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EVIDENCE FOR A CONNECTION BETWEEN γ-RAY AND UHECR EMISSIONS BY BL LACS

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OUTLINE:

— Clustering of UHECR

— BL Lacs as possible sources

— Correlation analysis

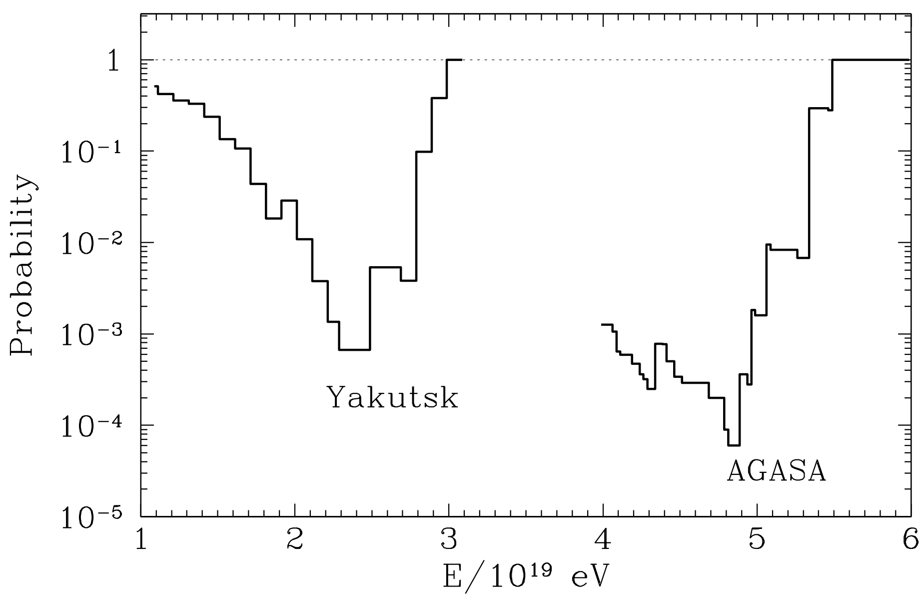
— γ-ray loud BL Lacs and their correlation with UHECR

— Conclusions

CLUSTERING OF UHECR

* N.N. Efimov, A.A. Mikhailov, Astropart.Phys. **2** (1994) 329: 4 directions (clusters) are identified as "significant" in the world data set of cosmic rays with energies $E > 10^{19}$ eV
* M. Takeda et al., Ap.J. **522** (1999) 225: 1 triplet and 3 doublets out of 47 AGASA events with energies $E > 4 \times 10^{19}$ eV; the chance probability $< 1\%$.
* Y. Uchihori et al., Astropart. Phys **13** (2000) 151: 2 triplets and 6 doublets at 3° in the world data set of 92 events with energy $E > 4 \times 10^{19}$ eV; the chance probability $\sim 1\%$.

- **Energy dependence** (Tinyakov & Tkachev, JETP Lett. 2001):



Correlations are largest for:

AGASA events with $E > 4.8 \times 10^{19}$ eV
Yakutsk events with $E > 2.4 \times 10^{19}$ eV
} 65 rays

- Quantitatively:

experiment	bin size	$E_{\rm min}$	probability of chance clustering
AGASA	2.5°	4.8×10^{19} eV	4×10^{-4}
Yakutsk	4°	2.4×10^{19} eV	3×10^{-3}

Combine all experiments assuming Poisson statistics:

AG + YK	9×10^{-6}
AG + YK + VR + HP	3×10^{-5}
AG + YK + VR	3×10^{-6}

Are experiments compatible with each other?

	$N_{\rm tot}$	observed	expected	probability
AG	39	6	$5.4 + 0.6$	–
YK	26	8	$2.9 + 1.6$	0.09
HP	32	2	$4.0 + 1.8$	0.07
VR	10	1	$0.7 + 0.1$	0.55

SOURCES

- Clustering favors small number of point sources

From purely statistical arguments (triplets/doublets/singlets) the number of sources is several hundred (Dubovsky, Tinyakov & Tkachev, PRL 2000)

$$N_{\rm sources} \sim \frac{N_{\rm tot}^3}{N_{\rm cl}^2}$$

At energies below GZK, this is a small number compared to the number of galaxies $\Longrightarrow$sources are rare

