Diffuse Galactic γ-ray and ν fluxes at very high energy and the Galactic/extragalactic Cosmic Ray transition

Silvia Vernetto, INAF-OATO &INFN Turin, Italy
Paolo Lipari, INFN Rome, Italy

ICRC 2001

The importance of measuring diffuse γ-rays and ν fluxes at energy 100 TeV – 10 PeV

- The study of the diffuse gamma ray and neutrino fluxes is an important tool to investigate the cosmic ray properties in the Galaxy

- The spectra and angular distributions of the diffuse emission encode the energy and space distribution of the parent CRs.

- **Measurements at energy > 100 TeV in different regions of the sky** could provide important information on two major questions concerning cosmic ray origin and propagation:

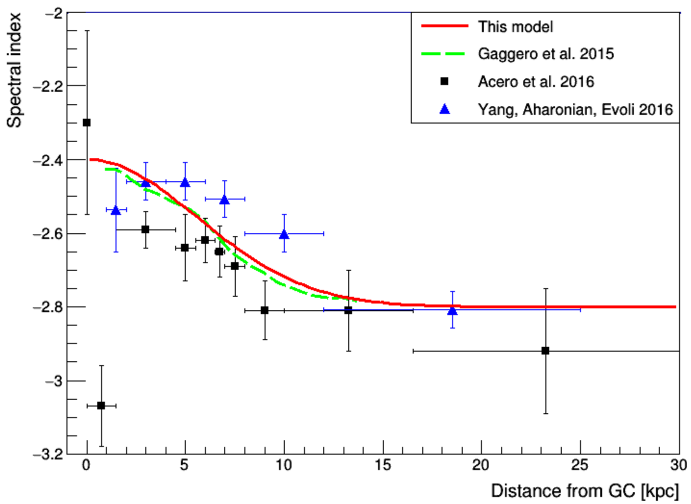
  - **Have cosmic rays the same spectral shape in all the Galaxy ?**

  - **At which energy the extragalactic component becomes dominant?**

Part one

The spectral shape of CRs in the Galaxy

The CR hardening towards the Galactic center



Analyzing Fermi-LAT data, some authors pointed out that the spectra of diffuse γ-rays become harder approaching the Galactic center.

This could imply that the **spectrum of CRs in the inner region of the Galaxy is harder than close to the Sun.**

If the CR spectral shape depends on the position, the gamma ray spectral shape will depend on the arrival direction.

The hardening towards the Galactic center would produce an enhancement of the high energy gamma ray flux at small Galactic longitudes.

Is this effect observable?

Our calculations of diffuse gamma ray flux of energy 10 GeV-10 PeV

Details in: *P. Lipari & S. Vernetto Phys.Rev. D 98, 043003, 2018*

Gamma ray production

- 2 Models for the CRs spectra in all the Galaxy
- Model for the interstellar matter
- Model for radiation fields (CMB, dust & stars emission)

Details in: *S. Vernetto & P. Lipari Phys.Rev.D 94, 6, 063009, 2016*

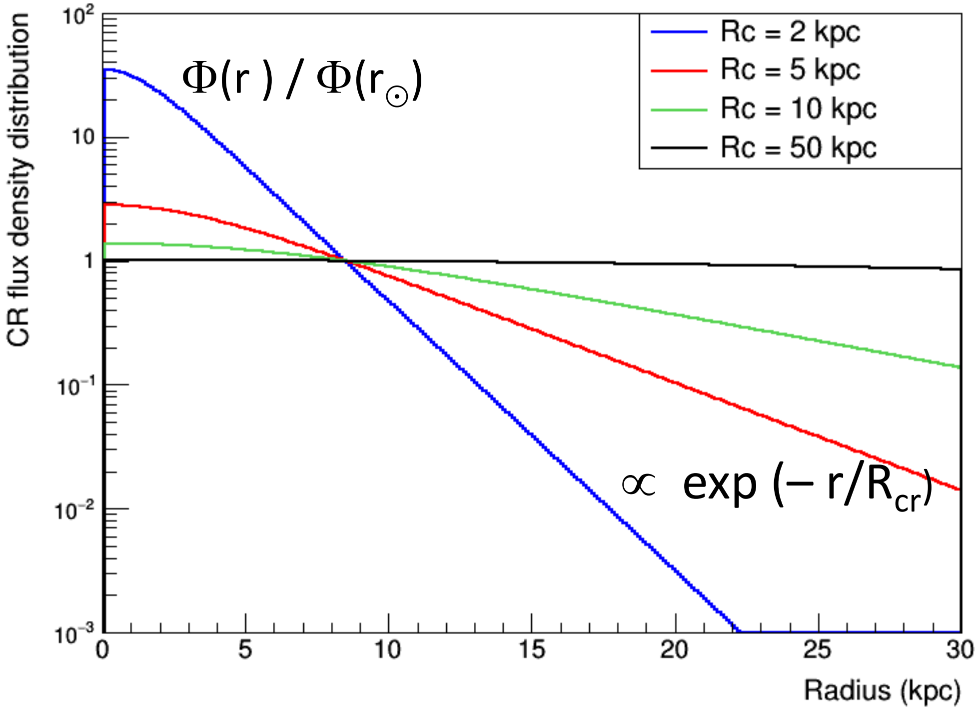
Gamma ray propagation

- Absorption of gamma ray by pair production

Model M1
CRs have the same spectral shape in all the Galaxy

The intensity decreases with the galactocentric distance r

$$\Phi(r) = \Phi_{\odot}\, \text{sech}(-r/R_{cr}) / \text{sech}(r_{\odot}/R_{cr})$$



