Auger anisotropy studies

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for the Pierre Auger Collaboration

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Right Ascension modulation

Fourier expansion of RA distribution: $\Phi(\alpha) = a_0 + \sum_{n>0} a_n^c \cos n\alpha + \sum_{n>0} a_n^s \sin n\alpha.$

First harmonic coefficients (equatorial dipole):

$$a_1^c = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos\alpha_i \qquad a_1^s = \frac{1}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin\alpha_i$$

account for exposure modulations

$$\omega(t, \theta, \phi, S_{38^\circ}) = n_{\rm cell}(t) \times a_{\rm cell} \cos\theta \times \epsilon(S_{38^\circ}, \theta, \phi)$$

construction phase and station dead-times induce spurious small modulation in sidereal time

affected by weather

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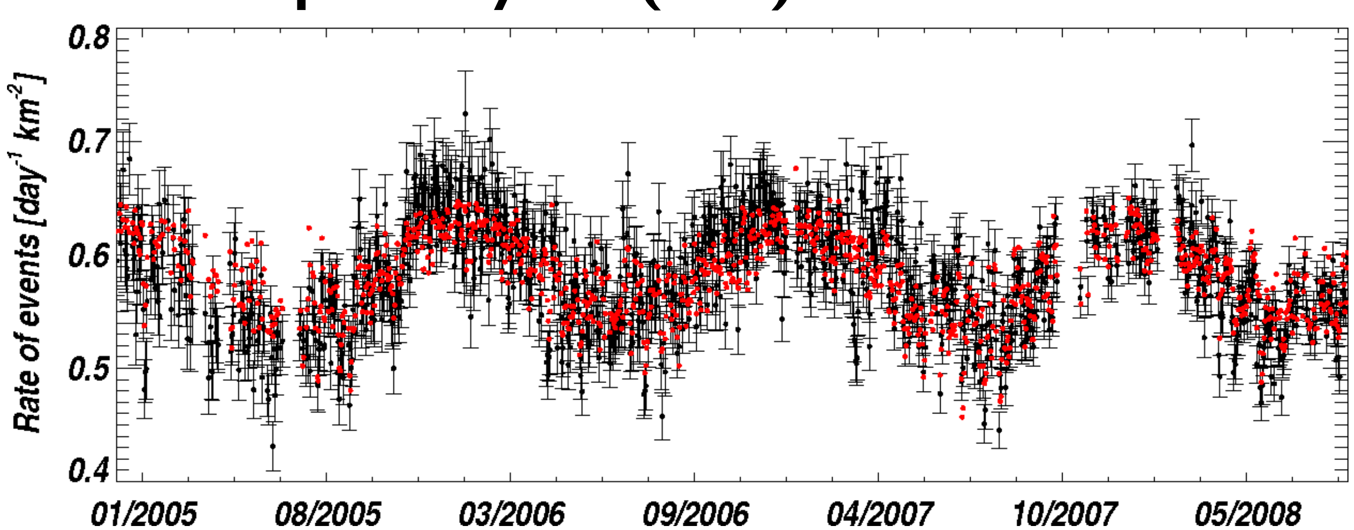
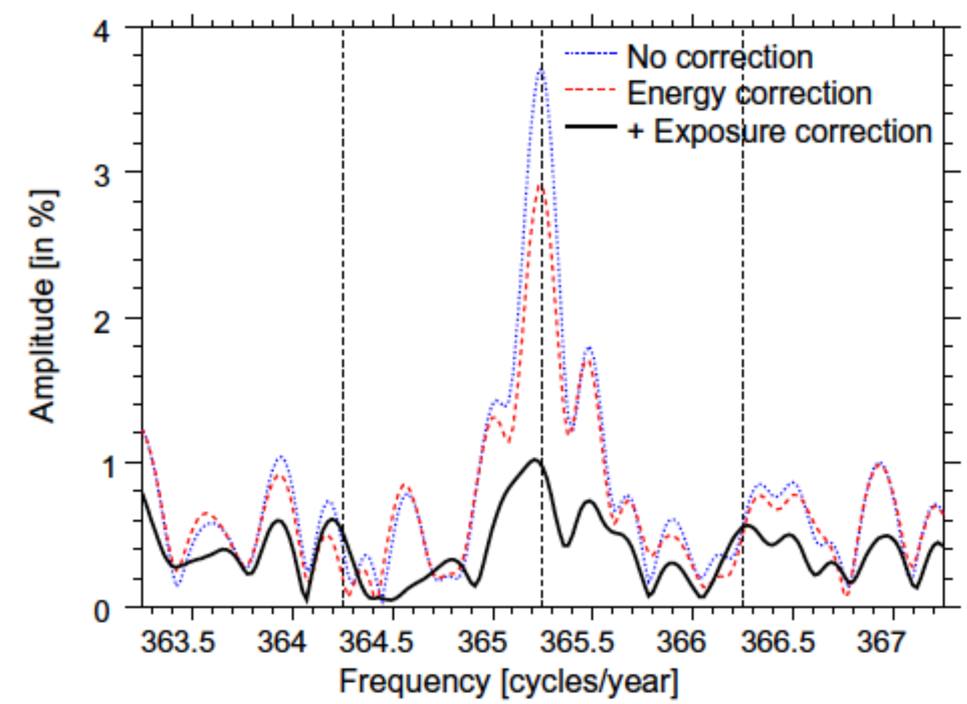
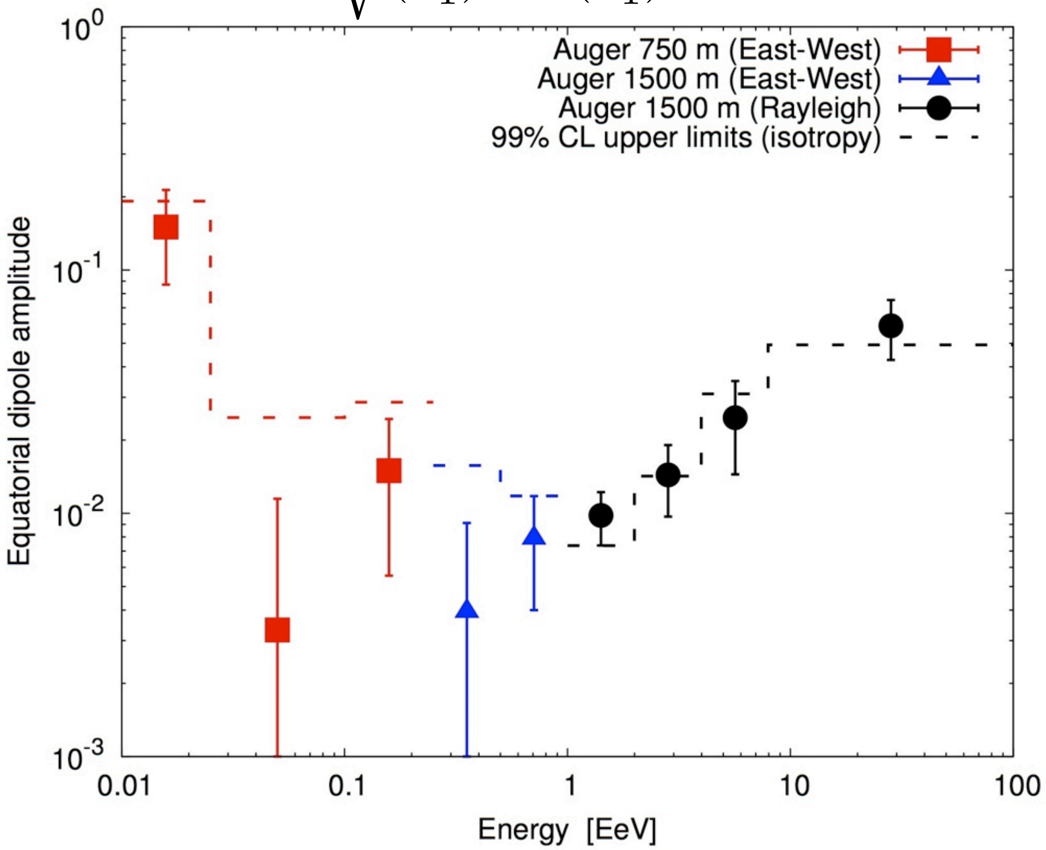




Right Ascension modulation

ICRC2013

$$r = \sqrt{(a_1^c)^2 + (a_1^s)^2}$$

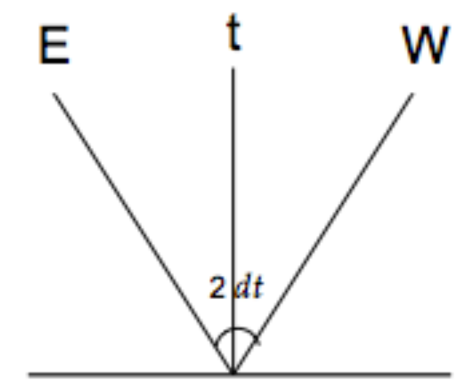


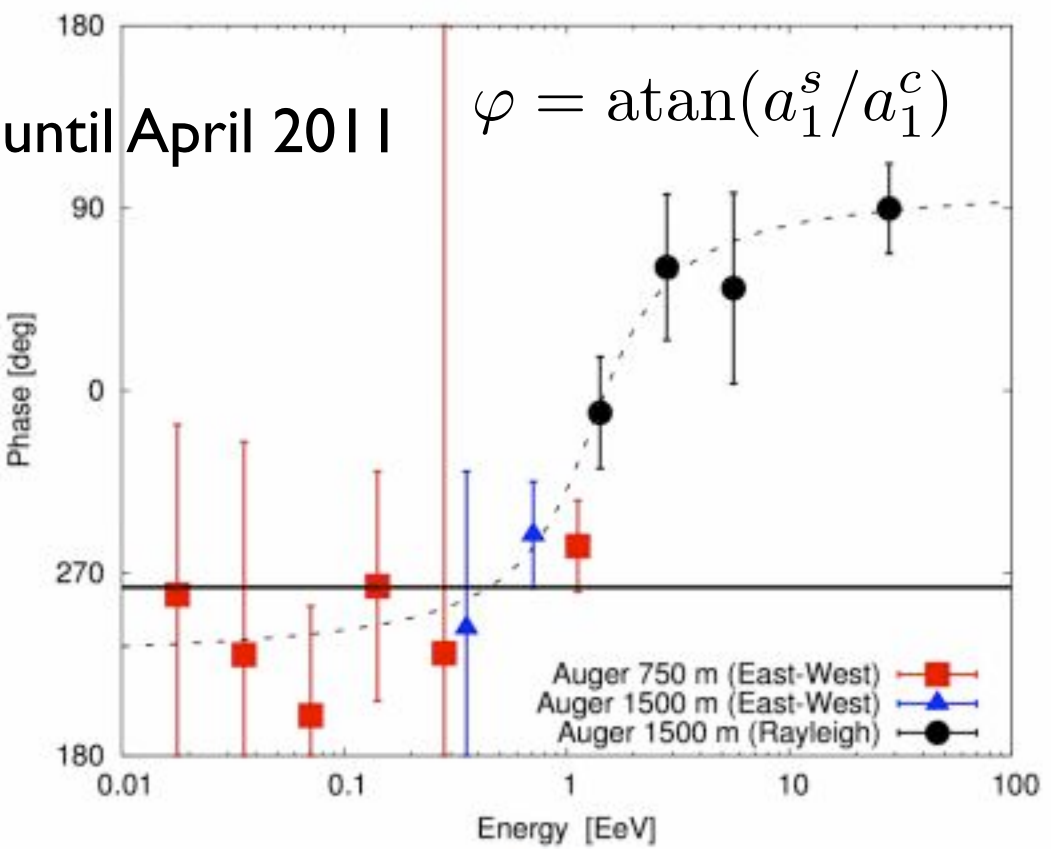
quality cuts

- ➤ theta<60 degrees (1500 m array)
- ➤ theta<55 degrees (750 m array)
- ➤ hottest station surrounded by active hex.
- ➤ periods of detector instabilities removed

