Anisotropy of High Energy Cosmic-Rays

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In collaboration with Eli Waxmann
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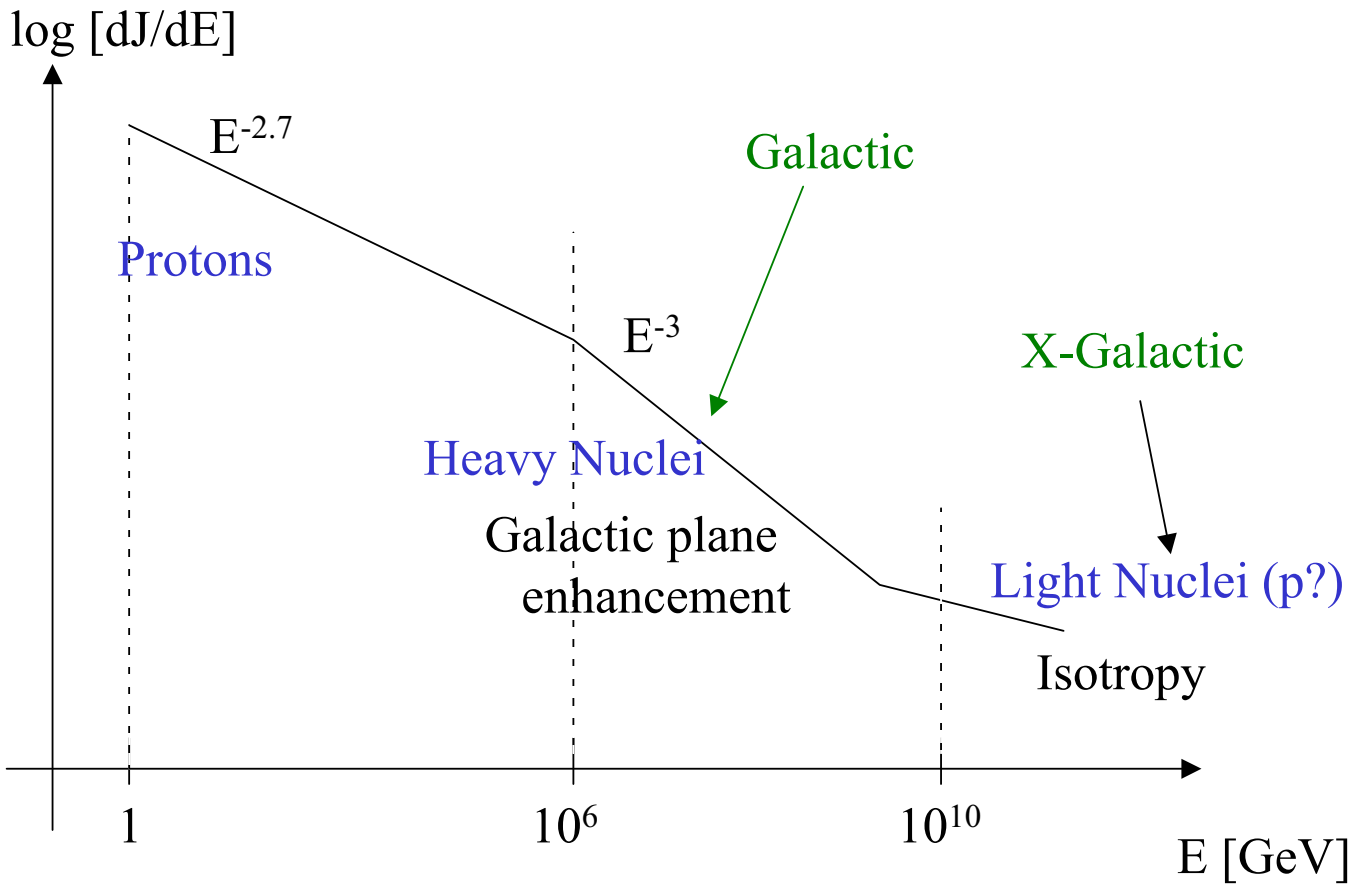
log [dJ/dE]
E-2.7
Protons
Galactic
E-3
X-Galactic
Heavy Nuclei
Galactic plane
enhancement
Light Nuclei (p?)
Isotropy
1
10^6
10^10
E [GeV]

Isotropy of $E > 10$ EeV Cosmic Rays - Motivation

- What are the sources?

$$L_{tot} > 5 \times 10^{44} \frac{\text{erg}}{s} \left(\frac{E_p}{100 \text{ EeV}} \right)^2 \frac{\Gamma^2}{\beta}$$

(1 EeV$= 10^{18}$ eV)
$\Rightarrow$ only GRB sources and AGNs are possible, have different correlation to galaxy density.

