Seeking Ultra High Energy Cosmic Ray Sources and Nature

Pierre Auger Observatory

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Theses observations can be most simply explained assuming that an extreemly penetrating radiation is coming from above » (V. Hess)

Synthèse des mesures de Hess et de Kolhörster (1912 - 1914)
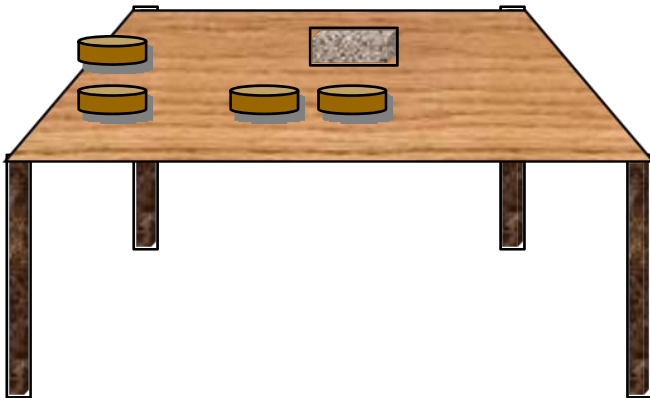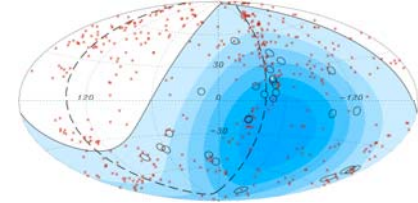
Intensité du rayonnement
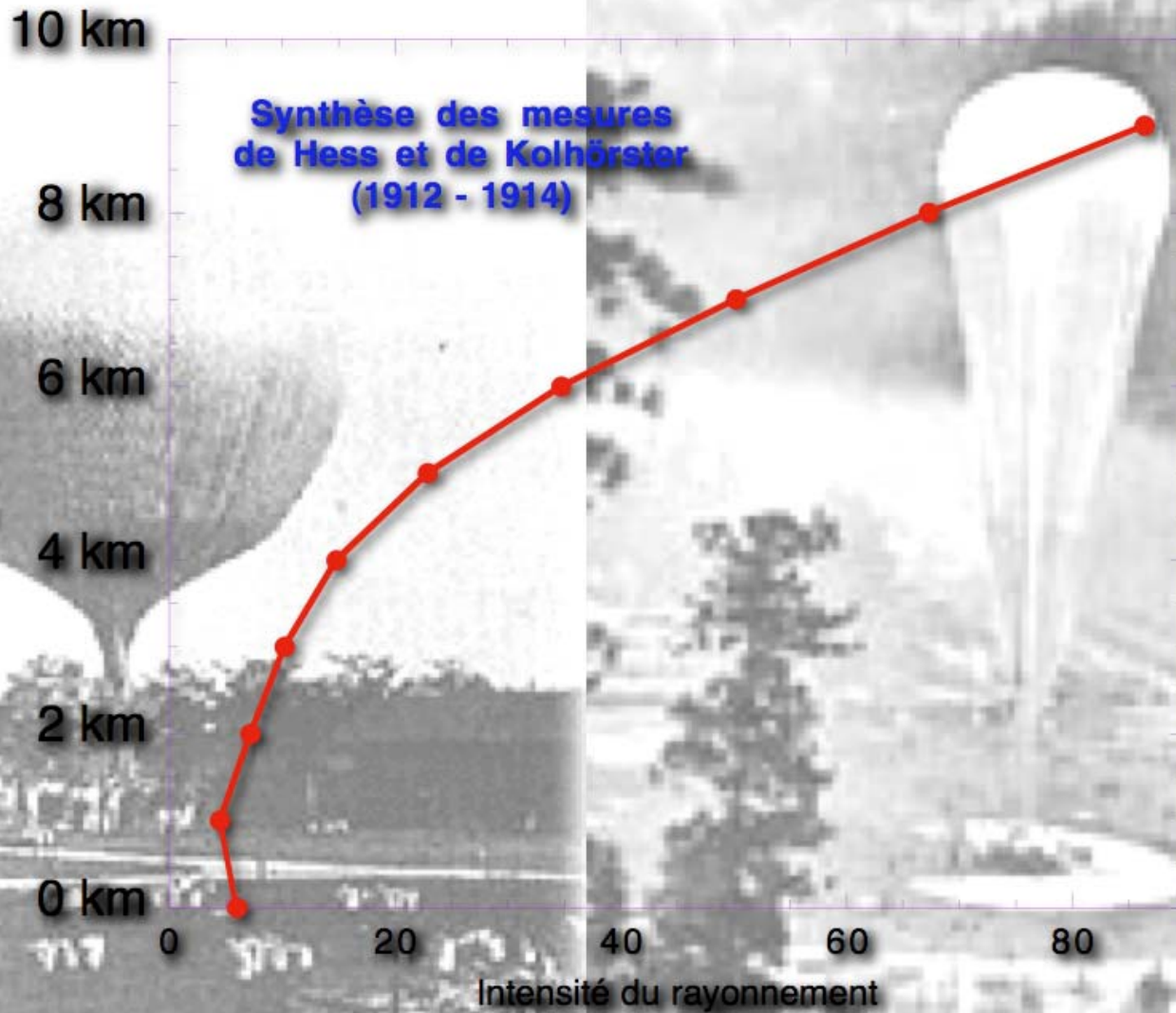
What is it?
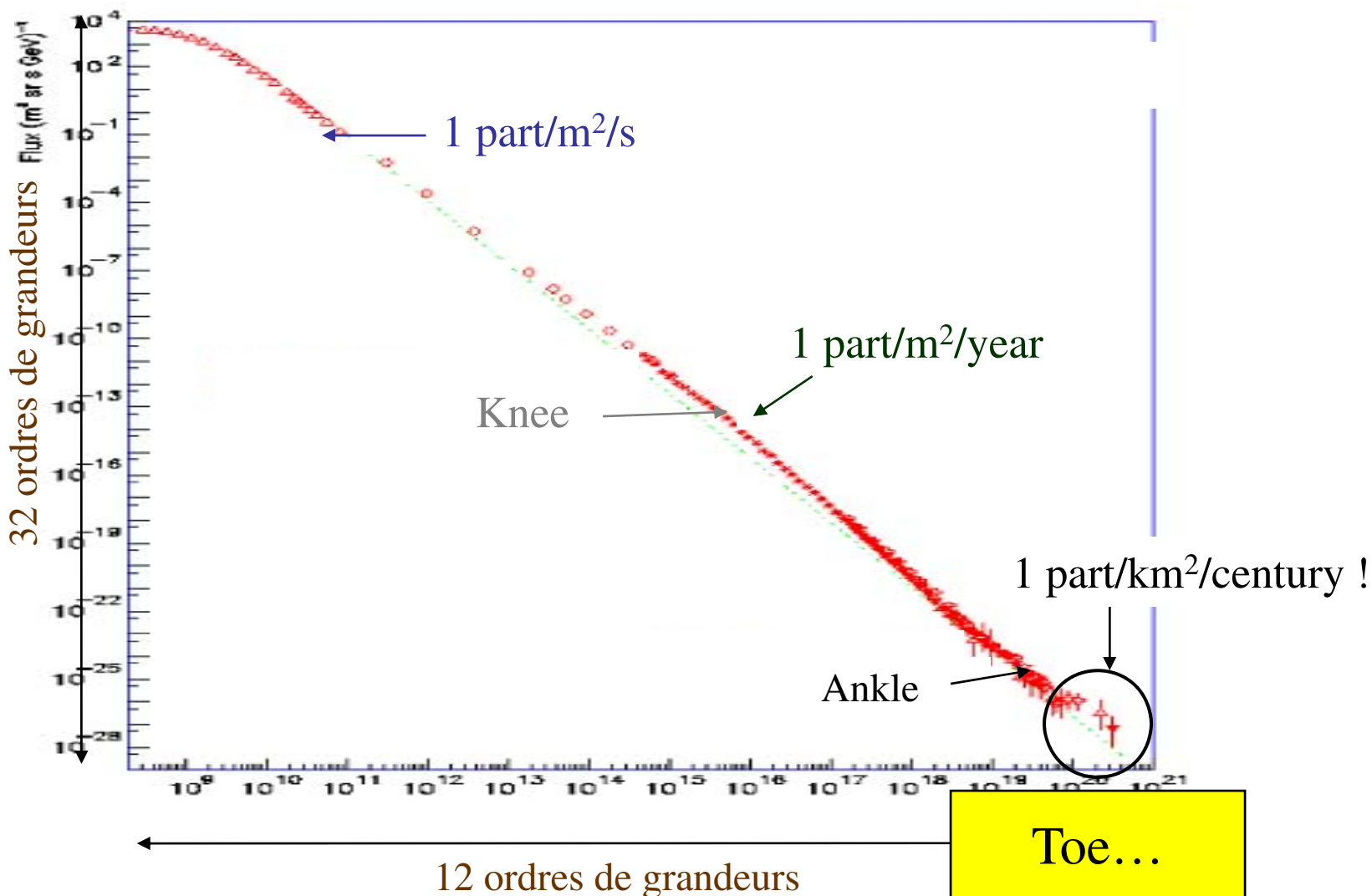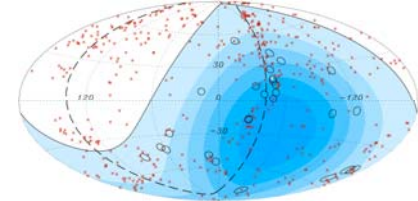
High Energy Astrophysics
CR --> Accelerators --> CR

