"The Possible Extragalactic Source of UHECRs at the Telescope Array Hotspot "

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RIKEN

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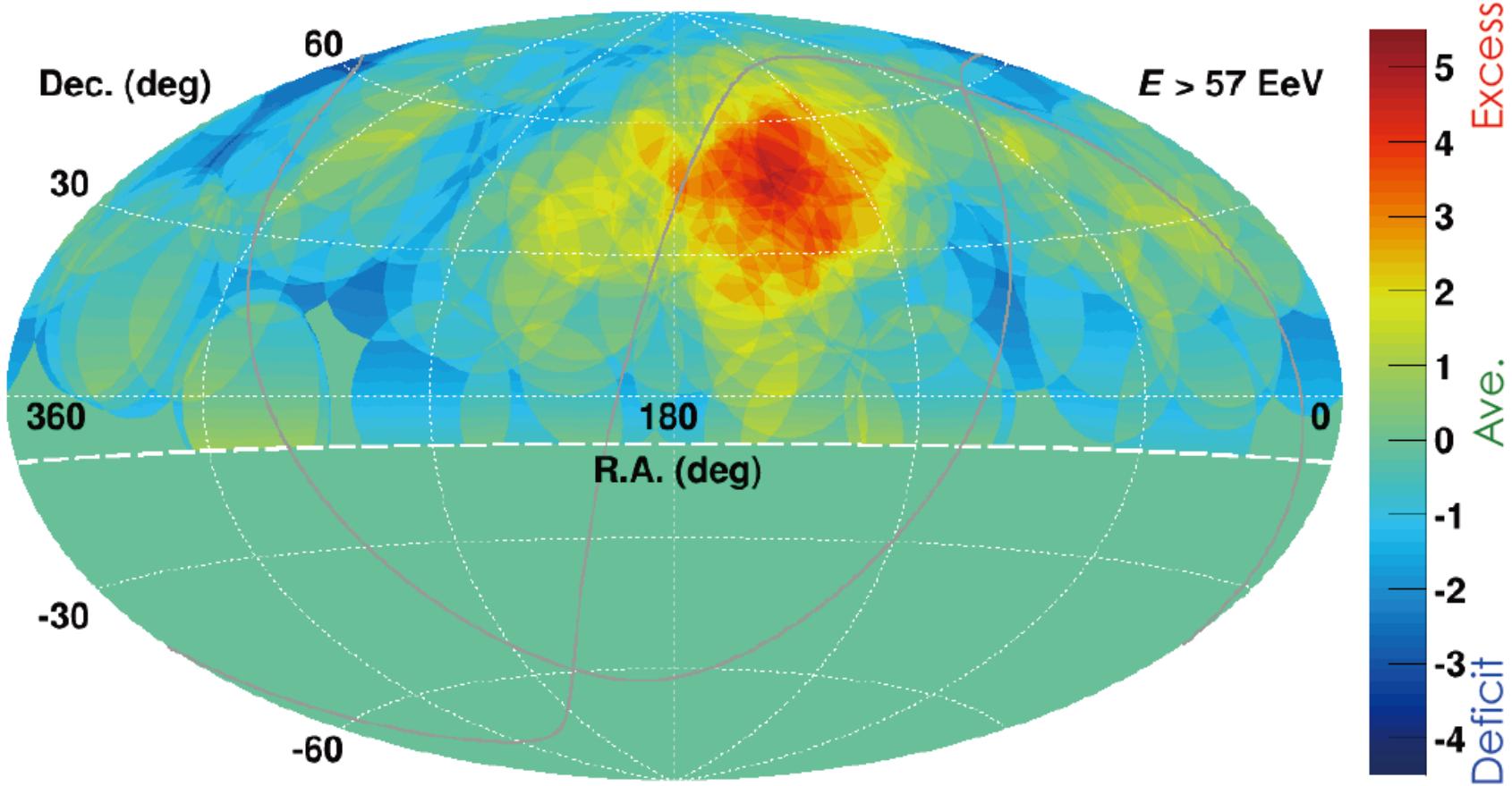
Kawata et al. @ ICRC 2015

