Anomalies in the gamma-ray diffuse emission of the Galaxy and implications for the interpretation of IceCube results

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The $\gamma$-ray diffuse emission of the Galaxy

$p(\text{He})_{\text{RC}} + p(\text{He})_{\text{ISM}} \rightarrow \ldots + \pi_0 \rightarrow \ldots 2\,\gamma$  hadron scattering

- $e_{\text{RC}} + \gamma_{\text{ISRF}} \rightarrow e + \gamma$  inverse Compton (IC)
- $e_{\text{RC}} + A \rightarrow e + A + \gamma$  bremsstrahlung
The $\gamma$-ray (and $\nu$) diffuse emission of the Galaxy

- $p(\text{He})_{\text{RC}} + p(\text{He})_{\text{ISM}} \rightarrow \ldots + \pi^0 \rightarrow \ldots 2\ \gamma$  
  hadron scattering

- $p(\text{He})_{\text{RC}} + p(\text{He})_{\text{ISM}} \rightarrow \ldots + \pi^\pm \rightarrow \ldots \mu^\pm + \nu_e + \nu_\mu$

- $e_{\text{RC}} + \gamma_{\text{ISRF}} \rightarrow e + \gamma$  
  inverse Compton (IC)

- $e_{\text{RC}} + A \rightarrow e + A + \gamma$  
  bremsstrahlung
The cosmic ray \textbf{local} population

It is not expected to be representative of the entire Galaxy!

Radial distribution of sources
The CR Galactic population

The CR transport equation

Ginzburg & Syrovatsky, 1964

\[
\frac{\partial N^i}{\partial t} = - \nabla \cdot (D \nabla N^i - v_c N^i) + \frac{\partial}{\partial p} \left( \frac{\dot{p}}{3} \nabla \cdot v_c \right) N^i - \frac{\partial}{\partial p} \frac{p^2 D_{pp}}{D} \frac{\partial N^i}{\partial p} + Q^i(p, r, z) + \sum_{j \neq i} c\beta n_{\text{gas}}(r, z) \sigma_{ji} N^j - c\beta n_{\text{gas}} \sigma_{\text{in}}(E_k) N^i
\]

SN source term.
We assume everywhere a power law energy spectrum

Diffusion tensor
\[ D(E) = D_0 \left( \frac{\rho}{\rho_0} \right) \delta \]
\( \rho = \text{rigidity} \sim p/Z \)

Convection term

Energy loss

Reacceleration
\[ D_{pp} \propto \frac{p^2 v_A^2}{D} \]

Spallation cross section. Appearance of nucleus i due to spallation of nucleus j

Total inelastic cross section. Disappearance of nucleus i

A large number of parameters to be fixed against data!
Commonly, propagation parameters are fixed on the basis of local observables

\[ D(E) = D_0 \left( \frac{E}{E_0} \right)^{-\delta} \]

e.g. the diffusion coefficient is fixed on the basis of the secondary/primary CR nuclei ratio (the B/C most importantly) and assumed (for conventional models) to be spatially uniform

**warning** !!

due to CR vertical escape and nuclear inelastic scattering onto the interstellar gas secondary nuclei probes only few kpc around us. Propagation may behave differently in the central region of the Galaxy
PAMELA (Science 2011) found an hardening of the p and He spectra at $\sim 250$ GeV/n. AMS-02 confirmed the feature (slightly smoother and starting at $\sim 300$ GeV/n). This is also required to match CREAM!

spectral index $p/He = -0.077$

A similar effect is found for heavier nuclei.
The CR hardening may be a local effect e.g. due to nearby SNR, see e.g. Thoudam & Hörandel 2011

or a large scale one due to propagation see e.g. Blasi, Amato & Serpico 2012

the effect may be spatial dependent! (see below)
The CR hardening may be a local effect e.g. due to nearby SNR, see e.g. Thoudam & Hörandel 2011

or a large scale one due to propagation see e.g. Blasi, Amato & Serpico 2012

Those scenarios should have different impact on the diffuse γ-ray emission

Thoudam & Hörandel 2013

Aloisio, Blasi & Serpico 2015
The measured flux is 5 times (4 σ) larger than computed with the reference conventional model.

An optimized model (augmented IC contribution) - proposed to account for the EGRET GeV excess - was found to match Milagro.
• the excess is present also respect to updated conventional models tuned on CR data and all-sky Fermi-LAT data

• this holds also accounting for the CR hardening at \( \sim 250 \text{ GeV}/n \) assuming it is a large scale effect.

