ULTRA-HIGH-ENERGY COSMIC RAY HOT SPOTS?

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OVERVIEW

- Two UHECR "hot spots" have been observed
  - Possible local sources
- Simple spectrum model
- Predictions
- Current observations v.s. future observations

PAO WARM SPOT

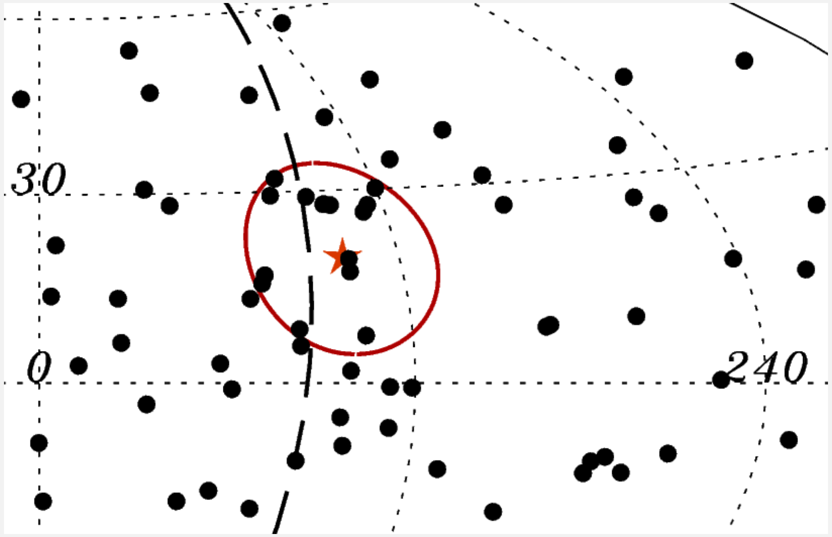


Image from Pierre Auger Collaboration arXiv:1411.6111

- Centered around Cen A
- $\approx 2\sigma$ detection
- $18°$
- RA: $201.°4$
- DEC: $-43.°0$
- 13 of 155 events
- ~3.2 expected events

TA HOT SPOT

- $\approx 3\sigma$ detection
- $20°$
- RA: $146.°7$
- DEC: $43.°2$
- 19 of 72 events
- ~4.5 expected events

