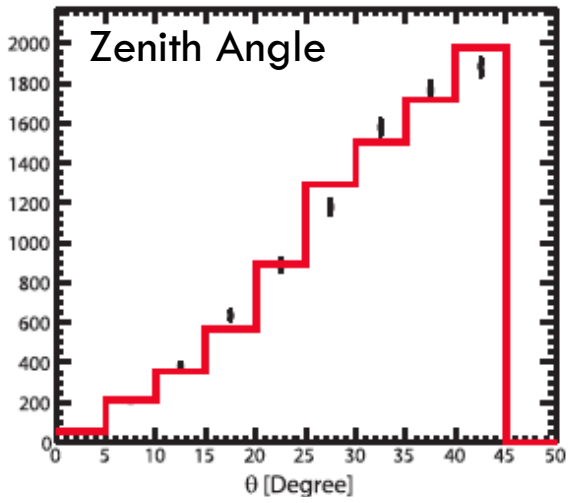
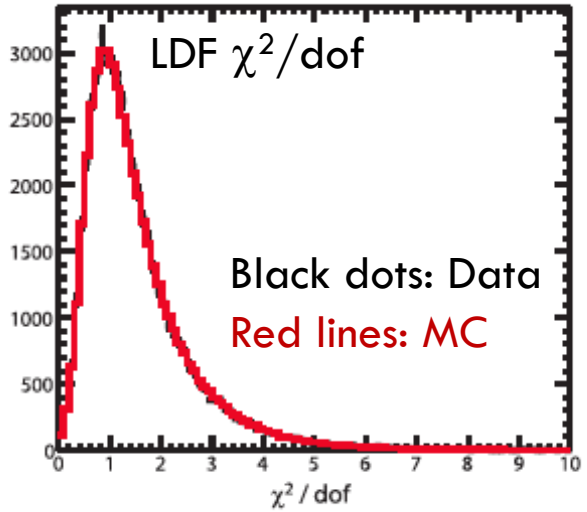
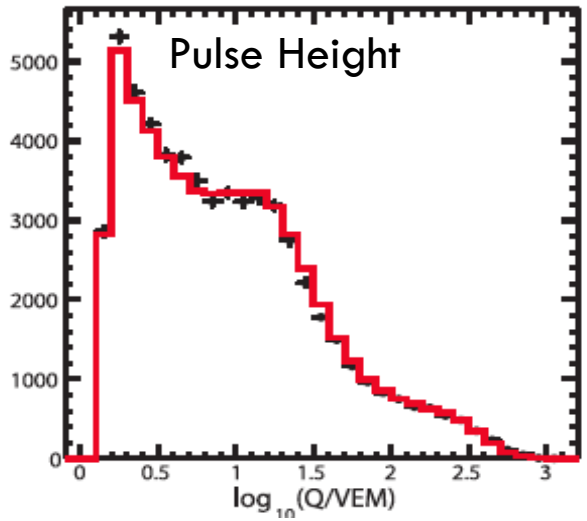
Updates on the Hotspot and the Perseus-Pisces supercluster Excess Observed by the Telescope Array Experiment

Jihyun Kim[1], Dmitri Ivanov[1], Kazumasa Kawata[2],
Hiroyuki Sagawa[2], and Gordon Thomson[1]
for the Telescope Array Collaboration
[1]University of Utah, [2]University of Tokyo

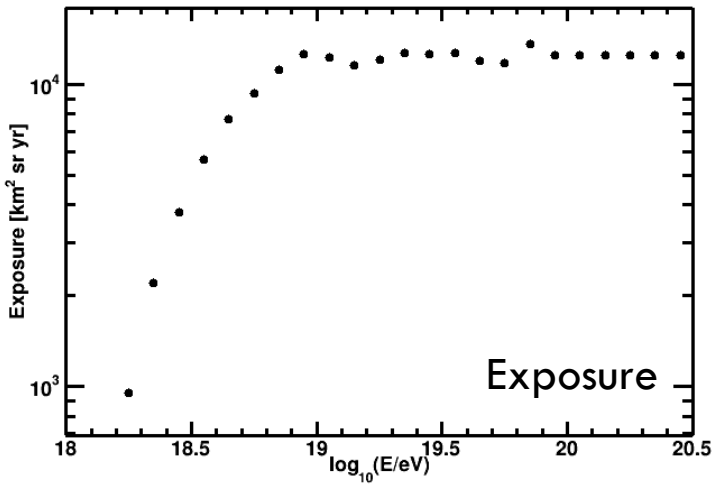
Resolution and Sensitivity by Monte Carlo Simulation







- Monte Carlo based on CORSIKA program used for resolution and exposure calculations.
- TA SD Resolution:
  - 20% energy, 1.4° angular, $E \geq 10^{19.0}$ eV
  - 29% energy, 2.1° angular, $10^{18.5}\text{eV} \leq E < 10^{19.0}$ eV
  - 34% energy. 2.4° angular, $10^{18.0}\,\text{eV} \leq E < 10^{18.5}$ eV

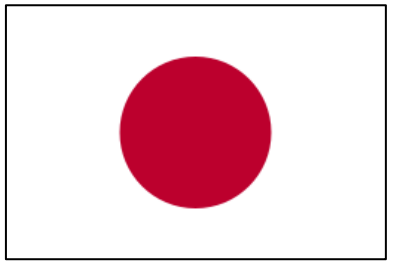


Outline

- Telescope Array experiment
- Update on the hotspot
  - Results using 14 years of data
  - Independent dataset analysis
  - Chance probability estimation
- Update on the Perseus-Pisces SuperCluster (PPSC) excess
  - Results using 14 years of data
  - Chance probability estimation

Telescope Array Collaboration

USA



Japan

Korea

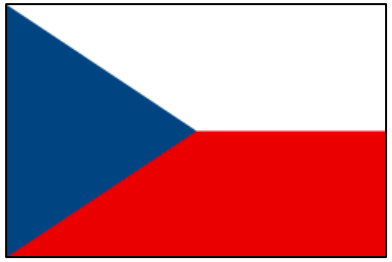
R.U. Abbasi,[1] M. Abe,[2] T. Abu-Zayyad,[1] M. Allen,[1] R. Azuma,[3] E. Barcikowski,[1] J.W. Belz,[1] D.R. Bergman,[1] S.A. Blake,[1] R. Cady,[1] B.G. Cheon,[4] J. Chiba,[5] M. Chikawa,[6] A. di Matteo,[7,*] T. Fujii,[8] K. Fujisue,[9] K. Fujita,[10] R. Fujiwara,[10] M. Fukushima,[9,11] G. Furlich,[1] W. Hanlon,[1] M. Hayashi,[12] Y. Hayashi,[10] N. Hayashida,[13] K. Hibino,[13] R. Higuchi,[9] K. Honda,[14] D. Ikeda,[15] T. Inadomi,[16] N. Inoue,[2] T. Ishii,[14] R. Ishimori,[3] H. Ito,[17] D. Ivanov,[1] H. Iwakura,[16] H.M. Jeong,[18] S. Jeong,[18] C.C.H. Jui,[1] K. Kadota,[19] F. Kakimoto,[3] O. Kalashev,[20] K. Kasahara,[21] S. Kasami,[22] H. Kawai,[23] S. Kawakami,[10] S. Kawana,[2] K. Kawata,[9] E. Kido,[9] H.B. Kim,[4] J.H. Kim,[10] J.H. Kim,[1] M.H. Kim,[18] S.W. Kim,[18] S. Kishigami,[10] V. Kuzmin,[20,†] M. Kuznetsov,[20,7] Y.J. Kwon,[24] K.H. Lee,[18] B. Lubsandorzhiev,[20] J.P. Lundquist,[1] K. Machida,[14] K. Martens,[11] H. Matsumiya,[10] T. Matsuyama,[10] J.N. Matthews,[1] R. Mayta,[10] M. Minamino,[10] K. Mukai,[14] I. Myers,[1] S. Nagataki,[17] K. Nakai,[10] R. Nakamura,[16] T. Nakamura,[25] Y. Nakamura,[16] Y. Nakamura,[16] T. Nonaka,[9] H. Oda,[10] S. Ogio,[10,26] M. Ohnishi,[9] H. Ohoka,[9] Y. Oku,[22] T. Okuda,[27] Y. Omura,[10] M. Ono,[17] R. Onogi,[10] A. Oshima,[10] S. Ozawa,[28] I.H. Park,[18] M.S. Pshirkov,[20,29] J. Remington,[1] D.C. Rodriguez,[1] G. Rubtsov,[20] D. Ryu,[30] H. Sagawa,[9] R. Sahara,[10] K. Saito,[9] Y. Saito,[16] N. Sakaki,[9] T. Sako,[9] N. Sakurai,[10] K. Sano,[16] L.M. Scott,[31] T. Seki,[16] K. Sekino,[9] P.D. Shah,[1] F. Shibata,[14] T. Shibata,[9] H. Shimodaira,[9] B.K. Shin,[10] H.S. Shin,[9] J.D. Smith,[1] P. Sokolsky,[1] N. Sone,[16] B.T. Stokes,[1] S.R. Stratton,[1,31] T.A. Stroman,[1] T. Suzawa,[2] Y. Takagi,[10] Y. Takahashi,[10] M. Takamura,[5] M. Takeda,[9] R. Takeishi,[18] A. Taketa,[15] M. Takita,[9] Y. Tameda,[22] H. Tanaka,[10] K. Tanaka,[32] M. Tanaka,[33] Y. Tanoue,[10] S.B. Thomas,[1] G.B. Thomson,[1] P. Tinyakov,[20,7] I. Tkachev,[20] H. Tokuno,[3] T. Tomida,[16] S. Troitsky,[20] Y. Tsunesada,[10,26] Y. Uchihori,[34] S. Udo,[13] T. Uehama,[16] F. Urban,[35] T. Wong,[1] K. Yada,[9] M. Yamamoto,[16] H. Yamaoka,[33] K. Yamazaki,[13] J. Yang,[36] K. Yashiro,[5] M. Yosei,[22] H. Yoshii,[37] Y. Zhezher,[9,20] and Z. Zundel.[1]