East-West method at low energies

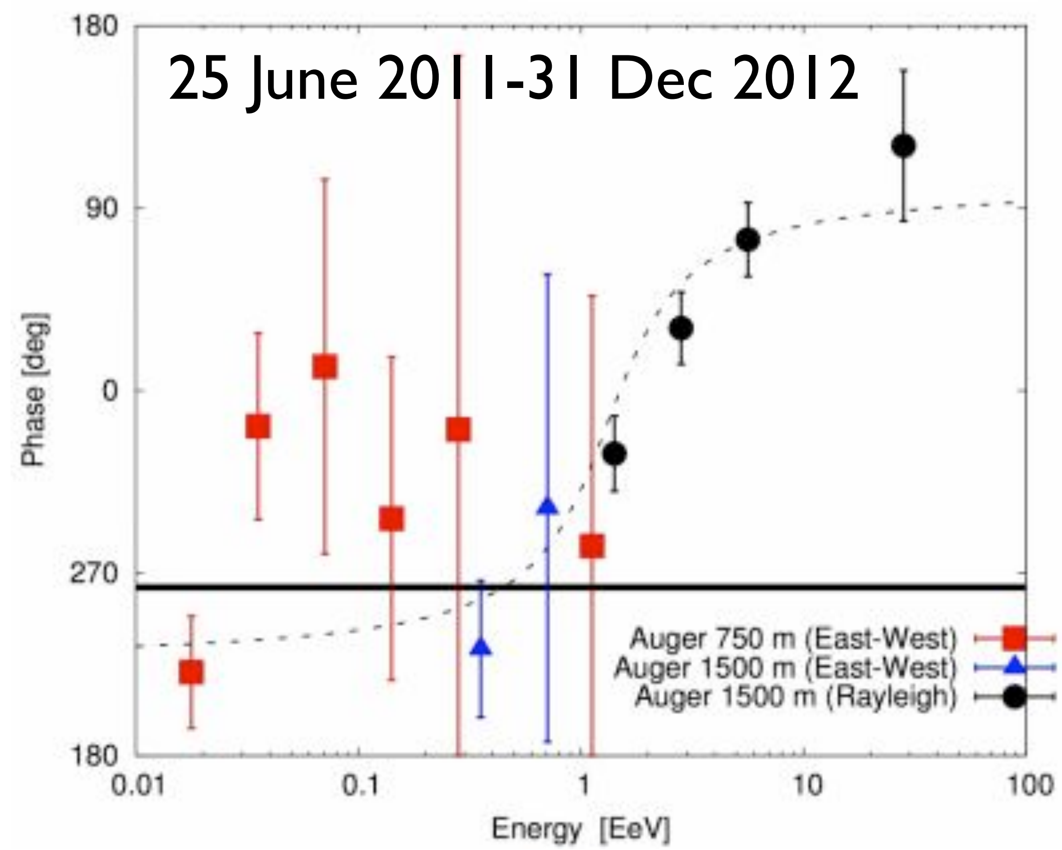
$$\frac{dI}{dt} = \frac{E(t) - W(t)}{\delta t}$$





Phase prescription:

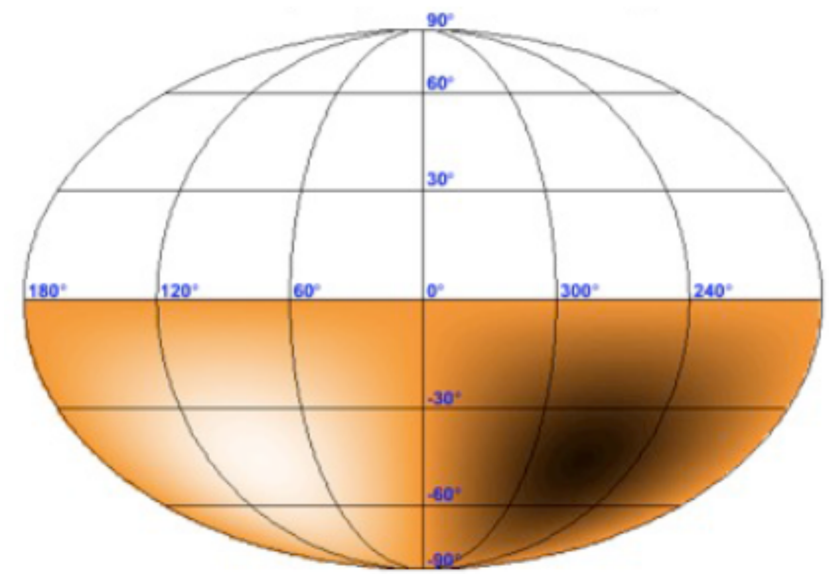
- ➤ Started on 25 June 2011
- ➤ Constancy of phase for E<1 EeV with INFILL
- ➤ Transition at high energies



Spherical harmonics with partial sky coverage

$$\Phi(\mathbf{n}) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n})$$

- ➤ anisotropy encoded in the set of alms
- ➤ dipole vector and quadrupole tensor of special interest



➤ partial and non-uniform sky coverage mix different multipoles

$$b_{\ell m} = \int_{\Delta\Omega} \mathrm{d}\Omega_{\mathbf{n}}\, \tilde{\omega}(\mathbf{n}, \Delta E) \Phi(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$

$$= \sum_{\ell' \geq 0} \sum_{m'=-\ell'}^{\ell'} a_{\ell' m'} \int_{\Delta\Omega} \mathrm{d}\Omega_{\mathbf{n}}\, \tilde{\omega}(\mathbf{n}, \Delta E) Y_{\ell' m'}(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$

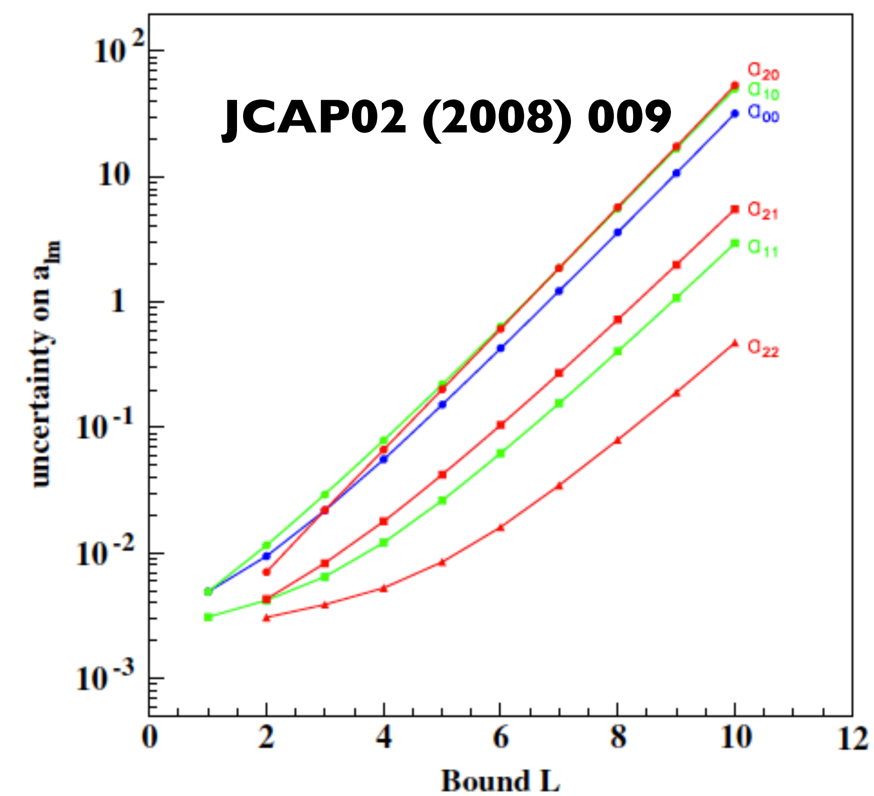
mixing matrix

$$\overline{a}_{\ell m} = \sum_{\ell'=0}^{\ell_{\max}} \sum_{m'=-\ell'}^{\ell'} [K^{-1}_{\ell_{\max}}]^{\ell' m'}_{\ell m} \overline{b}_{\ell' m'}$$

true coefficients

pseudo-coefficients

- ➤ multipole estimate is done truncating expansion at a max. value lmax
- ➤ resolution degrades as ~exp(lmax) !!!

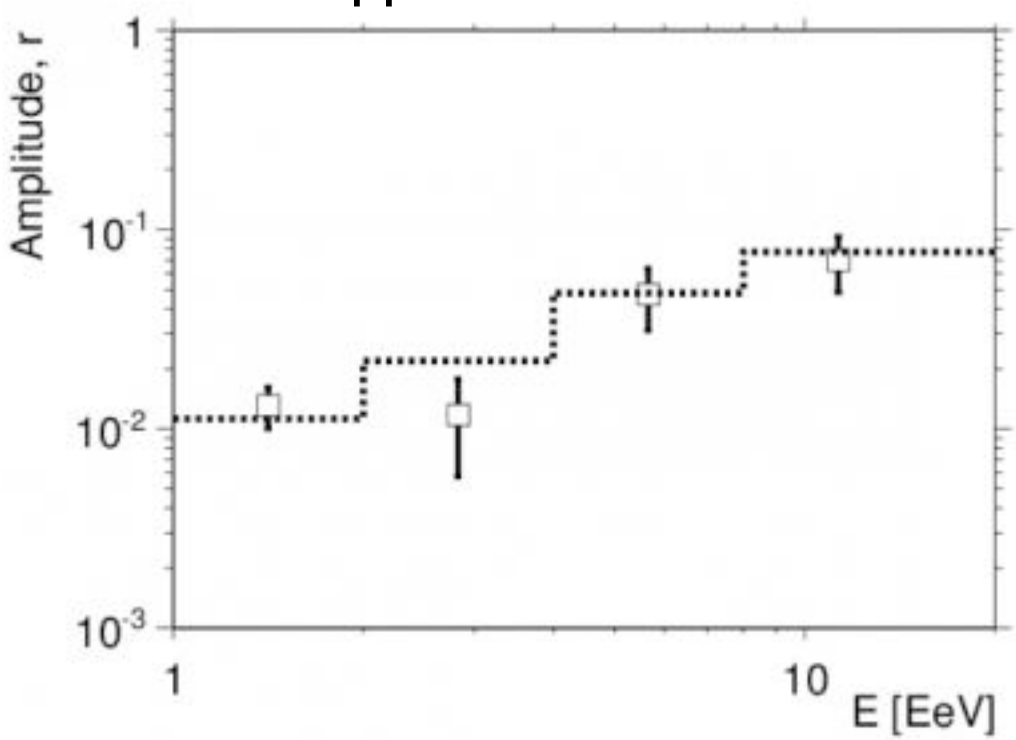


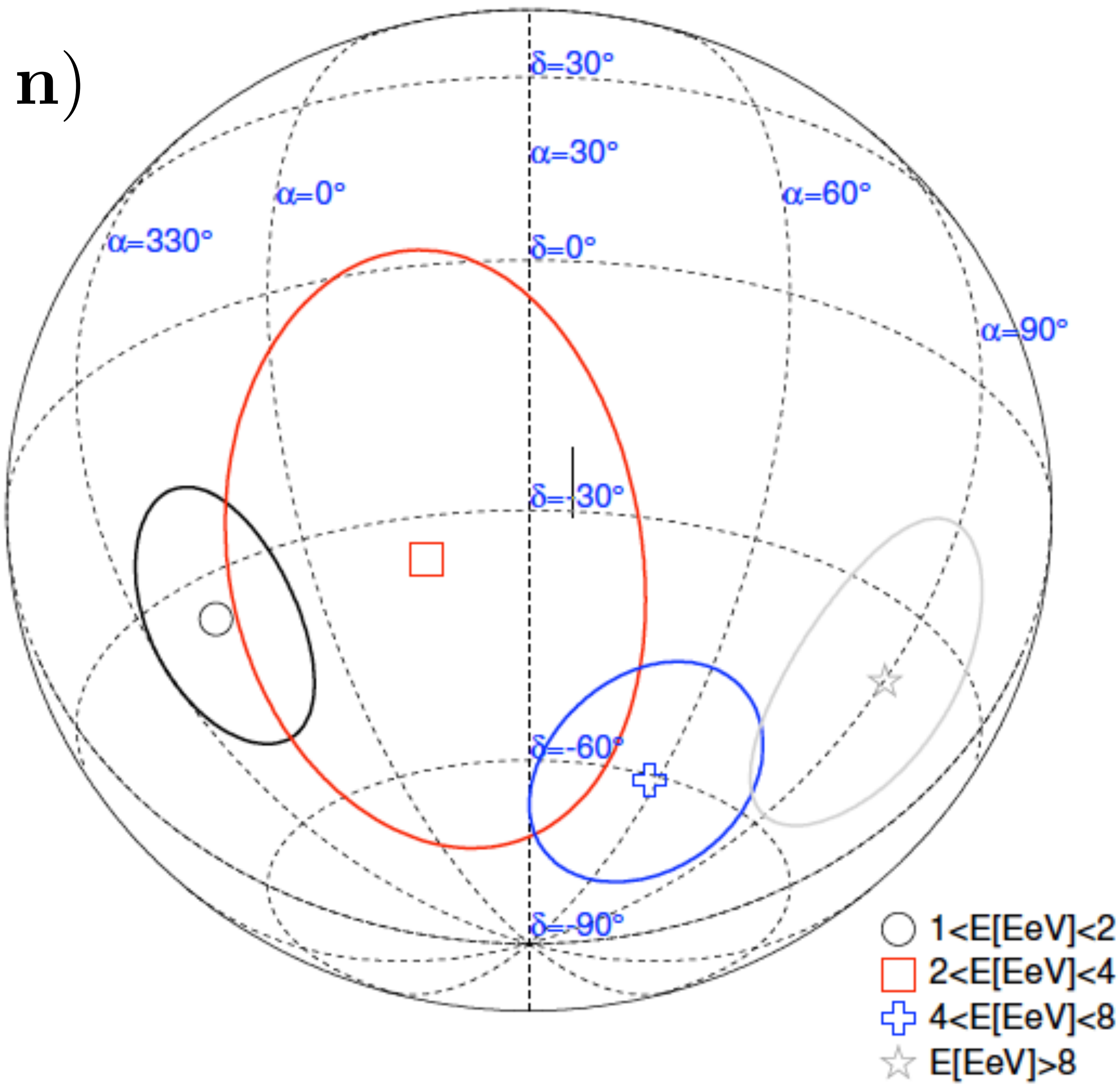
Spherical harmonics analysis

ApJL 762, L13 (2013)

