Galactic magnetic fields and unconventional cosmic ray propagation

Dario Grasso
INFN, Pisa

Texas Symp. 2015
Geneva

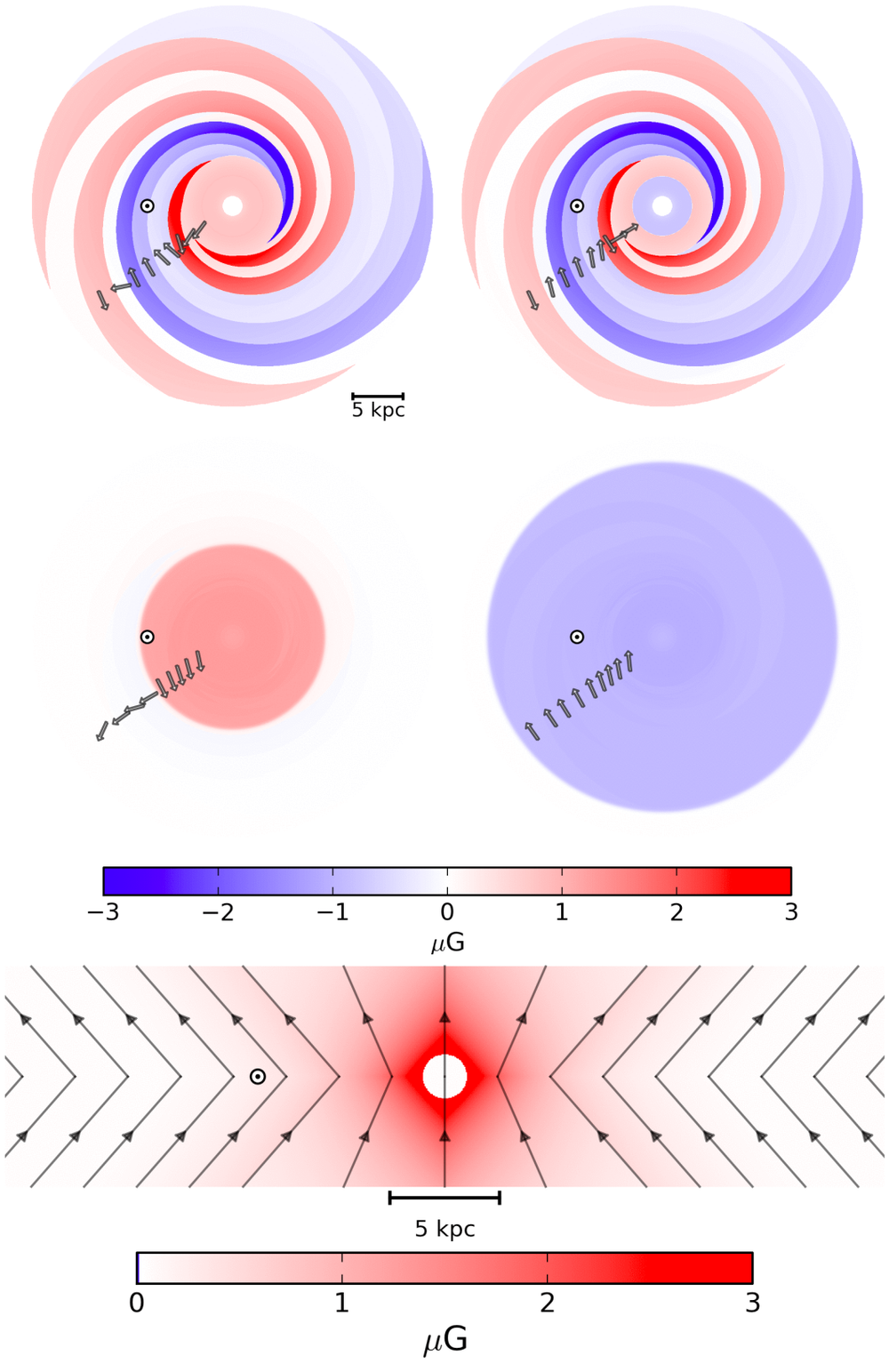
Galactic magnetic fields
as viewed by "astronomers"

Jansson & Farrar ApJ2012

- regular MF: disk, halo, decreasing with r,z ;
- regular disk MF follows a spiral arm structure
- poloidal/X-shape regular MF growing towards the GC
- isotropic random MF, likely to be non-uniform
- anisotropic random MF (striated)

based on RM + synchrotron emission

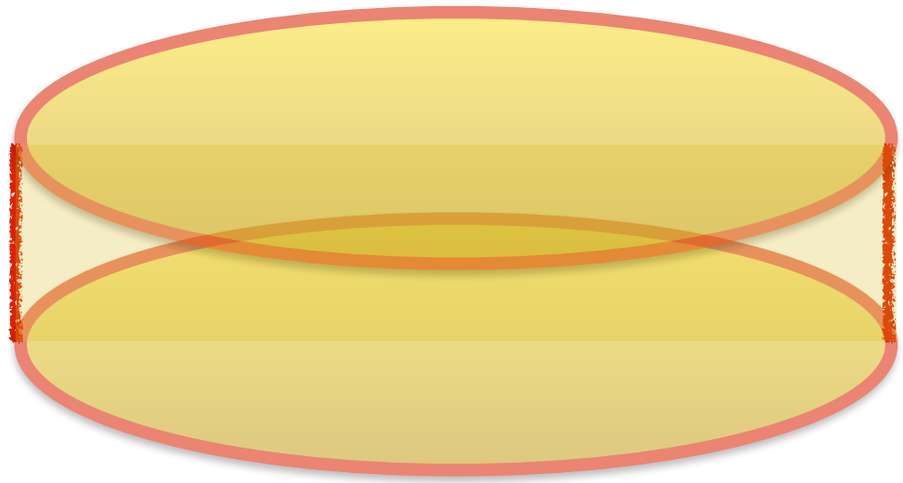
see also e.g. *Pshirkov et al. ApJ2012*



Galactic magnetic fields
as viewed by ("low" energy) cosmic ray physicist

"the wheel of cheese approximation"

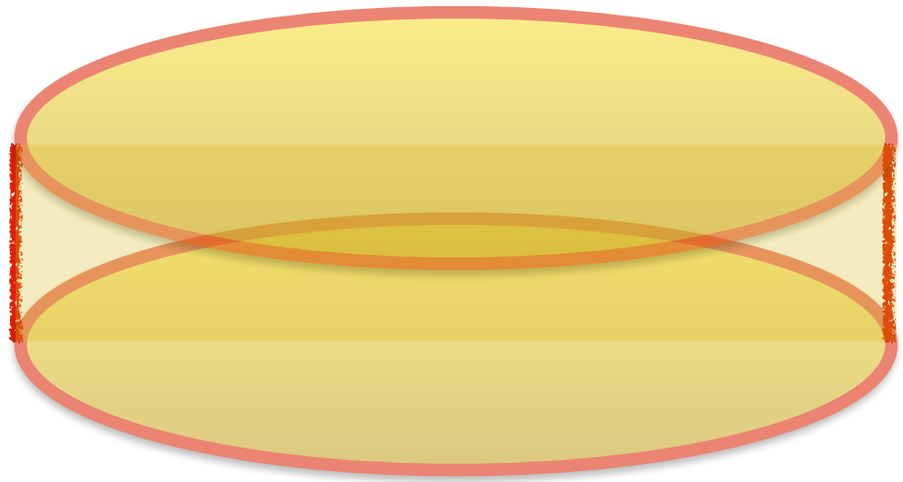
- no regular fields
  (or just azimuthal playing no role)
- no galactic arms
- uniform turbulent field in a thick disc



Galactic magnetic fields
as viewed by ("low" energy) cosmic ray physicist

"the wheel of cheese approximation"

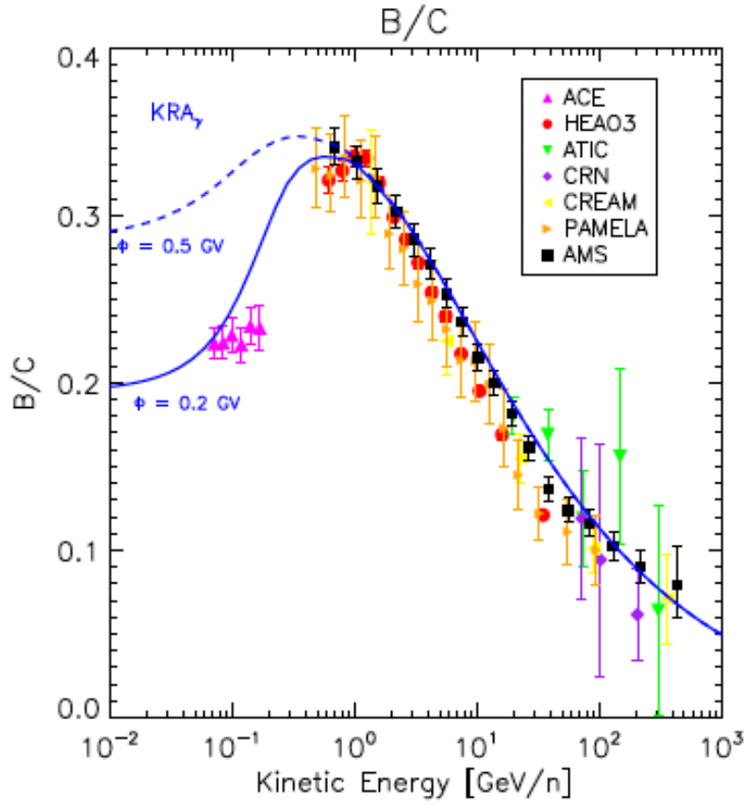
- no regular fields
  (or just azimuthal playing no effective role)
- no galactic arms
- uniform turbulent field in a thick disc



CR diffusion is generally treated in terms of a spatially uniform diffusion coefficient (leaky box/slab models, USINE, GALPROP)

normalization and rigidity dependence are fixed against secondary/primary CR

$$D(E) = D_0 (E/E_0)^{\delta}$$

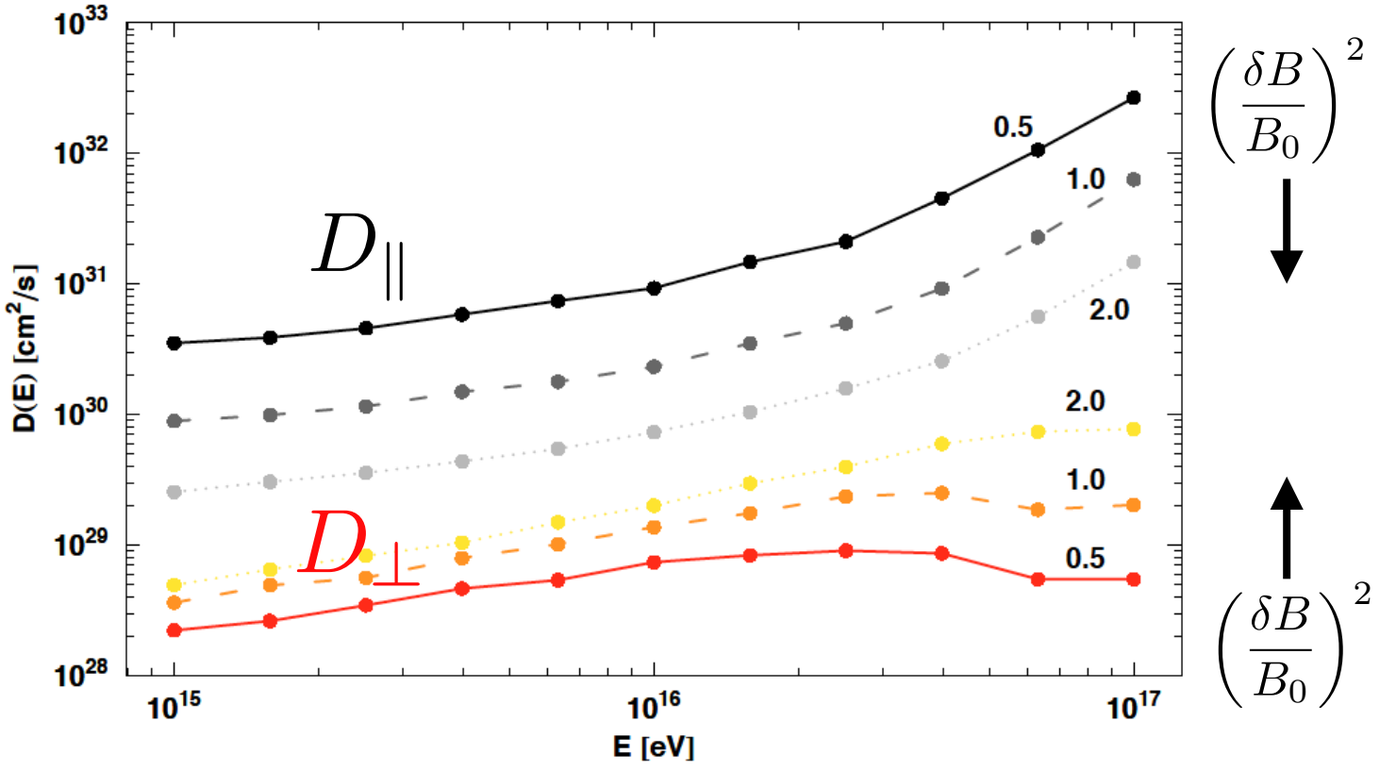


CR Diffusion under more realistic conditions

The presence of regular MF breaks isotropy $D \Rightarrow$

$$D_{ij}(\mathbf{x},\rho) = [\, D_{||}(\mathbf{x},\rho) - D_{\perp}(\mathbf{x},\rho) \,]\, b_i\, b_j + D_{\perp}(\mathbf{x},\rho)\, \delta_{ij} \qquad b_i = \mathbf{B}_i/B$$

