High Energy Messenger Workshop KICP, June 10 2014

Foteini Oikonomou

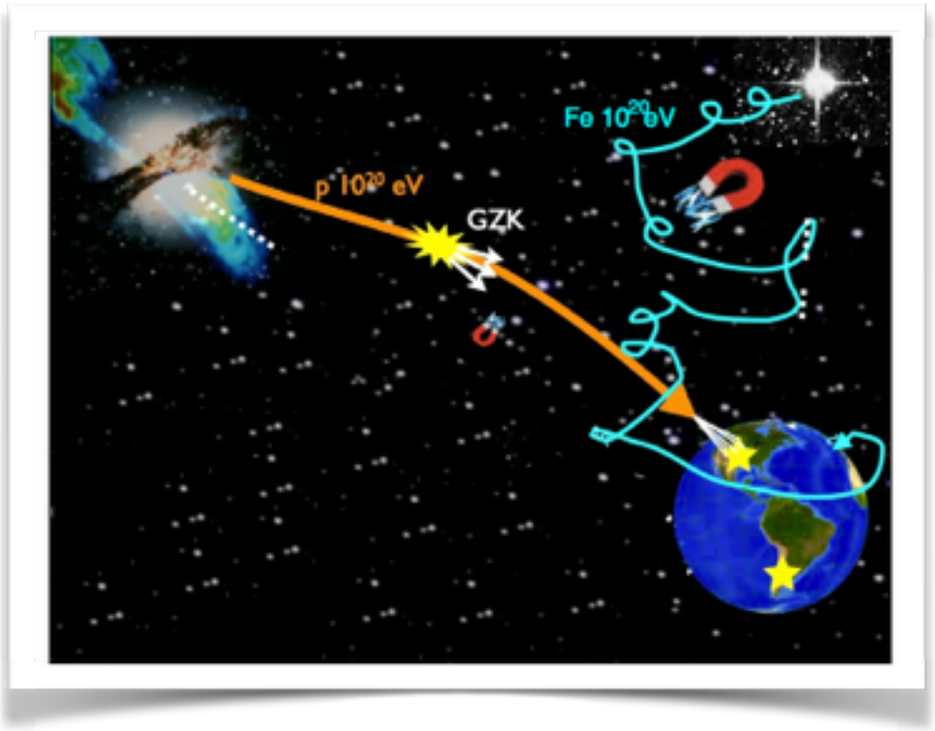
Anisotropies in the arrival directions of Ultra-High Energy Cosmic Rays: Current status and prospects with a next-generation instrument

PIERRE AUGER OBSERVATORY

PENNSTATE Eberly College of Science

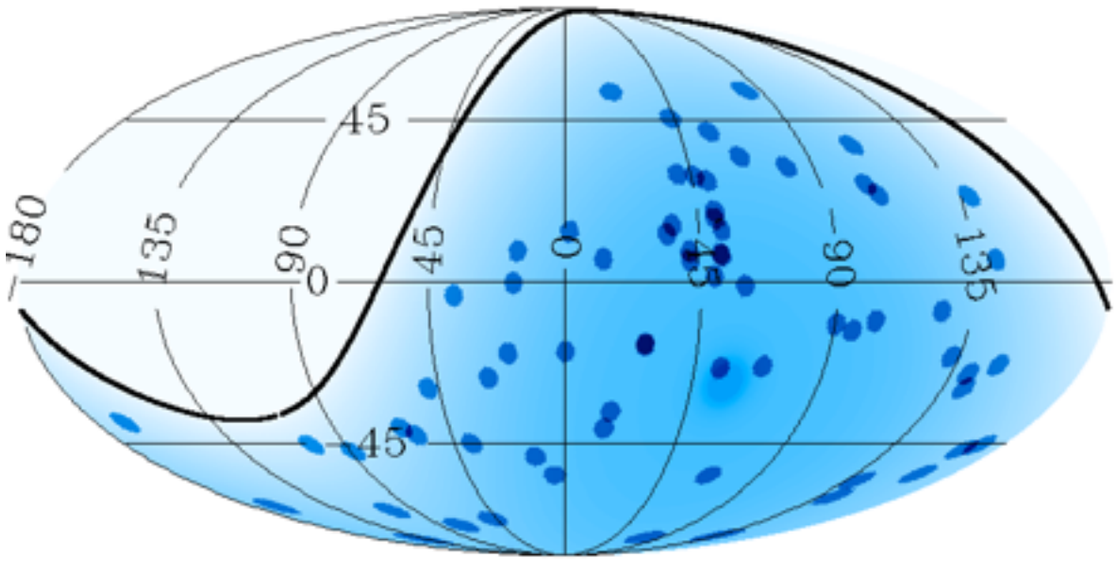
Introduction

- 50 EeV protons:
  - GZK Horizon ~ few hundred Mpc
  - Deflections ≲3° in IGMF
    - In the Galactic B-field $\theta \sim 2^\circ - 4^\circ$
    - Larger through Galactic centre
- Iron much larger deflections, $\theta \sim Z \times \theta_{proton}$
- Anisotropy expected for proton UHECRs
- Uncertain composition complicates expectations -> one way to model it, introduce an isotropic background (large deflections)



Arrival directions of UHECRs observed by Auger

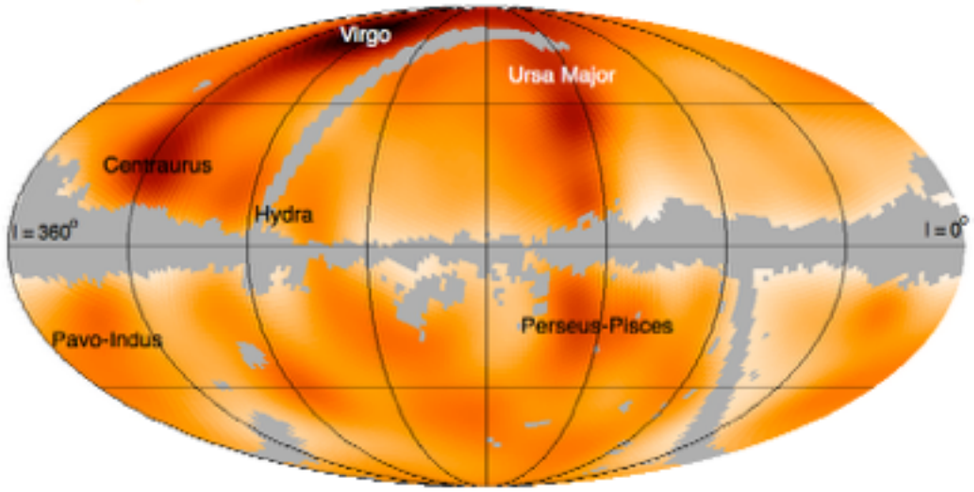
UHECRs with E > 55 EeV detected until end 2009



Calculations take into account:

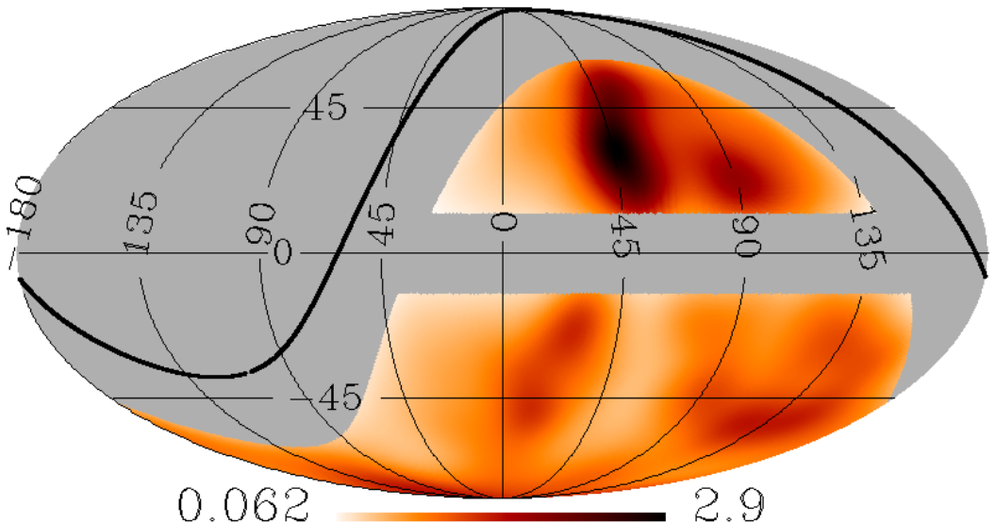
- proton energy losses
- galaxy weights as a function of redshift
- Auger exposure
- galaxy survey selection functions

Protons E > 55 EeV, PSCz



IRAS PSCz ~full sky ~ **10000 galaxies**, ~far-IR selected: excellent probe of star-formation activity

Protons E > 55 EeV, 6dF



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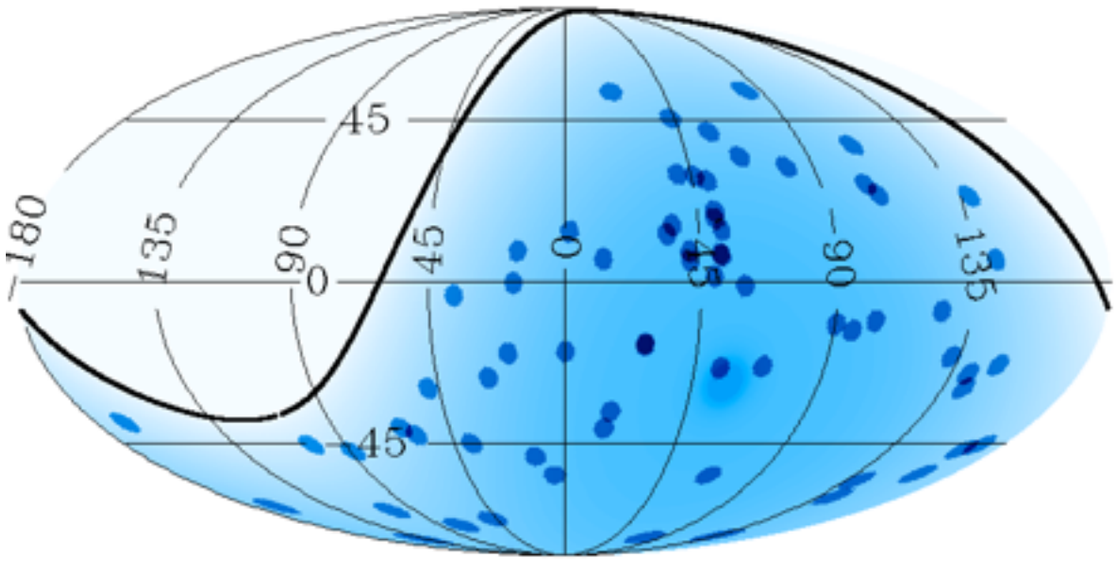

