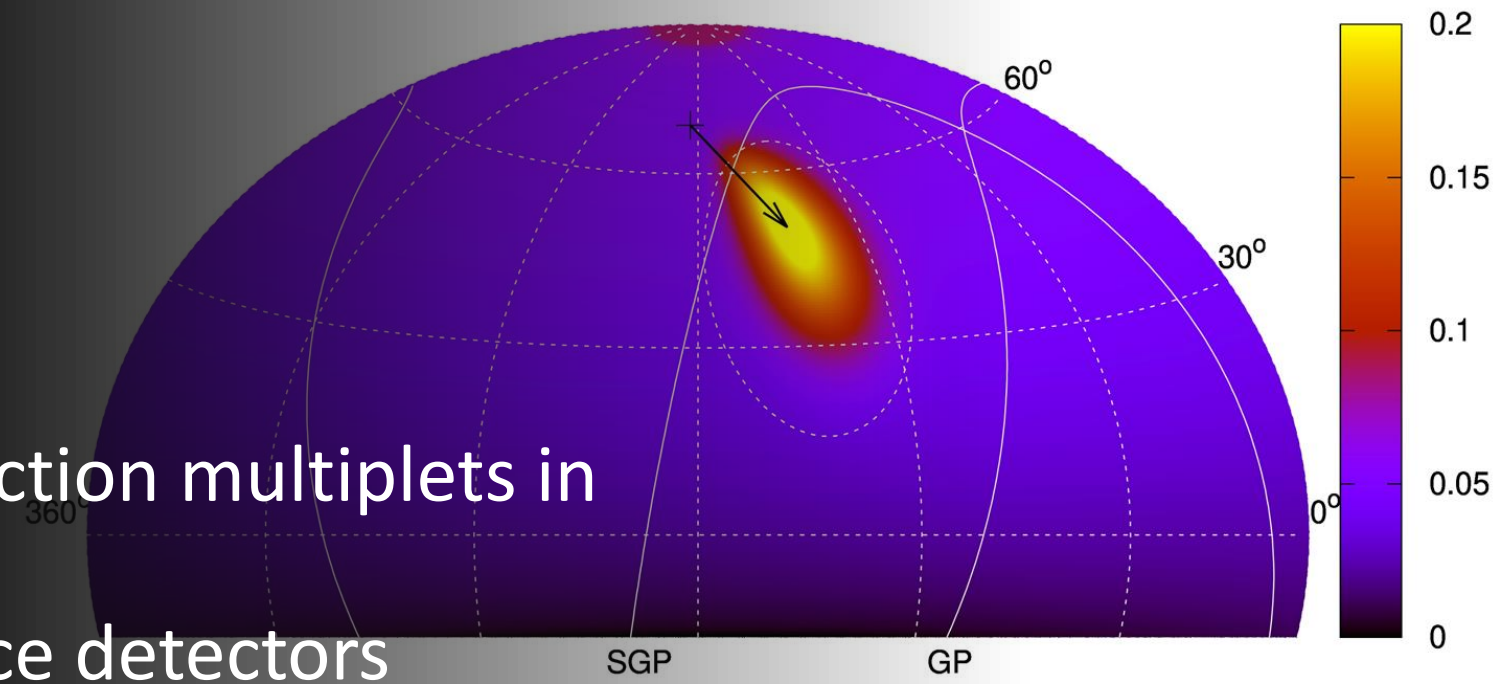

Search for magnetic deflection multiplets in the observed data by the Telescope Array surface detectors

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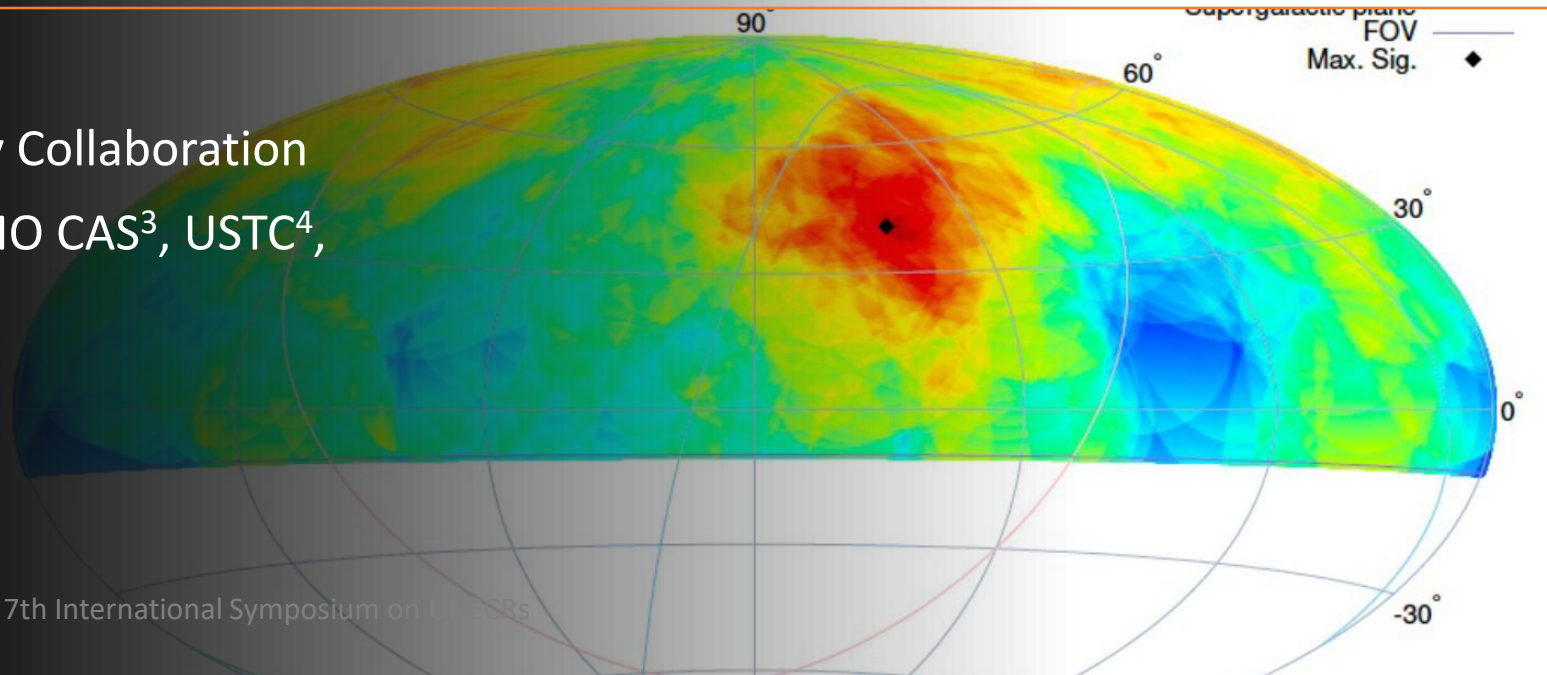
ICRR Univ. of Tokyo[1], ABBL RIKEN[2], PMO CAS[3], USTC[4],
iTHEMS RIKEN[5], OIST[6]

