Abstract

Ultra high energy cosmic rays and astrophysical neutrinos are two of the most energetic observables we have into the universe, yet their origins remain a mystery. Each class of particles has different advantages and disadvantages when it comes to determining their sources. I will present techniques well suited for each class. For cosmic rays, ground based experiments can't see the whole sky and I will discuss the penalty they pay for this. For neutrinos, I will present a general technique for determining their origin.

Finding Anisotropies in Cosmic Rays and Neutrinos

Peter B. Denton

NBIA Astroparticle Seminar

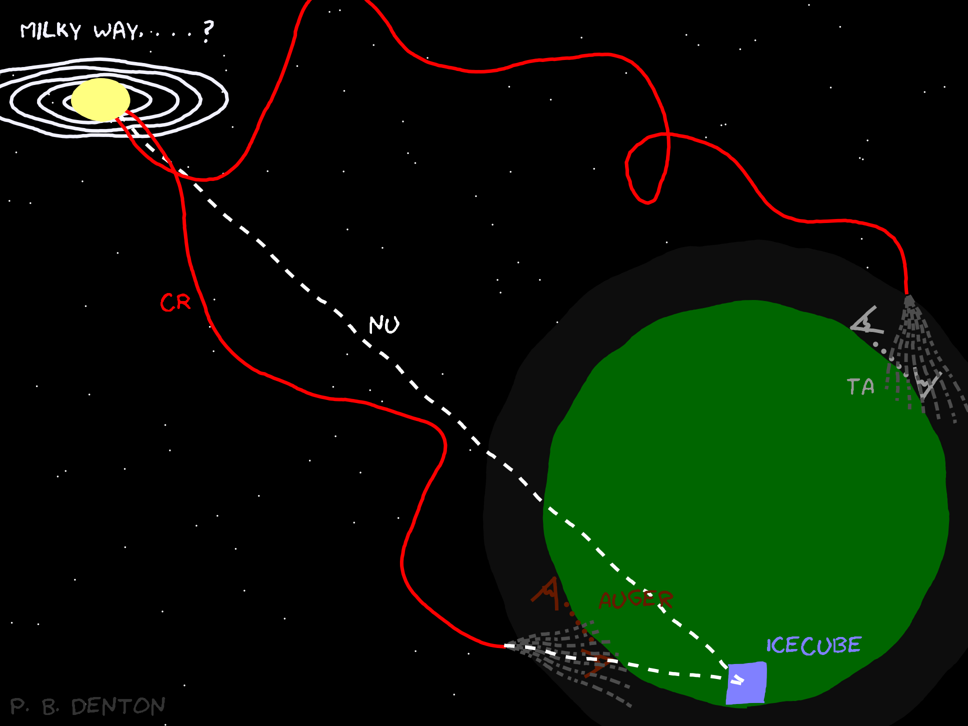
April 24, 2017

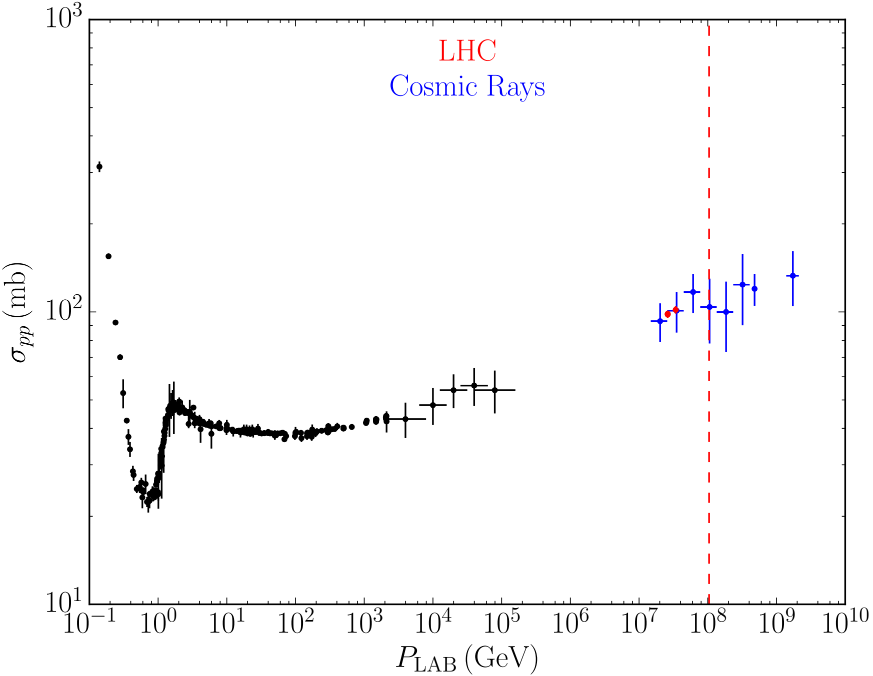
1409.0883, 1505.03922, 1703.09721
with Tom Weiler and Danny Marfatia

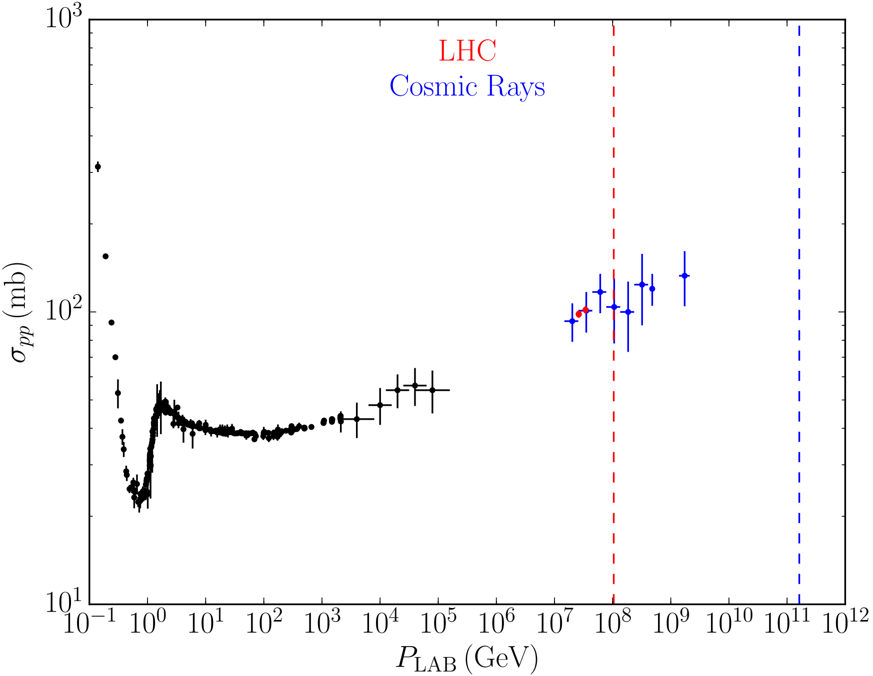
github.com/PeterDenton/ANA

The Niels Bohr International Academy

VILLUM FONDEN


MILKY WAY. . . . ?
CR
NU
TA
AUGER
ICECUBE
P. B. DENTON


LHC
Cosmic Rays
σ_{pp} (mb)
10^3
10^2
10^1
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
P_{LAB} (GeV)



LHC
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10^3
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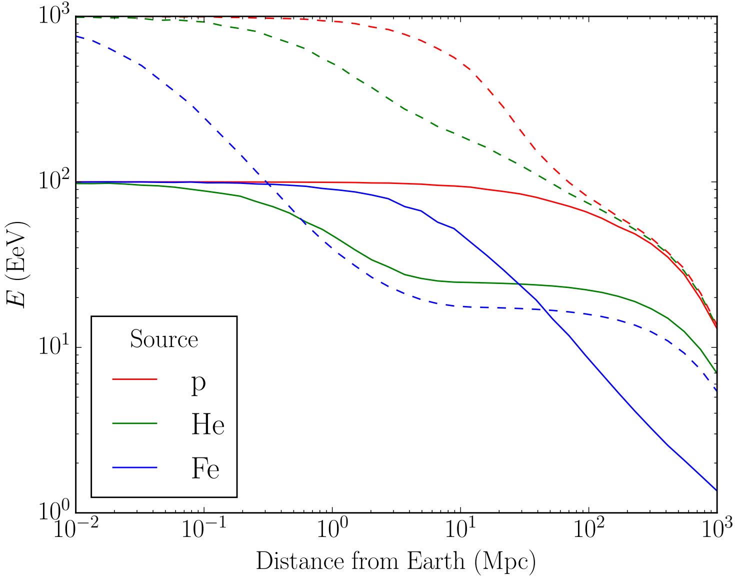
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
P_{LAB} (GeV)

