Detection of *anisotropies* in the arrival directions of 300 GeV – 10 TeV cosmic rays with the **ARGO-YBJ** experiment

presented by R. Iuppa

University of Rome Tor Vergata
INFN, sez.ne "Tor Vergata"

on behalf of the ARGO-YBJ collaboration

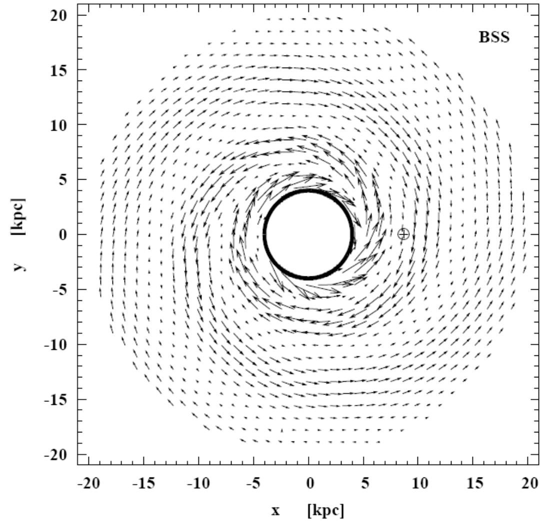
IFAE2011 Incontri di Fisica delle Alte Energie
Perugia - April 27th, 2011

Outline

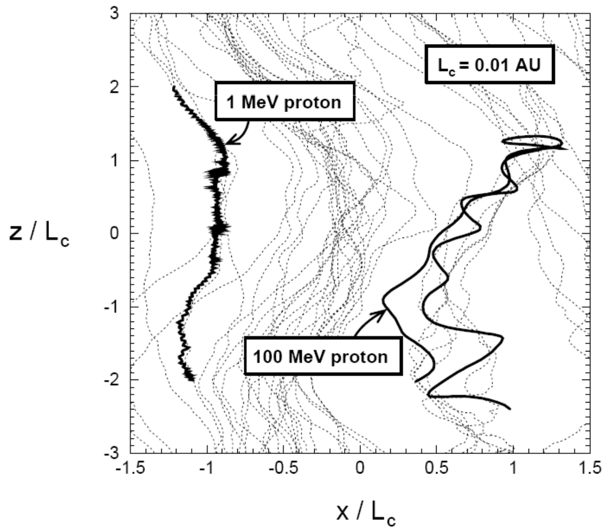
- What we expect: isotropy of cosmic rays
- Observations of CR anisotropies
- The ARGO-YBJ experiment
- The large scale anisotropy
- The intermediate scale anisotropy
- Conclusions

What is expected: isotropy

The galactic magnetic field is thought to be the superposition of a “regular” and a “chaotic” component (with intensities B_{reg}~2 μG and B_{ch}~0.5÷2 μG respectively).



Alvarez Muniz J. And Stanev T.
2006 J. Phys.: Conf. Ser. 47 126



J. Giacalone and J. R. Jokipii
1999 *ApJ* 520 204

The gyroradius of a particle of rigidity R TeraVolt is:

$$r = \frac{p}{ZeB} \approx R[TV] \times 5\,10^{-4}\,pc \approx R[TV] \times 100\,A.U.$$

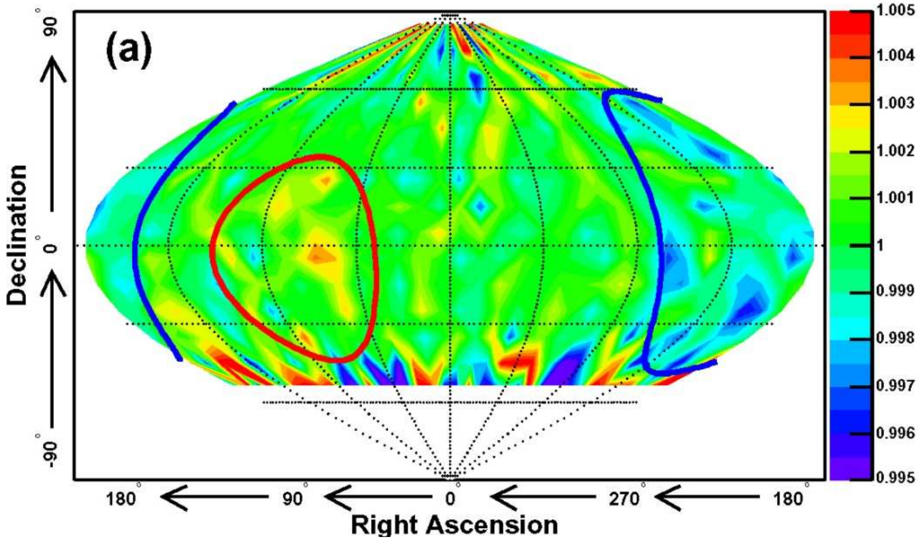
Cosmic rays interact with the interstellar medium (ISM), the interactions further scattering their trajectories (minor effect w.r.t. that of B).

We expect to observe their arrival directions are **ISOTROPICALLY DISTRIBUTED***

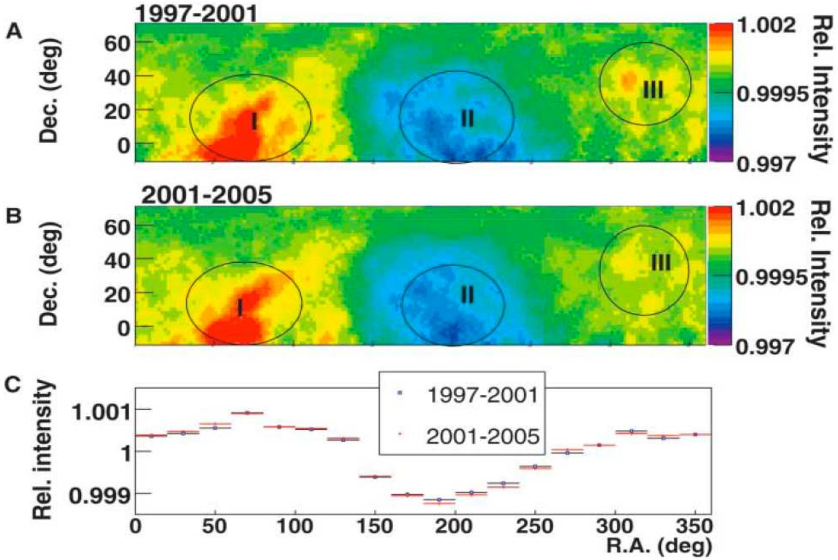
What the observation of CR anisotropies might suggest

- there are sources nearby.
- the galactic magnetic field is not what we think (only if the effect is due to charged cosmic rays):
  - the role of the Solar wind as well as the magnetic field in the solar system may be non-negligible.
  - there might be local (or non-local) magnetic field structures focusing CRs up to the Solar System.
  - the chaotic component of the magnetic field may overwhelm the regular one.
- any combination of the two facts above.

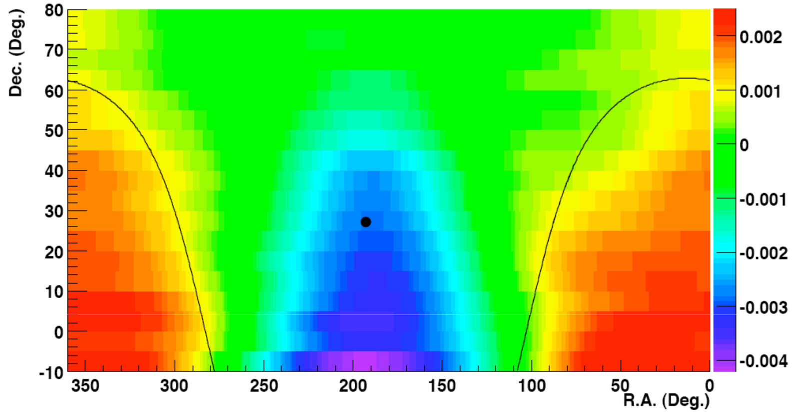
Observations of CR anisotropies



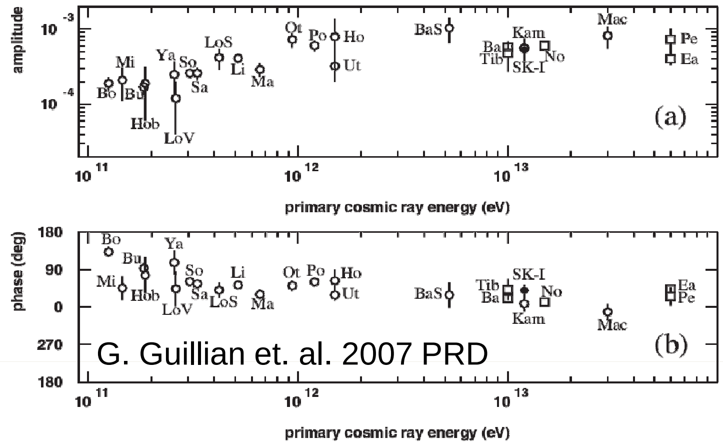
Super-Kamiokande – ICRC 2007 Proceedings



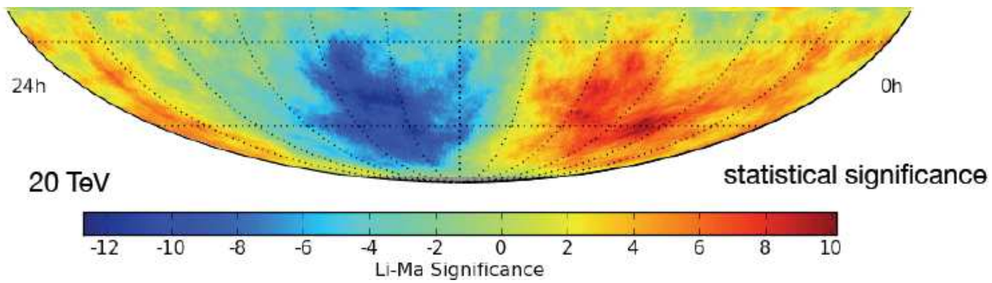
Tibet AS-γ - *Science* 20 October *2006*: Vol. 314 no. 5798 pp. 439-443