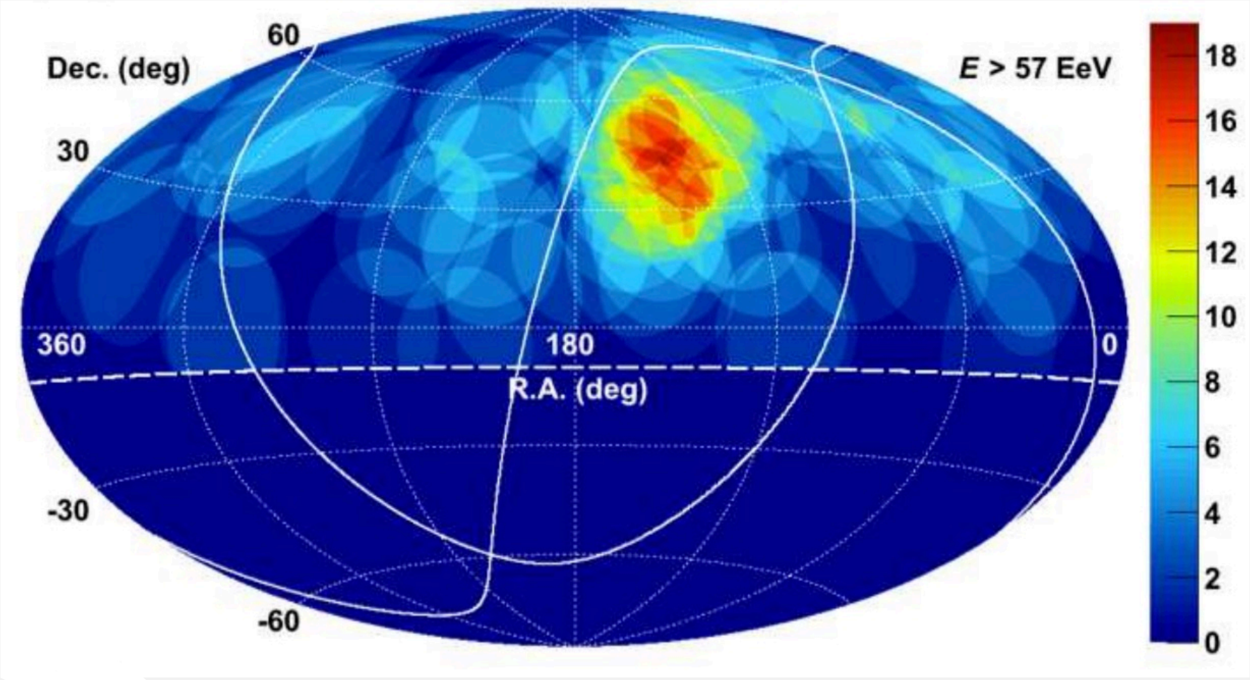
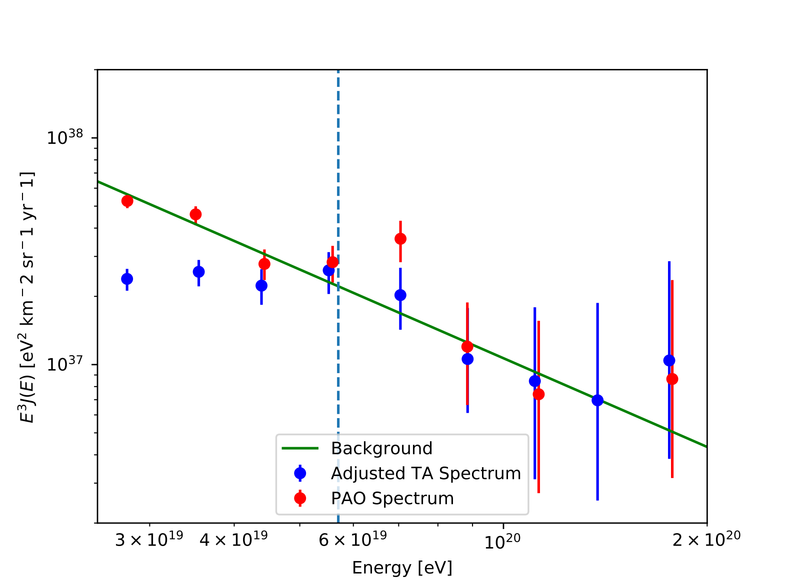


Image from Telescope Array Collaboration arXiv:1404.5890v3

MODEL: ENERGY



Data from Pierre Auger Collaboration arXiv:1002.1975 and Telescope Array Collaboration arXiv:1205.5067

- $\frac{dN}{dE} \propto E^{-s}$
- Care only about UHECRS ($E > 57$ EeV)
- Local s: 2.5[1]
- Background s': 4.3[2]

[1] Hopkins and Beacom 2006 arXiv:astro-ph/0601463
[2] Pierre Auger Collaboration 2009 arXiv:0906.2189

MODEL: ANGULAR DISTRIBUTION

- Deflections due to incoherent and coherent magnetic fields
- Affected by both IGMF and GMF
- Incoherent spreads out as a 2d Gaussian
- Coherent spreads in line

$$\frac{dN_s}{d\theta} \propto \frac{\left(\frac{E}{E_0}\right)^2 \theta}{\delta_\theta^2} e^{-\frac{\theta^2\left(\frac{E}{E_0}\right)^2}{2\delta_\theta^2}}$$

COMBINED MODEL: BACKGROUND AND LOCAL

- Local Source: $\frac{dN_s}{dE\,d\theta} \propto \left(\frac{E}{E_0}\right)^{-s} \frac{\left(\frac{E}{E_0}\right)^2 \theta}{\delta_\theta^2} e^{-\frac{\theta^2\left(\frac{E}{E_0}\right)^2}{2\delta_\theta^2}}$

