Ultra-High Energy Cosmic Rays

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APC , Paris

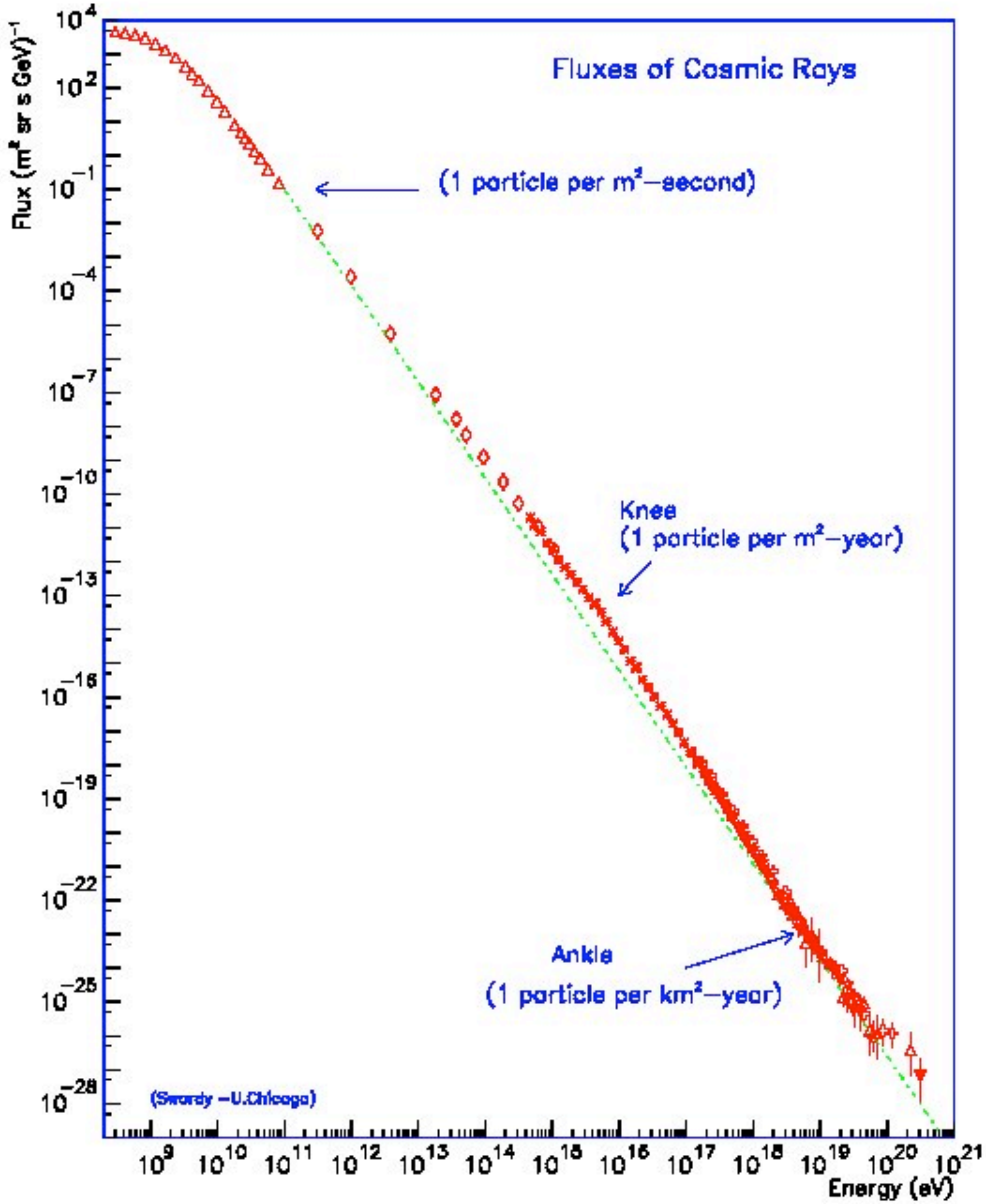
Overview:

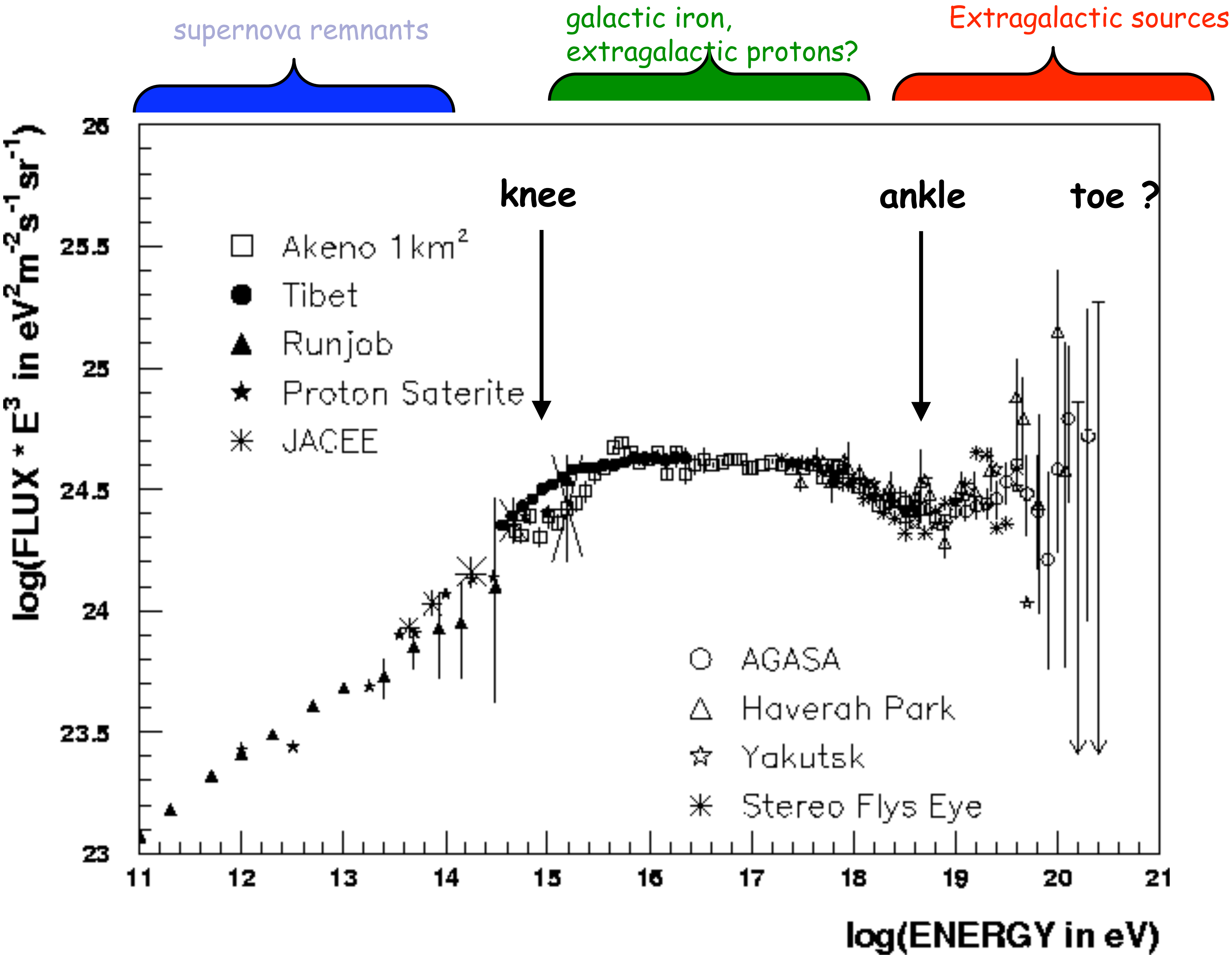
- *UHECR measurements*
- *Acceleration of UHECR in astrophysical sources*
- *Propagation of UHECR: energy losses, magnetic fields*
- *UHECR spectrum and GZK cutoff*
- *Theoretical models and composition*

Overview:

- *UHECR arrival directions, their sources and galactic and extragalactic magnetic field*
- *Correlations of UHECR E>56 EeV with LSS*
- *Particle physics and UHECR*
- *Multi-messenger observations with UHECR*
- *Conclusions*

INTRODUCTION


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy –U.Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)

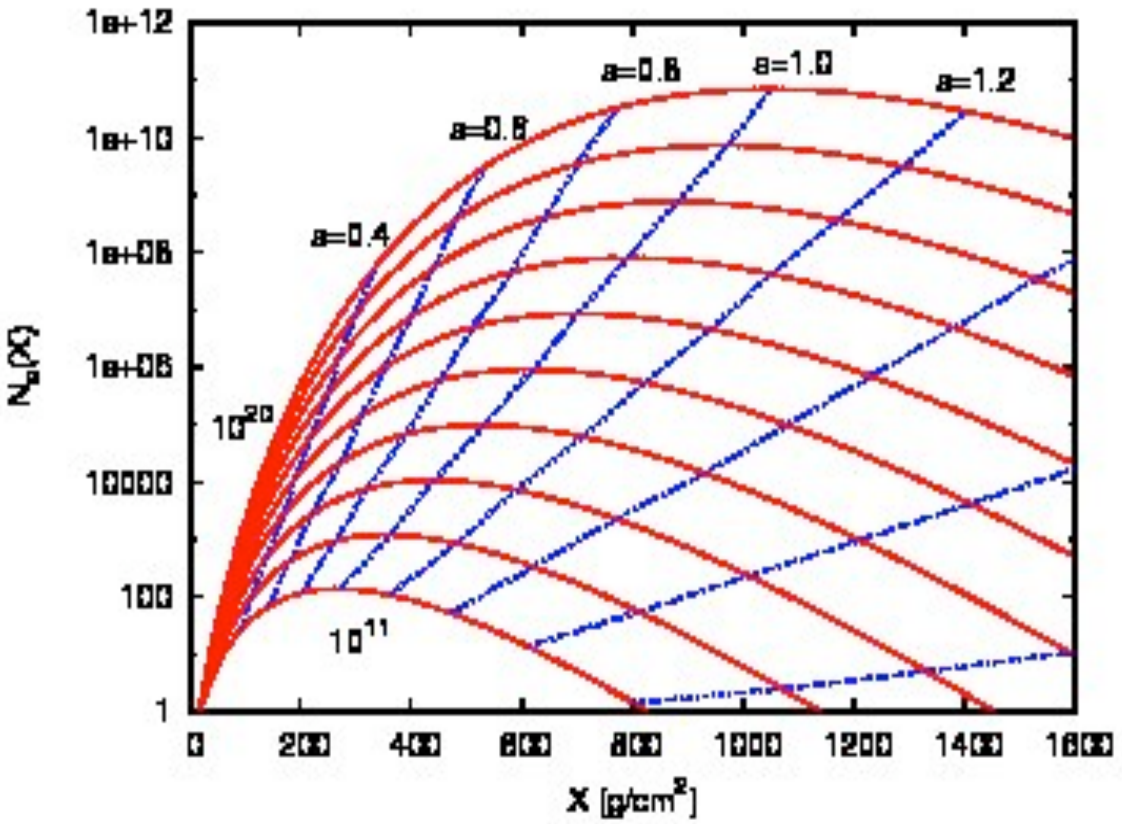


supernova remnants
galactic iron,
extragalactic protons?
Extragalactic sources
knee
ankle
toe ?
Akeno 1km²
Tibet
Runjob
Proton Saterite
JACEE
AGASA
Haverah Park
Yakutsk
Stereo Flys Eye
log(FLUX * E³ in eV²m⁻²s⁻¹sr⁻¹)
log(ENERGY in eV)
23
23.5
24
24.5
25
25.5
26
11
12
13
14
15
16
17
18
19
20
21

Measurements of UHECR

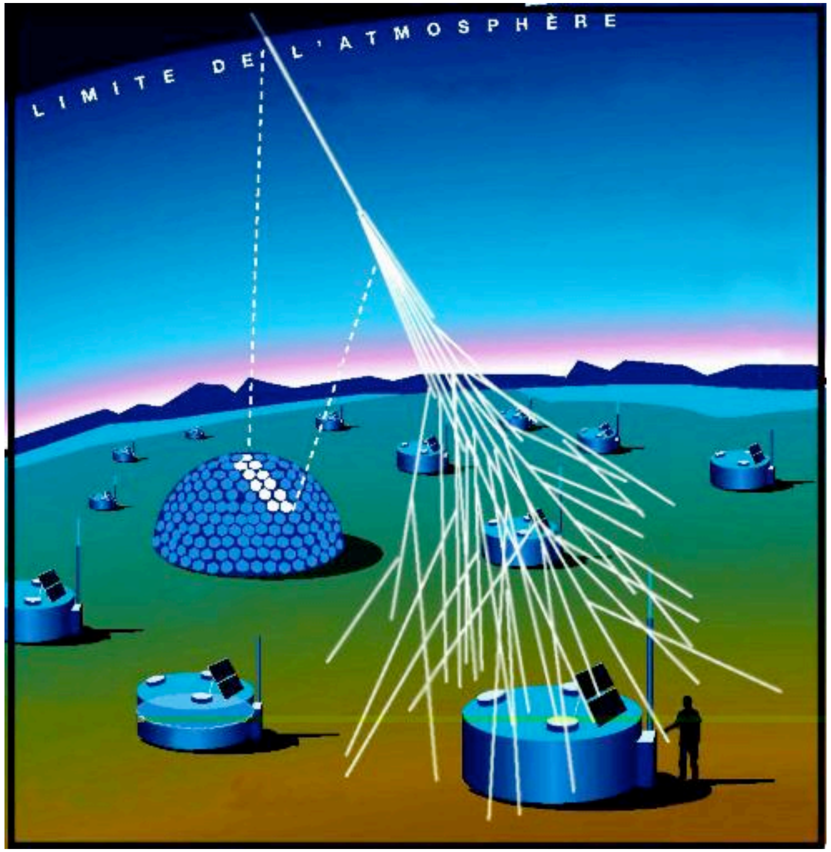
UHECR measurement

- Depth of atmosphere is 1000 g/cm^2
- Proton of 10^{20} eV energy interact within 60-80 g/cm^2. Center mass energy is 300 TeV: much larger then LHC!
- Shower develops with final number 10^{10-11} of low energy particles.



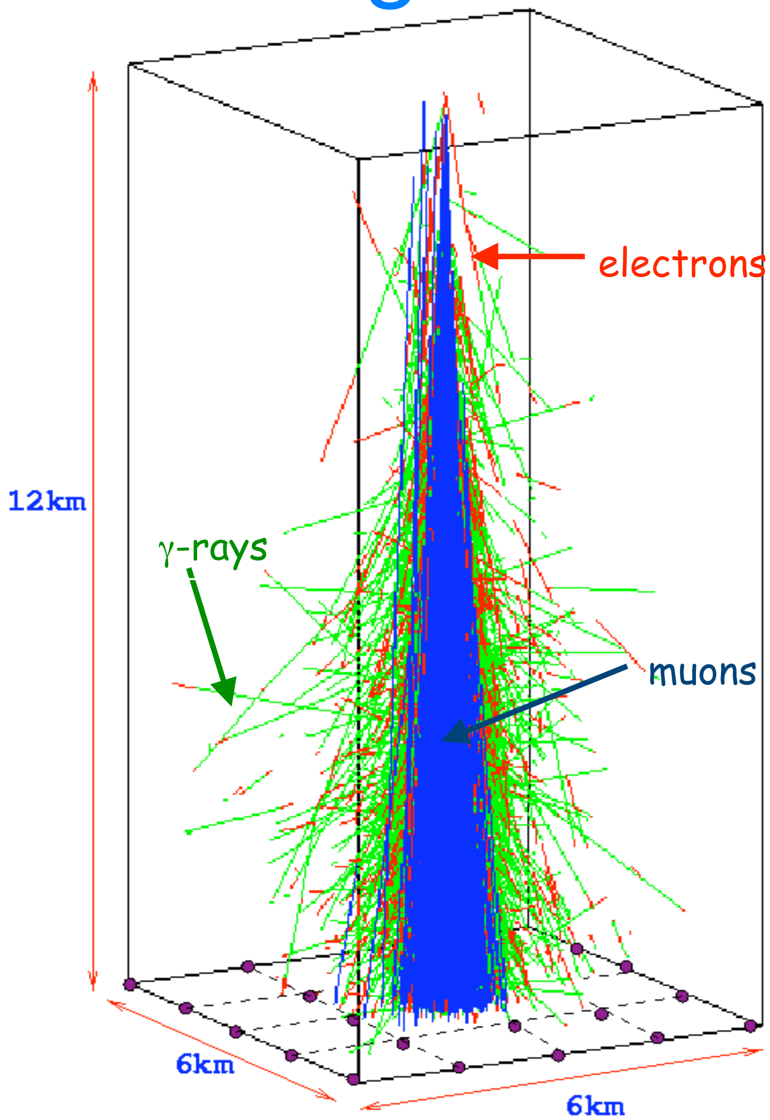
Parameters to measure:

- Energy of primary particle
- Arrival direction.
- Type of primary particle (proton, nuclei, photon, neutrino, new particle)
- Properties of primary particle: total cross section.



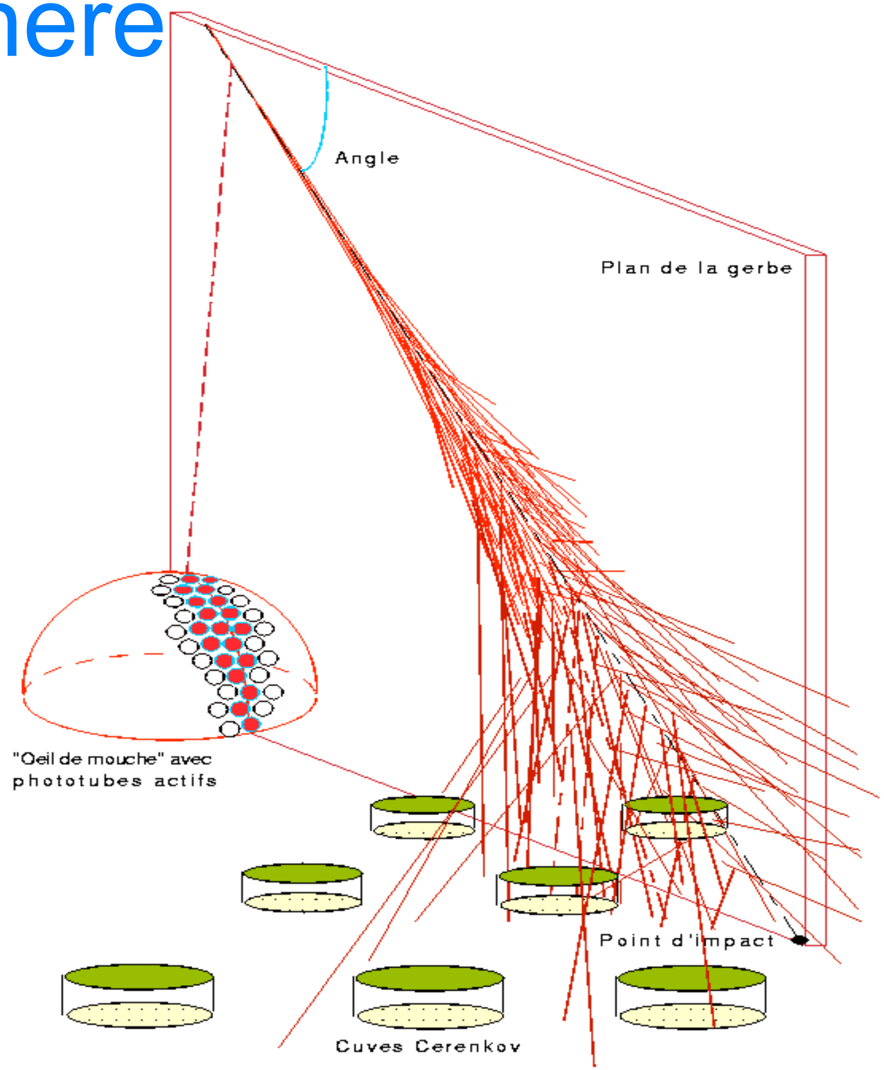
Detection of showers on ground

- Ground array measure footstep of the shower. Final particles at ground level are gamma-rays, electrons, positrons and muons.
- Typically 10^{10-11} photons, electrons and positrons in area 20-50 km^2. It is enough to have detectors with area of few m^2 per km^2. Number of low energy particles is connected to primary energy.
- Space/time structure of signal give information on arrival direction.
- Number of muons compared to number of electrons give information on primary particle kind.

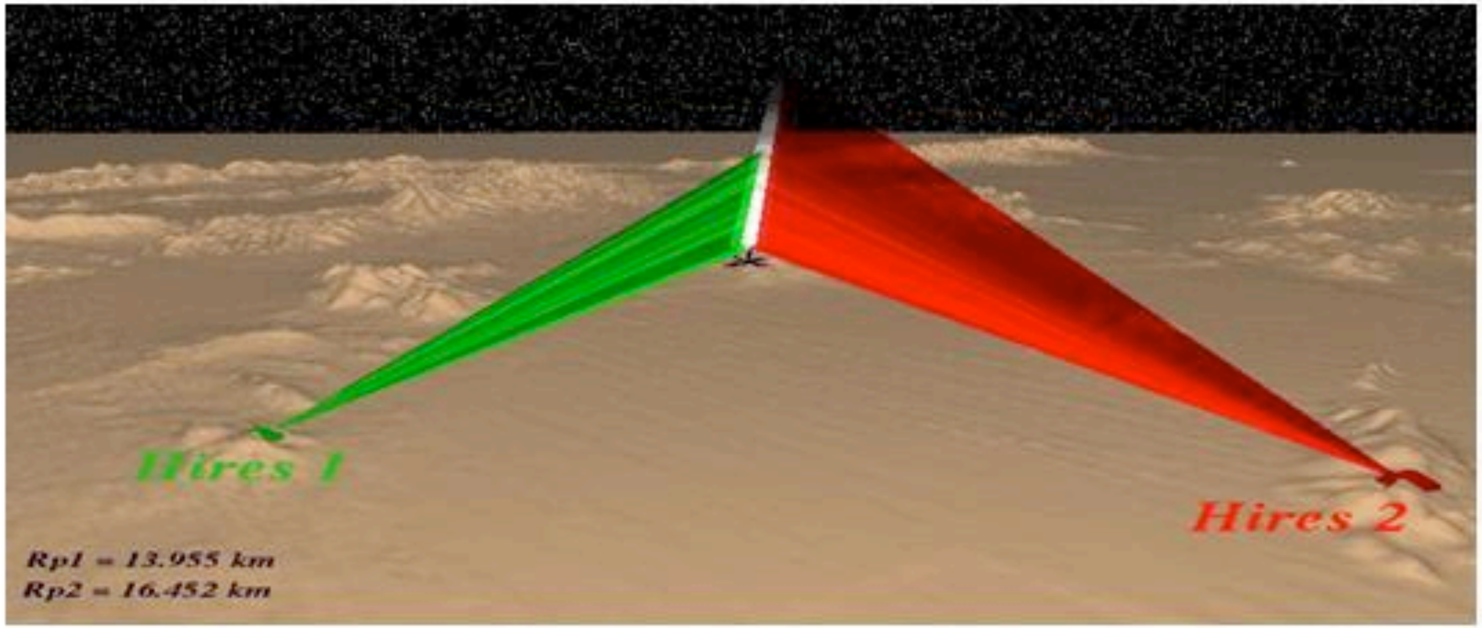


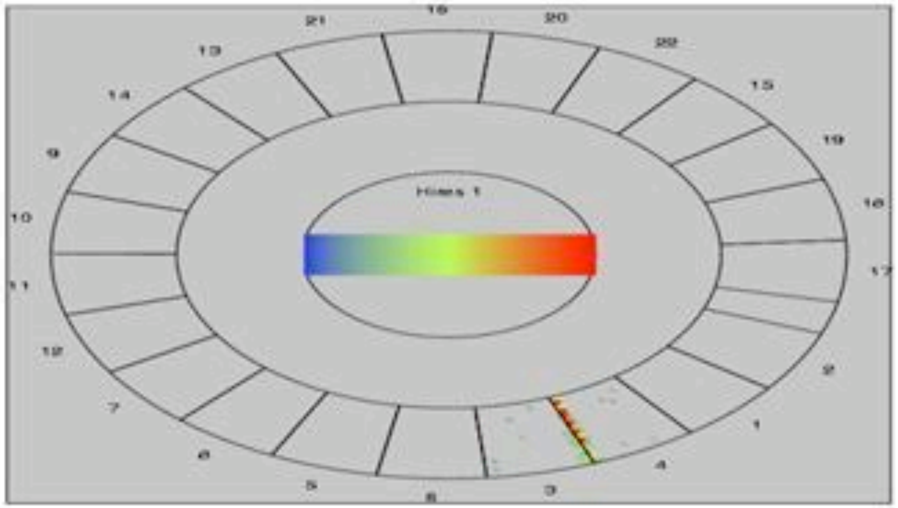
Detection of shower development in atmosphere

- Fly's Eye technique mesure fluorescence emision of N_2 by collection of mirrors: shape of the shower.
- Total amount of light connected to energy of primary particle.
- Time structure of signal gives information on arrival direction.
- Depth in atmosphere with maximum signal give information on primary particle kind.

