COSMIC RAY ANISOTROPIES

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Main aims:

the study of anisotropies in the arrival distribution of cosmic rays provides a handle to study several open questions

- which are the sources of cosmic rays?

- how do they propagate?

- how are the galactic and extragalactic magnetic fields?

- which is the CR composition?

THE COSMIC RAY FLUX IS VERY CLOSE TO ISOTROPIC

CAREFUL STUDIES ARE NEEDED TO DETECT ANISOTROPIES

LECTURE 1: INTRODUCTION AND ANISOTROPY STUDY TECHNIQUES

- The matter distribution in our neighborhood

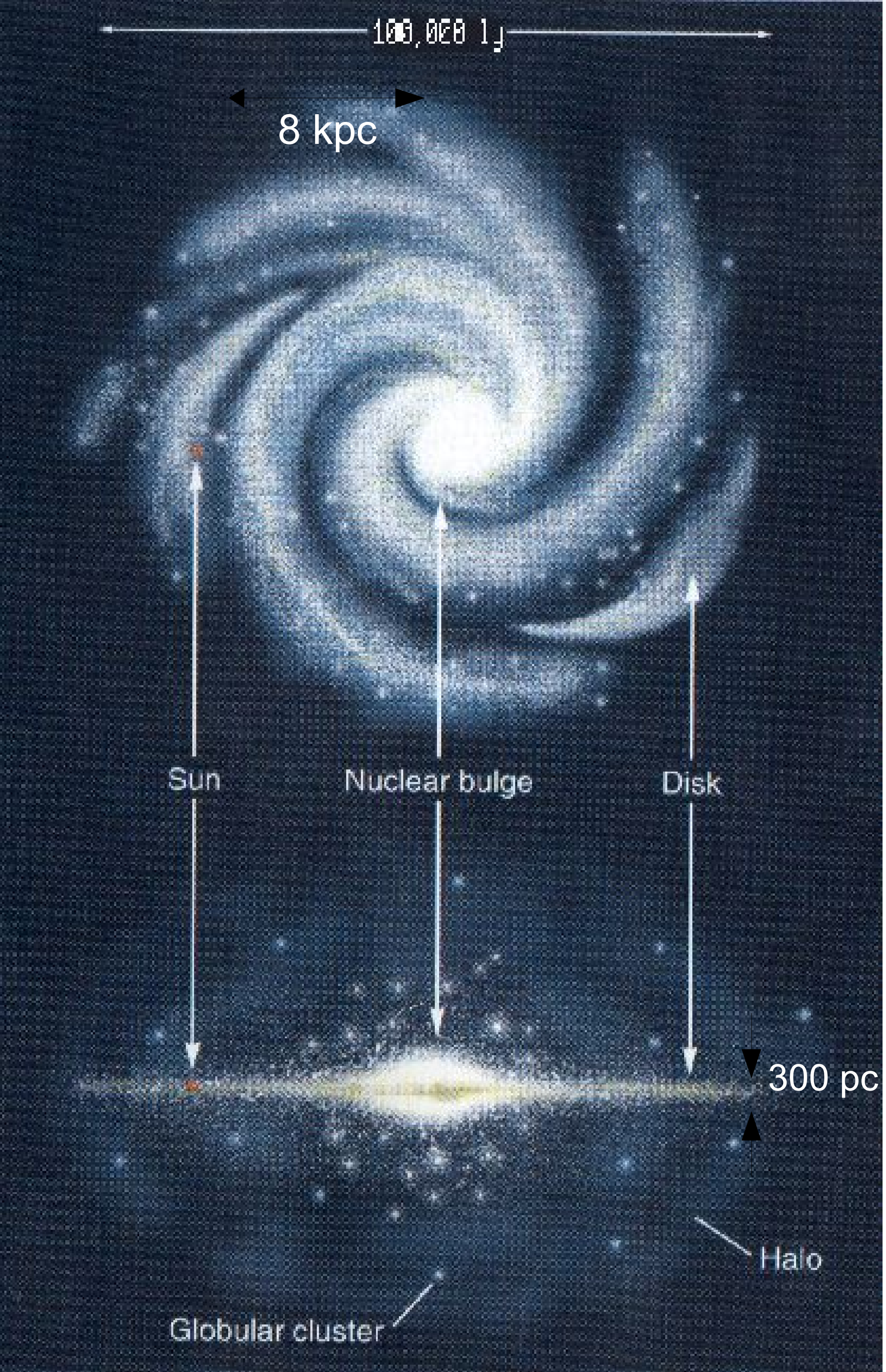
- Galactic & extragalactic magnetic fields

- Magnetic field effects on CR propagation

- Inhomogeneous experimental exposure

- Anisotropy signals at different scales

- Large scale anisotropies: Rayleigh analysis, Compton-Getting effect, sidereal and solar frequencies, observational results



THE GALAXY

Disk: contains most of the visible stars and atomic gas (90% H and 10% He, $n \sim 1/cm^3$) forming a spiral arm pattern. It has a regular magnetic field, $B_\odot = 3\ \mu G$.

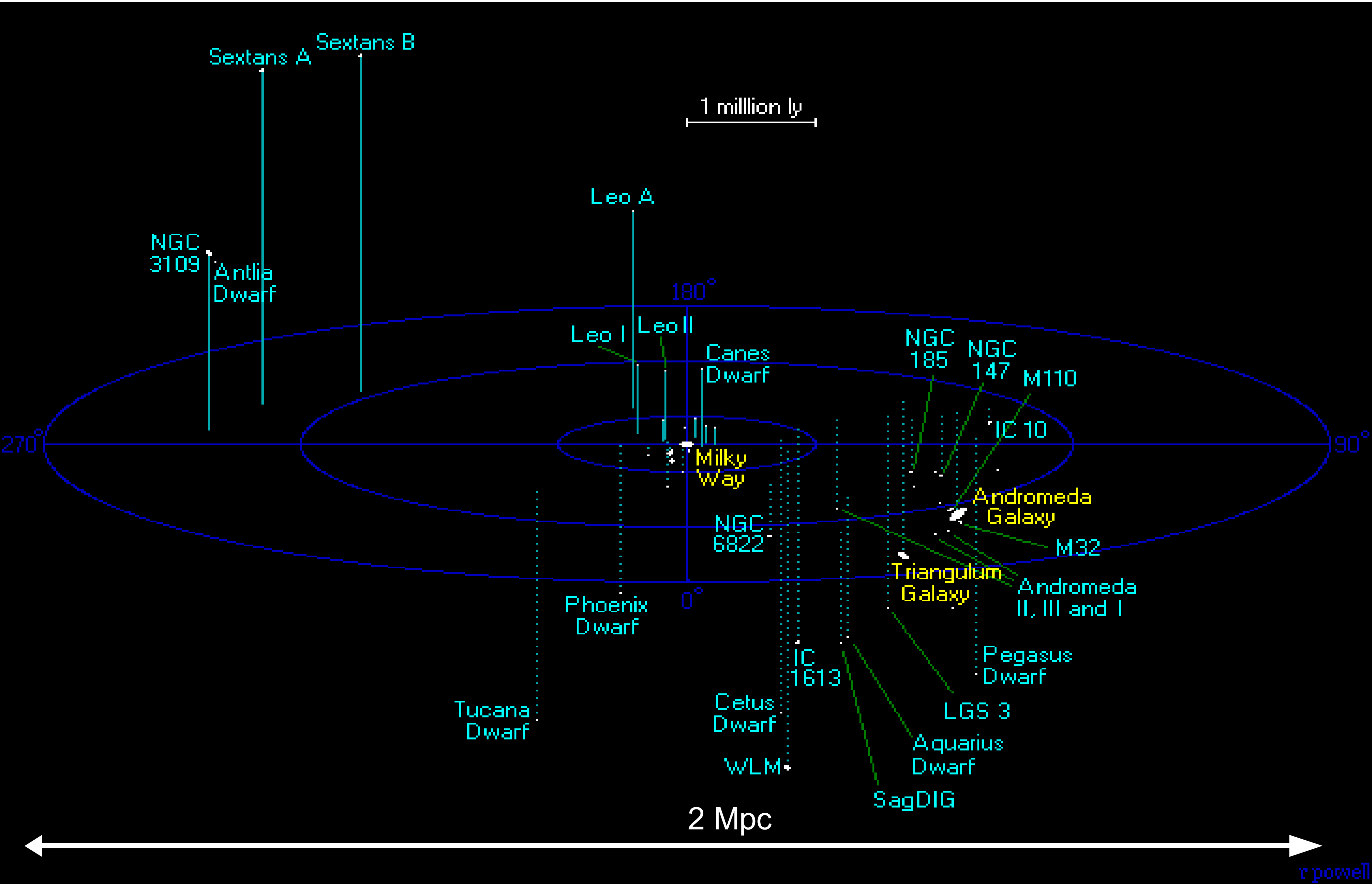
Spheroid (or stellar halo): older stellar population and gas ($n \sim 0.01/cm^3$). Extends up to ~15 kpc. Central bulge. Turbulent magnetic field than can exceed the regular one.

Dark matter halo: evidence from rotation curves of a much larger halo.

Massive black hole in the center $M \sim 10^6\ M_\odot$

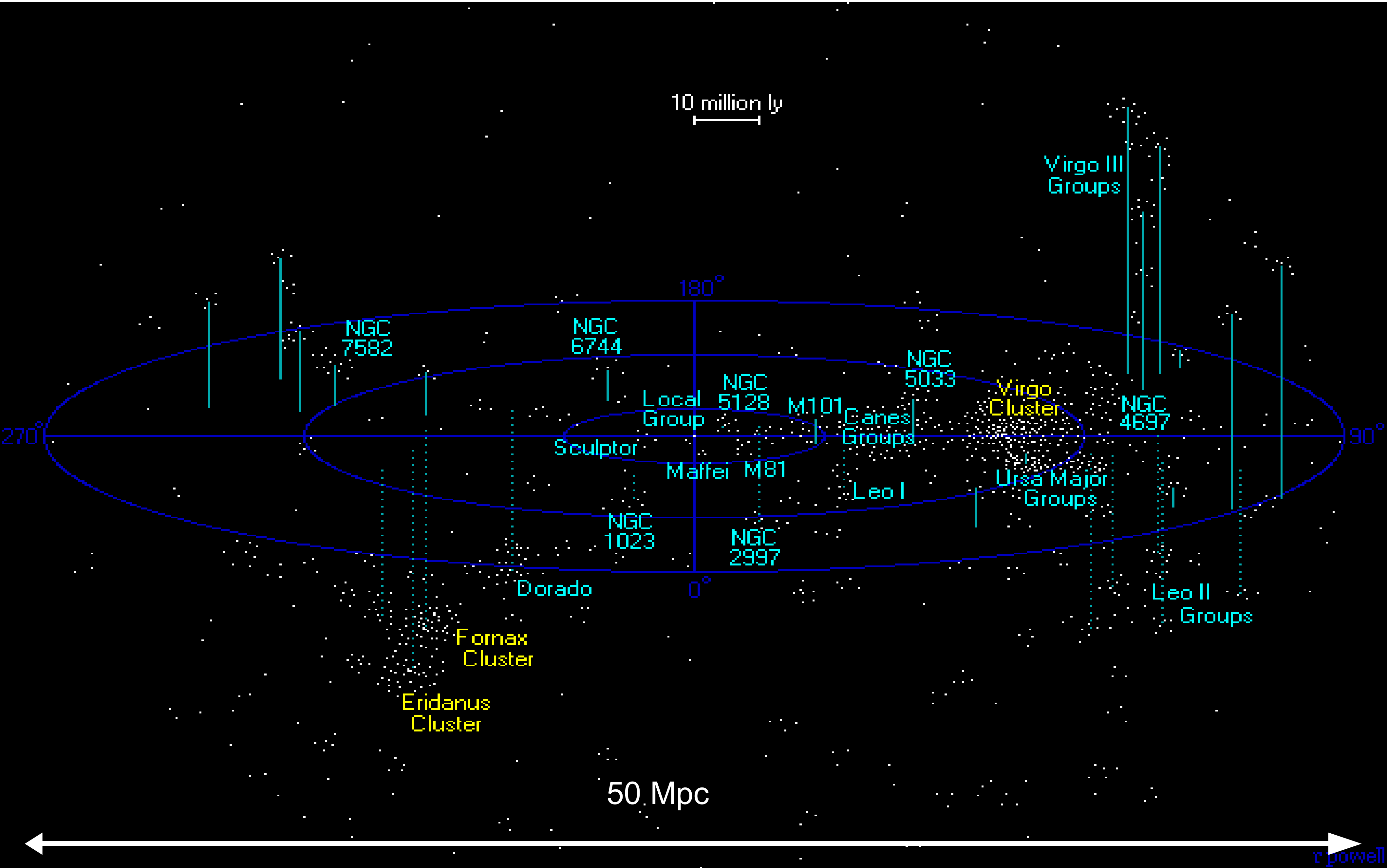
1 pc = 3 ly

THE LOCAL GROUP: Milky Way and Andromeda are the most prominent members of this small cluster of about 30 galaxies

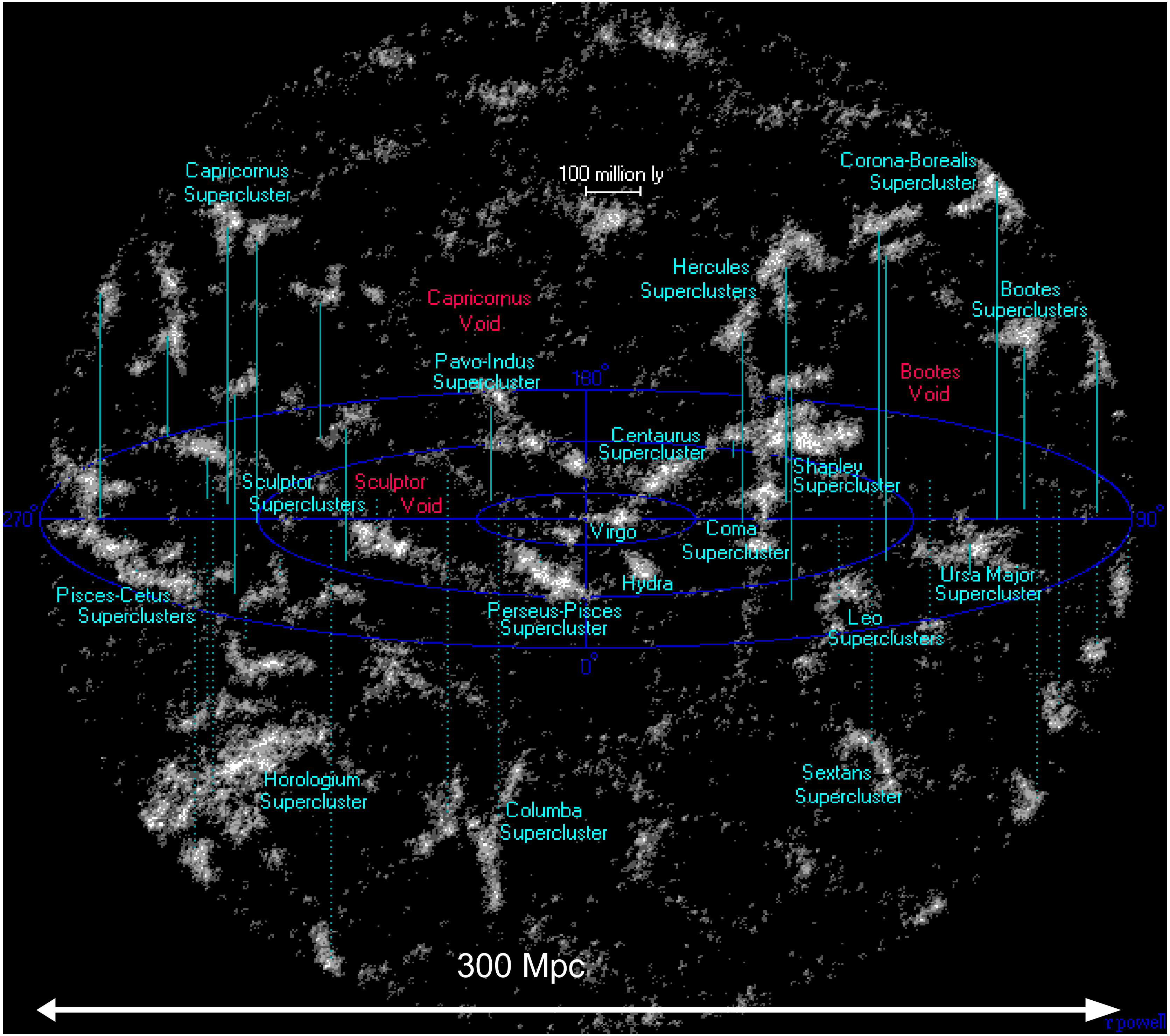


THE VIRGO SUPERCLUSTER:

Our closest cluster of galaxies Virgo (~18 Mpc), a large cluster (more than 2000 galaxies) including the prominent radio galaxy M87



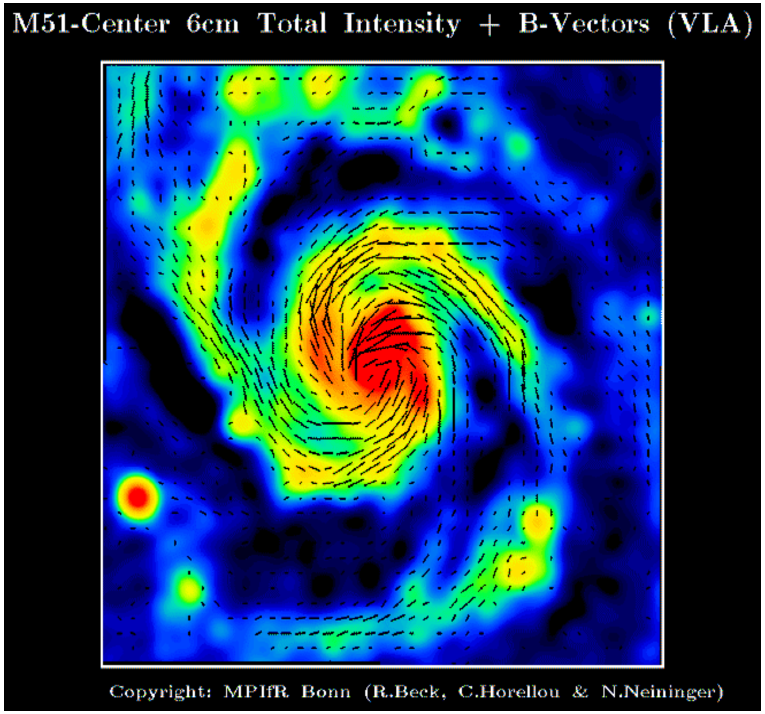
THE NEARBY SUPERCLUSTERS



Galactic magnetic field

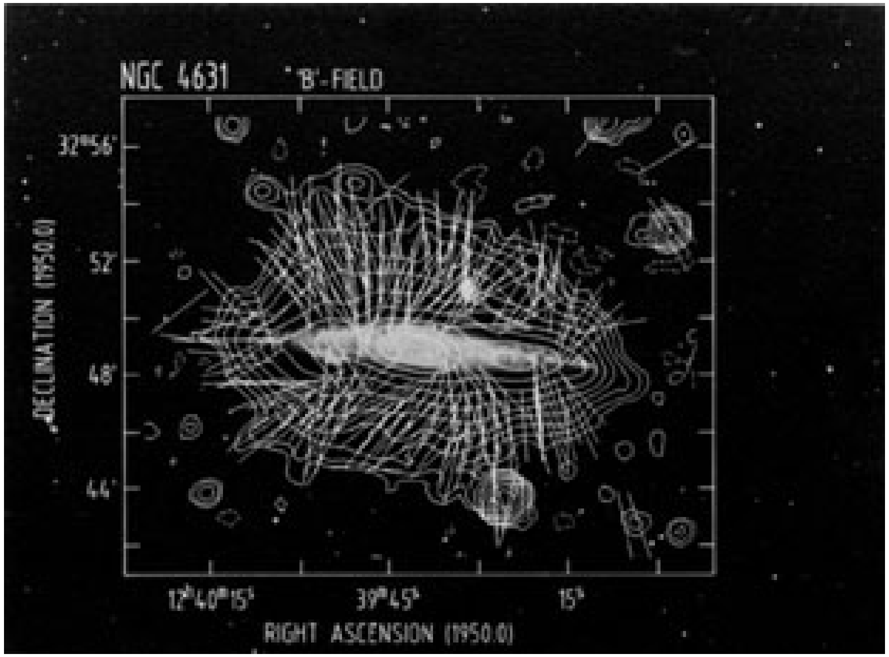
It has a regular + a turbulent component
It is not very well known
From observations of other spiral galaxies it is known that:

M51



Regular B field follows spiral arms as observed from polarized radio emission in face-on galaxy

NGC4631



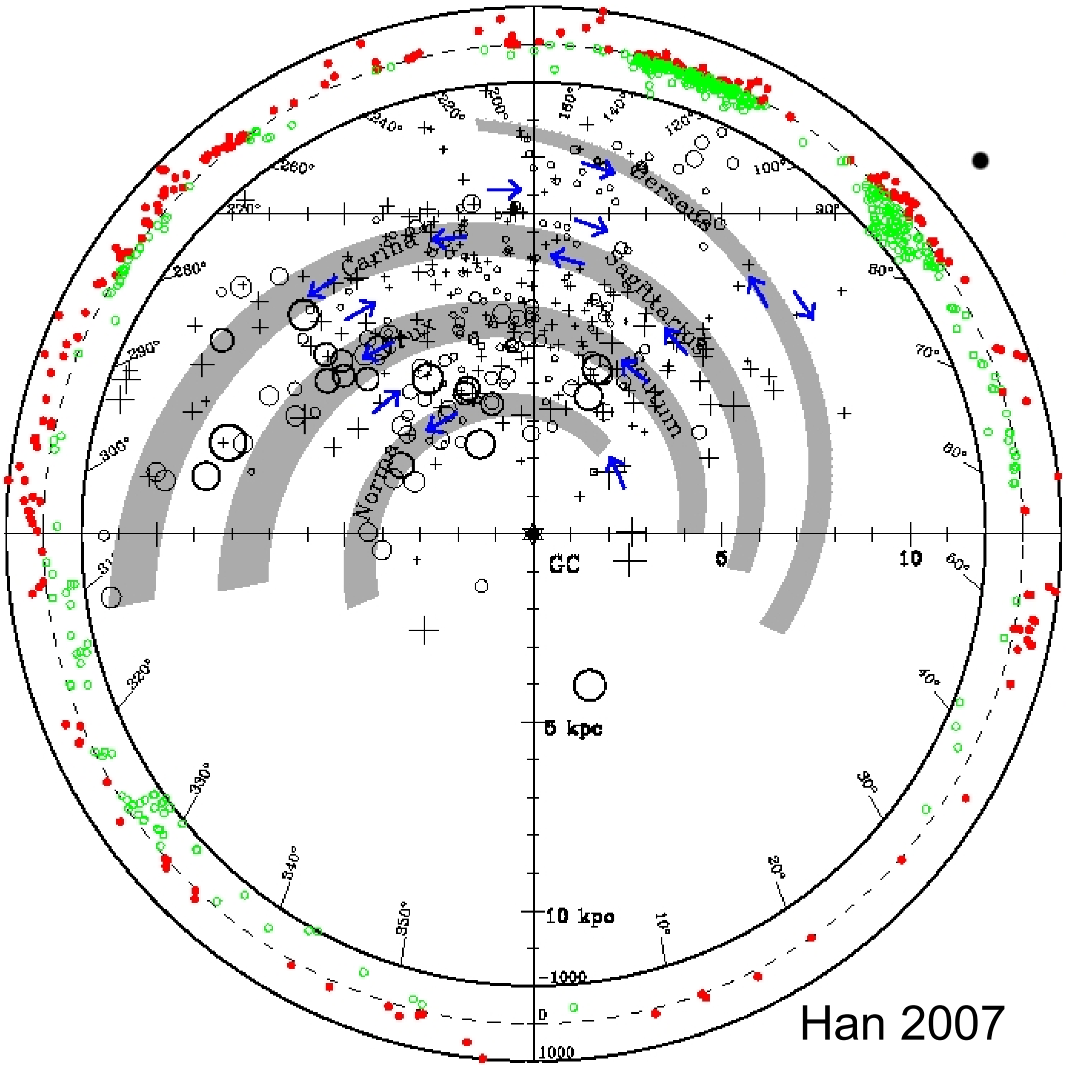
Hummel et al. '88

Magnetic halo from radio polarization measurement in edge-on galaxy (z_h~ few kpc)

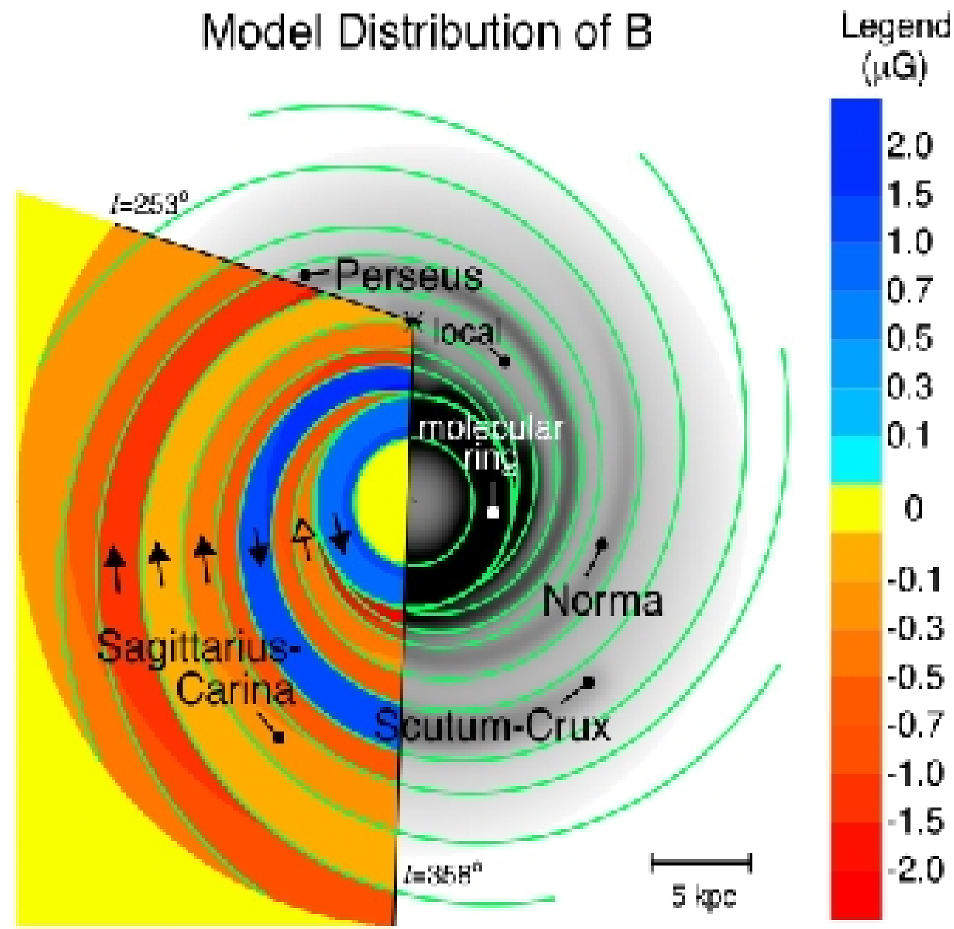
In our own Galaxy: Faraday rotation measures of pulsars and extragalactic radio sources

$$RM : \theta \propto \lambda^2 \int dx\, B_{par} N_e \qquad DM : \tau \propto \lambda^2 \int dx\, N_e$$

$$\boxed{\langle B_{par} \rangle = \frac{RM}{DM}}$$



Han 2007

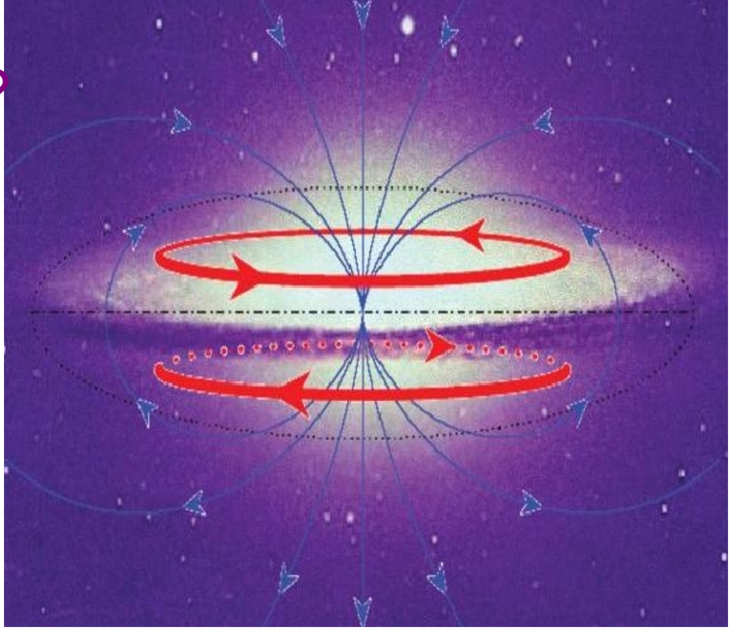


Brown 2007

Magnetic field in the disk follows the spiral pattern → $B_\odot$ ~ 2 – 3 μG

Not well known: reversal from arm to arm, or between arm and interarm region?