- Background: $\frac{dN_b}{dE\,d\theta} = N_b \frac{2\theta}{\theta_m^2} \frac{s-1}{E_0} \left(\frac{E}{E_0}\right)^{-s'}$

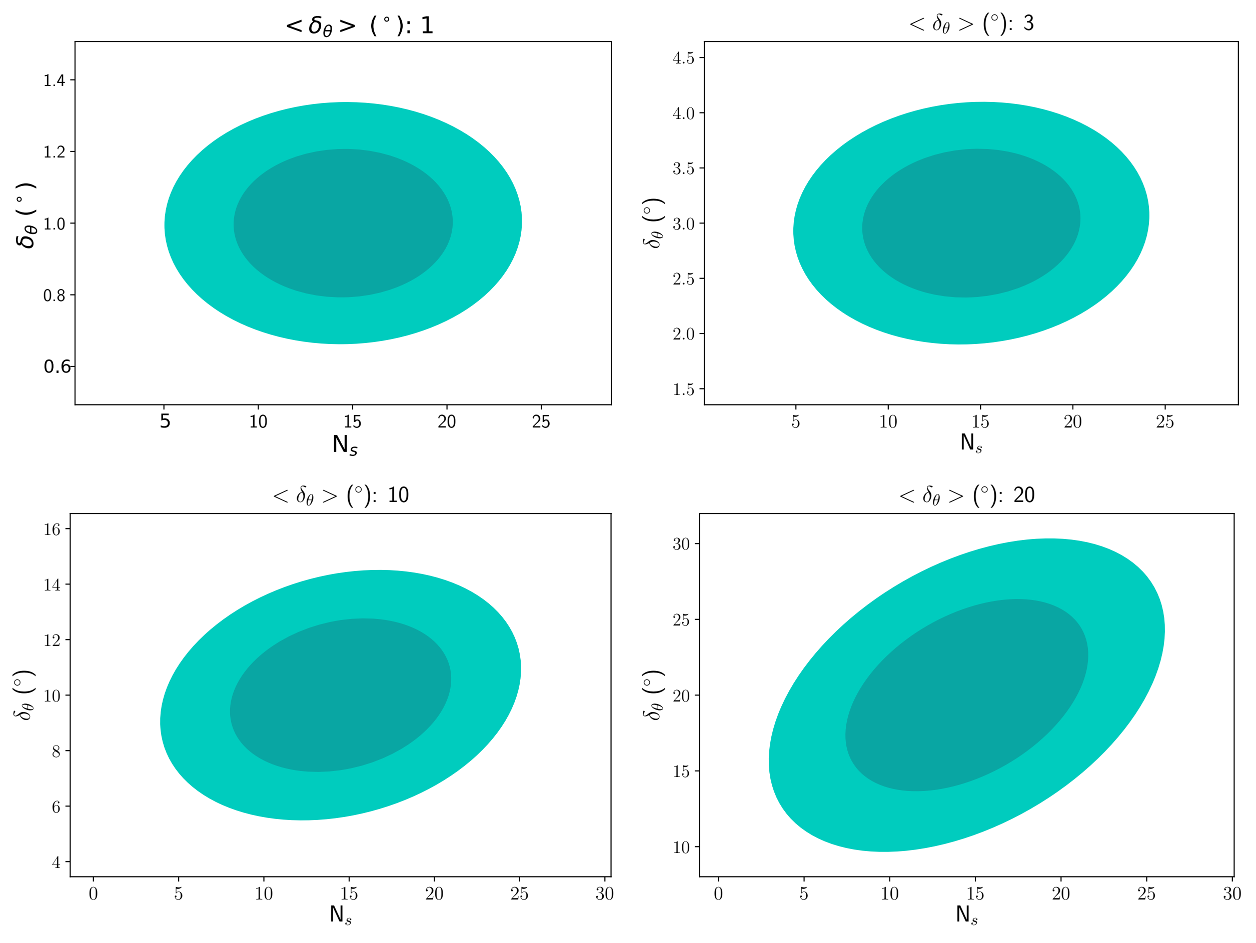
SIGNAL TO NOISE

- How well can we tell if an excess is from a local source
- Generally $\frac{S}{N} = \frac{N_s}{\sqrt{N_b}}$

