# Ultra-high energy cosmic rays and the strongest AGN flares.

arXiv:1804.01064

Quarks XX
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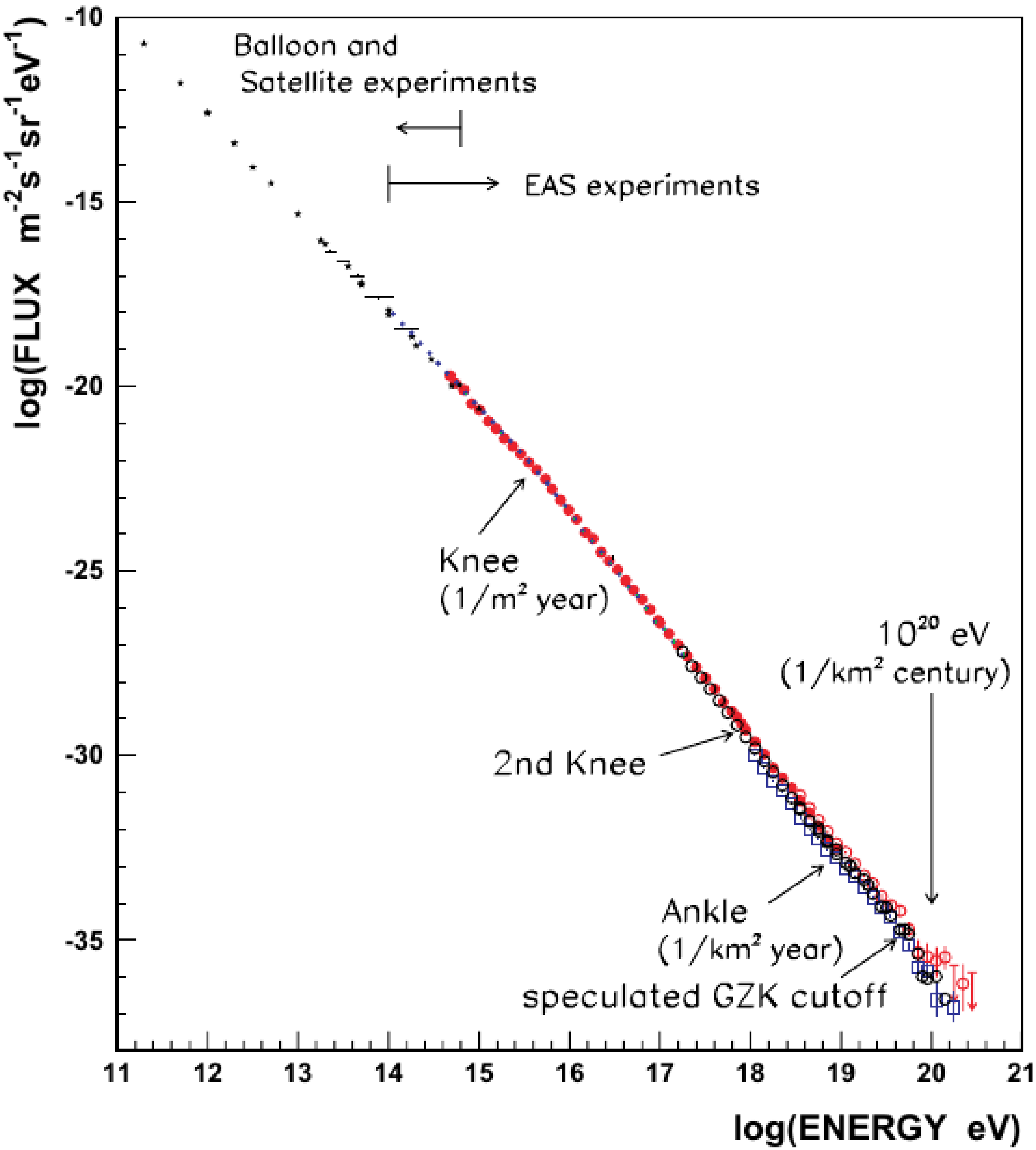
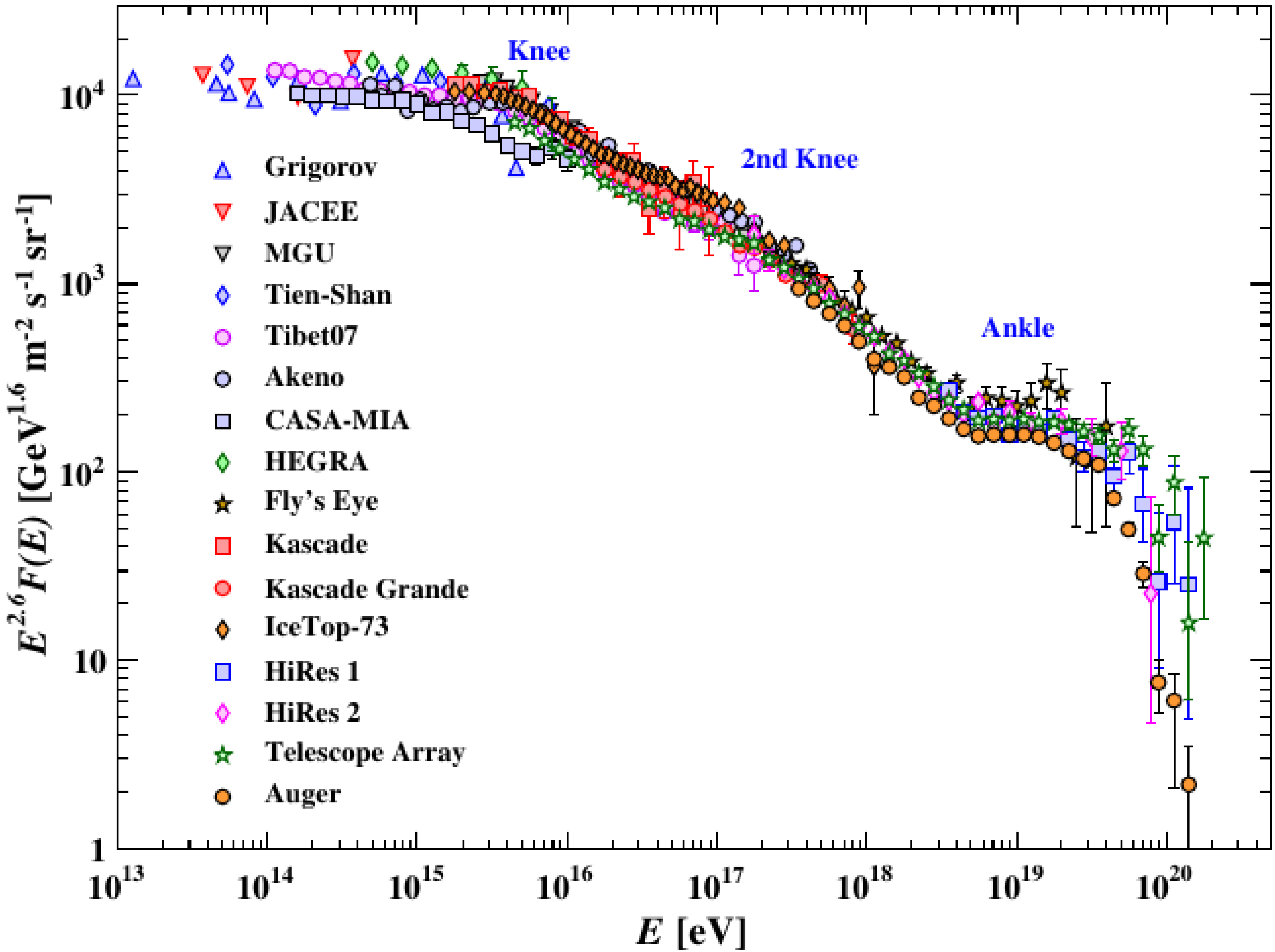
# Cosmic rays spectrum