Significance Map 7 years

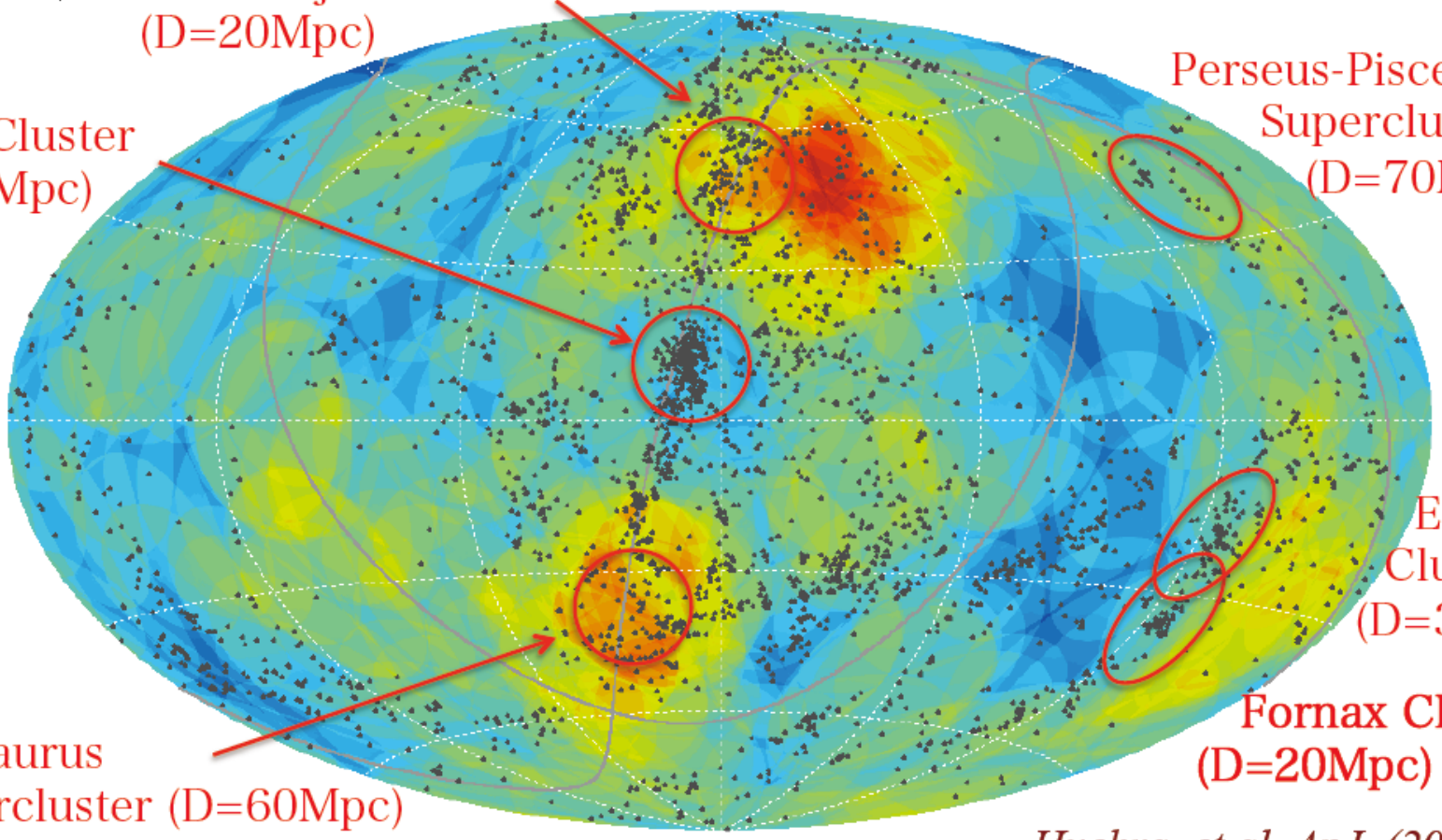
New!

Oversampling with 20°-radius circle



Max significance **5.1σ** (N_{on} = 24, N_{bg}=6.88) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)

Nearby Galaxy Clusters



Huchra, et al, ApJ, (2012)

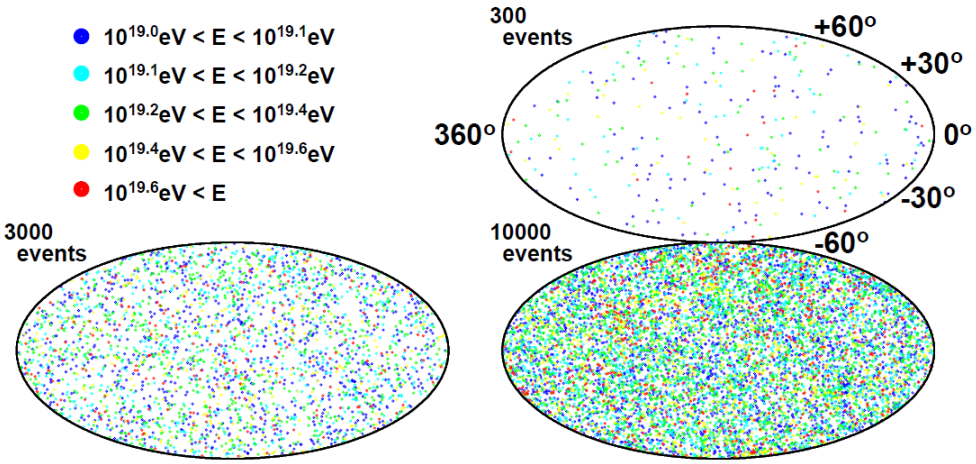
Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster
TA & PAO found no excess in the direction of Virgo.

