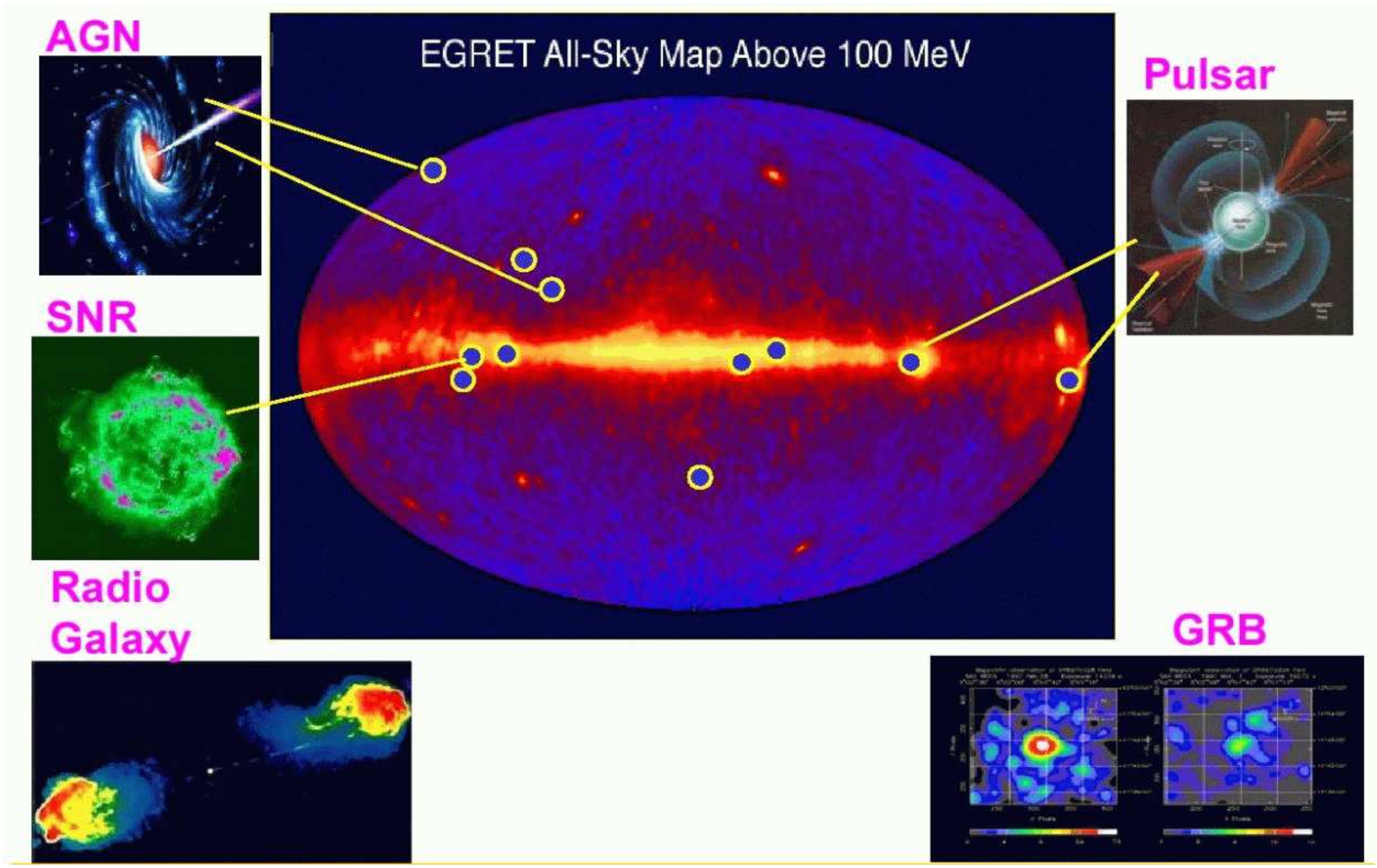
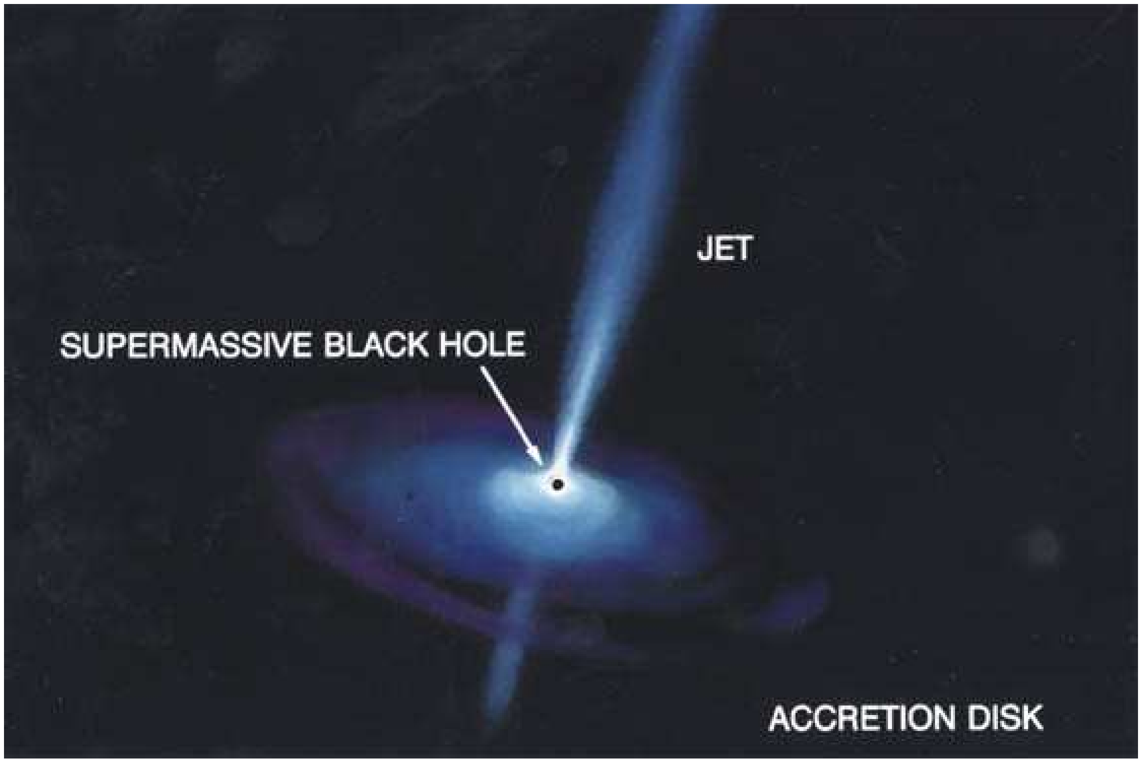
# Charged-particle and gamma-ray astronomy: deciphering charged messages from the world's most powerful

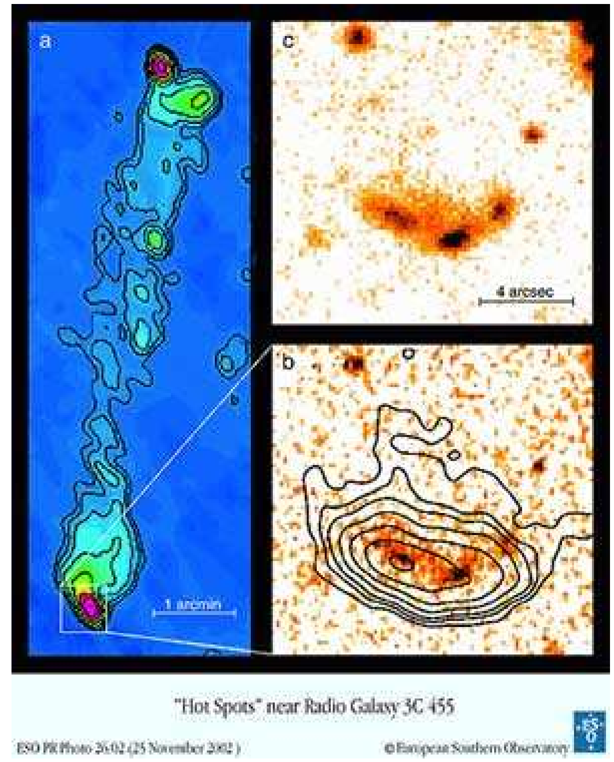
- Charged-particle astronomy coming of age
- How it is done
- The sources
- The signals
- What we have learned

# Cosmic accelerators

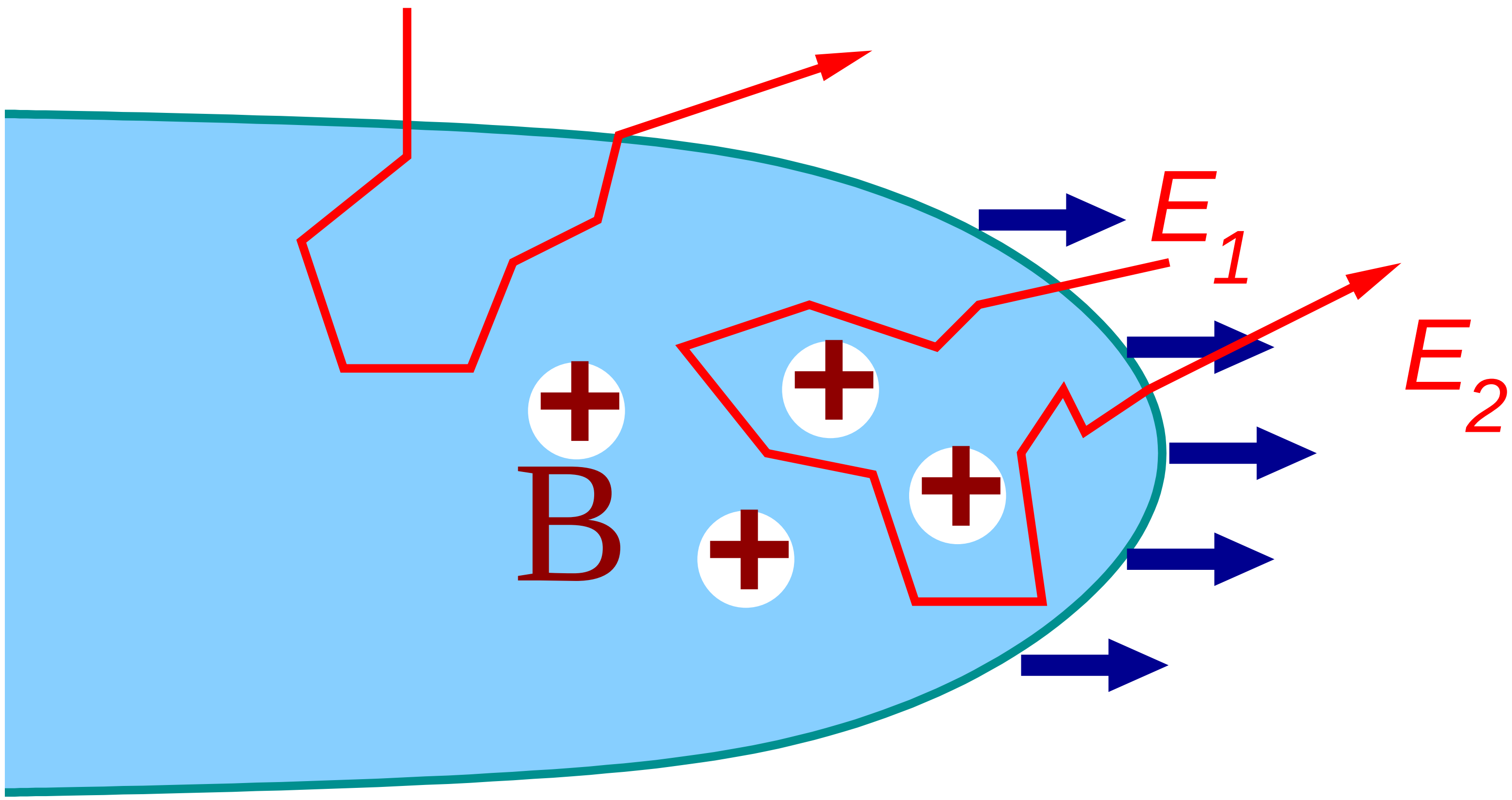


# Fermi acceleration in AGN and radio galaxies



## Fermi acceleration



# Fermi acceleration: simple estimates

Let us assume that each crossing give the particle acceleration by factor $\beta$, and the probability to remain in the acceleration region is $P$. Then the number of particles that cross the shock front $k$ times is

$$N = N_0 P^k, \quad \text{and their energy is} \quad E = E_0 \beta^k$$

Eliminate $k$ to get $N/N_0 = (E/E_0)^{\ln P/\ln \beta}$, or

$$\frac{dN}{dE} = E^{-\alpha}, \quad \text{where } \alpha = 1 - \frac{\ln P}{\ln \beta}$$

Hence, the **power-law spectrum**.

