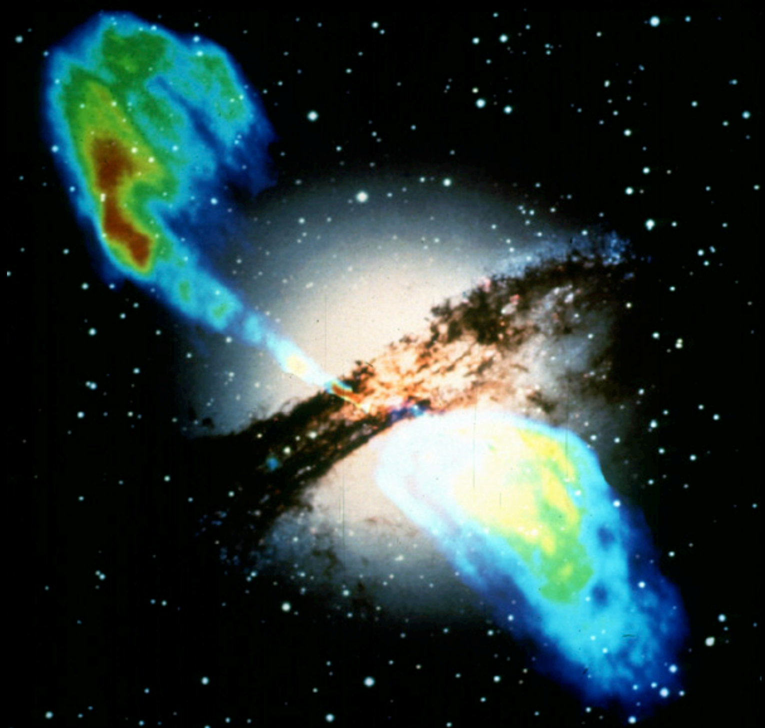
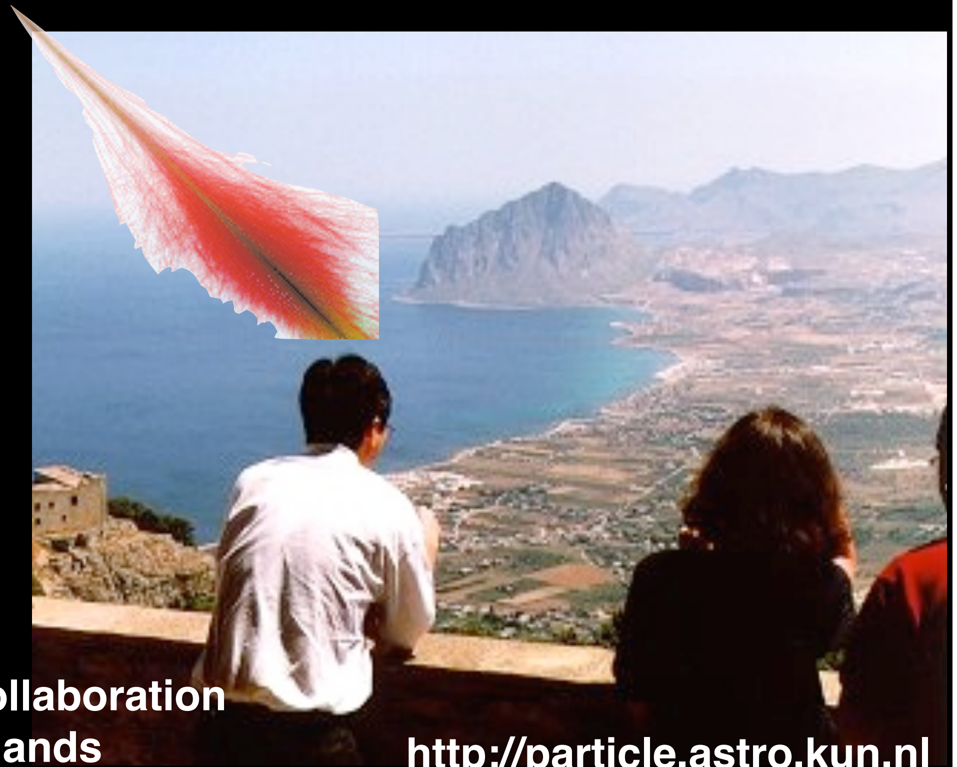
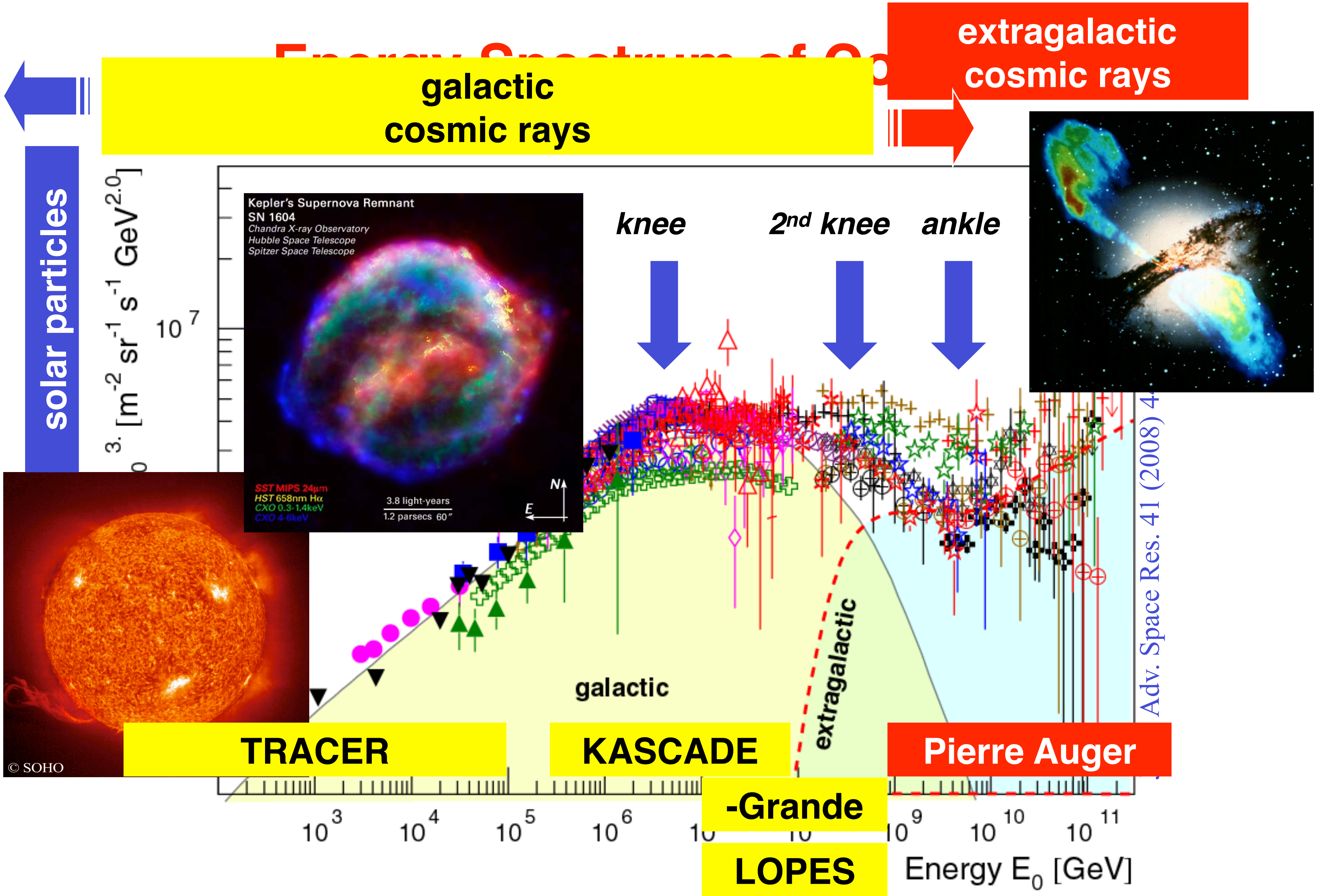
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
31st Course
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice-Sicily: 16 - 24 September 2009

Cosmic rays at the highest energies





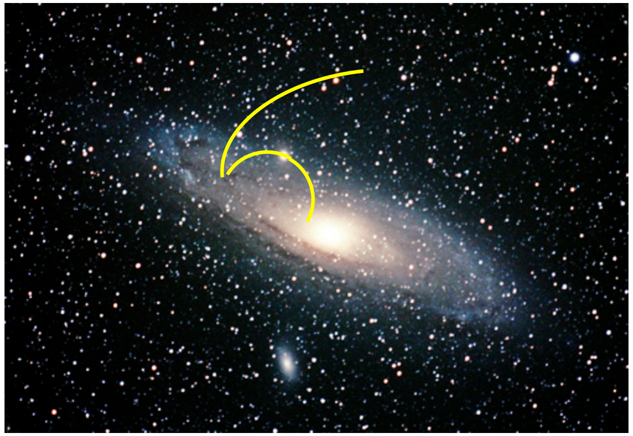
Jörg R. Hörandel for the Pierre Auger Collaboration
Radboud University Nijmegen, The Netherlands
http://particle.astro.kun.nl



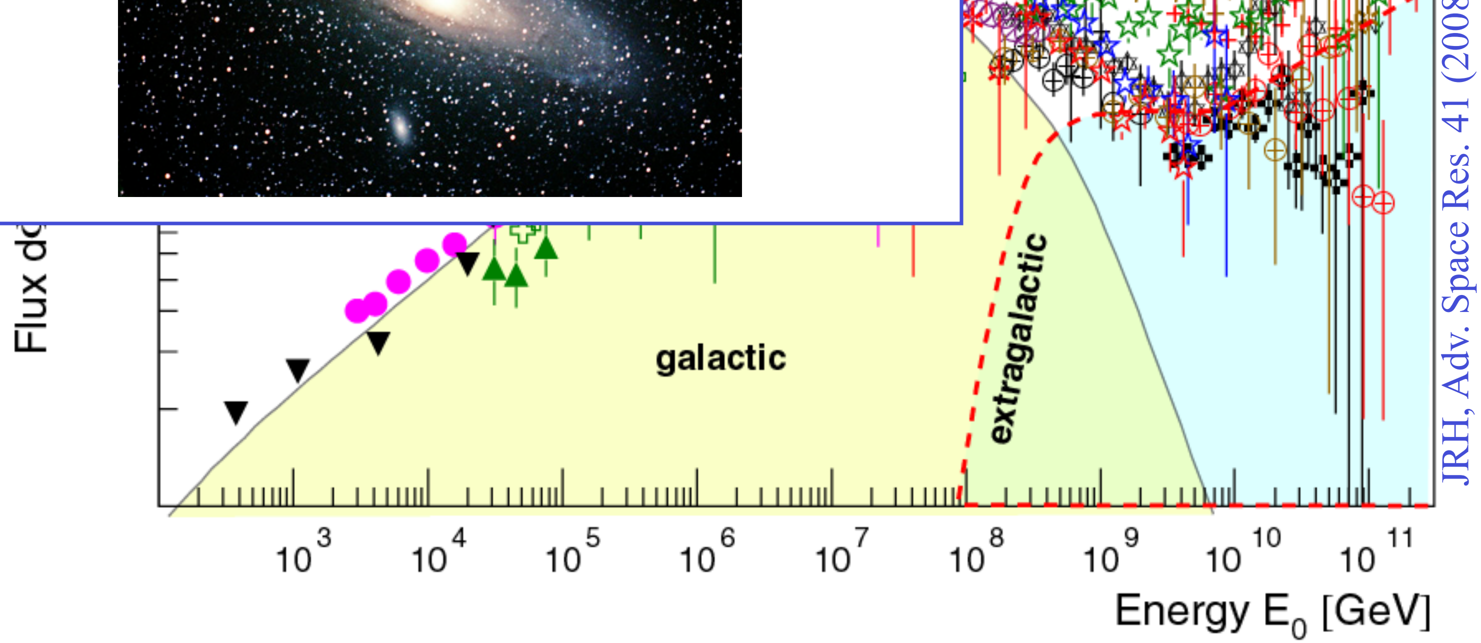
J. Blümer, R. Engel, JRH, Progr. Part. Nucl. Phys. 63 (2009) 293

