Recent Anisotropy Studies with the Pierre Auger Observatory

Roger Clay for the Pierre Auger Collaboration
Motivation

Astronomy usually deals with messengers (photons, neutrinos etc.) for which directional astronomy is possible.

Cosmic rays have measurable arrival directions and energy but now there is a further complication due to their various possible nuclear compositions, and the ways in which their (resulting) charges respond to (largely unknown) astrophysical magnetic fields.

However, cosmic rays are believed to be produced in very interesting environments, they may have a significant energy density, and their mode of propagation to us gives us a potential technique for studying the magnetic fields which permeate the Universe. There is much to learn.
The Pierre Auger Observatory

The Observatory is the largest cosmic ray observatory and studies the highest energy particles known. These particles are rare, so a large area is required plus a long data collection period. The accumulation of a large body of data is a key aim of the work, particularly for directional (anisotropy) studies.

The Observatory began operations in 2004 and has been fully operational since 2008.

It is located at a latitude of 35 deg S and records particles with energies to a little over 100 EeV.

<table>
<thead>
<tr>
<th></th>
<th>1500 m array</th>
<th>750 m array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time period</td>
<td>1/1/2005 - 31/12/2015</td>
<td>1/1/2011 - 31/12/2015</td>
</tr>
<tr>
<td>Exposure [km² sr yr]</td>
<td>46,438</td>
<td>159</td>
</tr>
<tr>
<td>Energy Threshold [EeV]</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Number of events</td>
<td>1,146,481</td>
<td>570,123</td>
</tr>
<tr>
<td>Median energy [EeV]</td>
<td>1.5</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of the data sets used in the analyses.
The Pierre Auger Observatory – 3000 km²

Moriond March 2017
A fluorescence site (180° x 32° elevation) and a surface detector (water-Cherenkov, 10 m²) station.
A cosmic ray event can be viewed by up to four fluorescence sites plus the surface array. In this case (any FD), a complete shower development profile can be derived.
Figure 2. Trigger and event selection efficiency of the SD array for showers with zenith angles between 60° and 80° as a function of shower energy derived from the hybrid data (circles) and from the Monte Carlo simulated showers (squares). The error bars indicate the statistical uncertainty (the 68% probability contour).
Figure 2: Left: energy spectra derived from SD and hybrid data recorded at the Pierre Auger Observatory. The error bars represent statistical uncertainties. The upper limits correspond to the 84% C.L. Right: fractional difference between the Auger spectra and a reference spectrum with an index of 3.26.
Ultra-High Energy Cosmic Rays: Recent Results and Future Plans of Auger

Karl-Heinz Kampert\textsuperscript{1,2}\textsuperscript{a} and the Pierre Auger Collaboration\textsuperscript{2}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Left: Combined energy spectrum of cosmic-rays (multiplied by $E^3$) as measured by the Auger Observatory and fitted with a descriptive flux model. Only statistical uncertainties are shown. The systematic uncertainty on the energy scale is 14\%. The number of events is given above the points, which are positioned at the mean value of $\log_{10}(E/eV)$. The upper limits correspond to the 84\% C.L. (from [25]). Right: Energy spectrum of UHECRs compared to the best-fit parameters for a propagation model along with Auger data points [25].}
\end{figure}
Measured composition changes through 10 EeV

FIG. 3 (color online). Fitted fraction and quality for the scenario of a complex mixture of protons, nitrogen nuclei, and iron nuclei. The upper panels show the species fractions and the lower panel shows the $p$-values.

Cosmic ray propagation in turbulent magnetic fields.

After an initial ‘ballistic’ path, the particle propagation reaches a diffusion condition (the horizontal line) for which one can define a diffusion coefficient – and for which forward propagation is slow (distance proportional to \( \sqrt{t} \)).

Diffusive particles now arrive from all directions with a distribution dominated by a dipole term.