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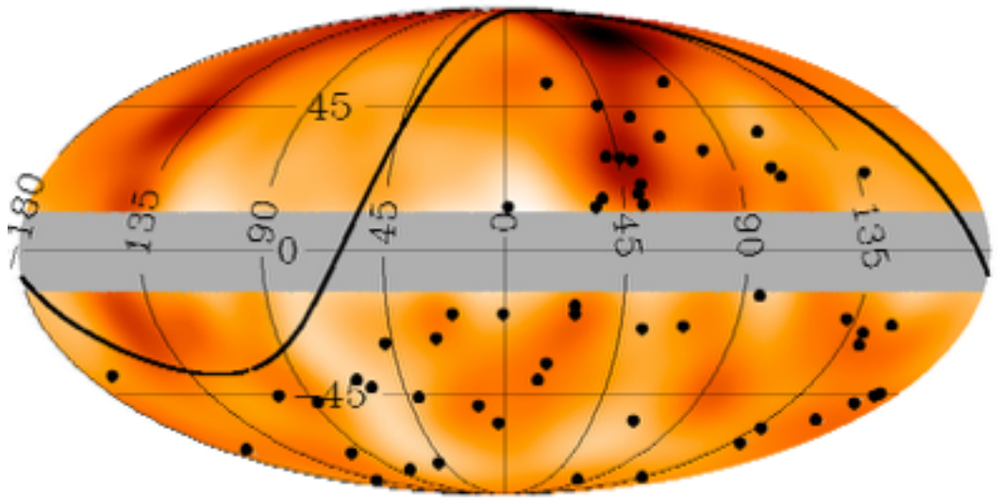

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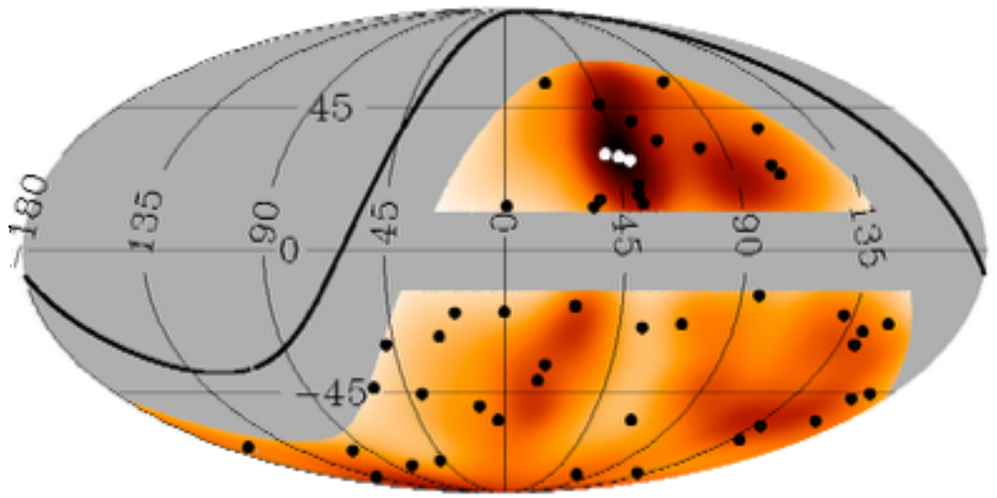

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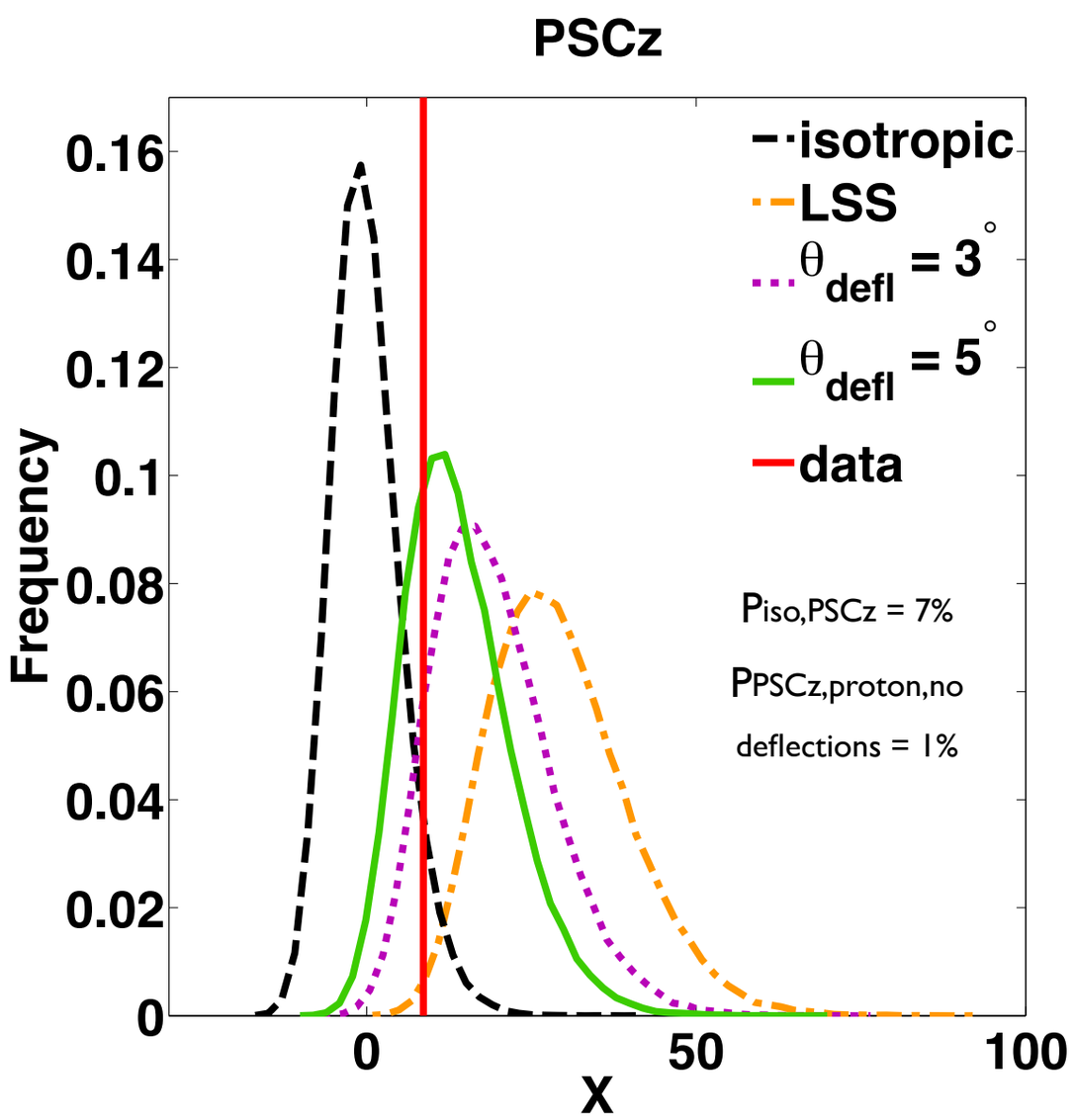
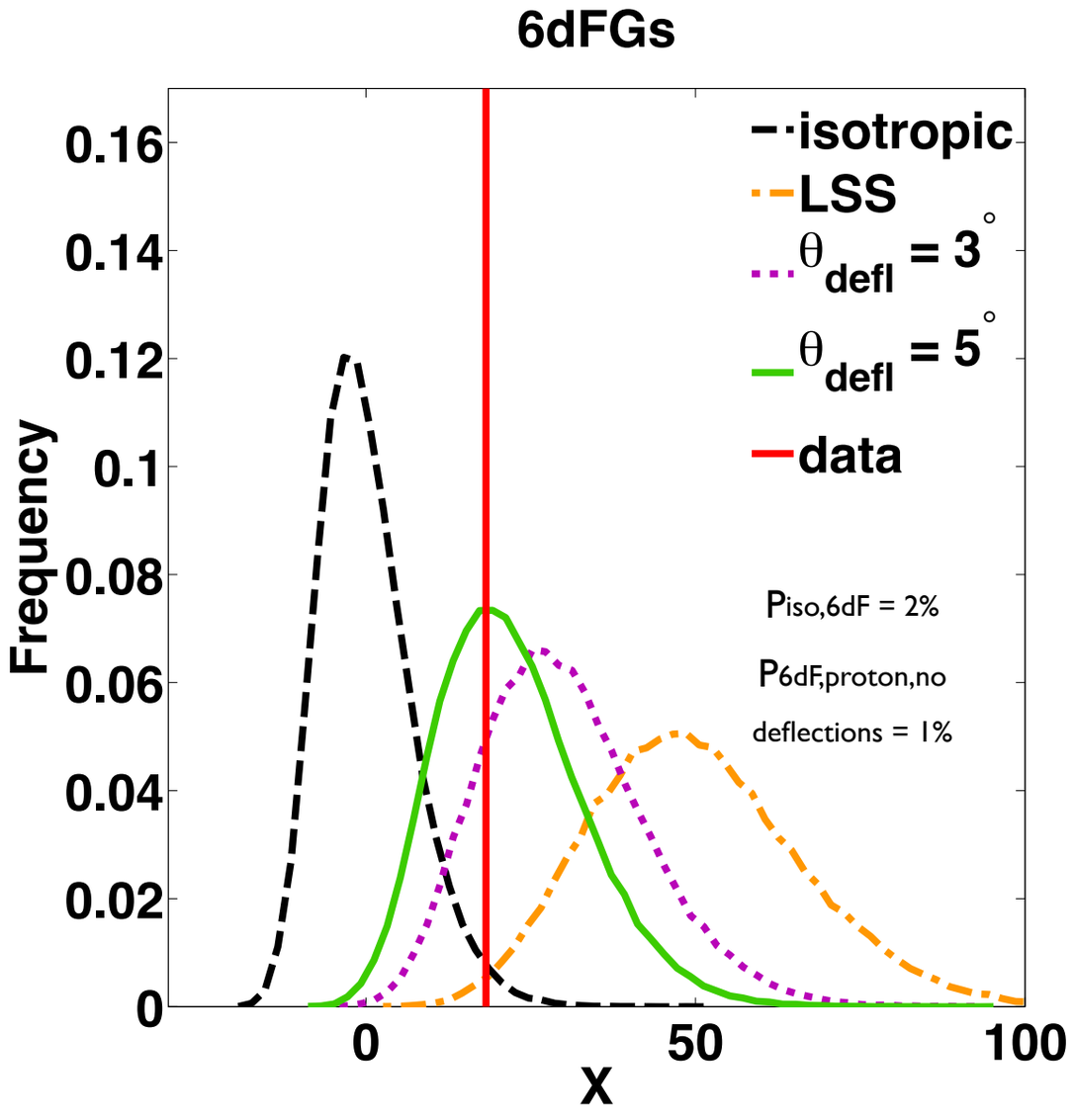
FO et al 2013: JCAP05(2013)015

