Results of Auger Follow-up Observations with VERITAS

Jamie Holder

Bartol Research Institute/ University of Delaware

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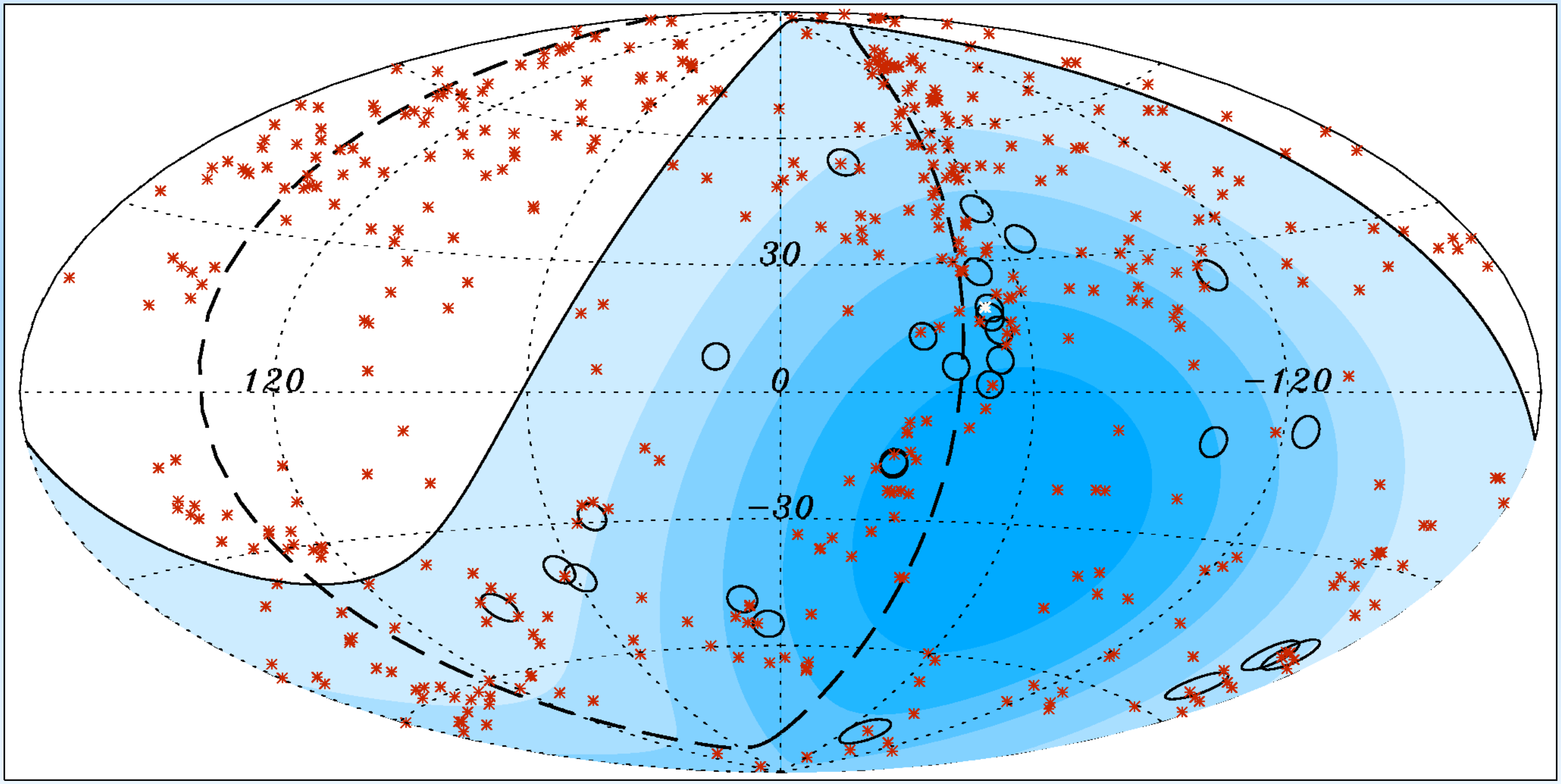
From the Unidentified…

...to the possibly Non-Existent

- Auger have measured a significant correlation between the arrival directions of UHE cosmic rays and a catalog of close AGN (Veron-Cetty & Veron, 12th Ed).



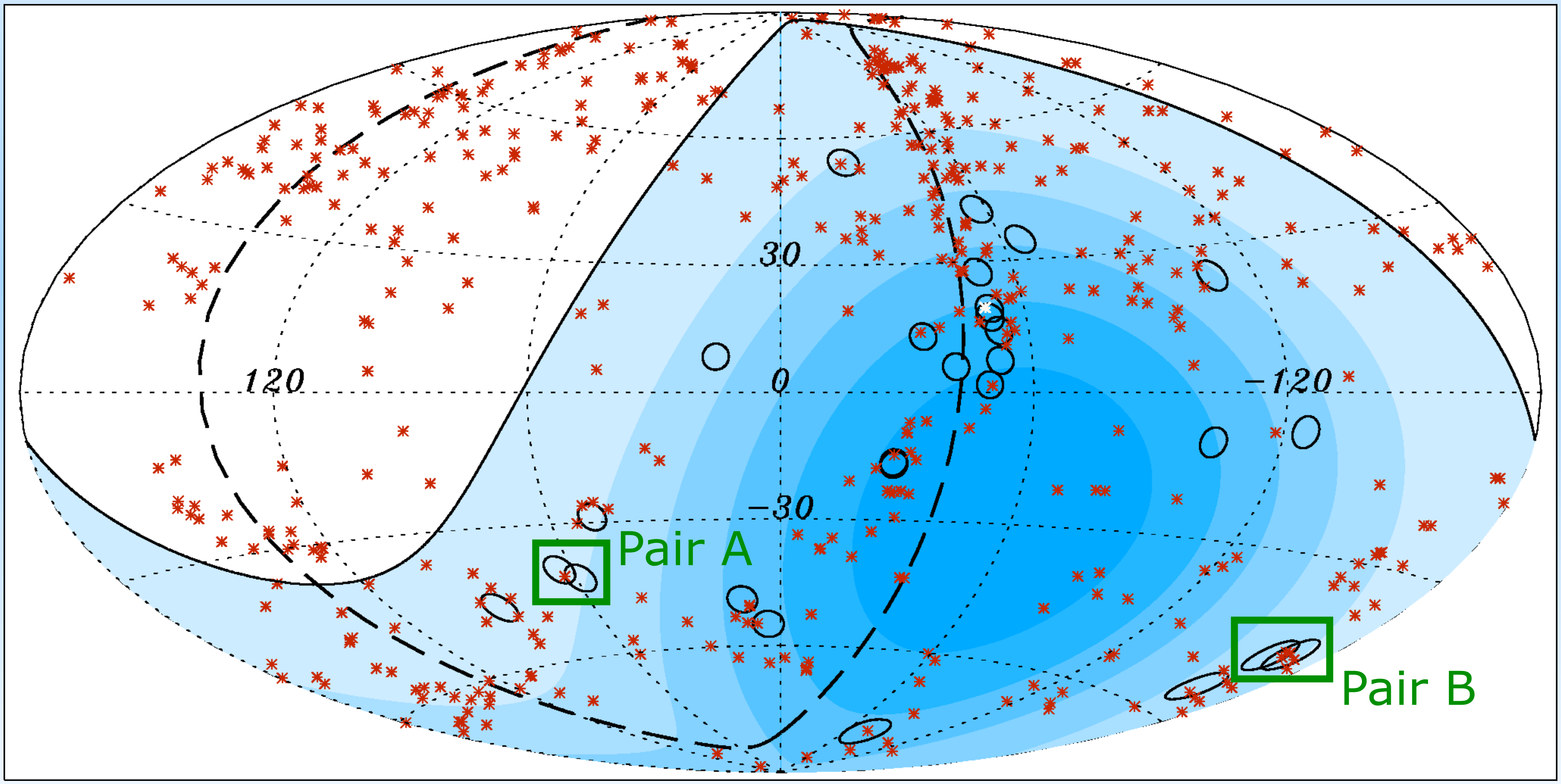
How was it done?

