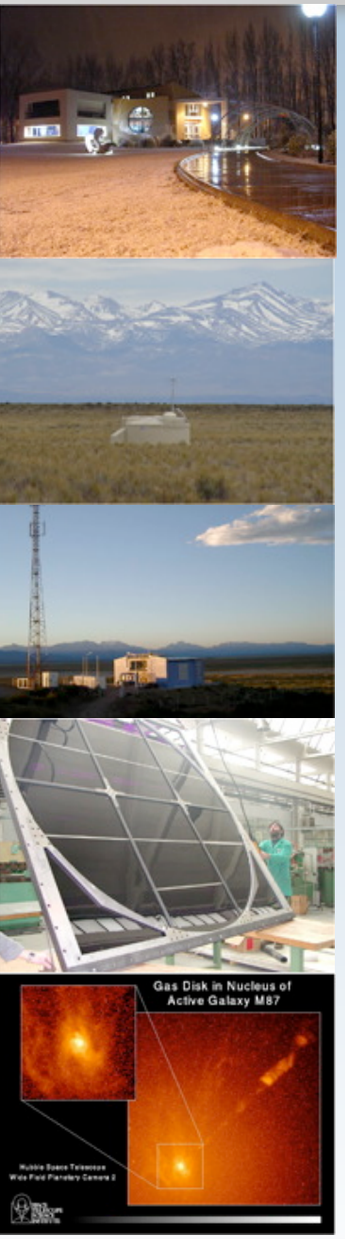
Cosmic Rays at the Highest Energies

First Science Results from the Pierre Auger Observatory

Karl-Heinz Kampert (Bergische Universität Wuppertal, Fachbereich Physik)

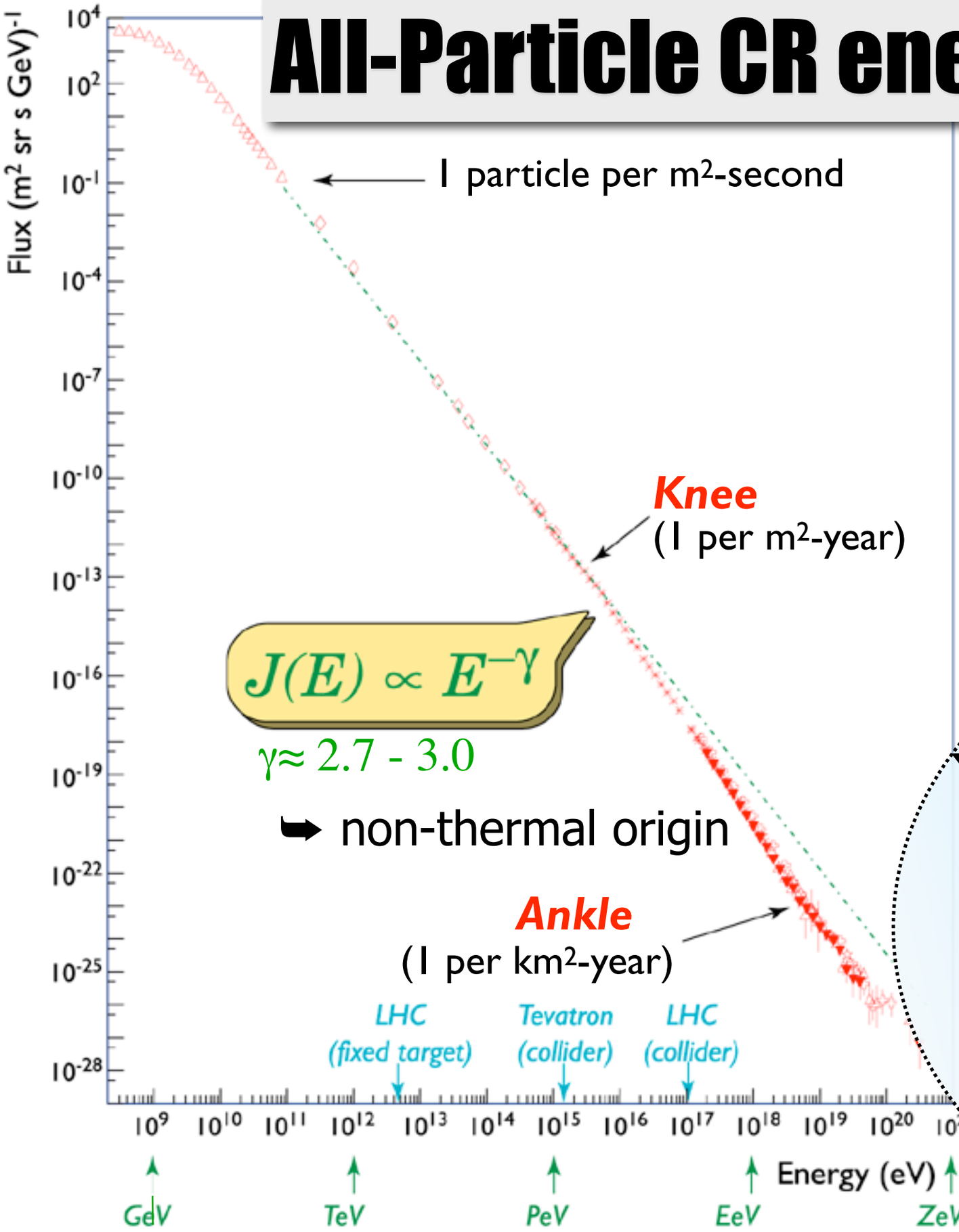


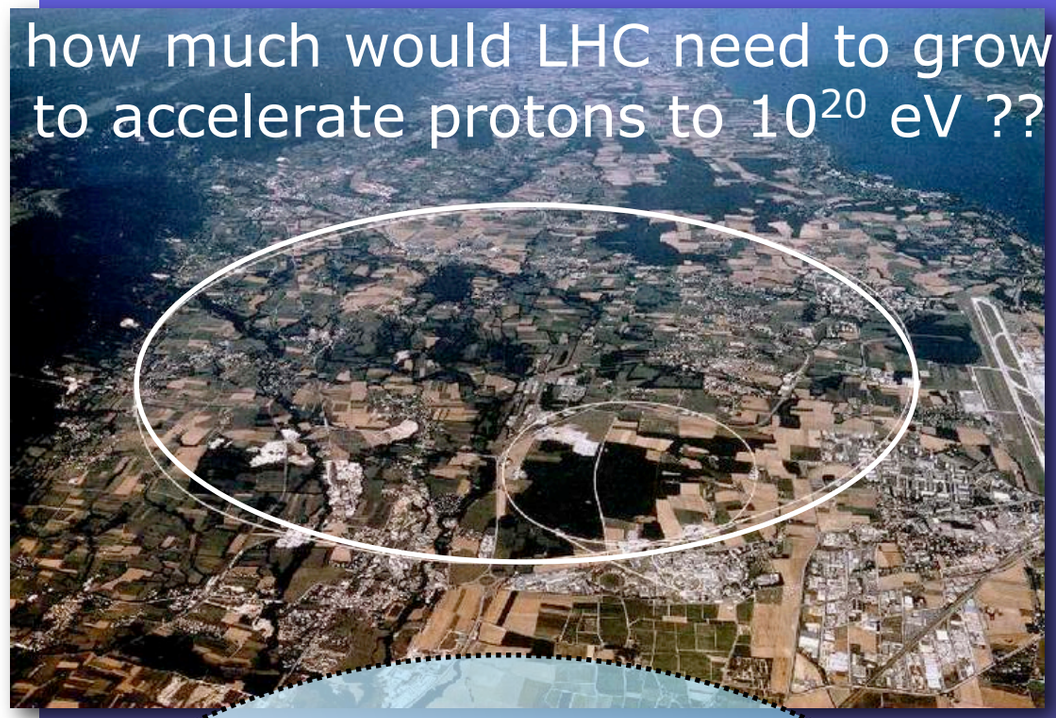
- **UHECR – Puzzles and Challenges**
- **The Pierre Auger Observatory**
  - ***Experimental Approach***
  - ***Status***
  - ***Performance***
- **First Physics Results**
  - ***Energy Spectrum***
  - ***Composition and Photon Limits***
  - ***Anisotropies & AGN-Correlations***
- **Outlook**

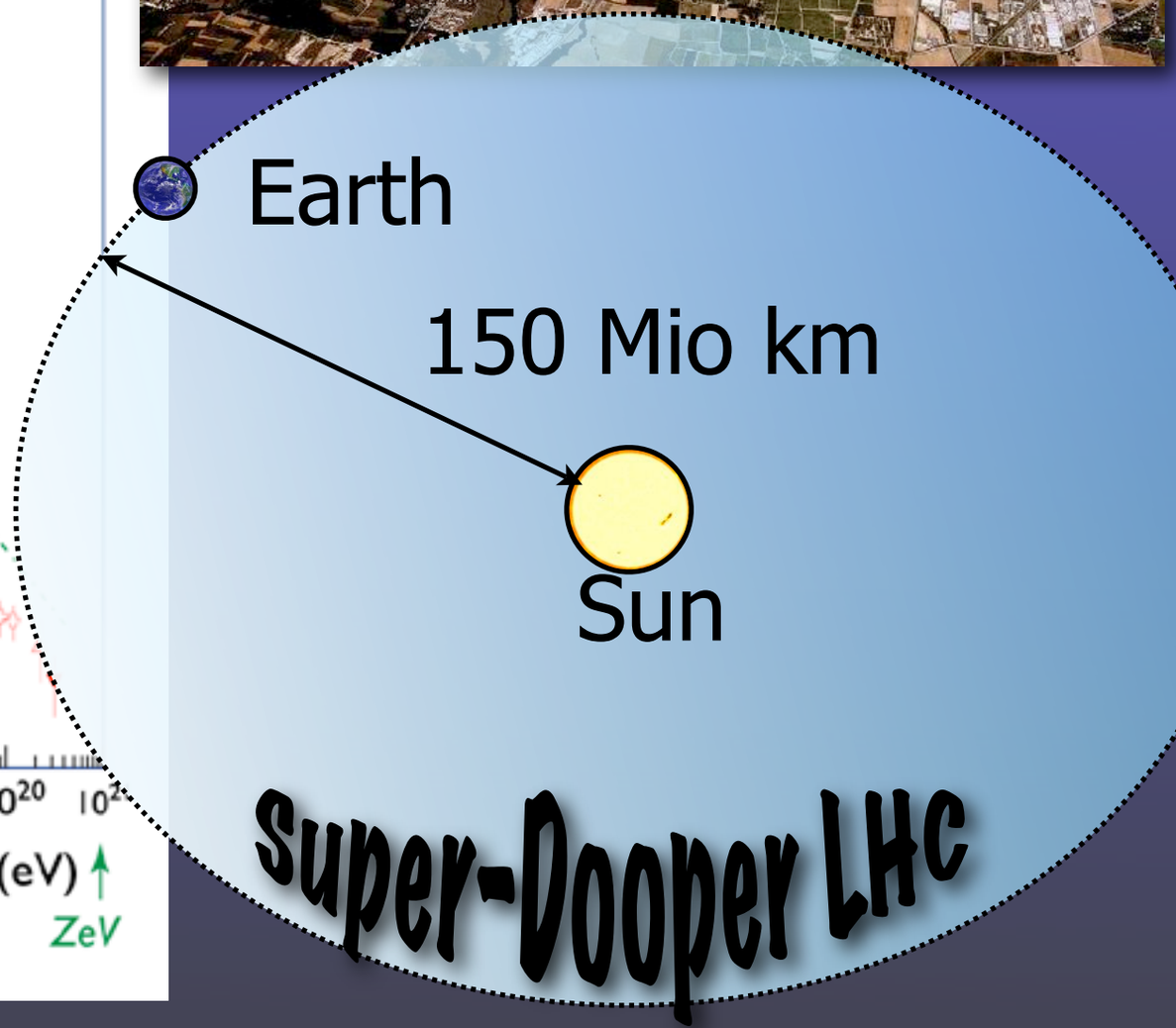
bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

kampert@uni-wuppertal.de

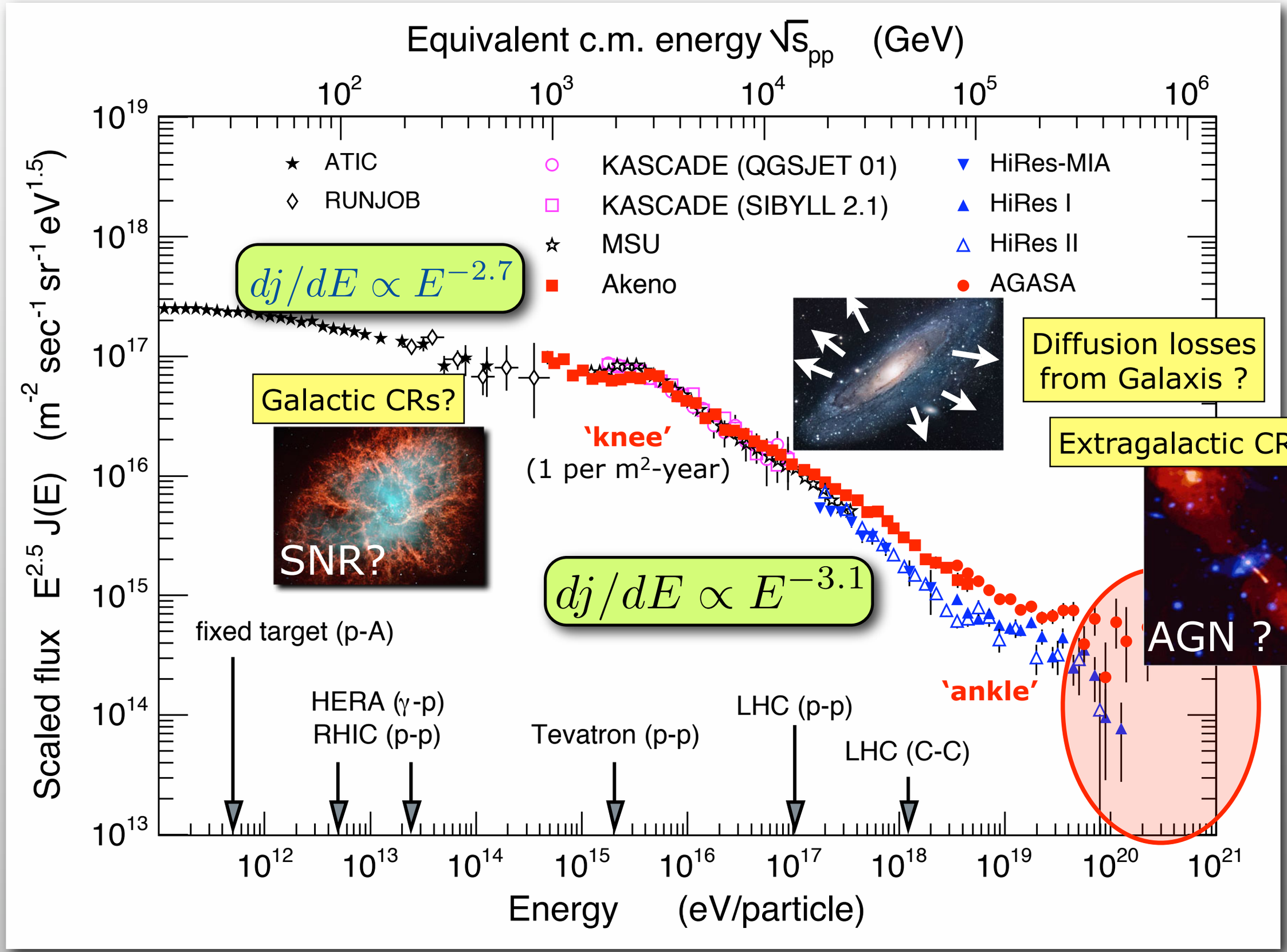
All-Particle CR energy spectrum





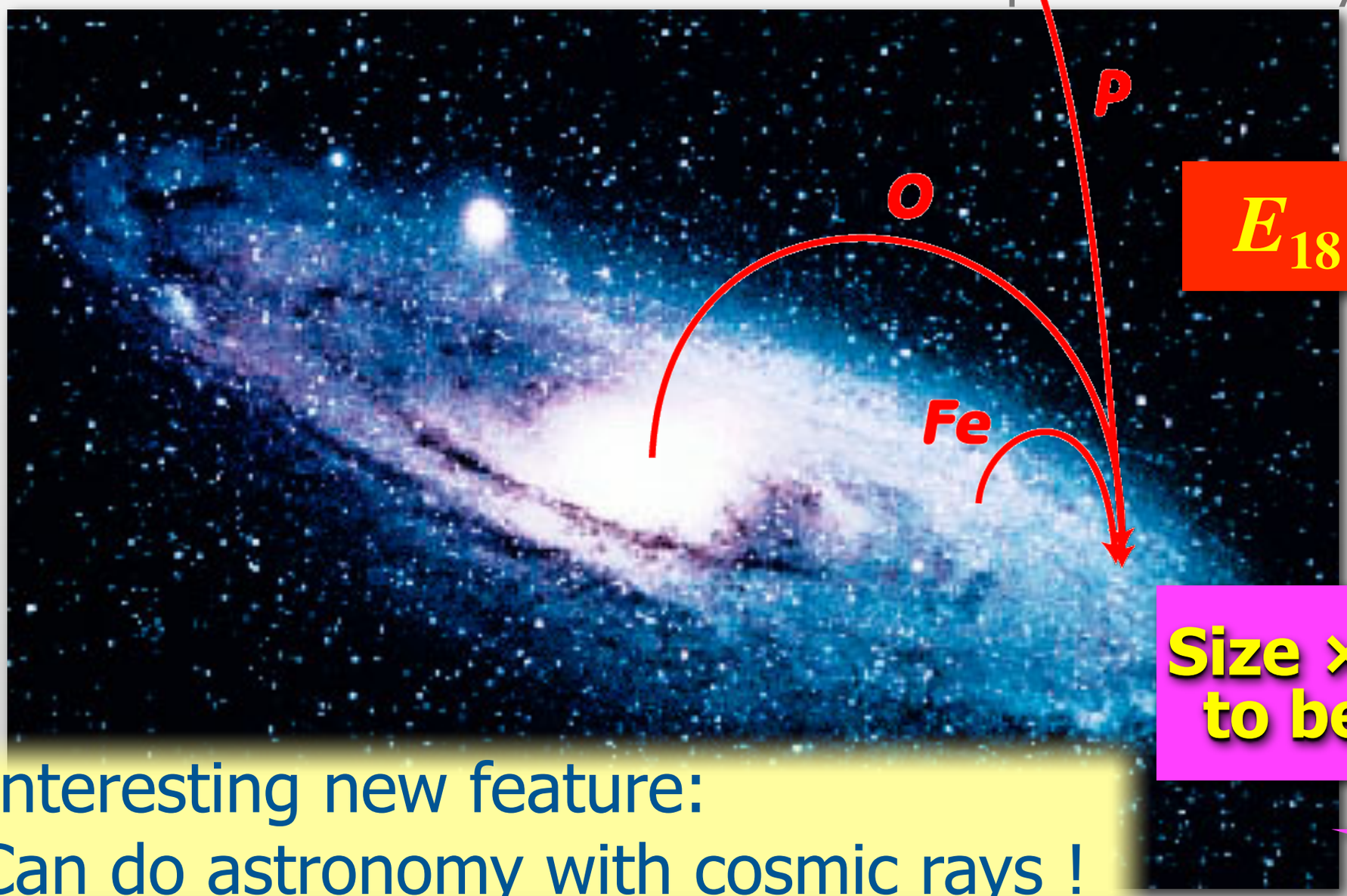


Ultra High-Energy Cosmic Rays



10^{20} eV CRs in our Galaxy ?

Lamor radii at **10^{20} eV** compared to Milky-Way



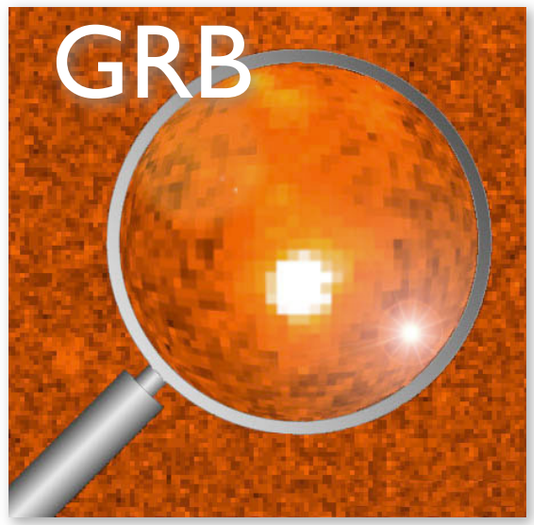
$$E_{18} \leq Z \cdot B_{\mu G} \cdot R_{kpc}$$

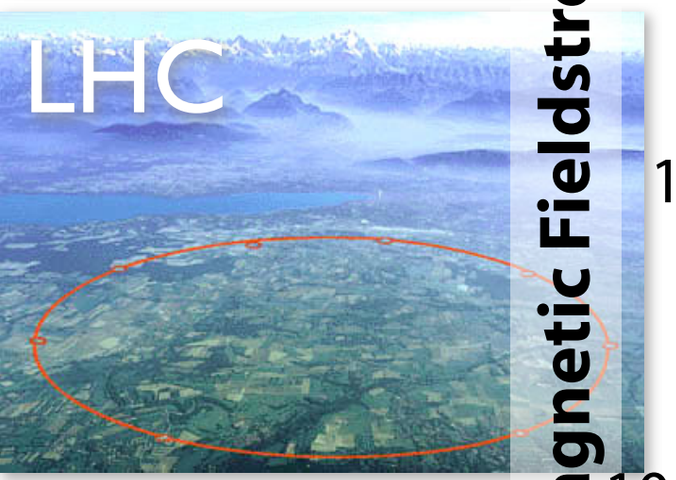
Size × B-Field needs to be very large ...