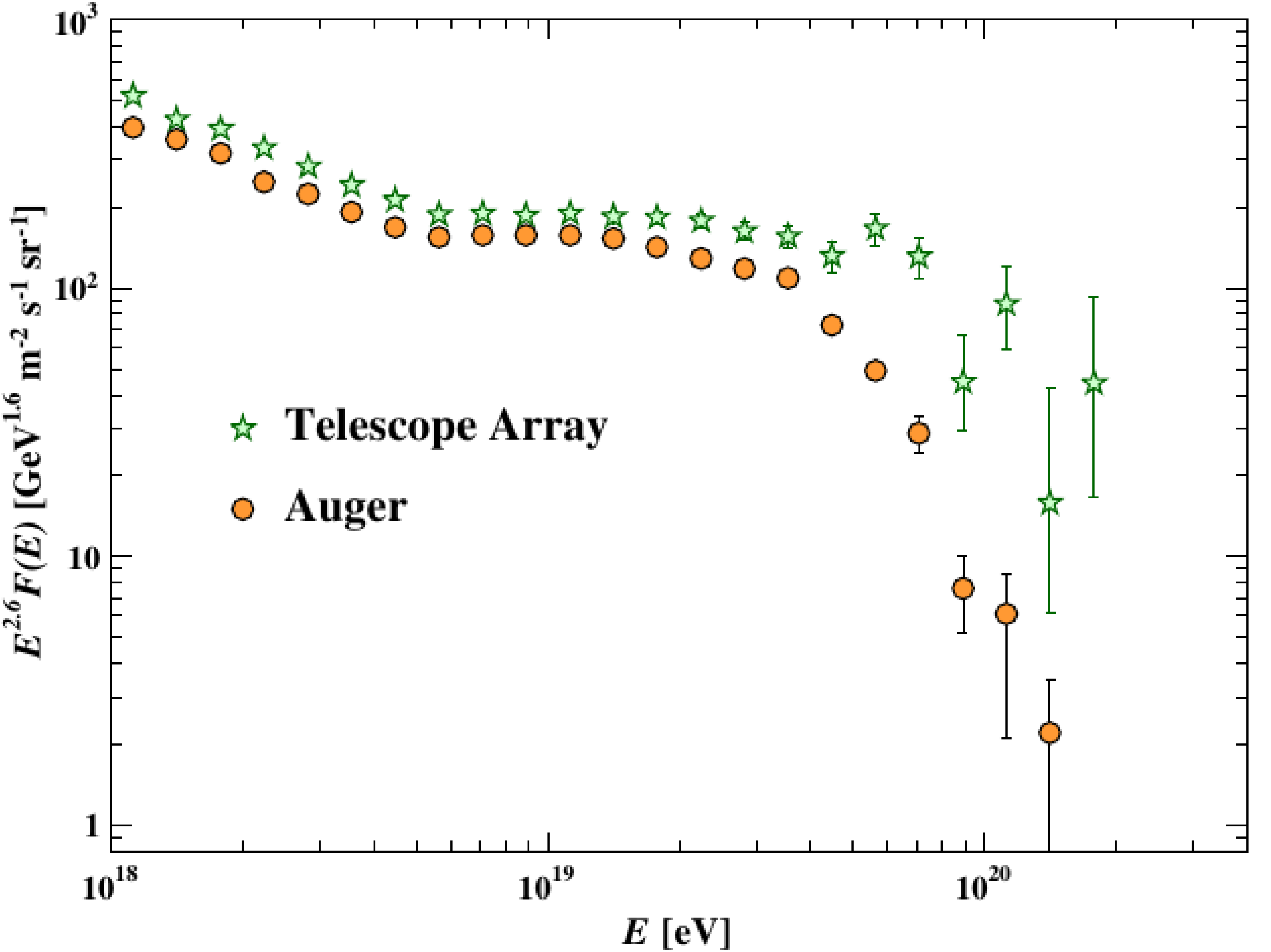

Nagano,2009

# Cosmic rays spectrum – EAS part




PDG, 2015

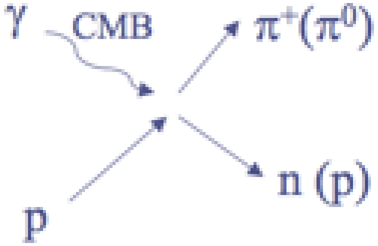
# UHECR spectrum



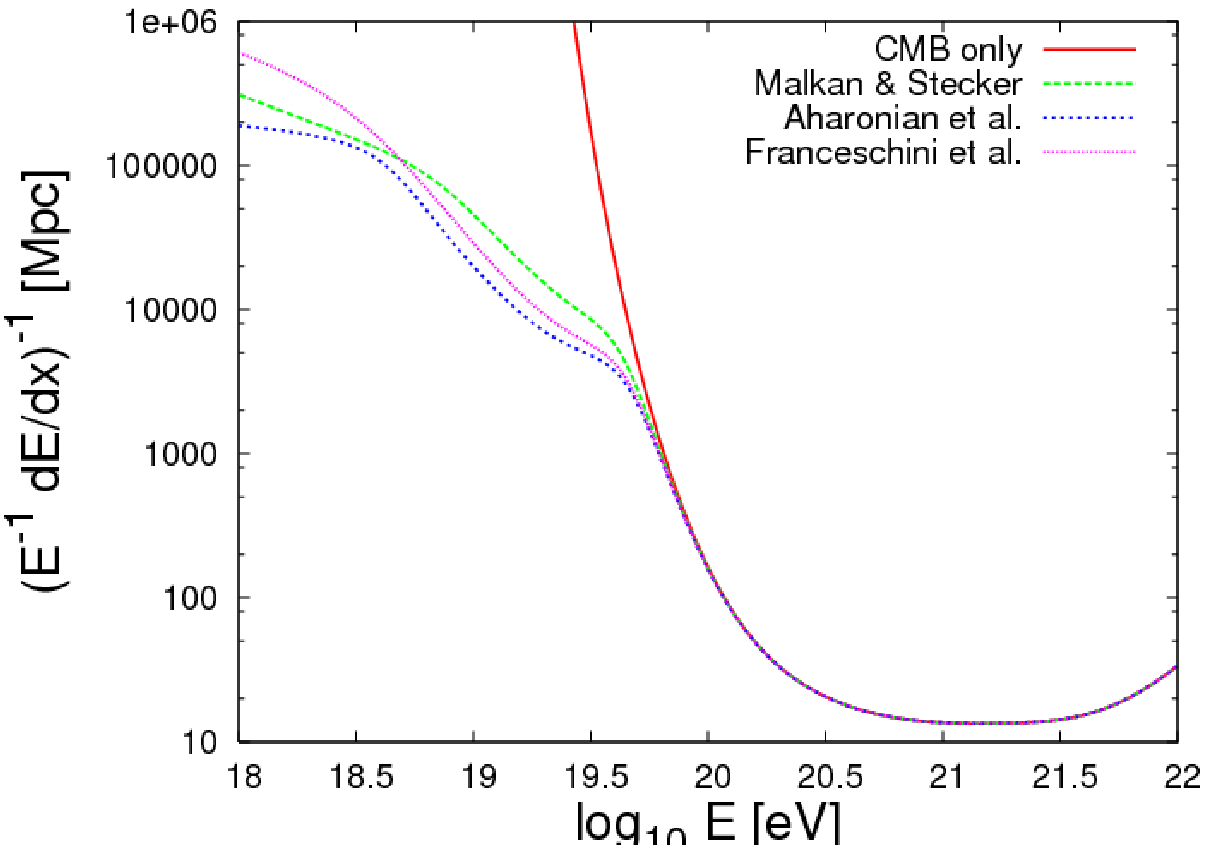

PDG, 2015

# GZK cut-off

- Dramatic energy loss at log(E)>19.7 due to p-CMB collisions
- Horizon shrinks to ~100 Mpc



