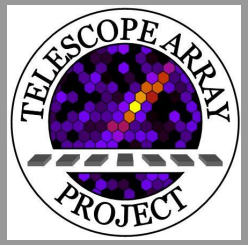

Search for anisotropy of UHECR with the Telescope Array experiment

P. Tinyakov,
for the **Telescope Array Collaboration**

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TA detector and data

Global distributions

Hot spot

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Other searches

Conclusions

TELESCOPE ARRAY COLLABORATION

T. Abu-Zayyad[a], R. Aida[b], M. Allen[a], R. Anderson[a], R. Azuma[c], E. Barcikowski[a], J. W. Belz[a], D. R. Bergman[a], S. A. Blake[a], R. Cady[a], B. G. Cheon[d], J. Chiba[e], M. Chikawa[f], E. J. Cho[d], W. R. Cho[g], H. Fujii[h], T. Fujii[i,*], T. Fukuda[c], M. Fukushima[j,t], W. Hanlon[a], K. Hayashi[c], Y. Hayashi[i], N. Hayashida[l], K. Hibino[l], K. Hiyama[j], K. Honda[b], T. Iguchi[c], D. Ikeda[j], K. Ikuta[b], N. Inoue[m], T. Ishii[b], R. Ishimori[c], H. Ito[u], D. Ivanov[a], S. Iwamoto[b], C. C. H. Jui[a], K. Kadota[o], F. Kakimoto[c], O. Kalashev[k], T. Kanbe[b], K. Kasahara[p], H. Kawai[q], S. Kawakami[i], S. Kawana[m], E. Kido[j], H. B. Kim[d], H. K. Kim[g], J. H. Kim[d], J. H. Kim[a], K. Kitamoto[f], S. Kitamura[c], Y. Kitamura[c], K. Kobayashi[e], Y. Kobayashi[c], Y. Kondo[j], K. Kuramoto[i], V. Kuzmin[k], Y. J. Kwon[g], J. Lan[a], S. I. Lim[s], J. P. Lundquist[a], S. Machida[c], K. Martens[t], T. Matsuda[h], T. Matsuura[c], T. Matsuyama[i], J. N. Matthews[a], I. Myers[a], M. Minamino[i], K. Miyata[e], Y. Murano[c], S. Nagataki[u], T. Nakamura[v], S. W. Nam[s], T. Nonaka[j], S. Ogio[i], J. Ogura[c], M. Ohnishi[j], H. Ohoka[j], K. Oki[j], D. Oku[b], T. Okuda[i], M. Ono[u], A. Oshima[i], S. Ozawa[p], I. H. Park[s], M. S. Pshirkov[w], D. C. Rodriguez[a], S. Y. Roh[r], G. Rubtsov[k], D. Ryu[r], H. Sagawa[j], N. Sakurai[i], A. L. Sampson[a], L. M. Scott[n], P. D. Shah[a], F. Shibata[b], T. Shibata[j], H. Shimodaira[j], B. K. Shin[d], J. I. Shin[g], T. Shirahama[m], J. D. Smith[a], P. Sokolsky[a], T. J. Sonley[a], R. W. Springer[a], B. T. Stokes[a], S. R. Stratton[a,n], T. A. Stroman[a,1,*], S. Suzuki[h], Y. Takahashi[j], M. Takeda[j], A. Taketa[x], M. Takita[j], Y. Tameda[j], H. Tanaka[i], K. Tanaka[y], M. Tanaka[h], S. B. Thomas[a], G. B. Thomson[a], P. Tinyakov[k,v], I. Tkachev[k], H. Tokuno[c], T. Tomida[b], S. Troitsky[k], Y. Tsunesada[c], K. Tsutsumi[c], Y. Tsuyuguchi[b], Y. Uchihori[z], S. Udo[l], H. Ukai[b], G. Vasiloff[a], Y. Wada[m], T. Wong[a], Y. Yamakawa[j], R. Yamane[i], H. Yamaoka[h], K. Yamazaki[i], J. Yang[s], Y. Yoneda[i], S. Yoshida[q], H. Yoshii[aa], R. Zollinger[a], Z. Zundel[a]

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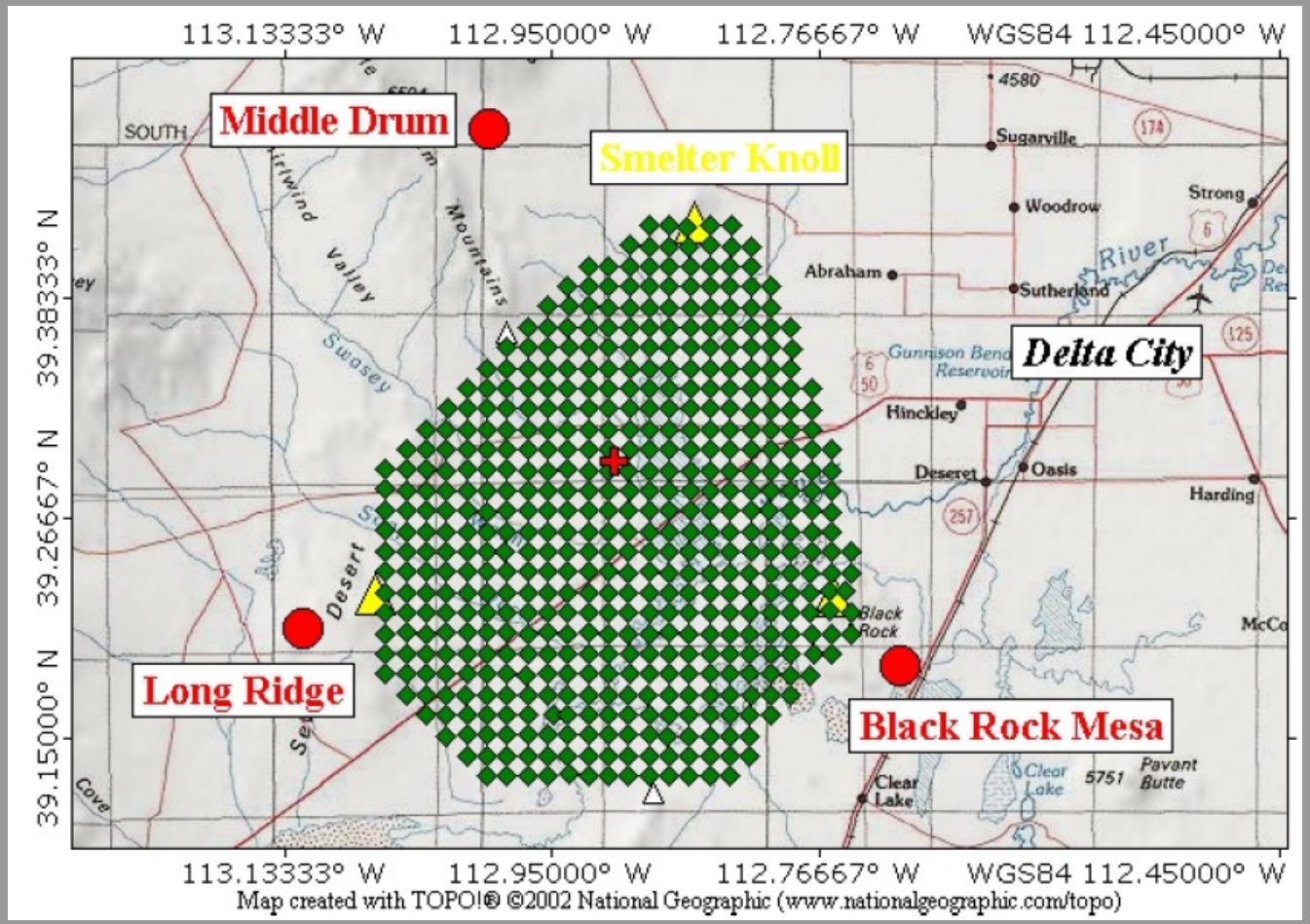
- TA detector and data
- Global distributions
- Hot spot
- Correlation with LSS
- Other searches
- Conclusions