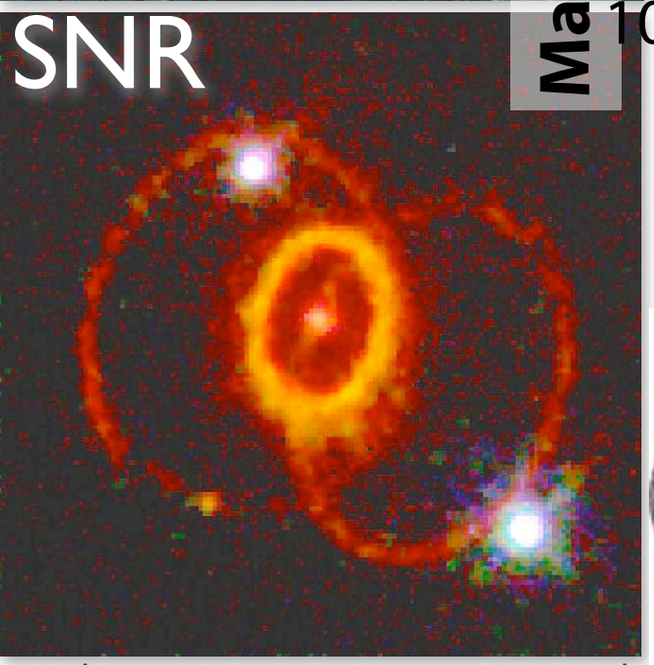
Interesting new feature:
Can do astronomy with cosmic rays !

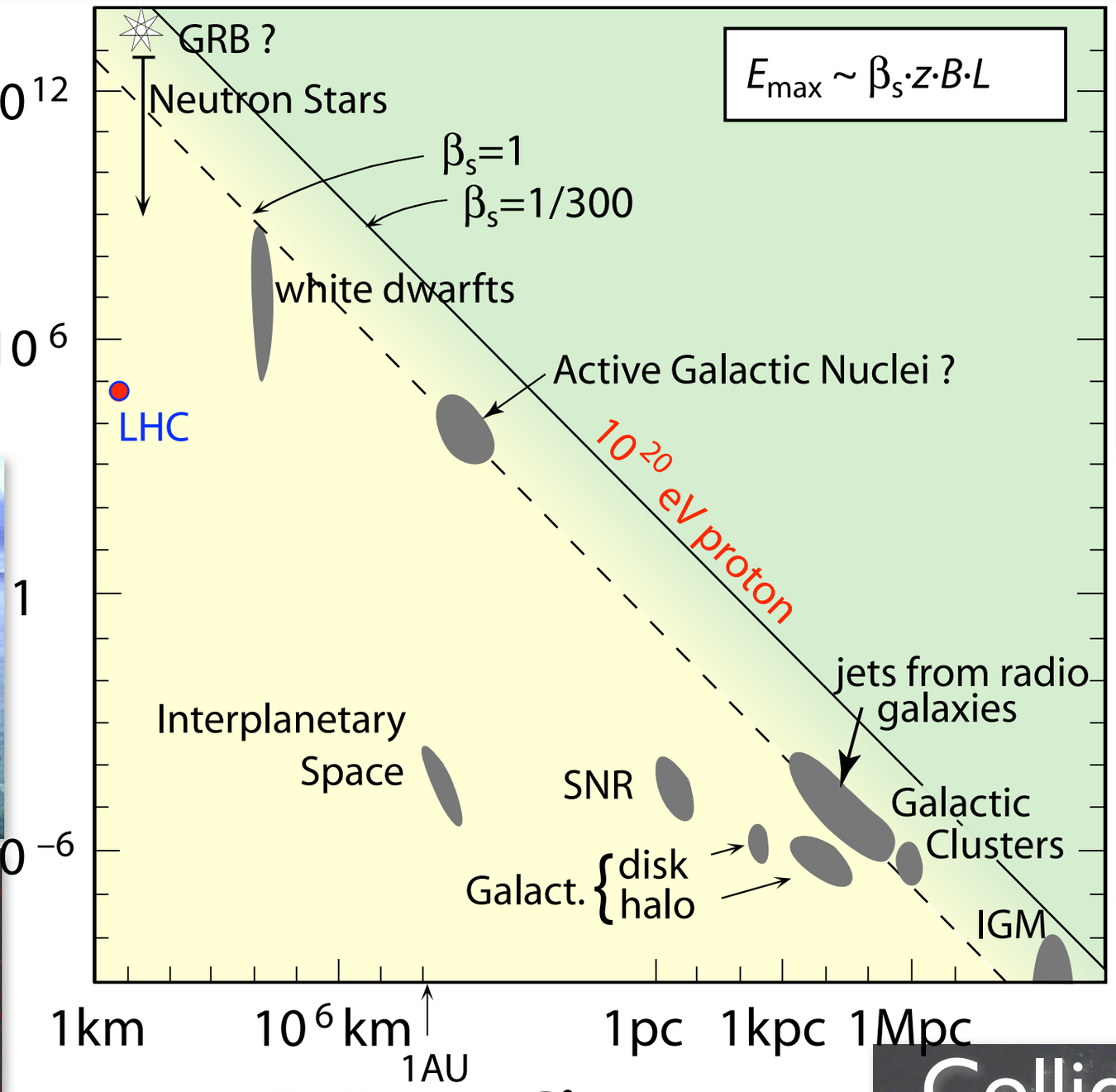
Conjecture:
Extragalactic origin

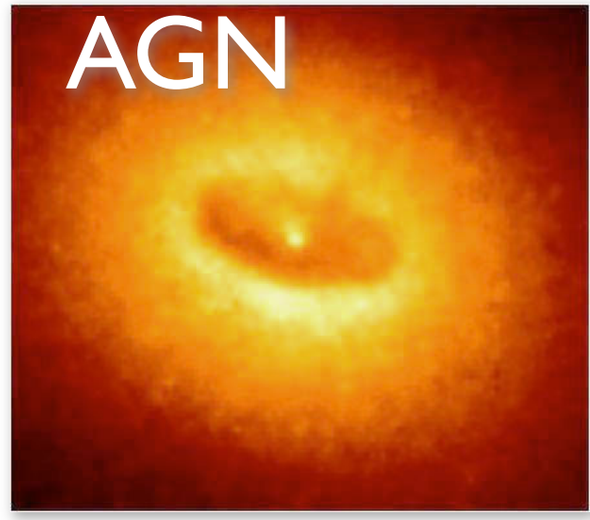
? Possible Candidates ?











Size

AGN Jets and Radio-Lobes

Cygnus A

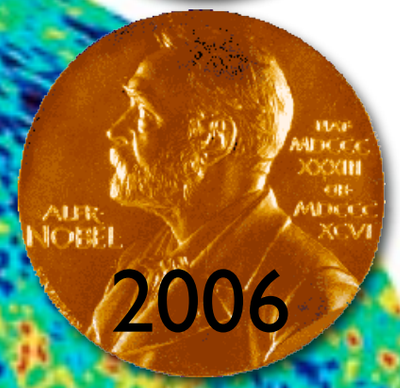
(z=0.056, d≈210 Mpc
5 GHz image, ø ≈ 20 kpc)

100 Mpc = 326 Mio. Lightyears

3C 219 (FR II)

z=0.1745, d≈800 Mpc

Problem: CMBR



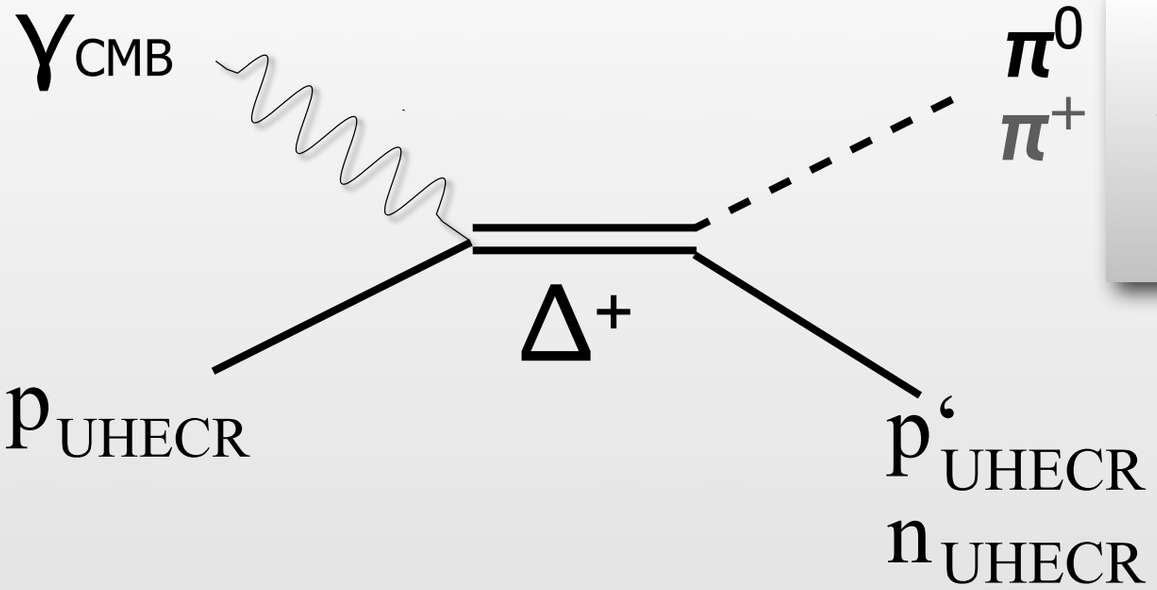
WMAP

Universe is filled with 3K photons: 412/cm^3

Discovered 1965 by Penzias and Wilson

The GZK-Effect

Greisen-Zatsepin-Kuz'min 1966



$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

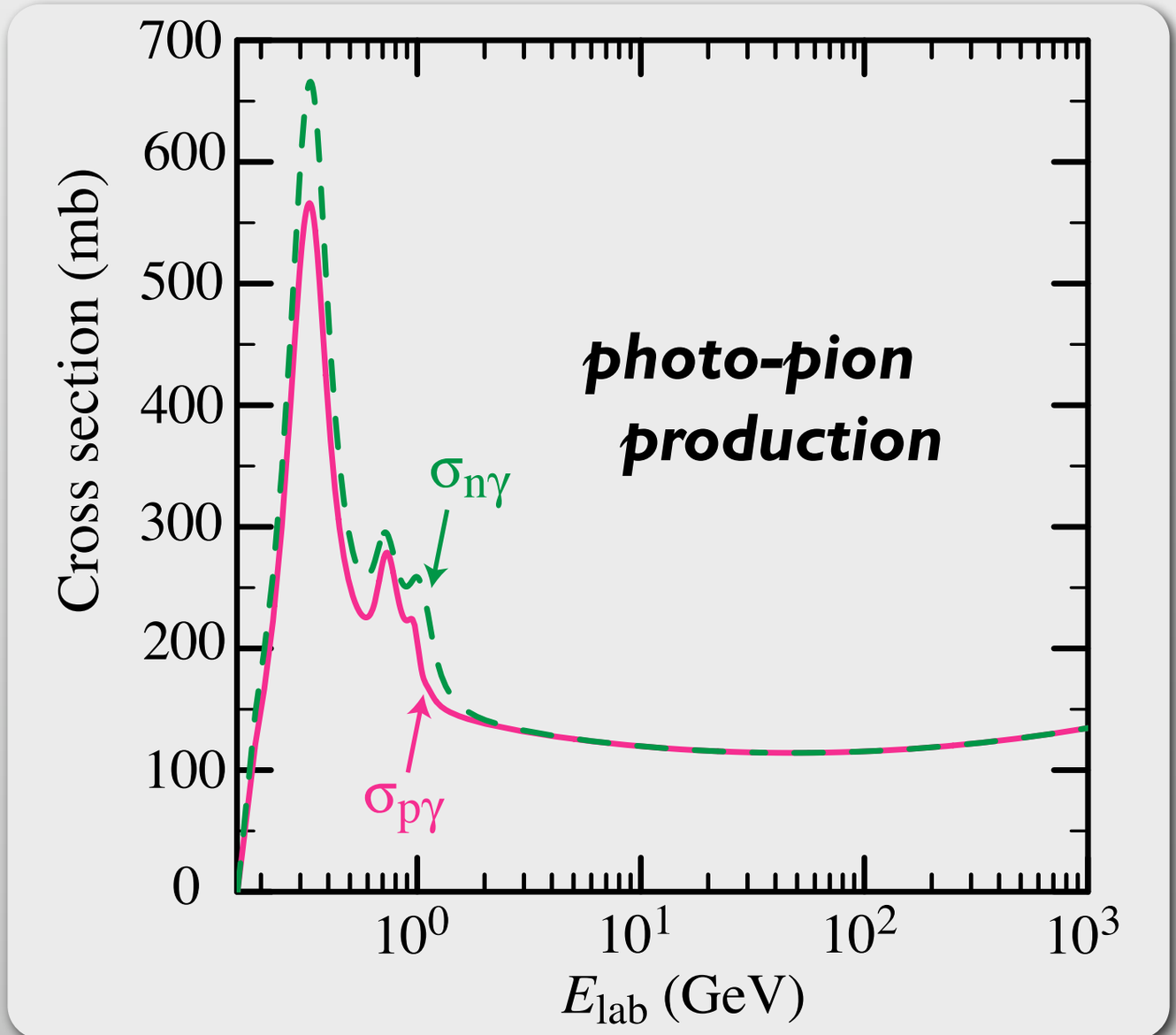
threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

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

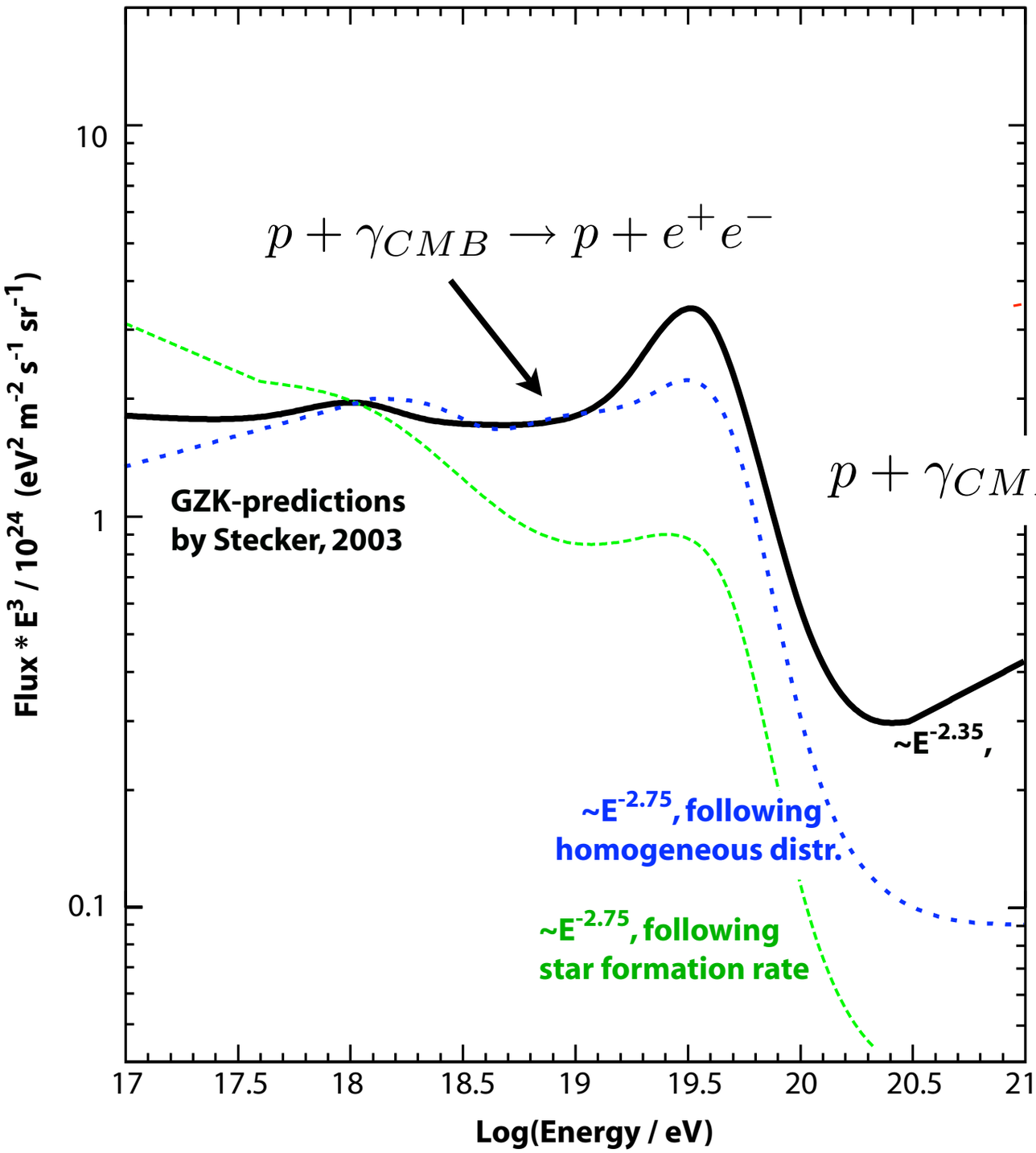
X-section is known,

$n_\gamma = 412/cm^3$ is known

$$\Rightarrow \lambda_{free} = \frac{1}{n_\gamma \cdot \sigma_{p\gamma}} \approx 8 \text{ Mpc}$$



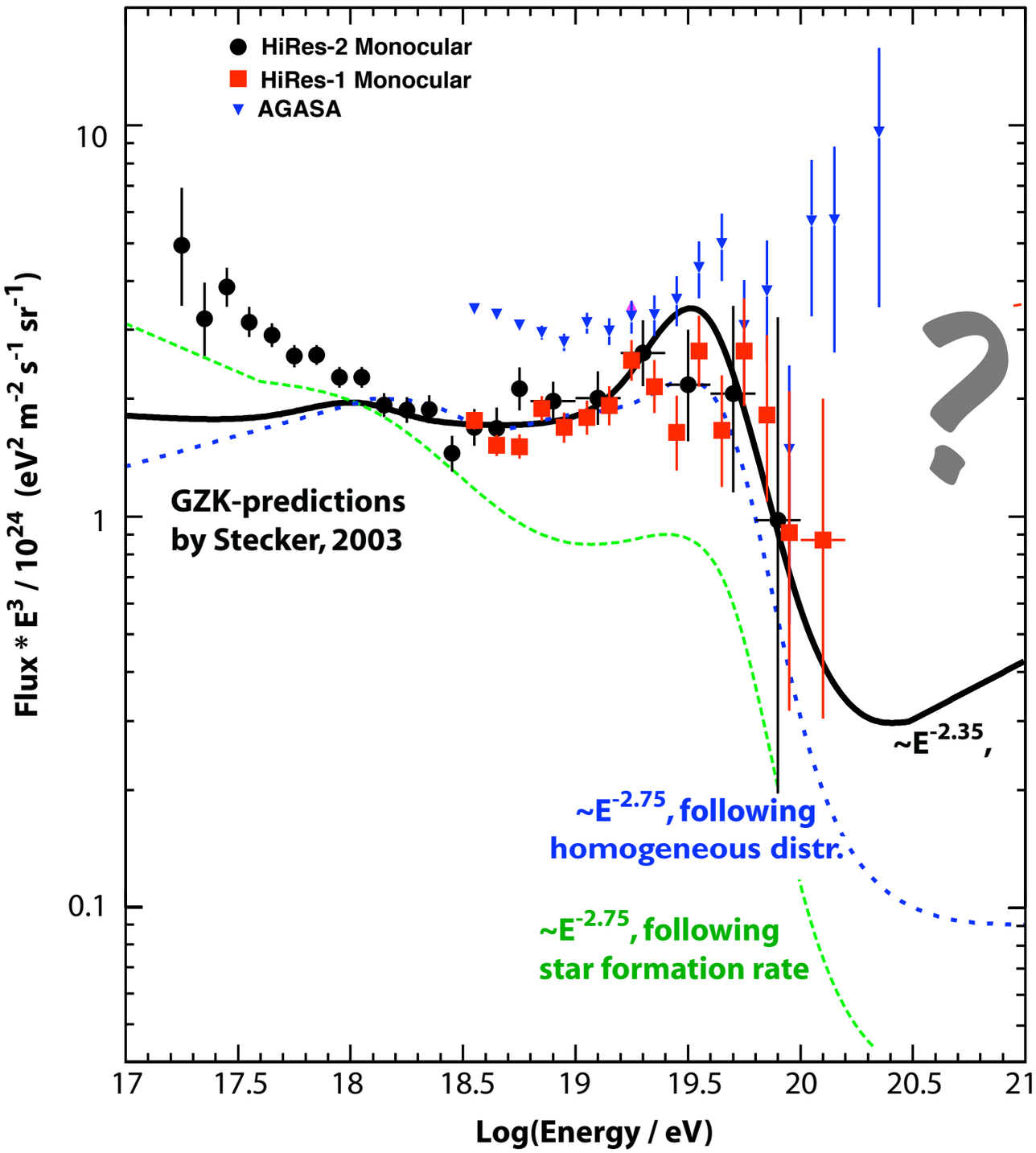
Expected Modulation of CR E-Spectrum



Expected deformation of energy distribution

➠ **Shape carries information about cosmological distribution of sources**

E-spectrum before Auger



Expected E-distribution

+ HiRes-2 Mono (FD: 0° - 30°)

