Anisotropy studies at the Pierre Auger Observatory

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The Pierre Auger Observatory

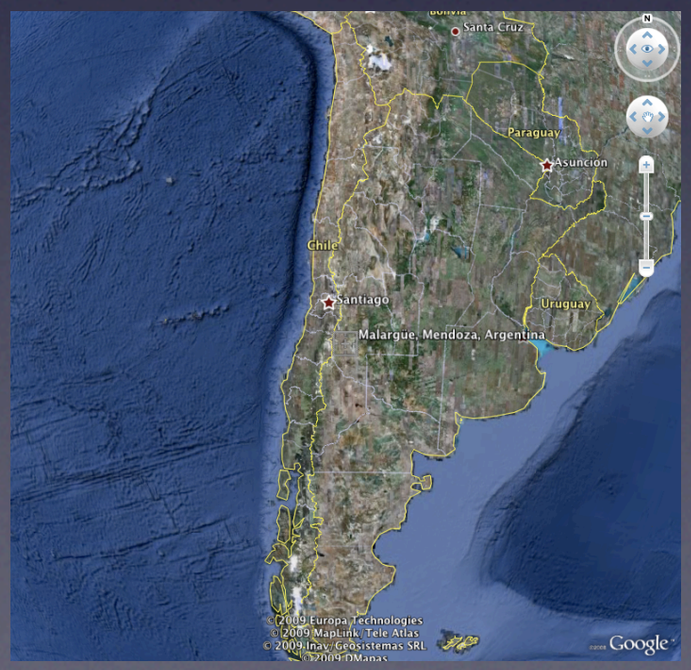
- Located in Malargue (Mendoza, Argentina, 1400m a.s.l)
- 1600 Water Cerenkov Tanks, spacing 1500 m

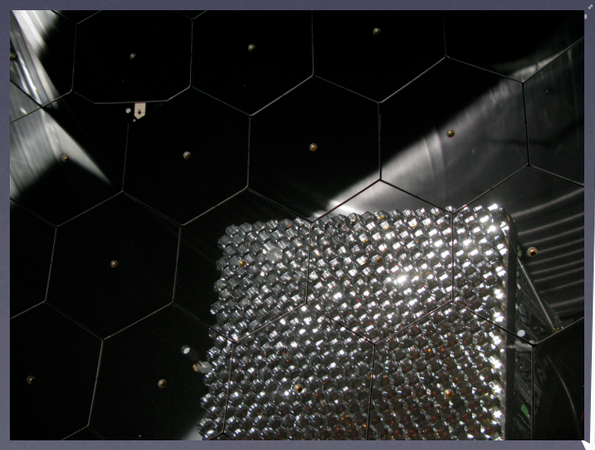
-> ground array surface 3000 km^2

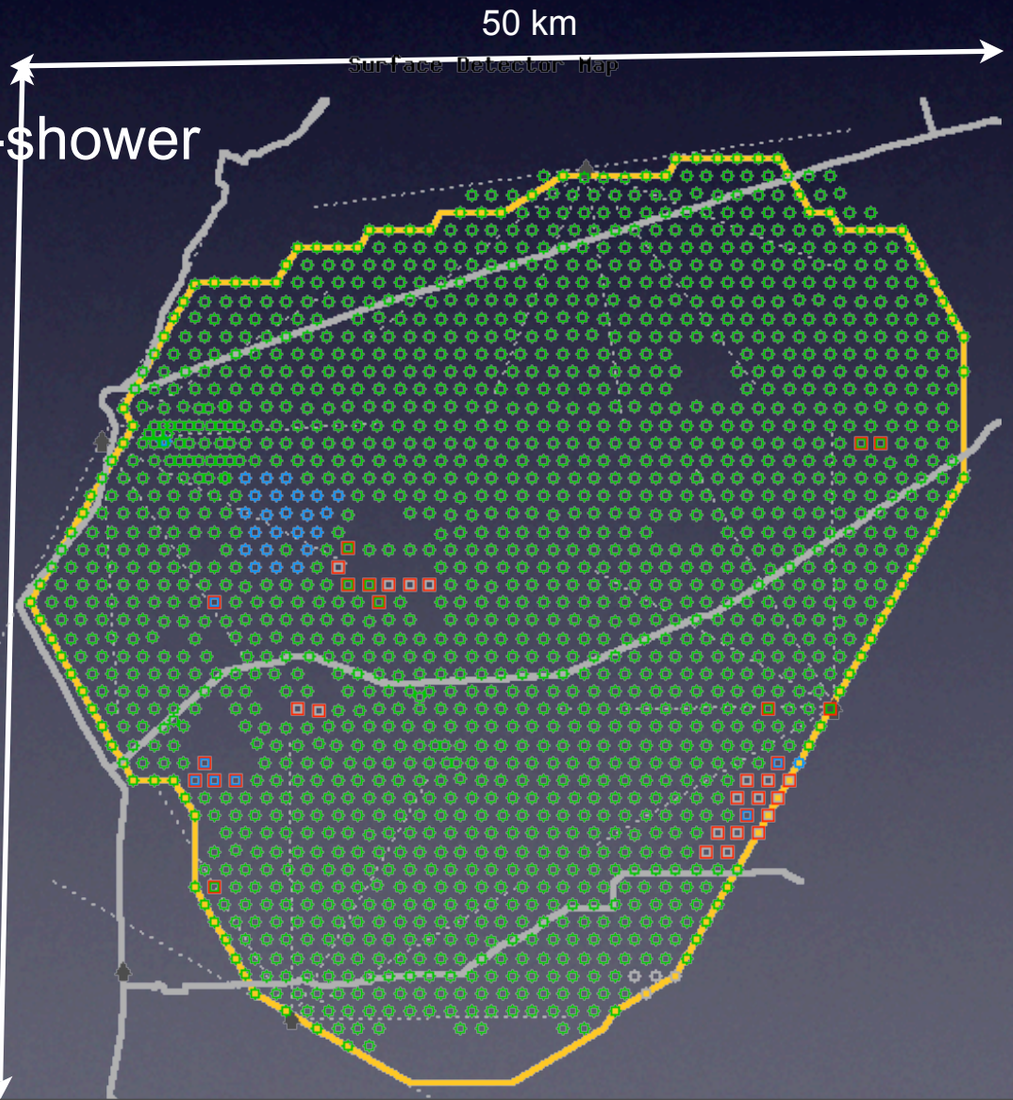
- 4 Fluorescence detectors overlook the array

Huge surface for an unprecedented statistics above 10^{19} eV

Hybrid detection for a good understanding of air-shower physics

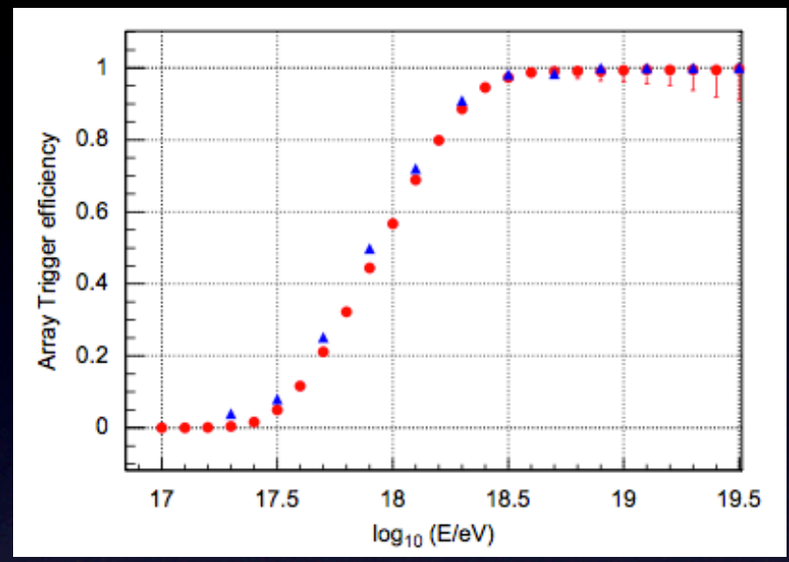






Some experimental facts

empirically estimated trigger efficiency : fully saturated
for $\theta \in [0; 60]$ deg above 3.10^{18} eV