R_{cr} is a free parameter

the only free parameter of the model

Fitting the longitude distribution to the Fermi data at 12 GeV,
we set **R_{cr}= 5.1 kpc**

Model M2
CRs have a spectral shape depending on r

Gamma rays are produced with a spectral shape depending on r

Emissivity:

$$q(E,\vec{r}) = q_{Mod1}(E,\vec{r})\left(\frac{E}{E_{ref}}\right)^{-[\alpha(r)-2.75]}$$

α depends on r:
α = - 2.4 at r=0
α = - 2.75 at $r_\odot$
α = - 2.8 at r > 15 kpc

E_{ref} = 12 GeV reference energy of the Fermi map

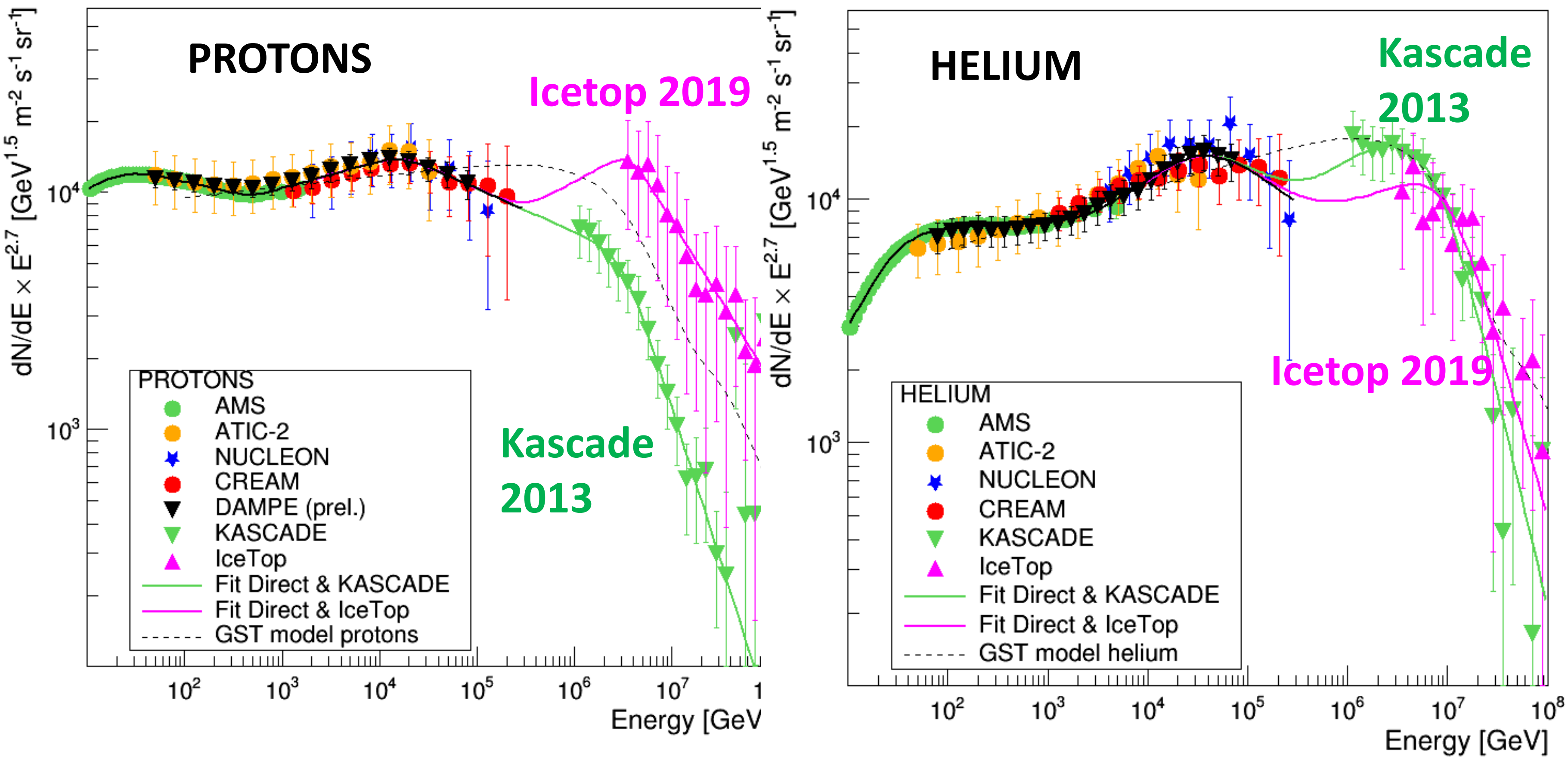
At energy E = E_{ref} the two models give the same flux and spectrum

Model 2 predics a larger flux at higher energy at small galactic longitudes

In our past work we used
the Gaisser-Stanev-Tilav model (GST, 2013)
to describe the local CR spectra