Halo component: symmetric or antisymmetric?
Extension?



Turbulent component: coherence length $L_c \sim 100$ pc

$\langle B_{rms} \rangle = 2 - 4\ \mu G$

EXTRAGALACTIC MAGNETIC FIELDS

Magnetic fields are also present outside galaxies, but the observational constraints are still very poor.

The amplitude in central region of clusters may reach ~ μG

The distribution may follow the filamentary pattern of the large scale matter distribution

In most of the space $\langle B_{rms} \rangle = 10^{-8} - 10^{-9}$ G

Coherence length $L_c \sim$ Mpc

Propagation of CR in galactic and extragalactic magnetic fields

Deflection of charged particles is inversely proportional to their energy

$$\vec{F} = m\,\gamma\,\dot{\vec{v}} = \frac{q}{c}\,\vec{v}\times\vec{B} \qquad \vec{v} = c\,\hat{u}\,, \qquad q = Ze$$

$$\hat{u} = \hat{u}_0 + \frac{Ze}{E}\int dl\,\hat{u}\times\vec{B} \qquad \text{(c =1)}$$

Larmor radius:

$$\boxed{r_L \simeq \frac{E/Z}{10^{18} eV}\,\frac{\mu G}{B}\,kpc}$$

In regular field, particles have helical trajectories.

For E/Z < 10^{18} eV (1 EeV) CR confined in the galactic MF
For E/Z > 10^{18} eV unconfined

But for E/Z < 10^{17} eV they scatter off magnetic field irregularities with scale $l \sim r_L$, they make a random walk and diffuse.

Liouville theorem $\rightarrow$ An isotropic flux of CR remains isotropic after propagating through a magnetic field

LT: Phase space distribution $f(\mathbf{r},\mathbf{p})$ is constant along CR trajectories

The intensity $\quad I = dN/(dA\, dt\, d\Omega\, dE)$

and $\quad dN = f(\mathbf{r},\mathbf{p})\; d^3r\, d^3p \qquad d^3r = dA\, v\, dt\,,\; d^3p = p^2\, dp\, d\Omega$

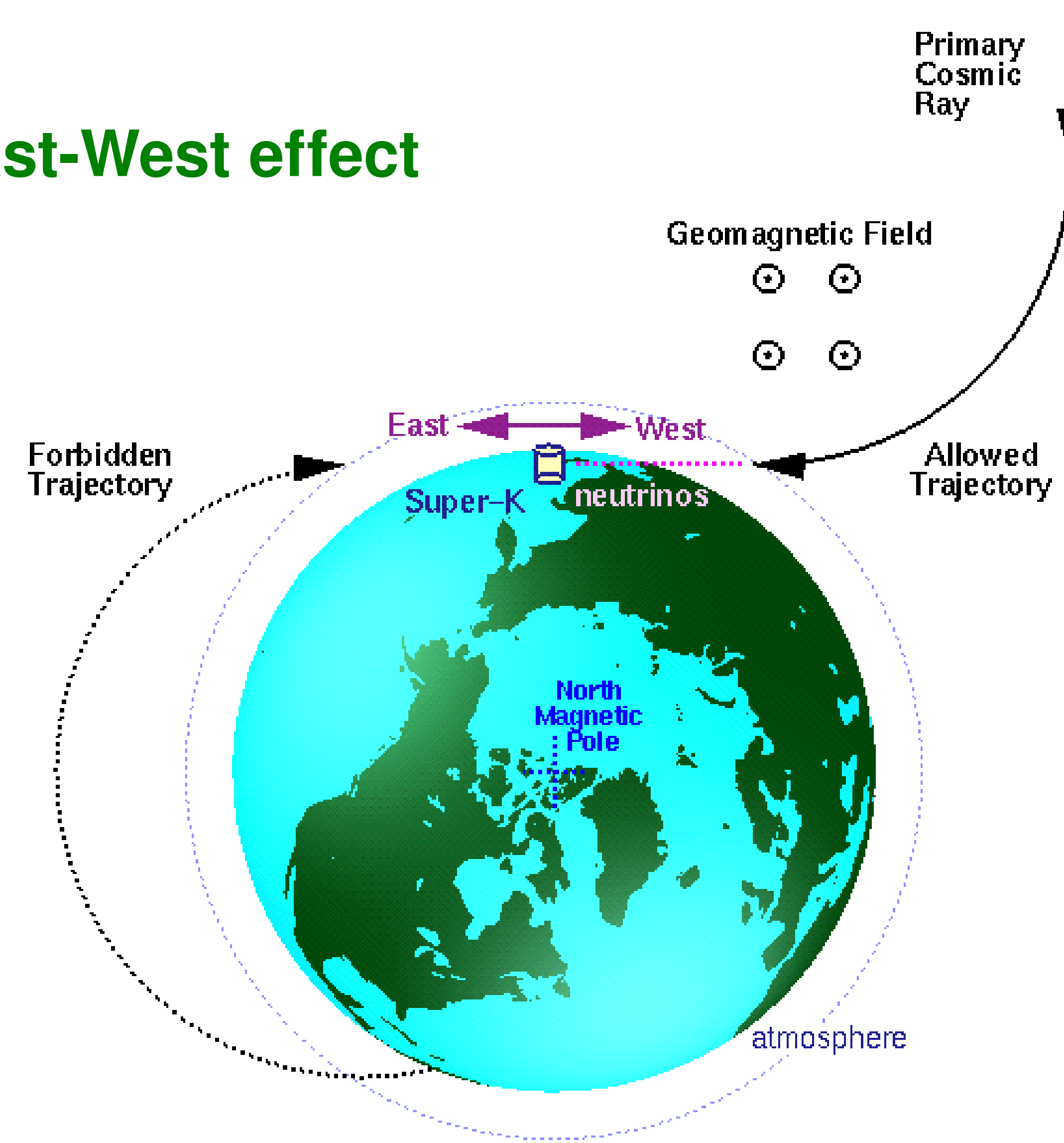
Then $\quad I = f(\mathbf{r},\mathbf{p})\, v\, p^2\, dp/dE = f(\mathbf{r},\mathbf{p})\, p^2$

Since p is constant along the trajectory $\rightarrow$ **I is constant**

An isotropic CR flux remains isotropic unless there is a 'shadowing effect': directions from which particles cannot reach the detector coming from infinity.

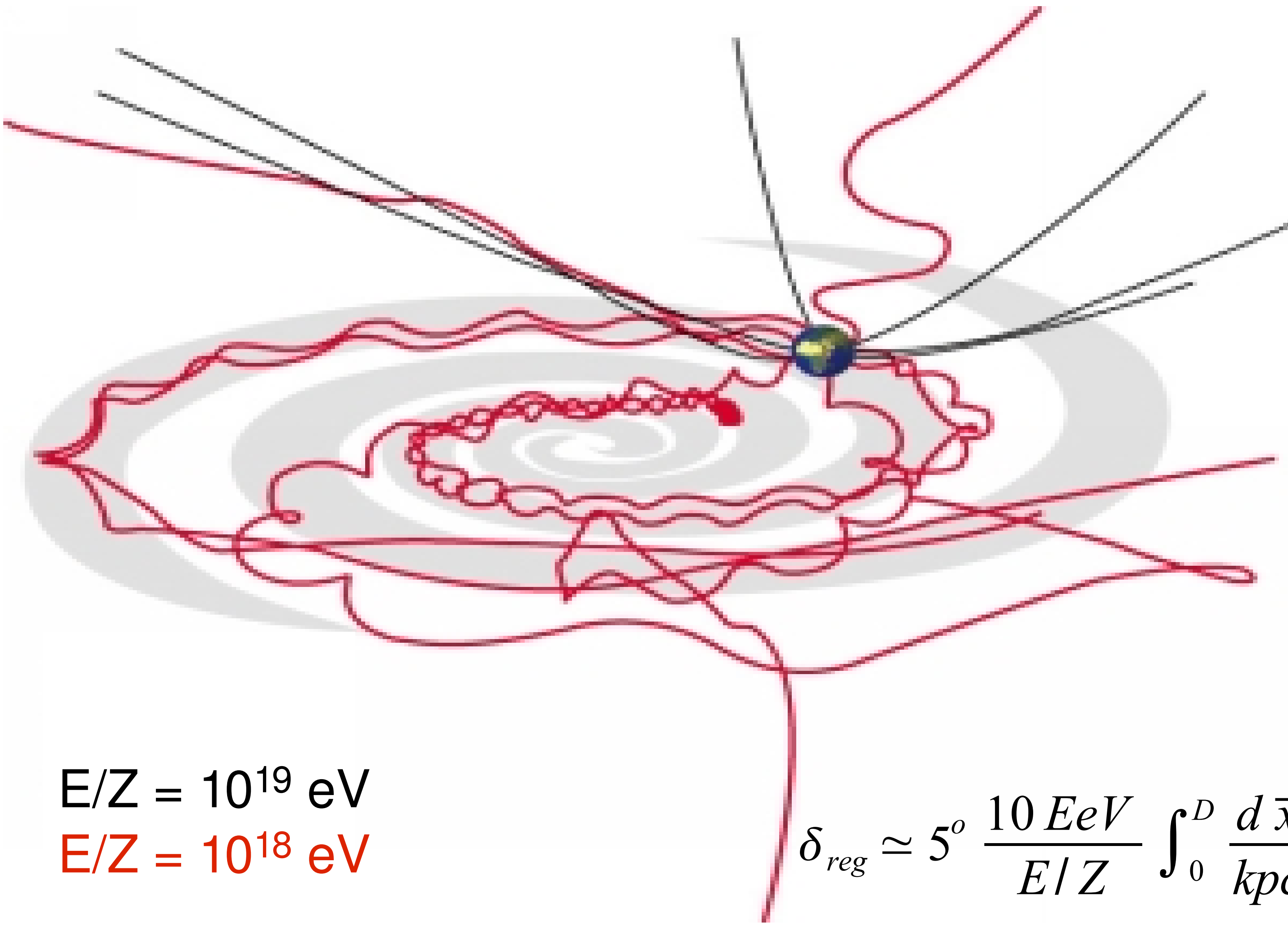
At low energies this happens because of the Earth `shadow': trajectories of antiparticles leaving from the detector hit the Earth due to the deflections in the geomagnetic field

East-West effect



Protons with energy smaller than 60 GeV are not able to reach the Earth from the east (at the equator). The sign of this E-W asymmetry was used to infer that CR primaries are positively charged.
Towards the poles the threshold is smaller → CR intensity increase with latitude at low energies ('latitude effect')

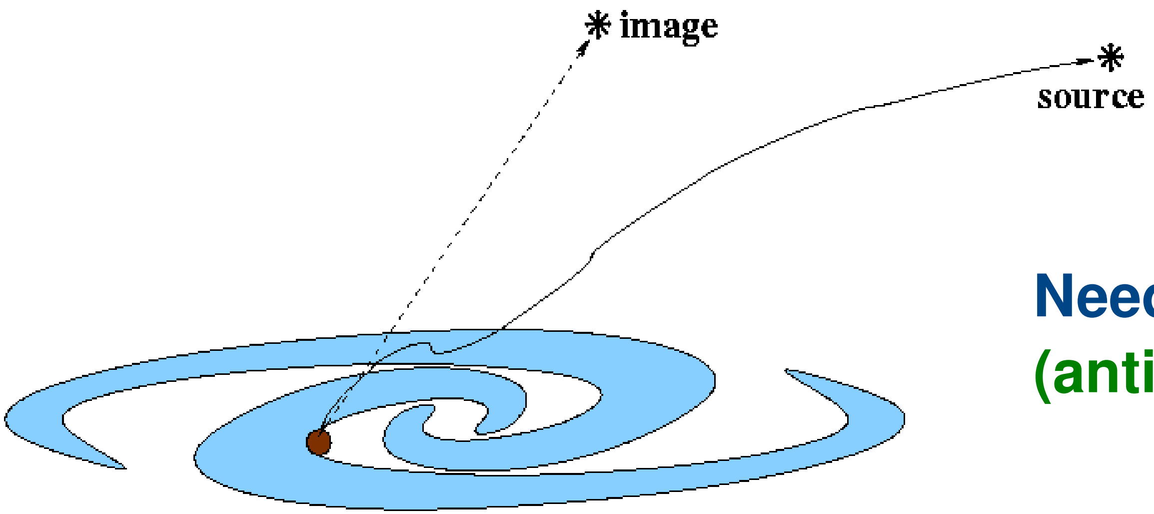
DEFLECTION OF CHARGED PARTICLES IN GALACTIC MAGNETIC FIELD



$$\delta_{reg} \simeq 5^o \, \frac{10\, EeV}{E/Z} \int_0^D \frac{d\,\vec{x}}{kpc} \times \frac{\vec{B}}{\mu\, G}$$

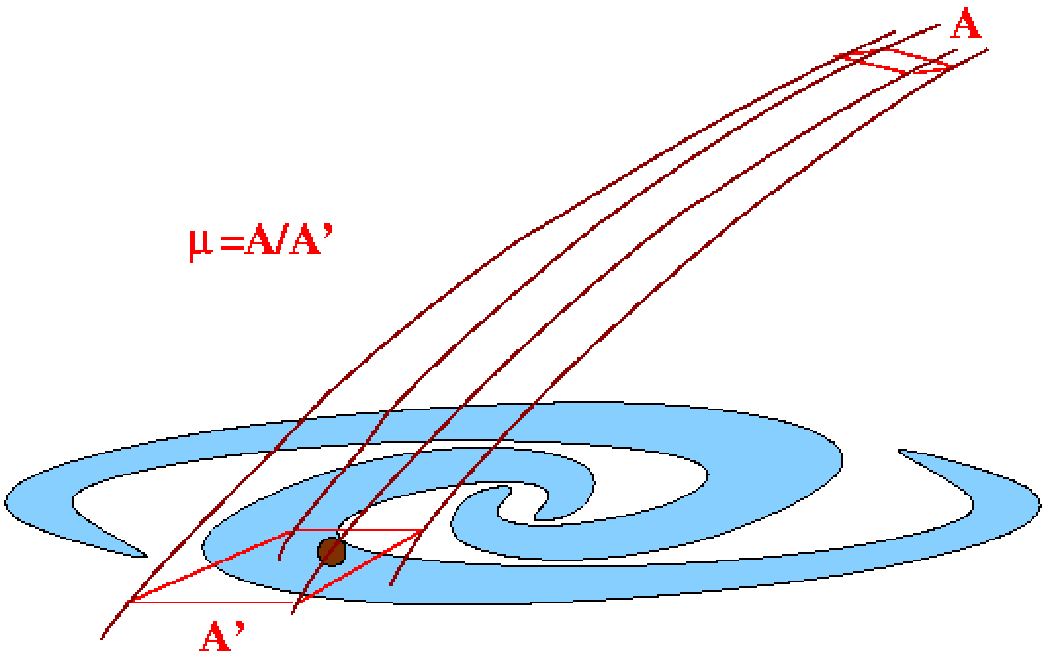
only for E/Z >> 10^{19} eV deflections become less than a few degrees and CR astronomy could become feasible

If Galactic B field (and composition) were known, one could correct the arrival direction to search for the source

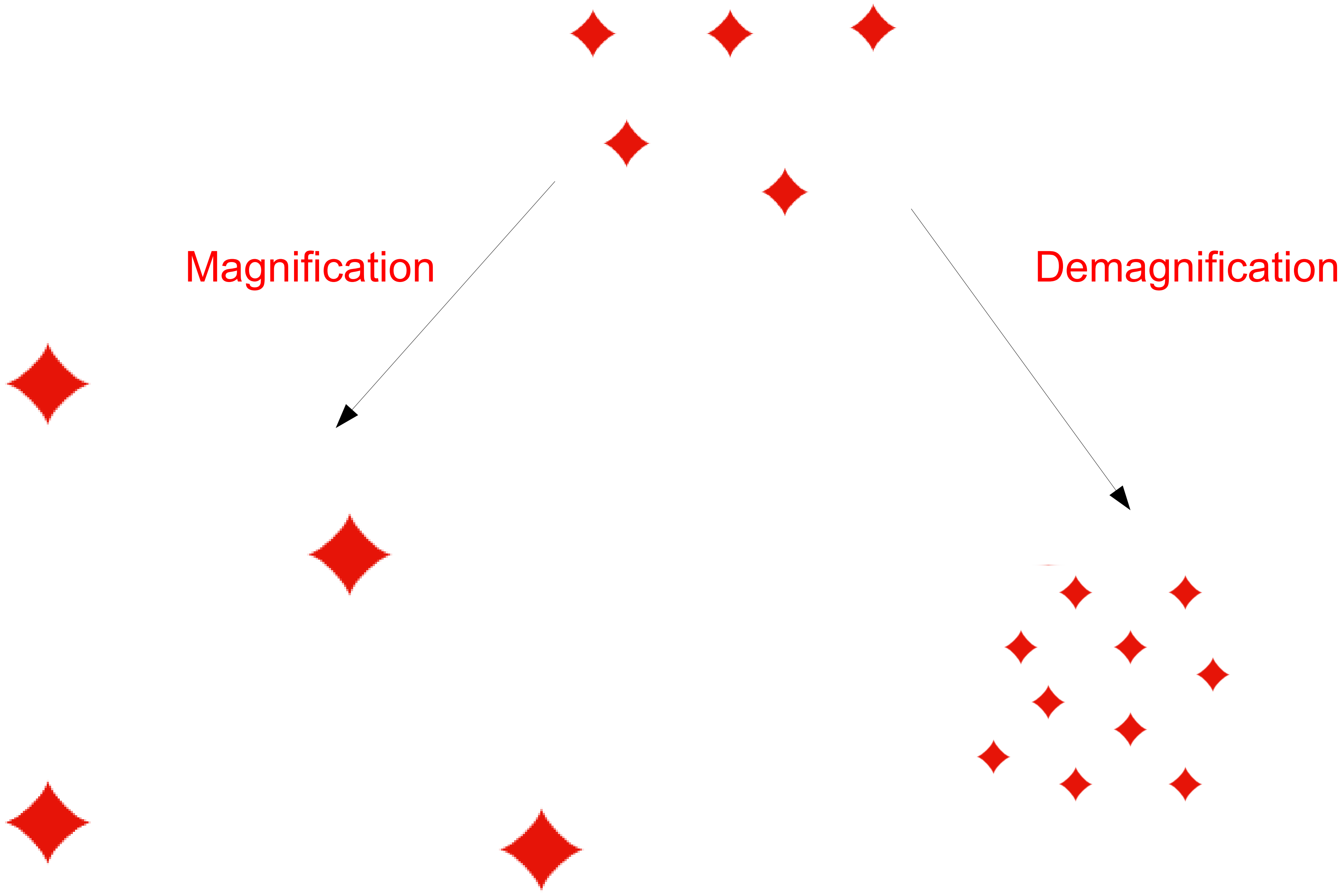


Need to 'backtrack antiprotons' (antinuclei)

CRs are not only deflected, but also magnified

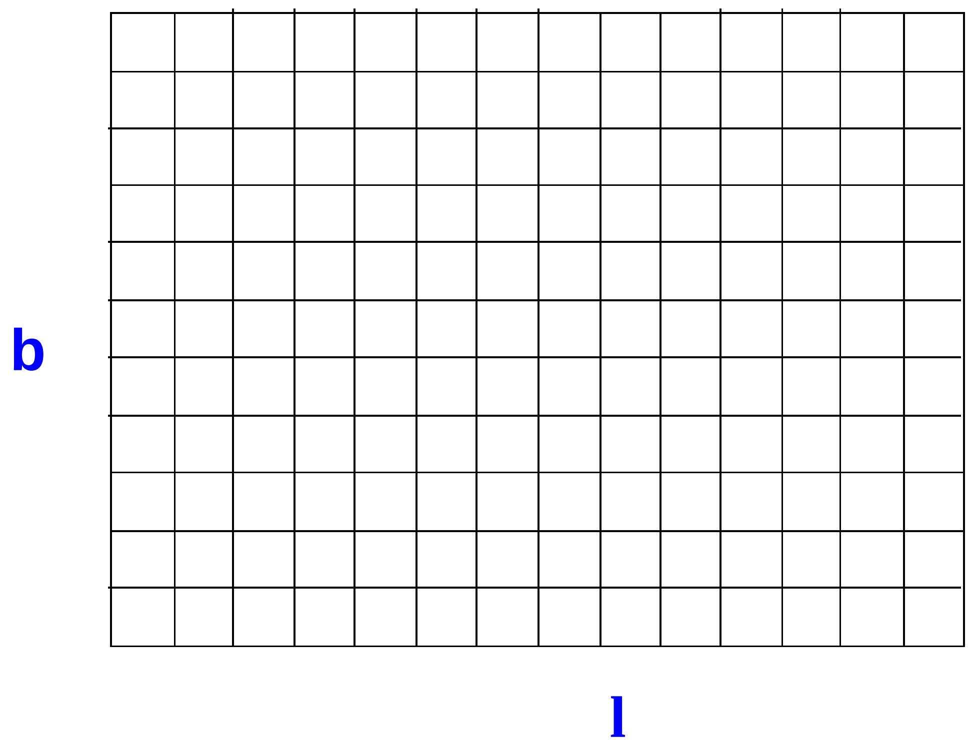


Liouville theorem says that the magnetics fields cannot produce anisotropies from an isotropic flux, but they do affect anisotropic fluxes

