Current status and future prospects
on anisotropies at ultra-high energies

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University College London

MACROS Workshop
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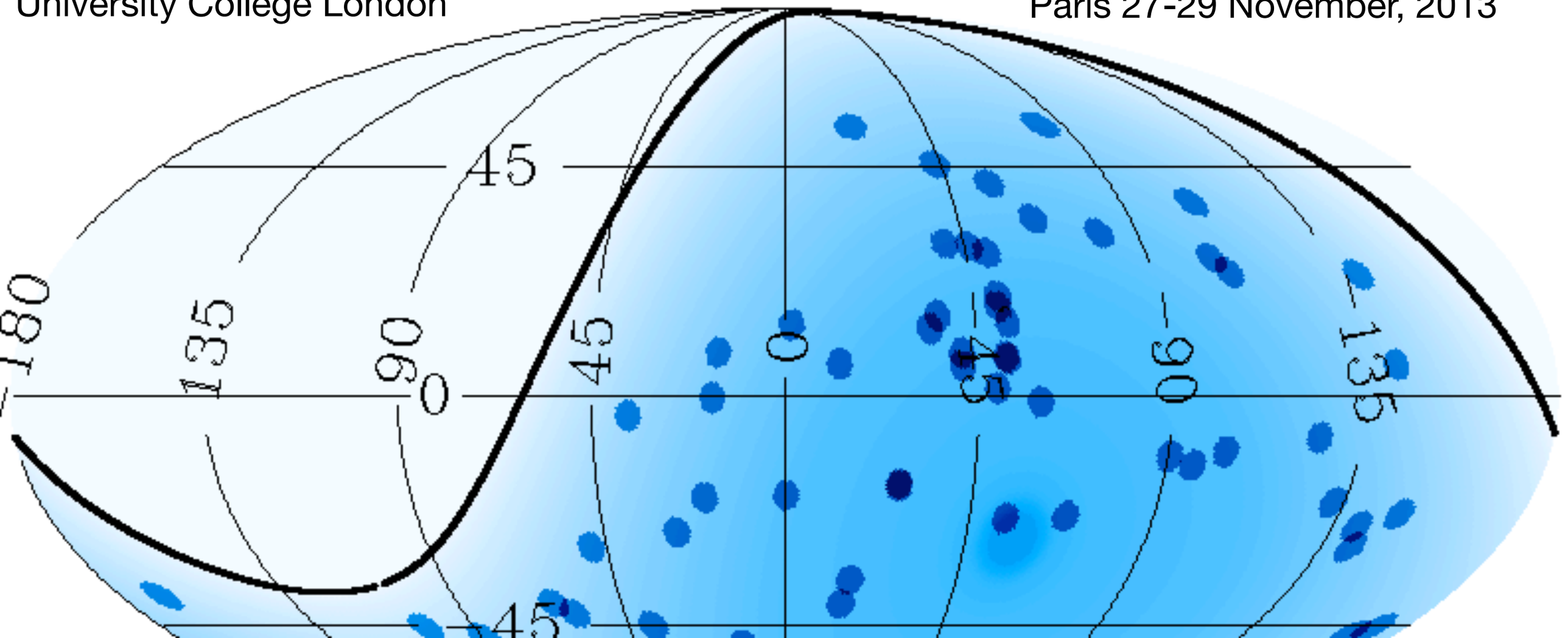


Outline

Introduction: UHECRs and the expected anisotropy

Clustering of observed UHECRs:
Implications for the density of UHECR sources

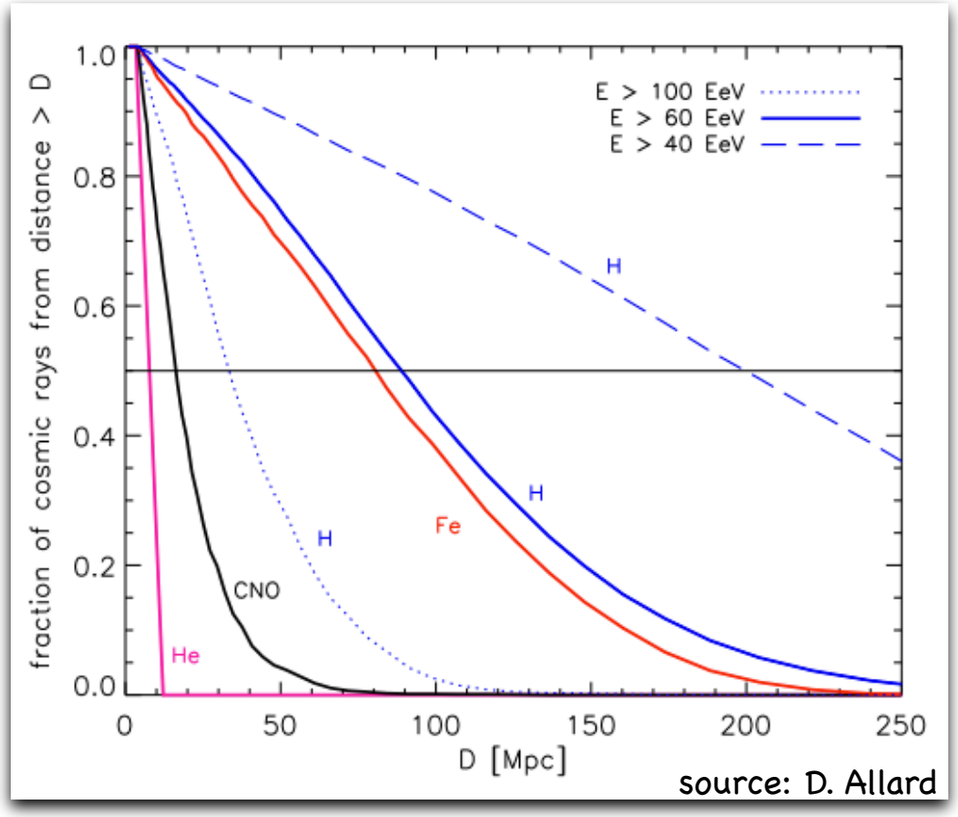
Searches for point sources

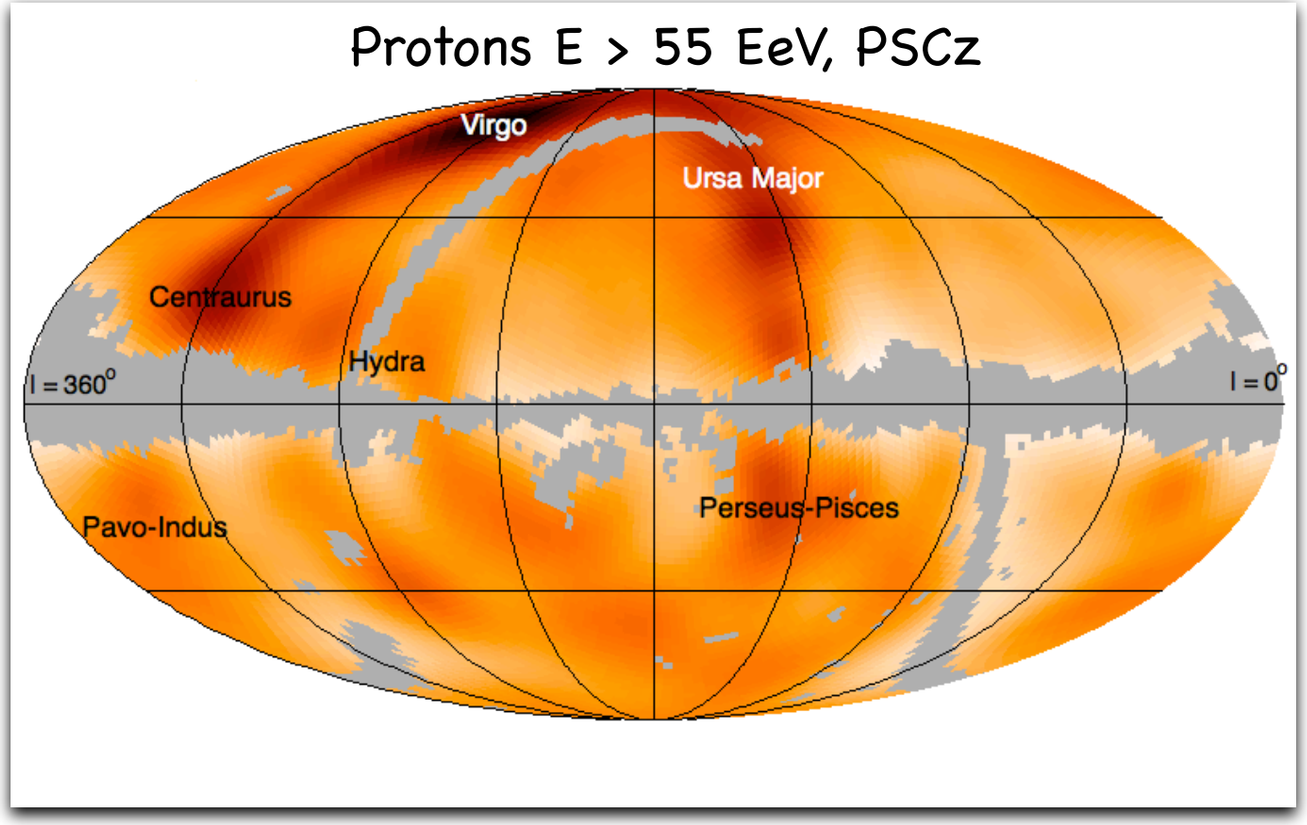
Correlation with the matter distribution

Lower energy searches

Prospects

Introduction: UHECR propagation





At E > 60 EeV UHECR propagation distance becomes 50-100 Mpc due to GZK suppression

Matter distribution at these scales anisotropic (overdensities of order ~ 3)

Anisotropy expected for proton UHECRs

Uncertain composition complicates expectations (see talks this morning by Tameda/Pierog)

Typical UHECR deflections:

$$\langle\theta\rangle \simeq 0.8^\circ \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1} \left(\frac{\lambda_B}{1\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{r}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\ \mathrm{G}}\right)$$

Waxman & Miralda-Escude 1995

For 100 EeV protons $\lesssim 2^\circ$ in extragalactic B-fields of order 10^{-9} G

In the Galactic B-field 2° - 4°, larger through Galactic center

For iron much larger $\theta \sim Z \times \theta_{proton}$ (But uncertainties in B-fields: see talks by Takahashi/Prosekin/Taylor)

Bounds on the local UHECR source density

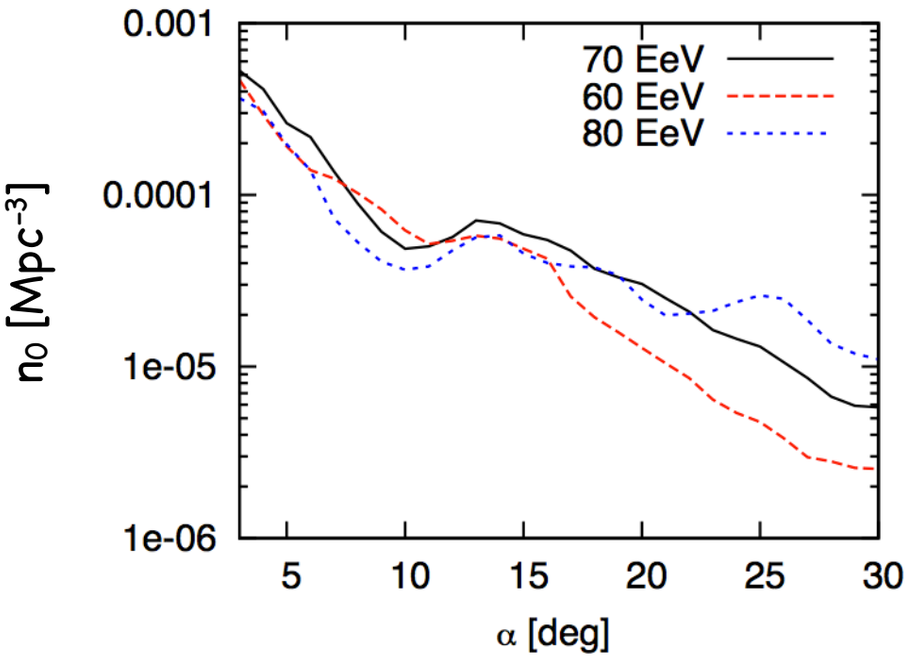
Clustering in dataset can constrain local UHECR source density (Waxman+ 1995, Dubovsky+ 2000, Decerprit+ 2011)

Absence of significant number of multiplets (4 pairs separated by < 3°) in Auger 2010 dataset suggests $n_0 \gtrsim 10^{-4}$ Mpc^{-3} if deflections are ~ 3° (FO+ 2013)

