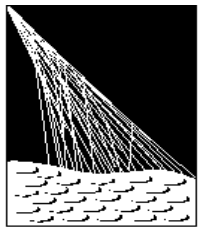


Rencontres de Moriond EW 2008

Study of the UHECR Arrival Directions with the Pierre Auger Observatory

Raffaella Bonino* for the Pierre Auger Collaboration

(*) IFSI – INFN – Università di Torino

Ultra High Energy Cosmic Rays

Particles with E ~ 10^{20} eV exist and have been detected

- **what are and where do they come from?**

Complementary studies:

- **Energy spectrum** and **composition**
- **Origin** → study of anisotropy in arrival directions:

  LARGE SCALE:

  transition from galactic to extra-galactic origin = change in the large scale angular distribution because of different mechanisms of propagation

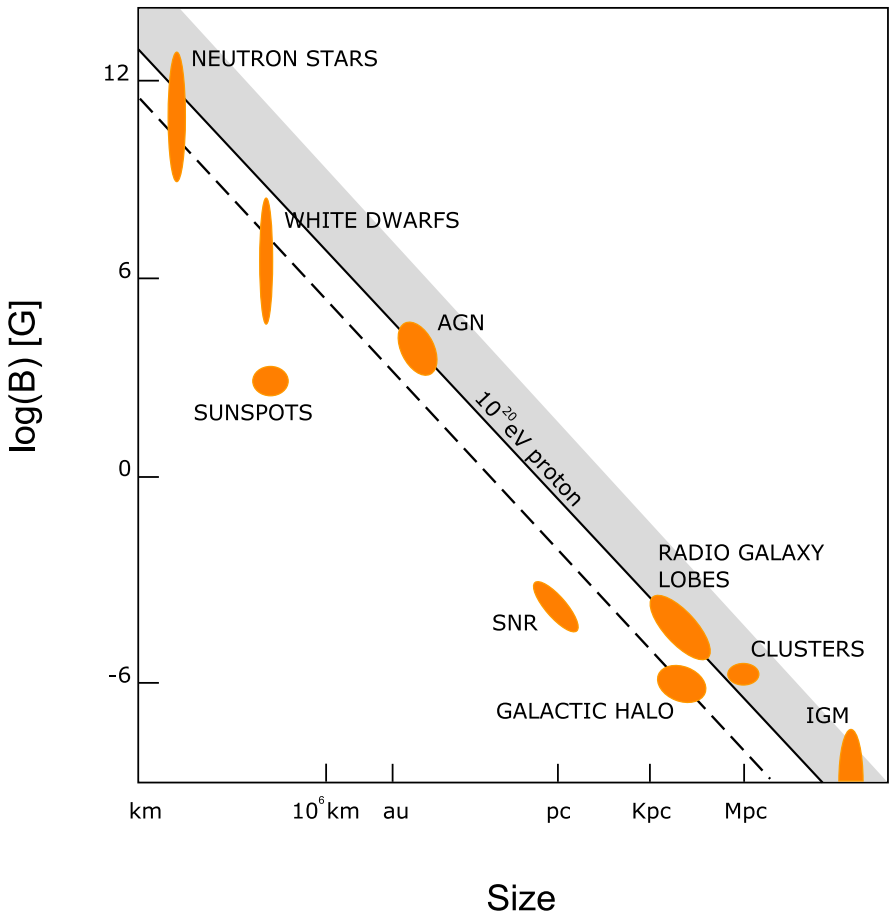
  SMALL SCALE:

  above $5 \cdot 10^{19}$ eV cosmic rays are only slightly deflected (2°-3°) by magnetic fields → direct way to search for **UHECR sources**

  If sources are nearby and not uniformly distributed, an anisotropic arrival directions distribution is expected ("clustering")

UHECR sources

Hillas plot

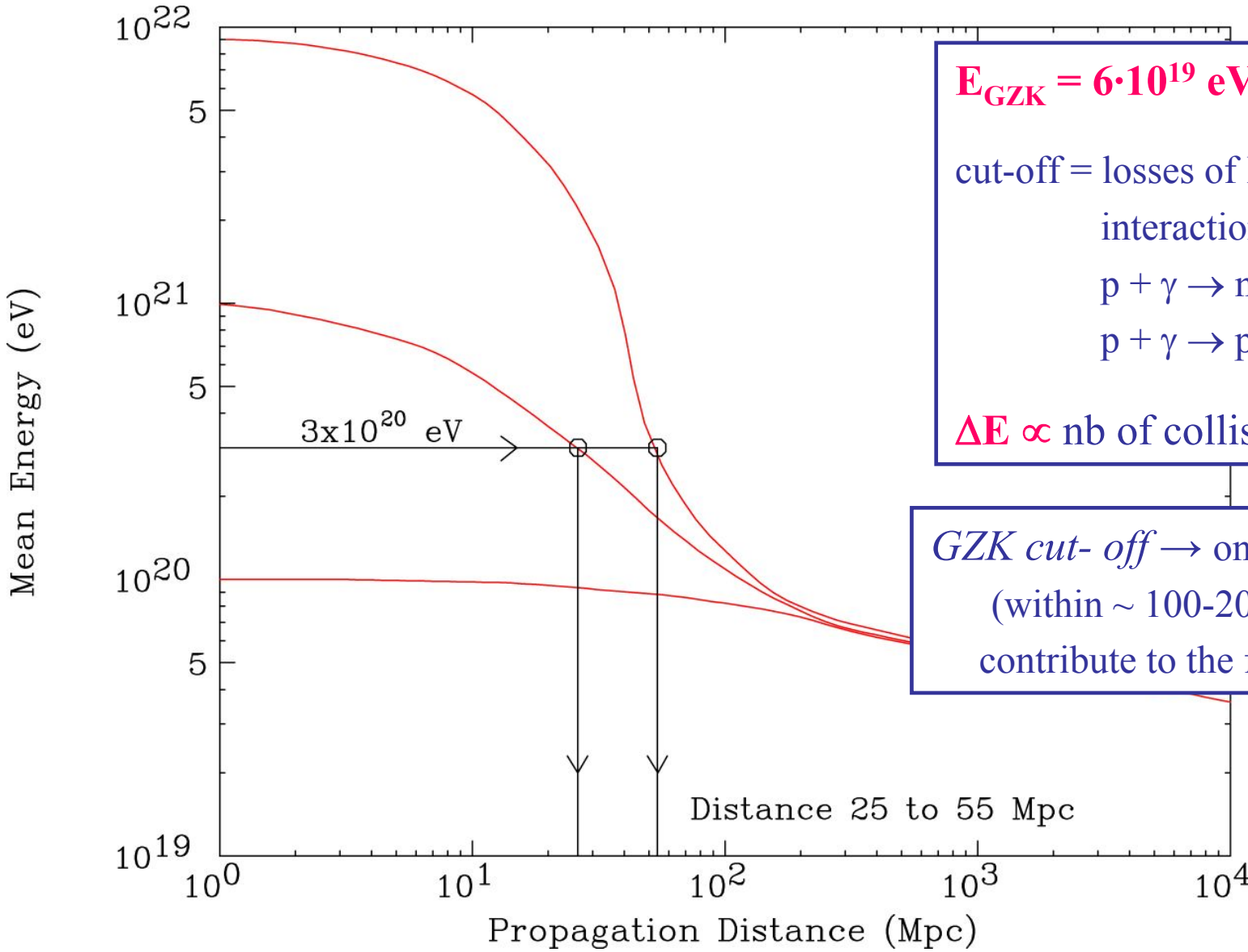


$$E_{\max}(10^{18}eV) = Z \cdot B(\mu G) \cdot R(Kpc)$$

Sizes and magnetic field strengths of astronomical objects that are possible candidates as CR sources

- AGN
- Radio Galaxies

GZK cut-off



$E_{GZK} = 6 \cdot 10^{19}$ eV

cut-off = losses of E due to the interactions with the $\gamma_{2.7K}$:

$p + \gamma \rightarrow n + \pi+$

$p + \gamma \rightarrow p + \pi^\circ$

$\Delta E \propto$ nb of collisions $\propto$ **d_{source}**

GZK cut- off $\rightarrow$ only **nearby sources** (within ~ 100-200 Mpc) should contribute to the flux above **E_{GZK}**

