Neutral UHE particles from BL Lacs: tests and implications

The Second International Workshop on
Ultra-high-energy cosmic rays and their sources

INR, Moscow, April 14-16, 2005

Dmitry S. Gorbunov
D.S.G., P.G. Tinyakov, I.I. Tkachev, S.V. Troitsky

Institute for Nuclear Research, Moscow

Observed correlations
Astrophysical sources of neutral primaries
Prediction of number of coincidences to be observed by future experiments

---

~ 1000 **UHECRs of** $E > 10^{19}$ **eV were observed,**

but sources are still unknown. . .

Extragalactic candidates:

— colliding galaxies
— radio galaxies FRI, FRII
— Seyfert galaxies
— HP-blazars
— BL Lacs
— γ-ray sources
— FSRQ
— GeV sources
— TeV sources
— dead quasars
. . .

The direct evidence:

coincidence
of arrival directions
of UHECR events
with
positions of the objects
on the celestial sphere

Major problems with this approach

- poor angular resolution ... $\delta \sim \#degrees$
- protons are strongly deflected in $\vec{B}_{Gal}$ ...

Search for the positional correlations:

a) neutral primaries...

b) $E \gtrsim 3 \cdot 10^{19}$ — deflection angle $\lesssim \#degrees$

~ 100 events... — tracing back through the Galaxy

in the framework of a model of $\vec{B}_{Gal}$

and neglecting $\vec{B}_{extragal}$

Testing various catalogues of UHECR

candidates:

— colliding galaxies
— radio galaxies FRI, FRII
— Seyfert galaxies
— HP-blazars
— BL Lacs
— γ-ray sources
— FSRQ
— GeV sources
— TeV sources
— dead quasars
...

(AGASA, Yakutsk,
Haverah Park, Volcano Ranch)

(E, θ, φ)

were measured
with a
reasonable accuracy

chance probability
of positional coincidences
candidates $\longleftrightarrow$ UHECR events

D.S.G., S.V. Troitsky, Astropart. Phys. **23**, 175 (2005)

Correlations with BL Lac's

BL Lac's subsample	UHECR subsample	$P(\delta_{ang.res.})$
$mag < 18$, $F_{6cm}^{radio} > 0.17$Jy	autocor AGASA+Yakutsk	$\lesssim 10^{-4}$
γ-ray-loud (EGRET)	autocor AGASA+Yakutsk	$10^{-4} - 10^{-7}$
$mag < 18$	AGASA $E > 4 \cdot 10^{19}$ eV	$10^{-2} - 10^{-4}$

P. Tinyakov, I. Tkachev, JETP Lett. **74**, 445 (2001)

D.G., P. Tinyakov, I. Tkachev, S. Troitsky, Astrophys. J. **577**, L93 (2002)

P. Tinyakov, I. Tkachev, Astropart. Phys. **18**, 165 (2002)

There are sources of UHECRs among the BL Lac's !!!

Check this hypothesis with independent data set

HiRes data: $N_r = 271$ events at $E > 10^{19}$ eV

arrival directions ($\vec{n}_i$) — $\delta_{exp.res.} = 0.6°$!!!

E_i unpublished — neutral correlations

Procedure:

1) real data $\alpha_{ij} = \angle$(UHECR event, object)

$$N^{real}(\delta) = \sum_{ij} \theta\left(\delta - \alpha_{ij}\right)$$

2) mock data: $N_m = 10^5$ sets of $N_r = 271$ events $\rightarrow$ 1)

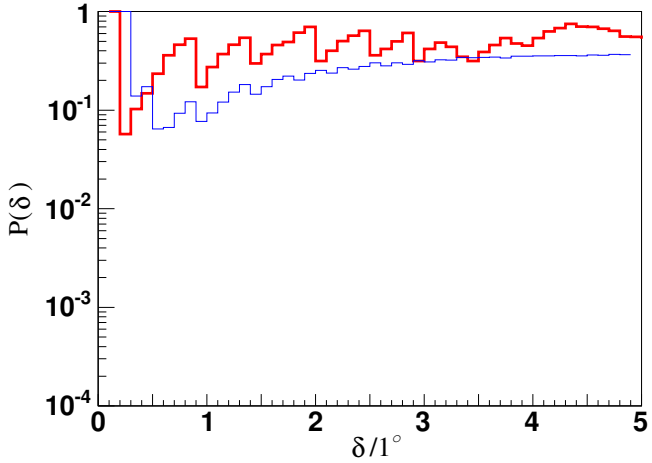
3) chance probability: $P(\delta) = \frac{\sum_{i=1}^{i=N_m} \theta\left(N_i^{mock}(\delta) - N^{real}(\delta)\right)}{N_m}$

