Diffusion of Cosmic Ray Nuclei in the Galaxy and γ-ray and ν diffuse emissions

D. Grasso (INFN, Pisa)

in collaboration with

C. Evoli (SISSA),

D. Gaggero (INFN, Pisa Un.),

L. Maccione (SISSA & INFN, Trieste)

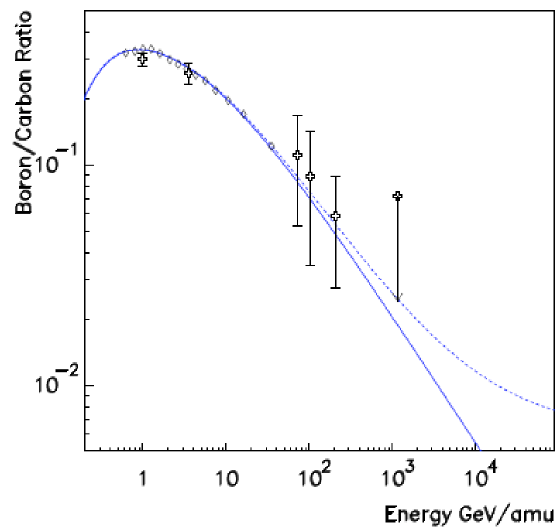
Multi-messenger approach to CR

Galactic cosmic rays (CRs) origin and propagation can be probed by:
- primary direct measurements (energy spectrum, composition and angular distribution)
- or indirectly by their **secondary products**

They include:

• secondary nuclei
(e.g. B, Be, subFe… produced by spallation)

Exp: ATIC, CREAM, TRACER…

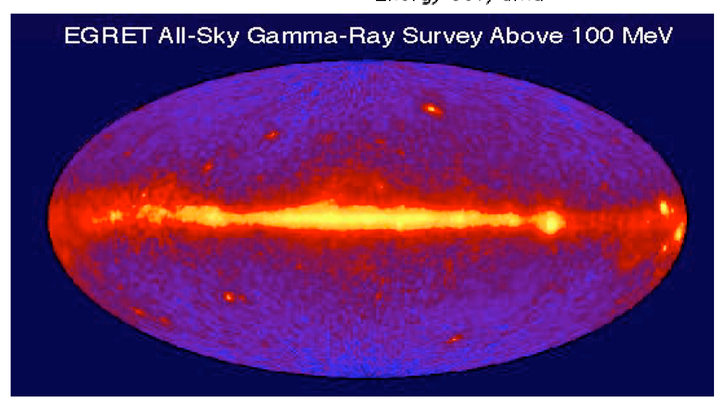


• Diffuse gamma-ray emission

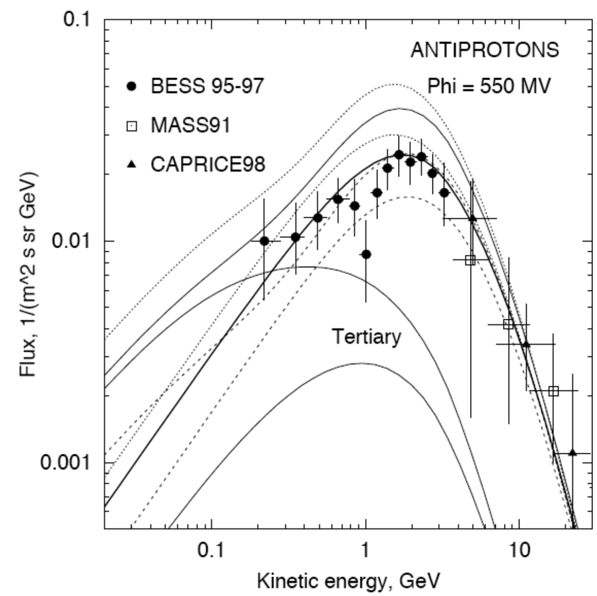
$p + p_{gas} \rightarrow p + p + \pi^0$

or $e + \square_{ISRF}\ \square\ \ e + \square$ ↳ $\gamma + \gamma$

Exp: GLAST, MILAGRO, TIBET AS□ ..



Multi-messenger approach to CR



- secondary antimatter (antiprotons, positrons)

Exp: BESS, PAMELA….

- for the future also neutrino detection

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

Exp: ICECUBE, ANTARES, KM3NET..

Diffusion models

While simple models like the leaky-box and modified slab model can explain the s/p ratios above the GeV, more complex models are called for to provide a comprehensive description of all available data.

The general approach:

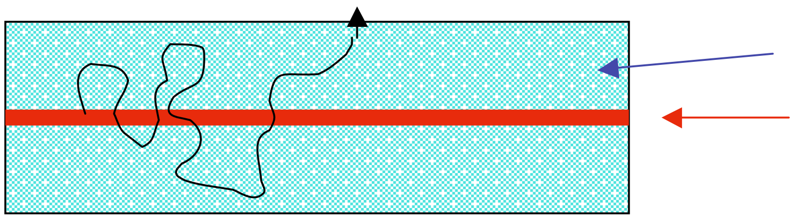
- assume a source (typically SNR) distribution
- assume a gas distribution (while details are not so crucial to reproduce the s/p they are to model the γ-ray diffuse emission)
- solve the transport equation numerically in the steady state limit

$$\frac{\partial N_i(E,r,z)}{\partial t} - \vec{\nabla}\left(D(r,z)\,\vec{\nabla}N_i(E,r,z)\right) = Q_i(E,r,z) - n_{\rm gas}\,\beta_i\,\sigma_i\,N_i + \sum_{j>i} n_{\rm gas}\,\beta_j\,\sigma_{ji}\,N_j$$

Energy losses/gains and convection are disregarded here (see below)

Main diffusion models

Two zone-diffusion model *Maurin, et al., 2001*



Uniform diffusion halo

Galactic Plane (sources, target gas)

The diffusion equation is solved analitically
Ok for secondary/primary and antimatter; cannot model γ-ray emission !

