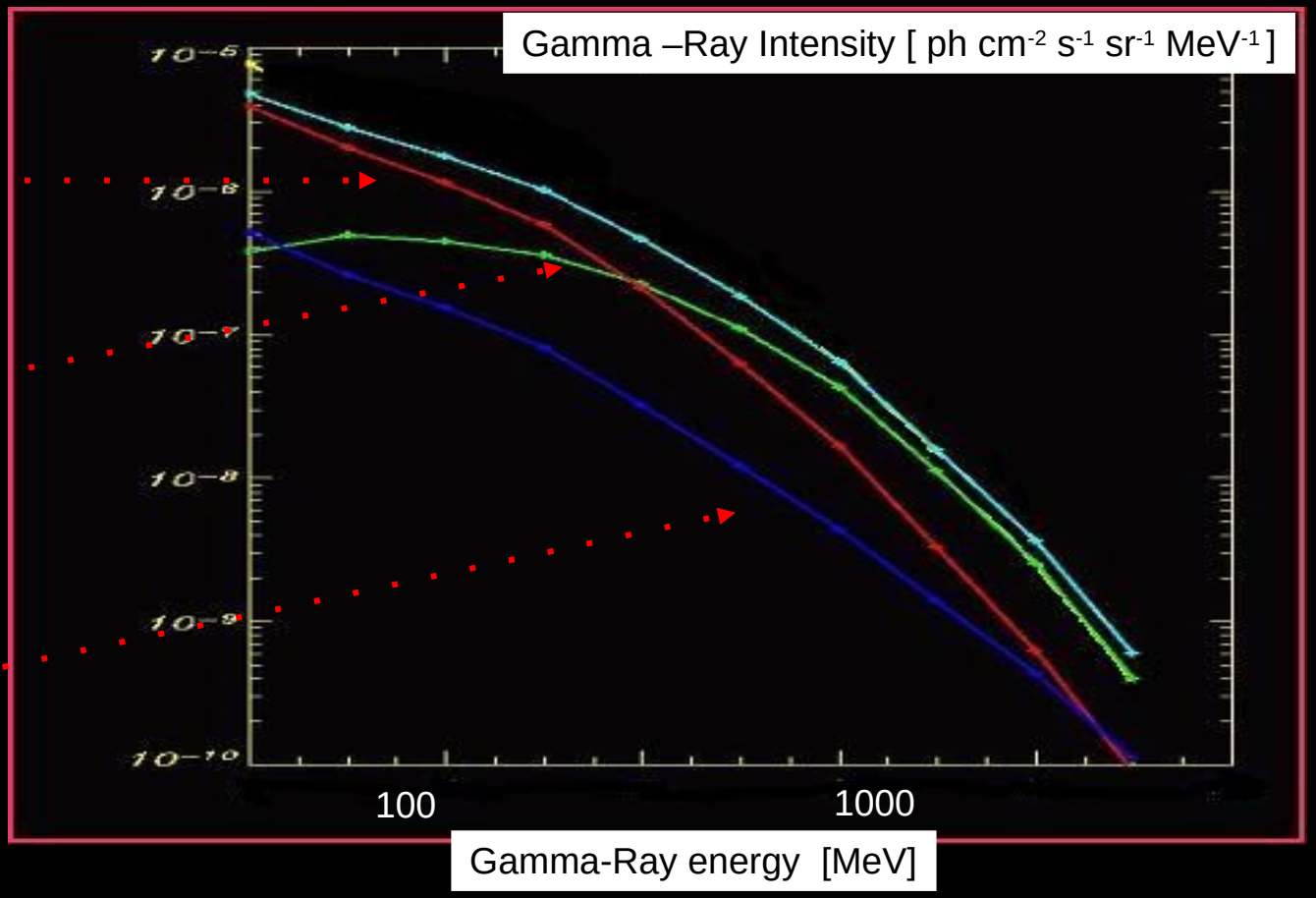
... need of a break in interstellar e-

Gamma-Ray Spectrum

Electron Bremsstrahlung

π^o decay

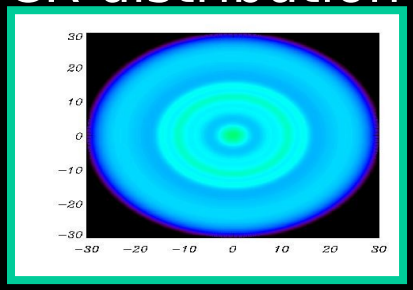
Inverse Compton



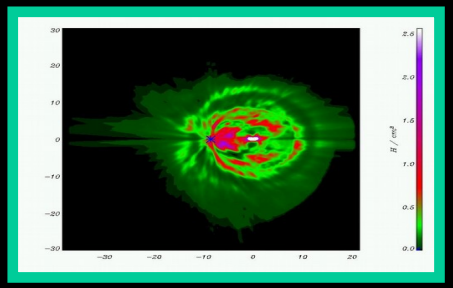
$$I(E) = \frac{1}{4\pi} \int_0^\infty \left[q_{pp}(E) + q_{br}(E) \right] n_H + q_{IC}(E)\ n_{ph}\ dr$$

Gamma rays / CR connections

CR distribution

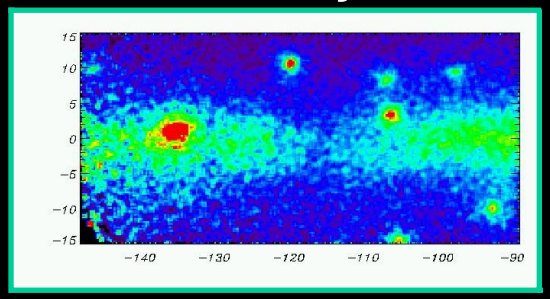


Targets distribution

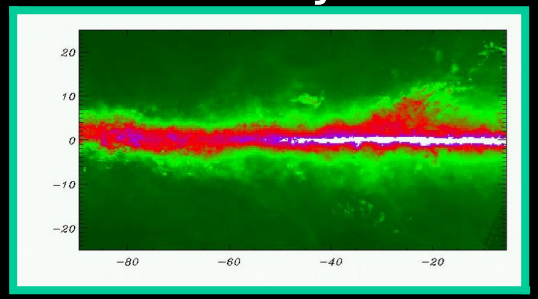


Integrating along the line of sight

Gamma Ray Data

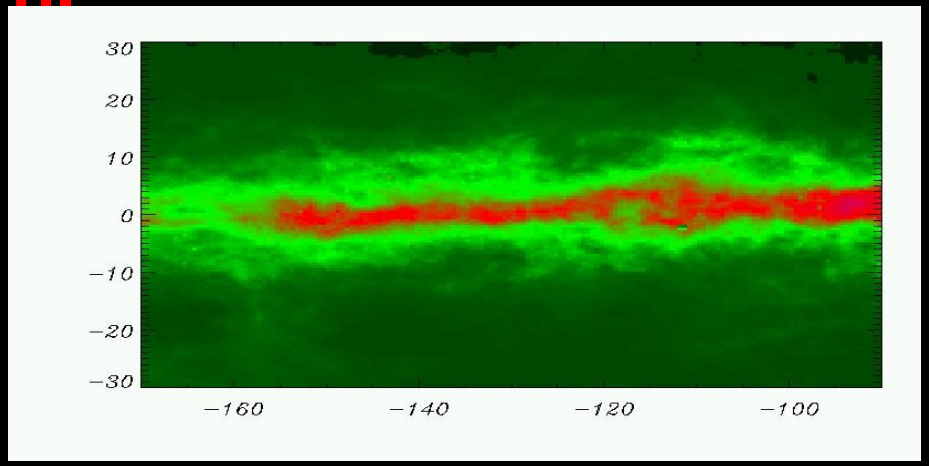


Gamma Ray model

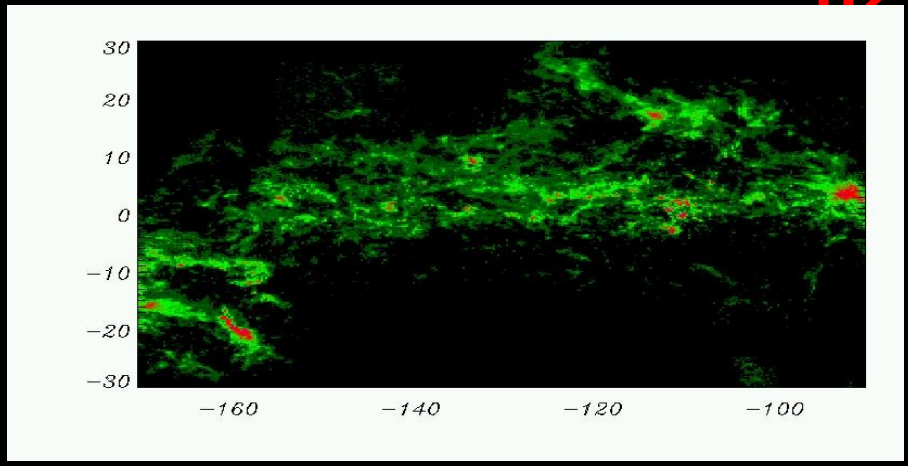


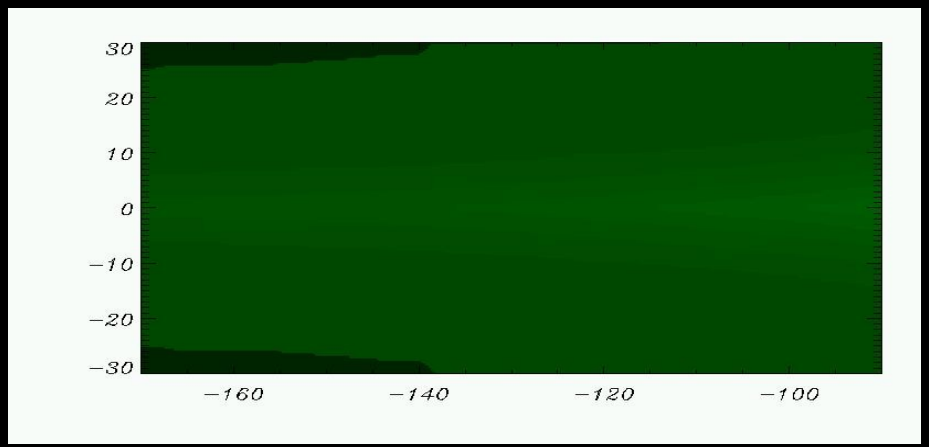
The γ-ray emission model (II quadrant)

