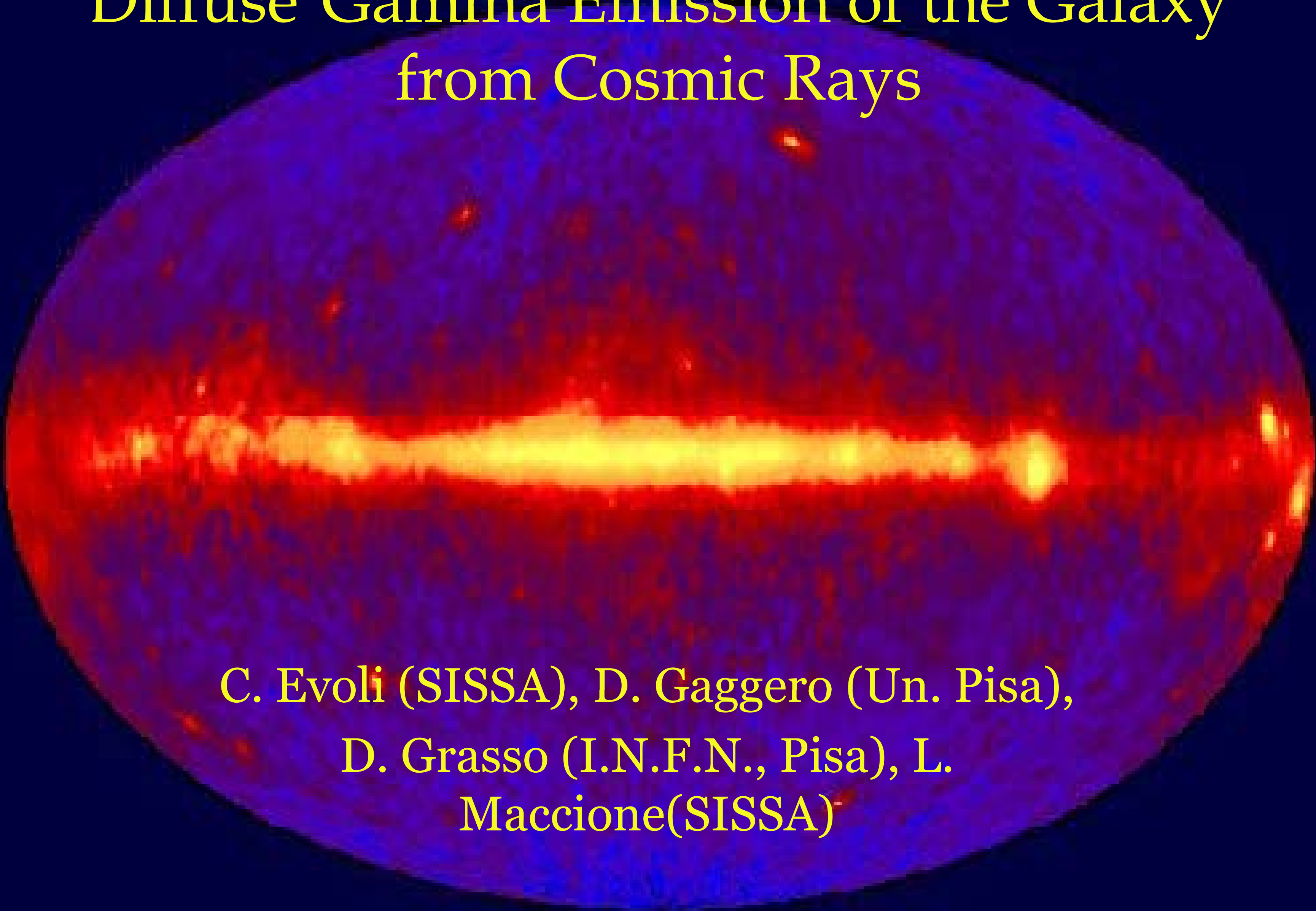
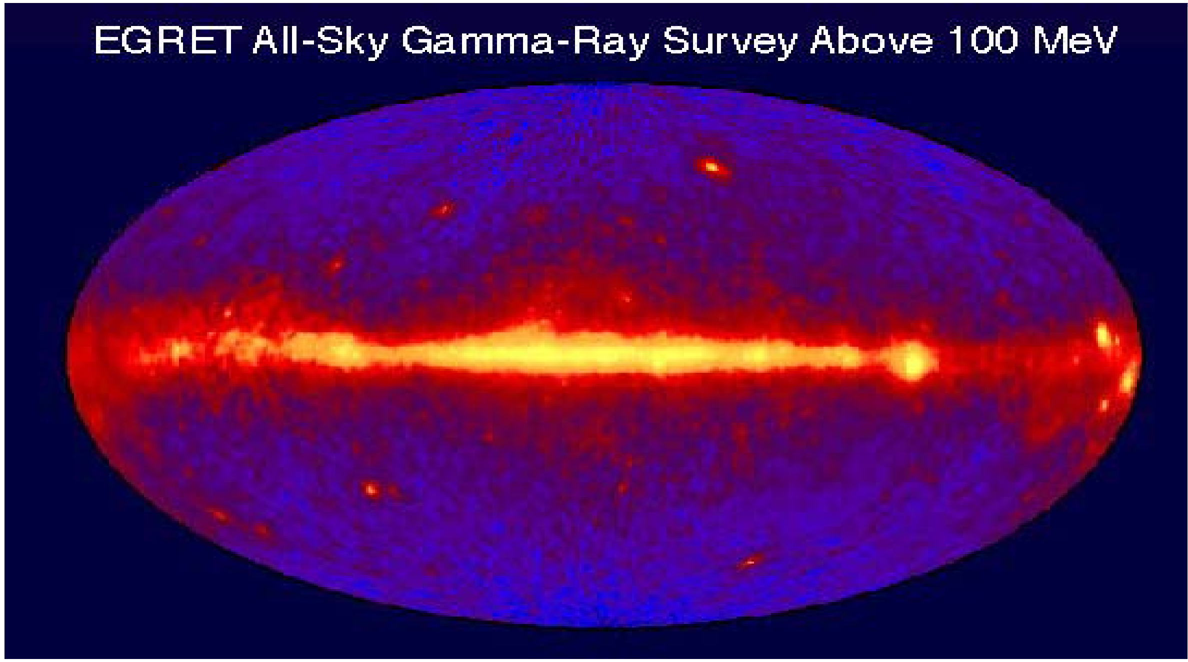
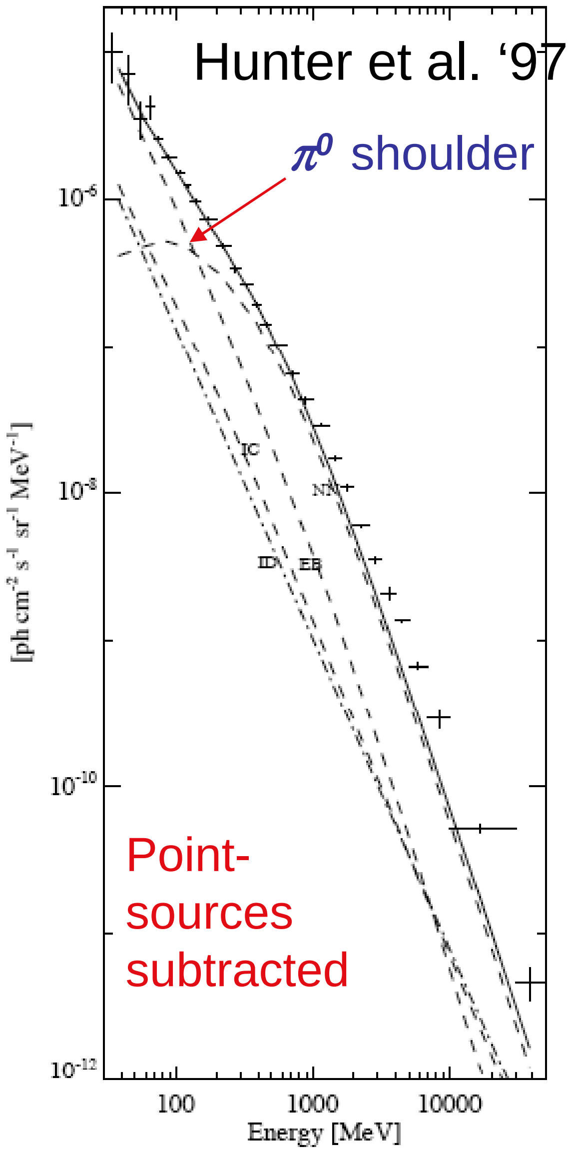
Diffuse Gamma Emission of the Galaxy from Cosmic Rays