GALPROP *Strong & Moskalenko, 1998, 2004*

- It adopts realistic continuous distribution for the sources and the gas
- The diffusion equation is solved numerically
- s/p ; antimatter; γ-ray spectrum and angular distributions can all be modelled

BOTH ASSUME ISOTROPIC AND UNIFORM DIFFUSION

Our model

We developed a new numerical diffusion code (DRAGON)

We adopt the same nuclei spallation, and antiproton production routines of the public GALPROP code

Differently from GALPROP

- we adopt a SNR distribution based on pulsars and progenitor stars (as in Ferriere '01)
- we adopt a more realist gas distribution in the bulge region (as in Ferriere '07)
- we allow for a spatially variable diffusion coefficient

$$\mathbf{D(E; r, z) = D_0 \, \beta \, (\rho/\rho_o)^{\delta} \; f(r) \exp(z/z_t)}$$

$$D_0 \equiv D(r_{\odot}, 0) \qquad r_{\odot} = 8.5 \text{ kpc}\,, \quad \rho_o = 3 \text{ GeV} \text{ reference rigidity}$$

- we allow for different nuclei injection spectra γ_i
- we focus only on $E_k > 1$ GeV/n which allows to neglect low energy physics (convection, re-acceleration: poorly known)
- so far we only consider nuclei (no electrons).

CR sources: *the gradient problem*

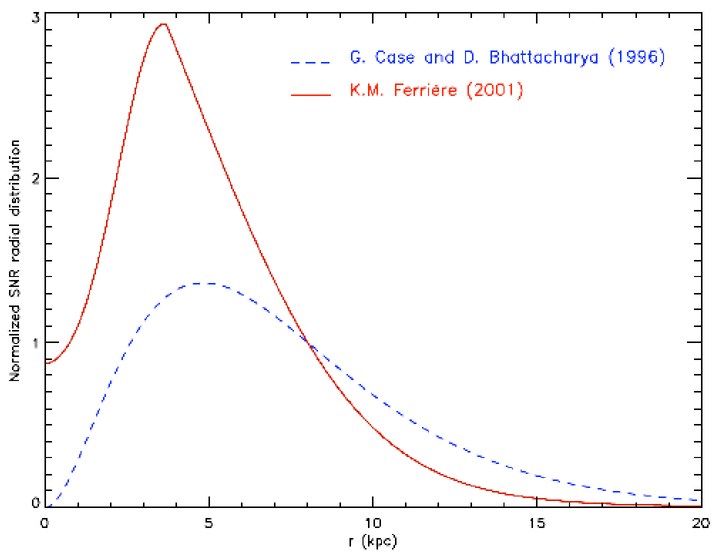
Energetic of CRs and recent X-rays and TeV observations point to SNRs as most likely sources

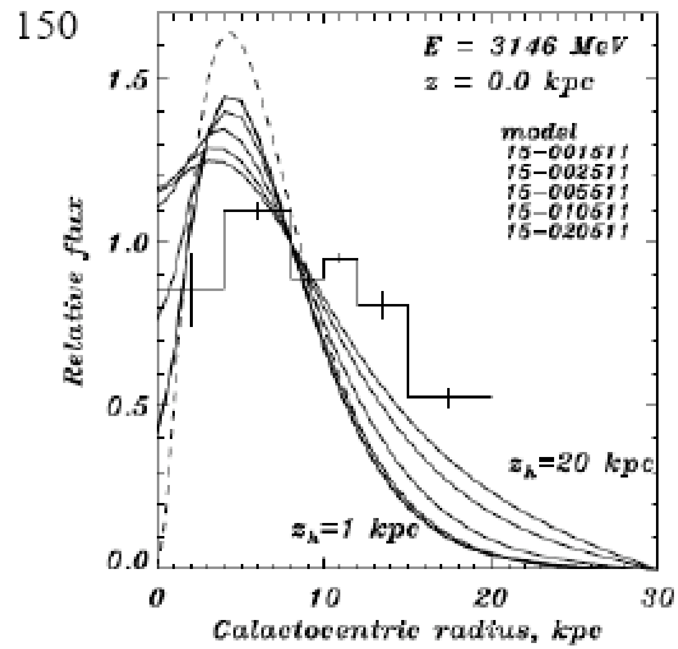
 CR spatial distribution should keep same memory of that of SNR

- SNR radio shells surveys (Case & Battacharya, '96, '98) rather flat profile

(<u>Several problems:</u> incomplete, selection effects, do not fit radioactive nuclides distribution)

- Pulsars and old stars (Ferriere '01, Lorimer '04) more peaked profile





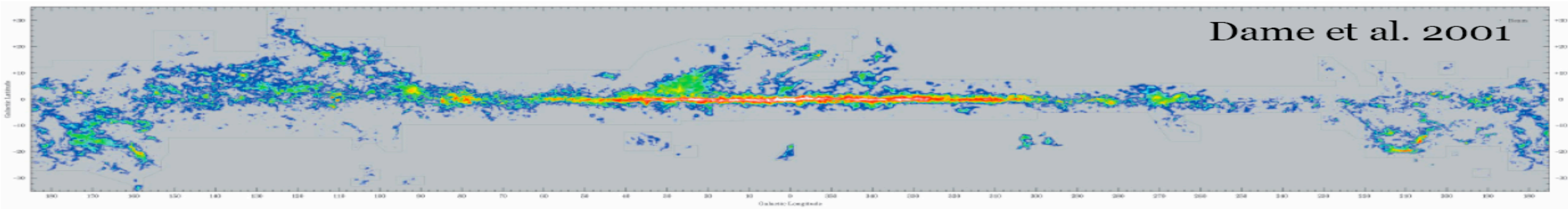
CB is already incompatible with EGRET

The problem is even more exacerbated using the more realistic pulsar based distribution