HI



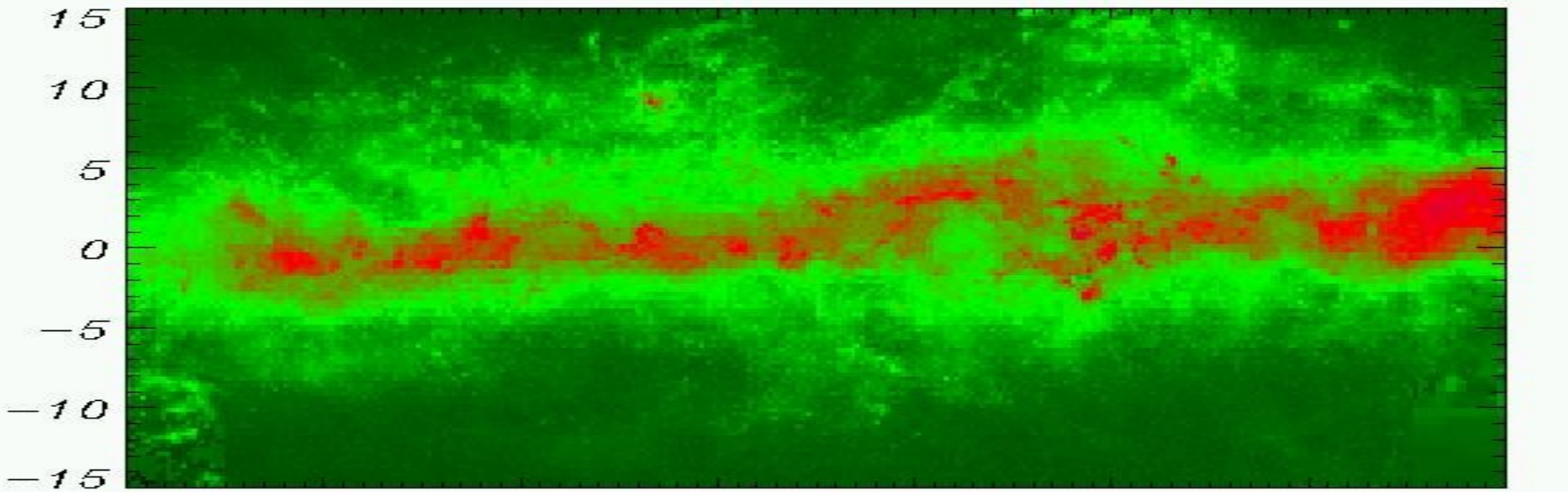
H2



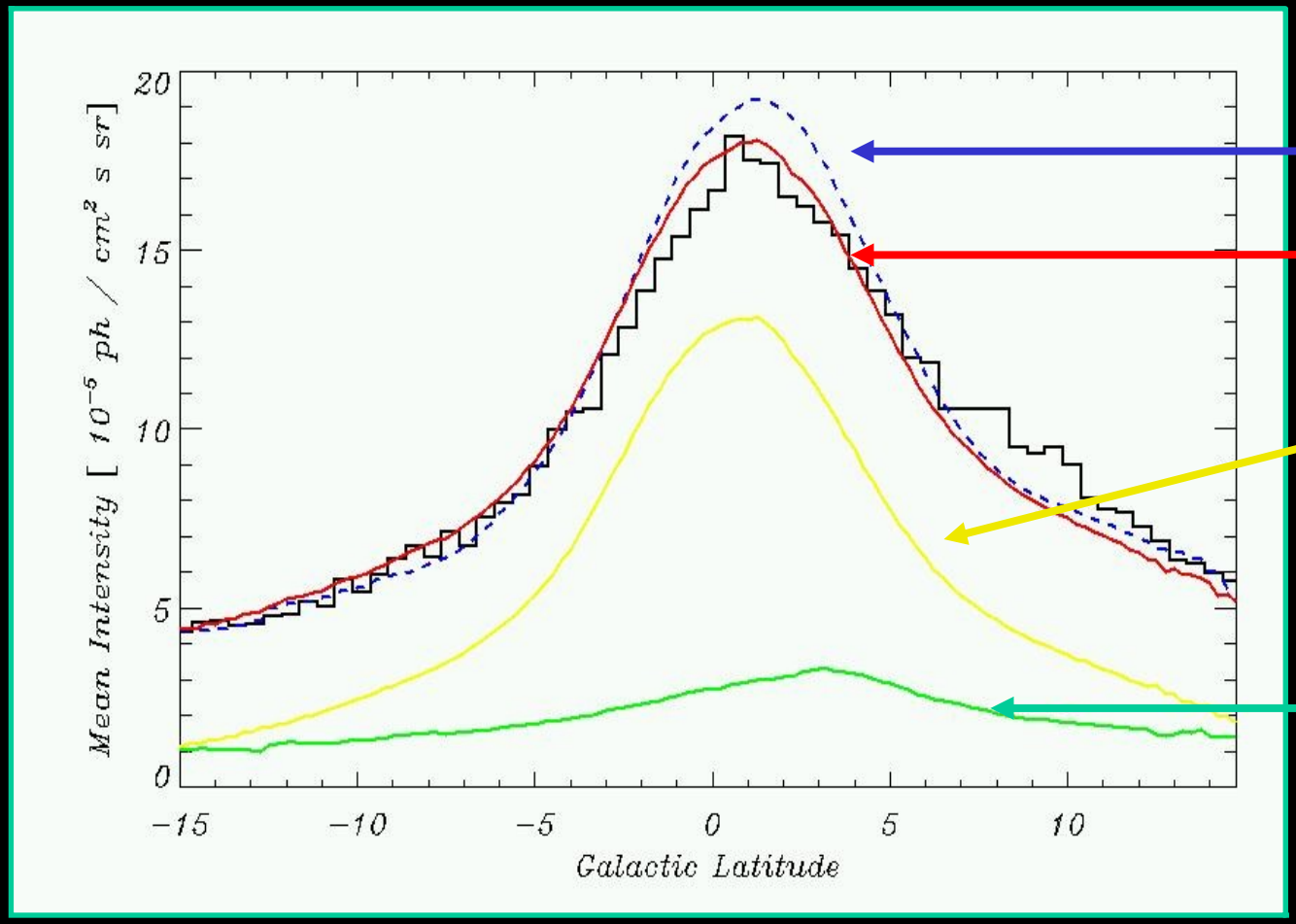


ISRF

The γ-ray emission model (II quadrant)



Model vs. Observations
(II quadrant)



EG. model

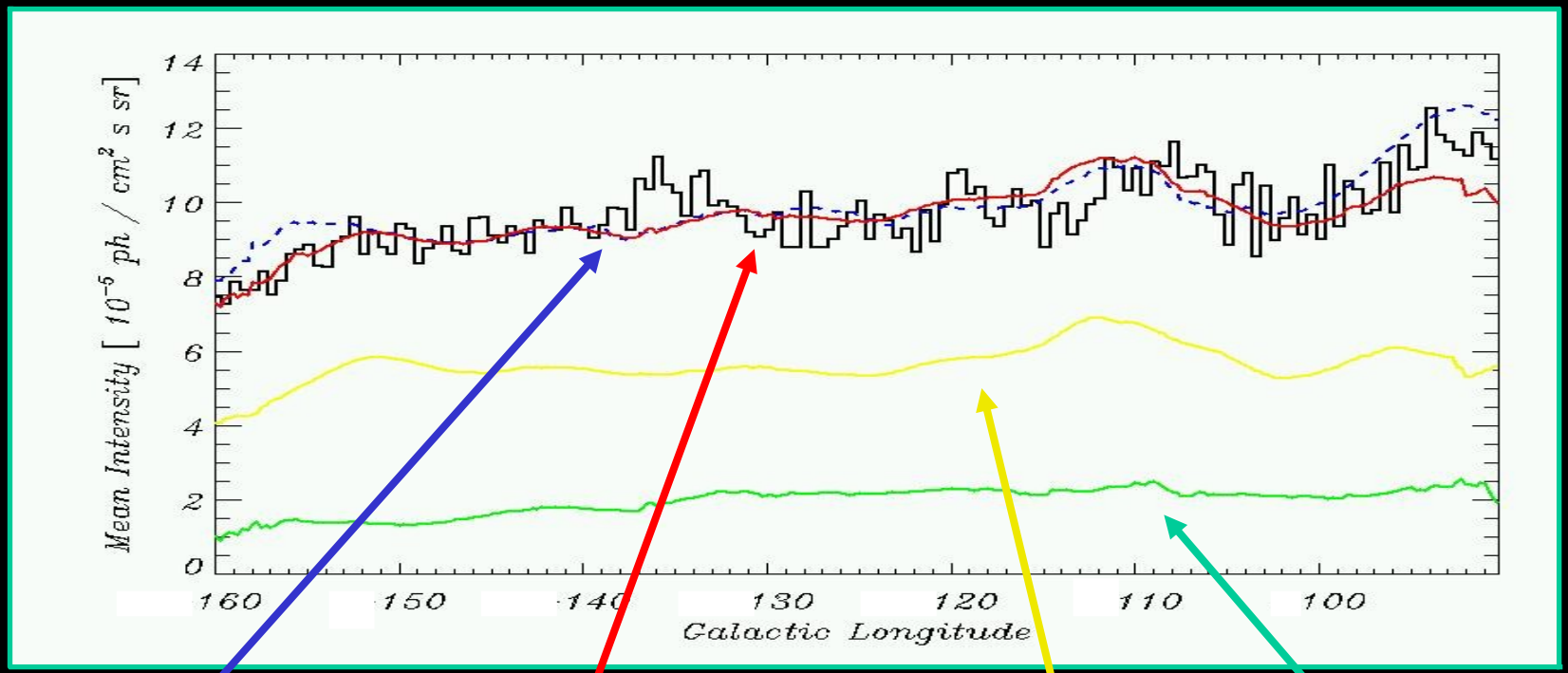
AG. model

Emission from HI regions

Emission from molecular clouds

Model vs. Observations

(II quadrant)



