Monte Carlo Bayesian search for the plausible source of the Telescope Array hotspot

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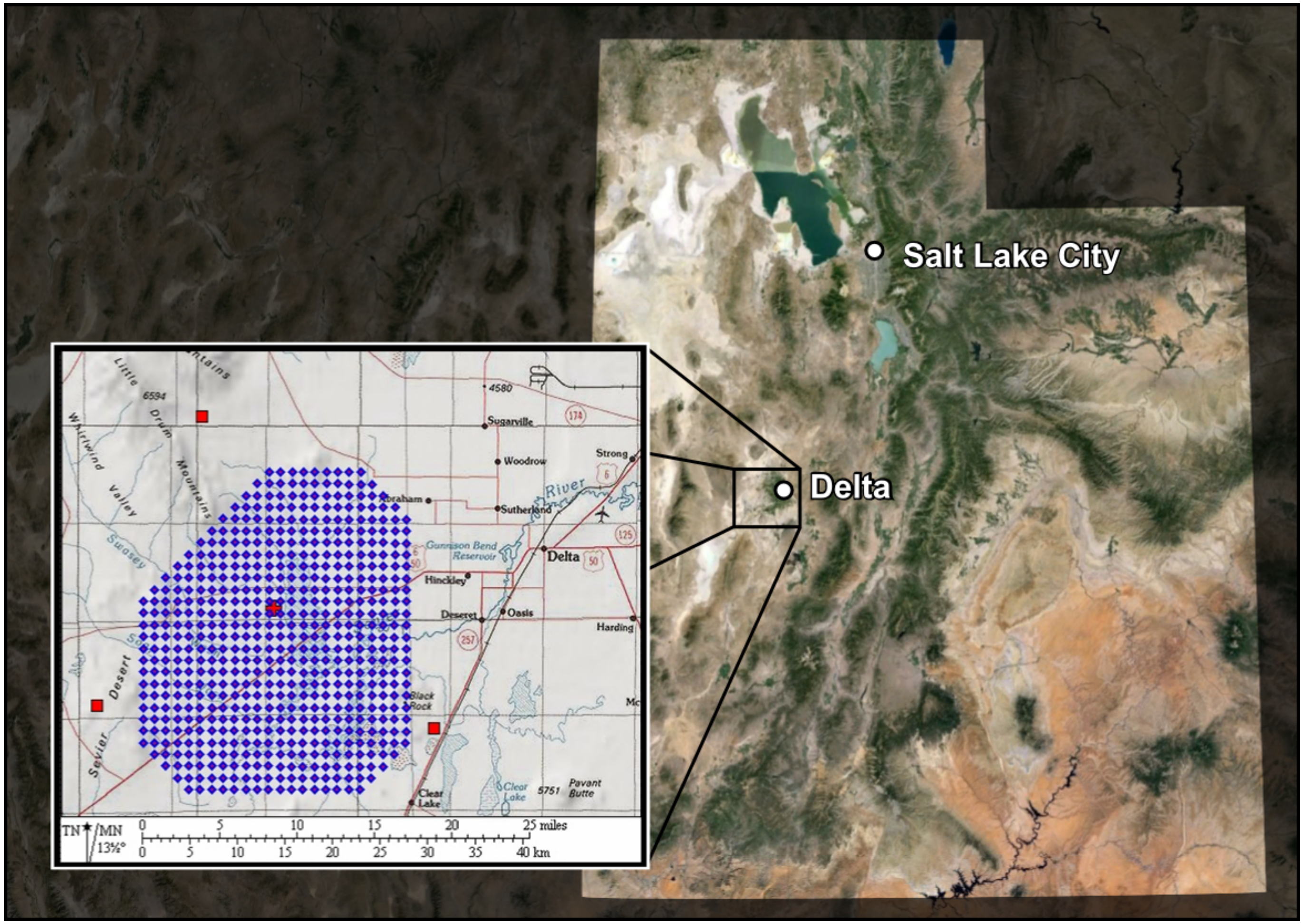
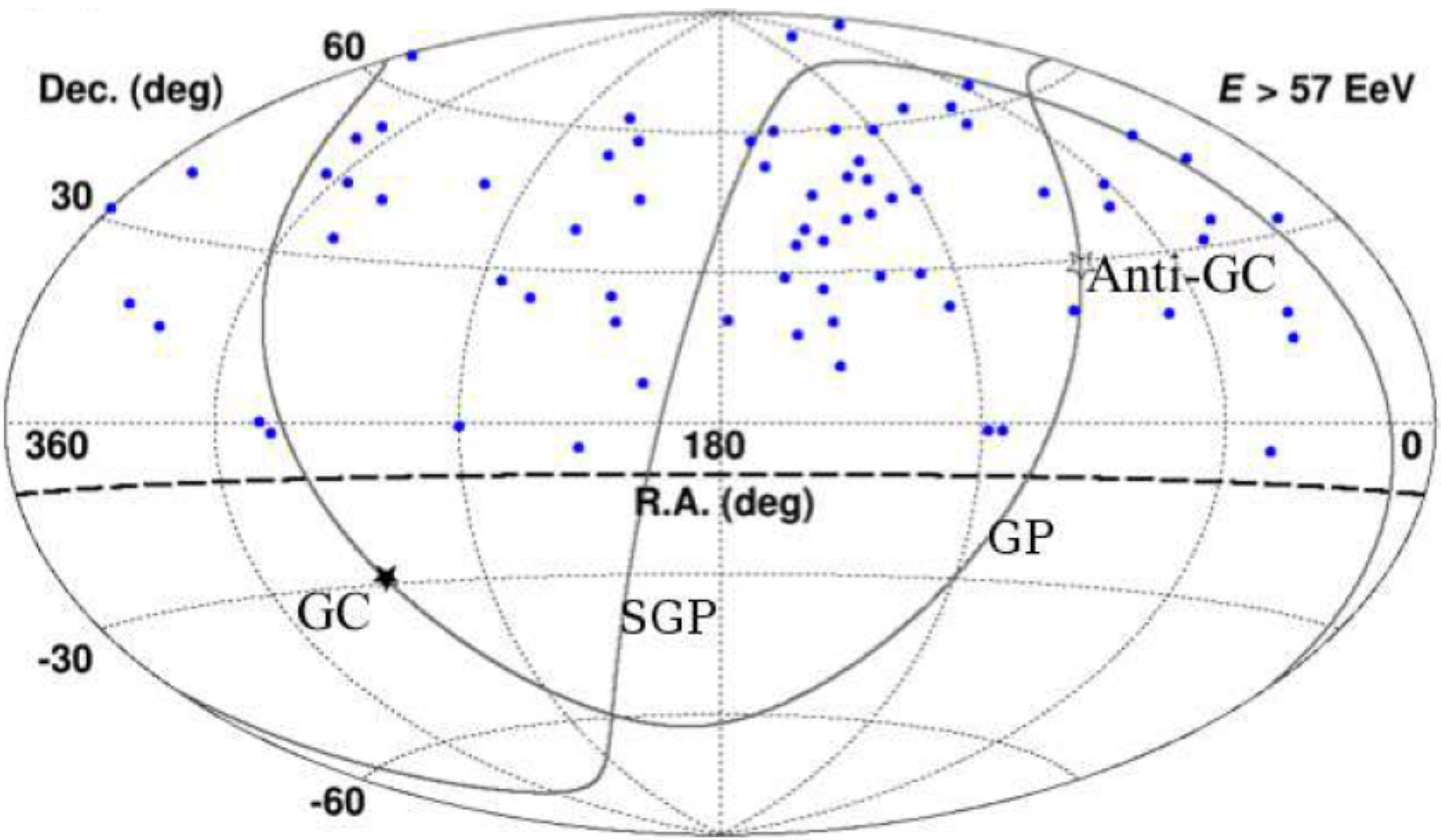
Telescope Array Experiment (Japan-US)