Outline

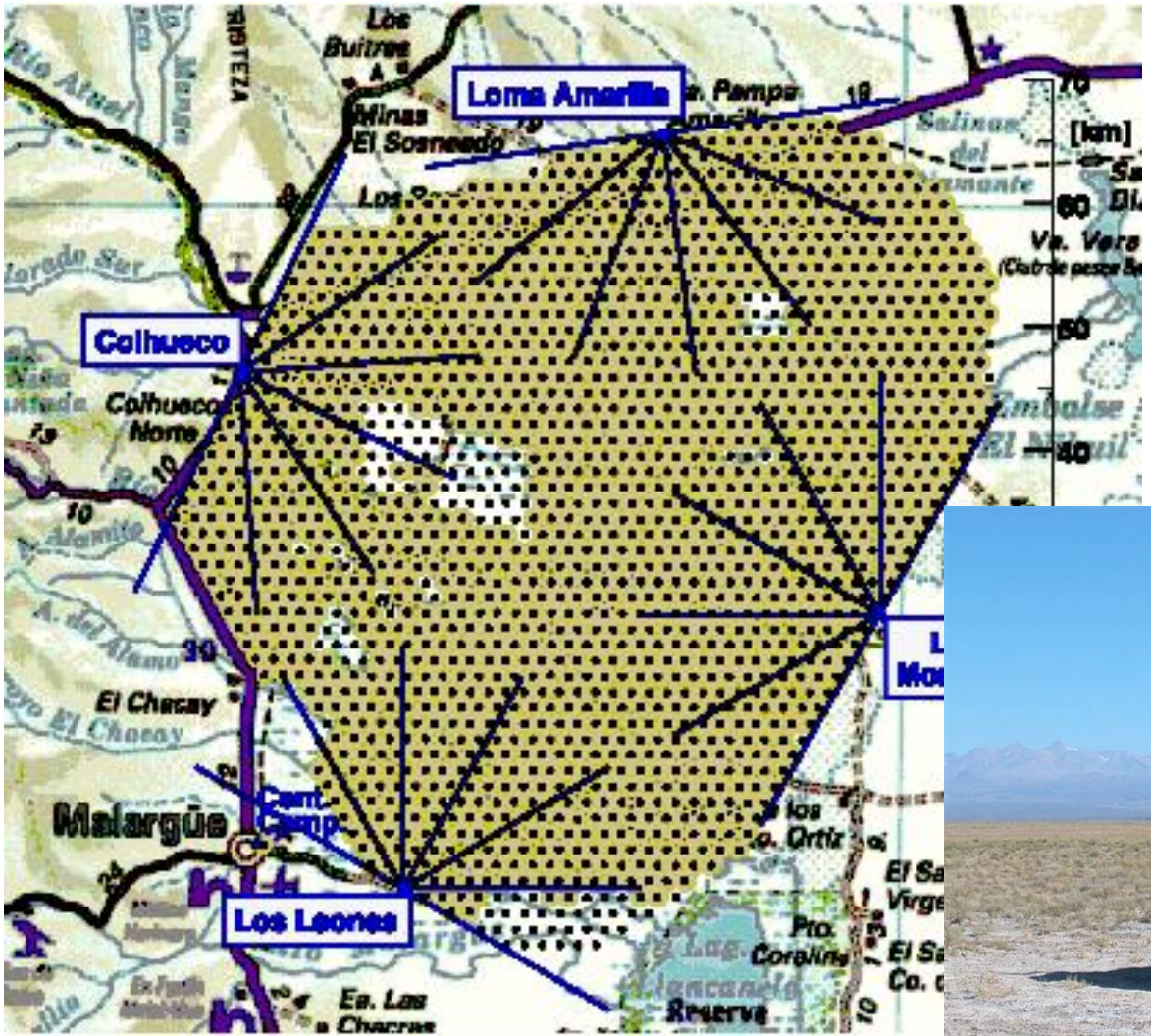
- The origin of the highest energies cosmic rays (>10^{19} eV) is expected to be **extra-galactic**
  - ✓ What are these extra-galactic sources? ⇒ ***search for correlations***
- Somewhere downwards in the spectrum, the **transition** from galactic to extra-gal. must occur
  - ✓ Where? ⇒ ***study of large scale anisotropies*** *(change in the large scale angular distribution)*
- The **Galactic Center** is one of the most interesting galactic target

  ⇒ ***look for localized excesses of CRs in the GC region at ~ 10^{18} eV***

Required tools: knowledge of the angular resolution of the Surface Detector

⇒ ***angular reconstruction and timing uncertainty model***

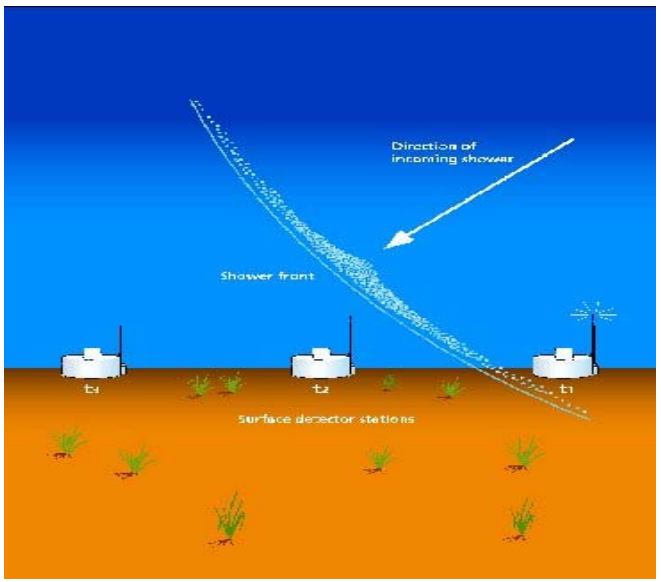
Auger Surface Detector



SD arrival directions
arrival times and angular resolution

- Especially for the analysis of small scale anisotropy a good **angular resolution** and detector stability are required

- The angular resolution is strictly dependent on the **accuracy** in the **arrival time measurement** of the particles in the tanks

