Physics of the highest energy cosmic rays

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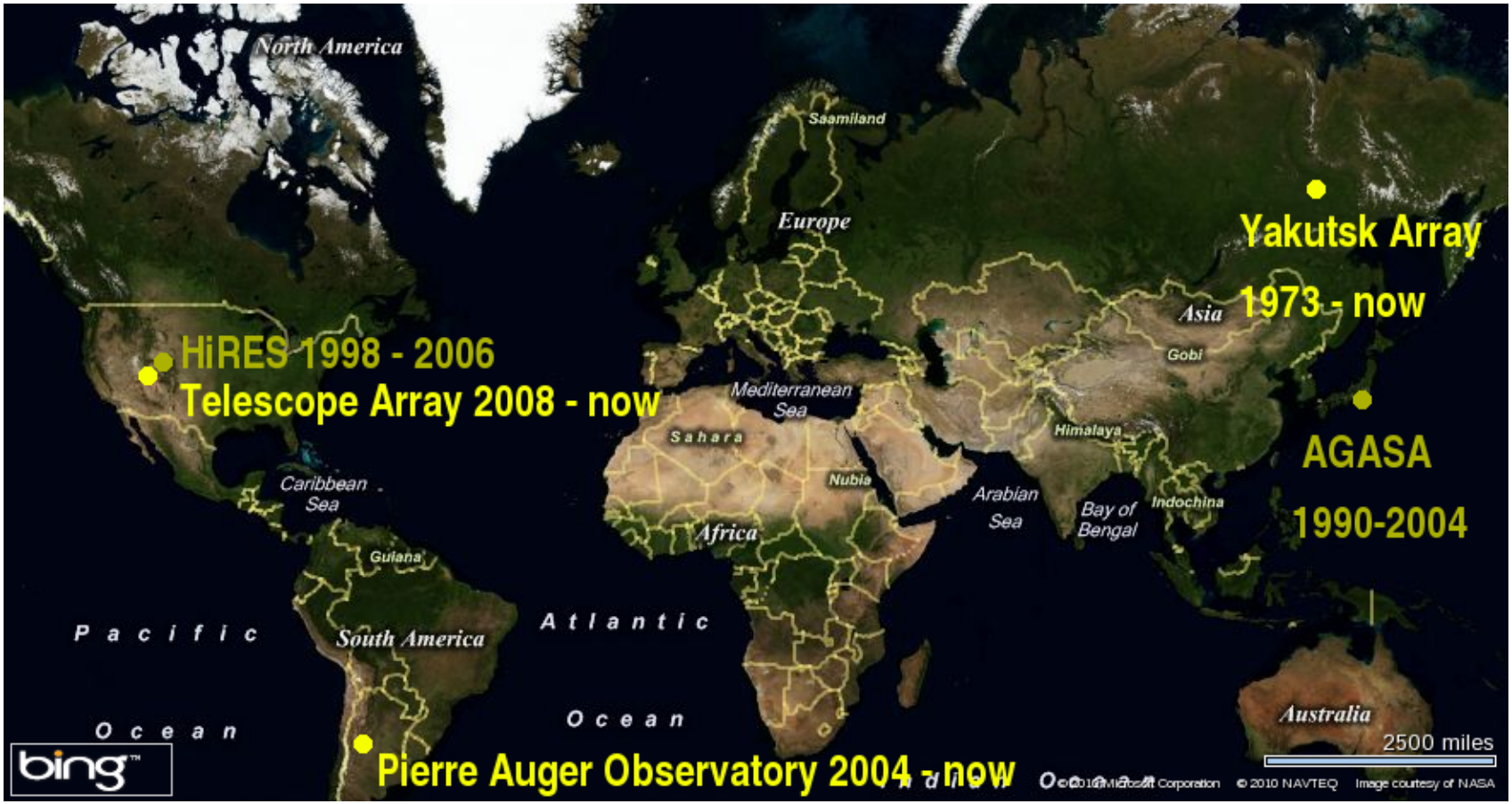
HELMHOLTZ GEMEINSCHAFT

РОССИЙСКИЙ ФОНД ФУНДАМЕНТАЛЬНЫХ ИССЛЕДОВАНИЙ
РФФИ

Outline

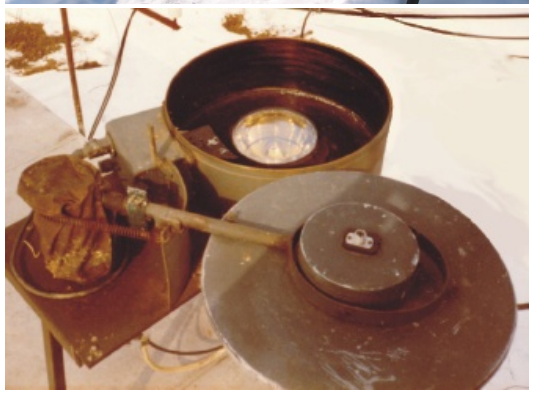
- UHECR experiments ($E \gtrsim 10^{18}\ eV$)
- GZK cut-off
- primary composition
- photons and new physics

UHECR experiments today ($E \gtrsim 10^{18}$ eV)

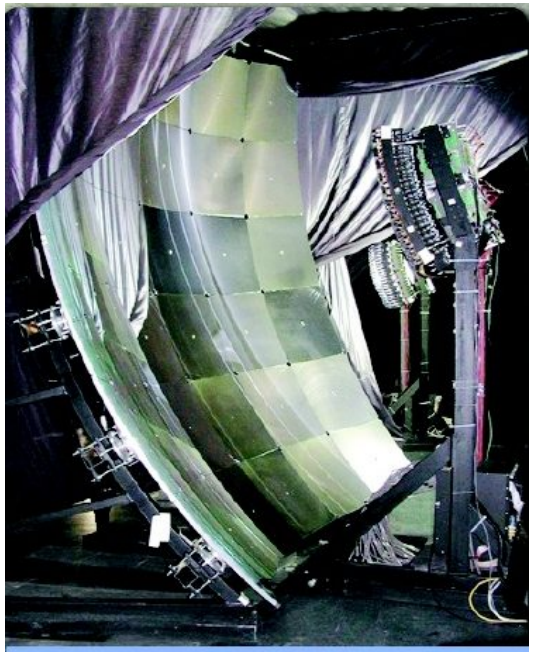


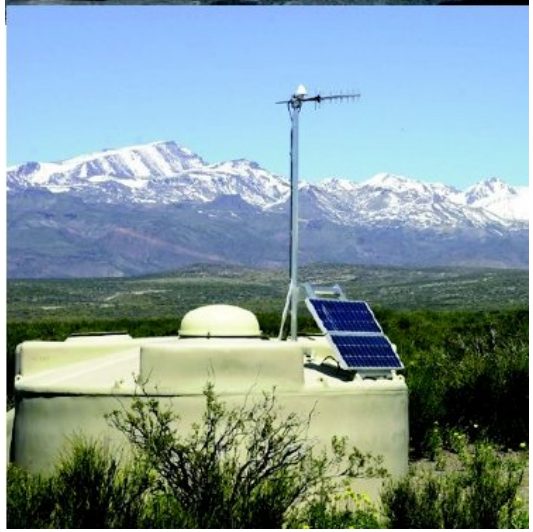
UHECR experiments today ($E \gtrsim 10^{18}$ eV)