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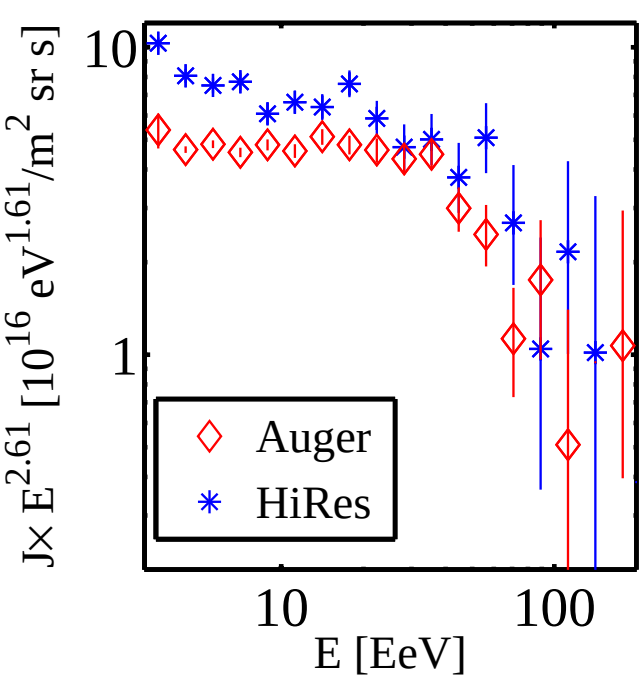
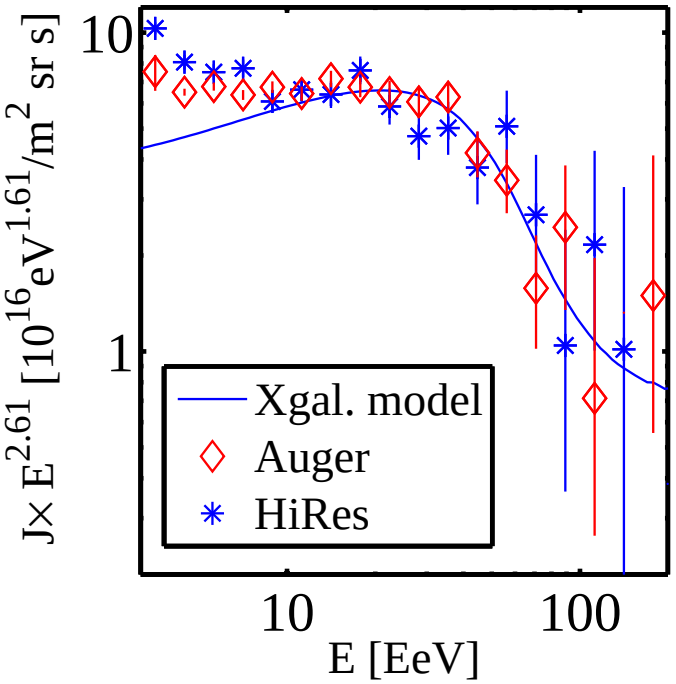
- New Auger Observatory - 3000 km^2: many events.
- Our work:
What is the best statistics to extract the correlation between UHCRs and LLS (Large scale structures)?

GZK suppression

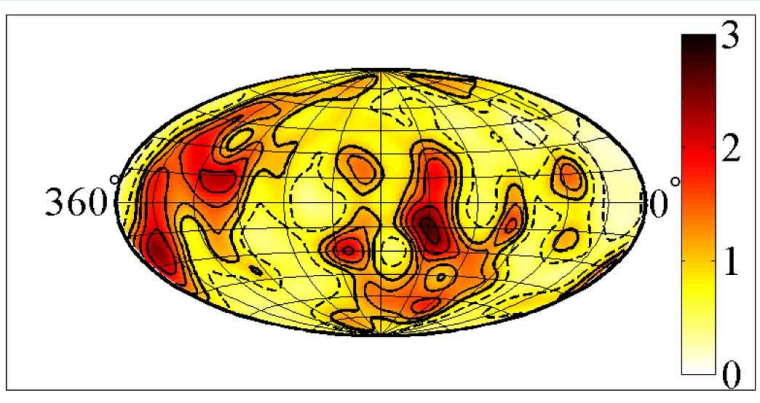
$$p\gamma \rightarrow \pi n \;\Rightarrow\; d_{GZK}(E \sim 60 \text{ EeV}) \sim 200 \text{ Mpc} \ll 4 \text{ Gpc}$$