TA HYBRID DETECTOR



SD : 507 scintillator detectors covering 680 km^2
fully operational from March 2008; $\sim$ 100% duty cycle

FD : 3 fluorescence sites, 38 telescopes; $\sim$ 10% duty cycle

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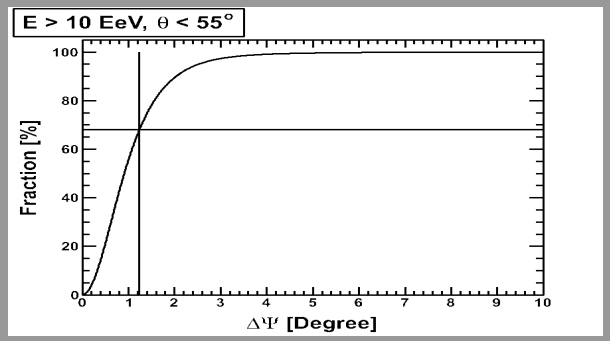
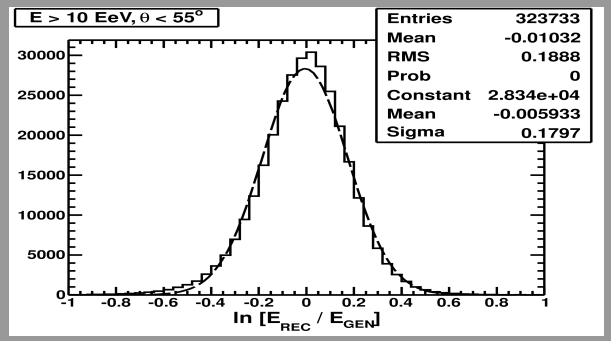
Anisotropy data set (SD)

- covers the period 12.05.2008 — 11.05.2015 (full 7 years)
- zenith angle up to 55°, loose border cut
- geometrical acceptance; exposure $\sim$ 8600 km^2 yr sr
- 2996 above 10 EeV
- 210 above 40 EeV
- 83 above 57 EeV
- angular resolution: better than 1.5°
- energy resolution: $\sim$ 20%





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GLOBAL DISTRIBUTIONS

Comparison to isotropic distribution by KS test

- Low energy sets $E > 10$ EeV and $E > 40$ EeV are compatible with isotropy; the smallest KS p-value is 0.12.
- $E > 57$ EeV

Frame	longitude	latitude
Equatorial:	0.07	0.04
Supergalactic:	0.01	0.03

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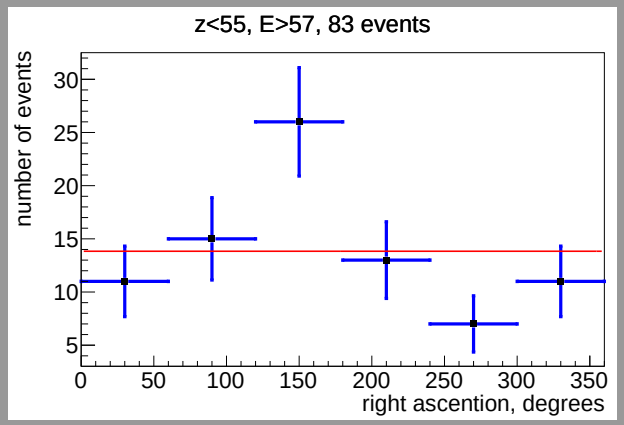