Yakutsk array

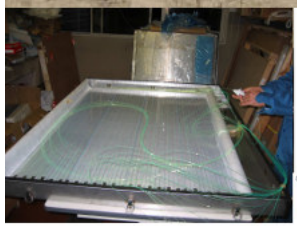


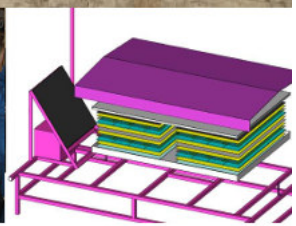
Pierre Auger



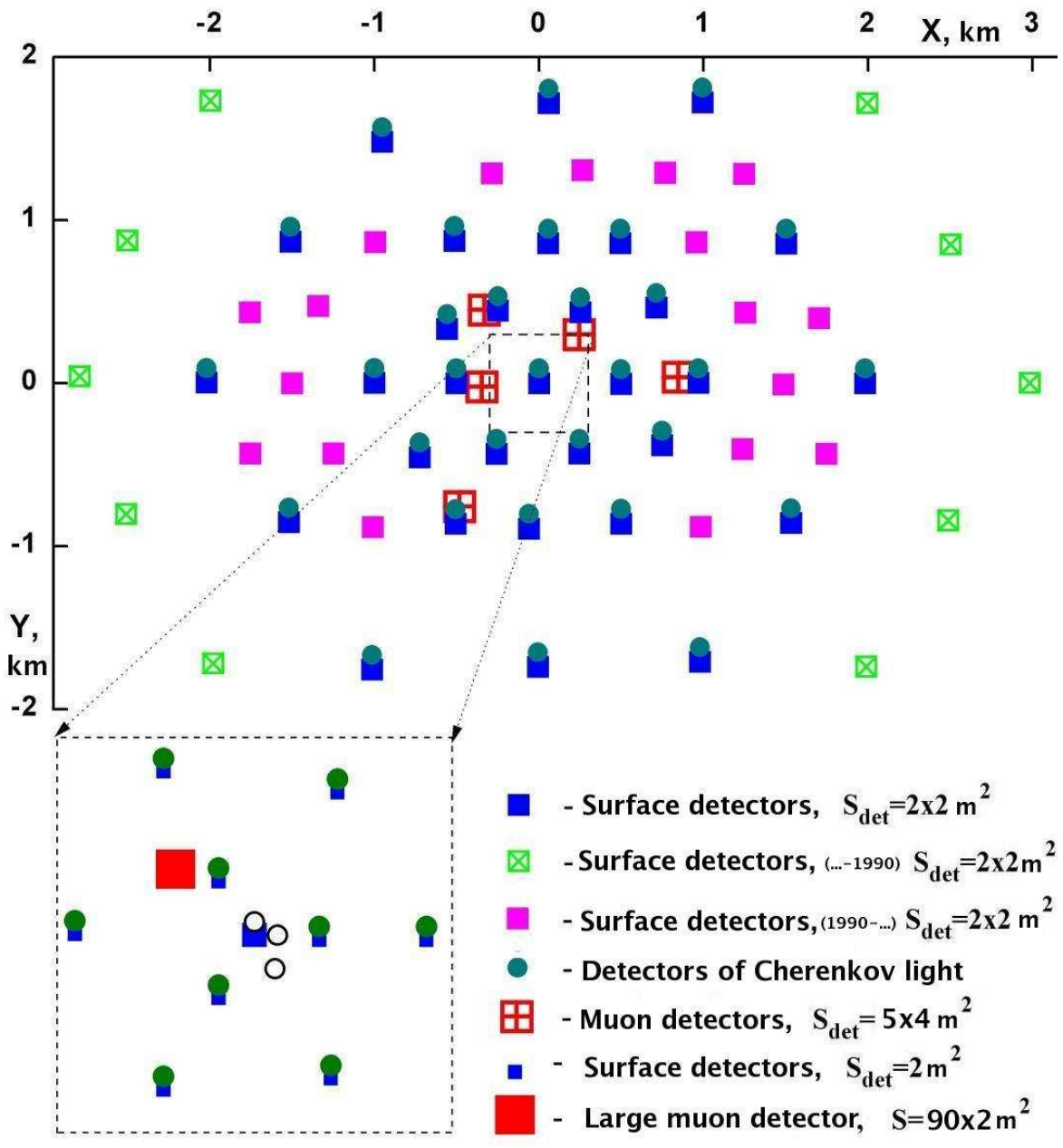


Telescope Array





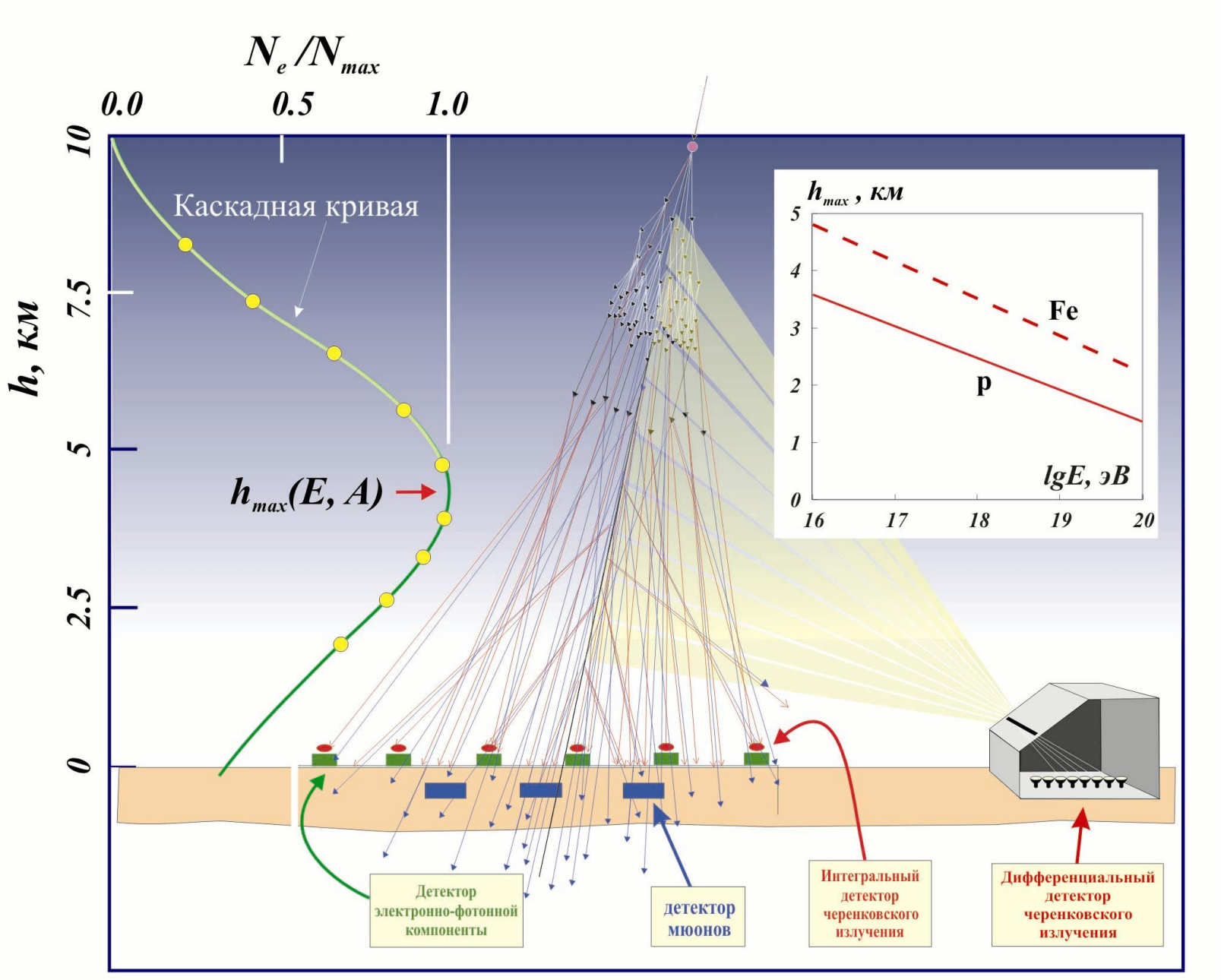
Yakutsk EAS Array



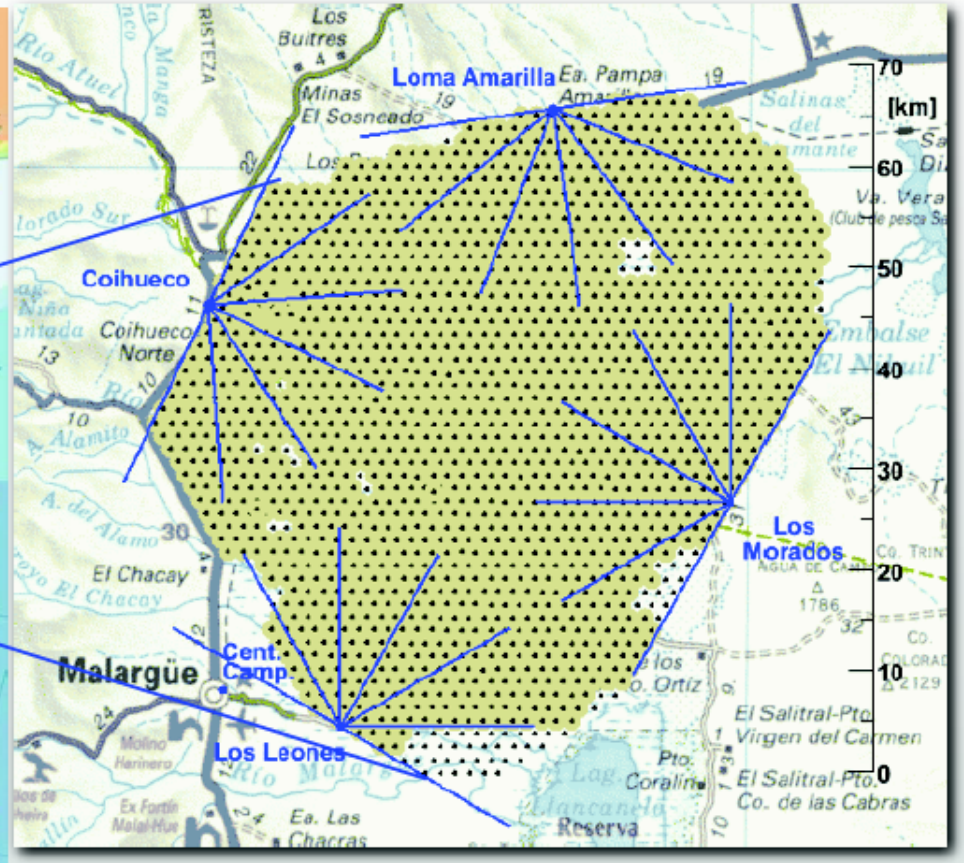
Yakutsk Array today

- Designed as pioneering hybrid array, now contains three types of detectors: scintillation, muons, Cherenkov.
- Unique facility to probe composition and hadronic interaction.
- The upgrade is ongoing: time resolved signals at SDs; new type of differential Cherenkov detectors.

Differential Cherenkov detector



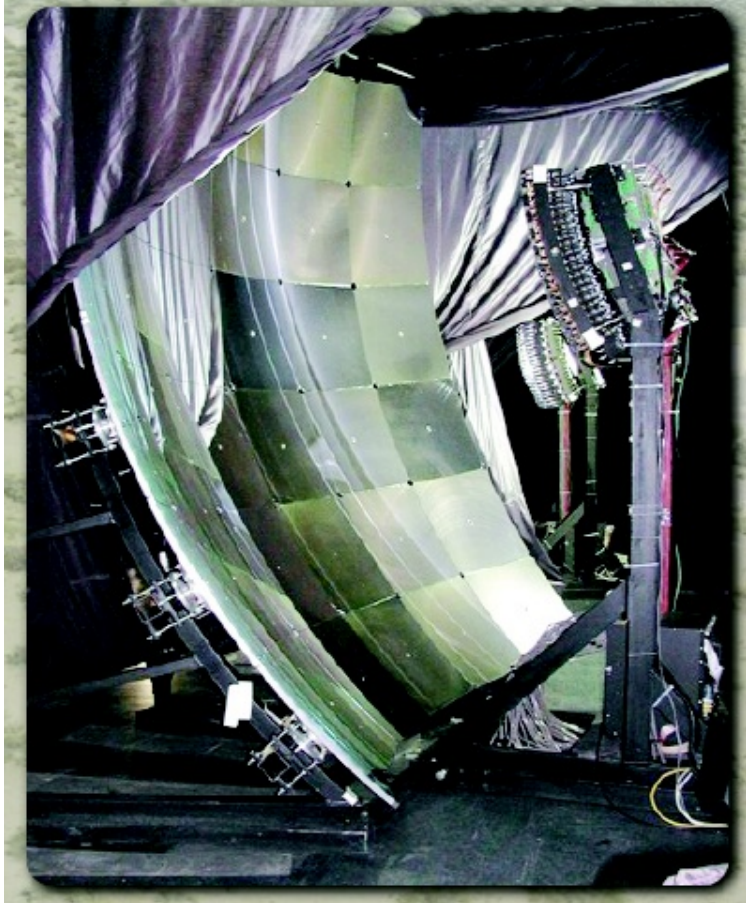
Pierre Auger Observatory in Argentina



3000 km² area on a plateau 1450 m a.s.l.
1660 Detector Stations +
27 FD Telescopes at periphery

Auger fluorescence and surface detector

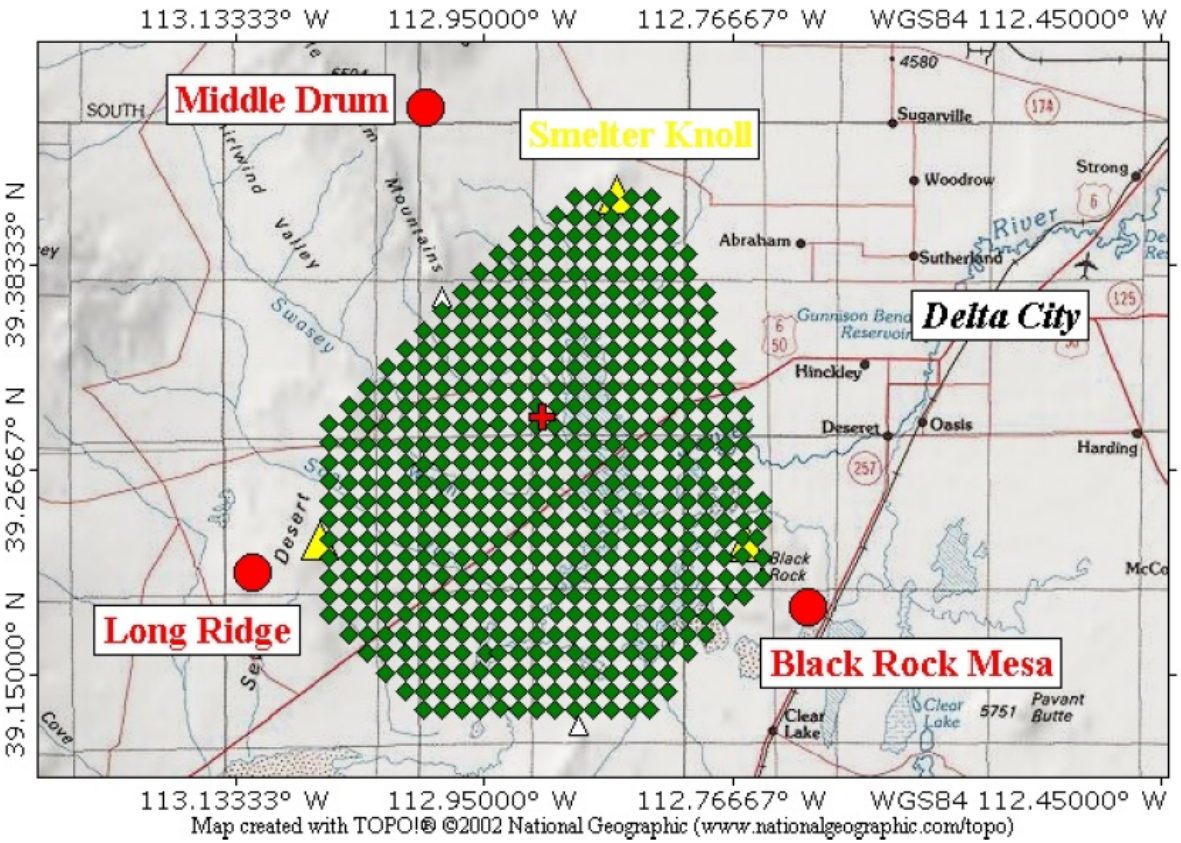
A Telescope and a Water Cherenkov Station



27 fluorescence telescopes...

