UHECR autocorrelation function after Auger

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based on work in collaboration with
A. Cuoco, S. Hannestad, T. Haugbølle, M. Kachelrieß
(arXiv:0709.2712; arXiv:0809.4003)

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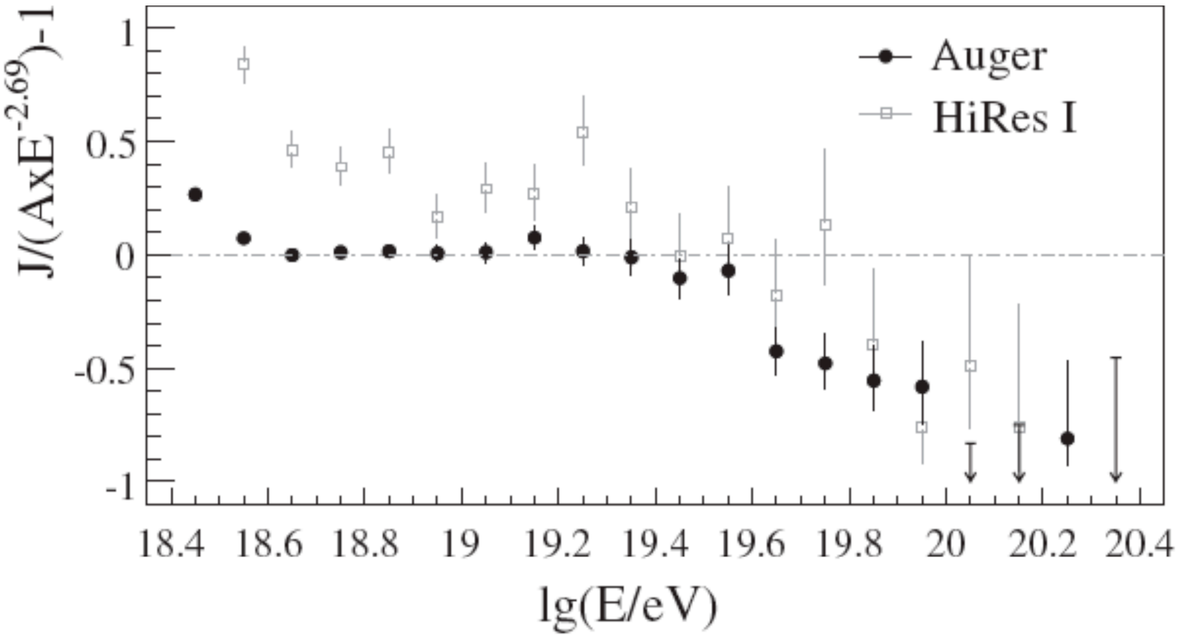
Outline

- Consensus & Open issues in UHECRs
- Towards source identification: UHECR astronomy ?
- The role of autocorrelation studies
- Issues & preliminary result, based on the first release of data by PAO
- Conclusions

Consensus: astrophysical origin of most UHECRs

- Both HiRes & PAO see GZK-like spectral features

HiRes, PRL 100, 101101(2008)
Auger, PRL 101, 061101(2008)



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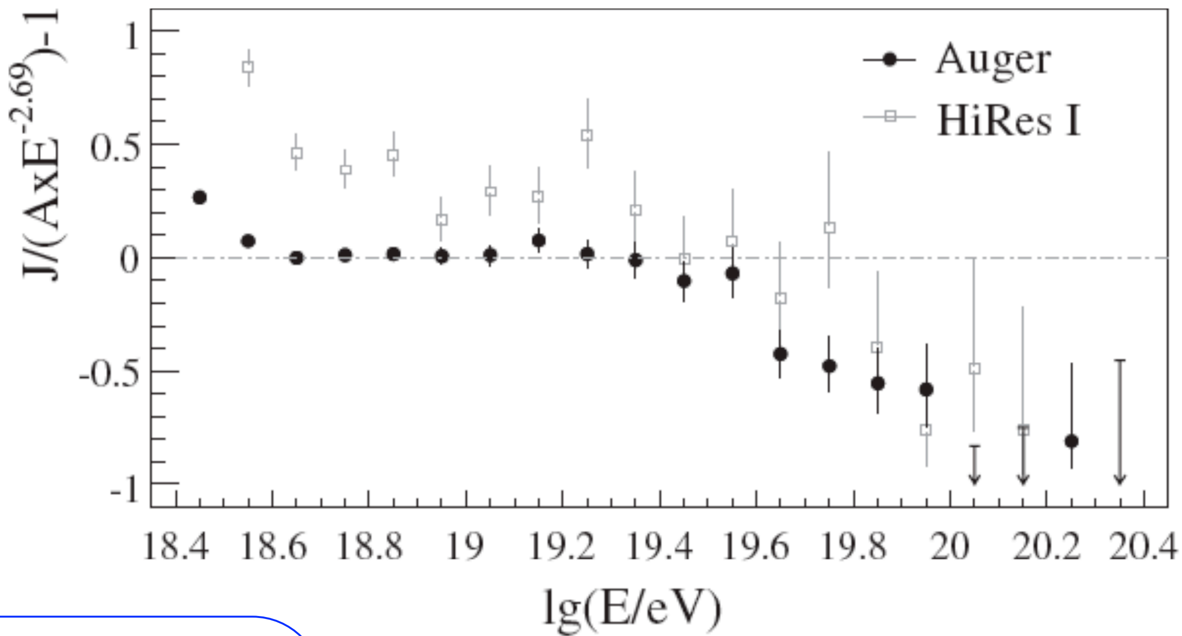


Other channels make the picture more robust

- Bound on photon fraction

  Astrop.Phys. 29, 243 (2008)
- Bound on neutrino fraction

  PRL 100 211101(2008)
- Bound on Galactic Center anisotropy

  Astrop.Phys. 27, 244 (2007)

✓ No *need* for exotica at UHE

✓ Most "new physics" models invoked to explain AGASA "excess" ruled out.