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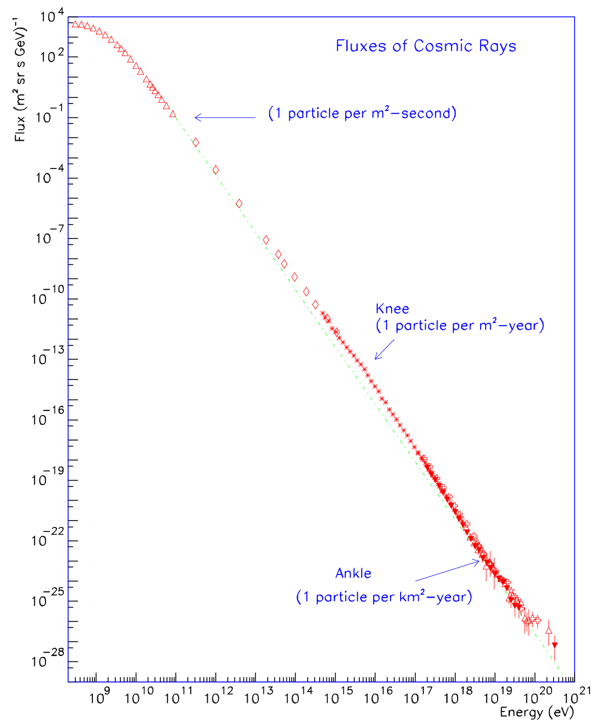
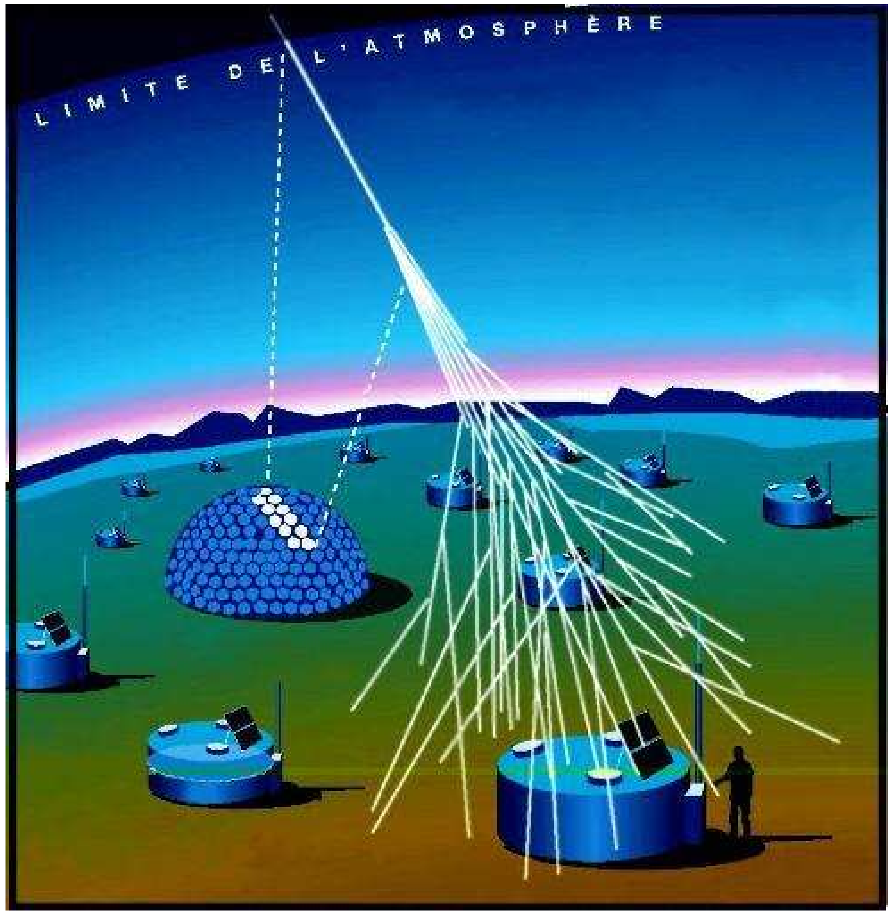
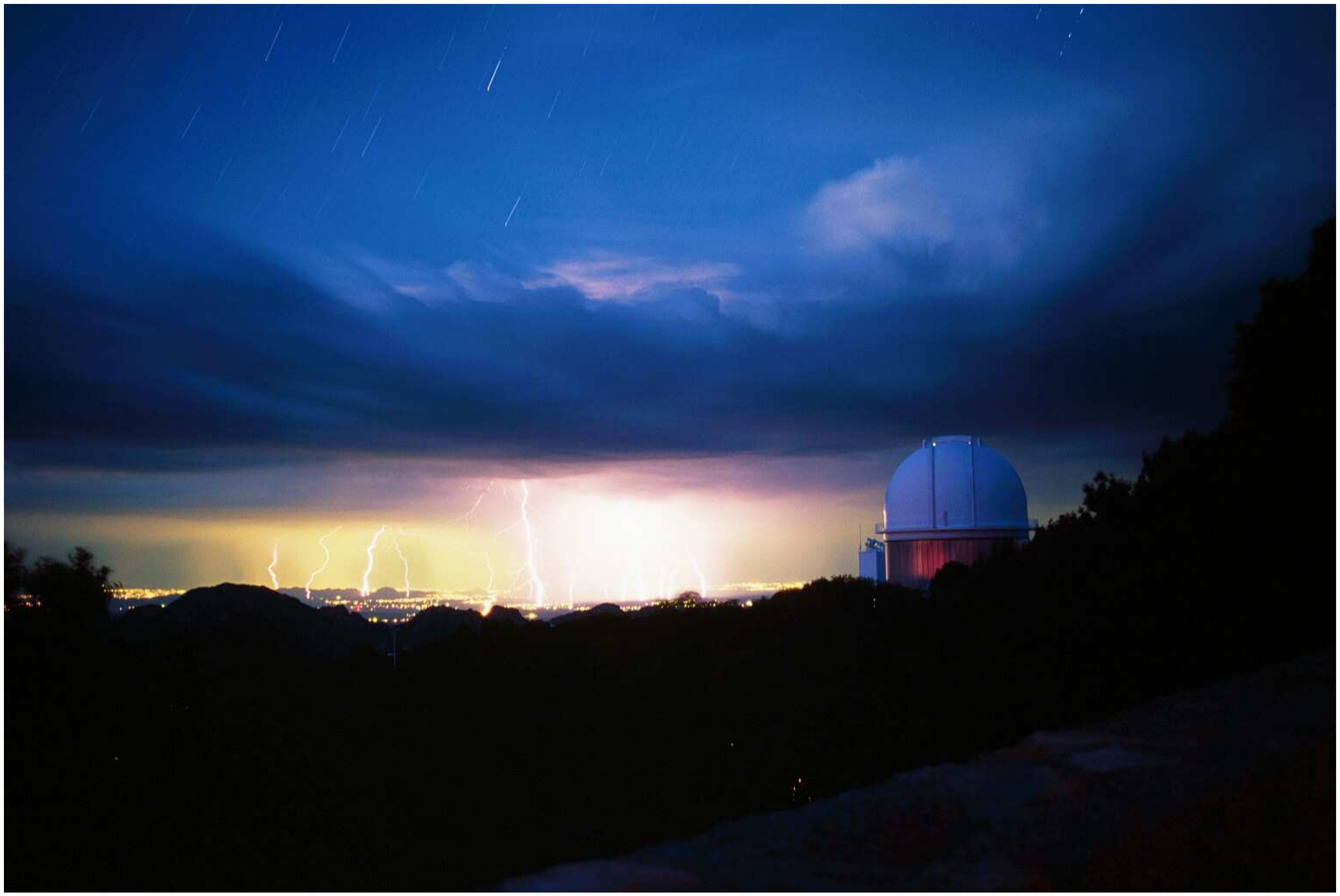
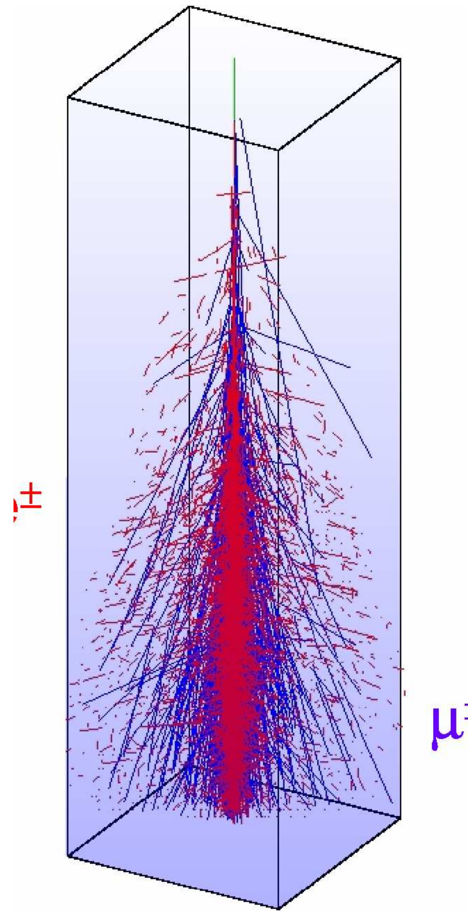


