

## **Observation of Galactic Cosmic Ray Anisotropy**

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#### Cosmic Ray Isotropy

- CRs below 10<sup>17</sup> eV are predominantly galactic.
- The bulk of CR is produced by shock acceleration in SN explosions.
- Diffusion of accelerated CRs through non-uniform, non-homogeneous ISM.
- At 1 TeV, B ~ 1  $\mu$ G, Gyro-Radius ~ 200AU, 0.001pc





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## Cosmic Ray an-isotropy in arrival direction ?

The question of a possible variation of the CR flux with time arose soon after its discovery.

The earliest evidence of a possible periodicity in the CR intensity was reported in 1932 by Hess and Steinmaurer

This observation, interpreted by Compton and Getting as an effect of the Earth motion relative to the sources of CRs, stimulated many measurements to verify this model.

Although different ground-based experiments reported evidence of a diurnal variation of galactic CRs long before the 50s, the existence of the anisotropy remained uncertain due to

- solar modulation
- geomagnetic field
- low event rate
- non uniform time coverage
- atmospheric effects: the amplitude of the temporal variation of the EAS trigger rate (a few percent), mostly due to the atmospheric pressure and temperature effects, is much larger than the expected amplitude of the CR anisotropy





## Measuring the anisotropy

Only during 50s, when large detectors were operated monitoring the atmospheric variations, a clear evidence of the existence of the galactic anisotropy was obtained.

In 1998 Nagashima, Fujimoto, and Jacklyn reported the first comprehensive observation of a large angular scale anisotropy in the sub-TeV CRs arrival direction by combining data from different experiments in the northern and southern hemispheres.

- Tail-in feature directed towards the heliospheric tail peak located at RA  $\sim$  6h (~90°).
- Amplitude and phase change with latitude
- North-South asymmetry
- Tail-in modulated in time: max in Dec. and min in June









## Cosmic Ray Anisotropy in arrival direction

In principle any anisotropy reflects a motion:

- (1) the motion of the Earth/Solar System with respect to the isotropic CRs rest frame (the Compton-Getting effect);
- (2) the motion of CRs from galactic sources to the extragalactic space and/or from extragalactic sources to the Earth.

The biggest problem in the quest to find the origin of CRs is the presence of magnetic field in the Interstellar Medium (ISM).

The detection of CRs provides directional information only up to distances as large as their gyro-radius

 $E < 10^{15} \text{ eV}$ , local galactic magnetic field (GMF) ~  $3\mu G \rightarrow \text{gyro-radii very short}$ :  $\leq 1 \text{ pc}$ 

isotropy is expected, as no structures of the GMF are known to focus CRs within such horizon. At most, a weak dipolar distribution may exist, reflecting the contribution of the closest CR sources.

The possibility that the anisotropy is related to the distribution of CR sources makes its study especially interesting.

## The experimental problem

✓ If an anisotropy of the order 10<sup>-4</sup> is looked for, operating conditions must be kept (or made up) stable down to this level, all across the field of view and during all the acquisition time. Spurious effects have instrumental and atmospheric origin.



- EAS arrays mostly located in "unfriendly" ambient, typically at mountain level: large variations of T, meteorological effects.
- ✓ EAS rate depends on atmospheric press atmosphere/pressure).

- s more or less absorbed depending on traversed
- ✓ Small amplitude, statistical problem. Necessity of long-term observations, and large collecting areas.
- ✓ Need for: detector uniformity (over area), detector stability (over time), continuity of operation.
- ✓ Exposure calculation crucial, as any mis-intepretation of the sky exposure may mimic a fake anisotropy.
- $\checkmark$  Consistency checks necessary.

### Principles of anisotropy measurement

- ★ To study anisotropy, for each detected EAS, the direction is determined locating its right ascension and declination on the celestial sphere
- ★ EAS arrays have uniform exposure in  $\alpha$  (thanks to Earth's rotation) but not in  $\delta$  (field of view limited by geographical position, zenith angle dependence of shower detection and reconstruction)

People exploited the rotation of the Earth to build 1D distributions of the CR relative intensity.