MILAGRO - 2009 *ApJ* **698** 2121

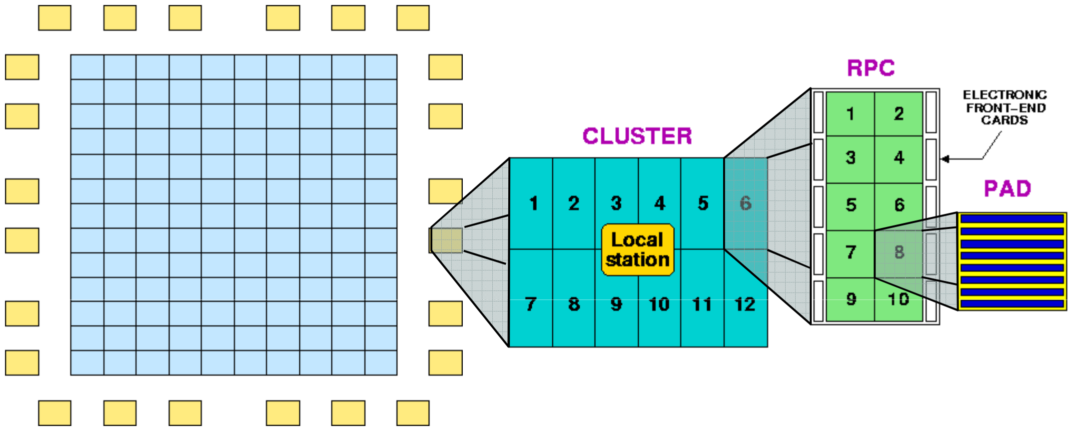


G. Guillian et. al. 2007 PRD

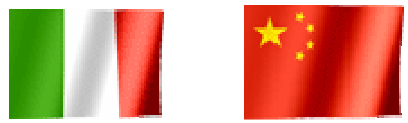


ICE-CUBE - 2010 *ApJ* 718 L194

The ARGO-YBJ experiment

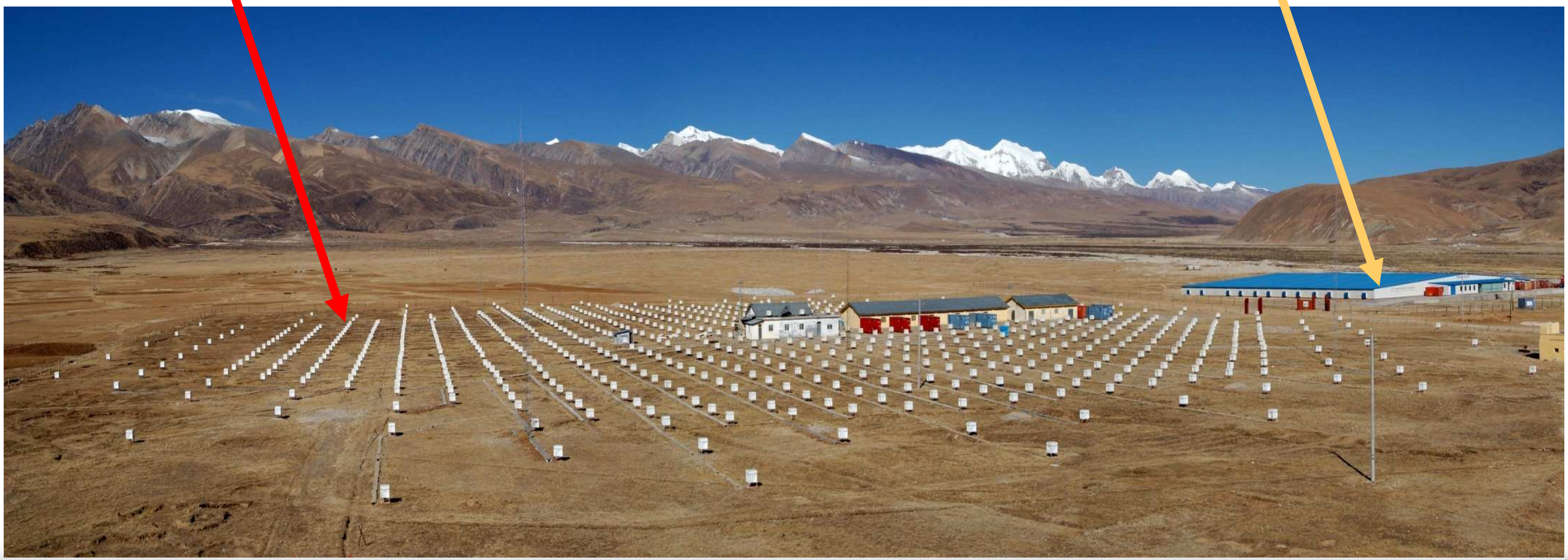


Altitude 4300 m a.s.l.
Longitude 90°31’ 50” East
Latitude 30°06’ 38” North



Astrophysical **R**adiation
with **G**round-based
Observatory at **Y**ang**B**a**J**ing

Tibet AS-γ



Operation modes

Shower mode

Trigger : number of fired pads (N_{pad}) within 420 ns
on the central carpet

for $N_{pad} \geq 20$, rate ~ 3.5 kHz (~220 GBytes/day)

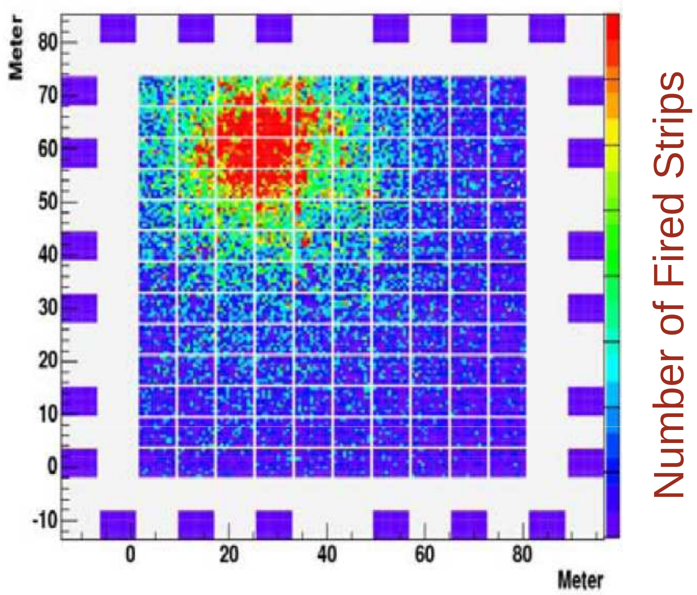
Detection of Extensive Air Showers (direction, size, core …)

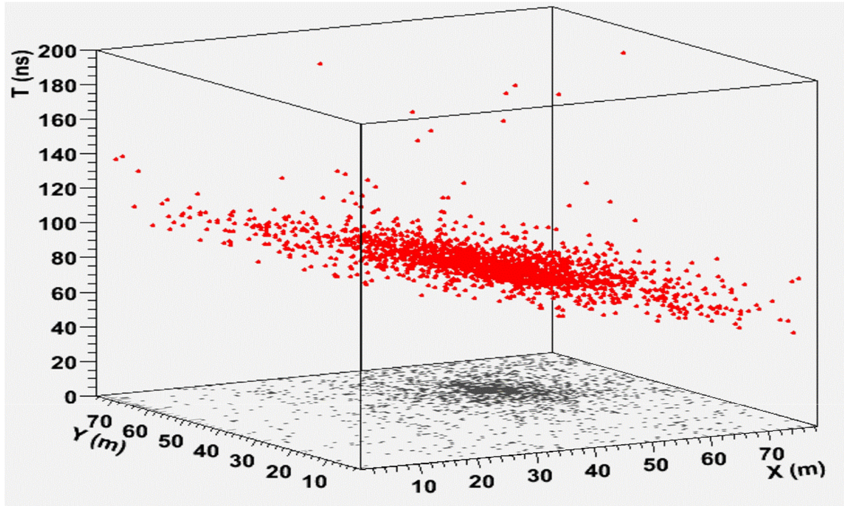
Aims : cosmic-ray physics (threshold ~ 1 TeV)
VHE γ-astronomy (threshold ~ 300 GeV)
gamma-ray bursts

Scaler mode

counting rates (≥ 1, ≥ 2, ≥ 3, ≥ 4 coincidences) for each cluster

Aims: detector and environment monitor
flaring phenomena (gamma ray bursts, solar flares)
with a threshold of few GeV



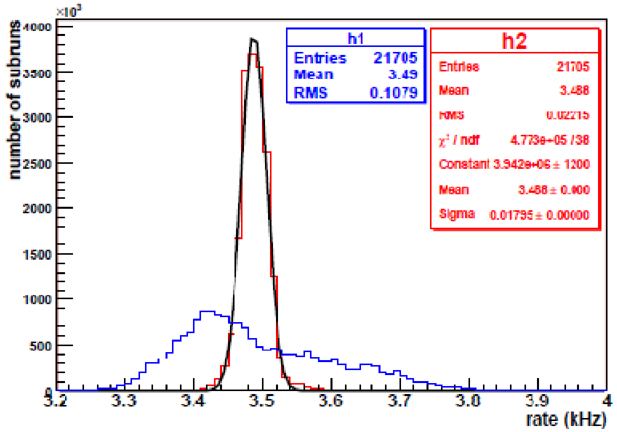


Space pixel: single strip (7×62 cm^2)

Time   pixel: pad (56×62 cm^2) is the OR of 8 strips, with a resolution of ~ 1.8 ns

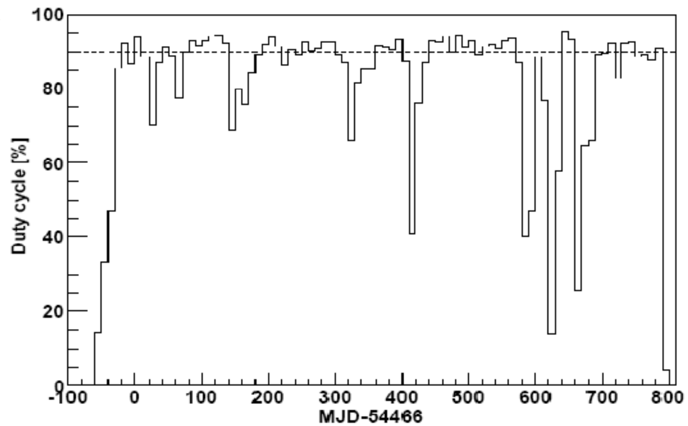
Dynamical range for protons by means of pads, strips and big pads : ~ 1 - 10^4 TeV

Excellent operating performance since November 2007.



Duty cycle > 85% →

←Rate stability 0.5% (intrinsic)



Data analysis

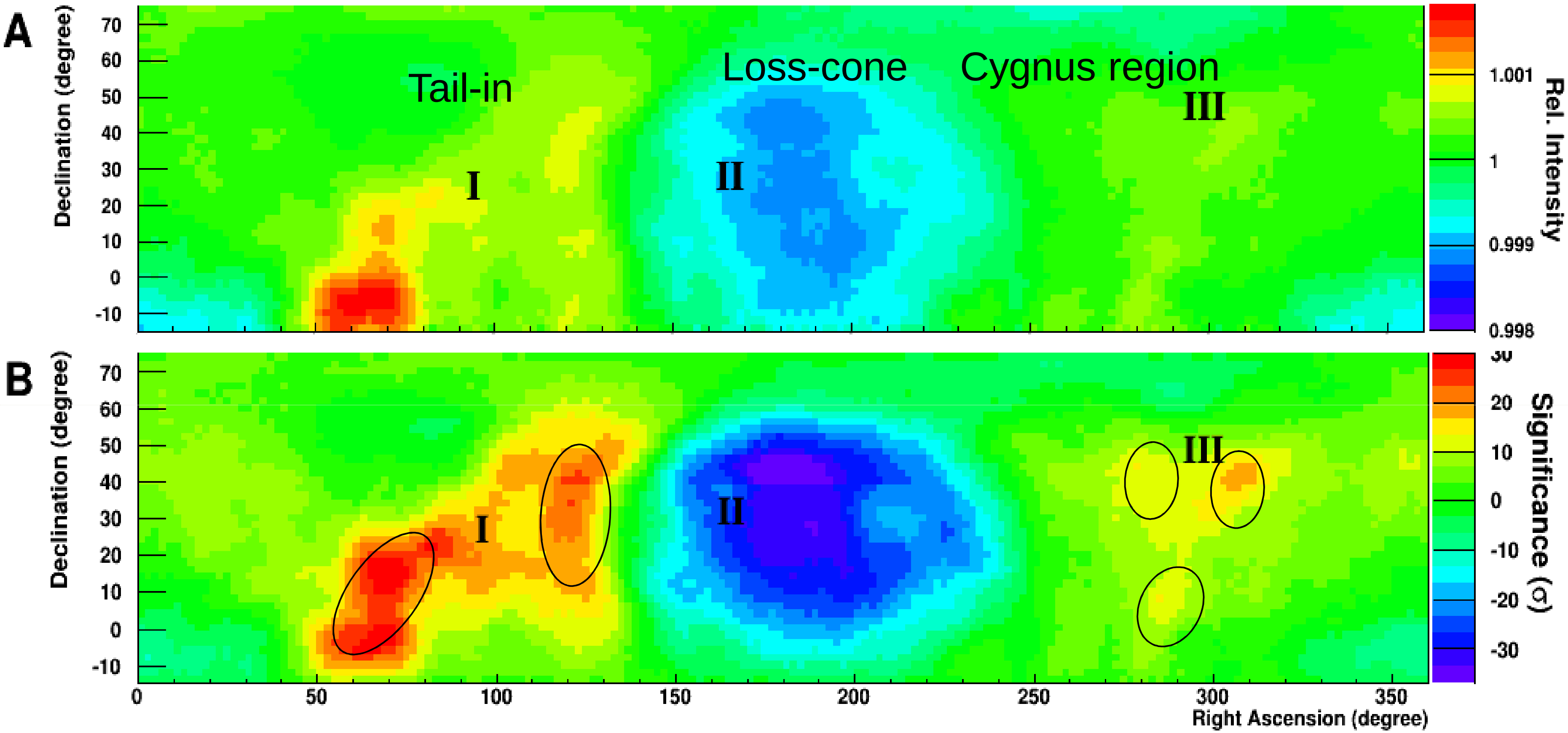
DATA SET:
2008-2010 data
N_{str}>40
Zenith angle < 50°
1.4 10^{11} events
NO SELECTION CUT APPLIED