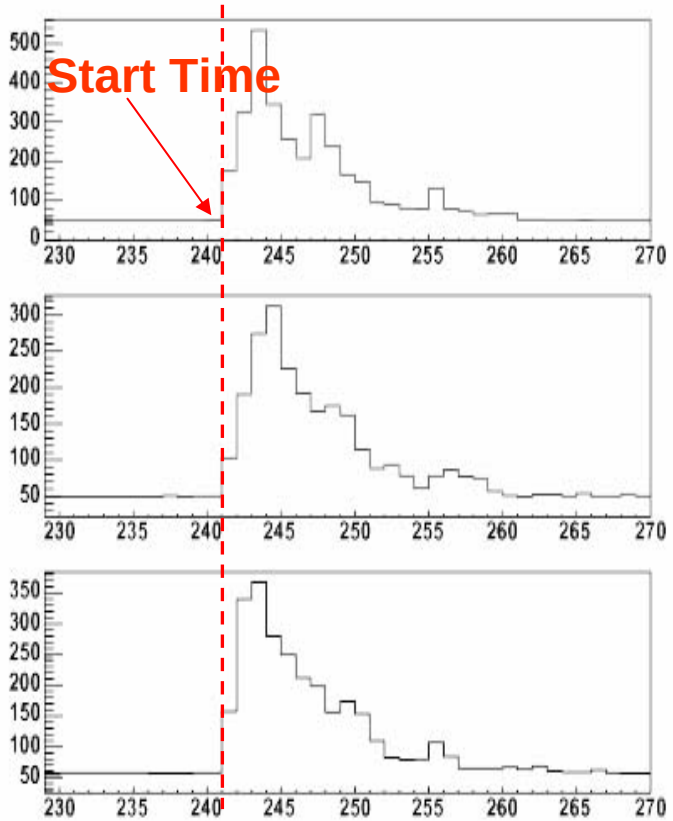


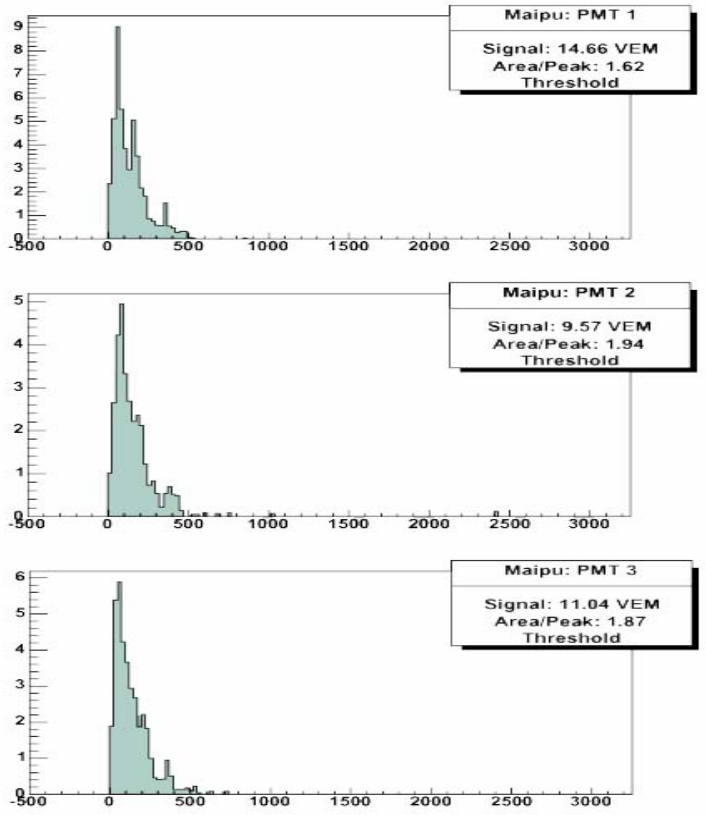
The arrival direction is measured from the delays among the hit tanks

“Start Time”

- It should correspond to the arrival time of the shower front to the detectors
- It’s identified with the arrival time of the first particle detected

  ⇒ the first bin above a fixed threshold in a 2 or 3-fold coincidence





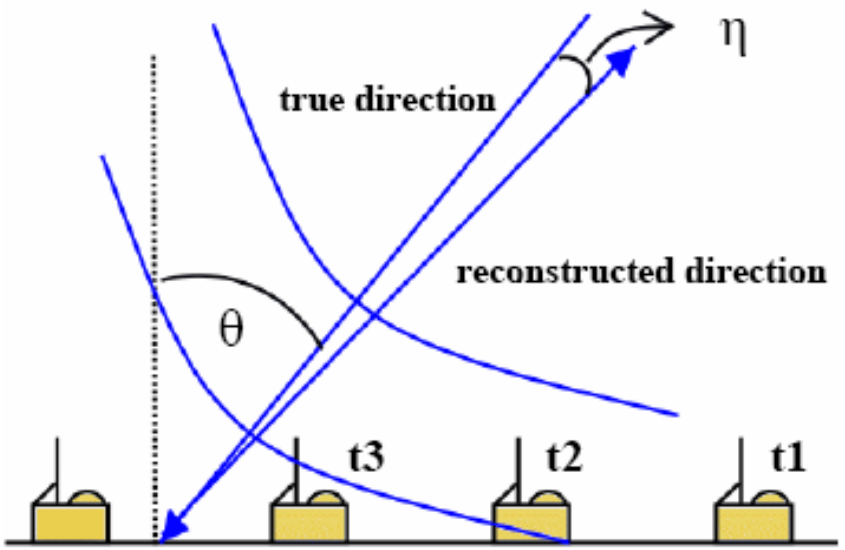
SD angular resolution

Computed on an event by event basis:

→ θ and φ derived from the fit of the arrival time of the first particle on the tank

Based on:

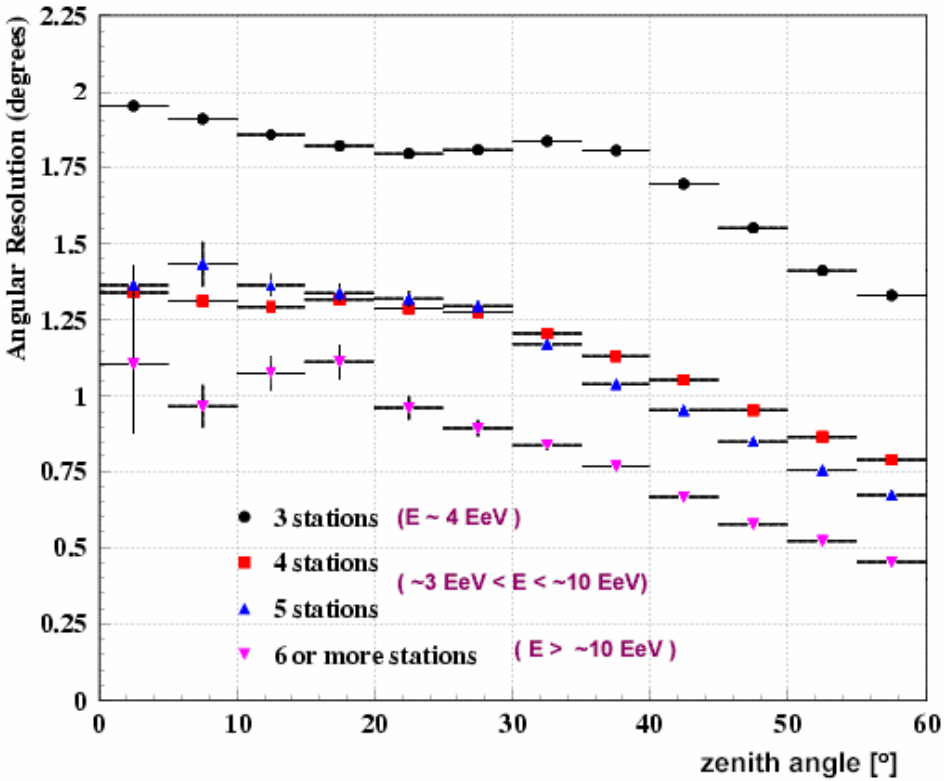
- Parabolic shower front model
- Semi-empirical timing uncertainty model



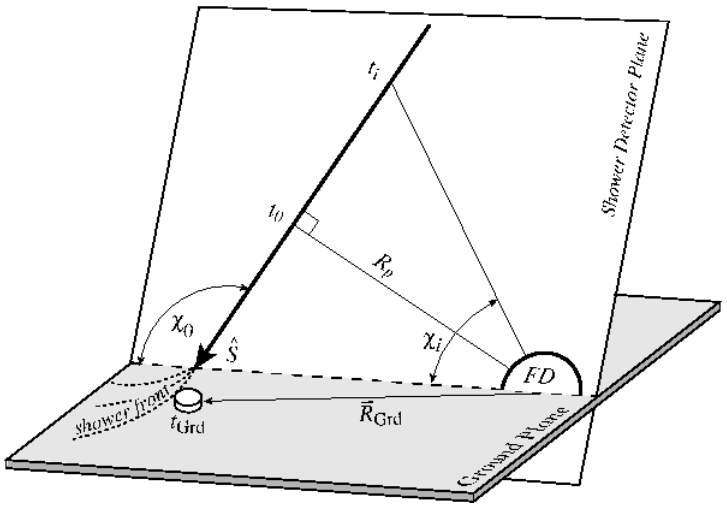
Angular resolution ≡ angular radius that would contain 68% of the showers coming from a point-like source

SD angular resolution

SD-only



Hybrid



#	AR hybr [°]	AR SD-only [°]
3	1.71 ± 0.05	1.54 ± 0.01
4	1.49 ± 0.07	1.03 ± 0.01
5	1.3 ± 0.1	0.92 ± 0.02
6	1.0 ± 0.1	0.62 ± 0.01

⇒ Comparison with hybrid reconstruction (σ_η~0.6°) confirms the SD-only result

Large scale anisotropy studies

Overview

Objective:

- **CR's origin** at ~10^{18}eV
  - **galactic:** %-level modulation (*models of gal. propagation*)
  - **extra-gal.:** no structure except for a CMB-dipole (~0.6%)
    at higher energies: GZK cut-off → sources → anisotropy