New PAO results in the same direction
arxiv:0906.2347, arxiv:0906.2354

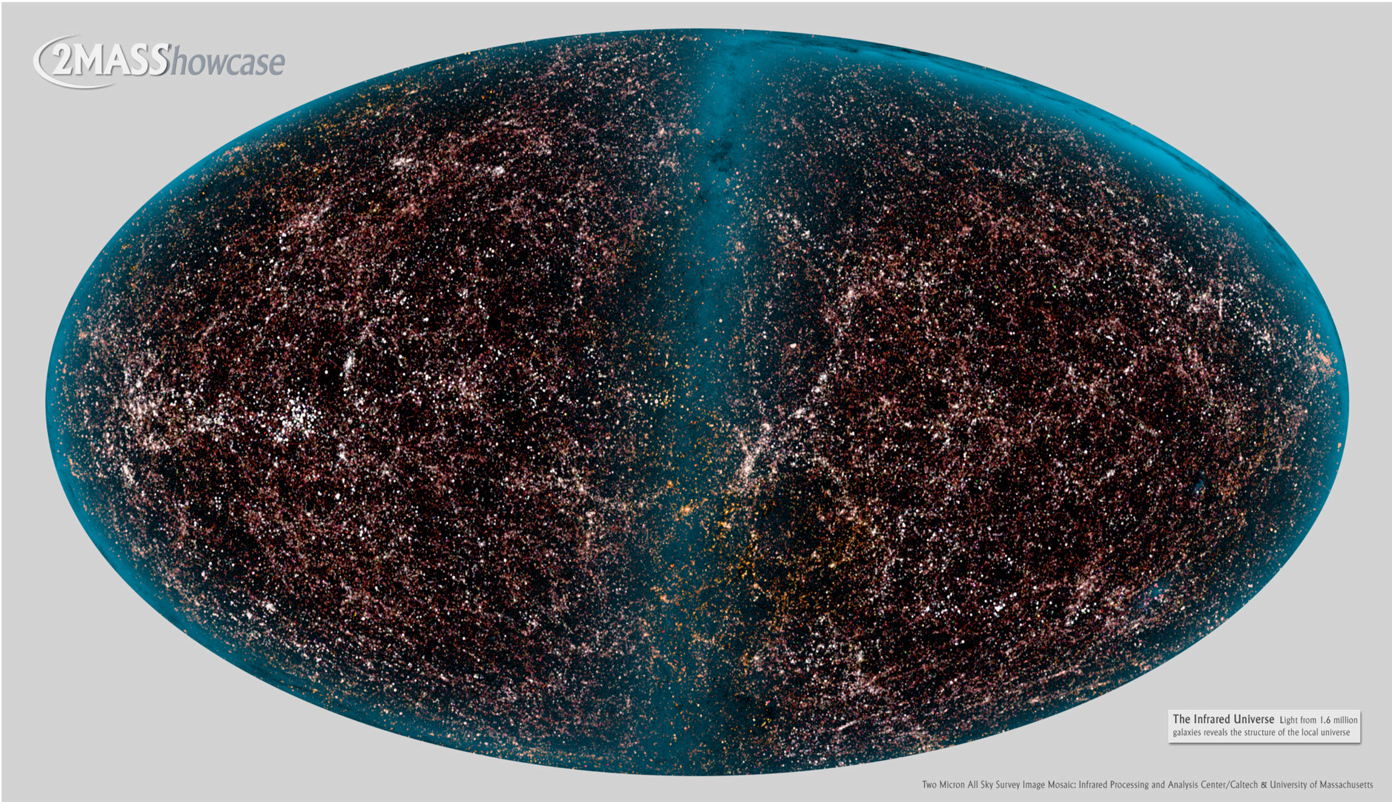
Toward source identification: UHECR Astronomy?

At UHE, CR astronomy may be possible!

✓ deflections in magnetic fields might be relatively small (in the GMF, few degrees at GZK energies for protons)

✓ Attenuation length sharply decreases: close sources should dominate the flux

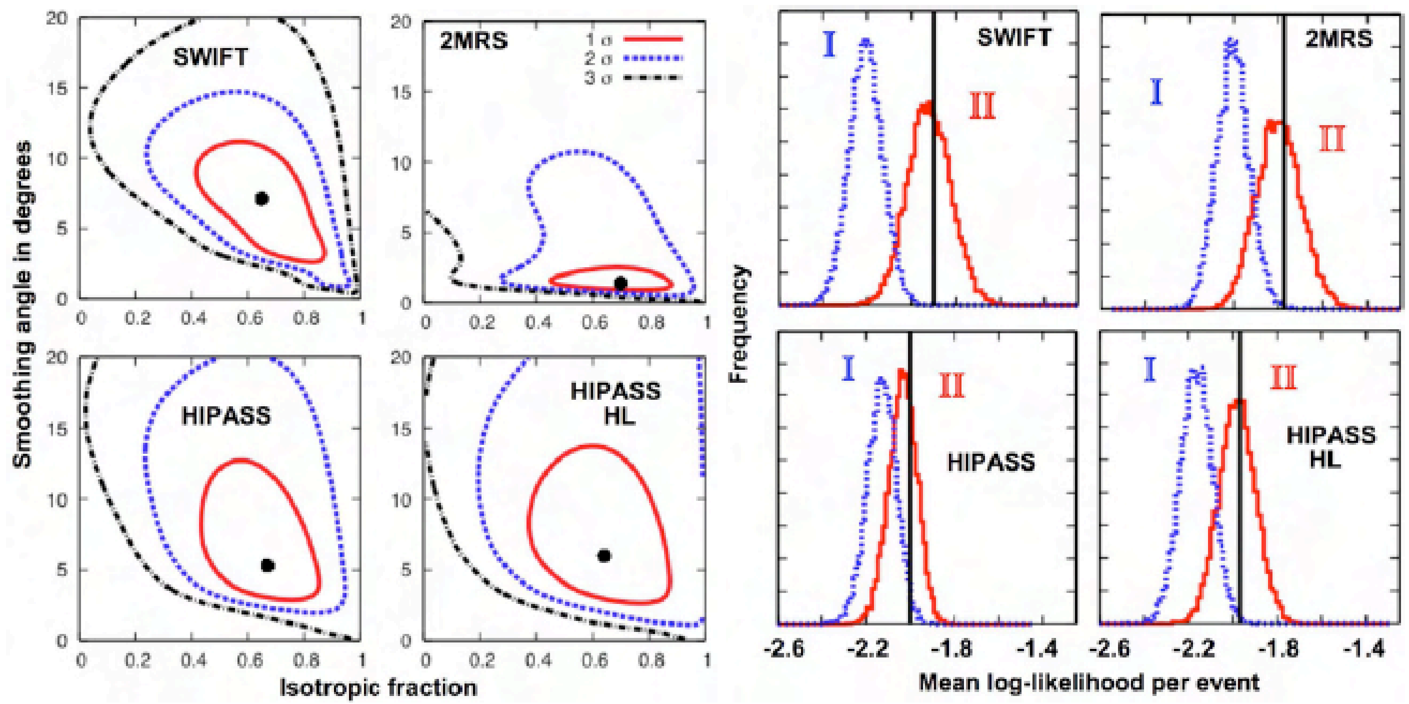
✓ Within ≈ O(100) Mpc, the Universe is not isotropic



Open Issues: tension btw composition & anisotropy?