Even in the quasi-linear theory $D_{||}$ and $D_{\perp}$ have opposite dependence on the turbulent power. This is confirmed by ray tracing simulations in strong turbulence regime



De Marco, Blasi & Stanev 2007 (see also Casse et al. 2002)

for Kolmogorov turbulence

$$D_{||}(E) \propto E^{1/3}$$

$$D_{\perp}(E) \propto E^{0.5 \div 0.6}$$

The DRAGON project

exploring more realistic CR diffusion conditions

DRAGON

Diffusion Reacceleration and Advection of Galactic cosmic rays: an Open New code

G. Di Bernardo, C. Evoli, D. Gaggero, DG, L. Maccione

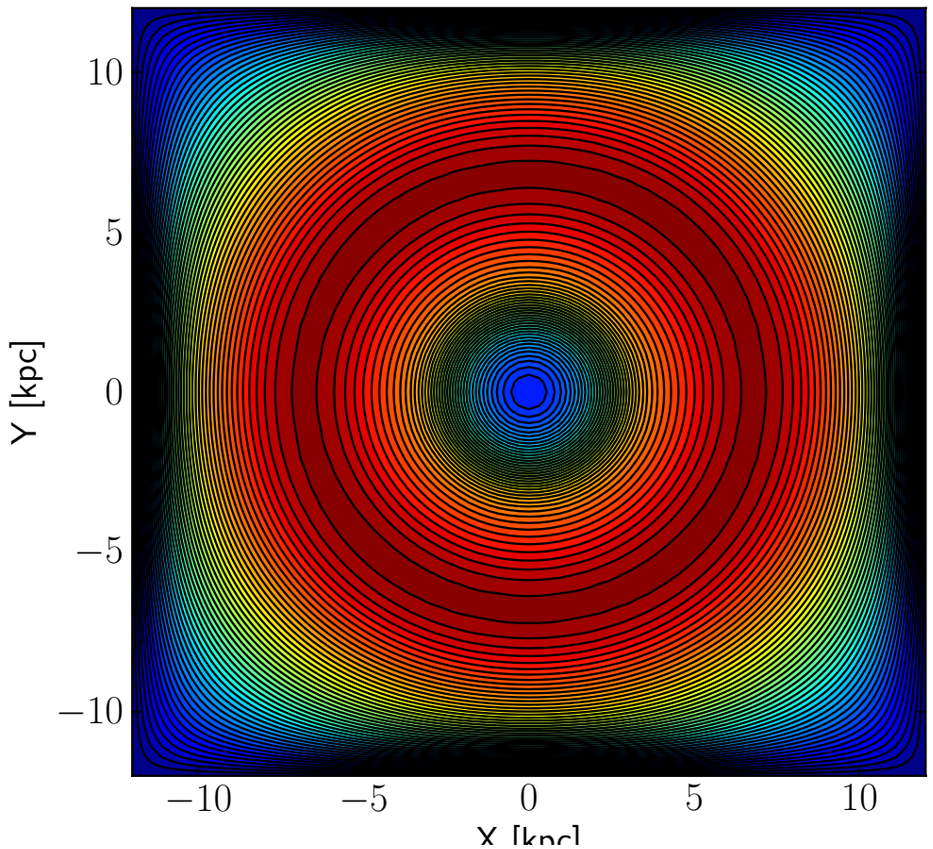
- ✦ Spatial dependent diffusion (both for iso/ani-sotropic)
- ✦ Separable rigidity and space dependent diffusion tensor components
- ✦ 3D, arm structure in the source distribution and in the “
- ✦ anisotropic diffusion

it reproduces GALPROP results under the same conventional conditions
(more technical details at http://www.dragonproject.org)

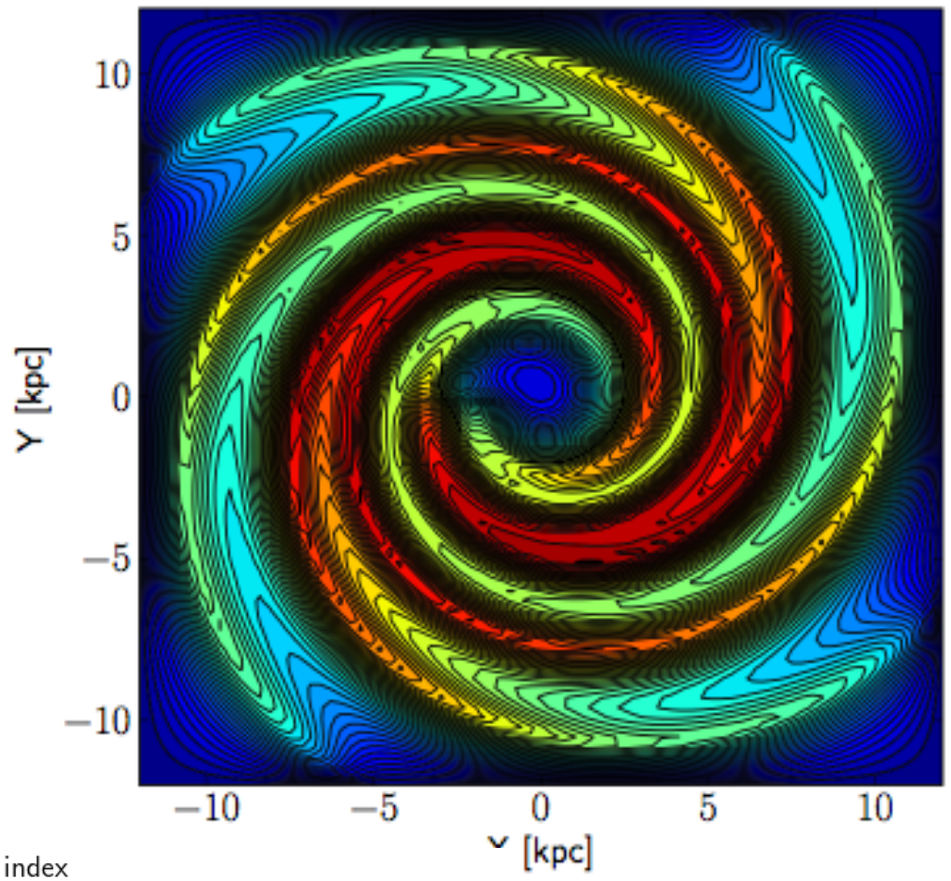
See also the PICARD project: http://astro-staff.uibk.ac.at/~kissmrbu/Picard.html

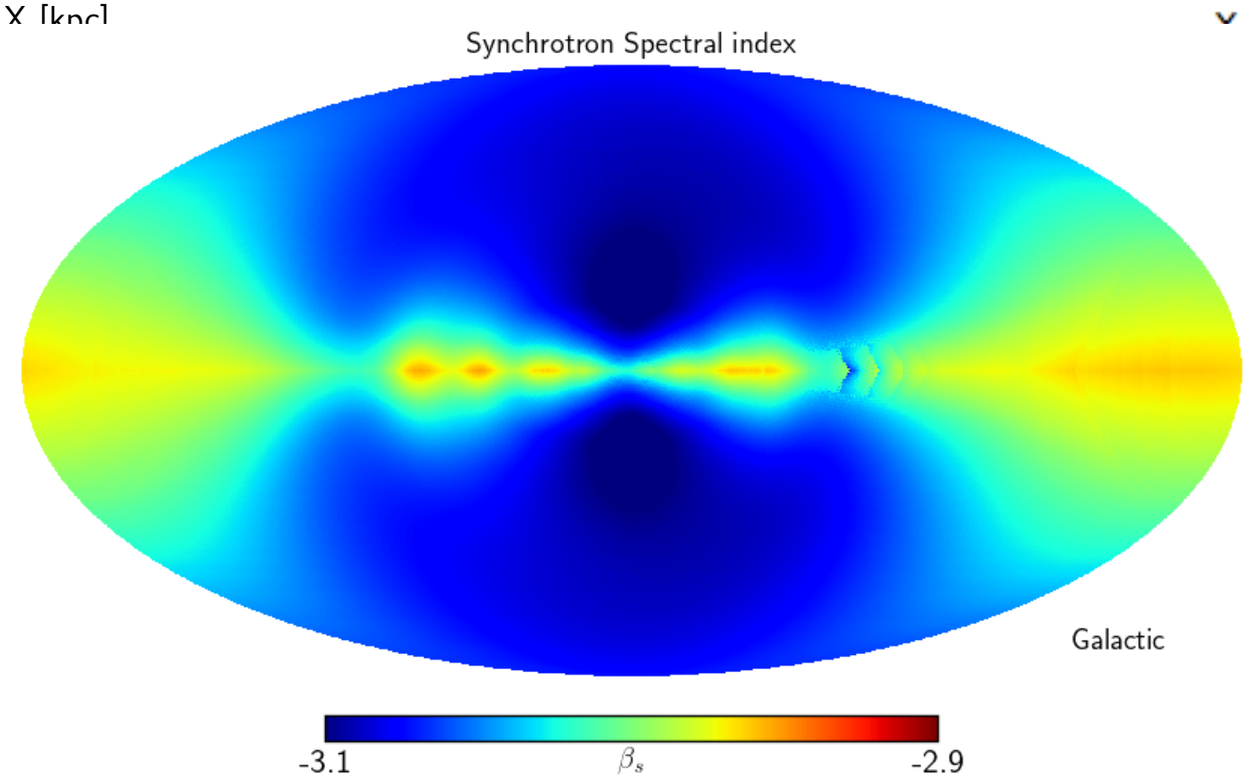
Di Bernardo, Evoli, Gaggero, DG PRL 2013