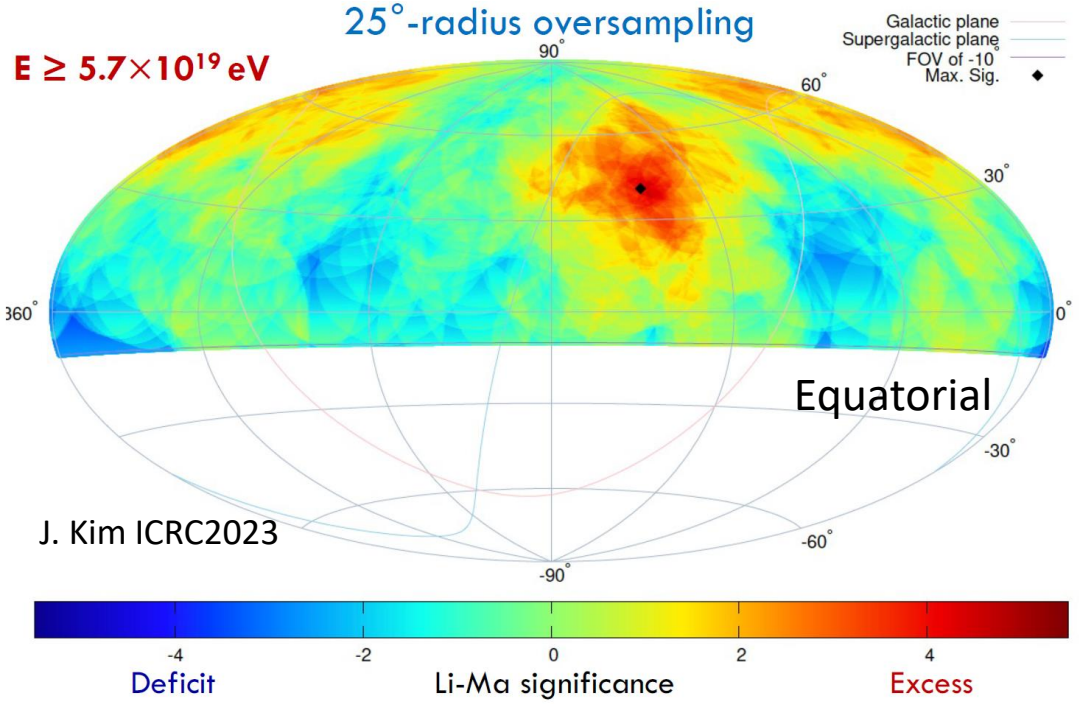


Outline

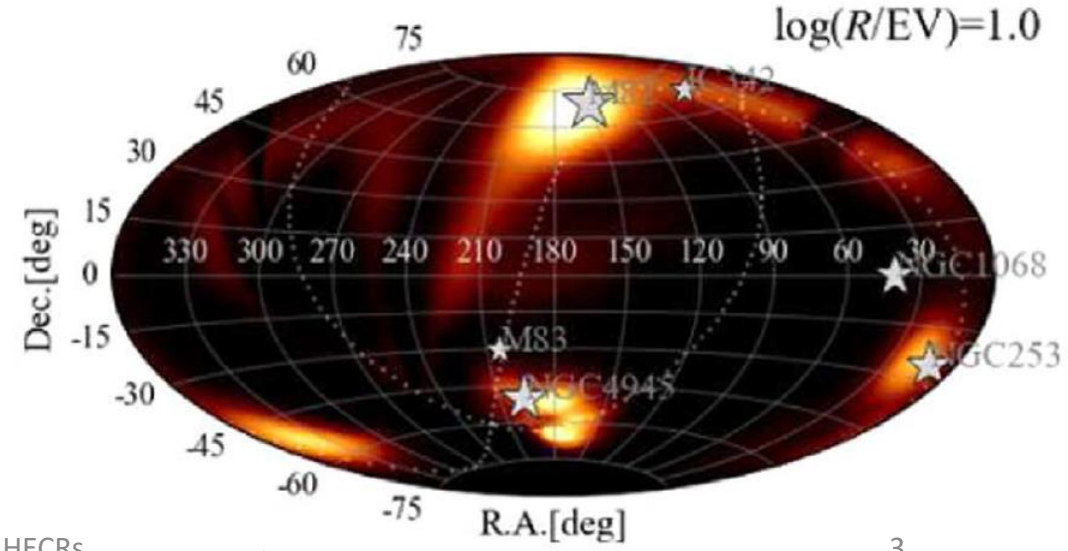
- Motivation
- Method
- Results
- Interpretation
- Conclusions

Motivation

- Evidence of anisotropy in the arrival directions is showing up at above several tens of EeV.
- Correlation studies of arrival directions with astrophysical objects considering **random** and **regular** magnetic field models were conducted to search for UHECR sources.
  (e.g. correlation analysis with nearby starburst galaxies (SBG), active galactic nuclei, etc.)
- There is considerable ambiguity in magnetic deflections of UHECRs in galactic and extragalactic magnetic field models.



Flux map of SBGs (w/ JF12 regular GMF model)



R. Higuchi+ 2023

Equatorial

Energy-dependent structure, magnetic deflection ``multiplet''

- Magnetic deflection ``**multiplet**'':
- Deflection angle (δ_{reg} and δ_{rms}) from the source direction $\propto$ **1/E**

