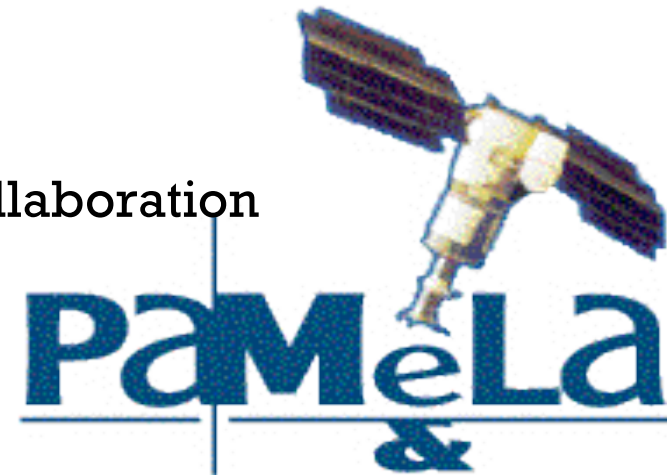


Anisotropy studies in the proton flux with the PAMELA apparatus

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On behalf of the PAMELA Collaboration



SciNeGHE 2012

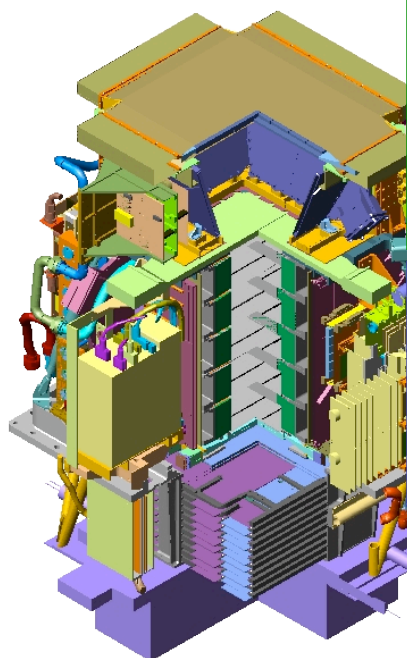
20-22 June, 2012
Lecce - Italy



PAMELA experiment

direct detection of CRs in space \Rightarrow main focus on antimatter component

Main requirements: high-sensitivity particle identification and precise momentum measurement



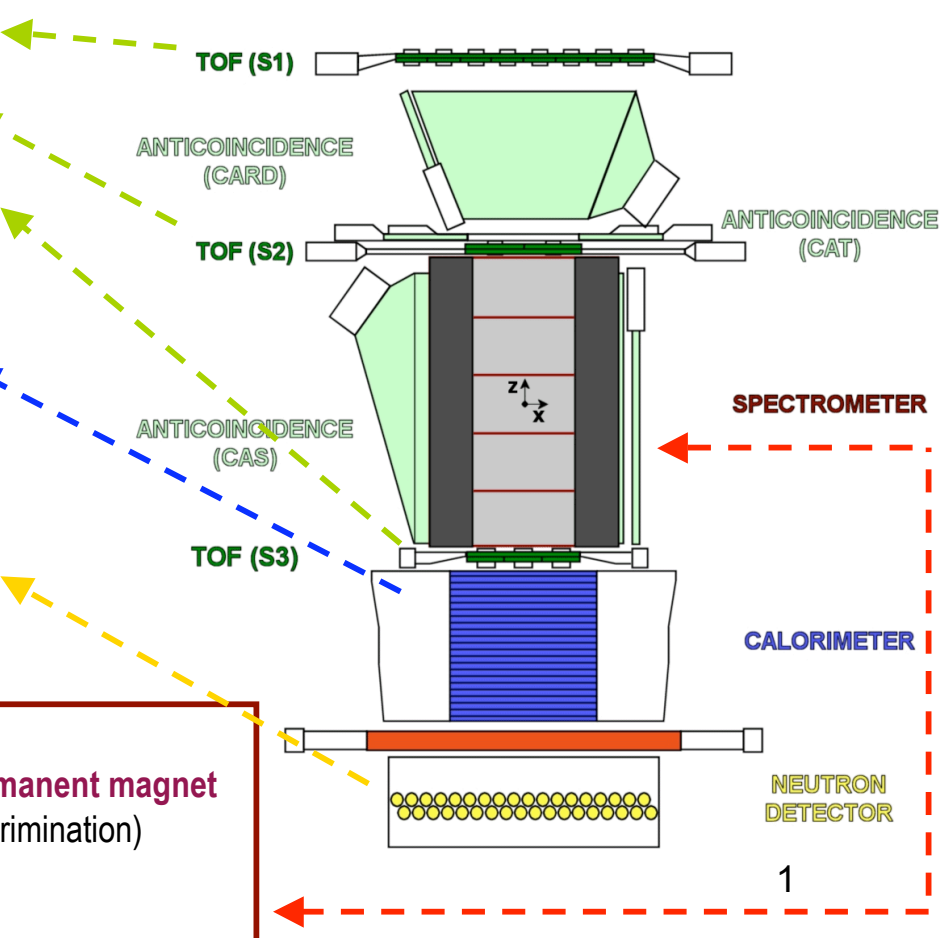
GF: 21.6 cm² sr
 Mass: 470 kg
 Size: 130 · 70 · 70 cm³
 Power Budget: 360 W

Time-Of-Flight (TOF)
 plastic scintillators + PMT:
 - Trigger
 - Upward-going rejection
 - Mass identification up to 1 GeV
 - Charge value from dE/dX

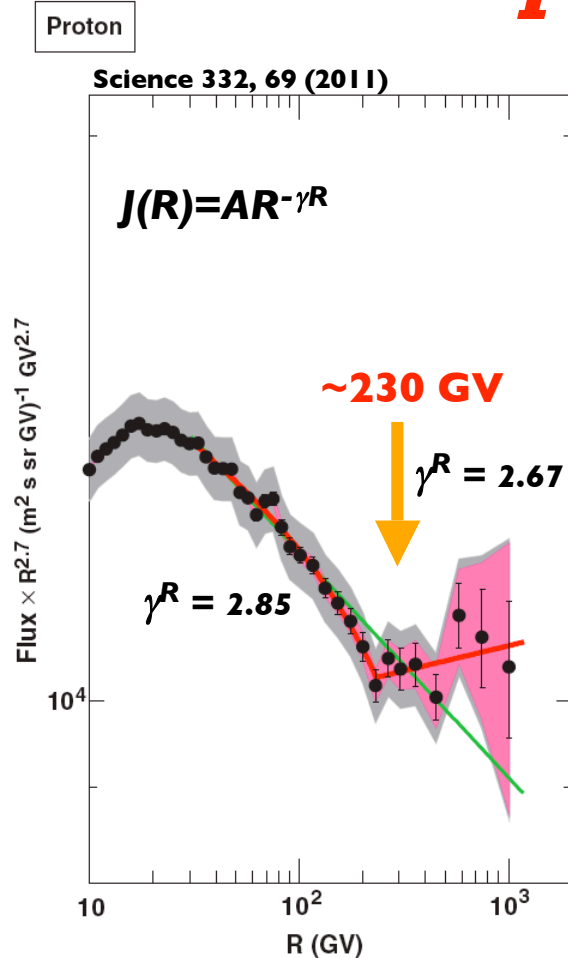
Electromagnetic calorimeter
 W/Si sampling (16.3 X₀, 0.6 λ_I)
 - Discrimination e⁺ / p, p-bar / e⁻
 (shower topology)
 - Direct E measurement for e⁻/e⁺