Electron density 100 TeV no arms

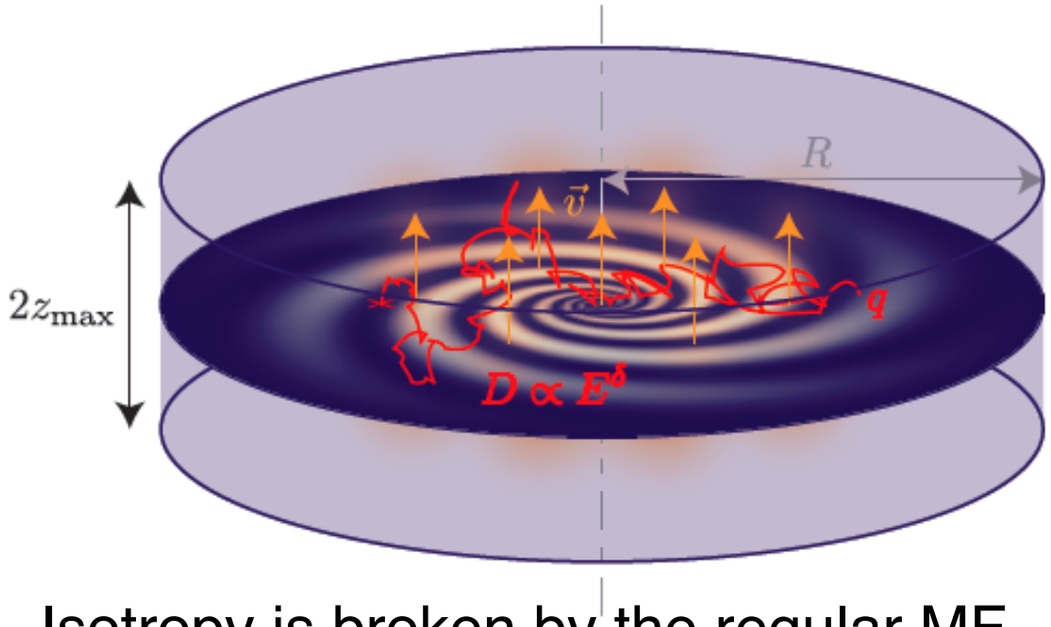


Electron density 100 TeV with arms





The effect of a spatial dependent $D_\perp$

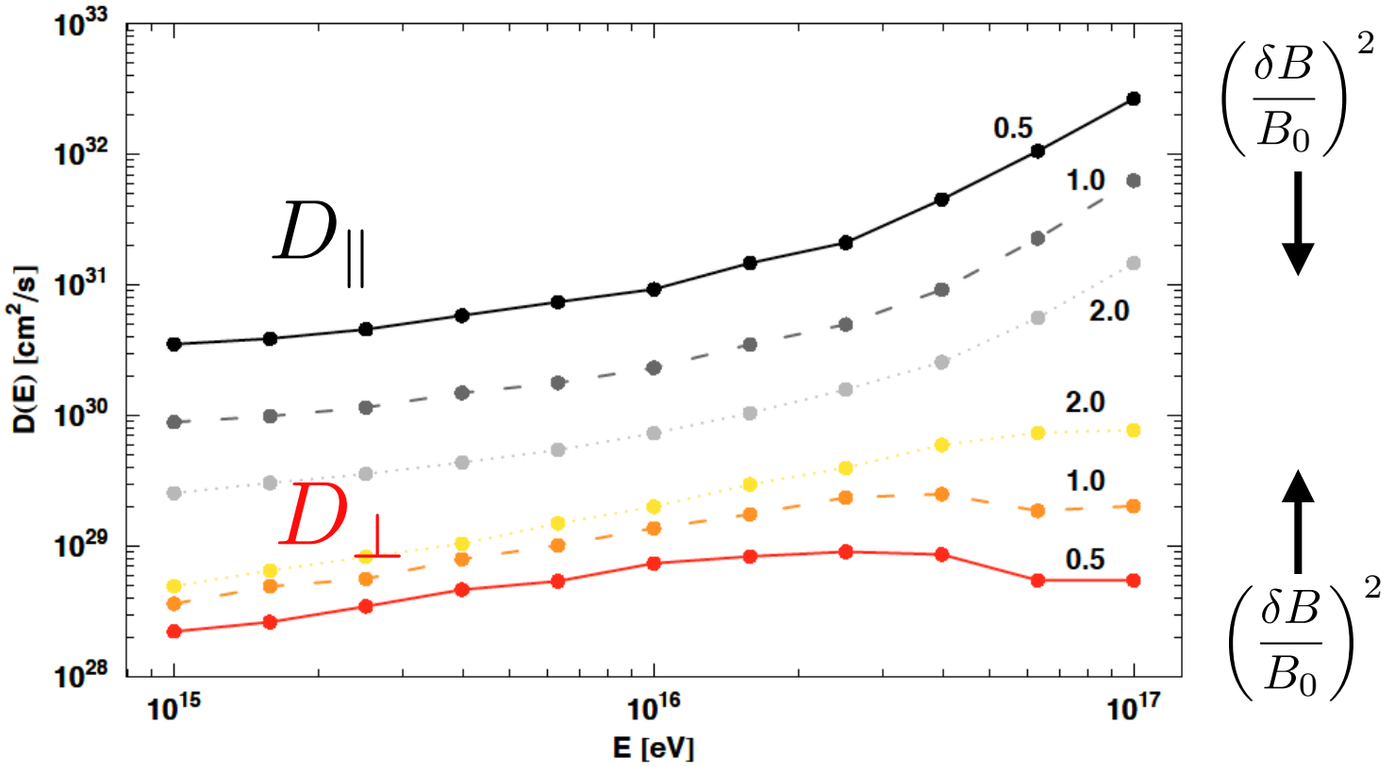


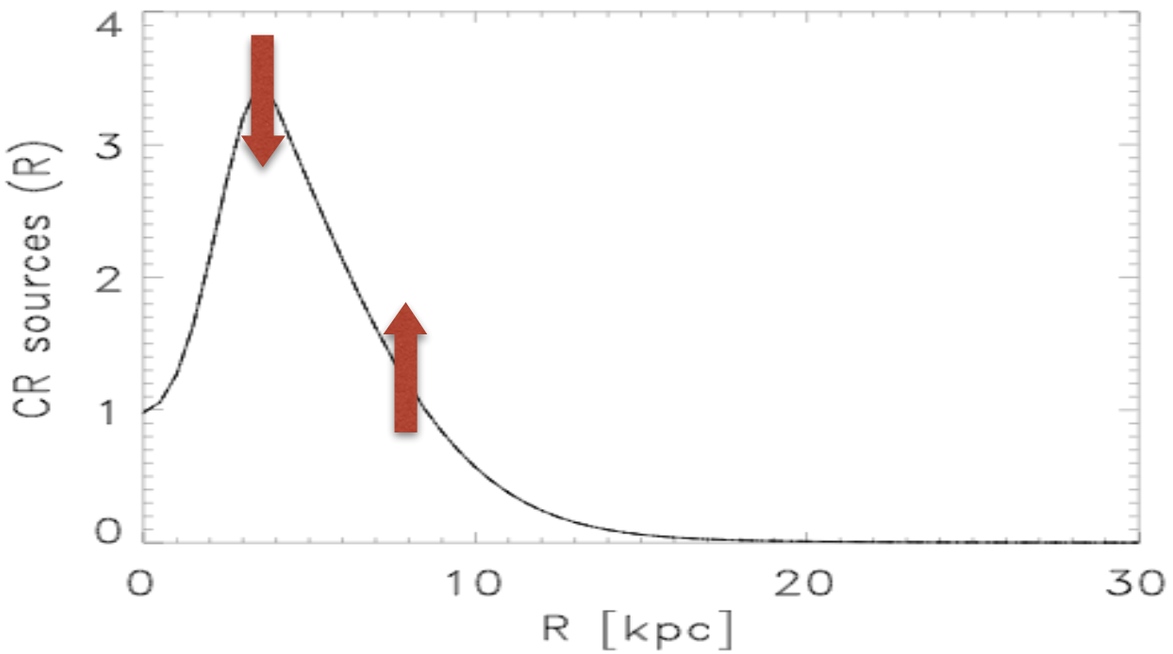
Isotropy is broken by the regular MF.
CR escape is expected to be determined by ⊥ diffusion

D⊥ is expected to grow with the (spatial dependent) turbulent power of MF fluctuations

in the inner region of the Galaxy, larger turbulence
larger D⊥ ⇒ faster CR escape ⇒