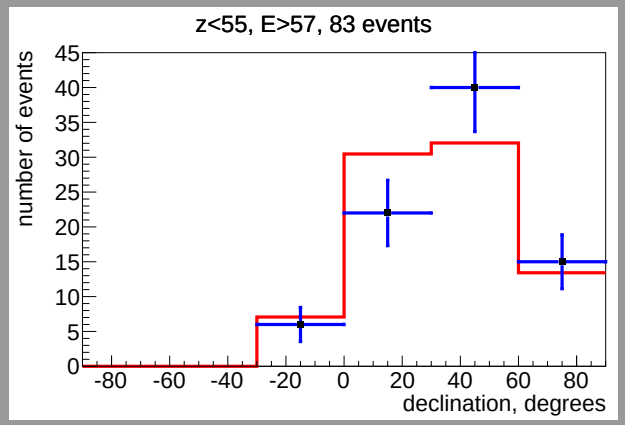

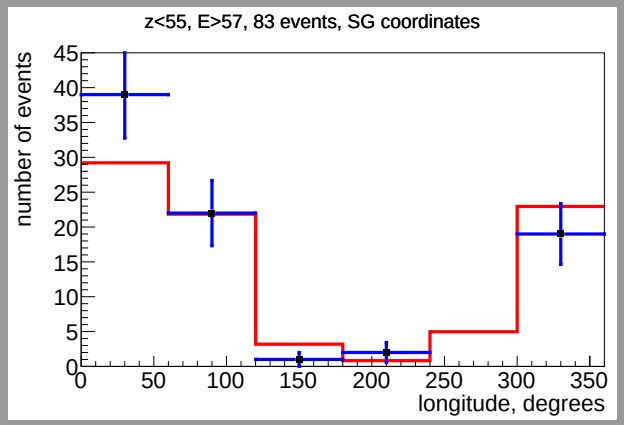

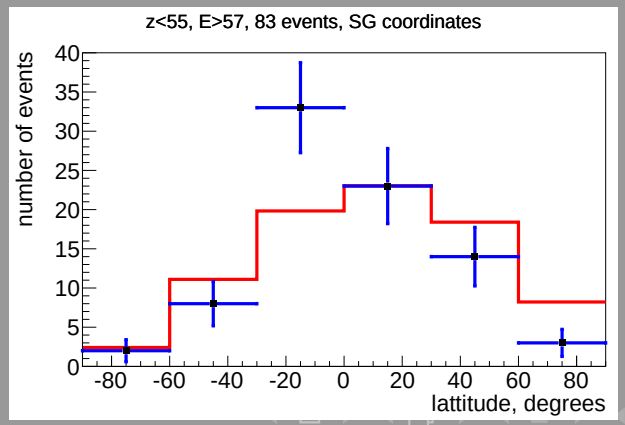

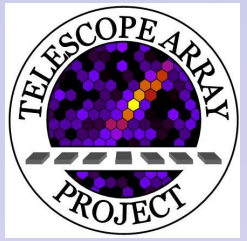

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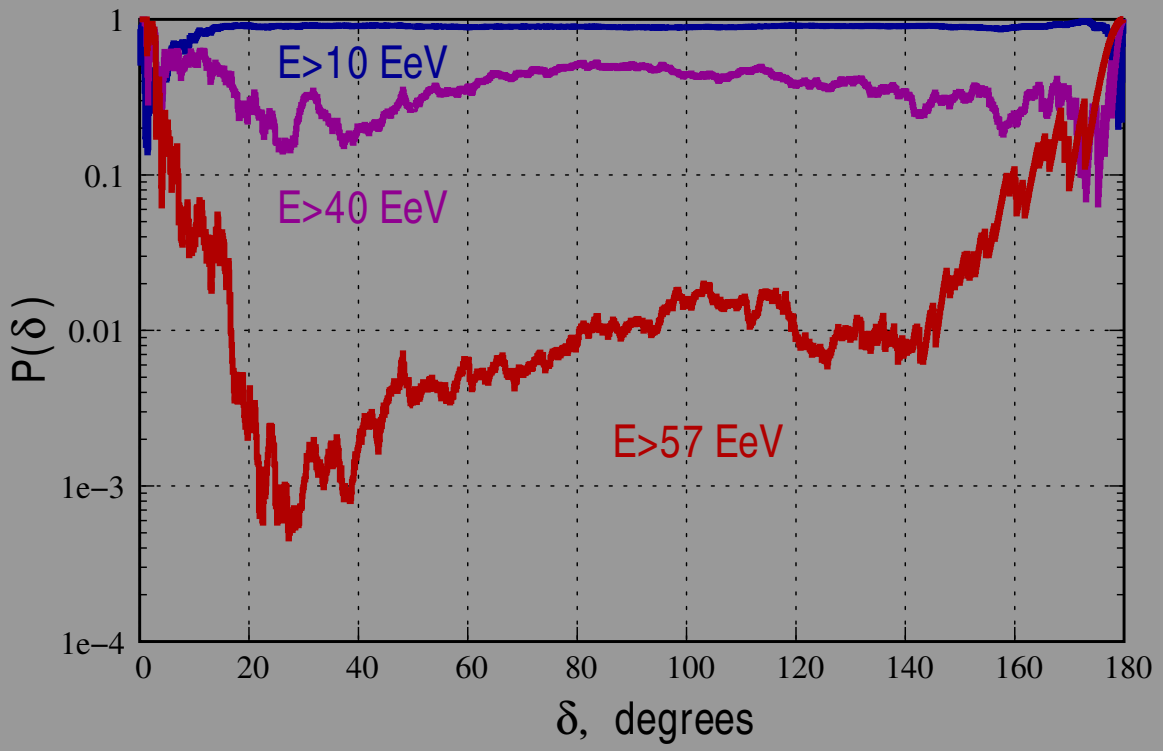
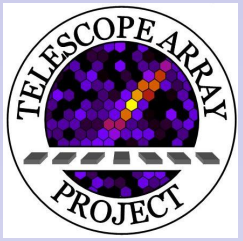
AUTOCORRELATION FUNCTION



- count number of pairs separated by the angle δ
- compare to isotropic distribution

$\Longrightarrow$ compatible with isotropy at $E > 10$ EeV and $E > 40$ EeV,
in tension with isotropy at $E > 57$ EeV