$$\left(\frac{S}{N}\right)^2 = \sum_{\alpha} \frac{N_{s,\alpha}^2}{N_{b,\alpha}} \approx \int_{E_0}^{E_m} dE \int_0^{\infty} d\theta \frac{\left(\frac{dN_s}{dE\, d\theta}\right)^2}{\left(\frac{dN_b}{dE\, d\theta}\right)}$$

- Considering only energy gives us $\frac{S}{N} = 1.51 \frac{N_S^{1.1}}{\sqrt{N_b}}$
- Including angular information gives $\frac{S}{N} = 0.54\ \frac{10^\circ}{\delta_\theta} \frac{N_S^{1.76}}{\sqrt{N_b}}$

FISHER MATRIX ANALYSIS



EXPECTED ENERGIES

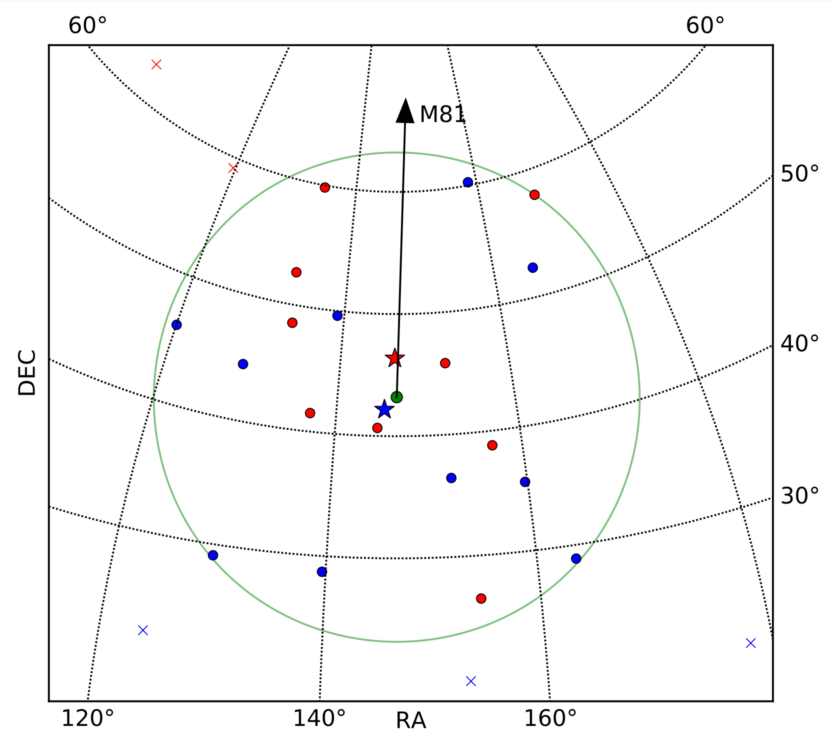
- Can possibly distinguish source based on average energies