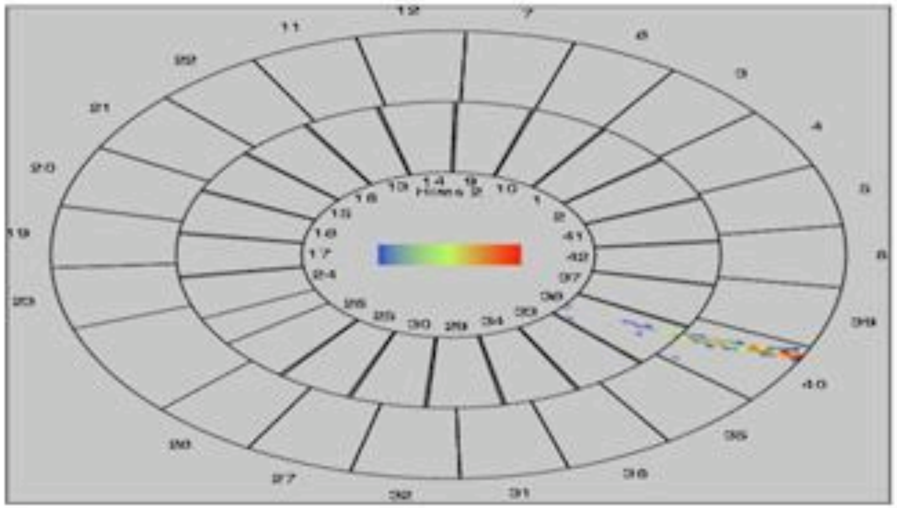


Stereo Event E ~50 EeV





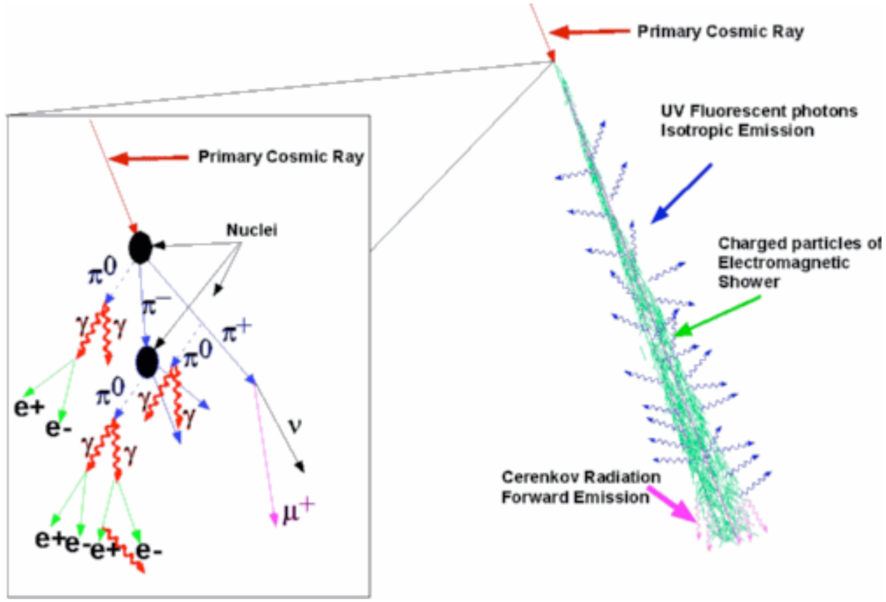
HiRes1



HiRes2

Shower structure: theoretical uncertainty

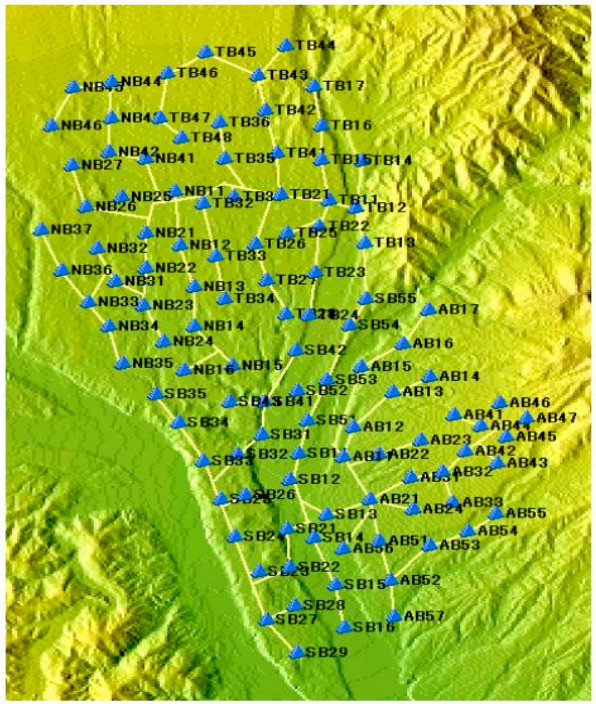
- Extrapolation of accelerator data to high energies with different approaches can give uncertainty up to 30 % in energy estimate for same shower and 100% important for chemical composition study.



AGASA

- AGASA covers an area of about 100 km^2 and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km.
- Operated 1993- 2003.

Akeno Giant Air Shower Array



High Resolution Fly's Eye: HiRes

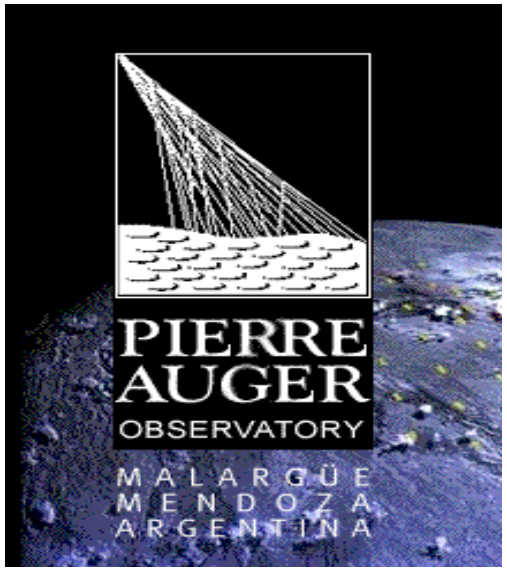
- HiRes 1 and HiRes 2 sit on two small mountains in western Utah, with a separation of 13 km.
- HiRes 1 has 21 three meter diameter mirrors which are arranged to view the sky between elevations of 3 and 16 degrees over the full azimuth range;
- HiRes 2 has 42 mirrors which image the sky between elevations of 3 and 30 degrees over 360 degrees of azimuth.
- Operated in stereo mode 1999-2006.

Auger Observatory

ort involving more than 450

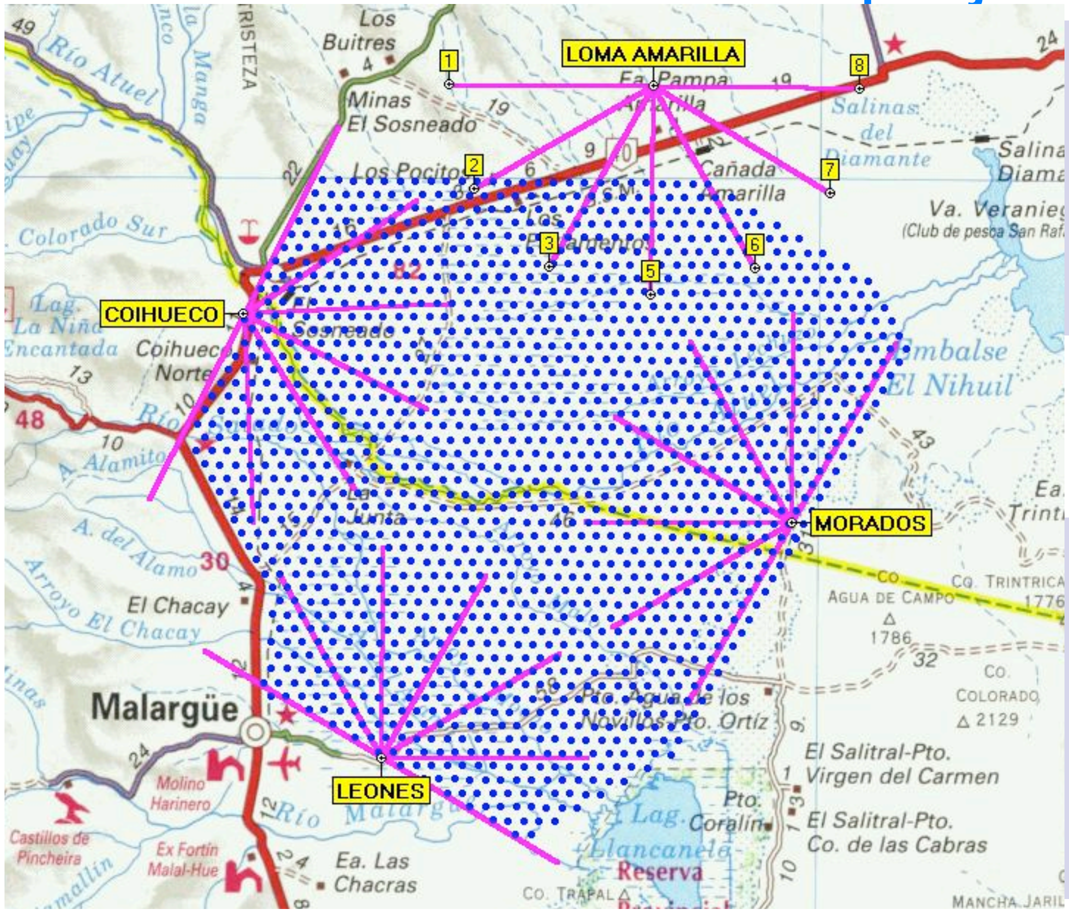
2 institutions in 17 countries:

istralia, Bolivia, Brazil, Czech Republic,
hany, Italy, Mexico, Netherlands, Poland,
venia, Spain, United Kingdom, USA,



Pierre Auger Observatory

South site in Argentina almost finished
North site – project



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km^2 (30xAGASA)

Fluorescence Detectors

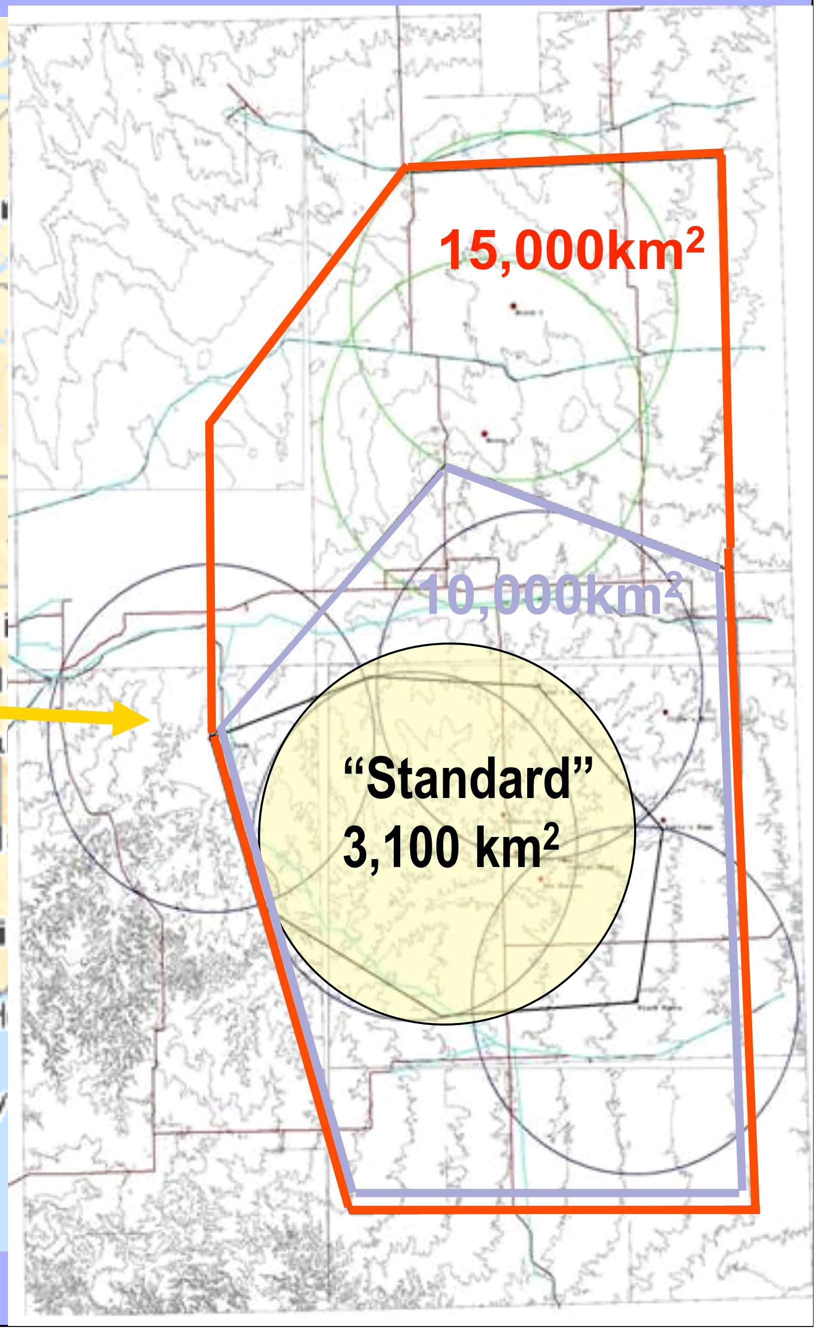
4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

AUGER NORTH


Edmonton
Saskatoon
Calgary
Regina
Winn
Victoria
Olympia
Helena
Bismarck
Salem
Pierre
Boise
Eugene
Sioux Falls
Salt Lake City
Lincoln
Denver
Sacramento
Colorado
Jefferson Ci
San Jose
Colorado Springs
Springfiel
Fresno
Las Vegas
Santa Fe
Okla
Salinas
Los Angeles
Phoenix
Amarillo
Lubbock
Dall
El Paso
San Diego
Austi
San Antonio
Hermosillo
Ciudad Obregón
Torreon
Monterrey
Culiacán


15,000km²
10,000km²
"Standard"
3,100 km²

Telescope Array

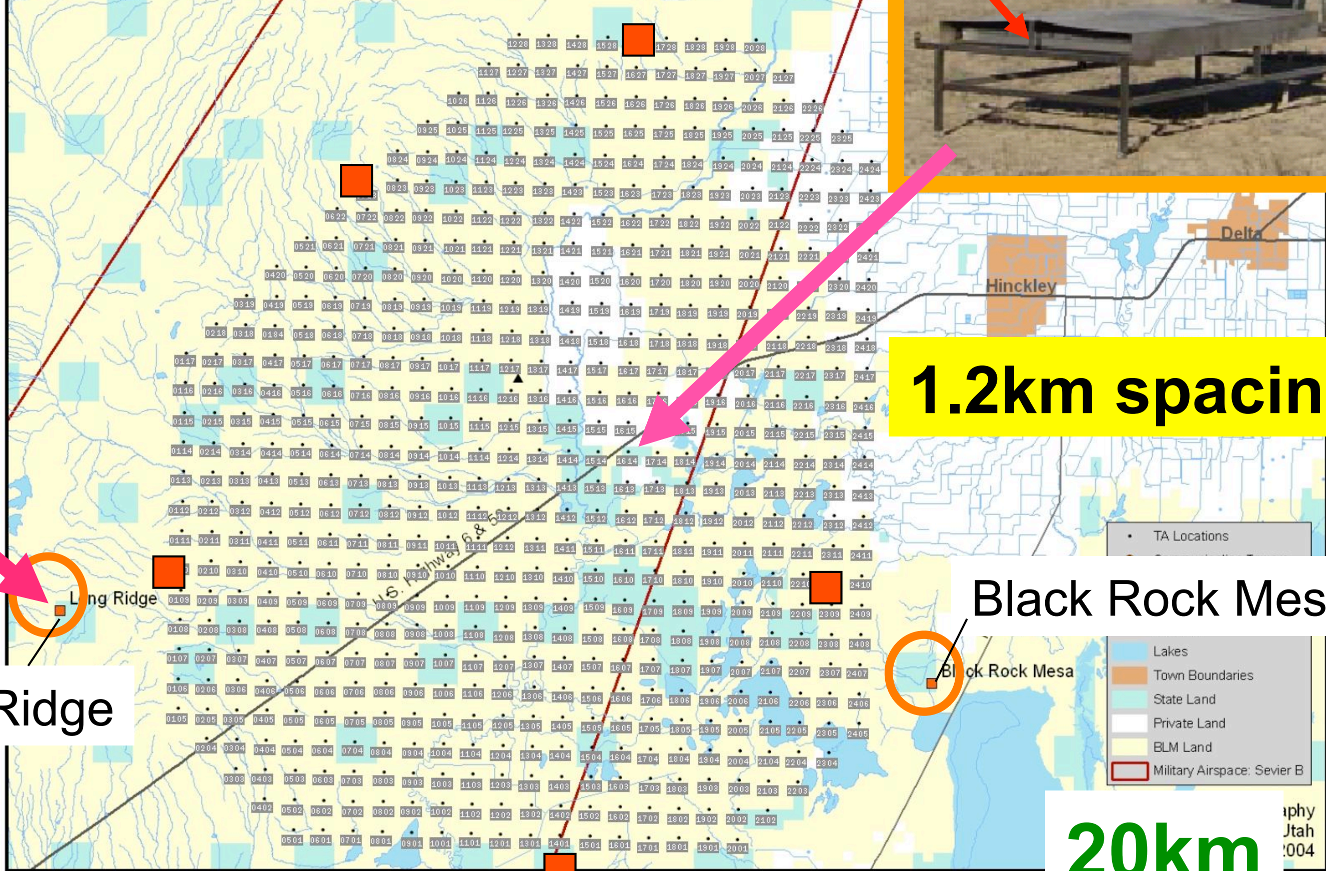
High Energy Cosmic Rays

576 plastic scintillation Surface Detectors (SD)

Atmospheric fluorescence telescope
3 stations **FD**

5 communication towers

3m^2 1.2cm t two layers



Middle Drum

Long Ridge

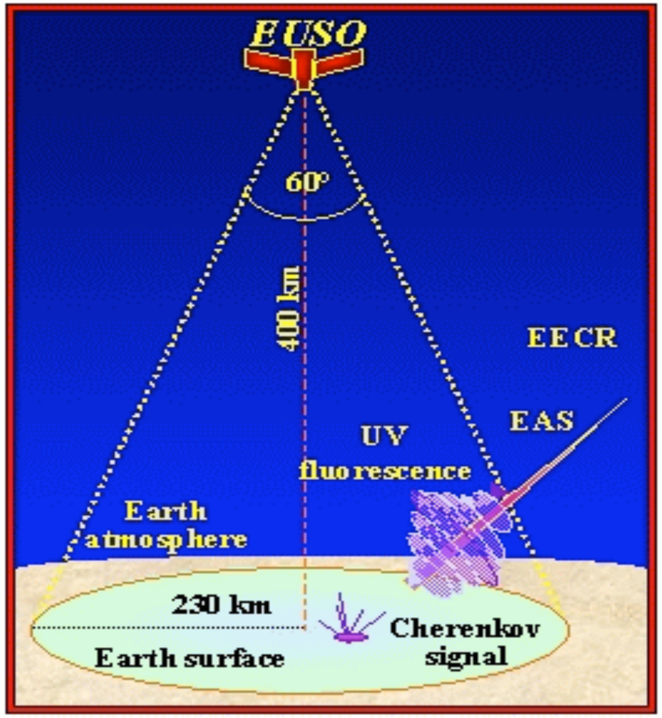
Black Rock Mesa

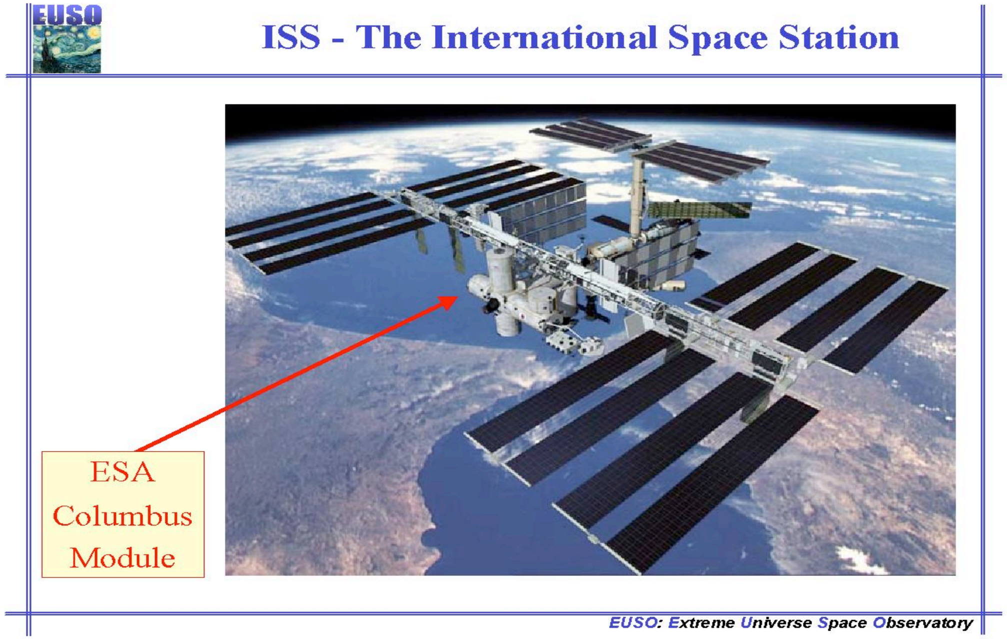
1.2km spacing

20km

Sensitivity of SD : ~9 x AGASA

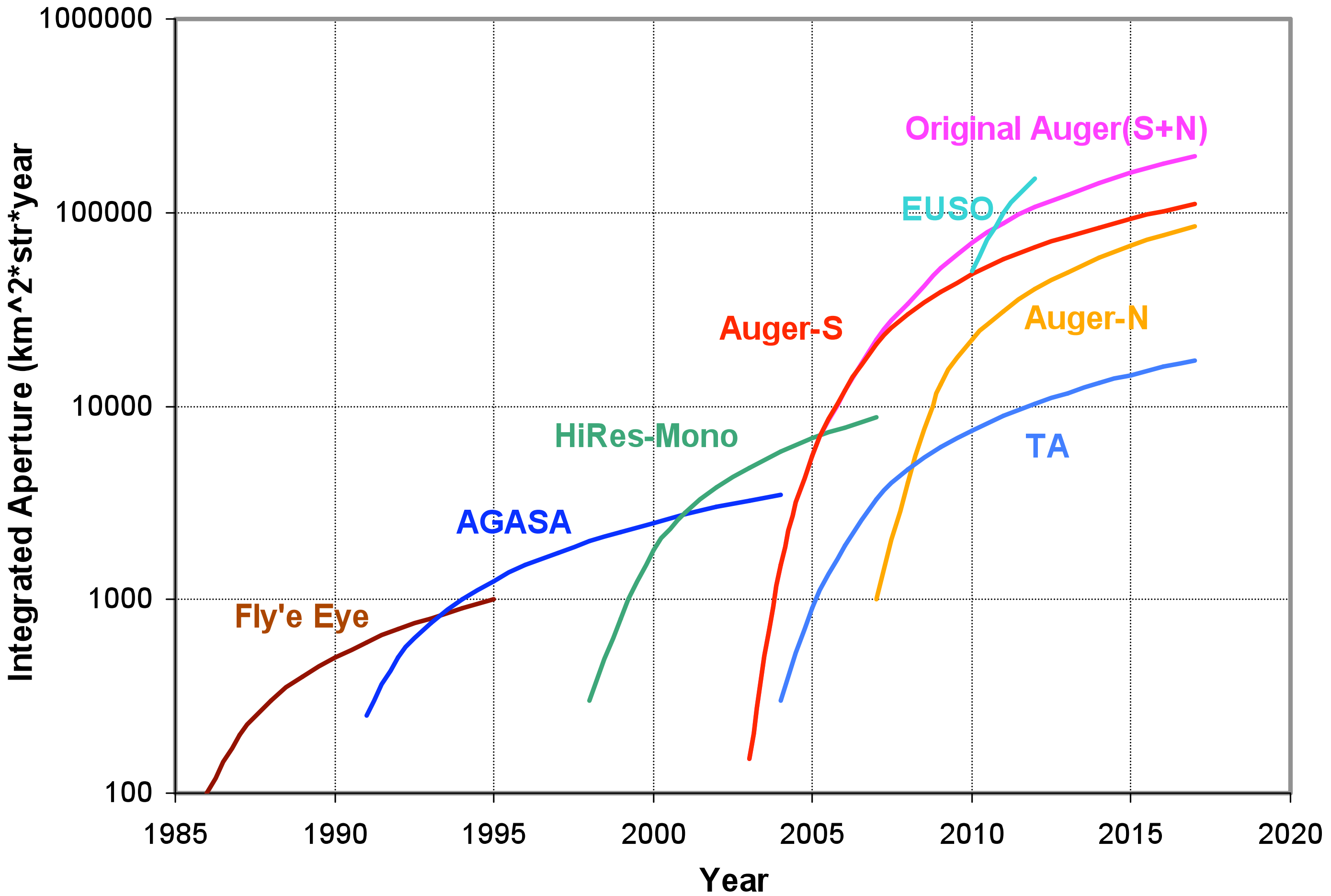
Extreme Universe Space Observatory: JEM-EUSO (project)





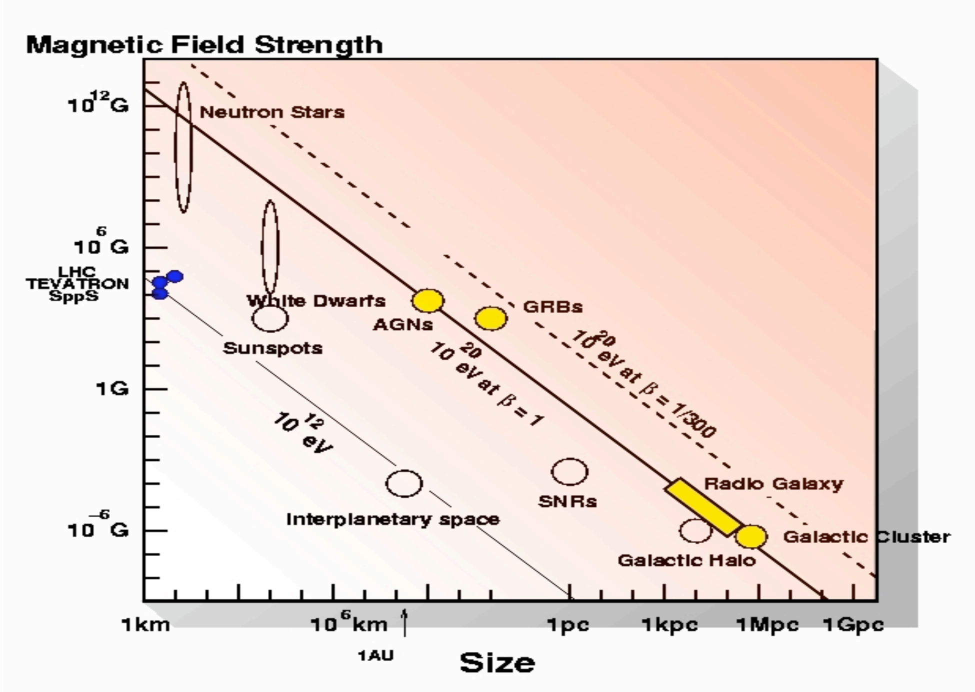
Integrated Exposure

(at 10^{20} eV)

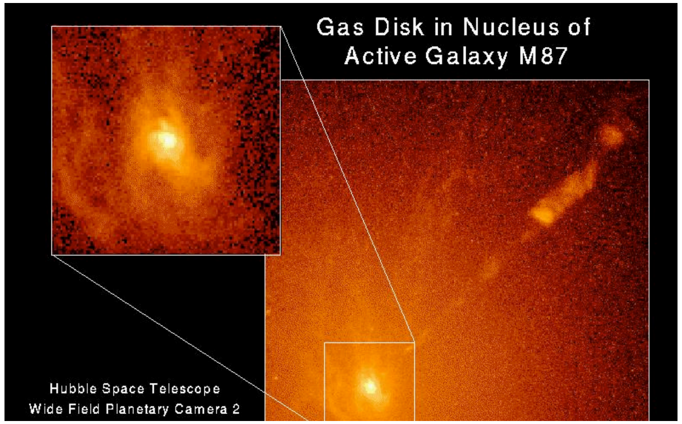


Acceleration of UHECR

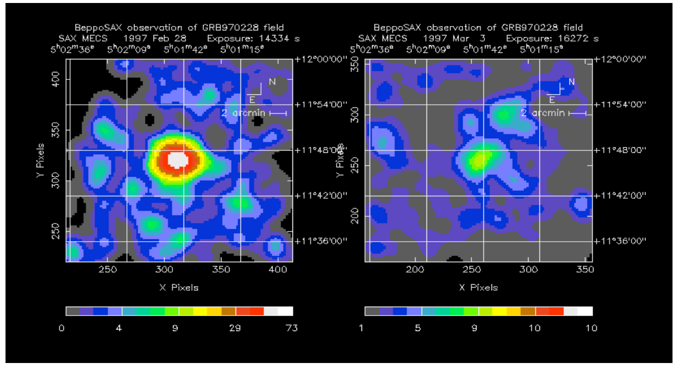
Acceleration of UHECR



A.G.N.

