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

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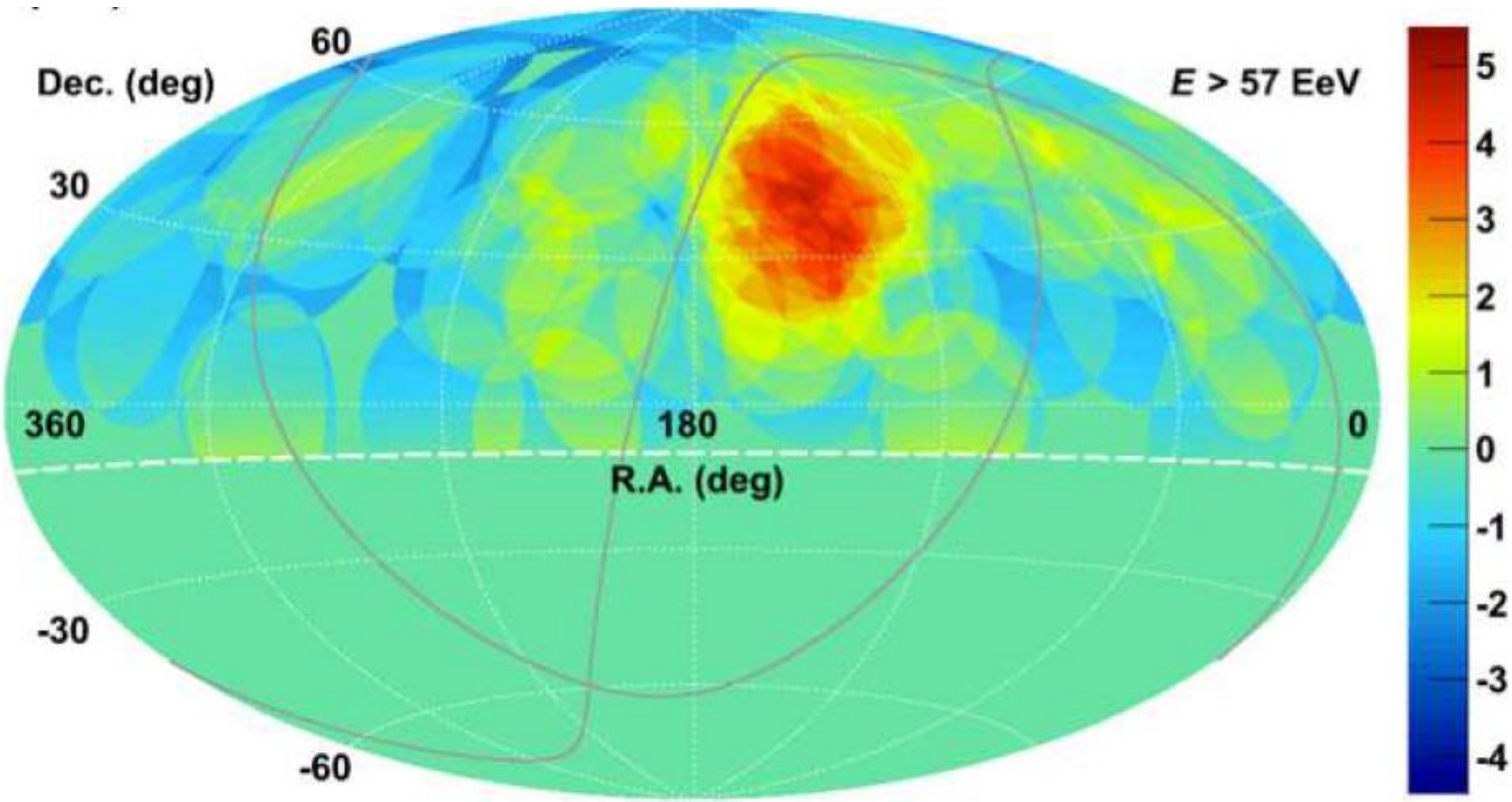
The Hotspot of UHECRs observed by the Telescope Array

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



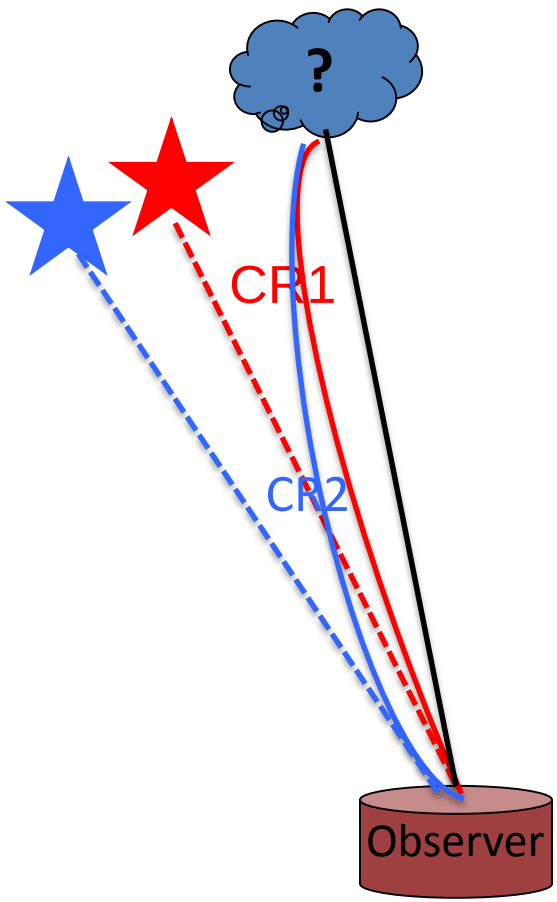
(Data between 2008 May 11 and 2013 May 4, The TA Collaboration, 2014)