+ HiRes-1 Mono (FD: 0° - 15°)

+ AGASA (SD array)

Science Objectives @ 10^{20} eV

Fundamental Problem

CRs with energies $>10^{20}$eV exist

Standard astrophysical models cannot account for such energies

If GZK is observed:

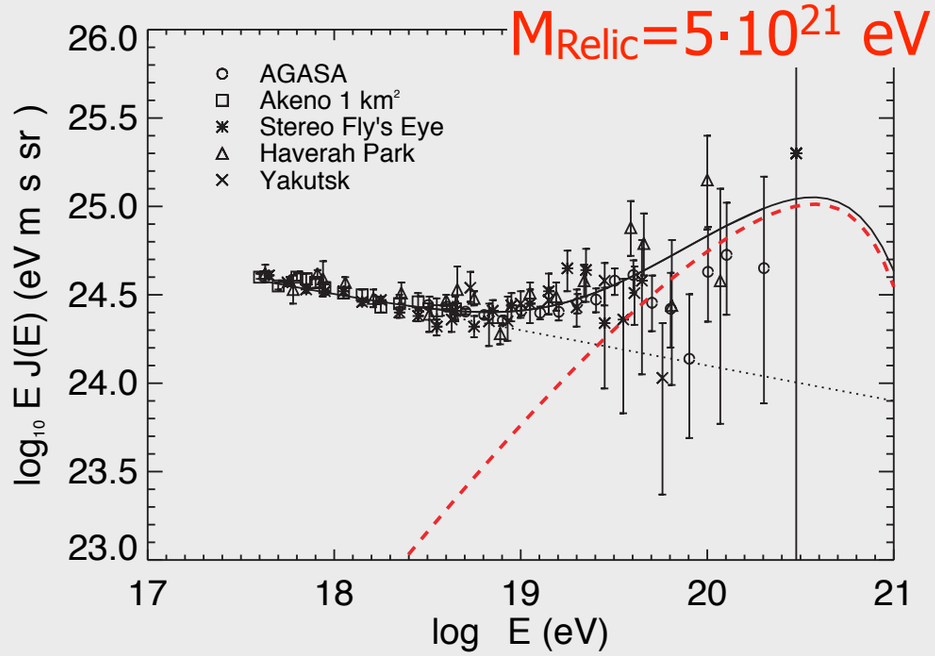
→ distance distribution of sources obtained from GZK shape

→ **location of sources from direction**
(New astronomy window to Universe!)

If GZK is not observed:

→ **new physics to be invoked**

- nearby sources
  e.g. GUT fossils (TD, DM, ...)
- or Propagation effects
  e.g. violation of Lorentz invariance, Z-Bursts, ...



New Particle physics:

gravitational radiation from CRs
(Koch, Drescher, Bleicher)

exotic neutrino physics
(Anchordoqui, Sakar, ...)

High density QCD
(Drescher, Dumitru...)

...

Measuring high energy CRs

Extensive Air Shower (EAS)

primary

leading particle

$\pi^\pm$ π^0 γ e^- e^+ ν_μ $\mu^\pm$ ν_e p

primary

≈ 20 km height

trajectory

≈ 1 m thickness

$v \approx c$

Particle Composition at ground:

- ≈ 80 % photons
- ≈ 18 % electrons
- ≈ 1.7 % muons
- ≈ 0.3 % hadrons

≈ 10^6 secondaries for 10^{15} eV proton

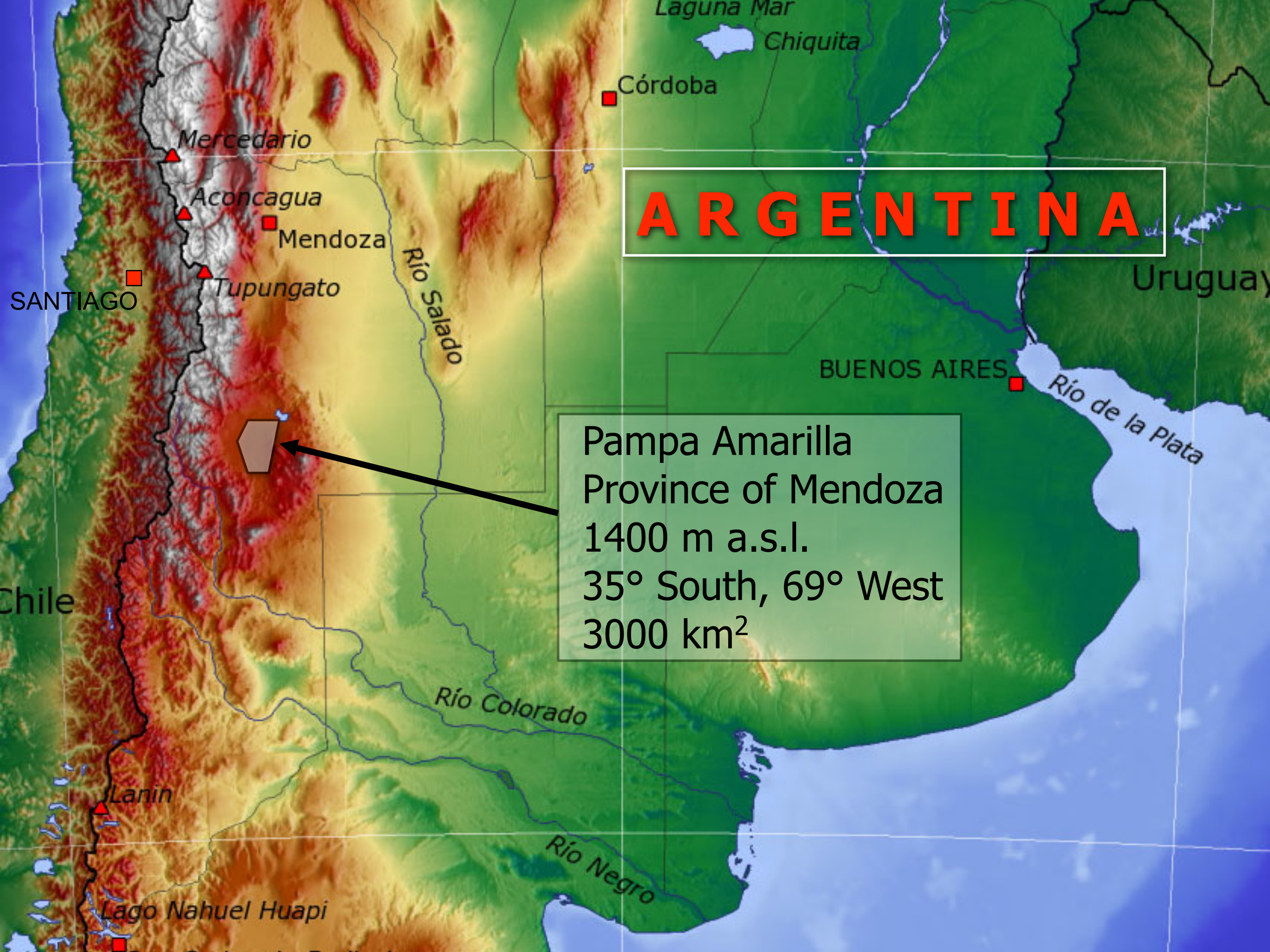
ely detector array

hadron calorimeter

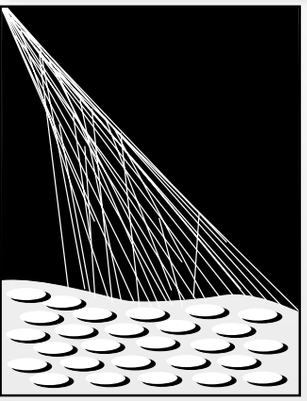
Fluorescence, Cherenkov light

radio signals

ca. 100-200 m


Laguna Mar
Chiquita
Córdoba
Mercedario
Aconcagua
Mendoza
Río Salado
ARGENTINA
Uruguay
SANTIAGO
Tupungato
BUENOS AIRES
Río de la Plata
Pampa Amarilla
Province of Mendoza
1400 m a.s.l.
35° South, 69° West
3000 km2
Chile
Río Colorado
Lanin
Río Negro
Lago Nahuel Huapi

Pierre Auger Collaboration



PIERRE AUGER OBSERVATORY

369 collaboration members in 63 Institutes from:

Argentina

Australia

Bolivia*

Brasil

Czech

France

Germany
- U- & FZ-Karlsruhe
- U-Wuppertal
- U-Siegen
- RWTH-Aachen

Italy

Mexico

Netherlands

Poland

Slovenia

Spain

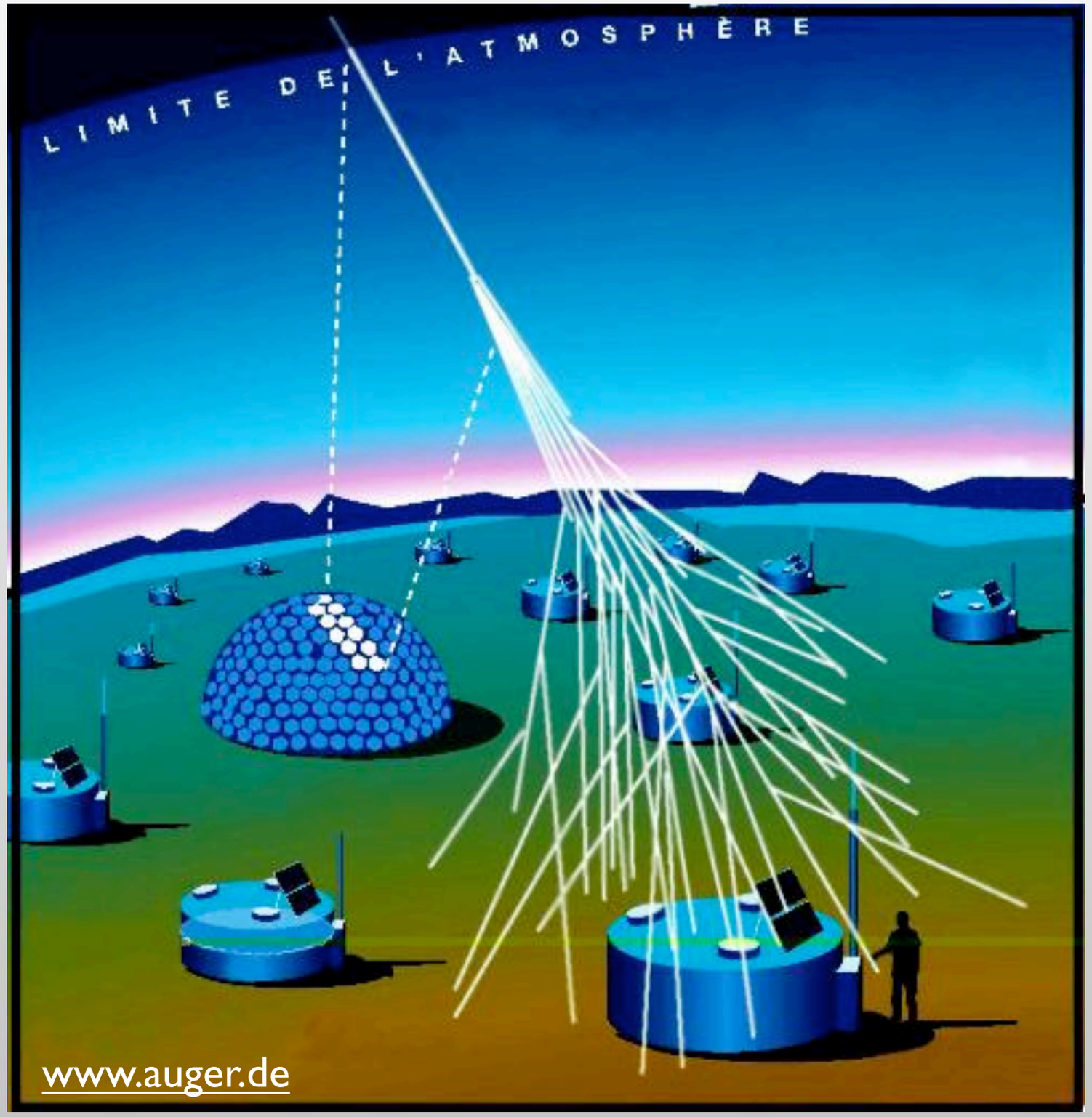
UK

USA

Vietnam*

***Associated**

Pierre Auger Experiment in Argentina



Hybrid-Concept…

1600 Water Ch-Detect.
on 1.5 km triangular grid
⇨ 3000 km^2 area
(optimized to E>10^{19} eV)

simultaneously
measured with
fluorescence light

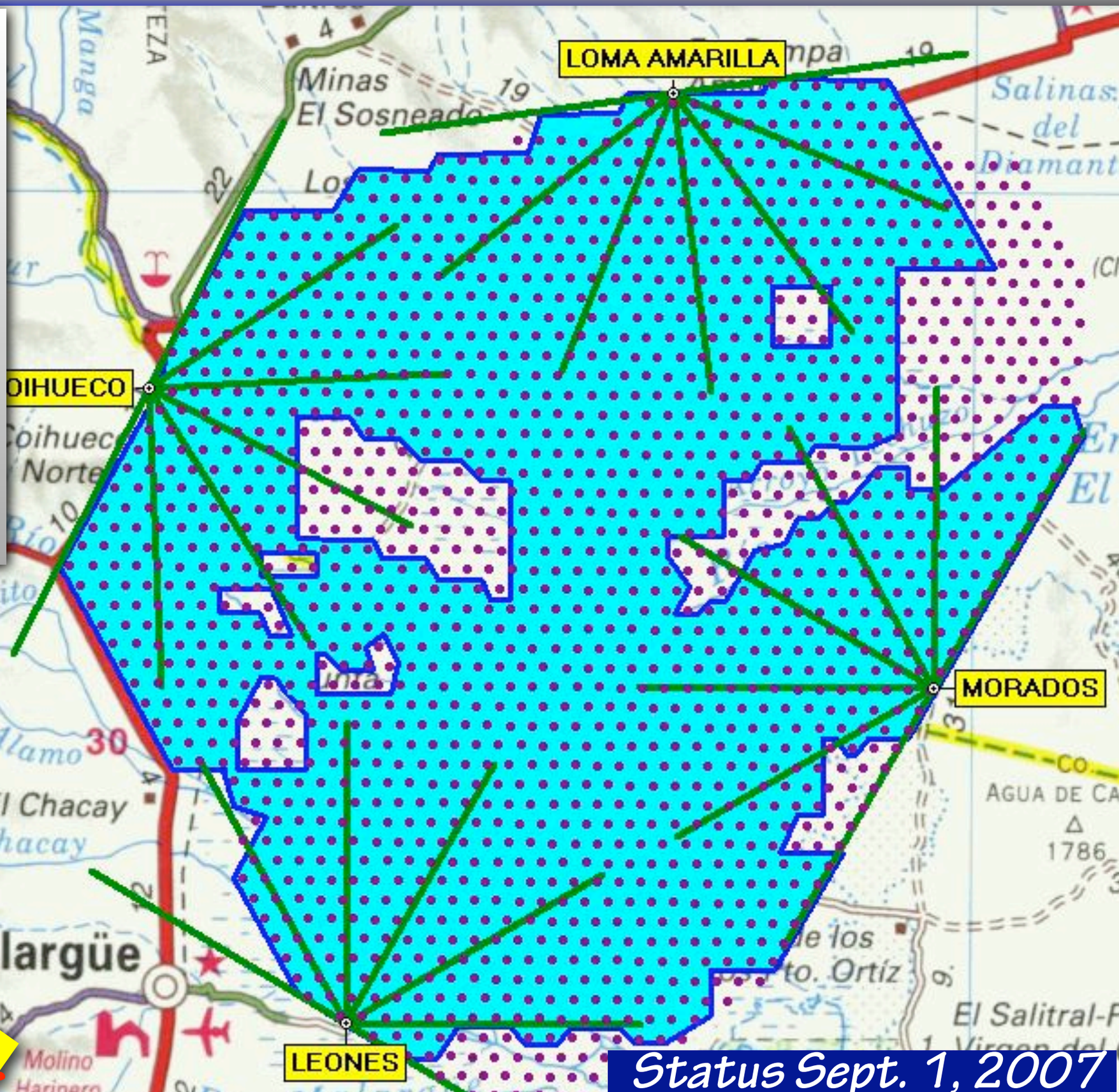
southern exp. nearly finished
northern exp. planned

Pierre Auger Status

Nov. 05, 2007
1501 tanks deployed
1455 with water
1411 with electronics

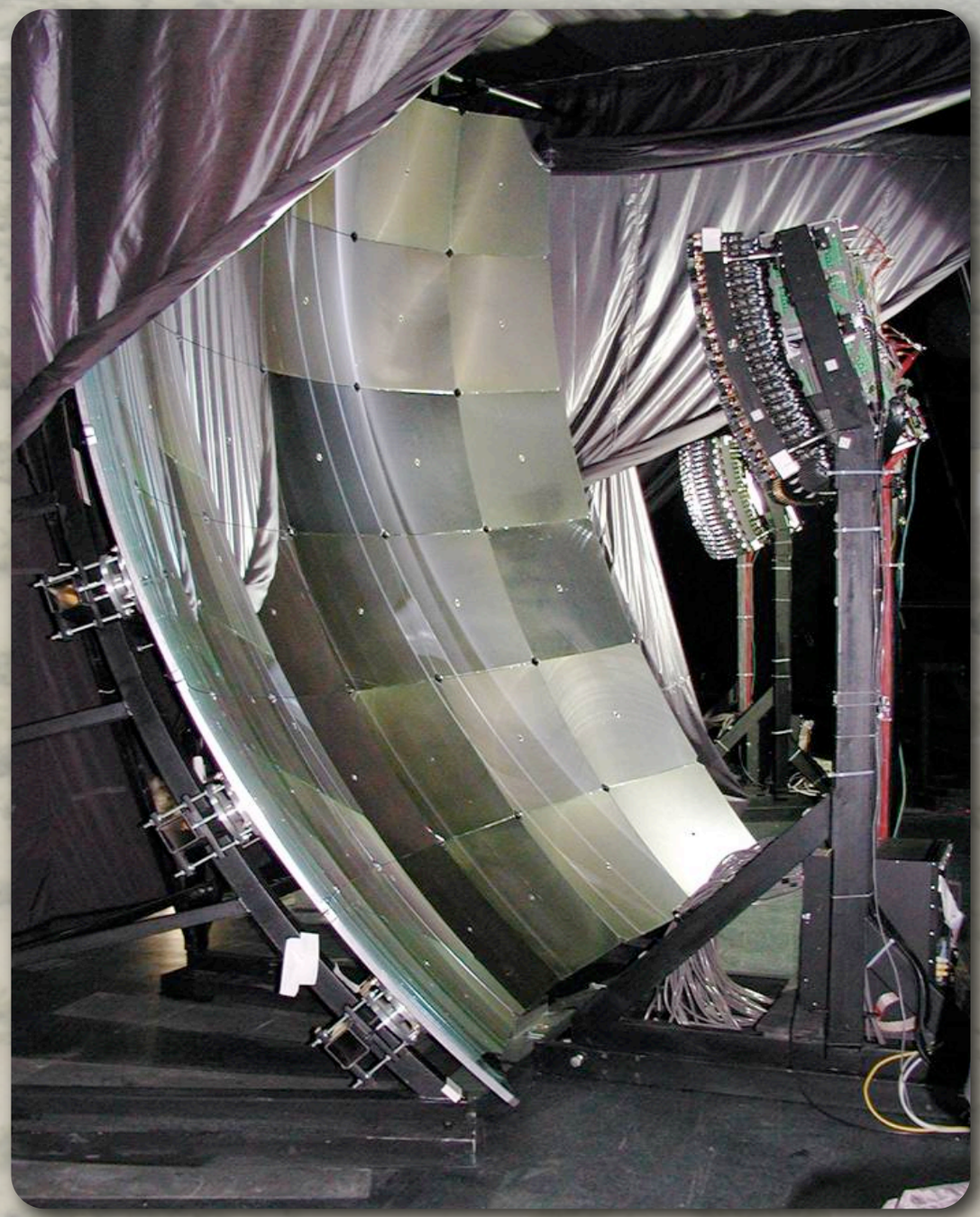
All 4 fluorescence buildings complete, each with 6 telescopes

Final: 1600 tanks



Karl-Heinz

The Auger Hybrid Observatory



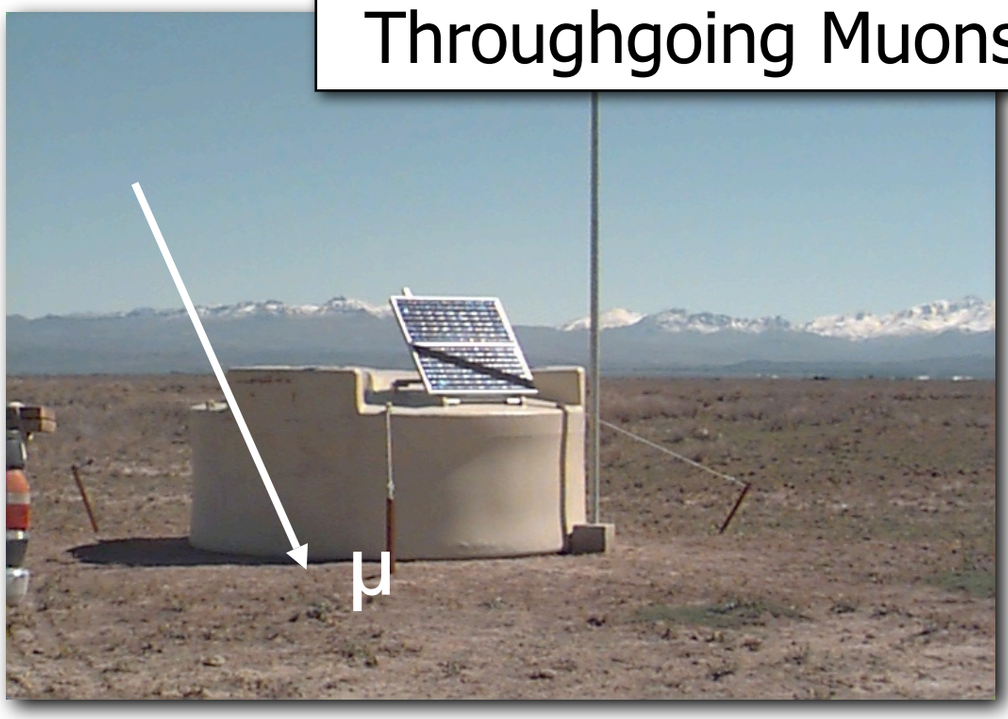
24 fluorescence telescopes...