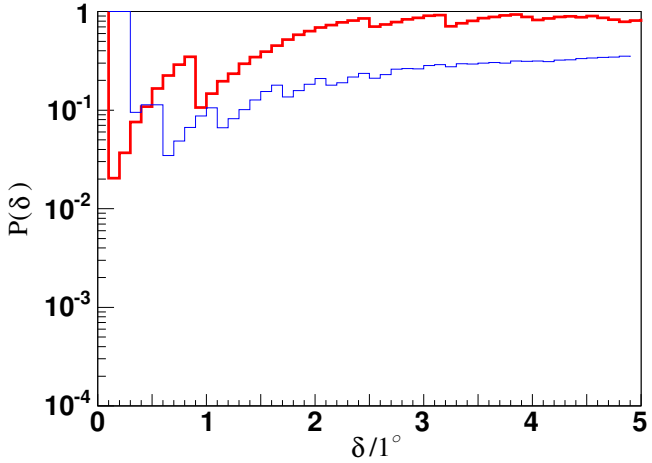
Expected signal: $\delta \sim \delta_{exp.res.}$

1) simulated set with 10 out of 271 from the sources (BL Lac's from the catalogue) $\rightarrow$ Procedure

2) repeat step 1) many times and evaluate average $P^{exp}(\delta)$

Obtained results

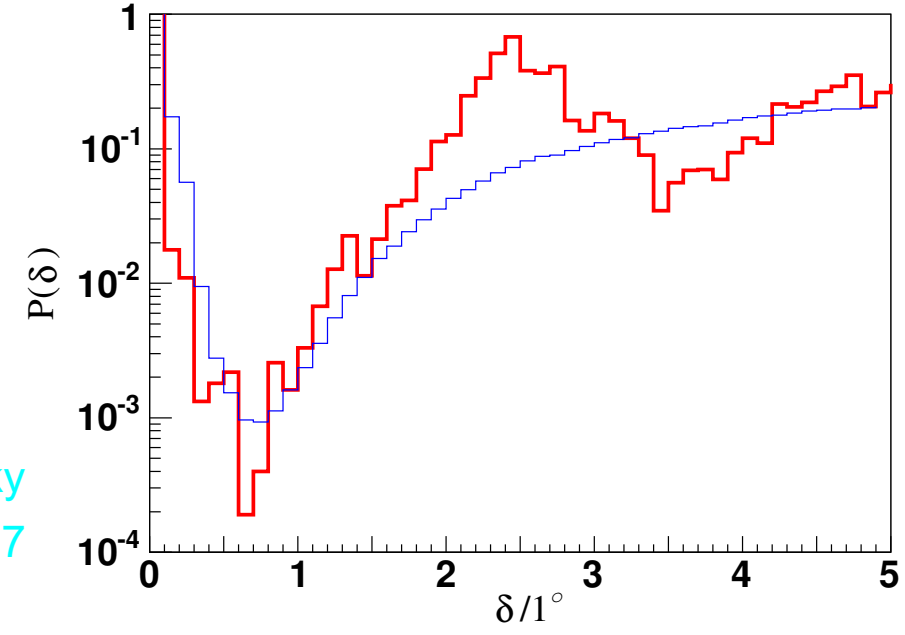




$mag < 18$ — 156 BL Lac's

min($P^{exp}(\delta)$) at $\delta^{exp} = 0.8°$

probability $P(0.8°) = 4 \cdot 10^{-4}$



D.S.G., P.G. Tinyakov, I.I. Tkachev, S.V. Troitsky (astro-ph/0406654, Pis'ma v ZhETF **80** 167 (2004))