- $< E_b > \sim 1.4\ E_0$
- $\text{Var}(E_b) \sim 0.5\ E_0^2$

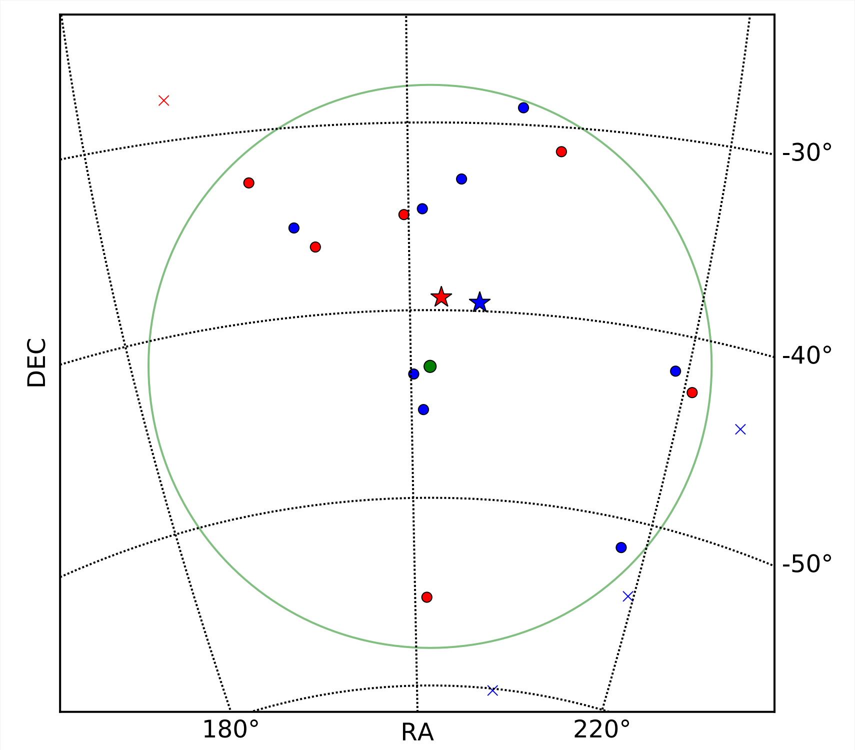
- $< E_s > \sim 3\ E_0$
- $\text{Var}(E_s) \sim \infty$