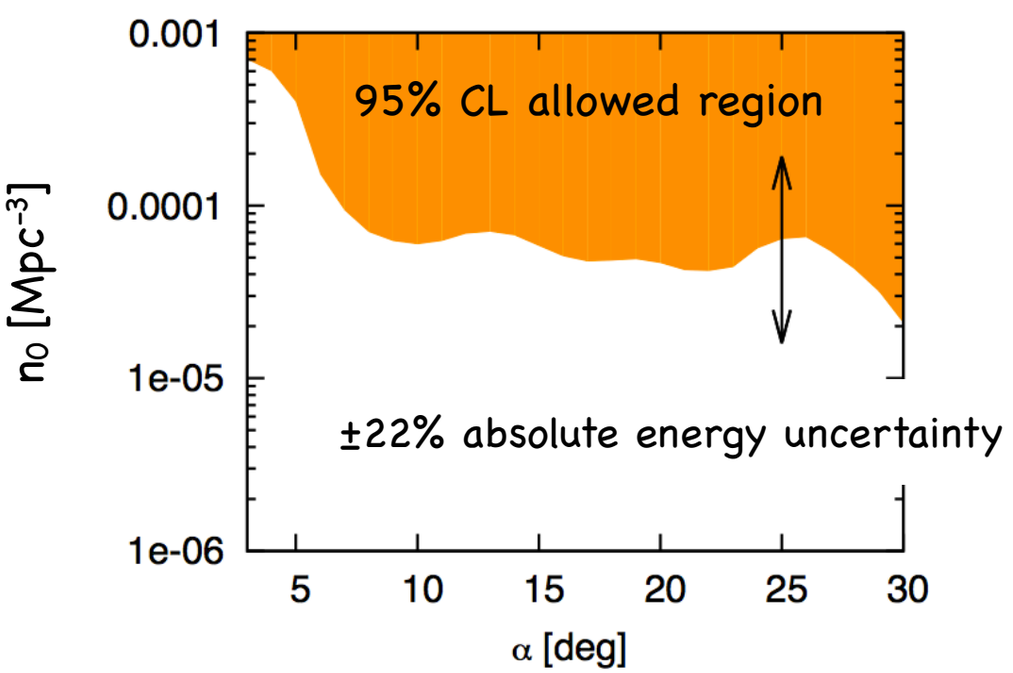
$n_{gal} \sim 10^{-2}$ Mpc^{-3}
$n_{AGN} \sim 5 \times 10^{-4}$ Mpc^{-3}
$n_{quasars} \sim 10^{-4}$ Mpc^{-3}
$n_{GRB} \lesssim 10^{-5}$ Mpc^{-3}
$n_{BL\ Lac} \lesssim 10^{-6}$ Mpc^{-3}
$n_{galaxy\ clusters} \sim 10^{-7}$ Mpc^{-3}

Auger Coll 2013

Isotropic source distribution



Source distribution that follows 2MRS



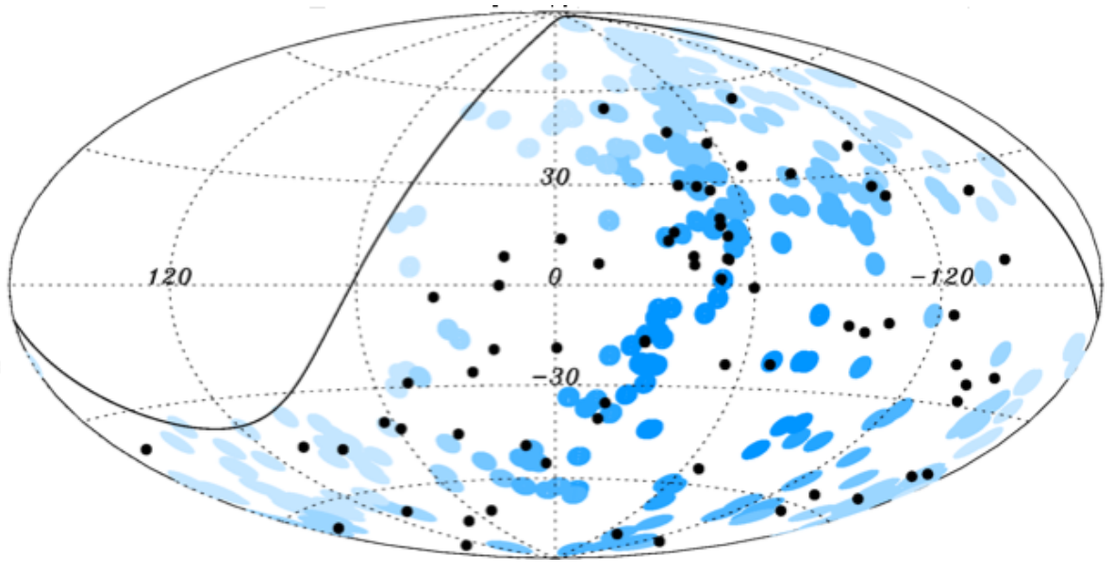
n_0 derived with 20 events above E_{thr} = 80 EeV

Large source density

Point source searches: Veron-Cetty & Veron analysis

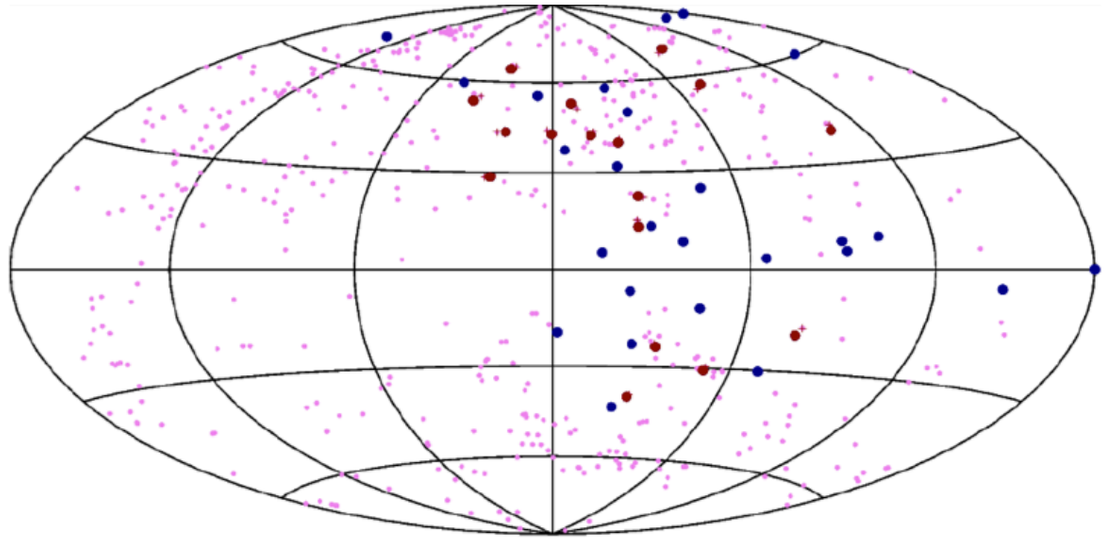
Auger

69 events
E ≥ 55 EeV
Auger Coll 2010



Telescope Array

42 events
E ≥ 57 EeV
TA Coll ICRC 2013



Auger prescription established 2004

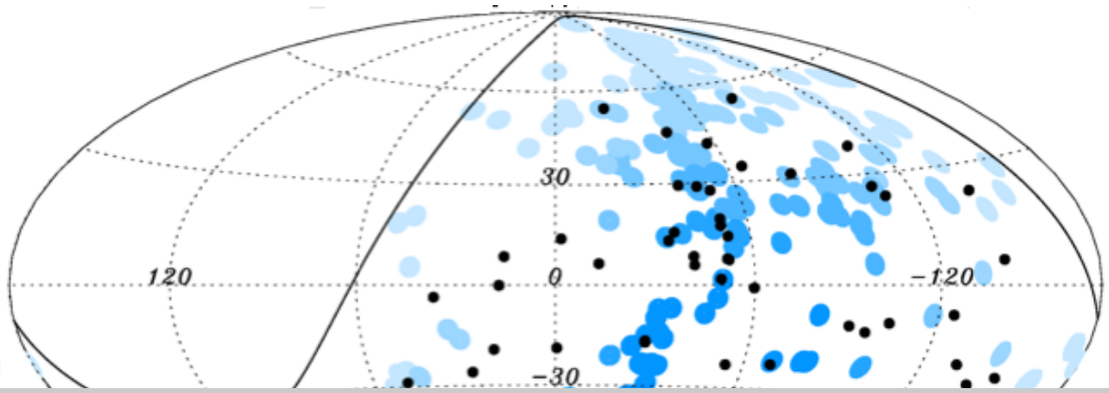
Scan δ = 3.1°, d ≤ 75 Mpc, E ≥ 55 EeV

In 2007 reported significant detection (9/13, P = 2 x 10^{-4} , isotropy ruled out at 99% CL)

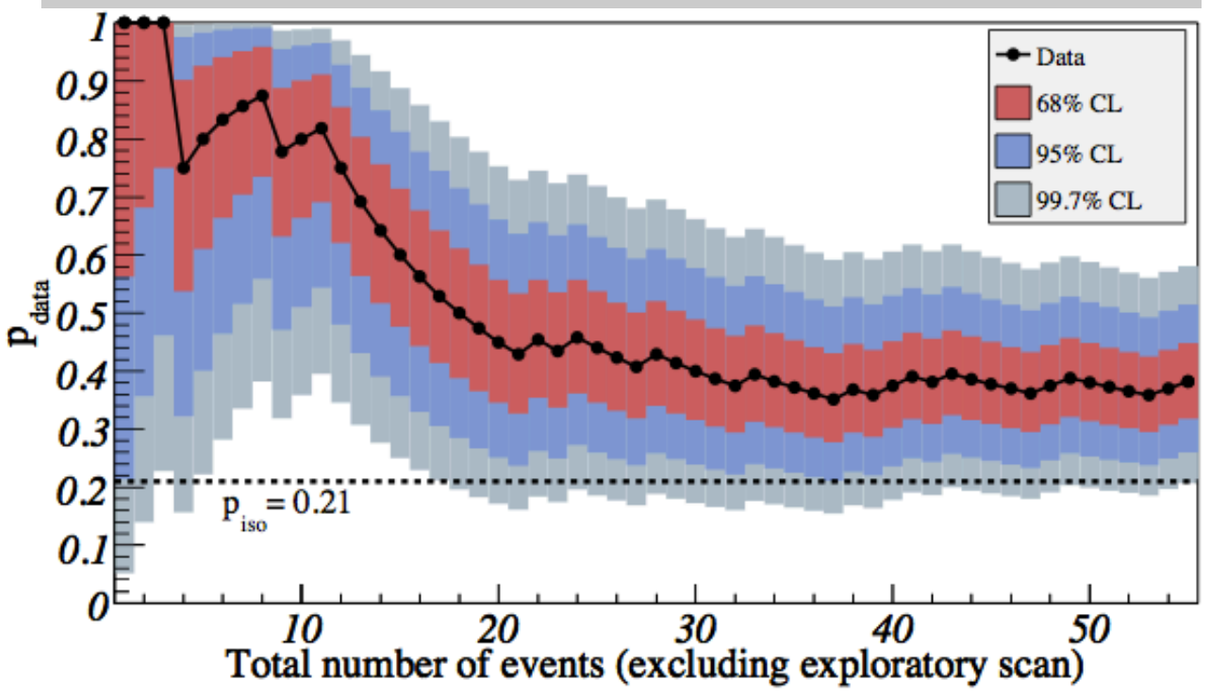
Point source searches: Veron-Cetty & Veron analysis