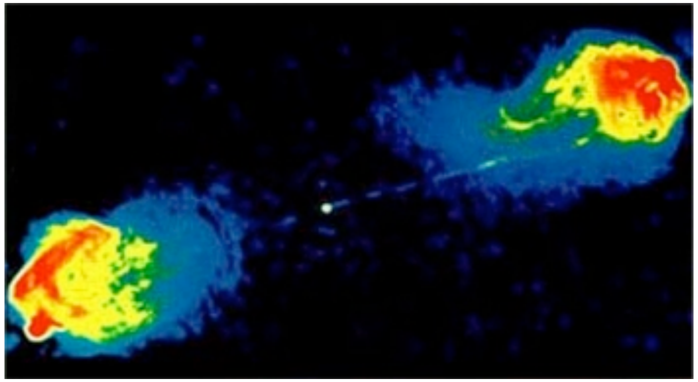


GRB



- Shock acceleration $1/E^{\alpha}$ $\alpha >= 2$
- Electric field acceleration line at E_{max}
- Converter acceleration can be both

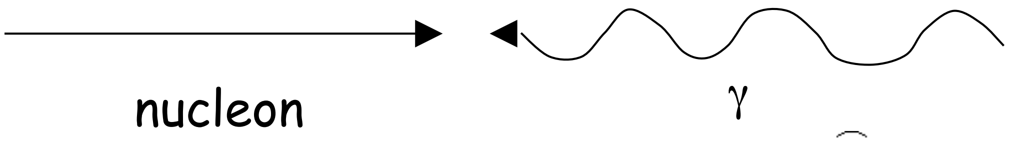
Radio Galaxy Lobe



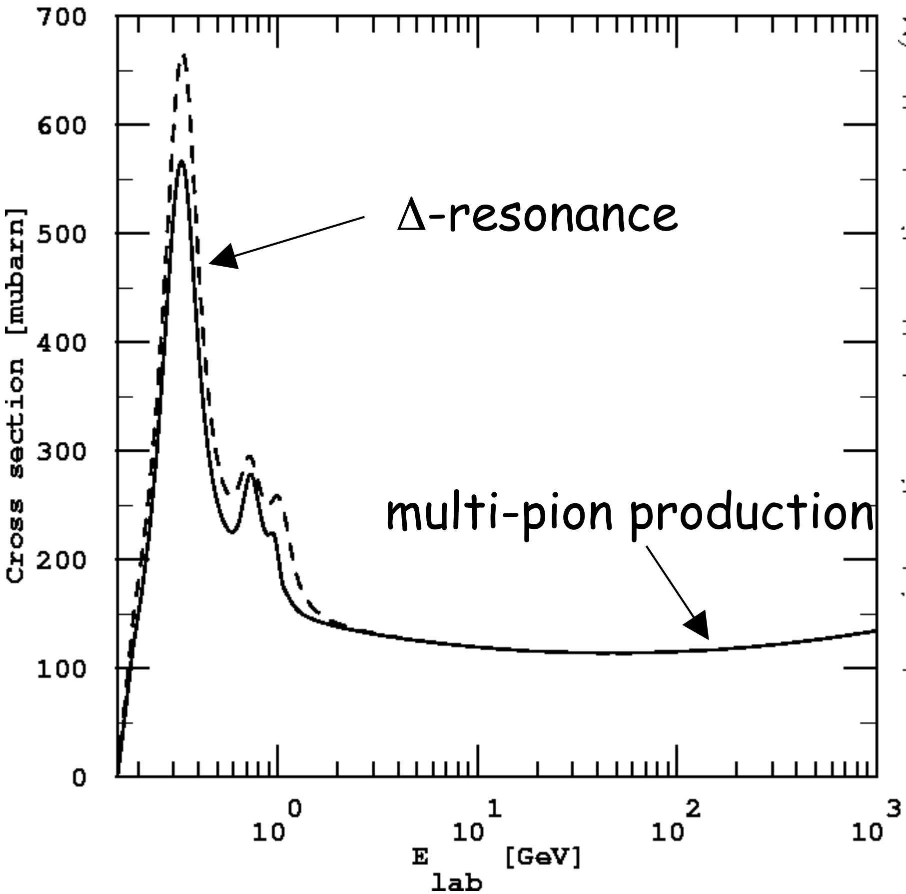
UHECR spectrum and GZK cutoff

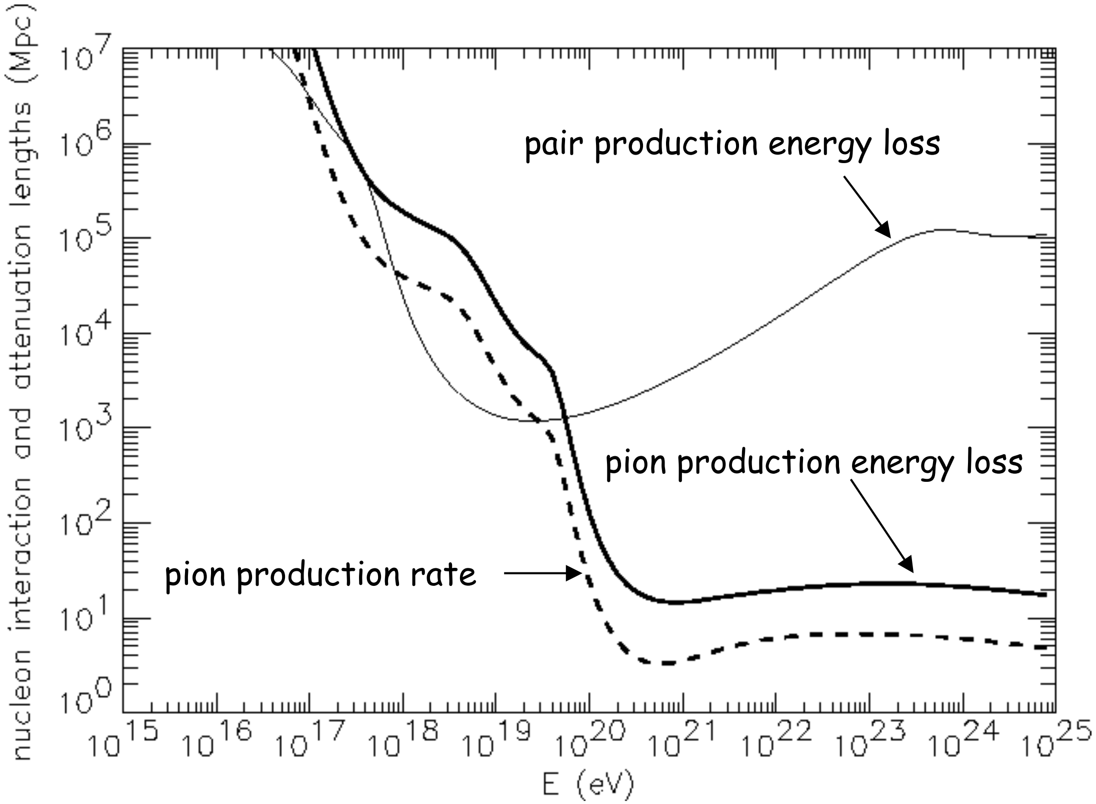
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



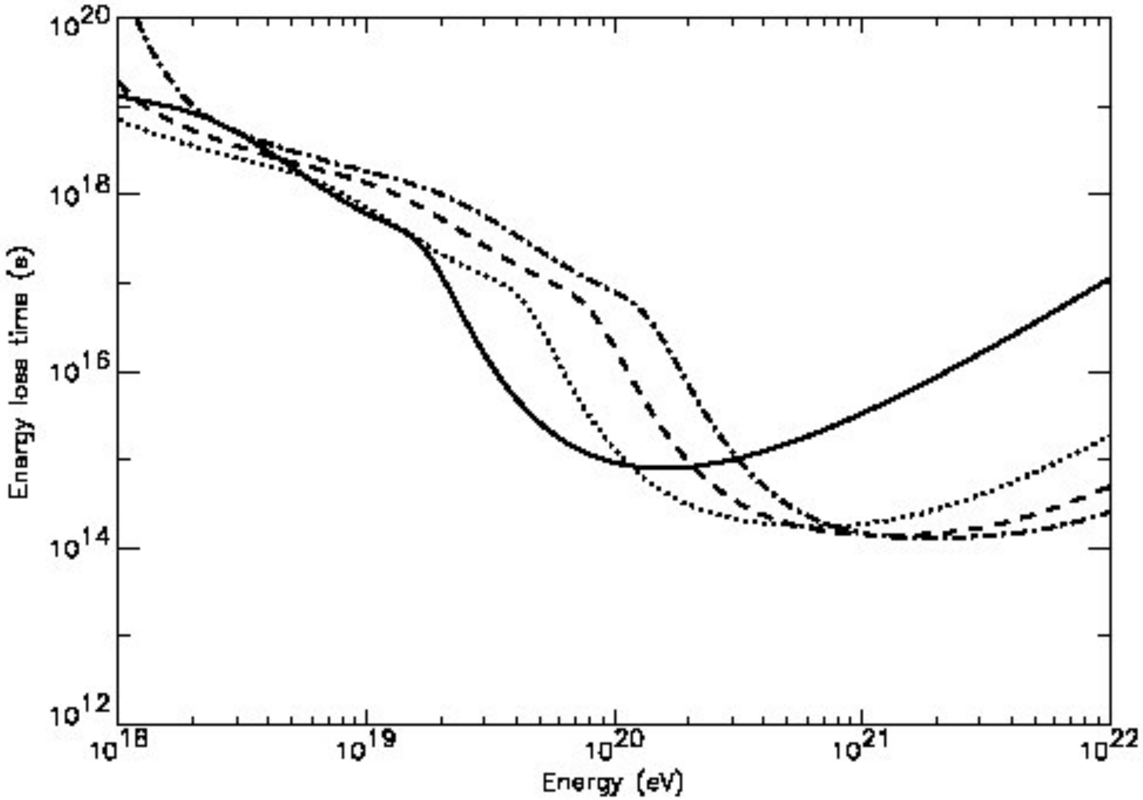
$$E_{\mathrm{th}} = \frac{2m_N m_\pi + m_\pi^{\ 2}}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$





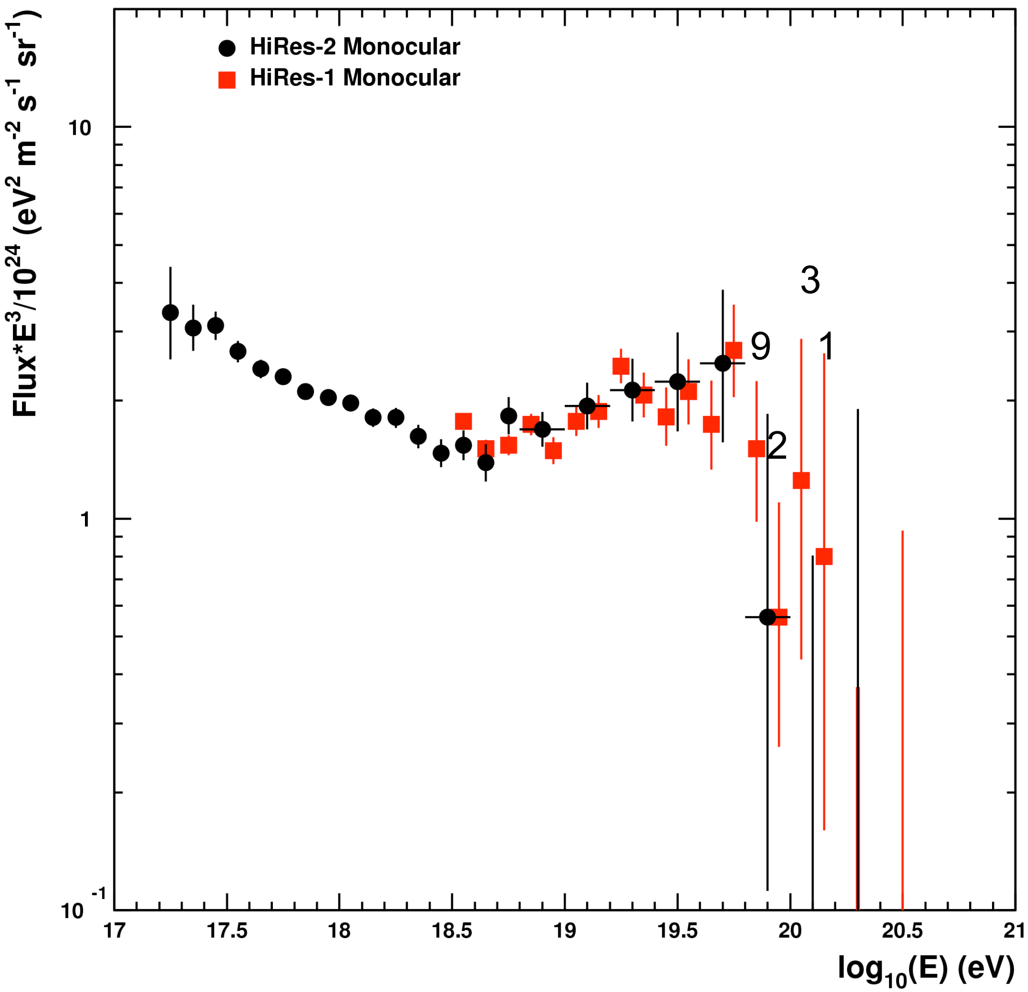
⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

Same true for heavy nuclei: Fe



Simulation by D.Allard

HiRes: cutoff in the spectrum

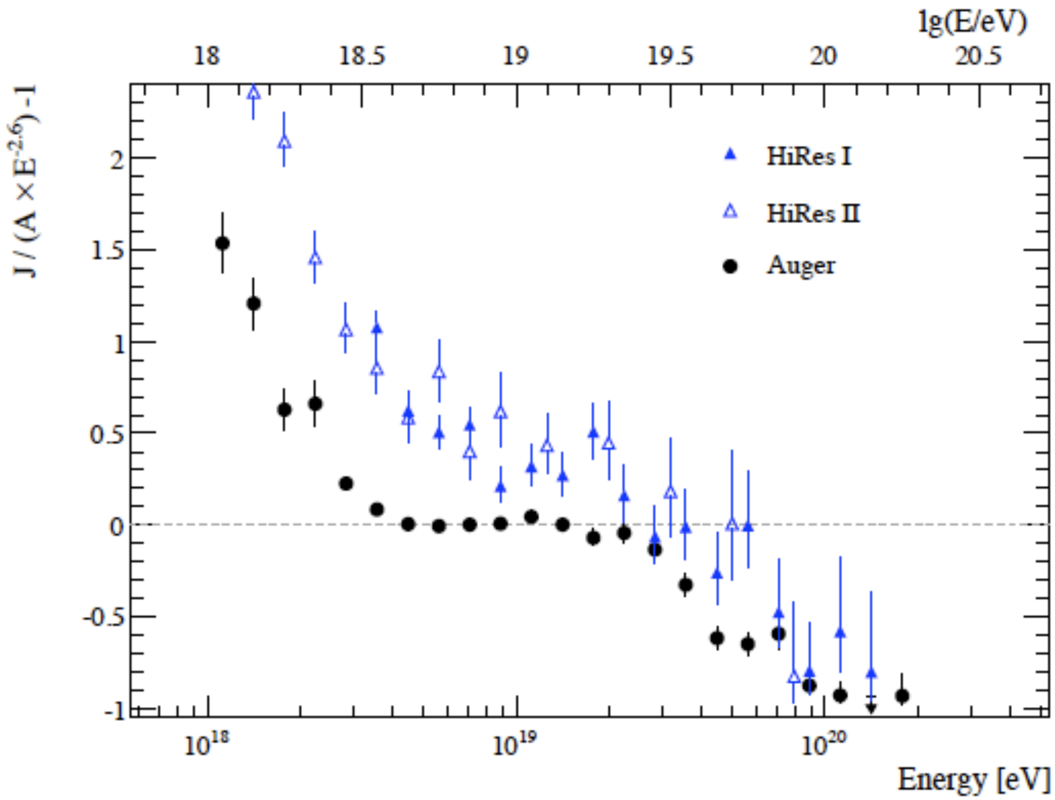


"GZK" Statistics

- Expect 42.8 events
- Observe 15 events
- ~ 5 σ

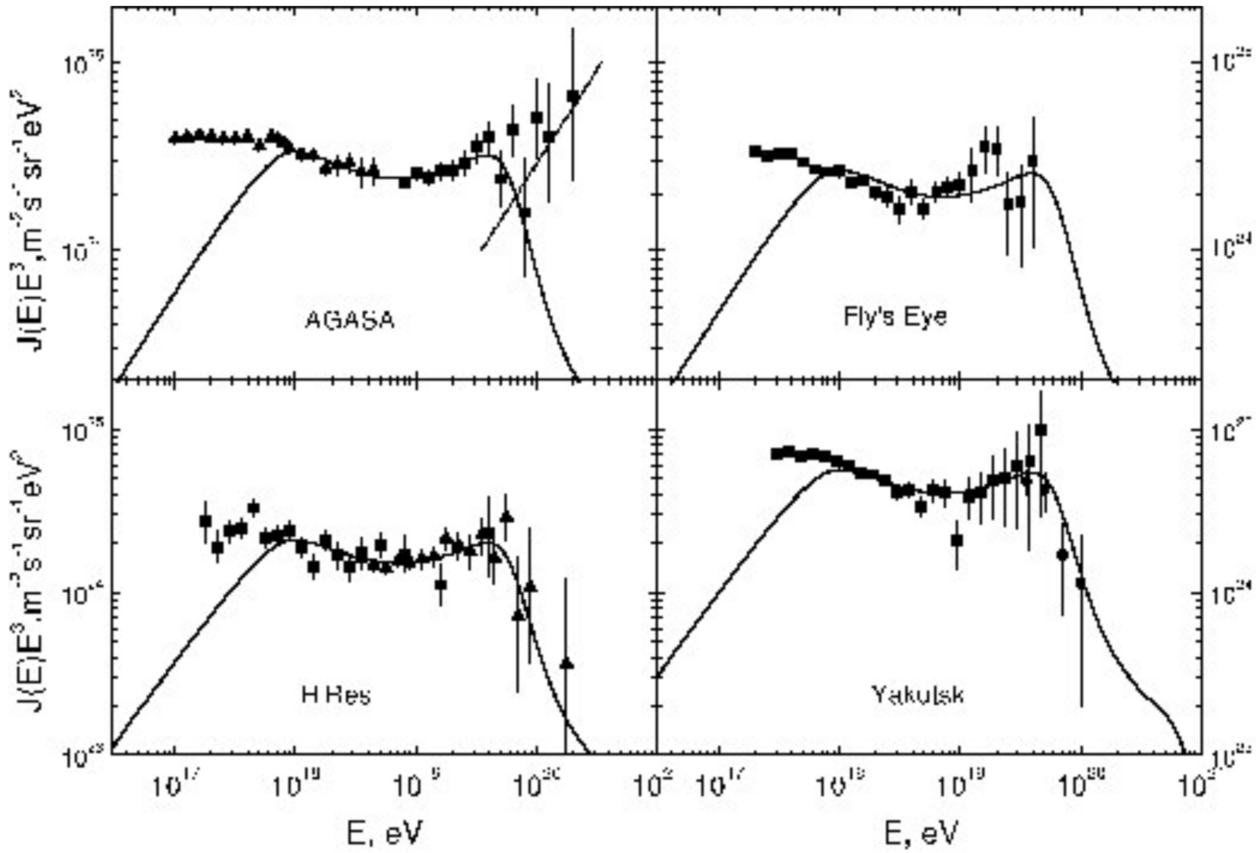
Bergman (ICRC-2005)