EG. model

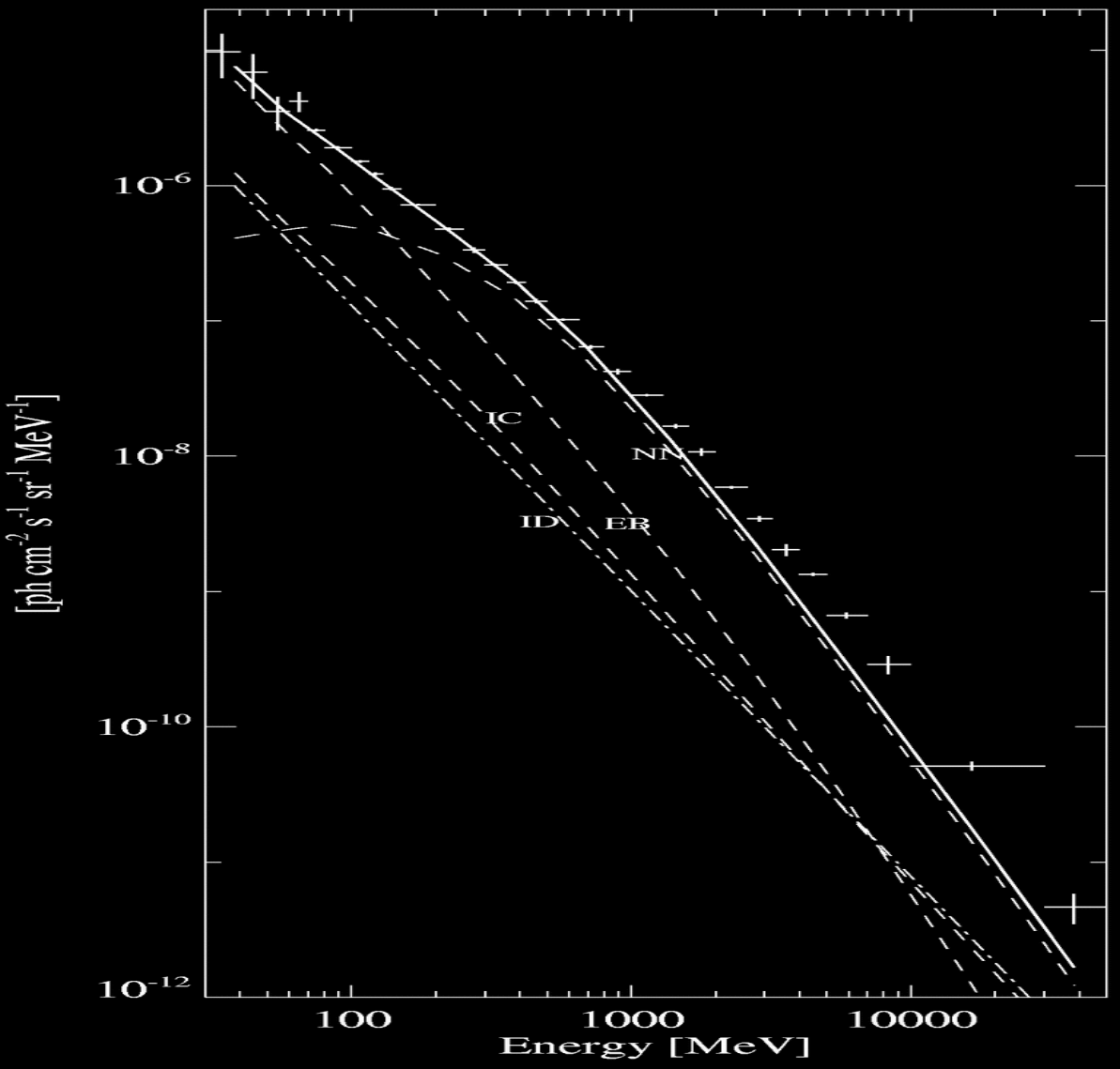
AG. model

Emission from HI regions

Emission from molecular clouds

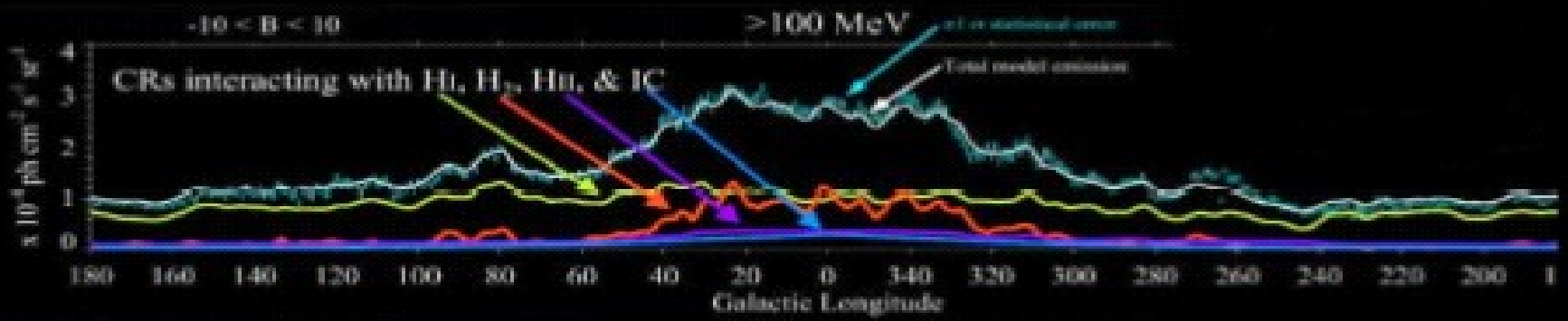
Results from EGRET

π^0 bump in the inner Milky Way
(Hunter et al. 1997)



Results from EGRET

Spatial correlation between gaz and γ-rays



Observations (EGRET):

- large scale spatial distribution well modelled by combination of ISM phases (assuming $I \propto \rho^2$)
- fraction of unresolved point sources is small (unless distributed like the interstellar gas)
- spectrum does not vary (within relatively small uncertainties) in the Galaxy
- deviations from perfect fit

Implications:

- Gamma-Rays probe galactic CR and ISM distributions
- CR electron-to-proton ratio roughly constant throughout Galaxy
- assumption of dynamic balance ($I \propto \rho^2$) between ISM and CR is reasonably correct
  (large matter density implies larger magnetic fields, allowing for larger CR energy density)

Galactic diffuse gamma rays

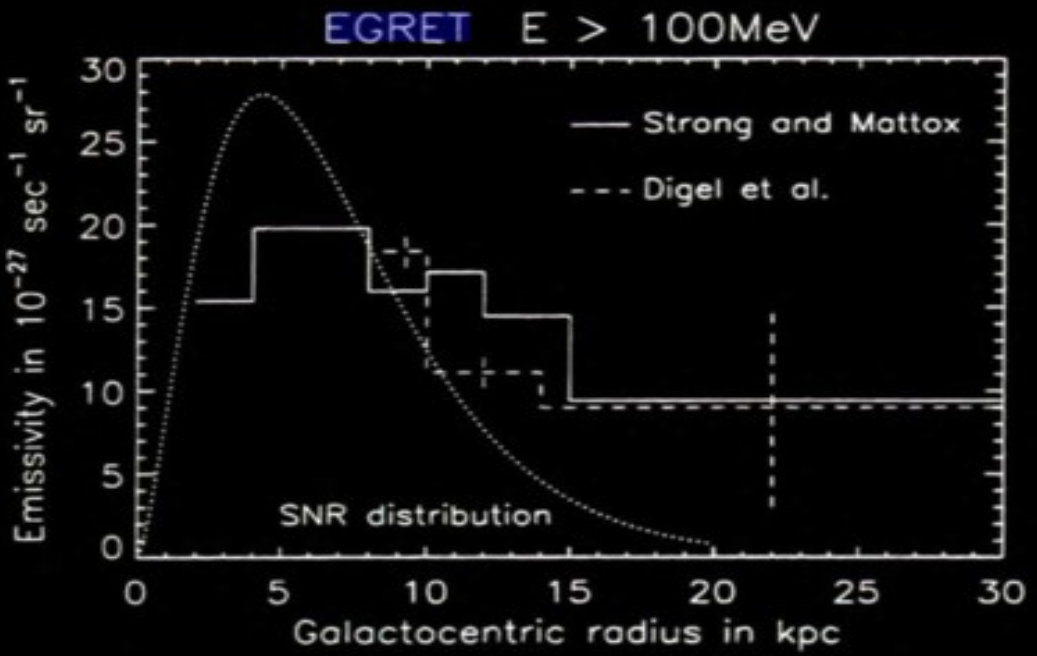
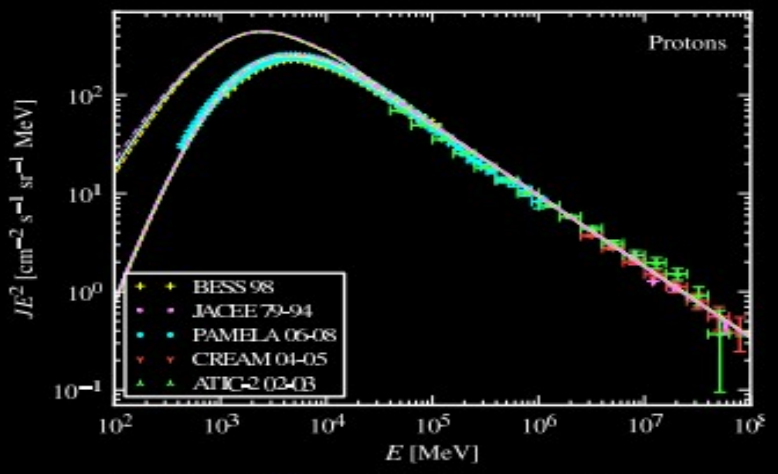
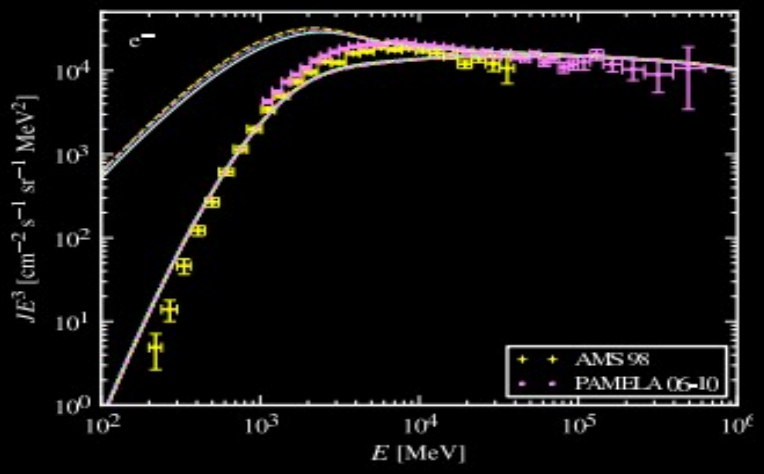
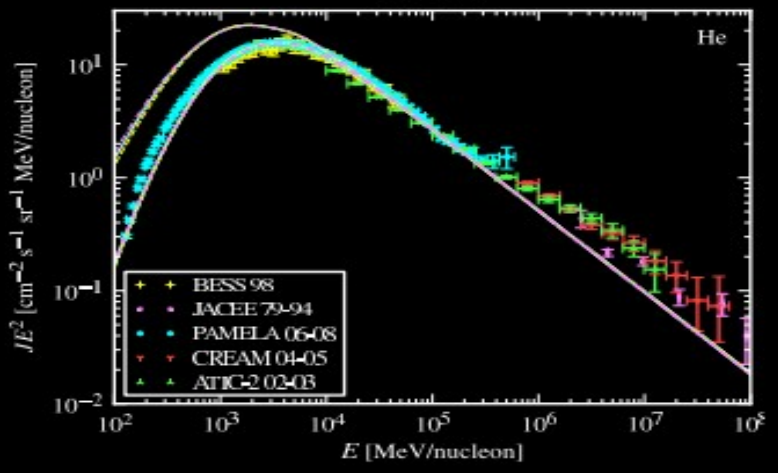


