A CLUSTER OF ULTRAHIGH ENERGY COSMIC RAYS

and what it teaches us

Glennys R. Farrar
Center for Cosmology and Particle Physics
New York University

Including work done in collaboration with:
- Chad Finley and Stefan Westerhoff -- Columbia
- The High Resolution Fly's Eye Collaboration (HiRes)
- Andreas Berlind and David Hogg -- NYU

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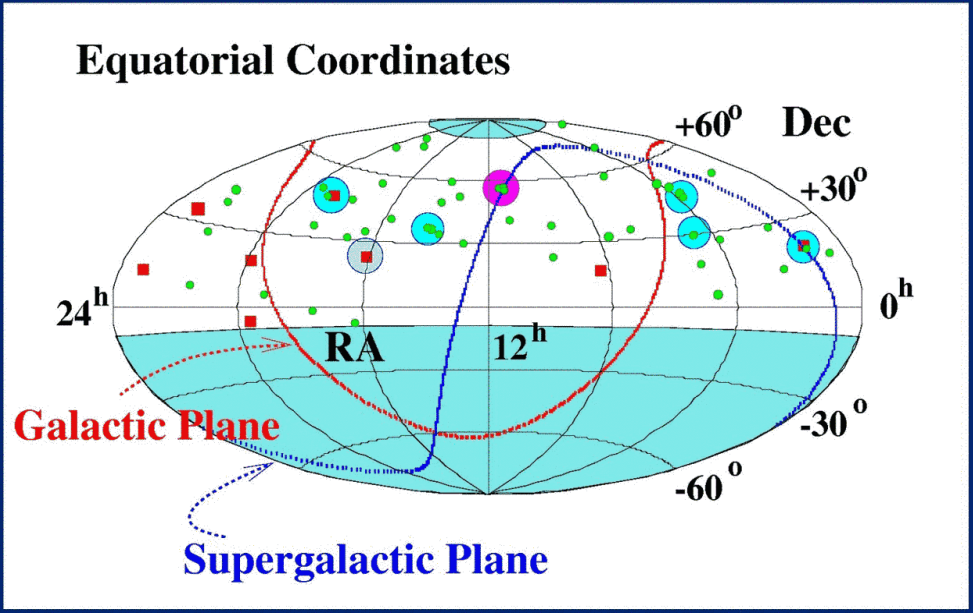
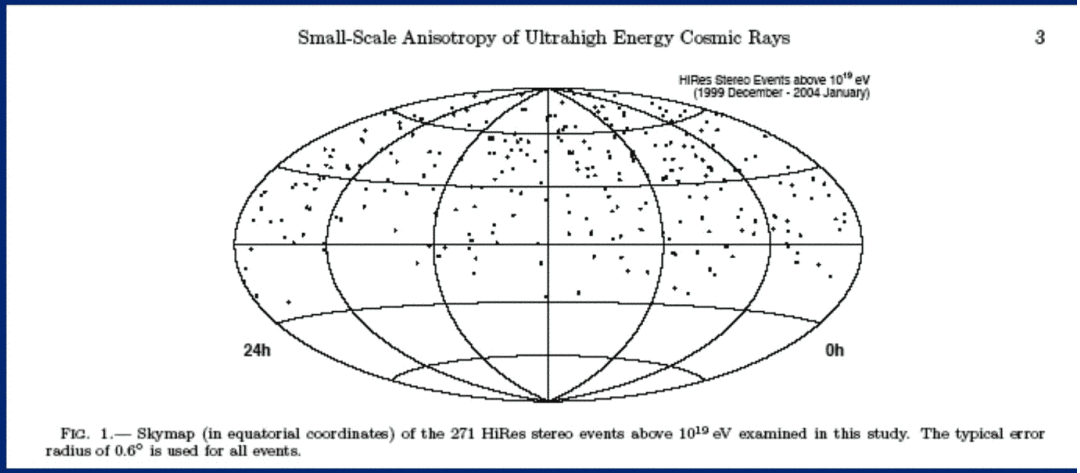
57 AGASA events above 40 EeV



271 HiRes Events above 10 EeV

ApJ 610 (2004) L73, Abbasi et al



Why could there be some clusters, while most UHECRs are singeltons?