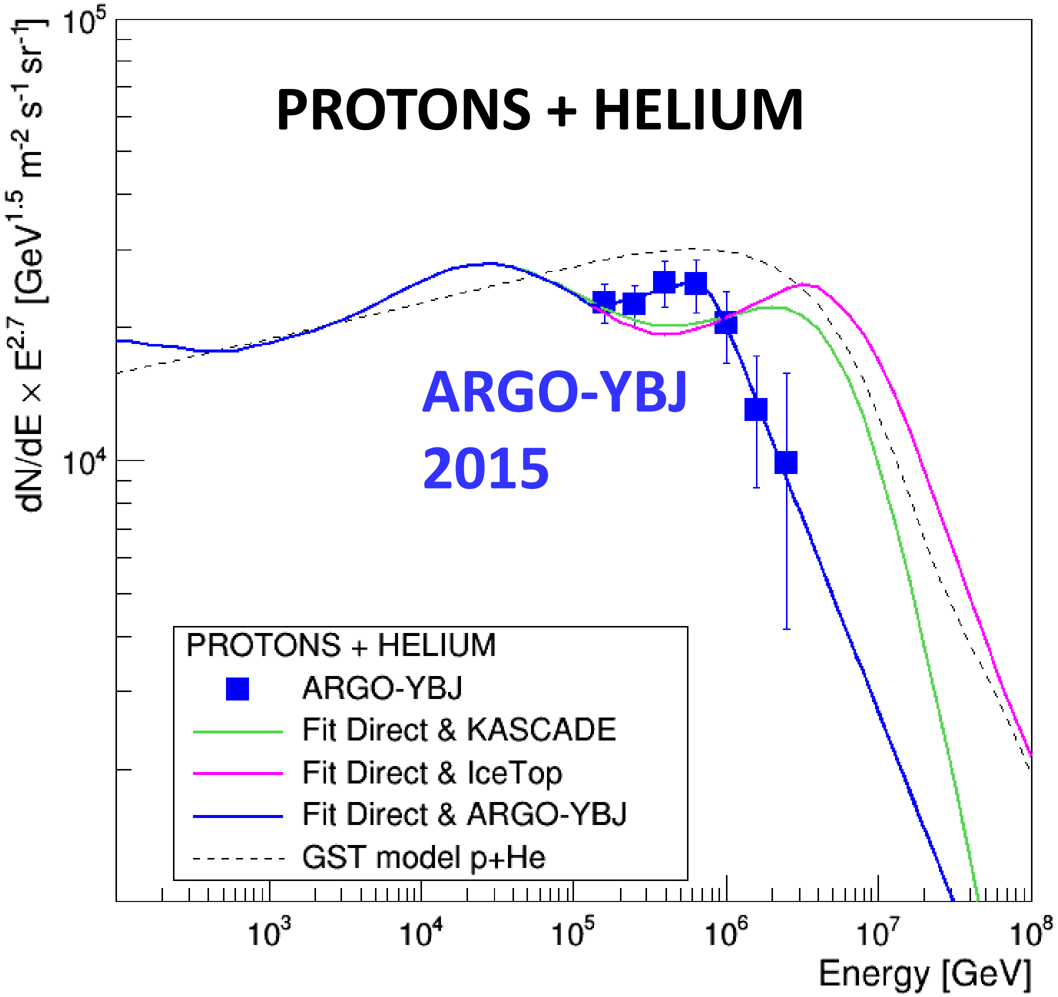
Here we start from the available CR data
from 10 GeV to 100 PeV

Protons and Helium: direct measurements + EAS array data



To connect direct measurements with EAS data , a further hardening is necessary

ARGO-YBJ protons +Helium



ARGO-YBJ observed a knee below 1 PeV in the p+He spectrum

in disagreement with both Icetop and Kascade

All-nucleon spectrum

- The diffuse γ-ray flux depends, in good approximation, only on the **all-nucleon spectrum**, that gives the total flux of nucleons, obtained summing the contributions of all nuclei.

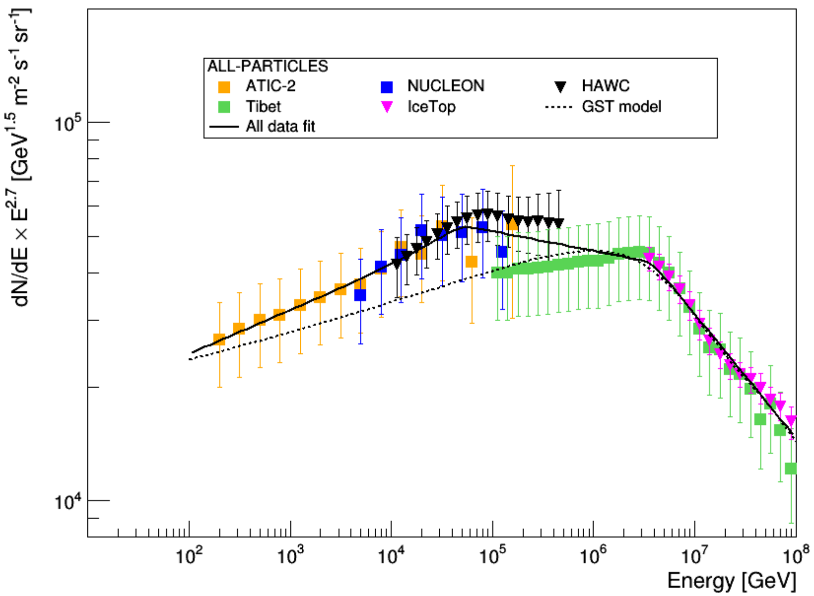
- Light elements, at a given energy, give a much higher contribution to the all-nucleon spectrum with respect to heavy nuclei, and will produce more gamma rays.

