Diffuse gamma-ray and neutrino emissions of the Galaxy above the TeV

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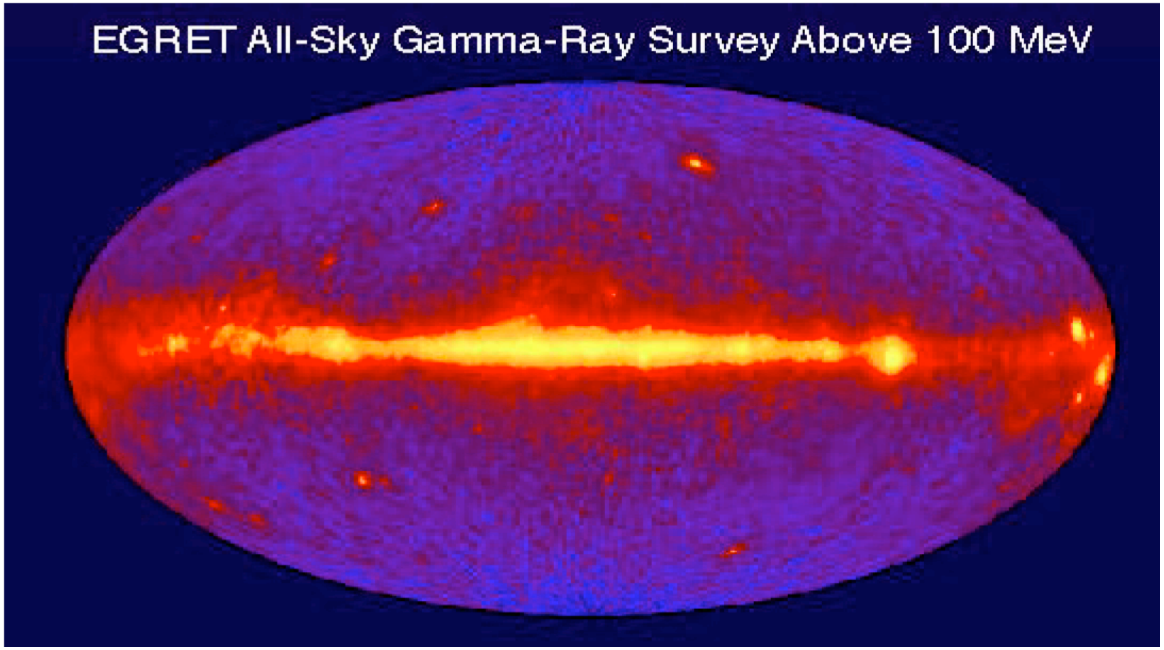
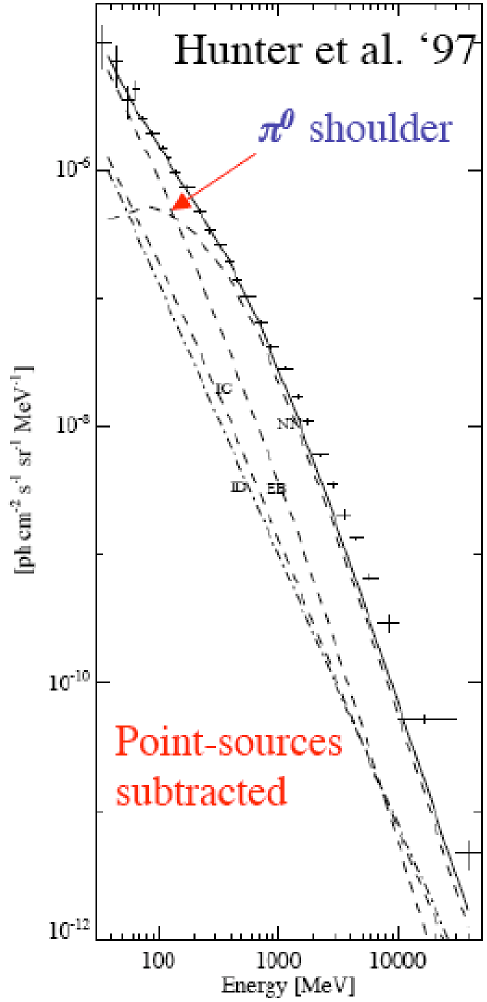
Motivations: EGRET observations





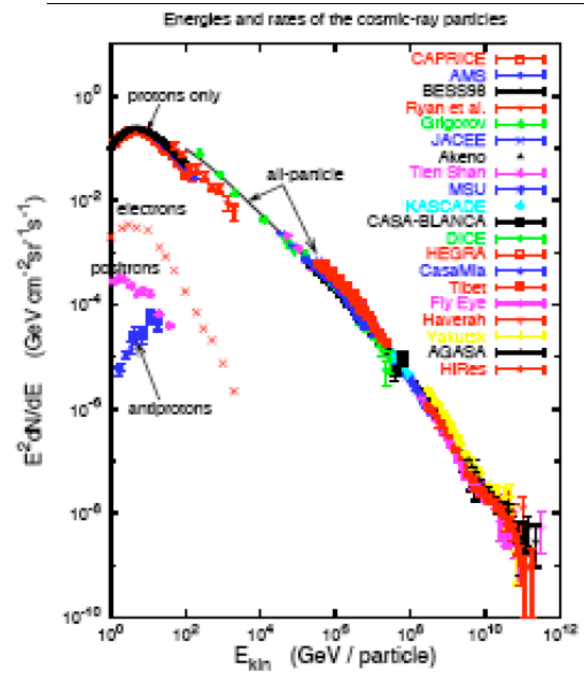
Large fraction of > GeV γ-rays should be originated by hadronic interactions.