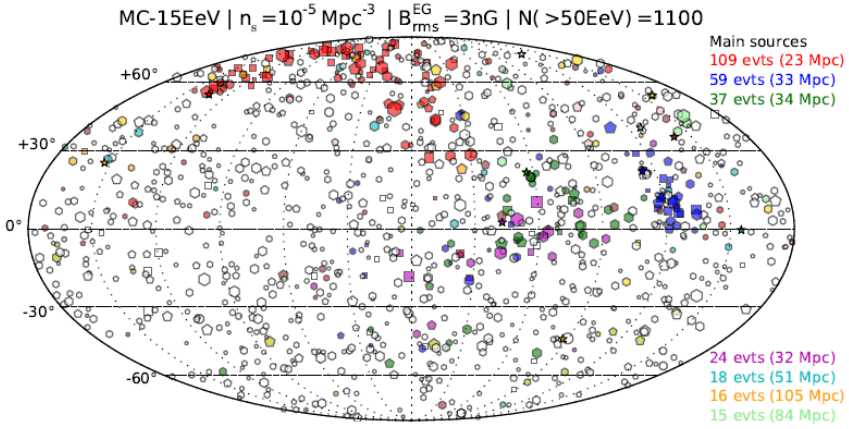
Previous Theoretical Studies

- Motivated by Past Observations of Multi-plets (AGASA) and the Cluster (PAO), detailed numerical studies were done (e.g. Yoshiguchi,S.N.,Sato +03,04; Takami+06,10,12; Yuskel+12; Rouille d Orfeuil, Allard,+14,…).

But Hard to Identify the Source(s) yet…



Yoshiguchi,S.N.,Sato +04



B. Rouillé d'Orfeuil[1,2], D. Allard[3], C. Lachaud[3], E. Parizot[3], C. Blaksley[3], and S. Nagataki[4]

2014

Deflection and Time Delay Due to B-Fields ?

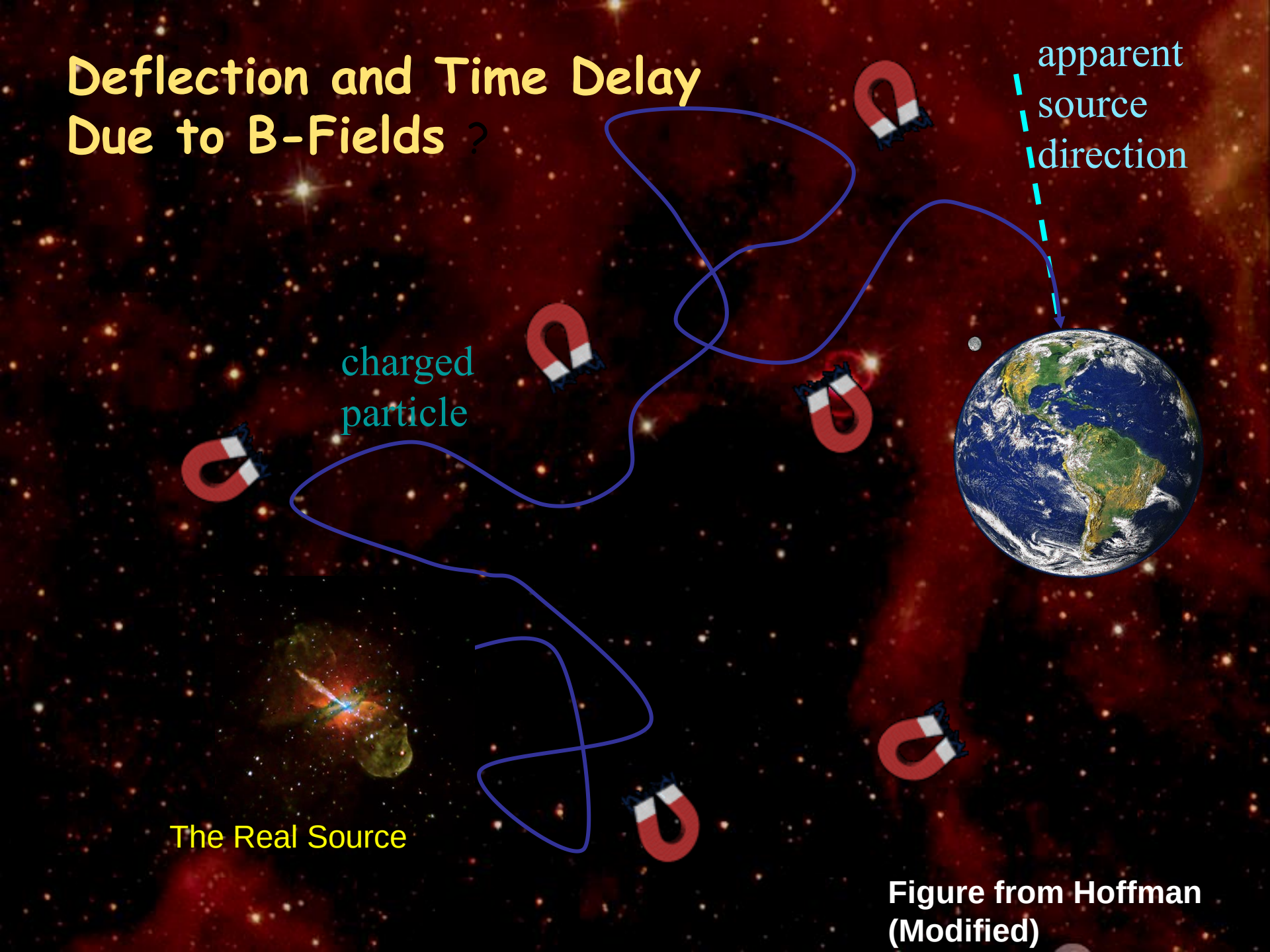
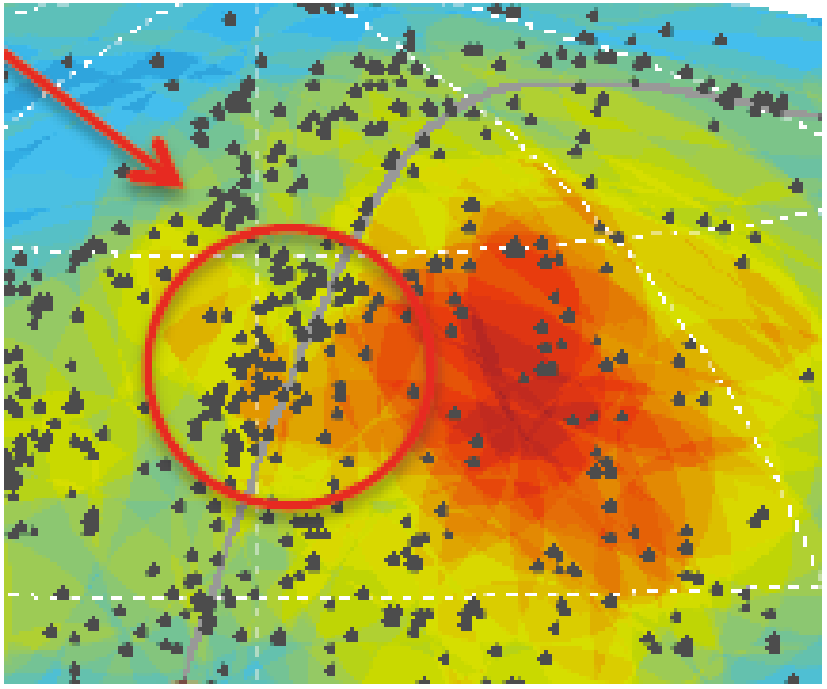


