

Ultra-relativistic Magnetic Monopole Search with the Pierre Auger Observatory



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Ultra-relativistic Magnetic Monopole

- ❖ Magnetic monopole is expected from Dirac quantization equation. Existence of Monopole would achieve complete symmetry to Maxwell's equation.
- ❖ Typical energy is $\sim 10^{25}$ eV accelerated in extra-galactic or intergalactic magnetic field or astrophysical site.

S.D. Wick, T.W. Kephart, T.J. Weiler, and P.L. Biermann, *Astropart. Phys.* **18**, 663 (2003).

- ❖ If assuming as a moderate mass, $m=10^{11}\sim 10^{20}$ eV, monopole requires **ultra-relativistic** velocities, and detectable with Auger.

No detection

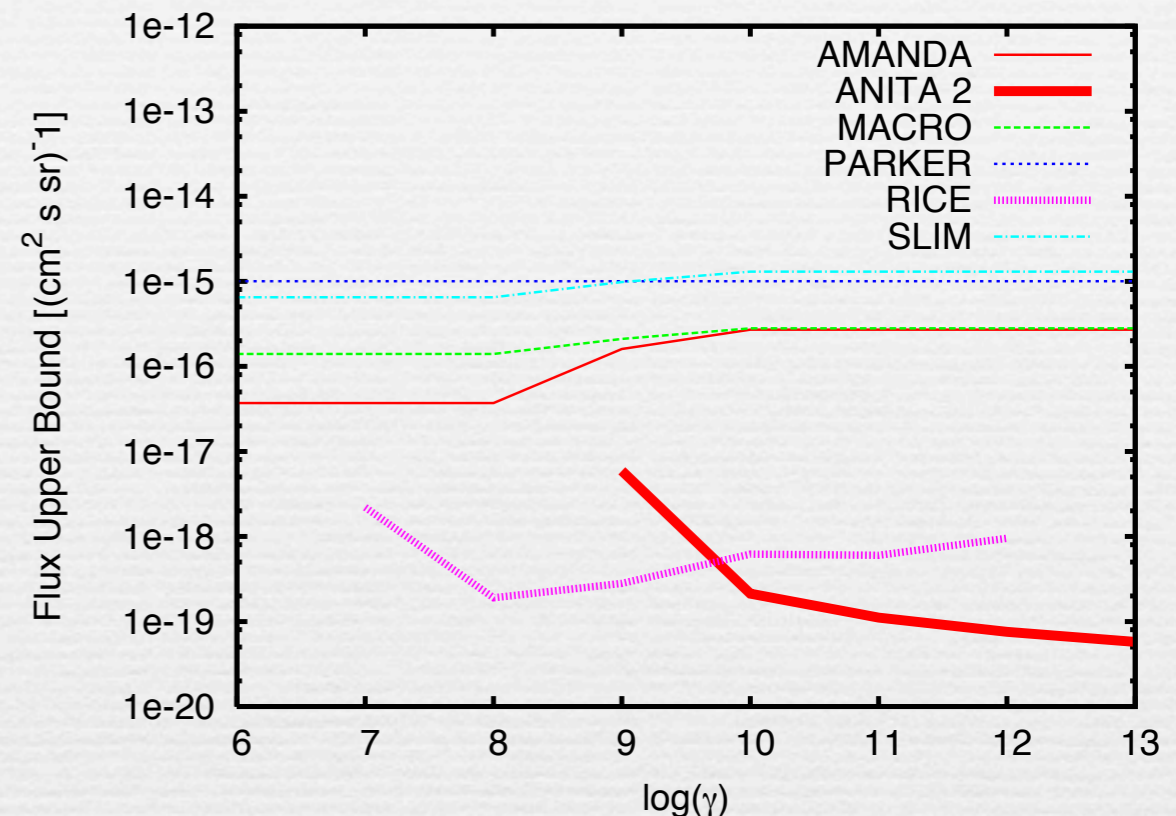


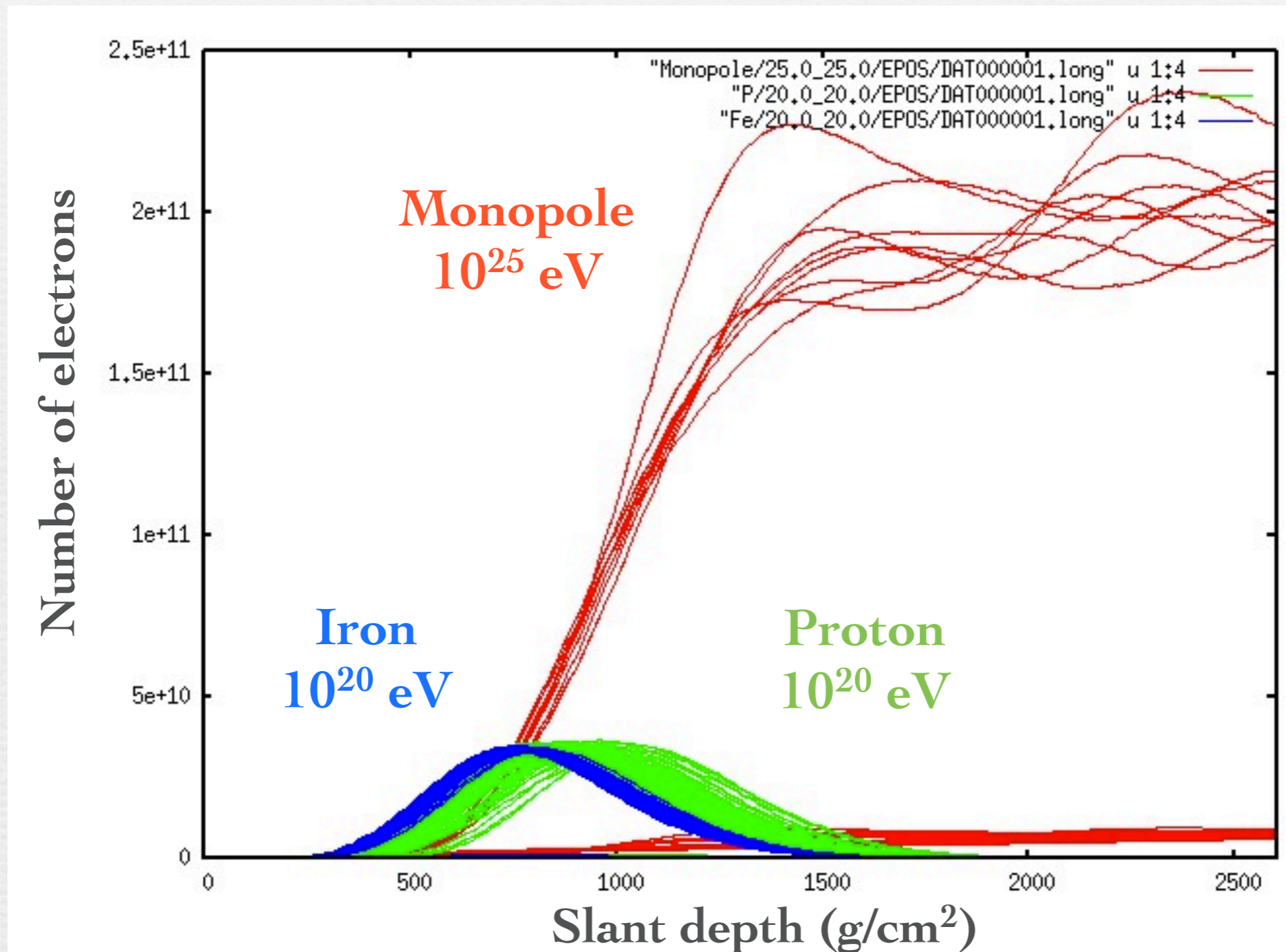
FIG. 12: Comparison of ANITA upper limit on diffuse monopole flux with other results. Save for RICE, other experimental results have been extrapolated up to our sensitive kinematic interval. In performing this extrapolation, the limits for $\gamma \geq 10^9$ have been weakened by a factor of two, to account for increasing Earth opacity.

ANITA-II: Upper Limit
 $\sim 10^{-19} \text{ (cm}^2 \text{ s sr)}^{-1}, 10^{10} \leq \gamma$