- Composition studies suggest a transition to heavier species in the "GZK-range" (with known caveats due to model-dependence, different E-ranges…)

- X-correlation studies indicate that UHECRs partially correlate with the distribution of local matter, with "deflections" ≤ O(10°) for the correlating part *(arxiv:0906.2347)*



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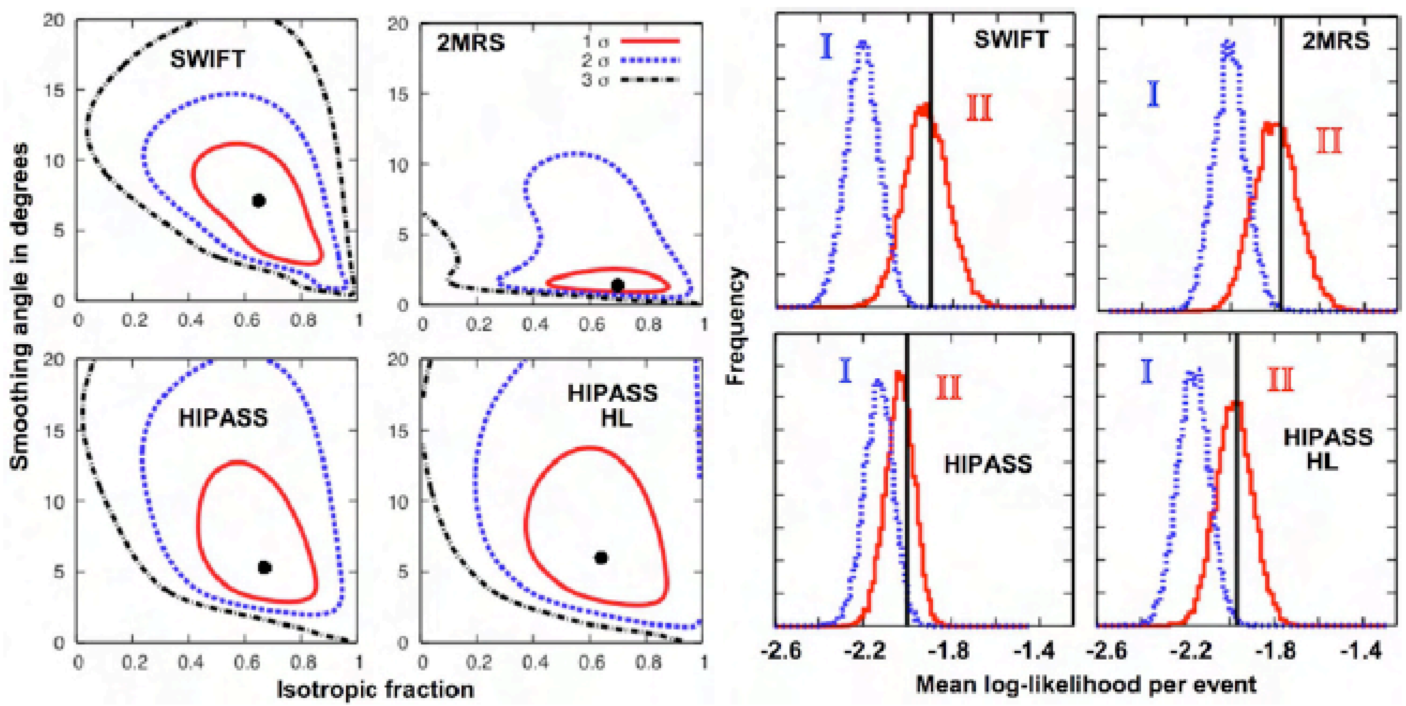
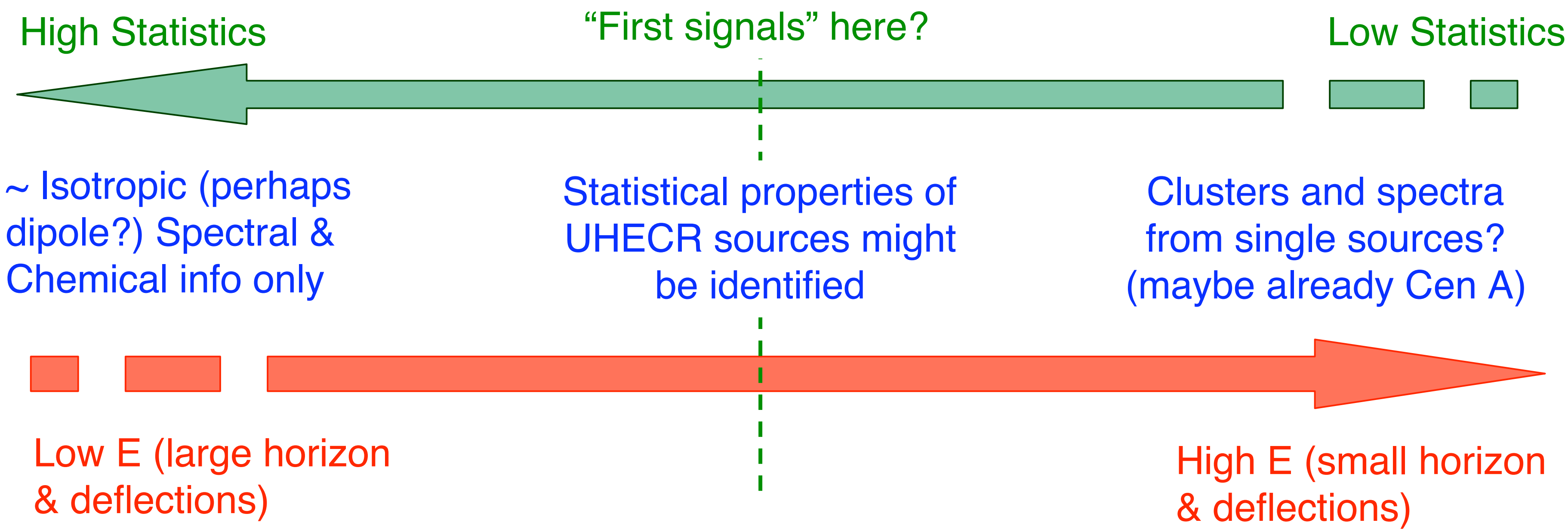


Possible puzzle:
A "Fe-dominated" flux would suffer larger deflections in typical GMF models alone (not to speak of role of EGMF)!

Why autocorrelations?



