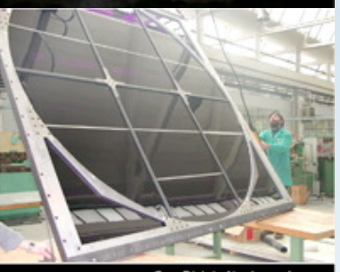
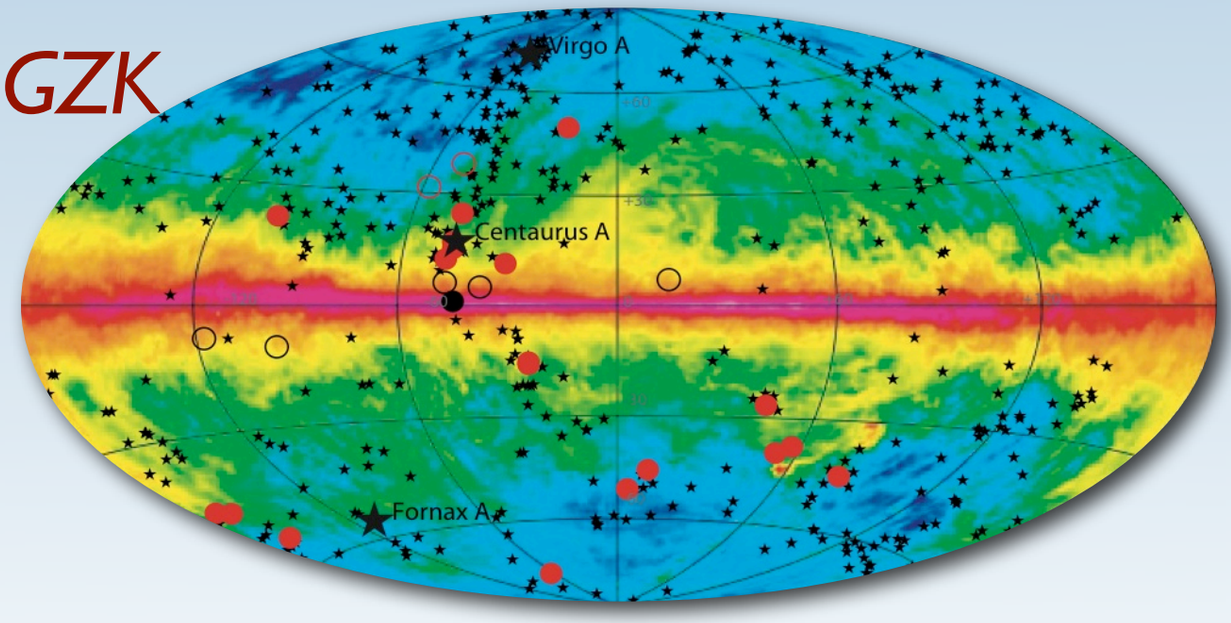
# Cosmic Rays at the Highest Energies

## Results from the Pierre Auger Observatory

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




- **Motivation (more general)**
- **The Pierre Auger Observatory**
- **Some Results**
  - ***Energy Spectrum:*** *GZK*
  - ***Photons***
  - ***Neutrinos***
  - ***Arrival Directions***
- **Discussion**

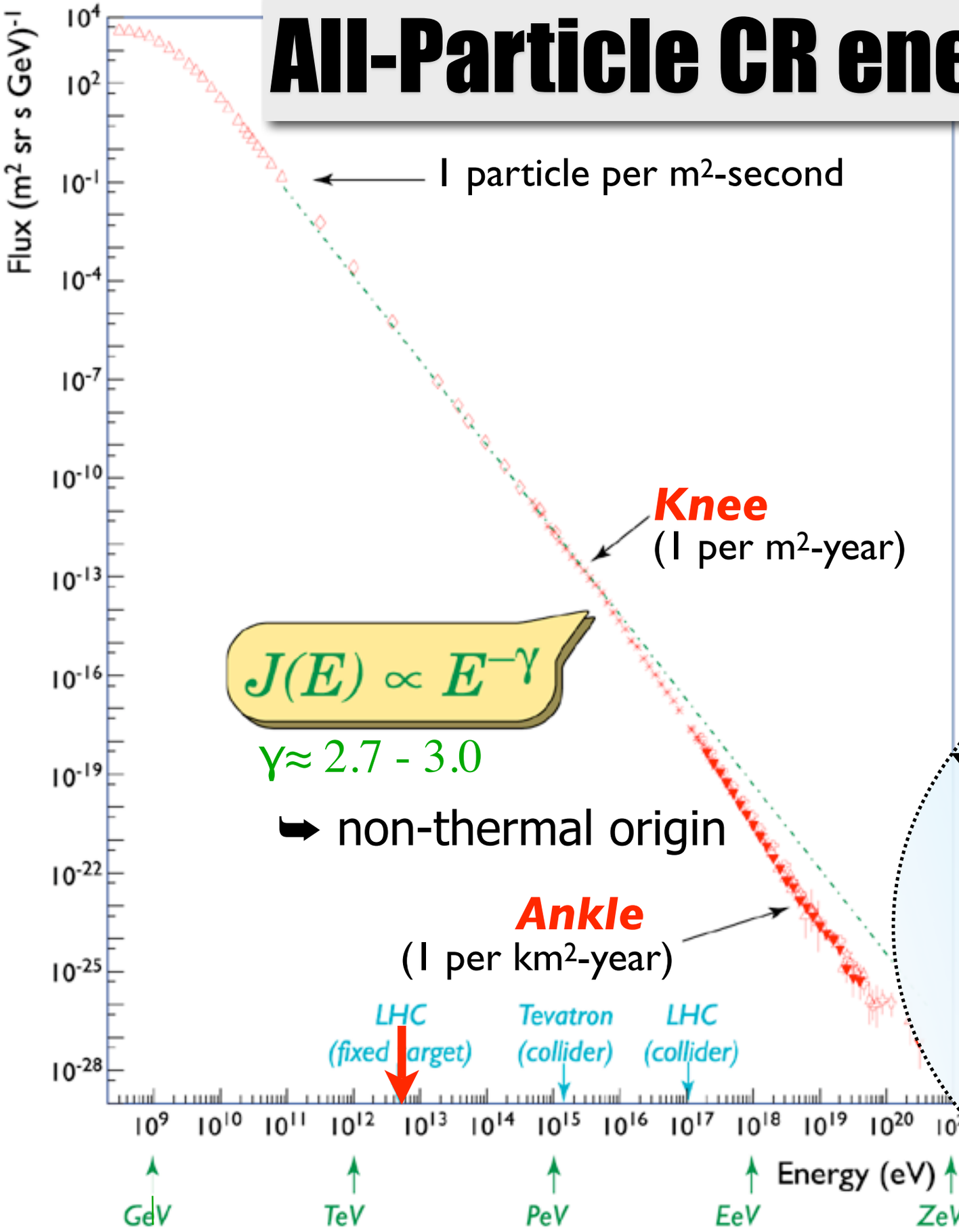


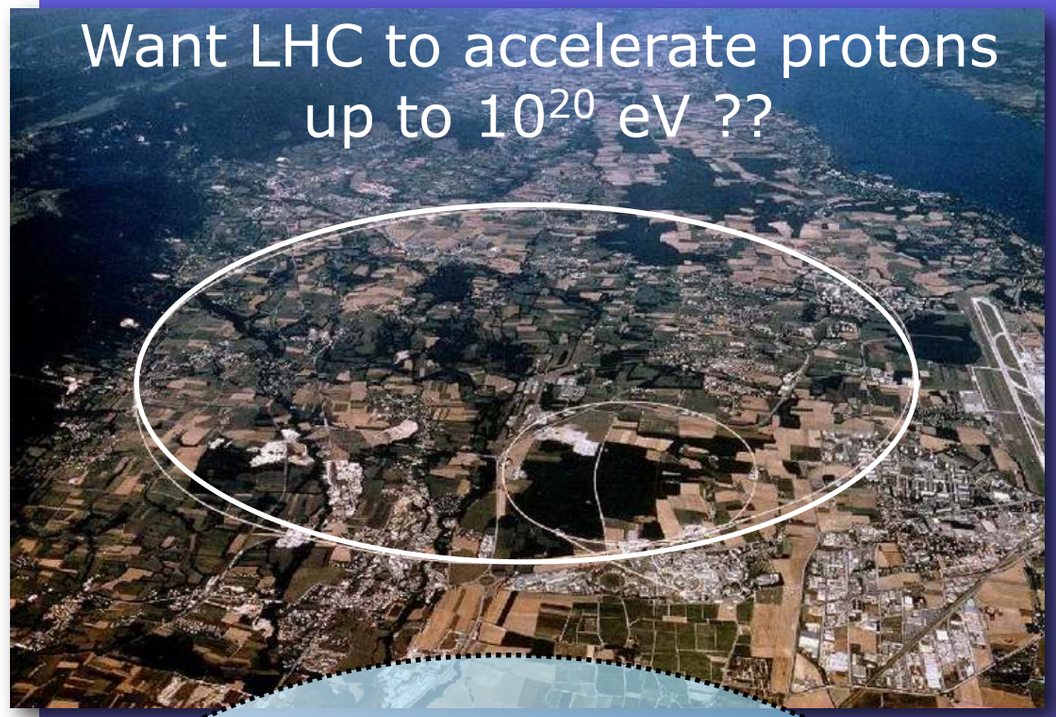

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

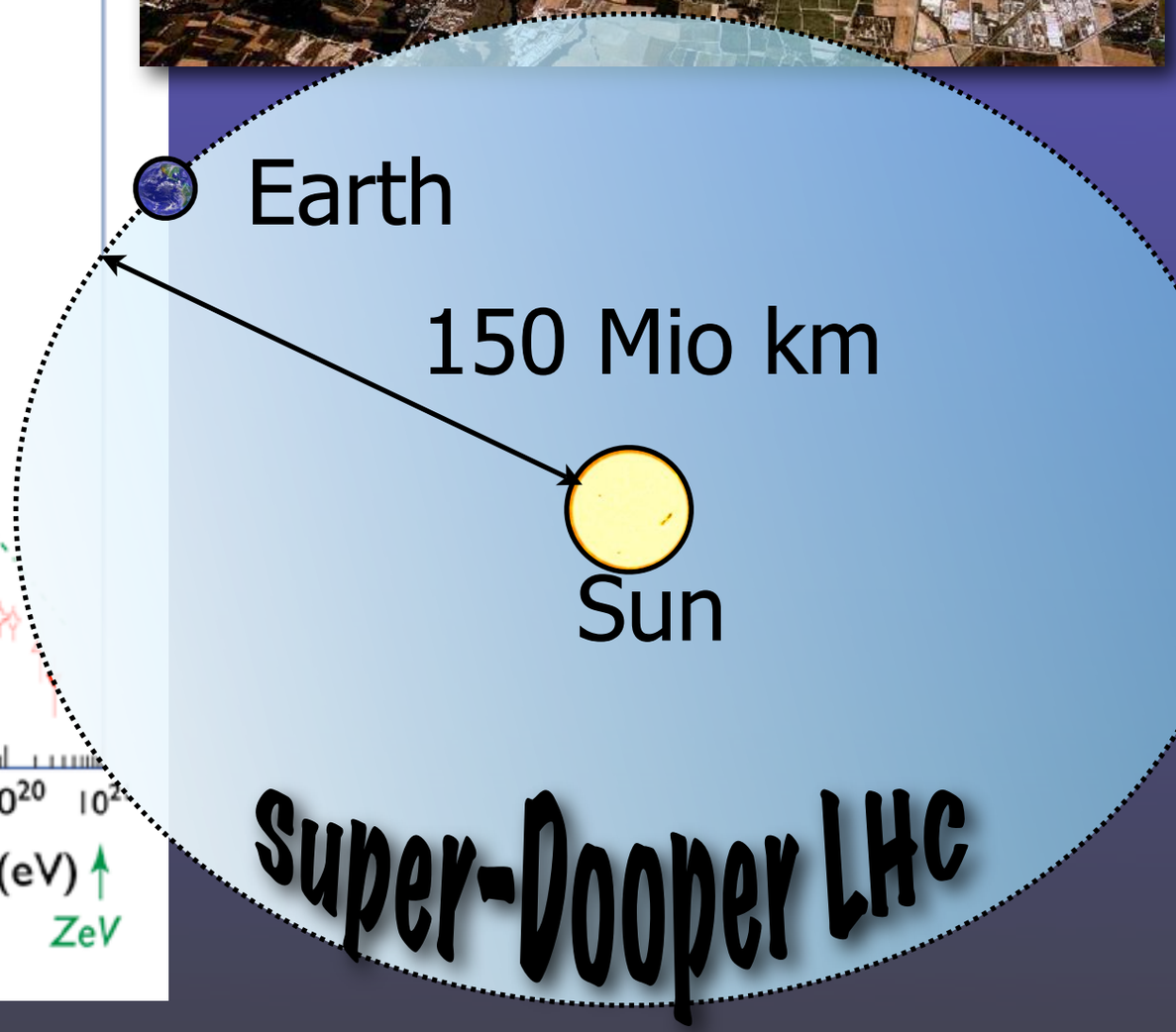


kampert@uni-wuppertal.de

# All-Particle CR energy spectrum



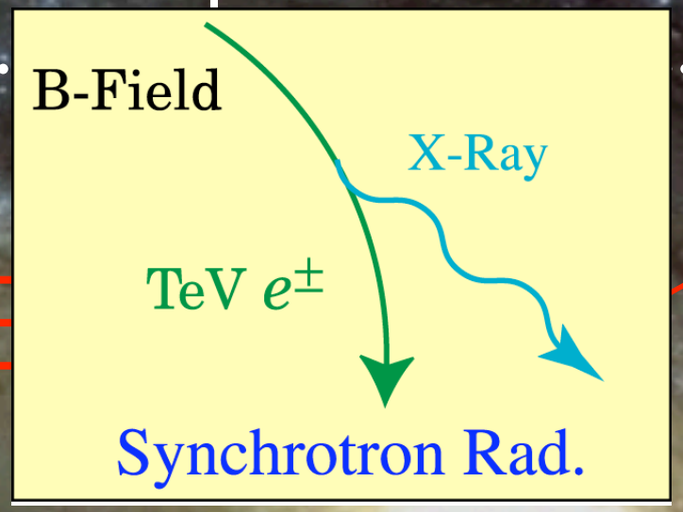



# The simple world of CRs

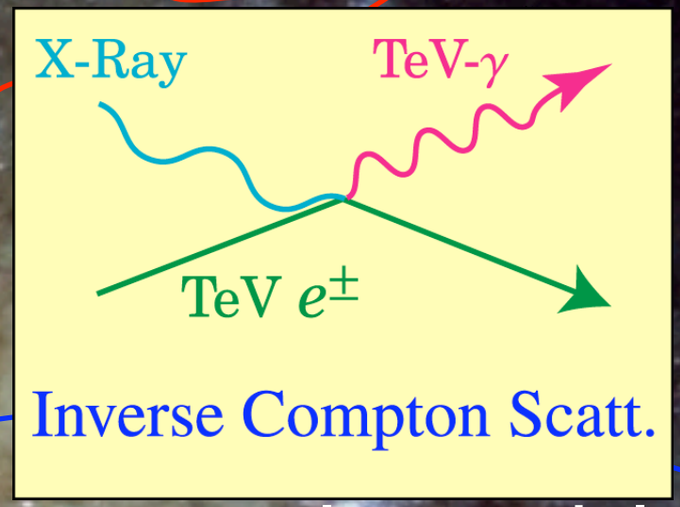
**Source:**
Nucleosynthesis,
stellar atmosphere..

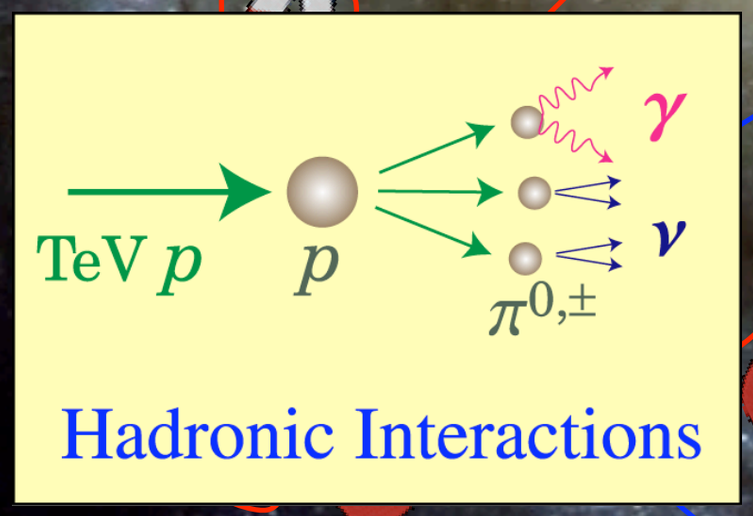
**Accelerator:**
Supernovae?,
..

**Propagation:**
Spallation,
radioactive decays,
magnetic fields,
*exotic stuff ...*

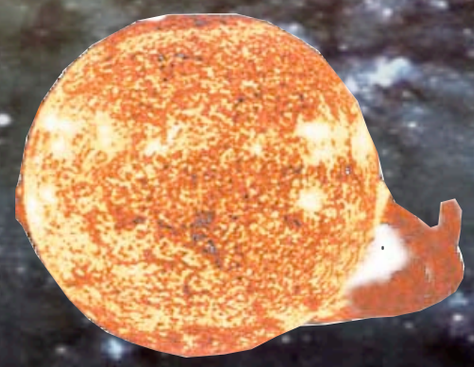




CR



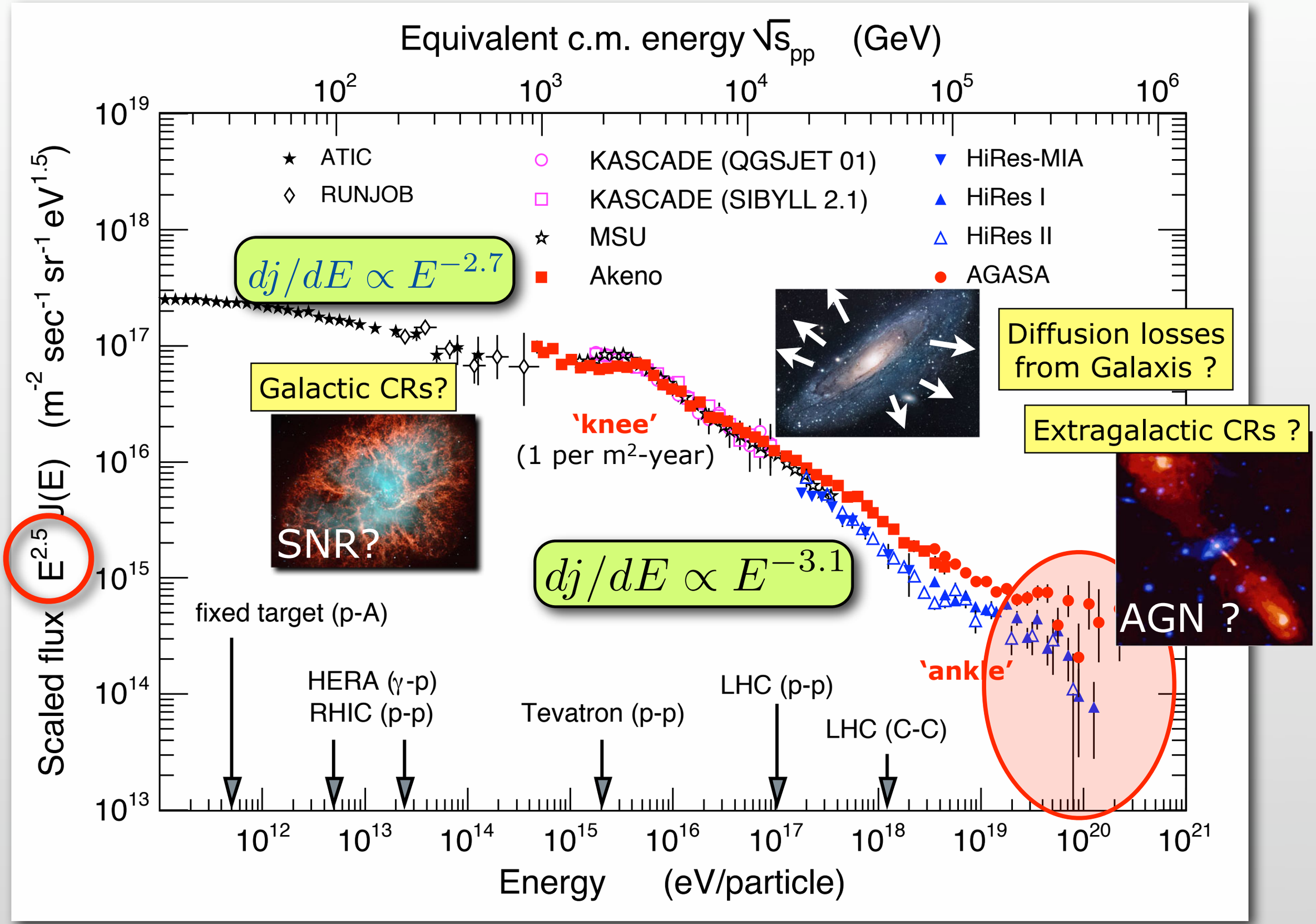




solar modulation



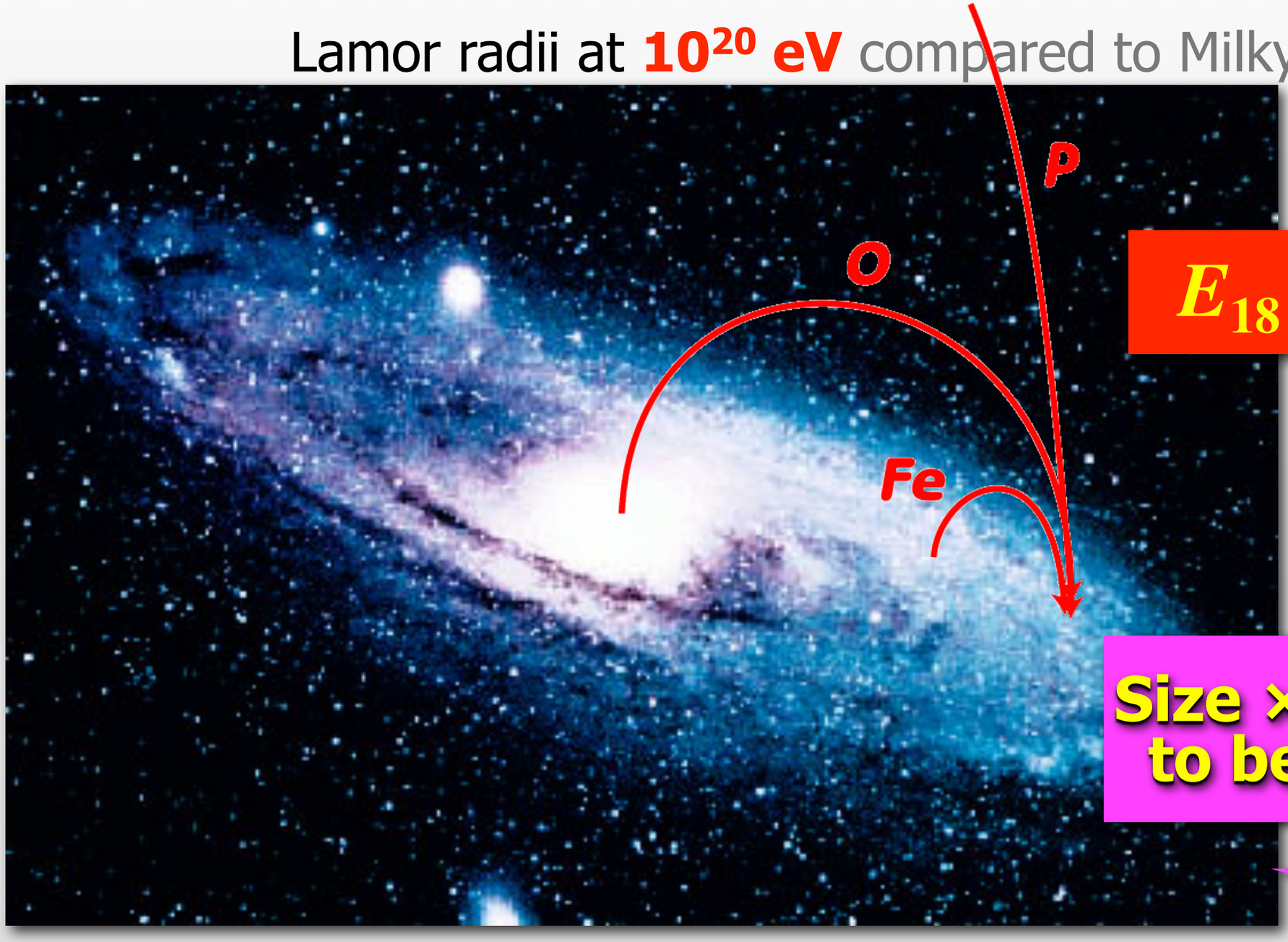
Earth atmosphere

# Ultra High-Energy Cosmic Rays



# $10^{20}$ eV CRs in our Galaxy ?

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



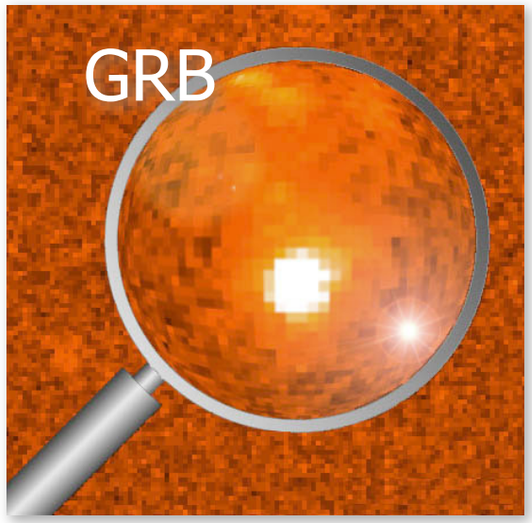

$$E_{18} \leq Z \cdot B_{\mu G} \cdot R_{kpc}$$

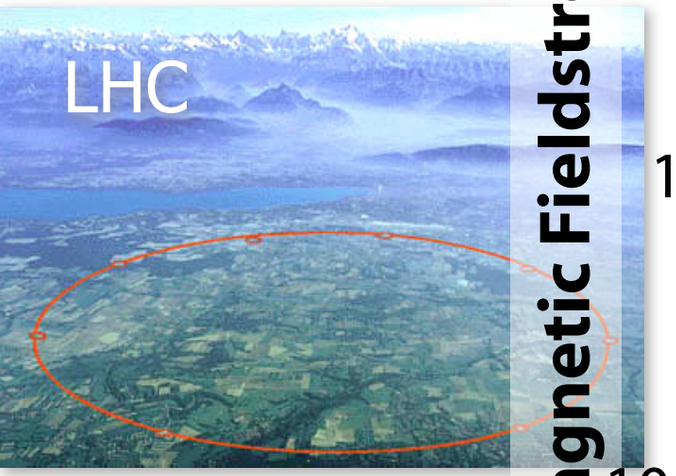
**Size × B-Field needs to be very large ...**

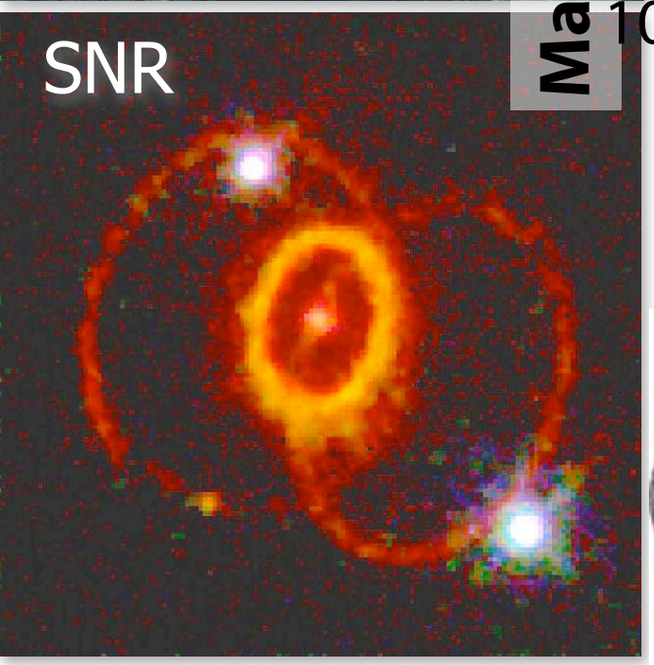
Interesting feature:
Can do astronomy with cosmic rays !