M. Detrixhe et al. (ANITA collaboration), *Phys. Rev. D*, **104**, 161101 (2010).

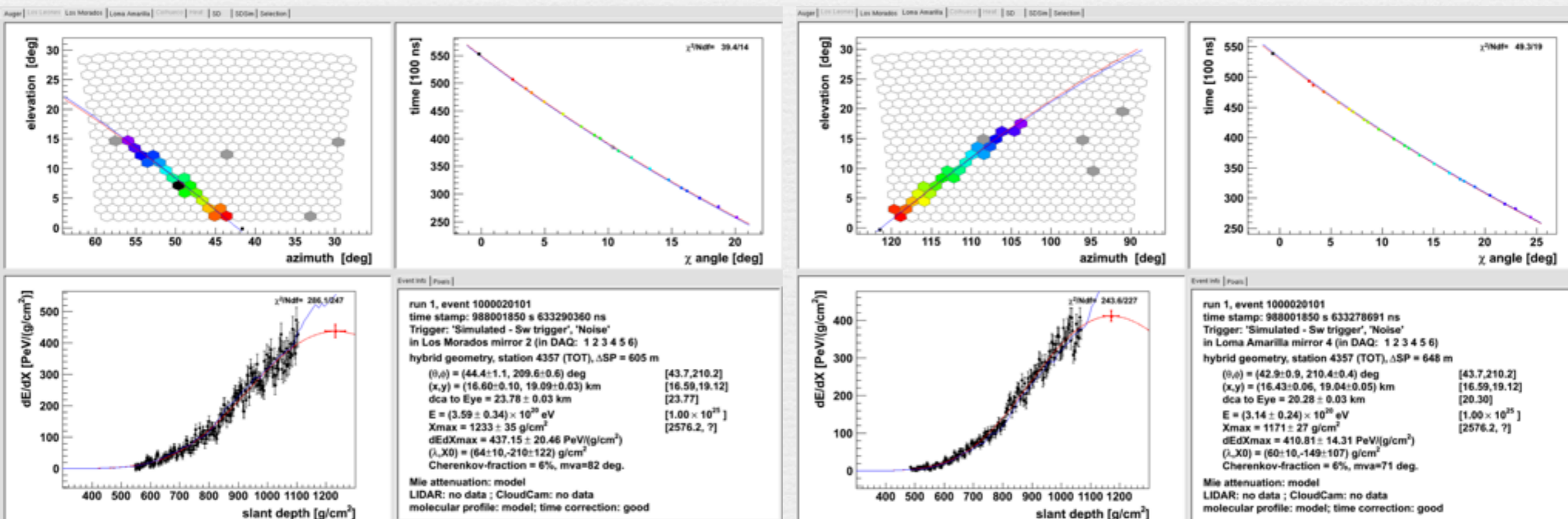
Longitudinal Developments

Monopole 10^{25} eV: Mass = 10^{14} eV, $\gamma = 10^{11}$



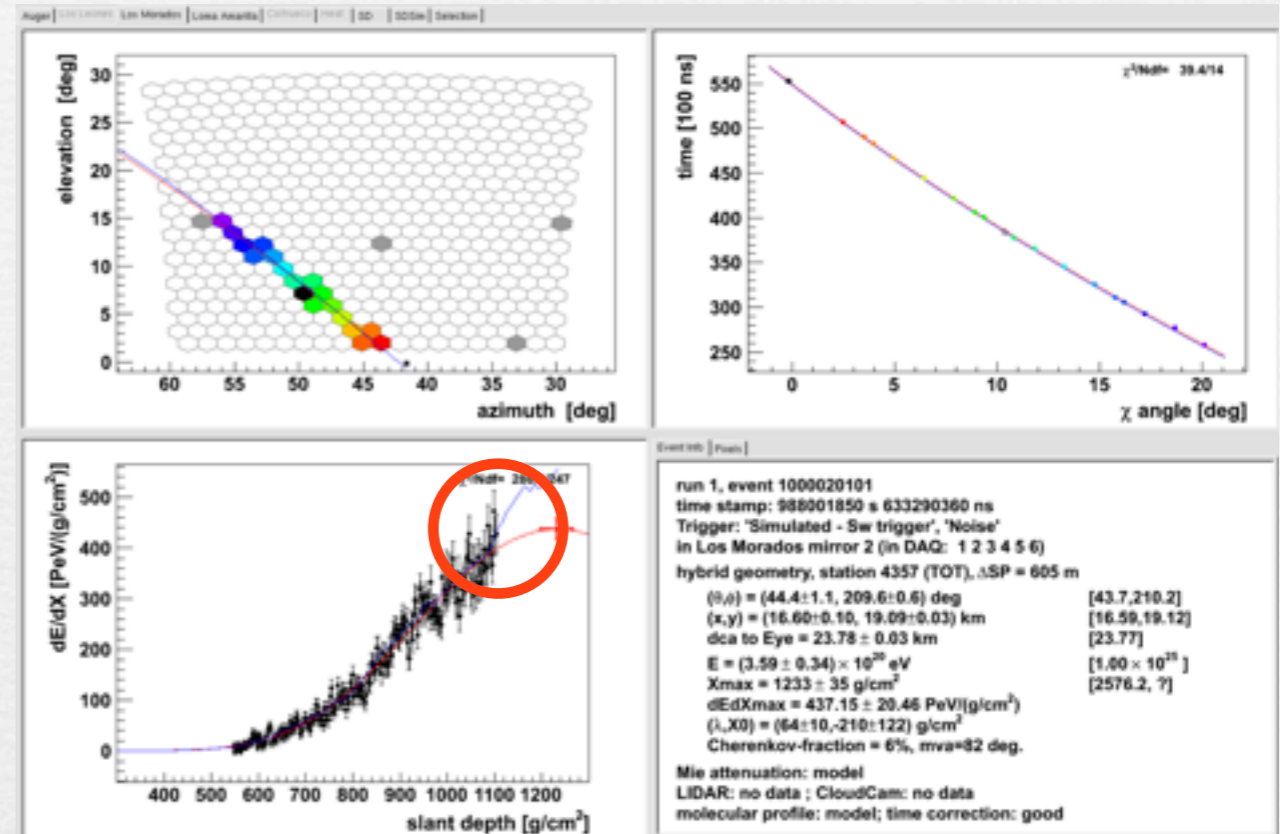
Feature of Monopole Showers with Auger FD

- Observe only “head” of developments.
- X_{\max} is out of the FD field of view.



Parameters for Monopole Search

Monopole shower generates an extraordinary large signal at the lower edge of FD field of view.



Shower

X_{up} (XTrackMax)

dE/dX_{up}

Field of View

FD

idealMC Study

Simulated region

- 0 < zenith < 60 degree, uniformly
- 0 < azimuth < 360 degree, uniformly
- Core: Auger SD region

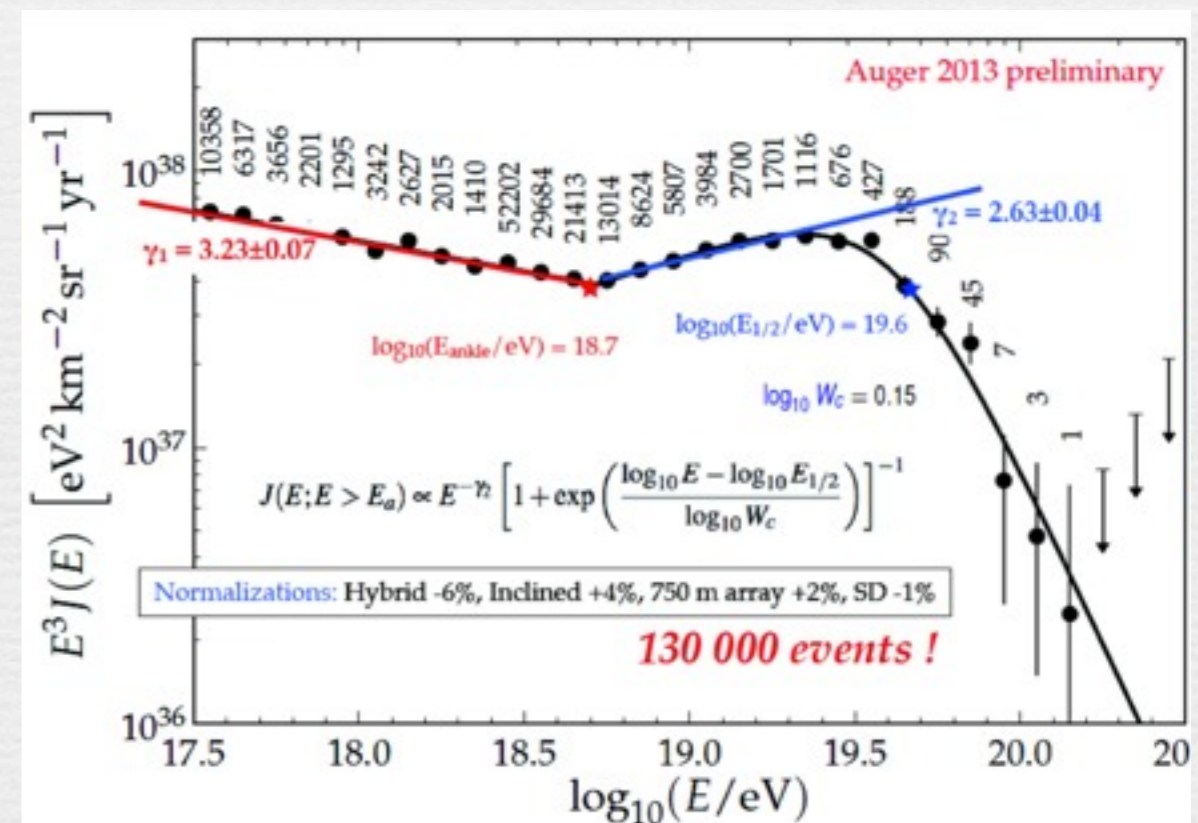
$$\text{Aperture}^{\text{MC}} \sim 7000 \text{ km}^2 \text{ sr}$$

Background

- Proton, Iron (Sibyll 2.1)
 - 17.0 < logE < 21.0
 - Wighted to fit Auger spectrum

Monopole

- Fixed total energy : 10^{25} eV (same energy with ANITA paper)
- $\gamma = 10^9, 10^{10}, 10^{11}, 10^{12}$
 - ex) If $\gamma = 10^{10}$, $m = 10^{15}$ eV. If $\gamma = 10^{12}$, $m = 10^{13}$ eV.