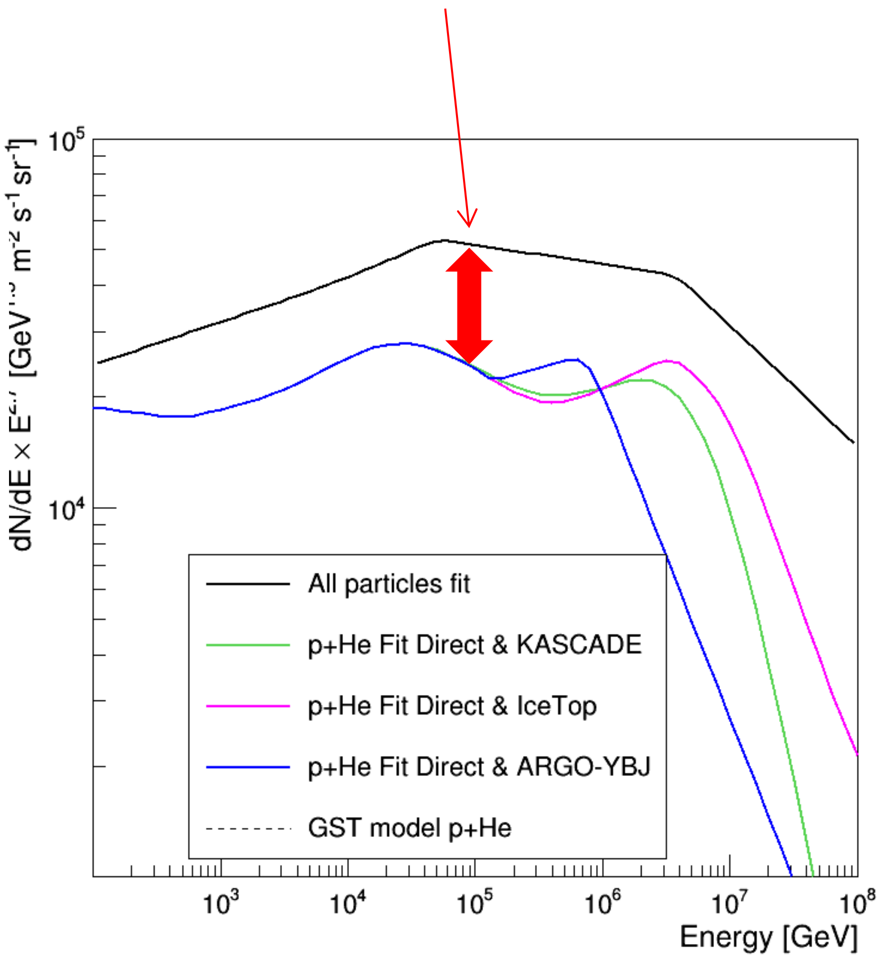
Higher proton contribution ⇨ higher gamma ray flux

Heavy elements (Z > 2)

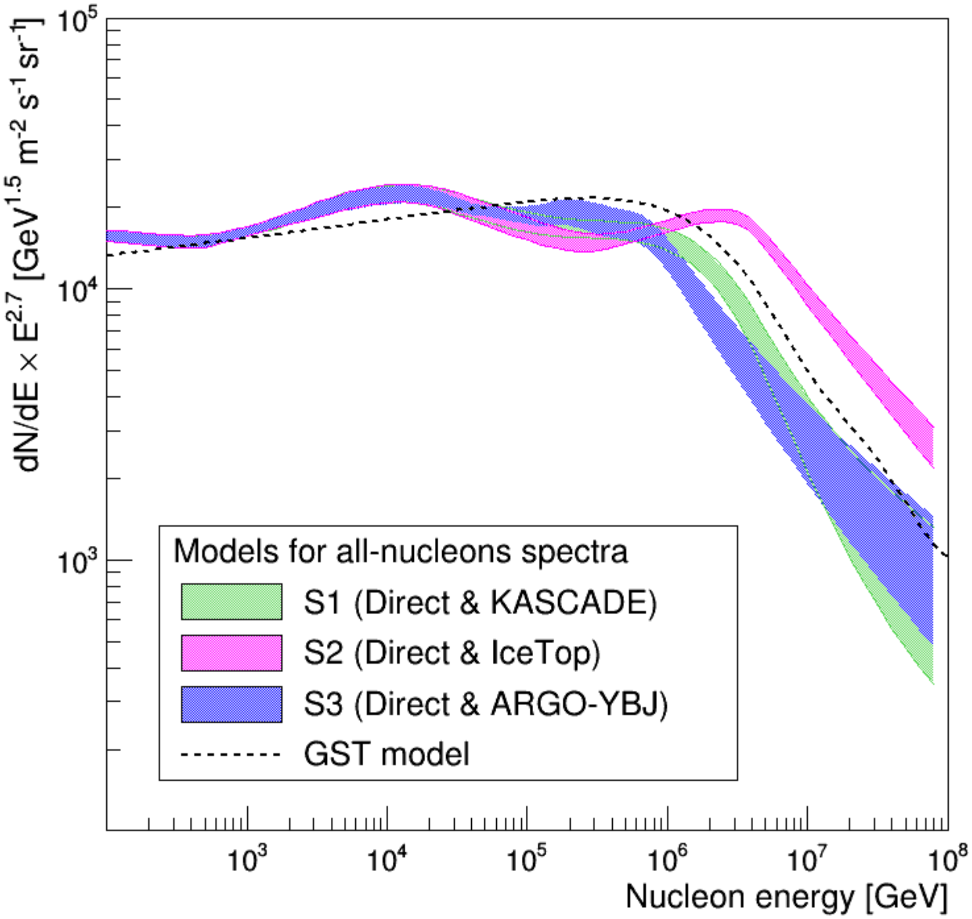
The total flux of heavy elements is evaluated by the difference between the all-particle flux and the p+He flux

All-particle spectrum





The local all-nucleon spectrum



Two extreme assumptions on elements with Z > 2:

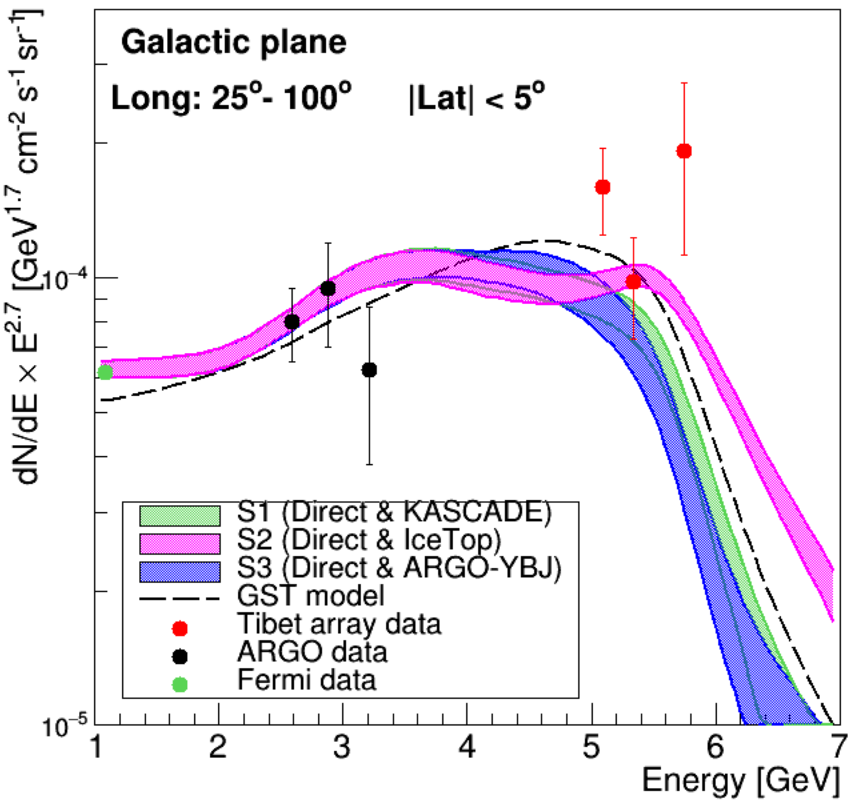
a) all nuclei are Carbon
b) all nuclei are Iron

The upper limit of each band is by assuming all heavy nuclei to be Carbon

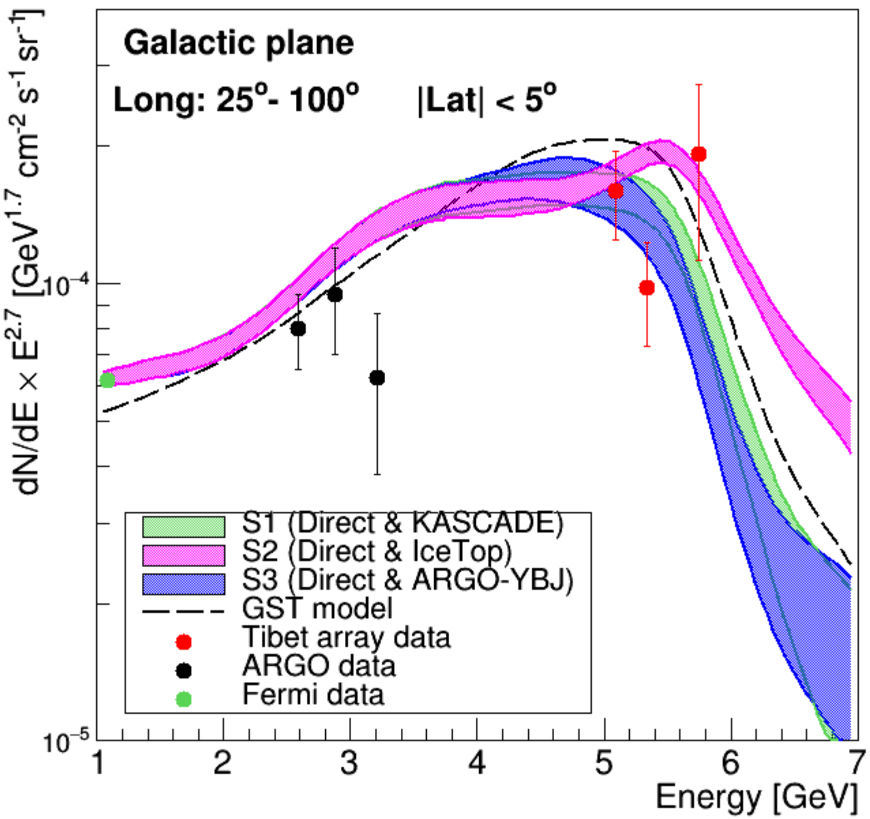
The lower limit of each band is by assuming all heavy nuclei to be Iron

Diffuse gamma rays in Tibet array FOV
Comparison models-data

CR model M1
Same spectra in all Galaxy



CR model M2
Hardening towards Galactic center



Part 1 – some conclusions

Tibet data are closer to predictions that include a CR hardening, however it is difficult to draw firm conclusions, because of:

- the large error bars of the Tibet flux;
- the uncertainties of the CR composition at the knee, in particular the proton fraction: a higher proton flux in the knee region could produce the observed gamma ray flux as well;
- the limited angular region studied; the CR hardening would produce an enhancement of the VHE gamma ray flux in the direction of the Galactic center region, and a depletion of the flux in the opposite direction.

More precise measurements in a broader range of Galactic longitudes are necessary to solve the question.