# Detection: Pierre Auger Observatory



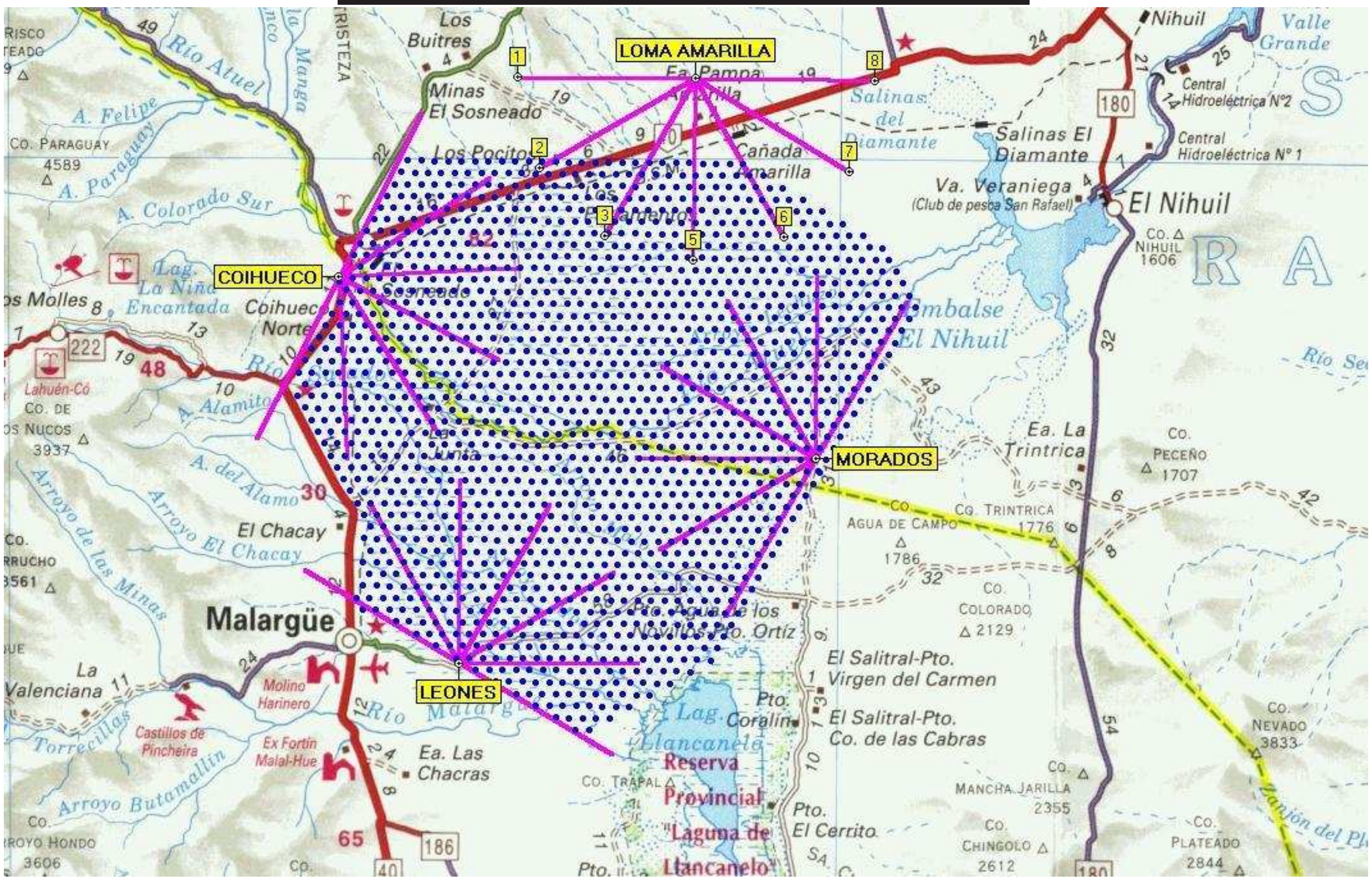
# Little known fact about lightnings





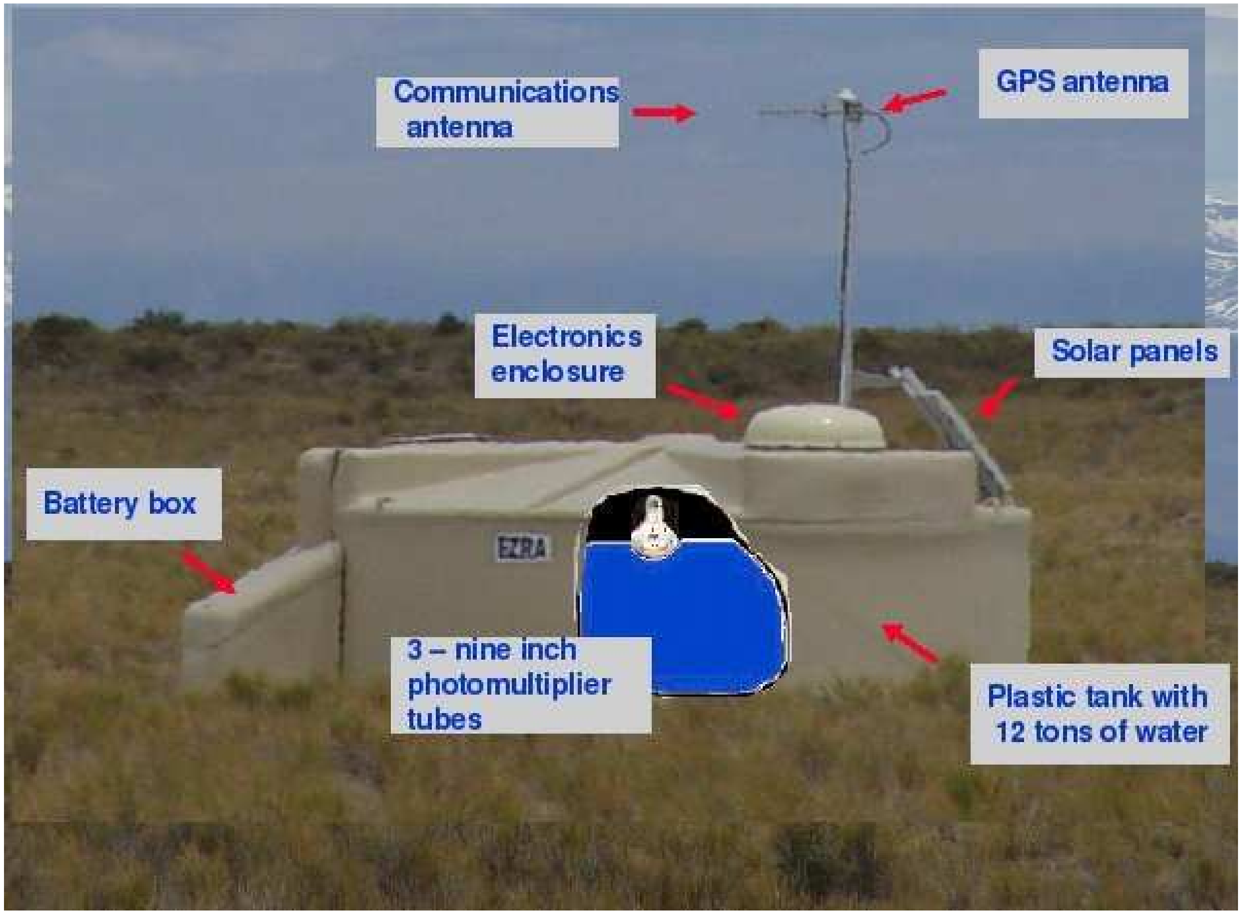
# Pierre Auger in Malargue, Argentina

# Pierre Auger Observatory

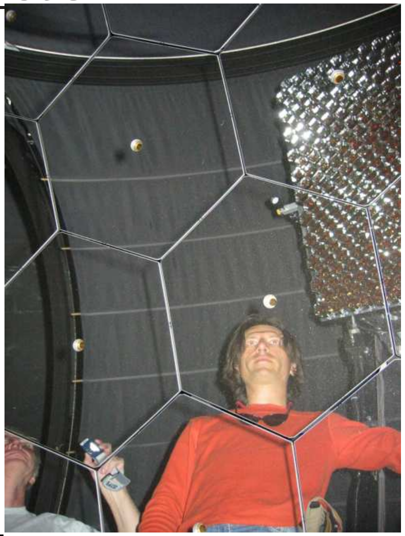


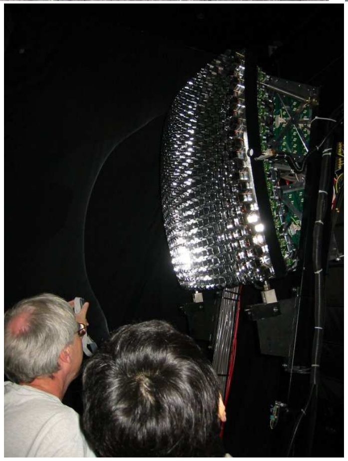
# Water tanks

# Water tanks

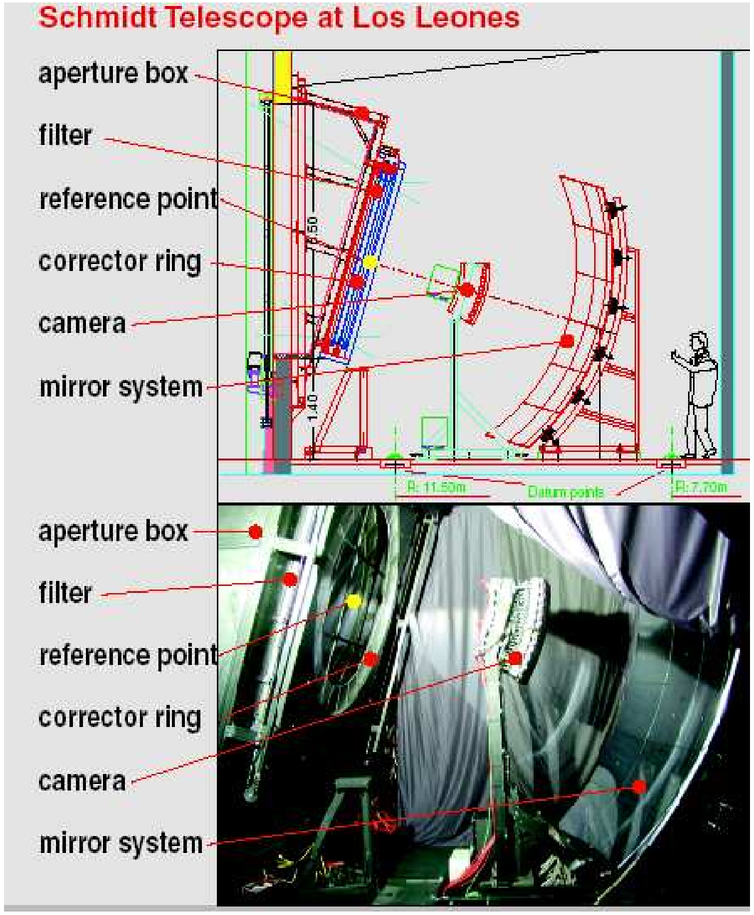

Communications antenna
GPS antenna
Electronics enclosure
Solar panels
Battery box
EZRA
3 – nine inch photomultiplier tubes
Plastic tank with 12 tons of water

# Fluorescence detector



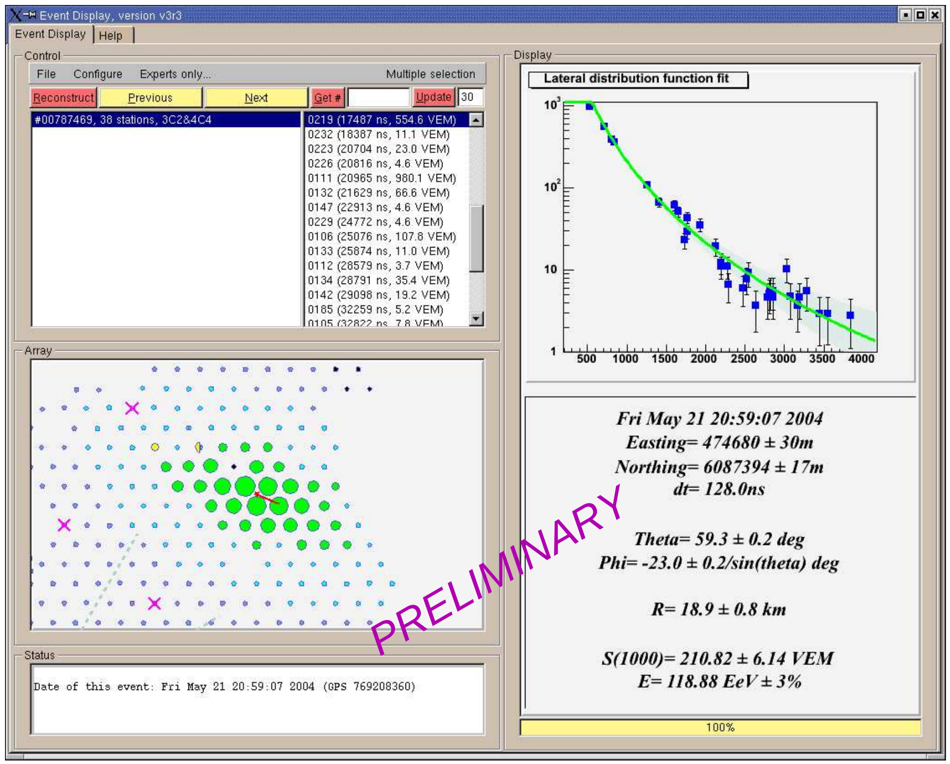


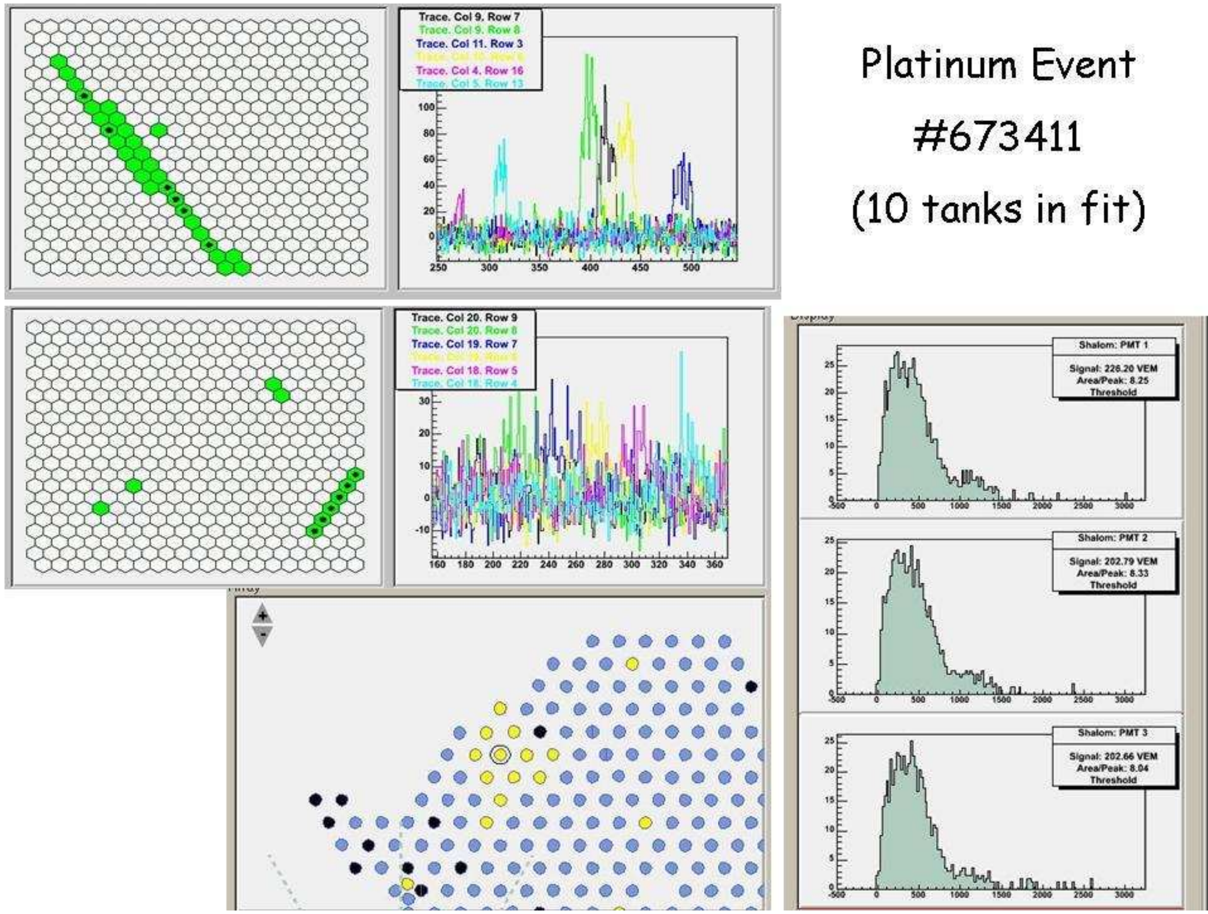
# Fluorescence detector



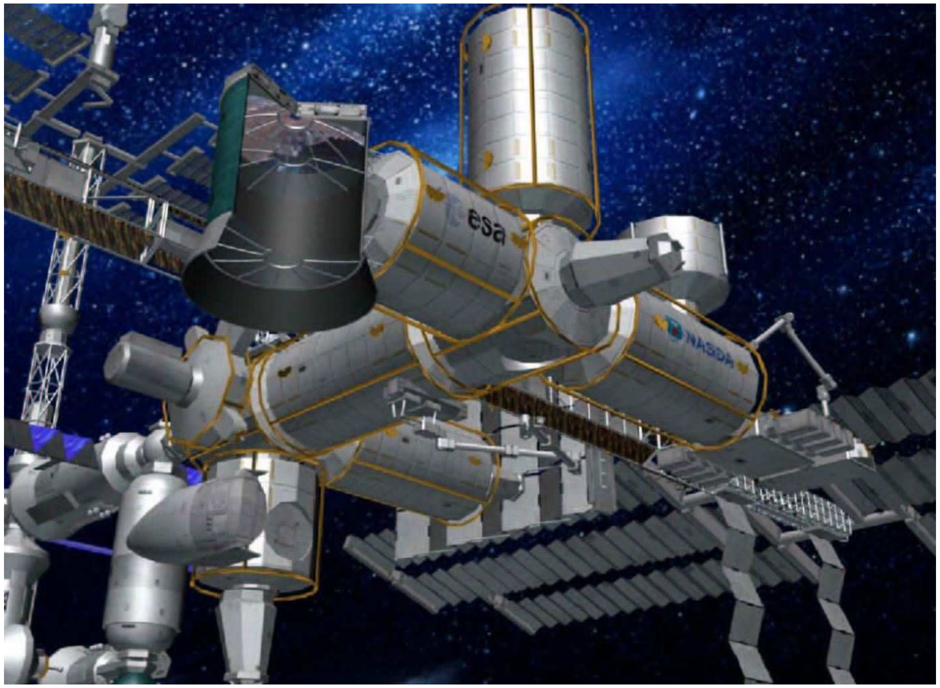
# Lidar is used to monitor the atmosphere