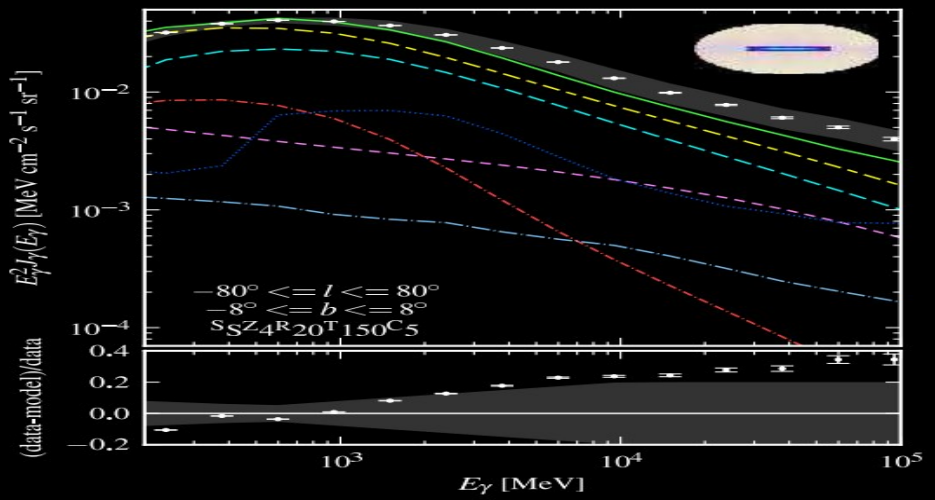
Fig. 6.10. A comparison between the γ-ray emissivity gradient (**solid histogram**) to the distribution of SNR as possible acceleration sites (**dotted line**). The statistical uncertainties of the gradient are typically below 10%. The obvious discrepancy implies that either SNR are not accelerating the bulk of GeV cosmic rays, or diffusive re-acceleration is operative, or galactic cosmic rays are confined on a scale of many kpc's. Note that locally derived emissivities (**dashed histogram**) can differ significantly from the global trend. From Strong and Mattox (1996 [528])

Galactic diffuse gamma rays





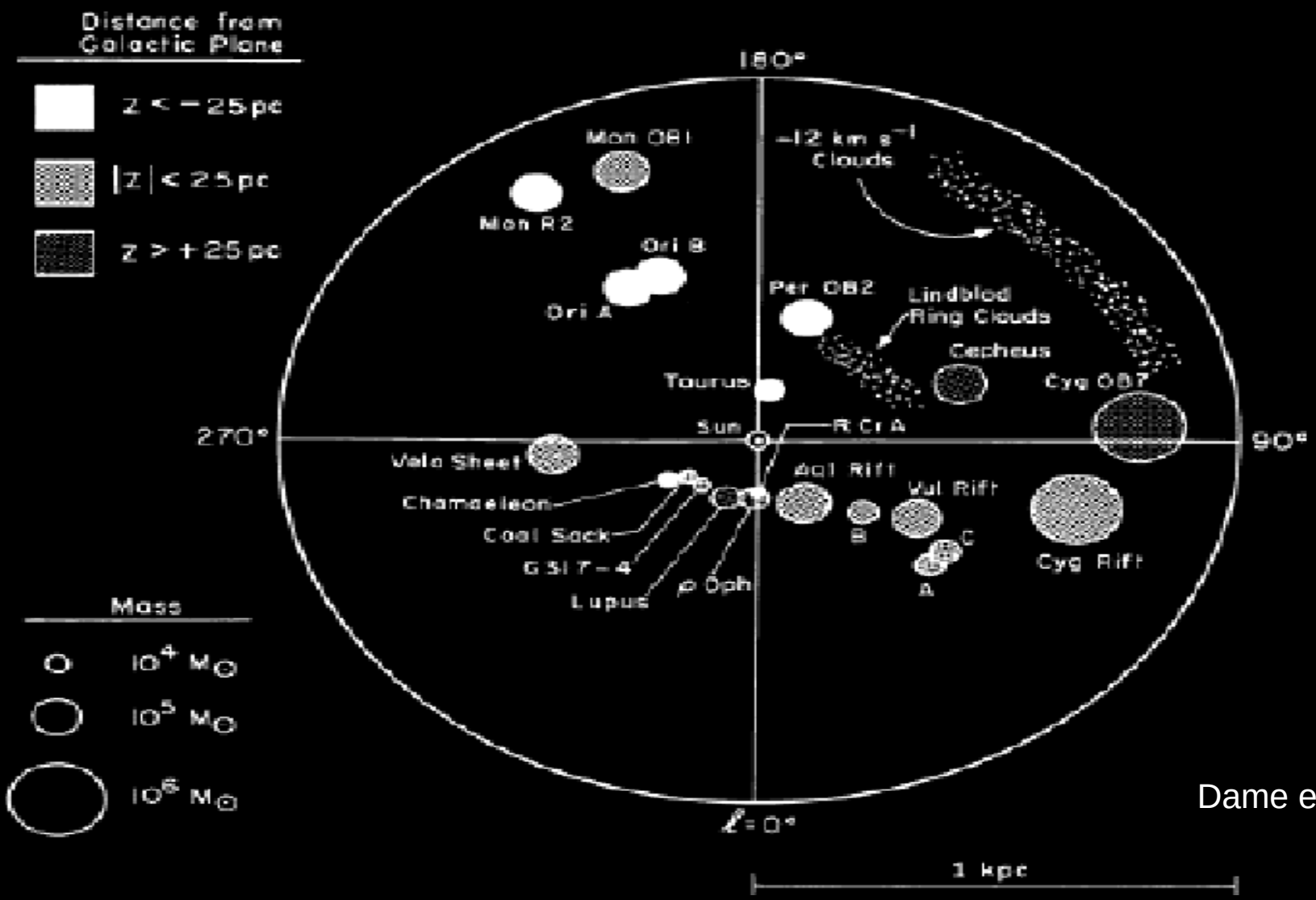




Fermi–LAT Observations of the Diffuse γ-ray Emission: Implications for Cosmic Rays and the Interstellar Medium

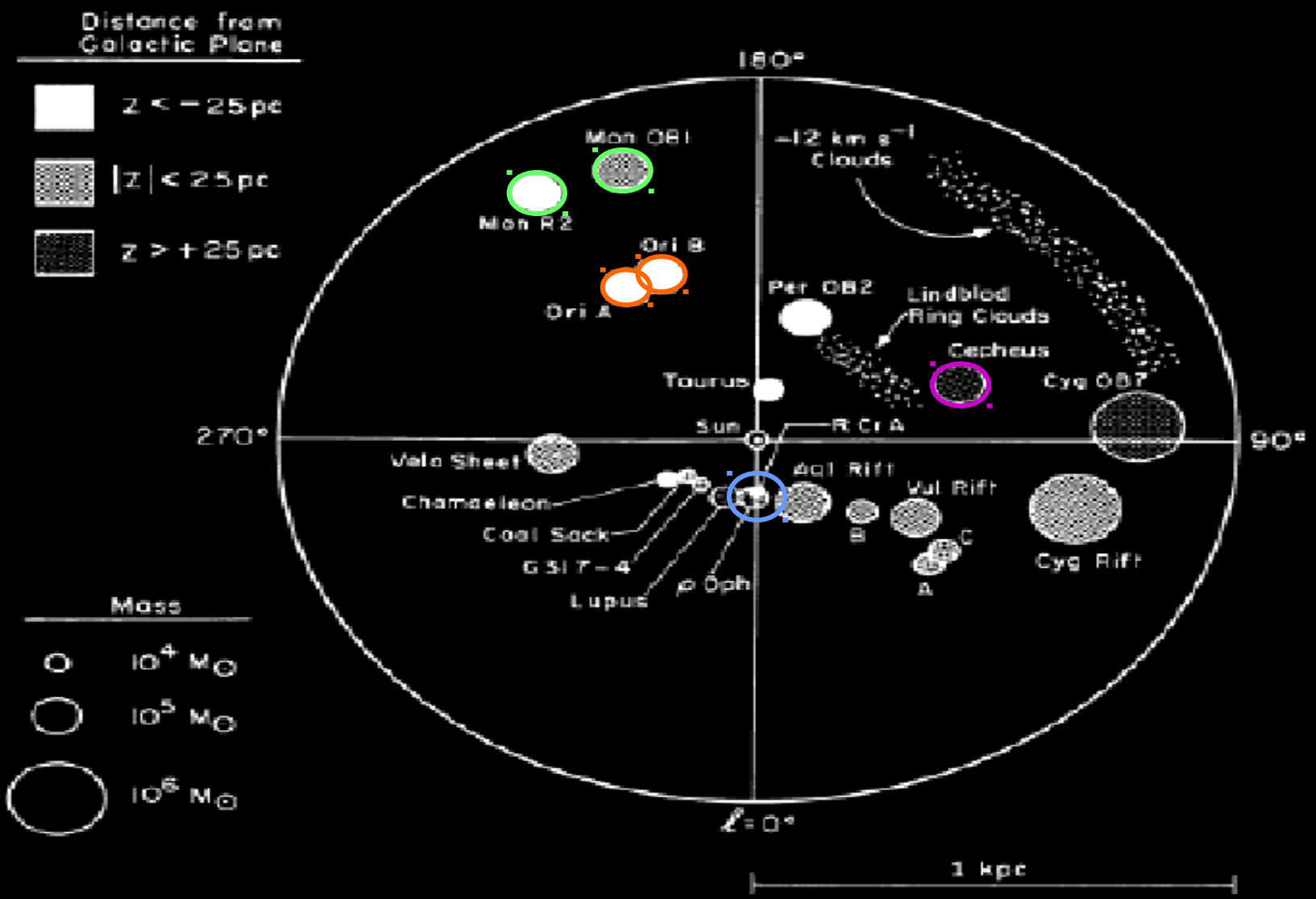
M. Ackermann[1], M. Ajello[2], W. B. Atwood[52], L. Baldini[3], J. Ballet[4], G. Barbiellini[5,6],