- Many sources, mostly giving 0-1 events, a few giving more.
  - Poisson statistics => ~300-1000 sources
  - **Why can't we find candidate sources?**
- Magnetic fields may be crucial (GRF+T. Piran, PRL 98, Dolag et al astro-ph/0310902, Sigl et al. astro-ph/0409098,…)
  - Measured to be few tens of μG in rich clusters.
  - Could be much weaker in voids (equipartition ~ 0.3 nG).
  - **Evidence for most UHECR sources may be obliterated due to strong magnetic deflections en route to detector.**
  - Perhaps, for a few lucky sources, foreground fields are weak => **some sources looks quasi-point-like.**

A cluster of 5 UHE Cosmic Rays, consistent with a single source

3 AGASA: 53.5, 55, and 77.6 EeV
2 HiRes: 38.7 EeV + 1 in range 10-30 EeV

- *HiRes Collaboration + GRF* (astro-ph/0412617, Ap J in press)
  - Combined HiRes, AGASA data > 30, 40 EeV
  - Introduced maximum likelihood method of analysis
  - * 4 events consistent with pointlike source *
  - Simulation: < 0.5% chance for clustering signal
  - *No discovery claimed, because of mixed dataset*
- *GRF,* astro-ph/0501388
  - More refined probability analysis on quad
  - Include all published data > 10 EeV -- 214 more events
  - Now 5 events in cluster
  - Magnetic field analysis constrains fields along trajectory
- *GRF, Andreas Berlind, David Hogg* (in preparation)
  - Use SDSS data to study the foreground and constrain location of source
  - Identify candidate sources
- *GRF* (in preparation)
  - What does the spectrum teach us?
  - How to best exploit data-in-the-can (AGASA < 40 EeV, new HiRes)

Maximum Likelihood Analysis

HiRes+GRF astro-ph/0412617, c.f. Westerhoff talk

$$P_i(\vec{\theta}) = \frac{n_s}{N} Q_i(\vec{\theta}, \vec{\theta}_s) + \frac{N - n_s}{N} R_i(\vec{\theta})$$

- N: total number of events.
- n_s: number of events from source.

- Q: probability density for *i*-th event to be from direction theta if source is at theta_s.
- R: probability density for *i*-th event to be background

$$ln\mathcal{R}(n_s) \equiv ln\frac{\mathcal{L}(n_s)}{\mathcal{L}(0)} = \sum_{i=1}^{N} ln\left\{\frac{n_s}{N}\left(\frac{Q_i(\vec{\theta}_i, \vec{\theta}_s)}{R_i(\vec{\theta}_i)} - 1\right) + 1\right\}$$

GRF astro-ph/0501388;

If resolution is Gaussian and the same for all events: $ln\mathcal{R} = -\frac{1}{2}\chi^2 - lnP_{\epsilon,n_s,N}$

where

$$P_{\epsilon,n_s,N} = \frac{N!}{n_s!(N-n_s)!}\epsilon^{n_s} \approx \left(\frac{N\epsilon}{n_s}\right)^{n_s} \quad \text{with} \quad \epsilon \equiv 2\pi\sigma^2 R$$

Angular Resolution

$$\frac{1}{2\pi\sigma^2}\exp\left(-\frac{(\Delta\vec{\theta})^2}{2\sigma^2}\right)$$

(n.b., $\sigma_{68} = 1.51\ \sigma$)