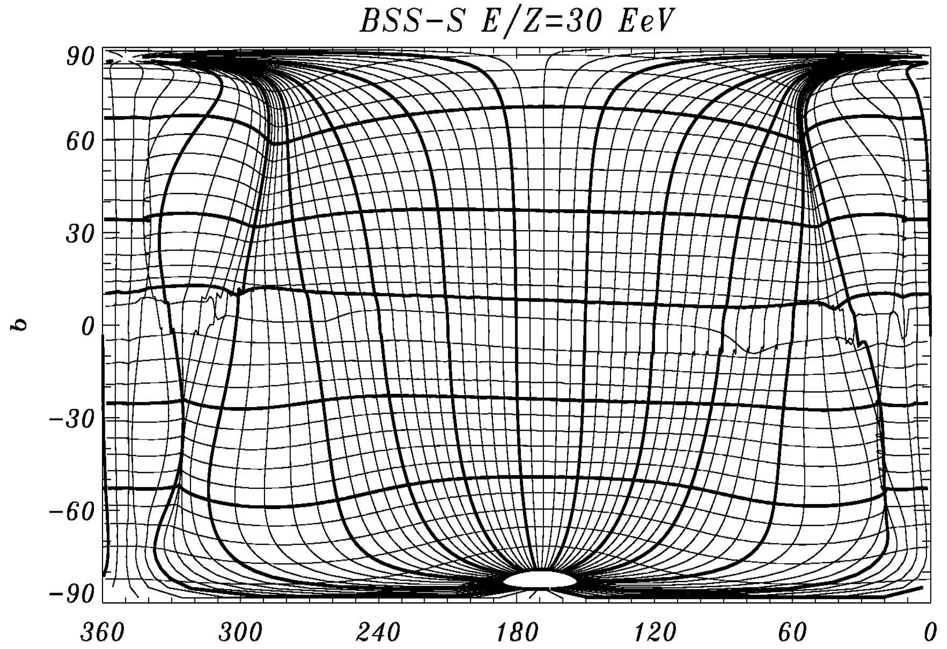


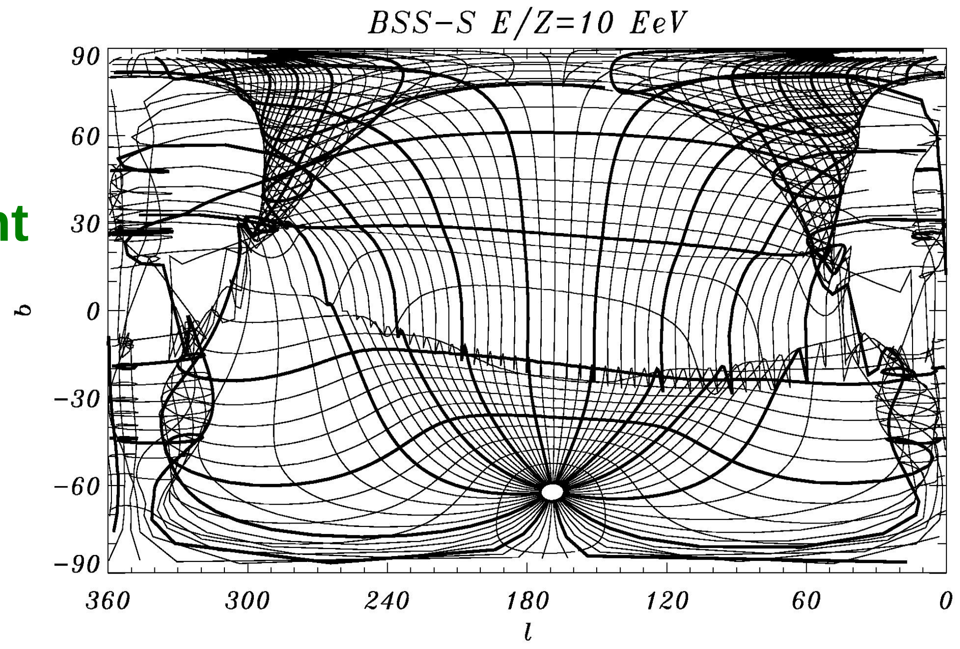
Multiple images can appear

Sky as seen on Earth



Sky projected into the halo





For every fold, two new images are present

sky stretching → demagnification

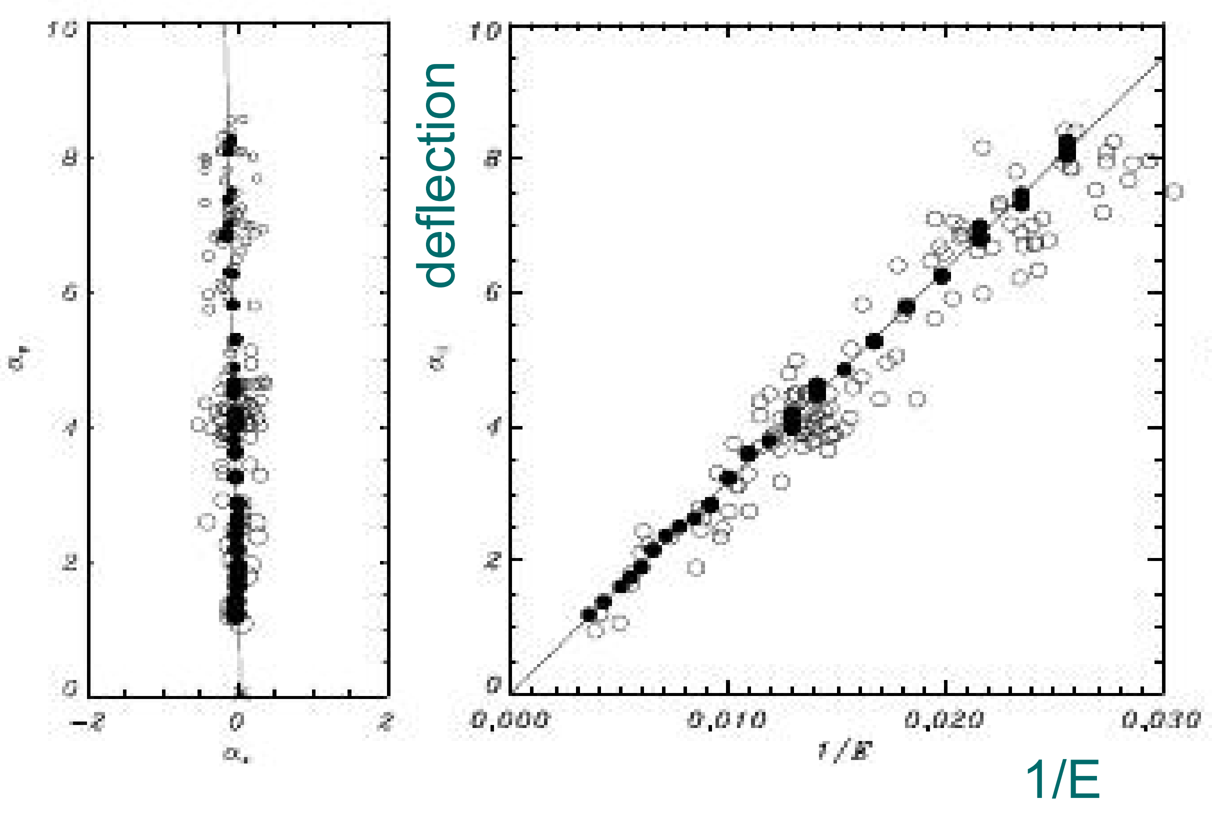
sky compression → magnification

at folds (caustics) magnification diverges

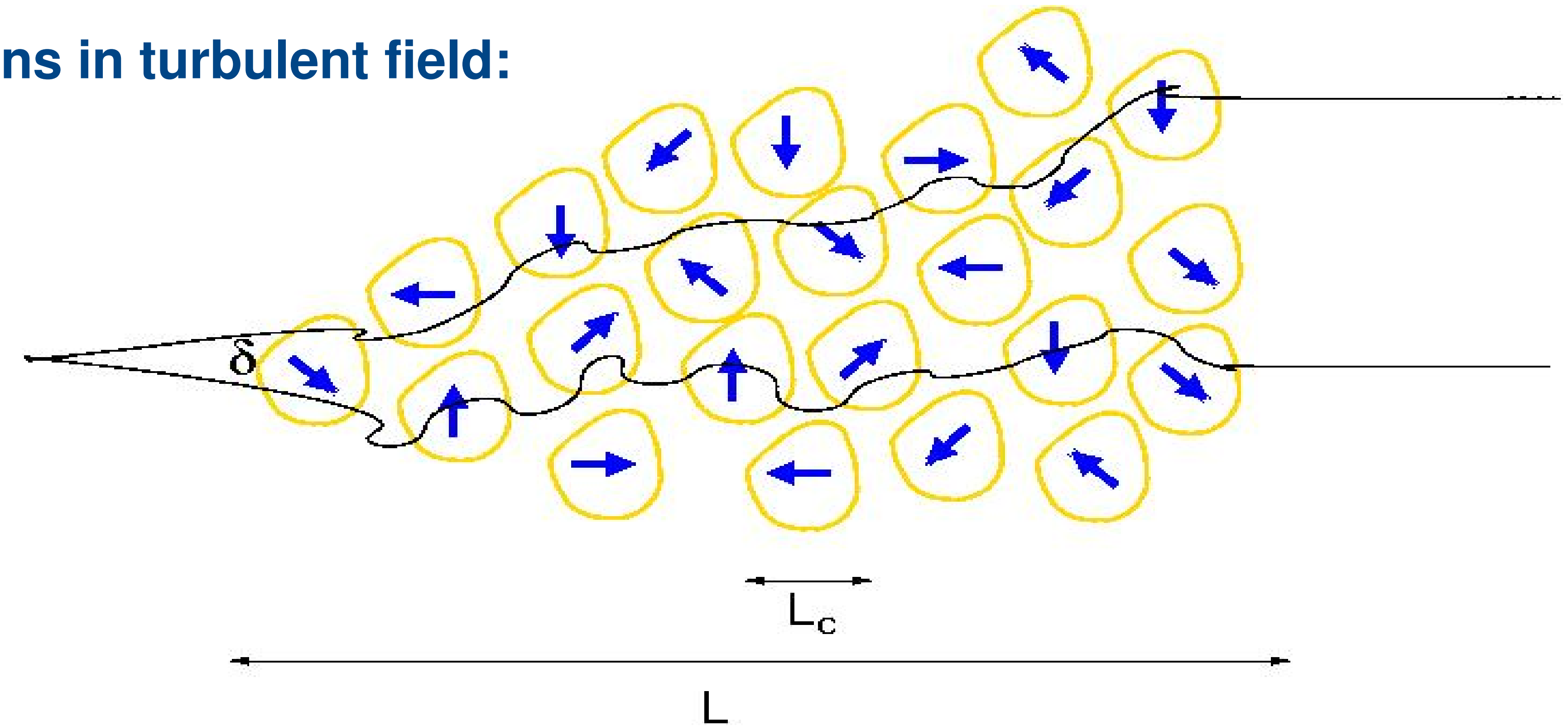
Magnetic field reconstruction

If several CR with different energies coming from one sources are detected it would be possible to measure the integrated perpendicular component of the magnetic field along the CR trajectory

$$\delta \simeq 8.1^\circ \frac{40\,\mathrm{EeV}}{E/Z} \boxed{\left| \int_0^L \frac{\mathrm{d}\mathbf{s}}{3\,\mathrm{kpc}} \times \frac{\mathbf{B}}{2\,\mu\mathrm{G}} \right|}$$



Deflections in turbulent field:



Random walk $\rightarrow \delta_{rms}$ = sqrt(n of deflections) x typical deflection in one domain

$$\delta_{rms} \simeq \sqrt{\frac{L}{L_c}}\frac{ZeB_{rms}L_c}{E} \simeq 1^o \frac{10^{19}\,eV}{E/Z}\frac{B_{rms}}{\mu G}\sqrt{\frac{L}{kpc}}\sqrt{\frac{L_c}{50\ pc}}$$

L: distance traversed in B field $\qquad$ L_c: coherence length

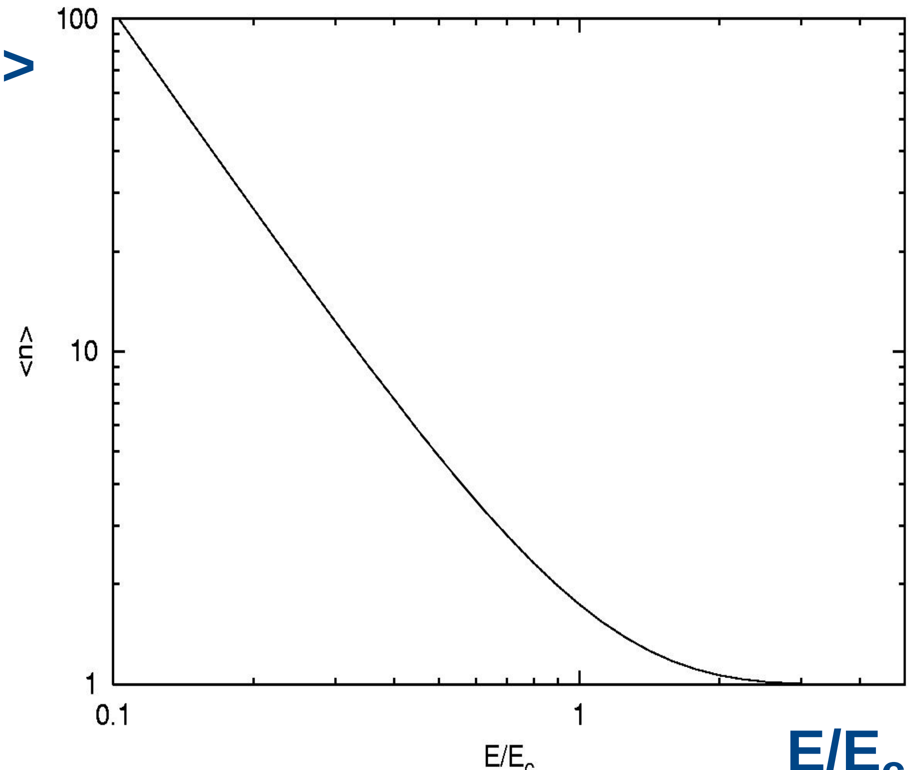
For $B_{rms} \sim B_{reg}$, deflections are smaller than those produced by the regular field, but can dominate the magnetic lensing effects

Multiple images appear below a critical energy E_c, such that typical transverse displacements among different paths become of order the correlation length of the B field ($\delta_{rms} \sim L_c/L$)

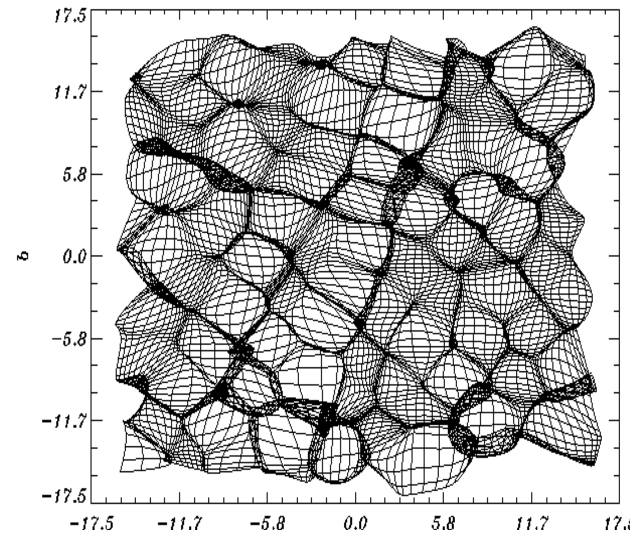
typically $E_c \sim 4\times10^{19}$ eV Z ($B_{rms}/5\mu G$) (L/2 kpc)$^{3/2}$ (L_c/50 pc)$^{-1/2}$

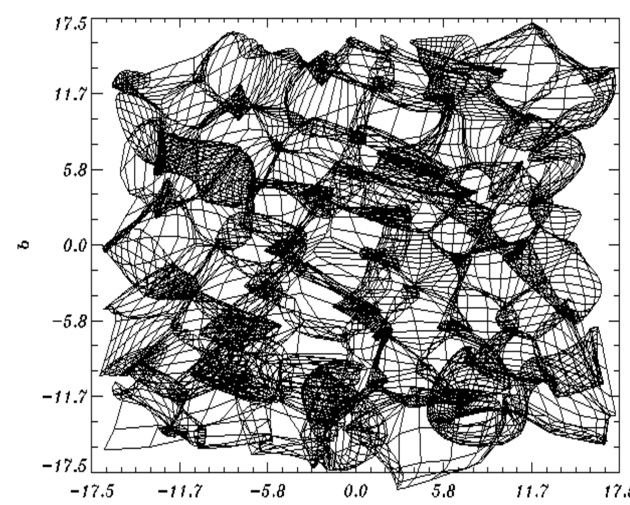
for $E \ll E_c$, the number of images grows exponentially

<n>



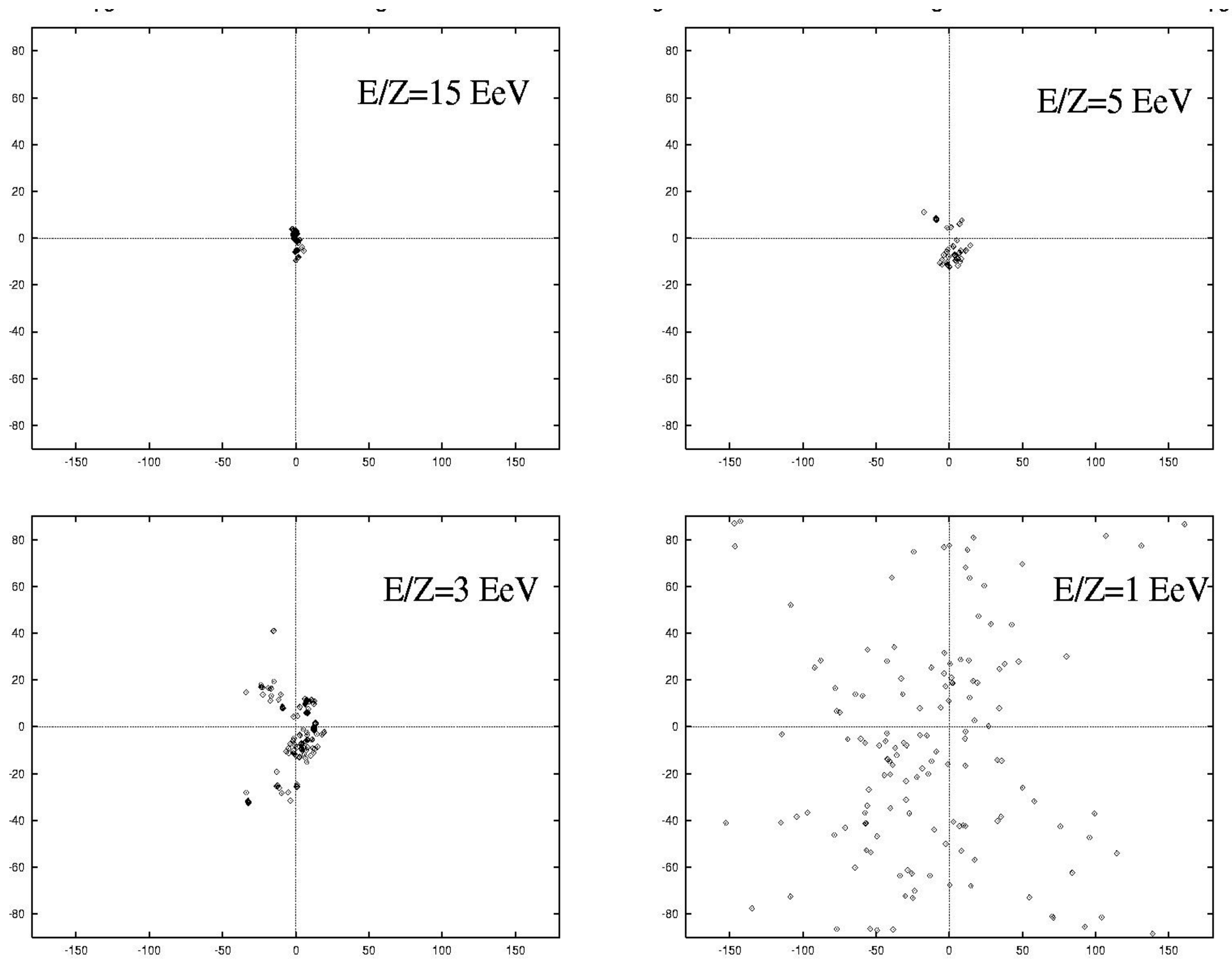
E/E_c





D Harari, S M, E. Roulet , F. Sanchez '02

The scintillation regime



A regime is reached with a large number of images, spread over $\Delta\alpha \sim \delta_{rms}$ and with <A> ~ 1 (like twinkling stars)

COSMIC RAYS FROM ONE SOURCE LOOK DIFFERENT ACCORDING TO THEIR ENERGY

DIFFUSION REGIME	SCINTILLATION REGIME	SEVERAL IMAGES	ONE IMAGE
$r_L < L_c$		$\frac{L_c}{3L} < \delta_{rms} < \frac{2L_c}{L}$	$\delta_{rms} \ll \frac{L_c}{L}$
TURBULENT DIFFUSION AND DRIFTS	$\langle n \rangle \gg 1$ $\langle A \rangle \sim 1$ $\Delta\alpha \sim \delta_{rms}$	LENSING PEAKS	SMALL DEFLECTION

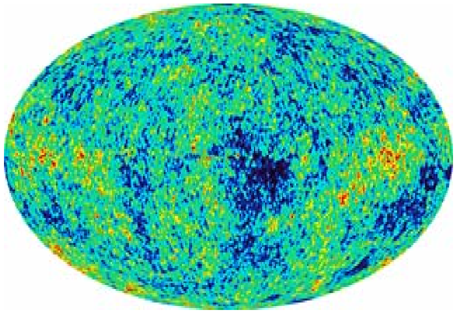
E →

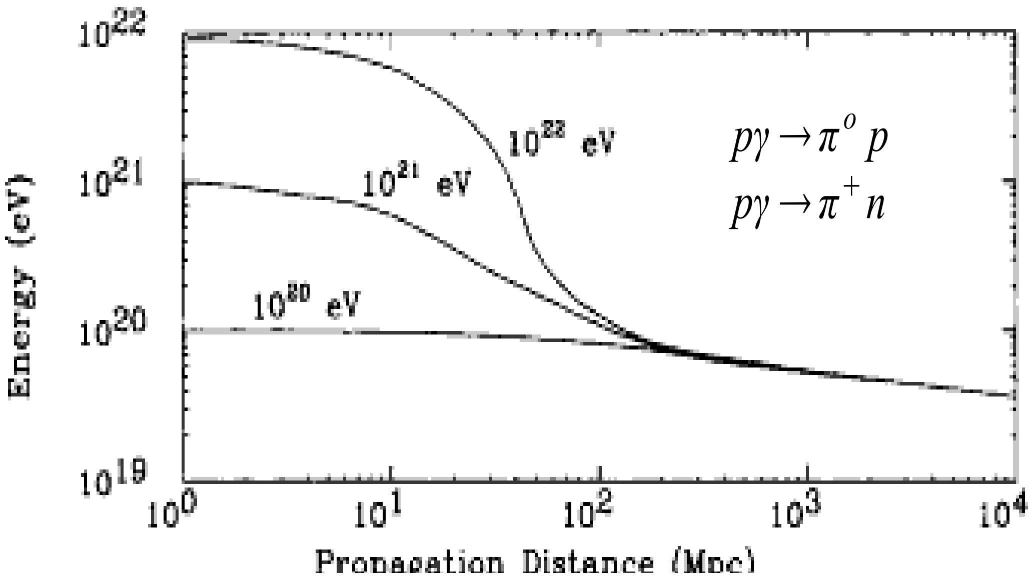
← GALACTIC

EXTRAGALACTIC →

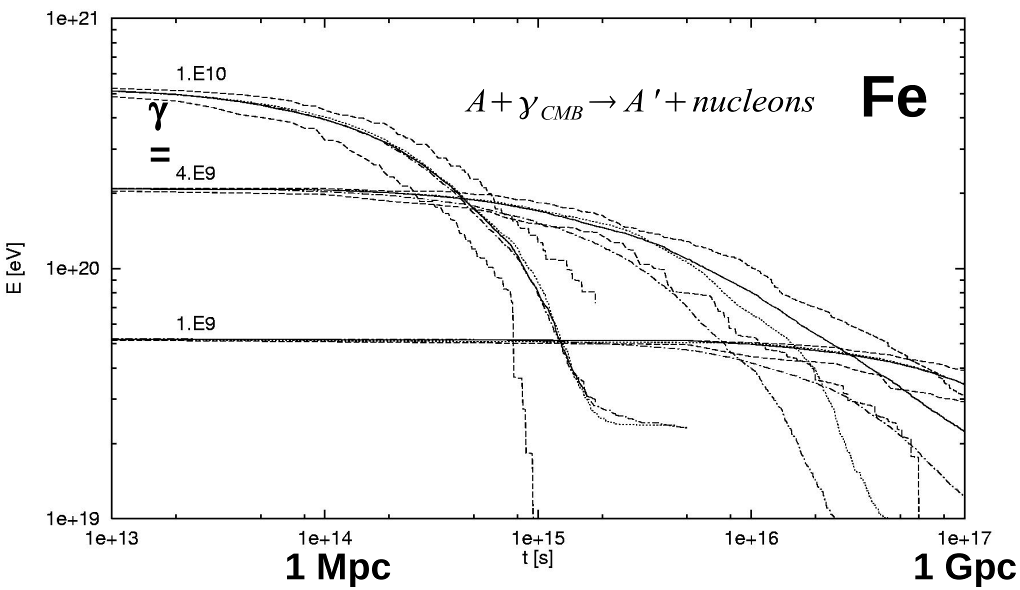
The Greisen-Zatsepin-Kuzmin effect (1967)

AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND





PROTONS WITH E > 6×10^{19} eV CAN NOT ARRIVE FROM D > 200 Mpc



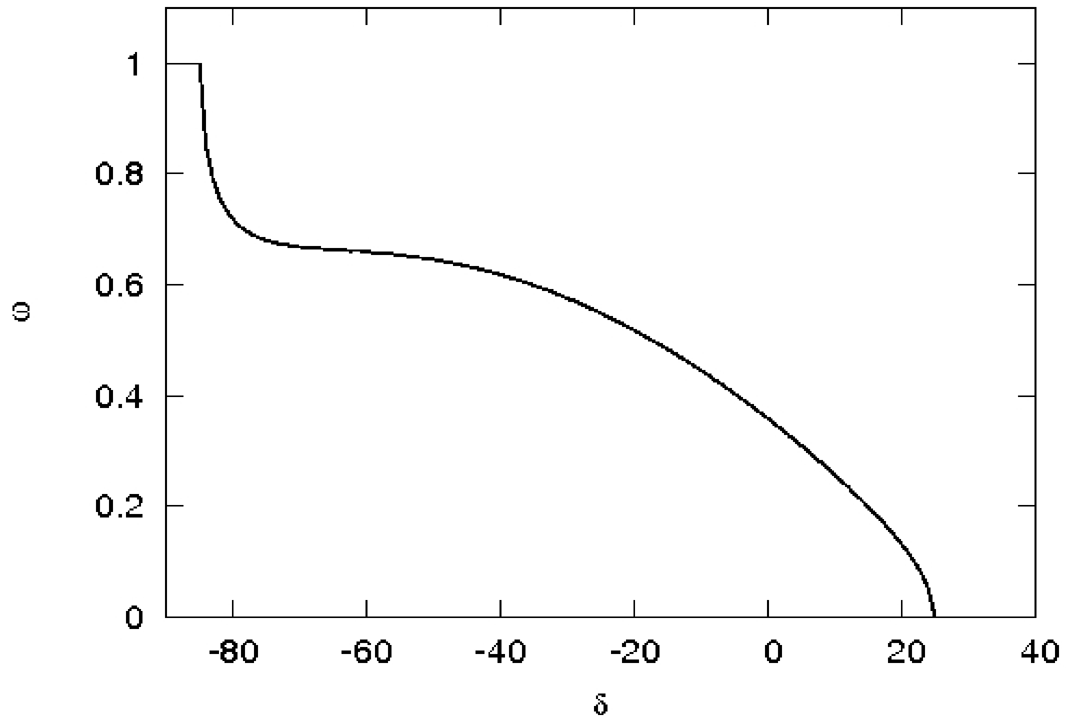
For Fe nuclei:
after ~ 200 Mpc the leading fragment has E < 6×10^{19} eV

ligther nuclei get disintegrated on shorter distances

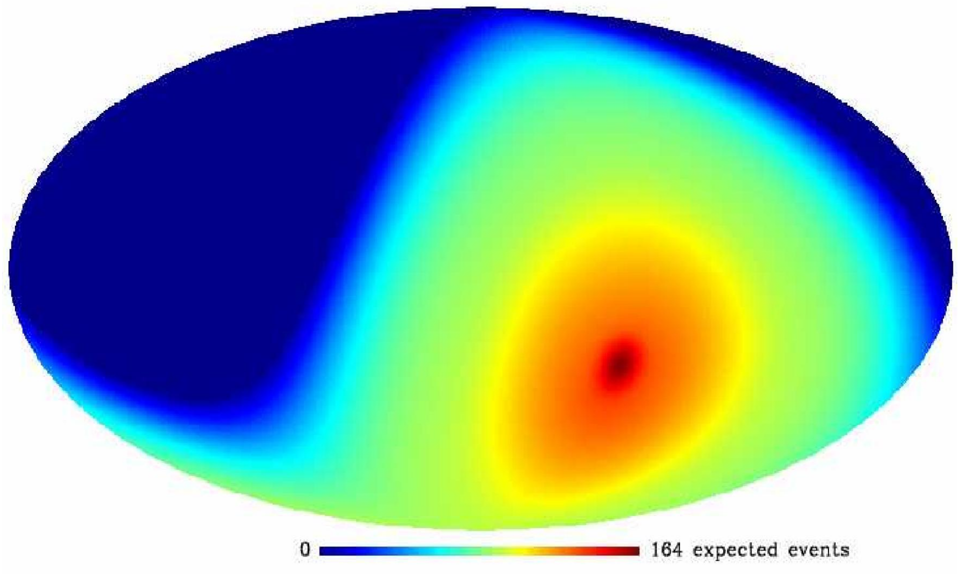
EXPERIMENTAL EXPOSURE

For any anisotropy analysis it is very important to have a good estimate of the expectation in the isotropic case.
The exposure measures the time integrated effective collecting area in units of km^2 yr. For each direction of the sky $\omega(\delta,\alpha)$ gives the relative exposure
For a detector in continuous operation it is uniform in RA $\rightarrow$ $\omega(\delta)$

If the detector is fully efficient for particles arriving with zenith angle $\theta < \theta_m$, the exposure has only $\cos\theta$ modulation due to the change in the effective area.



galactic coordinates



Example: detector at lat= -35 (Auger)

ANISOTROPIES: different signals are expected at different energies

E

small magnetic deflections and small GZK horizon → events coming from 'nearby' sources
- small scale clustering of events from the same source
- correlation of events with a population of source candidates
- intermediate scale clustering reflecting the clustering of local sources

GZK

deflections increase and GZK horizon increase
- CR flux expected to be more isotropic
- Some intermediate scale clustering /correlation with source distribution

ANKLE

large scale anisotropies from diffusion and drift
- Predictions depend on the model of the knee and anisotropy measurement can help to distinguish among them:
  - knee due to limit of galactic p acceleration: anisotropy decrease for increasing energy if Xgal CR are isotropic
  - knee due to more efficient escape of CR from the galactic magnetic field → CR transport change from dominated by diffusion to drift: anisotropy increases for increasing energy

KNEE

For neutral component: point-like signal & correlation with source

Large scale anisotropy from motion of the detector

LARGE SCALE ANISOTROPIES

Intensity $\mathbf{I}$: number of particles per unit solid angle that pass per unit time through a unit of area perpendicular to the direction of observation $\hat{\mathbf{u}}$