Neutron detector
 polyethylene + ³He counters:
 - High-energy e/h discrimination

Spectrometer
 microstrip Si tracking system + permanent magnet
 - Charge sign (particle/antiparticle discrimination)
 - Magnetic rigidity $\rightarrow R = pc/Ze$
 - Charge value from dE/dX



Proton absolute flux



Precise measurement proton flux in the rigidity range 1 GV to 1.2 TV

$\sim 230 \text{ GV}$ change of spectral index γ^R

not easily explained with CRs standard model (SN acceleration and homogeneous distribution.....)

Different population of proton sources ?

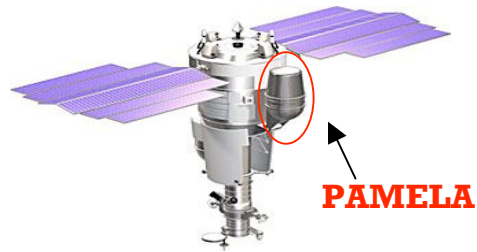
study of protons arrival directions could help to understand better the nature of the spectrum

- arrival directions are isotropized by the action of the magnetic fields

- information on the direction of CR sources is lost

- proton flux could reveal structures spanning over the full sky (**large scale patterns**)

Resurs-DK1 satellite and orbit

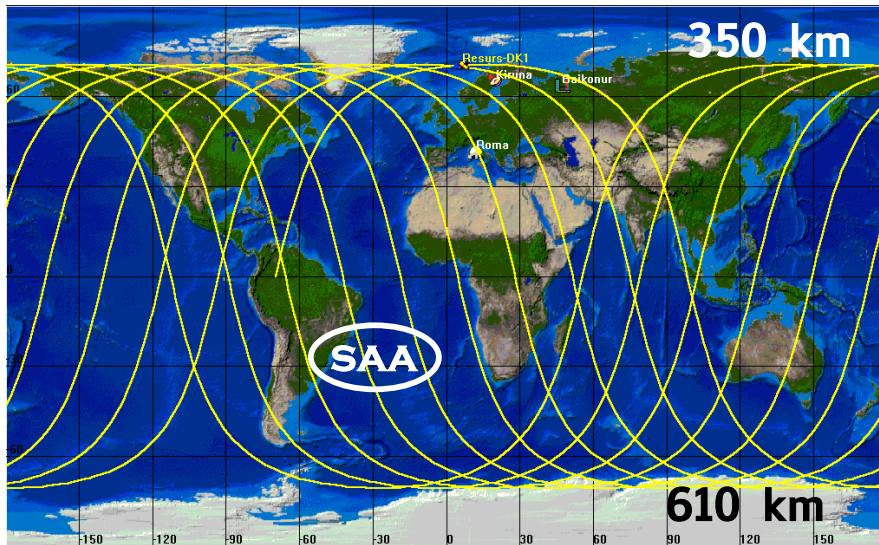


PAMELA mounted inside a pressurized container of the Resurs DK-1 spacecraft

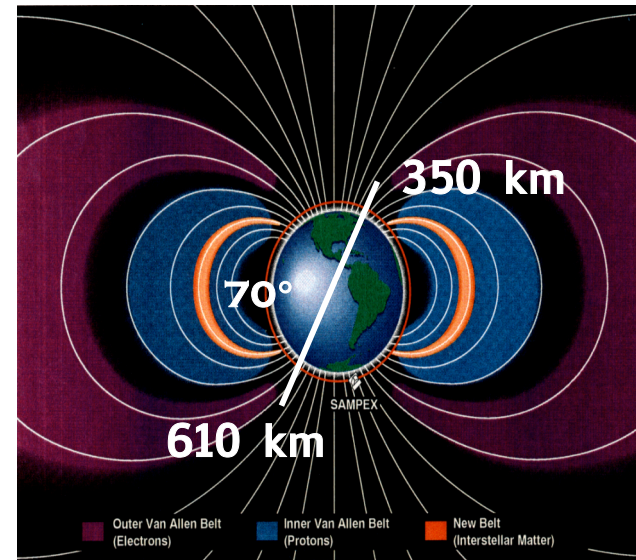
launched on 15th June 2006 and in continuous operation mode since then, 6 years of total lifetime

- Operational orbit parameters:
 - quasi polar and elliptical orbit inclination $\sim 70^\circ$, altitude ~ 360 - 600 k
 - from 2010 circular orbit ($\sim 70.0^\circ$, ~ 600 km)

Quasi polar orbit allows to perform a survey in each direction of the sky (coverage of the full sky)



orbit period ~ 90 min



Data set

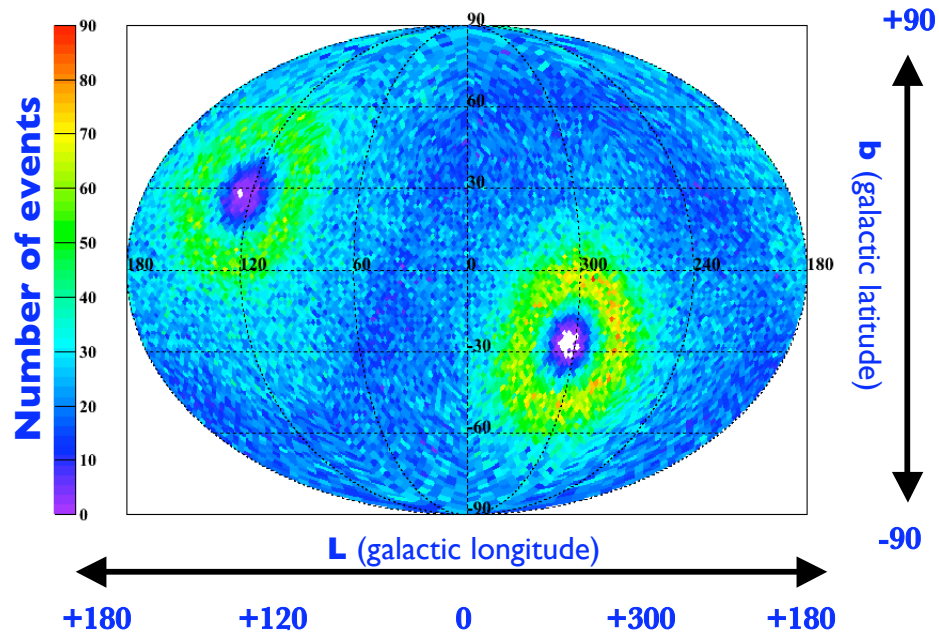
$R < 10$ GV solar modulation effects dominate \Rightarrow only events with $R \gg 10$ GV (30GV)

