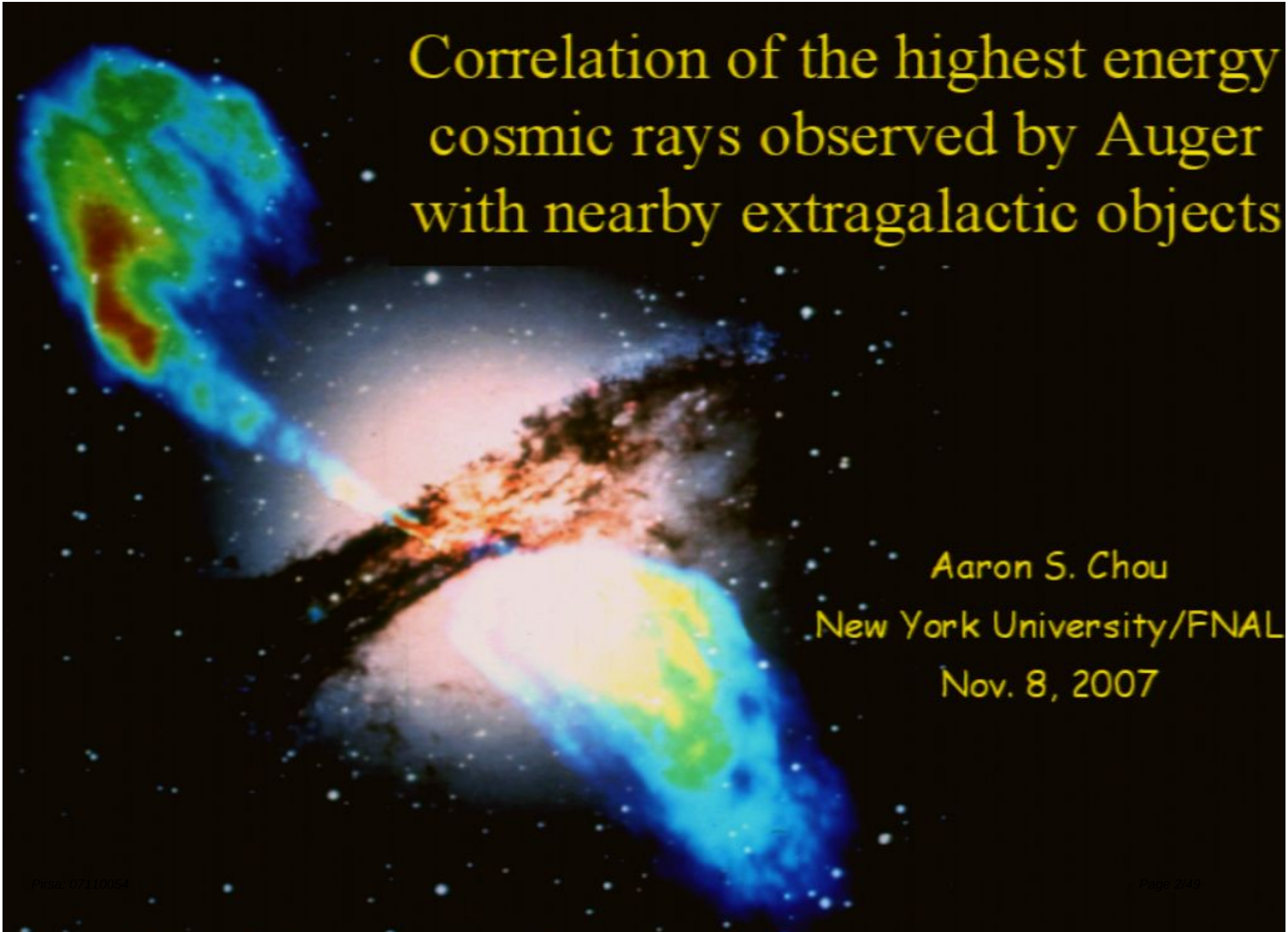
Title: Recent Results from the Pierre Auger Observatory.

Date: Nov 08, 2007 02:30 PM

URL: http://pirsa.org/07110054

Abstract:


Correlation of the highest energy cosmic rays observed by Auger with nearby extragalactic objects
Aaron S. Chou
New York University/FNAL
Nov. 8, 2007

The Auger Collaboration

67 Institutions, 369 Collaborators

ERRE
UGER
SERVATORY

Argentina
Netherlands
Australia
Poland
Bolivia*
Portugal
Brazil
Slovenia
Czech Republic
Spain
France
United Kingdom
Germany
USA
Italy
Vietnam*
Mexico

True International Partnership - *by non-binding agreement* -

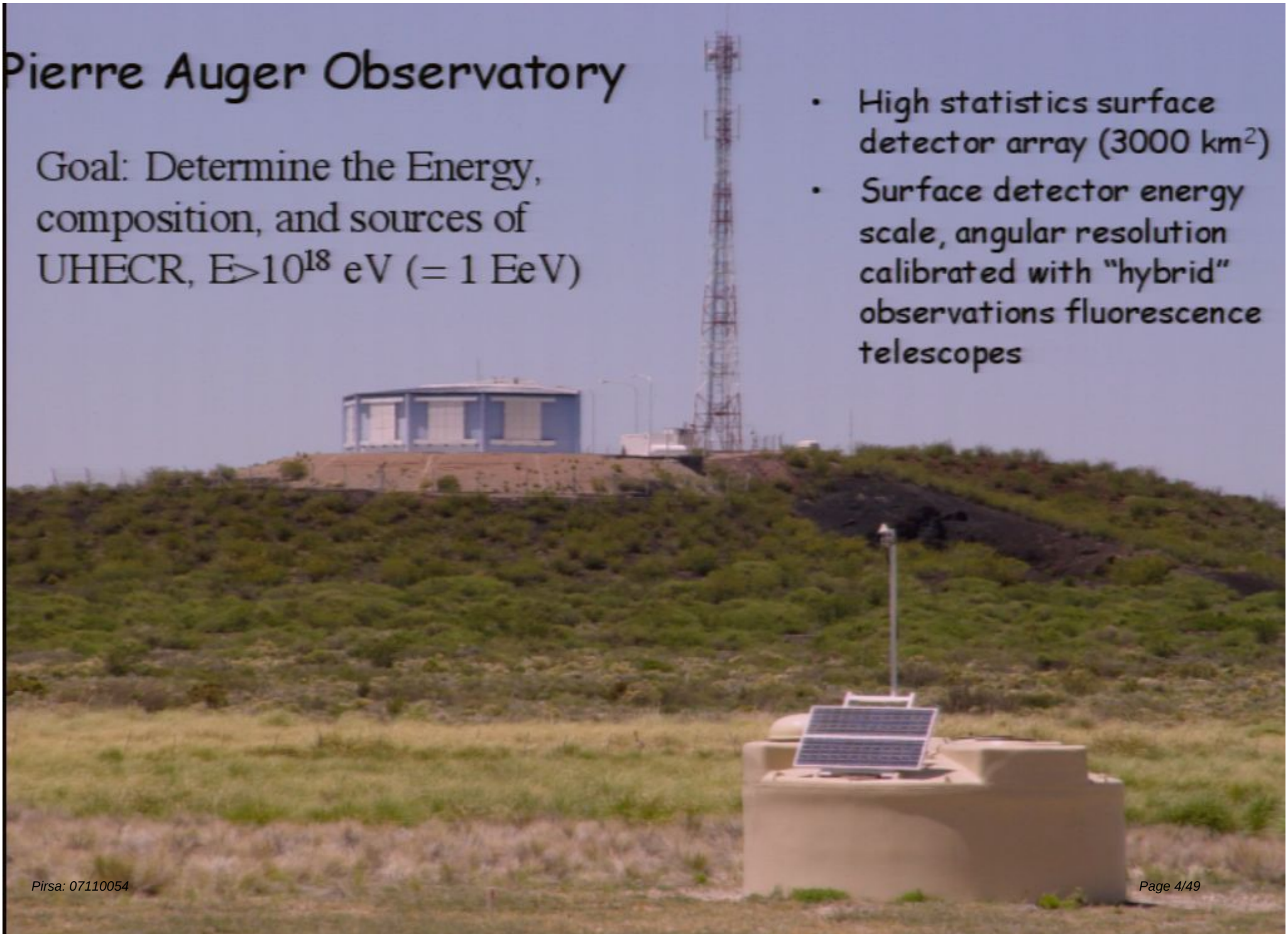
No country, region or institution dominates – No country contributes more than 25% to the construction.

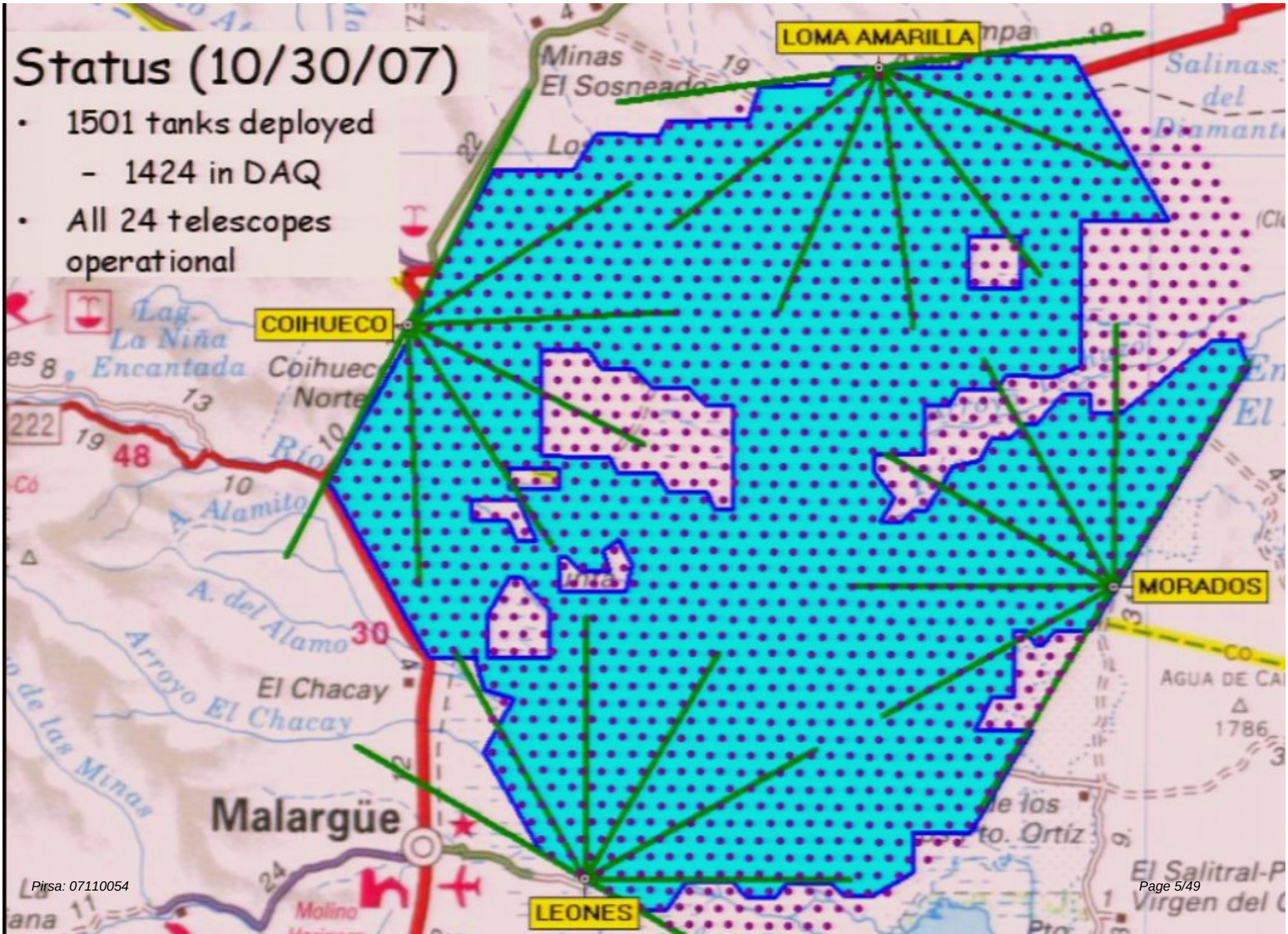
* associate

Pierre Auger Observatory

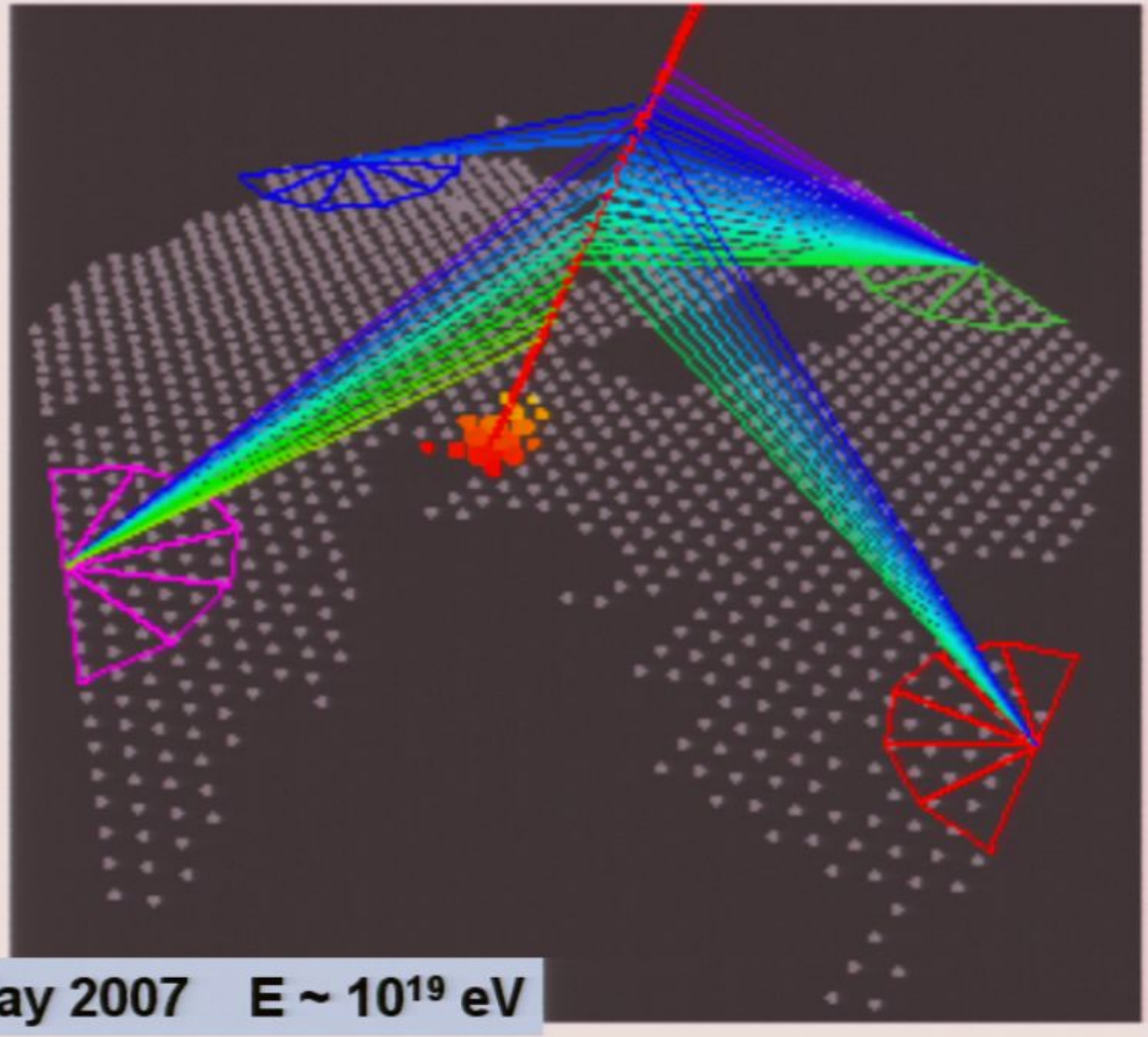
Goal: Determine the Energy, composition, and sources of UHECR, $E > 10^{18}$ eV (= 1 EeV)