The possible sources of UHECRs at the TA hotspot

Assumption: Pure composition from a single point source

- The time delay due to deflections —The duration and energy budget of the source
- Acceleration capability—Type of the source
- The GZK suppression—Distance of the source
- The event distribution due to deflections—Direction of the source

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 and energy budget of sources

A single long-term-active source

A single transient source

$$F_{\rm hs} \simeq (4.4 \pm 1.0) \times 10^{-11} {\rm erg\ s^{-1}\ cm^{-2}\ sr^{-1}}$$

$$\frac{dN}{dE} \sim E^{-2}$$

The requisite total isotropic injected energy of the single transient source $4 \times 10^{54} {\rm erg} \left(\frac{D}{1\ {\rm Mpc}}\right)^{-2}$

A past GRB with an extremely high kinetic energy at a distance ~ Mpc could produce the observed Hotspot.

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

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

+

$$R_{\mathrm{SN}} = 1.2\times10^{-2}\mathrm{yr}^{-1}\frac{\mathrm{SFR}}{M_{\odot}\mathrm{yr}^{-1}}$$

+

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

+

$$R_{\mathrm{GRB}} = (1-8)\times10^{-4}\mathrm{yr}^{-1}\frac{L_{\mathrm{FIR}}}{10^{10}L_{\odot}}$$

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

The source candidates

Within the distance of 200Mpc

- Massive galaxy clusters
  Ackermann, M., Ajello, M., Albert, A., et al. 2014, Astrophys.J., 787, 18
- BL Lac objects
  M. Ackermann, M. Ajello, W. Atwood et al., Astrophys. J.810, 14 (2015);
  Horan, D., & Wakely, S. 2008, AAS/High Energy Astrophysics Division #10, 10, #41.06
- Radio galaxies
- Starburst galaxies
  Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, Astrophys. J. Suppl. Ser., 199, 31

- Starforming galaxies
  M. Ackermann, M. Ajello, A. Allafort et al., Astrophys. J.755, 164 (2012).

http://tevcat.uchicago.edu

Magnetic Bending Effects

Assumption： Pure composition from a single source

Systematic Shift by regular magnetic field:

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

$$A_1 = 0.5^\circ Z \frac{D_{\rm reg}}{1{\rm Mpc}} \frac{B_{\rm reg,\perp}}{1{\rm nG}}$$

Deflections by random magnetic field:

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

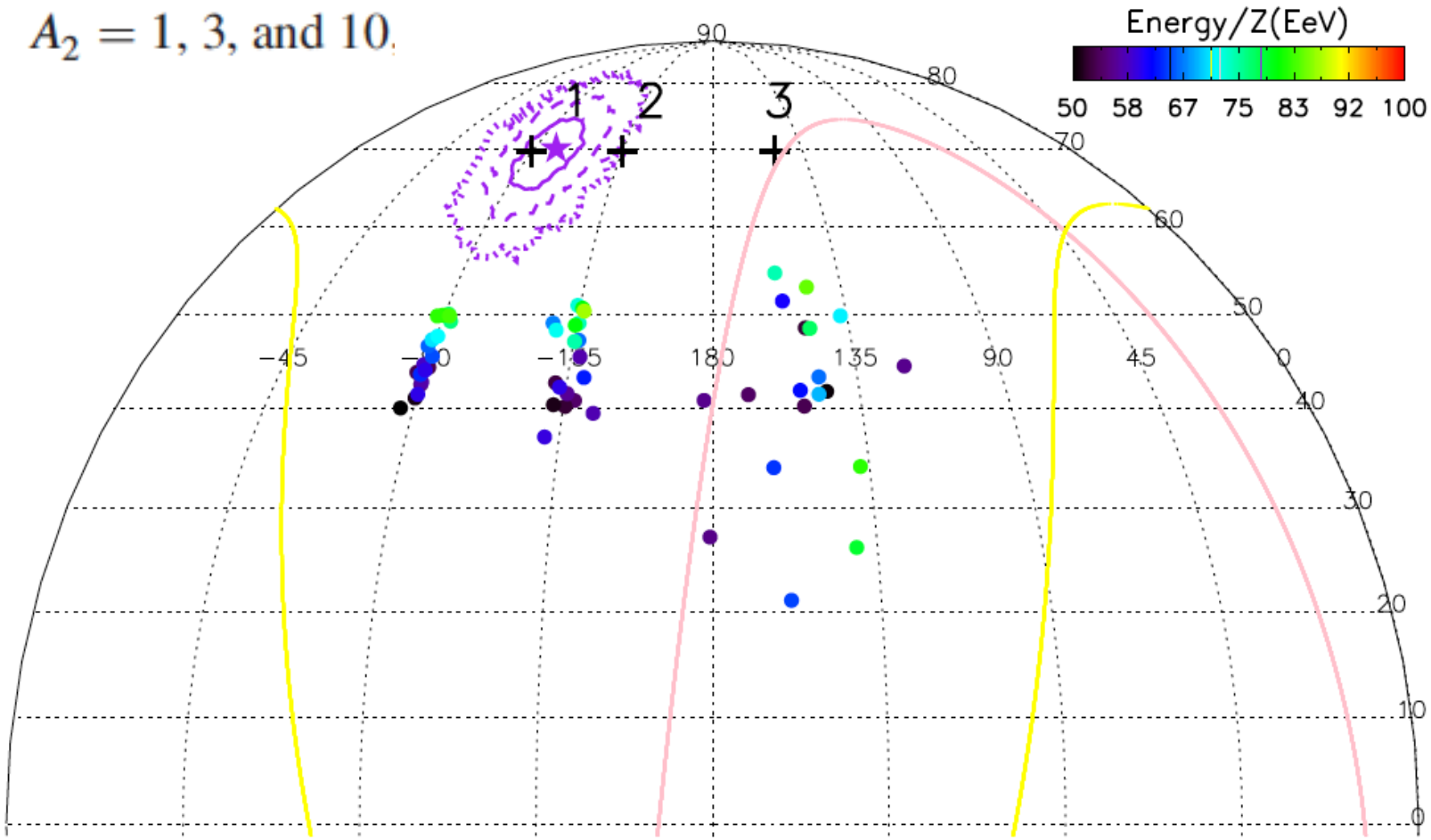
Probability of Bending Angle: $\delta_{\rm dif}$