Former experiments: poor angular resolution, poor statistics

- ✓ <u>Classical technique</u> (Linsley 1975): analysis in r.a., through harmonic analysis of the counting rate within a defined declination band (Raileigh formalism)
- Rayleigh formalism gives amplitude A, phase φ (hour angle of the maximum intensity) and probability P for detecting a spurious amplitude due to fluctuations of a uniform distribution



$$X(r) = \frac{2}{2} + \sum_{1 \le k \le \infty} \left( \frac{a_k \cos \frac{2\pi kt}{T} + b_k \sin \frac{2\pi kt}{T}}{T} \right)$$

$$\frac{2\pi k t_k b_k \sin \frac{2\pi kt}{T}}{T} = \frac{a_0}{2} + \sum_{1 \le k \le \infty} \left( \frac{a_k \cos \frac{2\pi kt}{T} + b_k \sin \frac{2\pi kt}{T}}{T} \right)$$

$$\frac{2\pi k t_k b_k \sin \frac{2\pi kt}{T}}{T} = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left( \frac{a_n \cos \frac{2\pi kt}{T} + b_k \sin \frac{2\pi kt}{T}}{T} + \frac{b_k \sin \frac{2\pi kt}{T}}{T}$$

### The Sidereal Time distribution: harmonic analysis

#### The CR arrival distribution in sidereal time was never found to be purely dipolar,



The CR plasma is supposed to co-move with the solar system and the origin of the observed anisotropy is probably related to "harder" effects, to be searched for in unknown features of the local ISM, either for the magnetic field and the closest CR sources.

## Amplitude and Phase of the first harmonic

- Consistency between different sets of data.
- Slow increase of A with increasing energy to a maximum at few TeV.
- Slow fall of A to a minimum at about 100 TeV.
- Evidence of increasing A above 100 TeV.
- Phase nearly constant (slowly decreasing) around 0 hrs.
- Clear change (decrease) of phase above 100 TeV.

1-dim approach:
 Morphological study precluded
 Analysis on different angular scales precluded





## 2-dim Maps of CR Intensity

The improvement in the measurement of the CR arrival direction, recently allowed the construction of 2-dim maps which confirmed the complicated structure of the CR sky and its analysis on different angular scales.



#### Milagro



- 34 × 10<sup>9</sup> events
- Angular resolution ~ 3°
- Median energy ~20 TeV



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C59 Abbasi et al., ApJ, **746**, 33, 2012

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# E ray anisotropy Jarge scale anisotropy



#### medium/small scale anisotropy

Tibet ASγ model fit to data (ICRC 2007)

Data

#### Model

uni-directional flow (dipole) + bi-directional flow (quadrupole)

#### Residual skymap



Amenomori M. et al., Astrophys. Space Sci. Trans., 6 (2010) 49.

### medium / small scale mestitropsmall scale anisotropy



the capability for suppressing the anisotropic structures at larger scales without, simultaneously, introducing effects of the analysis on smaller scales.

R. luppa and G. Di Sciascio, ApJ 766 (2013) 96

#### A real measurement of anisotropy: ARGO-YBJ



Longitude 90° 31' 50" East Latitude 30° 06' 38" North

90 Km North from Lhasa (Tibet)

4300 m above the sea level ~ 600 g/cm<sup>2</sup>



### The basic concepts

... for an unconventional air shower detector

♦ HIGH ALTITUDE SITE

(YBJ - Tibet 4300 m asl - 600 g/cm2)

#### FULL COVERAGE

(RPC technology, 92% covering factor)

#### HIGH SEGMENTATION OF THE READOUT

(small space-time pixels)