Radius of particle in magnetic field

$$r = \frac{p}{ZeB} \qquad r[pc]=1.08 * \frac{E\ [PeV]}{B\ [\mu G]}$$



extragalactic cosmic rays



r= 0.04 pc 3.6 pc 360 pc 36 kpc

Energy content of extragalactic cosmic rays

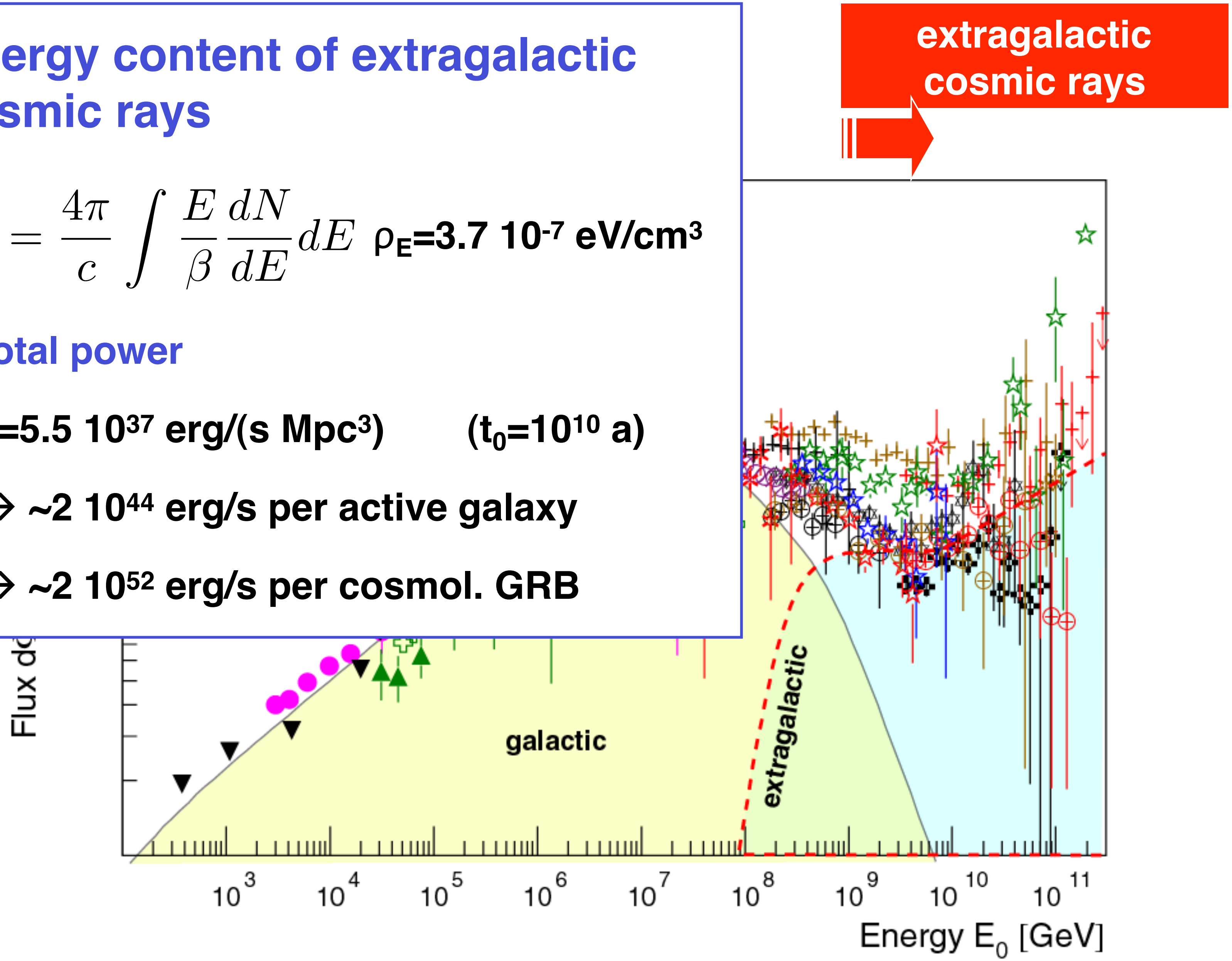
$$\rho_E = \frac{4\pi}{c} \int \frac{E}{\beta} \frac{dN}{dE} dE$$ $\rho_E = 3.7\ 10^{-7}$ eV/cm^3

total power

P=5.5 10^{37} erg/(s Mpc^3)   ($t_0 = 10^{10}$ a)

→ ~2 10^{44} erg/s per active galaxy

→ ~2 10^{52} erg/s per cosmol. GRB



JRH, Rev. Mod. Astron. 20 (2008) 203 (arXiv:0803.3040)

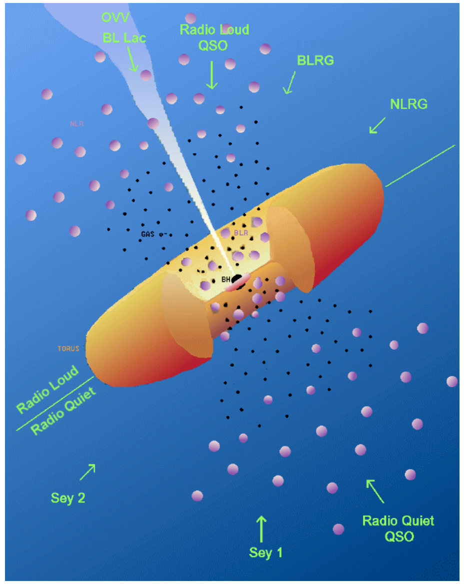
Possible sources of extragalactic cosmic rays

Bottom up models

- Active galactic nuclei (AGN)
- Coalescence of neutron stars,
  black holes
- Gamma ray bursts

$p+p$ or $p+\gamma \rightarrow \pi^{+/-} \rightarrow \nu_{\mu} + \nu_{e}$ + ...

$\rightarrow \pi^{0} \rightarrow \gamma + \gamma$



Top down models

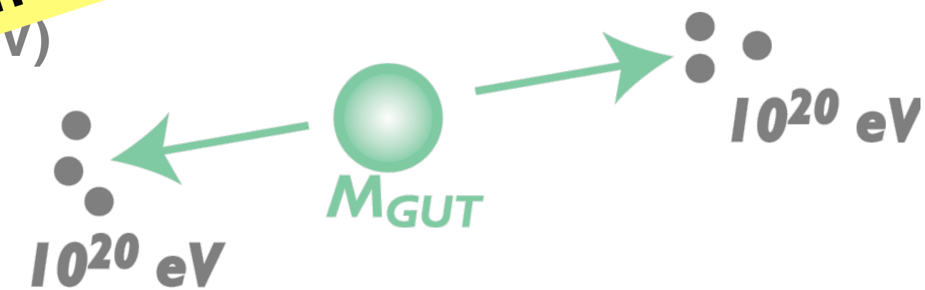
Super heavy relicts of Big-Ba... defects)

X-particle (m ... eV)

...ons

γ, ν, p...

Already severe constraints by Auger

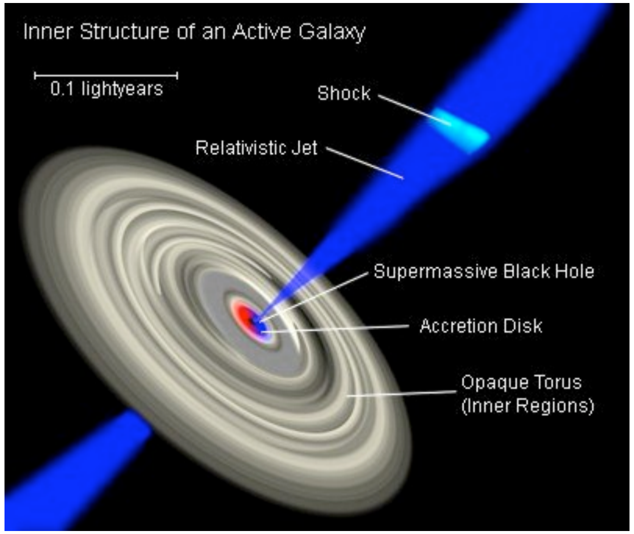


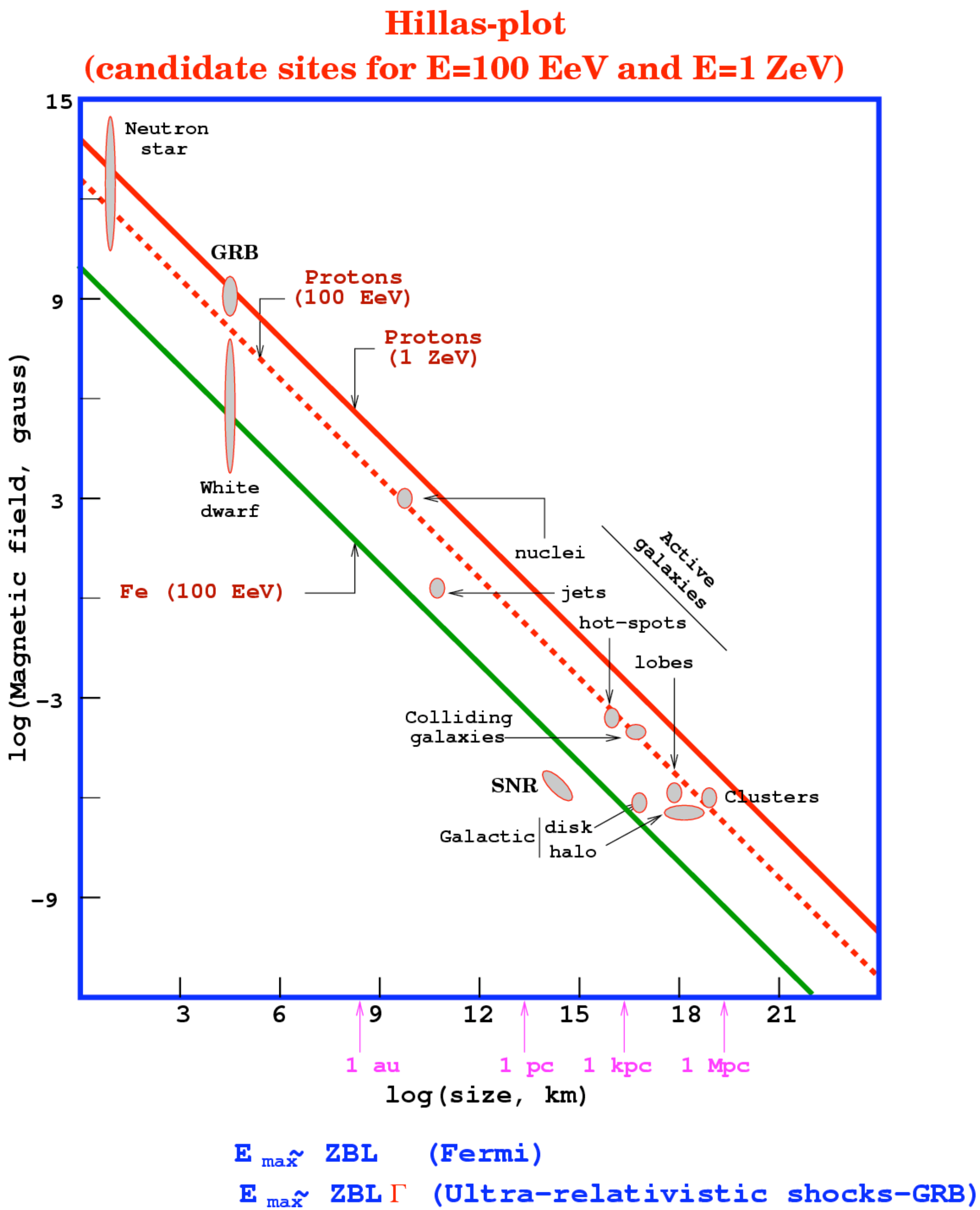
→ Multi Messenger Approach

Neutrino astronomy	Proton astronomy	TeV γ-ray astronomy
km³ net Ice Cube	Pierre Auger (full sky)	HESS, MAGIC, CTA

Accelerator dimensions and magnetic field

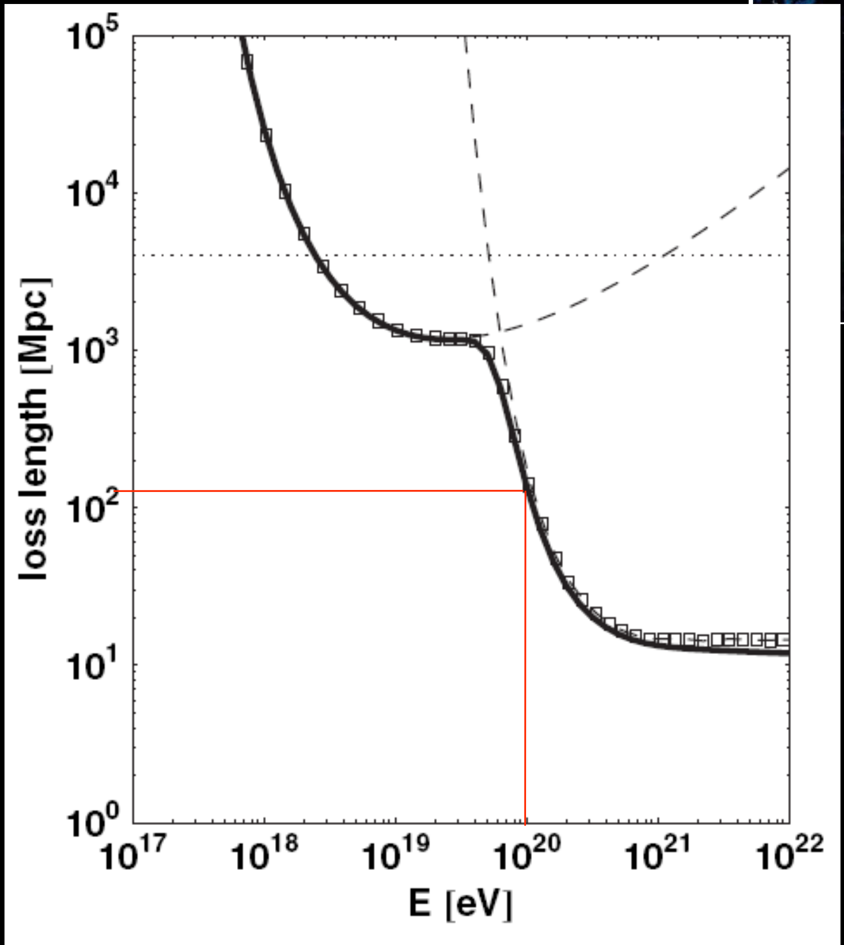
B[μG] L[pc] > 2 E[PeV]/(Zβ)

