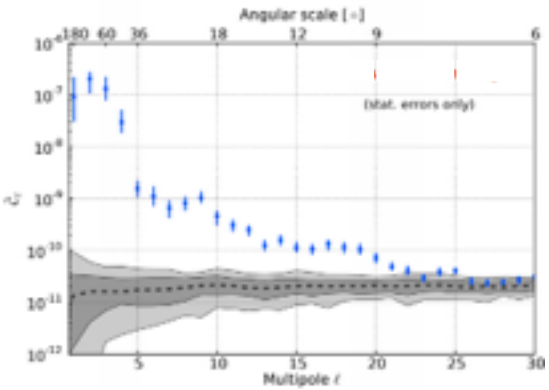
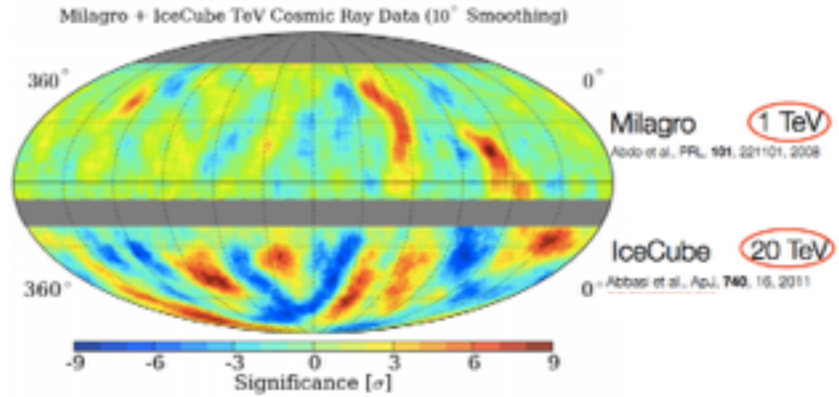
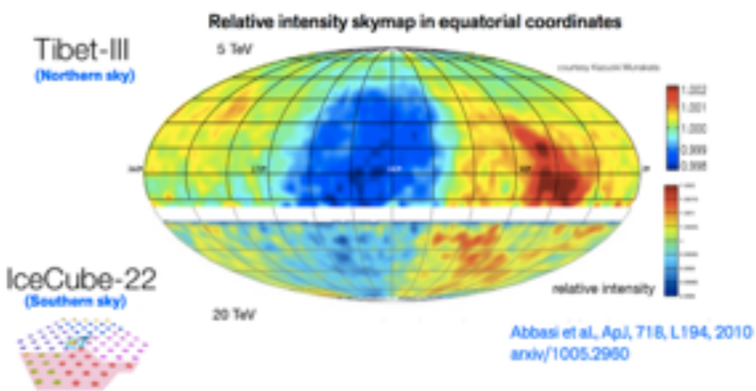
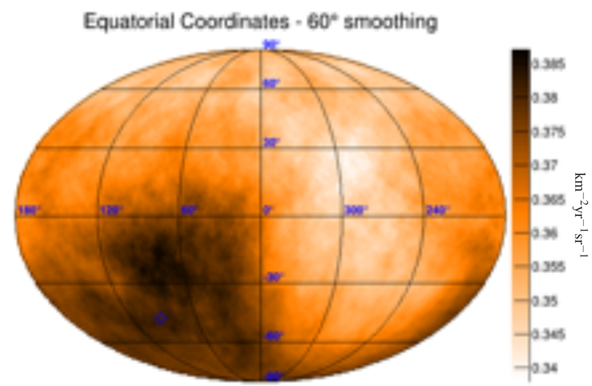






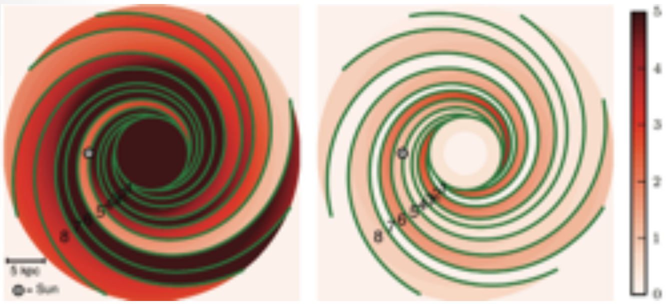
Auger/TA
>10 EeV



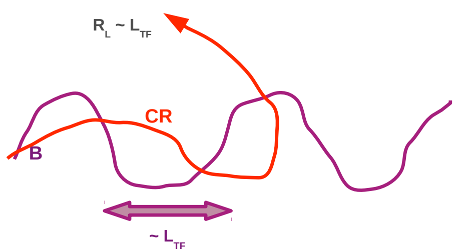
Cosmic Ray Anisotropies: A Review

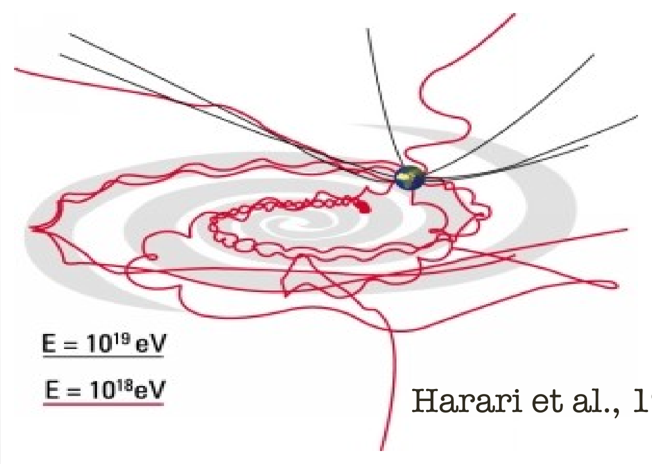
O. Deligny (CNRS/IN2P3 - IPN Orsay) - ECRS 2016

Cosmic Rays and Propagation Regimes

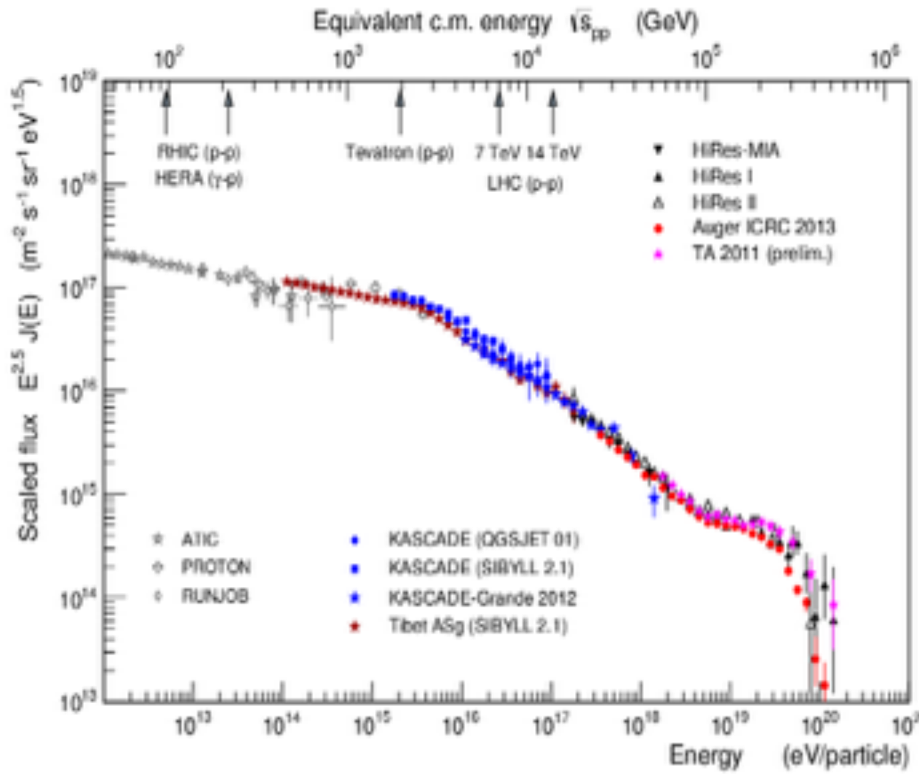


Janssen & Farrar, 2012





Harari et al., 1999



?

Diffusion

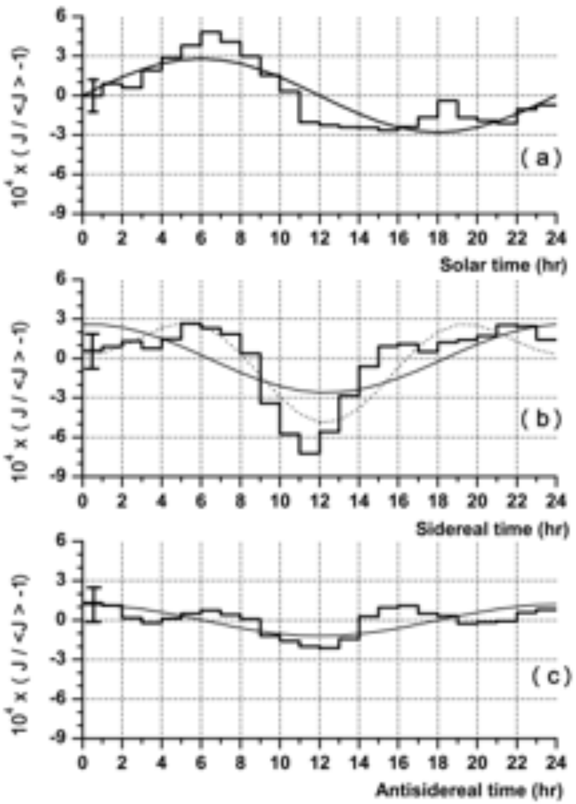
Diffusion/Drift

Ballistic?

