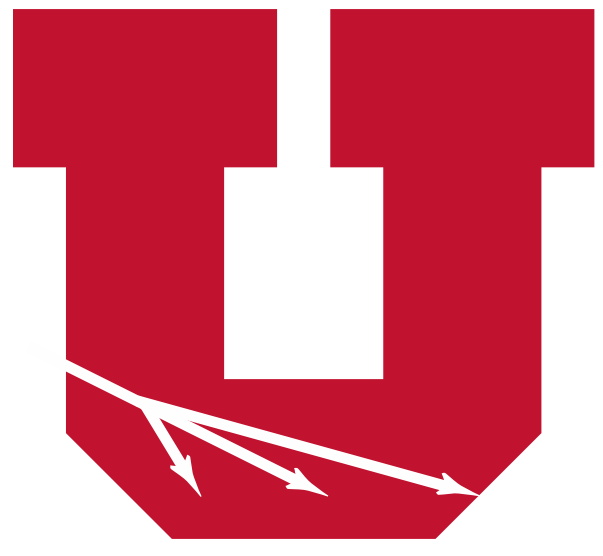# Telescope Array Surface Detector Medium-scale Anisotropy Analysis

Jihyun Kim[*1], Dmitri Ivanov[1], Kazumasa Kawata[2], Hiroyuki Sagawa[2], and Gordon Thomson[1], on behalf of the Telescope Array Collaboration

[1]*High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah*
[2]*Institute for Cosmic Ray Research, University of Tokyo*
contact: jihyun@cosmic.Utah.edu

Abstract

Ultra-high energy cosmic rays (UHECRs) are highly energetic charged particles originating from extragalactic sources, with energies exceeding 10^{18} eV. Elucidating the origin of UHECRs is a critical scientific objective. One approach is analyzing their arrival direction distribution for evidence of anisotropy. The Telescope Array (TA) experiment, the largest UHECR observatory in the Northern Hemisphere, has detected evidence of two medium-scale anisotropies: the TA hotspot in the constellation of Ursa Major and an excess in the direction of the Perseus-Pisces supercluster. This presentation will detail an oversampling analysis using TA surface detector data to identify event excesses. We will present the latest findings regarding the TA hotspot and the Perseus-Pisces supercluster excess.
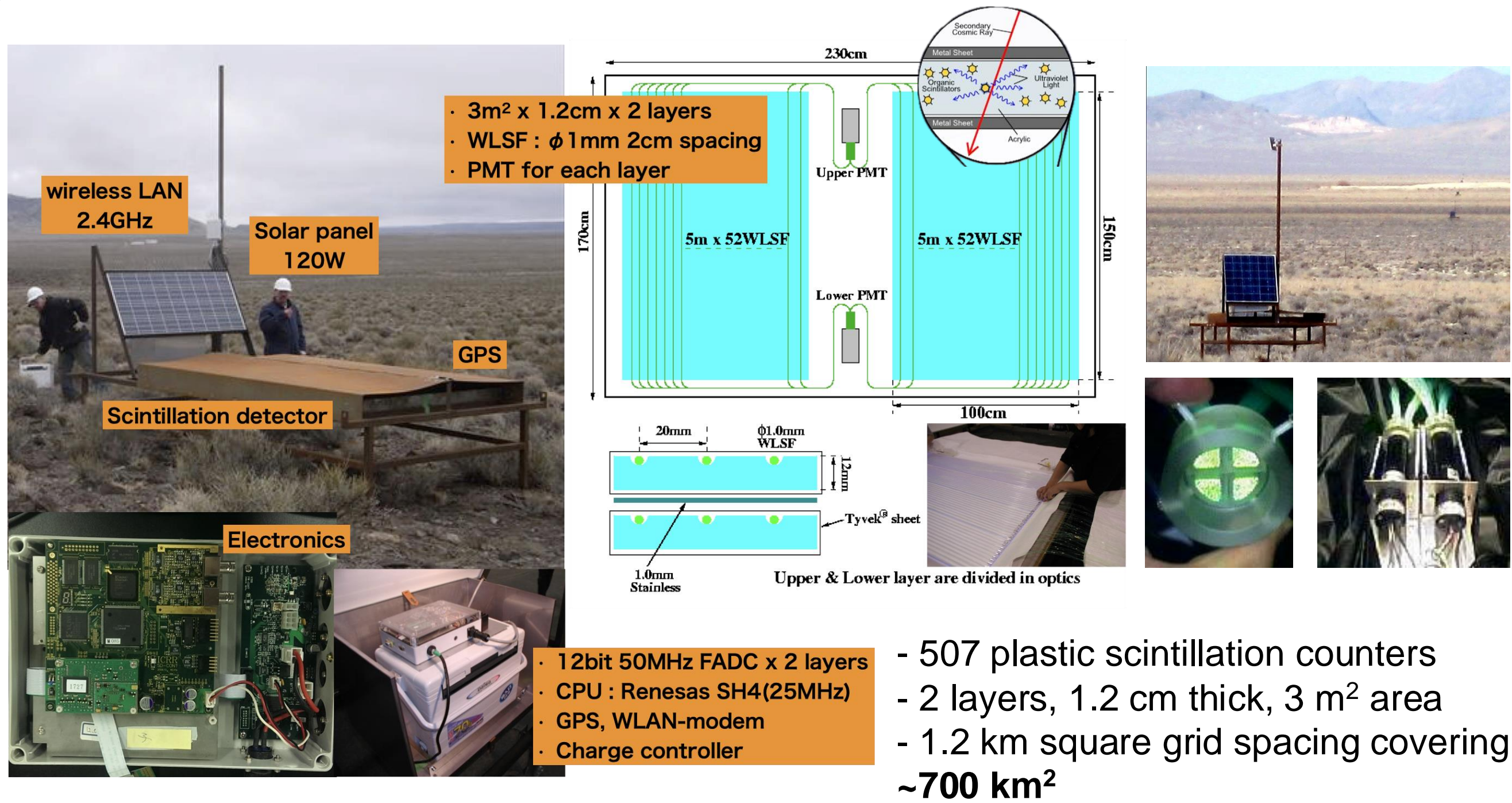
Telescope Array Experiment