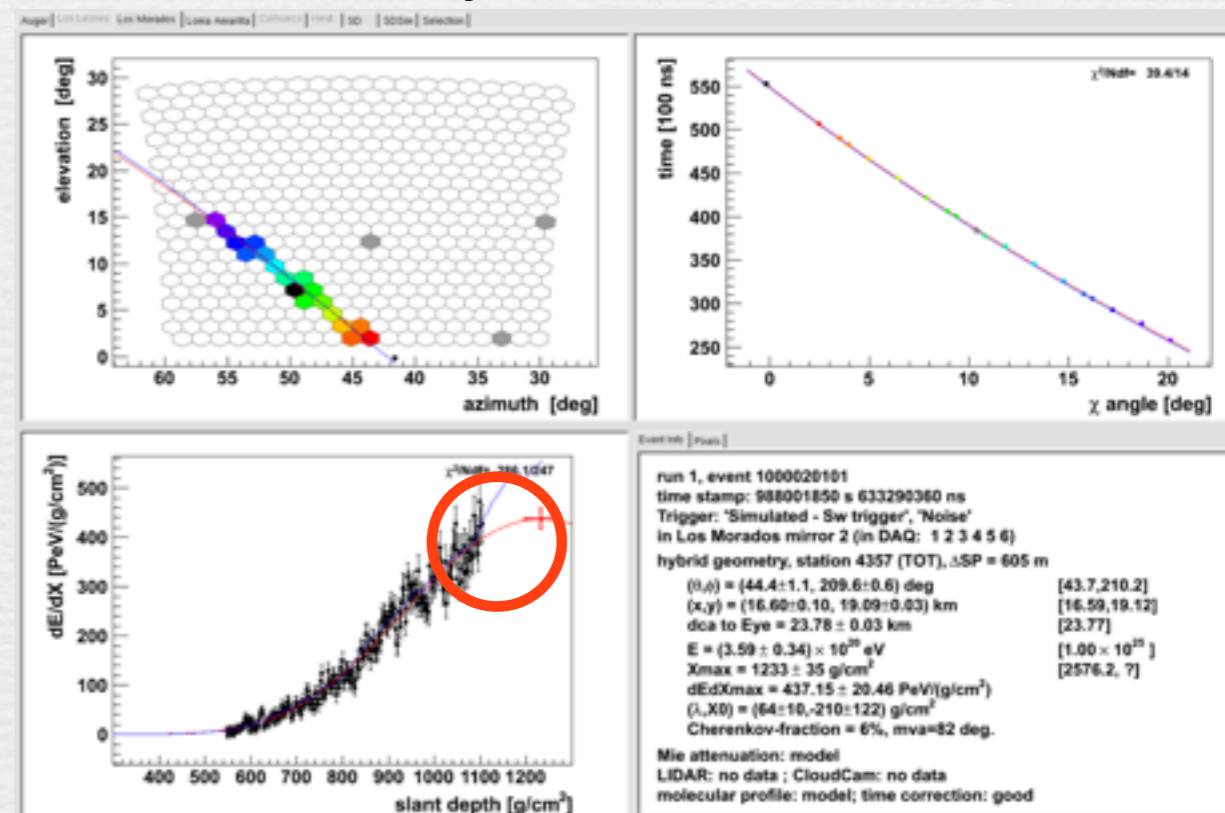
Quality Cuts

Pre-selection

- ☛ eyeCut 1111 (trigger efficiency)
- ☛ maxCoreTankDist 1e20 (geometry reconstruction efficiency)
- ☛ maxZenithFD 90
- ☛ minLgEnergyFD 1e-20 (shower profile reconstruction efficiency)

Event selection

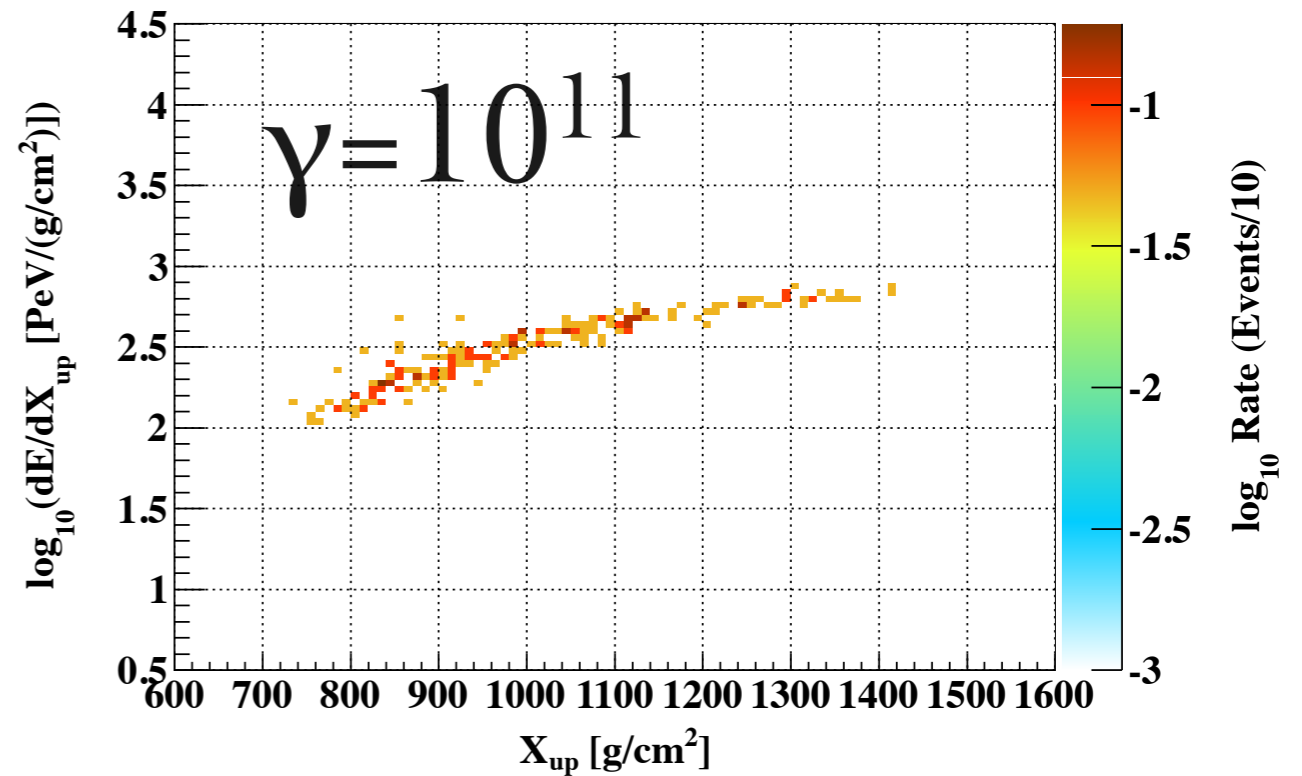
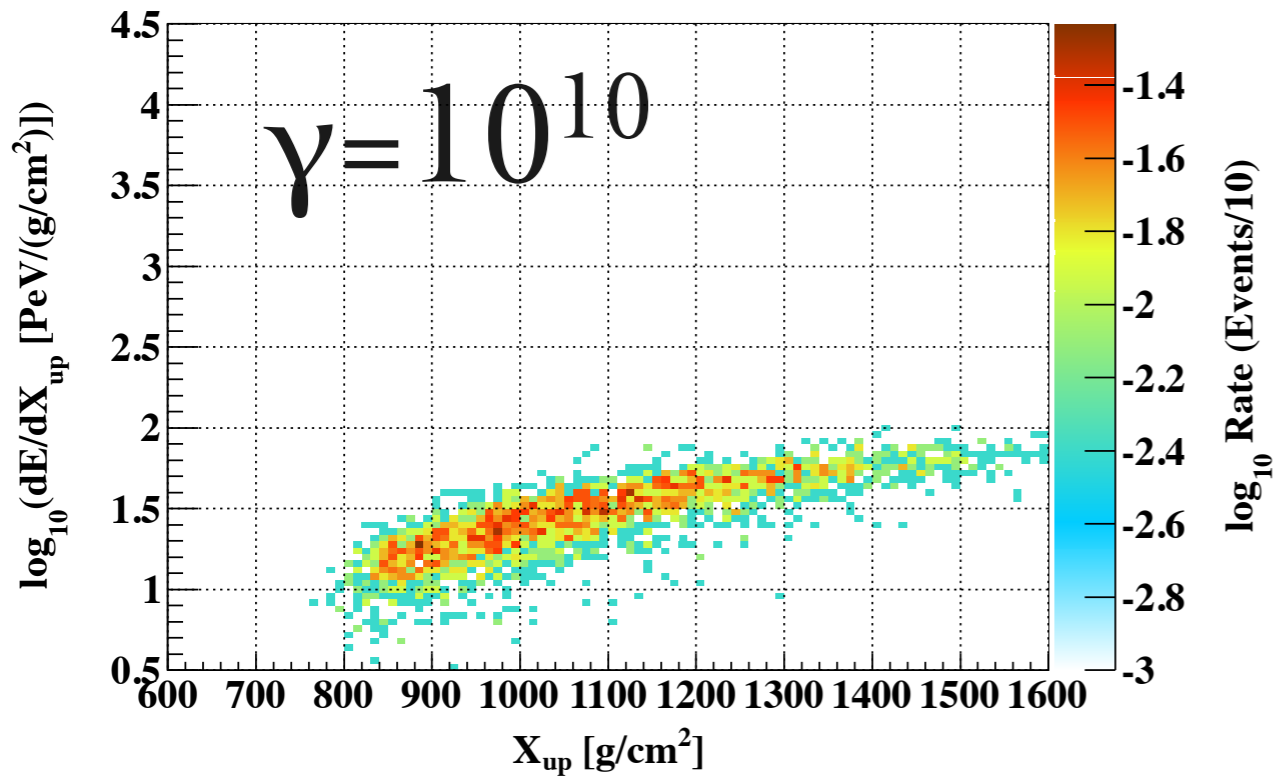
- ☛ maxCoreTankDist 1500
- ☛ xMaxError 150
- ☛ profileChi2 2.5
- ☛ depthTrackLength 200
- ☛ MaxDepthHole 20
- ☛ maxZenithFD 60
- ☛ mindEdXupFD 3.0 (PeV/(g/cm²))
- ☛ !maxShowerAge 1.0



