Observing UHECRs with Smartphones

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About me...

KamLAND 2008

POLARBEAR 2008 - 2011

ATLAS Experiment 2012 - present
and now…

Disclaimer — this is my first foray into the world of cosmic ray physics!

Observing Ultra-High Energy Cosmic Rays with Smartphones

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So then,

Why Comic Rays?
At LHC, I study Dark Matter because...
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We have no idea

(but we know it’s out there)

The universe (as we know it)
CR’s are Mysterious

$\sigma_{\text{sys}}(E) = 22\%$

$E^3 J(E) \text{ [km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2]$
CR’s are Mysterious

What are they?
Where do they come from?
How do they attain such energy?

$E^3 J(E) \: [\text{km}^{-2} \: \text{yr}^{-1} \: \text{sr}^{-1} \: \text{eV}^2]$
High Energy

But…

These go to eleven
GZK Limit

\[ \gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0 \]

Proton Energy [eV]

Propagation Distance [Mpc]

\(10^{20}\) eV

\(10^{21}\) eV

\(10^{22}\) eV

\(~100\ Mpc\)
GZK Limit

\[ \gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow \nu + \pi^0 \]

Proton Energy [eV]

\[ 10^{20} \text{ eV} \]

\[ 10^{21} \text{ eV} \]

\[ 10^{22} \text{ eV} \]

Propagation Distance [Mpc]

\[ \sim 100 \text{ Mpc} \]

"Oh-My-God Particle"

\[ 3 \times 10^{20} \text{ eV} \]

Fly's Eye

Oct. 1991
Extensive Air Showers
Air Showers
Air Showers

Showers develop longitudinally…
Air Showers

Showers develop longitudinally...

... and laterally
Air Showers

hadrons  muons  electrs  neutr

$0.00 \cdot 10^{-6} \text{ sec}$

Proton $10^{14} \text{ eV}$

$h^{1st} = 21311 \text{ m}$
Particle Content

$\geq$MeV $\gamma$\textsc{s/e}$^\pm$

$\geq$GeV $\mu$\textsc{ns}

$E_0 = 10^{19} - 10^{20}$ eV

![Graph showing particle content distribution with energy on the x-axis and number on the y-axis. The graph includes plots for $\gamma$, $e^\pm$, and $\mu^\pm$. The energy scale ranges from $10^4$ to $10^{10}$ GeV, and the number scale ranges from $10^1$ to $10^{10}$.]
Particle Content

Tremendous densities near shower core

\[ E_0 = 10^{19} - 10^{20} \text{ eV} \]
Detecting Cosmic Rays
Detection Techniques

Ways to detect air showers:

- Atmospheric fluorescence
Detection Techniques

Ways to detect air showers:

➡ Atmospheric fluorescence

➡ Cherenkov telescopes
Detection Techniques

Ways to detect air showers:

- Atmospheric fluorescence
- Cherenkov telescopes
- Radio frequency
Detection Techniques

Ways to detect air showers:

- Atmospheric fluorescence
- Cherenkov telescopes
- Radio frequency
- Ground arrays
Pierre Auger Observatory

1600 Cherenkov tanks
3000 km$^2$
Pierre Auger Observatory
Pierre Auger Observatory

Auger = $3 \times 10^3$ km$^2$
Earth = $5 \times 10^8$ km$^2$
Rare Events

How can we cover more ground?
Smartphones!
Smartphones are:
(tiny)
Particle Detectors

Camera Sensor
(Active area: ~0.3 cm²)
We are not the first to realize this!

- CellRad (Idaho Nat’l Lab)
- SafeCast (Non-profit)
- DECO (Wisconsin)
- “Chernobyl 2013: radioactive ant bites” (YouTube video)
Smartphones are:
Mobile Laboratories

GPS

Wi-Fi
But:

it’s not enough to simply observe particles...
Our goal: *network* a large number of smartphones into a *worldwide observatory*!
The App (android)
The App: Internals

Scan video for bright pixels. Upload any hits to our server.
Trigger Calibration

Set **trigger threshold** to maintain *average event rate* of ~0.1Hz
Photon Sensitivity

No source

Ra226

Time
Photon Sensitivity

Sources w/ varying activity, energy:

- Ra$^{226}$: ~180–600 keV
- Cs$^{137}$: 700 keV
- Co$^{60}$: 1.1/1.3 MeV
What do Photons *Look Like*?

Usually: a single pixel high above threshold

![Graph showing the distribution of photon hits]

**Ra226 Source**

![Plot of photon hits vs. number of pixels]

![Plot of photon hit locations]

Pixels from one event

Seemingly random pixel hits
What do Photons Look Like?

Sometimes we get interesting tracks:

- **Ra226 Source**
- **Co60 Source**
So far, no muon sources available…
Muon Sensitivity

Get them for free from the sky!