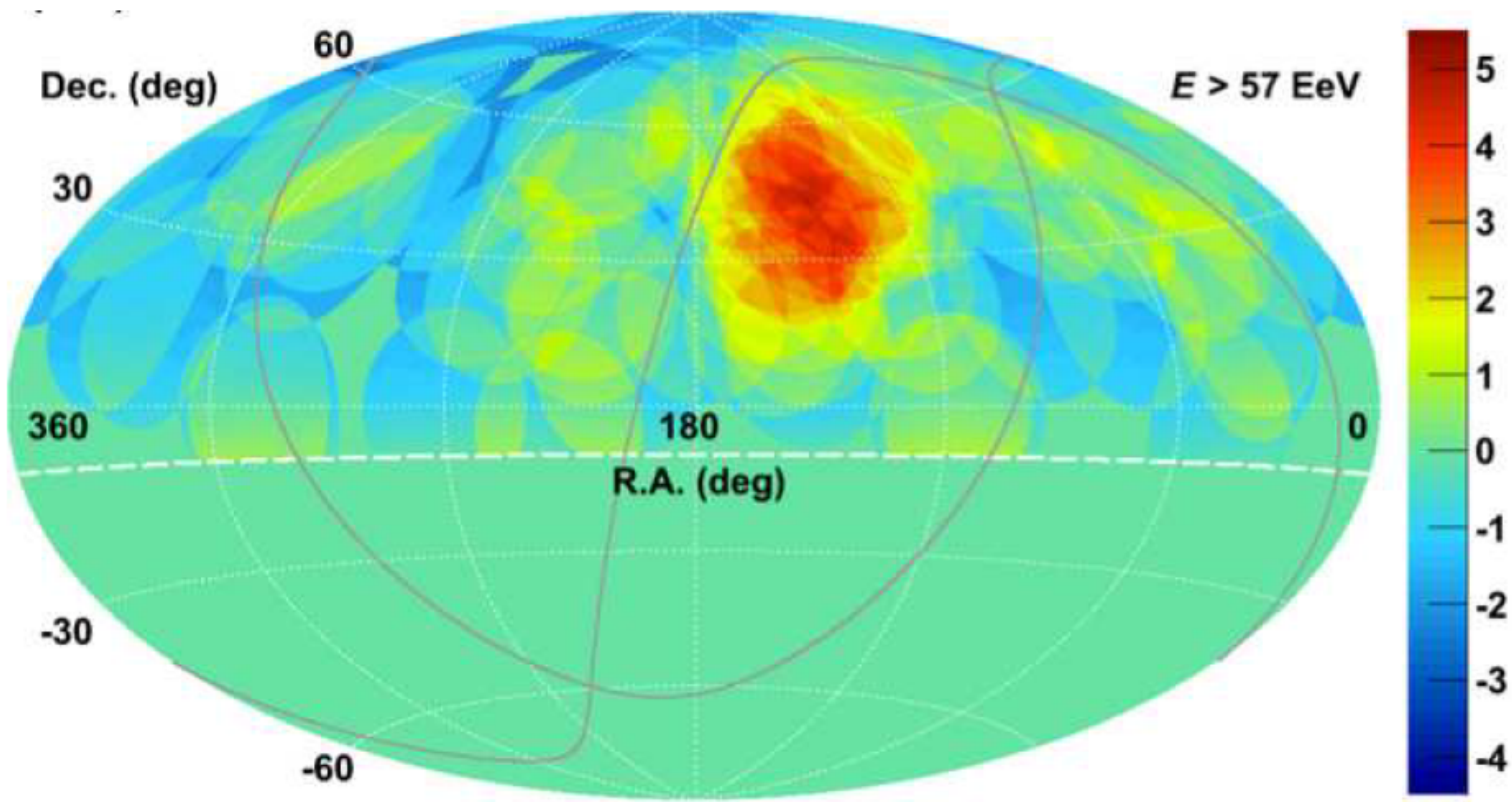
The Hotspot of UHECRs observed by the Telescope Array



(Data between 2008 May 11 and 2013 May 4, The TA Collaboration, 2014)