Figure from Hoffman (Modified)

Motivation & Method of This Study



Kawata et al. @ ICRC 2015

Black Dots are nearby galaxies.
Grey line represents the Super-Galactic-Plane.

Is the Source of the Hot Spot in the Spot?

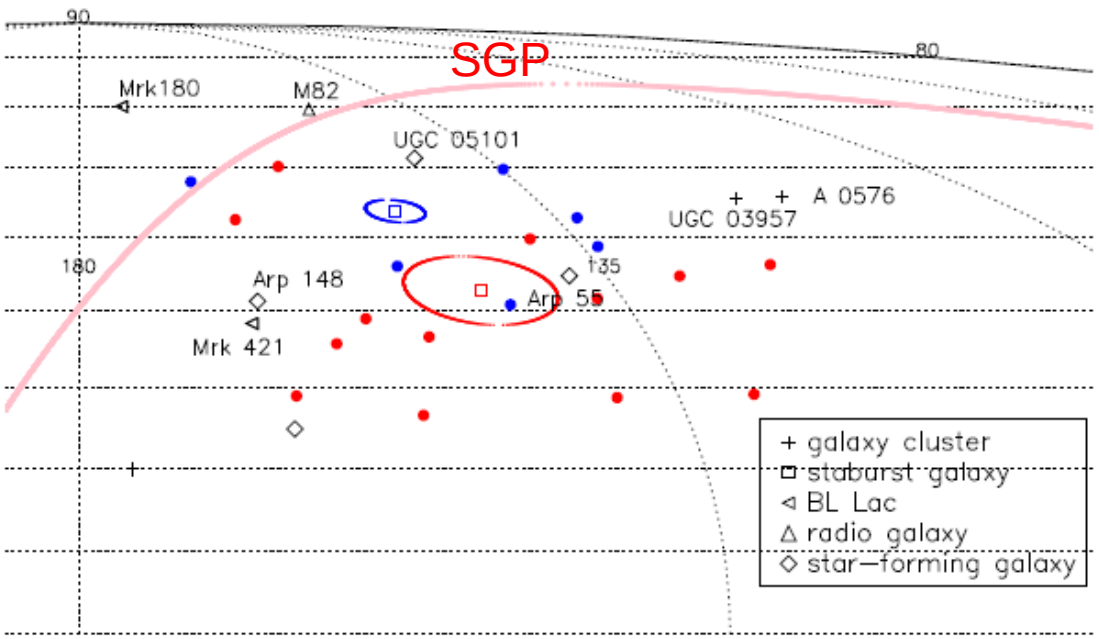
Or,

Is the Source away from the Spot due to B-Fields?