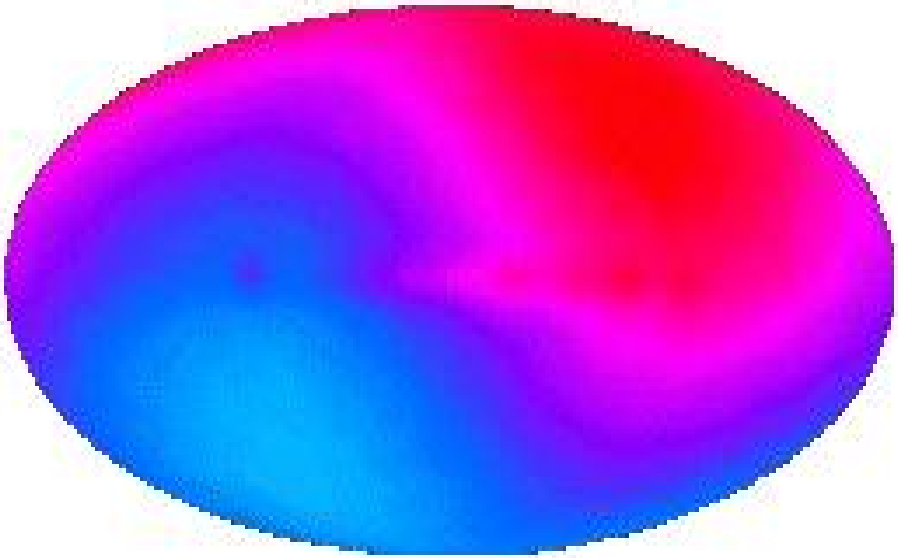
Differential (spectral) intensity $\mathbf{I(E)} \rightarrow$ I(E) dE is the intensity of particles with energy in the interval from E to E+dE

Dipole in the direction $\hat{\mathbf{j}}$:

$$I\,(\hat{\mathbf{u}}) = I_0 + I_1\, \hat{\mathbf{j}} \cdot \hat{\mathbf{u}}$$

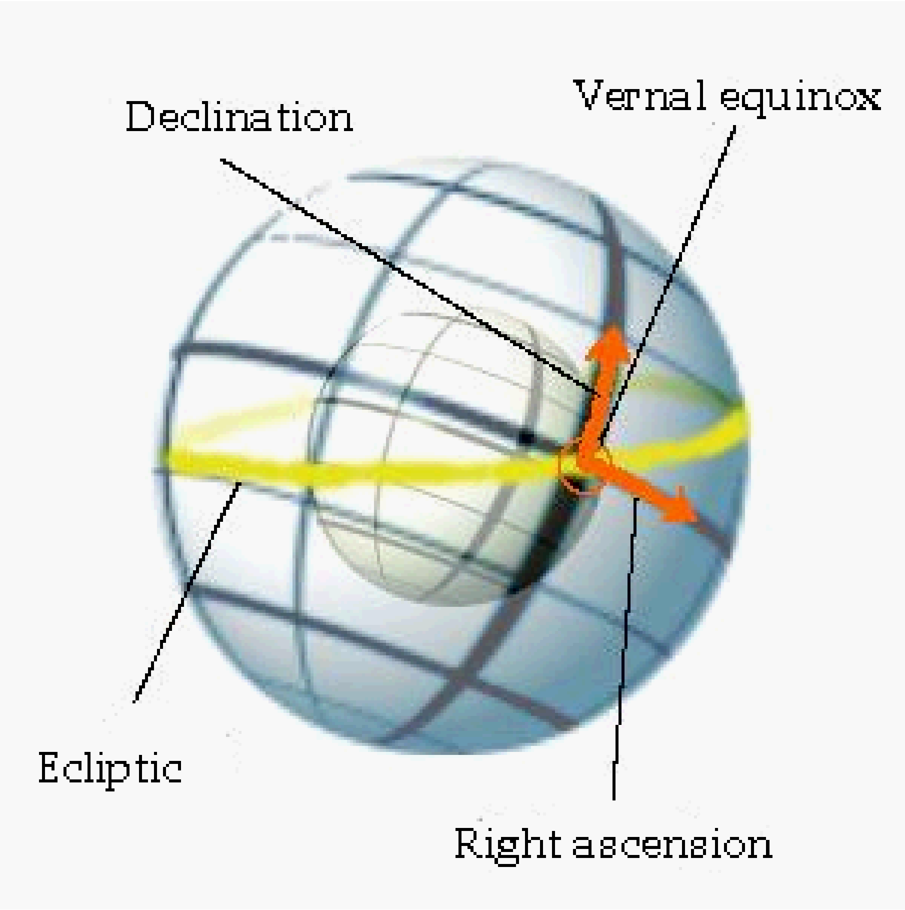
Amplitude

$$\Delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{I_1}{I_0}$$



LARGE SCALE ANISOTROPY MEASUREMENTS: 1- D ANALYSIS

Study only the RA harmonic dependence (of full dataset or a fixed declination band)
- The rotation of the Earth leads to a uniform exposure in RA for a stable operating detector
- Some experiments cannot reliably determine the δ dependence of the exposure



Celestial coordinates in equatorial system

Right ascension: α (like longitude)

Declination: δ (like latitude)

Rayleigh analysis: for n events with right ascension α_i

$$I(\alpha) = I_0 \left(1 + r_1 \cos(\alpha - \phi_1) + r_2 \cos(2(\alpha - \phi_2) + \ldots \right)$$

$$a_k = \frac{2}{n} \sum_{i=1}^{n} \cos(k\alpha_i)$$

$$b_k = \frac{2}{n} \sum_{i=1}^{n} \sin(k\alpha_i)$$

amplitude $\boxed{r_k = \sqrt{a_k^2 + b_k^2}}$

phase $\boxed{\phi_k = \arctan\left(\frac{b_k}{a_k}\right)}$

Significance: probability that an amplitude larger or equal than the observed r_k arises from an isotropic dataset

a_k and b_k Gaussians with $\sigma^2 = (2/n)$

$$\boxed{P(\geqslant r_k) = \exp(-n r_k^2/4)}$$

The Rayleigh amplitude in RA r_1 is proportional to the equatorial component of the dipole, but its value depends on the latitude and exposure of the observatory.

$$r_1 = \frac{A\,\Delta_\perp}{1 + B\,\Delta_z} \qquad A = \frac{\int_{\delta_{min}}^{\delta_{max}} \mathrm{d}\delta\ \omega(\delta)\cos^2\delta}{\int_{\delta_{min}}^{\delta_{max}} \mathrm{d}\delta\ \omega(\delta)\cos\delta} \qquad B = \frac{\int_{\delta_{min}}^{\delta_{max}} \mathrm{d}\delta\ \omega(\delta)\cos\delta\sin\delta}{\int_{\delta_{min}}^{\delta_{max}} \mathrm{d}\delta\ \omega(\delta)\cos\delta}$$

A and B can be estimated from the data:

$A \simeq <\cos\delta>$ $\qquad\qquad$ $B \simeq <\sin\delta>$

$$\boxed{r_1 = \frac{\Delta_\perp\langle\cos\delta\rangle}{1+\Delta_z\langle\sin\delta\rangle} \simeq \Delta_\perp\langle\cos\delta\rangle}$$

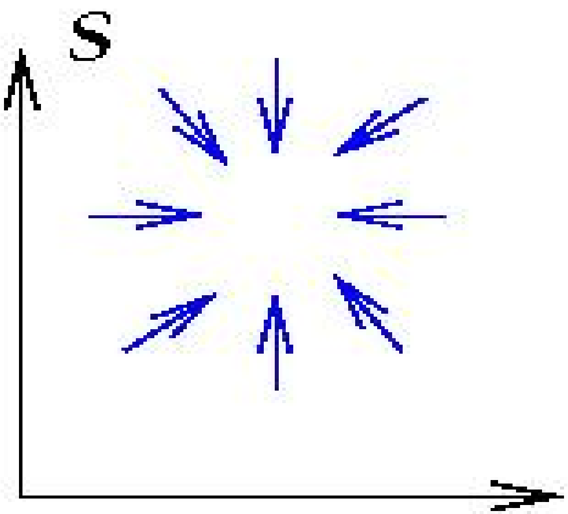
with $\Delta_\perp = \Delta \sin\delta_\Delta$
$\Delta_z = \Delta\cos\delta_\Delta$

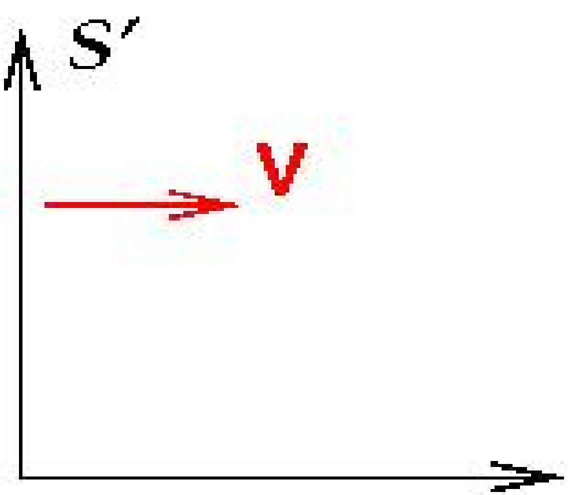
if $\Delta_z << 1$

- Reporting the estimation of the equatorial component of the dipole, $\Delta_\perp \simeq r_1 / <\cos\delta> \rightarrow$ allows to compare results from different observatories.
- ϕ_1: RA of the dipole

Compton Getting effect

If the CR flux is isotropic in a reference system S and the observer is moving with respect to that coordinate system with a velocity **V**, he will measure an anisotropic flux → DIPOLE





f(**p**,**r**) → distribution func. of part. in S, f ' → in S'

Lorentz invariance → f(**p**,**r**) = f '(**p'**,**r'**)

$$\vec{p}\,'=\gamma_V(\vec{p}-\frac{p}{u}\vec{V}) \qquad (V \ll c\,,\gamma_V \sim 1)$$

u: velocity of the relativistic particles

$$f\,'(\vec{p}\,')=f(\vec{p}\,')-\frac{\partial f}{\partial \vec{p}\,'}\cdot\vec{V}\,\frac{p}{u}=f\,(1-\frac{\vec{V}\cdot\vec{p}}{u\,p}\,\frac{\partial \ln f}{\partial \ln p})$$

I (t,E,**r**,**n**) = p^2 f(t,**r**,**p**) → ln I = 2 ln p – ln f

$$\frac{\partial \ln f}{\partial \ln p}=\frac{\partial \ln I}{\partial \ln p}-2\simeq\frac{\partial \ln E}{\partial \ln p}\,\frac{\partial \ln I}{\partial \ln E}-2=\frac{E^2-m^2c^4}{E^2}(-\gamma)-2\simeq-(\gamma+2)$$

for particles with spectrum I = $E^{-\gamma}$

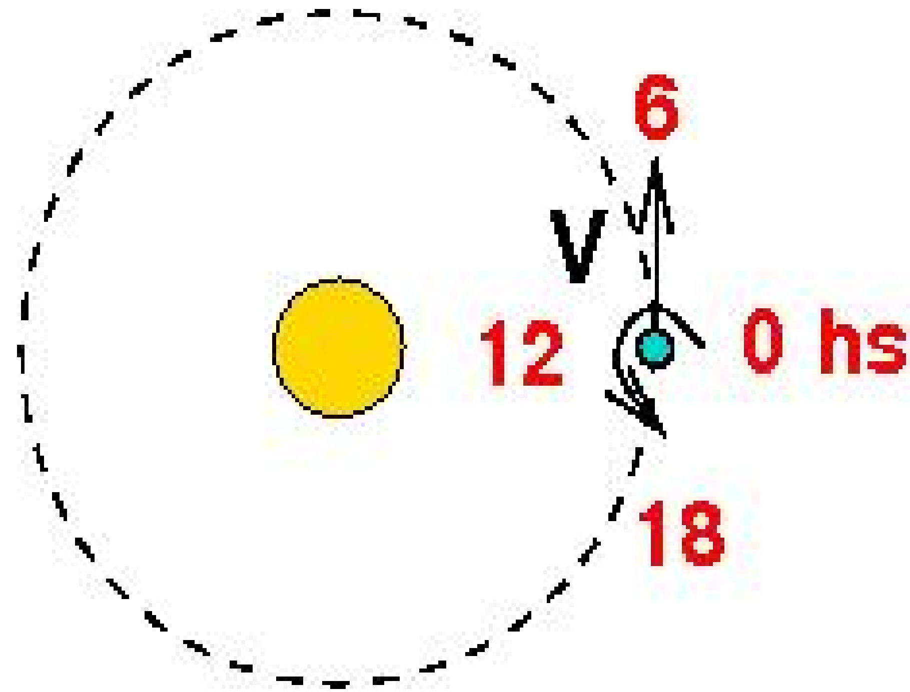
$$\boxed{\mathbf{I' = I\,(\,1 + (V/u)\,(\gamma+2)\,\cos\theta)}}$$

(ex: V = 100 km/s → Δ = 1.6 x 10^{-3})

CG from orbital motion of the Earth around the Sun

Rotation velocity V = 29.8 km/s

A vertically looking detector sees
a modulation of the intensity
with the solar time



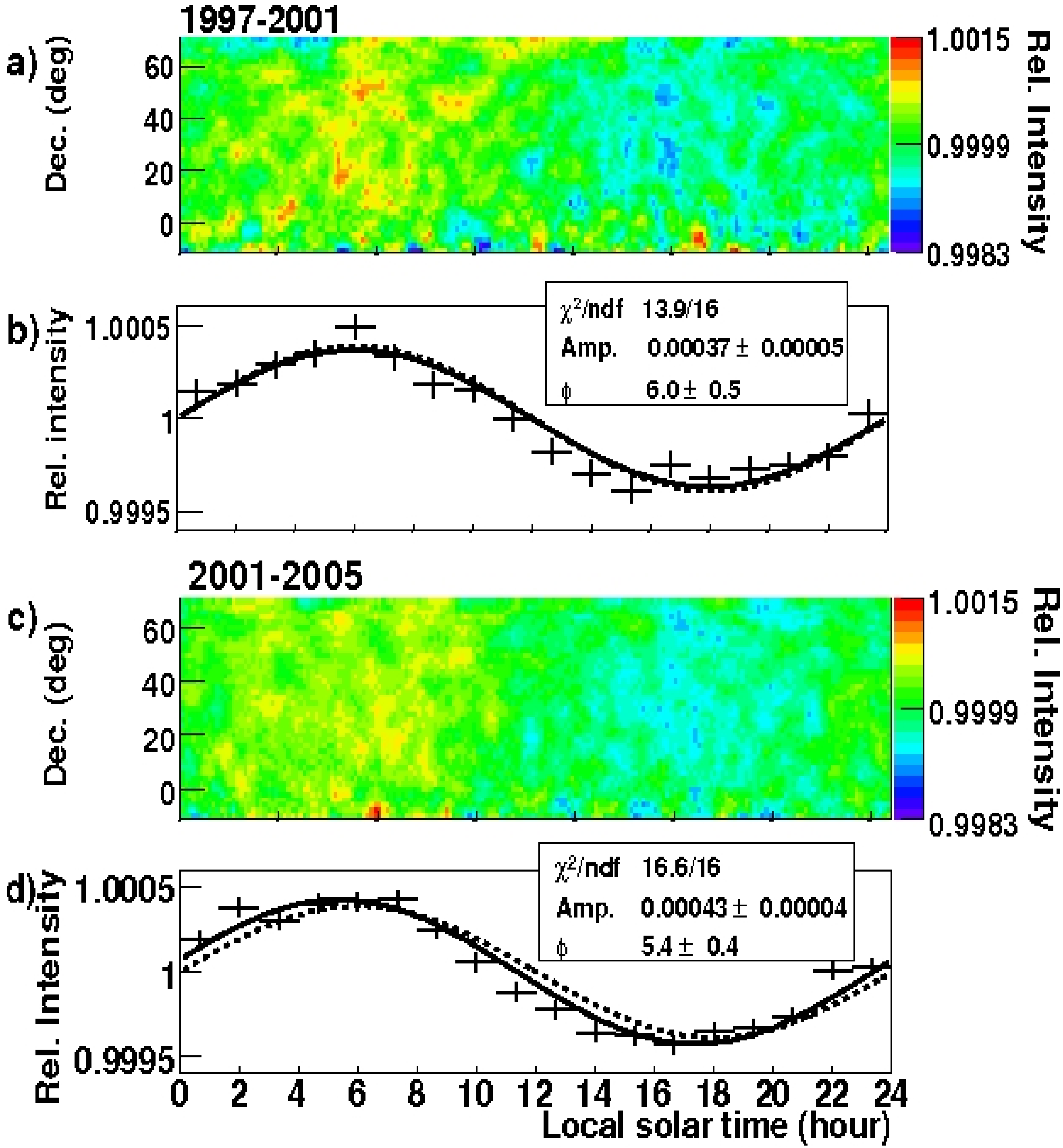
$I(t) = I_0\ (1 + r \cos((t - t_0)\ 2\pi/24\text{hs}))$

maximum at t_0 = 6 hs

Amplitude depends on the detector
latitude and can be as large as

$\Delta = (V/c)\ (\gamma + 2) \sim 5 \times 10^{-4}$

Solar time CR intensity map and Rayleigh amplitude for Tibet AS (E~10 TeV)



Amenomori '06

Best fit → solid line
CG exp → dashed line

Good agreement for the solar frequency, where the expectations are well known: this gives confidence that the measurements are reliable for the sidereal frequency analysis, where expectations are uncertain.

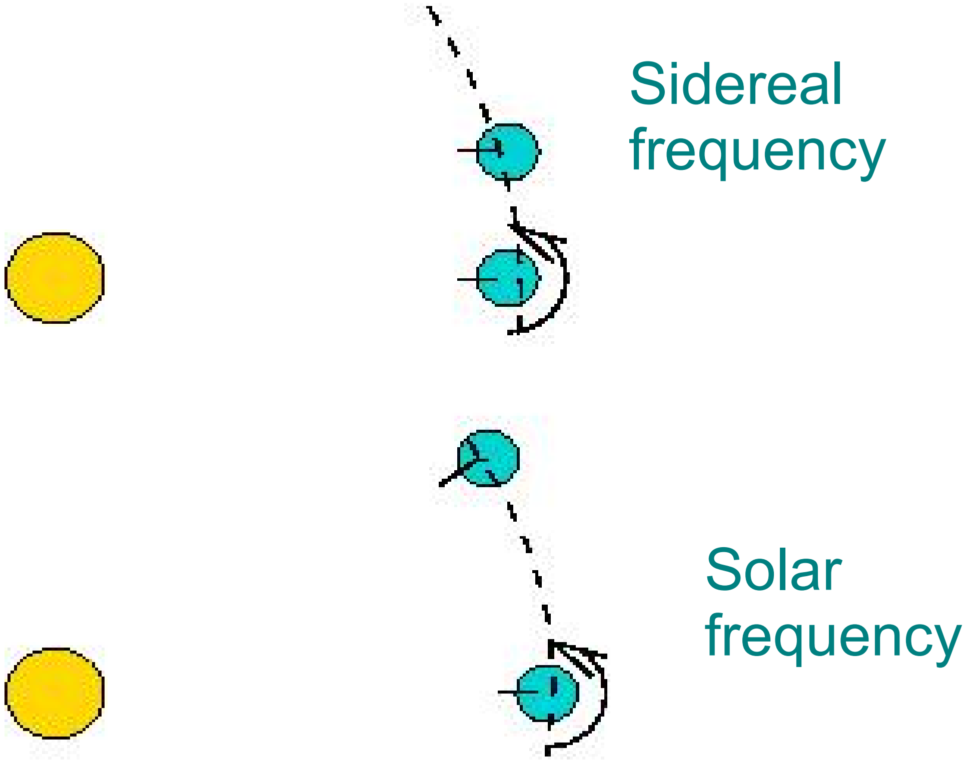
Also used to estimate the spectral index
γ = 3.03 ± 0.55 (6-40 TeV)

Amenomori '07

CG from the motion of the Solar system

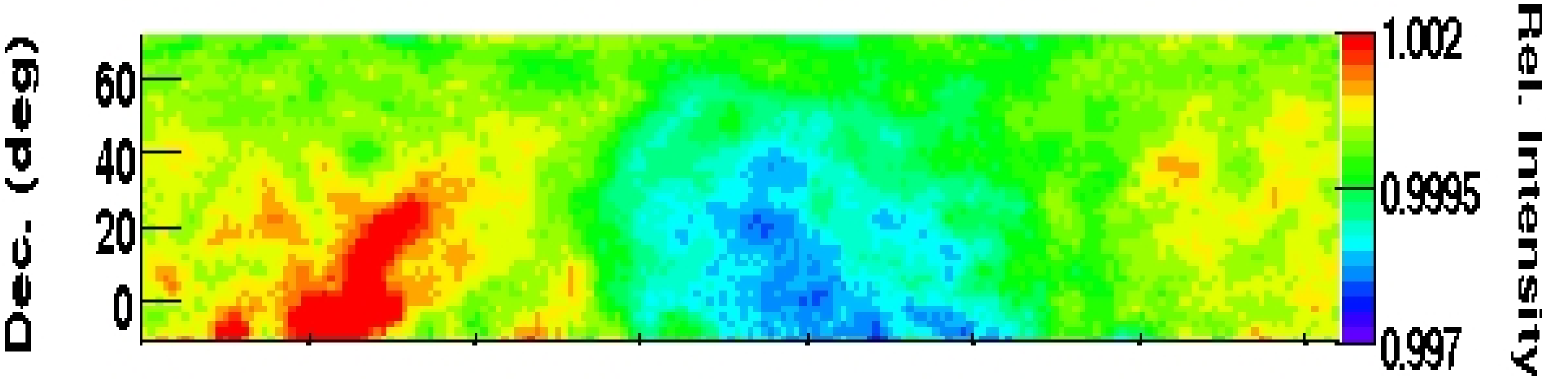
Motion of the solar system with respect to the rest frame of CR → modulation in the sidereal time frequency (RA).

The solar day is bit longer than the sidereal day
(1 year = 365.24 solar days = 366.24 sidereal days)



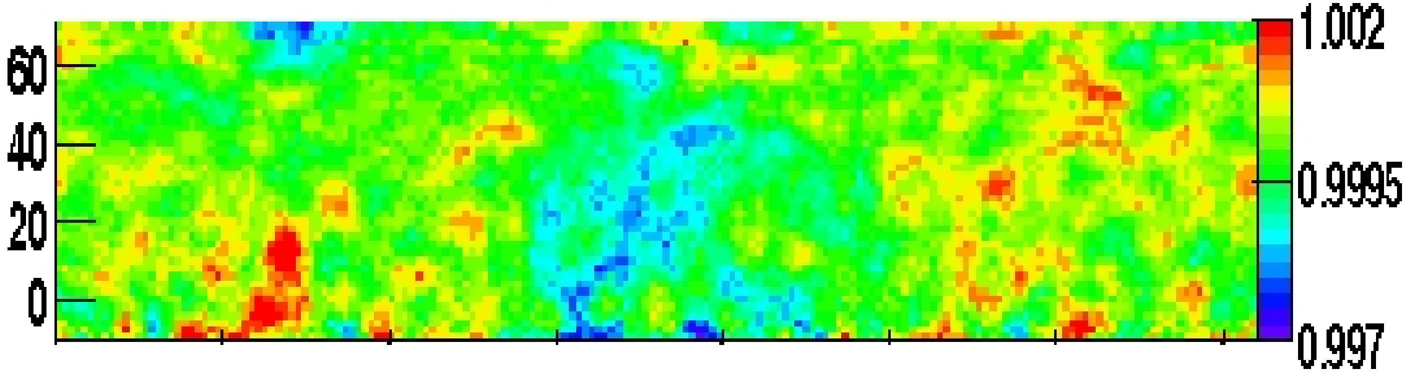
The sidereal time (or RA) modulation has the most interesting information

Sidereal frequency anisotropies (right ascension)

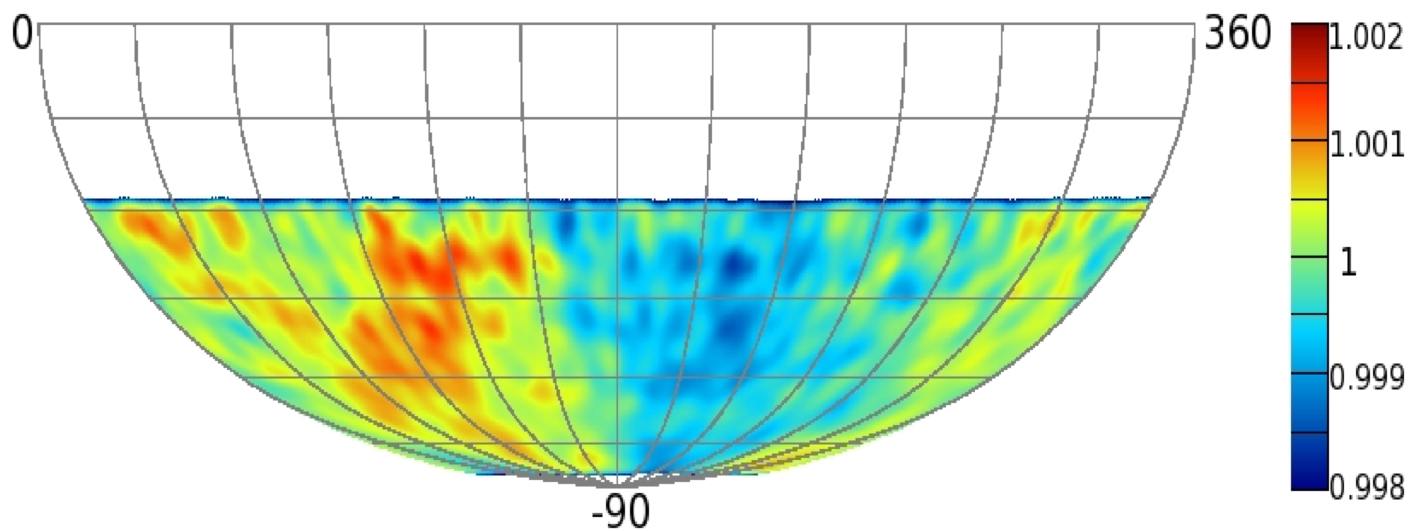


Tibet

E =12 TeV



E = 50 TeV

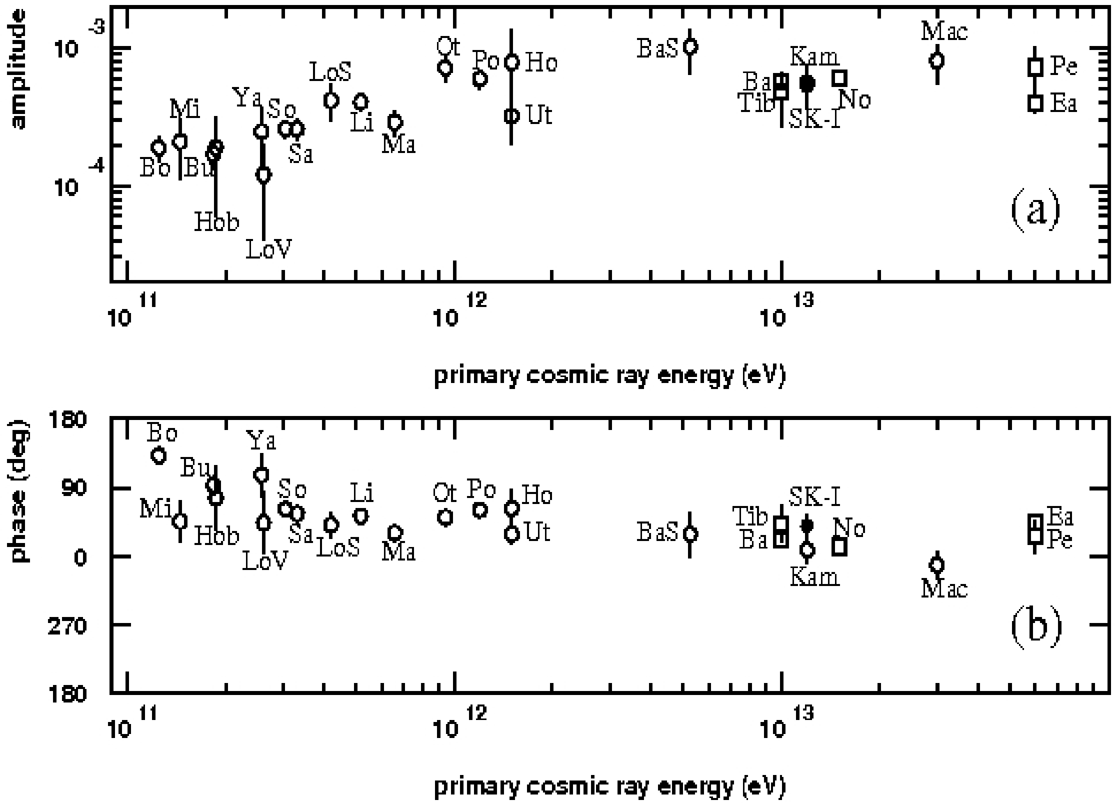


E = 20 TeV

IceCube '10

Consistent anisotropy in the north and south hemispheres, origin not well understood

