The Search for Super-Heavy Dark Matter from Ultra-high and Extremely-high energy cosmic rays

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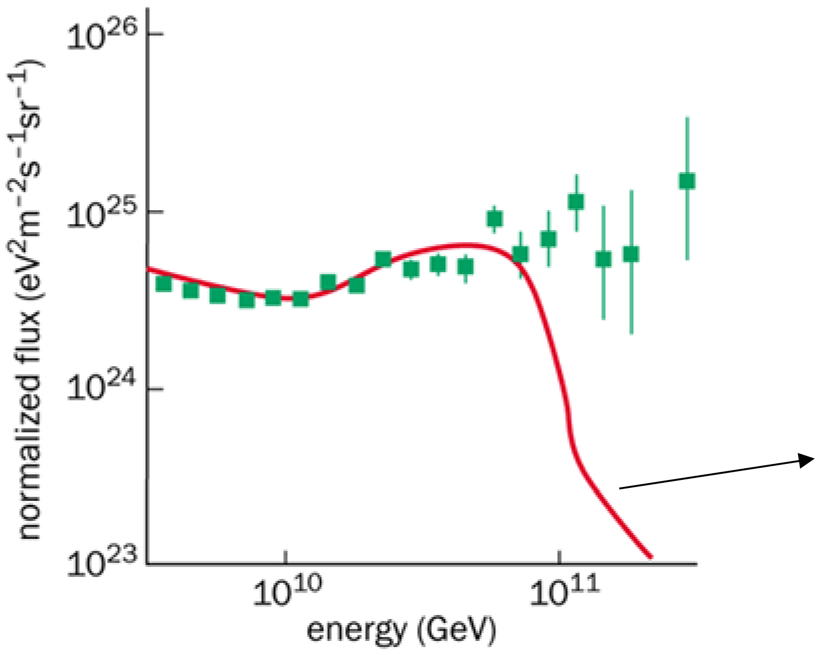
What is the connection between CRs and SHDM?

Charged particles above few x 10^{19} eV are not expected to reach the Earth from astrophysical sources since:

- Astrophysical objects are not large enough and/or do not have a huge magnetic field that is needed to accelerate particles to such high energies

- Protons and nuclei will interact with CMB photons loosing energy while travelling through the Universe (GZK effect)

However, AGASA experiment did not find a sharp suppression in the UHECRs spectrum in 1998



AGASA Spectrum (1998)

Expected spectrum from astrophysical sources

Then, how could be explained the trans-GZK excess?
SHDM was first proposed

SHDM models

- UHECRs and EHECRs are the byproducts of the decay of super-heavy dark matter particles, relic metastable particles (X particle).

- The observed cosmological density of DM determines that $m_\chi \approx 10^{21}$-10^{25} eV, being a natural candidate for the source of UHECR and EHECRs.

- When fitting the measured spectrum of UHECRs using the decay products of SHDM, the mass of the X particle is fixed and the free parameter is its life-time.

- Candidates: cryptons, LSP (lightest supersymmetric particle) in superheavy supersymmetry etc. that could be formed at the end of the inflationary phase.

Signatures

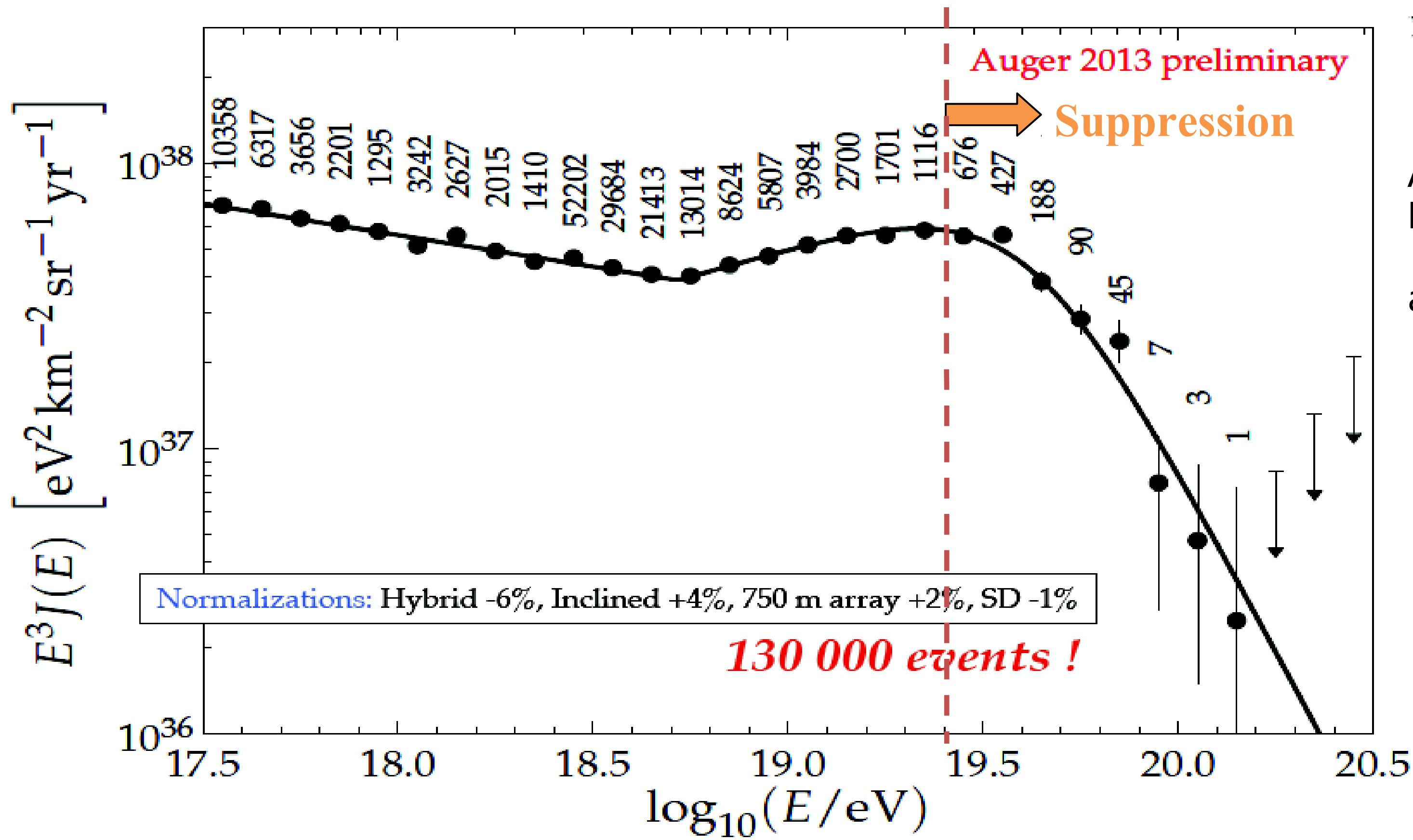
✓ No suppression in the spectrum above the GZK threshold since SHDM accumulate in the halo of our Galaxy.

✓ No correlation with ordinary matter and anisotropic UHECR flux from SHDM due to the non-central position of the Sun in the Galaxy and the fact that DM distribution shows an increase density in the direction of the GC. Therefore, an excess must be found in the direction of GC.

✓ UHE photons are the dominant component of the primary flux because in the decays and annihilations of X particles pions are more abundant than nucleons. Models predict a photon/nucleon ratio ~ 2-3.

1st signature: spectrum

Auger has confirmed the existence of the suppression



Auger Spectrum
ICRC 2013

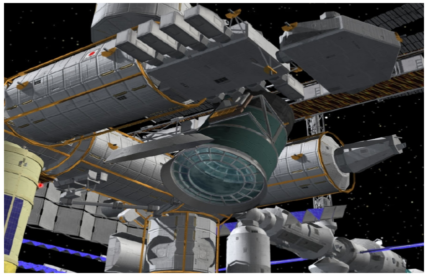
arXiv: 1307.5059

However, some authors has shown that Auger spectrum is compatible with extragalactic nuclei (mainly protons) from uniformly distributed sources and photon component from SHDM that contributes above $10^{19.5}$ eV (Aloisio et al. 2008).

The suppression makes **unnecessary** the additional **SHDM** component to explain Auger spectrum.

In the energy region where SHDM products would dominate the CRs flux (above $10^{19.5}$ eV) , Auger has low statistics, and will probably not get enough.

We need Jem-EUSO for conclusive results



It is expected to detect between 500 and 800 events with energy above 5.5×10^{19} eV which will allow to study SHDM contribution in the highest energy range.

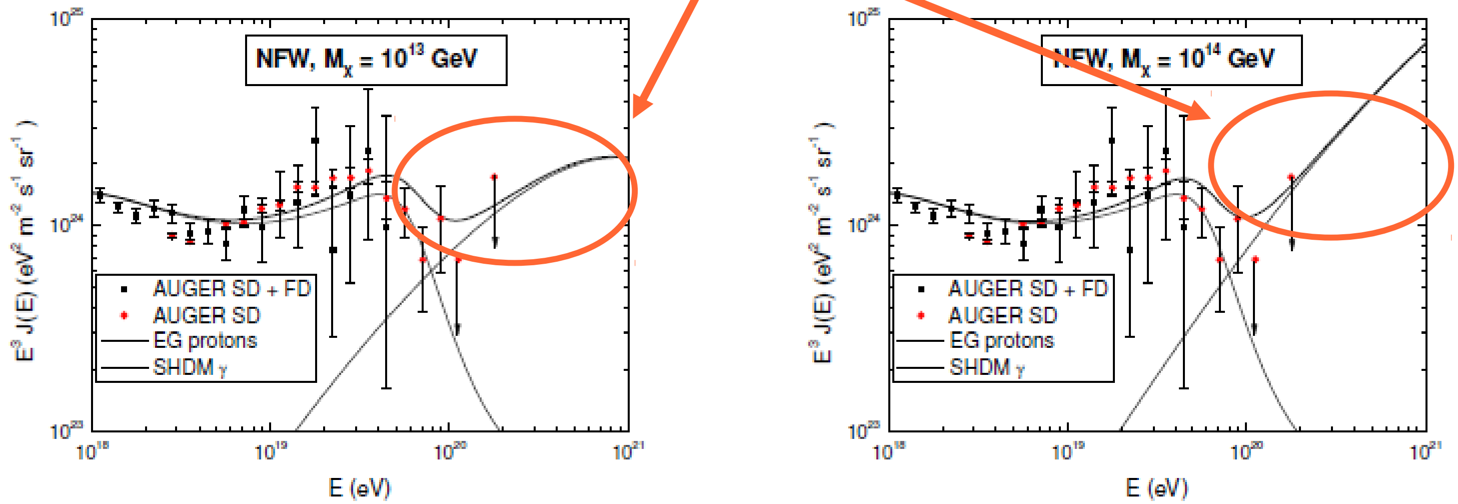


Fig. 2. The calculated spectrum of UHECRs from SHDM (dotted curve) in comparison with the Auger data ($M_X = 10^{13}$ GeV left panel, $M_X = 10^{14}$ GeV right panel). The continuos curve gives the spectrum of extragalactic protons (assuming the Dip model [6]). The sum of these two spectra is shown by thick continuos curve.

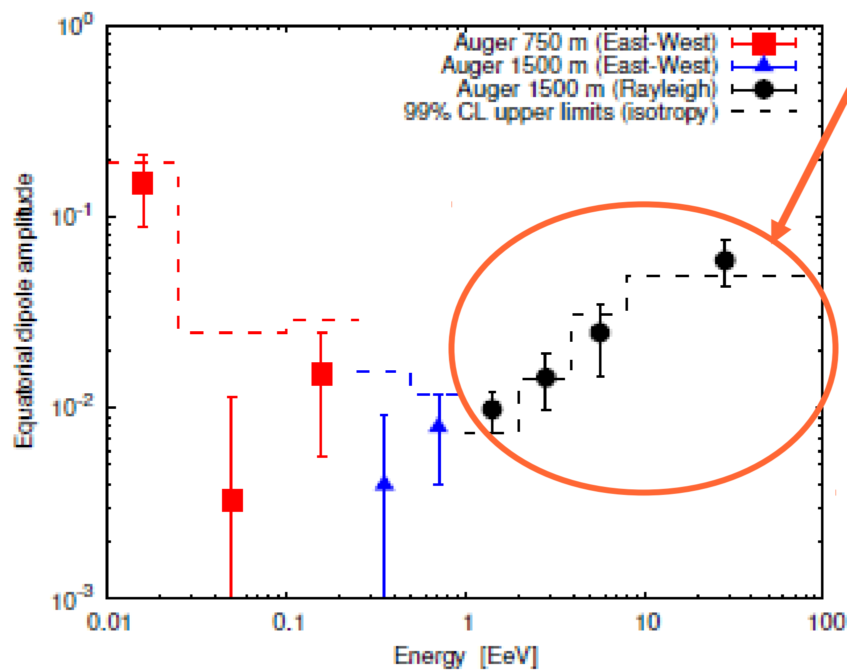
2^{nd} signature: Anisotropies

Large scale ansitropy

- Small anisotropy in the few percent level from SHDM decays may be a detectable signature.

- It should be easier to detect it at lower energies (10^{16}-10^{18} eV) because statistics are larger and, while protons are isotropised by EGMF, photons from SHDM decay are not deflected.

- No evidence for anisotropy has been found. While Auger results are compatible with fluctuations from an isotropic background, a first hint of anisotropy has been found.



Auger ICRC 2013

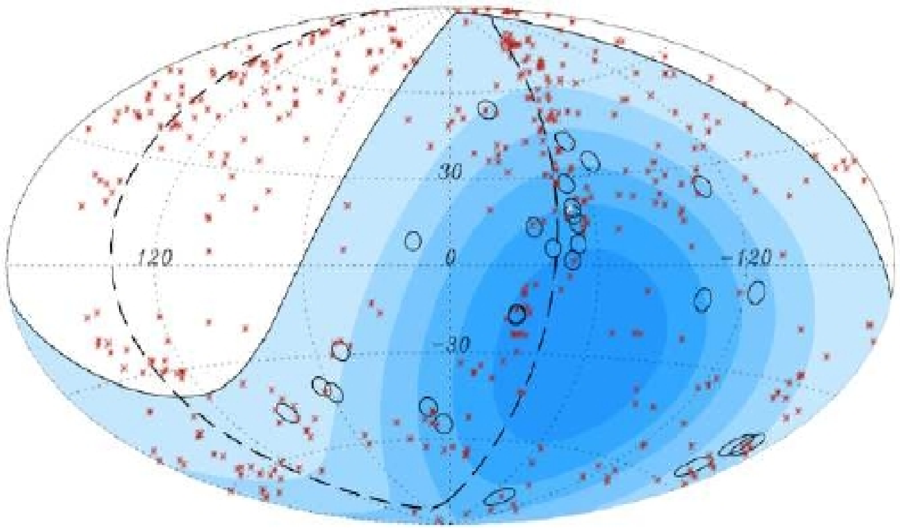
arXiv: 1307.5059

Figure 1: Equatorial dipole amplitude as a function of energy. The results of the modified Rayleigh analysis are shown with black circles and blue triangles corresponds to the analysis with East-West method, in both cases using data from the array with 1.5 km spacing. Red squares correspond to data from the infill array using the East-West method. The dashed lines are the 99% CL upper values of the amplitude that could result from fluctuations of an isotropic distribution.

The analysis requires more statistics. A new trigger will increase them in a factor of 5 in the 1-3 EeV range. The new prescription is expected for 2015.

Correlation with ordinary matter distribution

While contribution from other galaxies is strongly suppressed in SHDM models, Auger published the correlation of UHECRs direction with the position of nearby AGNs



Auger collaboration Science, 318:938–943, 2007

Auger results on anisotropy conclusively support the dominance of astrophysical sources in the energy range 10^{18} - 10^{20} eV.

Jem-EUSO main scientific goal is to search for astrophysical sources above $10^{19.5}$ eV

3rd signature: Photons

UHE and EHE photons should be the dominant component of the primary flux in SHDM scenario. However, no photon has been unambiguously identified up to now by any experiment.

Upper limits to the photon fraction in the UHECR and EHECR flux is the most promising chance to constrain SHDM models in a short-time scale.