Auger Energy Spectrum 2009



Theoretical models and composition

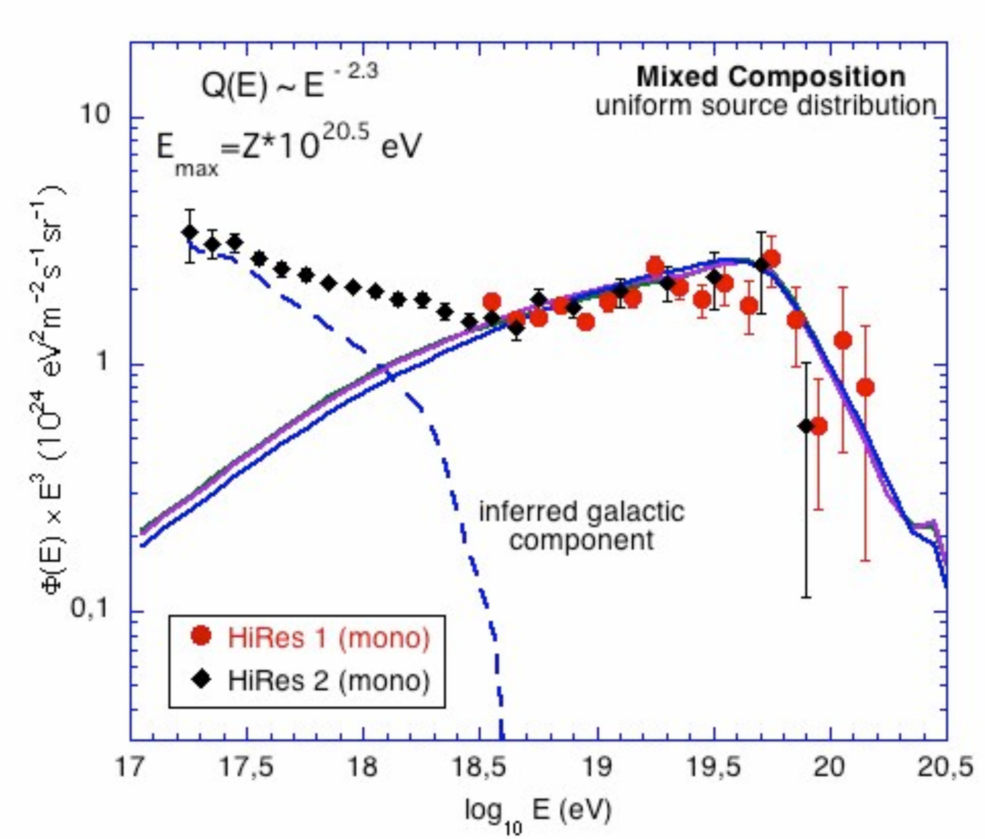
Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

problem: composition

Mixed composition model

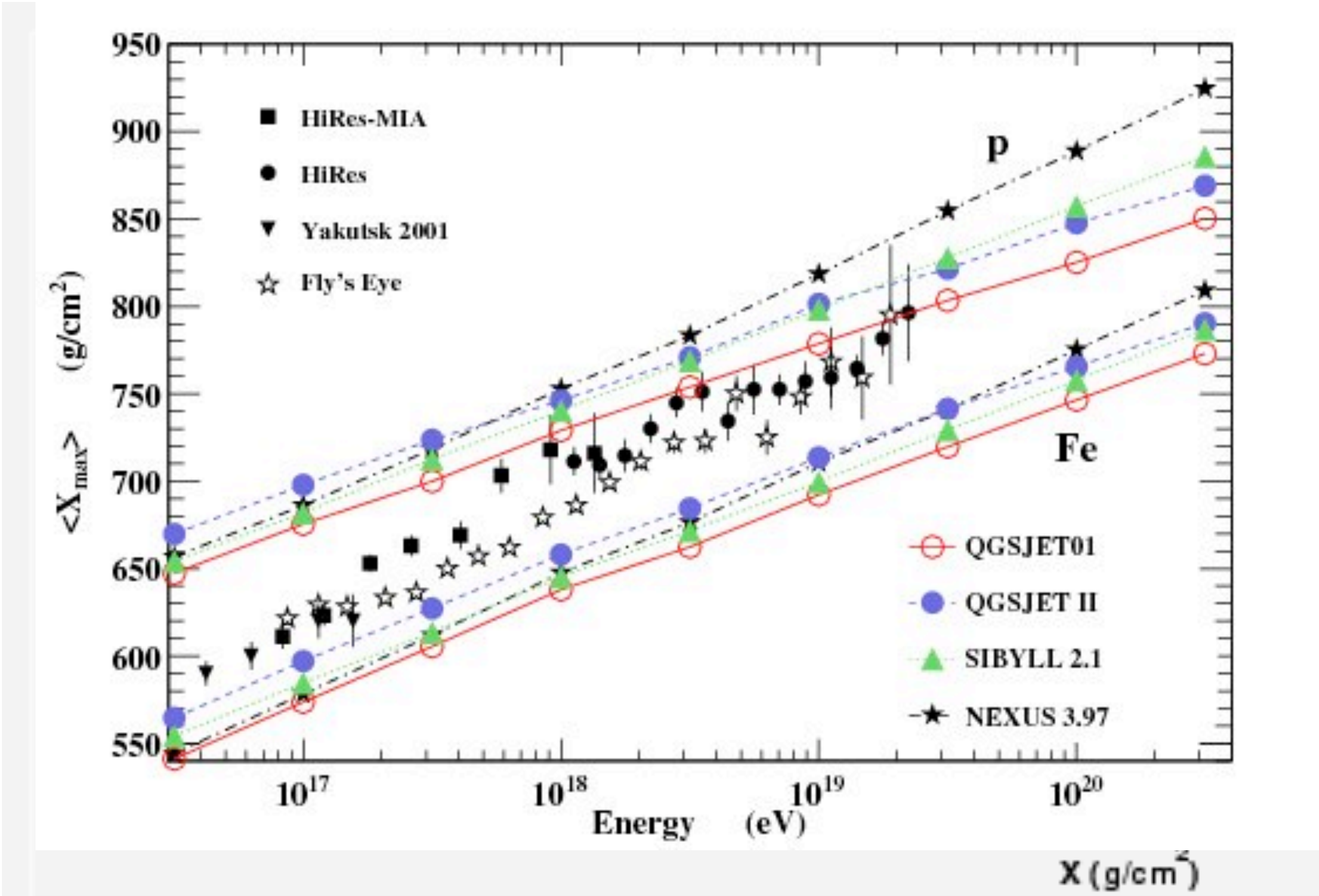


D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Problems: 1) escape of the nuclei from the source

2) How to accelerate Fe in our Galaxy

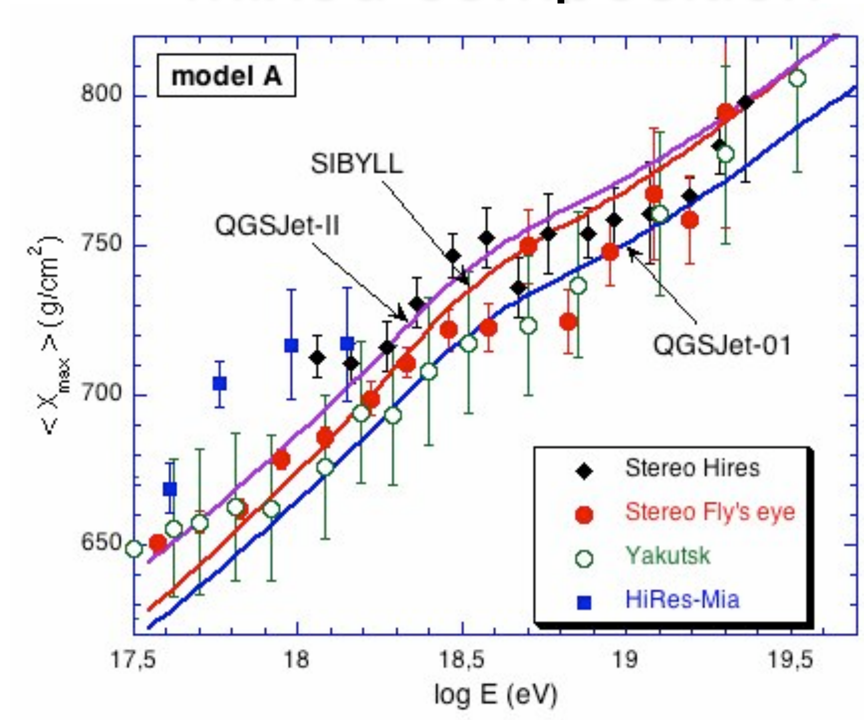
Composition study



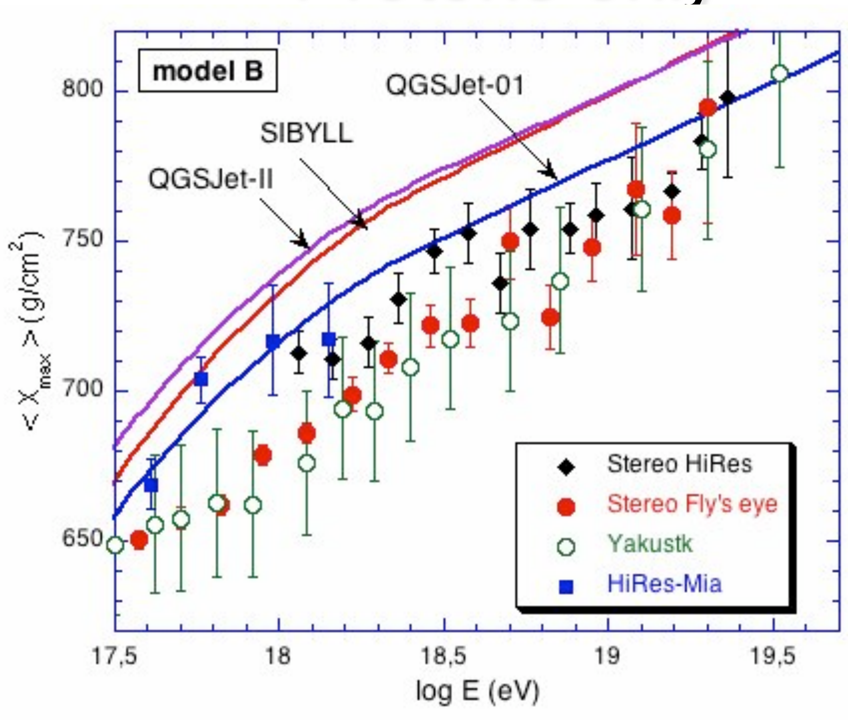
T.Pierog, R.Engel and D.Heck, astro-ph/0602190

Models and composition

Mixed composition



Protons only



D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

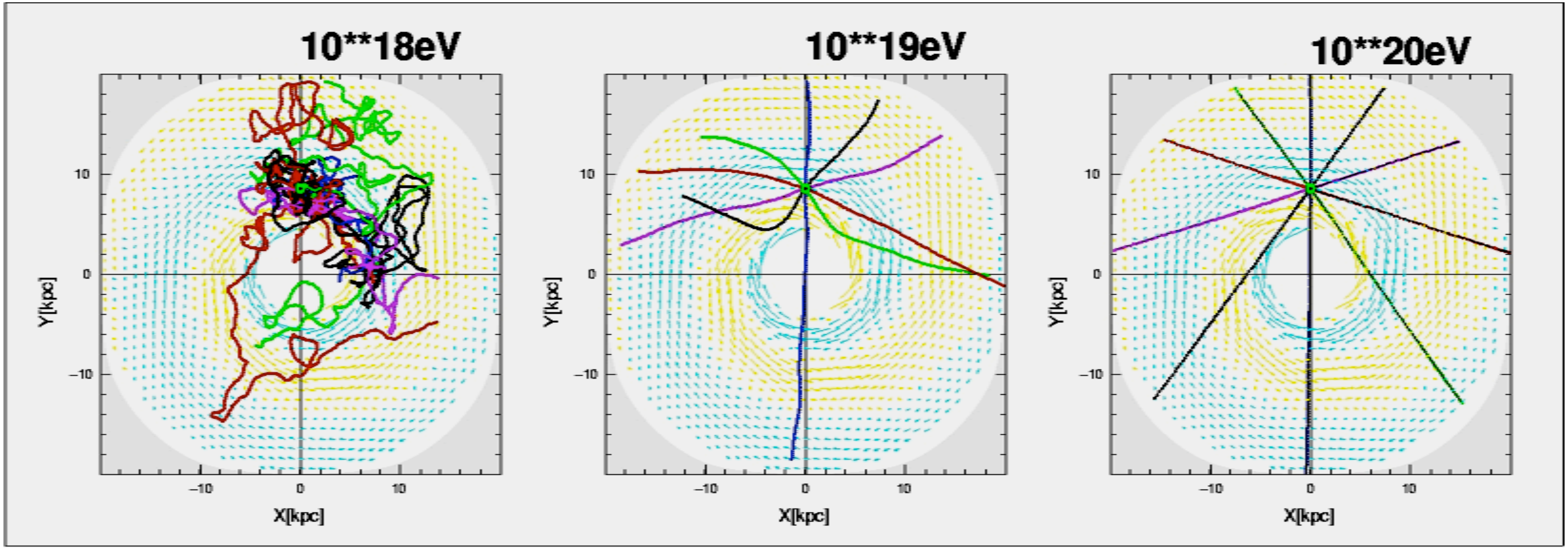
Composition study: AUGER 2009

Please, wait for ICRC!

Arrival directions of UHECR and magnetic fields.

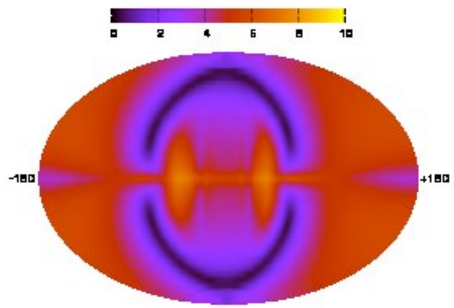
UHECR propagation in Milky Way

- Deflection angle ~ 1-2 degrees at 10^{20}eV for protons
  - Astronomy by hadronic particles?

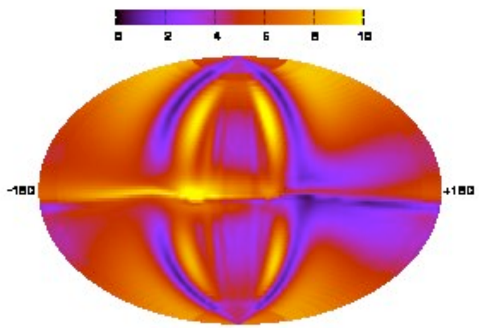


Uncertainty of GMF models

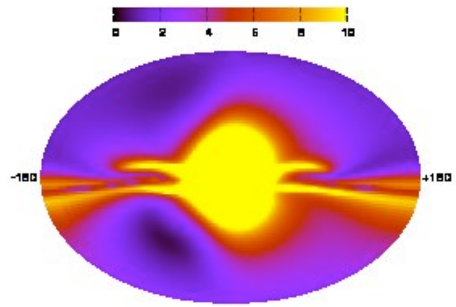
- From M.Kachelriess et al, astro-ph/0510444
- Protons with energy $4*10^{19}$ eV deflection in galactic magnetic field.



TT model



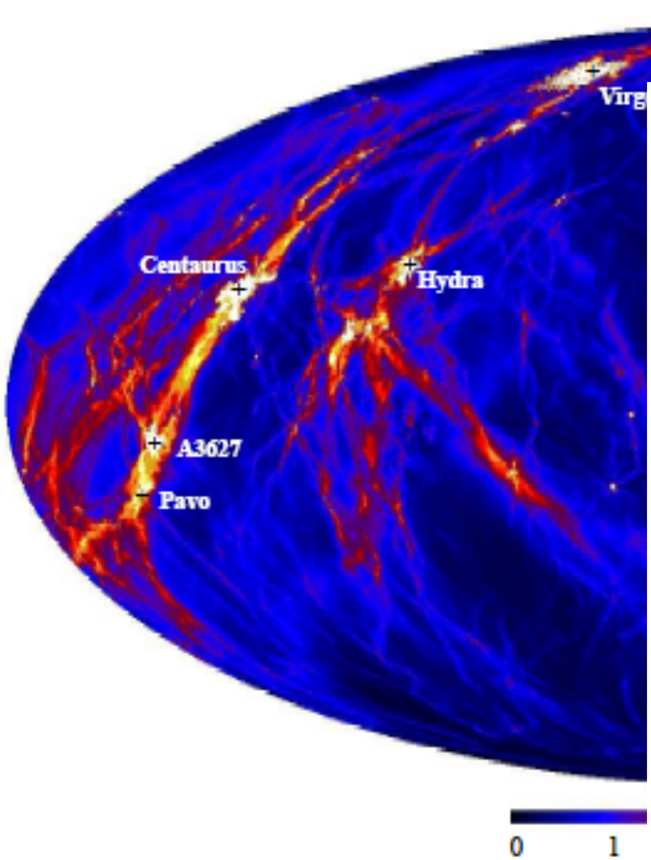
HMR model



PS model

Deflections by EGMF

By K.Dolag, D.Grasso, V.Springel, and I.Tkachev



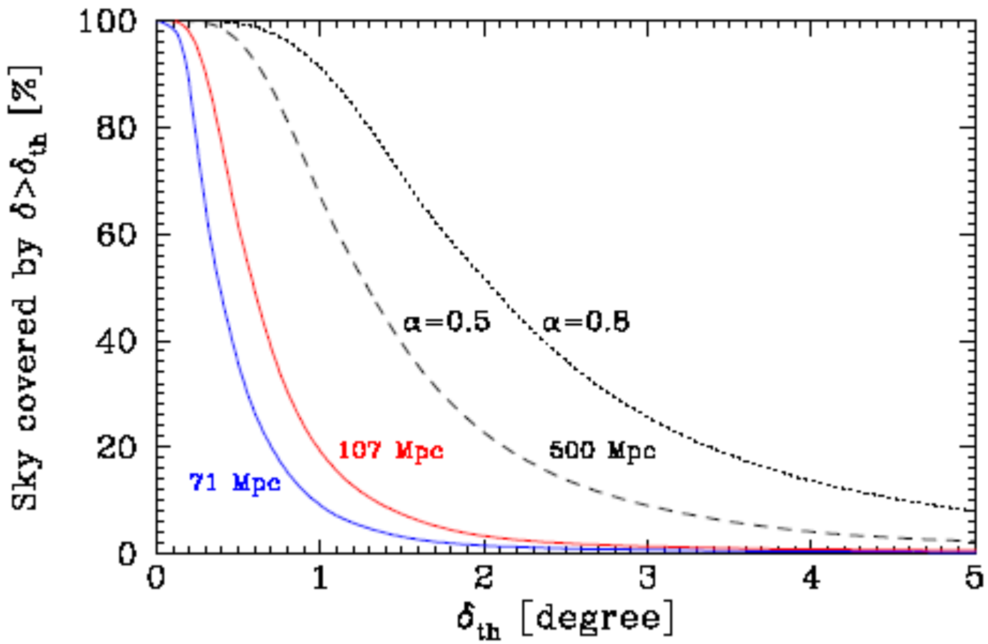
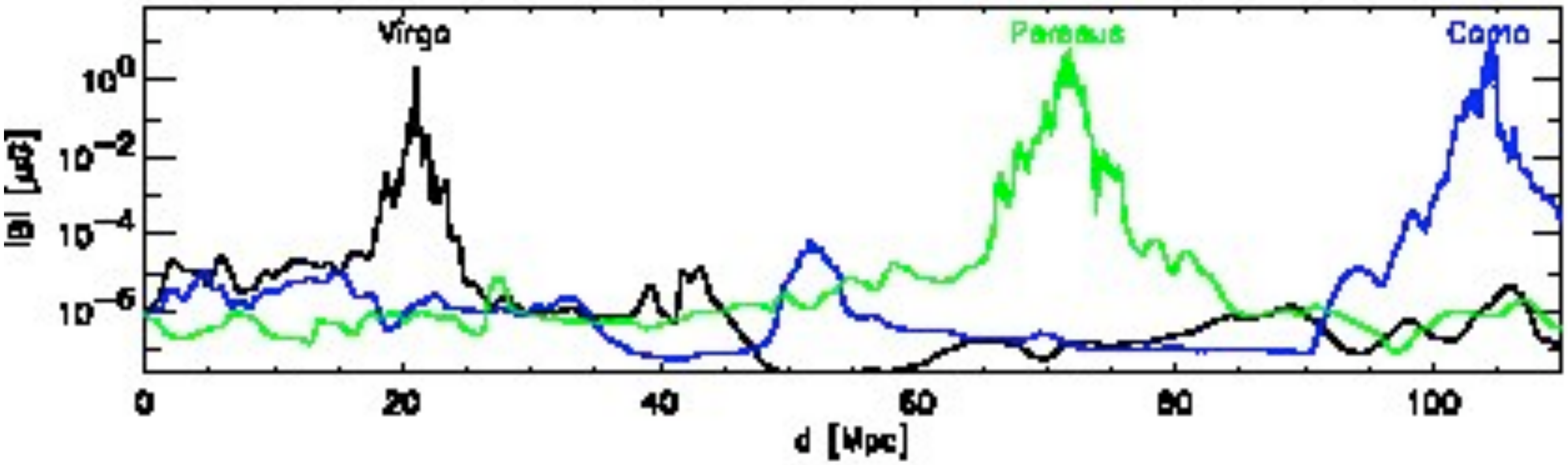


FIG. 2: Cumulative fraction of the sky with deflection angle larger than δ_{th}, for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy for all lines is 4.0×10^{19} eV.

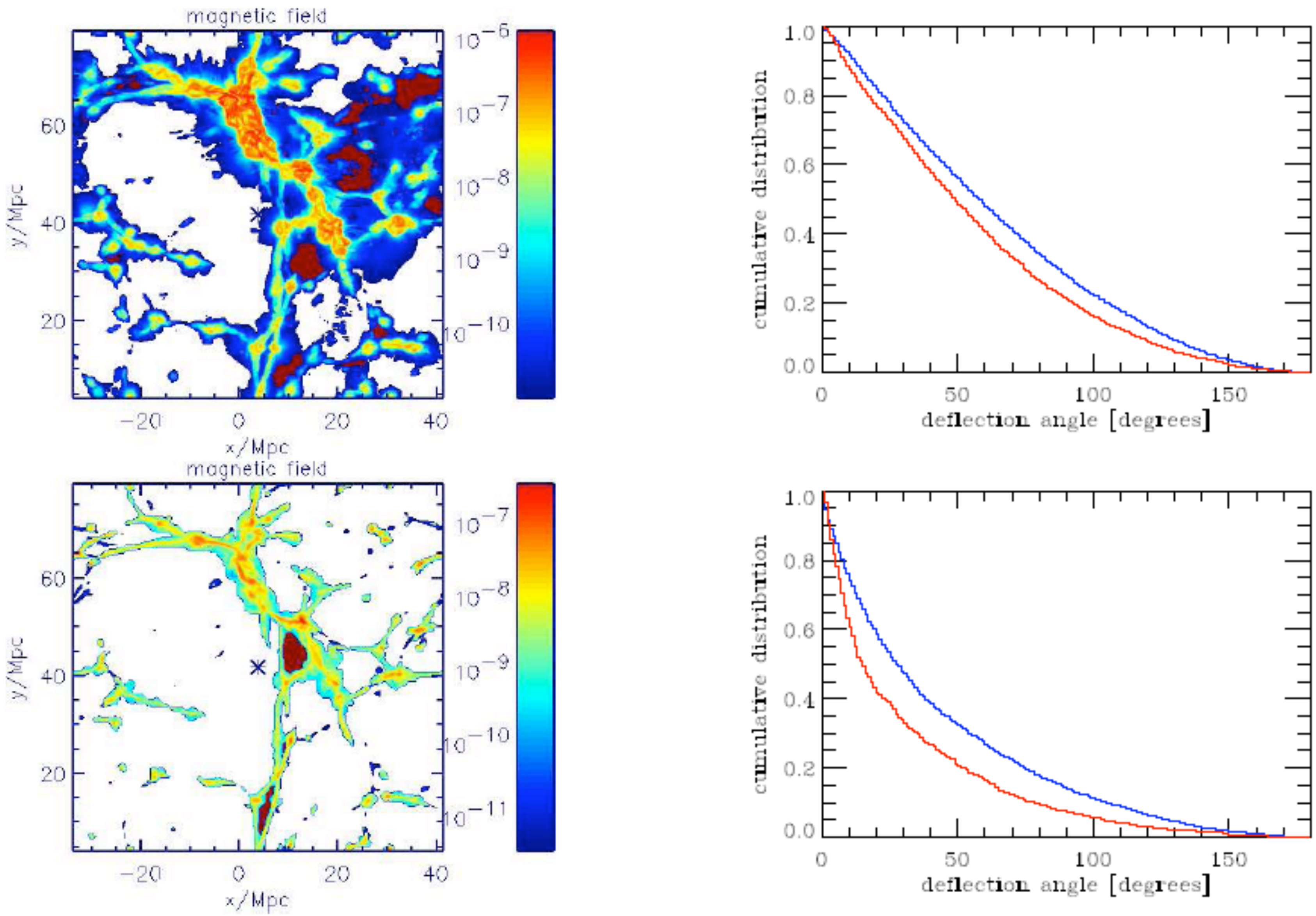
FIG. 1: Full sky map (area preserving projection) of d
scale. All structure within a radius of 107 Mpc aroun
with the galactic anti-center in the middle of the ma
corresponding halos in the simulation.

