Cosmic Rays

- Introduction
- Discovery
- Detection & Experiments
- End of energy spectrum
- Auger

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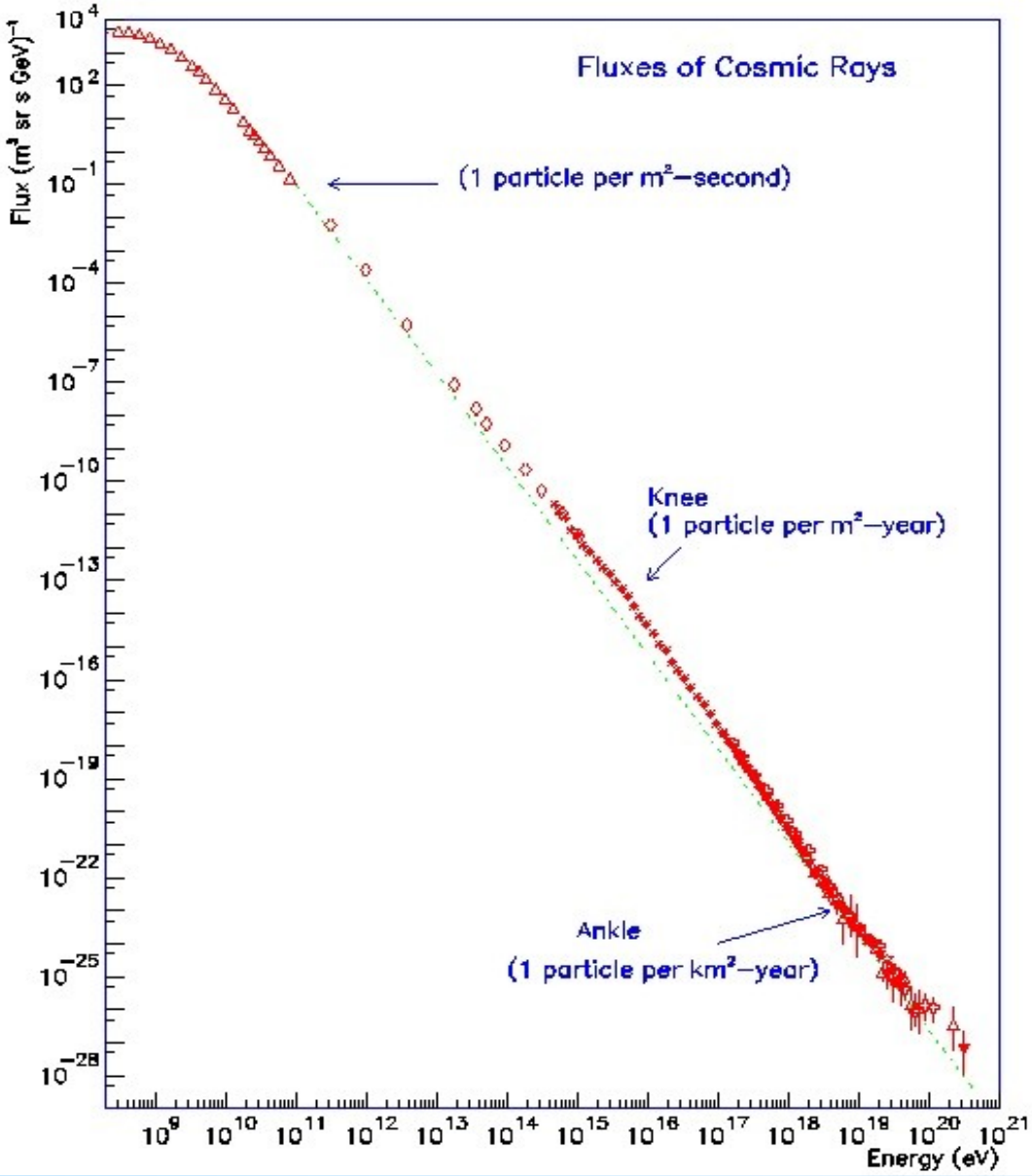
CR spectrum



- Flux of particles
- protons, nuclei, $e^{\pm}$, γ
- Sun: E < 10 GeV
- Power-law $E^{-\alpha}$

  Fermi acceleration ?

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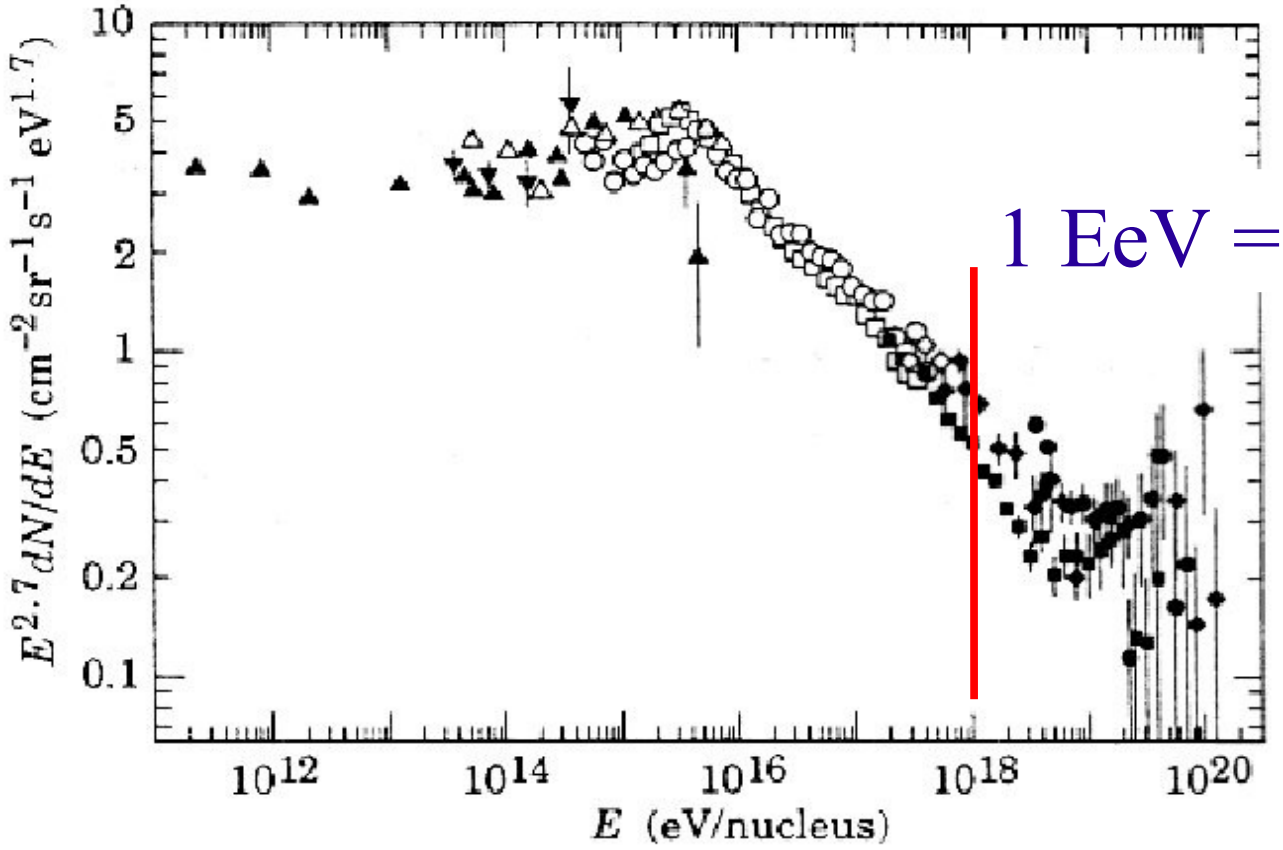
CR spectrum



1 EeV = 10^{18} eV

?

- Knee 3 * 10^{15} eV
- Ankle 4 * 10^{18} eV

Ultra High Energy Cosmic Rays

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Discovery

- 1912 Victor Hess
- Balloon flights
- 1936 Nobel Prize

- 1925 R. Millikan

  (“cosmic radiation”)

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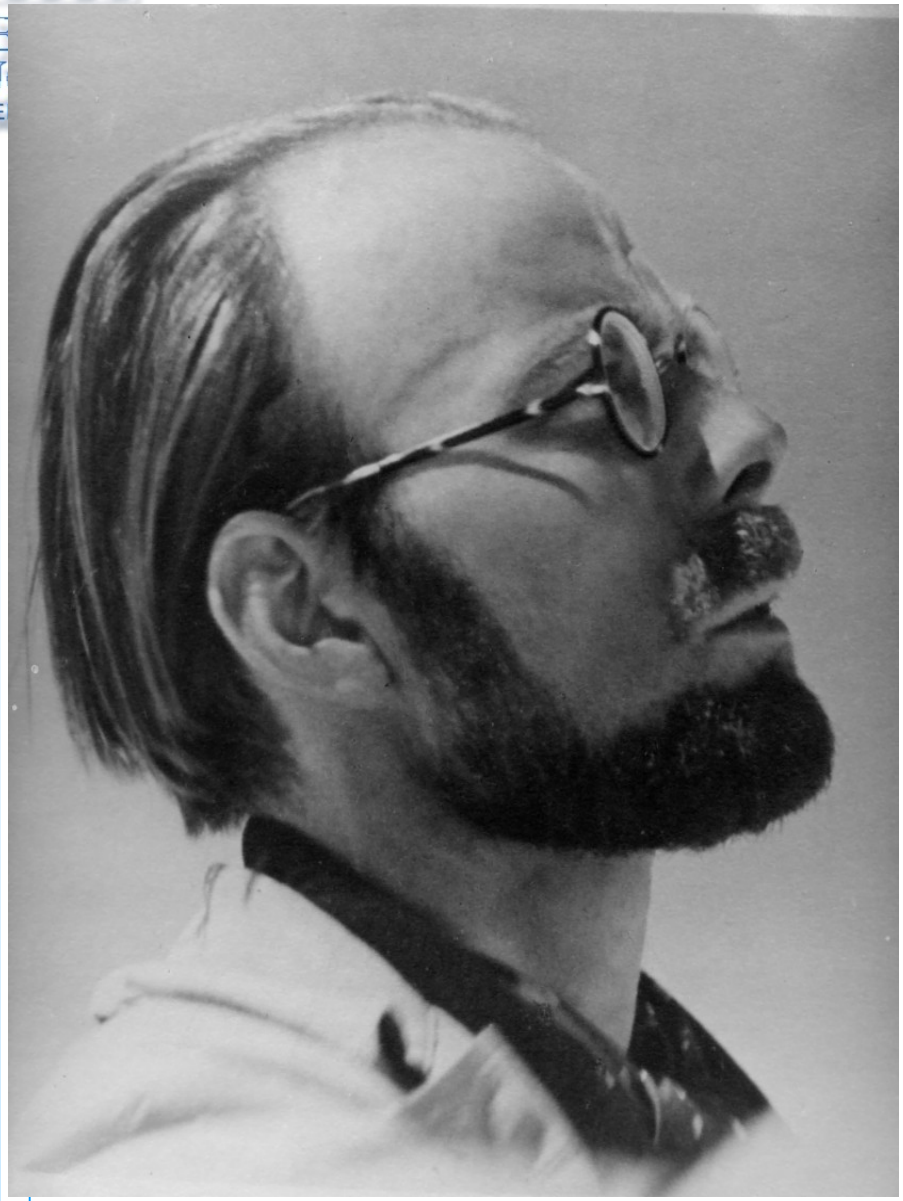
Air showers



- 1938 Pierre Auger
- Coincidences
- Secondary particles
- Primary particles with energy ~ 10^{15} eV

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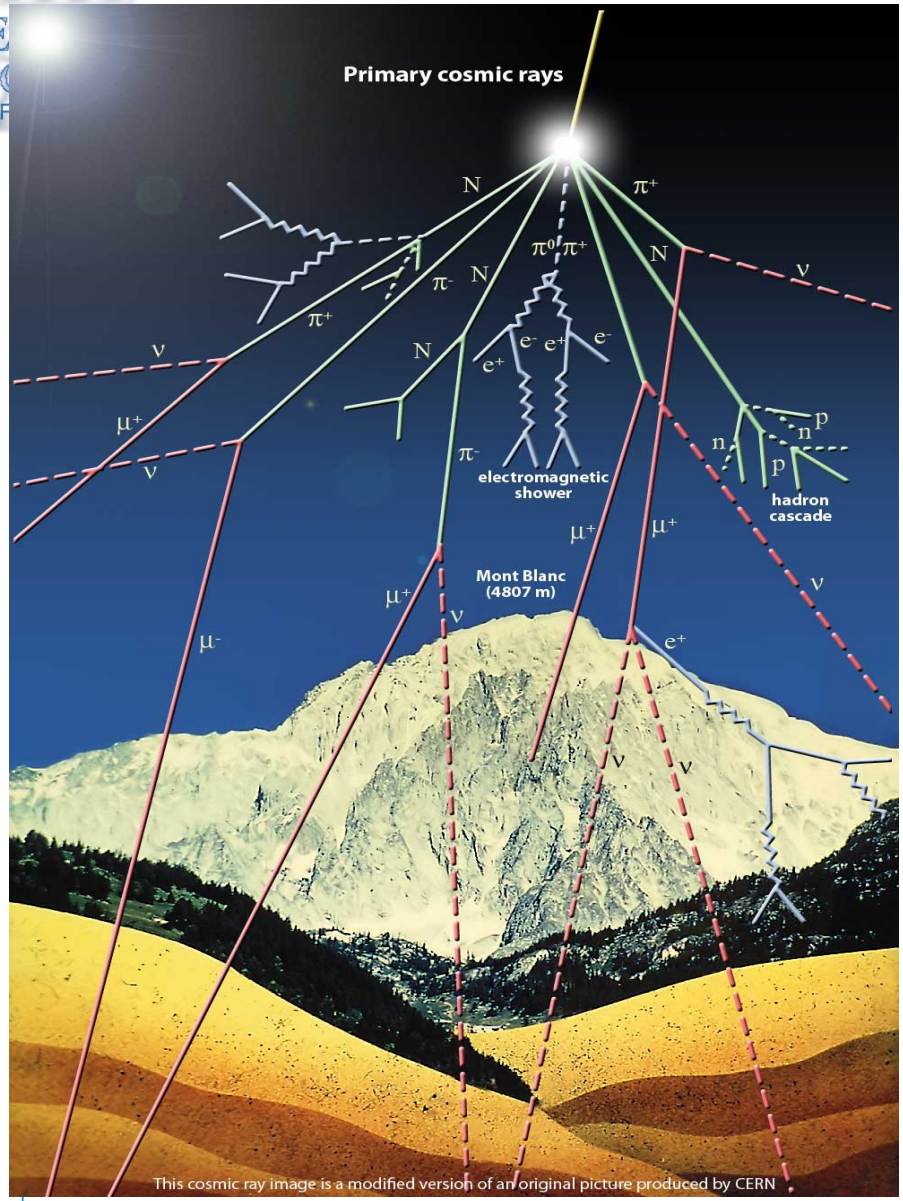
Air showers



- 1st interaction 20 - 30 km
- Interact. within 80 g cm^{-2}
- Depth of atmosphere

  800 - 1200 g cm^{-2}
- Cascade of particles:

  Electromagnetic

  Hadronic

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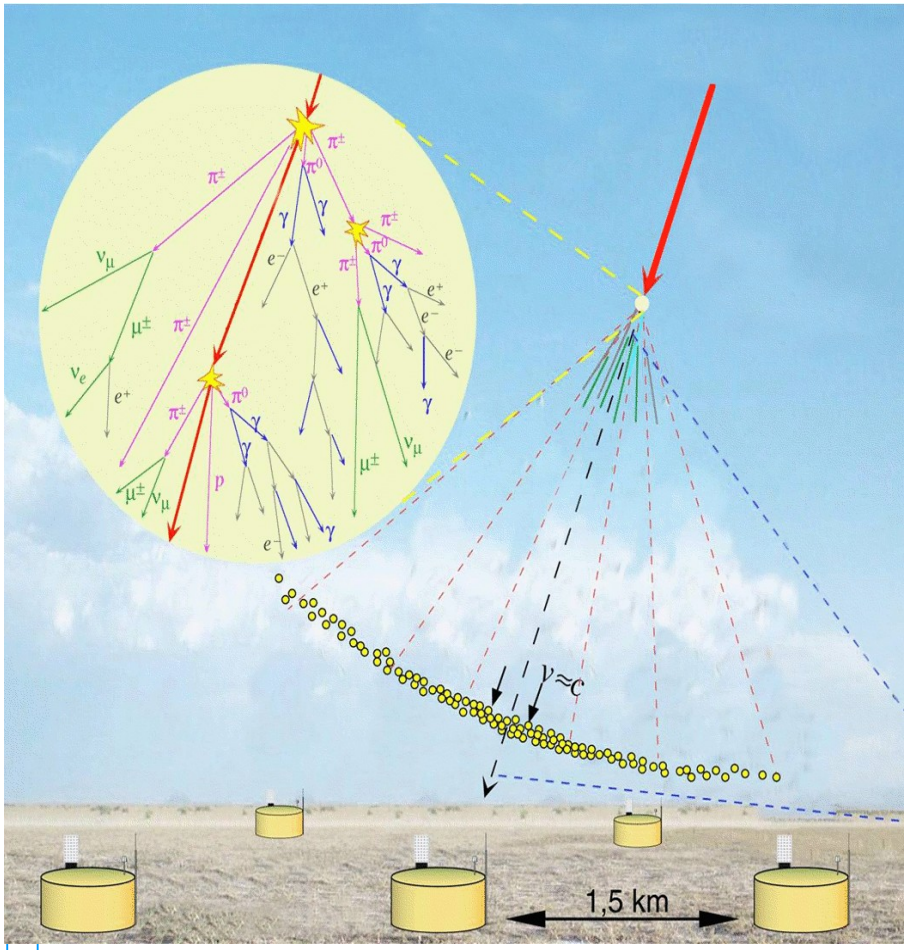
Ground array



- footstep of shower
- Water cerenkov, scintil.
- space-time signal -> arrival direction
- Number of particles -> primary energy
- Number of $e^{\pm}$ / $\mu^{\pm}$ -> type of primary particle