Auger

69 events
E ≥ 55 EeV
Auger Coll 2010



Update: 21/55 correlate P = 3 x 10^{-3}



Telescope Array

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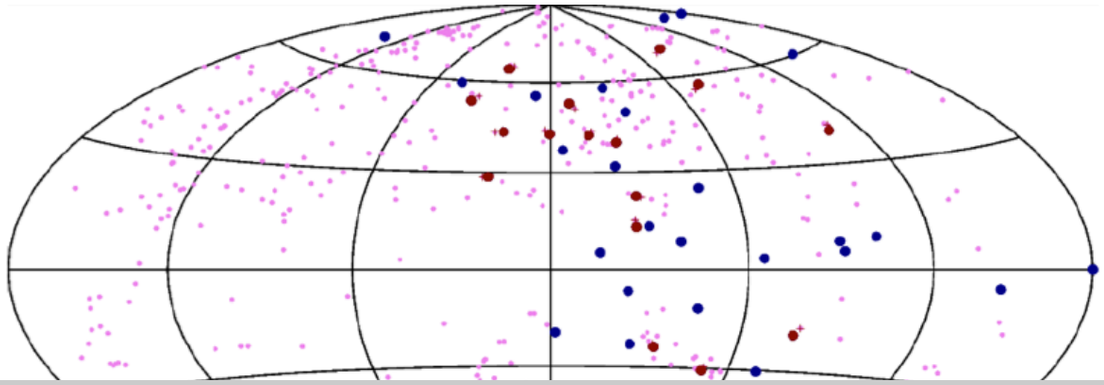
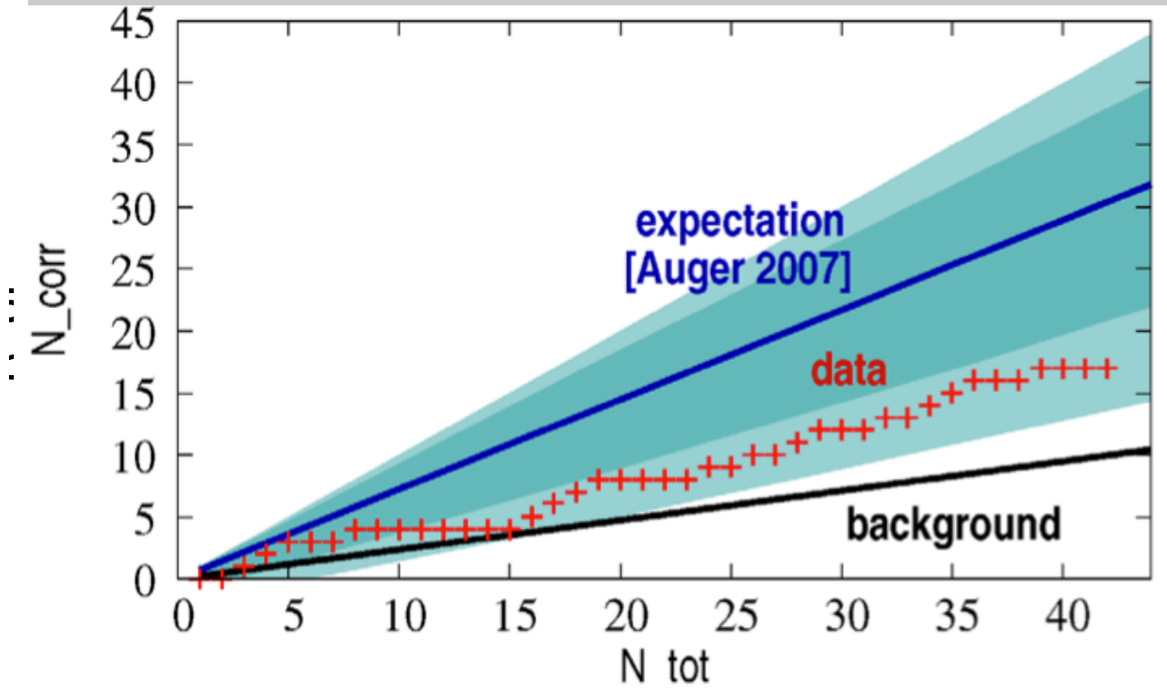
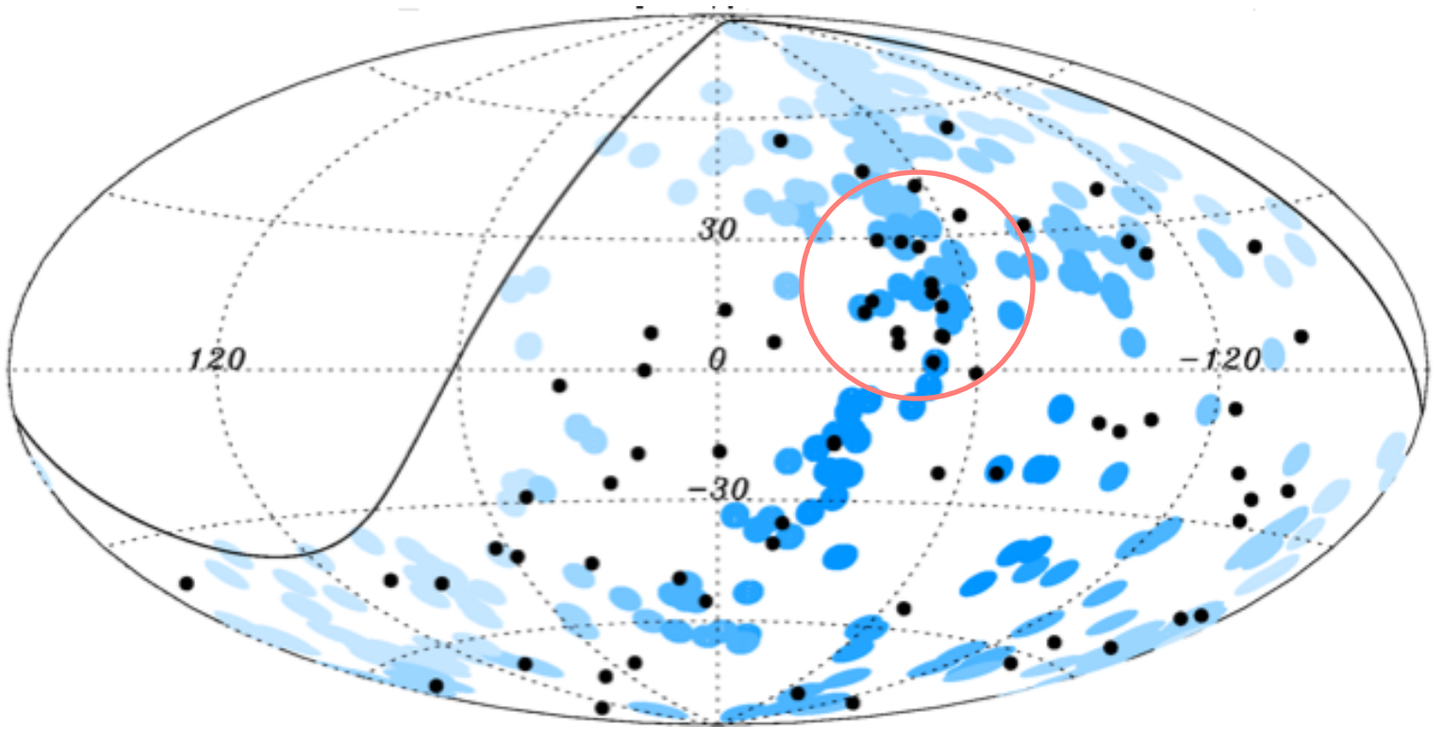


17/42 correlate p = 0.013

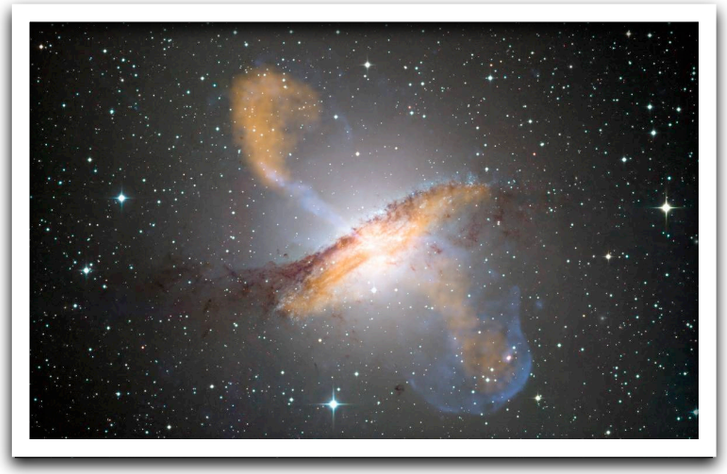


Hotspot in Cen A region

Auger Coll 2010



Nearest AGN ~ 3.8 Mpc

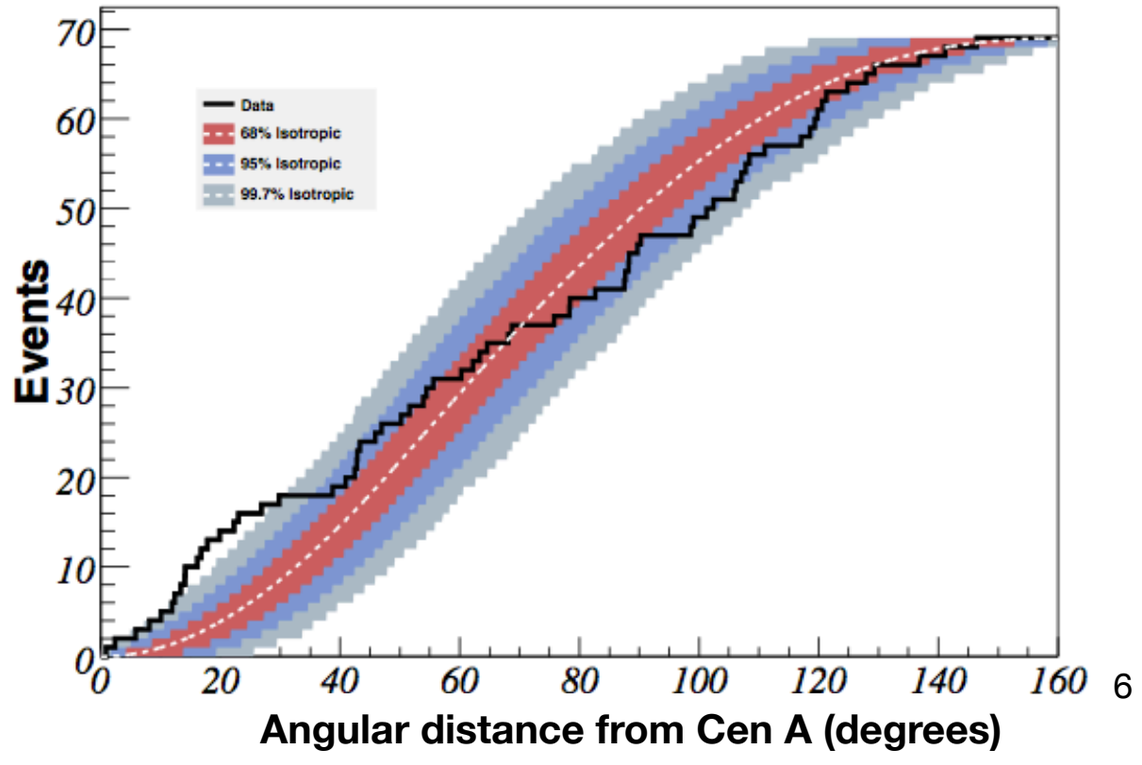


Circle of radius 18° centred on Cen A contains 13 of 69 events when 3.2 expected from isotropy

Note:

> 3σ but pre-trial

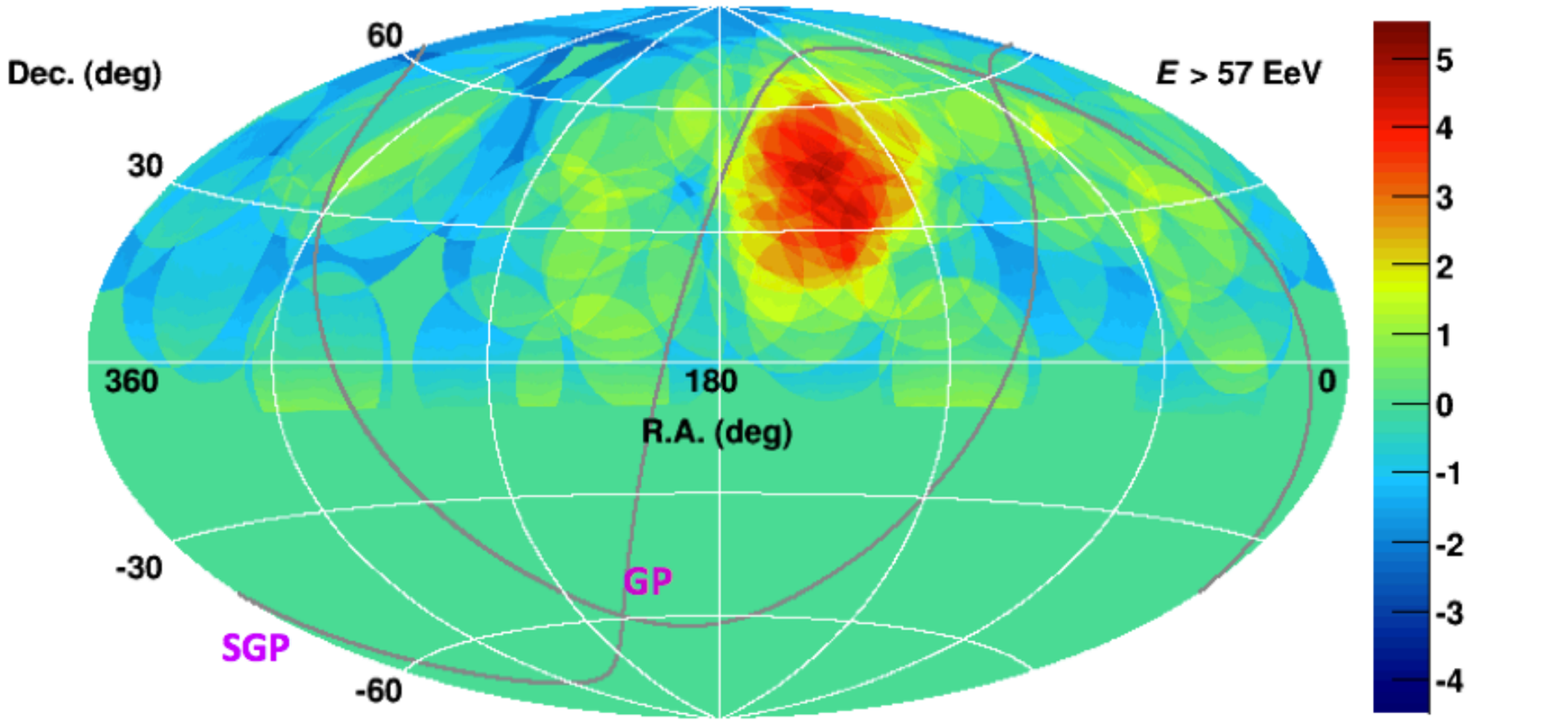
Cen A in front of Centaurus Supercluster



TA hotspot

72 events with E > 57 EeV (looser cuts than standard analysis)
Cluster of 20° radius near SG plane

TA CosPA 2013



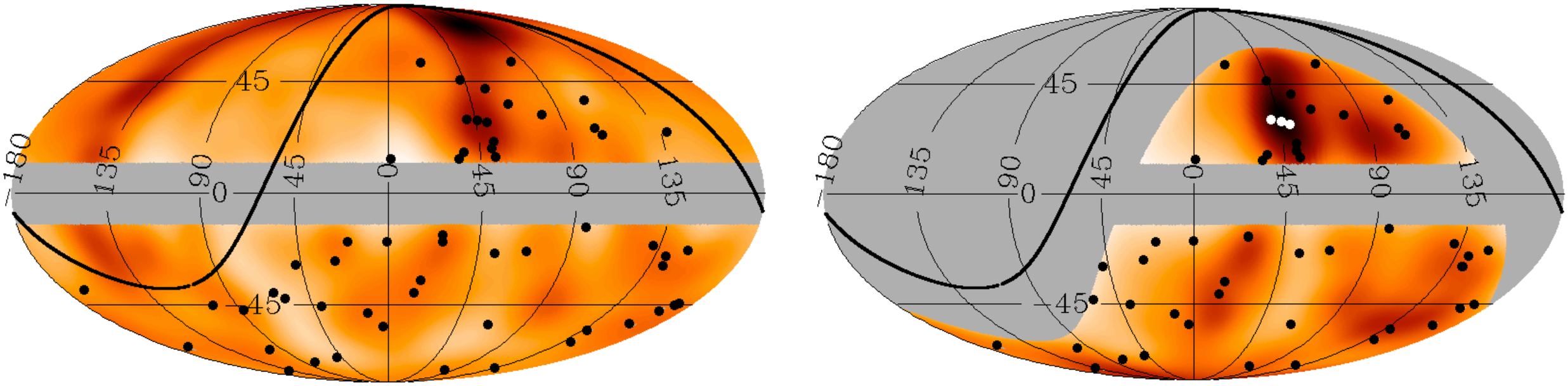
TA Coll are estimating post-trial chance probability