Background estimation methods:

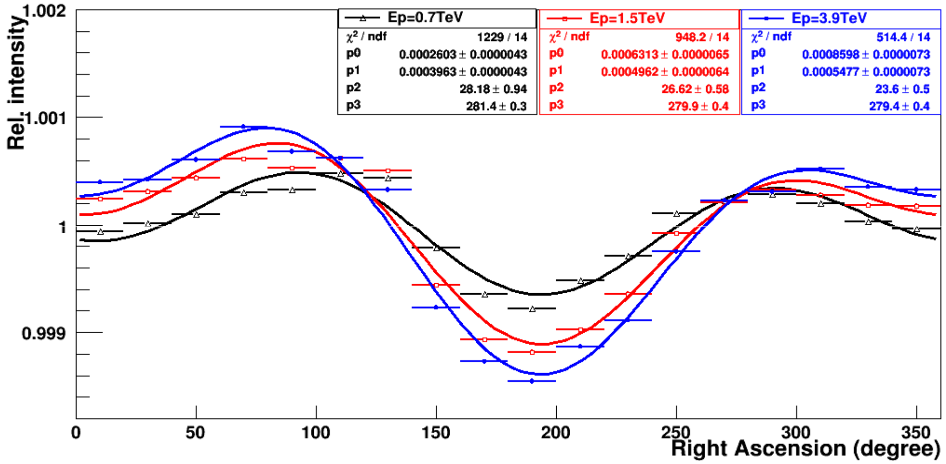
- Up to 45°-wide structures:
  - Time swapping/scrambling (3 hrs, N_{off}/N_{on}=10)
  - Direct integration (3 hrs)
  - (consistent each other within 7. 10^{-6})
- For larger scales: equizenith method

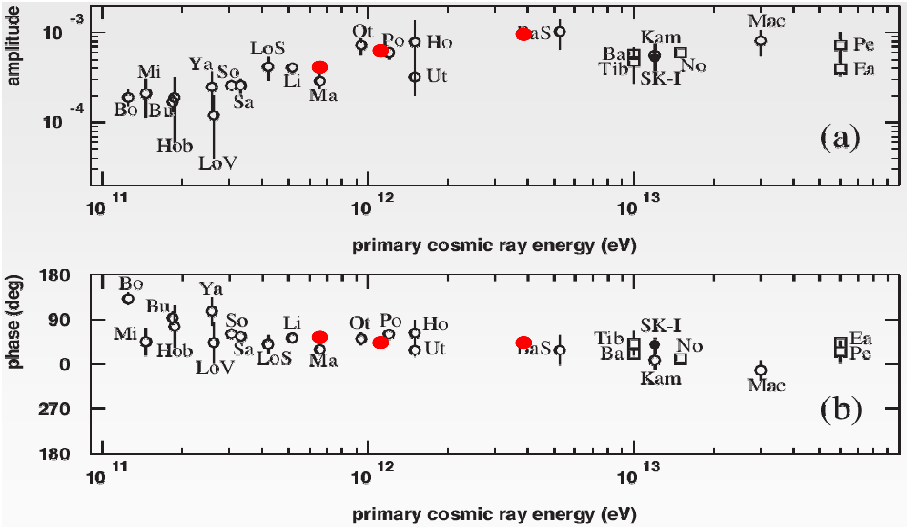
The large scale anisotropy as observed by ARGO-YBJ

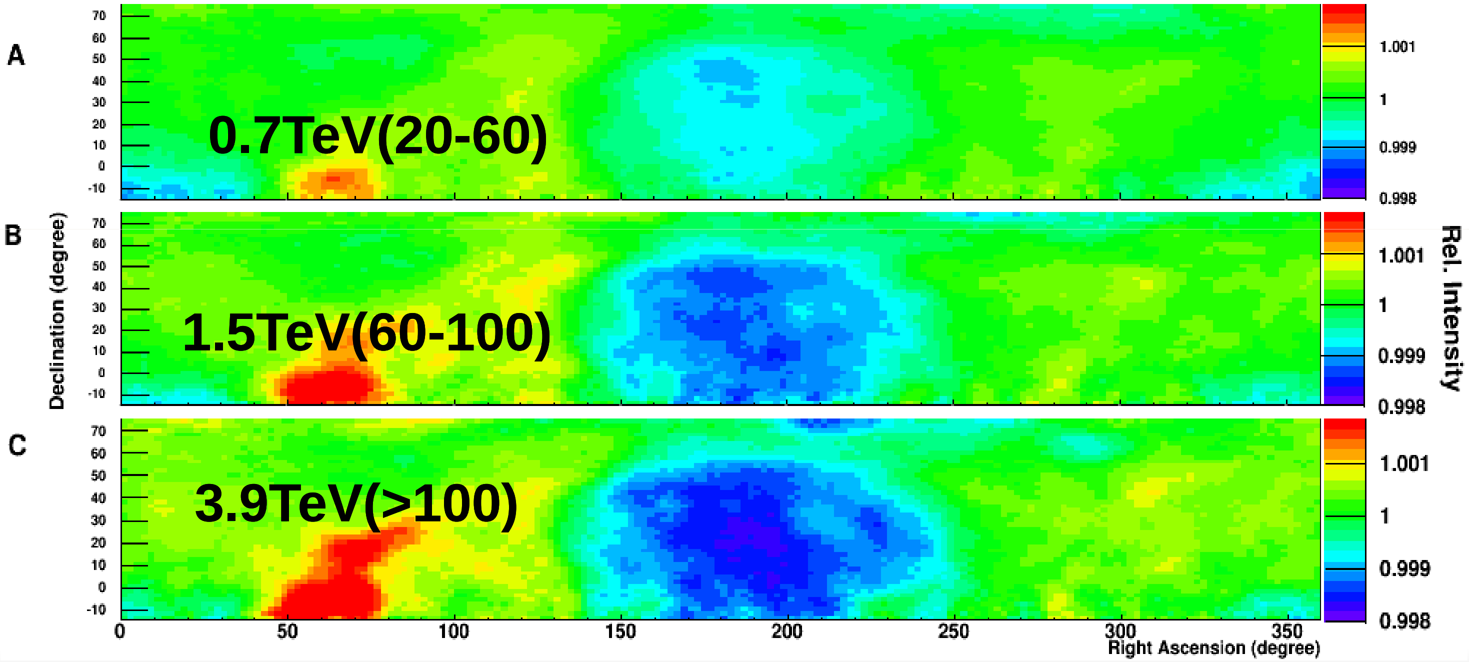
All-data sky-map. Analysis optimized to look at large scale anisotropies ("all-distance" equizenith background estimation technique).



Energy spectrum of the large scale anisotropy

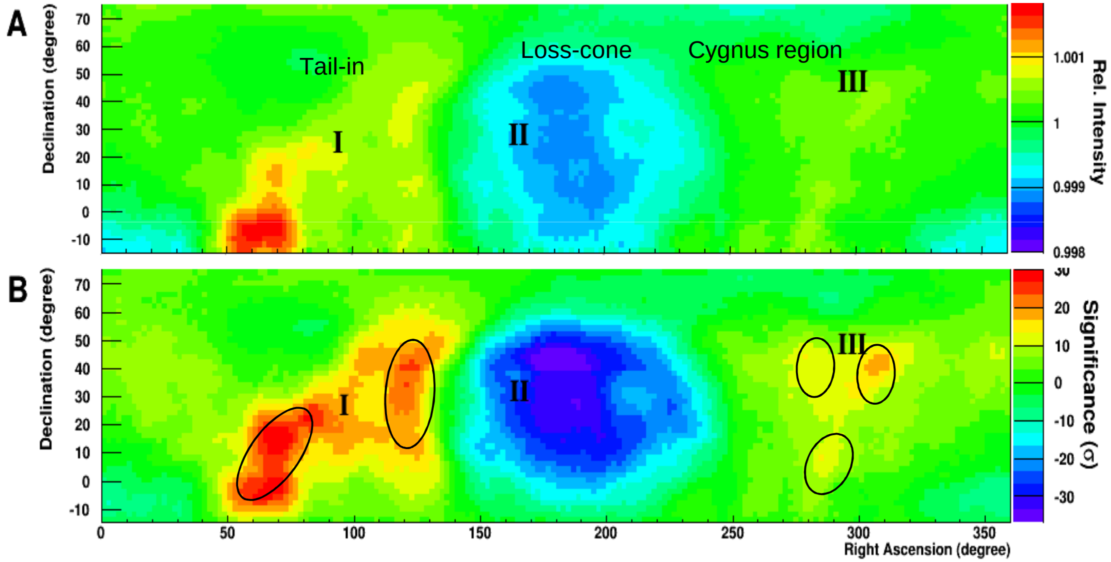


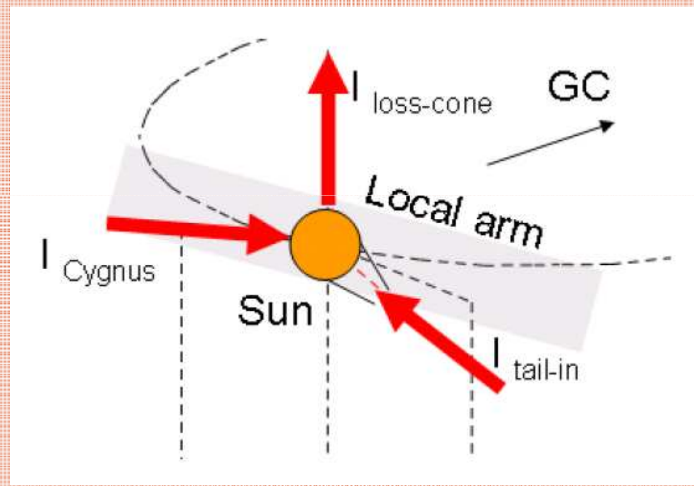




In agreement with standard diffusion models, where the anisotropy increases with the energy.