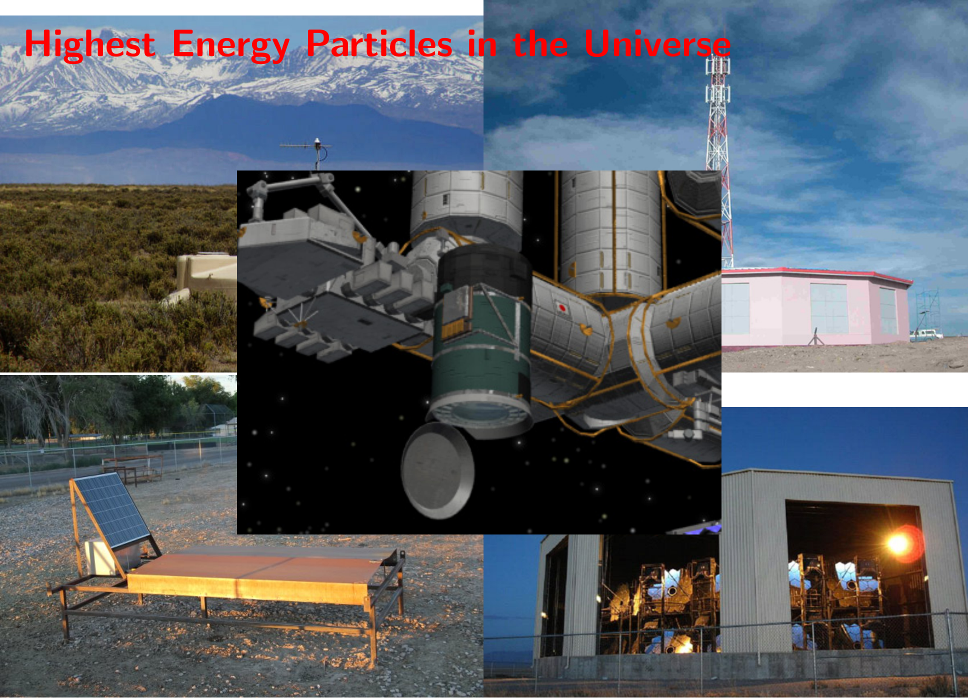
Energy Loss Rates



Highest Energy Particles in the Universe




Highest Energy Particles in the Universe



UHECR Anisotropy Unknowns

- How strong are the magnetic fields inside and between galaxies?

  Pshirkov et. al.: 1103.0814

  Jansson, Farrar: 1204.3662

- What is the composition of UHECRs? Protons? Iron nuclei?
- What are the sources of UHECRs?
- How are UHECRs accelerated to such extreme energies?

  Gunn, Ostriker: PRL 22 (1969)

  Pruet, Guiles, Fuller: astro-ph/0205056

  Groves, Heckman, Kauffmann: astro-ph/0607311

  Fang, Kotera, Olinto: 1201.5197

- What is the cause of the suppression at the end of the spectrum?
- New physics...?

UHECR Anisotropy Knowns

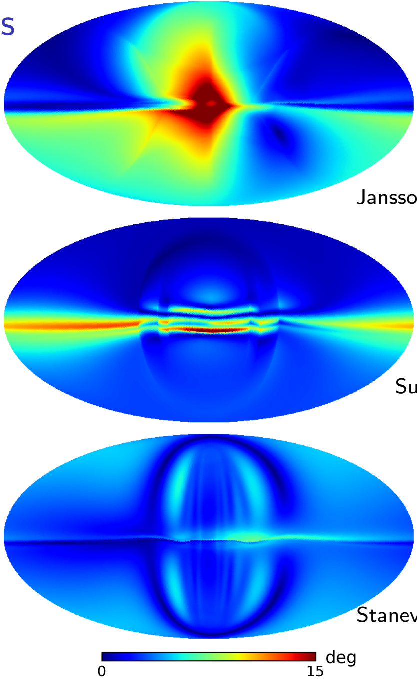
- UHECRs can't be contained by the Milky Way's magnetic field $\Rightarrow$ extragalactic.
- UHECRs with energies above ~ 50 EeV lose energy via interactions with the CMB.

Greisen: PRL 16 (1966)

Zatsepin, Kuzmin: JETP Lett. 4 (1966)

- UHECR sources must be close $\Rightarrow$ anisotropies.
- UHECRs bend in Galactic and extragalactic magnetic fields.
- No conclusive anisotropies found yet.

Galactic B Fields



60 EeV proton

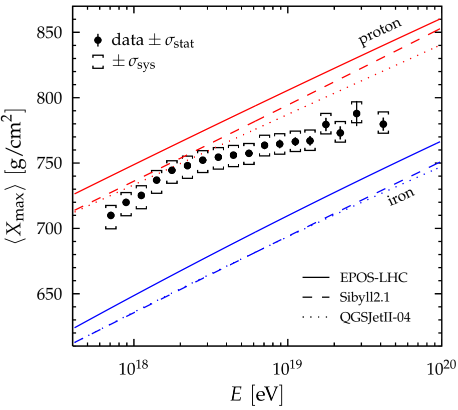
Jansson, Farrar: 1204.3662

Sun, et. al.: 0711.1572

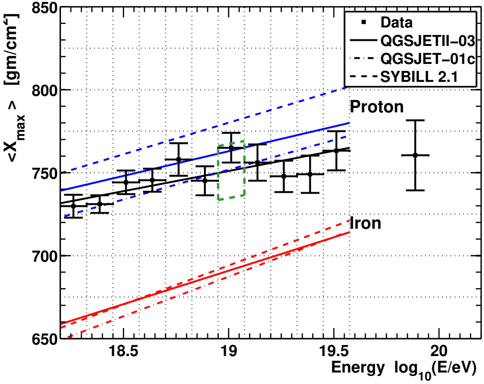
Stanev: astro-ph/9607086

Composition

Auger: heavy composition

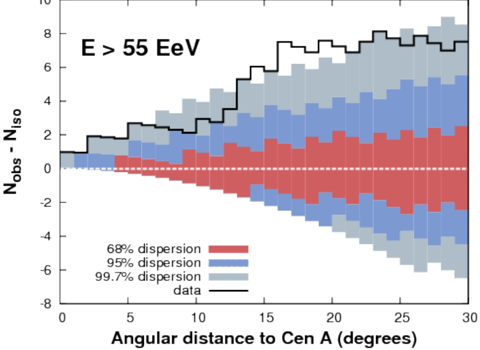


TA: light composition



Disagreement.

Auger and TA: 1503.07540

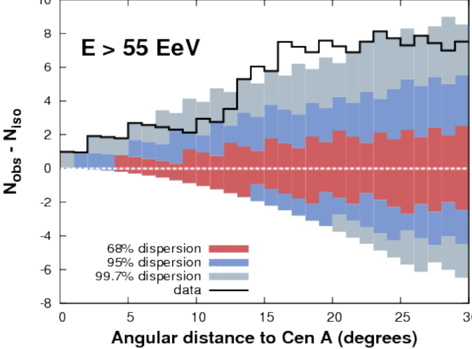


UHECR Anisotropy Searches

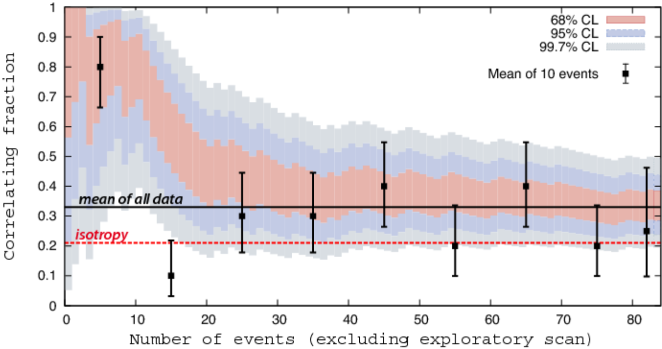
Targeted searches have weak evidence.