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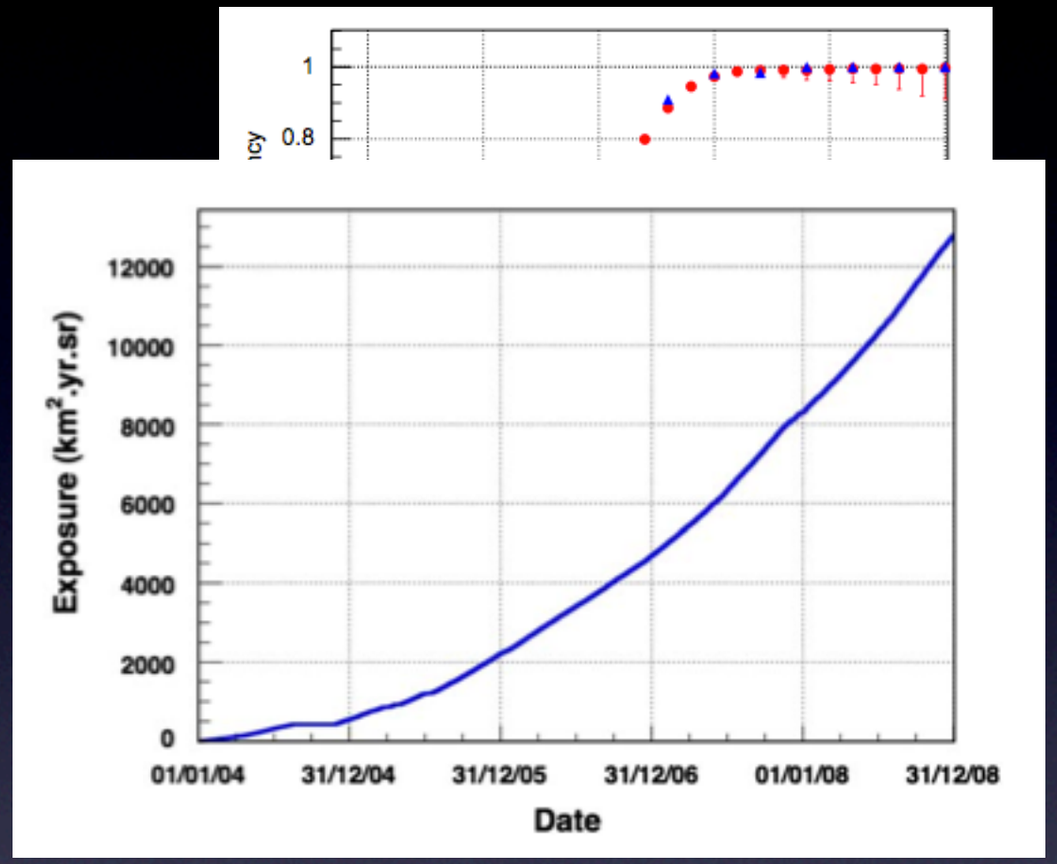
integrated exposure constantly monitored and estimated with an accuracy better than 3%

(Nuclear Instruments and Methods in Physics Research A 613 (2010) 29–39)



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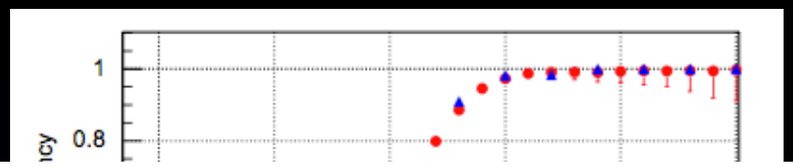

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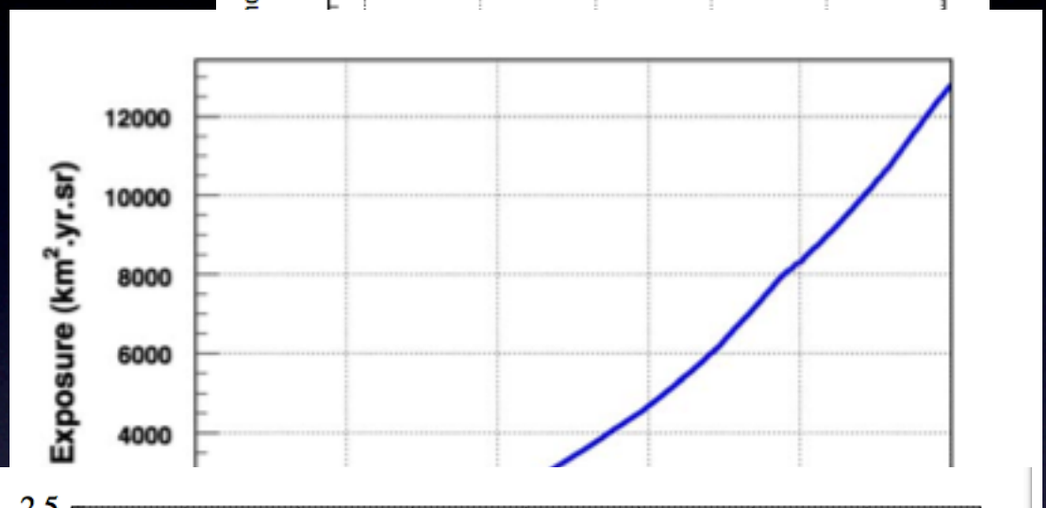
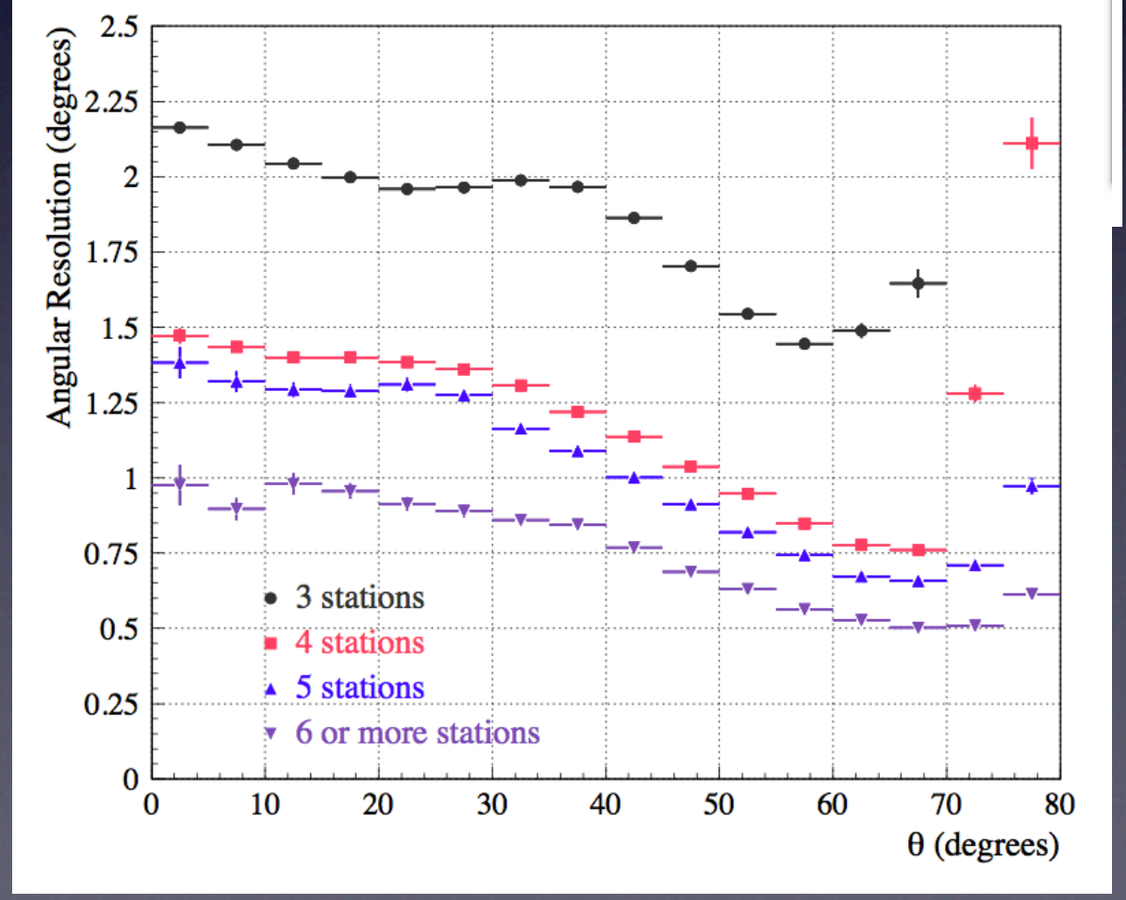


Angular resolution (empirically estimated) better than 1 deg at high energy (cross checked with hybrid events)

Nucl. Phys. Proc. Suppl. 190 (2009) 20-25.



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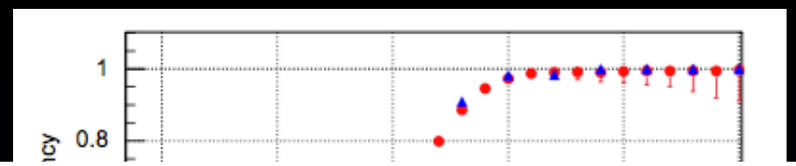

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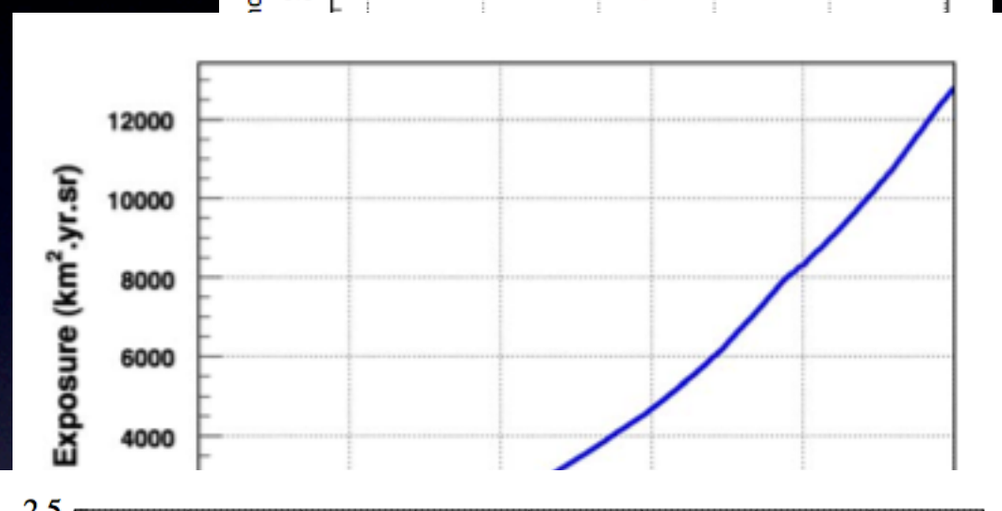