Magnetic field in several directions from Earth for constrained simulation

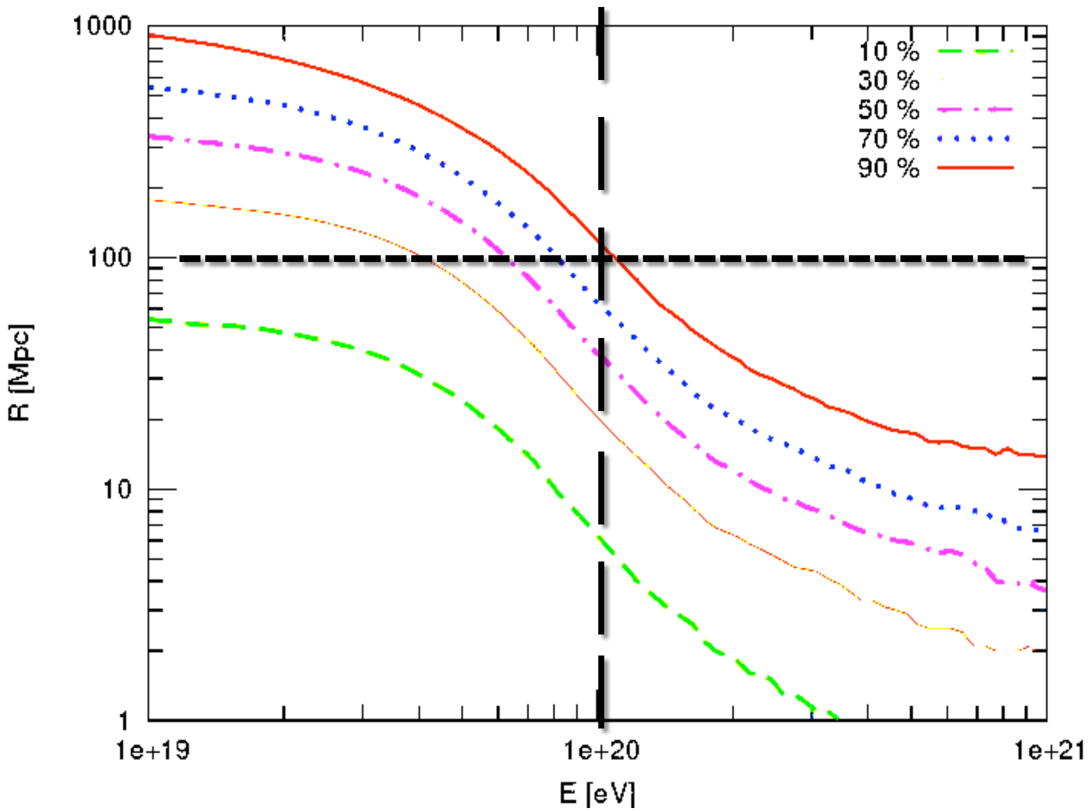


Dolag et al, astro-ph/0410419

EGMF by G. Sigl et al. astro-ph/0401084



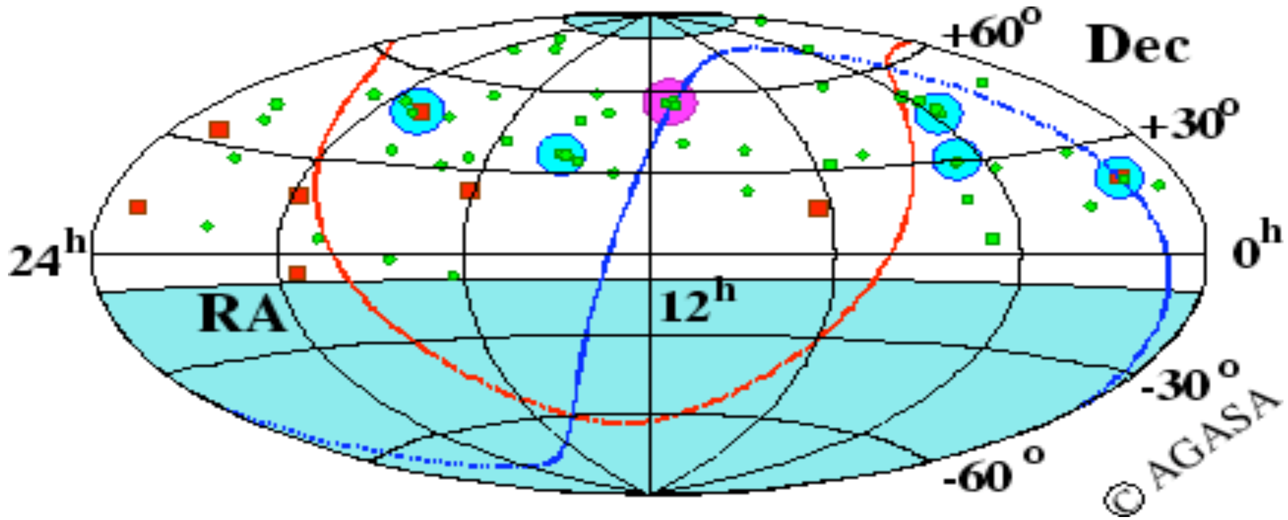
Horizon for protons



Simulation with SOPHIA, stochastic energy losses,

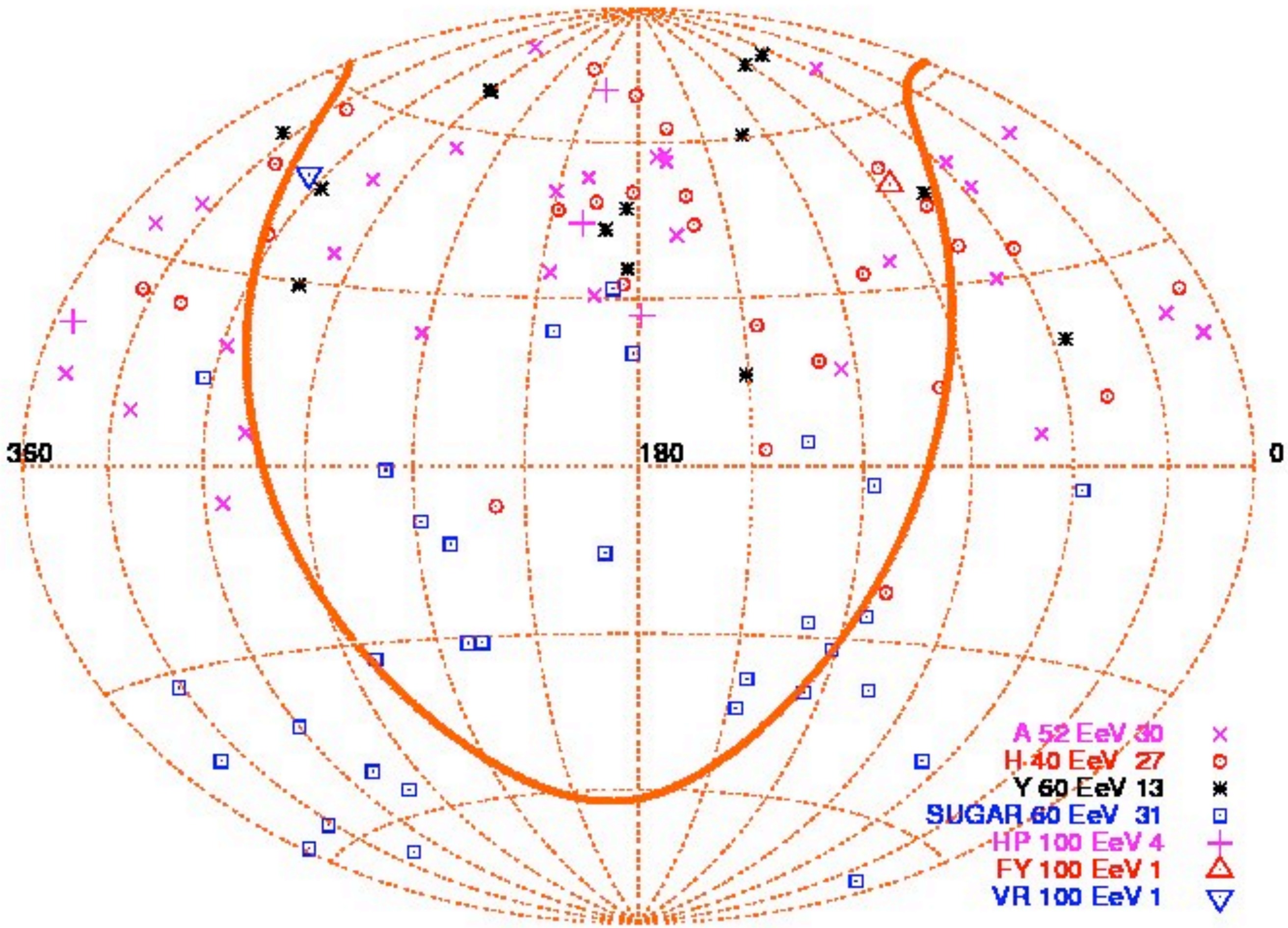
Assuming $\Delta E/E$ = 20% event by event

AGASA data E> 4x10^{19} eV ~60 events

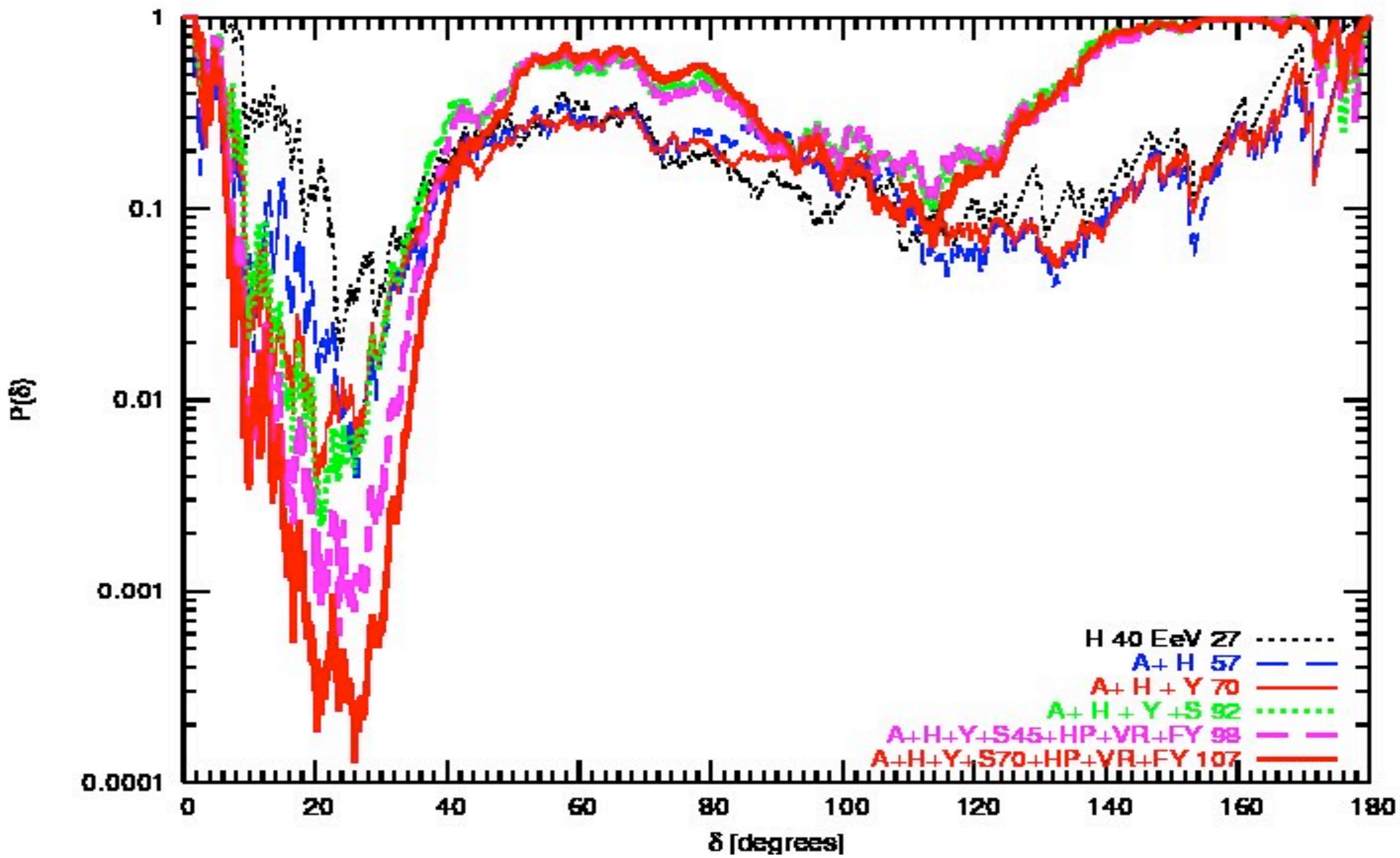


Clusters -- are events which came from the same part of sky within given (usually small) angle from each other. Angle is 2.5 degrees for AGASA.

Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)



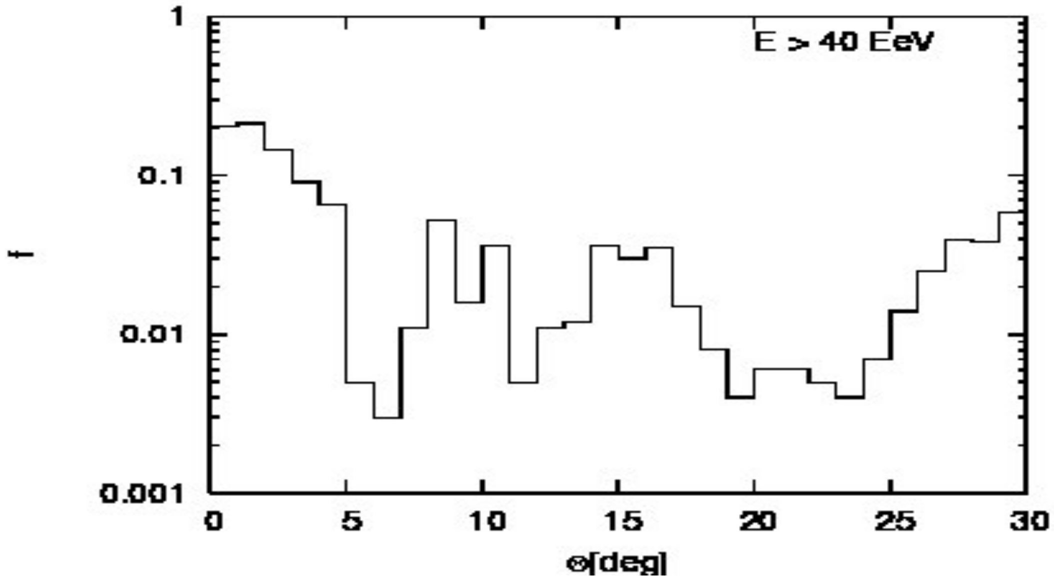
Probability of correlation



3 σ   after penalty on angle

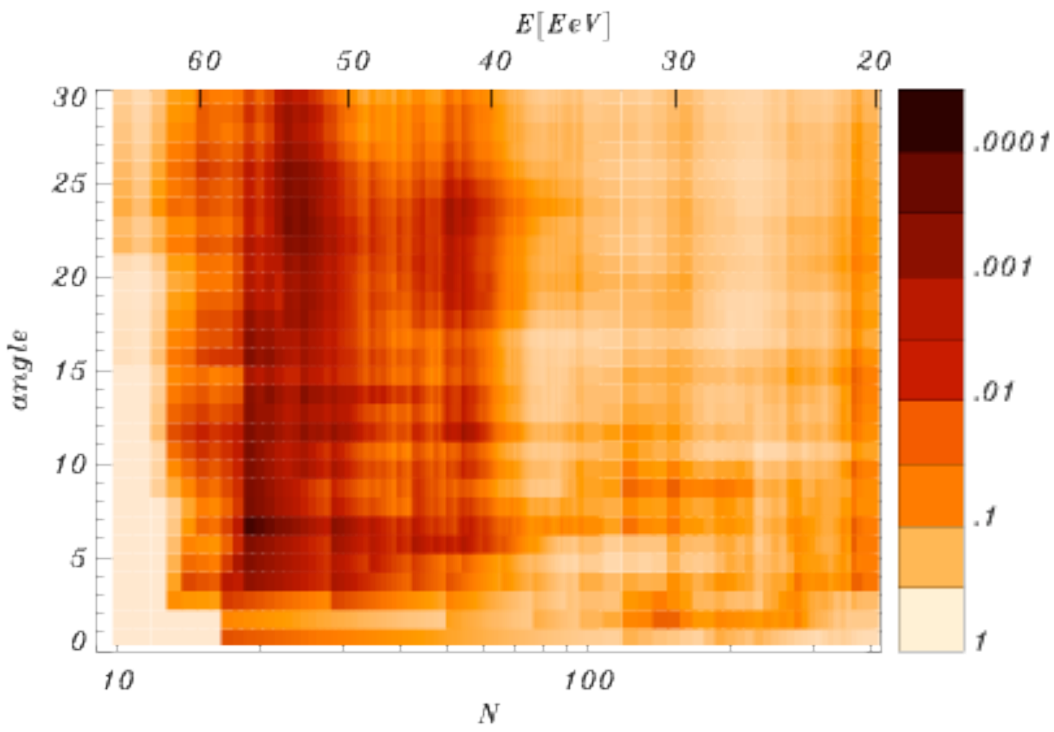
M.Kachelriess and D.S. astro-ph/0512498

Clustering signal in AUGER: 20-25 degree scales



~1-2 %, ~70 events, Pierre Auger Collaboration, ICRC 2007

Clustering signal in AUGER: scan



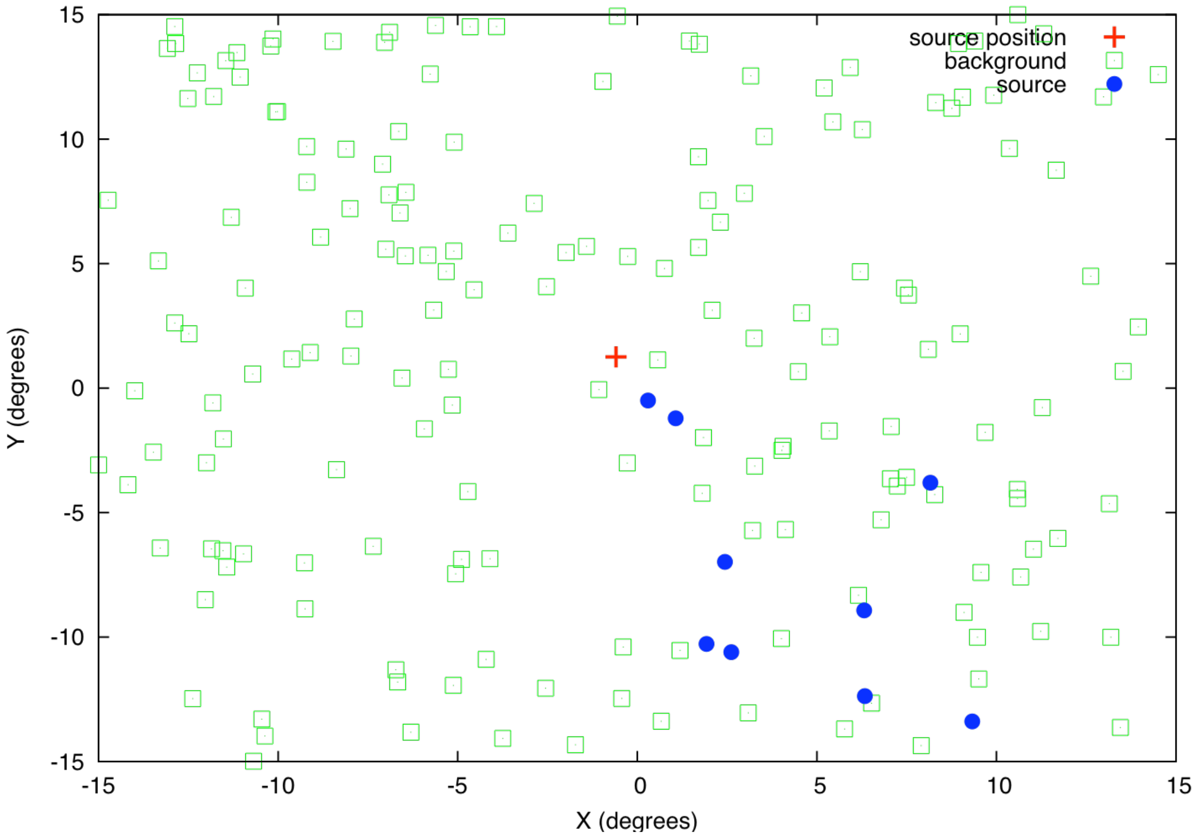
2% after scan and penalty between 7 and 23 degrees

Pierre Auger Collaboration, ICRC 2007

Statistically limited at the moment.

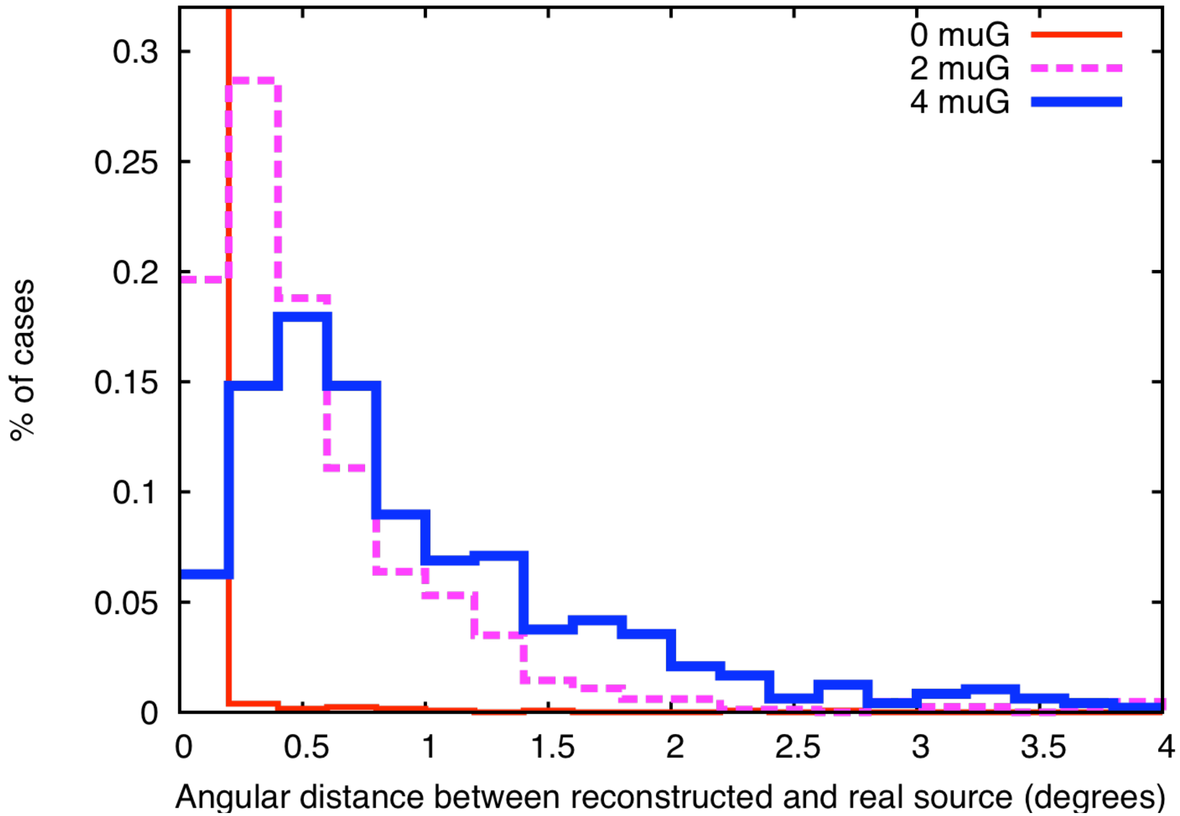
If real, connection to LSS and EGMF

Search for individual sources on sky



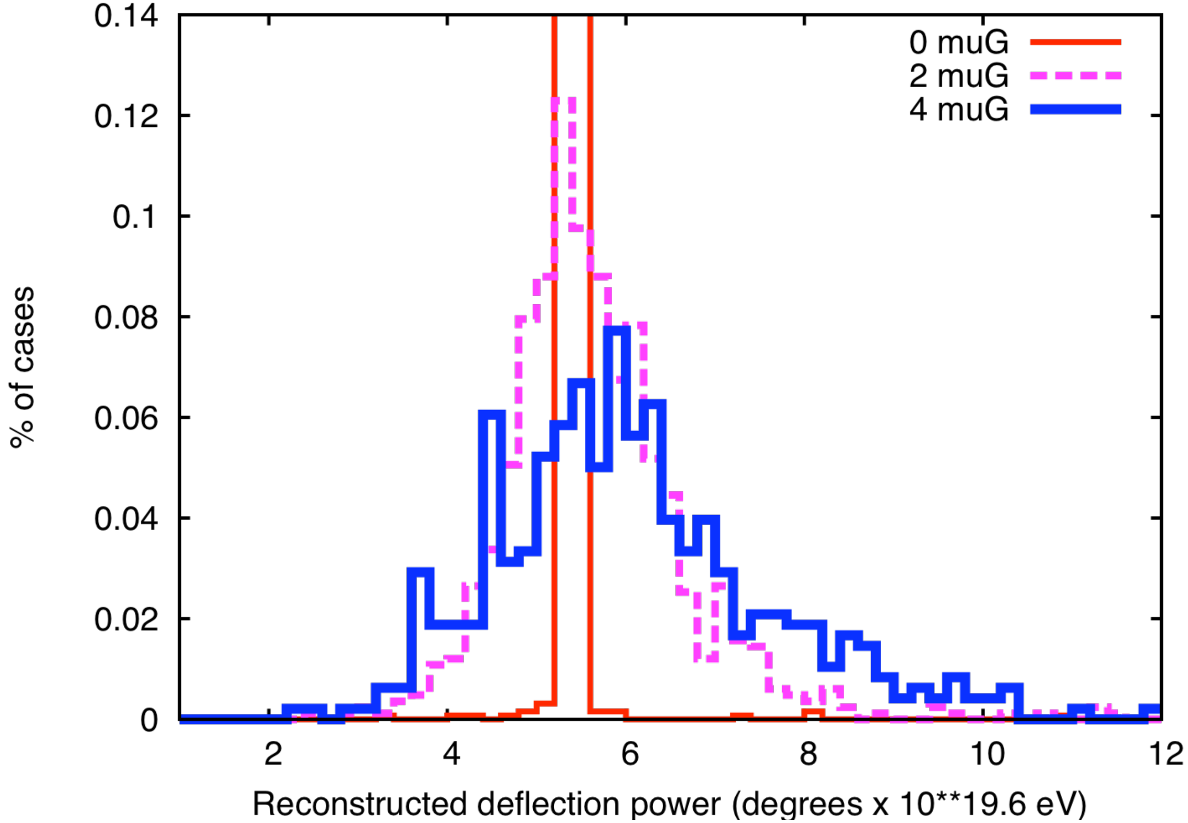
G.Giacinti, X.Derkx and D.S. to be published