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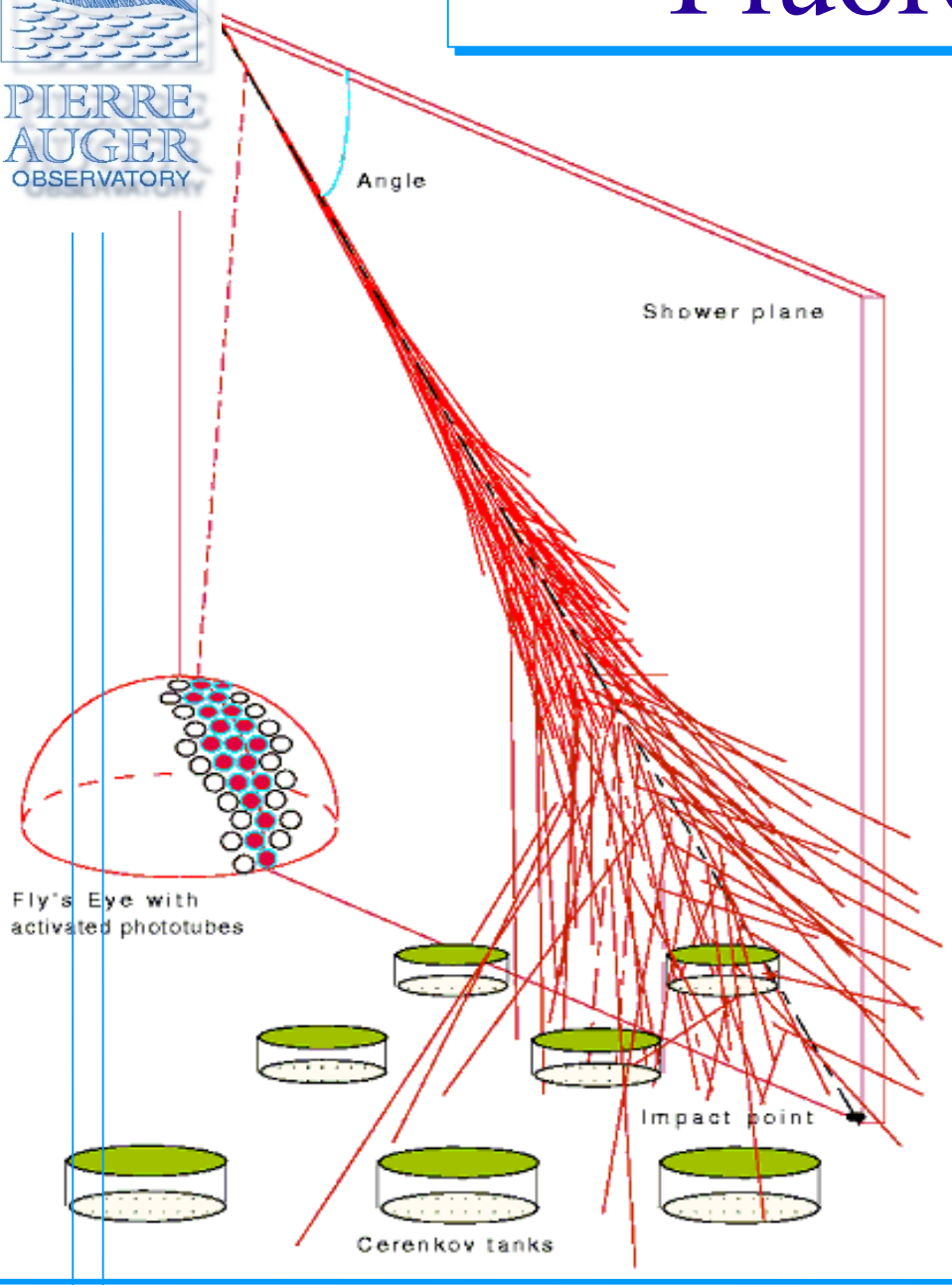
Fluorescence



- N_2 light along shower
- Time structure of signal -> arrival direction
- Total amount of light -> primary energy
- Shape of shower -> type of primary particle

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CR detectors

Volcano Ranch
(1959-1963), 19 SC (8 km^2)

J. Linsley (1963): $E > 10^{20}$ eV

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CR detectors

Volcano Ranch
(1959-1963)
SC (8 km²)

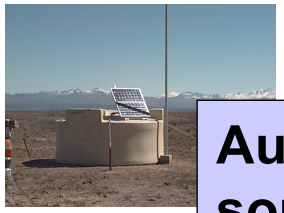
Havera Park
(1968-1987)
WC (12 km²)

Yakutsk
(1974 - …)
SC (18 km²)
AC (10 km²)

Fly's Eye
(1981-1993)
FD

HiRes
(1997-2006)
FD

AGASA
(1984-2004)
SC (100 km²)



Auger - south
(2004 - …)
hybrid (3000 km²)

Sugar
(1968-1979)
SC (60 km²)

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Fly's Eye & HiRes

- Fluorescence detectors
- $E = 3.2 * 10^{20}$ eV (Nov 1991)

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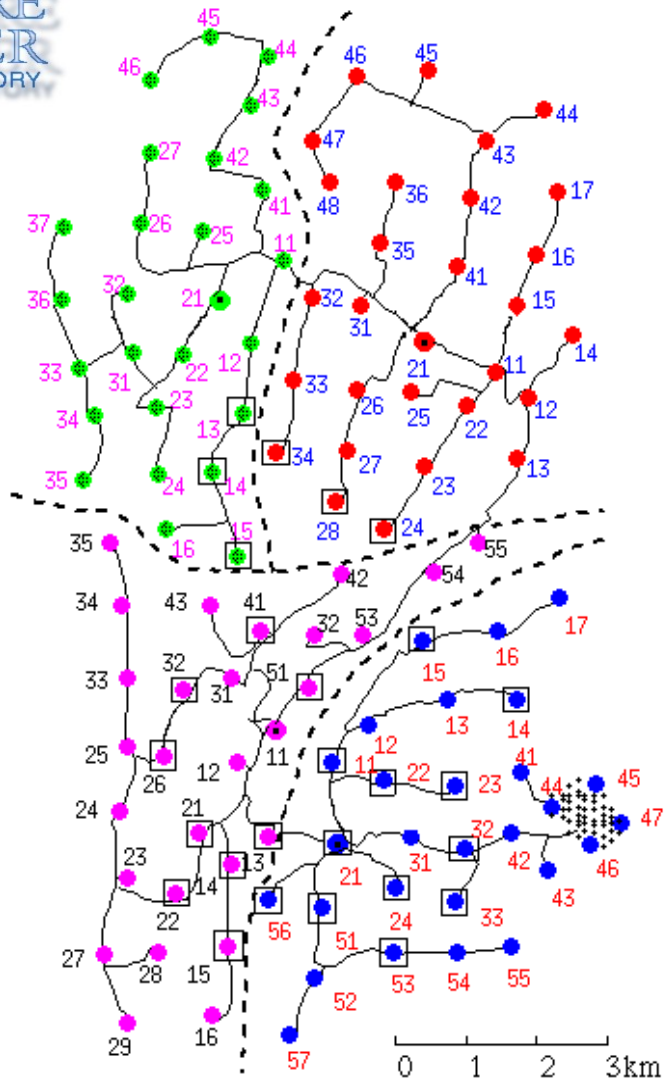
Agasa



- Scintillators, 100 km^2
- E = 2.0 * 10^{20} eV (Dec 1993)

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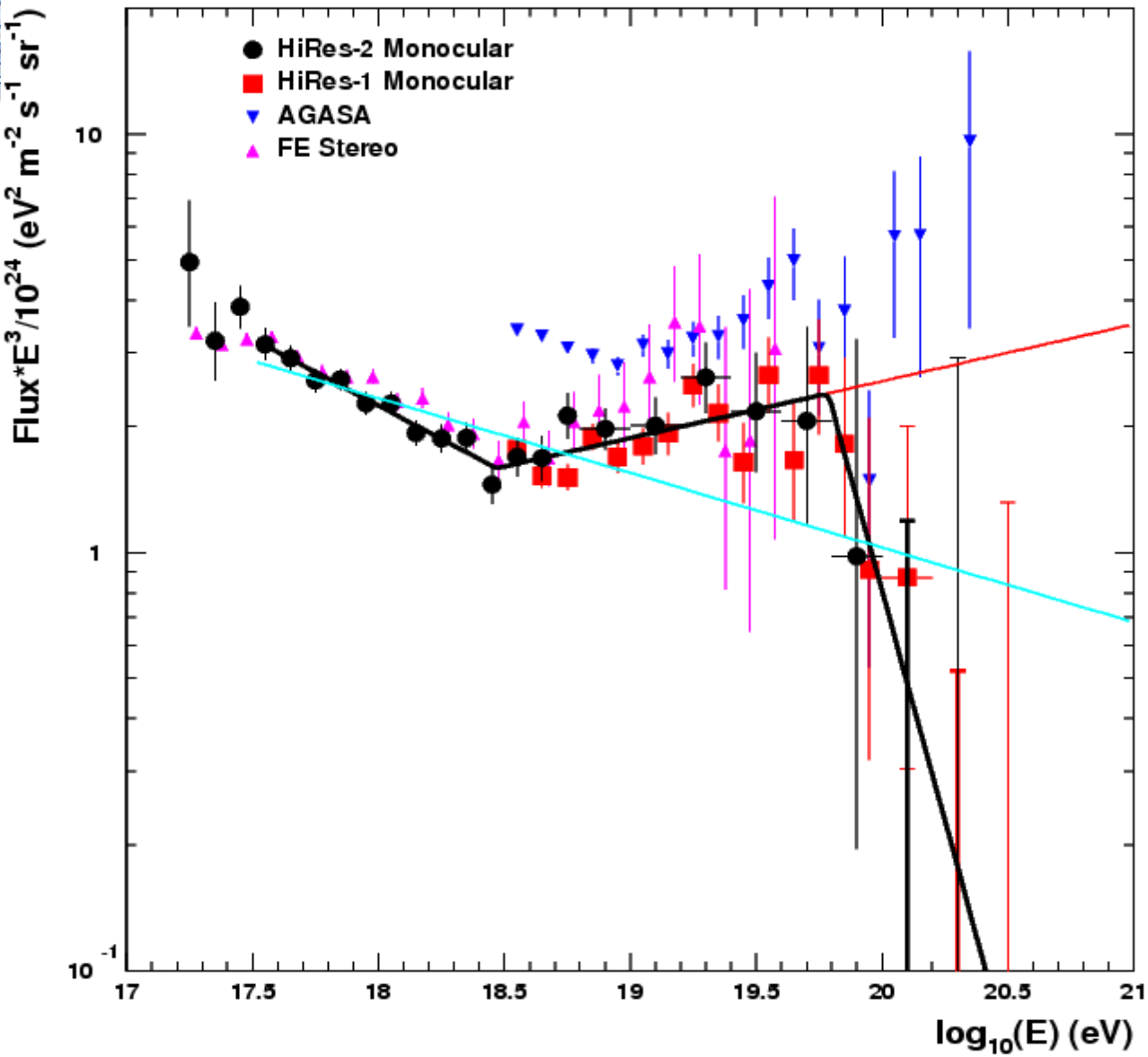
CR spectrum



- Discrepancy
- Agasa:

  no cutoff
- HiRes:

  end of spectrum

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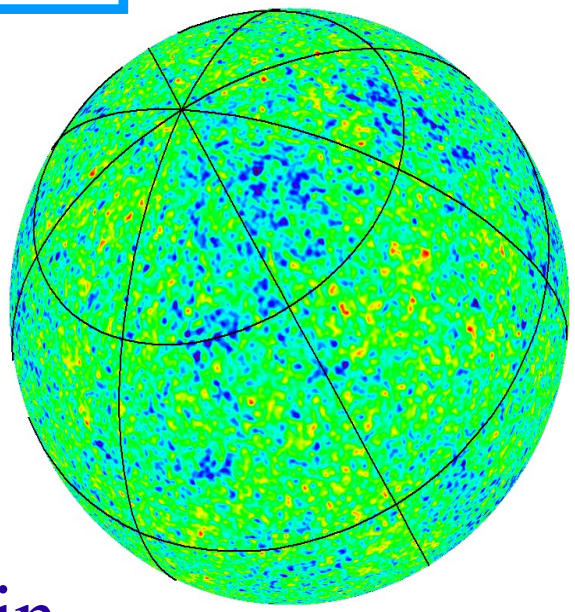
CMB and CRs



- 1964: Cosmic Microwave Background (2.7 K)

- 1966: Greisen, Zatsepin & Kuzmin

energy loss of CRs due to interactions with CMB

$$p + \gamma_{2.7k} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$n + \pi^{+}$$

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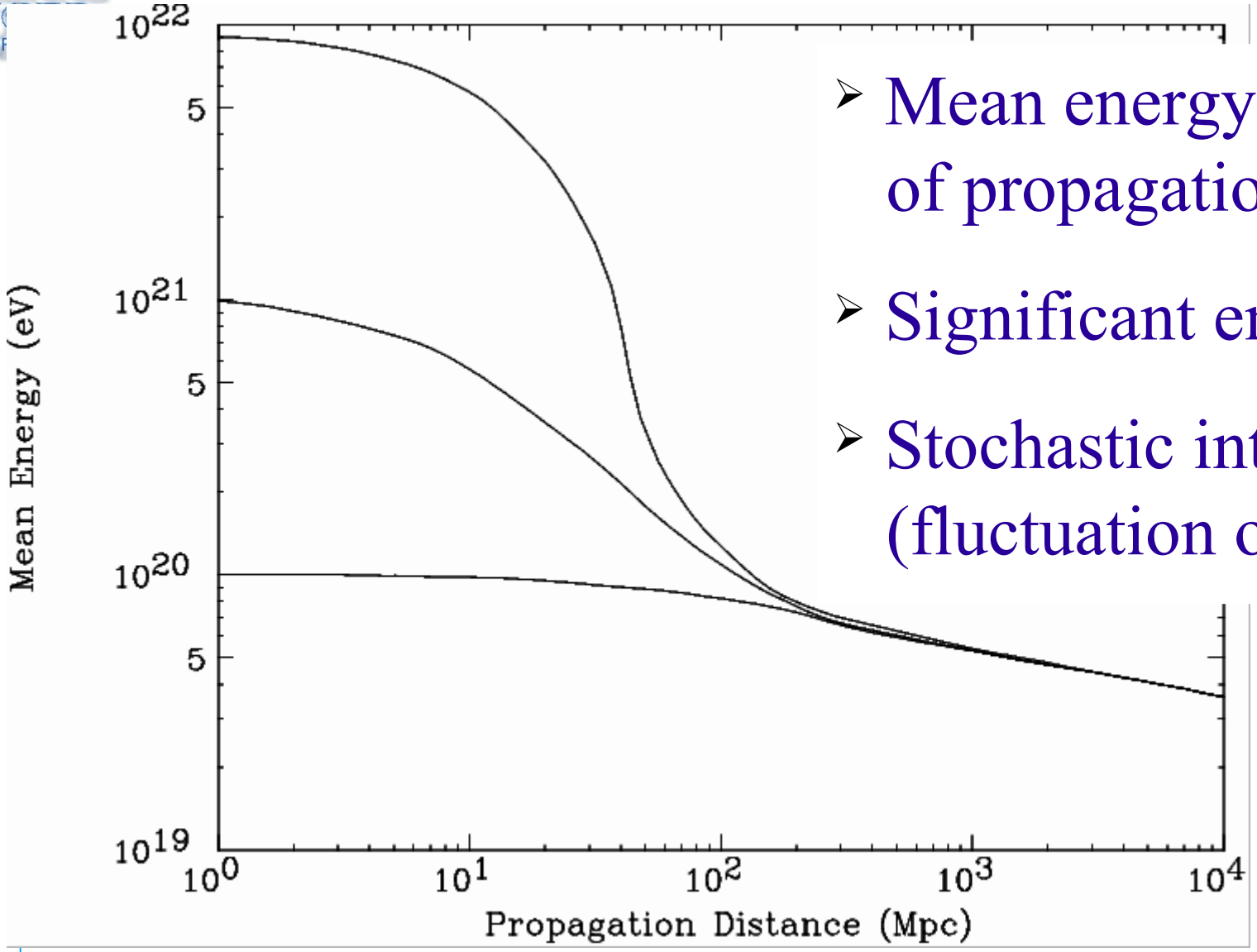
GZK cutoff



- Mean energy as function of propagation distance
- Significant energy loss
- Stochastic interaction (fluctuation of energy)