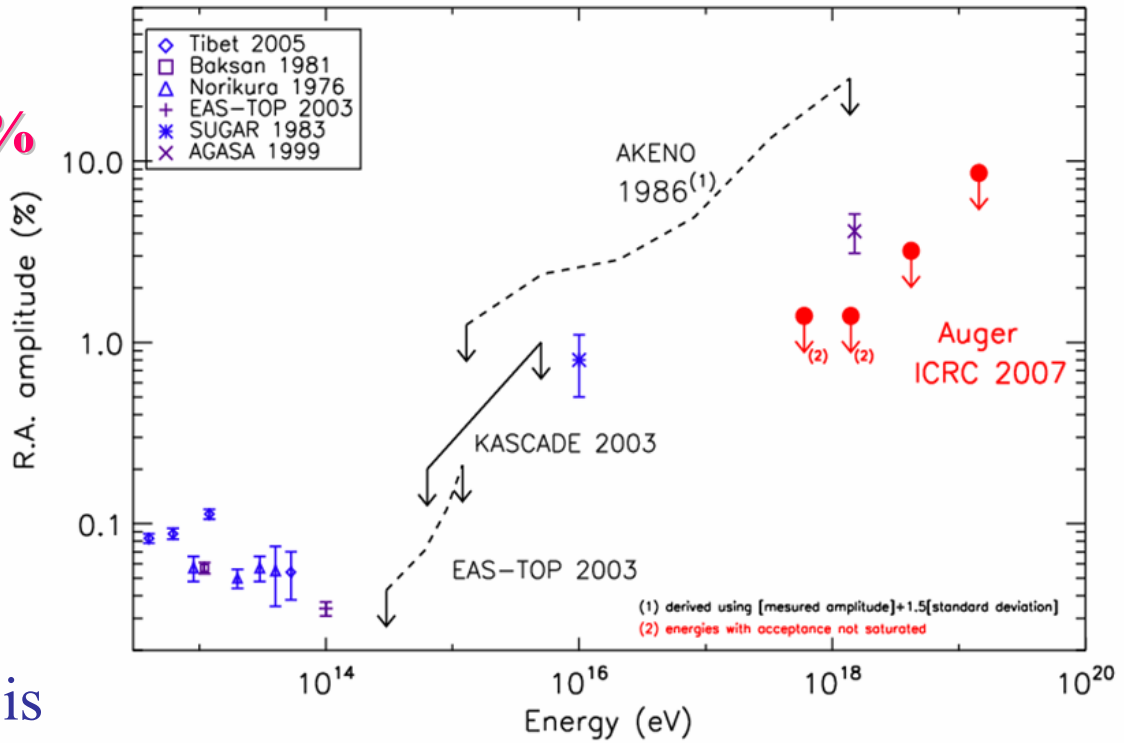
Difficulties: control of spurious modulations

- sky exposure
- instabilities due to atmospheric and instrumental effects
- not constant acceptance

- **3 complementary analysis in the EeV** (=10^{18}eV) **range** ($5 \cdot 10^5$ events)

Auger results

- Results from the search for large-scale patterns:
  - **no modulation in RA**
  - **95% c.l. upper limit = 1.4%** for $1 < E < 3$ EeV
- Exposure-independent cross-checks confirm the lack of significant pattern
- The AGASA 4% modulation is not confirmed (but the observed regions of the sky are different)



The Galactic Center region

Why the Galactic Center?

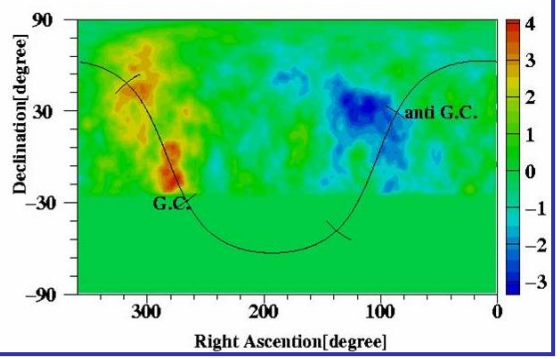
- GC **contains a super-massive black hole** → possible candidate to accelerate CR
- It passes only **6° away from the AUGER zenith**
- **Claims** in the past **from other experiments** of large excesses in GC region:

AGASA:

excess = 22%

$E = 10^{18}$-$10^{18.4}$ eV

$(\alpha,\delta) = (280°,-17°)$

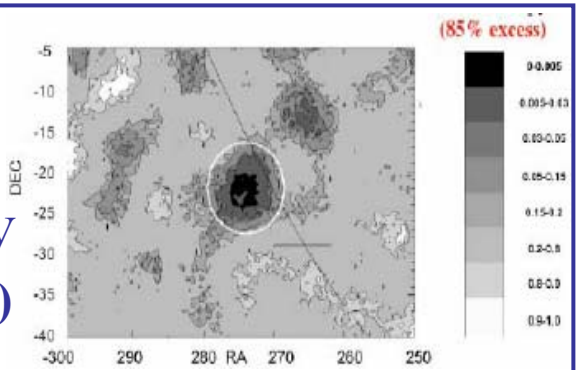


SUGAR:

excess = 85%

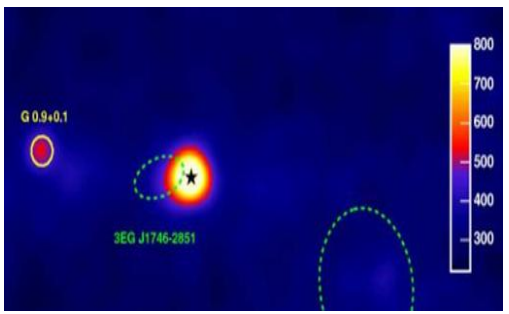
$E = 10^{17.9}$-$10^{18.5}$ eV

$(\alpha,\delta) = (274°,-22°)$



H.E.S.S.

detected a TeV γ-ray source close to Sagittarius A*



Auger results

- In our analysis GC treated both
  - as extended source
  - as point-like source
- Data set divided into 2 energy bands:

0.1 < E < 1 EeV $\Rightarrow$

search	window size	n_{obs}/n_{exp}
extended	10° (TH)	5663/5657 = 1.00 ± 0.02(stat) ± 0.01(syst)
	20° (TH)	22274/22440 = 0.99 ± 0.01(stat) ± 0.01(syst)
point-like	1.3° (G)	192.1/191.2 = 1.00 ± 0.07(stat) ± 0.01(syst)

1 < E < 10 EeV $\Rightarrow$

search	window size	n_{obs}/n_{exp}
extended	10° (TH)	1463/1365 = 1.07 ± 0.04(stat) ± 0.01(syst)
	20° (TH)	5559/5407 = 1.03 ± 0.02(stat) ± 0.01(syst)
point-like	0.8° (G)	16.9/17.0 = 0.95 ± 0.17(stat) ± 0.01(syst)

Conclusions:

- **No significant CRs flux excess** in both energy ranges
- Distribution of Li-Ma overdensity significances **consistent with isotropic sky**

Correlation of UHECR with nearby extra-gal. objects

Overview

- Extra-gal. nearby objects identified as possible candidates as UHECR sources (Hillas plot) → expected correlation of UHECR with such objects
- GZK effect
- Inhomogeneous distribution of sources → expected anisotropy