" CR gradient problem"

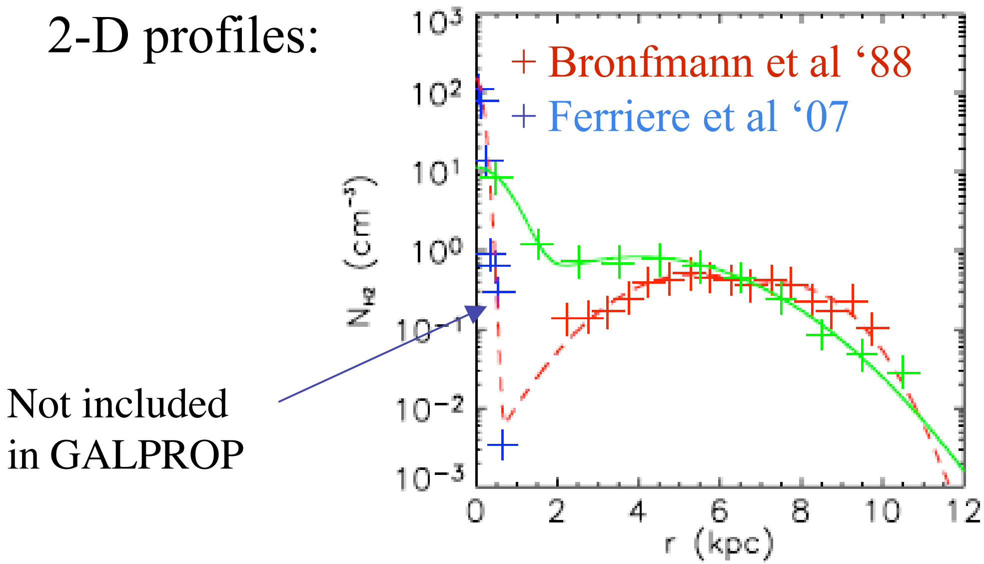
Gas distribution

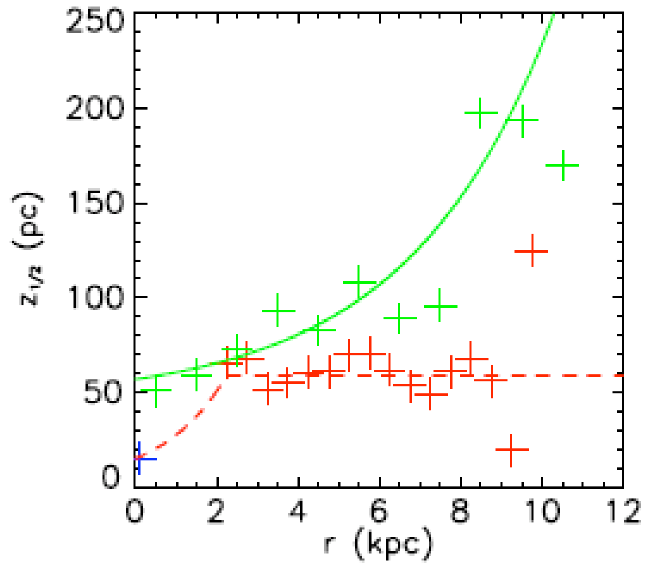
H_2 is the main target. Generally traced by ^{12}CO (J=1-0).



Doppler shift (velocity) + galactic rotation curve

2-D profiles:

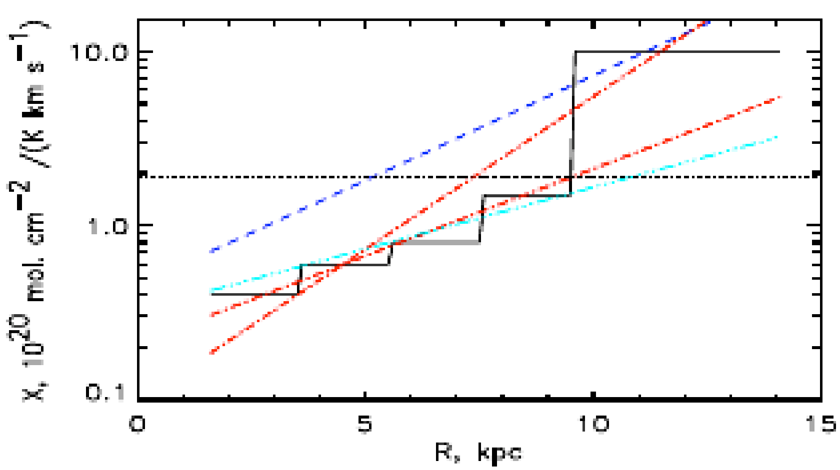


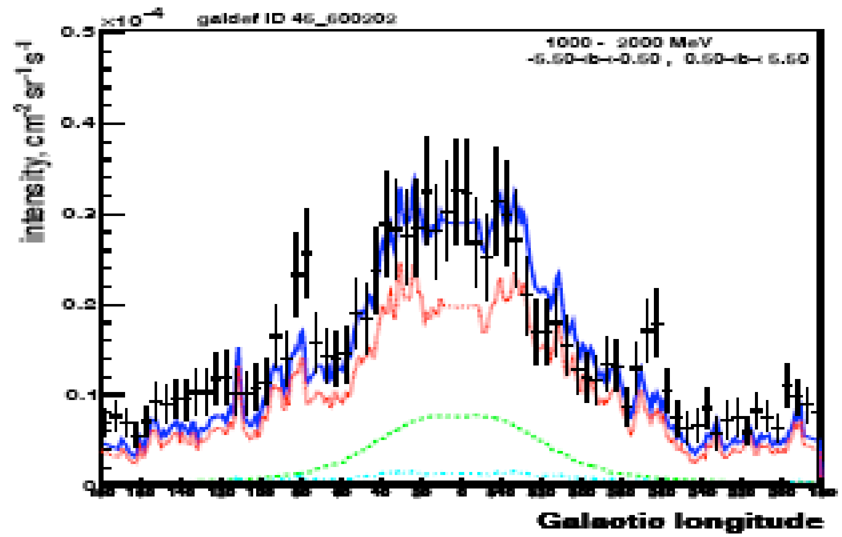


HI and HII are also considered with the same distributions as in GALPROP

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.
Some tuning needed to achieve agreement with EGRET measurements
(**“CR gradient” may be problem**, see Strong et al., 2004).





Take in mind, however, that the uncertainty on X_{CO} is about a factor of 2

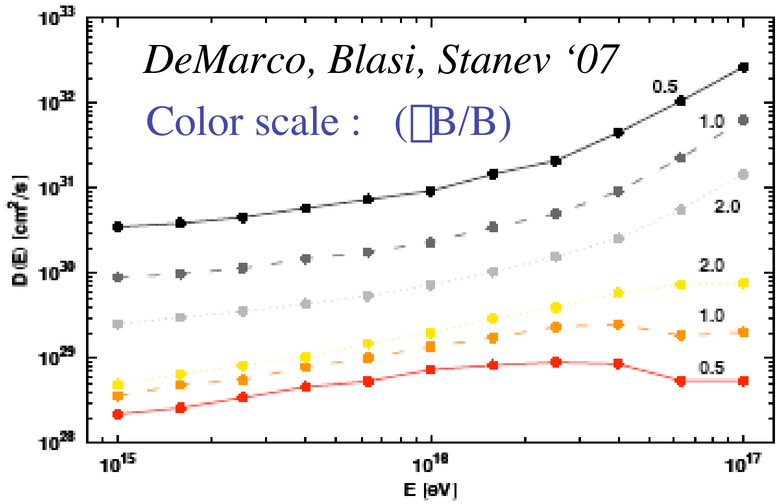
The slope of X_{CO} may be flatter outside the bulge

Few reasons to adopt a spatially changing D

In the quasi-linear theory of diffusion

$$D_\parallel \simeq \frac{1}{3}\, c\, r_L \left(\frac{\delta B_{\rm res}}{B_0}\right)^{-2} \qquad\qquad D_\perp \approx D_\parallel \left(\frac{\delta B_{\rm res}}{B_0}\right)^{4} \propto \left(\frac{\delta B_{\rm res}}{B_0}\right)^{2}$$

Montecarlo simulations: (see also *Casse et al. 2001*, *Candia et al. 2004*)

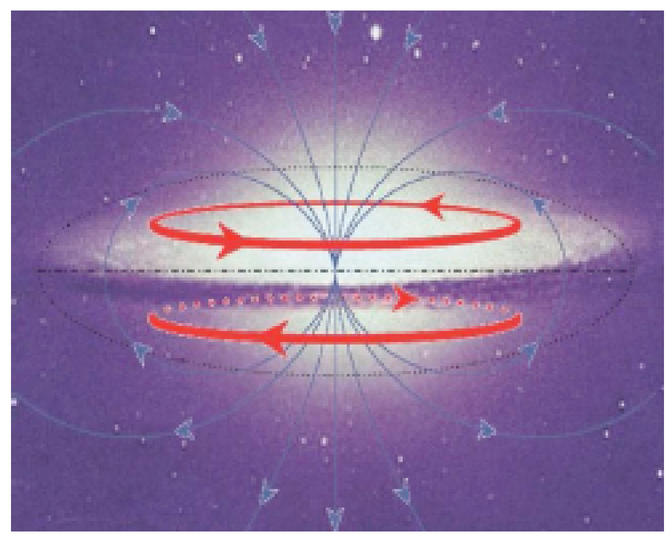


$D_\parallel$ ↓

Opposite behaviour for increasing turbulence strength

$D_\perp$ ↑

$D_\perp$ should be the relevant coefficient if the regular galactic magnetic fields is prevalently azimuthally oriented as suggested from Faraday RM of pulsars



Han er al. 2004

The effect of D(r)

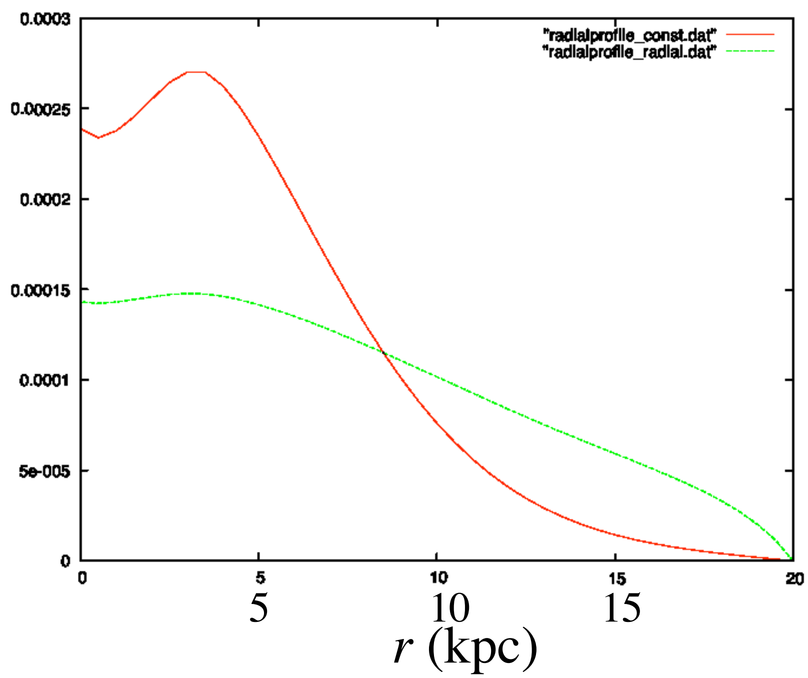
Turbulence is expected to be driven by CRs