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

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

Motivations: CR observations

From CR measurements we expect that the γ-ray diffuse emission should extend to > 100 GeV energies.

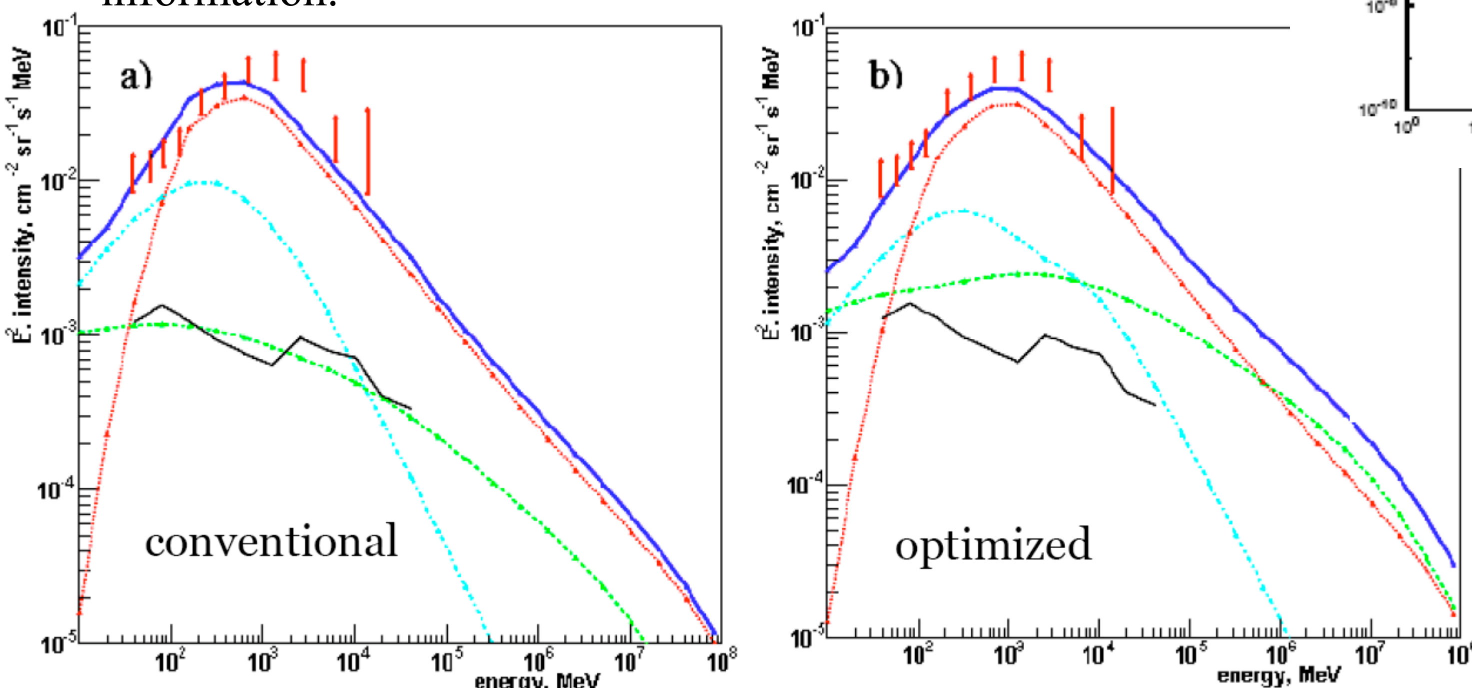


Strong et al ‘04 [GALPROP]

We don’t know however what fraction is due to hadronic processes and what is due to leptonic ones and how it depends on the position in the sky.

→ *leptonic / hadronic degeneracy*

Predictions are very uncertain due to lack of astrophysical information.



Experiments

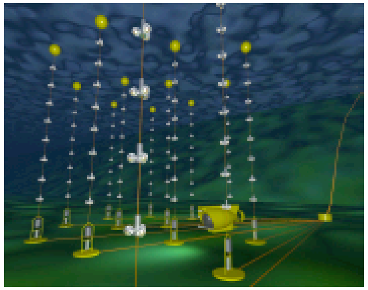
GLAST

E_{max} ~ 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

Problem set up

Estimate the hadronic emission above the TeV in **ν** and **γ-rays** (almost insensitive to local effects).