Molecular Clouds in gamma rays



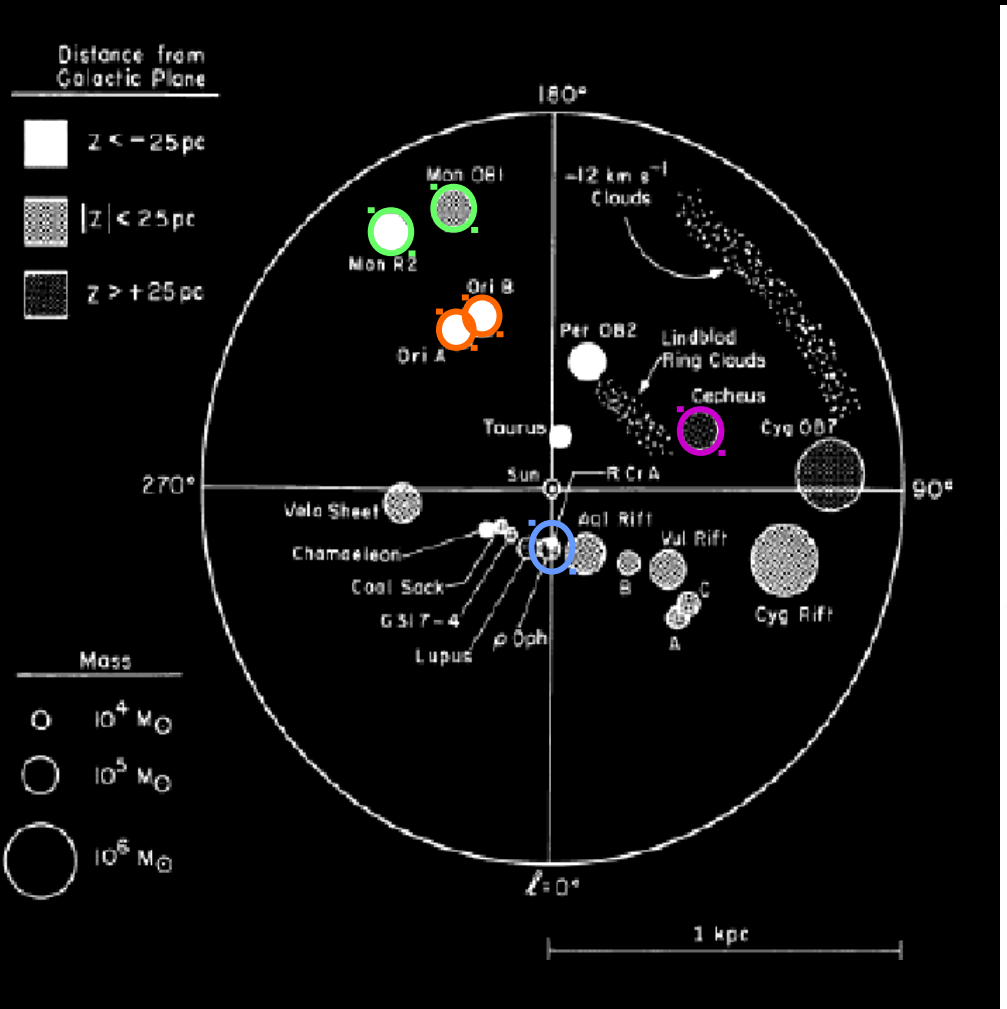
Dame et al. (1987)

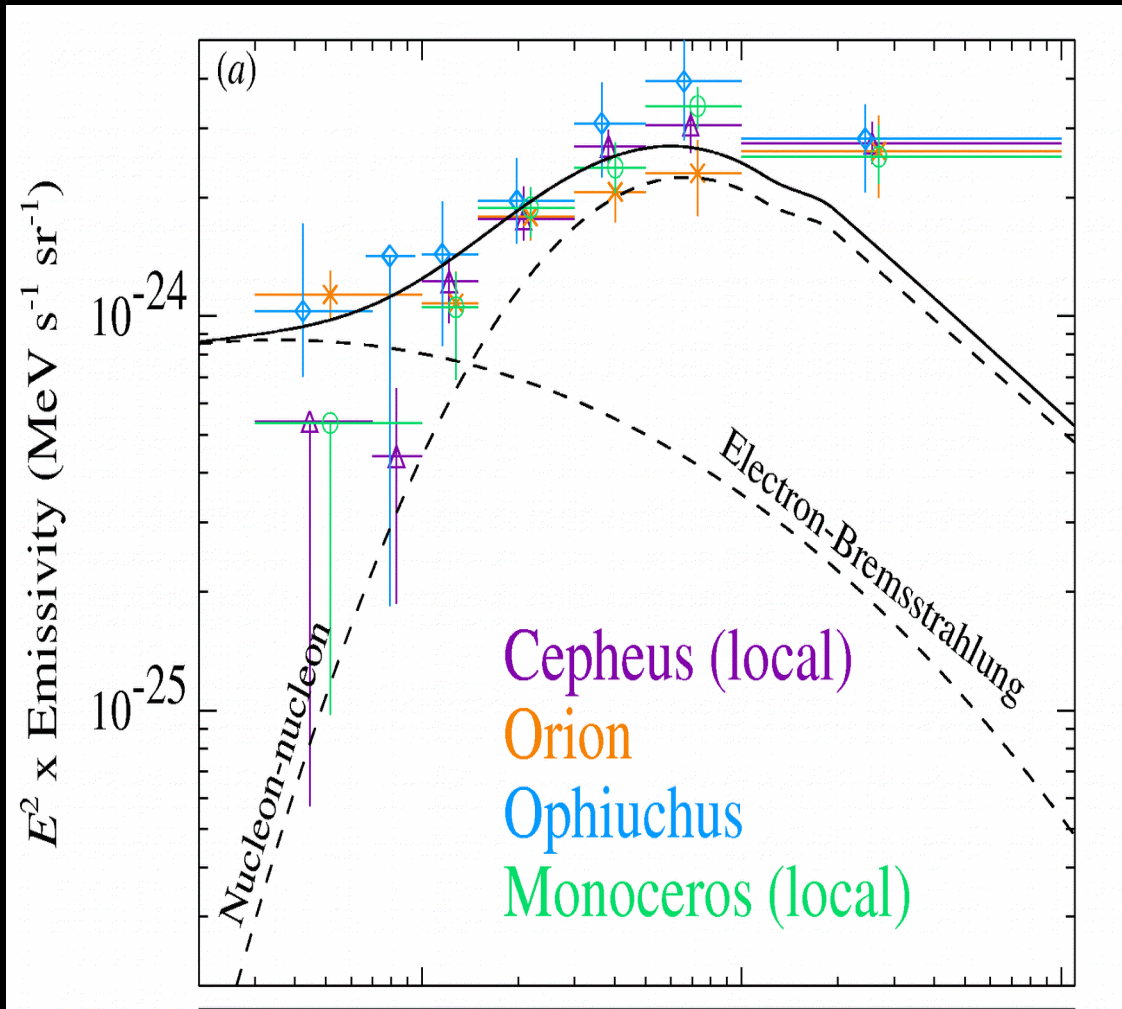
Molecular Clouds in gamma rays



Molecular Clouds in gamma rays

Digel et al. (1996 & 2001)





CRs in Molecular Clouds

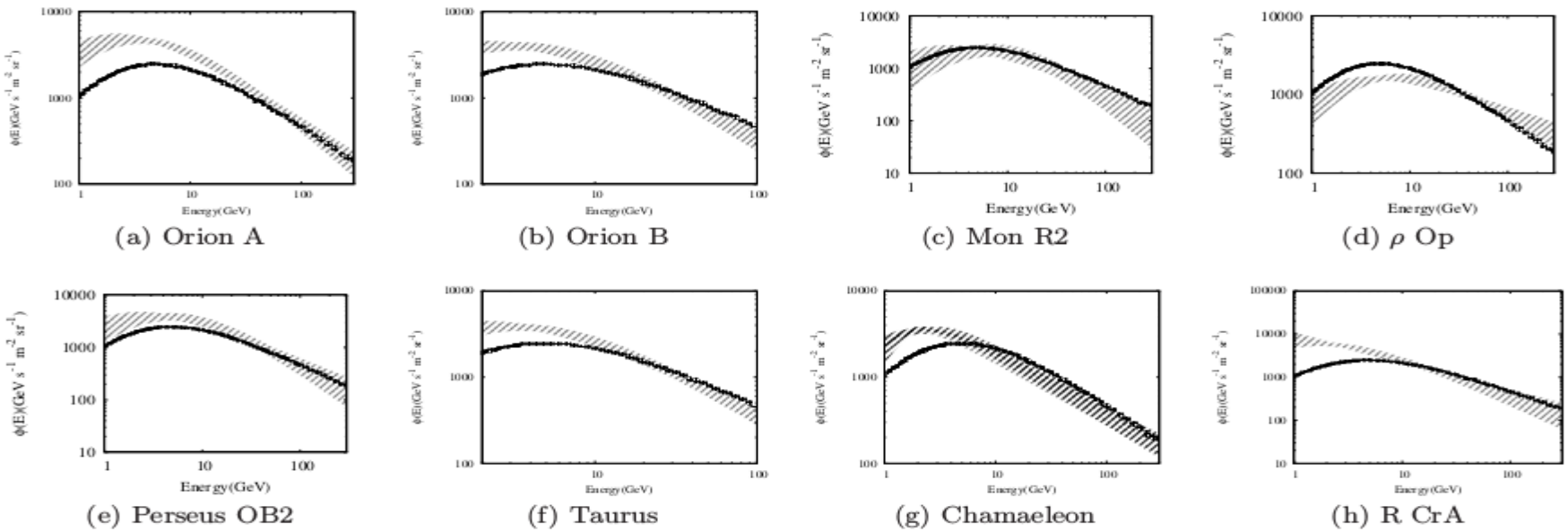


Fig. 5. Energy spectra of CR protons in different clouds derived from the γ-ray data. It is assumed that the interactions of CR with the ambient gas are fully responsible for the observed γ-ray fluxes. The shaded regions represent 1σ fits for the proton spectra. For comparison, the measurements of CR protons by PAMELA are also shown (black crosses).