Space pixels: 146,880 strips (7×62 cm<sup>2</sup>) Time pixels: 18,360 pads (56×62 cm<sup>2</sup>)

#### ... in order to

- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV





#### E = 1000 TeV

#### The basic concepts

...extending the dynamical range up to PeV

♦ ANALOG READOUT → PeV (3672 1.40 × 1.25 m<sup>2</sup> "big pads")







#### The ARGO-YBJ Collaboration

Collaboration Institutions: Chinese Academy of Sciences (CAS) Istituto Nazionale di Fisica Nucleare (INFN)



INAF/IASF, Palermo and INFN, Catania INFN and Dpt. di Fisica Università, Lecce INFN and Dpt. di Fisica Universita', Napoli INFN and Dpt. di Fisica Universita', Pavia INFN and Dpt di Fisica Università "Roma Tre", Roma INFN and Dpt. di Fisica Università "Tor Vergata", Roma INAF/IFSI and INFN, Torino



IHEP, Beijing Shandong University, Jinan South West Jiaotong University, Chengdu Tibet University, Lhasa Yunnan University, Kunming Hebei Normal University, Shijiazhuang

## Status and performance

- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ 4·10<sup>11</sup> from 100 GeV to PeV
- 100 TB/year data



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800

1000

1200

100

80

60

40

20

200

400

600

**Duty-cycle** 

Days

1400

#### Large scale anisotropy by ARGO-YBJ

2 years data: 2008- 2009, E  $\approx$  1 TeV, 3.6  $\times$  10<sup>10</sup> events

Tail-in excess region

Loss-cone deficit region



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First measurement with an EAS array in an energy region so far investigated only by underground muon detectors

The tail-in broad structure appears to dissolve to smaller angular scale spots



#### Amplitude and phase of the first harmonic



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### x-check: Compton-Getting effect



**N°** 

tion

★ Expected CR anisotropy due to Earth's orbital motion around the Sun: when an observer (CR detector) moves through a gas which is isotropic in the rest frame (CR "gas"), he sees a current of particles from the direction opposite to that of its own motion

A benchmark for the reliability of the detector and the analysis method. In fact all the features (period, amplitude and phase) of the signal are predictable without uncertainty, due to the exquisitely kinetic nature of the effect

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2) \frac{v}{c} \cos \vartheta$$

I = CR intensity  $\gamma$  = power-law index of CR spectrum (2.7) v = detector velocity  $\approx$  30 km/s  $\theta$  = angle between detector motion and CR arriv

A detector on the Earth moving around the Sun scans various directions in space while the Earth spins. Maximum at 6 hr solar time (when the detector is sensitive to a direction parallel to the Earth's orbit)



The first clear observation of the SCG effect with an EAS array was reported by EAS-TOP (LNGS) in 1996 at about 10<sup>14</sup> eV.

#### Compton-Getting effect by ARGO-YBJ

Bec

Dec

Solare Time (UT) 2008 – 2009 data

Nhit 500  $\rightarrow \approx 8 \text{ TeV}$ 

to avoid solar effects on low energy CRs

Evidence for an additional new anisotropy component at lower energy (solar effects ?) under study



## Medium Scale Anisotropy

#### How to focus on medium scale structures ?

Traditional background estimation methods:

- Time swapping/scrambling (3 hrs,)
- Direct integration (3 hrs) (consistent each other within 0.3 s.d.)

An effective high-pass filter for structures narrower than  $3 \text{ hrs} \times 15^{\circ}/\text{hrs} = 45^{\circ}$  in R.A. (35° safety-limit)



First systematic study of the time average-based methods

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every feature larger than  $\Delta T$  is brought to zero (apart from the peak)