[1] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[2] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[3] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[5] *Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[6] *Department of Physics, Kindai University, Higashi Osaka, Osaka, Japan*
[7] *Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[8] *The Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto, Japan*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[10] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[11] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan*
[12] *Information Engineering Graduate School of Science and Technology, Shinshu University, Nagano, Nagano, Japan*
[13] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[14] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[15] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[16] *Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan*
[17] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[18] *Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea*
[19] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[20] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[21] *Faculty of Systems Engineering and Science, Shibaura Institute of Technology, Minato-ku, Tokyo, Japan*
[22] *Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan*
[23] *Department of Physics, Chiba University, Chiba, Chiba, Japan*
[24] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[25] *Faculty of Science, Kochi University, Kochi, Kochi, Japan*
[26] *Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka City University, Osaka, Osaka, Japan*
[27] *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan*
[28] *Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[29] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia*
[30] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea*
[31] *Department of Physics and Astronomy, Rutgers University - The State University of New Jersey, Piscataway, New Jersey, USA*
[32] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan*
[33] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[34] *National Institute of Radiological Science, Chiba, Chiba, Japan*
[35] *CEICO, Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic*
[36] *Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaemun-gu, Seoul, Korea*
[37] *Department of Physics, Ehime University, Matsuyama, Ehime, Japan*

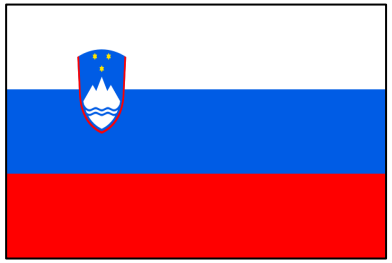
140 members, 32 institutes, 7 countries

Russia

Belgium



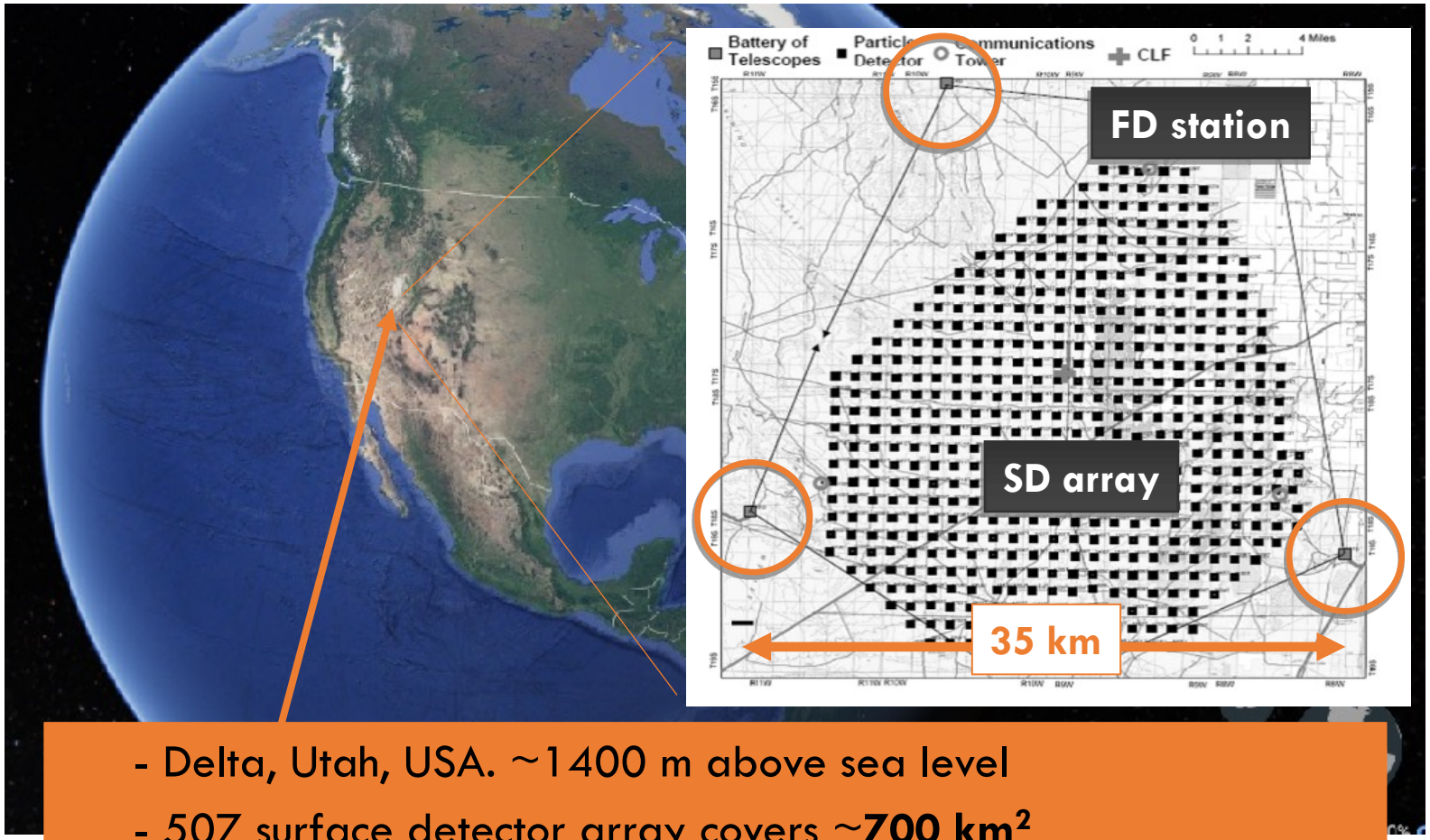
Czech Republic



Slovenia

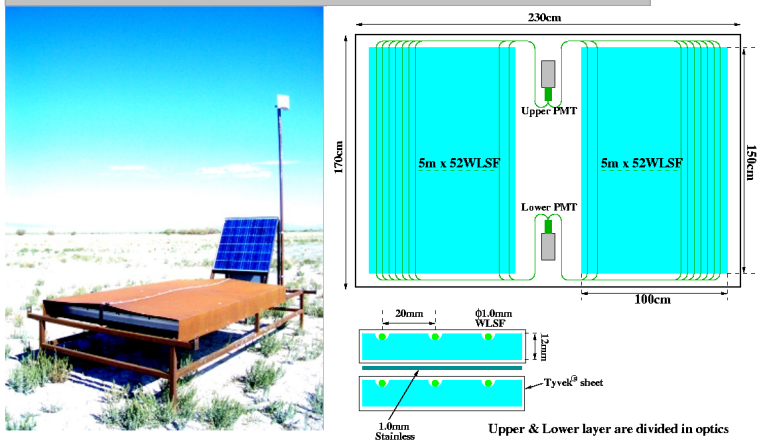
Telescope Array (TA) experiment

- The largest cosmic ray observatory in the northern hemisphere



- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km²**
- 38 telescopes in 3 stations look over the array