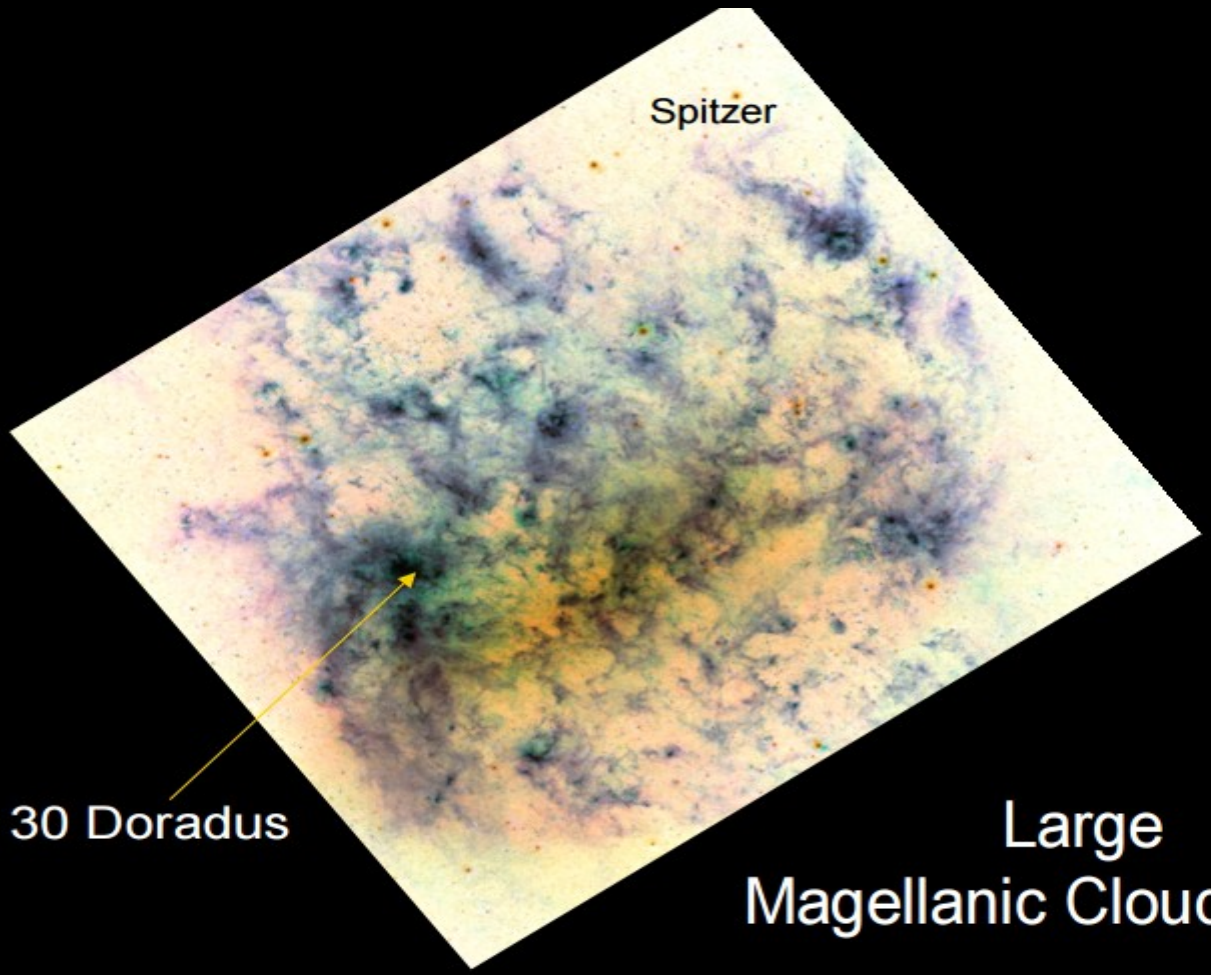
CRs in Molecular Clouds

Table 2. Spectral characteristics and statistic test (TS) value of the GMC listed in Table 1 obtained from the LAT data. The individual χ^2/d.o.f. of the spectral representation tested are also quoted with the corresponding probabilities in brackets (see text for more details).

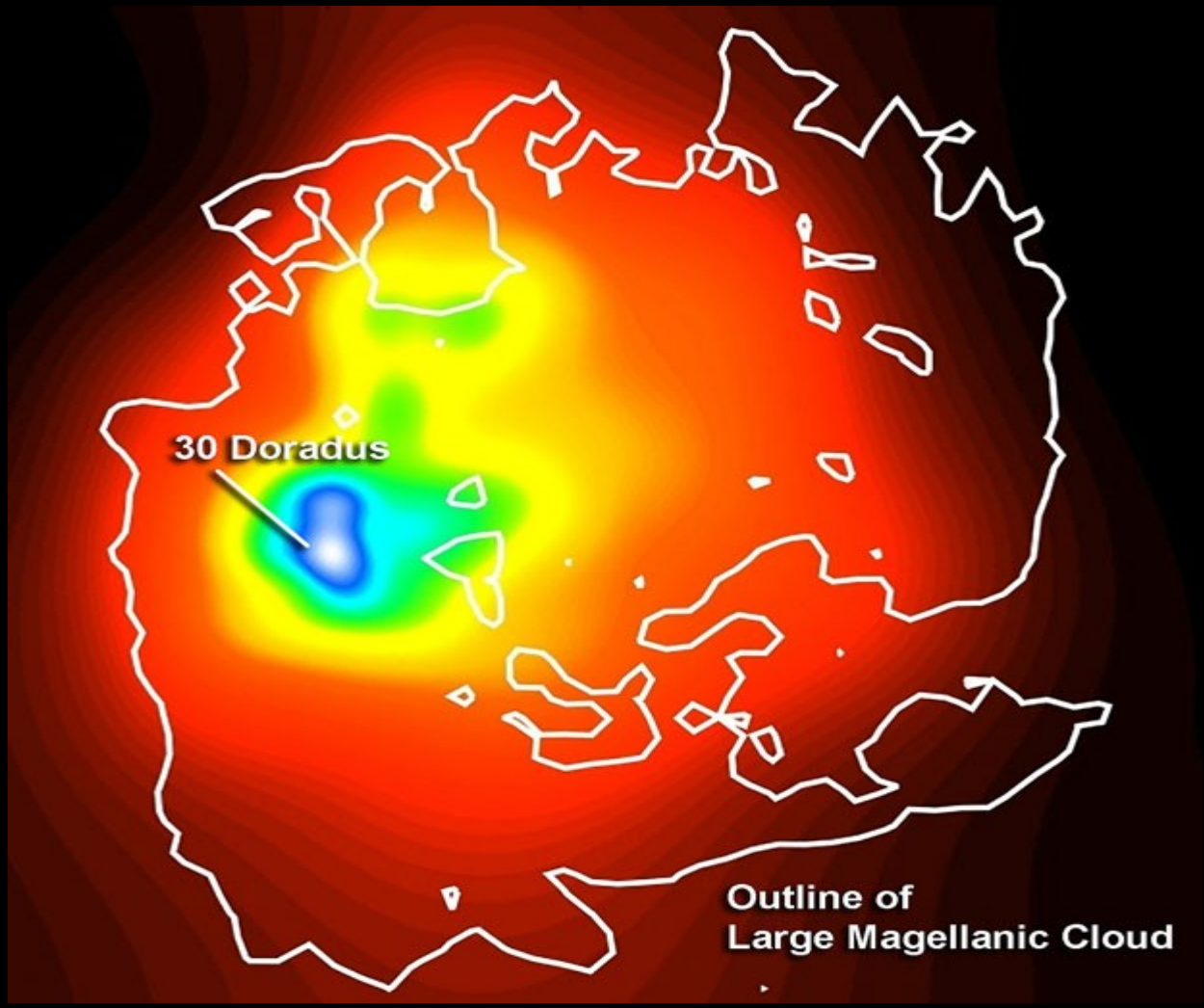
#	Region	TS	Flux at 3 GeV [10^{-9}GeV^{-1}cm^{-2}s^{-1}]	E_b [GeV]	χ^2/d.o.f. (BPL)	χ^2/d.o.f. (KPL)	χ^2/d.o.f. (TPL)
1	ρ Oph	11648	7.7 ± 0.8	4.7 ± 2.3	10.7/9 (0.30)	22.2/11 (0.024)	13.9/11 (0.24)
2	Orion B	6107	3.0 ± 0.6	3.6 ± 1.3	10.8/9 (0.29)	27.9/11 (2.3×10^{-3})	13.1/11 (0.29)
3	Orion A	22021	5.9 ± 0.7	4.3 ± 1.2	11.0/10 (0.35)	40.1/12 (4.9×10^{-5})	14.0/12 (0.30)
4	Mon R2	1607	1.3 ± 0.2	3.0 ± 0.7	10.5/10 (0.39)	29.4/12 (3.4×10^{-3})	13.4/12 (0.34)
5	Taurus	5670	9.8 ± 1.5	4.7 ± 1.5	10.5/10 (0.39)	36.9/12 (2.3×10^{-4})	16.5/12 (0.17)
6	R CrA	2315	1.2 ± 0.8	0.9 ± 0.8	5.1/9 (0.82)	7.4/11 (0.76)	15.0/11 (0.18)
7	Chamaeleon	2917	2.0 ± 0.5	2.0 ± 0.9	9.2/9 (0.42)	24.0/11 (0.01)	12.0/11 (0.36)
8	Perseus OB2	6410	3.8 ± 0.3	4.9 ± 2.1	11.7/10 (0.30)	20.8/12 (0.05)	17.3/12 (0.14)

Cosmic Rays in other galaxies

LMC diffuse gamma rays

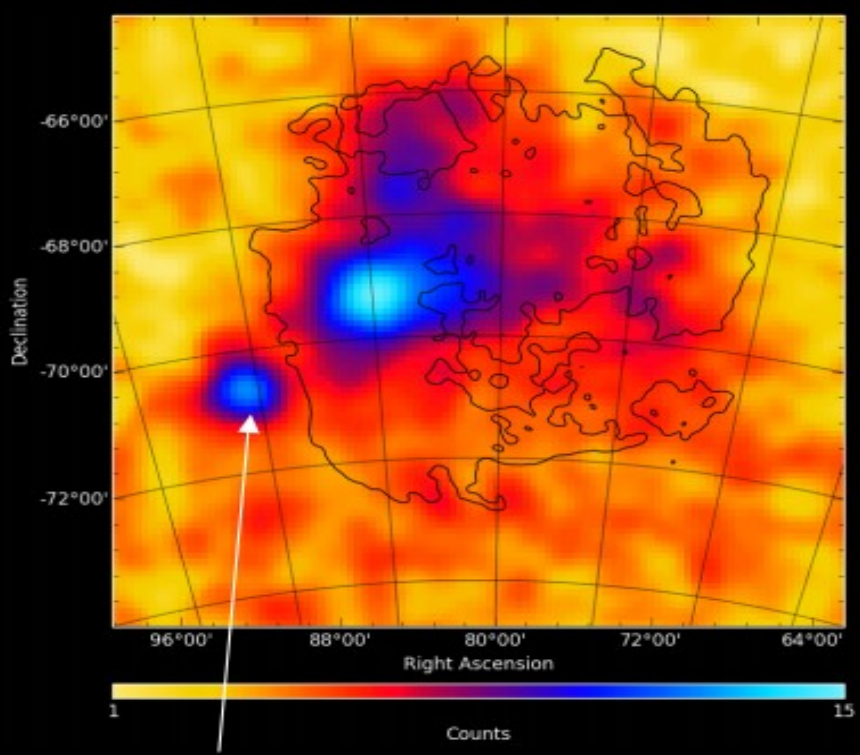


Large
Magellanic Cloud (LMC)