Anisotropy and CR Observatories

- Challenge: Control of the counting rate at the level of the anisotropy contrast searched for (weather modulations, local-angle dependences of the energy estimators, etc.)
- Of particular interest/difficulty: dipole
- In most cases, searches in right ascension only (be it in several declination bands): not the \`real\` dipole!

Example of \`good\` analysis:



Compton-Getting (solar)

Sidereal

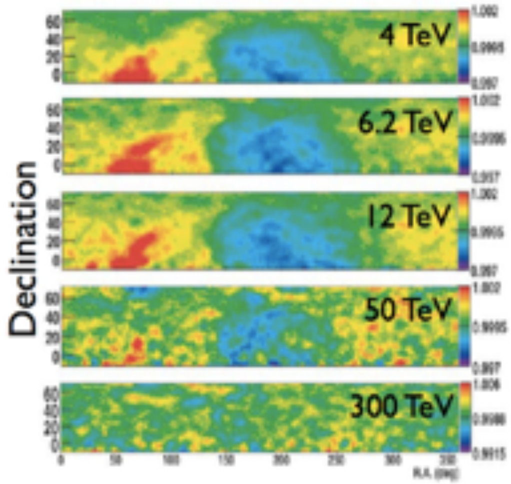
Fluctuations (anti-sidereal)

Aglietta et al. (EAS-TOP collaboration), ApJ 692 (2009) L130

Dipole Observations

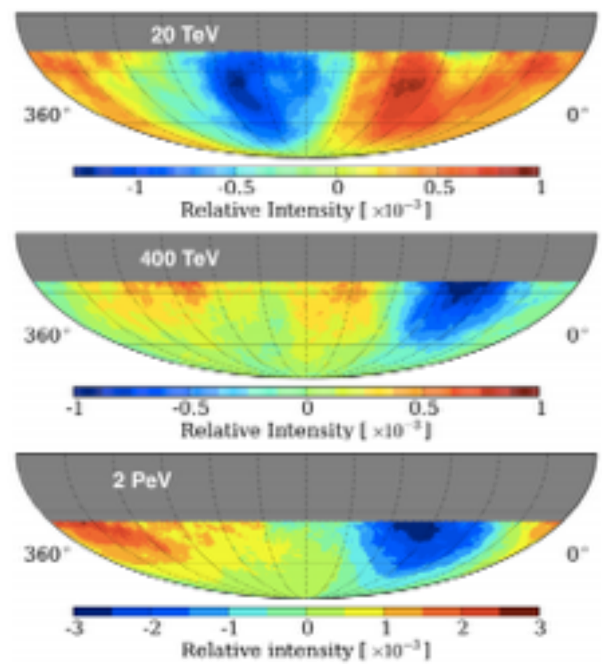
- Northern hemisphere: Tibet ASγ, Super-Kamiokande, Milagro, EAS-TOP, MINOS, ARGO-YBJ
- Southern hemisphere: IceCube/IceTop

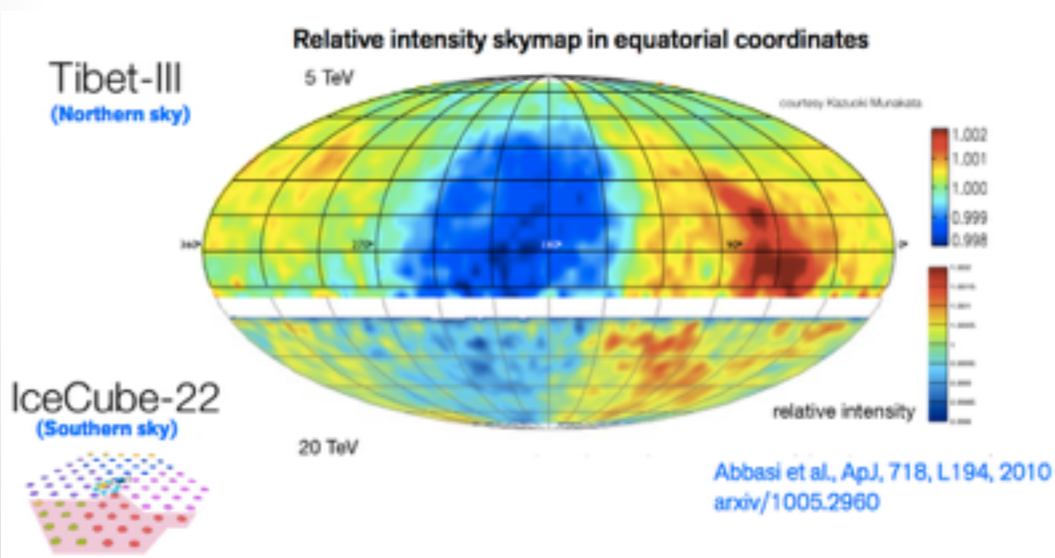
Tibet



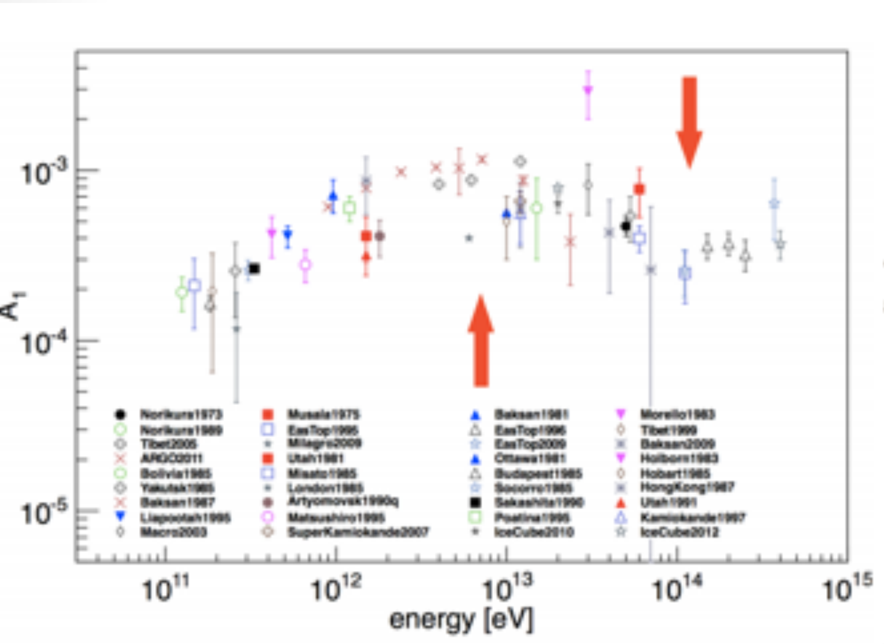
$\approx 10^{-3}$
anisotropy
contrast

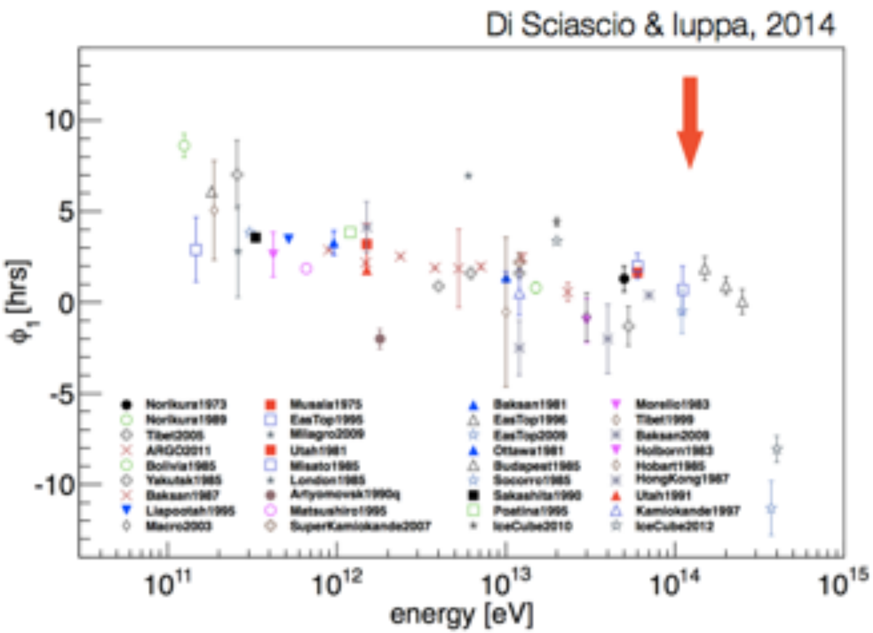
IceCube/IceTop





Dipole Observations



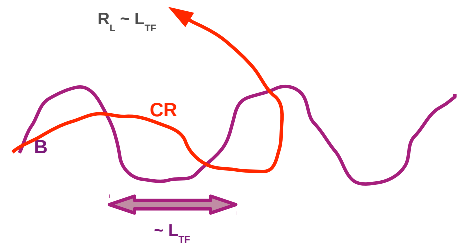


Amplitude increasing up to 10 TeV, and then decreasing

Phase steadily migrating and then suddenly changes/flips

Diffusion and Anisotropy

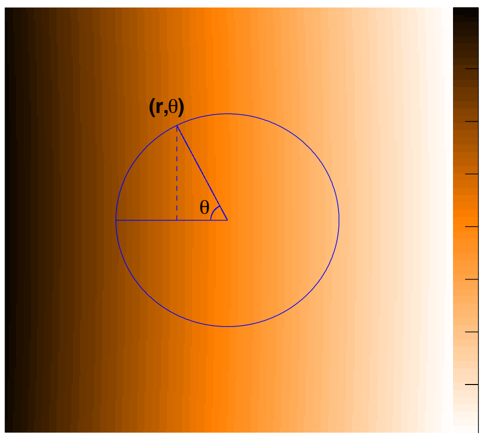
Propagation in a turbulent magnetic field - resonant mode:



Diffusion approximation: scattering on isotropic diffusion centers each λ

Angular distribution at the observation point:

$$\Phi_{\text{obs}}(\theta,\varphi) = \frac{c}{4\pi\lambda}\int_0^{\lambda} dr\ \tilde{n}(r,\theta,\varphi).$$



Density to first order:

$$\begin{aligned}\tilde{n}(r,\theta) &\simeq \tilde{n}(r\cos\theta,0)\\ &\simeq \tilde{n}(0) + r\cos\theta\frac{\partial\tilde{n}(0)}{\partial r}\end{aligned}$$

$$\Phi_{\text{obs}}(\theta,\varphi) \simeq \frac{c}{4\pi}\tilde{n}(0)\left(1 + \frac{\lambda}{2}\frac{1}{\tilde{n}(0)}\frac{\partial\tilde{n}(0)}{\partial r}\cos\theta + \ldots\right)$$

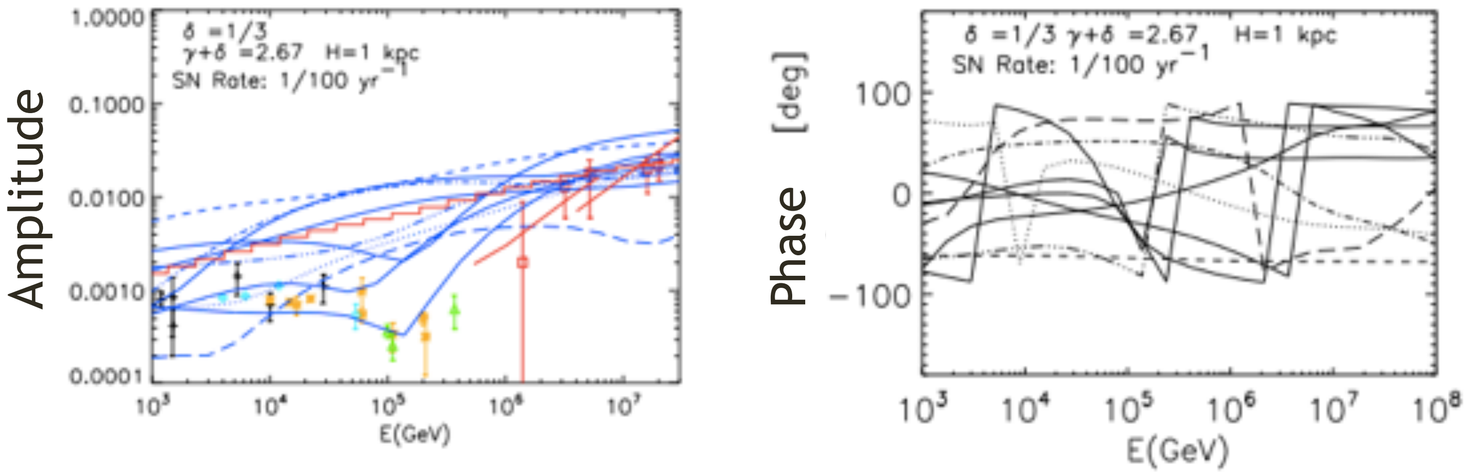
$$\Phi_{\text{obs}}(\mathbf{n}) \simeq \frac{c}{4\pi}\tilde{n}(0)\left(1 + \frac{3D}{c}\frac{\vec{\nabla}\tilde{n}(0)}{\tilde{n}(0)}\cdot\mathbf{n} + \ldots\right)$$

$$\vec{\Delta} = \frac{3D}{c}\frac{\vec{\nabla}\tilde{n}(0)}{\tilde{n}(0)} = \frac{3D}{c}\frac{\vec{\nabla}n(r_o)}{n(r_o)}$$

- For each single source, anisotropy ≈ dipole
- A dipole is represented by a vector
- Observed dipole = Sum of all individual dipoles

Diffusion and Dipole

- Relevant benchmark scenario: discrete sources stochastically distributed in space and time in the Galaxy [Erlykin & Wolfendale (2006)]



Amato & Blasi (2011): Green function satisfying the boundary conditions from the geometry of the Galaxy

(see also Erlykin & Wolfendale (2006), Ptuskin et al. (2012), Pohl & Eichler (2012), Streshnikova et al. (2013), Kumar & Eichler (2014), Mertsch & Funk (2014))

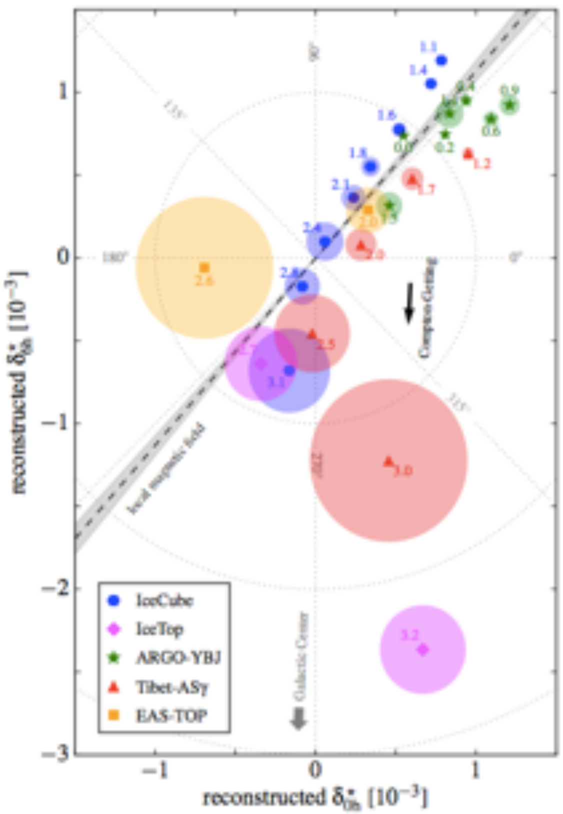
- Observed dipole dominated by the most `local` source at some energy
- In average, increase with energy (diffus. coeff.), but compensation mechanism due to the summing rule of the dipoles in each realization + changes in mass composition
- Abrupt changes of phase with energy, when the contribution of one source dominates the global vector (`local`source)

Impact of Local Environment

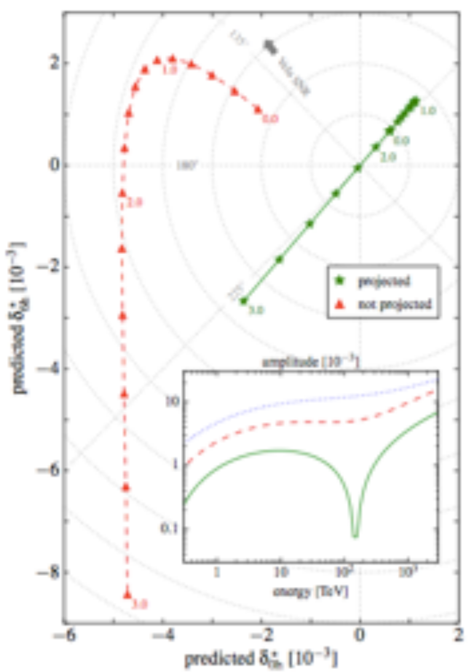
- Anisotropic diffusion induced by the local ordered magnetic field [Ahlers, 1605.06446]
  - Larmor radius much smaller than typical scattering length in local ordered **B**

    Diffusion tensor $K_{ij} = \frac{\hat{B}_i\hat{B}_j}{3\nu_\parallel} + \frac{\delta_{ij} - \hat{B}_i\hat{B}_j}{3\nu_\perp} + \frac{\epsilon_{ijk}\hat{B}_k}{3\nu_A}$ dominated by the first term
    - Projection of the CR gradient onto the magnetic field direction

- Subtracting CG effect corresponding to the Sun's motion towards the solar apex
- Equatorial components of the dipole corrected for projection effects



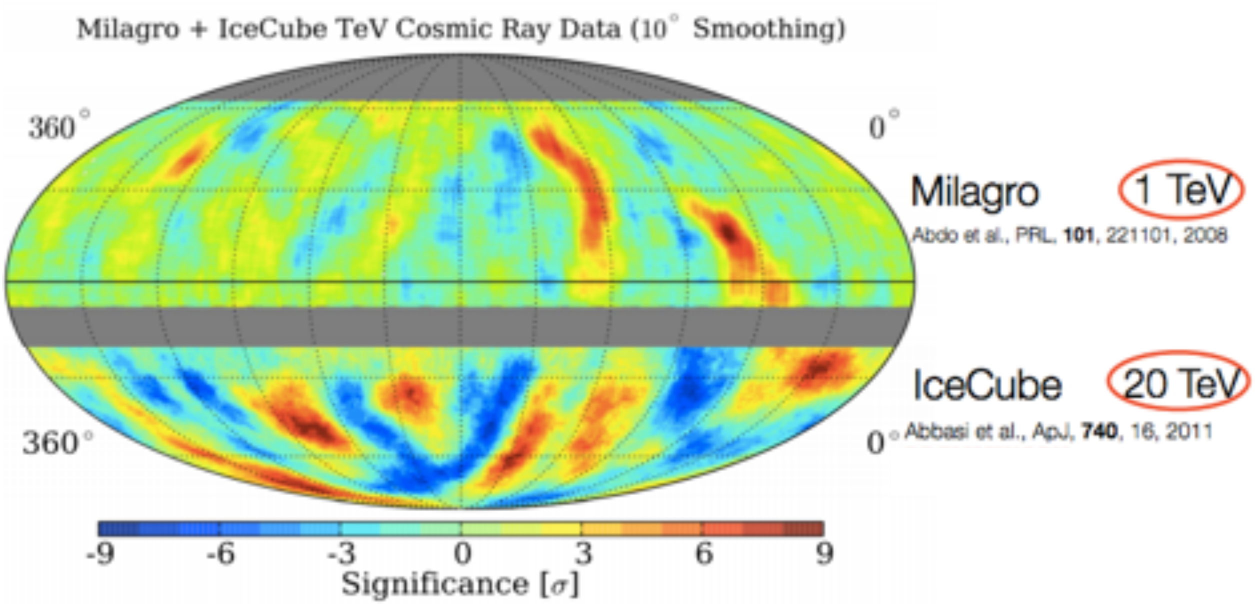
Toy model: impact of Vela SNR on the average anisotropy of all Galactic SNRs:

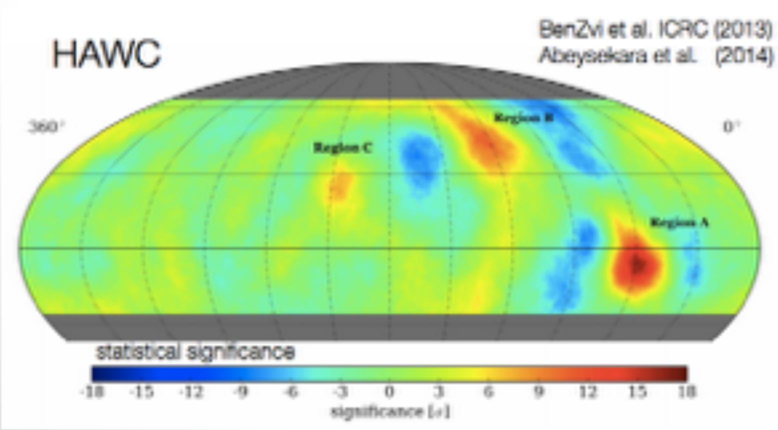


Beyond the Dipole Observations

- Features observed by Milagro, ARGO, IceCube, HAWC

$\approx 10^{-4}$ anisotropy contrast

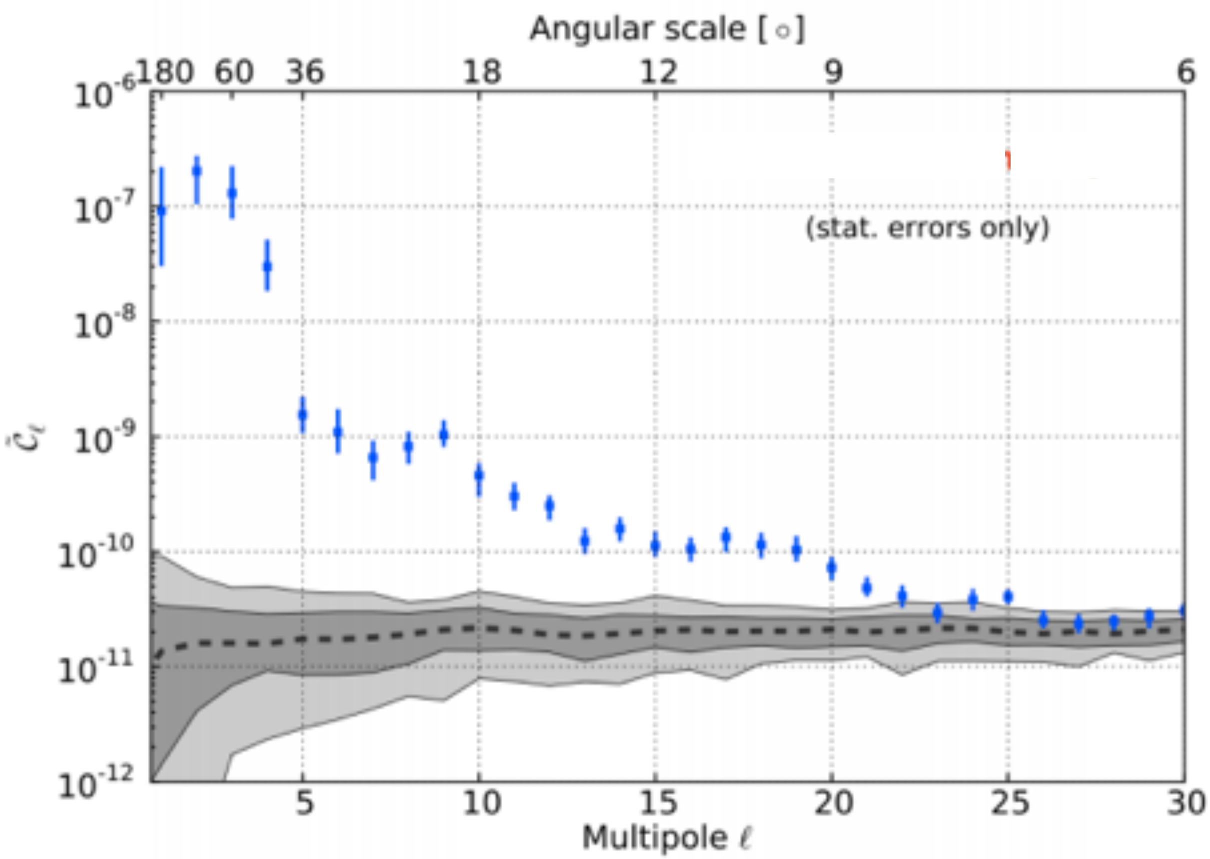




- Differences between Northern experiments and IceCube: energy dependence, trigger bias against heavy nuclei for IceCube

- Indications for harder spectra in some regions of excess

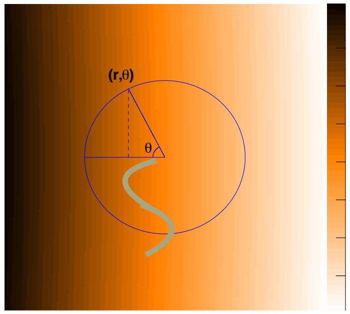
Beyond the Dipole Observations



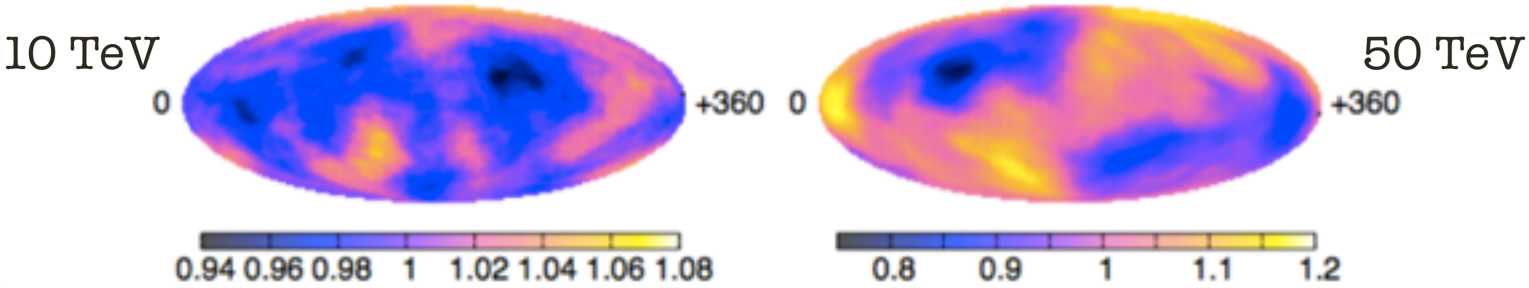
IceCube, update of ApJ 740 16 (2011)

From Gradient Density to Angular Distribution

Effect of the magnetic turbulence geometry within the last sphere of diffusion [Giacinti & Sigl, 2012, also Ahlers 2014]



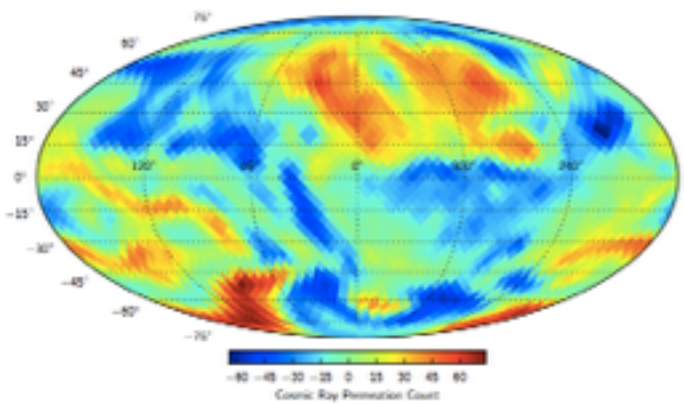
- Connect the observed direction **n** to the flux at the entrance point of the last diffusion sphere

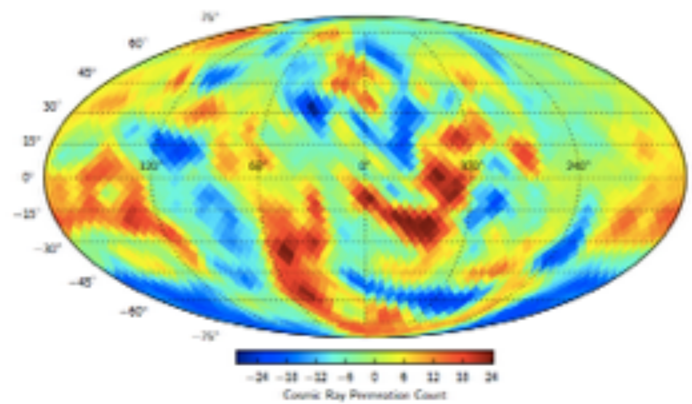


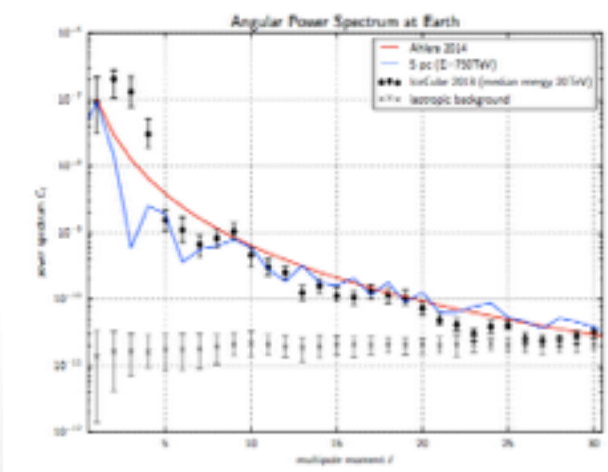
- Liouville: the isotropic flux outside the scattering mean free path remains isotropic
- Higher-order multipoles generated from the initial dipole, conserving the anisotropic fraction of the flux
- Energy-dependent structures at different angular scales

Probing the Magnetic Field Turbulence?