R. luppa and G. Di Sciascio, ApJ 766 (2013) 96

## Medium Scale Anisotropy

Data: November 8, 2007 - May 20, 2012 ≈ 3.70×10<sup>11</sup> events

dec. region  $\delta \sim -20^{\circ} \div 80^{\circ}$ 

Map smoothed with the detected PSF for CRs

#### **Proton median energy** $\approx$ 1 TeV

### CRs excess $\approx$ 0.1 % with signifincance up to 15 s.d.

Strip-multiplicity	number of		$\mathbf{E_p^{50}}$ [TeV]
interval	events		_
25 - 40	$1.1409 \times 10^{11}$	(38%)	0.66
40 - 100	$1.4317 \times 10^{11}$	(48%)	1.4
100 - 250	$3.088 \times 10^{10}$	(10%)	3.5
250 - 630	$8.86  imes 10^9$	(3%)	7.3
more than 630	$3.52 \times 10^9$	(1%)	20

TABLE I: Multiplicity intervals used in the analysis. The central columns report the number of events collected. The right column shows the corresponding isotropic CR proton median energy.



## MSA morphology



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# MSA in galactic coordinates



The regions 1 and 2 are distributed symmetrically with respect to the Galactic plane and have longitude centered around the galactic anti-center.

The regions 3 and 4 do not lie on the galactic plane. The 3 is very close to the galactic north pole.









For the region 1L a cut-off around 15-20 TeV can be noticed, compatible with that observed by Milagro in the region "A".

The statistics at high multiplicity is very poor and does not allow to establish whether the cut-off continues at higher energy or not.

Conversely, for region 1U a constantly increasing trend is obtained up to 26 TeV, what marks a possible difference between the sub-regions.

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7.9

12

16

 $0^{-3}$  <u>2.9 4.7</u>

× 1

 $E_p^{50}$ 

26

### Origin/explanation of these "hot spots"

#### There is currently no explanation for these local enhancements in the CR flux

Composition:

- Not photons or electrons (Milagro)
- Neutrons from a star ? Unlikely → 10 TeV neutrons decay in 0.1 pc → much closer than the nearest star.
- ▶ Gyro-radius of a 10 TeV proton in a 2µG magnetic field is only ~0.005 pc (1000 AU).
  - Magnetic field must connect us to the source and be coherent out to it (≥ 100 pc).

#### Tips:

- ✓ Connection to heliosphere? Region 1 coincides with the direction of the heliotail.
- The direction of both regions is nearly perpendicular to the expected Galactic magnetic field direction

#### Multiple explanations were proposed:

Salvati & Sacco, A&A 485 (2008) 527 Drury & Aharonian, Astrop. Phys. 29 (2008) 420. K. Munakata AIP Conf Proc Vol 932, page 283 Salvati, A&A 513 (2010) A28 Lazarian & Desiati , ApJ 722 (2010) 188.



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#### Conclusions

- ★ The anisotropy reveals a new feature of the Galactic CR distribution, which must be incorporated into theories of the origin and propagation of CRs.
- ★ ARGO-YBJ observed either a large and a small/medium angular scale CR anisotropy with high statistical significance and unprecedented detail.
- ★ The observation of the large scale anisotropy up to ≈25 TeV is in agreement with other experiments. Analysis with the full data sample is under way.
- ★ New TeV small/medium scale anisotropy regions are observed for the first time in the Northern hemisphere.
- ★ The solar Compton-Getting effect has been clearly observed.
- ★ Evidence for additional anisotropy components is reported.
- $\star$  Deeper analysis at all angular scales with new techniques is under way.
- ★ The possibility that a young nearby SN might have produced an anisotropic feature over the isotropic intensity of old CRs provides the possibility that the origin of CRs might be discovered through the study of their anisotropy.

## Future measurements in the Northern hemisphere



# The LHAASO experiment

LHAASO: a 1 km<sup>2</sup> multi-component EAS array at 4300 m a.s.l. in Shangri-La, Yunnan province, China.





- 90k m<sup>2</sup> Water Cerenkov Array
- 1 km<sup>2</sup> Scintillator Array
- Wide FoV Cerenkov detectors
- 400 burst detectors