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

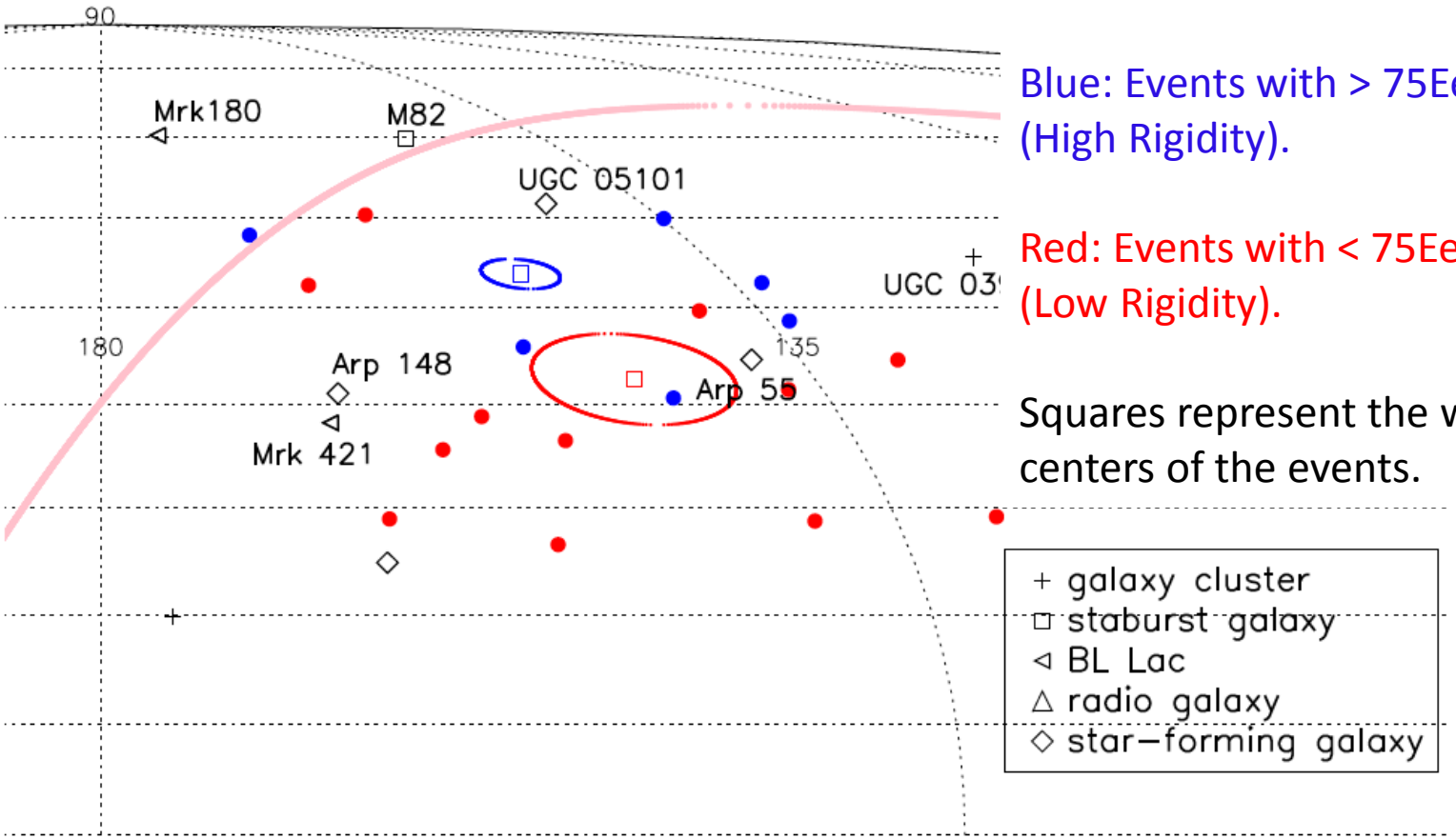
$$= A_2 \times \frac{100\ {\rm EeV}}{E},$$

$$A_2 = 0.36^\circ Z \left(\frac{D_{\rm dif}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}}$$

Three simulated cases



The distribution of TA hotspot events



Blue: Events with > 75EeV (High Rigidity).

Red: Events with < 75EeV (Low Rigidity).

Squares represent the weighted centers of the 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.)