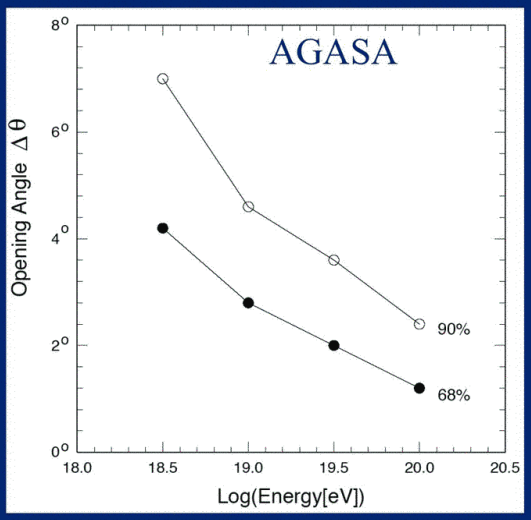
HiRes: $\sigma = 0.4$ deg

AGASA:

σ_g == core "well-contained"

σ_b == core just "inside"

$$\sigma_g(E) = 2.13^\circ - 0.80^\circ \log_{10}(E_{\rm EeV})$$
$$\sigma_b(E) = 4.49^\circ - 1.56^\circ \log_{10}(E_{\rm EeV})$$



ALL 3 AGASA EVENTS IN QUAD are well-contained => σ_g

Observed Quad: n_s

$ln\ R = 12.88$

$n_s = 3.9$

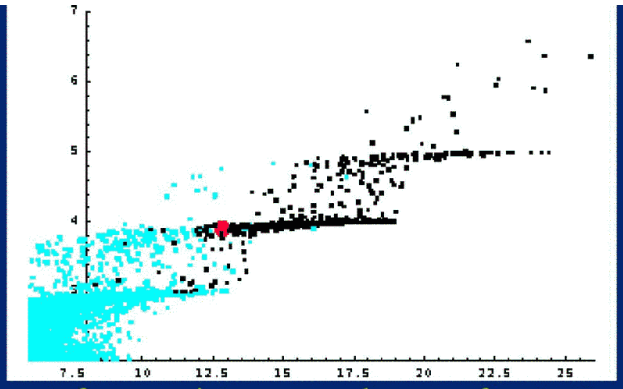


Figure:

• 1000 random datasets with 4 events from a point source and errors of observed quad => 1000 events in black

• 1000 random datasets, no source => 17 events in blue (3,000 shown)

Results:

- Data well-consistent with being a point-like quad.
- Chance probability $ln\ R \geq 12.88$ $2.0 \pm 0.4\ 10^{-3}$
- Chance probability $n_s \geq 3.9$ $1.6 \pm 0.3\ 10^{-3}$
- Chance probability $ln\ R \geq 12.88$, $n_s \geq 3.9$ $1.0 \pm 0.2\ 10^{-3}$
- Promotion probability: AGASA doublet ->quad $7 \pm 1\ 10^{-4}$

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Differences between analyses

- GRF astro-ph/0501388: approximate treatment of HiRes inhomogeneous exposure
- GRF: more exact treatment of AGASA errors
- HiRes+GRF
  - (Slightly) Binned analysis: 47 / 10,000
  - Un-Binned analysis: 27 / 10,000
- GRF: 10-20 / 10,000

Chance probability estimates -- remarks

- Chance probabilities insensitive to overall size of errors.
- 40 EeV AGASA energy threshold: Tuned to maximize initial 3-doublet signal (lowest energy doublet member had 43 EeV) but lowest energy quad event has 53.5 EeV. => AGASA threshold not tuned wrt quad signal
- HiRes energy threshold: 30 vs 40 EeV
  - Use discrepancy in spectra to determine appropriate HiRes energy threshold => HiRes threshold of 30-35 EeV equivalent to 40 EeV AGASA threshold
    - Depends weakly on spectrum, in 30-40 EeV range
    - Assumes exposure calculations are correct above 30 EeV
  - Reducing AGASA energies by 18% => HiRes 32.5 EeV == 40 EeV AGASA
  - 37.6 EeV HR event has ± 15% energy uncertainty.
    - Probability its energy is ≥ 40 EeV is 34%.
    - Then ML analysis would have 57 AGASA and 28 HR events, and chance probabilities are 33% lower.
- Conclusion: Estimate that chance probability of quad is ≤ 2 10^{-3} is realistic.