analyzed data July 2006 - June 2010 (~1200 days)

high quality data good pointing information

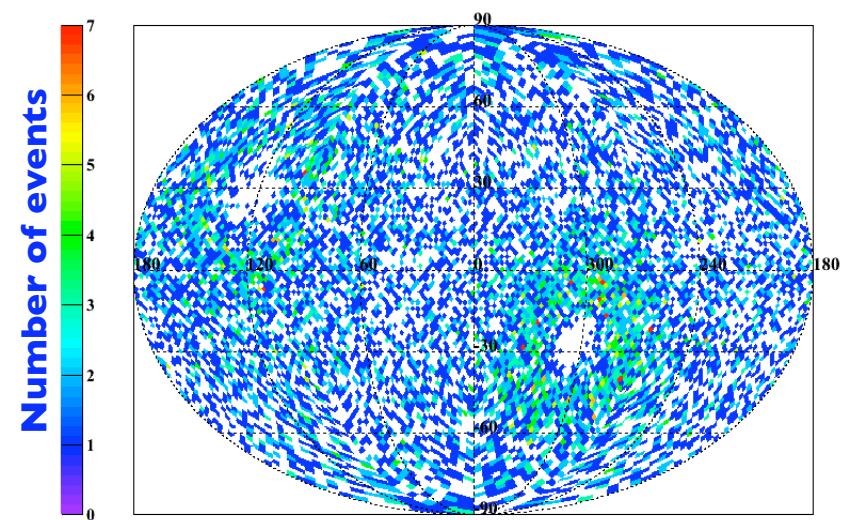
AR well below the angular scales used in this study

$R \geq 40$ GV $\sim 3.28 \times 10^5$ events



**the Galactic Center (l,b) = (0,0)
is in the middle of this map**

$R \geq 230$ GV $\sim 1.10 \times 10^4$ events



**The sky is visualized using the healpix pixelization
-bins with same solid angle
-12288 equal area pixel ($\sim 10^{-3}$ sr)
(nside = 32)**

Data analysis

- ***observed events (N_{on} -real map) in each angular window of the sky***
- ***calculate the expected number of events (N_{off}) in each angular bin of the sky (background or coverage map) under the assumption of an isotropic proton flux***

background map obtained with:

-) shuffling technique

- ***compare the real and the background map to study deviations from isotropy of the real map***

two approaches used to search flux excess:

-) significance test adopted by Li & Ma***
-) spherical armonic analysis***

Shuffling technique

- *background map estimated using the **shuffling method***

an isotropic distribution is created of arrival directions using the **real data**

one artificial data set is created combining the direction of each real event in local instrument coordinates with the arrival time of another randomly selected real event

the main idea behind of this method is that if the detector configuration is stable in a certain time window and the CRs flux is isotropic \Rightarrow time independent intensity of CR in any bin of the sky seen by the detector

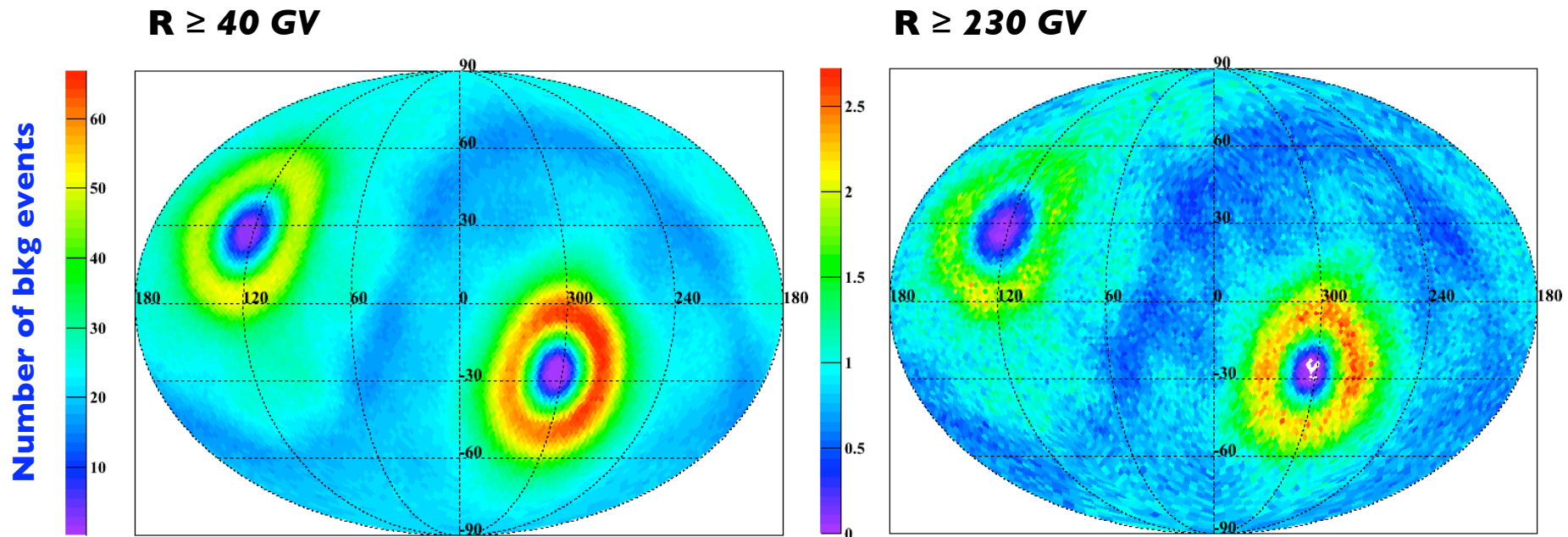
- *a certain number of simulated data sets are created with this process, each data set is consistent with the case of an isotropic arrival distribution*
- *the final background map is then obtained from the average of the simulated data sets to obtain the expected number of events in each region of the sky*

local arrival direction distribution of the real events and the dead times of the detector are preserved into the background map