S_b: new parameter for photon discrimination

G. Ros et al. Astropart.Phys. 35:140-151, 2011.

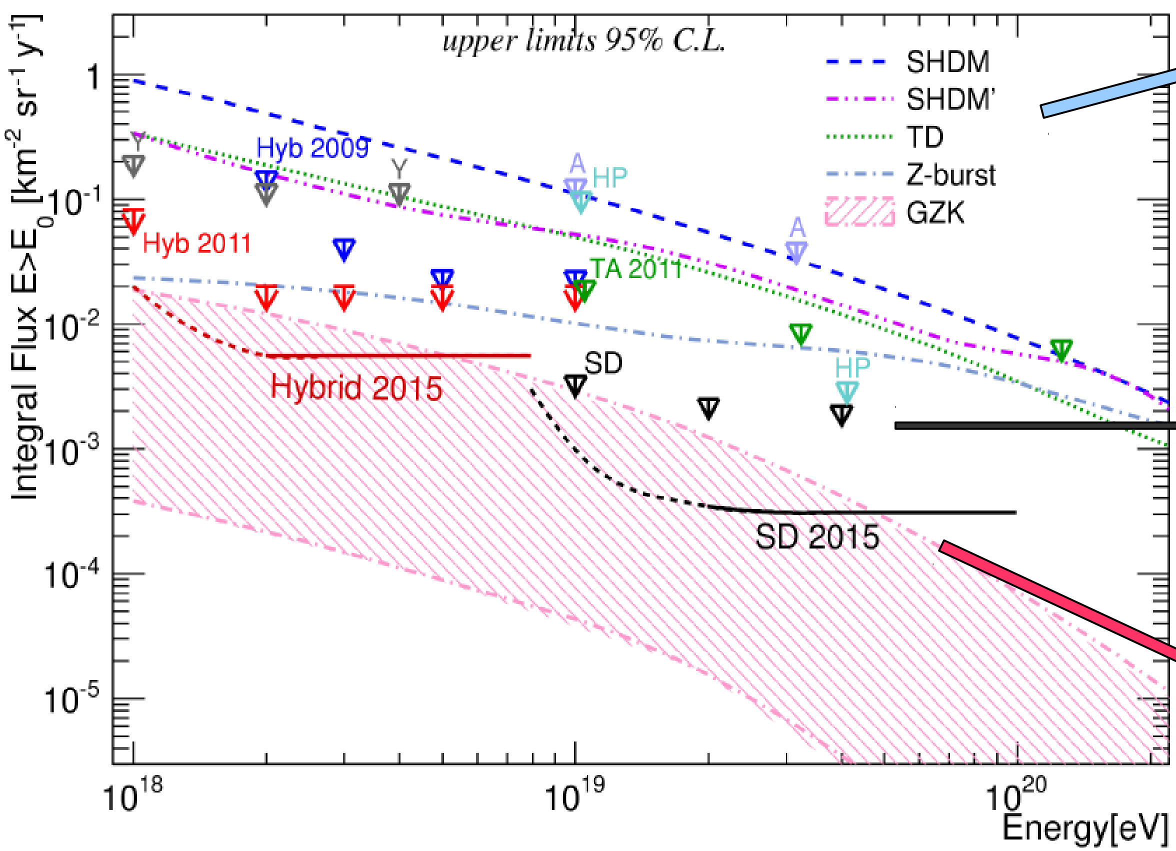
G. Ros et al. Astropart.Phys. 47:10-17, 2013.

S_b has been used in Auger to:

- put the most stringent upper limits to the photon flux at EeV energies up to now (2011 ICRC)

- start the search of photon point sources (2013 ICRC)

2012 UHECR International Symposium @ CERN): **Auger** predictions for 2015



Upper limits on the integral photon flux [7] along with the previous ones by the Pierre Auger Observatory [2][3][4] and by other experiments (AGASA, Haverah Park, TA and Yakutsk). GZK and top-down predictions from [9,10]. The thick lines show extrapolations for the Auger sensitivity (Hybrid and SD) to year 2015.

SHDM and GZK photon (optimistic) predictions

[9] G. Gelmini et al., J. Exp. Theor. Phys., 2008 106: 1061
[10] J. Ellis et al., Phys. Rev. D, 2006, 74: 115003:1-11

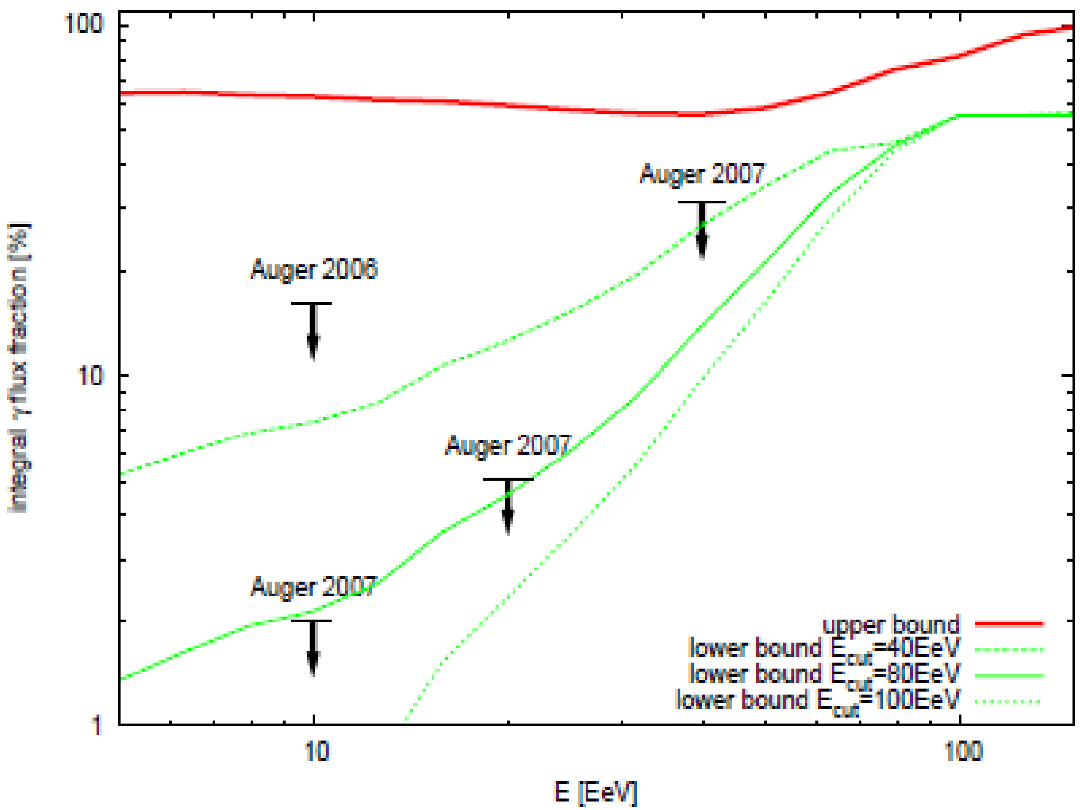
Recent upper limits from surface (black arrows) and hybrid data (red arrows) discard SHDM as the main source of UHECRs

Extrapolations suggest that Auger will reach the GZK region in 2015.

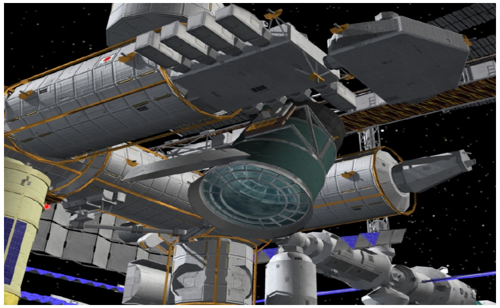
Detection of GZK photons will strongly support the astrophysical origin of UHECRs instead of SHDM models.

The new trigger will improve photon sensitivity at EeV

But be careful, increasing the energy threshold for SHDM, current limits could be still compatible with dominant SHDM contribution above 10^{20} eV

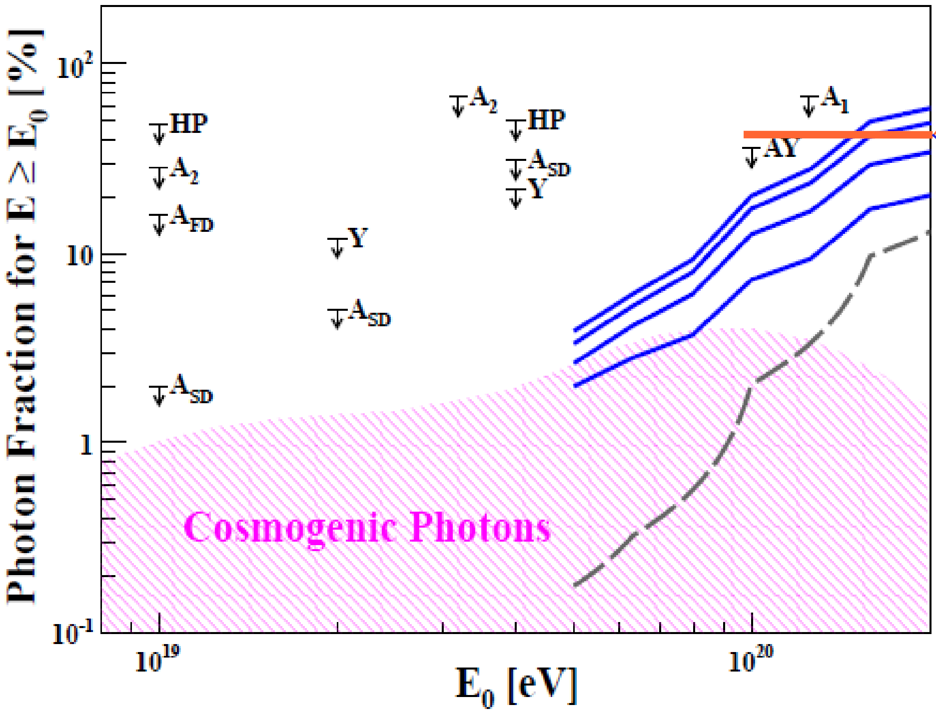


Auger ICRC 2007



We need Jem-EUSO for conclusive results

It will be sensitive to Extremely High Energy photons above $10^{19,5}$ eV where its fraction is expected to increase in SHDM scenario



Jem-EUSO Coll. ICRC 2011. ID:0930
A. D. Supanitsky and G. Medina-Tanco. Astroparticle Physics 34 (2011) 789–795

Conclusions

- All the Auger results (spectrum, anisotropy, correlation with ordinary matter, photon limits) point to the conclusion that UHECRs from SHDM decay could be only a subdominant contribution at $10^{18} – 10^{19,5}$ eV.

- However, SHDM contribution could still be dominant at higher energies, so the chance is still open. Jem-EUSO will have the capability to explore this energy region (detect photons, point sources).

- The mass and the life-time of SHDM particles could be constrained by UHECR and EHECRs experiments. But these results do not exclude it as a DM candidate.

- Waiting for more statistics in Auger and for the launching of Jem-EUSO this field is stand by (I have not found any paper after 2010 on this topic by the main authors of this area: Aloisio, Gelmini, Kachelriess, Semikoz, Berezinsky ...)

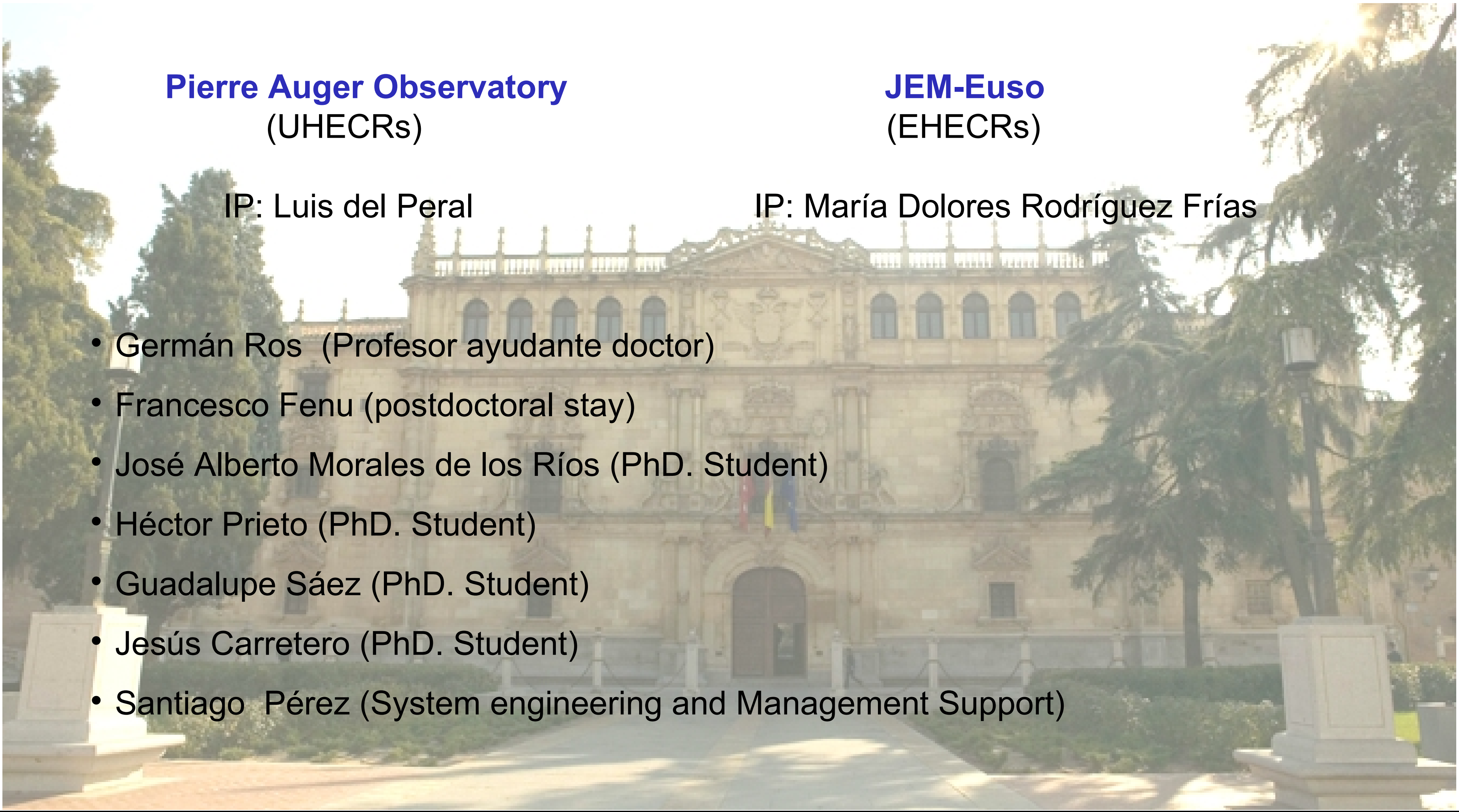
Take home message

To reject or not SHDM as the origin of UHECRs

- 10^{18} eV < E < $10^{19,5}$ eV → more hints from Auger results in ~ 3 years
- $10^{19,5}$ eV < E < 10^{21} eV → More conclusive results

SPAS Group

Space Plasma and AStroparticle Group http://spas.uah.es



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- Germán Ros (Profesor ayudante doctor)
- Francesco Fenu (postdoctoral stay)
- José Alberto Morales de los Ríos (PhD. Student)
- Héctor Prieto (PhD. Student)
- Guadalupe Sáez (PhD. Student)
- Jesús Carretero (PhD. Student)
- Santiago Pérez (System engineering and Management Support)

- In addition, several authors determined the minimum number of events that would be needed to detect anisotropy due to SHDM with 4 s.d. of significance. The current Auger statistics is enough to have detected it in the case of maximum anisotropy while not if it is minimum.

Energy (EeV)	r (NFW-min)	N(4 s.d.)	r (Moore-min)	N(4 s.d.)
> 3	0.015	150000	0.018	100000
> 10	0.045	16000	0.060	9000
> 30	0.100	3200	0.140	1600
> 100	0.300	350	0.440	150
Energy (EeV)	**r (NFW-max)**	**N(4 s.d.)**	**r (Moore-max)**	**N(4 s.d.)**
> 3	0.019	90000	0.027	45000
> 10	0.065	7500	0.092	4000
> 30	0.150	1400	0.215	700
> 100	0.480	150	0.690	70

Table 1
Amplitude of first harmonic in right ascension, and number of events required to a detection at 4 standard deviations. Upper panel shows the case with minimum anisotropy (with isotropization of SHDM protons), lower panel shows the case of maximum anisotropy (with no isotropization of SHDM protons).