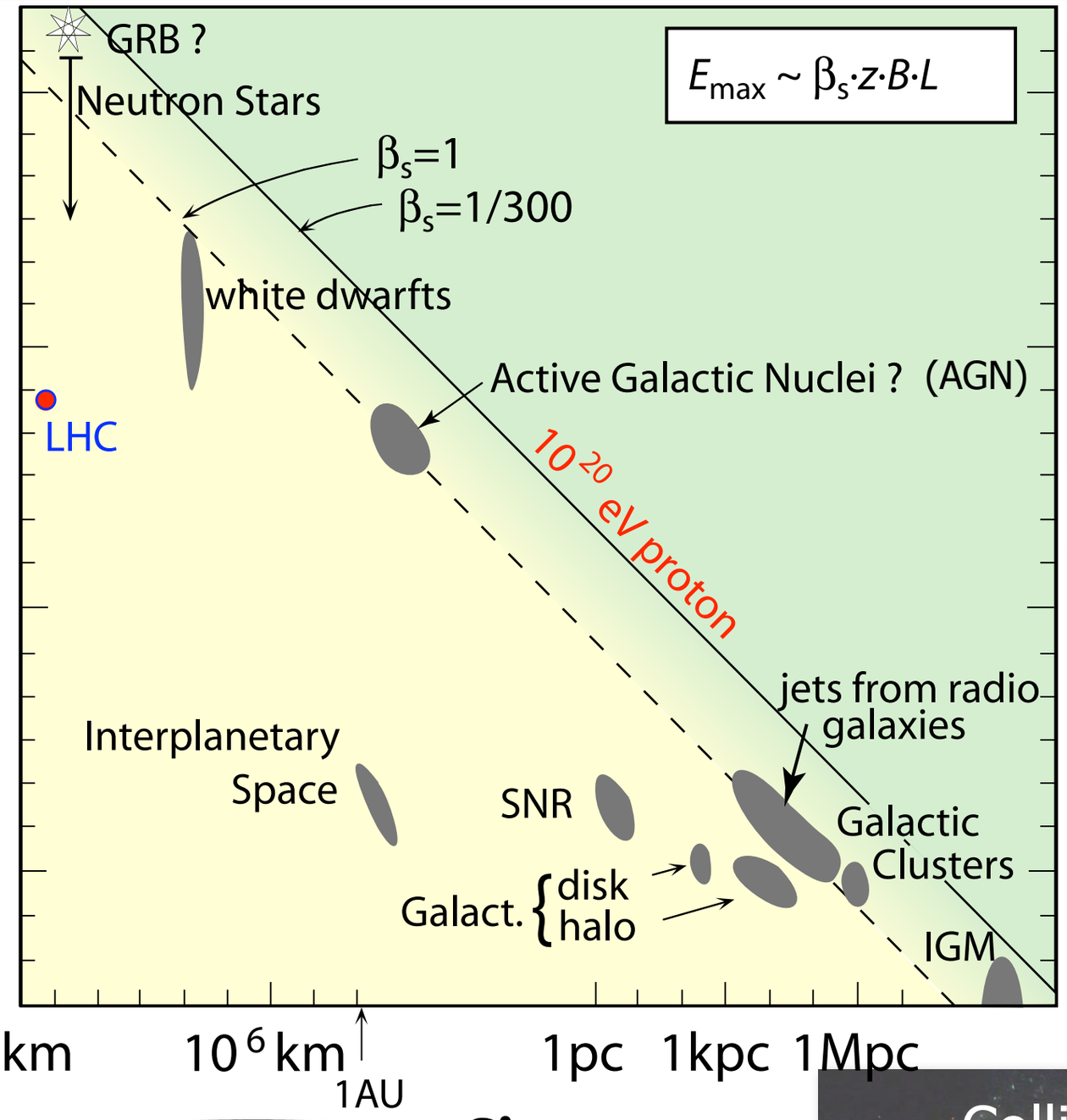
**Conjecture:**
**Extragalactic origin**

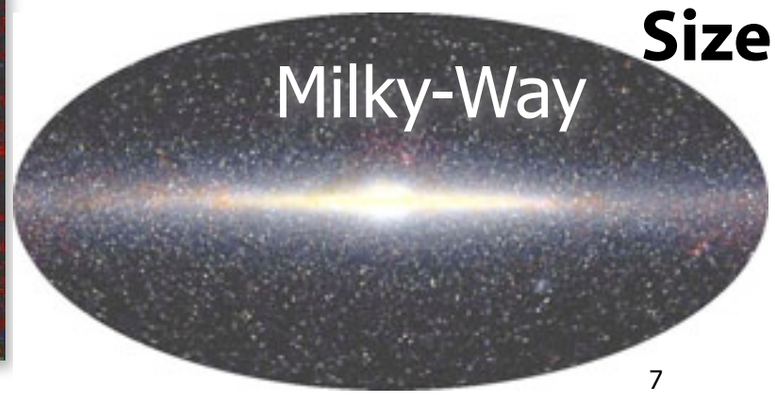
# ? Possible Candidates ?

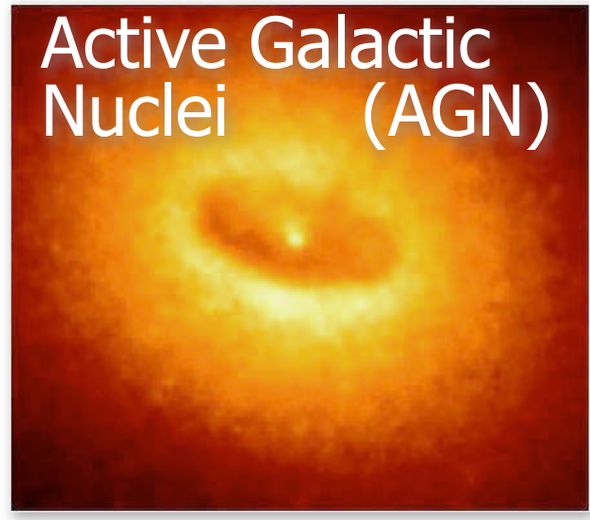


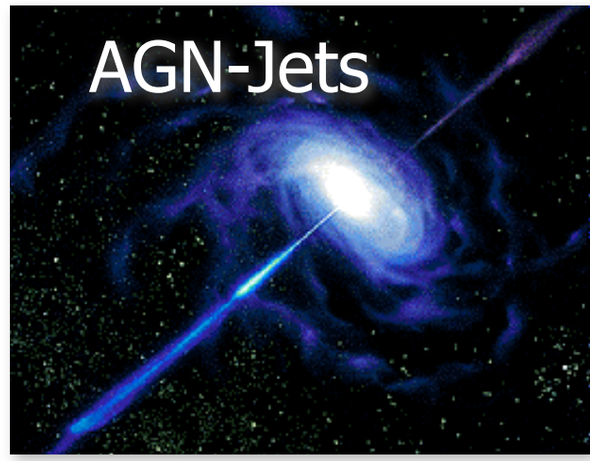




# AGN Jets and Radio-Lobes

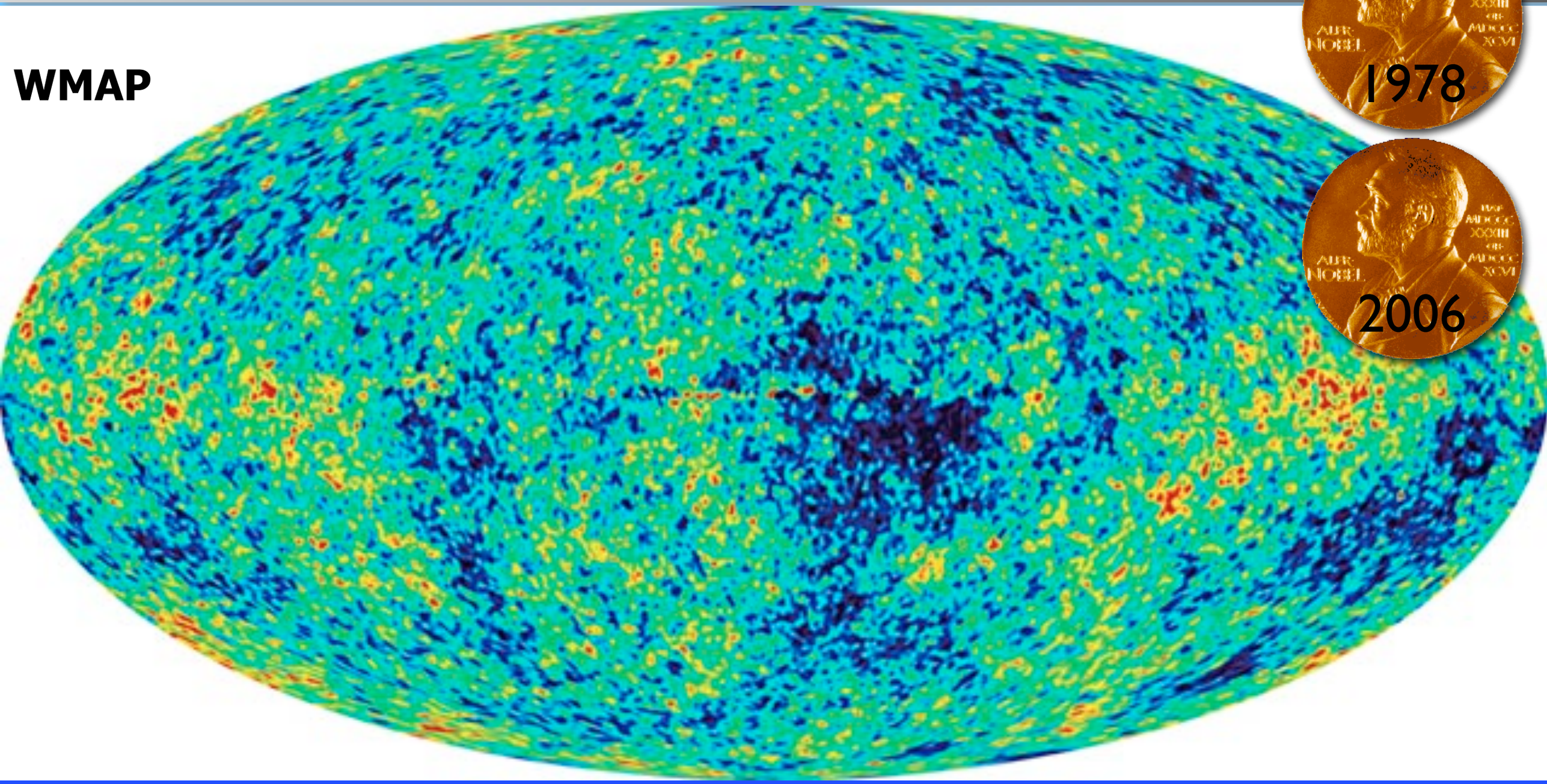
**Cygnus A**
(z=0.056, d≈210 Mpc
5 GHz image, ø ≈ 20 kpc)

100 Mpc = 326 Mio. Lightyears

**3C 219 (FR II)**

z=0.1745, d≈800 Mpc

# Problem: CMBR





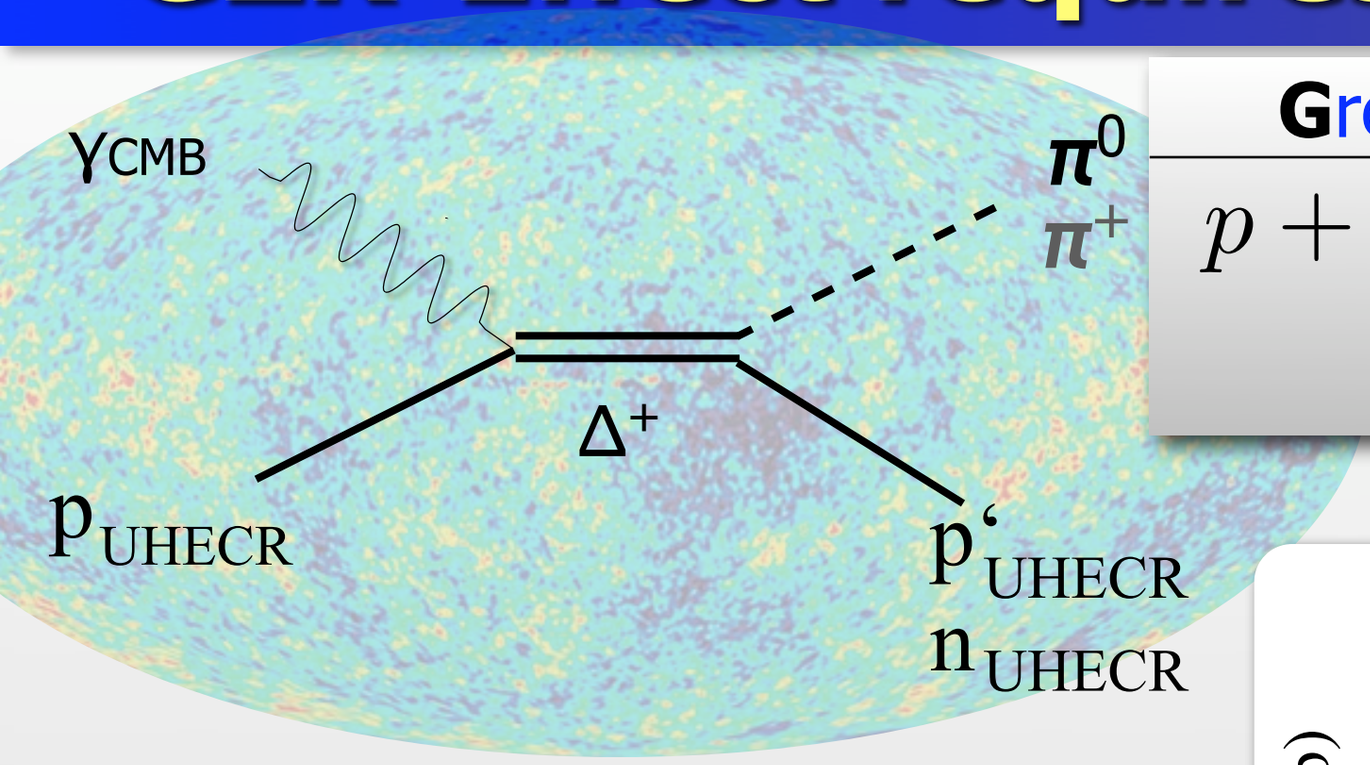





Universe is filled with 3K photons: 412/cm$^3$

Discovered 1965 by Penzias and Wilson

# GZK-Effect requires nearby Sources




**G**reisen-**Z**atsepin-**K**uz'min (1966)

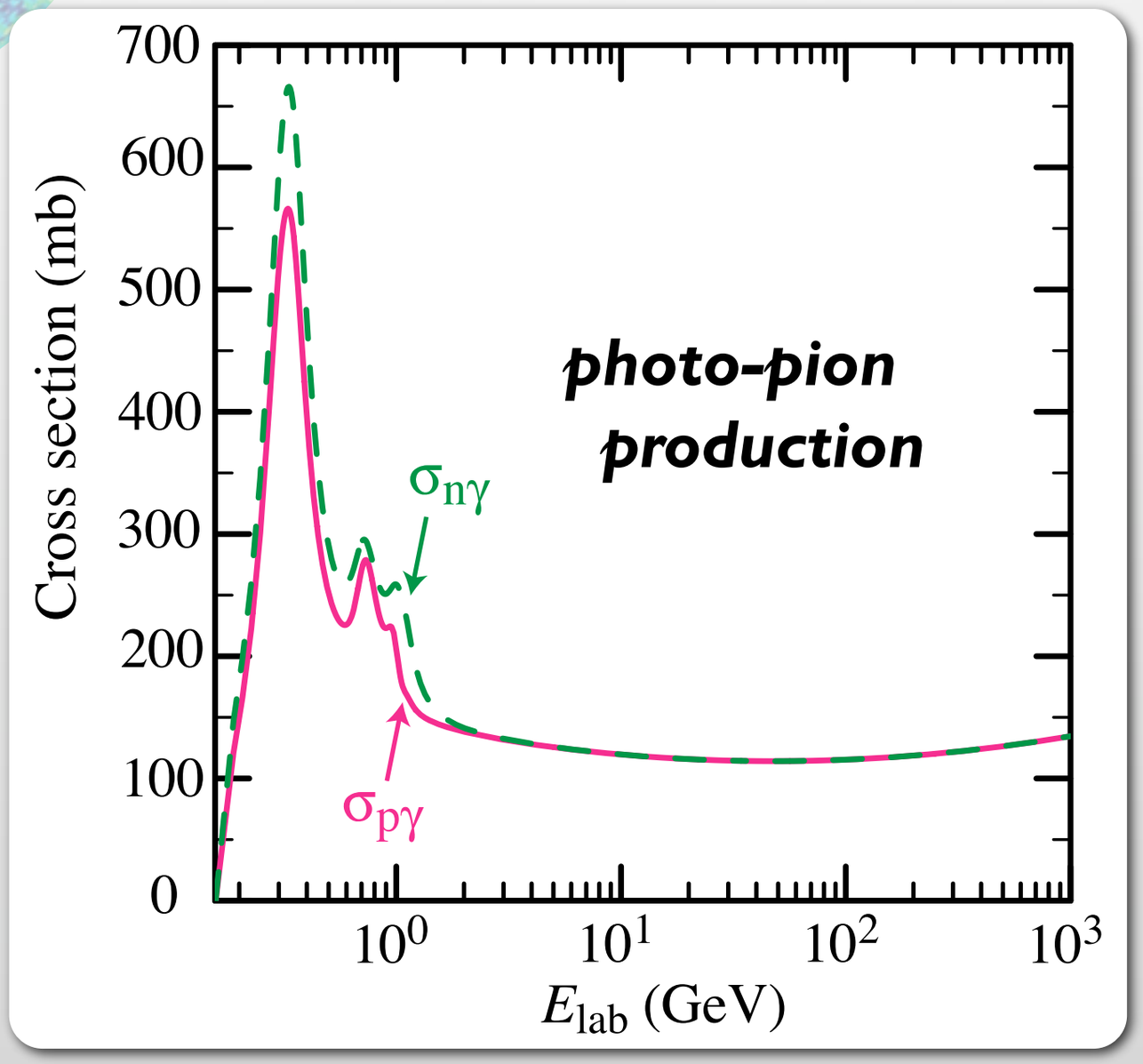
$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

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

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



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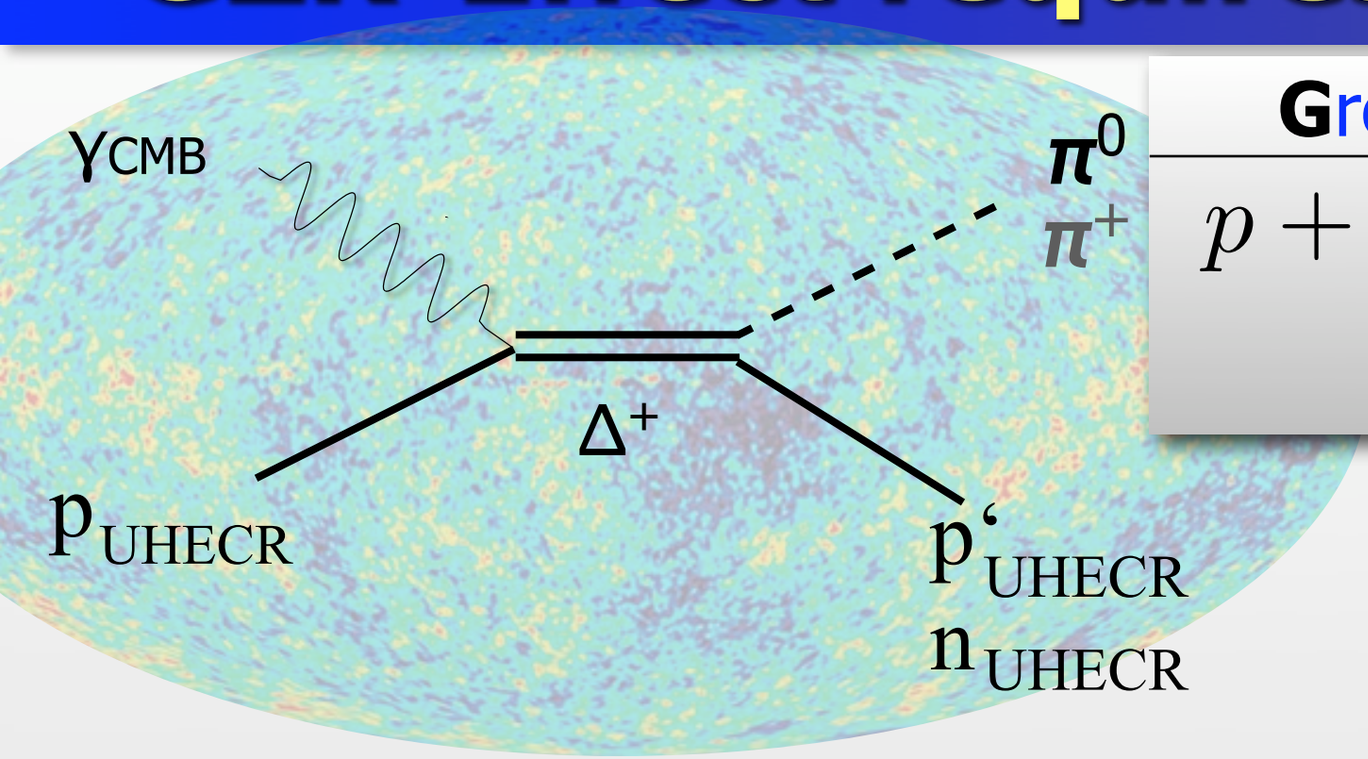


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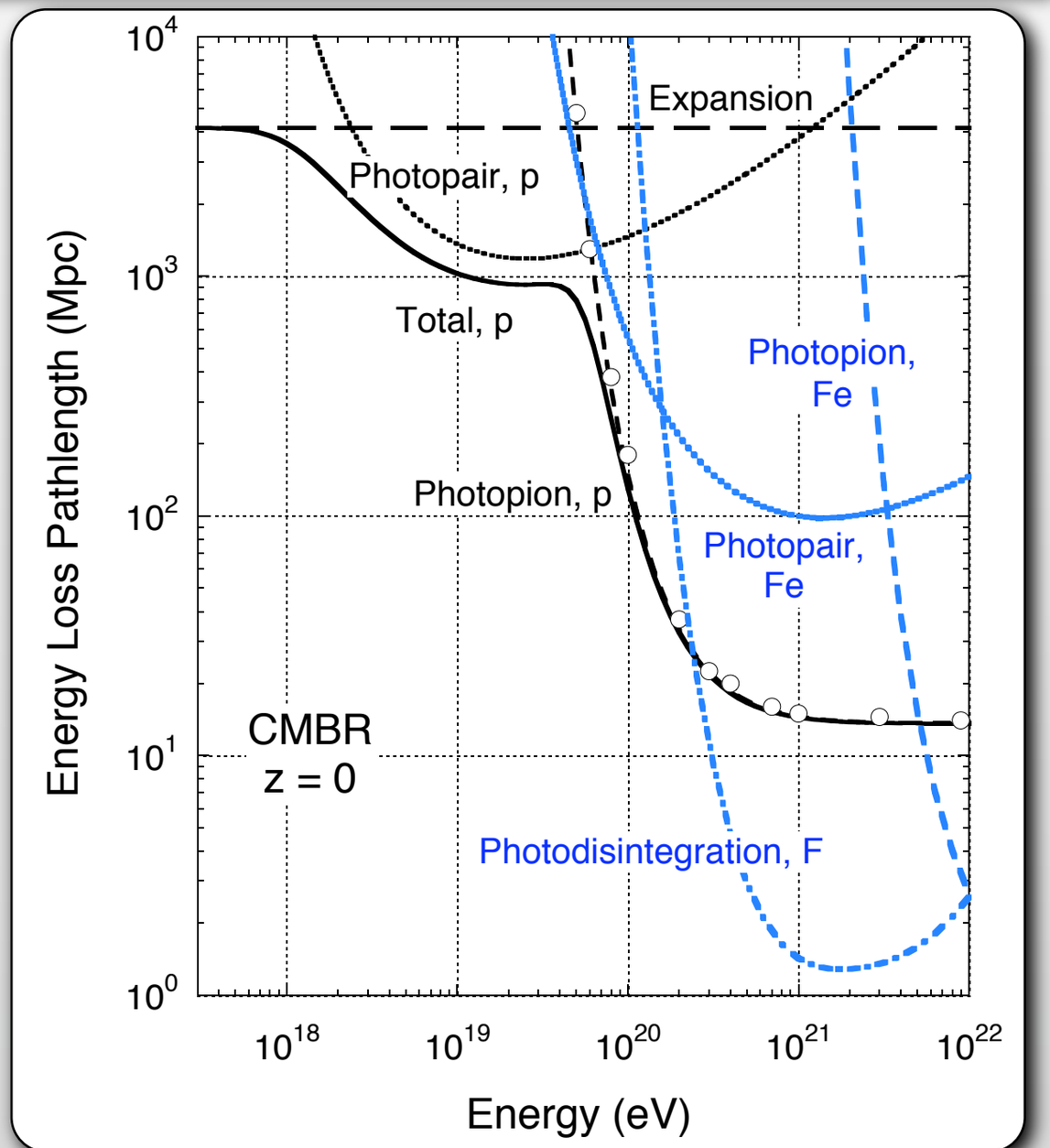


# Science Case

- **What & Where are the nearby Sources ?**
- **How do they work ?**

➠ *need to measure: direction, energy, particle-type*

*By-Products:*

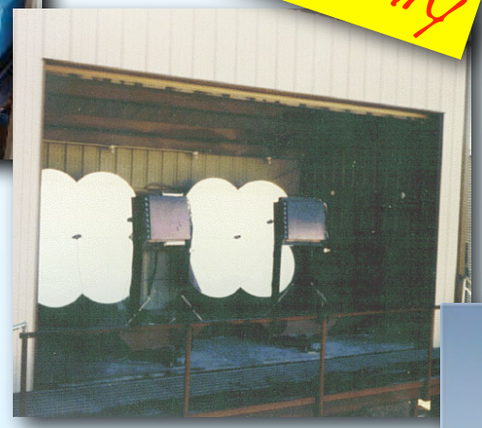
- *Do Particle Physics at the Highest Energies,*

  *e.g. pA and ν-sections*
- *Probe Fundamental Physics, e.g. Tests of LIV*
- *Learn about Cosmic Environments, e.g. B-Fields*