Background map

Expected number of events obtained with shuffling technique repeated 100 times

to minimize the effects due to the detector configuration the full data set is divided in 5 periods and the shuffling procedure is repeated in each period



quasi polar orbit \Rightarrow longer exposure near the poles

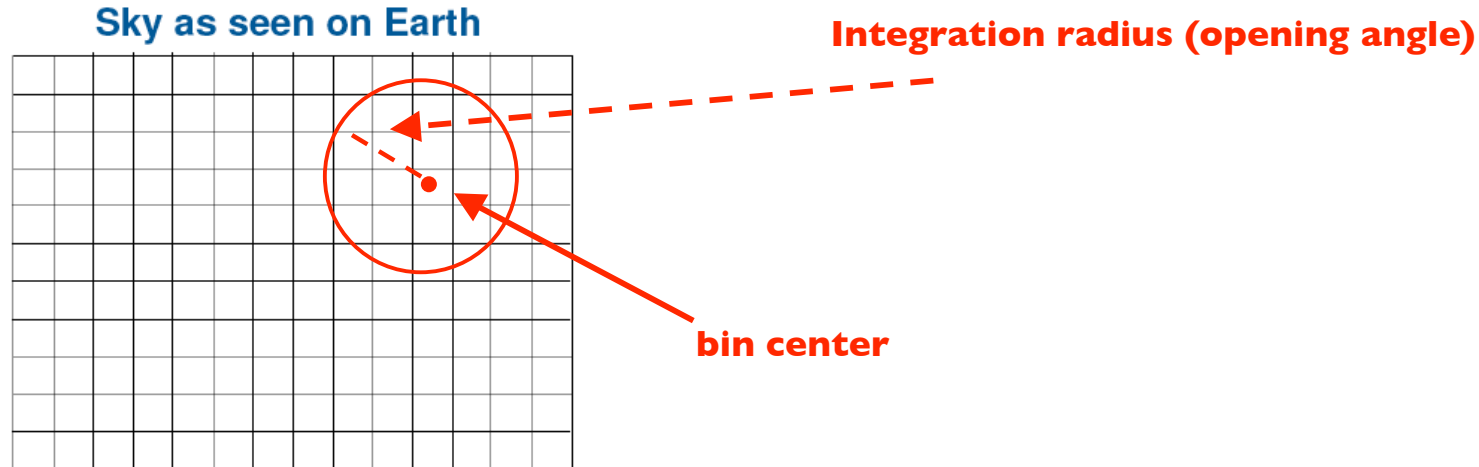
Li & Ma significance test

Integrated sky maps: to avoid to divide a possible signal in adjacent bins

to increase the sensitivity to the large scale features

measure the number of events in a window (top-hat or gaussian around a given direction)
then the content of a bin is given by the integrated number of events falling
in this window around this bin

⇒ ***several integrated sky maps with top-hat window: 10°, 30°, 45°, 60°, 90°***



Both event and background maps are treated in this way

Li & Ma significance test

Observed number of events $\Rightarrow N_{ON}$

Estimate the background $\Rightarrow N_B = \alpha N_{OFF}$ with $\alpha = t_{ON}/t_{OFF}$ ($= \omega_{ON}/\omega_{OFF}$)

Estimate the signal $\Rightarrow N_S = N_{ON} - N_B = N_{ON} - \alpha N_{OFF}$

Estimate the significance of the signal using Li&Ma formula

$$S = \sqrt{2} \left\{ N_{on} \ln \left[\frac{1 + \alpha}{\alpha} \left(\frac{N_{on}}{N_{on} + N_{off}} \right) \right] + N_{off} \ln \left[(1 + \alpha) \left(\frac{N_{off}}{N_{on} + N_{off}} \right) \right] \right\}^{1/2}$$

N_{ON} and N_{OFF} are independent measurements

If $\langle N_S \rangle = 0$ (no sources)

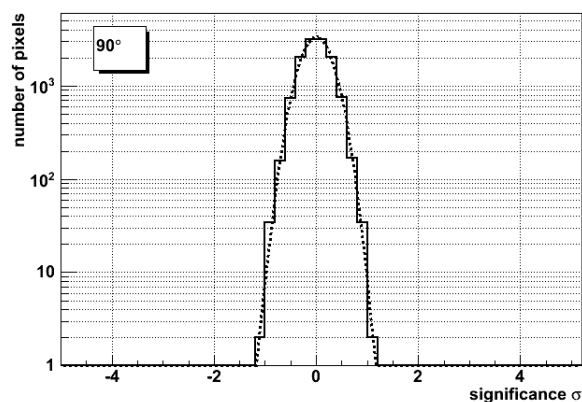
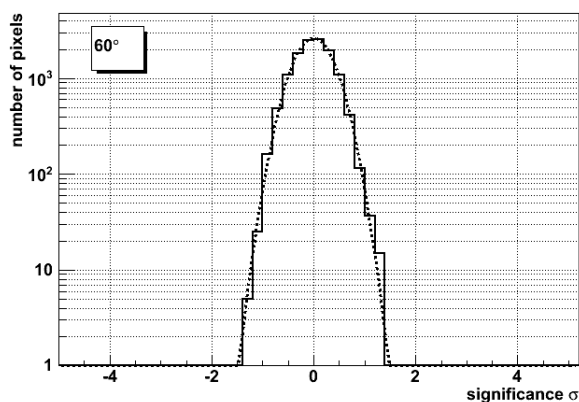
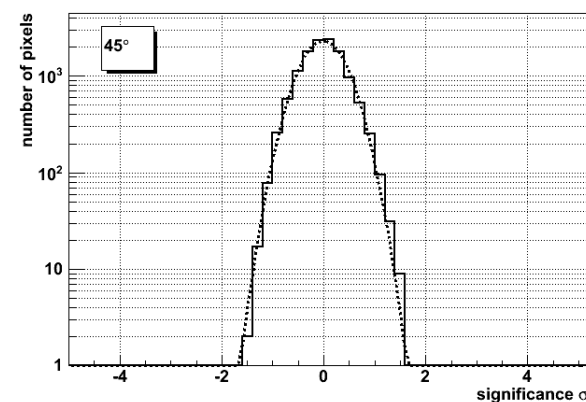
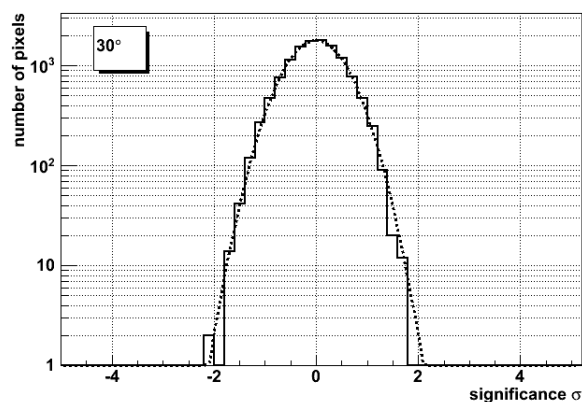
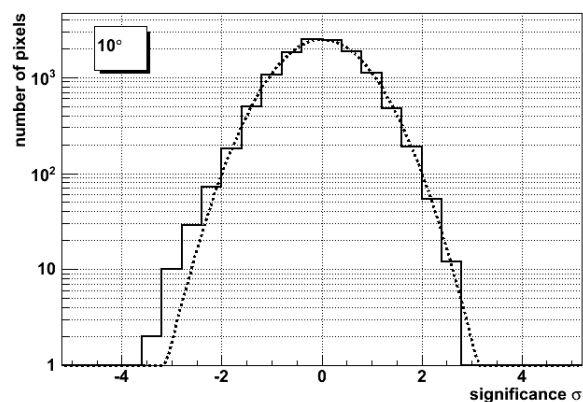