Surface Detector: Plastic Scintillator

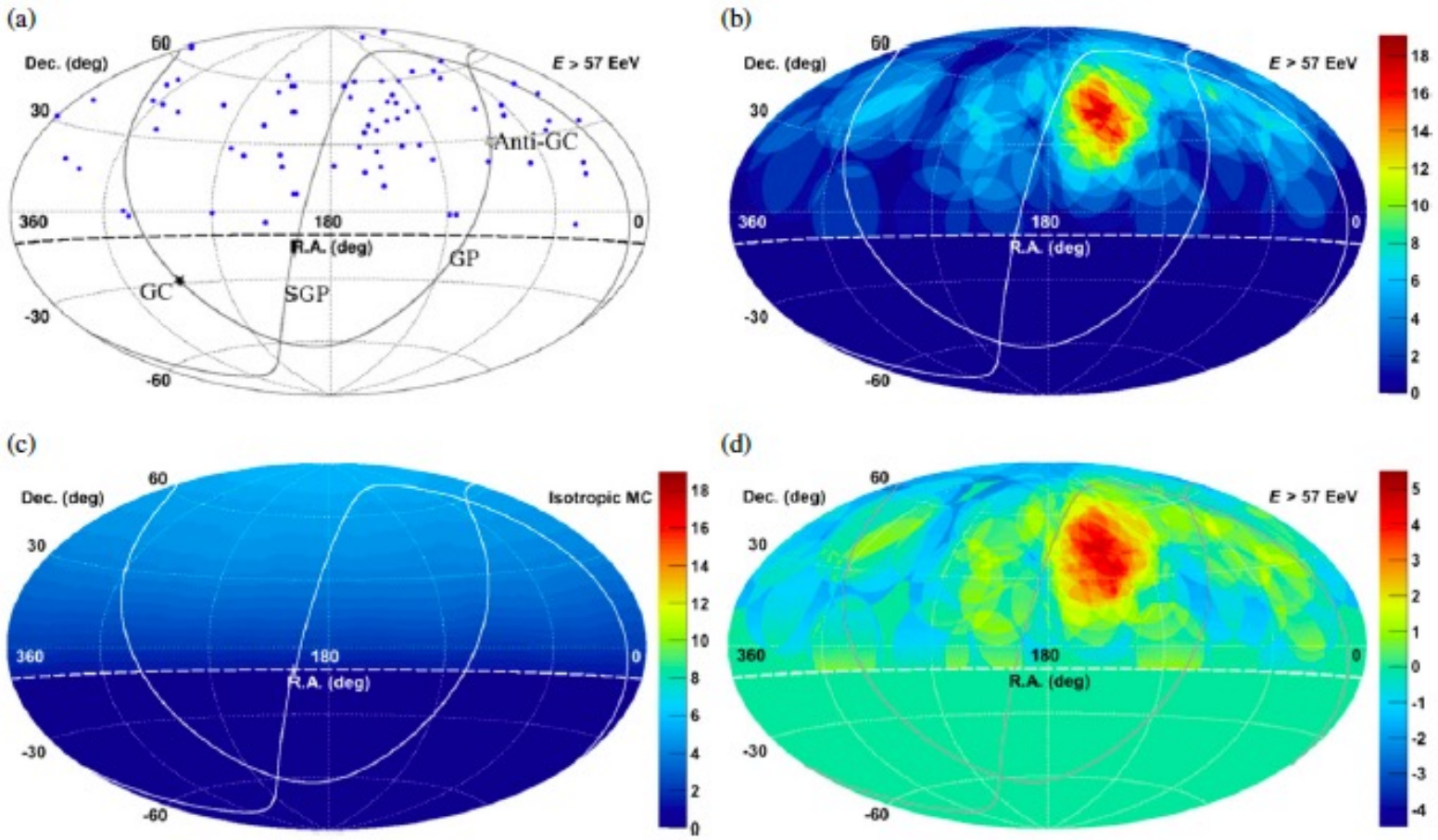


Fluorescence Detector: PMT camera

Hotspot analysis

Excess of events: TA Hotspot TA collab. (2014)

20°-radius oversampling



- 72 events (5-year TA SD data)
- Max local sig.: **5.1σ**

  at (146.7°, 43.2°)

  Obs. : 19 events

  Iso. : 4.49 events
- Post-trial probability:

$$P(S_{MC} > 5.1\sigma) = 3.7\times10^{-4}$$

→ **3.4σ**

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:

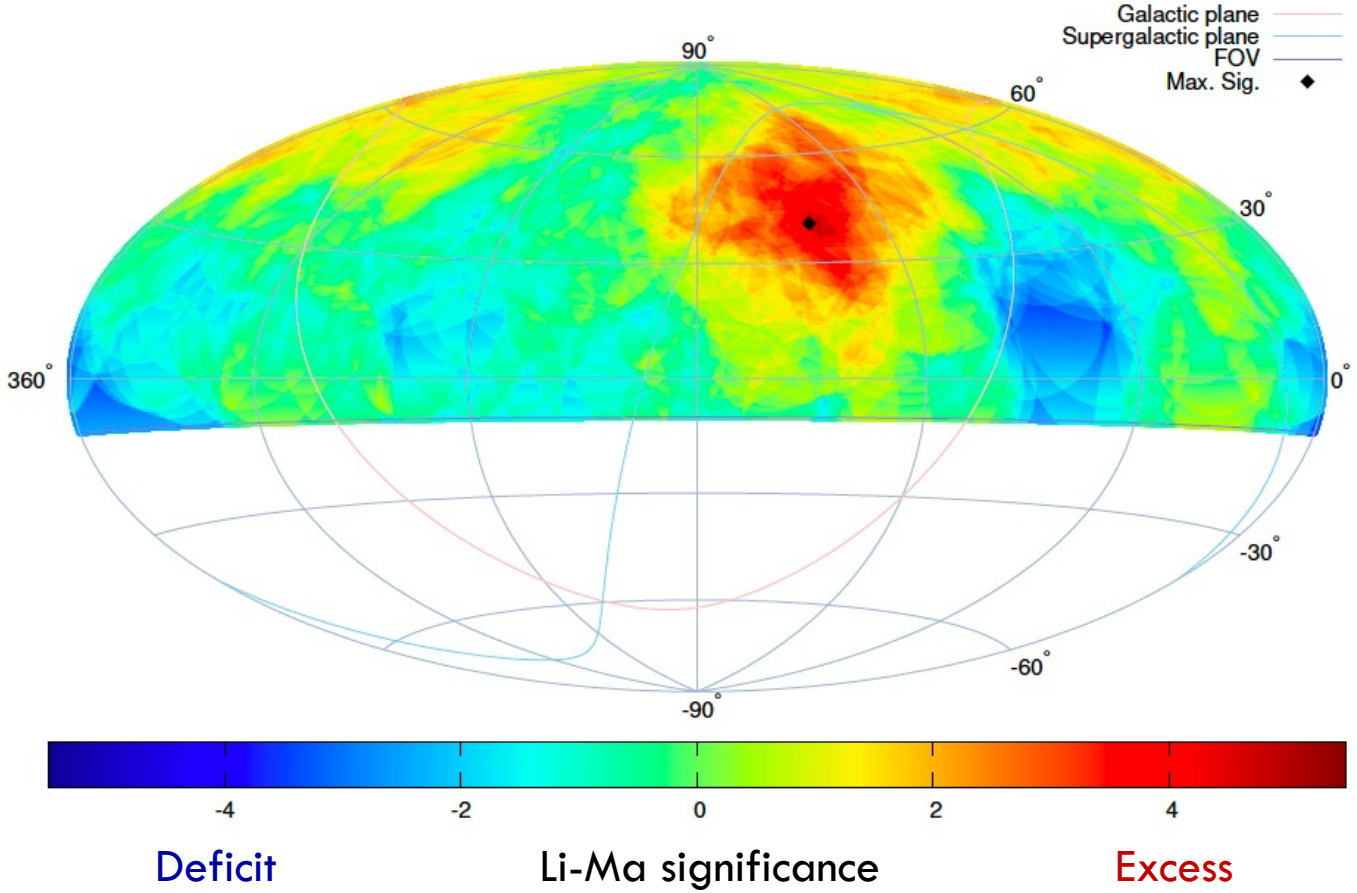
$$S_{\mathrm{LM}} = \sqrt{2}\left[N_{\mathrm{on}} \ln\left(\frac{(1+\alpha)N_{\mathrm{on}}}{\alpha(N_{\mathrm{on}}+N_{\mathrm{off}})}\right) + N_{\mathrm{off}} \ln\left(\frac{(1+\alpha)N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]^{1/2},$$

  - $N_{\mathrm{total}} = N_{\mathrm{on}} + N_{\mathrm{off}}$: total observed number of events
  - N_{on}: # of events inside the circle, N_{off}: # of events outside the circle
  - $N_{\mathrm{bg}} = \alpha \cdot N_{\mathrm{off}}$