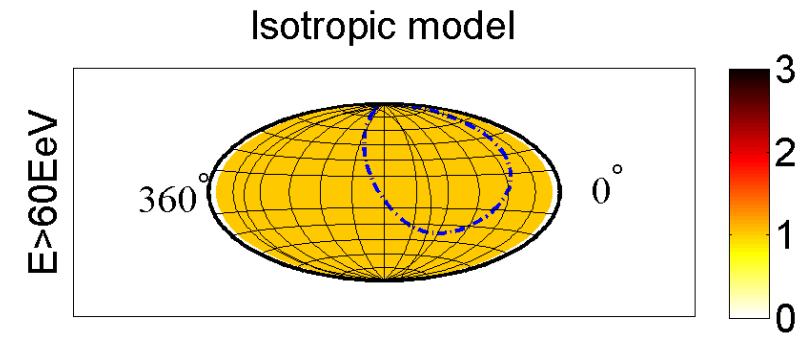


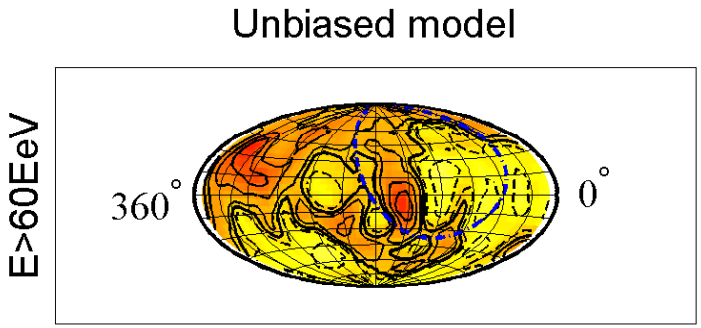


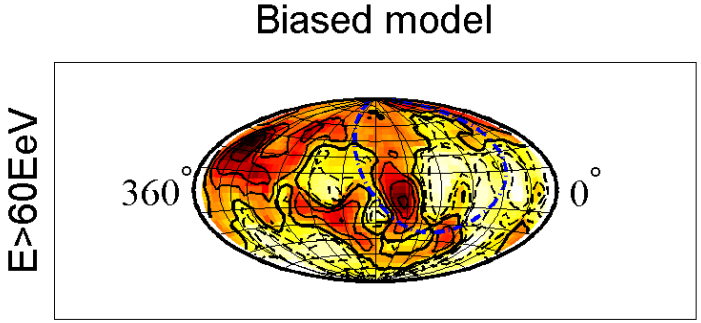
Cosmic ray intensity

IRAS catalog → Integrated galaxy density till $d = 75$ Mpc









How to measure correlation?

- Most of the literature: Two-point angular correlation:

$$W(D) = \sum_{i}^{N} \sum_{j<i} \Theta(D - D_{ij})$$

Angular power spectrum:

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} a_{\ell m}^2.$$

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- Here: Cross Correlation (i - bin no. of $6^\circ \times 6^\circ$)

$$X_{C,UB} = \sum_{\{i\}} \frac{(N_i - N_{i,ISO})(N_{i,UB} - N_{i,ISO})}{N_{i,ISO}}$$

To compare: $X_Y(\ell) = \sum_\ell \frac{(C_\ell - C_{iso,\ell})^2}{\sigma_\ell^2}$, σ_ℓ^2- the variance.

Results: cross correlation is better

P(I/UB) $\equiv$ probability for ruling out isotropy assuming unbiased.