UHECR Observatory

Telescope Array
Delta, Utah, USA
~1400 m above sea level
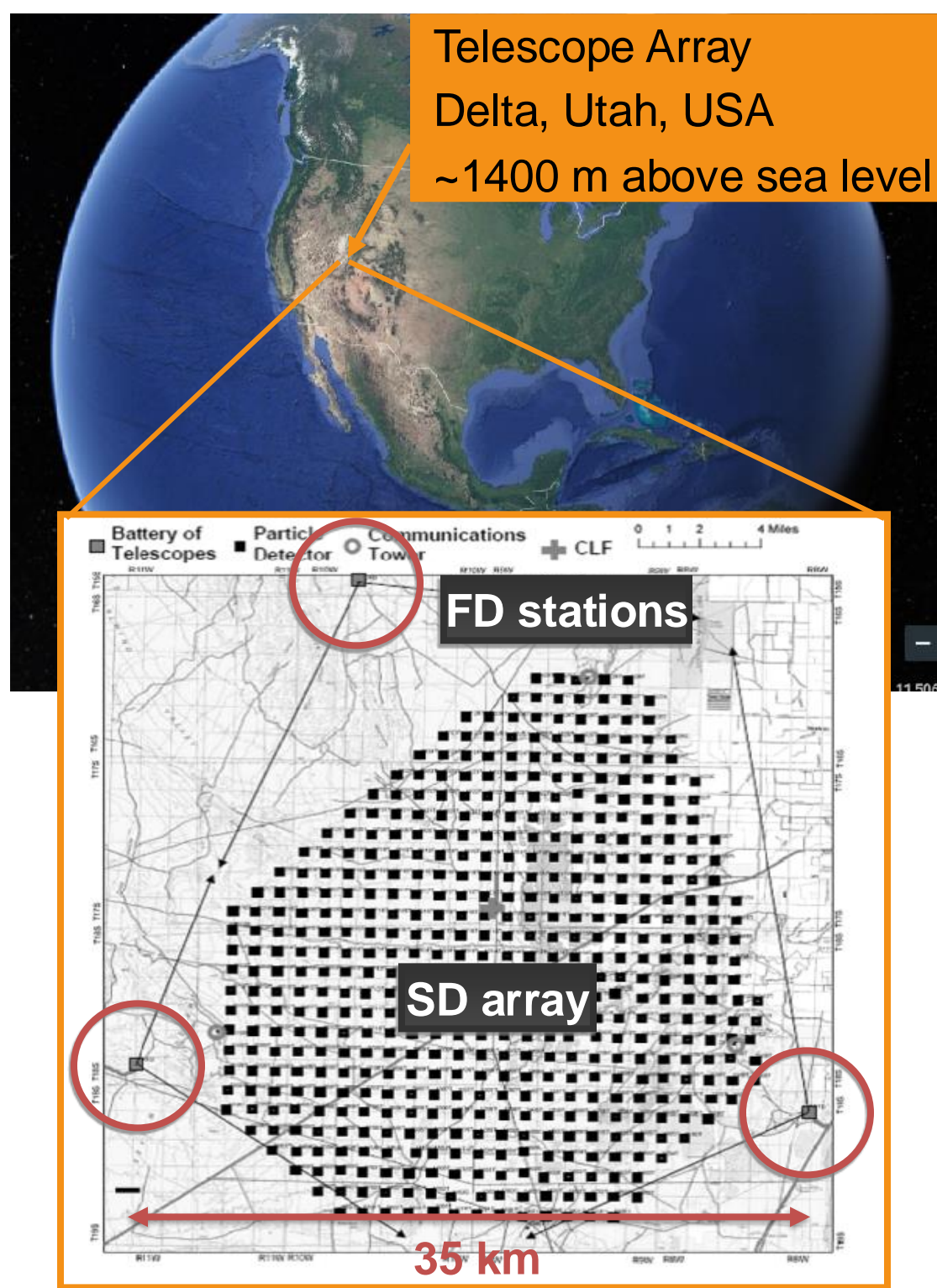
- **The largest cosmic ray observatory** in the northern hemisphere, located near Delta, Utah.
- Designed to detect extensive air showers (EAS) induced by a primary UHECR colliding with the atmosphere using **hybrid techniques**:
  - **- Fluorescence Detectors (FDs)**
  - **- Surface Detectors (SDs)**
- Using data from both sets of detectors, we explore the nature and origin of UHECRs by investigating
  - Energy spectrum
 - Mass composition
  - Arrival direction distribution

