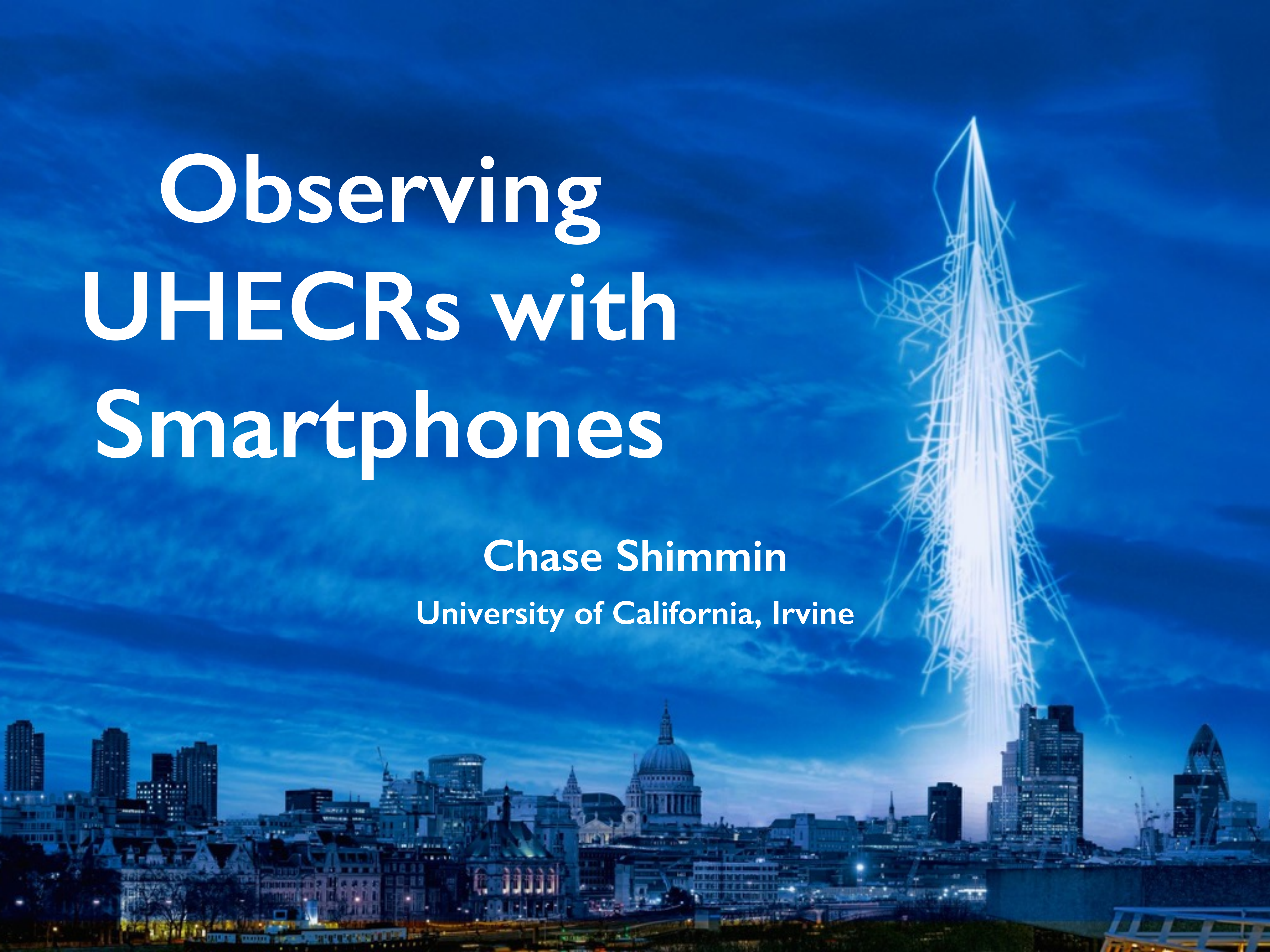
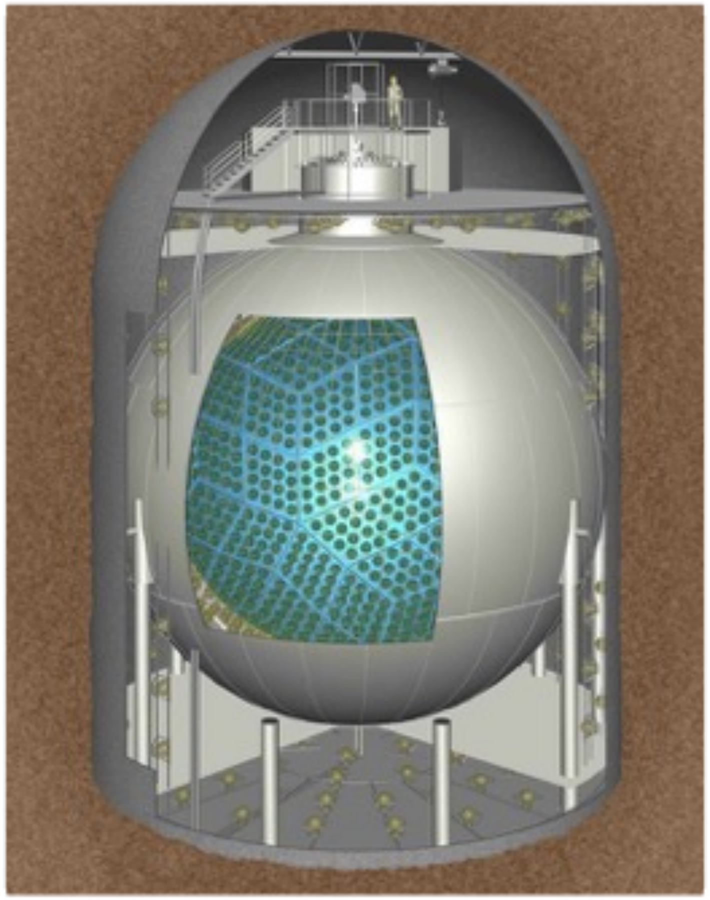
Observing UHECRs with Smartphones