Correlation with Large Scale Structure:

2009 dataset: 69 events E > 55 EeV





~ 10% uncertainty due to binning.

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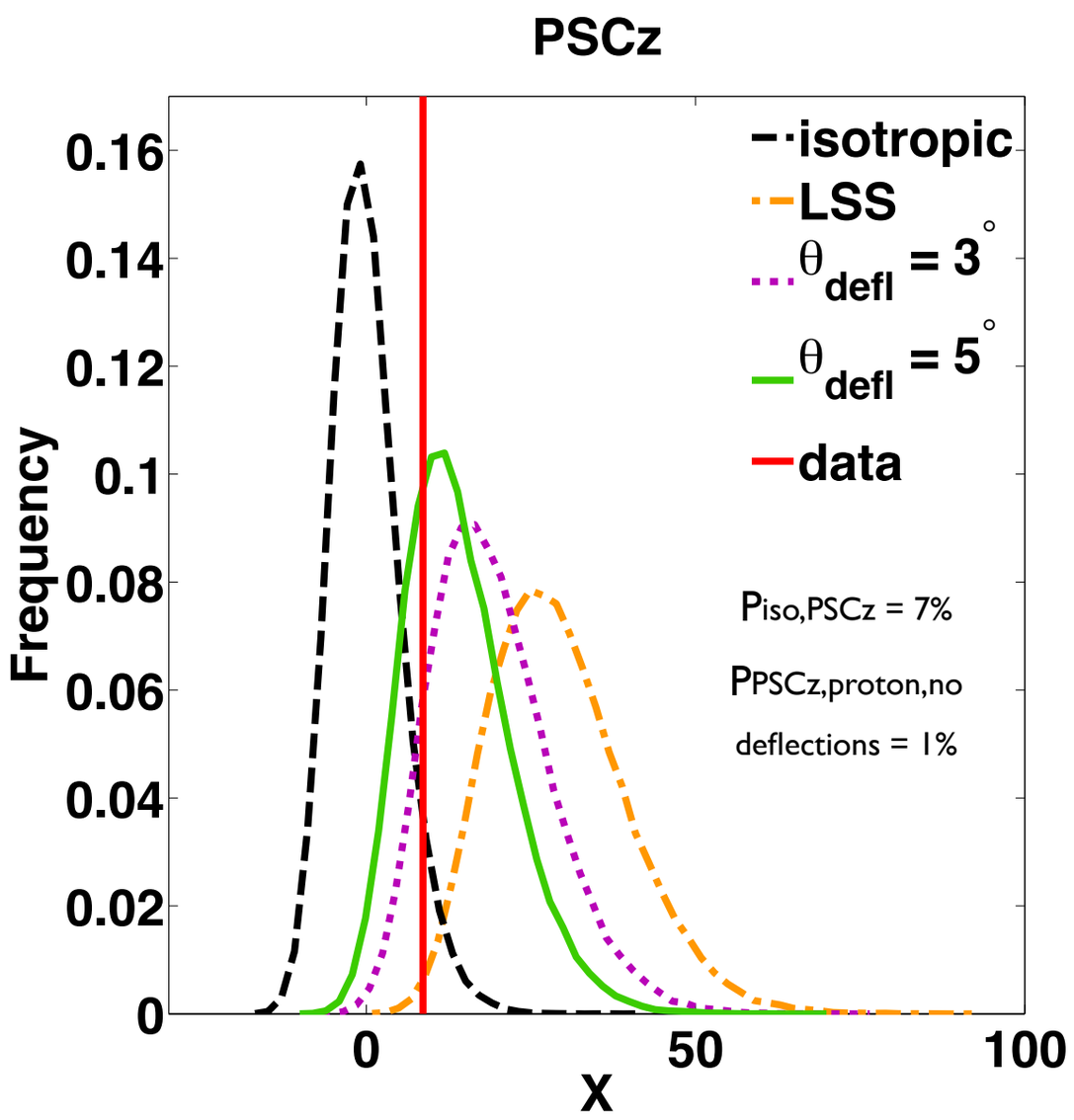
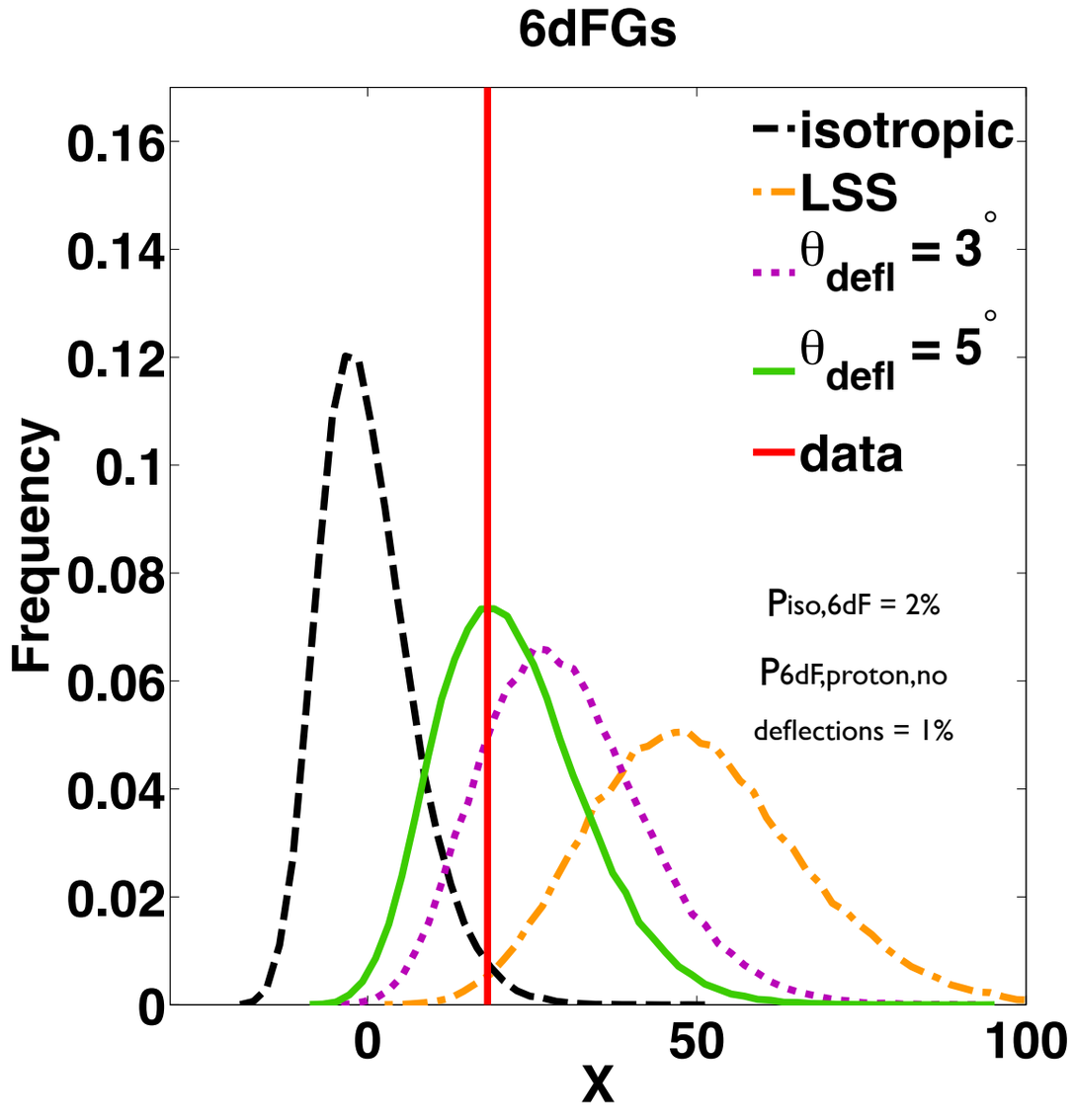




$$X = \sum_i \frac{\left(N_{\mathrm{CR,i}} - N_{\mathrm{iso,i}}\right)\left(N_{\mathrm{M,i}} - N_{\mathrm{iso,i}}\right)}{N_{\mathrm{iso,i}}}$$