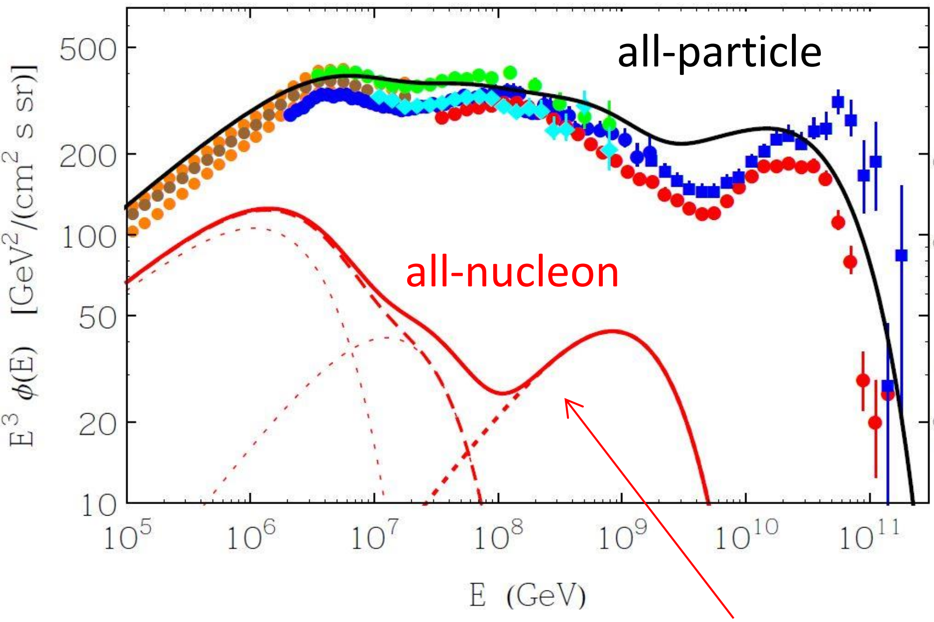
Part two

The emergence
of an extragalactic component
at energies above the knee

Galactic or extragalactic?

Gaisser – Stanev – Tilav (GST)

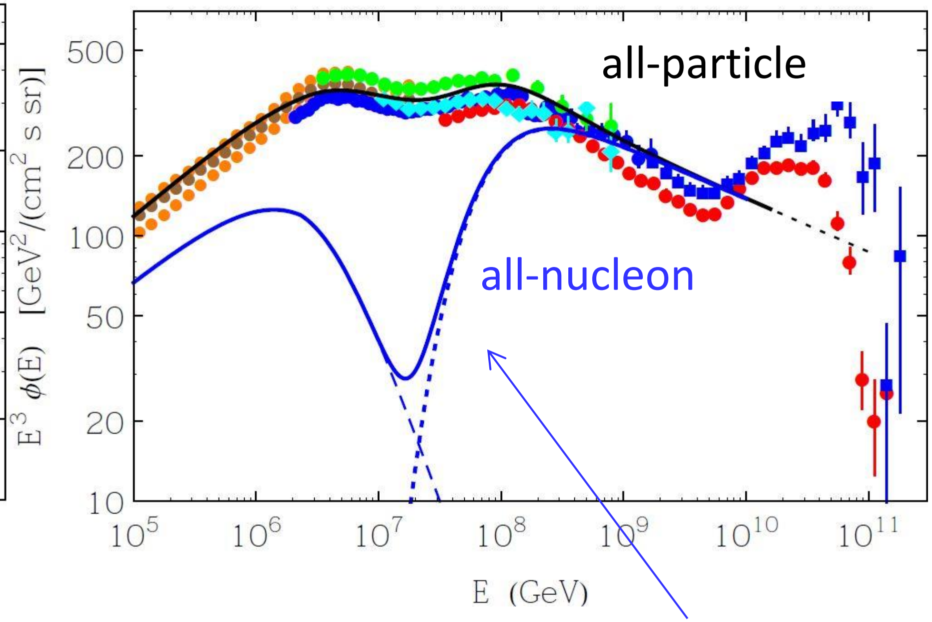
- Three source populations
- The 3rd population is extragalactic
- The transition corresponds to the *ankle* at E ~ 5 10^{18} eV



Extragalactic component

Mollerach & Roulet (MR)

- The transition corresponds to the *second knee* at E ~ 10^{17} eV
- The extragalactic component is light (here we assumed protons)



Extragalactic component

Calculation of gamma-rays and neutrino fluxes

Assumptions for CR spectra and space distribution:

For the **Galactic component** we use our model M1:

a) The CR spectral shape is the same in all the Galaxy

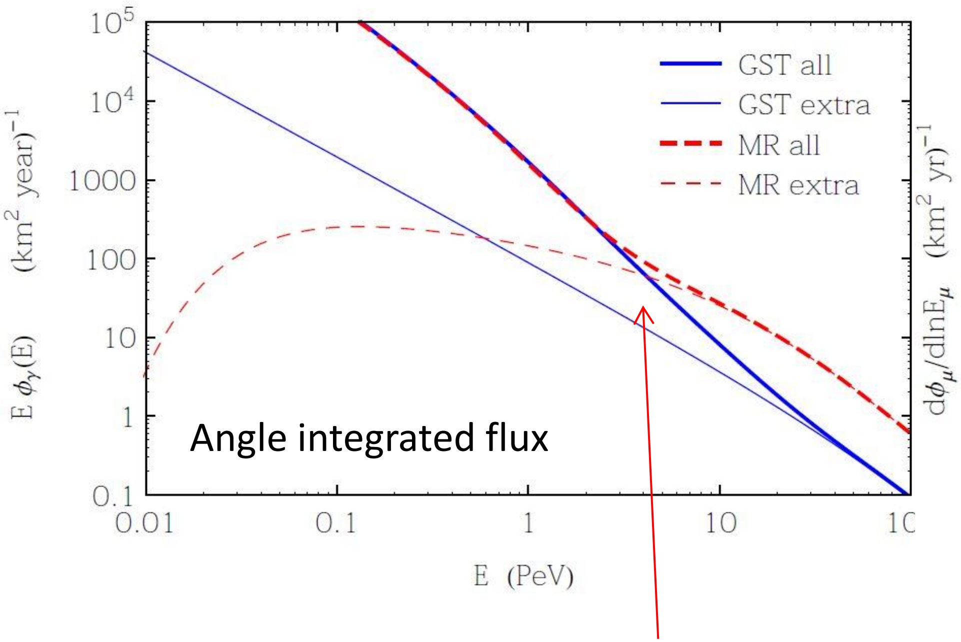
b) The CR density decreases with r as sech $(-r/R_{cr})$, R_{cr}=5.1 Kpc

For the **extragalactic component**, we assume the same CR density and spectral shape everywhere.