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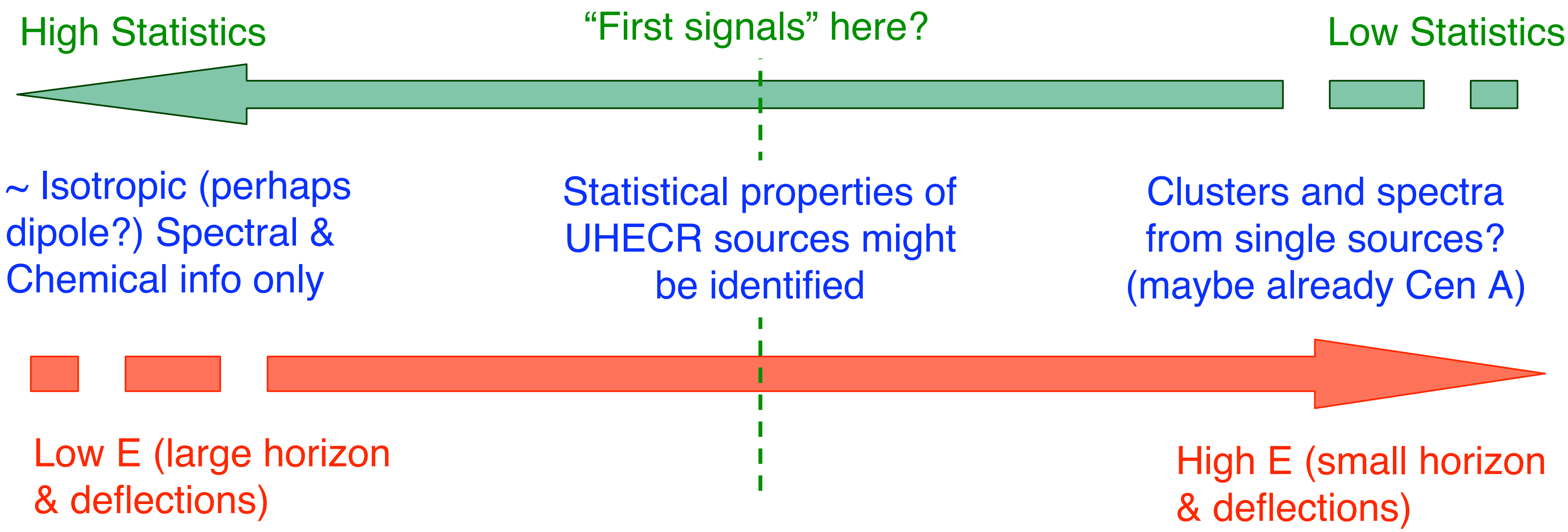


✓ **More robust than cross-correlation**: only relative deflection matters.

✓ **More robust wrt catalogue incompleteness**: if selection function is known, irrelevant to miss "single" sources, enough for a survey to catch the "statistical properties"

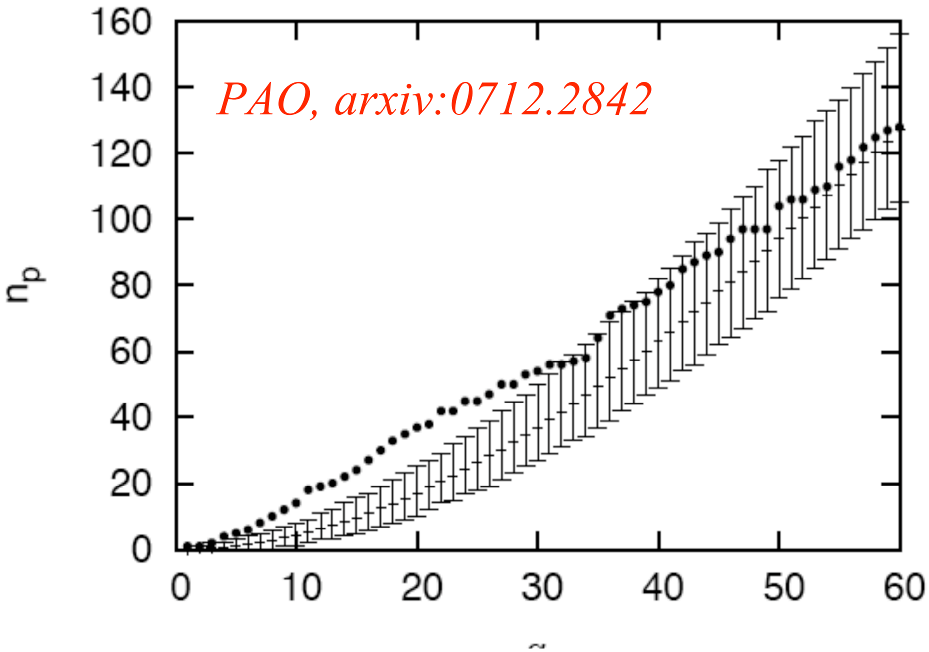
✓ **Larger scales are more robust**: due to geometric effects, the "completeness distance" of a catalogue for large angular scales is smaller. the catalogues available are "more complete" for medium-large scales (which are thus important to include in the analysis)

Why autocorrelations? (cont'd)

✓ **Model- & catalogue- independent test of isotropy possible**

✓ **Extra information wrt x-correlation**: in principle, x-correlation of PAO data with AGN possible also with a subsample of the catalogue consistent with isotropy

✓ **Consistency Check**
a source distribution explain x-correlation should also match autocorrelation data (vice versa not necessarily true)



Of course, there are still issues linked to:

➢ The limitations of the UHECR data

➢ Catalogue-related problems

(Some) Problems to address

- Catalogue (in)completeness
- Identification of (unknown) biases, luminosity function, etc.
- Limited UHECR Statistics (Poisson noise)
- Systematic Error on Energy
- Statistical Error on Energy
- Chemical composition
- …

Some of these issues are linked to each other

For UHECR data, further issues…

- With O(100) data or less 2-points correlation function dominated by statistical noise unless one uses the cumulative function

- Magnetic fields are not harmless: they may still destroy cross-correlation between catalogues and data and alter the 2pcf especially at small scales

- The most robust and useful information comes from the cumulative 2pcf $C(\theta)$, i.e. number of pairs within a given angle θ

$$C(\vartheta) \equiv \sum_{i=2}^{N} \sum_{j=1}^{i-1} \Theta(\vartheta - \vartheta_{ij})$$

We compared the function thus calculated for the distribution of AGNs (and subclasses), ordinary galaxies, etc.