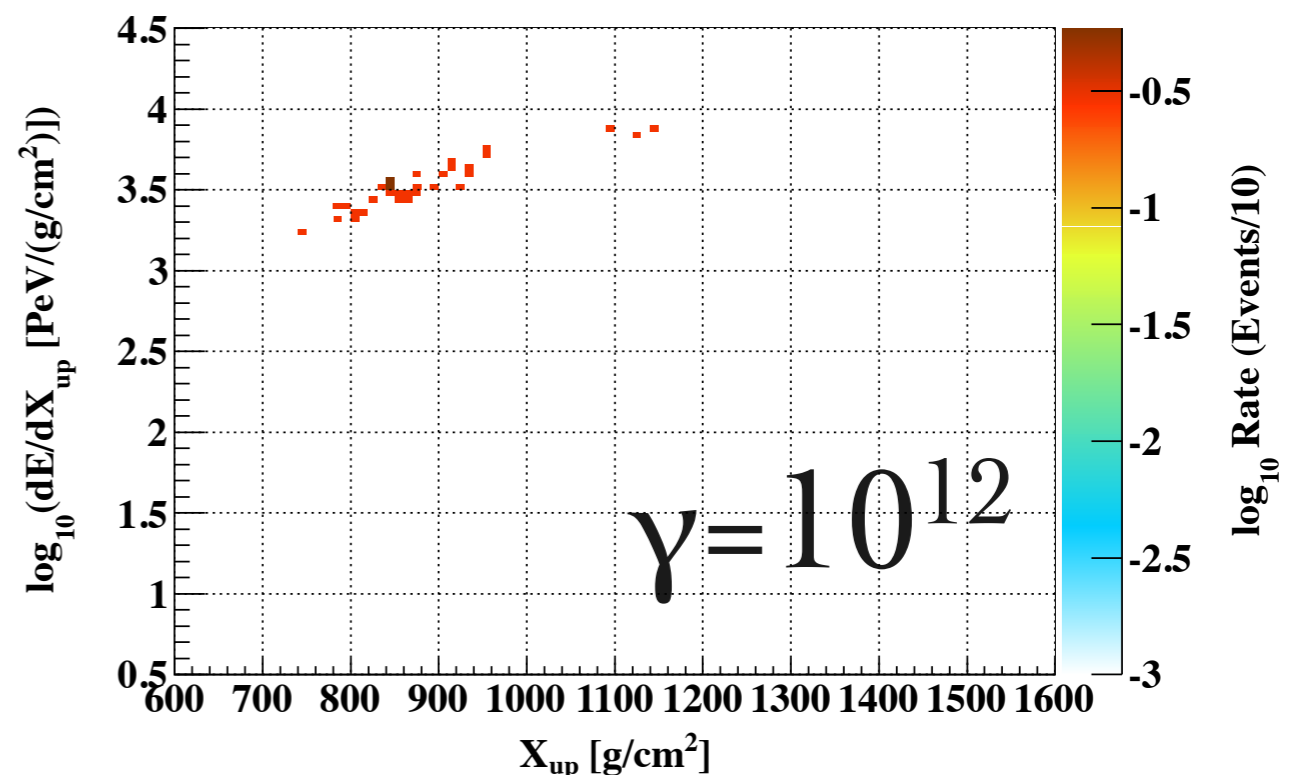
Large signal at Xup

Unbracketed Xmax

Monopole Signal



$\log(\gamma)$	$\varepsilon = N_{\text{reco}}/N_{\text{gen}}$
9	0.03
10	0.51
11	0.82
12	0.97

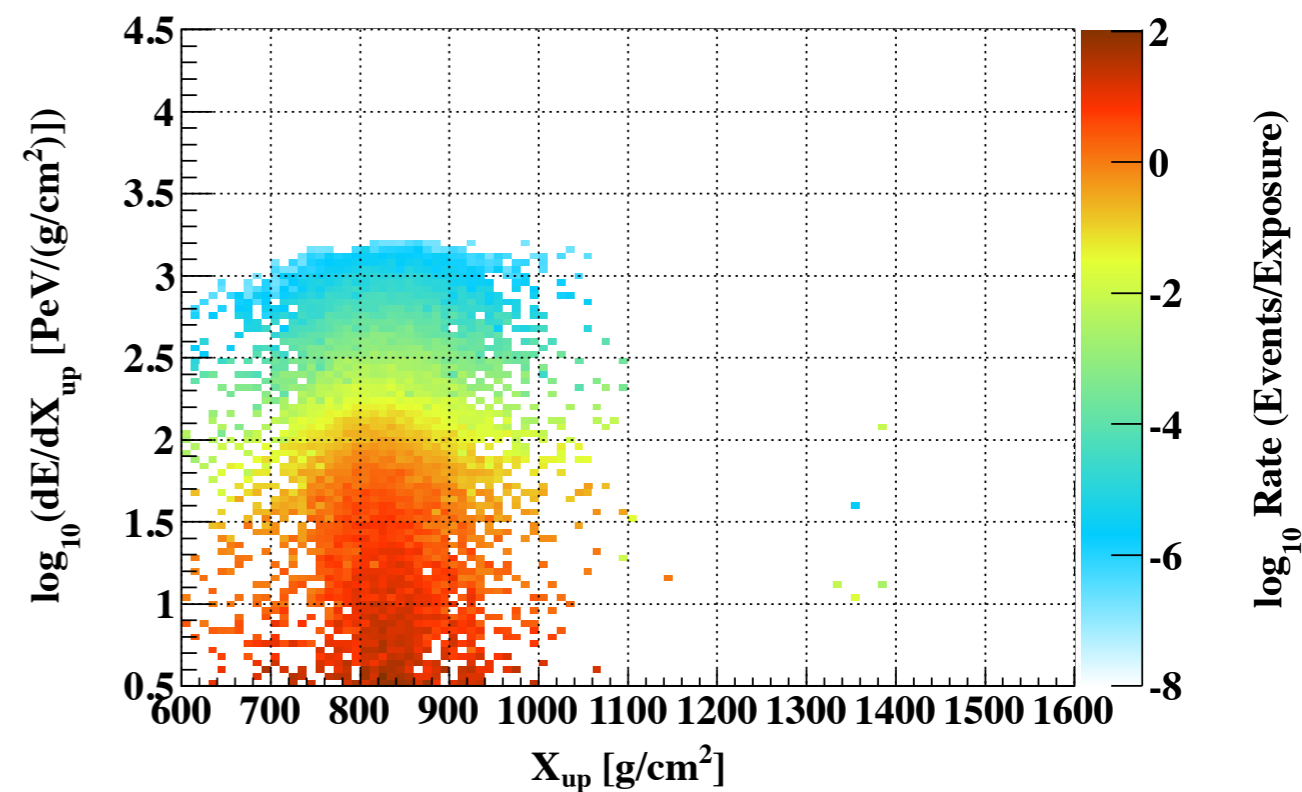
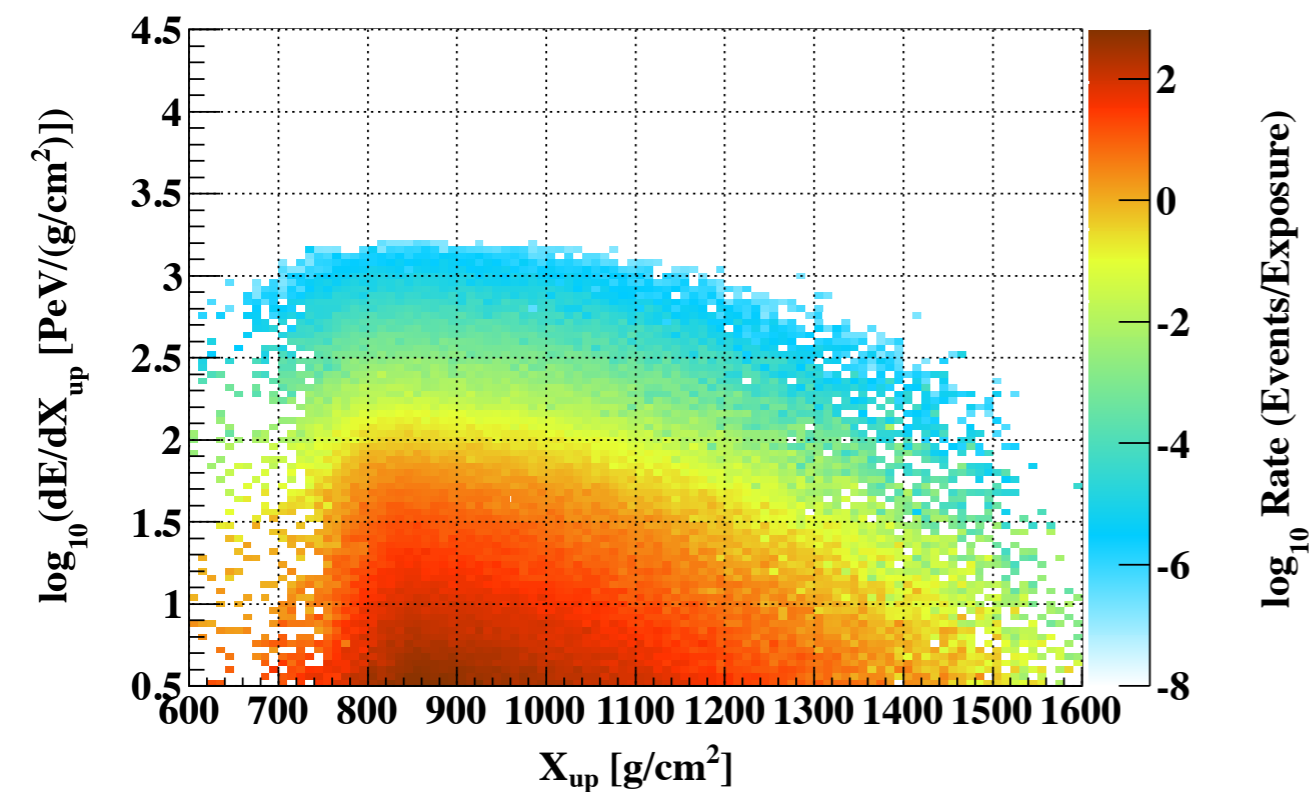