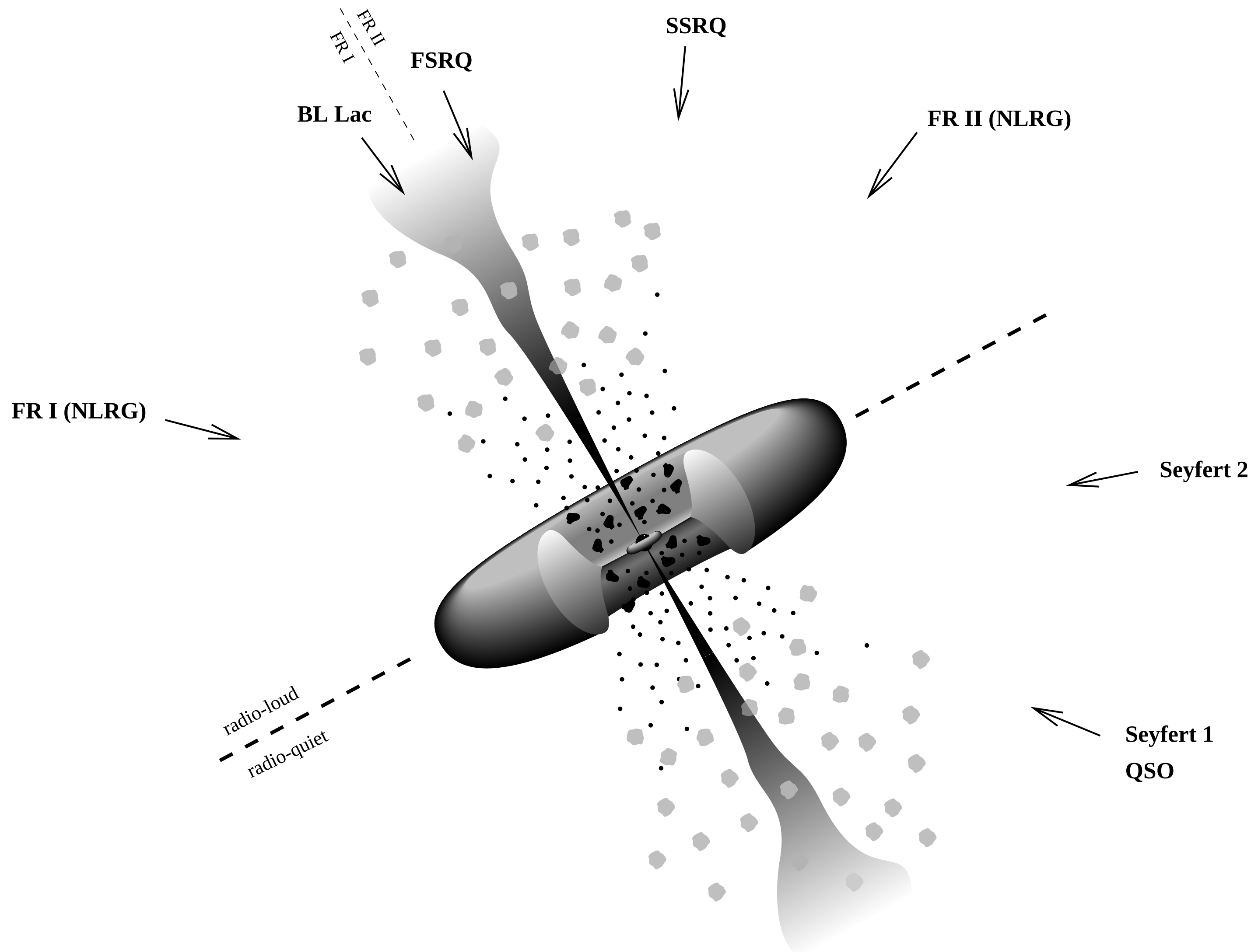
- One of the best astrophysical candidates — AGNs

  * large total power
  * possible acceleration to highest energies
  * enough individual power to be a source of clusters despite large distance:

    Required energy flux in UHECR ~ 1 eV/cm^{2}s. This corresponds to energy flux in optics at mag $= 18$.

  * However AGNs are very frequent; this does not match the expected number of sources

- Among AGNs, BL Lacs (subclass of blazars) are particularly good candidates
  * ultra-relativistic jets pointing at observer may accelerate particles to higher energies
  * absence of emission lines may indicate low density of ambient matter $\Longrightarrow$ lower losses
  * high collimation — "very rare" objects; recent catalog Veron & Veron 2001 contains 350 confirmed BL Lacs $\Longrightarrow$ number is roughly OK (may be slightly too many if not all BL Lacs are already found)
- BL Lacs are at cosmological distances (the closest is at $z \sim 0.03$). However roughly half of them have mag < 18.
- Acceleration mechanism suggests the existence of proton primaries. For them, deflections in GMF and EGMF are important.
- Acceleration mechanism suggests the existence of GZK cutoff (feature), unless primaries are exotic (neutrinos, light SUSY hadrons, etc.) or some of fundamental assumptions are wrong (e.g., Lorentz invariance is violated)



FR II
FR I
FSRQ
SSRQ
BL Lac
FR II (NLRG)
FR I (NLRG)
Seyfert 2
Seyfert 1
QSO
radio-loud
radio-quiet