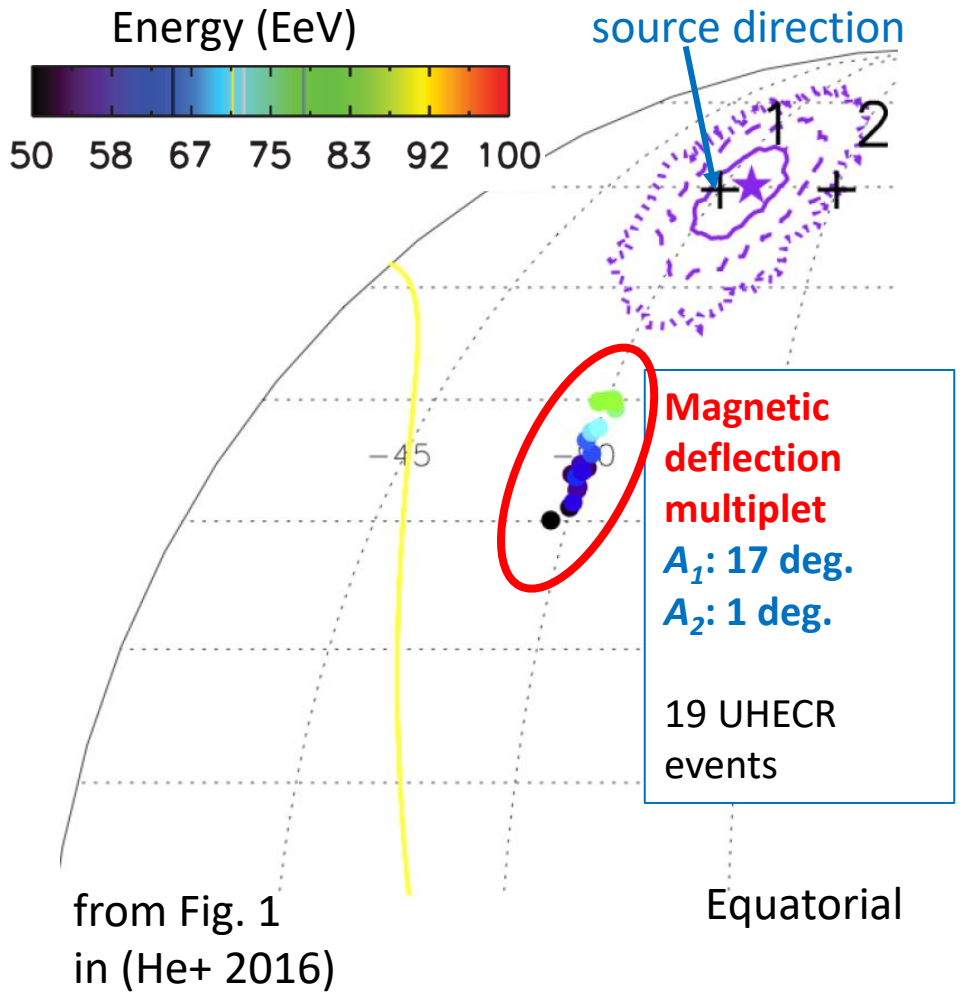
  (single nuclear charge is assumed)
  - regular component

$$\delta_{\mathrm{reg}} = A_1 \times \frac{100\ \mathrm{EeV}}{E}$$

  - random component

$$\delta_{\mathrm{rms}} = A_2 \times \frac{100\ \mathrm{EeV}}{E}$$

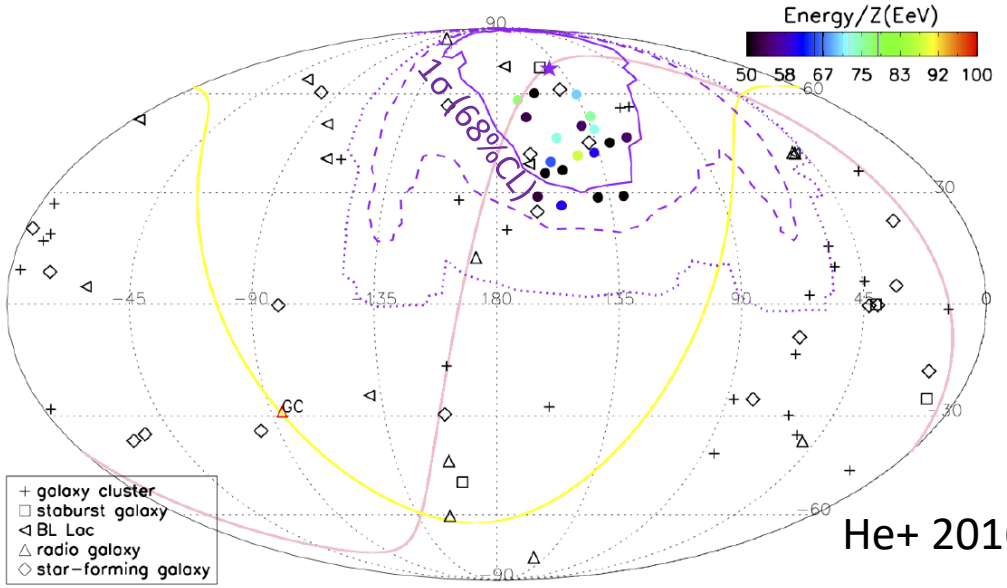
Search for the magnetic deflection multiplet
→ a **phenomenological way** to consider
both **random** and **regular** magnetic deflections



from Fig. 1
in (He+ 2016)

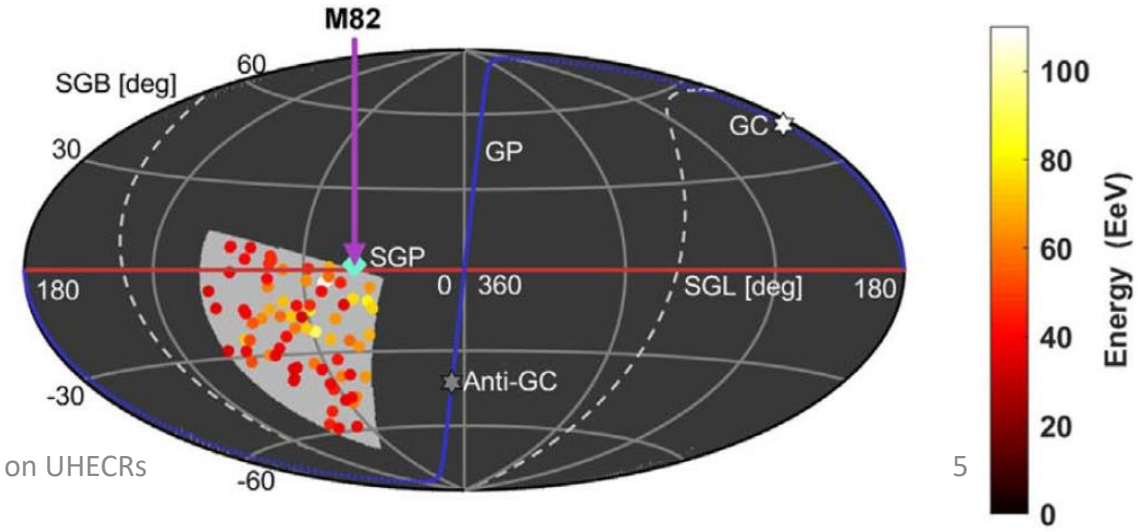
Search for a magnetic deflection multiplet

- We developed a likelihood analysis to search for the magnetic deflection multiplet based on He+2016.
- We implemented exposure, resolutions, isotropic background, and other details for the application to the experimental data.