Conclusions

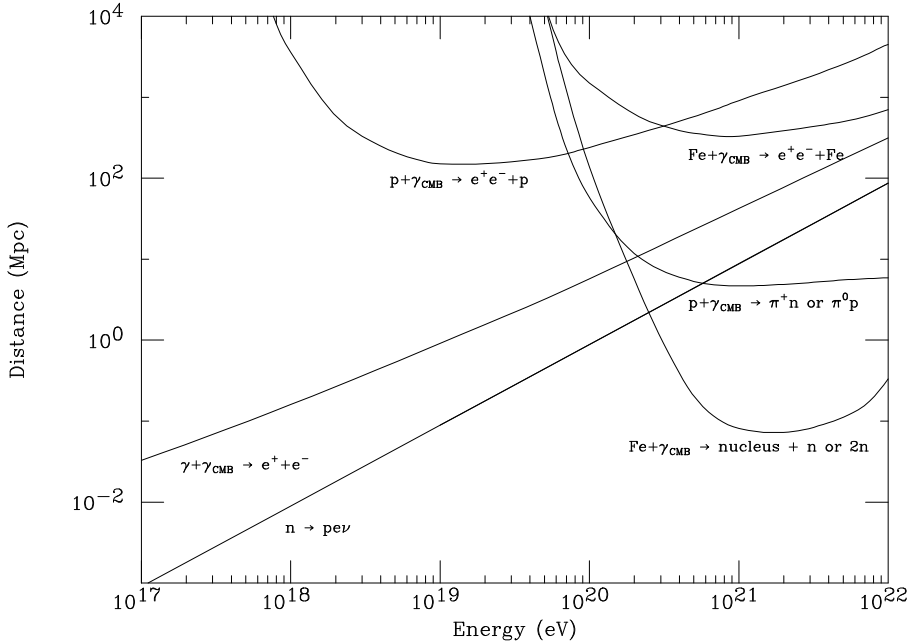
- Indeed, there are UHECR sources among BL Lac's !!!
- Expected deflection angle for protons is 5°-10° $\rightarrow$ there is a small fraction of neutral primaries at $E > 10^{19}$ eV !!!
- Only one catalogue (the largest) exhibits significant correlations $\rightarrow$ many sources of small luminosity in UHECR
- 20 BL Lacs correlate with HiRes events within 1° $\rightarrow$ One can try to understand which BL Lacs are UHECR emitters !!!

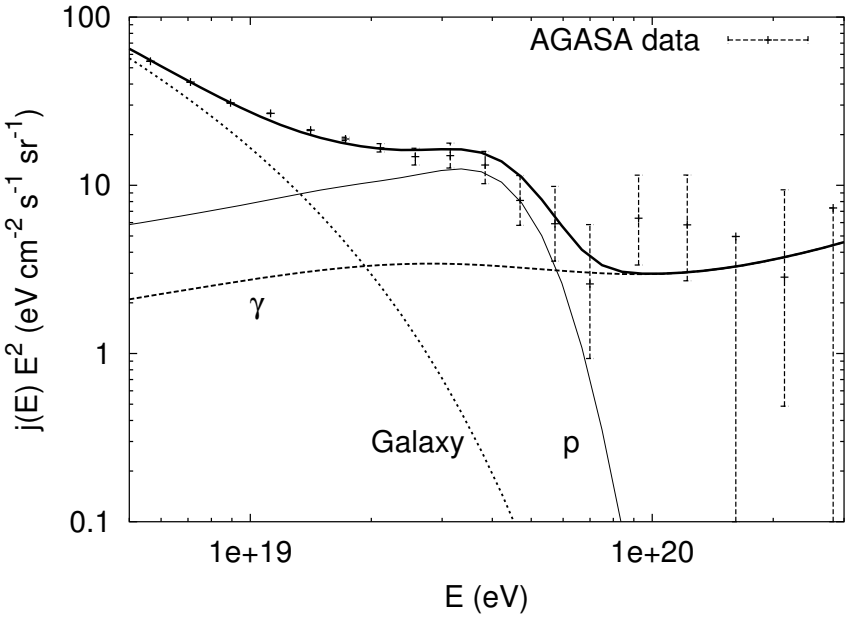
3% fraction of neutral primaries: γ ?