10 nG, \( l_{\text{max}} \) 1 Mpc

If we look for dipole anisotropies, we can look for dipole and higher order components as a function of angular position – usually R.A. (and dec) as these are the easiest to deal with.

Sum for the arrival (R.A.) direction of each event:

$$a = \frac{2}{N} \sum_{i=1}^{N} w_i \cos \alpha_i, \quad b = \frac{2}{N} \sum_{i=1}^{N} w_i \sin \alpha_i,$$

$$r = \sqrt{a^2 + b^2}, \quad \varphi = \arctan \frac{b}{a}. \quad (12)$$

As the deviations from an uniform right ascension exposure are small, the probability $P(>r)$ that an amplitude equal or larger than $r$ arises from an isotropic distribution can be approximated by the cumulative distribution function of the Rayleigh distribution $P(>r) = \exp(-k_0)$, where $k_0 = \frac{N r^2}{4}$. 

Moriond March 2017
The phase of the first harmonic usually shows consistency even when the measure of the amplitude is marginal.

(example data from lower energies)

Fig. 1. Phase of the first harmonic of the cosmic ray anisotropy between energies $10^{14}$ and $3 \times 10^{15}$ eV. Northern hemisphere results are identified by open circles and those from the south by filled circles. The result from the present observation at latitude $35^\circ S$ is marked by a cross at the most probable energy of the dataset.
A 2011 summary of first harmonic anisotropies at the highest energies

Fig. 11. Upper limits on the anisotropy amplitude of first harmonic as a function of energy from this analysis. Results from EAS-TOP, AGASA, KASCADE and KASCADE-Grande experiments are displayed too. An analysis of the KASCADE-Grande data with the East/West method delivers an additional limit for $3 \times 10^{15}$ eV. Also shown are the predictions up to 1 EeV from two different galactic magnetic field models with different symmetries (A and S), the predictions for a purely galactic origin of UHECRs up to a few tens of $10^{19}$ eV (Gal), and the expectations from the Compton-Getting effect for an extragalactic component isotropic in the CMB rest frame (C-GXgal).

Abreu et al. Astroparticle Phys. 34 627 2011

Moriond March 2017
Earlier Auger data on the amplitude and phase of the dipole.

Figure 1. Reconstructed amplitude of the dipole as a function of the energy. The dotted line stands for the 99% CL upper bounds on the amplitudes that would result from fluctuations of an isotropic distribution.

Figure 3. Reconstructed right ascension of the dipole as a function of the energy. The smooth fit to the data of Pierre Auger Collaboration (2011a) is shown as the dashed line (see the text).
The Auger dipole (>8 EeV)

Figure 3. Sky map in equatorial coordinates of flux, in km$^{-2}$ yr$^{-1}$ sr$^{-1}$ units, smoothed in angular windows of 45° and for the two energy bins.
Auger and TA

Figure 7. Arrival directions of Auger (red points in the south hemisphere) and Telescope Array events (black crosses in the northern hemisphere) above $10^{19}$ eV in equatorial coordinates, using a Mollweide projection.

Figure 11. Angular power spectrum.

Figure 2. Amplitude of first harmonic at the anti-sidereal timescale measured with Auger (black solid line) and Telescope Array (red dashed line) data. The curves are the background expectations from the respective Rayleigh distributions.

Equatorial Coordinates - L=4

Equatorial Coordinates - 15° smoothing

Figure 9. Left: flux sky map in km$^{-2}$ yr$^{-1}$ sr$^{-1}$ units, using a multipolar expansion up to $\ell = 4$. Right: significance sky map smoothed out at a 15° angular scale.
Large-scale anisotropies can result from a number of phenomena:

- Motion of the observer through a cosmic ray cloud.
- Diffusion from a cosmic ray source.
- Diffusion due to a density gradient (from many sources).