S approximates a gaussian variable with mean = 0 and variance = 1

Gaussian (S) \Rightarrow confidence level of the observational result

Significance distributions (1)

significance distributions for events with $R \geq 40$ GV
as a function of the integration radius



solid line - significant distribution
dotted line - best gaussian fit

significant approximates a gaussian distribution for each opening angle



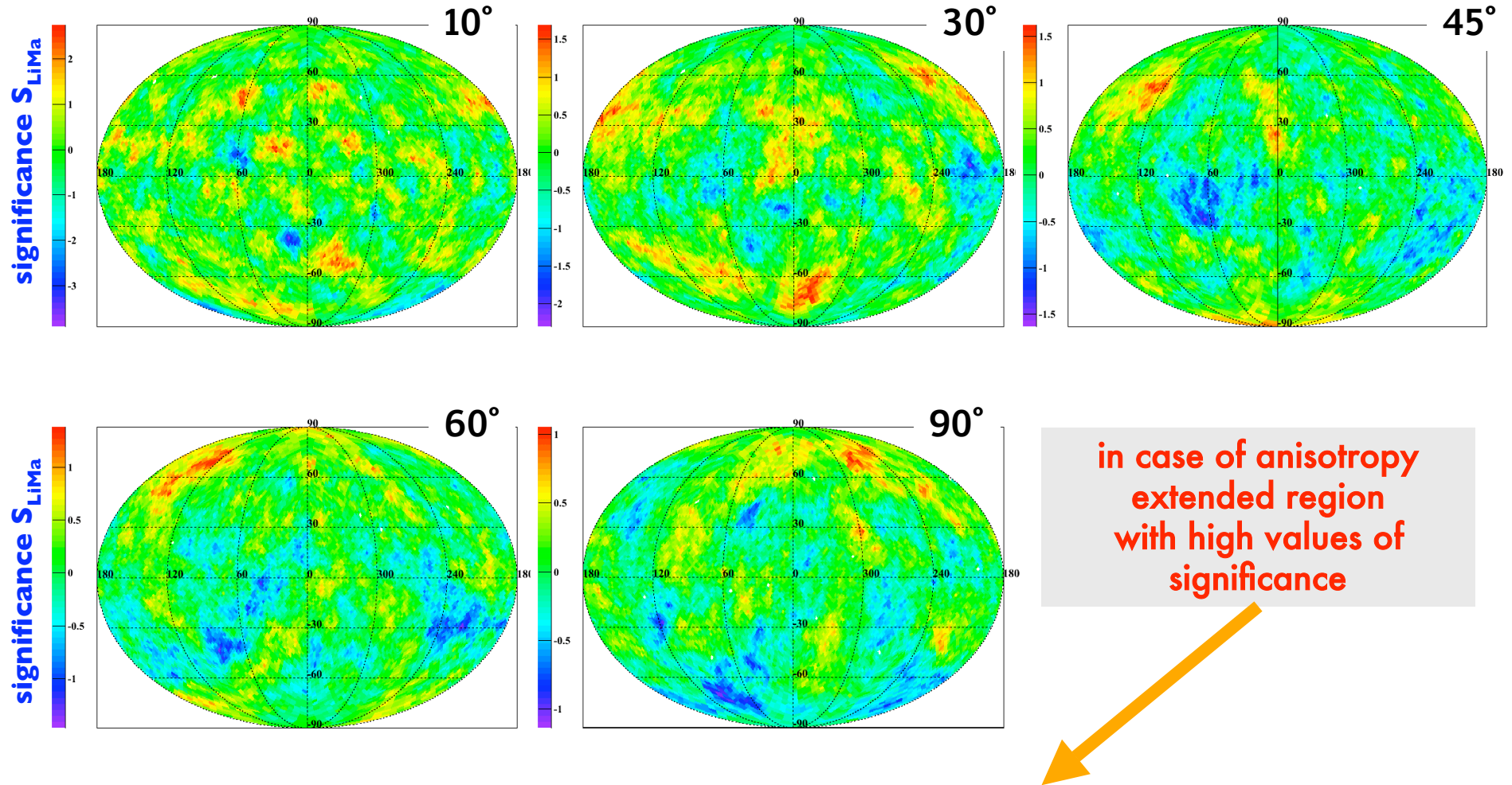
angular distribution consistent with an isotropic sky

variance decreases with the integration radius

Significance sky maps (1)

significance sky maps for events with $R \geq 40$ GV
as a function of the integration radius