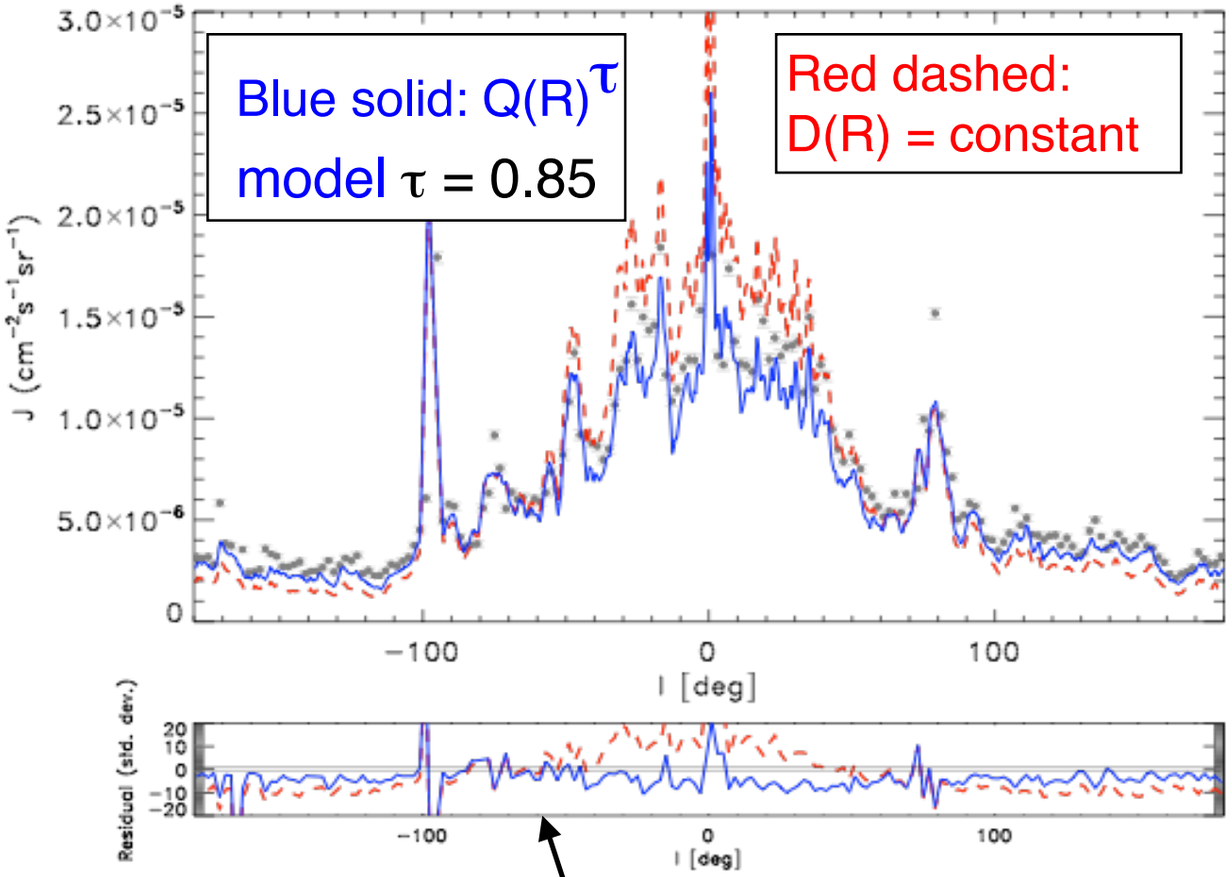
flatter CR profile



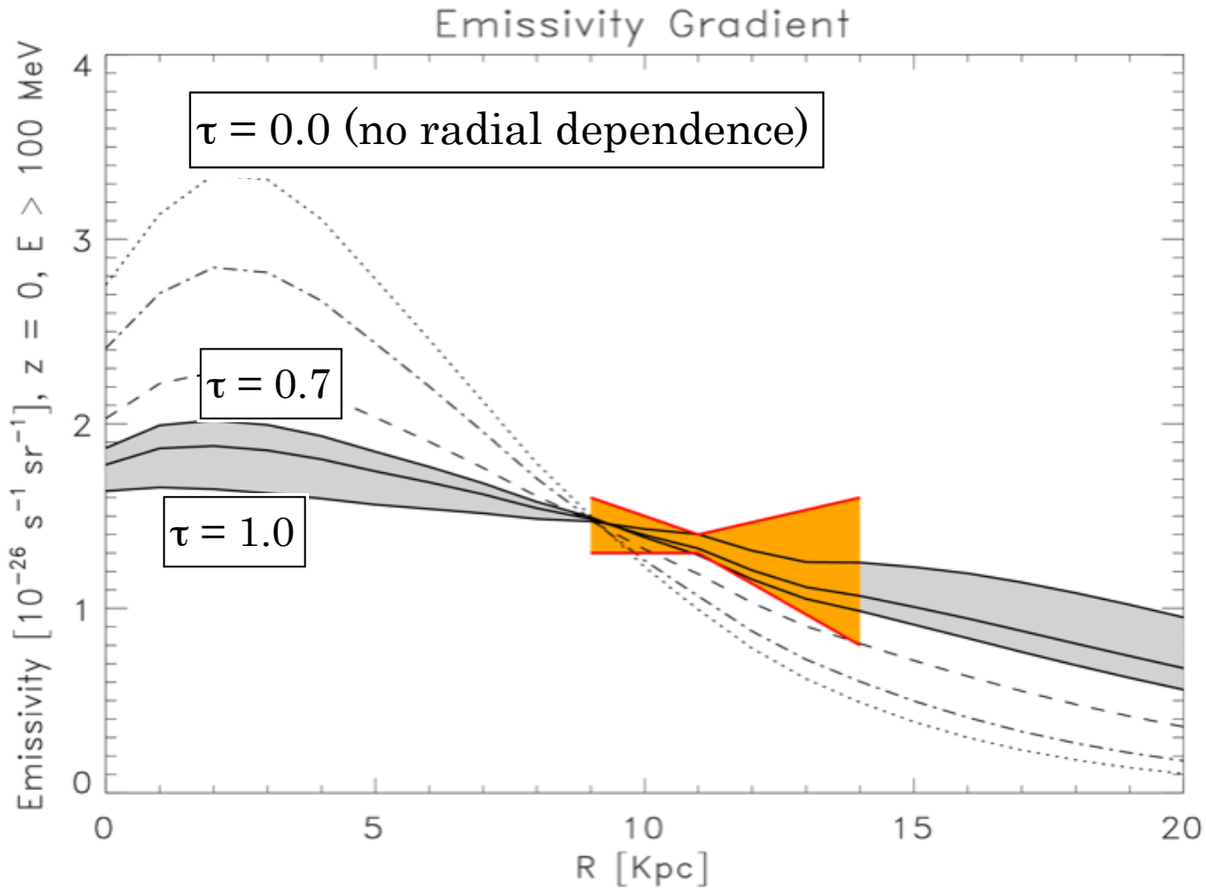


The effect on the gamma-ray longitude profile

Evoli, Gaggero, DG, Maccione, PRL 2012



Residuals against Fermi-LAT data

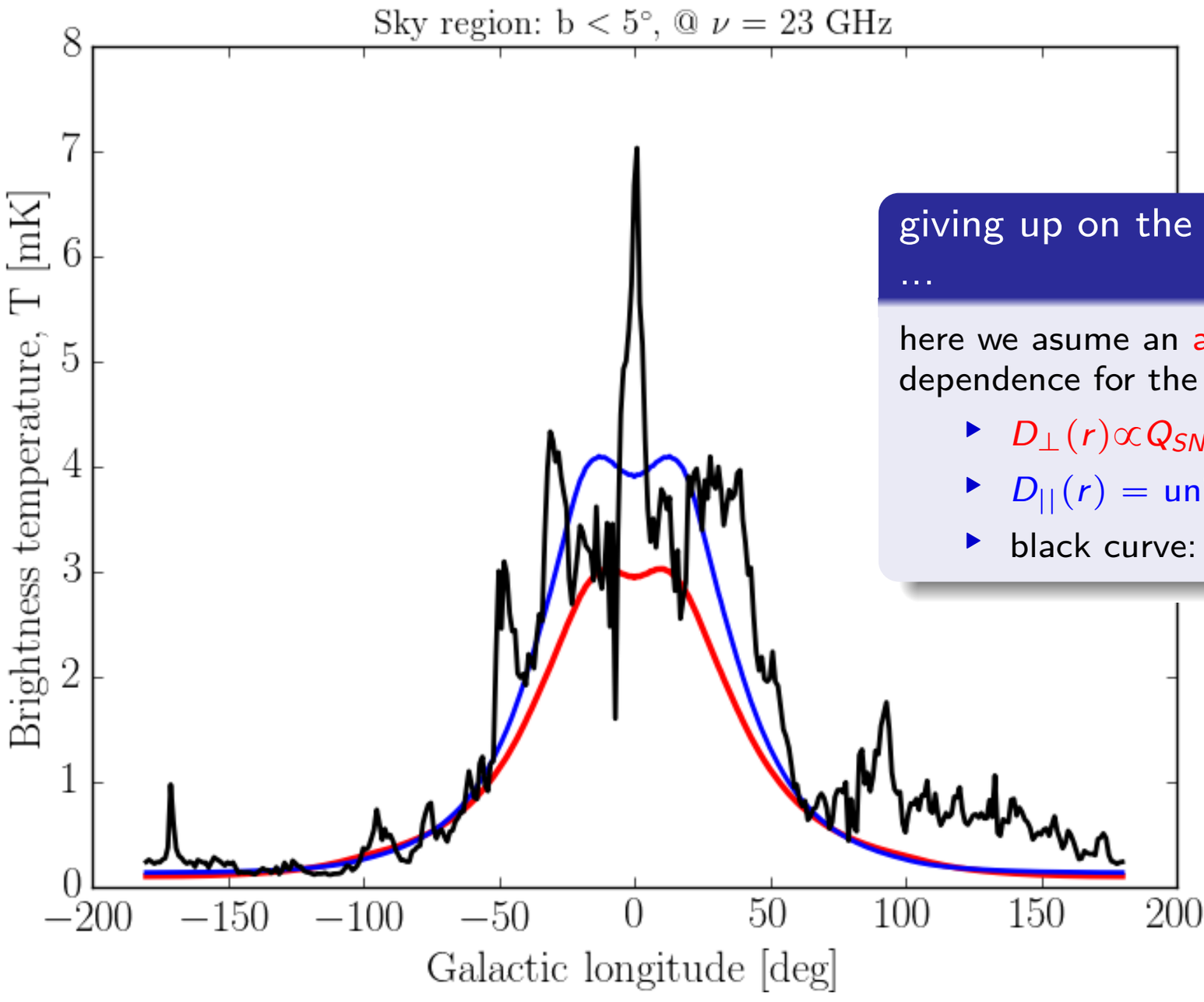


$$D_\perp(R) \propto Q^\tau(R)$$

source injection rate

The effect on the synchrotron longitude profile

Di Bernardo, Evoli, Gaggero, DG 2015



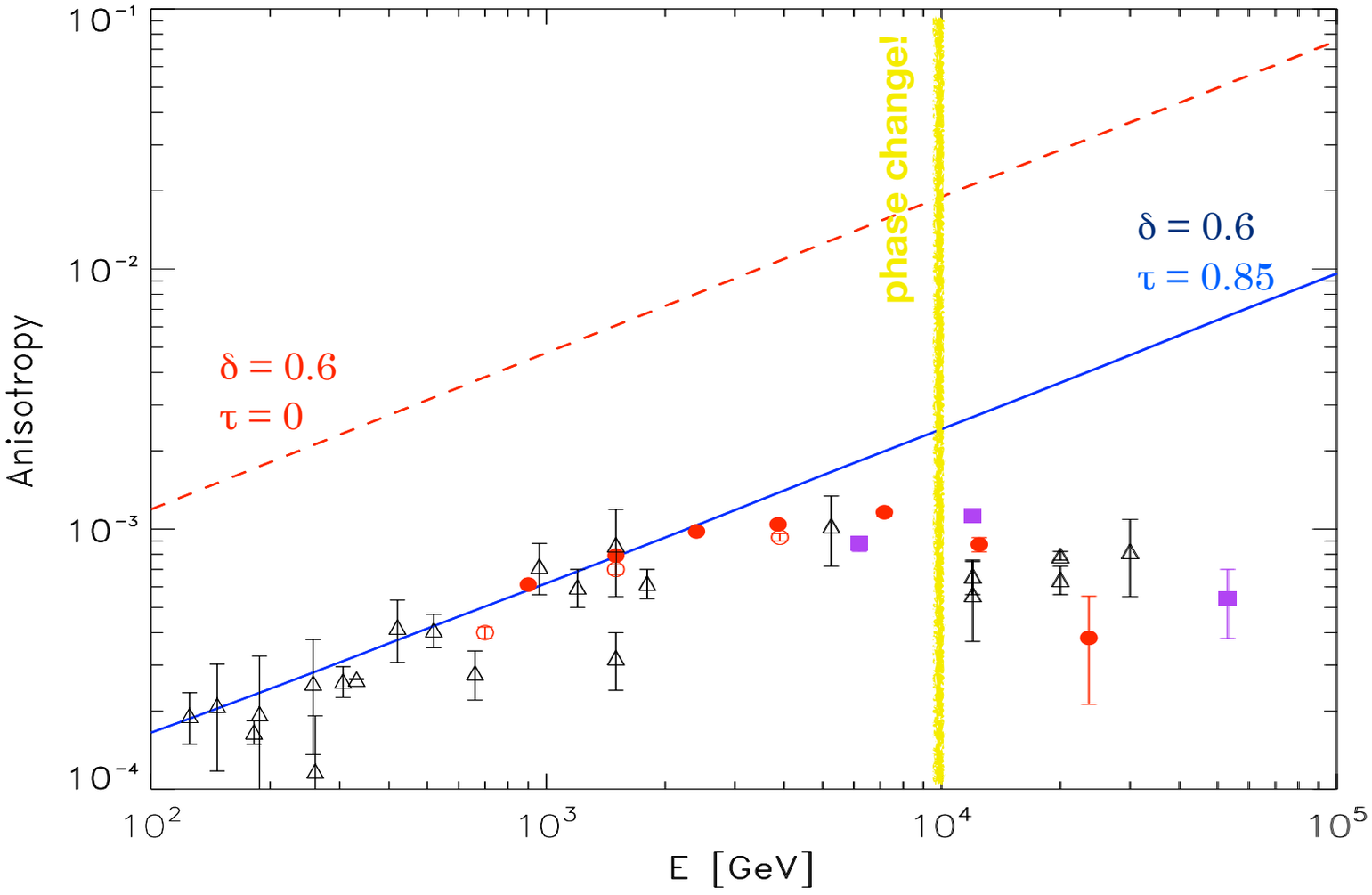
giving up on the isotropy assumption ...

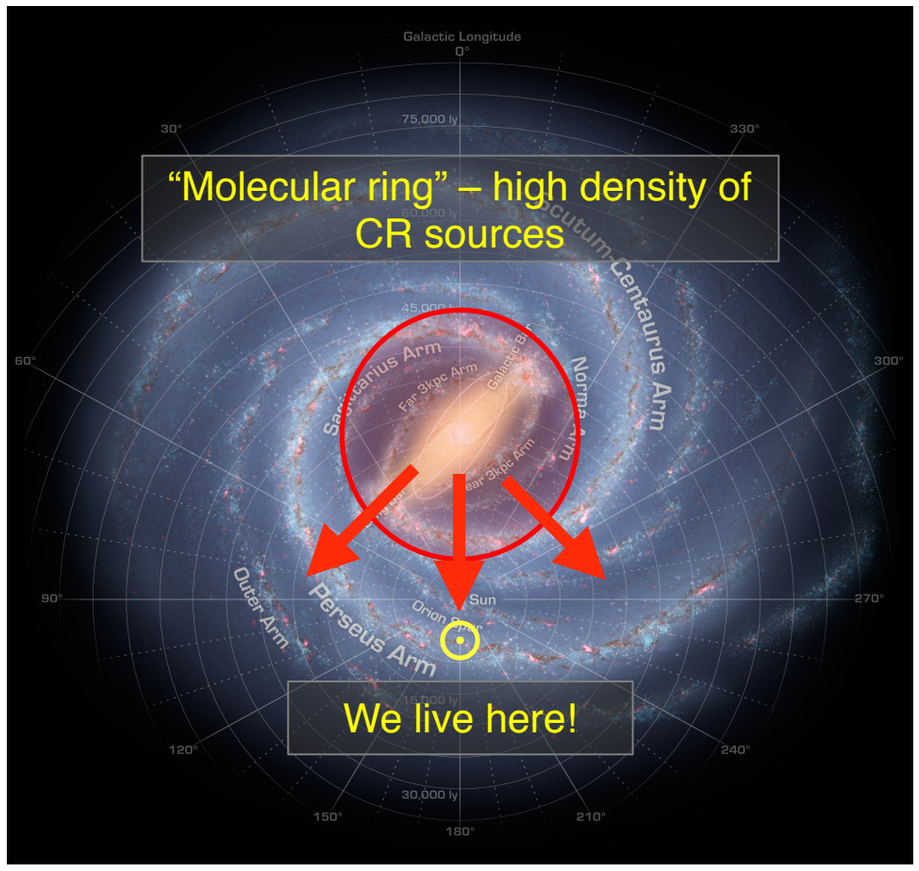
here we asume an anisotropic rigidity dependence for the diffusion coefficient:

- $D_{\perp}(r) \propto Q_{SNR}(r)^{\tau}$;
- $D_{||}(r)$ = uniform;
- black curve: WMAP K-band, 9yr

The effect on the CR anisotropy

Evoli, Gaggero, DG, Maccione, PRL 2012





The CR anisotropy is significantly ameliorated by spatial dependent diffusion !