The Hotspot of UHECRs observed by the Telescope Array

$$5.1\sigma \ (N_{\rm on} = 19, N_{\rm bg} = 4.49)$$

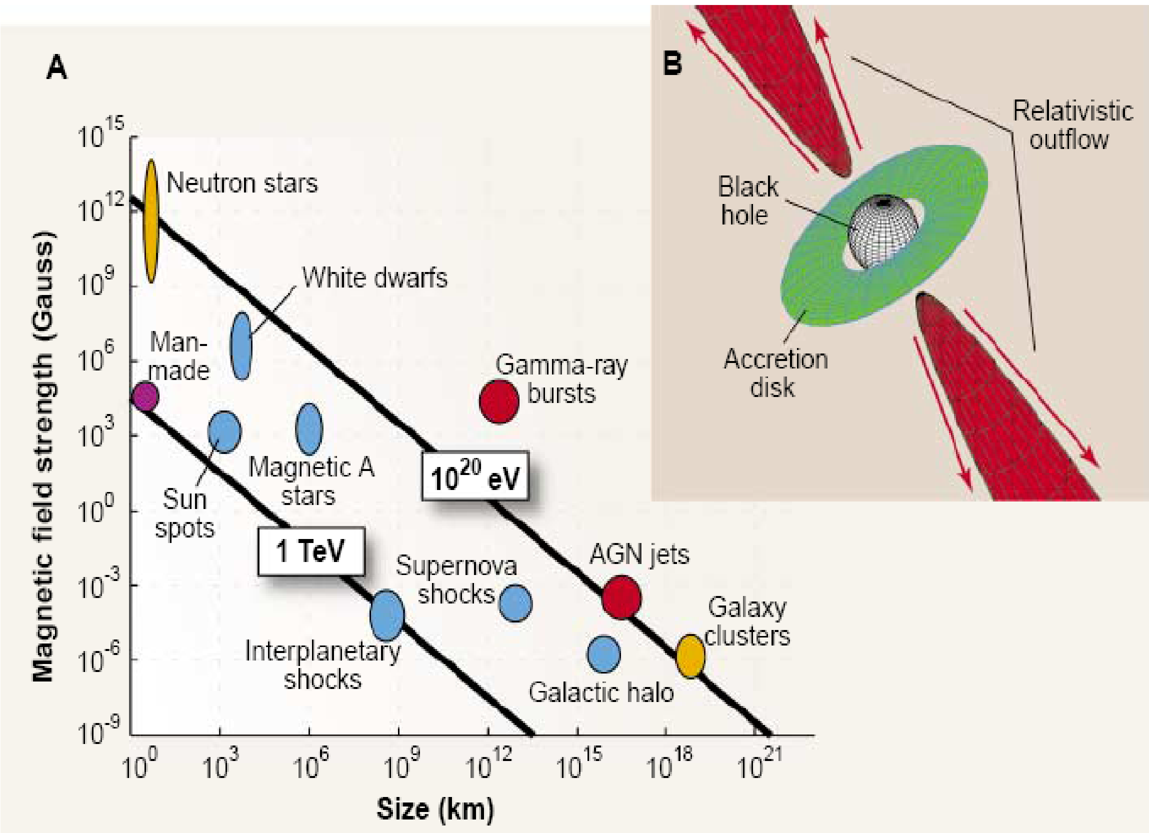


(Data between 2008 May 11 and 2013 May 4, The TA Collaboration, 2014)

The possible sources of UHECRs at the TA hotspot

- Acceleration capability—Type of sources
- The GZK suppression—Distances of sources
- The time delay —The duration of sources
- The deflection of the magnetic field—Directions of sources