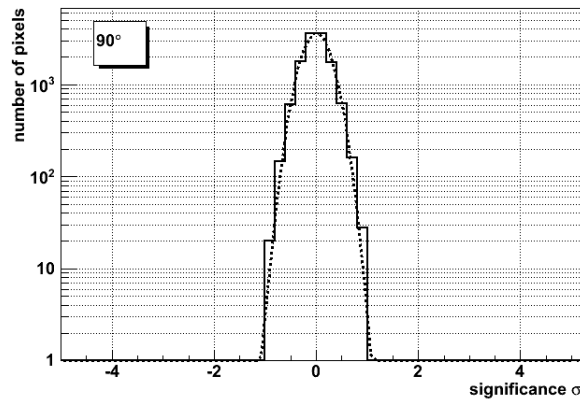
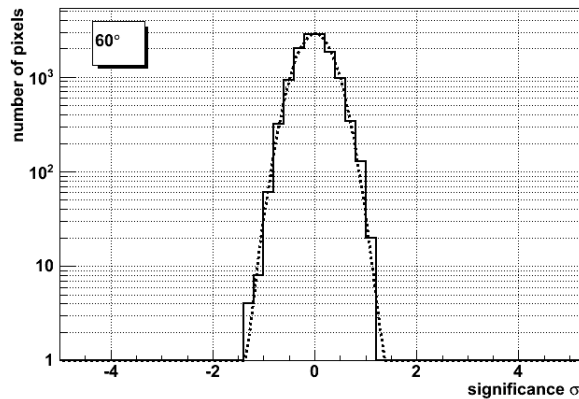
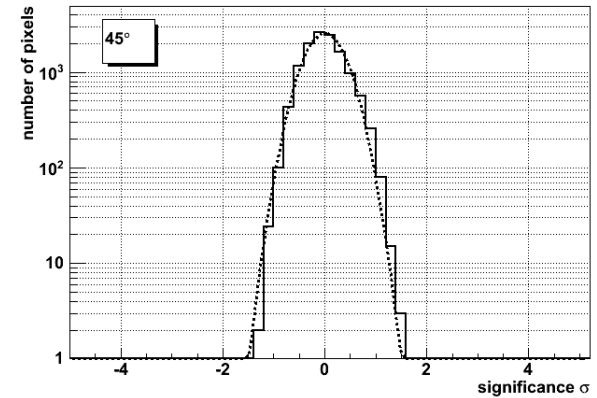
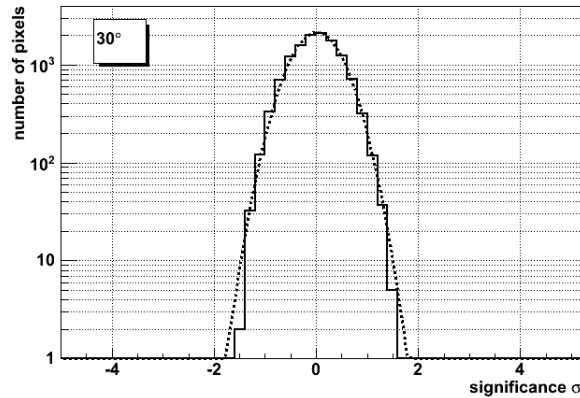
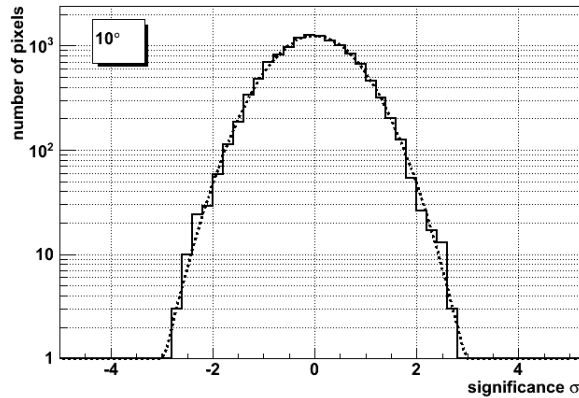
galactic
coordinates



no evidence of excess for each opening angle

Significance distributions (2)

significance distributions for events with $R \geq 230$ GV
as a function of the integration radius



solid line - significant distribution
dotted line - best gaussian fit

significant approximates a gaussian distribution for each opening angle



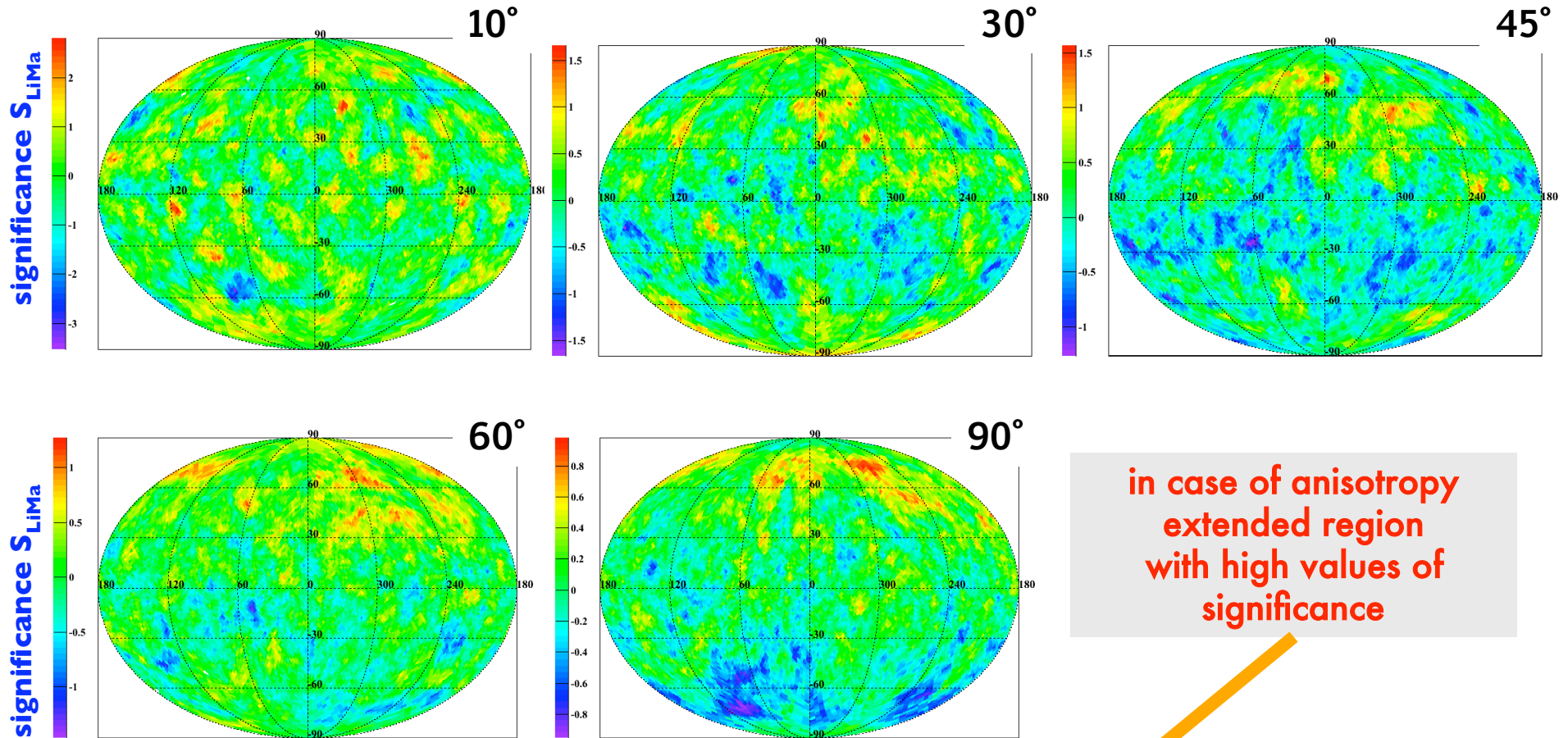
angular distribution consistent with an isotropic sky