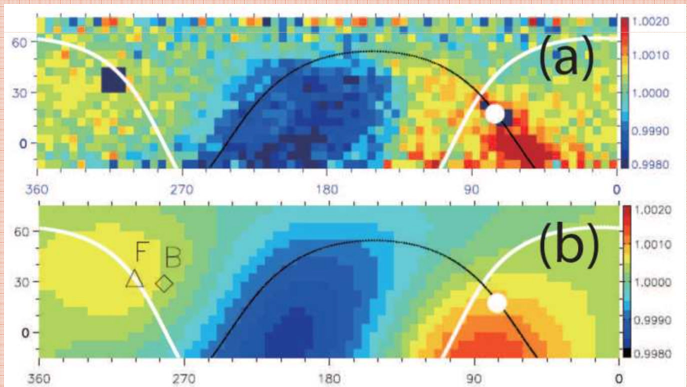
Large scale anisotropy: possible interpretations





Xiao-bo Qu et al 2011, arXiv:1101.5273

What we see is the combination of a Uni-Directional Flow and a Bi-Directional Flow (along the magnetic field arm). The characteristic lengths are so small that a local low-density feature must be advocated: the Local Interstellar Cloud (93 pc^3).



Mizoguchi et al, 31st ICRC 2009

The ***loss-cone*** is the signature of a "poloidal" component of the galactic magnetic field (in agreement with southern emisphere data from IceCube).
The "***tail-in***" and the "***Cygnus***" excess are both due to guiding by the magnetic fields along the local arm (the "tail-in" excess is slightly deformed by the Heliosphere).

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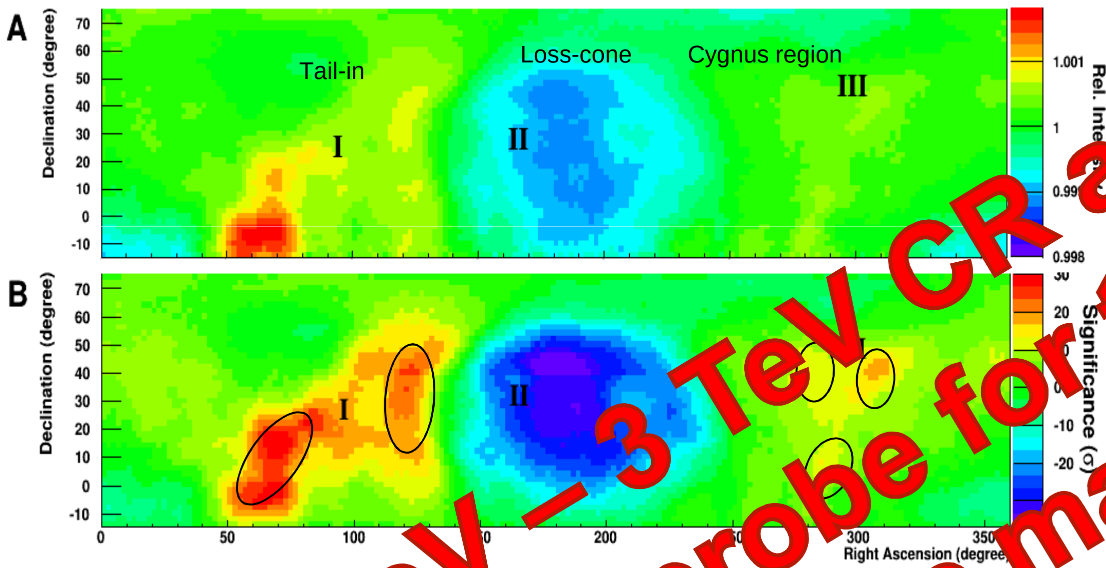

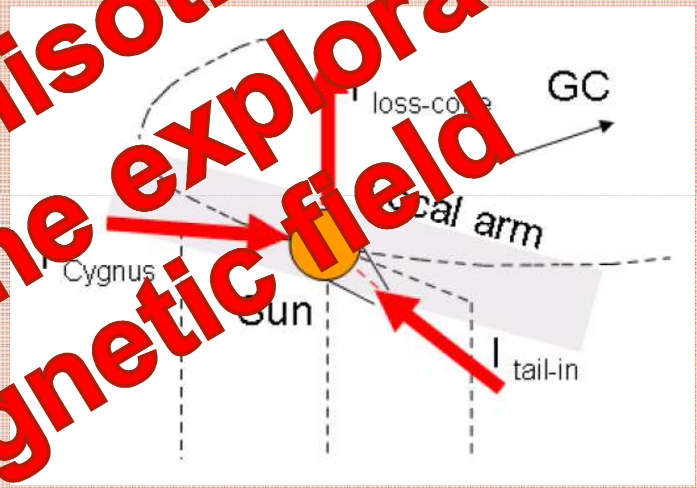

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300 GeV – 3 TeV CR anisotropy is a powerful probe for the exploration of the galactic magnetic field

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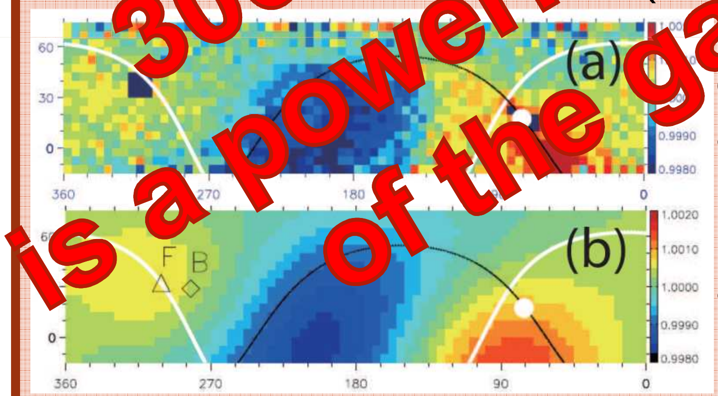

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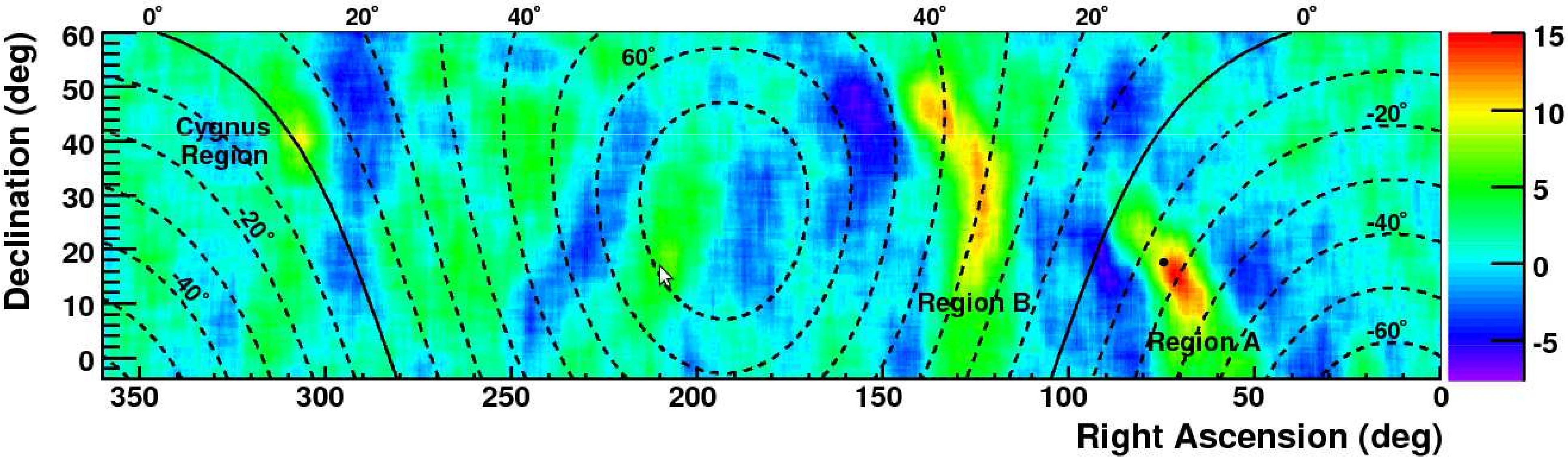
The intermediate scale anisotropy

MILAGRO: Discovery of Localized Regions of Excess 10-TeV Cosmic Rays

Phys.Rev.Lett.101:221101,2008



DATA SET:
Zenith angle < 45°

Smoothing radius 10°

2.2 10^{11} events
Median energy 1 TeV
NO GAMMA HADRON DISCRIMINATIN APPLIED

Background estimation technique: direct integration method (2 hours intervals)

The intermediate scale anisotropy

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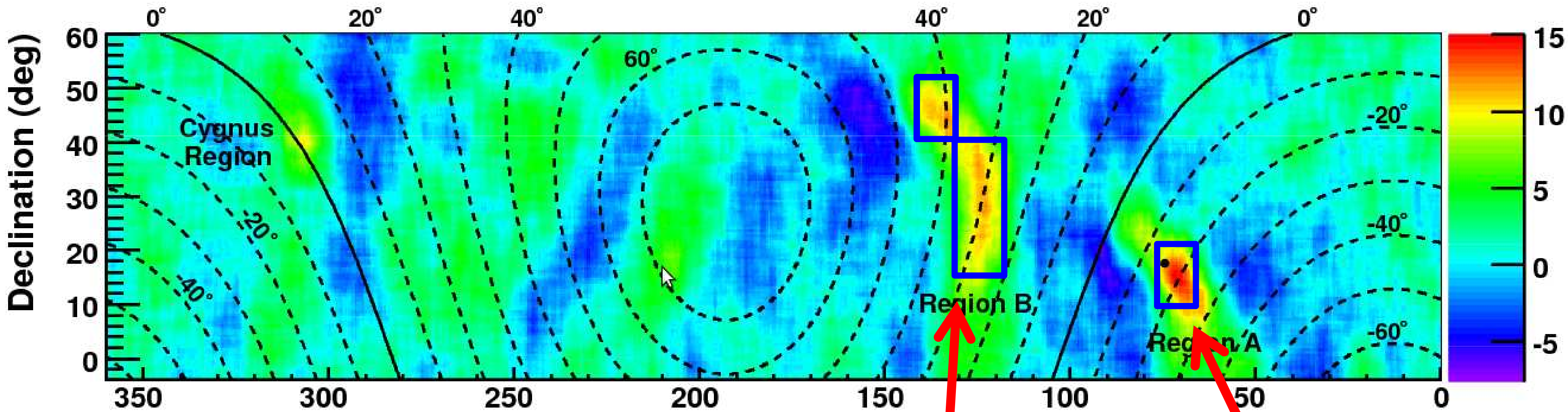

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Zenith angle < 45°

2.2 10^{11} events
Median energy 1 TeV
NO GAMMA HADRON DISCRIMINATIN APPLIED

Background estimation technique: direct integration method (2 hours intervals)