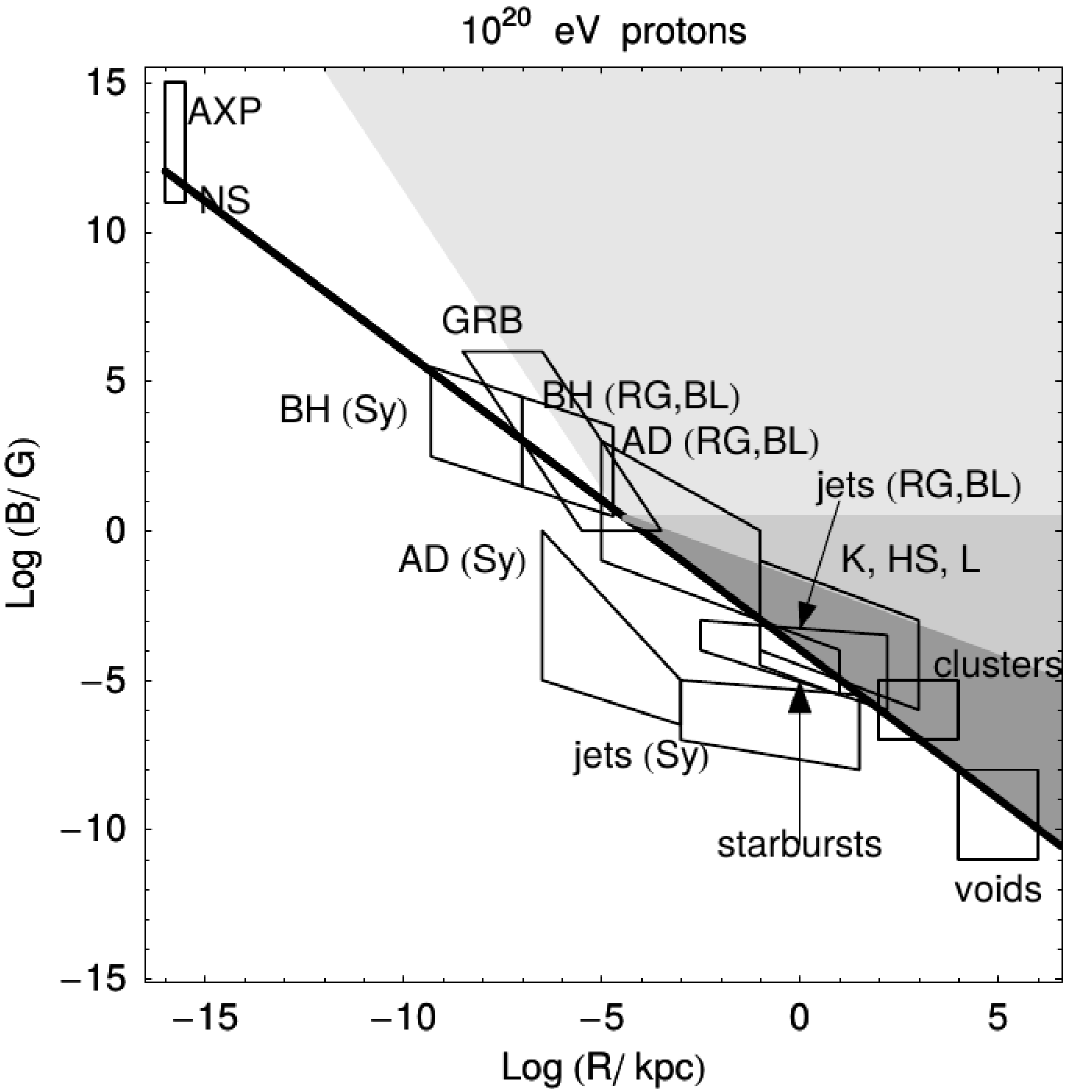

$$p+\gamma_{CMB} \rightarrow n+\pi^{+}$$
$$\rightarrow p+\pi^{0}$$




Hooper et al, 2007

# 'Hillas plot'

$$\mathcal{E} \leq \mathcal{E}_{\mathrm{H}} = qBR$$




Ptitsyna&Troitsky,2010

## Luminosity threshold

- We take the limiting case of protons.
- Hillas criterion can be written out explicitly, taking into account possible relativistic bulk motion:

$$RB \gtrsim 3 \times 10^{17}\, \Gamma^{-1}\, E_{20}$$

- In certain case of relativistic jets that allows to estimate corresponding magnetic (Poynting) flux:

$$L \sim \frac{1}{6} c \Gamma^4 B^2 R^2 \gtrsim 10^{45} \Gamma^2\, E_{20}^2\, \mathrm{erg/s}$$

- In AGN $\Gamma$~10, so we are talking about $10^{47}$ erg/s!

# Problems

- Summing up, there are two effects interplaying in the end of the spectrum:
  - Progressively smaller active volume, $V_{GZK}$
  - Increasing degree of 'extremeness' of the sources
- Still, we do observe UHECRs at these energies, thus there must be some sources
- NO steady astrophysical sources in $V_{GZK}$
- The only way out – HE transients.

# Transients

- Successful candidate shall simultaneously:
  i) Satisfy luminosity (or Hillas) criterion
  ii) Meet total energetics condition – there should be enough energy to accelerate observed UHECRs, at the very least

- Benchmark (observed emissivity at $E>10^{20}$eV):
  $\mathfrak{L}(TA)=8\times10^{43}$ erg $s^{-1}$ $Mpc^{-3}$
  or
  $\mathfrak{L}(PA)=1.5\times10^{43}$ erg $s^{-1}$ $Mpc^{-3}$

## Transients. GRB

- Gamma-ray bursts – natural candidate
- Easily pass the luminosity test
- The second point could be problematic, because $\mathfrak{L}_{GRB} \sim 5 \times 10^{43}$ erg $s^{-1}$ $Mpc^{-3}$
- Need some other mechanism (or LLGRBs?)

## Transients. AGNs

- AGNs are highly variable

- Flares with $L > 10^{50}$ erg/s were observed, so it is possible to fulfill the first criterion

- The crucial question is – whether there is enough luminous flares in the GZK volume?

- The idea is straightforward – take some fiducial volume $V_0 >> V_{GZK}$ ($z_0$=0.3, $R_0$~1.5 Gpc, $R_{GZK}$*~150 Mpc)

*$R_{GZK}$ is the mean attenuation length of the proton with the *initial* energy of $10^{20}$ eV.