Ingredients we need to study the CR propagation:

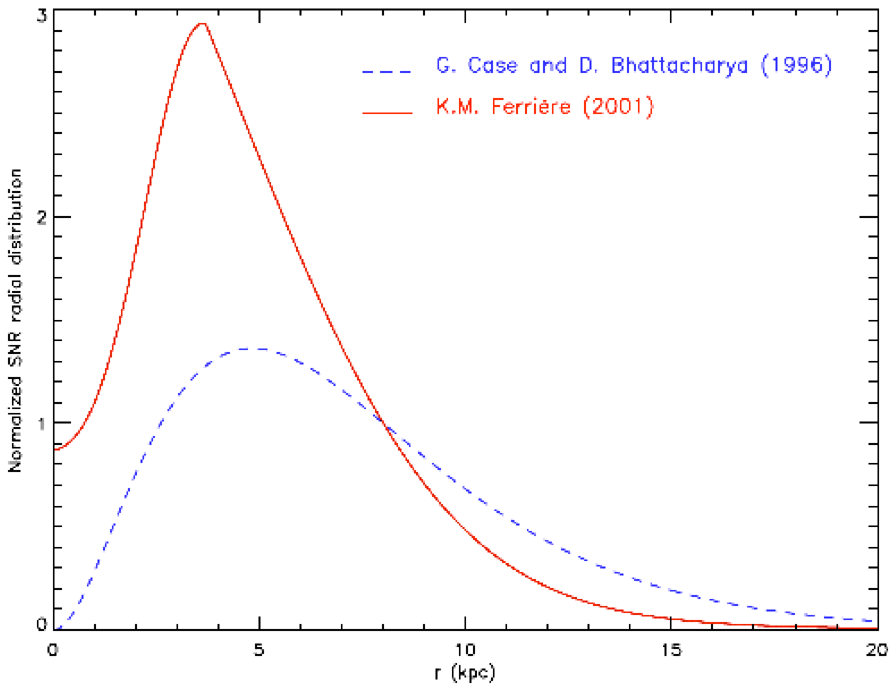
1. CR sources → SNR distribution
2. Magnetic fields → turbulence
3. Targets → gas distribution

Also try to estimate how the uncertainties on the knowledge of our ingredients reflect in the diffuse emission.

CR sources: SNR distribution

Past years: SNR (radio shells) surveys used (Case & Battacharya, '96, '98).
Several problems: incomplete, selection effects, do not fit radioactive nuclides (^{26}Al).

Other approach: SNR are traced by pulsars and old stars (Ferriere '01, Lorimer '04).



The Ferriere's distribution is more realistic but much more peaked.
It is harder to reproduce the EGRET diffuse emission along the GP.

"CR gradient" problem
Strong et al. '04

Galactic Magnetic Field

Galactic magnetic field is a superposition of a regular plus a random component. We assume, in axial symmetry:

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

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

$L_{\rm max} \sim 100 \text{ pc} \gg r_L(B_{\rm reg})$ → Propagation occurs in the **spatial diffusion regime**

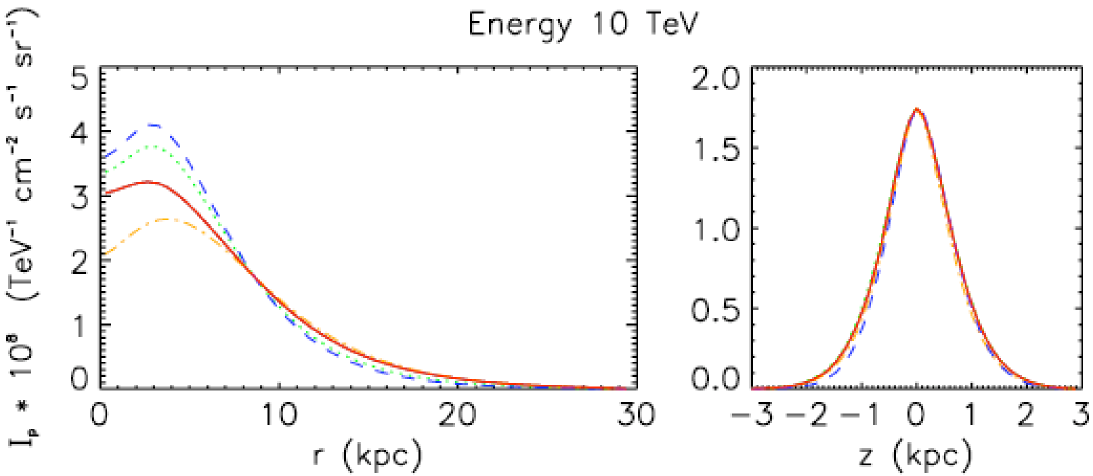
$\sigma \geq 1$ (strong turbulence)

Turbulence mainly driven by CRs → $\sigma(r)$ enhanced in SNR rich regions → **position dependent** diffusion coefficients (previous simulations adopted **uniform diffusion coefficients** and **isotropic diffusion**)

We adopt a position dependent $D_\perp(E, B_{\rm reg}, \sigma)$ as determined by MonteCarlo simulations (Candia & Roulet, '04). Other approaches (as B/C determination) only probe a diffusion coefficient averaged over the whole CR path.