- To determine the exposure ratio of α, we generated 10^5 events assuming an isotropic flux taking into account the geometrical exposure.
  - $\alpha = \frac{N_{\mathrm{sim,on}}}{N_{\mathrm{sim,off}}} = \frac{N_{\mathrm{sim,circle}}}{(N_{\mathrm{sim,total}} - N_{\mathrm{sim,circle}})}$
- Field of view: 90° to -10° in declination, 0° to 360° in right ascension
- Oversampling with **25°** of angular windows

Li-Ma significance map with E ≥ 57 EeV

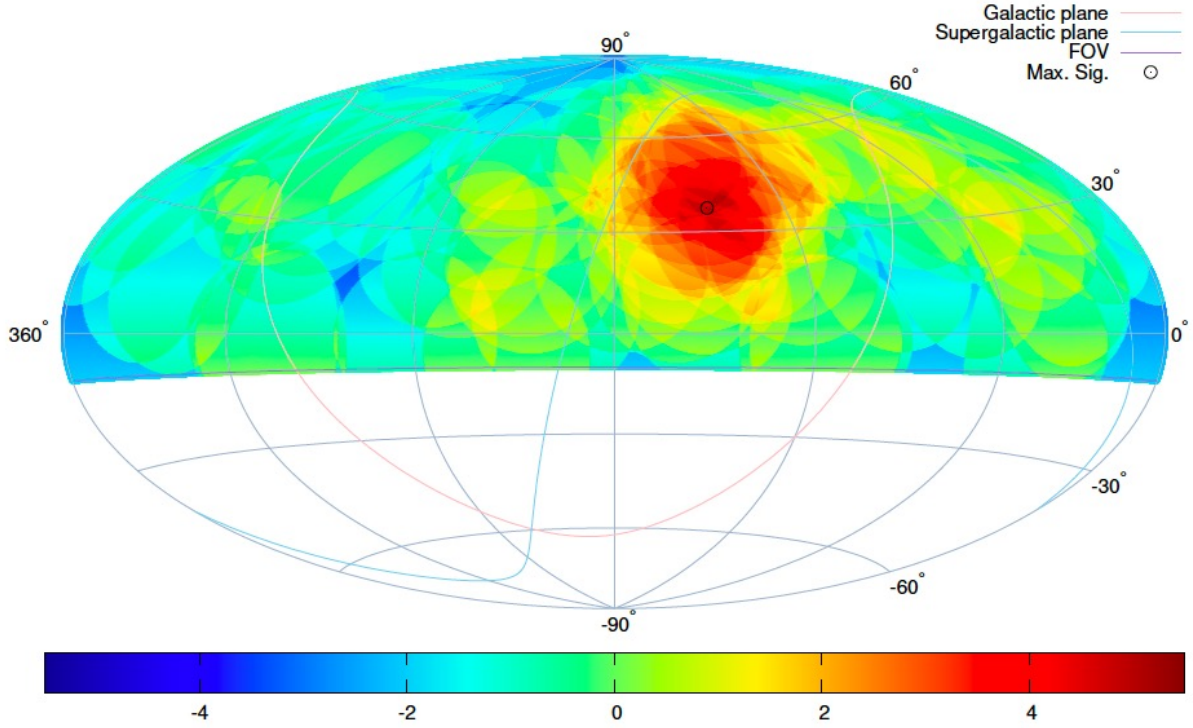
25°-radius oversampling

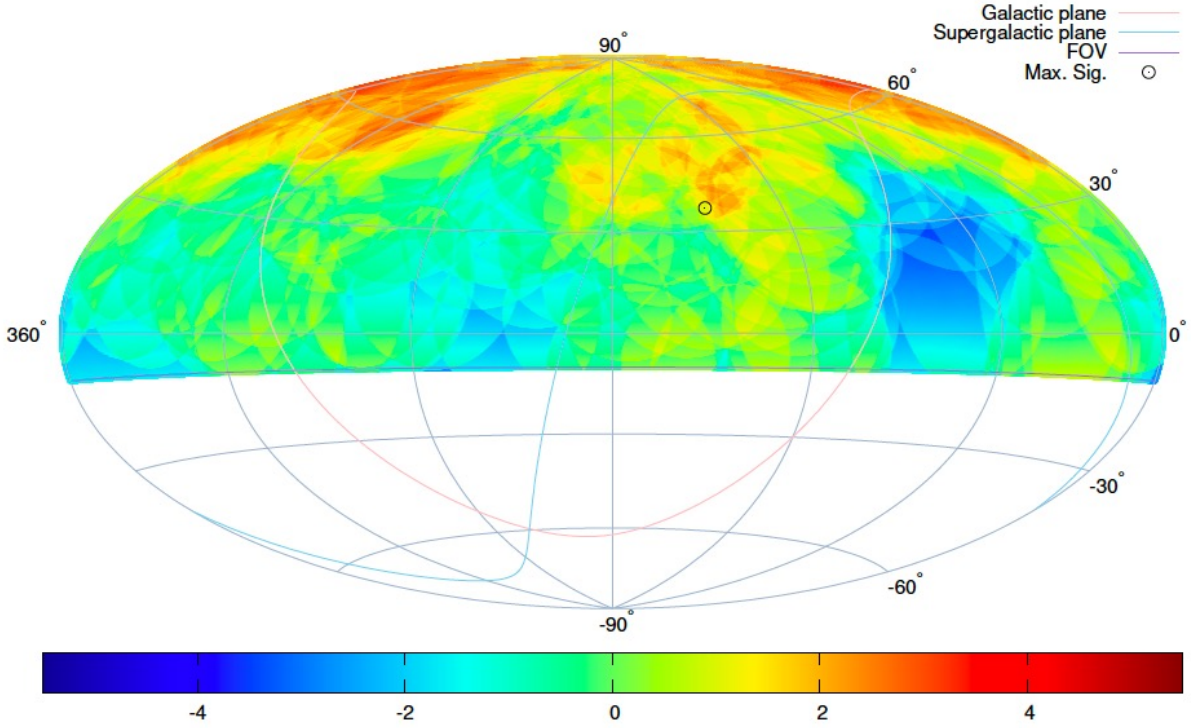


- 205 events (14-year TA SD data)
- Max local sig.: **5.1σ** at (144.0°, 40.5°)
  - Obs. : 44 events
  - Iso. : 16.9 events
  - } ~160% excess
- Post-trial probability:

$$P(S_{MC} > 5.1\sigma) = 7.4\times10^{-4} \rightarrow \mathbf{3.2\sigma}$$

Independent dataset analysis

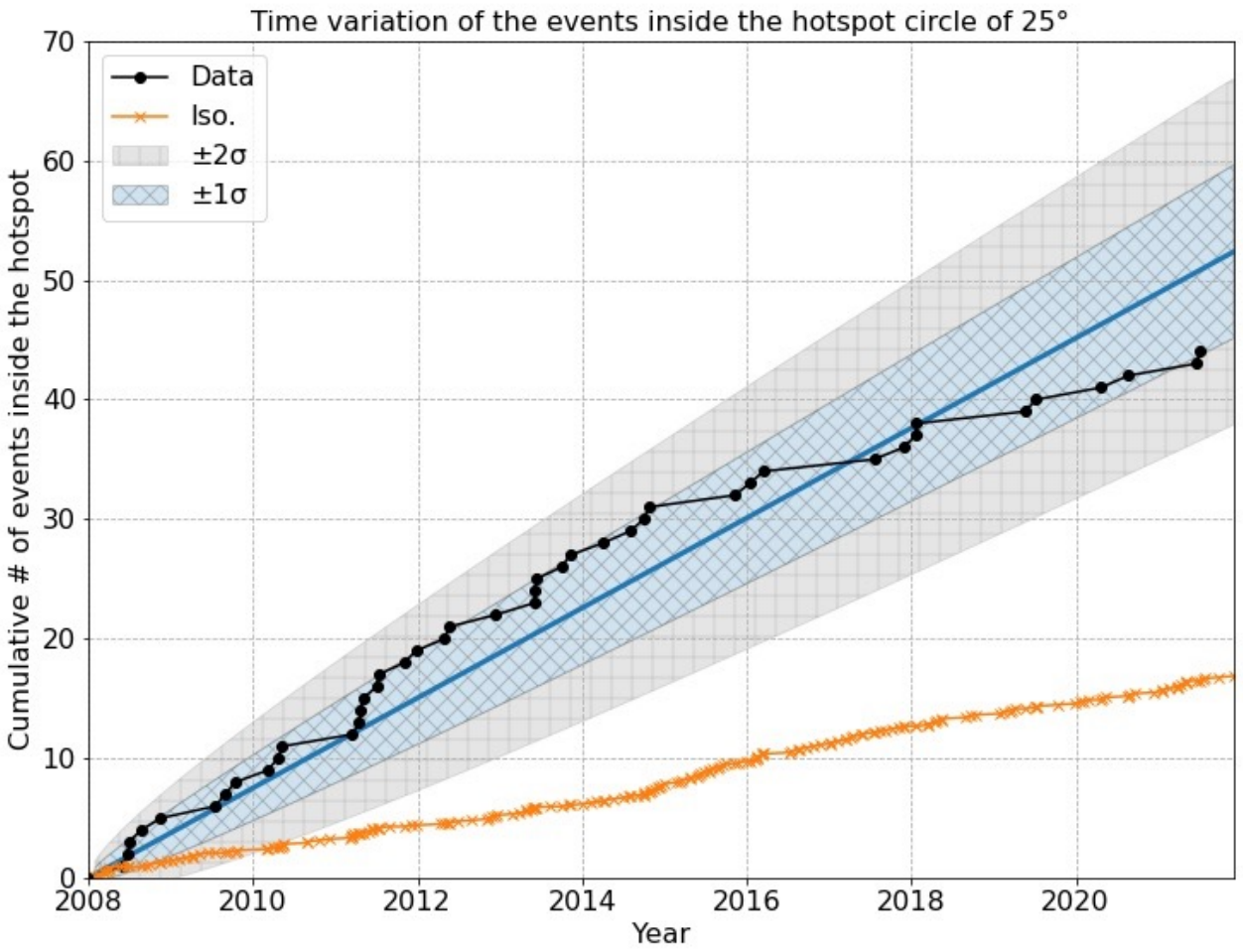




- 72 events (First 5-year)
- **5.0σ** at (144.0°, 40.5°)
  - Obs. : 22 events
  - Iso. : 5.2 events

- 133 events (Last 9-year)
- **2.5σ** at (144.0°, 40.5°)
  - Obs. : 22 events
  - Iso. : 11.6 events

Time variation of the hotspot

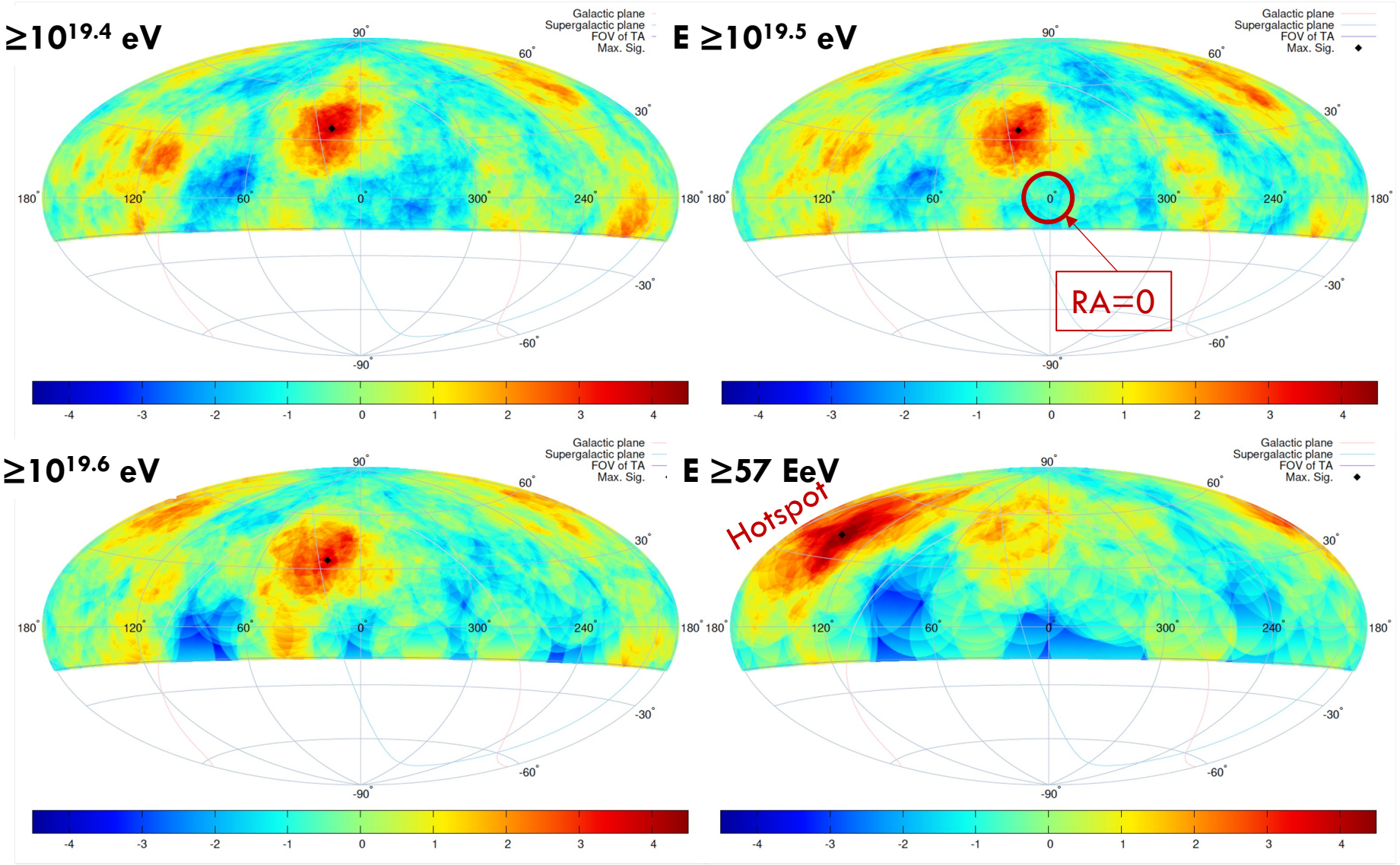


- Black dots: cumulative # of events falling inside the hotspot circle of 25°
- Orange x's: cumulative # of isotropic events inside the hotspot
- Blue solid line: estimated event rate inside the hotspot

The increase rate of the events inside the hotspot circle is **consistent with the linear increase within ~1σ.**

New excess in the direction of the Perseus-Pisces supercluster

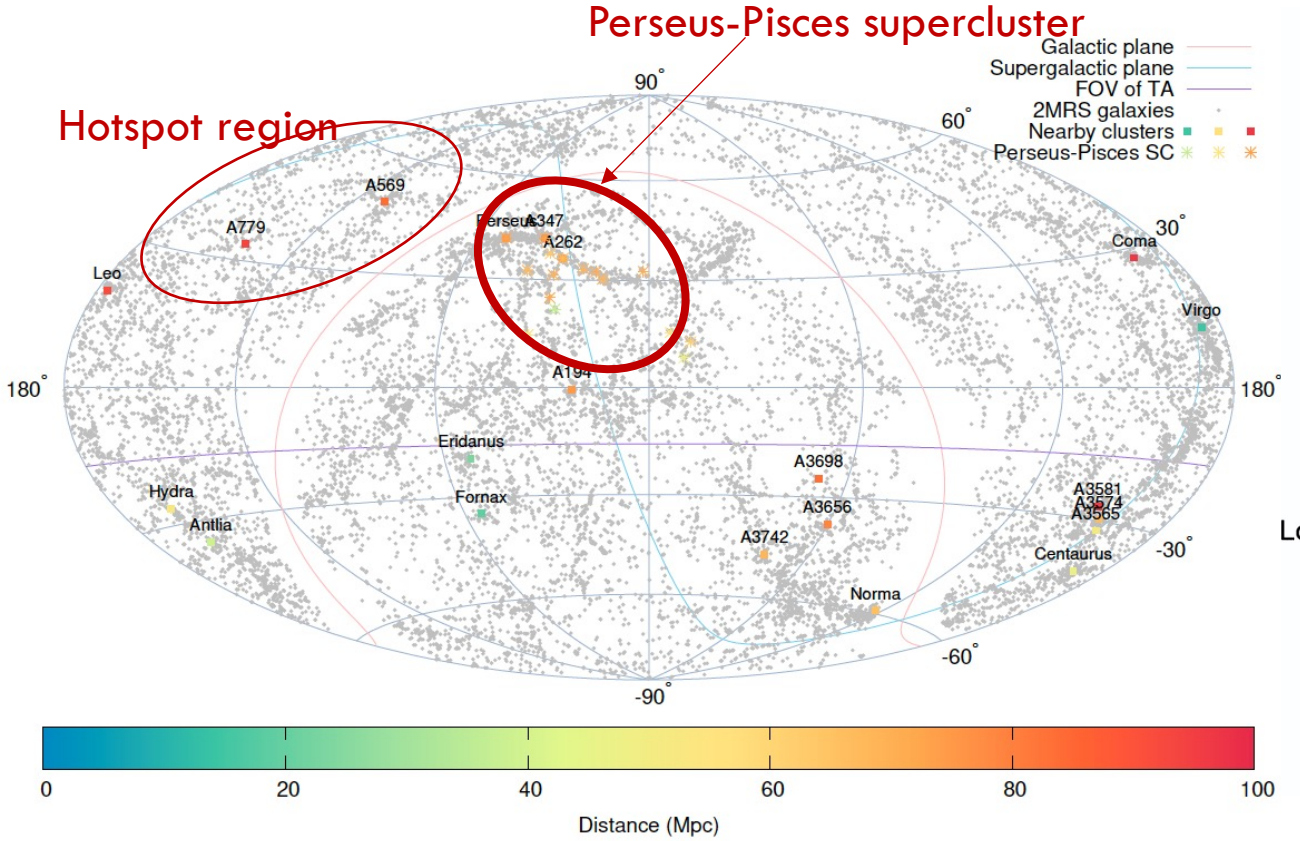
New excess in slightly lower energy events JK+, ICRC2021