- Deflection in magnetic fields:
  - ⋆ Regular magnetic field (e.g., Galactiac field)

$$\theta \sim 0.52^\circ \, q \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{R}{1\mathrm{kpc}}\right) \left(\frac{B_\perp}{10^{-6}\mathrm{G}}\right)$$

  - ⋆ Random magnetic field

$$\theta \sim 1.8^\circ \, q \left(\frac{E}{10^{20}\mathrm{eV}}\right)^{-1} \left(\frac{l_c R}{50\mathrm{Mpc}^2}\right)^{1/2} \left(\frac{B}{10^{-9}\mathrm{G}}\right)$$

where

l_c	—	correlation length
B	—	magnetic filed
$R \gg l_c$	—	propagation distance
q	—	particle charge in units of e

$\Longrightarrow$ Arrival directions should (roughly) point back to the source.

CORRELATION ANALYSIS

- Start from the standard definition: number of neighbors of i-th object in $(\theta, \theta + d\theta)$:

$$n_i = (N-1)[1 + w(\theta)] I_i(\theta) \sin\theta\delta\theta$$

Here

N	–	total number of objects
$I_i(\theta)$	–	acceptance integrated over the ring
$w(\theta)$	–	correlation function

Number of pairs with separations $(\theta, \theta + d\theta)$:

$$N_p(\theta) = \frac{1}{2} N(N-1)[1 + w(\theta)] \langle I(\theta) \rangle \sin\theta\delta\theta$$

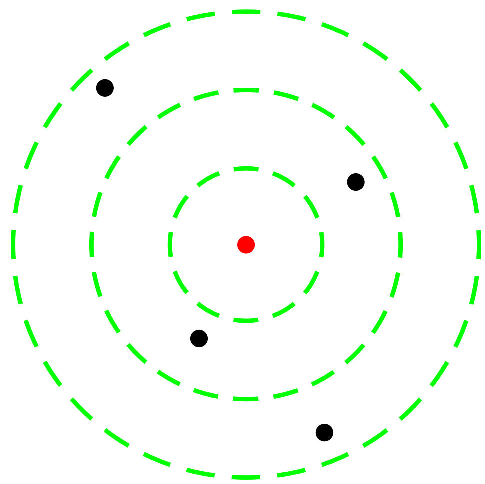
One mock catalog of M objects:

$$1 + w(\theta) = \frac{N_p(\theta)}{N_p^{\rm MC}(\theta)} \frac{M(M-1)}{N(N-1)}$$

Many mock catalogs, N objects each:

$$w(\theta) = \frac{N_p(\theta) - \langle {N_p}^{\rm MC}(\theta) \rangle}{\langle {N_p}^{\rm MC}(\theta) \rangle}$$

- Algorithm:



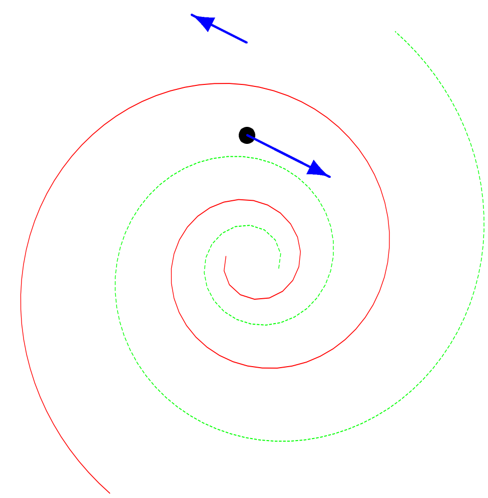
  - ⋆ take a reference event; define concentric bins of equal angular size
  - ⋆ count number of events in each bin
  - ⋆ sum over all reference events; divide over 2 in case of auto-correlations to avoid double counting → this gives data counts N_i
  - ⋆ repeat the same for a large number of random sets; calculate N_i^{MC} and σ_i

- The quantities of interest:
  - $f_i = \dfrac{N_i - N_i^{\rm MC}}{\sigma_i}$: this quantity characterizes correlations at angular scale corresponding to i-th bin; when correlations are absent it is zero
  - the probability $p(\delta)$ of the excess in the first bin (δ is the bin size). It characterizes quantitatively the significance of correlations at angular scale δ
- Important ingredient — Monte-Carlo acceptance
  - We take purely geometrical acceptance,

$$dn \propto \sin\theta_z \cos\theta_z d\theta_z$$

    where θ_z is zenith angle in horizon frame
- In case of protons correct for deflection in GMF before calculating correlation function. Note: Each mock set has to be corrected in the same way.