- With an initial dataset, they optimized the significance of the correlation by varying:
  - ψ = angular separation between CR arrival direction and source = 3.1°
  - z_{max}=maximum source redshift = 0.018 = 75Mpc
  - E_{th} = minimum energy of CR events = 57 EeV
  - 15 events in this dataset remain after cuts
- They then applied these cuts *a priori* to a new dataset, and measured a correlation (13 events, 8 correlate within 3.1°, expect 2.7, Probability of chance occurrence=1.7×10^{-3})

Handle with Care...

- What this is not:
    - Clear identification of close AGNs as the sources of the highest energy cosmic rays, with a measured maximum distance of 75Mpc and a measured IGMF deflection of 3.1°
- What this is:
    - Statistical evidence for a correlation between the CR arrival directions and a source population with a similar distribution to that of close AGNs
- GZK absorption allows for sources out to ~200Mpc – and the distribution of distances of the source population is unknown
- Significant correlation is seen for ψ up to 6°. The magnitude of the deflection is expected to vary across the sky (e.g galactic B-fields).
- Starting from the best guess cosmic ray arrival directions, gamma-rays can be used as tracers to identify the true sources.

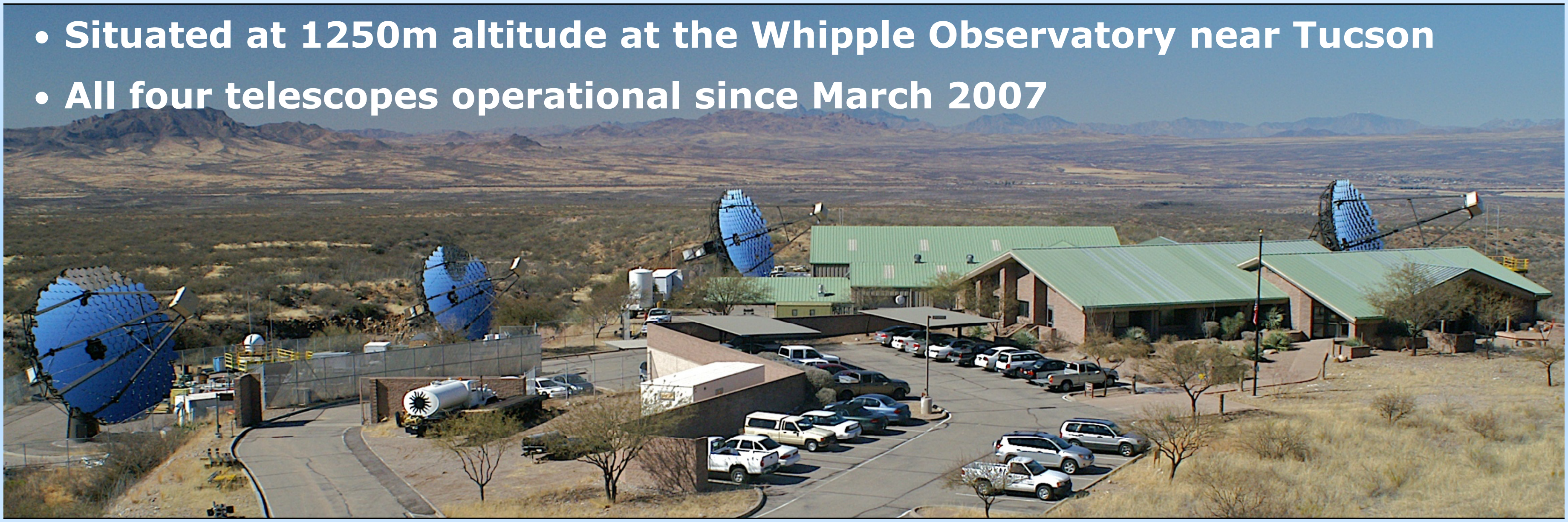
- ~50% of the Auger sky is at declination >-10°
- Of the final 27 event dataset, 7 events have declination> -10°
- 4 of these overlap in two pairs:



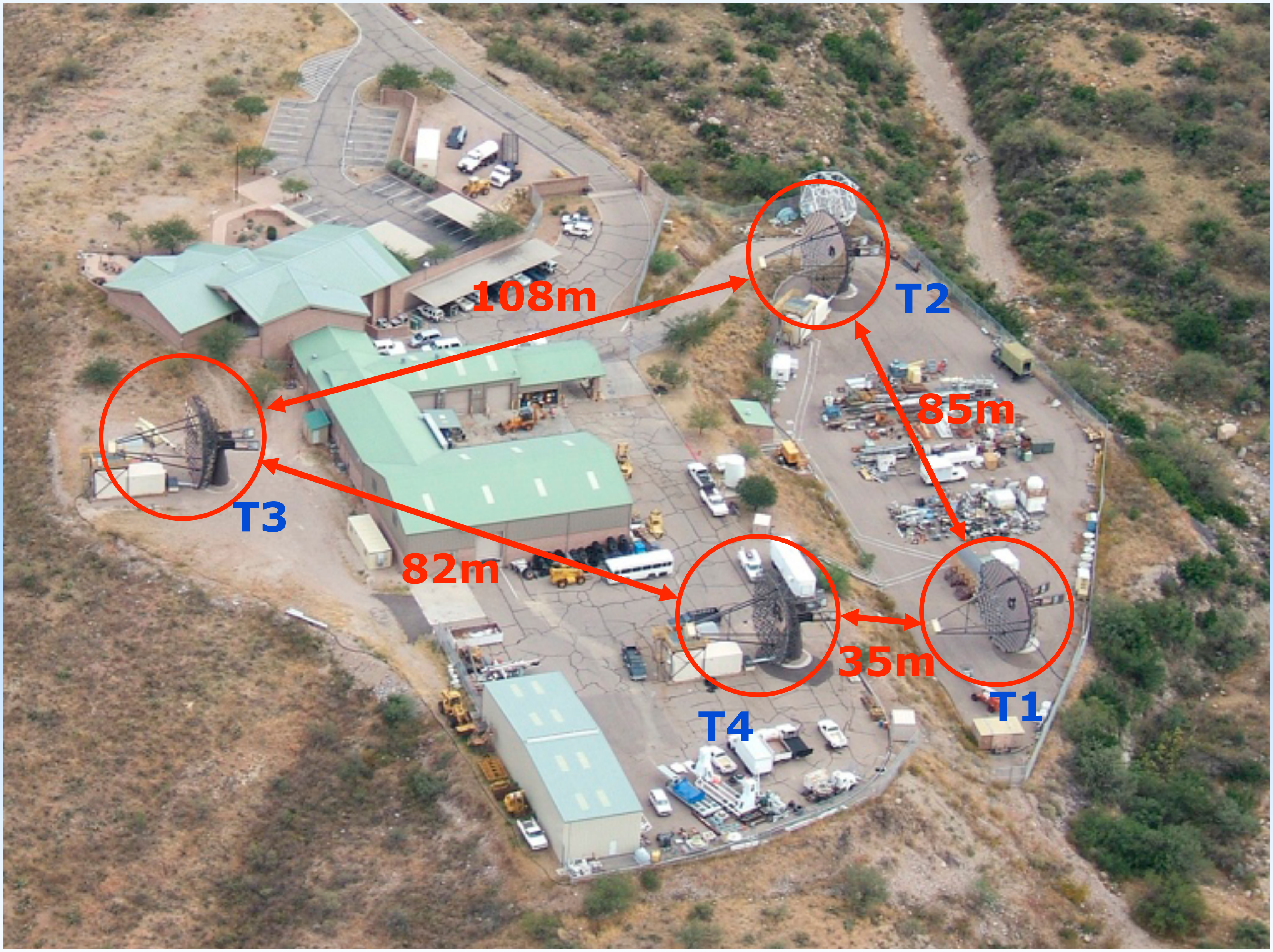
- Of the final 27 event dataset, 7 events have declination> -10°
- 4 of these overlap in two pairs.
- A number of AGN from the V-C catalogue correlate within 3.1°, with distances above and below 75 Mpc

Field	Source Name	Alternative Name	z	Classification	Angular Size (arcmin)
Pair A	Q 2207+0122	PC 2207+0122	0.013	Emission Line	0.18×0.15
Pair A	Q 2207+0121B	2MASX J22102668+0136432	0.047	Emission Line	0.53×0.24
Pair A	Q 2205+0120	2MASX J22080139+0135290	0.045	Emission Line	0.27×0.17
Pair A	SDSS J22064+0106	2MASX J22062439+0106455	0.049	Seyfert 2	0.28×0.13
Pair A	Q 2212+0215	2MASX J22151024+0230415	0.041	Emission Line	0.27×0.13
Pair A	Q 2213+0218	PC 2213+0218	0.041	Emission Line	0.26×0.14
Pair B	NGC 1358	-	0.013	Seyfert 2	2.6×2.0
Pair B	SDSS J03302-0532	NGC 1346	0.014	Seyfert 1	1.27×0.76
Pair B	SDSS J03349-0548	2MASX J03345798-0548536	0.018	Seyfert 1	0.41×0.27