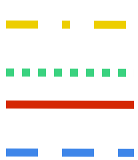
Results: CR profiles

We solved the diffusion eq. (see e.g. Ptuskin et al.'93).
Boundary conditions $N(r = \pm 30 \text{ kpc}, z = \pm z_t) = 0$



Simulated proton fluxes normalised according to the observed values at the Sun position (Horandel '03). Injection spectral slope tuned to reproduce $\alpha = 2.7$.

Table 1. The main properties of the models considered in this section.



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

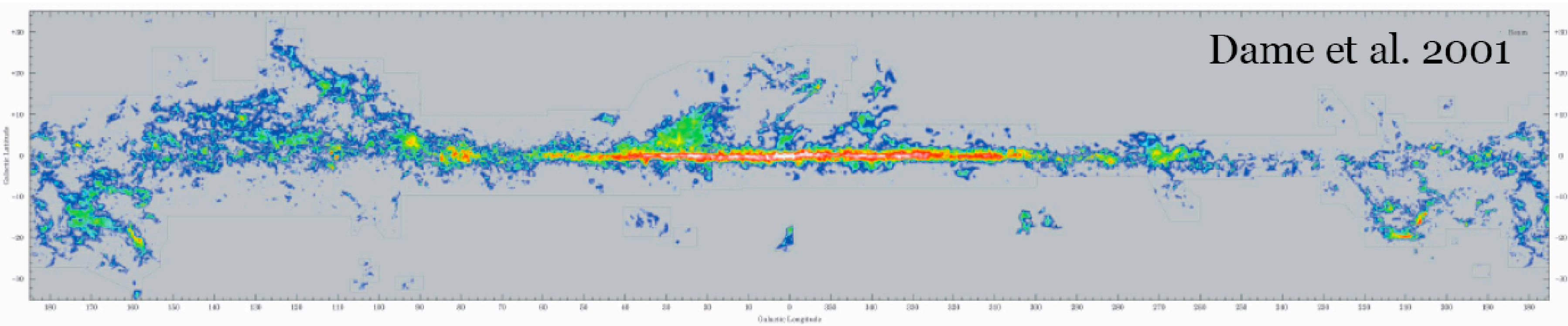
Evoli, Grasso, L.M., JCAP 0706:003,2007

Notice: position dependent diffusion helps smoothing the CR distribution!

Ameliorate the "CR gradient" problem

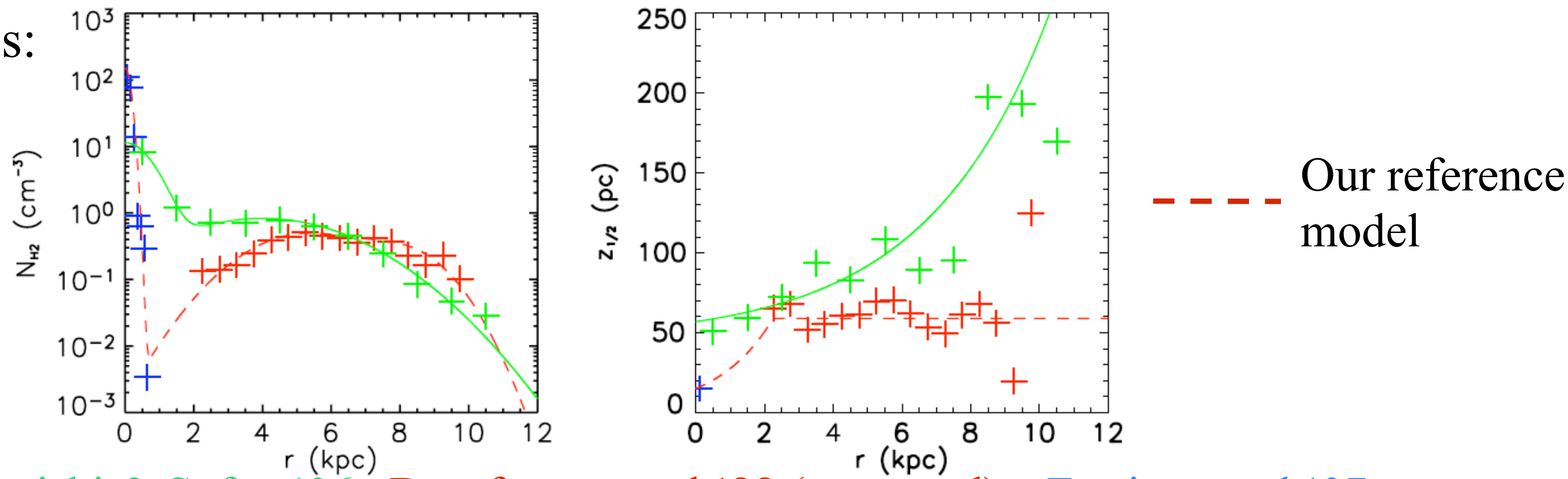
Gas distribution

H_2 is the main target. Generally traced by ^{12}CO (J=1-0).