...1660 Water Cherenkov tanks

Telescope Array observatory

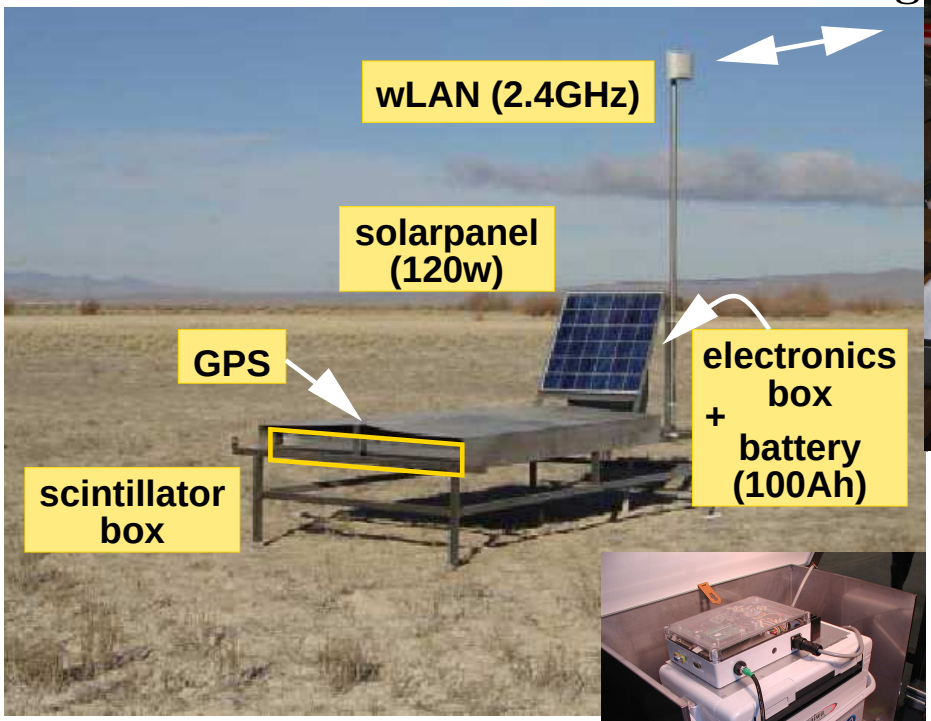


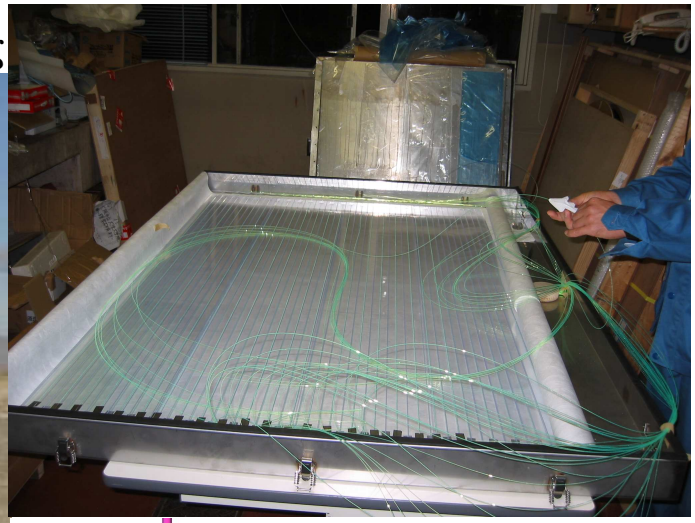
- 507 SD's, $S = 3m^2$
- 3 FD's
- CLF

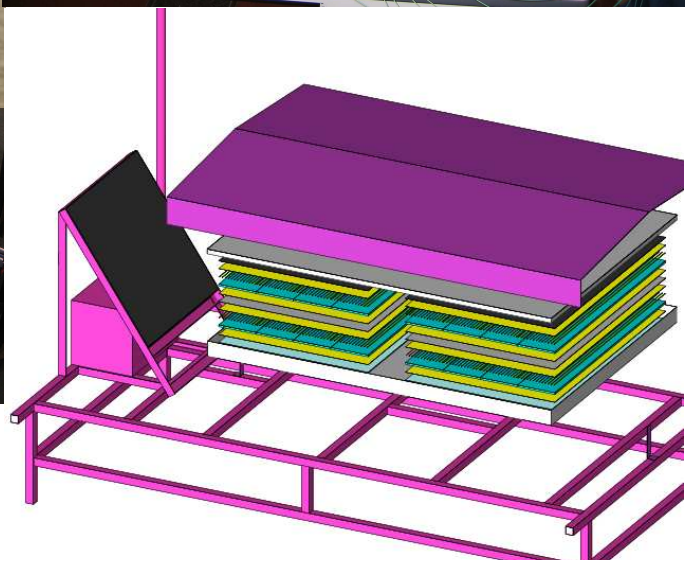
TA surface detector

< Surface Detector >

~200kg





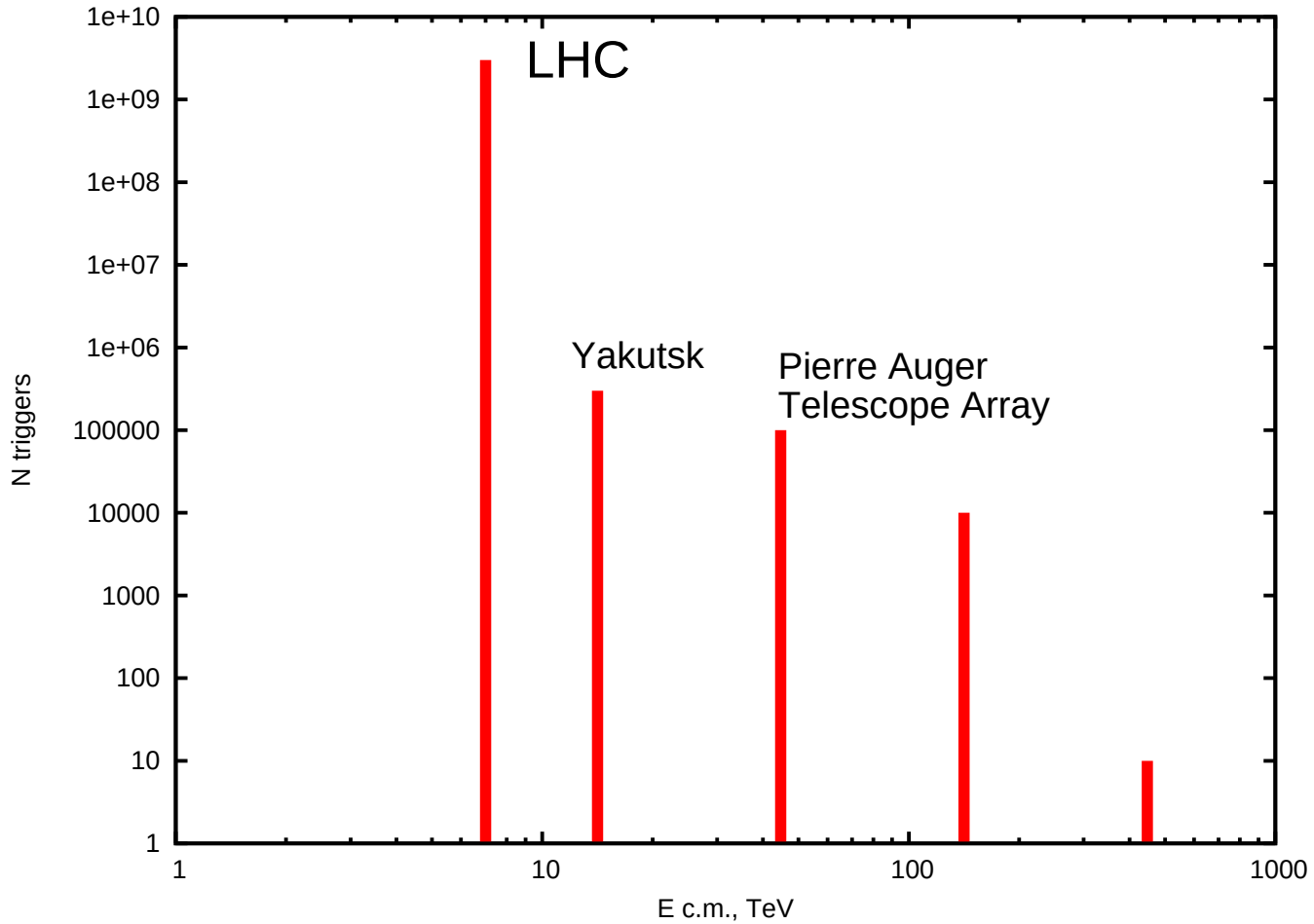


- WLSF: 1.0mmϕ (2cm separation)
- PMTs: ET 9123SA $\times$ 2
- 3m^2 (12mm $\times$ 2 layers)

Telescope Array Middle Drum fluorescence detector

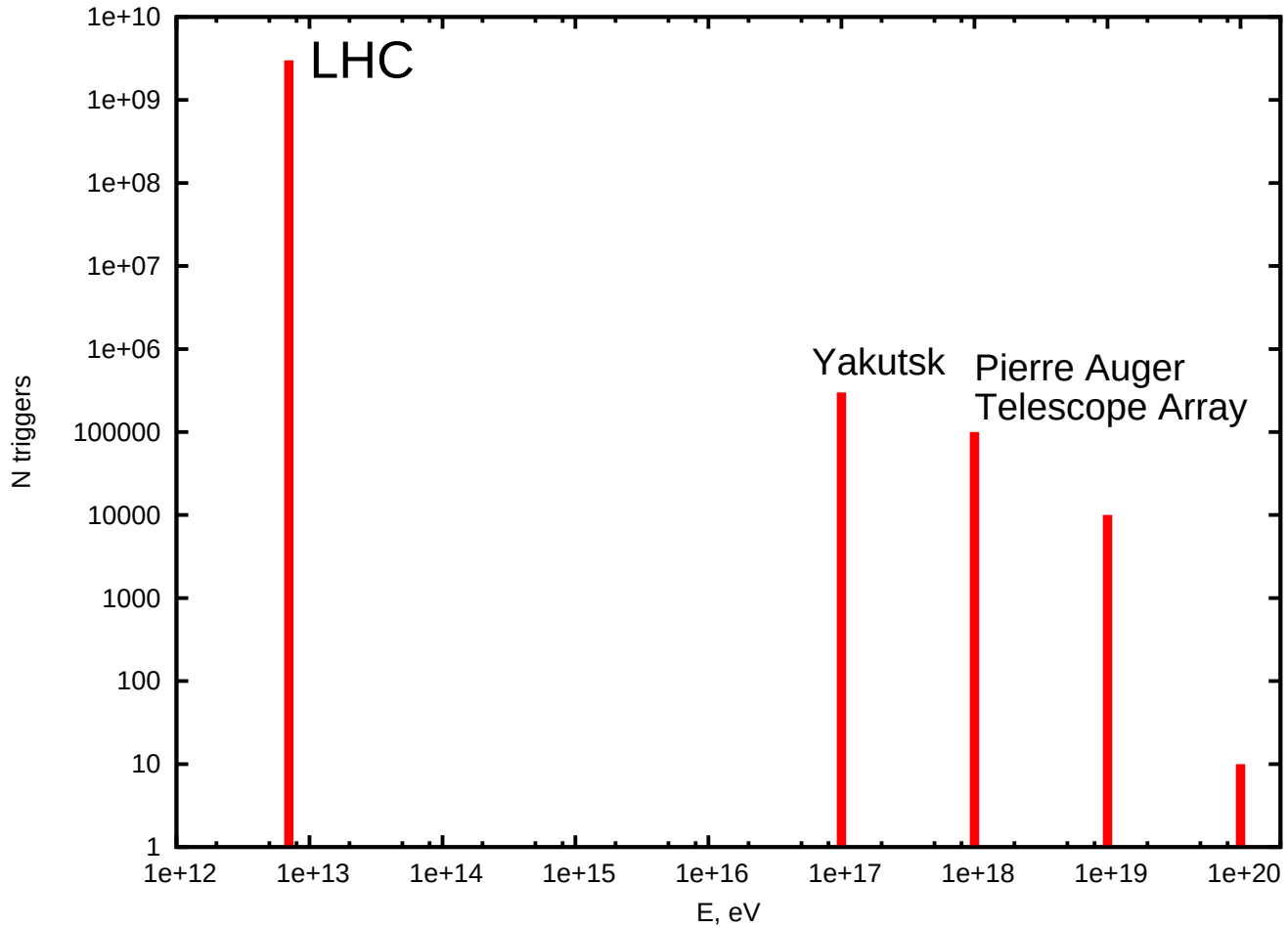
photo by Benjamin Stokes

UHECR c.m. energy/detection rate



- UHECR are good to probe high energy interaction

UHECR lab energy/detection rate



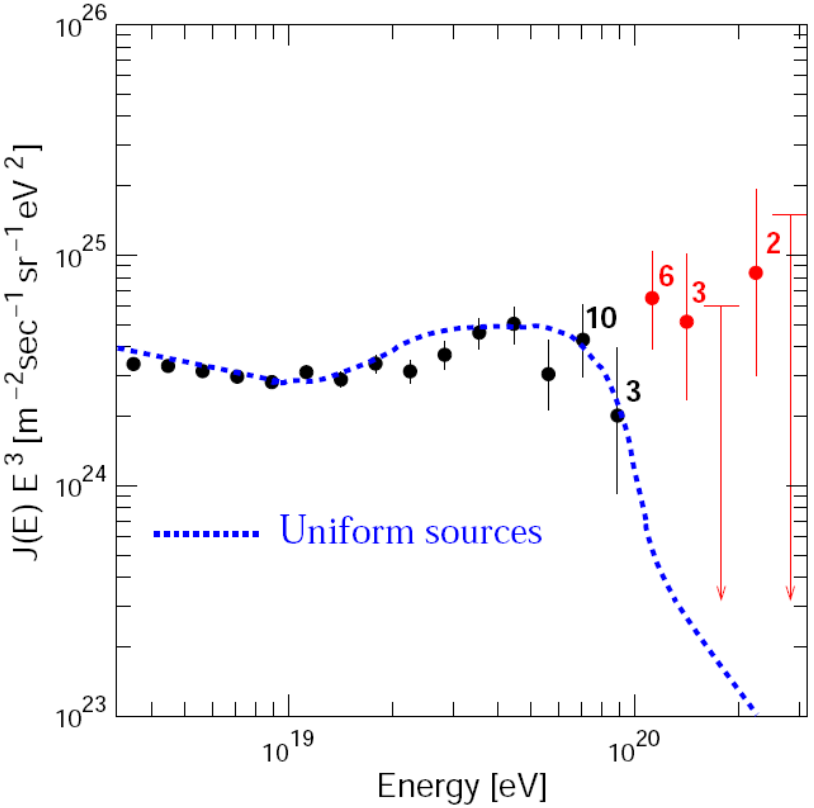
- UHECR are exceptional to probe Lorentz invariance