Auger: 1207.4823

UHECR Anisotropy Searches

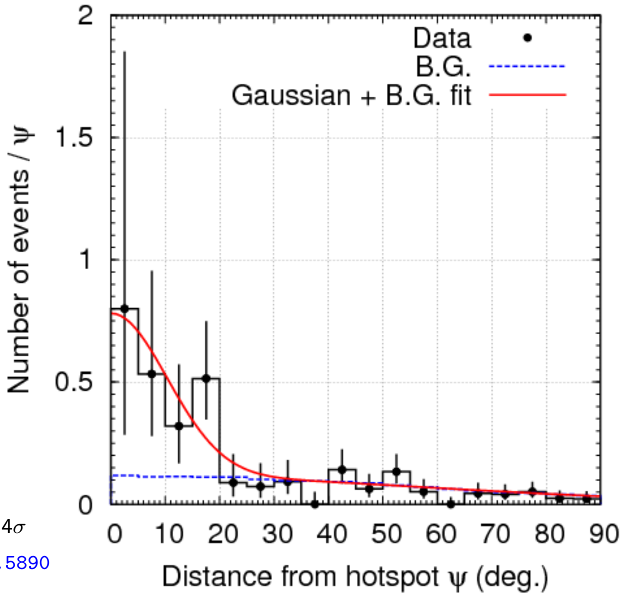


Targeted searches
have weak evidence.



Auger: 1207.4823

UHECR Anisotropy Searches



$5.1\sigma \to 3.4\sigma$

TA: 1404.5890

Spherical Harmonics: Distributions on the Sky

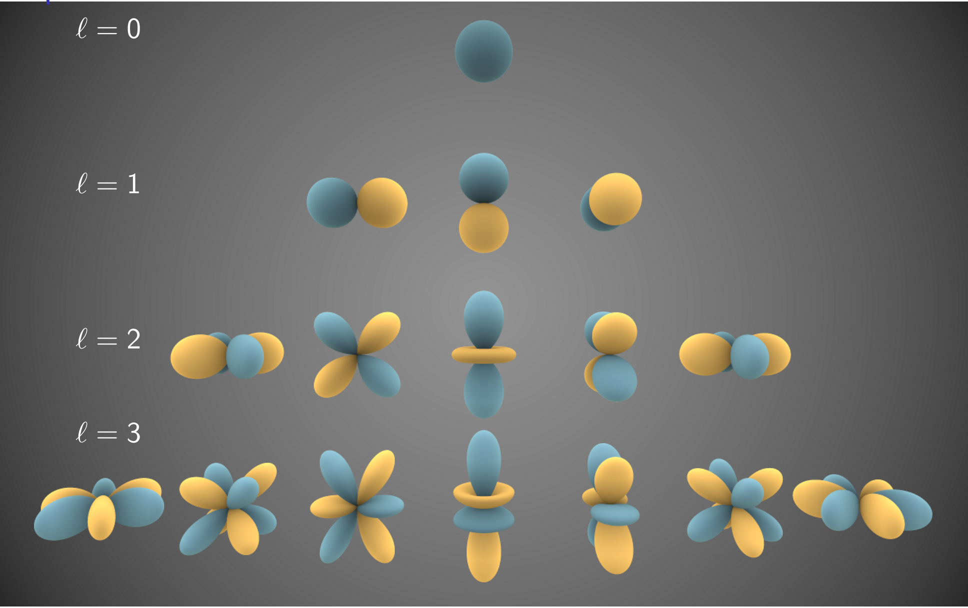
- Y_ℓ^m's provide an orthogonal expansion of any distribution on the sky.
- Useful in low statistics, high uncertainty experiments:
  - unknown magnetic fields,
  - unknown UHECR composition.
- The true distribution as seen at earth:

$$I(\Omega)=\sum_{\ell,m}a_\ell^m Y_\ell^m(\Omega)\,.$$

- The power spectrum is rotational invariant.

$$C_\ell=\frac{1}{2\ell+1}\sum_m|a_\ell^m|^2\,.$$

Spherical Harmonics Visualizations



en.wikipedia.org/wiki/Spherical_harmonics

Spherical Harmonics: Possible Sources

Identifiable sources: Cen A, TA hotspot, supergalactic plane, etc. use specific Y_ℓ^m's.

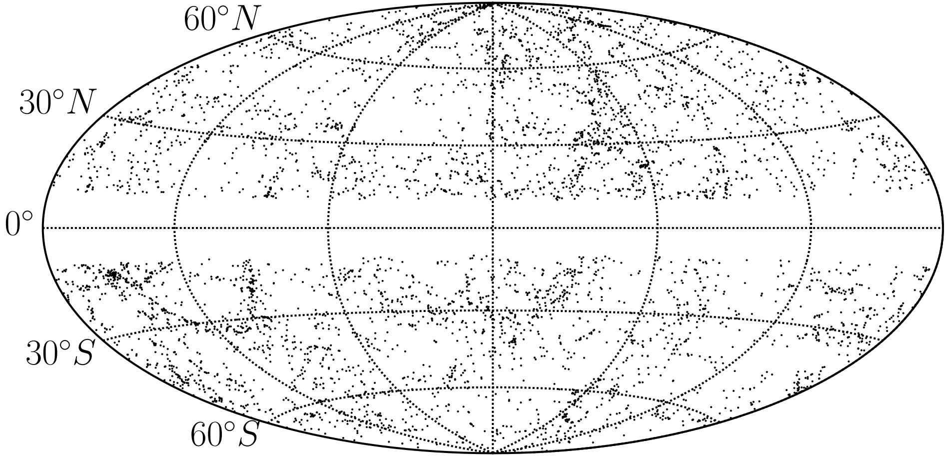
$$\begin{array}{llll} \text{Point source} & \Rightarrow & \text{dipole:} & I_D \propto a_0^0 Y_0^0 + a_1^0 Y_1^0. \\ \text{Planar source} & \Rightarrow & \text{quadrupole:} & I_Q \propto a_0^0 Y_0^0 + a_2^0 Y_2^0. \end{array}$$

Each Y_ℓ^m partitions the sky into nodal zones,

$$\langle N_Z(\ell) \rangle = \frac{\ell+1}{3(2\ell+1)}(2\ell^2+4\ell+3) \xrightarrow[\ell\to\infty]{} \frac{\ell^2}{3}\,,$$

so $\ell_{\max} < \sqrt{3N}$.

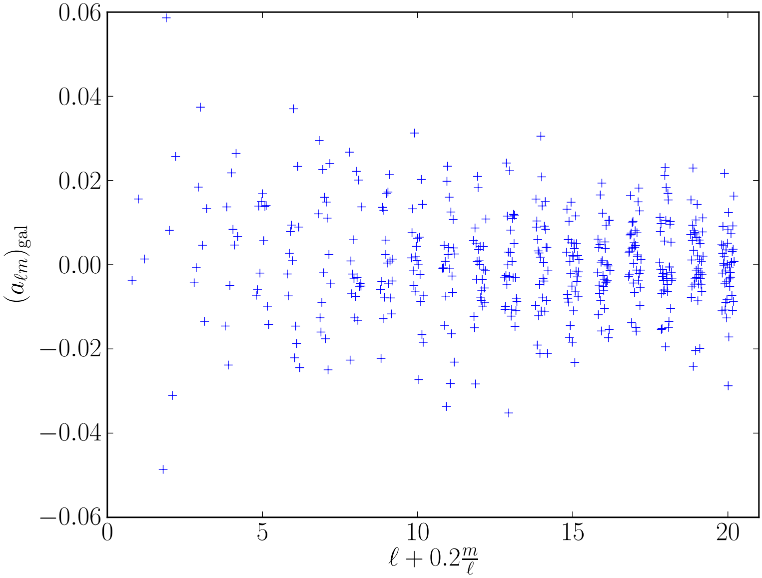
2MRS Sky Map



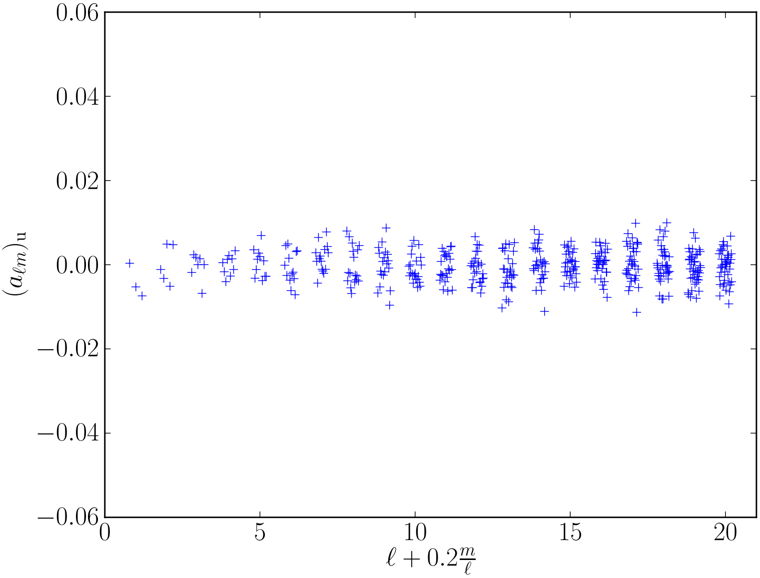
Structure in the local universe ⇒ anisotropies in UHECRs.