3-D structure: Doppler shift (velocity) + galactic rotation curve.

2-D profiles:



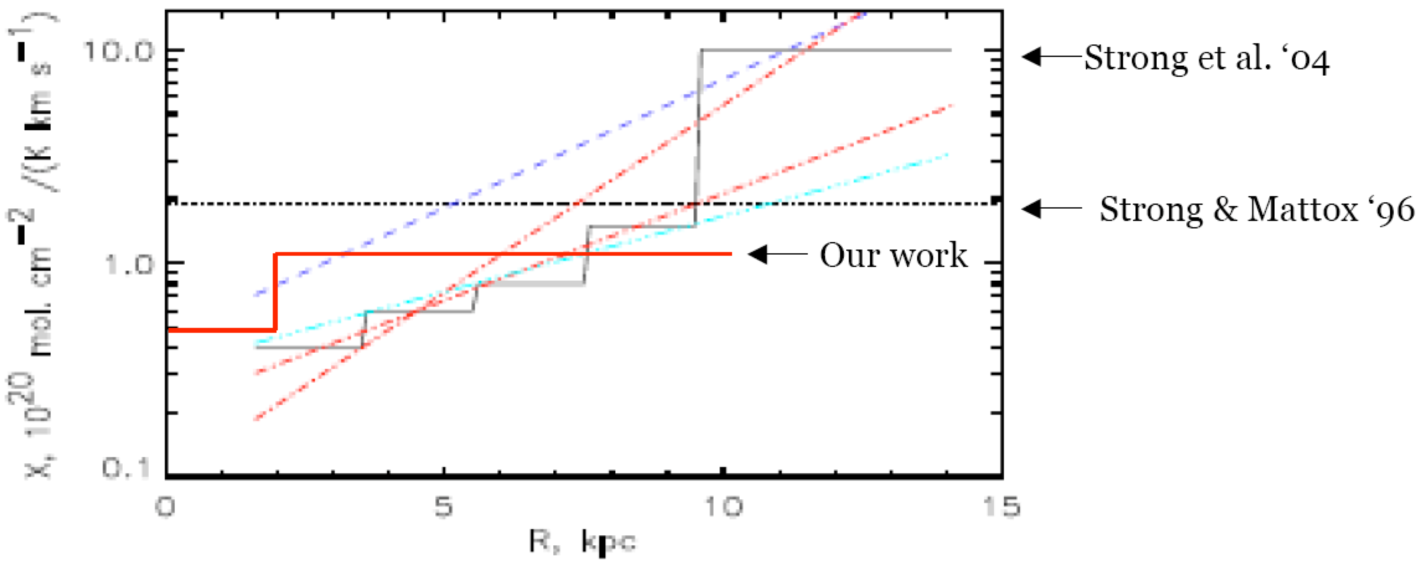
Nakanishi & Sofue '06 Bronfmann et al '88 (corrected) Ferriere et al '07

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

Wolfire et al. '03 and ref.s therein

Gas distribution: X_{CO}

A scaling factor is needed to convert CO maps into gas column density.
Expected to change with *r*, dependence on the metallicity.
Fine tuning needed to achieve agreement with EGRET measurements (**“CR gradient” problem**, see Strong et al., A&A 422).



The uncertainty is about a factor of 2.

Results: γ-ray emission

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

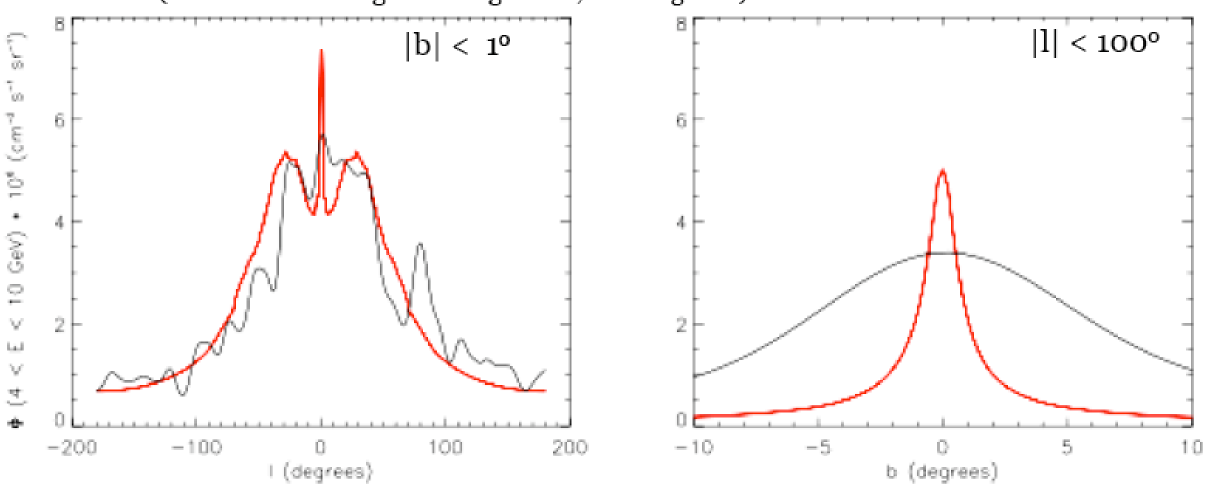
$f_N \sim 1.44$ accounts for nuclei in CR and ISM.
s distance to the observer.
$\alpha = 2.7$ proton spectral index.