Region B
12.4 s.d.
Fractional excess:
4 10^{-4}

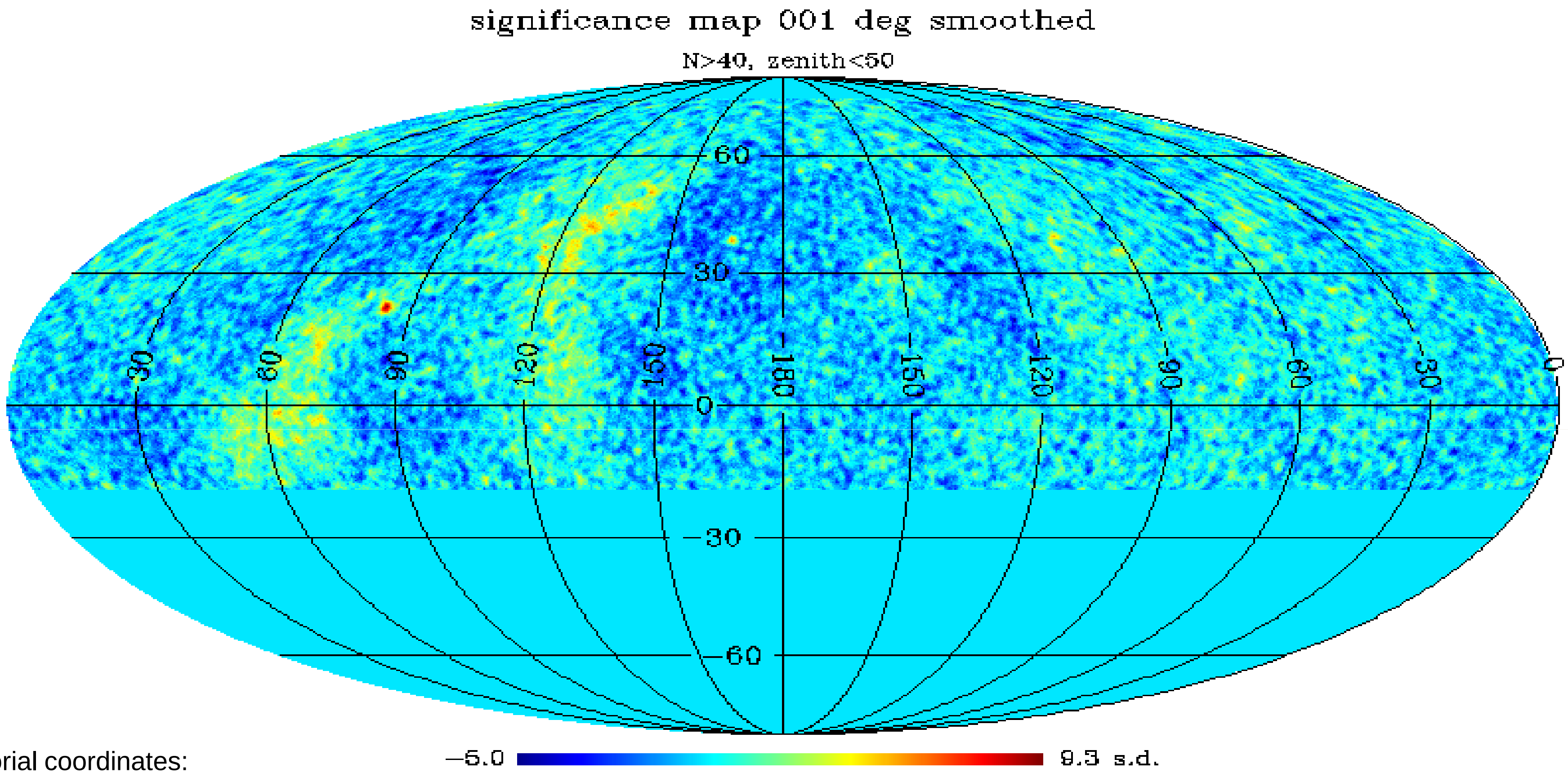
Ra: 117°–131° | 131°–141°
De: 15°–40° | 40°–50°

Region A
15 s.d.
Fractional excess:
6 10^{-4}

Ra: 66°–76°
De: 10°–20°

The intermediate scale CR anisotropy as observed by ARGO-YBJ

All-data sky-map. Analysis optimized to look at small and medium scale anisotropies (direct integration and time-swapping background estimation technique).
Several extended features are already visible at 1° scale .



Equatorial coordinates:
projection of the earth longitude and latitude

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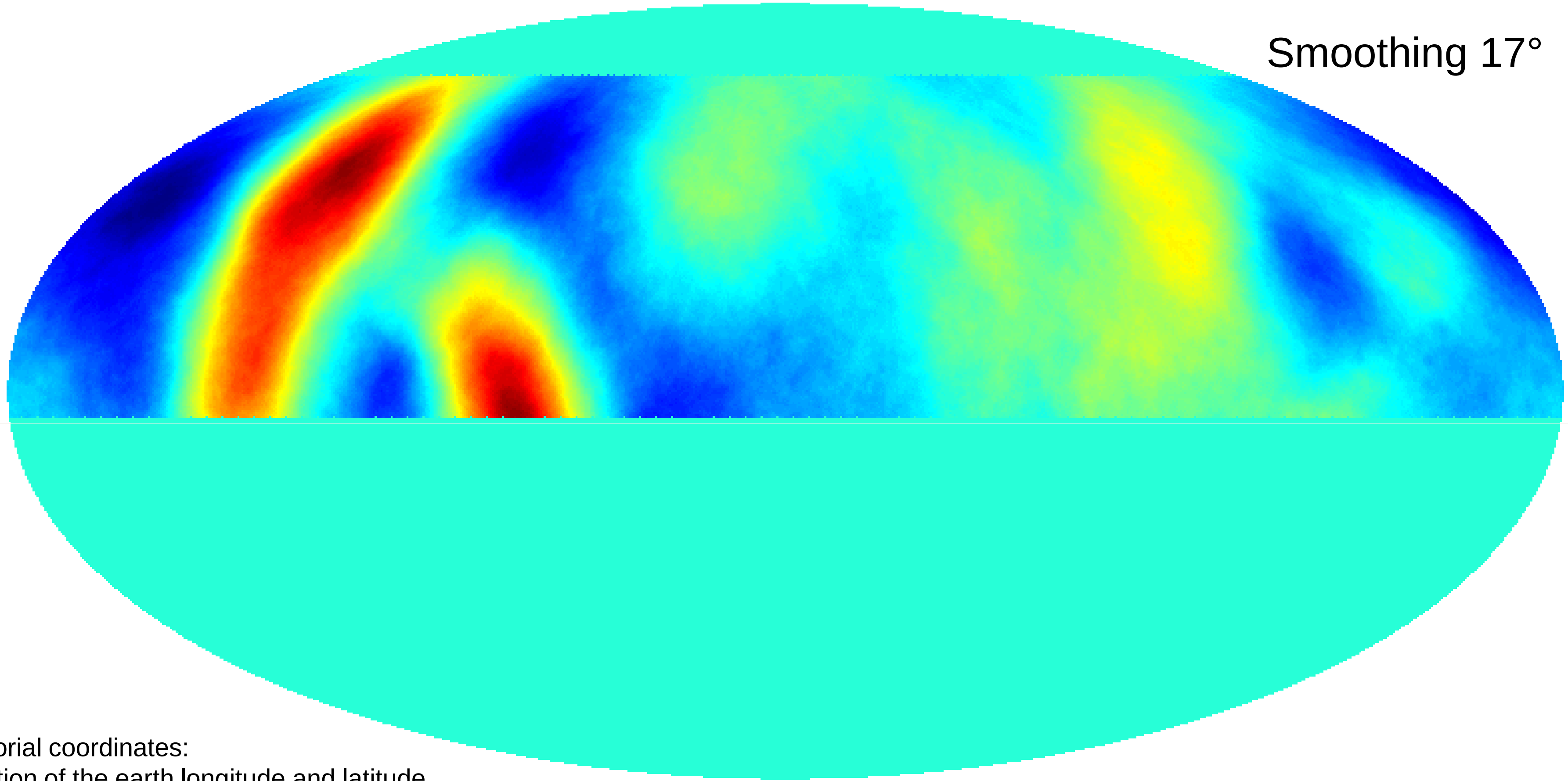
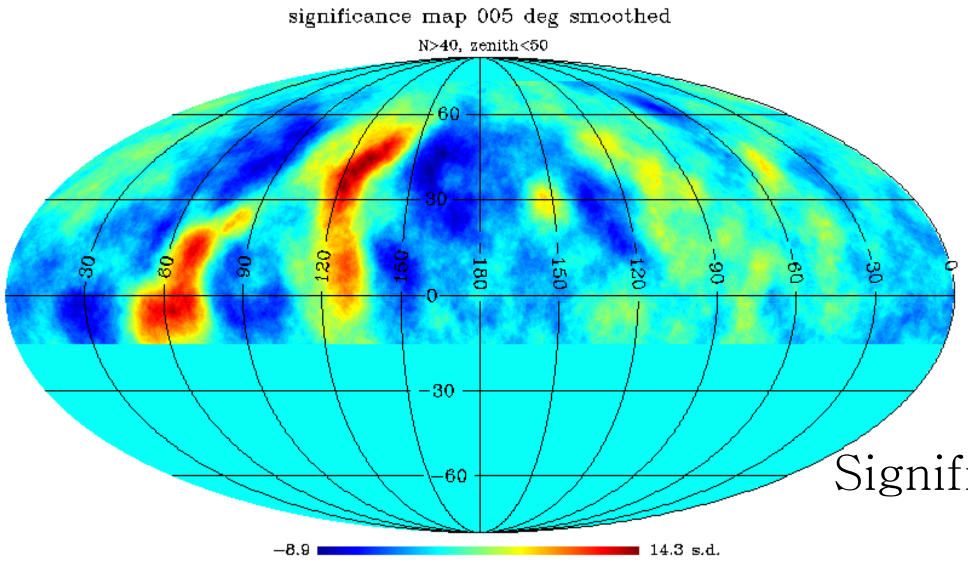


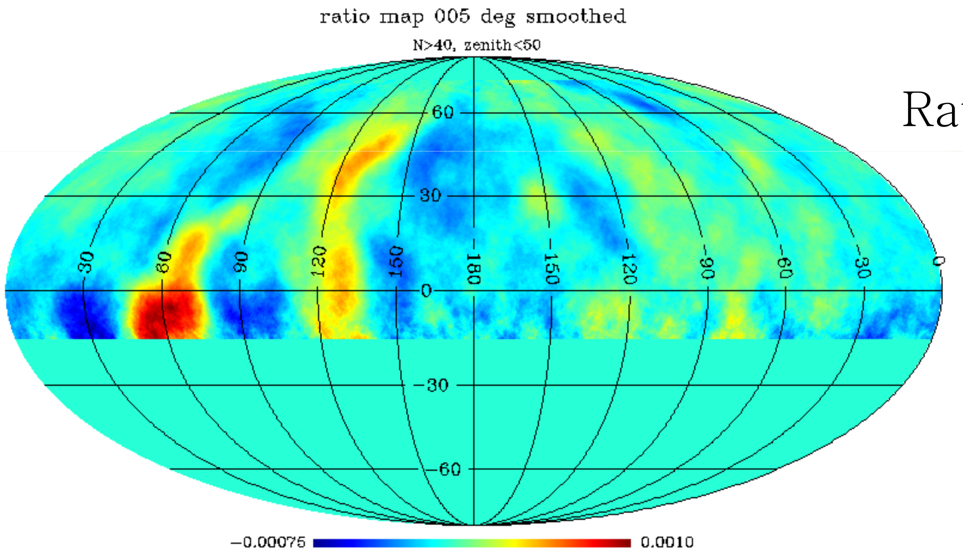
Equatorial coordinates:
projection of the earth longitude and latitude