- High statistics surface detector array (3000 km^2)
- Surface detector energy scale, angular resolution calibrated with "hybrid" observations fluorescence telescopes




Status (10/30/07)
• 1501 tanks deployed
– 1424 in DAQ
• All 24 telescopes operational
LOMA AMARILLA
COIHUECO
MORADOS
LEONES
Malargüe
Minas El Sosneado
Salinas del Diamante
Lag. La Niña Encantada
Coihueco Norte
Río Alamito
A. del Alamo
Arroyo El Chacay
El Chacay
Arroyo de las Minas
AGUA DE CA
1786
El Salitral-P
Virgen del C
Molino

First 4-fold Event



20 May 2007 E ~ 10^{19} eV

Auger SD Event reconstruction

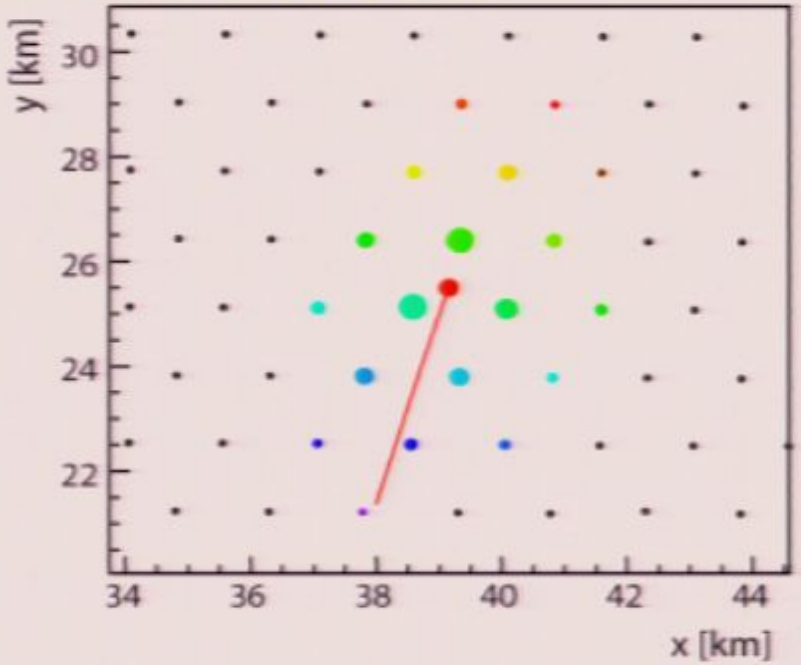
Reconstruction procedure:

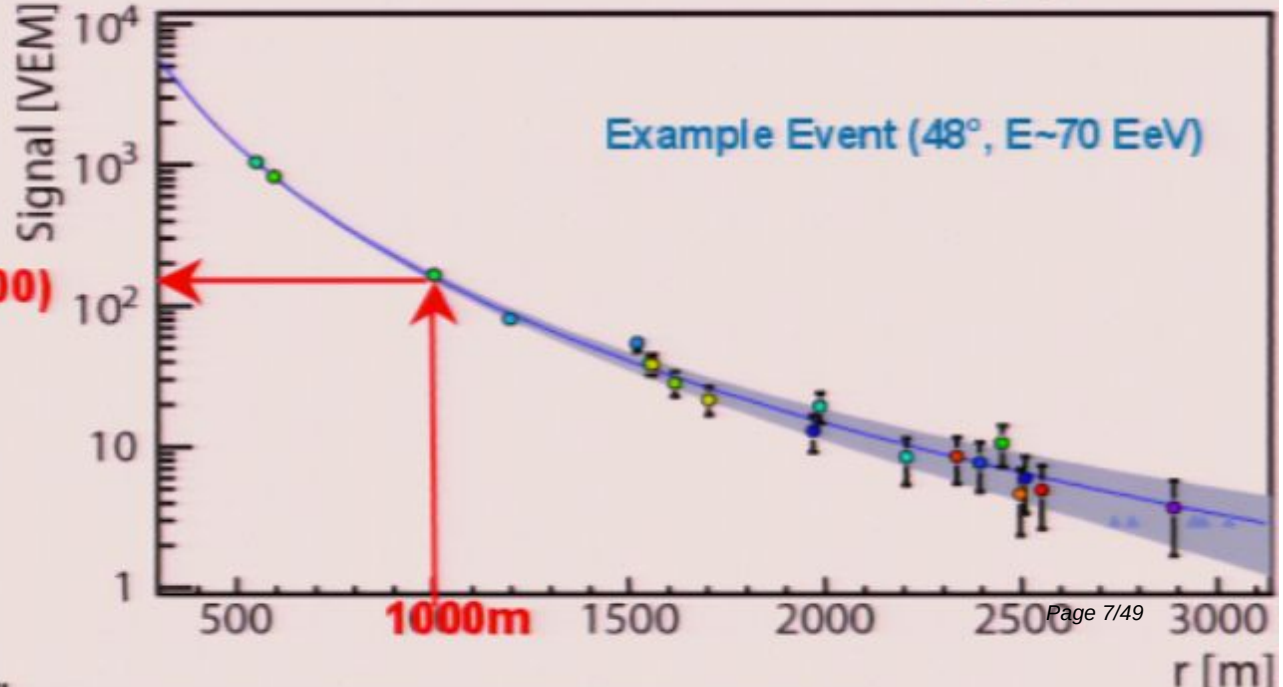
- χ^2-method to fit angles (θ,ϕ) based on 25 ns FADC trigger timing

- Likelihood method to fit a NKG-type LDF with fixed slope β

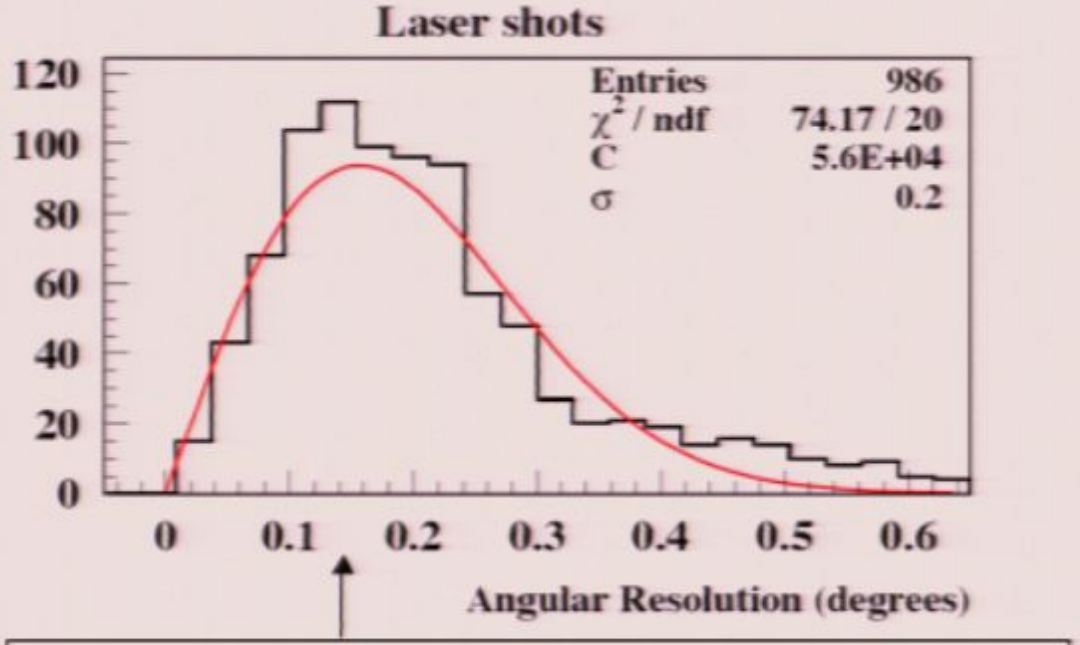
- Simultaneous fit for
  - core position
  - S(1000)

- Interpolated signal at 1000m is well-measured

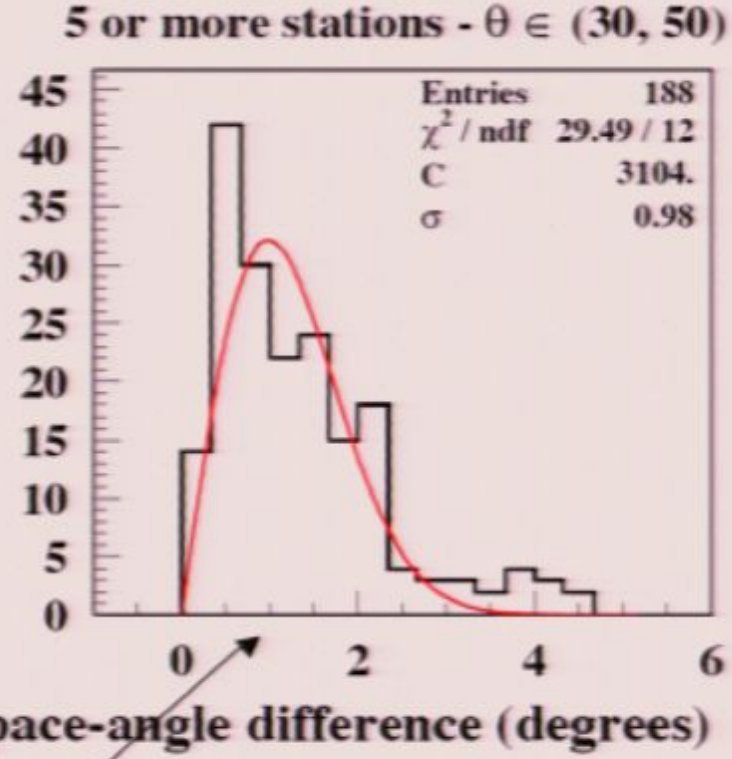




Surface detector angular resolution < 1° at high energies, calibrated with laser shots