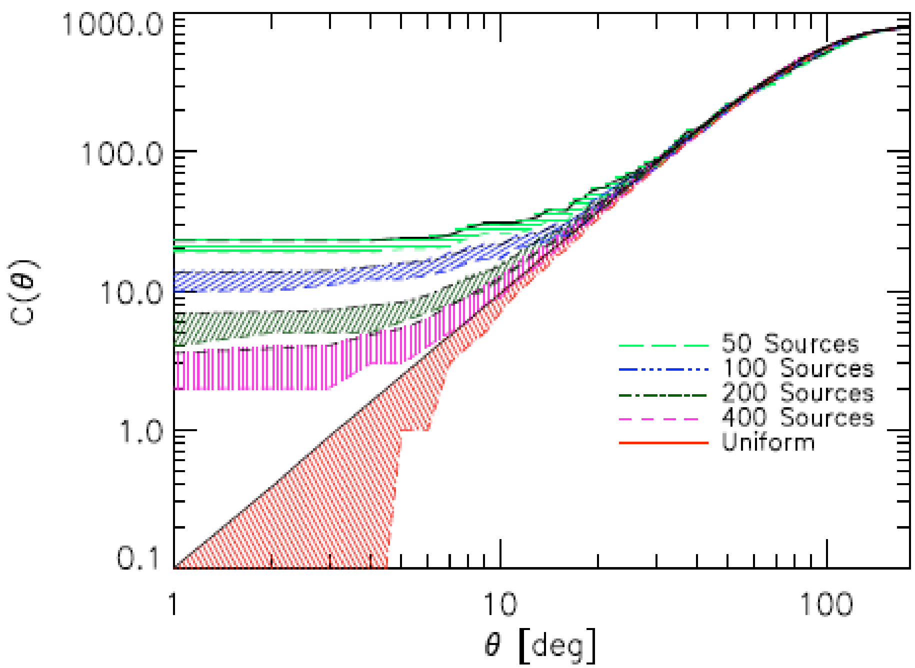
Cuoco, Hannestad, Haugbølle, Kachelrieß, PS,
ApJ 676, 807 (2008) [arXiv.0709.2712]

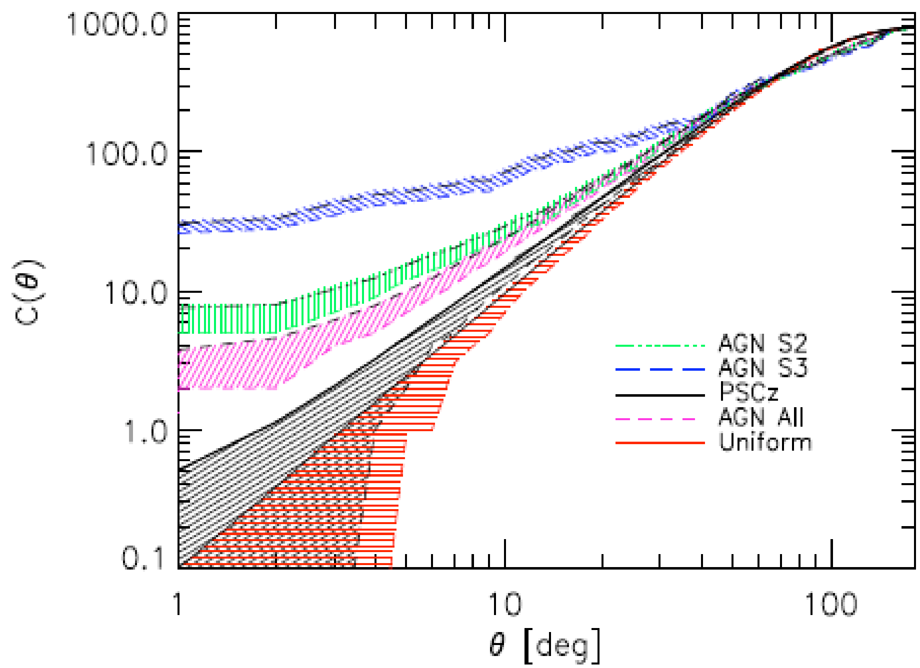
(at the time of publication, PAO data not publicly available)

Ideal case (no catalogue systematics): Poisson error

- A sufficiently large statistics is required to start discriminating among sources with densities differing by a factor of a few.

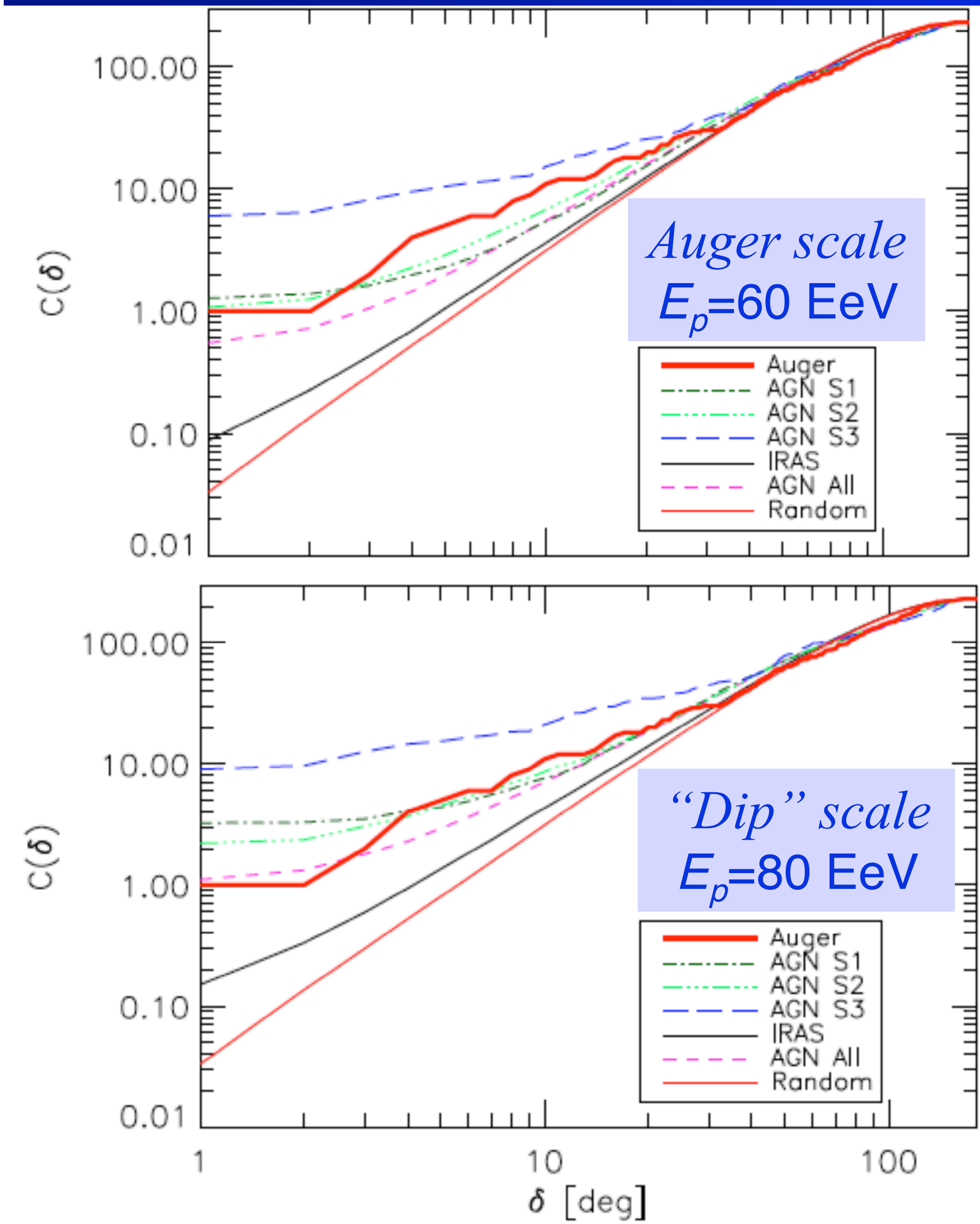
- Comparing clustering at different scales might discriminate among different classes of sources with similar densities, but this is even more challenging