For simulated events with Auger exposure and $\bar{s}_0 = 10^{-4}/\mathrm{Mpc}^3$ at 95% CL:

$E > 40$ EeV 100 events	P(I/UB)	P(I/B)	P(UB/B)
$\mathbf{X_C(UB)}$	**23%**	**79%**	**42%**
$X_W(\{D\} = \{0:10:40\})$	7%	12%	10%
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One should take the cutoff at $E > 40$ EeV for isotropy analysis:

$X_{C,UB}$ 300 events	P(I/UB)	P(I/B)	P(UB/B)
$E > 20$ EeV (1205 events)	45%	94%	45%
E > 40 EeV 300 events	**39%**	**94%**	**52%**
$E > 60$ EeV (94 events)	31%	87%	42%
$E > 80$ EeV (31 events)	22%	63%	24%

Analyzing Auger's signal

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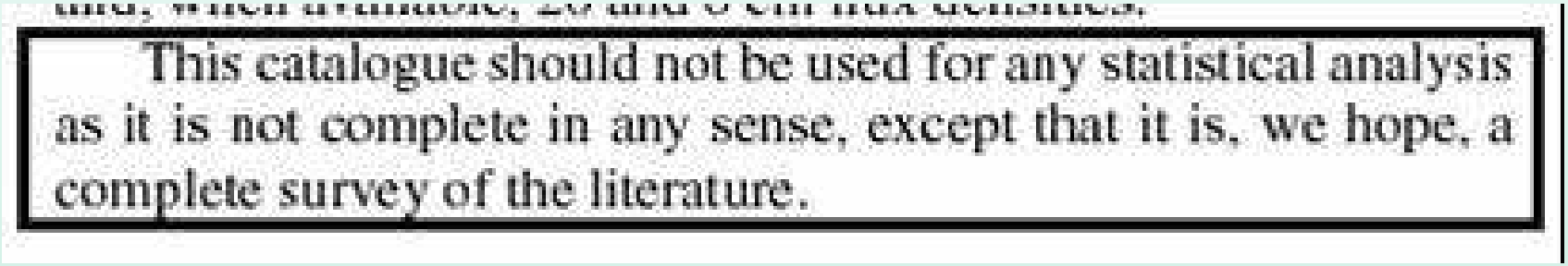
Veron-Cetty and Vernon paper:



This catalogue should not be used for any statistical analysis as it is not complete in any sense, except that it is, we hope, a complete survey of the literature.

HiRes: 24%.

Correlation with LSS? Unclear.

Analyzing Auger's signal

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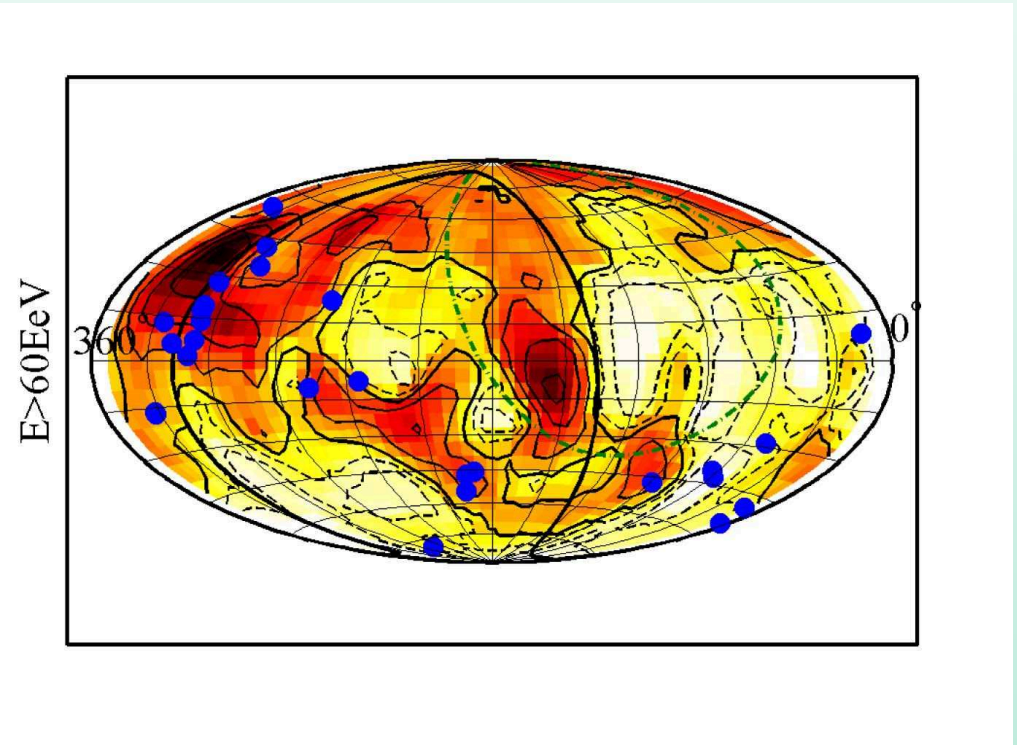
Our cross correlation with LSS:

- Isotropy ruled out at 98% CL.
- Consistent with source density following LSS.