> « **On voit d'après ces résultats que les** averses soudaines de rayons cosmiques **décrites ici peuvent couvrir des surfaces de l'ordre de** 1000 m² **, et comportent donc** plusieurs dizaines de milliers de corpuscules, **dont une moitié environ peut traverser 5 cm de plomb. »**
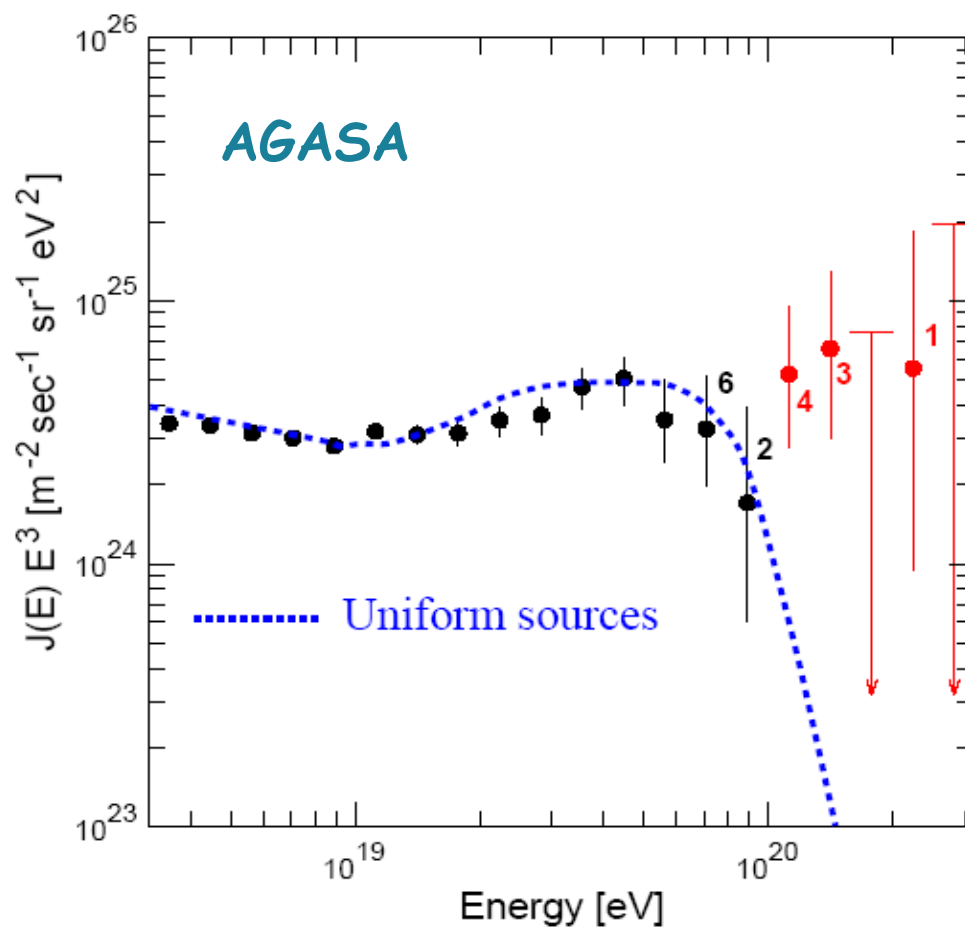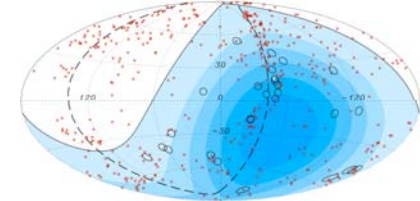
Académie des sciences, séance du 18 juillet 1938

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Energy spectrum

Flux (m² sr s GeV)⁻¹

32 ordres de grandeurs

1 part/m²/s

1 part/m²/year

Knee

1 part/km²/century !

Ankle

Toe…

12 ordres de grandeurs

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AGASA results (end of 90's)

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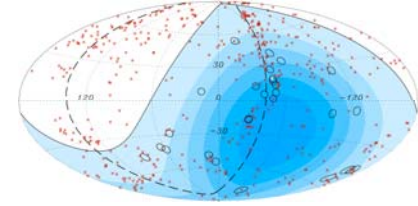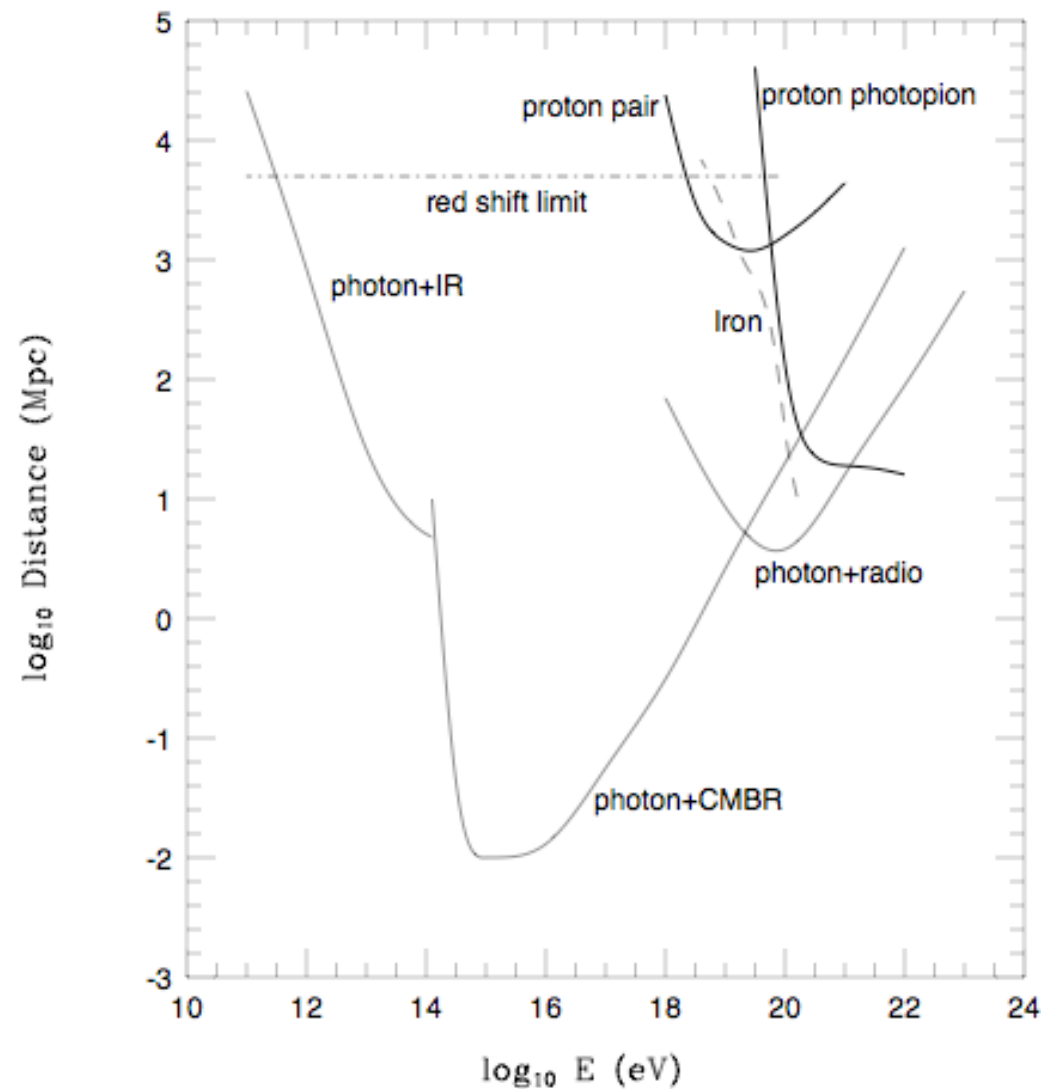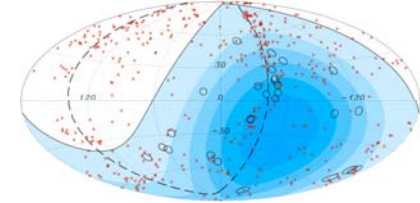LPNHE - In2p3/CNRS - Univ. P6 & P7