C. Evoli (SISSA), D. Gaggero (Un. Pisa),
D. Grasso (I.N.F.N., Pisa), L. Maccione(SISSA)

EGRET observation



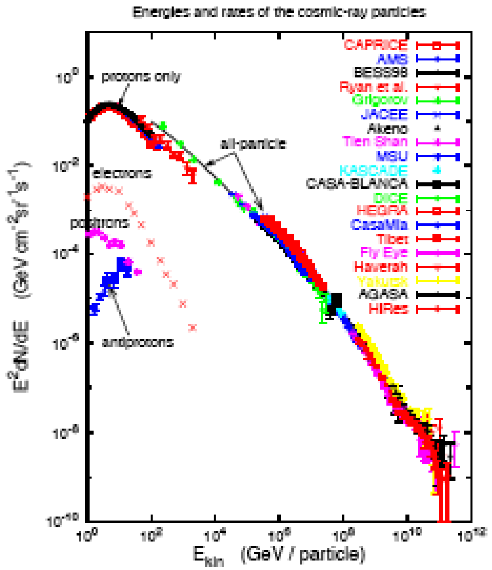


Above the GeV a large fraction must be originated by hadronic processes, mainly

$$p + p_{gas} \rightarrow p + p + \pi^0$$
$$\hookrightarrow \gamma + \gamma$$

$$(\; p + p_{gas} \rightarrow p + p + \pi^{\pm}$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}$$
$$\hookrightarrow e^{\pm} + \nu_{\mu} + \nu_{e} \;)$$

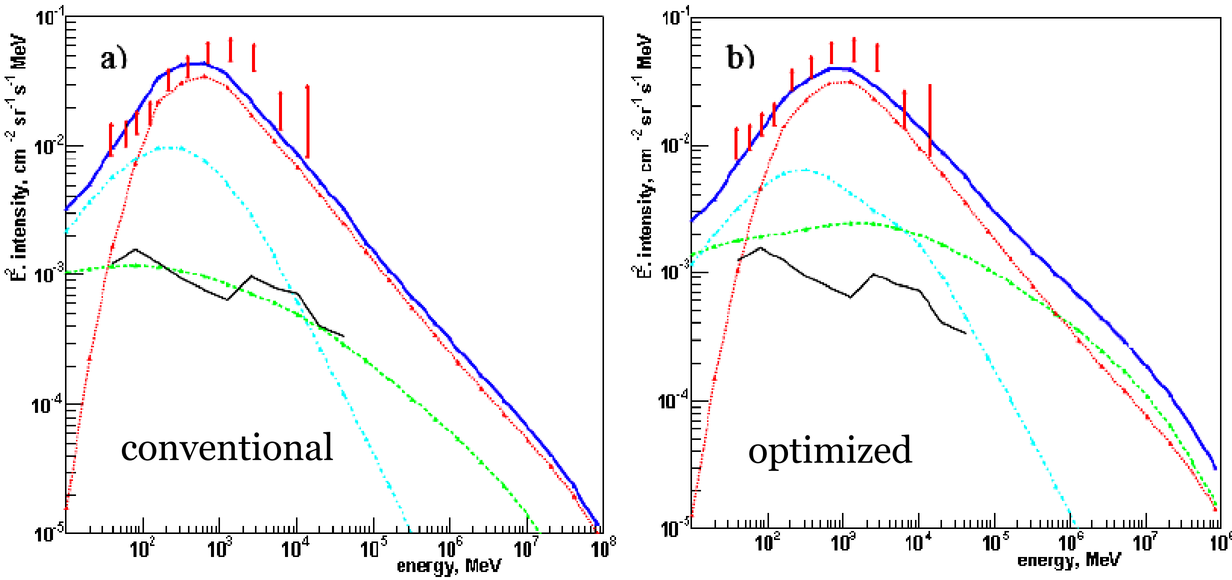
How the γ-ray spectrum extends at high energies ?



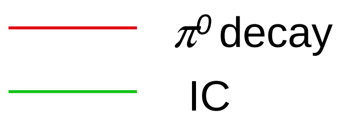
We expect the γ-ray spectrum to continue well above 100 GeV

It is unknown, however, which fraction is due to hadrons and how that changes across the sky

Predictions are still quite model dependent due to poorly known astrophysical parameters

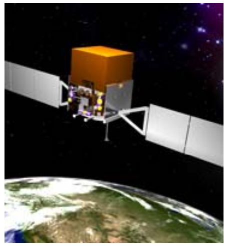


Strong et al. '04
[GALPROP]



100 TeV

High energy observatories

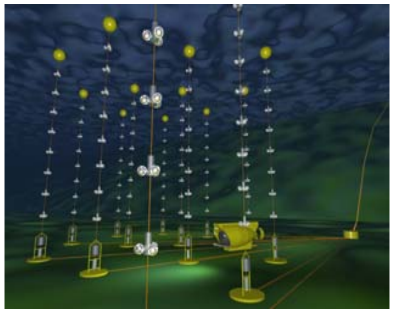


GLAST
$E_{max} \sim 300$ GeV

Atmospheric Cherenkov Telescopes
(HESS, MAGIC, Whipple..)
$0.1 < E < 100$ TeV
(best suited for localised sources)

Air Shower Arrays (MILAGRO, TIBET AS Gamma)

$1 < E < 100$ TeV



Neutrino Telescopes (ICECUBE,ANTARES,NESTOR,NEMO…)
$E > 1$ TeV

May help to solve the hadronic-leptonic origin degeneracy

Our work

We focused on the hadronic emission trying to map it as better as possible

This component is less (even if not completely) sensitive to local effects

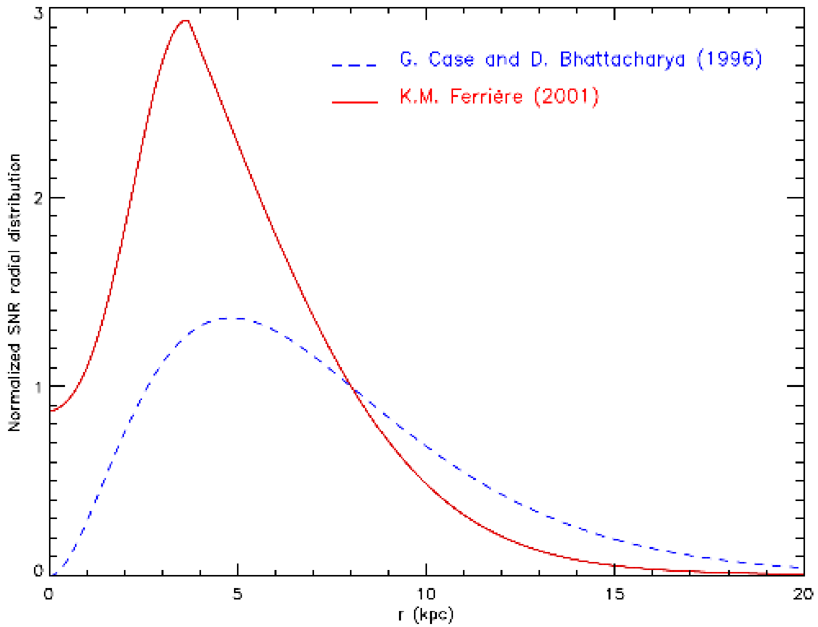
We paid attention to:

1. the CR source (SNR) distribution;
2. the Galactic Magnetic Fields and their effects on CR diffusion;
3. the gas distribution

and tried to estimate how the uncertainties in the knowledge of those quantities may affect the expected γ-ray and ν fluxes

1. SNR distribution

Until few years ago SNR (radio shells) survey were used (*Case & Bhattacharya '96,'98*)
(problems: incomplete; selection effects; do not fit radioactive nuclides distr. , e.g. ^{26}Al)
SNR are better traced by pulsars and old stars (see *Ferriere'01*, *Lorimer '04*)
Ferriere'01 accounts also for SNR not giving rise to pulsars.