- relic heavy X-particles
- ruled out Z-burst

3% fraction of neutral primaries: γ ?

- relic heavy X-particles
- ruled out Z-burst
- astrophysical accelerators: pure photonic source?





J.Cronin astro−ph/0402487

$$z_{min} = 0.03,\ N_\gamma/N_p = 3,\ dN_{p,\gamma}/dE \propto E^{-1.5},\ E_{max} = 10^{23}\ \text{eV}$$

O.Kalashev *et al.* astro−ph/0107130

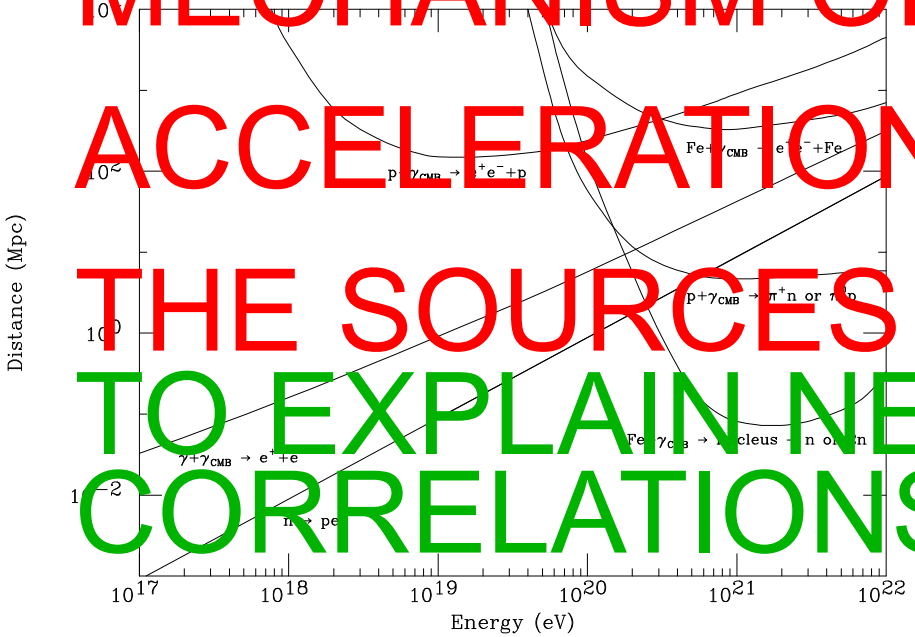
$$z_{min} = 0.03,\ N_\gamma/N_p = 45,\ dN_{p,\gamma}/dE \propto E^{-1.75},\ E_{max} = 10^{22}\ \text{eV}$$

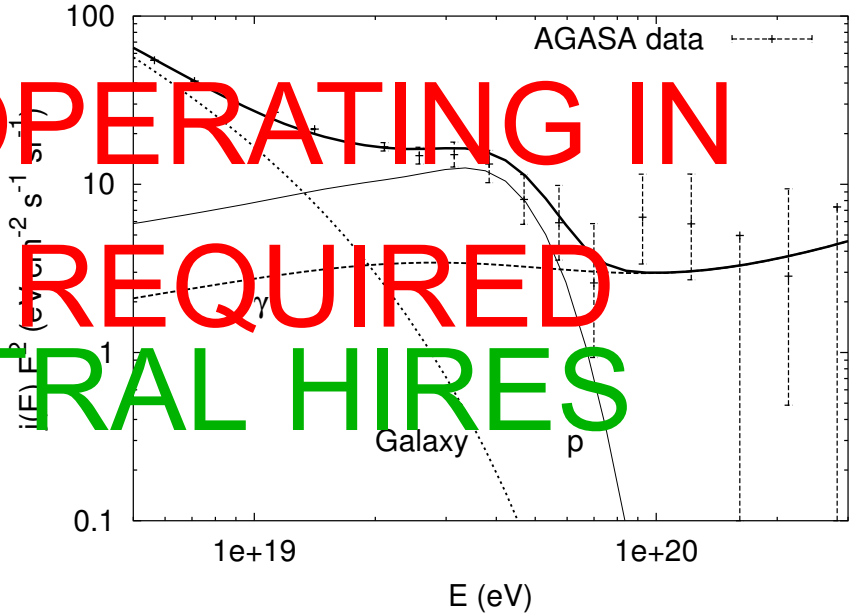
Unrealistic spectrum: power law with α and E_{max}

3% fraction of neutral primaries: γ ?