GZK effect

Greisen, 1966; Zatsepin, Kuzmin, 1966

Cut-off predicted for $E \gtrsim 10^{19.7}$ eV.

$$p + \gamma_{2.7K} \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

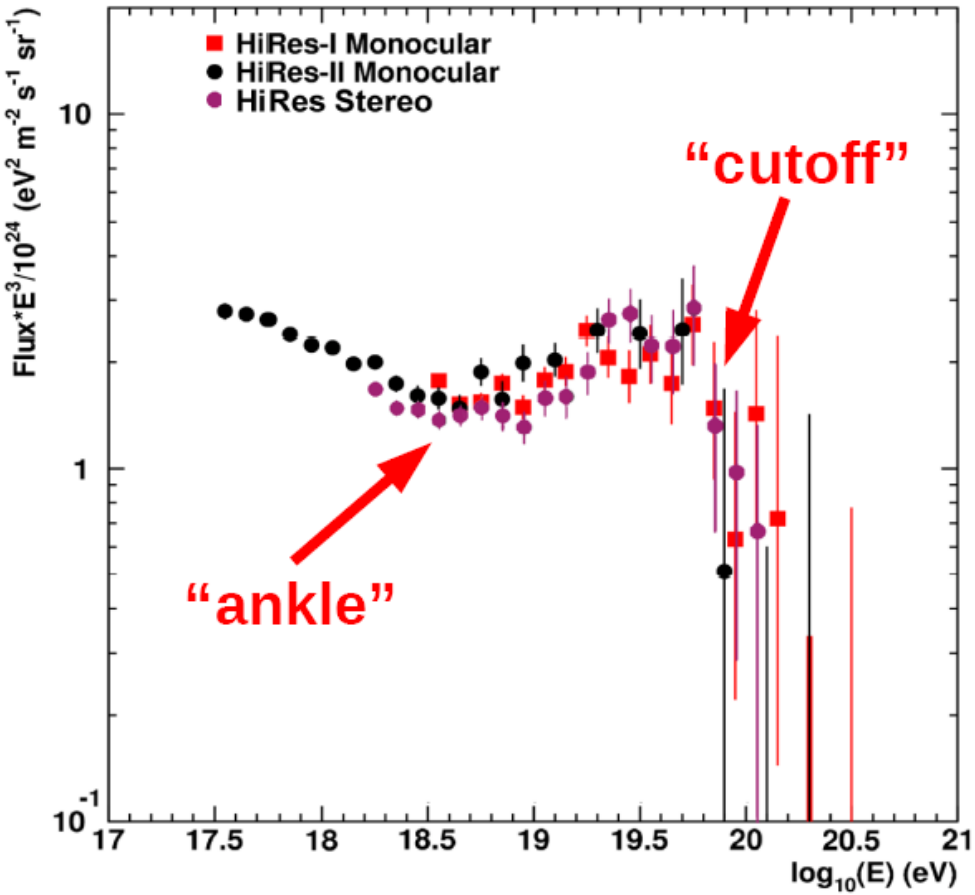


AGASA spectrum, 2003

Takeda, M. et al., Astropart. Phys 19(2003)

- Expected 1.9 event
- Observed 11 events above 10^{20} eV

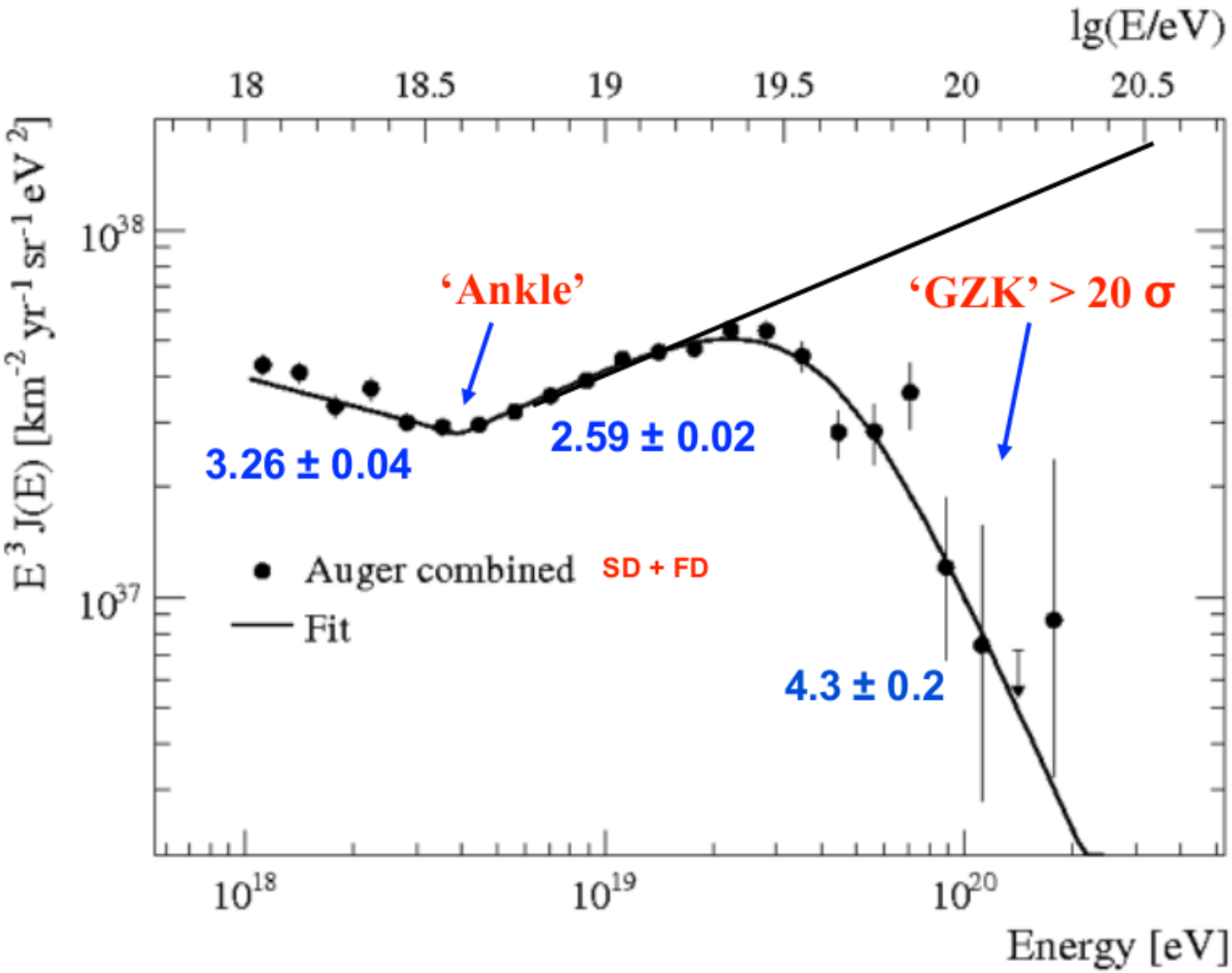
Cut-off observation by HiRES



Monocular: Quarks'06; PRL 100 (2008)

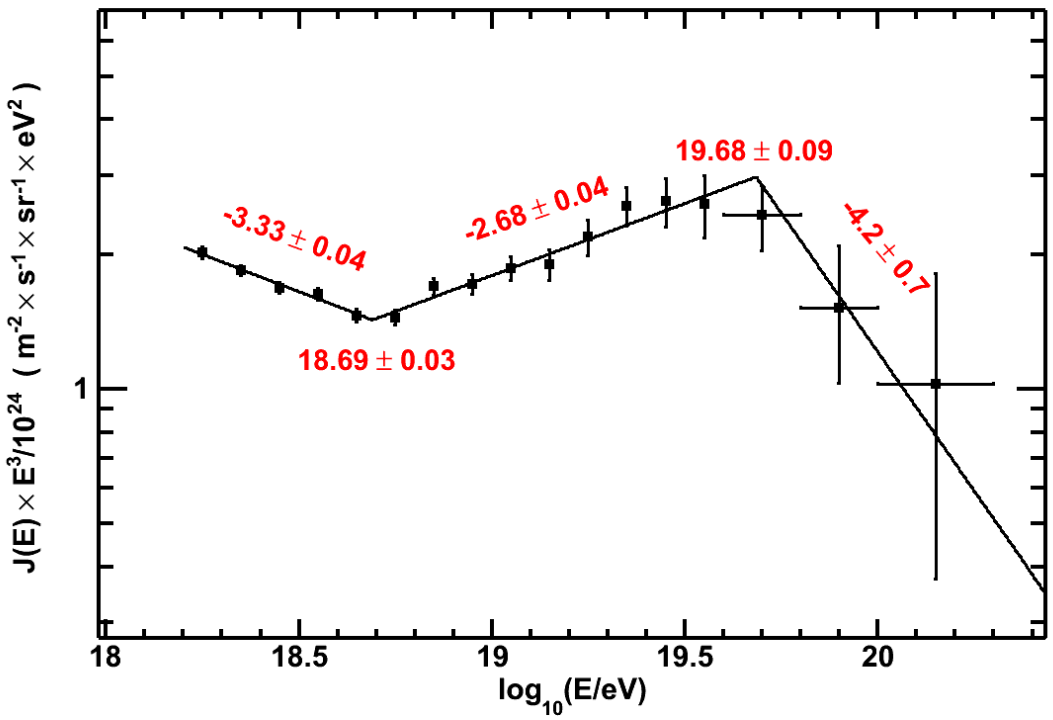
Stereo: Astropart. Phys. 32 (2010)

Pierre Auger spectrum



PRL 101 (2008) & Phys. Lett. B 685 (2010)

Telescope Array surface detector spectrum



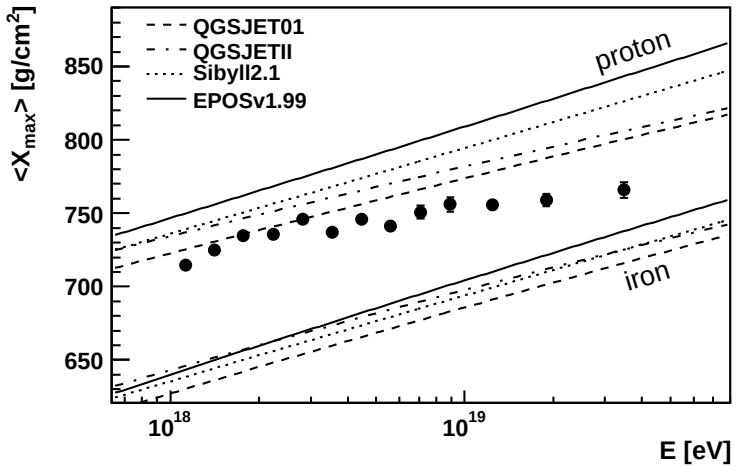
GZK confirmed by plastic scintillator SD (AGASA-like)