Background

Proton

Without unbracketed
Xmax Cut

WITH unbracketed
Xmax Cut

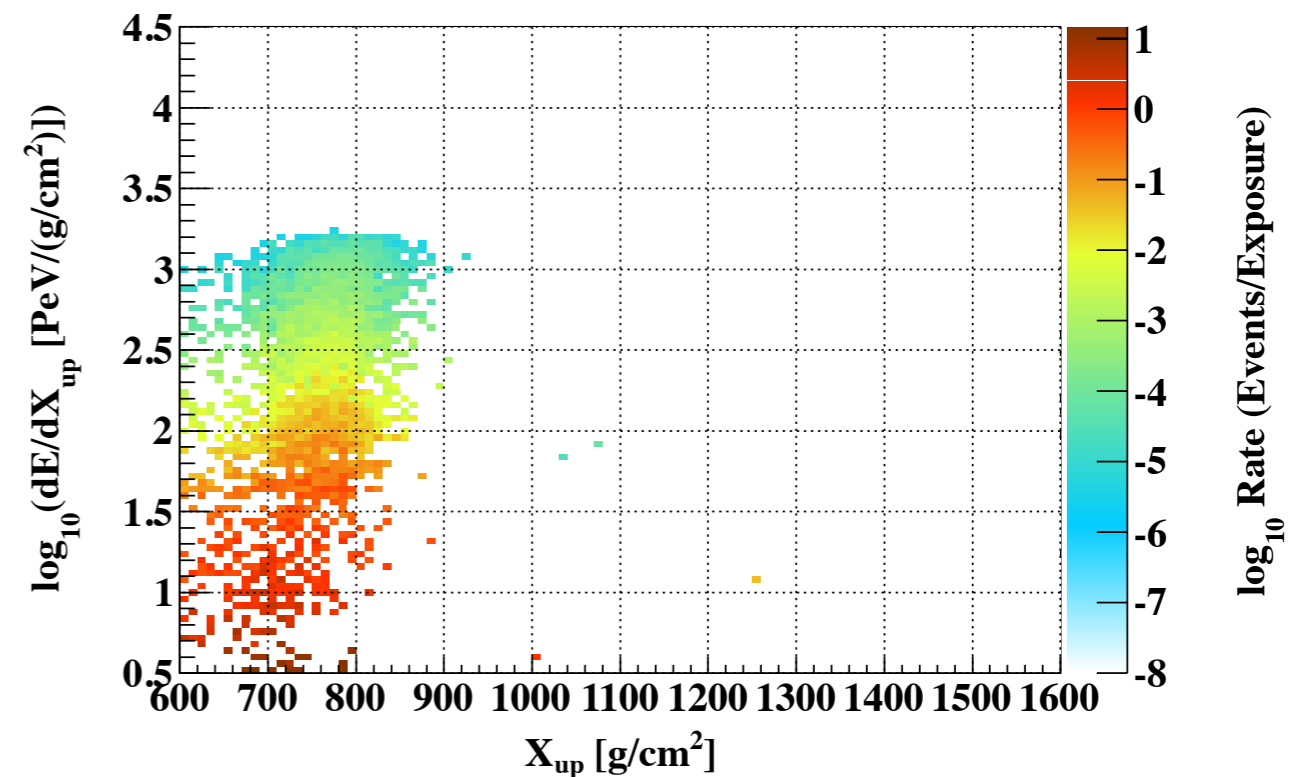
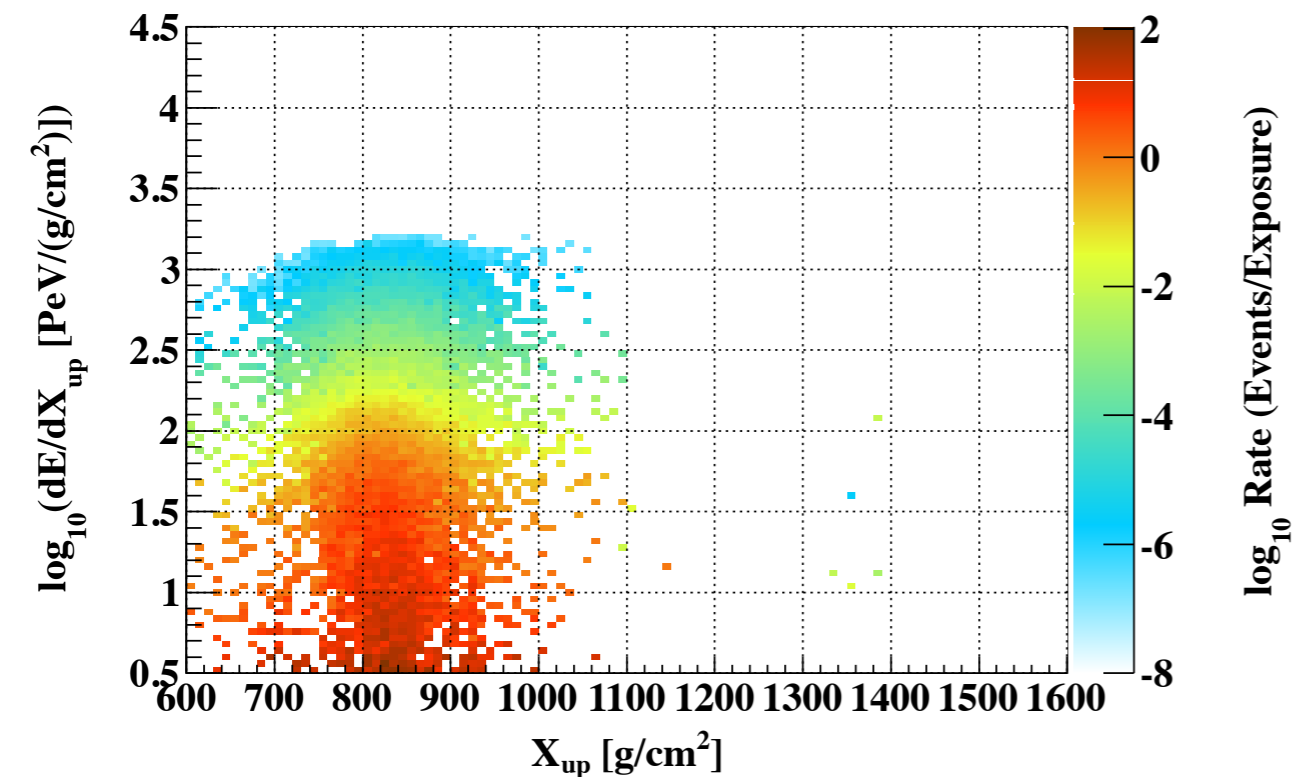


Assuming FD Exposure $\sim 7000 \text{ km sr}^2 \text{ yr}$
($T_{\text{live}} \sim 1 \text{ yr.}$ including duty cycle)

