On the interpretation of cosmic ray anisotropy at highest energies

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Gorbunov, P.T., Tkachev, Troitsky,
arXiv:0711.4060 [astro-ph]
arXiv:0804.1088 [astro-ph]

OUTLINE

- Introduction: correlations with AGN in PAO data and AGN hypothesis
- Generic shortcomings of correlation analysis
- Tension between AGN hypothesis and the data. Deficit from Virgo
- Alternative explanations: Cen A?
- Conclusions

Correlation with AGN in PAO data

Science 318:938-943,2007 [arXiv:0711.2256]
Astropart.Phys.29:188-204,2008 [arXiv:0712.2843]

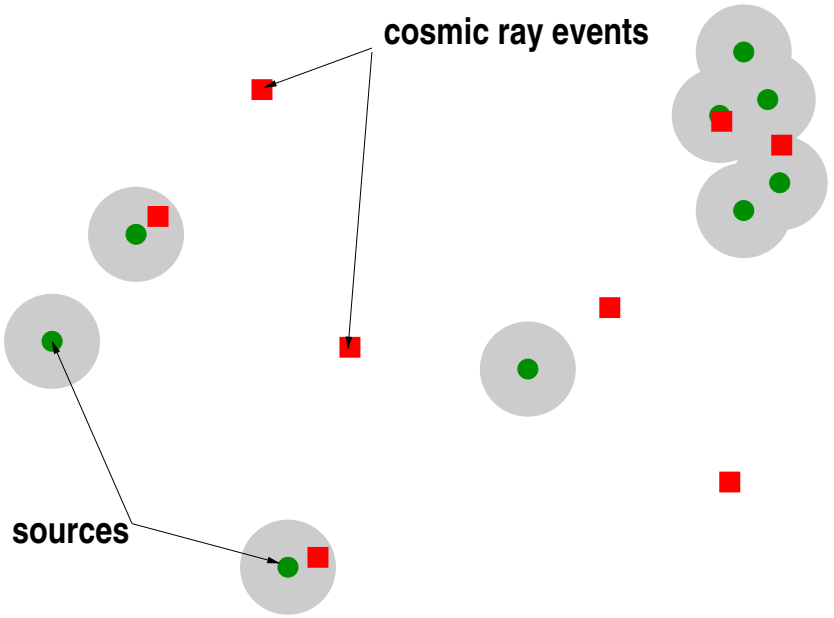
- energy cut $E > 5.6 \times 10^{19}$ eV $\Longrightarrow$ 15+13 events
- angular size $\delta = 3.1^\circ$
- 472 AGN with redshift $z < 0.018$ (distance $D < 75$ Mpc)
- significance of correlation: 1.7×10^{-3} (derived from "control" set)

One may formulate a hypothesis: highest-energy cosmic rays originate from AGN or sources with a similar spatial distribution (the AGN hypothesis)

This hypothesis explains the observed correlation. But is it the only one? Should one consider the correlation in PAO data as confirmation of this hypothesis?

— NOT UNIQUE. OTHER INTERPRETATIONS ARE POSSIBLE.

Correlation analysis



P.T., I. Tkachev, JETP Lett.74:1-5,2001 [astro-ph/0102101]
JETP Lett.74:445-448,2001 [astro-ph/0102476]
Phys.Rev.D69:128301,2004 [astro-ph/0301336]

Correlation analysis compares data to isotropic distribution. If there is a correlation signal, it means only that the data are not isotropic. It does not tell anything about the actual sources. The chances of confusion increase when candidate sources are themselves distributed non-uniformly.