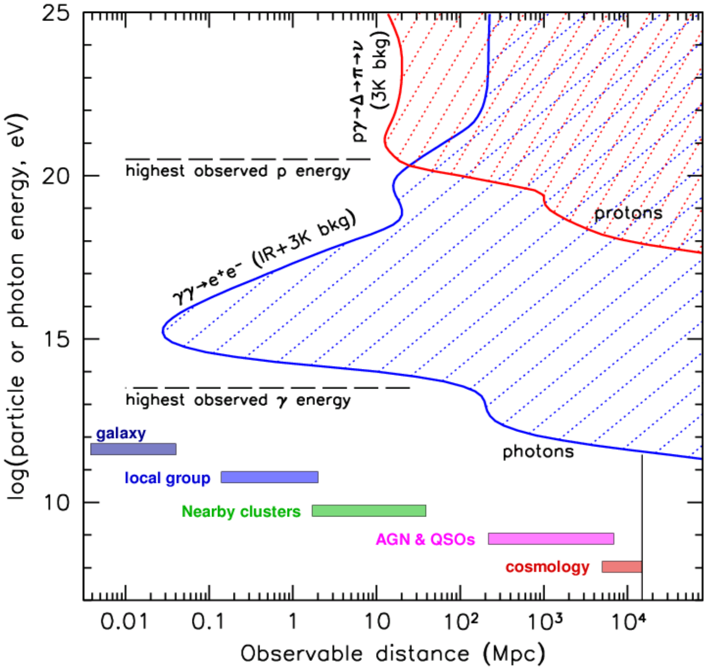
Acceleration capability

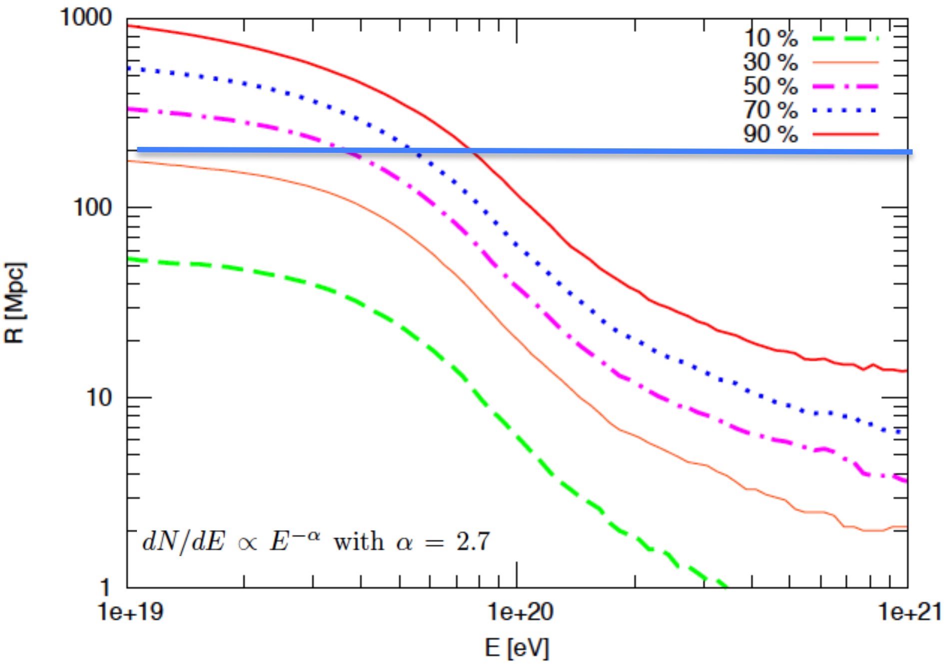


Lamor Radius=Typical scale of sources

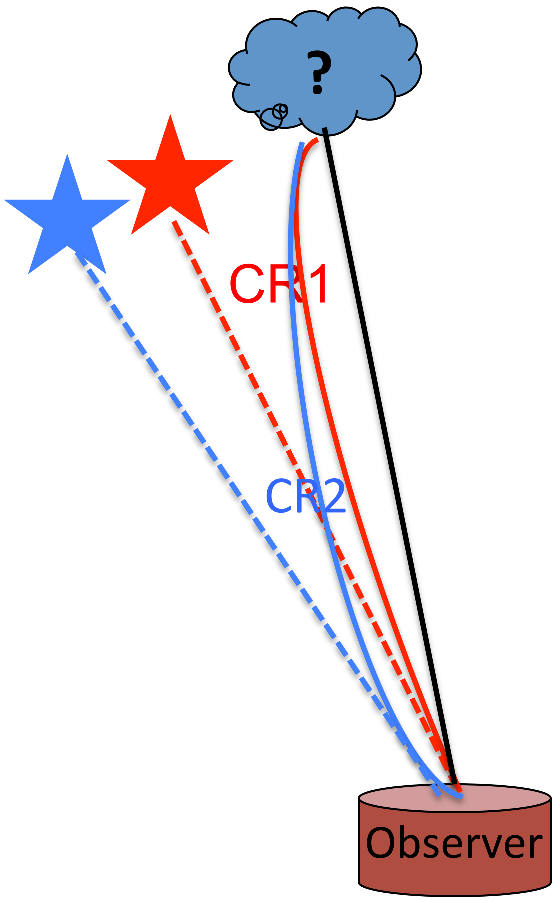
Emax=ZBL

The GZK suppression—Distances of sources





The effect of the magnetic field, the time delay



The time delay between photons and the deflected cosmic rays

$$\Delta T = 3.3 \times 10^6 \mathrm{yr} \frac{D}{1\mathrm{Mpc}} \left(\frac{\theta}{\sin\theta} - 1 \right)$$

The time delay between cosmic rays with different deflected angles

$$\Delta t = \Delta T_1 - \Delta T_2 = 3.3 \times 10^4 \mathrm{yr} \frac{D}{1\mathrm{Mpc}} \frac{\Delta}{0.01}$$

$$\Delta = \frac{\theta_1}{\sin\theta_1} - \frac{\theta_2}{\sin\theta_2}$$

(Finley, C. B. 2006, Ph.D. Thesis)

The time delay —The duration of sources

Not a single transient source

Either a single long-term-active source
Or a groups of transient sources in one galaxy

GRBs in Star-forming Galaxy

At least 19 GRBs occurred during a delayed time

+

a beaming correction factor for the GRB rate 75 ± 20

GRB rate in the star-forming galaxy $(0.04 \pm 0.01)\left(\frac{D}{1\mathrm{Mpc}}\right)^{-1} \mathrm{yr}^{-1}$ per galaxy

$R_{\mathrm{GRB}}/R_{\mathrm{SN}} = 0.5\text{–}4\%$

+

$R_{\mathrm{SN}} = 1.2 \times 10^{-2}\mathrm{yr}^{-1} \frac{\mathrm{SFR}}{M_{\odot}\mathrm{yr}^{-1}}$

+

$\mathrm{SFR} = 1.71 M_{\odot}\mathrm{yr}^{-1} \frac{L_{\mathrm{FIR}}}{10^{10} L_{\odot}}$

$\Rightarrow$ $R_{\mathrm{GRB}} = (1-8) \times 10^{-4}\mathrm{yr}^{-1} \frac{L_{\mathrm{FIR}}}{10^{10} L_{\odot}}$

+

The far-infrared luminosity $\frac{L_{\mathrm{FIR}}}{10^{10} L_{\odot}} > 400 \left(\frac{D}{1\mathrm{Mpc}}\right)^{-1}$

The source candidates

Sources among the long-term active sources from Fermi LAT catalogue and TeV catalogue (http://tevcat.uchicago.edu) within the distance of 200Mpc

- Massive galaxy clusters
- BL Lac objects
- Radio galaxies
- Starburst galaxies

- Starforming galaxies

The deflection of the magnetic fields

For a group of UHECRs from a single source and propagting in similar path

Systematic Shift by regular magnetic field:

$$\delta_{\rm reg} \simeq 0.5^\circ Z \frac{100\ {\rm EeV}}{E} \frac{D_{\rm reg}}{1\ {\rm Mpc}} \frac{B_{{\rm reg},\perp}}{1\ {\rm nG}} = A_1 \times \frac{100\ {\rm EeV}}{E}$$

Deflection by random mangetic field:

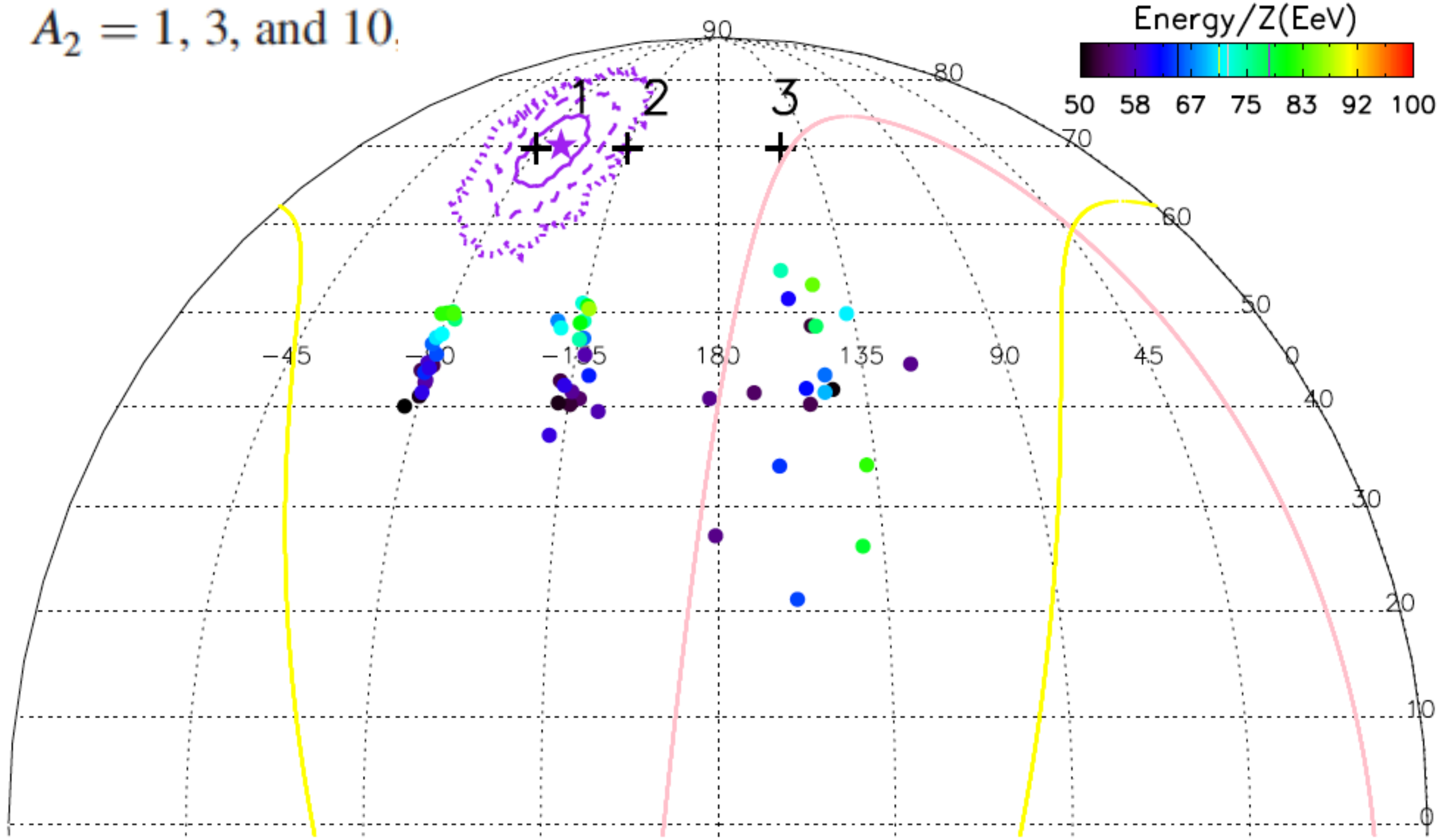
$$f(\delta_{\rm dif}, \delta_{\rm rms}) = \frac{1}{\delta_{\rm rms}\sqrt{2\pi}} exp\left(-\frac{\delta_{\rm dif}^2}{2\delta_{\rm rms}^2}\right)$$

$$\delta_{\rm rms} \simeq 0.36^\circ Z \frac{100\ {\rm EeV}}{E} \left(\frac{D_{\rm dif}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}}$$

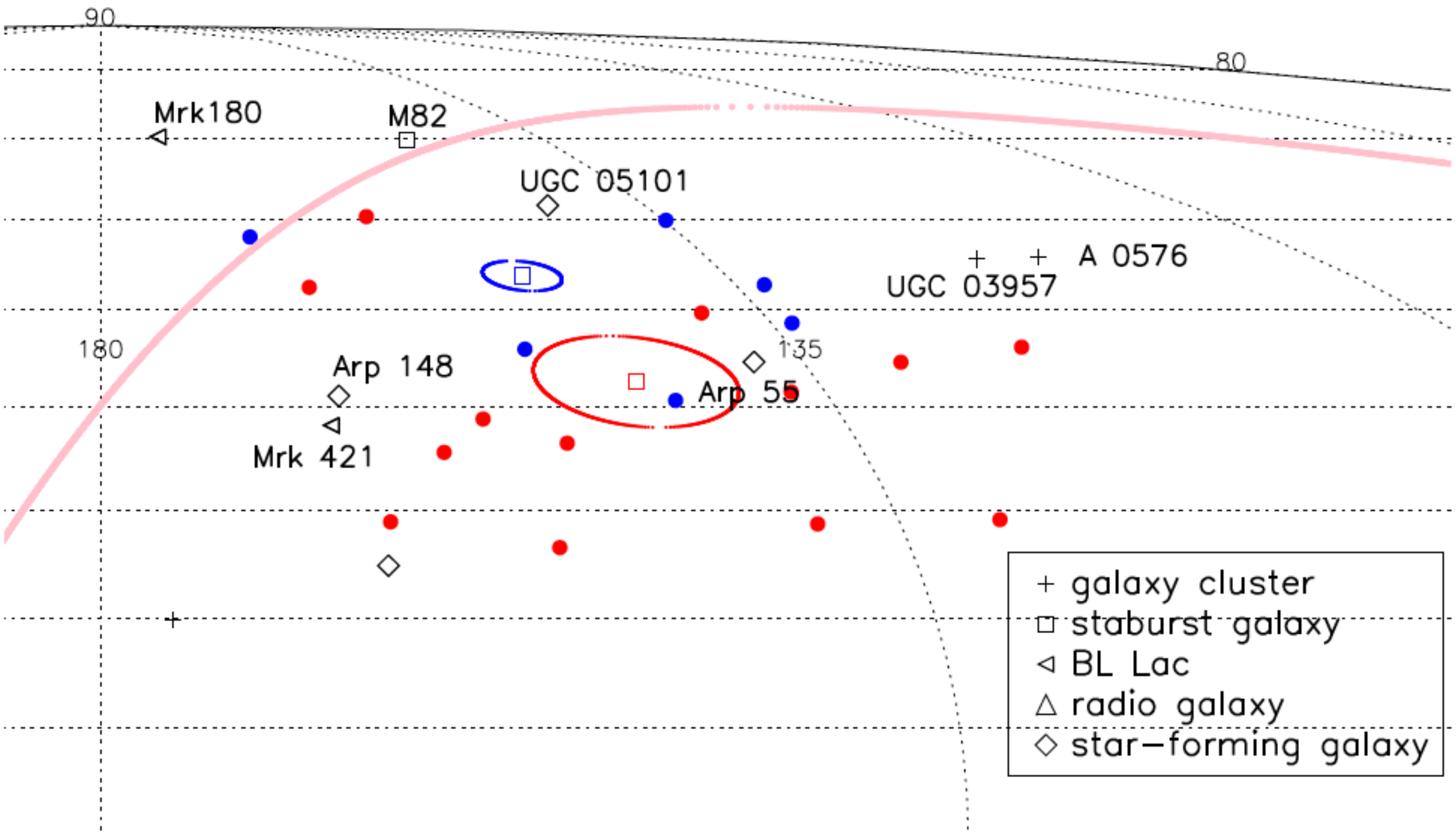
$$= A_2 \times \frac{100\ {\rm EeV}}{E},$$