Surface Detectors

- 3m² x 1.2m x 2 layers
- WLSF : φ1mm 2cm spacing
- PMT for each layer

- 12bit 50MHz FADC x 2 layers
- CPU : Renesas SH4(25MHz)
- GPS, WLAN-modem
- Charge controller

- 507 plastic scintillation counters
- 2 layers, 1.2 cm thick, 3 m² area
- 1.2 km square grid spacing covering **~700 km²**

Medium-scale Anisotropy Search

TA Hotspot (2014)

Anisotropy search is critical to narrowing down source candidates of UHECRs.
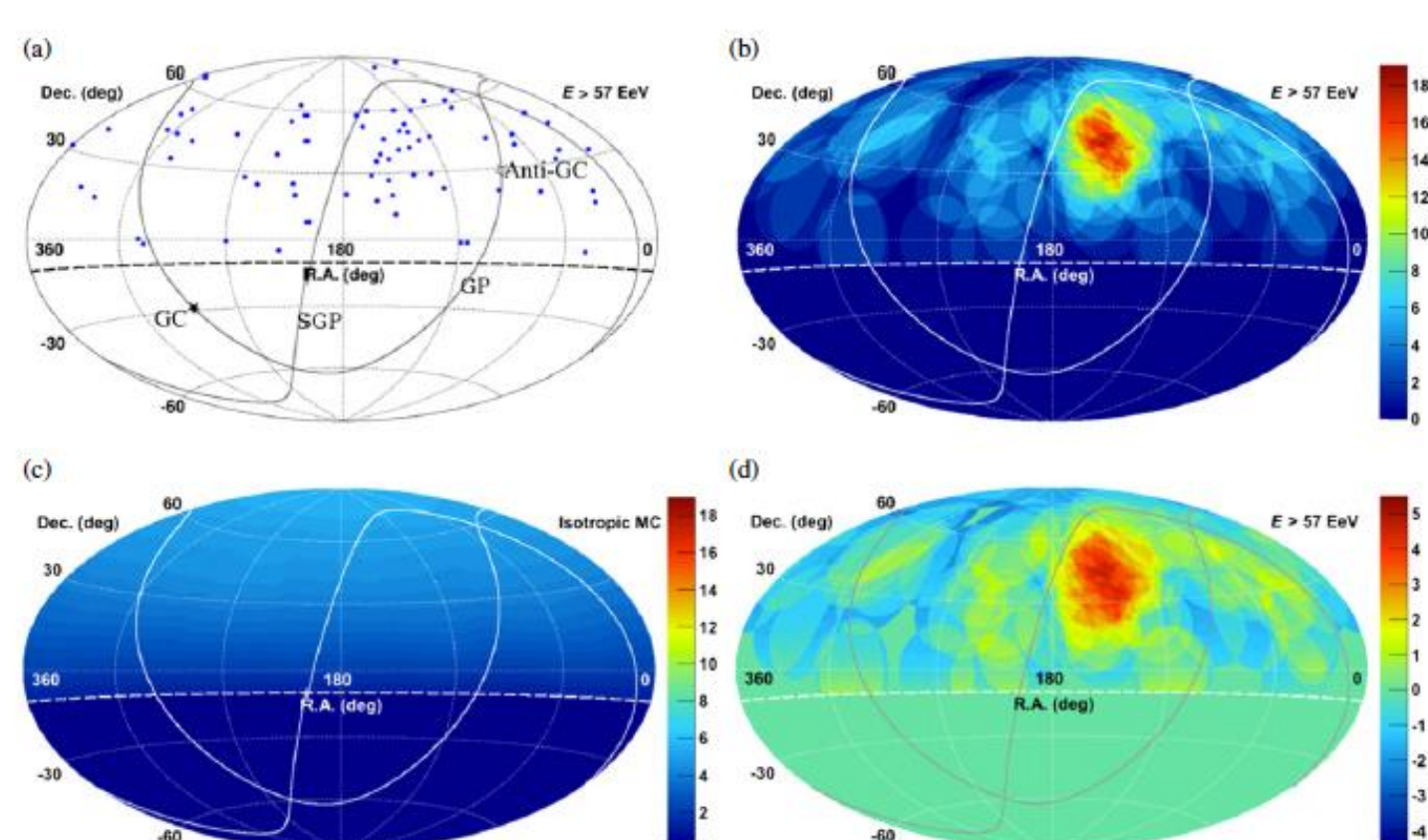
- We performed **medium-scale anisotropy** searches.
- 72 events with **E > 5.7×10¹⁹ eV** (5-year TA SD data)
- Maximum local significance: **5.1σ**
  - N_{obs}: 19 events
  - N_{bg}: 4.5 events
- Post-trial probability:
  $P(p_{pre} > 5.1\sigma) = 3.7 \times 10^{-4} \rightarrow$ **3.4σ**

Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. = −10°. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by the TA SD array, and the closed and open stars indicate the Galactic center (GC) and the anti-Galactic center (Anti-GC), respectively; (b) color contours show the number of observed cosmic-ray events summed over a 20° radius circle; (c) number of background events from the geometrical exposure summed over a 20° radius circle (the same color scale as (b) is used for comparison); (d) significance map calculated from (b) and (c) using Equation (1).

Oversampling Searches: Li-Ma analysis

- The statistical significance of the excess of events compared to background events at each grid point is calculated by the Li-Ma method:

$$S_{LM} = \sqrt{2}\left[N_{on}\ln\left(\frac{(1+\alpha)N_{on}}{\alpha(N_{on}+N_{off})}\right) + N_{off}\ln\left(\frac{(1+\alpha)N_{off}}{N_{on}+N_{off}}\right)\right]^{1/2},$$

- $N_{total} = N_{on} + N_{off}$: total observed number of events
- N_{on}: # of events inside the circle, N_{off}: # of events outside the circle
- $N_{bg} = \alpha \cdot N_{off}$
- To determine the exposure ratio of α, we generated 10^5 events assuming an isotropic flux taking into account the geometrical exposure.

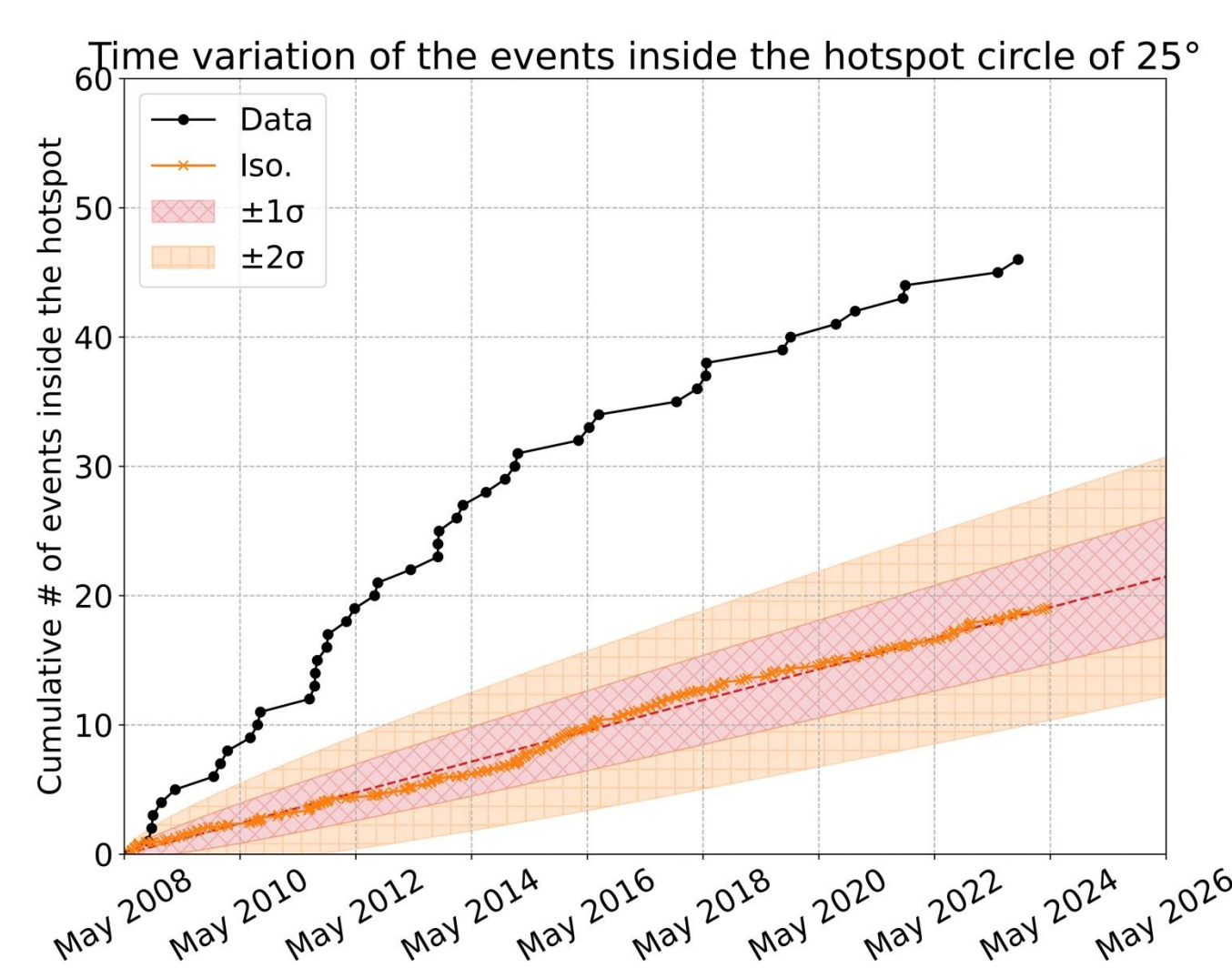$$\alpha = \frac{N_{sim,on}}{N_{sim,off}} = \frac{N_{sim,on}}{(N_{sim,total} - N_{sim,on})}$$

- Oversampling has been done with given of angular windows.

Results: Medium-scale Anisotropies

TA Hotspot (2024)