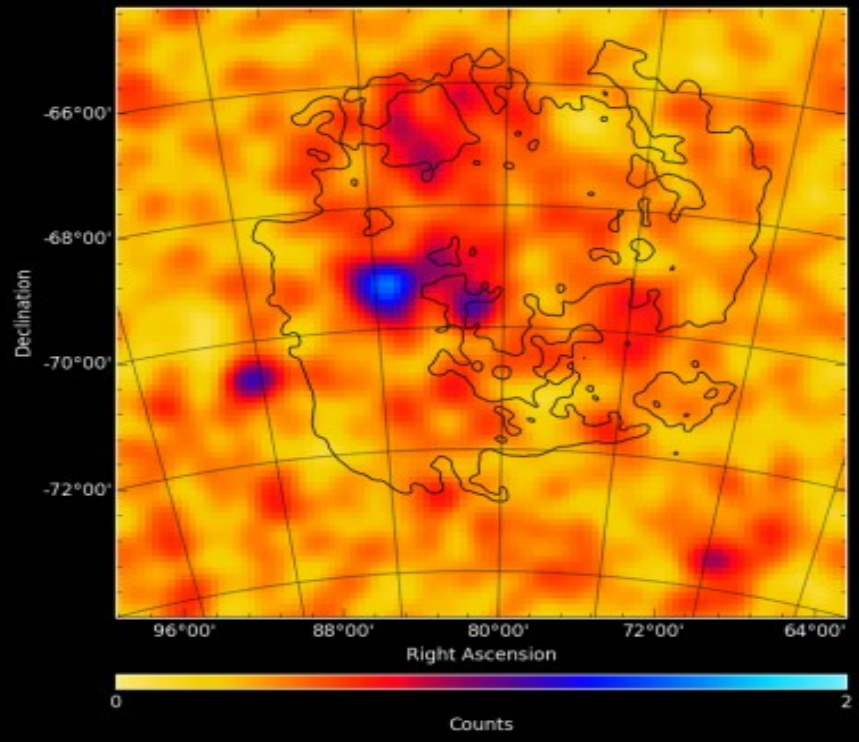

30 Doradus
Outline of
Large Magellanic Cloud

LMC diffuse gamma rays

LMC: counts maps **800MeV-8GeV and 8-80GeV** (smoothing with gaussian of 0.2°)



PKS0601-70



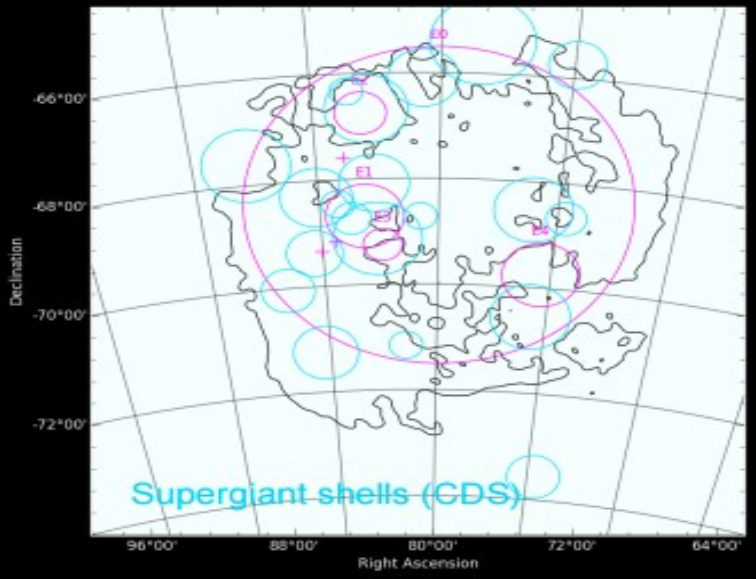
- A bright region, 30 Dor : what lies behind ?
- Extended emission not filling the galaxy or following the gas
- A few hard sources