Composition Dependence

Proton

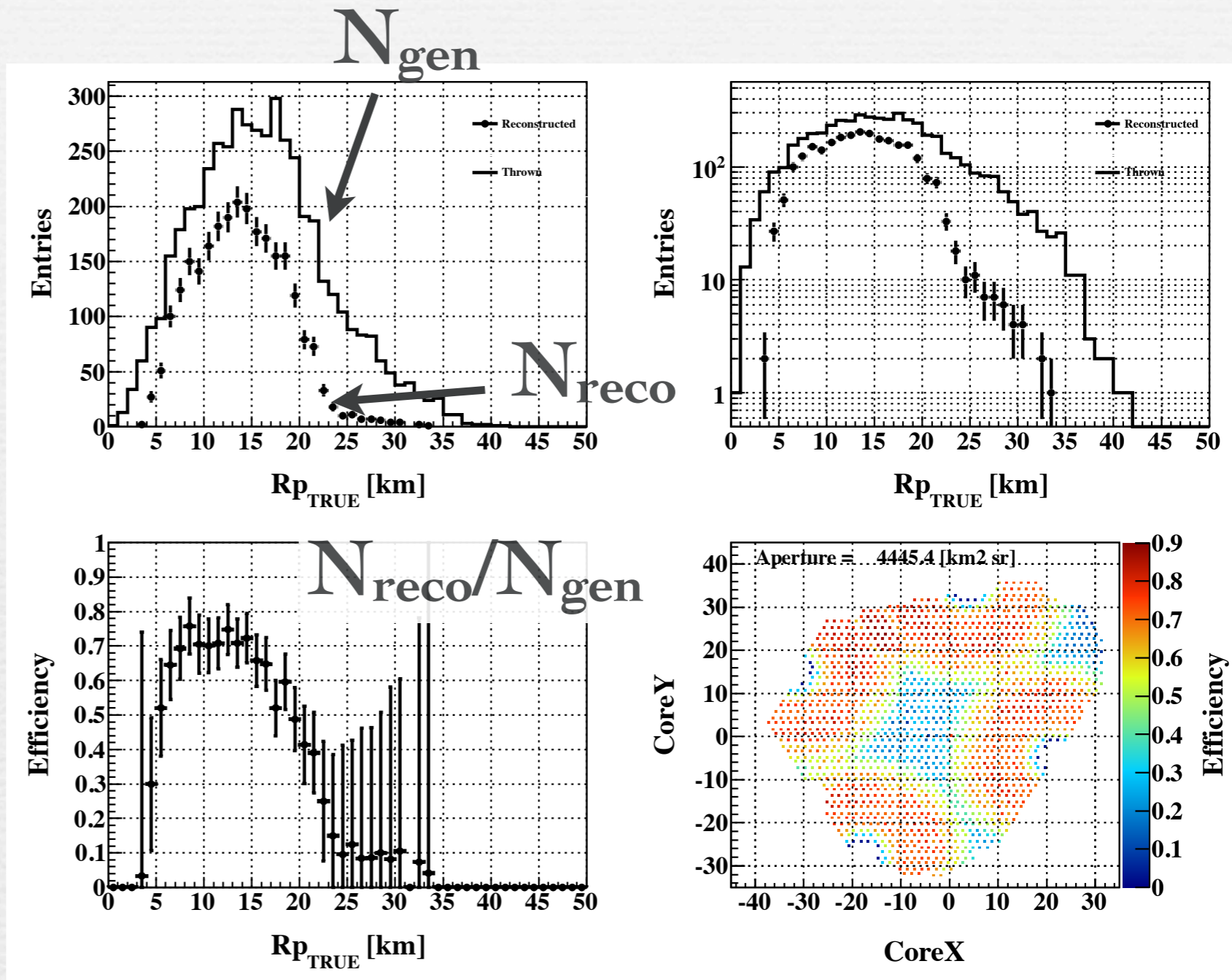
Iron



Proton showers are larger contamination than iron ones.

Simple Aperture Estimation

- Monopole $\gamma=10^{10}$
- Reconstruction efficiency as a function of $R_{p\text{TRUE}}$.
- Considering stereo or triplet
 - Thrown : sum up stereo or triplet event.
 - Reconstructed : no double counting.

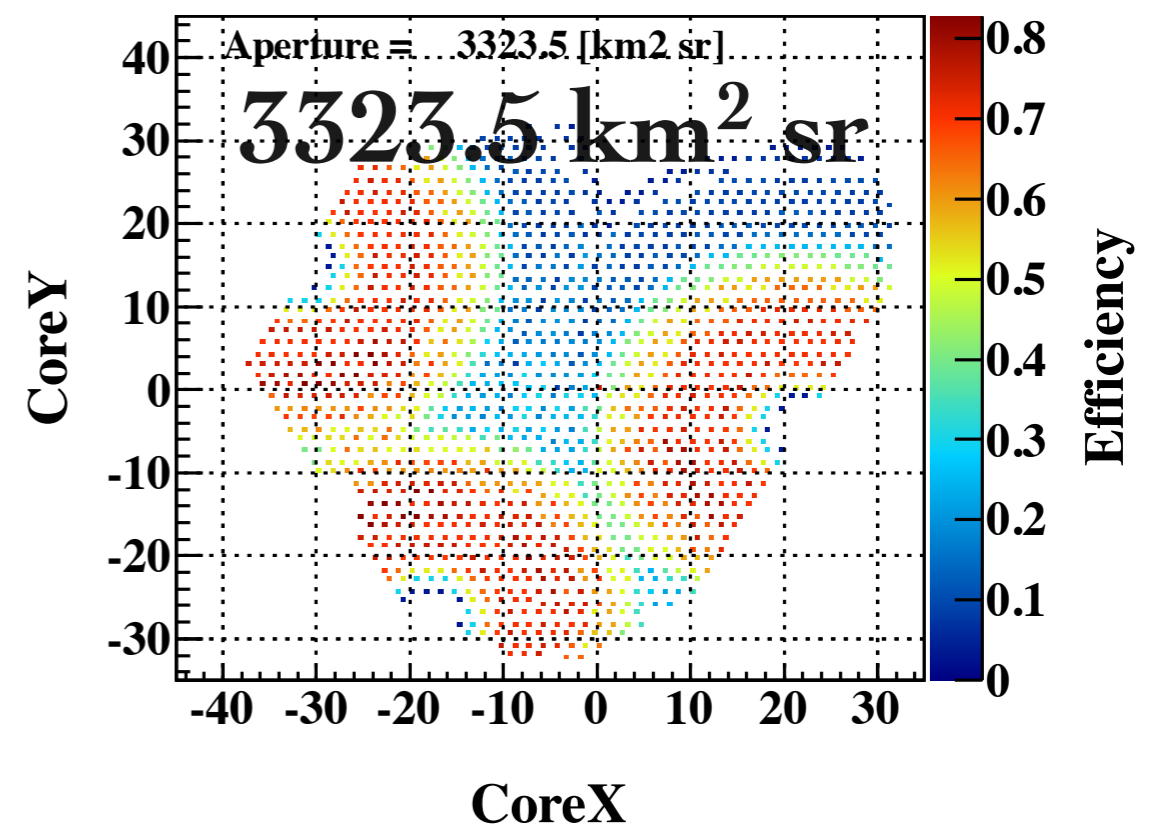
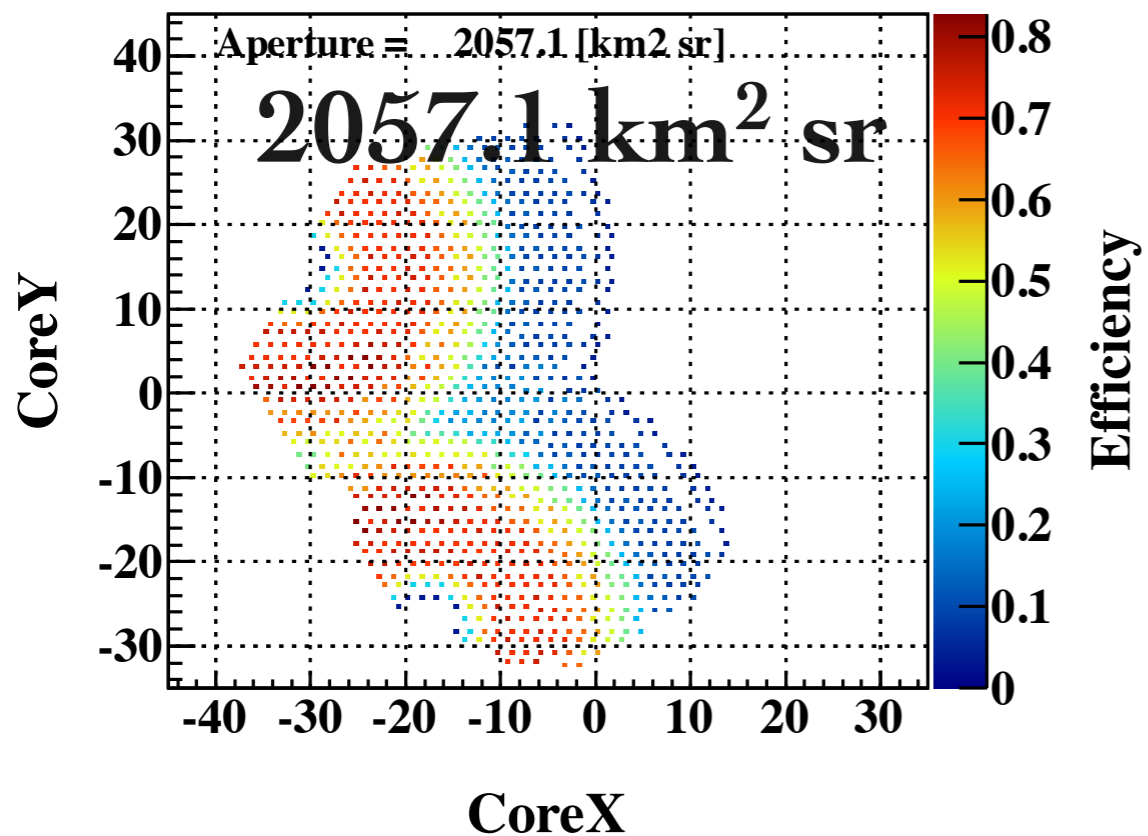
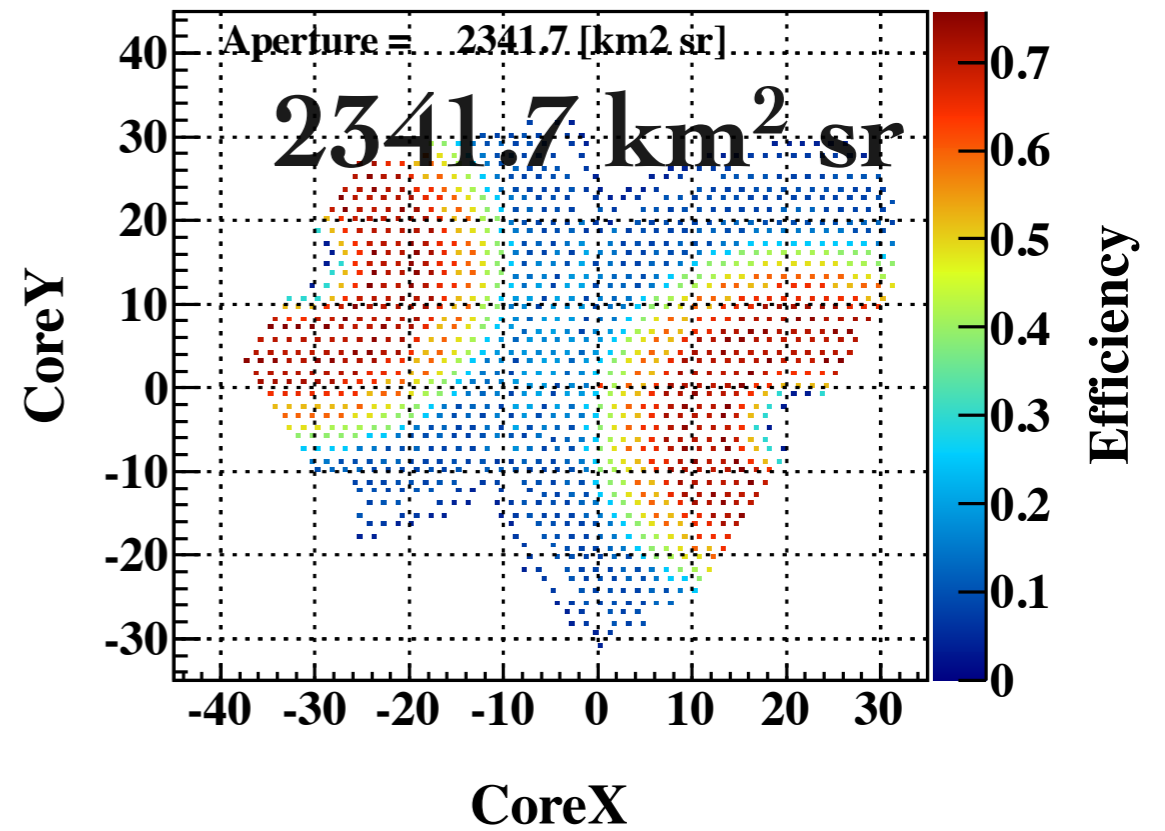
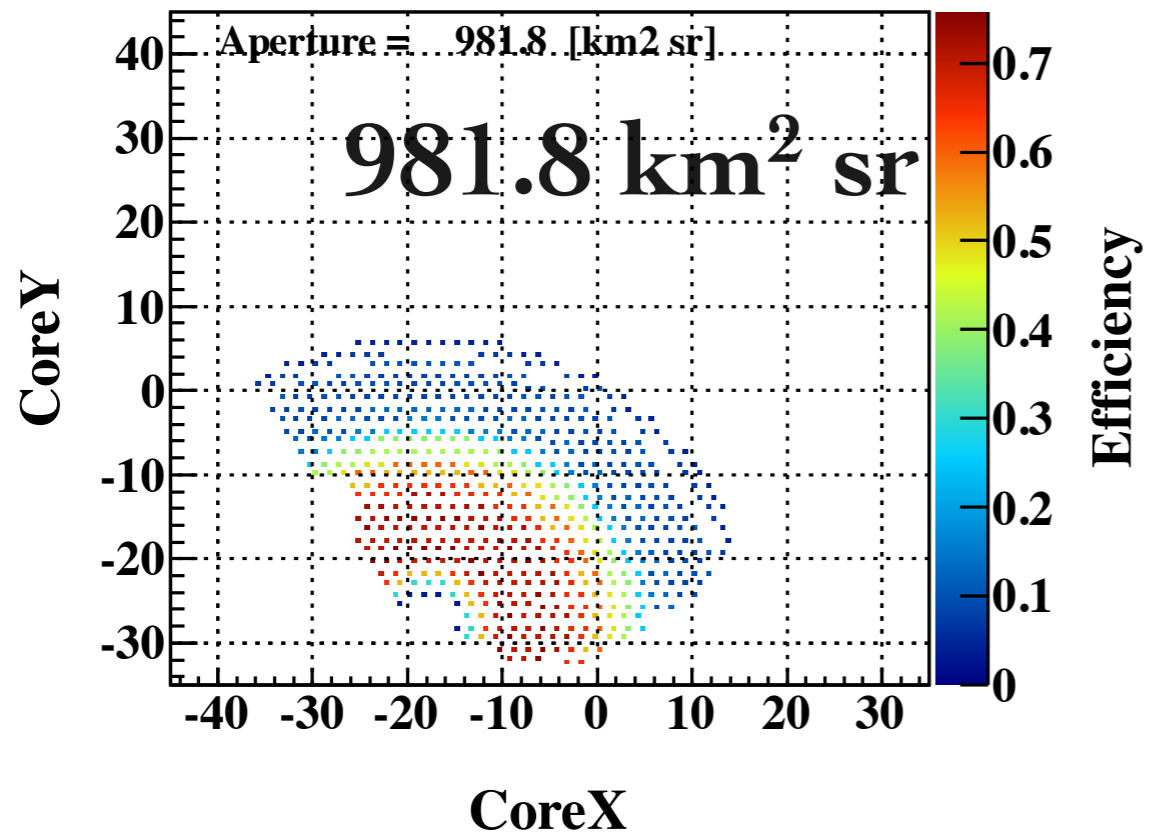