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Interactions with CMB

- photons produce pairs

- Nuclei are photo-desintegrated

- Hadrons produce pions (GZK)

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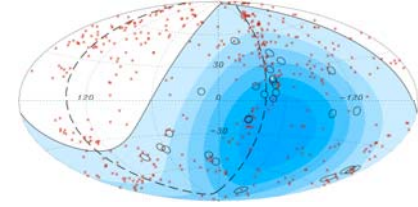
Possible sources

Bottom up

- AGNs
- Radio Galaxies
- Young Neutron stars
- GRBs

Barion dominance

Top down

- Topological defects
- Massive relics from Big-Bang
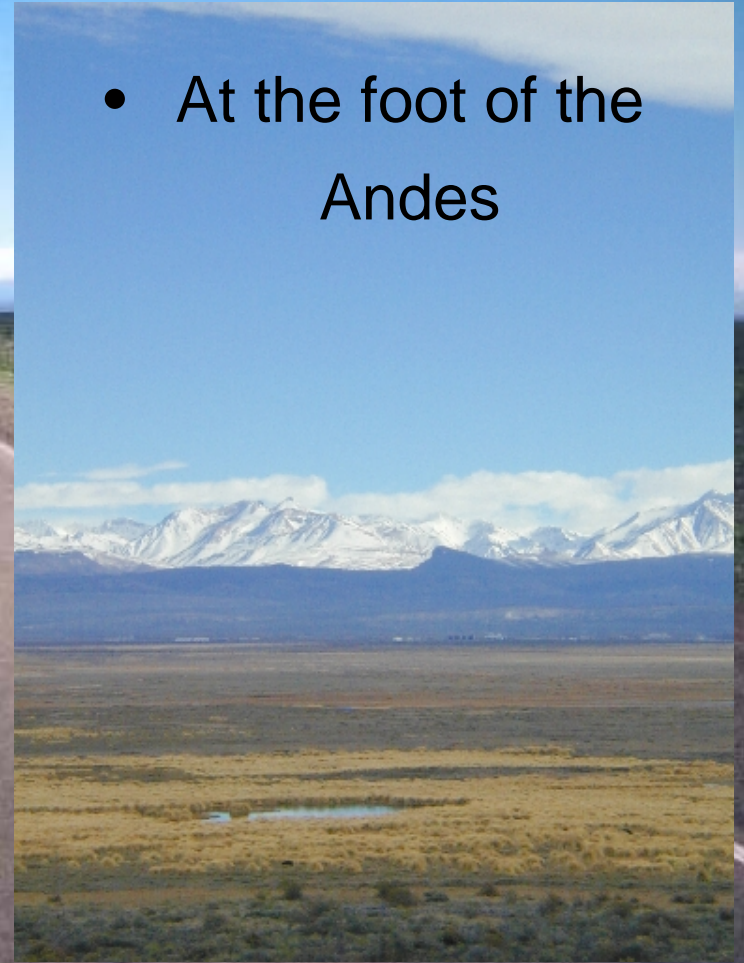
Photon and neutrino dominance

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High Energy Cosmic Rays
at
The Pierre Auger Observatory

3.7 years of Surface array data

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- At the foot of the Andes
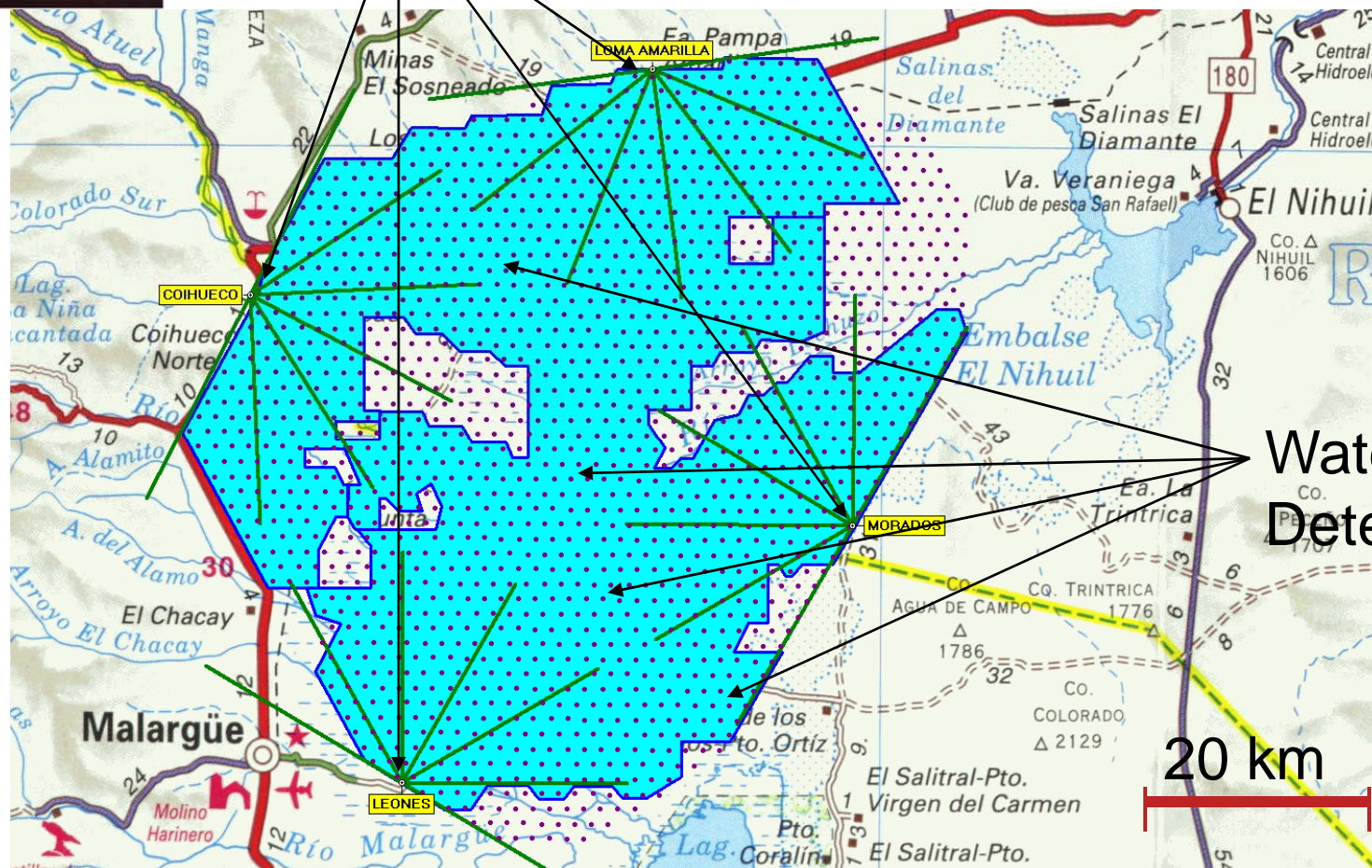
- 3000 km^2 over the argentinian pampa

space, altitude

quiet

dark

Fluorescence Telescopes
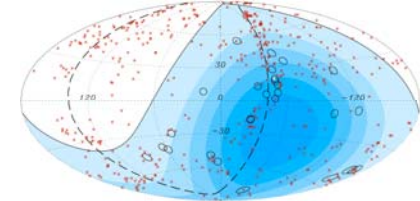
Water Cherenkov Detectors