The first case gives a reliable anisotropy at low energy ($E \lesssim 10^{19}$ eV) where the effect of the galactic magnetic field is important; the second case is more reliable at the highest energies ($E \gtrsim 3 \times 10^{19}$ eV) where the galactic magnetic field has no effect on the UHECR proton propagation.

Aloisio et al. (2008)

Auger ICRC 2013 spectrum:

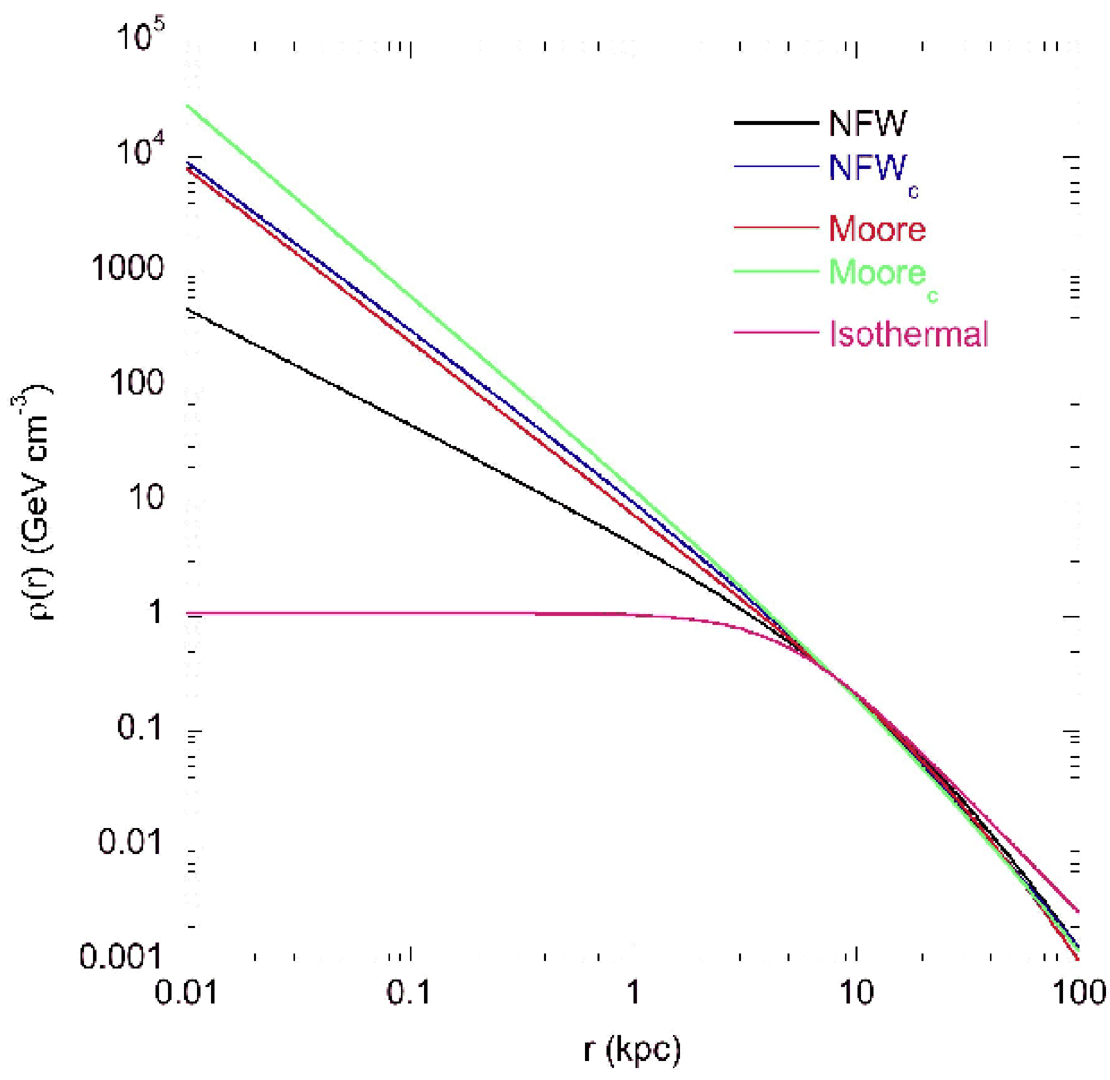
E > 3 EeV → 89480 events

E > 10 EeV → 10938 events

E > 30 EeV → 761 events

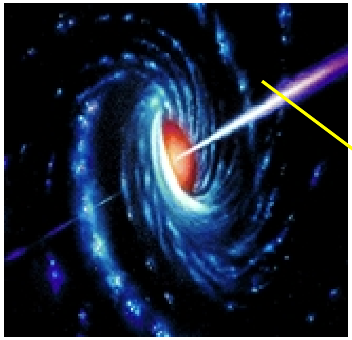
E > 100 EeV → 4 events

Dark matter density profile in our Galaxy

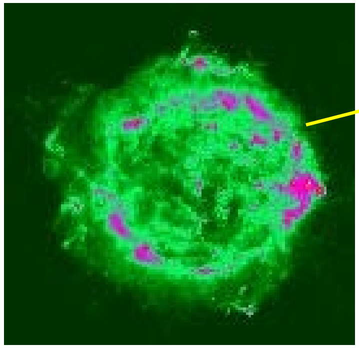


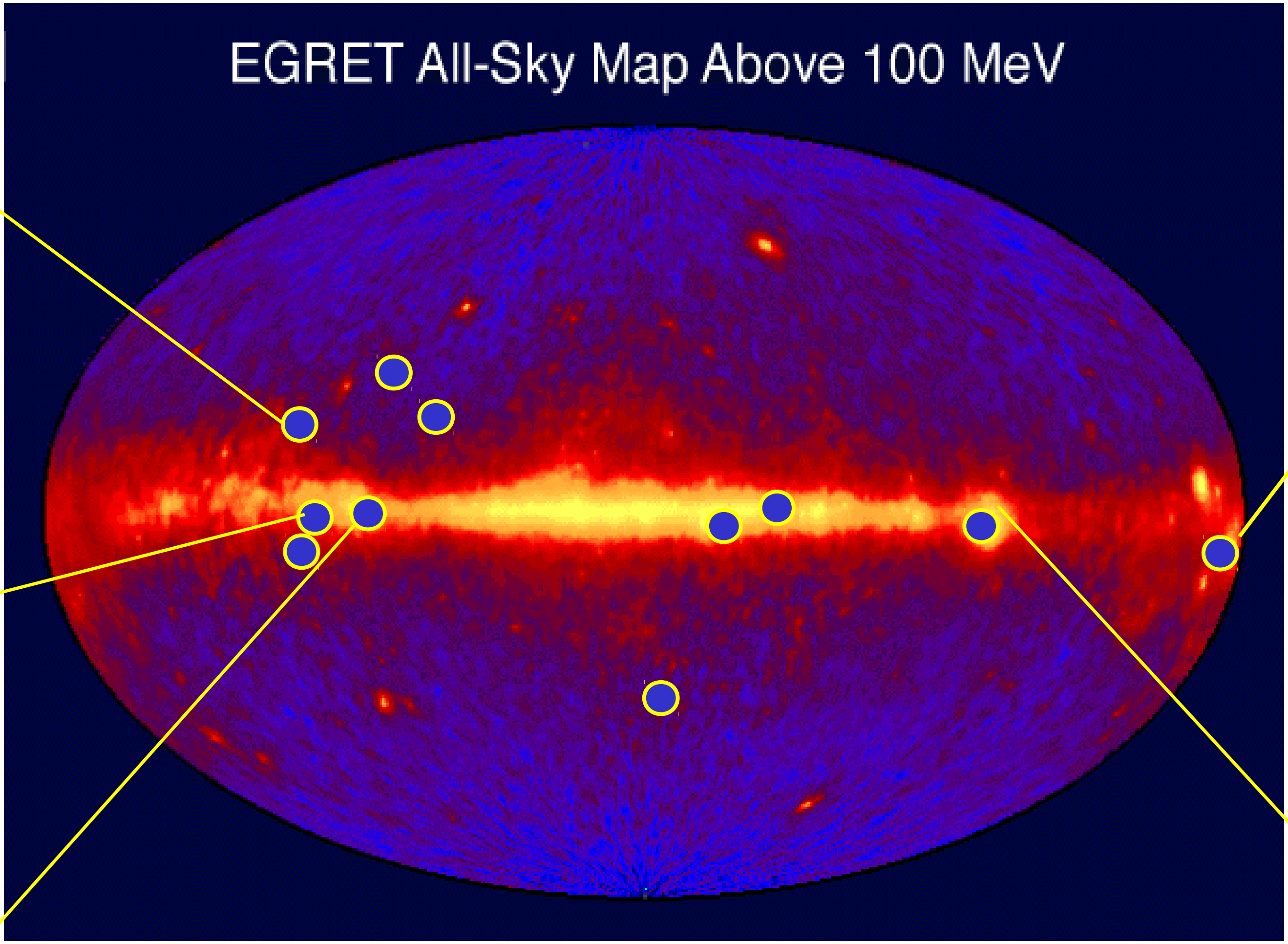
Astrophysical candidates

AGN

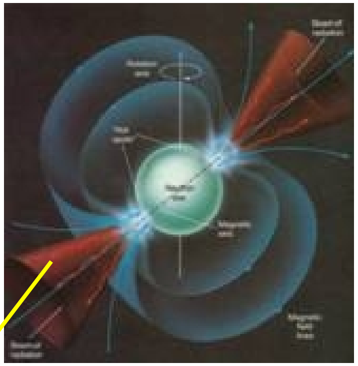


SNR

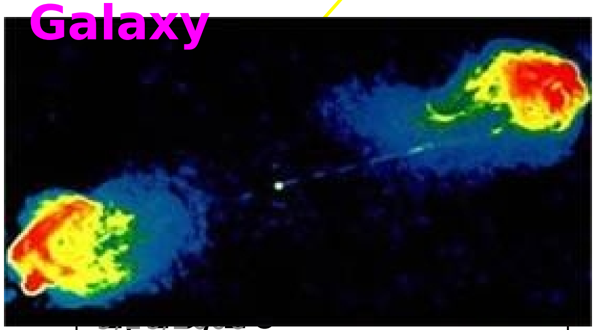




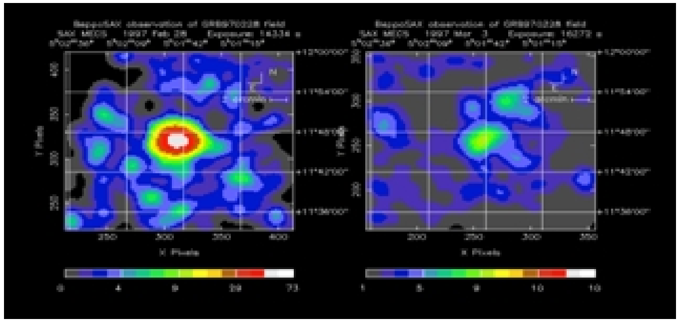
Pulsar



Radio Galaxy

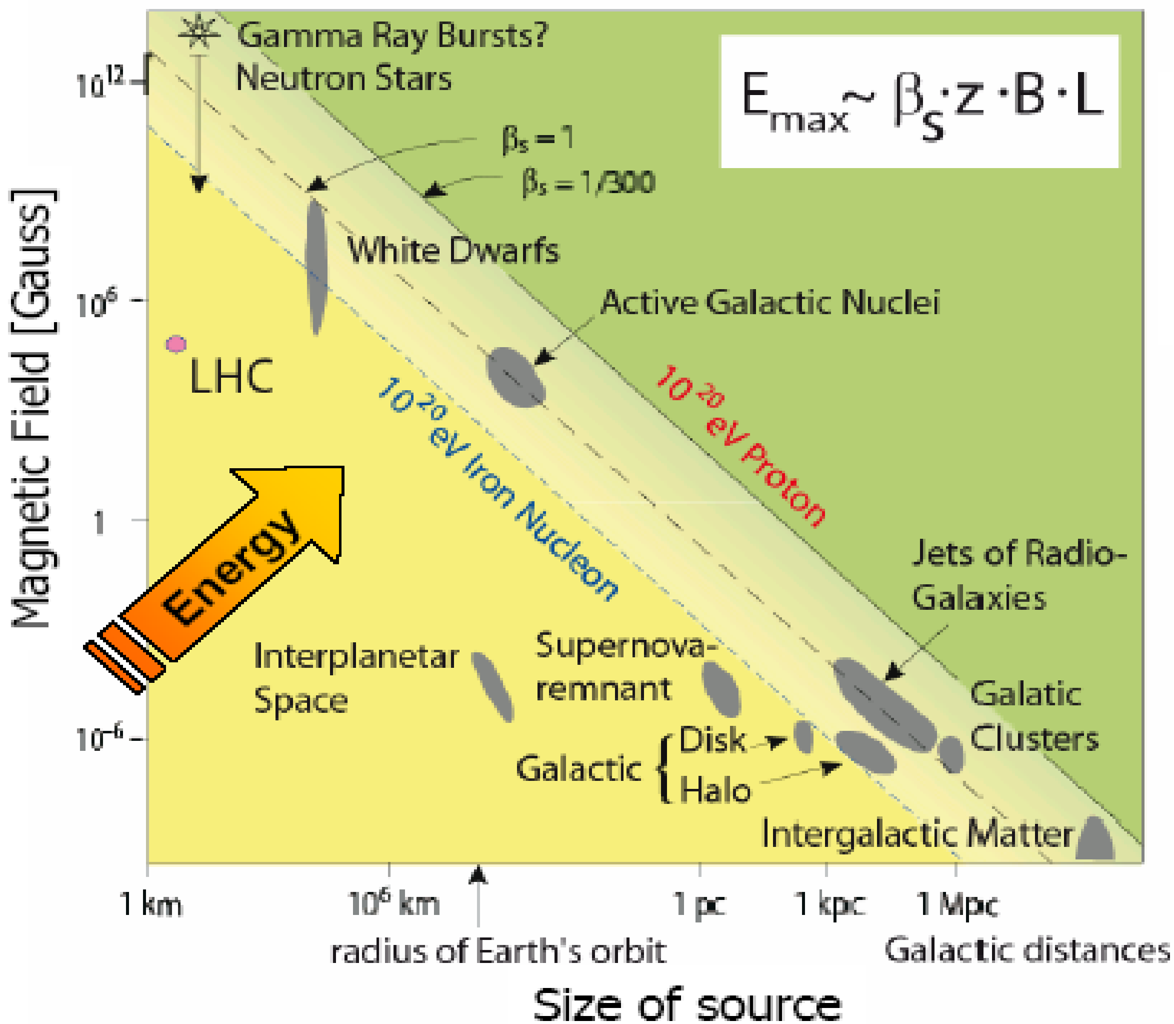


GRB



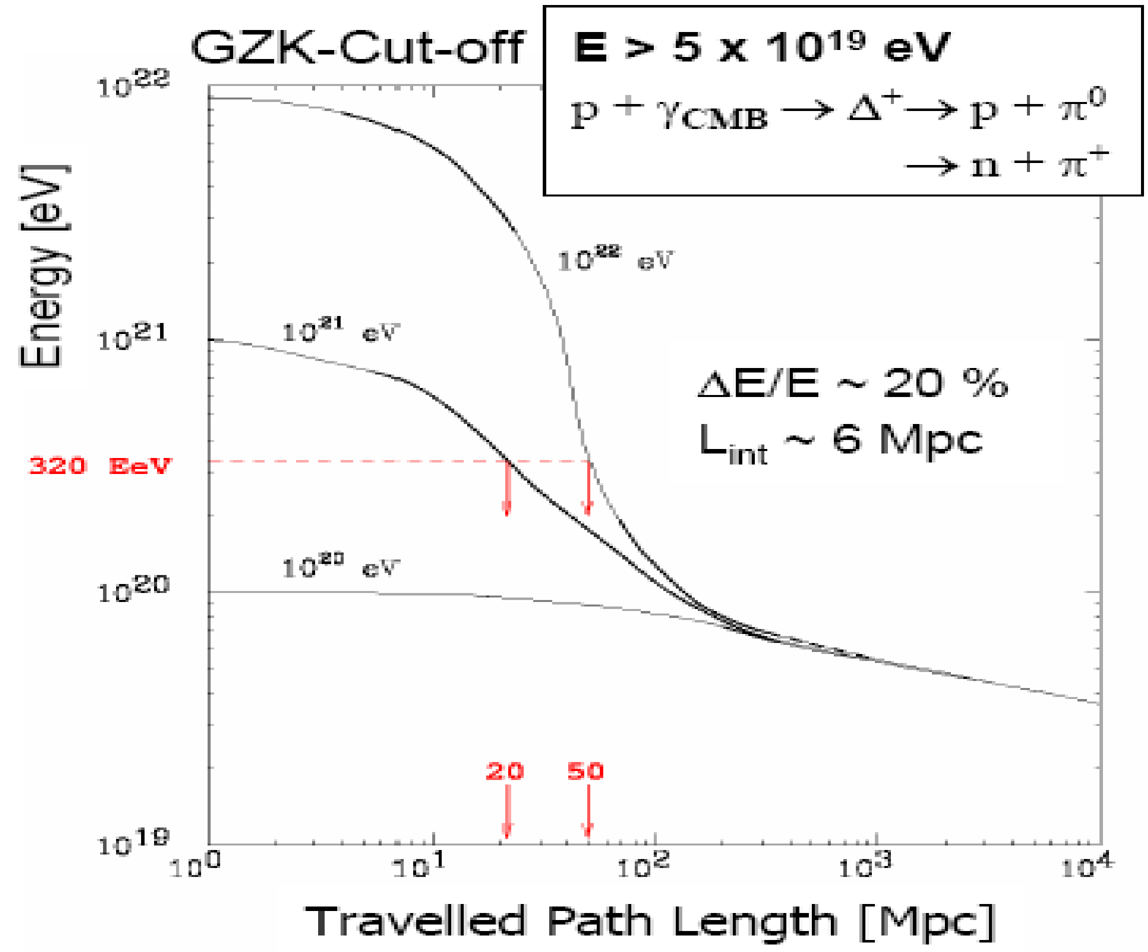
Maximum energy achievable is: $$\frac{E_{max}}{10^{18}eV} \simeq \frac{\beta Z}{2}\frac{B}{\mu G}\frac{L}{kpc}$$