Pure dipole: $\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}(1 + r\mathbf{d}\cdot\mathbf{n})$

99% upper limits

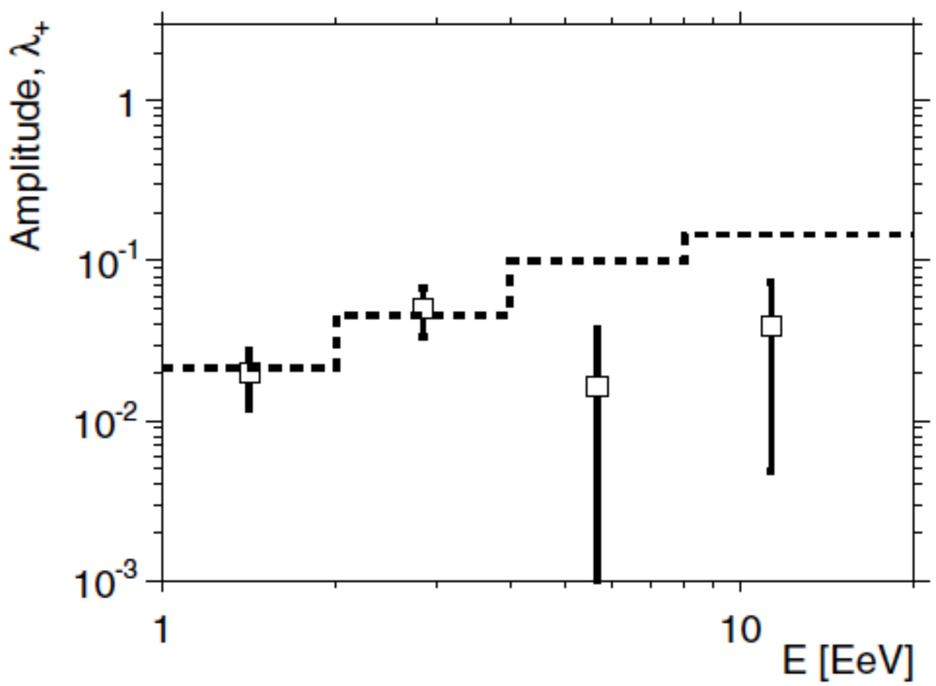


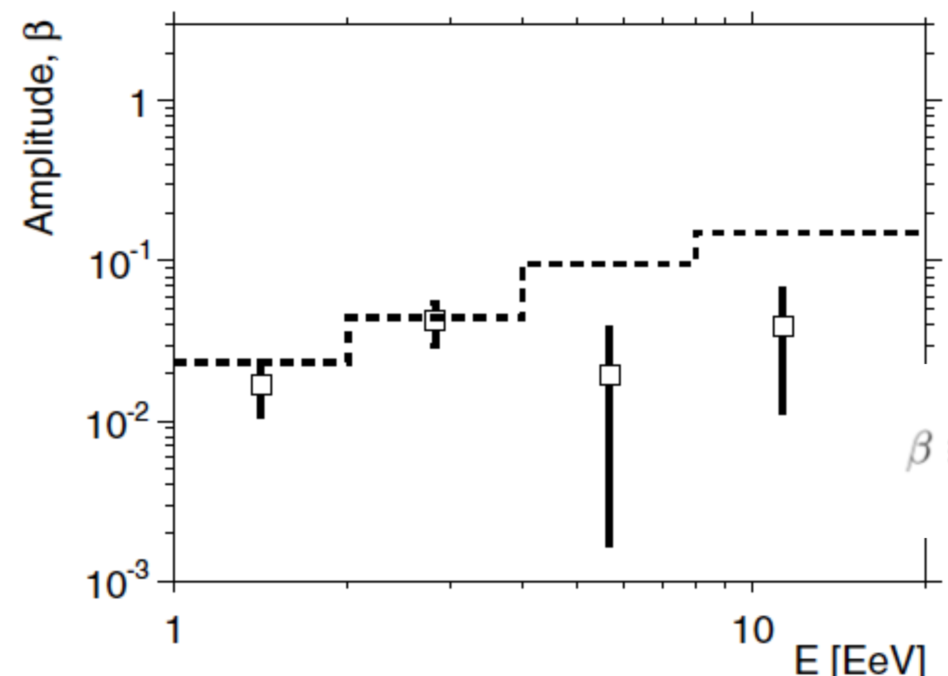


Spherical harmonics analysis

Including the quadrupole: $\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}(1 + r\mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q_+}\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q_0}\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q_-}\cdot\mathbf{n})^2)$

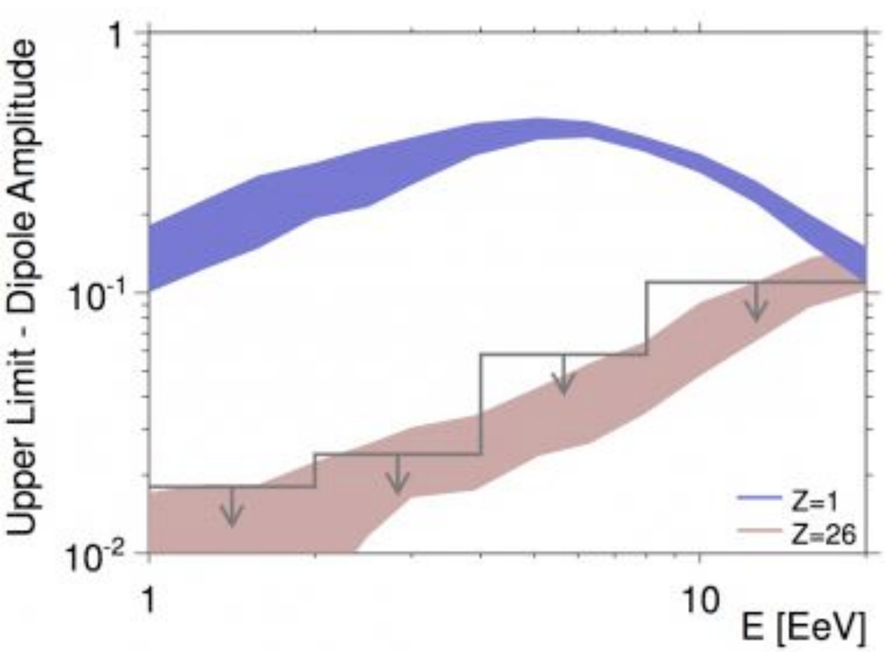
ApJL 762, L13 (2013)
ApJS 203, 34 (2012)



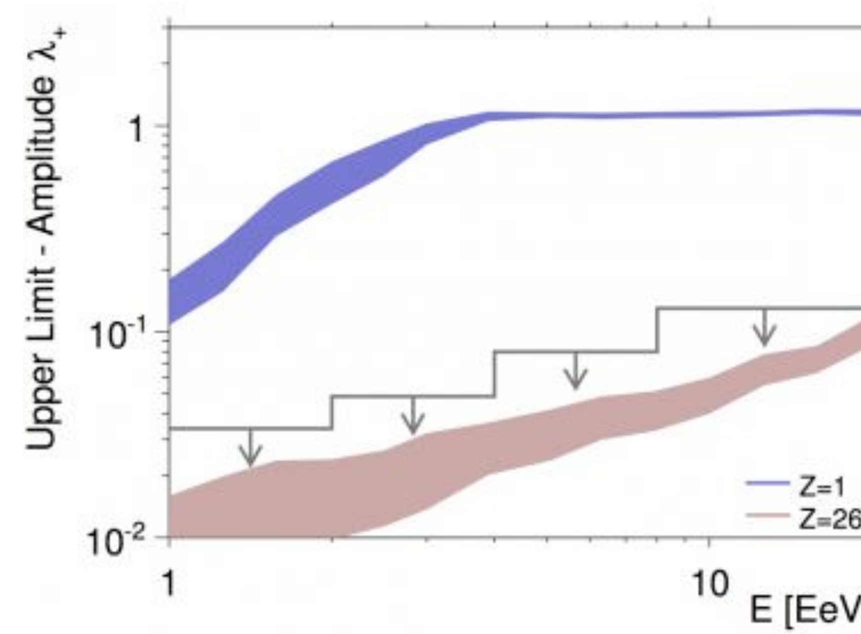


$$\beta \equiv \frac{(\lambda_+ - \lambda_-)}{(2 + \lambda_+ + \lambda_-)} = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}}$$

Comparison with anisotropy expectations from stationary galactic sources on the disk



galactic magnetic field:
regular (arms+halo)
+
turbulent (Kolmogorov spec.)