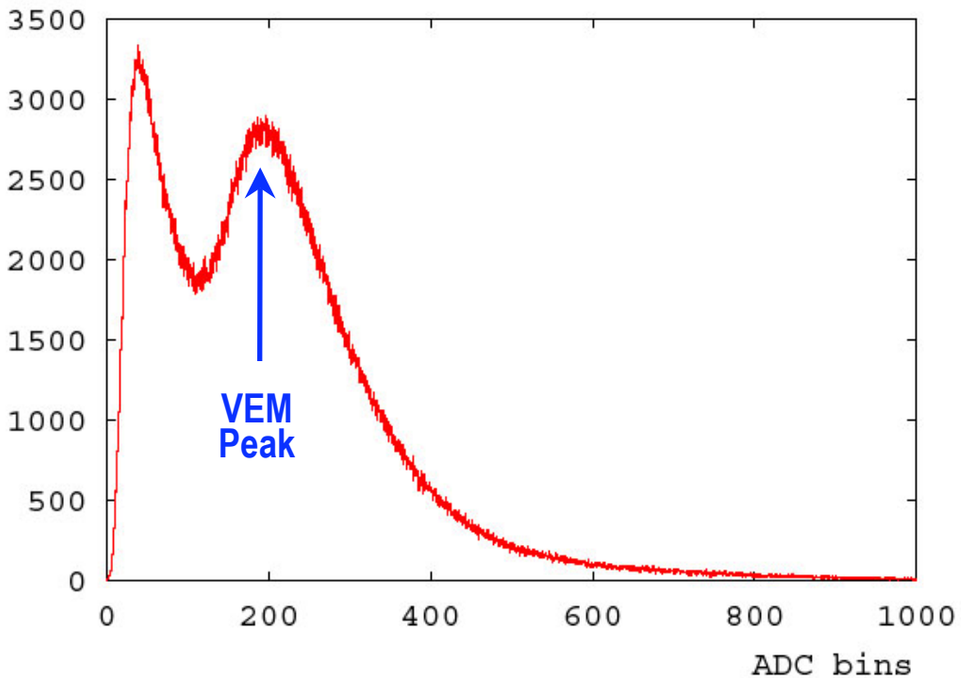
...1600 Water Cherenkov tanks

Detector Calibration

Ground-Array

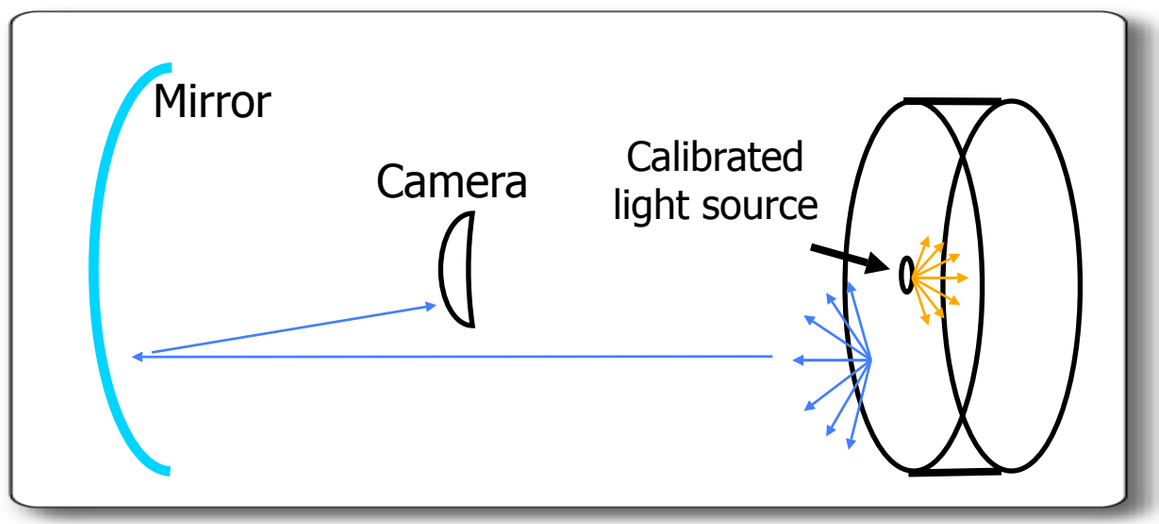
Throughgoing Muons



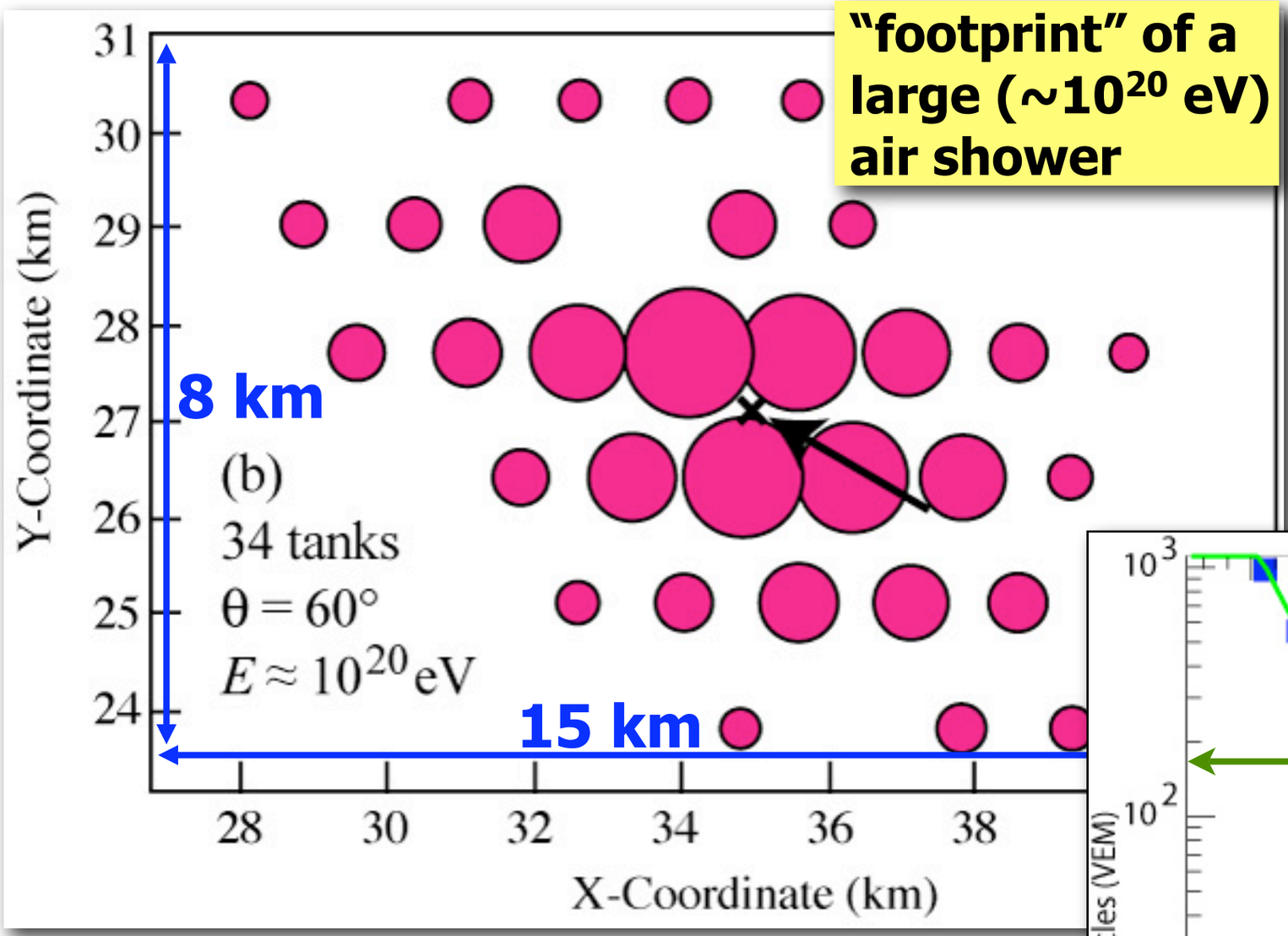


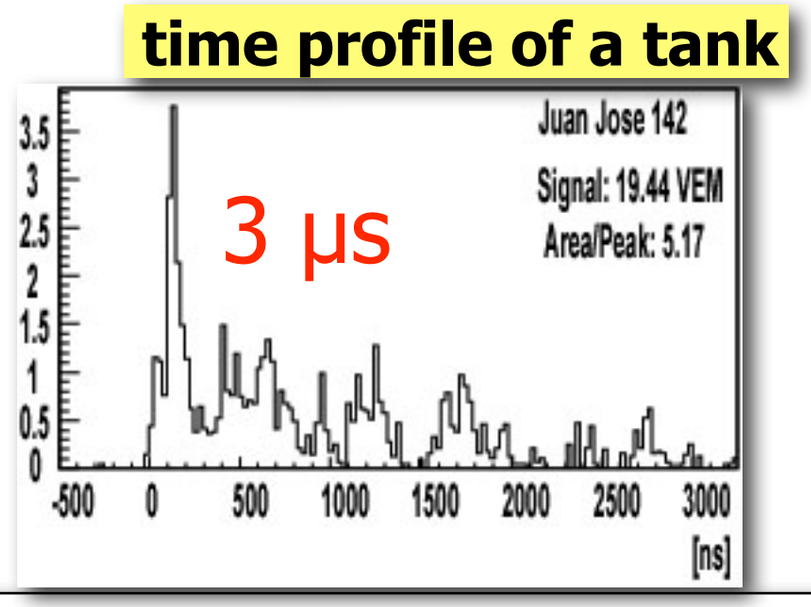
Fluorescence Telescopes

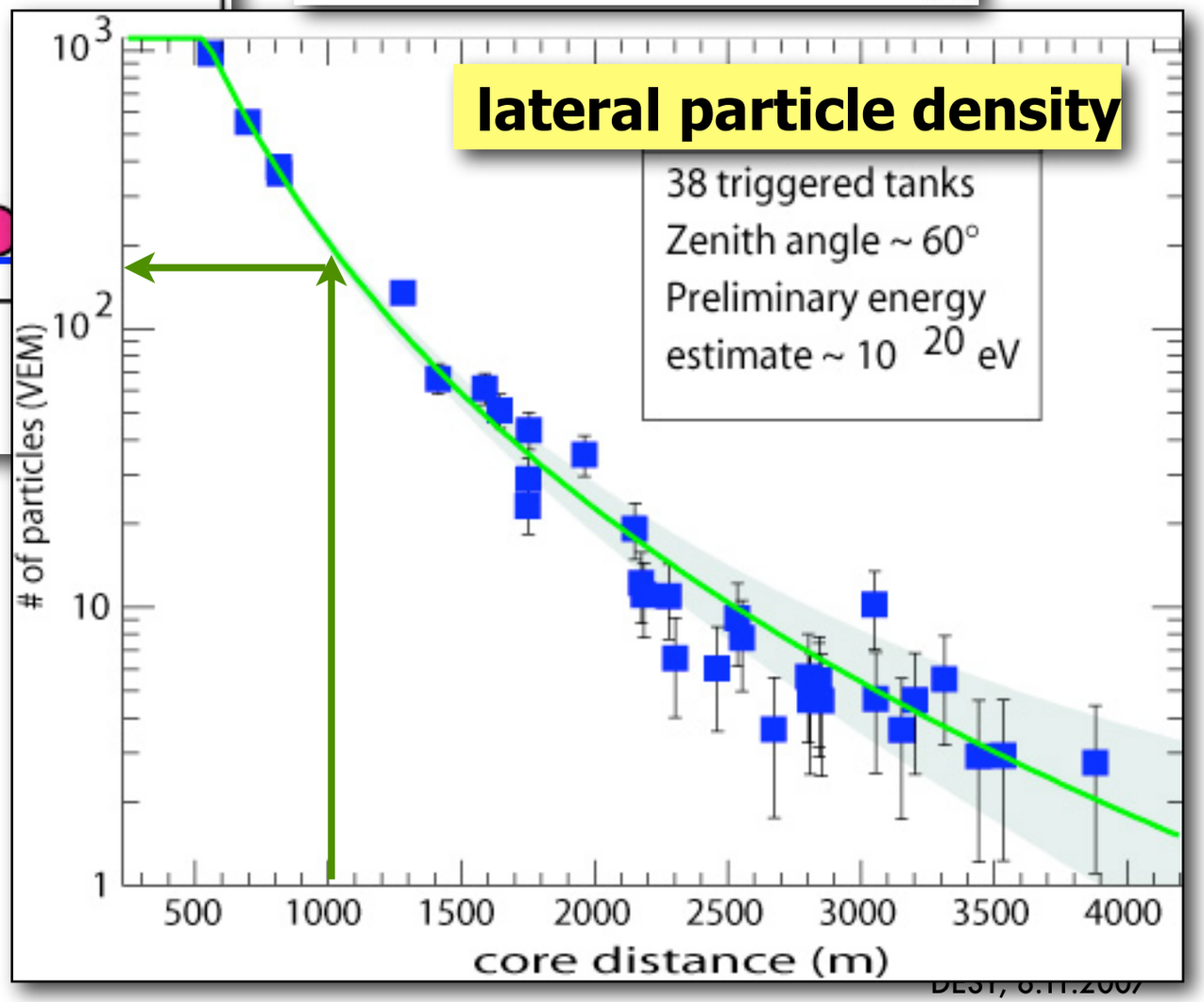
Diffuse Lightsource



SD Event & Reconstruction





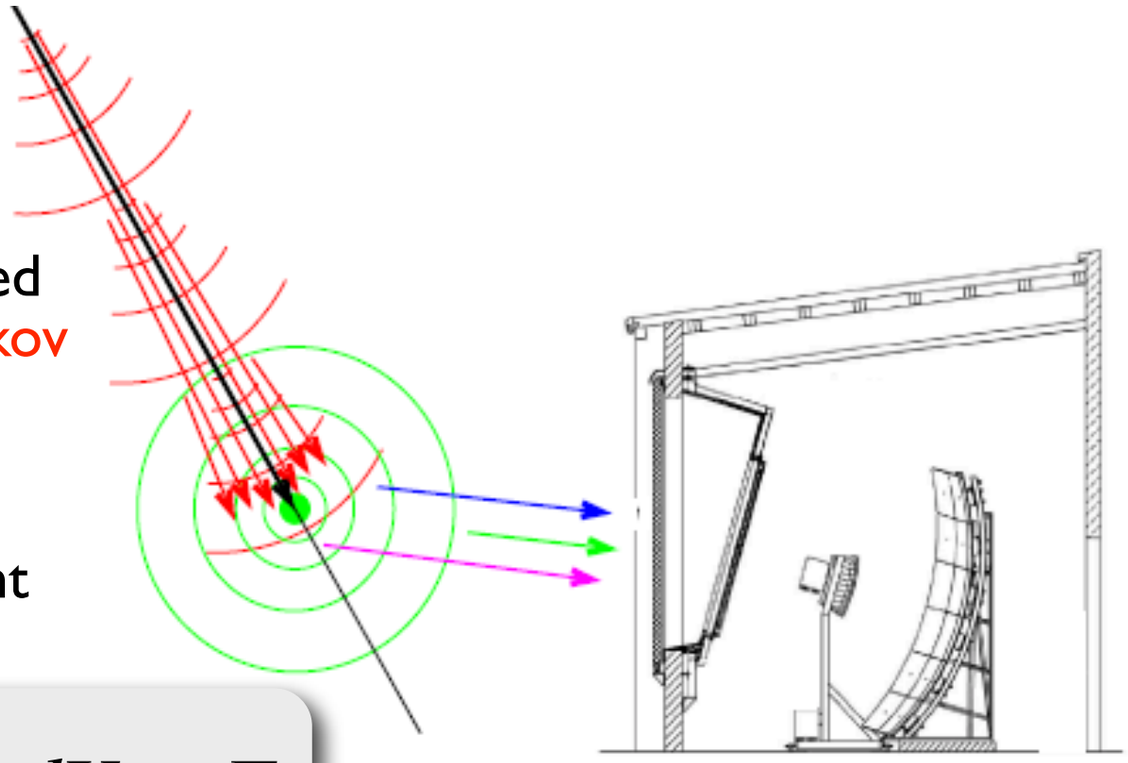


Simulations: particle density at 1000 m (S_{1000}) provides good estimate of primary energy

different models: ~20 syst. errors

FD-Energy Reconstruction

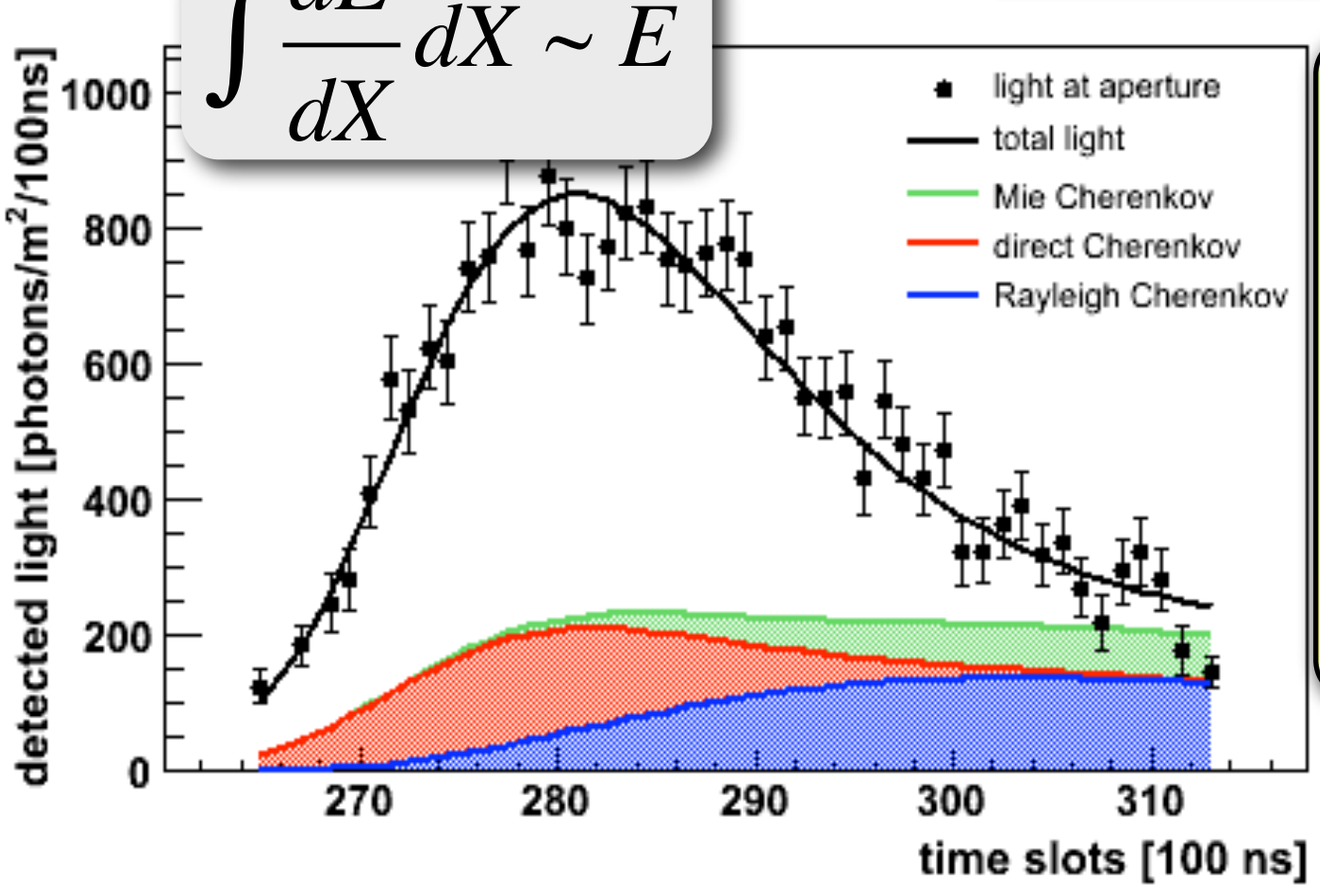
- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleight- and Mie-scattered Cherenkov light