Correlation with Large Scale structure

FO et al 2013

PSCz

6dF



Knowing matter distribution calculate predicted UHECR flux and compare to observations

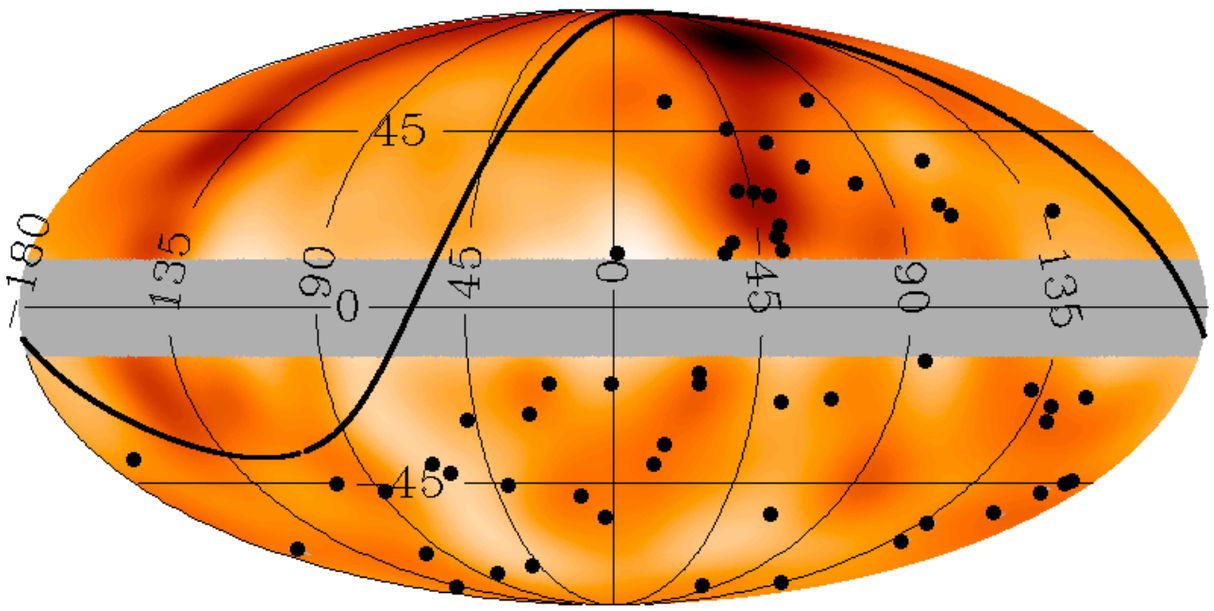
Two galaxy catalogues used: IRAS-PSCz (see also Cuoco 2005, Takami+ 2008, Kashti, Waxman 2005, Berlind+ 2010 with earlier datasets), 2MASS-6dF (10^5 galaxies $z < 0.02$)

Statistical test: Cross-correlation test

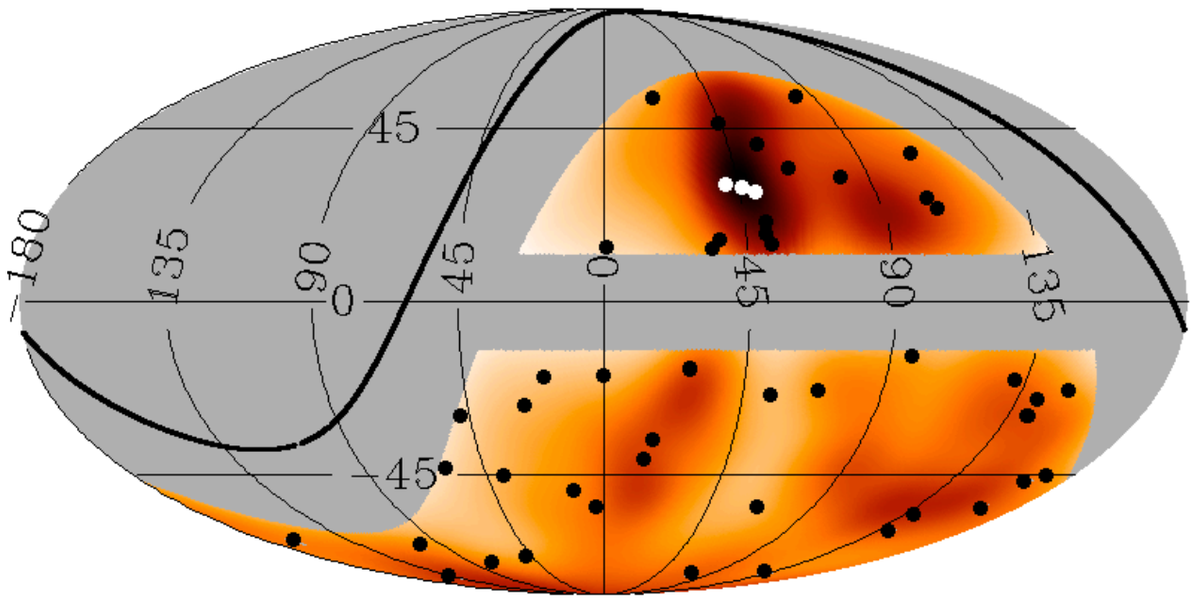
Correlation with Large Scale structure

FO et al 2013

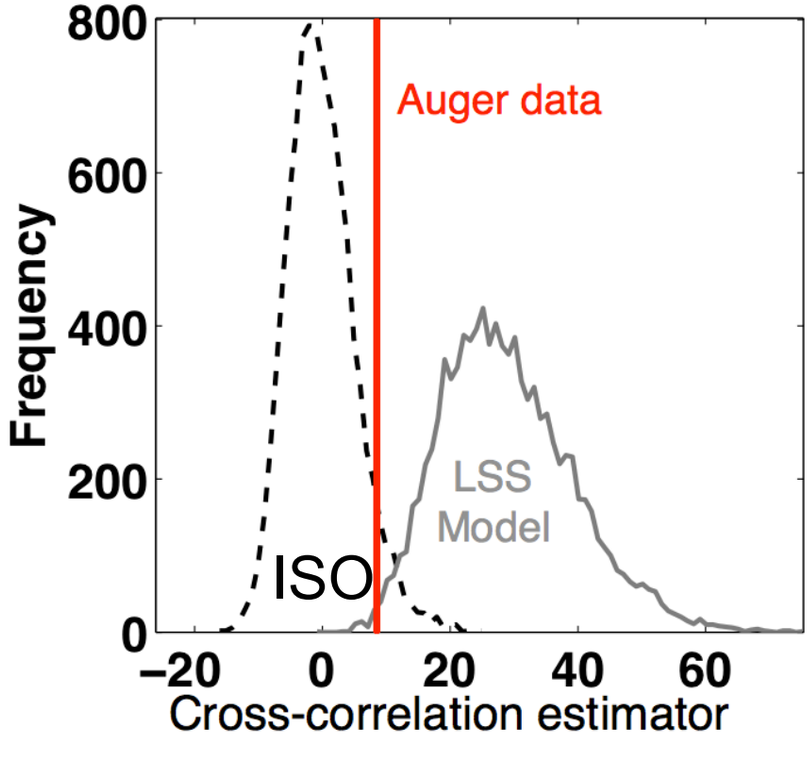
PSCz

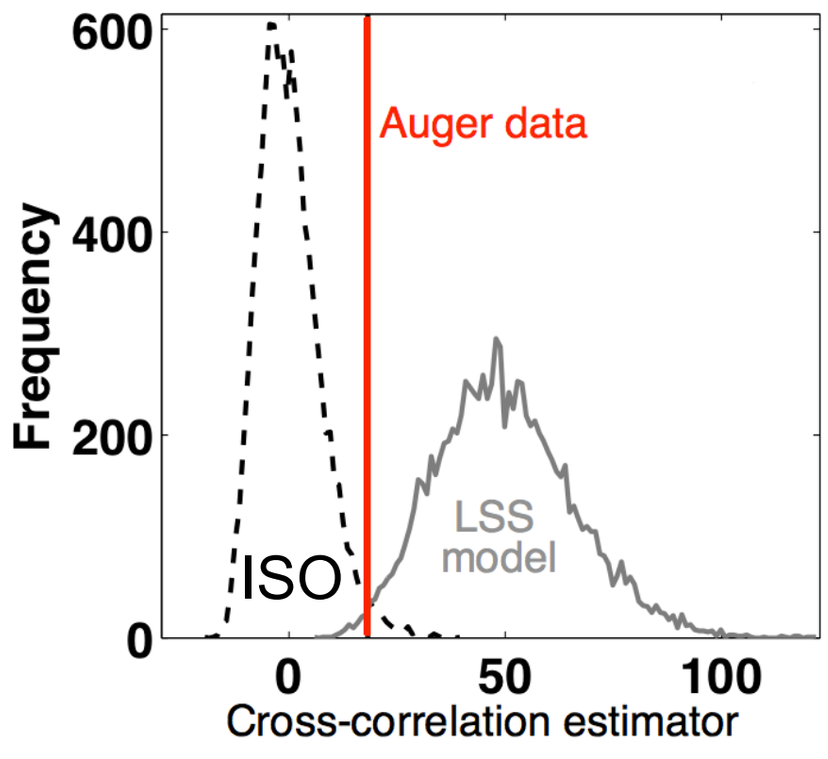


6dF



Data incompatible with isotropy at the ~ 2σ C.L.