He+ 2016

The TA Collaboration 2020



Likelihood analysis to search for a magnetic deflection multiplet (1/2)

Event selection (same as the TA hotspot analysis):

- E > **57 EeV**
- Zenith angle < 55 deg.
- No. of SDs > 4 used for the event reconstruction
- Angular uncertainty of the geometry fit < 10 deg.
- > 0.2 secs from nearby lightening strikes

Data: **217** SD events (**15** years TA SD data)

Likelihood of i-th UHECR event:

$$L_i = \frac{f_i \omega_i}{\int_{4\pi} f \omega d\Omega} \qquad f_i = g_{\rm iso} f_{\rm iso} + (1 - g_{\rm iso}) f_{{\rm src},i}$$

magnetic deflection multiplet from a single source

f: probability distribution of an event / solid angle
ω: geometrical exposure of the TA SD
g_{iso}: fraction of isotropy background

→ maximize likelihood $L = \prod_{i=1}^{N_{\rm tot}} L_i$

→ **search for 6 free parameters** (next slide) of ***L***

Likelihood analysis to search for a magnetic deflection multiplet (2/2)

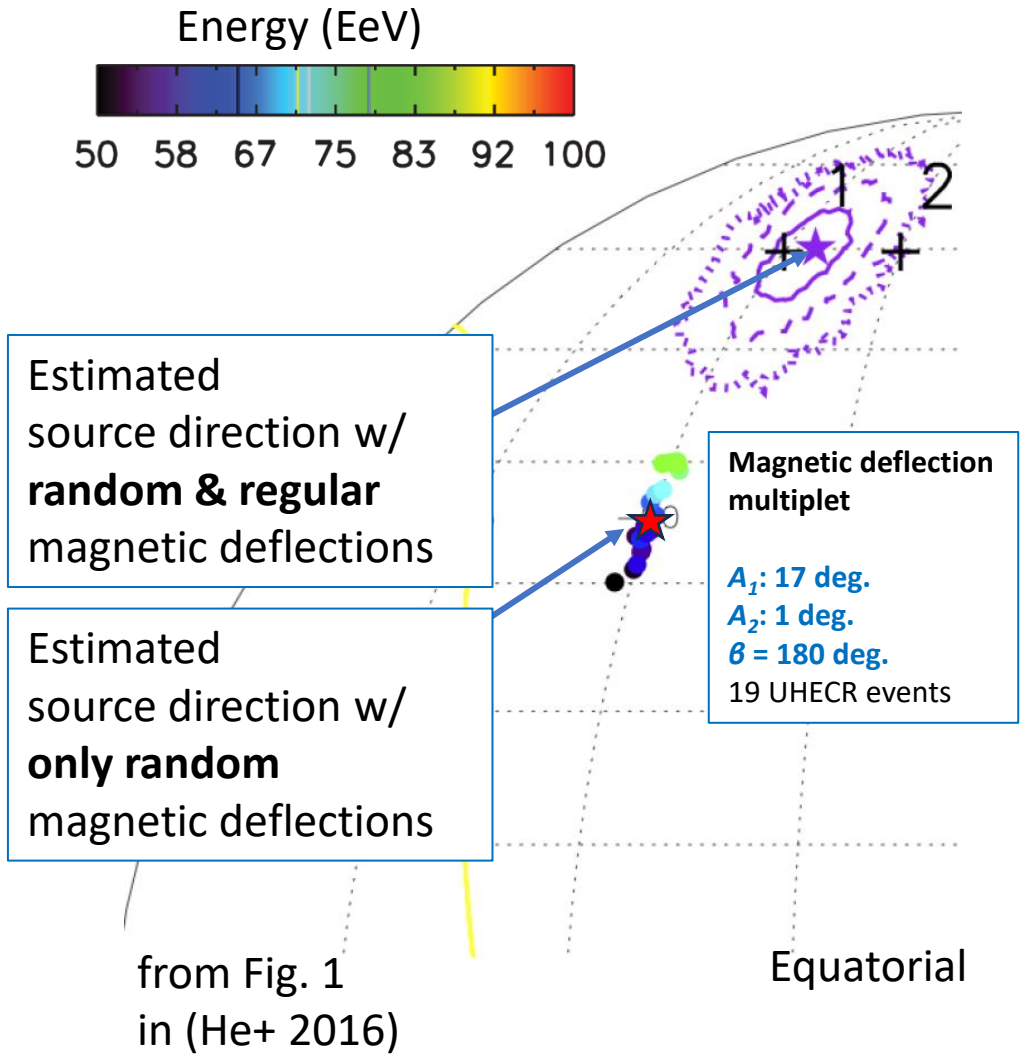
- 6 free parameters of L (β, A_1, A_2, α, δ, g_{iso})
  - β: direction of the regular deflection (north pole: 0°)
  - A_1: regular deflection at 100 EeV (degrees)
  - A_2: Gaussian σ at 100 EeV (degrees)
  - α and δ: right ascension and declination of the source
  - g_{iso}: fraction of isotropy background
- Deflection angle (δ_{reg} and δ_{rms}) from the source direction ∝ **1/E**