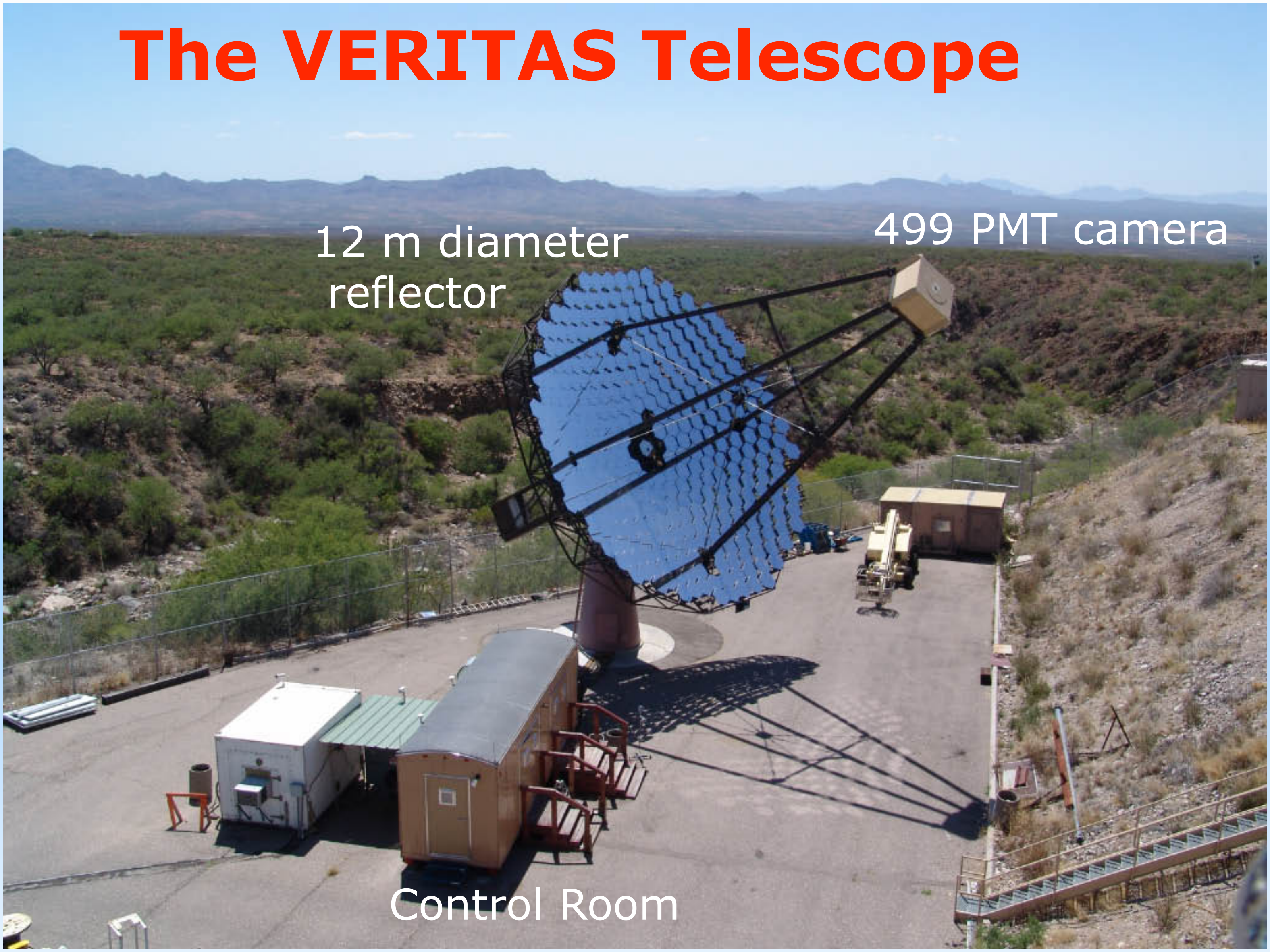
VERITAS



~80 members over ~20 Institutions in the US, UK, Ireland and Canada

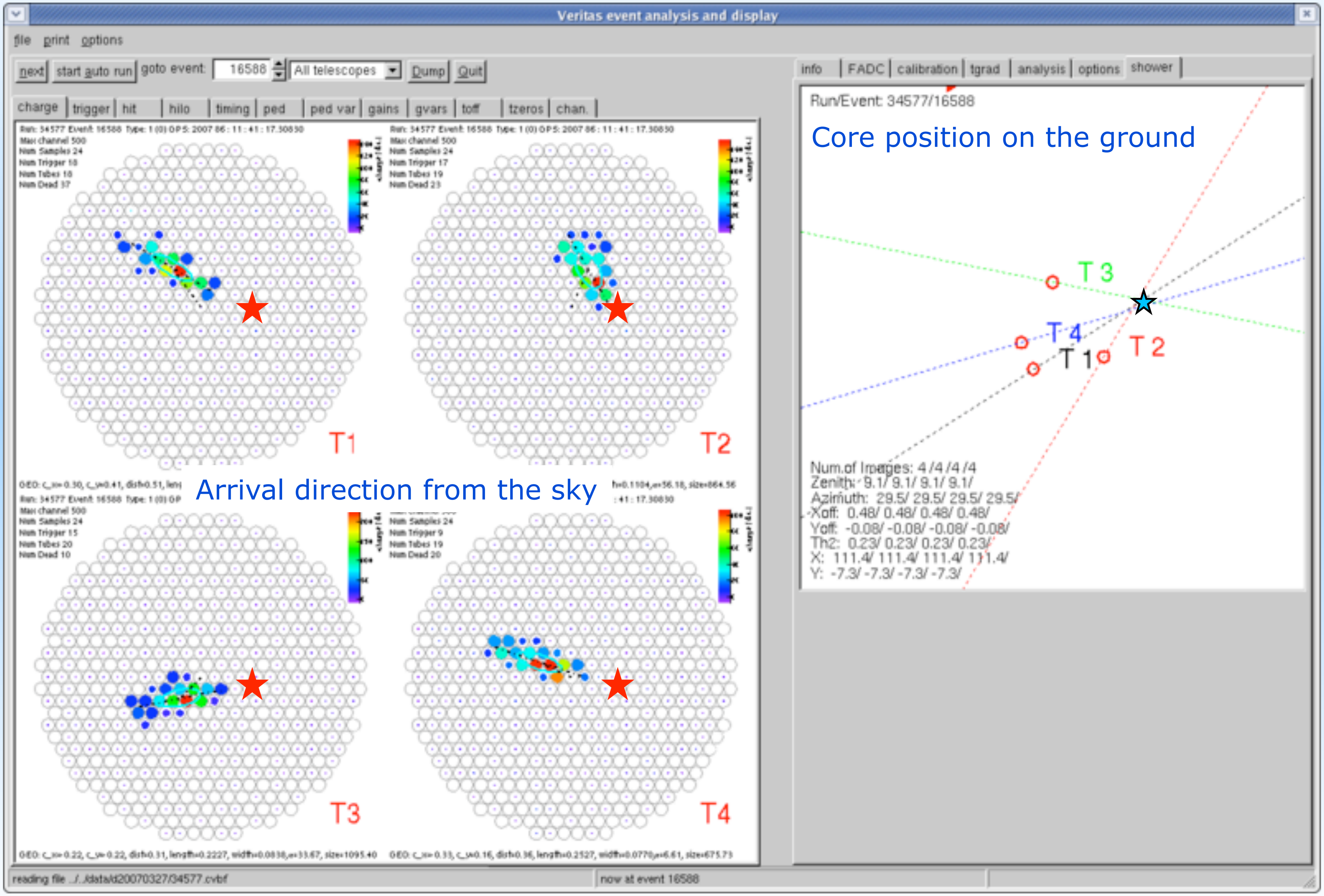

108m
T2
85m
T3
82m
35m
T1
T4

The VERITAS Telescope



- Davies-Cotton f/1.0 Optics. Total area=$110m^2$
- Installed at Whipple Basecamp on Mt. Hopkins (1275m) in January 2005

Shower reconstruction



Observations

- Fall 2007, Triggered using Director's Discretionary Time
  - Pair A, centred on PC2207+0122
  - 200 minutes, A/B weather
  - Pair B, centred half-way between NGC1358 and NGC 1346
  - 608 minutes, A/B weather