<table>
<thead>
<tr>
<th>Predicted sources of unidirectional anisotropies.</th>
<th>Direction of Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Celestial Coord RA(hr) Dec.</td>
</tr>
<tr>
<td>Motion of solar system relative to neighbouring stars</td>
<td>1800 30^\circ</td>
</tr>
<tr>
<td>Motion of solar system relative to extragalactic medium</td>
<td>2100 50^\circ</td>
</tr>
<tr>
<td>Diffusion outward from central regions of galaxy</td>
<td>-1800 -30^\circ</td>
</tr>
<tr>
<td>Diffusion along Orion arm IN</td>
<td>-2000 +35^\circ</td>
</tr>
<tr>
<td>Diffusion along Orion arm OUT</td>
<td>-0800 -35^\circ</td>
</tr>
<tr>
<td>Motion of solar system relative to interstellar gas in Orion arm</td>
<td>-0400 -45^\circ</td>
</tr>
<tr>
<td>Density gradient towards side boundary of Orion arm</td>
<td>0100 -27^\circ</td>
</tr>
</tbody>
</table>

Jacklyn, R. M. PASA 6 425 1986
What limits are there on the source distance?

Figure 4: Mean energy of protons as a function of propagation distance through CMB. Curves are for energy at the source of $10^{22}$ eV, $10^{21}$ eV, and $10^{20}$ eV.

10 EeV 100 EeV

Figure 6: Probability that an observed event at a given energy has its source at a distance greater than the indicated distance. A source spectrum proportional to $E^{-2.5}$ is assumed. Figure provided Paul Sommers, University of Utah.

Cronin, J. Nucl Phys B
138 465 2005

Moriond March 2017
One can measure a dipole for a random (or real) source distribution. The dipole amplitude depends on the source density. (10 micro-Gauss assumed)

Figure 7: Mean total dipole amplitude and its dispersion as a function of the energy for a distribution of sources with density $\rho = 10^{-4}$ Mpc$^{-3}$ homogeneously distributed in space (black dashed line) and following the local matter distribution (blue solid line) that accelerate a mixed nuclei composition with the same injected fractions as in Figure 6.

We need to look for an anisotropic source distribution or a ‘strong’, turbulent extragalactic magnetic field.

Maybe the super-galactic plane, representing the local matter distribution?

Careful -- it is not a simple ‘plane’.

Figure 1. The distributions of ORS and IRAS galaxies in a sphere of radius of $40h^{-1}\text{Mpc}$, projected on the standard $(SGX-SGZ)$, $(SGX-SGY)$ and $(SGY-SGZ)$ planes. The SGP is visible edge-on as the linear feature at $SGZ = 0$ in the $(SGX-SGZ)$ and $(SGY-SGZ)$ projections.
in the respective gas. Using this, it is easy to calculate the relation between the amplitude of the first harmonic of the anisotropy of cosmic rays at $E \sim 10^{17}$ eV and the dipole anisotropy of the microwave radiation $\Delta T \approx (2.9 \pm 0.7) \cdot 10^{-3}$ K [126]:

$$\delta = (2 + \gamma) \Delta T / T \approx 5 \cdot 10^{-3}.$$  

(4.82)

The anisotropy amplitude (4.82) is found to be at variance with the experimental value $\delta = 1.7 \cdot 10^{-2}$ for $E \sim 1 \cdot 10^{17}$ eV. The discrepancy can be removed by means of a small, but strongly anisotropic flux from another source (galactic sources or a nearby galaxy).

The phase of the anisotropy of the cosmic rays may be shifted relative to the phase of the anisotropy of the microwave radiation due to the effect of the regular magnetic field of the Galaxy.
The extra-galactic dipole which we measure will have been changed from its original direction. (Liouville)

Figure 9. Forward-tracked 10 EV CRs in the coherent + random field used in Fig. 7, for 12 representative source directions (crosses); events from a given source have the same color as the source. More figures showing the difference in CR deflections in different random field realizations are presented in [22].


Moriond March 2017
What are likely to be sources of UHE (10 EeV) particles?

These are not ‘local’.