  (single nuclear composition is assumed)
  - regular component

$$\delta_{\mathrm{reg}} = A_1 \times \frac{100\ \mathrm{EeV}}{E}$$

  - random component

$$\delta_{\mathrm{rms}} = A_2 \times \frac{100\ \mathrm{EeV}}{E}$$

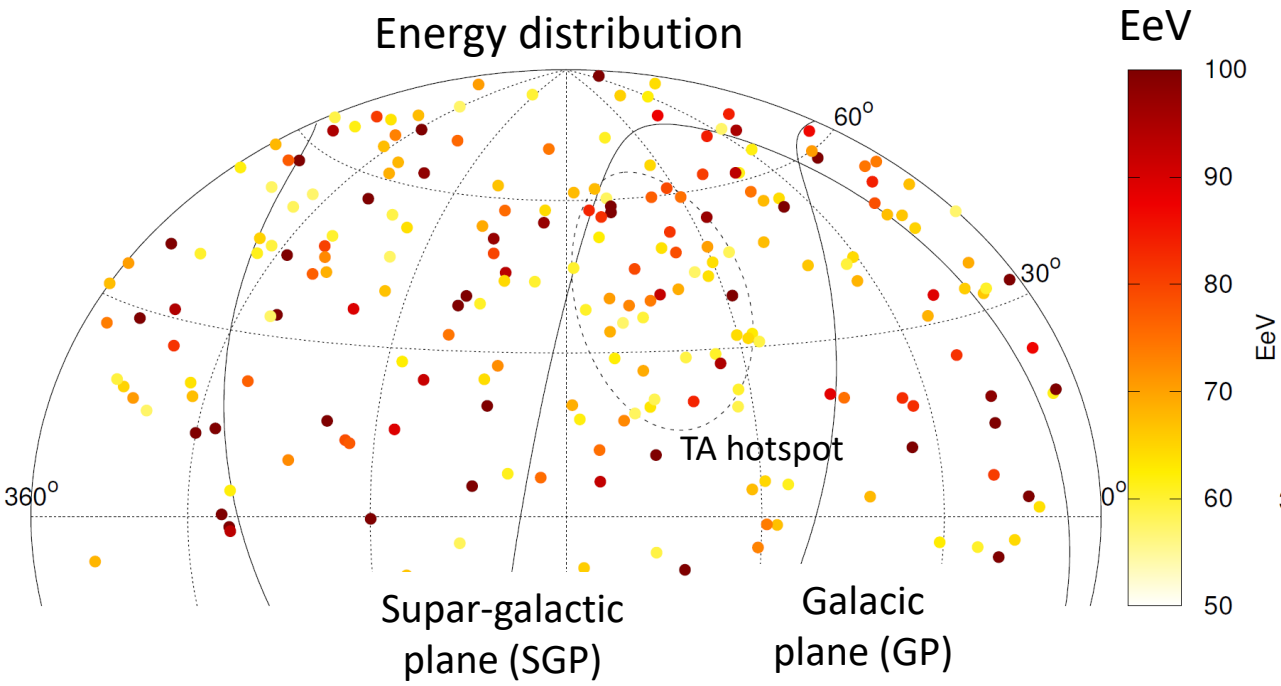


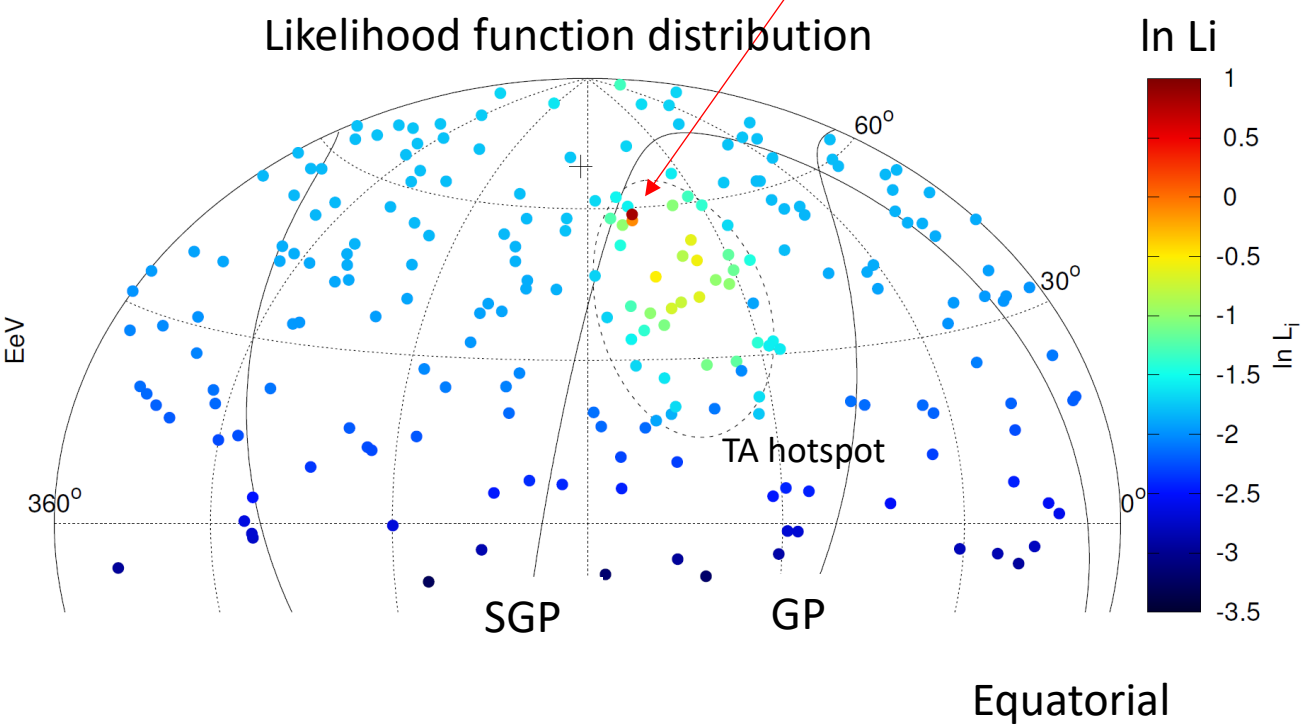
from Fig. 1 in (He+ 2016)