- relic heavy X-particles
- ruled out Z-burst
- astrophysical accelerators: pure photonic source?

SPECIAL UNKNOWN MECHANISM OF ACCELERATION OPERATING IN THE SOURCES IS REQUIRED TO EXPLAIN NEUTRAL HIRES CORRELATIONS





J.Cronin astro−ph/0402487

$$z_{min} = 0.03,\ N_\gamma/N_p = 3,\ dN_{p,\gamma}/dE \propto E^{-1.5},\ E_{max} = 10^{23}\ \text{eV}$$

O.Kalashev *et al.* astro−ph/0107130

$$z_{min} = 0.03,\ N_\gamma/N_p = 45,\ dN_{p,\gamma}/dE \propto E^{-1.75},\ E_{max} = 10^{22}\ \text{eV}$$

Unrealistic spectrum: power law with α and E_{max}

Predictions for future experiments

Which result of a future (past) experiment would be consistent with HiRes correlations?

Assumptions:

- All 156 sources are of equal luminocity in UHECR: the brightest among them are distributed isotropically on the celectial sphere
- Each UHECR experiment E has an angular resolution well-described by Gaussian distribution with characteristic angle $\sim \sigma_E$: the extension to the more complicated cases is straightforward
- The fluxes measured by different experiments match one with each other: one can relax this assumption
- We make a prediction for the total number of coincidences "BL-event" within the angle $\delta_{th} = \sqrt{2}\sigma_E$: the validity of the prediction does not depend on the choice of this angle
- The number of observed coincidences (within a given angle) is determined by the Poisson distribution

Predictions for 156 BL Lac's with mag> 18

Input: HiRes Stereo: $n_H^0 = 12$ coincidences within $\delta_{th} = 1.4 \cdot 0.6°$ with $b_H^0 = 2.4$ expected from background (MC) per $N_H^0 = 271$ collected events

Output: The experiment E collects N_E events with the number of background coincidences