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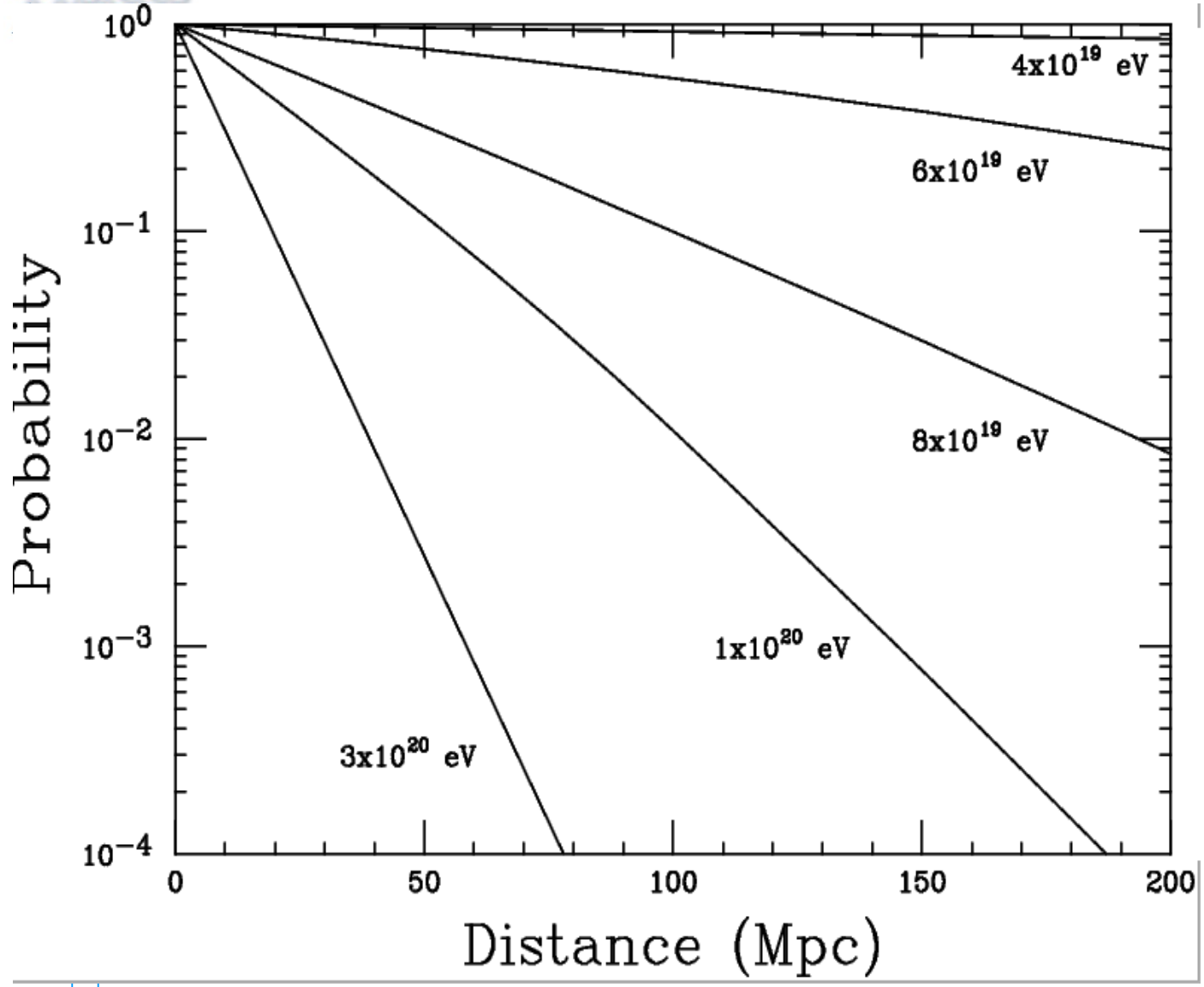
GZK cutoff



- Probability that proton came from greater distance than specified
- Assumed source spectrum $E^{-2.5}$
- P=10% for 80 EeV, 100 Mpc

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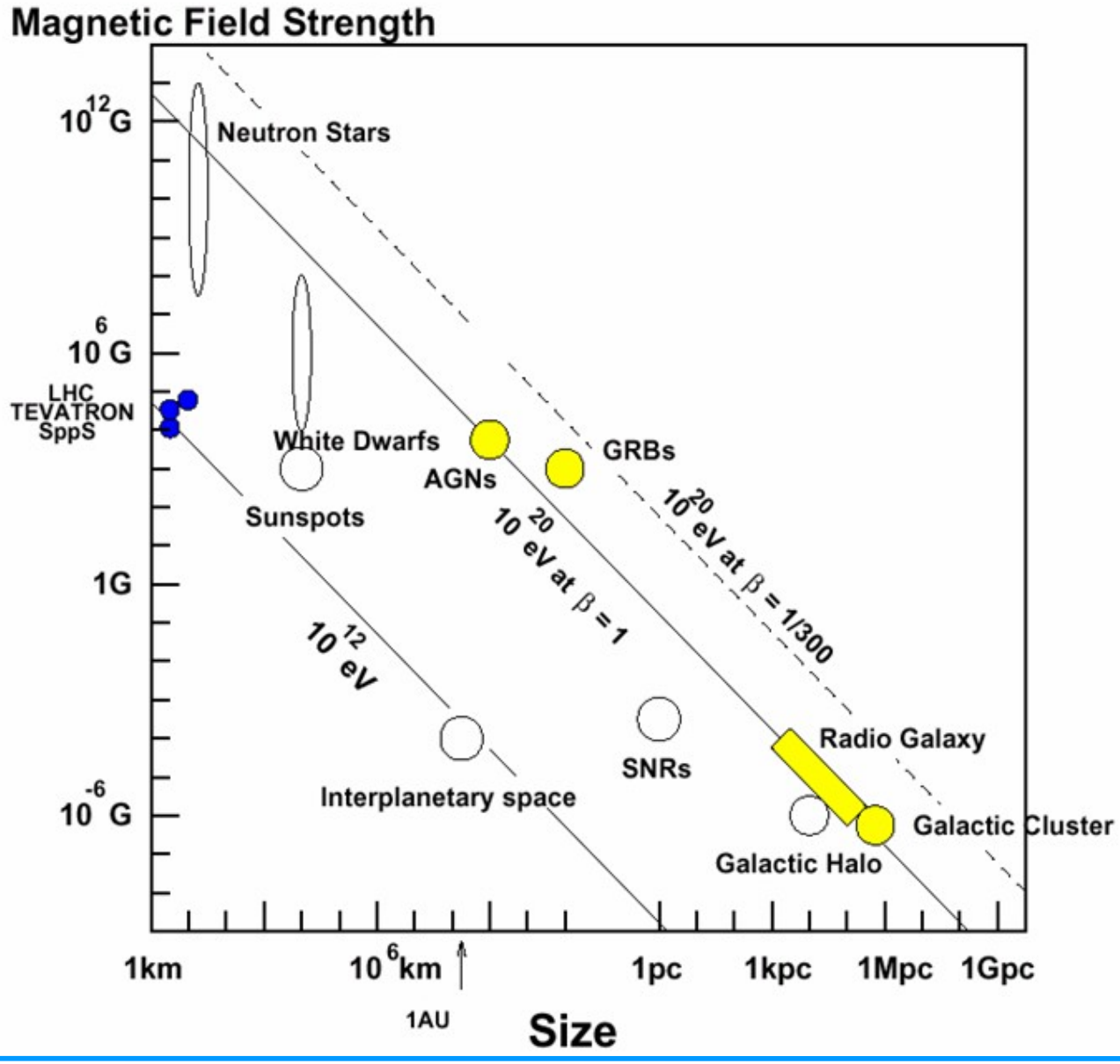
Hillas diagram

- Local sources
- Isotropically distributed
- Acceleration
- Top-down



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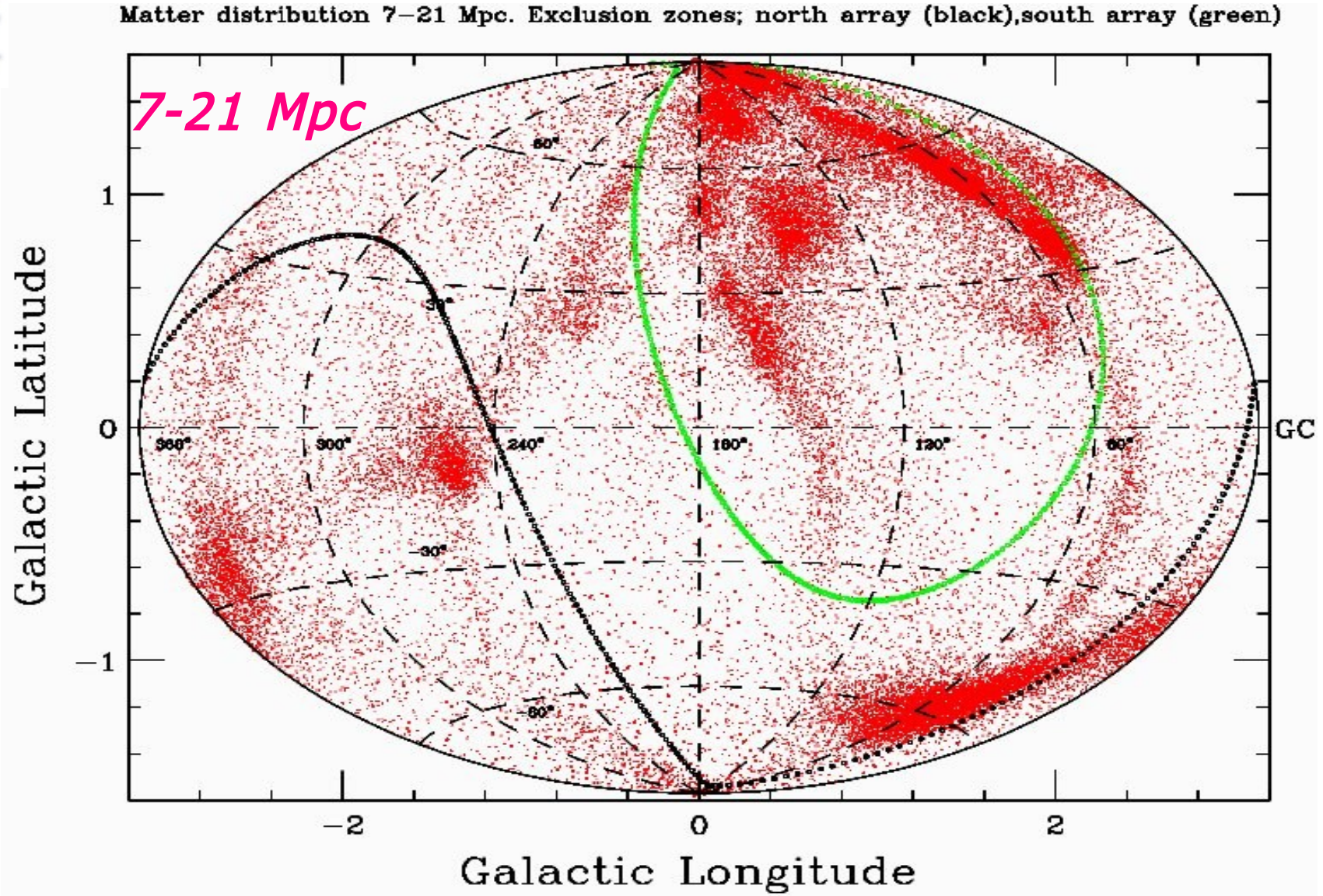
Matter distribution



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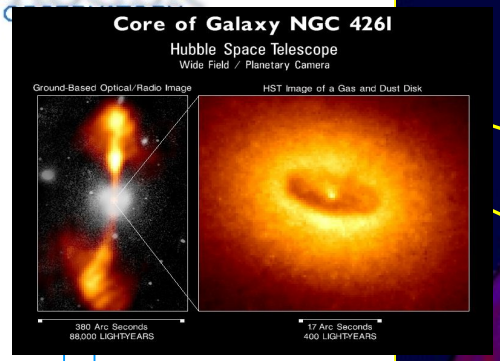
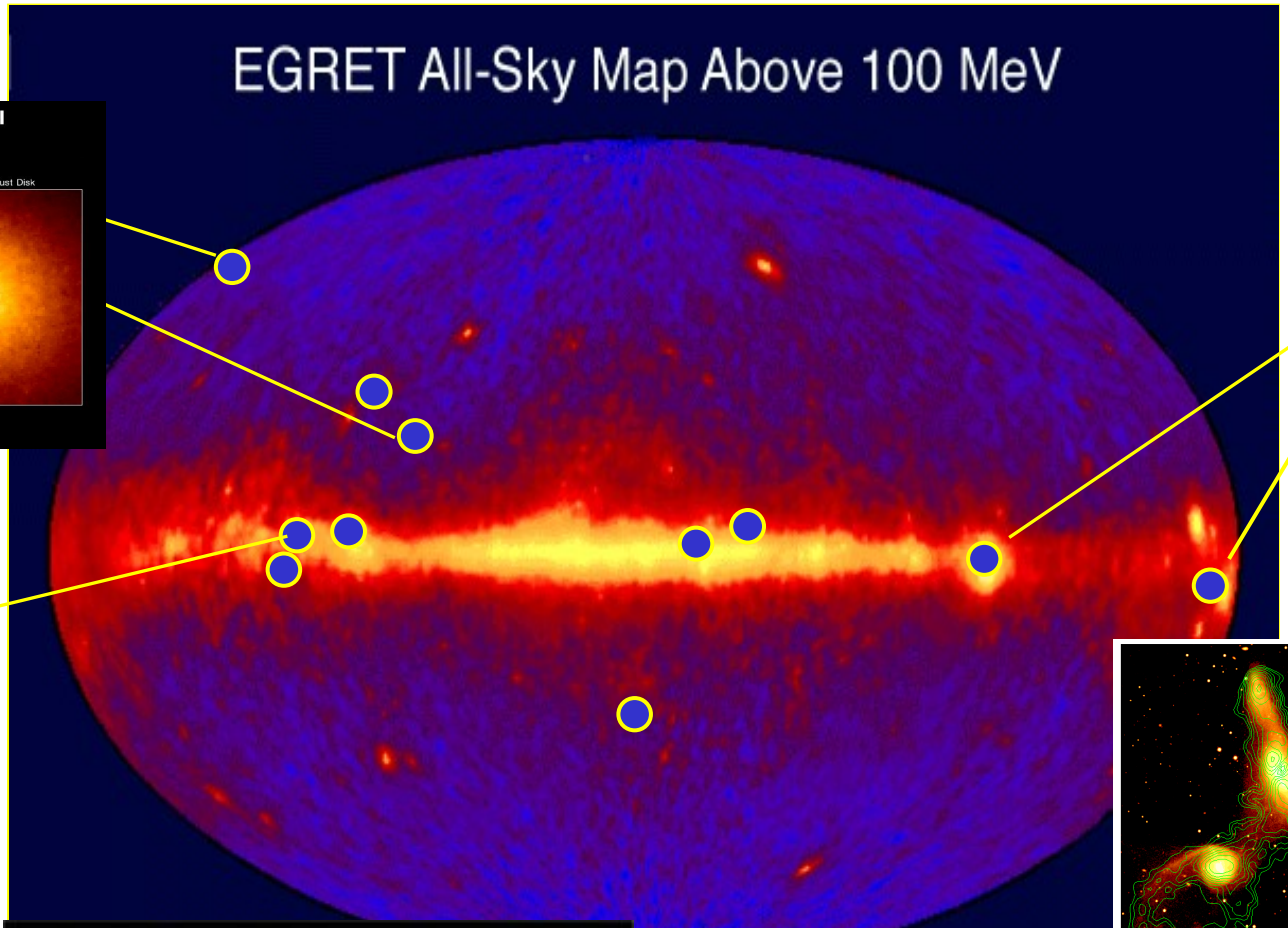
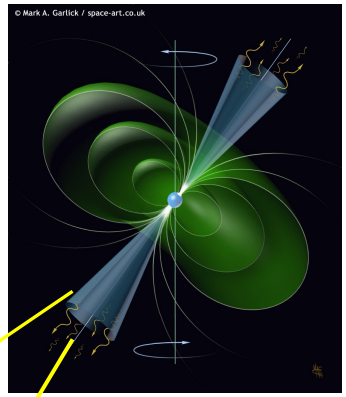
Extreme universe