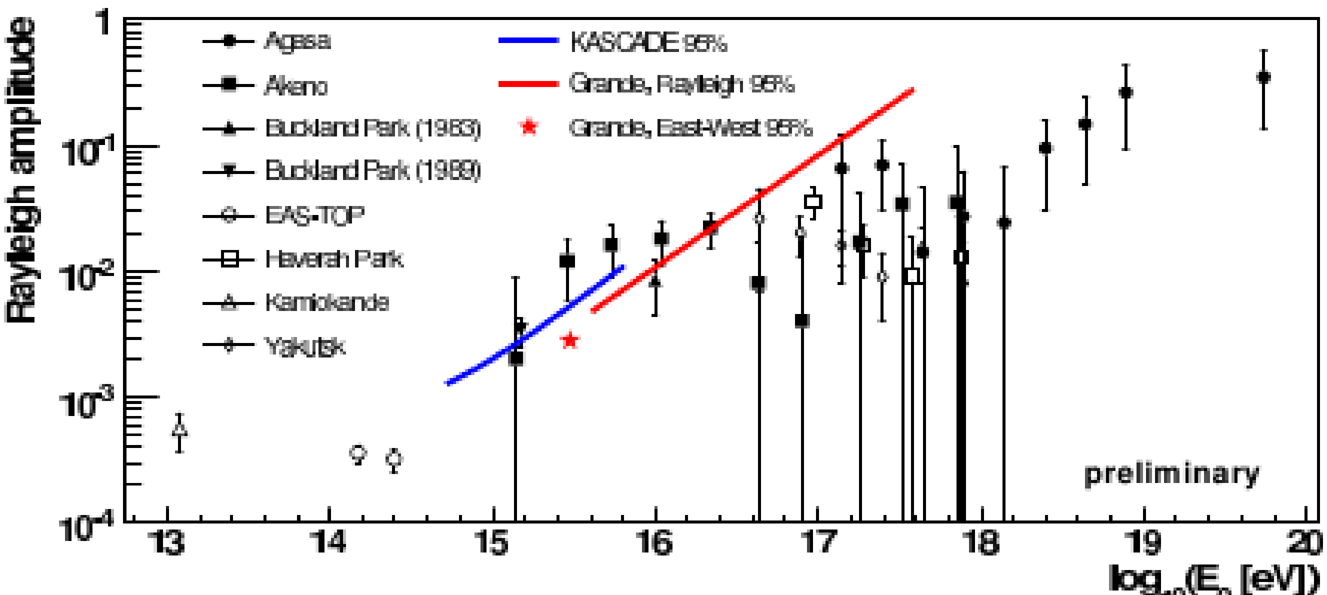
Results of sidereal harmonic analysis



Amplitude Δ = few x 10^{-4}

Velocity of solar system around the Galaxy is V ≃ 220 km/s, if CR rest frame fixed to inertial frame at GC → Δ = few x 10^{-3}

CR plasma corrotate with the local stars



Over '07

AGASA: 4% amplitude for the dipole at E > 10^{18} eV

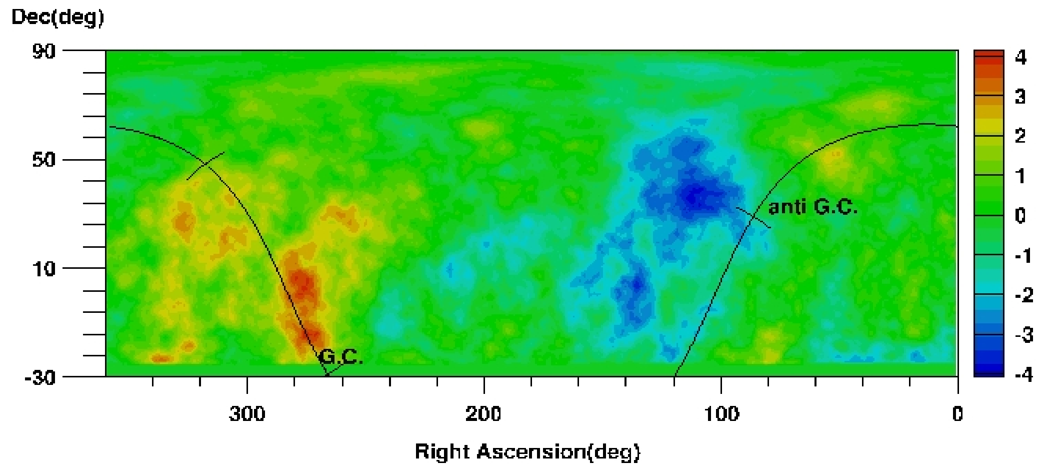
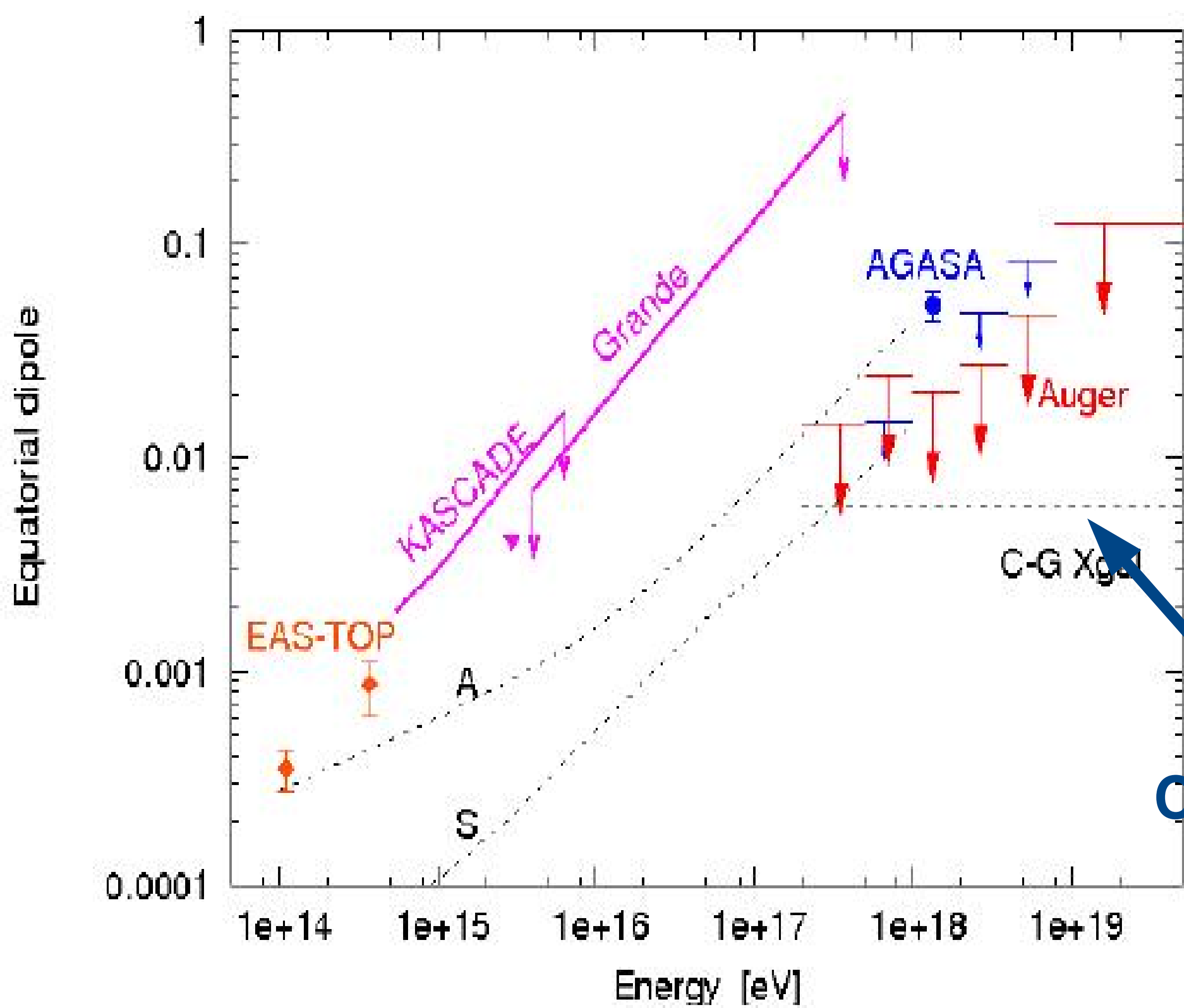


Fig. 2. The significance of event density in equatorial coordinates. The statistical significance of deviation is evaluated for each 1° grid with us. The excess and deficit can be seen with 4 σ statistical significance near the Galactic center and anti-galactic



Auger: amplitude of the dipole < 1.6% at 10^{18} eV and < 10% at 10^{19} eV

Compton-Getting of extragalactic CR isotropic in CMB frame (v = 370 km/s → $\Delta \approx 0.006$)

LECTURE 2: FURTHER TECHNIQUES & RESULTS

- Small and intermediate scale anisotropies: autocorrelation function

- Point-like and extended excesses in the sky

- The Galactic center region

- Searches for correlation with objects: crosscorrelation function, maximum likelihood, binomial probability scan, loglikelihood per event

- The UHECR anisotropy and possible sources

AUTOCORRELATION FUNCTION

Measures the excess (deficit) in the number of pairs with respect to an isotropic distribution as a function of the angle

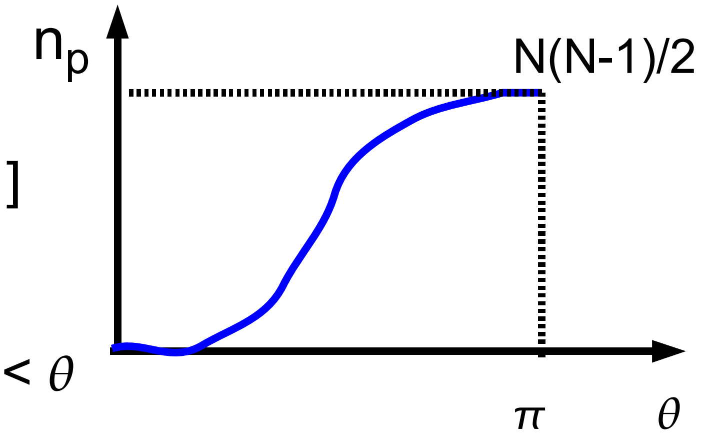
For an isotropic distribution of N points on the full sphere

$$dn_P = \frac{N(N-1)}{2}\sin(\theta)\, d\theta$$

number of pairs in [θ,θ+dθ]

$$n_P(\theta) = \frac{N(N-1)}{2}(1-\cos(\theta))$$

number of pairs with angle < θ



For partial/non-uniform sky coverage the expected number of pairs from an isotropic flux has to be computed simulating isotropic event realizations following the exposure and counting the pairs as a function of the angle

- Count the number of pairs n_p with separation < θ

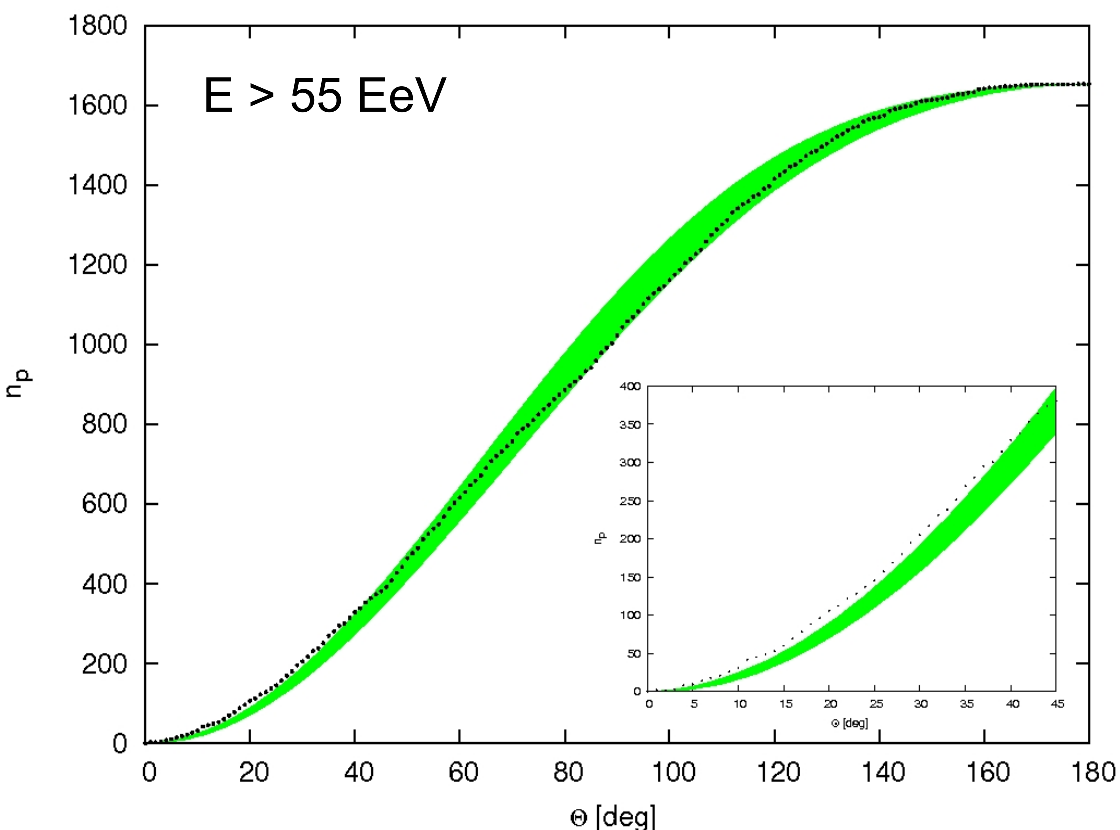
$$n_p(\theta)=\sum_{i=2}^{N}\sum_{j=1}^{i-1} H(\theta-\theta_{ij})$$

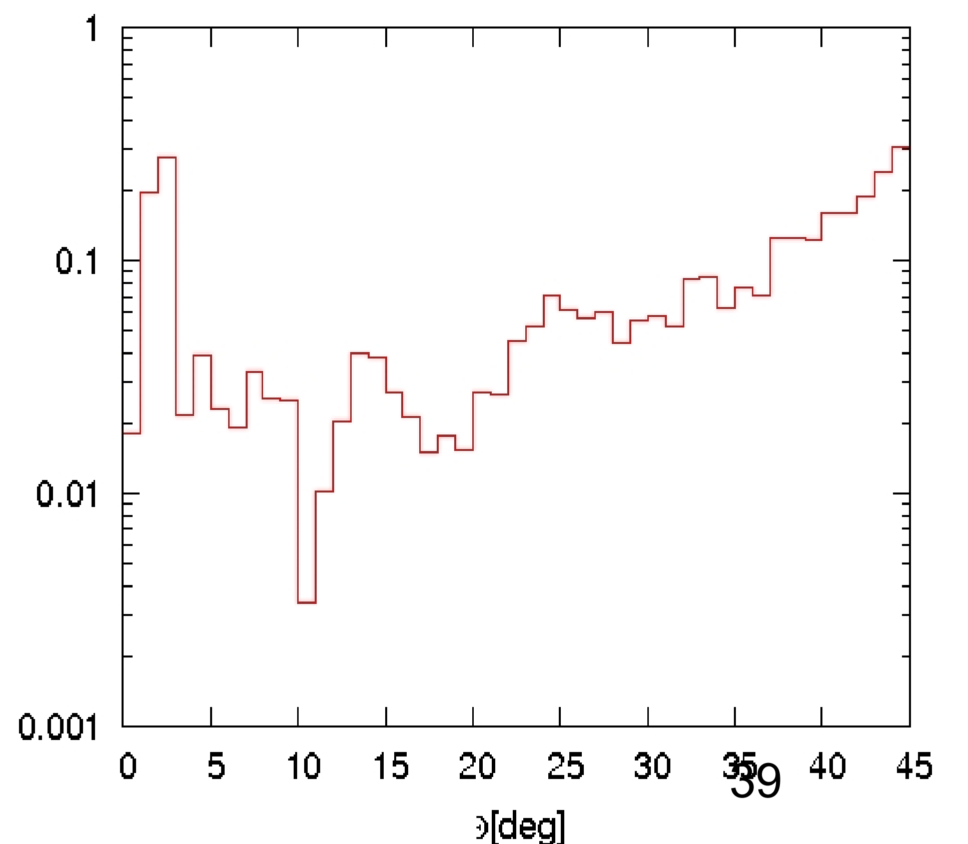
- Using Monte Carlo simulations with an isotropic distribution: obtain the expected n_{iso}

- If an excess is observed at some angular scale: how to estimate the significance? Run many simulations with the same nº of events N

Probability of observing n_p or more pairs with separation < θ = fraction of simulations with larger $n_p(\theta)$ than the data

Auger '09



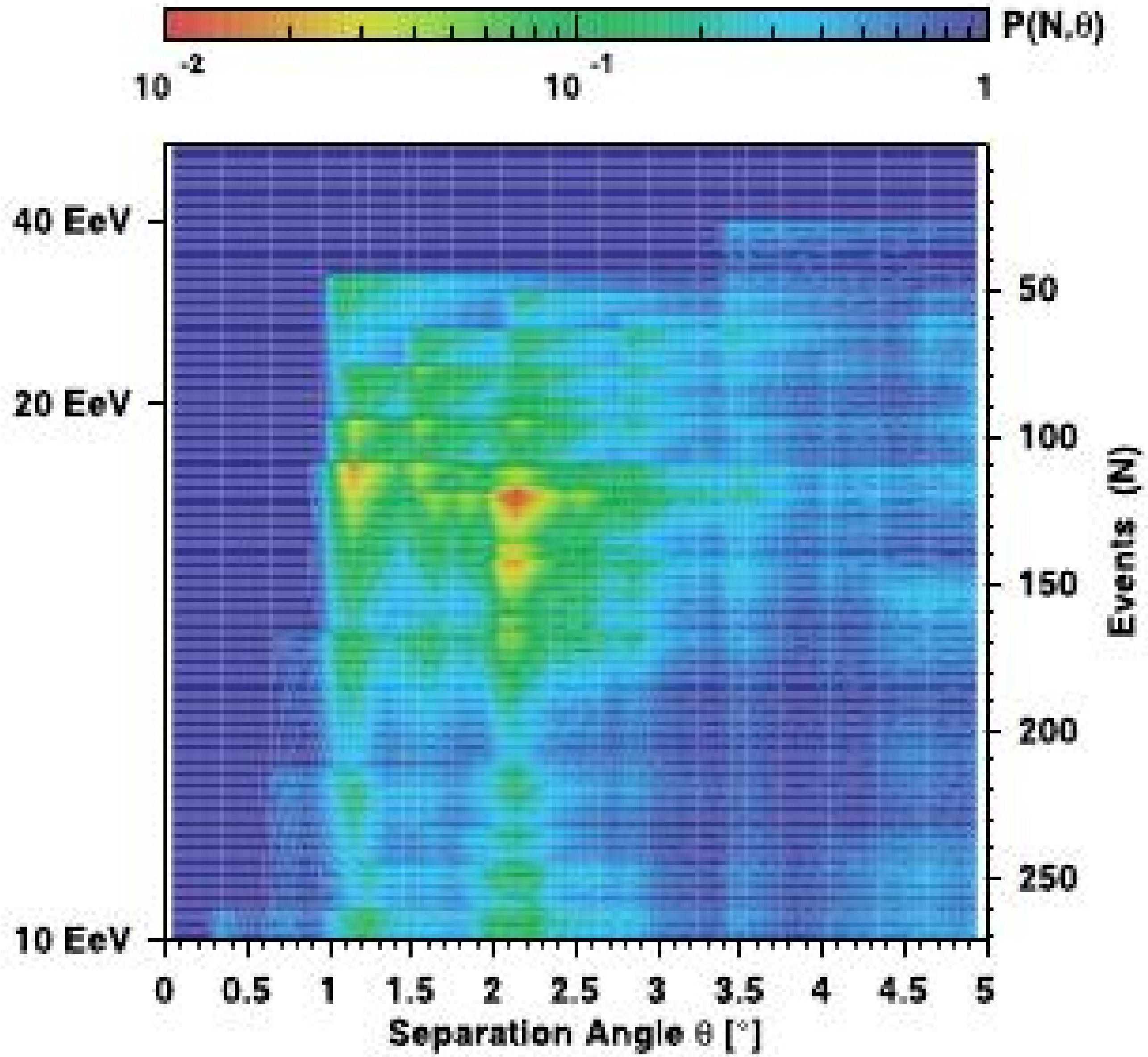


Caveat: if one looks at many angular scales, this is not a good estimation of the significance
This probability needs to be penalized for choosing a posteriori the angle where we found the largest departure from isotropy

Possible solution: do the same for a large set of isotropic simulations → for each one choose the angle with maximum departure from isotropy and compute f_{sim} (fraction of simulations with $n_p(\theta)$ larger than the value obtained in that simulation)
Chance Probability P = fraction of simulations with $f_{sim} < f_{data}$

The same problem arises if the energy threshold (or range) is not fixed a priori and we look for excesses of pairs in different E ranges
Same solution: scan the data in angle and energy and choose the values θ and E with smallest f_{data} (larger number of pairs compared to isotropic sims).
Perform the same scan in a large set of simulations → f_{sim}
Chance probability that an excess like the one observed arises by chance from an isotropic flux → P = fraction of simulations with $f_{sim} < f_{data}$

HiRes: NO evidence of clustering for any energy E >10 EeV



f_{min} = 0.019

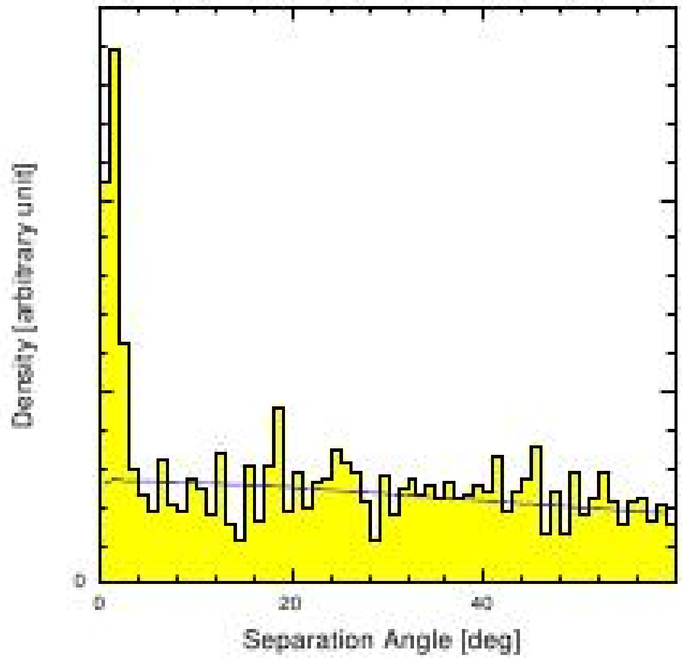
Chance probability

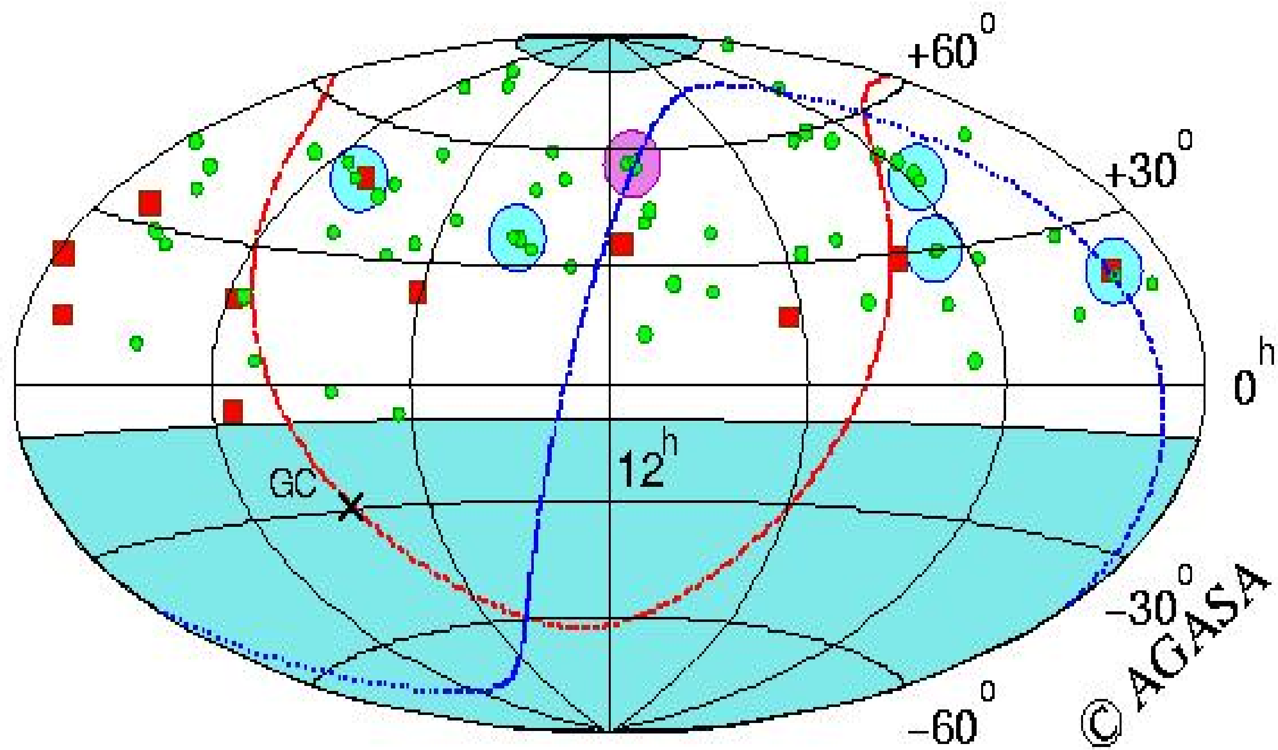
P_{ch} = 0.52

Abbasi et al. 2004

AGASA CLAIM OF CLUSTERING:

5 doublets and 1 triplet with separation $\theta < 2.5°$ out of 59 events with E > 40EeV