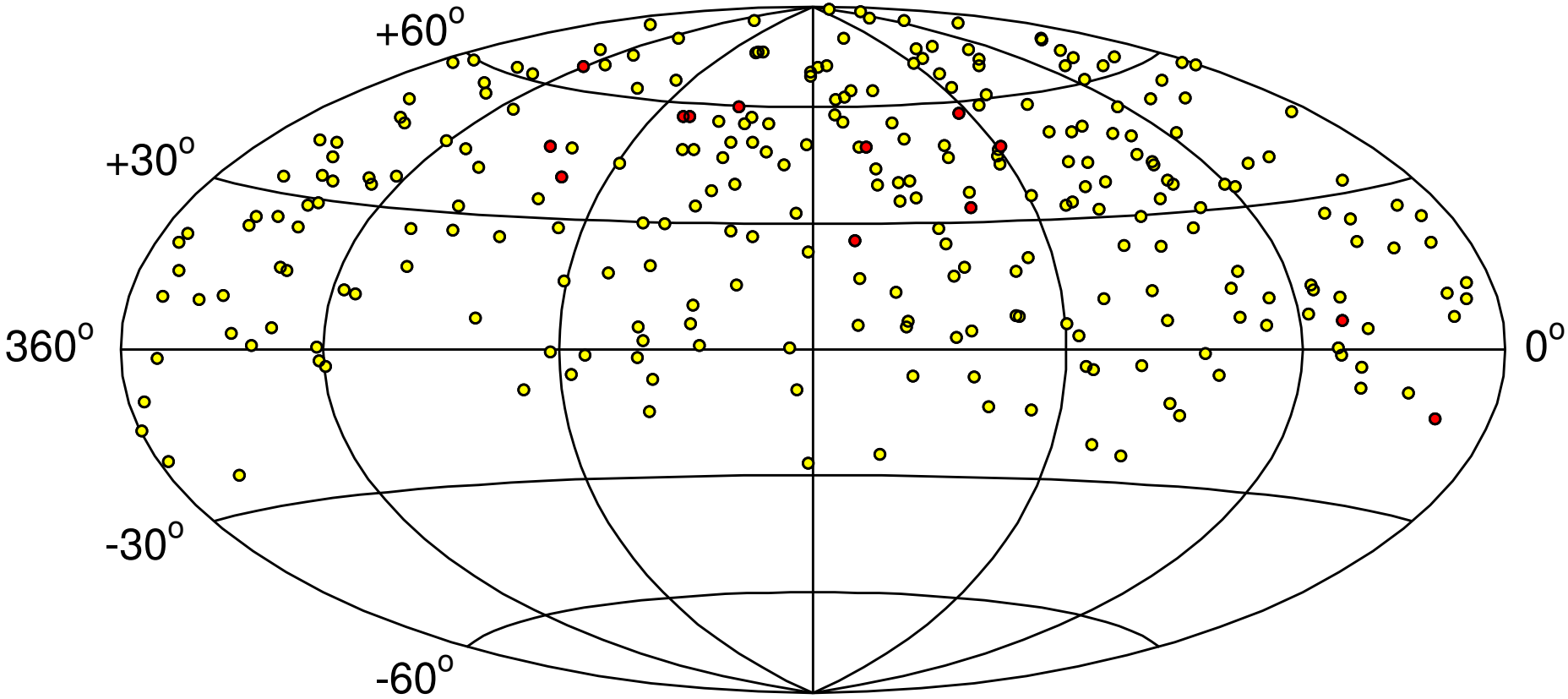
$$b_E = b_H^0 \cdot \frac{N_E}{N_{HiRes}^0} \cdot \frac{B_E}{B_{HiRes}} \ ,$$

where B_E is an effective exposure of the experiment E with respect to the background:

$$B_E = \int_{\Omega_{156}} \mathcal{E}(\Omega) d\Omega \ , \quad \Omega_{156} = \bigcup_i^{156} \omega_i \ ,$$

ω_i are circles of $R_s = \sqrt{2}\sigma_E$ with i-th sources in the centers.

Ω_{156} for the original HiRes data



The numbers of signal events

$$s_E = s_H^0 \frac{N_E}{N_{HiRes}^0} \frac{A_E}{A_{HiRes}} \ ,$$

where A_E is an effective exposure with respects to observation of sources from a given catalog: the convolution of the exposure with the distribution of the objects. For each object the integration is confined to the circles of R_s.

Signal events in real HiRes data:

$$f(s_H) = \frac{(s_H + b_H^0)^{n_H^0}}{\Gamma(n_H^0 + 1, b_H^0)} \mathrm{e}^{-(s_H + b_H^0)} \ .$$

Final estimate

The probability to have n_E coincidences in experiment E *on the conditions that HiRes exhibits* n_H *coincidences*:

$$\tilde{L}(n|s_E) = \int_0^\infty \frac{(s_E + b_E)^n}{n!} \mathrm{e}^{-(s_E+b_E)} f(s_H) ds_H \ .$$

To estimate the probability to collect less than n^E coincidences one can sum up

$$\tilde{P}(n_E) = \sum_{n=0}^{n=n_E} \tilde{L}(n|s_E) \ .$$

The 95% confidence intervals

$$N_{95} = n_{E,0.05} - n_{E,0.95} \ , \quad \text{with } n_{E,x} \text{ from } x = \tilde{P}(n_{E,x}) \ .$$