Energies and likelihood functions

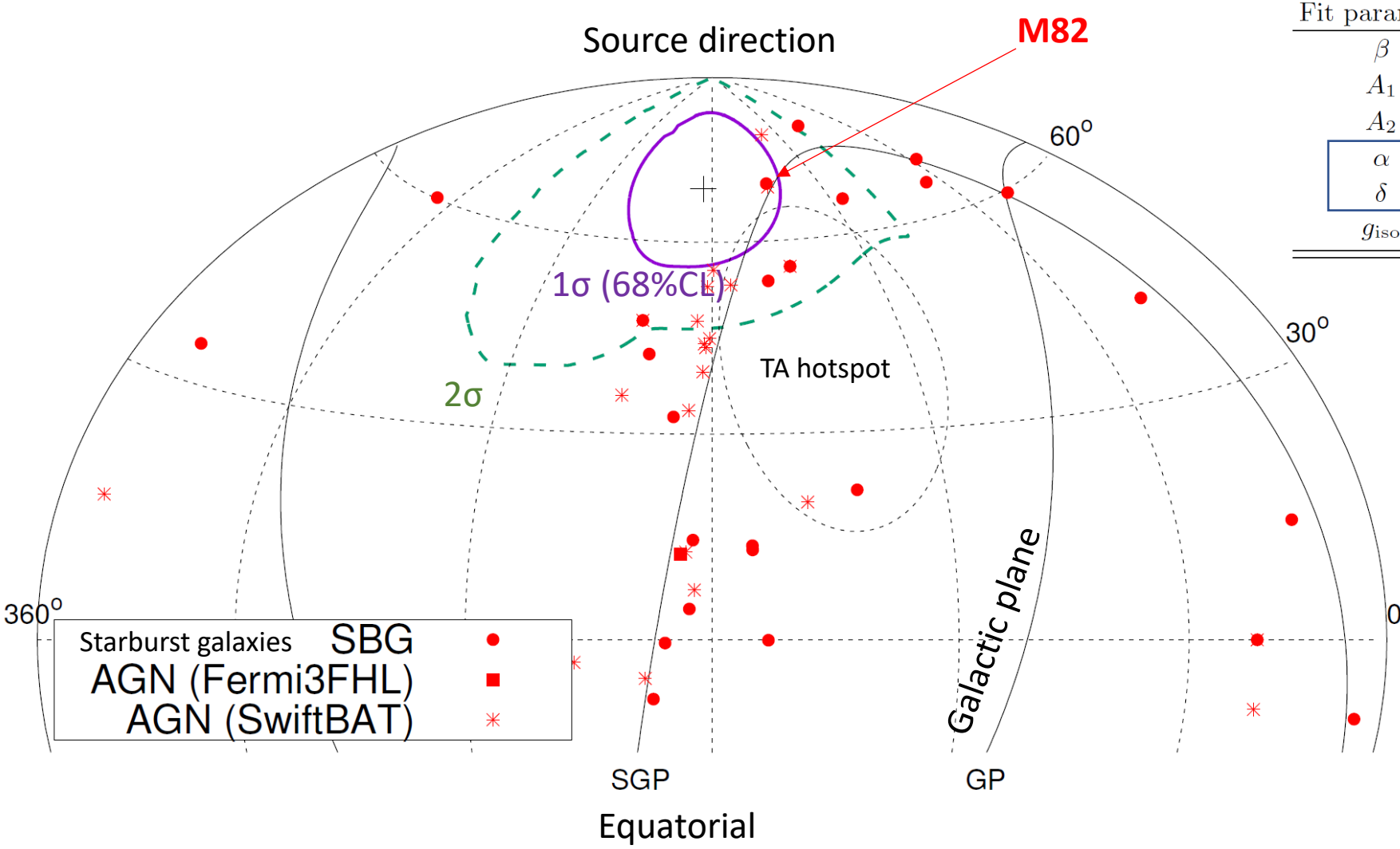
217 SD events E > 57 EeV

Max. likelihood function: **171 EeV**
2nd max. likelihood function:**107 EeV**





Fit parameters



6 parameters

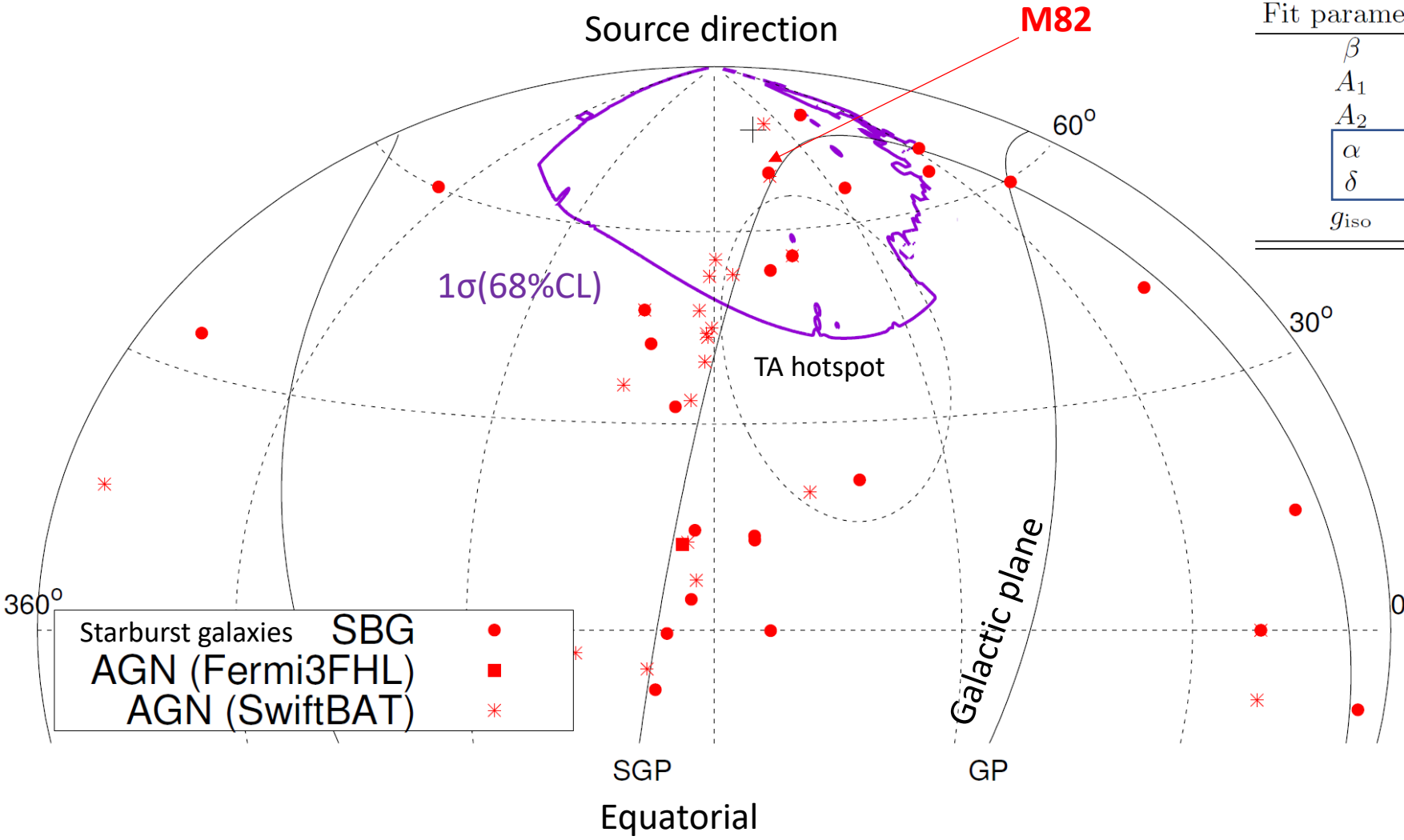
Fit parameter	Best-fit value
β	$116°.4^{+47°.3}_{-34°.4}$
A_1	$23°.5^{+7°.7}_{-8°.0}$
A_2	$6°.2^{+2°.2}_{-5°.0}$
α	$184°.8^{+25°.1}_{-27°.8}$
δ	$69°.1^{+8°.8}_{-8°.6}$
$g_{\rm iso}$	$0.952^{+0.016}_{-0.018}$

Source direction (+ point)
35.7 degrees away from the hotspot

Red points: astrophysical objects within 30 Mpc
(E = 171 EeV protons and irons can arrive on the earth.)

M82 (starburst galaxy, 3.4 Mpc) is within 1σ confidence region.