N=40

Effect of UHECR systematics: Energy Uncertainty



N=27 (22)
(-5 falling in the Galactic Mask)

✓ The difference in predictions based on systematic differences in E-scale is larger than differences between different astrophysical models!!!

➢ The statistical uncertainty in the Energy (~20%) and the stochastic nature of E-losses are important as well in “smearing” the horizon size in the GZK range, adding “confusion” in diagnostics

Can we extract any information from present data?

Previous considerations suggest that discrimination between astrophysical models based on angular distribution alone is premature. As a first step, we narrow our study to the extraction of the main parameter, n_s (arXiv:0809.4003)

To estimate the sensitivity to the distribution of sources, we compare a Uniform model with a LSS-tracing one (based on the PSCz catalogue)

To have an idea of the systematics, we compare the results obtained with the two previously mentioned energy scales.

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Further limitations:

- Ansatz of pure proton composition
- Forced to take the data after Auger E-cut
- …

Application: Estimate of source density

NOTE: To estimate n_s, usual analyses limited to the "first-bin" only.
But choice of the first bin size is model-dependent!!!
(e.g. angular resolution, hint from x-correl., estimate of magnetic deflections…)

A **global** analysis is more justified (and more robust): the distribution of events should fit also at large scales!

$$P_{\pm}(\vartheta \mid X) \equiv \frac{1}{M}\sum_{i=1}^{M}\Theta[\pm\{C(\vartheta \mid X) - C_{*}(\vartheta)\}]$$

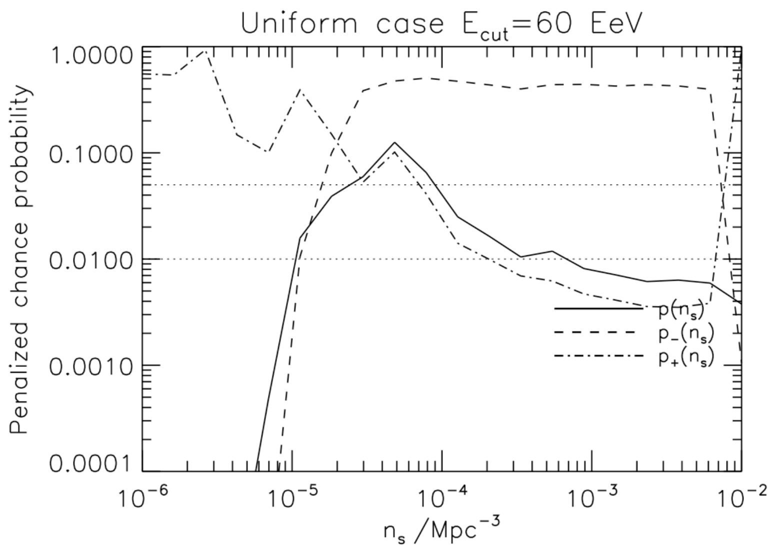
X= {$n_{s,}$ $E_{cut,}$ LSS vs. Uniform}
"model parameters"

$$P_{\pm}(X) = \min_{\vartheta\in[0,\pi]}\{P_{\pm}(\vartheta \mid X)\}, \qquad P(X) \equiv P_{+}(X)P_{-}(X)$$

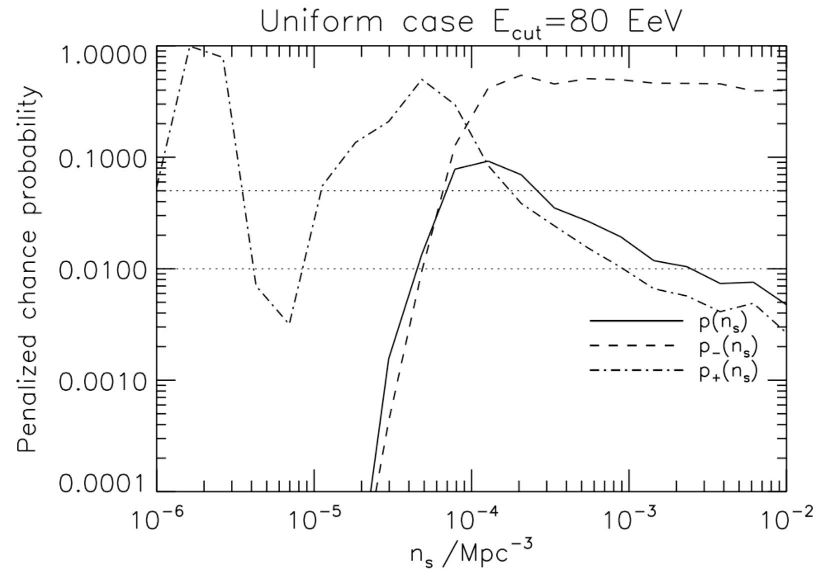
The procedure is repeated for mock data sets, and the (penalty corrected) probabilities $p_{+}(X)$, $p_{-}(X)$, $p(X)$ are obtained