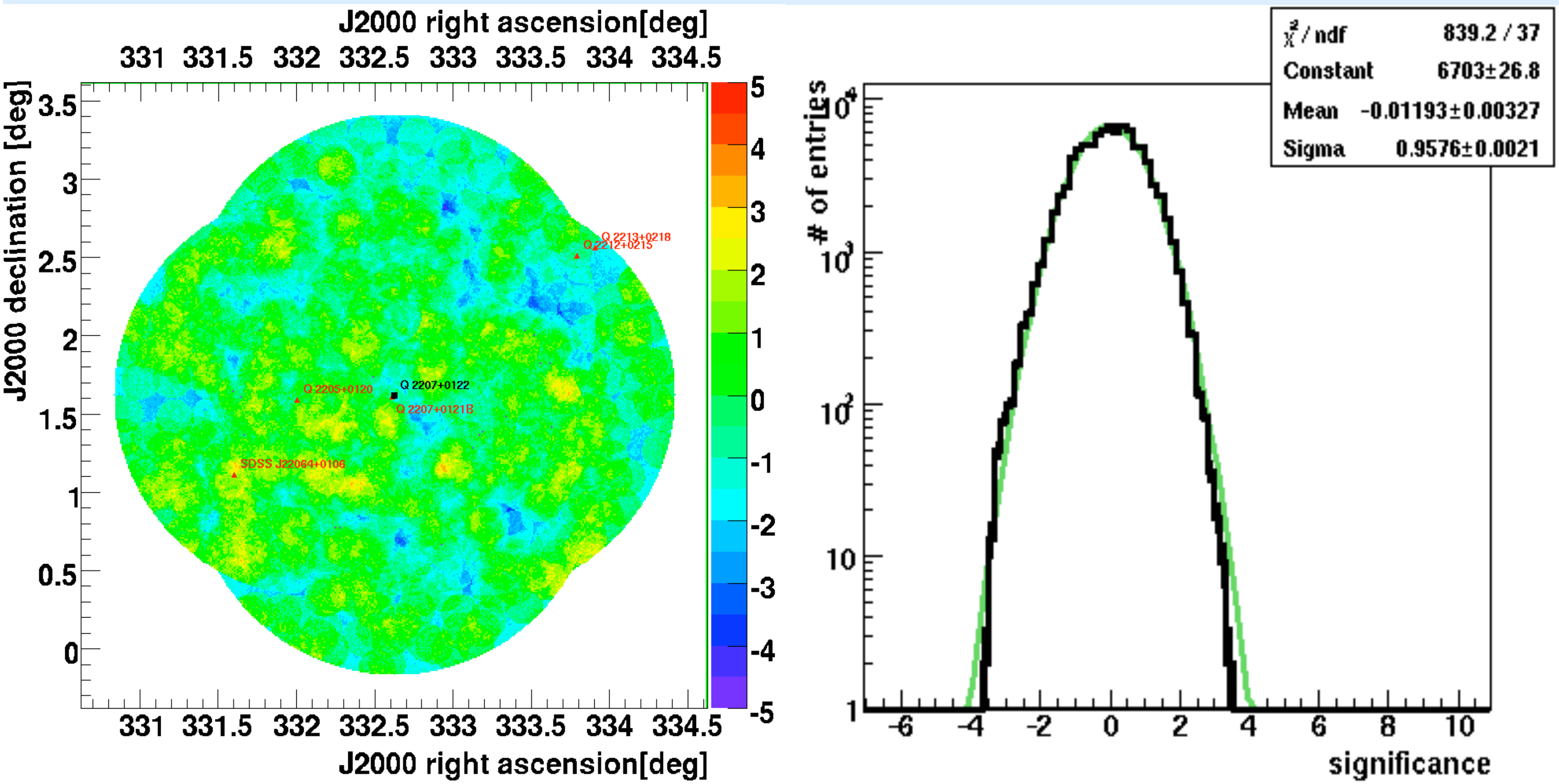
Analysis

- Analysis designed for weak, point-like sources
  - Reflected Region background analysis
  - Cuts :
    - *size*/image > 400dc
    - N_{tel} = 4
    - -1.2 < *MSCW/MSCL* < 0.5
    - θ^2<0.015