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Maximum Likelihood Analysis

including Magnetic Dispersion

in the many-small-deflections approximation, astro-ph/0501388

$$\sigma_B^2 = \frac{2B^2\lambda D}{9E^2} \equiv \frac{E_*^2}{E^2}$$

$$\sigma_i = \sqrt{\sigma_{i,0}^2 + \sigma_B(E_i)^2}$$

energy	date	{RA, dec} (degrees)	σ_0 (σ_{26})
77.6	1995,01,26	{168.5,57.6}	0.62 (0.63)
55	1992,08,01	{172.25,57.1}	0.74 (0.74)
53.5	1998,04,04	{168.25,56.0}	0.75 (0.75)
37.6	2003,04,29	{169.0,55.85}	0.4 (0.45)
10-30	—	{171.7,57.8}	0.4 (1.33)

E_5 : mean value ($E^{-2.7}$spectrum) is 15 EeV

* Find value of E* that gives chi-square == number of degrees of freedom
* Do analysis with and without net deflection (magnitude and direction)
* Combine 53.5 and 55 EeV events before analysis
  "quad" : 2*3 - 3 = 3 dof [1 with net deflection]
  "quint" : 2*4 - 3 = 5 dof [3 with net deflection
- quad => E* = 32.5° EeV
- Quint:
  - E_5 = 15 EeV => E* = 23.9° EeV
  - E_5 = 10-30 EeV; 90% CL => E* = (9 - 65)° EeV
- *Best fit has no net magnetic deflection*

Consistent with direct observations of galactic magnetic field, but not with standard models

5/7/05 G. Farrar@KITP 12

Quint or Quad?

- Magnetic dispersion results for either interpretation are CONSISTENT! => there are likely to be ***FIVE EVENTS from a single source***
- BUT n.b. chance "promotion probability" to get the quint at random from the quad, when 214 events are added at random, is 1 in 6
- *Chance probabilities are nearly the same with or without magnetic field and with or without 5th event.*

Implications of the Magnetic Dispersion Analysis

- **$E^* > 0$** argues ***cosmic ray primaries are charged***.
- First unambiguous evidence for multiple events from a single source
  - ***excludes decaying superheavy particle as source.***
  - ***problematic for annihilating DM or Z-burst.***
- Constraint on average extragalactic magnetic field strength, coherence length, and distance of source:

$$\sqrt{\langle B^2 \lambda \rangle D} \approx 1 \text{ nG Mpc}$$

Locating the source

Quad; no magnetic smearing:

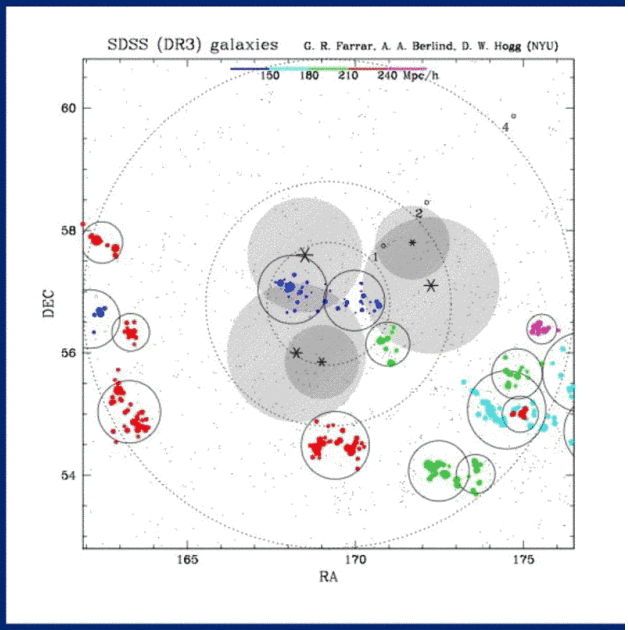
- RA, dec: 169.2°, 56.4°
- error radius (99 %): $\sigma_{99} = 0.75°$

Quint; magnetic smearing:

- RA,dec: 169.2°, 56.8°
- error radius (99 %): $\sigma_{99} = 1.2°$

Net magnetic deflection:

- *Best fit has no net deflection.*
- Event energies vary by factor 2 => conspiracy would be needed.