Takeda et al 1999,
Teshima et al. 2003

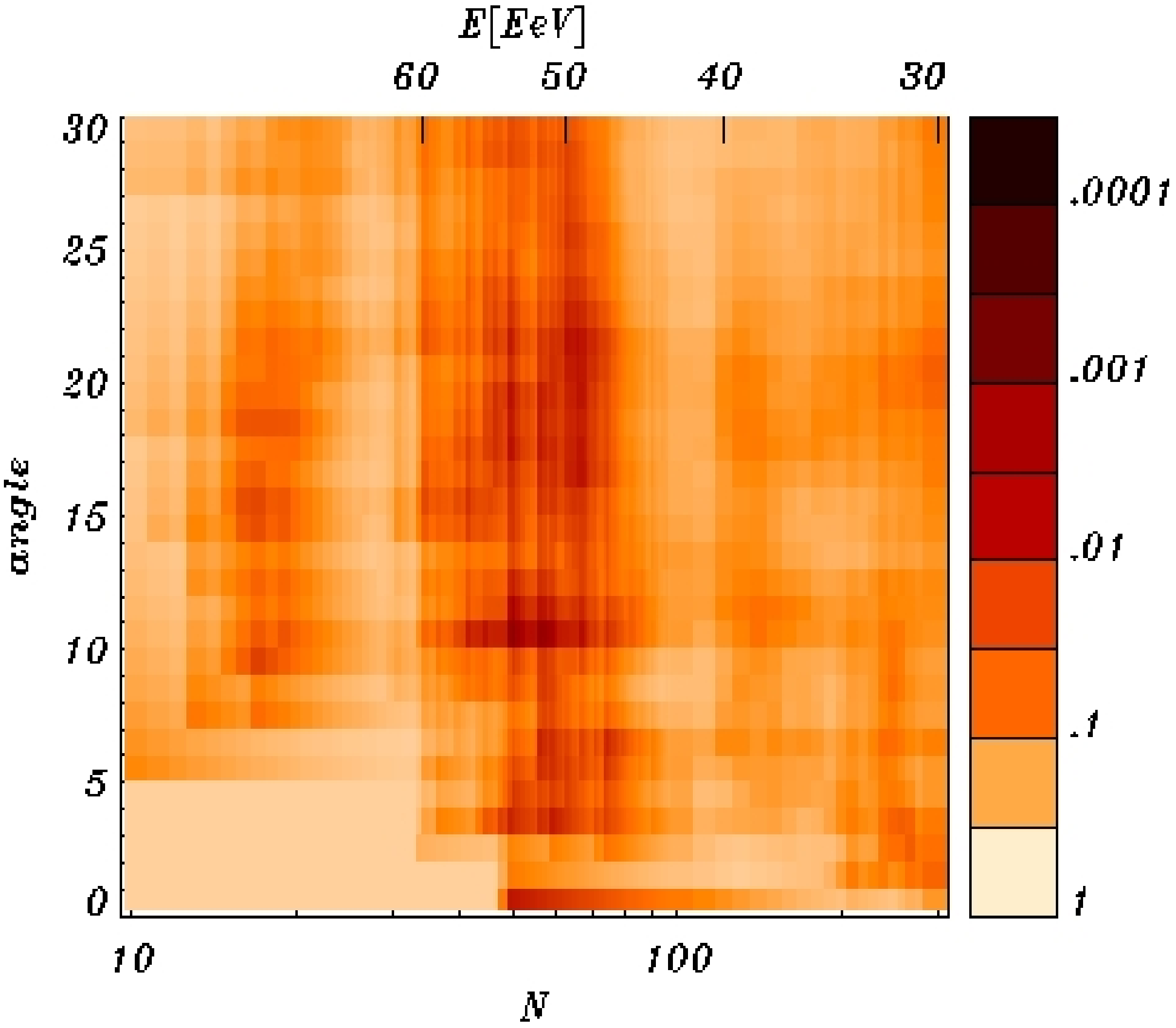
Chance probability was estimated P ~ 10^{-4}

Controversy arose because the angular scale and the energy threshold had not been fixed a priori

Taking into account a penalization for scanning in angle and energy P ~ 3 x 10^{-3}

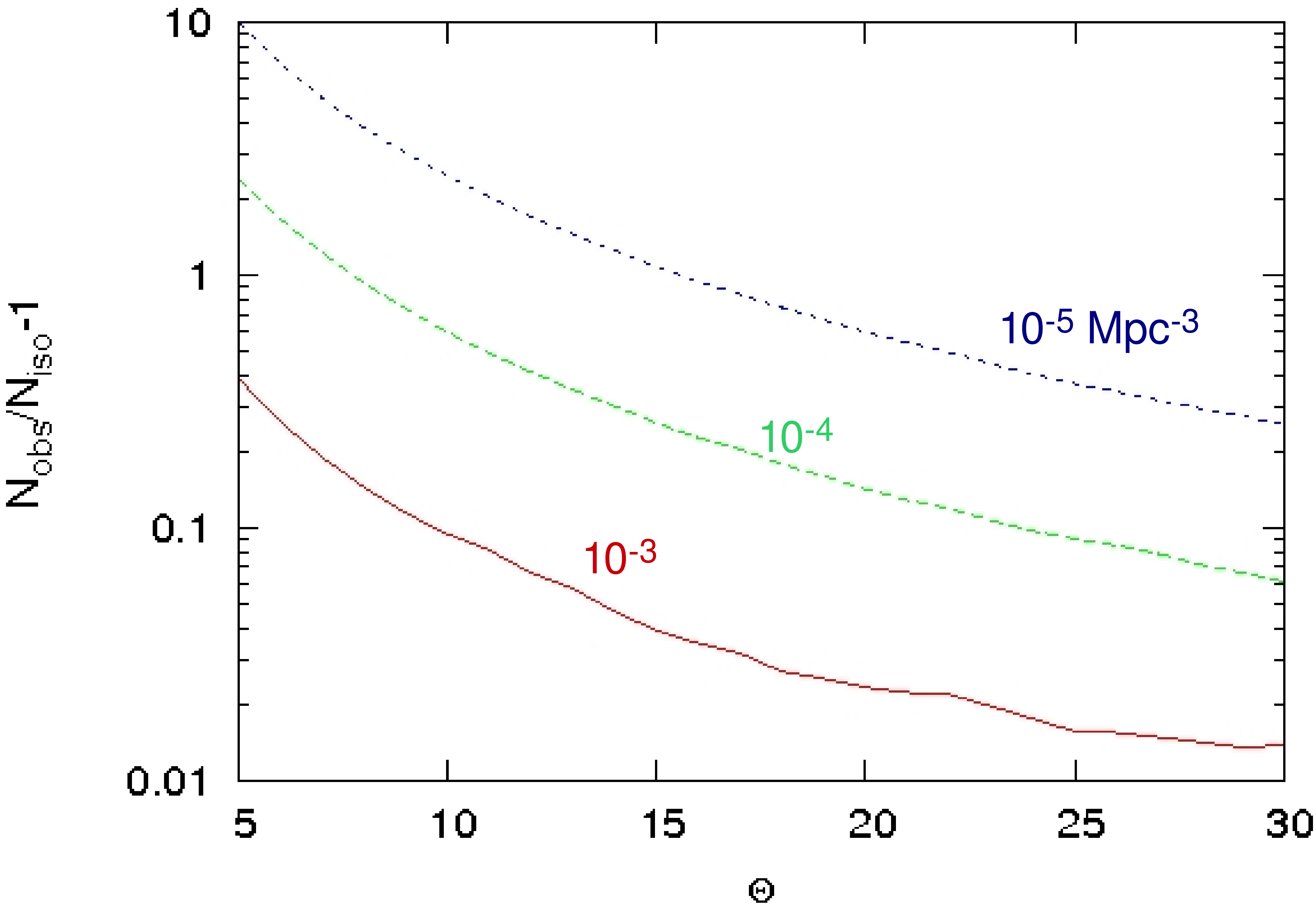
AUGER SCAN IN ANGLE AND ENERGY

MINIMUM: $\theta = 11°$, E > 55 EeV (N = 58), obs/exp = 18/5.2, $P_{min} \simeq 3 \times 10^{-3}$



CHANCE PROBABILITY: $P \simeq 15\ \%$

The autocorrelation function can give information on the spatial density of sources → help to identify source population



SEARCH FOR POINT-LIKE OR EXTENDED EXCESS OF EVENTS AROUND A GIVEN DIRECTION IN THE SKY

- Measure the observed number of events in a window (top-hat, Gaussian,...) around the given direction. For a point-like excess (as could arise for neutral primaries) use the angular resolution size $\rightarrow N_{ON}$

- Estimate the background: use the detector measurements in other regions of the sky $\rightarrow$ $N_B = \alpha\, N_{OFF}$ 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

Variance of the signal (N_{ON} and N_{OFF} independent measurements)

$\sigma^2(N_S) = \sigma^2(N_{ON}) + \alpha^2\, \sigma^2(N_{OFF})$

Different possibilities to evaluate the variances:

1) 2 Poisson processes

$$\hat{\sigma}_1(N_S) = \sqrt{N_{ON} + \alpha^2 N_{OFF}} \qquad S_1 = \frac{N_{ON} - \alpha N_{OFF}}{\sqrt{N_{ON} + \alpha^2 N_{OFF}}}$$

2) Likelihood ratio method: Li-Ma

$$\lambda = \frac{L(data|null\,hyp)}{L(data|alternative\,hyp)} = \frac{P(data|\langle N_S\rangle = 0)}{P(data|\langle N_S\rangle \neq 0)}$$

If the null hyp is true and N_{ON}, N_{OFF} are large then sqrt(-2 ln λ) is Gaussian distributed with σ^2=1

$$P(data|\langle N_S\rangle=0) = P\left(N_{ON}, N_{OFF} \middle| \langle N_S\rangle = 0, \langle N_B\rangle = \frac{\alpha}{1+\alpha}(N_{ON}+N_{OFF})\right)$$

$$= Poisson(N_{ON}, \langle N_{ON}\rangle = \langle N_B\rangle)\, Poisson(N_{OFF}, \langle N_{OFF}\rangle = \langle N_B\rangle/\alpha)$$

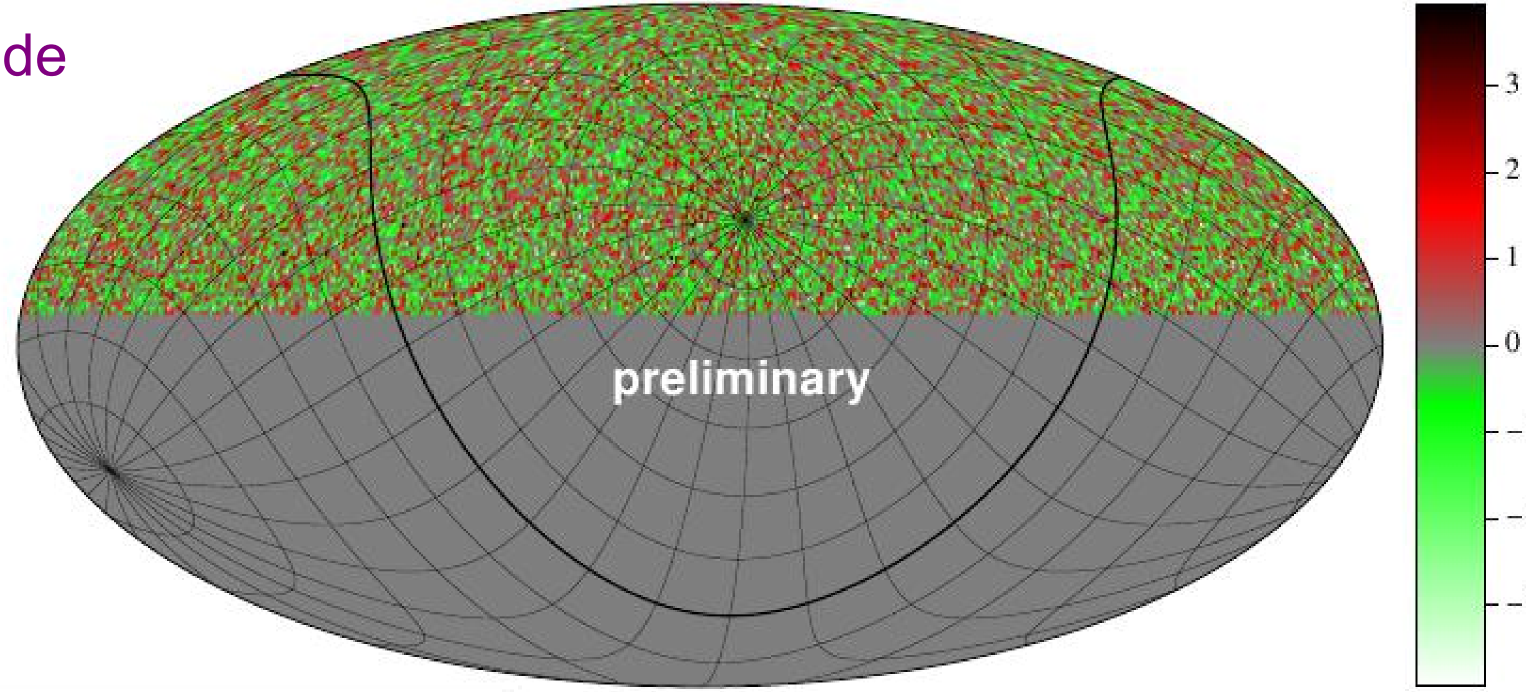
$$P\left(data \middle| \langle N_S\rangle = N_{ON} - \alpha N_{OFF}, \langle N_B\rangle = \alpha N_{OFF}\right) = Poisson(N_{ON}, \langle N_{ON}\rangle = N_{ON})\, Poisson(N_{OFF}, \langle N_{OFF}\rangle = N_{OFF})$$

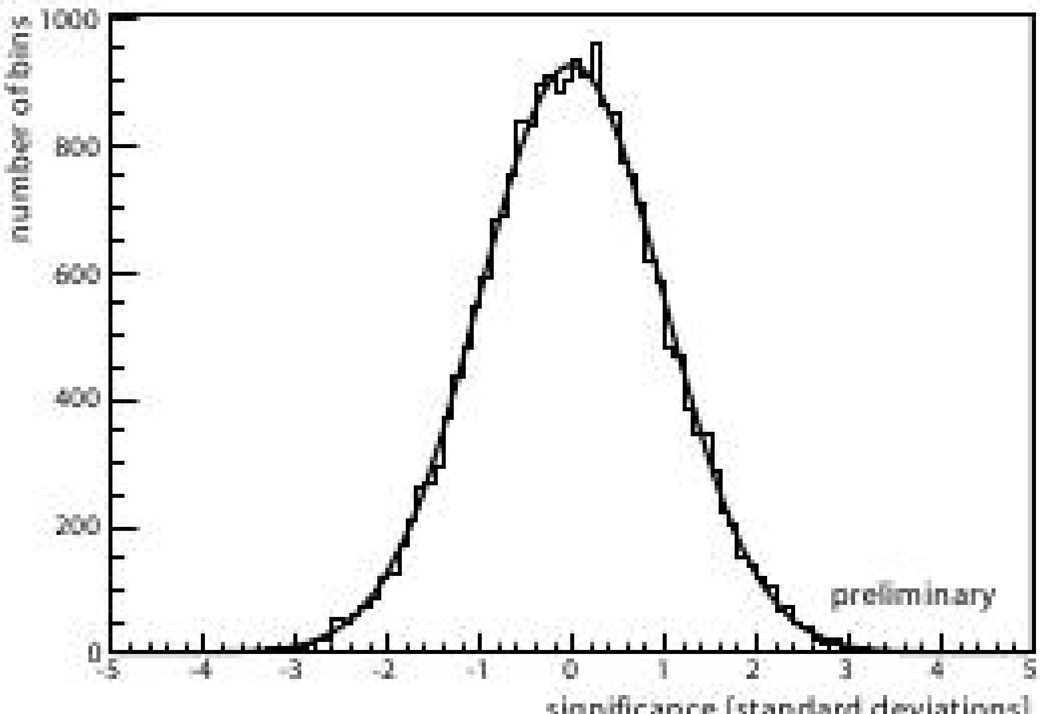
$$\lambda = \left[\frac{\alpha}{1+\alpha}\left(\frac{N_{ON}+N_{OFF}}{N_{ON}}\right)\right]^{N_{ON}} \left[\frac{1}{1+\alpha}\left(\frac{N_{ON}+N_{OFF}}{N_{OFF}}\right)\right]^{N_{OFF}}$$

$$\boxed{S_2 = \sqrt{-2\ln(\lambda)}}$$

Li-Ma significance follows a Gaussian better than S_1

KASCADE-Grande

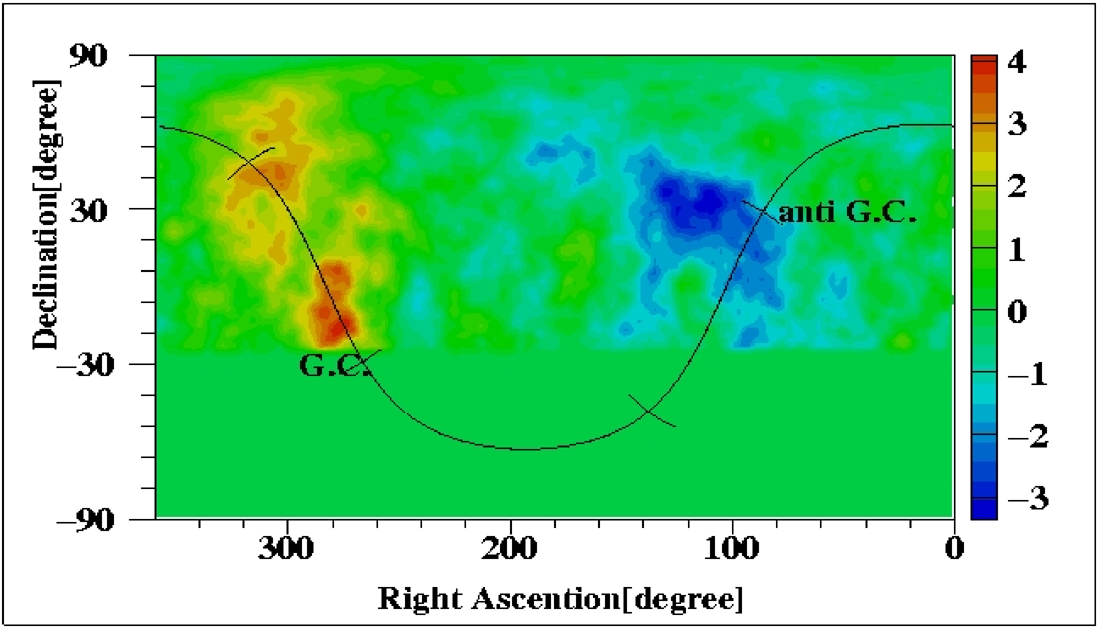




Over '07

No sign of point-like excess

Galactic center: interesting region, central black hole, high density of stars

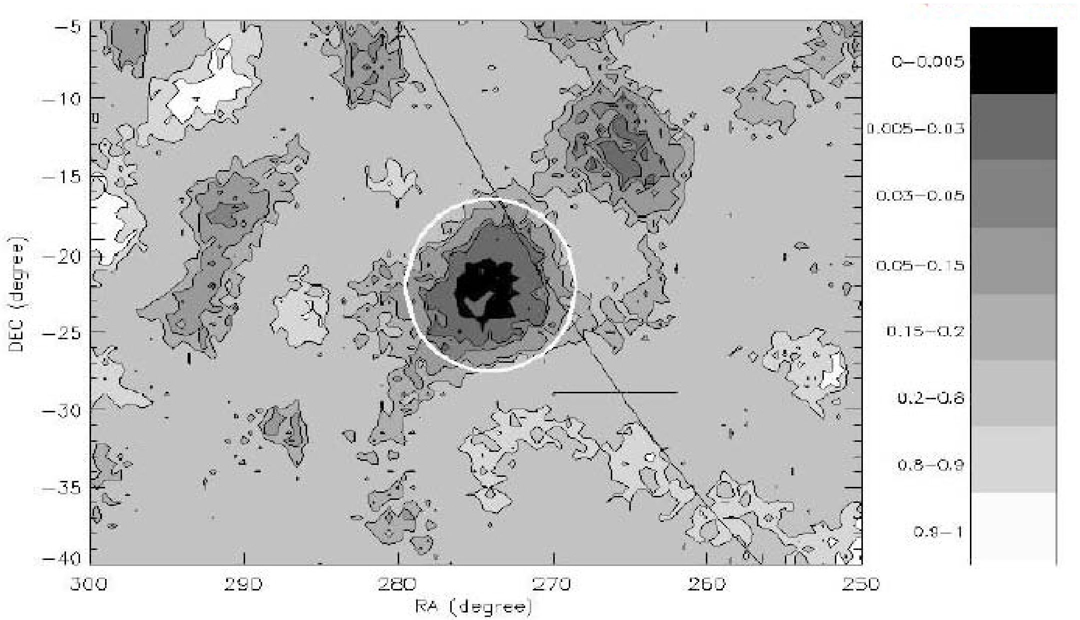


AGASA (Japan):
Excess 4.5 σ (1999)
Circle of 20º radius
Energy :1 - 2.5 EeV

$$\frac{obs}{exp} = \frac{506}{413.6} \quad (+4.5\sigma) \ \textbf{at} \ (\delta, \alpha) = (-15{,}280)$$

(22% excess)

AUGER got $\boxed{\frac{obs}{exp} = \frac{2116}{2159.6} \quad (-1\sigma)}$



SUGAR (Australia):
Excess 2.9 σ (2001)
Circle of 5.5º radius
Energy :0.8 - 3.2 EeV

$$\frac{obs}{exp} = \frac{21.8}{11.8} \quad (+2.9\sigma) \ \textbf{at} \ (\delta, \alpha) = (-22{,}274)$$

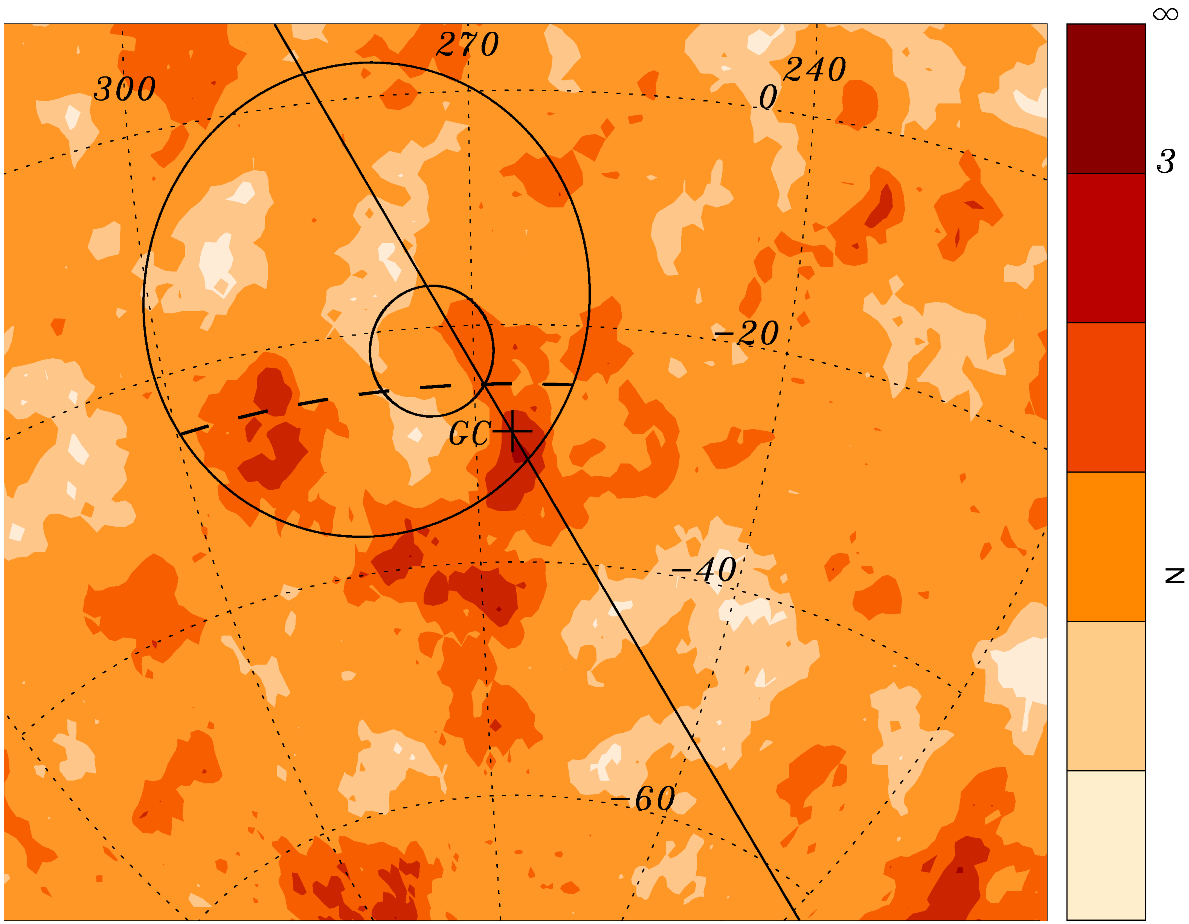
(85% excess)

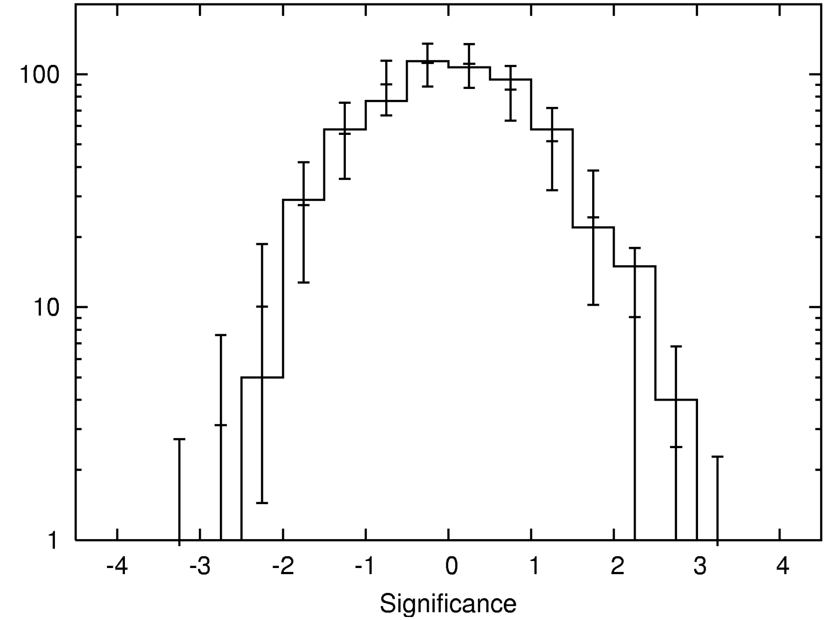
AUGER got $\boxed{\frac{obs}{exp} = \frac{286}{289.7} \quad (-0.3\sigma)}$

AUGER: GALACTIC CENTRE RESULTS

$10^{17.9}$ eV < E < $10^{18.1}$ eV

Sky map and distribution of significances of overdensities near the GC on 5° radius windows





SEARCHES FOR CORRELATIONS WITH OBJECTS

Given a population of candidate sources there are different proposed tests to search a correlation with CR arrival directions

CROSSCORRELATION FUNCTION:

Looks for an excess of pairs of CR separated less than a given angle From any candidate source in the set with respect to the expectations from an isotropic CR distribution.

Similar procedure as in the autocorrelation analysis:

- Count the pairs CR-objects as a function of the angle in the data.

- Repeat the procedure for a large number of isotropic simulated datasets.