Hillas plot

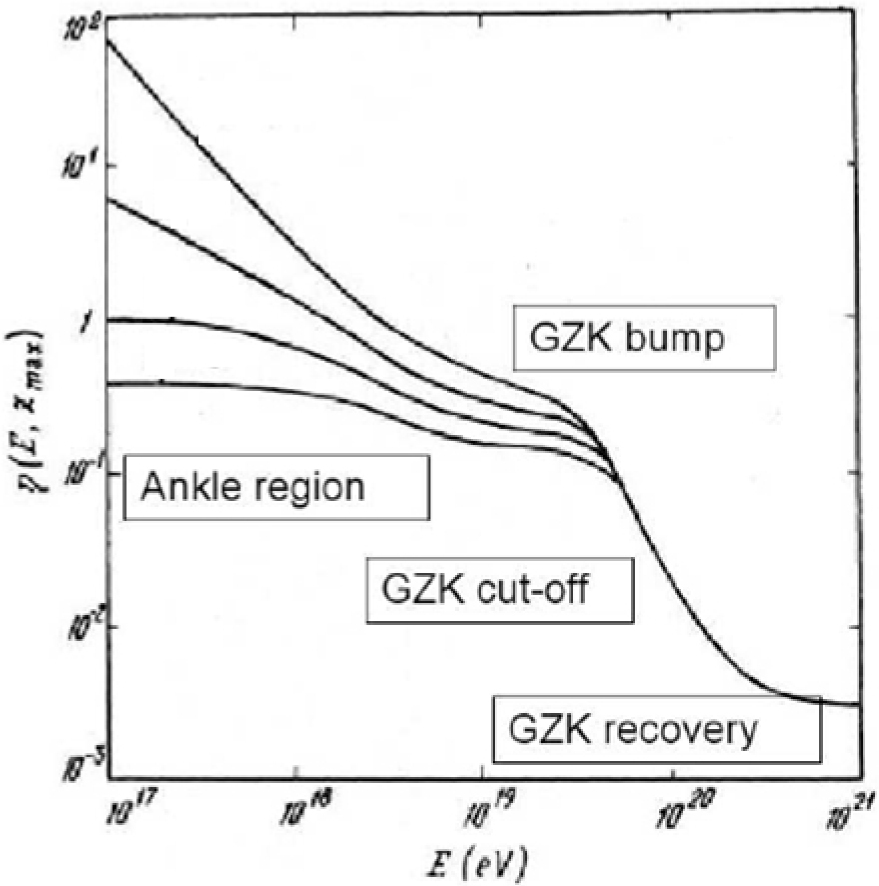


There is no theoretical reason why no object locates in the blank corner (upper right) of the Hillas plot.

Interaction of CRs with cosmogenic photon background



The end of the spectrum?
The GZK suppression and beyond



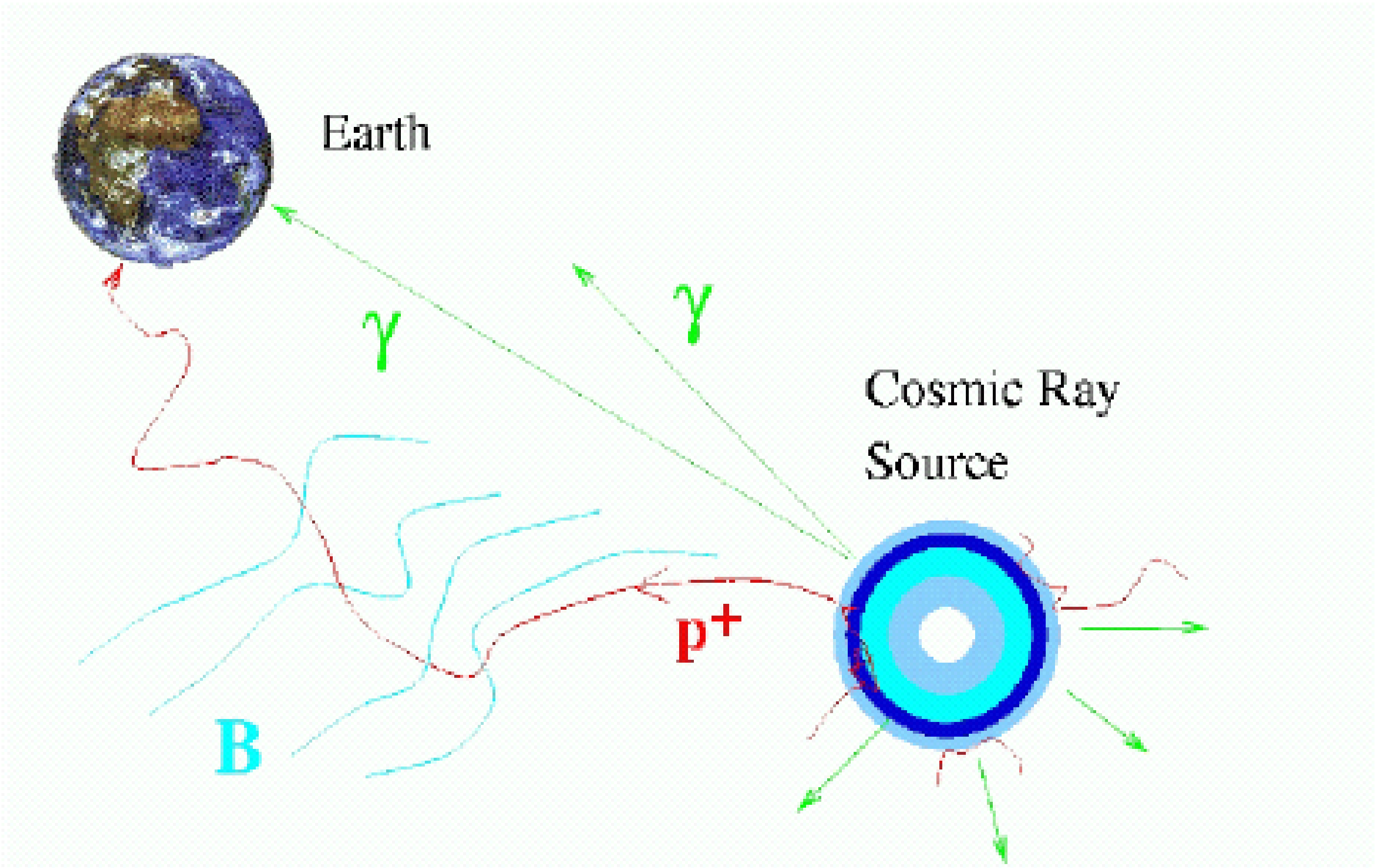
(JEM-Euso design report)

•Suppression is caused by GZK interaction or an intrinsic limit in the acceleration at sources?

- Acceleration limit: sharp cut-off
- GZK signatures: bump and recovery

but not definitive answer... (new sources or top-down models)

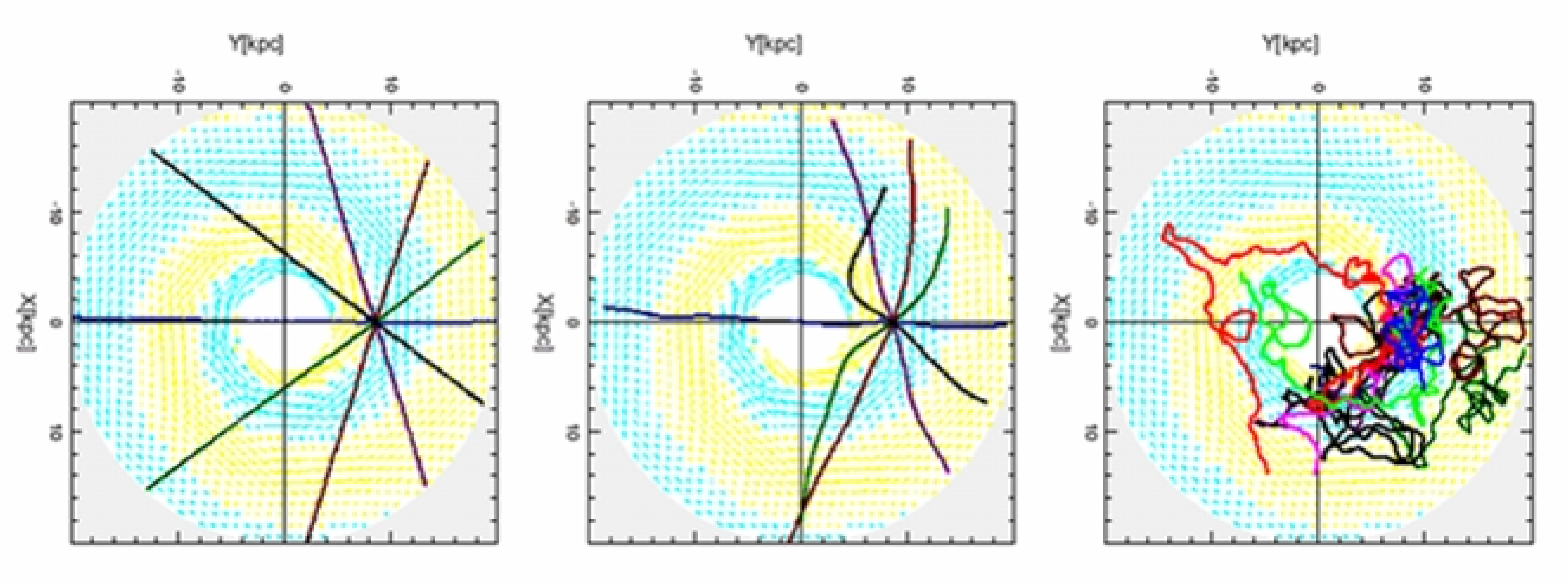
Magnetic Fields



Charged particles are deflected by Galactic and Extra-Galactic Magnetic Fields

To point back to their sources we need to know the strength of the magnetic field, its orientation, the charge of the cosmic particle and the distance between the source and the Earth.

Galactic Magnetic Field ~ 2 μG



$E=10^{20}$ eV | **$E=10^{19}$ eV** | **$E=10^{18}$ eV**

Astronomy is opened at the higher energies

Signatures: photons

Gelmini et al. 2008. Update their study and show that SHDM models are still compatible with Auger photon fractions but severely constrain the energy (E_{th}) above which SHDM provide the bulk of UHECRs. (Fitting HiRes spectrum)

$E_{th} = 10^{20}$ eV

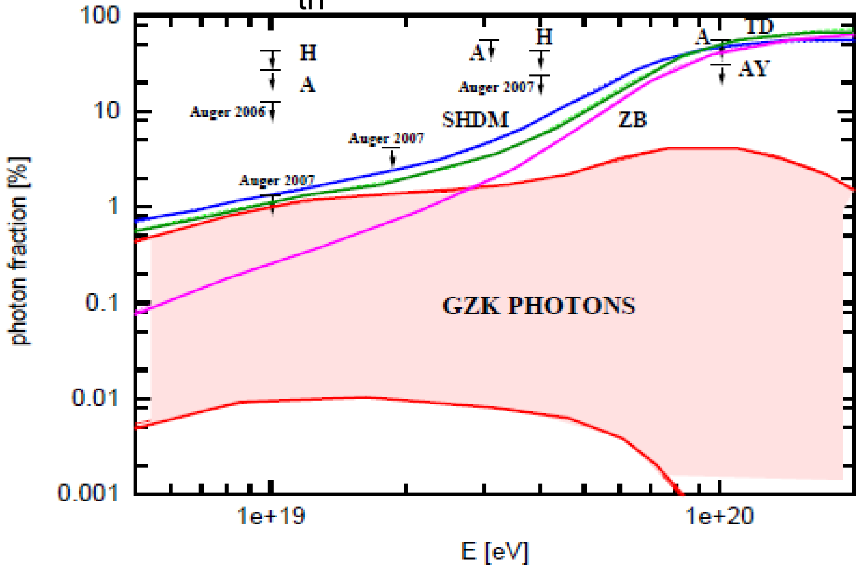


FIG. 17: Photon fraction in percentage of the total predicted integrated UHECR spectrum above the energy E for (a) the AGASA spectrum (upper panel) and (b) the HiRes spectrum (lower panel). The pink regions show the range of GZK photon fractions expected if only nucleons are produced at the sources (see Sect. III). The curves labeled ZB (Z-bursts), TD (topological defects) and SHDM (Super Heavy Dark Matter model) show examples of minimum photon fractions predicted by these models (see Sect.IV). Upper limits: **A** from AGASA, Ref. [10] at $1-3\times10^{19}$ eV, Ref [51] and obtained with AGASA data at 10^{20} eV); **AY** from the Yakutsk collaboration combining data from Yakutsk and AGASA, above 1×10^{20} eV [70]; **H** from Haverah Park [18]. The 2006 [71] and 2007 [72] Auger upper bounds on the photon fraction are also shown.

$E_{th} = 4 \times 10^{19}$ eV

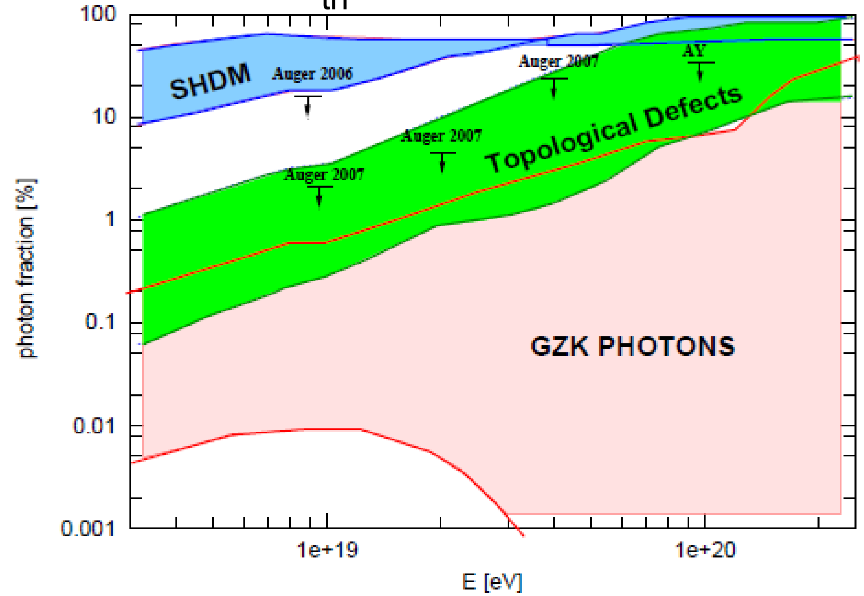


FIG. 18: Photon fraction in percentage of the total predicted integrated UHECR spectrum above the energy E for (a) the AGASA spectrum (upper panel) and (b) the HiRes spectrum (lower panel). Shown in pink is the wider range of GZK photon fractions expected if only nucleons are produced at the sources derived in Ref. [67] (see Fig. 7 therein). Shown in green and blue are respectively the ranges of photon fractions in Fig. 14 (for TD models) and in Fig. 16 (for SHDM models) also obtained with the method of Ref. [67] (see the last paragraphs of IV.B and IV.C). The 2006 [71] and 2007 [72] Auger upper bounds on the photon fractionas well as the upper bound by the Yakutsk collaboration combining data from Yakutsk and AGASA, above 1×10^{20} eV [70] (**AY**) are also shown.