Results of TA SD 5 years data for comparison



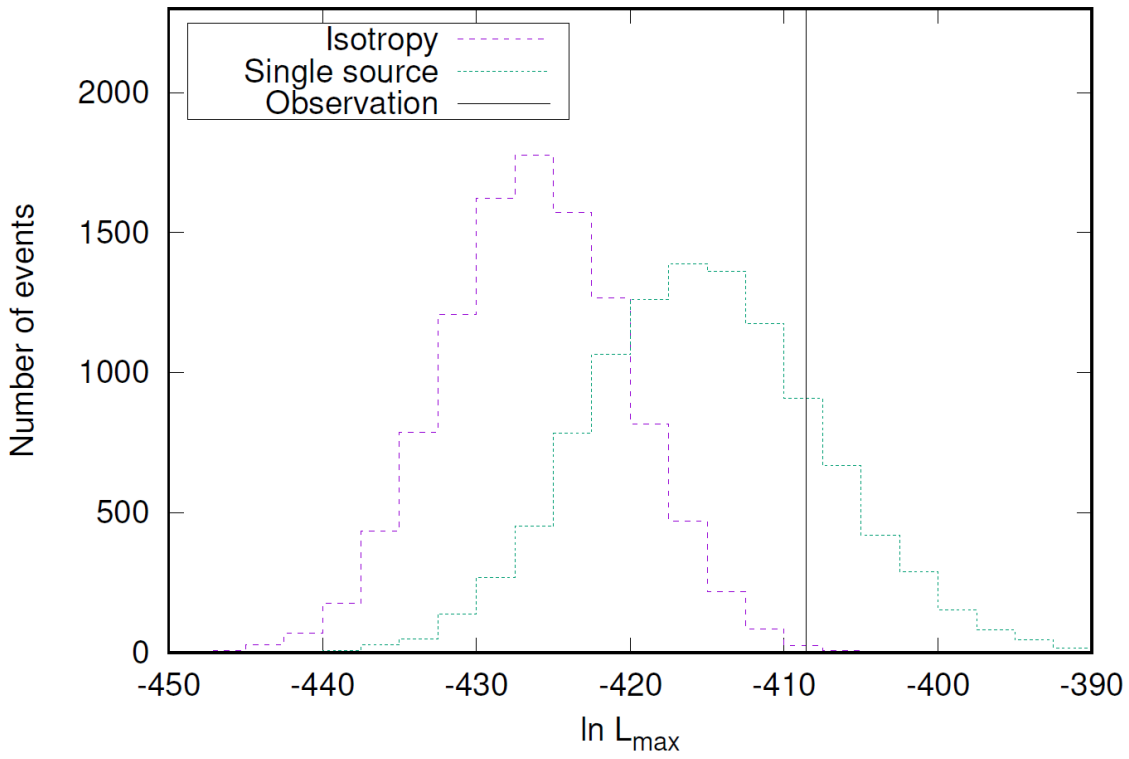
6 parameters

Fit parameter	Best-fit value
β	$176°.9 \pm 125°.6$
A_1	$23°.9 \pm 15°.2$
A_2	$7°.0 \pm 1°.1$
α	$146°.4 \pm 100°.8$
δ	$77°.4 \pm 21°.2$
$g_{\rm iso}$	0.880 ± 0.037

Source direction (+ point)

Red points: astrophysical objects within 30 Mpc
(E = 171 EeV protons and irons can arrive on the earth.)

Statistical significance of L_{max}



- Isotropy (20,000 sets, 1 set: 217 events) mock events
- Parameter search of each mock event set

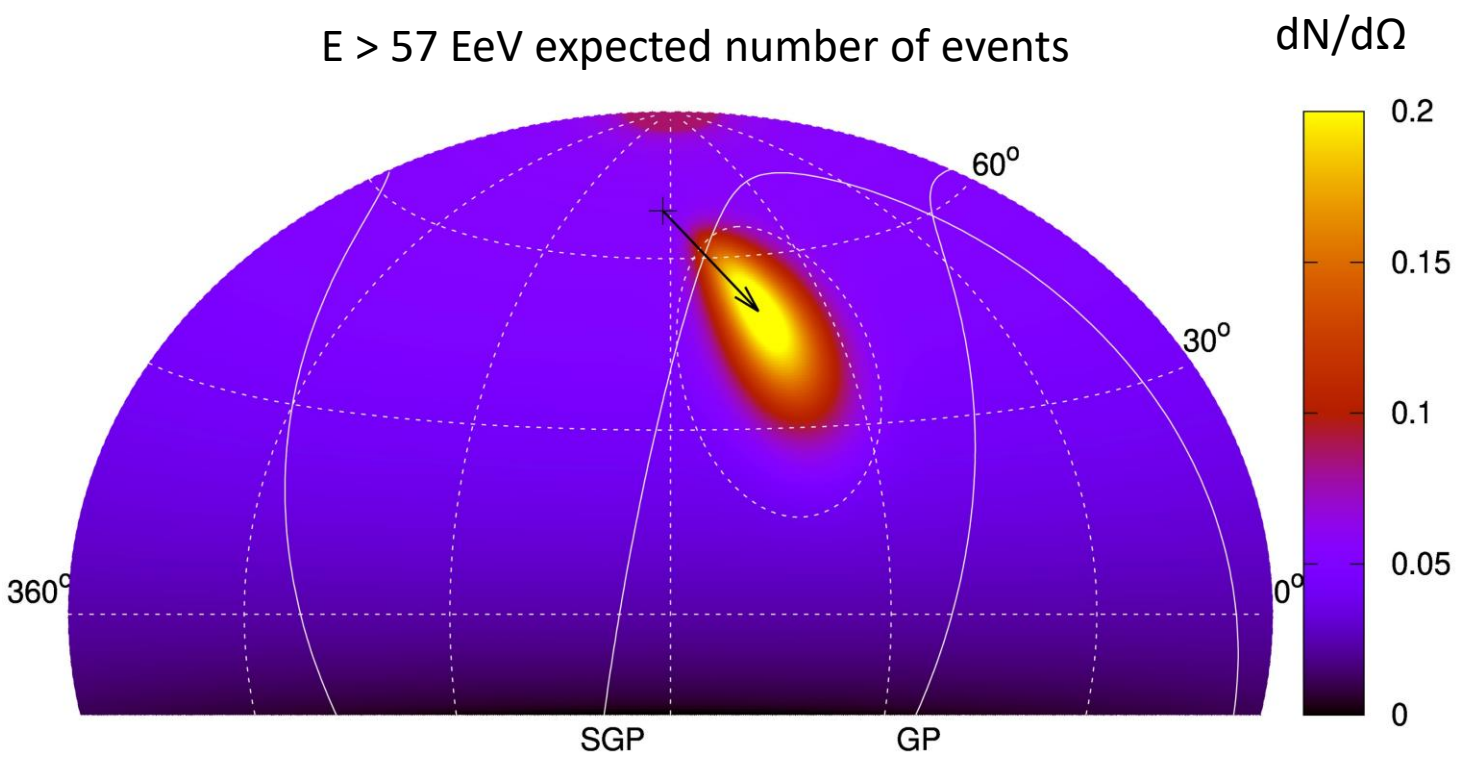
  →L_{max} of 30/20,000 mock sets exceed observed L_{max}.