AGN

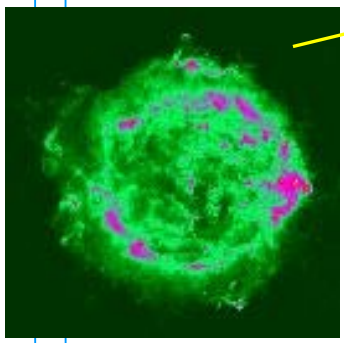




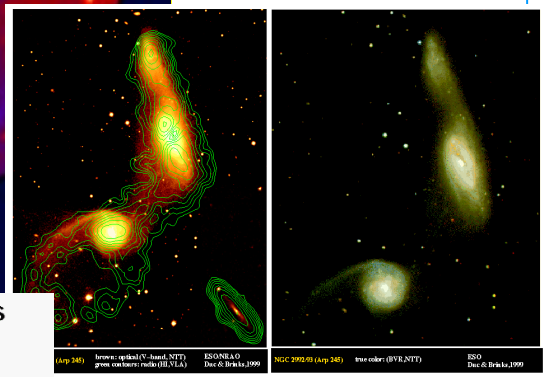
Pulsar

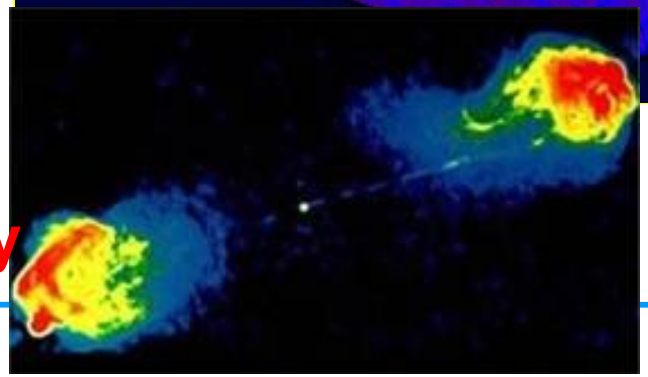


SNR

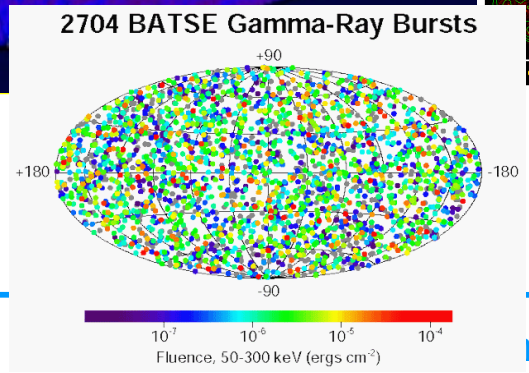


Galaxy Collisio





Radio Galaxy



GRB

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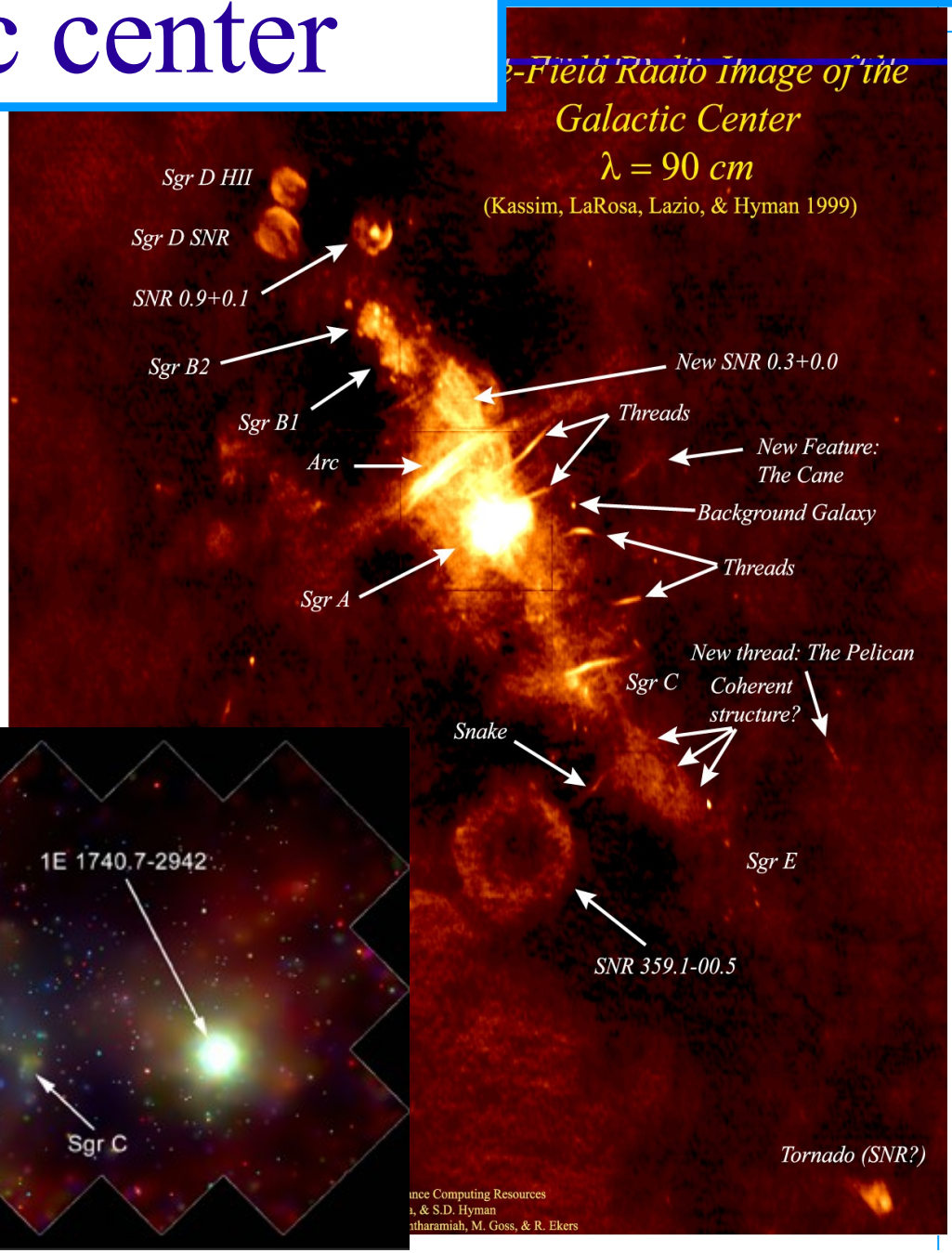
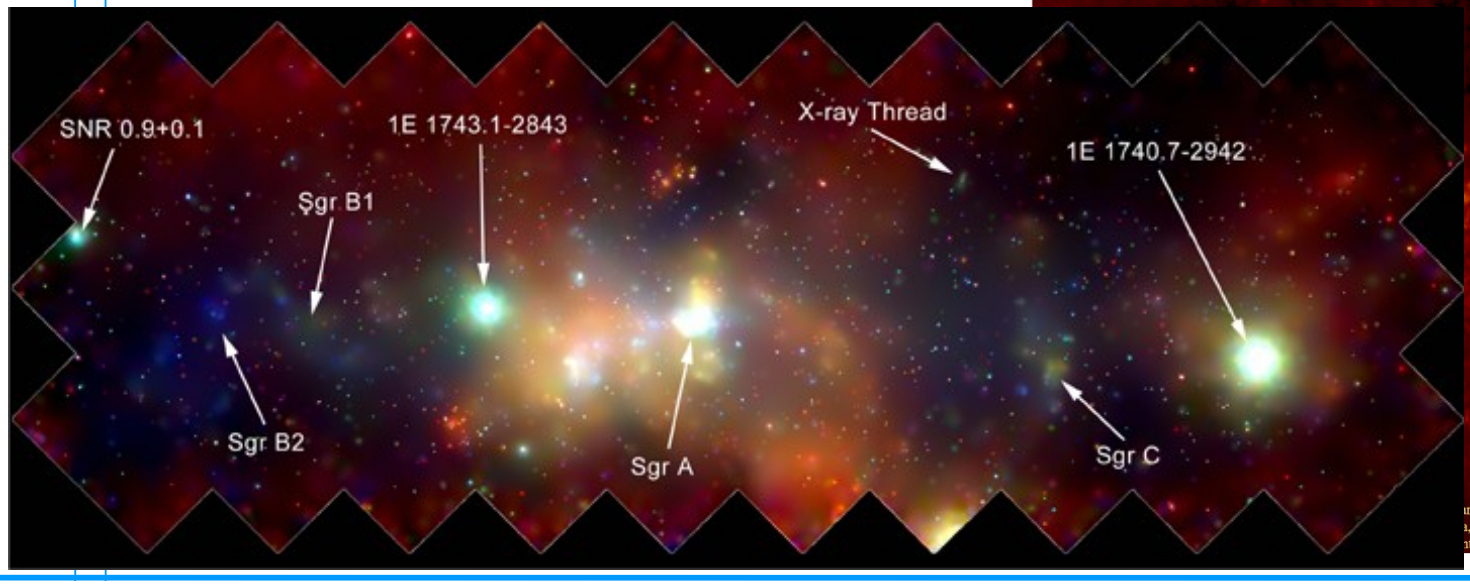
Galactic center

- Galactic center
- Galactic plane
- Egret, Chandra,

  Integral, HESS etc.





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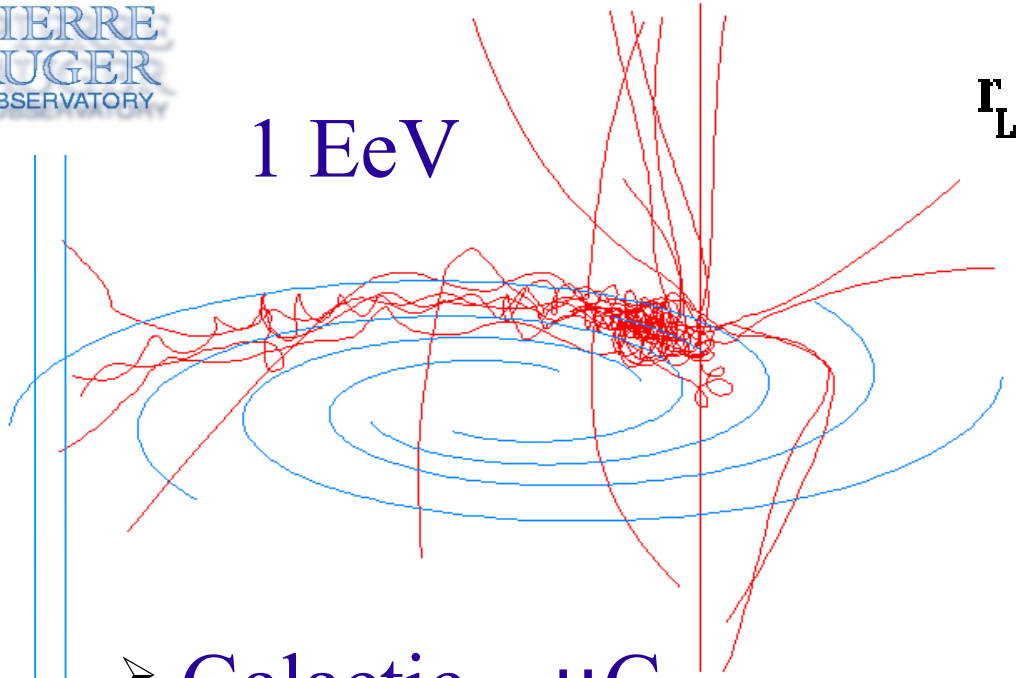
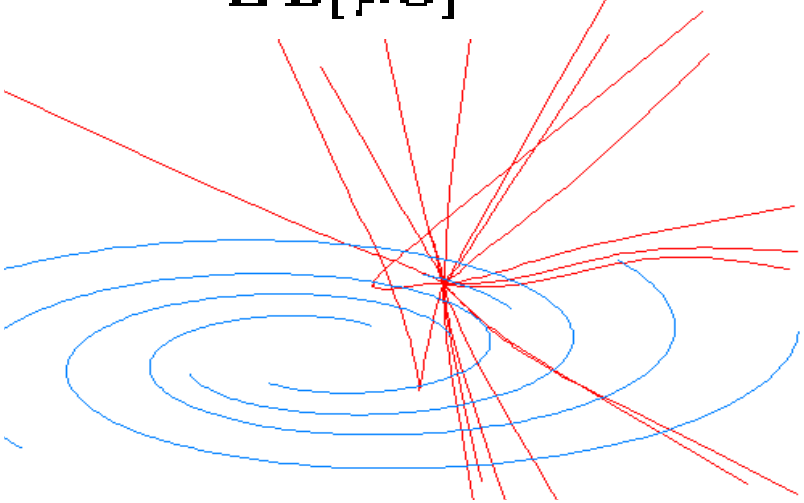
Magnetic field

$$r_L[\mathrm{kpc}] = \frac{E\ [\mathrm{EeV}]}{Z\ B[\mu\mathrm{G}]}$$

1 EeV

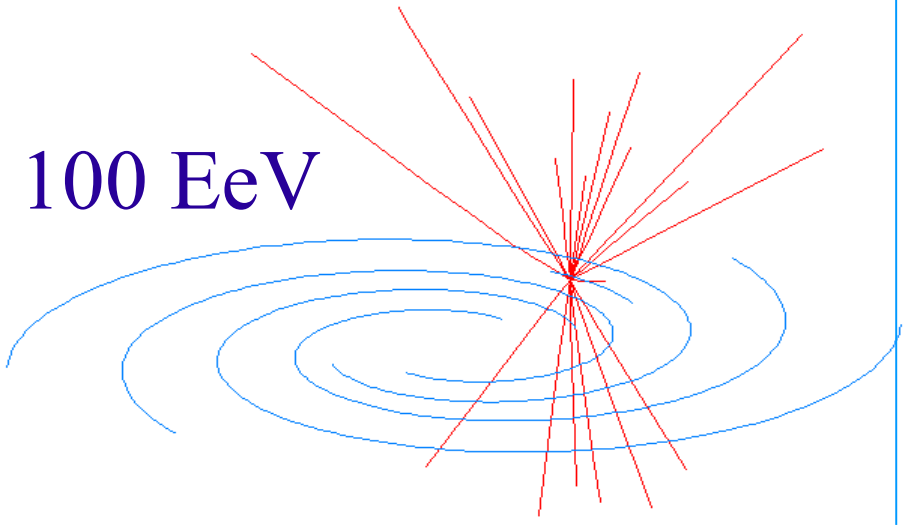


10 EeV



- Galactic ~ μG
- Extragalactic ~ nG
- less than 3 degrees for 100 EeV proton

100 EeV



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Before Auger

- Discrepancy between FD and SD experiments
- Absolute calibration, fluorescence yield
- GZK cutoff ?
- Extremely poor statistics (only 11 events above 10^{20} eV)
- Anisotropy (Galactic center, BL Lacs)
- Clustering of CRs

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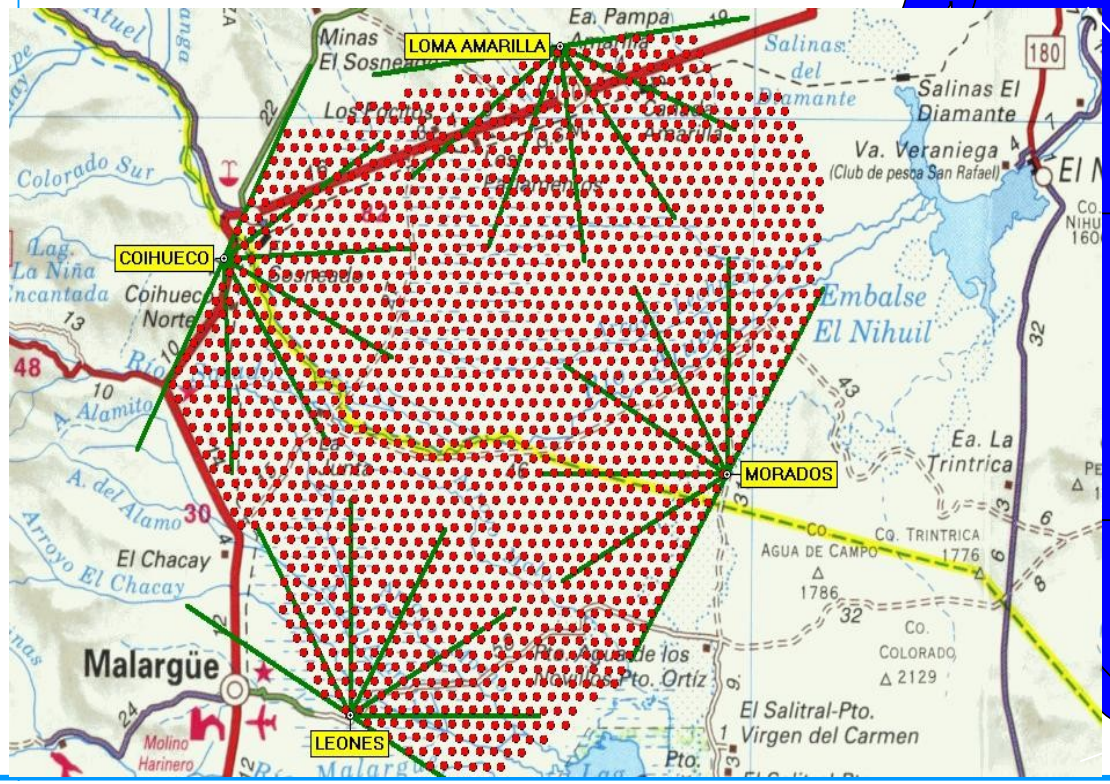
Auger

- Malargue, Argentina
- 3000 km^2
- 4 FD, 1600 SD



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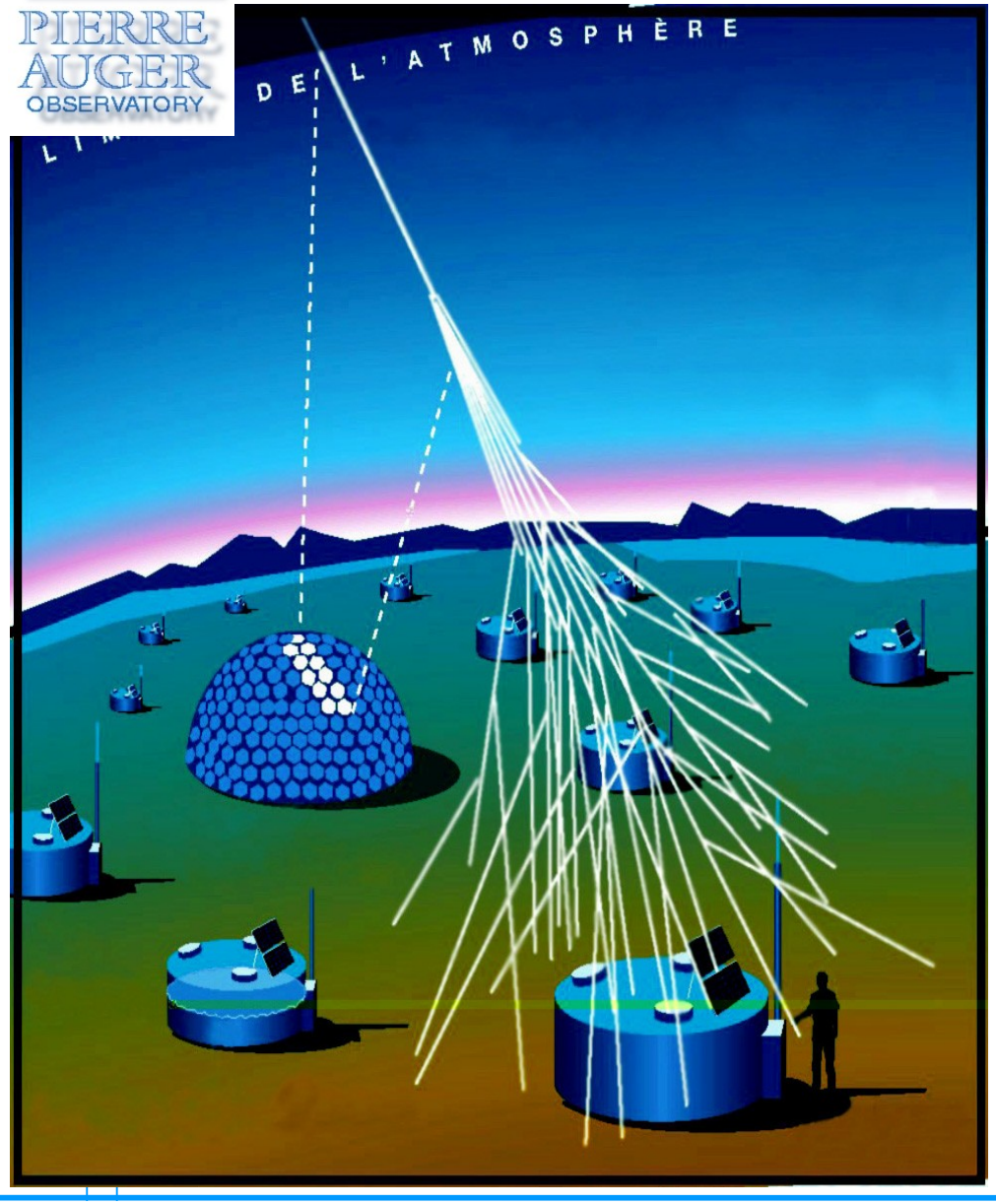
Hybrid detector