Preliminary Results

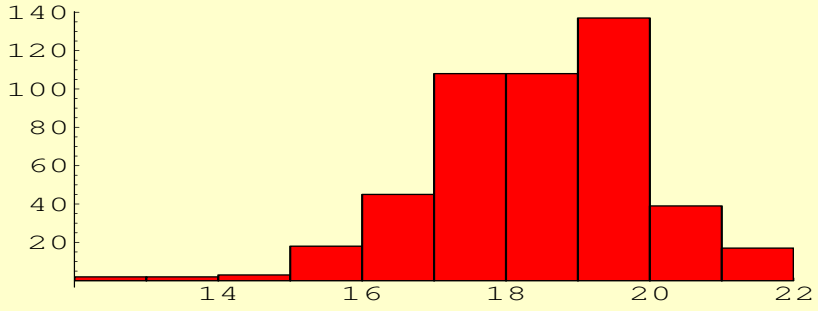
Experiment	σ_E	R_s	N_E	A_E	b_E	N_{95}
HiRes, original	0.6°	0.85°	271	14.5	3.5	
HiRes,	0.6°	0.85°	300	14.5	3.9	5 - 22
HiRes, $z < 60^\circ$	0.6°	0.85°	300	14.9	5.1	6 - 24
AGASA, $z < 45^\circ$	2.4°	3.39°	1500	15.3	270	277 - 365
Ground PA, $z < 60^\circ$	3.0°	4.24°	1500	8.1	227	223 - 286
Ground PA, $z < 60^\circ$	3.0°	4.24°	8000	8.1	1210	1248 - 1470
Hybrid PA, $z < 60^\circ$	0.45°	0.64°	200	7.3	0.81	0 - 8
Hybrid PA, $z < 60^\circ$	0.45°	0.64°	1500	7.3	6.1	13 - 49
TA, $z < 60^\circ$	0.62°	0.88°	1500	15.5	22.8	40 -112

Comments:

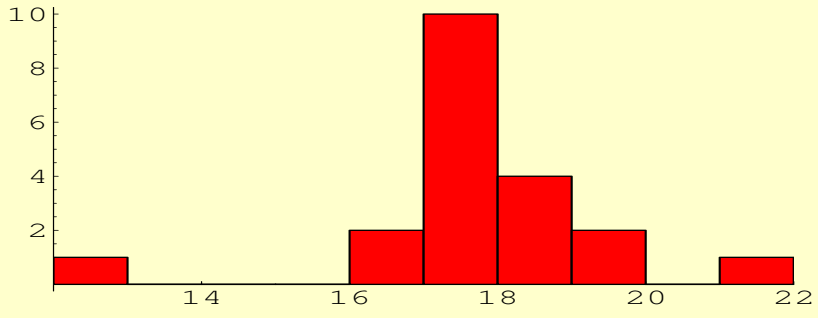
- δ_{th}
- other catalogs of sources or UHECR

Looking for intrinsic properties:

Distributions of BL Lacs in visual magnitude m (482):

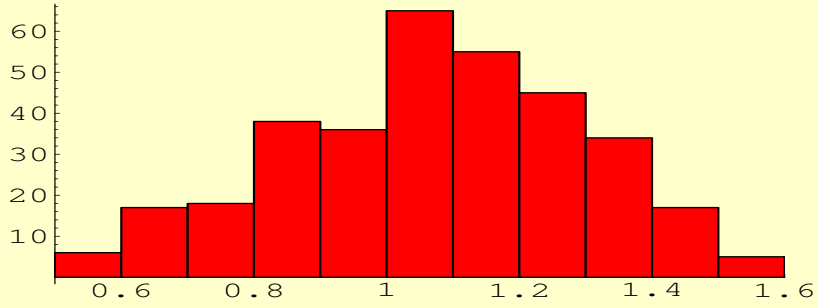


Correlating with HiRes events (20):

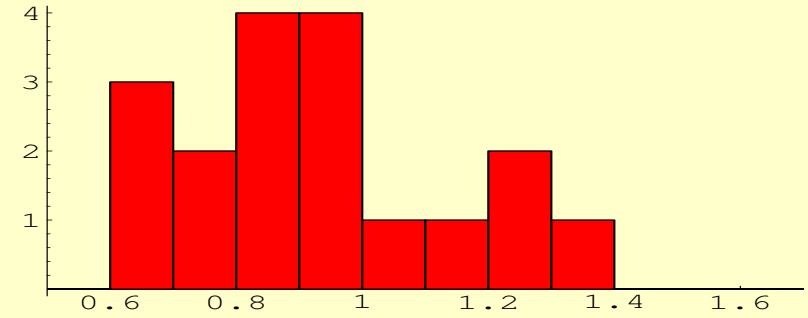


KS-test: the probability for the lower distribution to be a fluctuation of the upper one ~ 0.01