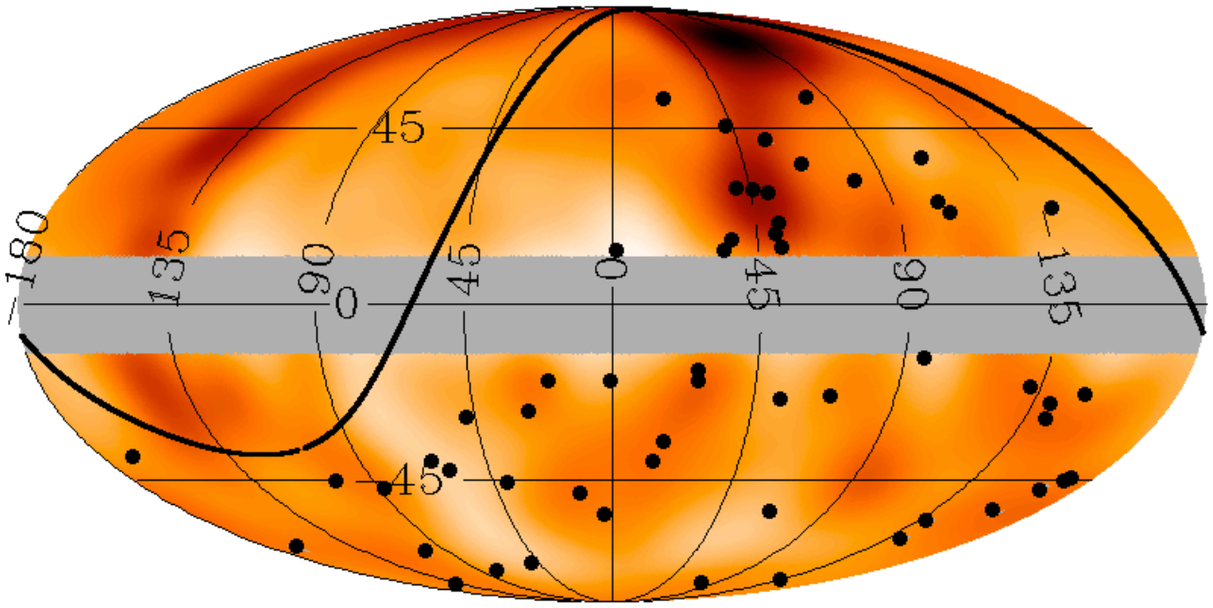




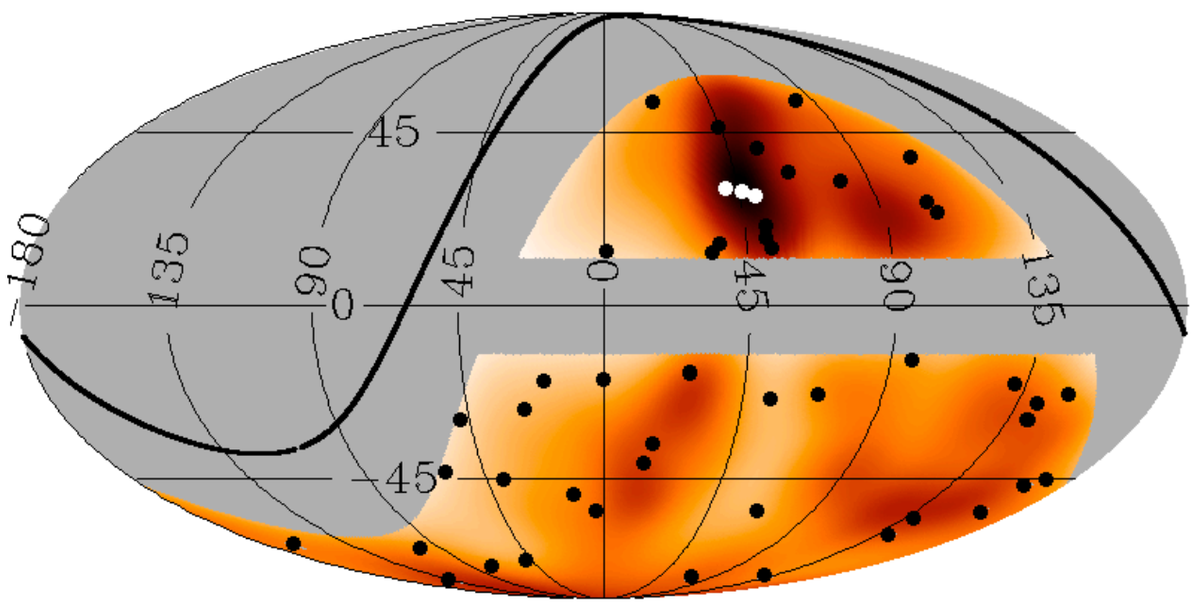
Correlation with Large Scale structure

FO et al 2013

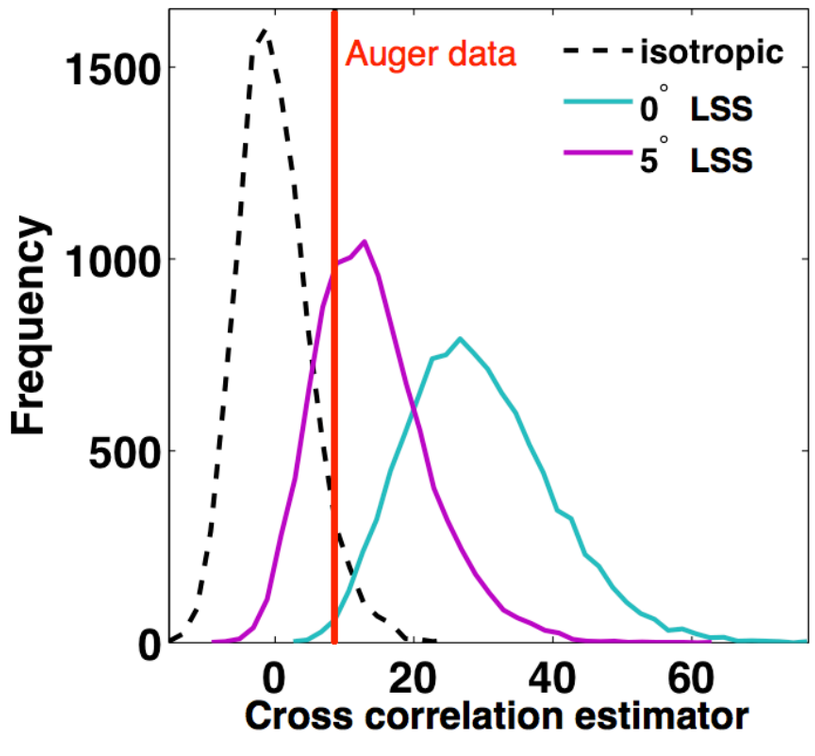
PSCz

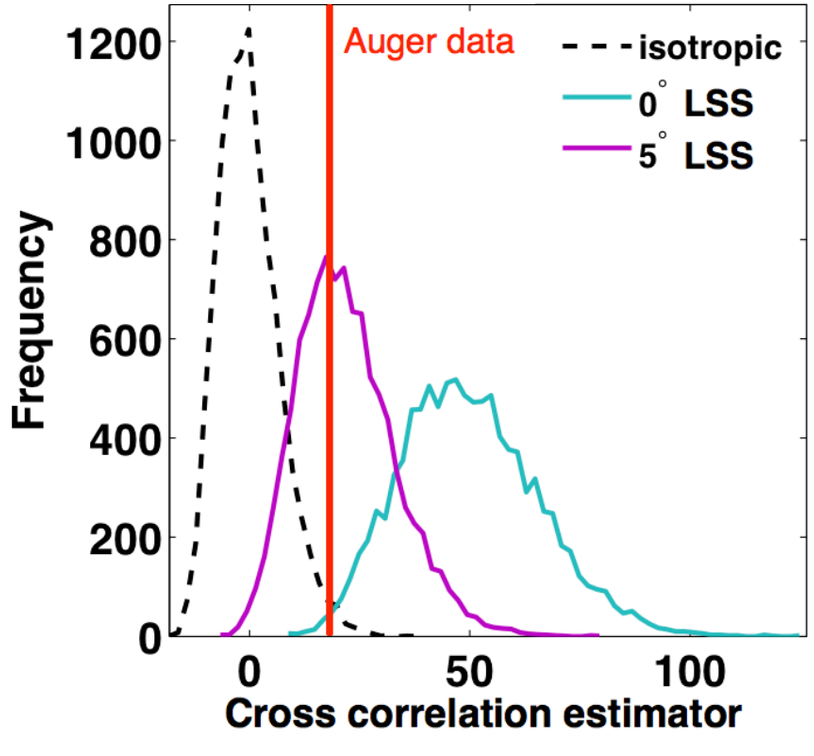


6dF



Data compatible with galaxy distribution if θ > 5°

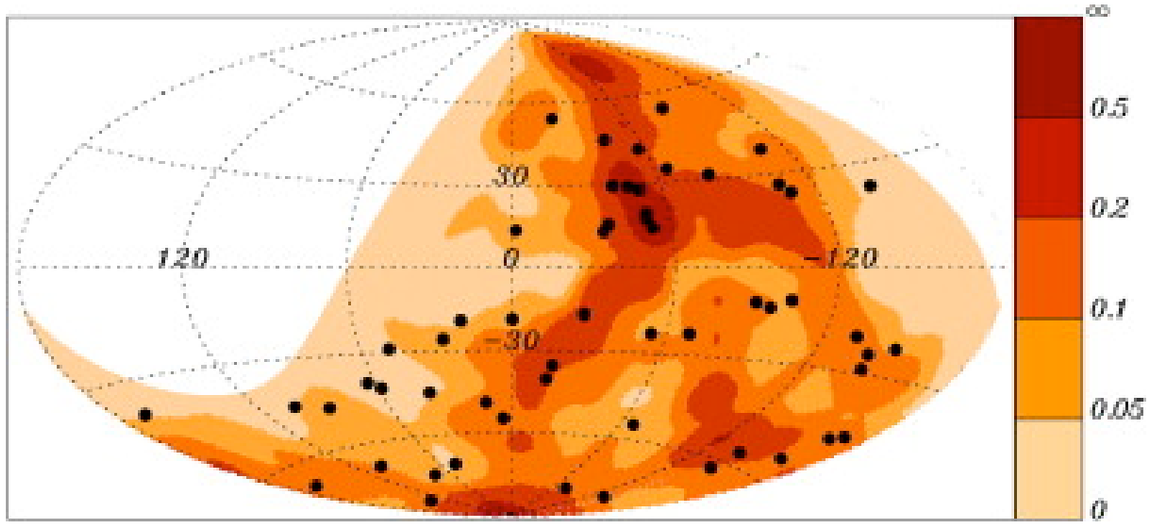




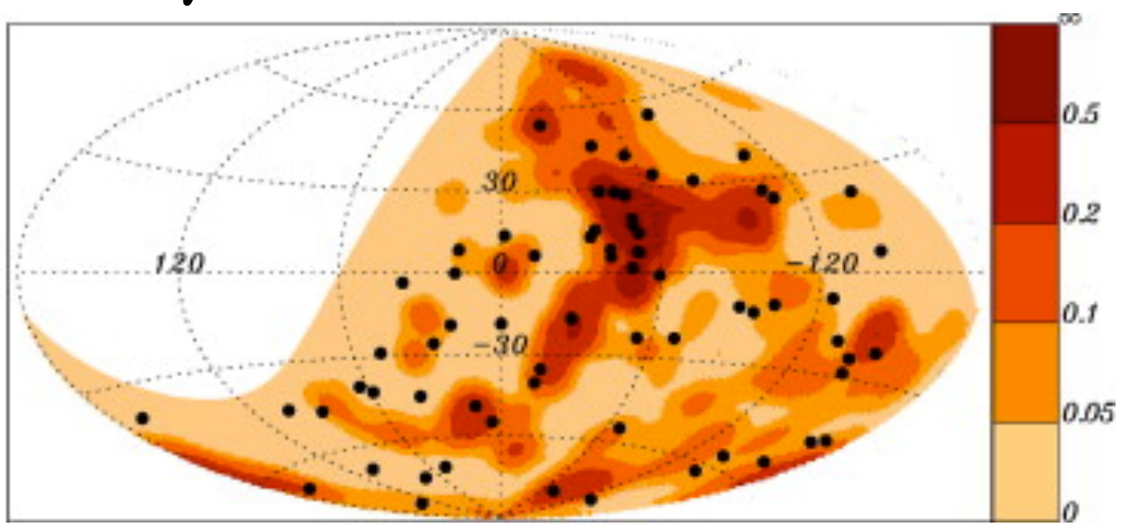
Correlation with Large Scale structure

Auger Coll 2010

2MRS



2 years Swift-BAT

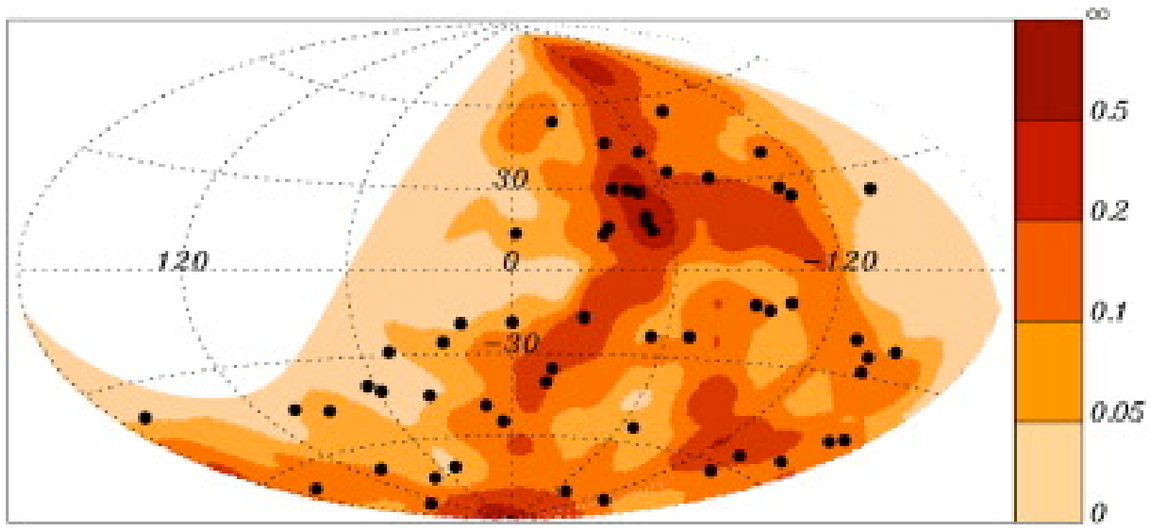


69 events with E > 55 EeV.
Two galaxy catalogues used: 2MRS and Swift-BAT 2 year data
Statistical test: Cross-correlation test