# UHECR Experiments: Past-Present-Future

analysis only

**AGASA**
100 km$^2$



**HiRes-I & II**
~1000 km$^2$

operating

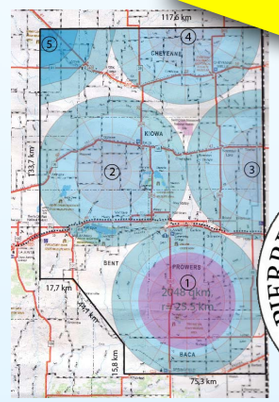
**Auger**
3000 km$^2$

construction

*– Starting the Golden Hybrid Era –*

**Telescope Array**
860 km$^2$

preparing

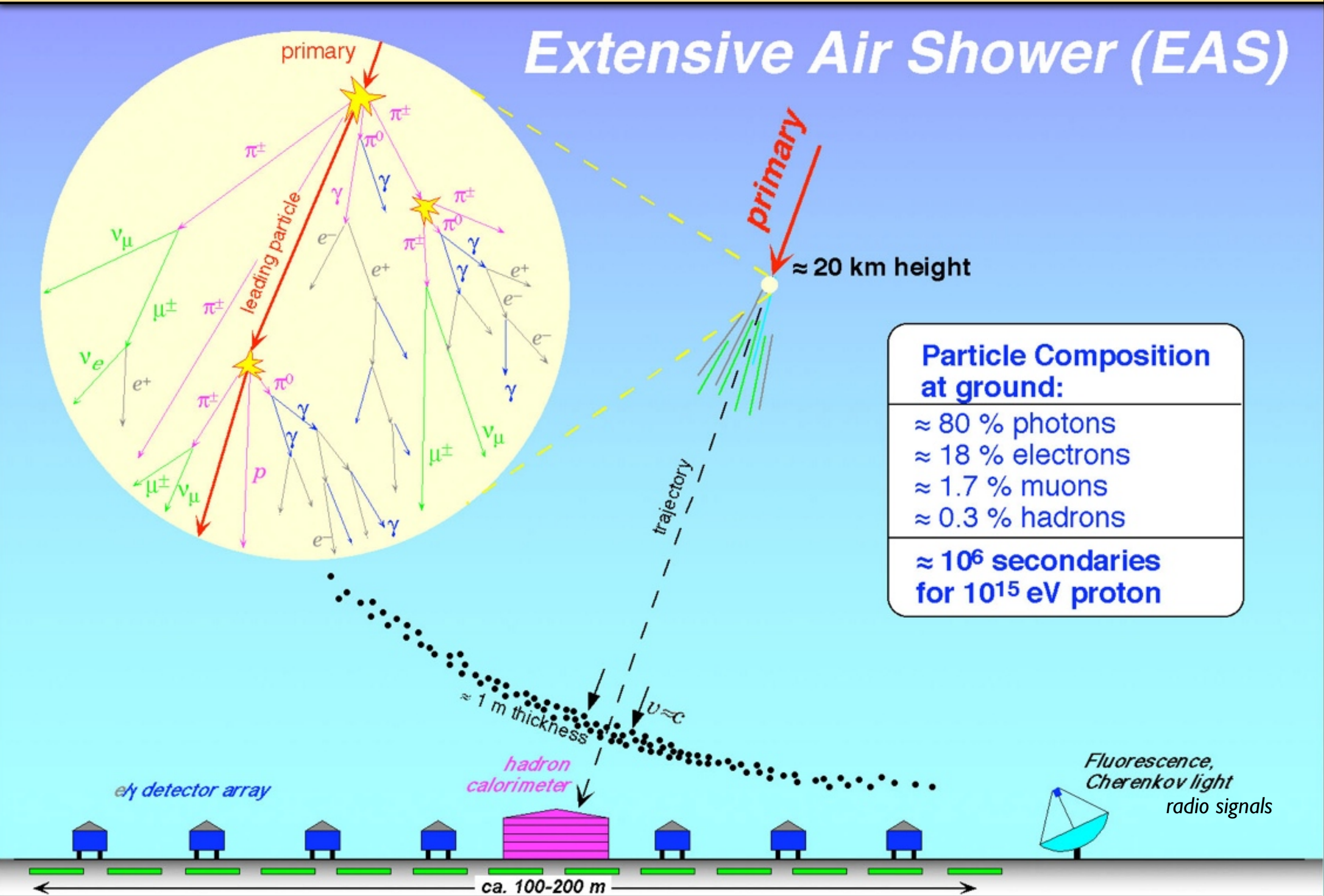



**Auger-North**
~20000 km$^2$

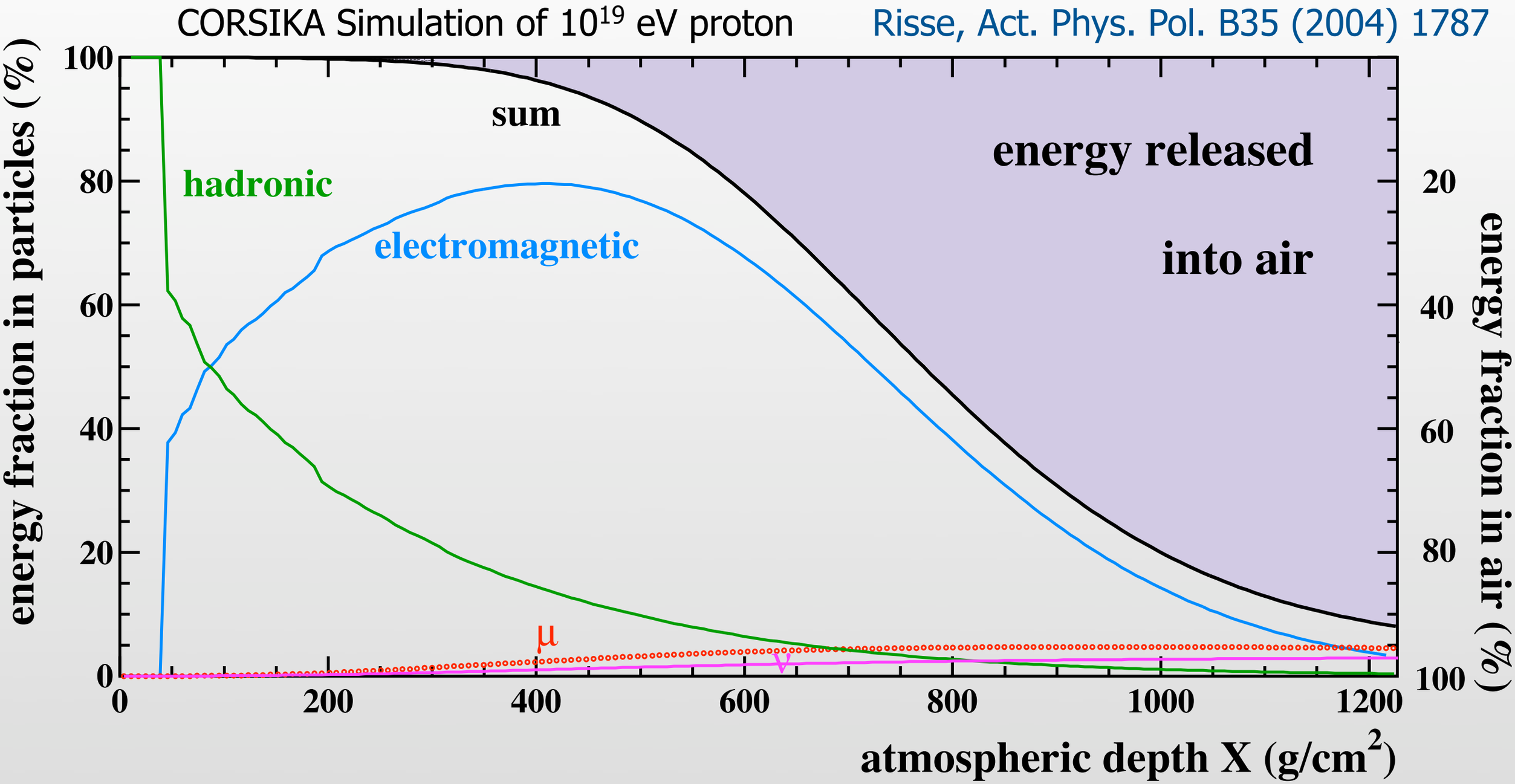
preparing

**JEM-EUSO**
~20000 km$^2$

# Measuring high energy CRs

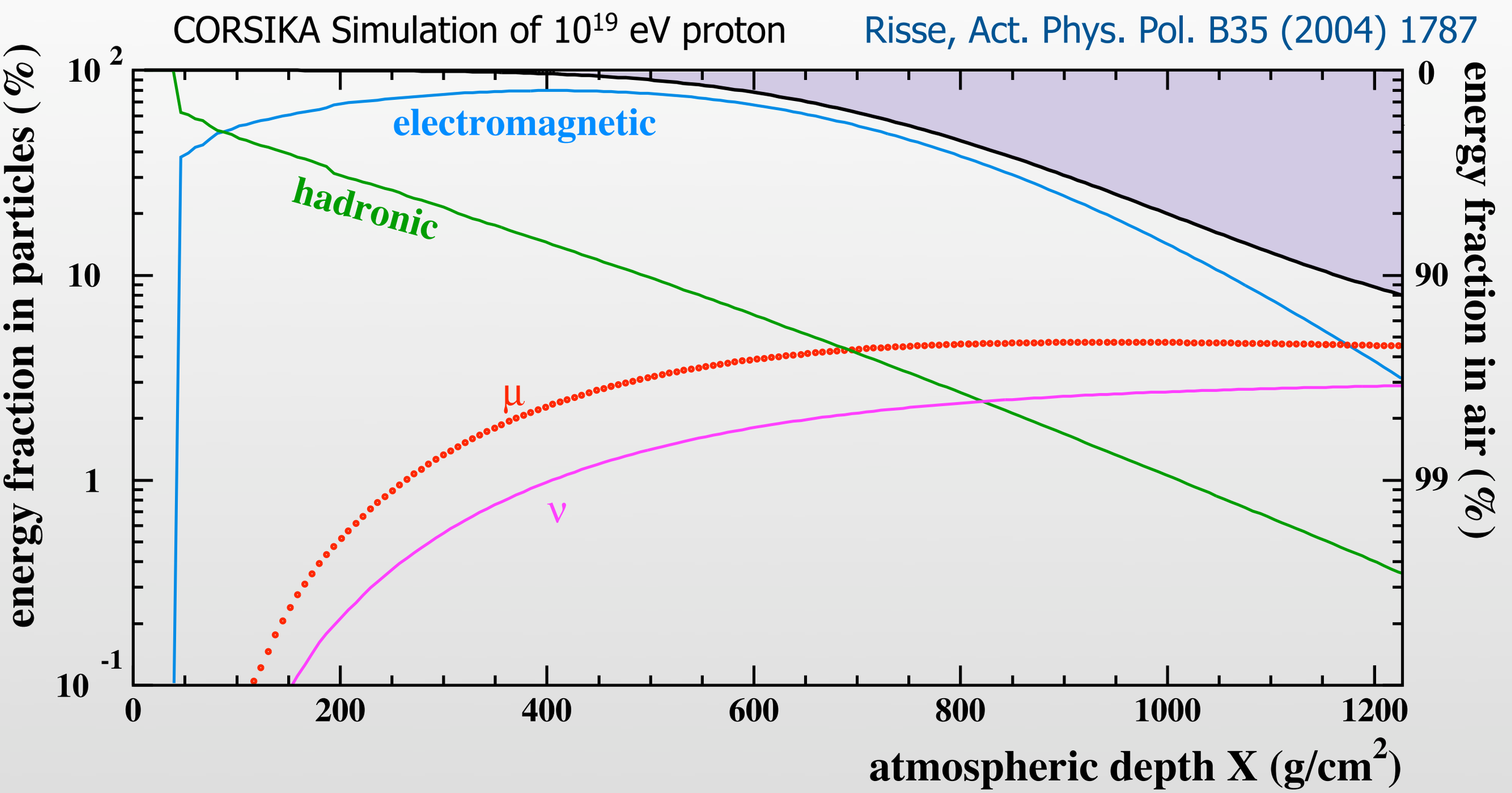


# Energy Flow in EAS (lin)




**~ 90 % of primary energy dumped into atmosphere**

# Energy Flow in EAS (log)




**~ 90 % of primary energy dumped into atmosphere**

# EAS Observables

- **Particle numbers at ground**
  - **electrons**
  - **muons (also underground)**
  - **hadrons**

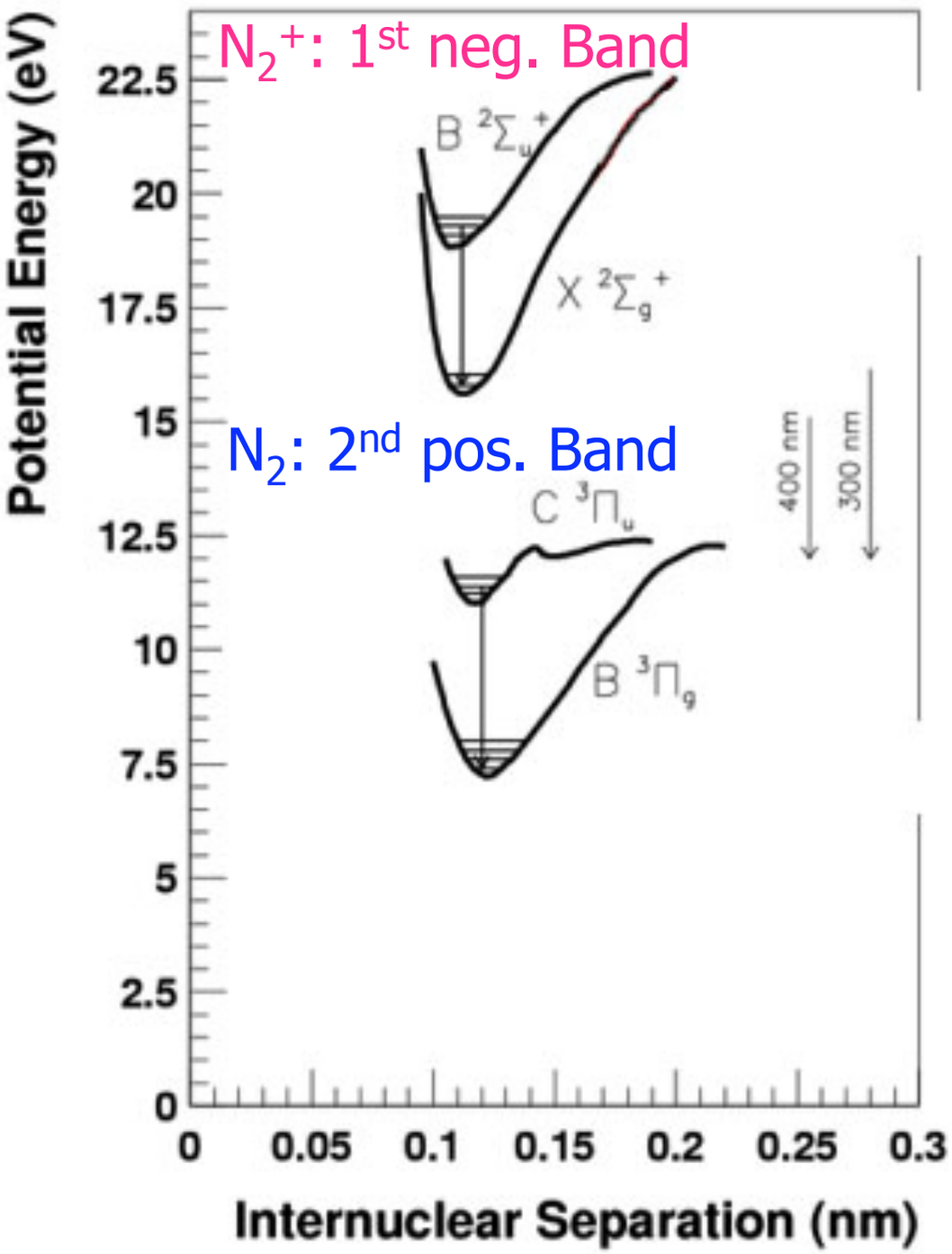
$E > 10^{14}$ eV

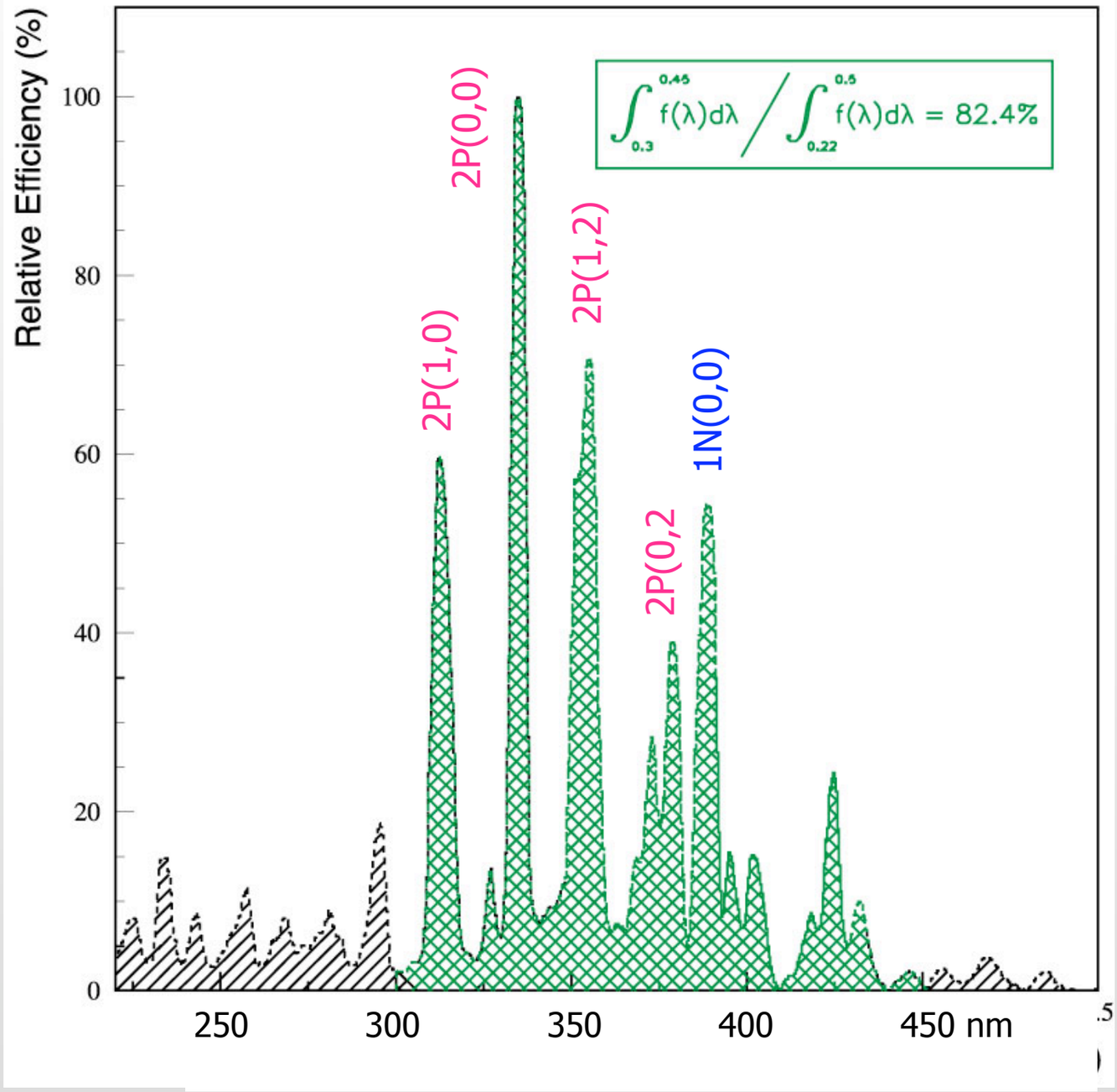
- **Cherenkov light**
- **Fluorescence light**
- **Radio signals** (recently proven ...)

$E > 10^{17}$ eV

- **Acoustic signals** (perhaps far future)
- **Infrared signals** (just an idea...)
- **...?**

# Fluorescence Spectrum

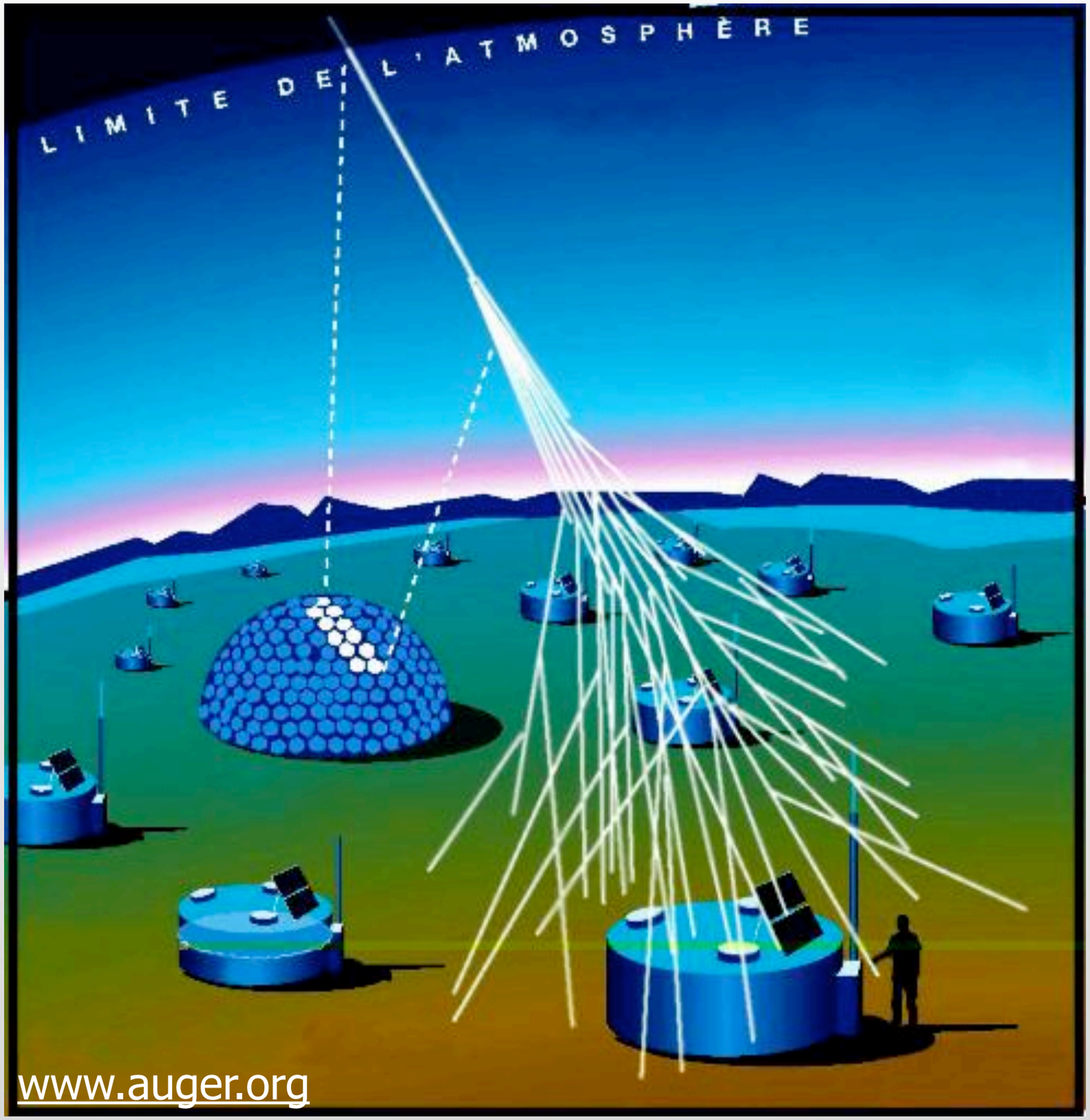



**Fluorescence yield ~ 4 photons / electron / metre (isotropic ! )**

(overall efficiency ~ $5 \times 10^{-5}$; Cherenkov ~ $10^{-3}$)

# Pierre Auger Observatory

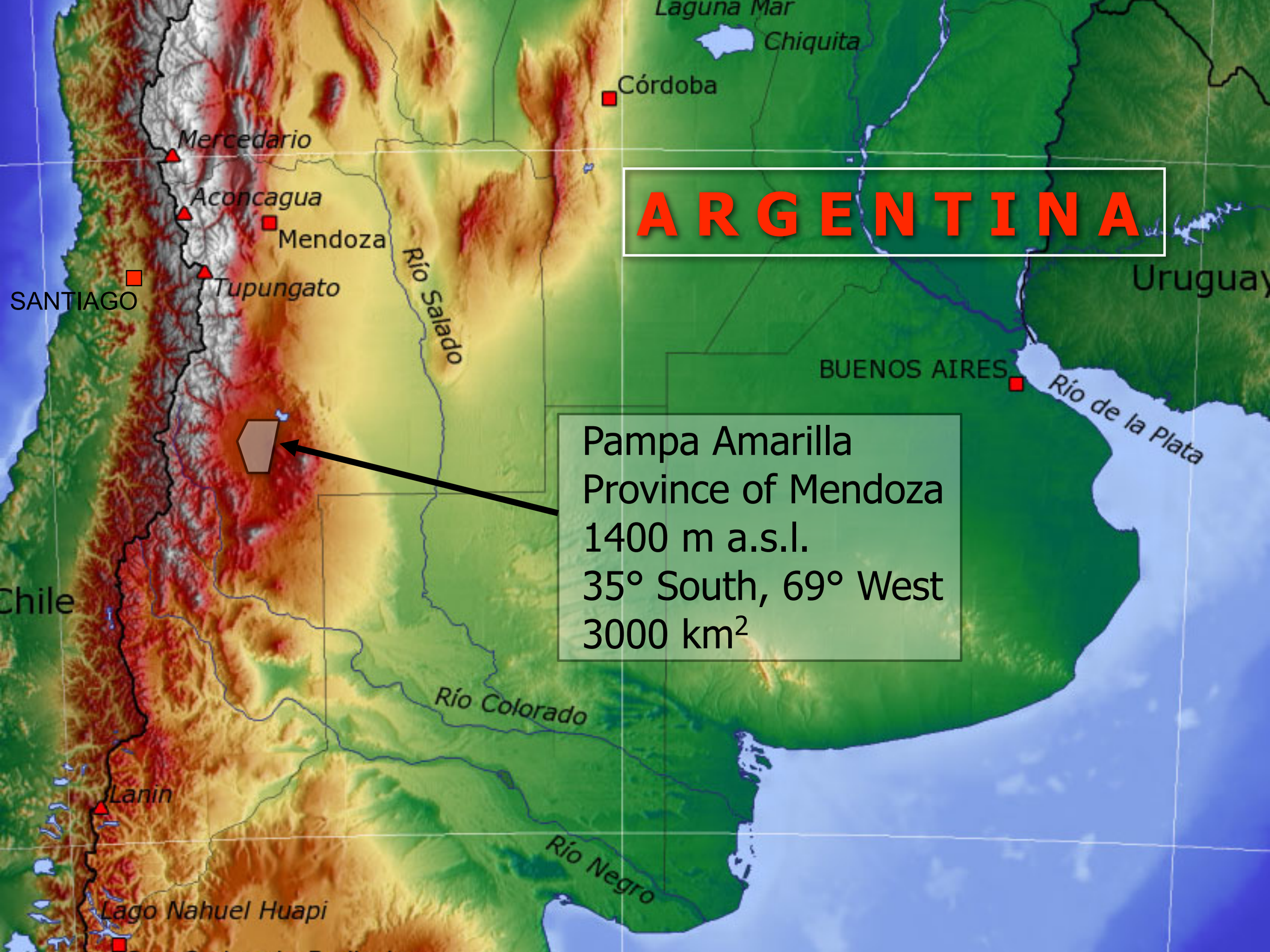



## Hybrid-Concept...

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**


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

## ~370 collaboration members in 63 Institutes from:

**Argentina**

**Australia**

**Brasil**

**Czech**

**France**

**Germany**
- U- & FZ-Karlsruhe
- U-Wuppertal
- U-Siegen
- RWTH-Aachen
- U-Bonn (MPIfR)
- U-Hamburg
- U-Frankfurt

**Italy**

**Netherlands**

**Poland**

**Portugal**

**Slovenia**

**Spain**

**UK**

**USA**

**Bolivia***

**Vietnam***

***Associated**

# Pierre Auger Observatory in Argentina

**1600 Water Cherenkov tanks**

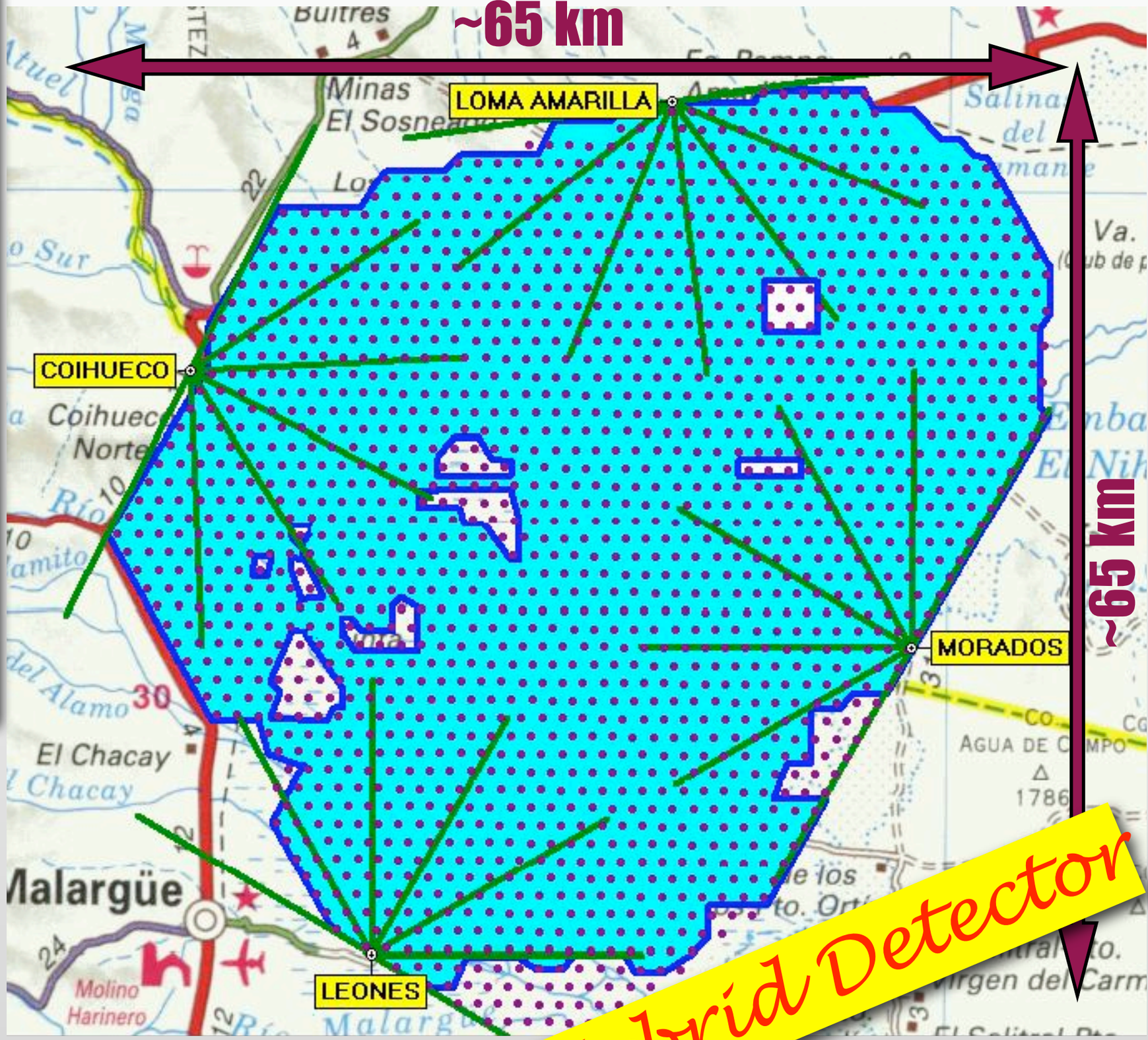
1.5 km grid
1650 tanks deployed
1600 taking data