The magnetic field & composition

(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

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

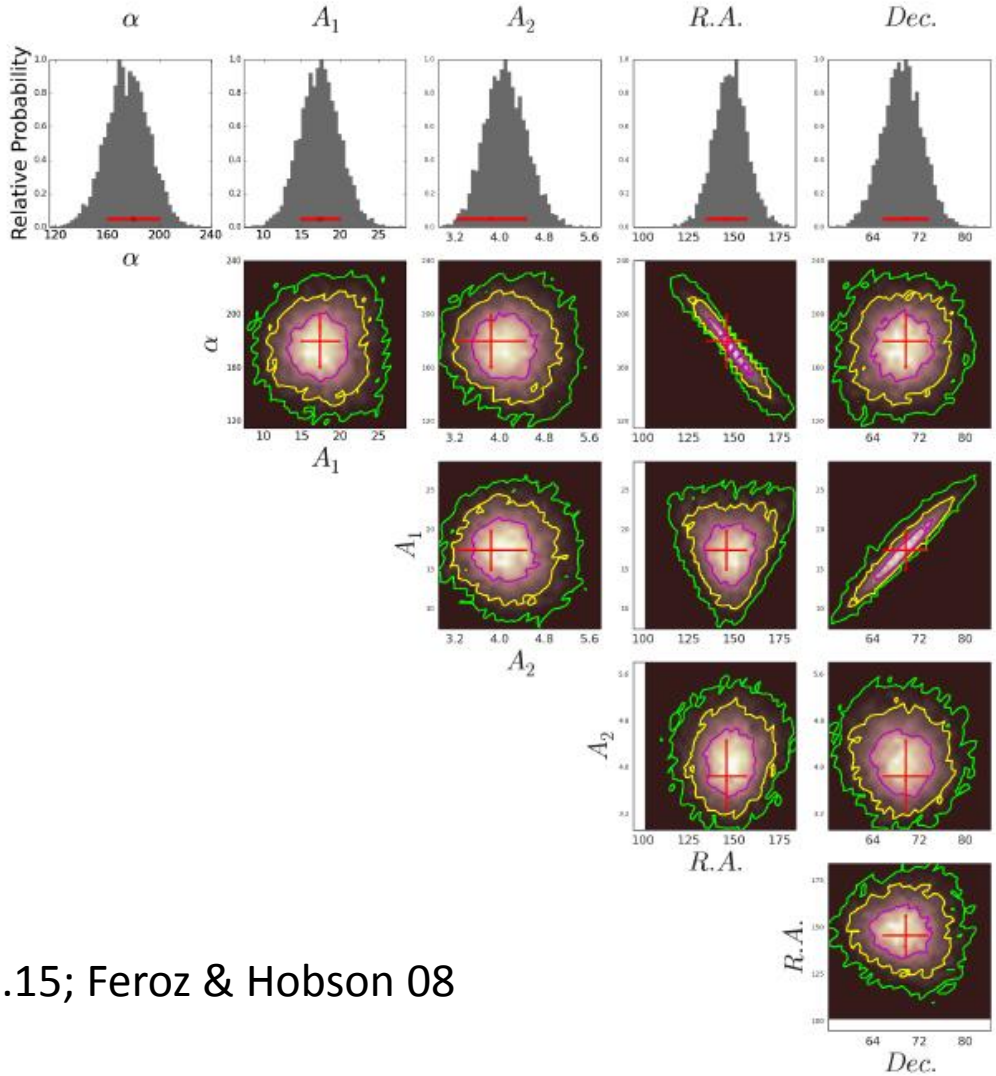
$$P \propto \prod_{i=0}^{N} f_i(\delta_{\mathrm{dif},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1, E_i), \delta_{\mathrm{rms},i}(A_2, E_i)).$$

The log-likelihood function with 5 parameters

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

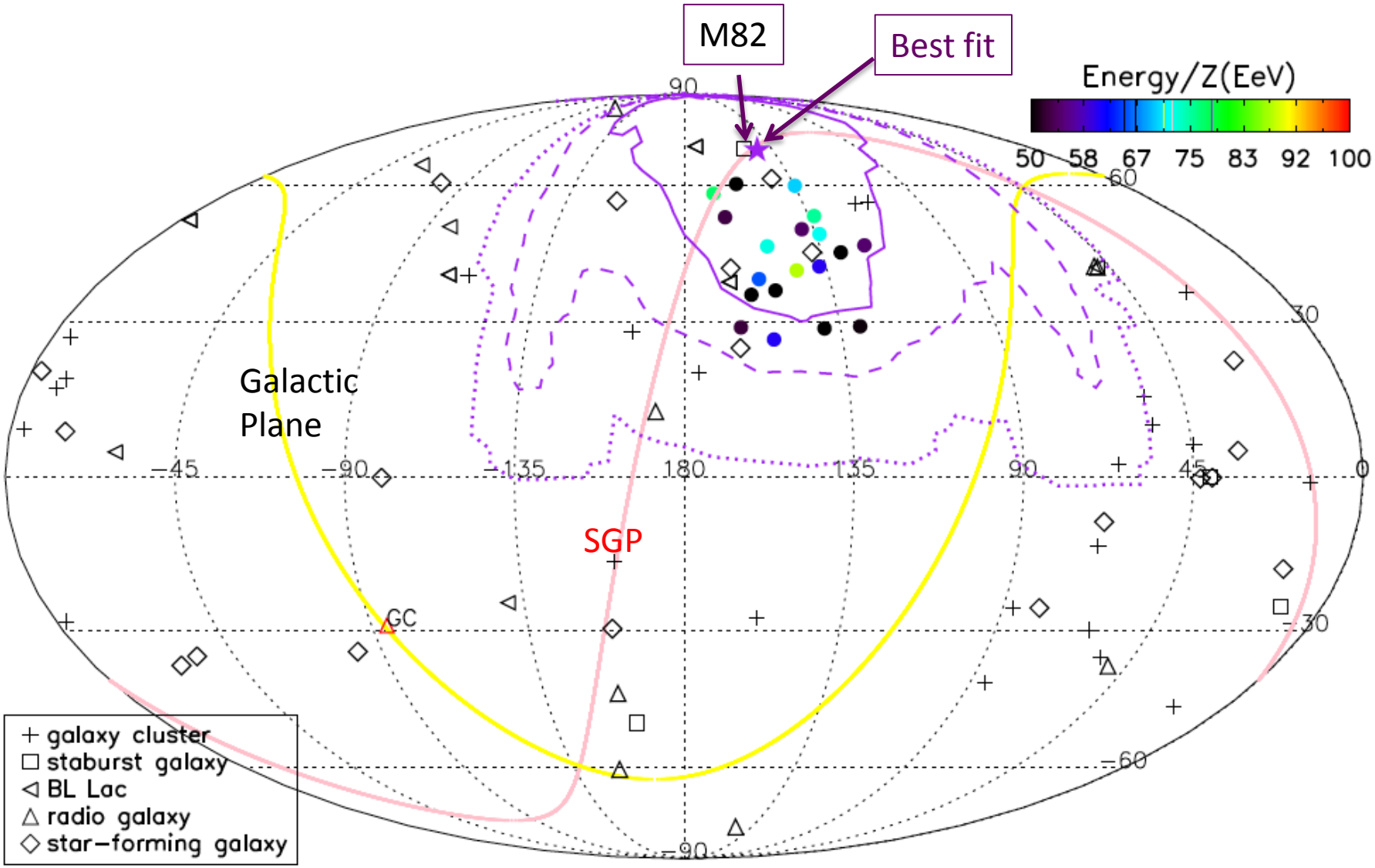
Parameters constraints by fitting the model to the observation data using MC approach