HOT SPOT

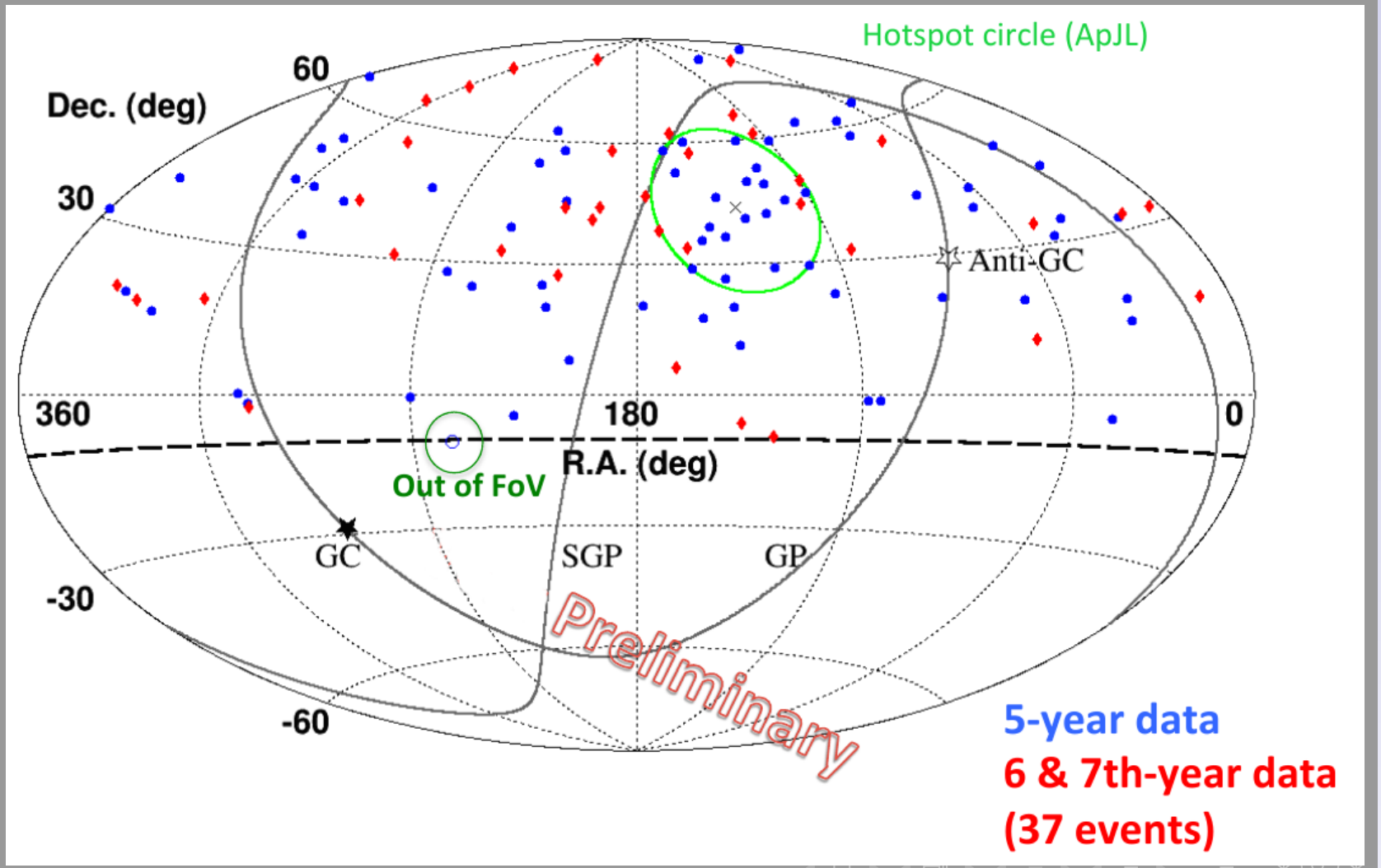


Hot spot in 5 yr data [ApJ 790:L21 (2014)]

- Reconstruction with even looser cuts optimized for statistics (72 events above 57 EeV in 5 yr).
- "Hot spot": excess of events within the circle of radius 20° centered at $\mathrm{RA} = 146°$, $\mathrm{DEC} = 43°$.
- After accounting for arbitrary position and opening angles 15°, 20°, 25°, 30°, 35° the significance is 3.4σ post-trial (5.1σ pre-trial).

HOT SPOT: 7 yr update

Same cuts as for 5yr; 109 events with $E > 57$ EeV in 7yr set



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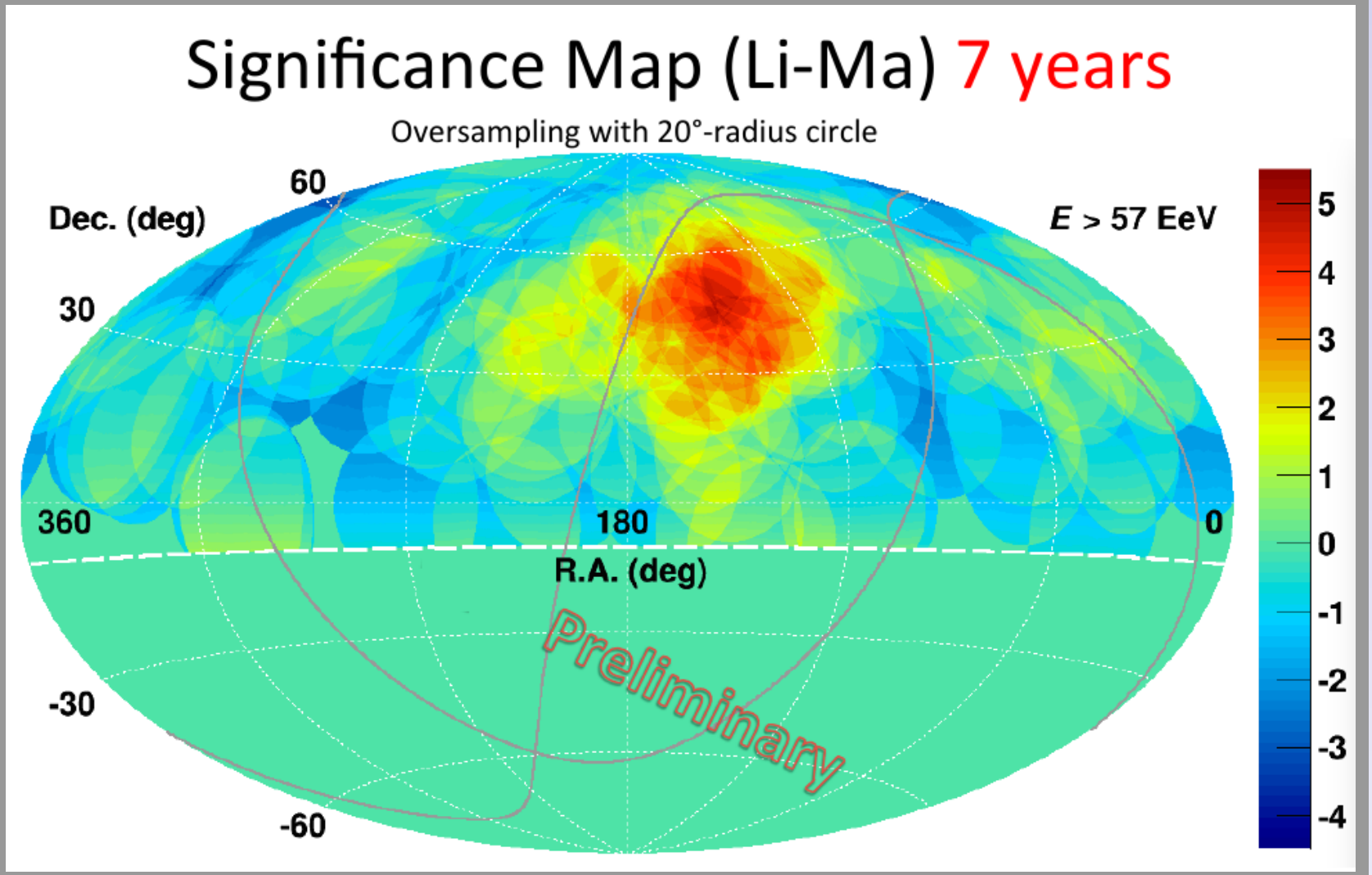
HOT SPOT: 7 yr update