**24 telescopes**

in 4 buildings at the boundary

**3000 km² area**

*official inauguration:*
*next month !*




Satellite Photo
Image © 2006 DigitalGlobe

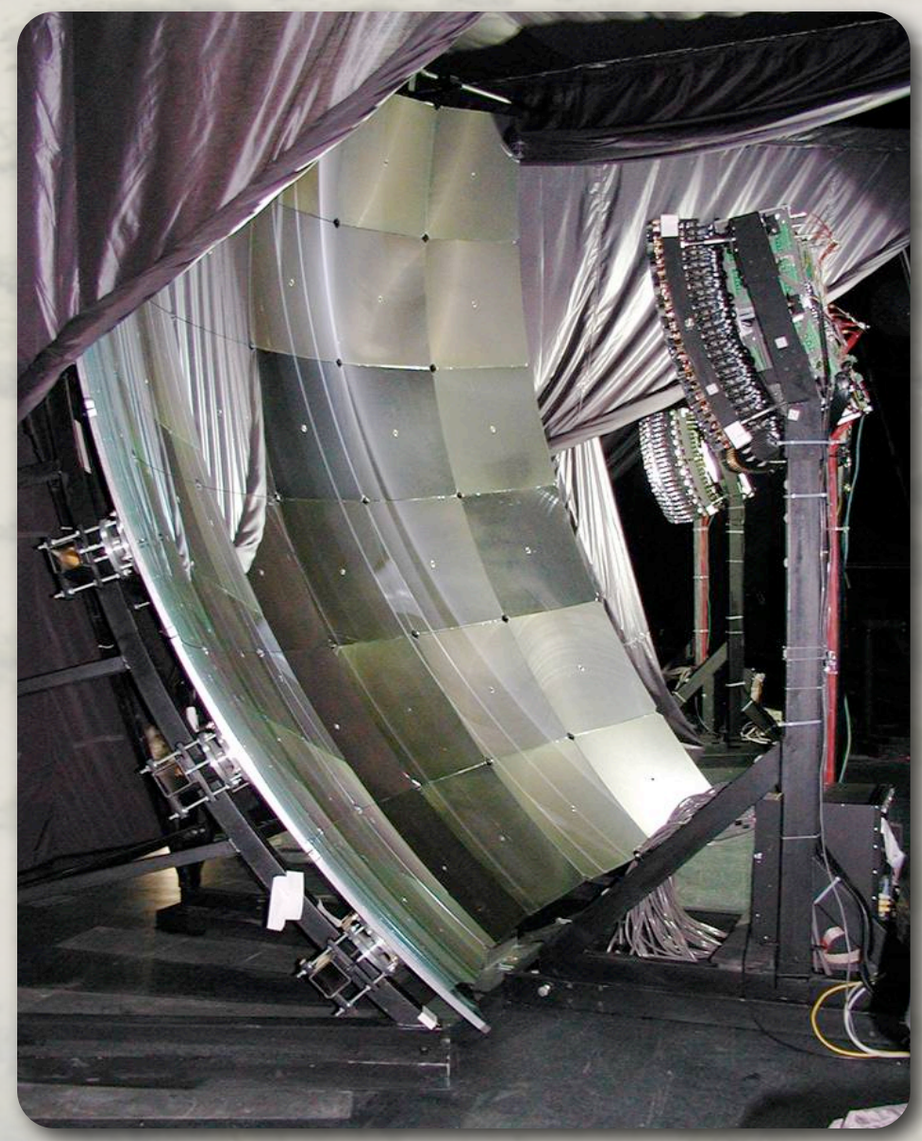
## Stonehenge

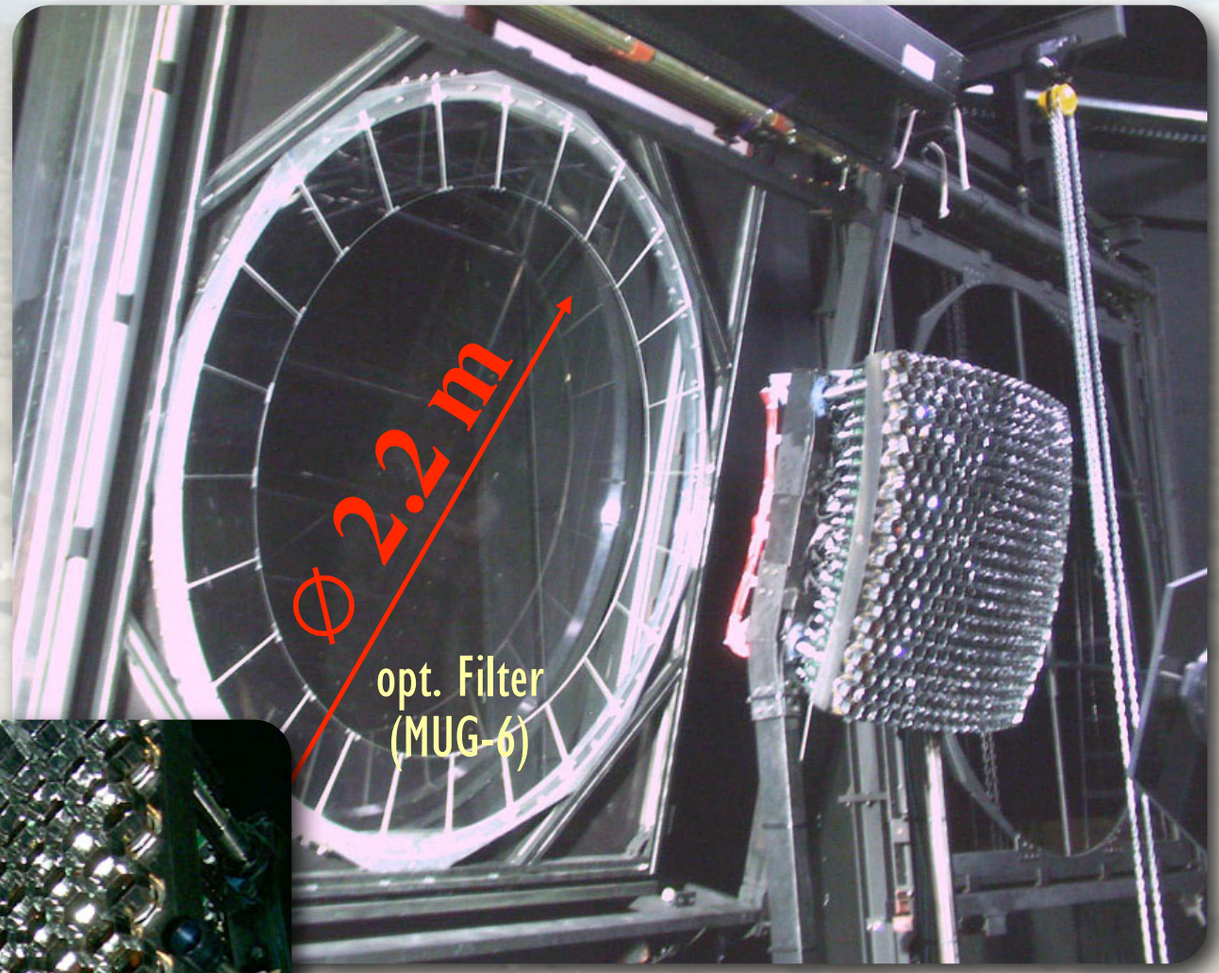
## Pierre Auger Observatory
## Fluorescence Telescope building

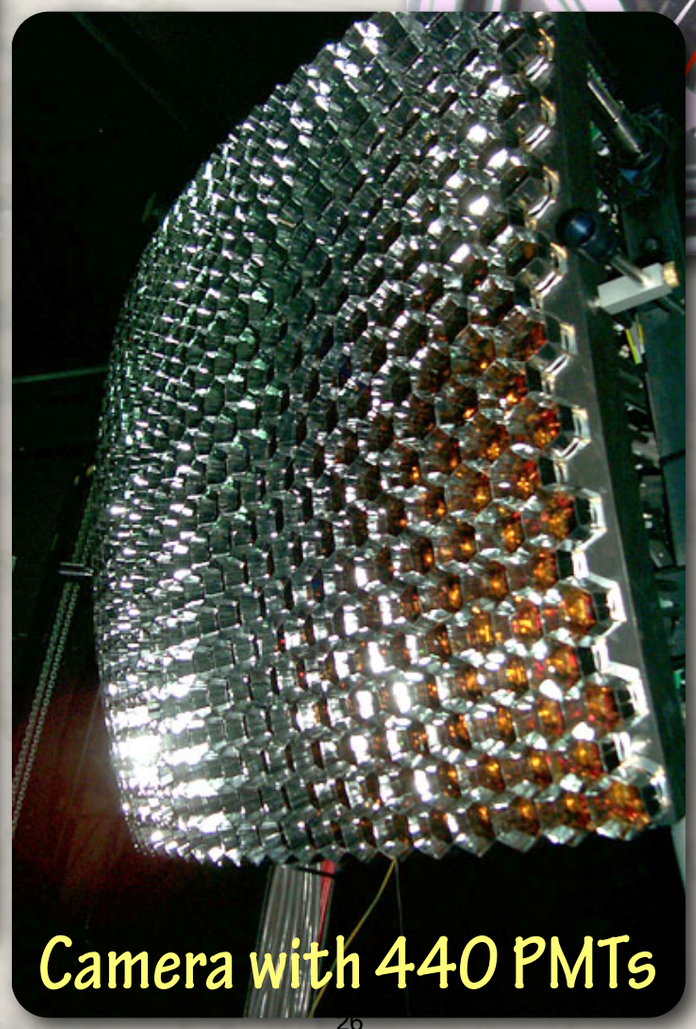
adapted from H. Blümer

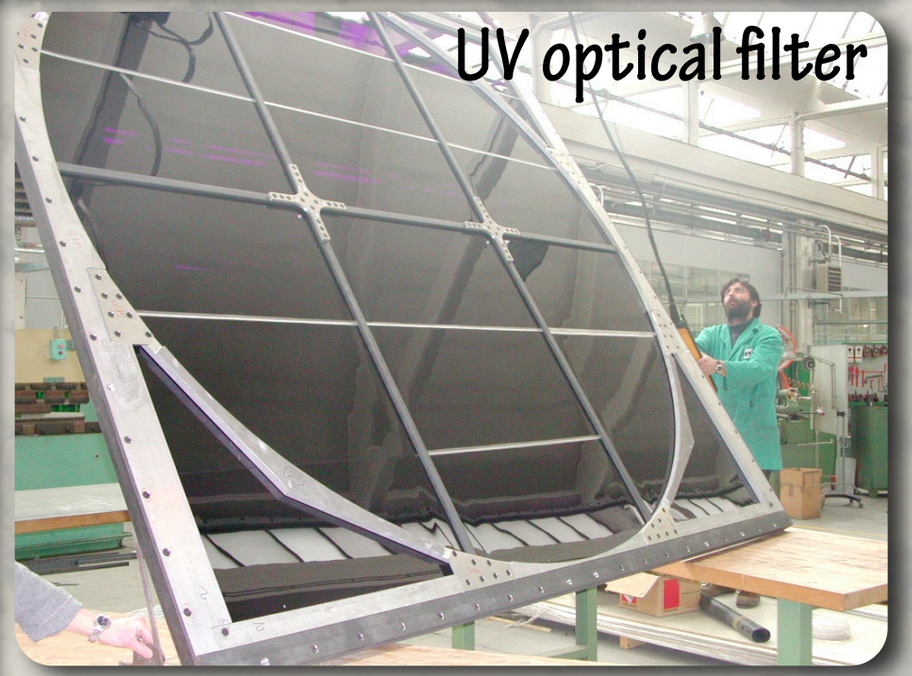
# Camera System of Auger

**24 telescopes (6 per site)**
**12 m$^2$ mirrors, Schmidt optics**
**30°x30° deg field of view**
**440 PMTs/camera**
**10 MHz FADC readout**

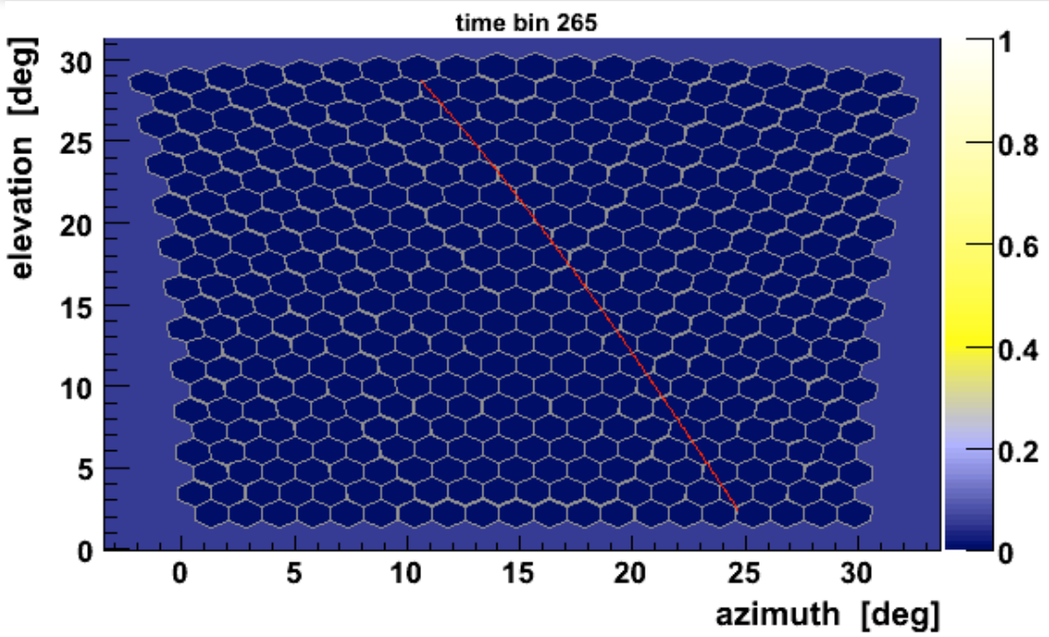


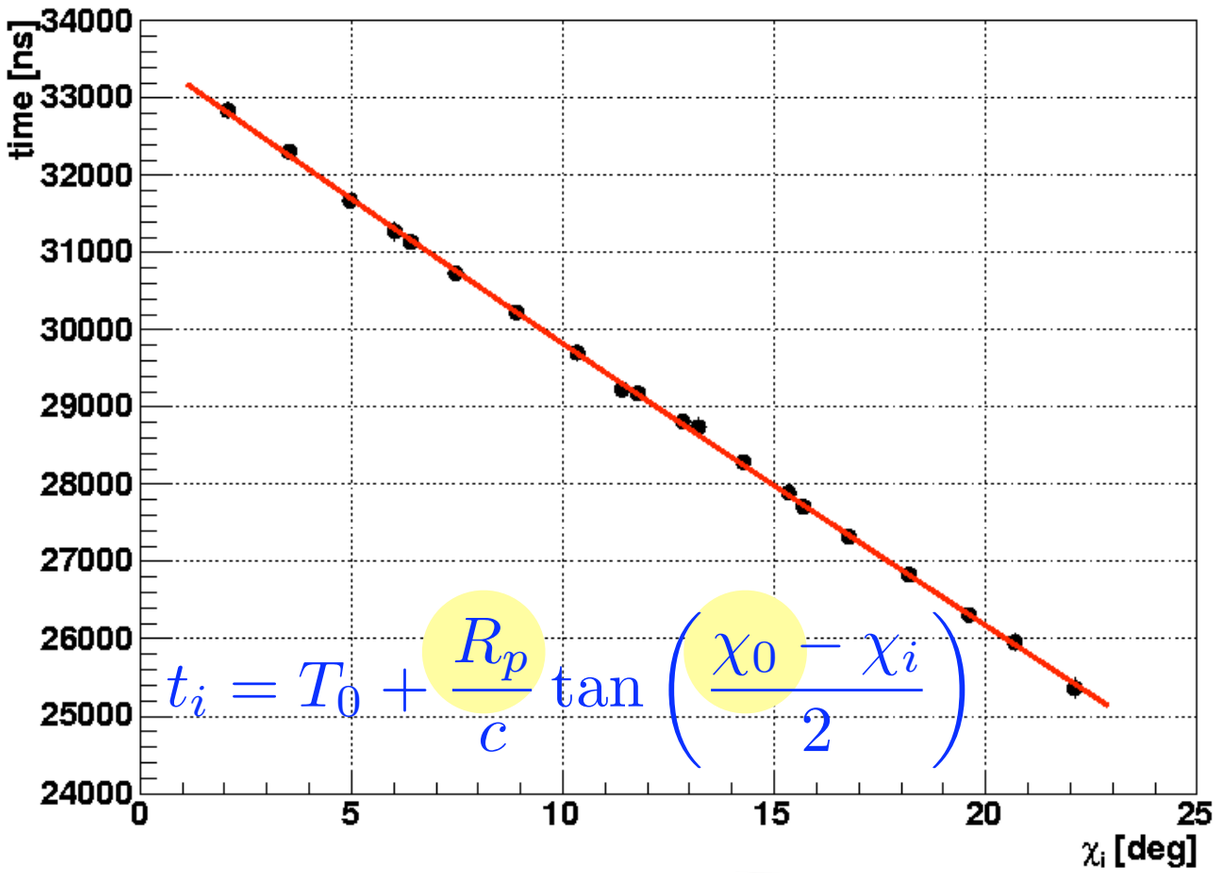


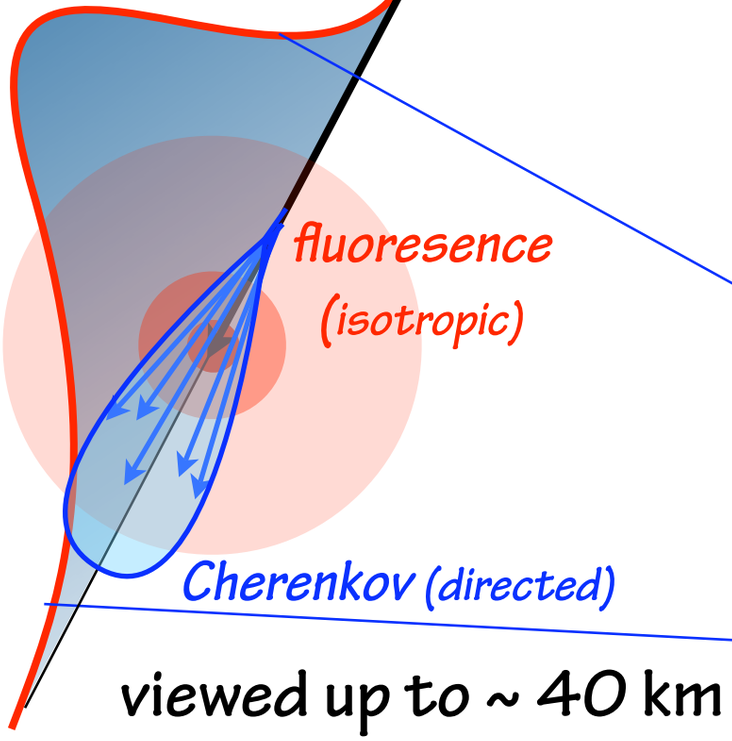



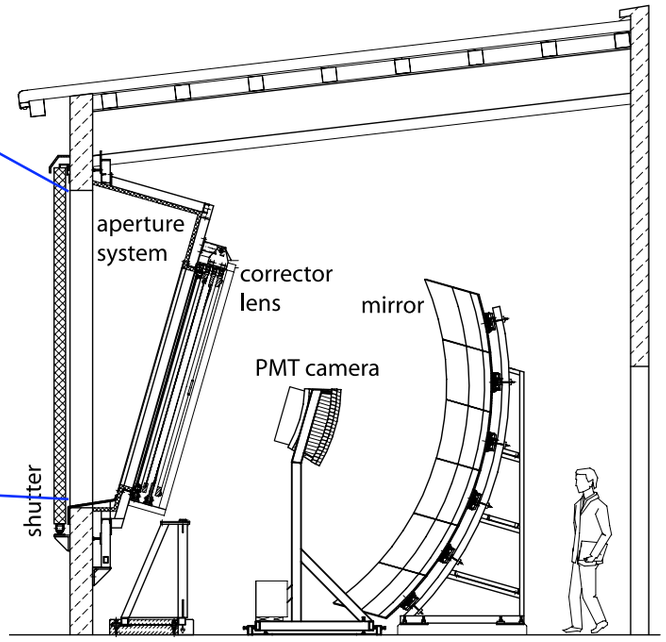



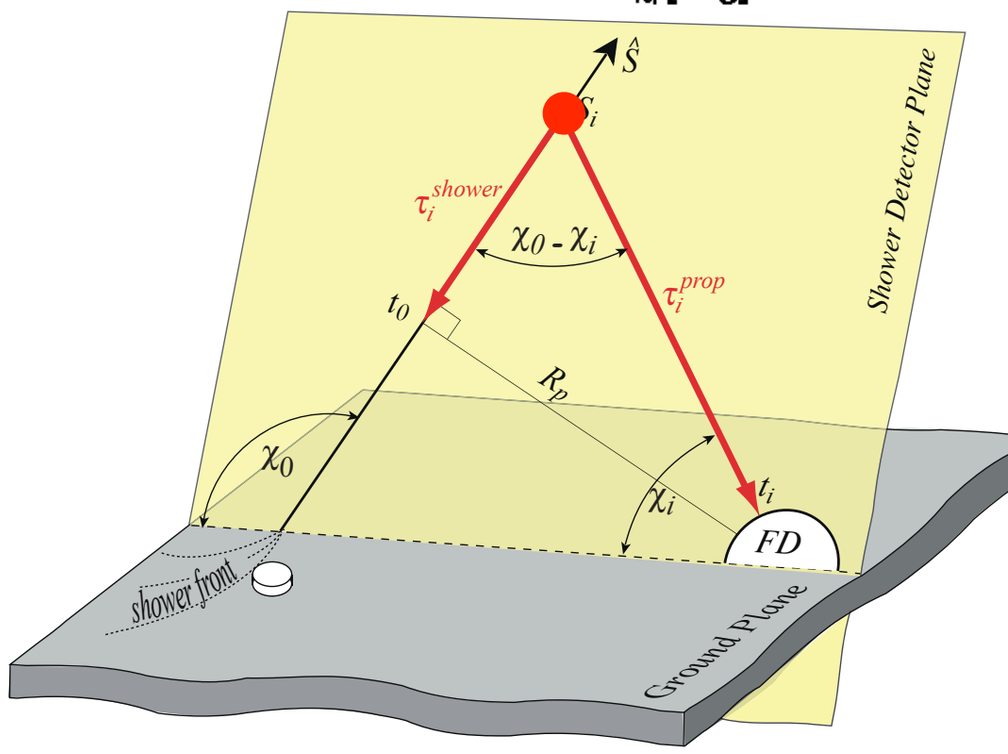
# FD Observation & Reconstruction



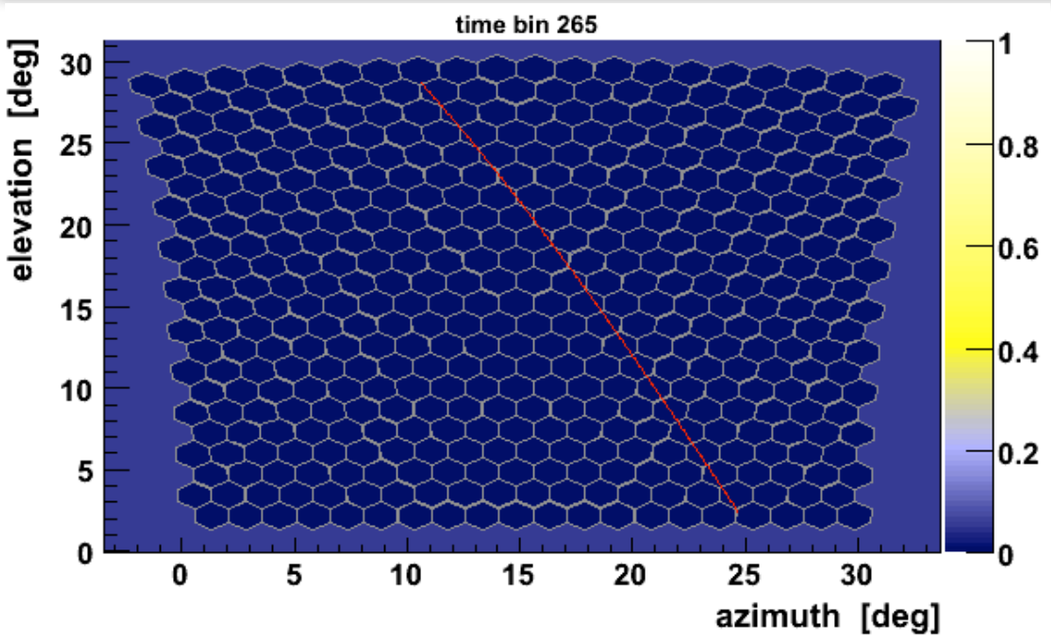



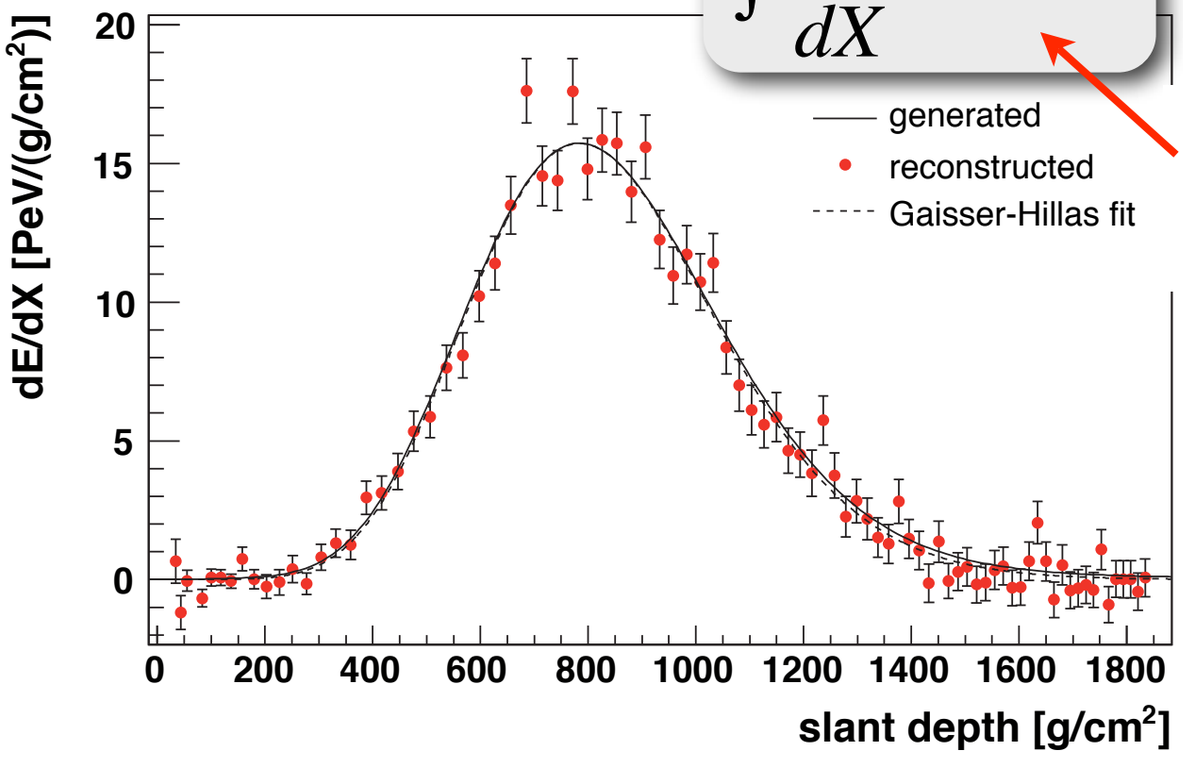



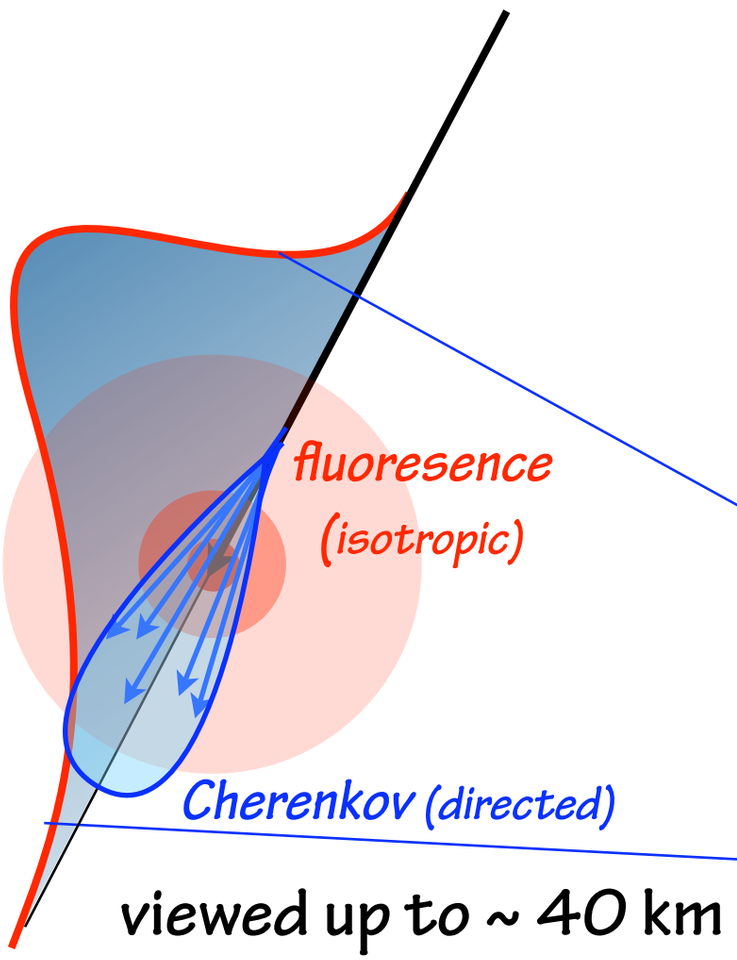
# FD Observation & Reconstruction

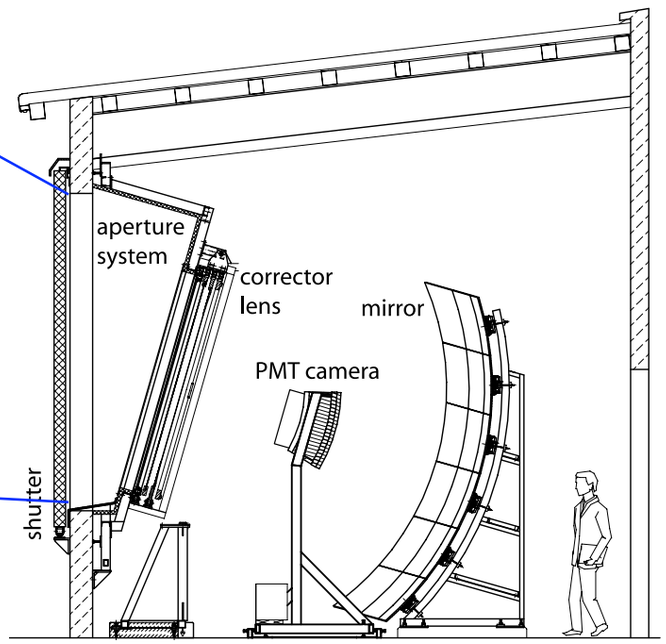


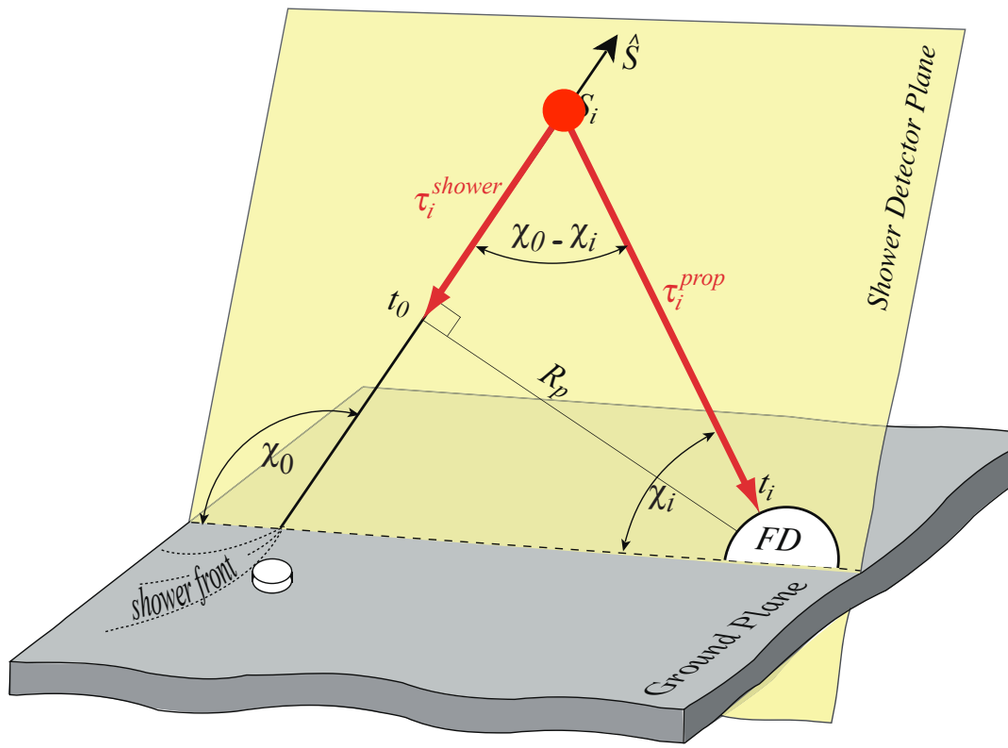

$$\int \frac{dE}{dX} dX \sim E$$

only input: fluoresence yield



# The Auger Ground Array

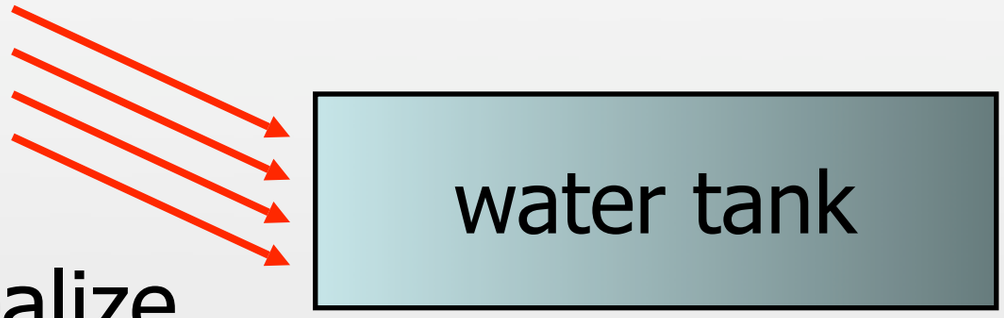
1600 Water Cherenkov tanks
12,000 ltrs of purified Water
(1.2 m height, 10 $m^2$ area)