- Li-Ma significance map: excess (red) / deficit (blue) of events compared to isotropy
- Black diamond (◆): the maximum Li-Ma significance position
- Equatorial coords. having RA=0 at center

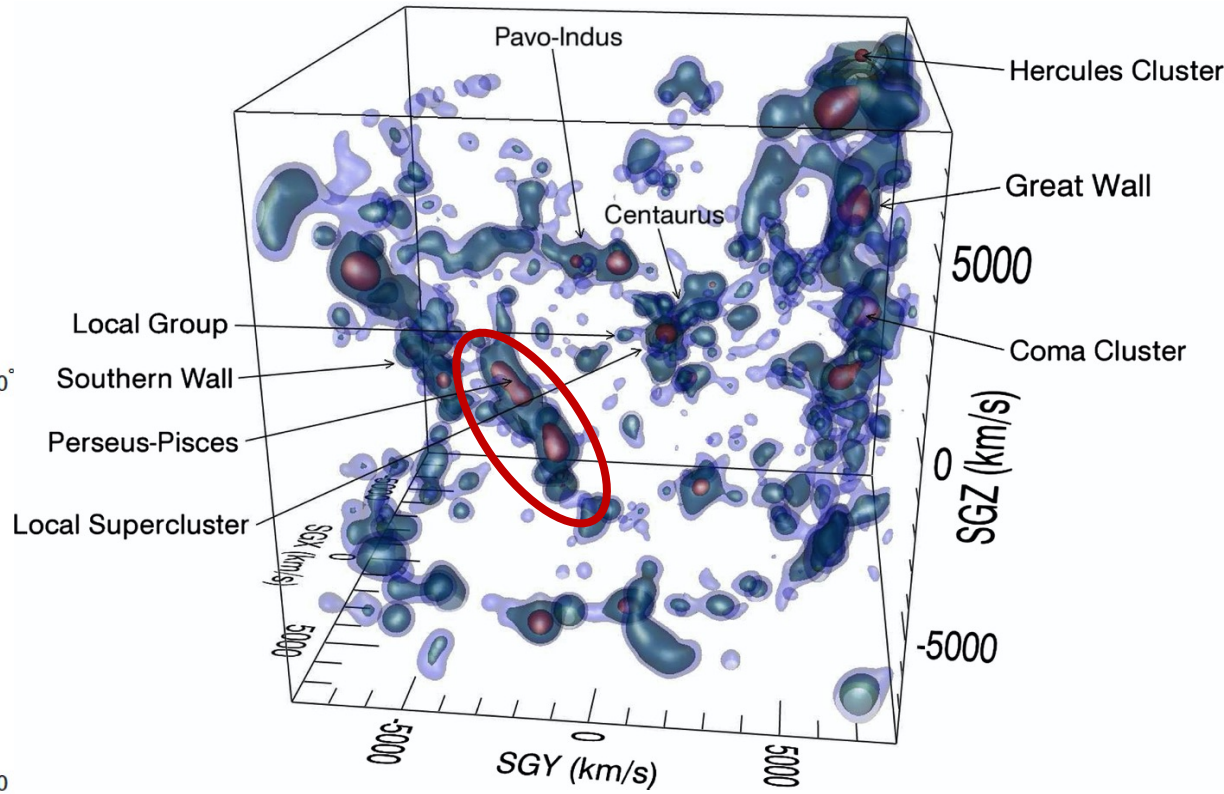
What is behind the new excess?