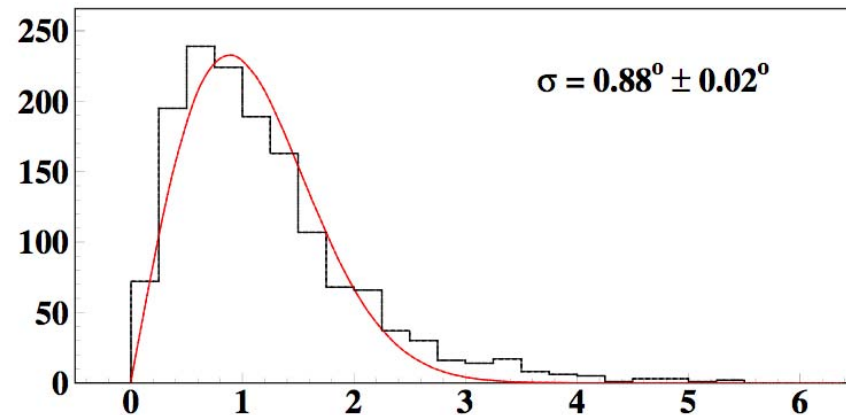20 km

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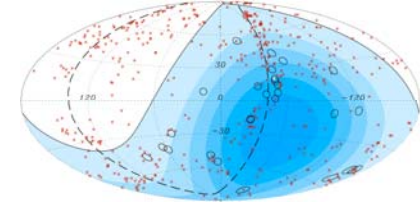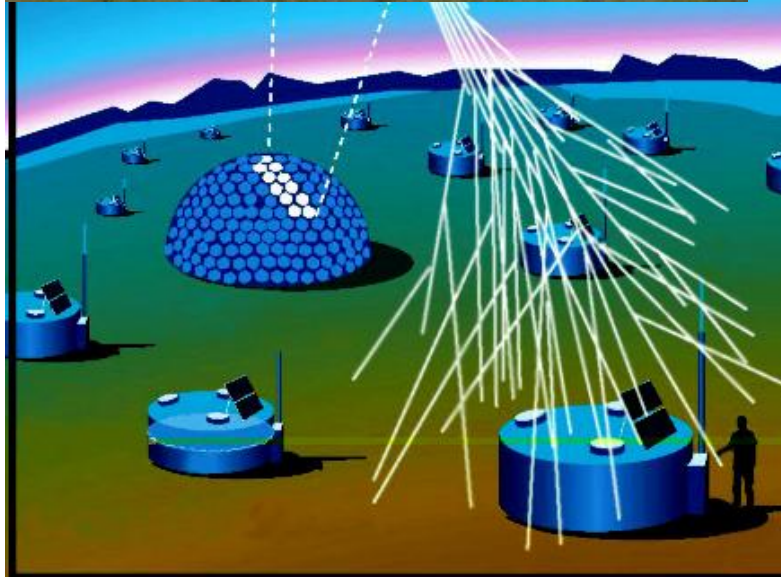
A large surface detector array with air fluorescence detectors results in the

$\sigma = 0.88^{o} \pm 0.02^{o}$

$\sigma = 0.59^{o} \pm 0.05^{o}$

Space-angle difference (degrees)
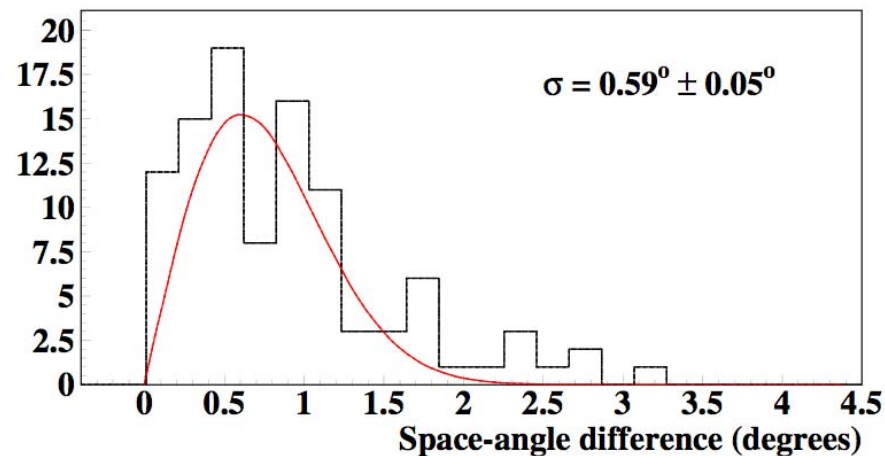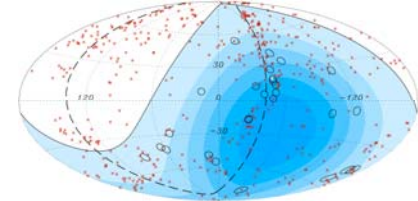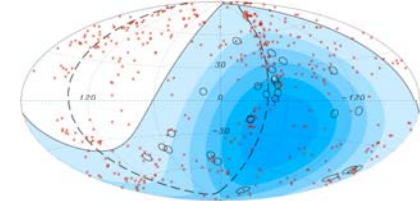
- Auger south : Lat -35.2⁰ South, Long. 69.5⁰ West, m.a.s.l. 1400 m

  – 154 surface array detectors and 2 FD sites in January 2004
  – 1388 surface array detectors and 4 FD sites in September 2007

- Over a million CR events recorded above about 0.2 EeV.

- Full acceptance above 3 EeV for zenith < 60⁰

- Data set : January 1st 2004 until August 31st 2007, 81 events
  – T5,
  – E > 40 EeV,
  – Θ < 60⁰

- Geometrical exposure α sin[θ] or rate α sin^2[θ]. Array growth modulation or atmospheric effects < 1%.

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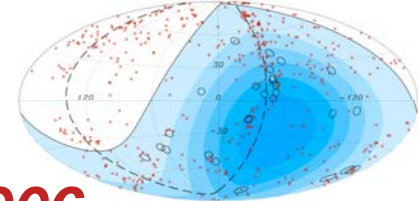
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Anisotropy search method

- Define a data set (adjusting minimum energy E)
- Define a tentative source catalog (adjusting catalog depth z)
- Count number of events k at less than angular distance ψ from a source (we call this a correlation)
- Calculate probability for such a number of correlations to occur by chance :

$$P(E, z, \psi) = \sum_{j=k}^{N(E)} \binom{N(E)}{j} p(z, \psi)^j (1 - p(z, \psi))^{N(E)-j}$$

where $P(E,z,\psi)$ is the cumulative binomial probability and $p(z, \psi)$ is the probability for a random CR seen by Auger (exposure weighted) to fall within ψ^0 of one of the sources in the catalog

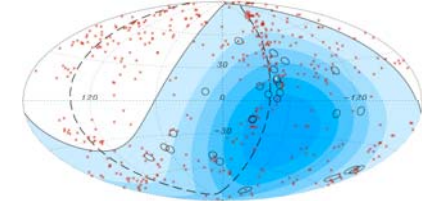- Look for the minimum of $P(E,z,\psi)$ as a function of E, z and ψ.

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Exploratory search *__done before June 2006__*

- Scan on parameter E, z and ψ to find minimum of P.