This is a calorimetric measurement, i.e. almost free from model assumptions !

correction for invisible energy ~ (10±3)%

$$\int \frac{dE}{dX} dX \sim E$$



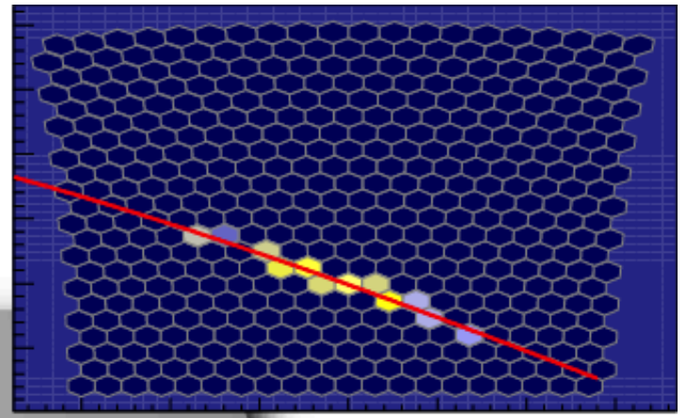
Auger Energy Scale Uncertainties

– Fluorescence Yield	14 %
– p, T, & humidity effects on yield	7 %
– Photometric Calibration	9.5 %
– Atmospheric Conditions	4%
– Reconstruction	10%
– Invisible Energy	4 %
• Total	21 %

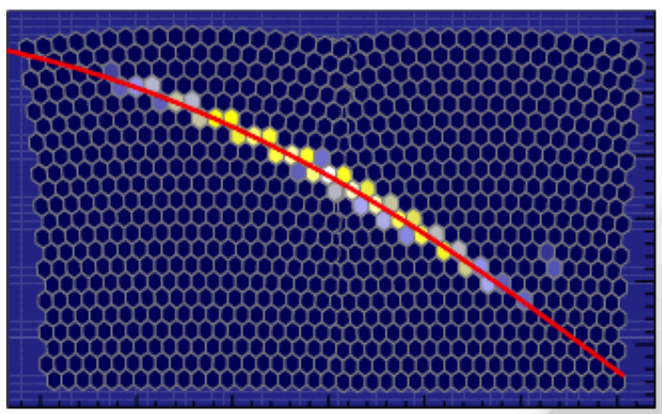
Stereo Hybrid Observations

Advantage of Hybrid:
Shower axis reconstr. improved by footprint (timing) of SD

Los Morados

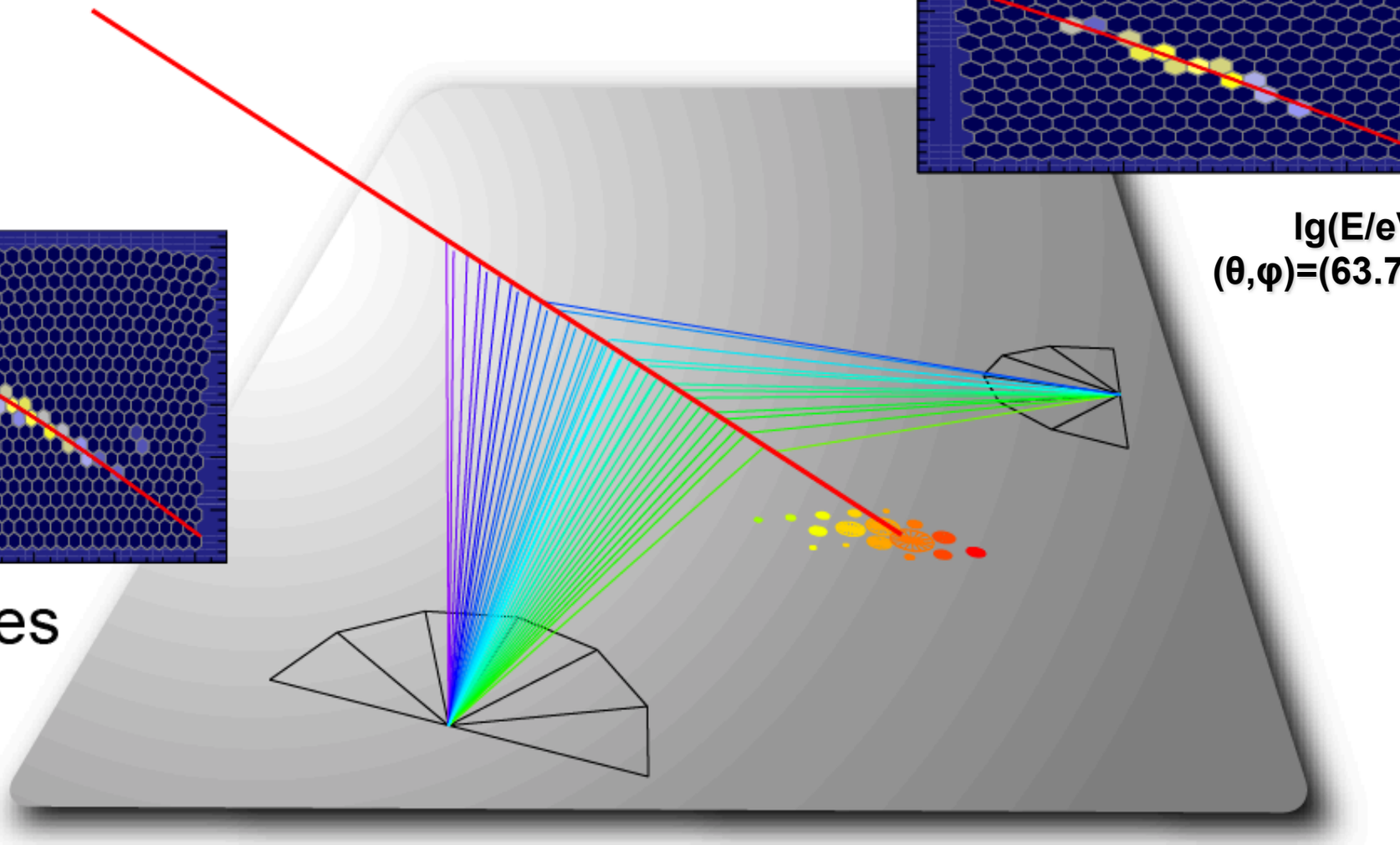


lg(E/eV)~19.2
(θ,φ)=(63.7, 148.4) deg



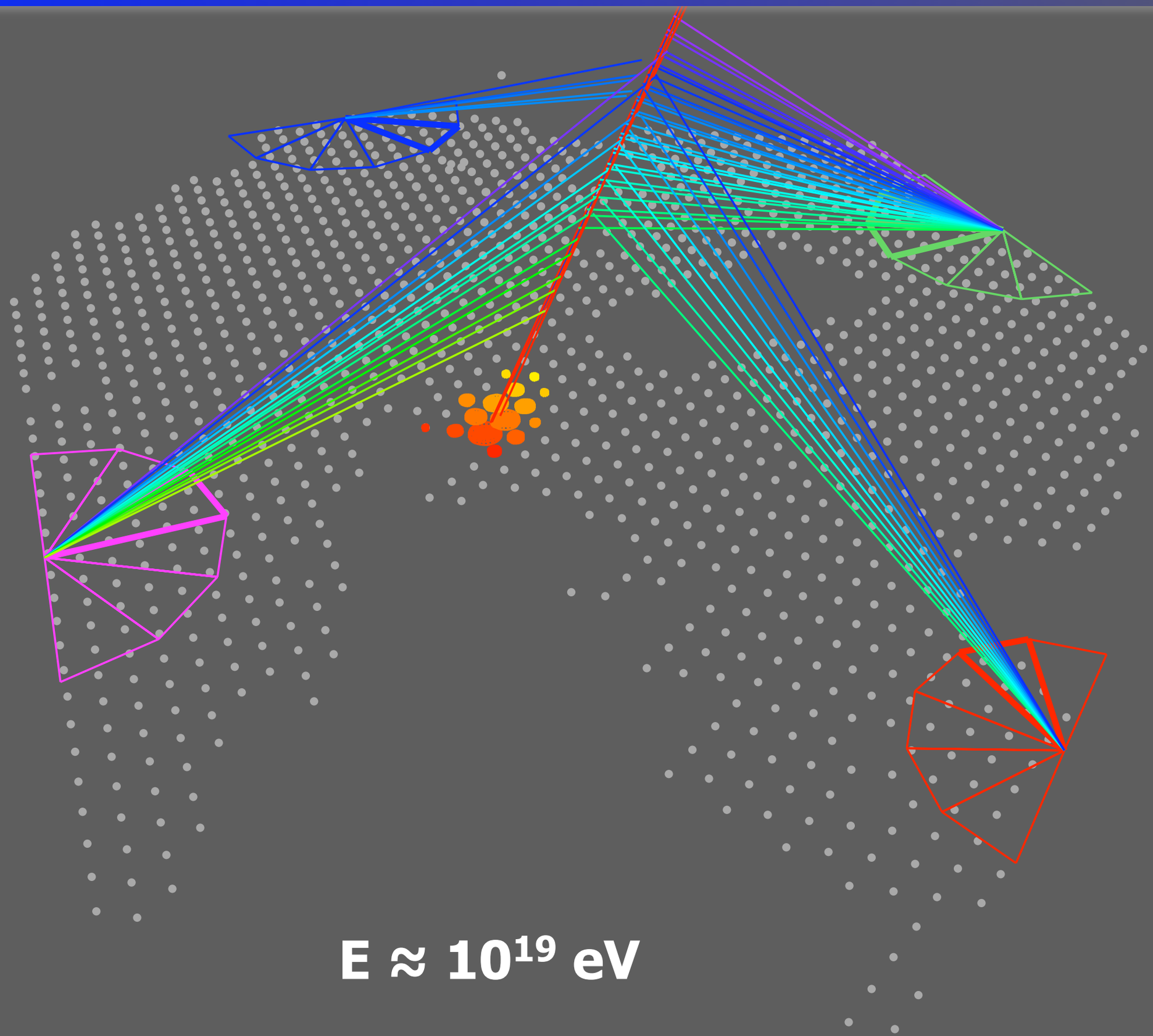
Los Leones

lg(E/eV)~19.3
(θ,φ)=(63.7, 148.3) deg



SD array: lg(E/eV)~19.1
(θ,φ)=(63.3, 148.9) deg

1st Quadruple Event (21.5.2007)



E ≈ 10^{19} eV

The Power of Hybrid

	Hybrid	SD-Only	FD-only
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	Flat model ind.	Flat model ind.	growing model depend.
Energy	model ind.	model dep.	model ind.

The combination is more than the sum of the individuals !

Energy Spectrum

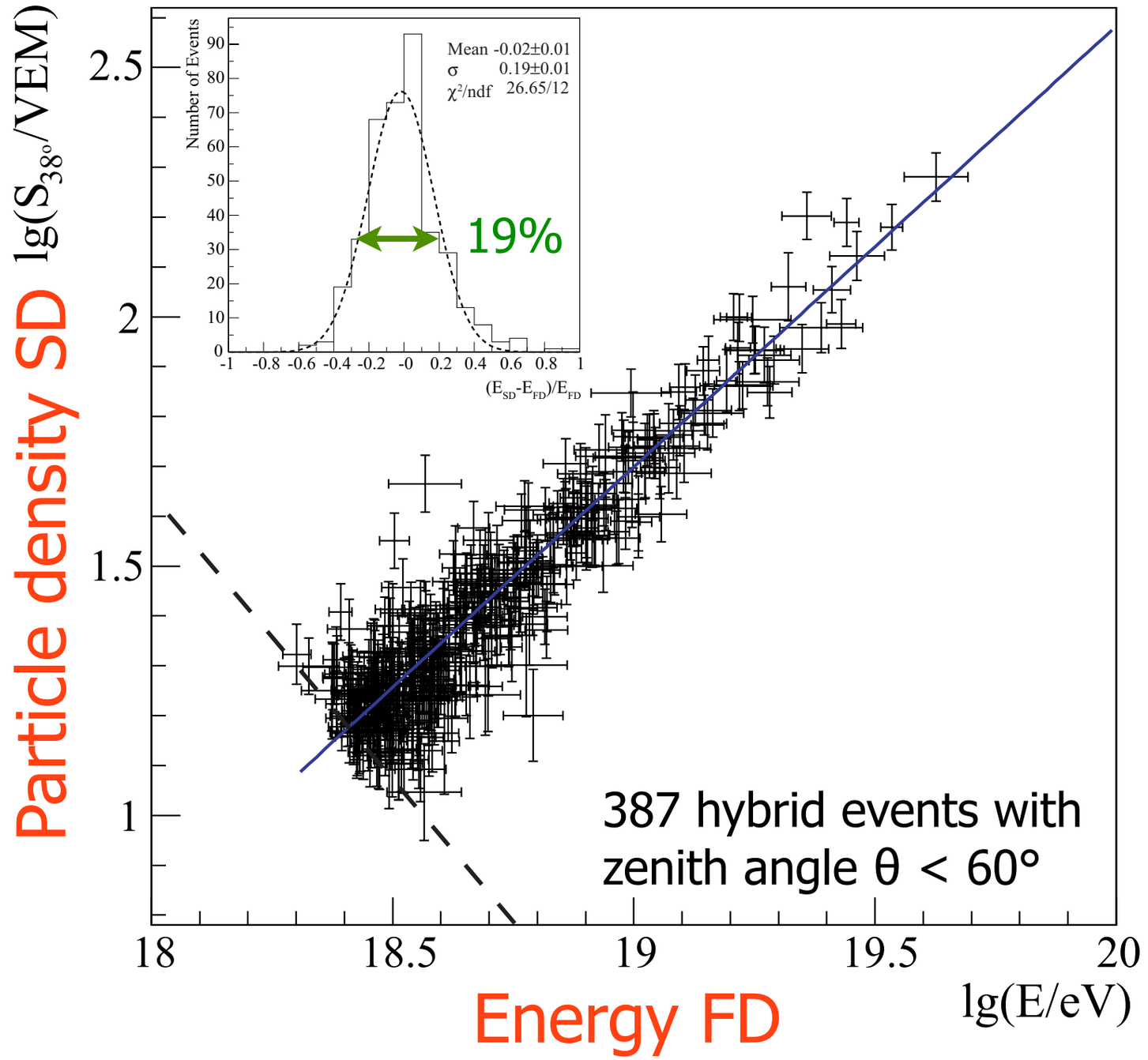
Calibration of SD by FD

Idea:

1. Energy equivalent S(1000) is calibrated by hybrid-FD data
2. Additional correction applied to dependence on zenith angle, based on real data

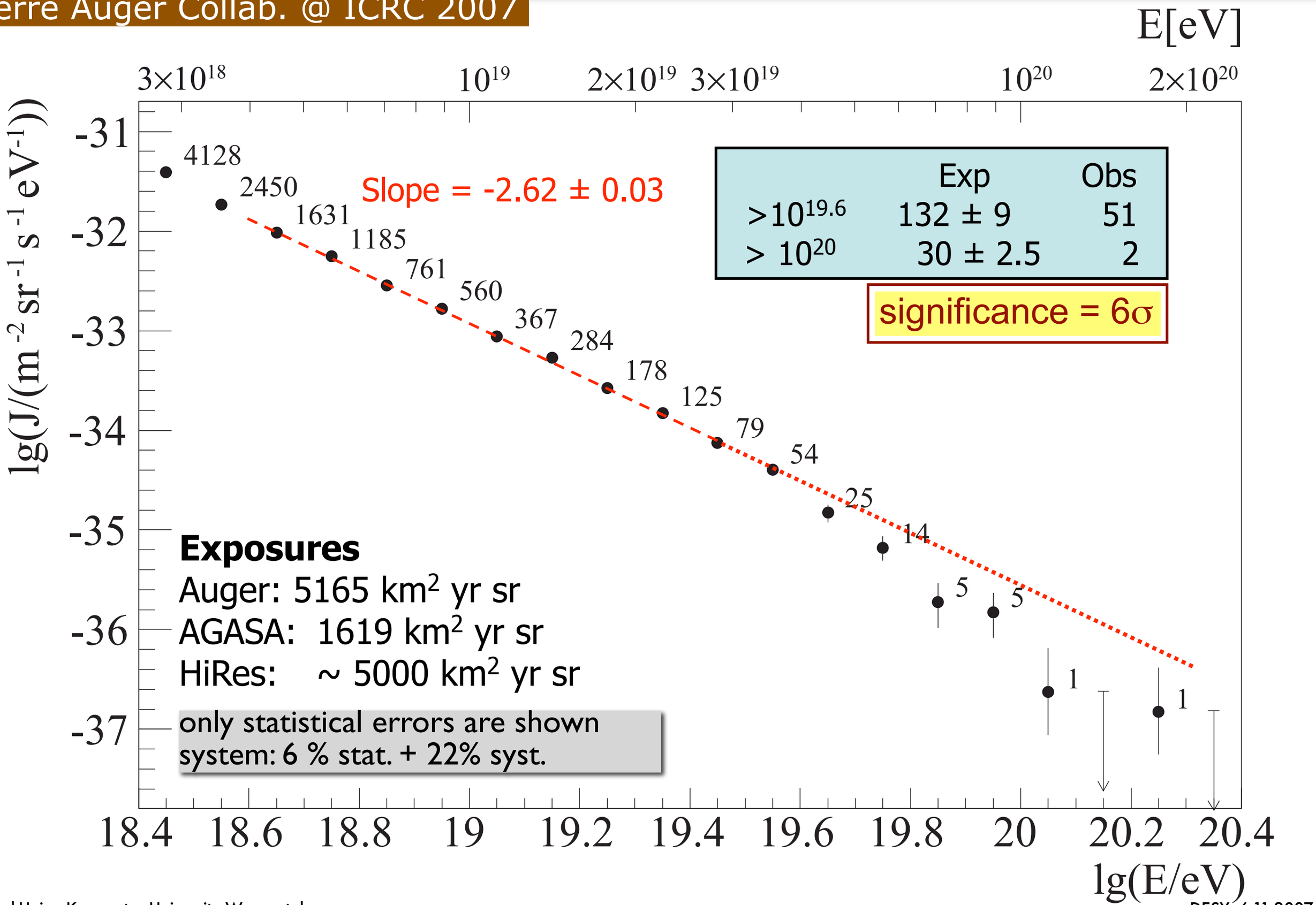
⇒ That calibration is then used for all SD data