Lets take a look!

GF, Andreas Berlind and David Hogg

The Large Scale Structure toward the Quad from SDSS

GRF, A. A. Berlind, D. W. Hogg, forthcoming

Density in the source direction: ***exceptionally low, out to 140 Mpc***

Foreground void supports irregular B field hypothesis

In voids:

$n_e = 0.1 < n_e >$

$T = T_3\ 10^3\ K \Rightarrow$

$B_{equip} = 0.3\ T_3^{1/2}\ nG.$

Expect $B < B_{equip}$

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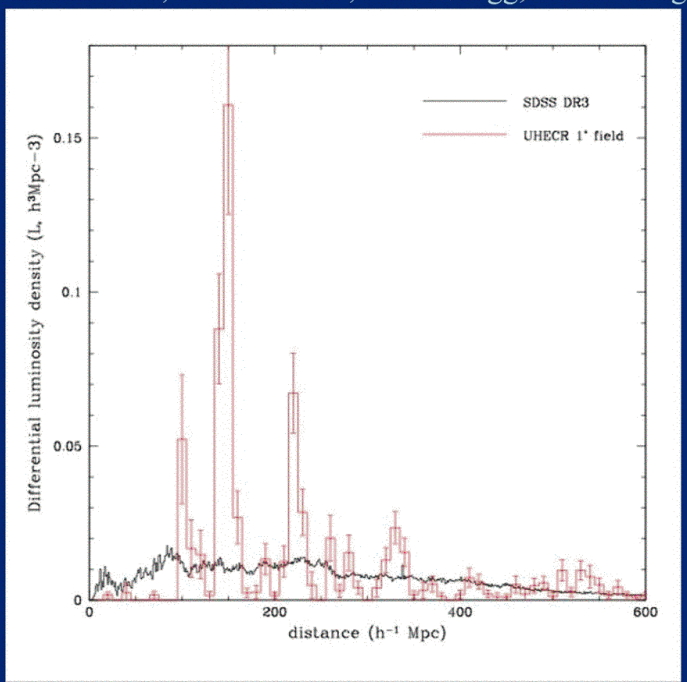
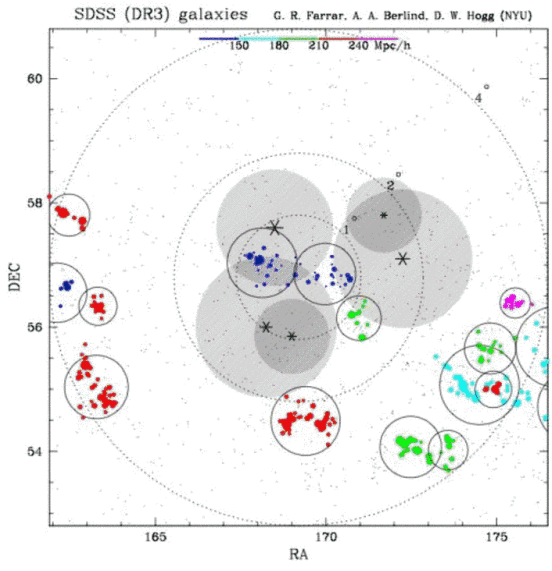
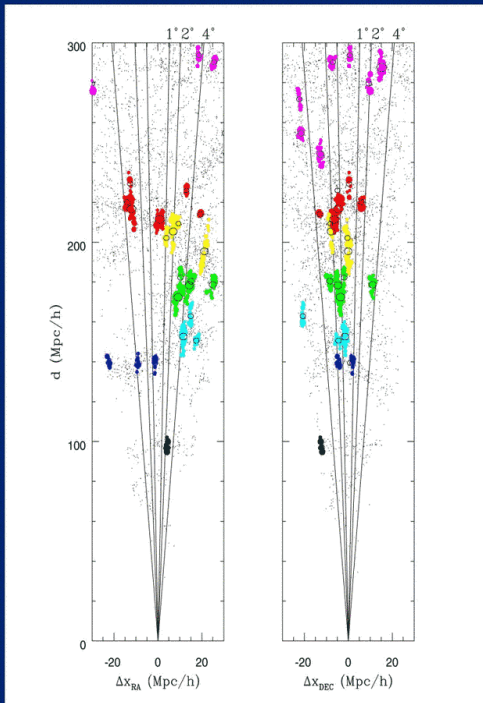