- Hybrid: FD + at least 1 SD
- SD full time
- FD 10% (clear & moonless nights)
- Geometrical reconstruction
- SD calibration

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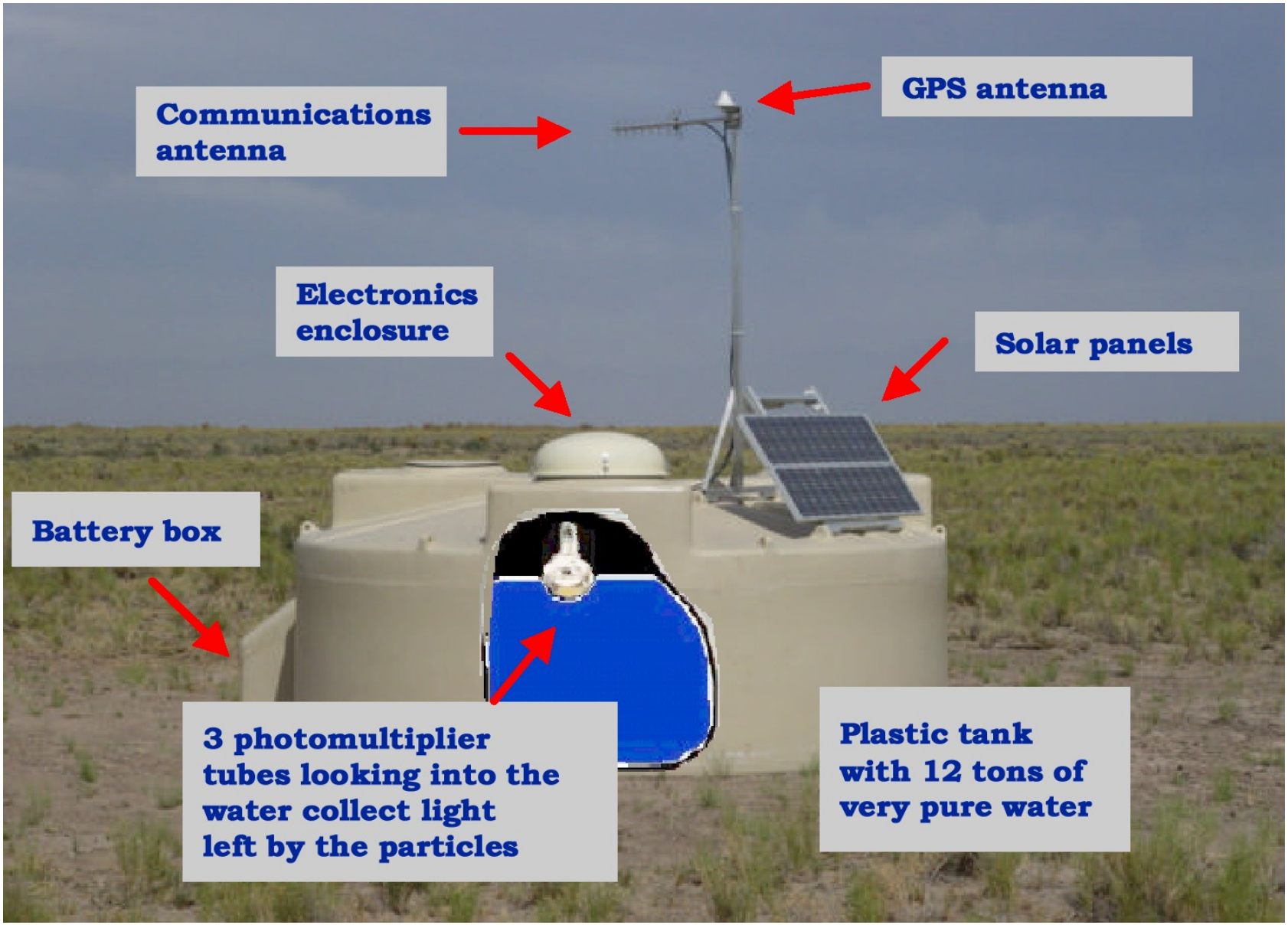
SD



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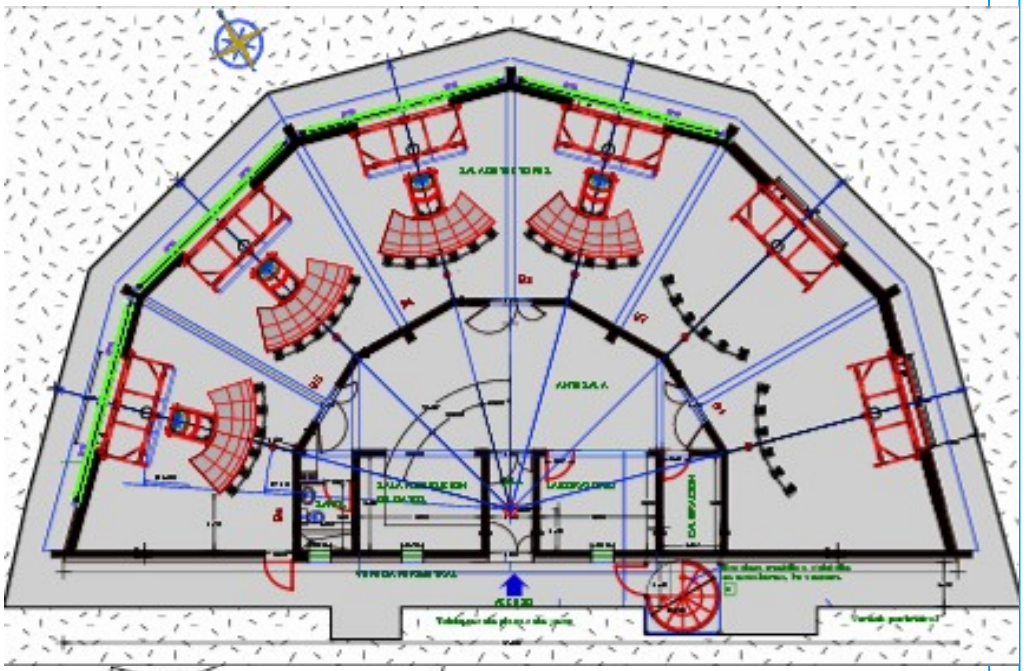
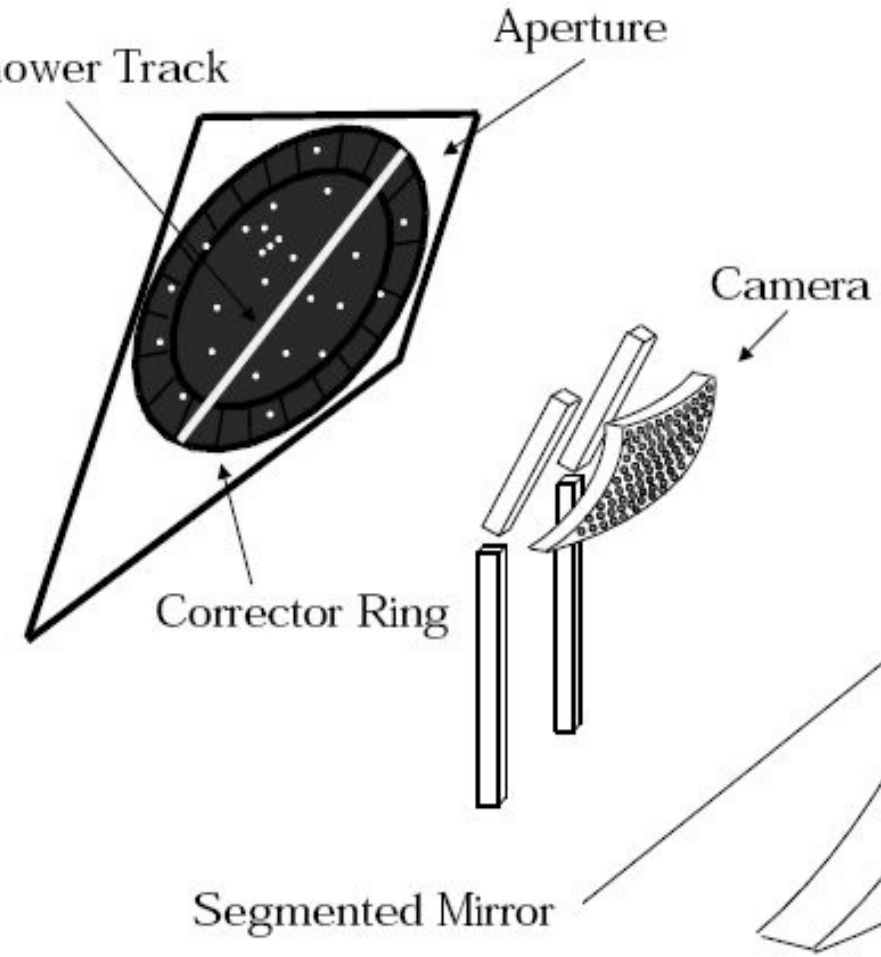
FD schema





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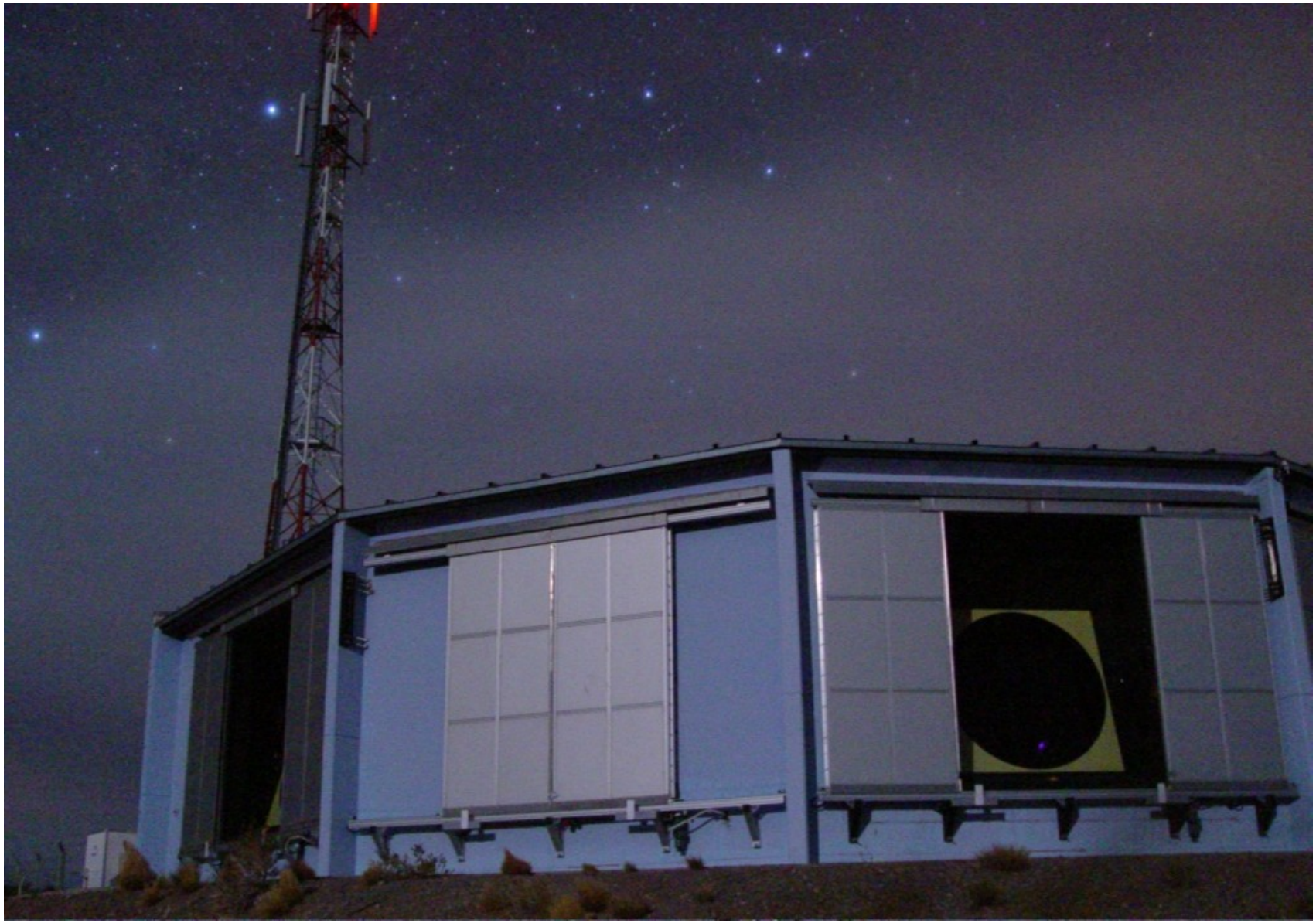
FD outside



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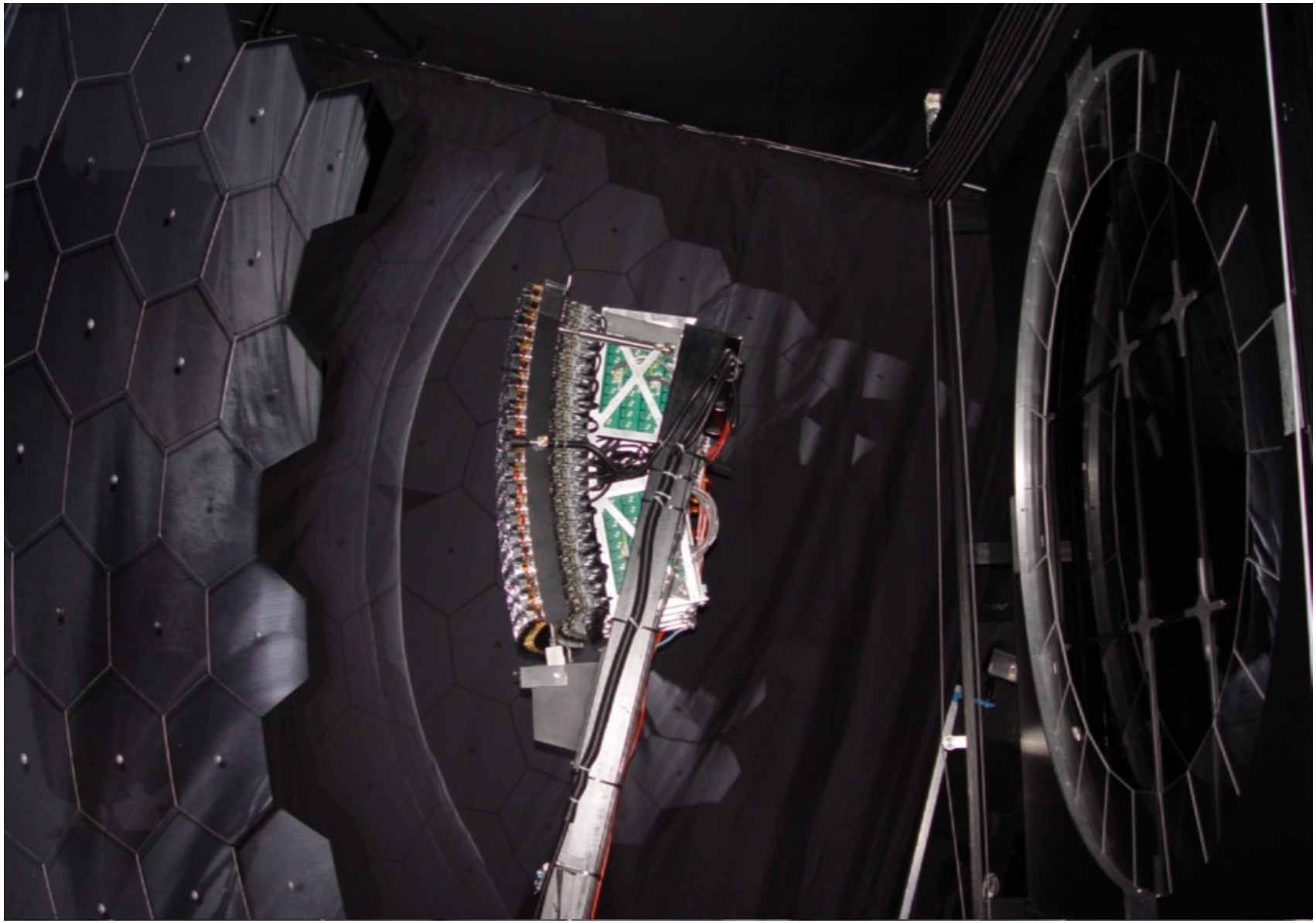
FD inside



