Searching for Correlation of Ultra-High Energy Cosmic rays with IRAS-PSCz and 2MASS-6dF Galaxies
The Puzzle of UHECRs

- Sources and acceleration mechanisms are unknown.
- Energies much higher than can be achieved in accelerators.
- Observables are:
  - Spectrum
  - Arrival direction distribution
  - Composition

Feature consistent with GZK has been observed by HiRes, TA, PAO > 5 \sigma
Magnetic Deflection

- The universe is magnetised (Galactic and extragalactic magnetic fields) and UHECRs are charged particles.
- Deflections proportional to $Z/E$.
- Proton UHECRs with $E > 40$ EeV, expected to be deflected by $\leq 3^\circ$ in $\sim 100$ Mpc of propagation by extragalactic magnetic fields.


- Discrepancy in composition measurements between PAO/TA-HiRes.
The Dataset

- 69 events observed at PAO until December 2009 with $E \geq 55$ EeV.

- Absence of significant number of multiplets separated by $< 3^\circ$ (4 pairs) suggests source density $> 5 \times 10^{-4}$ Mpc$^{-3}$ (bright galaxies $\sim 10^{-2}$ Mpc$^{-3}$).

- If the 4 pairs are accidental ($P_{\geq 4 \text{ pairs}} \sim 22\%$) source density may be higher.

- Dataset consistent with a faint source distribution.
Predicted source distribution

- We have searched for a correlation with the distribution of luminous matter in the nearby universe, which should imprint an anisotropy in the arrival directions of the UHECRs.
- Even if only a specific source type contributes to the UHECR flux a correlation with luminous matter should be seen, since matter is clustered.
Predicted source distribution

**PSCz**
- 14000 objects
- Median $z = 0.0028$ (~120 Mpc)
- Covers 84% of sky
- Far – IR selected sample

**6dF**
- 125000 objects
- Median $z = 0.053$ (~225 Mpc)
- Covers Southern Celestial Hemisphere where the PAO is most sensitive.
- Near – IR selected sample
Predicted source distribution

- We assume identical sources.
- We weight individual sources for:
  - Particle energy losses and flux suppression:
    \[
    \omega(r_L) = \frac{1}{r^2} \int_{E_f}^{E_{i,\text{max}}} dE_i \int_{E_f}^{E_f} dE_f \left| \frac{\partial P_p(r_L, E_f; E_f)}{\partial E_f} \right| \mathcal{J}(E_i)
    \]
    - [Z. Fodor, S.D. Katz, 2001]
  - PAO exposure
  - Survey selection function
  - Exclude Galactic plane
Cross-correlation with LSS

• Measurement of correlation between predicted and observed distributions:

\[ X_{c,M} = \sum_{i \in \hat{i}} \frac{(N_{c,i} - N_{\text{true}}) \cdot (N_{M,i} - N_{\text{true}})}{N_{\text{true}}} \]  

[Kashti & Waxman, 2008]

• $6^\circ \times 6^\circ$ bins to average over possible random deflections of a few degrees.

Each histogram 10000 realisations of the model considered

\[ \sim 10\% \text{ uncertainty due to binning.} \]
Cross-correlation in Shells

• We split the predicted source distribution into 3 equal predicted UHECR flux shells with distance.

• Can help localise UHECR sources.
Cross-correlation in Shells

No signal in nearest shell where source clustering is highest.

We use the normalised correlation coefficient to characterise correlation between predicted and observed arrival directions in each shell:

\[ R = \frac{\sum \left( N_{CR,i} - N_{iso,i} \right) \cdot \left( N_{M,i} - N_{iso,i} \right)}{\sqrt{\sum \left( N_{CR,i} - N_{iso,i} \right)^2} \cdot \sqrt{\sum \left( N_{M,i} - N_{iso,i} \right)^2}} \]
Deflections

• We simulate random magnetic deflections with a 2D Gaussian function.
• Propagation weights apply to H, Fe (coincidence).
• The 69 PAO events are consistent with the LSS scenario if random deflections are $5 \gtrsim$ degrees.
• With more detected events we should be able to rule out large (or small) random deflections (requires faint sources).
Conclusions & Outlook

• We have used the PSCz and for the 1st time the 6dF survey to cross-correlate the arrival directions of the highest energy PAO events.
• No model of source distribution can be ruled out at present but we see no evidence for correlation with the galaxy distribution, unless random deflections $\gtrsim 5$ degrees.
• Cross-correlation in shells, may help localise the sources with more events and can be optimised to ask interesting questions.
Back up Slides
P-values as a function of cell-size

**PSCz**

- $P_{iso} \%$
- $P_{PSCz} \%$

**6dF**

- $P_{iso} \%$
- $P_{6dF} \%$
Likelihood ratio as function of bin size

PSCz

6dF
Shells PSCz

![Graphs showing PSCz for different shells](image)
Shells 6dF
## Systematics

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<th>$(\alpha, r_{\text{min}} \text{ [Mpc]})$</th>
<th>Entire PSCz</th>
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<th>Shell 1</th>
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<th>Shell 2</th>
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<th>Shell 3</th>
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<td>$P_{\text{iso}}$ (%)</td>
<td>$P_{\text{PS cA}}$ (%)</td>
<td>$P_{\text{PS cA}}(\text{ISO/PAO})$ (%)</td>
<td>$P_{\text{iso}}$ (%)</td>
<td>$P_{\text{PS cA}}$ (%)</td>
<td>$P_{\text{PS cA}}(\text{ISO/PAO})$ (%)</td>
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Common field of view result

- **6dF, $l_b \geq 12^\circ$, $\delta < 0^\circ$**
- **PSCz, $l_b \geq 12^\circ$**
- **PSCz, $l_b \geq 12^\circ$, $\delta < 0^\circ$**