- Start with highest energy event and add events one by one down to a minimum energy of 20 EeV. (241 events total)

- Use 12th edition of Veron-Cetty & Veron AGN catalog, using sources up to z=0.05 in steps of 0.002

- Evaluate correlations for ψ varying form 1.1º up to 6.1º in step of 0.5º

- Minimum of $P(E,z,\psi)$:
    - $E = 56$ EeV
    - $Z = 0.018$
    - $\psi = 3.1º$

  12 out of the 15 events selected correlate, $P = 10^{-6}$

- But…

  We have made a scan so P must be penalized (penalization is of order 10^3 as evaluated from MC samples). We cannot be sure to properly calculate the penalization.

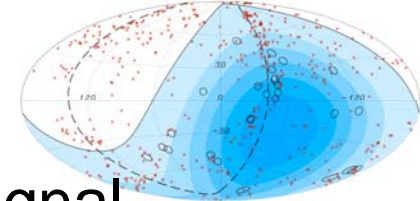## Motivation for a prescription

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A prescription

- We decided to test this putative signal on an independent data set
- We fixed the correlation parameters as those given by the minimum of the exploratory scan:
  - E = 56 EeV
  - Z = 0.018
  - ψ = 3.1º

- We constructed a series of tests, each one being applied after the arrival of each new event with energy > 56 EeV
- The data would be declared anisotropic (CL>99%) if any of the test succeeds before the arrival of the 34th event. If, at the 34th event no test succeeded, the prescription would be dropped definitively and no conclusion could be drawn regarding the (an)isotropy of the data

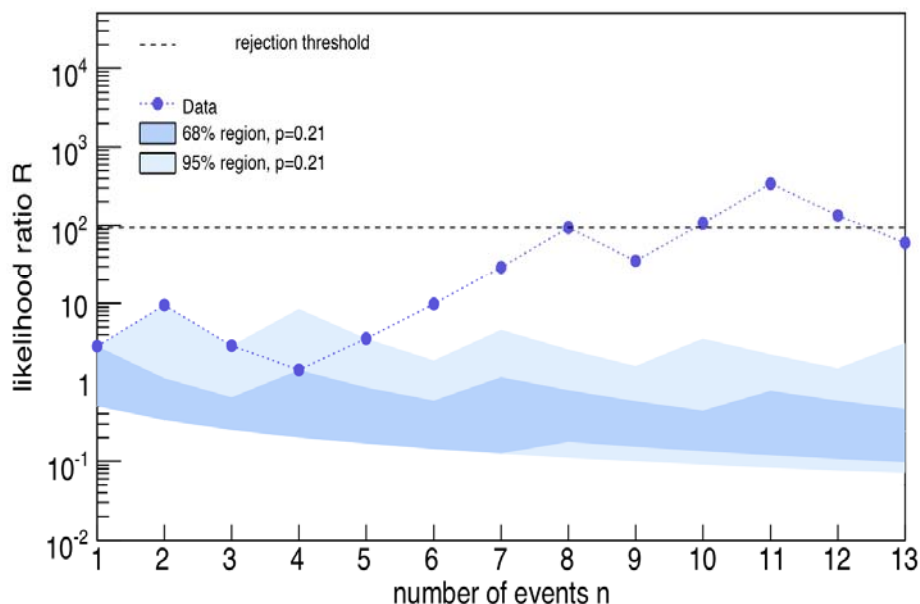- On May 28th 2007 the test was successful with 6 out of 8 events in correlation

N	4	6	**8**	10	12	...	30	31	33	34
k_{min}	4	5	**6**	7	8	...	14	14	15	15
Cumul. p (%)	0.19	0.32	**0.40**	0.44	0.47	...	0.83	0.87	0.89	0.92

We can now study our signal

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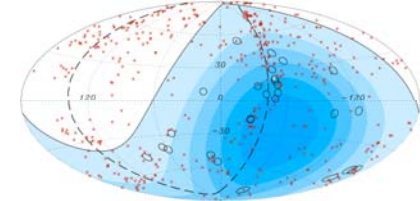# Likelihood ratio to monitor evolution of signal

$$R = \frac{\int_{0.21}^{1} p_1^k (1 - p_1)^{n-k} \, dp_1}{0.21^k (1 - 0.21)^{n-k+1}}$$

Likelihood ratio R as a function of the number of events observed in the prescribed test.

The null hypothesis (anisotropy) was rejected at the 99% likelihood threshold with 10 events.
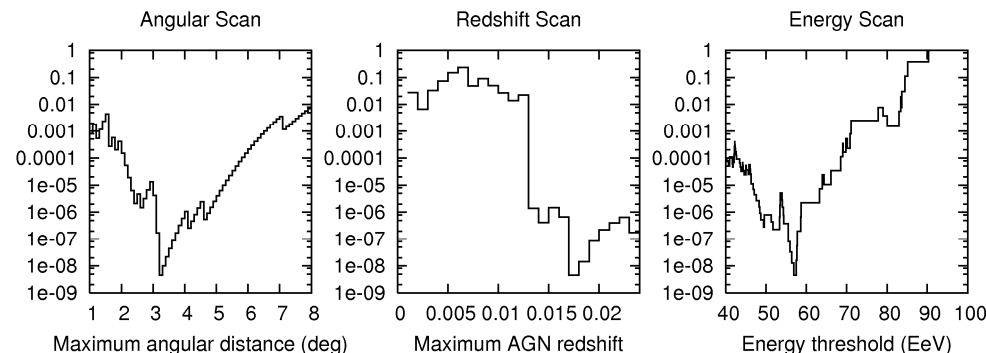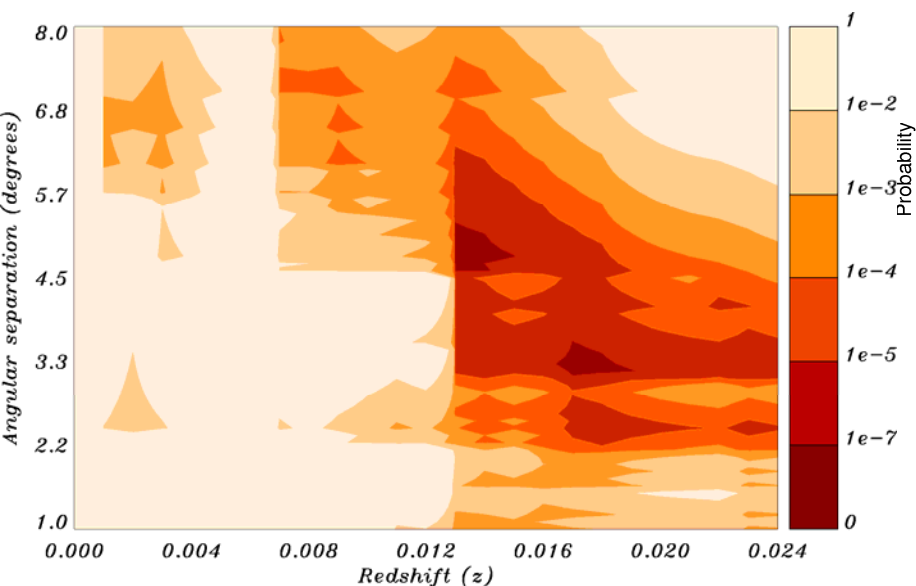
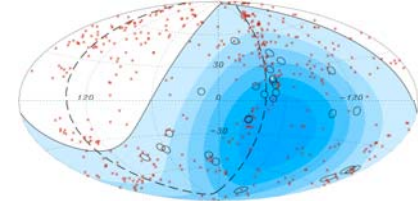Shaded regions indicate expectations from isotropy at the 68% and 95% CL.