（Bin-Bin Zhang zhang.grb@gmail.com）



Zhang et al.15; Feroz & Hobson 08

The 1,2,3-sigma error Contours



Sources in 1-sigma contour and constraints on magnetic fields

Source Name	Source Type	Distance (Mpc)	RA (°)	Dec (°)	α (°)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
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

Random Field: $Z\left(\frac{D_{\rm dif}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}}\left(\frac{D_{\rm c}}{1\ {\rm Mpc}}\right)^{\frac{1}{2}}\frac{B_{\rm rms}}{1\ {\rm nG}} = 25\text{–}28$

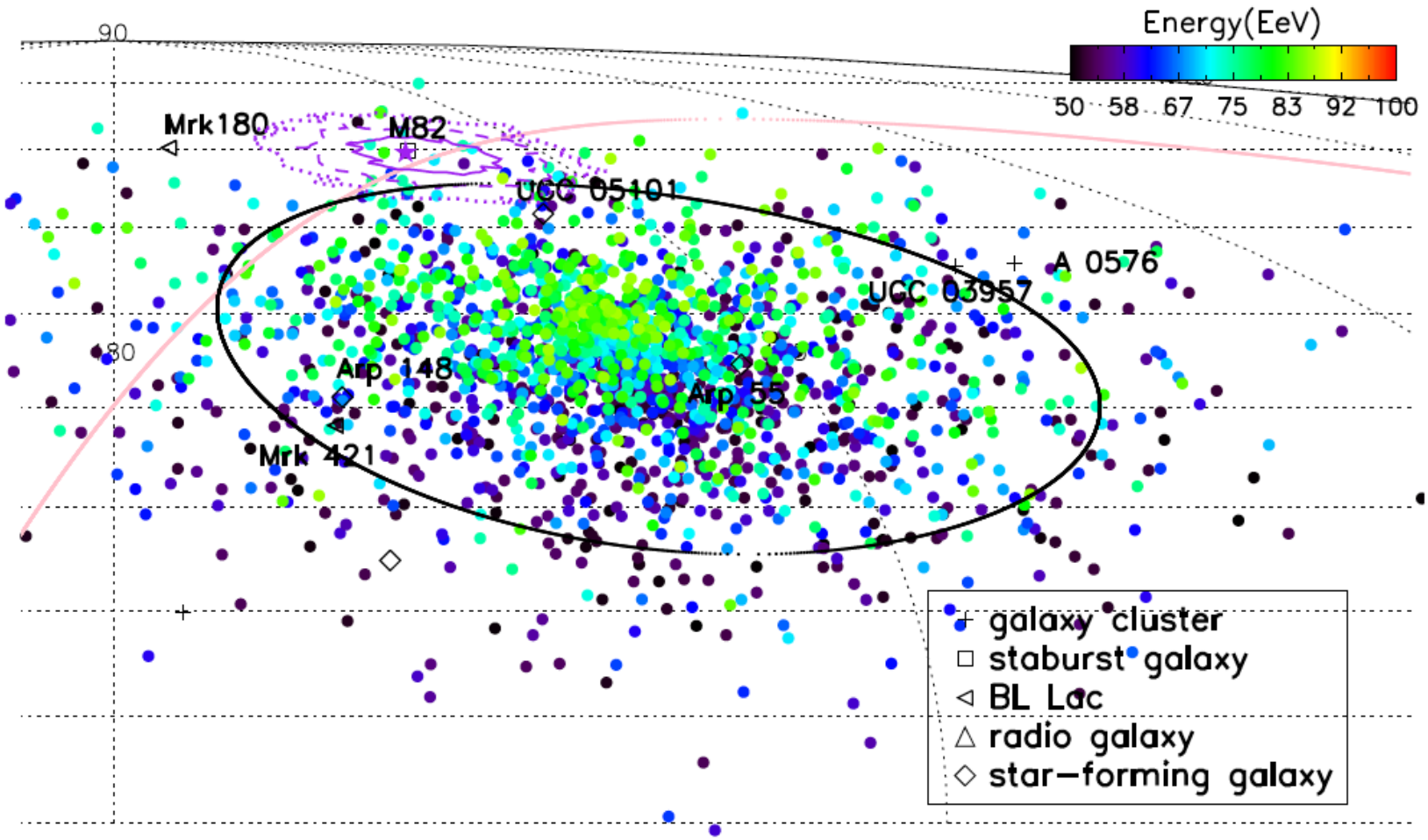
GMF (∼1kpc): 25μG/z. EGMF (∼1Mpc): 25nG/z.