The peaked distribution exacerbate the problem of reproducing the relatively smooth EGRET flux profile along the GP
(see also Strong at al. 2004)

"CR gradient problem"

Most of the times an "*ad hoc*" source distribution was chosen to reproduce γ-rays observations.
We adopt Ferriere's distribution.

2. CR diffusion in the Galactic Magnetic Field(s)

The GMF is a superposition of regular and random fields of comparable strength.
By assuming axial symmetry

$$B_{\rm reg}(r,z) = B_0 \exp\left\{-\frac{r-r_\odot}{r_B}\right\} \frac{1}{2\cosh(z/z_h)}$$ $z_h \sim 1.5$ kpc

$$B_{\rm ran}(r,z) = \sigma(r)\ B_{\rm reg}(r,0)\ \frac{1}{2\cosh(z/z_t)}$$ $z_t \geq 3$ kpc

$\sigma \geq 1$ (strong turbulence) $L_{max} \sim 100$ pc $<<$ $r_L\ (B_{reg})$

Propagation takes place in the spatial diffuse regime

Most likely turbulence is driven by CR $\Rightarrow$ $\sigma(r)$ may be higher in SNR rich regions
$\Rightarrow$ diffusion coefficients may also be spatial dependent

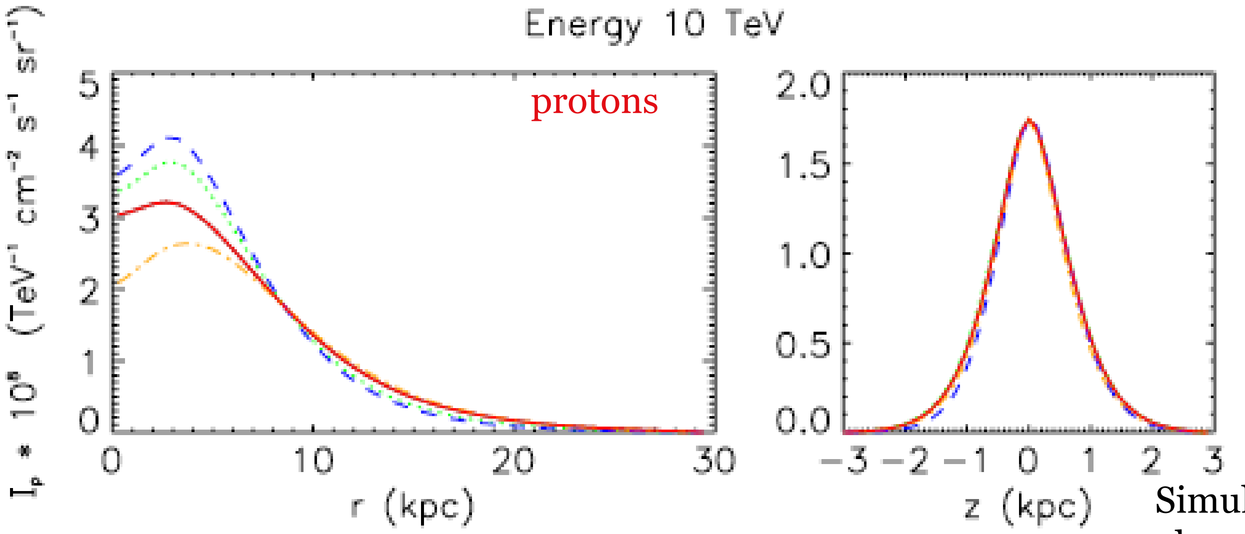
Rather than taking a uniform $D_\perp(E)$ as estimated from secondary/primary species (e.g. B/C) we adopt $D_\perp(E;\ B_{reg},\sigma)$ as derived from MC simulations of particle propagation in turbulent MFs . We adopt exp. from *Candia & Roulet 2004*

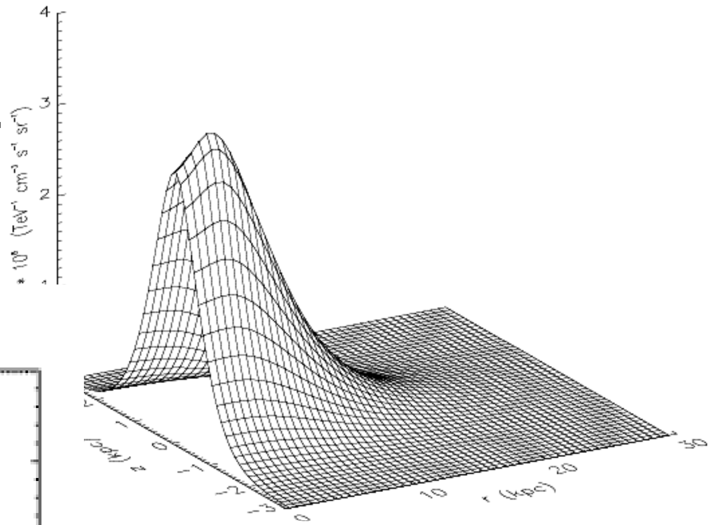
Erlykin & Wolfandale '02 considered a spatial dependent turbulent spectrum

CR distribution

Diffusion eq. is solved with boundary conditions

$N(r = \pm 30\ \text{kpc}, z = \pm z_t\ ) = 0$ *See e.g. Ptuskin et al. 1993*





Simulated fluxes are normalized to the observed values (*Horandel 2003*) at $(r_\odot, 0)$

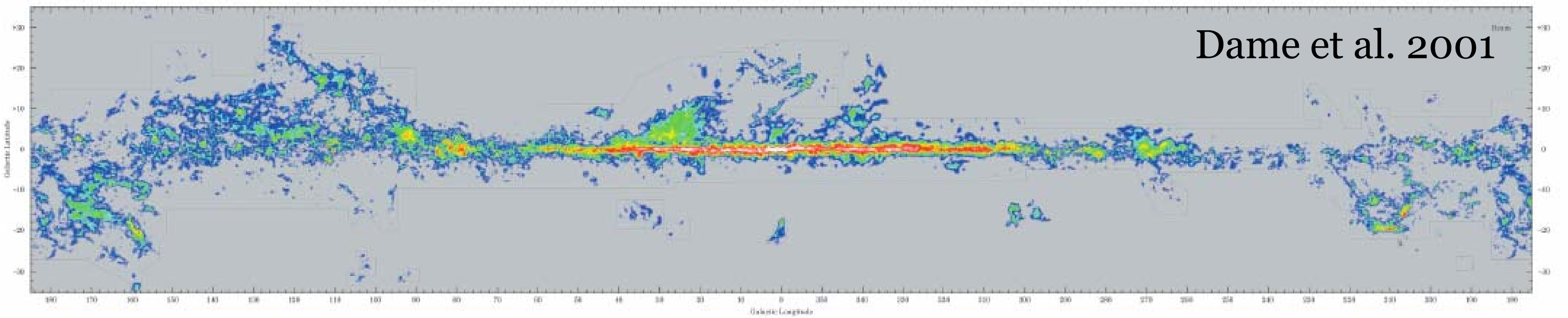
Model No	SNR	$\sigma(r)$	Turbulence	z-symmetry
0	CB [29]	1	Kolmogorov	S
1	Ferriere [32]	1	Kolmogorov	S
2	Ferriere [32]	Like SNR	Kolmogorov	S
3	Ferriere [32]	1	Kraichnan	S
4	Ferriere [32]	1	Kolmogorov	A

Injection spectral slope is tuned to reproduce that observed for protons $\alpha = 2.7$

Inhomogeneous turbulence helps smoothing the CR distribution !