Three 9" PMTs
40 MHz FADCs
solar powered
GPS based timing
micro-wave communication

# Water or Scintillators? What to choose?

**Advantages of scintillators:**

- much light ⇨ may use cheaper PMTs
- less sensitive to abundant photons close to shower core



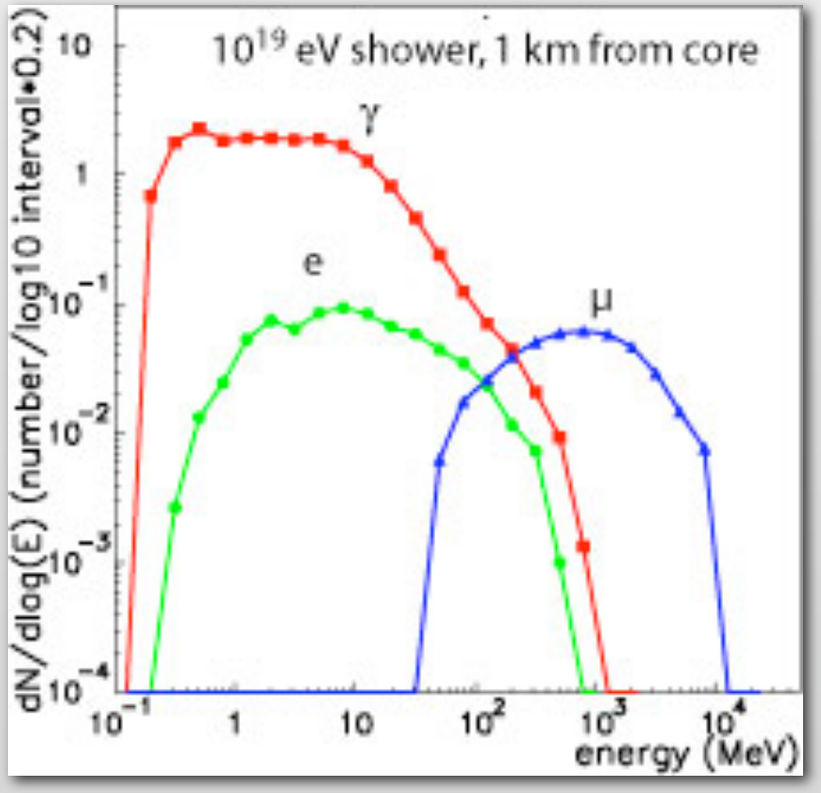

**Advantages of water:**

- large volumes easy and cheap to realize
- large cross-section to horizontal showers

## How to choose depth of water ?

- muon signal ∝ water depth
- low energy electrons absorbed mostly within upper 30-40 cm

→ can be optimized for 'μ-counting'



# Installation Chain


Water deployment

# Secret Business: Honeyfarm Auger

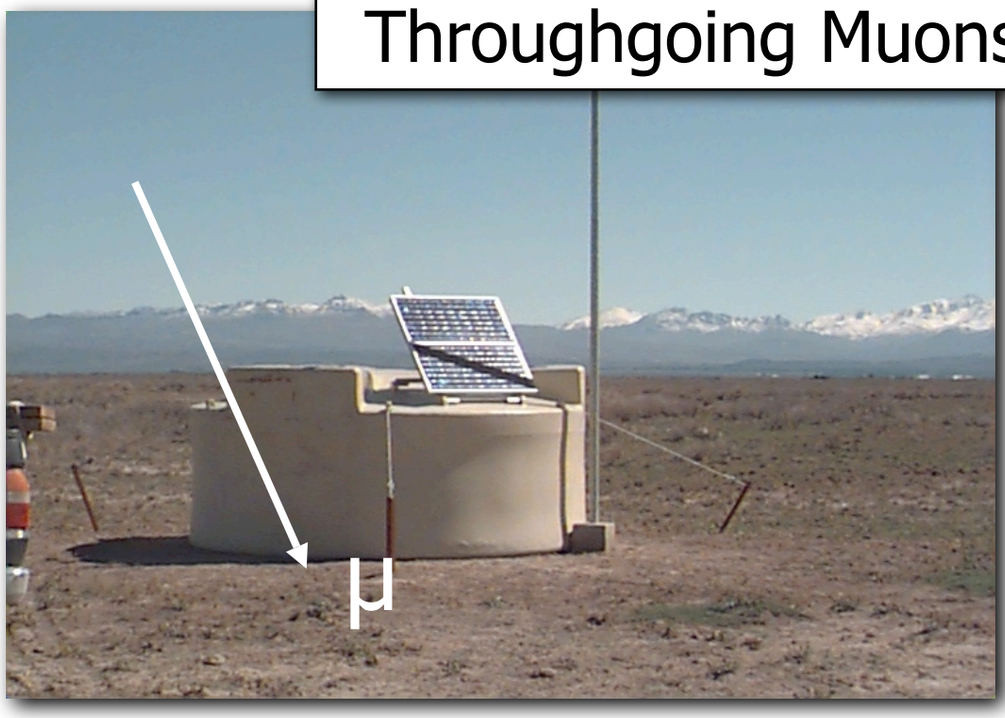


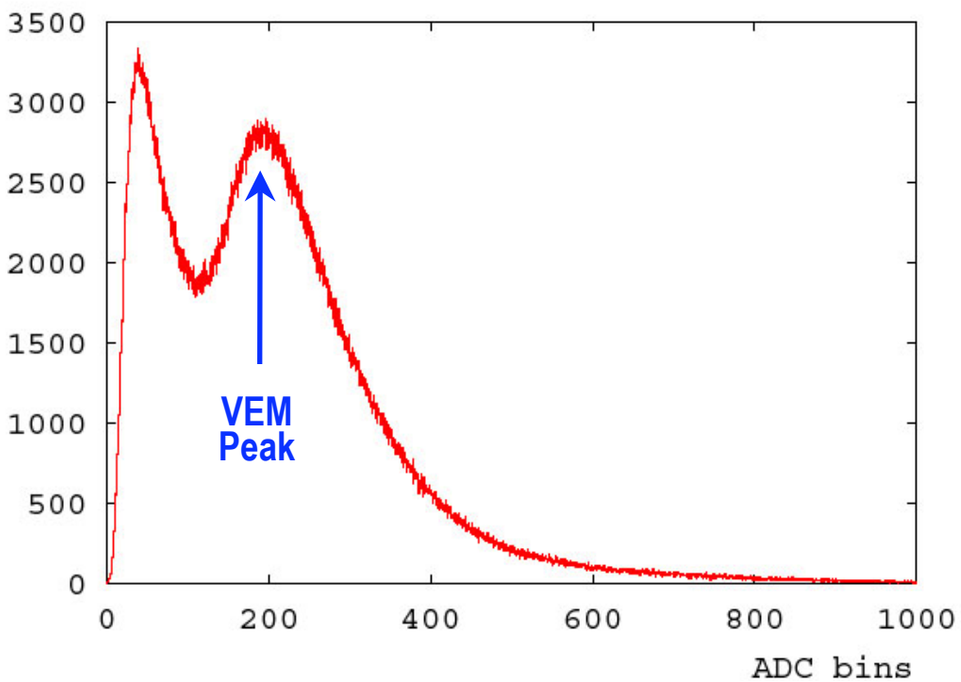
Karl-Heinz Kampert – University Wuppertal

# Detector Calibration

## Ground-Array

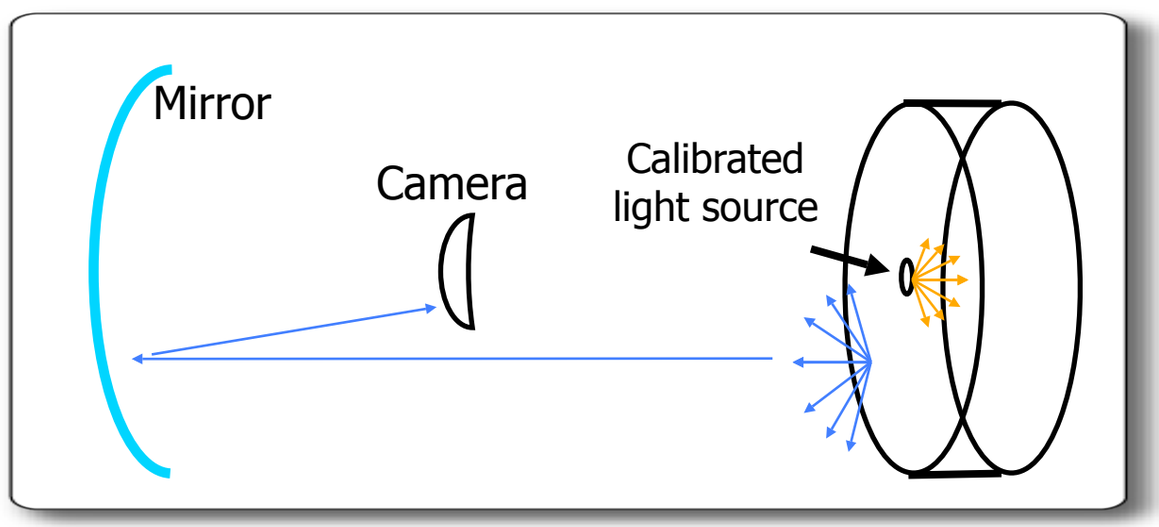
### Throughgoing Muons



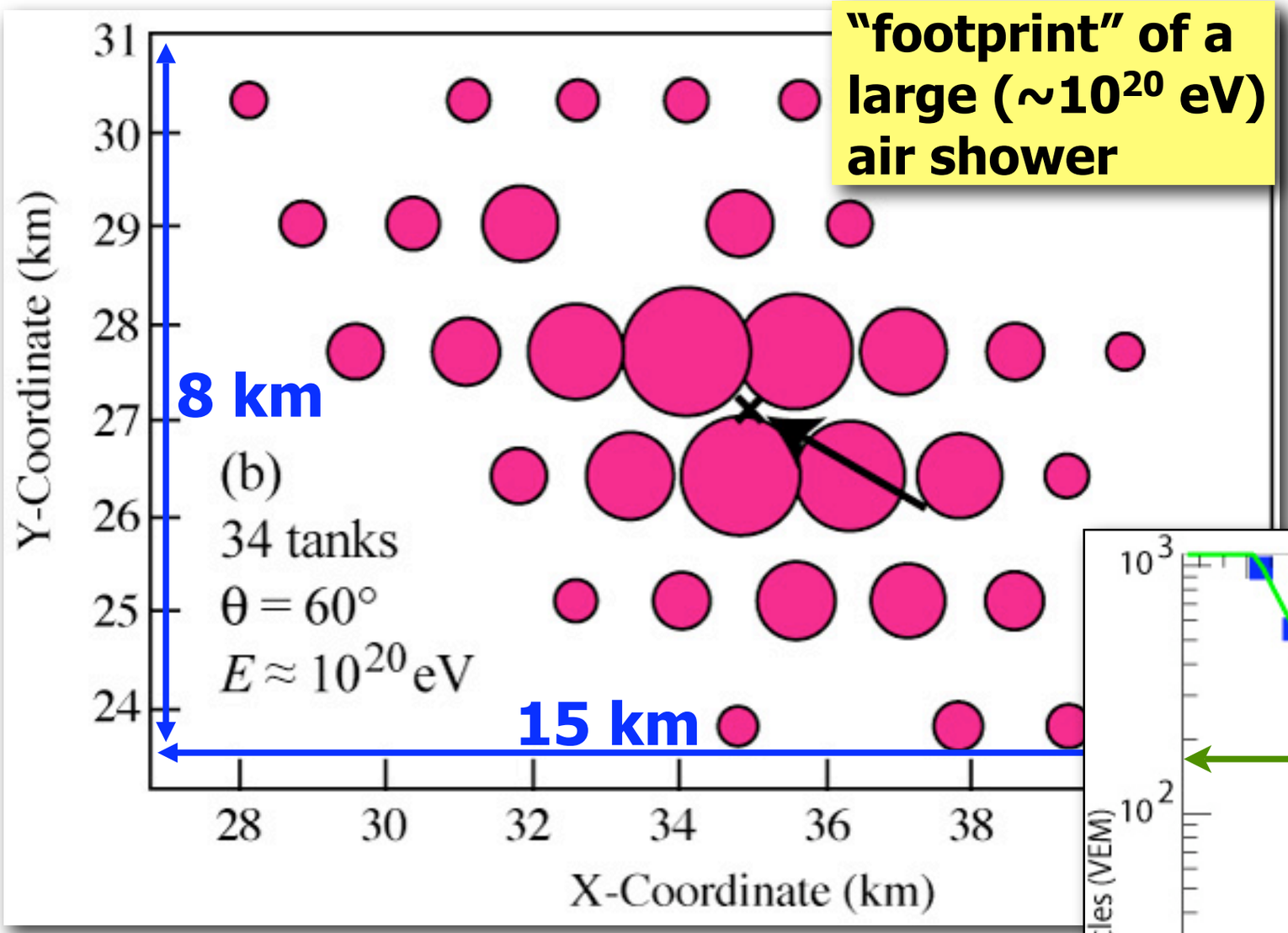

## Fluorescence Telescopes

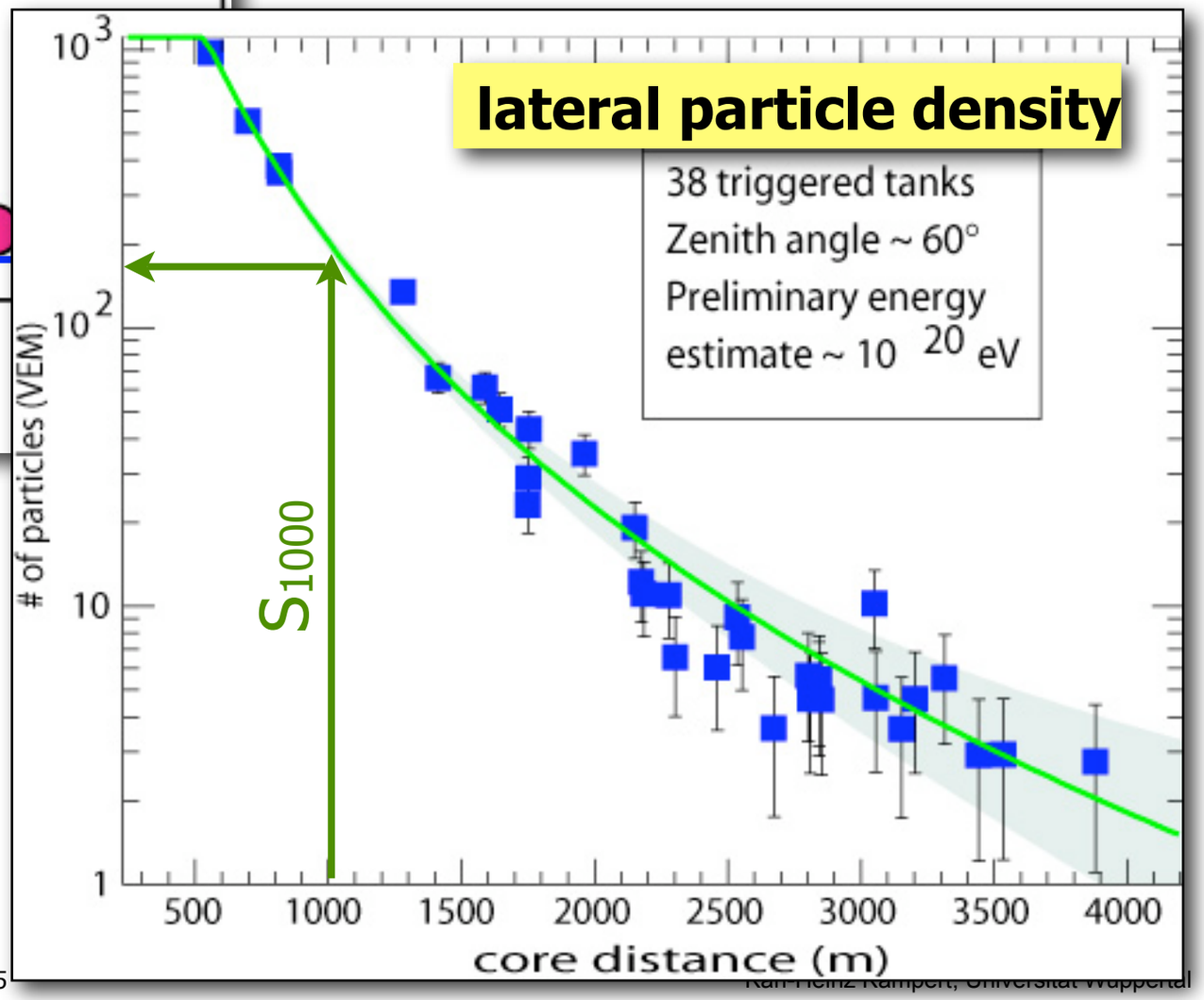
### Diffuse Lightsource



# Energy Spectrum

# SD Event & Reconstruction

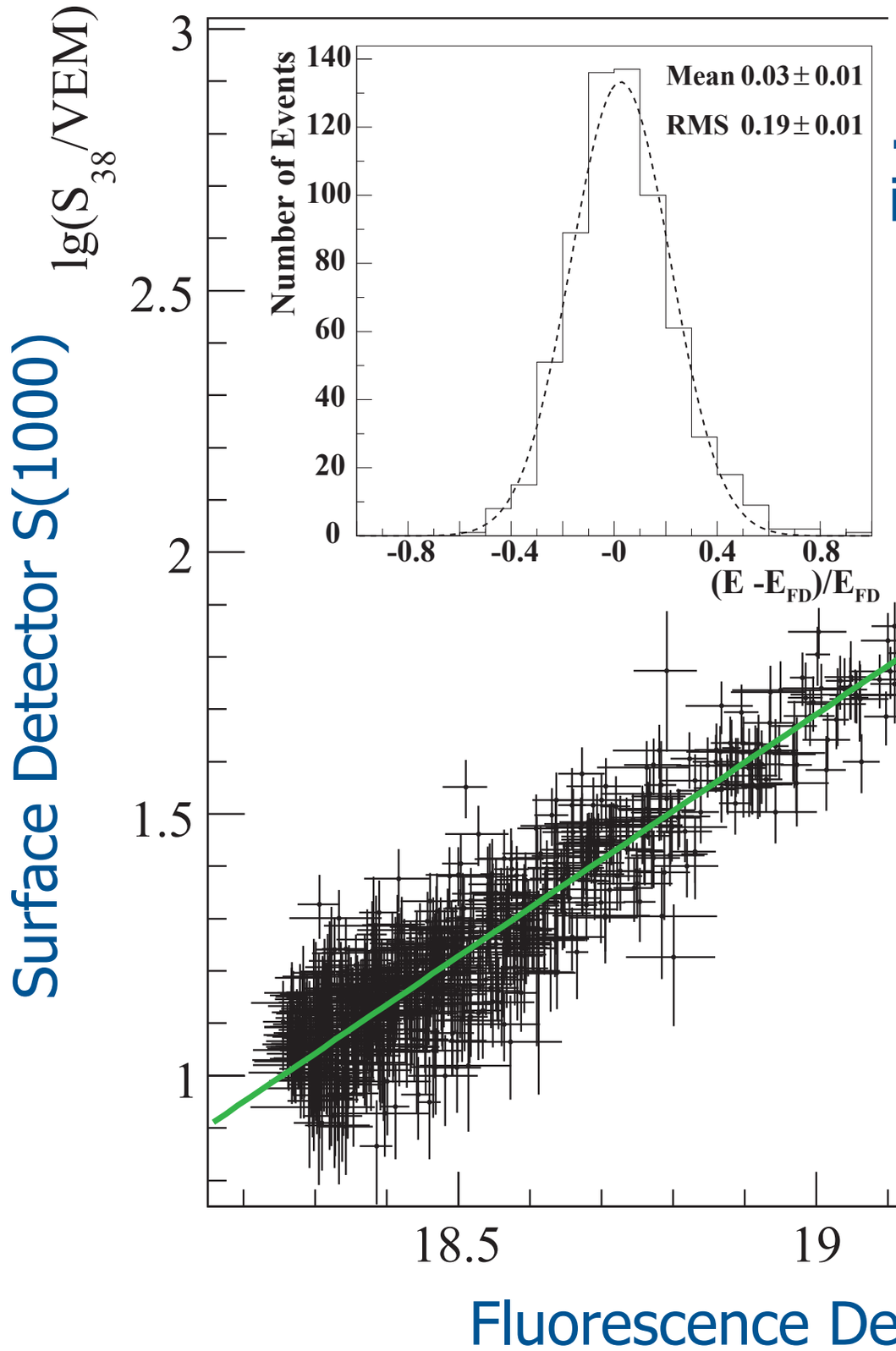



Simulations: particle density at 1000 m ($S_{1000}$) provides good estimate of primary energy

**different models: ~20-30 % syst. errors**

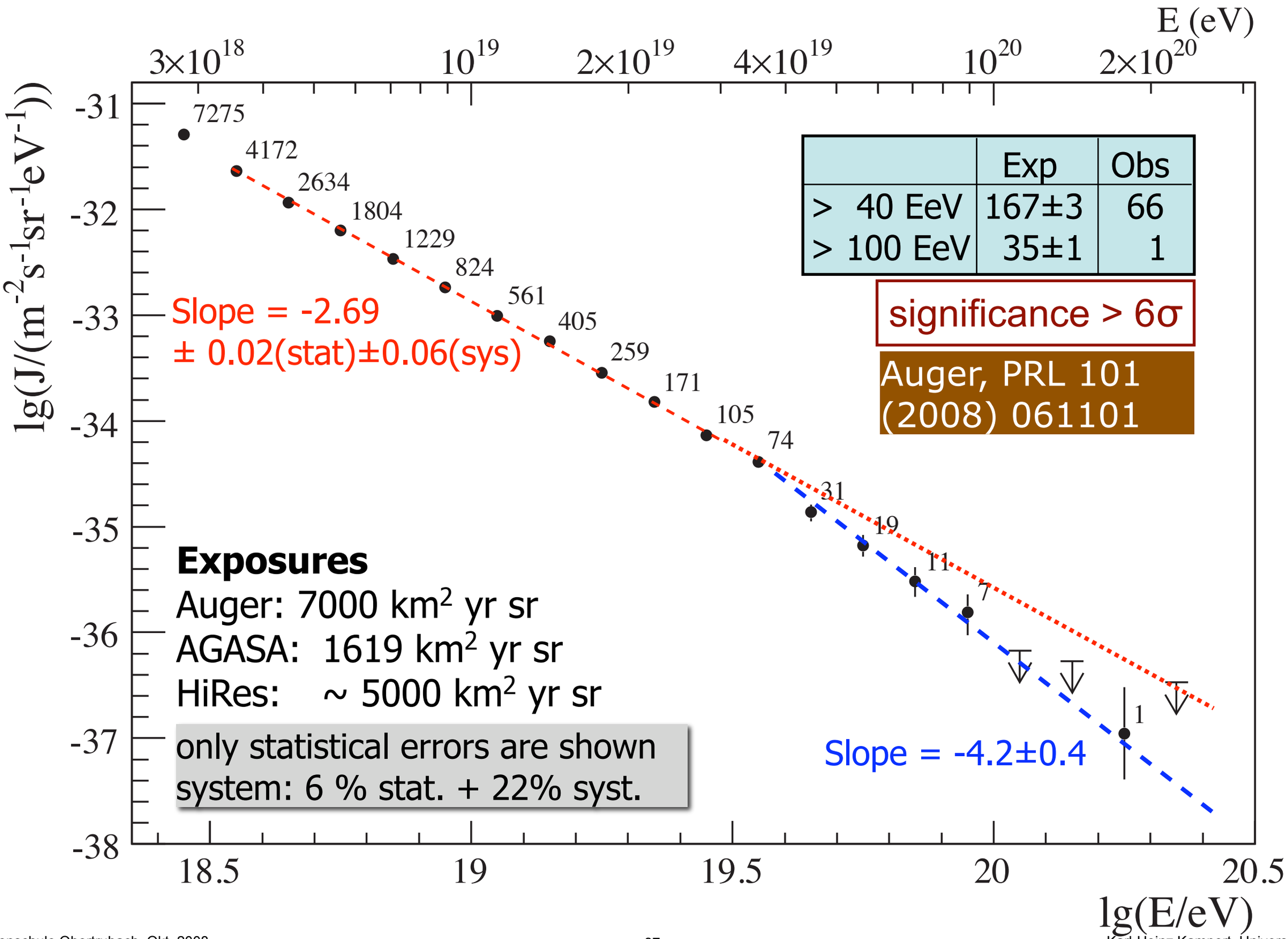
# Ground Array Calibrated by FD




$\sigma$ ($E_{FD}$-$E_{SD}$)= 19%

... improves as energy increases !

# Energy Spectrum & GZK-Effect




| | Exp | Obs |
|---|---|---|
| > 40 EeV | 167±3 | 66 |
| > 100 EeV | 35±1 | 1 |

significance > 6σ

Auger, PRL 101 (2008) 061101

**Exposures**

Auger: 7000 km² yr sr

AGASA: 1619 km² yr sr

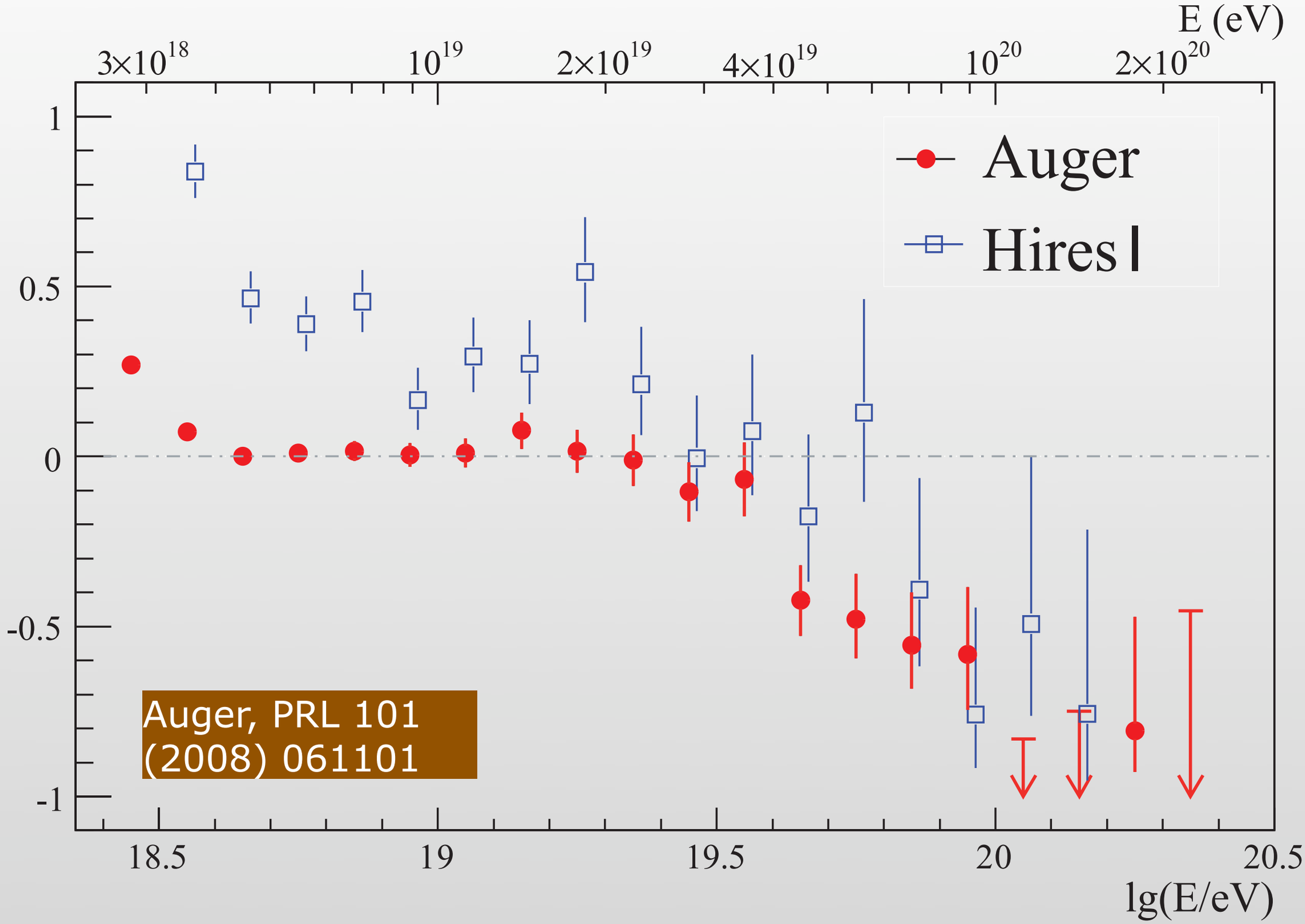
HiRes: ~ 5000 km² yr sr

only statistical errors are shown

system: 6 % stat. + 22% syst.