Correlation with Large Scale structure

Auger Coll 2010

2MRS



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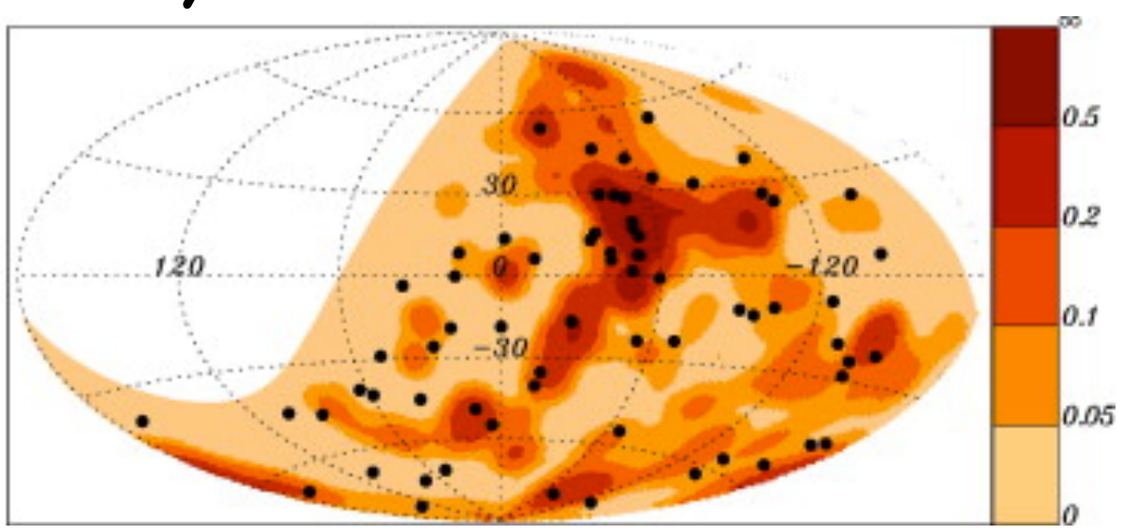
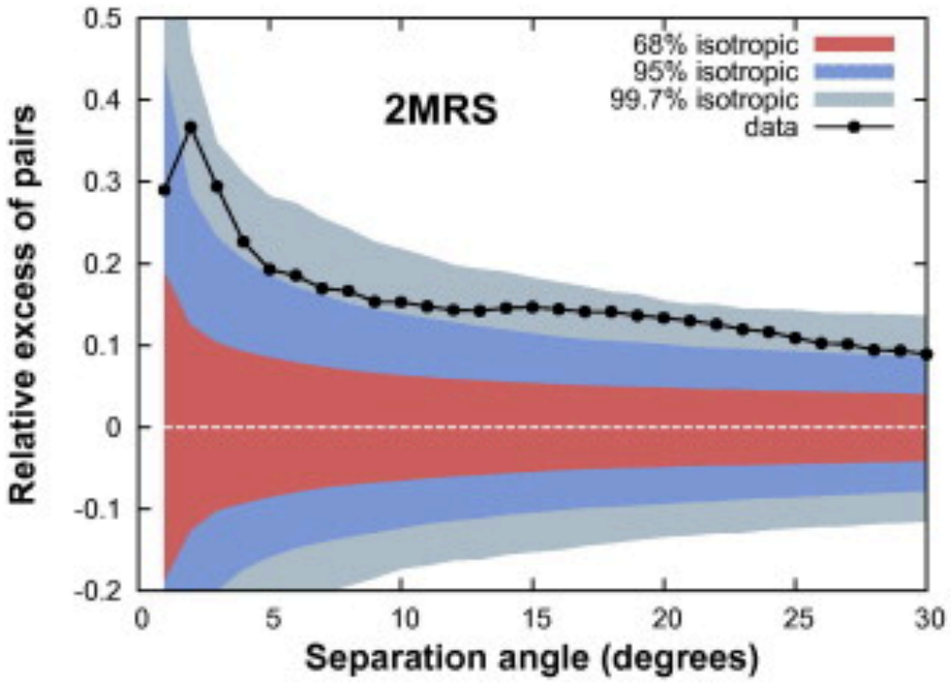
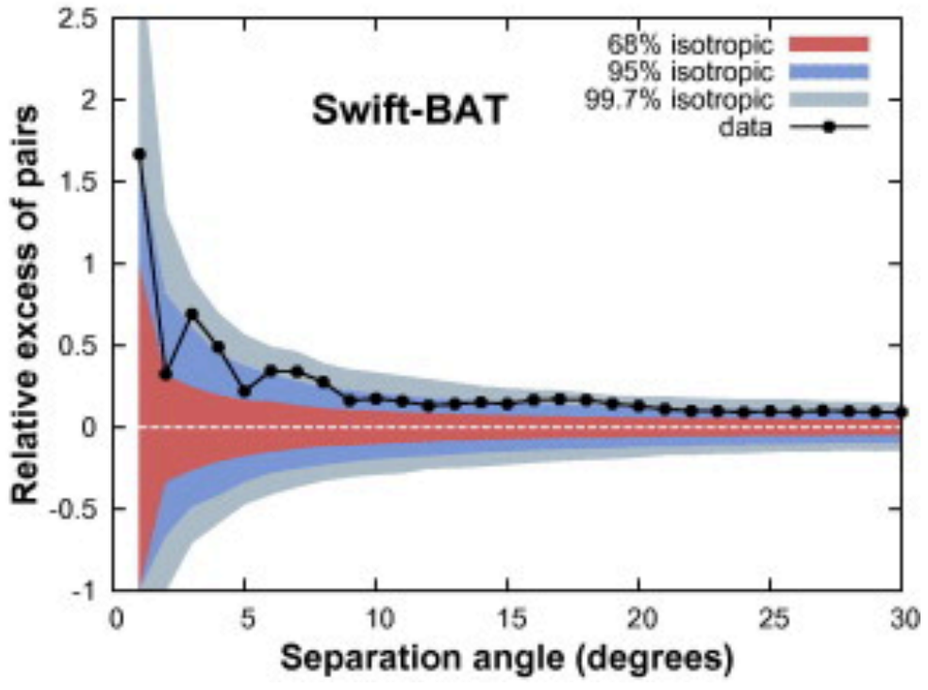
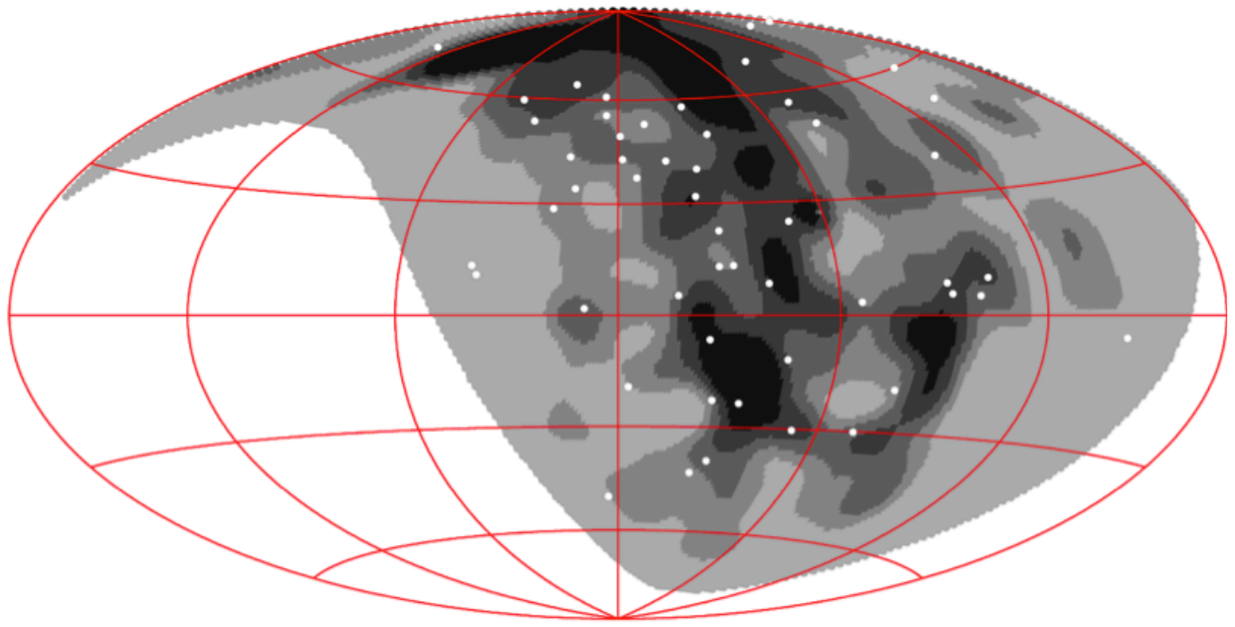


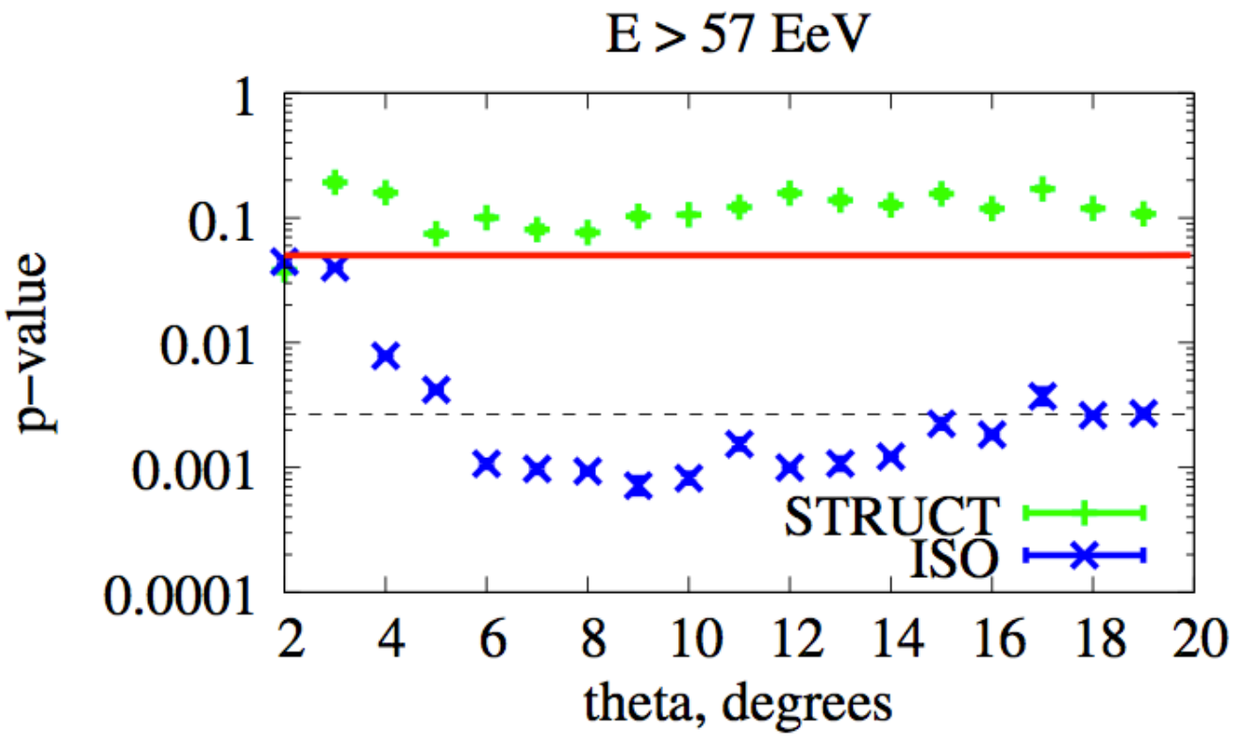




Correlation with Large Scale structure

TA ICRC 2013





42 E > 57 EeV UHECRs
2MASS-XSCz used (106 000 galaxies)
Expected flux calculated from galaxy distribution, Gaussian smoothing of width θ free parameter.
Test: Flux sampling test

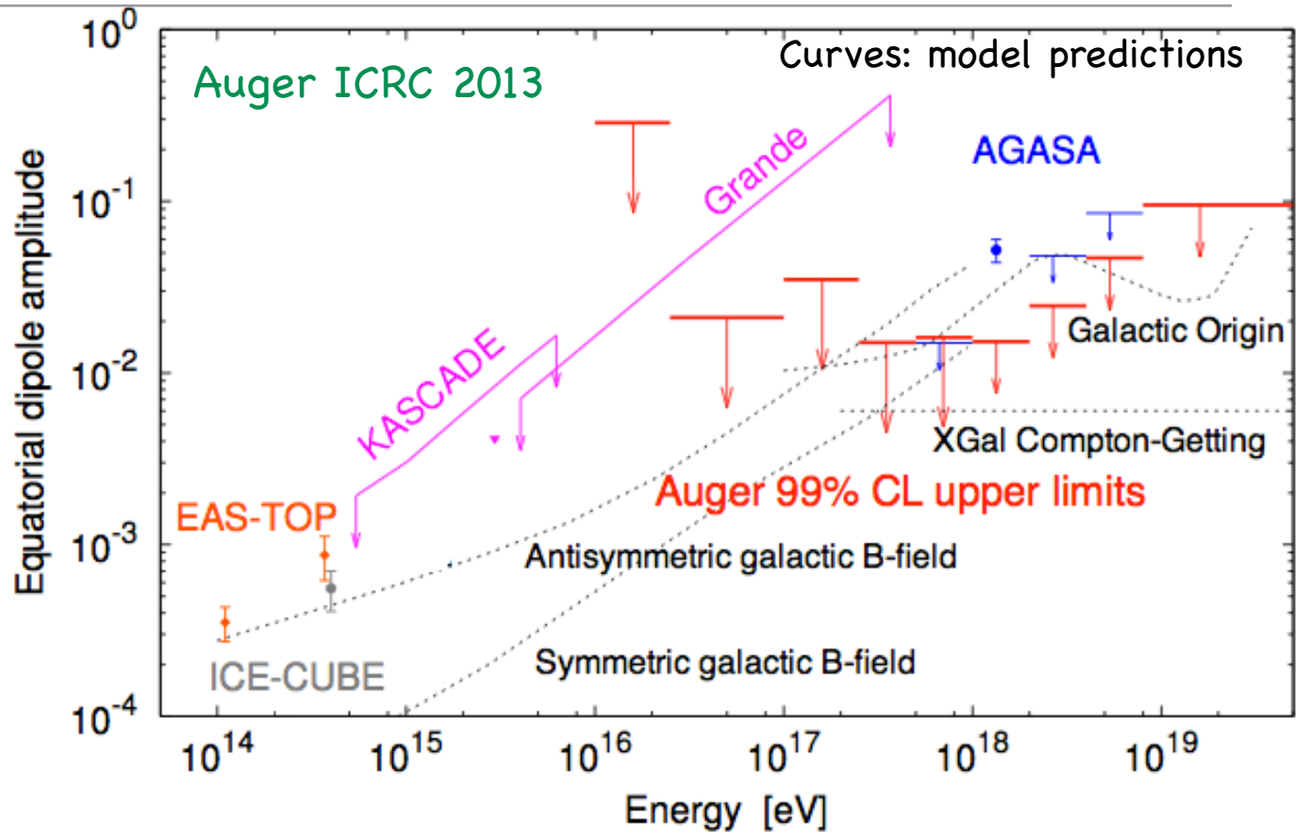
Data compatible with LSS model but incompatible with isotropy at the ~ 3σ C.L. (pre-trial), for most smearing angles.

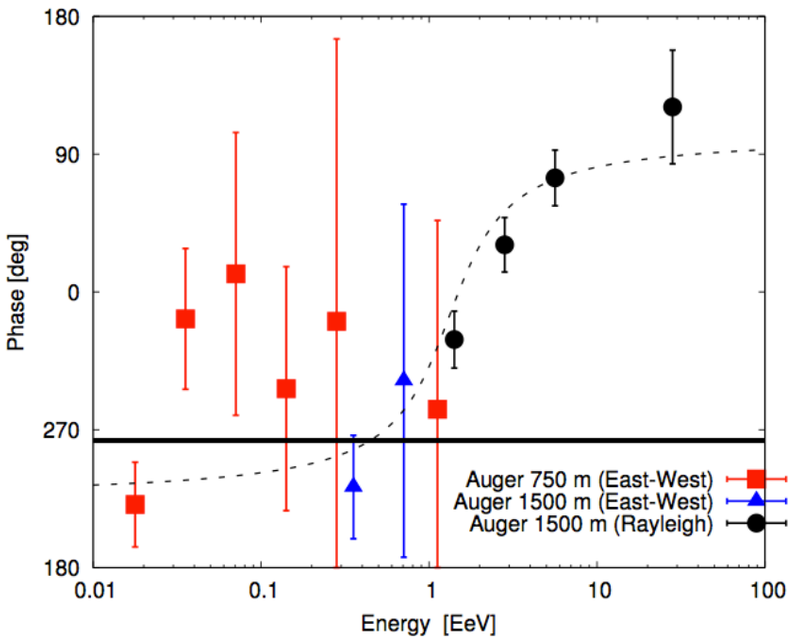
Anisotropy searches at lower energies:

1. Harmonic analyses

Data collected in Auger put upper limits on amplitude of dipole anisotropy between 10^{16} - few x 10^{19} eV.