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Full data set analysis (01/01/2004-31/08/2007)
81 events above 40 EeV

- New minimum : 20 out of the 27 events selected correlate, P = 5x10⁻⁹
  - E = 57 EeV
  - Z = 0.017
  - ψ = 3.2⁰

  20 out of the 27 events selected correlate, 5.6 expected. P = 5x10⁻⁹

- After penalization P ~ 10⁻⁵ note that this is about:

  10⁻³(exploratory) x 10⁻²(prescribed)

Angular Scan | Redshift Scan | Energy Scan

Similar minima in the region
E~60 EeV, z<=0.024, ψ <=6⁰

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An iso-exposure Mollweide map

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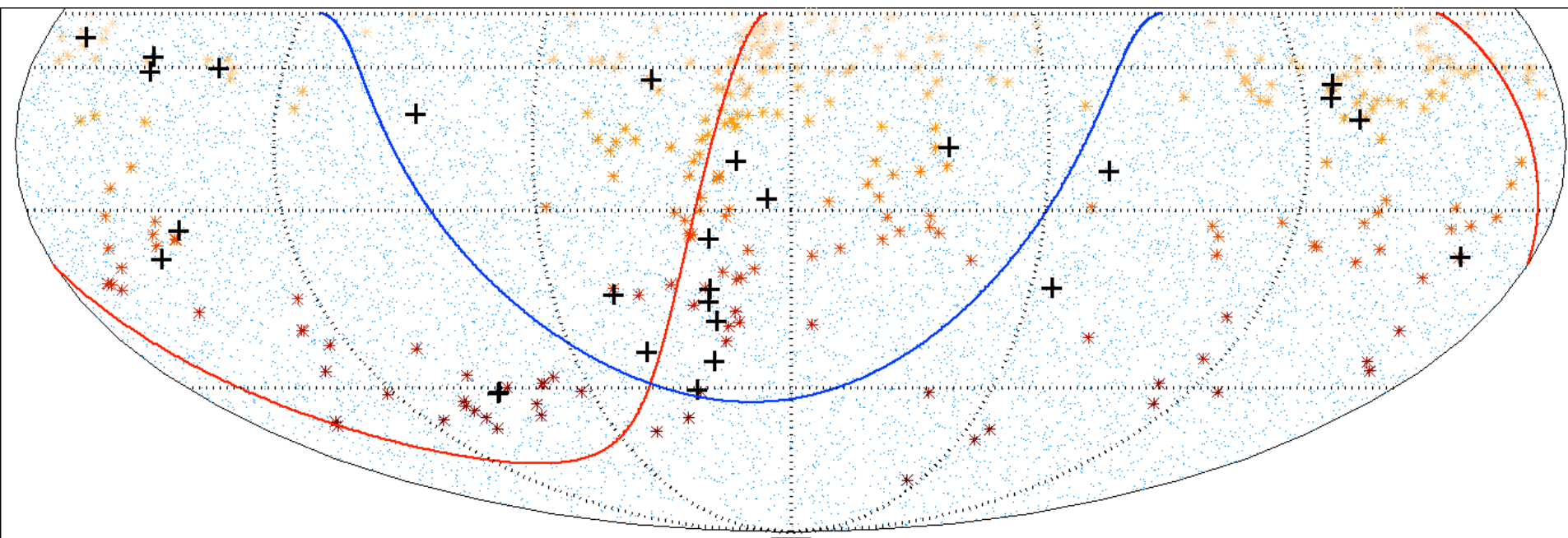
Aitoff projection in Galactic coordinates
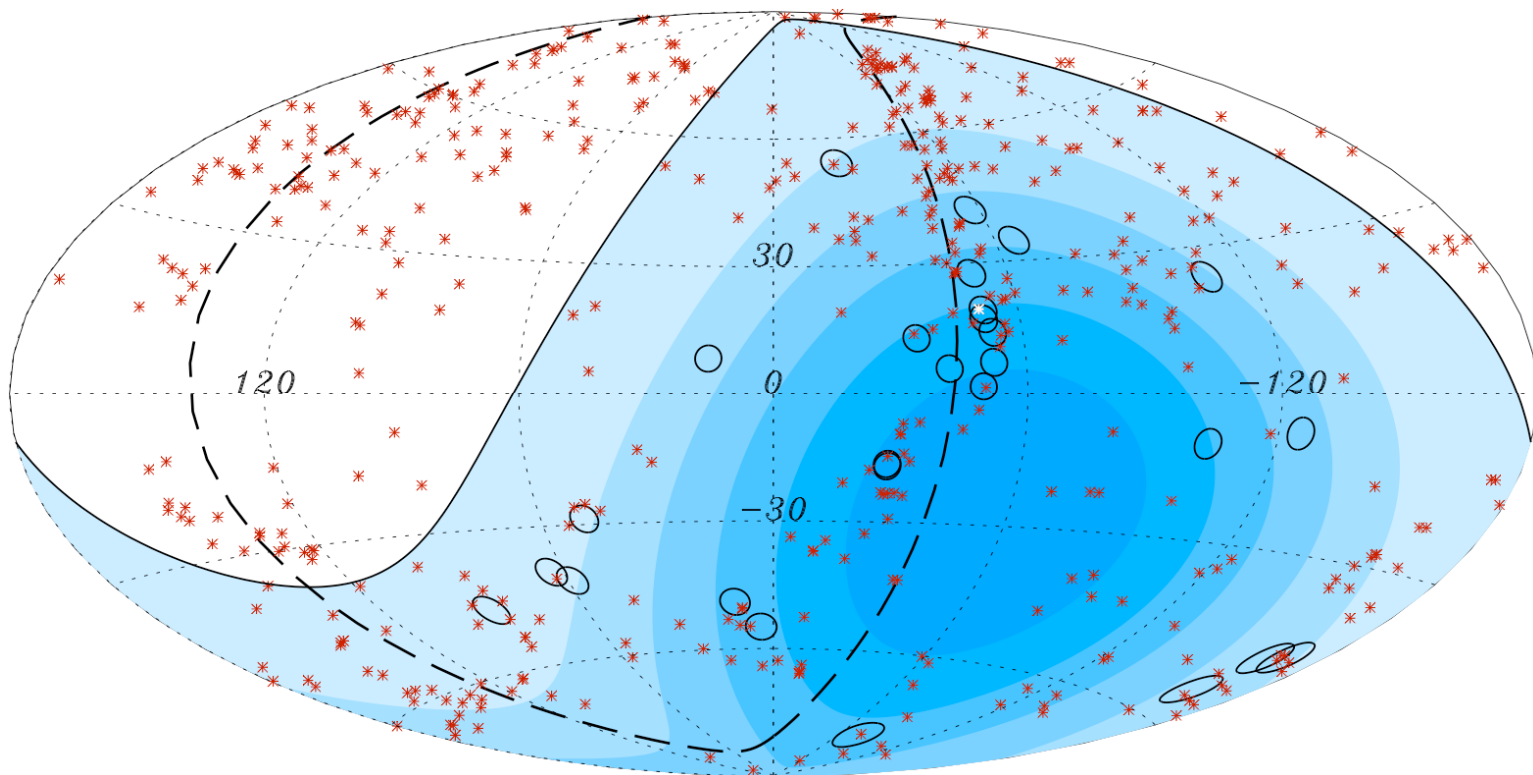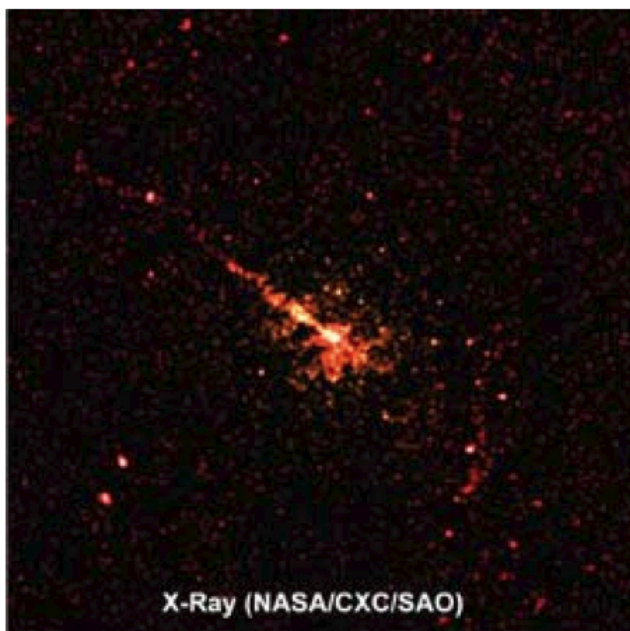

- Circles of radius 3.1º centered at the arrival directions of 27 CR with E > 57 EeV.
- Red asterisks positions of the 472 AGN (318 within the field of view) with z<= 0.018.
- Solid line border of the field of view for the southern site of the Observatory (Θ <60º).
- Dashed line super-galactic plane.
- Color bands indicates relative exposure. Each colored band has equal integrated exposure.
- White asterisk Centaurus A