Before going to detailed numerical simulations, We did some simple analysis, and found some Very Interesting Implications!

Our First Analysis

- Data Sample: 72 Events with > 57EeV (5years, TA-Collaboration ApJ 2014.)
- We analyzed the 19 events of the hot-spot.



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

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

Circles represent the mean Positions of the events.

The Source is at around The Super-Galactic-Plane?

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Magnetic Bending Effects

Effect of Regular Field:

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

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

$D_{\rm reg}$: Propagation length
In the regular B-field.

Effect of Random 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: $\delta_{\rm dif}$

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

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

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

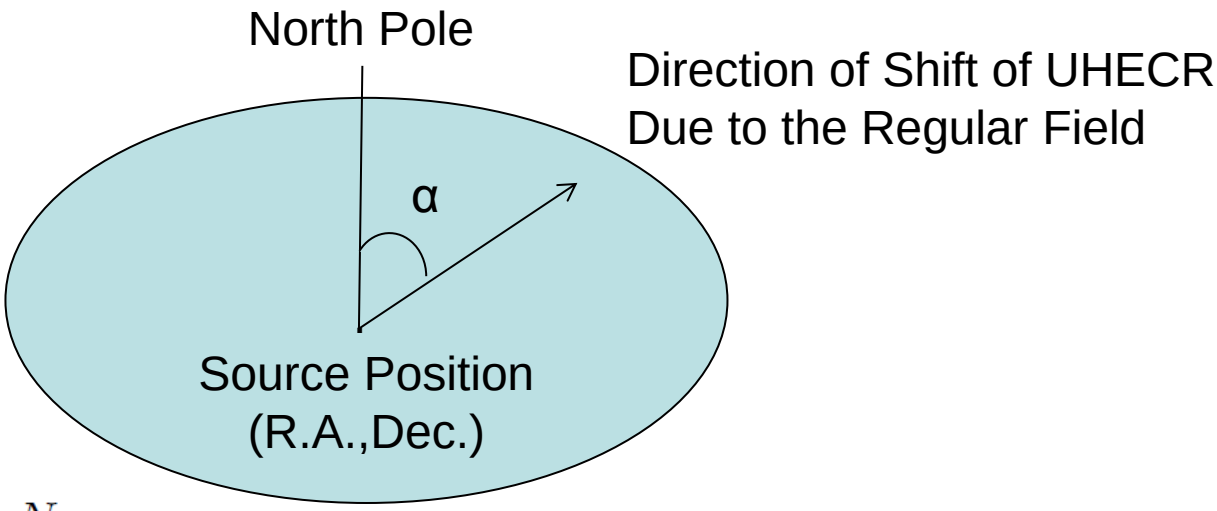
$D_{\rm dif}$: Propagation length
In the random B-field.

$D_{\rm c}$: Coherent length
of the random B-field.

Monte Carlo Fitting Engine

Probability for i-th UHECR arrives at the Earth from the observed direction
From the source at (R.A.,Dec.) with A1, A2, and α.