25° angular distance oversampling
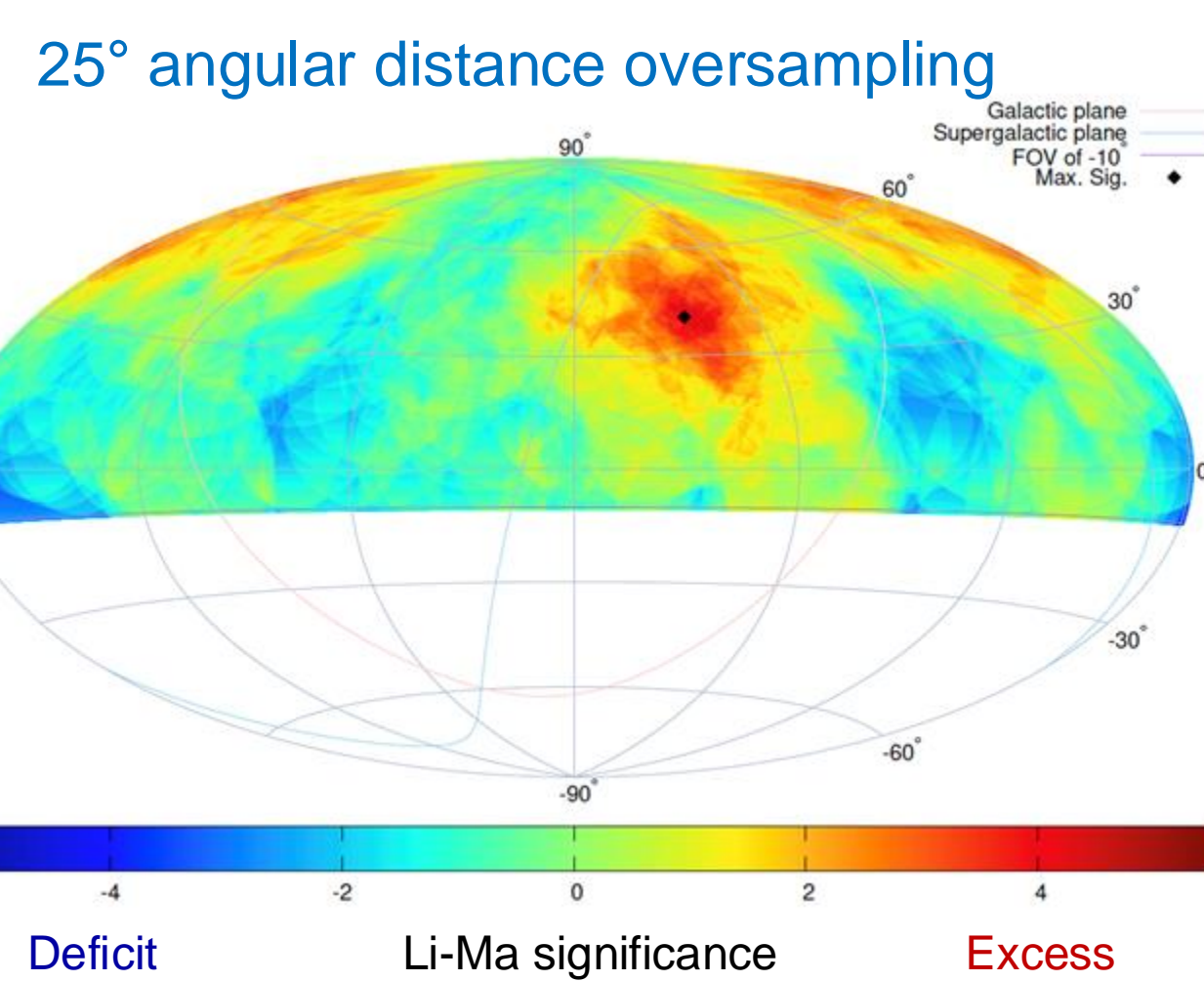
- 16-year TA SD data, E > 5.7×10¹⁹ eV
- 228 events (16-year TA SD data)