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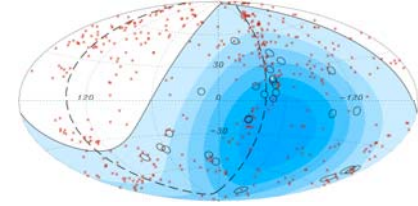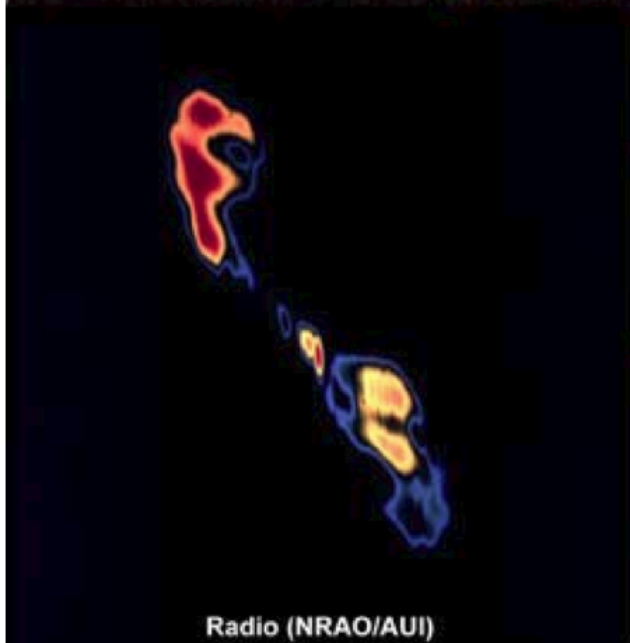
Acceleration sites

- Can we say something about the sources?

    - They are not in the Milky Way

    - They are likely bottom up (astrophysical)

    - AGN are plausible acceleration sites

- More data are needed to identify the sources and their characteristics

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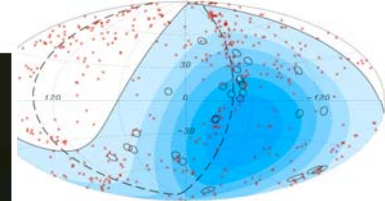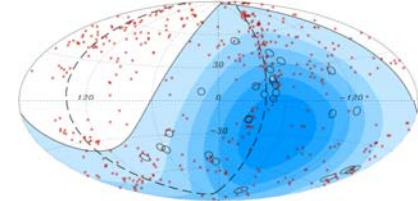
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X-Ray (NASA/CXC/SAO)

Optical (AURA/NOAO/NSF)

Radio (NRAO/AUI)

Infrared (2MASS)

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?

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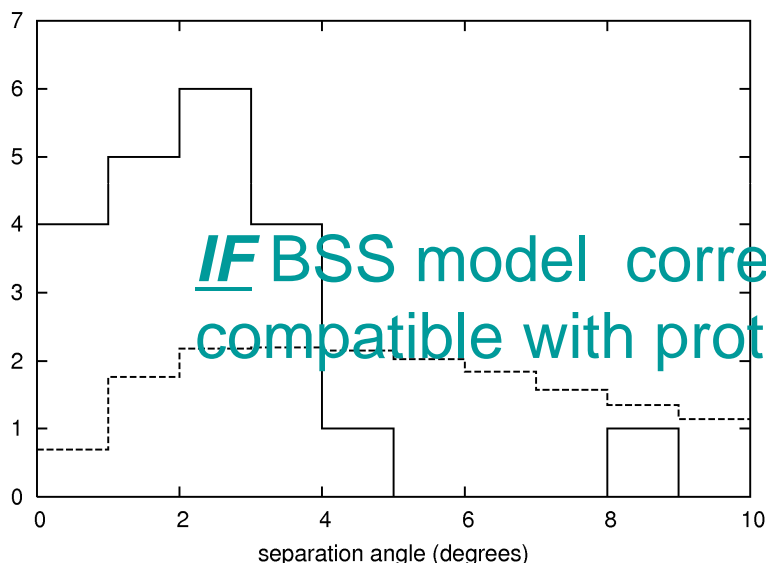LPNHE - In2p3/CNRS - Univ. P6 & P7
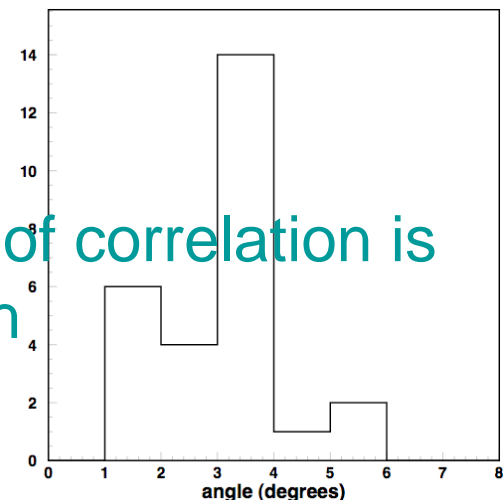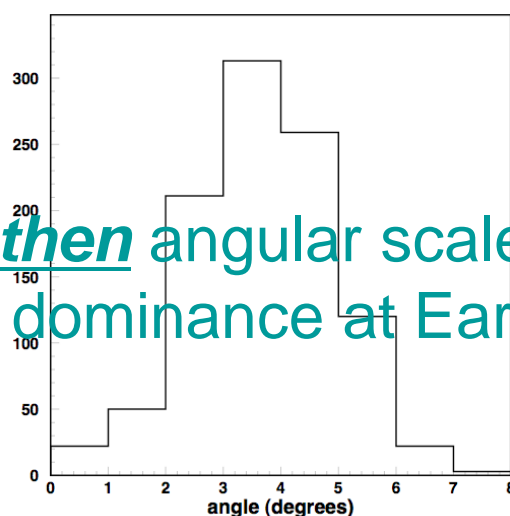
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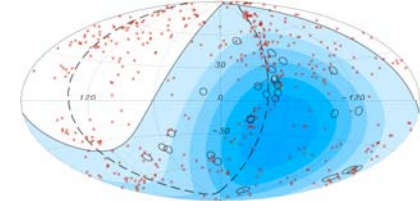
Magnetic deflections

$$\delta \simeq 2.7° \frac{60 \text{ EeV}}{E/Z} \left| \int_0^D \frac{d\mathbf{x}}{\text{kpc}} \times \frac{\mathbf{B}}{3 \, \mu\text{G}} \right|$$

IF BSS model correct **then** angular scale of correlation is compatible with proton dominance at Earth

separation angle (degrees)