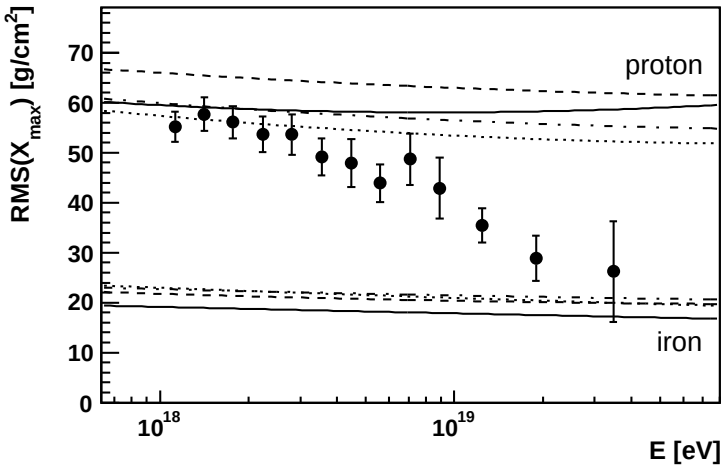
Cut-off significance 3.9σ *B.Stokes, ICRC'11, Beijing*

Composition: Auger/HiRES XMAX results

Auger

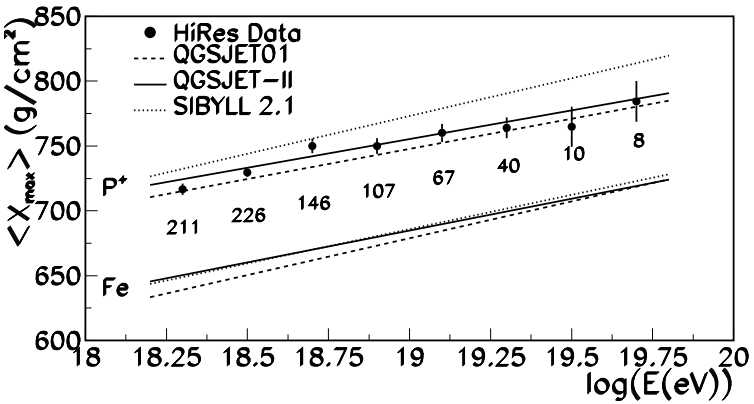
Phys.Rev.Lett.104.091101, 2010

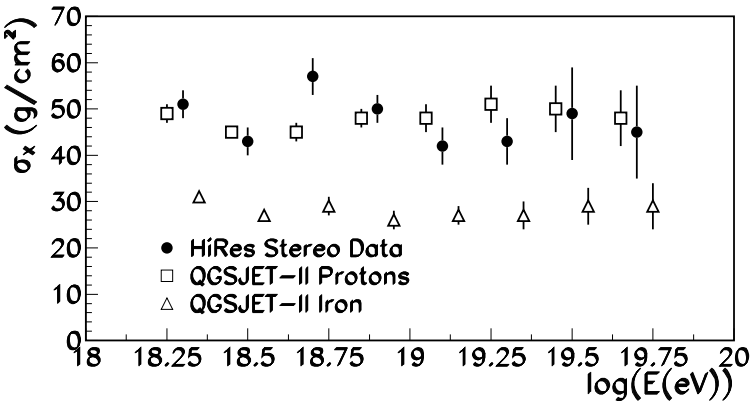




HiRES

Phys.Rev.Lett.104.161101, 2010

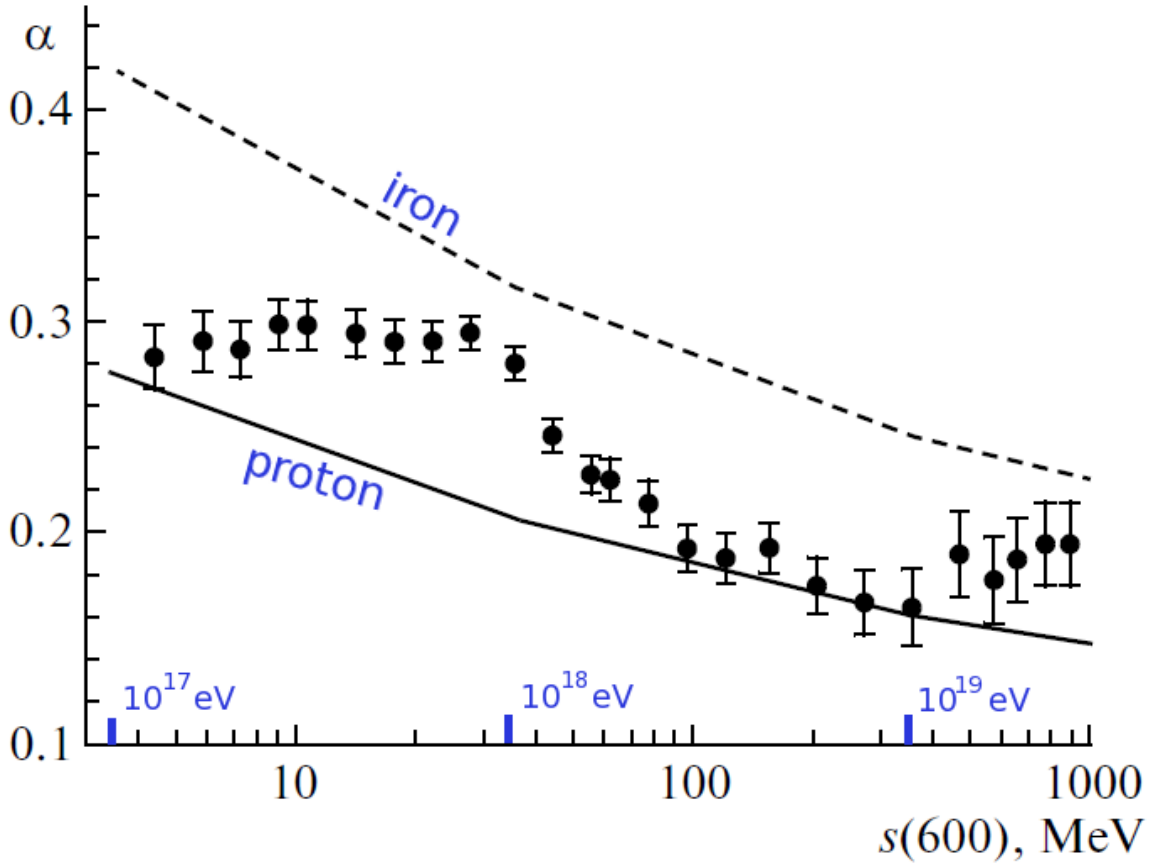




Yakutsk array results on chemical composition

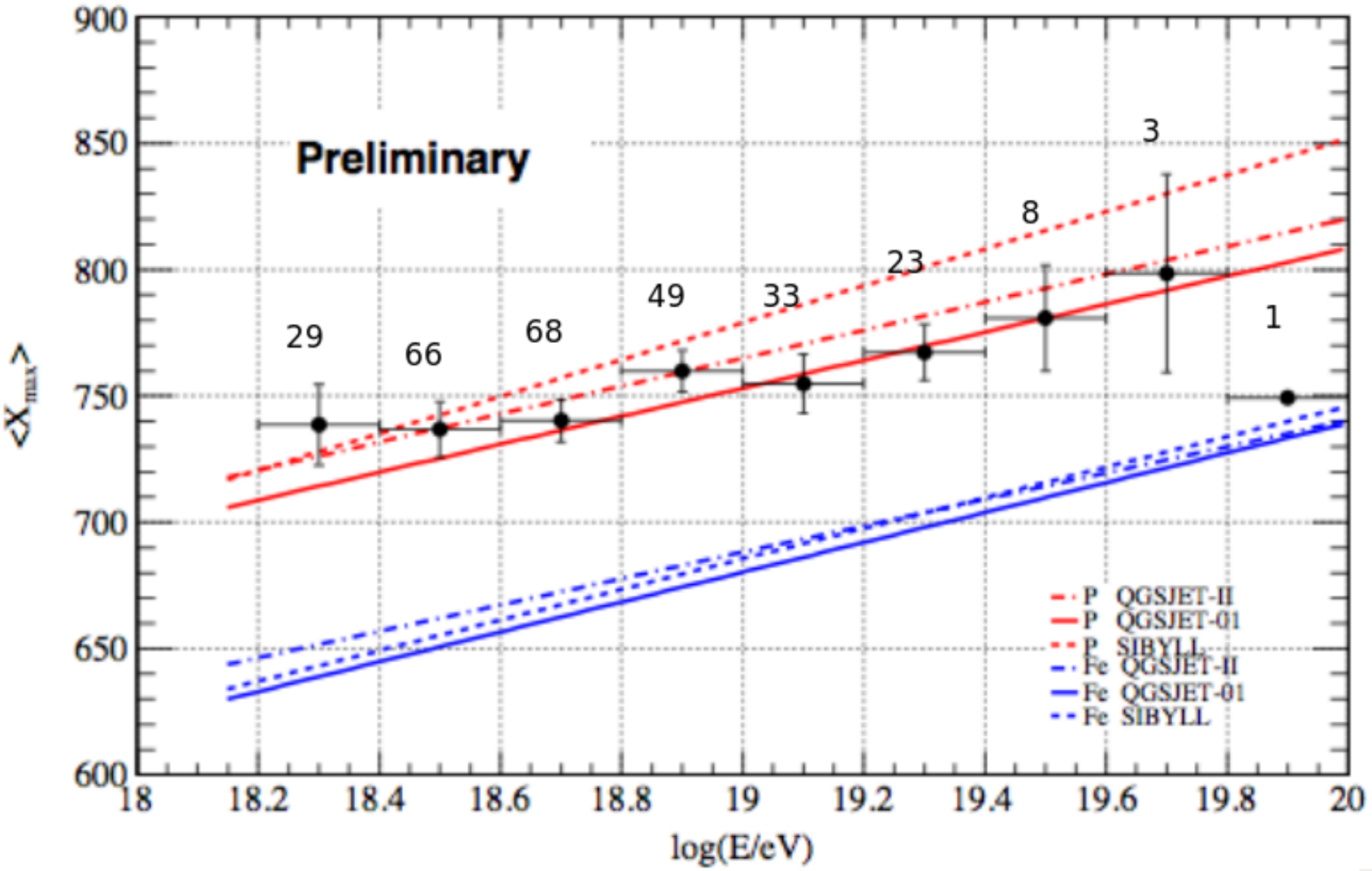
$$0.29 \leq \epsilon_{\mathrm{Fe}} \leq 0.68 \quad (95\%\mathrm{CL}), \qquad E > 10^{19}\ \mathrm{eV}$$

A. Glushkov et al., JETP Letters 87:190-194,2008



L. Dedenko et al.,Izv. RAN. Fiz. 75:325, 2011

Telescope Array stereo result



Y. Tameda, ICRC'11, Beijing

Ultra-high energy photons

- $10^{18} - 10^{19}$ eV photons are everpresent secondaries of GZK process

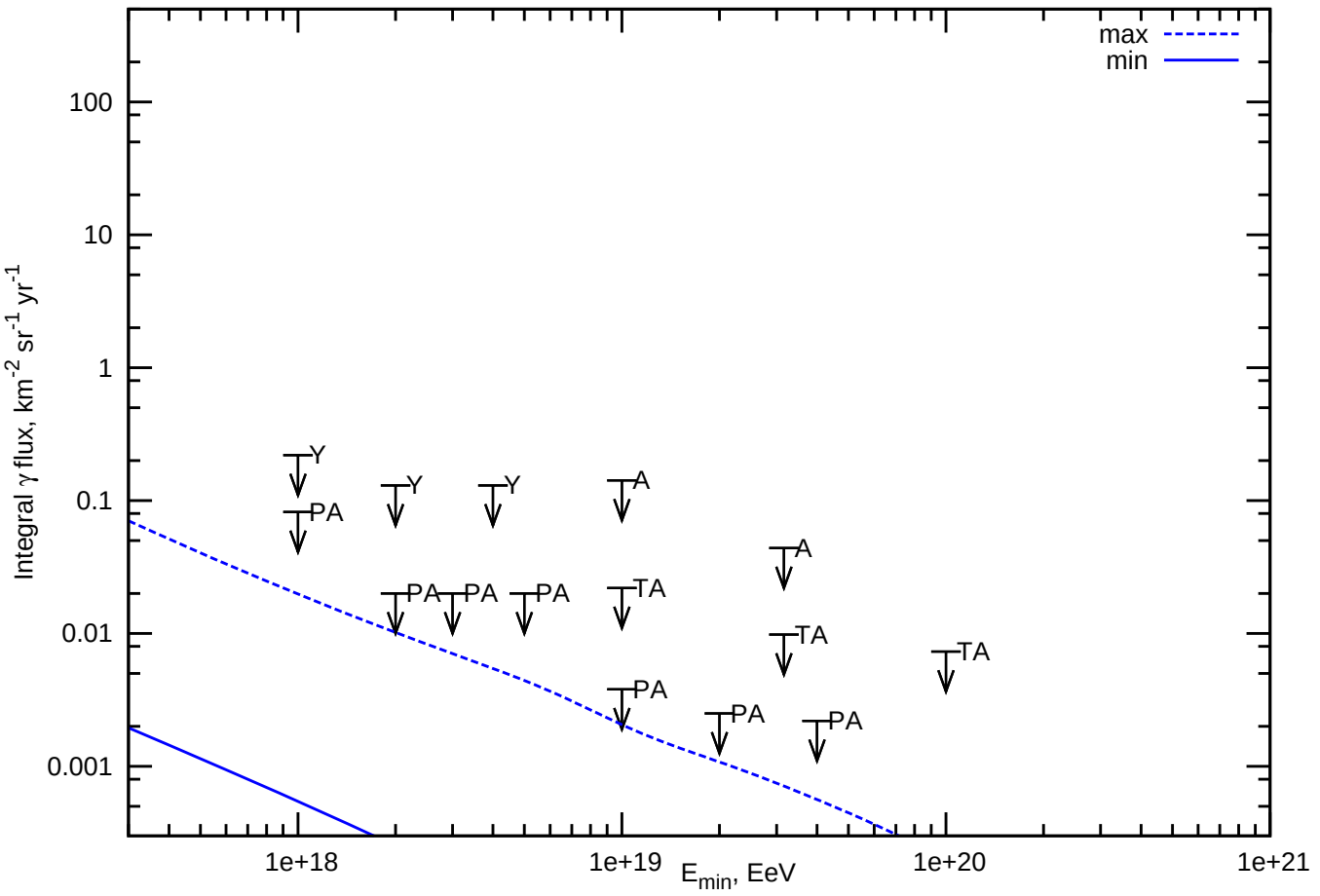
$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma\gamma$$