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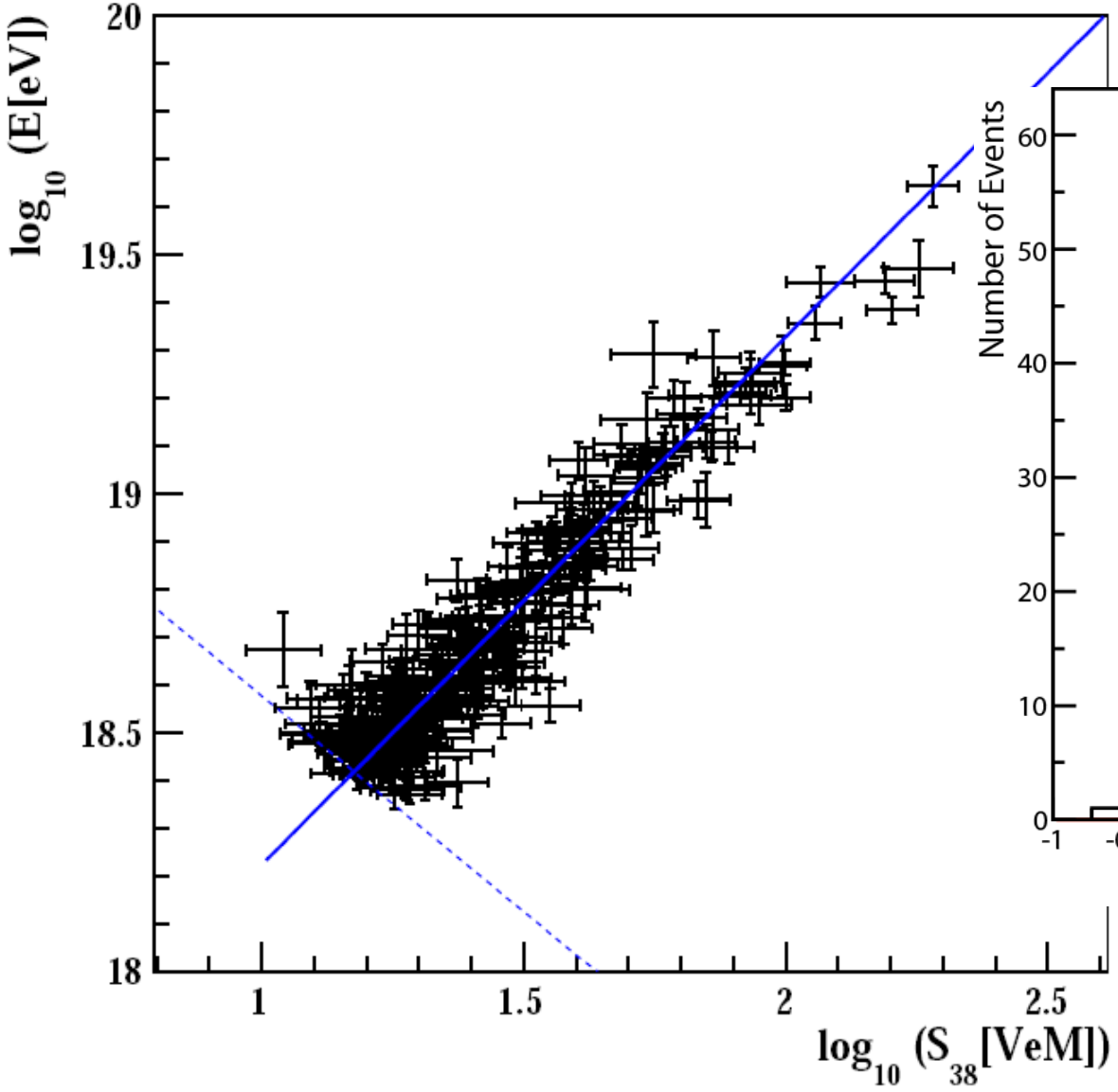
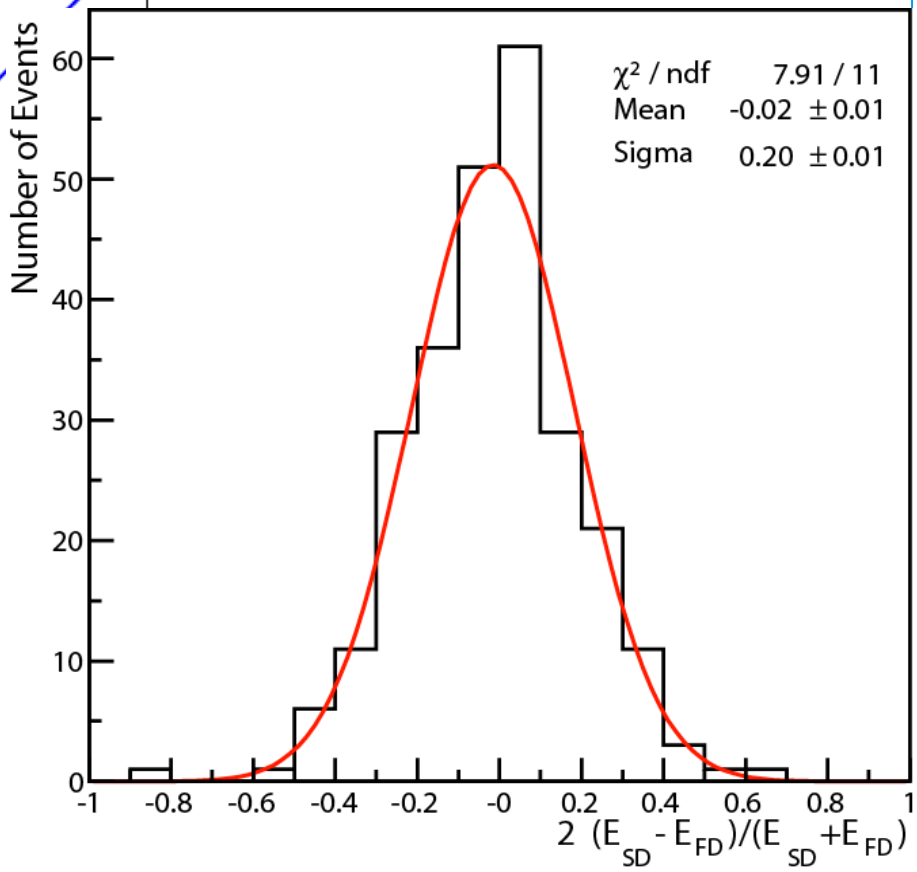
Energy conversion





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Fluorescence yield

- Nitrogen molecules
- 300 - 400 nm
- Experiment Airfly and others
- Absolute yield
- Temperature, pressure, humidity

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Calibration

- Absolute (at least 2 times per year)
- Relative (during measurement)
- Time dependance
- Gain of PMT
- Reflectivity of mirrors, ...

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Atmosphere

- Detailed study of atmospheric conditions
- Local monthly model of atmosphere
- Lasers (Lidars, Central Laser Facility)
- Low layer of atmosphere (HAM, APF)
- Cloud cameras, meteorological balloons
- FRAM
- The worst case: 5-10 % error in energy

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Systematic uncert.

Source	$\Delta E_{SD}/E_{SD}(\%)$
Absolute Fluorescence Yield	14
Pressure dependence of Fluorescence Spectrum	1
Humidity dependence of Fluorescence Spectrum	5
Temperature dependence of Fluorescence Spectrum	5
FD absolute calibration	11
Time dependence of FD calibration	10
FD wavelength dependence response	3
Rayleigh atmosphere	1
Wavelength dependence of aerosol scattering	1
Aerosol phase function	1
FD reconstruction method	10
Invisible energy	4
TOTAL SYST.	24

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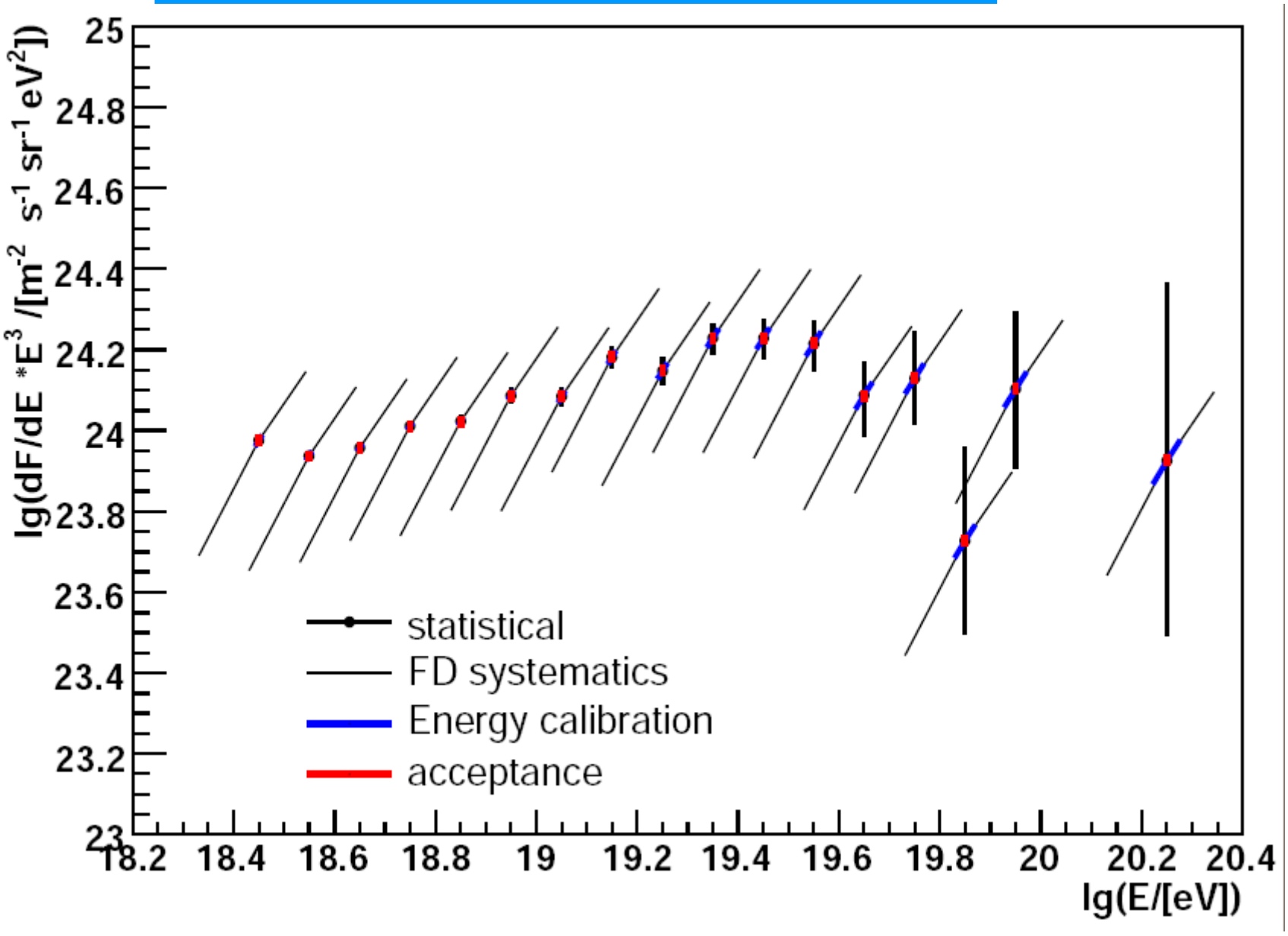
CR spectrum



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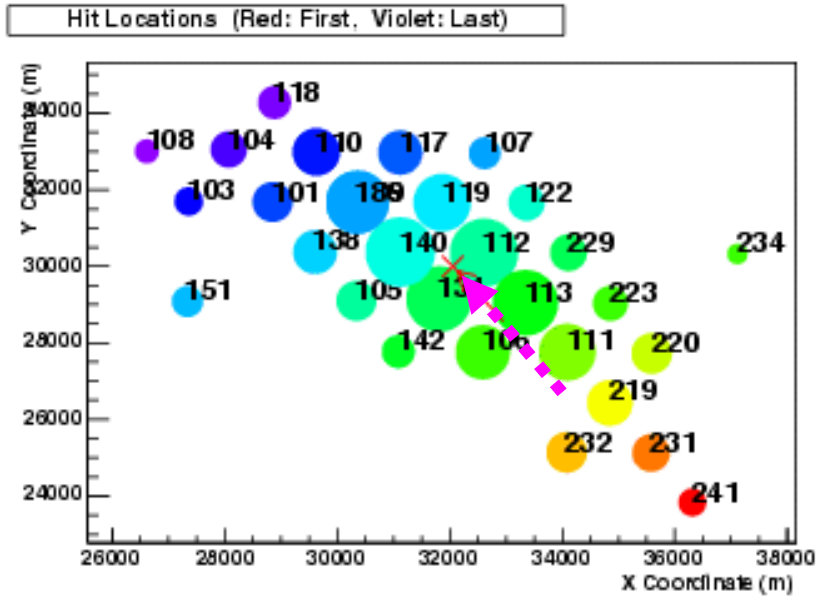
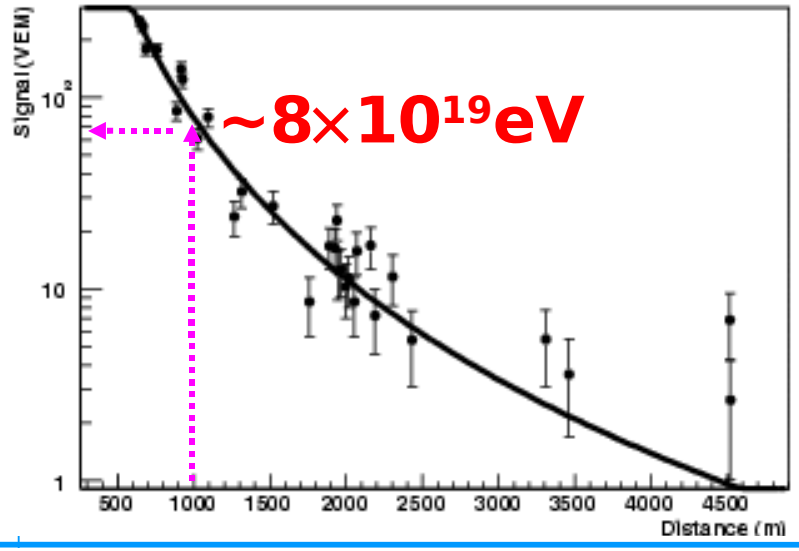
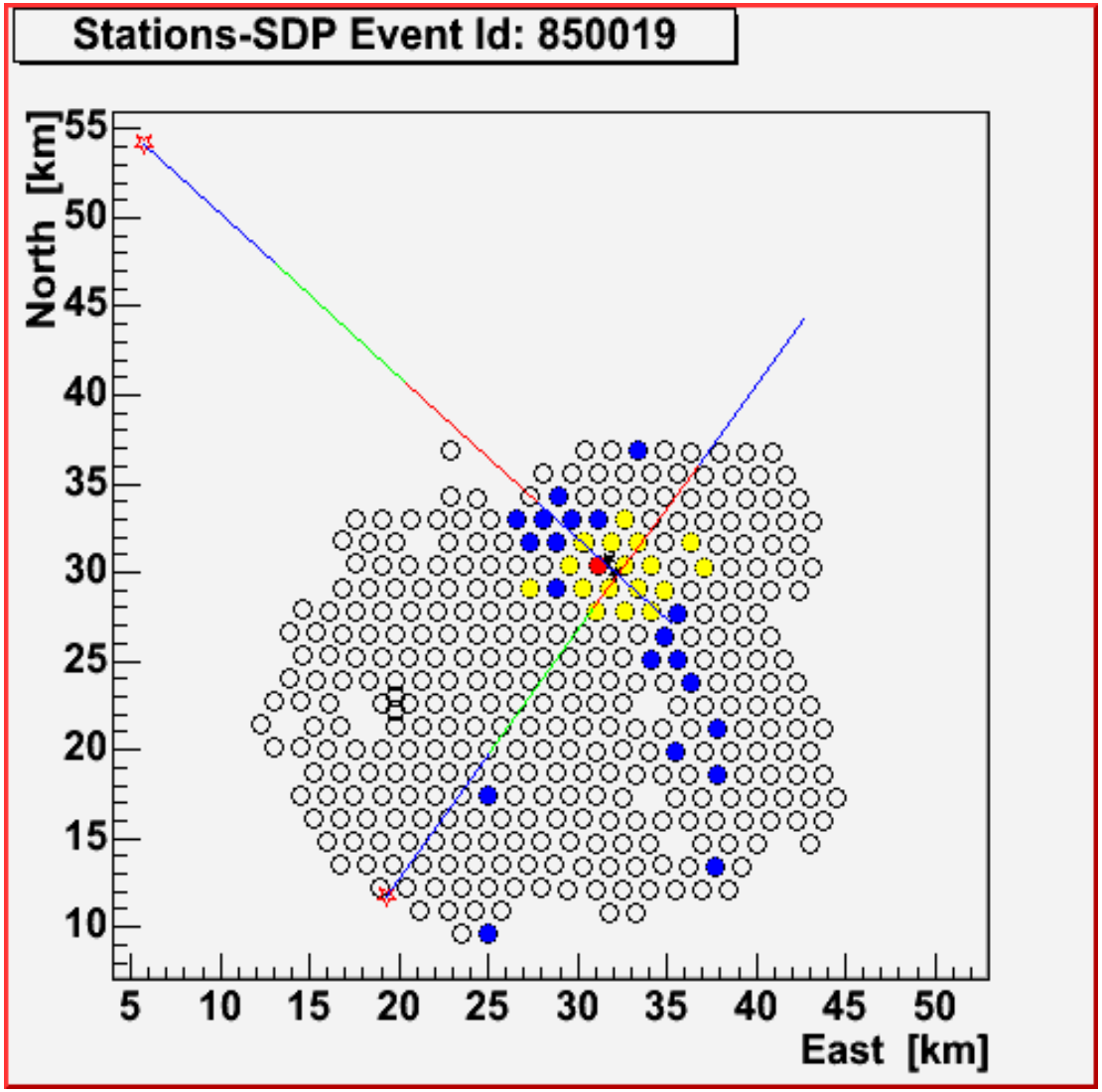
Stereo hybrid