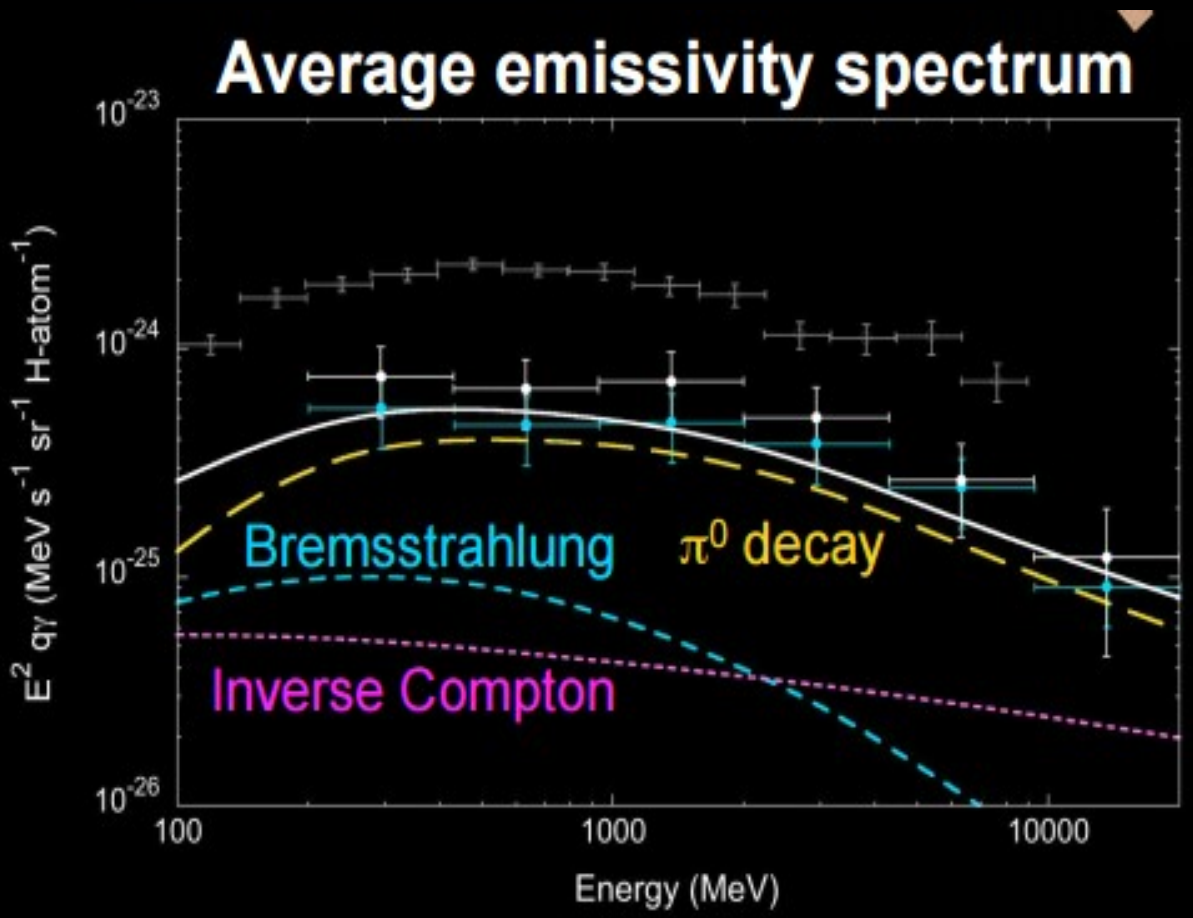
LMC diffuse gamma rays

LMC: cosmic-ray population

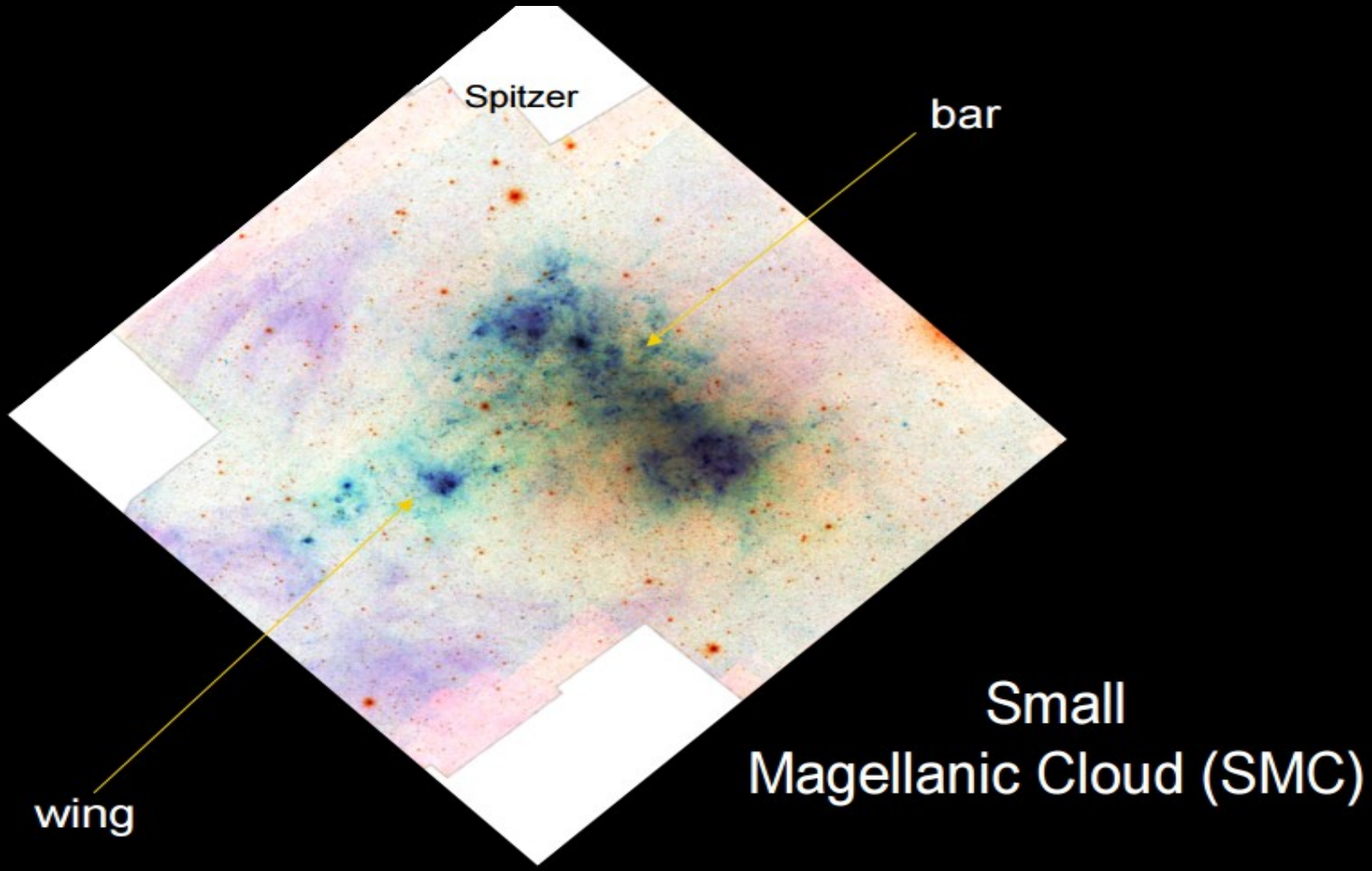
An inhomogeneous distribution

- CR sea has 1/3 the local CR density
- CR enhancements by factors 2-8
- No CR enhancement in 30 Dor…
- … but >0.5° offset from it
- Correlation with cavities and shells



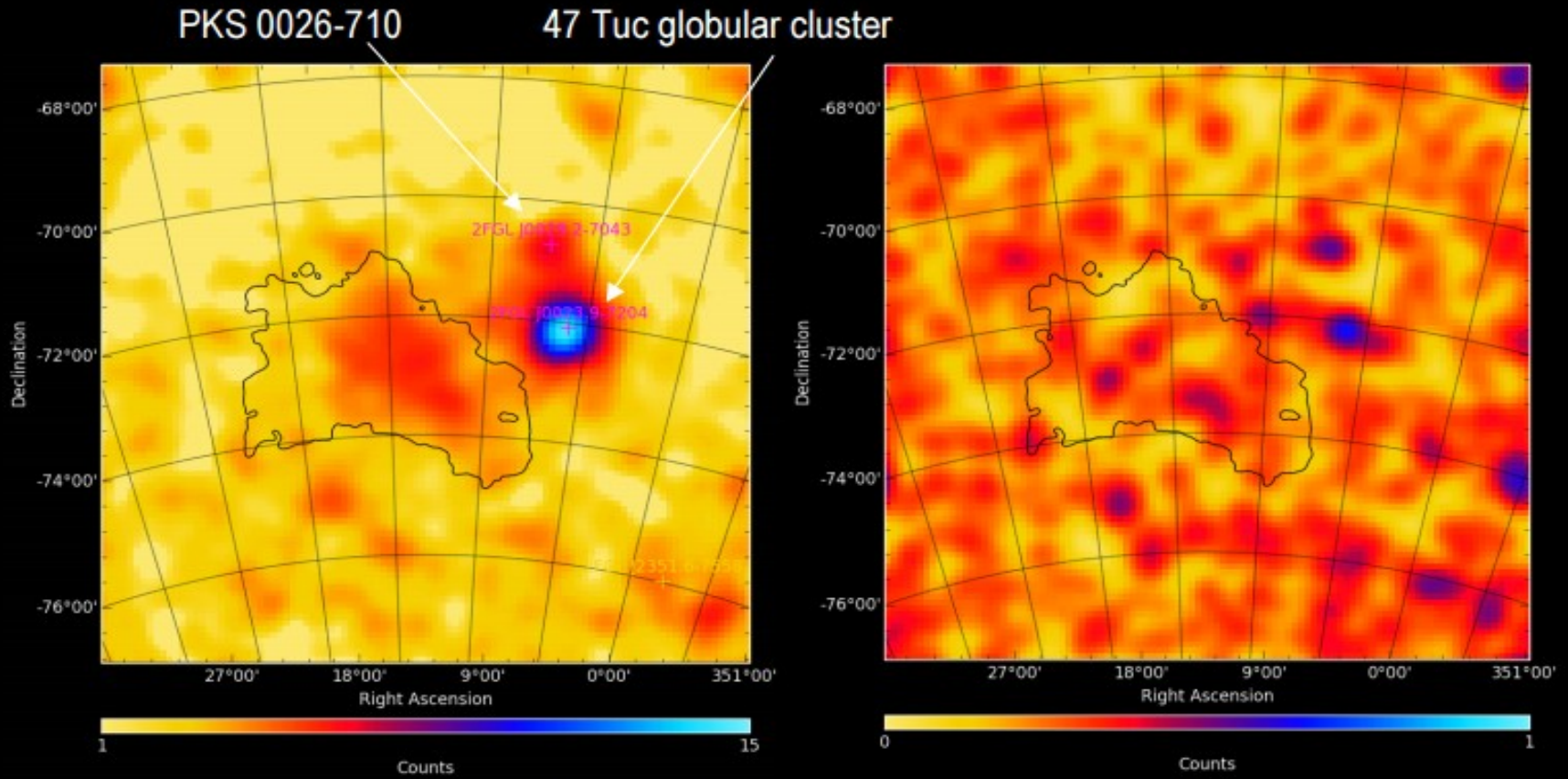


SMC diffuse gamma rays



SMC diffuse gamma rays

SMC: counts maps **800MeV-8GeV and 8-80GeV** (smoothing with gaussian of 0.2°)



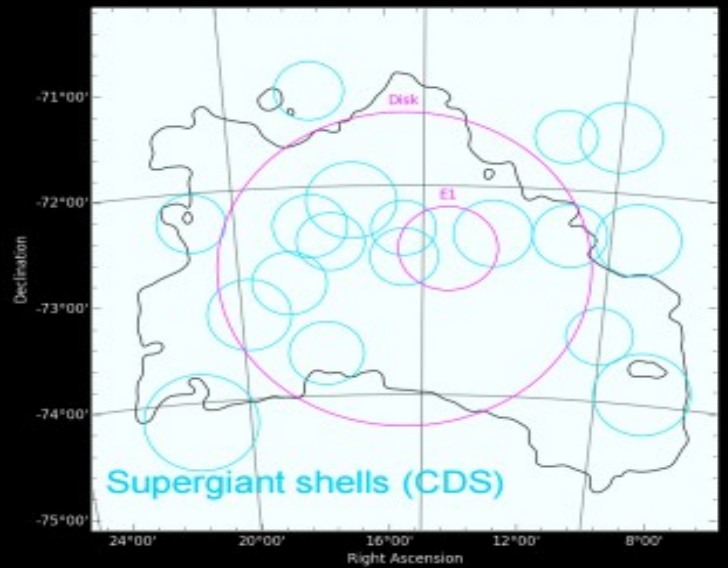
- Extended emission following the bar of the SMC
- No hard sources within SMC boundaries

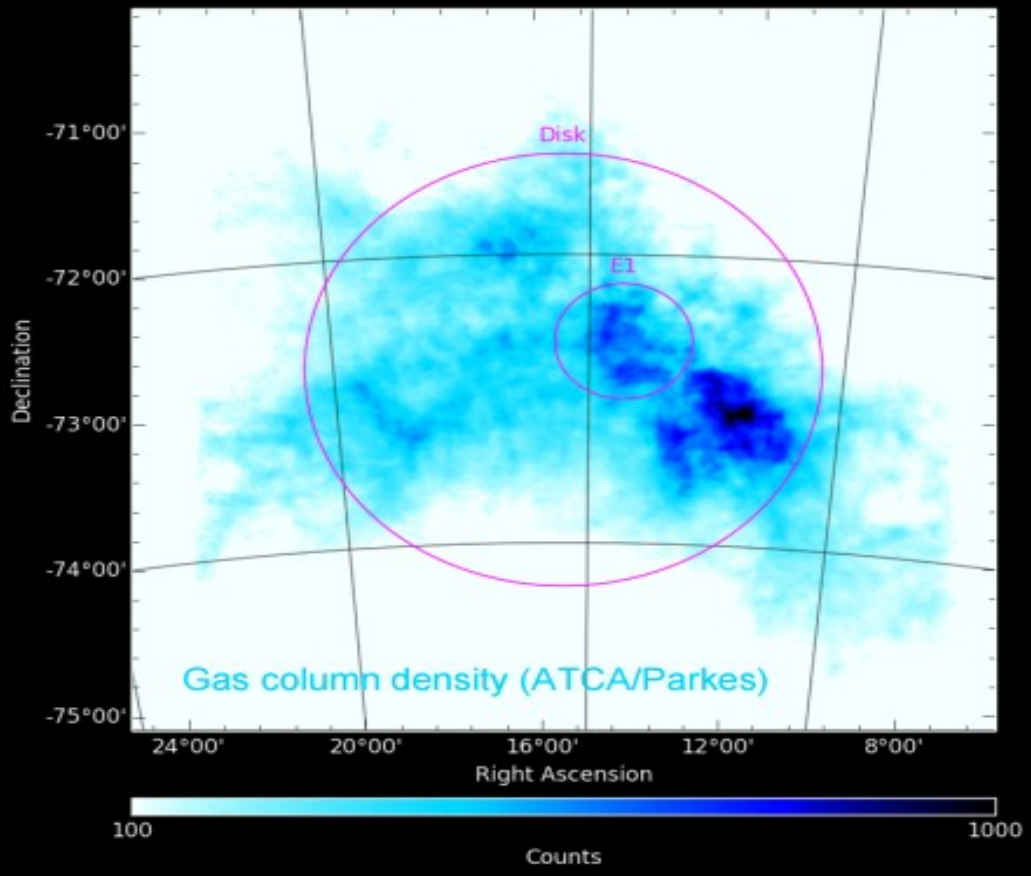
SMC diffuse gamma rays

SMC: cosmic-ray population

Global picture differs from LMC

- No point-like source in SMC
- CR sea has ~5% the local CR density
- CR enhancement in the bar by ~4
- No obvious correlation with cavities
  …or star forming regions
  (but geometry is different)





CR in other galaxies