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



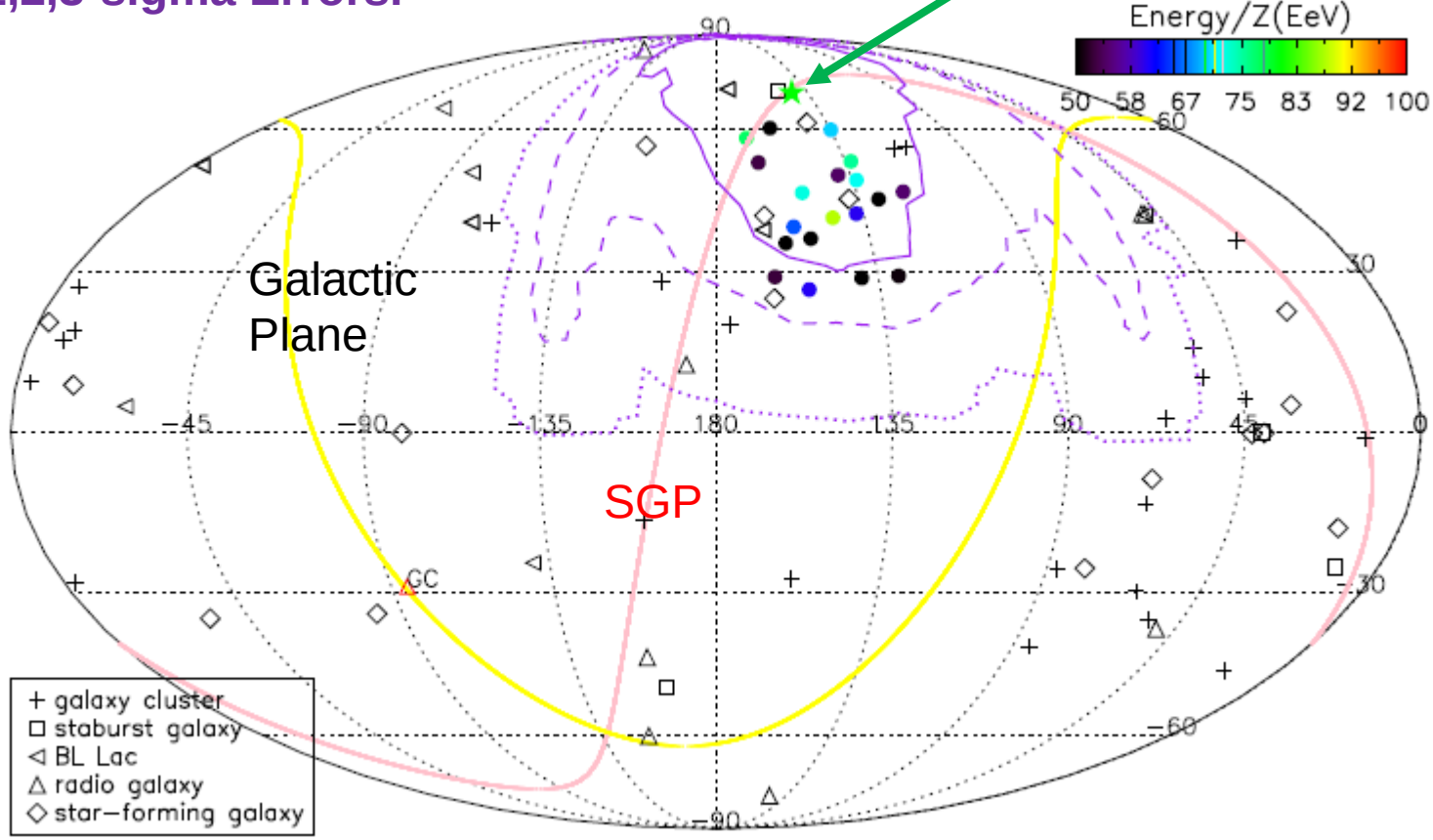
$$P \propto \prod_{i=0}^{N} f_i$$ Total Probability.
N (=19) is the number of the events in the hot-spot.

→ By the Monte-Carlo likelyhood fitting, we can obtain the best values for (R.A.,Dec.,A1, A2, α) (Zhang et al.15; Feroz & Hobson 08).

The Source is on the SGP?

The most likely Source Position As a Result of Our Analysis.

Purple Lines are Source Positions With 1,2,3-sigma Errors.



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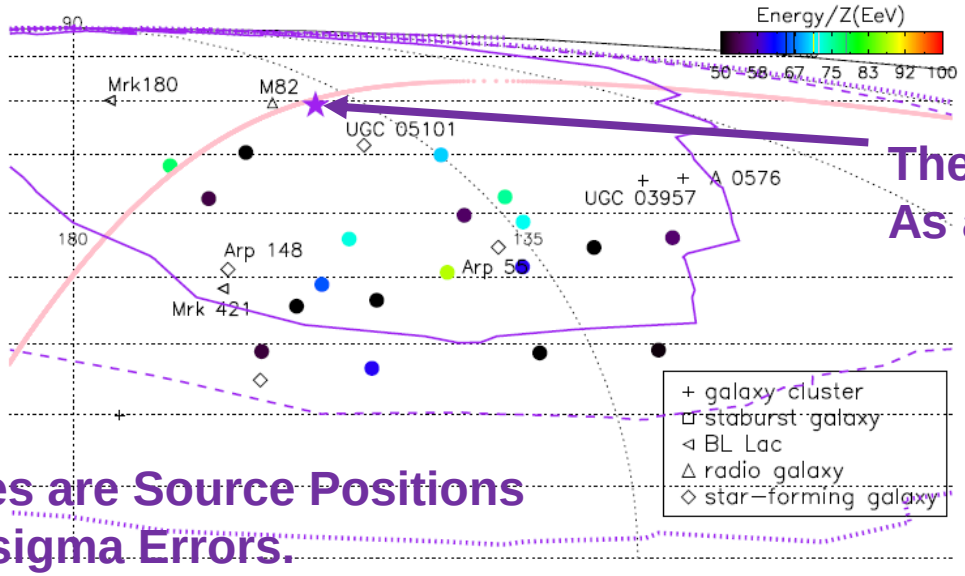


The most likely Source Position As a Result of Our Analysis.

Purple Lines are Source Positions With 1,2,3-sigma Errors.

M82 is very Close from the most likely Source Position!

Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\mathrm{bes-fit}}$ (%)
best-fit	-	-	$17.4^{+17.0}_{11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	10.5	10.0	41.8
Mrk 421	blazar	134	11.2	9.9	35.6

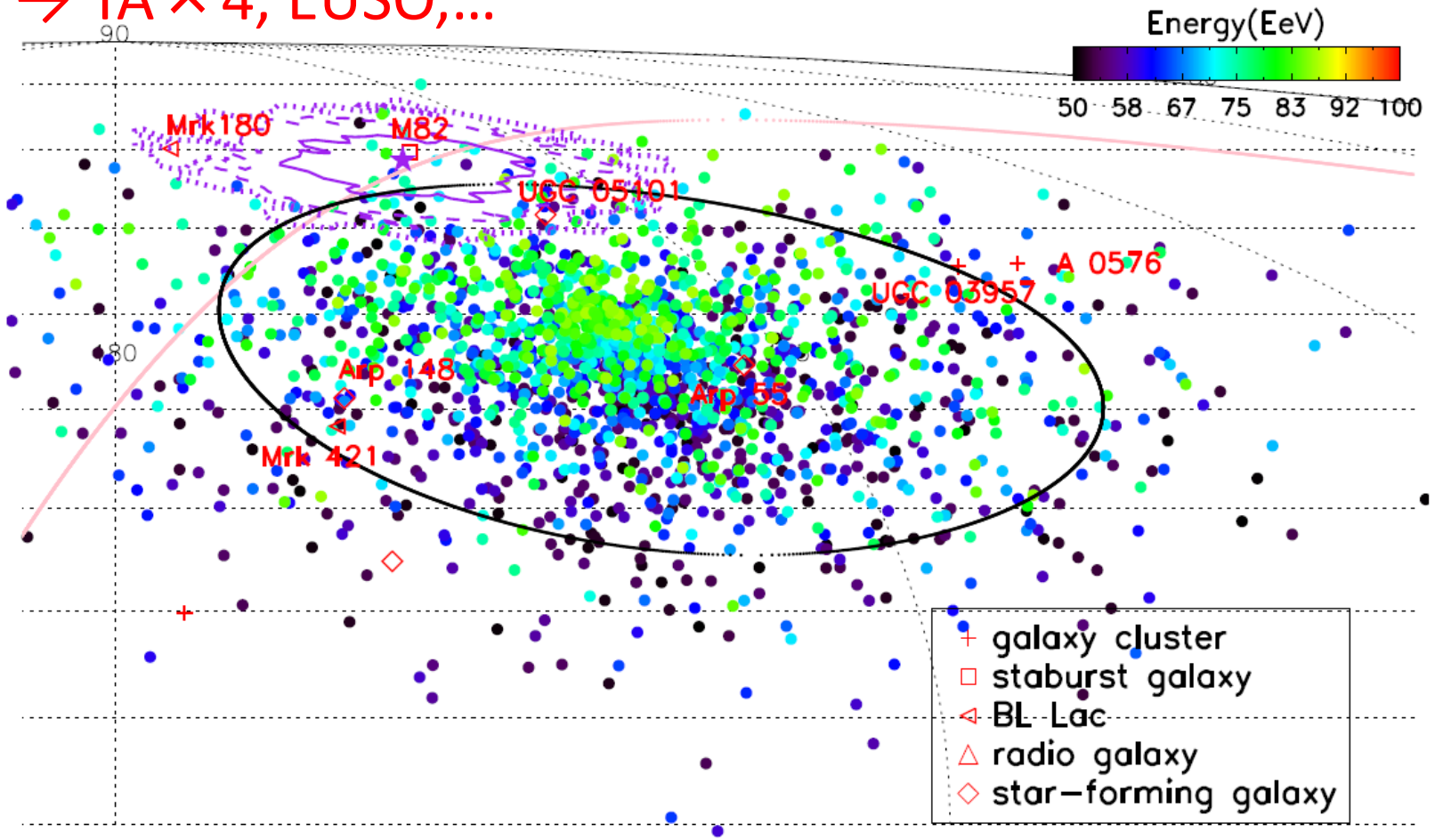
M82

§ Discussions

Discussion - I

We can Identify the Source if we have 2000 Events.

→ TA × 4, EUSO,…



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Discussion - II

A transient source is NOT favored.
A long-duration source is favored.
Multiple transient sources (e.g. some GRBs in a star burst galaxy) are also accepted.

Arrival Time Delay relative to Neutral Particles (photons) due to magnetic bending effect.

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

Arrival Time Delay between two UHECRs.

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

>> 5 years (TA's Observation)

= The former UHECR should be ejected
From the source about $3.3 \times 10^4 \mathrm{yr}$ before.

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

~0.01 for a few degs.

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Discussion - III

Where are the B-Fields?

Random Field: $A_2 \sim 9 - 10$

$$\longrightarrow \quad Z \left(\frac{D_{\rm dif}}{1{\rm Mpc}} \right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1{\rm Mpc}} \right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}} = 25 - 28$$

$\longrightarrow$ GMF (∼1kpc): 25μG. EGMF (∼1Mpc): 25nG. For z=1

Regular Field:

$$A_1 \times 2 = Z \frac{D_{\rm reg}}{1{\rm Mpc}} \frac{B_{{\rm reg},\perp}}{1{\rm nG}} = 35.2^{+6.8}_{-5.4}$$

For M82.