- No GZK photons observed yet, but existing limits are coming close to predicted flux

Note: GZK-photons are produced effectively only in case of proton primaries while UHECR composition is generally unknown (there is disagreement between experiments)

Ultra-high energy photon limits



A – Agasa, Y – Yakutsk, PA – Pierre Auger, TA – Telescope Array

lines - min and max GZK photon flux for acceptable source models

Gelmini, Kalashev, Semikoz, Astropart.Phys.28, 2007

Lorentz-invariance violation in QED

- Novel approaches to quantum gravity predict Lorentz-invariance violation (LIV) at high energies (e.g. Horava-Lifshitz).

Let's consider Lorentz-violated QED with dispersion relations:

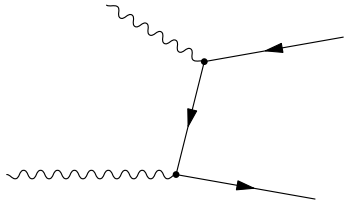
$$\gamma: \qquad k_0^2 = k^2 + \alpha \frac{k^4}{M_{Pl}^2}$$

$$e^{\pm}: \qquad p_0^2 = (1+\xi)p^2 + m^2 + \beta \frac{p^4}{M_{Pl}^2}$$

- QG models require large violation: $|\alpha|, |\beta| \gg 1$
- ξ is constrained by LEP synchrotron energy losses
- Violation in hadronic sector is not included in the model

Photons in LIV model

- Photons undergo e^+e^- pair production on intergalactic backgrounds (CMB, IR, radio).



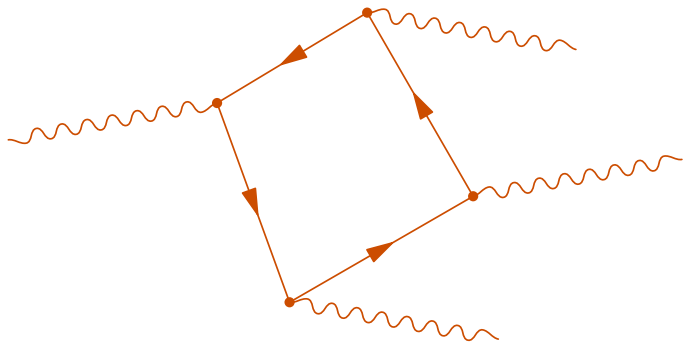
- In LIV case, the threshold of the reaction may be upshifted and Universe becomes transparent for UHE photons.
- Flux on Earth exceeds already existing limits.

$$\alpha - \beta/4 > -10^{-6}$$

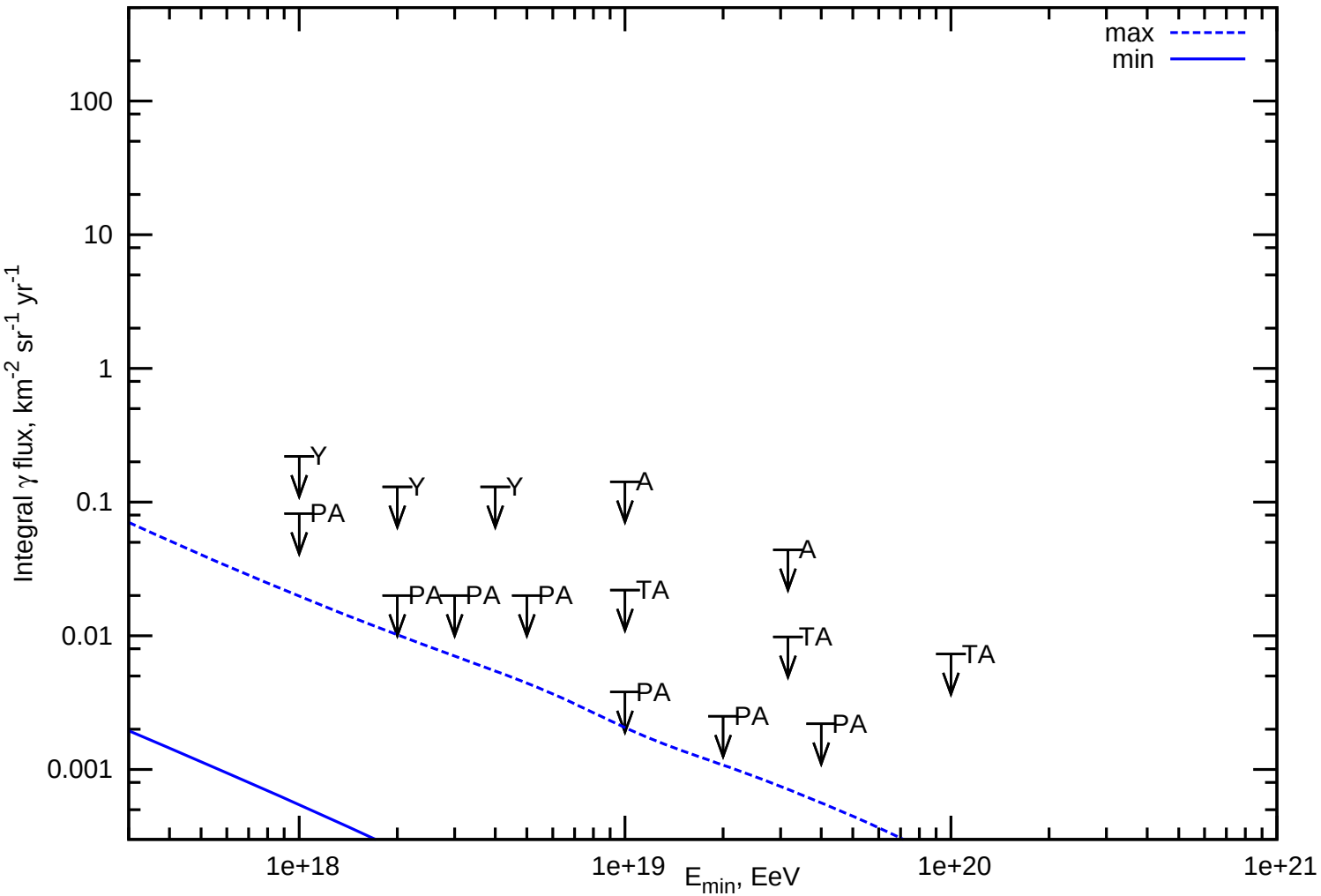
Galaverni, Sigl, Phys.Rev.D. 78, 2008

On the other side: $\gamma \to 3\gamma$

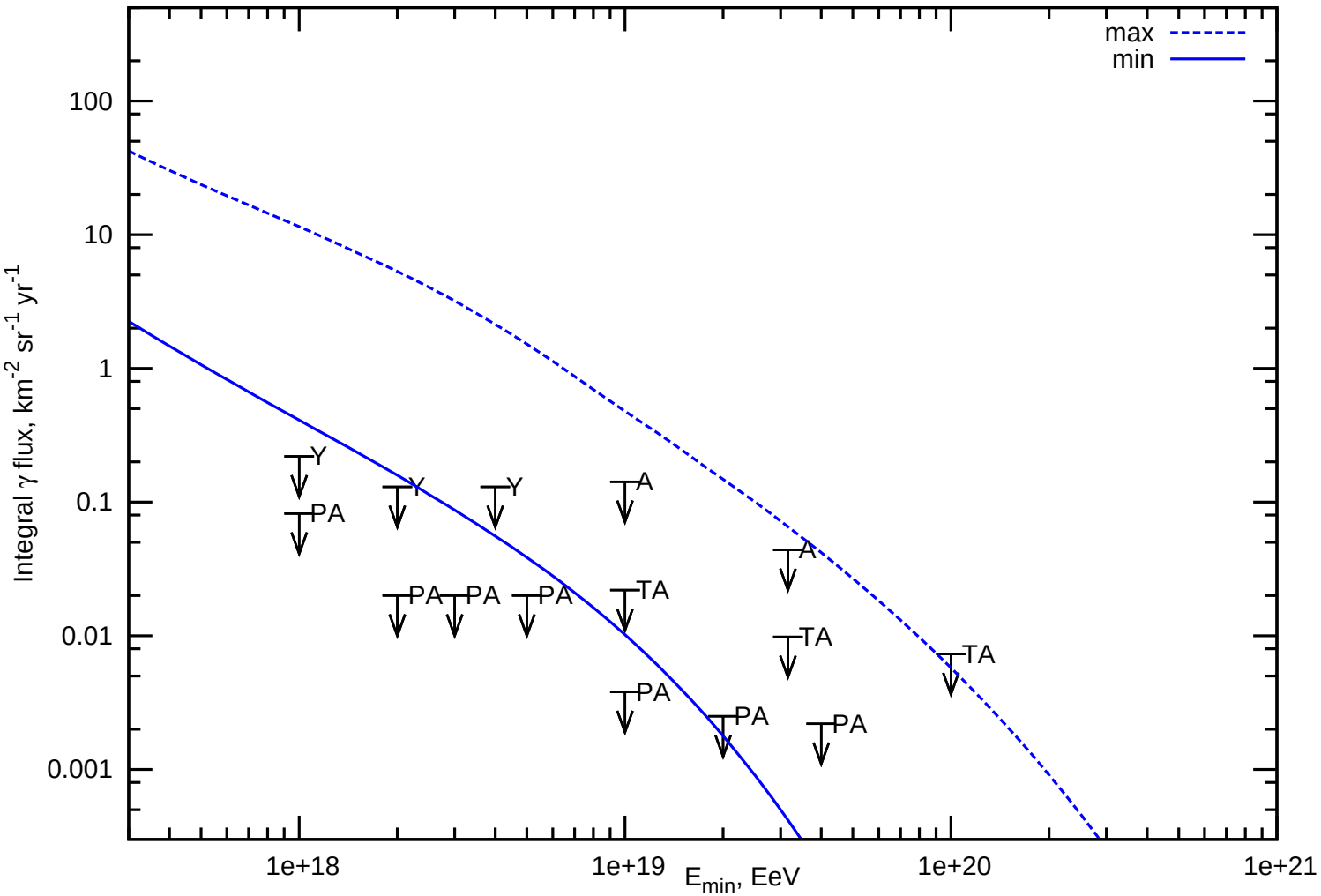
- no threshold
- rapidly grows with energy
- photons escape detection