Need to use real MC.
(with F. Salamida)

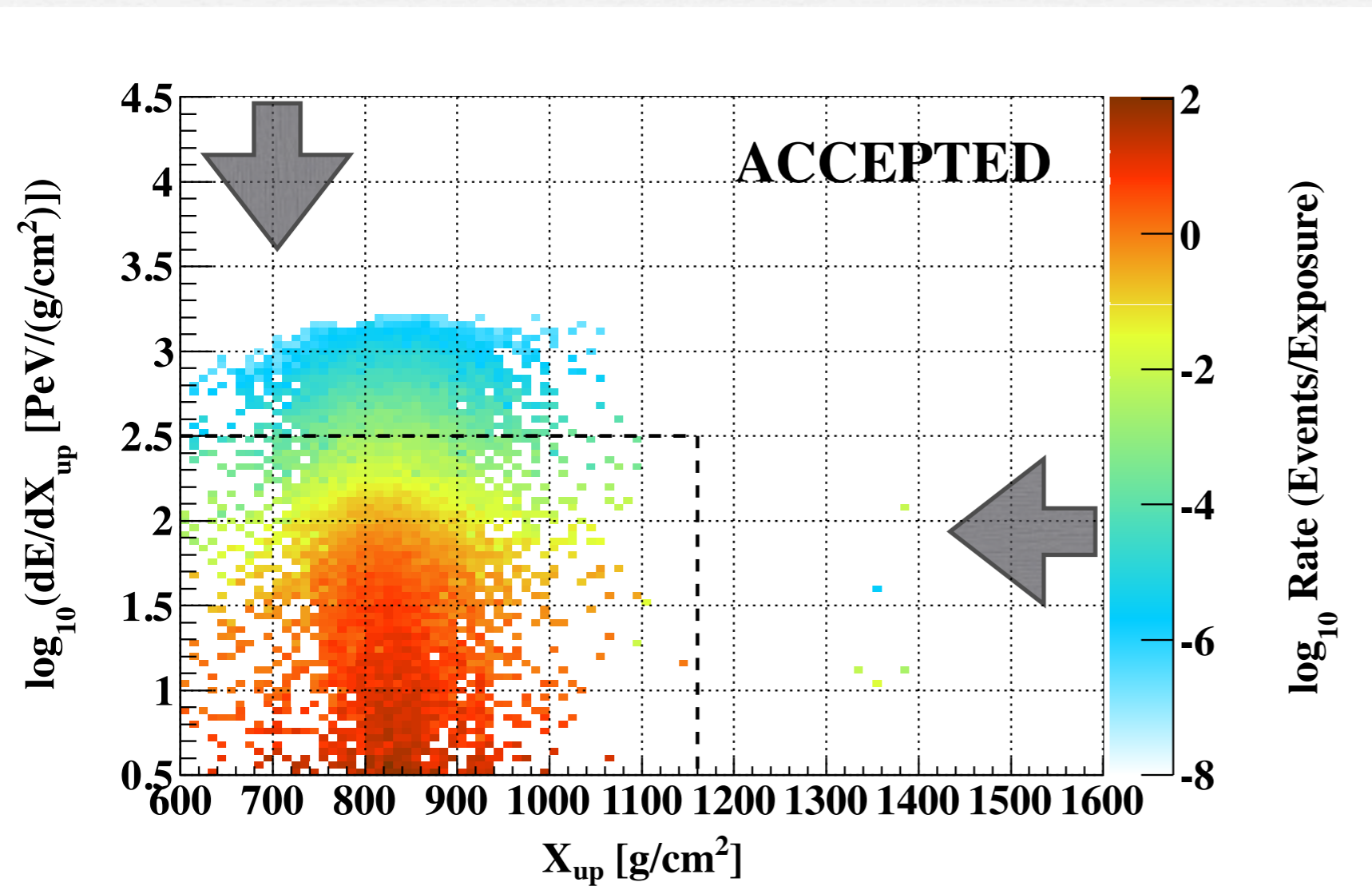
$$SD_{\text{cell}} = 4.59 \text{ km}^2 \text{ sr}$$

$$A\Omega = \sum 4.59 \times \epsilon(R_p) = 4445 \text{ km}^2 \text{ sr}$$

Operation mode



Optimization of Final Selection



- Pure proton primaries (conservative)
- Expected BG > 0.1 events for X_{up}
- Expected BG > 0.1 events for $\text{dE}/\text{dX}_{\text{up}}$

$$\text{dE}/\text{dX}_{\text{up}} > 316 \text{ PeV}/(\text{g}/\text{cm}^2) \parallel X_{\text{up}} > 1160 \text{ g}/\text{cm}^2$$