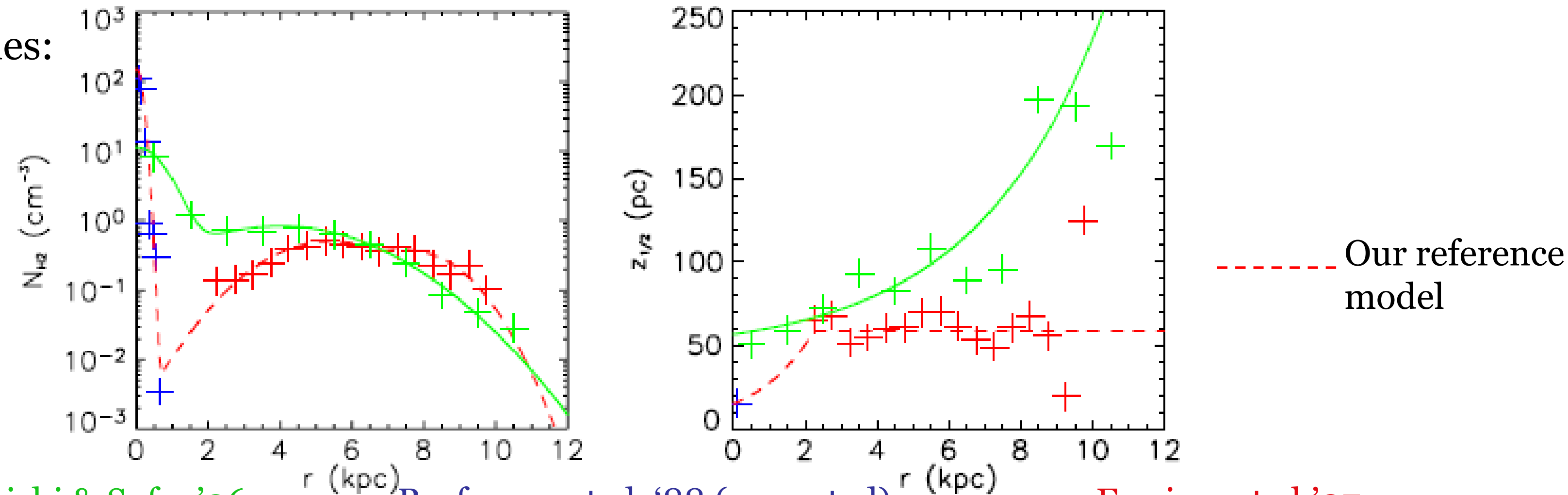
3. Gas distribution

H_2 is the main target along the Galactic plane. That is generally traced by ^{12}CO (J = 1-0)



The Doppler shift (velocity) + Galaxy rotation curves are used to model the 3-D structure

2-D profiles:

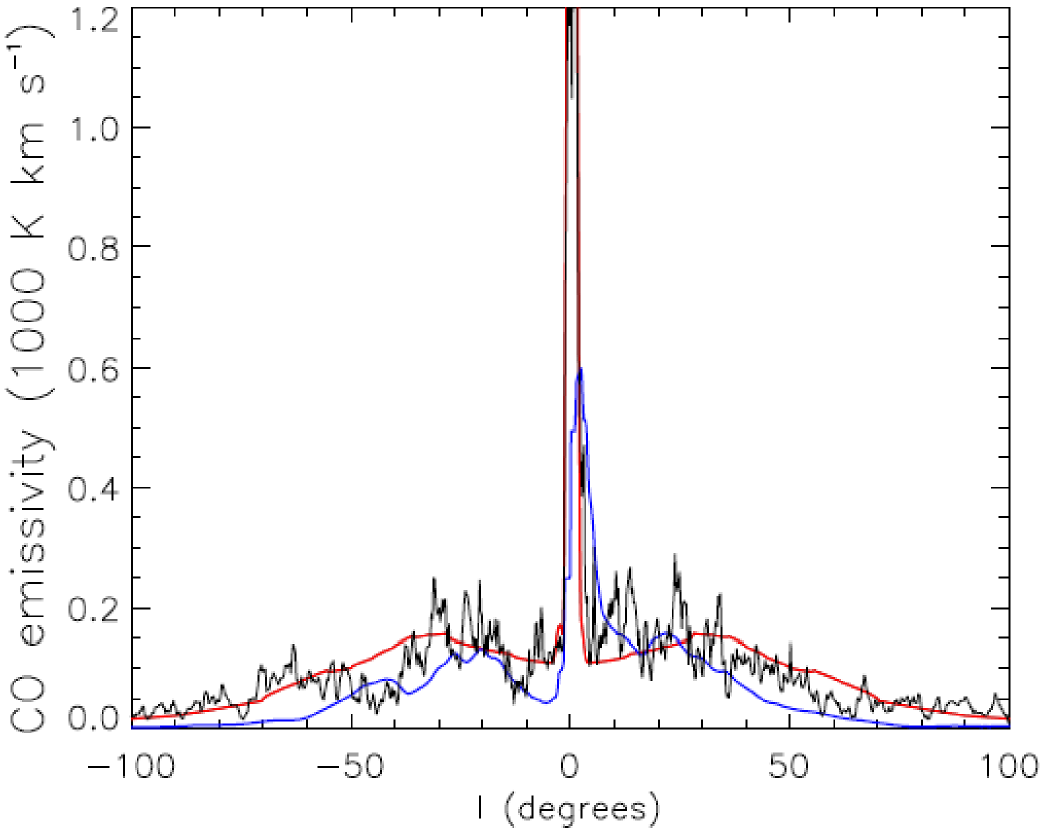


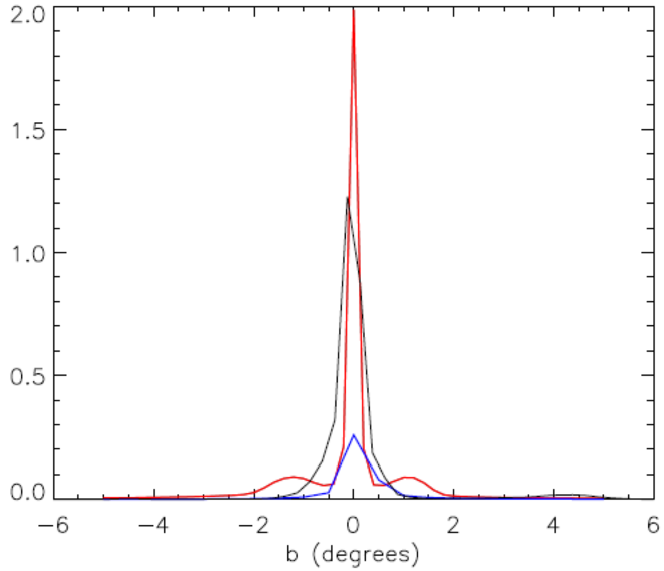
Nakanishi & Sofue'06 Brofnman et al. '88 (corrected) Ferriere et al.'07