The 3FHL Sky: Count Map

About 1,720 sources at E>10 GeV in 84 months of Fermi-LAT data (~700,000 photons)

The Third Catalog of Hard Fermi-LAT Sources (3FHL)

Alberto Dominguez*, Benoit Lott, Sara Cutini,
Marco Ajello, Pascal Fortin
for the Fermi-LAT Collaboration

*(Grupo de Altas Energías, Universidad Complutense de Madrid)
Who looks for non-local dipoles?

CMB? We saw that this was not sufficient.

2MRS?

Figure 7. Top panel: likelihood associated with each dipole direction on the sky, marginalized over amplitude, shown for 2MRS redshift shells $0.00 < z < 0.01$ (leftmost multicoloured oval), $0.00 < z < 0.03$ (uppermost multicoloured oval) and $0.00 < z < 0.10$ (rightmost multicoloured oval). We assume a $|b| < 8^\circ$ cut, and incorporate the SFD dust systematic template and quadrupole and octopole templates. The colour scale represents normalized likelihood as a function of direction. The single-coloured disc that overlaps with one of the multicoloured likelihood ovals represents the direction of the CMB kinematic dipole, with error bars exaggerated to a circle of $2^\circ$ in order to make the position clearly visible on the map. Bottom panel: confidence intervals for the direction of the dipole in the full 2MRS survey, with the position of the CMB dipole shown. Agreement was not expected, but it is reassuring that the 2MRS projected dipole does lie in the same general region of sky as the CMB dipole.

Gibelyou and Huterer
MNRAS 427 2012 1994-2021
2MRS amplitude ~12%
CMB amplitude equivalent to about 400 km/s
z=0.1 is ~400 Mpc

March 2017
Figure 13. Confidence intervals to go with results for the dipole direction in the 2MASS XSC, $K_s < 13.5$ (smaller circles) and $K_s < 12.5$ (larger circles). In both cases we apply a cut eliminating $|b| < 20^\circ$, and apply the SFD map and quadrupole and octopole maps as systematic templates. The CMB kinematic dipole direction is indicated. Like 2MRS, 2MASS is too shallow to expect agreement between its dipole direction and the direction of the CMB dipole, so this is not an anomalous result.

Table 5. Comparison of dipole parameters without any templates, with SFD template, and with SFD, quadrupole and octopole templates, for 2MASS, for two different limiting $K$-band magnitudes.

| $|b|$ | Template | NSIDE | $N$ | $A_{\text{peak}}$ | $l$ | $b$ | 68 per cent CI | 95 per cent CI |
|------|----------|-------|-----|-------------------|----|----|----------------|----------------|
|      |          |       |     |                   |    |    |                |                |
| 20.0 | None     | 128   | 386008 | 0.089  | 303.4 | 7.3 | 0.086–0.092 | 0.083–0.095    |
| 20.0 | SFD      | 128   | 386008 | 0.088  | 305.0 | 4.5 | 0.085–0.091 | 0.082–0.094    |
| 20.0 | SFD + Quad + Oct | 128 | 386008 | 0.104  | 268.4 | 0.0  | 0.100–0.108 | 0.096–0.112    |
|      |          |       |     |                   |    |    |                |                |
| 20.0 | None     | 128   | 91008  | 0.0848 | 275.0 | 28.2 | 0.078–0.091 | 0.072–0.097    |
| 20.0 | SFD      | 128   | 91008  | 0.0812 | 276.3 | 25.9 | 0.075–0.088 | 0.069–0.094    |
| 20.0 | SFD + Quad + Oct | 128 | 91008  | 0.134  | 267.3 | 8.5  | 0.126–0.142 | 0.117–0.150    |
Astrophysical Dipoles