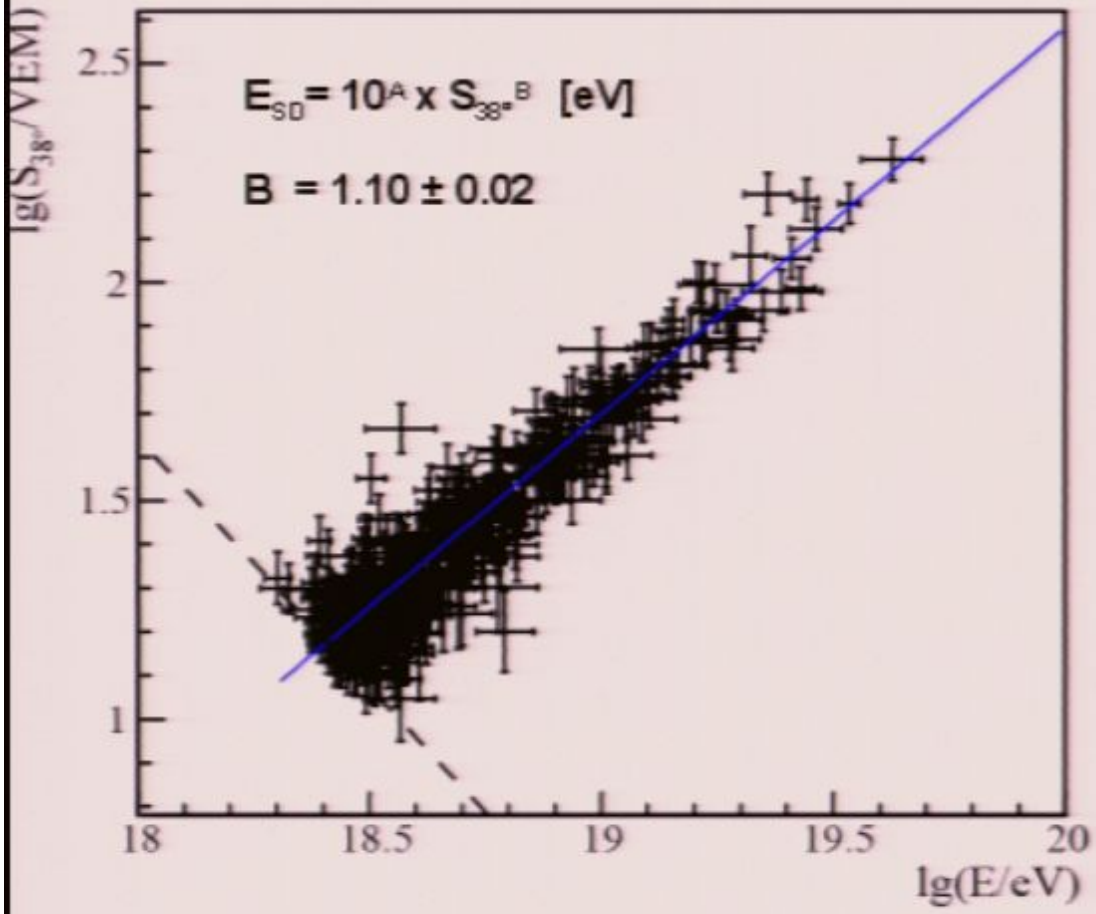


Hybrid recon - laser direction ~ 0.2°



Surface detector recon - Hybrid recon ~ 1°

Correlate S_{38} to FD energy with hybrid dataset



Selection of high quality hybrid data without introducing Xmax biases

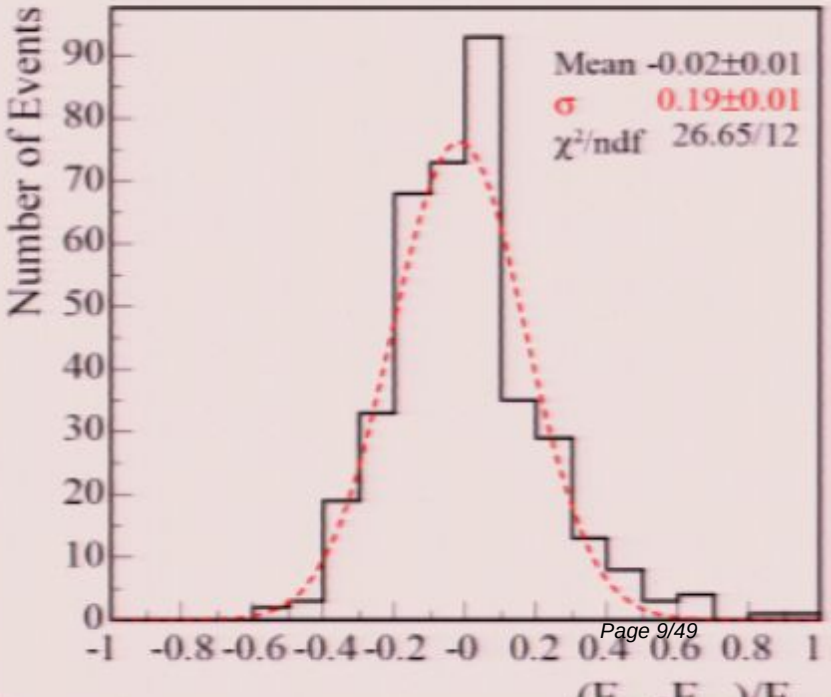
387 events

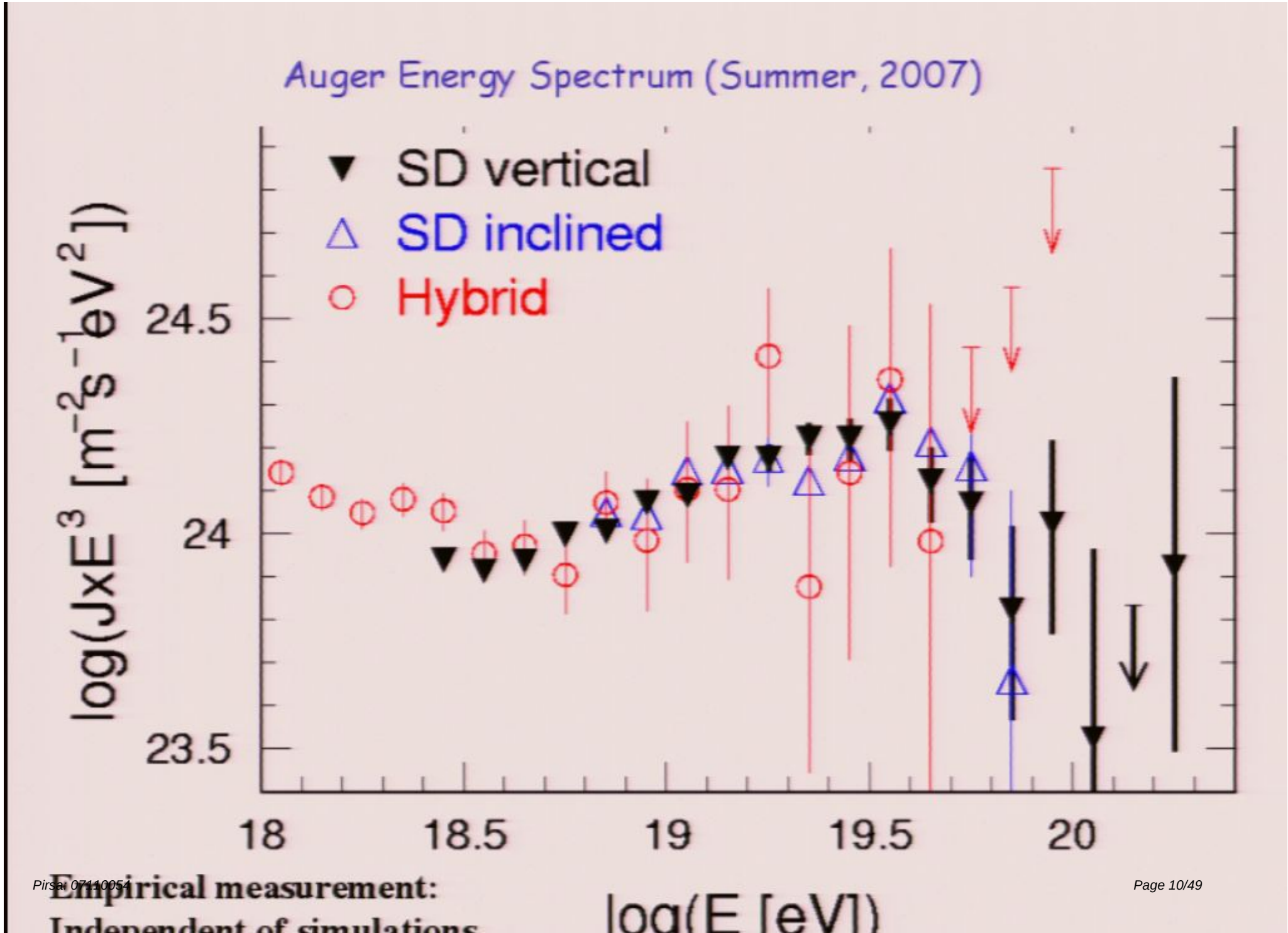
$$\frac{\sigma_E}{E} = \frac{\sigma_{E_{SD}(\sigma_{S_{38}})}}{E_{SD}} \otimes \frac{\sigma_{E_{FD}}}{E_{FD}} = 18\%$$

16%

8%

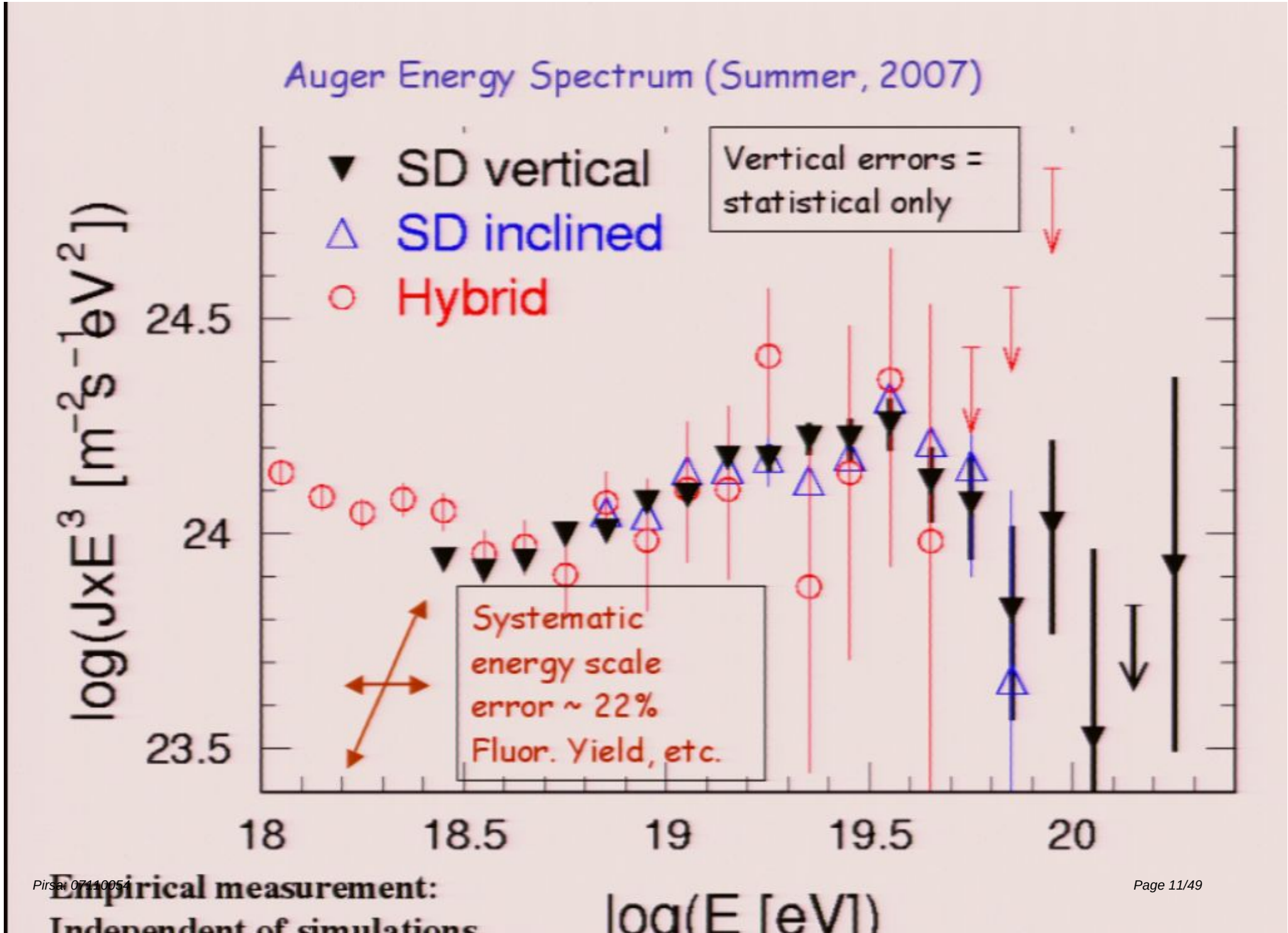
Energy resolution





Empirical measurement:

Independent of simulations



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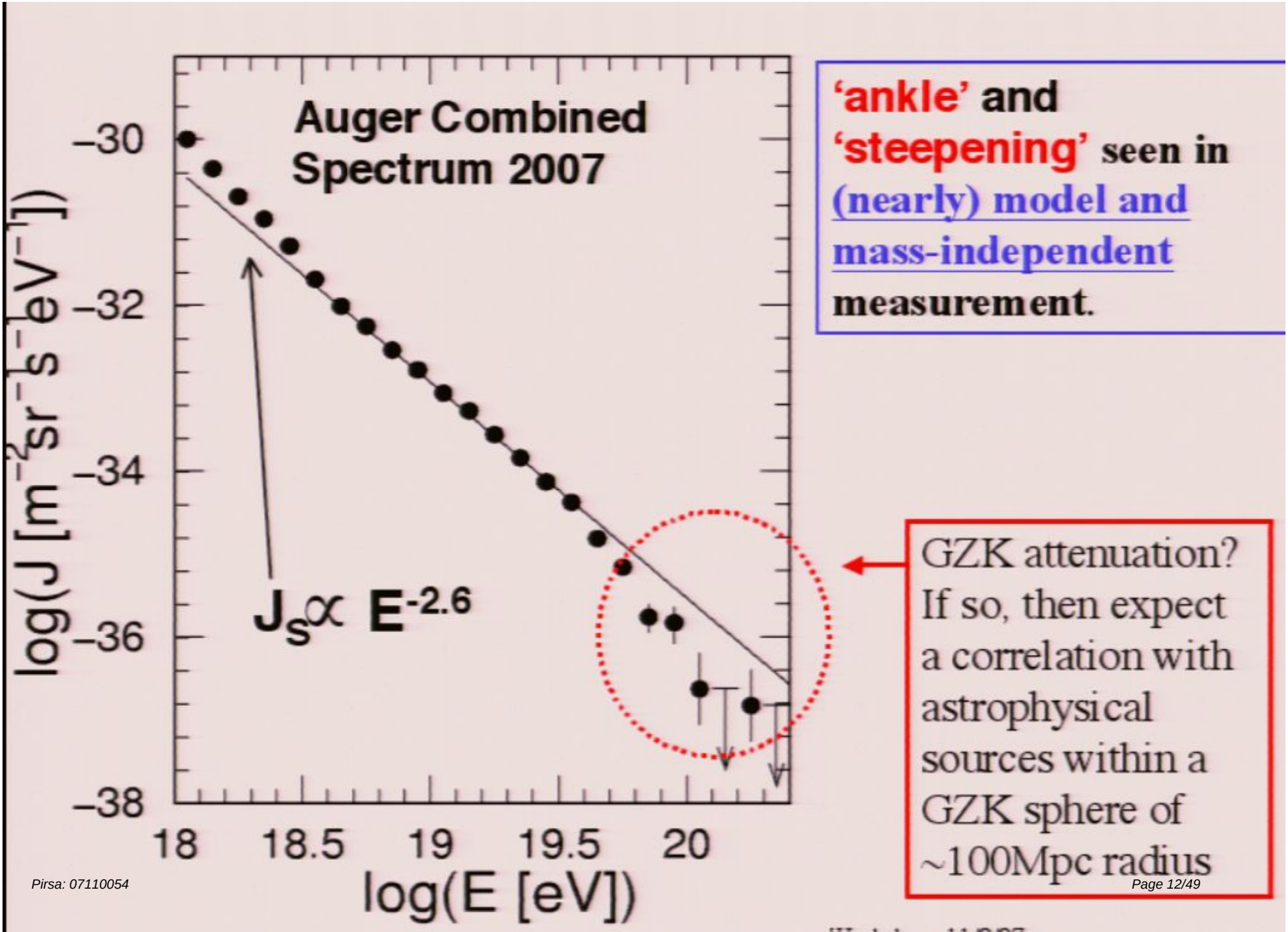
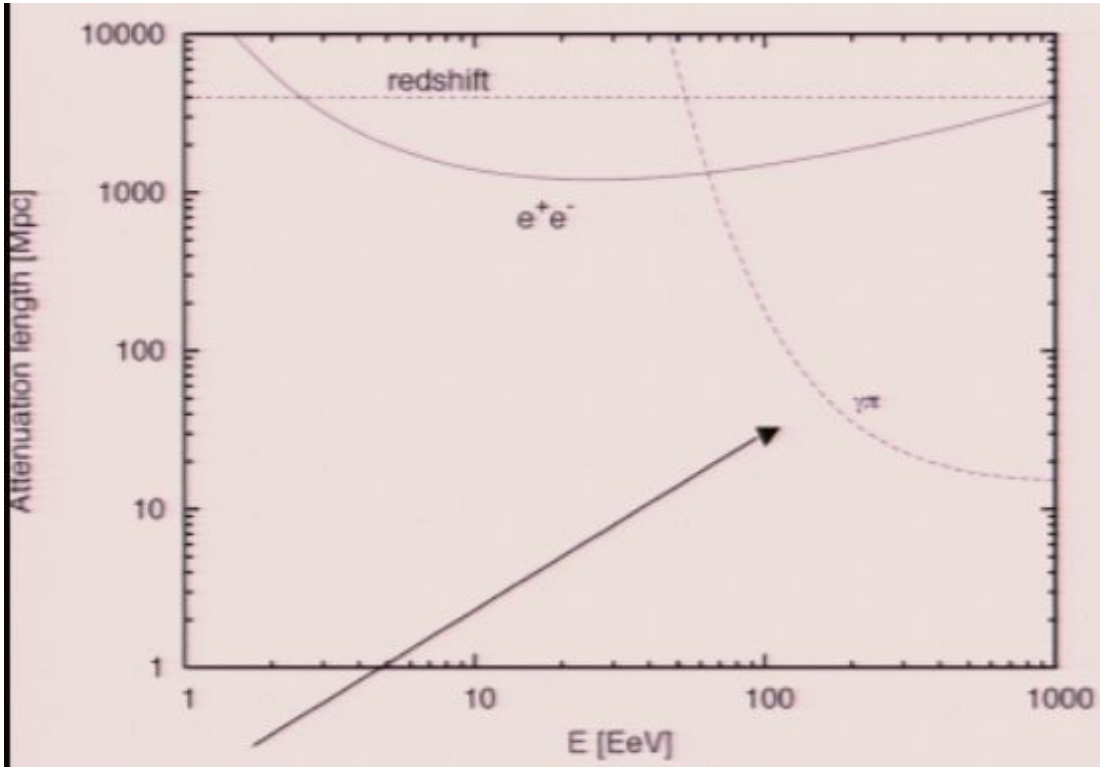
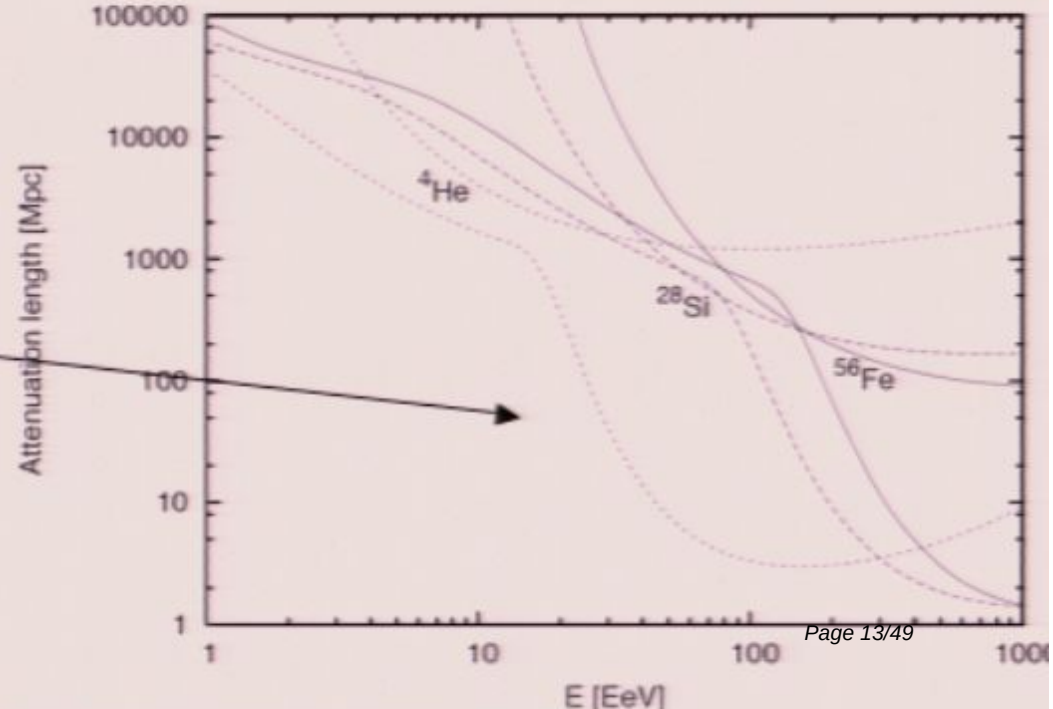

Auger Combined Spectrum 2007
'ankle' and 'steepening' seen in (nearly) model and mass-independent measurement.
GZK attenuation? If so, then expect a correlation with astrophysical sources within a GZK sphere of ~100Mpc radius
$J_s \propto E^{-2.6}$
log(J [m^{-2}sr^{-1}s^{-1}eV^{-1}])
log(E [eV])
−30
−32
−34
−36
−38
18
18.5
19
19.5
20



GZK attenuation lengths in the cosmic microwave background photon bath define a maximum distance for possible sources of UHECR

Protons: Photo-pion production from Δ resonance

Photo-disintegration of nuclei



Plots from Harari, Mollerach, Roulet

Energetics of possible sources (R. Blandford)

- To confine an UHECR proton of energy E, we need a Zevatron with

  $B^*R = E/e$

- The required luminosity of a source in Poynting flux at radius R is:
- **$L > (4\pi R^2)\ B^2/8\pi \sim (E/e)^2$**

  $> (137) * (10^{20}\ eV)^2 * (1.6\ 10^{-12}\ erg/eV) / (6.6\ 10^{-15}\ eV*s)$

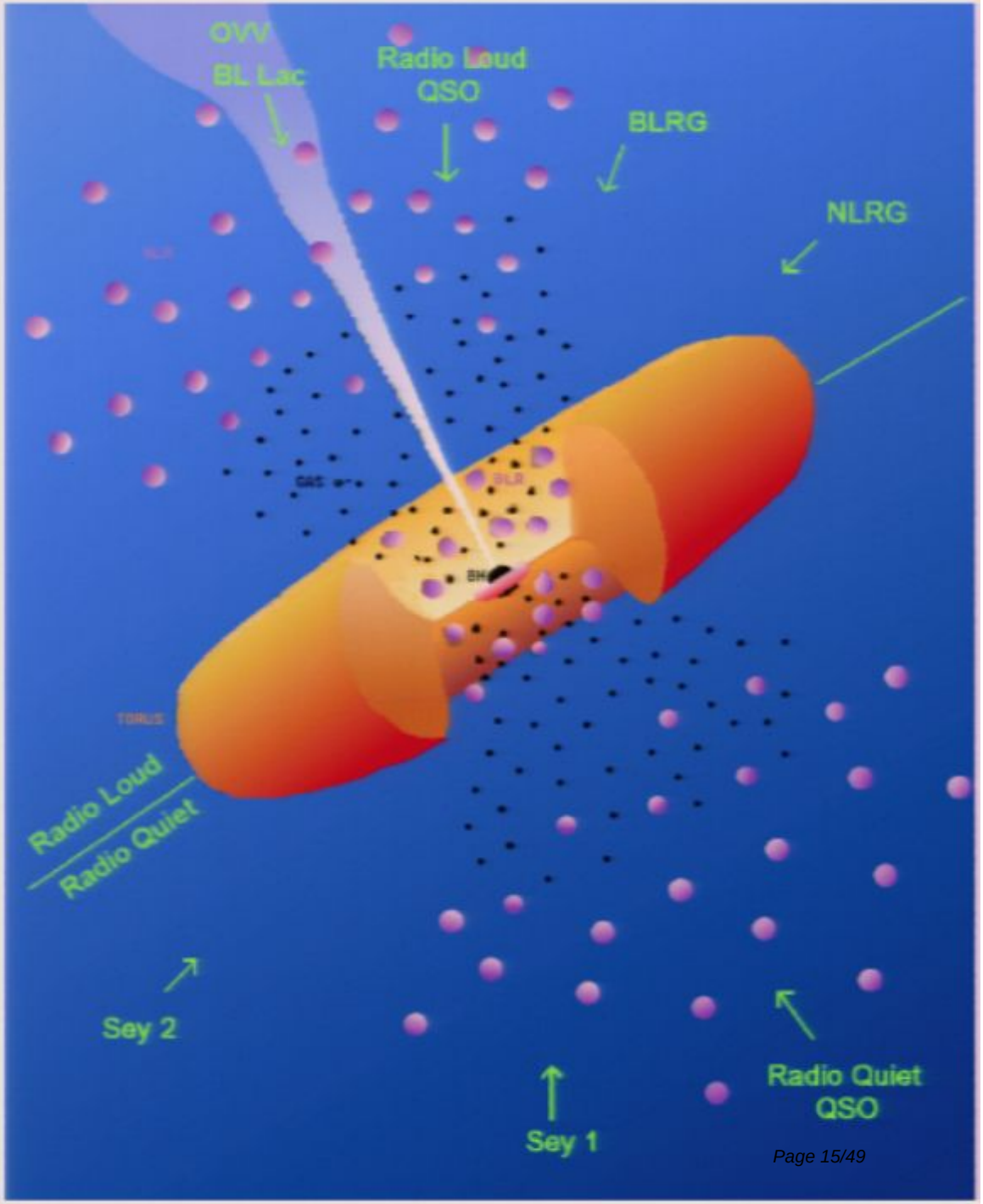
  $> \sim 10^{45}\ erg/s$

- **Active Galactic Nuclei (AGN): $L<10^{46}$ erg/s**
- **Gamma Ray Bursts (GRB) : $L \sim 10^{51}$ erg/s**

Classification of AGN

Various observationally-defined classes of AGN are thought to be the same kind of object (super-massive black holes) viewed from different angles.

The most massive ones are thought to emit jets and are called Blazars (BL Lac is a subcategory)



Veron-Cetty 12th edition catalog of AGN

- 694 AGN within 100 Mpc, identified via optical observations
- Most are ordinary Seyfert galaxies--only 4 BL Lacs
- Sample has unknown bias. For example, it is missing large fractions of the set of radio-identified AGN, i.e. not seen in optical.
- Completeness of the catalog is unknown, but it is believed to be fairly complete for nearby, high luminosity AGN, away from the galactic plane.

Dataset for the current anisotropy result

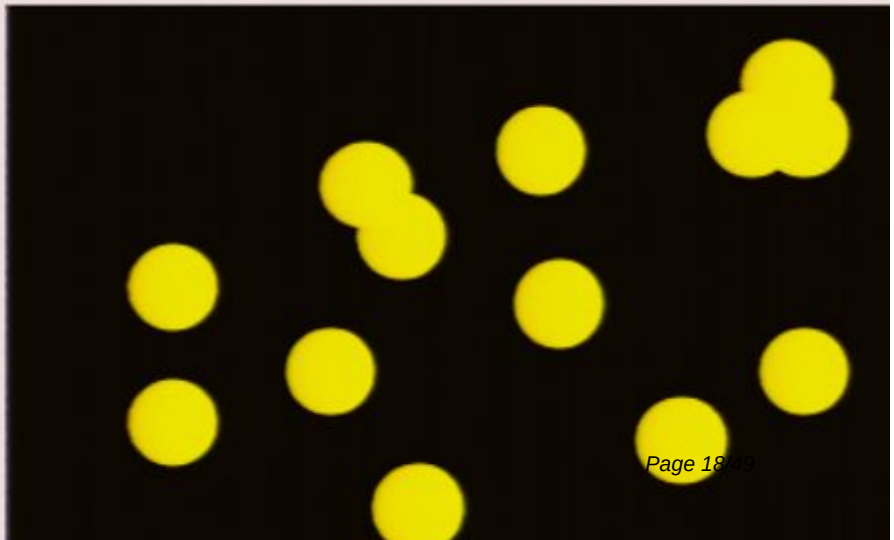
- Surface detector (SD) triggered events
  - Time-over-threshold triggers in each tank
  - At least 3-tanks triggered in a triangular pattern.
  - Highest signal tank surrounded by 5 active neighbor tanks
  - Shower core lies in a triangle of 3 active tanks
  - For E>10 EeV, angular resolution better than 1 deg

- Exposure = 9.0 10^3 km^2 sr yr (January 1, 2004 - August 31, 2007)
- = **1.2 Full-Auger-years**
- = 5.4 * *AGASA* = 1.5(?)*HiRes

A preliminary search (mining the data)

- Data from January 1, 2004 - May 26, 2006
- Take the subset of AGN with redshift $z<z_{max}$
- Assume that charged UHECR of energy $E>E_0$ are deflected by angles $\theta<\theta_0$ in galactic+extragalactic magnetic fields
- Evaluate the chance probability $p(z_{max}, \theta_0)$ that an event sampled randomly from the Auger exposure would coincide within an angle θ_0 with any of the AGN. (i.e. what fraction of the sky as seen by Auger is covered by this "AGN mask".)