- Cryptons: give photon fraction still compatible with Auger limits depending on the decay mode (Ellis et al. 2006)

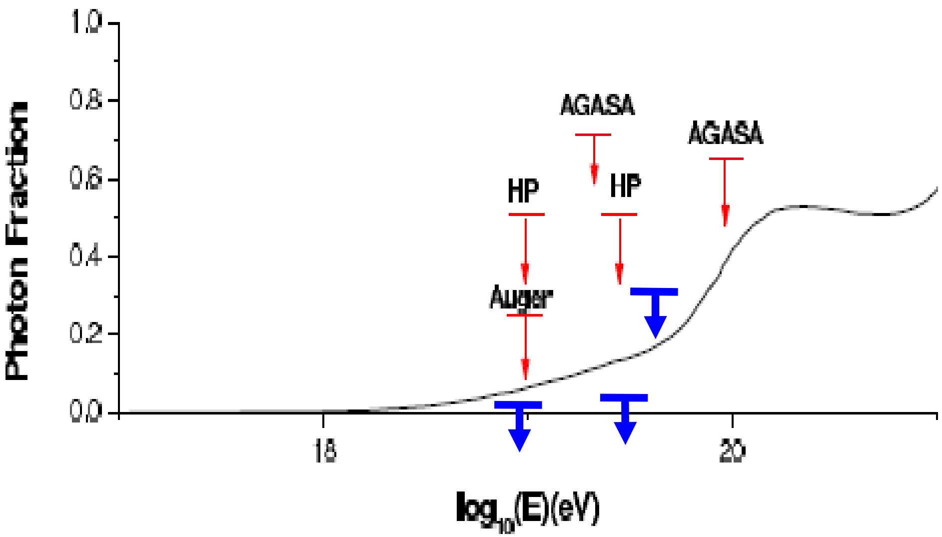


FIG. 3: The top panel shows the total UHECR spectrum and the bottom panel the photon fraction from the decay mode $\Psi^0 \to b\, b^c\, h_d\, \phi^3$.

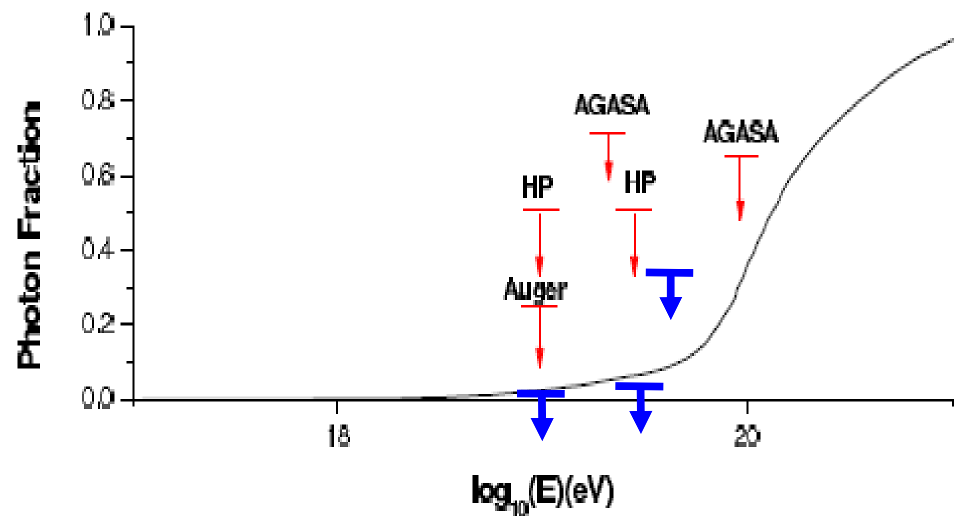
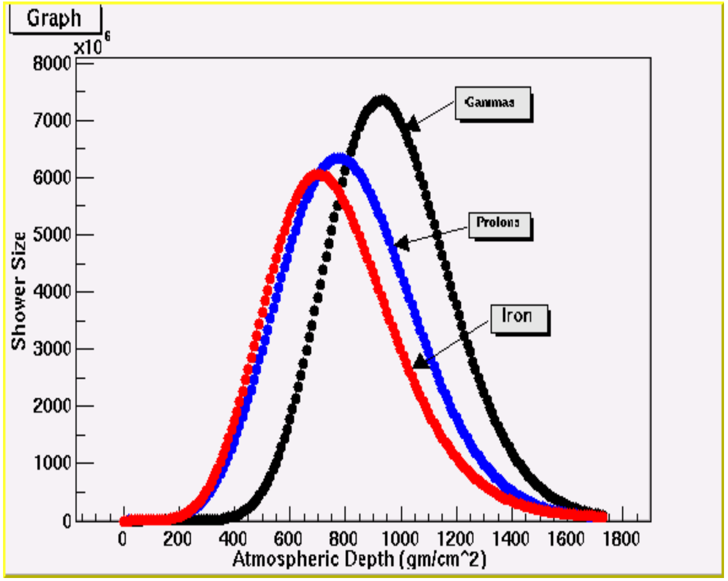
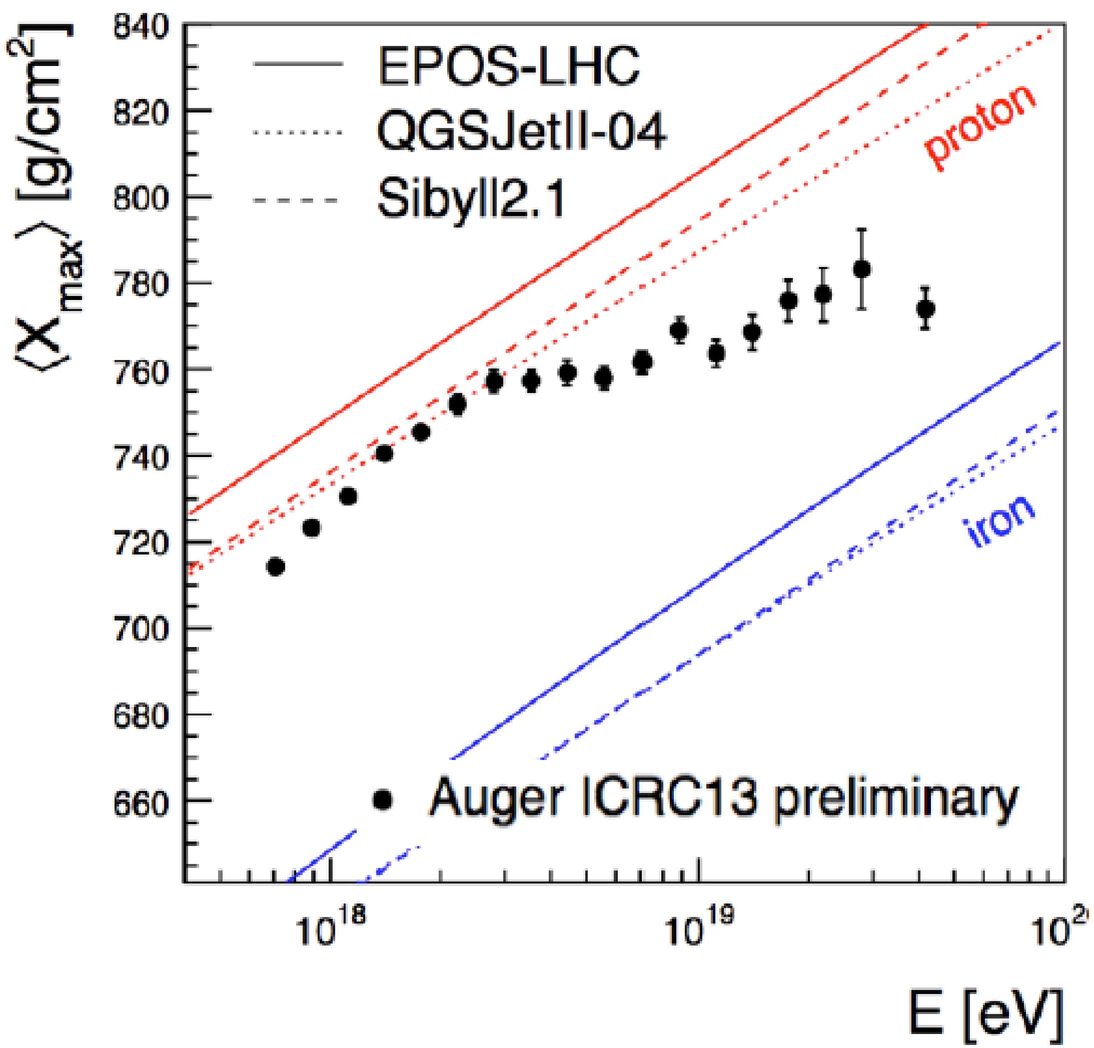


FIG. 8: The top panel shows the total UHECR spectrum and the bottom panel the photon fraction from the decay mode $\Psi^0 \to \tau\, \tau^c\, h_d\, \phi^3$.

↓ Auger SD Limit

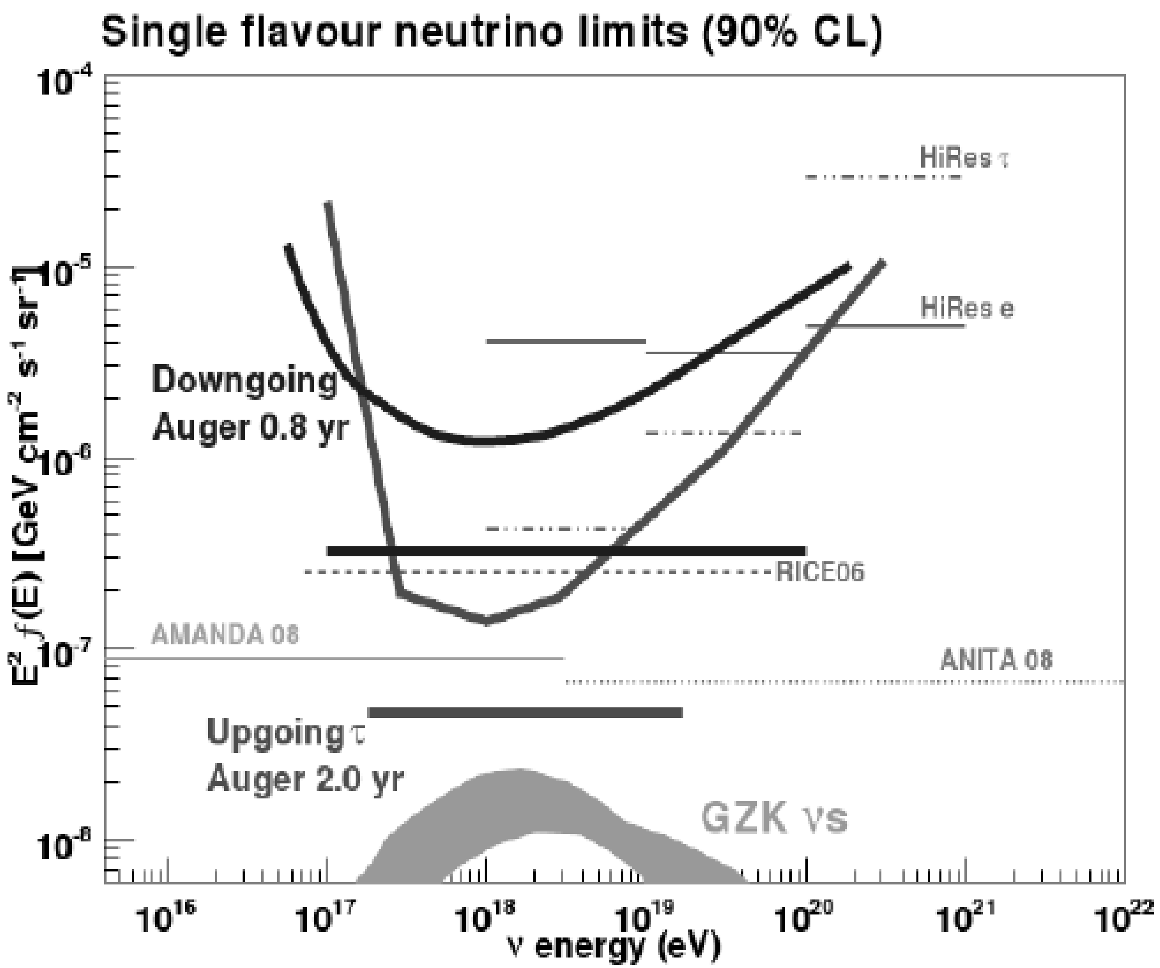
Composition: Xmax ICRC13





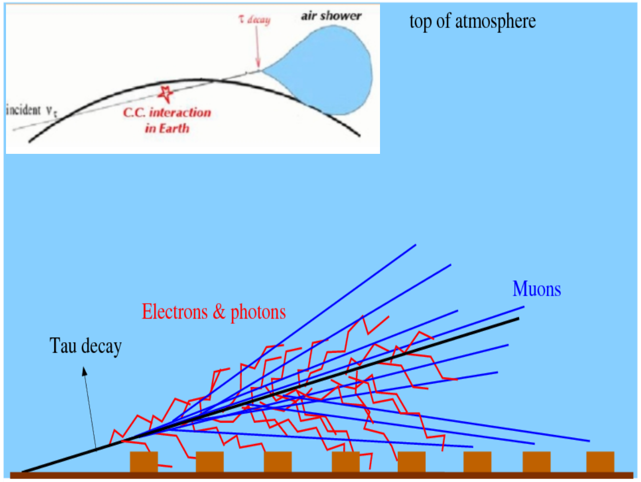
Neutrinos

Auger results

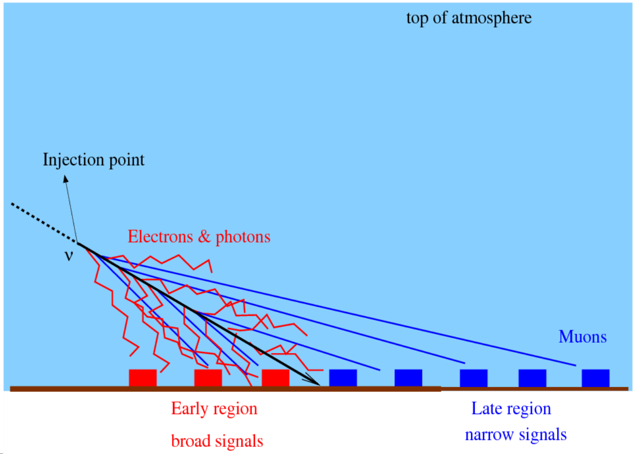


Tiffenberg et al. Auger ICRC '09

Earth-skimming ντ



Down-going ν



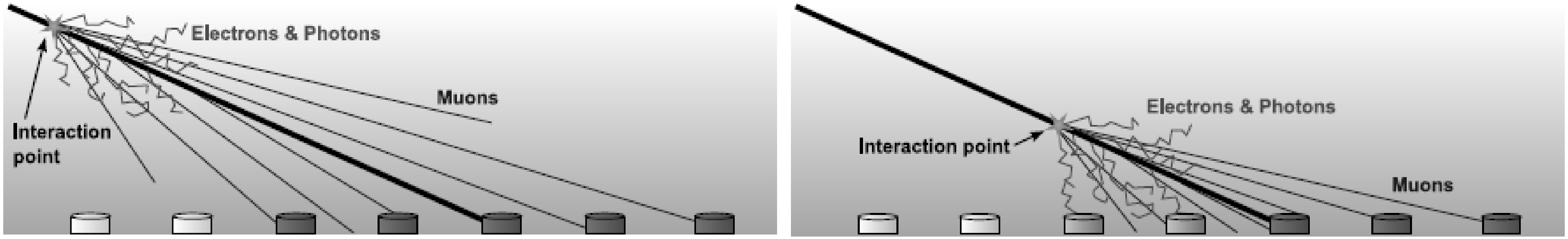


Fig. 1. Left panel: sketch of an inclined shower induced by a hadron interacting high in the atmosphere. The EM component is absorbed and only the muons reach the detector. Right panel: deep inclined shower. Its early region has a significant EM component at the detector level.