□ □B/B, hence $D_{□}$, may be enhanced in CR (SNR) rich regions

□ faster CR escape from those regions

□ **smoothing of the CR distribution**

CR density



uniform $D_{□}$

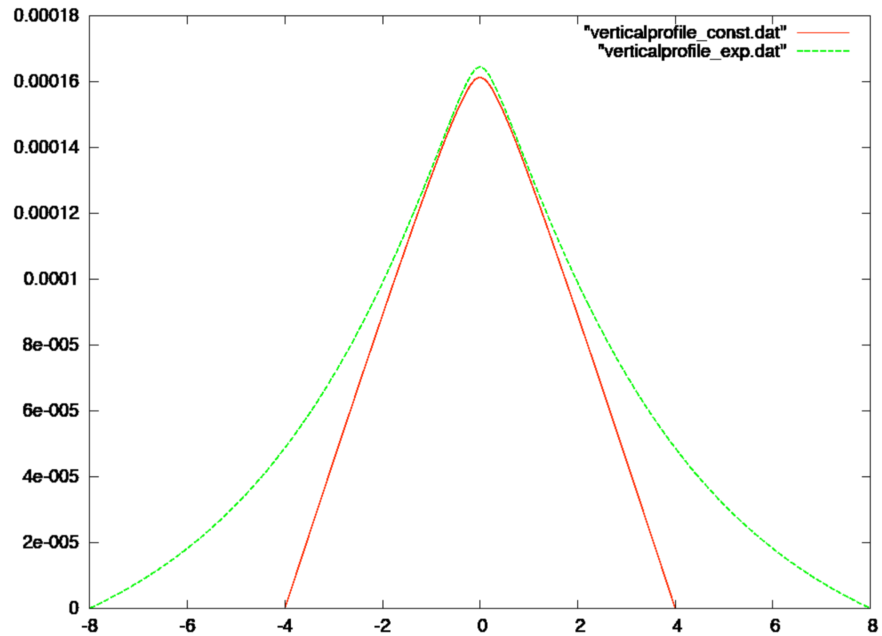
$D_{□}(r)$ $f(r)_{SNR}$

Evoli, D.G. Maccione 2007

The effect of D(z)

D(E; r, z) **$\exp(z/z_t)$**

CR density



z (kpc)

Not a big effect on the spallation products (production takes place for $z \ll 1$ kpc)

The effect may be large for the γ-ray emission at high latitudes and the propagation of DM annihilation products

Preliminar New Results

B/C

It is generally used to normalise the D and its energy dependence

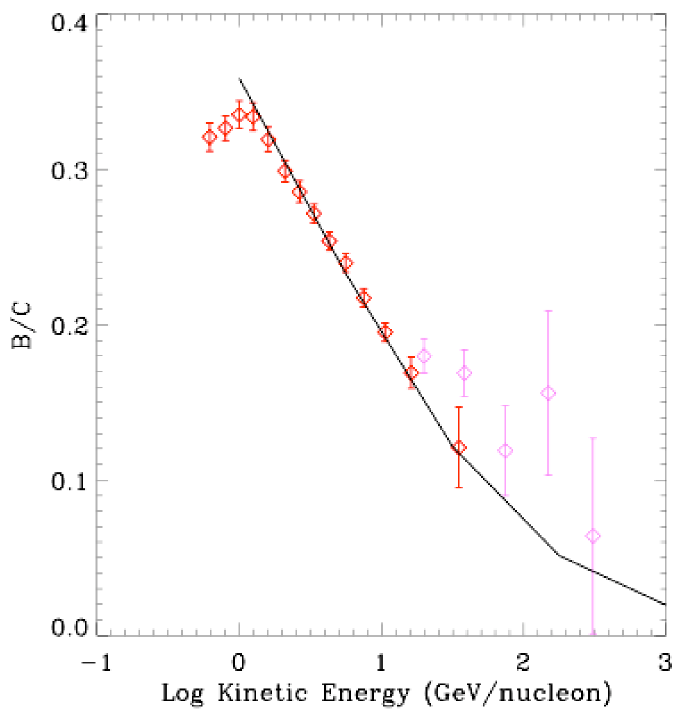
$D_o = 2.1$ □ 10^{28} cm^2/s
(radial + exp vertical prof.)