The intermediate scale anisotropy at 5°



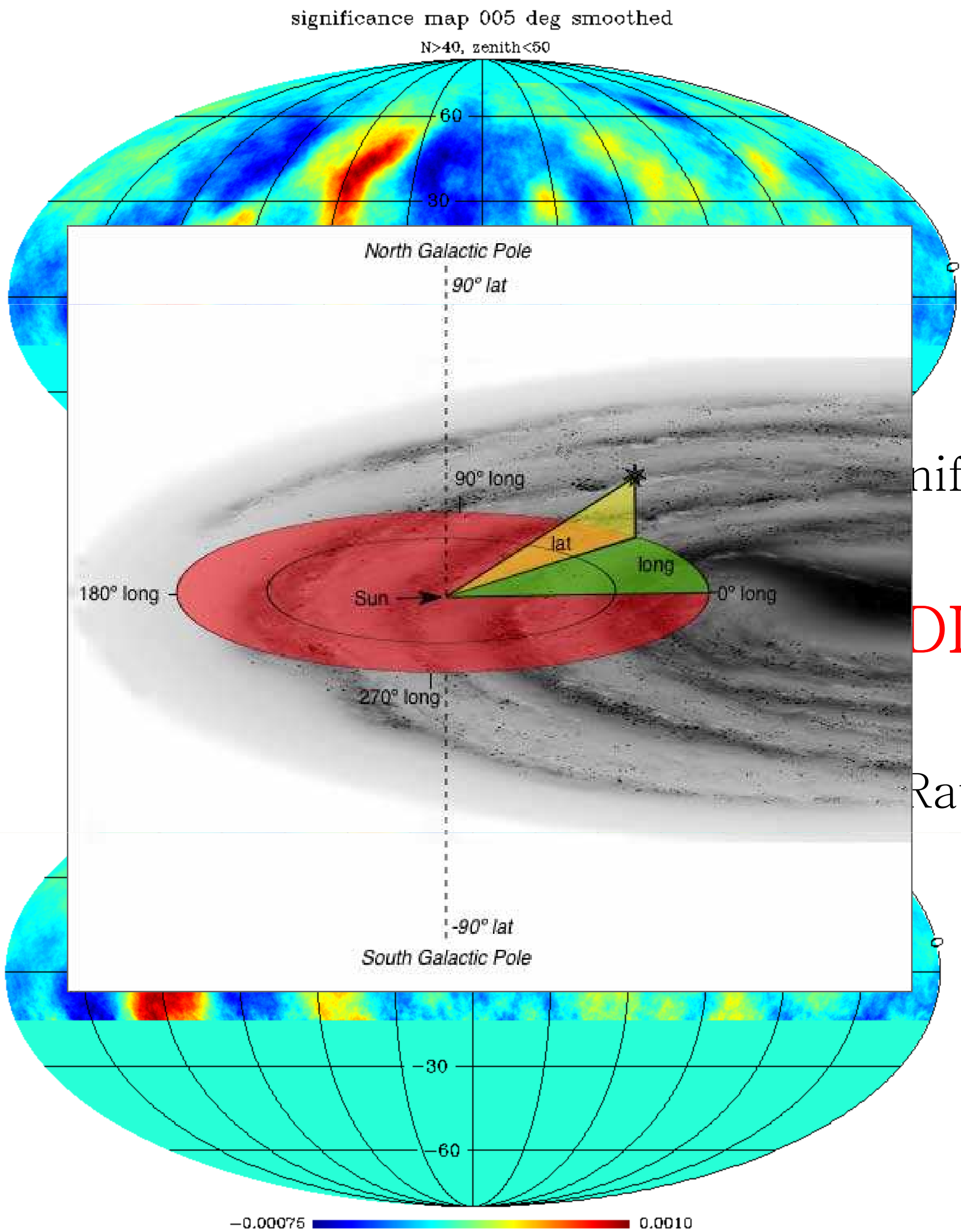
Significance

SMOOTH RADIUS 5°



Ratio

The intermediate scale anisotropy at 5°



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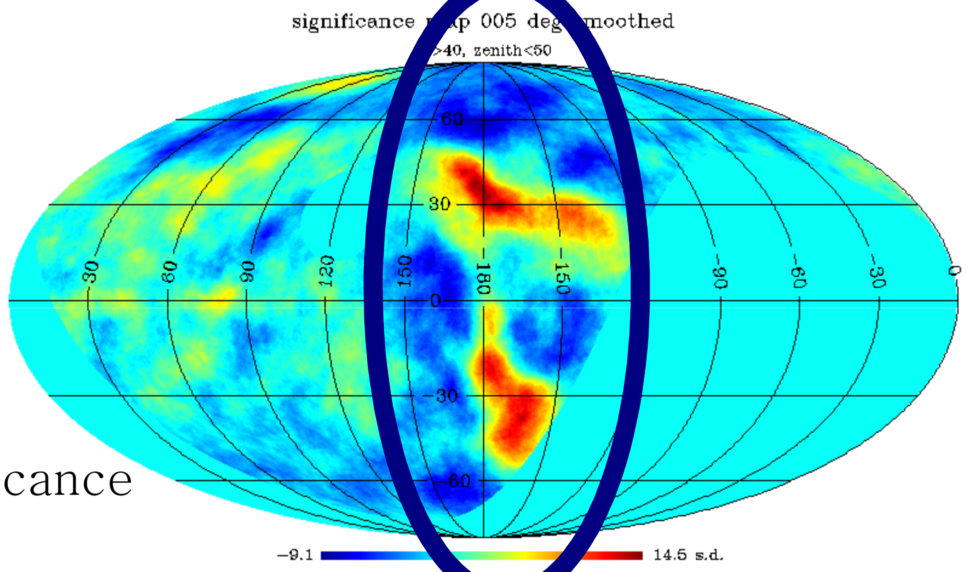
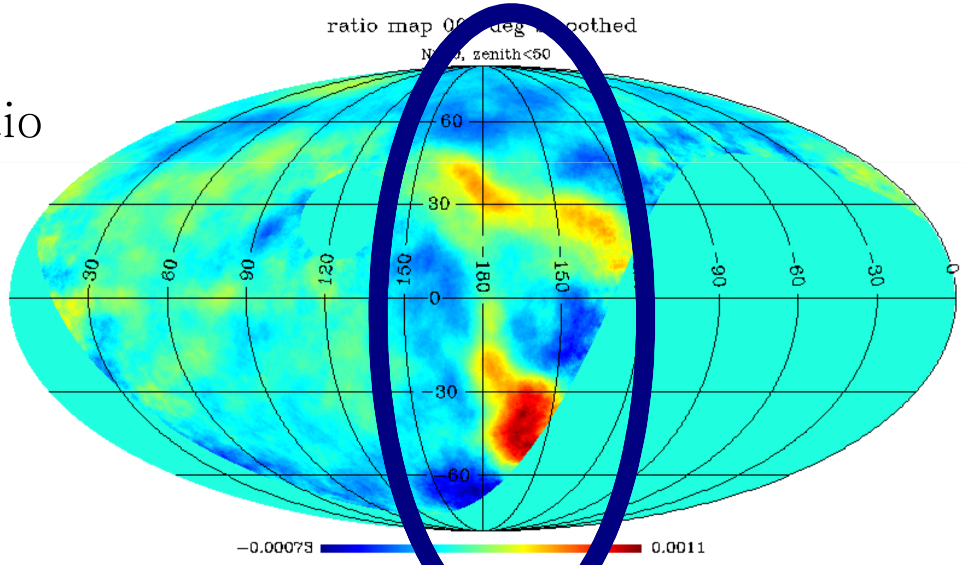
DIUS 5°

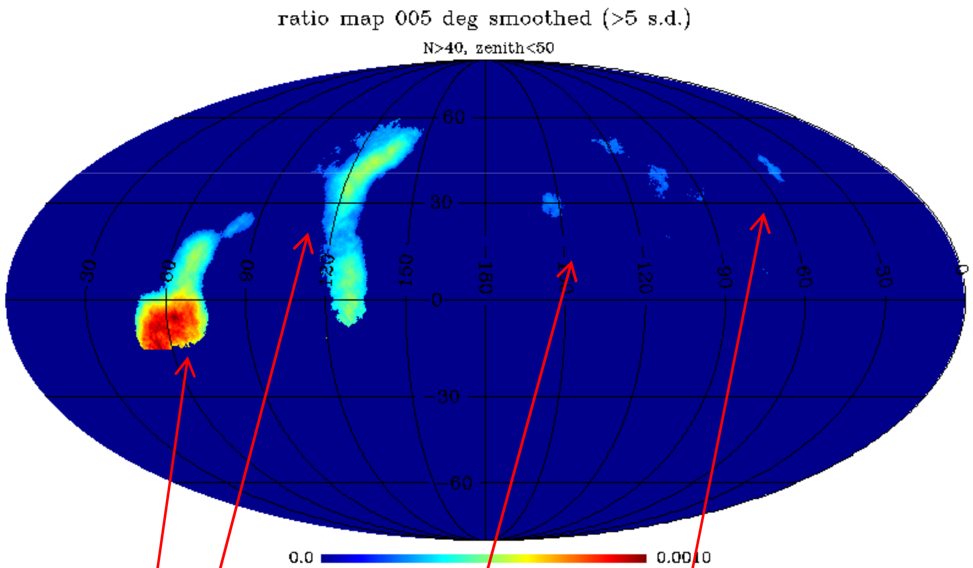
Ratio



GALACTIC ANTI-CENTER



The intermediate scale anisotropy: focus on >5 s.d. significant regions



SMOOTH RADIUS 5°

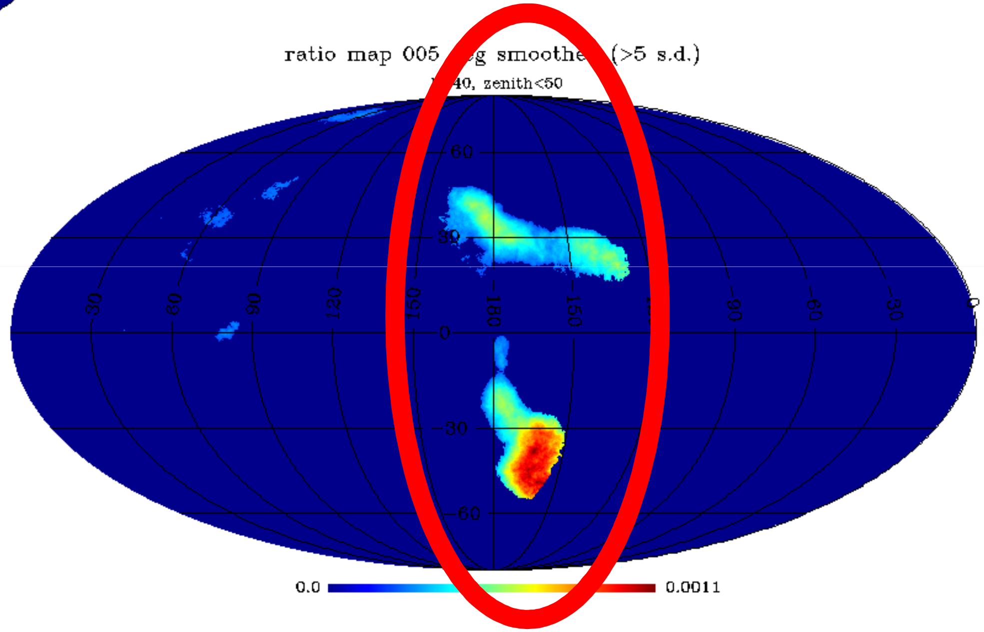
Ratio (> 5 s.d.)

Sub-structures?

New-structures?