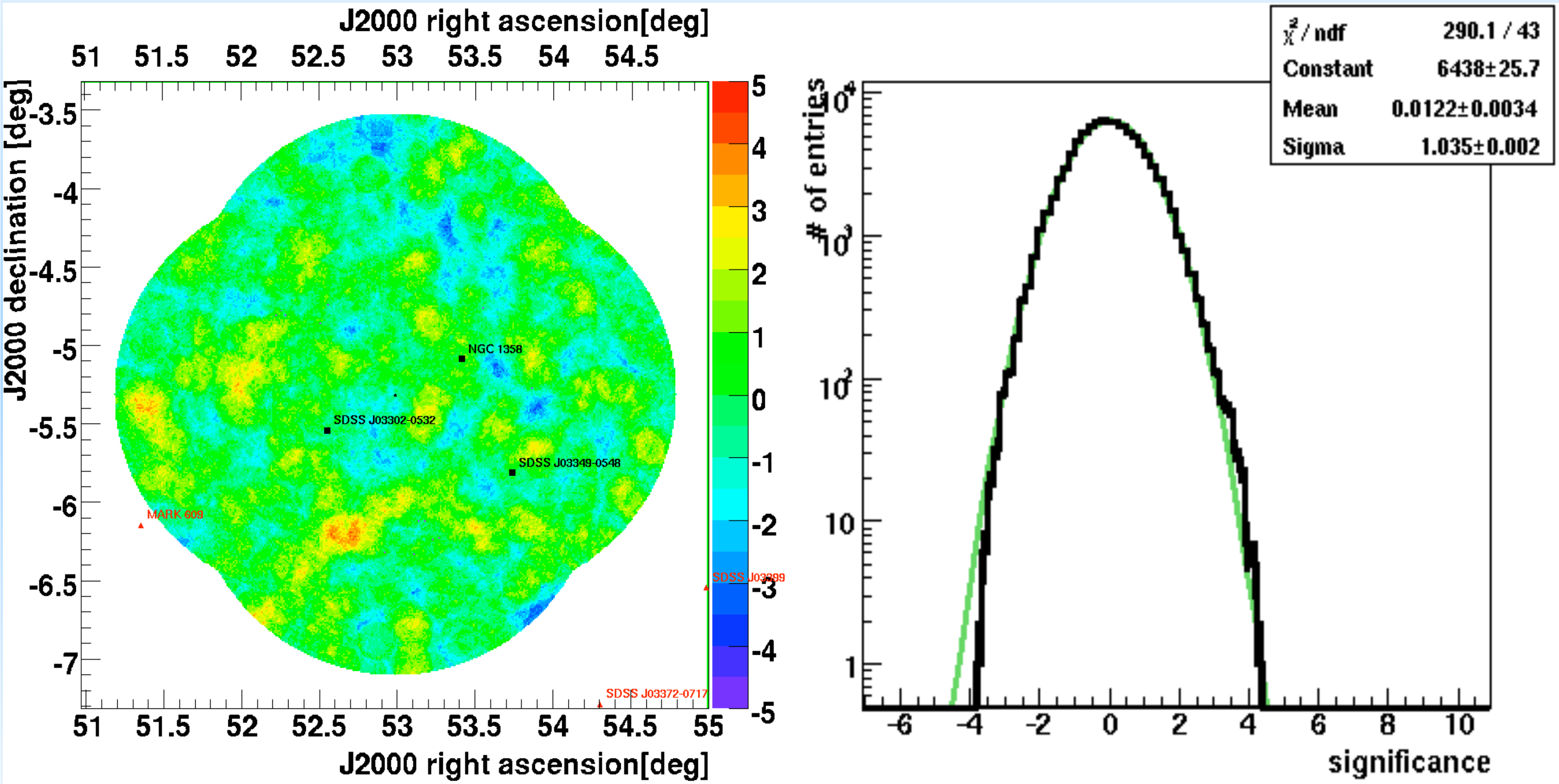
Sensitivity

Flux (Crab Units)	Time for 5σ detection
1	2 minutes
0.1	48 minutes
0.05	2.5 hours
0.03	6.1 hours
0.01	47 hours

Results: Pair A



Results: Pair B



Results

Source Name	*ON-source* (events)	*OFF-source* (events)	Background Normalization	99% confidence upper limits (events)	99% confidence upper limits (ph m^{-2} s^{-1} $>$ 500 GeV)
Q 2207+0122	4	78	0.10	4.6	8.6×10^{-9}
Q 2207+0121B	4	78	0.10	4.6	9.6×10^{-9}
Q 2205+0120	7	73	0.10	9.5	2.3×10^{-8}
SDSS J22064+0106	7	34	0.10	13.4	4.9×10^{-8}
Q 2212+0215	3	35	0.10	7.0	3.9×10^{-8}
Q 2213+0218	0	10	0.10	3.8	3.8×10^{-8}
NGC 1358	26	179	0.10	19.1	1.4×10^{-8}
SDSS J03302-0532	13	170	0.10	6.1	4.9×10^{-9}
SDSS J03349-0548	13	137	0.10	10.8	8.3×10^{-9}

Implications

- Production mechanisms for a gamma-ray flux :
  - (I) efficient particle acceleration associated with the same central engine - i.e. "bright" CR AGN are bright gamma -ray sources.

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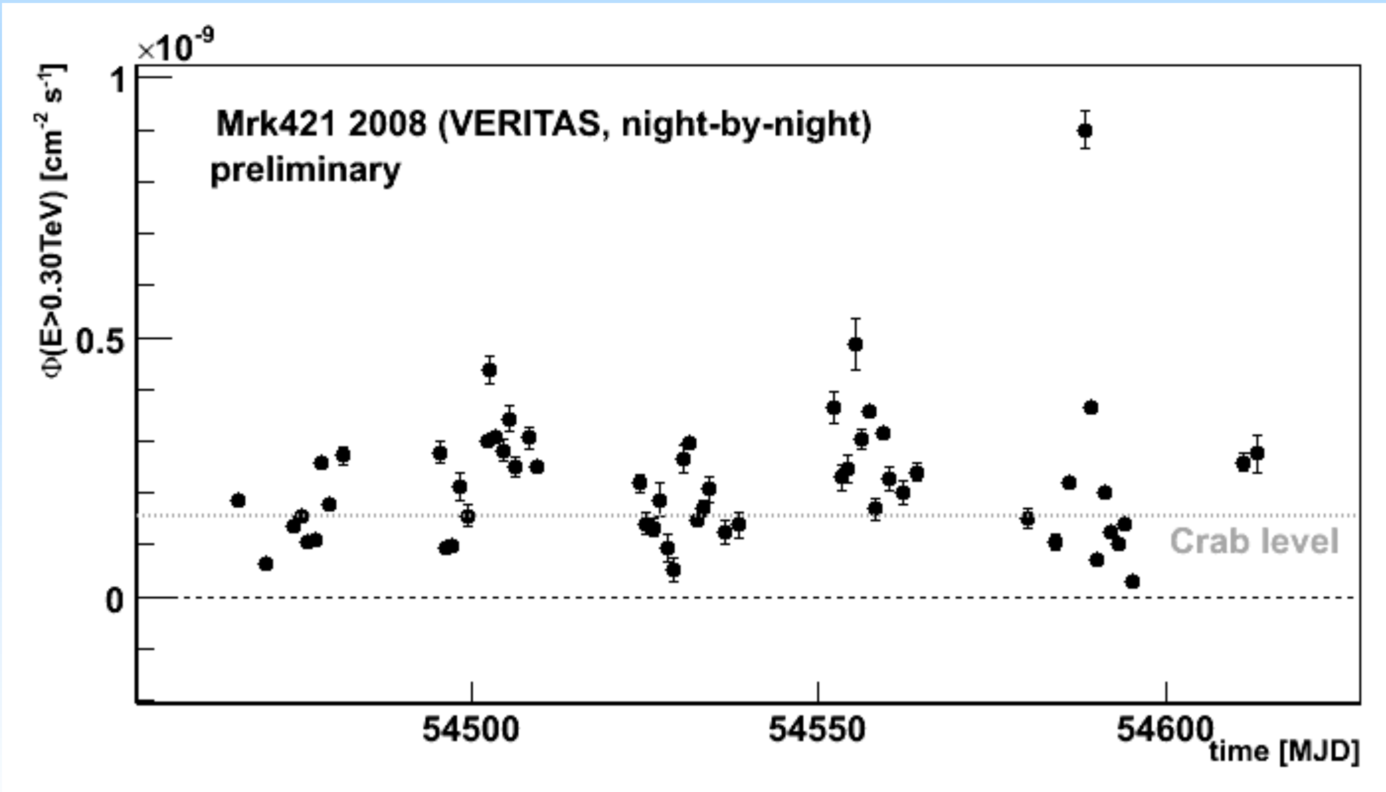

Implications

- Production mechanisms for a gamma-ray flux :
  - (I) efficient particle acceleration associated with the same central engine - i.e. "bright" CR AGN are bright gamma -ray sources.
  - None of the AGN targeted here are good standard TeV candidates
  - M87 detection shows that misaligned AGN can be detected
  - …but M87 is unusual - extremely prominent jets
  - note none of the Auger events are coincident with M87
    - (l=76, b=75)
  - 2 overlap with Cen A
    - Cen A is the best (though problematic) TeV target