Three simulated cases

$A_2 = 1, 3, \text{ and } 10.$



The distribution of TA hotspot events



Probability: 0.2% random realizations would produce a similar hotspot detection, implying the probability of 99.8% that the magnetic-selected structure of the TA hotspot is not from a fluctuation.

A Monte Carlo Bayesian Search

Coordinates of the original source

(R.A., Dec.)

Parameters describing the magnetic field

(α, A_1, A_2)

The diffusion angle $\delta_{\mathrm{dif},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1, E_i)$

The probability for i-th TA hotspot event

$$f_i(\delta_{\mathrm{dif},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1, E_i), \delta_{\mathrm{rms},i}(A_2, E_i))$$

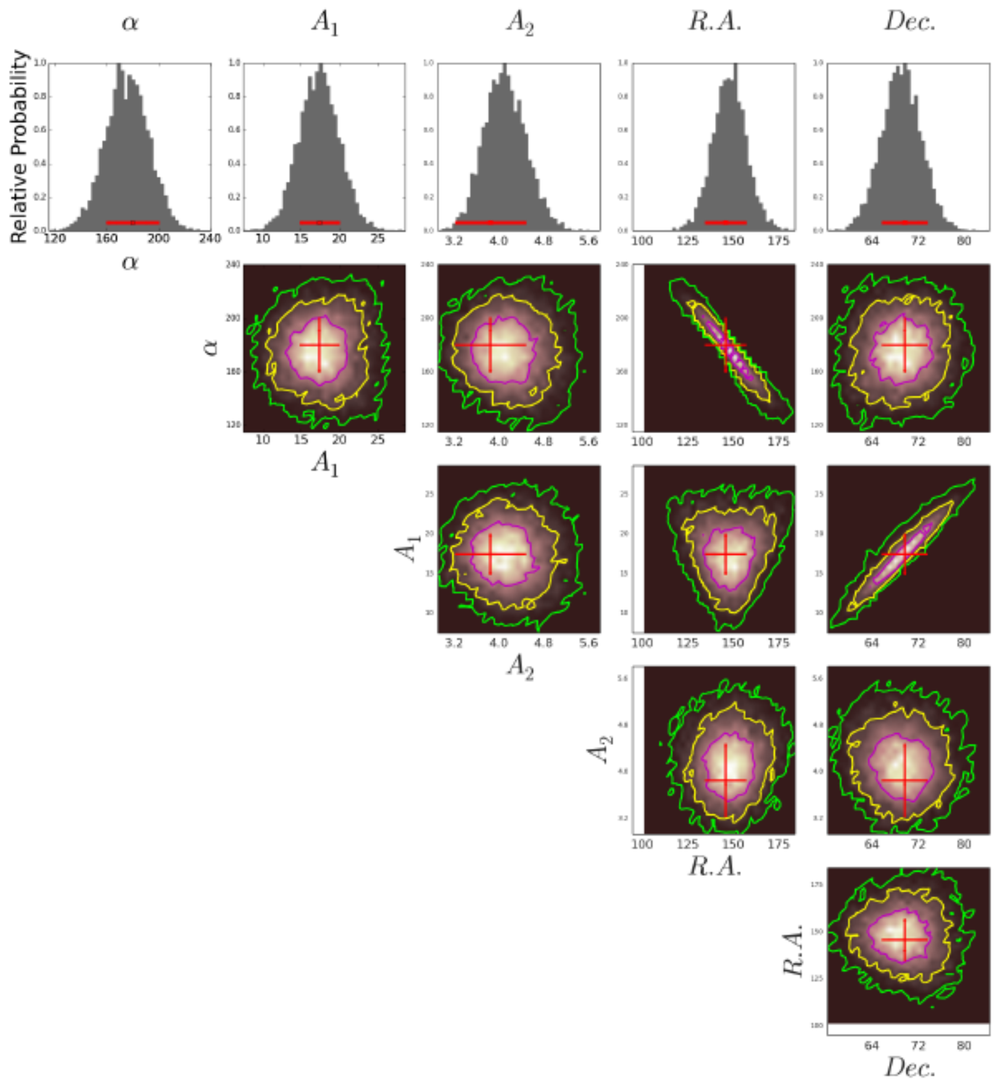
$$P \propto \prod_{i=0}^{N} f_i(\delta_{\mathrm{dif},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1, E_i), \delta_{\mathrm{rms},i}(A_2, E_i)).$$

$$\begin{aligned} L &\equiv ln(P) \\ &= \sum_{i=0}^{N} ln(f_i(\delta_{\mathrm{dif},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1, E_i), \delta_{\mathrm{rms},i}(A_2, E_i)) \\ &\quad +\mathrm{const.} \end{aligned} \tag{7}$$