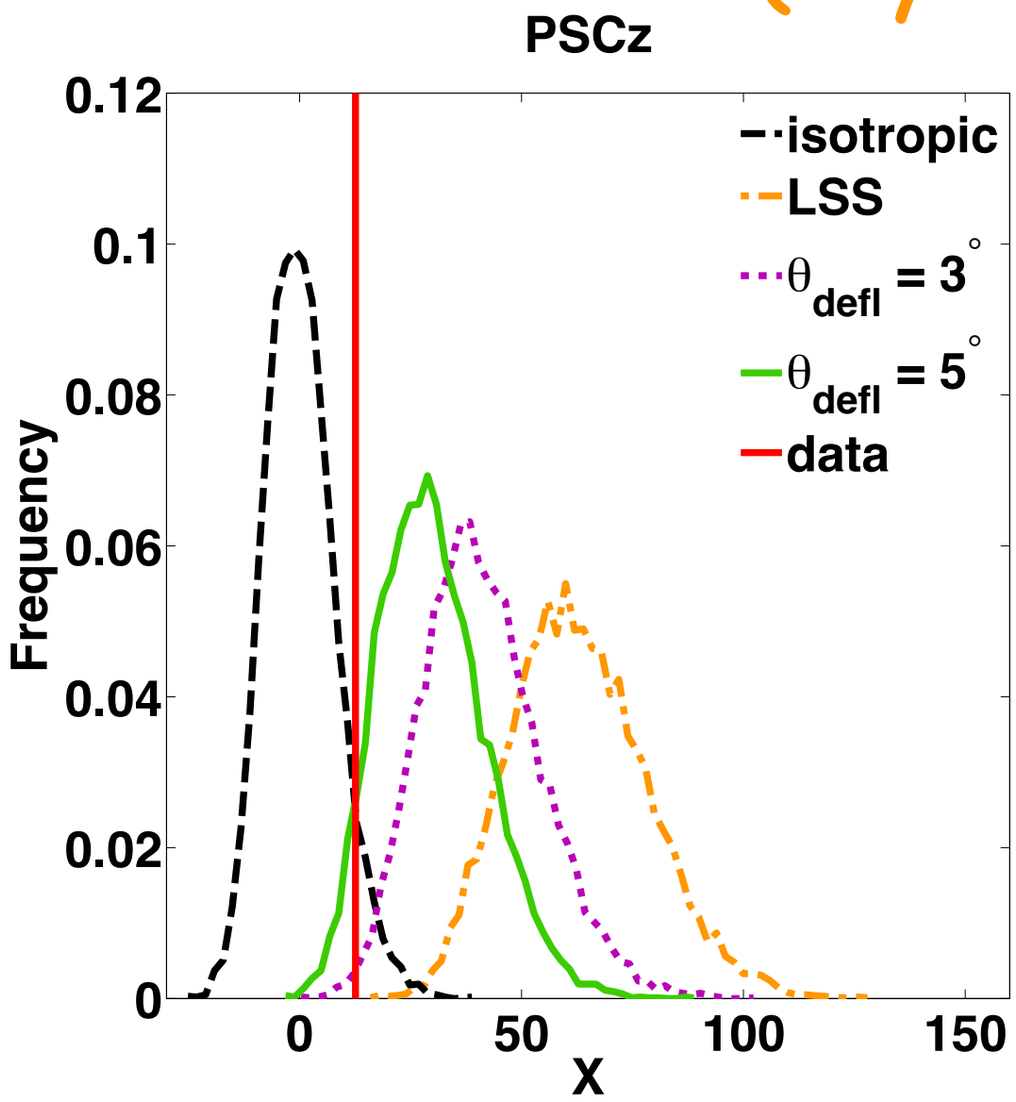
data — LSS model — isotropic expectation

~ 10% uncertainty due to binning.

Correlation with Large Scale Structure:

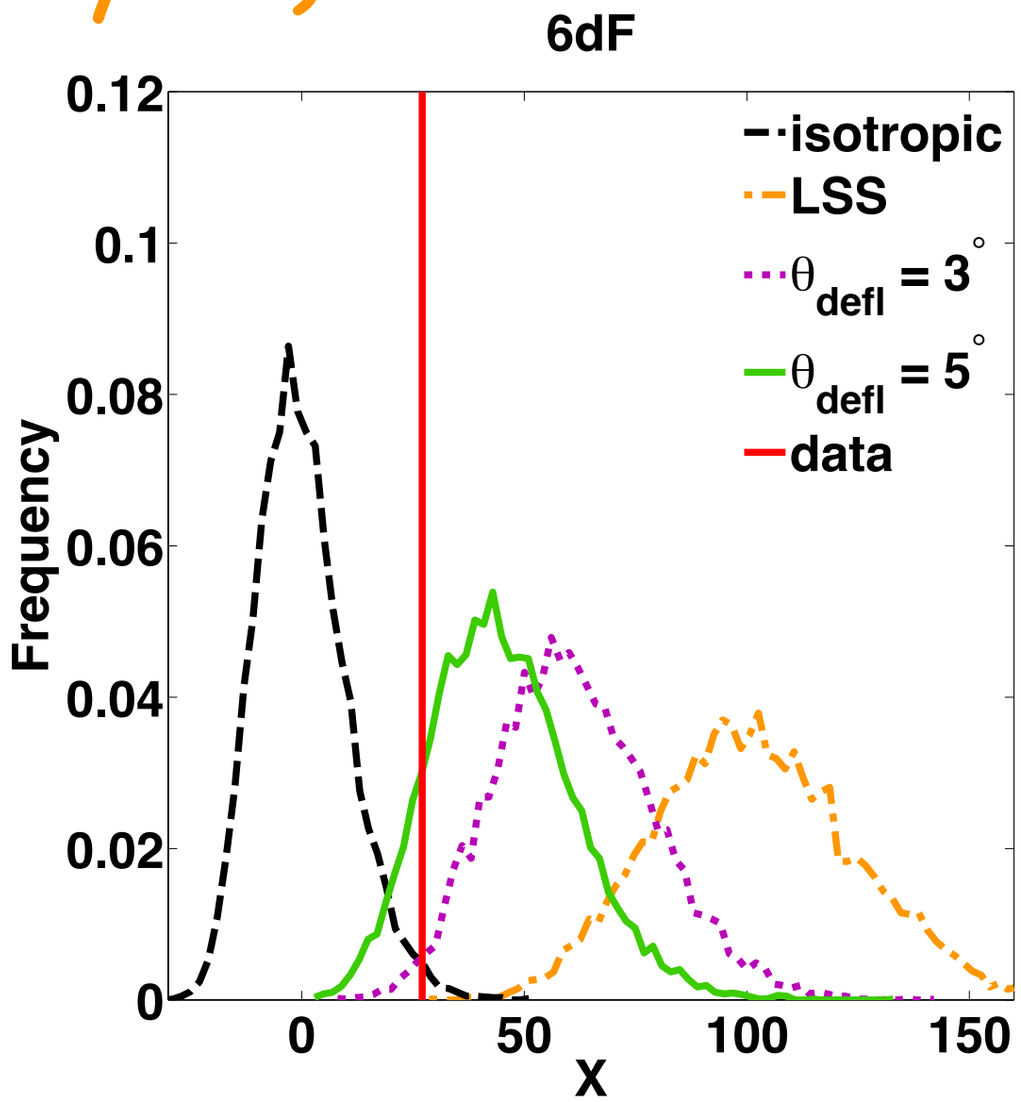
Full set to April 2014: 142 events E > 55 EeV

(my analysis)



Piso,PSCz = 7%

PPSCz,protons,no deflections < 0.1%



Piso,6dF = 1%

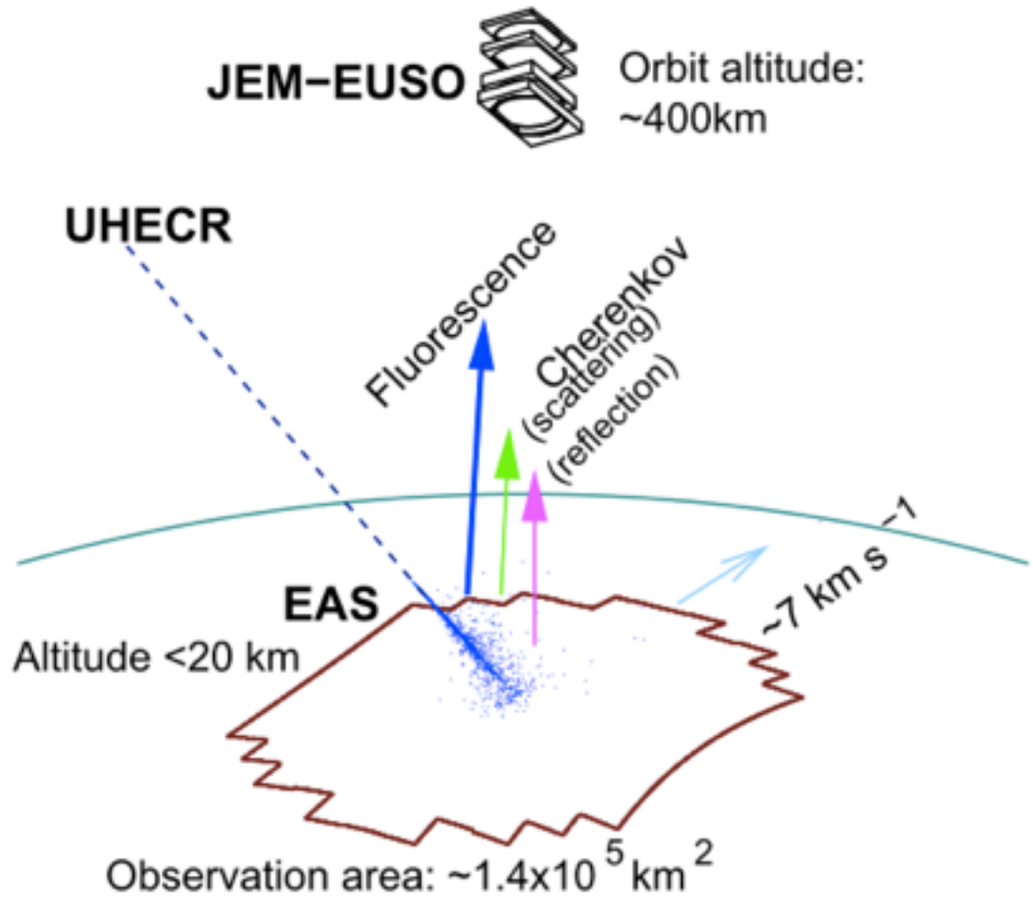
P6dF,protons,no deflections < 0.1%

The future: Will better statistics help?

e.g.,go to space..