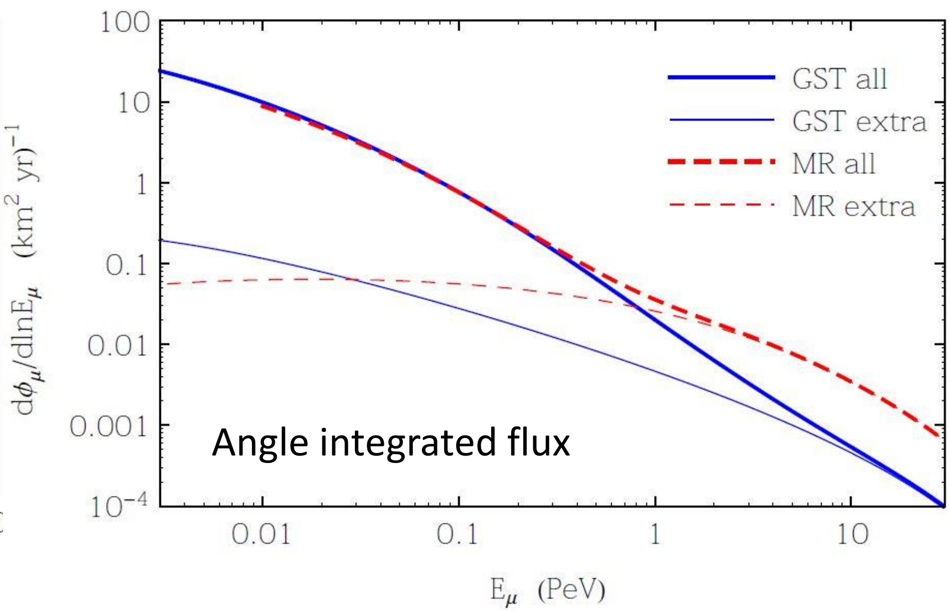
➡ The difference in spatial distribution is a crucial point for the identification of the two components

Diffuse gamma-ray and ν-induced muon flux

Gamma rays



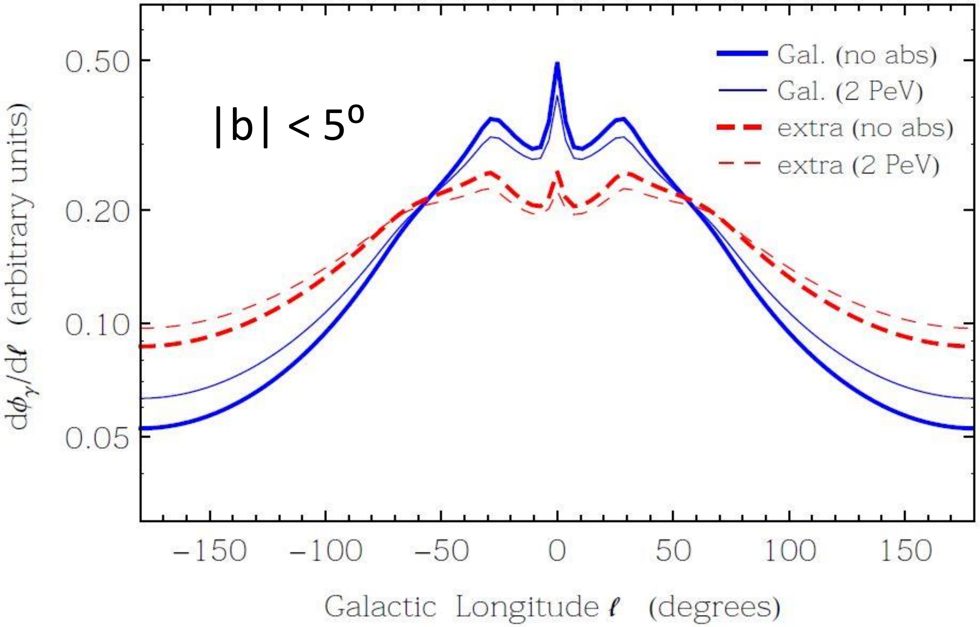
Neutrino-induced muons



- At $E_\gamma \sim 3$ PeV the two models separate and gamma rays from extragalactic CRs become dominant in MR model. The same happens for muons at $E_\mu \sim 0.5$ PeV
- The higher MR flux with respect to GST above the transition energy is due to the lighter composition

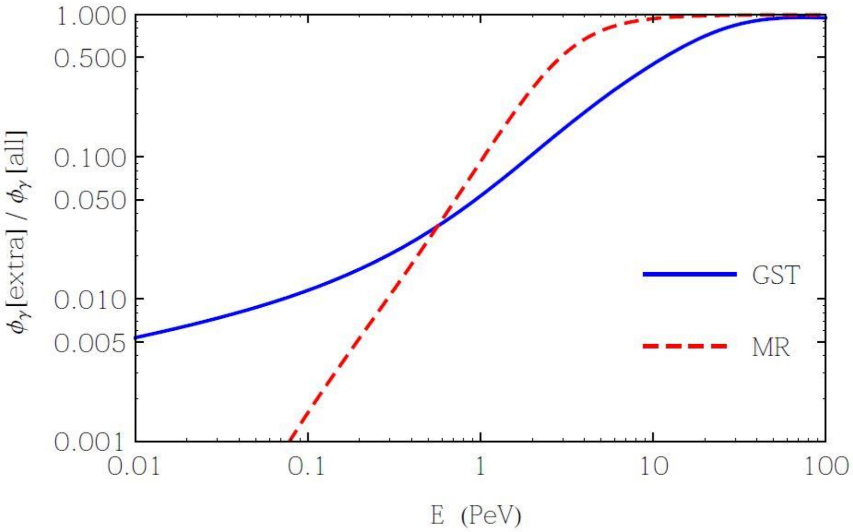
Gamma-ray and neutrinos
Galactic longitudinal distribution