2MRS: 1108.0669

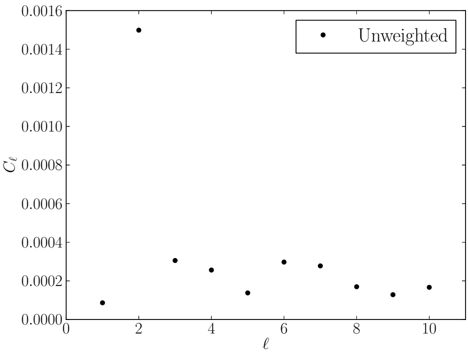
Spherical Harmonic Coefficients: Galaxies

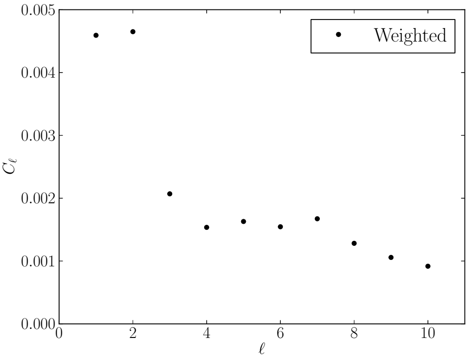


Spherical Harmonic Coefficients: Uniform



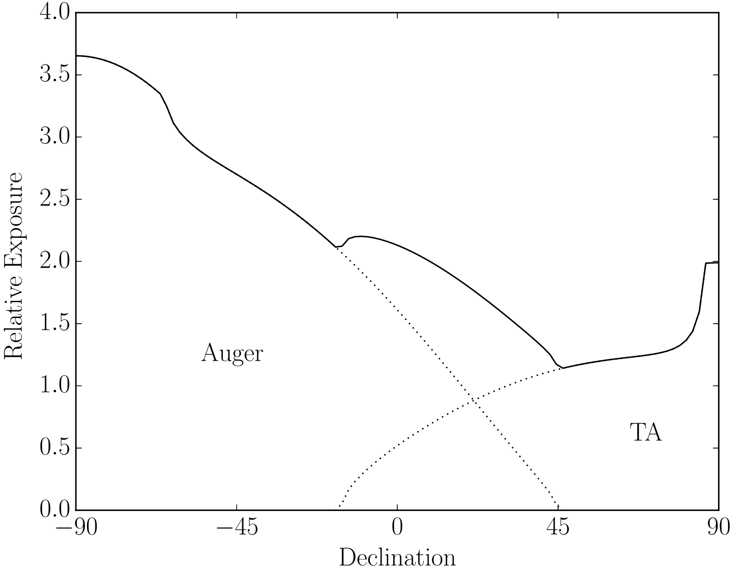
Spherical Harmonics: Possible Sources





Dipole and quadrupole: well motivated.

Auger and TA's Nonuniform Partial Sky Coverage



Auger and TA Exposure Combination

Combined exposure:

$$\omega(\Omega, b) = \omega_{\rm TA}(\Omega) + b\omega_{\rm Auger}(\Omega)$$

"Fudge factor":

$$\bar{b}^{(0)} = \frac{\Delta N_{\rm Auger}}{\Delta N_{\rm TA}} \frac{\int_{\Delta\Omega} d\Omega \omega_{\rm TA}(\Omega)}{\int_{\Delta\Omega} d\Omega \omega_{\rm Auger}(\Omega)}$$

P. Billoir for Auger 1403.6314

Problems:

1. Statistics are low in the intersection region.
2. $\bar{b}^{(0)}$ is a zeroth order approximation to b under the assumption of isotropy.
3. Corrections to $\bar{b}^{(0)}$ need to be fit iteratively along with anisotropy parameters.
4. Large systematic energy uncertainty between the experiments.

Anisotropy Measures

A general anisotropy measure:

$$\alpha \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \in [0, 1] \,.$$

Define

$$\alpha_D \equiv \sqrt{3}\frac{|a_1^0|}{a_0^0} \qquad\qquad \alpha_Q \equiv \frac{-3\sqrt{\frac{5}{4}\frac{a_2^0}{a_0^0}}}{2+\sqrt{\frac{5}{4}\frac{a_2^0}{a_0^0}}} \quad (\text{'New' later})\,,$$

Then $\alpha_D = \alpha$ for a purely dipolar distribution and $\alpha_Q = \alpha$ for a purely quadrupolar distribution.

Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

Nonuniform exposure is a manageable problem:

$$\bar{a}_\ell^m = \frac{1}{N}\sum_i^N Y_\ell^{m*}(\Omega_i) \to \frac{1}{\mathcal{N}}\sum_i^N \frac{Y_\ell^{m*}(\Omega_i)}{\omega(\Omega_i)}\,,$$

where $\mathcal{N} = \sum_i^N \frac{1}{\omega(\Omega_i)}$,
ω is the exposure function.

Sommers: astro-ph/0004016

Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

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where $\mathcal{N} = \sum_i^N \frac{1}{\omega(\Omega_i)}$,
ω is the exposure function.

Sommers: astro-ph/0004016

Partial sky is more challenging: no information from part of the sky.

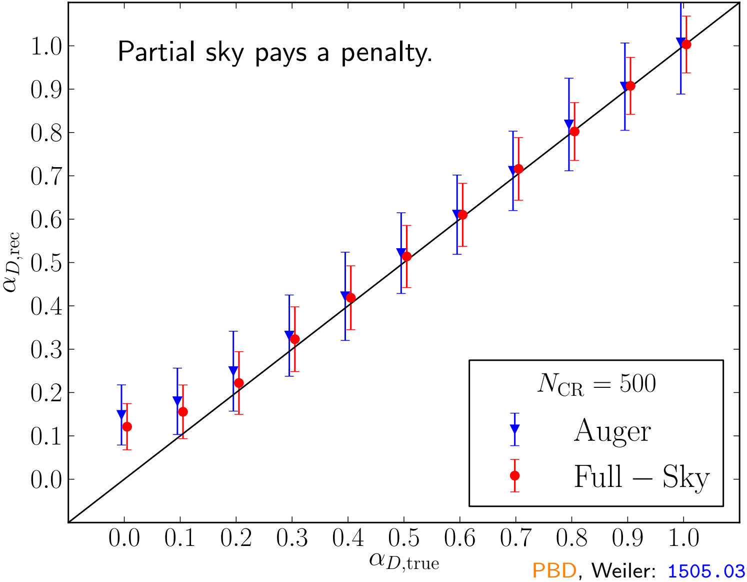
$$[K]_{\ell m}^{\ell' m'} \equiv \int d\Omega\,\omega(\Omega) Y_\ell^m(\Omega) Y_{\ell'}^{m'}(\Omega)$$

$$b_\ell^m = \sum_{\ell' m'} [K]_{\ell m}^{\ell' m'} a_{\ell'}^{m'} \quad \Rightarrow \quad a_\ell^m = \sum_{\ell' m'}^{\ell_{\max}} [K^{-1}]_{\ell m}^{\ell' m'} b_{\ell'}^{m'}$$

$b_\ell^m \to$ uncorrected (observed on earth),
$a_\ell^m \to$ nature's true anisotropy.