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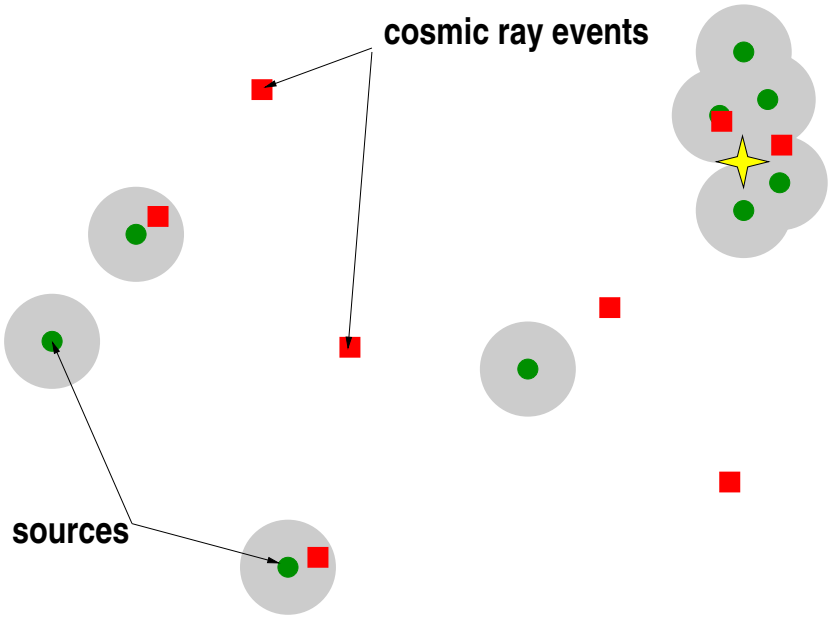

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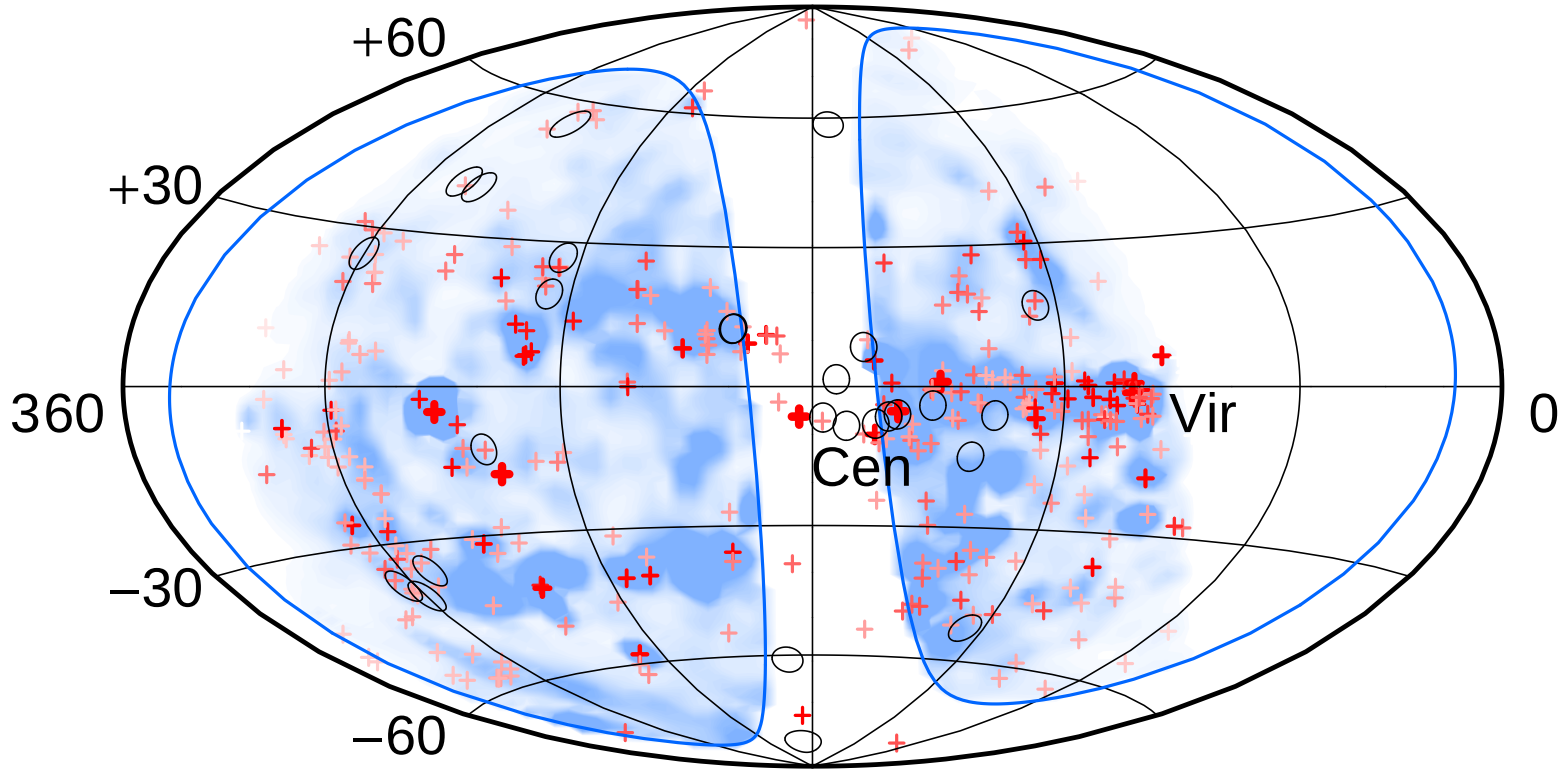
Sky map in supergalactic coordinates.