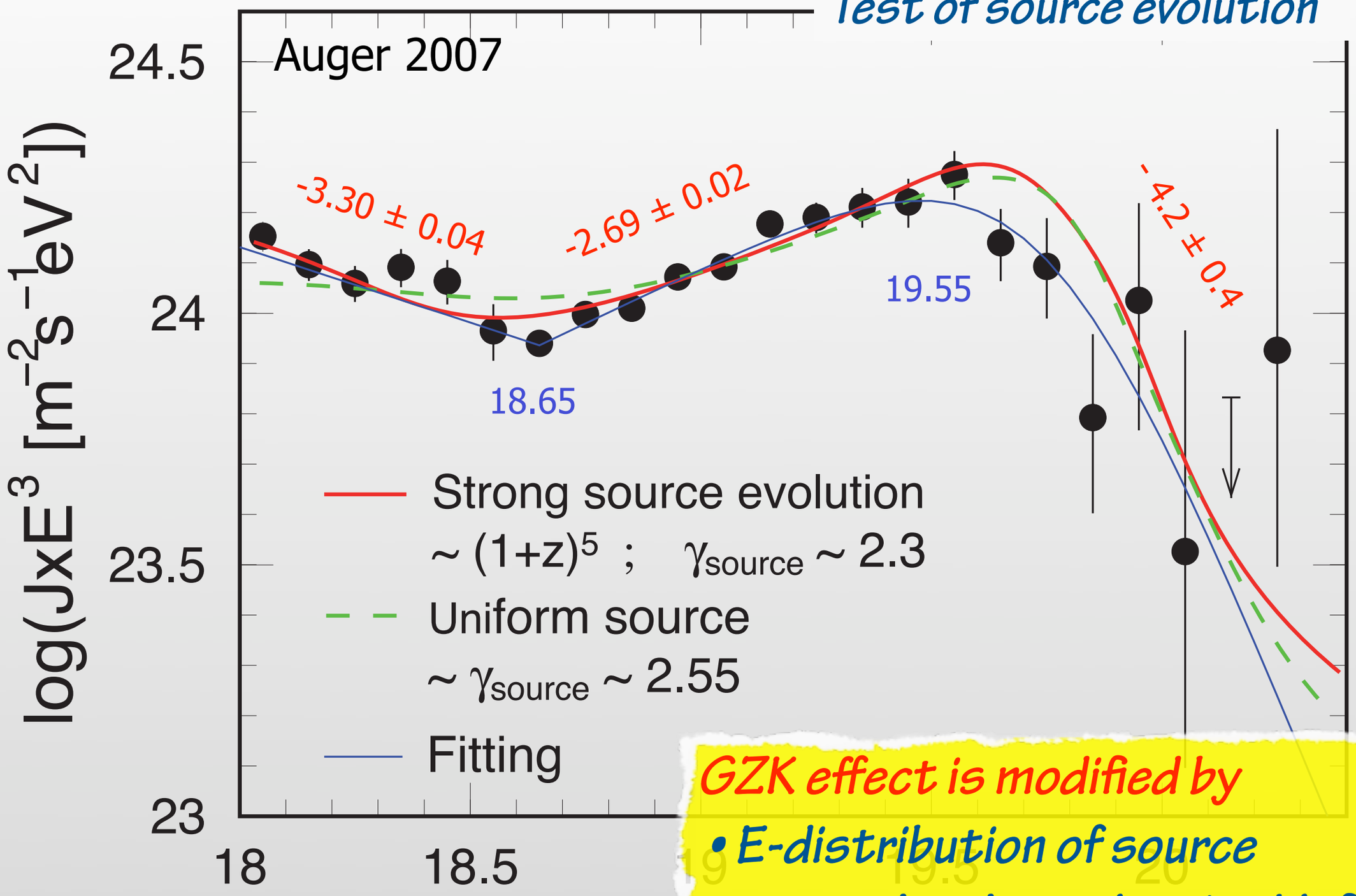
# Auger & HiRes Energy-Spectrum

Fractional difference between $E^{-2.69}$ and Auger & HiRes



# Auger Spectrum & Source Distr.

*Test of source evolution*




*GZK effect is modified by*

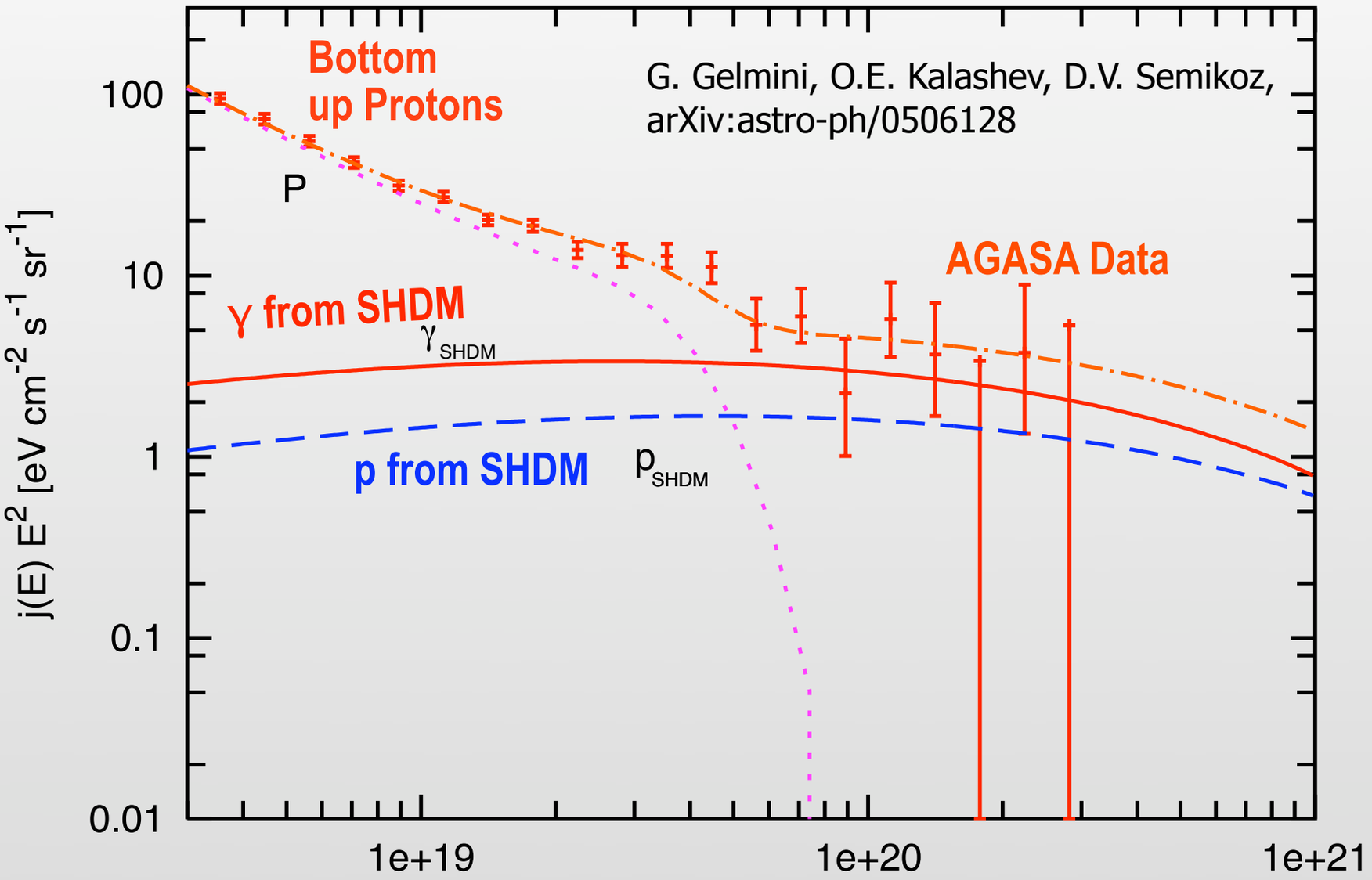
- *E-distribution of source*
- *source local overdensity/deficit*
- *different values of $E_{max}$*

# Composition

# Photons

# Photons: Physics Case

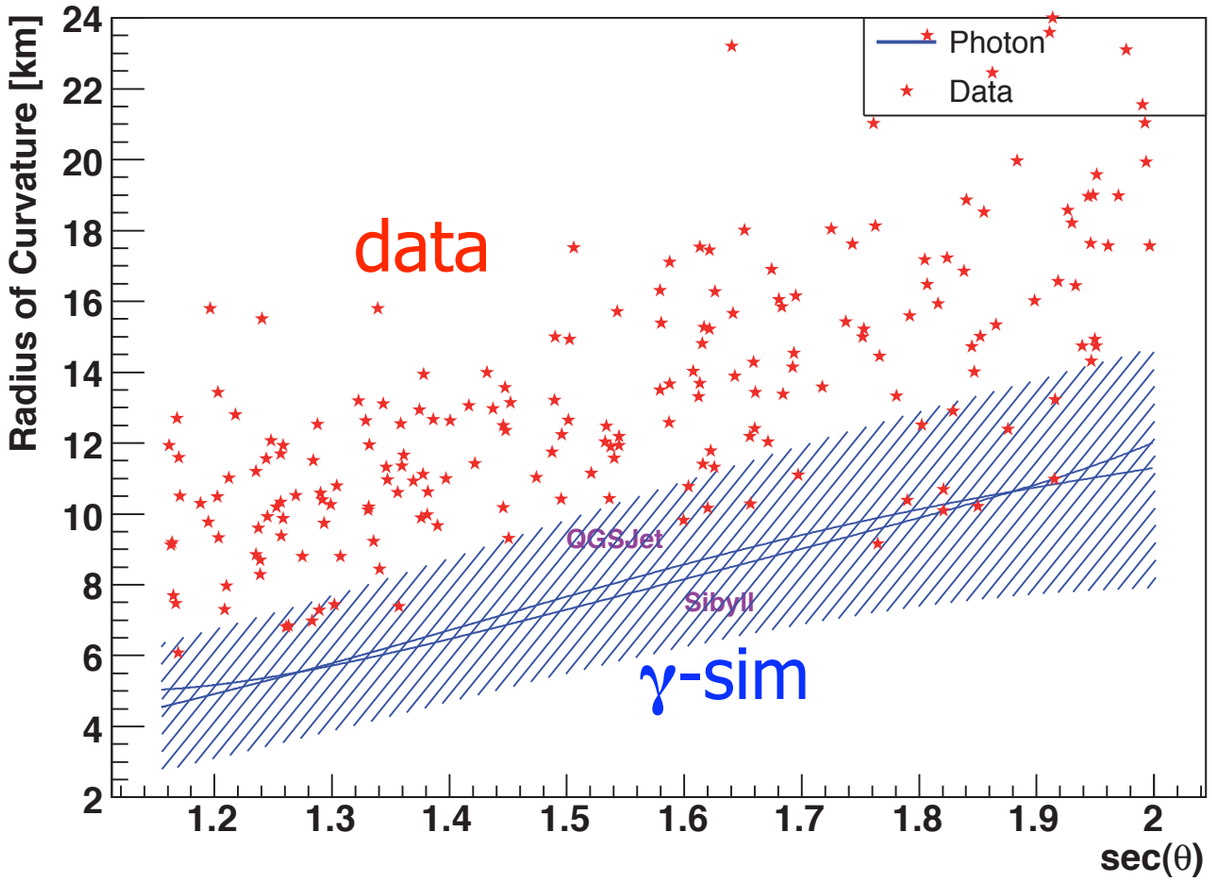
**Top-Down Models,** like Super-Heavy Dark Matter Models, topological defect, Z-Burst-Models, etc. **predict photon** and **neutrino dominance**

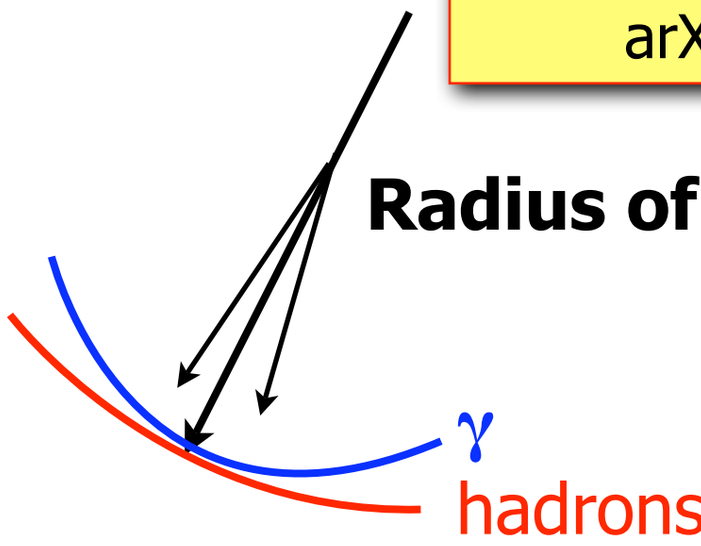



- relatively save to simulate
- relatively easy to separate from hadron primaries
- never done by observation of longitudinal profile

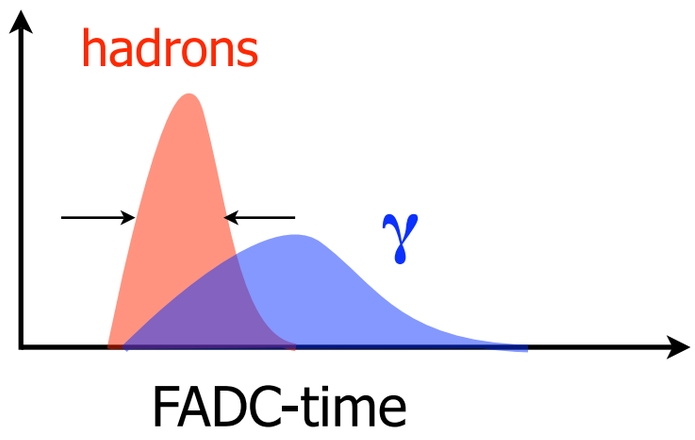
# Photon Signatures in Ground Arrays

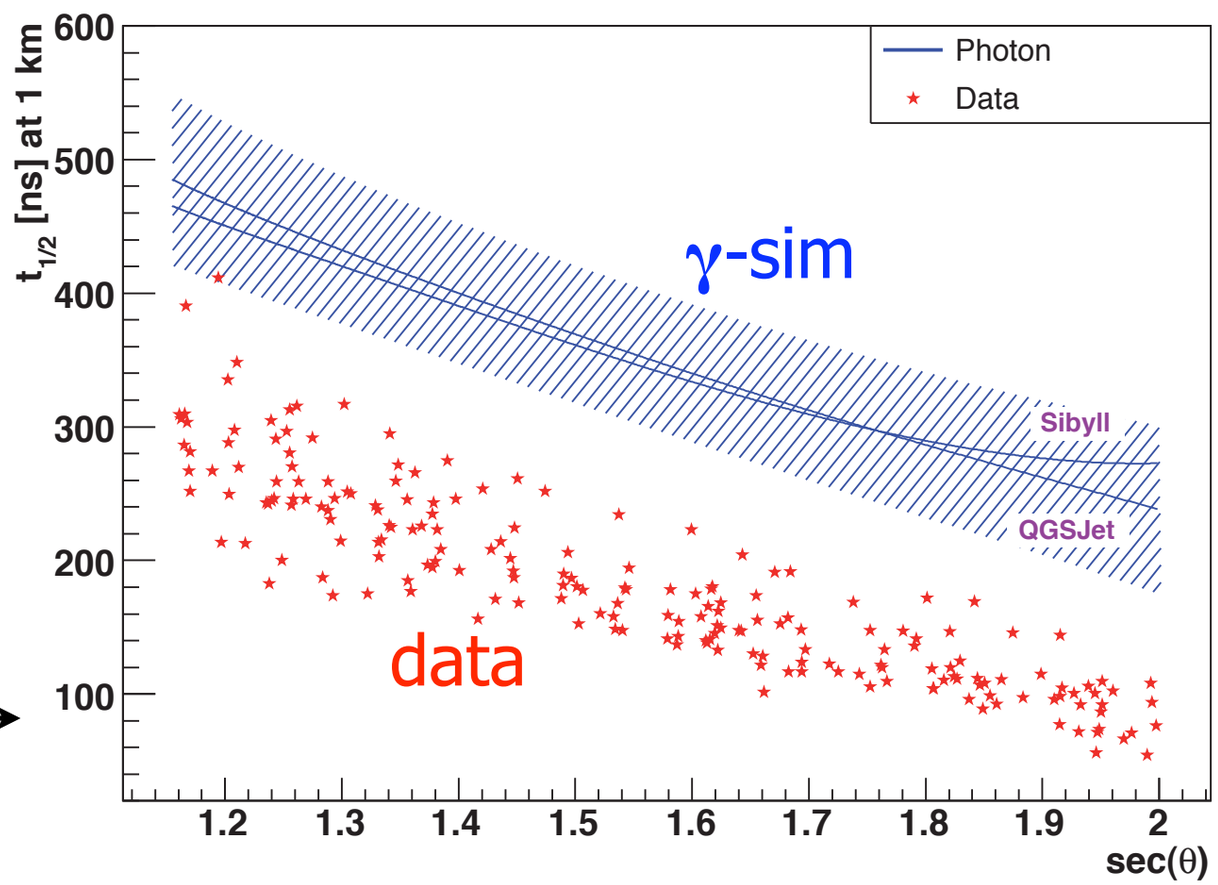
Auger; APP 29 (2008) 234
arXiv:0712.1147



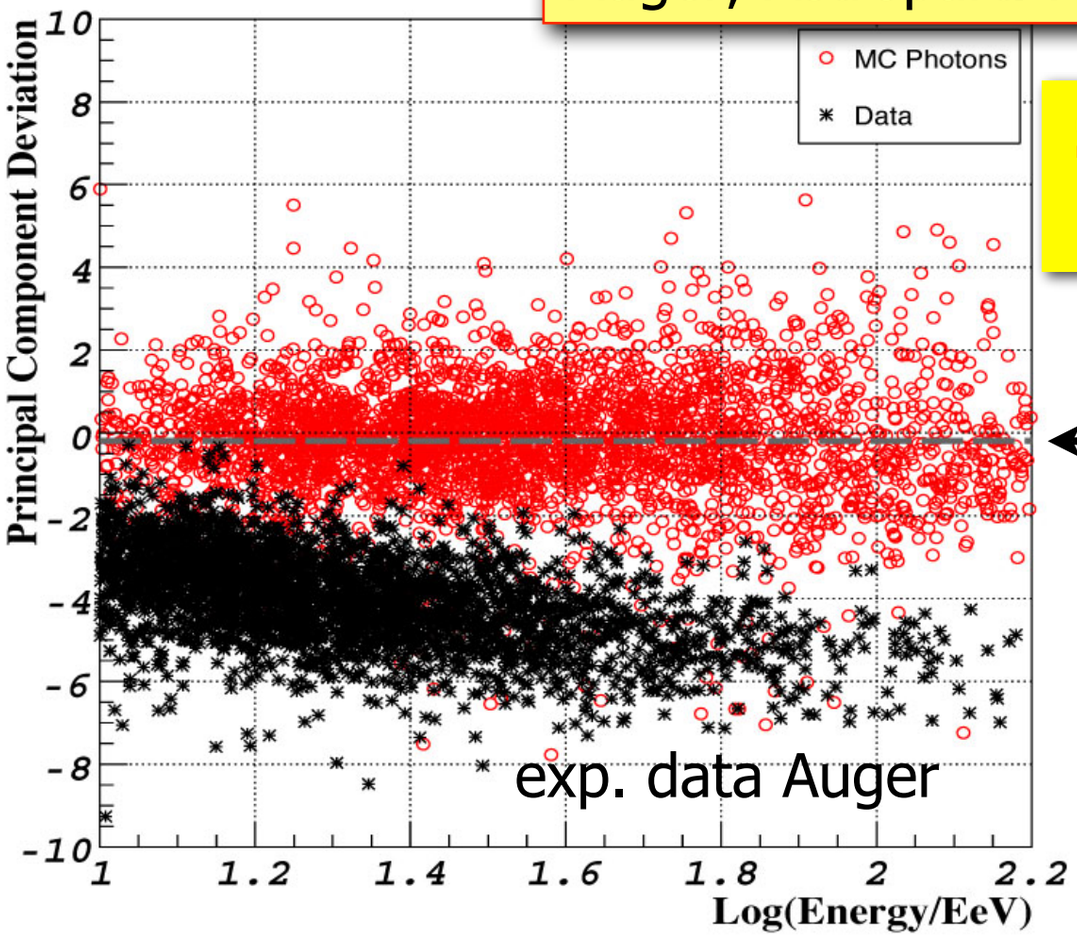

## Signal width



# UHE-Photon Limits: Results

Auger; Astropart. Phys. 27 (2007) 155; Astropart. Phys. 29 (2008) 234

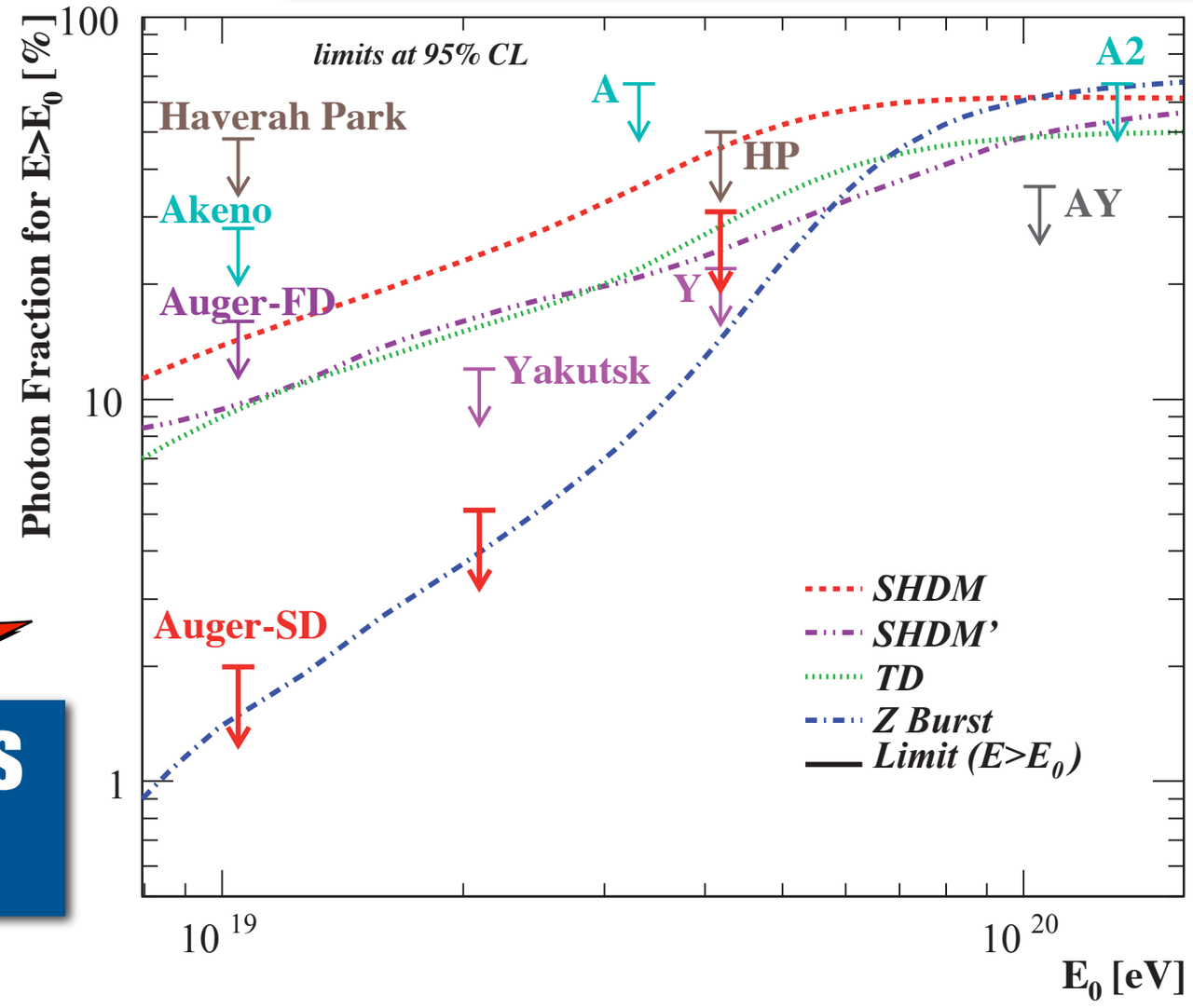



**SD-Data: rise-time & shower-front curvature ⇔ μ # ⇔ primary mass**

$\gamma$ -simulation

← (median)

**95% CL on photon fraction**




**SHDM & TD models largely ruled out**

# Tests of Lorentz Invariance Violation

LIV ➙ may modify photon dispersion relation

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

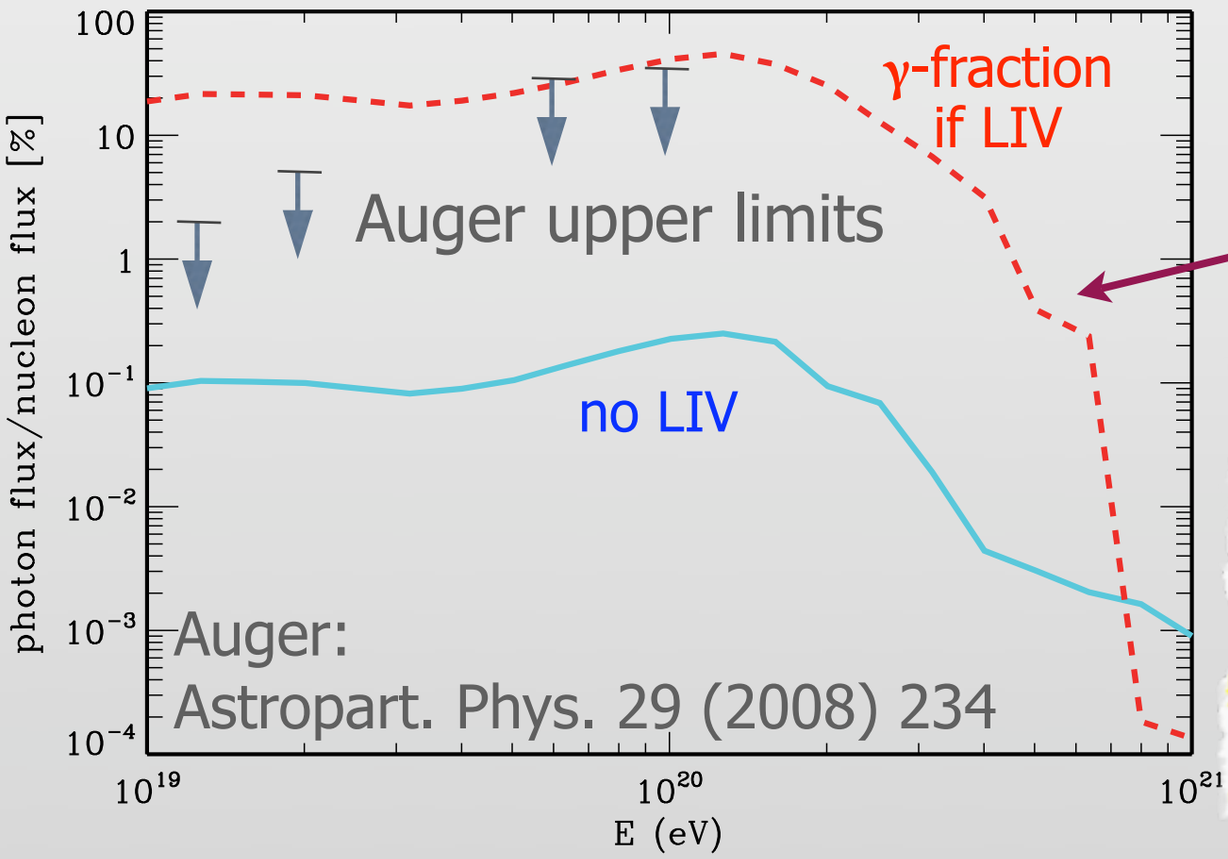
➙ affect the threshold for $e^+e^-$ pair production