Reconstructed of source position



G.Giacinti, X.Derkx and D.S. to be published

Reconstructed direction of magnetic field



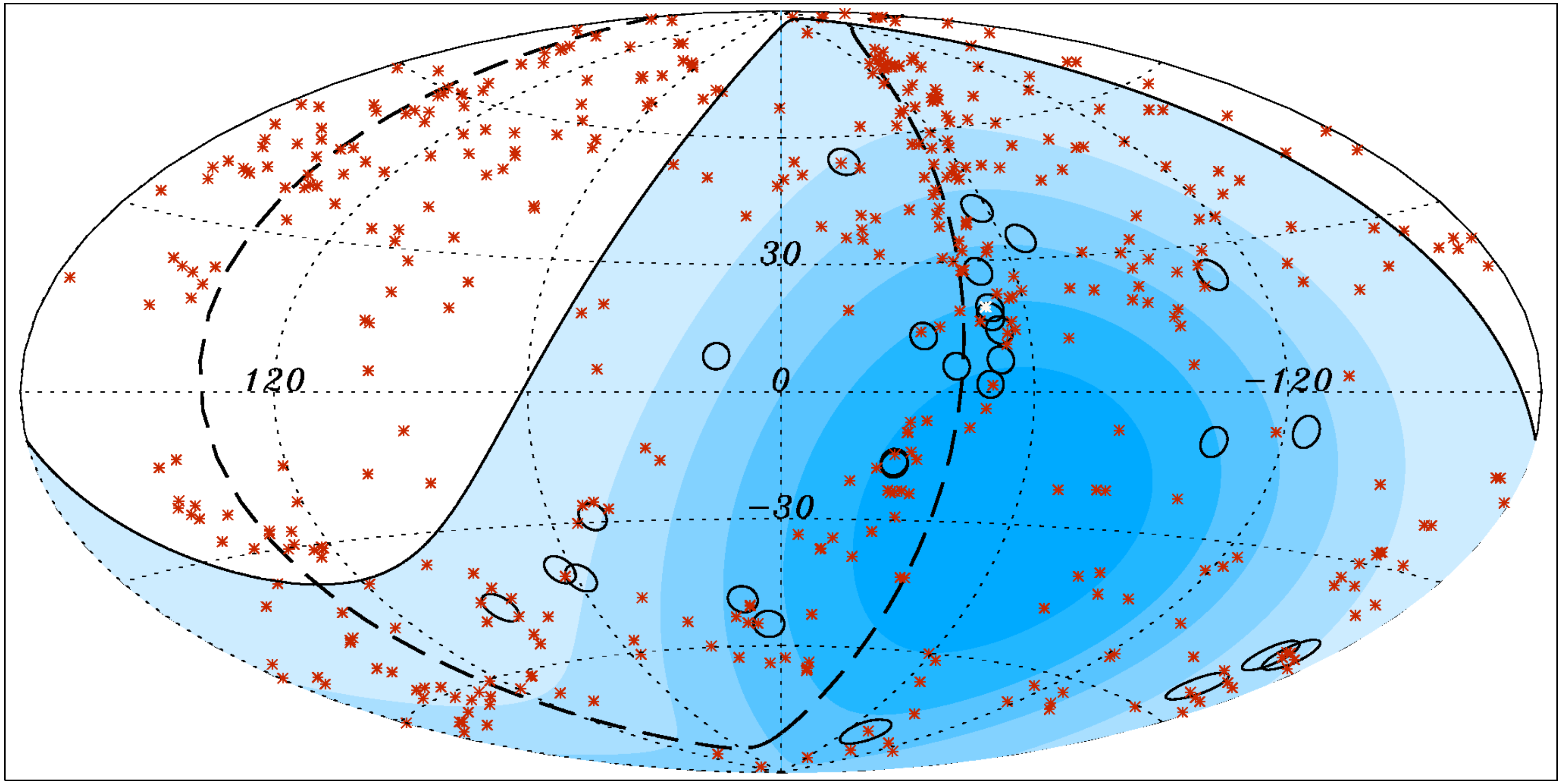
G.Giacinti, X.Derkx and D.S. to be published

Correlations with local LSS

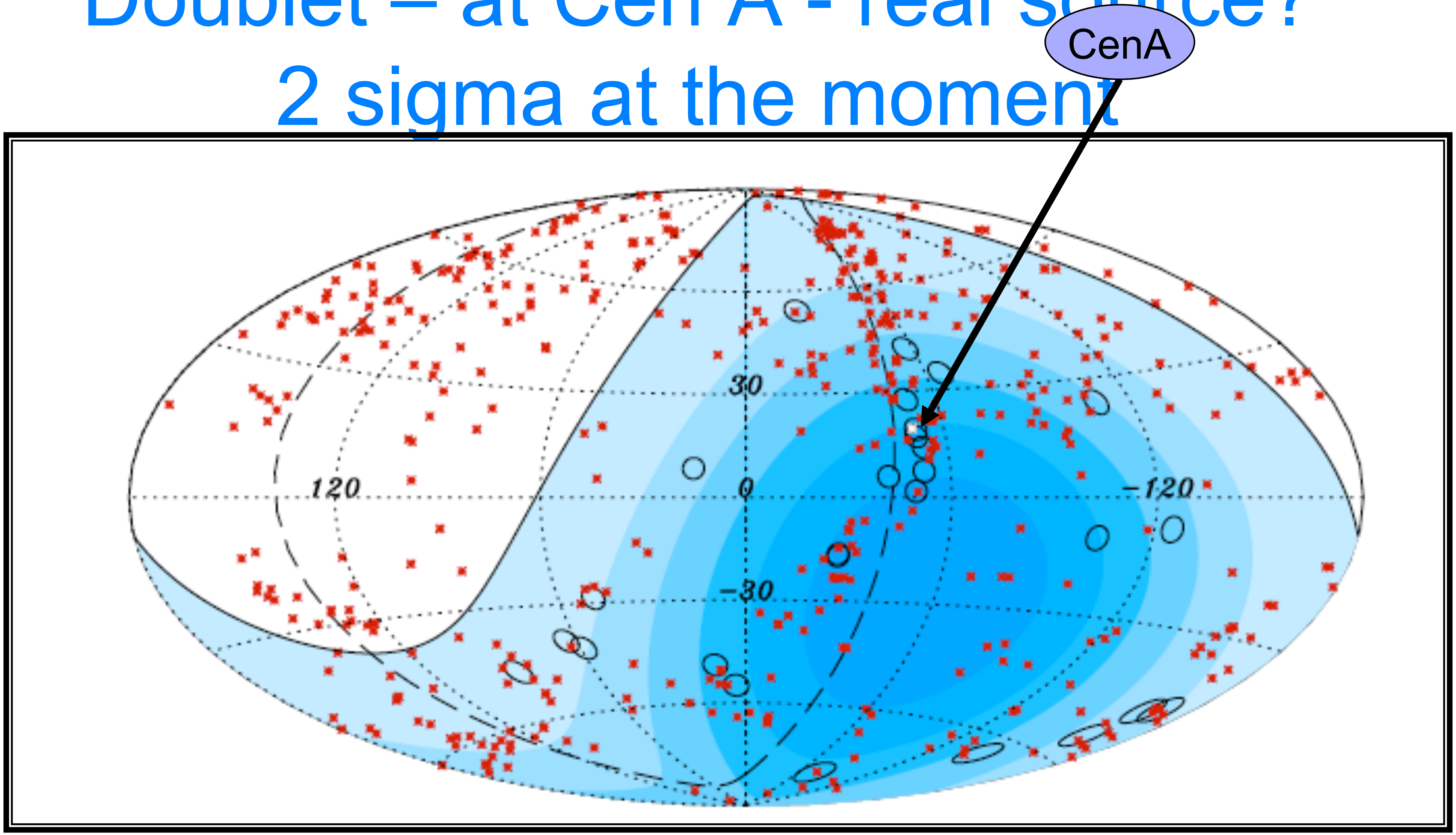
Prescription of blind test

- Based on 15 events E>56 EeV period
  January 1, 2004 - May 28, 2006
- 12th Catalog of AGN's by Veron
- Z<=0.018 or R<=75 Mpc 472 objects
- PAO data with ICRC T5 E>=56 EeV Herald v4
- Search of correlations in 3.1 degree angle from AGN's. Within this angle P_{chance}=0.21
- Running prescription until P=0.01 or up to 34 events
- Status: passed 6/8 May 2007
- At August 31, 2007 8/13 P=1.6e-3

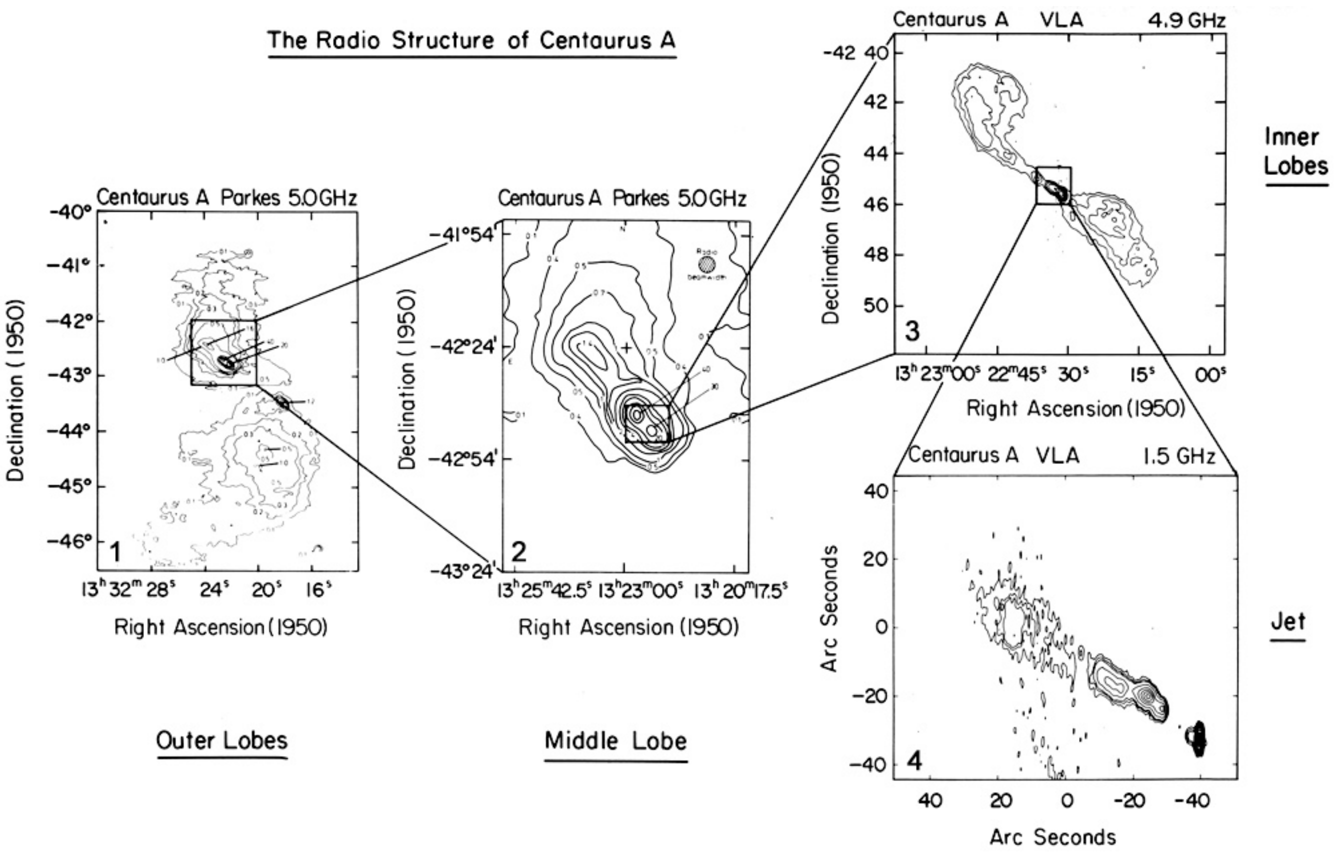
Arrival directions for E>57 EeV in Auger



Doublet – at Cen A - real source? 2 sigma at the moment

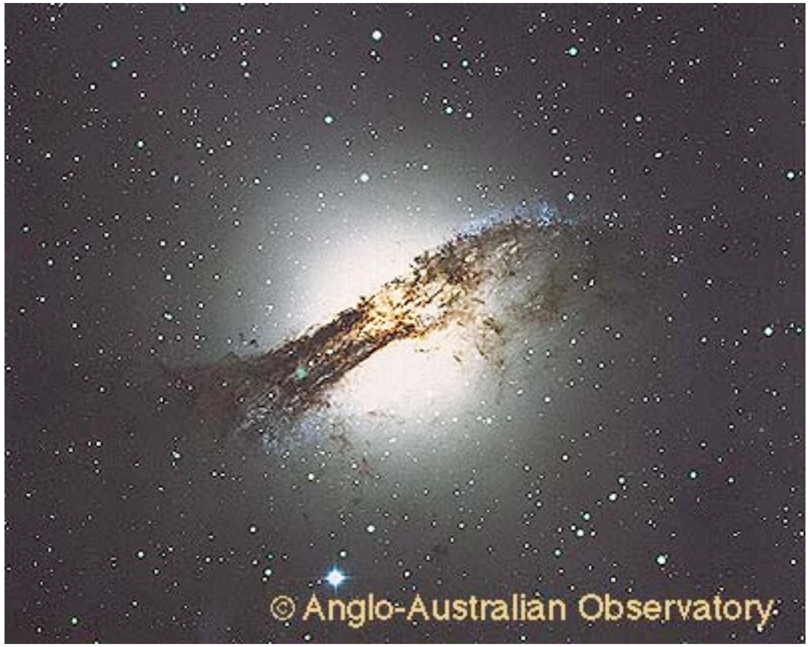


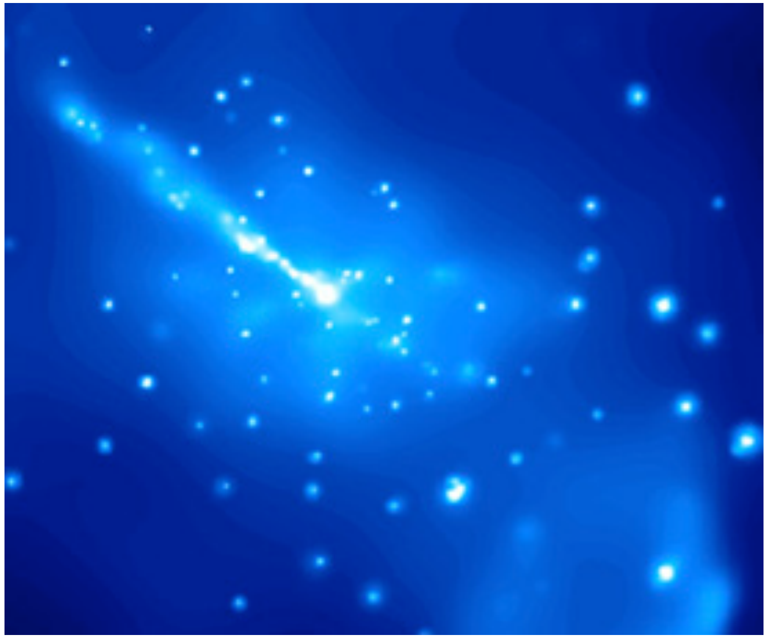
Cen A: radio galaxy



Cen A

- Radio galaxy with AGN located at 4 Mpc from our galaxy: extremely nearby !!!
- Typical distance between radio galaxies is 20-40 Mpc





- Most nearby AGN: typical distance between AGN's is 10 Mpc (if not in clusters)

Cen A: Auger ICRC 2009

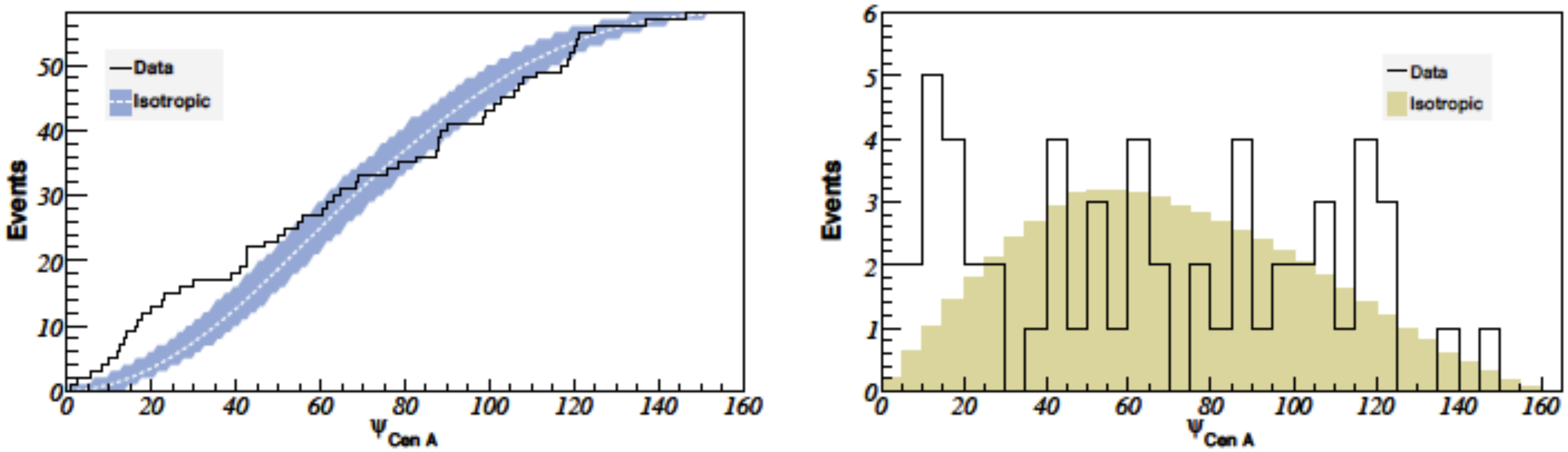


Fig. 3. *Left:* The cumulative number of events with $E \geq 55$ EeV as a function of angular distance from Cen A. The average isotropic expectation with approximate 68% confidence intervals is shaded blue. *Right:* The histogram of events as a function of angular distance from Cen A. The average isotropic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

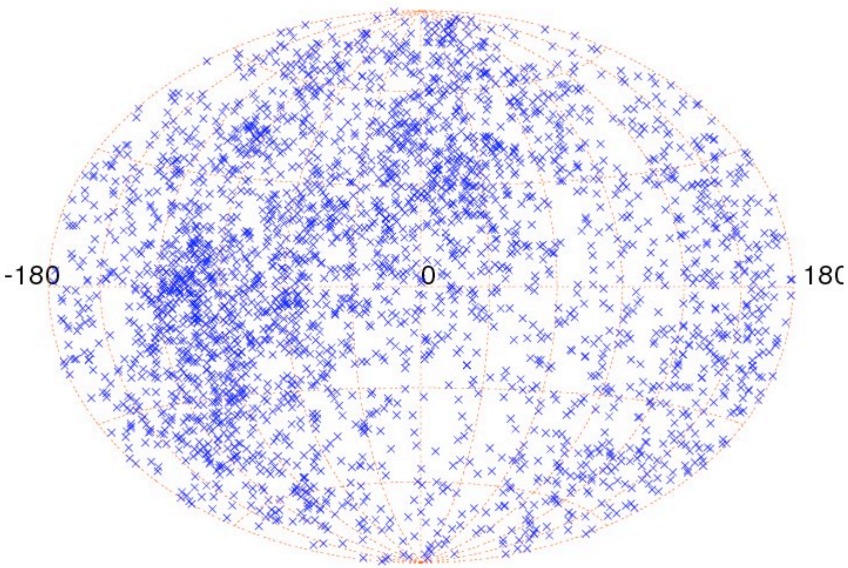
Statistics with Galactic plane cut

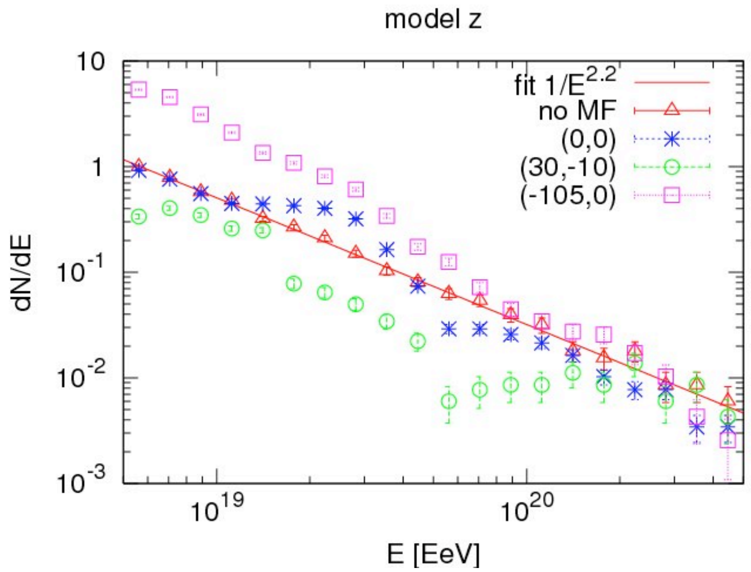
- Z<=0.018 R=75 Mpc: 425 AGN |b|>12 degrees
- 6 events in Galactic plane only one correlate
- Out of Galactic plane 21 event /19 correlate 90%.
- Only new events: 11/9 correlate P=0.0002

SUMMARY of Auger correlation study 2007:

- Evidence that UHECR sky is anisotropic above GZK cutoff
- 3 degree angle mean that magnetic fields are not very large + <Z> is not very large ? Contradict composition!
- Independent confirmation of GZK cutoff from correlations with NEARBY sources.
- AGN's can be sources or tracers of sources in local LSS
- --
- ONLY PROTONS from AGN's: Energy scale has to move up E->E+30% Warning: There is no signal from Virgo cluster, 2-3 sigma
- New data?