Distributions of BL Lacs in spectral index α BL Lacs with known α (338):



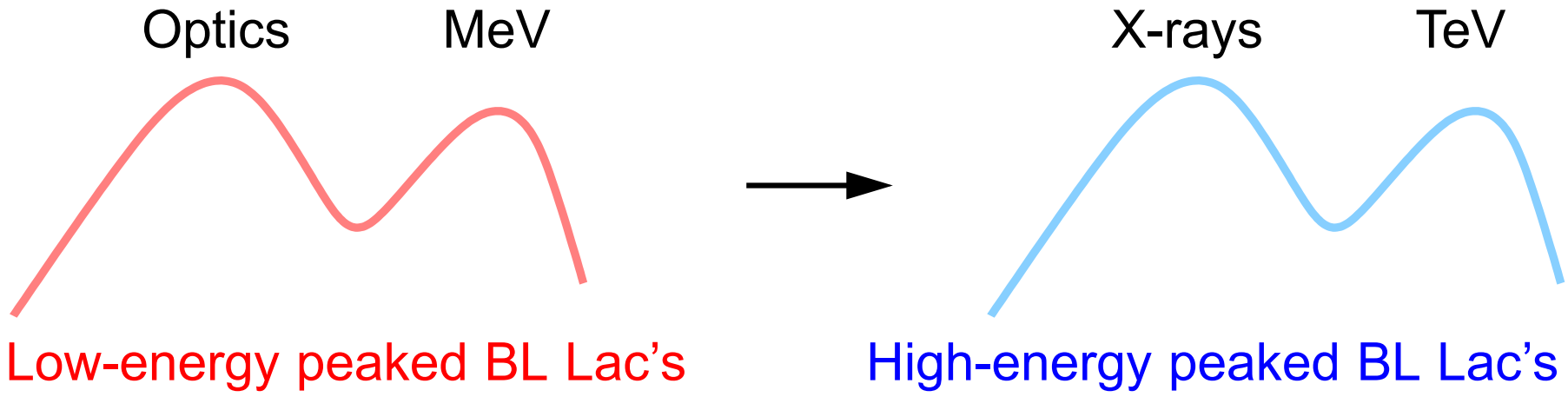
Correlating with HiRes events (18):



KS-test: the probability for the lower distribution to be a fluctuation of the upper one ~ 0.003

BL Lac's with optical-to-X-ray index $\alpha < 1$ $\quad P(\delta = 0.7°) < 10^{-5}$

Possible obstacle: propagation of UHECR



mag< 18: closest brightest sources? — multiplets

intrinsic property — increase in number of correlating objects with new objects in the catalog

Propagation: E_{max} - dependence?

Preliminary Results

Experiment	σ_E	R_s	N_E	A_E	b_E	N_{95}
HiRes, original	0.6°	0.85°	271	14.5	3.5	
HiRes,	0.6°	0.85°	300	14.5	3.9	5 - 22
HiRes, $z < 60^\circ$	0.6°	0.85°	300	14.9	5.1	6 - 24
AGASA, $z < 45^\circ$	2.4°	3.39°	1500	15.3	270	277 - 365
Ground PA, $z < 60^\circ$	3.0°	4.24°	1500	8.1	227	223 - 286
Ground PA, $z < 60^\circ$	3.0°	4.24°	8000	8.1	1210	1248 - 1470
Hybrid PA, $z < 60^\circ$	0.45°	0.64°	200	7.3	0.81	0 - 8
Hybrid PA, $z < 60^\circ$	0.45°	0.64°	1500	7.3	6.1	13 - 49
TA, $z < 60^\circ$	0.62°	0.88°	1500	15.5	22.8	40 -112