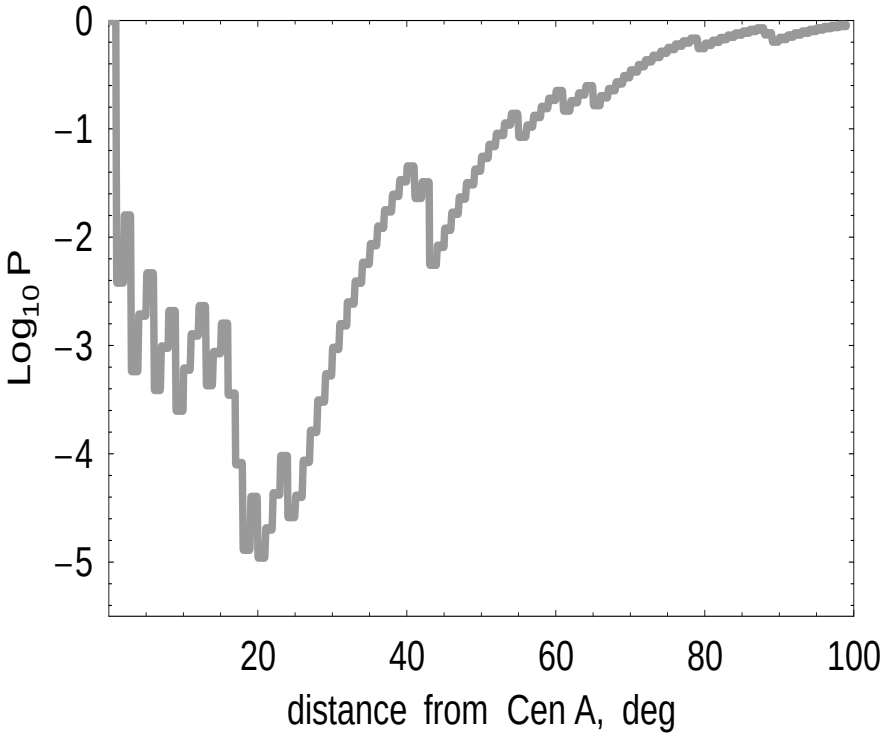
Open circles — positions of CR events.

Red crosses — AGN

Signifcance of the excess around Cen A

P = the probability to obtain by chance, in the uniform distribution, the excess of CR events within given angle from Cen A equal or larger than that found in the data.

Note: this is not a real significance, because no penalties are included



If AGN are indeed sources, the correlation with Cen A will increase with statistics, since Cen A is located in the region with the overdensity of background AGN.