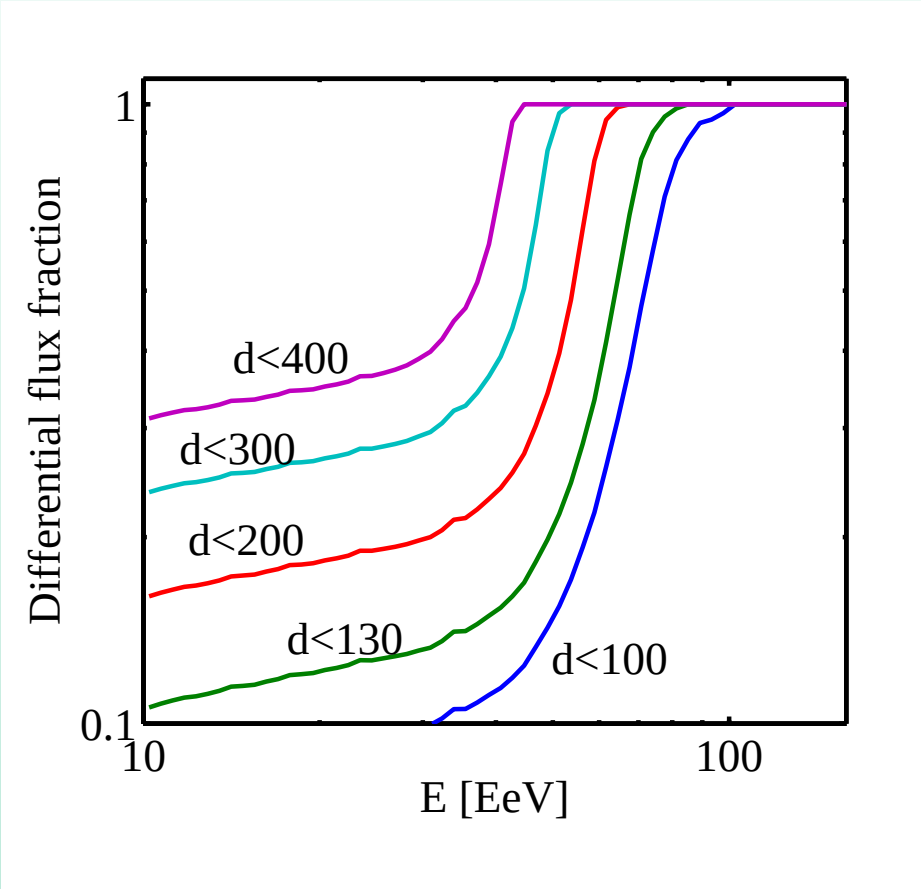


Conclusions

1. Cross-correlation statistics is more sensitive to the expected anisotropy signature than power spectrum and two point correlation function.
2. In order to distinguish between the different bias models, $\Delta E/E_{abs}$ should be reduced (currently $\simeq 25\%$).
3. The angular distribution reported by Auger is:
   - inconsistent with Isotropy at 98% CL.
   - consistent with LSS with slight preference to a biased distribution.

The GZK Suppression

[tb]



Differential Flux function in ΛCDM.

The Model

- The generation spectrum of cosmic rays above 10^{19}eV:

$$\frac{d\dot{N}}{d\epsilon} = \Phi_0 \epsilon^{-\alpha} \qquad \text{with } \alpha \approx 2,$$

  with energy production rate of $\Phi_0 = 0.8 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$.
- Proton sources trace large-scale galaxy distribution.
- The number density of CR sources is Poisson distributed.
- The protons lose energy due to interactions with CMB photons, produce e^+e^- and π's ($\Rightarrow \nu$'s).

The Model parameters

- $\bar{s}(z)$ - the average comoving number density of CR sources at redshift z:

$$s(z) = \bar{s}_0(1+z)^{m+3}$$

where $\bar{s}_0 = 10^{-2} - 10^{-4}/\mathrm{Mpc}^3$, $m = 0 - 3$.