Table 8. Summary of most reliable single results from each survey. From left to right in the table appear the name of the survey, the redshift range probed by the survey, the fraction of the sky covered, the number of sources available in the most reliable subset of the data set, the observed dipole amplitude with error bar, the theoretical dipole amplitude (with cosmic-variance error bar if applicable), the direction of the best-fitting observed dipole in Galactic coordinates \((l, b)\), and the most important systematic effect (in some cases, out of several candidates) that must be taken into account in attempting to detect a dipole in the data set.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Redshift</th>
<th>(f_{\text{sky}})</th>
<th>(N)</th>
<th>(A_{\text{obs}}) (\pm) (A_{\text{err}})</th>
<th>(A_{\text{th}}) (\pm) (A_{\text{err}})</th>
<th>((l, b)_{\text{obs}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MRS</td>
<td>(0 &lt; z &lt; 0.1)</td>
<td>0.86</td>
<td>41834</td>
<td>0.120 (\pm) 0.009</td>
<td>0.311 (\pm) 0.122</td>
<td>(213^\circ 8, 35^\circ 2)</td>
</tr>
<tr>
<td>2MASS</td>
<td>(0 &lt; z \lesssim 0.2)</td>
<td>0.65</td>
<td>386008</td>
<td>0.104 (\pm) 0.004</td>
<td>0.084 (\pm) 0.033</td>
<td>(268^\circ 4, 0^\circ 0)</td>
</tr>
<tr>
<td>BATSE</td>
<td>(z \gtrsim 2)</td>
<td>1.00</td>
<td>2702</td>
<td>(&lt;0.051) (\text{68 per cent CI})</td>
<td>(\text{unc. prediction})</td>
<td>(\text{weak constraints})</td>
</tr>
<tr>
<td>NVSS</td>
<td>(z \approx 1)</td>
<td>0.42</td>
<td>211487</td>
<td>0.027 (\pm) 0.005</td>
<td>0.0046 (\pm) 0.0035</td>
<td>(214^\circ 5, 15^\circ 6)</td>
</tr>
</tbody>
</table>
Conclusions on the Dipole

- Auger has measured a significant anisotropy dipole at 10 EeV.
- This is a major step forward.
- The interpretation depends on what one believes to be the strength of the intergalactic field BUT there is an upper limit of a few nG and the strength may be much less.
- These particles will have travelled at least an average of 500 Mpc – maybe almost in straight lines.
  \[1 \text{nG @ 10 EeV} \Rightarrow r_g > 10 \text{ Mpc for a regular field} \text{ – more for a turbulent field}\]
Fig. 2. Aitoff projection of the celestial sphere in galactic coordinates with circles of 3.2° centred at the arrival directions of 27 cosmic rays detected by the Pierre Auger Observatory with reconstructed energies $E > 57$ EeV. The positions of the 442 AGN (292 within the field of view of the Observatory) with redshift $z \leq 0.017$ ($D < 71$ Mpc) from the 12th edition of the catalogue of quasars and active nuclei [11] are indicated by asterisks. The solid line draws the border of the field of view for the southern site of the Observatory (with zenith angles smaller than 60°). The dashed line is, for reference, the super-galactic plane. Darker colour indicates larger relative exposure. Each coloured band has equal integrated exposure. Centaurus A, one of the closest AGN, is marked in white.
Previous most unlikely findings:

E>58 EeV, 15 deg around CenA, obs/exp=14/4.5  (f=2E-4,  P=1.4% penalized probability)

E>58 EeV, 18 deg around 10 brightest Swift AGNs within 130 Mpc, o/e=62/32.8 pairs  
(f=2E-6 , P=1.3% )

Figure 10. Correlation of events with the Cen A radio galaxy as a function of the angular distance and the energy threshold, $E_{\text{th}}$ (top-left panel). The top-right panel shows the cumulative number of events for the threshold $E_{\text{th}} = 58$ EeV, exploring the whole angular range. The bottom panel displays the map (in Galactic coordinates) of the region around Centaurus A, showing the arrival directions of the events with $E > 58$ EeV (black dots) and a red circle of 15° radius around the direction of Cen A, indicated by a star.
Large-scale anisotropies can result from a number of phenomena:

Motion of the observer through a cosmic ray cloud. Now the Universe – Planck – amp. too small.