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

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

Galaverni & Sigl PRL 100, 021102 (2008); see also Maccione arXiv: 0805.2548

cascading of UHE photons suppressed




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

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

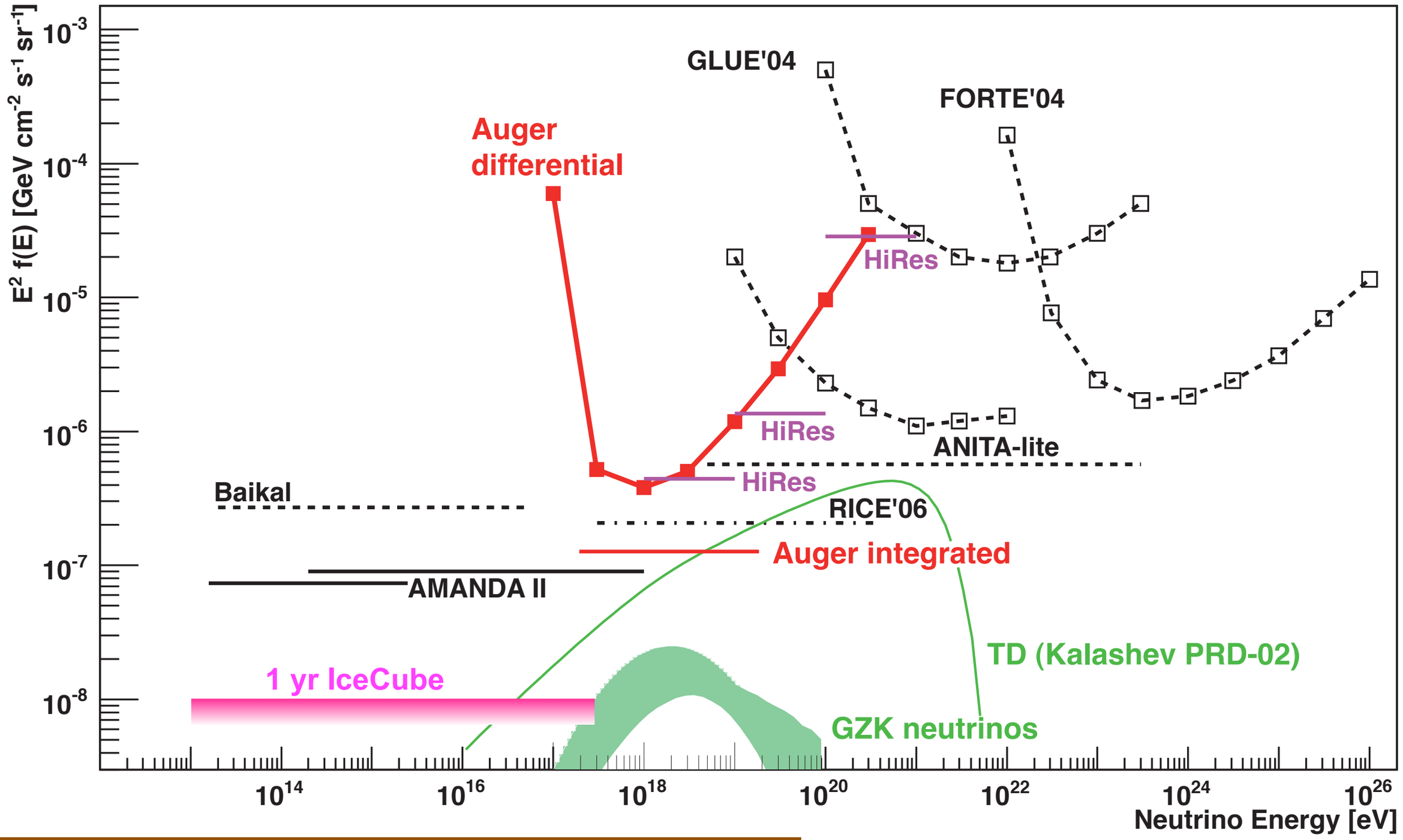
$$\xi_2 \geq -2.4 \times 10^{-7}$$

*7 orders of magnitudes better than previous limits!*

# Composition Neutrinos

# Search for Earth-skimming $\nu_\tau$

## Largest Source of Uncertainty: QCD structure function & X-section



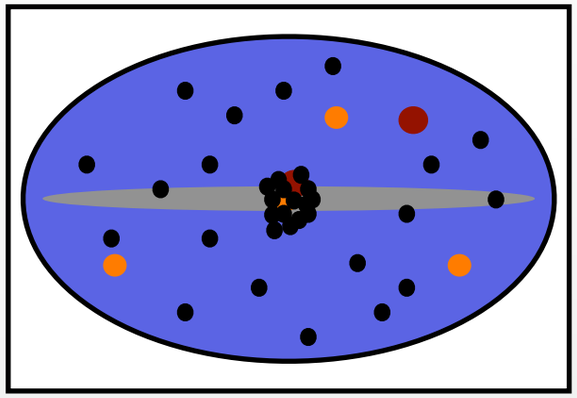

Pierre Auger Collab. PRL 100, 211101 (2008)

# Arrival Directions

# Anisotropy Searches

## 1 Galactic Center

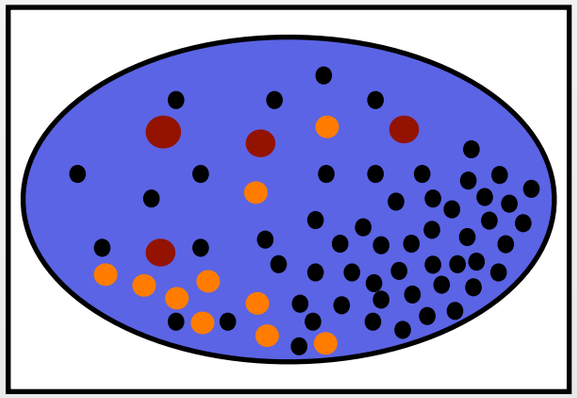
AGASA & SUGAR: yes



$E_1 < E_2 < E_3$

AUGER: not at this level

## 2 Multipole Search
(Large scale anisotropy)

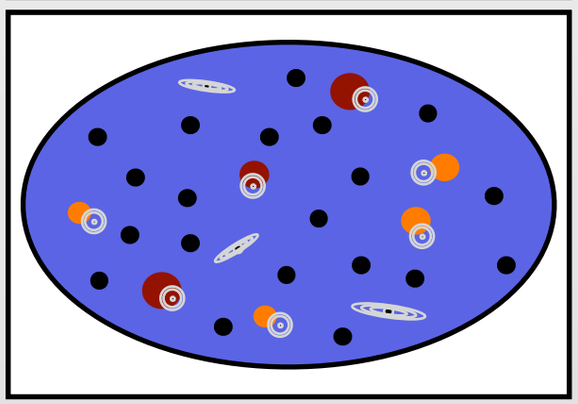


no evidence yet...

## 3 Point Sources

**BL Lacs** HiRes: yes

**AGN** Auger: Yes

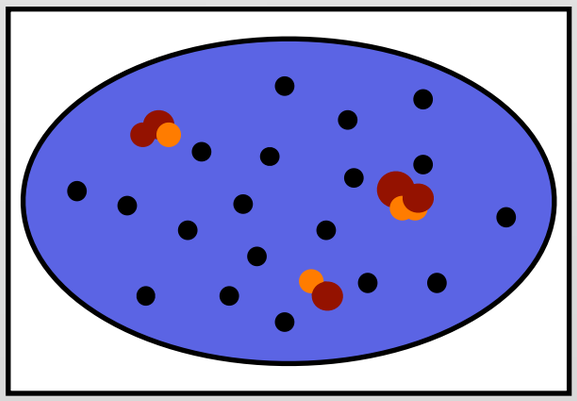


Auger: No

HiRes: ??

## 4 Cluster Search
(Autocorrelation)

AGASA: yes

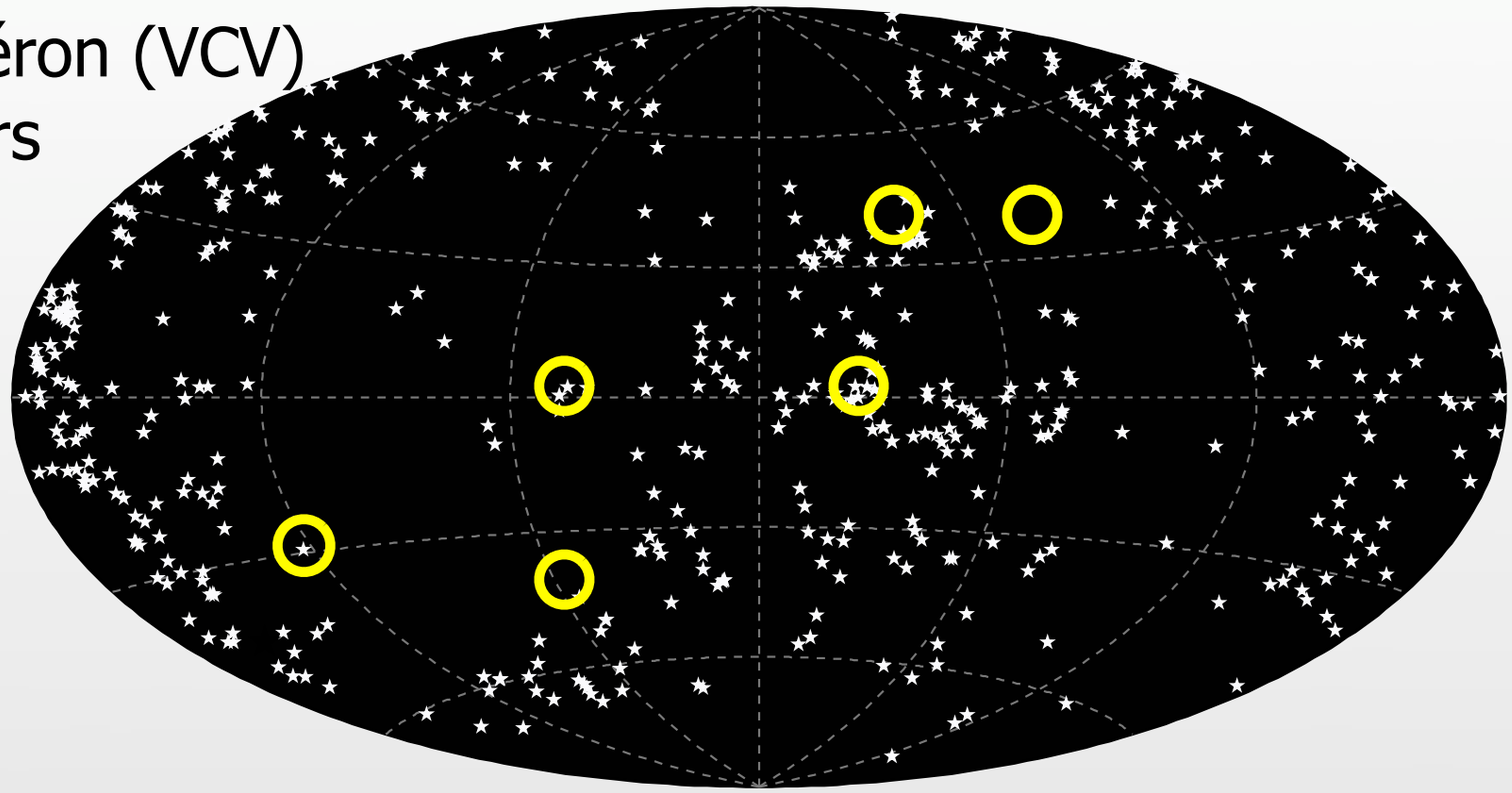


HiRes: No

Auger: at different scale

# Anisotropy Search Method

Véron-Cetty & Véron (VCV) 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. VCV

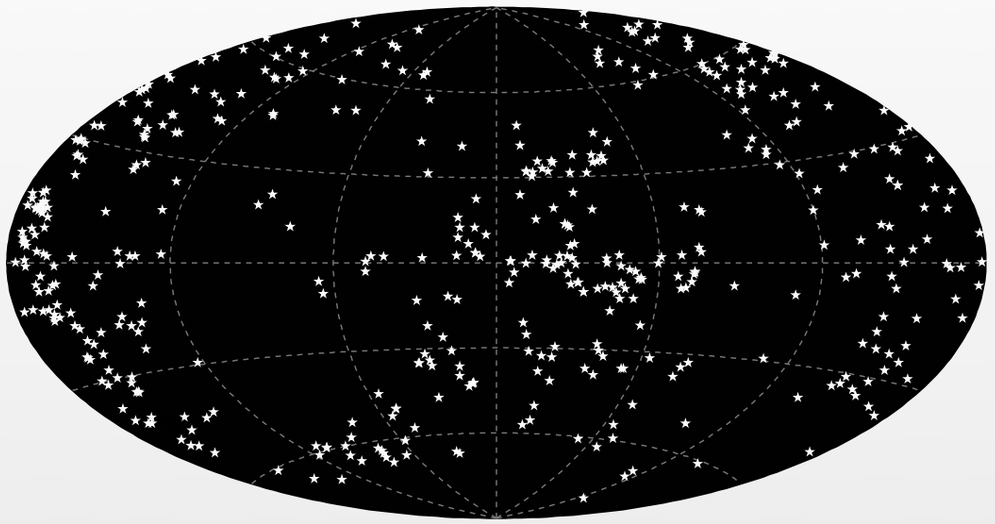
Probability to find a single event of an isotropic distr. within a certain opening angle from a source. $p = p(\psi, n_{sources}) = p(\psi, z_{max})$

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

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

# Analysis Strategy for AGN-correlation

Véron-Cetty - Véron Cataloguee



## Two-step analysis

- Exploratory search to determine the optimal parameter set that maximizes the correlation
  - $z_{max}$ = 0.018 ($D_{max}$ = 75 Mpc)
  - $E_{th}$ = 56 EeV
  - $\Psi$ = 3.1º (p = 0.21)
- Test of the correlation with independent data to determine the chance probability of the correlation using the parameter set determined in the exploratory scan

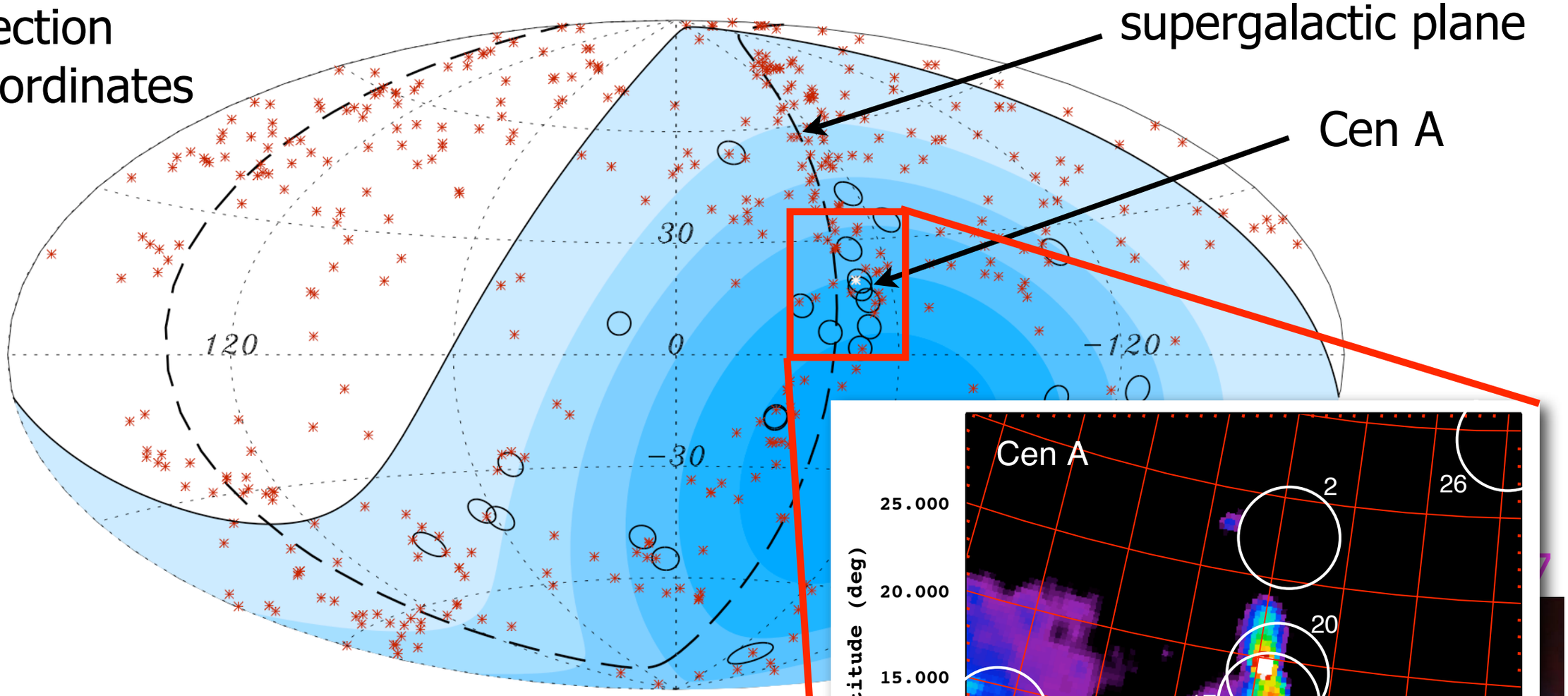
| | # events E > 57 EeV | # correlated with AGN | # expected for isotropy |
|---|---|---|---|
| Exploratory set 1 Jan 04 – 26 May 06 | 15 | 12 | 3.2 |
| Independent set 26 May 06 – 31 Aug 07 | 13 | 8 | 2.7 |

- Chance probability in independent set : < 1%

# AGN Correlation Plot

Aitoff projection
galactic coordinates

472 AGNs
z≤0.018
318 in fov




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

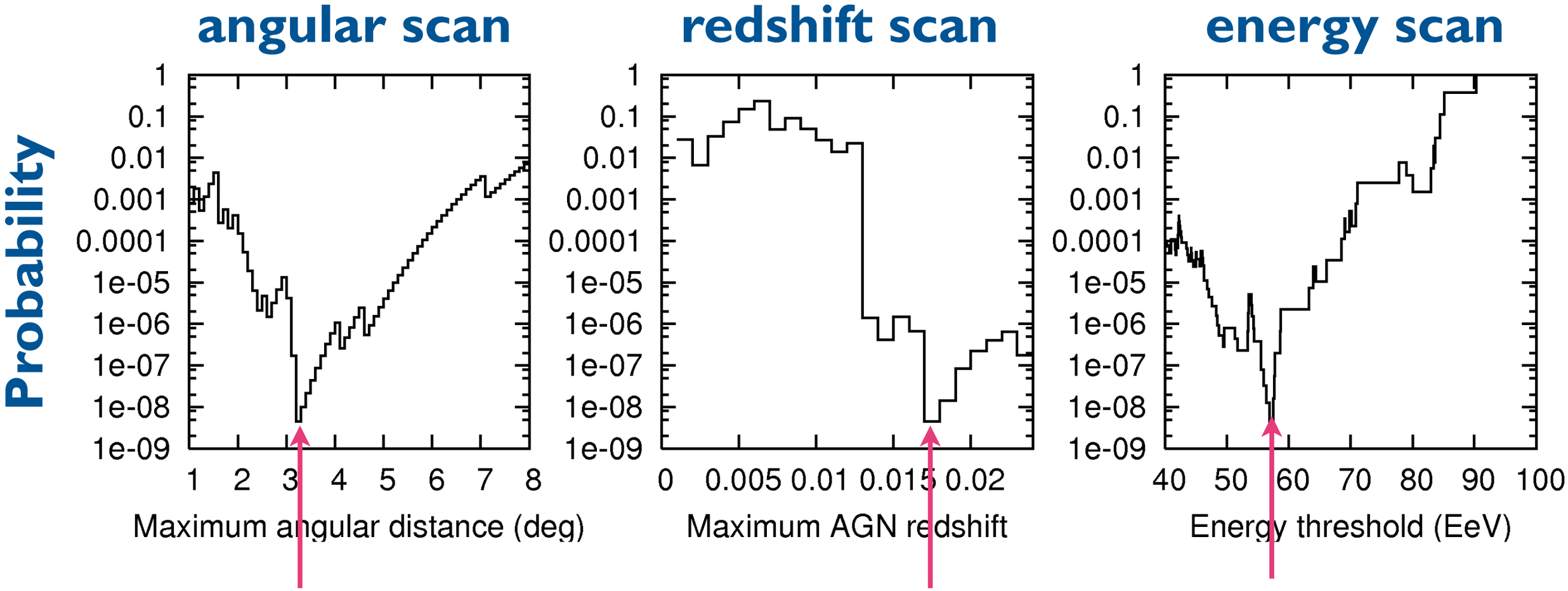
Auger Coll.; Science 318 (2007) 938

# Properties of Correlation Signal

Auger; arXiv:0712.2843

Correlation with AGN positions established by new data

➞ redo scan of correlation parameters with improved statistics




$\Psi = 3.1°$

(exploratory scan 3.1°)

$z_{max} = 0.017$

(0.018)

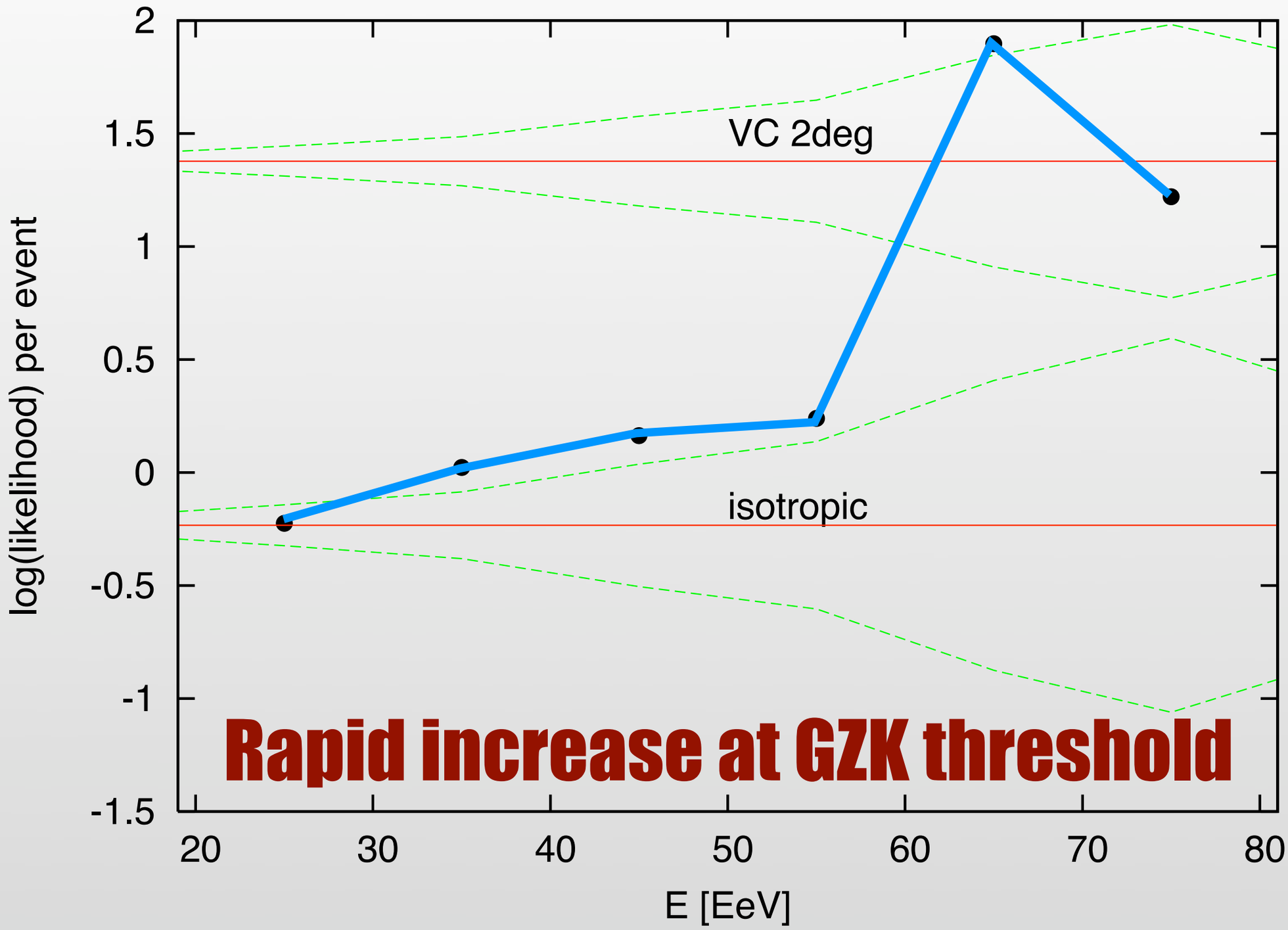
$E_{th} = 57$ EeV

(56 EeV)