Test particle trajectories integrated in a compressible sub-Alfvénic isothermal MHD turbulence in low gas-to-magnetic pressure value β [Lopez-Barquero et al., 2015]





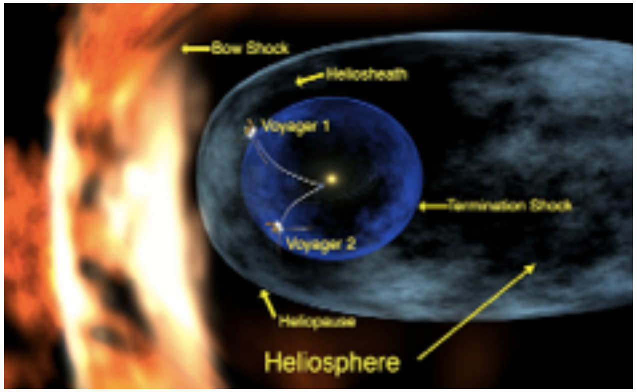


- β=0.2, M_A=0.773
- Controlled parameter in this MHD model of the turbulence: external mean magnetic field
- Reasonable reproduction of the power spectrum

Small Scales and Heliospheric Electric Field

[Drury, 2013]

- e.m. field purely magnetic in the plasma rest frame, but appearing with an induced electric component in a moving frame
- Above TeV energies, little deflections while penetrating the heliosphere
- With heliospheric length scale of ≈100 AU, velocity scale of ≈10^4-10^5 m/s and magnetic field of ≈nT, induced potential shift of ≈100 MV-1 GV



- For same incoming directions/ energy bands, TeV energies shifted at the ≈10^{-4} level
- Small-scale TeV anisotropies as the signatures of the heliospheric electric field structure

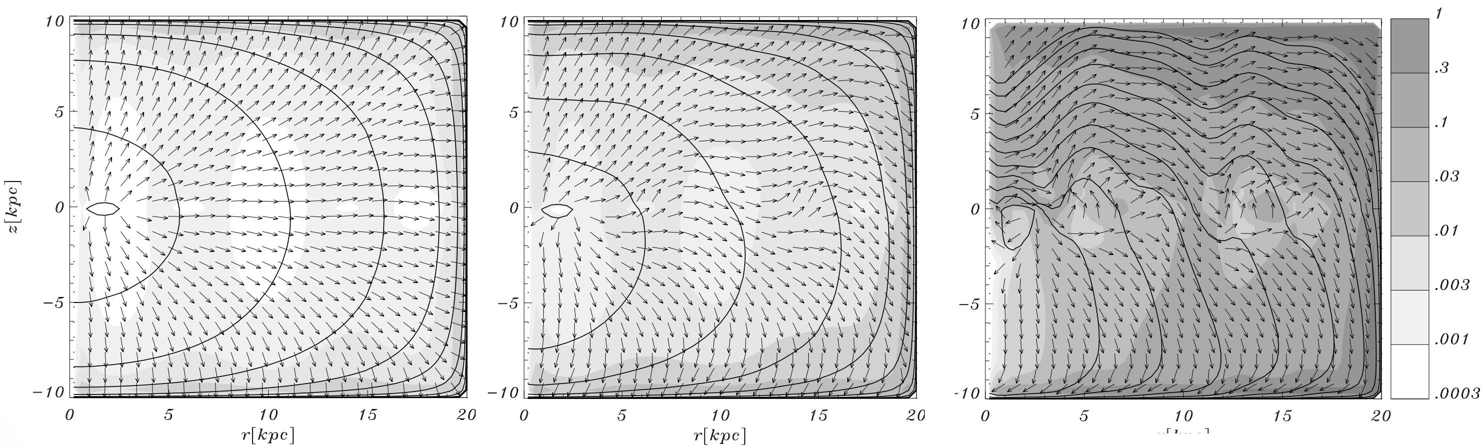
Alternative: Magnetic funnelling [Drury & Aharonian 2006, Salvati 2010], Anisotropic turbulence [Malkov et al., 2010], Local source in the heliotail [Lazarian & Desiati, 2010], Dark matter [Harding 2013], etc.

PeV-EeV Anisotropies

- Energy range where the Larmor radius exceeds the largest turbulence scales → Effect of the regular field amplified
- The full diffusion tensor matters, the non-diagonal elements inducing drift motions (Ptuskin et al., 1993)
- Direction of the dipole: not necessarily aligned with the dominant source(s):

$$\delta_r = \frac{3}{c\,N}\left(-D_\perp \frac{\partial N}{\partial r} + D_A \mathrm{sign}(B^\phi_{reg}) \frac{\partial N}{\partial z}\right) \quad \delta_z = \frac{3}{c\,N}\left(-D_\perp \frac{\partial N}{\partial z} - D_A \mathrm{sign}(B^\phi_{reg}) \frac{\partial N}{\partial r}\right)$$

- Amplification/Distortions of the density gradients:

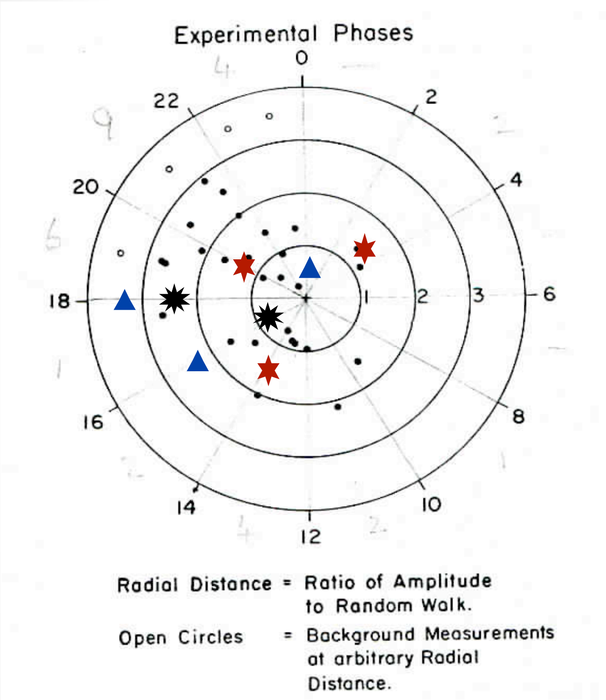


Candia et al. (2002)

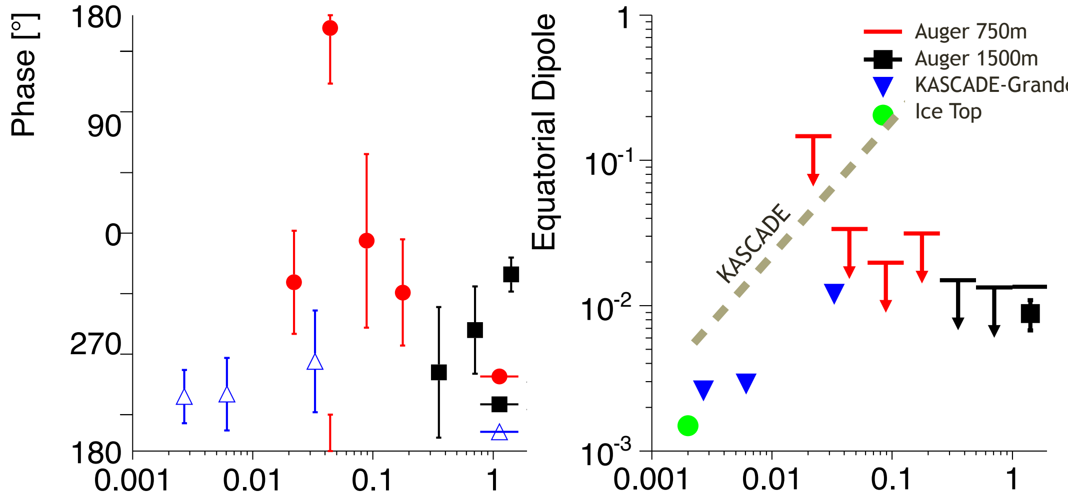
★ Solutions for stationary states only

PeV-EeV Observations

direction/amplitude of the dipole in right ascension:

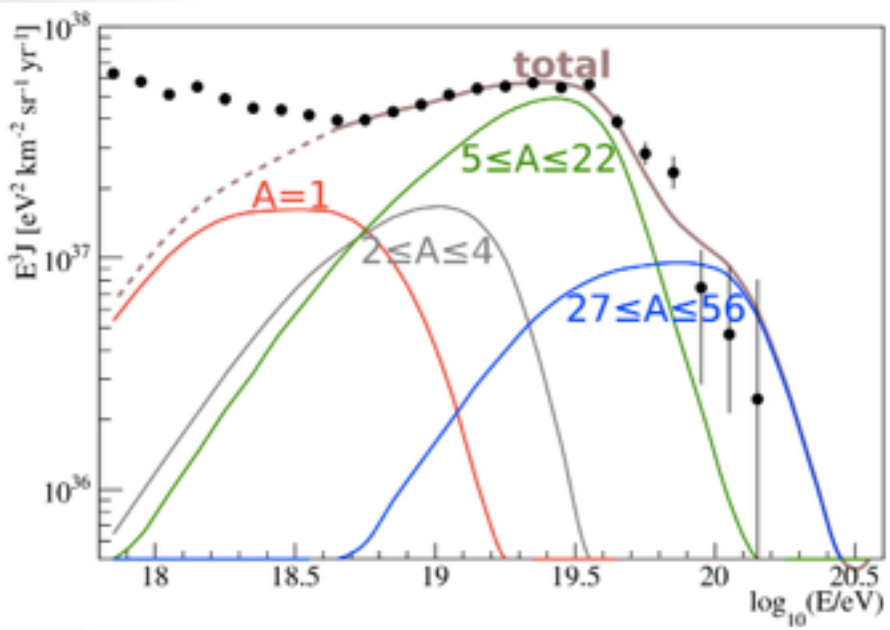


Greisen et al. (1962)