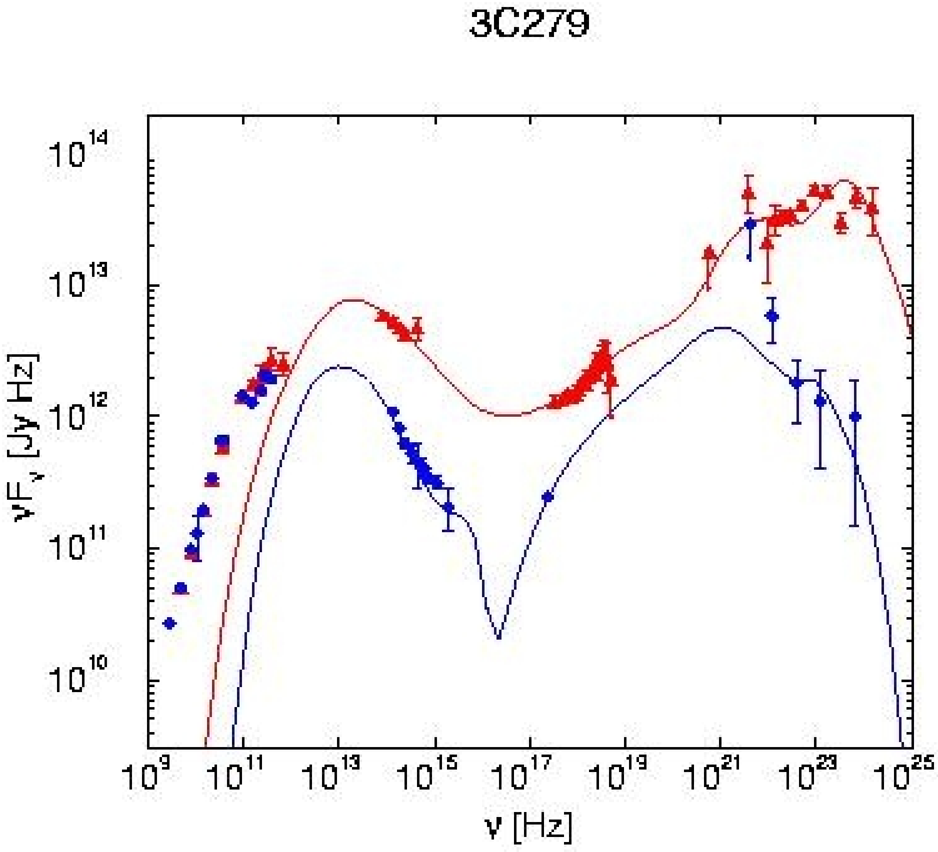
## Sample

- We tried to construct a full sample of candidate flares using the Fermi LAT observations
- Advantages: long time span and uniform coverage of the celestial sphere with high (3h) cadence→ there's no chance to miss a flare at these distances.
- On the other hand, there is no way to directly measure the Poynting luminosity, we estimate it assuming equipartition and that the jets radiate effectively
- In this case $L_{mag} \sim L_{bol}$

# Transients. $L_{bol}$

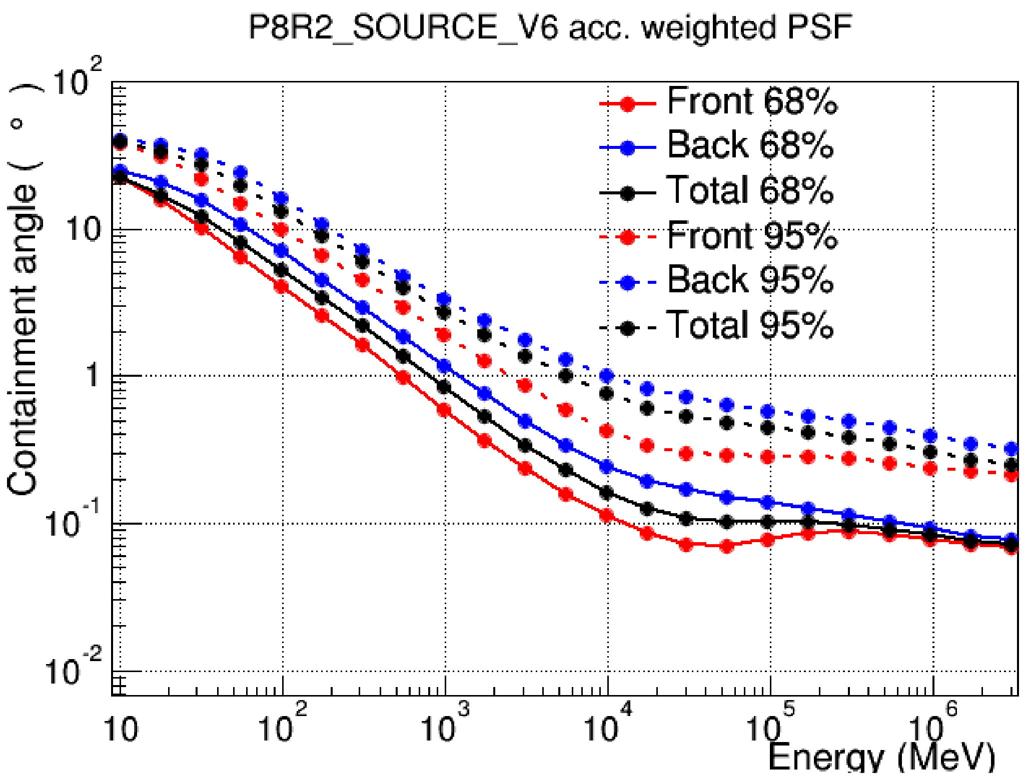
- Luckily, $\gamma$-luminosity in 0.1– 100 GeV energy range is a good proxy for the bolometric one

$$L_{\rm bol} \sim 2L_\gamma$$



# Aperture photometry

• It is rather difficult to find luminosity for full 0.1-100 GeV energy range
• Proxy again, now it is 1-100 GeV. As the Fermi-LAT angular resolution improves, we can employ the easiest way to build the needed lightcurves – aperture photometry



## Aperture photometry

- AP – it is just photon counts in 2 deg circle fdivided by an actual exposure in the time bin (week)
- PRO: simple and robust. Makes possible to investigate all the lightcurves of Fermi sources
- CONTRA: too rough. Inevitably include background and photons from another sources, so great care should be taken when dealing with AGNs at low galactic latitudes and/or in the vicinity of some strong sources.
- NEVERTHELESS: we set high luminosity threshold and the sources are not too far away, so they'll dominate over the bckg. Eventually candidate flares was checked using more precise ML method (*gtlike*).