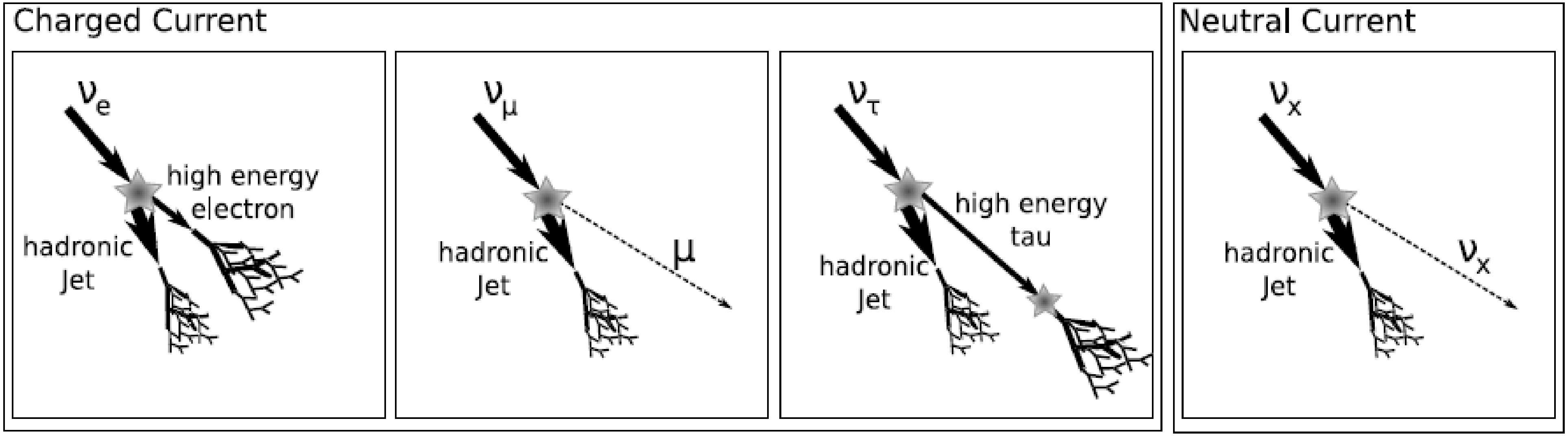


Fig. 2. Neutrinos can initiate atmospheric showers through charged (CC) or neutral (NC) current interactions. On ν_e CC interactions all the energy of the primary neutrino is transferred to the shower. This is not the case of the NC channel where the primary neutrino energy is only partially transferred to the shower while a significant fraction is carried away by the scattered neutrino. Similar behaviour is seen on the ν_μ CC induced showers where the emerging high energy muon usually decays under the ground and doesn't produce a shower. Note that ν_τ CC initiated showers may have a "double bang" structure due to the fact that the out-coming high energy τ may travel a long distance before decay producing a second displaced shower vertex.

Tiffenberg et al. Auger ICRC '09

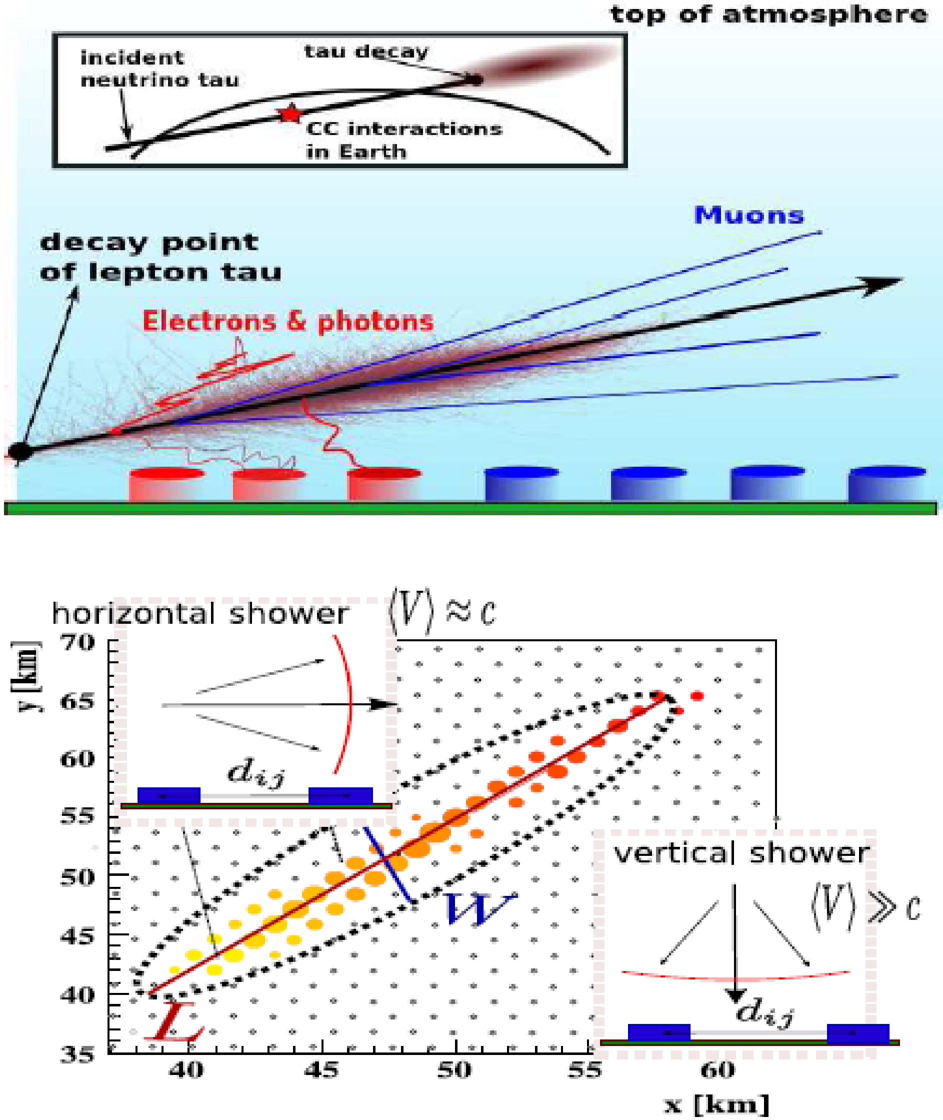


Fig. 1. (Upper panel) The sketch of a shower induced by the decay of a τ lepton emerging from the Earth after originating from an Earth-skimming ν_τ. The earliest stations are mostly triggered by electrons and γs; (bottom panel) sketch of length (L) over width (W) of a footprint and determination of the apparent velocity ($\langle V \rangle$). The $\langle V \rangle$ is given by averaging the apparent velocity, $v_{ij} = d_{ij}/\Delta t_{ij}$ where d_{ij} is the distance between couples of stations, projected onto the direction defined by the length of the foorprint, L, and Δt_{ij} the difference in their signal start times.

Earth-skimming neutrino identification:

- young showers close to ground.

- elongated footprint at ground.

- mean apparent velocity compatible with c

Gora et al. Auger ICRC ‘09

Gora et al. Auger ICRC 09

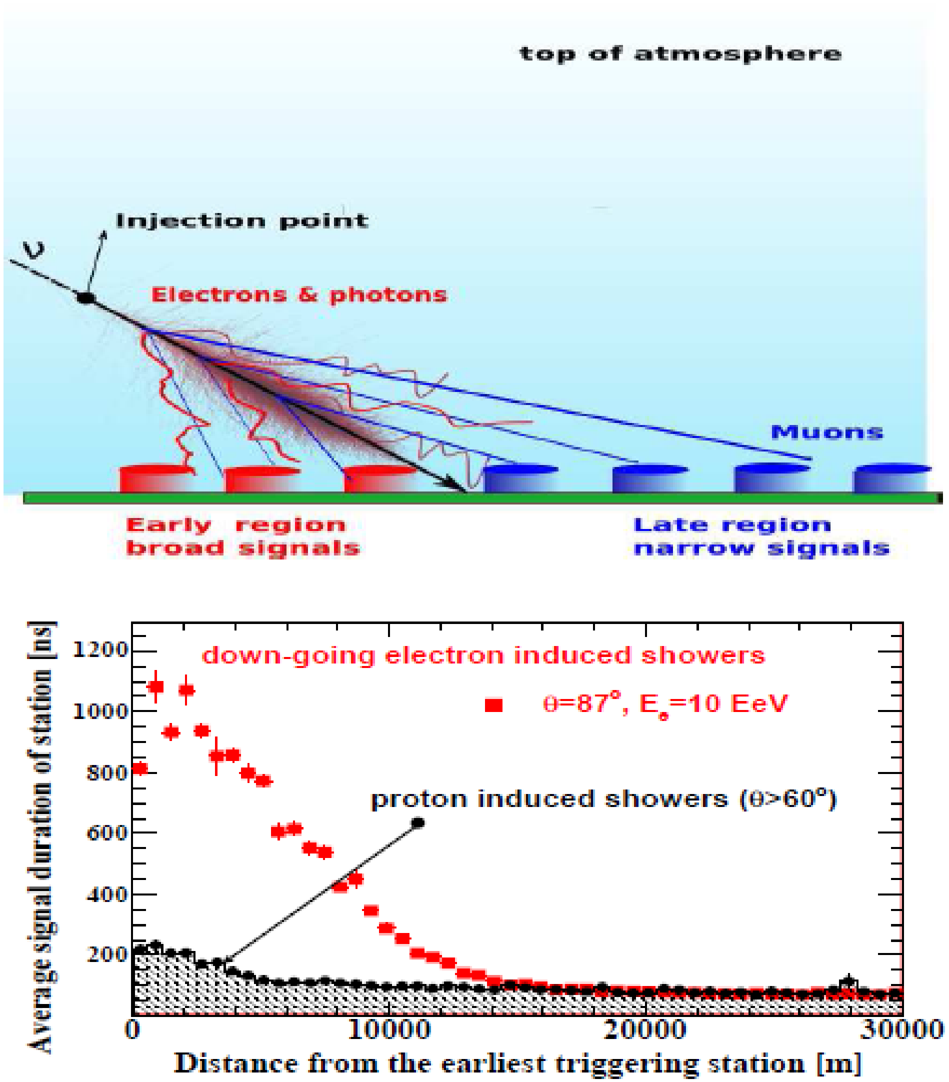
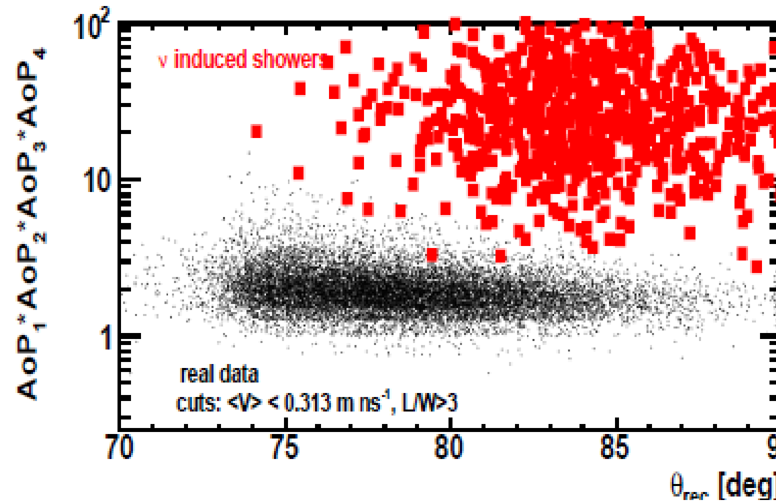
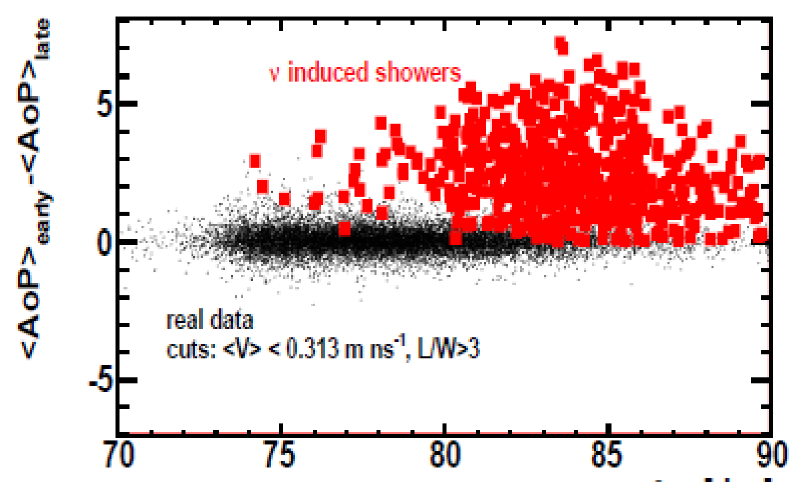


Fig. 2. (Upper panel) Sketch of a down-going shower initiated in the interaction of a ν in the atmosphere close to the ground; In the "early" ("late") region of the shower before (after) the shower axis hits the ground we expect broad (narrow) signals in time due to electromagnetic (muonic) component of the shower; (bottom panel) the average signal duration of the station as a function of the distance from the earliest triggering station.

Down-going neutrino identification:

- young showers close to ground.
- elongated footprint at ground.
- broader FADC signals.





GZK-neutrinos or cosmogenic neutrinos (JEM-Euso design report)

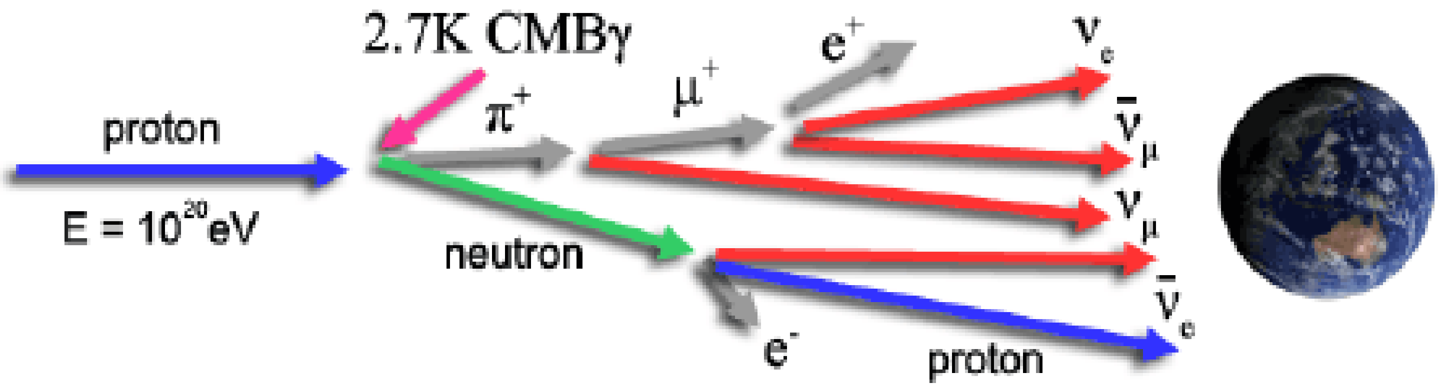


Figure 2-12 Cosmogenic Neutrinos are expected by the GZK mechanism in vacuum.