Objectives for next generation instrument:

- 10 - 30 x Auger annual exposure
- 100 x Auger FD annual exposure
- 40 EeV < E < 1000 EeV
- 1000-2000 events/5 years



JEM-EUSO Coll. 2013-arXiv:1305.2478

What type of clustering?

Source Density:

Absence of significant number of **multiplets** in Auger data suggests a **relatively large** source number density

$$\bar{n}_0 \gtrsim 10^{-5} - 10^{-4}\ \mathrm{Mpc}^{-3}$$

(cf. $n_{gal} \simeq 10^{-2}$ Mpc^{-3})

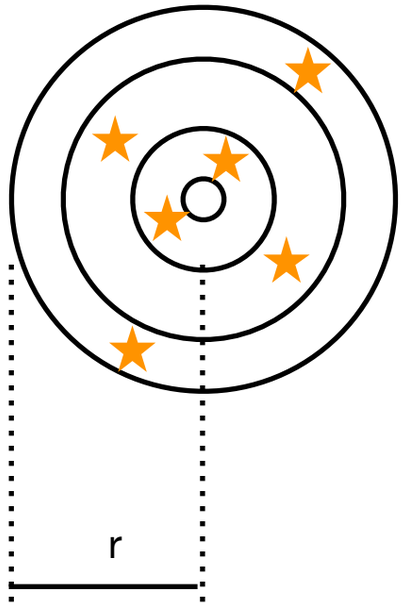
Auger Coll 2013, FO et al 2013, Takami & Sato 2009..

2 regimes

- E > 100 EeV
- low source density $\lesssim 10^{-5}$ Mpc^{-3}

anisotropy dominated by clustering around few sources

(see e.g., Blaksley et al 13, D'Orfeuil et al 2014)



horizon for ~ 50 EeV protons

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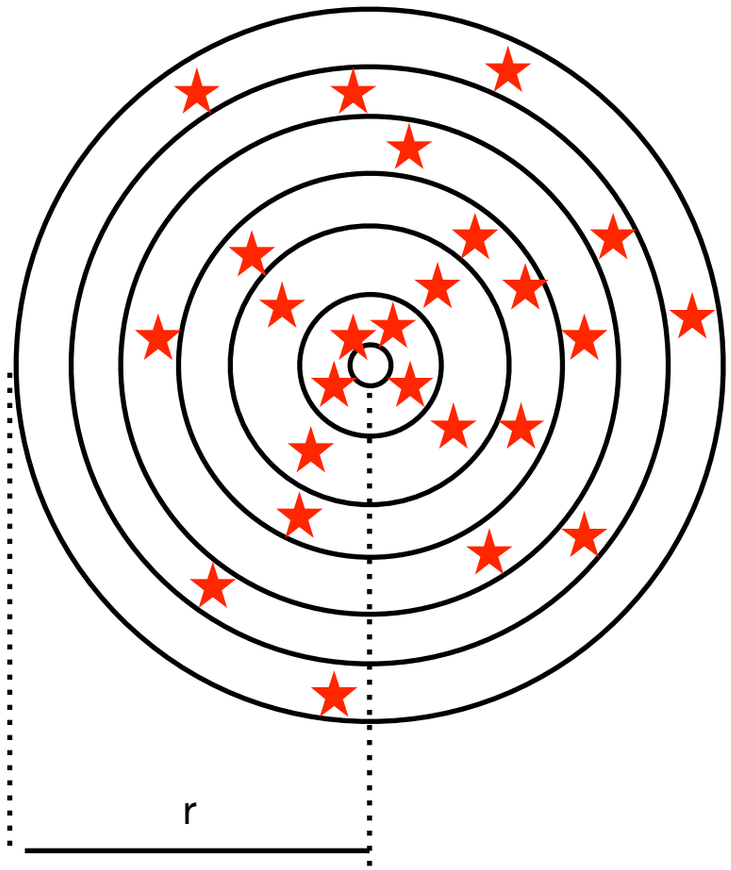
- **E > 50 EeV**
  - low source density $\gtrsim 10^{-4}$ Mpc^{-3}
    - → anisotropy imprinted by galaxy distribution



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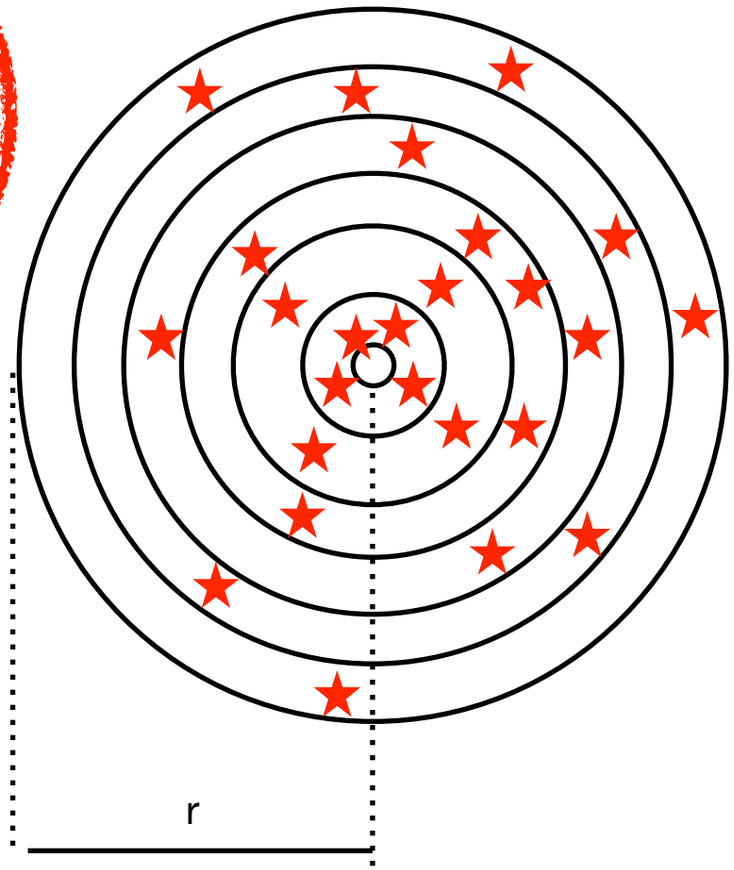
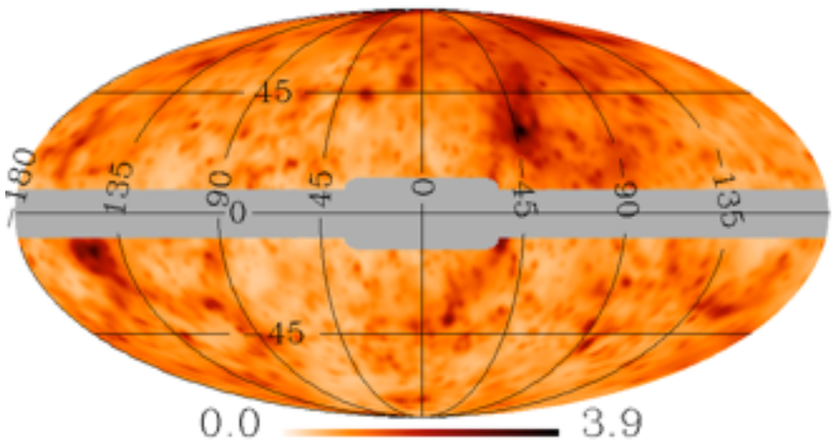


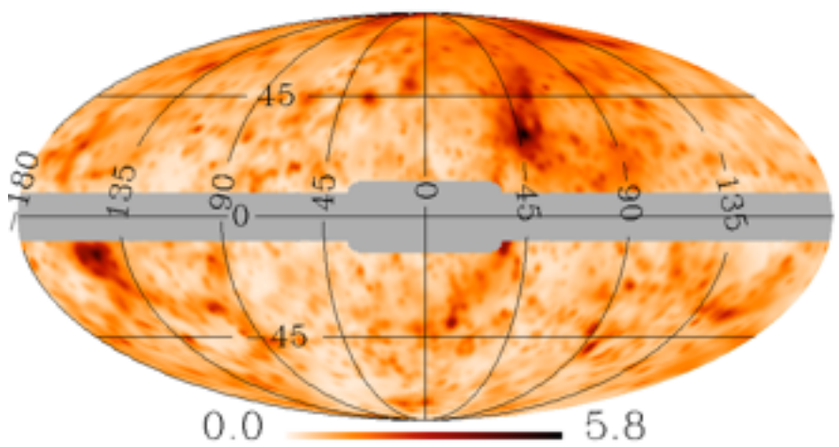
Modelling different UHECR source populations