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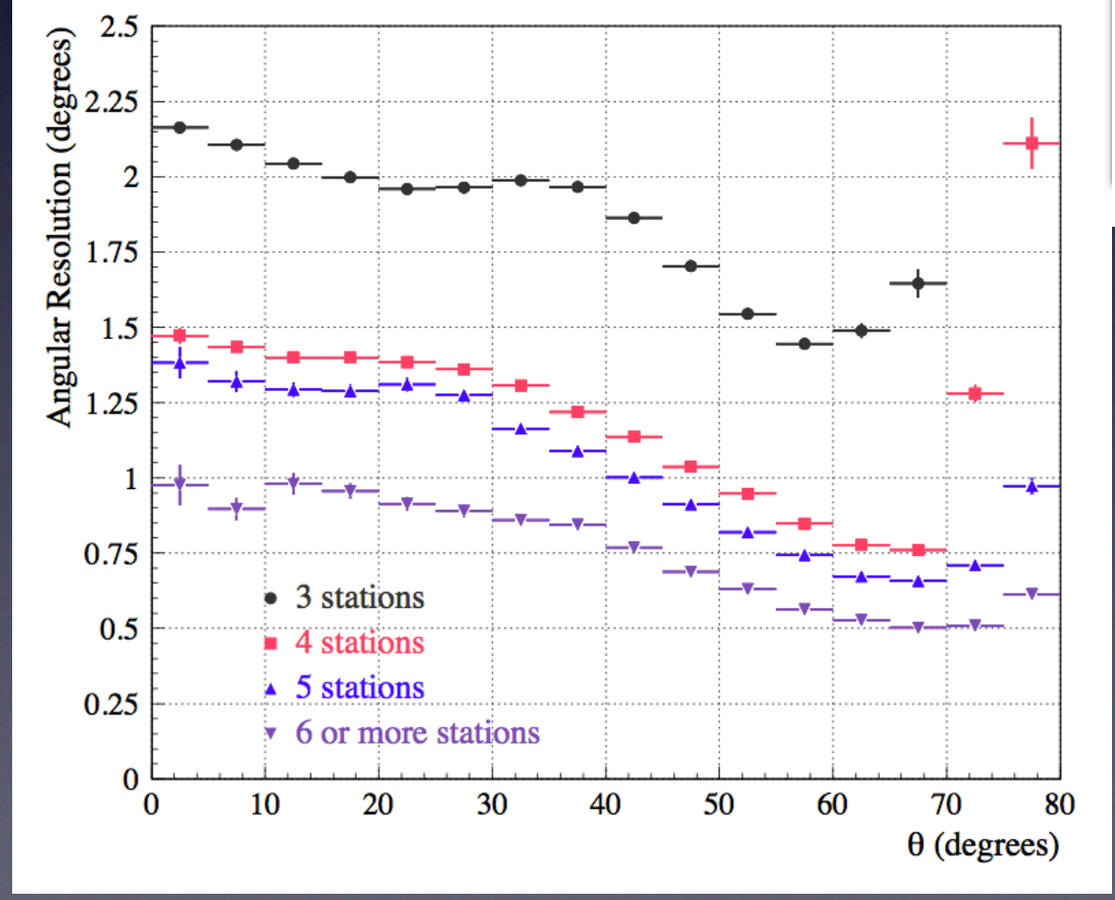
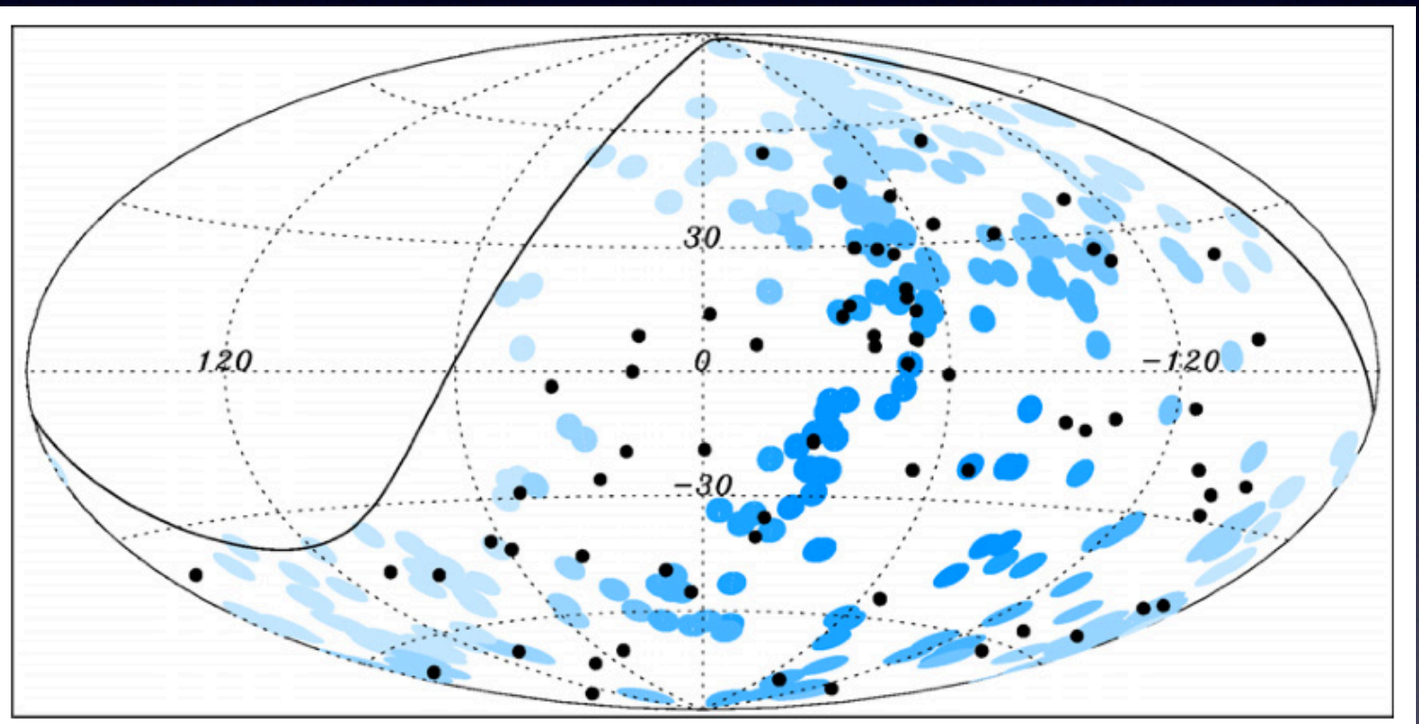


data set from January 1st 2004 to December 31st 2009
integrated exposure 20,370 km².sr.yr
the stability of the angular resolution, energy resolution, energy estimator on the whole period has been checked

Correlation of the CR arrival direction above 55 EeV and the position of nearby AGNs from the VCV catalogue

Astroparticle Physics 34 (2010) 314–326

- The correlation of arrival direction with AGN from the VCV catalogue was used to reject isotropy with 99 C.L with a prescribed statistical test (Science 318 (2007) 938)
- Although the prescription is passed, the collaboration continues to monitor the correlation fraction (keeping the parameters used for the prescription : Ψ=3.1 deg, z_{max}=0.018, E_{min}=55 EeV)



3 periods :
I, exploratory scan
II, prescription data
III, post-prescription
-> total 69 events above 55 EeV
-> correlation fraction very high for period I and II
-> period III : no significant deviation from isotropy expectations
-> much weaker correlation than at the time of the science publication

Period	Dates	Exposure (km^2 sr y)	N	k	k_{iso}	P
I	1 January 2004–26 May 2006	4390	14	8	2.9	–
II	27 May 2006–31 August 2007	4500	13	9	2.7	2×10^{-4}
III	1 September 2007–31 December 2009	11,480	42	12	8.8	0.15
Total	1 January 2004–31 December 2009	20,370	69	29	14.5	–
II + III	27 May 2006–31 December 2009	15,980	55	21	11.6	$\mathbf{3 \times 10^{-3}}$