Clusters of Galaxies

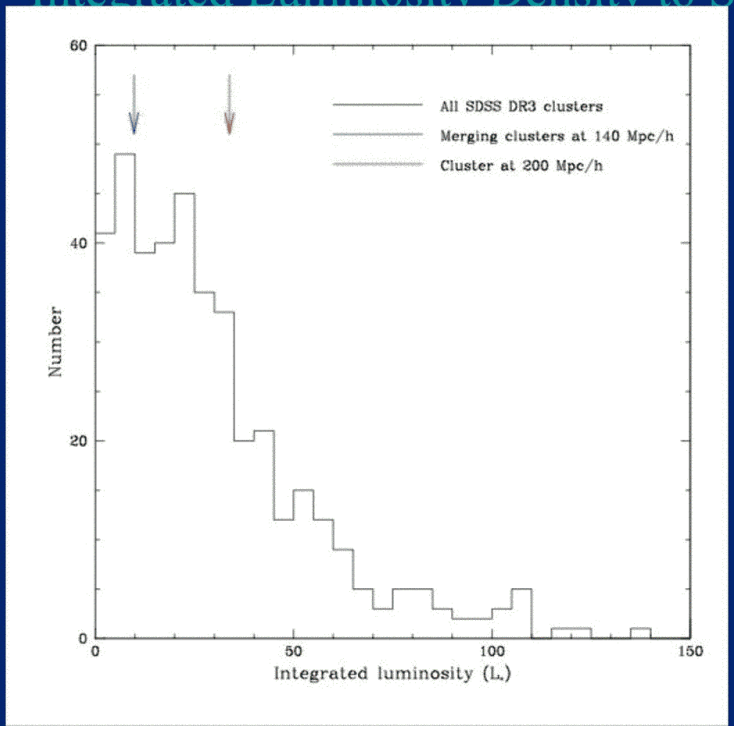
identified in the SDSS DR3 by Andreas Berlind (NYU)