50 EeV protons

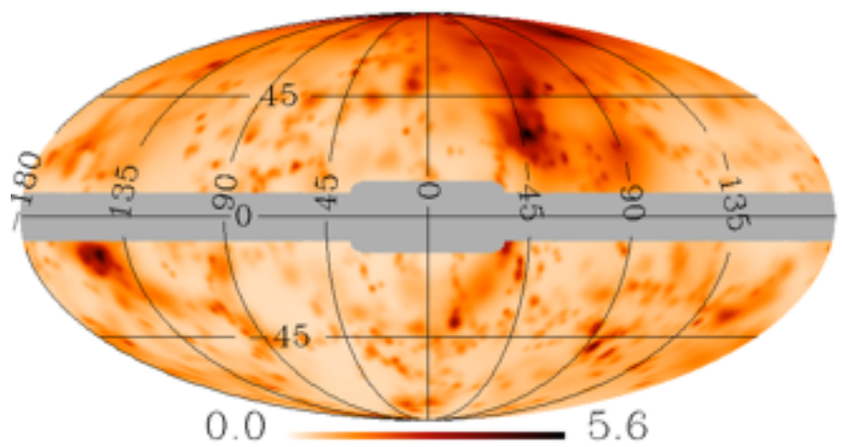
Unbiased (e.g.,GRBs/pulsars)



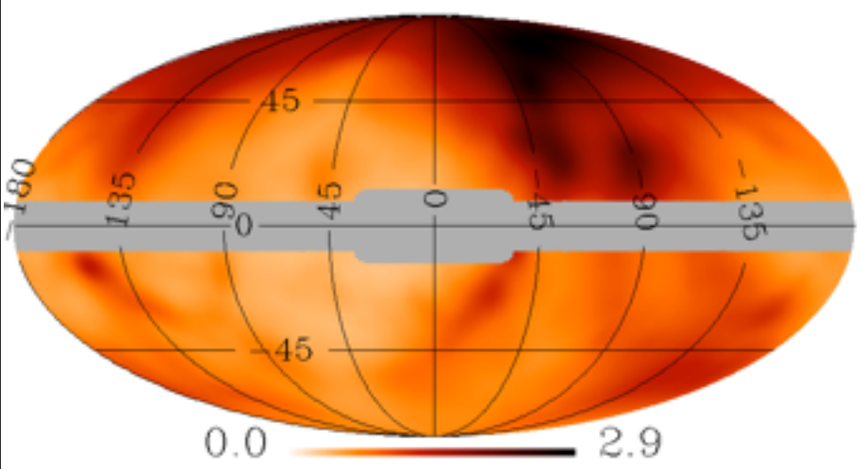
Linear (e.g.AGN)

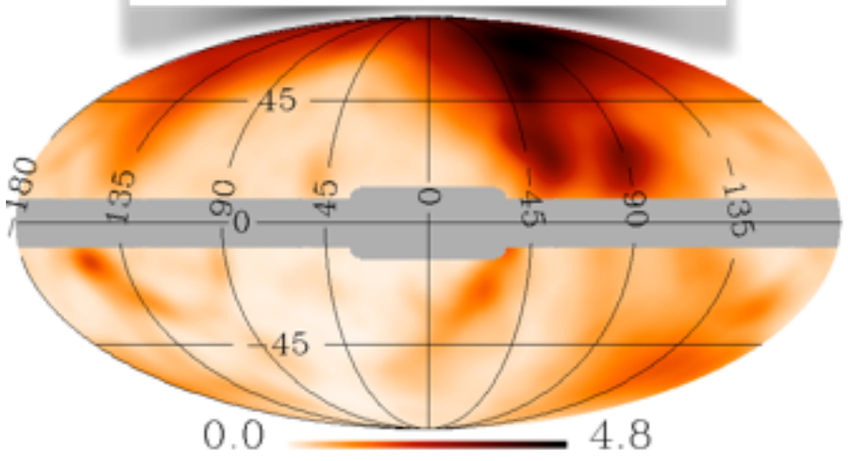


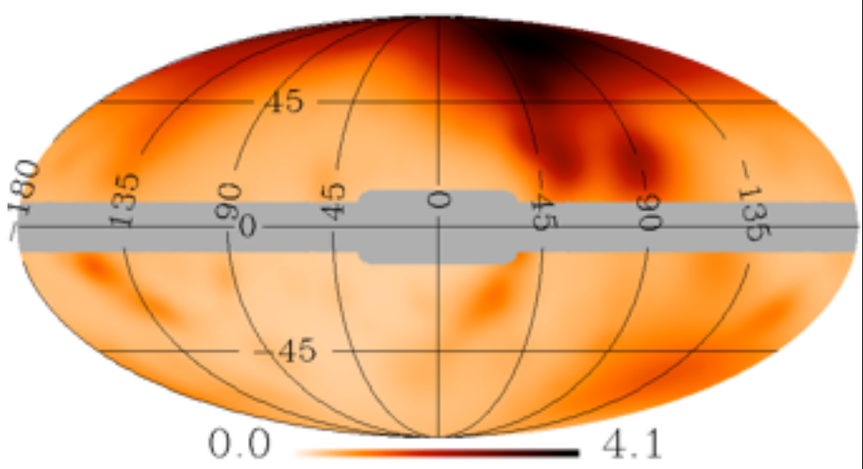
Threshold (galaxy clusters)



100 EeV protons





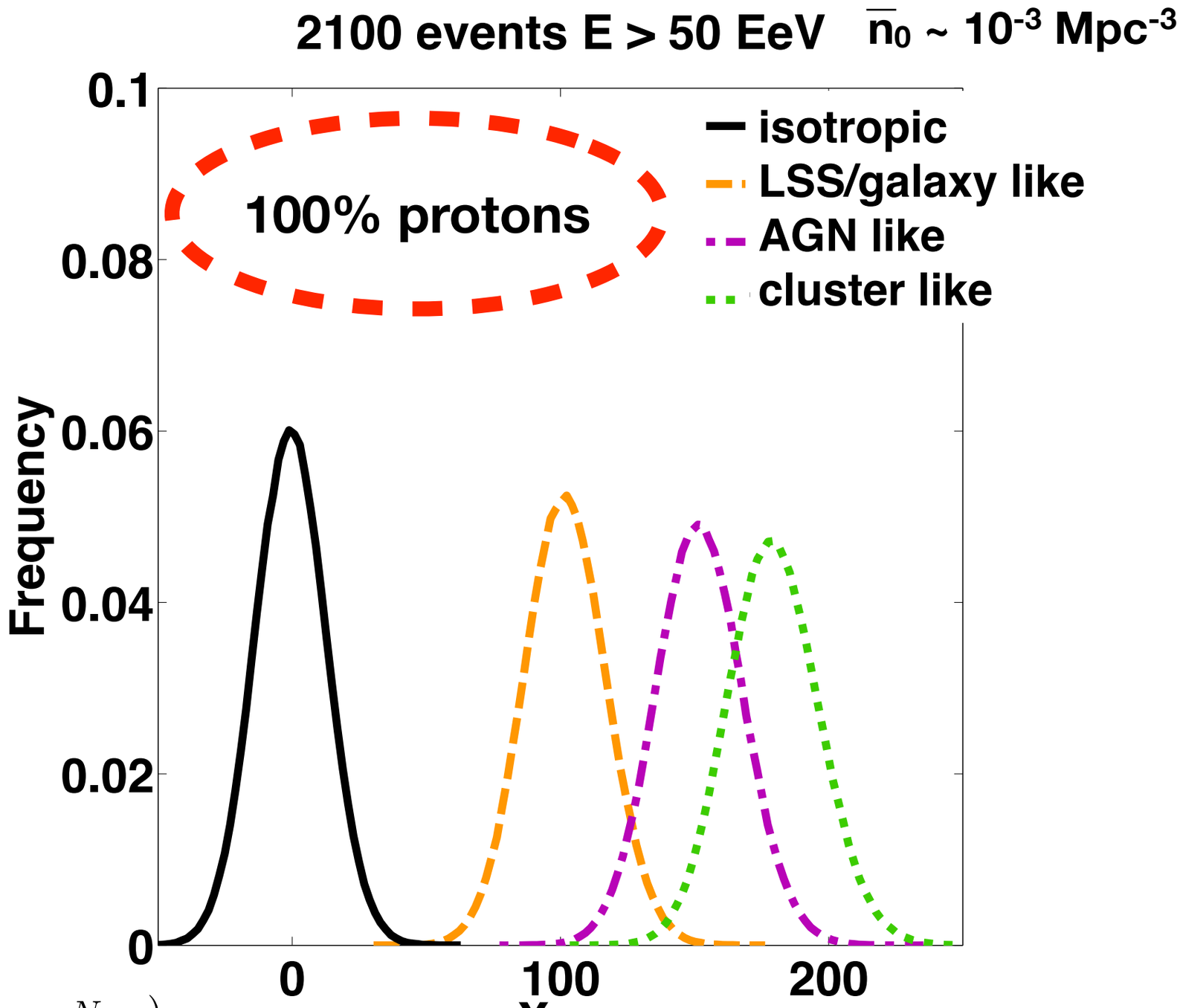


toy models based on K<11.75 2MRS

FO, Kotera, Abdalla, in prep.

Can we distinguish between astrophysical scenarios with anisotropy?