If instead Cen A is actual source of CRs and produces a cloud of events around it (say, deflected by $\lesssim 20^\circ$ by magnetic fields) while other AGN have nothing to do with UHECR, the correlation between AGN and UHECR will also increase with statistics, for the same reason.

$\Longrightarrow$ Correlation analysis alone cannot distinguish between the two cases.

$\Longrightarrow$ Other signatures are needed

SIGNATURES OTHER THAN CORRELATIONS

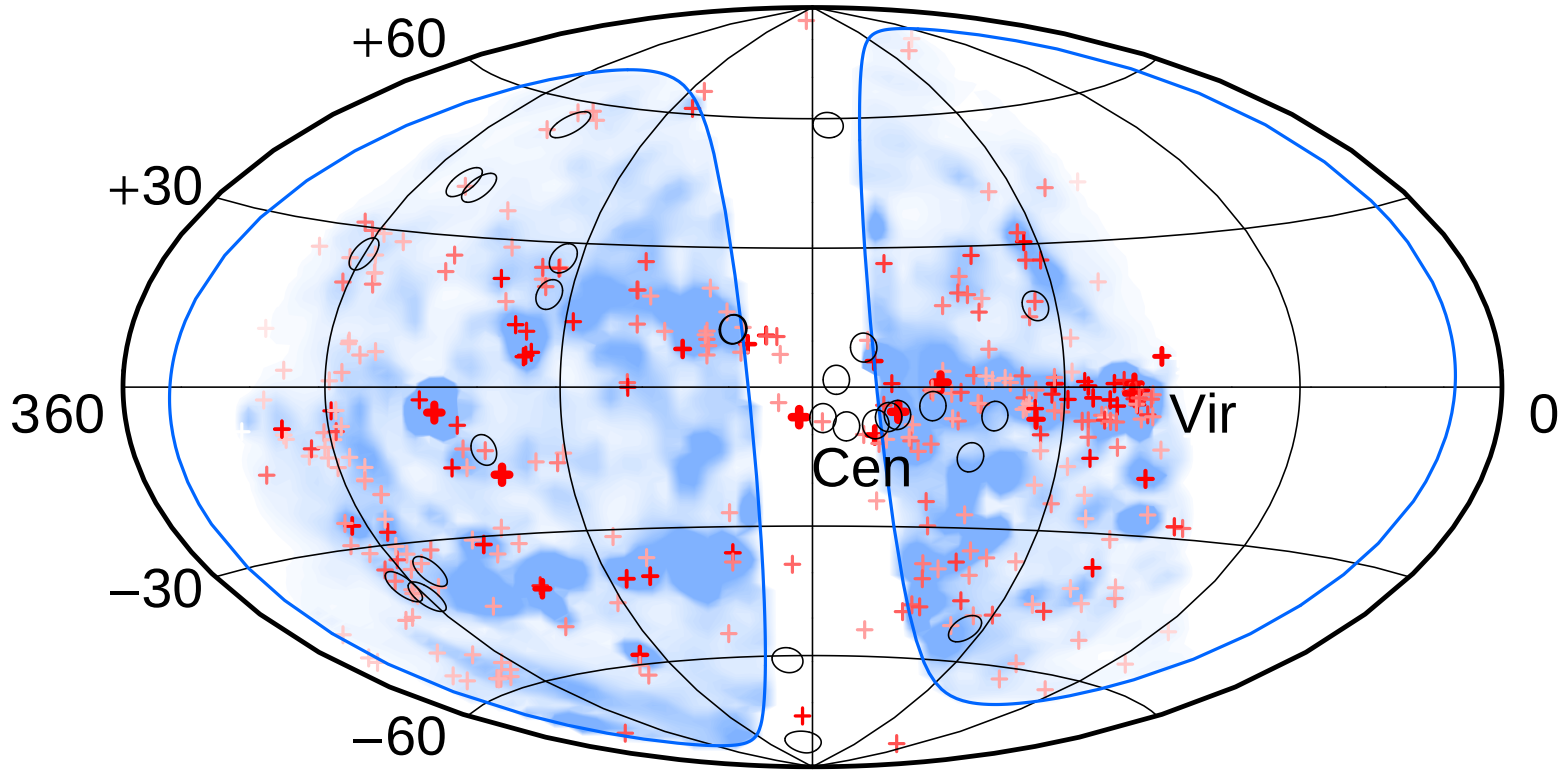
Let us accept the AGN hypothesis and try to test it. More precisely, assume that:

- Cosmic rays are produced by sources that trace matter distribution in the nearby ($\lesssim 100$ Mpc) Universe - AGN or other
- Cosmic rays propagate rectilinearly, that is extragalactic magnetic fields are small and do not cause significant deflections
- Cosmic rays are protons; then the deflections in the Galactic magnetic field are also small and CRs must roughly point back to their sources.

The last two assumptions imply, by statistical properties of clustering, that the number of sources contributing to the flux is large, order of several hundred. $\longrightarrow$ assumptions are self-consistent

Dubovsky, P.T., Tkachev
PRL 85:1154-1157,2000.

$\Longrightarrow$ One may calculate the CR flux and compare to the observed one.

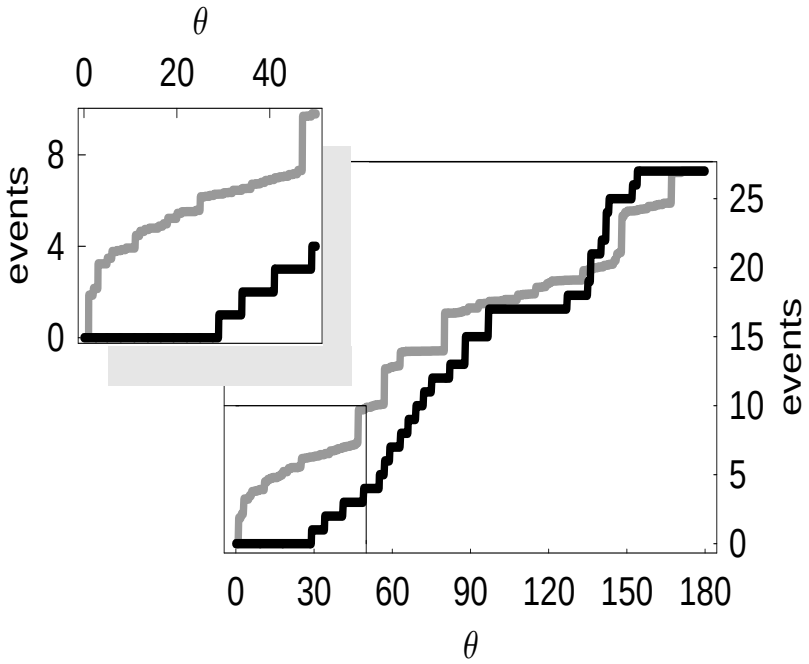


The color saturation of red crosses representing AGN shows CR flux expected from a particular AGN, including the effect of the distance and the GZK attenuation.

Striking feature of the CR distribution over the sky — the absence of events from Virgo where large flux is expected.

In the circle of 20° from the center of Virgo 6 events are expected while zero are observed ($P \sim 10^{-3}$).

Distributions of observed and expected events in angular distances from Virgo are different ($P = 2 \times 10^{-4}$ according to KS test).



Control tests:

* Distributions of observed and expected events in Galactic longitude and latitude are inconsistent: the probability that the distributions are the same are 2% and 10^{-4}, respectively.
* Distributions of observed and expected events in supergalactic longitude and latitude are also inconsistent; the probability that the distributions are the same are 7% and 10^{-4}, respectively.
* The results are insensitive to the (technical) assumption of equal AGN luminosity. To check this, the same tests were performed assuming that the CR flux of AGN is proportional to its optical flux.
* The results are insensitive to incompleteness of the AGN catalog. To check this, the same tests were performed with the AGN catalog replaced by a complete catalog of galaxies within the distance $\lesssim 270$ Mpc *[Kalashev et al, JCAP 0803, 003 (2008)]*. The inconsistency between the observed and expected distributions persists.