The longitudinal distribution of γ-rays and neutrinos traces the CR space distribution



The longitude distribution of γ-rays produced by extragalactic CRs is flatter than that by galactic CRs.

Fraction of γ-rays induced by extragalactic CRs for GST and MR models



At 10 PeV, 90% of gamma rays are extragalactic according to the MR model, 44% according to GST

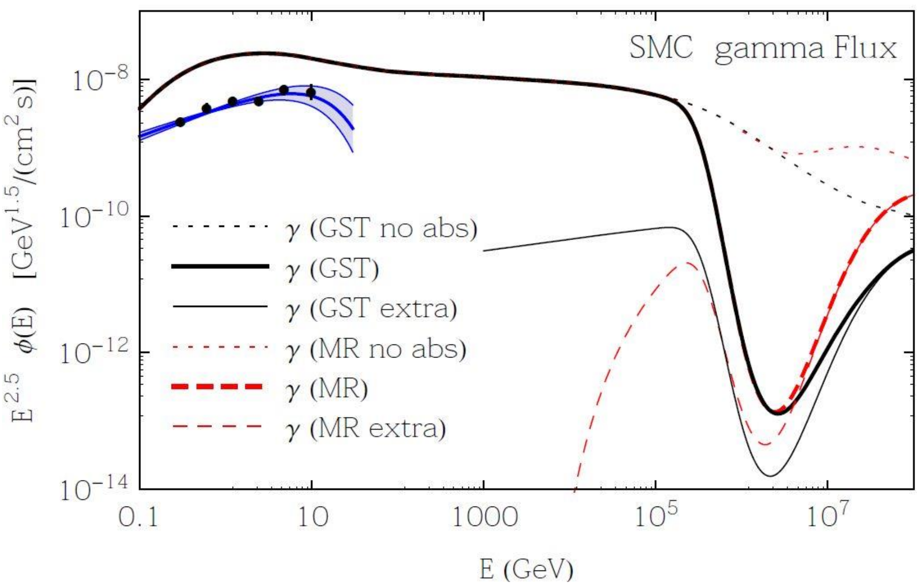
Extragalactic CRs?

- The observation of a flatter longitudinal distribution of γ-rays or ν's above 10 PeV, would not demonstrate that parent CRs are extragalactic.
- A more conclusive measurement would be the detection of a diffuse emission from an object outside our Galaxy, like **the Small or the Large Magellanic clouds.**
- The observation that the density of CR of energy above 10^{17} eV inside the clouds is equal to the local one would constitute a robust demonstration of the extragalactic origin of the particles.
- This measurements would require detectors of higher sensitivity than those are available today, but could be **a goal for future studies**

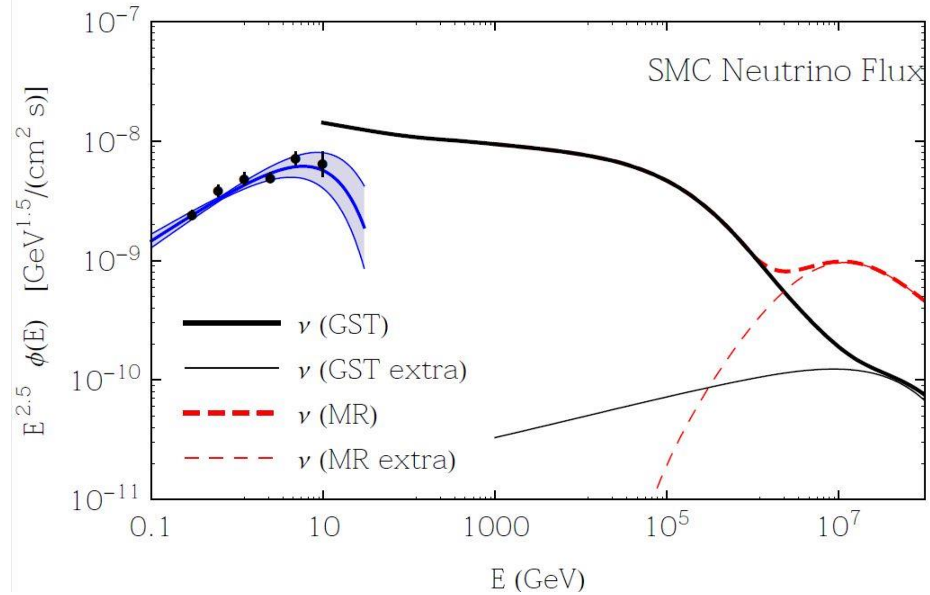
The ideal measurement of extragalactic CRs: detection of γ-rays and ν's from the Magellanic Clouds

The Small Magellanic Clouds contains a very low CR density, according to Fermi data.

Expected gamma ray flux



Expected neutrino flux



Data points are by Fermi-LAT.
The CR density in SMC is assumed to be equal to the local one.
The dip at a few PeV in the gamma-ray flux is due to the absorption by CMB.

The end