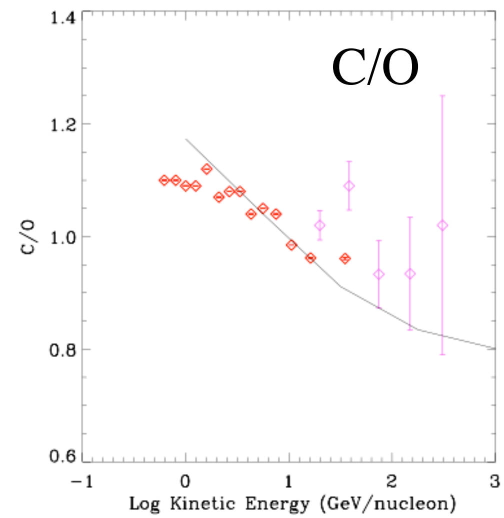
$D_o = 2.5$ □ 10^{28} cm^2/s
(uniform)
OK with GALPROP

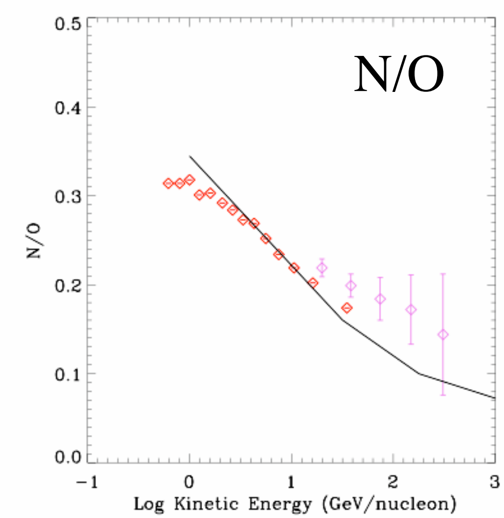
z_t / z_{max} = 4 kpc

□ = 0.6

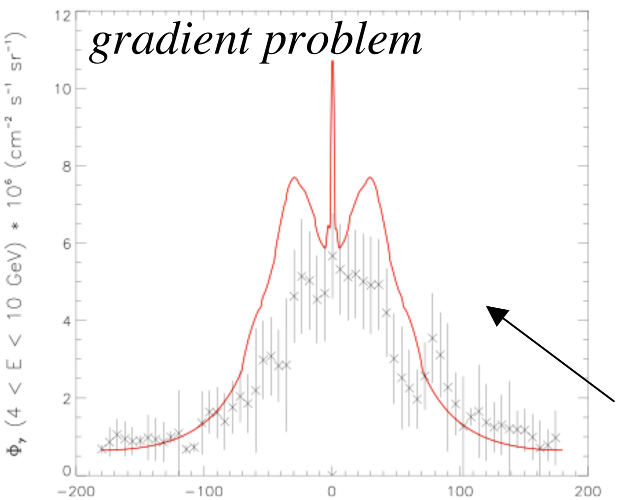
all injection spectra have the same slope □ = 2.1







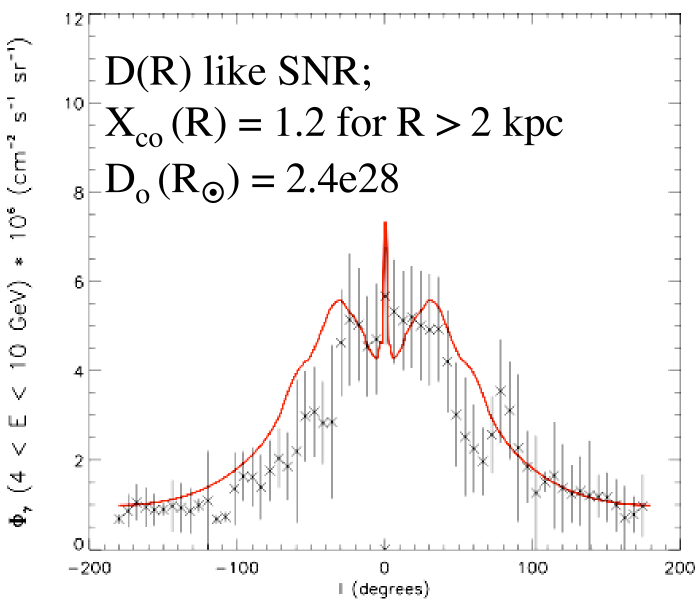
γ-ray distribution - comparison with EGRET

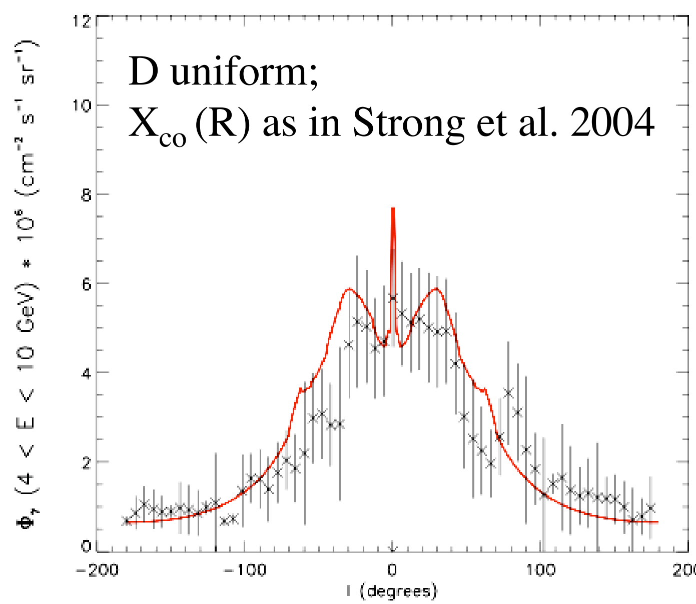


$4 < E < 10$ GeV; $|b| < 1^o$

There is a degeneracy between the X_{CO} and D radial dependences

D(R) uniform;
X_{co} (R) uniform





□-ray and □ diffuse emission in the TeV

MILAGRO found $\Phi_{\square}$(15 TeV) = (23.1±4.5) □ 10^{-13} (TeV cm^2 s sr $)^{-1}$