# Candidates

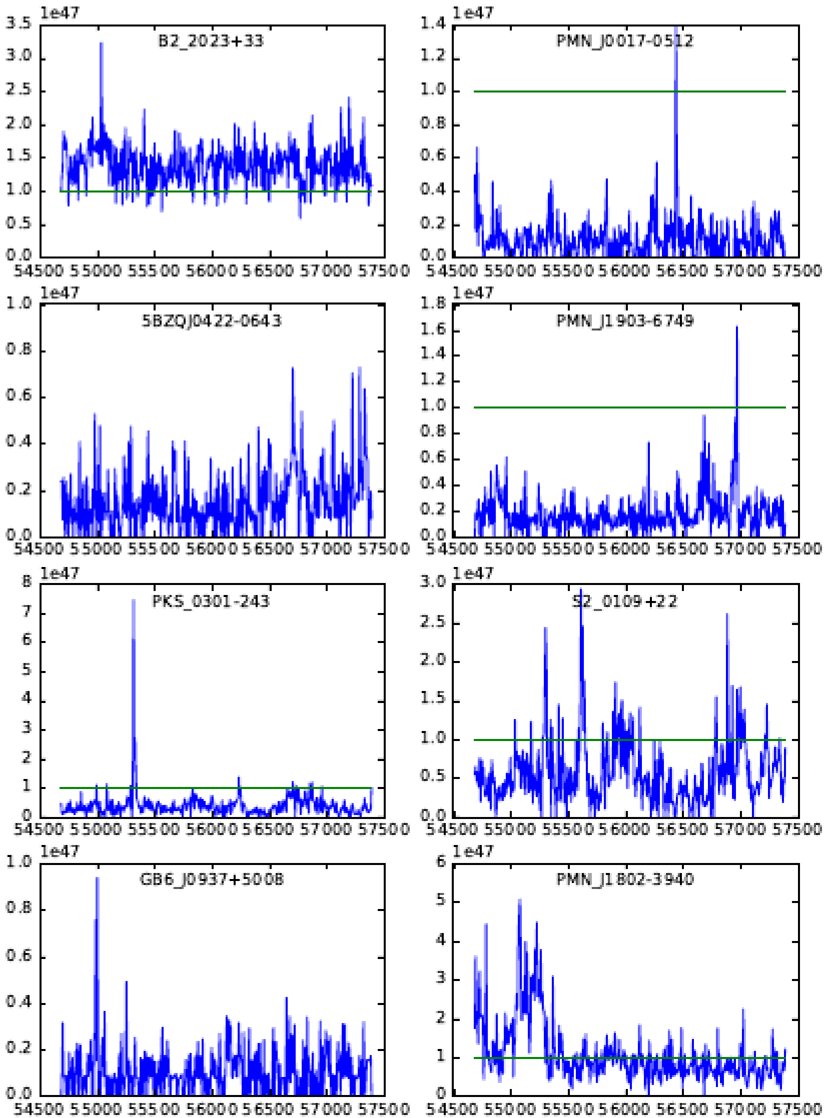


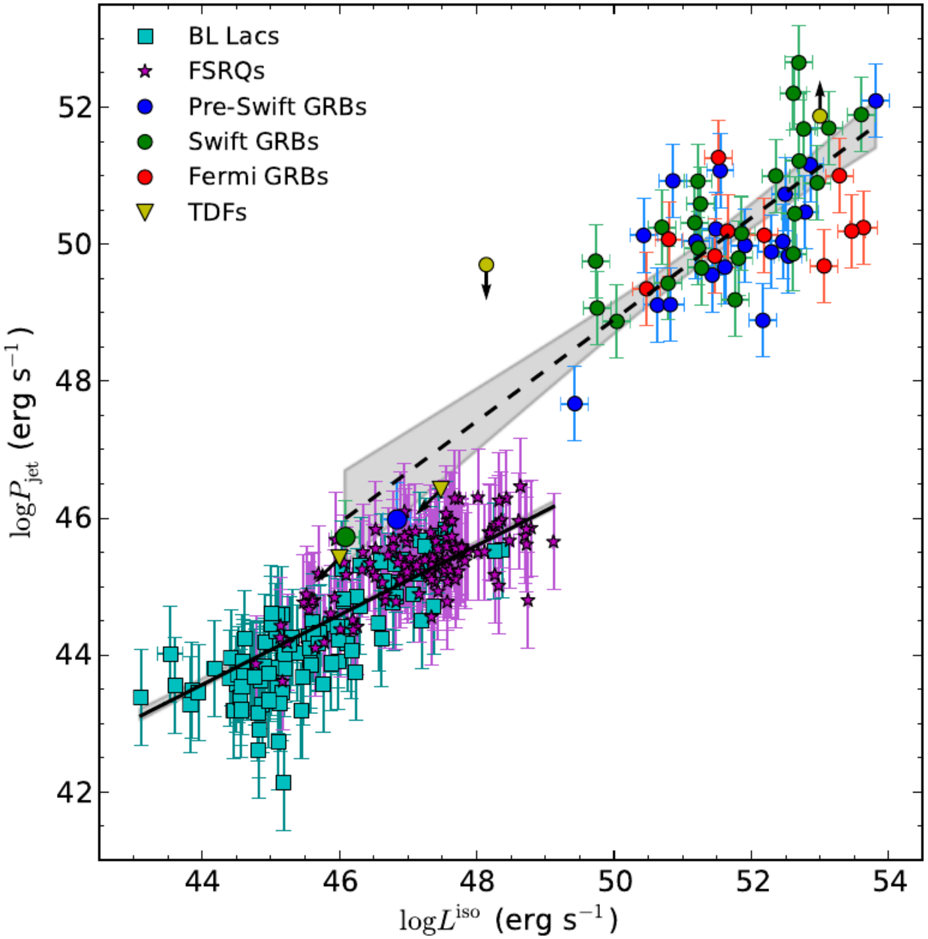

TABLE I. The list of the analyzed AGNs. $z$, $l$, $b$ are the redshift and galactic longitude and latitude, $N_{\rm flare}$ is the number of flares, $L_{\rm max}$ is the maximum isotropic equivalent bolometric luminocity in the observation period, in units of $10^{47}$erg s$^{-1}$.

| Name | $z$ | $l$ | $b$ | $N_{\rm flare}$ | $L_{\rm max}$ |
|---|---|---|---|---|---|
| PKS 0056-572 | 0.02 | 300.9 | -60.1 | 0 | $1.7 \times 10^{-3}$ |
| PKS 0131-522 | 0.02 | 288.3 | -63.9 | 0 | $6.7 \times 10^{-3}$ |
| Mkn 421 | 0.03 | 179.8 | 65.0 | 0 | $8.9 \times 10^{-2}$ |
| 3C 120 | 0.03 | 190.4 | -27.4 | 0 | $2.2 \times 10^{-2}$ |
| Mkn 501 | 0.03 | 63.6 | 38.9 | 0 | $3.0 \times 10^{-2}$ |
| 1ES 1959+650 | 0.05 | 98.0 | 17.7 | 0 | $7.2 \times 10^{-2}$ |
| SBS 1646+499 | 0.05 | 76.6 | 40.1 | 0 | $2.8 \times 10^{-2}$ |
| 3C 111 | 0.05 | 161.7 | -8.8 | 0 | $4.1 \times 10^{-2}$ |
| AP Librae | 0.05 | 340.7 | 27.6 | 0 | $4.7 \times 10^{-2}$ |
| 5BZBJ1728+5013 | 0.06 | 77.1 | 33.5 | 0 | $4.6 \times 10^{-2}$ |
| PKS 0521-36 | 0.06 | 240.6 | -32.7 | 0 | 0.1 |
| 1H 0323+342 | 0.06 | 155.7 | -18.8 | 0 | 0.9 |
| PKS 1441+25 | 0.06 | 34.6 | 64.7 | 0 | 0.3 |
| BL Lacertae | 0.07 | 92.6 | -10.4 | 0 | 0.3 |
| TXS 0518+211 | 0.11 | 183.6 | -8.7 | 0 | 0.7 |