Diffusion from a cosmic ray source. Cen A (ballistic?) M87? Virgo cluster? TA hot spot?

Diffusion due to a density gradient (from many sources). Large-scale structure? 2MASS?

Jacklyn, R. M. PASA 6 425 1986
Thanks
Spares
An aside: Photon and Neutrino upper limits

\[ p + \gamma_{\text{CMB}} \rightarrow \pi^+ + n \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ p + \gamma_{\text{CMB}} \rightarrow \pi^0 + p \]
\[ \pi^0 \rightarrow \gamma + \gamma \]
UHE photons have modest attenuation lengths

Figure 1. Photon attenuation length as a function of the initial primary energy. The thick black line indicates the attenuation length (survival probability $e^{-1} \approx 36.8\%$) and the dashed line a reduced survival probability of 1%. The energy range of this paper between $10^{17.3}$ eV and $10^{18.5}$ eV is indicated by the yellow shaded region and the vertical dotted lines. The expected increase of the observable distance by including secondary photons (detected in the energy range of this paper and with less than 1° deflection with respect to the primary photon) is shown as the green area using an average magnetic field strength of 0.1 nG.
An important question relates to the energy limit of galactic sources.

**Figure 2.** Photon flux as a function of energy from the Galactic center region. Measured data by H.E.S.S. is indicated as well as the extrapolated photon flux at Earth in the EeV range given the quoted spectral indices (Abramowski et al. 2016) (conservatively the extrapolation does not take into account the increase of the $p-p$ cross section towards higher energies). The Auger limit is indicated by a green line. A variation of the assumed spectral index by $\pm 0.11$ according to systematics of the H.E.S.S. measurement is denoted by the light green and blue band. A spectral index with cutoff energy $E_{\text{cut}} = 2.0 \cdot 10^6$ TeV is indicated as well.
Figure 6. Upper limits on the integral photon flux derived from 9 years of hybrid data (blue arrows, Hy 2016) for a photon flux $E^{-2}$ and no background subtraction. The limits obtained when the detector systematic uncertainties are taken into account are shown as horizontal segments (light blue) delimiting a dashed-filled box at each energy threshold. Previous limits from Auger: (SD [20] and Hybrid 2011 [19]), for Telescope Array (TA) [59], AGASA (A) [60], Yakutsk (Y) [61] and Haverah Park (HP) [62] are shown for comparison. None of them includes systematic uncertainties. The shaded regions and the lines give the predictions for the GZK photon flux [14, 16] and for top-down models (TD, Z-Burst, SHDM I[63] and SHDM II [21]).
Targets for photon searches:

Table 1. Combined unweighted probabilities $P$ and weighted probabilities $P_w$ for the 12 target sets. In addition, information on the most significant target from each target set is given. The number of observed (Obs) and expected (Exp) events and the corresponding exposure are shown. The numbers in brackets in the observed number of events column indicate the number of events needed for a $3\sigma$ observation unpenalized and penalized (*). Upper limits (UL) are computed at 95% confidence level. The last two columns indicate the $p$-value unpenalized ($p$) and penalized ($p^*$). Due to the discrete distribution of $p$-values arising in isotropic simulations, $P$ can differ from $p$ in the sets that contain only a single target.