Regular Field: $Z\frac{D_{\rm reg}}{1\ {\rm Mpc}}\frac{B_{\rm reg,\perp}}{1\ {\rm nG}}$ ~35 For M82.

GMF (∼1kpc): 35μG/z. EGMF (∼1Mpc): 35nG/z.

Reduced error with increasing statistics

2000 events TA × 4 JEM-EUSO



Summary and Discussion

- The MCB method can be adopted for future increasing statistics
- Compositions of hotspot events & Magnetic fields
- Spectrum of hotspot events (GZK cutoff?)
- EeV Neutrinos $\sim(2.2 \pm 0.5) \times 10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$

For sources with distance about 200 Mpc, assuming a pure proton composition, 90% UHECRs are strongly attenuated by photo-meson interactions with CMB photons, and produce neutrinos.

Thank you!

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.

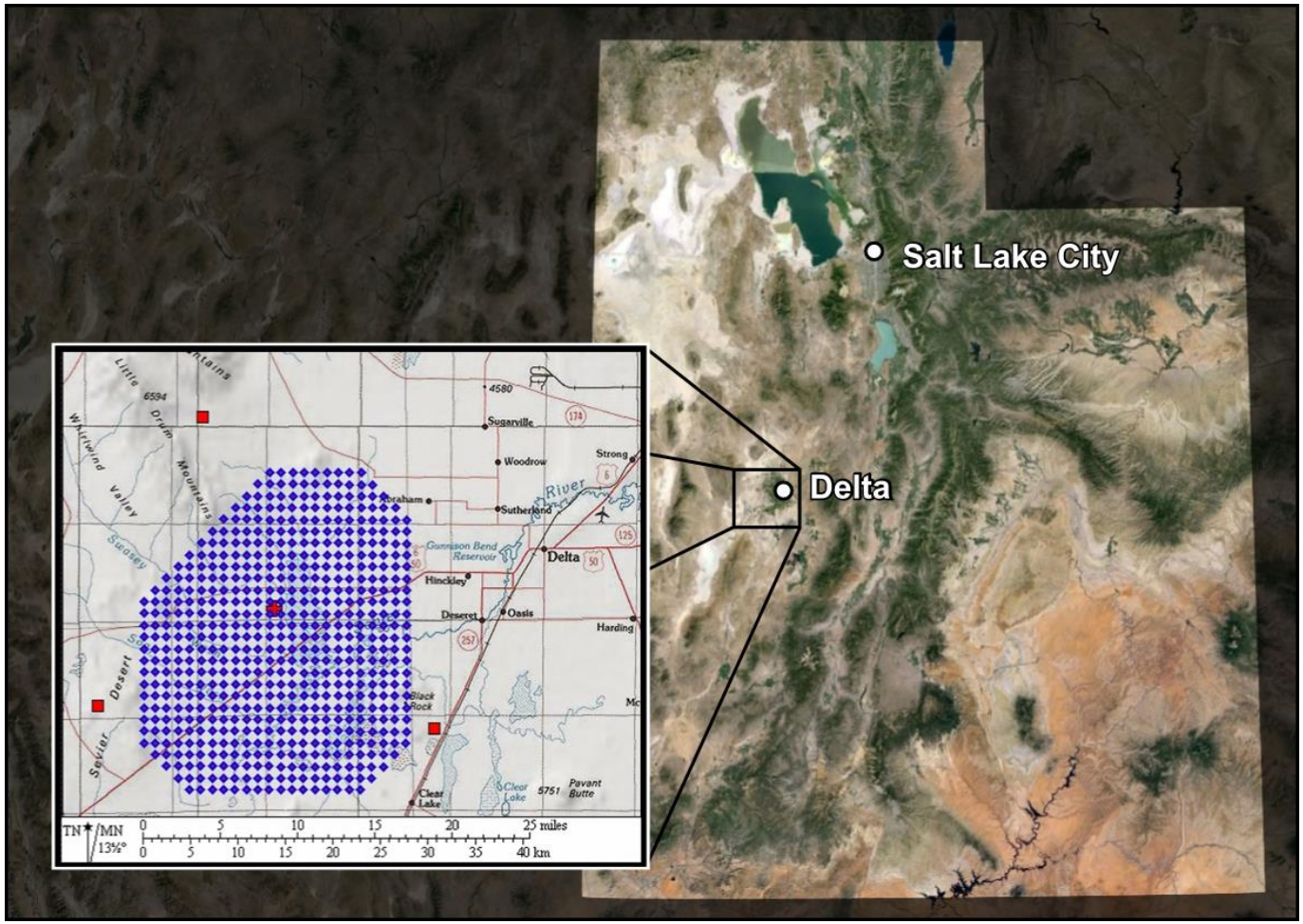
- Our analysis reveals that the distribution of the TA hotspot events is diffused strongly by the random magnetic field, consistent with the single source hypothesis, and the chance probability of this distribution is 0.2%.