Source in magnetized region

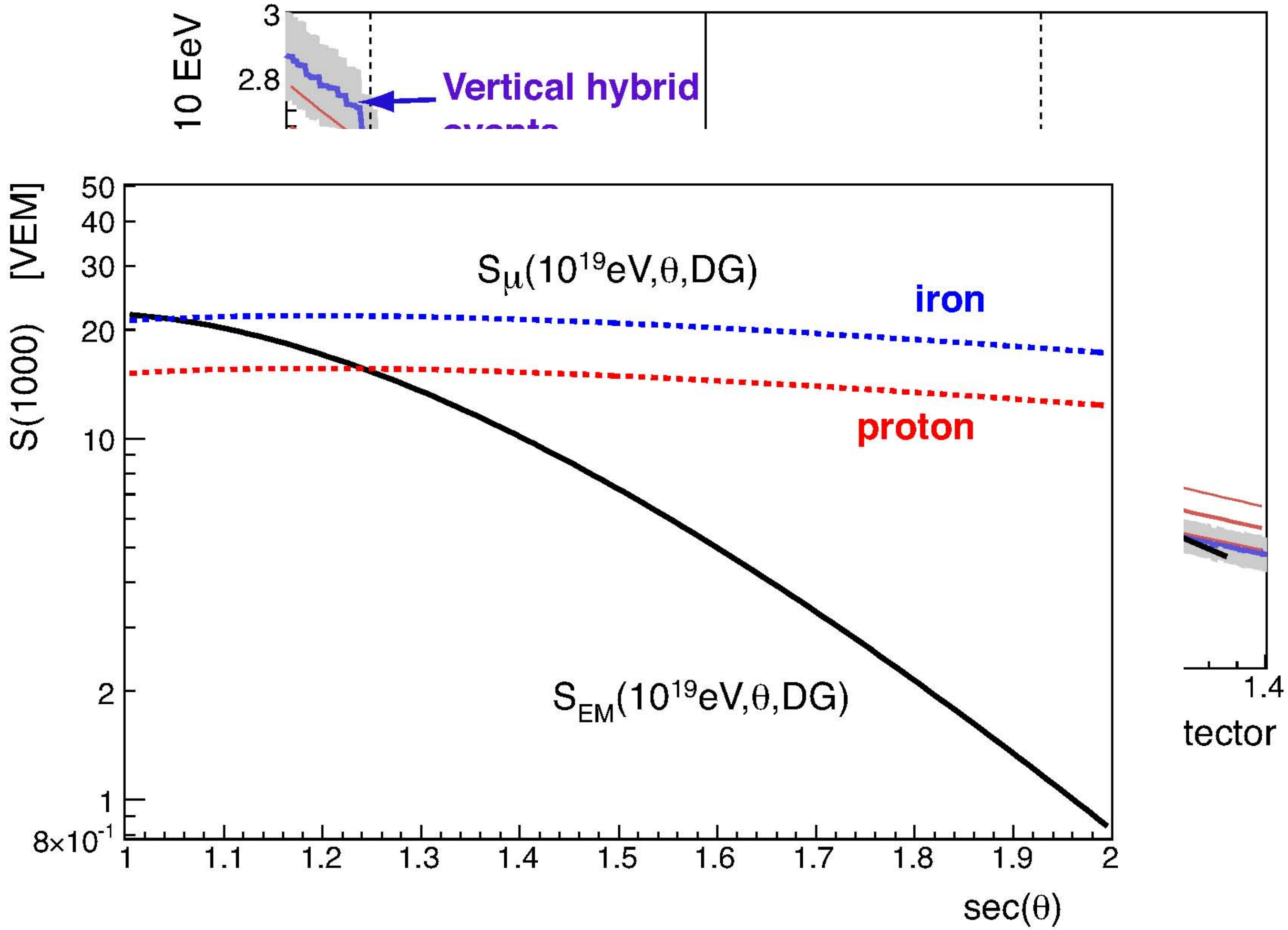




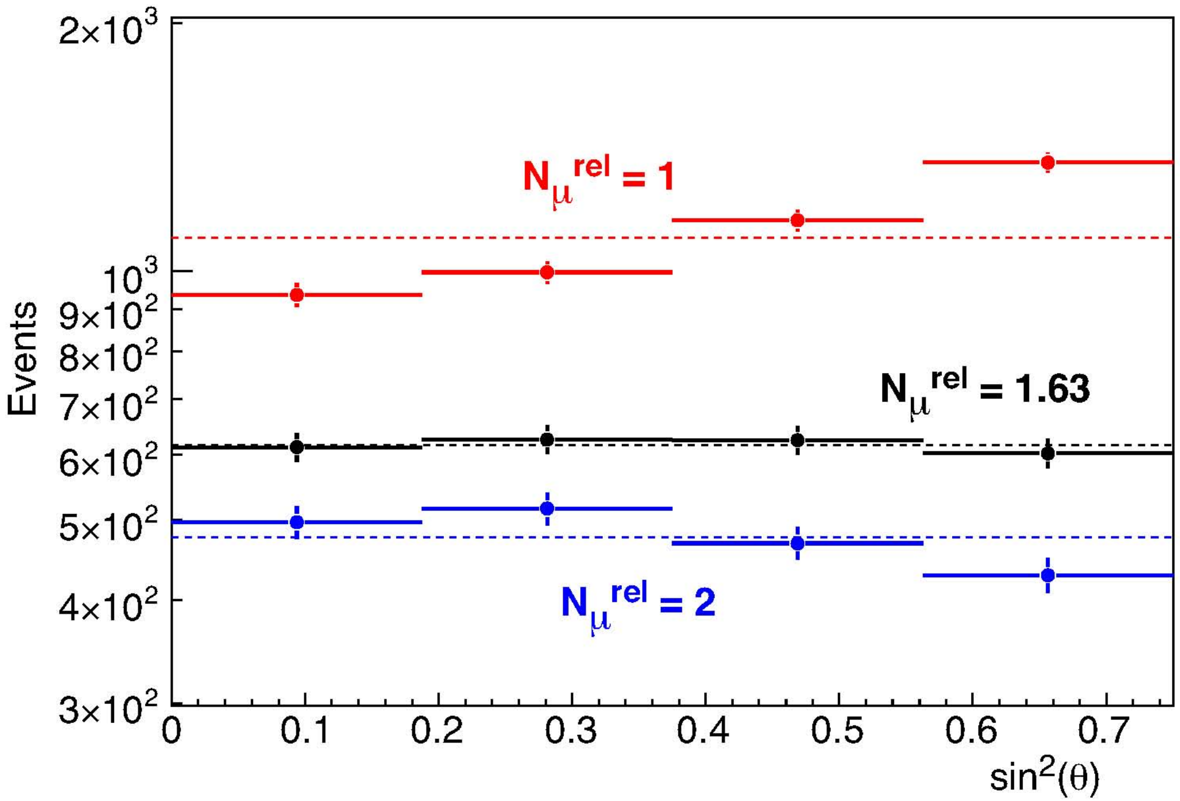
K.Dolag, M.Kachelriess and D.S., 2008

Particle physics at ultra-high energies

Number of muons and energy scale



Relative number of muons

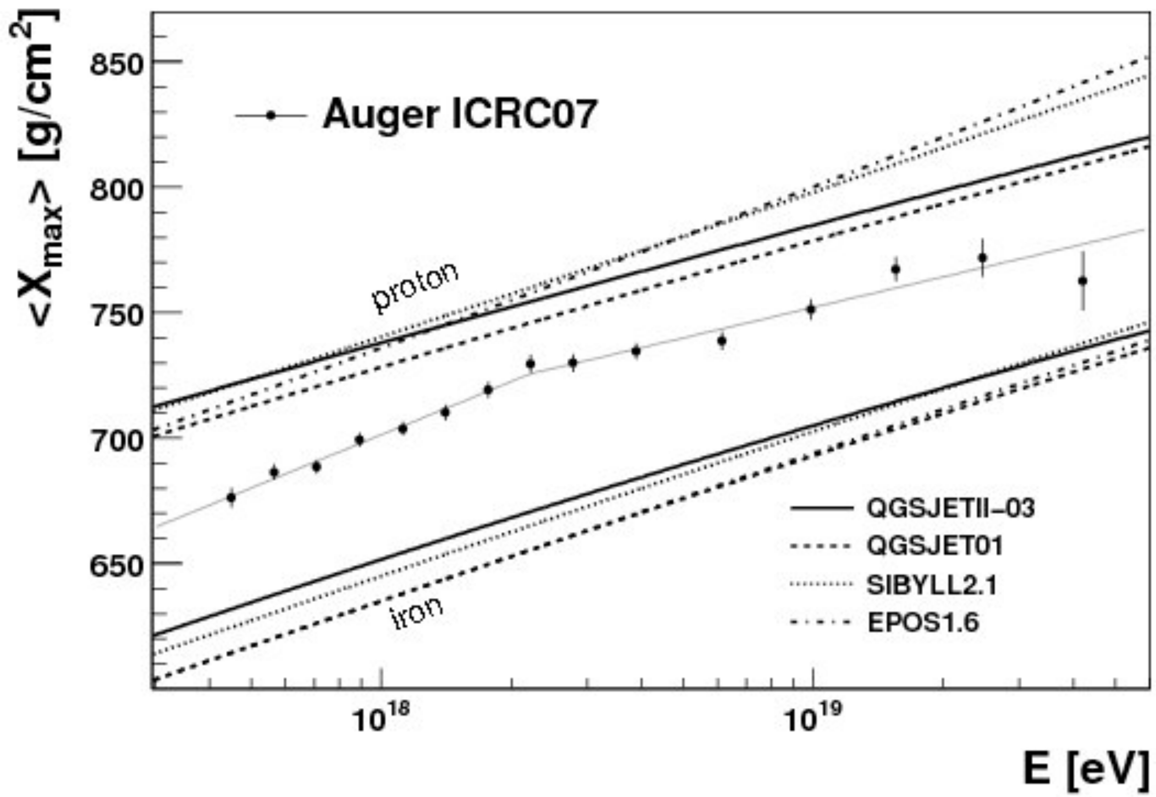


we need in 1.5 times more muons

as compared to QGSJET-II model:

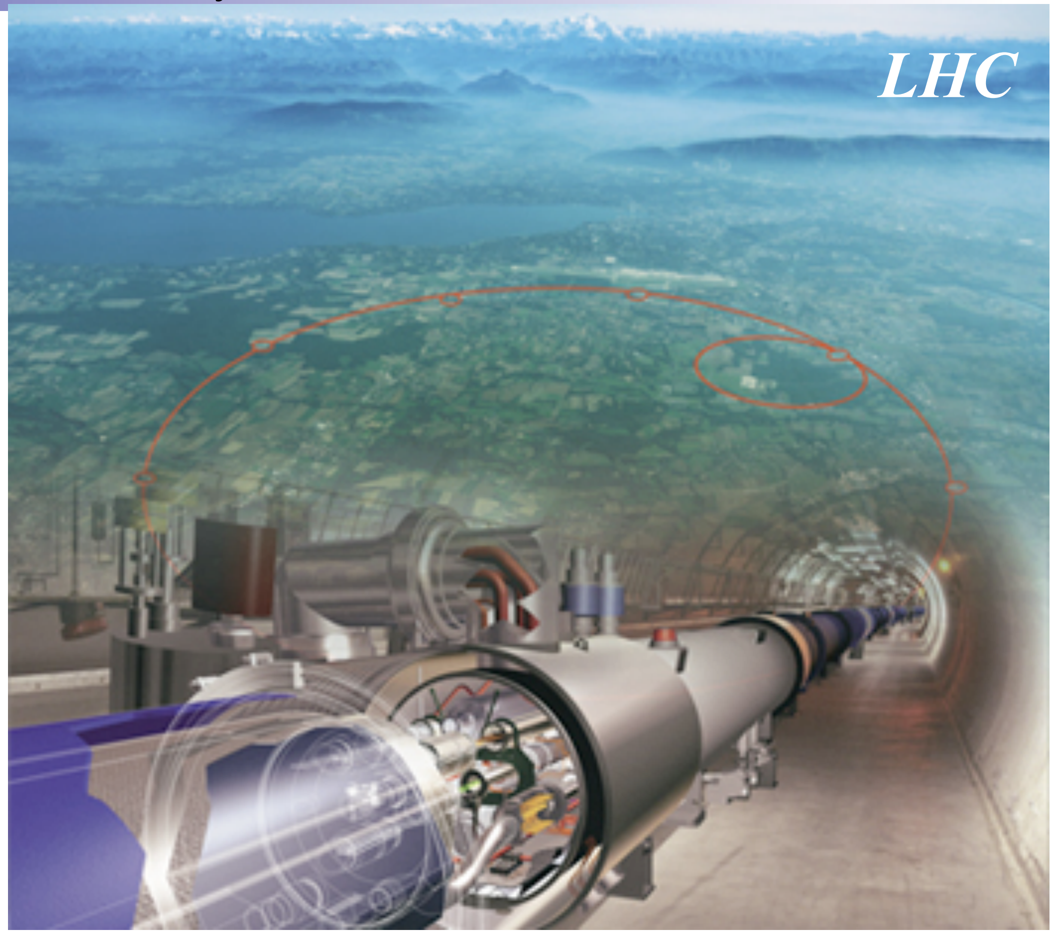
Heavier then Fe or wrong model prediction

Composition study: depends on hadronic interaction models



LHC-CR interplay

Calibration of the models at high energy is mandatory



14 TeV in the center of mass

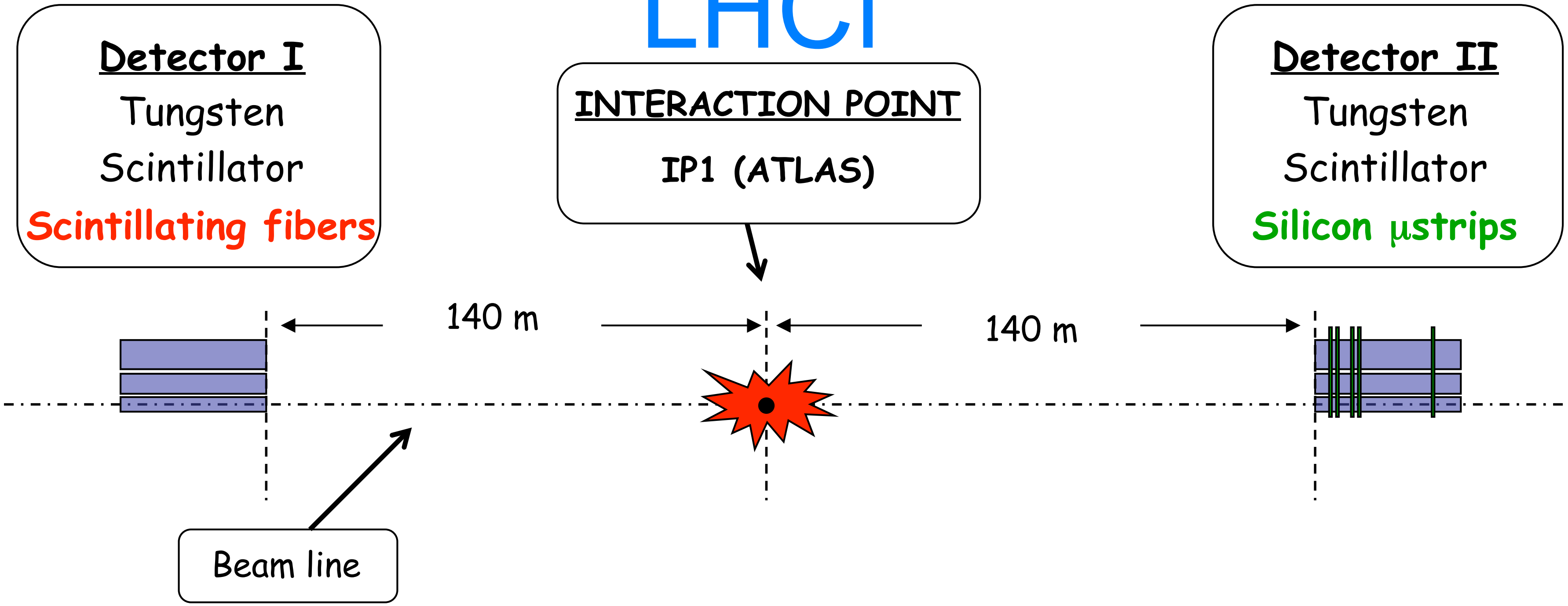
$E_{lab}=10^{17}$ eV ($E_{lab}= E^2_{cm}/2\ m_P$)

Major LHC detectors (ATLAS, CMS, LHCB) will measure the particles emitted in transverse directions

LHCf is a tool to calibrate MC code to energy relevant for CR physics. It will cover the very forward part

May be also Heavy Ion runs?

LHCf



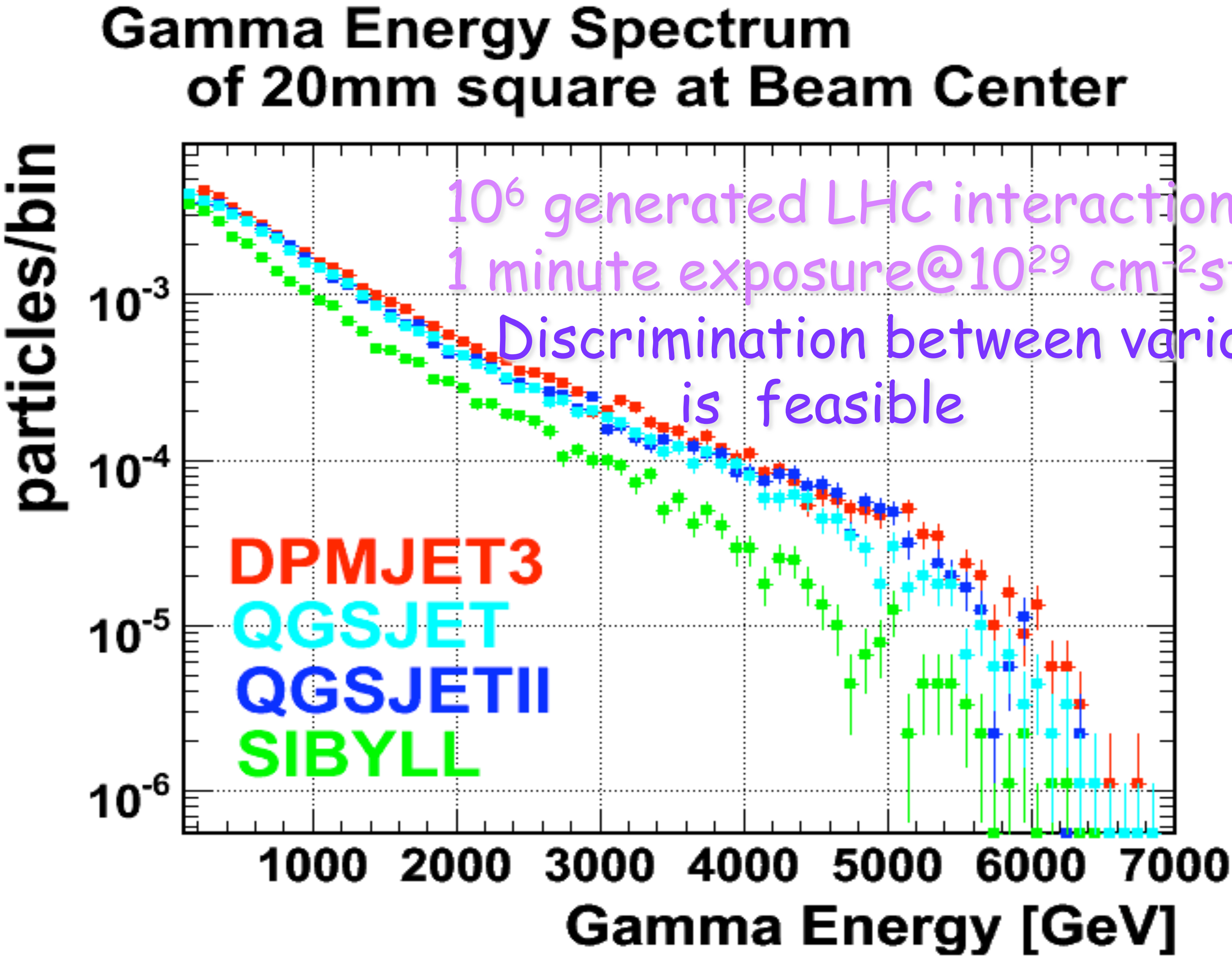
Detectors should measure energy and position of γ from π^0 decays → e.m. calorimeters with position sensitive layers

Two independent detectors on both side of IP1

- ✓ Redundancy
- ✓ Background rejection (especially beam-gas)

LHCf Arm 1 – Installation

LHCf performances: Monte Carlo γ-ray energy spectrum

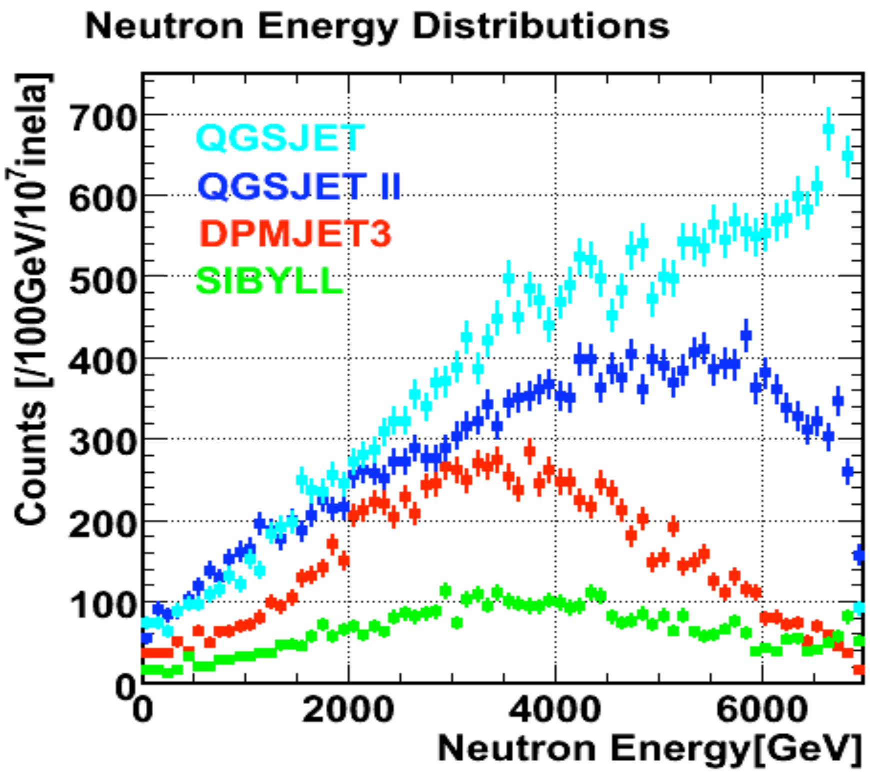


10^6 generated LHC interactions → 1 minute exposure@10^{29} $cm^{-2}s^{-1}$ luminosity

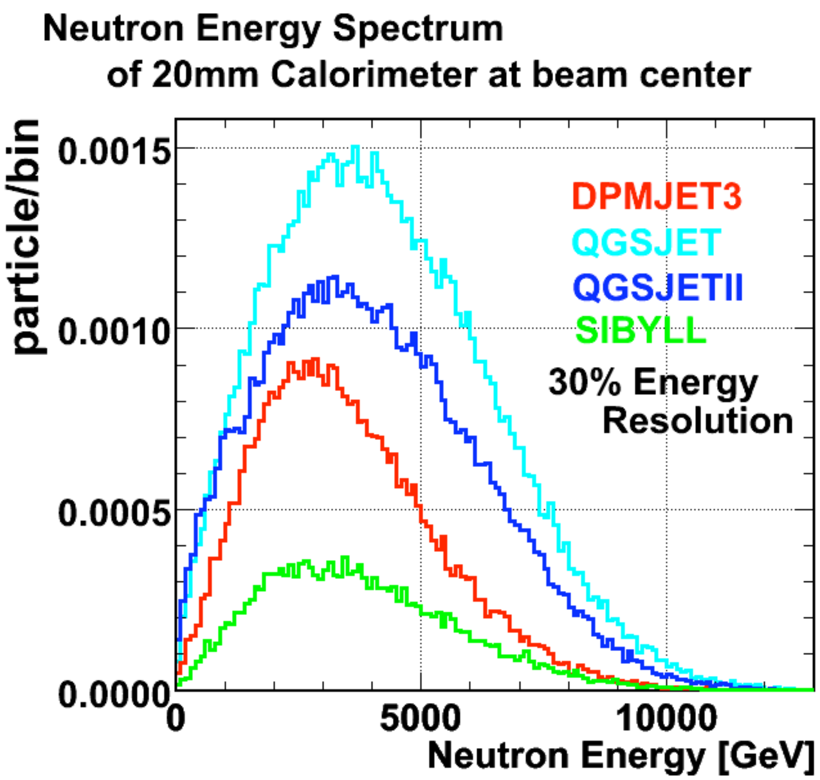
Discrimination between various models is feasible

LHCf performances: model dependence of neutron energy distribution

Original n energy



30% energy resolution



Secondary photons and neutrinos from UHECR

Pion production

$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

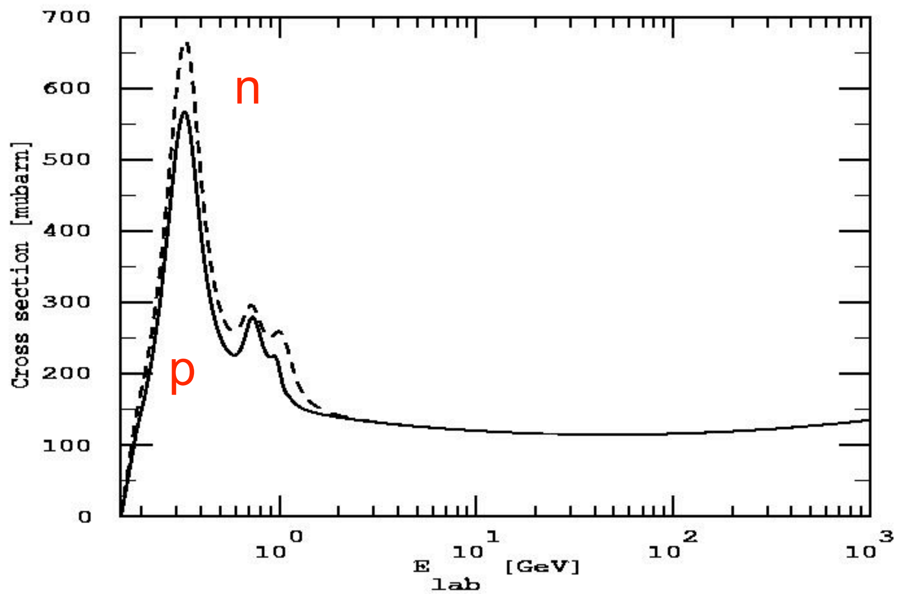
$$P + P_b \Rightarrow \sum \pi^i + \ldots$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

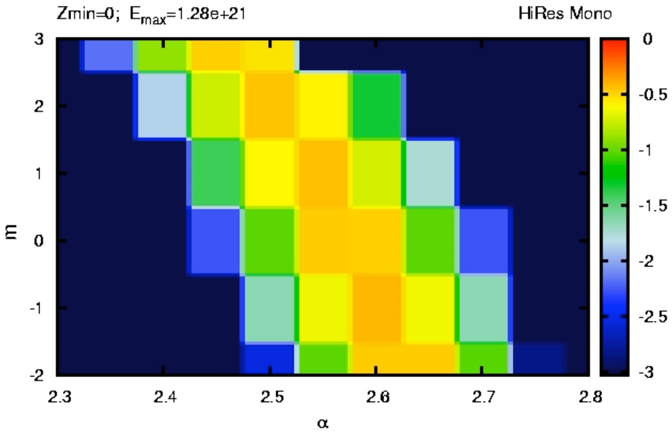
$$n \Rightarrow p + e^- + \overline{\nu}_e$$