AGN correlation

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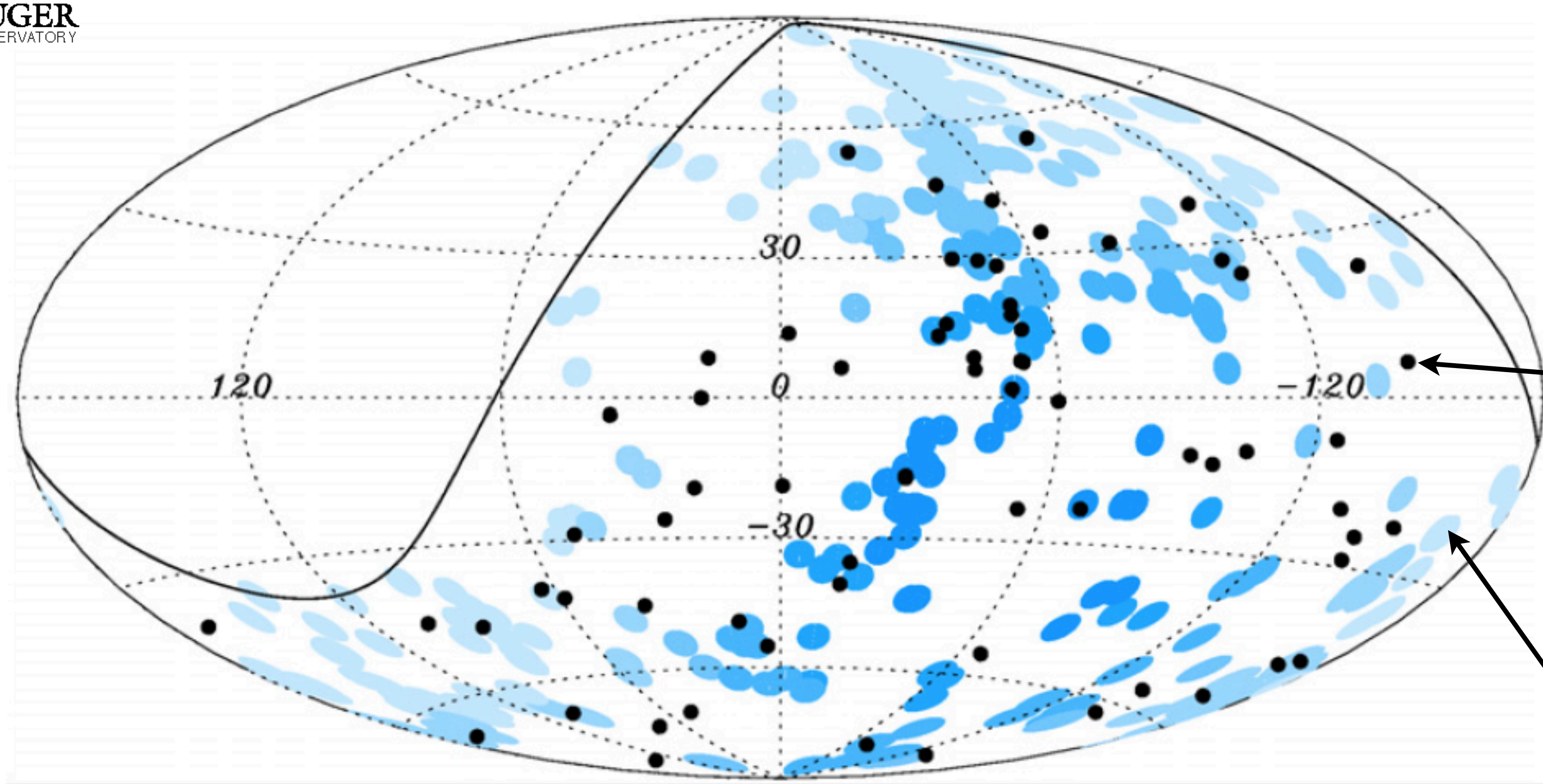
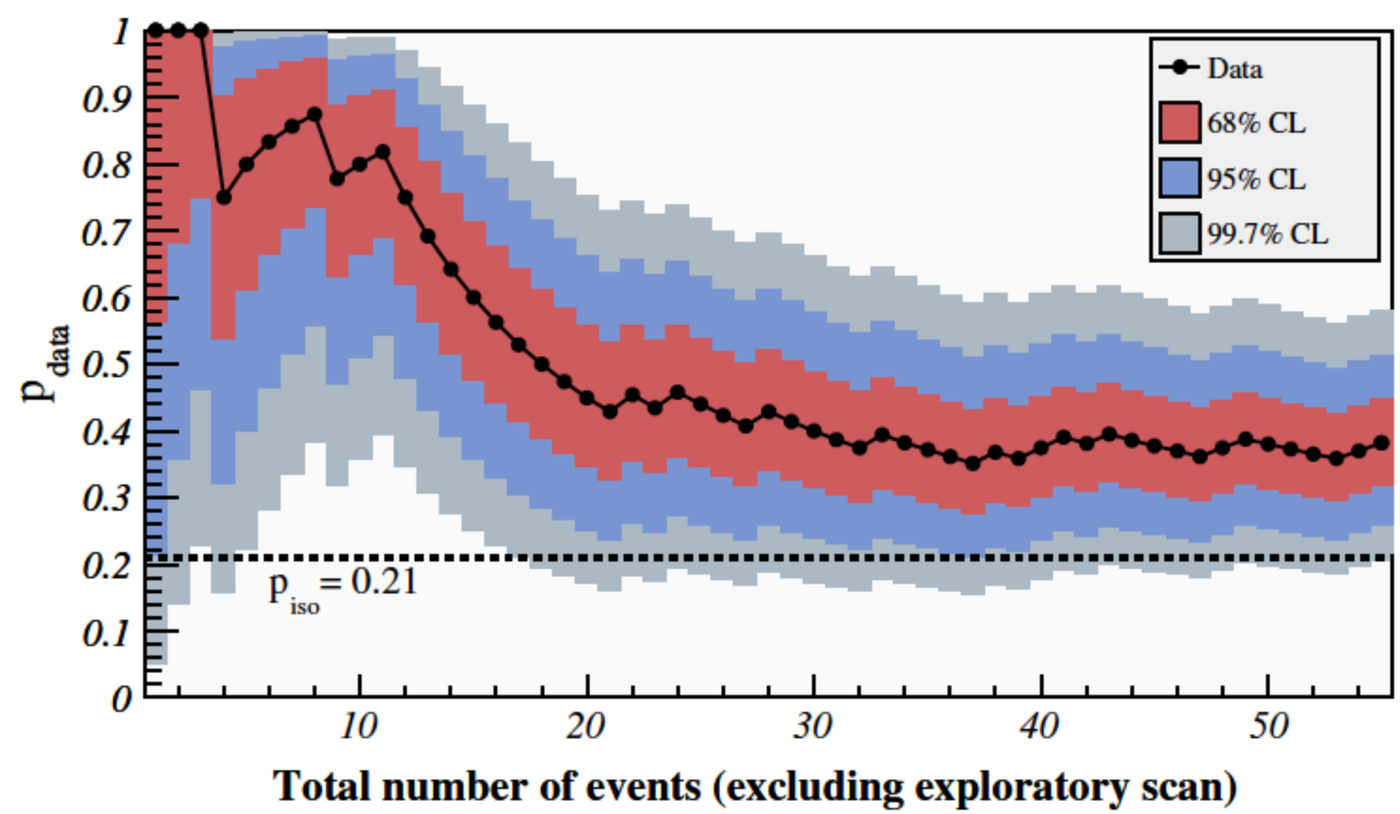


Angular window 3.1°
Energy threshold 55 EeV
Dmax: 75 Mpc (redshift < 0.018)

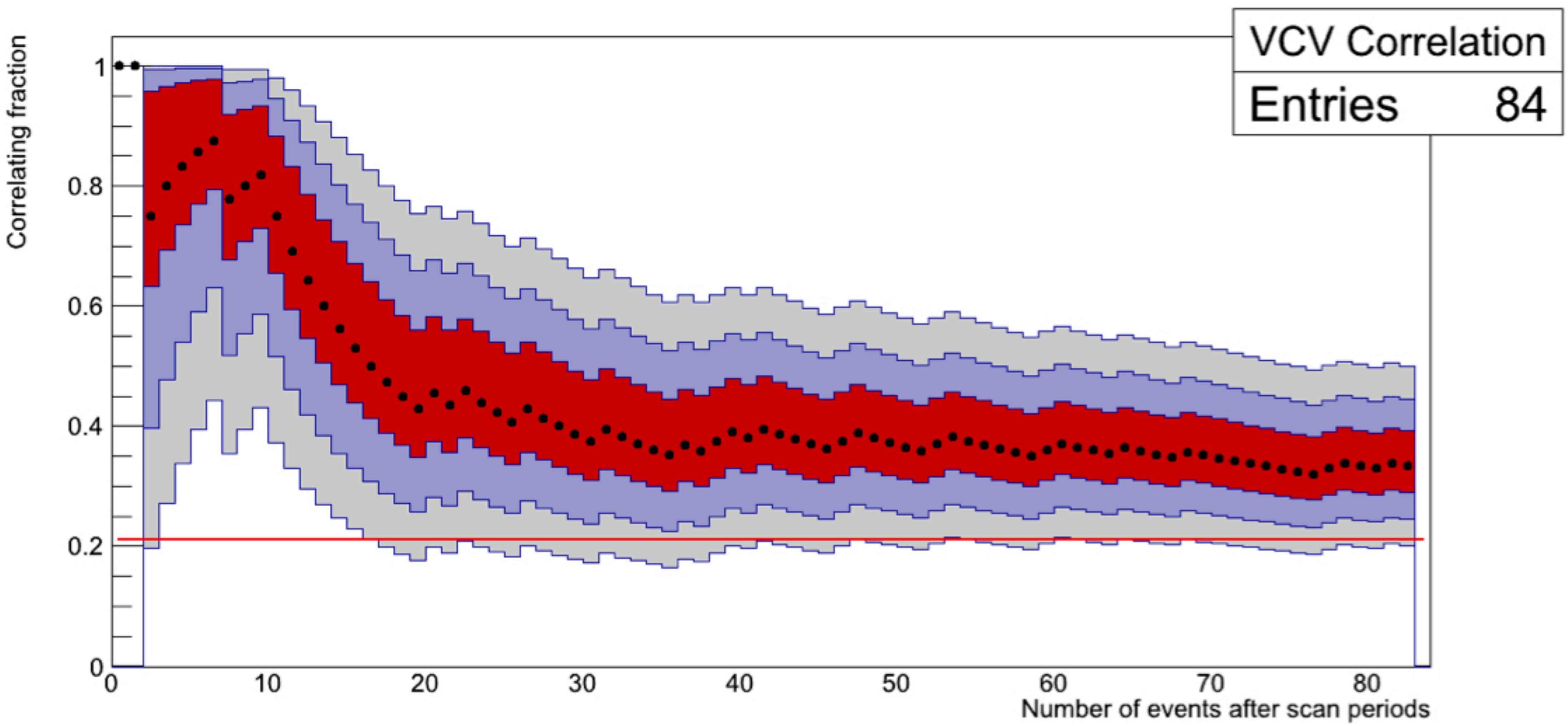
29/69 events (up to Dec 2009)

21/55 (excluding exploratory scan)



AGN correlation

28/84 events (up to Jun 2011)
(33 ± 5)%
P = 6x10^{-3}

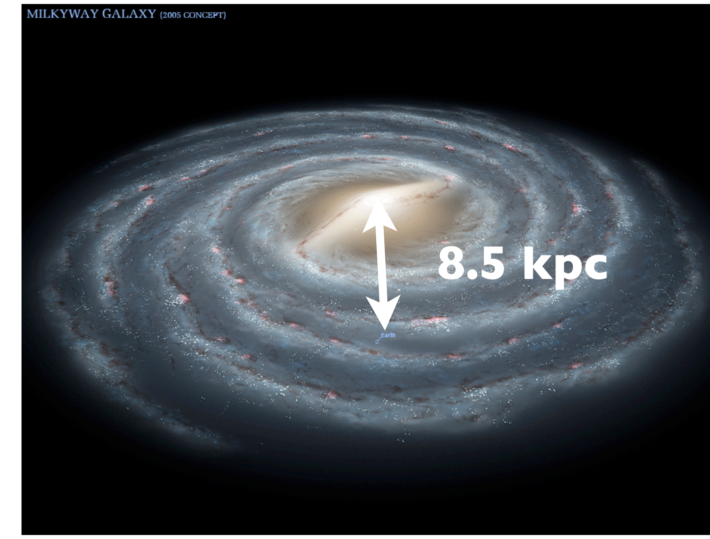


Blind search for neutron excesses

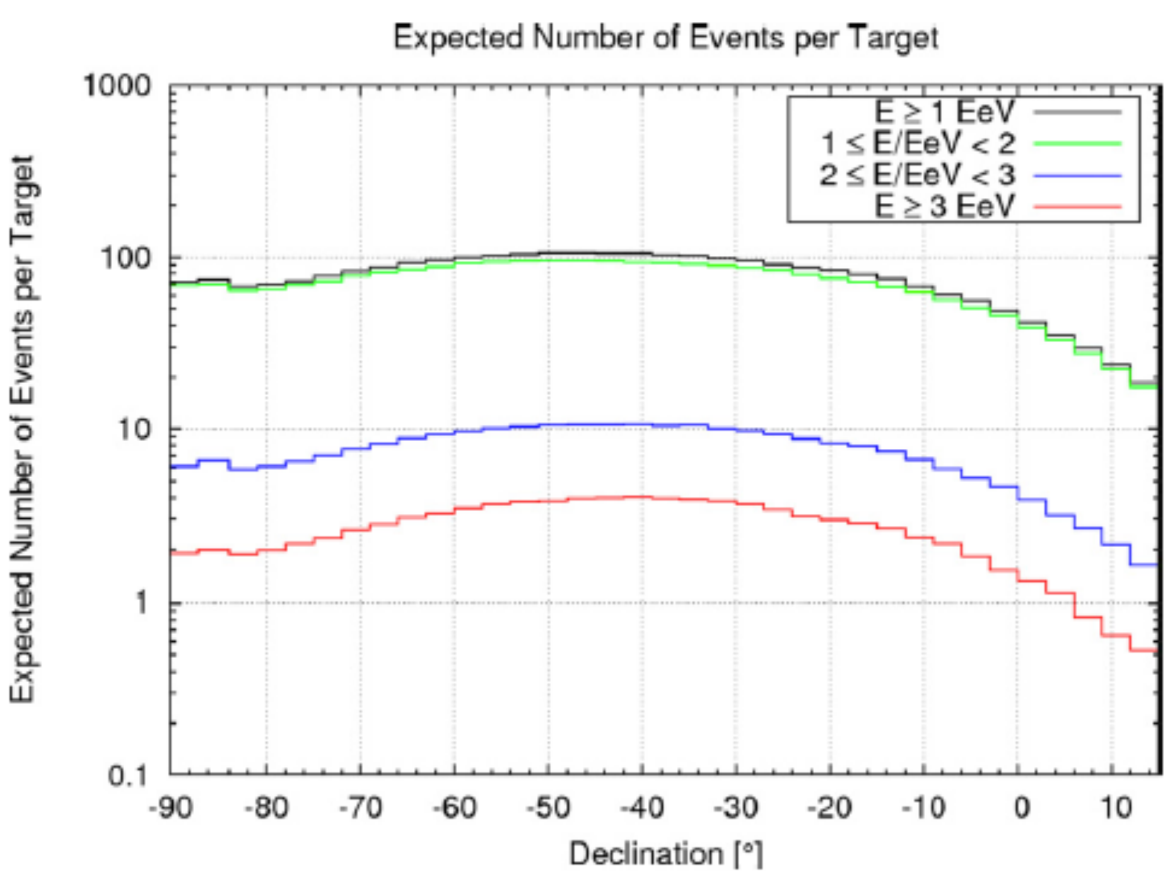
ApJ, 760,148 (2012)