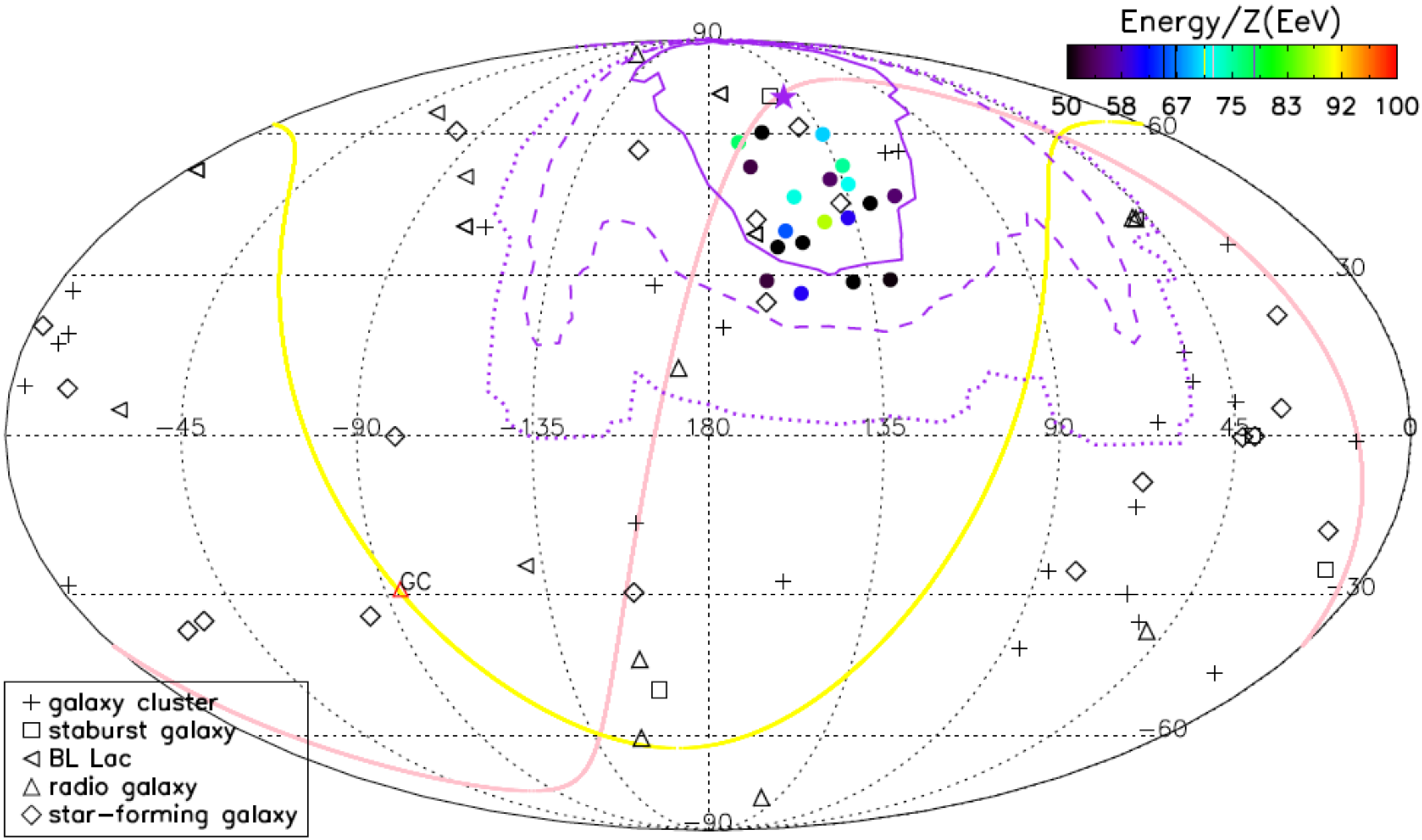
The log-likelihood function with 5 parameters

Parameters constraints by fitting the model to the observation data using MC approach