# Events


Event Display, version v3r3
Event Display
Help
Control
File
Configure
Experts only...
Multiple selection
Reconstruct
Previous
Next
Get #
Update
30
#00787469, 38 stations, 3C2&4C4
0219 (17487 ns, 554.6 VEM)
0232 (18387 ns, 11.1 VEM)
0223 (20704 ns, 23.0 VEM)
0226 (20816 ns, 4.6 VEM)
0111 (20965 ns, 980.1 VEM)
0132 (21629 ns, 66.6 VEM)
0147 (22913 ns, 4.6 VEM)
0229 (24772 ns, 4.6 VEM)
0106 (25076 ns, 107.8 VEM)
0133 (25874 ns, 11.0 VEM)
0112 (28579 ns, 3.7 VEM)
0134 (28791 ns, 35.4 VEM)
0142 (29098 ns, 19.2 VEM)
0185 (32259 ns, 5.2 VEM)
Array
Status
Date of this event: Fri May 21 20:59:07 2004 (GPS 769208360)
Display
Lateral distribution function fit
Fri May 21 20:59:07 2004
Easting= 474680 ± 30m
Northing= 6087394 ± 17m
dt= 128.0ns
Theta= 59.3 ± 0.2 deg
Phi= -23.0 ± 0.2/sin(theta) deg
R= 18.9 ± 0.8 km
S(1000)= 210.82 ± 6.14 VEM
E= 118.88 EeV ± 3%
100%
PRELIMINARY


Platinum Event
#673411
(10 tanks in fit)
Trace. Col 9. Row 7
Trace. Col 9. Row 8
Trace. Col 11. Row 3
Trace. Col 4. Row 16
Trace. Col 5. Row 13
Trace. Col 20. Row 9
Trace. Col 20. Row 8
Trace. Col 19. Row 7
Trace. Col 18. Row 5
Trace. Col 18. Row 4
Shalom: PMT 1
Signal: 226.20 VEM
Area/Peak: 8.25
Shalom: PMT 2
Signal: 202.79 VEM
Area/Peak: 8.33
Shalom: PMT 3
Signal: 202.66 VEM
Area/Peak: 8.04

# Extreme Universal Space Observatory (EUSO)




EUSO is designed to observe fluorescent air showers initiated by extremely high energy cosmic rays - and neutrinos

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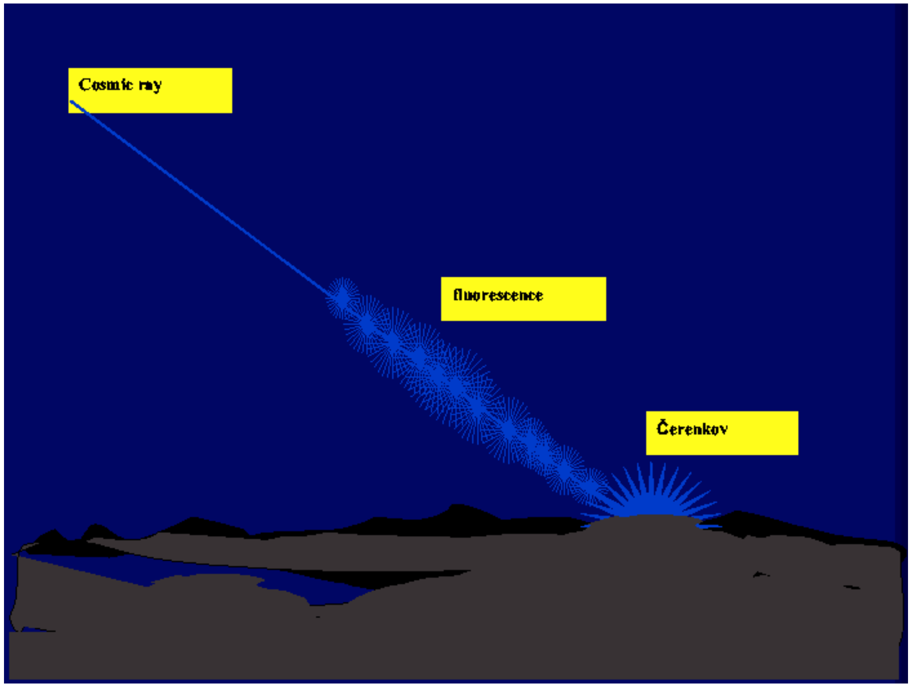
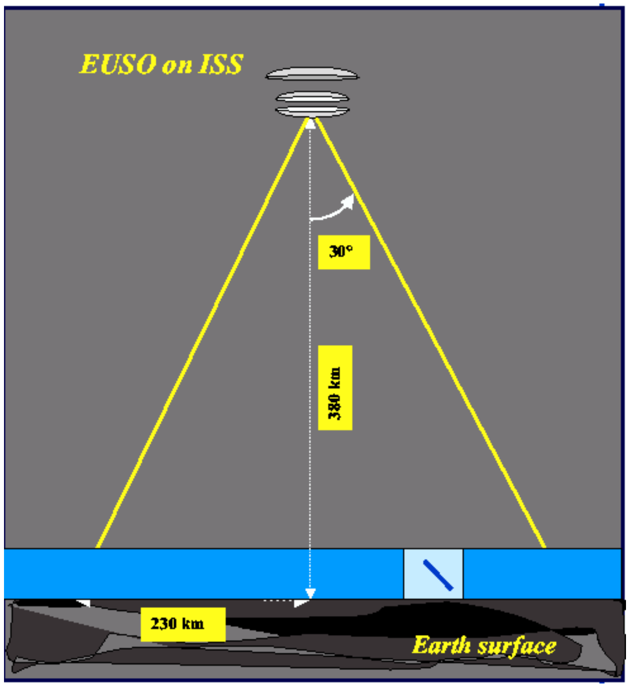
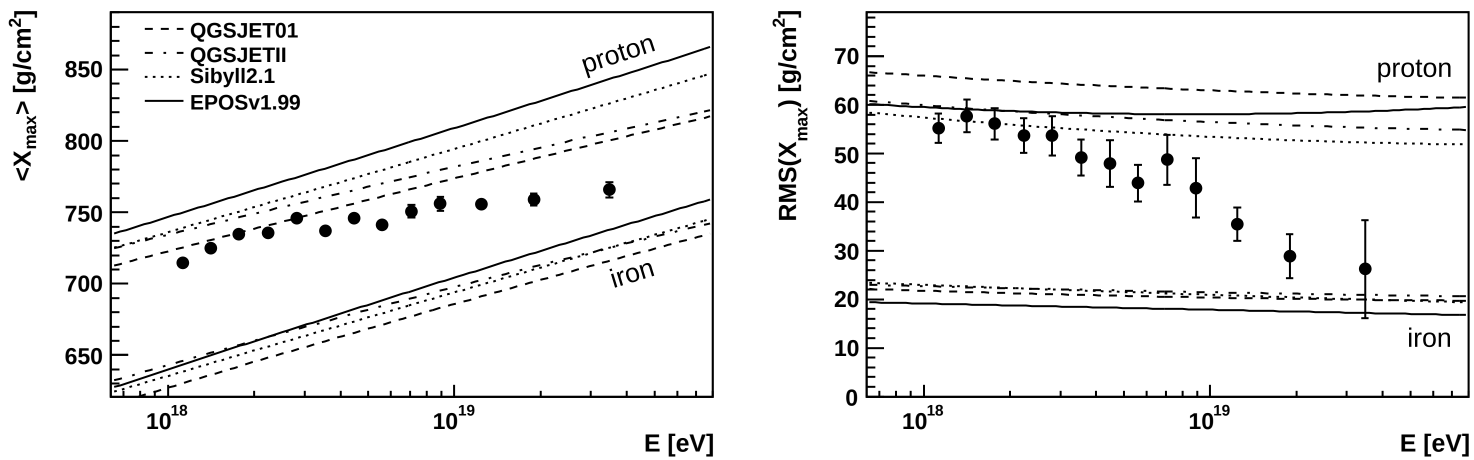


# A recent discovery by Pierre Auger

## energy-dependent chemical composition




**Why should any source accelerate nuclei rather than protons at high energies??**

# Composition puzzle

It is hard to imagine an extragalactic source that accelerates selectively heavy nuclei. In fact, the opposite is expected from photodissociation of nuclei at the source.

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If sources accelerate all the particles, can propagation effects alter the observed composition?

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It is hard to imagine an extragalactic source that accelerates selectively heavy nuclei. In fact, the opposite is expected from photodissociation of nuclei at the source.

If sources accelerate all the particles, can propagation effects alter the observed composition?

Yes, if the sources are **Galactic**.

Diffusion times for nuclei are longer than for protons of the same energy.

$$t_D \sim \frac{R^2}{D} \sim 10^8 \mathrm{yr} \left(\frac{R}{10\ \mathrm{kpc}}\right)^2 \left(\frac{26}{Z}\,\frac{10^{19}\ \mathrm{eV}}{E}\right)^2$$

Diffusion is also energy-dependent.

# Galactic sources likely to exist... in the past

Long list of candidates (in possibly overlapping categories):

- GRBs
- hypernovae
- collapsars
- other unusual supernovae

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Do these events occurred in our our own galaxy?

# Hypernova observed in our Galaxy


# GRBs as sources in Milky Way Galaxy

- GRBs have been proposed as sources of *extragalactic* UHECRs [Vietri; Waxman; Dermer (cf. talks by Dermer, Waxman)]
- Galactic GRBs have been considered as sources of UHECRs [Dermer *et al.*, Biermann *et al.*]
- Long GRBs: probably unusual supernova explosions. Short GRBs: probably mergers of compact stars.
- Both should have happened in our own Galaxy in the past, at a rate of one per $\mathbf{10^4 - 10^5}$ **years**.
- Past Galactic GRBs have been considered as the explanation of 511 keV line from the Galactic Center [Bertone, et al.; Parizot et al., Calvez, AK], as well as the electron excess of PAMELA/Fermi [Ioka; Calvez, AK]
- How long will the UHECRs diffuse in the Galactic magnetic fields, and how isotropic will they become? Depends on composition.

# Transport equation (a simple exercise)

$$\frac{\partial n_i}{\partial t} - \vec{\nabla}(D_i \vec{\nabla} n_i) + \frac{\partial}{\partial E}(b_i n_i) =$$

$$Q_i(E, \vec{r}, t) + \sum_k \int P_{ik}(E, E') n_k(E') dE'.$$

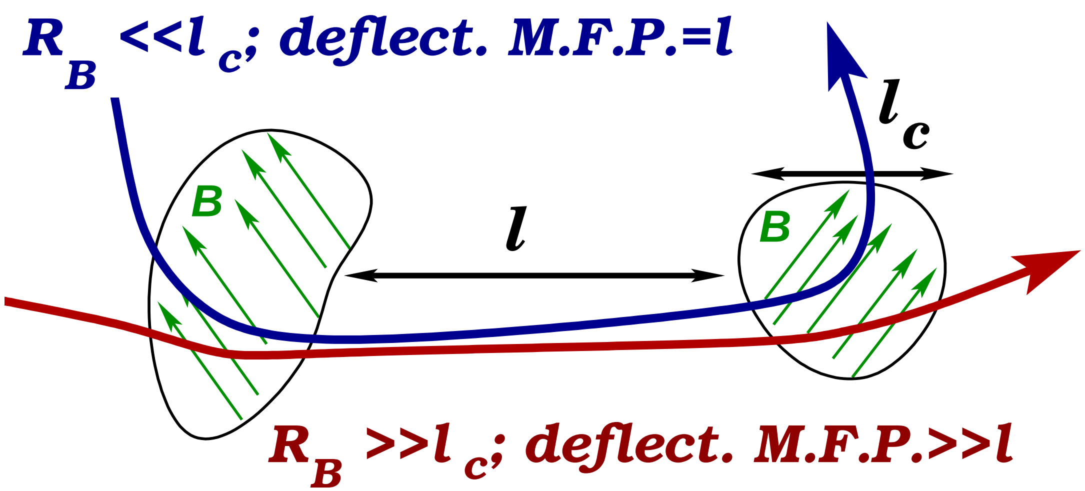
For energies below GZK cutoff, neglect energy losses; consider just diffusion. For a pointlike source

$$Q_i(E, \vec{r}, t) = \delta(\vec{r}) Q_0 \left(\frac{E_0}{E}\right)^{\gamma}$$

the solution is

$$n_i(E, r) = \frac{Q_0}{4\pi r \, D_i(E)} \left(\frac{E_0}{E}\right)^{\gamma}.$$