GMF MODEL



Spiral field:

$$B_z = 0; \qquad B_\theta = B\,\cos(p); \qquad B_r = B\,\sin(p)$$

$$B = \frac{b}{r}\cos\left[\theta - \beta\ln\left(\frac{r}{R}\right) + \phi\right]\exp\left(-\frac{|z|}{h}\right)$$

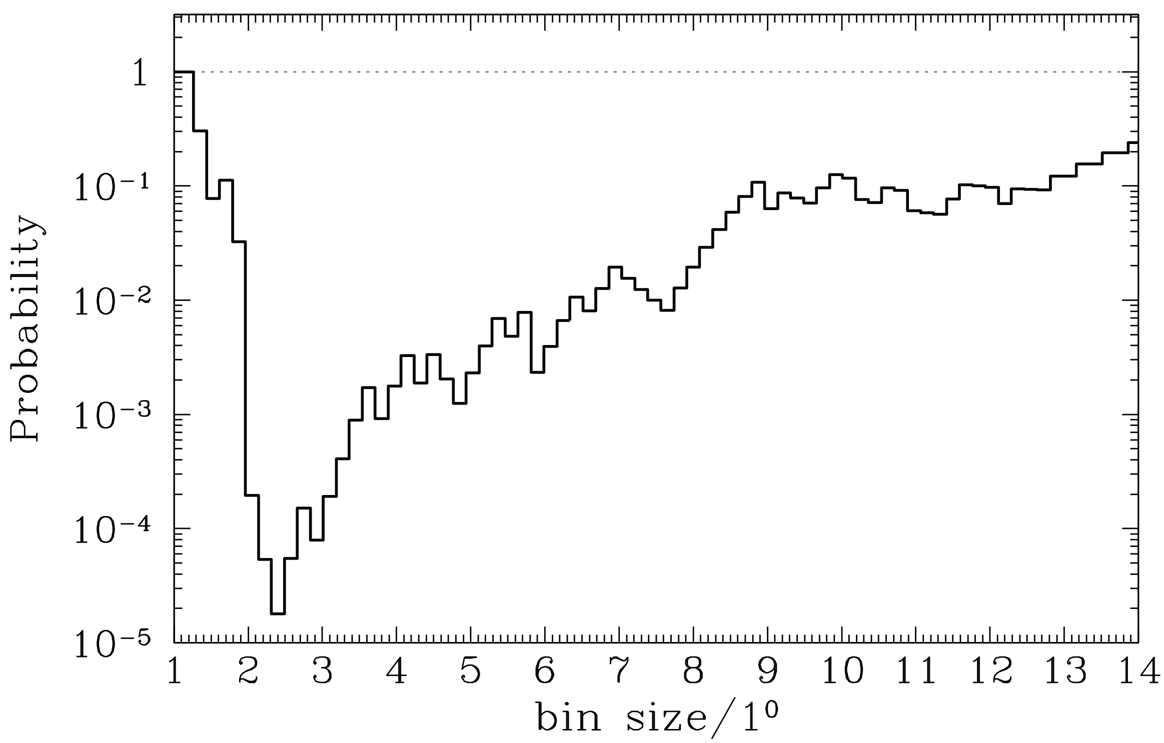
Here $R = 8.5$ kpc - distance to the Galactic center.

Constants b, β, ϕ and h are expressed through 4 parameters:

$B_0 = 1.4\mu$G	—	local value
$p = -8^\circ$	—	pitch angle
$d = -0.5$ kpc	—	distance to field reversal
$h = 1.5$ kpc	—	extent in halo