for $30^o < l < 65^o$, $| b | < 2^o$ *Abdo et al. 2008*

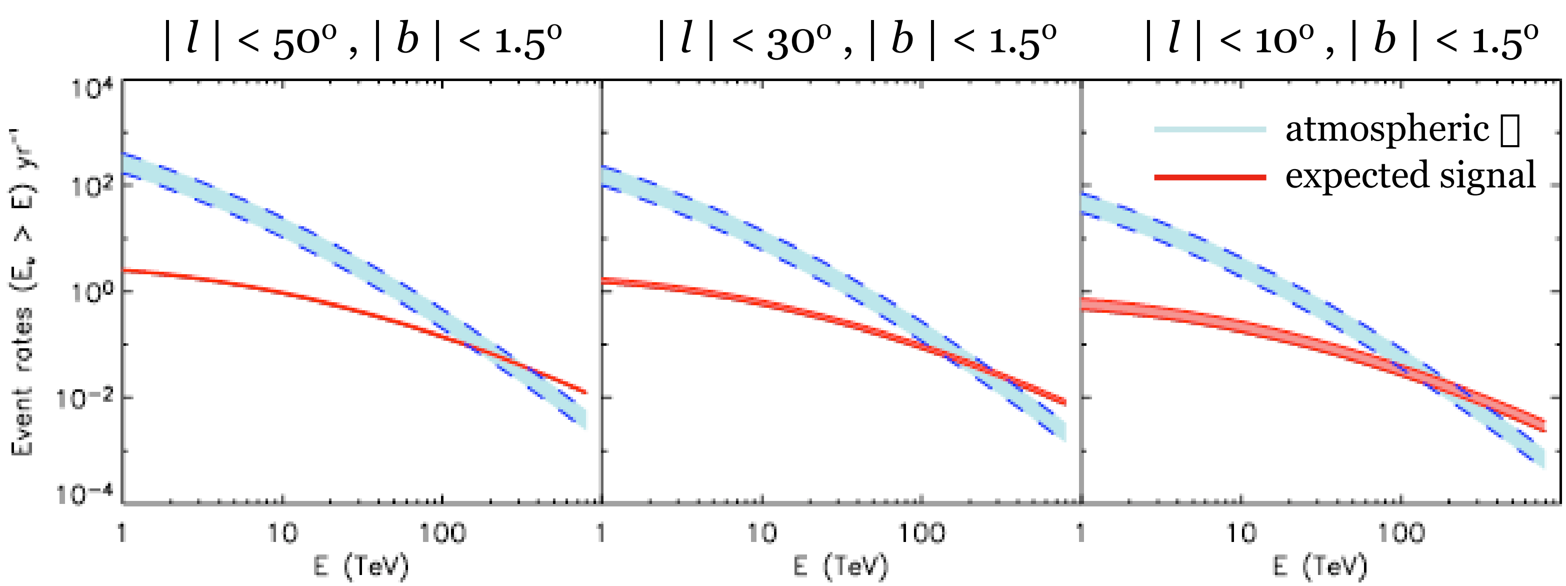
see S. Casanova talk !

Our model: $\Phi_{\square}$(15 TeV) □ 4 □ 10^{-13} (TeV cm^2 s sr $)^{-1}$

The same as for the conventional GALPROP model

A strong IC component or harder spectrum in the inner Galaxy have to be invoked !

For a **km³ neutrino telescope in the** Mediterraneous we found



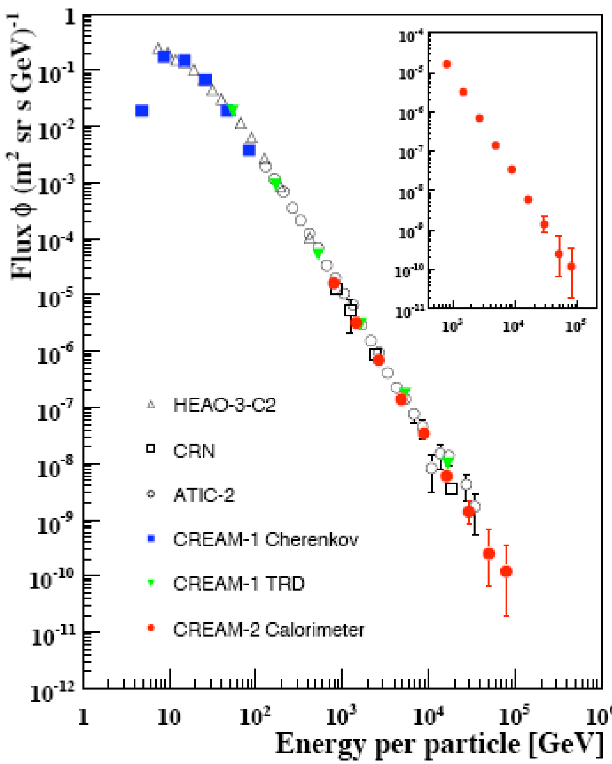
Hard to detect !