$Y_\gamma(2.7) = 0.036$ $Y_\nu(2.7) = 0.012$ (ν oscillations accounted for) determined by PYTHIA simulations with a ~20% uncertainty.

Cavasinni, Grasso, L.M. '06; Evoli, Grasso, L.M. '07

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

model 2 (turbulence strength tracing SNRs; Kolmogorov)

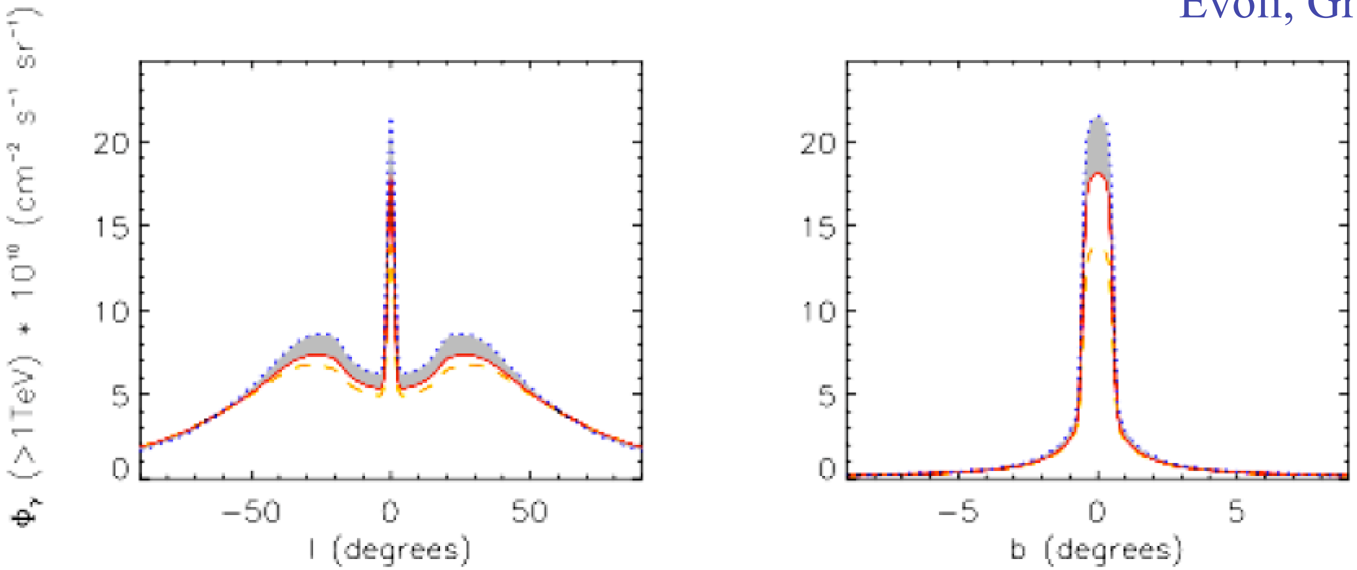


using a 3-D gas distribution (*Evoli, Gaggero, Grasso, L.M., in progress*)
With more realistic X_{CO} a better fit should be achieved and there should be room for IC scattering contribution, needed to match the latitude profile (Strong et al. '04).