Given the largest inconsistency observed and the total number of tries, we estimate the overall significance of discrepancy to be $\sim 99\%$.

$\Longrightarrow$ AGN hypothesis seems to be disfavored by present data

Note: a correlation between UHECR and large-scale structure has been recently studied in *[Kashti, Waxman, JCAP 0805:006,2008]* where the *consistency* between observed PAO events and expected distribution of CRs from structure was found. There is no contradiction with the present analysis, because the particular statistic used by Kashti&Waxman is insensitive to the type of anomaly (Virgo deficit) present in the data.

ALTERNATIVE EXPLANATIONS

* Large magnetic fields in clusters? Kotera, Lemoine, arXiv:0801.1450

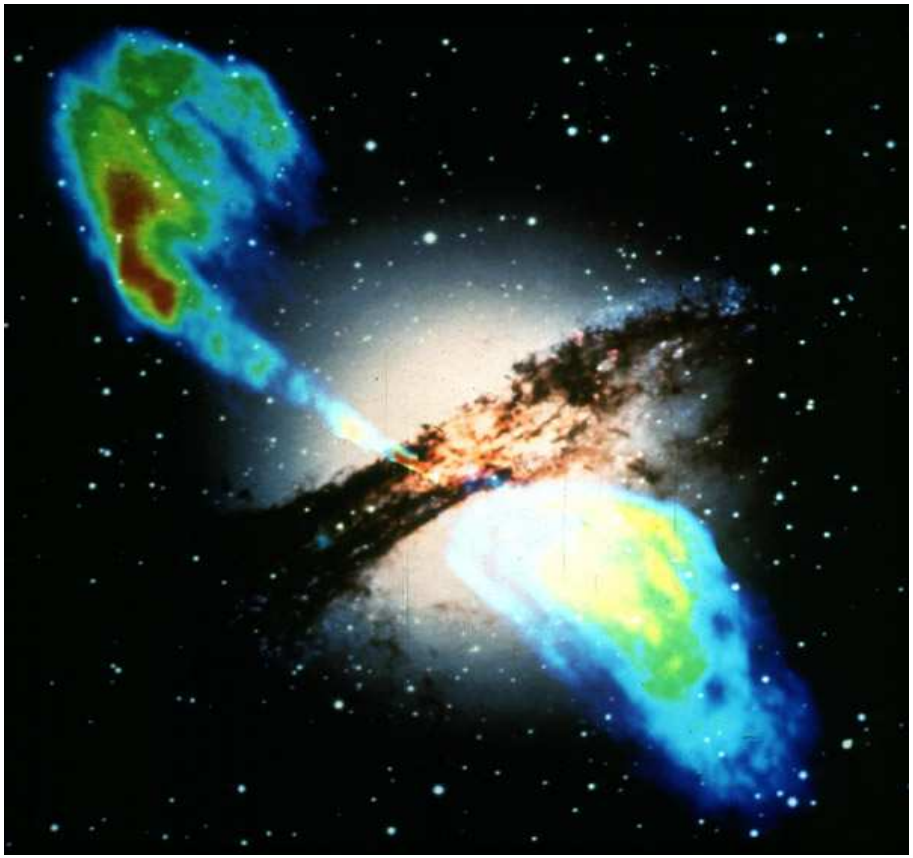
* Light nuclei instead of protons? Fargion, arXiv:0801.0227

* One (at most a few) source which happened by chance to be in the direction of Centaurus supercluster (perhaps some other overdensities)? Gorbunov, P.T., Tkachev, Troitsky, arXiv:0711.4060 Wibig, Wolfendale, arXiv:0712.3403