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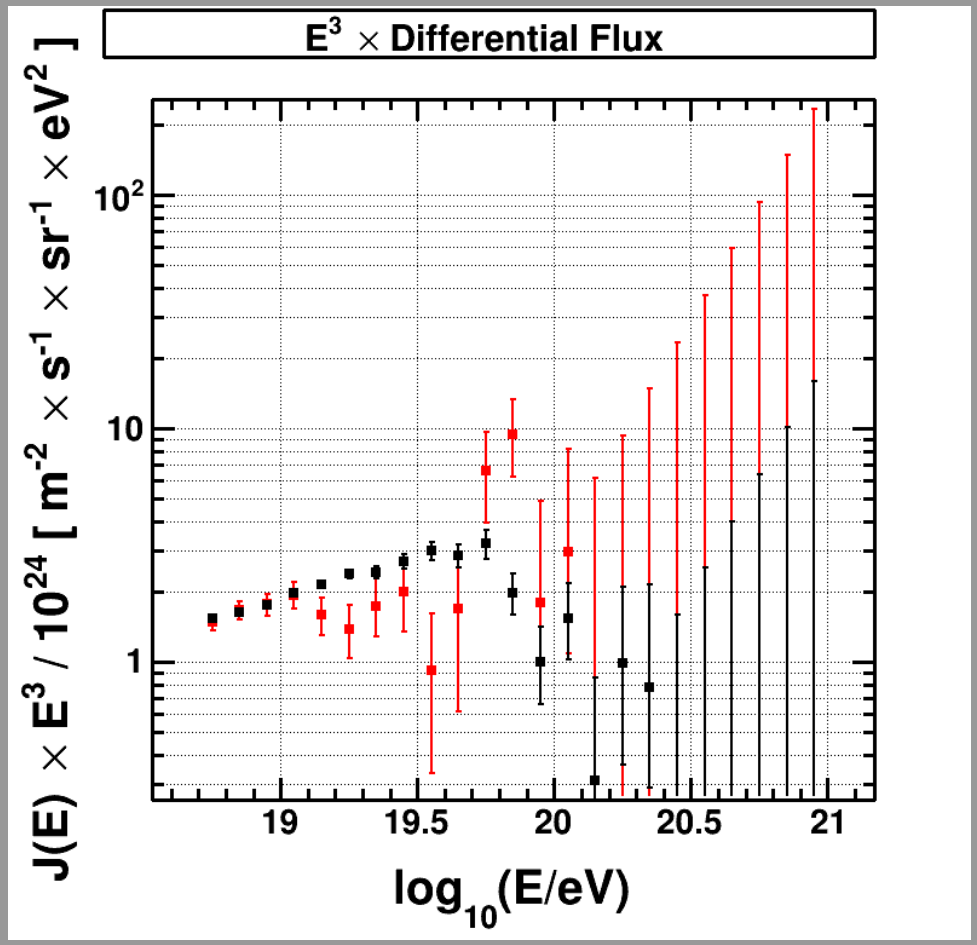
HOT SPOT: 7 yr update

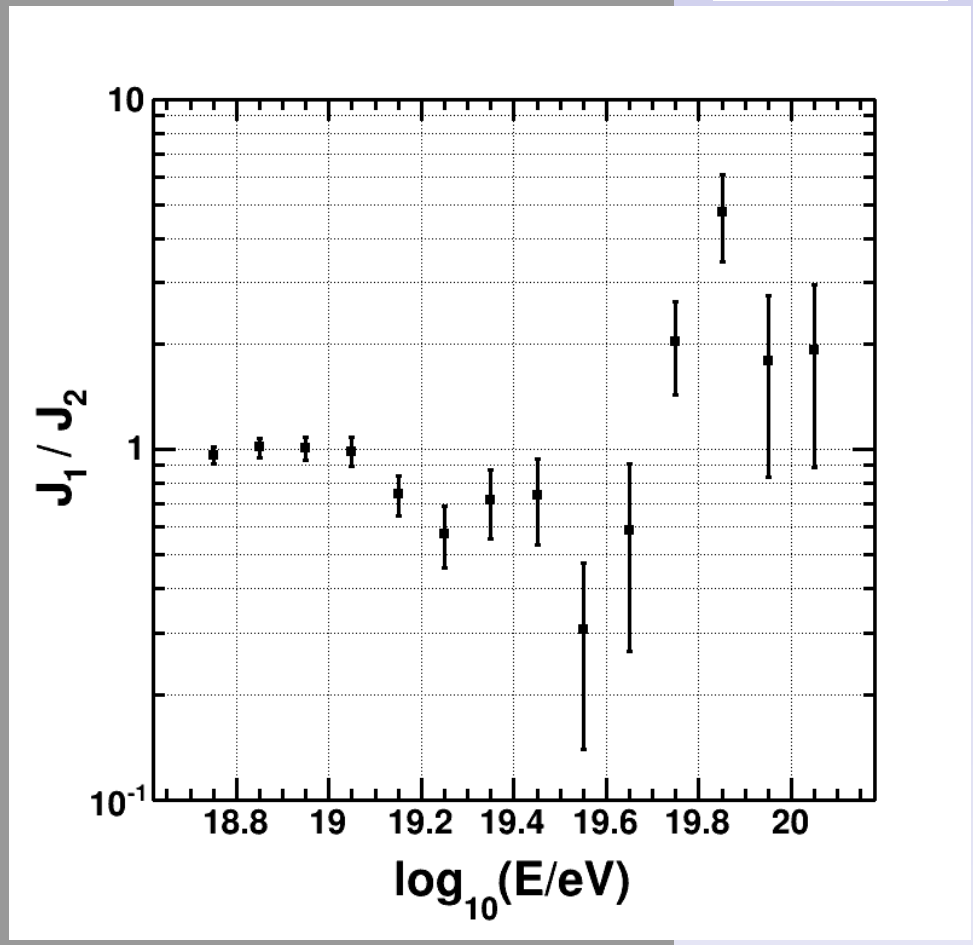
Significance (same procedure as for 5 yr):

- oversampling at 15°, 20°, 25°, 30°, 35°, moving center
- Pre-trial: $P = 5.07\sigma$; $N_{\rm on} = 24$; $N_{\rm bg} = 6.88$; Post-trial $P = 3.7 \times 10^{-4}$ (3.4σ)
  $\Longrightarrow$ same as for 5 yr

- Blind search with 2yr data (6th and 7th yr): expected in the spot region 2.31, observed 4, $P = 0.2$