| PKS 2155-304 | 0.12 | 17.7 | -52.2 | 0 | 0.9 |
| GB6 J1542+6129 | 0.12 | 95.4 | 45.4 | 0 | 0.2 |
| 1ES 1215+303 | 0.13 | 188.9 | 82.1 | 0 | 0.8 |
| ON 246 | 0.14 | 232.8 | 84.9 | 2 | 1.2 |
| PKS 1717+177 | 0.14 | 39.5 | 28.1 | 0 | 0.6 |
| 1ES 0806+524 | 0.14 | 166.2 | 32.9 | 0 | 0.4 |
| OQ 530 | 0.15 | 98.3 | 58.3 | 0 | 0.4 |
| 3C 273 | 0.16 | 290.0 | 64.4 | 3 | 2.8 |
| PKS 0829+046 | 0.17 | 220.7 | 24.3 | 0 | 0.9 |
| PKS 0736+01 | 0.19 | 217.0 | 11.4 | 5 | 2.7 |
| MG1 J021114+1051 | 0.20 | 152.6 | -47.4 | 2 | 1.4 |
| B2 2107+35A | 0.20 | 80.3 | -8.4 | 0 | 0.6 |
| OX 169 | 0.21 | 72.1 | -26.1 | 1 | 1.1 |
| 1H 1013+498 | 0.21 | 165.5 | 52.7 | 2 | 2.0 |
| B2 2023+33 | 0.22 | 73.1 | -2.4 | 36 | 3.2 |
| PMN J0017-0512 | 0.23 | 101.2 | -66.6 | 1 | 1.4 |
| 5BZQJ0422-0643 | 0.24 | 200.8 | -36.1 | 0 | 0.7 |
| PMN J1903-6749 | 0.26 | 327.7 | -26.1 | 1 | 1.6 |
| PKS 0301-243 | 0.26 | 214.6 | -60.2 | 10 | 7.4 |
| S2 0109+22 | 0.27 | 129.1 | -39.9 | 31 | 2.9 |
| GB6 J0937+5008 | 0.28 | 167.4 | 46.7 | 0 | 0.9 |
| PMN J1802-3940 | 0.30 | 352.5 | -8.4 | 61 | 5.1 |
| NVSS J223708-392137 | 0.30 | 0.59 | -59.6 | 2 | 1.5 |
| S5 0716+71 | 0.30 | 144.0 | 28.0 | 42 | 8.7 |

# Kinetic energy

- We can select 13 candidate sources

- Next step – we calculate corresponding kinetic energy deposited in this flares, using correlation from (Nemmen et al, 2012)