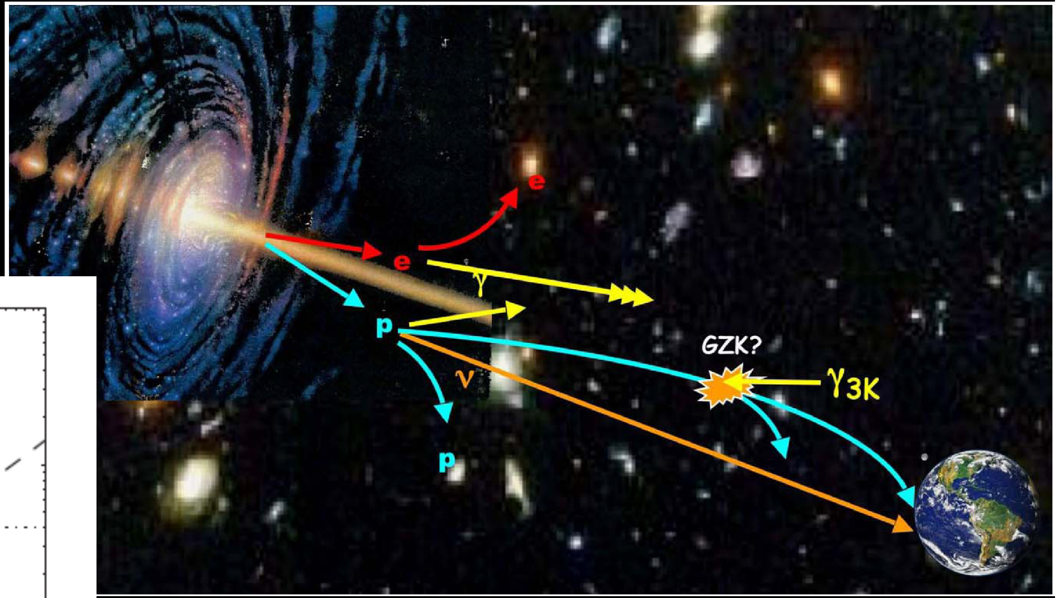




„Optical depth“ of the Universe – The GZK Effect

Energy loss length





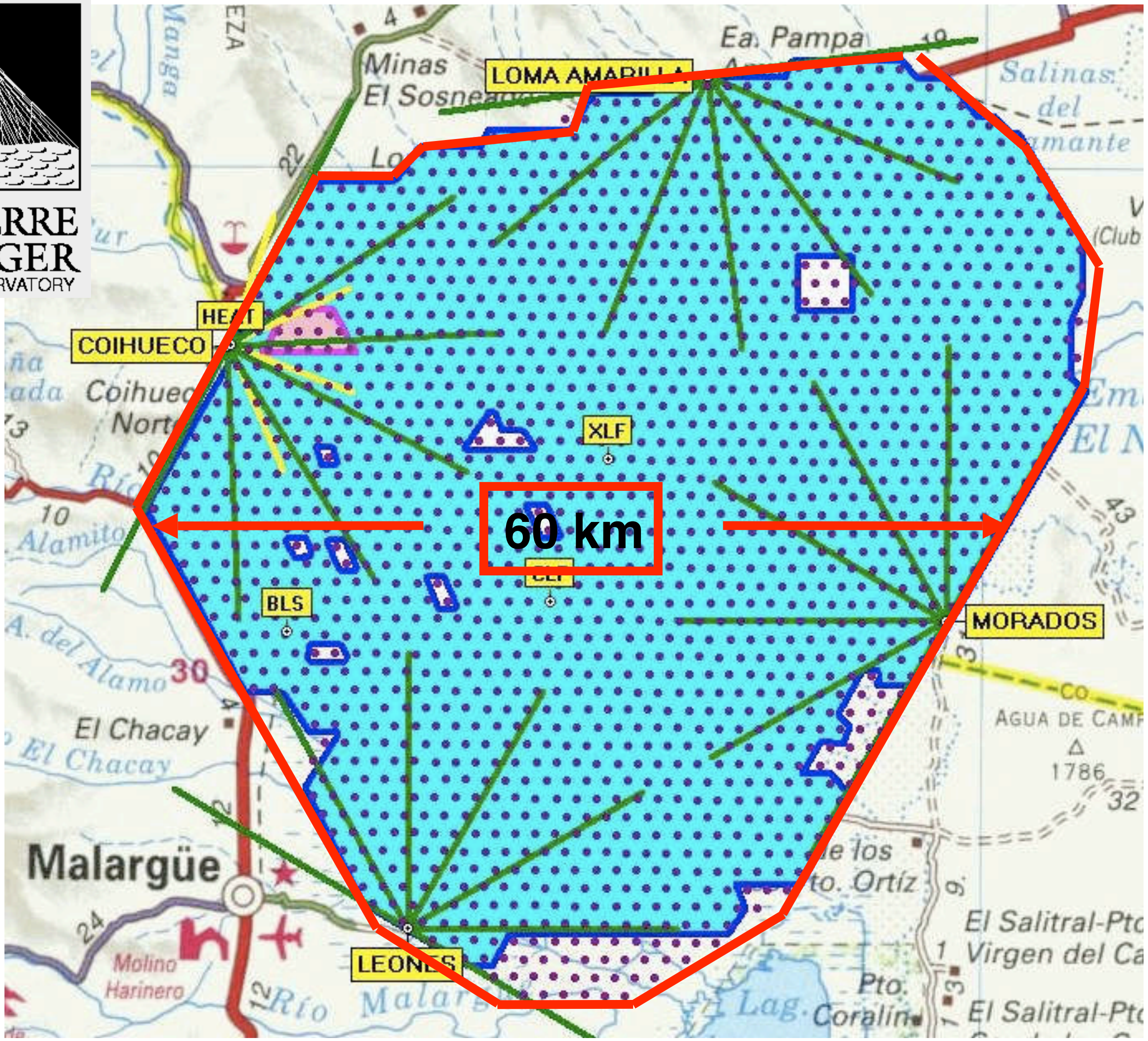
$p + \gamma_{3K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}\ ;\ n + \pi^{+}$