We also accounted for HI as determined from 21cm surveys Nakanishi & Sofue'03

Wolfire et al. '03 and ref.s therein

W_{co} models /observations



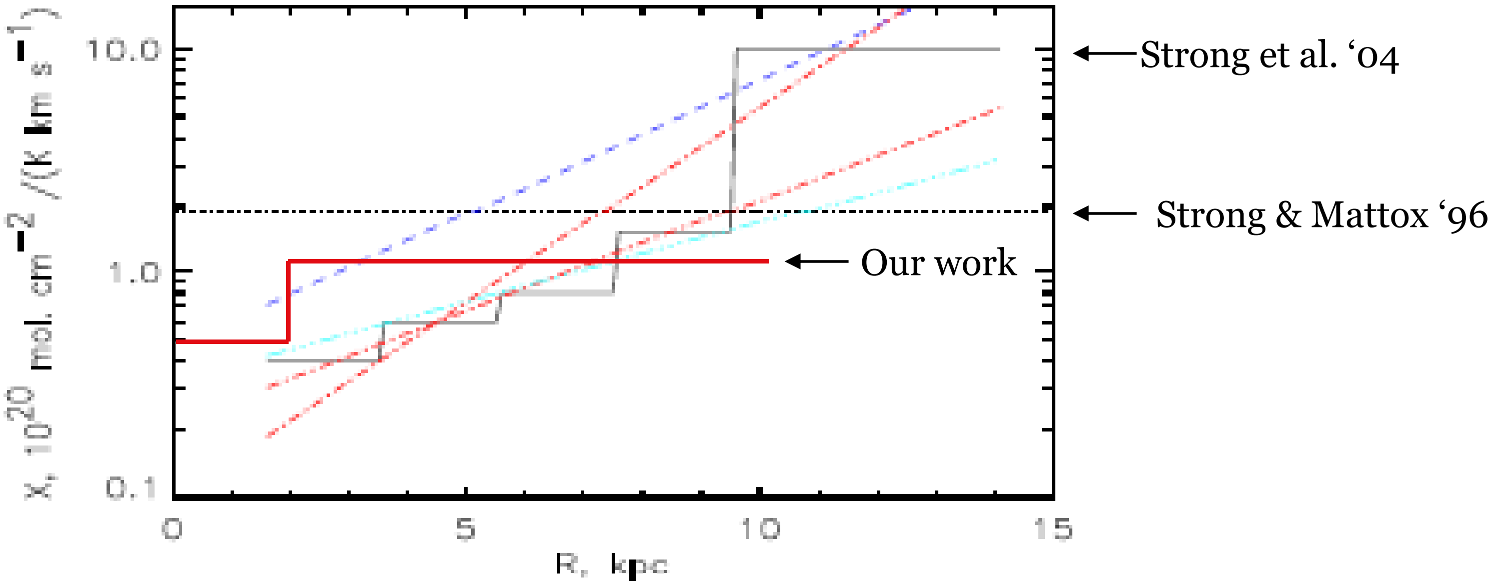


D. Gaggero, thesis work

Dame et al. ‘01 (W_CO maps)
Nakanishi & Sofue’06
Ferriere et al. ‘07 + Bronfman et al. ‘88 (our model)

X_{CO}

The scaling factor $X_{CO} = N_{H2} / W_{CO}$ is required to convert CO maps into gas column density
It is expected to change with *r* through its dependence on the metallicity
That is also required to smooth the γ-ray profile to make it compatible with
the peaked SNR distribution *Strong et al. 2004, A&A 422*



There is a factor ~ 2 uncertainty.
In the inner Galaxy X_{CO} may be lower than what we assumed

Mapping the γ-ray and ν emissions

$$\frac{dn_{\gamma/\nu}(E;\ b,l)}{dE} \simeq f_N\ \sigma_{pp}\ Y_{\nu,\gamma}(\alpha) \int \mathrm{d}s\ I_p(E;\ r,z)\ n_H(r,z)$$

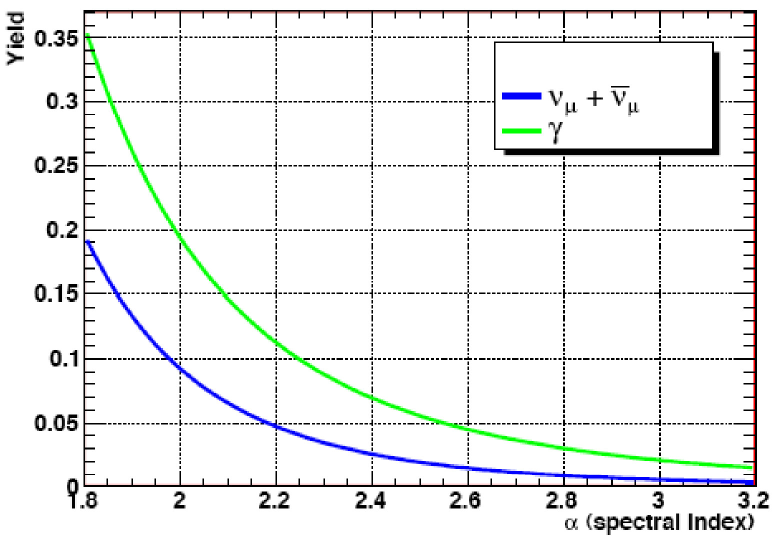
(as well as its 3-D generalization)

where $\alpha = 2.7$ (proton power law index) ; $f_N \cong 1.4$ accounts for the contribution of other nuclear species in the CR and in the ISM (mainly helium assumed to be distributed like hydrogen nuclei); *s* is the distance from the observer.

Photon and neutrino yields (determined with PYTHIA (ν oscillations are accounted for):

$Y_\gamma(2.7) = 0.036$ $Y_\nu(2.7) = 0.012$

Uncertainty ~ 20 %

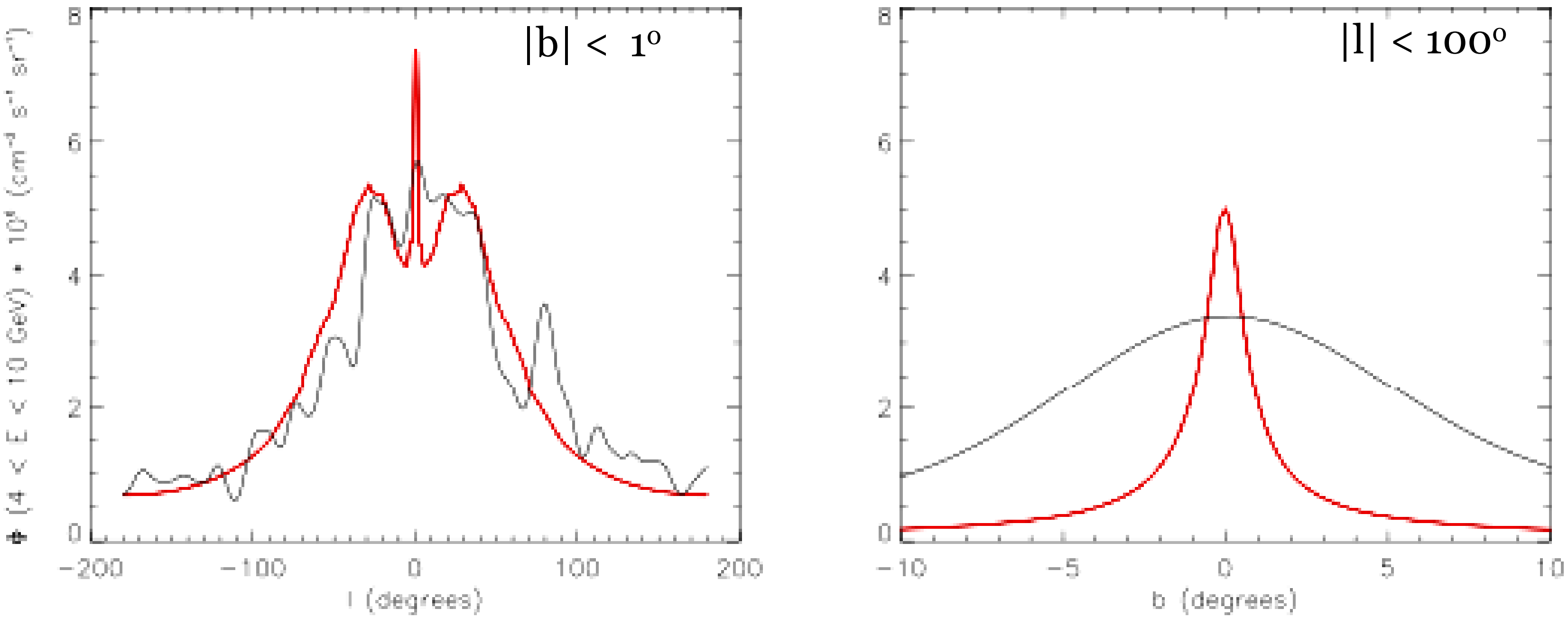


Cavasinni, D.G. and Maccione '06; Evoli, D.G. and Maccione '07

Comparison with EGRET map (4 < E < 10 GeV)

Performed by using a 3-D gas distribution *C. Evoli, D. Gaggero, D.G. and L.Maccione, in progress*

model 2 (turbulence strength tracing SNRs; Kolmogorov)

