The optical depth of the Universe seen through ultrahigh energy cosmic ray spectacles
Extragalactic magnetic fields are likely distributed as the baryonic gas
Depending on energy and magnetic field strength, propagation can be
**nearly rectilinear**, **diffusive**, or ‘**semi-diffusive**’…
A simplified view of extragalactic magnetic fields for UHECR

- At high energies, particles are weakly deflected at each interaction.
- At low energies, particles bounce on magnetic inhomogeneities as in a random billiard.

Kotera & Lemoine 08
Optical depth to scattering

- \( \theta > 1 \) opaque
- \( \theta < 1 \) translucent
- effective optical depth: number of interactions that 'highly' deflect the particle
- optical depth to scattering: number of interactions

\[ 6 \times 10^{19} \text{ eV} \]
Maps of optical depth

Total deflection angle: \[ \delta \alpha^2 = \frac{\tau}{3} \delta \theta_i^2 \]

Maps of optical depth:

\[ \tau(l_{\text{gal}}, b_{\text{gal}}) = \langle \tau \rangle_{160 \text{ Mpc}} \frac{N_g}{\langle N_g \rangle} \]

\( \tau \) varies from <1 to ~1 for typical parameters
Two effects of the optical depth

- If sources are gamma-ray bursts, flux from regions of $\tau < 1$ smaller by $\tau$ than flux in regions with $\tau > 1$.

- Sources of UHECRs and scattering centers share a similar property: large regions of intense magnetic field.

  "Do not mistake the last scattering center on the line of sight with the source!"

Signature:
- Inferred source distance scale $d_{\text{obs}}$
- Smaller than expected distance scale $\sim l_{\text{max}}(E)$
The PAO has detected a highly significant correlation of the arrival directions of cosmic rays with energy $E > 5.7 \times 10^{19}$ eV with the known AGN within 75 Mpc.

\[ F(<l) = n_{\text{source}} \hat{N}_{\text{UHECR}} l \]

\[ \rightarrow \text{source distance scale } \sim l_{\text{max}}(E) \]

\[ \sim 200 \text{ Mpc at } 6 \times 10^{19} \text{ eV} \]

Probability of seeing 20+ events out of 27 above $6 \times 10^{19}$ eV from within 75 Mpc:

\[ P \approx 3\% \]

\[ \rightarrow \text{PAO: inferred source distance scale appears smaller than expected source distance scale} \]

Two possibilities:

1. PAO energy scale is underestimated by $\sim 30\%$
2. PAO is imaging the last scattering surface…
If PAO is imaging the last scattering surface...

fraction of contaminated events:

fraction of background galaxies
(= source within 200 Mpc)
situated at less than 3° from an AGN
used by Auger:

\[ \delta \alpha = 0 \quad f \sim 31\% \]
\[ \delta \alpha = 3^\circ \quad f \sim 48\% \]
\[ \delta \alpha = 6^\circ \quad f \sim 44\% \]

correlation should not exceed 50% 
(unless GRB are sources of UHECR, in which case the correlation with the foreground density is artificially enhanced due to non-detection of GRB if \( \tau < 1 \))
the counterparts seen by the PAO are unlikely to be the source of UHECR

the PAO may be mistaking the counterparts with the last scattering centers

or, if the energy scale is underestimated (30%), the PAO may have located the invisible source within a few Mpc

   no counterpart will ever be found: photons have passed by Argentina  $10^4$ years ago
   no high energy gamma-ray, no neutrino, no gravitational wave will be seen from these sources

in any case, the PAO opens up a new era of data acquisition…