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

⇨ at highest energies field of view is reduced to < 100 Mpc

Stanev & de Marco, PRD 72 (2005) 081301

The Pierre Auger Observatory

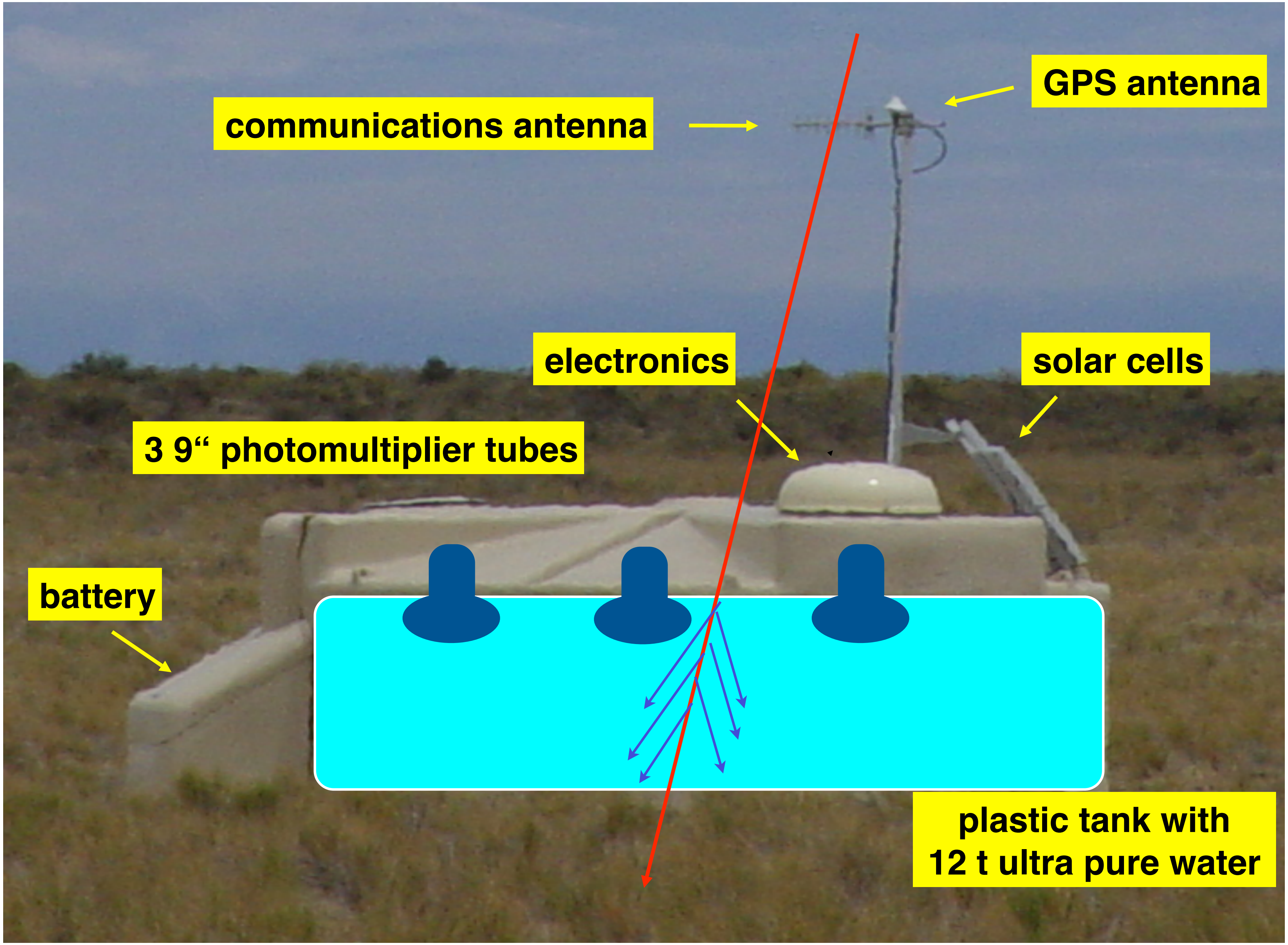


Pierre Auger Observatory

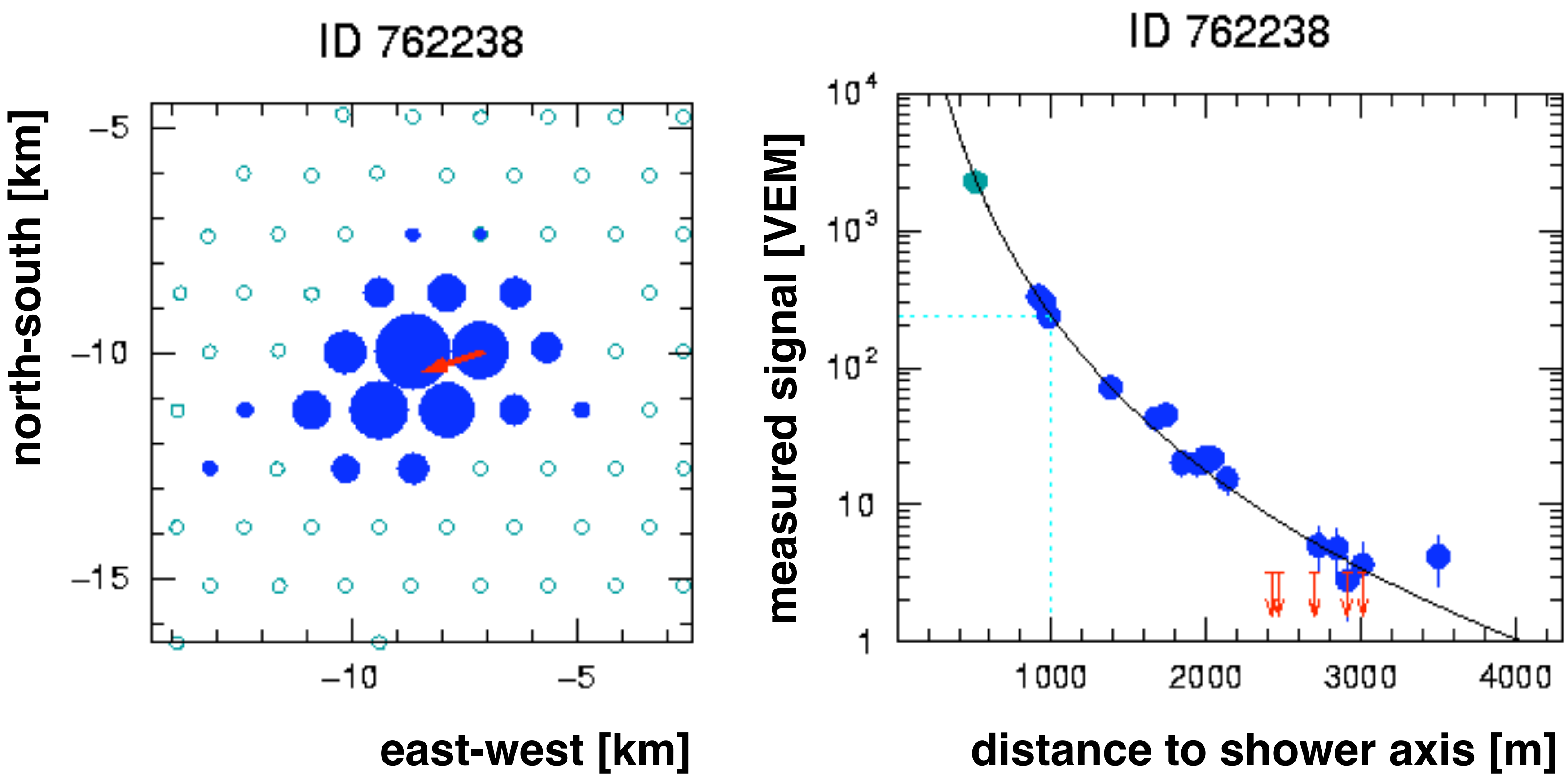
3000 km²

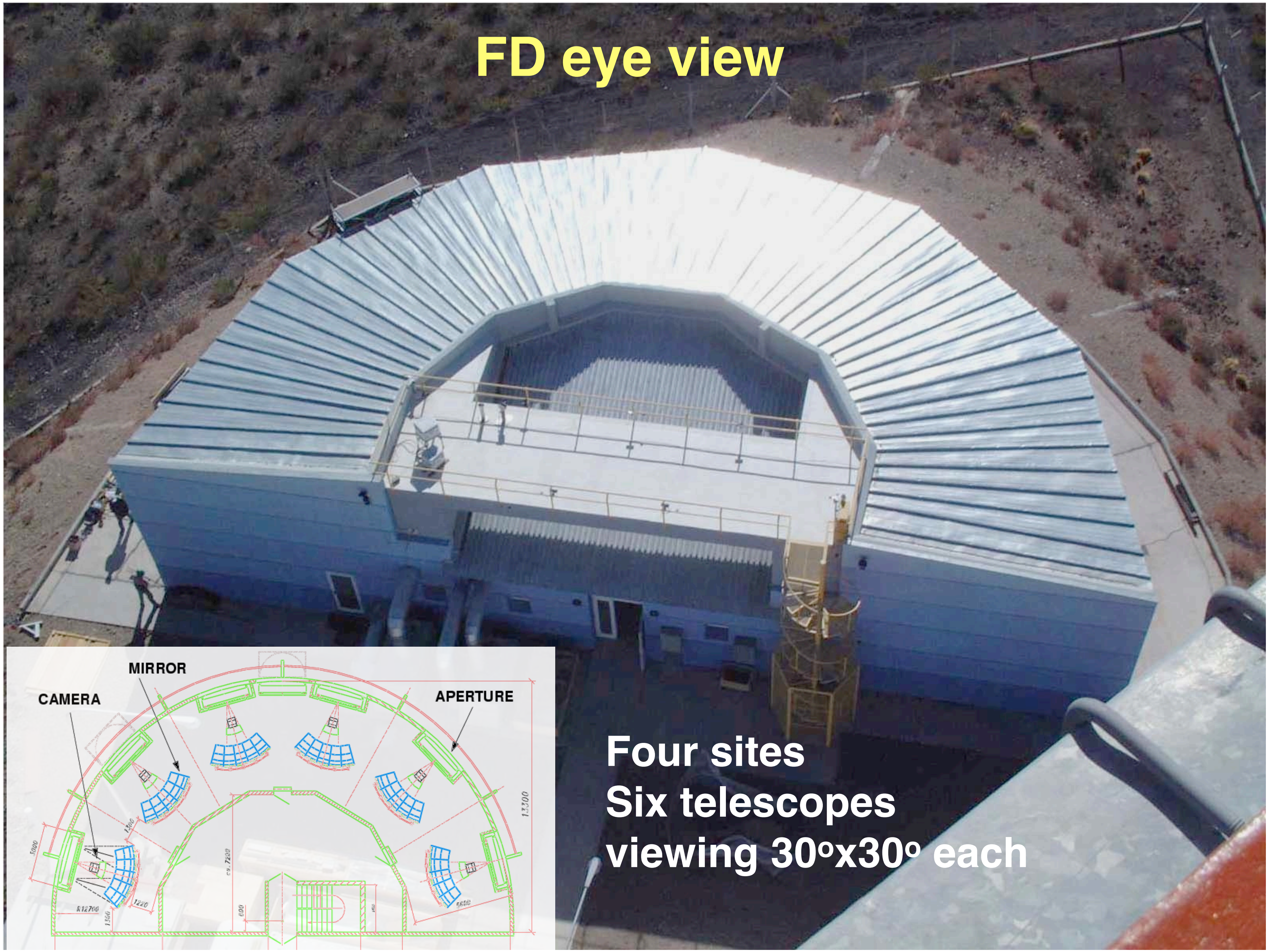
4 telescope buildings
6 telescopes each

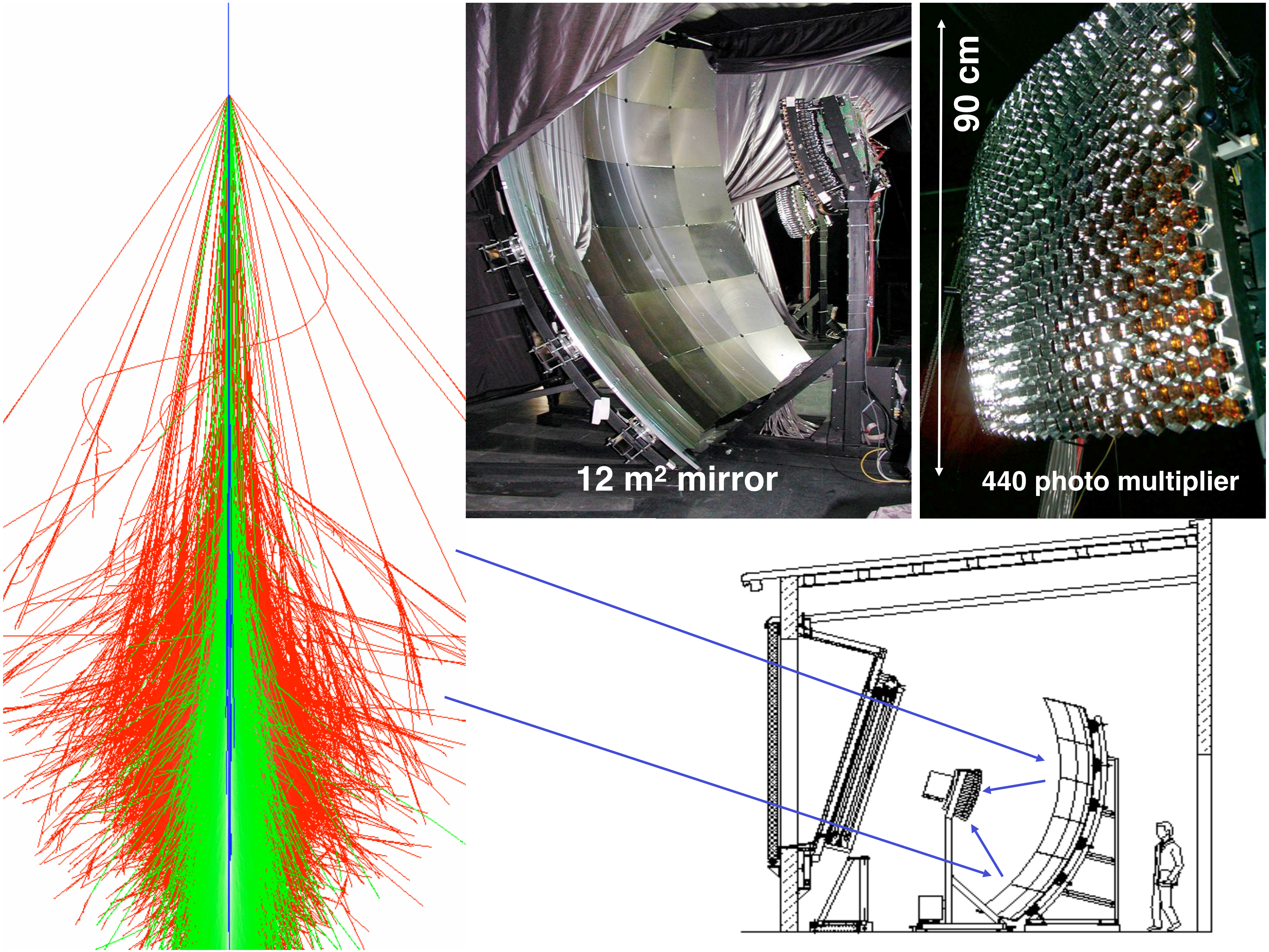
Spring 2008:
water Cherenkov detector array completed
1600 tanks operating

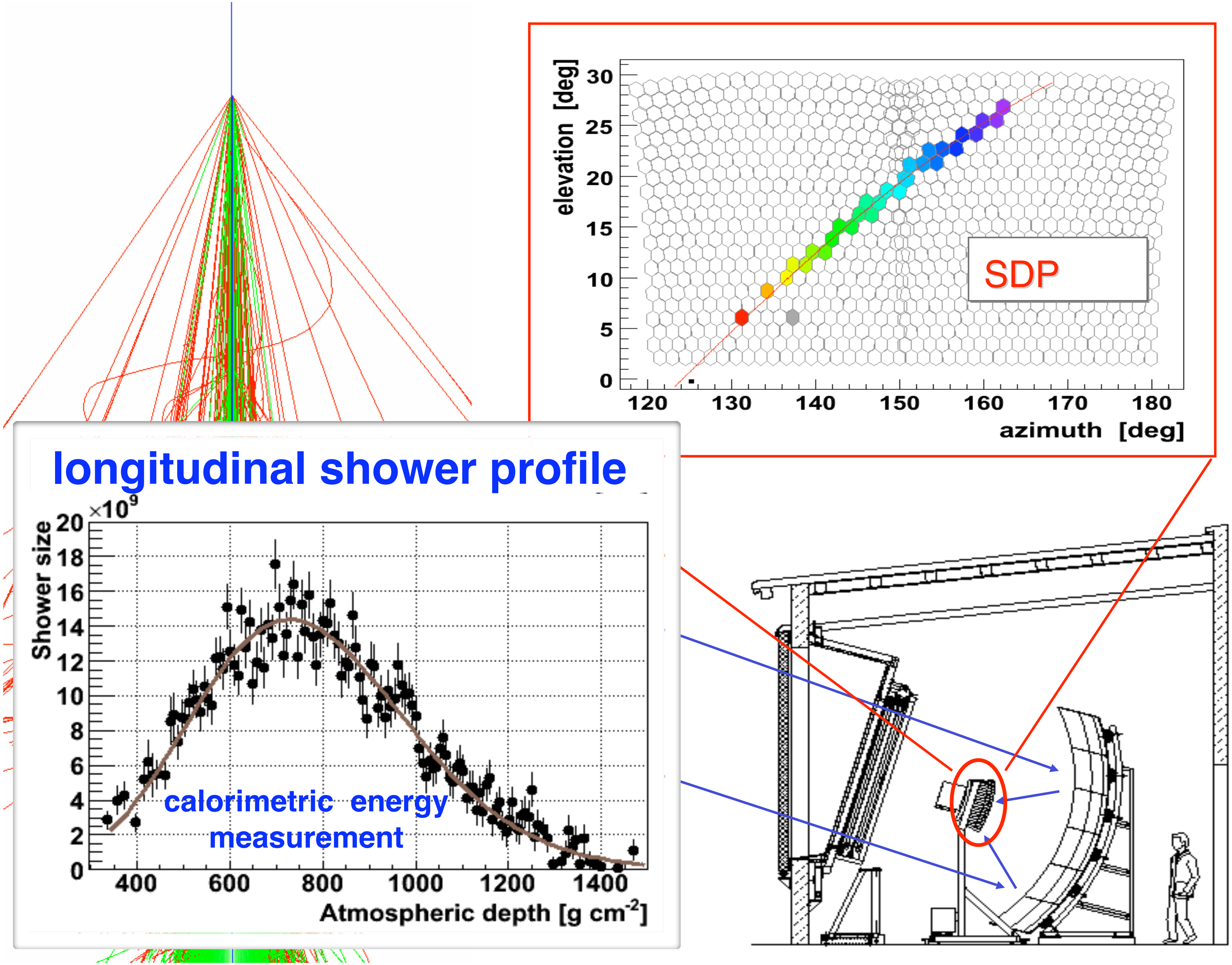

communications antenna
GPS antenna
electronics
solar cells
3 9“ photomultiplier tubes
battery
plastic tank with
12 t ultra pure water

Air shower registered with water Cherenkov detectors




FD eye view
MIRROR
CAMERA
APERTURE
Four sites
Six telescopes
viewing 30ºx30º each


12 m^2 mirror
90 cm
440 photo multiplier



elevation [deg]
30
25
20
15
10
5
0
120
130
140
150
160
170
180
azimuth [deg]
SDP
longitudinal shower profile
×10^9
Shower size
20
18
16
14
12
10
8
6
4
2
0
400
600
800
1000
1200
1400
Atmospheric depth [g cm^-2]
calorimetric energy
measurement