Billoir, Deligny: 0710.2290

Dipole Reconstruction Effectiveness



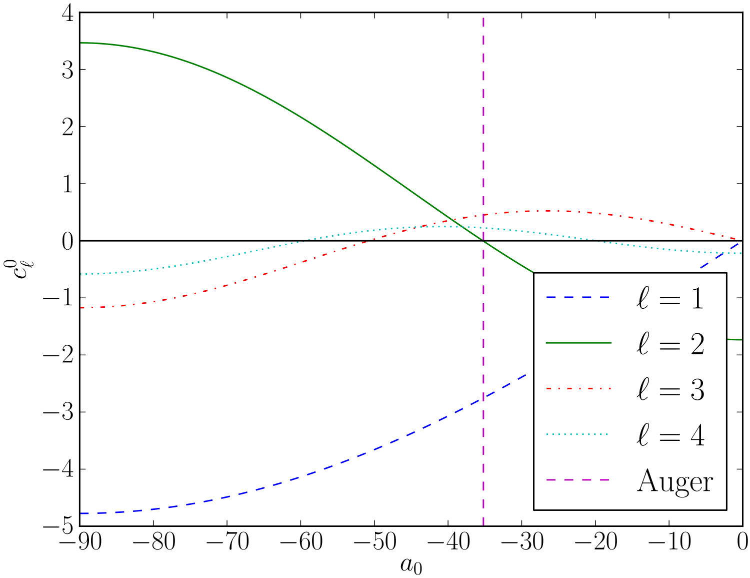
PBD, Weiler: 1505.03922

Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

- An alternative formalism to the K-matrix approach.
- Expand the exposure $\omega(\Omega) = \sum_{\ell,m} c_\ell^m Y_\ell^m(\Omega)$.
- ω does not depend on RA $\Rightarrow$ only $m = 0$ coefficients are nonzero.
- Fortuitously, $c_2^0 = 0$ for Auger's exposure (nearly equal to zero for Telescope Array).

PBD, Weiler: 1409.0883

Quadrupole Component of Exposure



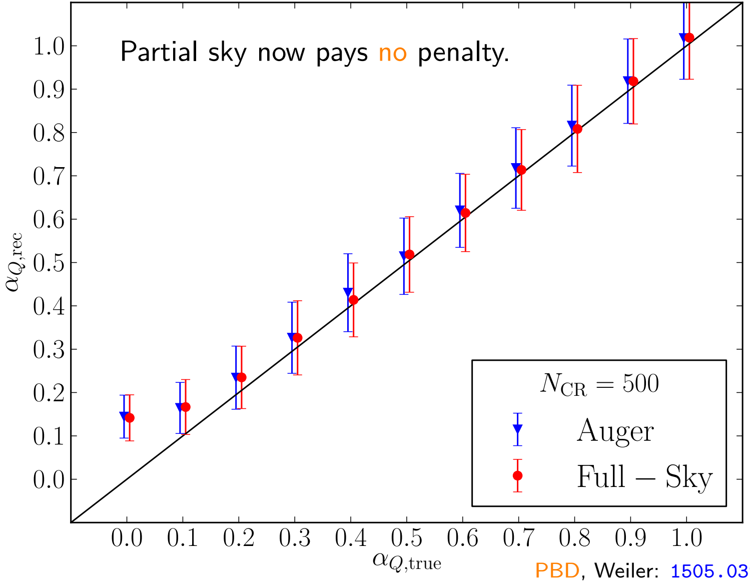
Reconstructing a_ℓ^m's for Nonuniform Partial Sky Coverage

When reconstructing a pure quadrupole, Auger and TA's exposures may be ignored,

$$b_2^m = a_2^m \left[1 + \frac{(-1)^m c_4^0 f(m)}{7\sqrt{4\pi}}\right]$$

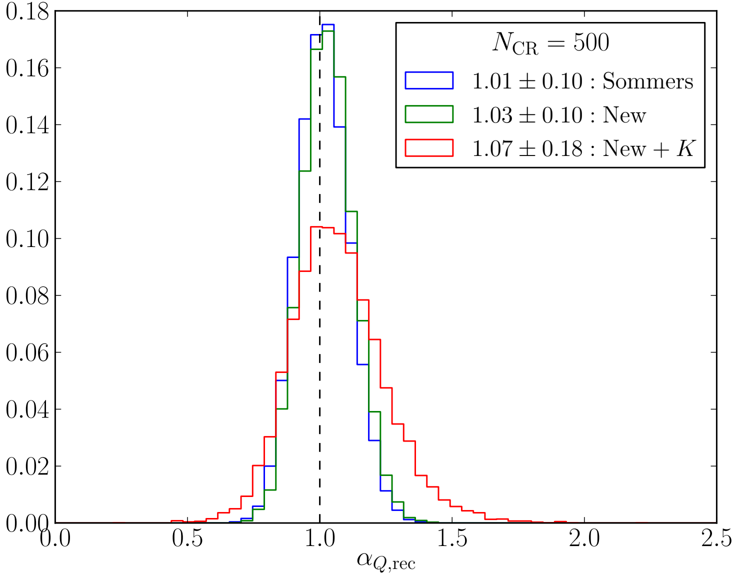
A correction of $0.05, -0.04, 0.009$ for $|m| = 0, 1, 2$.

Quadrupole Reconstruction Effectiveness



PBD, Weiler: 1505.03922

Quadrupole Reconstruction Technique Effectiveness

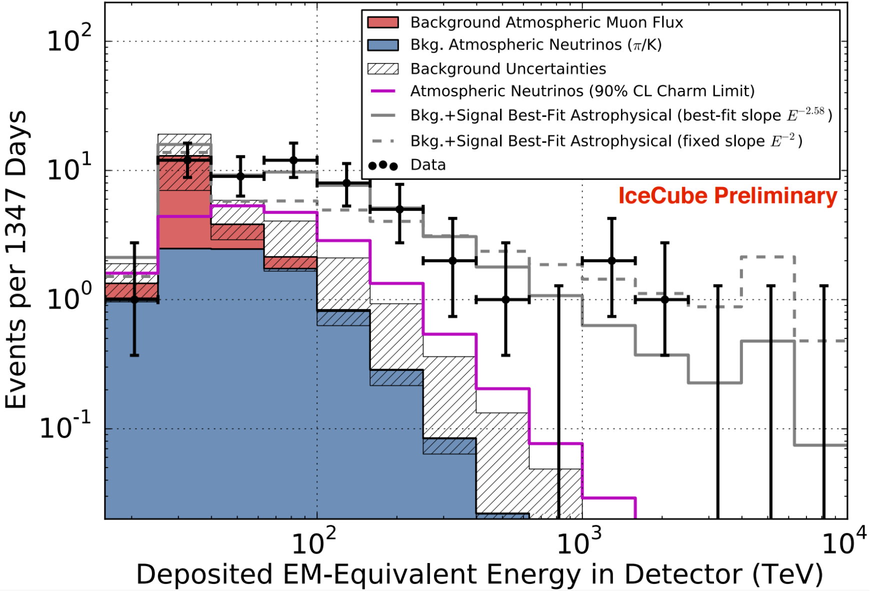


UHECR Conclusions

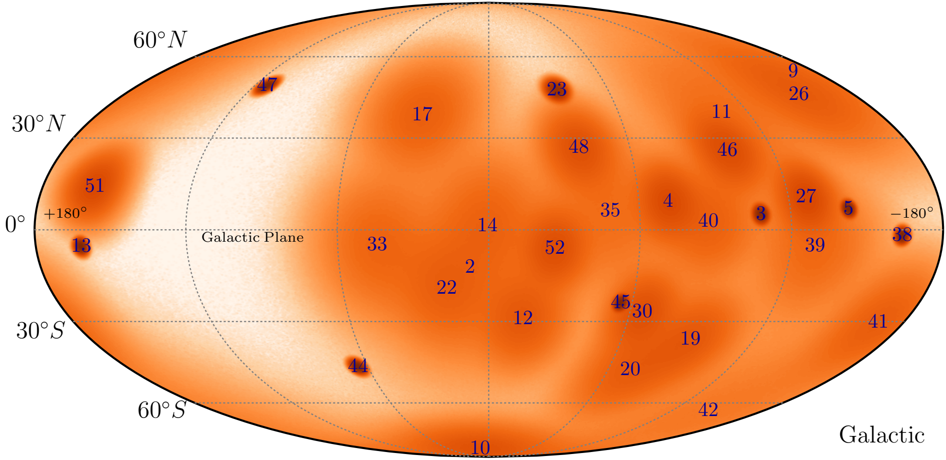
- Theoretical uncertainties in composition and magnetic fields makes point source searches difficult.
- Spherical harmonics provide a good multi-purpose tool to overcome these.
- An analytic treatment can improve sensitivity of certain analyses.