**Parameters of exploratory search confirmed by full data set !**

# Correlation Strength as fct of E

Auger; APP29 (2008) 188



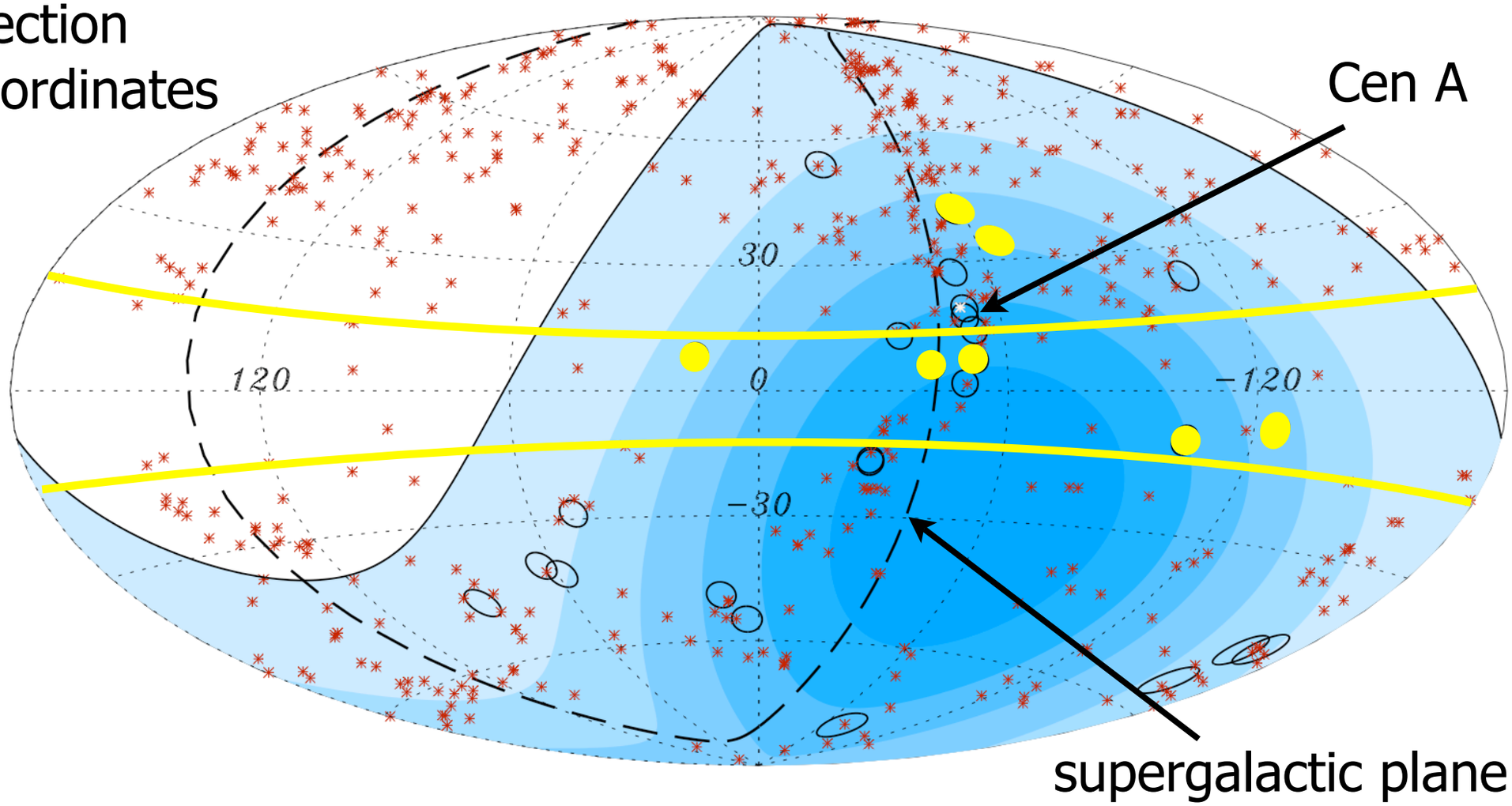

**Rapid increase at GZK threshold**

**Angular deflection ~ 1/E would give much softer effect**

# Effect of Galactic Plane

Aitoff projection
galactic coordinates

472 AGNs
z≤0.018
318 in fov

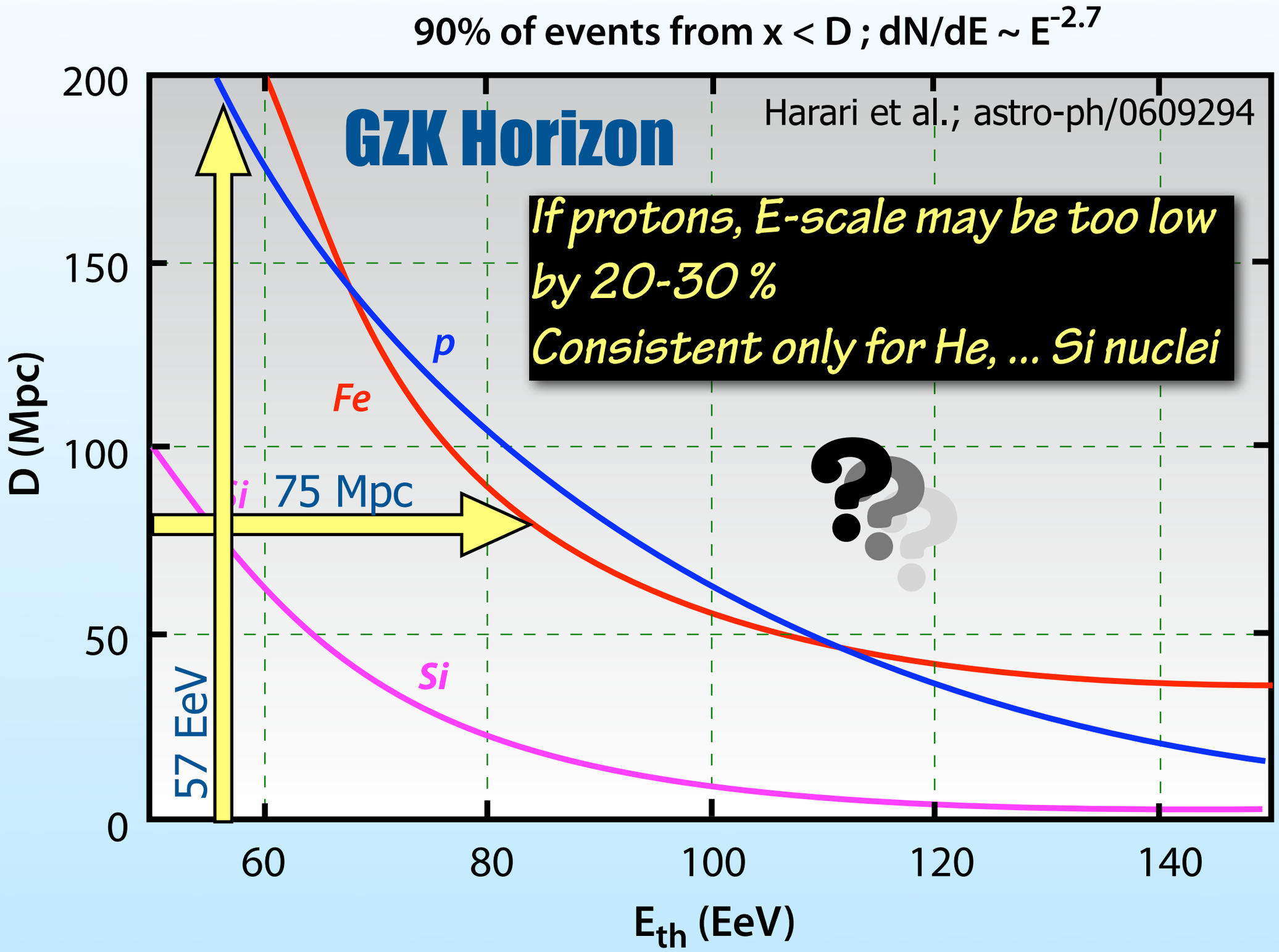



In total 27 events at E > 57 EeV, 20 of which correlate

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

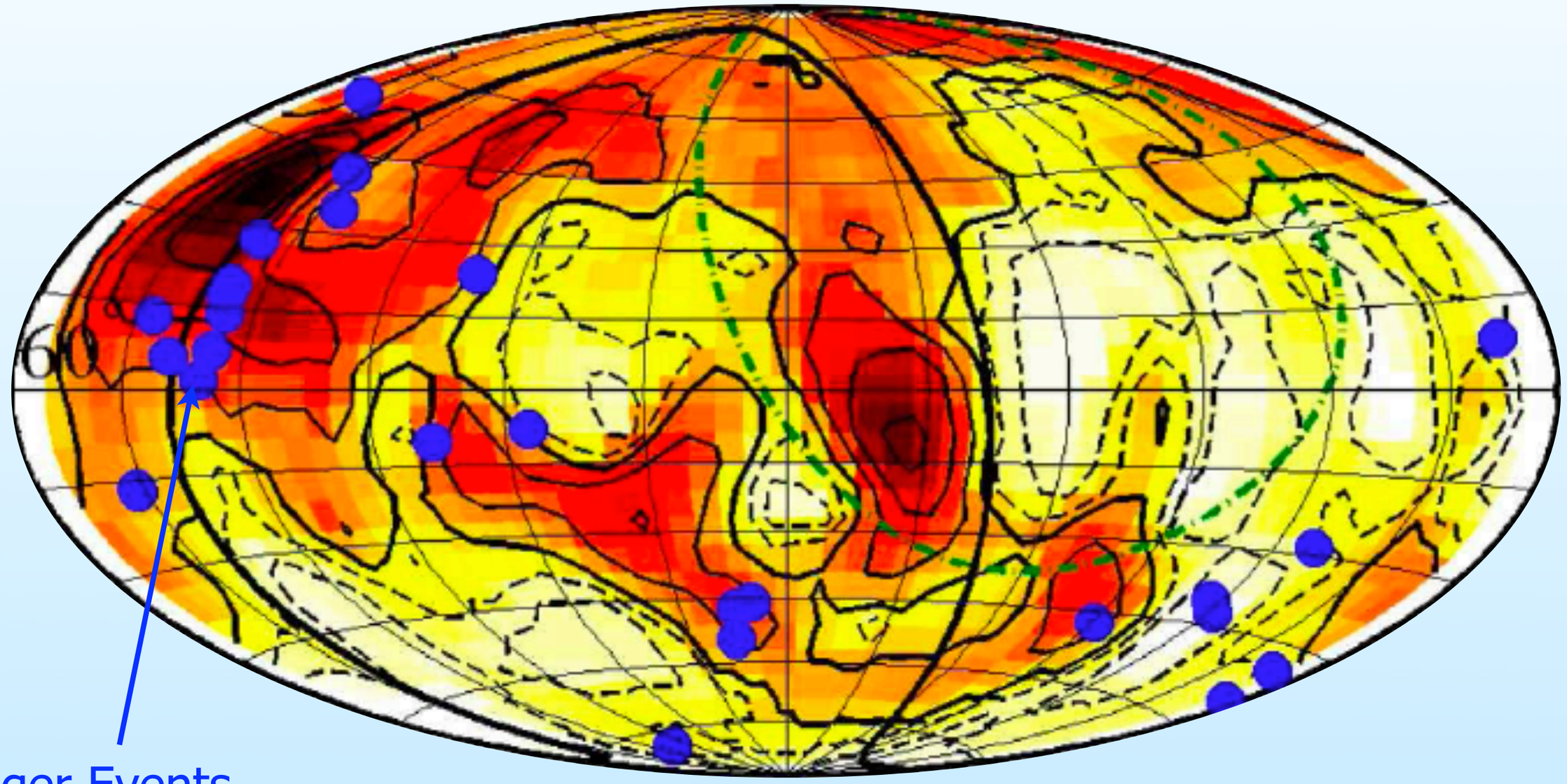
likely to happen because of incomplete catalogue and large deflections in magnetic fields

# Do we understand the correlation?



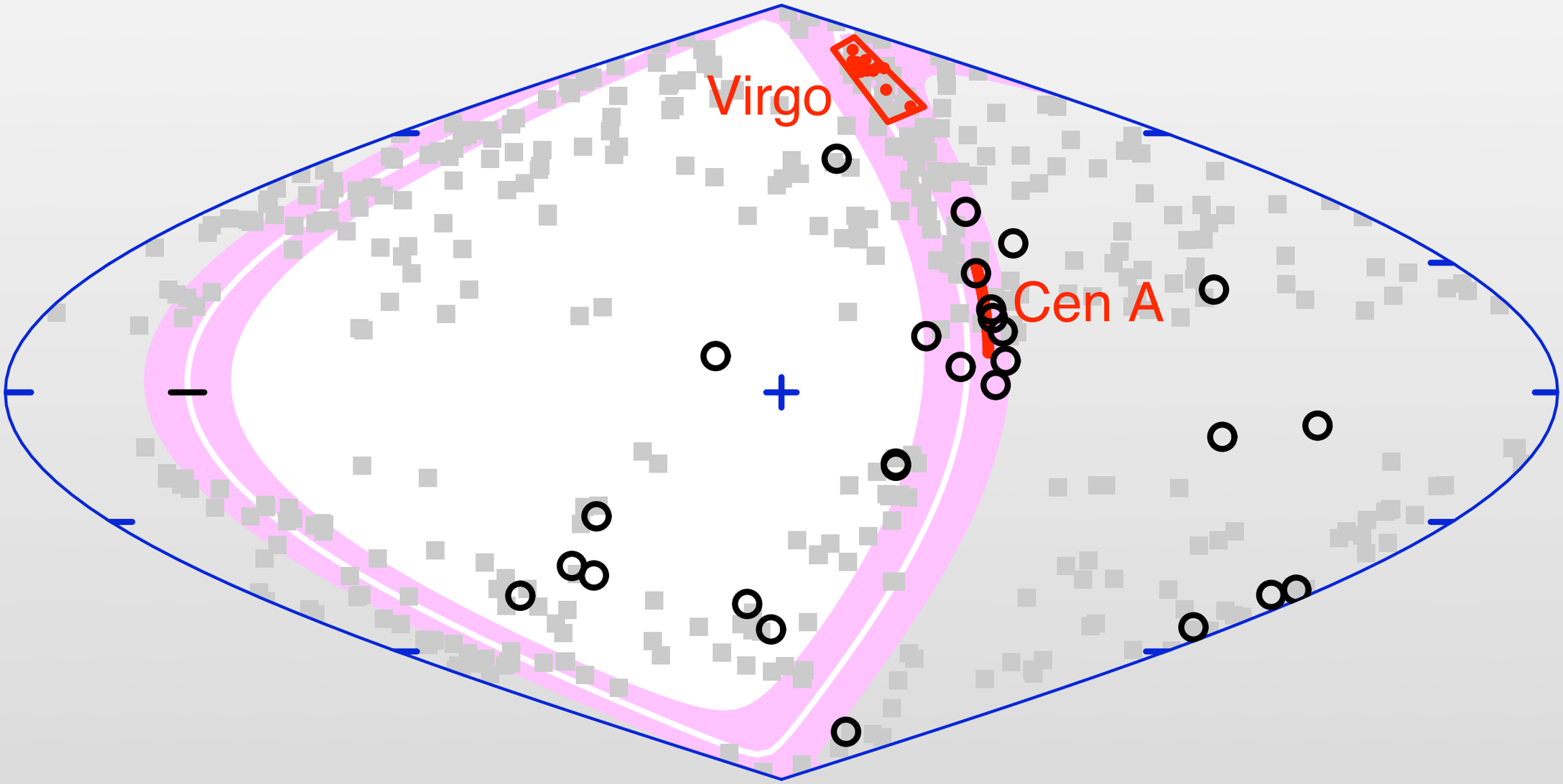
# Correlation with LSS ?

Kashti & Waxman, arXiv:0801.4516



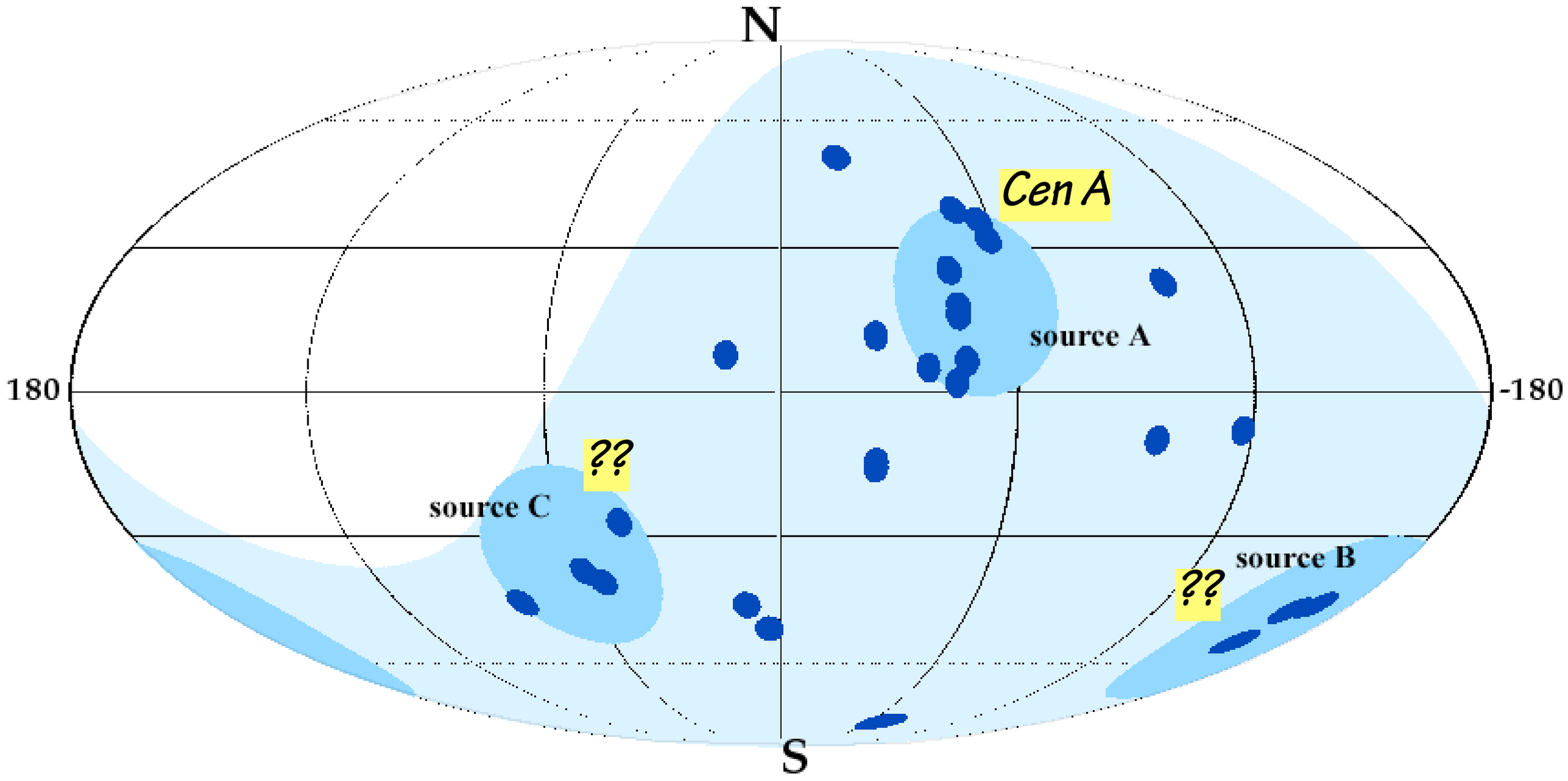
# Correlation with SGP

T. Stanev, (arXiv:0805.1746):
strong correlation of Auger event with supergalactic plane
even stronger for redefined supergalactic plane



# Or few sources and heavy primaries ?

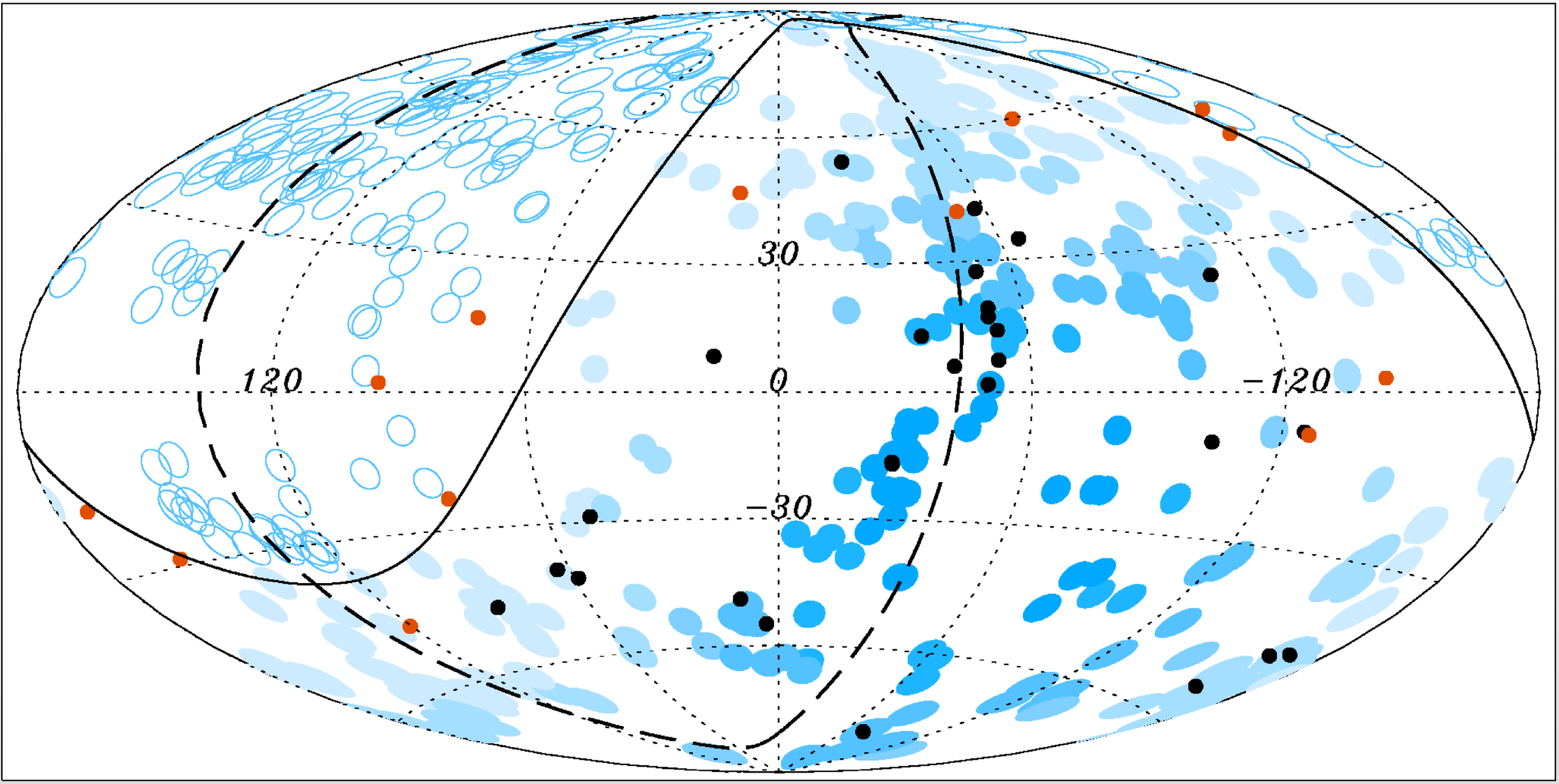
Wibig & Wolfendale, arXiv:0712.3403



# Auger vs HiRes

red dots: 13 HiRes events

black dots: 27 Auger events




Note: HiRes is located in Northern Hemisphere, Auger in Southern

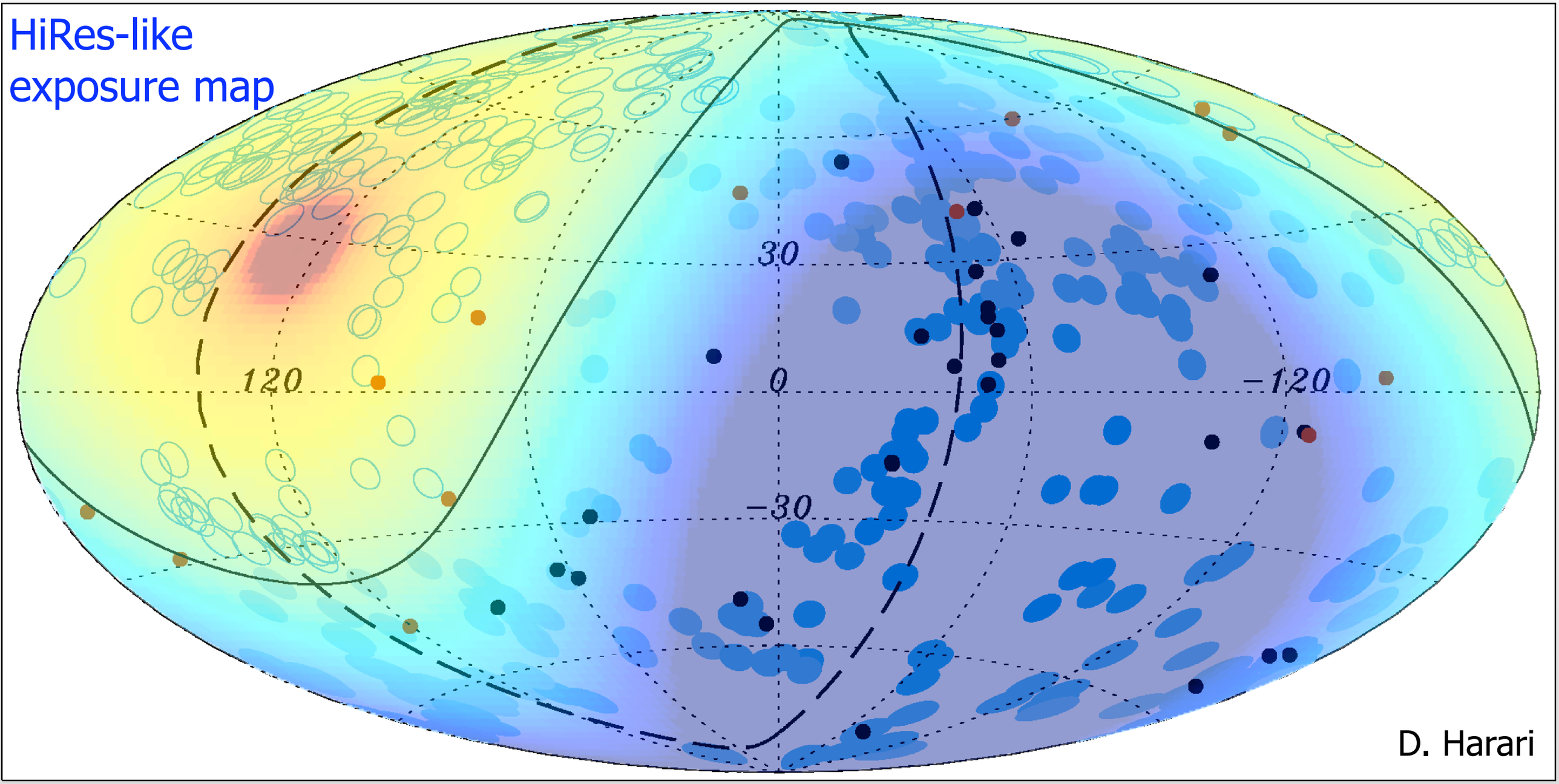
but 9 (11) of 13 events of HiRes in Auger exposure region....

D. Harari

# Auger vs HiRes

red dots: 13 HiRes events

black dots: 27 Auger events




Note: HiRes is located in Northern Hemisphere, Auger in Southern

but 9 (11) of 13 events of HiRes in Auger exposure region....

# What does all this tell us ?

**1) No doubt about existence of UHECR anisotropies**

**2) Be careful when interpreting correlation parameters opening angle and redshift** (both are likely biased)

**3) Question about AGNs being tracers or sources cannot be answered yet**

**4) Need to account also for AGN specific properties and study their effects**

**5) Need more event statistics** (factor of 2 by end of this year)

# AUGER NORTH IN SE-COLORADO




PIERRE AUGER OBSERVATORY NORTH

**Plan:**

20 000 km²

SD with $\sqrt{2}$ miles grid

+

FD with full coverage

Karl-Heinz Kampert – University Wuppertal

# Summary

- **GZK established** (seen by Auger and HiRes)
  **Top-Down models** almost **ruled out**
  by absence of UHE photons & neutrinos
- **Trans-GZK events correlate with AGN positions**
  entering era of CR-Astronomy

- **Establish CR sources and verify in $\nu$ and $\gamma$ telescopes**
- **Multi-Messengers becomes reality** (CR-Lumi ➛ $\nu$ & $\gamma$-flux)
- **Questions of Fundamental Physics addressed**
- **Several Puzzles remain; Need to understand**

  - Energy spectrum
  - Mass composition
  - Directional distributions

  } consistently !

Pierre Auger Observatorium
Öffentlicher Ereignis-Betrachter

http://auger.uni-wuppertal.de/ED/

# Öffentlicher Ereignis-Betrachter

Herzlich Willkommen beim öffentlichen Ereignis-Betrachter des Pierre Auger Observatoriums.

Die Pierre Auger-Kollaboration hat beschlossen, 1% der Daten öffentlich verfügbar zu machen. Auf dieser Webseite, die täglich aktualisiert wird, können die seit 2004 gesammelten Ereignisse angezeigt werden.

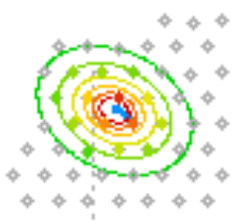
Sie können eine Ereignisnummer (ID) im Suchfenster eingeben, das Menü "Ereignis-Selektion" benutzen oder ein Ereignis anschauen, das schon im Cache geladen ist. Zum Abspeichern auf dem eigenen Computer steht eine ascii Datei mit allen Ereignissen zur Verfügung.

Der aktuelle Datensatz besteht aus 8507 Ereignissen mit Energien zwischen 0 EeV und 41.1 EeV. Das letzte Ereignis hat die ID 4507700 und der Zeitpunkt der Messung war Feb 05 2008 04:34:52, UTC Time.

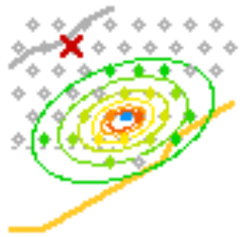
## Ereignisse im Zwischenspeicher

Die 3 meistbetrachteten Ereignisse

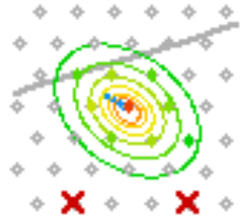
★★★ 000001234800



★★ 000004128900



★ 000004044700



Alle zwischengespeicherten Ereignisse, geordnet nach ihrer Energie, mit Anzeigehäufigkeit (längerer Balken bedeutet häufiger betrachtet):

000004128900: 41.05 EeV, 18 Stationen, 54.5 Grad
000001234800: 37.36 EeV, 14 Stationen, 43.4 Grad
000001673300: 33.10 EeV, 11 Stationen, 32.3 Grad
000002126300: 32.84 EeV, 14 Stationen, 53.4 Grad

**Pierre Auger Observatorium**
**Ereignis-Betrachter**

**Ereignis-Selektion**

| | Min | Max |
|---|---|---|
| Anzahl Stationen | 5 | |
| Zenitwinkel | 0 | 60 |
| Energie (**EeV**) | 5 | |

Sortiert: Datum (rückwärts)
Zeige 10 Ereignisse
Suchen

Gehe zu Ereignis 1234800

FAQ | Über

Impressum astro.uni-wuppertal

Pierre Auger Observatorium
Öffentlicher Ereignis-Betrachter

http://auger.uni-wuppertal.de/ED/

## Ereignis 1234800

Ansicht der rekonstruierten Daten | Ansicht der Stations-Daten

Die Herkunftsrichtung des Ereignisses:
Galaktische Länge: 267.0 ± 0.6 Grad
Galaktische Breite: -69.8 ± 0.2 Grad

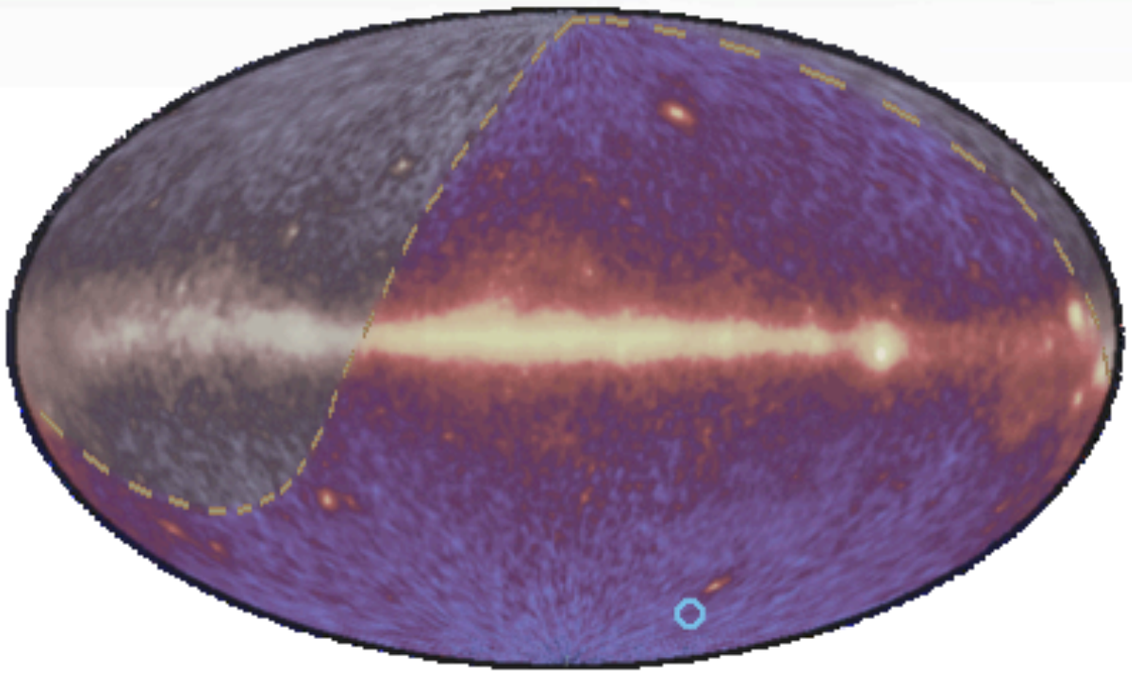


Bild 4: Ankunftsrichtung des Ereignisses

Das Hintergrundbild ist gemessen von EGRET (Gamma-Strahlungshimmel über 100 MeV, von EGRET). Das Ereignis ist mit einem blauen Kreis markiert, und die gestrichelte Linie kennzeichnet den für das südliche Pierre Auger Observatorium sichtbaren Himmel

**Pierre Auger Observatorium**
**Ereignis-Betrachter**

**Ereignis-Selektion**

| | Min | Max |
|---|---|---|
| Anzahl Stationen | 5 | |
| Zenitwinkel | 0 | 60 |
| Energie (**EeV**) | 5 | |

Sortiert: Datum (rückwärts)
Zeige 10 Ereignisse
Suchen

Gehe zu Ereignis 1234800

**Ereignis 1234800**

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| FAQ | Über

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# Pampa Amarilla