(the proton and He spectra were assumed to match CREAM data up to 100 TeV/n)
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Troubles, however, start already at low energy!!
Conventional models against Fermi data

Fermi Benchmark (FB) conventional model based on GALPROP (Moskalenko, Strong et al.). The model does not account for CR hardening at $\sim 250$ GeV/n.

$\delta = 0.3$, $\gamma_P = 2.72$ in the whole Galaxy

$h = 4$ kpc
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\[ \delta = 0.3 \], \( \gamma_P = 2.72 \) in the whole Galaxy

\( z_h = 4 \text{ kpc} \)
showed also that Fermi data requires a radial dependence of the CR spectral index, hence of the $\gamma$-ray emission spectrum. This was independently reported by the Fermi collaboration and confirmed recently (see below). This is clearly incompatible with conventional models implemented with GALPROP.
Yang, Aharonian & Evoli arXiv:1602.04710

also found a similar dependence of the $\gamma$-ray spectral index on the longitude/distance to GC.
The KRA\(\gamma\) model: Radial dependency of CR transport

**Gaggero, Urbano, Valli & Ullio**  *arXiv: 1411.7623  PRD 2015*

The **KRA\(\gamma\) model** - implemented with the **DRAGON code** - adopts a radial dependent diffusion coefficient

\[
\delta(R) = A R + B \quad \text{for } R < 11 \text{ kpc, const. above such that } \delta(R_{\text{sun}}) = 0.5
\]

and convective velocity

\[
\frac{dV_C}{dz} = 100 \text{ km s}^{-1} \text{ kpc}^{-1} \quad \text{for } R < 6.5 \text{ kpc}
\]

The model is tuned to reproduce the proton spectrum measured by PAMELA (including the hardening @ 250 GeV/n) up to 1 TeV, the B/C (antiprotons also matched by secondary prod.) as well as updated diffuse \(\gamma\)-ray Fermi data
The project started in 2008, more than 20 peer reviewed papers based on this code. The present version use (among other options) the same nuclear cross sections and gas distribution as in GALPROP

Main innovative features respect to previous codes:

- spatial dependent diffusion coefficient(s) (both normalization $D_0(R,z)$ and rigidity dependence index $\delta(R,z)$ )
- 3D: it allows spiral arm source distribution
- it allows anisotropic diffusion (2D) $D_\perp \neq D_\parallel$

See also the PICARD project: http://astro-staff.uibk.ac.at/~kissmrbu/Picard.html
A new version of DRAGON

Evoli, Gaggero, Vittino, Di Bernardo, Di Mauro, Ligorini & DG

• updated spallation cross section based on Fluka (see Mazziotta et al. 1510.04623, ApJ 2016)

• many update in the solver, with significant improvements in the implementation of energy losses, advection and reacceleration

• non-equidistant spatial binning (to better probe local bubble, Gal. center, …) and the possibility to model transient sources

• anisotropic diffusion in 3D

will soon be released.

A first (of a series) of technical papers to appear in a few days.
The KRA$_\gamma$ model reproduces the full-sky Fermi spectrum and angular distribution. It also provides a better fit in the inner GP region.

Gaggero, Urbano, Valli & Ullio  
*arXiv: 1411.7623  PRD 2015*
Fig. 8.— Radial distributions across the Galaxy of (a) the $\gamma$-ray emissivity per H atom measured at 2 GeV; (b) the proton flux integrated above 10 GeV, with the prediction from the GALPROP model; (c) the proton spectral index, $P_{\alpha}$, with statistical error bars and the prediction for proton rigidities above 1 TeV from the same GALPROP model (solid line) and from Gaggero et al. (2015) (dashed line). In all plots, the horizontal bars span the radial widths of the gas annuli used for the measurements. The two data points with smallest Galactocentric radii have large systematic uncertainties (see text). Panel (d) shows the proton flux integrated above 10 GeV, normalized to its value at the Sun Galactocentric radius, with the star formation rate traced by supernova remnants, H II regions, and pulsars (Stahler & Palla 2005).
The KRA$_\gamma$ model nicely matches MILAGRO consistently with Fermi data (point sources cleaned) no further tuning is required!
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Beside inhomogeneous diffusion the CR hardening at $\sim 250$ GeV/n must also be accounted for. This result suggests that hardening is not a local feature but it is may also be related to unconventional diffusion!
Comparison with other high energy $\gamma$-ray data