IceCube Detects Astrophysical Neutrinos

IC: 1510.05223



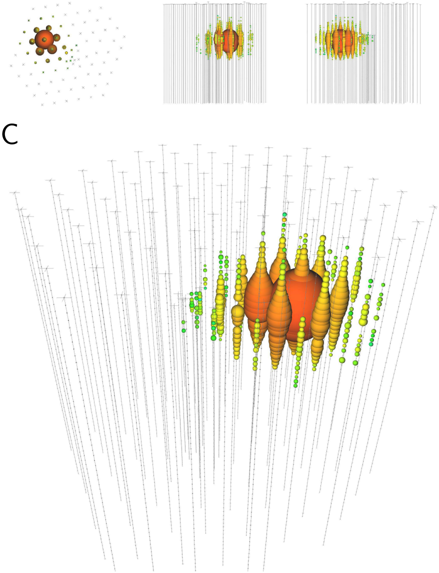
IceCube Detects Astrophysical Neutrinos



32 events with $E_{\rm dep} > 60$ TeV from IC 4 year HESE

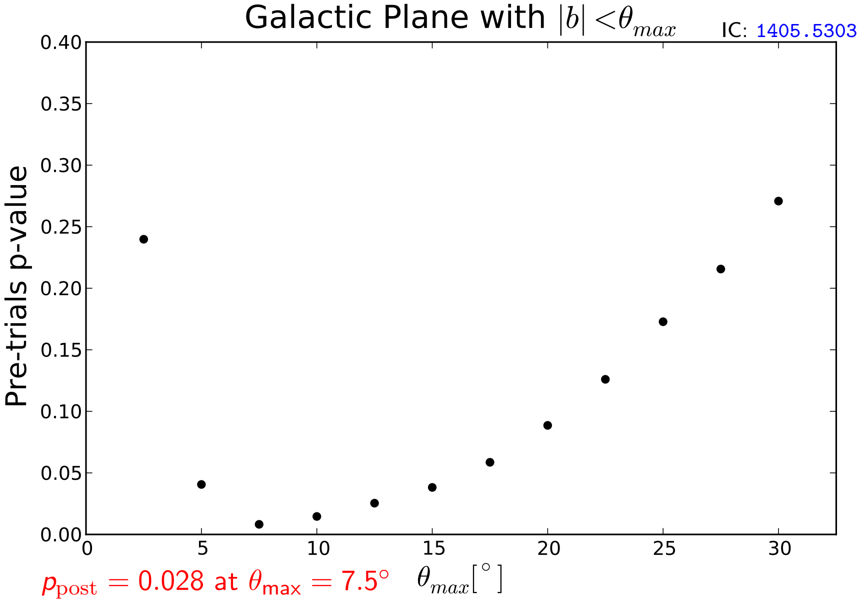
IceCube Detects Astrophysical Neutrinos

Event 14
$E = 1$ PeV
1.2° from the GC
$\alpha_{50\%} = 13.2^\circ$



IC: 1311.5238

Significance of the Galaxy as the Source



$p_{\rm post} = 0.028$ at $\theta_{\rm max} = 7.5^\circ$

Galactic or Extragalactic?

Various methods to search for anisotropies:

- Windowed search around the Galactic center/plane.

  IC: 1311.5238, 1405.5303

  Ahlers, Murase: 1309.4077

  Anchordoqui, et. al.: 1410.0348

  Palladino, Vissani: 1601.06678

- Known Galactic sources:
  CRs, γ-ray correlations, GC, misc. Galactic catalogs, ...

  IC: 1406.6757

  Ahlers, et. al.: 1505.03156

  Troitsky: 1511.01708

  Celli, Palladino, Vissani: 1604.08791

- Known extragalactic sources: AGNs, blazars, SFGs, GRBs, ...

  Bechtol, et. al.: 1511.00688

  Murase: 1511.01590

  IC: 1601.06484

  Padovani, et. al.: 1601.06550

A More General Approach

- Treat the extragalactic flux as isotropic, $\Phi_{\rm exgal}(\Omega)=\frac{1}{4\pi}$.
- Scale the galactic flux with the matter distribution $\rho_{\rm gal}$,

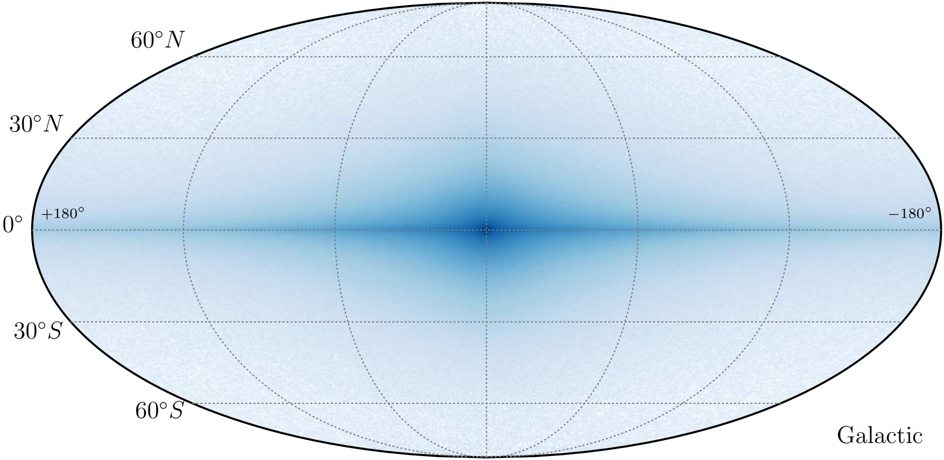
McMillan: 1102.4340

$$\Phi_{\rm gal}(\Omega)=\frac{\int ds\,\rho_{\rm gal}(s,\Omega)}{\int dsd\Omega'\,\rho_{\rm gal}(s,\Omega')}\,.$$

- $f_{\rm gal}$ is the fraction of the astrophysical flux from the Galaxy,

$$\Phi_{\rm astro}(\Omega,f_{\rm gal})=f_{\rm gal}\Phi_{\rm gal}(\Omega)+(1-f_{\rm gal})\Phi_{\rm exgal}(\Omega)\,.$$

Expected Distribution From the Galaxy



Energy and Topology Information for Backgrounds

- For $E_{\rm dep} > 60$ TeV, we expect < 4 events from backgrounds.
- $\Gamma_{\rm bkg} \sim 3.7$ while the best fit $\Gamma_{\rm astro} \sim 2.58$.

Results are largely independent to uncertainties in the spectra.

- The background and astrophysical likelihoods for event i are,

$$\mathcal{L}_{{\rm bkg},i} = f_{{\rm bkg},i}\frac{dN_{\rm bkg}}{dE}(E_i)\,,$$

$$\mathcal{L}_{{\rm astro},i} = f_{{\rm astro},i}\frac{dN_{\rm astro}}{dE}(E_i)\,,$$

where $f_{{\rm bkg(astro)},i}$ is the expected fraction of events with topology and declination that are background (astrophysical).

Galactic or Extragalactic?

Given that an event is astrophysical, the conditional likelihoods are,

$$\mathcal{L}_{\mathrm{gal|astro},i}(f_{\mathrm{gal}}) = f_{\mathrm{gal}}\Phi_{\mathrm{gal}}(\Omega_i)\,,$$

$$\mathcal{L}_{\mathrm{exgal|astro},i}(f_{\mathrm{gal}}) = (1 - f_{\mathrm{gal}})\Phi_{\mathrm{exgal}}(\Omega_i)\,.$$