The case of a spatially dependent δ

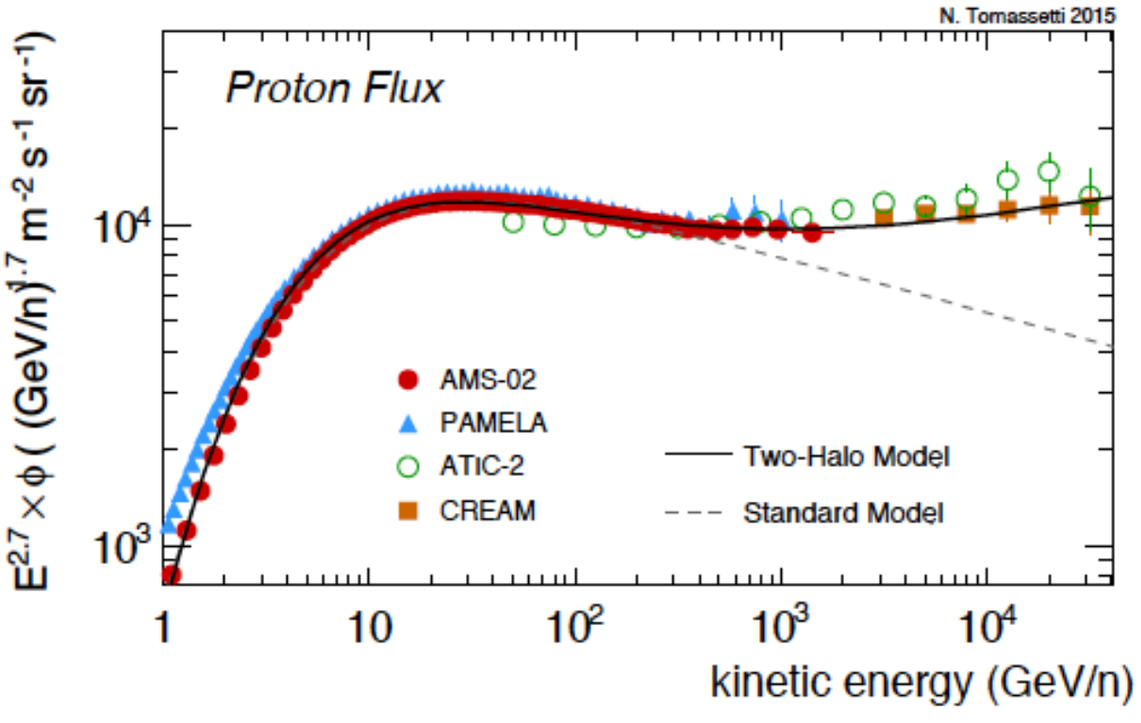
- *Non-linear effects* may induce a radial or vertical dependence *Erlykin & Wolfendale 2012, Yan & Evoli ApJ 2014*

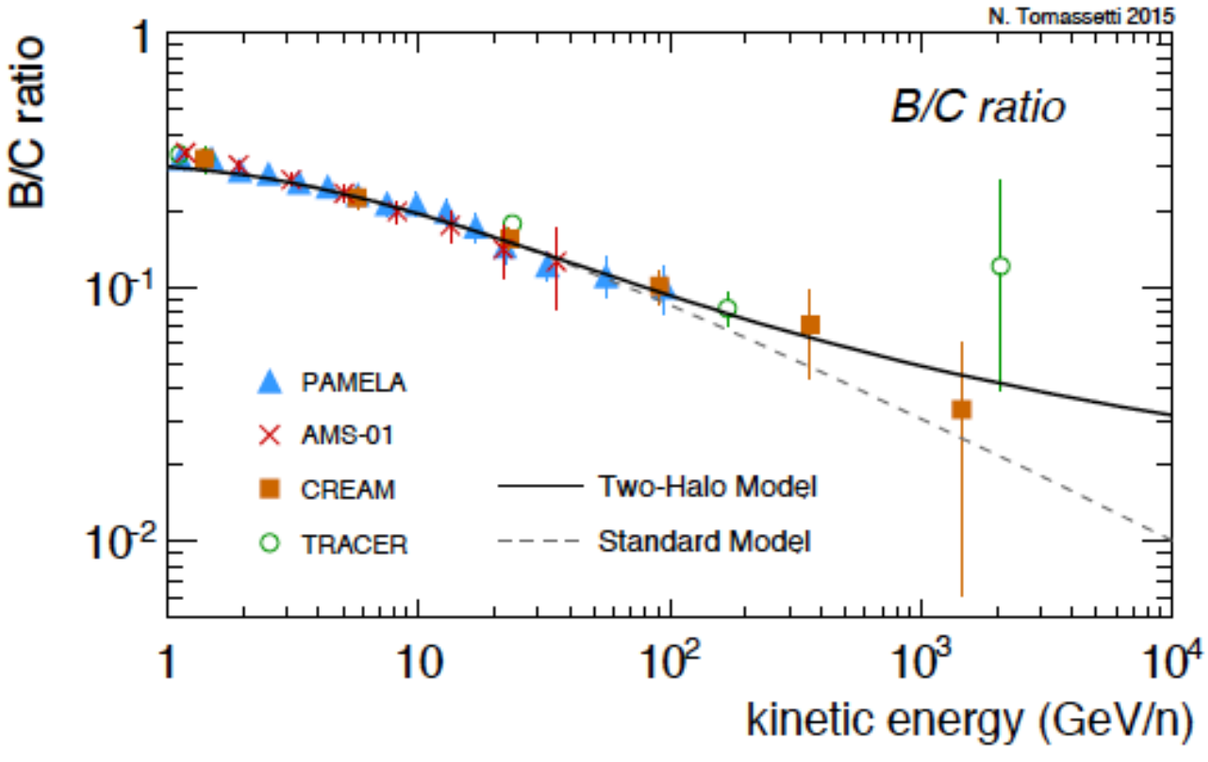
- *Tomassetti ApJ 2012* considered the case of a two-zone regime showing that this may explain the hardening in the primary CR spectra observed by PAMELA, AMS-02 … at ~ 250 GeV/n

$\Delta \simeq 0.5 - 1$

$$D(z,\rho) = \begin{cases} k_0 \beta \rho^{\delta} & for\ |z| < \xi L\ (inner\ halo) \\ k_0 \beta \rho^{\delta+\Delta} & for\ |z| > \xi L\ (outer\ halo) \end{cases}$$

Tomassetti, ICRC 2015, using DRAGON





The case of a spatially dependent δ

the presence of a poloidal component of the GMF in the GC region should make the role of $D_{||}$ growing respect to $D_{\perp}$ (standard case)

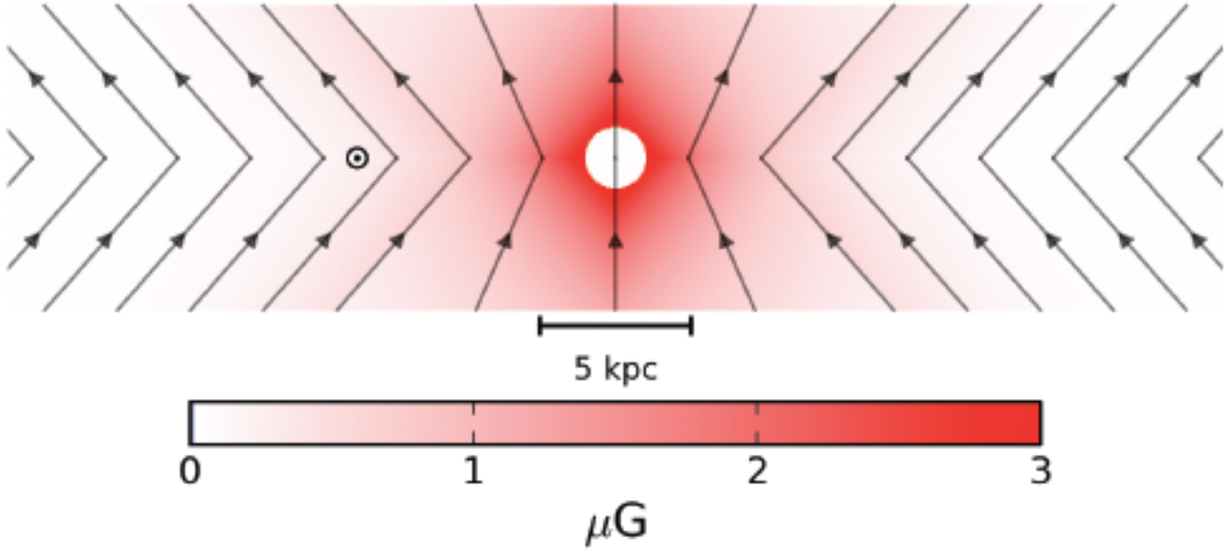
Since, for Kolmogorov turbulence

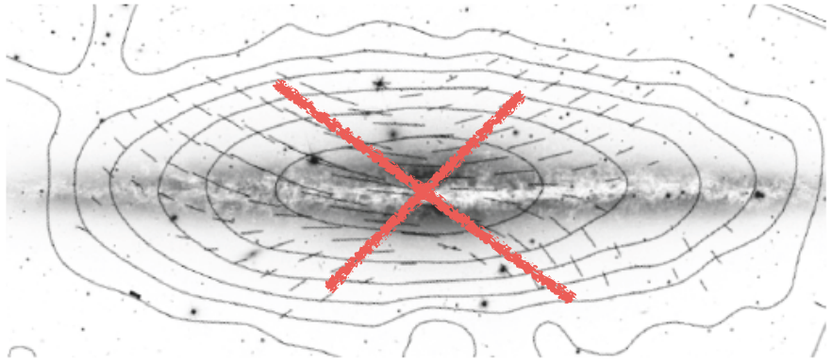
$$D_{||}(E) \propto E^{1/3} \quad D_{\perp}(E) \propto E^{0.5 \div 0.6}$$

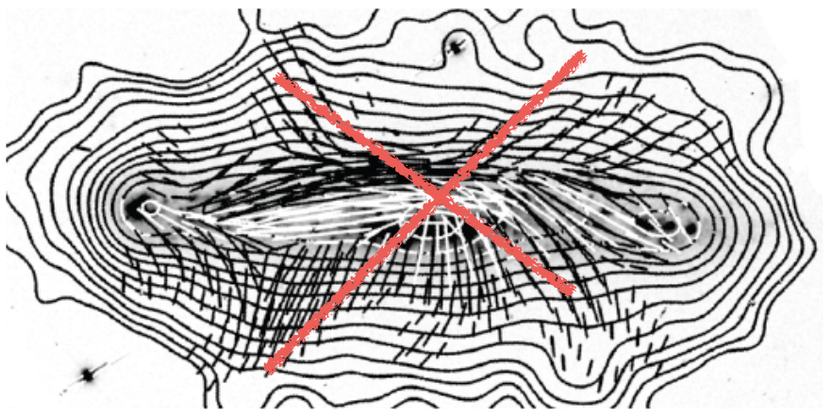
De Marco, Blasi & Stanev 2007

this may cause the effective value of δ decreasing with R !