**Left Diagram:**
- $65^\circ < l < 85^\circ$, $|b| < 5^\circ$
- $E_{\gamma}$ vs. $E_{\gamma}^2 \frac{d\Phi}{dE_d\Omega}$ [TeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
- ARGO-YBJ coll., ApJ 2015

**Right Diagram:**
- Comparison with CASA-MIA
- $50 < l < 200$ deg
- $E$ vs. $E^2 \frac{d\Phi}{dE_d\Omega}$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
- upper limits

Graphs illustrating data comparison and upper limits.
- CR advect/diffuse in self-generated Alfven-waves below/above $\sim 50$ GeV
- harder CR (hence $\gamma$-ray) spectrum if advection dominate
- the effect is larger in the inner Galaxy, larger $D \rightarrow$ larger $p$ at which diffusion dominate

Note however that this is a low energy effect !
This is at odd with Fermi data and Milagro anomaly (HAWC may soon confirm !)
HESS (Nature 2006) measured a spectrum harder ($\Gamma \sim -2.3$) 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 conv. model. The spectrum normalization is correctly reproduced using an improved gas model in the GC region (Ferriere et al. 2007). See A. Marinelli talk in a few min!
What all this implies for neutrinos?
IceCube found evidence for 28 (2 years) then 37 HESE events (3 yrs) with reconstructed direction above 30 TeV corresponding to a 5.7σ excess respect to the atm. bkg.

angular distribution compatible with isotropy (see however below)

composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

Best fit spectral index above 60 TeV

- 2.3 ± 0.3
IceCube astrophysical neutrinos: present status

ArXiv1510.05223, ICRC2015

IceCube found evidence for 54 events (4 yrs preliminary) with reconstructed direction above 30 TeV corresponding to 7σ excess respect to the atm. bkg. (9+8 -2.2)

angular distribution compatible with isotropy (see however below)

composition compatible with a equal mixture of e, μ, τ as expected for astrophysical generated neutrino

Best fit spectral index $\Gamma \sim -2.58 \pm 0.25$

A similar spectrum found from a template fit analysis including severa kind of events down to 25 TeV, IceCube coll. ApJ 2015
- astrophysical muon neutrinos from the Northern hemisphere with $E > 100$ TeV.
The neutrinos collected during 659.5 days of live time between May 2010 and May 2012 are inconsistent with the background at the level of $3.7 \sigma$.

- Assuming a single power-law the best-fit spectral index is $\Gamma = -2.2 \pm 0.2$. 
A measurement of the diffuse astrophysical muon neutrino flux
Sebastian Schoenen | TeVPa 2015, Kashiwa | 29.10.2015

Comparison to HESE 4 year

HESE 4 year unfolding
(→ dominated by shower-like events)

- Energy threshold @ about 60 TeV
  - Softer spectral index currently driven by low energy bin

- Energy threshold @ about 200 TeV
  - @ high energies (≳ 200 TeV)
  - HESE 4 year analysis (left) compatible with $E^{-2}$

6 year up-going numu analysis

just copied
Results of a simple galactic plane analysis

**Question:** Could a dominant galactic component be the reason for the tension?

- Split data into two right ascension regions with similar amount of statistics

- Fits compatible: p-value = 49%
  - No evidence for a dominant flux from the galactic plane

- Fit of region with galactic plane has slightly higher norm. and softer spectral index
  - Hint for a galactic component?

A measurement of the diffuse astrophysical muon neutrino flux
Sebastian Schoenen | TeVPa 2015, Kashiwa | 29.10.2015
Other hints of an anisotropic flux?

Neronov & Semikoz \(\text{arXiv:1509.03522}\)

use only events above 100 TeV in the IC 4-year sample (19 events, 1 bkg)

9 events for \(|b| < 10^\circ\); 0 events for \(|b| > 50^\circ\)

They found \(\sim 4\sigma\) inconsistency with isotropy.