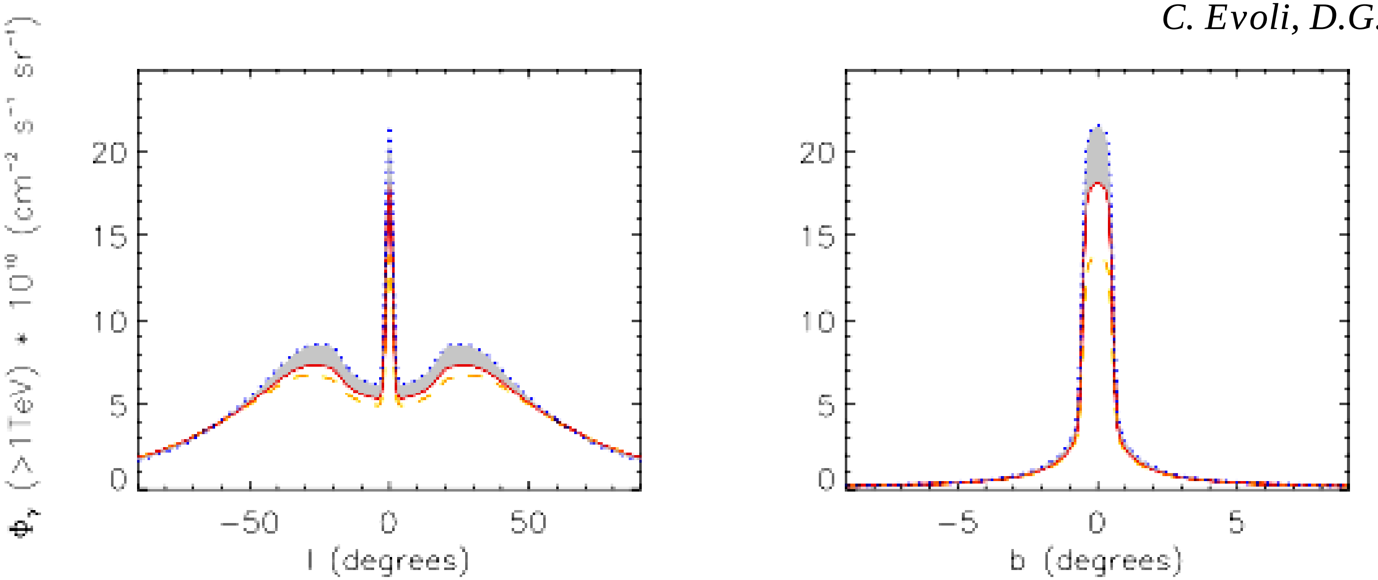


The longitude profile is reasonably reproduced without tuning X_{CO}(r) and the SNR profile !

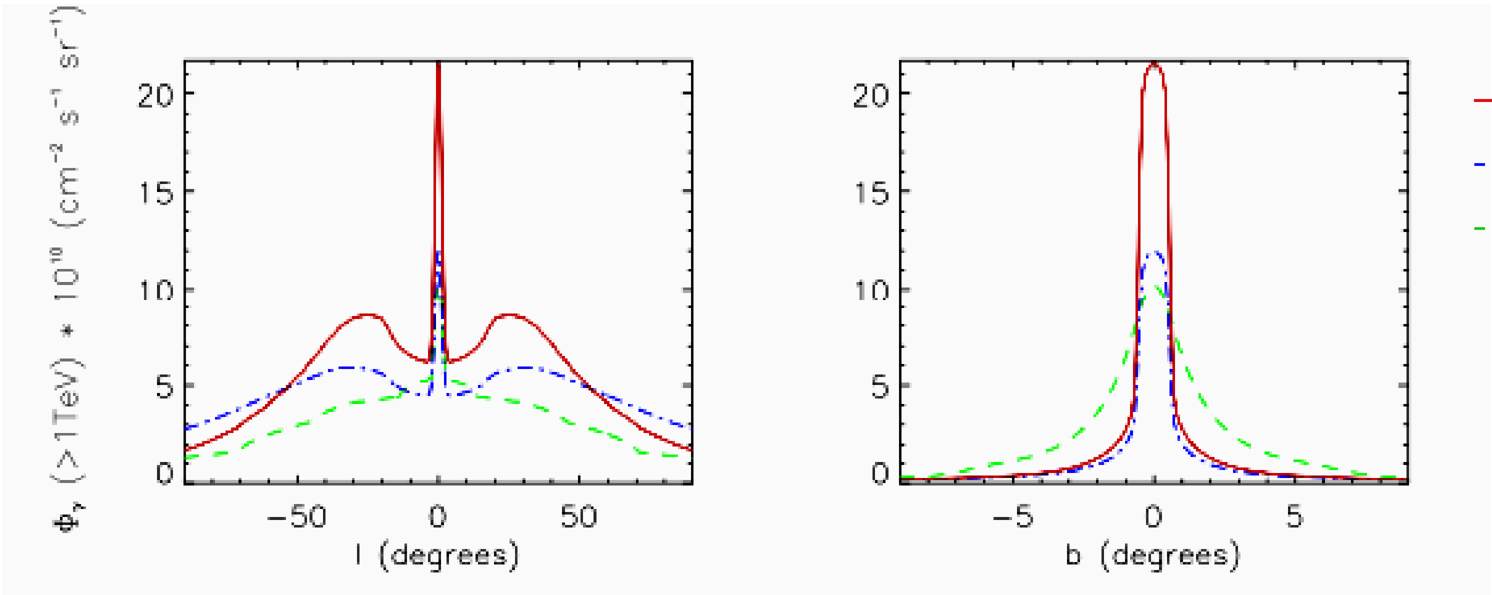
The adoption of a more realistic X_{CO}(r) should allow to improve our fit and leave room for a no negligible IC contribution which is also required to match the latitude profile measured by EGRET (see also Strong at al. 2004)

