Large-scale Anisotropy of Ultra-high Energy Cosmic Rays: A Single Source in Turbulent Magnetic Fields

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Motivation (I) - Observations

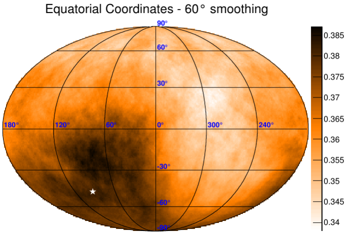

Figure: Smoothed Skymap Auger+TA, ref: ICRC2015, arxiv:1511.02103

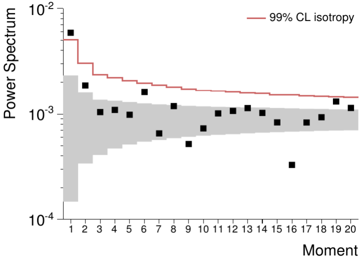

Figure: Angular Power Spectrum Auger+TA, ref: ICRC2015, arxiv:1511.02103

- a highly isotropic sky can be caused by strong intervening magnetic fields or/and homogeneous source distribution
- the signature of dipole...

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Motivation (II) - Monte Carlo simulations

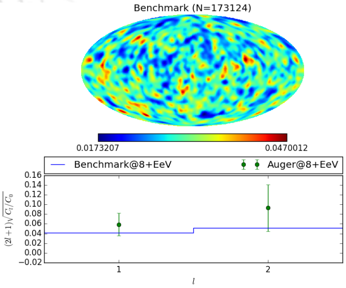

Figure: Dipole and quadrupole from the benchmark scenario (8+EeV), CRPropa3

- Complex Monte Carlo simulations can reproduce observations
- Local sources are giving the main contribution to the large-scale anisotropies
- ...although space of parameters is too big to draw clear conclusions
- Many technical burdens (e.g. the effect of the finite-size observer in forward-tracking MC)
- *Can't see the forest for the trees*

- **A simple analytical model can shed some light on the subject and to serve as a cross-check for MC simulations**

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Ingredients

A simple model:

- distant sources contribute isotropically
- a nearby source is the sole responsible for the anisotropy
- turbulent magnetic fields smear arrival directions
- for start, neglect interactions and mixed composition

Details:

- The single source (Fisher – von Mises distribution):

$$f(\hat{\mathbf{r}}) = \frac{\kappa}{4\pi \sinh(\kappa)} \exp(\kappa \hat{\mathbf{r}} \cdot \hat{\mathbf{r}}_{\rm src}) \Rightarrow C_\ell = j_{\rm src} \left(\frac{\mathcal{I}_\ell}{\mathcal{I}_0} \right)^2$$

$\mathcal{I}_0$ can be reduced to the following recursion:

$$\mathcal{I}_\ell = \int_{-1}^{1} du \, \exp(\kappa u) \, P_\ell(u) \Rightarrow \mathcal{I}_0 = \frac{2}{\kappa} \sinh(\kappa) \quad \mathcal{I}_1 = \frac{2 \sinh(\kappa)}{\kappa} \left(1 - \frac{1}{\kappa}\right) = \mathcal{I}_0 \left(1 - \frac{1}{\kappa}\right)$$

$$\mathcal{I}_\ell = \mathcal{I}_{\ell-2} - \frac{2\ell - 1}{\kappa} \mathcal{I}_{\ell-1}$$

- Isotropic background (uniform distribution) $\Rightarrow C_0^{\rm bg} = j_{\rm bg}$

Isotropic background just lowers the total anisotropy: to quantify it a ratio between fluxes η is introduced.

Parameters:

- $\kappa = \frac{1}{\theta^2_{\rm rms}} = f(L, L_c, B, E/Z)$
- $\eta = j_{\rm src}/j_{\rm bg}$

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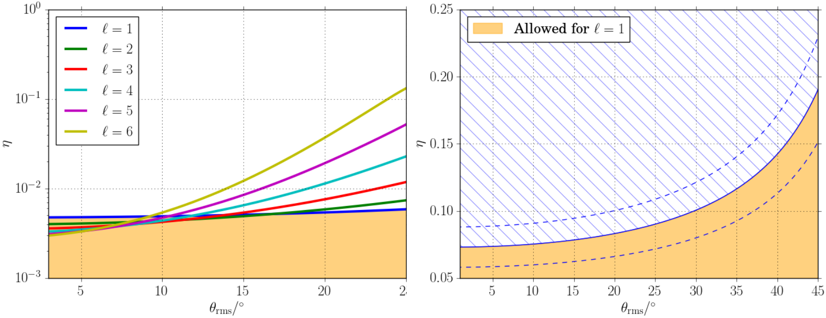
Results: Allowed parameter space



- the most constraning moment for the model is the dipole ($\ell = 1$)
- $\eta \to 0$ the less relevant is the single source which is causing anisotropy;
- $\kappa \to 0$ ($\theta_{\mathrm{rms}} \to 4\pi$) the anisotropy is washed out due to stronger magnetic fields, greater distance of the source from the observer etc.
- the nearby source is allowed if the flux from it is rather weak or if the intervening magnetic fields are substantial

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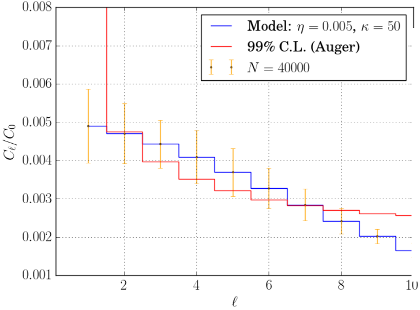
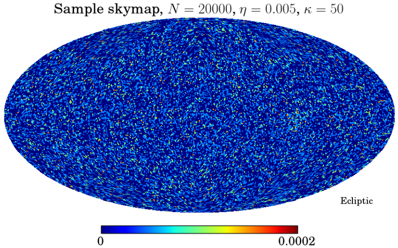
Results: Convergence / Errorbars





- Errorbars for $N = 20k$ events are quite high compared to the current 99% C.L. from Auger
- Convergence: $\sigma \sim \frac{1}{N^2}$

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Summary

- Results of Monte Carlo simulations in the context of anisotropies are hard to interpret unambiguously due to many involving parameters and acquiring acceptable levels of statistics is a really demanding in a sense of computation time
- Analytical approach is considered to support numerical results and to narrow the parameter space
- Although there are no strong constrains due to relatively high uncertainty for a given number of events, there is a sign-post for Monte Carlo simulation users: **"Don't put too luminous sources closed to the observer if you want to avoid high anisotropies!"**
- Outlook: on the presented basis, investigate the influence of structured magnetic field and how would it change the argument

Thank you for your attention