  →Statistical significance (global): 3.0σ
- Removed 2 parameters (A_1, β) related to the regular deflections: 2.6σ (4 parameters fit)

  → 2 parameters increase ln L_{max} by ∼3, and increase stat. significance by 0.4σ.

Single source + isotropy model with best-fit parameters

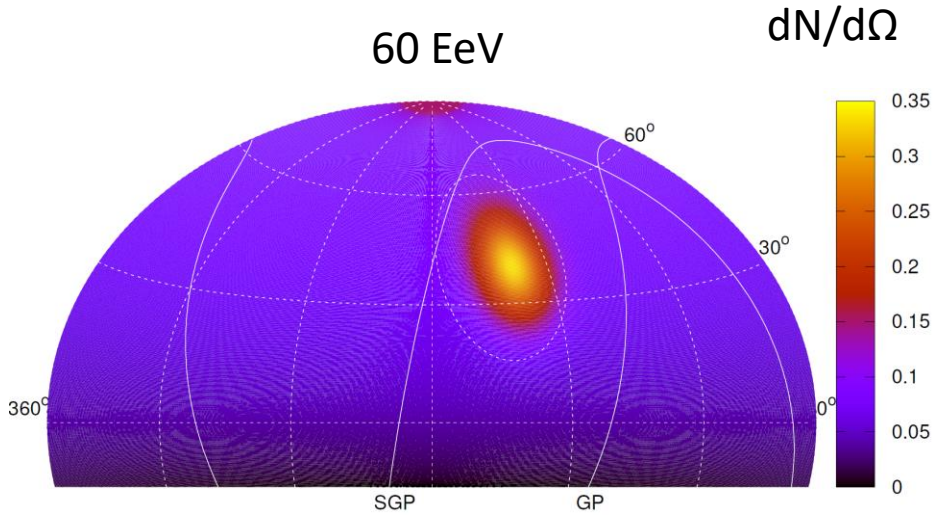
E > 57 EeV expected number of events



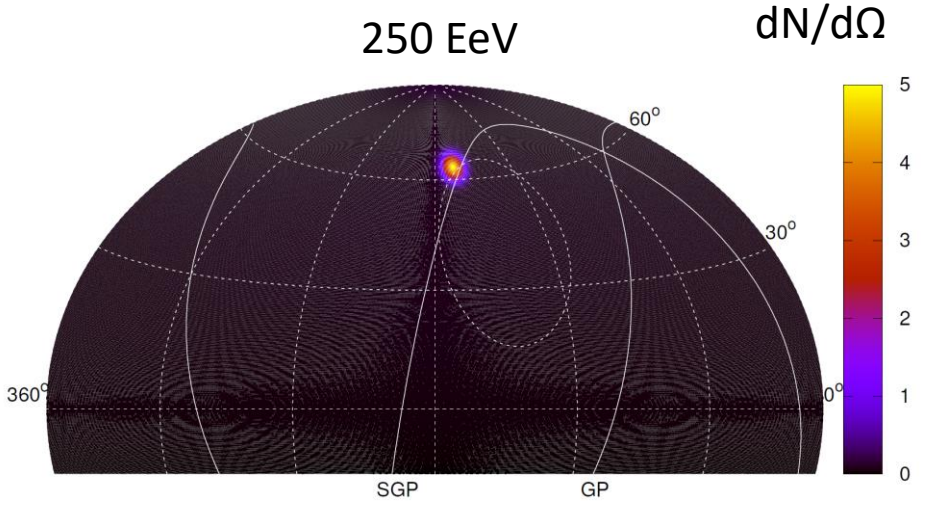
Equatorial

+: source direction
→: direction of the regular magnetic deflection

60 EeV



250 EeV



Implications on magnetic fields

$A_1 \sim 6^\circ Z \left(\frac{D}{3\ \mathrm{kpc}}\right)\left(\frac{B_\perp}{4\ \mu\mathrm{G}}\right)$ (galactic)

$0^\circ.5 Z \left(\frac{D}{1\ \mathrm{Mpc}}\right)\left(\frac{B_\perp}{1\ \mathrm{nG}}\right)$ (extragalactic)

$A_2 \sim 0^\circ.6 Z \left(\frac{D}{3\ \mathrm{kpc}}\right)^{1/2}\left(\frac{D_c}{50\ \mathrm{pc}}\right)^{1/2}\left(\frac{B_r}{4\ \mu\mathrm{G}}\right)$ (galactic)

$0^\circ.4 Z \left(\frac{D}{1\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{D_c}{1\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B_r}{1\ \mathrm{nG}}\right)$ (extragalactic) (e.g. Harari+ 2002)

D: source distance
D_c: coherent length
B: magnetic field strength
- $B_\perp$: perpendicular to the motion of the CR
- B_r: r.m.s. strength

If M82 (*D* = 3.4 Mpc) is the source and the simple formulae on the extragalactic magnetic field are applied,
A_1 = 23.5° +7.7° -8.0° → **$B_\perp$ = 13.8+4.5-4.7 / *Z* (nG)**
A_2 = 6.2° +2.2° -5.0° → **B_r = 8.4+3.0-6.8 / *Z* (nG)**

Conclusions

- We developed a **phenomenological way** to consider both **random** and **regular** magnetic deflections in the search for the source direction of UHECRs by searching for the magnetic deflection multiplet.
- **217** TA SD events with E > **57** EeV collected over 15 years were used in the analysis.
- Source direction: (α = 184.8+25.1-27.8 (deg.), δ = 69.1+8.8-8.6 (deg.)).
  Nearby galaxies such as M82(starburst galaxy) is within 1σ confidence region.
  The source direction is **35.7** degrees away from the hotspot (α = 144.0 (deg.), δ = 40.5 (deg.)).
- Statistical significance (global) of the max. likelihood function L_{max} : **3.0σ**

  → indication of the source direction and magnetic deflections of the TA hotspot
- If (A_1, β) parameters related to the regular magnetic deflection were removed in the analysis, statistical significance of the max. likelihood function L_{max} **: 2.6σ**

  → adding the two parameters increased the stat. significance by 0.4σ
- If M82 (D = 3.4 Mpc) is the source of the multiplet for example, implications on magnetic fields can be obtained by parameters, $\boldsymbol{A_1}$ and $\boldsymbol{A_2}$.