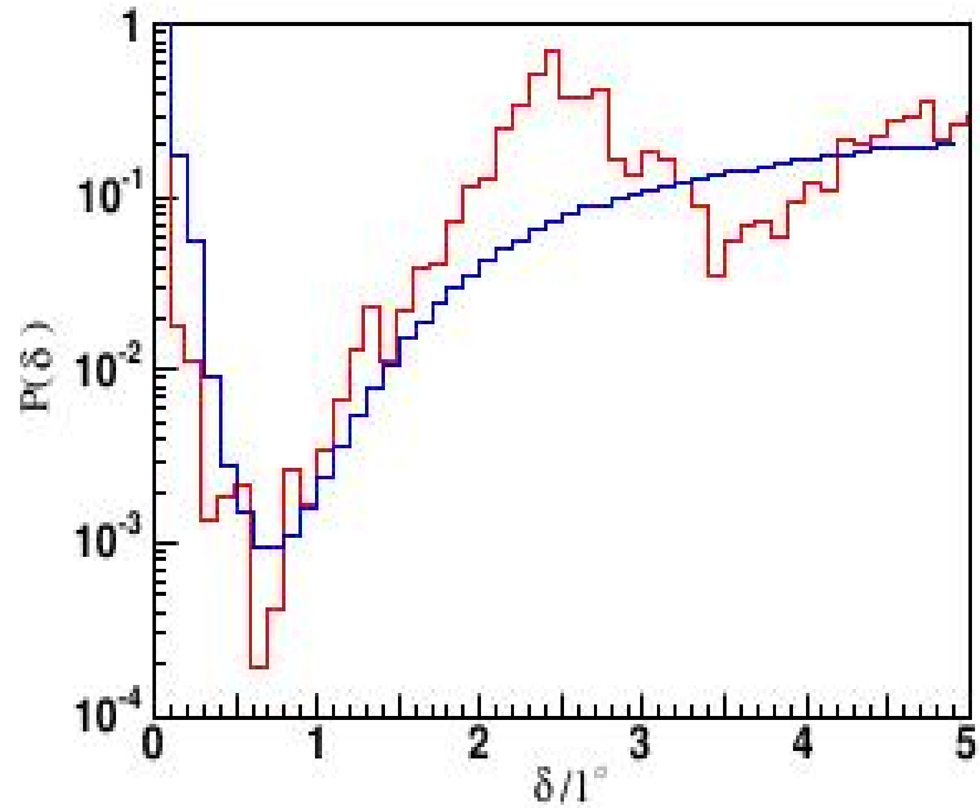
- To estimate the significance of any excess compute the fraction of the simulations with larger number of pairs than those present in the data

Example: correlation of CR with E > 10 EeV and BL Lacs with m < 18 at the resolution angular scale (first found in HiRes data by Gorbunov et al. 2004)

156 BL Lacs
271 events

$n_p(0.8^o) = 11$ (data)
$\langle n_p(0.8^o) \rangle_{iso} = 3$
$f\ (0.8^o) = 4 \times 10^{-4}$

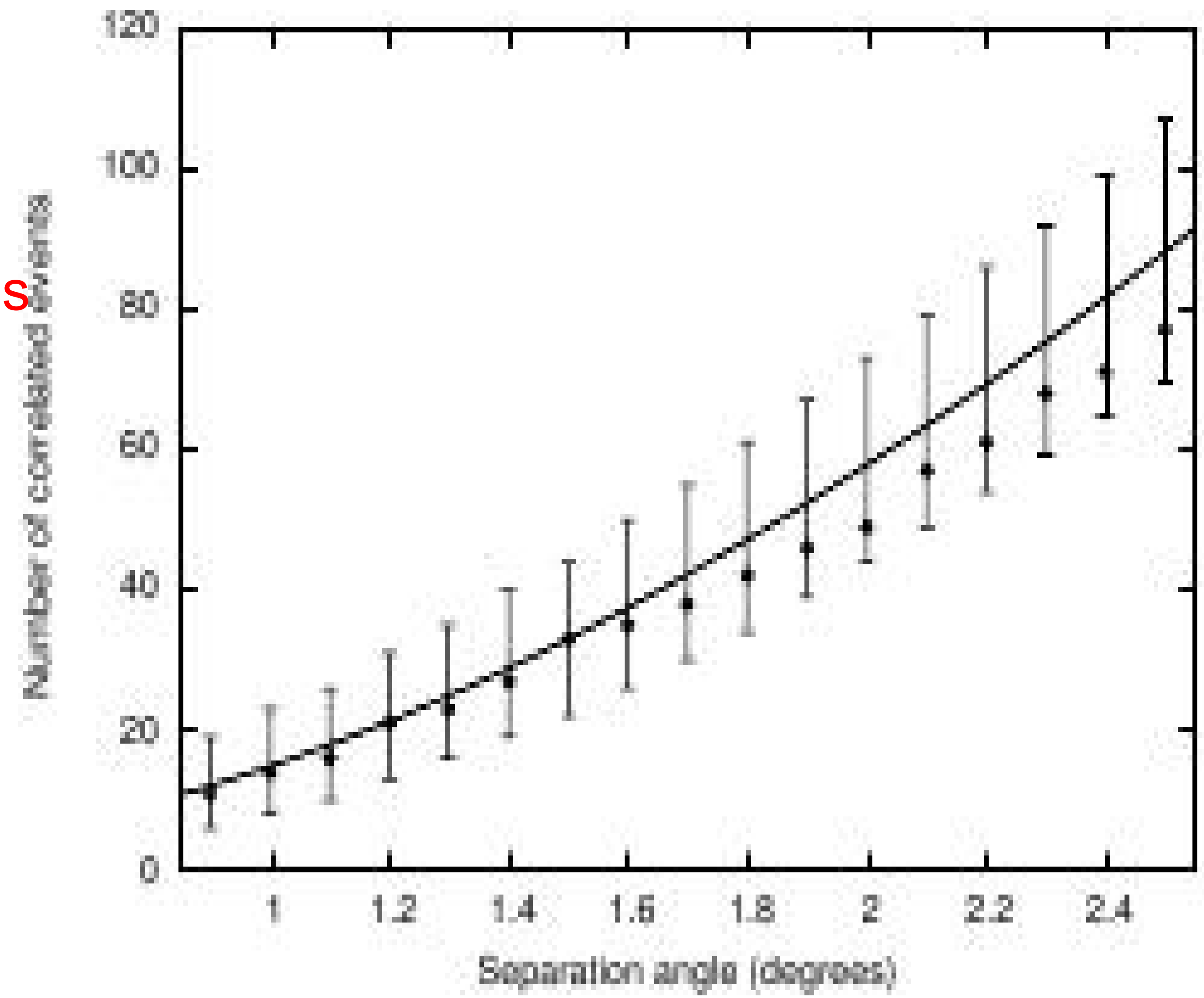
Penalization for search at different angles and with different sets of objects not included



data
9 from BL Lac + 262 isotropic

Test of the signal with Auger data

1736 events with E > 10 EeV

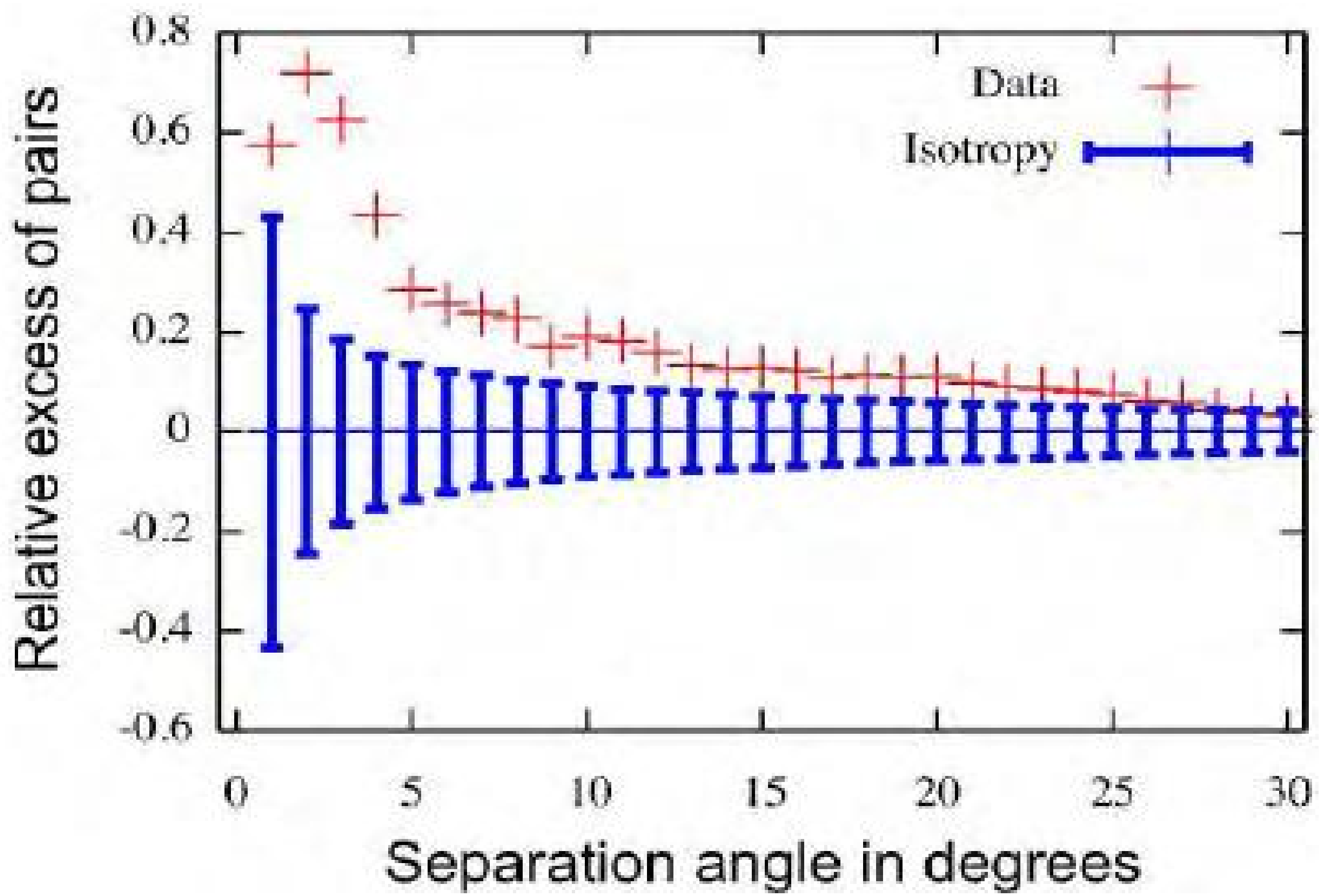


No evidence of excess in Auger data

Harari et al. ICRC07

AUGER: CROSSCORRELATION WITH 2MRS GALAXIES

Volume selected bright (M_k < -25.25) nearby (d < 200 Mpc) → 1940 objects
Auger events E > 55 EeV



ICRC'09

Excess of pairs up to 30 deg **f_{min} = 1.5 x 10^{-3} at 3 deg**

BINOMIAL PROBABILITY SCAN

For a given candidate source population, e.g. AGNs, galaxy clusters, radio galaxies, there are different unknown variables that will influence the correlation with events

- angular scale: magnetic deflections are not known
- maximum distance to the objects: UHE events from distant sources will have their energy diminished by interactions with CMB (GZK effect)
- energy threshold: only high energy events are expected to be correlated with local sources

Idea: scan over all of them. For a given candidate source population

1) Compute: $p(\psi, D_{max}) \rightarrow$ Probability that a CR from an isotropic flux arrives with angular separation smaller than ψ from a candidate source at a distance smaller than D_{max}

2) For each ψ, D_{max} and E_{min} obtain the number k of correlated events, and look for the set of values having the minimum probability

$$P = \sum_{j=k}^{n} \binom{n}{j} p^j (1-p)^{n-j}$$

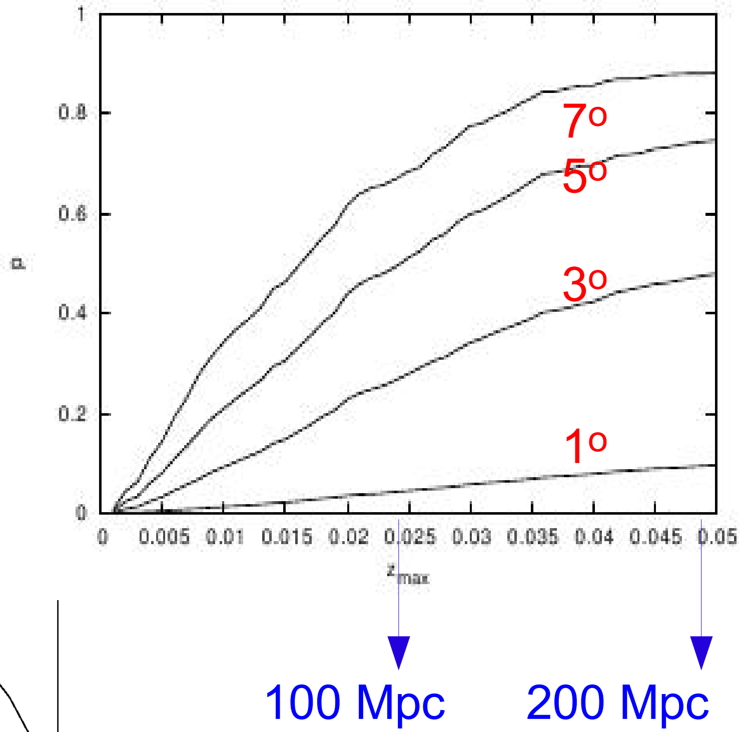
$\rightarrow P_{min}$

3) Significance: perform isotropic simulations and under the same scan in ψ, D_{max} and E_{min} obtain the fraction f having a P_{min} smaller than the data

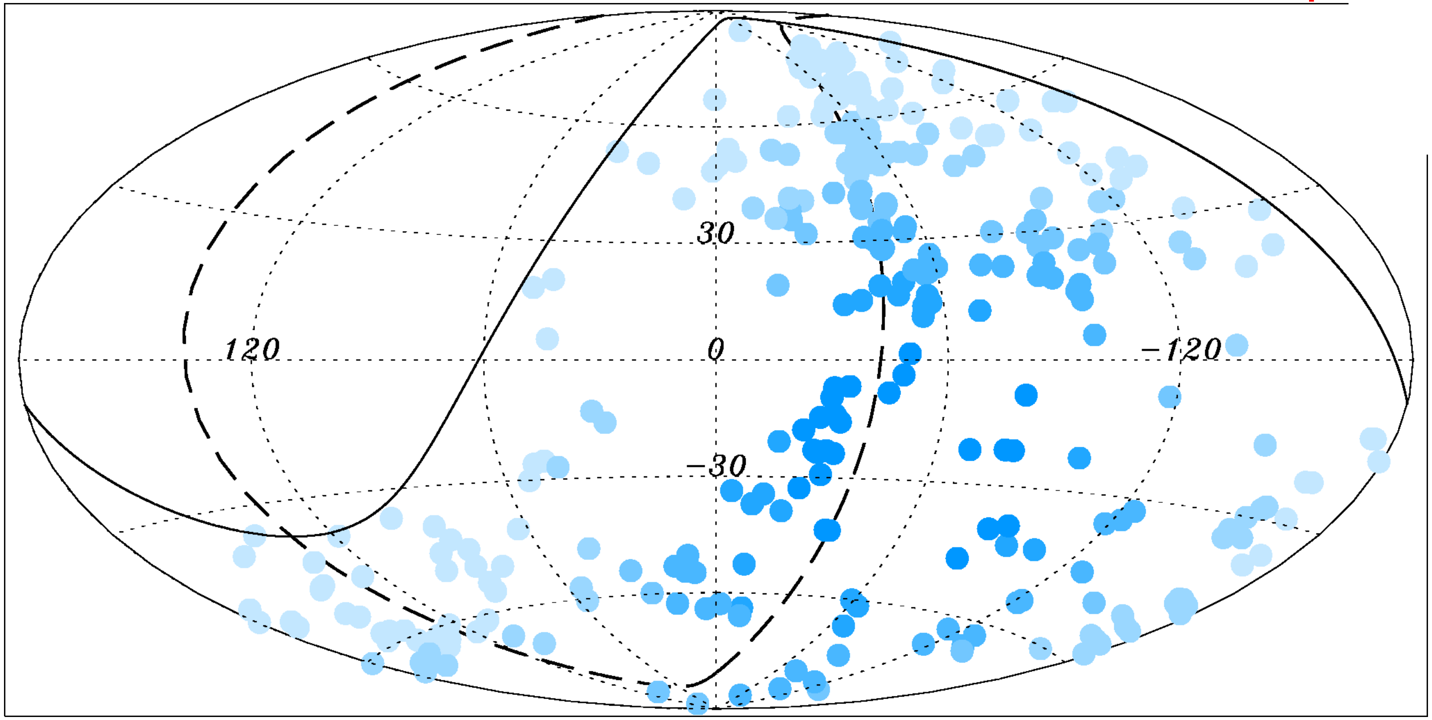
Auger search for correlation with AGN from the Veron-Cetty and Veron catalog

1. Evaluate $p(\psi, D_{max})$

Probability that a CR from an isotropic flux arrives with angular separation smaller than ψ from an AGN at a distance smaller than D_{max}



p = Fraction of the area, weighted by the relative exposure, covered by circular windows of radius ψ



e.g. p = 0.21 for D_{max} = 75 Mpc and ψ = 3.1º

2. Scan over ψ, D_{max}, E_{min}

(using 81 events up to 31 august 2007 with $E > 4 \times 10^{19}$ eV)

P = probability to have k or more correlations in a set of n isotropic events, with individual chance probability $p(\psi, D_{max})$:

$$P = \sum_{j=k}^{n} \binom{n}{j} p^j (1-p)^{n-j}$$

Minimum of P:

$E_{min} \sim 6 \times 10^{19}$ eV ($n = 27$) ,

$\psi \sim 3^o$, D ~ 75 Mpc

20 of the 27 events correlate
while 6 were expected in
the isotropic case

3. fraction of isotropic simulations of 81 events which have a smaller P_{min} under the same scan

$f \sim 10^{-5}$

HISTORICAL NOTE

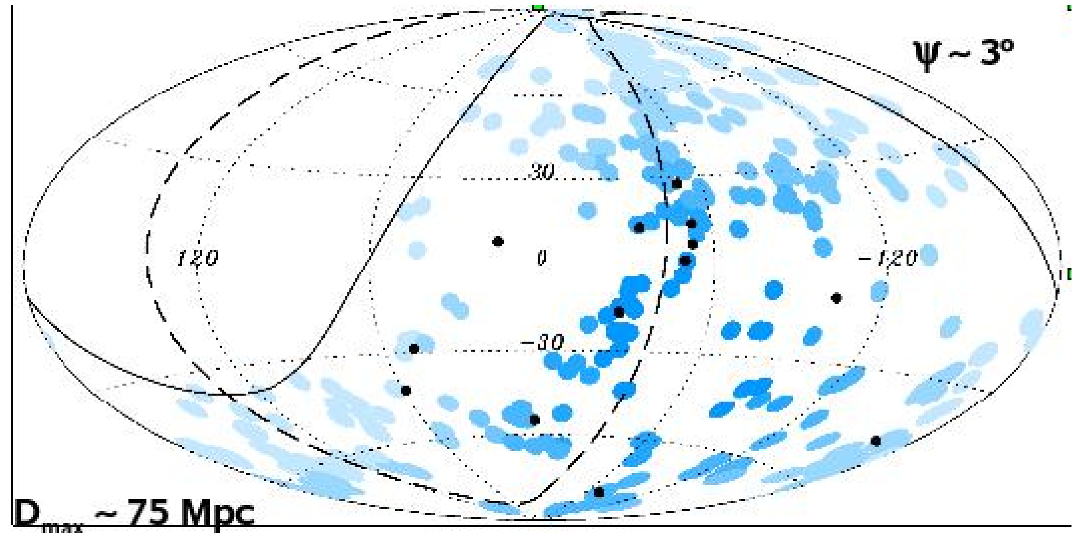
Data analysed from Jan 2004 up to 26 May 2006
First hints of correlations obtained through this scan

12/15 correlations
(3 expected)

D_{max} = 75 Mpc ψ = 3.1°

E_{min} = 5.6x10^{19} eV

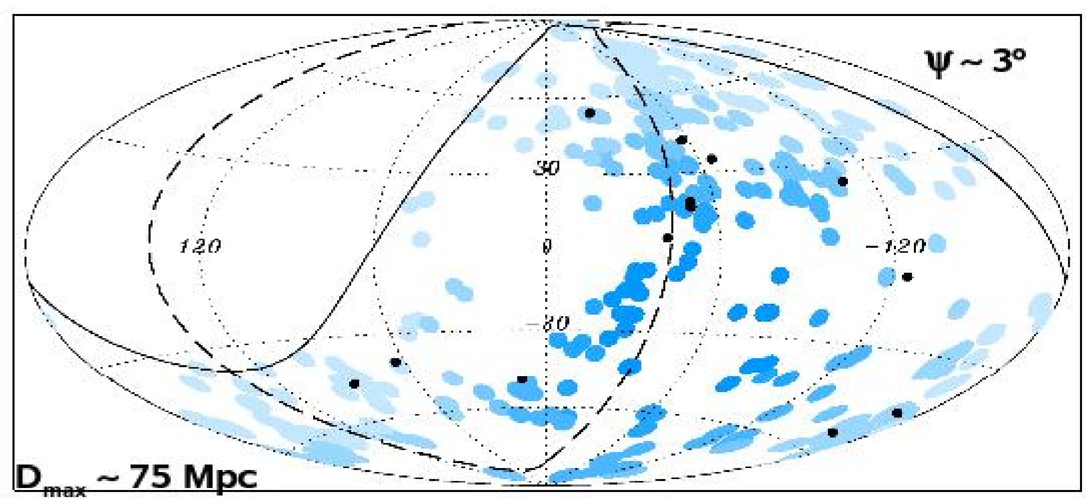
f ~ 10^{-3}



To determine the significance: test new data (from 27 May 2006 up to 31 Aug 2007) with parameters fixed a priori

8/13 correlations

P(iso) < 1%



Update of AGN correlation results:

(ICRC09)

From 31 August 2007 until 31 March 2009:

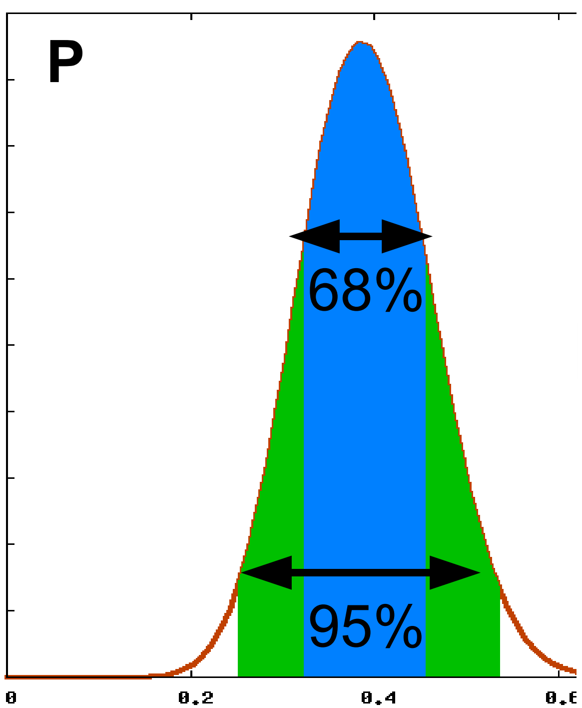
there are 31 events with E > 55 EeV (new calibration)

and 8 are within 3.1 deg of an AGN closer than 75 Mpc

Probability that the fraction of correlating events be p given that k of n observed events correlate

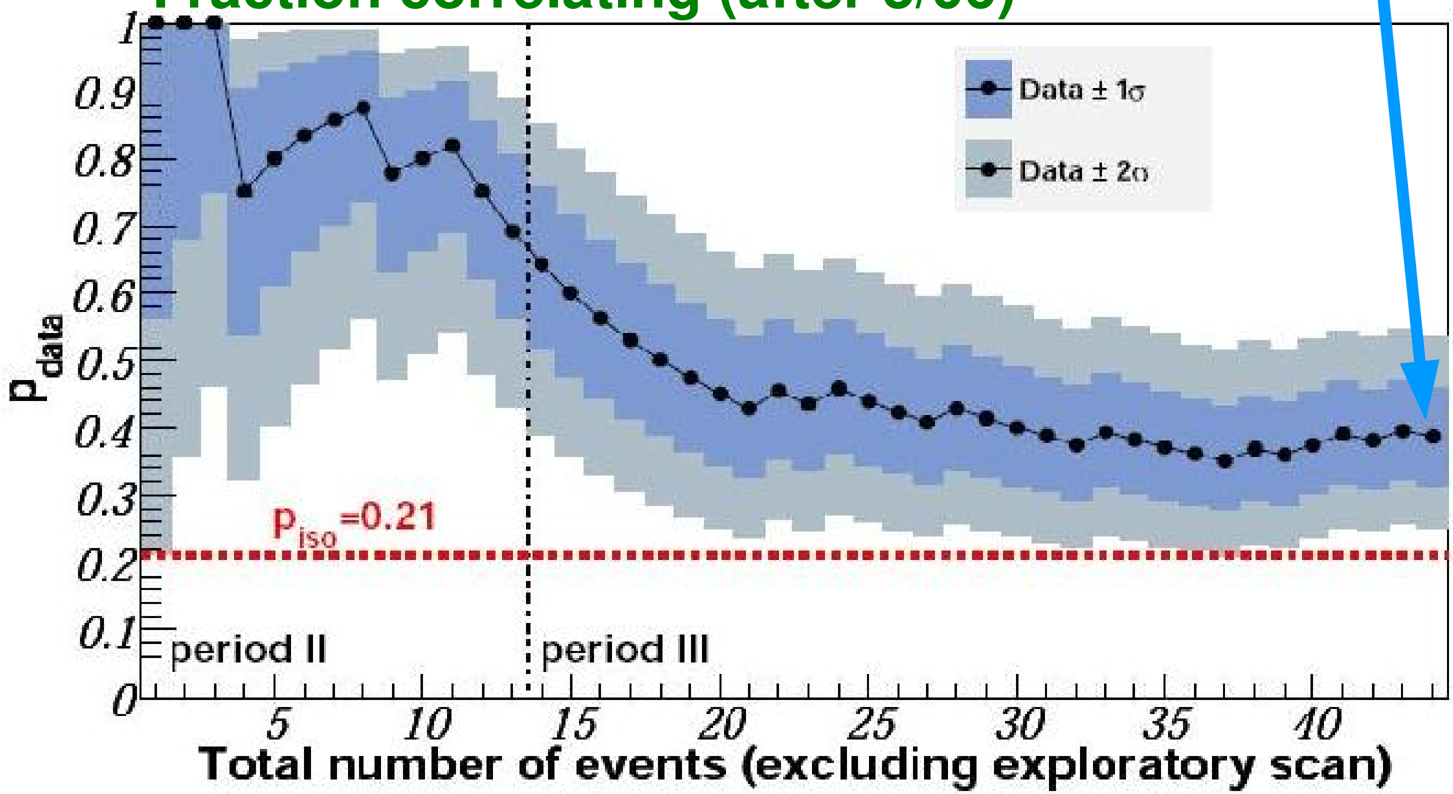
$$P(p|k,n)=\frac{(n+1)!}{k!(n-k)!}p^k(1-p)^{n-k}$$

p=0.39 ± 0.07

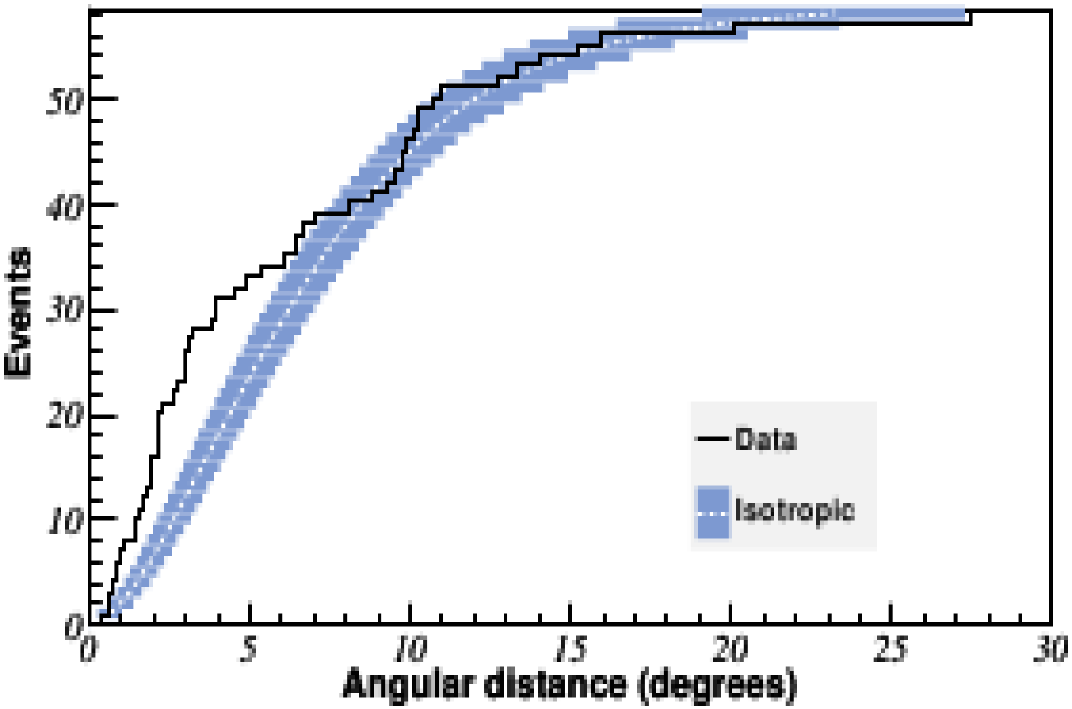


max = k/n

Fraction correlating (after 5/06)