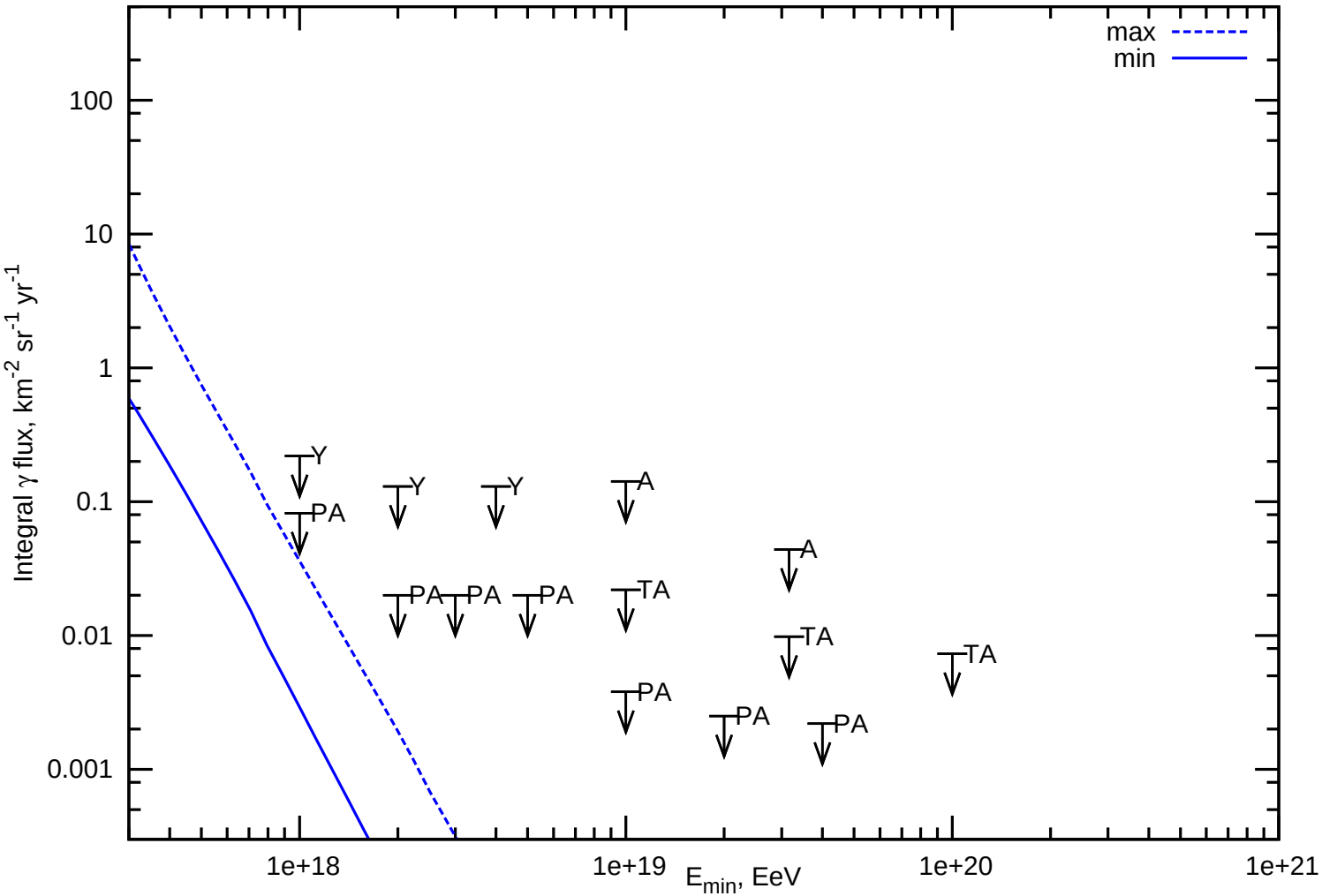
Lorentz-invariant GZK-photon fluxes



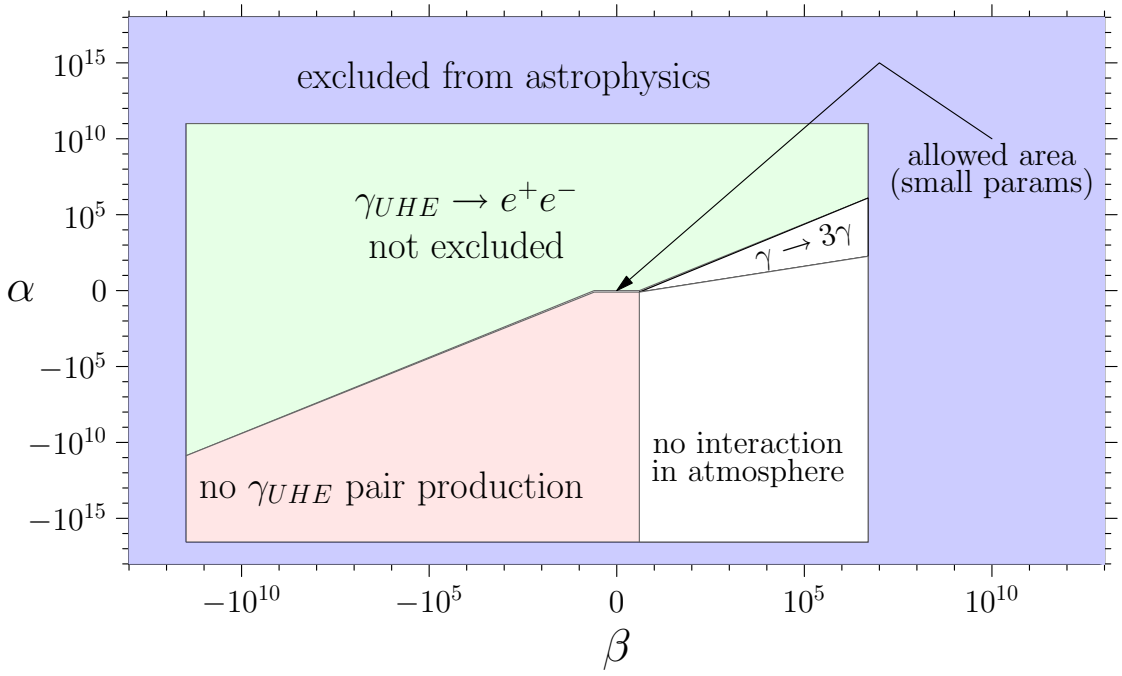
LIV Example 1: pair production **OFF**



LIV Example 2: pair production **OFF**, γ splitting **ON**



Observational signatures of LIV



no UHE pair production – excluded

"no" interaction in atmosphere – still photonuclear interactions, showers will be very deep (like neutrino)

$\gamma_{UHE} \to e^+e^-$ – no GZK photons

$\gamma \to 3\gamma$ – no GZK photons and excess of PeV–EeV photons (target for HiSCORE)

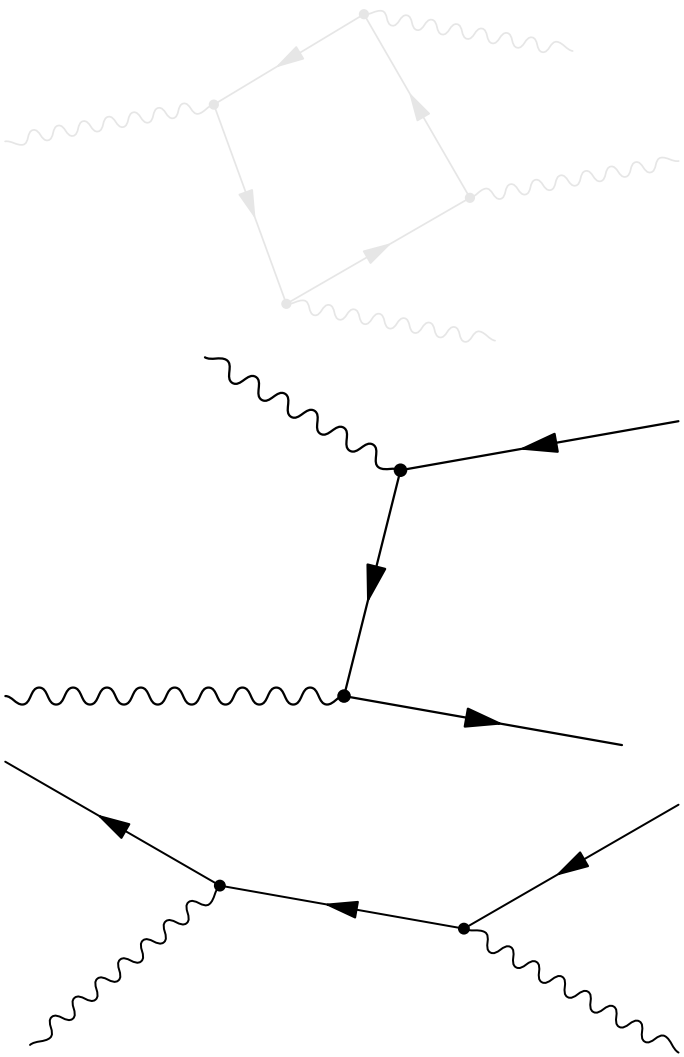
O. Kalashev,GR,P. Satunin,S. Sibiryakov, to appear

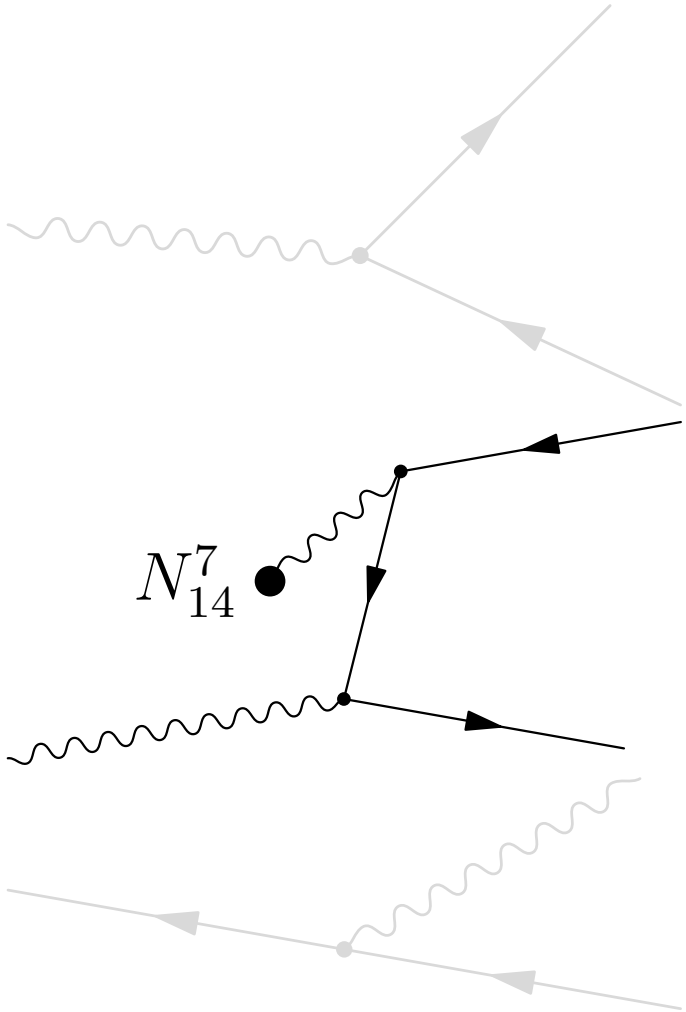
Conclusion

- GZK cut-off is observed
- For immediate discovery:
  - highest energy composition
  - sources of UHECR
  - GZK secondary photons
- HiSCORE experiment will open new gamma window $10^{15} - 10^{18}$ eV and test Lorentz invariance
- We probe the most energetic particle processes in the Universe