For example,
$p(0.024, 3°) = 26\%$
$p(0.024, 6°) = 60\%$



A preliminary search (mining the data)

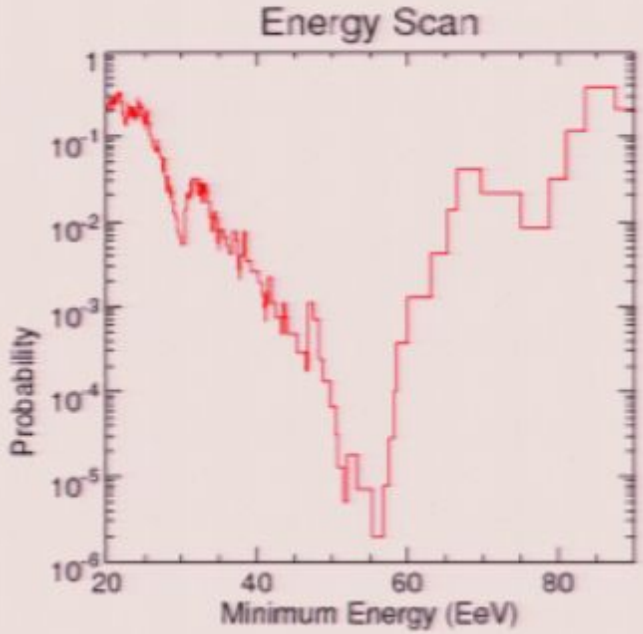
- Now, for the set of N events with energy $E>E_0$, compute the binomial chance probability that an ***isotropic*** set of UHECR would yield k or more events in coincidence with the AGN directions.

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

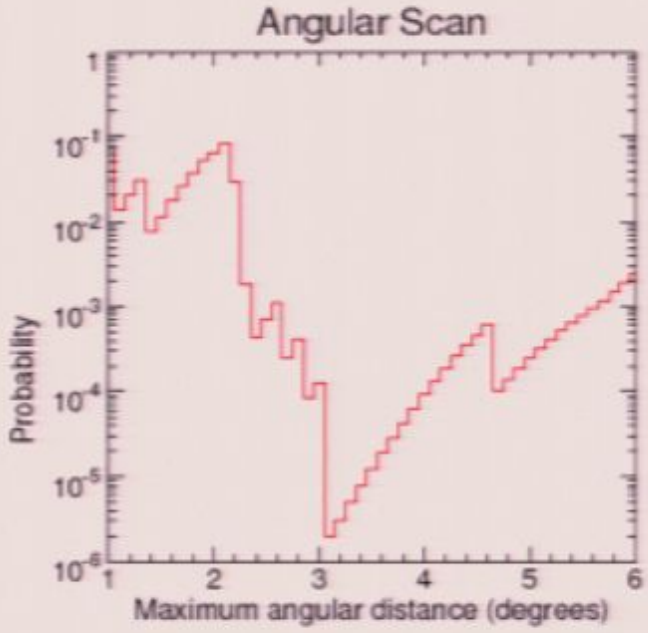
- Scan in the 3-dim space (E_0, z, θ_0) to find a combination which minimizes P(E_0, p(z,θ_0))

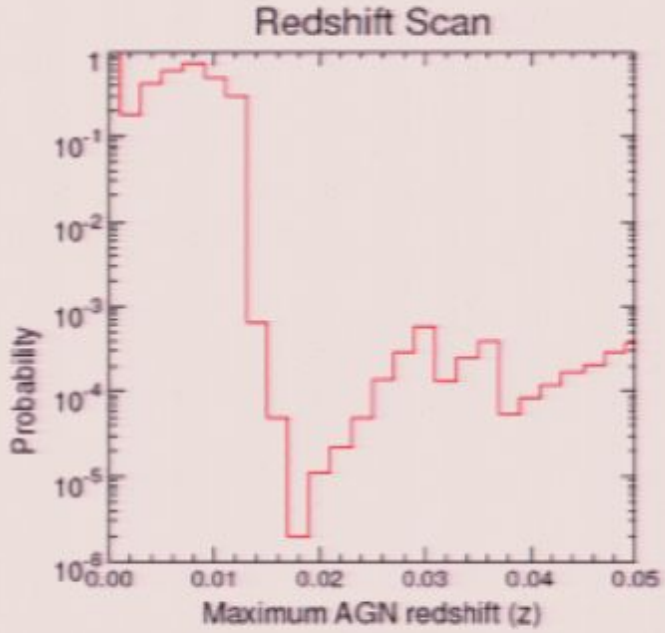
Results of the preliminary scan

- Minimum found with E_0=56 EeV, z_{max}=0.018 (472 AGN within 75 Mpc), θ_0= 3.1°
  - **12 out of 15 UHECR correlate.**
  - **Accidentals: p=21% so only expect 3.**
  - P ~ 10^{-6} (a postiori)



Prob. of false positive ~ 0.1%, evaluated by applying the scan procedure to many isotropic Monte Carlo datasets





A Toy Model of magnetic fields (Dolag et.al, 2004)

Larmor radius: $r_L = 110\ \mathrm{kpc}\ Z^{-1}\ (E / 10^{20}\ \mathrm{eV})\ (B / 1\ \mu\mathrm{G})^{-1}$

Source

Halo B ~ μG with correlation length ~ 1 kpc

Deflection angle for **protons**:
~ sqrt(100)* 1 kpc/100 kpc
= **few degrees**

0.1 Mpc = 100 correlation lengths?

thanks to M.Lemoine

A Toy Model of magnetic fields (Dolag et.al, 2004)

Larmor radius: $r_L = 110\ \mathrm{kpc}\ Z^{-1}\ (E / 10^{20}\ \mathrm{eV})\ (B / 1\ \mu\mathrm{G})^{-1}$

Source

weak deflection
(Extra-galactic B ~nG)

Halo B ~ μG with correlation length ~ 1 kpc

Deflection angle for **protons**:
~ sqrt(100)* 1 kpc/100 kpc
= **few degrees**

0.1 Mpc = 100 correlation lengths?

thanks to M.Lemoine

Verification of the signal:

- By collaboration policy, only ***a priori*** anisotropy searches may be published.
  - Too many examples of signals with high ***a posteriori*** significance (from other experiments/theorists) which later went away.

- New "blind" analysis protocol defined for the set of data acquired after May 27, 2006. Protocol is specified in an internal note.
  - Use the parameters from the scan: E_0=56 EeV, z_{max}=0.018, θ_0=3.1°
- To prevent an open-ended search, design a test to be performed with the next 34 events with E>56 EeV.

- Use a sequential test methodology so that results can be reported as soon as a test probability threshold is passed.
  - **A sequence of up to 20 pre-defined tests are performed as the new events are collected.**

Design of the Sequential Method

- 2 criteria for "errors of the 1st and 2nd kind"
  - The total probability of false positives summed over all possible trials is < ~1%.
  - The "efficiency" or "power" for successfully detecting a correlation if it really exists is > 95%.

  - By tuning the parameters within a small range, the correlation rate of 12/15 = 80% easily goes to 8/14 = 57%. We take 57% as the minimum probability of correlation when designing the test to achieve the desired "power."
    - **(We do not expect 100% correlation if the catalog is incomplete, if the AGN are not the only sources, or if AGN are only incomplete "tracers" of the true sources.)**

The sequential test for k correlations at the Nth event

- For 95% test power, we require up to 34 events with 15/34 events giving a success rate of:
  - BinoI(15,34,57%) = 95%

N	k_{min}	Summed Prob.	Power (P=57%)
4	4	0.19	11
6	5	0.32	19
8	6	0.40	26
10	7	0.44	31
12	8	0.47	36
13	8	0.55	49
15	9	0.58	52
16	9	0.67	63
18	10	0.70	64
20	11	0.71	66
21	11	0.75	74
23	12	0.77	75
24	12	0.81	82
26	13	0.82	82
27	13	0.86	87
29	14	0.87	87
30	14	0.91	91
31	14	0.99	93
33	15	1.00	93
34	15	1.05	95

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- Since the false positive rate for this signal from an isotropic sky, BinoI(15,34,21%) = 0.21%, we set an individual test threshold of:
  - BinoI(k,N,21%)<0.23%.
  - This defines a set of 20 tests we can perform along the way, the first being 4/4

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  - BinoI(k,N,21%)<0.23%.
  - This defines a set of 20 tests we can perform along the way, the first being 4/4
- The probabilities of false positive is summed over all 20 tests, being careful not to double count the configurations of (k,N). The total rate of false positive over all trials is 1.05%.

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The signal was validated on:

- May 31, 2007, when 6/8 events were found to be correlated.
  - *a priori* isotropic probability ~ 0.4%
    - (but to be honest, we really should use 1.05%)

N	k_{min}	Summed Prob.	Power (P=57%)
4	4	0.19	11
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  - *a priori* isotropic probability ~ 0.4%
    - (but to be honest, we really should use 1.05%)
- By July 31, 2007, 7/10 correlated
- By August 31, 2007, 8/13 correlated
  - *P(8,13,21%)* ~ 0.17%

- **This a priori analysis establishes the anisotropy of the UHECR with at least 99% CL.**

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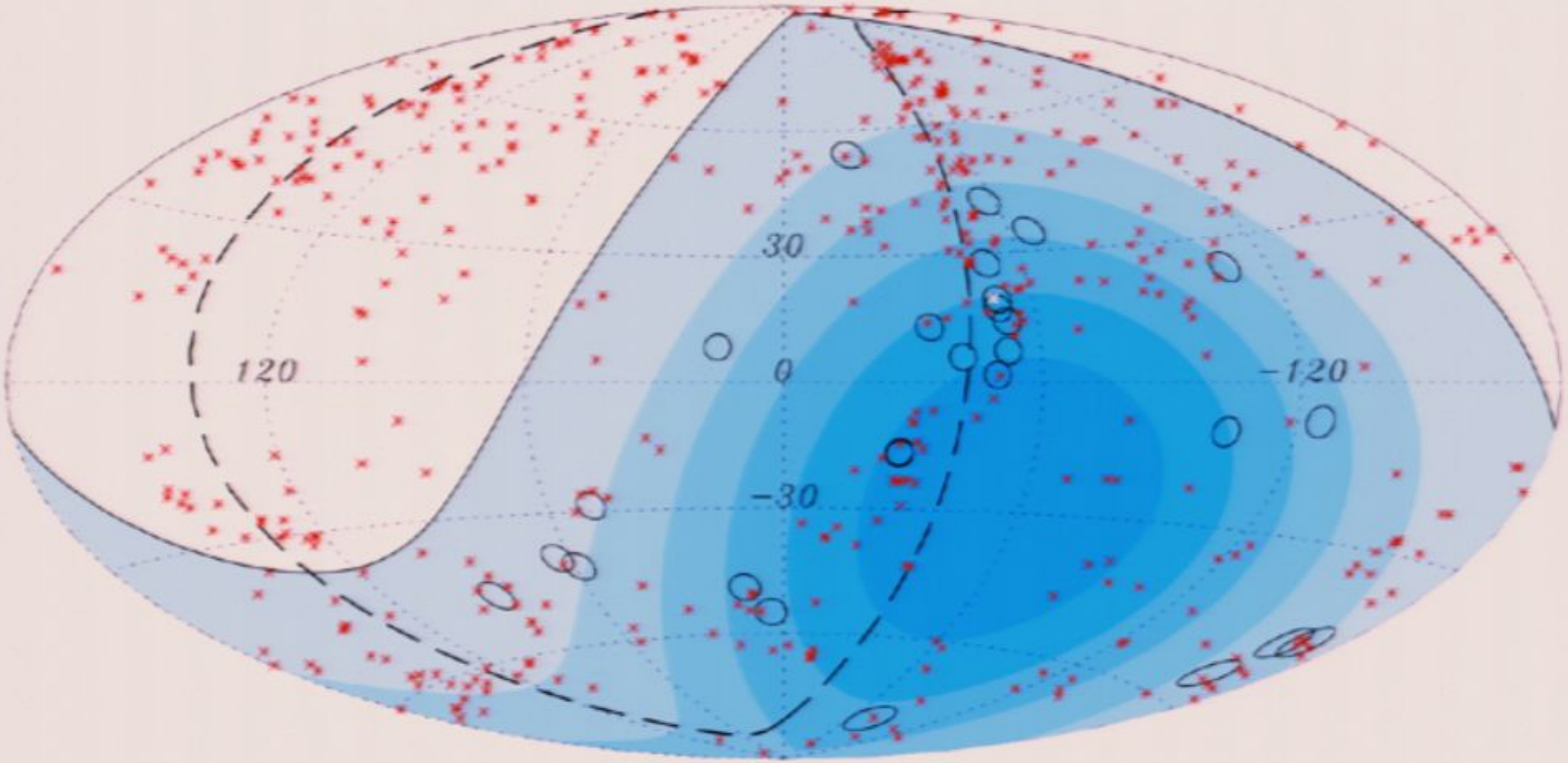
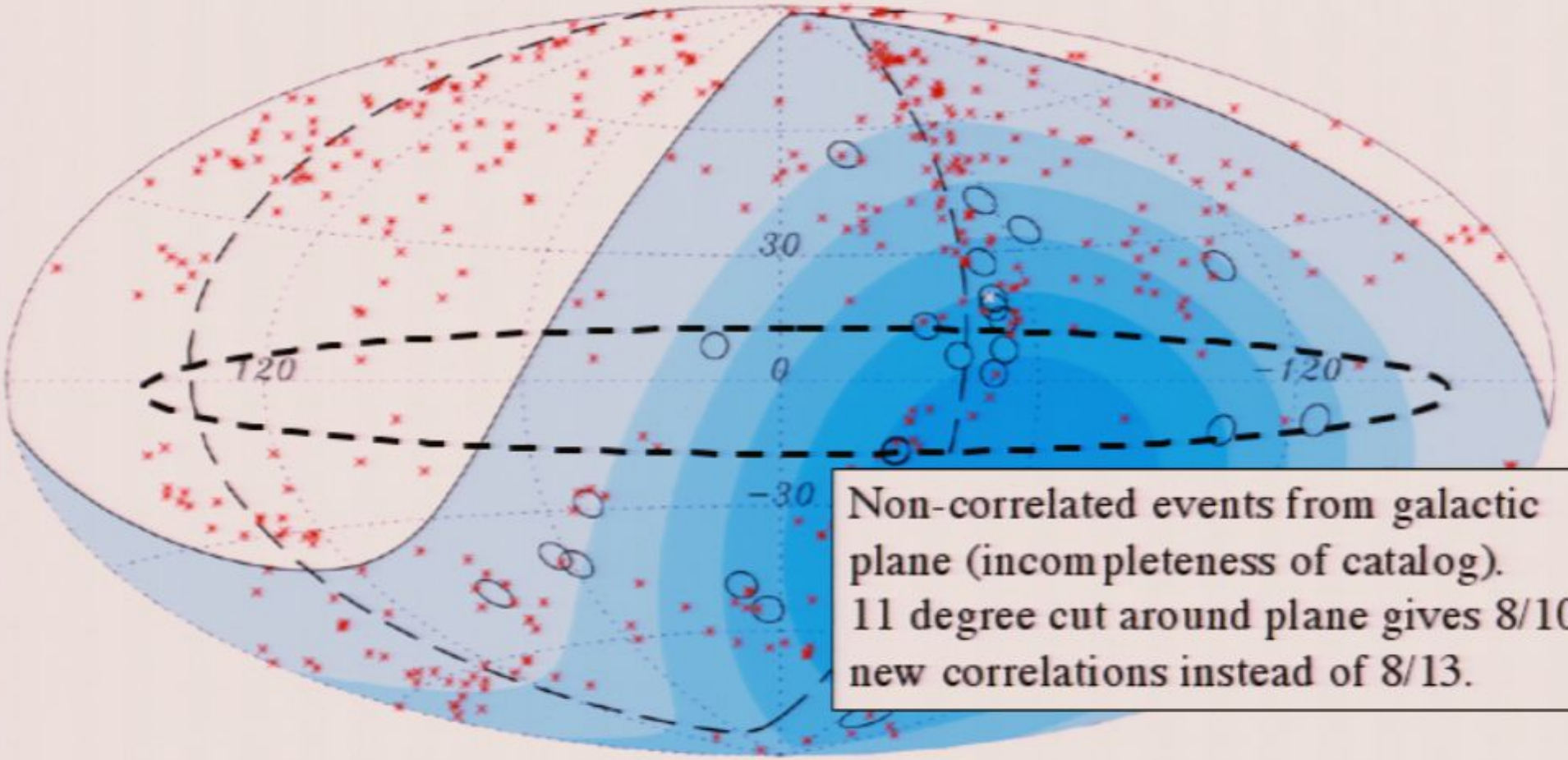
Sky Map (Galactic coordinates)



3.1° circles: UHECR directions. Red asterisks: AGN within 75 Mpc.
Blue: equal-exposure regions. Dashed Line: superGalactic plane.
Solid Line: edge of Auger acceptance.