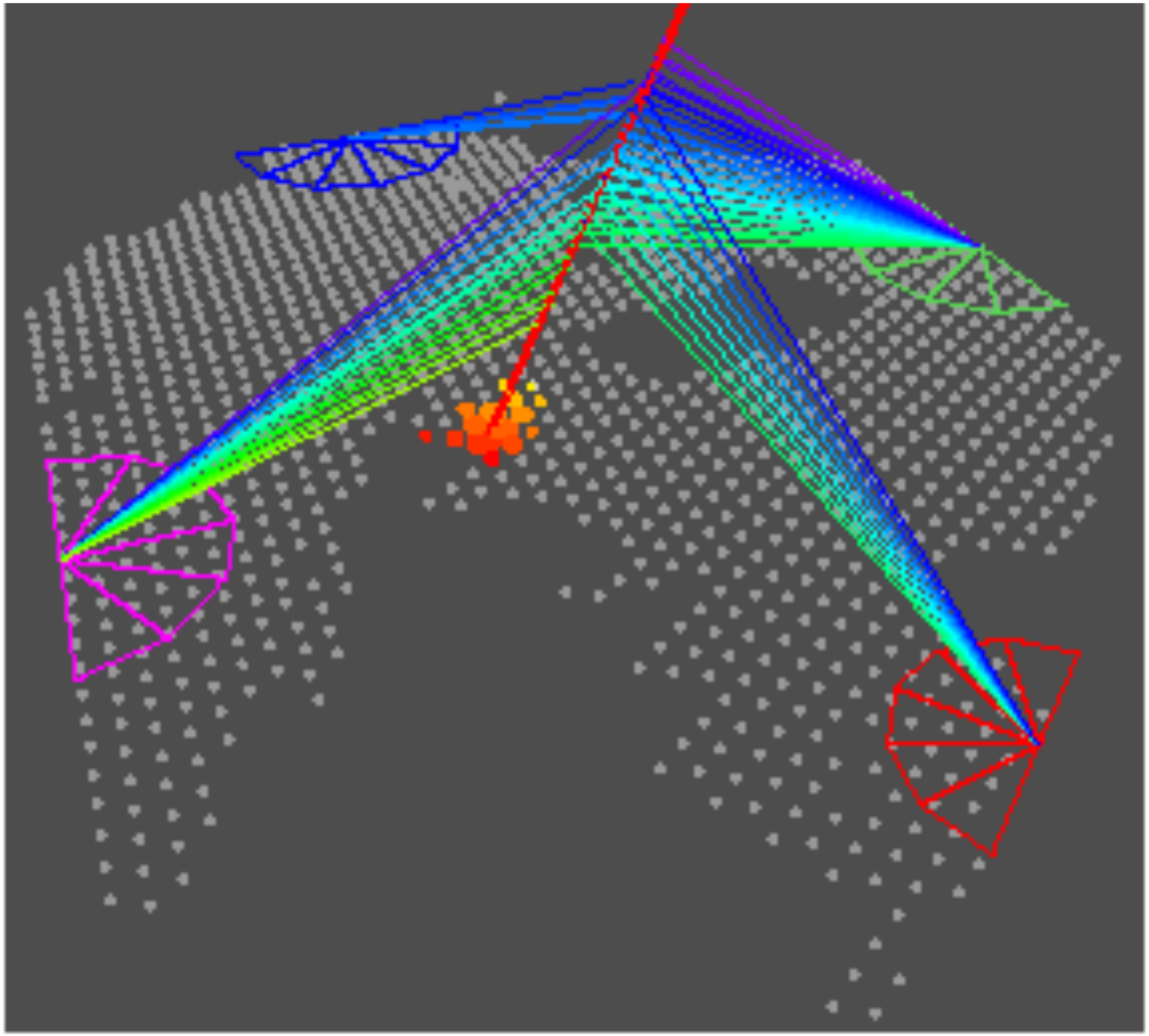
The Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

Czech Republic	Argentina
France	Australia
Germany	Brasil
Italy	Bolivia*
Netherlands	Mexico
Poland	USA
Portugal	Vietnam*
Slovenia	
Spain	**Associate Countries*
United Kingdom	~300 PhD scientists from ~ 70 Institutions and 17 Countries

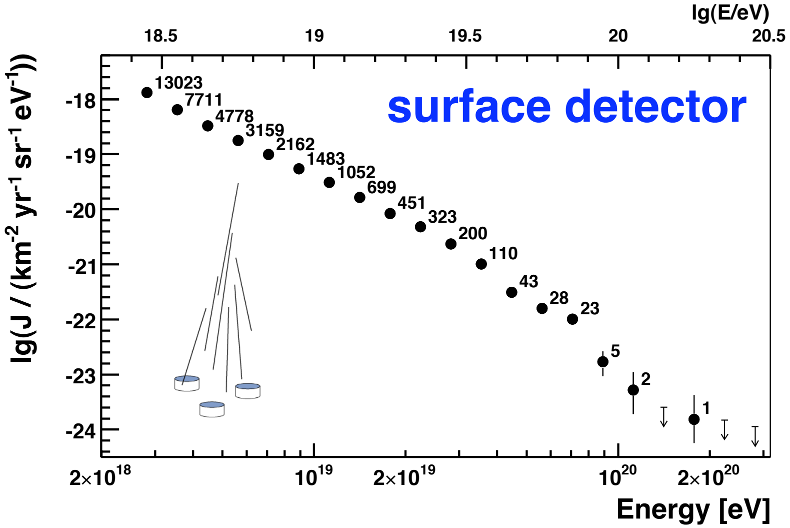
Aim: To measure properties of UHECR with unprecedented statistics and precision

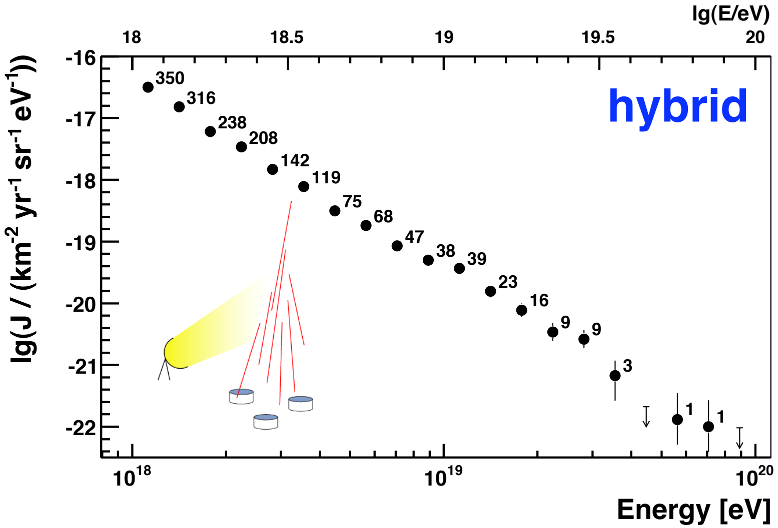
A Hybrid Event



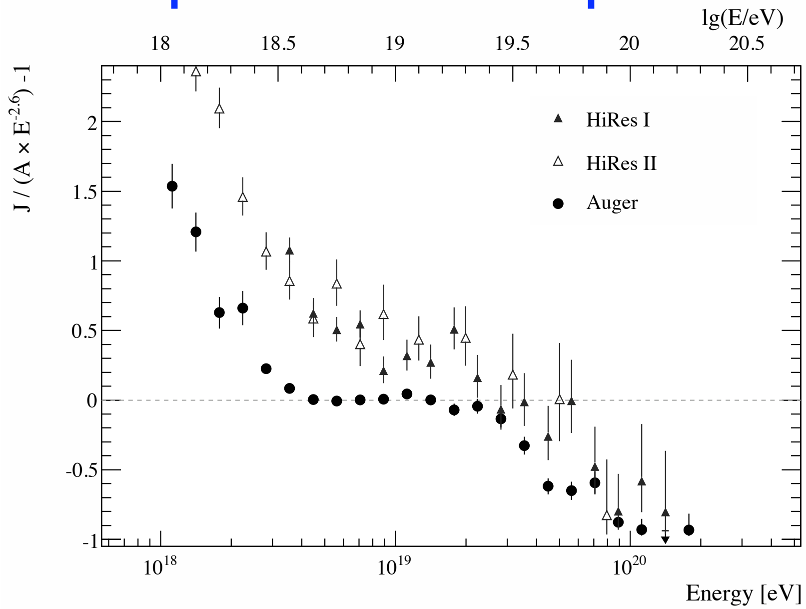
20 May 2007 E ~ 10^{19} eV

Energy spectrum





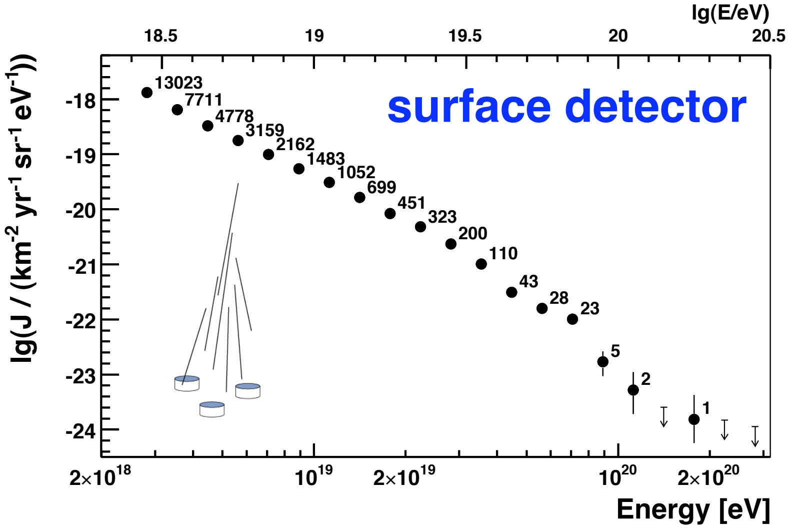
comparison to other experiments

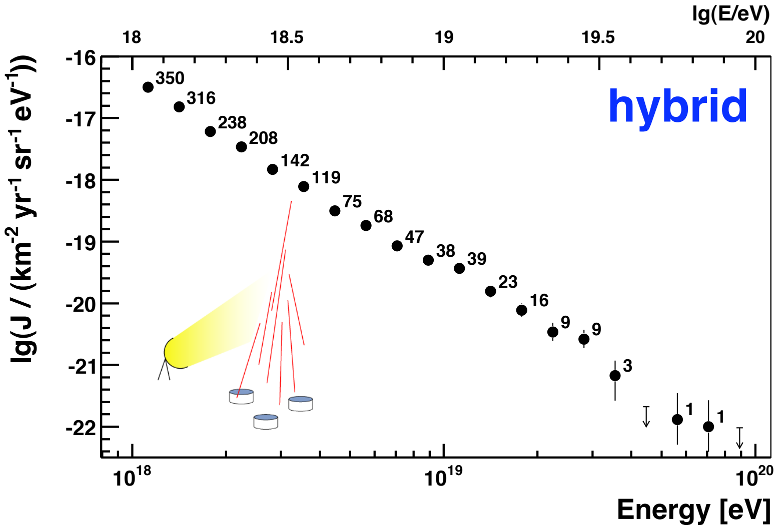


parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\text{ankle}})$	3.26 ± 0.04	3.26 ± 0.04
$\lg(E_{\text{ankle}}/\text{eV})$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{\text{ankle}})$	2.59 ± 0.02	2.55 ± 0.04
$\lg(E_{\text{break}}/\text{eV})$	19.46 ± 0.03	
$\gamma_3(E > E_{\text{break}})$	4.3 ± 0.2	
$\lg(E_{1/2}/\text{eV})$		19.61 ± 0.03
$\lg(W_c/\text{eV})$		0.16 ± 0.03

F. Schüssler et al., ICRC 2009

Energy spectrum





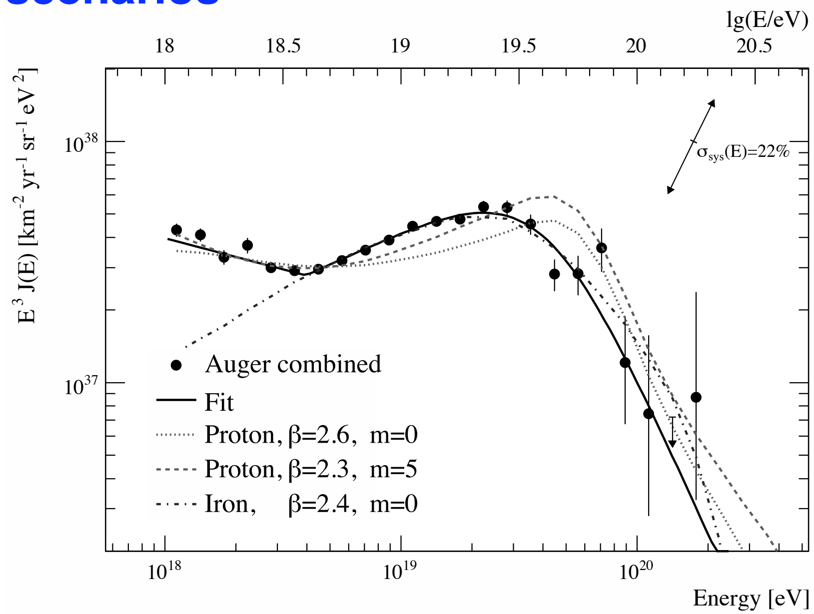
astrophysical scenarios

power law injection spectrum

$$\propto E^{-\beta}$$

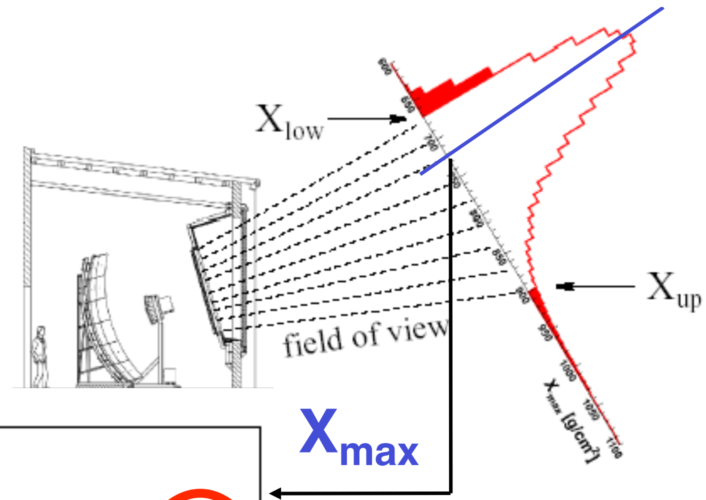
cosmological evolution of source luminosity