Jansson & Farrar ApJ 2012





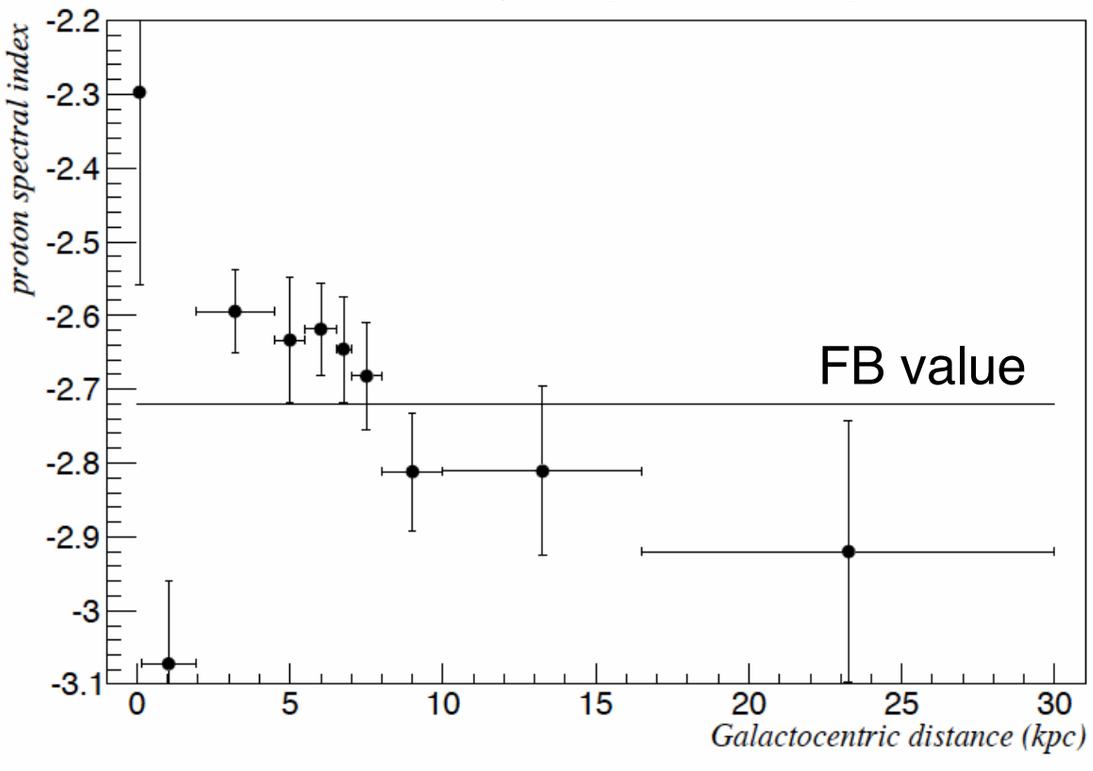


The Fermi-LAT inner Galaxy anomaly

The GALPROP based Fermi benchmark (FB) model underestimate the diffuse emission in the inner Galactic Plane (GP)
Fermi coll. ApJ 2012

a longitude dependent γ-ray (hence CR protons) spectral index has also been found

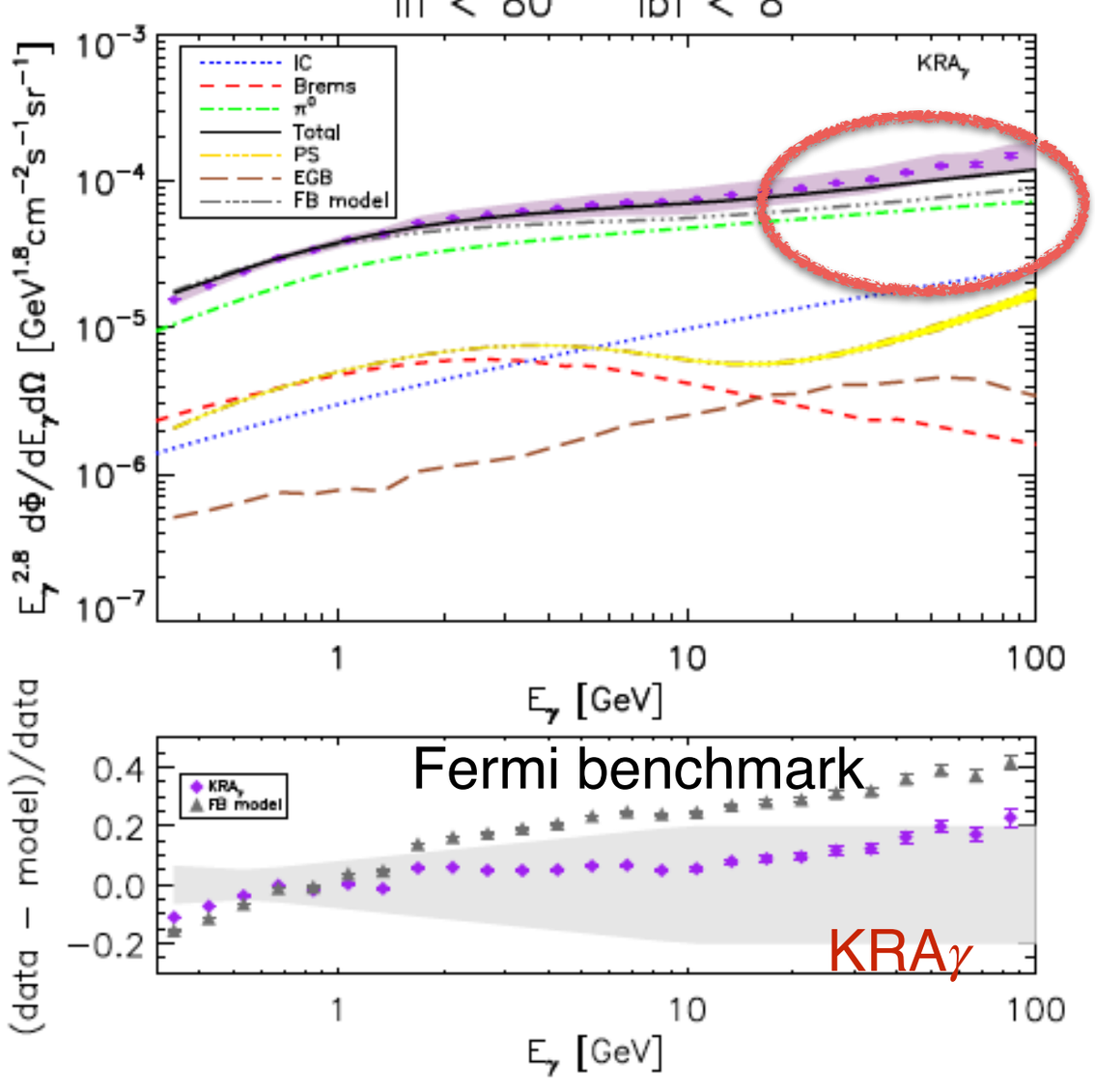
Casandajian [Fermi coll.] 2014



Gaggero et al. 2015 confirmed the excess using updated Fermi data/tools and proposed a phenomenological model (KRAγ) implemented with DRAGON with

$\delta(R) = A\,R + B$ such that $\delta(R_{sun}) = 0.5$

Gaggero,Urbano, Valli, Ullio, PRD 2015



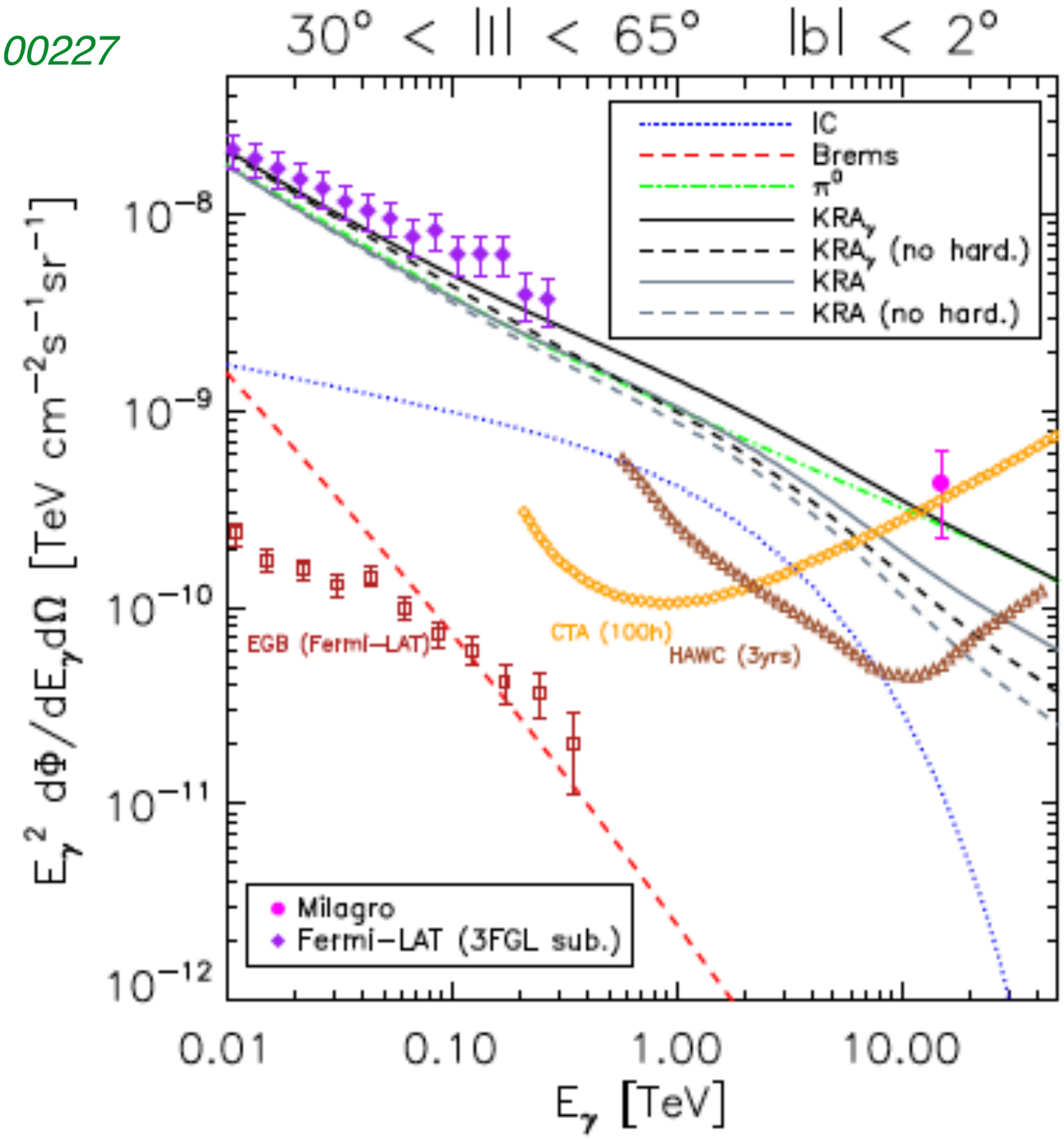
Solving long standing problems of conventional models MILAGRO anomalv

Gaggero, DG, Marinelli, Urbano, Valli arXiv:1504.00227 accepted by ApJL

While the conventional models under predict the flux measured by MILAGRO in the inner GP (even accounting for the hardening at 250 GeV/n)

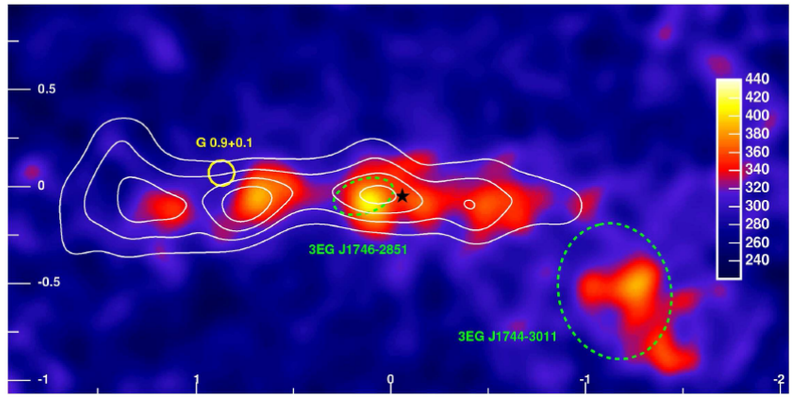
The KRAγ model matches MILAGRO consistently with Fermi (point sources subtracted) without further tuning !