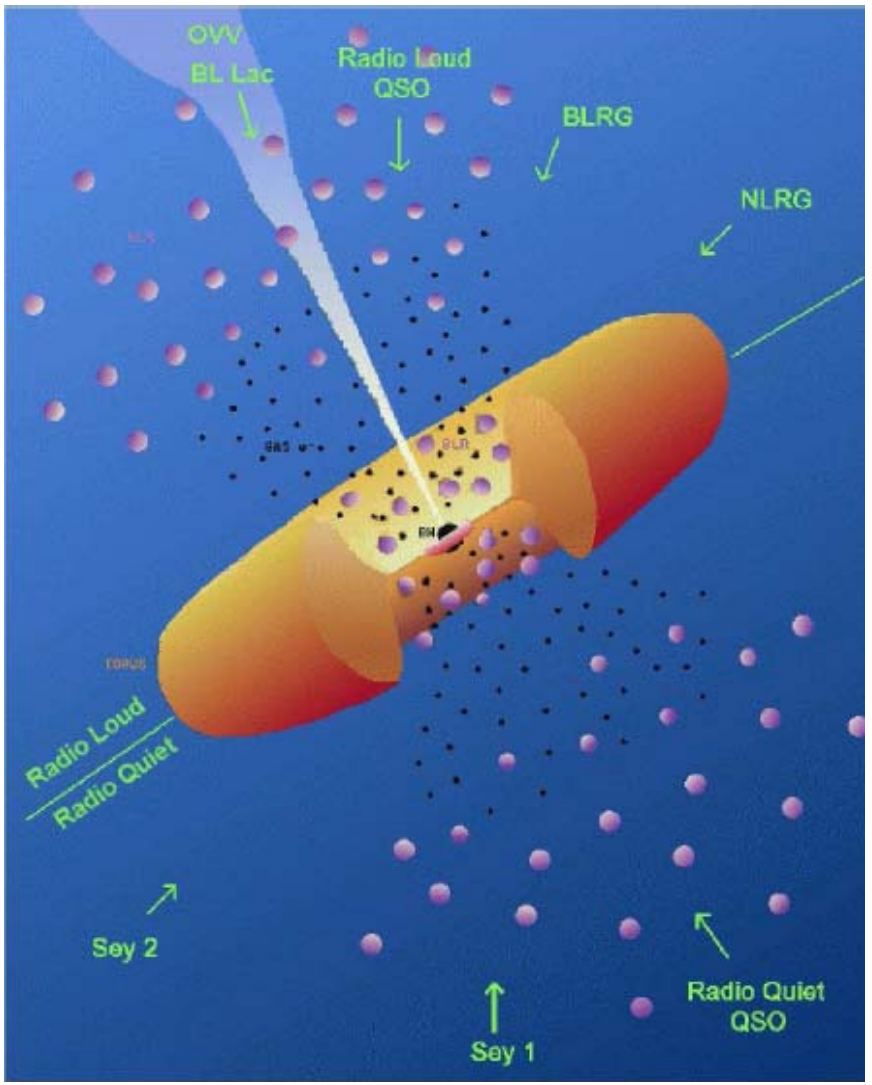
Véron-Cetty / Véron Catalogue (12^{th} edition, 2006):

- ✓ Large collection of quasars, BL Lacs and active galaxies (thorough survey of all such objects in the literature)
- ✗ Not an unbiased statistical sample because it's incomplete around the galactic plane and for objects distances >> 100 Mpc
- Not an obstacle to demonstrate anisotropy
- Affects sensitivity to identify sources unambiguously

What are AGN ?

Active Galactic Nuclei:
galaxies hosting central black holes that feed on gas and stars and may eject vast plasma jets into intergalactic space

Different names → ***unified scheme*** ⇒

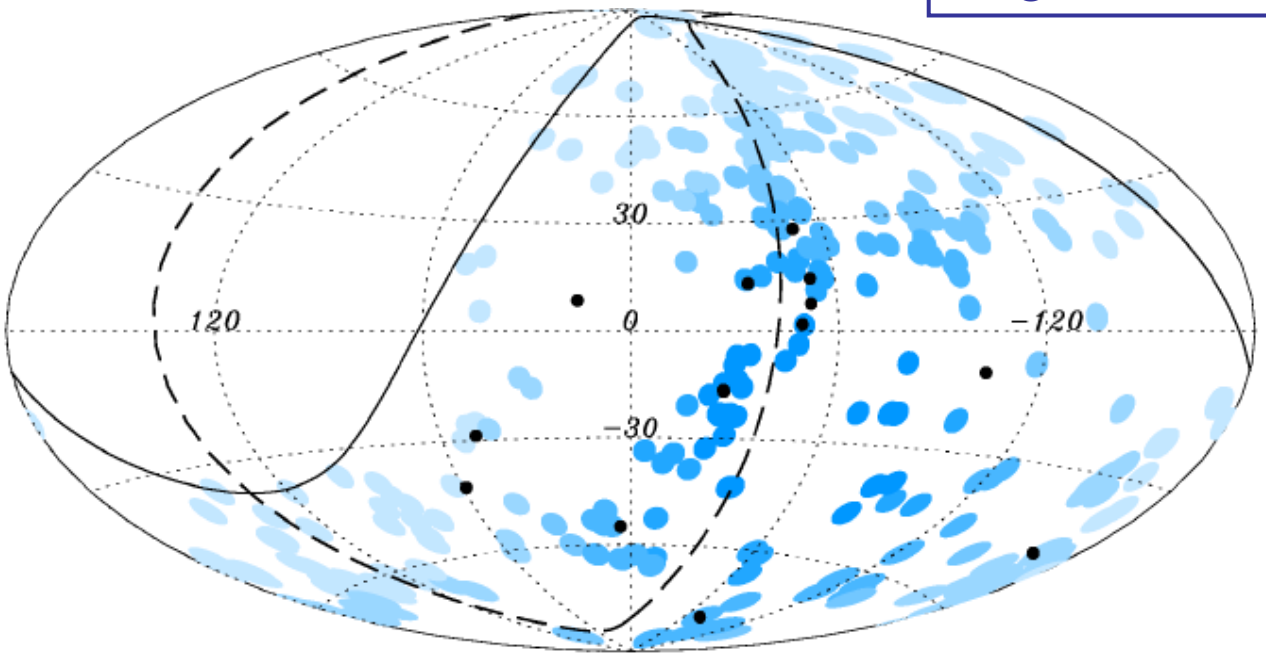


Search method

Scan over ψ, D_{max}, E_{th}:

cumulative binomial probability for k/n correlations with individual chance probability $p(\psi, D_{max})$*

(*) **$p(\psi, D_{max})$:** *isotropic prob. for a CR to arrive with angular separation smaller than ψ from the given AGN within D_{max}*

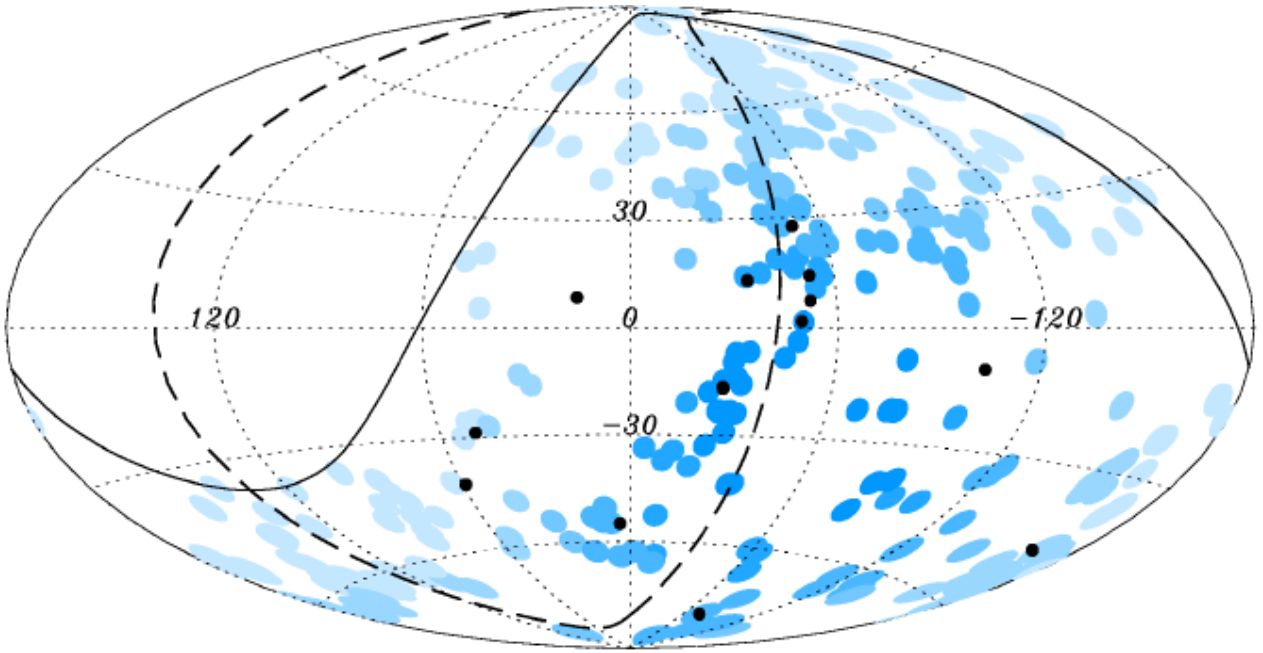


Search method

Scan over ψ, D_{max}, E_{th}:

cumulative binomial probability for k/n correlations ⇒ $P = \sum_{j=k}^{n} \binom{n}{j} p^j (1-p)^{n-j}$