Angular separations to the closest AGN (21 events) and average expectation for an isotropic flux (dashed line).
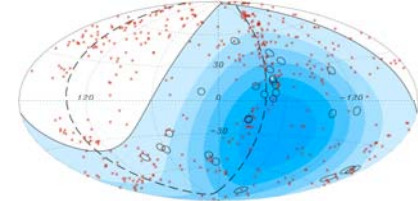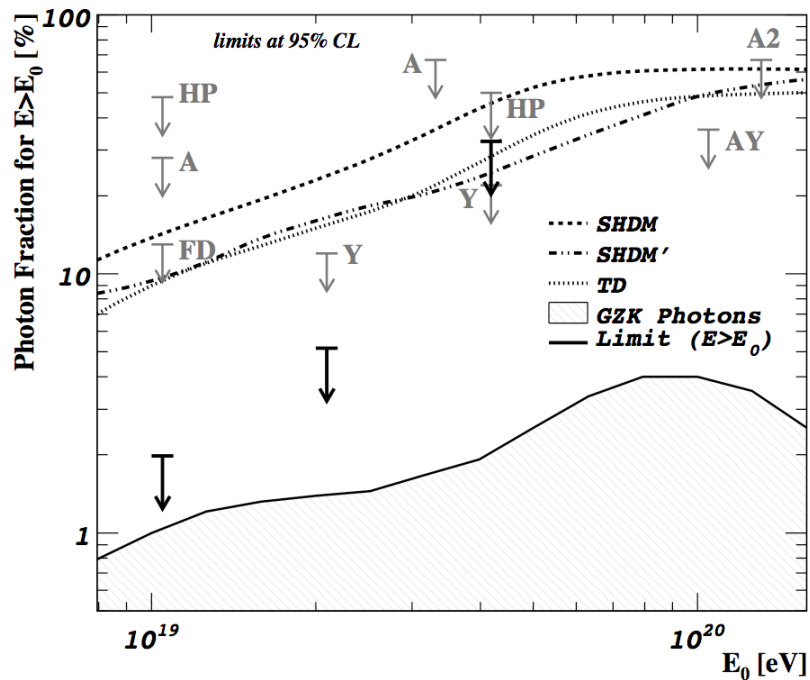
Distribution of the deflections for protons in the BSS-S model of the galactic magnetic field.
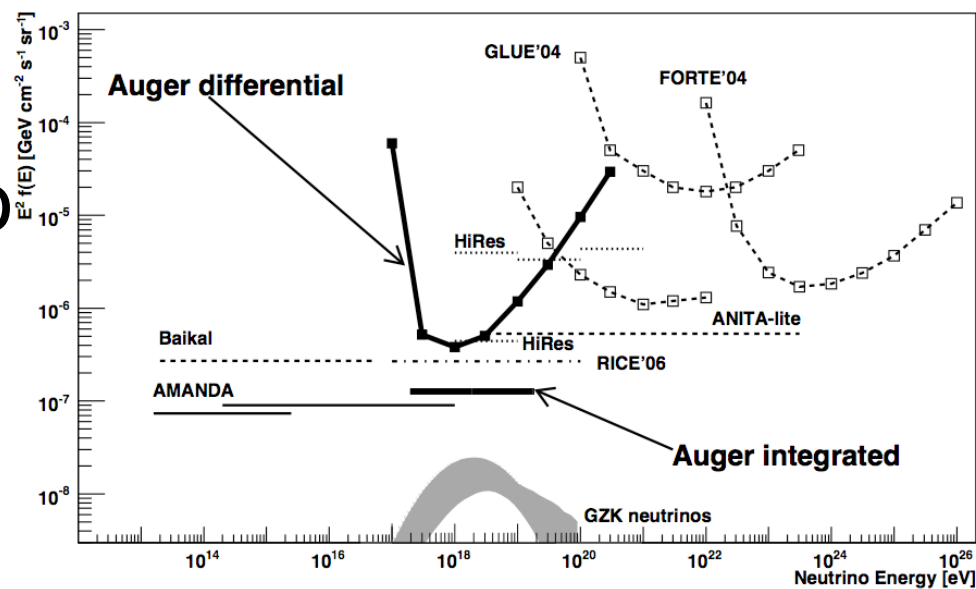Left: 1000 directions, isotropic flux in proportion to the exposure of the Observatory, for E> 60 EeV.
Right: deflections of the 27 arrival directions of the observed events with E> 57 EeV

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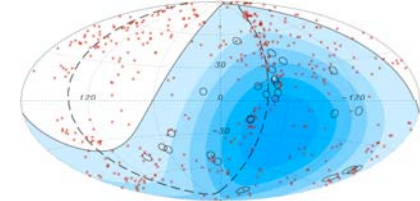LPNHE - In2p3/CNRS - Univ. P6 & P7

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Photon Limit

Neutrino Limit

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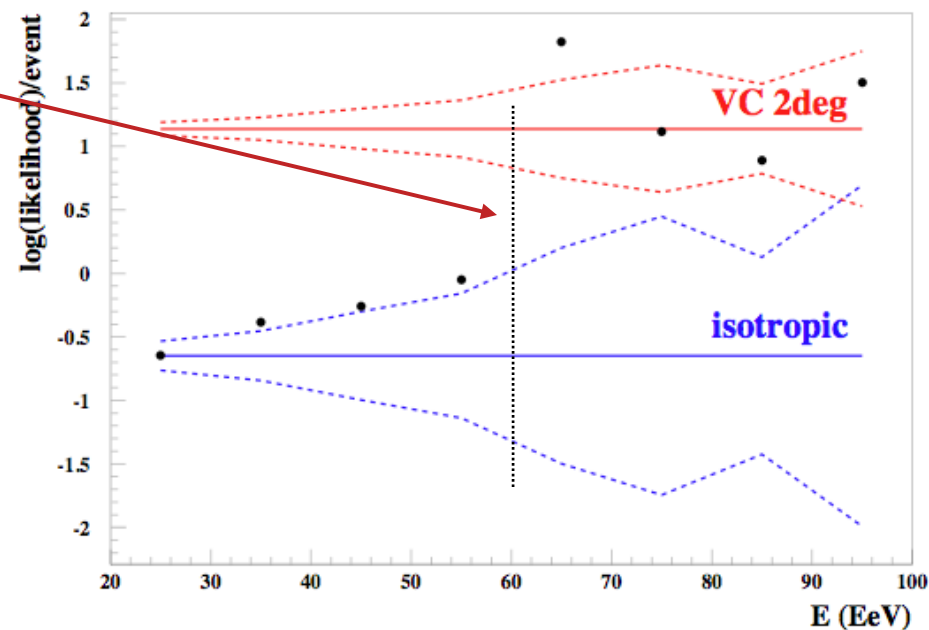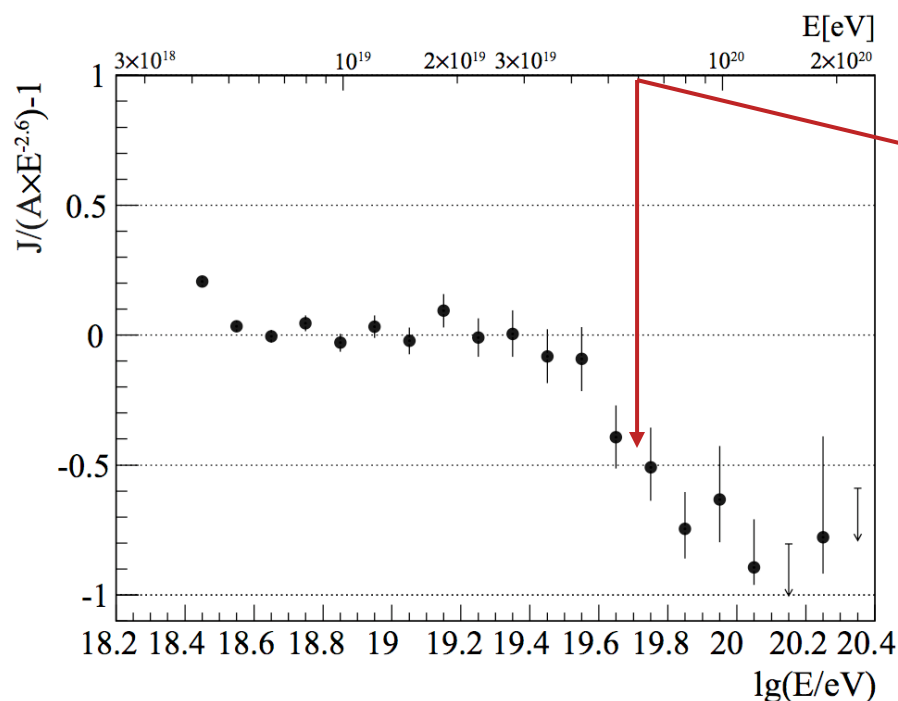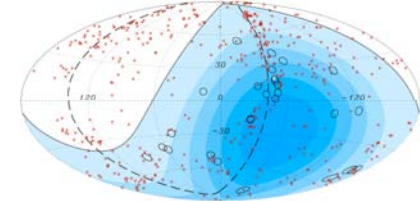
The GZK cut off

The anisotropy signal is maximum at theenergy where the flux is reduced by 50% with respect to a power law extrapolated from lower energies.

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Conclusions

It is just the beginning….

- Anisotropy of UHECR has been established at > 99% CL for the parameters E~60 EeV, D~100 Mpc, ψ~4^0

- Nature of the correlation provides evidences for the 'GZK' effect and the hypothesis that the CR are dominantly protons from AGN (or a subset of them) within our 'GZK' horizon

- Sources are very likely astrophysical (Bottom-up)

- Sources could be other than AGN as long as they have similar spatial distributions

- Increased statistics (+Auger North) will allow source identification as well as measurements of MF along the line of sight and maybe some surprises….

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