# Diffusion in two different regimes

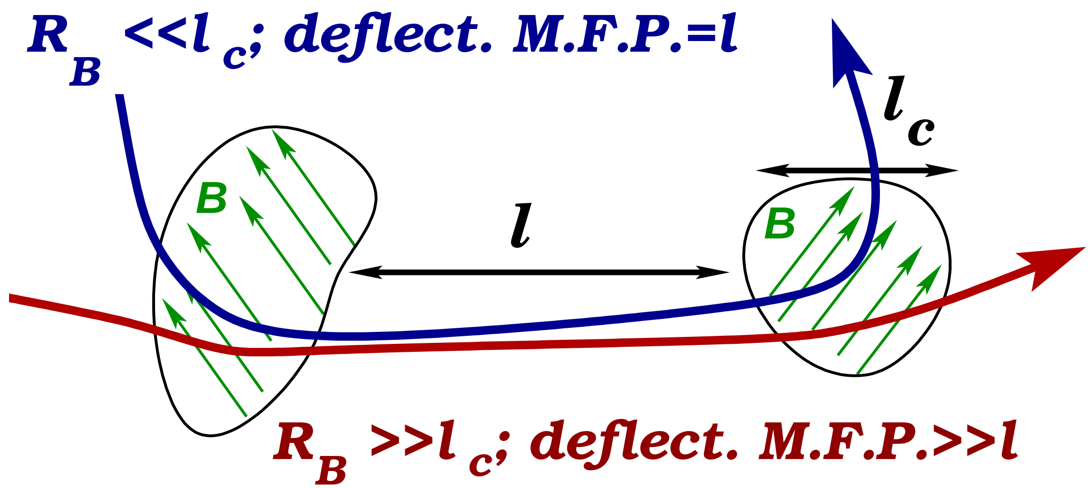



$D(E)=D_0=l/3$, for $E \ll E_0$

$D(E)=D_0(E/E_0)^2$, for $E \gg E_0$

critical energy, $E_0$: $R_B=l_c$

## Diffusion in two different regimes

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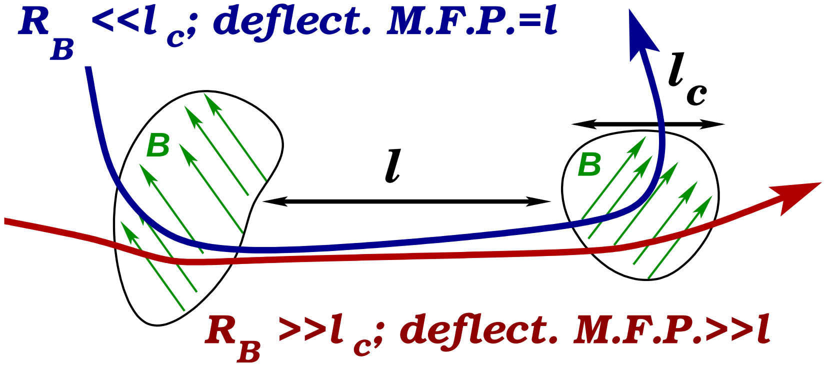
$E_0$ depends on $Z$ of a nucleus.

# Diffusion in two different regimes




***D(E)=D$_0$=l/3, for E<<E$_0$***

***D(E)=D$_0$(E/E$_0$)$^2$, for E>>E$_0$***

***critical energy, E$_0$: R$_B$=l$_c$***

$E_{0,i}$ depends on $Z_i$ of a nucleus $i$.

Critical energy $\boldsymbol{E_{0,i}}$, at which $\boldsymbol{R_{B,i} = l_c}$, depends on $\boldsymbol{Z_i}$

$$
\begin{aligned}
R_i &= \frac{E}{Bq_i} = l_0 \left(\frac{E}{E_{0,i}}\right), \text{ where} \\
E_{0,i} &= eBl_0Z_i, \\
\boldsymbol{E_{0,i}} &= \boldsymbol{Z_i \times 10^{18}\,\mathrm{eV}} \\
&\quad \boldsymbol{\times \left(\frac{B}{3\times 10^{-6}\,\mathrm{G}}\right)\left(\frac{l_0}{0.3\,\mathrm{kpc}}\right)}
\end{aligned}
$$

Diffusion in two different regimes:

$$D_i(E) = \begin{cases} D_0 \left(\frac{E}{E_{0,i}}\right)^{\delta_1}, & E \leq E_{0,i}, \\ D_0 \left(\frac{E}{E_{0,i}}\right)^{(2-\delta_2)}, & E > E_{0,i}. \end{cases}$$

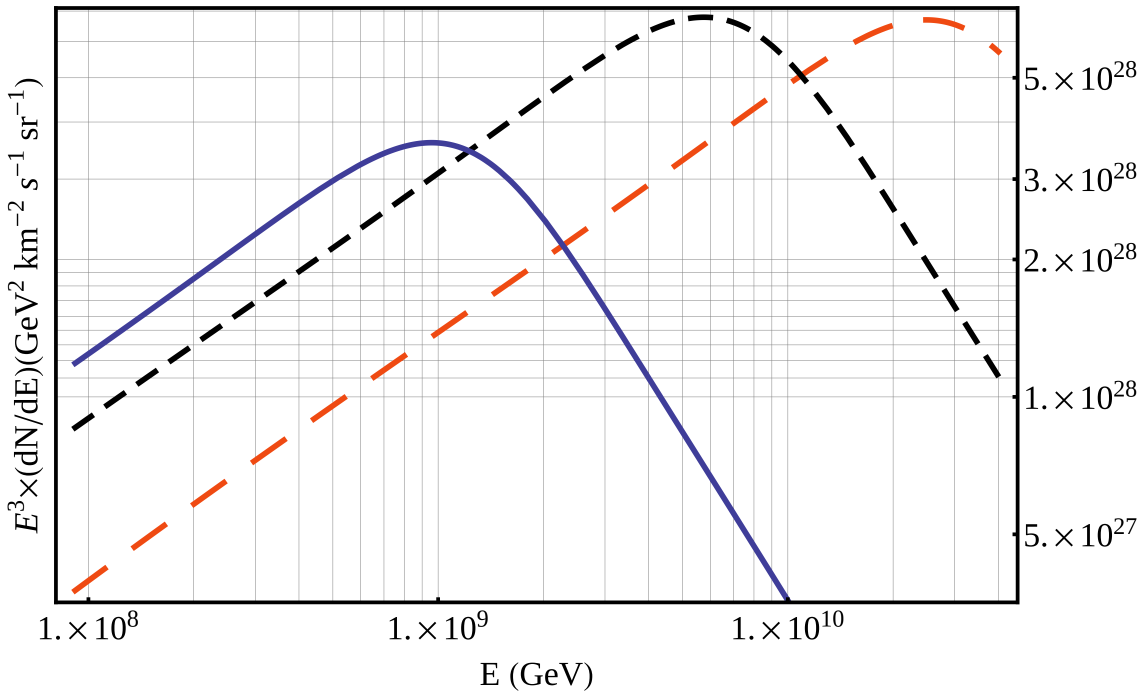
What about our solution?

$$n_i(E, r) = \frac{Q_0}{4\pi r\, D_i(E)} \left(\frac{E_0}{E}\right)^{\gamma}$$

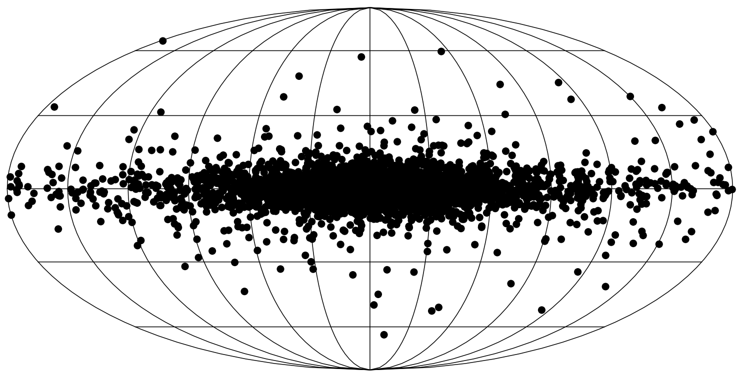
The spectral slope changes at $E \sim E_{0,i}$, and the flux drops dramatically because the particles escape from the galaxy. The flux drops for protons at lower energies than heavy nuclei.

# Energy-dependent composition due to diffusion

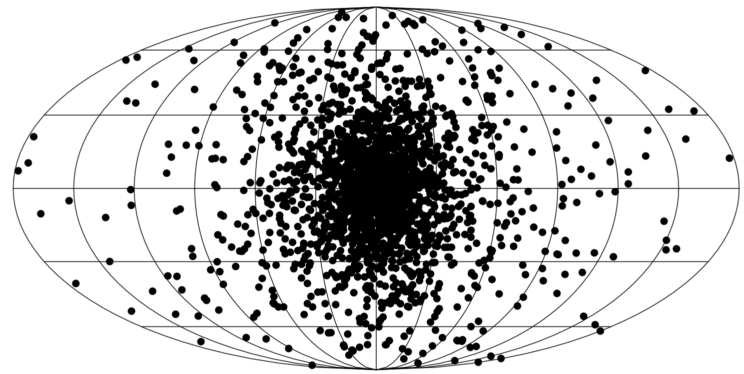
## protons, C, Fe



# More realistic source distribution

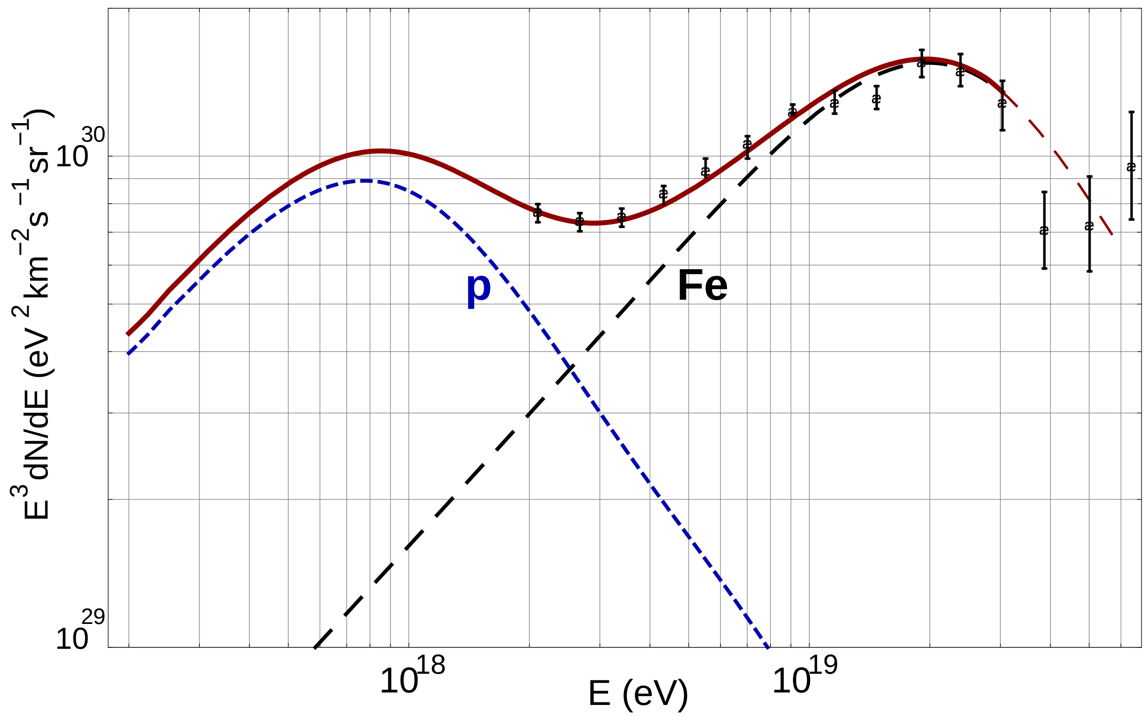


Supernovae or long GRBs, assuming they follow star counts [Bahcall et al.]