HOT SPOT: spectral differences inside vs. outside the spot

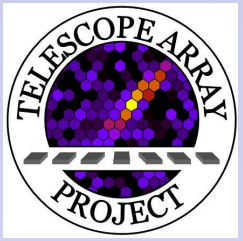




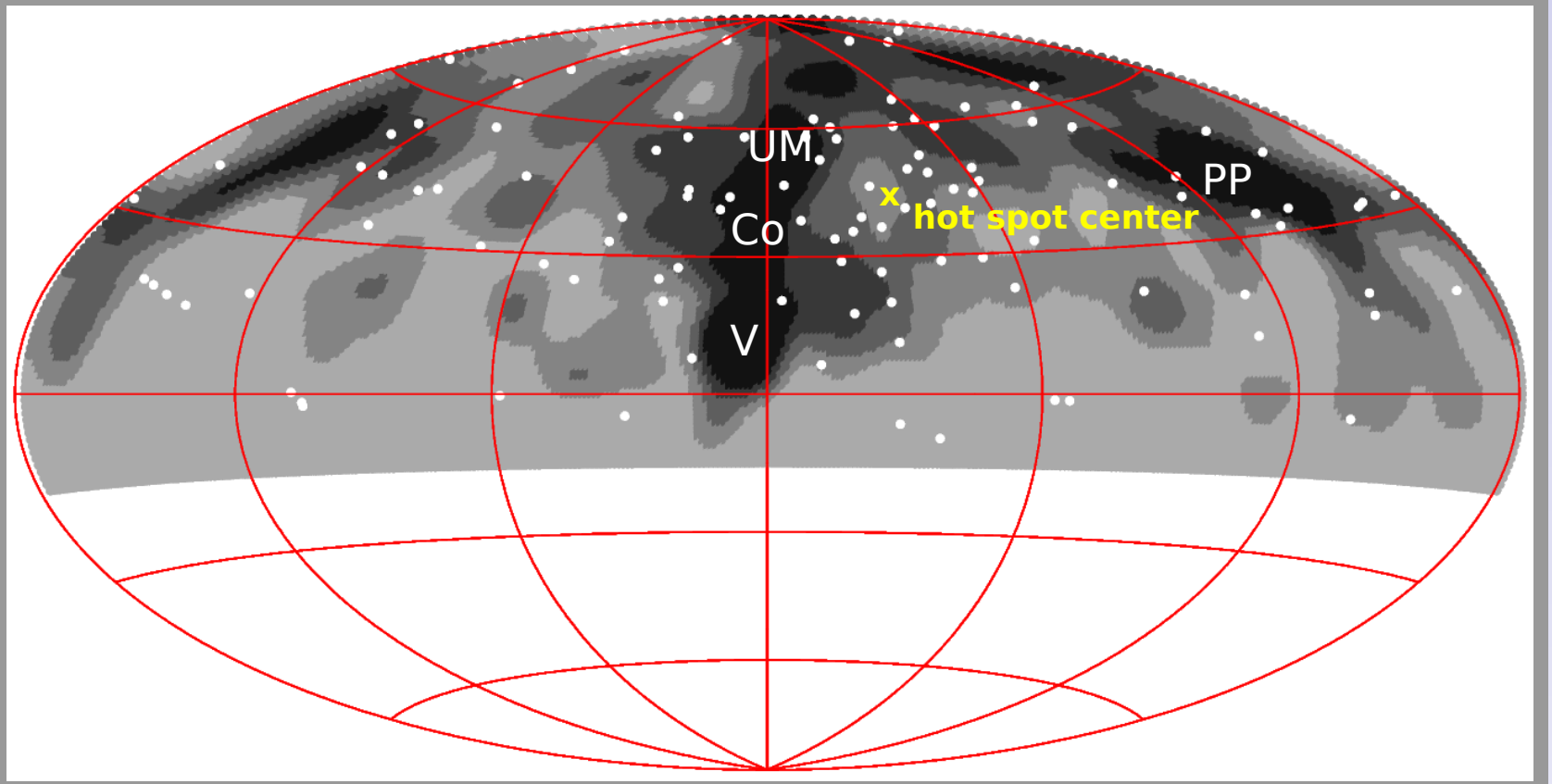
inside = red; outside = black

inside/outside ratio

CORRELATION WITH LSS



7 yr events vs. expectation from LSS (protons of 57 EeV)



Equatorial coordinates. Darker color represents larger flux. UM — Ursa Major; Co — Coma; V — Virgo; PP — Perseus-Pisces

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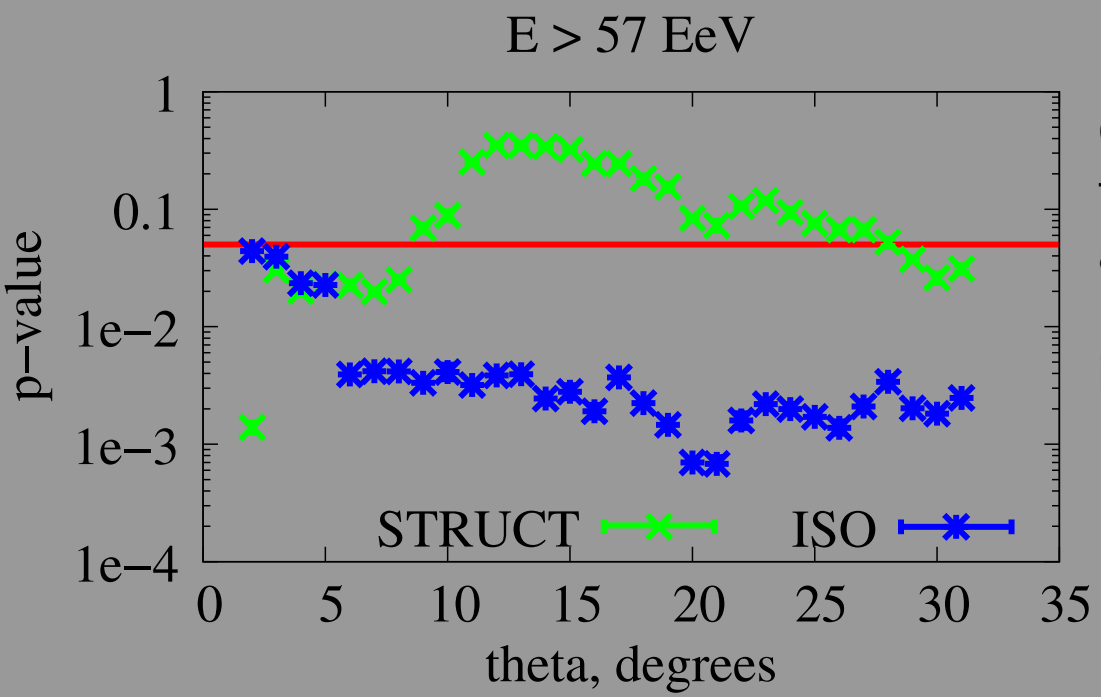
Statistical test for compatibility with LSS & isotropy



Compatibility as a function of smearing angle theta (low p-values = incompatibility).

$\Longrightarrow$ High energy $E > 57$ EeV events are:

- COMPATIBLE with LSS prediction
- IN TENSION with isotropy

OTHER SEARCHES

Anisotropy in energy spectrum

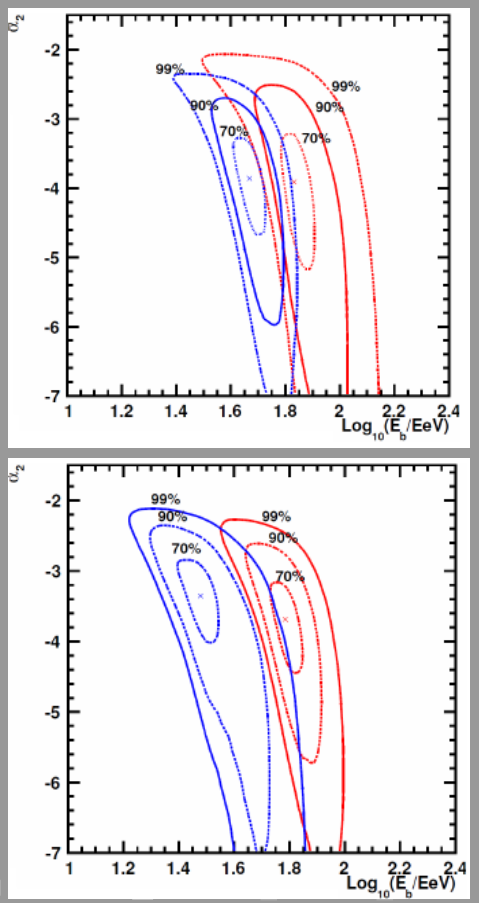
Strategy:

T. Nonaka, ICRC-2015

- Split the event set into “on-source” and “off-source” parts
- compare the “on-source” and “off-source” energy spectra

Two analyses:

- “On-source” = within 30° from Supergalactic plane
  $\Longrightarrow \sim 3.2\sigma$ difference
- “On-source” = within 11° from VCV AGNs
  $\Longrightarrow \sim 2.4\sigma$ difference



Search for EeV protons of Galactic origin

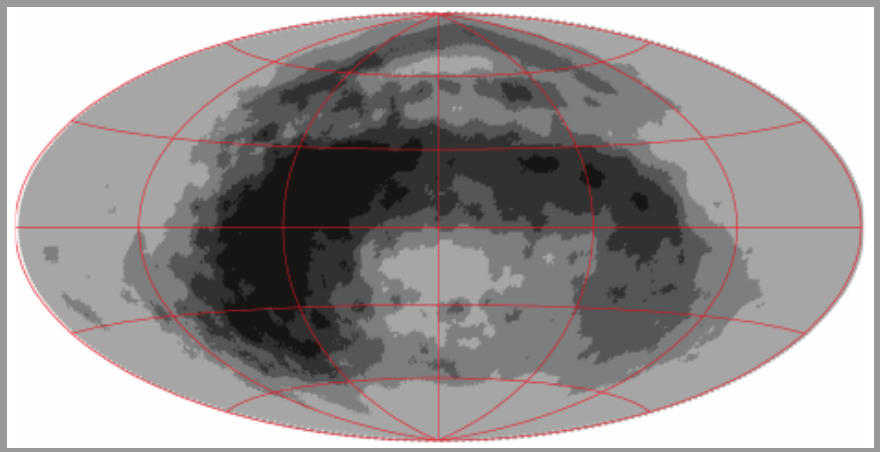
Motivation:

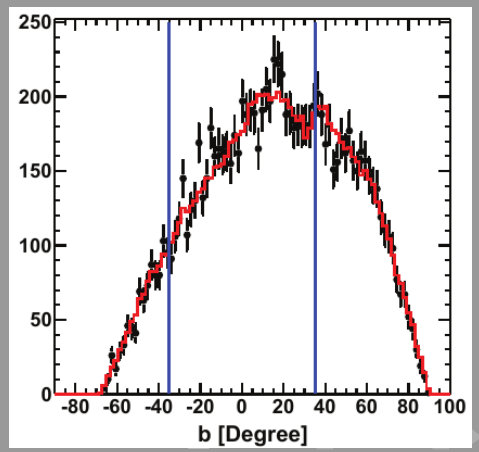
D. Ivanov, ICRC-2015

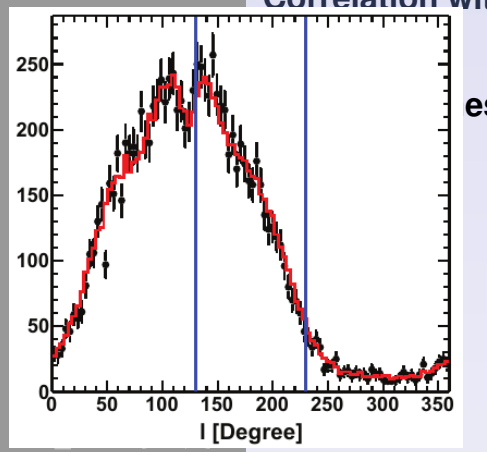
- At the transition from ballistic to diffusive regime ($E \sim 1$ EeV), the proton flux from galactic sources is *strongly anisotropic* in a predictable way.
- Comparing to observed flux, the proton component of a Galactic origin may be constrained.

Results:

- fraction of Galactic protons at $E \sim 1$ EeV is $\lesssim 1\%$ at 90% CL.







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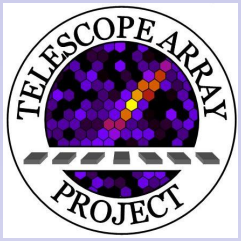
INTER-EXPERIMENT COMBINED ANALYSES

- Auger + TA: Large-Scale Distribution of Arrival Directions of Cosmic Rays Detected at the Pierre Auger Observatory and the Telescope Array above 10^{19} eV *arXiv:1511.02103*
  - harmonic analysis of combined data set at $E > 10^{19}$ eV
    $\Longrightarrow$ non-zero dipole @ 2.8σ

- IceCube + Auger + TA: Correlation between the UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube *JCAP 1601 (2016) no.01, 037*
  - highest energy $E > 57$ EeV Auger + TA events vs. neutrinos
    $\Longrightarrow$ correlation @ 3.4σ