with individual chance probability $p(\psi, D_{max})$*



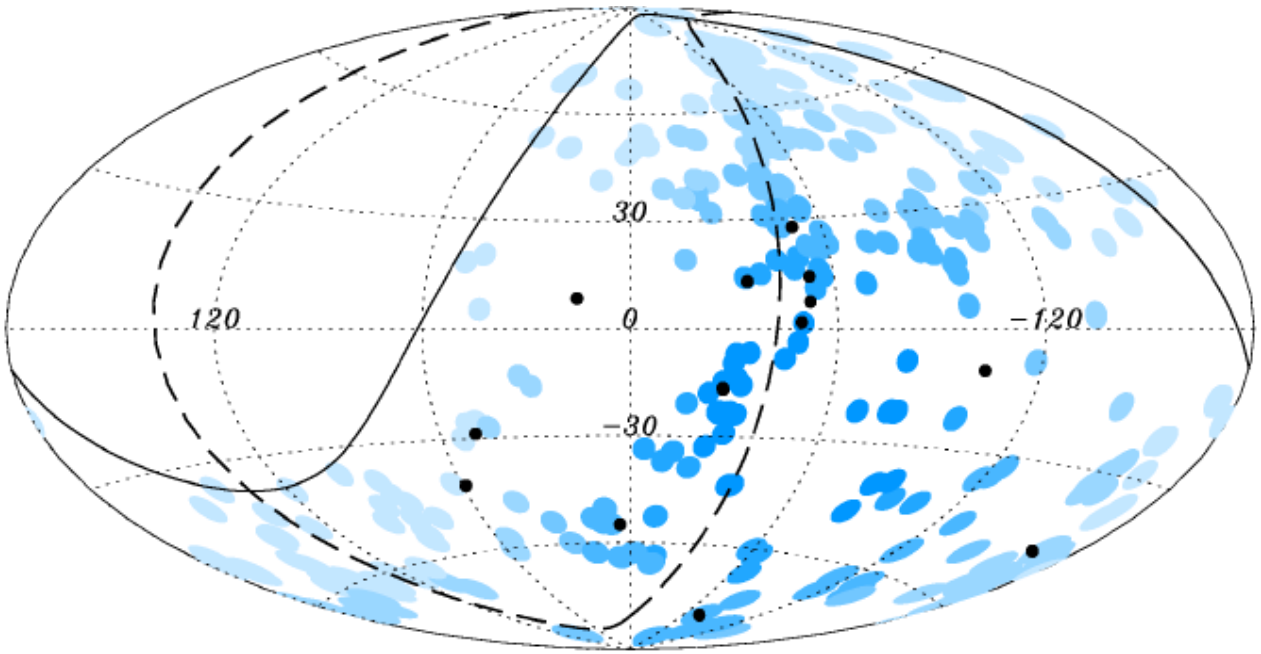
Search method

Scan over ψ, D_{max}, E_{th}:

cumulative binomial probability for k/n correlations

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

with individual chance probability $p(\psi, D_{max})$*



Exploratory scan: over data until 27 May 2006

12/15 events correlated (only 3.2 expected)

Minimum P found for $E_{th} \sim 6 \times 10^{19}$ eV, $\psi \sim 3°$ *and* $D_{max} \sim 75$ Mpc

Prescription

- Parameters: E_{th} = 56 EeV , D_{max}= 75 Mpc , ψ = 3.1°
- Same reconstruction algorithm
- Data set independent from exploratory scan (from 27 May 2006)

- α=1% → probability to incorrectly reject isotropy
- β=5% → probability to incorrectly reject correlation

N	4	6	8	10	12	...	30	31	33	34
k_{min}	4	5	6	7	8	...	14	14	15	15

Prescription fulfilled: on 25 May 2007

99% CL Anisotropy

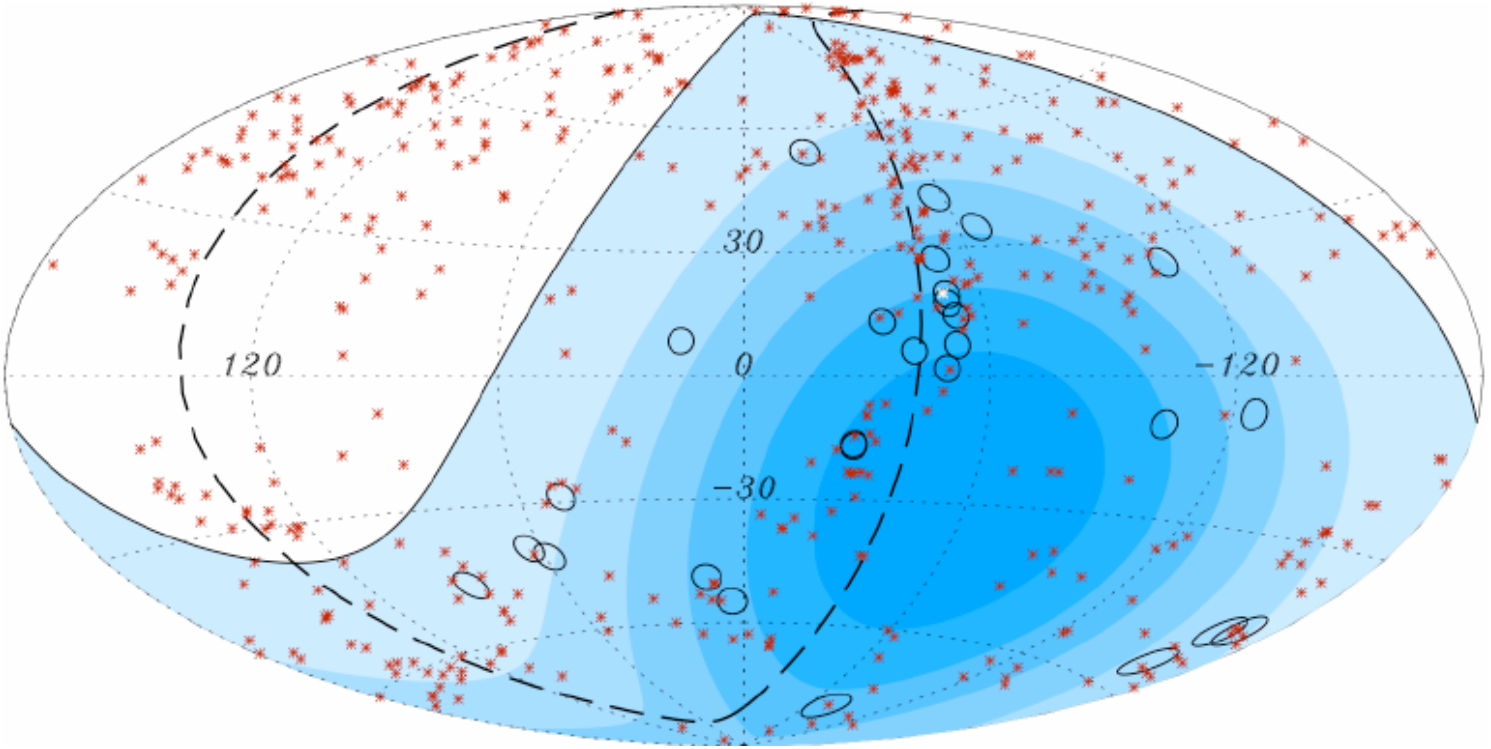
Scan of full data set

(1 Jan 2004 – 31 Aug 2007)

- Re-optimized the scan parameters:

⇒ **E_{th} = 57 EeV , D_{max} ≈ 71 Mpc , ψ = 3.2°**

- **20/27 events correlated** (only 5.6 expected)
- $P_{min} = 5 \times 10^{-9}$ → MC isotropic simulations: only 10^{-5} have smaller P_{min}



Scan of full data set
(1 Jan 2004 – 31 Aug 2007)