Short GRBs, based on observed distribution in other galaxies [Cui, Aoi, Nagataki]

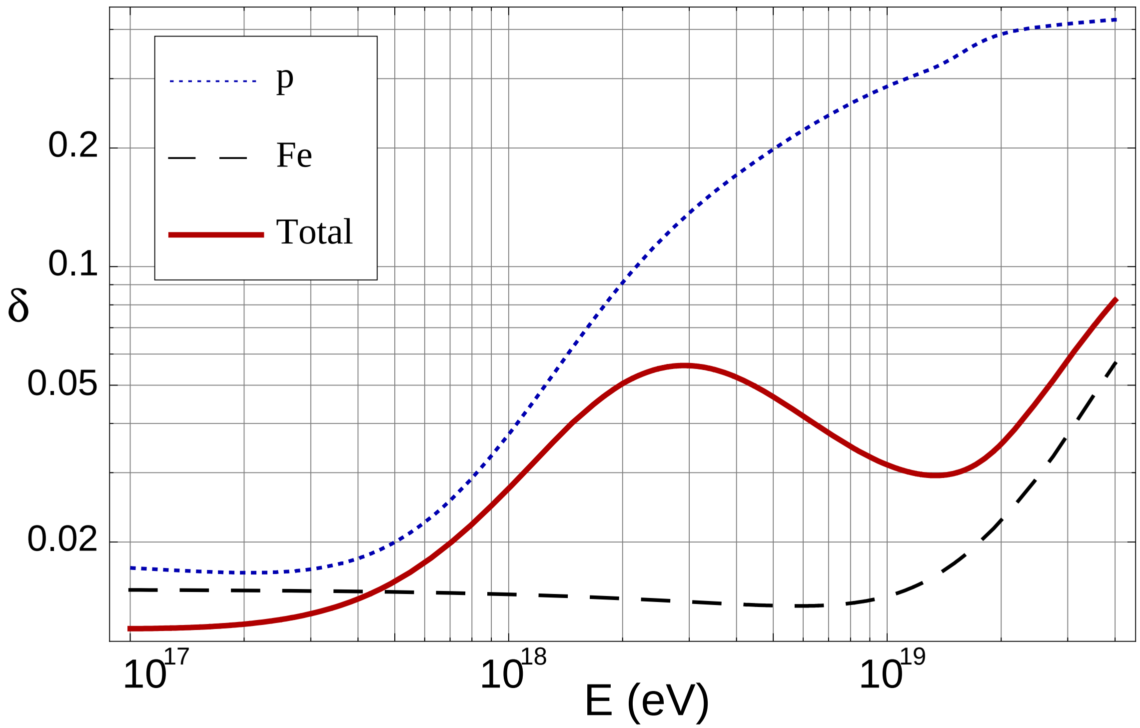
# Comparison with Pierre Auger data




**[Calvez, AK, Nagataki, PRL '10]**

Energy in UHECR per source (GRB, hypernova, etc.) is $10^{44}$ erg above $10^{19}$ eV.

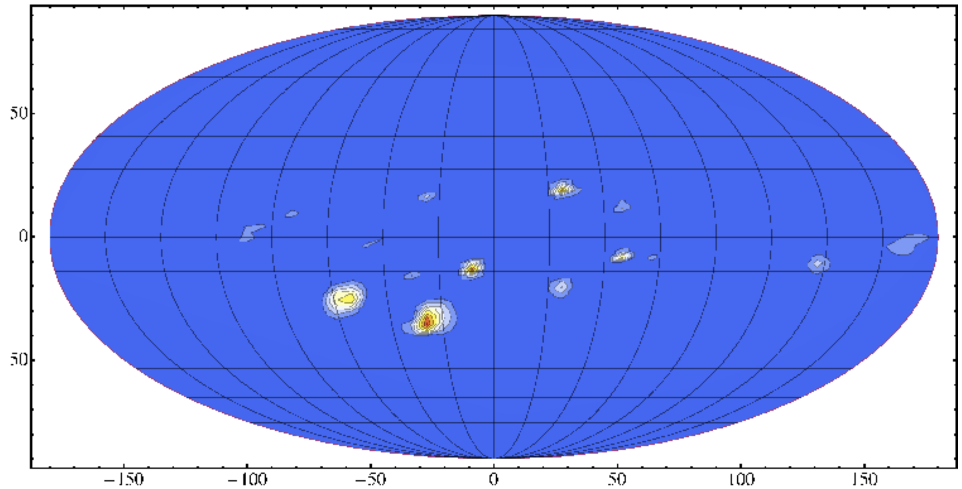
# Galactocentric anisotropy (sources follow stars)

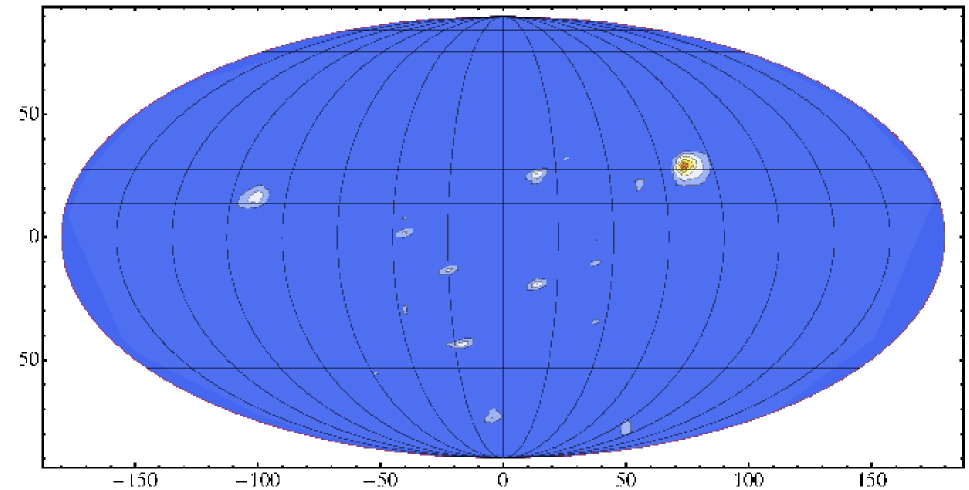



**[Calvez, AK, Nagataki]**

# Clusters of events from recent/closest GRBs

**supernovae/long GRBs** **short GRBs**




In addition, extragalactic **protons** can show correlation with distant sources.

# Which story is true?

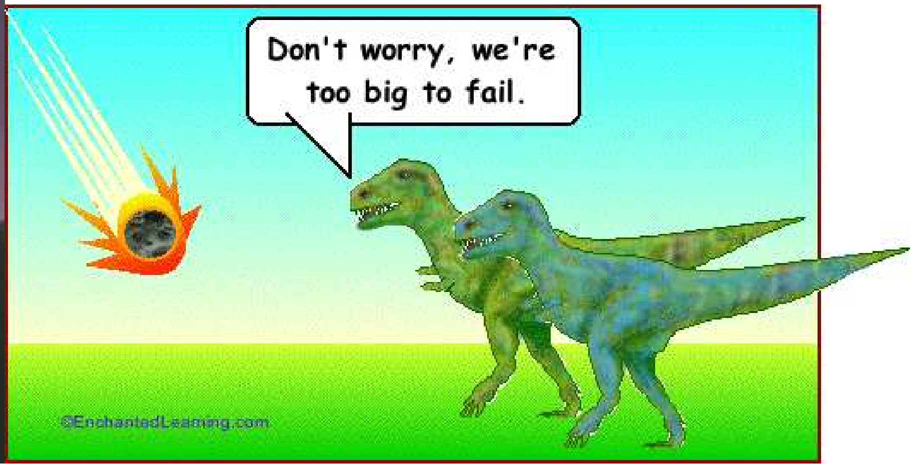
### Galactic sources

- energy-dependent composition with nuclei dominating at $10^{18} - 10^{19}$ eV
- Galactocentric anisotropy $\sim 2\%$
- extragalactic sources contribute in protons $> 10^{18}$ eV.
- any correlation of extragalactic protons with sources is diluted by the uniform Galactic nuclei
- Galactic nuclei cluster in directions of closest sources


### No Galactic sources

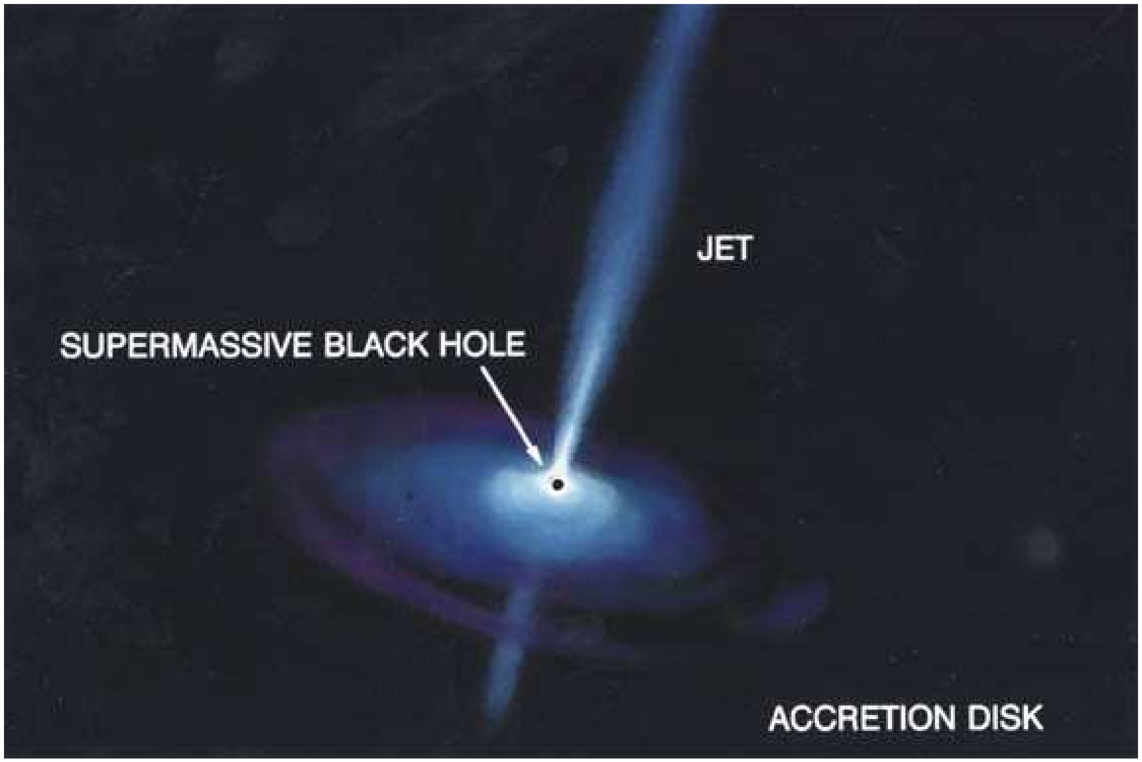
- protons dominate at high energy
- small-scale anisotropy in UHECR arrival directions determined by sources (and intervening magnetic fields)
- no Galactocentric anisotropy

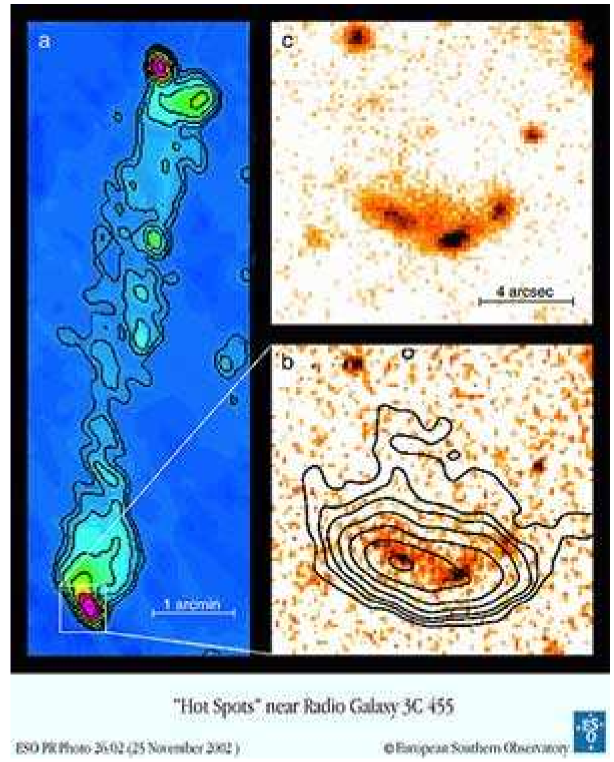
Cosmic acelerators going off every so often in our own Galaxy?



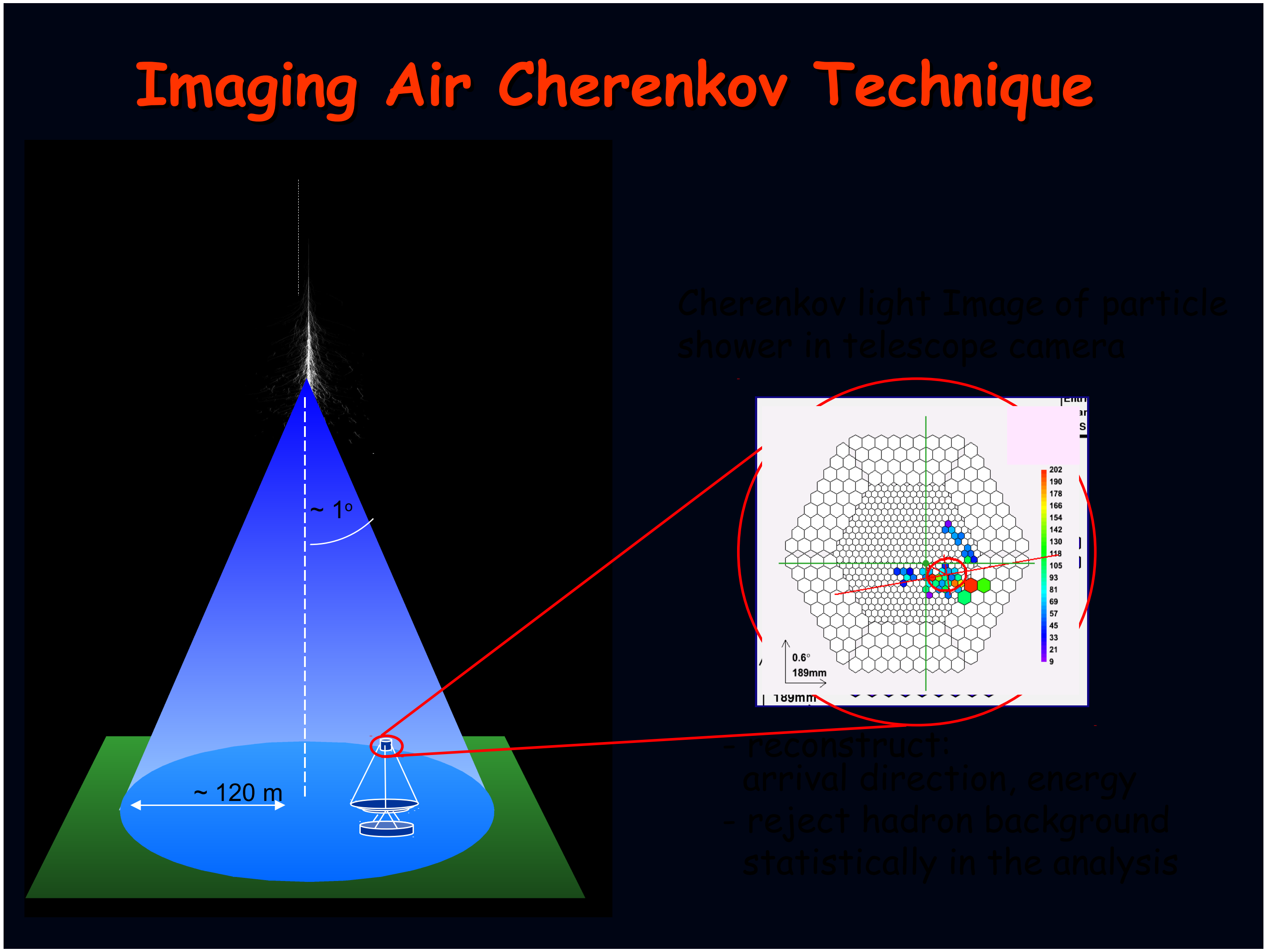

We are looking into the possible connection of Galactic GRBs with mass extinctions.