Lateral Distribution Function





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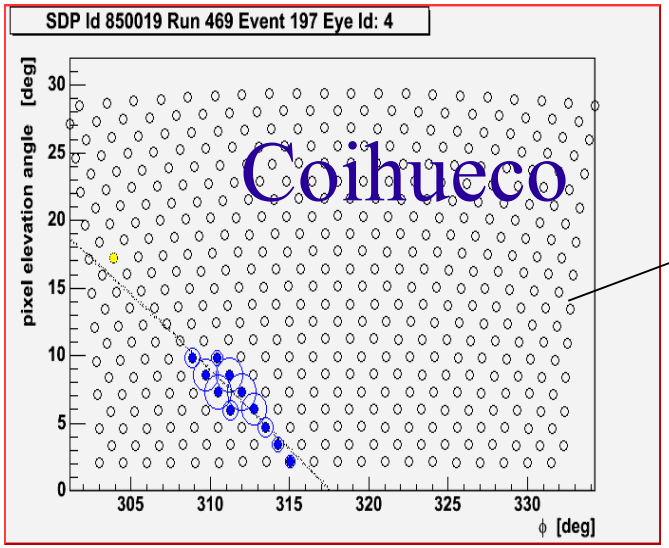
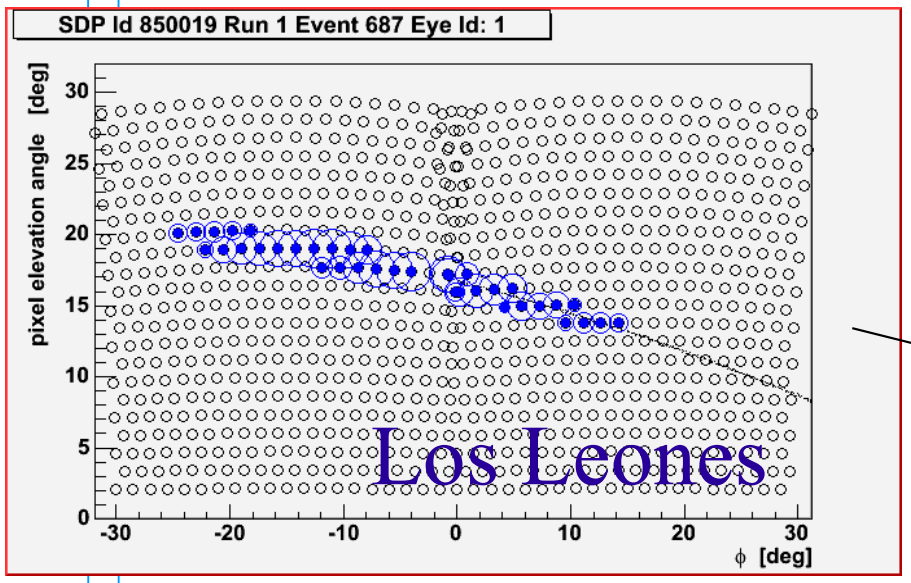
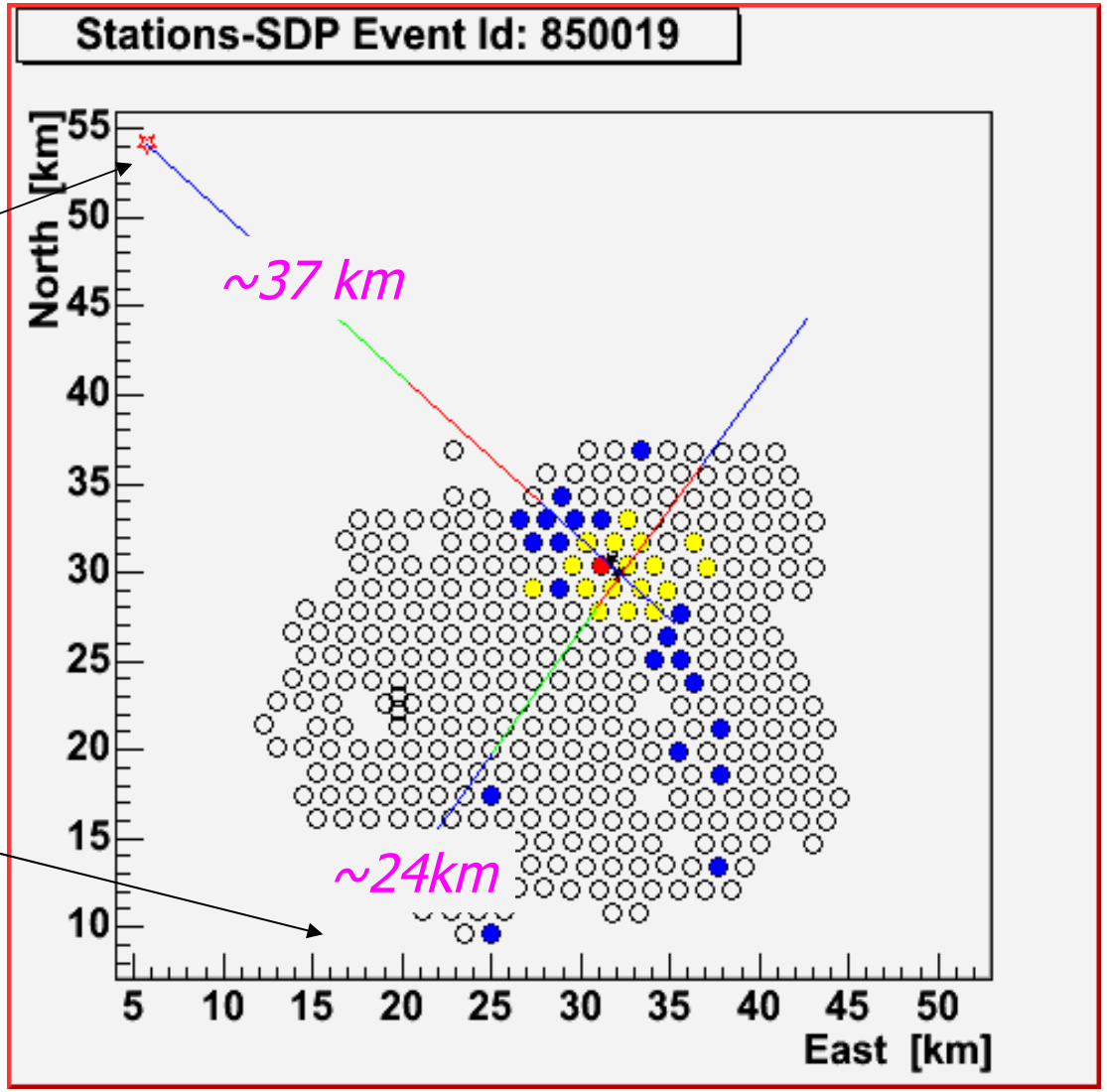
Stereo hybrid







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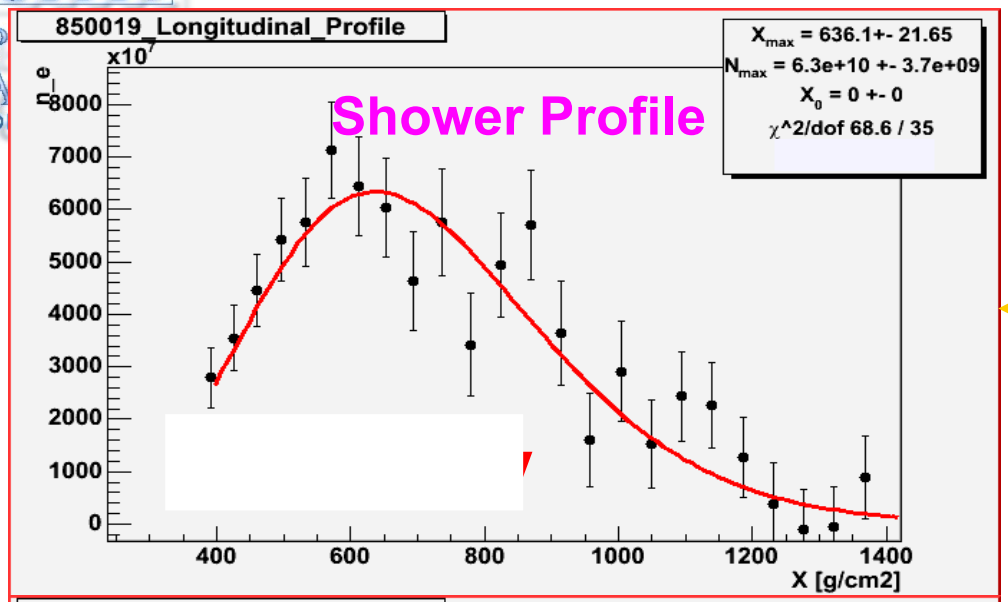
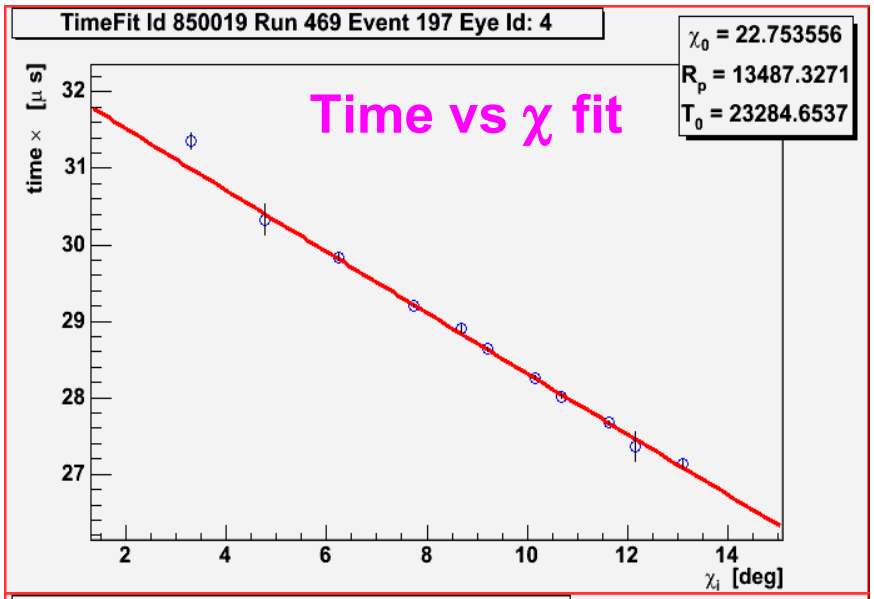
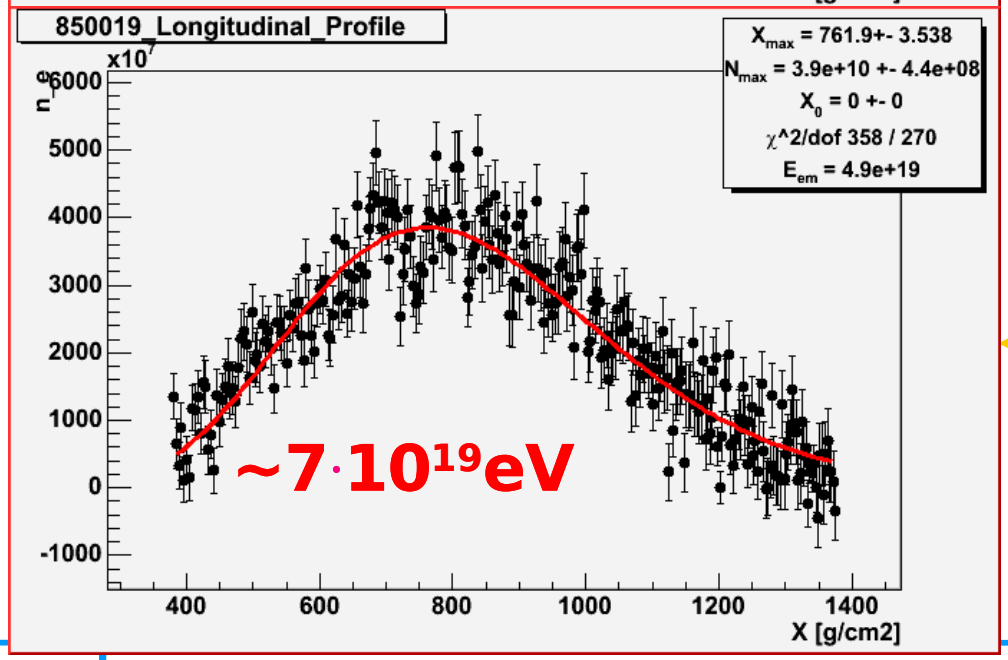
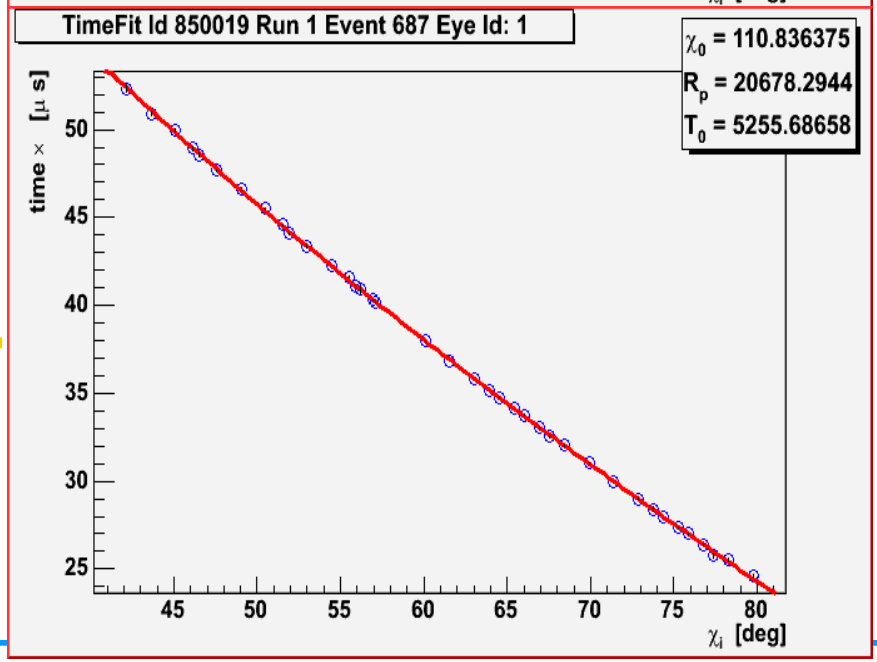
Stereo hybrid









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Auger results

- All results are preliminary!
- International Cosmic Ray Conference, Mexico 2007

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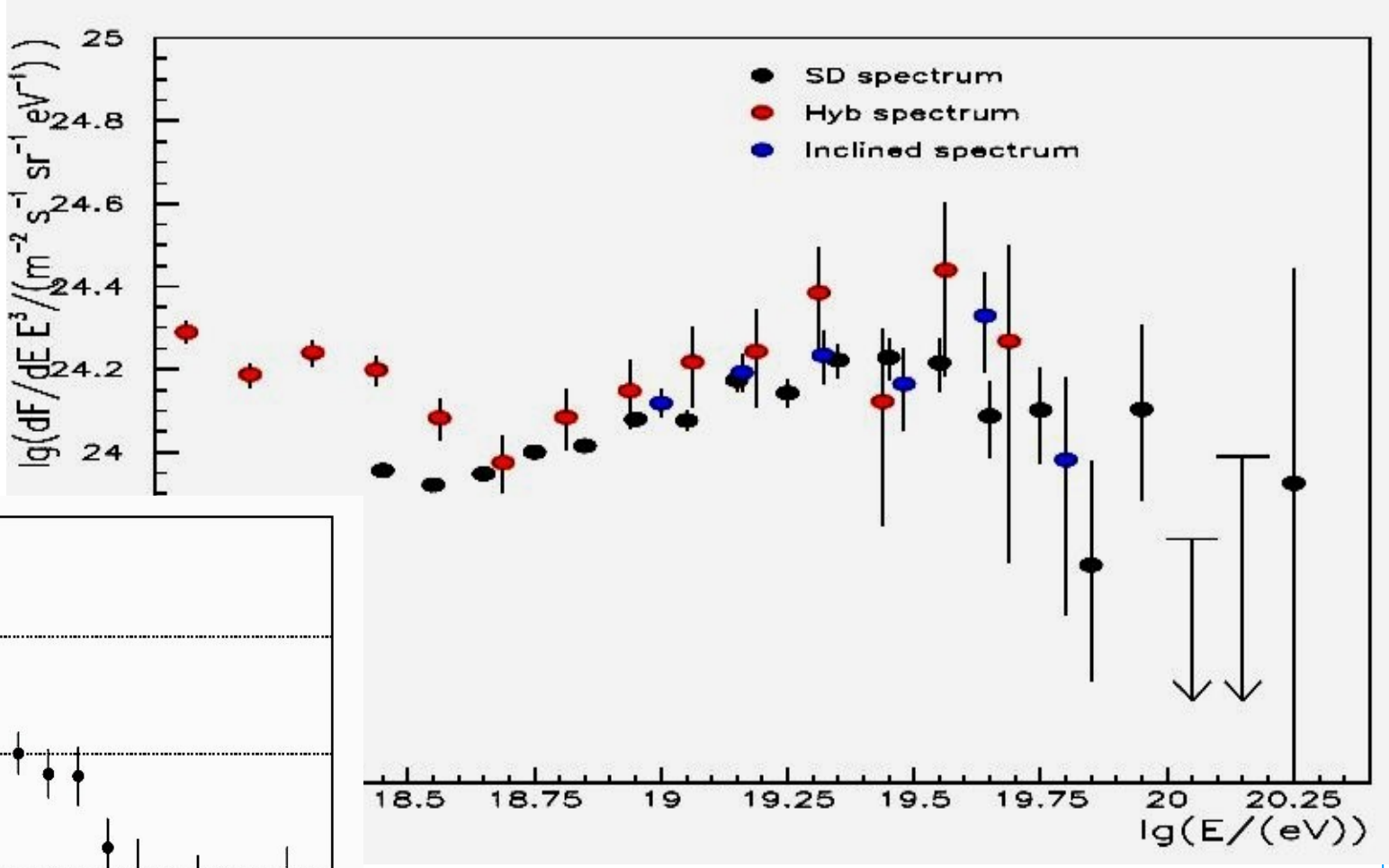
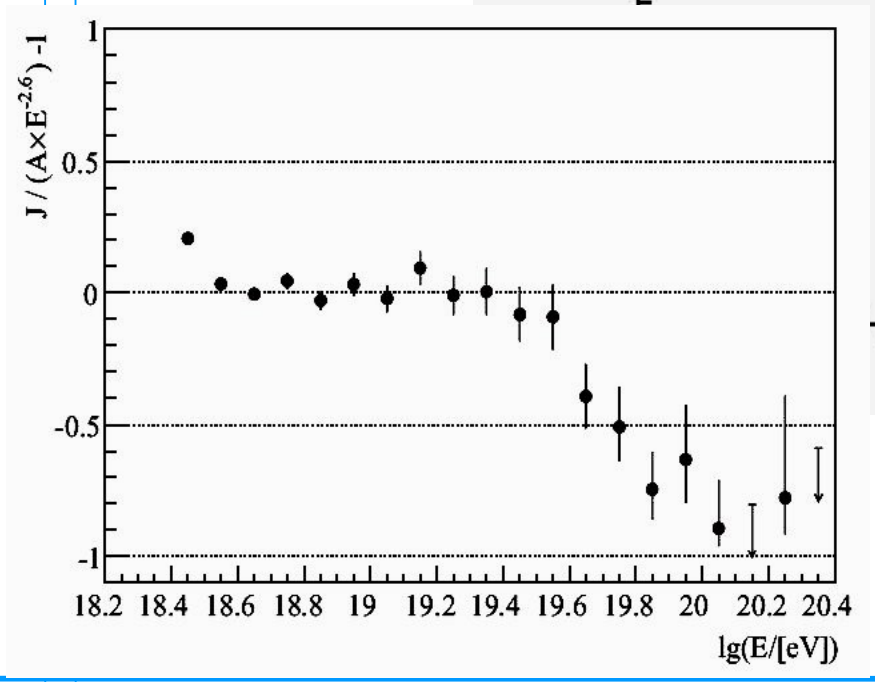
CR spectrum