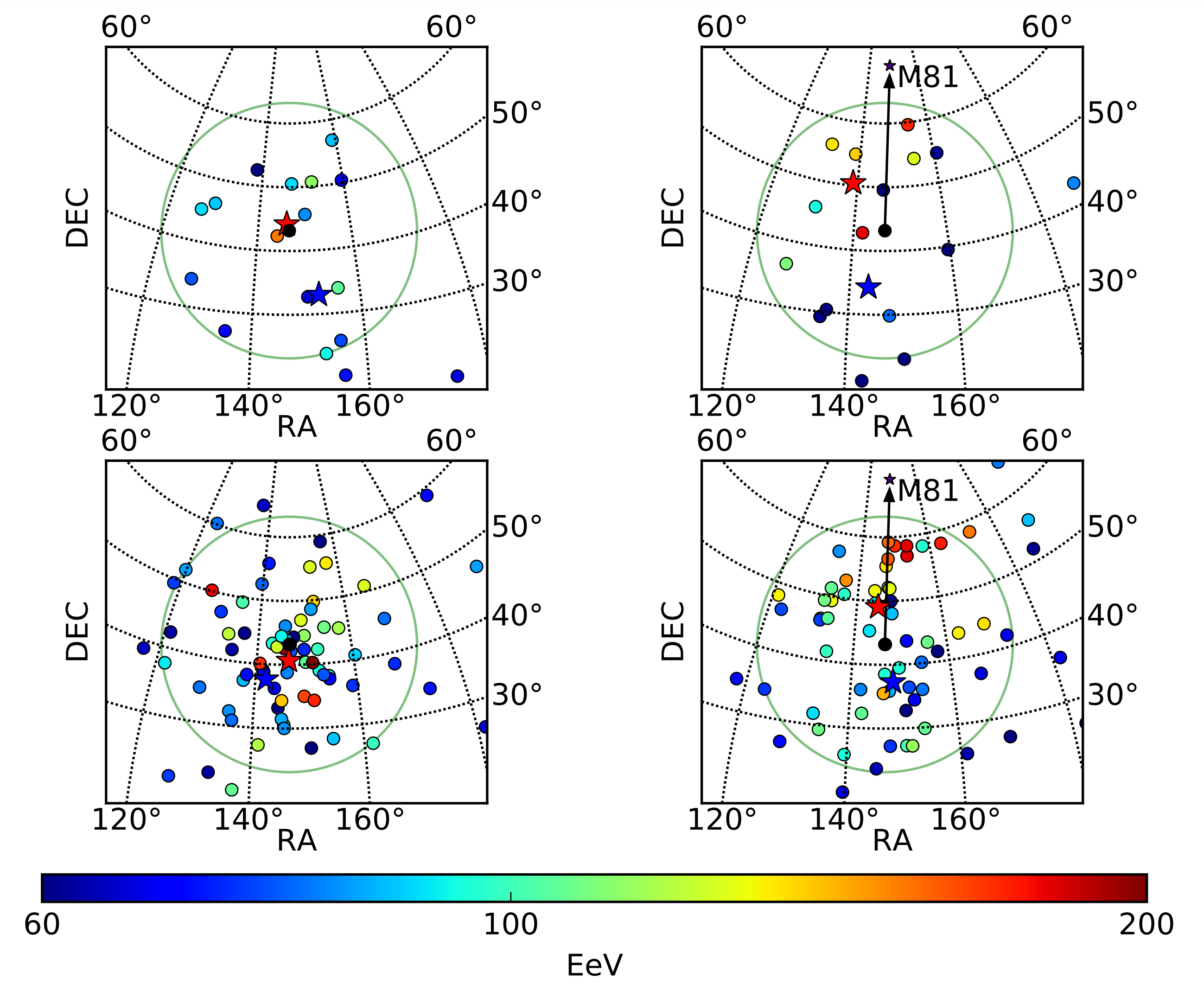
LOOK AT CURRENT DATA

TA HOT SPOT



PAO WARM SPOT





SIMULATED DATA

CONCLUSION

- Simple modeling leads to higher signal-to-noise

- Model can produce results that look similar to what is observed

BACKUP

BASIC SIMULATED DATA

- Simulate spectra from a local source
- Assume $\frac{dE}{dN} \propto E^{-s}$ and no GZK affects
- Force a coherent magnetic field to place center of hot spot where observed (From M81 to observed TA hot spot center)
- Stretches particle starting location on line between source and observed center based on energy
- Incoherent magnetic spreads out events from their starting locations based on energy and magnetic field
- Can be dispersed in any direction

MAGNETIC DISPERSION

- *Coherent Magnetic Field*
- $\delta \propto \frac{d}{R_L} \approx \frac{ZBd}{E}$

- Incoherent Magnetic Field
- $\delta_{rms} \propto \sqrt{\frac{d}{\lambda}}\frac{\lambda}{R_L} \approx \sqrt{d\lambda}\frac{ZB}{E}$