# Acceleration in AGN and radio galaxies

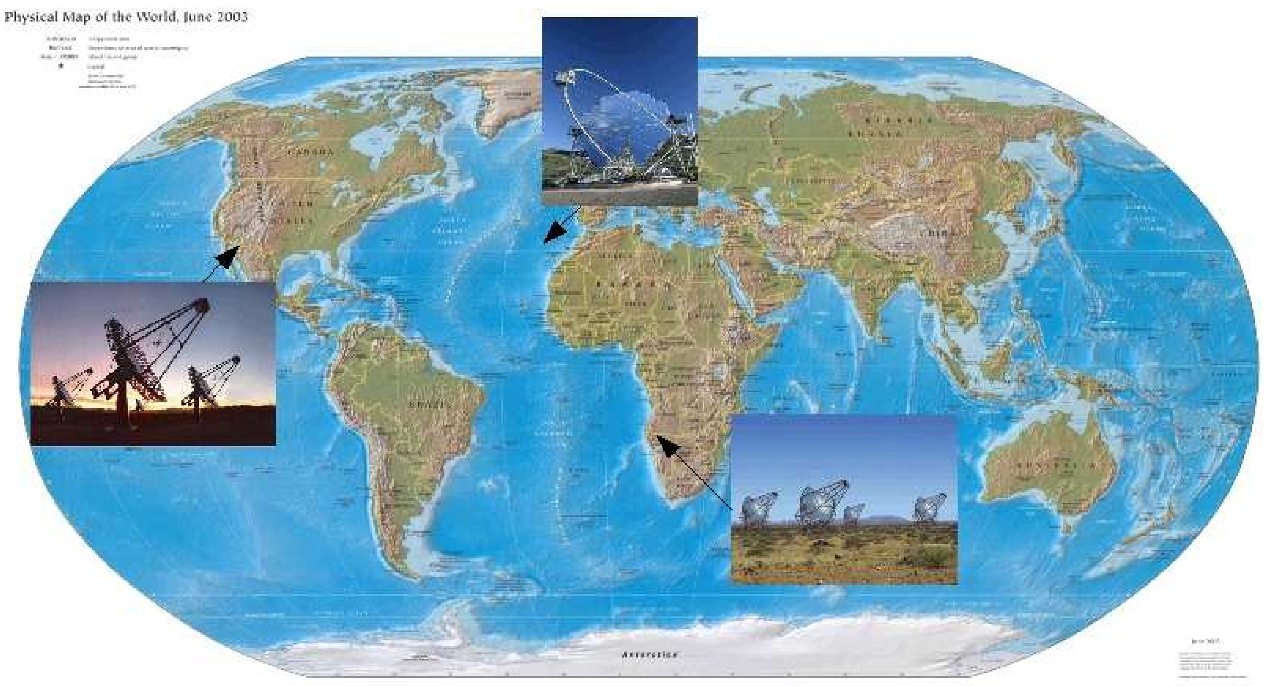


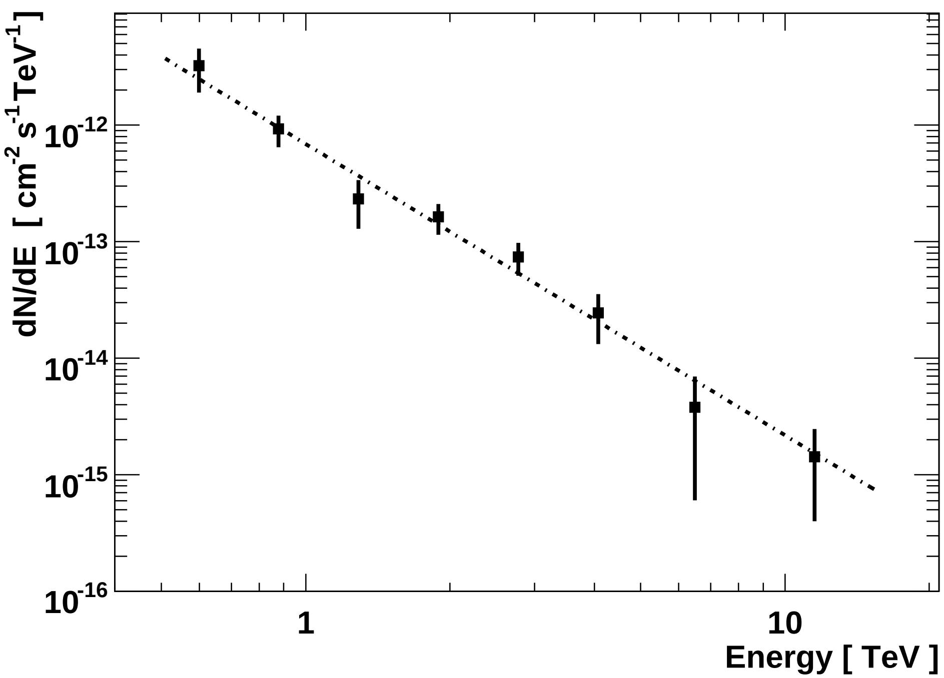

**when AGN jet points at Earth, called** *blazar*

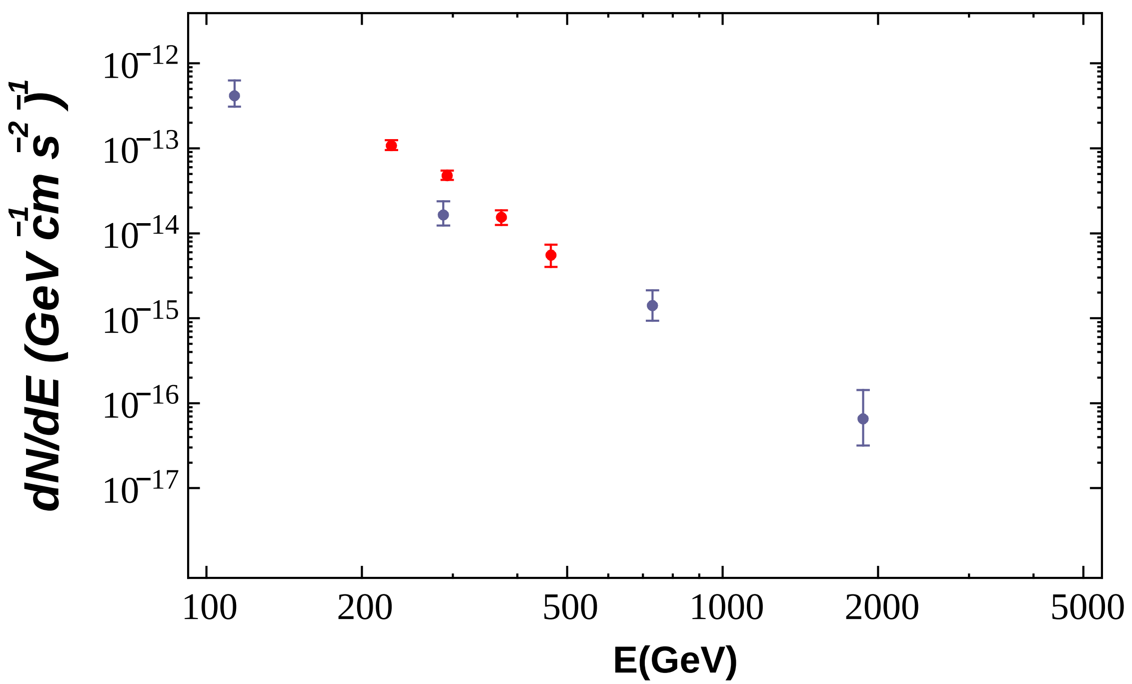

Imaging Air Cherenkov Technique
~ 1°
~ 120 m
Cherenkov light Image of particle shower in telescope camera
0.6°
189mm
- reconstruct: arrival direction, energy
- reject hadron background statistically in the analysis