Assume:
- 2° angular resolution
- JEM-EUSO detection efficiency (*Adams et al 2013*)
- 30% energy resolution (Gaussian response)
- 5 years JEM-EUSO (optimistic)



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P(not iso|LSS model)$_{99.7\%}$ > 99.9%

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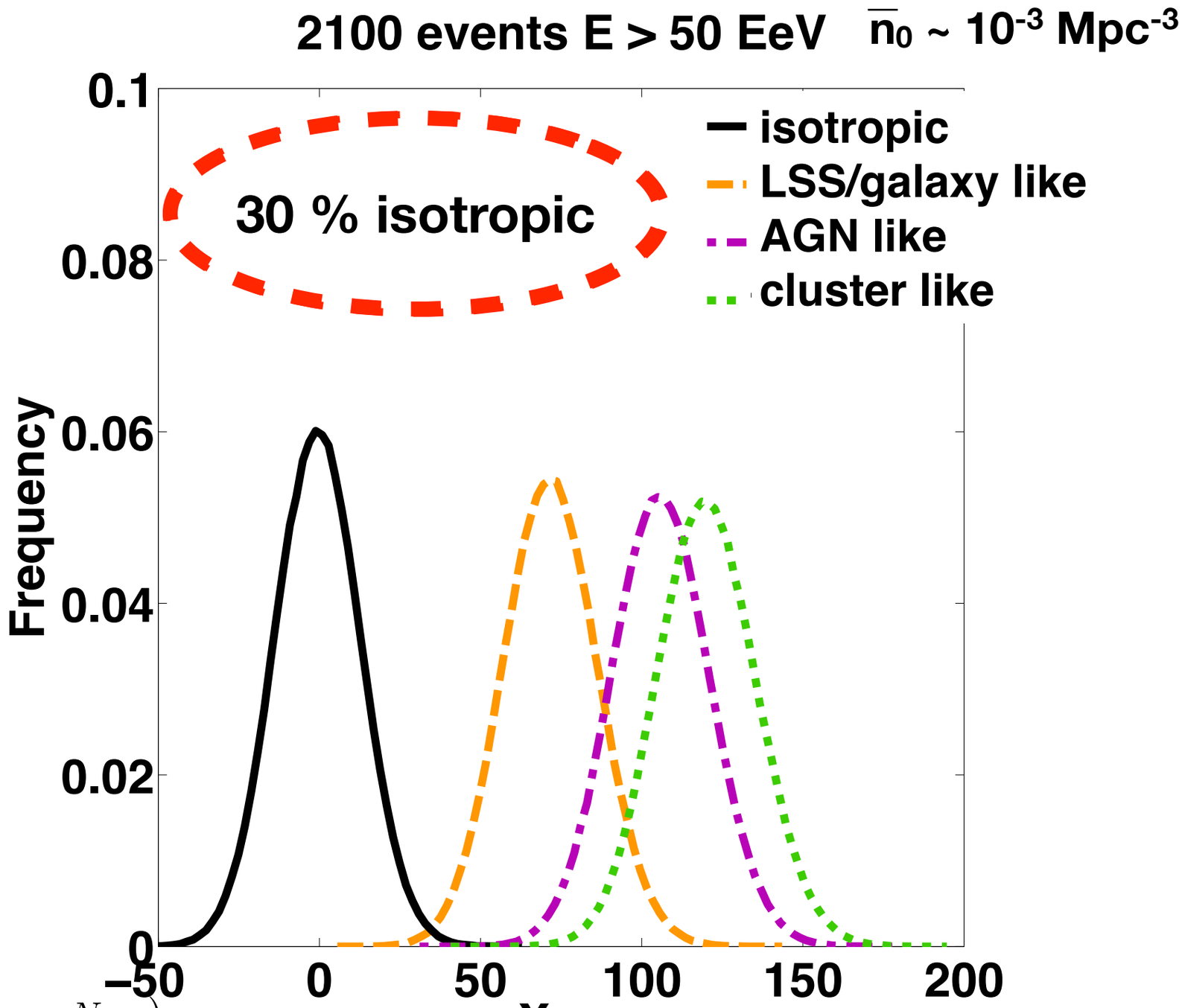

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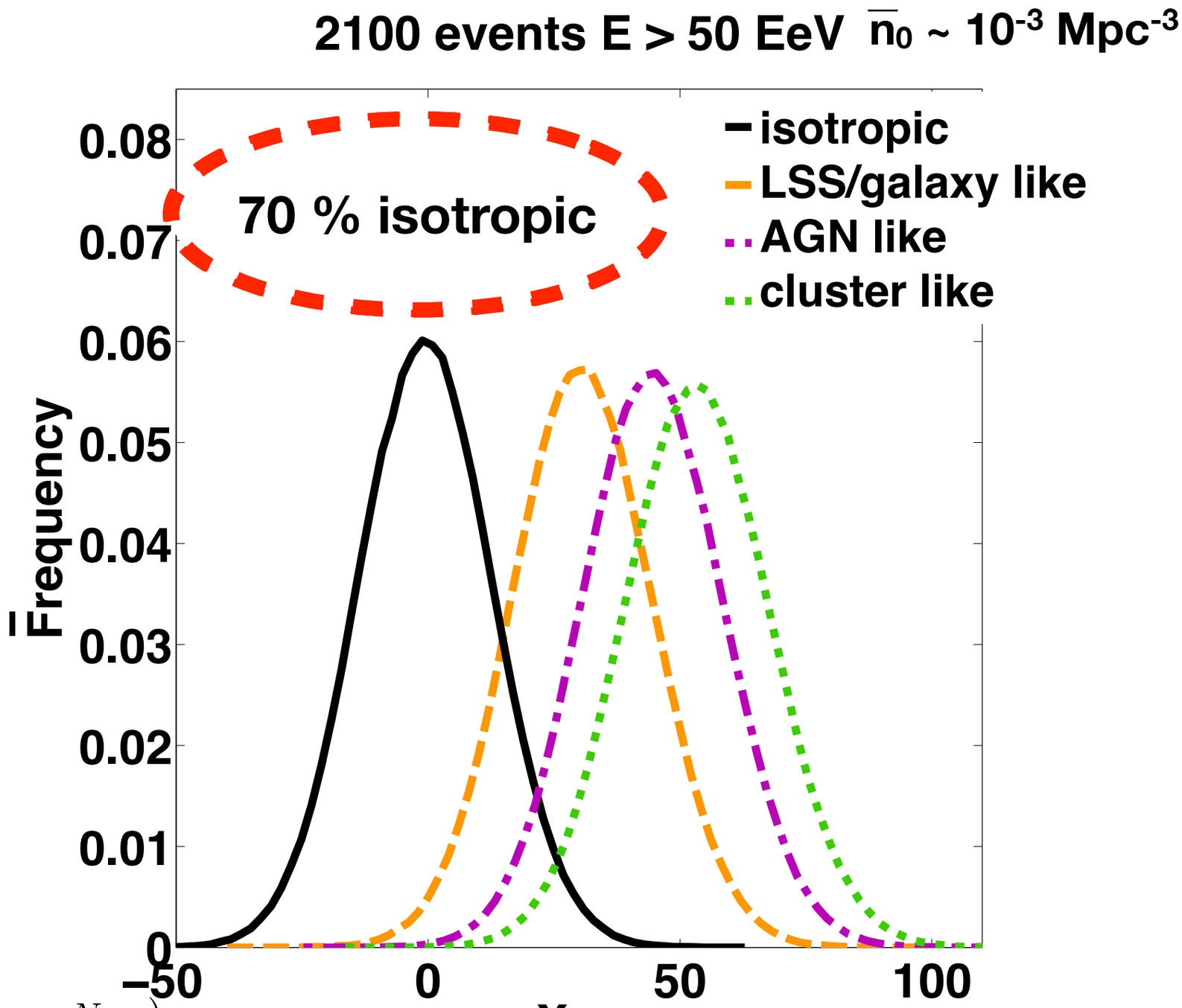

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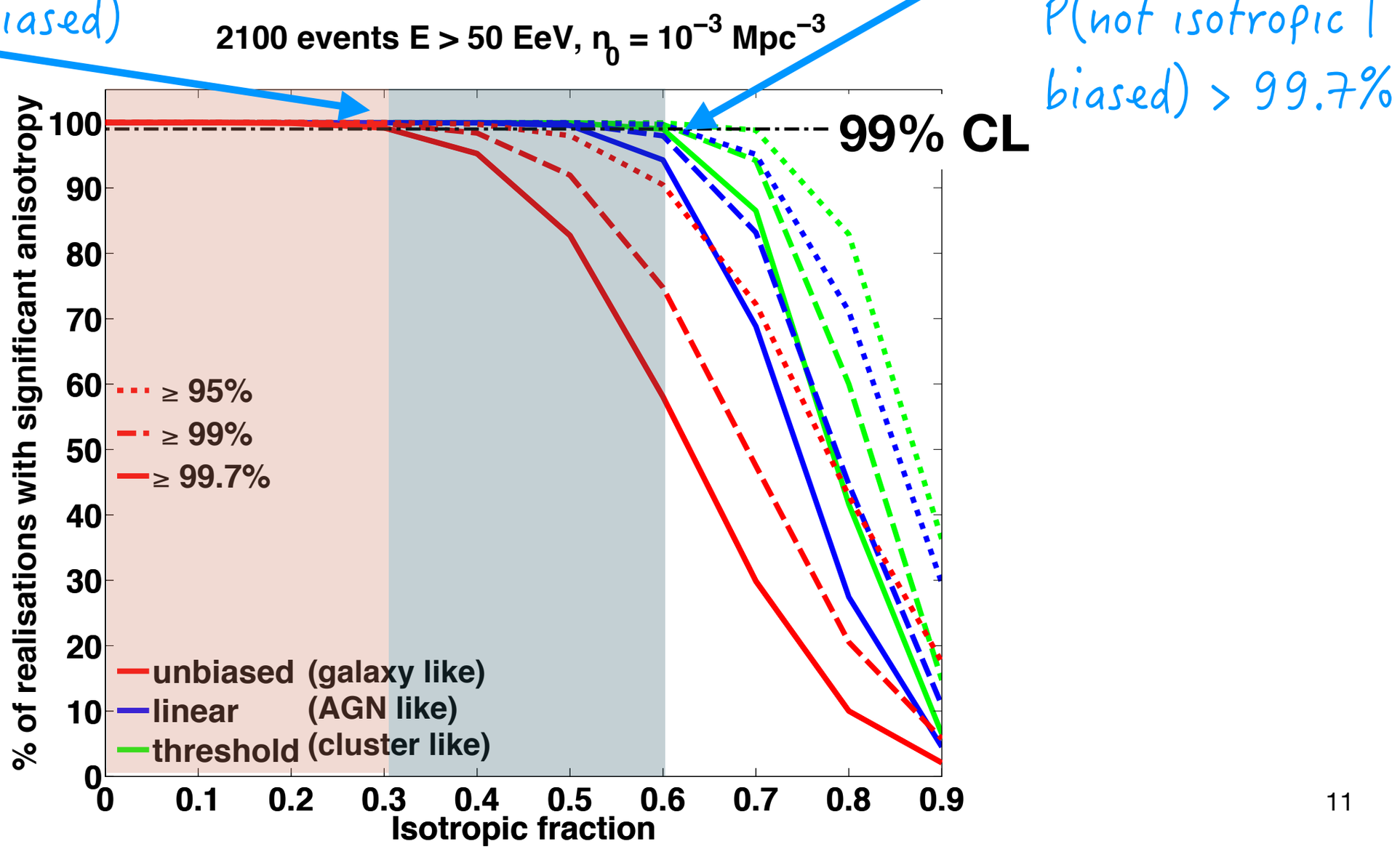
P(not iso|LSS model)$_{99\%}$ > 70%

Are we going to see anisotropy with JEM-EUSO?