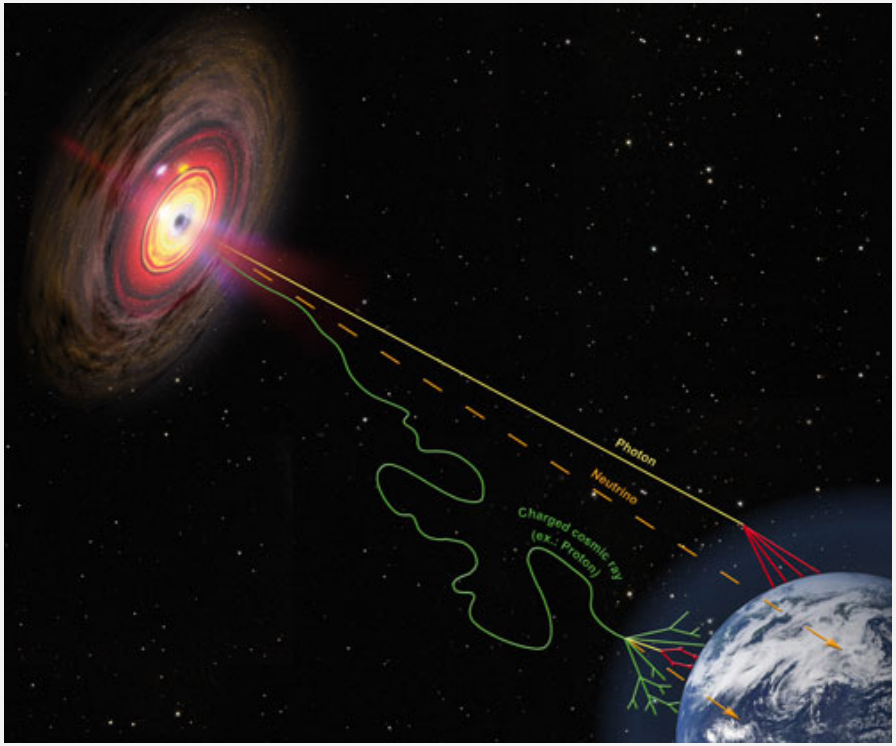


Image from http://www.hap-astroparticle.org/

MODELS

- Uniform: No source emissivity evolution (maybe for FRI galaxies)
- SFR1:
  - z < 1: $(1+z)^{3.4}$
  - 1 < z < 4: $(1+z)^{-0.26}$
  - 4 < z: $(1+z)^{-7.8}$
- SFR2:
  - z < 1: $(1+z)^{3.4}$
  - 1 < z < 4: $(1+z)^{-0.3}$
  - 4 < z: $(1+z)^{-3.5}$

- FRII: $\log(\dot{\rho}) = 2.7z + 1.45z^2 + 0.18z^3 - 0.01z^4$
- Source emissivity evolution follows that of FRII galaxies
- Models all match the isotropic background of UHECRs
- From Kotera, Allard and Olinto 2010 (arXiv: 1009.1382v2)

SIGNAL TO NOISE RESULTS

ENERGY ONLY

$$\frac{S}{N} = \frac{s-1}{\sqrt{(\gamma-1)(1\ -2s+\gamma)}} \frac{N_s^{\frac{\gamma-1}{2s\ -2}}}{\sqrt{N_b}}$$

ENERGY AND ANGLE

$$\frac{S}{N} = \frac{(s-1)(\theta_m/\delta_\theta)}{2\sqrt{(\gamma-1)(3\ -2s+\gamma)}} \frac{N_s^{\frac{\gamma+1}{2s\ -2}}}{\sqrt{N_b}}$$

FISHER MATRIX

- $F_{i,j} = \sum_\alpha \frac{1}{\sigma_\alpha^2} \frac{\partial N_\alpha}{\partial S_i} \frac{\partial N_\alpha}{\partial S_j}$
- $N_\alpha = N_{s,\alpha} + N_{b,\alpha}$
- $\sigma_\alpha = \sqrt{N_\alpha}$
- $\boldsymbol{S} = \{N, s, \delta_\theta\}$
- $\frac{\partial N_\alpha}{\partial N} = \frac{N_\alpha}{N}$
- $\frac{\partial N_\alpha}{\partial s} = N_{s,\alpha}\left[\frac{1}{s-1} - \ln\frac{E}{E_0}\right]$
- $\frac{\partial N_\alpha}{\partial \delta_\theta} = \frac{N_{s,\alpha}}{\delta_\theta}\left[\theta^2 \frac{\left(\frac{E}{E_0}\right)^2}{\delta_\theta^2} - 2\right]$

- Inverse of the Fisher matrix is the covariance matrix
- $[F^{-1}]_{ii}$ gives the variance of the ith parameter after marginalizing over the other parameters
- $[F_{ii}]^{-1}$ gives the variance if all of the other parameters are fixed independently

EXPECTED ENERGIES DERIVATION

- $< E > = \frac{1}{N}\int_{E_0}^{\infty} E \ \frac{dN}{dE} dE$
- $= \frac{1}{N}\int_{E_0}^{\infty} E \ N(s-1)\left(\frac{E}{E_0}\right)^{-s} dE$
- $= \frac{s-1}{s-2} E_0$
- $< E^2 > = \frac{1}{N}\int_{E_0}^{\infty} E^2 \ \frac{dN}{dE} dE$
- $= \frac{s-1}{s-3} E_0^2$

- Var(E) = $< E^2 > - < E >^2$
- Var(E) = $\left(\frac{s-1}{s-3} - \left(\frac{s-1}{s-2}\right)^2\right) E_0^2$