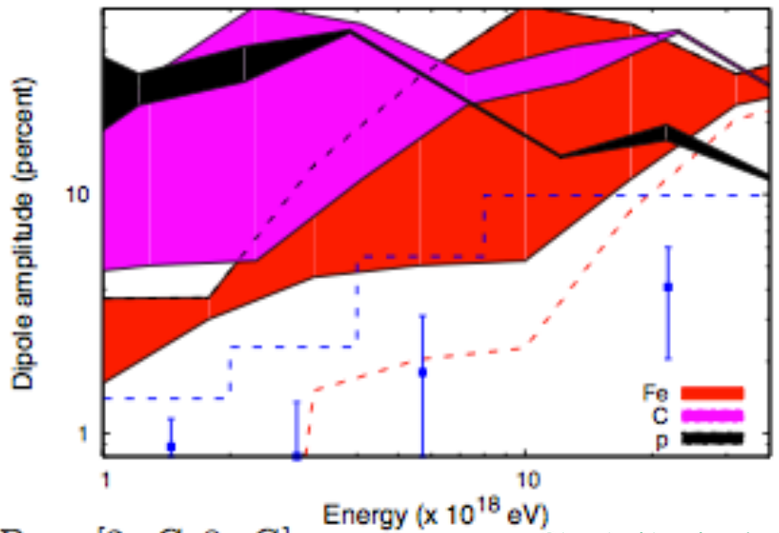
Exclude some models of G - XG transition/galactic B-field and constrain others.





- Auger sees hints of change in phase of dipole anisotropy at 5 EeV
- Prescription in place for 99% test (to run until 2015).
- TA sees compatible trend! Stay tuned...

Galactic p,C,(Fe) ruled out above EeV(10 EeV)



$B_0 \in [2\,\mu\mathrm{G}, 8\,\mu\mathrm{G}]$

Giacinti et al 2011

Anisotropy searches at lower energies:

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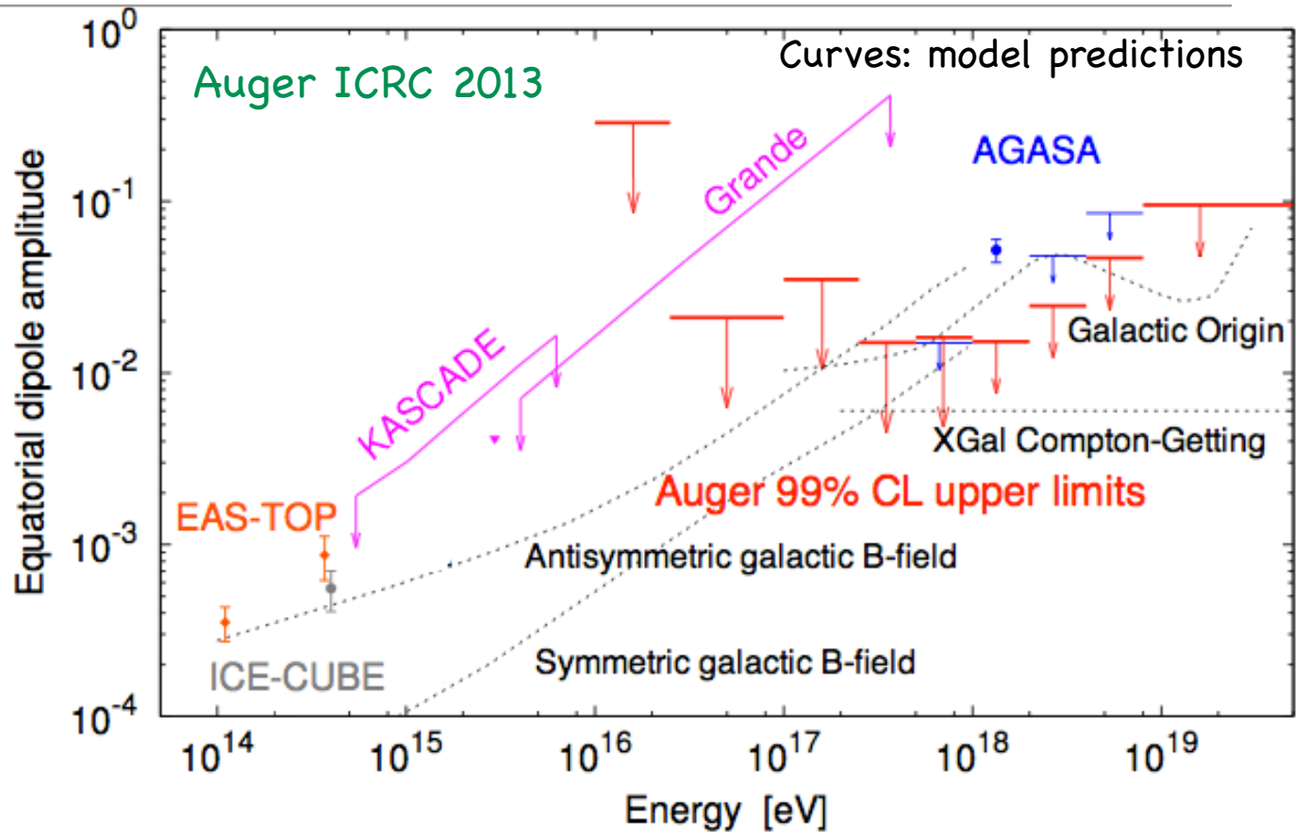
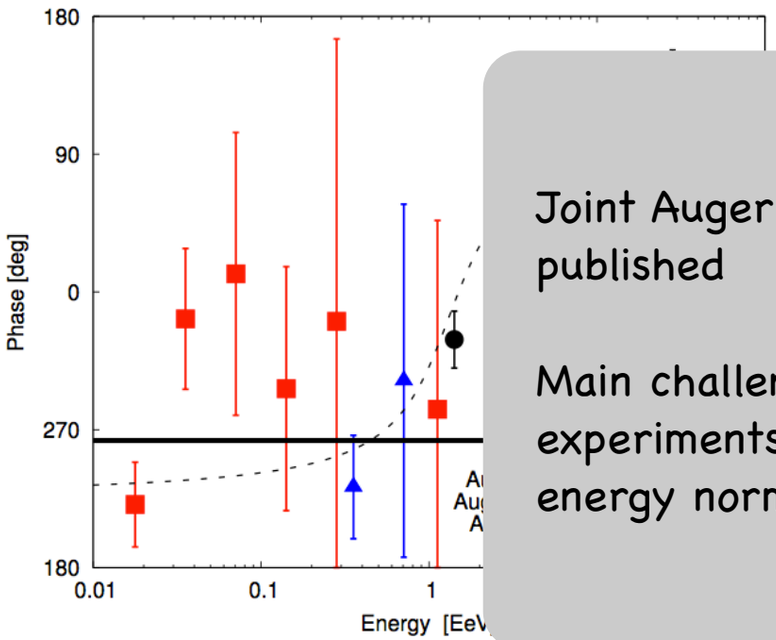
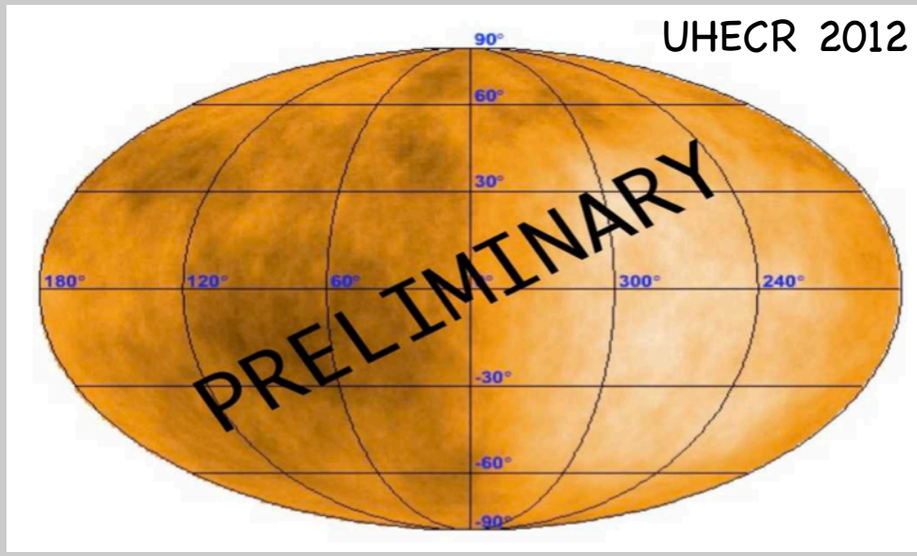




Joint Auger + TA anisotropy analysis to be published

Main challenge relative exposures of two experiments and possibly different absolute energy normalisations

Galactic p,C,(Fe) ruled out above EeV(10 EeV)



Anisotropy searches at lower energies:

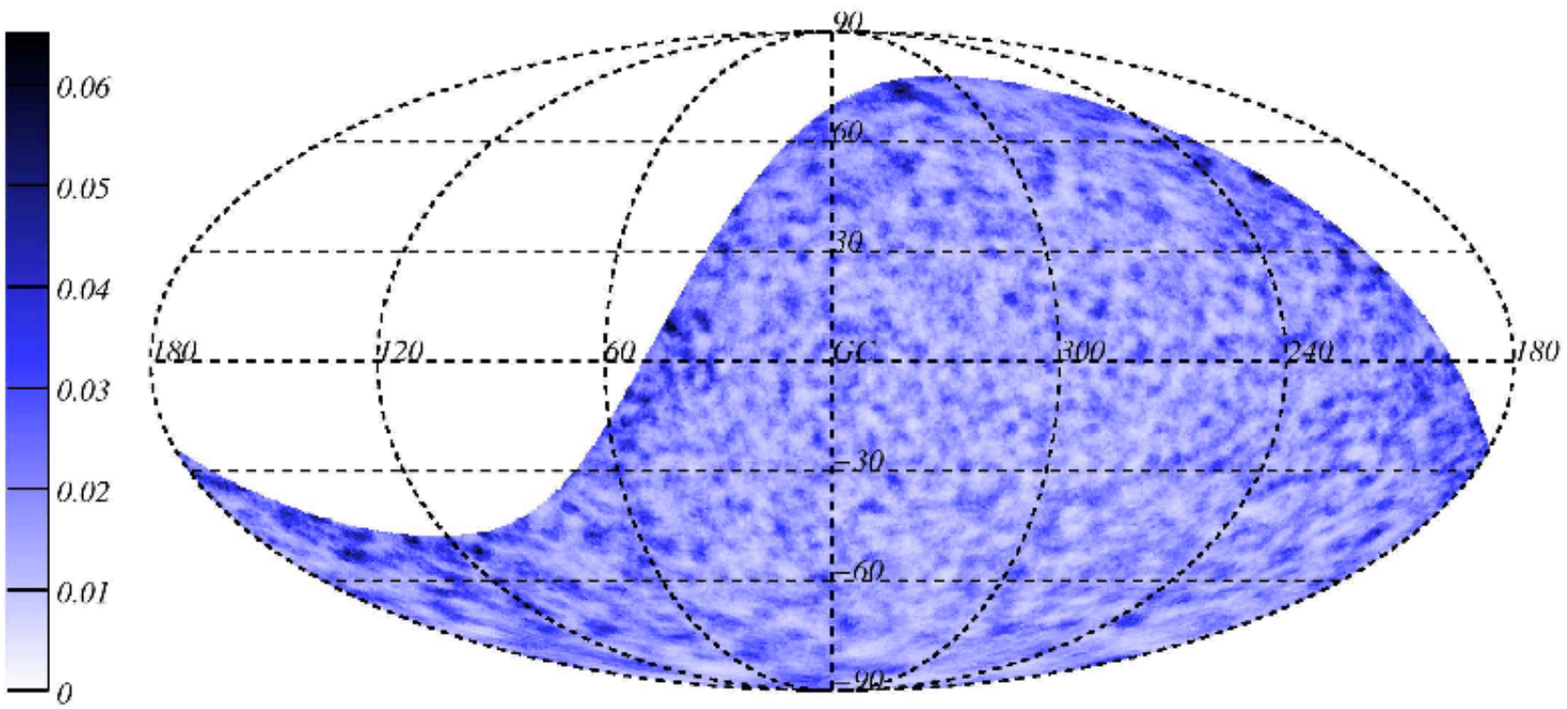
2. Neutron searches

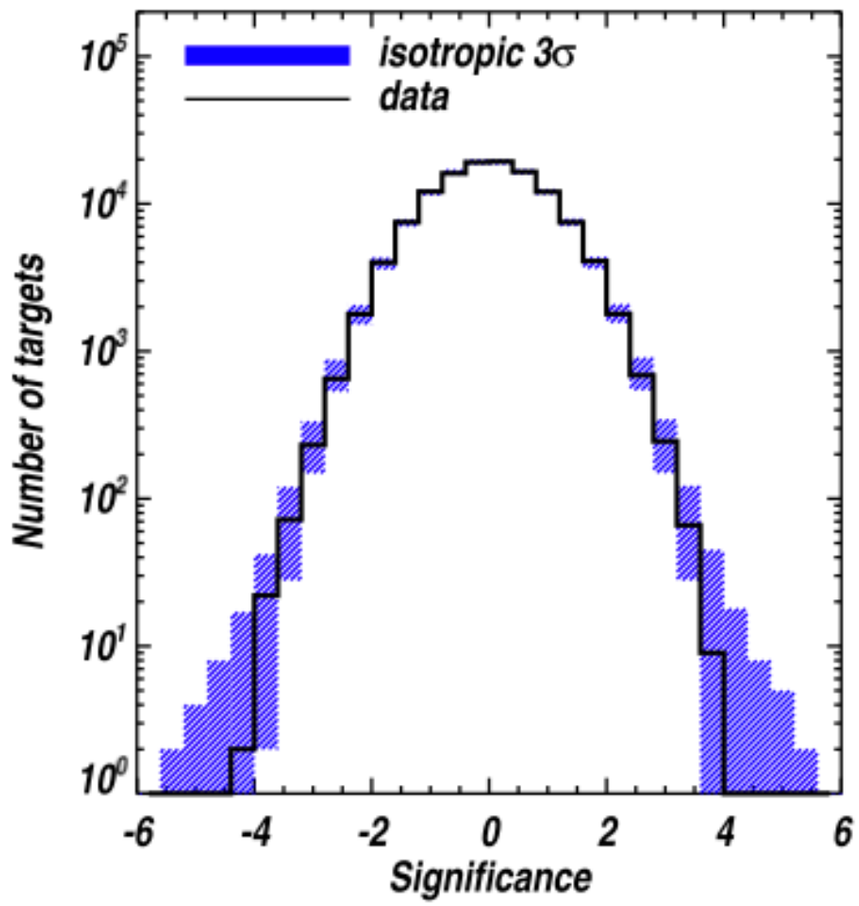
Auger Coll (Rouille d'Orfeuil ICRC 2011/ Astrophys. J. 760, (2012) 148 / Salesa Greus ICRC 2013)