- The obtained energetics corrected for the beaming effects is $10^{45}$ erg s$^{-1}$ Mpc$^{-3}$

- Correction ($2\Gamma^2$) implies that we need effective isotropisation

# Isotropisation&anisotropy

- We need effective isotropisation. There are several possible sites:
  - » Immediate vicinity of AGNs. Strong MFs
  - » Host galaxy
  - » Intercluster medium
  - » (least likely) EGMF

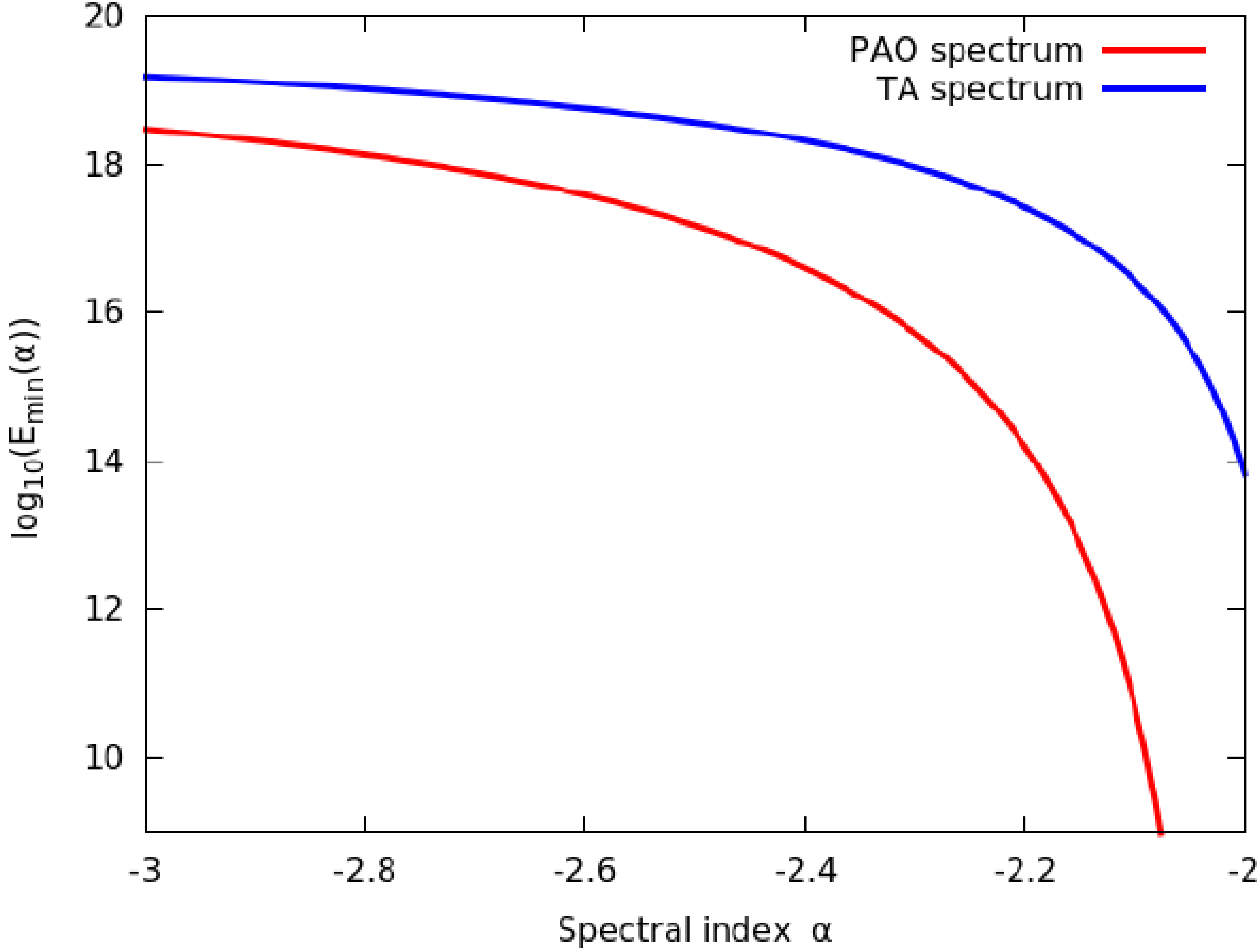
- Also we need to solve the problems of anisotropy and steady flux – there were observed 13 candidate sources in 7.4 years of observations in 1000 $V_{GZK}$ volume. That gives $\mathfrak{R}$=0.2 $yr^{-1}$ (with beaming correction) in the $V_{GZK}$.
- Delay due to the MF $\tau \sim d\theta_s^2/2$ greatly increase the number of 'active' UHECR sources at any given time, because $\tau$ could exceed $10^6$ years and we observe CRs from $10^5$ flares simultaneously.

## Spectrum in the sources

- Even in the case of isotropisation the UHECRs with $E>10^{20}$ eV consume a significant fraction of AGN kinetic energy, 1.5(PA)-7.5(TA)%.

- That makes possible to put strong constraints on the allowed shape of the spectrum. It should be hard and/or narrow. This shape is predicted in a large number of different models of acceleration in relativistic shocks

# Spectrum in the sources



## Conclusions

- Fermi LAT observations show that it is possible that the strongest AGN flares can be sources of UHE protons of even the highest energies, $E>10^{20}$ eV, if effective isotropisation takes place

- A significant part of kinetic energy of flares is still needed for that, this fact allows to strongly constrain shape of the CR spectrum in the sources – it must be hard  (sp.index ~-2) and/or narrow.

# Thank you!

FIG. 2. Deviations of the energy flux computed in the assumption of a flat spectrum from the actual value as a function of “known” spectral index.