For what proton fraction?

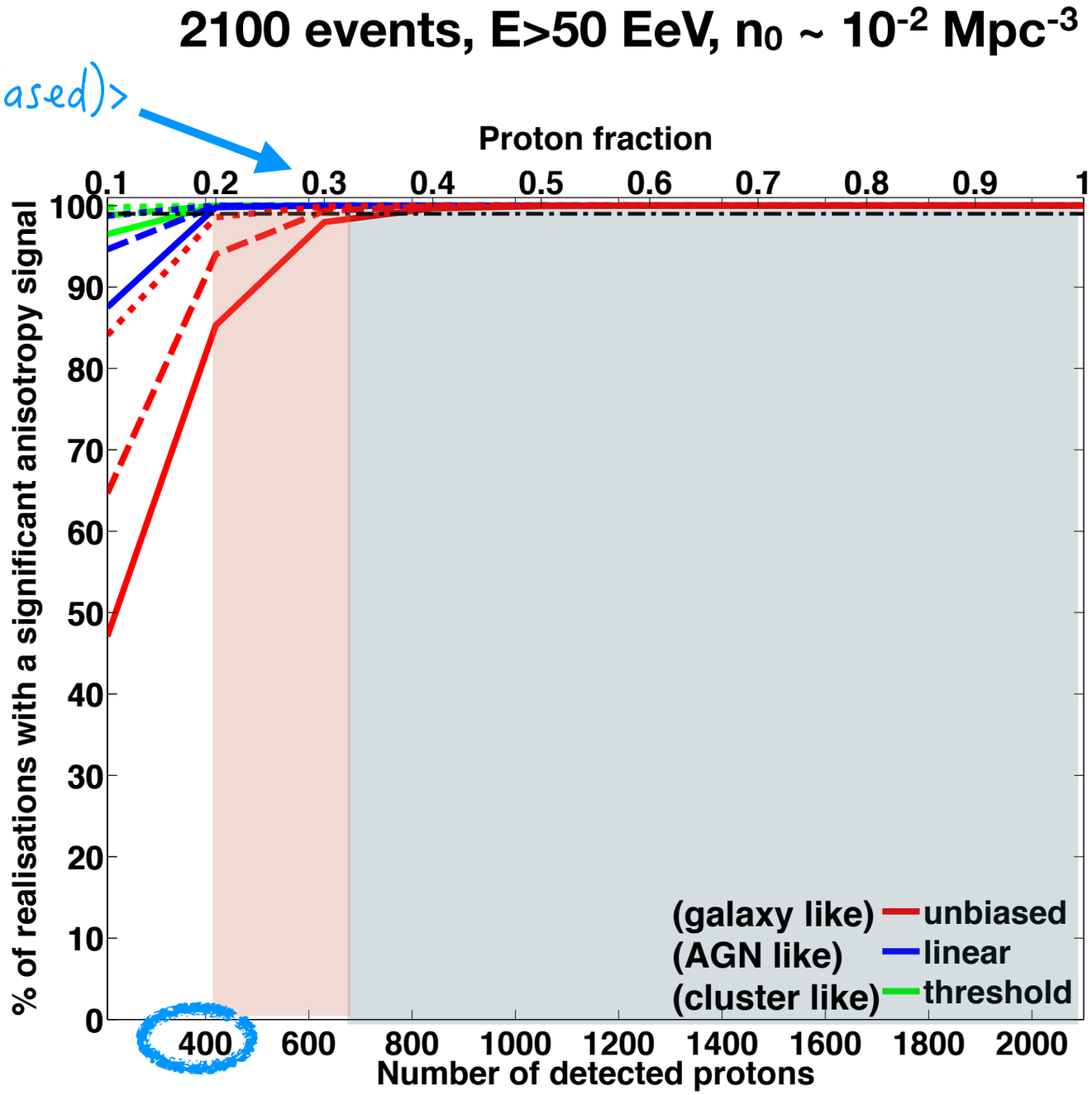
70% Protons
P(not isotropic | unbiased)
> 99.7%

40% Protons
P(not isotropic | biased) > 99.7%



If we can determine the composition?

P(not isotropic | unbiased)>
99.7%



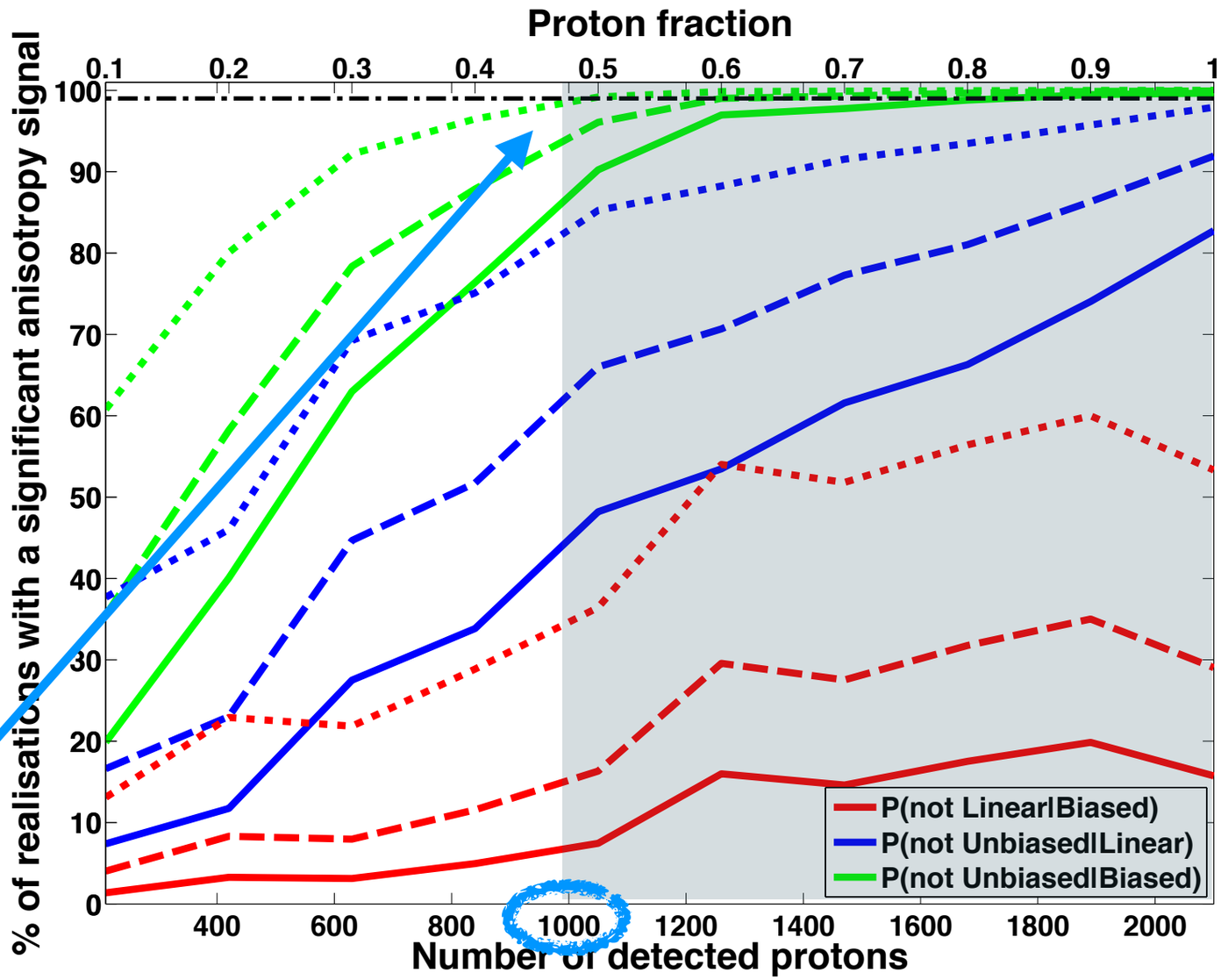
99% CL

Yes!

With ≳400 protons

Distinguish between bias models?

2100 events, E>50 EeV, $n_0 \sim 10^{-2}$ Mpc^{-3}



99% CL

≥ 95%

≥ 99%

≥ 99.7%

Yes!

With ≳1000 protons

Conclusions

* Auger (my analysis): ~2σ anisotropy hints - look out for new Auger publication soon.

* Next generation instrument (~2000 events):

  - Clustering of events around a few sources

  - or: Clustering of source distribution (lower E and/or higher number density):

  - ≳40% proton composition, >400 protons -> statistically significant anisotropy

  - 1000 protons: distinguish different astrophysical scenarios

Aims:

✦ High statistics will help whatever the source number density and threshold energy
✦ Distinguishing p/heavy elements would help

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