Neutrinos from AGN, TD, GZK and sensitivity of JEM-Euso (Ebisuzaki et al. 2008)

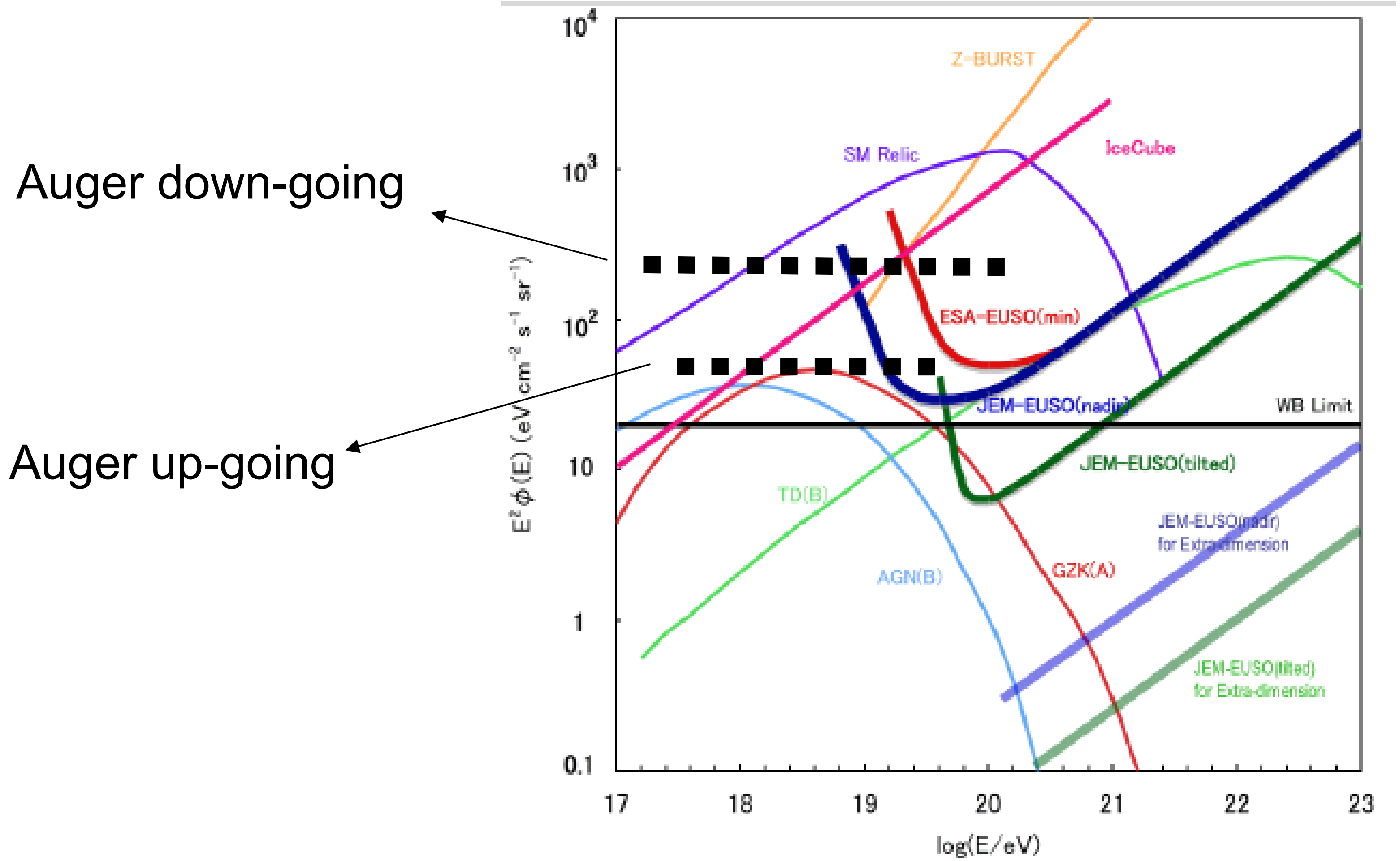


Figure 2-11 The flux-sensitivity of JEM-EUSO of 1 event/energy-decade/year; an observational efficiency of 25% is assumed. Red Thick Line: ESA-EUSO (min); Blue Thick Line: JEM-EUSO Nadir; Green Thick Line: JEM-EUSO-Tilt. As for Ice cube (Pink line), a few events/energy-decade/10years is assumed. Black Line denotes the Waxman-Bahcall limit.

Aloisio (2006): Neutrino flux prediction by fitting AGASA spectrum with extragalactic proton component and top-down model.

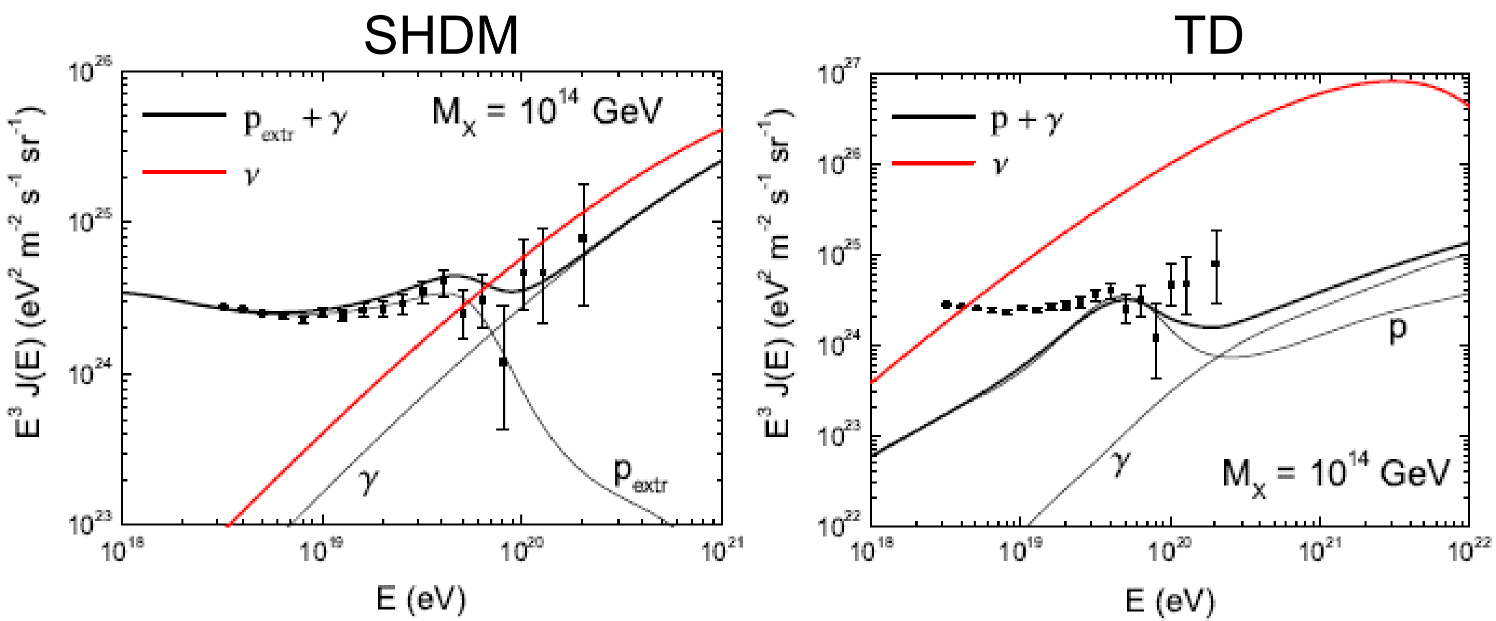


Fig. 1. [Right Panel] Comparison of SHDM prediction with the AGASA data. The calculated spectrum of SHDM photons is shown by the label γ and by the label p_{extr} the spectrum of extragalactic protons (uniformly distributed astrophysical sources). The sum of these two spectra is shown by the thick black curve. The red thick line is the SHDM neutrino flux. [Left Panel] Diffuse spectra from necklaces. The red thick curve shows neutrino flux, the black thick curve is the sum of protons and photons fluxes produced by necklaces (labeled thin black lines).

- The largest fraction of UHE particles produced in top-down models are neutrinos.

- **The neutrino flux from Topological Defect models is lower the GZK-neutrino flux below 10^{20} eV.**

- **The neutrino fraction from SHDM is lower than from topological defects.**

- **Auger is able to detect GZK neutrinos while their energy is too low for full efficiency in JEM-Euso.**

- **On the other hand, JEM-Euso could detect neutrinos from topological defects while the flux is too low for Auger**

- JEM-Euso can set up an upper-limit on neutrino flux lower than the Waxman-Bahcall limit (neutrino flux from baryon interacting with material surrounding cosmic ray source. They estimate production from a measured spectrum assuming a low density target and neutrino produced from standard pion/kaon production and decay. They arbitrarily multiply this value by 5 and call it a limit).

Neutrinos from AGNs in the dip model

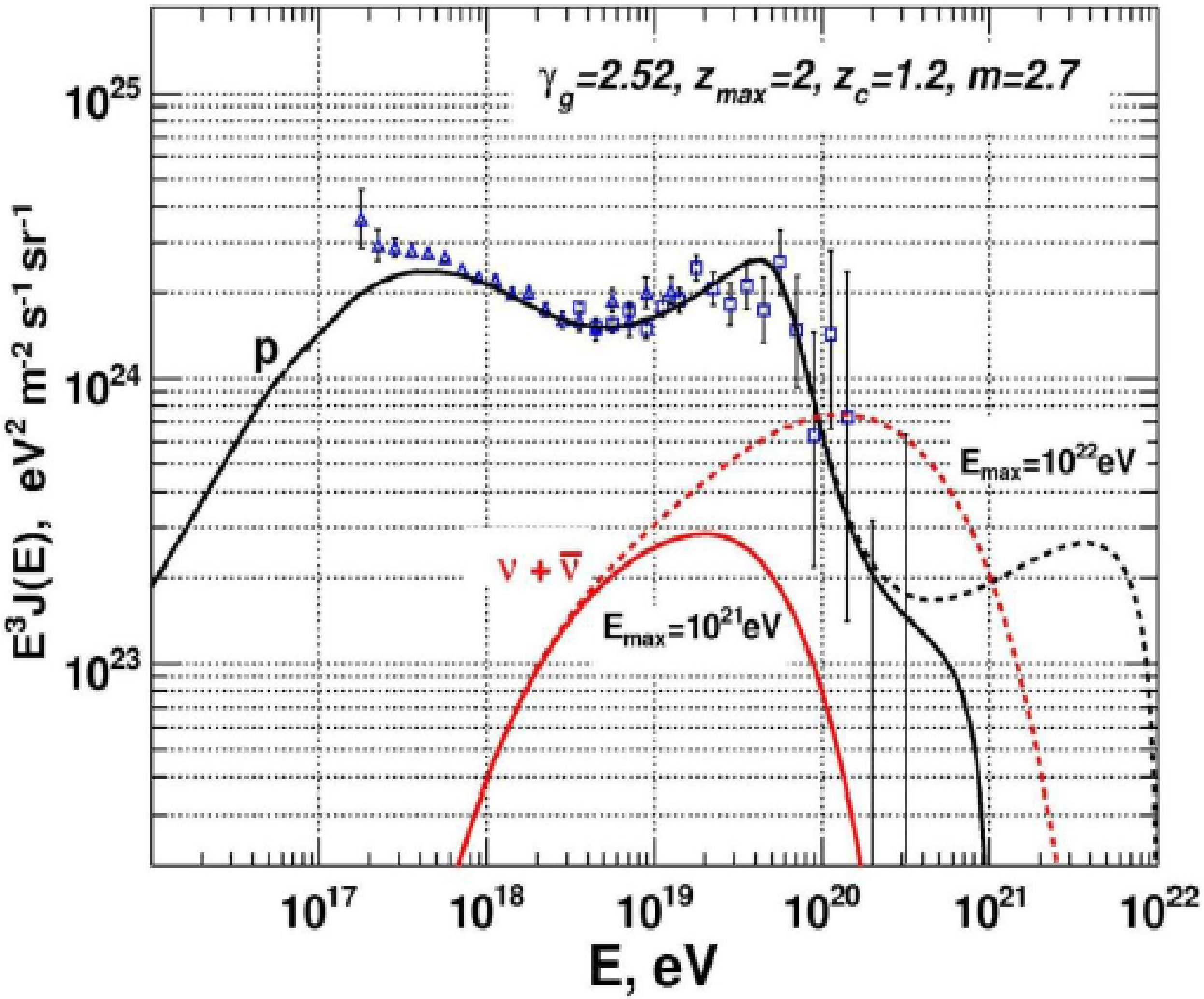


Figure 2: UHE neutrino flux in the dip model with AGN as the sources of UHECR. The cosmological evolution of AGN with $m = 2.7$ up to $z_c = 1.2$ is taken from X-ray observations of AGN. At larger z the evolution is frozen up to $z_{max} = 2.0$. The fit of the dip is very good, though requires $\gamma_g = 2.52$ different from the non-evolutionary case $m = 0$. The neutrino fluxes are given for one neutrino flavor.

V. Berezinsky

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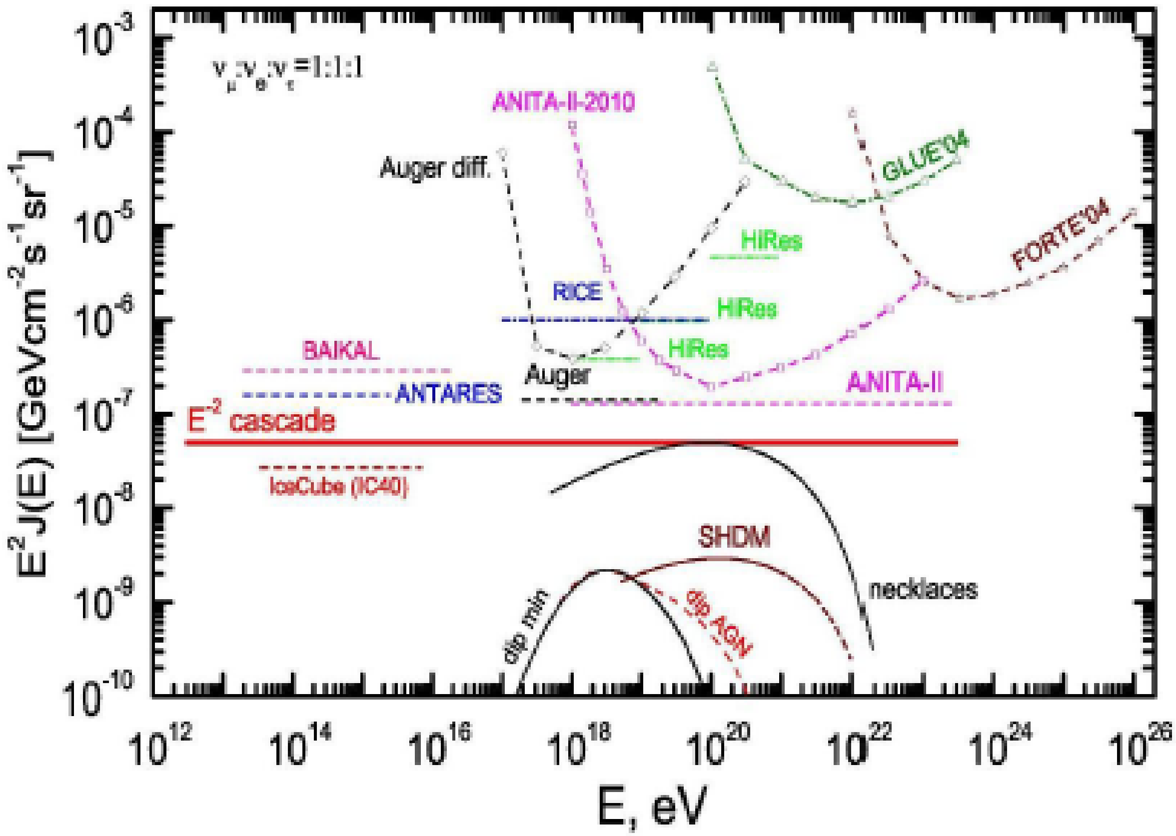


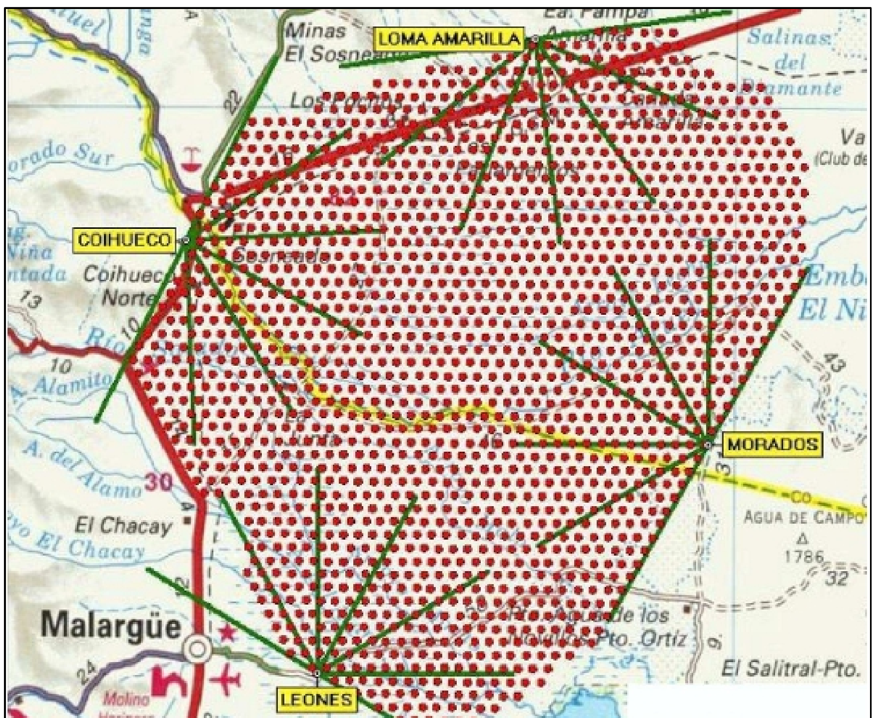
Figure 4: The experimental upper limits on UHE neutrino fluxes in comparison with e-m cascade upper limit in assumption of E^{-2} generation spectrum (curve E^{-2} cascade) and with predictions for cosmogenic neutrinos in the dip model (curves dip-min and dip-AGN), for neutrinos from necklaces and from SHDM. Neutrino fluxes from necklaces and SHDM are normalized by AGASA data, and for normalization by HiRes data the fluxes should be diminished by factor 3 - 5. Neutrino flux from superconducting strings is given by $E^2J(E)$ =const and it can reach the upper limit 'E^{-2}cascade'. Neutrino fluxes are given for three flavors.