Evoli. D.G, Maccione, 2007

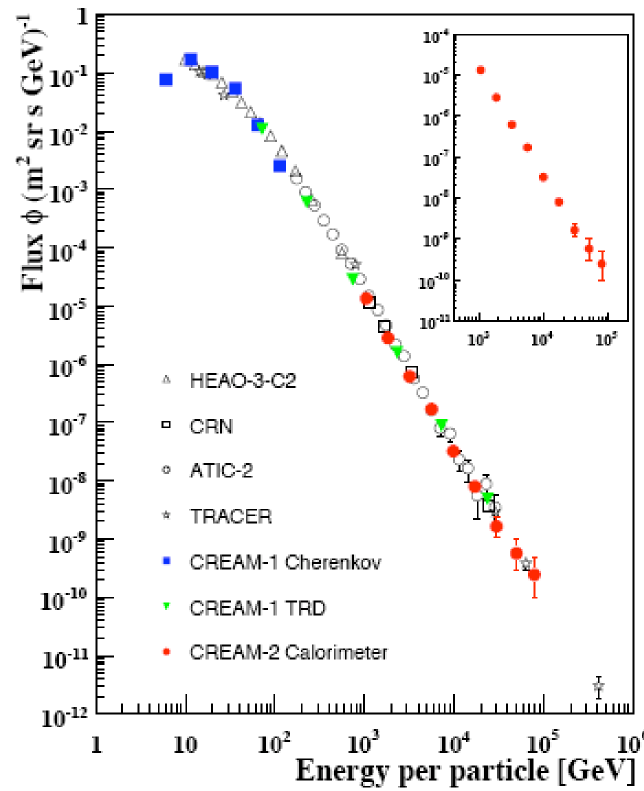
Different spectra for C and O ?

Zei et al. [CREAM], ICRC 2007

CARBON



OXIGEN



$\gamma_C = 2.56 \pm 0.11$ $\gamma_O = 2.61 \pm 0.10$

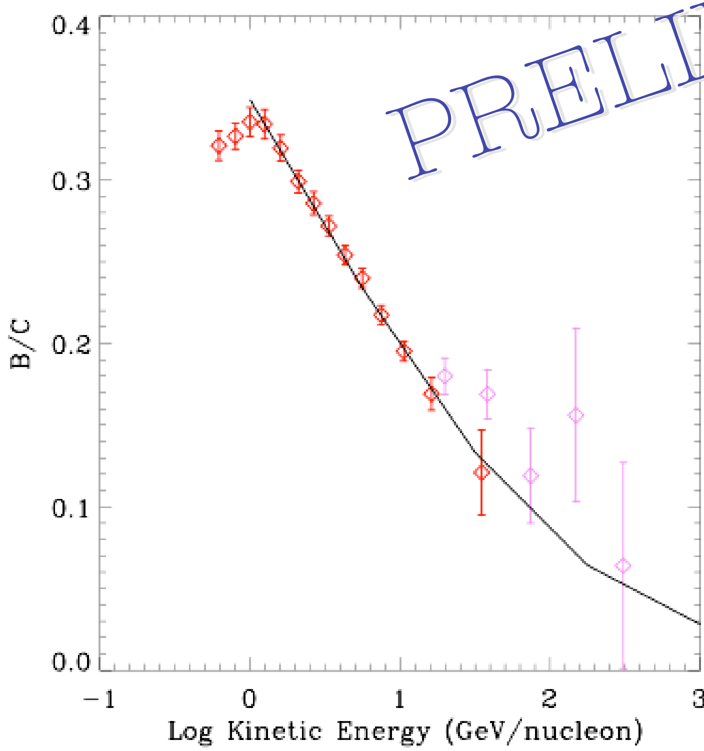
B/C (with a less steep C spectrum)

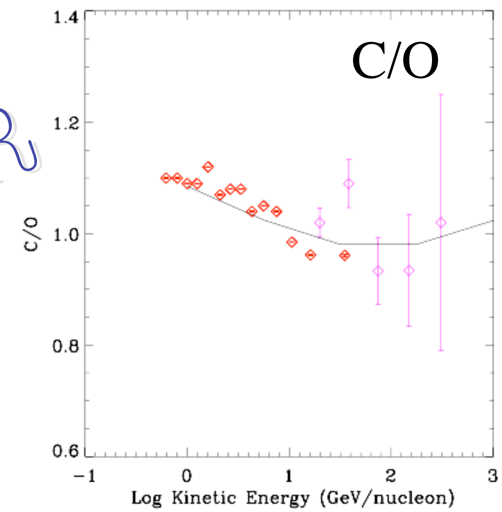
D_o = 2.5 □ 10^{28} cm^2/s

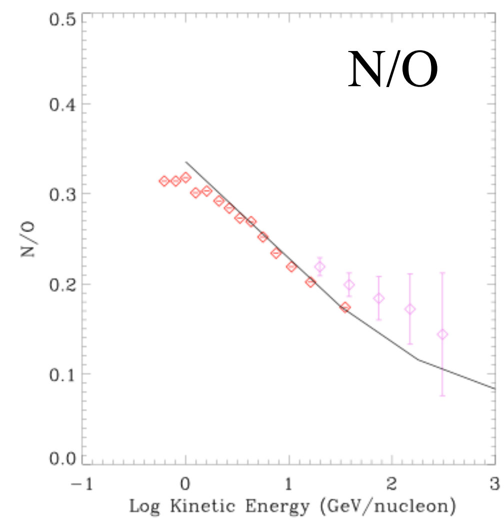
z_t = 4 kpc

□ = 0.5

PRELIMINARY







□ = 0.5 (Kraichnan) may be the preferred value !

Conclusions

- DRAGON is a new numerical code to model galactic CR nuclei propagation and interaction
- It allows for a spatially changing D both in r and in z
- Observed B/C abundances and energy slopes are nicely reproduced for
  $E_k > \sim 1$ GeV/n
- (Other secondary nuclei and antiproton spectra also reproduced - in progress)
- Re-acceleration seems not to be required to explain the B/C at those energies
- The preferred rigidity dependence of D is □ = 0.6 if C, O share the same spectral slope and closer to 0.5 if the C spectrum is smoother as suggested by CREAM
- The □-ray profile along the GP observed by EGRET is reproduced either with a radially changing X_{co} or assuming a physically motivated D(r) profile

Future work: - adopt more detailed gas-models

- include energy losses to model electrons and IC emission

- apply to study dark matter annihilation product propagation