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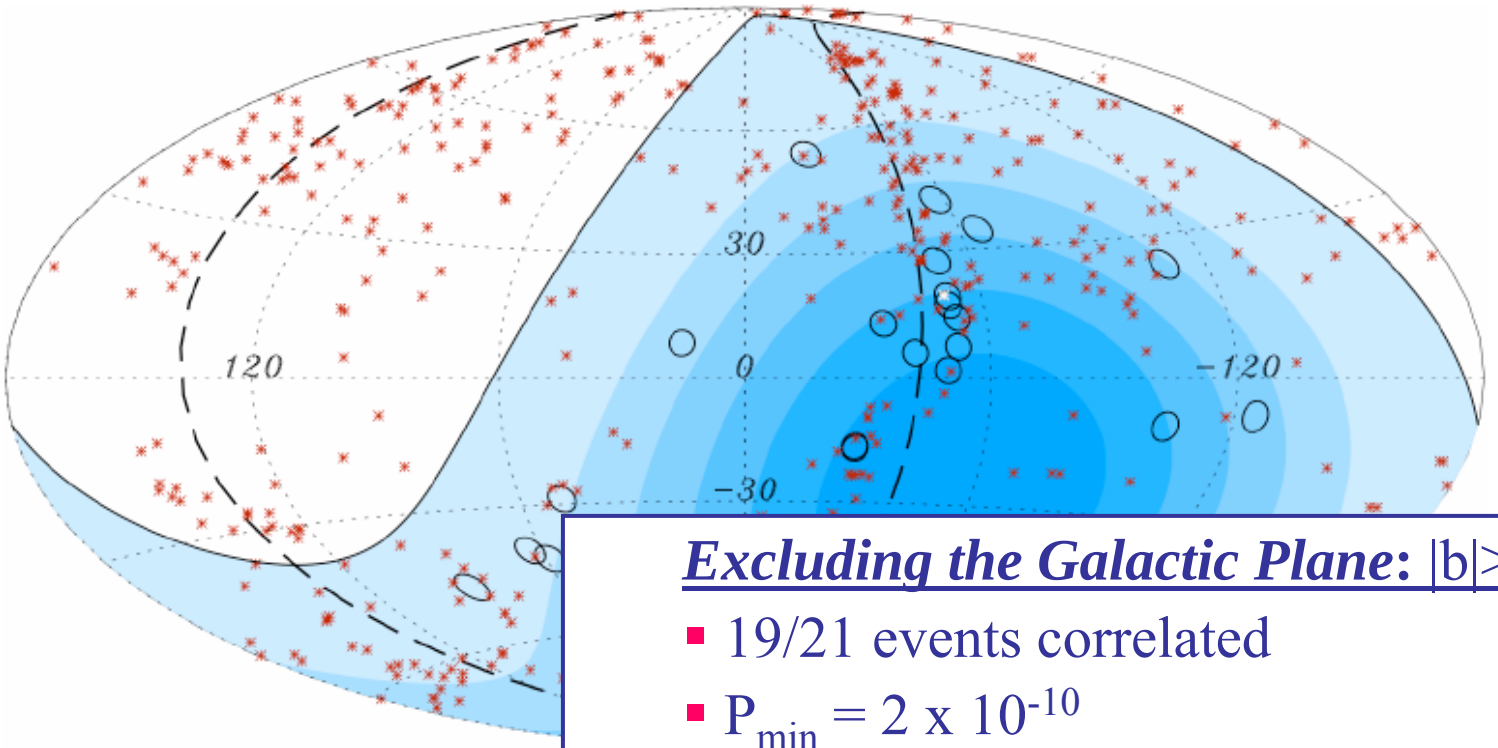
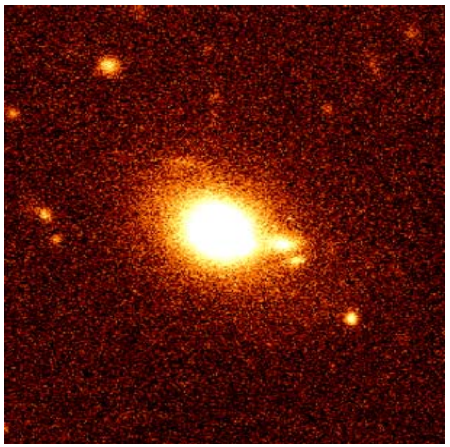


***Excluding the Galactic Plane*: |b|>12°**

- 19/21 events correlated
- $P_{min} = 2 \times 10^{-10}$

Other possible UHECR sources

BL – Lacs = subclass of blazars, active galaxies with beamed emission from a relativistic jet aligned toward our line of sight
→ potential sources of UHECRs



AUGER results:

Test	Ref.	E_{th} (EeV)	Number of events	Angular size	Observed	Expected (isotropic)	Probability
A	[1]	24	267	2.5°	1	1.0	0.63
B	[2]	40	62	2.5°	2	2.5	0.71
C	[3]	24	267	2.9°	1	0.5	0.41
D	[4]	10	1672	0.9°	11	12.1	0.66
a)	[4, 5]				8	8.9	0.67
b)	[4]				3	3.2	0.62

- AUGER doesn't support correlations reported by **AGASA, Yakutsk** and **HiRes** data
- no excess from an extended search

Conclusions on the correlation with nearby extra-gal. objects

- **Anisotropy** confirmed at 99% CL with a priori test on independent data set
- Compatible with origin in **extragalactic sources** within GZK horizon
- Angular scale of few degrees suggests predominantly **light composition**
- **AGN = tracers** $\Rightarrow$ we do not identify unambiguously AGN as the sources
  - Objects with a similar spatial distribution (GRBs, quasar remnants, …) can not be excluded
  - Plausible that only a subclass of AGN are the sources
- Several events close to the super-galactic plane (particularly Cen A) and paucity of events from Virgo

➡ More data (+ Auger North) are needed to identify the sources and their characteristics

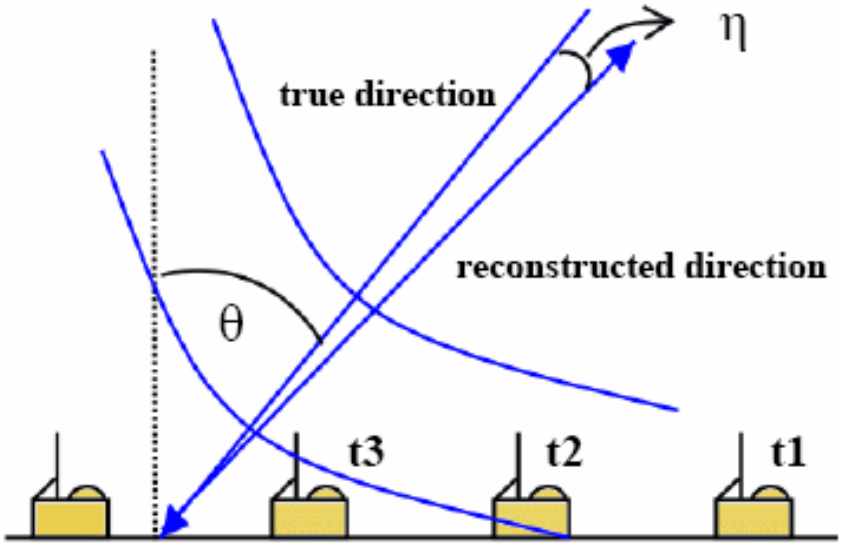
SD angular resolution

Computed on an event by event basis:

→ θ and φ derived from the fit of the arrival time of the first particle on the tank

Based on:

- Parabolic shower front model
- Semi-empirical timing uncertainty model *[C.Bonifazi et al., astro-ph0705.1856]*

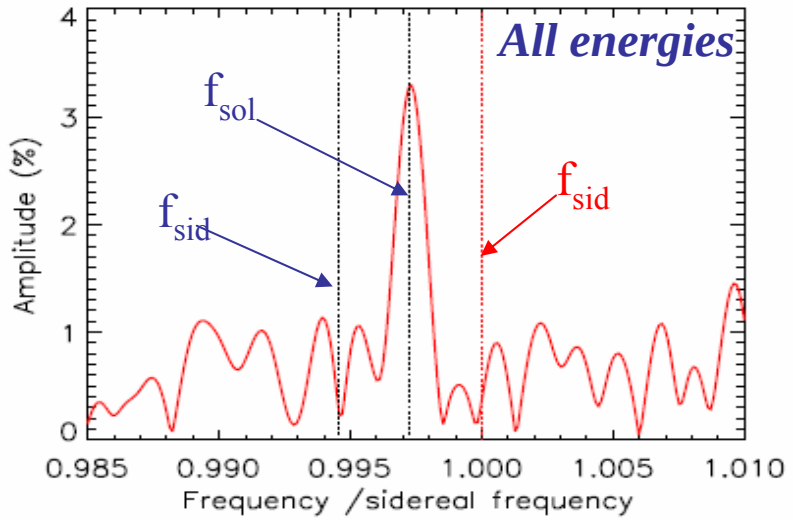


Space-angle uncertainty computed from σ_θ and σ_φ: $F(\eta) = \frac{1}{2}\left[\sigma_\theta^2 + \sin^2(\theta)\sigma_\phi^2\right]$