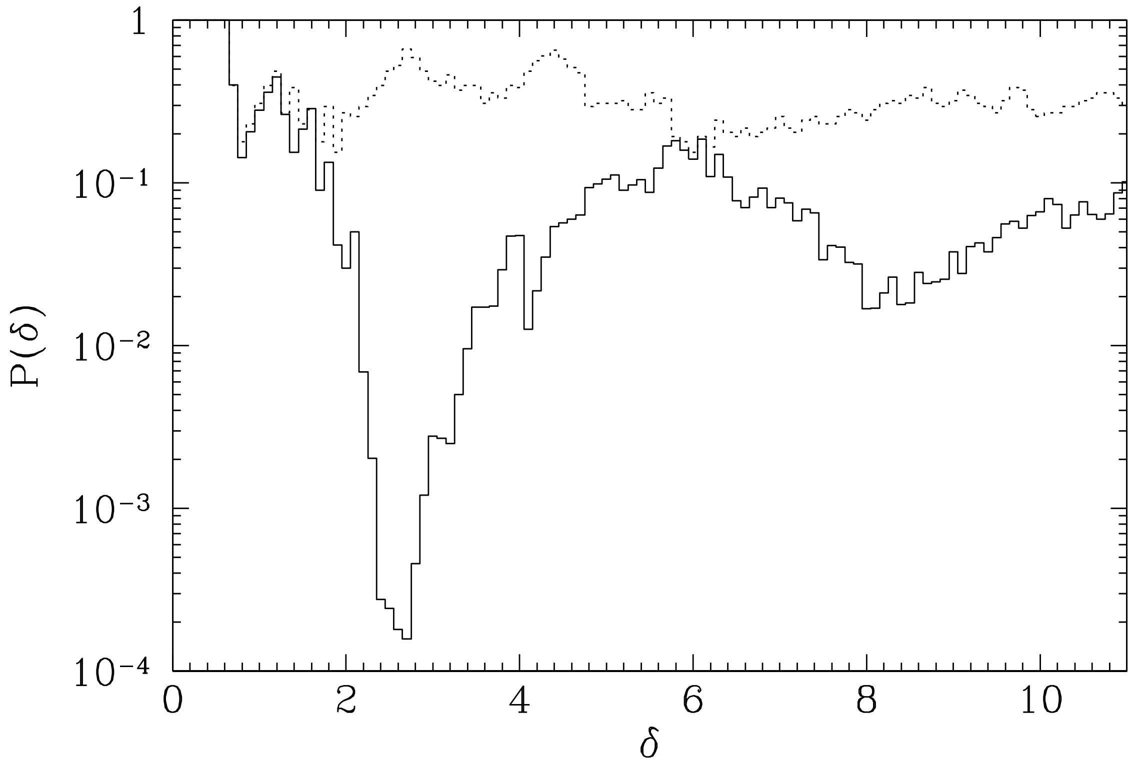
CORRELATIONS WITH BL LACS

- Significant correlations between 65 rays (AGASA with $E > 4.8 \times 10^{19}$ eV & Yakutsk with $E > 2.4 \times 10^{19}$ eV) and 22 brightest BL Lacs with $z \geq 0.1$, selected by cuts on magnitude and 6 cm radio flux (Tinyakov & Tkachev, JETP Lett. 2001):



- ⋆ Particles are assumed to be neutral
- ⋆ Selection of BL Lacs is arbitrary; freedom in cuts has to be compensated by penalty factor to get correct significance ($\sim 10^{-4}$).

- AGASA with $E > 4 \times 10^{19}$ eV
  BL Lacs with mag < 18
  all primaries are assumed to be charged
  (Tinyakov & Tkachev, Astropart. J. 2002)



Red curve: $Q = +1$

Blue curve: $Q = +2$ (for control)

Note: the signal stays at a good level (significance $\sim 10^{-3}$) even when the cut on magnitude is relaxed.

BL LACS AND EGRET SOURCES

- How to select actual UHECR emitters among all BL Lacs? $\Longrightarrow$ γ-ray emission.

  Both acceleration and propagation of UHECR is accompanied by energy losses. Large part of this energy ends up in electromagnetic channel where it degrades down to EGRET region.

- EGRET catalog:

67	-	AGNs
27	-	possible AGNs
5	-	pulsars
170	-	unidentified
...		
271		object

  Note: EGRET energy fluxes are 1-2 orders higher than needed to match UHECR flux

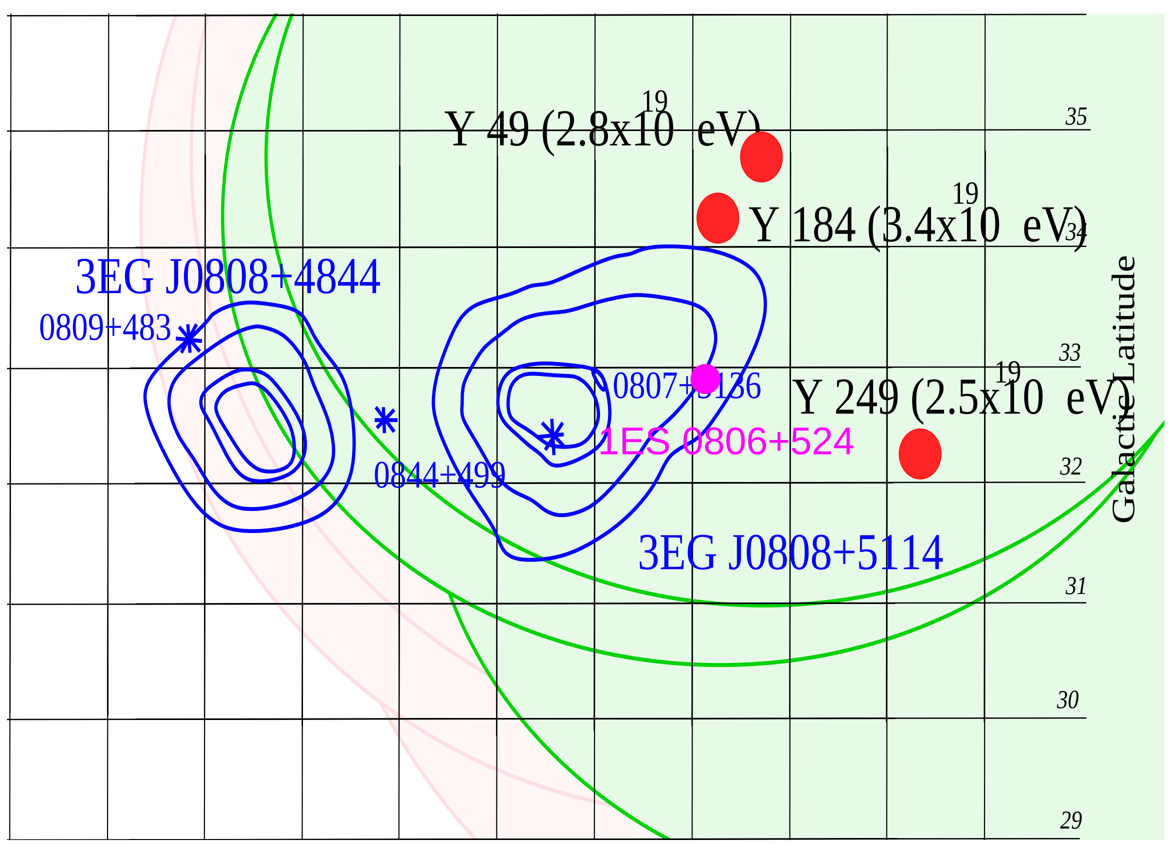
- Intersection of BL Lac and EGRET catalogs