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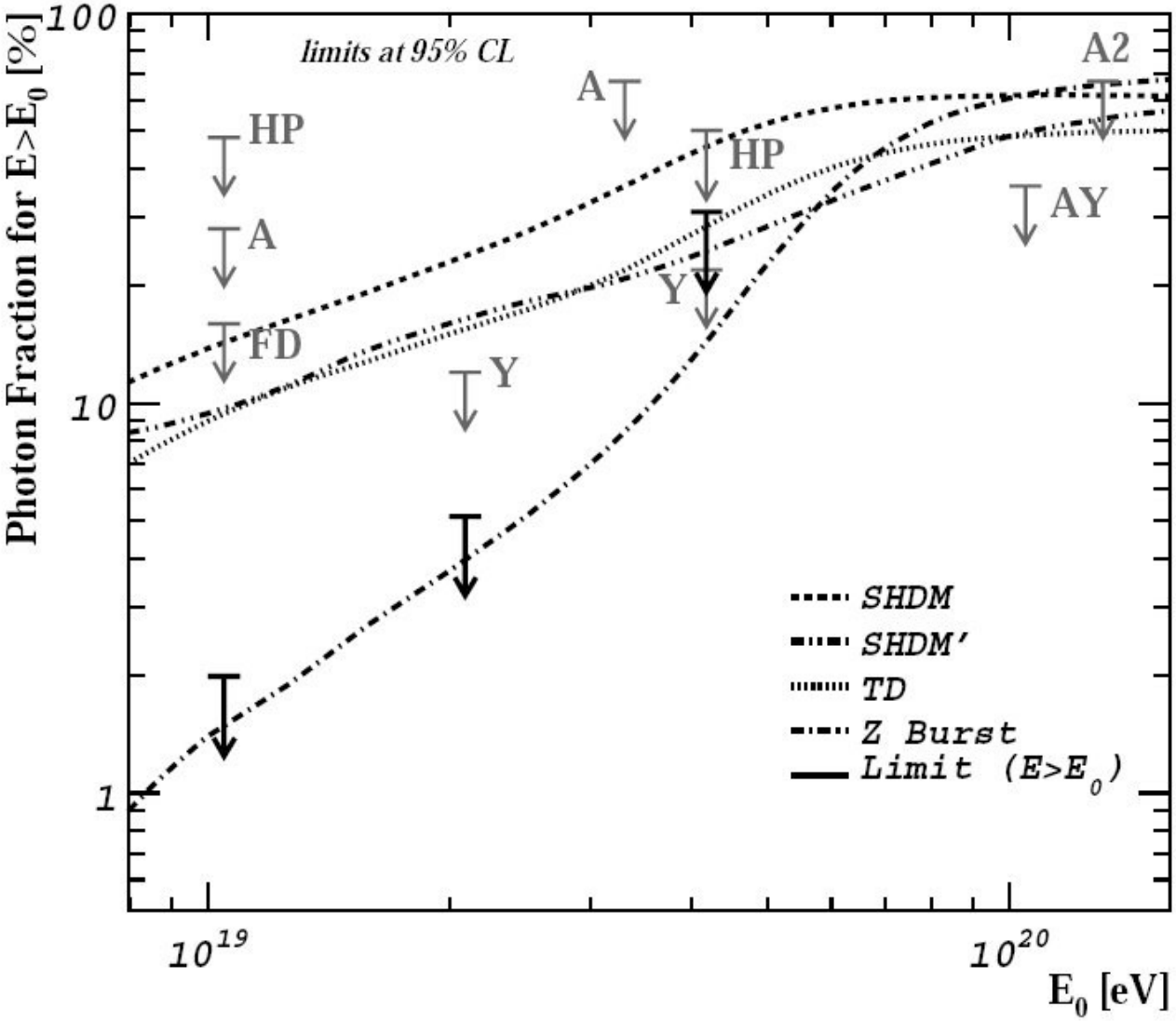
Photon limit



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Anisotropy

- No large scale anisotropy
- No clustering
- Coincidences between CR arrival direction and positions of astronomical objects are studied
- No time and spatial coincidence between CRs and GRBs
- More data are needed

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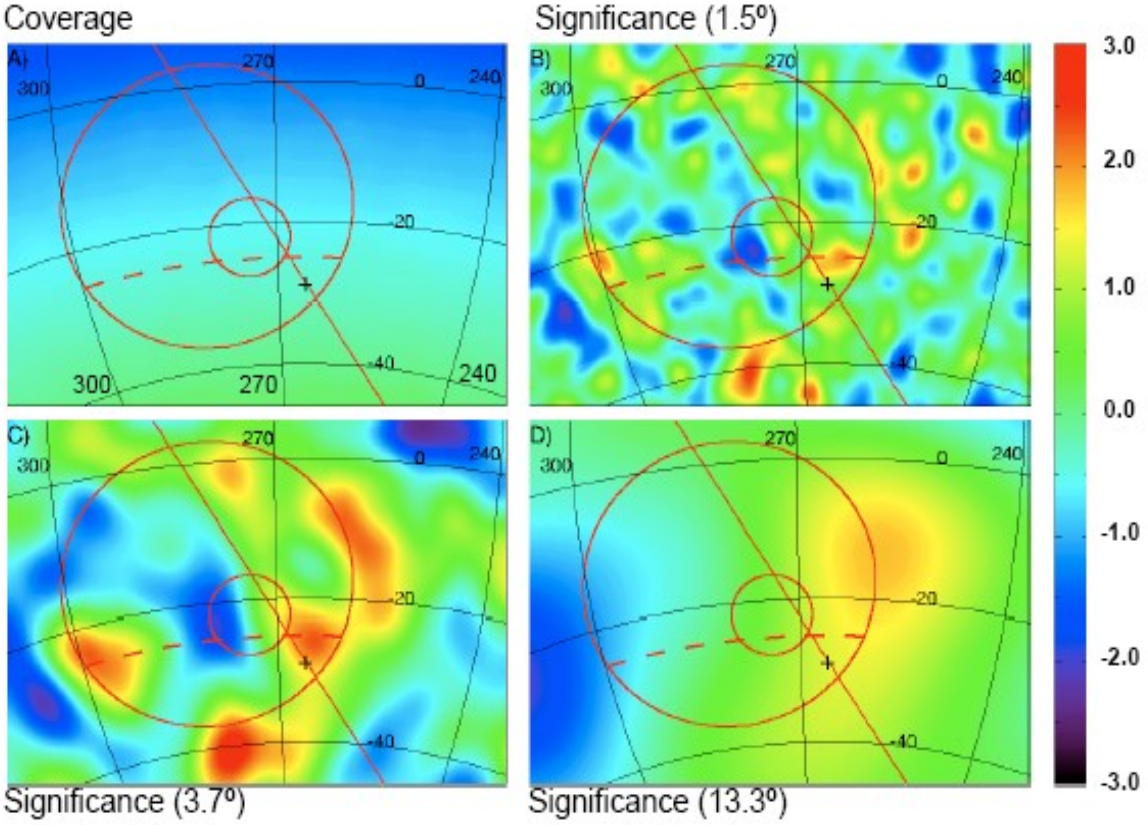
Galactic center

1 < E < 10 EeV

search	window size	n_{obs}/n_{exp}
extended	10° (TH)	1463/1365 = 1.07 ± 0.04(stat) ± 0.01(syst)
	20° (TH)	5559/5407 = 1.03 ± 0.02(stat) ± 0.01(syst)
point-like	0.8° (G)	16.9/17.0 = 0.95 ± 0.17(stat) ± 0.01(syst)



- 8.5 kpc
- GC is inside f.o.v.
- No signal observed
- (Claims from Agasa and Sugar were not confirmed)

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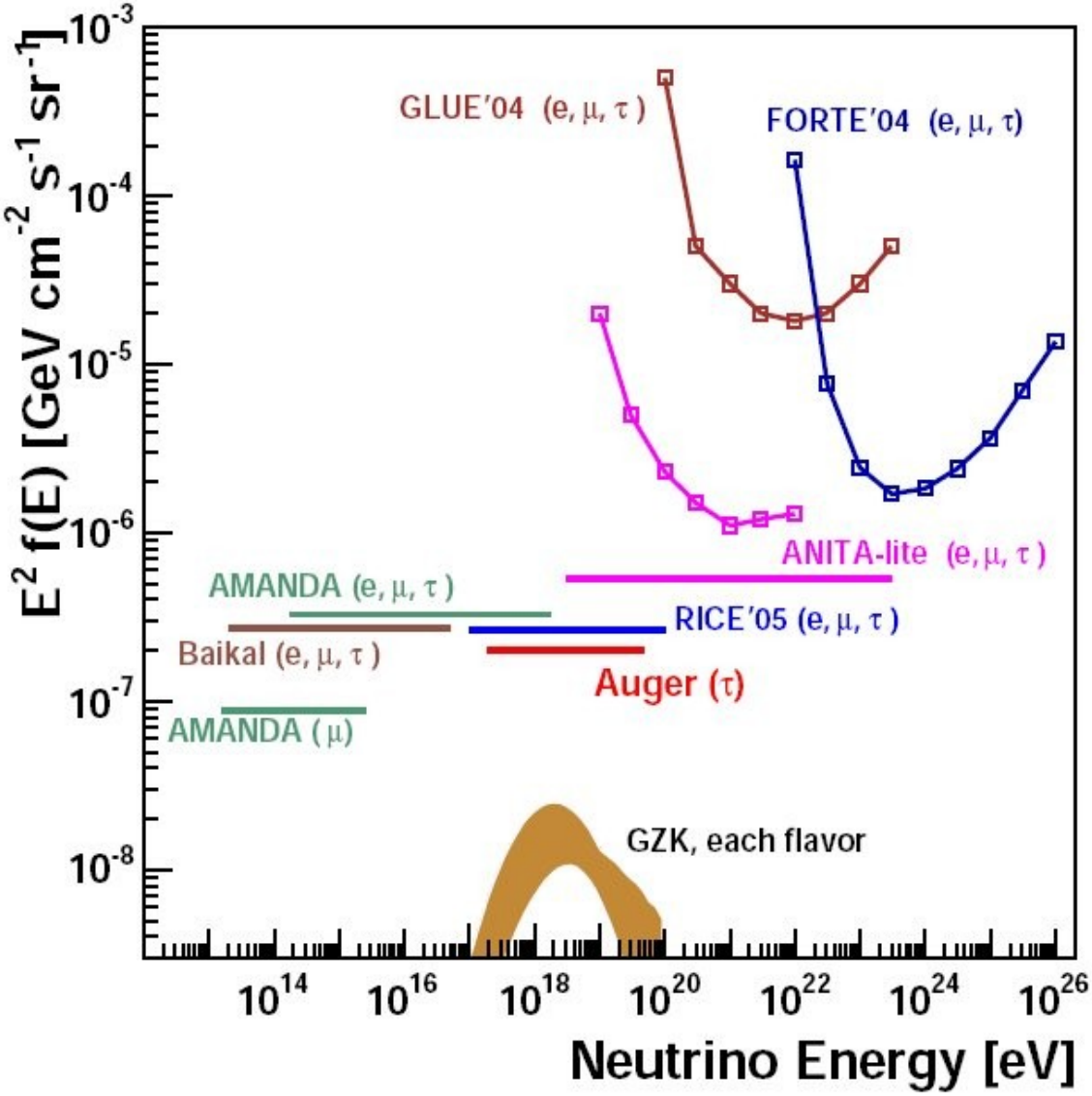
Tau neutrinos



- Inclined showers
- $\theta < 60^{o}$
- Depth of atm. for horizontal particles is 36,000 g cm^{-2}
- Deep in atmosph.
- Earth skipping
- Tau lepton

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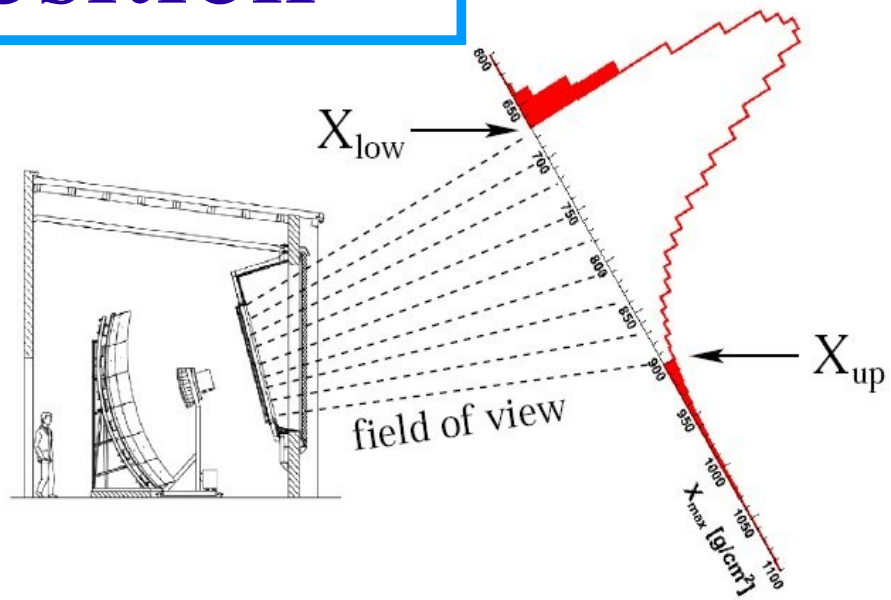
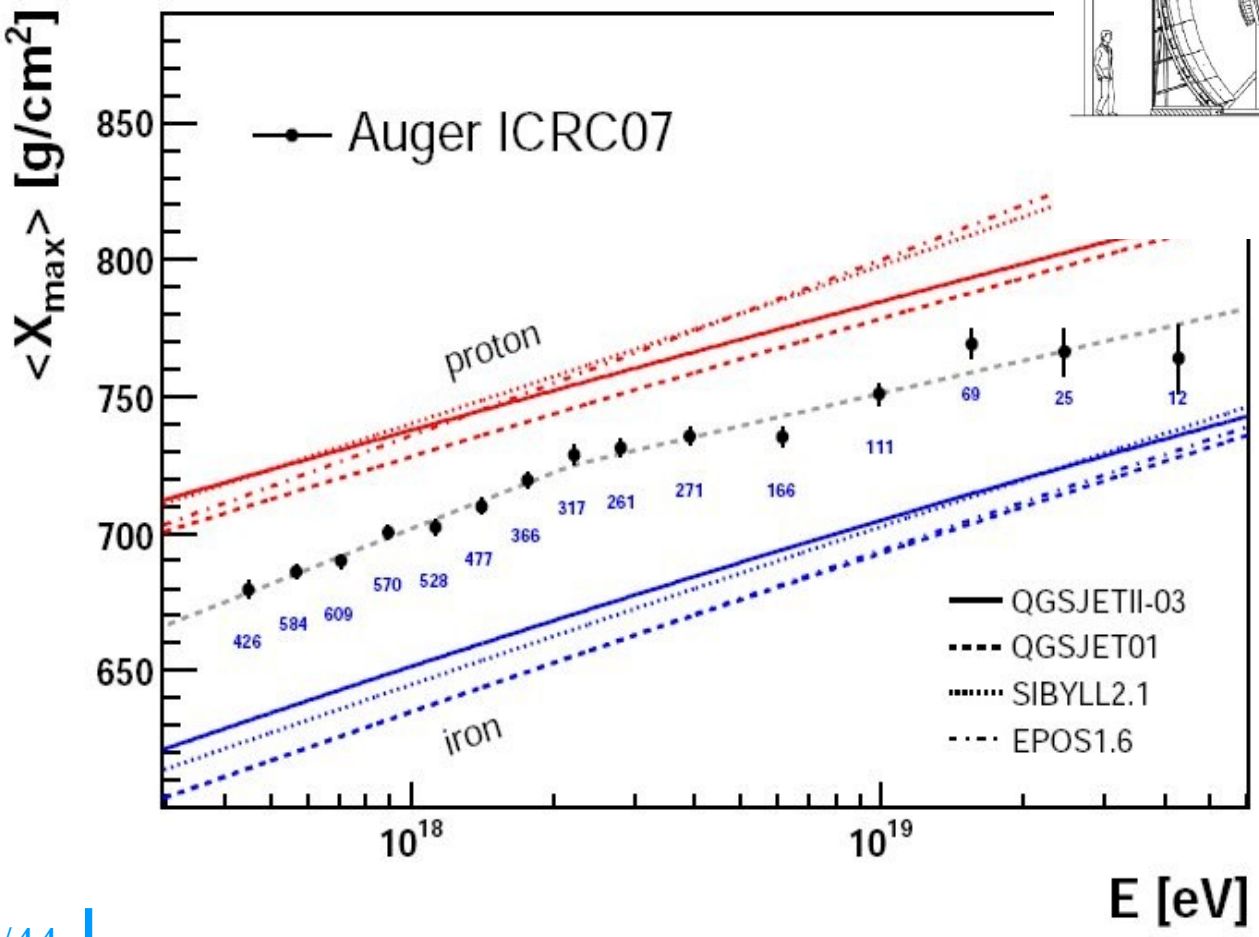
CR composition





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