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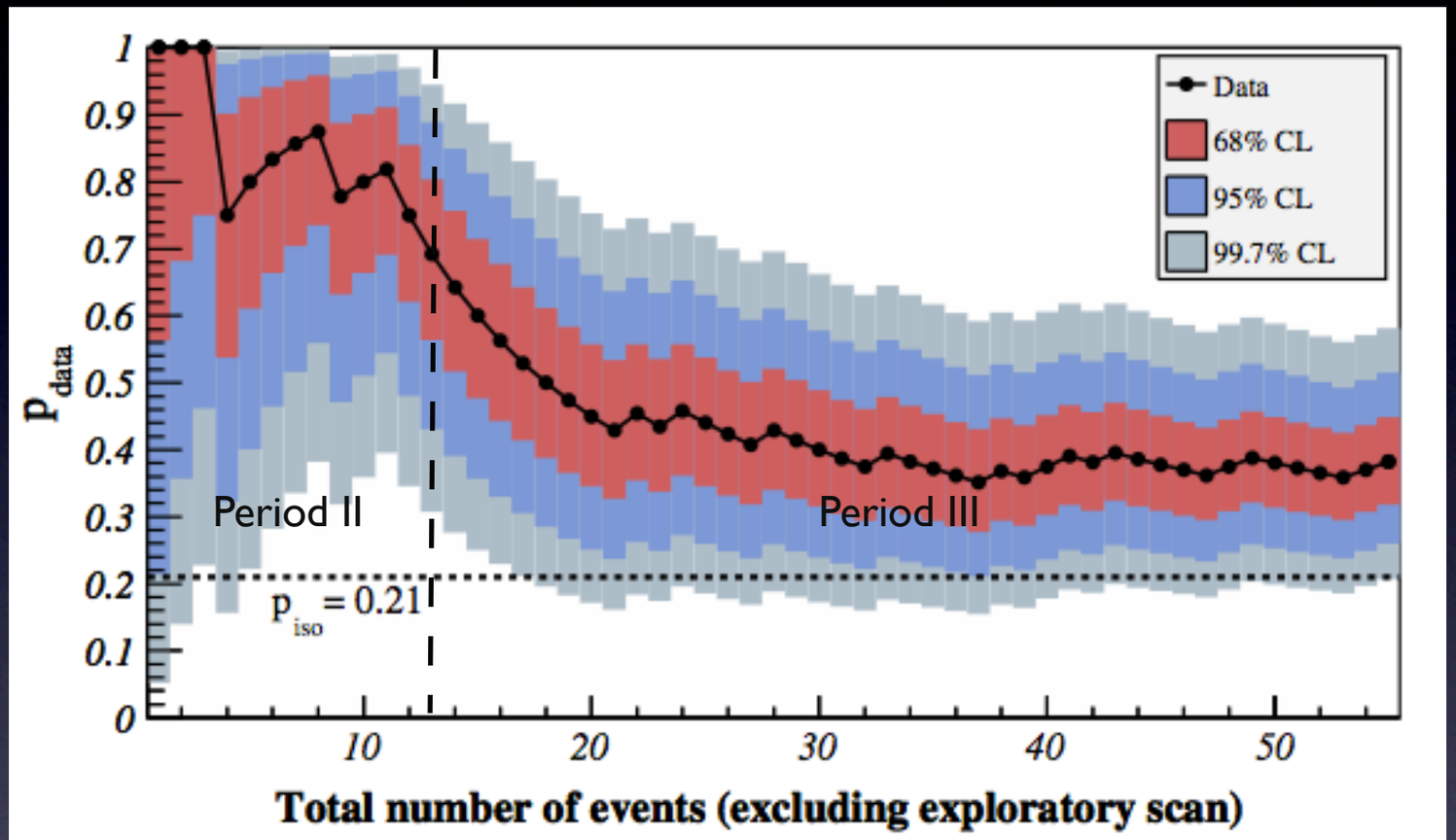

at the end of the dataset (II+III):
$P_{data}=(38^{+7}_{-6})\%$ $P_{iso}=0.003$
was $(69^{+11}_{-13})\%$ after period II

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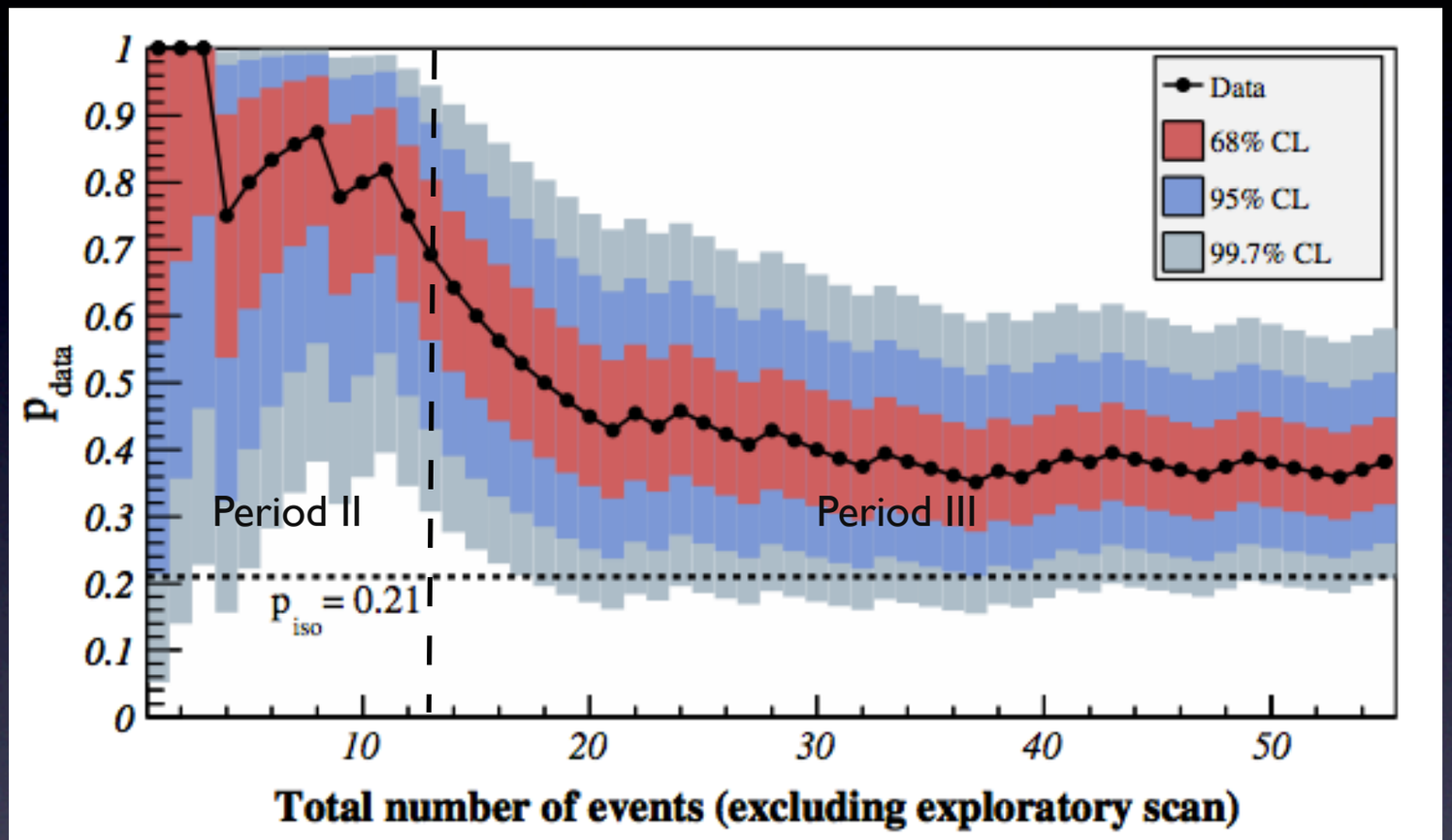

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additionnal facts :
the correlation fraction is larger when removing the galactic plane
$(46\pm6)\%$ ($f_{iso}=24\%$)
none of the five highest energy events correlate

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Test of the data on other astrophysical catalogues