Sky Map (Galactic coordinates)



Non-correlated events from galactic plane (incompleteness of catalog). 11 degree cut around plane gives 8/10 new correlations instead of 8/13.

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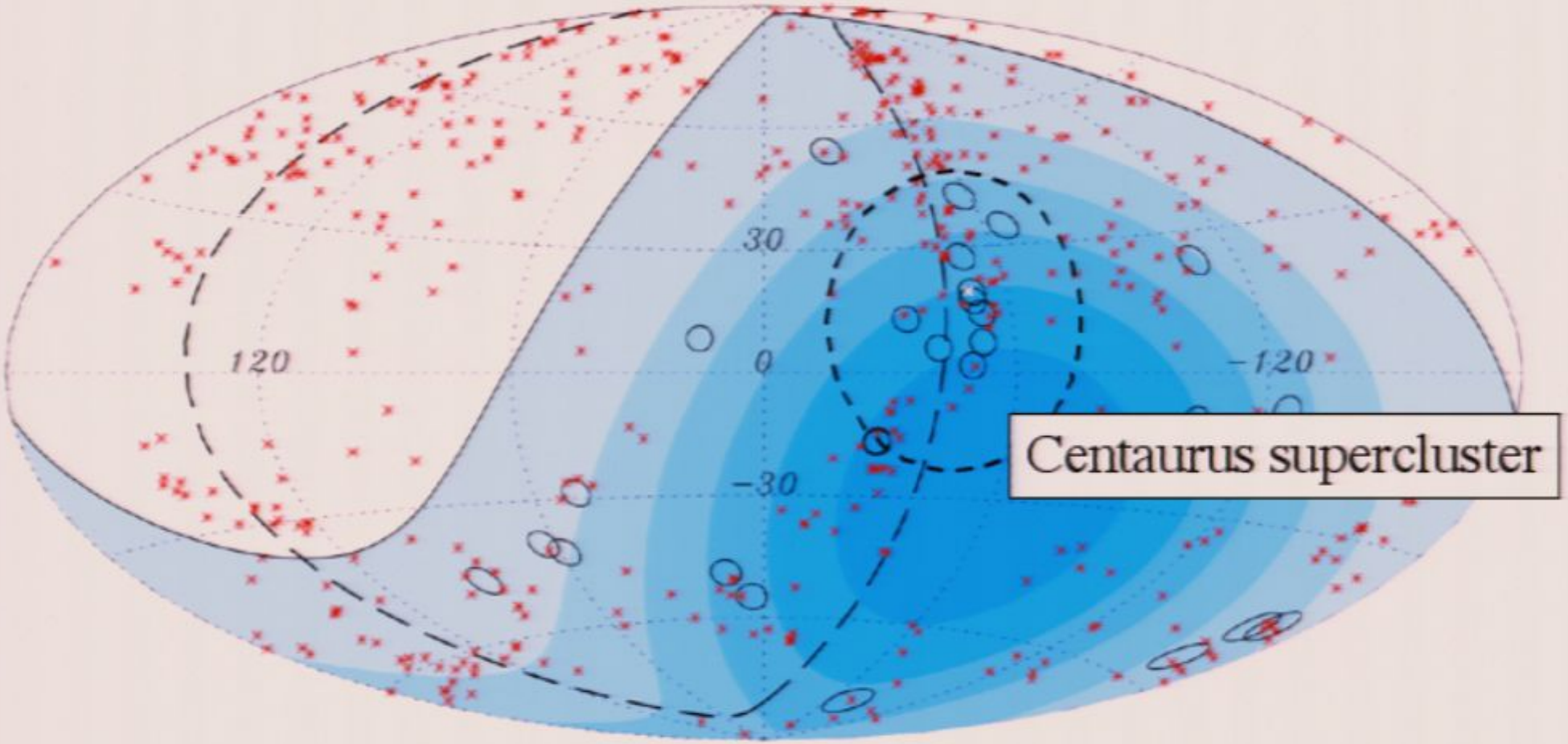
Sky Map (Galactic coordinates)



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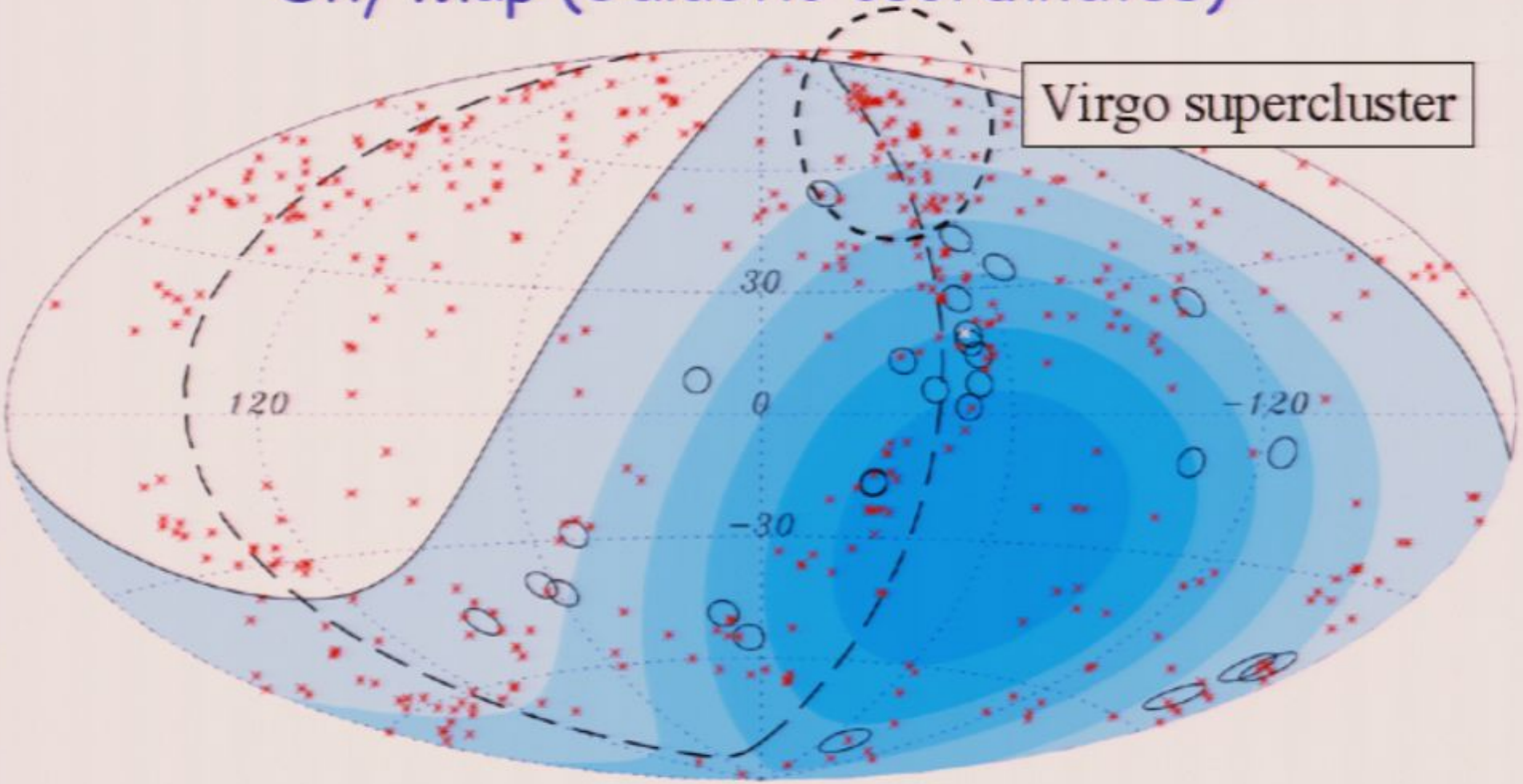

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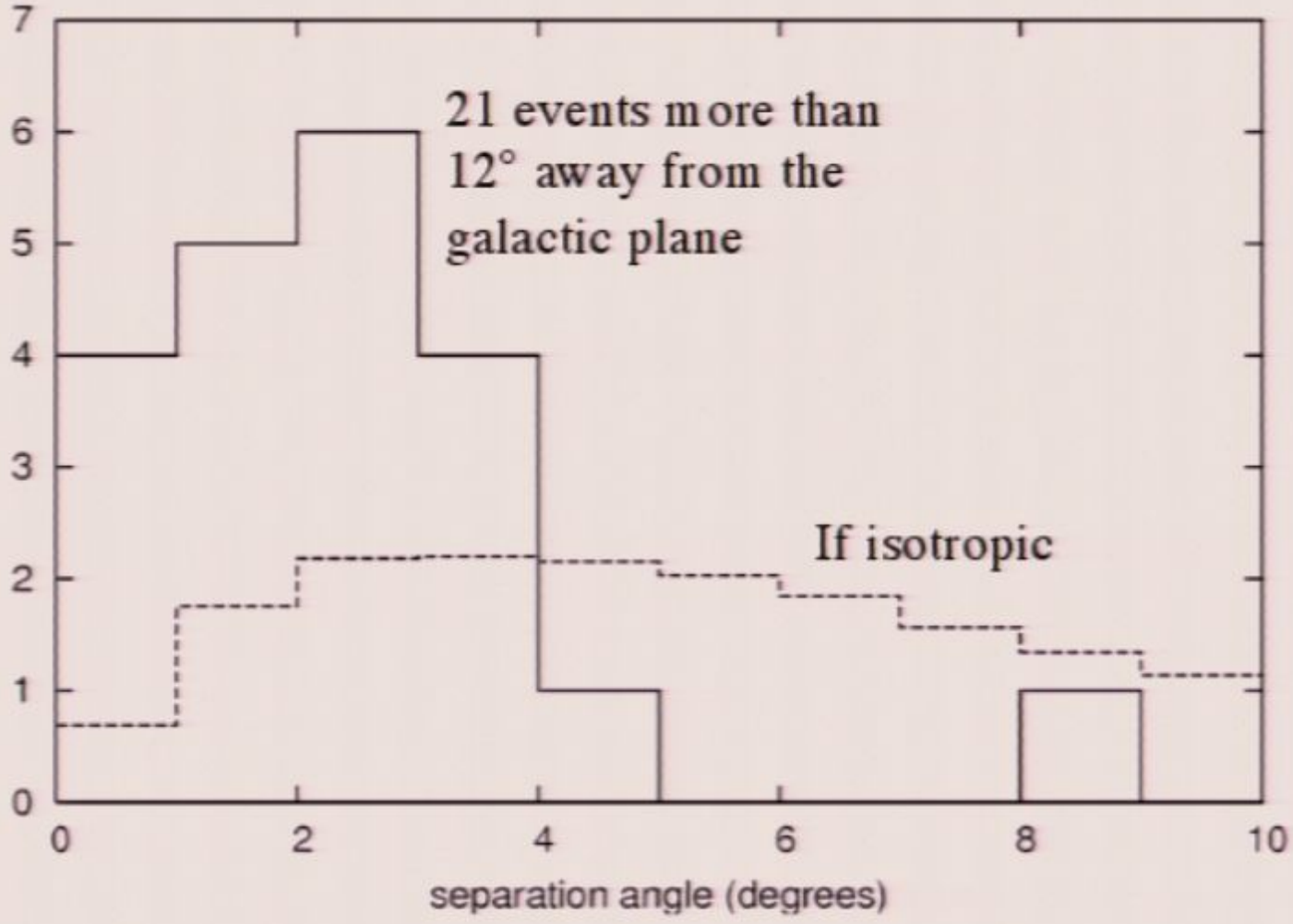
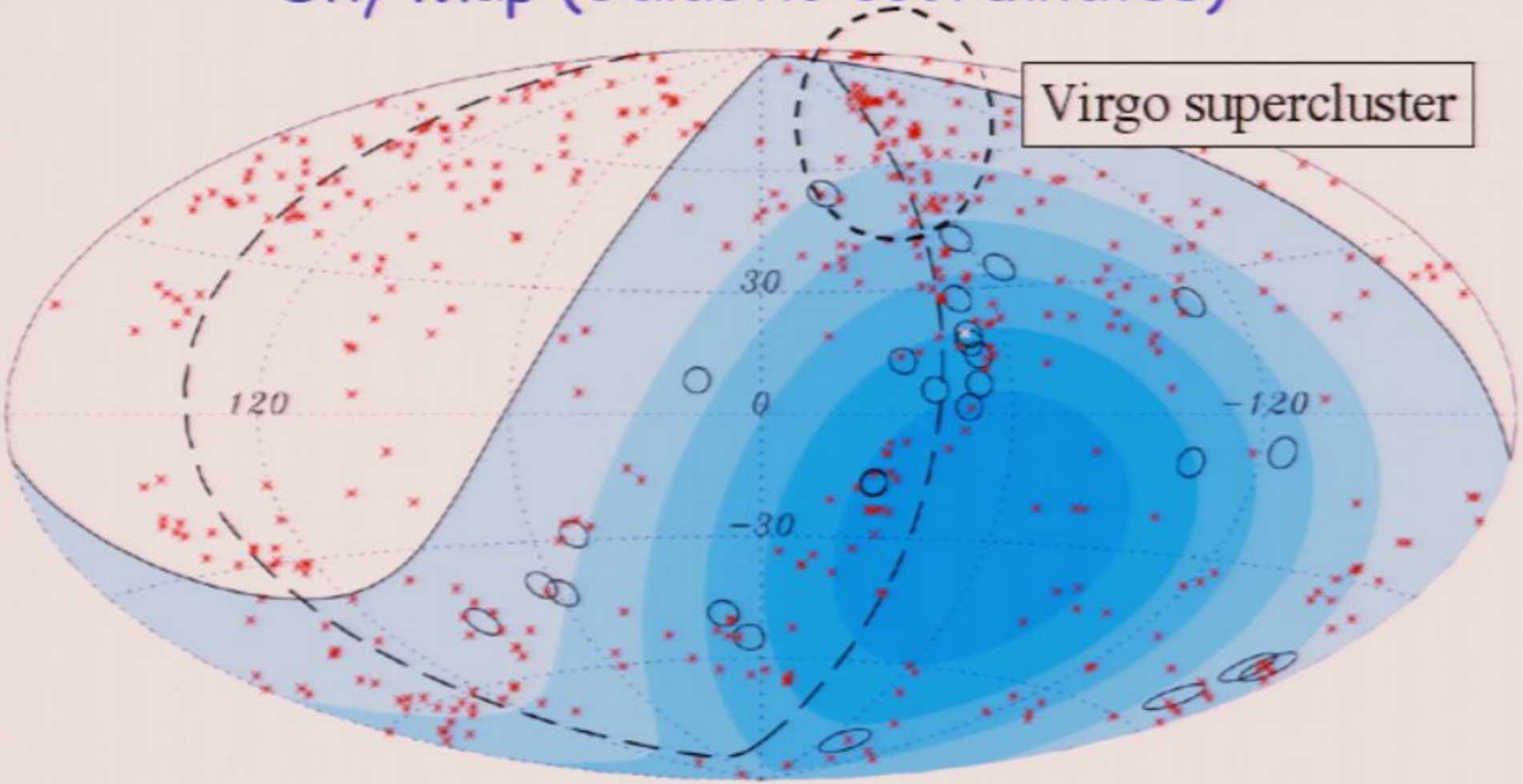
Separation angle to closest AGN