Pierre Auger Collab. @ ICRC 2007

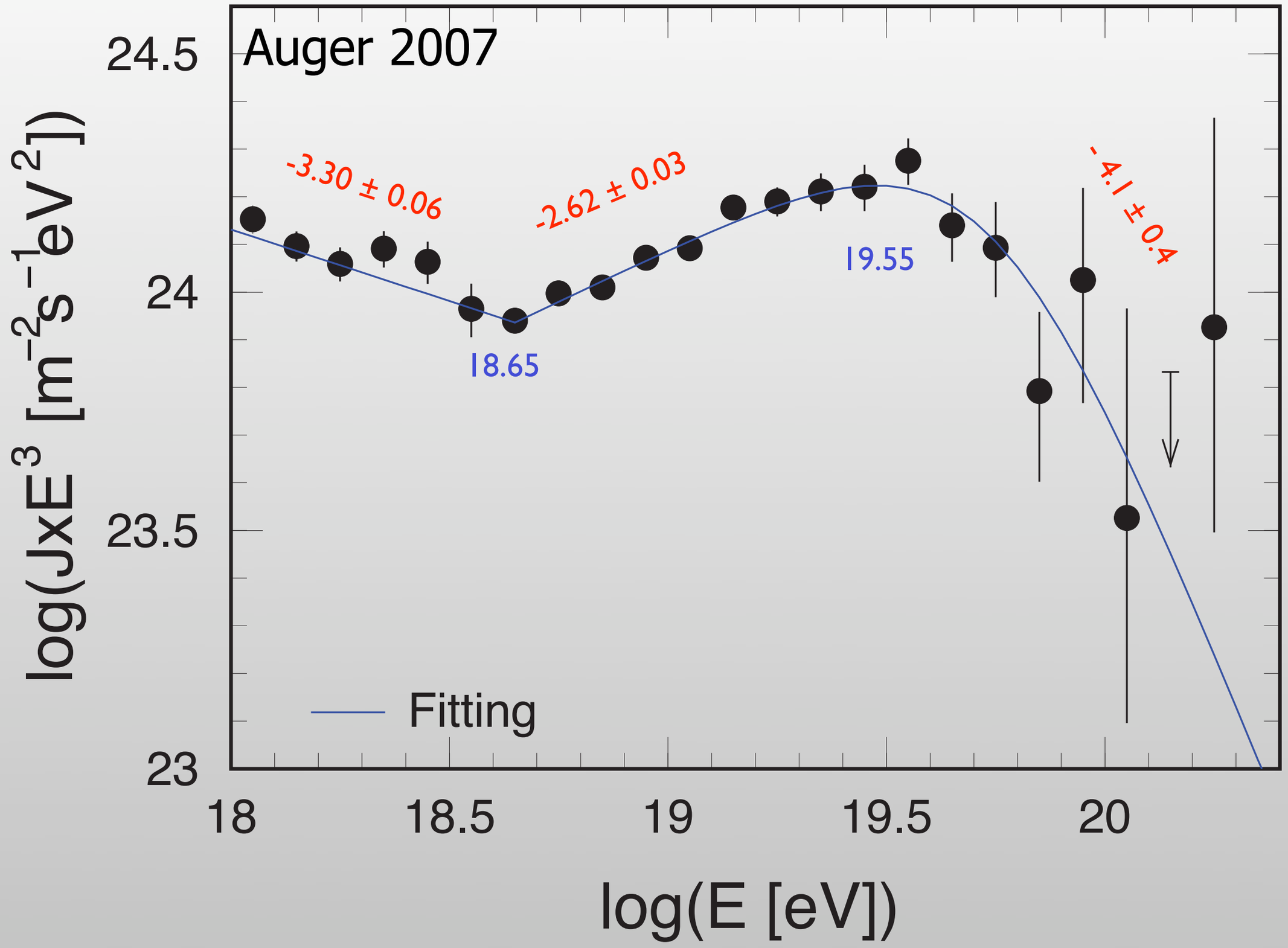


Auger E-Spectrum (Θ< 60°)

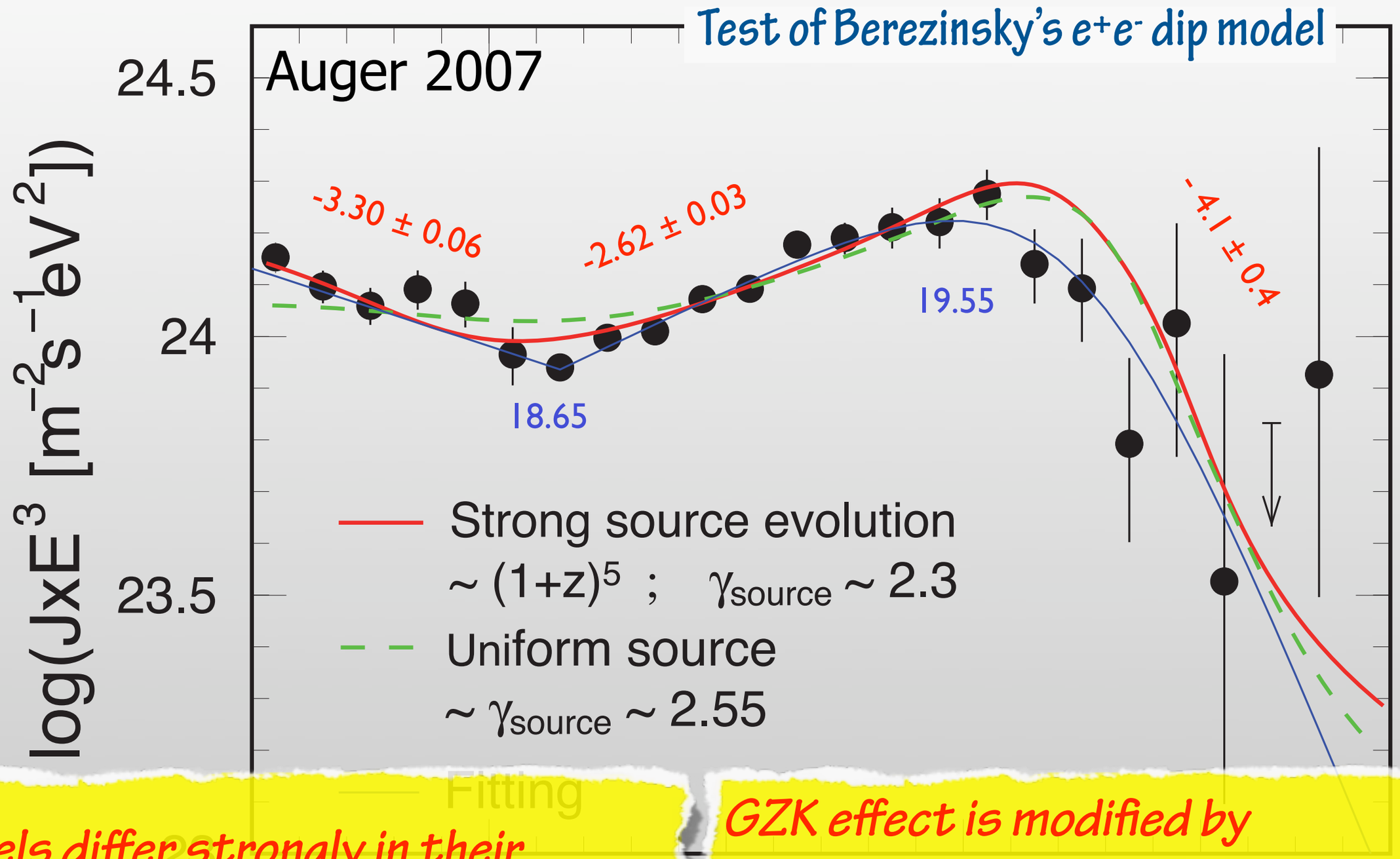
Pierre Auger Collab. @ ICRC 2007



Auger Energy Spectrum



Auger Spectrum & Source Distr.



Models differ strongly in their

- *chemical composition*
- *transition galactic - extragalactic*

GZK effect is modified by

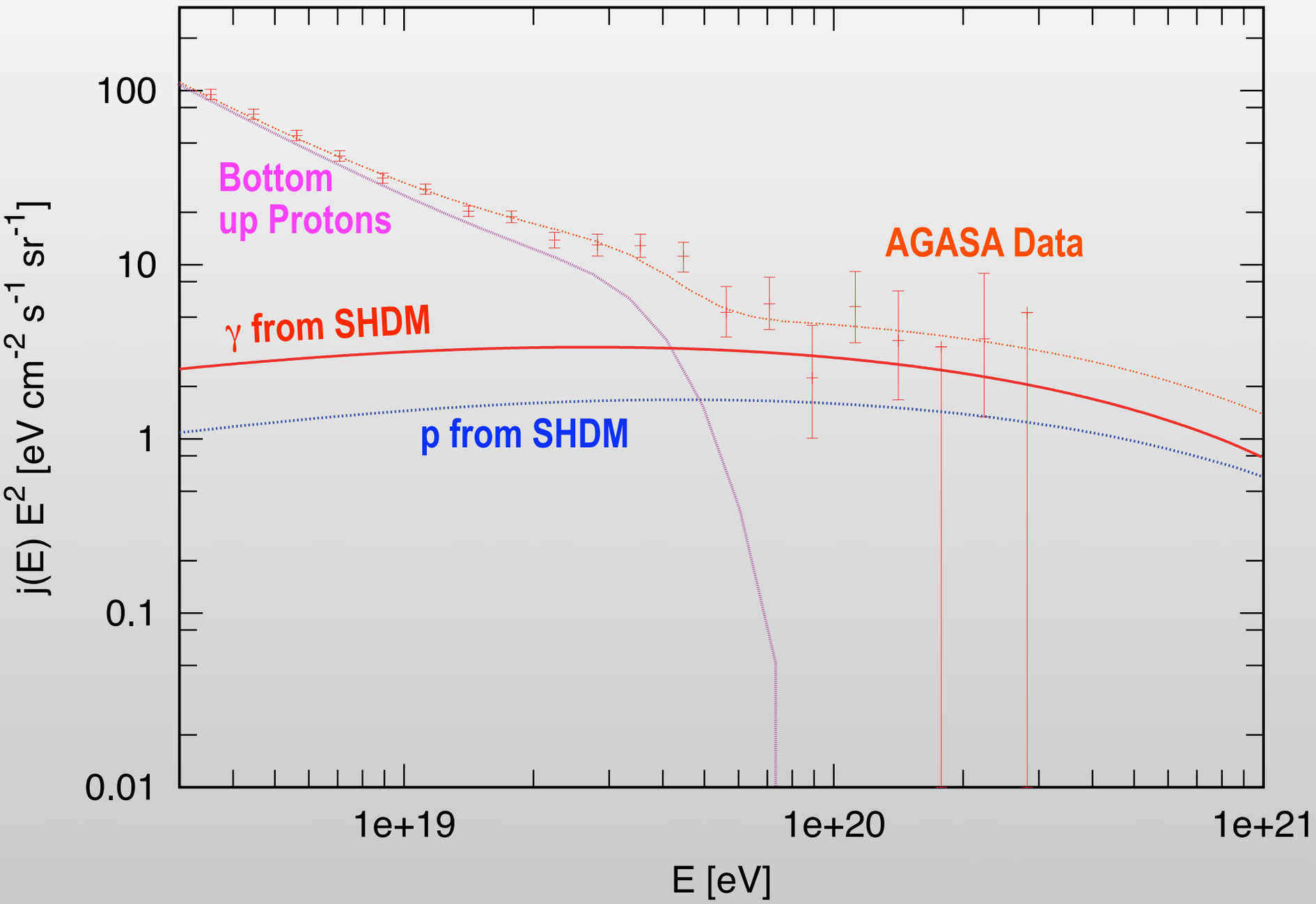
- *E-distribution of source*
- *source local overdensity/deficit*
- *different values of E_{max}*

Composition

Photons

UHE Photons ? *Expected by Top-Down models*

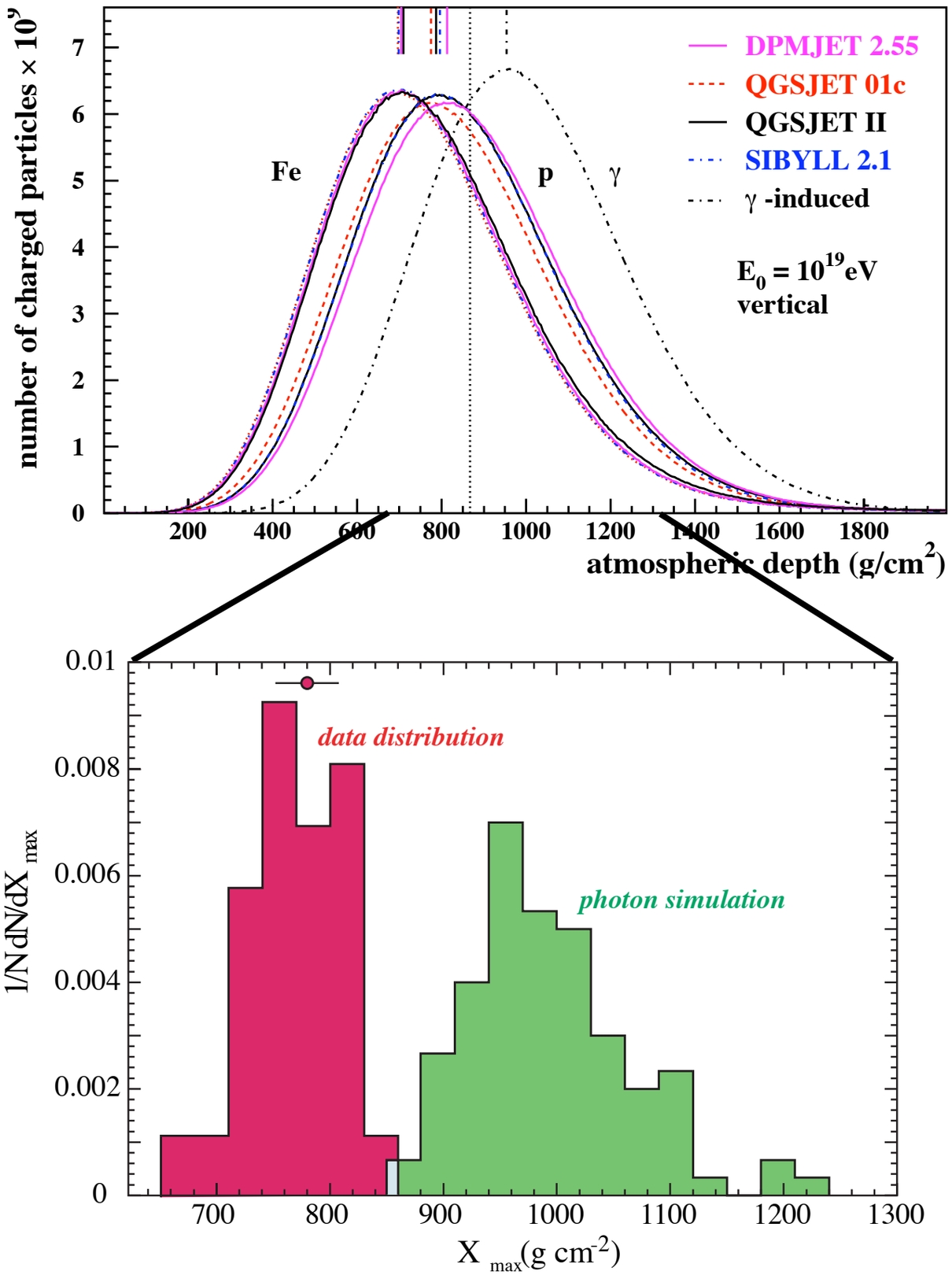
e.g.: **S**uper **H**eavy **D**ark **M**atter fit to AGASA



Gelmini, et al, astro-ph/0506128

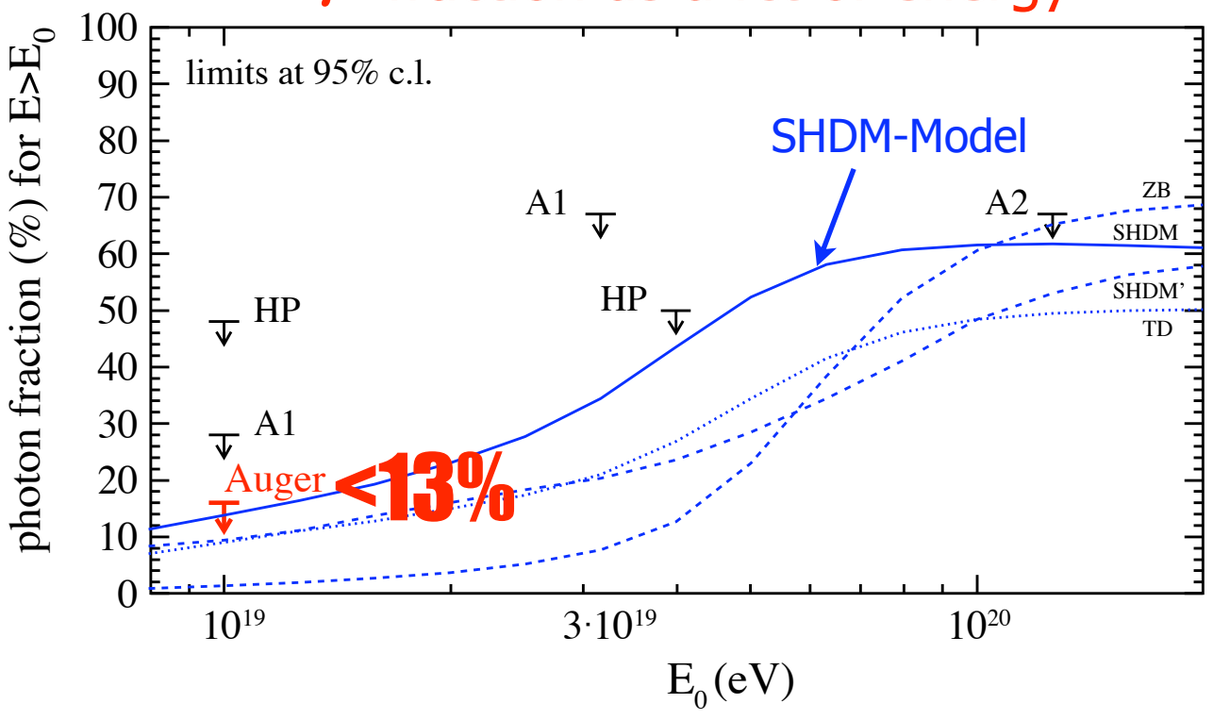
Upper Limit on Primary Photon Fraction

Astropart. Phys. 27 (2007) 155



Position of shower maximum ⇔ primary mass

γ -fraction as a fct of energy



Most stringent limits; tests of

- **Z-Burst model**
- **Superheavy dark matter**
- **Topological defects**
- Limited by statistics only