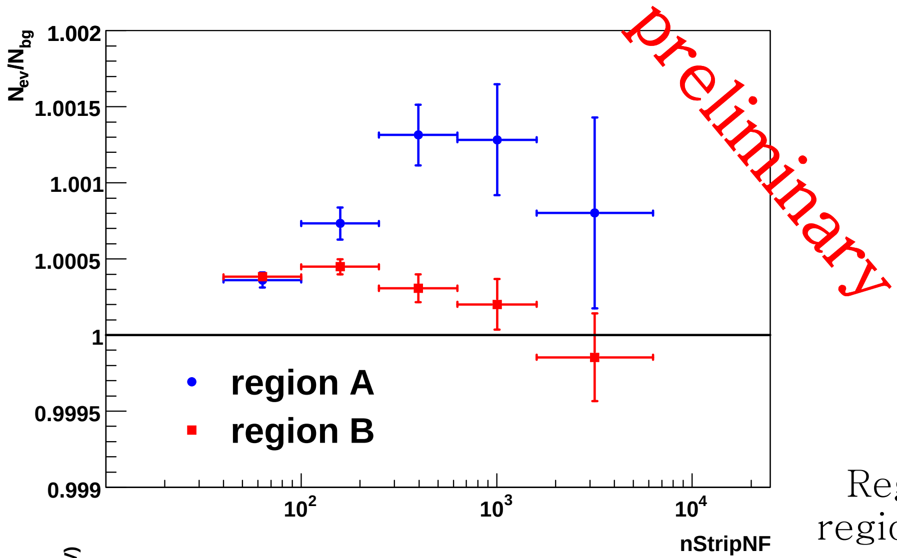
Cygnus region

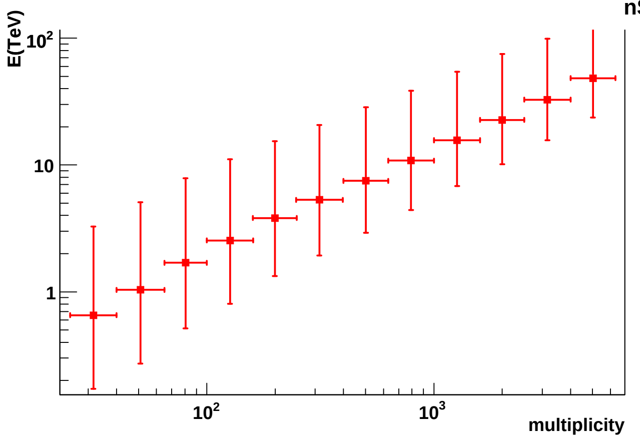
GALACTIC ANTI-CENTER



Intermediate scale anisotropy energy spectrum

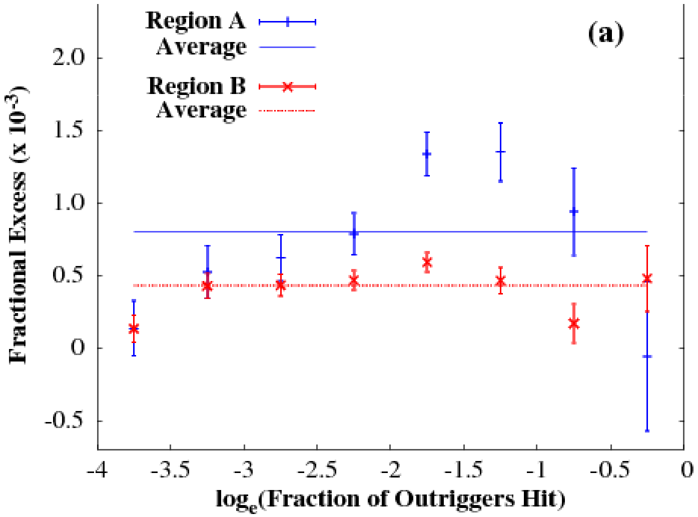
ARGO-YBJ

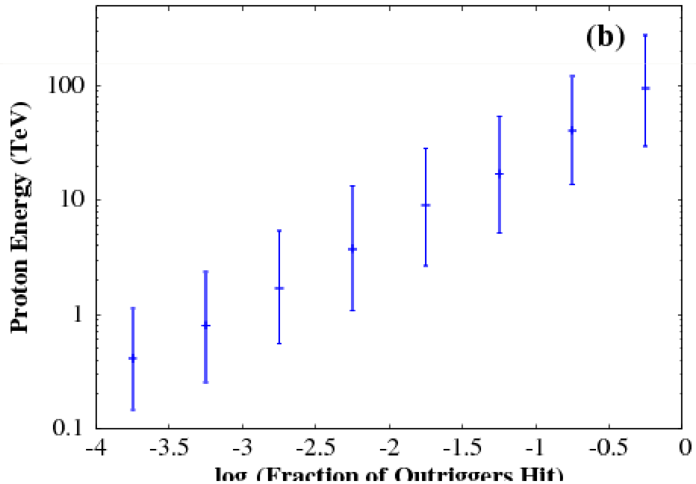




Region A and region B defined as in slide 3

MILAGRO 2008





What is behind
the intermediate scale anisotropies

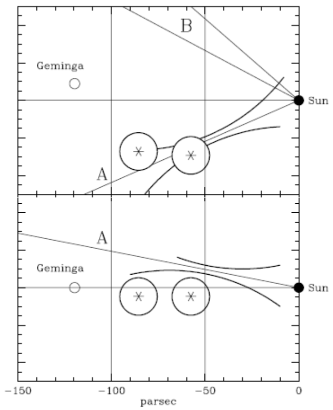


Fig. 1. Projection of the anticenter region on the meridian plane at Galactic longitude 195° (upper panel) and on the Galactic plane (lower panel). See text for details.

Salvati & Sacco, Astronomy&Astrophysics 2008

The excesses are due to **nearby sources** (Geminga, Vela, Monogem…) emitting CR. In any case it looks as **particular features of the local magnetic** *field are needed to bring us the radiation so beamed*. The spectrum and the cut-off are explained with the age of the source.

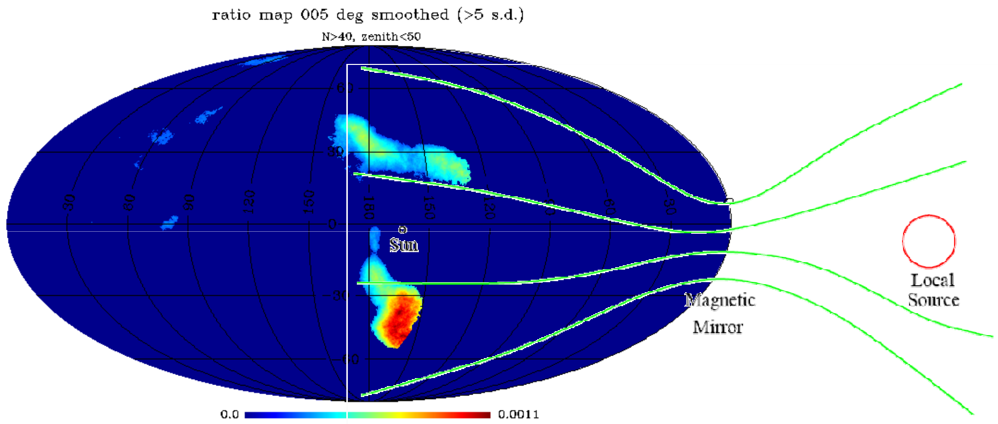
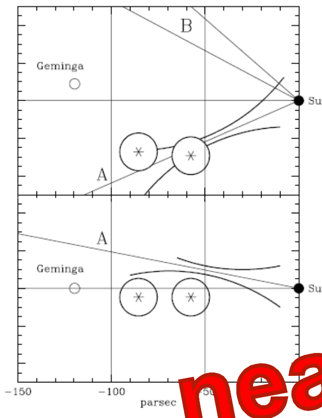


Fig. 1. A cartoon representation of the suggested model. The magnetic field near the sun is linked through a strong field region where most particles are mirrored to a region containing a slightly higher amplitude and harder spectrum of cosmic rays, presumably as a result of a local source event such as a supernova explosion. Only particles with pitch angles closely aligned to the field can penetrate through the mirror and emerge as a field-aligned beam on the other side (another possibility would be to locate the source inside the strong field region itself rather than behind the trap).

Drury & Aharonian, Astroparticle Physics 2008

What is behind the intermediate scale anisotropies



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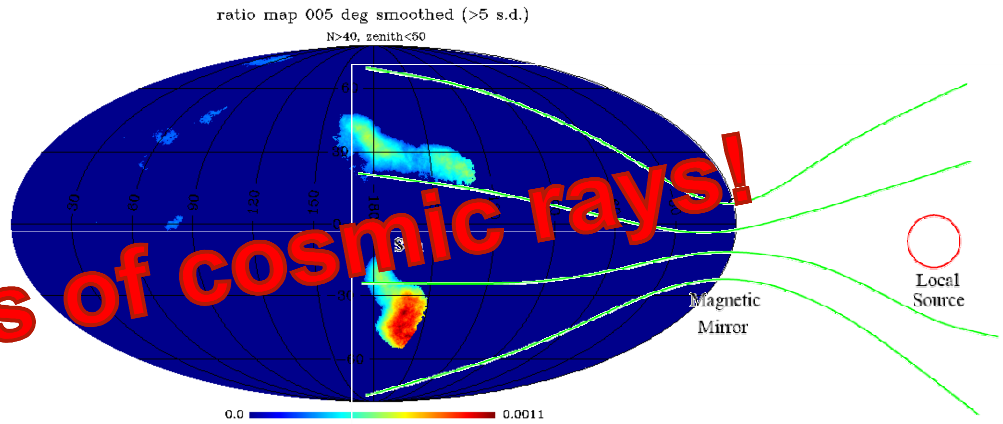
nearby sources of cosmic rays!



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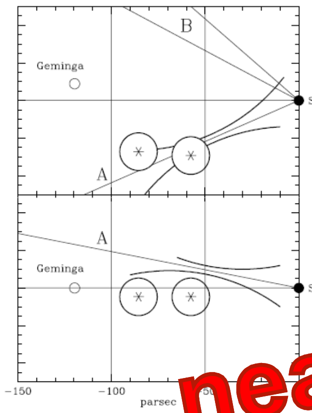

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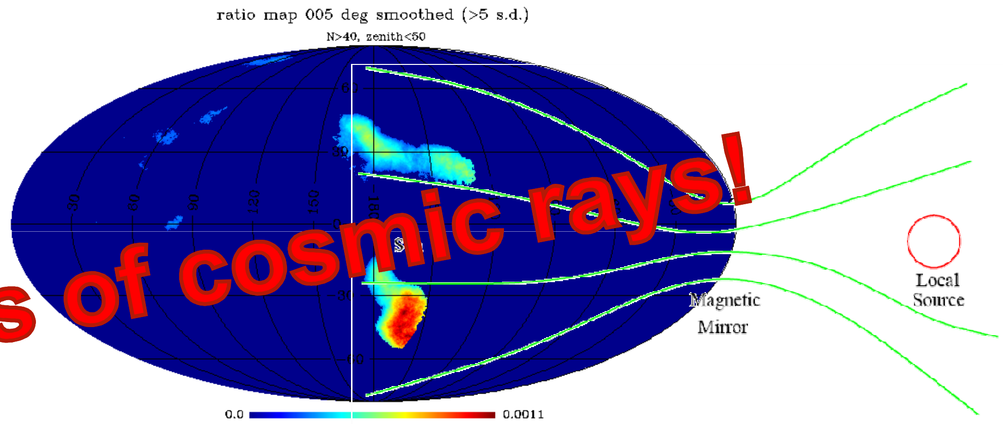

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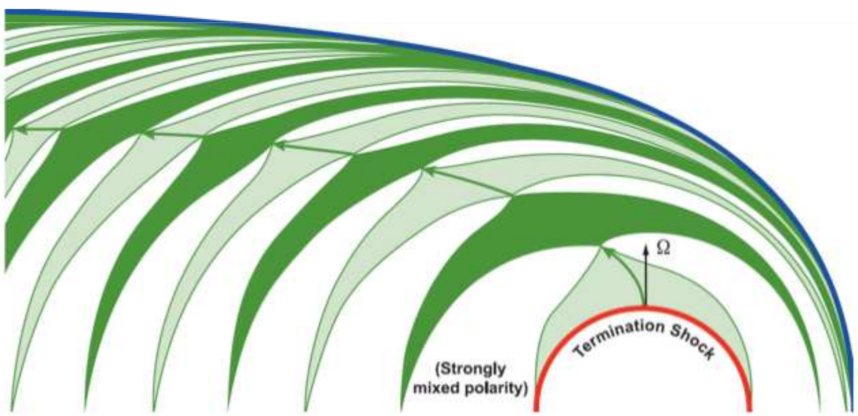
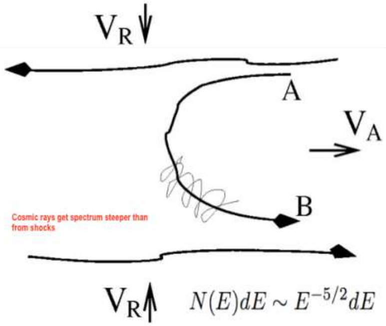




$$E_{max} \approx 10^{13}\, eV \cdot \left(\frac{B}{1\,\mu G}\right) \cdot \left(\frac{L_{zone}}{134\,AU}\right)$$

What we see is the effect of the **magnetic reconnection in the heliotail**. The spectrum and the cutoff are due to the efficiency of the process.