Observed neutrons must come from d = 9.2· (E/1 EeV) [kpc] , $r_{\text{Milky Way}} \simeq 15$ kpc

If TeV γ-rays are hadronic π^0 ($\Delta^+ \rightarrow p + \pi^0$), neutrons should be emitted too ($\Delta^+ \rightarrow n + \pi^+$)

Blind search (search for excess in the data), targeted search (search in direction of bright galactic γ-ray sources), stacked search





No deviation from isotropy

Limit on flux from the GC at E > 1 EeV: f < 0.01 $\text{km}^{-2}\,\text{yr}^{-1}$ (f < 0.0062 $\text{km}^{-2}\,\text{yr}^{-1}$ from stacked search)

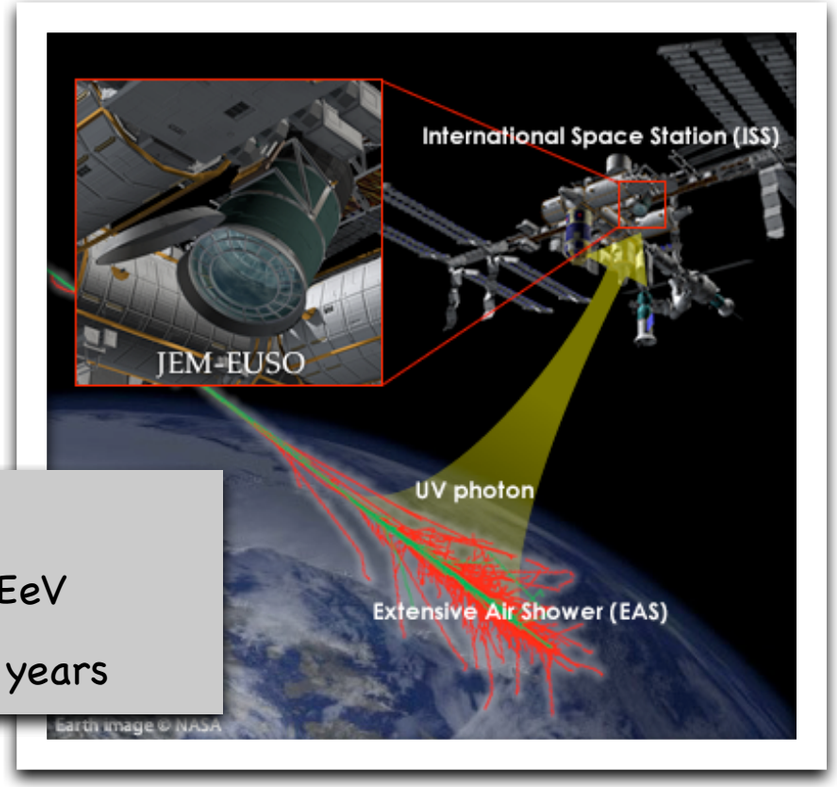
Prospects at UHE

O(10) increase in statistics needed for anisotropy progress between $10^{17.5}$ eV - $10^{20.5}$ eV

Lower energies:

G to XG transition (source models)/Compton-Getting amplitude

Auger upgrades (see talks Friday talks by Maris/Bohacova/Williams)



10 - 30 x Auger

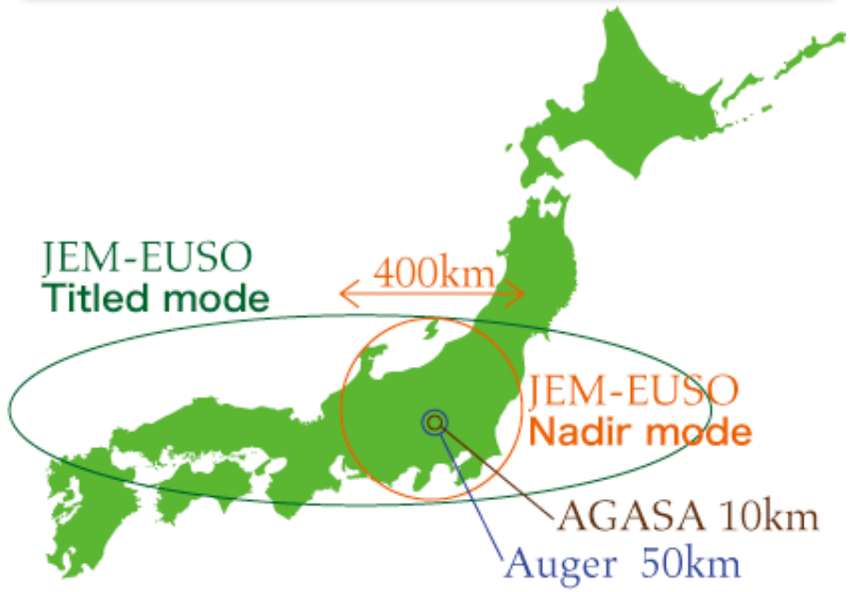
70 EeV < E < 1000 EeV

~ 1000 events/few years

Highest energies:

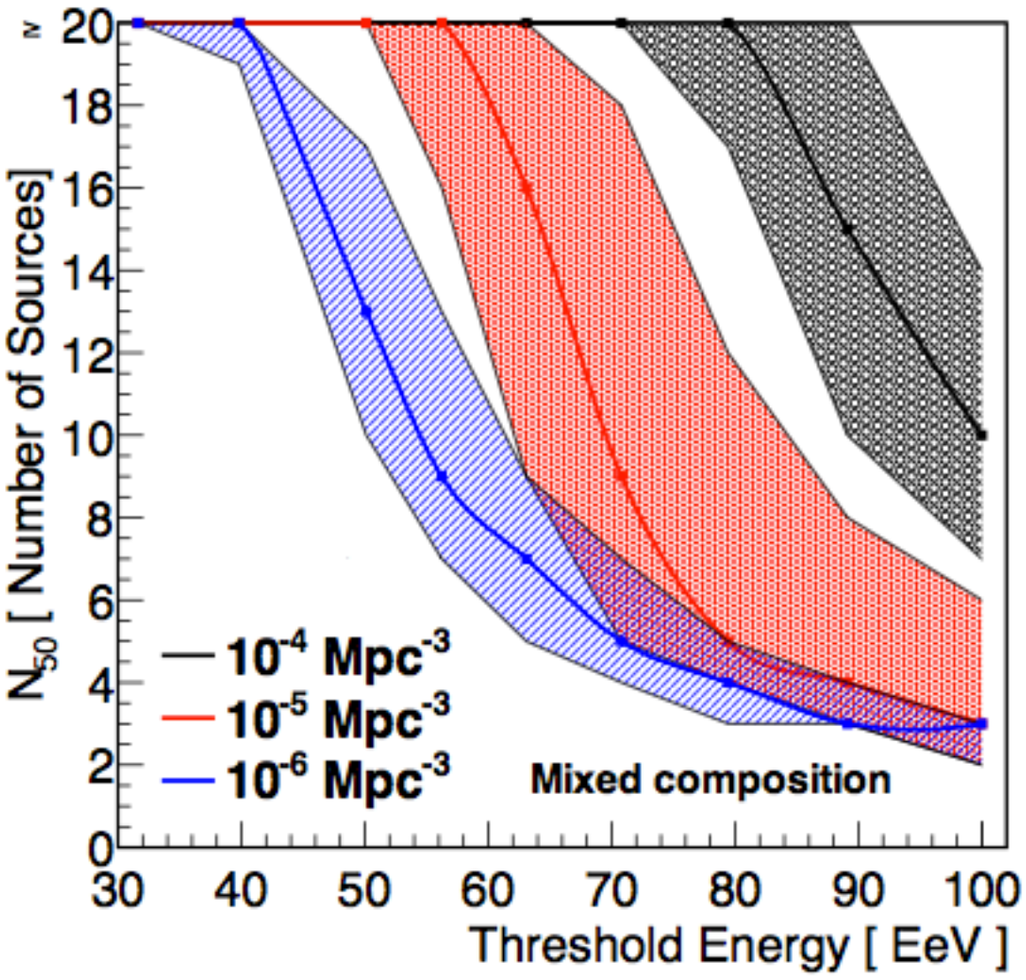
Point sources / small GZK horizon

How to increase statistics: Go to space! (see Friday talk by Guzman)



Prospects at UHE:

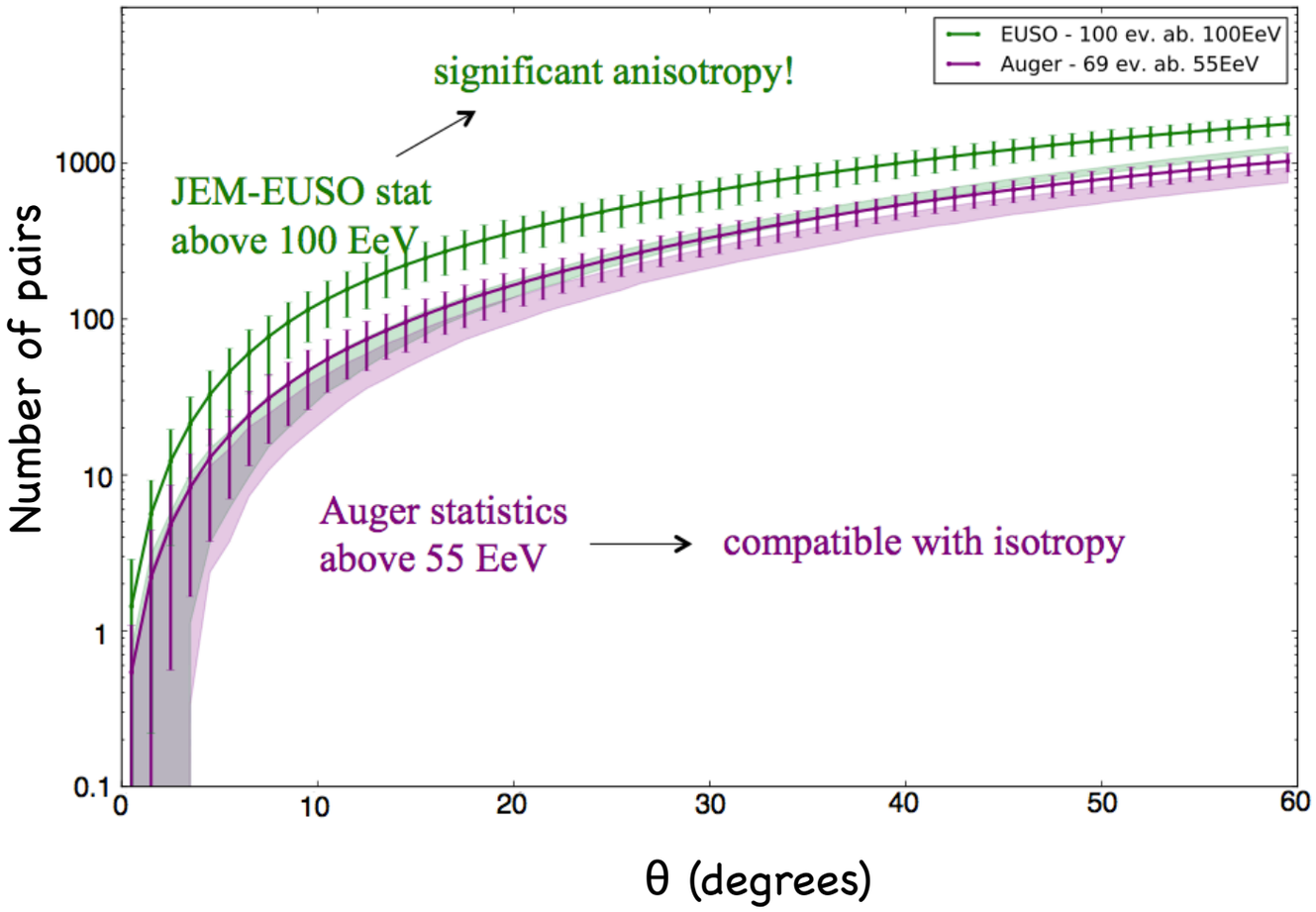
How will a JEM-EUSO type instrument help identify UHECR sources?



At E > 100 EeV horizon ~ 30 Mpc
Above 100 EeV 50% of UHECR flux comes from ≲ 10 sources (Blaksley+ 2013, see also Younk 2012)

With 100 events with E > 100 EeV even for the most unfavourable composition and source density significant anisotropy is expected (D'Orfeuil+ 2013)

E_{max}(proton) = 15 EeV (heavy-dominated) $n_0 = 10^{-5}$ Mpc^{-3}



Few years of JEM-EUSO would also probe the dependence of the UHECR energy spectrum on ensemble fluctuations due to cosmic variance (Ahlers+ 2012/2013).

Conclusions

No anisotropy detected with certainty but various hints exist

No small scale clustering (suggests relatively large source density)

Expectations crucially depend on composition

O(10) increase in statistics needed for definitive progress in anisotropy at highest energies ⇒ Space based fluorescence (eg. JEM-EUSO).

Earth based instruments needed for observation of Galactic-Extragalactic transition ⇒ Auger extensions/ super-ground array?