(from the 9 events which have $|b_G|$ < 12 deg, none correlate)



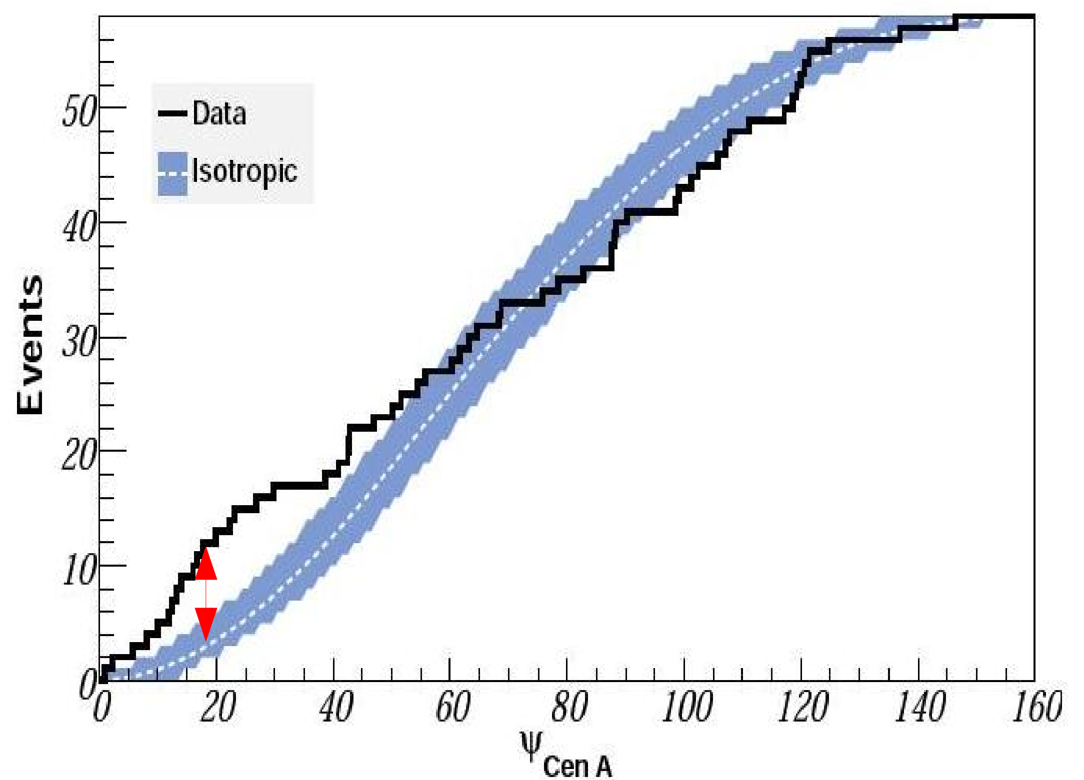
Cumulative number of events around AGN

excess of events up to 6 deg

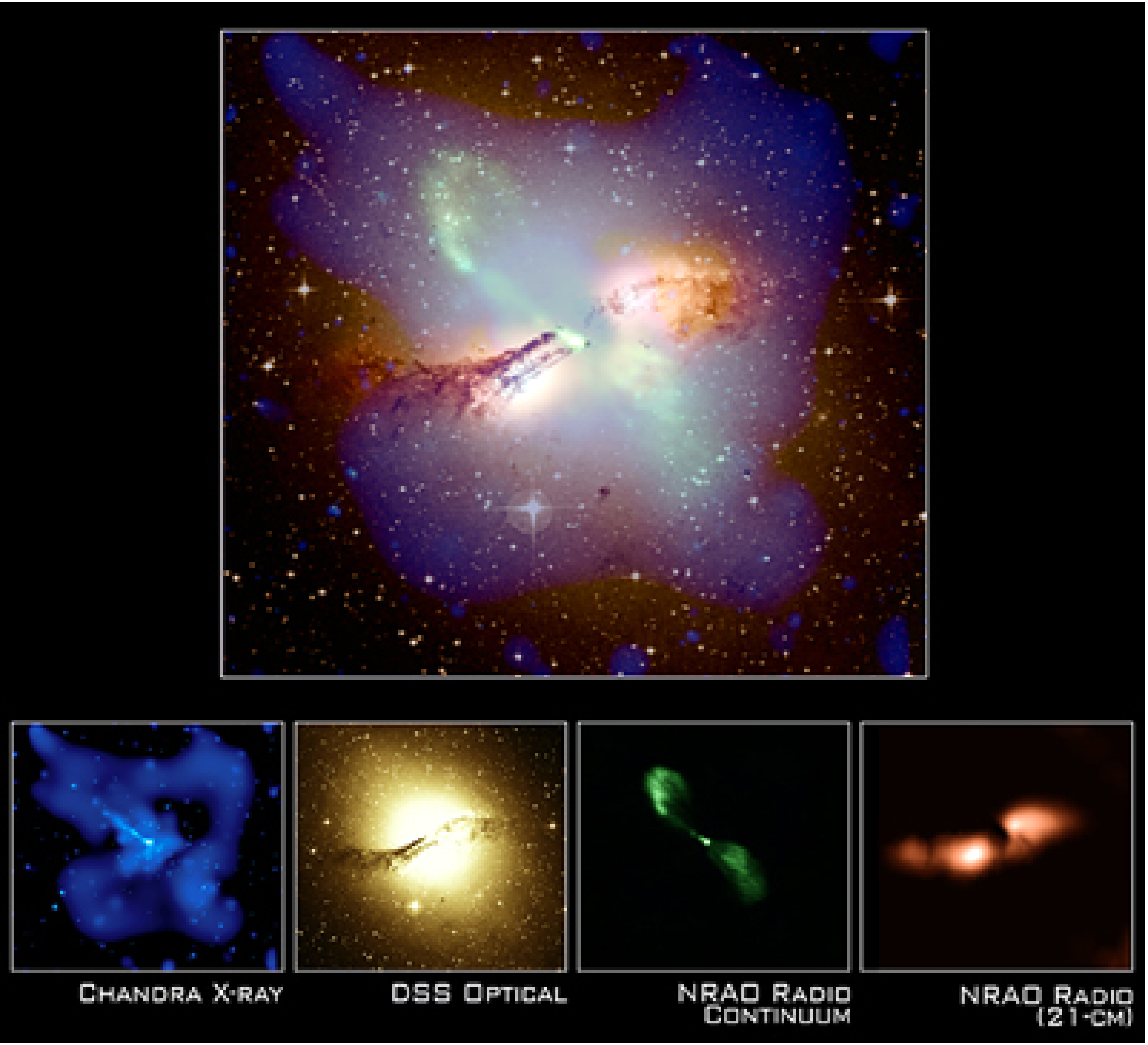
Excess around Centaurus A

Maximum distance of the cumulative distance distribution from the isotropic expectation at 18 deg: n_{obs}/n_{iso} = 12/2.7

Kolmogorov-Smirnov test 2% probability



Closest Active galaxy: Centaurus A (~ 4 Mpc)



2 events at less than 3 deg from it

within 18 deg:
12 obs / 2.7 exp

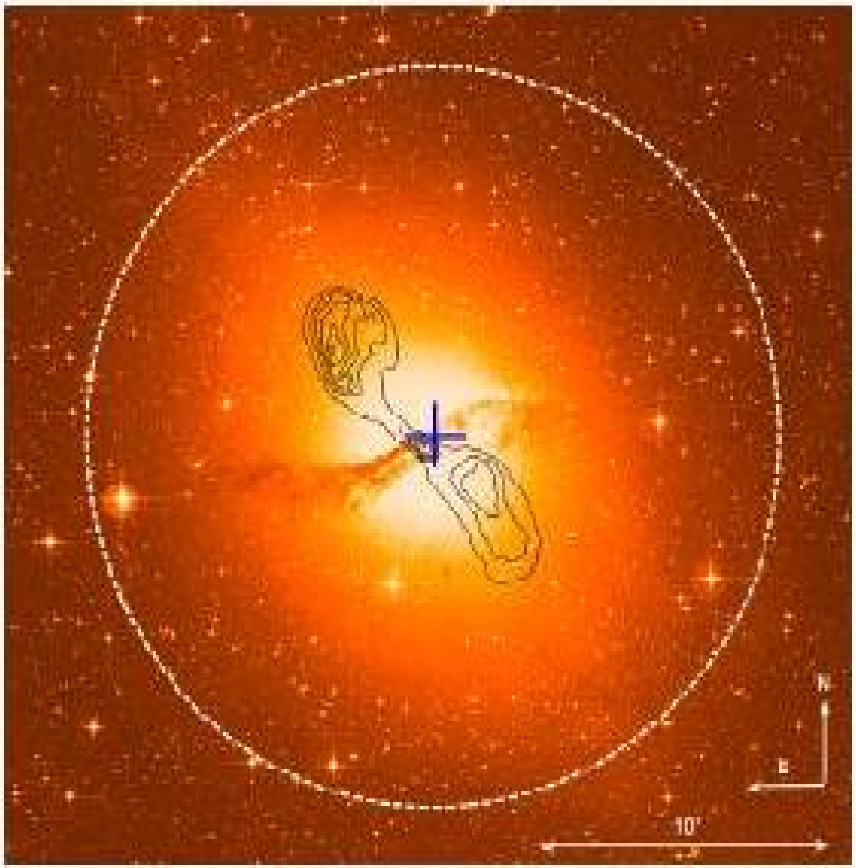
central black hole of about 100 million solar masses

collision of 2 galaxies

relativistic jet

HESS observation of Centaurus A
(0.1 – 10 TeV gammas)

Discovery of very high energy γ-ray emission from Centaurus A



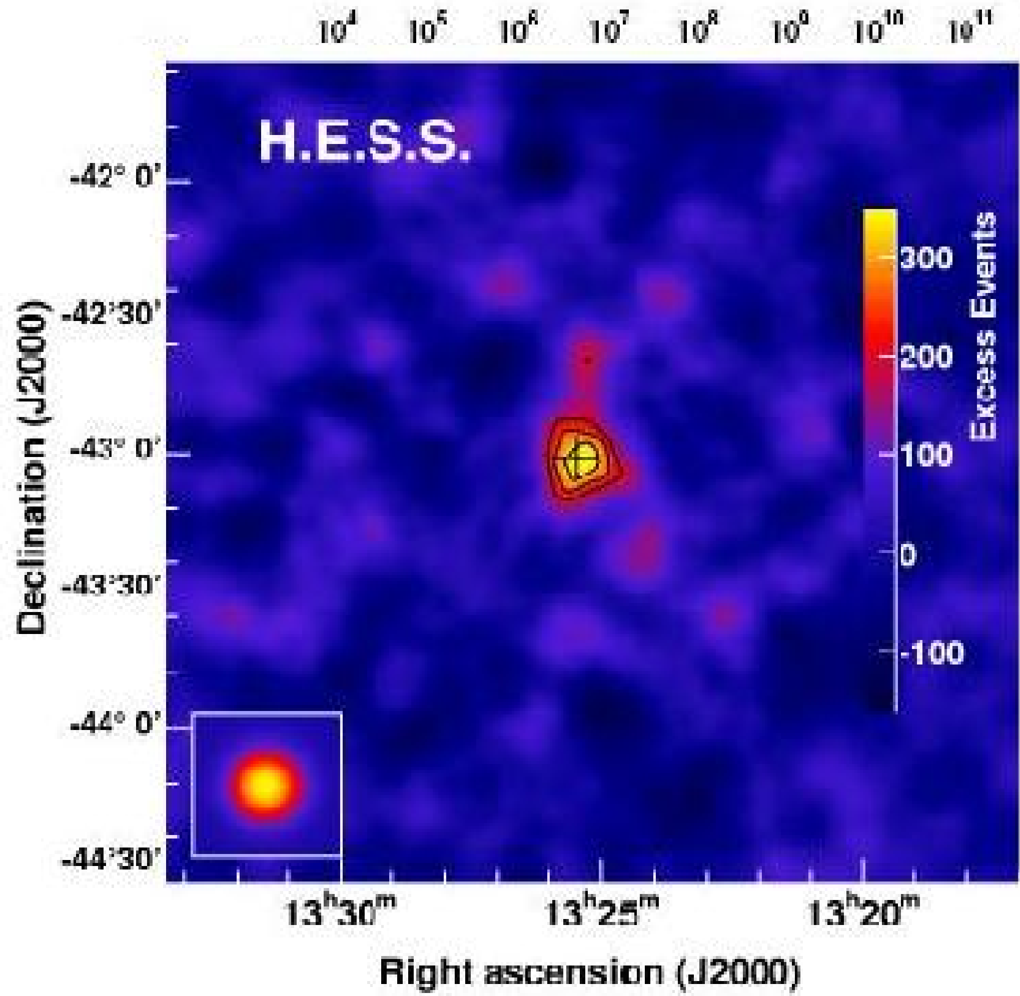


Fig. 2.— Optical image of Cen A (UK 48-inch Schmidt) overlaid with rad
ontours (black, VLA, Condon et al. 1996), VHE best fit position with 1
tatistical errors (blue cross), and VHE extension upper limit (white dash
ircle, 95% confidence level).

New data indicates that the degree of correlation with AGN from VCV is weaker than suggested by the earliest data

AGNs may be just tracers of nearby large scale structure which may host other CR sources (GRBs, colliding Galaxies, galaxy clusters, ...)

Only a certain AGN subclass may accelerate UHECRs

LOG LIKELIHOOD PER EVENT

The binomial scan method cannot be applied when the number of sources is large, as the fraction of the sky covered p becomes very large. A more general method is to build a probability map for the expected arrival directions of events above a given threshold

Map construction: Take a Gaussian of given σ around the direction of each object in the catalog

$$P(\hat{u}) \propto \epsilon(\hat{u}) \left[f_{iso} + (1 - f_{iso}) \sum_{i=1}^{N_{obj}} \omega(z_i)\, \mathrm{e}^{-d(\hat{u},\hat{u}_i)^2/2\sigma^2} \right]$$

f_{iso}: fraction of the flux not associated to the catalog (e.g. from sources not included or suffering large magnetic deflections)

weight factor:

$$w(z, E_{th}) = \frac{1}{4\pi d_L^2(z)} \int_{E_i(z,E_{th})}^{\infty} E^{-s}\, \mathrm{d}E.$$

d_L: distance to the object

integral term: fraction of the flux from a source at redshift z that reaches the Earth with $E > E_{th}$.

E_i : initial energy at the source needed to arrive at Earth with $E = E_{th}$

s: source spectral index.

Log Likelihood per event

- The likelihood associated to a given set of N observed events is

$$L = \prod_{i=1}^{N} P(\hat{u}_i)$$

with P proportional to the map density in each event direction.

- Better to consider the log likelihood per event

$$LL = \frac{1}{N} \sum_{i=1}^{N} \ln(P(\hat{u}_i))$$

- Measure LL for a model reference map

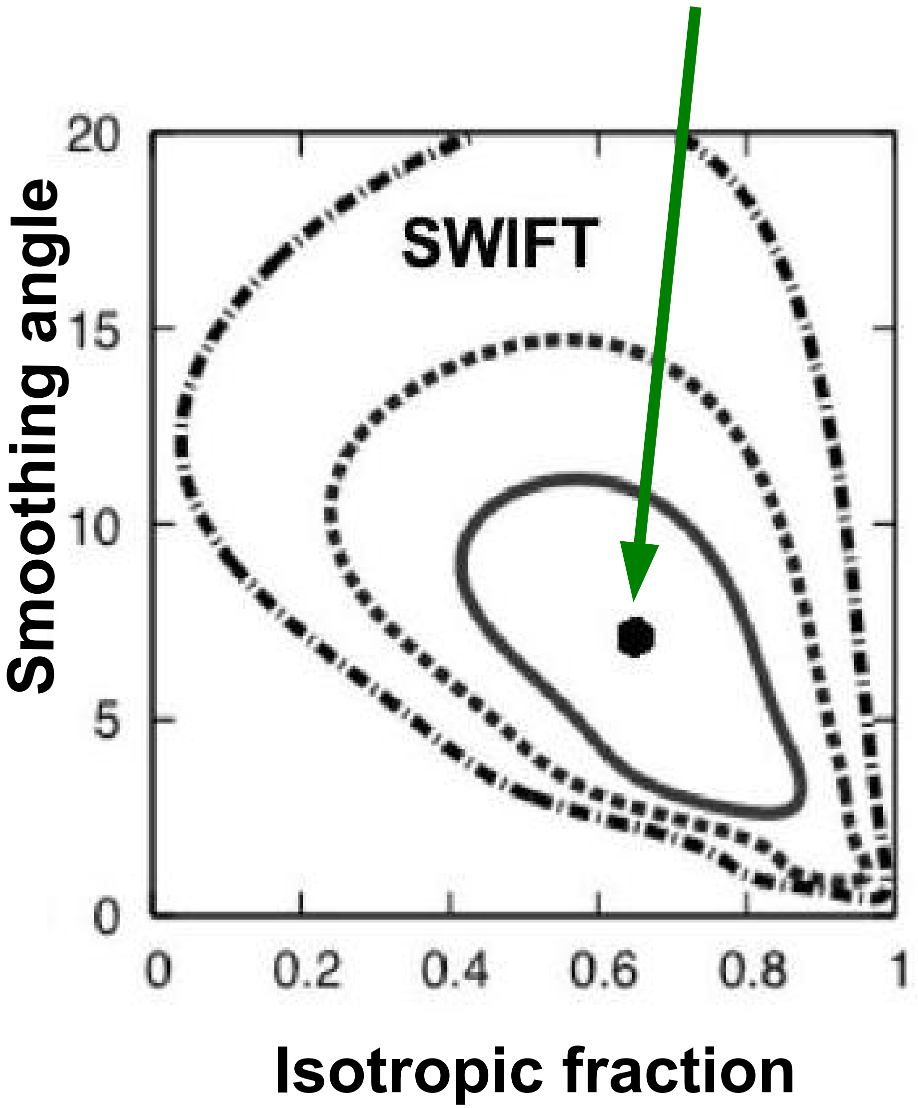
- Simulate events distributed isotropically and according to the map

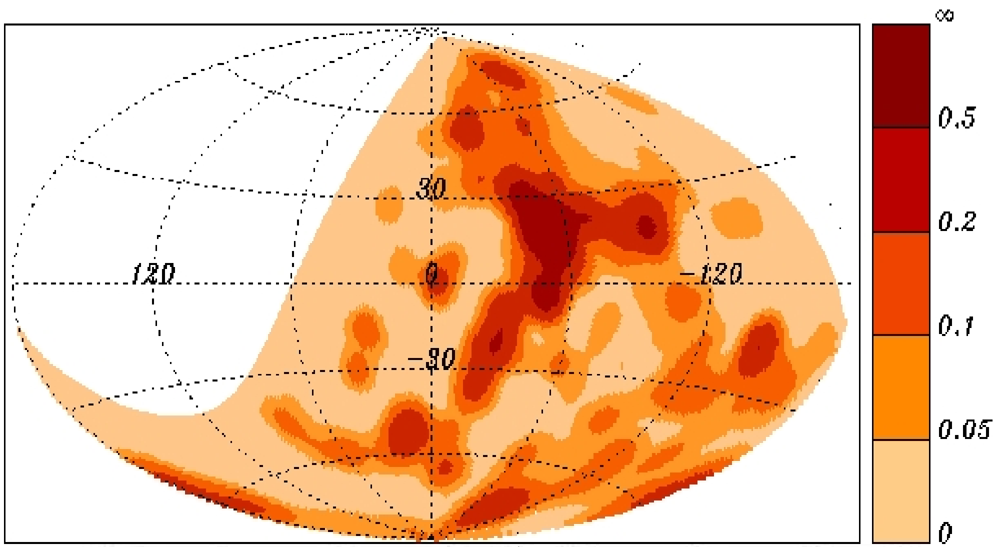
- Histogram LL for each hypothesis (the mean of the distribution is independent of the number N of observed events, but the width becomes smaller as N grows)

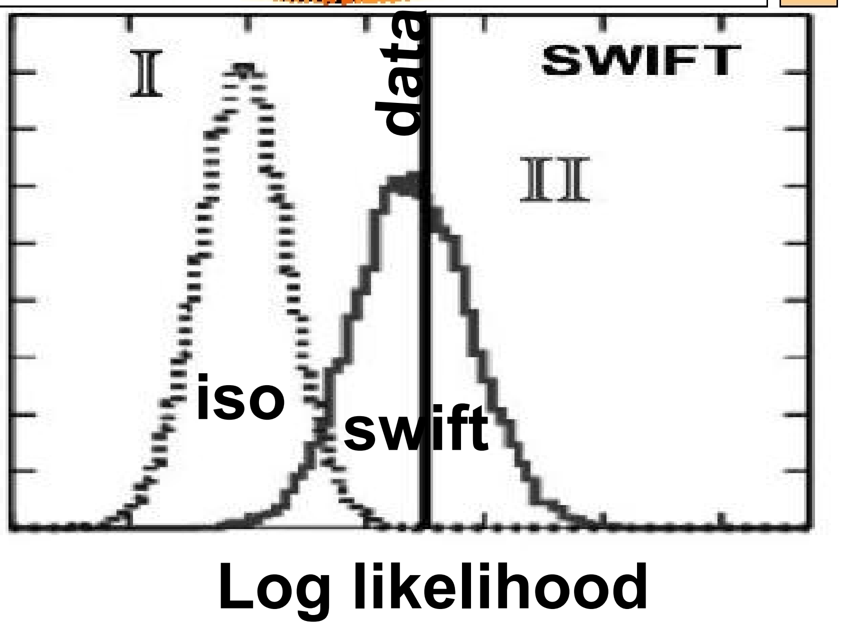
- Compare with LL for the data

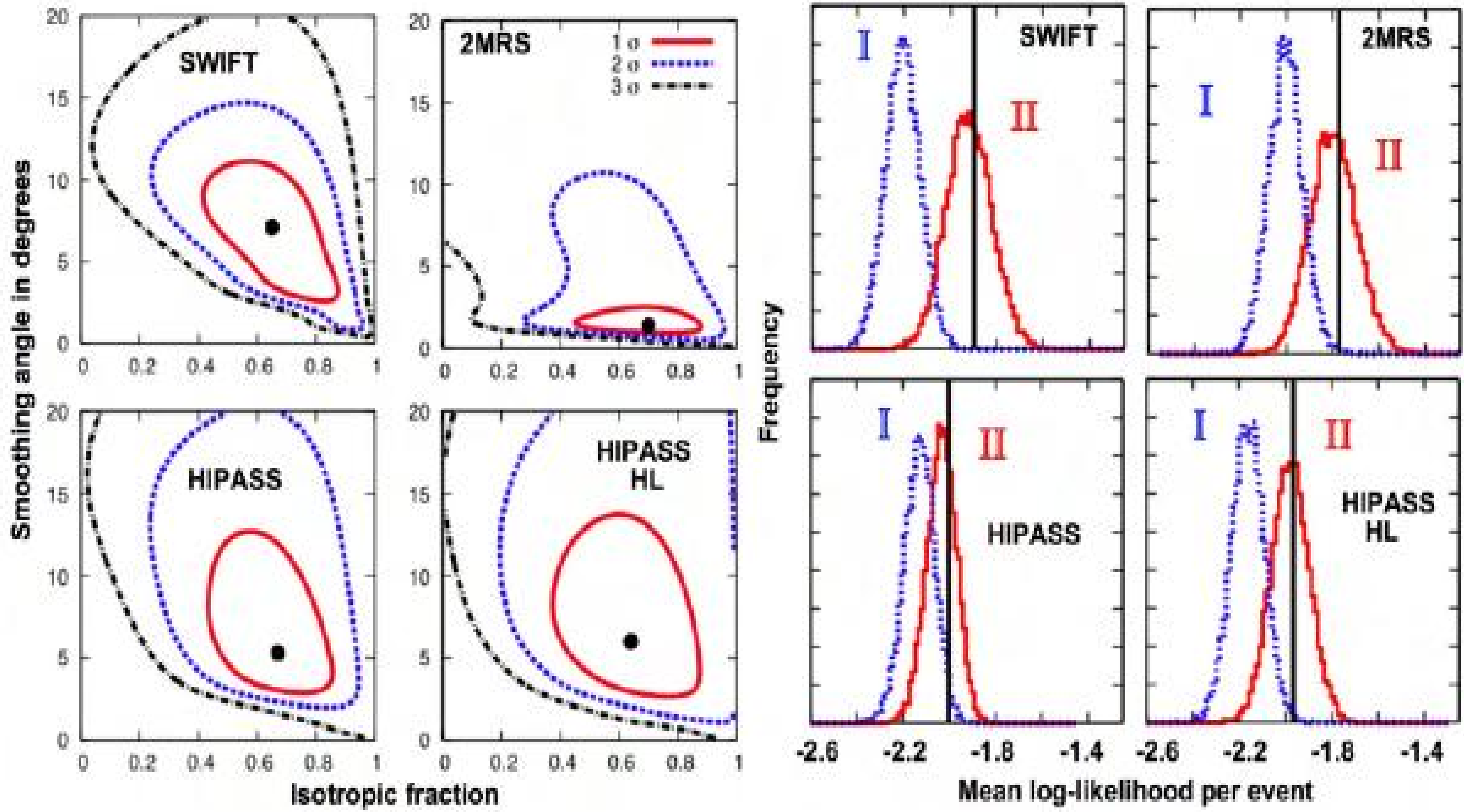
Adopting a model where a fraction f of the flux is isotropic, and (1 – f) comes from SWIFT sources (hard X-ray selected AGN),

maximizing likelihood of data gives f ≃ 0.4 - 0.8 , α < 10 deg









- Different models have likelihood that agree with the data

- Large values of f_{iso} (0.4 - 0.8) indicative of missing sources or large magnetic deflections for a fraction of the events

FINAL REMARKS

A variety of different methods are needed to study anisotropies at different energies and angular scales

CR astronomy is finally starting and we are getting the first clues on the UHECR origin: they are correlated with nearby extragalactic matter

Still many open questions: sources, composition, magnetic fields?

New data waited to clarify these issues ...