Sky map with nearby galaxies and clusters of galaxies



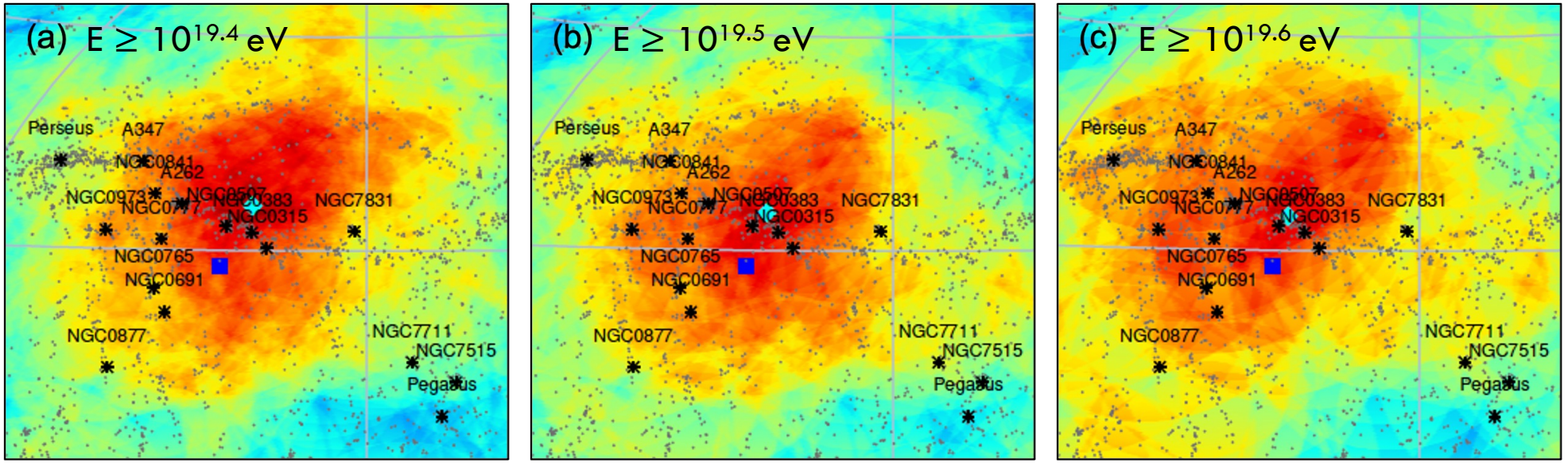
Equatorial coordinates

3-dimensional density maps



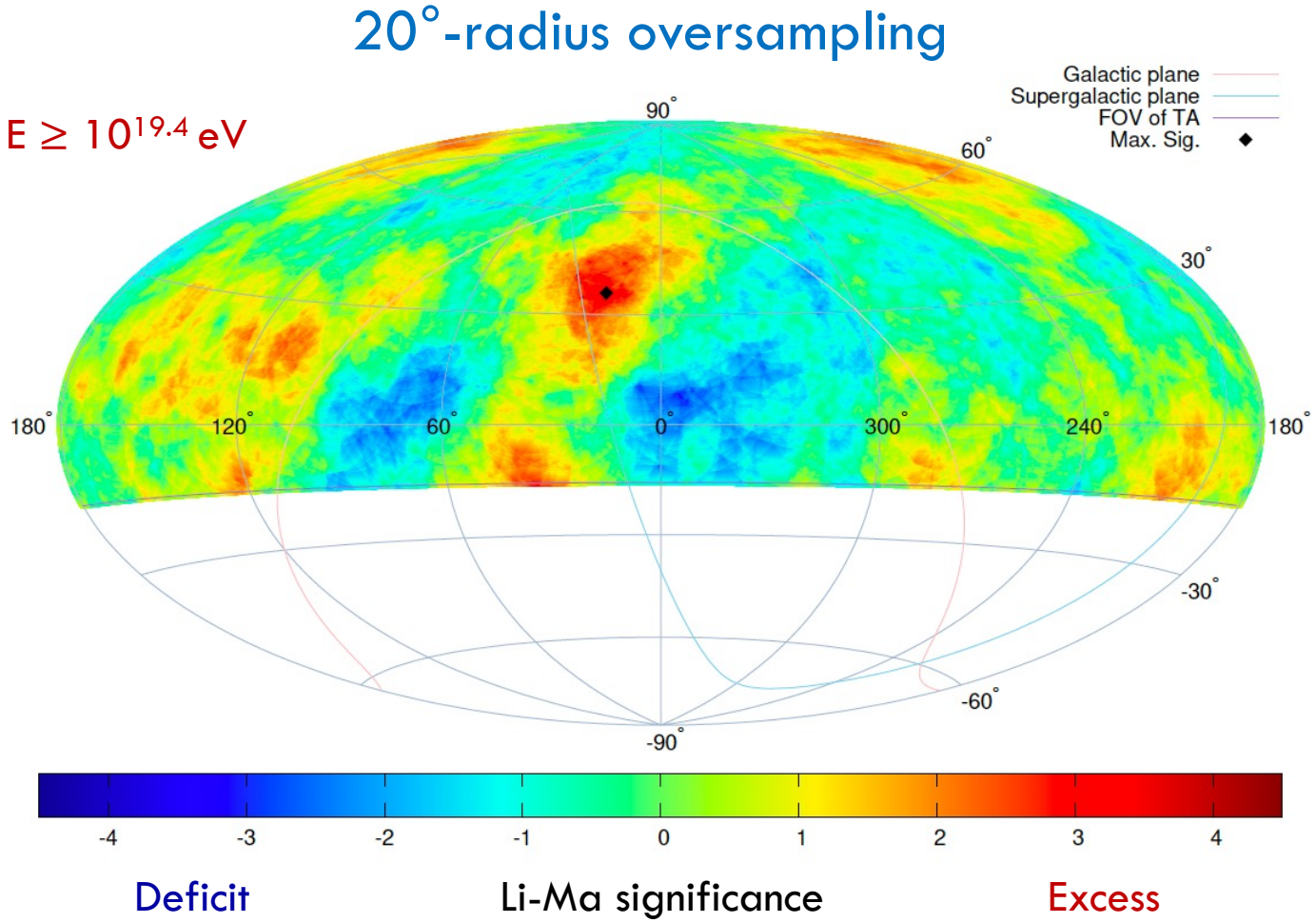
Courtois et al. (2013). AJ **146**(3).

New excess with the Perseus-Pisces supercluster (PPSC)



- Black asterisks (*): the representative elements of the PPSC; Gray dots (·): Galaxies from the 2MASS Redshift Survey catalog (35–100 Mpc); Cyan diamonds (◆): the positions of maximum excesses; Blue squares (■): the center of the PPSC.
- It is seen that the excess is coincident with the overall distribution of the PPSC. The angular separations between the positions of the maximum excesses and the center of the PPSC are less than ~10°.

Li-Ma analysis with 20° oversampling with $E \geq 10^{19.4}$ eV

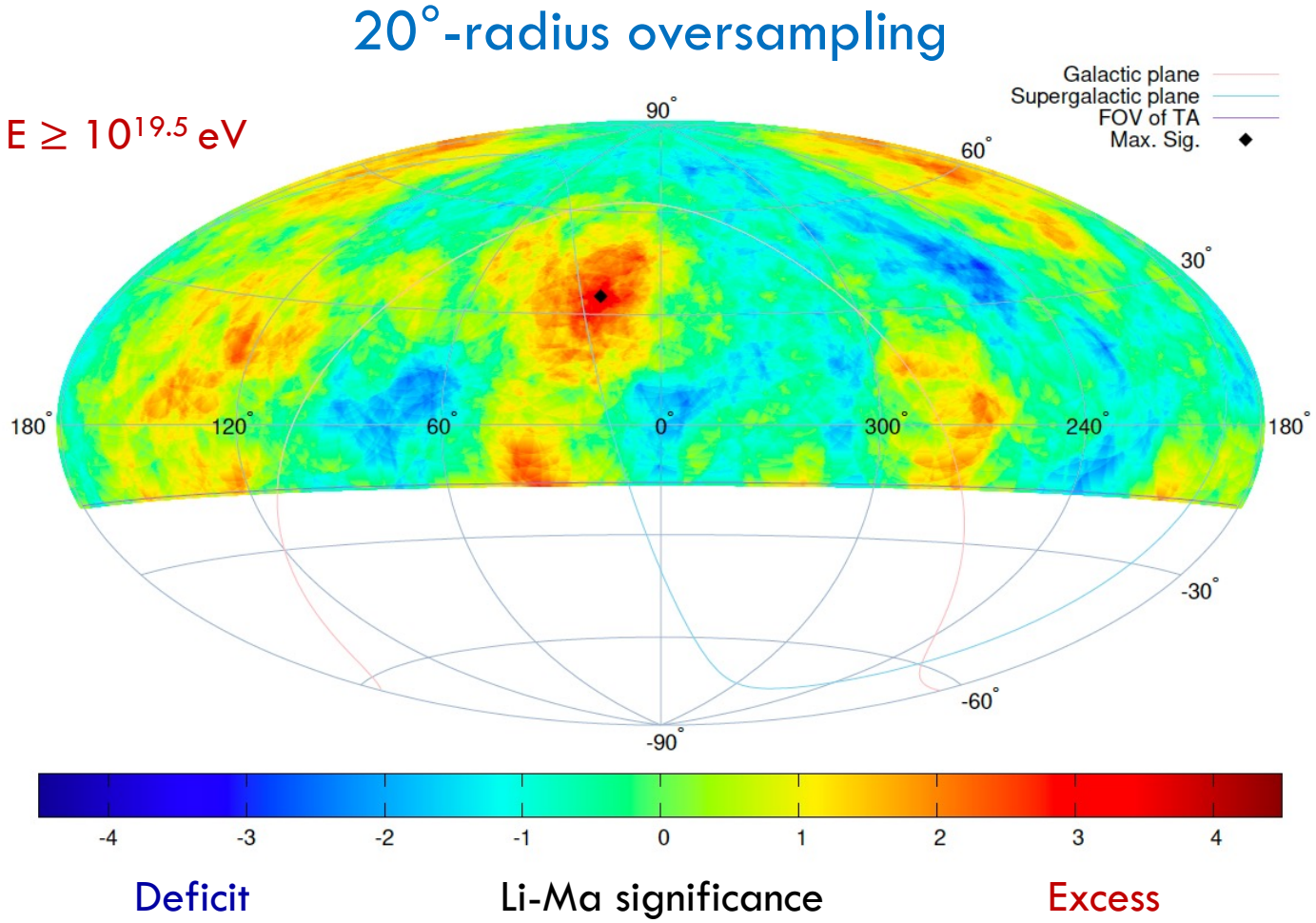


- 1060 events (14-year TA SD data)

- Li-Ma sig.: 3.8σ at (17.4°, 36.0°)

  Obs. : 95 events
  Iso. : 61.4 events
  } ~55% excess

Li-Ma analysis with 20° oversampling with $E \geq 10^{19.5}$ eV



- 685 events (14-year TA SD data)