Neutron average traveled distances @ EeV energies:

$$\frac{d_n}{\mathrm{kpc}} = 9.2 \times \frac{E}{\mathrm{EeV}}$$



- Nice view of the GC
- Above 2 EeV, detection volume would contain most of the galaxy



- Blind search over the whole FoV in 4 energy ranges:

1-2 EeV | 2-3 EeV | E>3 EeV | E>1 EeV

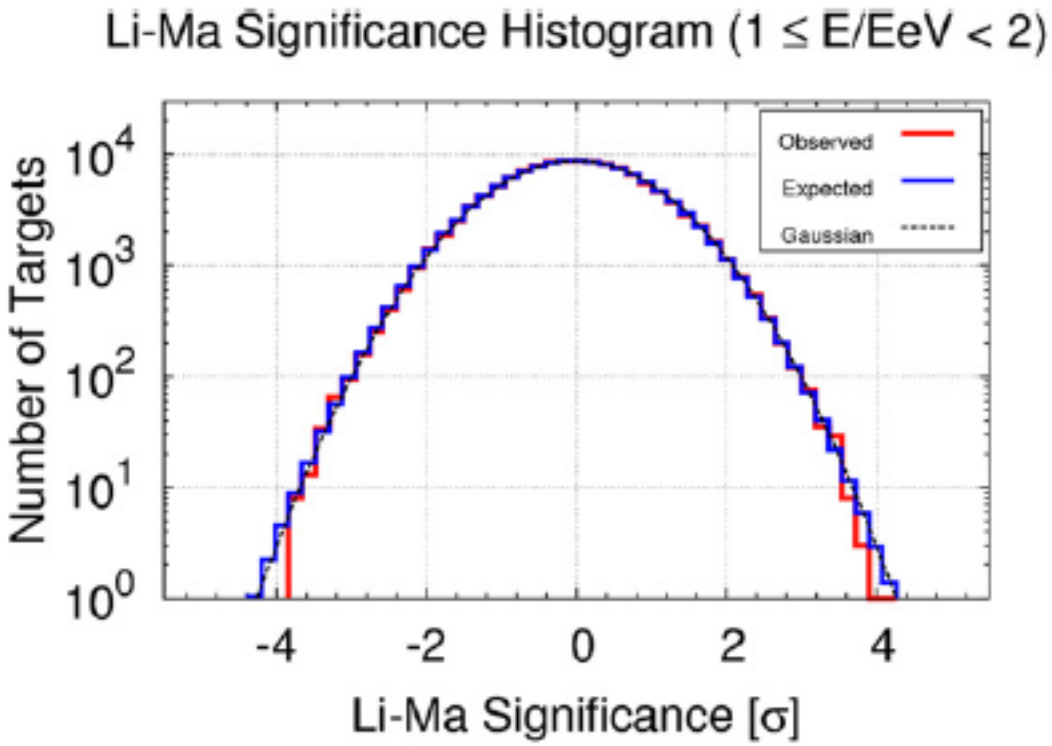
- isotropic expectations from shuffling of the data
- Target size tuned to the detector angular resolution to maximize sensitivity to point sources:

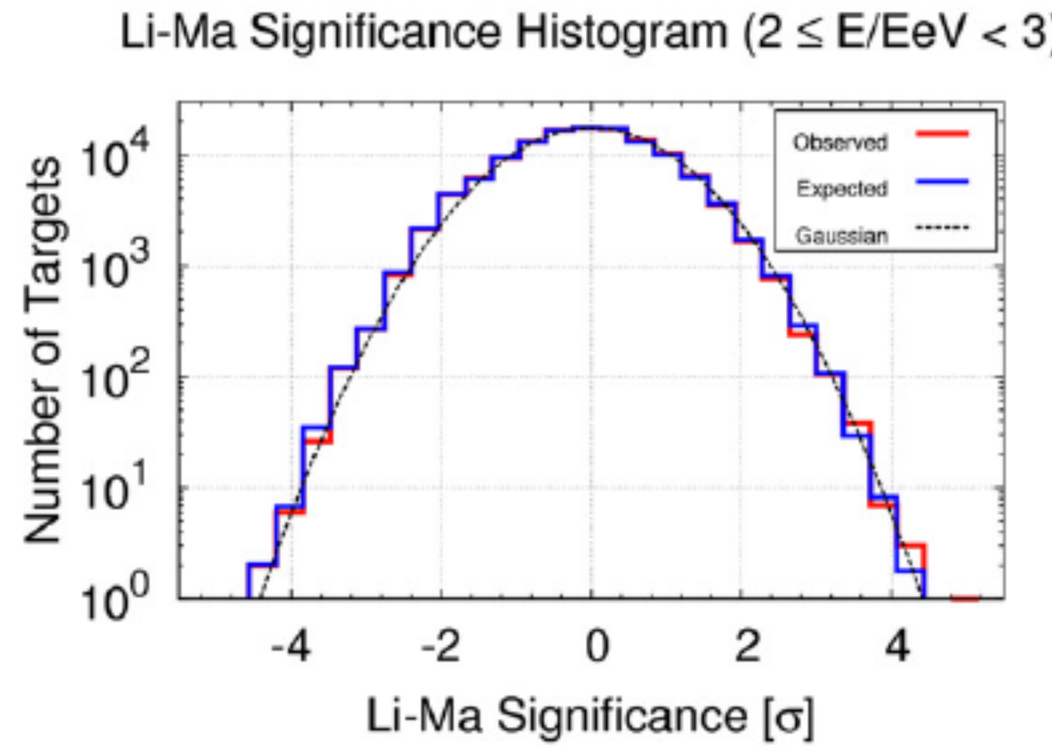
$$(S/N)_{max} \text{ for } \chi = 1.05\psi \text{ (top-hat)}$$

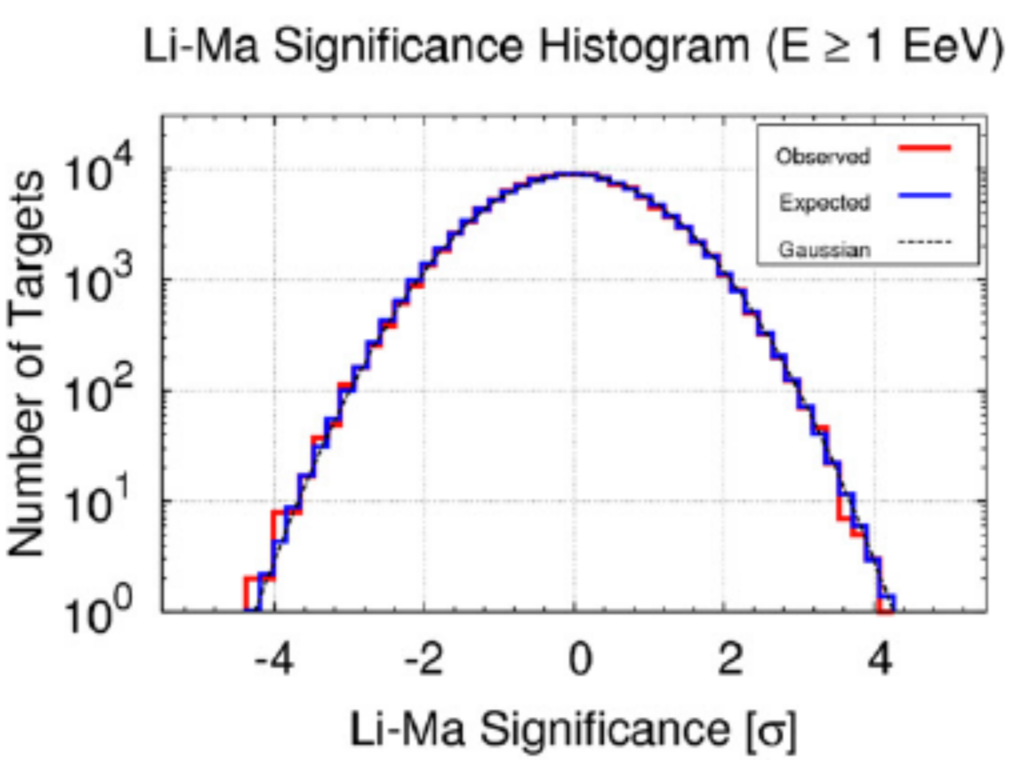
median AR in energy bin

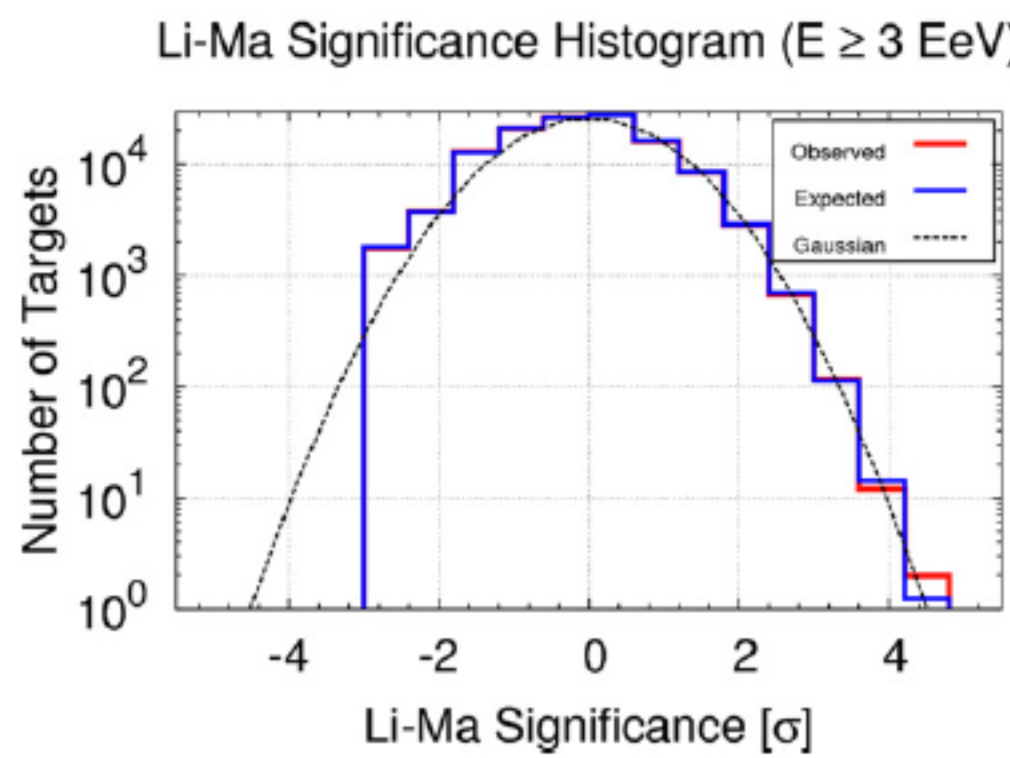
Blind search for neutron excesses

ApJ, 760,148 (2012)