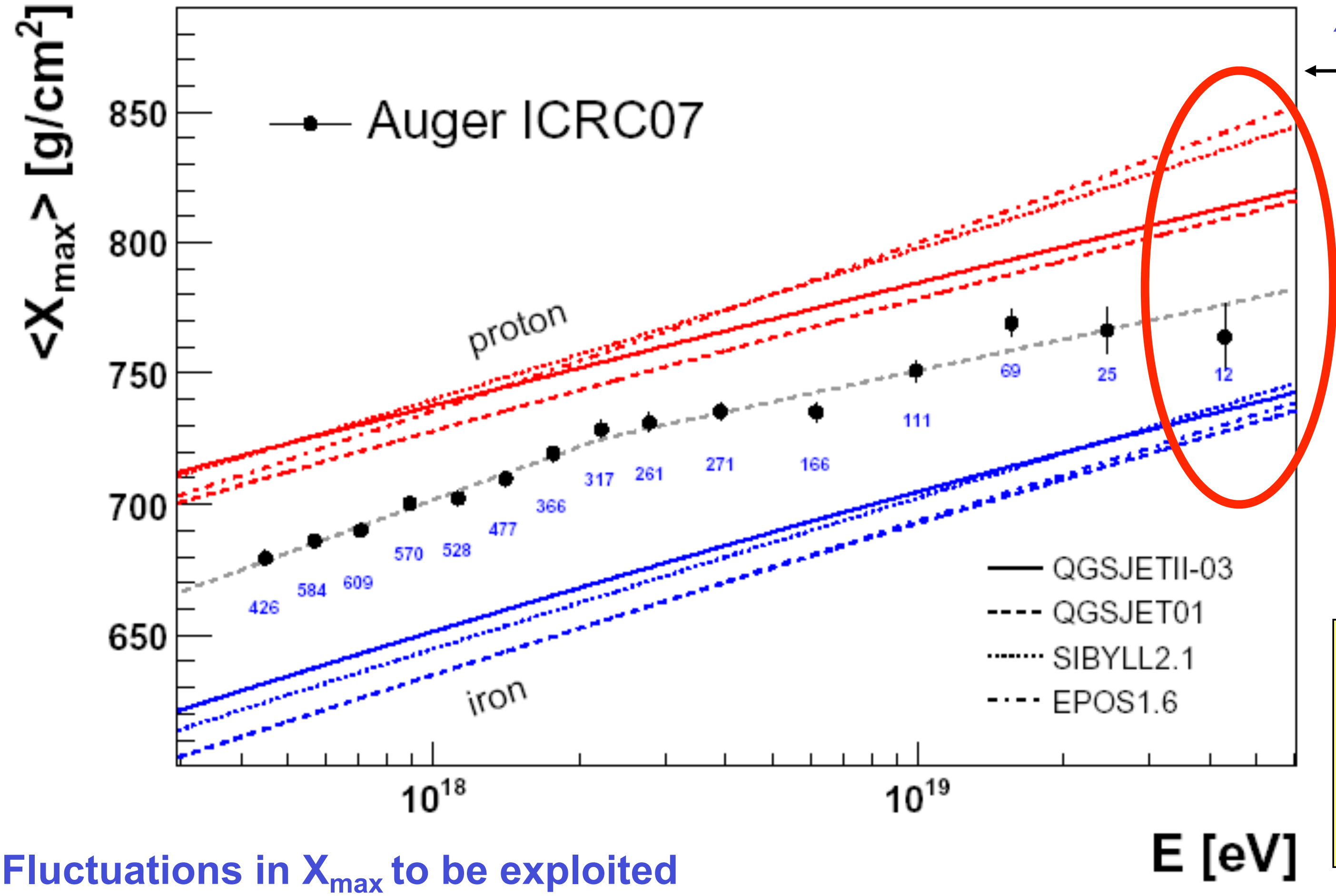
$$\propto (1+z)^m$$



F. Schüssler et al., ICRC 2009

Depth of the shower maximum X_{max}



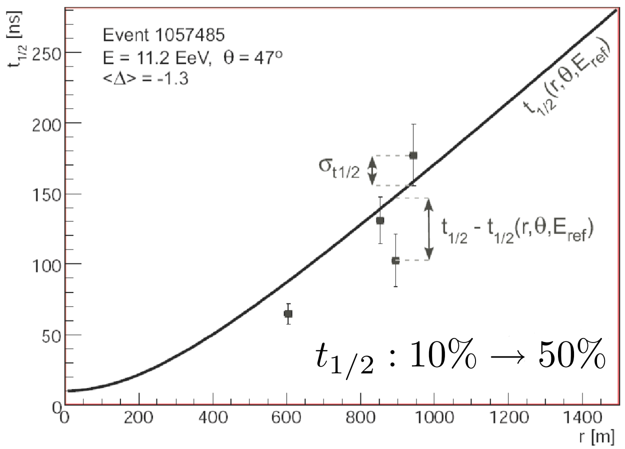


Fluctuations in X_{max} to be exploited

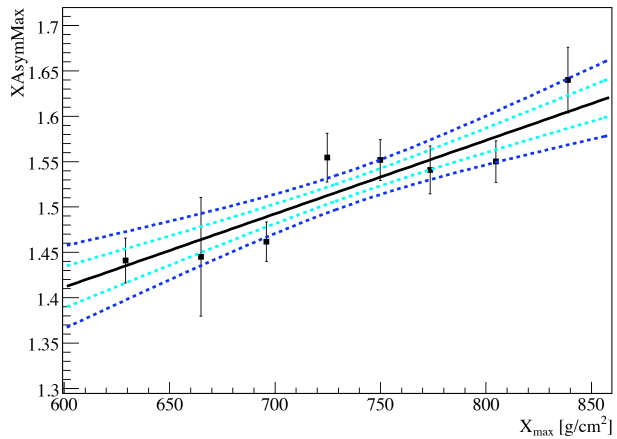
remember:
GZK effect requires light particles!

Mass composition - rise time

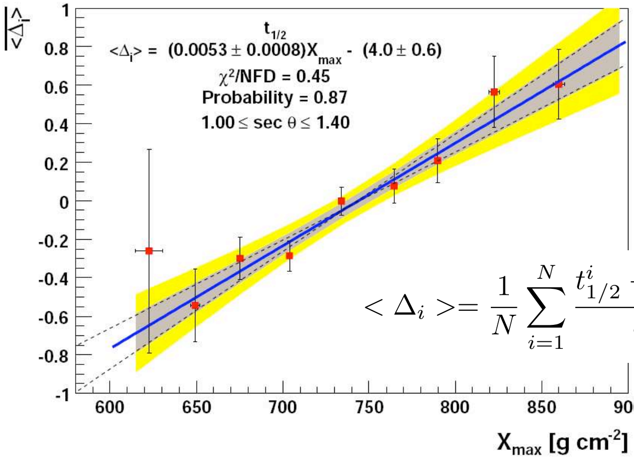
rise time vs. distance to shower axis



azimuthal asymmetry

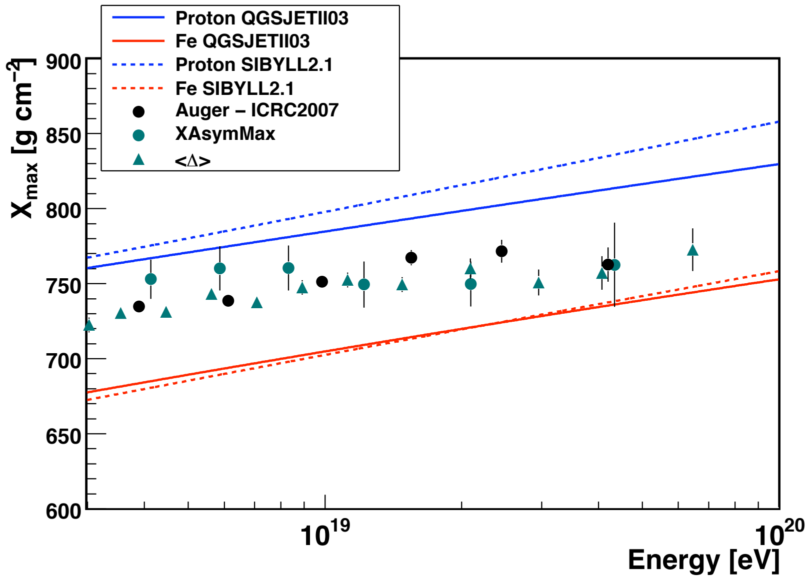


calibration



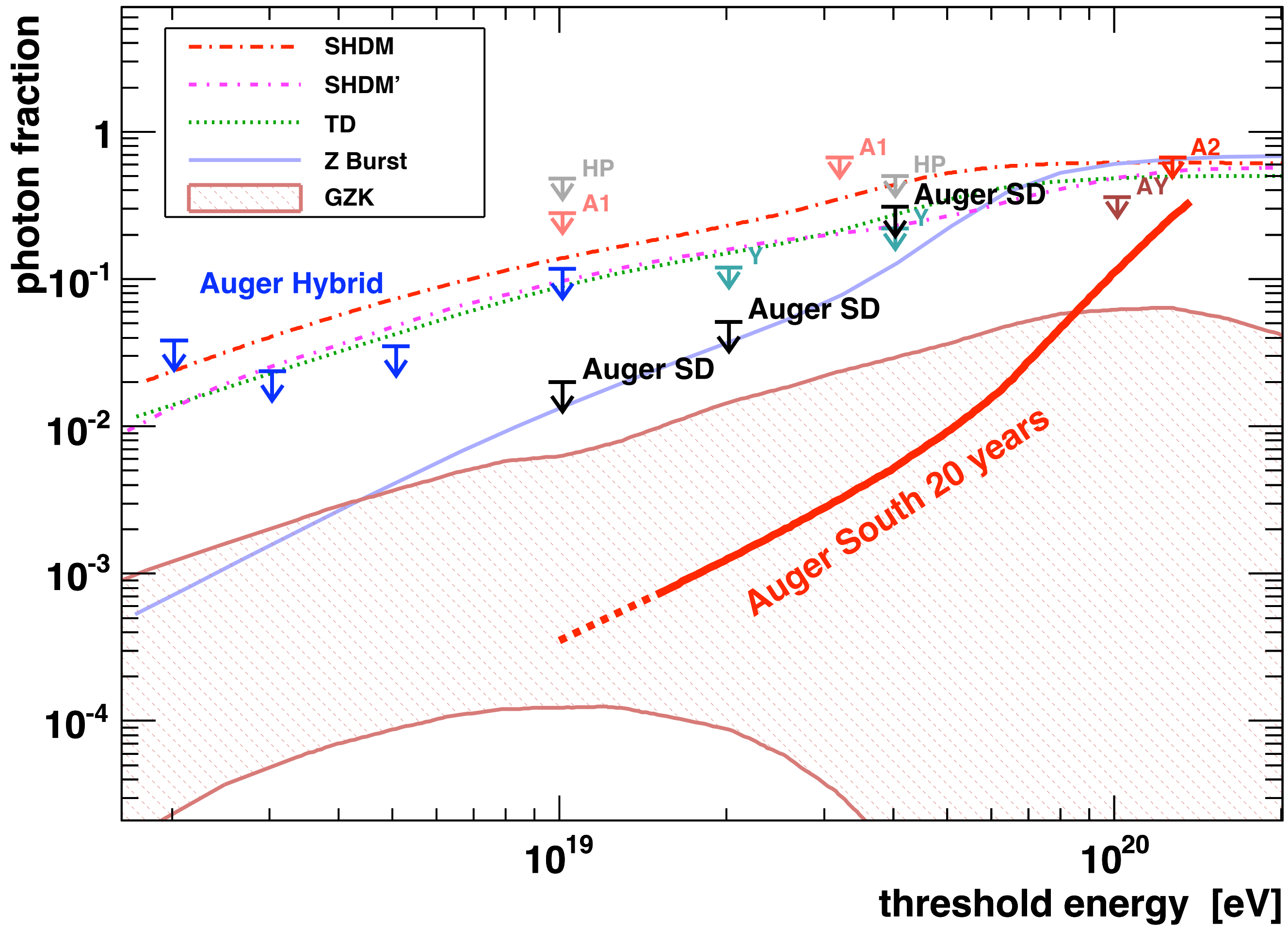
$$< \Delta_i >= \frac{1}{N}\sum_{i=1}^{N}\frac{t^i_{1/2} - t_{1/2}(r,\theta,E_{ref})}{\sigma^i_{1/2}(\theta,r,S)},$$