variance decreases with the integration radius

Significance sky maps (2)

significance sky maps for events with $R \geq 230$ GV
as a function of the integration radius

galactic
coordinates



in case of anisotropy
extended region
with high values of
significance



no evidence of excess for each opening angle

Spherical harmonic analysis

- relative intensity map

$$I(l, b) = \frac{N(l, b) - \langle N(l, b) \rangle}{\langle N(l, b) \rangle}$$

$N(l, b)$ observed events
 $\langle N(l, b) \rangle$ expected events in each angular bin

- expand the relative map in the basis of spherical harmonics

$$I(l, b) = \sum_{l=1}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}$$

the full anisotropy information is encoded into the set of spherical harmonics coefficients a_{lm}

- Angular power spectrum (PS) obtained from average variance of a_{lm}

$$C(l) = \frac{1}{2l + 1} \sum_{m=-l}^{m=l} a_{lm}^2$$

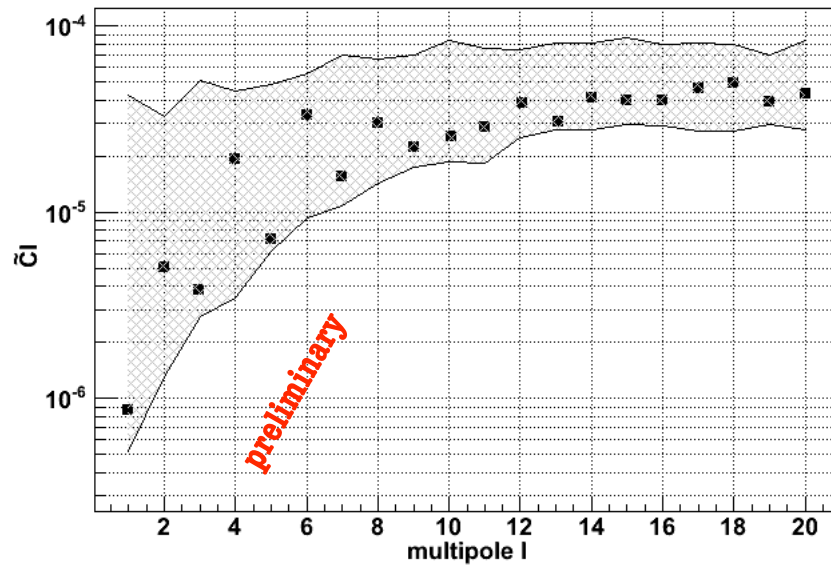
- amplitude of the PS $C(l)$ at some moment $l \Rightarrow$ structures on sky at angular scale $180^\circ / l$

power spectrum calculated with anafast code (healpix framework)

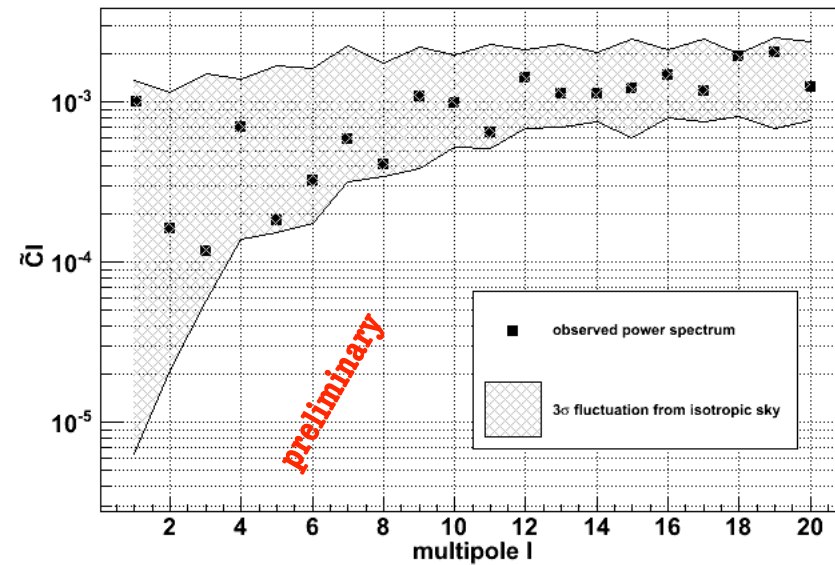
Angular power spectrum

fluctuations angular power spectrum for the relative intensity map

$R \geq 40$ GV



$R \geq 230$ GV



gray bands show the 3 sigma fluctuation of an isotropic sky

probability calculated from 1000 of power spectra for isotropic data sets obtained with the shuffling technique

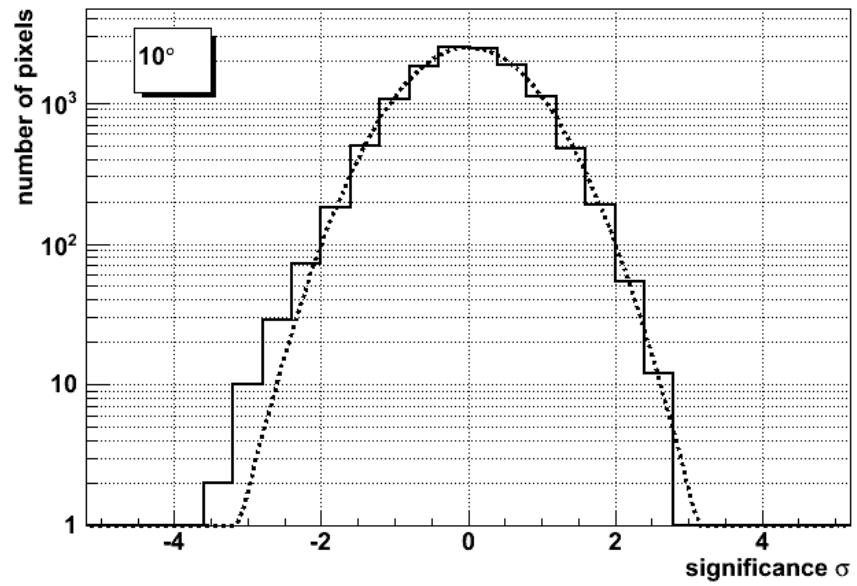
no significant angular power detected in this multipole range

conclusion

- ***preliminary search for large scale structures in the Pamela proton spectrum***
- ***both methods used in the search \Rightarrow no significant evidence of anisotropies***