HAWC may soon test this prediction



Solving long standing problems of conventional models
HESS anomaly

Gaggero, DG, Marinelli, Urbano, Valli arXiv:1507.07796
ICRC 2015

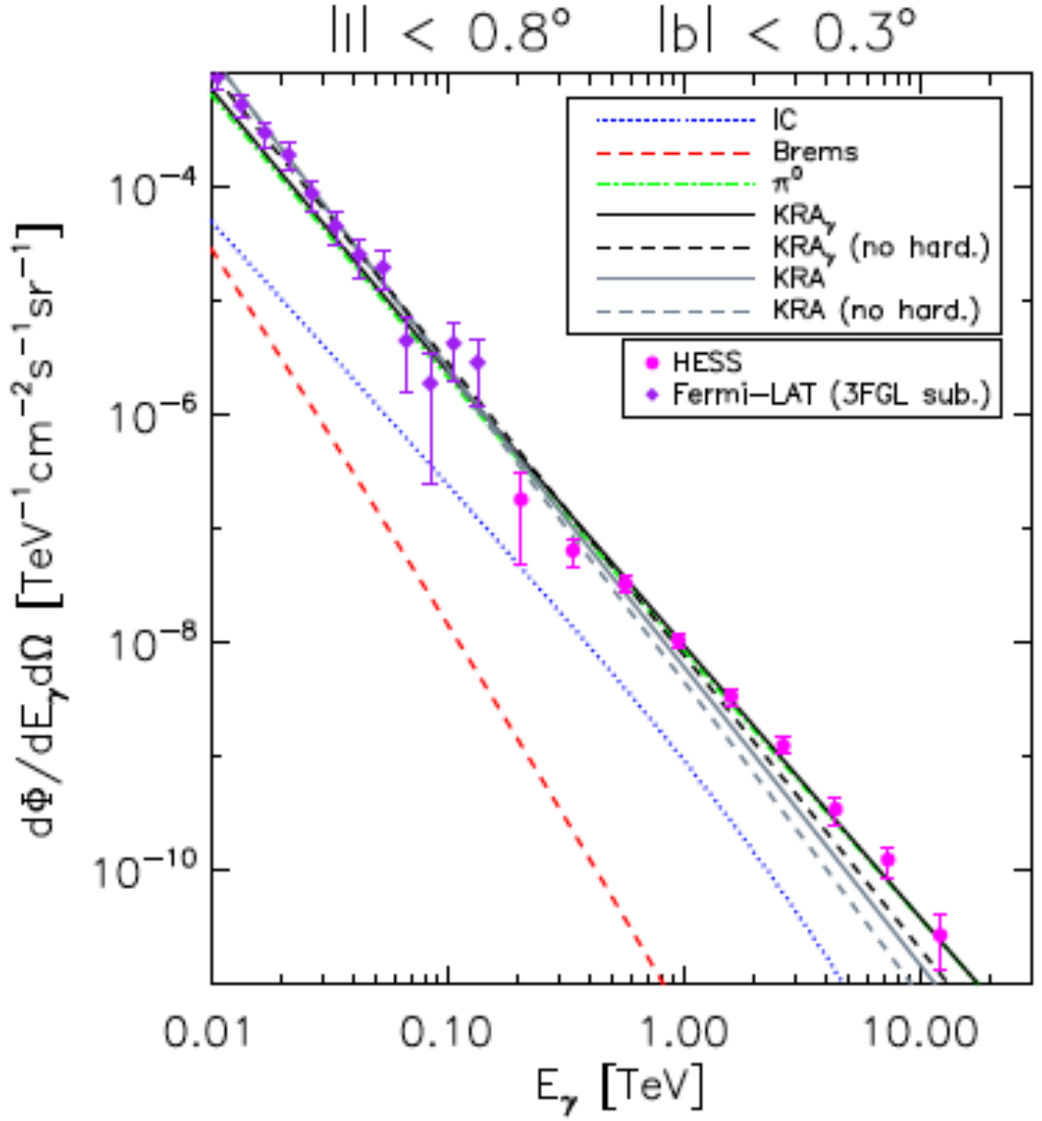


HESS (*Nature 2006*) measured a spectrum harder ($\Gamma \simeq -2.3$) than expected on the basis of conventional CR models, associated with the molecular complex in the inner 200 pc of Galaxy. This is also the case for the updated Fermi benchmark model.

The KRAγ model matches FERMI + HESS

KRAγ: $\chi 2 = 1.79$

against $\chi 2 = 2.92$ for a corresponding conventional model



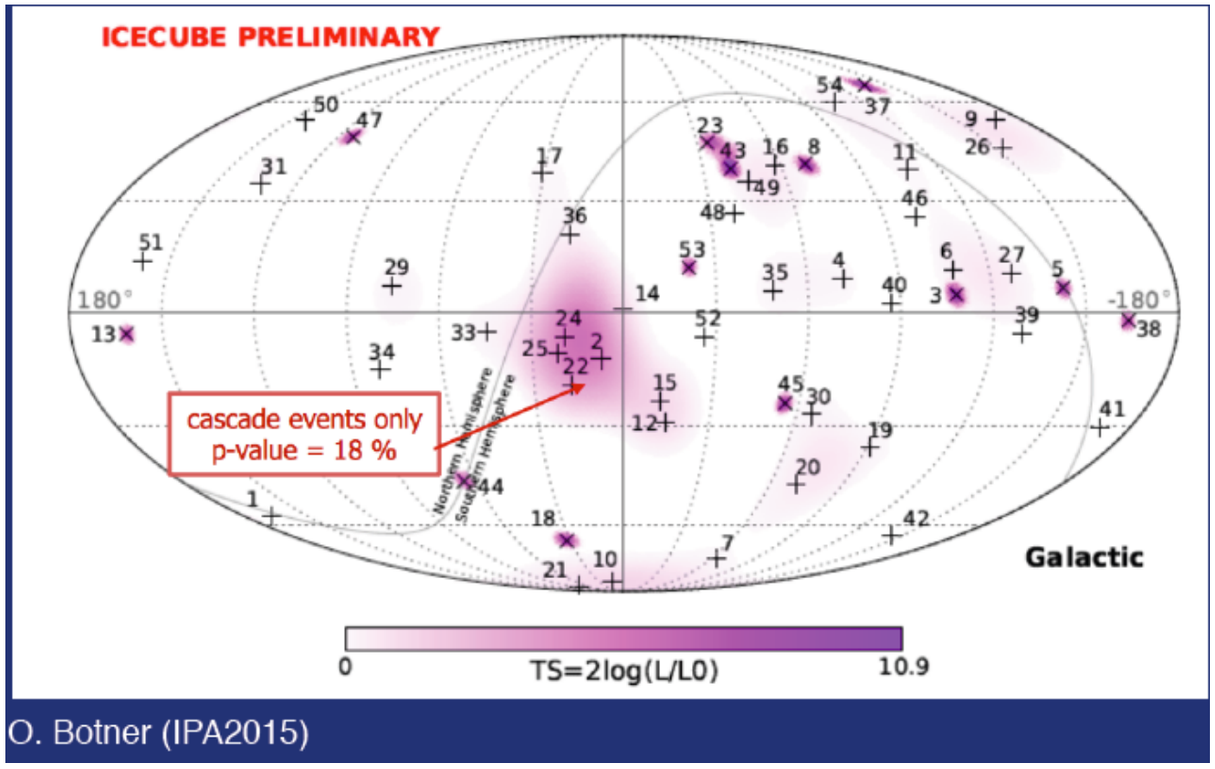
Possible implications for high energy neutrinos
IceCube results

IceCube found evidence for 37 events PRL 2014 (54 preliminary) with reconstructed direction above 28 TeV corresponding to a 5.7σ (7σ) excess respect to the atm. bkg. (follow F. Halzen plenary talk tomorrow !)

angular distribution compatible with isotropy but up to 50 % may be Galactic, Ahlers 2015 (see Neronov & Semikoz arXiv:1509.03522)

spectrum seems to be softer than expected for most conventional extragalactic astrophysical sources (AGNs, GRBs ..) but present uncertainties do not allow firm conclusions

IceCube coll. ICRC2015



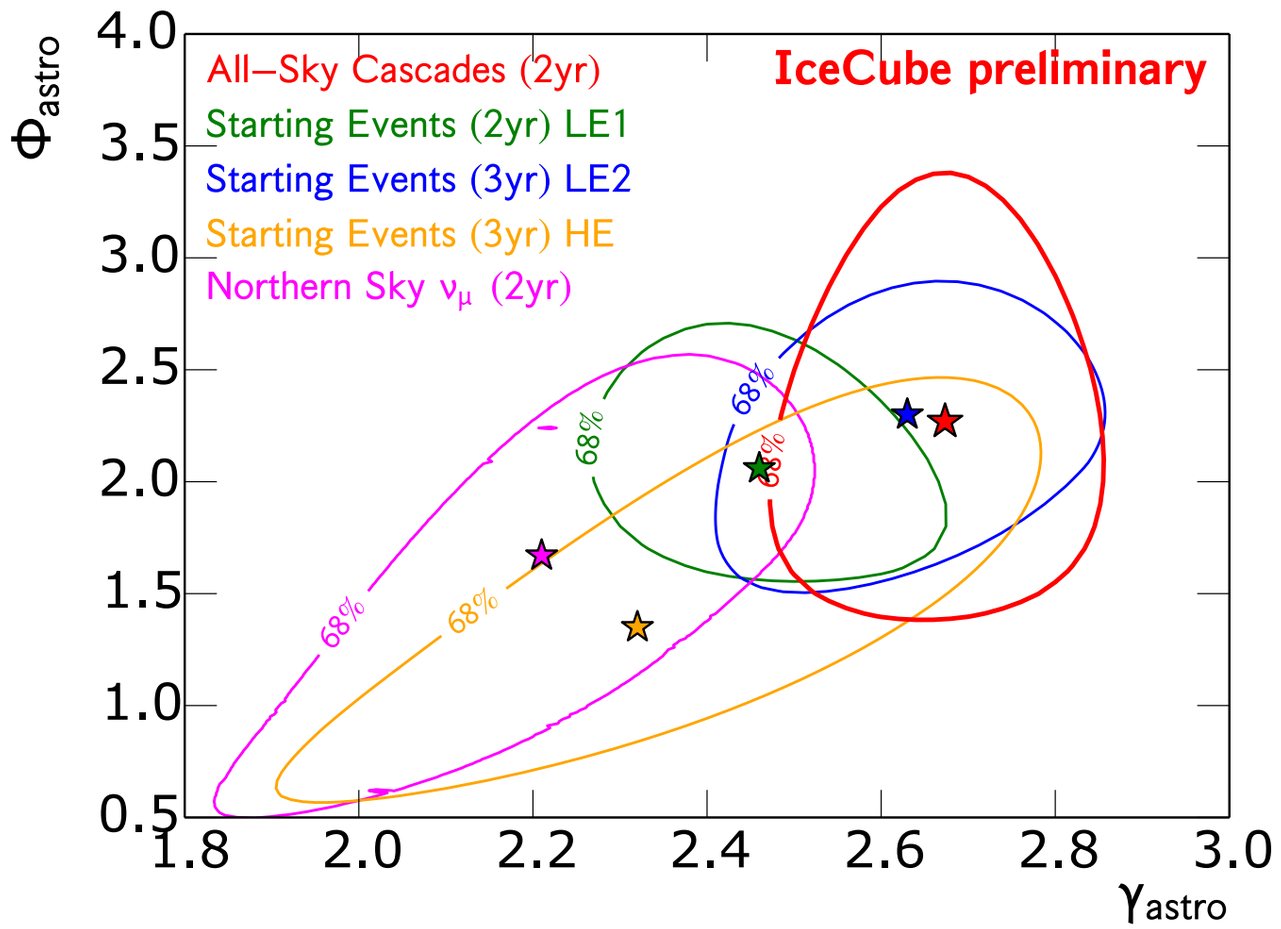
Possible implications for high energy neutrinos IceCube results

ICRC (2015), E > 10 TeV
PRD 91, (2015) all event E > 1 TeV
PRL 114 (2015), HESE E > 35 TeV
PRL 101101 (2014), HESE E > 60 TeV

PRL 115 (2015) ν_μ, E > 100 TeV probes the northern hemisphere should be representative of the extra-Galactic flux

hints for a higher and steeper spectrum in the southern hemisphere !