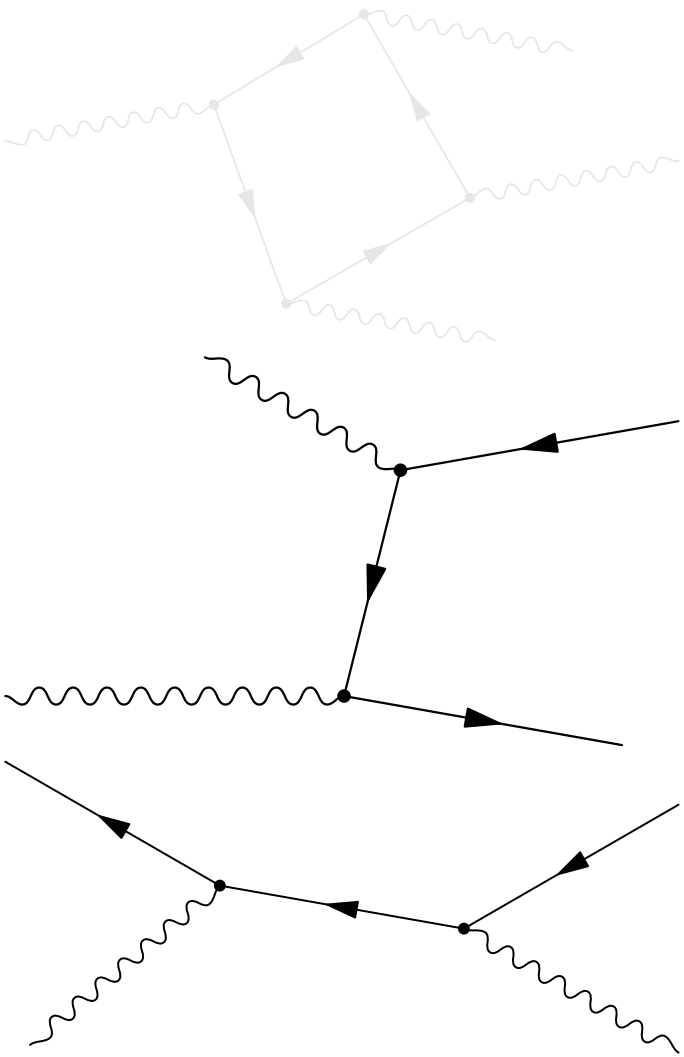
Backup slides

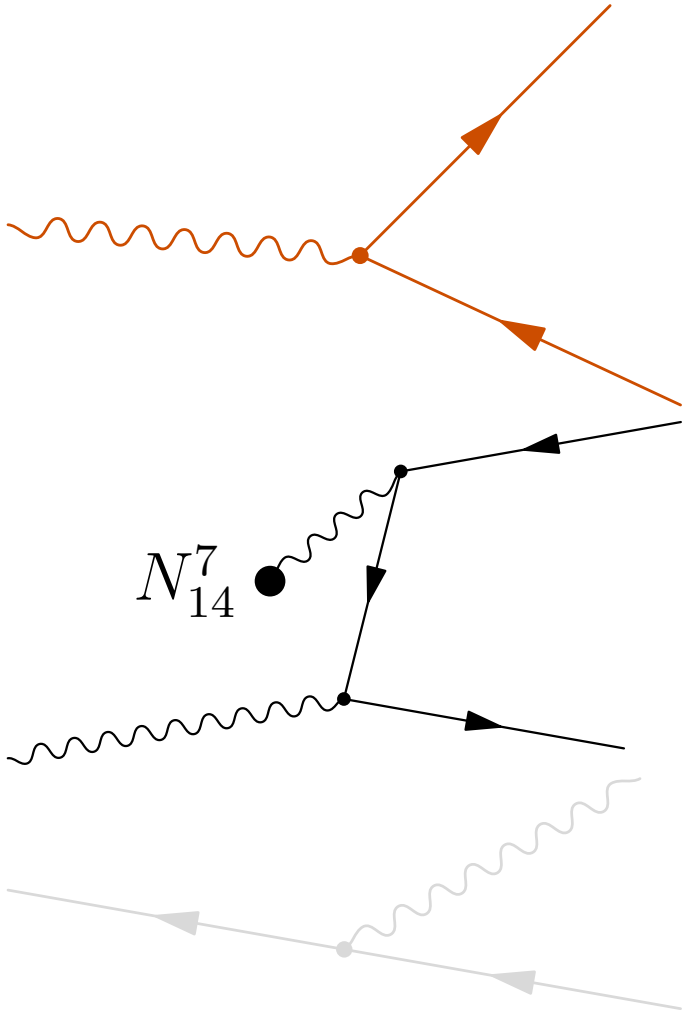
QED reactions, $\alpha = 0$, $\beta = 0$



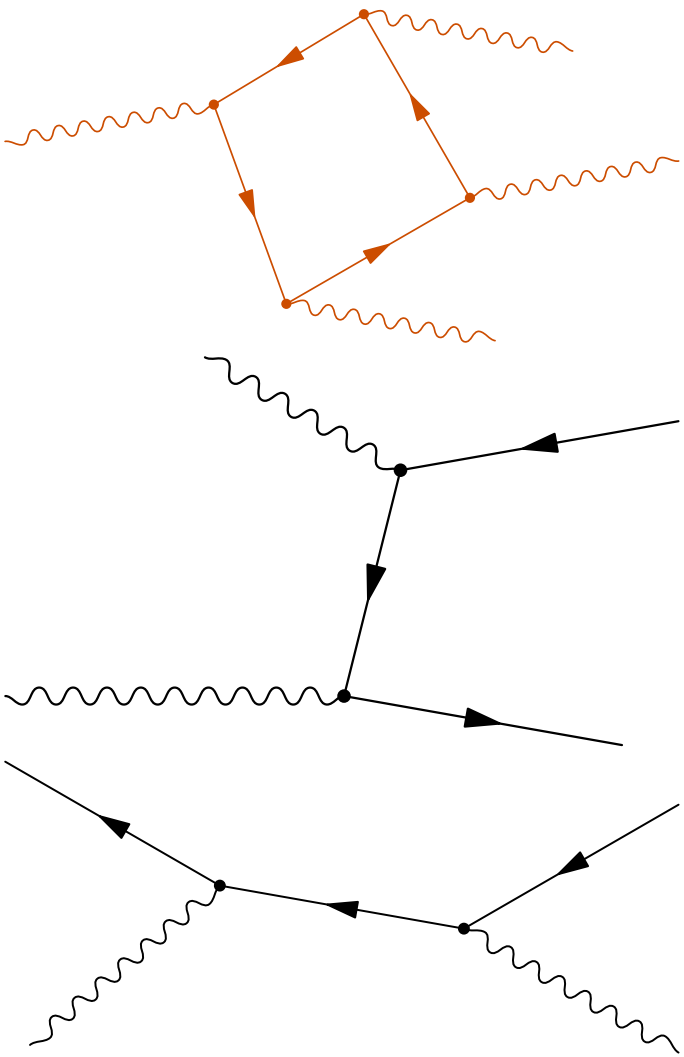


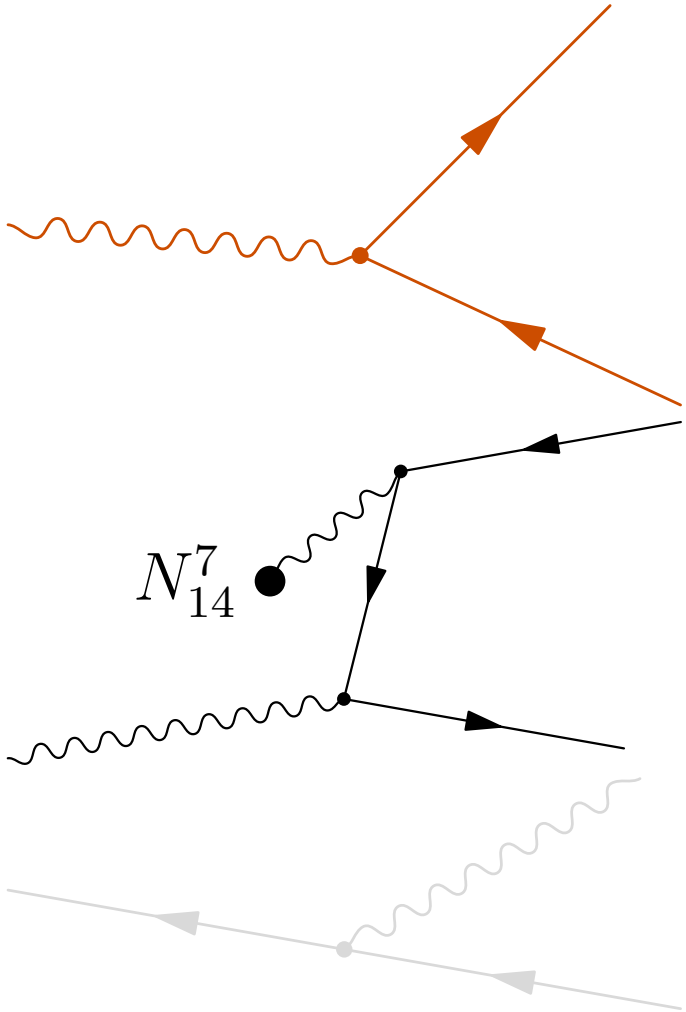
QED reactions, $\alpha = 0$, $\beta < -1$



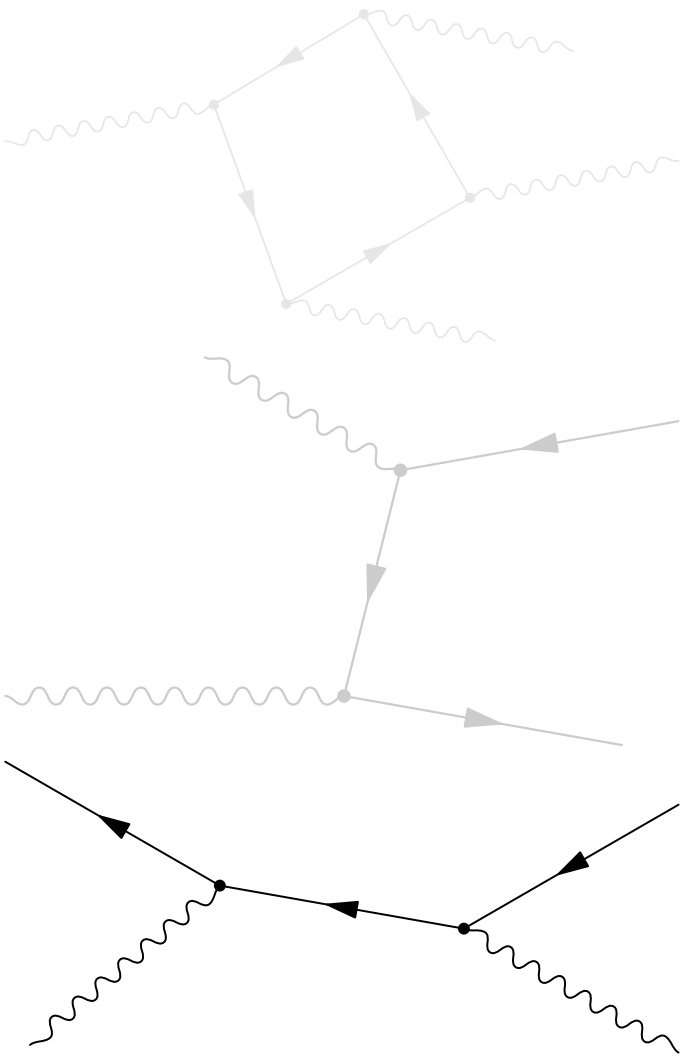


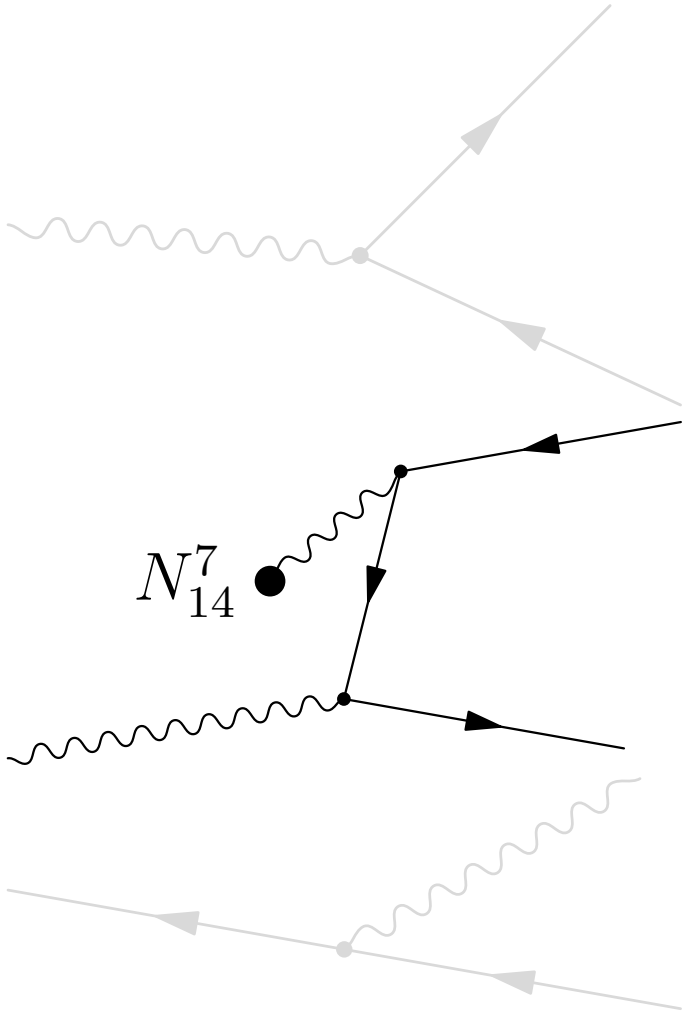
QED reactions, $\alpha > 1$, $\beta = 0$





QED reactions, $\alpha < -1$, $\beta = 0$





QED reactions, $\alpha = 0$, $\beta > 1$