Expected flux profiles above the TeV

C. Evoli, D.G. and L.Maccione, '07



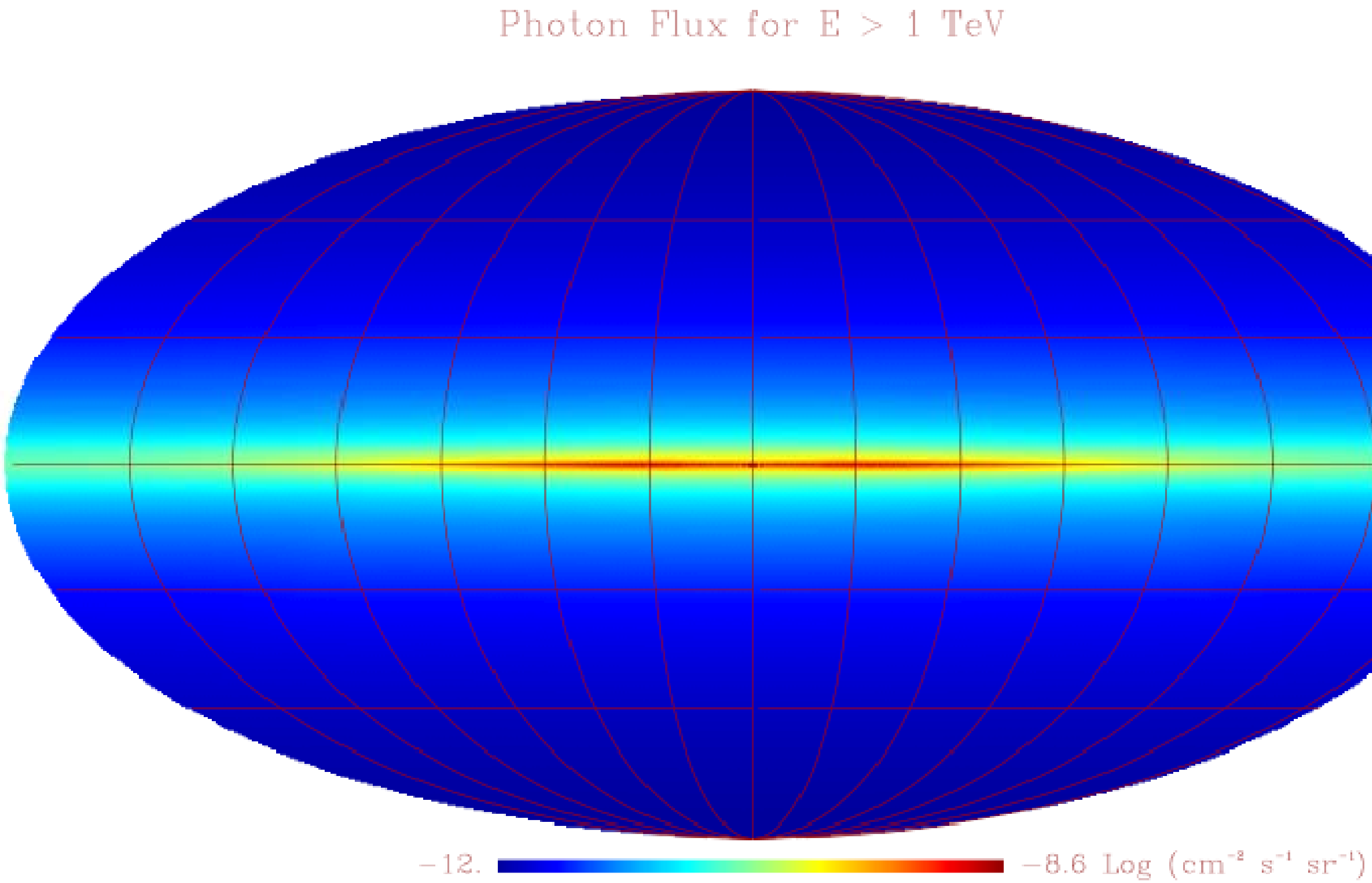
CR models 0-3



model 3

uniform CR

Berezinsky et al.'93



Performed with HealPix

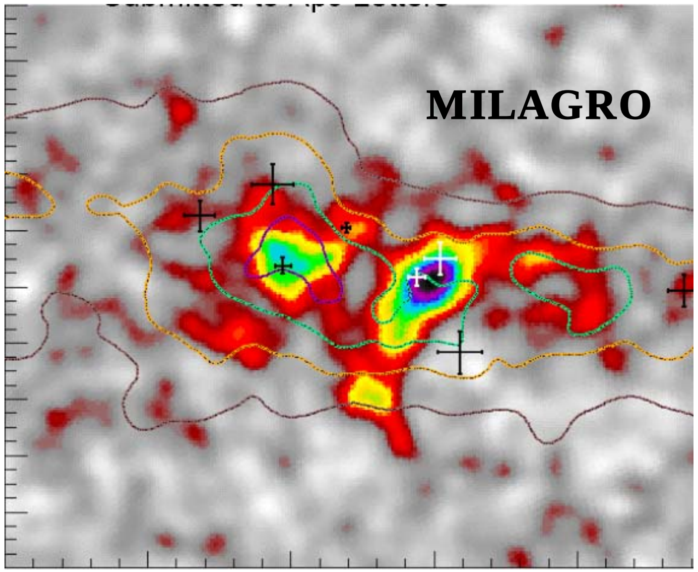
Comparison with ASA experiments measurements

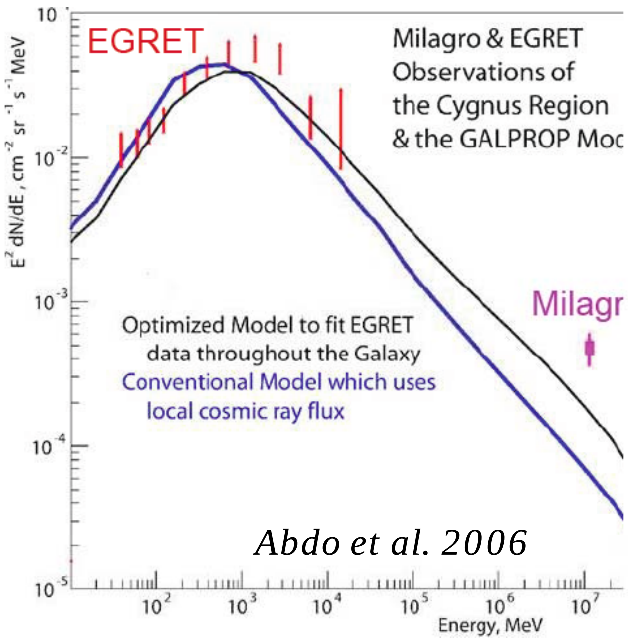
		$\Phi_\gamma(>E_\gamma)$ $(\mathrm{cm}^2\ s\ \mathrm{sr})^{-1}$		
Sky window	E_γ	Our model	Measurements	
$\lvert l\rvert < 10°,\ \lvert b\rvert \leq 2°$	4 GeV	$\simeq 4.7 \times 10^{-6}$	$\simeq 6.5 \times 10^{-6}$ [63]	EGRET
$20° \leq l \leq 55°,\ \lvert b\rvert \leq 2°$	3 TeV	$\simeq 5.7 \times 10^{-11}$	$\lesssim 3 \times 10^{-10}$ [10]	TIBET
	4 GeV	$\simeq 4.4 \times 10^{-6}$	$\simeq 5.3 \times 10^{-6}$ [63]	
$73.5° \leq l \leq 76.5°,\ \lvert b\rvert \leq 1.5°$	12 TeV	$\simeq 2.9 \times 10^{-12}$	$\simeq 6.0 \times 10^{-11}$ [11]	MILAGRO (Cygnus)
	4 GeV	$\simeq 2.4 \times 10^{-6}$	$\simeq 3.96 \times 10^{-6}$ [63]	EGRET
$140° < l < 200°,\ \lvert b\rvert < 5°$	3.5 TeV	$\simeq 5.9 \times 10^{-12}$	$\lesssim 4 \times 10^{-11}$ [9]	MILAGRO
	4 GeV	$\simeq 5.9 \times 10^{-7}$	$\simeq 1.2 \times 10^{-6}$ [63]	EGRET

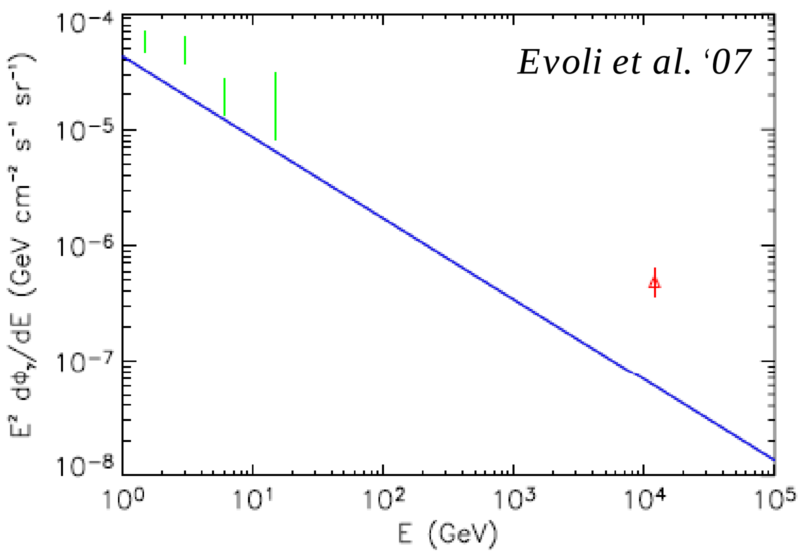
The uncertainty factor on those predictions is ~ 2
A possible IC contribution is not included

It is evident an excess in the Cygnus region
A CR local over-density (~ × 10) has to be invoked to explain it (see also *Abdo et al. 2006*)

The Cygnus Excess







Perspectives for neutrino astronomy

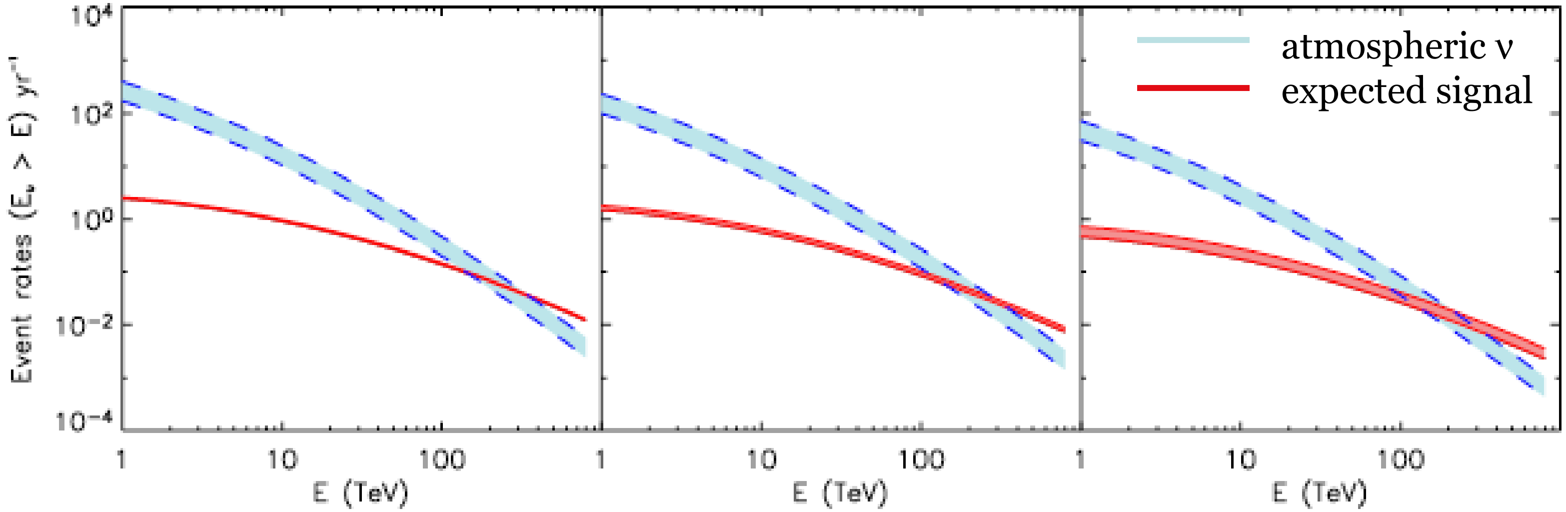
The only experimental limit available so far is by AMANDAII [Kelley at al. 2005]:

$$\Phi_{\nu_\mu+\bar{\nu}_\mu}(>1\ \mathrm{TeV}) < 3.1 \times 10^{-9}\ (\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr})^{-1} \qquad 33^\circ < l < 213^\circ,\ |b| < 2^\circ$$

our prediction is $\sim 4 \times 10^{-11}$!! (undetectable even for IceCube)

For a **km³ neutino telescope in the North hemisphere** we found

$|l| < 50^\circ$, $|b| < 1.5^\circ$ $\quad$ $|l| < 30^\circ$, $|b| < 1.5^\circ$ $\quad$ $|l| < 10^\circ$, $|b| < 1.5^\circ$



still quite hard to detect !

Neutrinos from molecular clouds complexes

J2032 (MILAGRO obs. of Cygnus region) 7.1 σ sig.

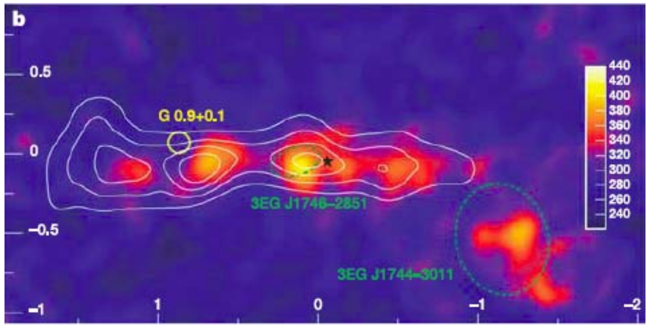
corresponding ν-flux : 8×10^{-11} $(\mathrm{TeV\ cm^2\ s})^{-1} \rightarrow N_\nu = 9\ \mathrm{yr}^{-1}$ (2.5 bkg) in IceCube

Anchordoqui et al. astro-ph/0612699

detectable in 1 year by IceCube

(see also Kistler & Beacom astro-ph/0701751)

J1745-290 + GCR (HESS Galactic Centre)



$F_\gamma = (2.4 \pm 0.3) \times 10^{-12}$ $(E_{TeV})^{-(2.29 \pm 0.15)}$ $\mathrm{cm^{-2}\ s^{-1}\ TeV^{-1}}$ point-like
compatible with the energetic of a SNR (Sgr A East) - *D.G. & Maccione '05*

$F_\gamma(E) = (4.97 \pm 0.4) \times 10^{-12}$ $E_{TeV}^{-(2.29 \pm 0.07)}$ $\mathrm{cm^{-2}\ s^{-1}\ TeV^{-1}}$ GCR ($|l| < 0.8^o$ $|b| < 0.3^o$)

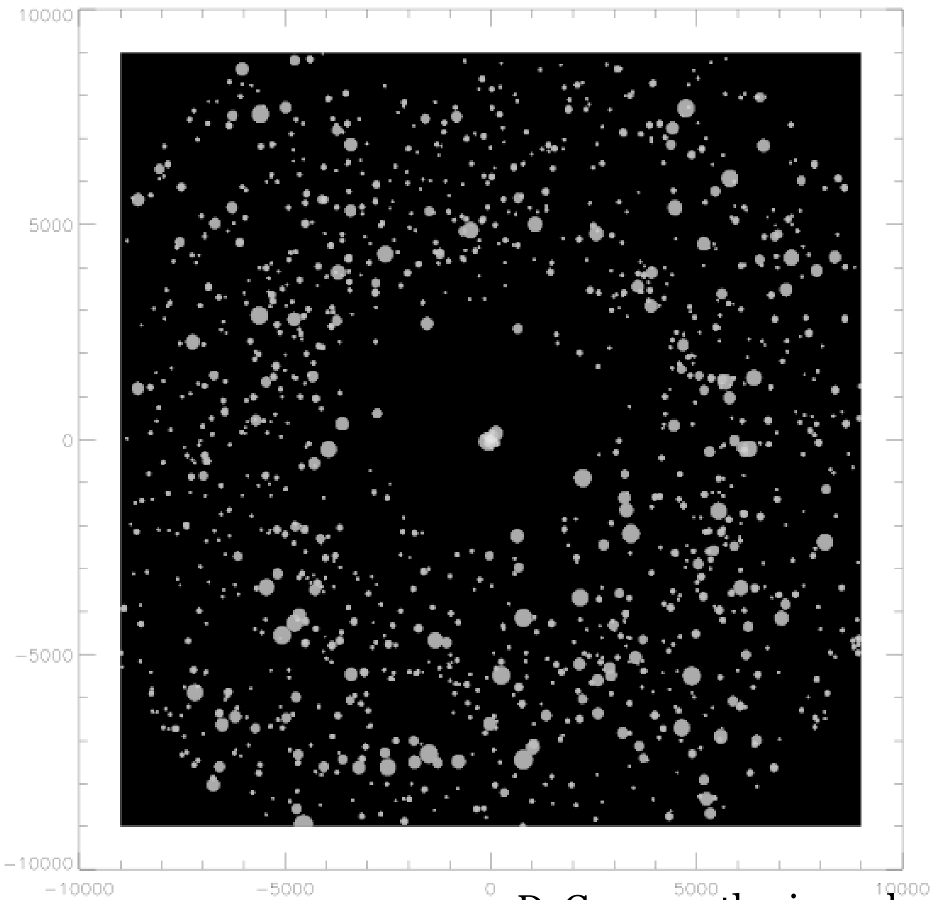
$N_\nu \cong 1.5\ \mathrm{yr}^{-1}$

detectable in 3 year by Nemo (km³)

Cavasinni, D.G., Maccione '06, Kistler & Beacom astro-ph'06, Kappes et al. '06

The possible effect of clumped gas and CR distributions

The kind of analysis performed so far didn't account for the clumped distribution of H_2



D. Gaggero, thesis work

Furthermore, since the star formation rate is correlated with the H_2 the emission from some dense regions may be significantly enhanced

That may be the case of the Galactic Centre (see Aharionan et al. [HESS], Nature 2006) and the Cygnus (Abdo et al. [Milagro] 2006)

It was showed that the ν emission may be detectable from those regions (see e.g. Kistler&Beacom'06 , '07; Cavasinni et al.'06, Anchordoqui et al. '07)

We are trying to model this effect globally

Conclusions

• We solved the diffusion equation for CR nuclei accounting for a possible spatial dependence of the diffusion coefficients and assuming a realistic distribution of sources (SNR). The good matching of EGRET observations along the GP show that this is a viable approach.

• Inhomogeneous diffusion may ameliorate the CR gradient problem interpreting EGRET. The effect on the γ-ray spatial distribution may be tested by GLAST

•Those effect may be included in GALPROP (or in a similar code) to better model what GLAST may observe above the GeV

• We estimated the (not including IC) and ν flux above the TeV from the GP and compared it with ASA upper limits and the expected NT sensitivity

• A positive detection may be possible only from dense molecular gas cloud complexes embedding active CR sources.