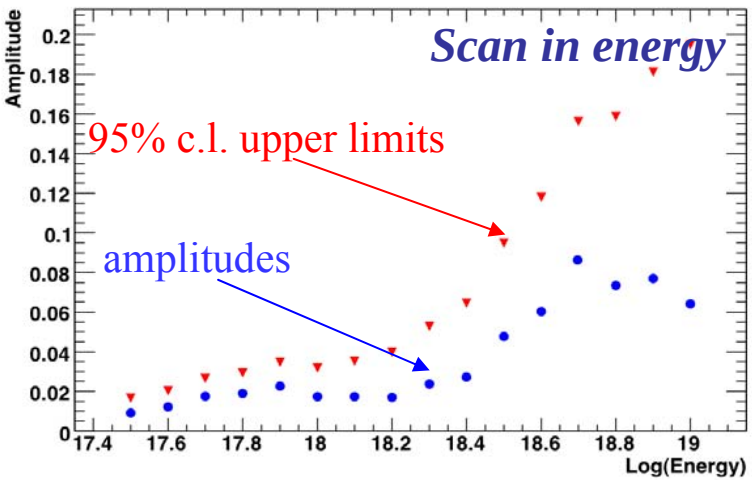
Angular resolution ≡ angular radius that would contain 68% of the showers coming from a point-like source: $AR = 1.5\sqrt{F(\eta)}$

Large scale anisotropy

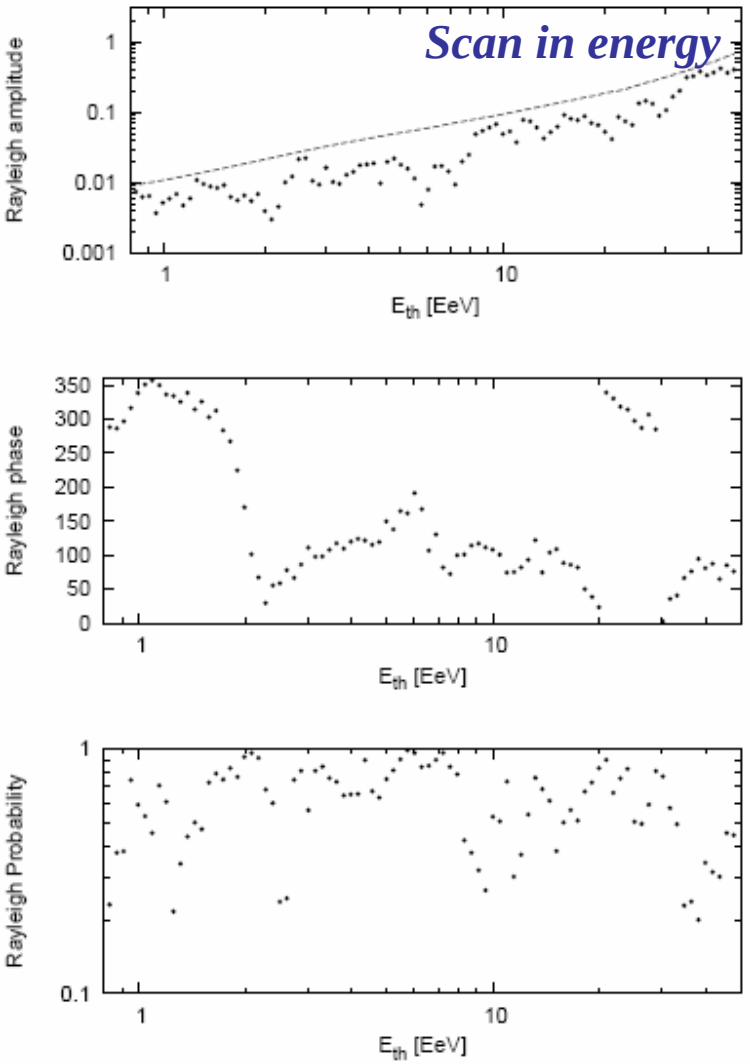
1st method



2nd method

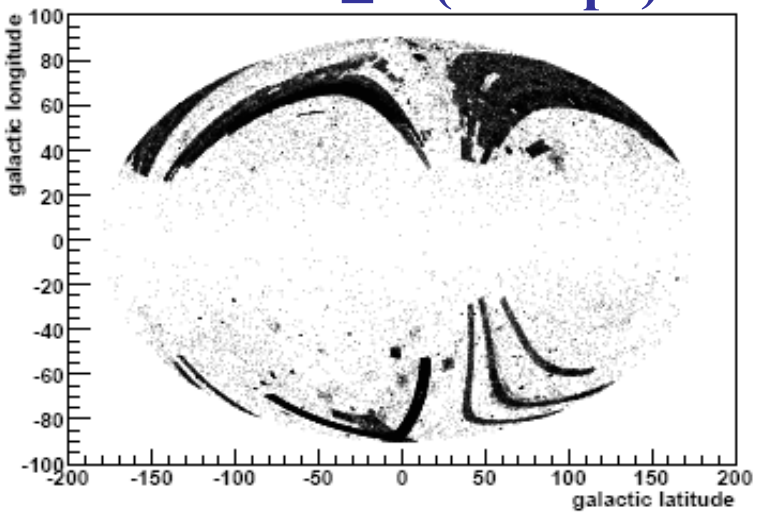


3rd method

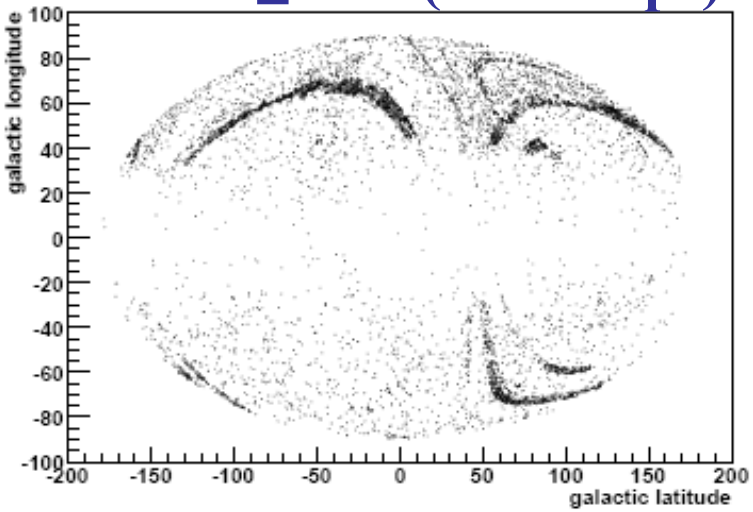


Véron-Cetty / Véron catalogue

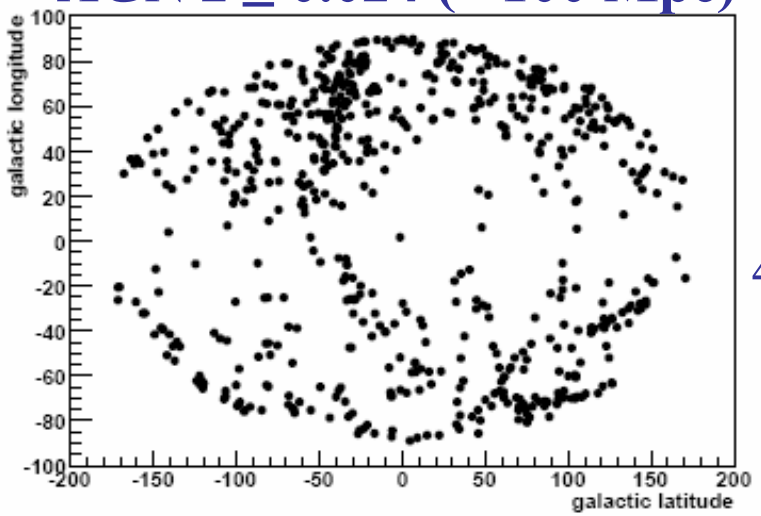
AGN $z \leq 5$ (~ 5 Gpc)



AGN $z \leq 0.15$ (~ 550 Mpc)



AGN $z \leq 0.024$ (~ 100 Mpc)



694 AGN

472 in AUGER f.o.v.

[by Fabian Schüssler]