- Max local sig.: **4.9σ** at (144.0°, 40.5°)
  - N_{obs}: 46 events
  - N_{bg}: 19.1 events   ~141% excess
- Post-trial probability:
  $P(S_{MC} > 4.9\sigma) = 2.1 \times 10^{-3} \rightarrow$ **2.9σ**
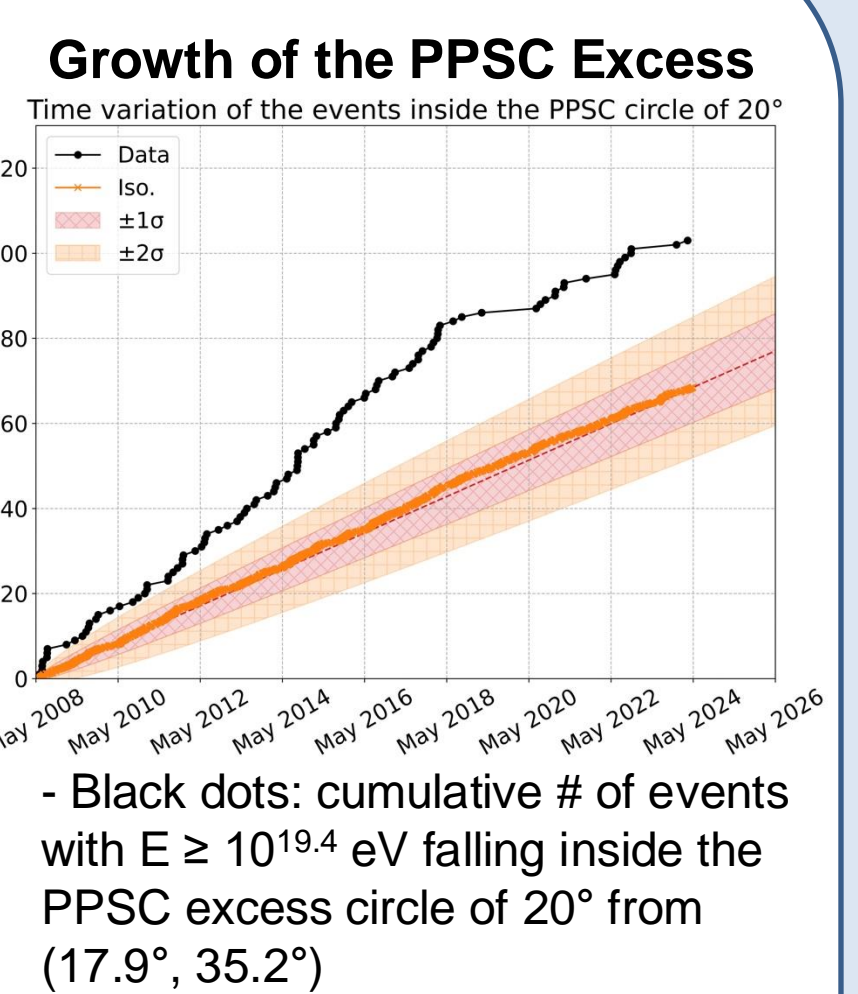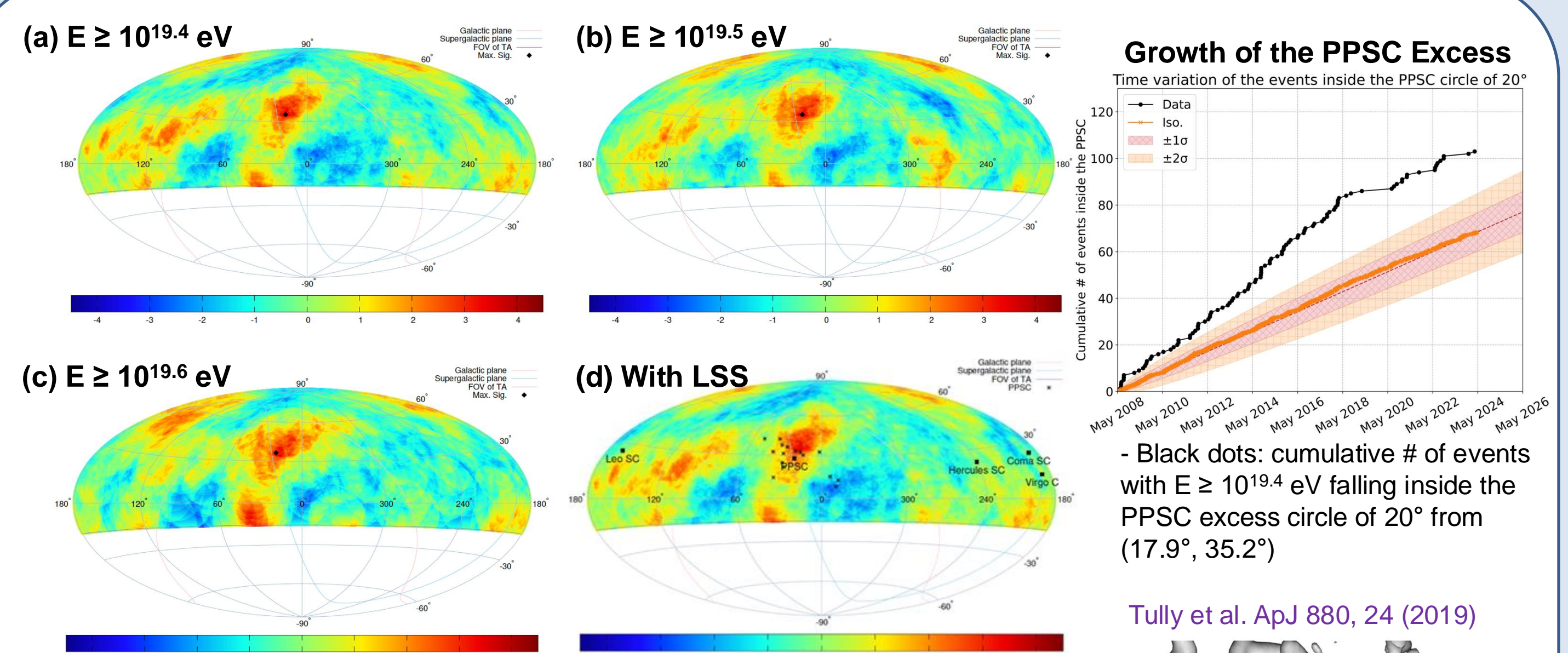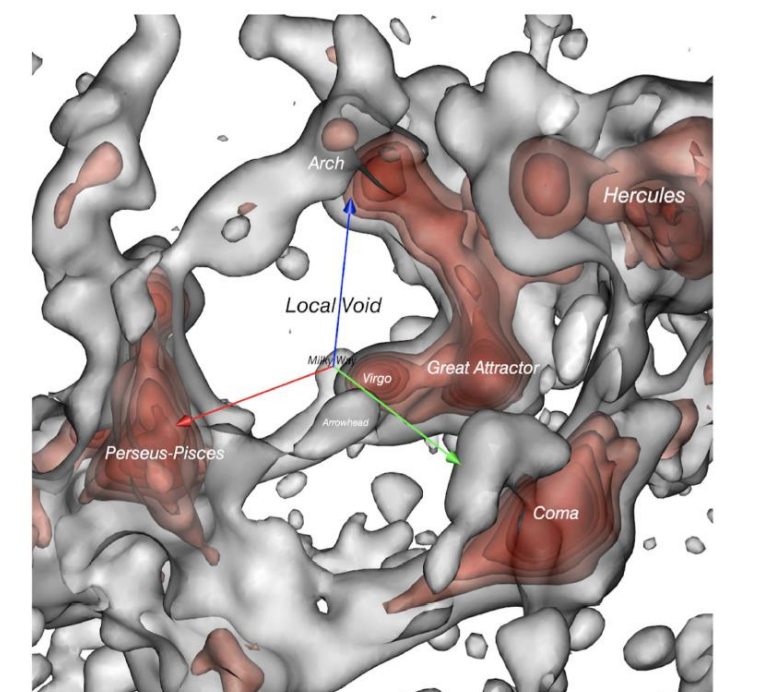