Estimate of source density: Uniform case

E_{cut}=60 EeV - Uniform



E_{cut}=80 EeV - Uniform

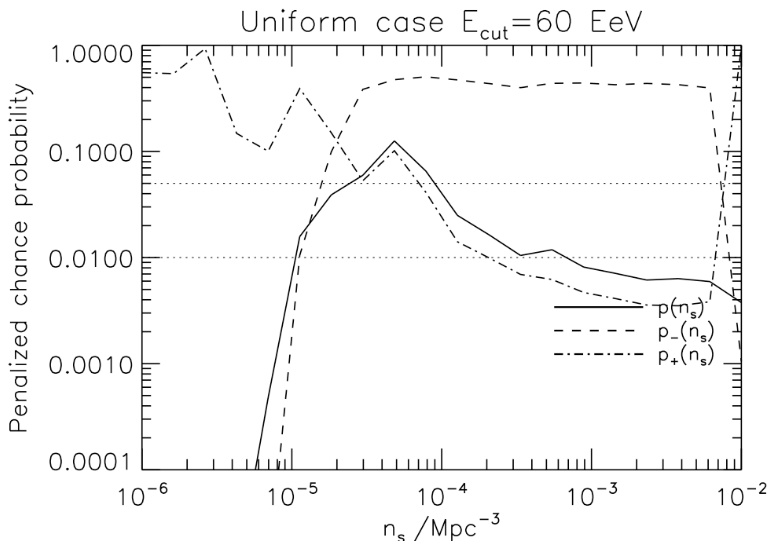


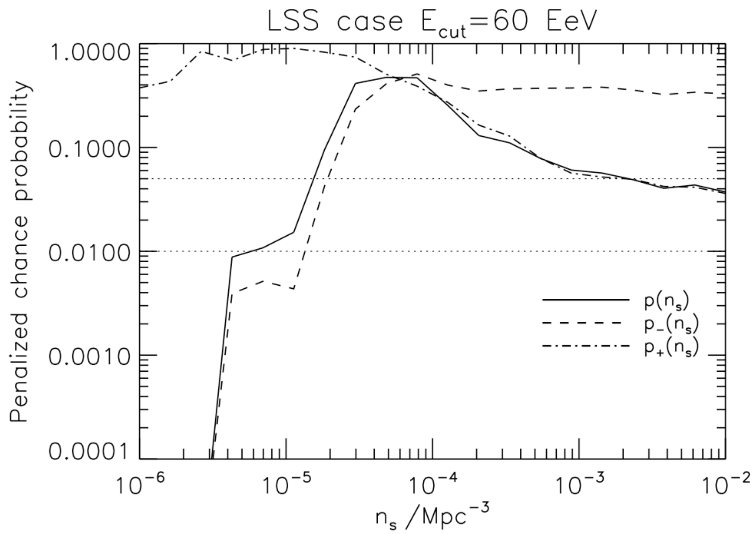
At better than 99% C.L, the Auger data exclude a structureless sky.
The result is independent from a given angular scale and the use of a catalogue.

(This remains true at~98%C.L. if we scan over E-cut > 57 EeV)

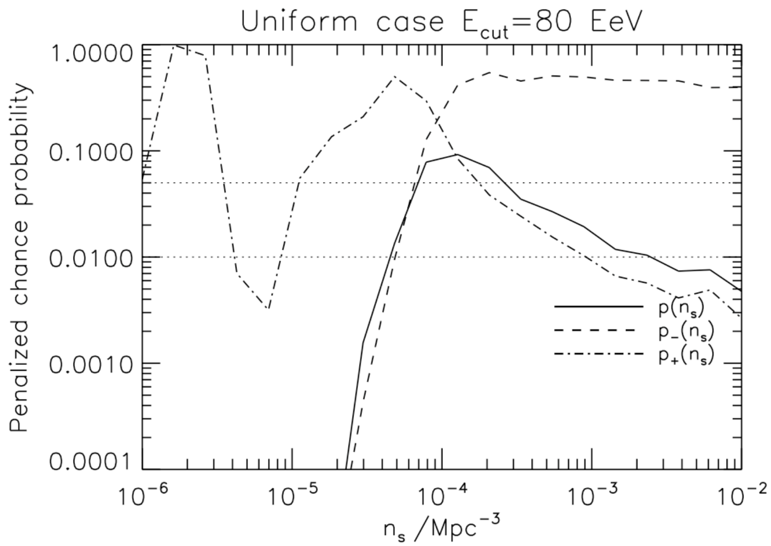
For proton primaries, in this case one can derive an upper bound $n_s < 10^{-3}$ Mpc^{-3}

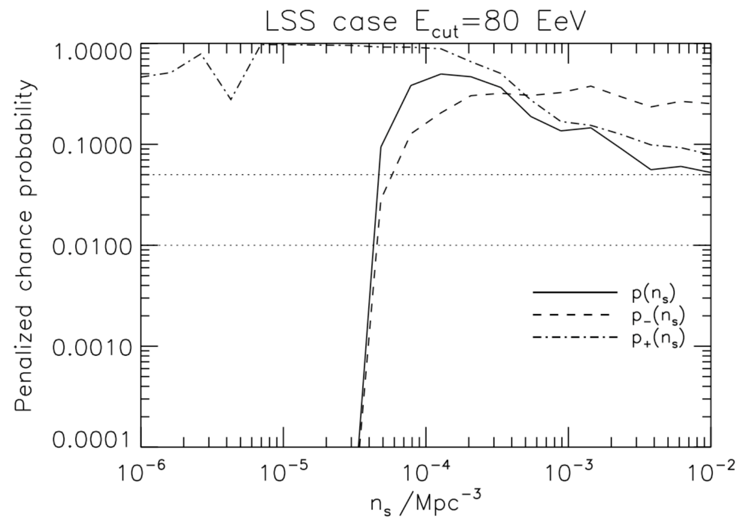
Estimate of source density: Uniform vs. LSS





LSS-like distribution preferred (but evidence is not conclusive)