Direction of Source Very Under-dense

Integrated Luminosity Density to SDSS Clusters



GRF, A. A. Berlind, D. W. Hogg, forthcoming

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The Big Picture

SDSS volume-limited wedge

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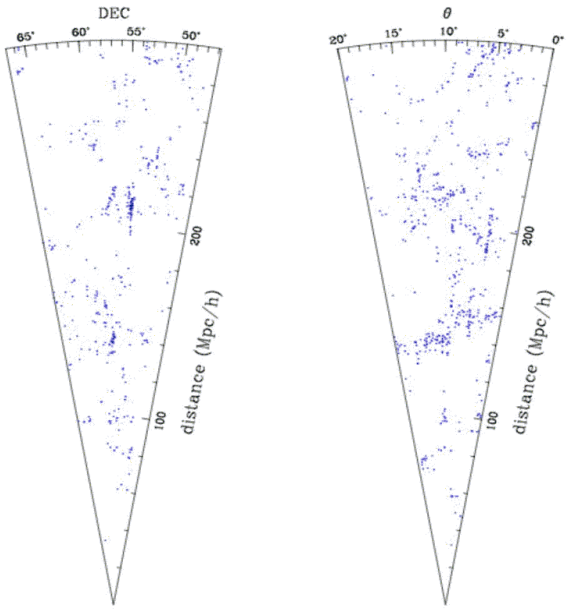
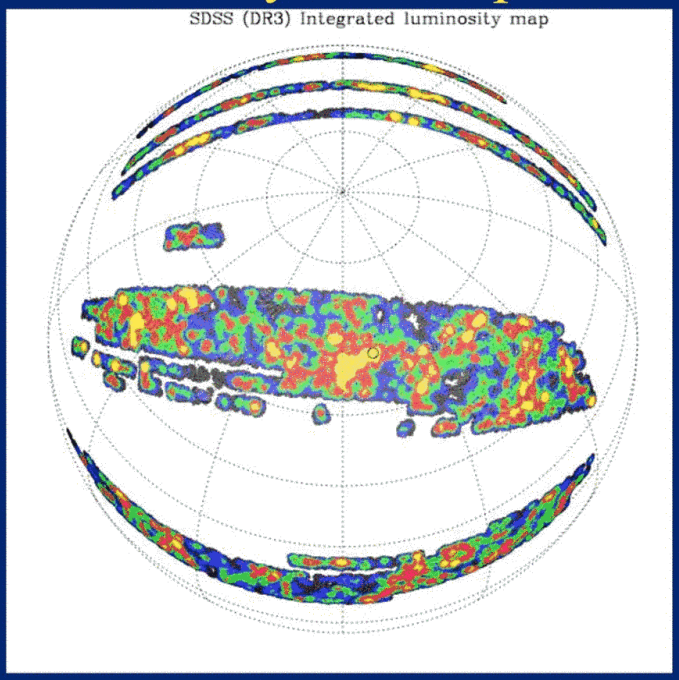


But -- SDSS Column-Integrated Luminosity is Exceptionally BIG!



Yellow <=> top 95% in integrated column density.

Maybe its <u>not</u> the void in front which is special about this field…

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Possible sources

- Cataclysmic event, e.g., GRB or magnetar birth.
- Jets in AGNs (accreting supermassive BH)
- Long, gradual acceleration in large scale magnetic shocks taking 100's millions of years
- New Physics -- e.g., decay of invisible, super-heavy particle created in the Big Bang

What's in this field?

- No remarkable or suitable sources found (yet) in this field (z <
  - No bright sources or AGNs within ~2°
  - Merging galaxy clusters are not x-ray clusters
  - SN1983w at 26 Mpc and GRB831221 are compatible in time and almost in space (Hurley) with being same event, but SN1983w is a type 1a (Branch, Fillippenko)
- **BUT,,,**
  - > ~50% of AGN's are obscured (not visible in optical).
  - Only minimal coverage in x-ray and radio in this field.
- SDSS summary
  - Direction to UHECR source is almost empty out to 140-200 Mpc. ***Explains low magnetic dispersion?***
  - Then: ***rich clusters of galaxies merging!***
  - The merging clusters of galaxieds may contain the source:
    - New possibility: acceleration by intense large scale magnetic shocks
    - Obscured AGN? + All the usual suspects…
    - Galaxy merging may be stimulated by merging clusters => greater star formation => enhanced rate of cataclysmic events (GRBs, magnetar births…)
  - Currently searching SDSS for starburst galaxies (GRBs, magnetars)

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Spectrum Disfavors Continuous Source

(GRF, forthcoming)

Above 30 EeV: 4 events in source region, of 94 total

10 - 30 EeV: 1 event " " ", of 214 total

- Naïve analysis: same spectrum for source and bkg
  - Don't need to understand exposures
  - Total of 94 and 214 events => expect source to show $\mathbf{n_{10\text{-}30} = 2.3\ n_{>30}}$
  - Probability of observing $n_{10\text{-}30} \leq 1$ and $n_{>30} \geq 4$:

    < 0.003 maximized for $\langle n_{>30} \rangle = 1.9$
- More sophisticated analysis with different power-law spectra

  $\mathbf{N_{E1\text{-}E2} / N_{>E2} = (E_2/E_1)^{(p-1)} - 1}$
  - Source:
    - Shock Acceleration (e.g., AGN, GRB): p_s = 2-2.3
    - Magnetar, decaying relic: p_s = 1-2
  - Propagation can soften power, e.g., magnetic entrapment in high-field regions.
  - Roughly maximize probability for $p_{bkg} = 2.6$, $p_s = 2$, $E_2 = 40$ EeV

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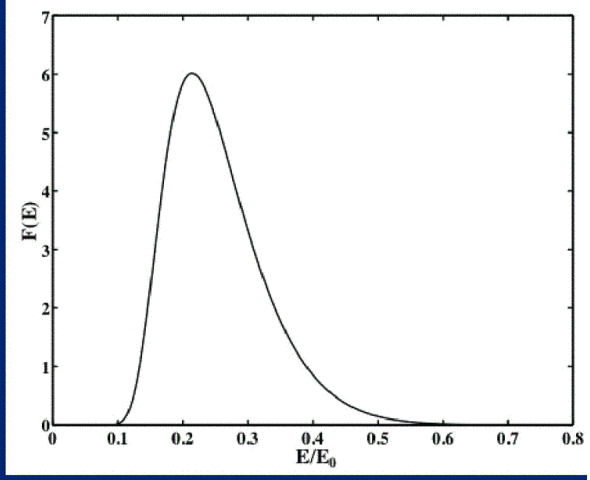
Probability of observing $n_{10\text{-}30} \leq 1$ and $n_{>30} \geq 4$: **$\leq$ ~16%**

Observed Spectrum of a Bursting Source is not a power law!

- *Highest energy particles tend to arrive first.*
- *At any given time,*
  ~ factor-2 spread in energies.
- ***Energies of quad events have factor-2 spread:***
  38, 54, 55, 78 EeV
- 5th event at low energy?
  - Need energy (30 EeV ok, 10 not)
  - Maybe accidental (1 in 6 chance)
  - Relative HiRes-AGASA energy complicates interpretation
  - Need energy & exposure from HiRes
- **Need AGASA data < 40 EeV!**
- For source at 100 Mpc, t <~ few kyr <=> bursting



Waxman Miralde-Escuda 96
Alcock Hatchett 73
GRF in preparation

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Astrophysics Conclusions

- *Extragalactic magnetic fields probably have dramatic structures (e.g., walls and voids) like matter does.*

  If source at 200 Mpc: $\langle B_{\rm void} \rangle \lesssim 0.07/\sqrt{\lambda_{\rm Mpc}}$ nG
- Merging galaxy clusters at 200 Mpc is the most distinctive object in field -- shock acceleration site? Merger-induced star formation?
- *Spectrum favors bursting source (GRB, magnetar);* need more UHECR data to clarify.
- Unambiguous evidence for multiple events from a single source: *excludes decaying superheavy particle* & severe *challenge for other top-down models.*

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The Future

- **Definitive confirmation of common origin for quad events awaits further data**
  - AGASA full data-set to be released this spring (?)
  - HiRes continuing => 75% more HiRes data on quad.
- Identify the Quad's source and analyze B fields
  - Use X-Ray Satellite Telescopes (Chandra, XMM) to search for evidence of large scale shock acceleration (G.F. + D. Helfand proposal)
  - Locate likely sites for GRB or magnetar sources
- Rich opportunities ahead for UHECR astrophysics
  - *Lets hope for point sources visible with AUGER in Southern Hemisphere, and pray for Auger North.*
  - *But not a field for people who can't tolerate uncertainty…*