# Gamma-ray telescopes



# Observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)




HESS (black), MAGIC (blue) and VERITAS (red) data points

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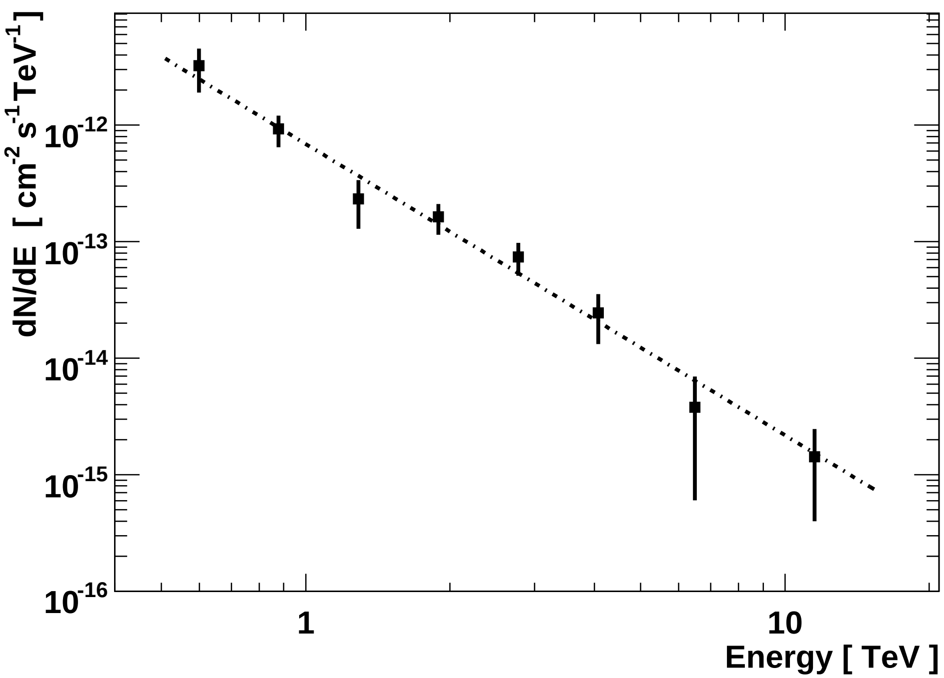
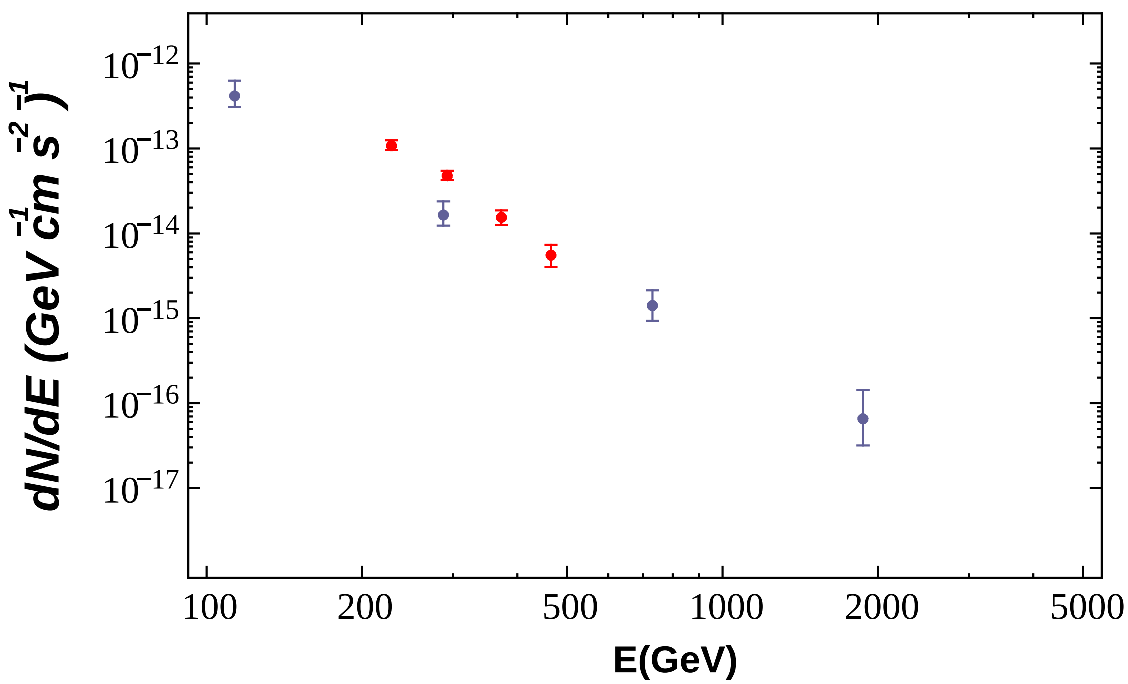
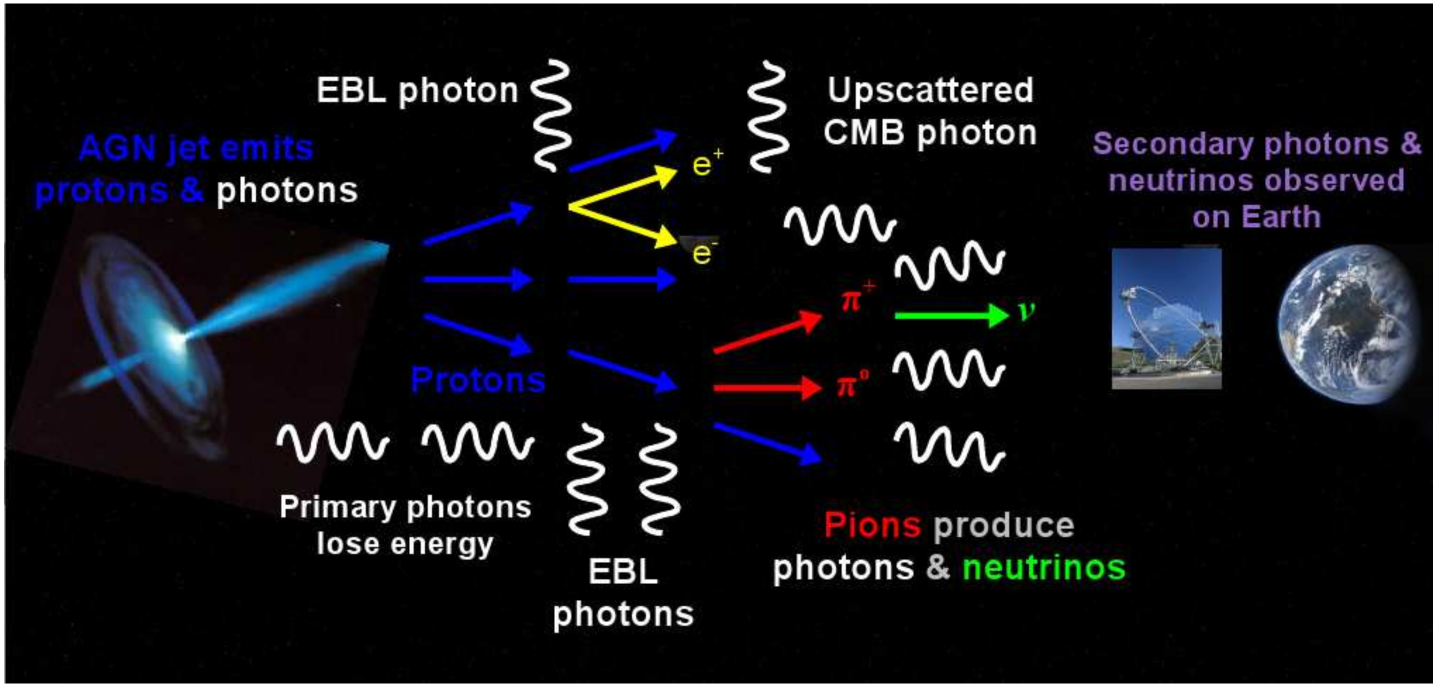



HESS (black), MAGIC (blue) and VERITAS (red) data points

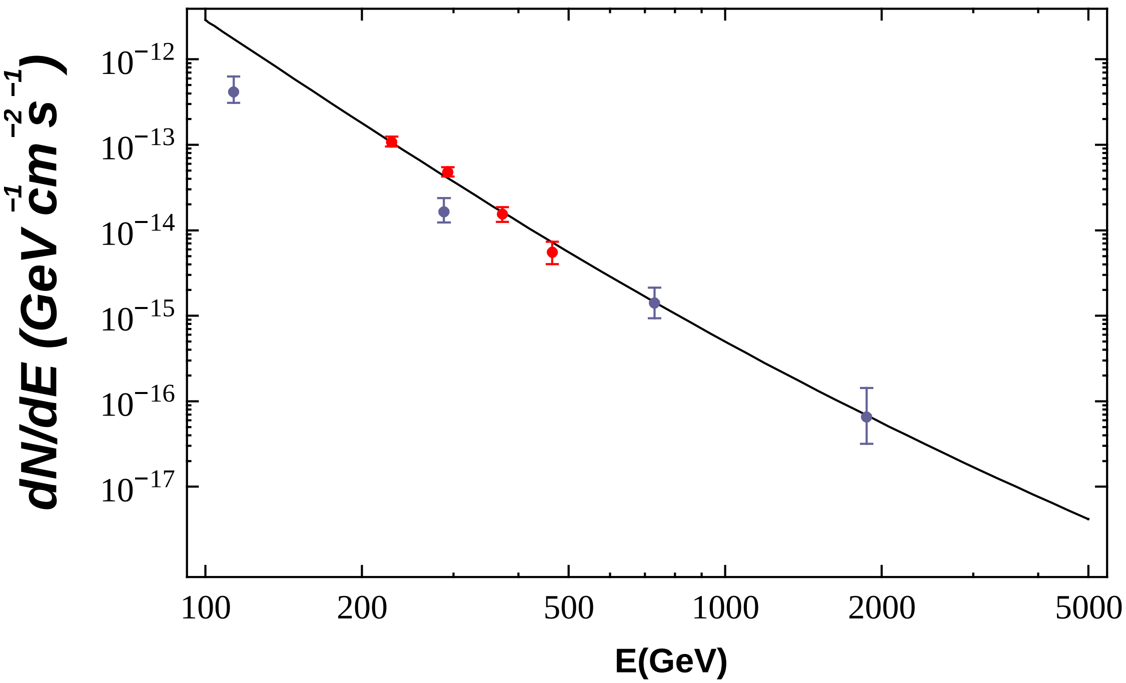
**Surprise: no signs of absorption due to $\gamma\gamma_{EBL} \rightarrow e^+e^-$!**

# Possible solution:



# A one parameter fit, 3C66A

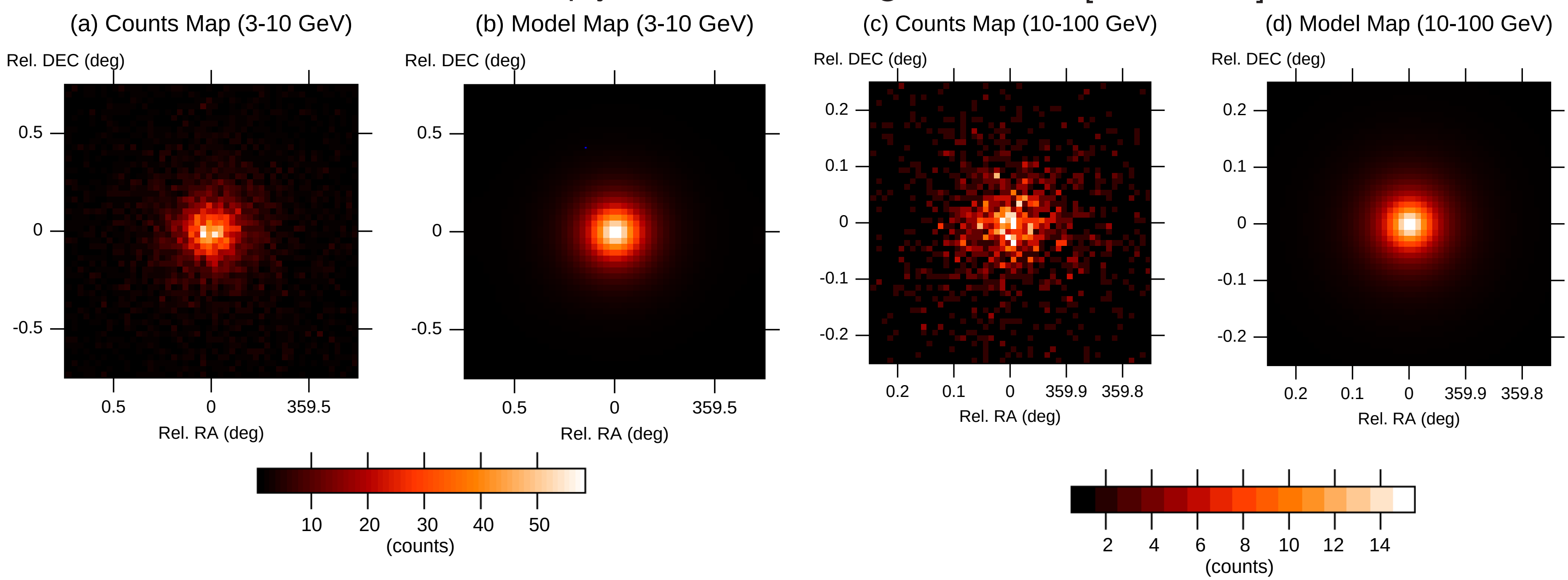
## (param = the power of ANG in CR, subject to constraints)




[Essey, AK]

# Something else we've learned: IGMF $\sim 10^{-15}$ Gauss

**Intergalactic magnetic fields** make the images of blazars diffuse. We have discovered halos around blazars, which imply $10^{-15}$ Gauss mgnetic fields [Ando, AK].




Small fields, small correlation length $\Rightarrow$ We are probably seeing the **seed fields from the Big Bang!** [Ando, AK, ApJL]

## Simple analogy


To see the halo at night, one could stack the images of stars.

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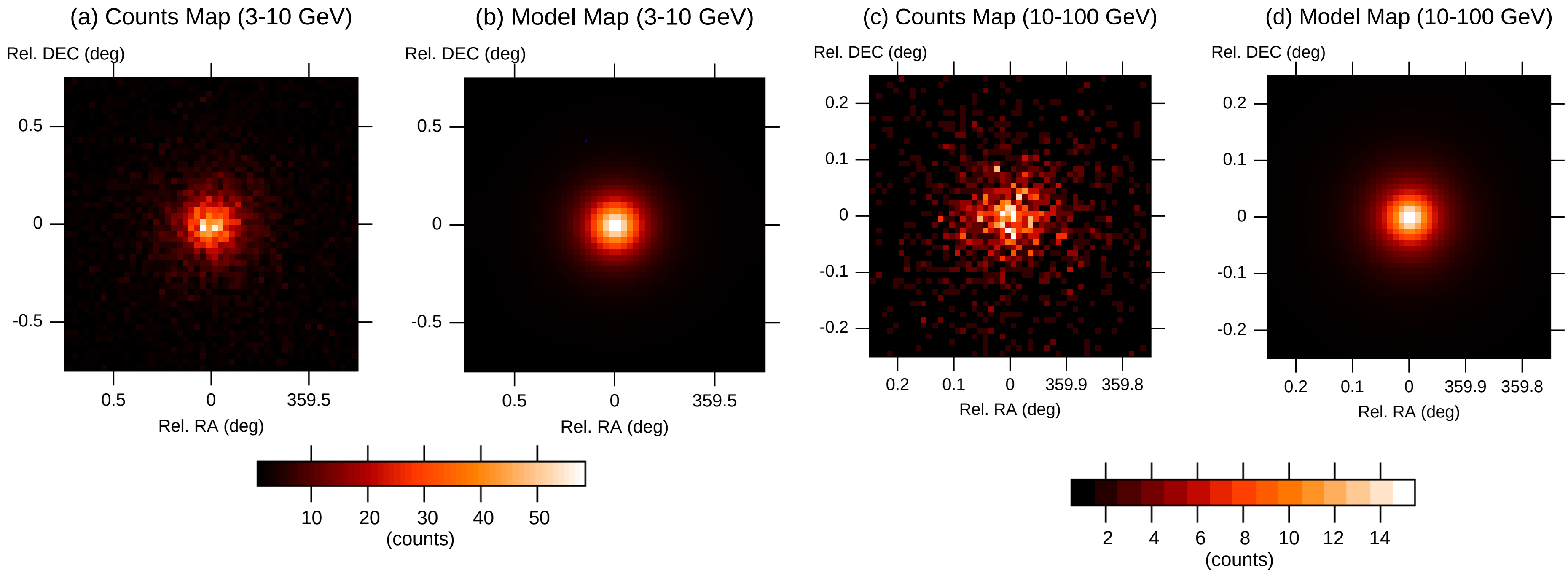


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# Conclusion

Deciphering the messages from the most powerful objects in the universe has taught us about

- the acceleration of cosmic rays and gamma rays,
- intergalactic magnetic fields
- gigantic explosions in our own Galaxy

***Undoubtedly, more discoveries ahead!***