CONCLUSIONS

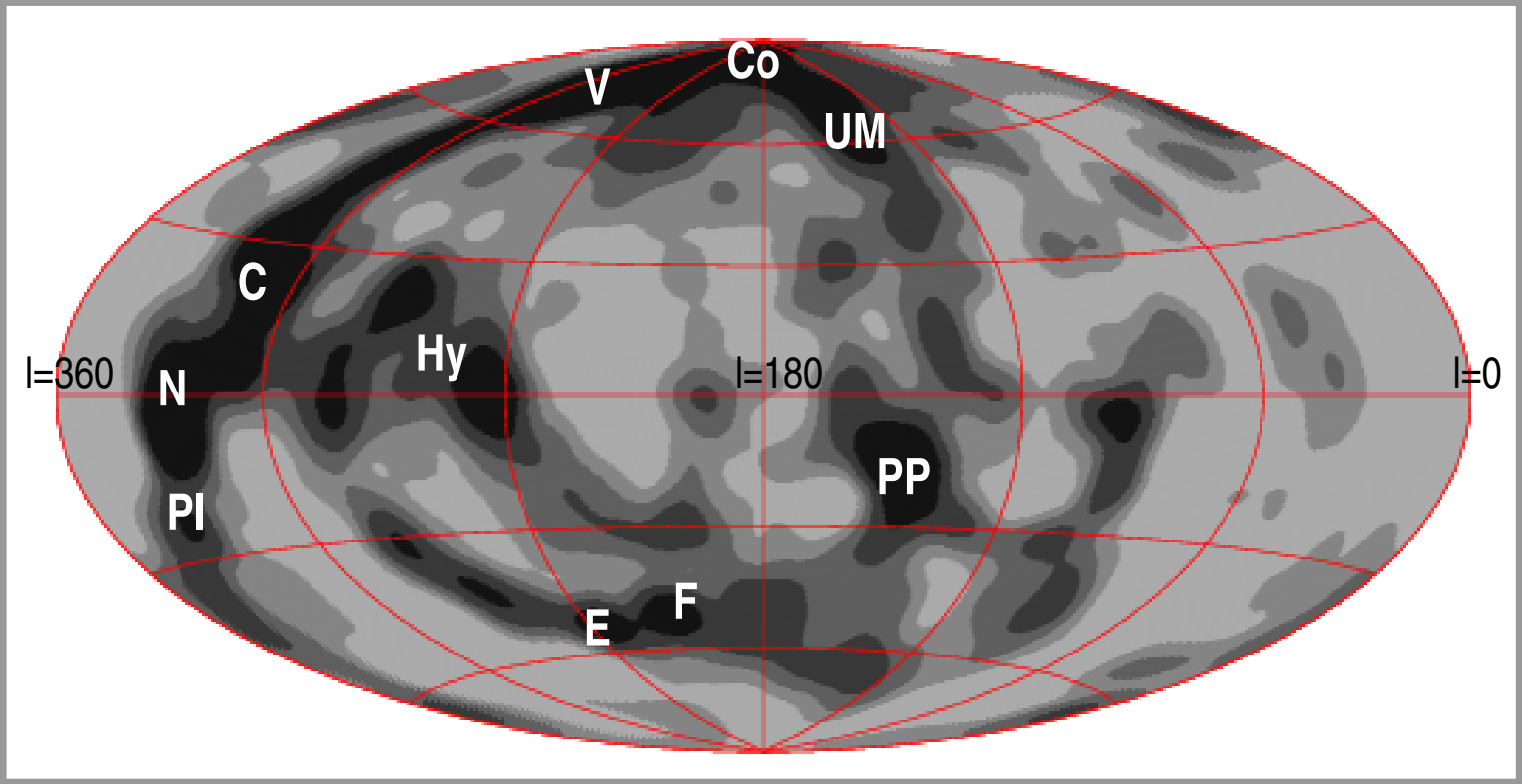
- Possible indications of anisotropy of UHECR start to emerge:
  - dipole at low energies
  - “hot spot” in the GZK region
- Their significance is limited by statistics; an upgrade TA$\times$4 (being built) will be very helpful



BACKUP SLIDES

CR flux expected in LSS model

Example: $E > 57$ EeV, $\theta = 6°$, Galactic coordinates



C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); Ursa Major North group (20 Mpc) South group (20 Mpc); V: Virgo cluster (20 Mpc).

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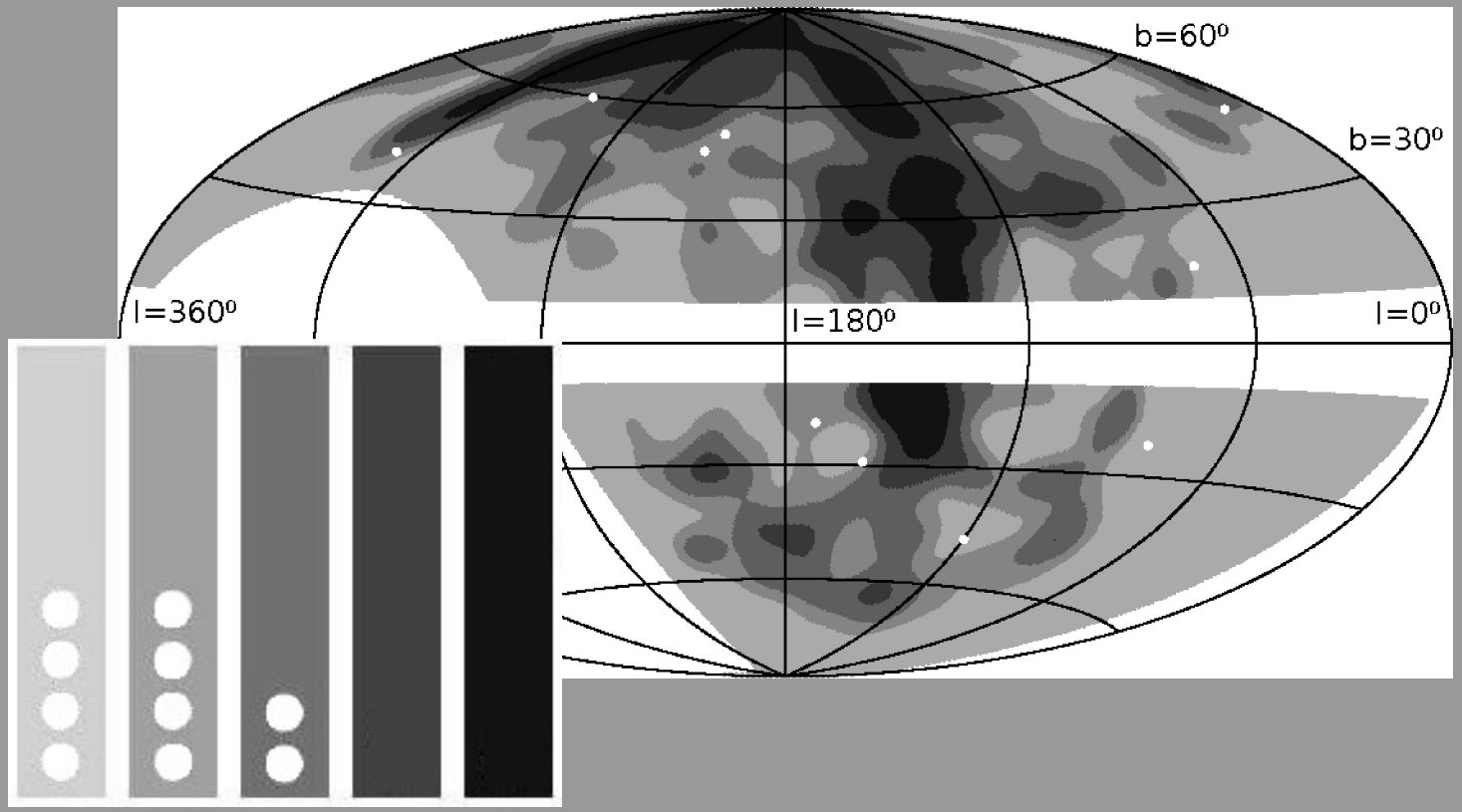
THE FLUX SAMPLING STATISTICAL TEST



- Events following the model would produce uniform distribution over the bands
- No binning is needed (on the picture it is for illustration only): two distributions may be compared by the KS test