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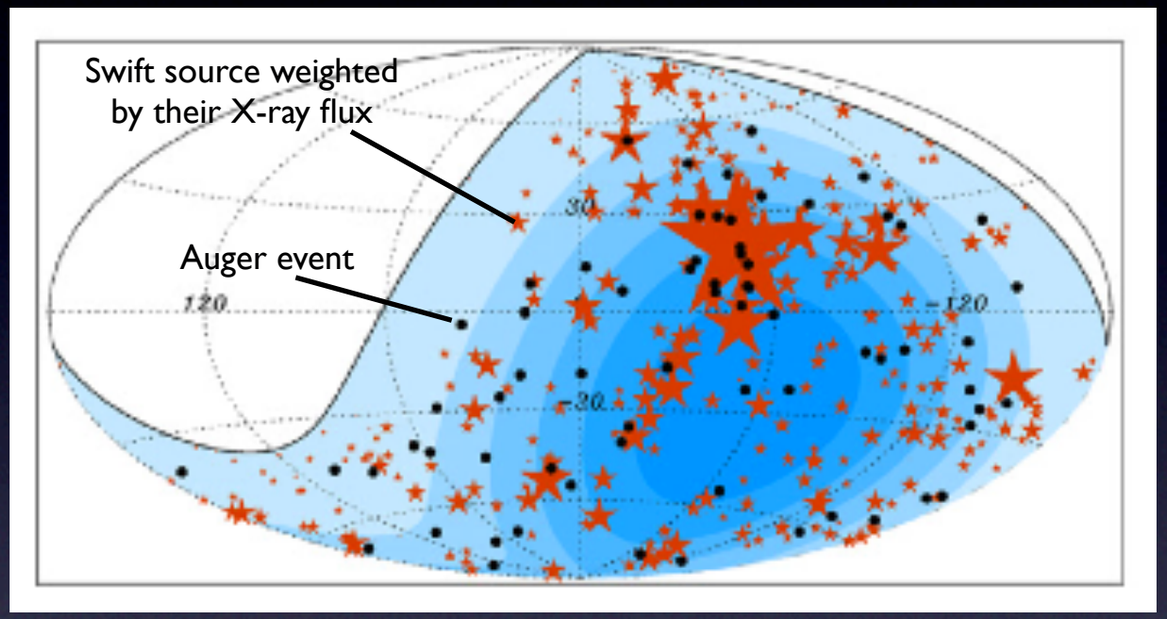
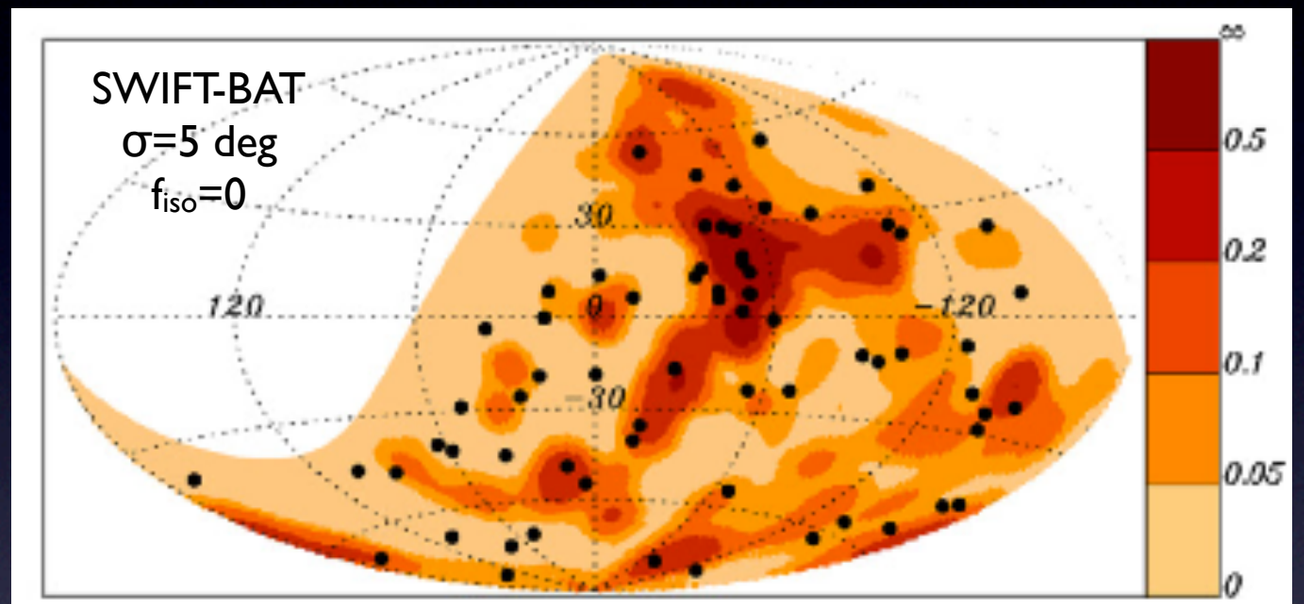
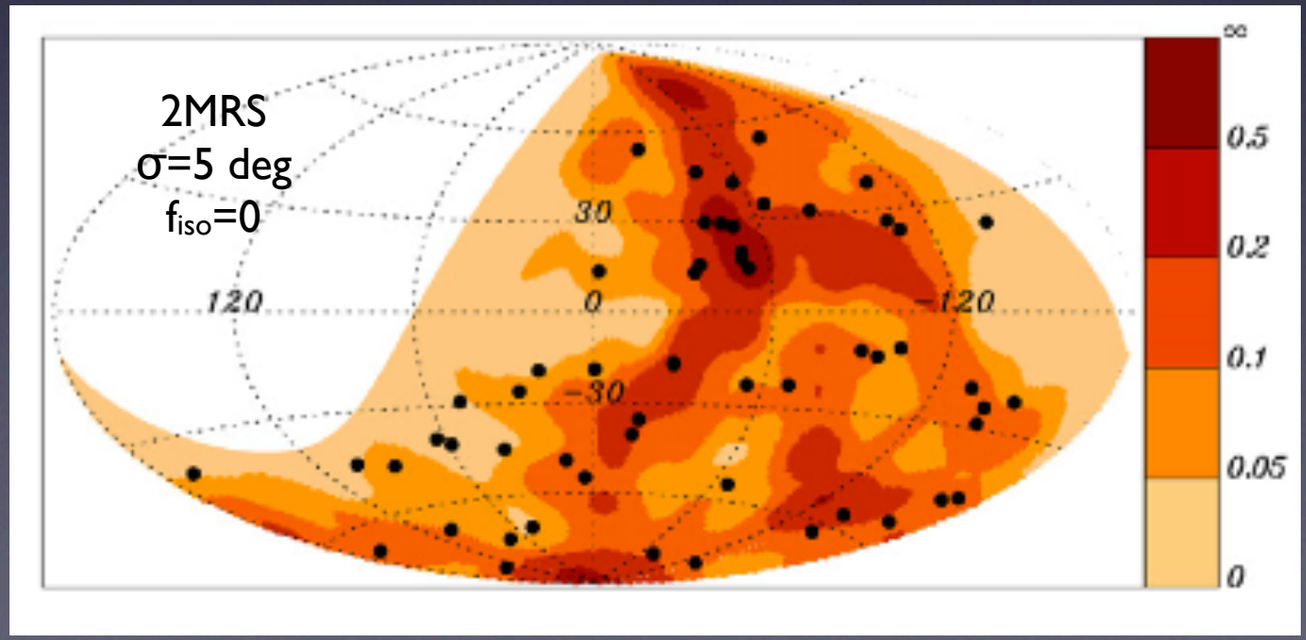
smoothed maps using 2MRS and SWIFT-BAT





We build density maps assuming a gaussian smearing of σ deg of the source image and an isotropic fraction f_{iso}
weight for the sources :
$\Phi_{source} \times \omega_{GZK}(z_{source})$
(ω_{GZK} is calculated assuming protons)



Test of the data on other astrophysical catalogues

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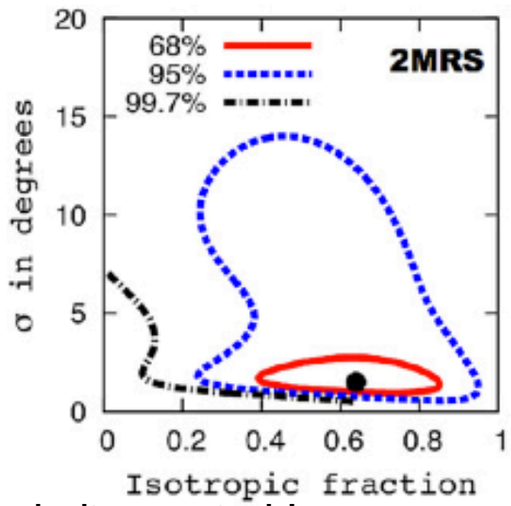
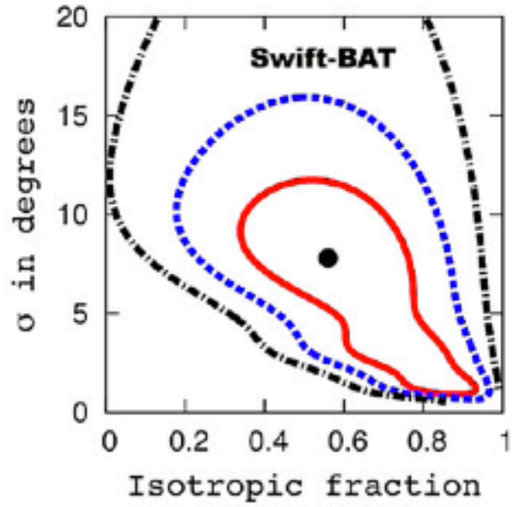
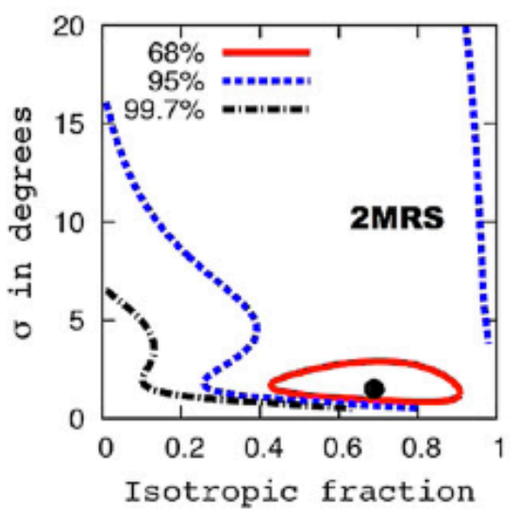
- using a log-likelihood method we estimate the optimal values of the smearing angle
- the second parameter of the log-likelihood is the isotropic fraction f_{iso} that could either account for the incompleteness of the catalogues or a component with larger deflexions