UHE-Photon Limits from Ground Array

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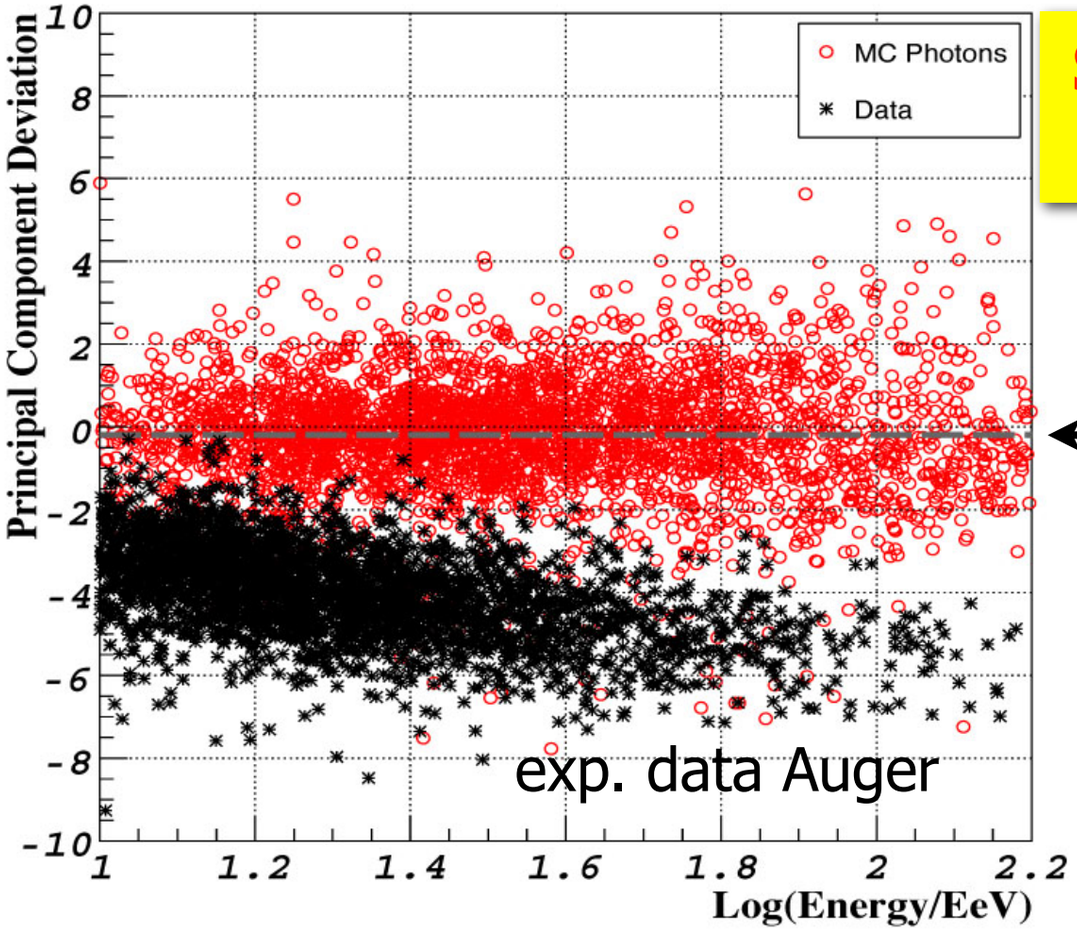
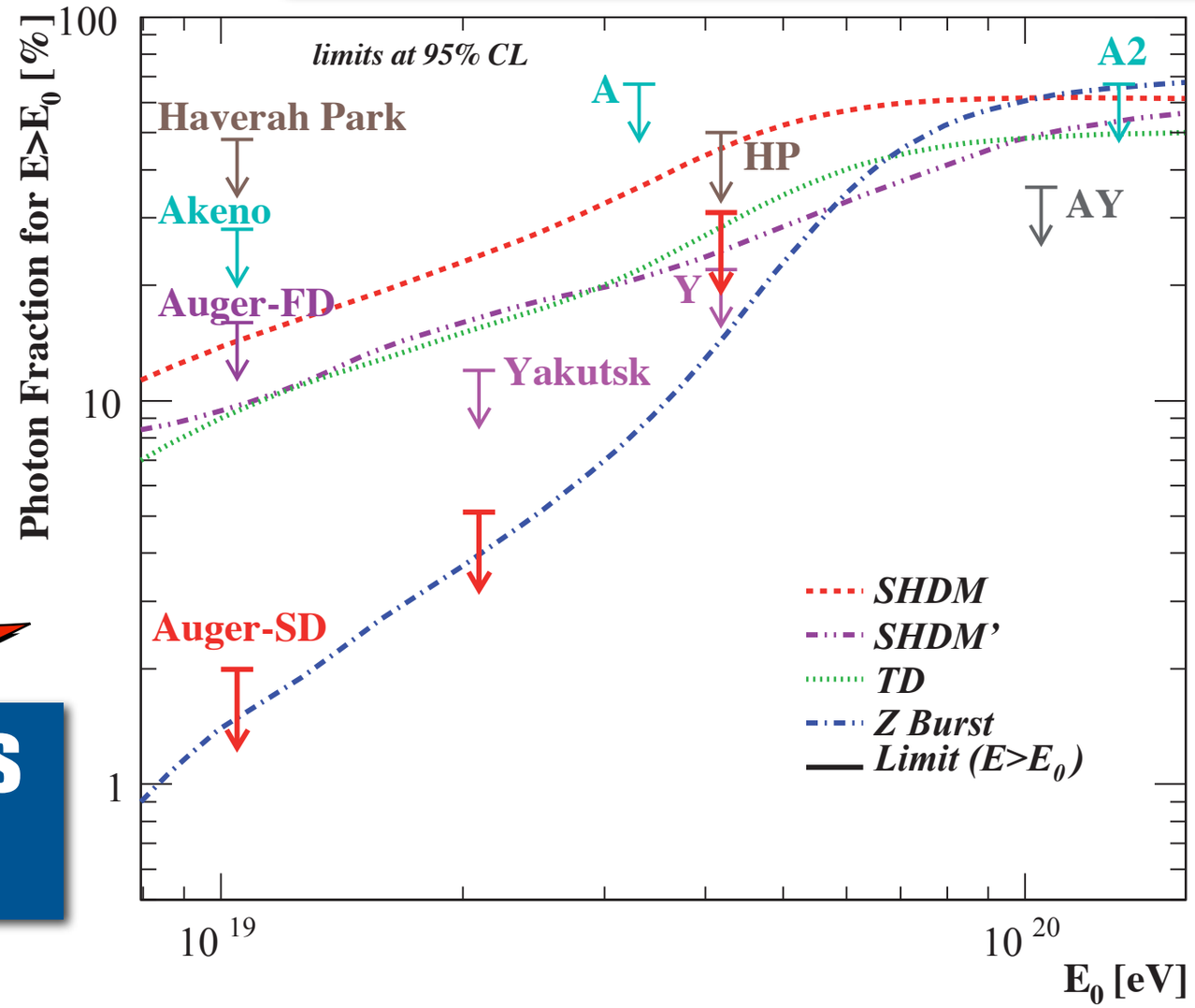


SD-Data: rise-time & shower-front curvature ⇔ μ # ⇔ primary mass

γ -simulation

← (median)

95% CL on photon fraction



SHDM & TD models largely ruled out

GZK-effect: Yes

UHE Photons: No

Top is Down
Bottom is Up

Test of Lorentz Invariance Violation

Galaverni & Sigl
arXiv:0708.1737

LIV → may modify photon dispersion relation

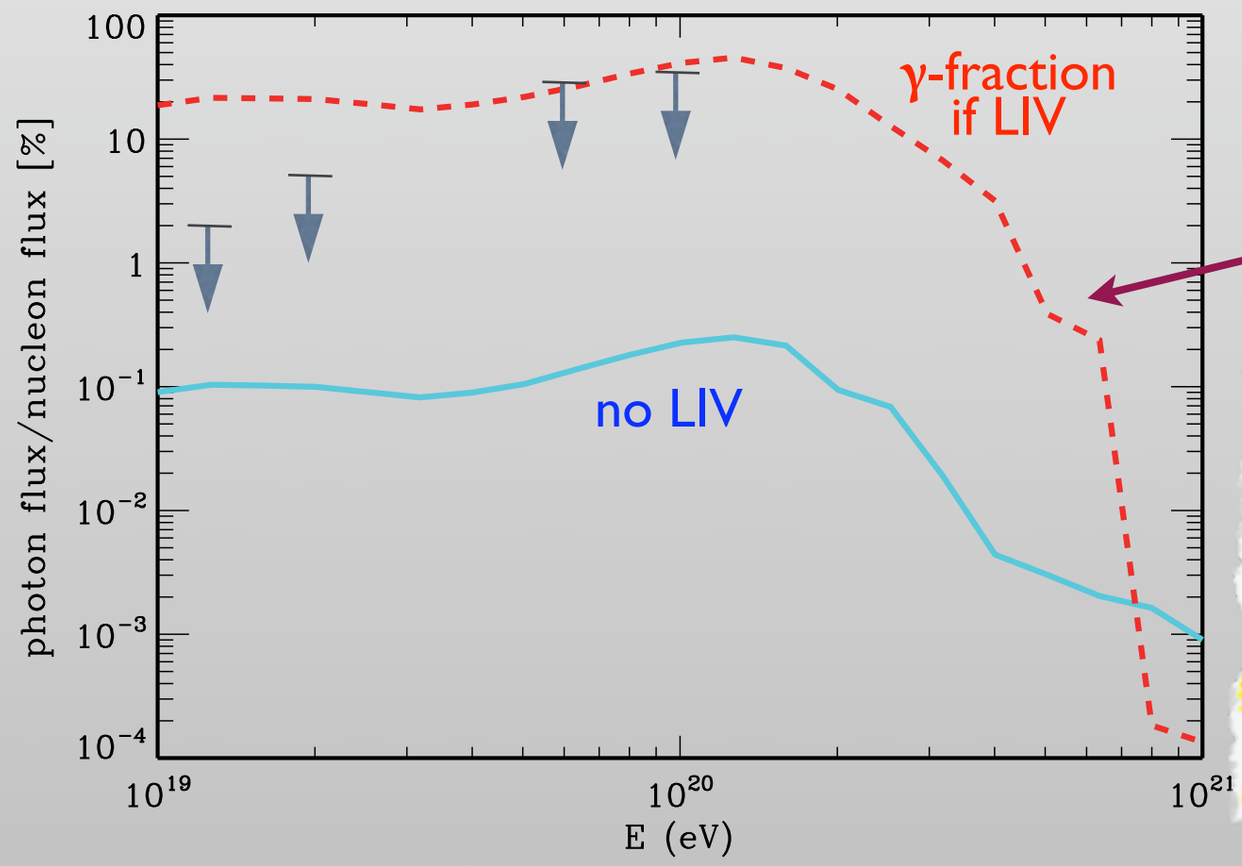
$$\omega^2 = k^2 + m^2 + \xi_n k^2 (k/M_{Pl})^n$$

→ affect the threshold for e^+e^- pair production

→ $p + \gamma_{CMB} \rightarrow \Delta \rightarrow n + \pi^0$

↳ $\gamma\gamma \not\rightarrow e^+e^-$

cascading of UHE photons suppressed



expect significant photon fraction above ~ 10^{19} eV

$$\xi_1 \leq 2.4 \times 10^{-15}$$
$$\xi_2 \geq -2.4 \times 10^{-7}$$

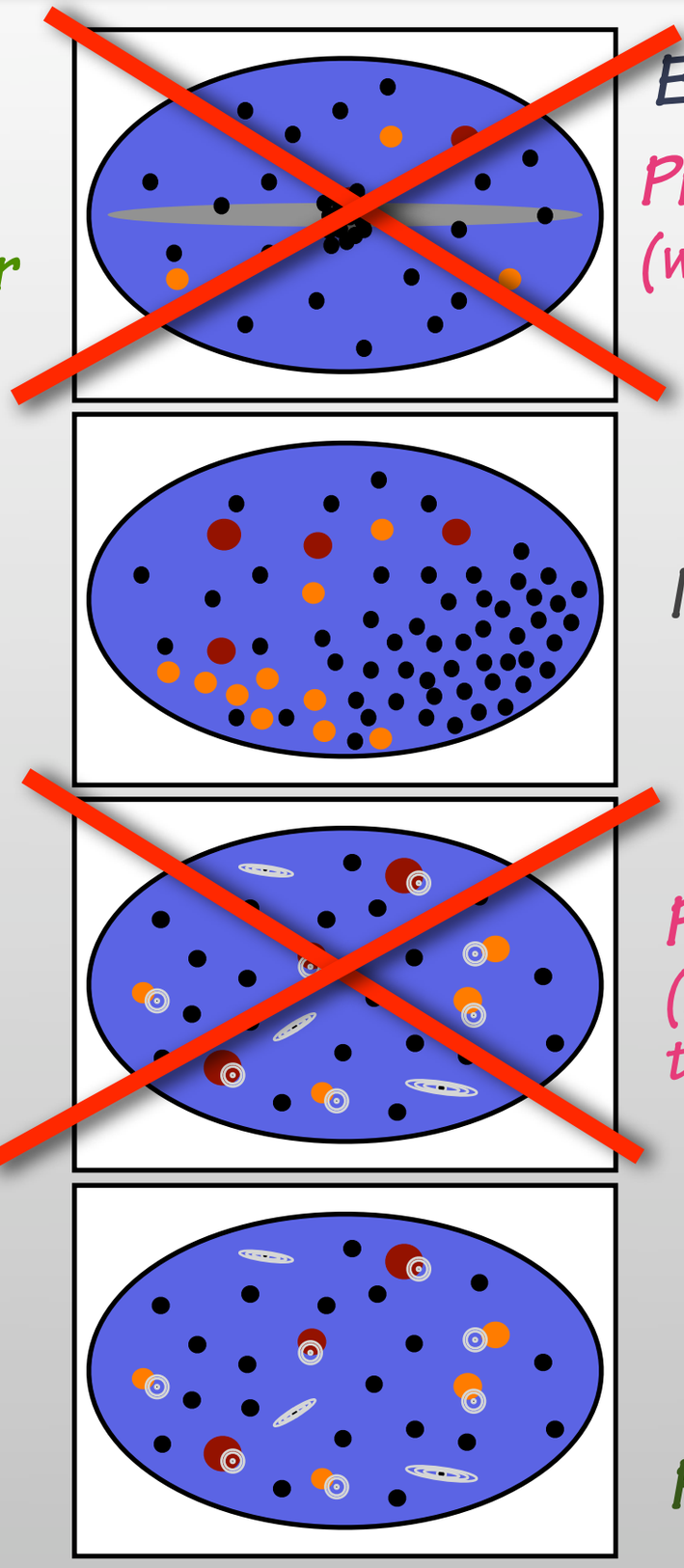
7 orders of magnitudes better than previous limits!

Arrival Directions

Anisotropy Searches

1 Galactic Center

seen by AGASA & Sugar



$E_1 < E_2 < E_3$

Pierre Auger Obs.
(would see 20-30 σ)

2 Large Scale Anisotropy

No significance yet

3 Correlation to BL Lacs

seen by HiRes

Pierre Auger Obs.
(no confirmed with 6 times better exposure)

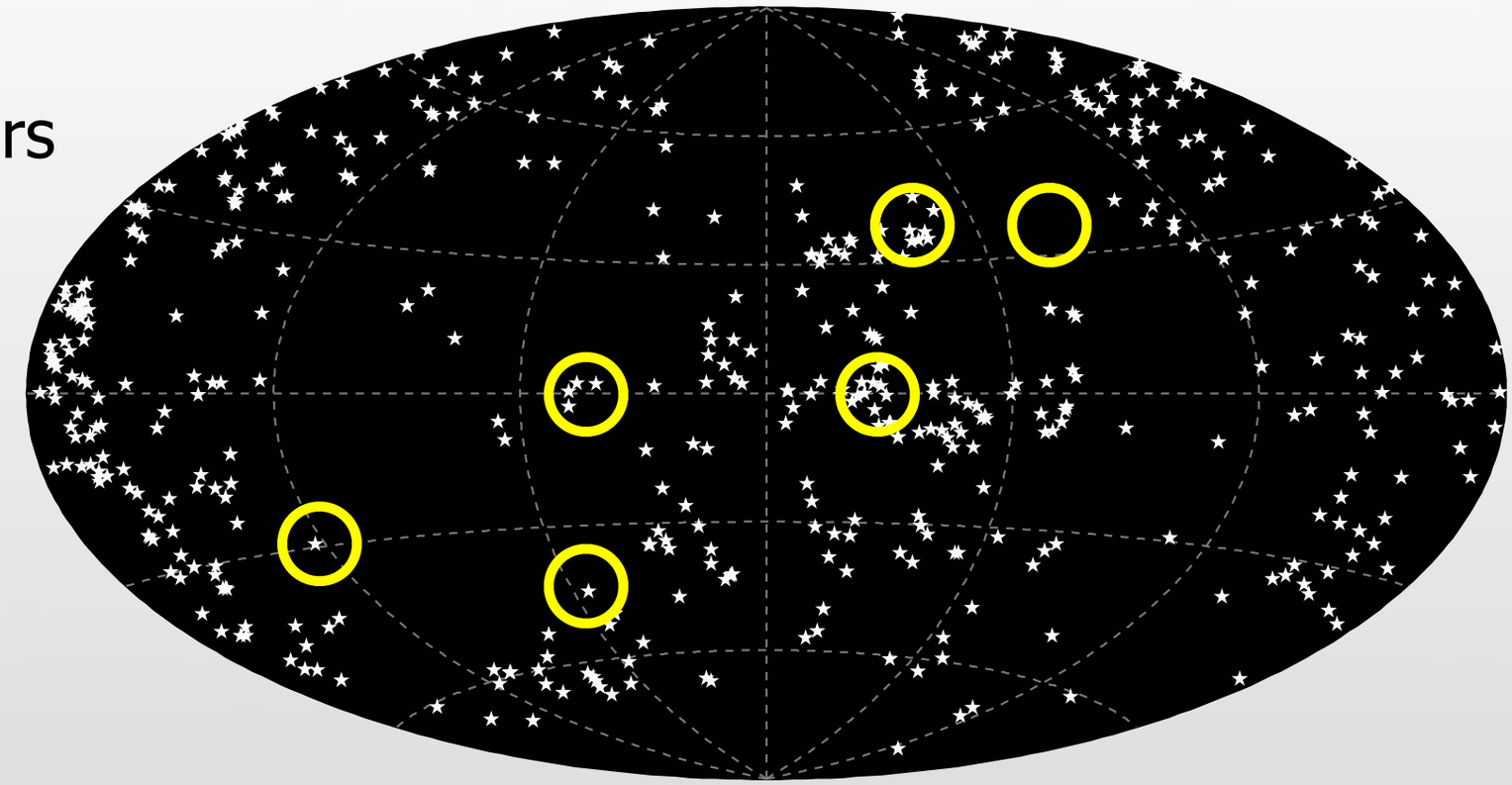
4 Correlation to nearby AGNs

✔

Pierre Auger Obs.

Anisotropy Search Method

Véron-Cetty
catalog of quasars
and AGNs



Total:
85221 quasars
1122 BL Lacs
21737 AGNs

z<0.024
(100 Mpc)
694 objects

Take CR source candidates from some catalog, e.g. Veron-Cetty

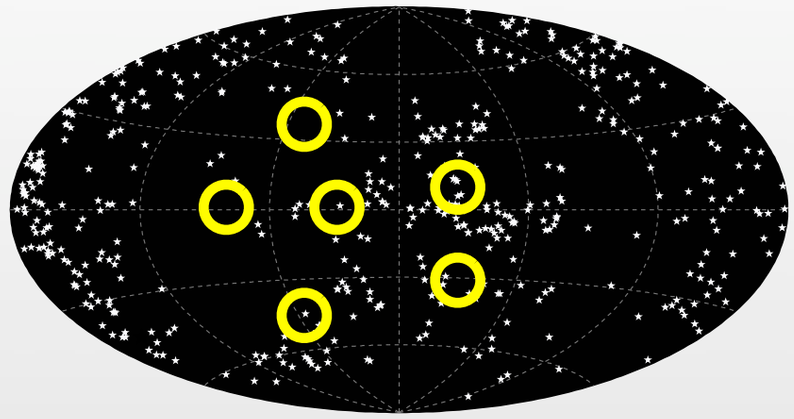
Probability to find a single event of an isotropic distr. within a certain opening angle from a source. $p = p(\psi, n_{sources}) = p(\psi, z_{max})$

Probability that k or more of N isotropic events correlate by chance:

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

Exploratory Search (1.1.04 - 27.05.06)

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



for **3 free parameters**:

z_{max} → no. of sources
Ψ → allowed angular separation
E_{th} → threshold Energy

} Minimum of P, i.e. largest deviation from isotropy found for

z_{max} = 0.018 (d_{max}=75 Mpc)
Ψ = 3.1°
E_{th} =56 EeV

Result: 12 among 15 measured events correlate with at least one source; 3.2 expected if flux was isotropic (p=0.21) and exposure was accounted for

Verify *a posterio* result by applying these correlation parameters to new data instead of using penalty factors to account for # of searches

Running Prescription (27.5.06 - ...)