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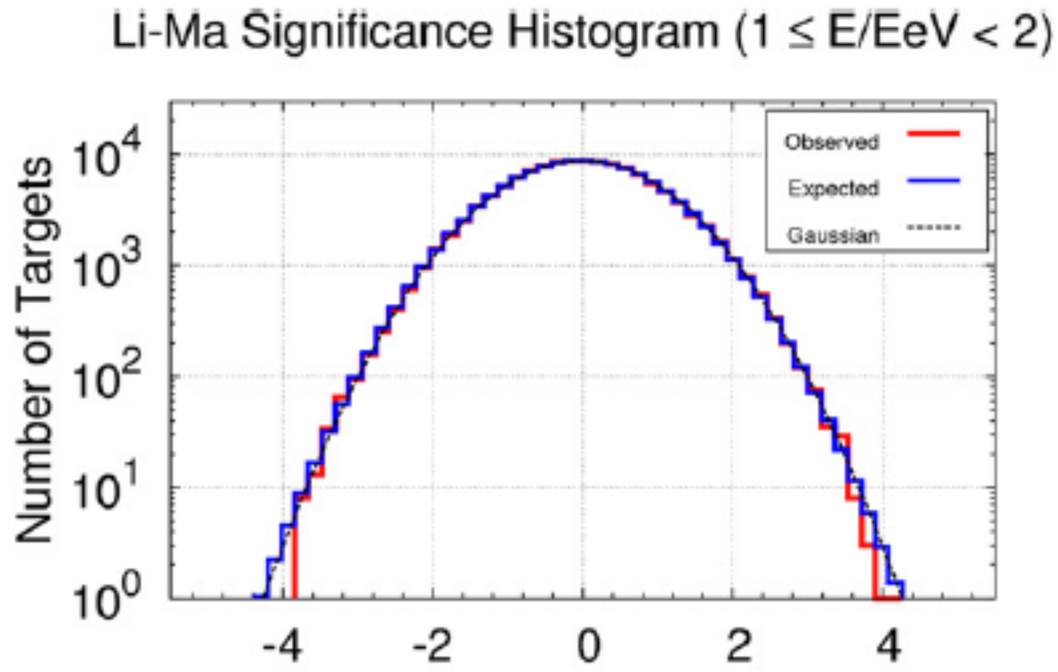
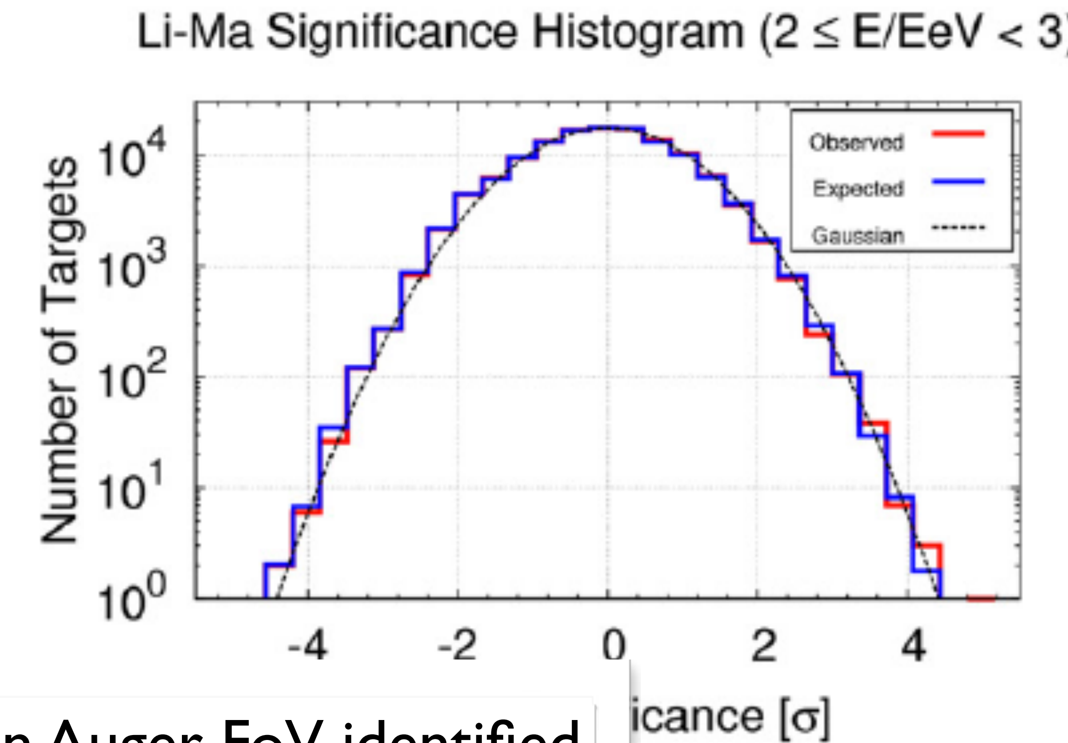
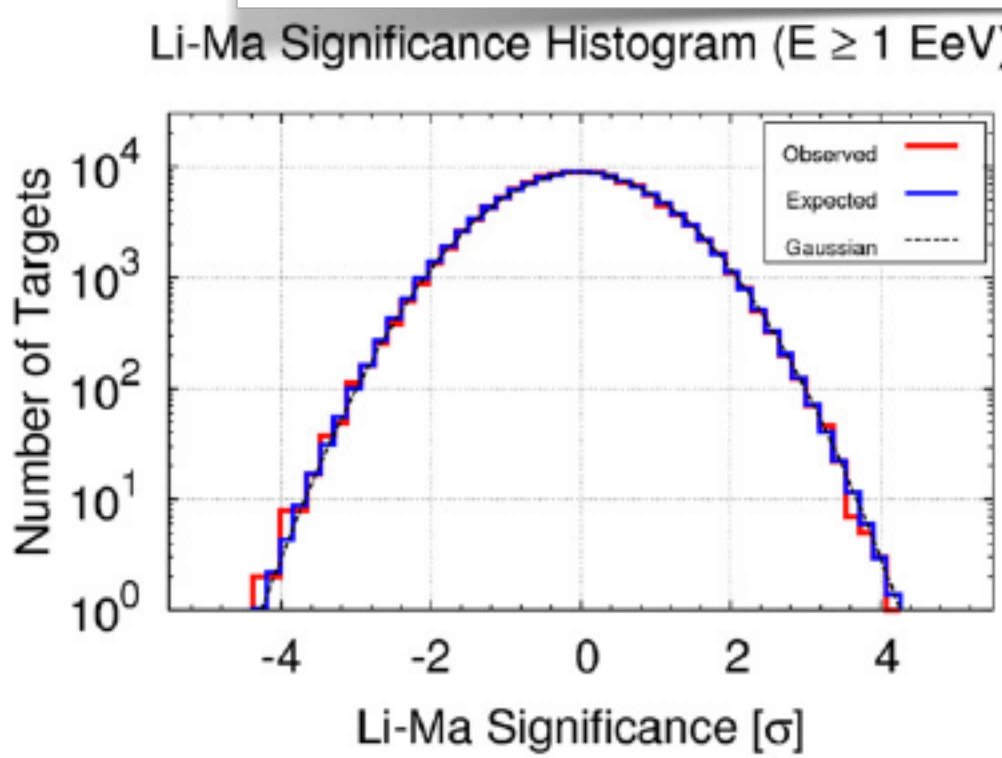
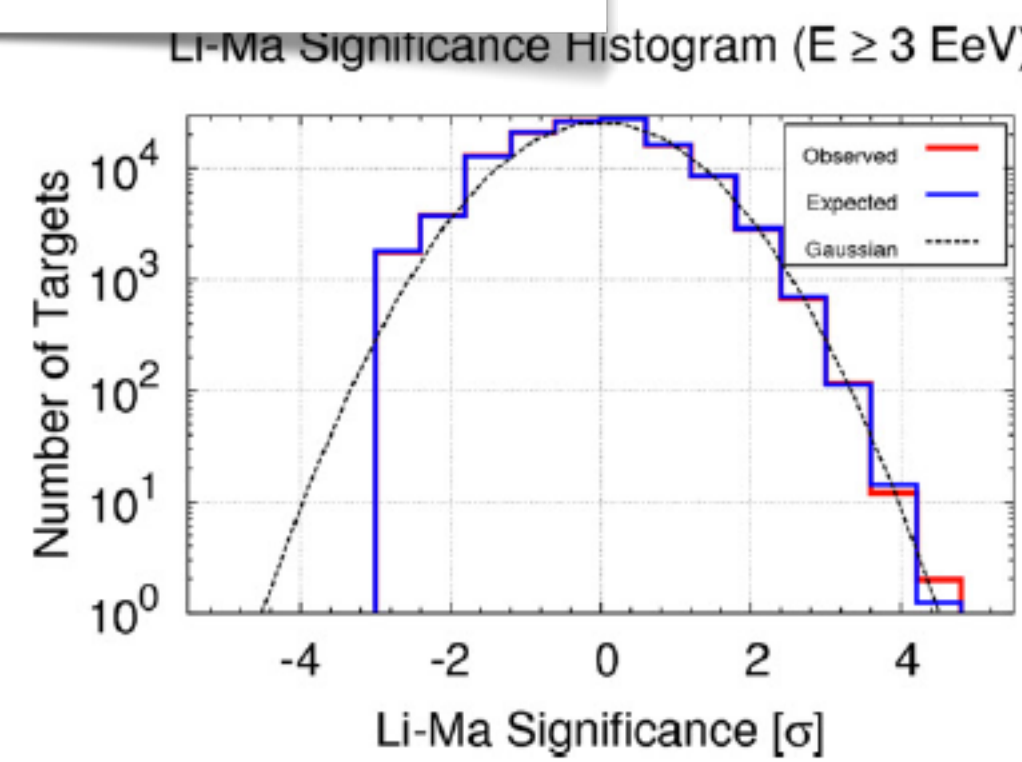




No candidates for neutron sources in Auger FoV identified

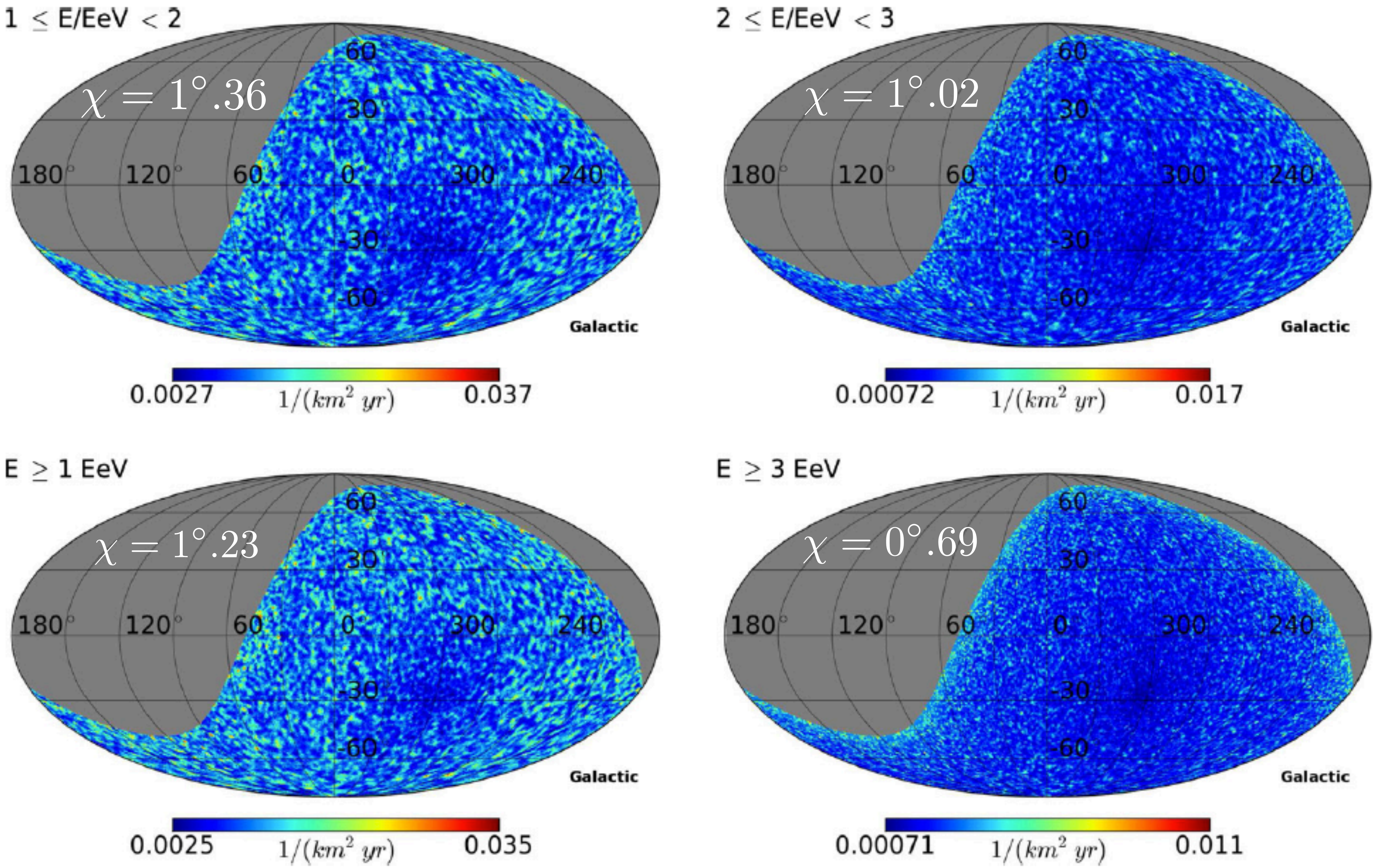




Blind search for neutron excesses

ApJ, 760,148 (2012)