$$\Downarrow$$

14 γ-ray loud BL Lacs

- Selection procedure:

  EGRET sources are defined as 4σ excess of signal over the background. Each event has an associated contour containing 95% of the signal. The area of this contour defines, event by event, the radii R_{95}. We define BL Lac to be associated with EGRET source if it falls within $2R_{95}$ from EGRET best fit position. Note: R_{95} contours are often non-circular.

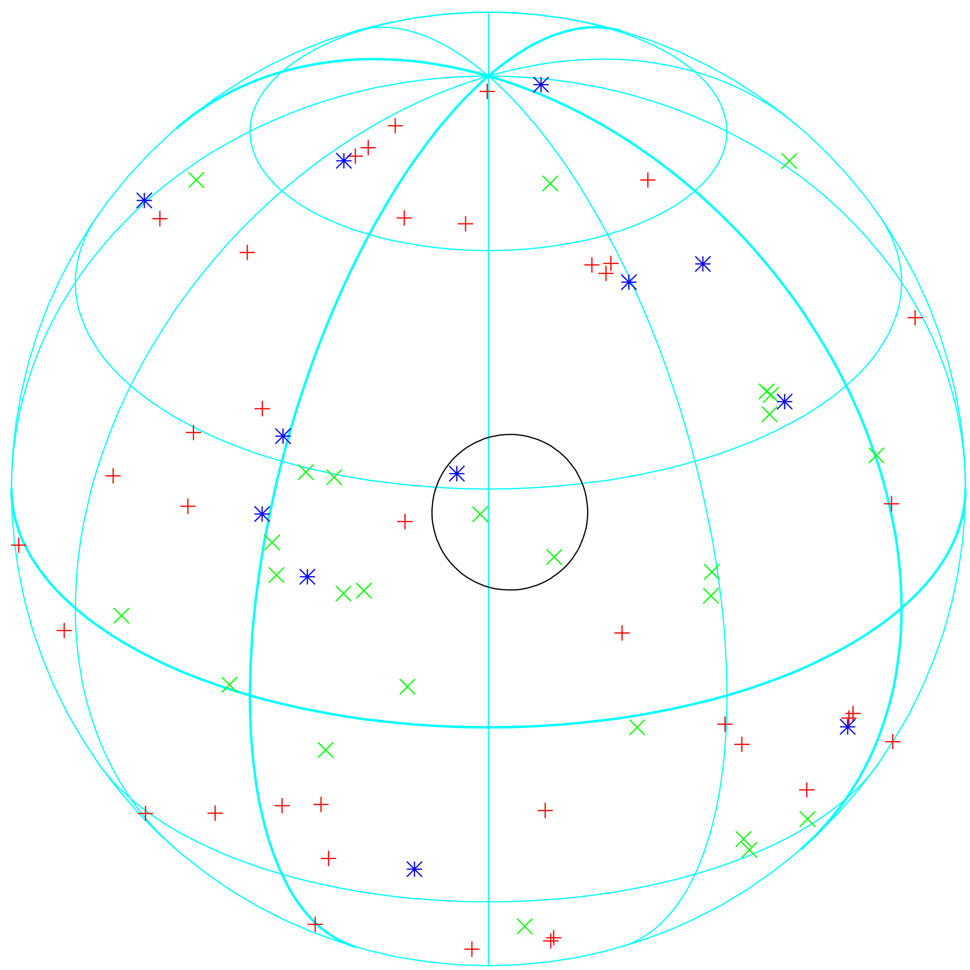


CANDIDATE SOURCES

3EG J	ID	Possible BLL		z	E	Q
0433+2908	A	2EG J0432+2910	*	—	5.47	0 + −
					4.89	0 +
0808+5114	a	1ES 0806+524	*	0.138	3.4	0
					2.8	0
					2.5	0
0812-0646	a	1WGA J0816.0-0736		0.04	—	
1009+4855	a	GB 1011+496		0.2	—	
1052+5718	a	RGB J1058+564	*	0.144	7.76	0 −
					5.35	0 −
					5.50	−
1222+2841	A	ON 231	*	0.102	—	
1310-0517		1WGA J1311.3-0521		0.16	—	
1424+3734		TEX 1428+370		0.564	4.97	0 +
1605+1553	A	PKS 1604+159	*	—	—	