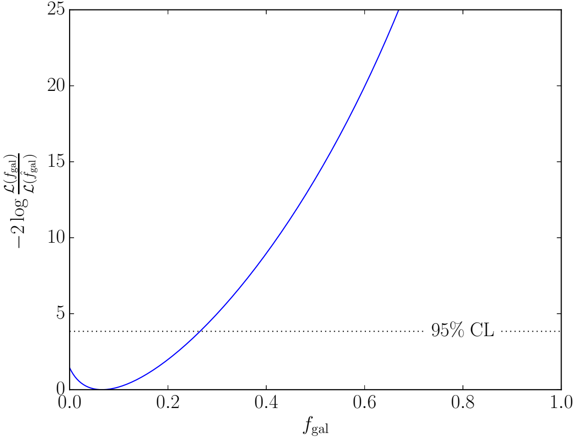
The likelihood that event i is described by this model is,

$$\mathcal{L}_i(f_{\mathrm{gal}}) = \mathcal{L}_{\mathrm{bkg},i} + \mathcal{L}_{\mathrm{astro},i}\left[\mathcal{L}_{\mathrm{gal|astro},i}(f_{\mathrm{gal}}) + \mathcal{L}_{\mathrm{exgal|astro},i}(f_{\mathrm{gal}})\right]\,,$$

and the total likelihood is the product,

$$\mathcal{L}(f_{\mathrm{gal}}) = \prod_i \mathcal{L}_i(f_{\mathrm{gal}})\,.$$

Results



$\hat{f}_{\rm gal} = 0.066^{+0.090}_{-0.058}$
$f_{\rm gal} = 0$ allowed at 1.2σ

CL	$f_{\rm gal}$
1σ	$[0.008, 0.16]$
90%	< 0.23
2σ	< 0.27
3σ	< 0.4

Likelihoods to Probabilities

$$p_{\mathrm{bkg},i} = \frac{\mathcal{L}_{\mathrm{bkg},i}}{\mathcal{L}_{\mathrm{astro},i} + \mathcal{L}_{\mathrm{bkg},i}}$$

$$p_{\mathrm{gal},i} = p_{\mathrm{astro},i} \frac{\mathcal{L}_{\mathrm{gal|astro},i}(\hat{f}_{\mathrm{gal}})}{\mathcal{L}_{\mathrm{gal},i}(\hat{f}_{\mathrm{gal}}) + \mathcal{L}_{\mathrm{exgal},i}(\hat{f}_{\mathrm{gal}})}$$

$$p_{\mathrm{exgal},i} = p_{\mathrm{astro},i} \frac{\mathcal{L}_{\mathrm{exgal|astro},i}(\hat{f}_{\mathrm{gal}})}{\mathcal{L}_{\mathrm{gal},i}(\hat{f}_{\mathrm{gal}}) + \mathcal{L}_{\mathrm{exgal},i}(\hat{f}_{\mathrm{gal}})}$$

$$\sum_i p_{\mathrm{gal},i} = 1.7\,, \qquad \sum_i p_{\mathrm{exgal},i} = 29.3\,, \qquad \sum_i p_{\mathrm{bkg},i} = 1.0$$

Event-By-Event Probabilities

At $\hat{f}_{\rm gal} = 0.066$:

E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$
2003	35	0.048	0.95	0
1140	20	1.8e-4	1	0
1040	14	0.75	0.25	5.7e-4
885	45	4.1e-4	1	0
512	13	0.0016	0.98	0.02
404	38	0.0035	0.95	0.045
384	33	0.058	0.93	0.016
219	22	0.2	0.79	0.0084
210	26	4.2e-5	0.98	0.018
199	17	0.0012	0.98	0.019
165	4	0.0093	0.99	8.2e-4
164	44	1.9e-4	0.82	0.18
159	23	7.4e-6	0.93	0.067
158	52	0.19	0.81	0
158	46	2e-4	0.99	0.012
157	40	0.007	0.99	8.7e-4

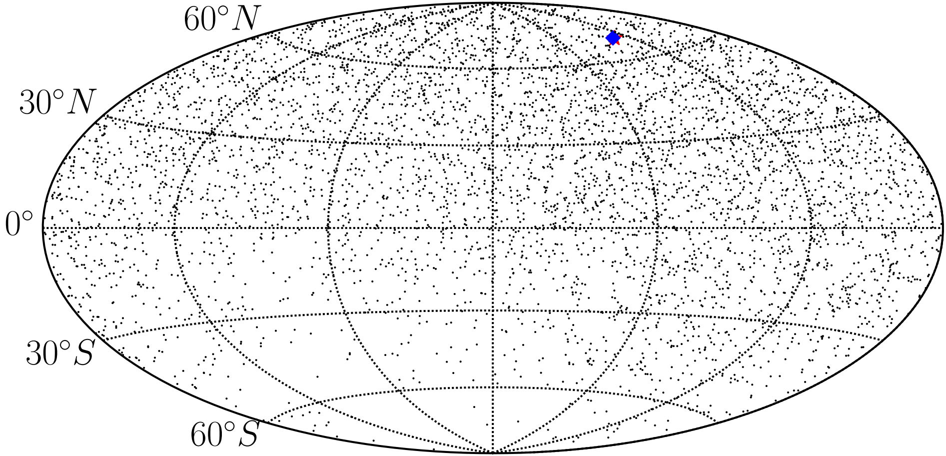
E	id	$p_{\rm gal}$	$p_{\rm exgal}$	$p_{\rm bkg}$
152	3	0.0024	0.96	0.041
143	47	3.9e-4	0.95	0.051
137	5	3.7e-4	0.82	0.18
128	30	5.9e-4	1	0
117	2	0.42	0.57	0.0066
104	48	0.0015	0.99	0.0074
104	12	0.01	0.99	0.0014
101	39	0.001	0.98	0.02
97	10	1.5e-5	0.99	0.008
88	11	1.7e-4	0.93	0.065
87	41	9e-5	0.92	0.081
76	42	3.9e-5	0.99	0.011
71	19	7.4e-5	1	0
66	51	3.2e-4	0.98	0.024
63	9	5.5e-5	0.95	0.046
60	27	0.0013	0.96	0.035

Conclusions

- The sources of UHECRs and astrophysical ν's is still an open question.
- UHECRs are still a background-free observable, but with large uncertainties.
- Handling partial sky exposure analytically can be useful.
- High energy neutrinos point at their sources, but carry backgrounds.
- The astrophysical neutrino flux is largely extragalactic.
  - A small galactic component $\sim 7\%$ is allowed.

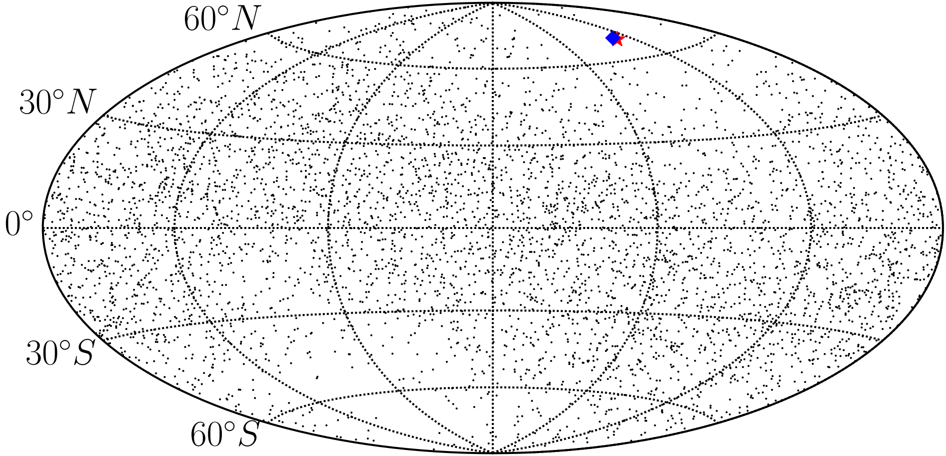
Backups

Sample Dipole



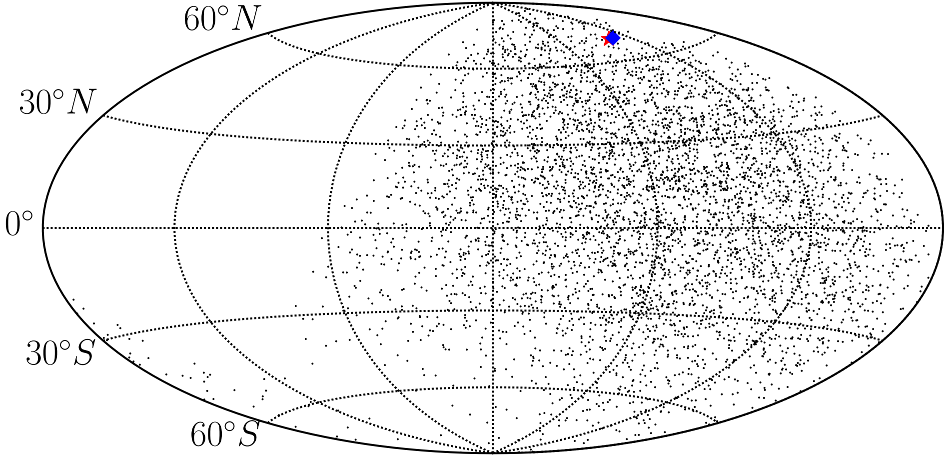
5000 events, $\alpha_D = 1$.
$\theta = 0.3^\circ$, $\Delta\alpha_D = 0.03$.