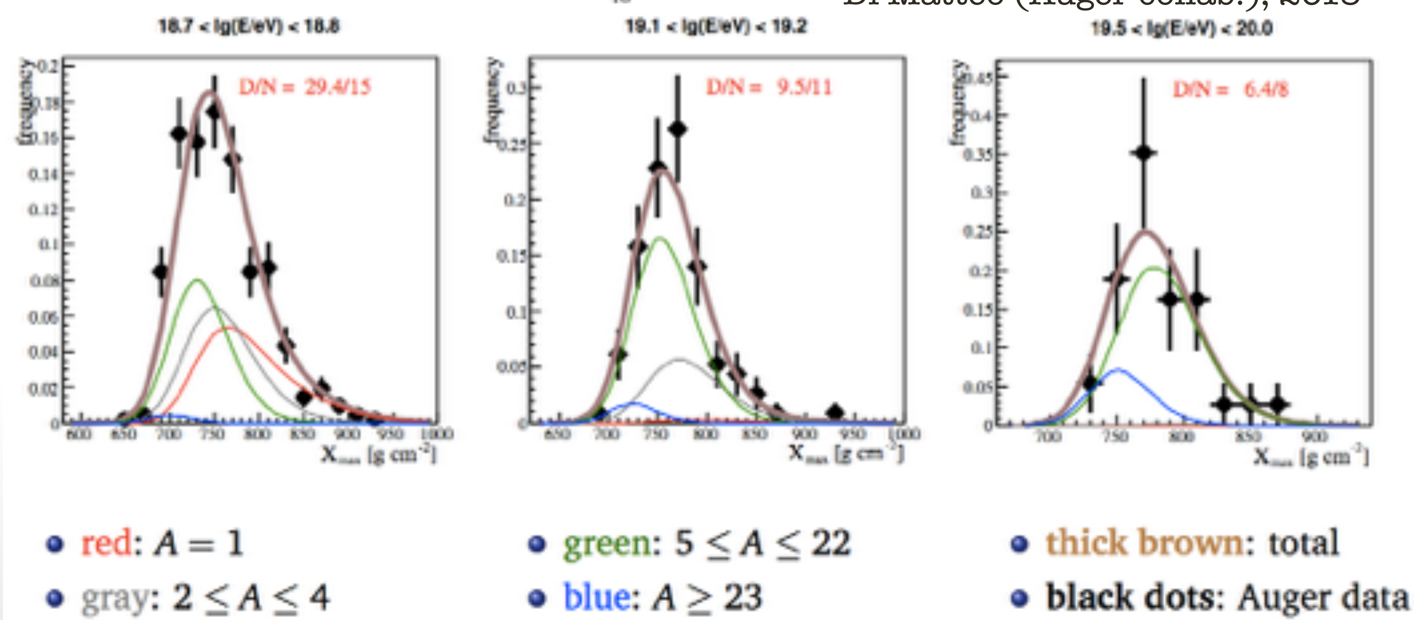
- Phases fairly consistent about the RA of the GC
- Possible/expected increase of amplitudes do not compensate the decrease in statistics
  - Much larger exposure needed to probe the amplitudes

EeV and >EeV CRs



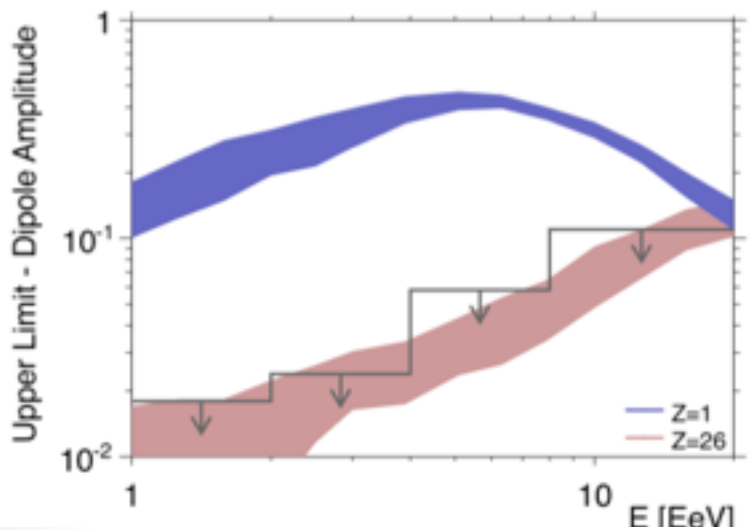
- ➡ Hard, meal-rich injection, low cutoff (R_{cut}<$10^{18.7}$ V)!
- Mainly due to narrow X_{max} distributions (little mixing of different masses at the same energy)
- **NB: Relies on extrapolations of the mass at UHE**

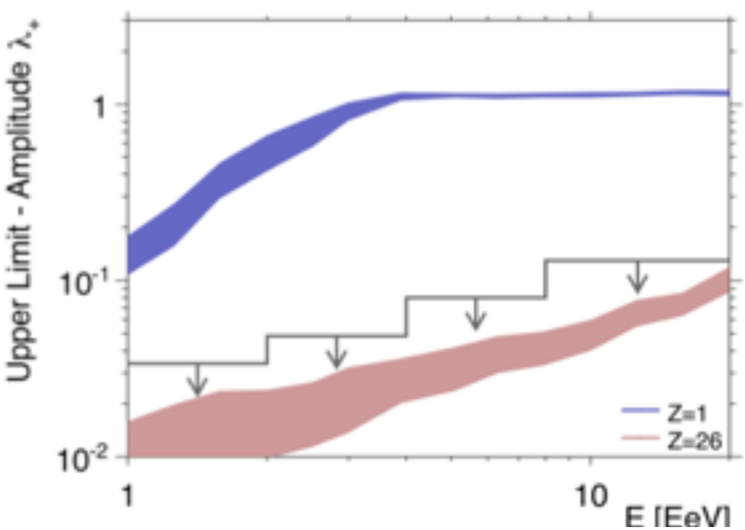
Di Matteo (Auger collab.), 2015



EeV and >EeV Large-Scale Anisotropies

- Back-tracking anti-particles with random directions from the Earth to outside the Galaxy [Thielheim & Langhoff 1968, J. Phys A 694]
- Each test particle probes the total luminosity along the path of propagation from each direction as seen from the Earth
- For stationary sources emitting equally in all directions, the time spent in the source region s proportional to the flux detected in that direction