- $b(\delta\rho)$ - a (bias) function of the local galaxy overdensity $\delta = \frac{\delta\rho}{\bar{\rho}}$:
  1. Isotropic model: $b[\delta] = 1$
  2. Unbiased model: $b[\delta] = 1 + \delta$
  3. Biased model

$$b[\delta] = \begin{cases} 1+\delta & \delta > \delta_{\min} \\ 0 & \delta < \delta_{\min} \end{cases} .$$

All distributions are Poisson distributions

1. The mean number density of CR sources in dV at z

$$\bar{S} = \bar{s}(z) b(\delta\rho) dV$$

2. The mean number of detected CR events produced by source at redshift z is

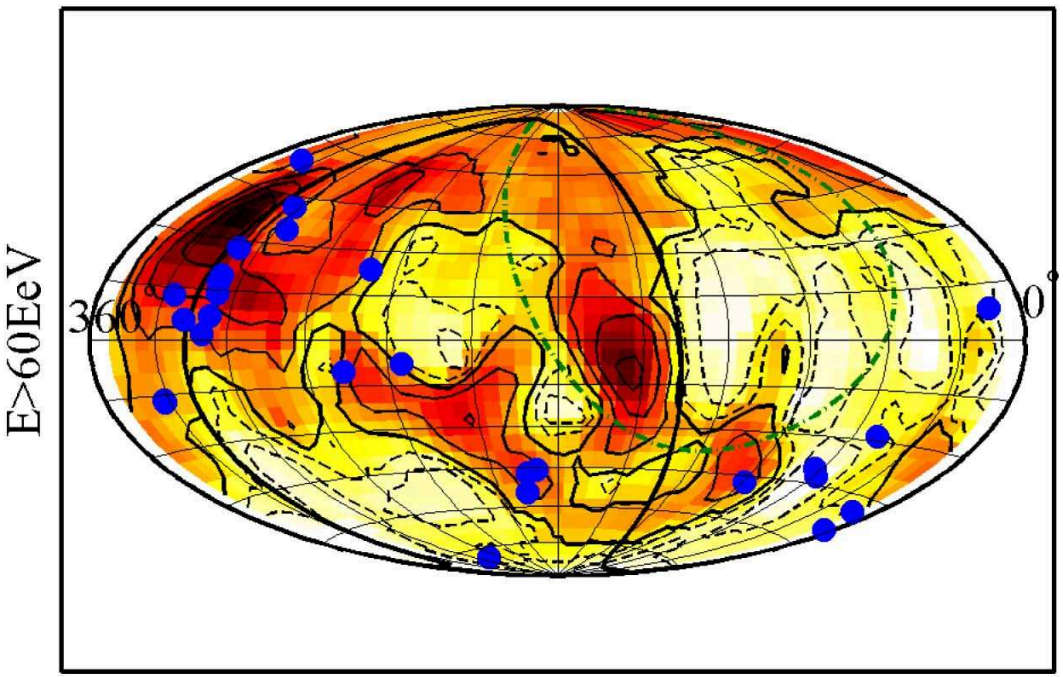
$$\bar{N}(> E, z) = \frac{dn}{dt dA} AT = \frac{\dot{n}_0 \left[E_0(E, Z)\right]}{\bar{s}_0} \frac{(1+z)AT}{4\pi d_L(z)^2}$$

   - A and T are the detector area and observation time,
   - $\dot{n}_0(E)$ is the CR production rate above energy E per unit volume,
   - $d_L(z)$ is the luminosity distance.

3. $\Rightarrow$ The mean number of observed CR events per steradian

$$\bar{N}_0(E, \hat{\Omega}) = \int dr r^2 \bar{N}(E, z) s(z) b[\delta\rho(z, \hat{\Omega})]$$

Auger: correlation to AGNs? [Auger, Science 2007]



27 events with $E > 57$ EeV	P(I)	P(UB)	P(B)
$X_{C,UB}(E > 57\ EeV)$	0.9%	3.8%	20.4%
$X_{C,UB}(E > 68\ EeV)$	1.5%	5.7%	27.6%

Sensitivity to parameters

Figure: Dashed:(a) $\alpha = -2.2$; (b) $\bar{s} \propto (1+z)^0$;
(c) $\bar{s}_0 = 10^{-2}\mathrm{Mpc}^{-3}$;(d) 30 EeV (50 EeV) systematic energy uncertainty (actual energy 40 EeV).