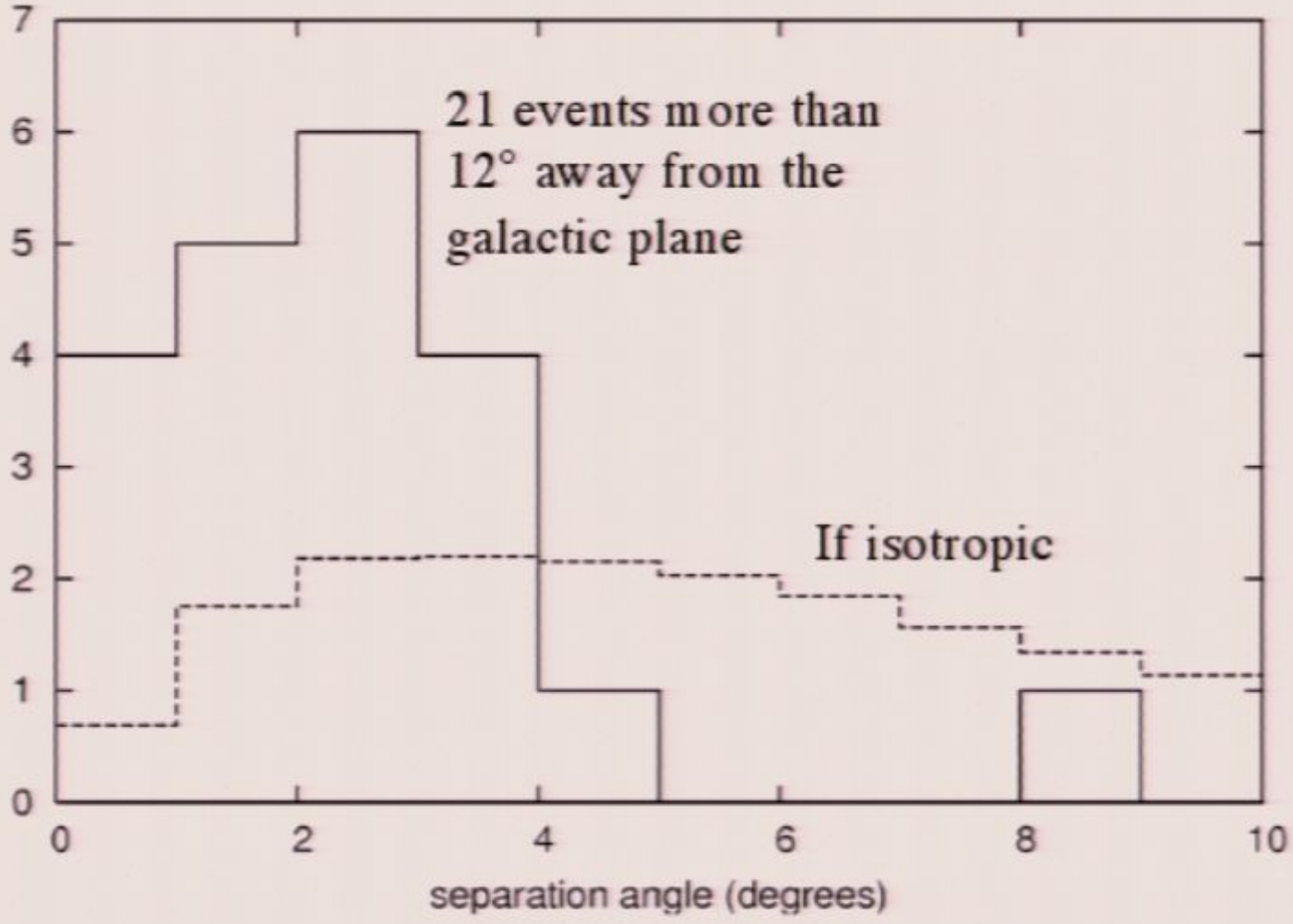


Sky Map (Galactic coordinates)



3.1° circles: UHECR directions. Red asterisks: AGN within 75 Mpc.
Blue: equal-exposure regions. Dashed Line: superGalactic plane.
Solid Line: edge of Auger acceptance.

Separation angle to closest AGN



AGN correlation evidence of GZK effect?

- 3.1 degree correlation suggests proton composition.
  - However, 60 EeV threshold --> 200 Mpc GZK horizon for protons
  - For 80 EeV threshold --> 90 Mpc GZK horizon for protons
- Our correlation is maximized for 57 EeV(±22%) and a maximum distance of 75 Mpc which might point more towards heavy nuclei with a shorter attenuation length, propagating in a smaller magnetic field.
- **Independent energy scale calibration is crucial!**
- Caveats:
  - The VC catalog becomes increasingly incomplete with distance
  - A larger distance cut gives more AGN which means that a larger fraction of the sky is covered by the "AGN mask" and thus the sensitivity of the technique is reduced.
- **Ultimately: independent measures of energy/composition will allow determination of the GZK effect and the galactic magnetic field.**

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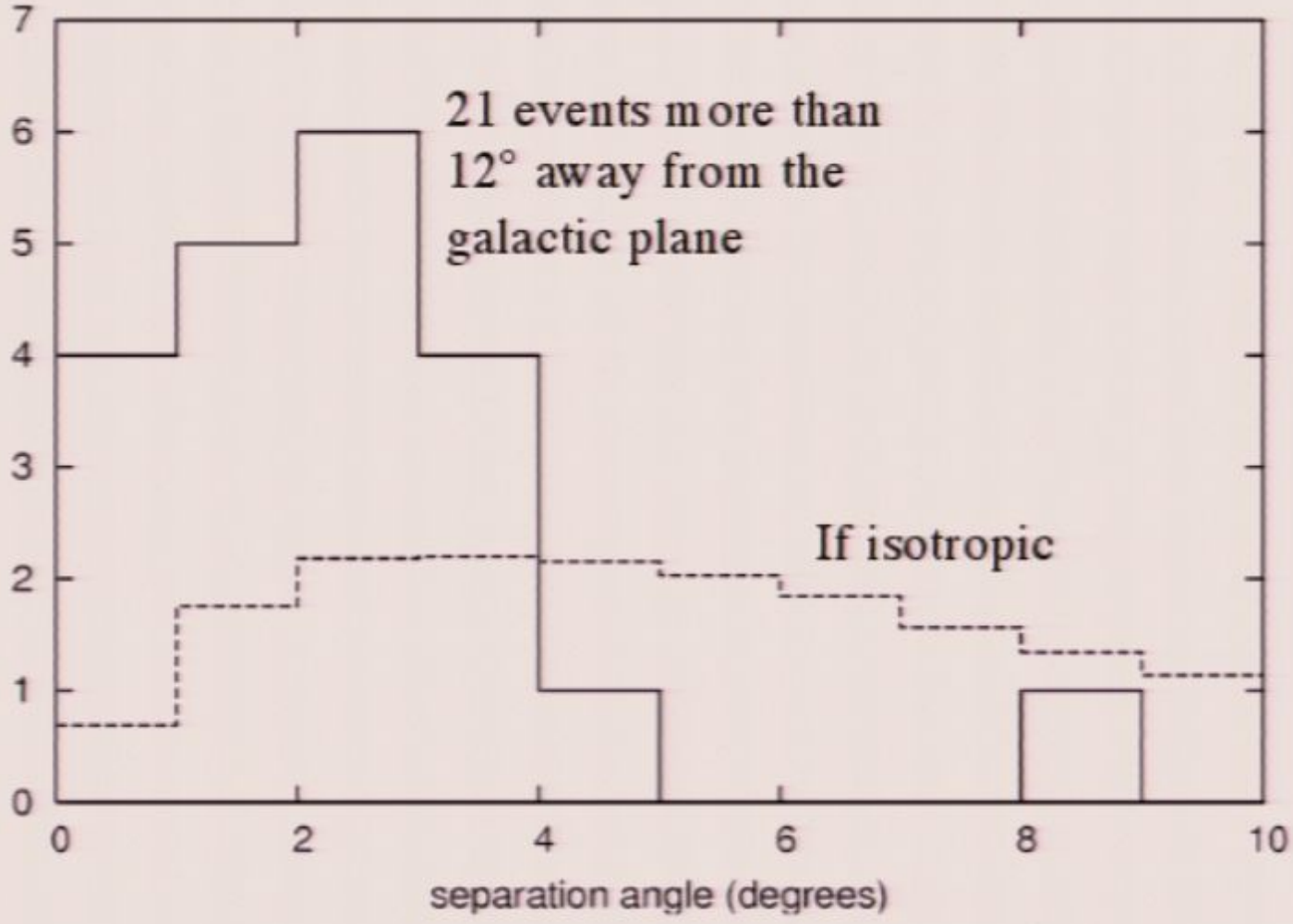

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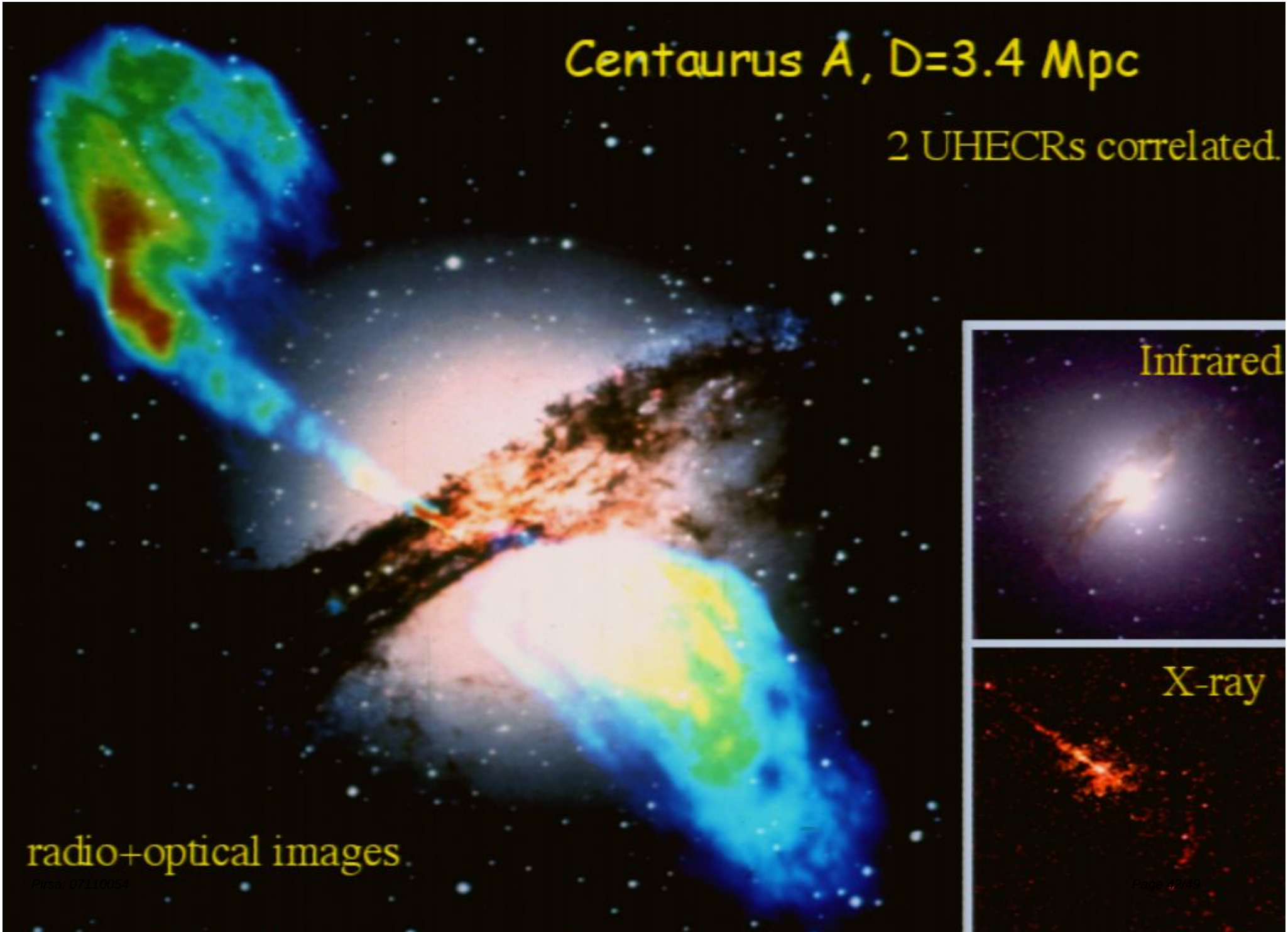
Extragalactic Sources