- (II) electromagnetic cascades initiated by proton-photon interactions of the UHECRs on the CMBR.

$$p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma_{EeV} + \gamma_{EeV}$$

- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
- Discussion based on Gabici & Aharonian (2005)

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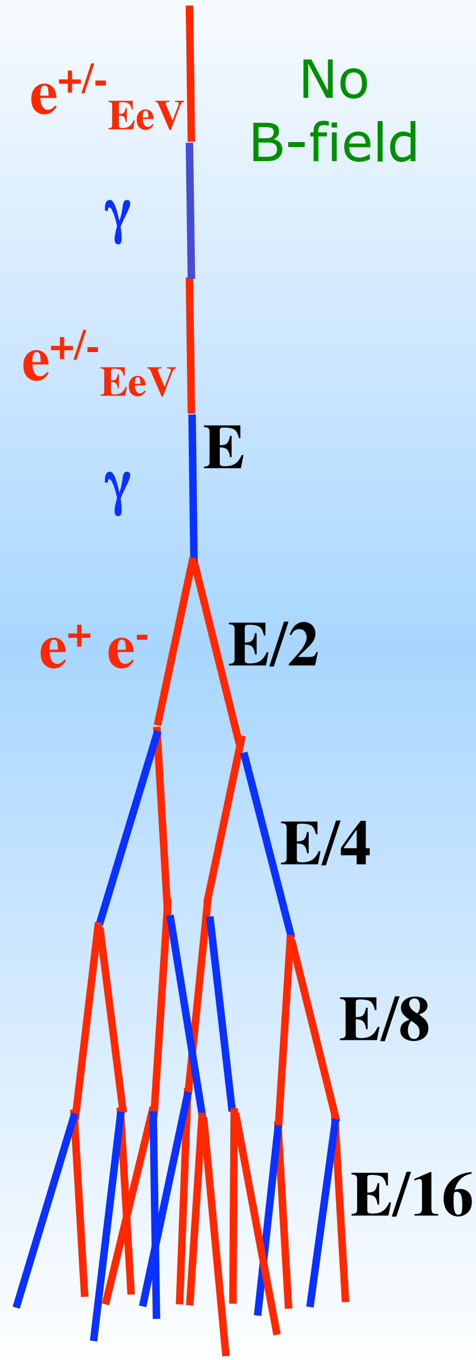
- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
  - A) low IGMF ($< 10^{-12}$ G) = point-like source. TeV photons from cascade.
- Cascade develops through pair production and Inverse Compton, initially in the extreme Klein-Nishina regime

$$\gamma_{EeV} + \gamma_{CMB} \rightarrow e^-_{EeV} + e^+$$

$$e^-_{EeV} + \gamma_{CMB} \rightarrow e^- + \gamma_{EeV}$$

- i.e "oscillates" from photon to electron, losing energy until $\Gamma<1$, when particle multiplication phase begins



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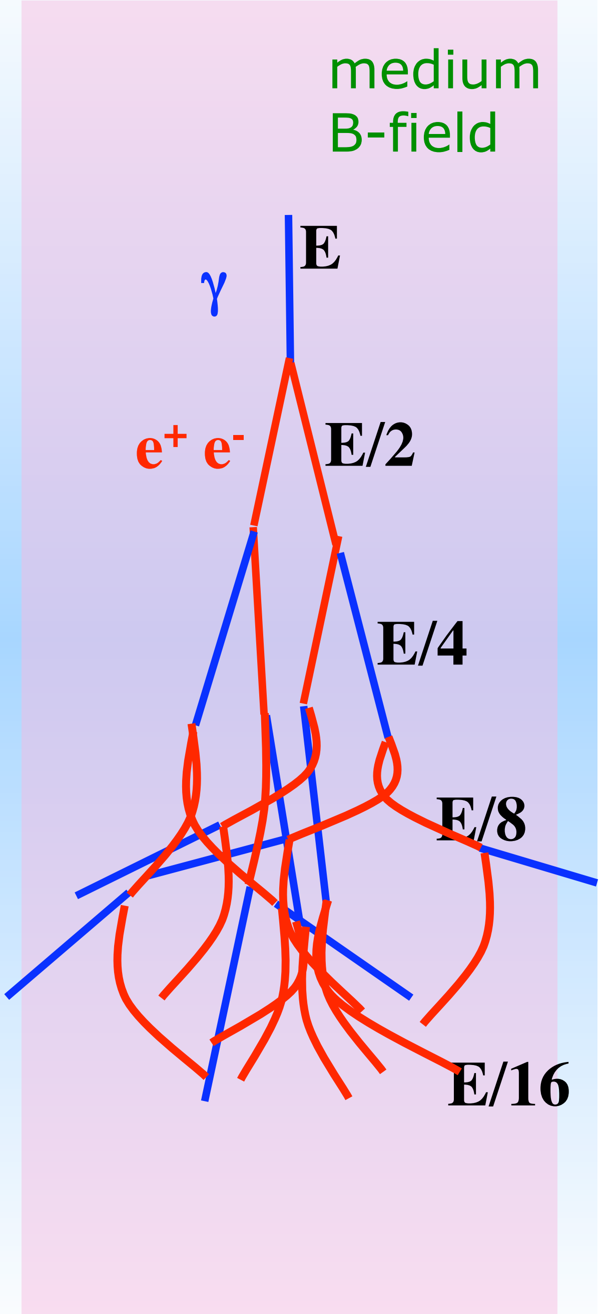
- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
  - B) medium IGMF (10^{-12} to 10^{-9} G) = extended source. TeV photons from cascade.
- Cascade develops through pair production but electrons are deflected and isotropized
- Leads to an "extended pair halo" 10° - 20° in extent
- Extremely difficult to detect or put limits on
- Milagro limits might be interesting!