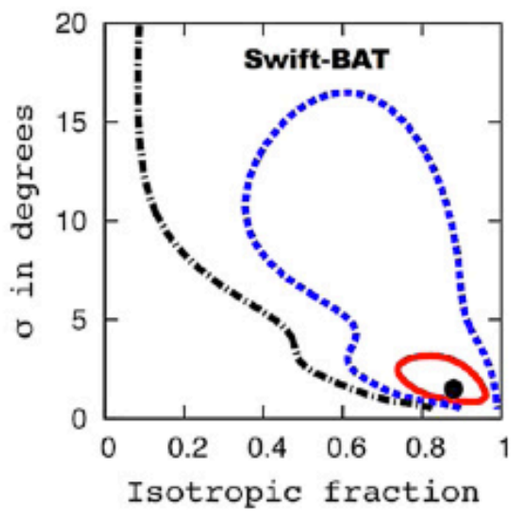
including period I





excluding period I





best fit values of (σ,f_{iso})
(smearing angle and isotropic fraction):
including period I,
2MRS : (1.5 deg, 0.64); SWIFT : (7.8 deg, 0.56)
excluding period I,
2MRS : (1.5 deg, 0.69); SWIFT : (1.5 deg, 0.88)
the wide contours show the likelihood parameters are not strongly constrained with the present statistics

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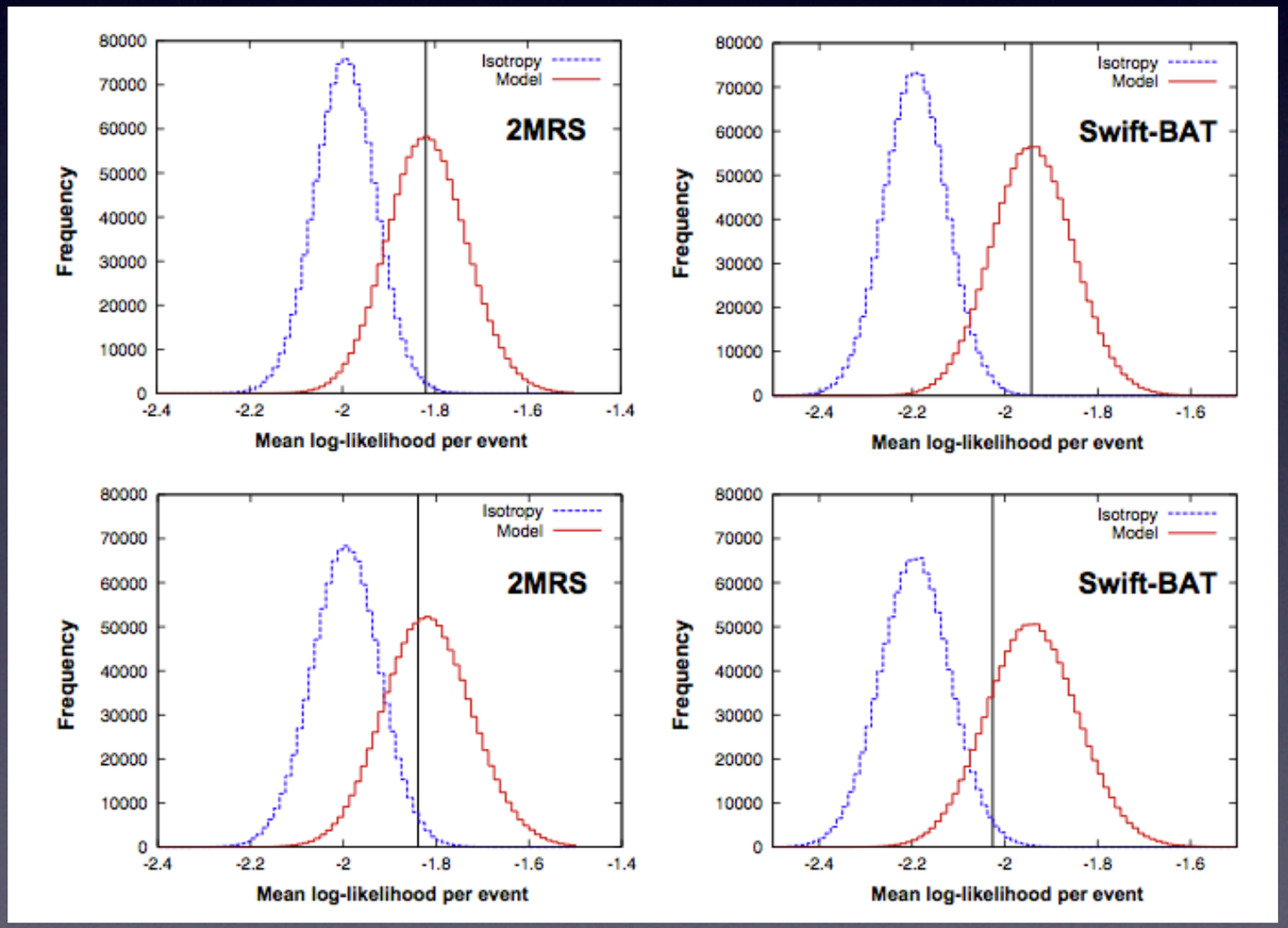

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mean log-likelihood per event distribution
the data are more with the models
fraction of realizations of isotropy with a larger likelihood than the data :
including period I,
2×10^{-4} for SWIFT, 4×10^{-3} for 2MRS
excluding period I,
f~0.02 for both