IceCube coll. ICRC2015

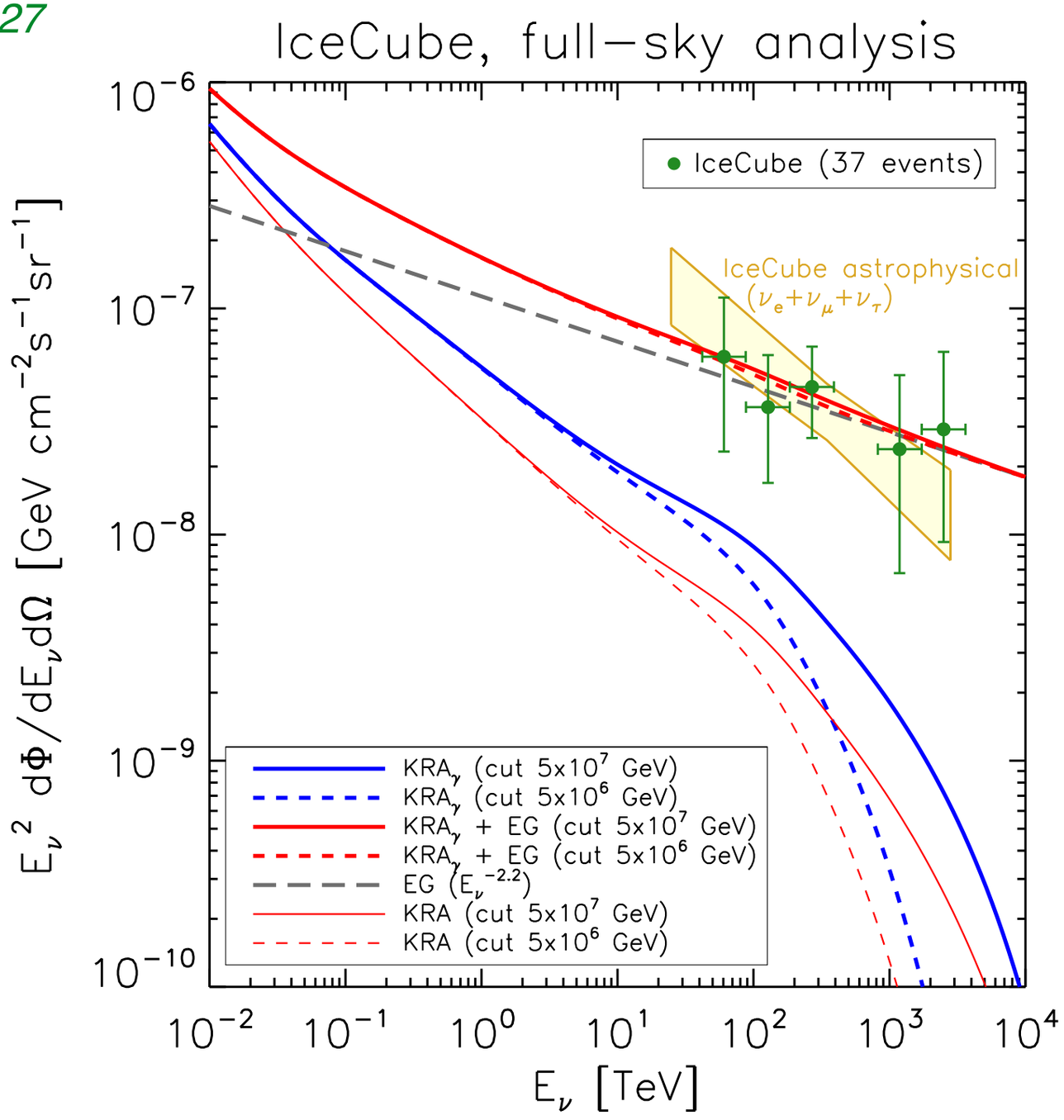


Possible implications for high energy neutrinos

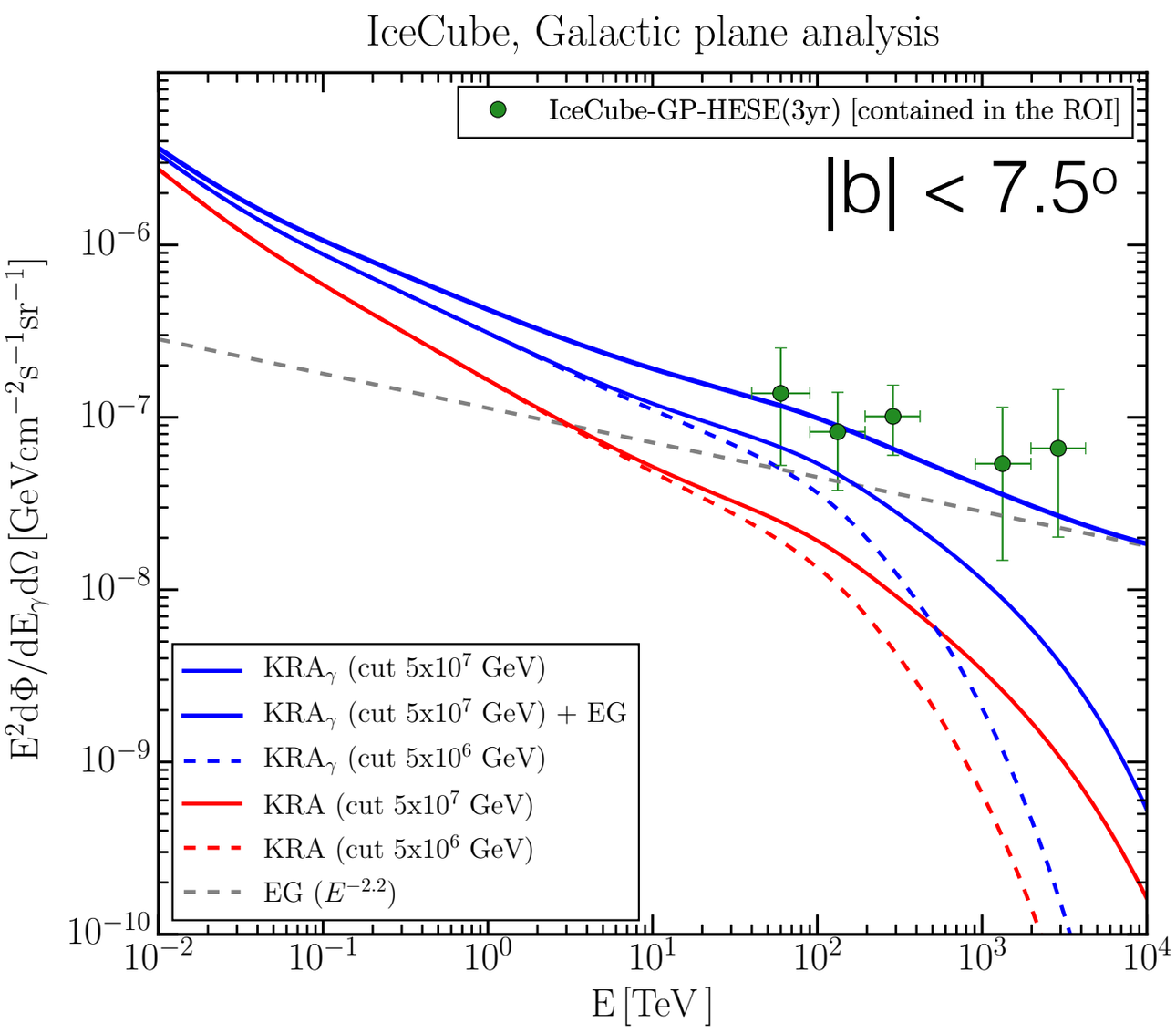
Gaggero, DG, Marinelli, Urbano, Valli arXiv:1504.00227 accepted by ApJL

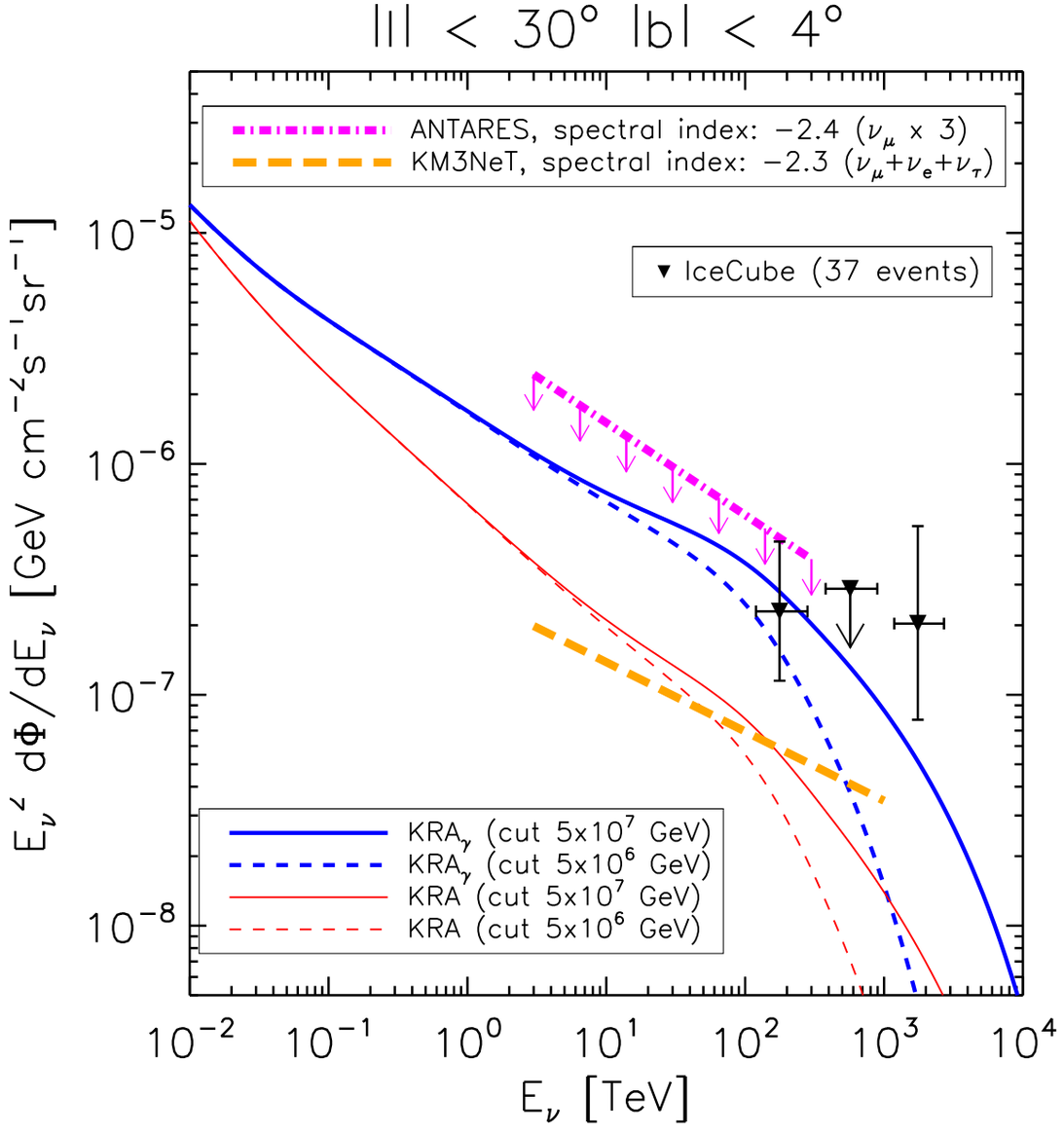
- On the full-sky the KRAγ model predicts a flux double than the corresponding conventional model (KRA)

- The sum of best-fit ν flux measured by IC in the Norther hemisphere (taken to be representative of the isotropic extra-Galatic flux) and of the KRAγ reproduces the full-sky measure by IceCube



Possible implications for high energy neutrinos
The Galactic plane





- The flux estimated from the IC events in the GP region is reproduced, this is more critical in the absence of the Galactic component

- This should soon be testable by ANTARES + IC and Km3NeT

CONCLUSIONS

- We need better knowledge of GMF to improve CR models but we also need better CR data/theory to correctly model GMF against radioastronomical and microwave data

- The increasing richness and accuracy of γ-ray and CR data motivate going beyond the homogeneous and isotropic treatment of CR transport in the Galaxy

- Several experimental results already provide hints that inhomogeneous and anisotropic CR transport is indeed playing a role. In particular we showed that may be the case for the diffuse γ-ray and neutrino emission of the Galaxy. Forthcoming results should clarify it quite soon.