<table>
<thead>
<tr>
<th>Class</th>
<th>No.</th>
<th>$P_w$</th>
<th>$P$</th>
<th>RA</th>
<th>Dec</th>
<th>Obs</th>
<th>Exp</th>
<th>Exposure</th>
<th>Flux UL</th>
<th>$E$-flux UL</th>
<th>$p$</th>
<th>$p^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>msec PSRs</td>
<td>67</td>
<td>0.57</td>
<td>0.14</td>
<td>286.4</td>
<td>4.0</td>
<td>5 (7,9*)</td>
<td>1.433</td>
<td>236.1</td>
<td>0.043</td>
<td>0.077</td>
<td>0.010</td>
<td>0.476</td>
</tr>
<tr>
<td>$\gamma$-ray PSRs</td>
<td>75</td>
<td>0.97</td>
<td>0.98</td>
<td>312.8</td>
<td>-8.5</td>
<td>6 (8,10*)</td>
<td>1.857</td>
<td>248.1</td>
<td>0.045</td>
<td>0.080</td>
<td>0.007</td>
<td>0.431</td>
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<td>LMXB</td>
<td>87</td>
<td>0.13</td>
<td>0.74</td>
<td>258.1</td>
<td>-40.8</td>
<td>6 (8,11*)</td>
<td>2.144</td>
<td>233.9</td>
<td>0.046</td>
<td>0.083</td>
<td>0.014</td>
<td>0.718</td>
</tr>
<tr>
<td>HMXB</td>
<td>48</td>
<td>0.33</td>
<td>0.84</td>
<td>285.9</td>
<td>-3.2</td>
<td>4 (7,9*)</td>
<td>1.460</td>
<td>235.2</td>
<td>0.036</td>
<td>0.066</td>
<td>0.040</td>
<td>0.856</td>
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<tr>
<td>H.E.S.S. PWN</td>
<td>17</td>
<td>0.92</td>
<td>0.90</td>
<td>266.8</td>
<td>-28.2</td>
<td>4 (8,10*)</td>
<td>2.045</td>
<td>211.4</td>
<td>0.038</td>
<td>0.068</td>
<td>0.104</td>
<td>0.845</td>
</tr>
<tr>
<td>H.E.S.S. other</td>
<td>16</td>
<td>0.12</td>
<td>0.52</td>
<td>258.3</td>
<td>-39.8</td>
<td>5 (8,10*)</td>
<td>2.103</td>
<td>233.3</td>
<td>0.040</td>
<td>0.072</td>
<td>0.042</td>
<td>0.493</td>
</tr>
<tr>
<td>H.E.S.S. UNID</td>
<td>20</td>
<td>0.79</td>
<td>0.45</td>
<td>257.1</td>
<td>-41.1</td>
<td>6 (8,10*)</td>
<td>2.142</td>
<td>239.2</td>
<td>0.045</td>
<td>0.081</td>
<td>0.014</td>
<td>0.251</td>
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<tr>
<td>Microquasars</td>
<td>13</td>
<td>0.29</td>
<td>0.48</td>
<td>267.0</td>
<td>-28.1</td>
<td>5 (8,10*)</td>
<td>2.044</td>
<td>211.4</td>
<td>0.045</td>
<td>0.080</td>
<td>0.037</td>
<td>0.391</td>
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<tr>
<td>Magnetars</td>
<td>16</td>
<td>0.30</td>
<td>0.89</td>
<td>257.2</td>
<td>-40.1</td>
<td>4 (8,10*)</td>
<td>2.122</td>
<td>253.8</td>
<td>0.031</td>
<td>0.056</td>
<td>0.115</td>
<td>0.858</td>
</tr>
<tr>
<td>Gal. Center</td>
<td>1</td>
<td>0.59</td>
<td>0.59</td>
<td>266.4</td>
<td>-29.0</td>
<td>2 (8,8*)</td>
<td>2.048</td>
<td>218.9</td>
<td>0.024</td>
<td>0.044</td>
<td>0.471</td>
<td>0.471</td>
</tr>
<tr>
<td>LMC</td>
<td>3</td>
<td>0.52</td>
<td>0.62</td>
<td>84.4</td>
<td>-69.2</td>
<td>2 (8,9*)</td>
<td>2.015</td>
<td>180.3</td>
<td>0.030</td>
<td>0.053</td>
<td>0.463</td>
<td>0.845</td>
</tr>
<tr>
<td>Cen A</td>
<td>1</td>
<td>0.31</td>
<td>0.31</td>
<td>201.4</td>
<td>-43.0</td>
<td>3 (8,8*)</td>
<td>1.948</td>
<td>214.1</td>
<td>0.031</td>
<td>0.056</td>
<td>0.221</td>
<td>0.221</td>
</tr>
</tbody>
</table>