- Data rule out local Galactic sources
  - Young neutron stars, pulsars, magnetars, microquasars, SHDM
- **The AGN distribution follows the large scale structure, and hence may merely be correlated with the true source distribution rather than being the actual sources themselves**
- Work underway to study the clustering properties of various classes of sources. For example:
  - Optically-identified AGN follow the average galaxy distribution.
  - Gamma ray bursts are more likely to happen in relatively overdense star-formation regions.
    - **Note that correlations with other observations of transient phenomena are unlikely due to the time delay of magnetically deflected particles:**

$$\Delta t \sim 1/2\ (3^\circ)^2\ /\mathrm{sqrt}(N_{scat}) * 75\ \mathrm{Mpc} \sim 500\text{-}5000\ \mathrm{years}$$


Centaurus A, D=3.4 Mpc
2 UHECRs correlated.
Infrared
X-ray
radio+optical images

Other UHECR-correlated AGN

- No strong radio emitters other than Cen A are correlated.
  - In fact, there are no events from M87 (20 Mpc) or any other AGN in the the densely populated Virgo cluster… (???)
  - Cen A is the only "BL Lac" within 75 Mpc

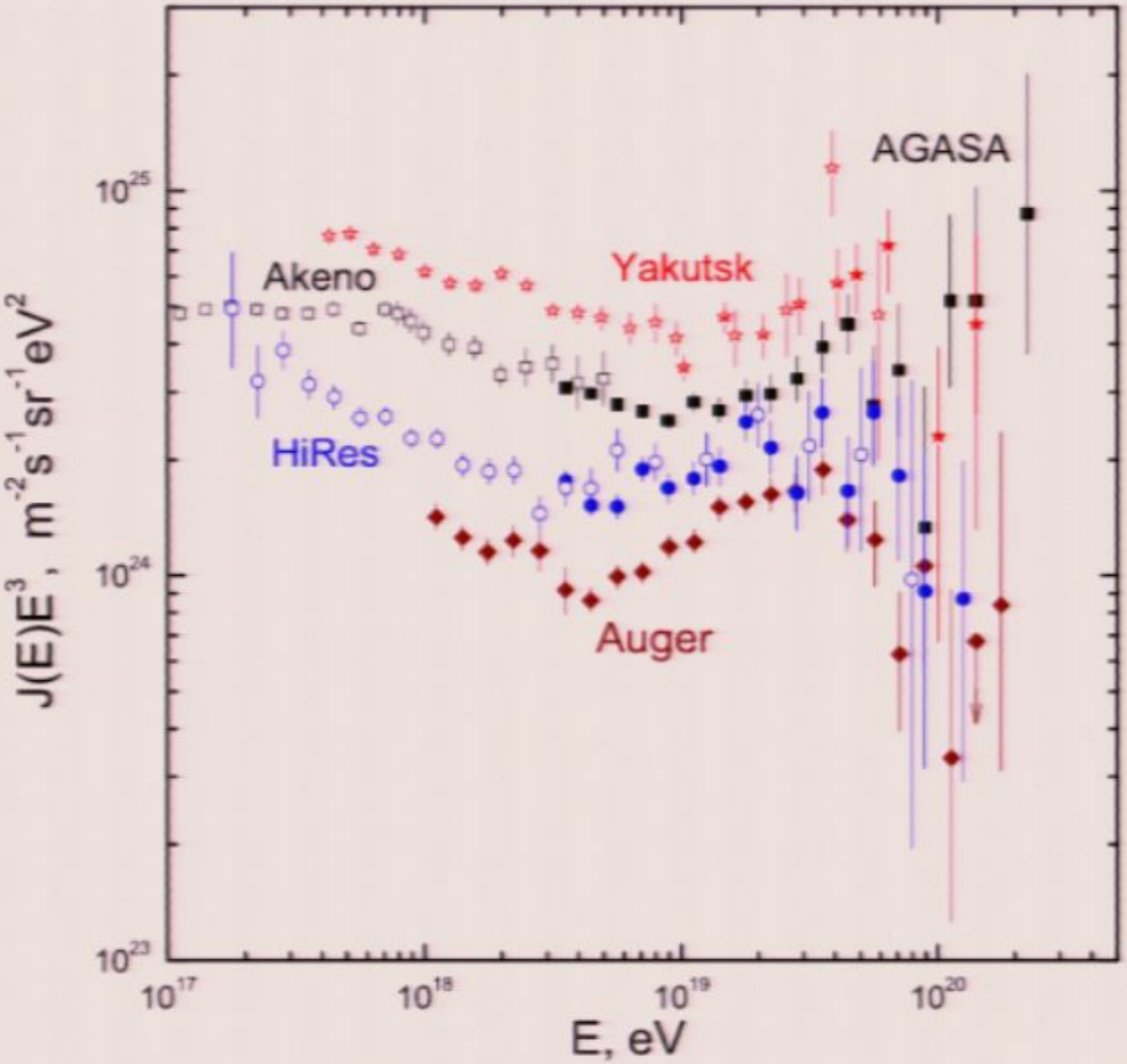
- AGN types (of closest correlated AGN)
  - 5 Seyfert 1 (broad optical lines)
  - 7 Seyfert 2 (narrow optical lines)
  - 2 intermediate Seyfert
  - 1 unclassified Seyfert
  - 2 HII regions (star formation)
- **Statistics too low to form conclusions.**

Conclusions

- With ~1 Auger-year of data, we have established the **anisotropy** of arrival directions of the highest energy cosmic rays with E > 60 EeV.
- Correlations are seen with nearby AGN on angular scales of a few degrees suggestive of **proton** deflection.
- This parameters of these correlations are roughly consistent with the proton energy attenuation length due to scattering on the CMB
  - Better energy scale calibration will tell us for sure.
  - **If so, we have a pure proton beam impacting a known target at a CM energy of 300 TeV!**
  - The galactic magnetic field can also be measured with a known beam.
- **Astronomy colleagues can search for missing sources!**
- With the next few years of data, we hope to obtain unambiguous identification of the UHECR sources

- The future: Charged particle astronomy with Auger North and expanded Auger South. **Cen A may be next Crab!**

Comparison with other experiments



The signal was validated on:

- May 31, 2007, when 6/8 events were found to be correlated.
  - *a priori* isotropic probability ~ 0.4%
    - (but to be honest, we really should use 1.05%)

N	k_{min}	Summed Prob.	Power (P=57%)
4	4	0.19	11
6	5	0.32	19
8	6	0.40	26
10	7	0.44	31
12	8	0.47	36
13	8	0.55	49
15	9	0.58	52
16	9	0.67	63
18	10	0.70	64
20	11	0.71	66
21	11	0.75	74
23	12	0.77	75
24	12	0.81	82
26	13	0.82	82
27	13	0.86	87
29	14	0.87	87
30	14	0.91	91
31	14	0.99	93
33	15	1.00	93
34	15	1.05	95

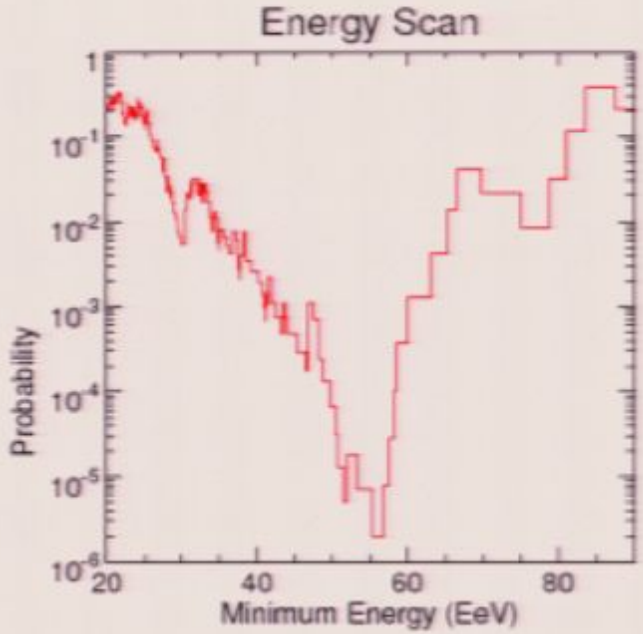
Dataset for the current anisotropy result

- Surface detector (SD) triggered events
  - Time-over-threshold triggers in each tank
  - At least 3-tanks triggered in a triangular pattern.
  - Highest signal tank surrounded by 5 active neighbor tanks
  - Shower core lies in a triangle of 3 active tanks
  - For E>10 EeV, angular resolution better than 1 deg

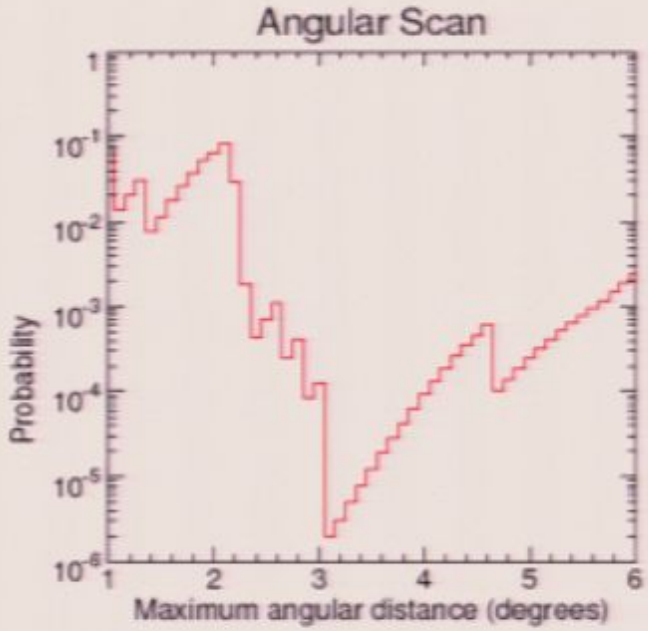
- Exposure = 9.0 10^3 km^2 sr yr (January 1, 2004 - August 31, 2007)
- = **1.2 Full-Auger-years**
- = 5.4 * *AGASA* = 1.5(?)*HiRes

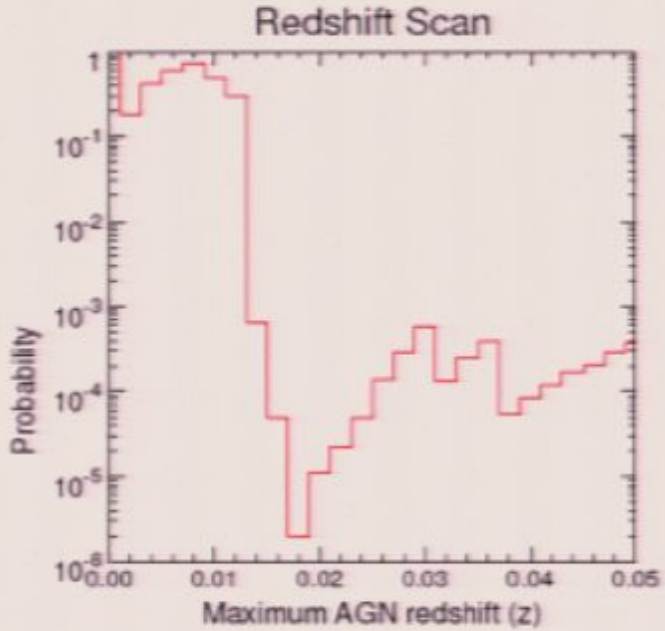
Results of the preliminary scan

- Minimum found with E_0=56 EeV, z_{max}=0.018 (472 AGN within 75 Mpc), θ_0= 3.1°
  - **12 out of 15 UHECR correlate.**
  - **Accidentals: p=21% so only expect 3.**
  - P ~ 10^{-6} (a postiori)



Prob. of false positive ~ 0.1%, evaluated by applying the scan procedure to many isotropic Monte Carlo datasets





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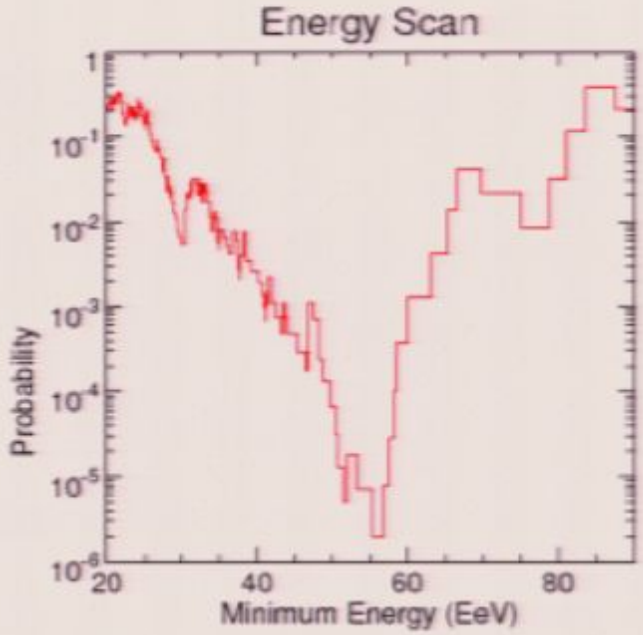

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