Autocorrelation

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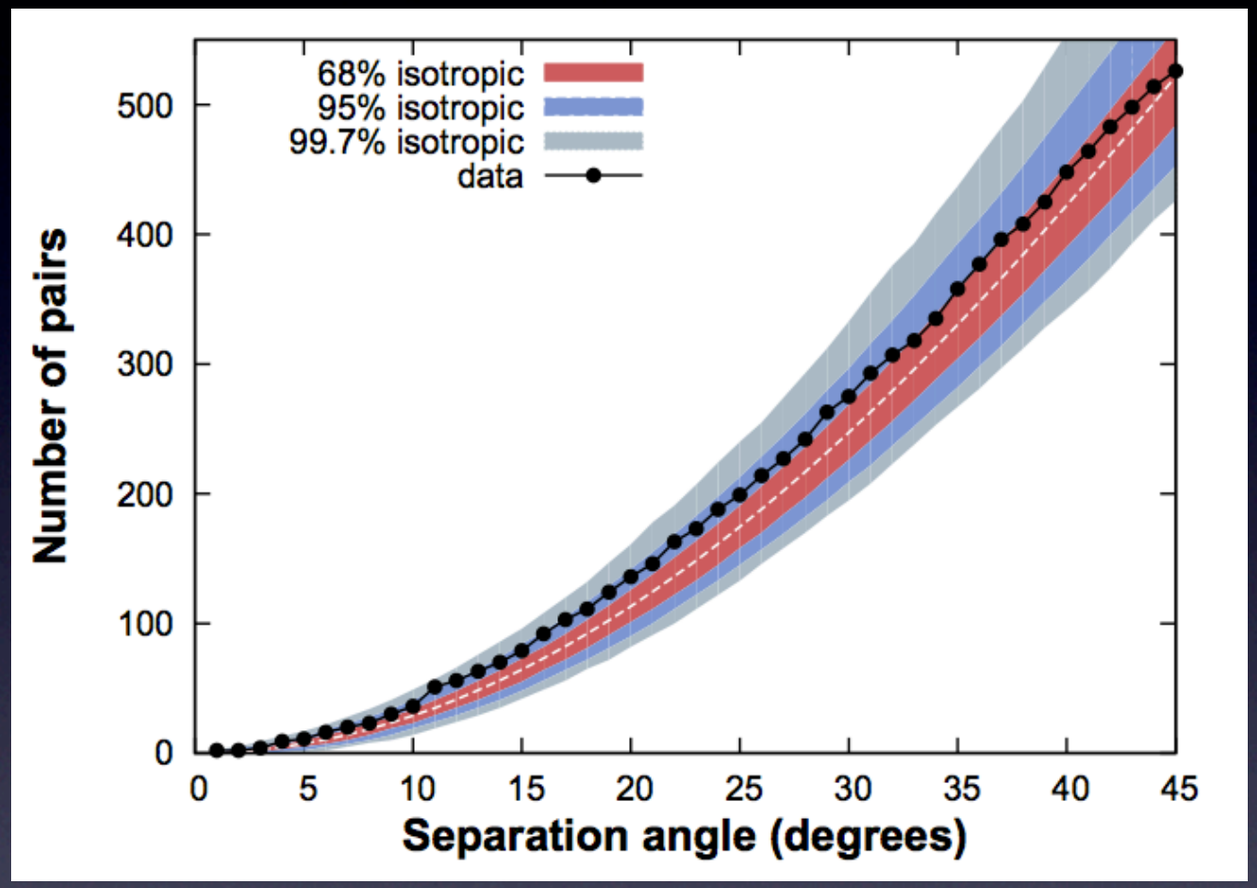
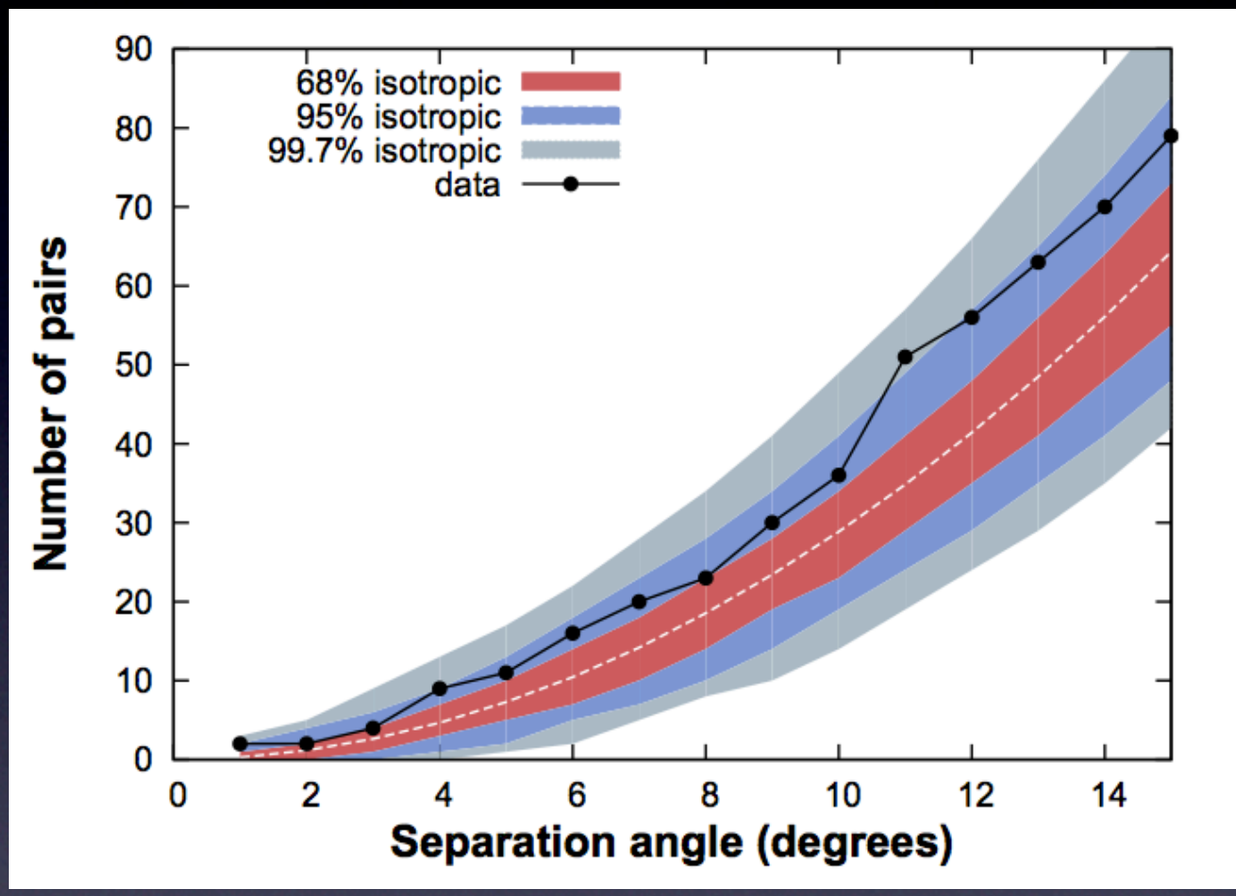
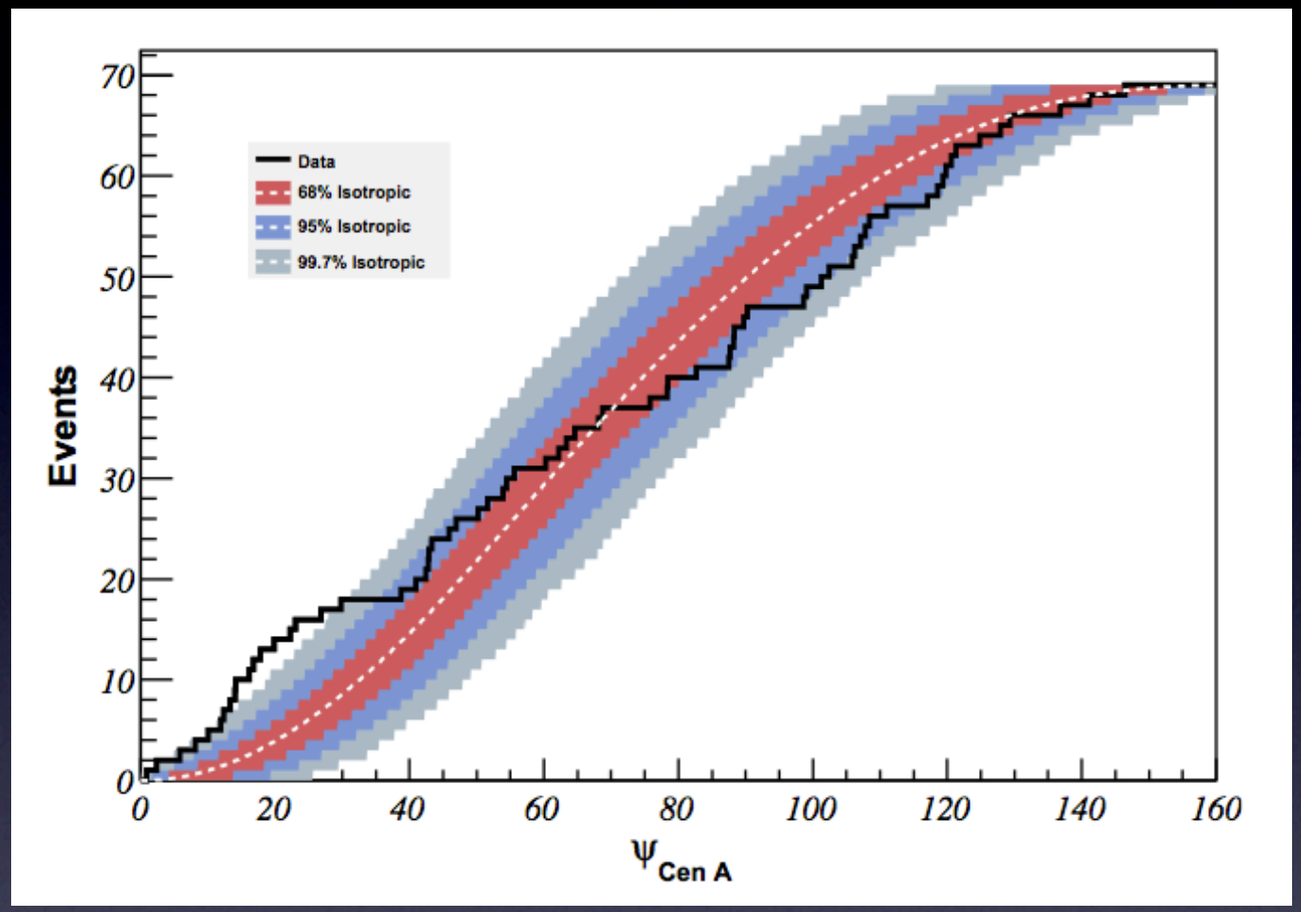




maximal deviation from isotropy expectations at 11 deg
10% of isotropic realizations achieve a deviation equal or greater
-> no significant signal

excess in the around the direction of CEN A



Virgo region, no events within 18 deg around M87
but Virgo is in a low exposure region
1.1 expected for isotropy, ~4 expected using 2MRS weights and ~2 using swift

by eye one can see that a lot of high energy events are coming from the Centaurus region
-> strong weight on the result of the tests with astrophysical catalogues
Cross correlation with the position of Cen A :
largest deviation from isotropy at 18 deg,
13 events (18.8%) observed 3.2 expected
KS test 4% of isotropic realization present a deviation equal or larger deviation

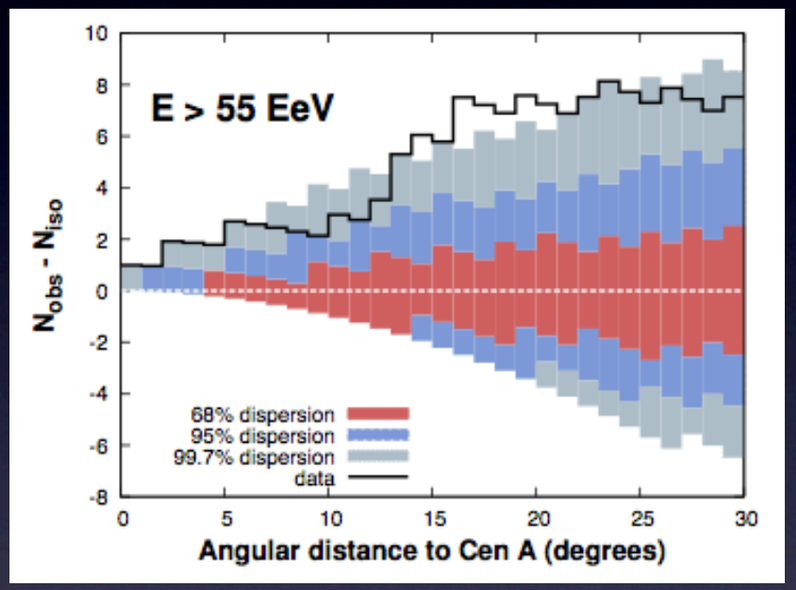
Hint for an overdensity of events in the Centaurus region needs to be confirmed with larger statistics