（Bin-Bin Zhang zhang.grb@gmail.com）



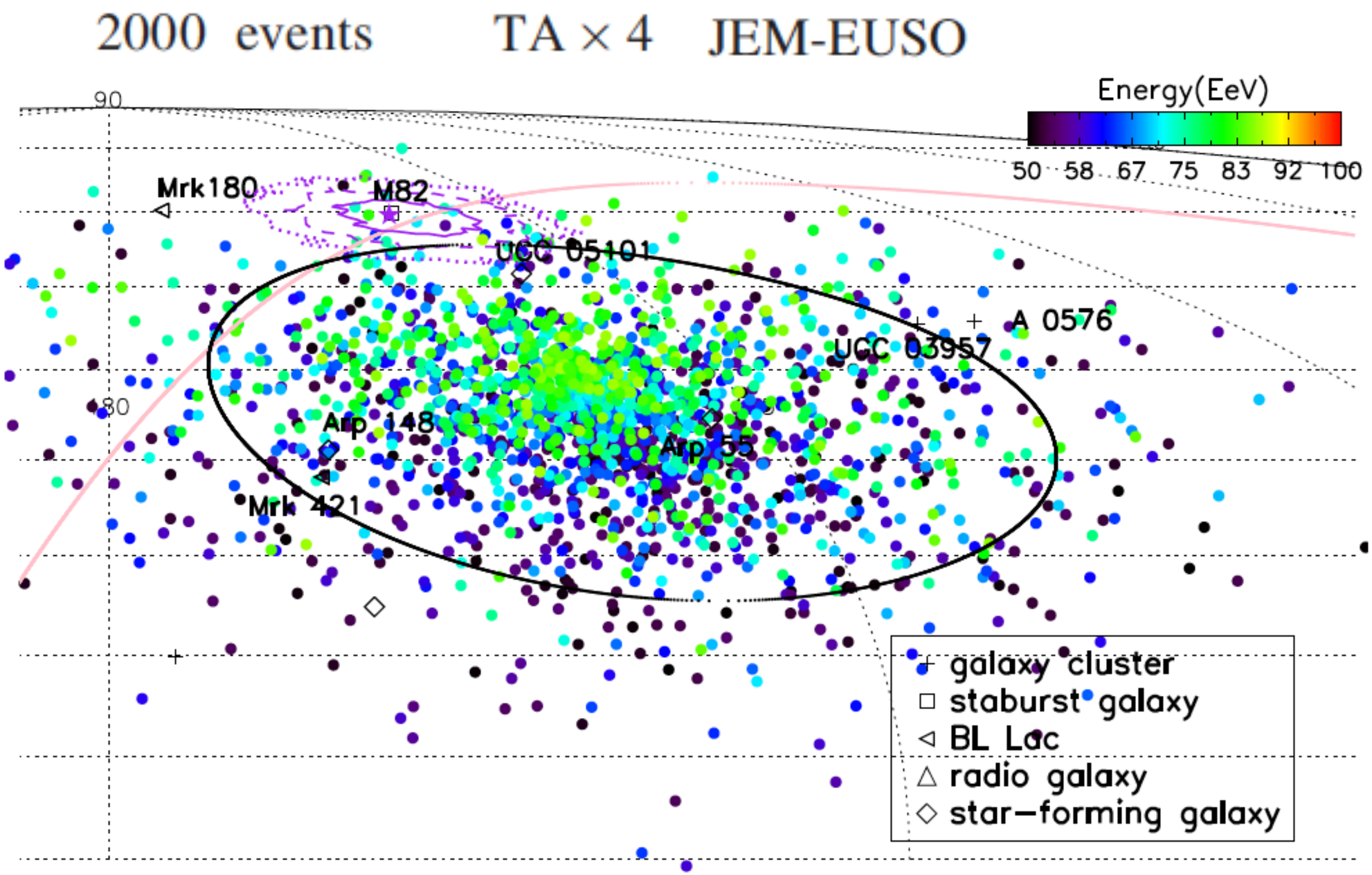
The 1,2,3-sigma error Contours



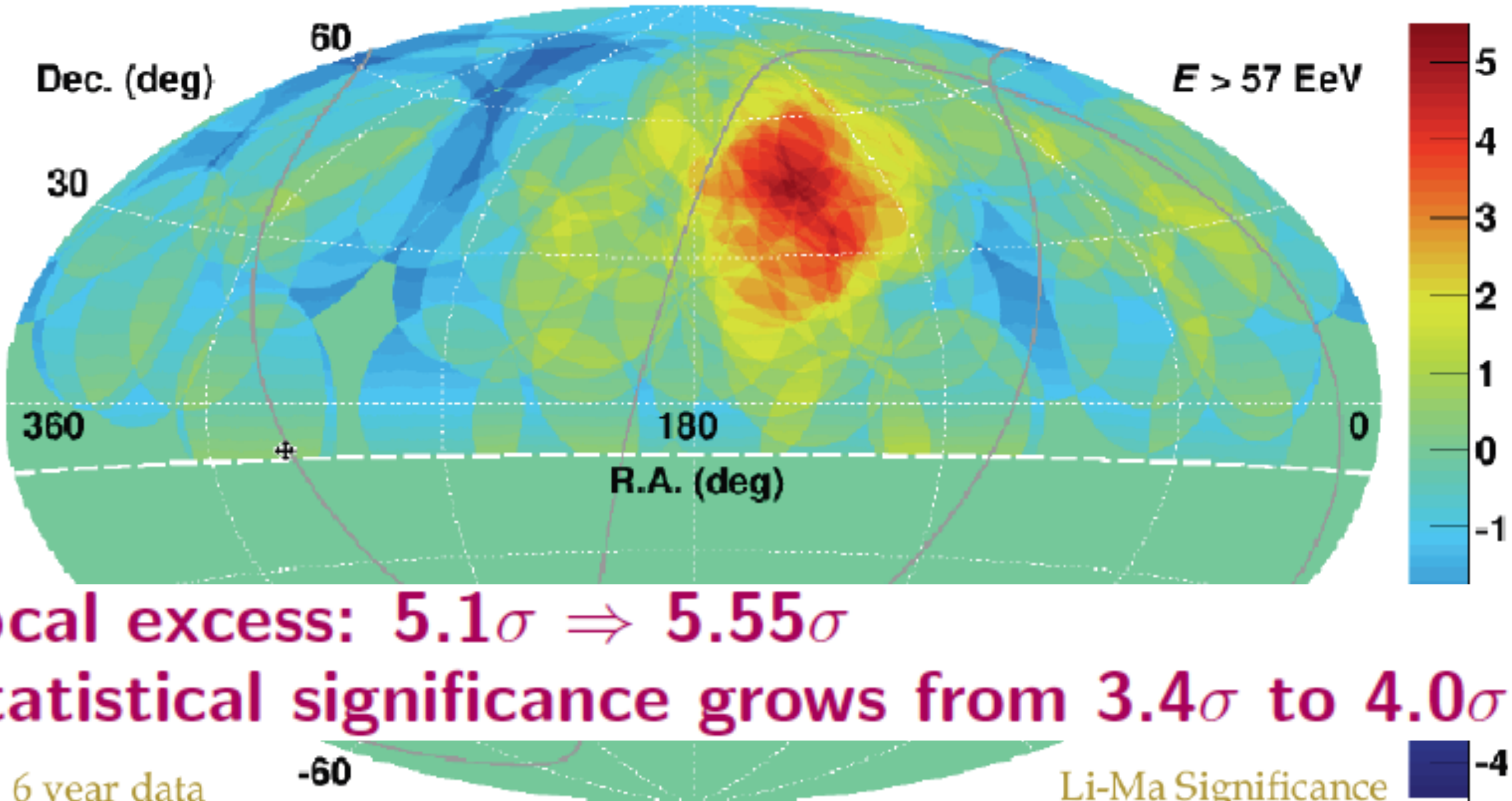
Sources in 1-sigma contour

Source Name	Source Type	Distance (Mpc)	RA (°)	Dec (°)	α (°)	A_1 (°)	A_2 (°)	$P/P_{\mathrm{bes-fit}}$ (%)
best-fit	-	-	$142.8^{+47.6}_{-40.0}$	$69.2^{+11.7}_{-27.6}$	$185.7^{+109.6}_{-121.2}$	$17.4^{+17.0}_{11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	149.0	69.7	174.2	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	143.0	61.5	182.9	11.6	9.2	96.9
Mrk 180	blazar	185	174.1	70.2	136.1	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	115.2	55.4	253.4	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	110.4	55.7	259.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	138.2	44.5	279.6	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	165.3	41.1	69.3	10.5	10.0	41.8
Mrk 421	blazar	134	166.1	38.2	61.5	11.2	9.9	35.6

Reduced error with increasing statistics



6 year data



local excess: 5.1σ $\Rightarrow$ 5.55σ

statistical significance grows from 3.4σ to 4.0σ

D.Bergman, COSPAR'2014

Summary

- We have explored the hypothesis of a single source for the TA hotspot, and studied a universal model that cosmic rays from a single source are deflected by magnetic fields.

- Our analysis reveals that the distribution of the TA hotspot events is diffused strongly by the random magnetic field, consistent with the single source hypothesis, and the chance probability of this distribution is 0.2%.

- The MCB method can be used to find out the best-fit source coordinates and magnetic field parameters.

- The MCB method can be adopted to other magnetic-selected hotspots possibly observed in the future, and constrain the magnetic field.

Thank you!