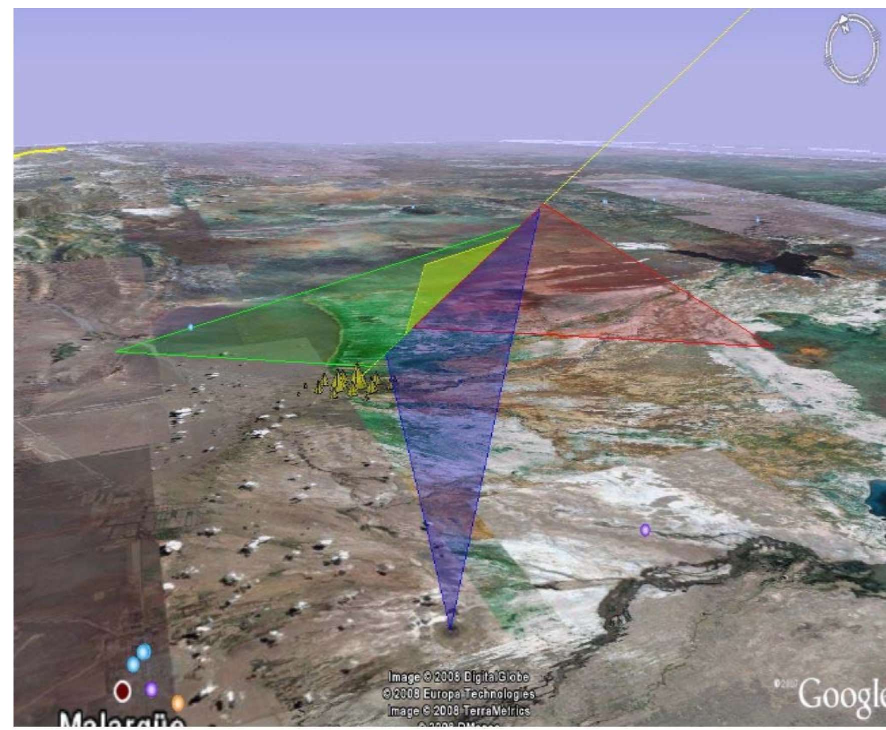
Auger overview

PIERRE AUGER OBSERVATORY

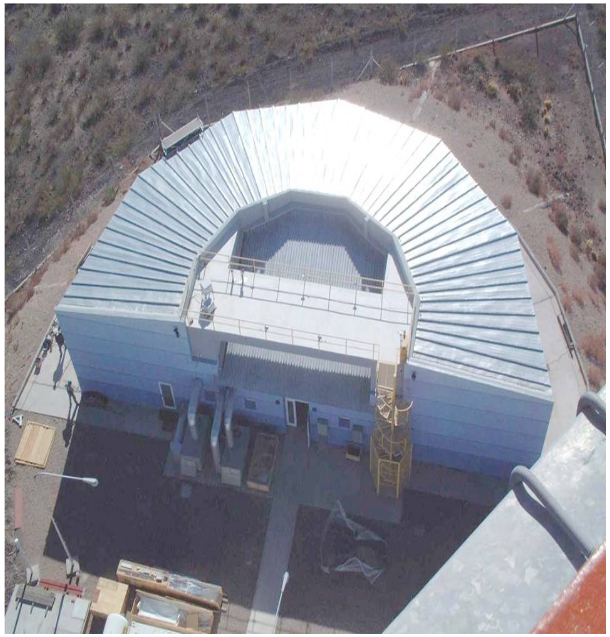
The biggest surface array (~3000 km^2)

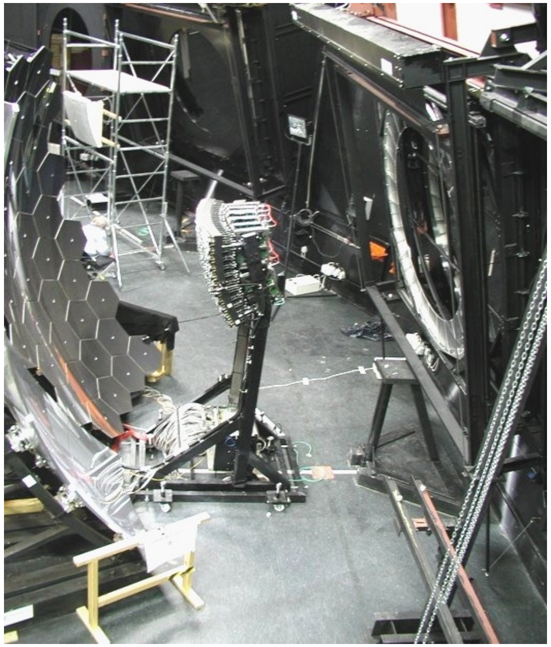
Hybrid detection (HD)

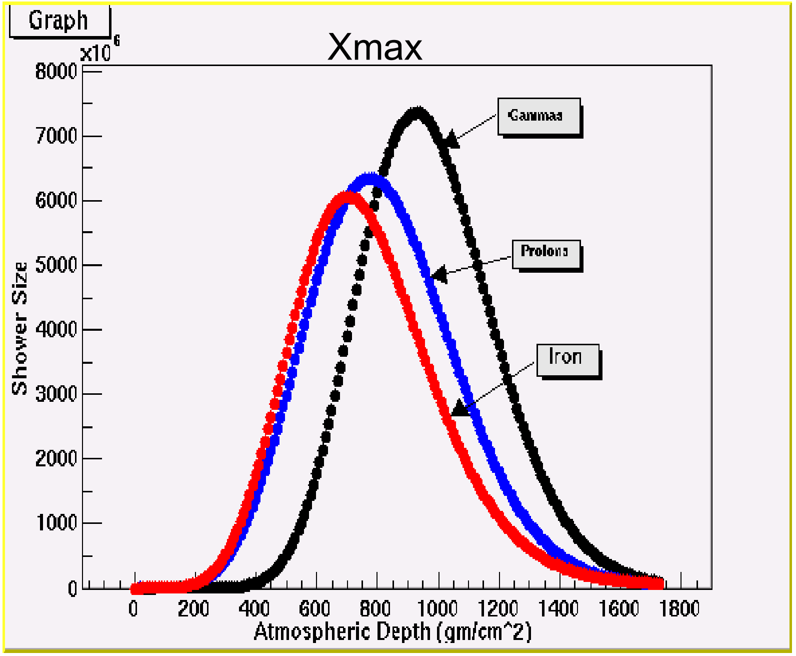




Fluorescence Telescopes





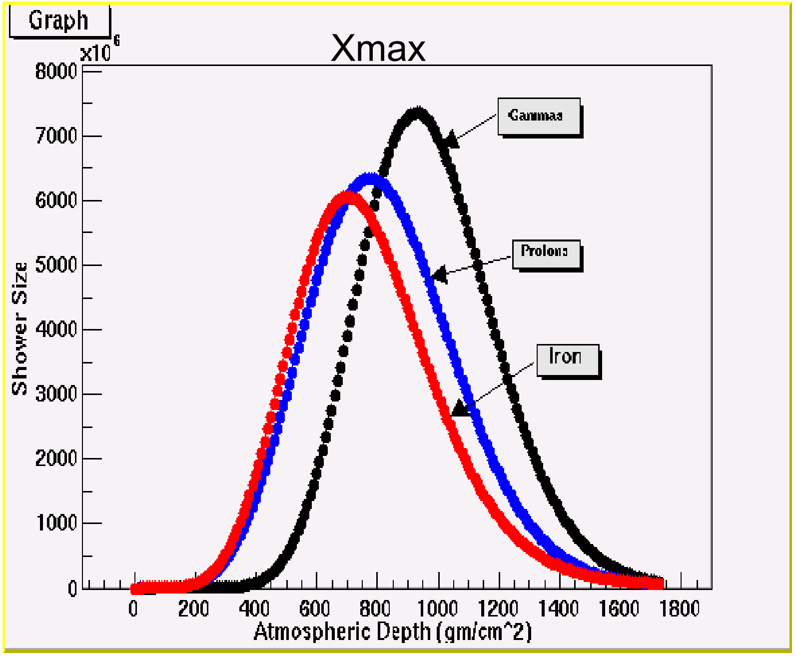


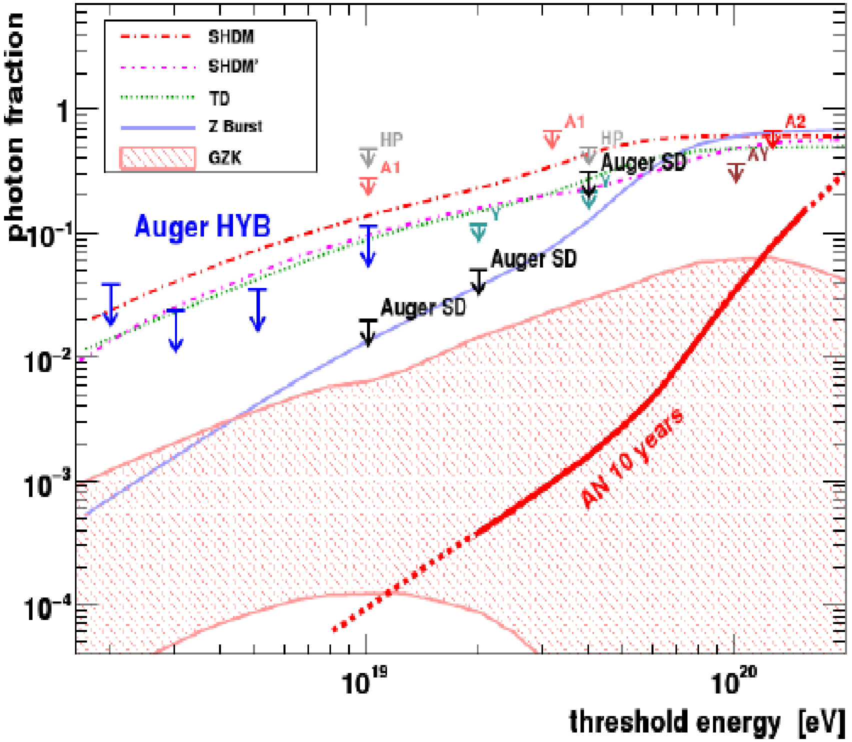
- Measure the longitudinal profile

- Determine Xmax → the best composition-sensitive parameter

- Duty cycle is only ~10%

Photon limit with hybrid events

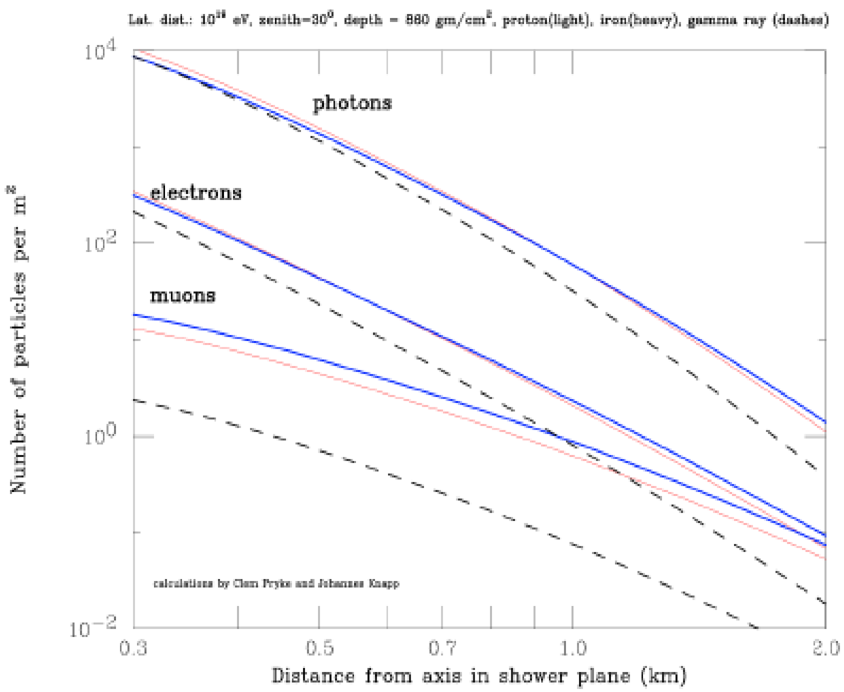




- Using Xmax, calculate a photon limit above 10 EeV.

- Limited statistics.

Surface detectors



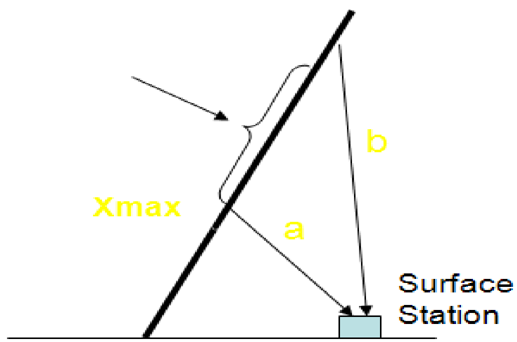
-Measure the lateral profile.

- Primary composition could be inferred by using several parameters sensitive to the different em-muonic components and the spatial and temporal distribution of particles at ground.

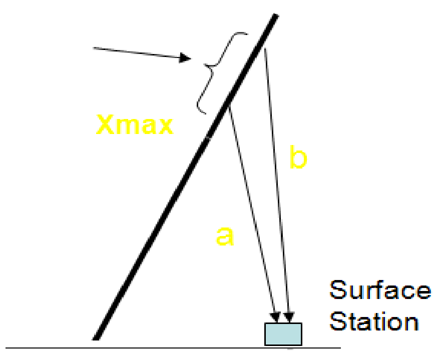
- Duty cycle is ~100%

Photon limit with surface events

Tank signal Rise-time $t_{1/2}$ (at 1000m from the core)

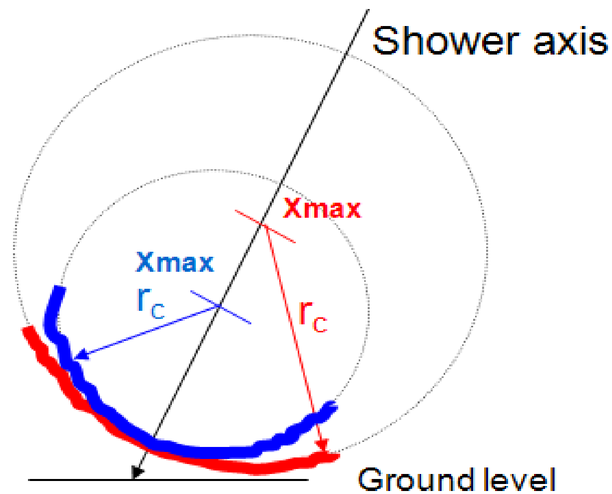


Deep Xmax, t_a-t_b ~ $\mathbf{t_{1/2}}$ large.



Shallow Xmax, $\mathbf{t_{1/2}}$ small.

Radius of Curvature R_c



Shallow Xmax, Large r_c
Deep Xmax, Smaller r_c