It is claimed that “a model which contains 50% contributions from the Galactic and extragalactic components provides a satisfactory fit to the data”

A more recent analysis by Palladino & Vissani \(\text{arXiv:1601:06678(v2)}\) found that a \(\sim 20\%\) contribution is more likely.
The Galactic $\nu$ emission with conventional models

Ahlers et al. arXiV:1505.03156

8% of IceCube HESE (2013) signal at most

- based on GALPROP
- it adopts harder CR spectra above 250 GeV/n so to match CREAM
- it adopts phenomenological models for CR spectra in the knee region (two different models)
Galactic Plane neutrinos with a variable $\delta$

Gaggero, DG, Marinelli, Urbano & Valli arXiv: 1505:03156

- based on DRAGON ($\text{KRA}_\gamma$ model, the same which matches FERMI and Milagro)
- it adopts harder CR spectra above 250 GeV/n so to match CREAM
- it adopts phenomenological models for CR spectra in the knee region [two exponential cutoff at $E/Z = 5, 50$ PeV (dashed, solid lines)]
2007-2013 $\nu_\mu$ data $E > 1$ TeV
no events found in the sky region $|b|<4^\circ$ and $|l|<30^\circ$ which turns into an upper limit (in the fig. $\Gamma = 2.5$ is assumed)

- 3 IceCube (shower-like) events are reconstructed to be compatible with the same region. This turns in a maximal flux in that region.

- From the neutrino spectra obtained with KRA and KRA$_\gamma$ models we can estimate the galactic component of the IceCube observation in this region of the sky.
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The KRA$_\gamma$ setup predicts a flux which is $\sim$ double and slightly harder than the corresponding conventional model. This may account for $\sim$ 15% of the full-sky $\nu$ astrophysical flux measured by IceCube full-sky above 60 TeV (3 years HESE anal.)

this is clearly compatible with the IC events angular distribution
clearly, a dominant extra-Galactic contribution is required
For illustrative purposes here we assume the $\nu_\mu$ (tracks) flux (best-fit) measured by IceCube from the northern hemisphere to be representative of the extra-Galactic emission (Gal. emission negligible in that region)
Galactic Plane neutrino with an analytical model with $\delta$ variable

Pagliaroli, Evoli & Villante arXiv:1606.04489

$\nu$ flux at 100 TeV

- A: uniform CR density
- B: CR density profile proportional to SNR
- C: CR spectrum changing with R

5% Gal. contribution to IC HESE $E > 100$ TeV

7% “

13% “

correction to CR density

$$h(E, r) = \left(\frac{E}{E_0}\right)^{\Delta(r)}$$

$$\Delta(r, z) = 0.3 \left(1 - \frac{r}{r_\odot}\right)$$
G+EG emission in the GP constrained by IceCube

For the whole galactic plane with $|b| < 7.5$ half of astrophysical flux can be explained with KRA$_\gamma$ and the other half with EG best fit analysis. The IceCube spectrum is obtained considering the contained events for this region.
Forthcoming theoretical work

- use updated Fermi-LAT data (PASS8) to get better statistic at high energy and find-out a range of allowed models with $\delta(R)$ and make better predictions for HAWC
- use more (better/updated) CR models in the knee region
- explore different physically motivated models which may explain such behavior (anisotropic diffusion; non-linear diffusion; …)
- combine with models of extra-galactic emission (starting with including the emission of external normal galaxies)
- any other suggestion?
Conclusions

• The $\gamma$-ray Galactic diffuse emission measured by Fermi along the GP, which is not reproduced by conventional models, can be interpreted in terms of a radially dependent CR transport model. The same model, when accounting for the CR hardening at 250 GeV/n, allows to reproduce Milagro excess at 15 TeV

• Respect to conventional models this scenario predicts a significantly larger Galactic neutrino flux along the Galactic center/plane testable by IceCube, ANTARES (marginally) and Km3NeT

• The CR population in the Galactic center region is harder and higher than in conventional model which is in agreement with HESS results (see Marinelli’s talk)
Backup slides
Our CR primary spectra

Protons and Helium

Hydrogen and all-particle spectra
Applying the KRA$_\gamma$ to the “pacman” region we can see how big is the slot left in the SED for the Pevatron injector.
A possible origin of $\delta(R)$ from anisotropic diffusion

The presence of regular MF breaks isotropy

$$D_{ij}(x,\rho) = [D_{\parallel}(x,\rho) - D_{\perp}(x,\rho)] b_i b_j + D_{\perp}(x,\rho) \delta_{ij}$$

Even in the quasi-linear theory $D_{\parallel}$ 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

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

$$D_{\perp}(E) \propto E^{0.5\div0.6}$$
A possible origin of $\delta(R)$ from anisotropic diffusion

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

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

this may cause the effective value of $\delta$ decreasing with $R$!
The Neronov & Semikoz model

The model assumes a harder CR spectrum ($\Gamma \sim 2.4$) in most of the Galaxy but the local bubble where a young SNR enhances the CR population producing an effective softening.

This seems to be excluded by ANTARES upper limit.