Growth of the Hotspot
- Black dots: cumulative # of events falling inside the hotspot circle of 25° from (144.0°, 40.5°)
- Orange X's: cumulative # of isotropic background expectation

$$N_{bg} = \alpha \cdot N_{off} = \frac{N_{sim,on}}{(N_{sim,total} - N_{sim,on})} \cdot (N_{total} - N_{on})$$

Perseus-Pisces Supercluster Excess (2024)

(a) E ≥ 10¹⁹·⁴ eV   (b) E ≥ 10¹⁹·⁵ eV   (c) E ≥ 10¹⁹·⁶ eV   (d) With LSS

Growth of the PPSC Excess

- Black dots: cumulative # of events with E ≥ 10¹⁹·⁴ eV falling inside the PPSC excess circle of 20° from (17.9°, 35.2°)

Tully et al. ApJ 880, 24 (2019)

- The PPSC is a unique and significant structure in TA's field of view because it is the **closest** supercluster, and its location is **next to the Local Void** where the magnetic field strength is presumed to be weaker than other structures in the cosmic web.

- We count as successes the number of sets where the point of maximum Li-Ma significance is at least as significant as in the data, and also occurs at least as close to the PPSC as in the data: $(S_{mc} \geq S_{obs})$ and $(\theta_{mc} \leq \theta_{obs})$.
- Chance probability of having such an excess as close to PPSC as data:

Summary of the Monte-Carlo studies that estimate the chance probability of having an excess

Energy (eV)	Events	Criteria	PPSC
E ≥ 10¹⁹·⁴	1186	$(S_{mc} \geq 3.7\sigma)$ & $(\theta_{mc} \leq 7.7°)$	3.1σ
E ≥ 10¹⁹·⁵	767	$(S_{mc} \geq 3.9\sigma)$ & $(\theta_{mc} \leq 7.4°)$	3.2σ
E ≥ 10¹⁹·⁶	464	$(S_{mc} \geq 3.7\sigma)$ & $(\theta_{mc} \leq 8.3°)$	3.0σ

Summary

- We have persistent evidence for the **Hotspot** at the highest energies, E ≥ 5.7×10¹⁹ eV, near the Ursa Major constellation: local significance **4.9σ**, global significance **2.9σ**.
- A new excess in slightly lower energy events, E ≥ 10¹⁹·⁴ eV, has been identified in the direction of **the Perseus-Pisces supercluster**: local significance **4.0σ**, the chance probability of having an excess as close to the PPSC as the data is estimated to be **3.3σ**.
- The four-fold extension of the Telescope Array experiment, the TA×4 project, would accelerate data taking and is expected to play a vital role in resolving the enigma surrounding the origin of UHECRs.

Projections of Hotspot measurement

Projections of PPSC Excess Measurement