X_{max} vs. energy



H. Wahlberg et al., ICRC 2009

Limit on γ flux

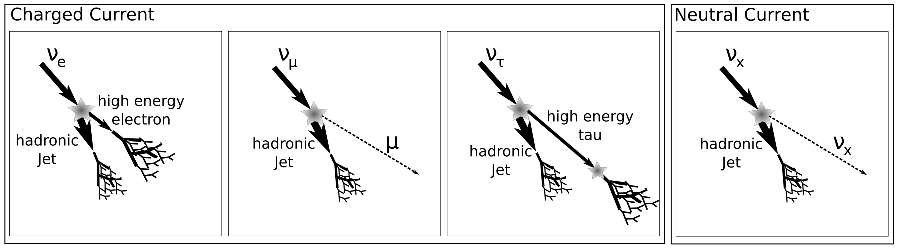


constraints on exotic CR models

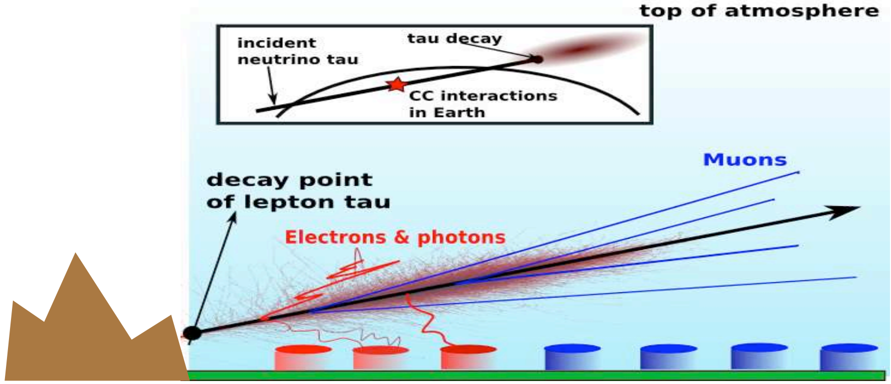
J. Abraham et al., Astroparticle Physics 29 (2008) 243

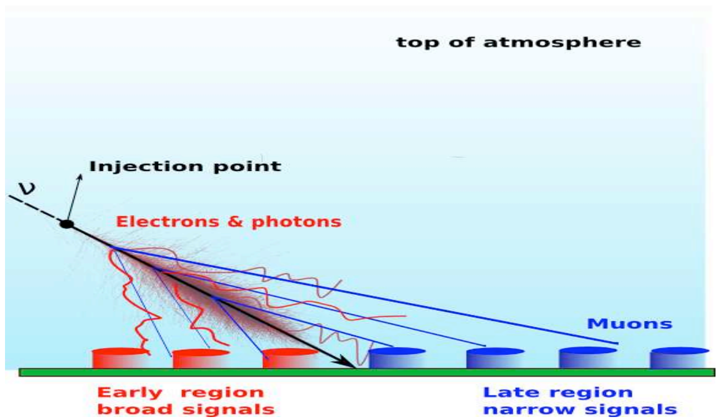
P. Homola et al., ICRC 2009

Neutrino Detection in Auger

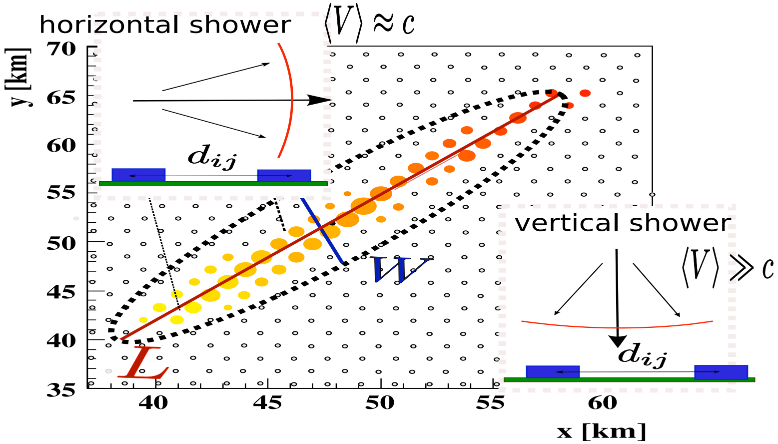


neutrinos initiate showers in atmosphere

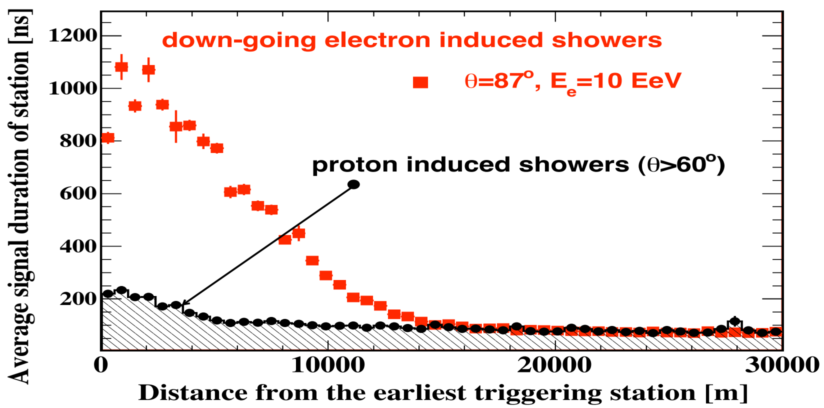




horizontal shower

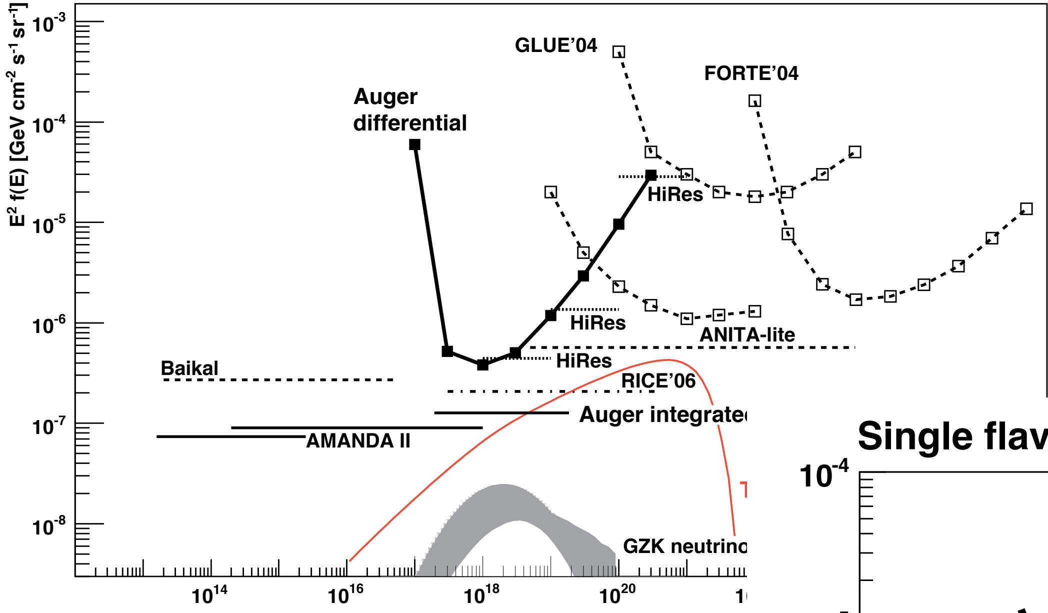


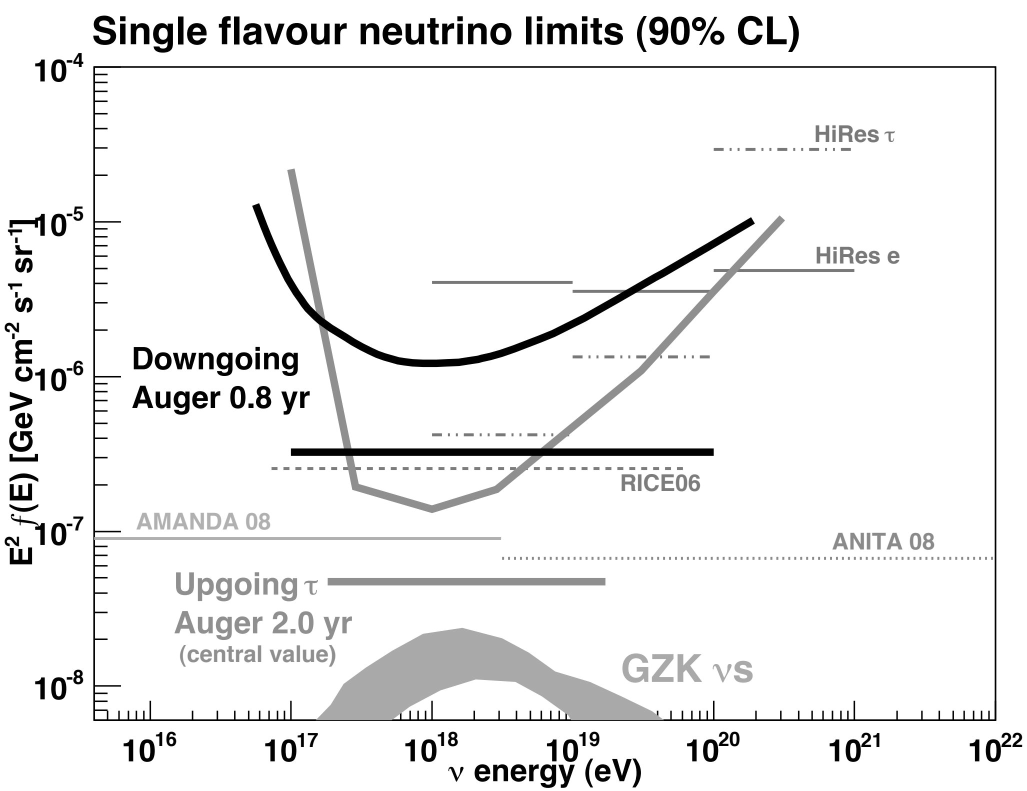
time structure



D. Gora et al., ICRC 2009 J. Tiffenberg et al., ICRC 2009 J. Abraham et al., PRL 100 (2008) 211101

Limit on τ neutrino flux



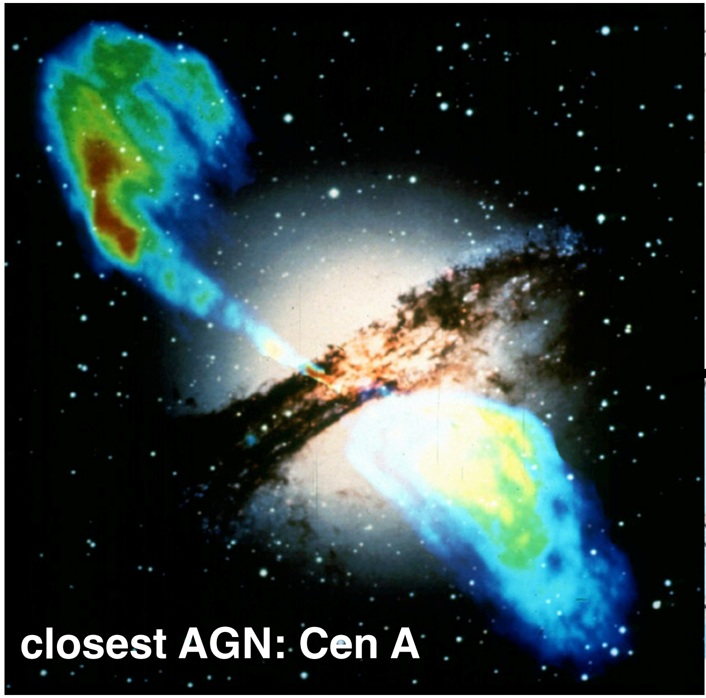


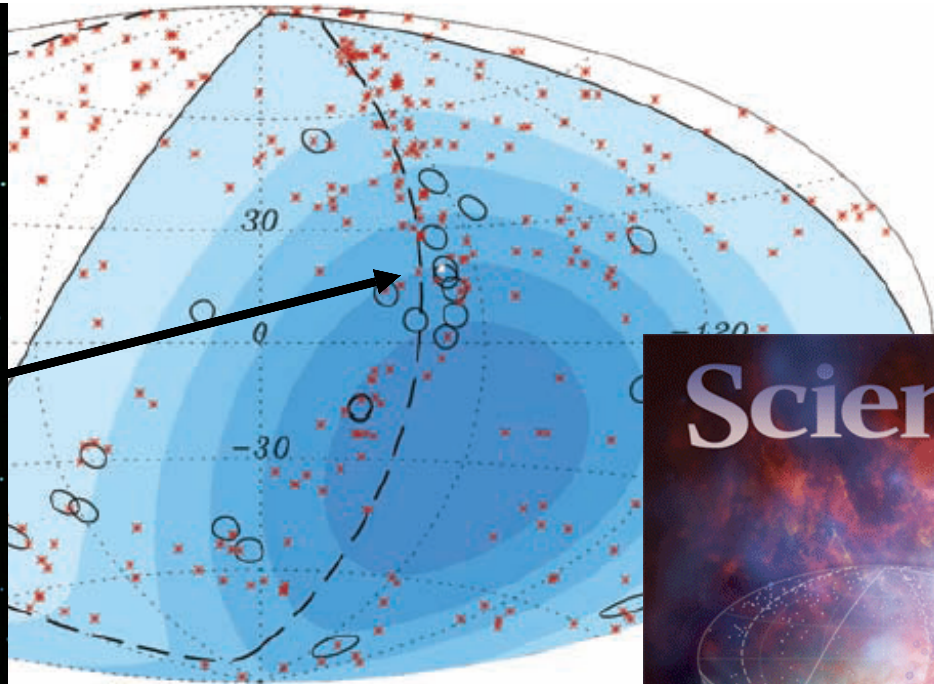
➡ constraints on exotic CR models

D. Gora et al., ICRC 2009 J. Tiffenberg et al., ICRC 2009 J. Abraham et al., PRL 100 (2008) 211101

Arrival directions of highest energy cosmic rays

Best correlation between arrival directions and positions of AGNs for
$E>5.7\ 10^{19}$ eV - d<75 Mpc - $\Theta<3.1°$