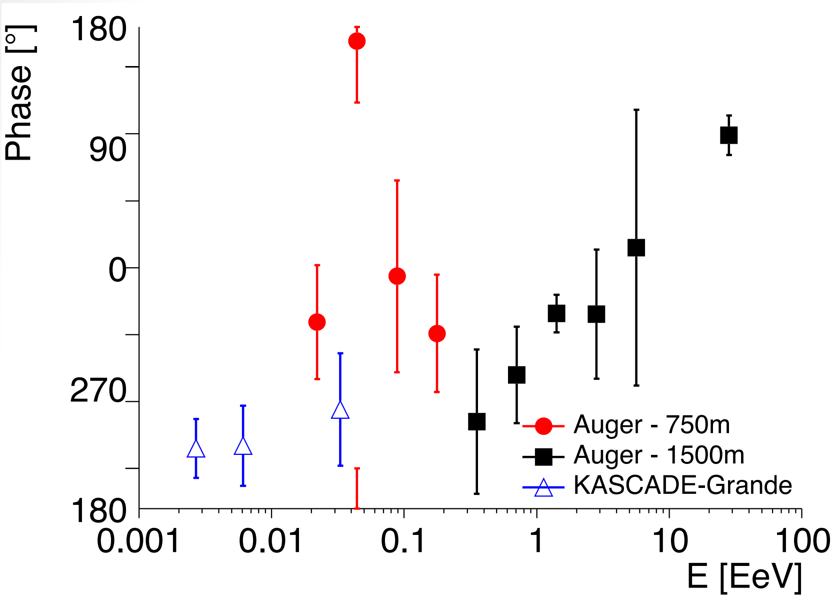


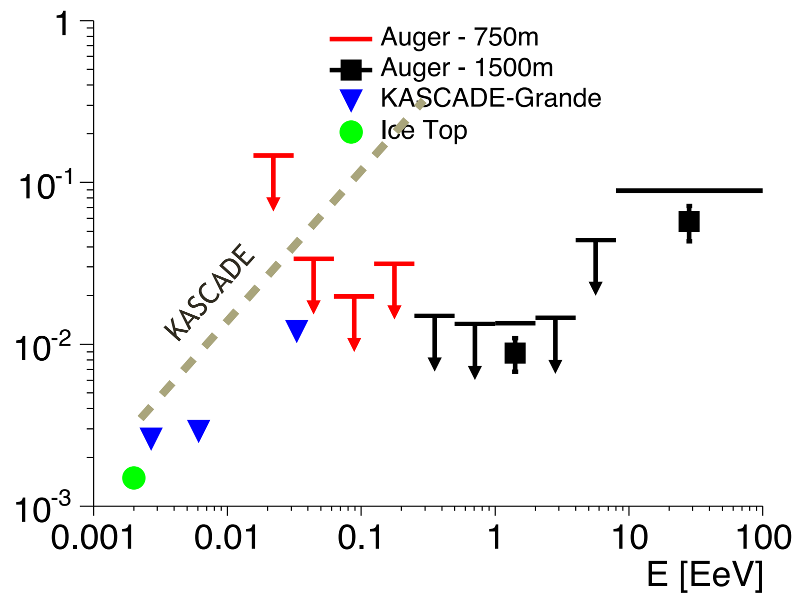
Auger collab., ApJS 2012

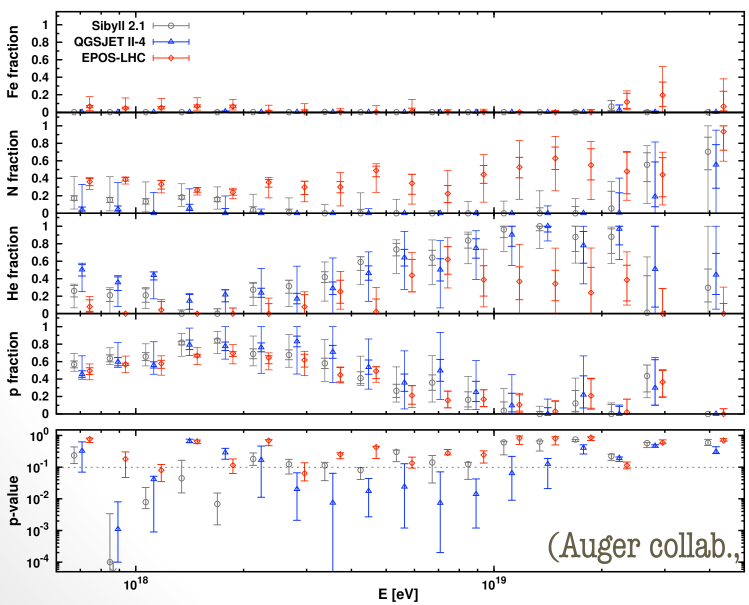
➡ EeV protons not from the Galaxy

★ Caveat: Temporal-dependent solutions for discrete sources?

EeV and >EeV Observations





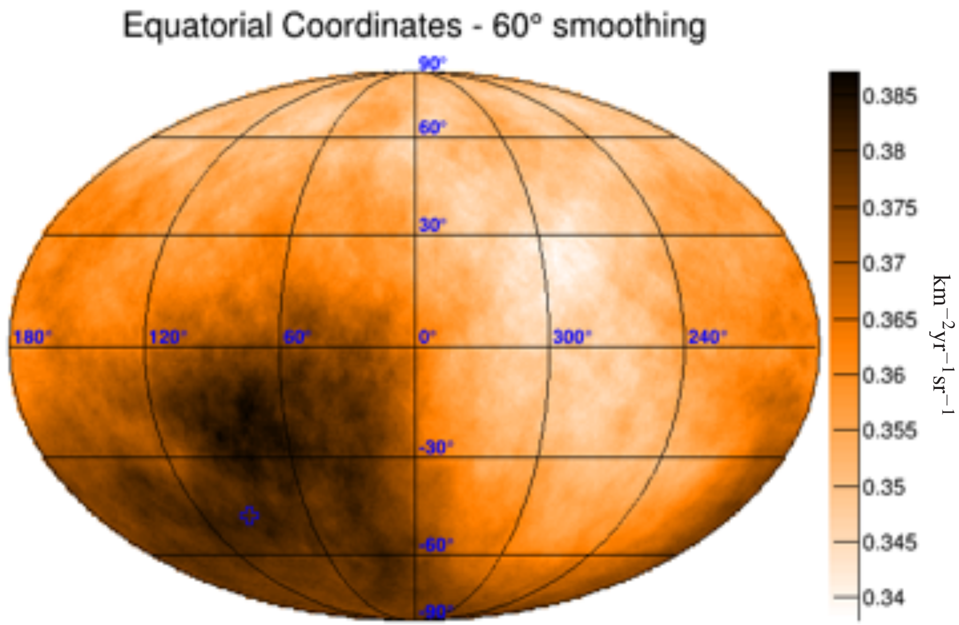


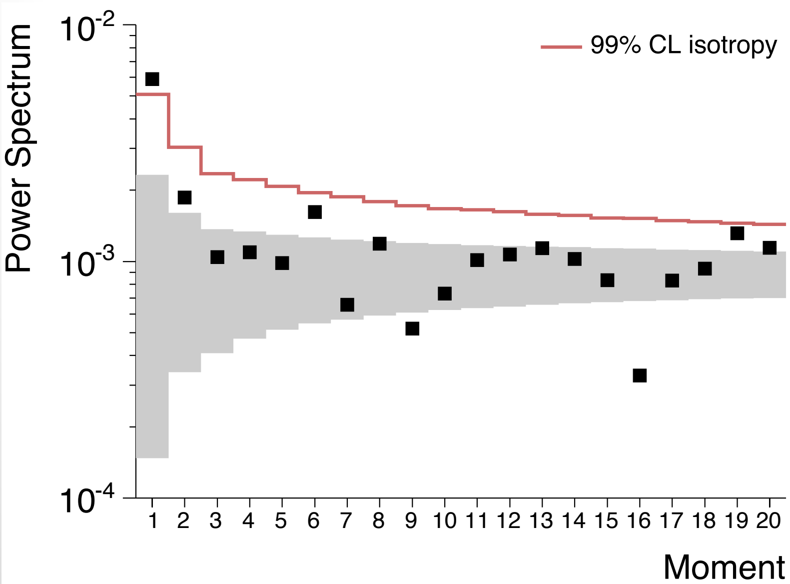
(Auger collab., 2013)

➡ At EeV energies, two different components with (almost) opposite phases?

- Need for composition-based measurements of anisotropies…

Full-Sky Map > 10 EeV (Auger/Telescope Array)

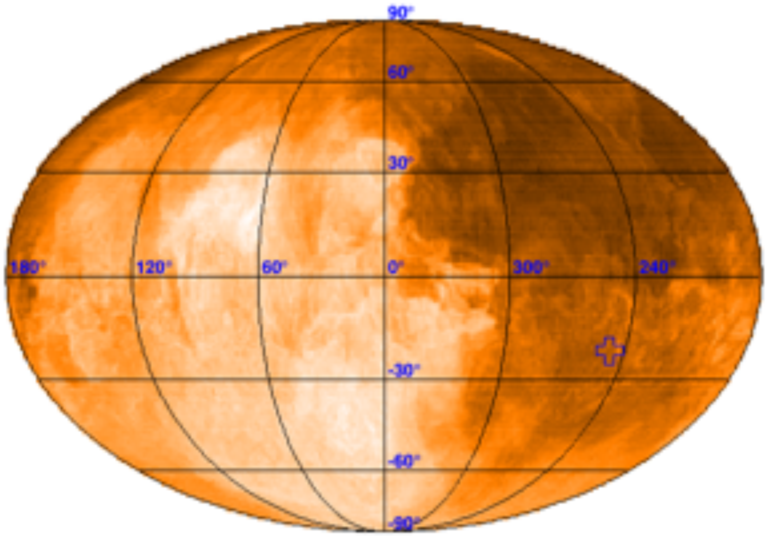


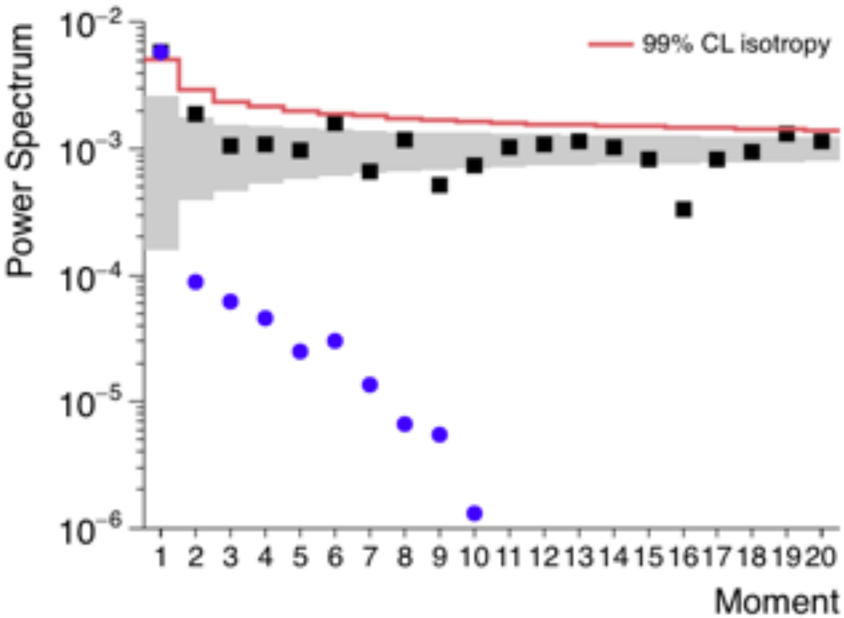


Auger/TA collab., ApJ 2014, ICRC 2015

- Interesting dipole effect (≈3σ) to monitor

Constraints on Extragalactic Scenarios?