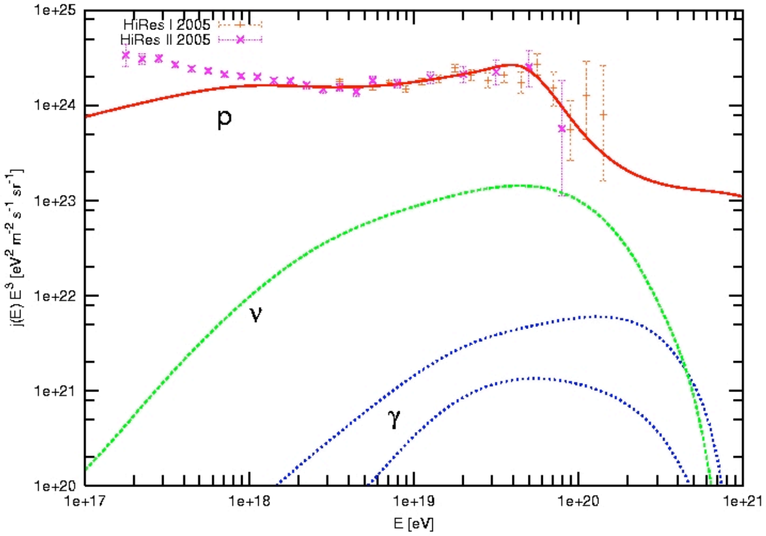


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

GZK photons with E>10 EeV

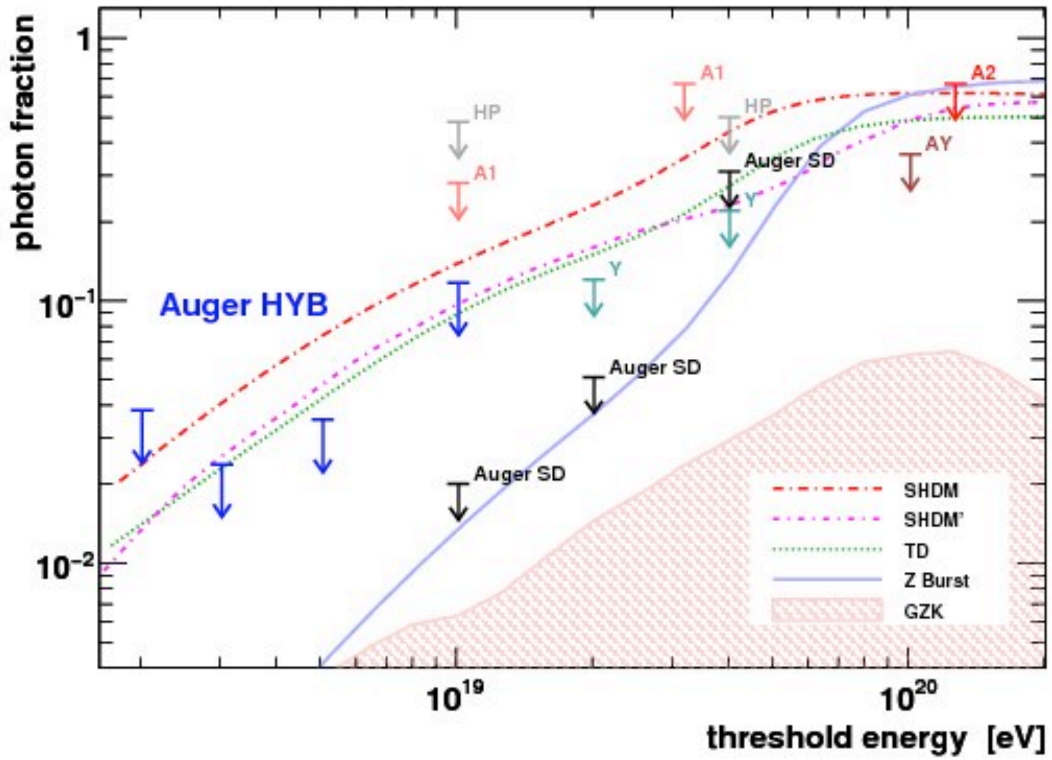
Secondary photons and neutrinos





G.Gelmini et al, astro-ph/0702464

Search for secondary photons



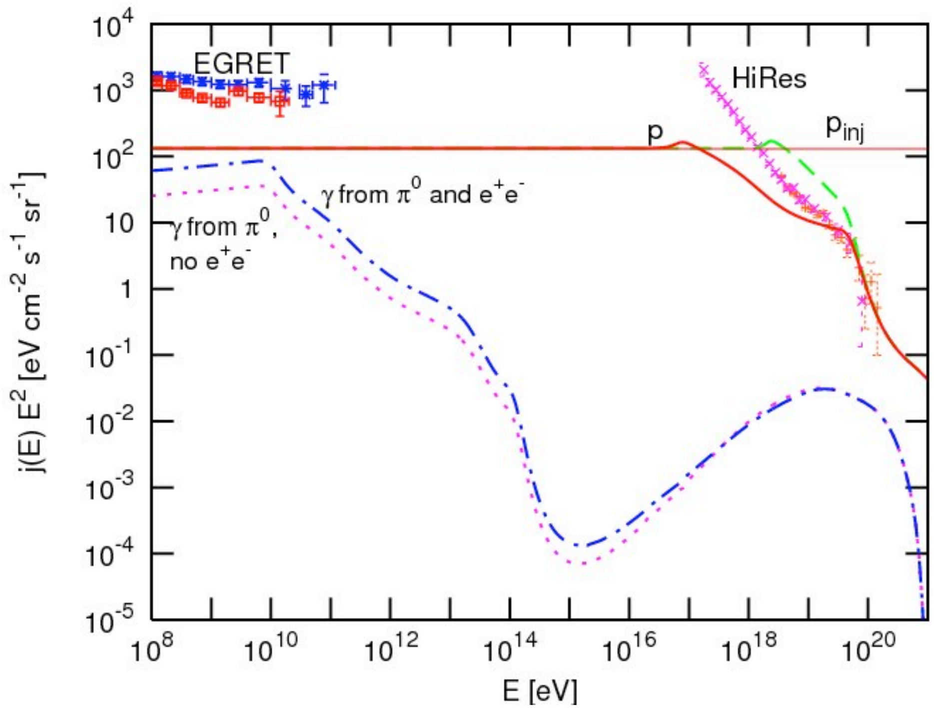
Cascade photons with GeV - TeV energies

Cascade photons for 1/E^2.

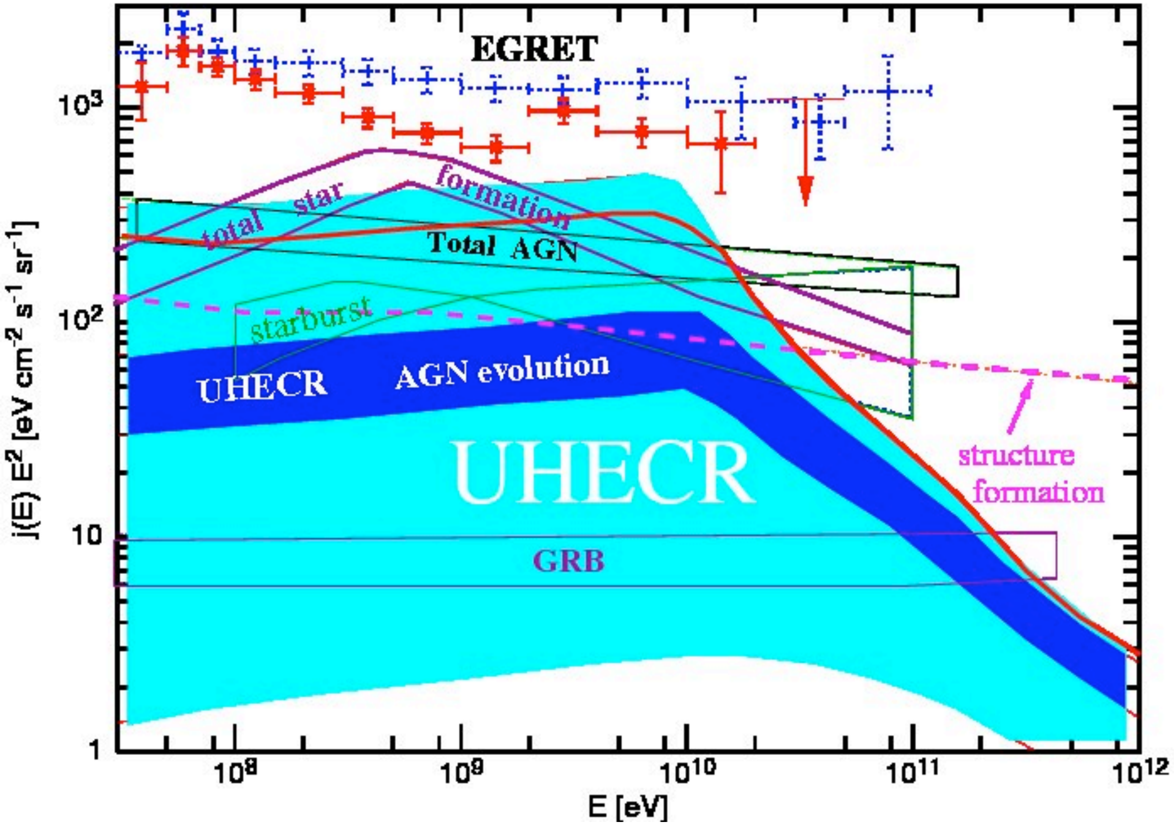
$$\gamma + \gamma_{CMB} \Rightarrow e^- + e^+$$

$$e^\pm + \gamma_{CMB} \Rightarrow e^\pm + \gamma$$

$$e^\pm + B \Rightarrow e^\pm + \gamma_{synch}$$



Contribution of UHECR to EGRET



O.Kalashev , D.S. and G.Sigl, astro-ph/0704.2463

UHE neutrinos.

Pion production

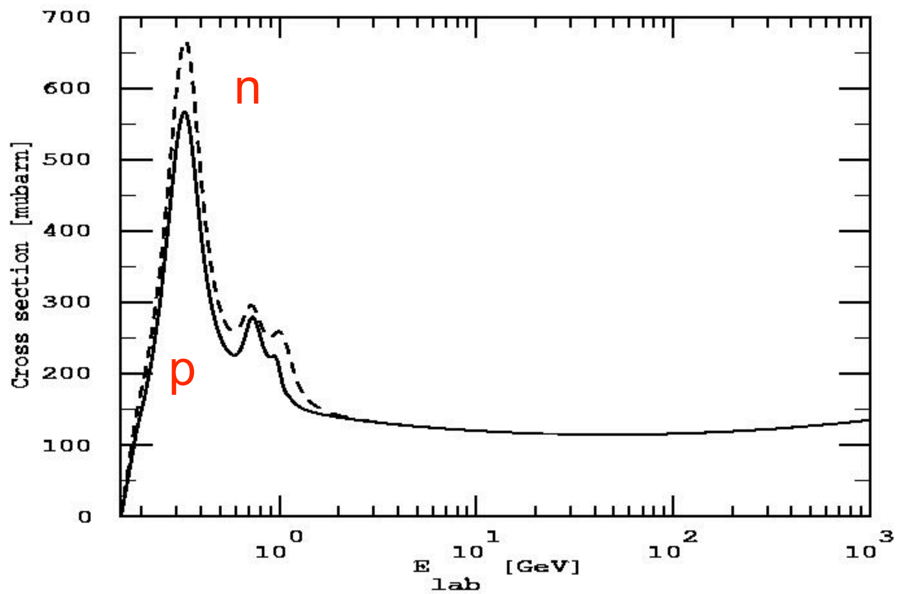
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

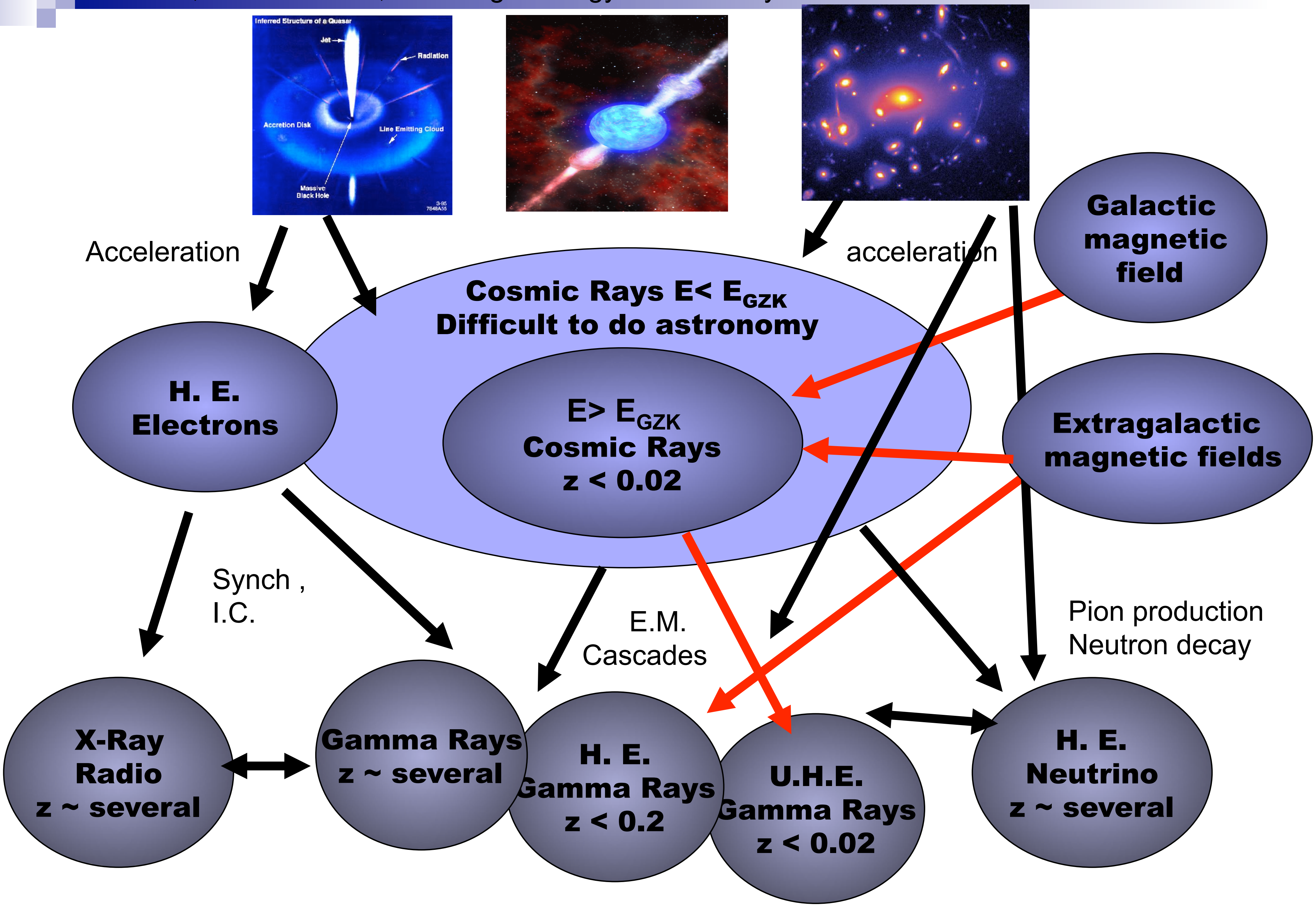
$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

$$n \Rightarrow p + e^- + \overline{\nu}_e$$



Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

Multi-messenger observations of sky.

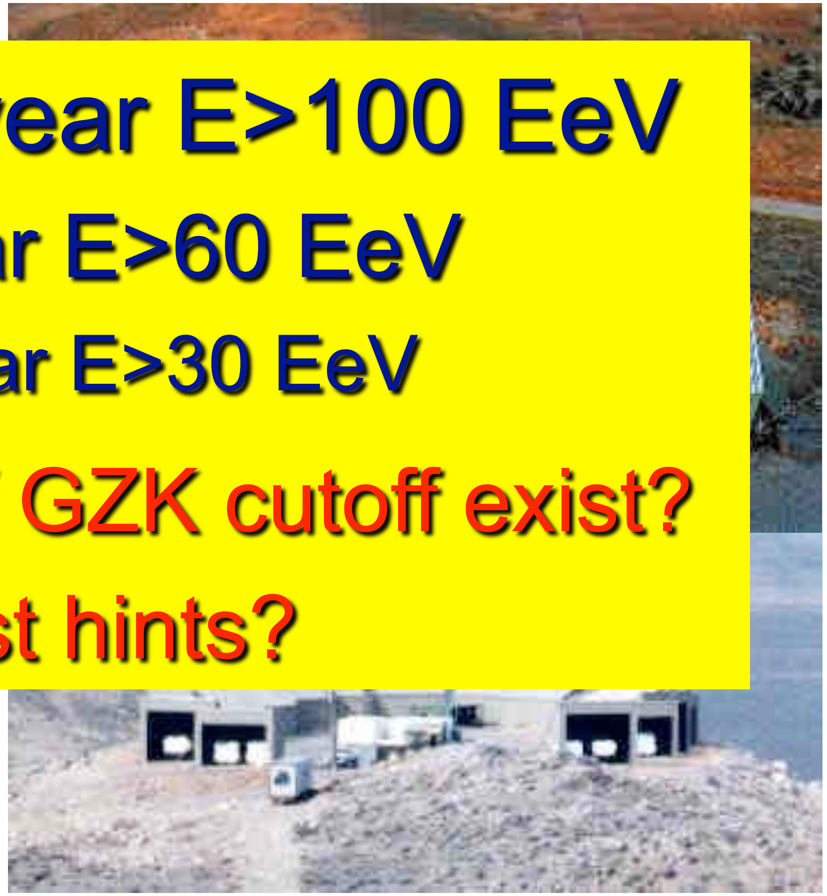

Inferred Structure of a Quasar
Jet
Radiation
Accretion Disk
Line Emitting Cloud
Massive Black Hole
Acceleration
acceleration
Galactic magnetic field
Cosmic Rays E< E_{GZK}
Difficult to do astronomy
H. E. Electrons
E> E_{GZK}
Cosmic Rays
z < 0.02
Extragalactic magnetic fields
Synch ,
I.C.
E.M.
Cascades
Pion production
Neutron decay
X-Ray
Radio
z ~ several
Gamma Rays
z ~ several
H. E.
Gamma Rays
z < 0.2
U.H.E.
Gamma Rays
z < 0.02
H. E.
Neutrino
z ~ several

Previous generation: AGASA, HiRes

AGASA ~100km^2
(closed in 2004)
111 scintillation detectors
27 muon detectors
~4M$ (~30 Scientists)

HiRes ~300km^{2}yr/yr
(closed in 2006)
HiRes-I, HiRes-II

~10M$ (~60 Scientists)



0.5-1 event/year E>100 EeV

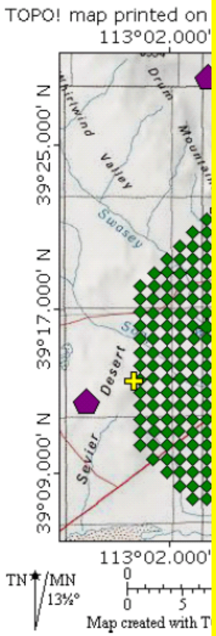
3-5 events/year E>60 EeV

20-40 events/year E>30 EeV

Goal: check if GZK cutoff exist?

Anisotropy: first hints?

New Generation



10 events/year E>100 EeV

50 events/year E>60 EeV

400 events/year E>30 EeV

2007: !!!

July: Cutoff confirmed !!!

November 9th: Anisotropic sky !!!.

Sources - astrophysical objects in LSS !!!!

Goal: establish first UHECR sources: 3-5 years of Auger data?

Auger

1600 W
with 1.5
4 Fluore

~50M$ (

ations

(``Eyes'')
ure

Future Projects: Auger North, JEM-EUSO

Auger North

~10,000km2 * (¾ π sr)/yr for 10 years

JEM-EUSO (~20% duty cycle)

Nadir mode ~40,000km2yr / yr for 2 years
Tilted mode ~200,000km2yr / yr for 3 years

Total ~680,000km2 yr ~2M km2 str yr

Northern Site

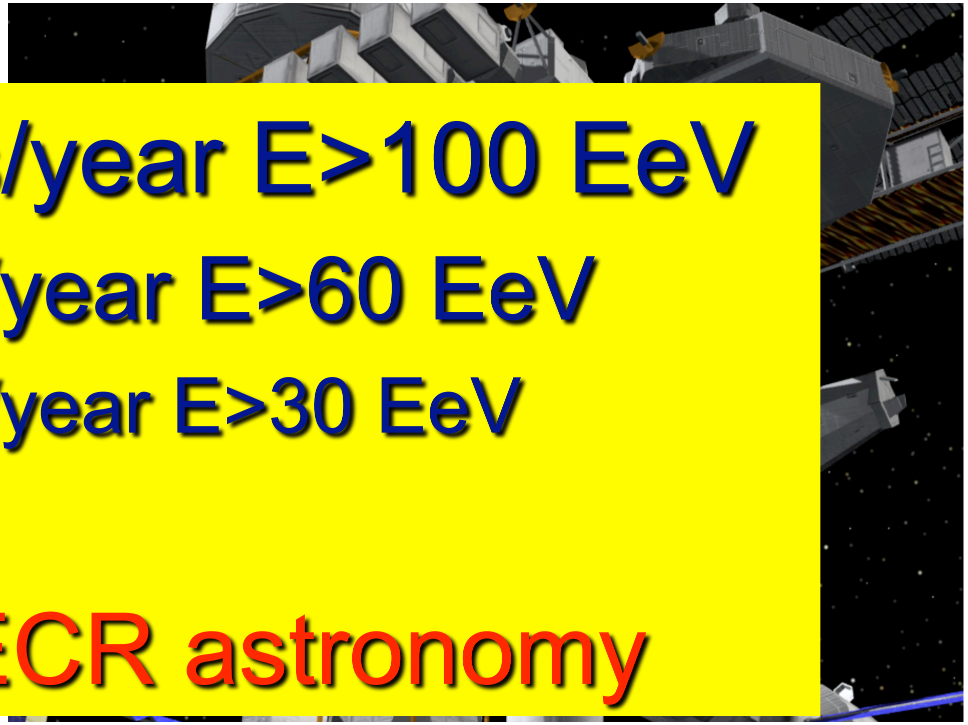
Southeastern Color

Energy ≥ 10^{19} eV

1.6 km square grid

A single FD 30^0 x 3

Propose 10,000 km



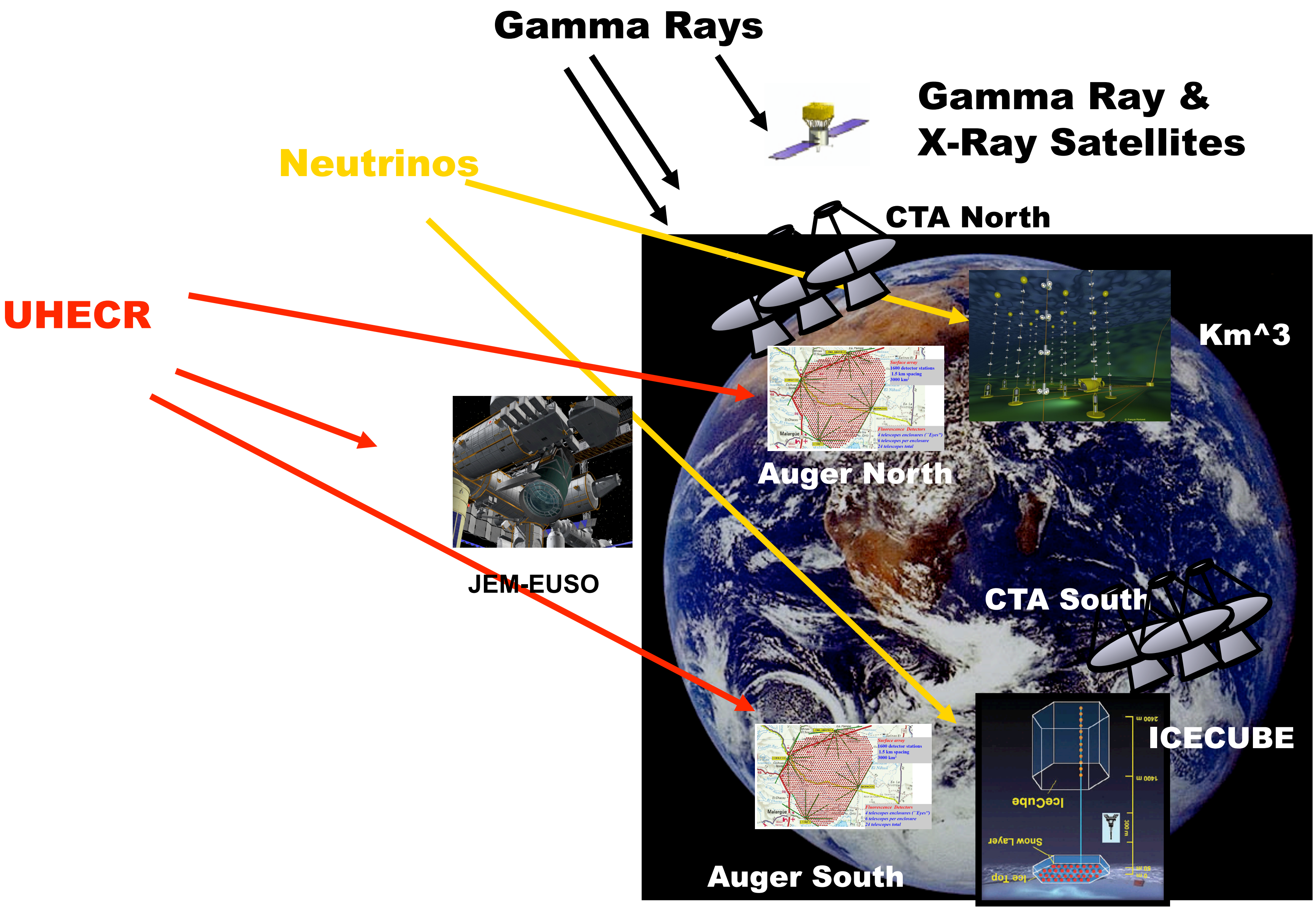
100-300 events/year E>100 EeV

500-1500 events/year E>60 EeV

4000-10000 events/year E>30 EeV

Goal: start UHECR astronomy

Multi-Messenger observation all-sky



Conclusions

- Cutoff in UHECR spectrum exist. UHECR come from astrophysical sources. Open questions:
  - Cutoff from acceleration or/and cutoff from propagation.
  - Composition: protons or/and nuclei?
- November 9, 2007: Evidence that sources are in local LSS.
- A lot of astrophysics can be done: Galactic and extragalactic magnetic fields, individual sources of UHECR, acceleration mechanism, etc. Larger detectors needed (Auger North, JEM-EUSO, etc.)!
- Input from LHC needed to reduce uncertainty in hadronic models: energy determination and composition of UHECR. Definitely revision of calculations with high-energy interactions.
- Secondary photons and neutrinos can give additional information on sources when they will be detected