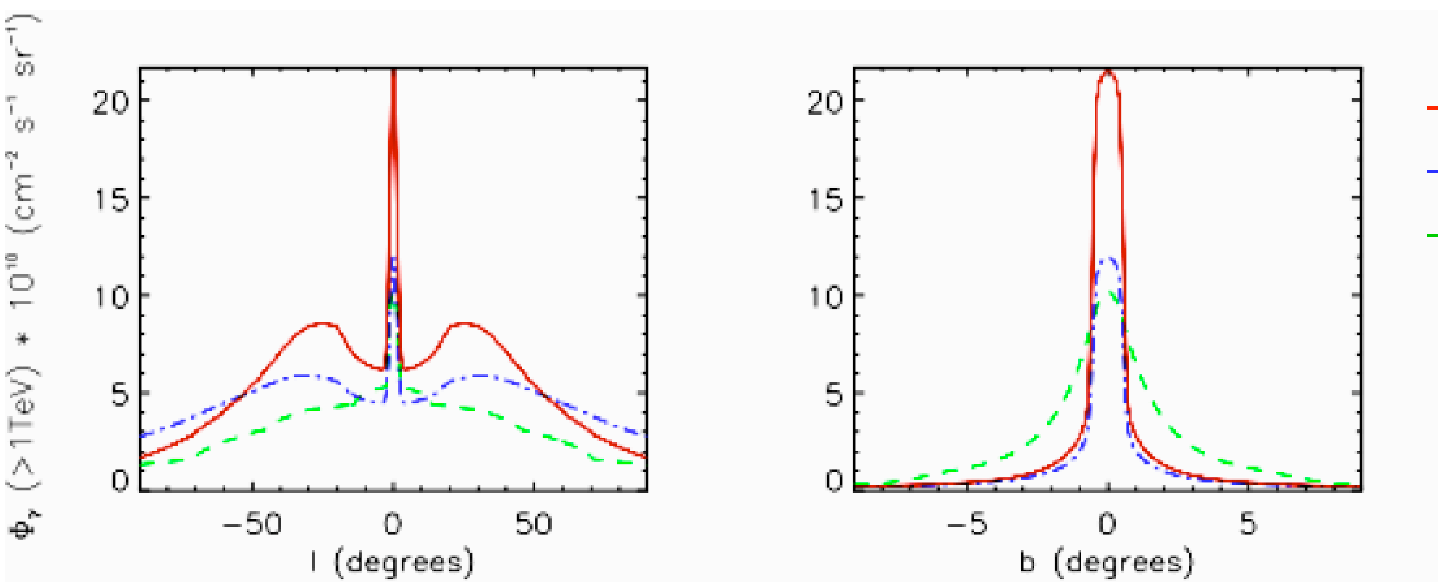
The longitude profile is reasonably reproduced without tuning $X_{CO}(r)$ and the SNR profile !

Results: γ-ray emission

Evoli, Grasso, L.M. '07



CR models 0-3



model 3

uniform CR

Berezinsky et al.'93

Results: γ-ray emission

We compared our predictions with ASA experiments' results

Sky window	E_γ	$\Phi_\gamma(> E_\gamma)$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$ 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]	
$140° < l < 200°,\ \lvert b\rvert < 5°$	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]	

We didn't account for a possible IC contribution.
Overall uncertainty is a factor of ~ 2.

Evident excess in the Cygnus region. A local overdensity (factor ~10) has to be invoked (see Abdo et al. '06).

Results: ν emission

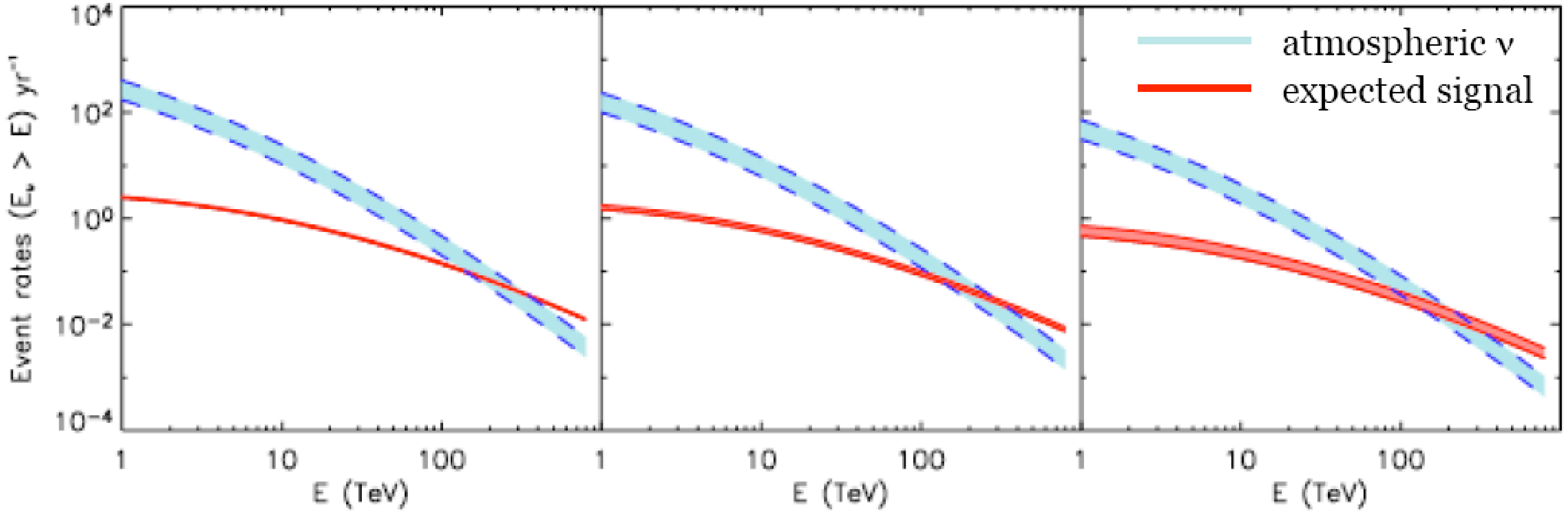
The only experimental limit available so far is by AMANDAII [Kelley at al. 2005]:

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

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

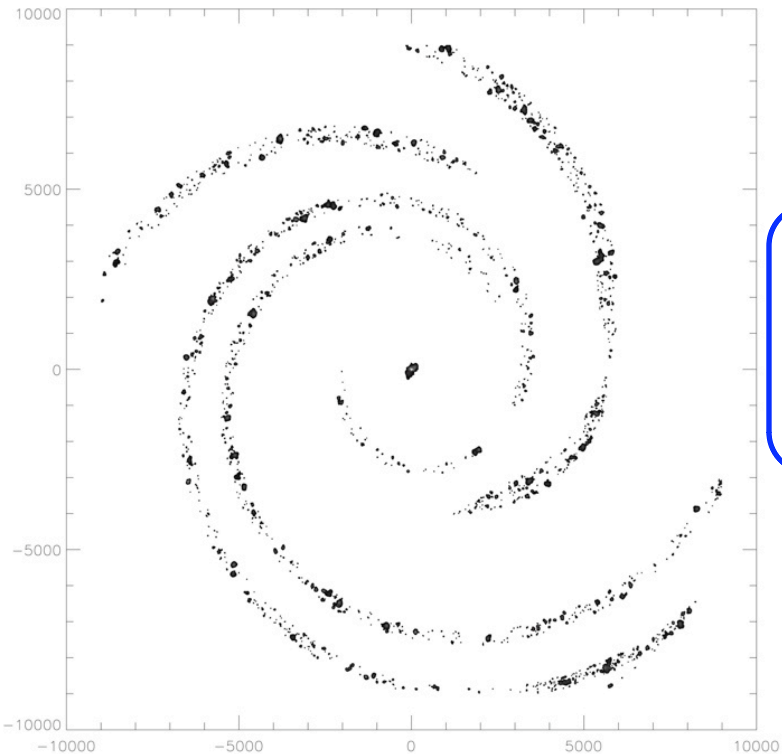
For a **km³ neutino telescope in the North hemisphere** we found

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



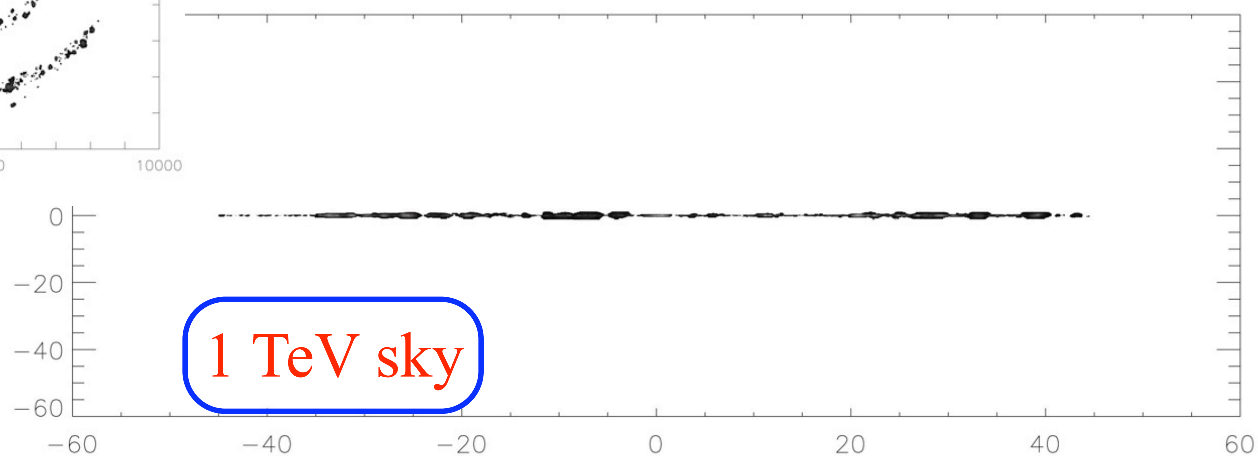
still quite hard to detect !

New developments: clumpy H_2



Simulation *(in progress)* of the H_2 clumpy structure.

Face-on map of the GP obtained with the observed cloud power-law distribution



Conclusions

- We solved the diffusion eq. assuming **inhomogeneous diffusion** and a **realistic distribution of CR sources (SNR)**. Results are encouraging and motivate further study. Inhomogeneous diffusion also helps in addressing the "CR gradient" problem (together with spatial variation of X_{CO}).

- **IC scattering contribution is not accounted for**. It may be dominant at high galactic latitudes especially if EGRET excess will be confirmed by GLAST.

- We **estimated** the γ-ray and ν emission above the TeV from the GP and **compared** them to the results from ASA experiments and Neutrino Telescope present limits.

- Positive diffuse neutrino detection only possible from dense molecular cloud regions embedding CR sources.

- Further progresses can then be achieved by considering the **clumpy distribution of the gas (H_2) in the ISM**, also related to the star formation rate in those regions.