Sample Quadrupole



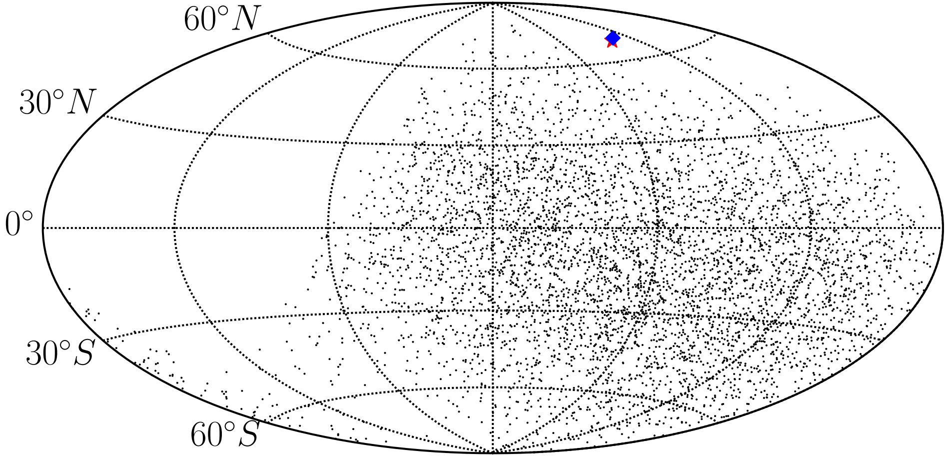
5000 events, $\alpha_Q = 1$.
$\theta = 0.8^\circ$, $\Delta\alpha_Q = 0.02$.

Sample Dipole with Auger's Exposure



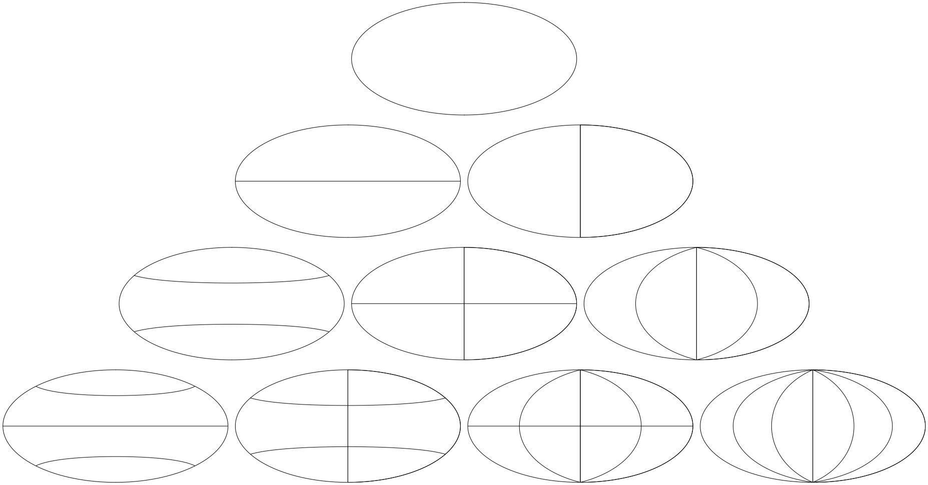
5000 events, $\alpha_D = 1$.
$\theta = 2^\circ$, $\Delta\alpha_D = 0.002$.

Sample Quadrupole with Auger's Exposure



5000 events, $\alpha_Q = 1$.
$\theta = 2^\circ$, $\Delta\alpha_Q = 0.02$.

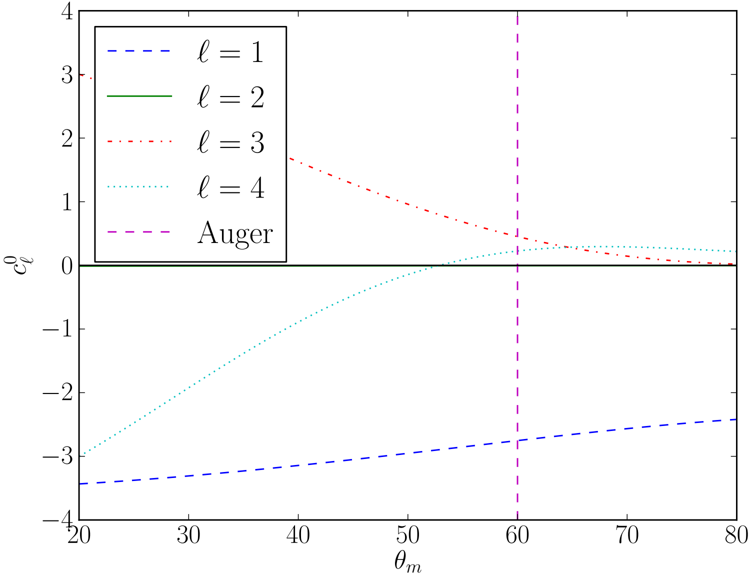
Spherical Harmonics Visualizations



Catalogs

- We consider galactic catalogs.
- The catalog used is the 2MRS.
- Contains 5310 galaxies out to redshift 0.03: 120 Mpc.
- Nearby galaxies need their distances adjusted for peculiar velocities.

Quadrupole Component of Exposure



Rotational Invariance of the Power Spectrum

$$I(\Omega) = \frac{1}{N}\sum_{i=1}^{N}\delta(\mathbf{u}_i, \Omega)\,,$$

$$\bar{a}_\ell^m = \frac{1}{N}\sum_{i=1}^{N} Y_\ell^{m*}(\mathbf{u}_i)\,,$$

$$\bar{C}_\ell = \frac{1}{N^2(2\ell+1)}\sum_{|m|\leq\ell}\left|\sum_{i=1}^{N} Y_\ell^{m*}(\mathbf{u}_i)\right|^2\,.$$

The addition formula for spherical harmonics:

$$P_\ell(\mathbf{x}\cdot\mathbf{y}) = \frac{4\pi}{2\ell+1}\sum_{|m|\leq\ell} Y_\ell^{m*}(\mathbf{x})Y_\ell^m(\mathbf{y})\,.$$

e.g. Arfken, Weber: *Mathematical Methods for Physicists*

$$\bar{C}_\ell = \frac{1}{4\pi N} + \frac{1}{2\pi N^2}\sum_{i<j} P_\ell(\mathbf{u}_i\cdot\mathbf{u}_j)\,.$$

b10-cut: Analytical Derivation

We conservatively fill in the unknown region of the Galactic distribution with a uniform distribution,

$$I_g(\Omega) = I_{g,>10}(\Omega) + I_{u,<10}(\Omega)\,.$$

$$(a_\ell^m)_g = (a_\ell^m)_{g,>10} + (a_\ell^m)_{u,<10}\,,$$

Note the following properties of the $(a_\ell^m)_{u,<10}$:

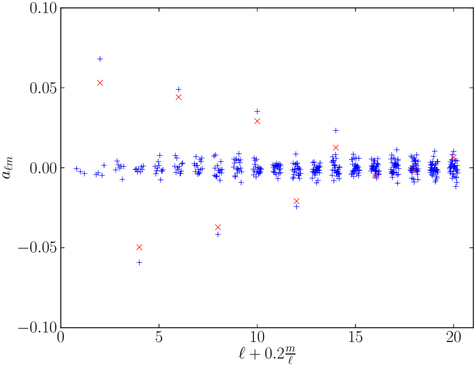
- $I_{u,<10}$ isn't a function of ϕ.

$$a_\ell^m = 2\pi\sqrt{\frac{2\ell+1}{4\pi}}\int P_\ell(x)I(x)dx\delta_{m0}\,.$$

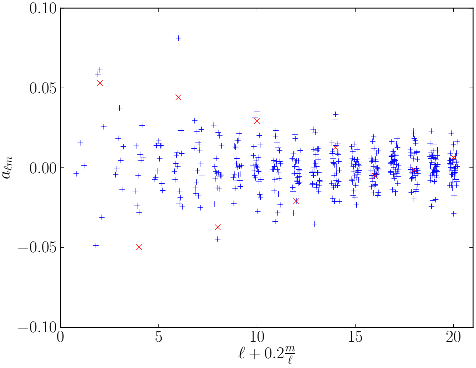
- $I_{u,<10}$ has even parity (the P_ℓ have definite parity).

$$(a_\ell^0)_{u,<10} = \sqrt{\frac{2\ell+1}{4\pi}}\int_0^{\cos(80^\circ)} P_\ell(x)dx\,.$$

b10-cut: Numerical Verification



Uniform



2MRS