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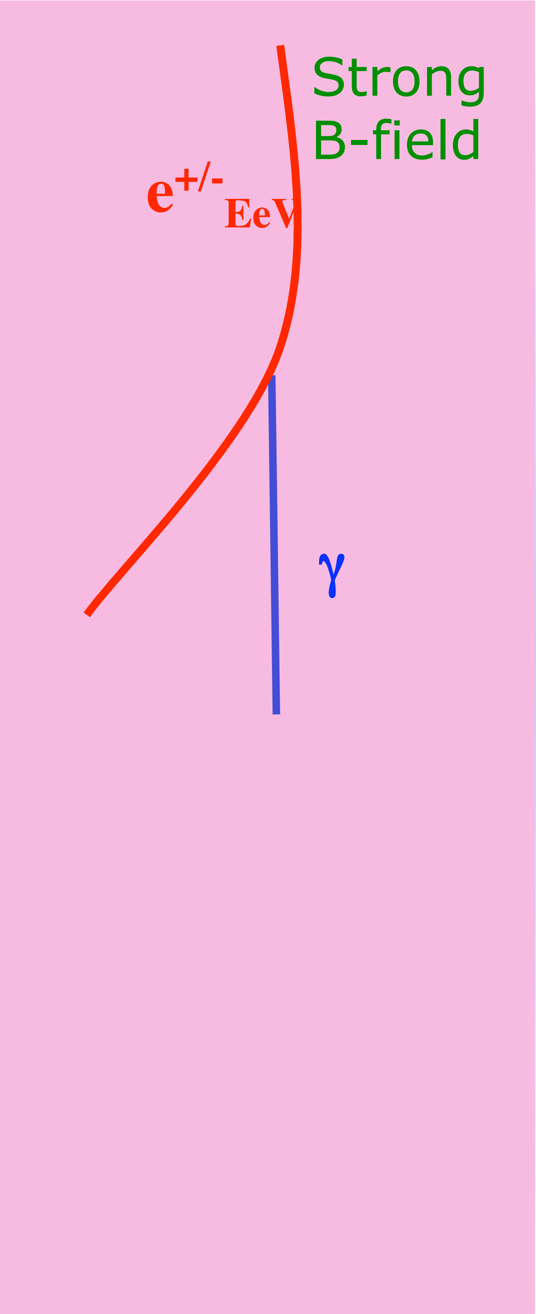
- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
    - C) strong IGMF (> 10^{-9} G) = slightly extended source. Synchrotron TeV photons.
- Electromagnetic cascade suppressed by synchrotron losses, but synchrotron photons are in the GeV - TeV range
- Angular size of the emission region for 300 GeV photons is dominated by deflections of the path of the UHECR by the IGMF during the first interaction length.
- a source at a distance of 50 Mpc would have an angular extent of ~0.16°, for B=10^{-9}



Gabici & Aharonian, 2005

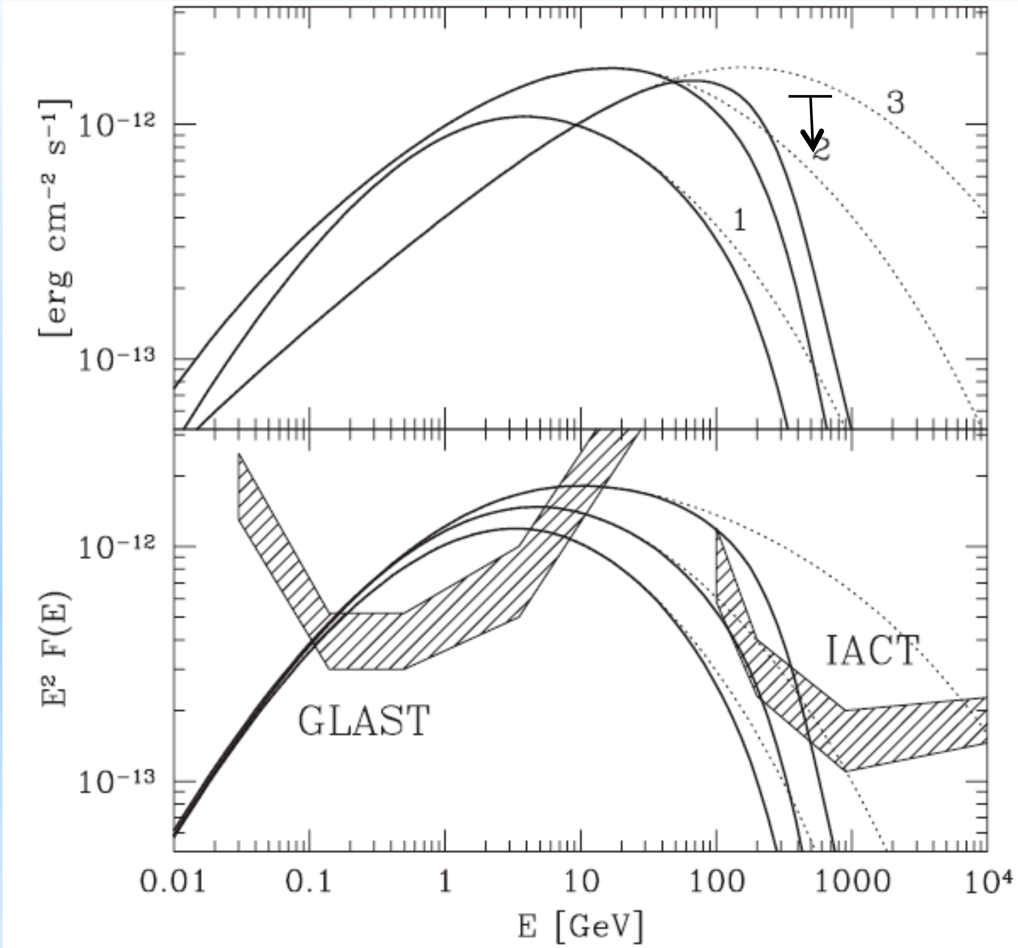


Figure 4. Figure taken from [30]. Spectra for a source located at a distance of 100Mpc. The luminosity in UHECRs is 2 10^{44}erg/s, with a spectral index of $\delta = 2$. TOP: $B_{IGMF} = 0.5$(curve 1), 5 (2), 50nG(3), $E_{cut} = 10^{21}$eV. BOTTOM: $E_{cut} = 5\,10^{20}$, 10^{21}, $5\,10^{21}$eV, $B_{IGMF} = 1$nG. Dotted: intrinsic spectra. Solid: spectra after absorption. The VERITAS limit is indicated by the arrow.

Synchrotron flux:
Highest TeV flux for
high CR energy cut
-off and high B-field

Implications

- Reasons we might miss a gamma-ray flux:
  - Flux is below our sensitivity
  - True source is outside of our field of view
  - Source is very extended
  - Source is time variable

Summary

- 'Speculative' observations - but a positive result would
  - Clearly identify the origin of the UHECRs
  - Probe the strength and structure of the IGMF
- Future Auger results will hopefully identify interesting regions more clearly
- With their high sensitivity and excellent angular resolution, ground-based TeV observatories *may* provide the definitive measurements to identify the sources of the highest energy cosmic rays.