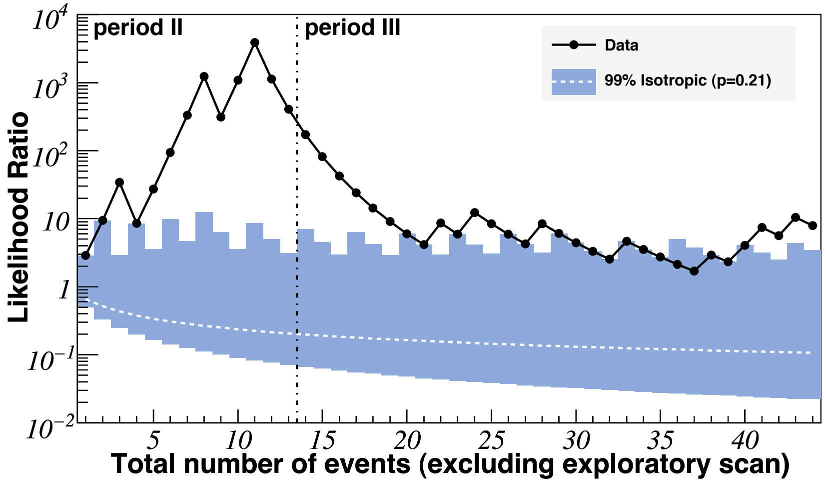
The Birth of Charged-Particle Astronomy

J. Abraham et al., Science 318 (2007) 938

Evolution of correlation with time

$$P = \sum_{j=k}^{N} \left(\begin{array}{c} N \\ j \end{array} \right) {p_{\rm iso}}^j (1 - p_{\rm iso})^{N-j}$$

probability for correlations in isotropic flux



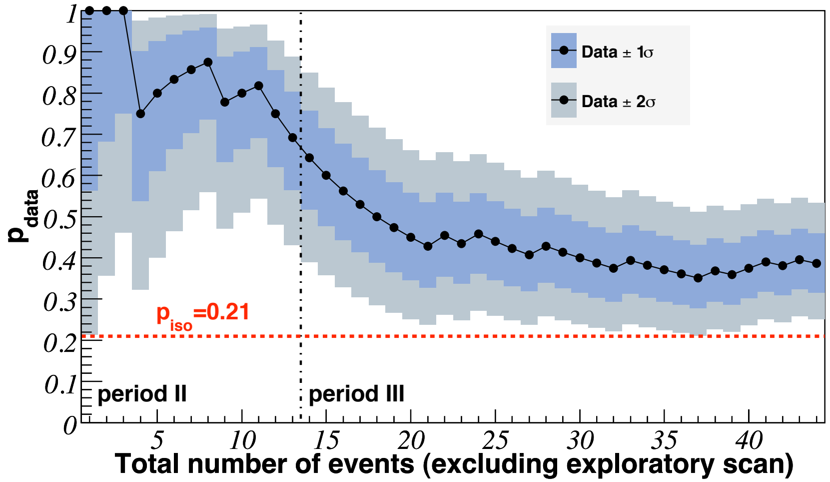


Fig. 1. Monitoring the correlation signal. *Left:* The sequential analysis of cosmic rays with energy greater than 55 EeV arriving after 27 May, 2006. The likelihood ratio $\log_{10} R$ (see Eqn (2)) for the data is plotted in black circles. Events that arrive within $\psi_{\rm max} = 3.1°$ of an AGN with maximum redshift $z_{\rm max} = 0.018$ result in an up-tick of this line. Values above the area shaded in blue have less than 1% chance probability to arise from an isotropic distribution ($p_{\rm iso} = 0.21$). *Right:* The most likely value of the binomial parameter $p_{\rm data} = k/N$ is plotted with black circles as a function of time. The 1σ and 2σ uncertainties in the observed value are shaded. The horizontal dashed line shows the isotropic value $p_{\rm iso} = 0.21$. The current estimate of the signal is 0.38 ± 0.07. In both plots events to the left of the dashed vertical line correspond to period II of Table I and those to the right, collected after [1], correspond to period III.

J.D. Hague et al., ICRC 2009

Angular separation

VCV catalog

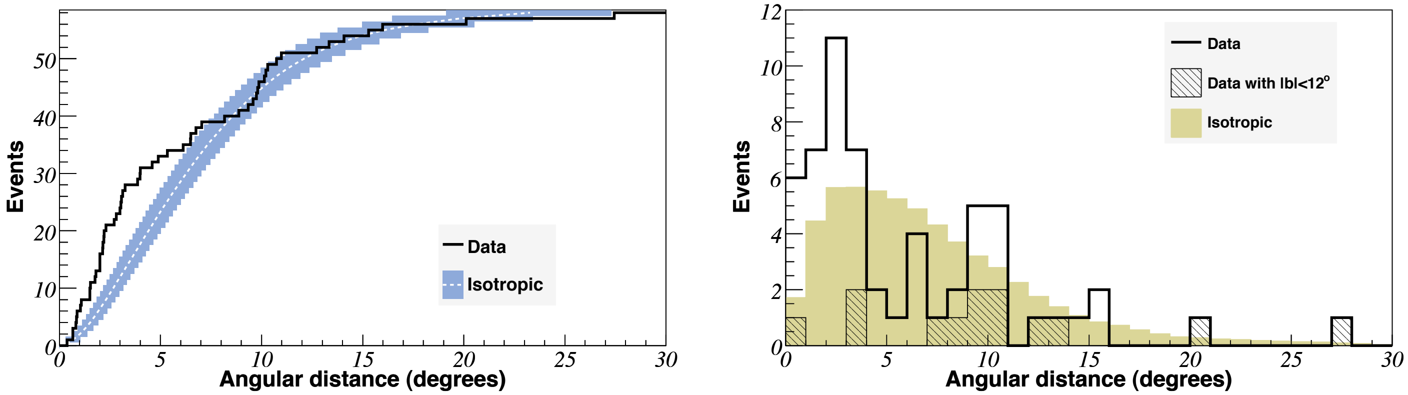


Fig. 2. The distribution of angular separations between the 58 events with $E > 55$ EeV and the closest AGN in the VCV catalog within 75 Mpc. *Left:* The cumulative number of events as a function of angular distance. The 68% the confidence intervals for the isotropic expectation is shaded blue. *Right:* The histogram of events as a function of angular distance. The 13 events with galactic latitudes $|b| < 12°$ are shown with hatching. The average isotropic expectation is shaded brown.

Cen A

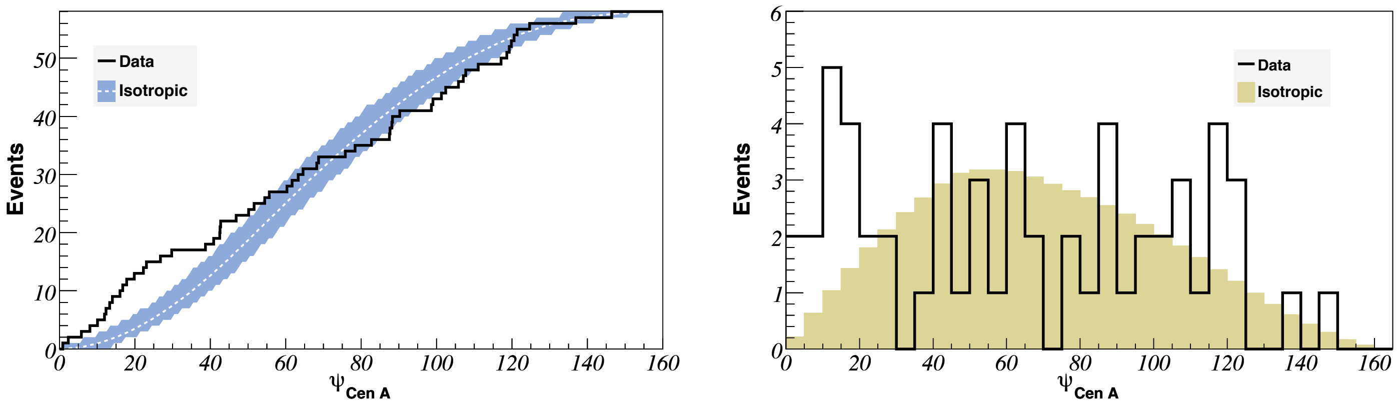
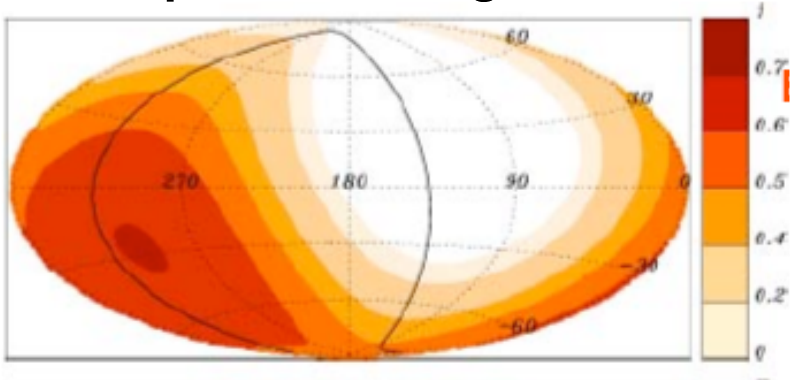


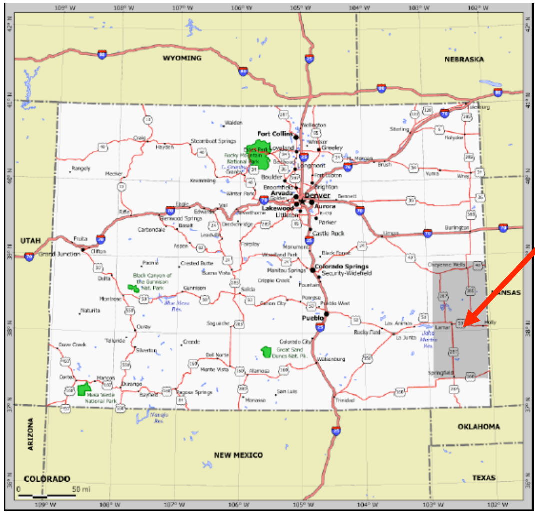
Fig. 3. *Left:* The cumulative number of events with $E \geq 55$ EeV as a function of angular distance from Cen A. The average isotropic expectation with approximate 68% confidence intervals is shaded blue. *Right:* The histogram of events as a function of angular distance from Cen A. The average isotropic expectation is shaded brown.

J.D. Hague et al., ICRC 2009

Pierre Auger Experiment – Northern Observatory

Exposure of Auger South

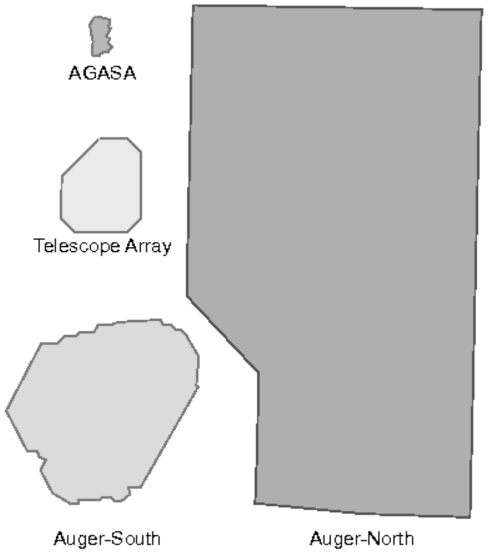


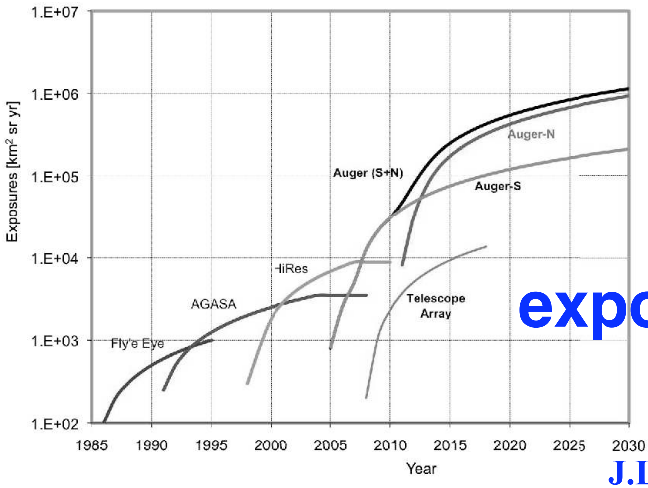


Lamar, Colorado, USA

for anisotropy studies full sky coverage desired

20000 km² array
water Cherenkov detectors
& fluorescence telescope systems





exposure vs. time

J.L. Harton et al., ICRC 2009

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Cosmic rays at the highest energies

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Radboud University Nijmegen, The Netherlands

http://particle.astro.kun.nl