Expected background is 0.135 events under $7000 \text{ km}^2\text{sr yr}$

Expected Upper Limit

Assuming no
monopole candidate,

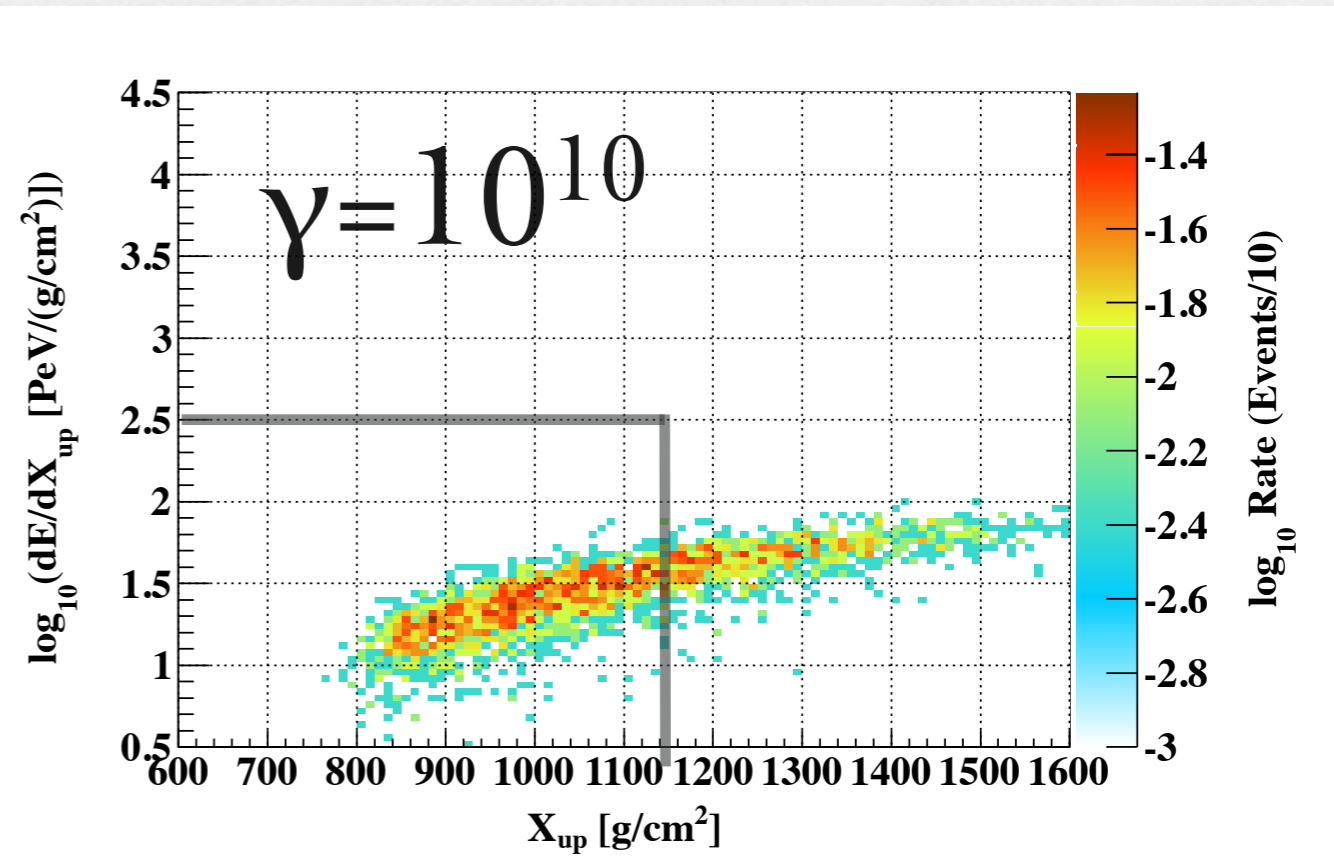
$$F_{\text{limit}}^{90} = 2.3(90\% \text{ C.L.}) / (A\Omega T_{\text{live}}\epsilon)$$

$T_{\text{live}} \sim 1 \text{ yr.}$

including duty cycle

$A\Omega = 7000 \text{ km}^2\text{sr}$

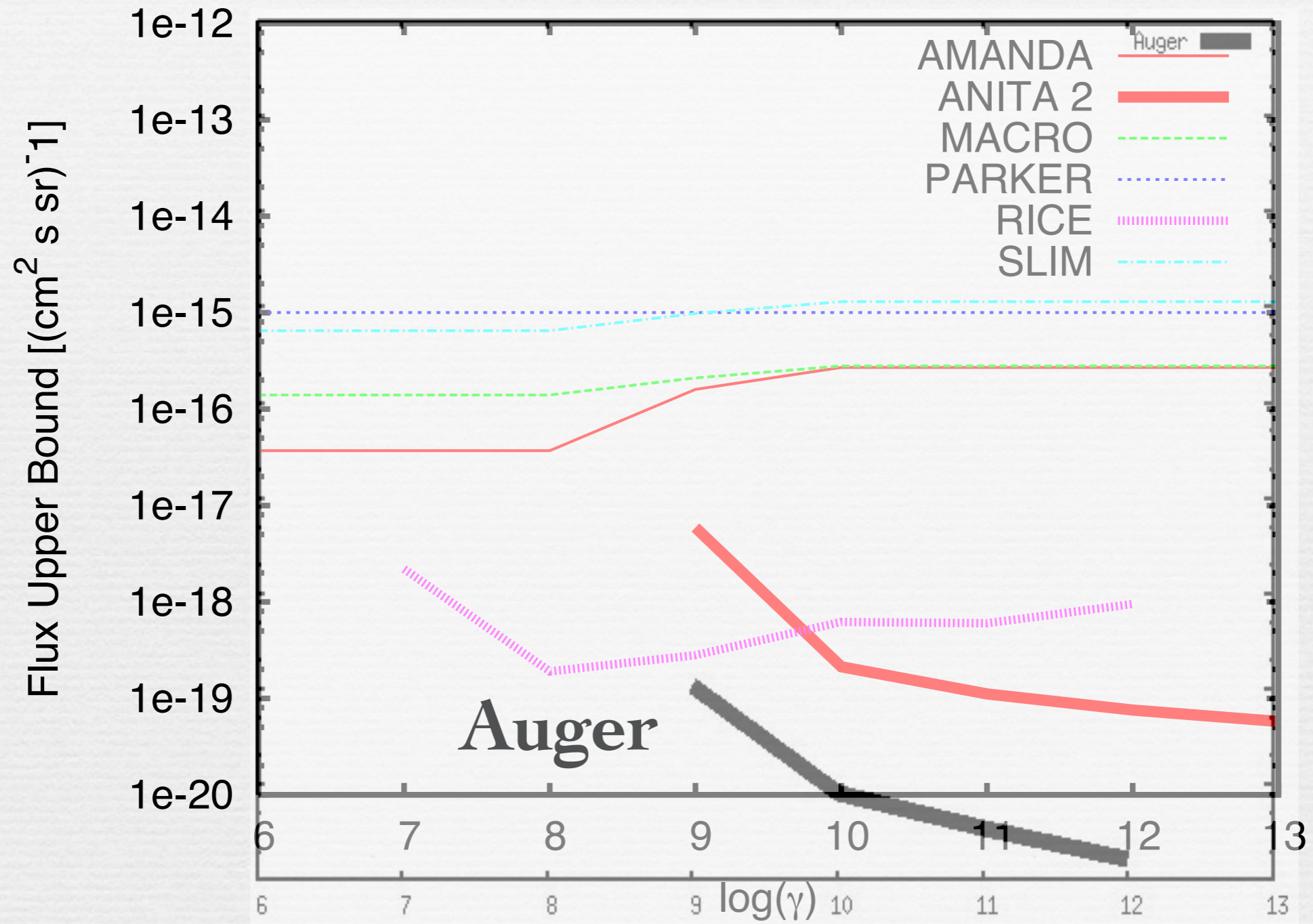
$\log(\gamma)$	ϵ	F_{limit}^{90}
9	0.024	1.1×10^{-19}
10	0.21	8.4×10^{-21}
11	0.46	3.6×10^{-21}
12	0.97	1.7×10^{-21}



$dE/dX_{\text{up}} > 316 \text{ PeV}/(\text{g}/\text{cm}^2)$

$\parallel X_{\text{up}} > 1160 \text{ g}/\text{cm}^2$

Expected Upper Limit



A order of magnitude lower than ANITA-II Limit.

Summary and Future Plans

- Search ultra-relativistic magnetic monopoles by X_{up} and dE/dX_{up} .
- Expected upper bound with Auger FD is a order of magnitude lower than ANITA-II limit.
- Need to determine a final selection for monopole search.
- Need to estimate a real exposure of monopole.
- Open the observed data.