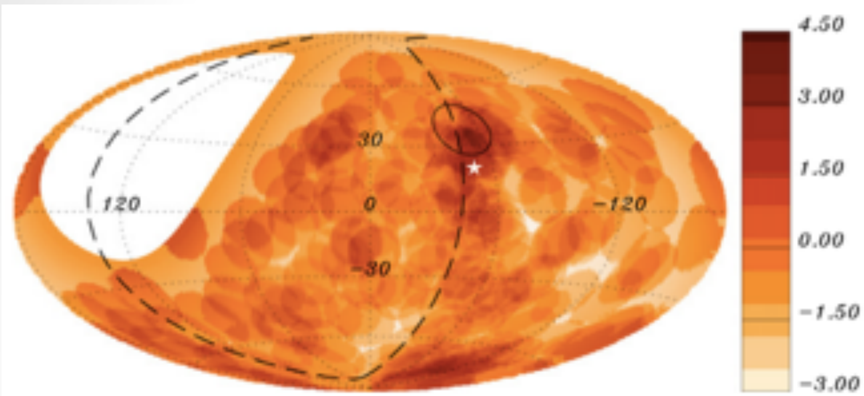


- Benchmark-scenario: Dipole at the entrance of the Galaxy
- Back-tracking technique to connect the observed **n** (random) to the flux outside from the Galaxy
  - Dipole not `destroyed` by the GMF (JF12 model here)
  - Detection of higher orders: probe of the extragalactic CR gradient outside from the Galaxy

UHE Anisotropies (?)

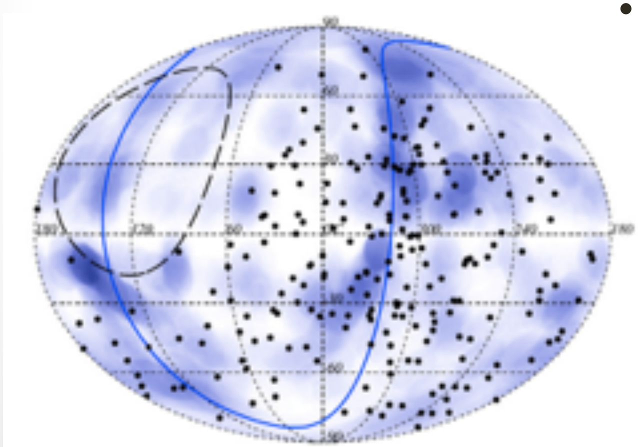
J. Miró - Drowned Sun

Southern hemisphere (Auger, 2015)



Significance map for Ψ=12° and E>54 EeV

- Scan on energy threshold E and circular window radius Ψ to compute the obs/exp number of events
- 4.3 σ for E>54 EeV and Ψ=12°
- Post-trial p-value: 69%



Map for E>52 EeV and 2MRS objects < 90 Mpc

- Cross-correlation with catalogs of extragalactic matter:

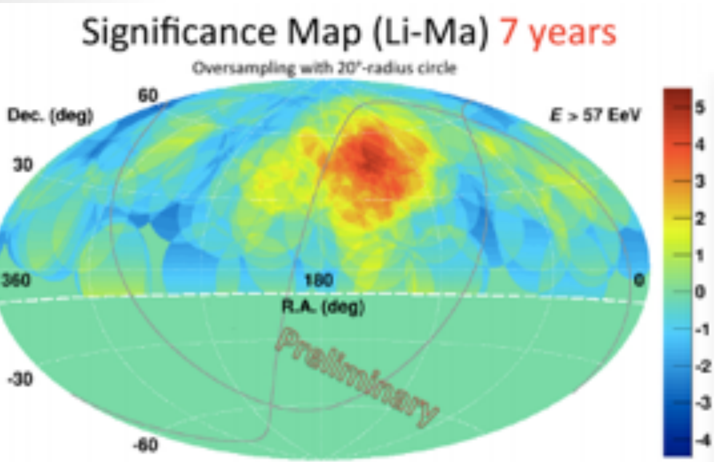
Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	1.5×10^{-3}	24%
Swift AGNs	58	1	80	6×10^{-5}	6%
Radio galaxies	72	4.75	90	2×10^{-4}	8%

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%

➡ No significant indication of anisotropy

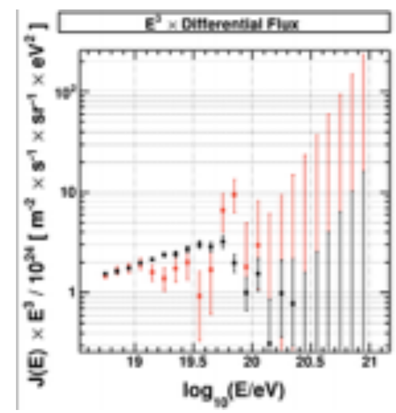
Northern hemisphere (Telescope Array, 2016)

- `Hot spot` status above 57 EeV



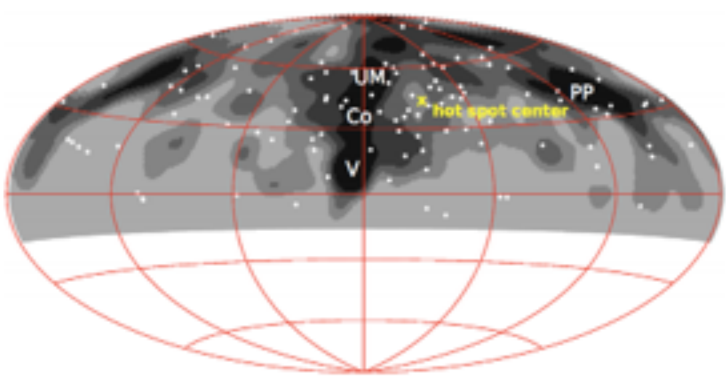
Map for E>57 EeV, smoothed at 20 deg.

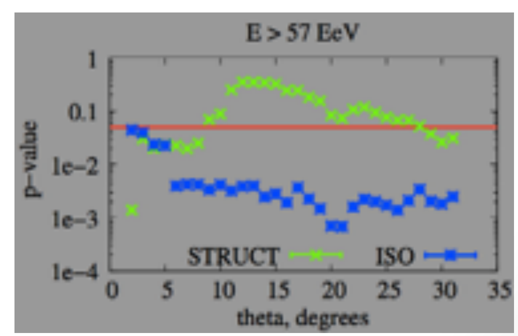
- 109 events, 24 within the 20° window (6.88 exp.)
- Post-trial significance: P=3.7 10^{-4} (3.4σ)
- Same significance as in 2014 (2 more years of data analysed here)
- Energy spectrum ON/OFF:



- Correlation with LSS?

Expectations from LSS for protons >57EeV smeared through GMF:



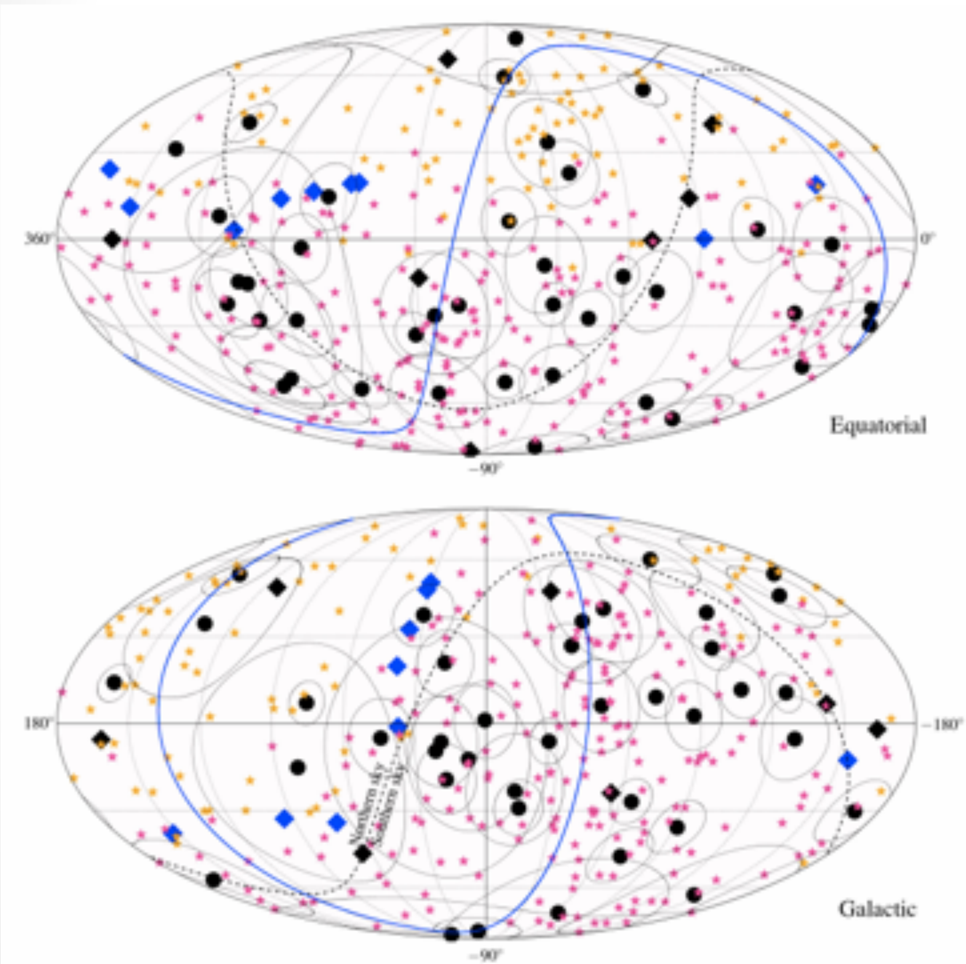


- Tension with isotropy?

Multi-Messenger Approach: IceCube/Auger/TA

JCAP 01 (2016) 037

- Cross-correlations between UHECRs and IceCube neutrinos



- Smallest p-value: IceCube high-energy cascades, angular scale of 22°, post-trial p-value: 5 10-4 (considering isotropic UHECRs)
- To be continued…

Summary

- Anisotropies up to ≈PeV energies well established
  - Not only dipoles!
  - Important developments for local CR propagation
- Quest of UHECR origin more difficult than expected
  - No small-scale clustering observation, only dipoles seem at reach!
  - Need for composition-based searches
  - Need for (much) larger exposure keeping similar resolutions…