1621+8203		1ES 1544+820		—	2.7	+
1733+6017		RGB J1742+597		—	2.5	+
					6.93	−
1850+5903		RGB J1841+591		0.53	5.8	+
					2.8	+
1959+6342		1ES 1959+650		0.047	5.5	+
2352+3752	a	TEX 2348+360		0.317	—	

List of gamma-loud BL Lacs and UHECR which contribute to correlations.

- Sky map of 14 selected BL Lacs (blue), 39 AGASA events with $E > 4.8 \times 10^{19}$ eV (red) and 26 Yakutsk events with $E > 2.4 \times 10^{19}$ eV (green). Galactic coordinates.



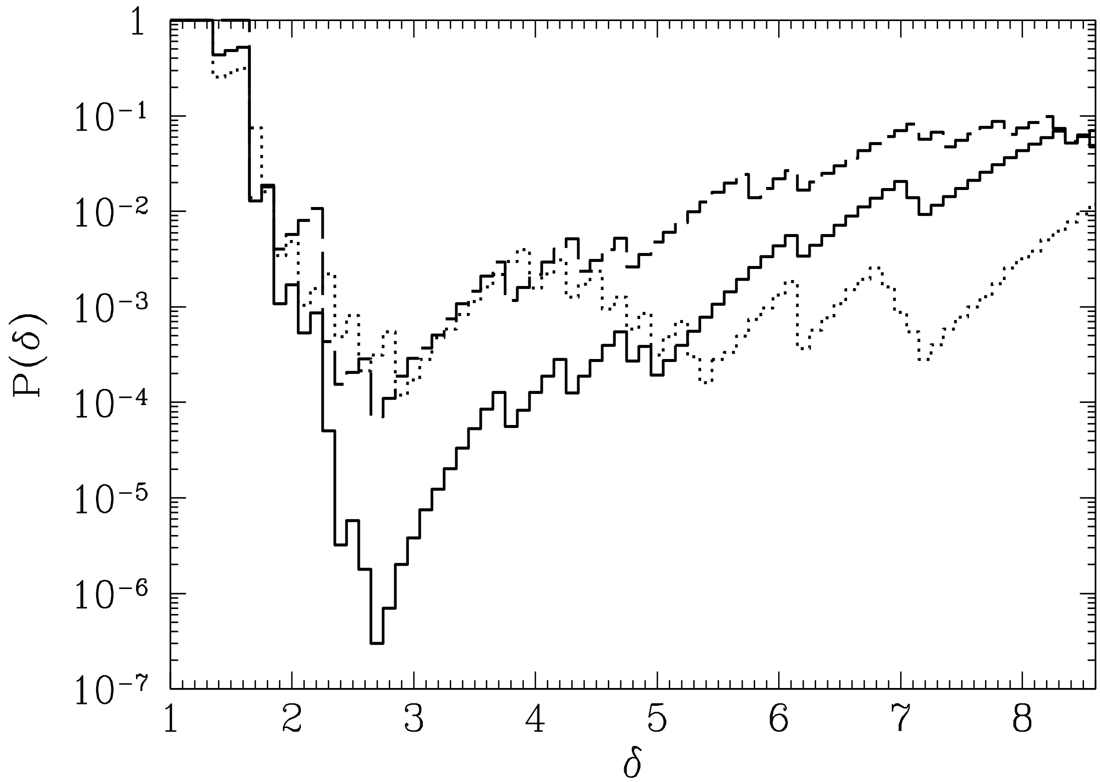
- Correlations with UHECR (combined AGASA and Yakutsk set of 65 events)
  - ⋆ 2 types of Galactic magnetic field: symmetric and antisymmetric with respect to Galactic disk
  - ⋆ 4 different charge combinations:

0	—	exotic primaries
$+$	—	protons
$0,+$	—	protons $+$ exotic primaries
$0,\pm$	—	Z-burst models

  - ⋆ Event-by-event charge selection: choose the charge which gives better correlation. (EXACTLY the same for each Monte Carlo set!)