- 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!

Telescope Array Experiment (Japan-US)



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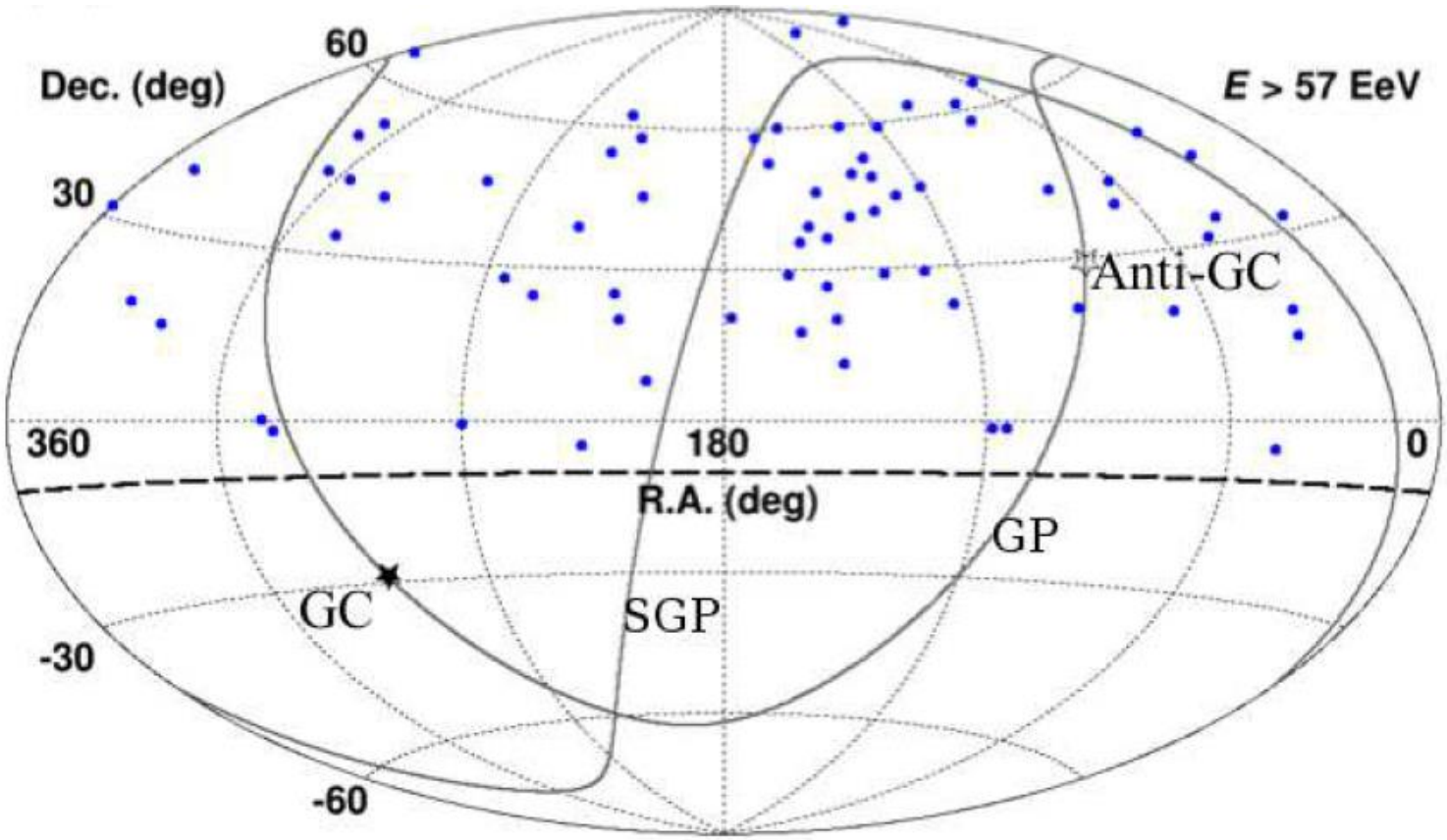
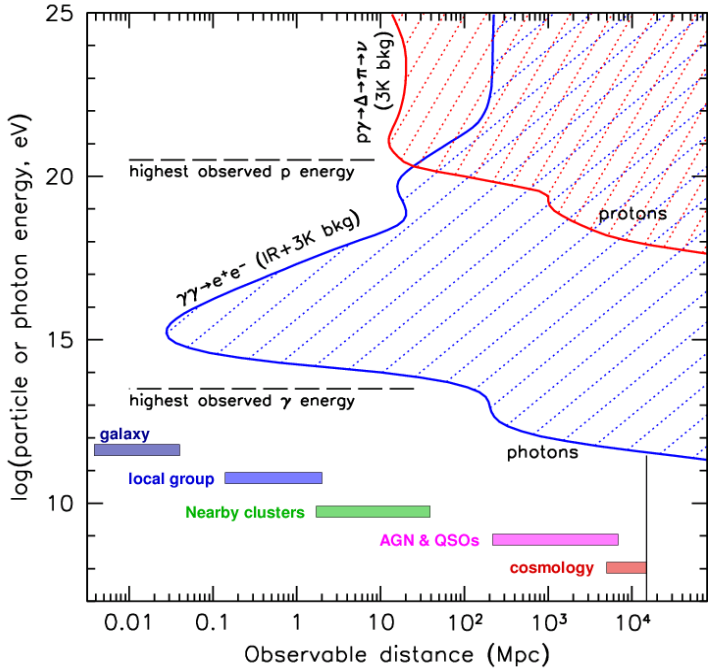
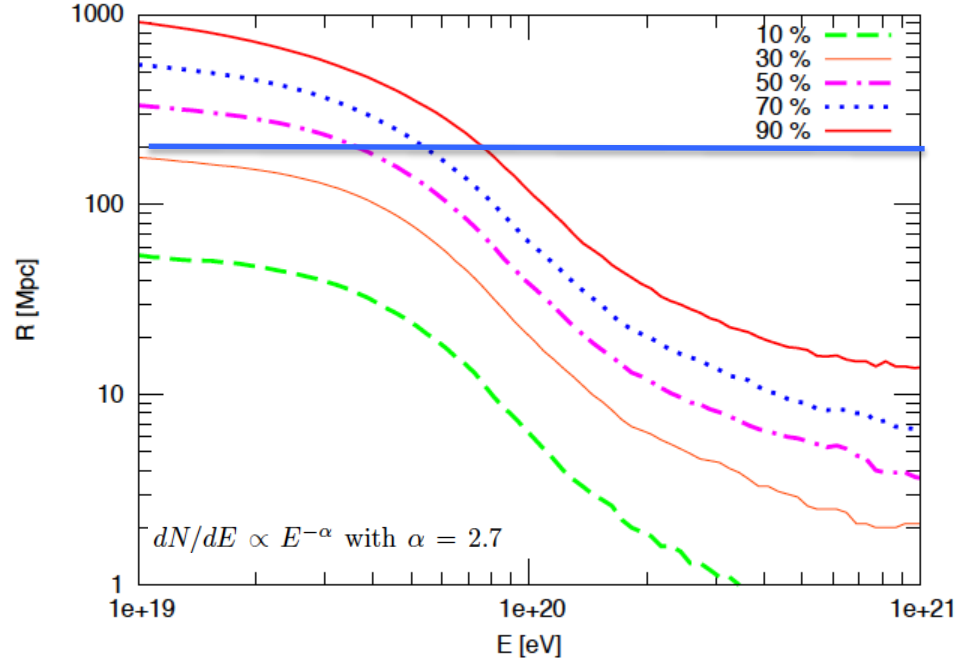