1 muon/cm²/min  \implies  1 muon every 4 mins

MIP track w/ over 125 pixel hits!
Muon Sensitivity

Get them for free from the sky!

1 muon/cm$^2$/min $\Rightarrow$ 1 muon every 4 mins

23 pixel hits
Muon Sensitivity
Timing

For measuring coincident hits

Timing test
Random blinking LED
Measure capture time on two phones.
Putting it All Together
Shower Reconstruction

Auger: highly sensitive detectors w/ picosecond timing
Shower Reconstruction

\( t \in [0.0 - 0.2s] \)

- Red circles: hit
- Blue circles: nohit
Shower Reconstruction

t∈[0.1 - 0.3s]
During a shower event, the expected number of particle hits is:

$$\lambda = A \epsilon \cdot \rho(x, y) + \eta$$

- $A$ — active area
- $\epsilon$ — detection eff.
- $\rho$ — LDF [particles/m$^2$]
- $\eta$ — noise term
During a shower event, the expected number of particle hits is:

\[ \lambda = A \epsilon \cdot \rho(x, y) + \eta \]

Probability of seeing nothing:

\[ P_0(x, y) = e^{-\lambda} \]
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\[ \lambda = A \epsilon \cdot \rho(x, y) + \eta \]

Probability of seeing nothing:
\[ P_0(x, y) = e^{-\lambda} \]

Likelihood function, given phones that were / weren’t hit:
\[ L(E_0, \theta, \phi, s) = \prod_i P_0(x_i, y_i) \cdot \prod_j (1 - P_0(x_j, y_j)) \]
Shower Reco Efficiency

Sensitive only at the very highest energies

(those are the interesting ones!)
Shower Reco Efficiency

Sensitive only at the **very highest energies**

*(those are the interesting ones!)*
Energy Resolution

Higher energy → more hits → better measurement

![Graph showing the relationship between primary energy and fractional energy resolution, with different line styles and markers for various device densities and event types.]
Energy Resolution

Higher energy $\rightarrow$ more hits $\rightarrow$ better measurement

![Graph showing the relationship between Primary Energy and Fractional Energy Resolution for different device densities and energy types.](image-url)
Angular Resolution

Except in the most optimistic scenario, almost no pointing information.
Keeping up with Auger

Auger observing power

~800k smartphones!
800k phones?!

- Over a billion smartphone users in the world
- Initial media response netted over 50k signups
I'm still worth something :)

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Image: Five smartphones with broken screens. The最后一部手机 says, "I’m still worth something :)"
To Summarize

- Phones can see muons and gamma rays
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- A giant network can search of UHECR showers
To Summarize

- Phones \textit{can} see muons and gamma rays
- A giant network can search of UHECR showers
- Under the right conditions, can even compete with the \textit{state-of-the-art}!
To Summarize

- Phones *can* see muons and gamma rays via phones.
- A giant network can search for gamma-ray bursts of UHECR showers.
- Under the right conditions, can even compete with the state-of-the-art!

Not possible on Mars!
To Summarize

- Phones can see muons and gamma rays

- A giant network can search of UHECR showers

- Under the right conditions, can even compete with the state-of-the-art!

- There’s never been a global observatory of this scale... who knows what else we may find!
Going Beyond

In [6]: #Now we can make a plot of the pixel frequency
ds.events.Draw("log10(pix_freq)"
canvas.SetLogy()
print ds.events.GetEntries()
canvas

293825

Out[6]:

In [7]: # now we can plot the pixel value (brightness) for all pixels and the ones that are do
ds.events.SetLineColor(1)
ds.events.Draw('pix_val') # all pixels
ds.events.SetLineColor(4)
ds.events.Draw('pix_val', 'log10(pix_freq)<-4.5','same') # the clean pixels
canvas

Out[7]:

pix_val
Going Beyond

Users own the data!
Going Beyond

**PEACE 4 SPACE**

- **Pixel values**
  - Number of Pixels

- **Counts of pixels per event**
  - Number of Events

*Event numbers are listed for clean / total.*

**Exposure**
- Total: 48 days, 8 hours
- Current run: 35 minutes

**Events**
- Total: 238,669 / 959,535
- Current run: 0 / 286

*Live plots from each device!*
Going Beyond

Opening the data to the community:

- **rewards** the users
- broadens **research** applications
- provides exciting **education** opportunities

*Event numbers are listed for clean / total.*

Live plots from each device!
The End
Not sure where/if I’ll use these:
GZK Limit

Cutoff is observed, but is it GZK?

How rare are events above the cutoff?
Primary Composition

One of the most basic questions to ask:

what **are** the UHECR's *made of*?
Primary Composition

One of the most basic questions to ask:

what are the UHECR’s made of?

The short answer: probably protons or iron nuclei.
Primary Composition

Hadronic physics dictates the atmospheric depth of the shower maximum.
Primary Composition

Hadronic physics dictates the atmospheric depth of the shower maximum.