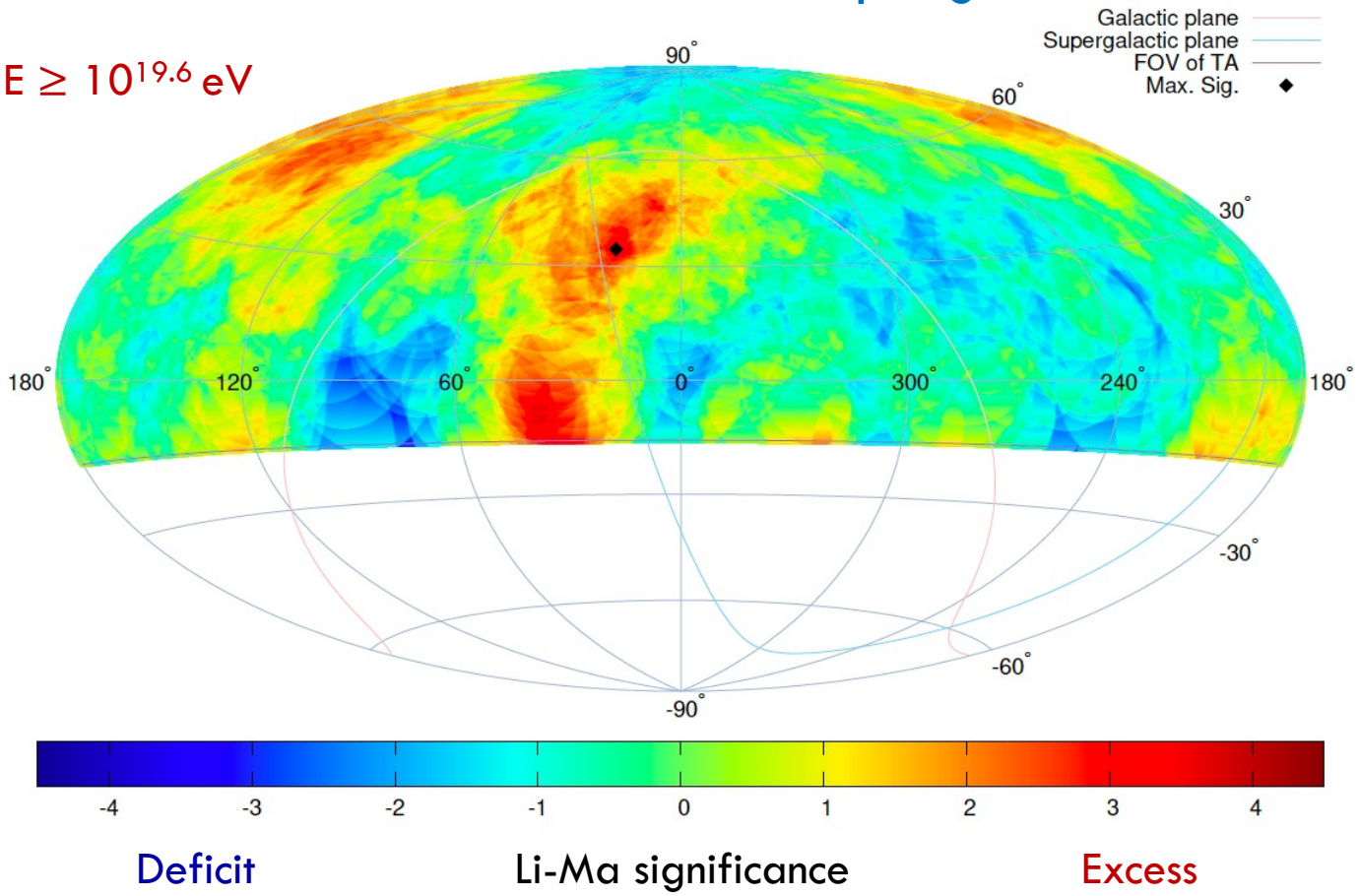
- Li-Ma sig.: 3.8σ at (19.0°, 35.1°)

  Obs. : 66 events
  Iso. : 39.1 events
  } ~69% excess

Li-Ma analysis with 20° oversampling with $E \geq 10^{19.6}$ eV

20°-radius oversampling

$E \geq 10^{19.6}$ eV

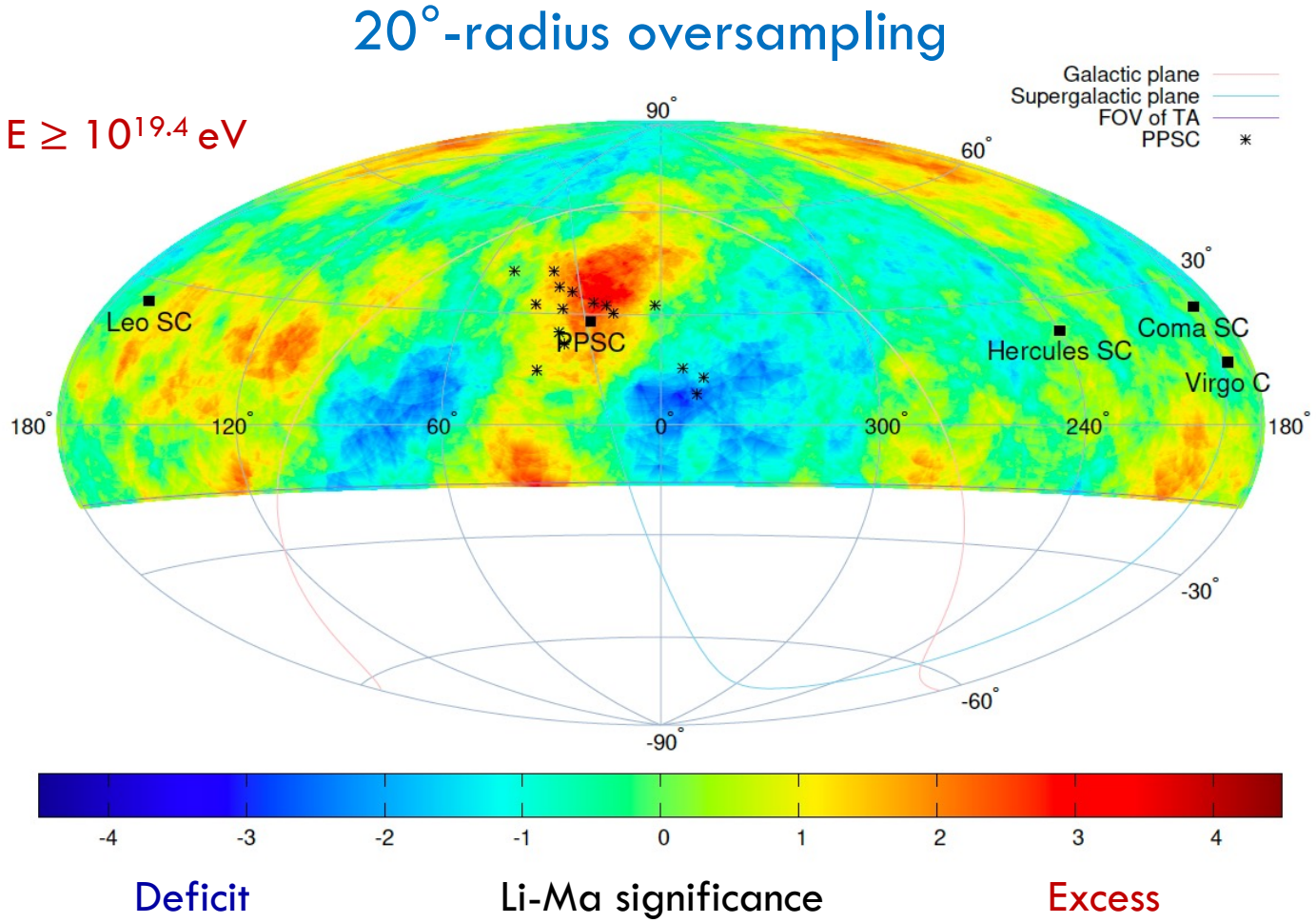


- 413 events (14-year TA SD data)

- Li-Ma sig.: 3.5σ at (19.7°, 34.6°)

  Obs. : 43 events
  Iso. : 23.2 events
  } ~85% excess

Compare new excess with the PPSC and other major structures



- Choose all the similar major structures to the Perseus-Pisces supercluster in TA's field of view within 150 Mpc.

- Virgo cluster (17 Mpc)
  PPSC (70 Mpc),
  Coma supercluster (90 Mpc)
  Leo supercluster (135 Mpc)
  Hercules supercluster (135 Mpc)

Chance probability estimation

- To quantify how often this happens by chance, we generate many Monte-Carlo event sets, each containing the same number of events as the data, thrown isotropically according to the acceptance of the TA SD.
- 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 equal or higher excess on top of the PPSC / major structures {PPSC, Virgo cluster, Coma SC, Leo SC, Hercules SC}

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

Energy (eV)	Events	Criteria	PPSC	Major structures
$E \geq 10^{19.4}$	1060	$(S_{mc} \geq 3.8\sigma)$ & $(\theta_{mc} \leq 8.6^\circ)$	3.1σ	2.5σ
$E \geq 10^{19.5}$	685	$(S_{mc} \geq 3.8\sigma)$ & $(\theta_{mc} \leq 7.4^\circ)$	3.2σ	2.6σ
$E \geq 10^{19.6}$	413	$(S_{mc} \geq 3.5\sigma)$ & $(\theta_{mc} \leq 6.8^\circ)$	3.0σ	2.4σ

- **This result indicates that a cosmic ray source may exist in the direction of PPSC.**

Summary

- Intermediate-scale anisotropy studies have been conducted using 14 years of TA SD data.
- We have persistent evidence for **the hotspot** at the highest energies, $E \geq 5.7\times10^{19}$ eV, near the Ursa Major group. The global significance of such excess appearing by chance anywhere in TA's field of view is estimated to be **3.2σ**.
- A new excess in slightly lower energy events, $E \geq 10^{19.4}$ eV, in the direction of **the Perseus-Pisces supercluster** has been identified. The local significance of excess is now estimated to be **3.8σ**. The chance probability of having an excess as close to the PPSC as the data is estimated to be **3.2σ**.