Q	antisymmetric field			symmetric field		
	$p(\delta)$	N	δ	$p(\delta)$	N	δ
0	10^{-4}	8	$2.9°$	10^{-4}	8	$2.9°$
$+$	$7 \cdot 10^{-5}$	8	$2.7°$	$9 \cdot 10^{-4}$	9	$3.7°$
$0,+$	$3 \cdot 10^{-7}$	13	$2.7°$	$2 \cdot 10^{-6}$	12	$2.6°$
$0,\pm$	10^{-6}	15	$2.8°$	$2 \cdot 10^{-6}$	15	$2.9°$

- Significance plot in the case of antisymmetric field (14 γ-ray loud BL Lacs vs. 65 rays).



Black: $Q = 0, +$

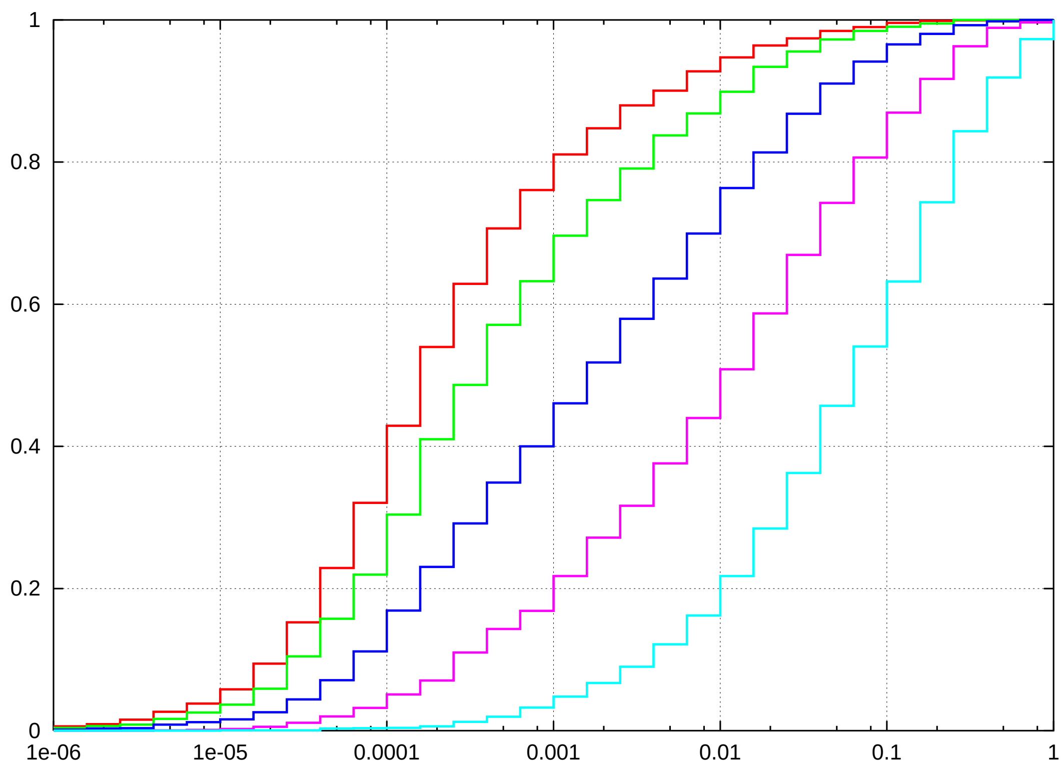
Blue: $Q = +$

Red: $Q = 0$

- How bright are these 14 sources in UHECR?

Perform the following simulation:

- ⋆ generate random sets of 65 events, each containing given number of events from 14 sources in average
- ⋆ deflect events from sources in GMF
- ⋆ measure correlations with sources and count how often its significance exceeds 10^{-4}



Cumulative fraction vs. best probability:

red:	4.8	events from sources
green:	3.6	events from sources
blue:	2.7	events from sources
pink:	1.4	events from sources
light blue:	0.4	events from sources

$\Longrightarrow$ Number of events from sources > 3.6 at 1σ

CONCLUSIONS:

- Clustering of UHECR is not a statistical fluctuation. Models which do not explain it are strongly disfavored.
- Gamma-ray loud BL Lacs are likely sources of UHECR. Monitoring of most probable candidates may be suggested. In case of neutral primary particles time correlations may be present.
- Present statistics does not allow to distingwish between cases $Q = 0$, $Q = +$, $Q = 0, +$ and $Q = 0, \pm$; this will be possible in the future.
- If correlations of charged particles is not a fluctuation, it implies:
  - ⋆ EGMF is small
  - ⋆ GMF model is roughly correct