$\longrightarrow$ GMF (∼1kpc): 35μG. EGMF (∼1Mpc): 35nG.

GMF Model is challenged by them? EGMF will be OK.

Discussion - IV

We still believe that past Gamma-Ray Bursts/Hypernovae happened in Milky Way Can Contribute to (Sub-) UHECRs Partially.

This study was Motivated by the analysis of composition by PAO.

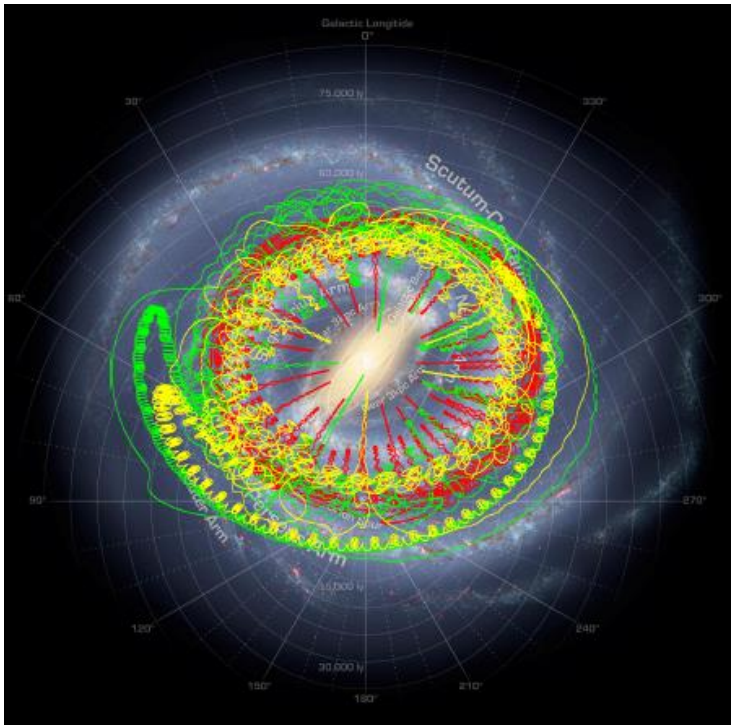
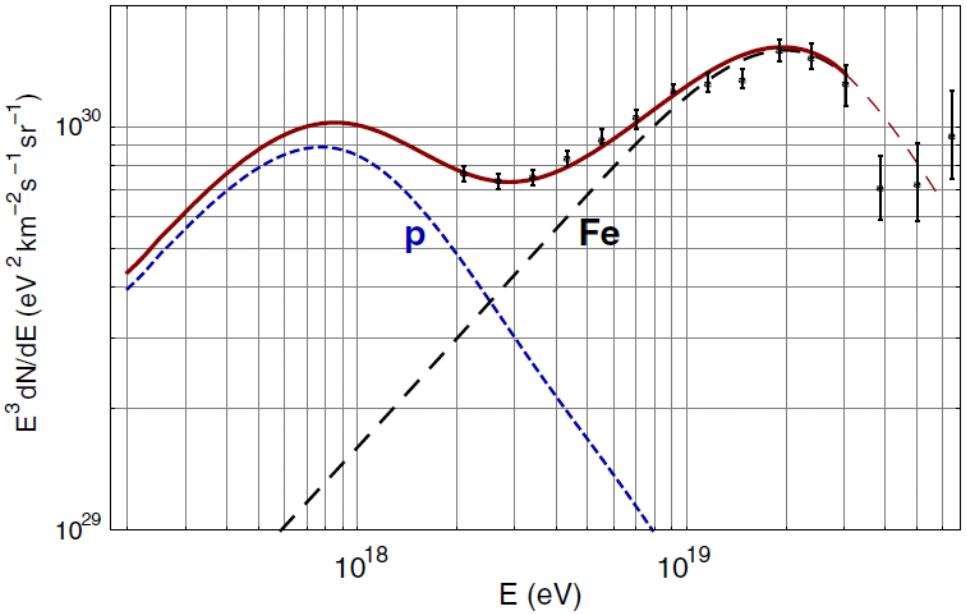


Image: UHE-Nuclei in Milky Way



Calvez, Kusenko, S.N. PRL 2010

Summary

- Our Analysis Suggests that the Source of the Hot-Spot is NOT in the Hot-Spot, but around (or on) the Super-Galactic Plane.
- M82 is the closest, active star-burst galaxy from the most likely position of the source in our analysis.
- ～2000 events are necessary to pin down the source position (TA×4, EUSO,…).
- A single transient source is not favored. A long-duration and/or multiple transient source(s) are favored.
- The origin of B-fields that are responsible for the distribution of the events of the hot-spot may be extra-galactic.
- We still believe that past GRBs/Hypernovae in Milky Way can contribute to the (sub-) UHECRs.