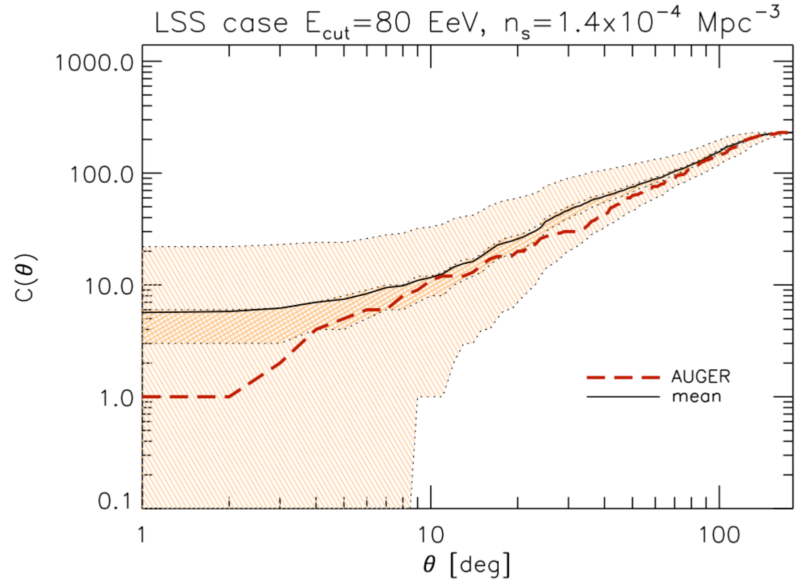
Some comments

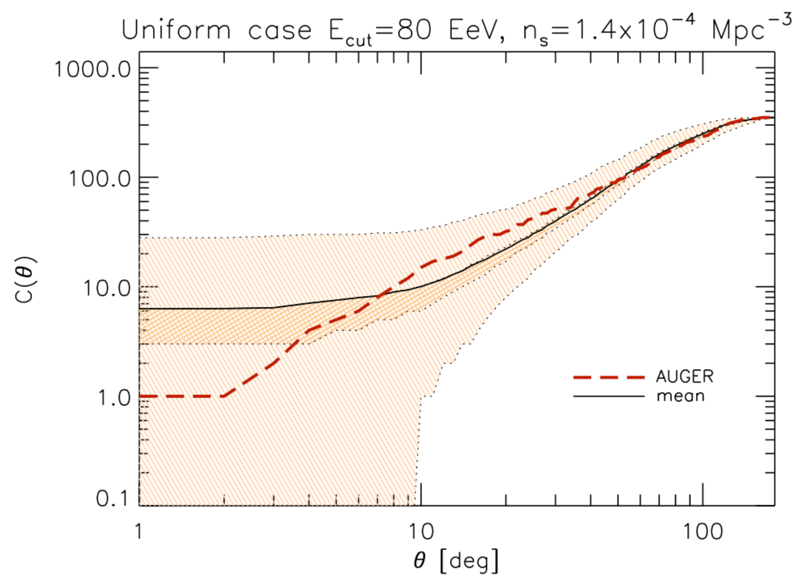
✓ Essentially,LSS fits better because can more easily accommodate the small-scale features with the large scale ones.

✓ Shape of $p(n_s)$ agrees with older analyses of AGASA, but not the best-fit value;
Peak at larger n_s due to the absence of prominent small scale clustering: Hint of magnetic smearing? Consistent with x-correlation!

✓ Energy-cut Scan would not change qualitatively the conclusions

✓ Many effects may move the “true” density of sources below the value inferred in this example: from energy resolution to bursting/transients…





Effects of a-priori choice of bin-size

	6^o	$3\sqrt{2}^o$	3^o	global
LSS (80)	$1.3^{+5.7}_{-1.0}$	$2.0^{+8.0}_{-1.6}$	$2.0^{+\infty}_{-1.4}$	$1.3^{+100}_{-0.8}$
Uni (80)	$0.8^{+0.8}_{-0.5}$	$1.2^{+0.8}_{-0.8}$	$2.5^{+\infty}_{-1.8}$	$1.4^{+1.4}_{-0.7}$
LSS (60)	$0.3^{+1.7}_{-0.2}$	$0.3^{+1.7}_{-0.2}$	$0.7^{+100}_{-0.5}$	$0.8^{+19}_{-0.6}$
Uni (60)	$0.2^{+1.0}_{-0.1}$	$0.3^{+1.7}_{-0.2}$	$0.8^{+70}_{-0.6}$	$0.5^{+0.5}_{-0.2}$

Best fit and 95% C.L. allowed range of n_s in 10^{-4} Mpc^{-3}

- ✓ single bin analysis may lead to “biased result”: the interpretation of “small scale clustering” might be misleading if not defined wrt a proper model of source distribution! (already mentioned in Harari et al. astro-ph/0404304)

- ✓ Already systematic uncertainty on E_{cut} has a major role in the uncertainty on n_s

Effects of smearing (due to magnetic fields)

30°	10°	3°	global	
$0.5^{+\infty}_{-0.4}$	$0.5^{+30}_{-0.4}$	$1.0^{+100}_{-0.8}$	$1.3^{+100}_{-0.8}$	LSS (80)
$0.3^{+\infty}_{-0.2}$	$0.3^{+1.7}_{-0.2}$	$0.8^{+1.5}_{-0.6}$	$1.4^{+1.4}_{-0.7}$	Uni (80)
n.c.	$0.1^{+5}_{-0.09}$	$0.3^{+20}_{-0.28}$	$0.8^{+19}_{-0.6}$	LSS (60)
n.c.	$0.1^{+0.9}_{-0.09}$	$0.2^{+0.8}_{-0.1}$	$0.5^{+0.5}_{-0.2}$	Uni (60)

- Estimates are robust if relative deflections within ~3°, i.e. within the same scales suggested by x-correlations (no evidence for very small scale clustering, consistent with a magnetic smearing picture)

- Still some constraints can be obtained if small scale info is retained above a smearing of ~10°

- Larger relative deflections imply probably that source identification is not viable, not even at a statistical level.

Disclaimer

I am aware that the above analysis assumes many simplifications. The true picture might well be the following:

- The composition is mixed: 4 populations of objects contribute to UHECRs, 3 of which are overabundant in the Northern emisphere (all with different luminosity functions).
- Galactic Magnetic fields are more relevant in the Southern emisphere (Galactic Center), EGMF mostly in the norther emisphere (Virgo, etc.).
- The two above effects produce differences in the sky of the 2 Emispheres.
- Each population has different Z-ratios at the source and has different bias wrt LSS.
- By chance, the two main populations (one steady state & one bursting) run out of steam for protons right in the GZK range.
- The correlating signal is due to the fraction of source p coming to us. A quasi-isotropic background is due to “far” nuclei which have been almost isotropized in B-fields.
- For a few exceptional nearby sources (Cen A, + the only UHECR-bright Watson 2015A and Cronin 2016C) we also detect a “halo” of nuclei at moderate deflection angles.
- New hadronic physics “just beyond” the reach of LHC kicks in, explaining the remaining discrepancy in chemical composition data.

I took here the theorist’s point of view: assuming that the UHECR phenomenon is simple enough to be described at leading order with a few parameters, what can we learn? What are the main variables/factors to worry about in the extraction of a main parameter?

Summary

➢ Extragalactic astrophysical sources are likely responsible for (the bulk of) UHECRs. If protons dominate, relatively small magnetic deflections are expected, and an extragalactic contribution from a "small" horizon around us. These conditions conspire to make UHECR astronomy viable

➢ Present data suggest that UHECR astronomy is born, although is still at a very immature stage. Errors on Energy & chemical composition are essential!

➢ Autocorrelation studies (eventually comparing data with expected properties from different astrophysical candidates) provide a complement to cross-correlation studies towards a first identification, in a statistical sense, of what are UHECR sources. Preliminary results are consistent with hints from x-correlation (with caveats).

➢ With more statistics (also in Northern Emisphere?) & a multiwavelength approach (γ and ν data) one may try to disentangle the "few sources'' hypothesis (with heavy composition) vs the LSS one (analysis in different energy bins, multiplets within the EAS detector angular resolution, searching for chemical differences btw correlating and non-correlating events, etc.)