Goal:

confirm results from exploratory scan by new data set (*a priory search*)

Base Hypothesis: Isotropic Flux

Predefined stopping rule:

a) incorrectly reject isotropy hypothesis < 1% (i.e. p<1%)

b) incorrectly accept isotropy hypothesis < 5%

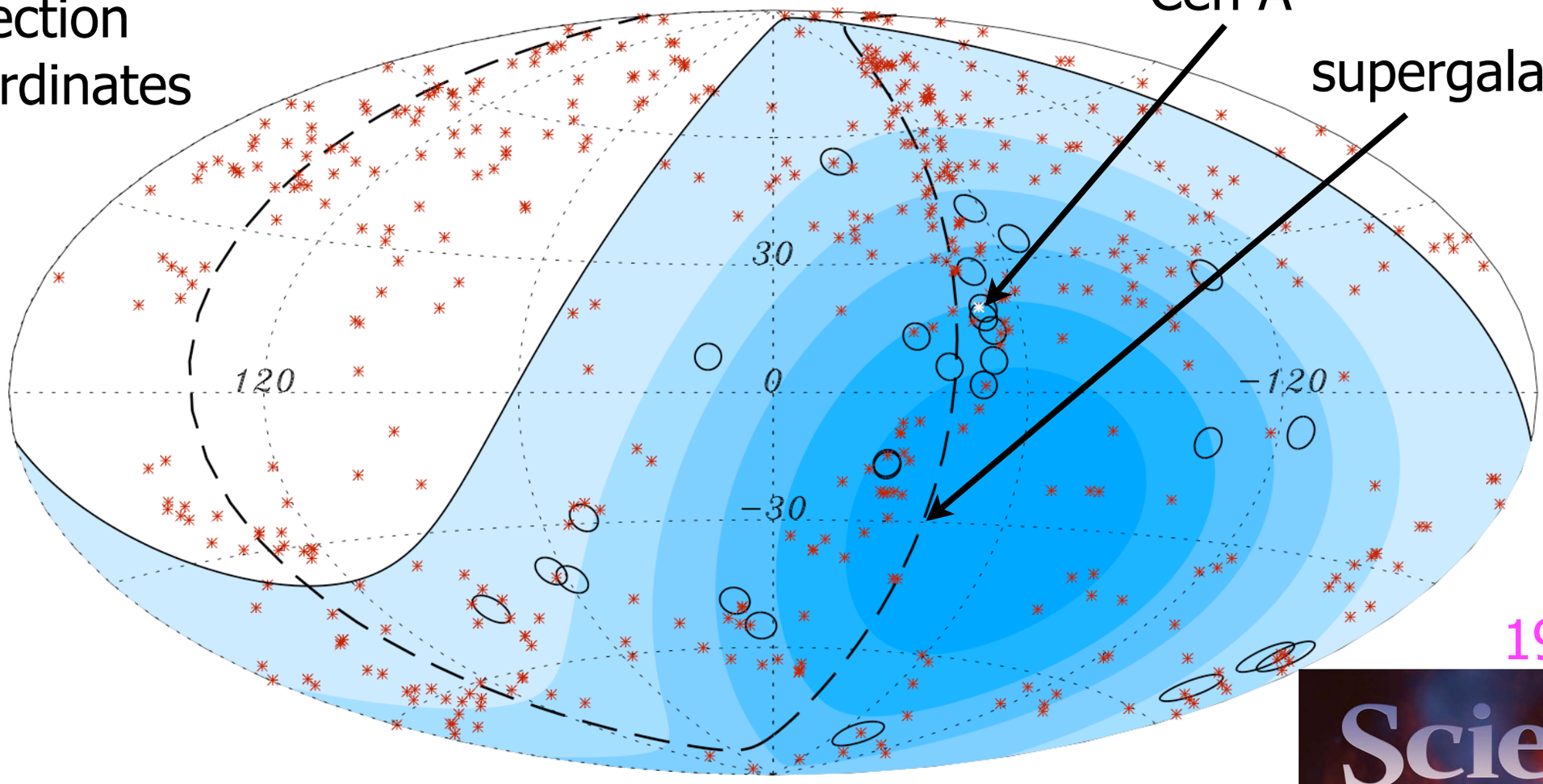
N (E>56 EeV)	4	6	**8**	10	12	...	30	31	33	34
k (corr. events)	4	5	**6**	7	8	...	14	14	15	15
$P_{Isotropy}$ (%)	0.19	0.32	**0.40**	0.44	0.47	...	0.83	0.87	0.89	0.92

prescription fulfilled
on May, 25th 2007

AGN Correlation Plot

Aitoff projection
galactic cordinates

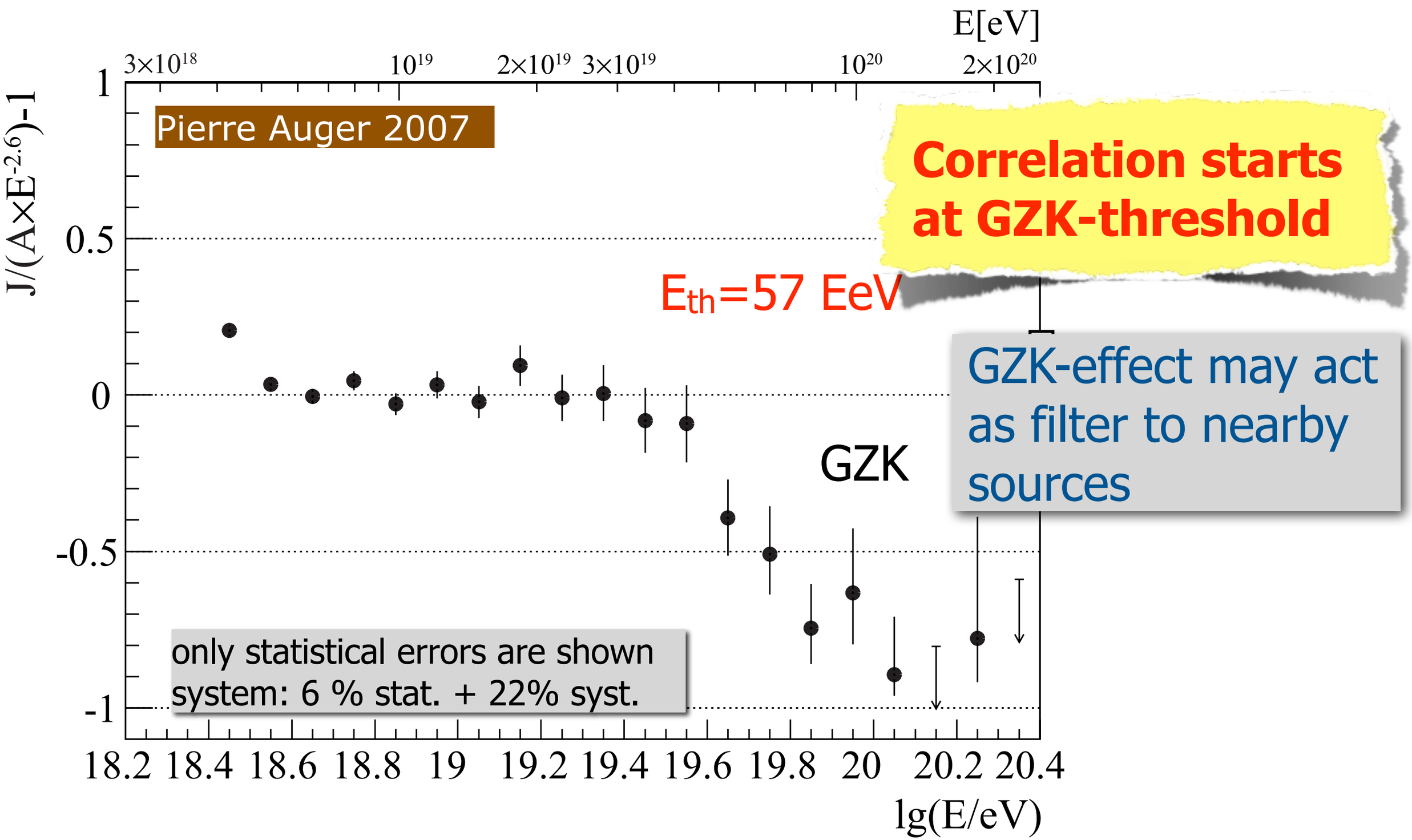
472 AGNs
z≤0.018
318 in fov



19.11.2007

In total **27 events** at E > 57 EeV
20 of which correlate
5.6 expected (p=0.21)
Net chance for isotropic distr. **$P < 10^{-5}$**
Darker colors indicate larger exposure

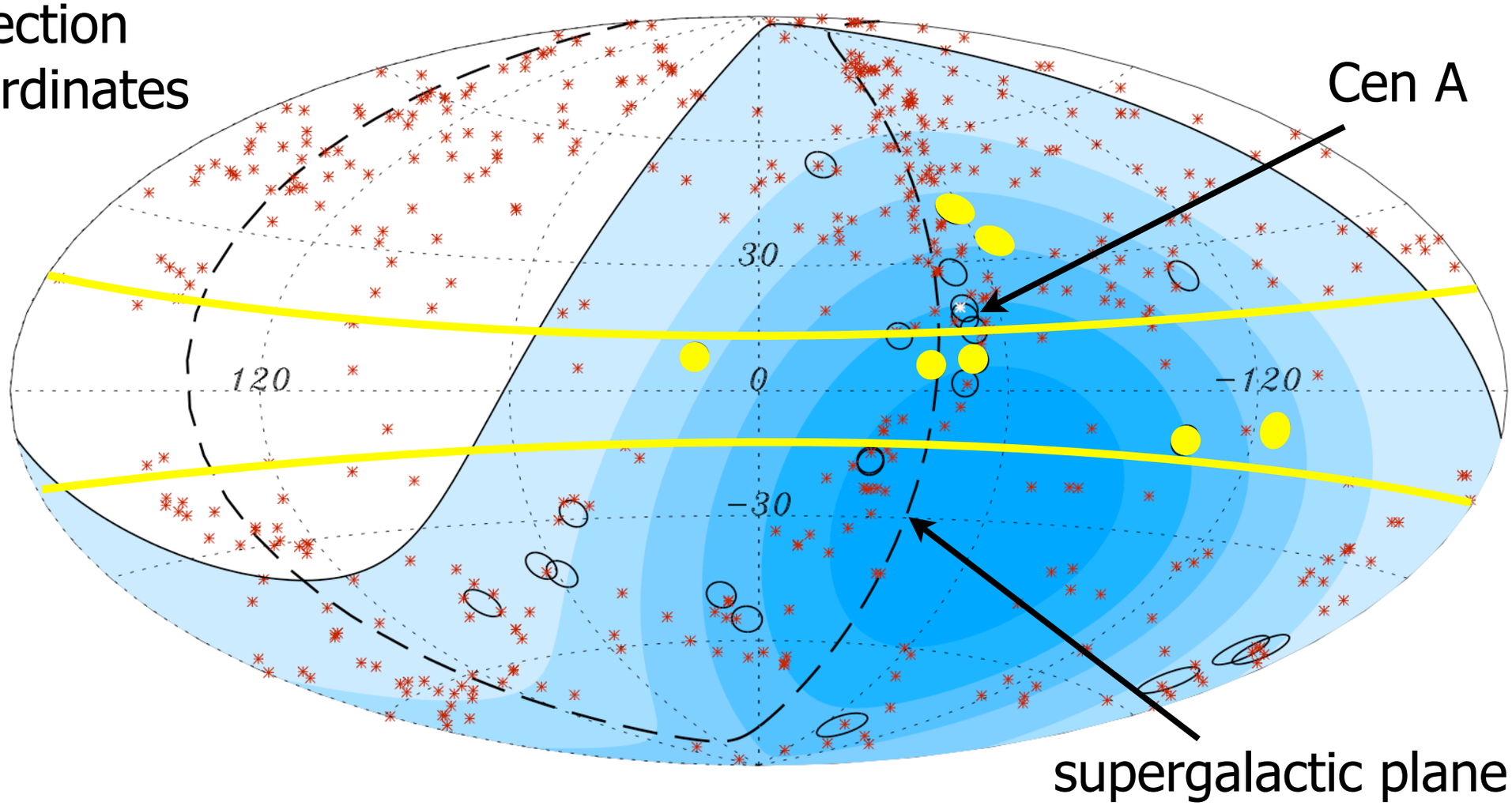
Interpretation of Correlation Parameters



Effect of Galactic Plane

Aitoff projection
galactic cordinates

472 AGNs
z≤0.018
318 in fov



In total 27 events at E > 57 EeV, 20 of which correlate

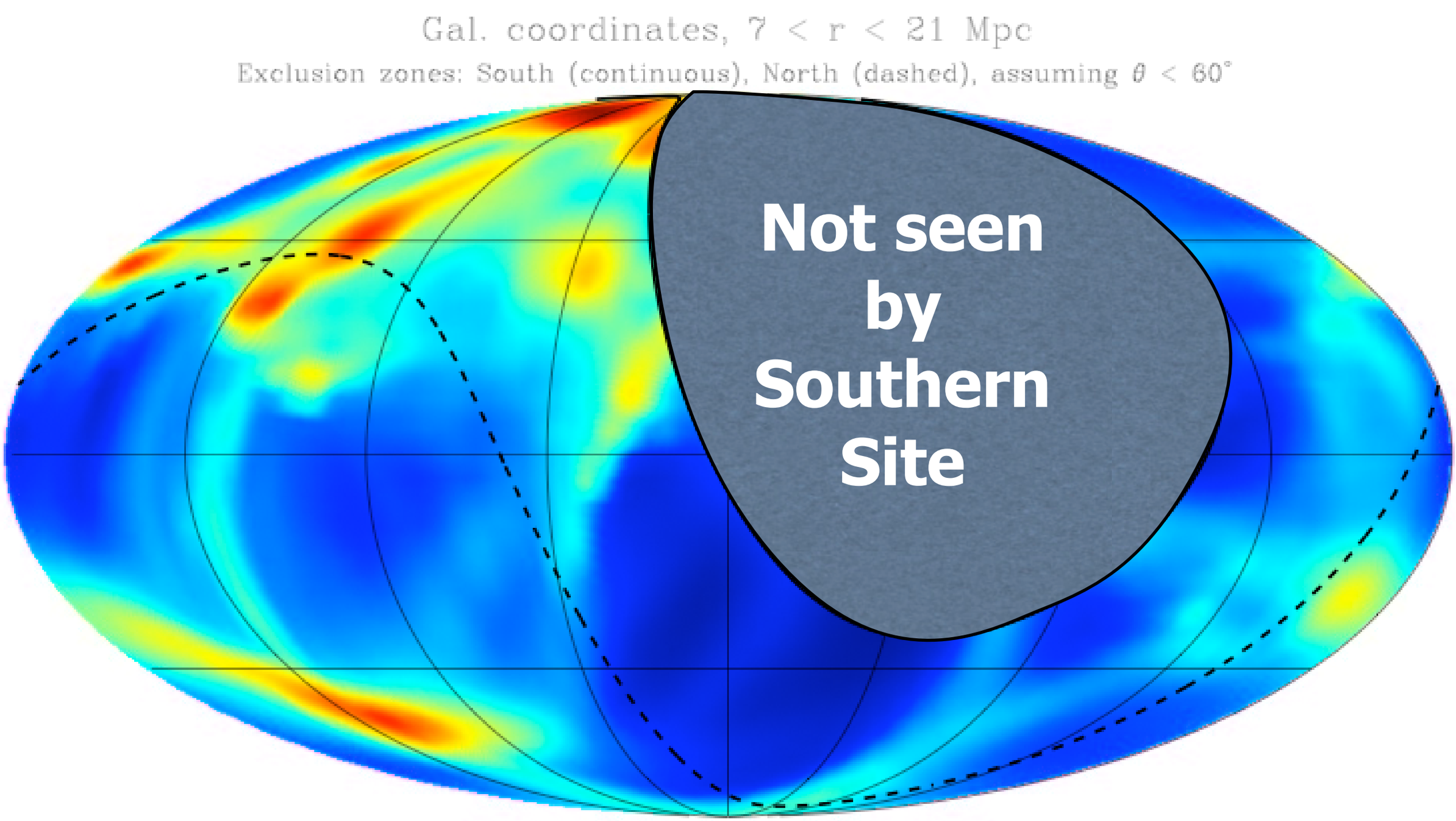
5 of the 7 non-correlating events from nearby the galactic plane

likely to happen because of incomplete catalogue and large deflections in magnetic fields

Some Remarks on Correlations

- AGNs may just act as tracer to true CR sources
  in case the AGNs correlate with them
- Correlations provide independent evidence for GZK-effect
- Spatial correlations surprisingly strong
  may indicate proton primaries and small intergalactic magnetic fields (but does not agree to Xmax)
- Autocorrelation of event directions provide confirmation
- Likelihood Method worked out for discriminating different source scenarios also at large source densities
- energy - opening-angle correlation analysis ...

AGN ≈ Large Scale Structure



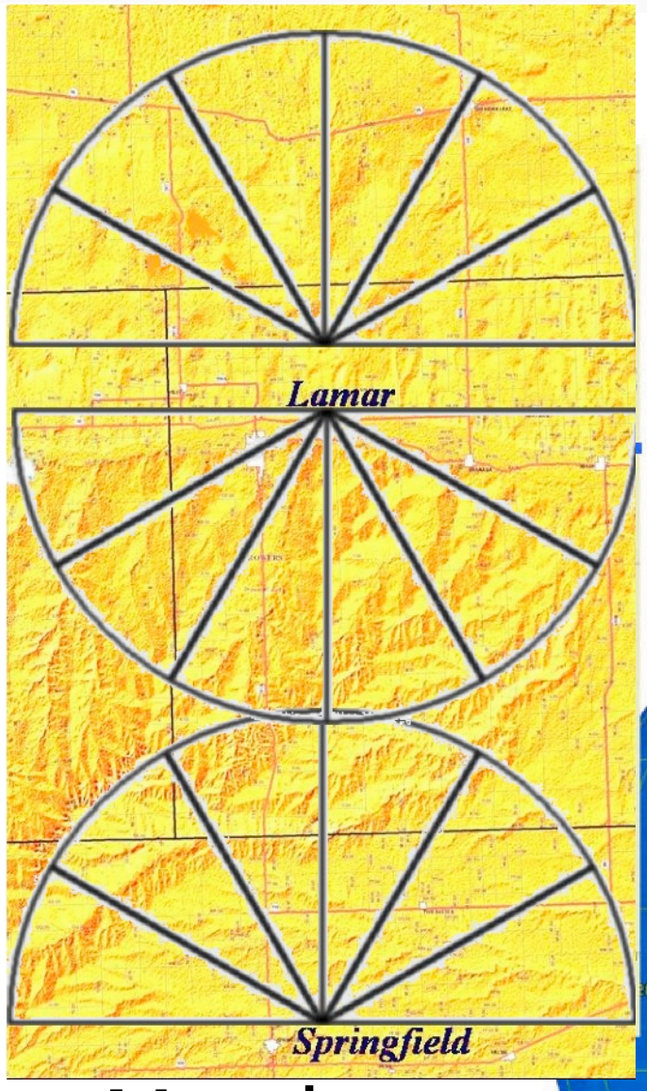
7 to 21 Mpc Kravtsov data

Auger is Marching North

Auger North

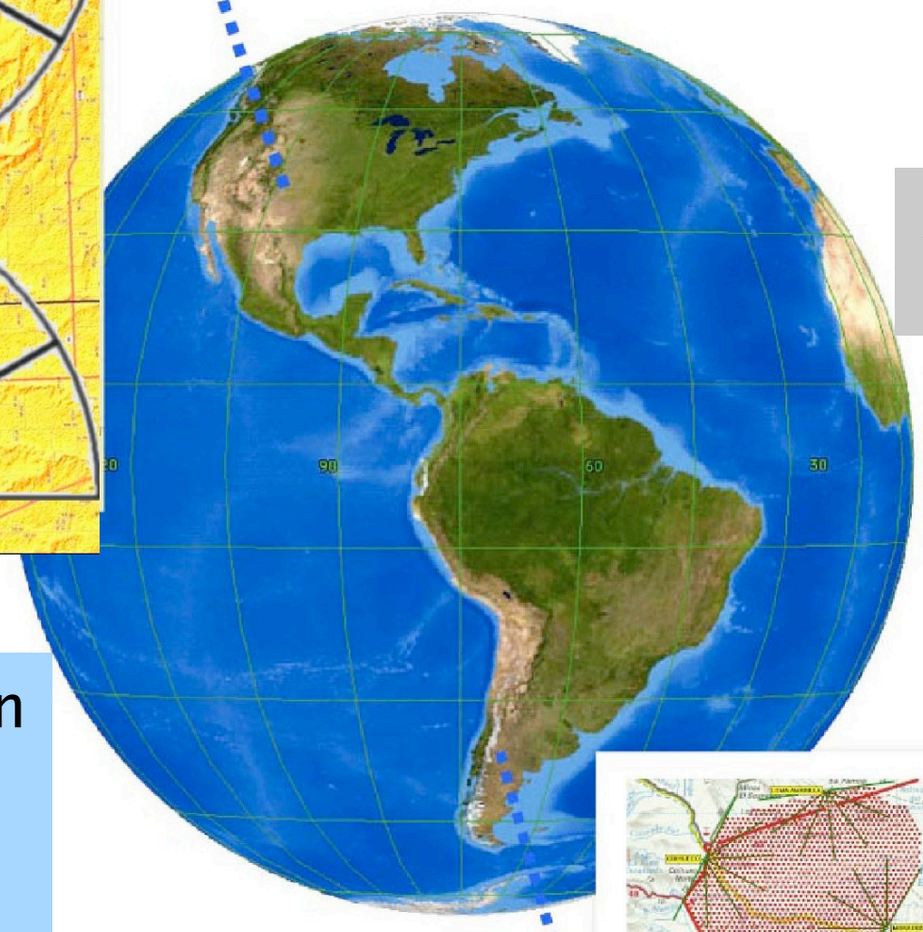
Need for two sites realized from the early beginning

expandable to ~ 25,000 km^2



Northern Site: Colorado

- Retain features & functionality of Southern Site
  - Hybrid detection & energy calibration
  - Water Cherenkov surface array
    - 4000 stations, 10,370 km^2
    - Square mile grid

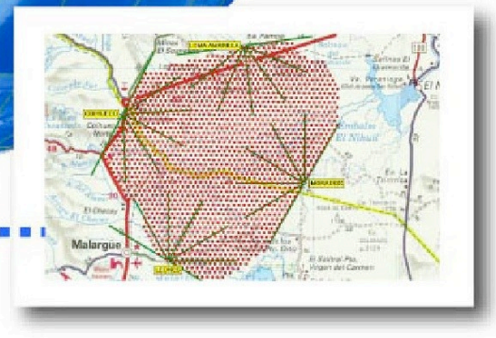


Altitude and latitude are similar

Southern and Northern sites are shown at the same scale

Southern Site: Mendoza

- Hybrid detection & energy calibration
- Water Cherenkov surface array
  - 1600 stations, 3000 km^2
  - 1.5 km triangular grid
- Completion end 2007



Summary & Outlook

- Auger South will be completed by end of this year
- Highly relevant results obtained already at this stage:

  - Ankle & GZK-effect observed
  - Top Down & SHDM models largely ruled out by E-spec & photon fraction
  - (Best upper limits on EHE neutrinos)
  - No CR excess from galactic centre
  - **Correlations with AGNs established**

➳ **Astronomy of charged particles becomes feasible**

➳ Multi-Messenger with γ's and ν's next natural step

➳ Need for full sky-coverage

Just opening the window to the high energy Universe!

see www.auger.org for list of authors, auger.uni-wuppertal.de for public event display
Contributions by many collaboration members are gratefully acknowledged