So far: No photons – but this is an important quest.
Neutrinos are even more important

FIG. 4 (color online). Top panel: Upper limit (at 90% C.L.) to the normalization of the diffuse flux of UHE neutrinos as given in Eqs. (2) and (3), from the Pierre Auger Observatory. We also show the corresponding limits from ANITA II [31] and IceCube [32] experiments, along with expected fluxes for several cosmogenic neutrino models that assume pure protons as primaries [33,34] as well as the Waxman-Bahcall bound [13]. All limits and fluxes converted to single flavor. We used $N_{\text{up}} = 2.39$ in Eq. (2) to obtain the limit (see text for details). Bottom panel: Same as top panel, but showing several cosmogenic neutrino models that assume heavier nuclei as primaries, either pure iron [33] or mixed primary compositions [9].

FIG. 5 (color online). Upper limit to the normalization of the diffuse flux of UHE neutrinos (at 90% C.L., and in bins of width 0.5 in $\log_{10}{E_{\nu}}$—see text for details) from the Pierre Auger Observatory (straight steps). We also show the corresponding limits from ANITA II [31] (dot-dashed line) and IceCube [32] (dashed line) experiments (with appropriate normalizations to take into account the energy bin width, and to convert to single flavor), along with expected fluxes for several cosmogenic neutrino models [9,33,34] as well as the Waxman-Bahcall bound [13] (all converted to single flavor).
Fig. 2. Aitoff projection of the celestial sphere in galactic coordinates with circles of 3.2° centred at the arrival directions of 27 cosmic rays detected by the Pierre Auger Observatory with reconstructed energies $E > 57$ EeV. The positions of the 442 AGN (292 within the field of view of the Observatory) with redshift $z \leq 0.017$ ($D < 71$ Mpc) from the 12th edition of the catalogue of quasars and active nuclei [11] are indicated by asterisks. The solid line draws the border of the field of view for the southern site of the Observatory (with zenith angles smaller than 60°). The dashed line is, for reference, the super-galactic plane. Darker colour indicates larger relative exposure. Each coloured band has equal integrated exposure. Centaurus A, one of the closest AGN, is marked in white.
Previous most unlikely findings:

E>58 EeV, 15 deg around CenA, obs/exp=14/4.5  \( (f=2\times10^{-4}, \ P=1.4\% \ \text{penalized probability}) \)

E>58 EeV, 18 deg around 10 brightest Swift AGNs within 130 Mpc, o/e=62/32.8 pairs  \( (f=2\times10^{-6} , \ P=1.3\% ) \)

Can we define a direction of the source using the energies and positions of the observed events?

– a magnetic spectrometer

Figure 8.1: Skymap in Galactic co-ordinates of the arrival directions and energies of the 69 events above an energy of 5\(\text{EeV}\) detected by the Pierre Auger Observatory between 2004 and 2009. The arrival direction of each event is indicated by a triangle coloured according to the energy of the event.

Figure 8.2: Skymap in Galactic co-ordinates, of \(S_{ij}\) values after applying the magnetic spectrometer analysis to the data of Figure 8.1. The parameters used in this analysis are \(\Delta \theta_{\text{cut}} = 45^\circ\) and \(\zeta_{\text{min}} = 10^\circ\). The location of the highest value of \(S_{ij}\) is marked by a black dot.
Large-scale anisotropies can result from a number of phenomena:

Motion of the observer through a cosmic ray cloud. Now the Universe – Planck – amp. too small.

Diffusion from a cosmic ray source. Cen A (ballistic?) M87? Virgo cluster? TA hot spot?

Diffusion due to a density gradient (from many sources). Large-scale structure? 2MASS?

Jacklyn, R. M. PASA 6 425 1986
Thanks