(Data between 2008 May 11 and 2013 May 4, The TA Collaboration, 2014)

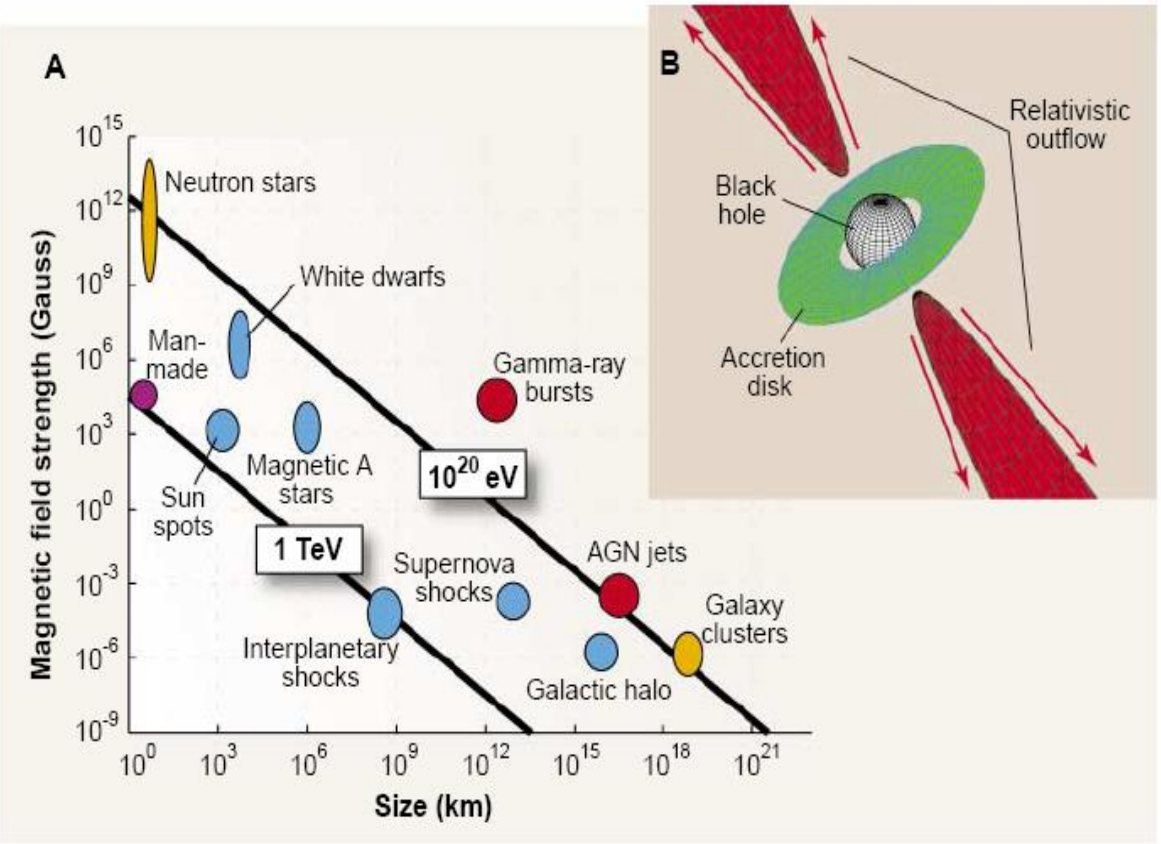
The GZK suppression—Distances of sources





Kotera & Olinto 2011

Acceleration capability



Lamor Radius=Typical scale of sources

Emax=ZBL