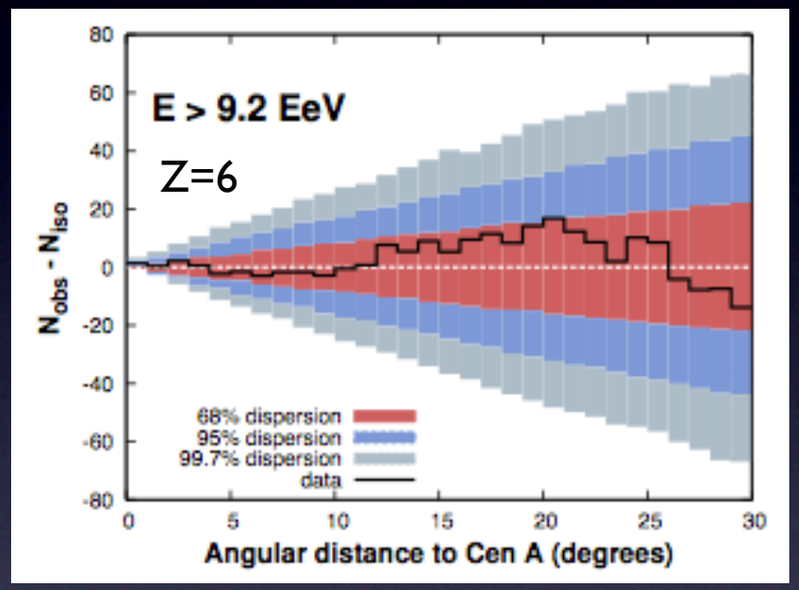
Same conclusion for the potential underdensity in the Virgo region

anisotropy and chemical composition

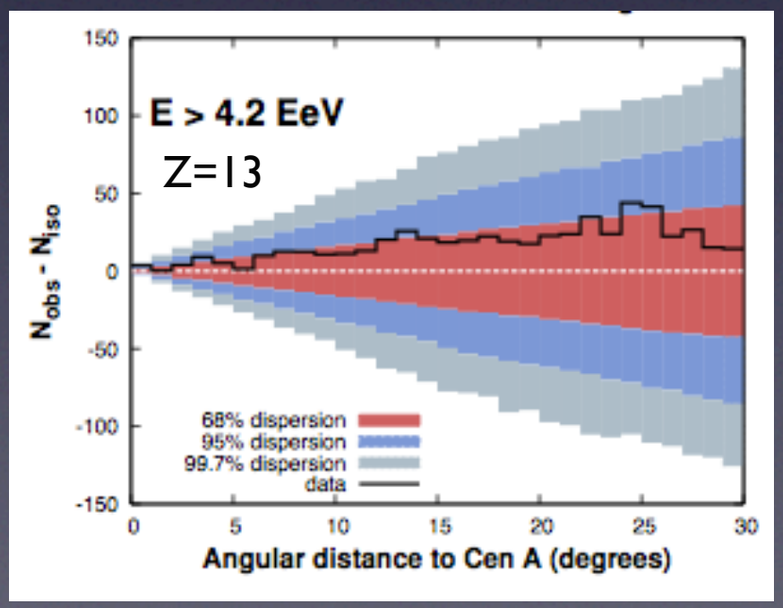
(JCAP 2011)

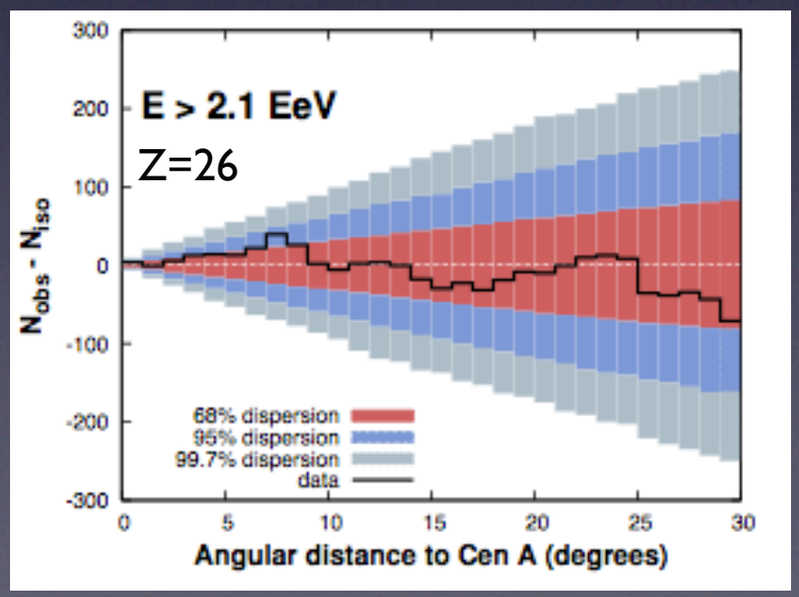
Lemoine and Waxman 2010 : In a rigidity dependent maximum energy scenario ($E_{max}(Z)=Z\times E_{max}(^1H)$), where protons dominate the low energy injection at the source, if the "Centaurus A" excess is due to an element of charge Z then a more significant excess is expected at an energy E_{th}/Z due to the proton component (JCAP 2009)





Z	E_{min} [EeV]	N_{tot}	N_{obs}	N_{bkg}
6	9.2	4455	219	207 ± 14
13	4.2	16640	797	774 ± 28
26	2.1	63600	2887	2920 ± 54





No significant excess in this angular window at lower energy -> one can derive upper limits on the proton fraction at the sources assuming the excess is dominated by a given element

anisotropy and chemical composition

(JCAP 2011)

From event counts to relative abundances :

$dN_z/dE=k_z\Phi(E/Z)$

(k_z relative abundance at a given rigidity)

$N_p(>E_{th}/Z)=k_p/(Z.k_p)\times N_z(>E_{th})$

we estimated $N=N_{obs}-N_{bkg}$

and $R_z=N(>E_{th}/Z)/N(>E_{th})$ U.L with 95%

R_z=12.9; 17.3; 9.1 for Z=6; 13 and 26

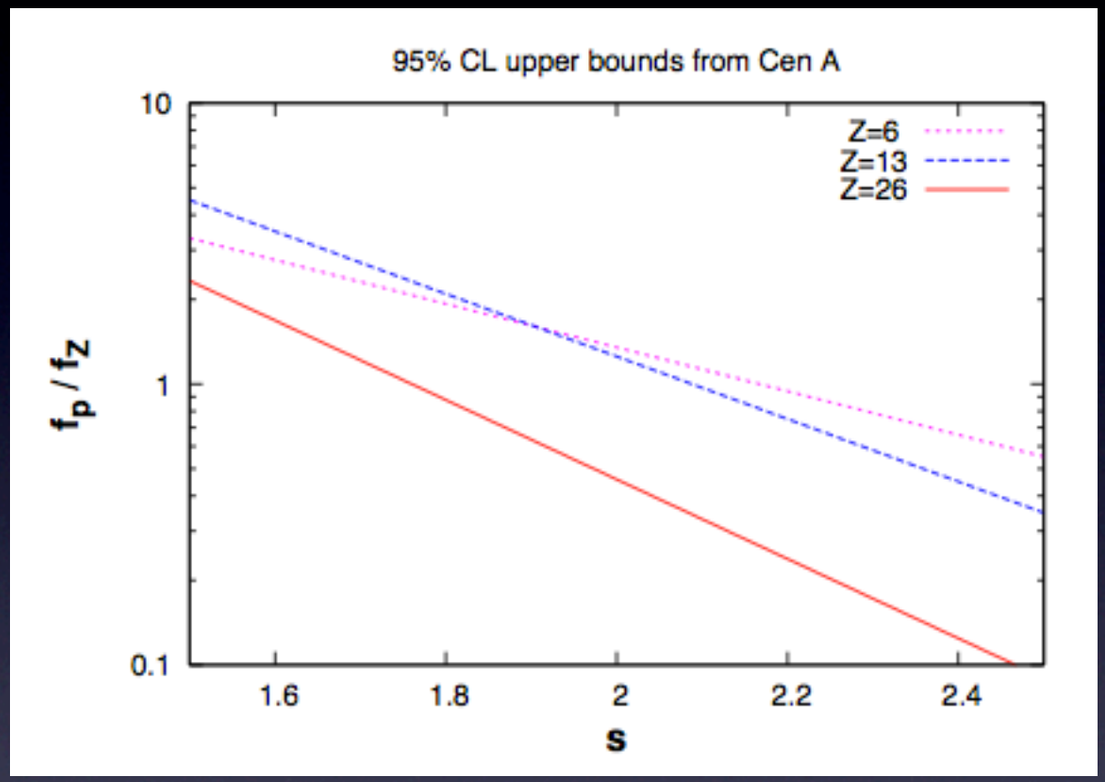
(values are ~doubled for 99 C.L)

we get $k_p/k_z<Z\times(R_z-1)$

if one assumes a power law spectrum below $E_{max}(Z)$

$k_p/k_z=f_p/f_z\times Z^{\beta}$

(f_i relative abundance at a given energy, β spectral index)



Most stringent constraints for soft spectral indexes

Transition from a dominant proton component to iron (via a rigidity cut-off) disfavored unless very hard source spectral index

For Z=6 relatively large fractions at the sources are required

Summary

• Follow up of the AGN correlation : the fraction of correlating events has decreases, still a significant deviation from isotropy expectations

• Tests with SWIFT and 2MRS catalogues : data compatible with models with suitable σ and f_{iso}
These parameters are not well constrained, more data need

• No significant signal in the autocorrelation

• A hint for a diffuse excess of events in the region of the Cen A can be found in the data
-> needs to be confirmed and understood

• The excess (if confirmed) can be used to constrain the composition