Flux upper limits maps

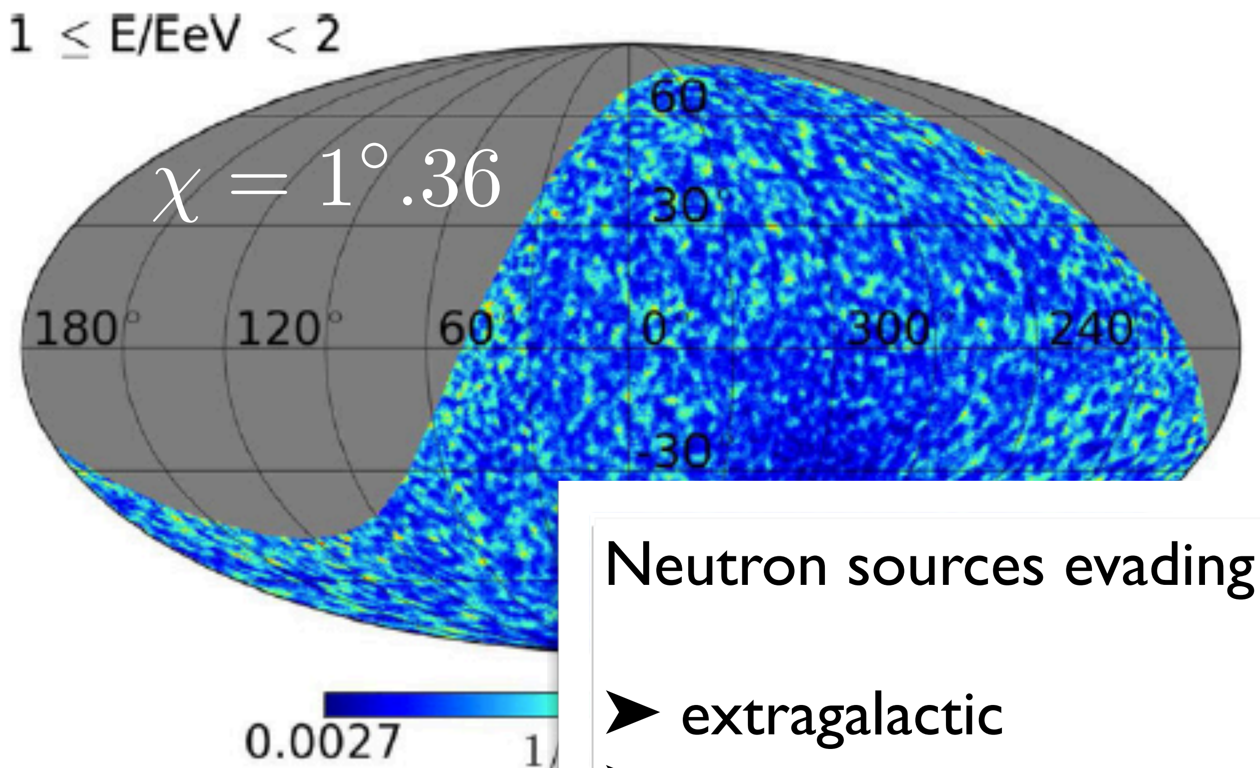


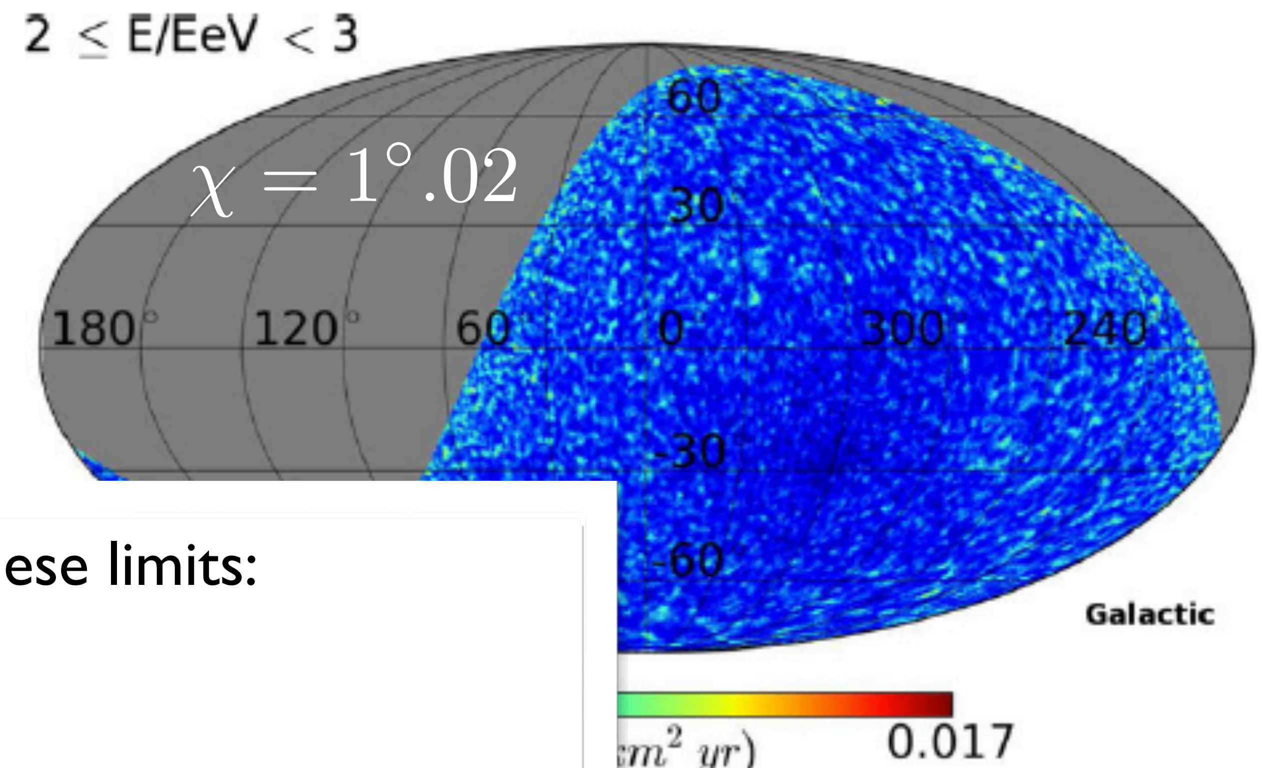
Blind search for neutron excesses

PIERRE AUGER OBSERVATORY

ApJ, 760,148 (2012)

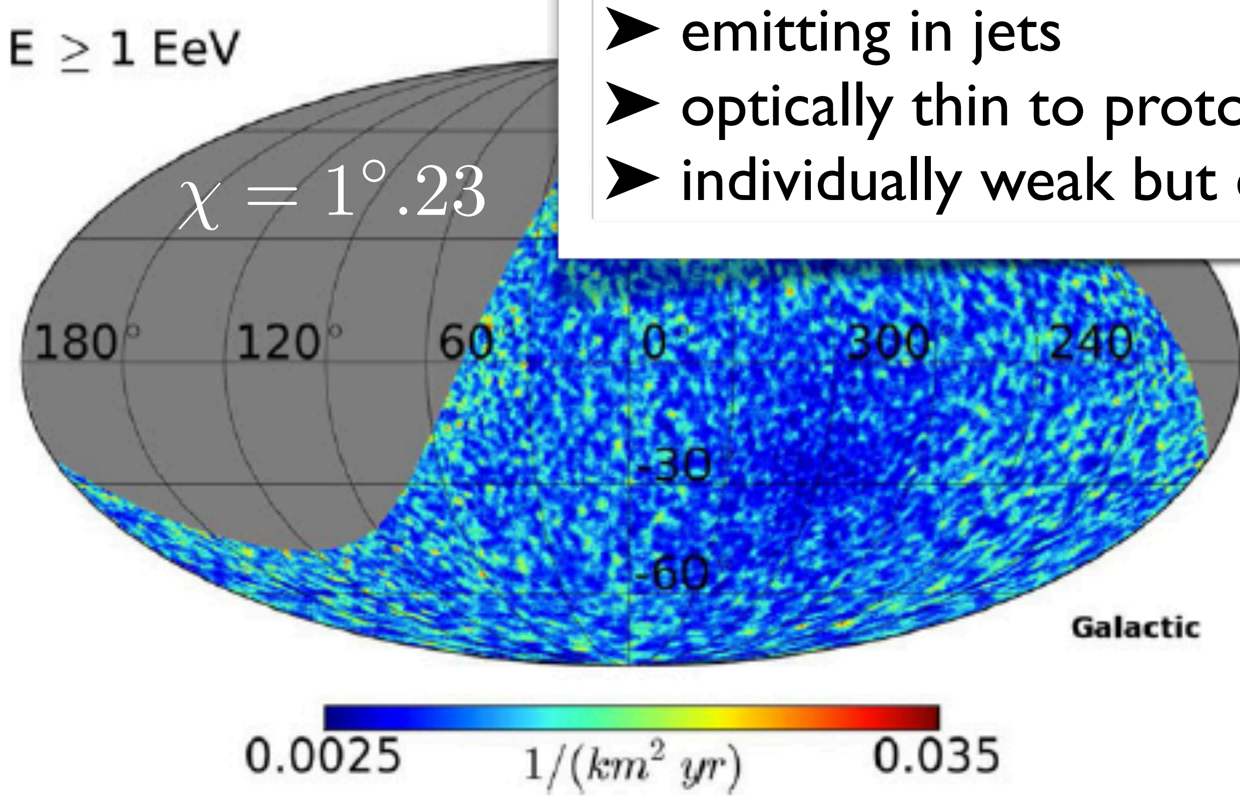
Flux upper limits maps

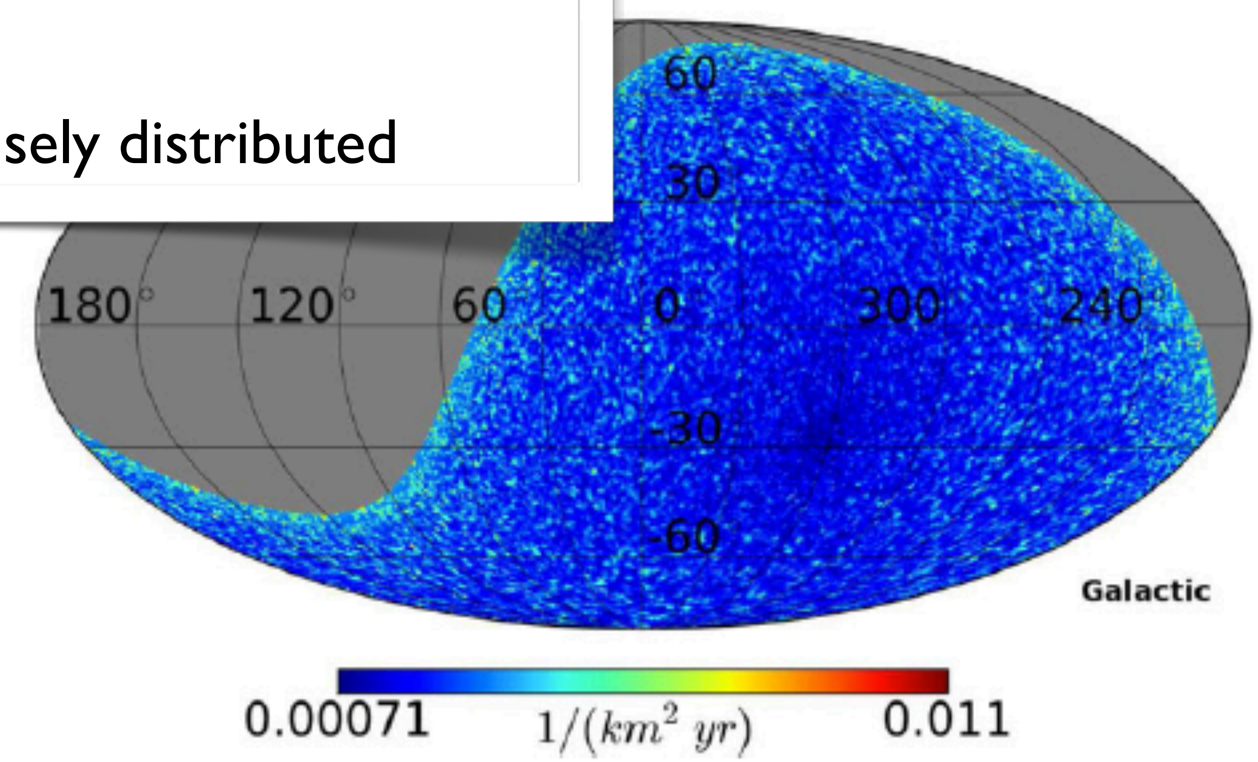




Neutron sources evading these limits:

- ➤ extragalactic
- ➤ transient
- ➤ emitting in jets
- ➤ optically thin to protons
- ➤ individually weak but densely distributed





Multiplets

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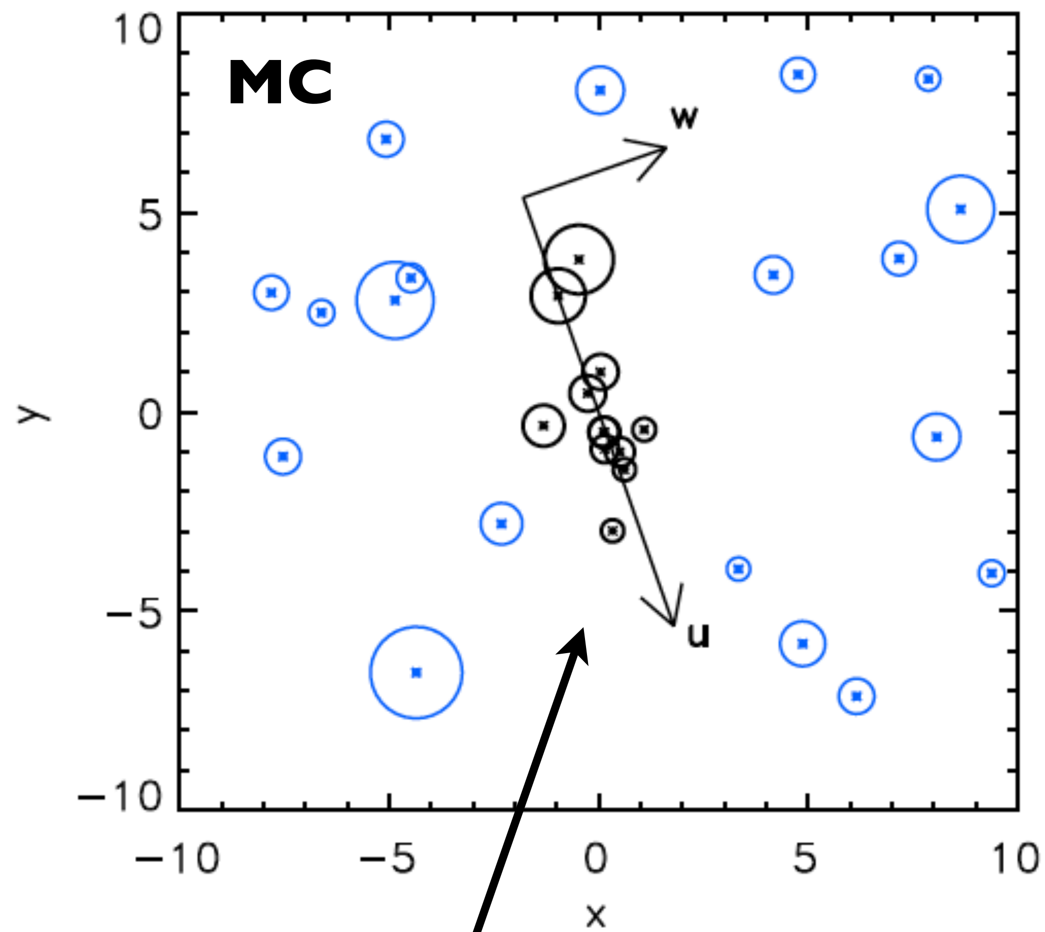
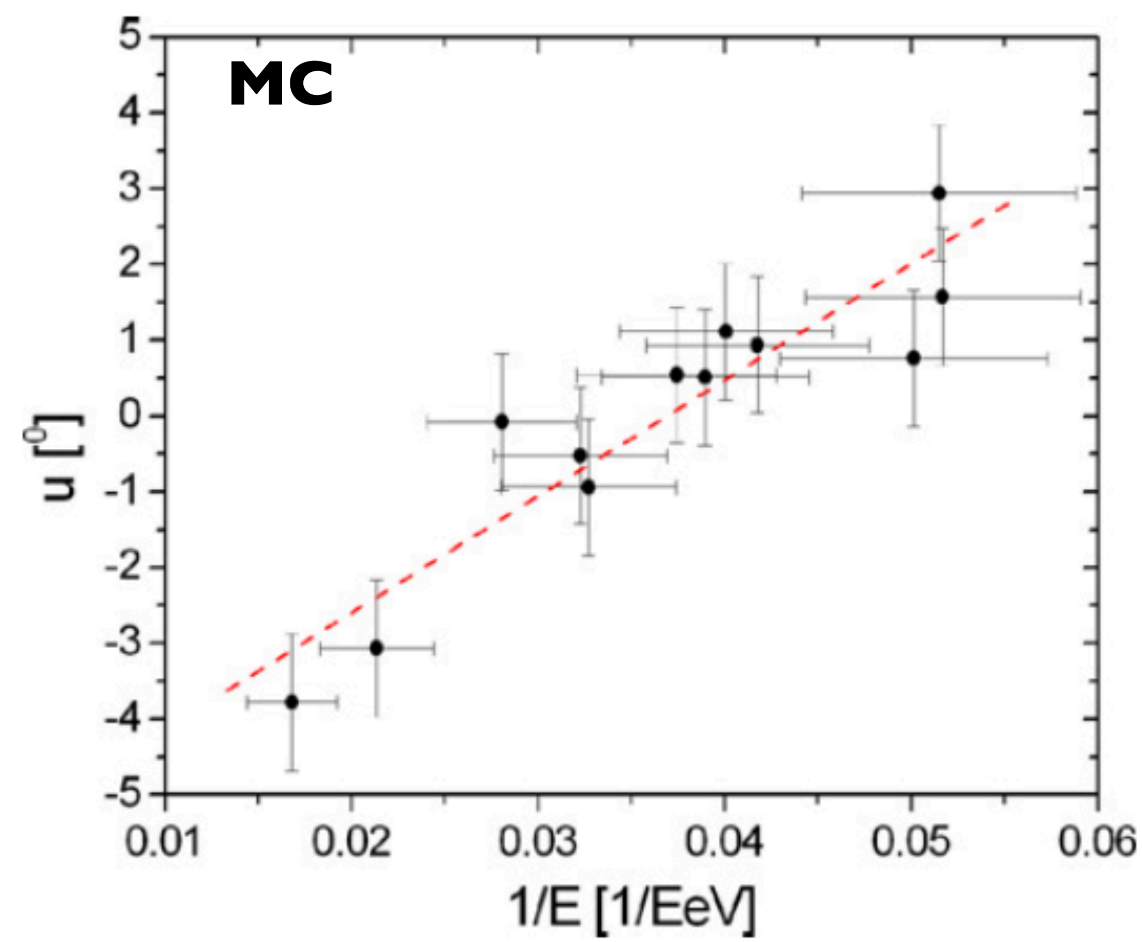
➤ Assuming deflections in the linear regime:

$$\vec{\theta} = \vec{\theta_s} + \frac{Ze}{E}\int_0^L d\vec{l} \times \vec{B} \simeq \vec{\theta_s} + \frac{\vec{D}(\vec{\theta_s})}{E}$$

$$\mathrm{Cov}(x, 1/E) = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(1/E_i - \langle 1/E\rangle)$$





(u,w) system has maximal **u x 1/E** covariance

multiplet defined by correlation coeff. **C** and width **W**

$$C(u, 1/E) = \frac{\mathrm{Cov}(u, 1/E)}{\sqrt{\mathrm{Var}(u)\mathrm{Var}(1/E)}}$$

Cmin and Wmax chosen from simulations
with extragal. sources and BSS-S gal. field

Multiplets

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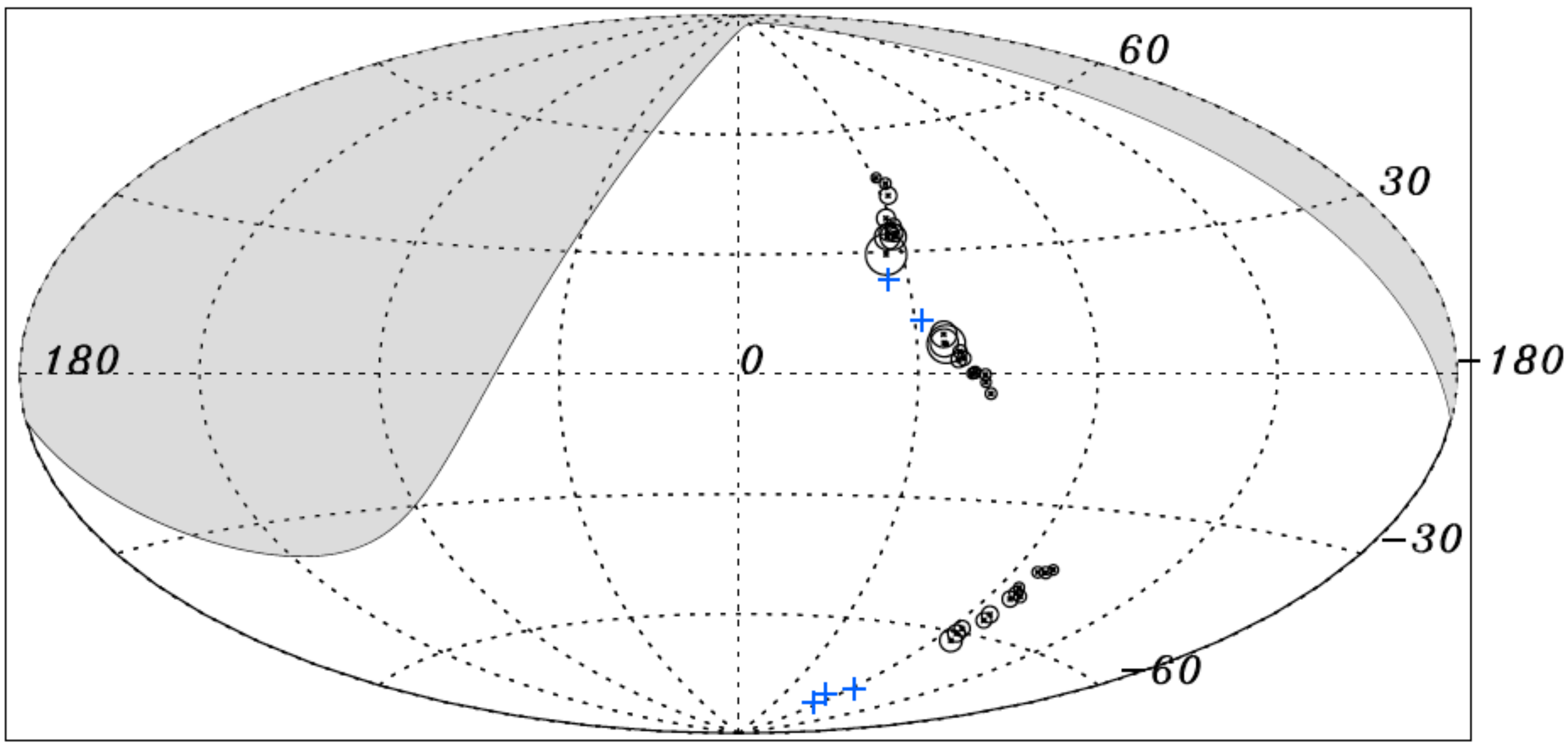
- E>20 EeV (1509 events)
- 5T5 + core inside active triangle
- AR<1 degree
- W_{max}=1.5 degree
- C_{min}=0.9
- At least one event with E>45 EeV



Fraction of isotropic skies with multiplets of at least 12 events: 6%

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Summary

- First harmonic amplitudes marginally in agreement with isotropic expectation in a few energy bins above 1 EeV
- Non-random phases over a large energy range.
- Constraining upper limits on dipole and quadrupole amplitudes. Derived limits on galactic composition + magnetic fields
- No neutron excesses identified above 1 EeV
- No significant evidence for the existence of correlated multiplets in the data