Lazarian & Desiati, 2010, arxiv 1008.1981

What is behind the intermediate scale anisotropies

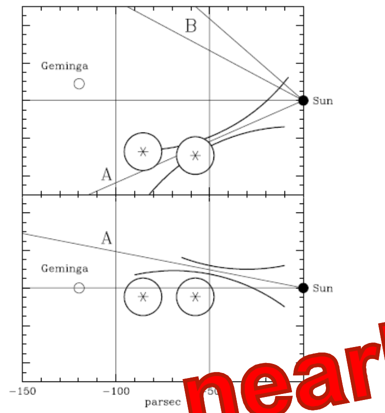


Fig. 1. Projection of the anticenter region on the meridian plane at Galactic longitude 195° (upper panel) and on the Galactic plane (lower panel). See text for details.

Salvati & Sacco, Astronomy&Astrophysics 2008

The excesses are due to **nearby sources** (Geminga, Vela, Monogem…) emitting CR. In any case it looks as **particular features of the local magnetic field** are *needed to bring us the radiation so beamed*. The spectrum and the cut-off are explained with the age of the source.

nearby sources of cosmic rays!

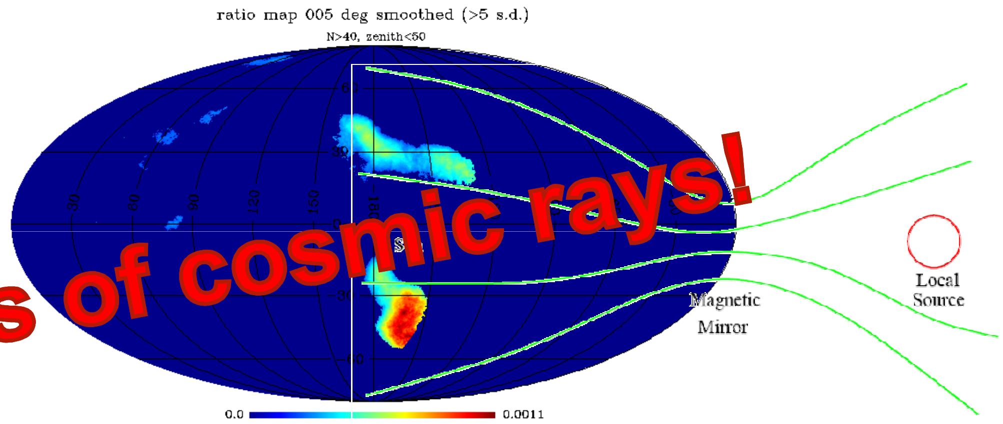
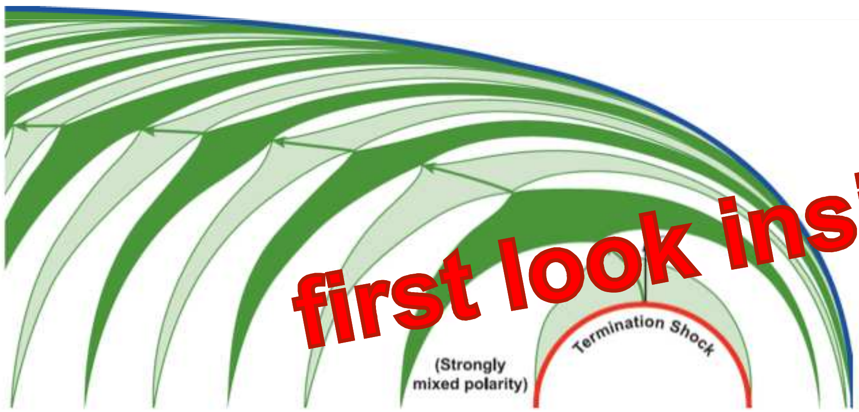
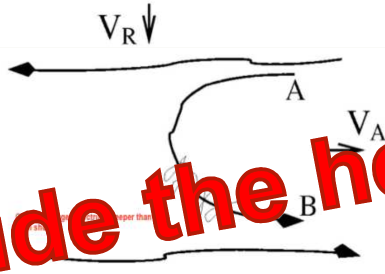


Fig. 1. A cartoon representation of the suggested model. The magnetic field near the sun is linked through a strong field region where most particles are mirrored to a region containing a slightly higher amplitude and harder spectrum of cosmic rays, presumably as a result of a local source event such as a supernova explosion. Only particles with pitch angles closely aligned to the field can penetrate through the mirror and emerge as a field-aligned beam on the other side (another possibility would be to locate the source inside the strong field region itself rather than behind the trap).

Drury & Aharonian, Astroparticle Physics 2008





$N(E)dE \sim E^{-5/2}dE$

$$E_{max} \approx 10^{13}\, eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right)$$

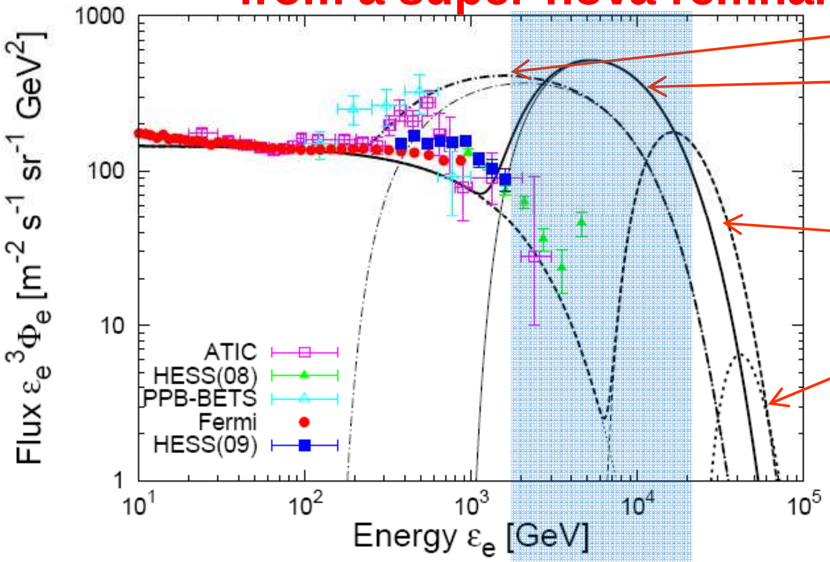
first look inside the heliotail!

What we see is the effect of the **magnetic reconnection in the heliotail**. The spectrum and the cutoff are due to the efficiency of the process.

Lazarian & Desiati, 2010, arxiv 1008.1981

Are we inside a CR “local bubble”?

Cosmic ray energy-dependent escape from a super-nova remnant



$2X10^4$ yrs

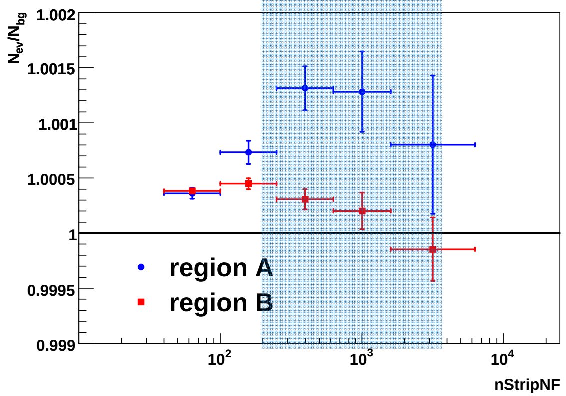
$1X10^4$ yrs

Assumed source distance **290 pc**

e+/e- energy: $0.5X10^{48}$ erg

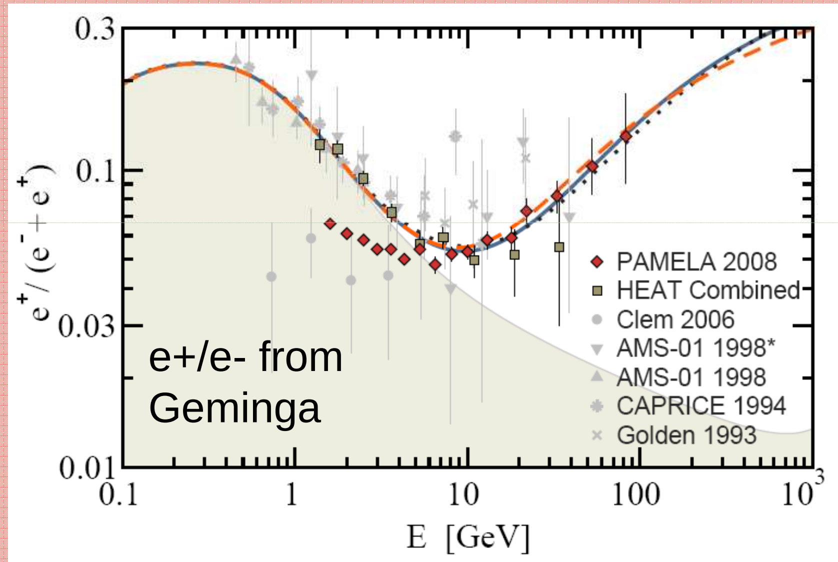
$5X10^3$ yrs

$3X10^3$ yrs



All these violation of the standard CR model lay in the **100 GeV - 10 TeV** interval. Notice that **ARGO-YBJ measurements give localized excess**.

Are these feature related to the positron excess observed by PAMELA?



Yuksel et al, 2009, arxiv 0810.2784

Conclusions

- ARGO-YBJ observed either the large scale and the intermediate scale cosmic ray anisotropies.
- The observation of the large scale CR anisotropy is in agreement with the other experiments and provides useful data to constrain diffusion models.
- The 300 GeV - 3 TeV large-scale data form ARGO-YBj may provide essential informations about the local and galactic magnetic field.
- The observation of the intermediate scale excesses showed several interesting features still uninvestigated. Anyway, each model would imply deep revisions of the standard model of cosmic rays:
  - Unexpected magnetic field configurations:
    - Magnetic lenses?
    - Helio-tail reconnection?
  - Nearby sources:
    - Geminga, Vela, Monogem → is there any connection with FERMI/PAMELA findings?
    - What are the implications on the fine structure of the CR spectrum? Is the CR “knee” a feature of the nearby source emission?
- The implications of such observations on the cosmic ray physics might be decisive, mostly as far as the medium scale features are concerned.