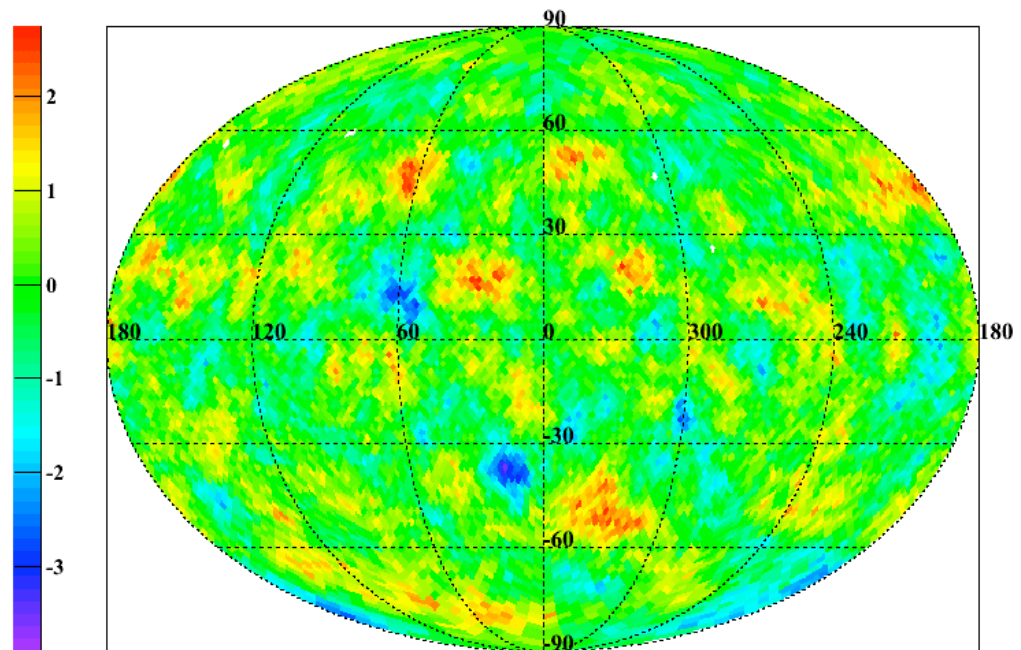
improvements in the analysis ongoing

- use different background estimation (direct integration method)

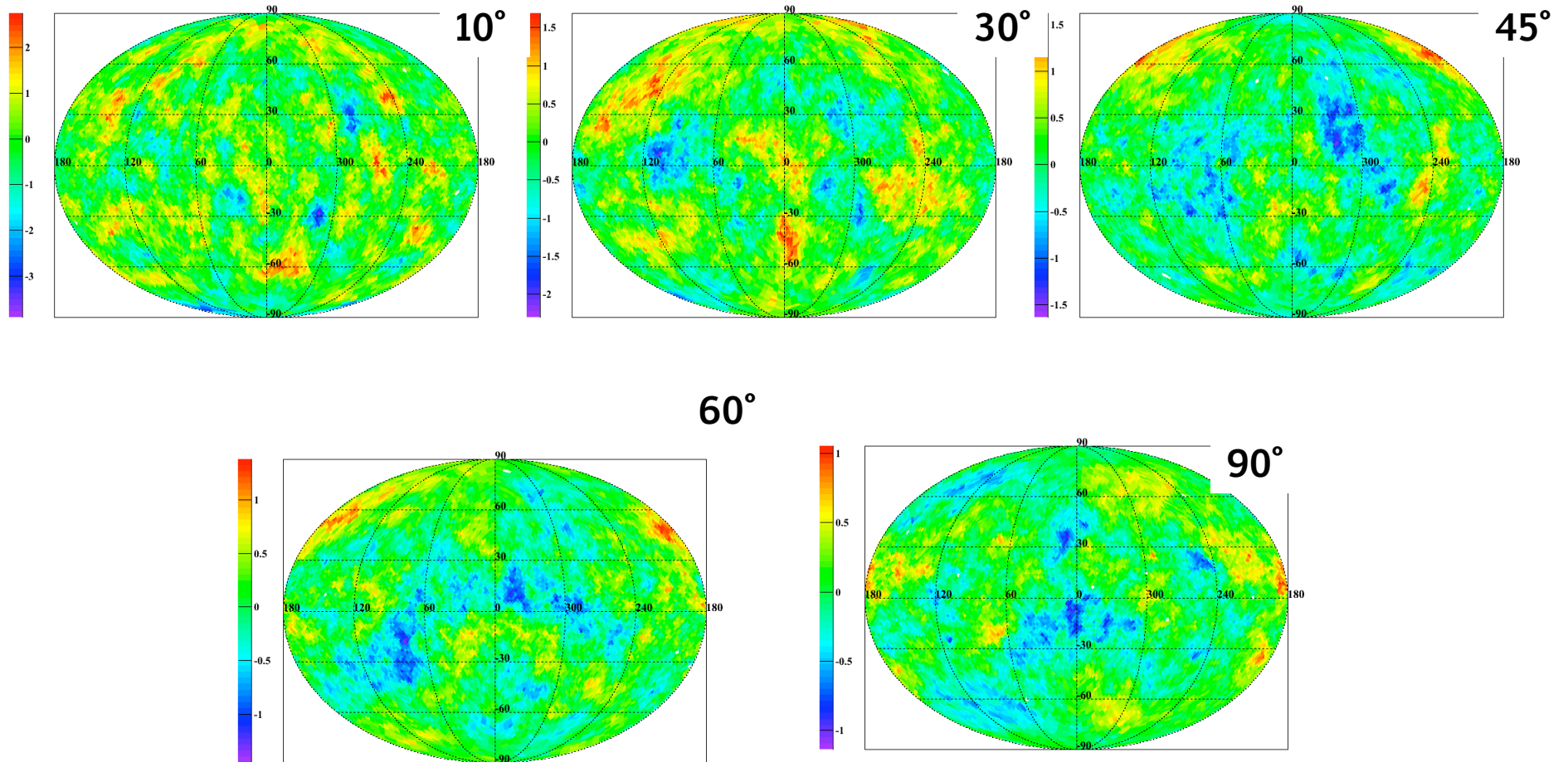


10°

R > 40 GV



Equatorial coordinates -- $R > 40$ GV



Equatorial coordinates -- R230 GV