  Cen A is a promising candidate:

  – anomalously close (~ 3.5 Mpc) powerful radio-galaxy
  – possesses jets and radio-lobes usually considered as potential acceleration sites

- has been proposed as a potential source of UHECR by many authors
- the study of composition of UHECR by PAO indicates heavy or mixed composition $\Longrightarrow$ larger deflections in GMF
- outer lobes of Cen A extend to about 10° roughly in the direction of the supergalactic plane $\Longrightarrow$ a number of events may be associated with Cen A without assuming large deflections *[Moskalenko et al, arXiv:0805.1260]*



CONCLUSIONS

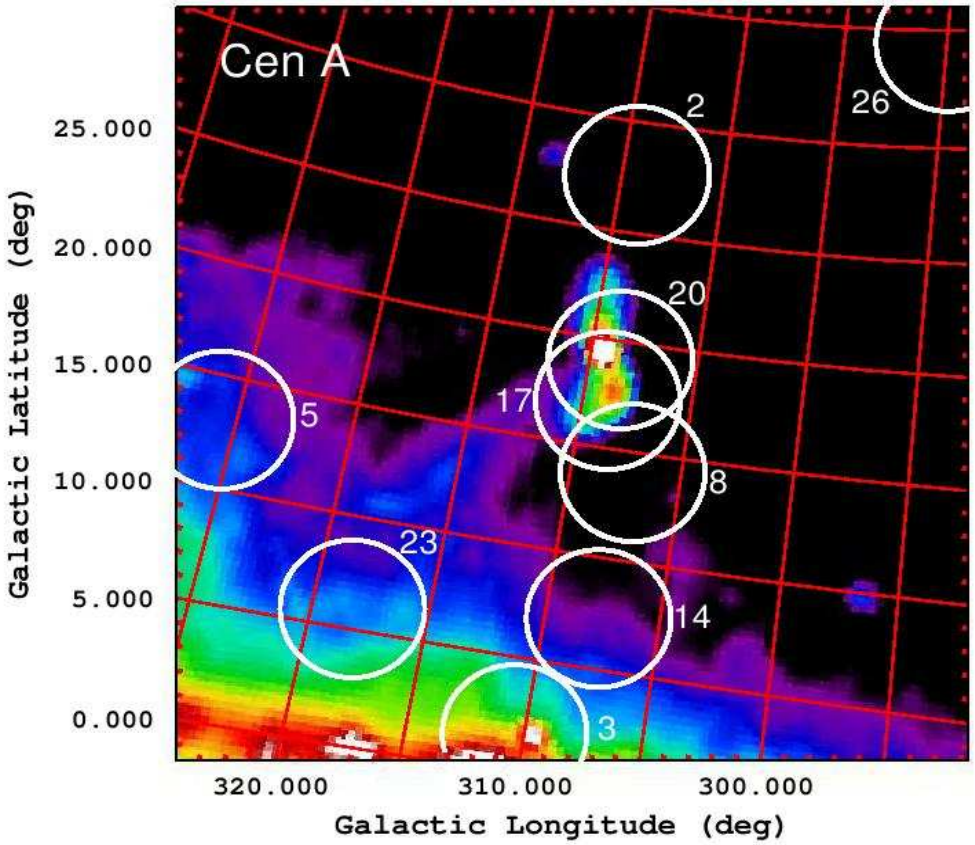
* Correlation analysis alone cannot distinguish between quite different source models $\Longrightarrow$ different signatures have to be studied

  Alternative hypotheses and testing procedures should be formulated now before the new data arrive in order to avoid *a posteriori* analysis

* It is premature to conclude that observed CR events are produced by AGN or other sources with similar spatial distrbution

  Other interpretations are possible, including one or a few nearby sources, Cen A being a promising candidate

Cen A local skymap with CR events



From: Moskalenko et al, arXiv:0805.1260 [astro-ph]