Chase Shimmin
University of California, Irvine



About me…

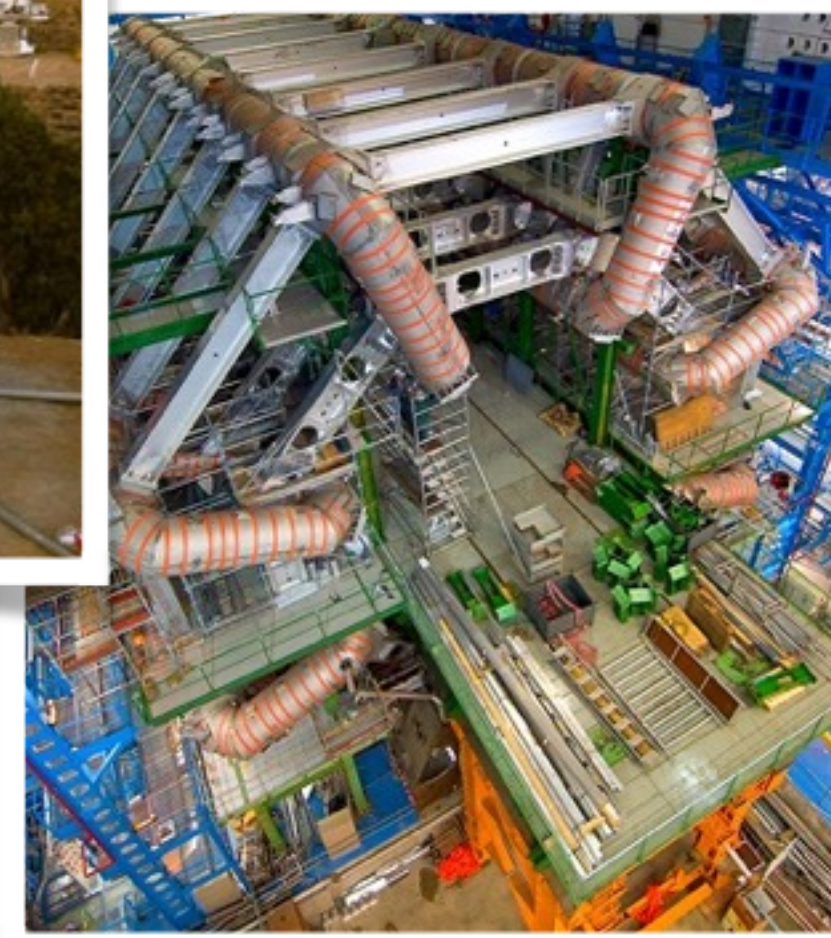


KamLAND

2008

POLARBEAR

2008 - 2011



ATLAS EXPERIMENT

2012 - present

and now…

CRAYFIS

cosmic rays found in smartphones

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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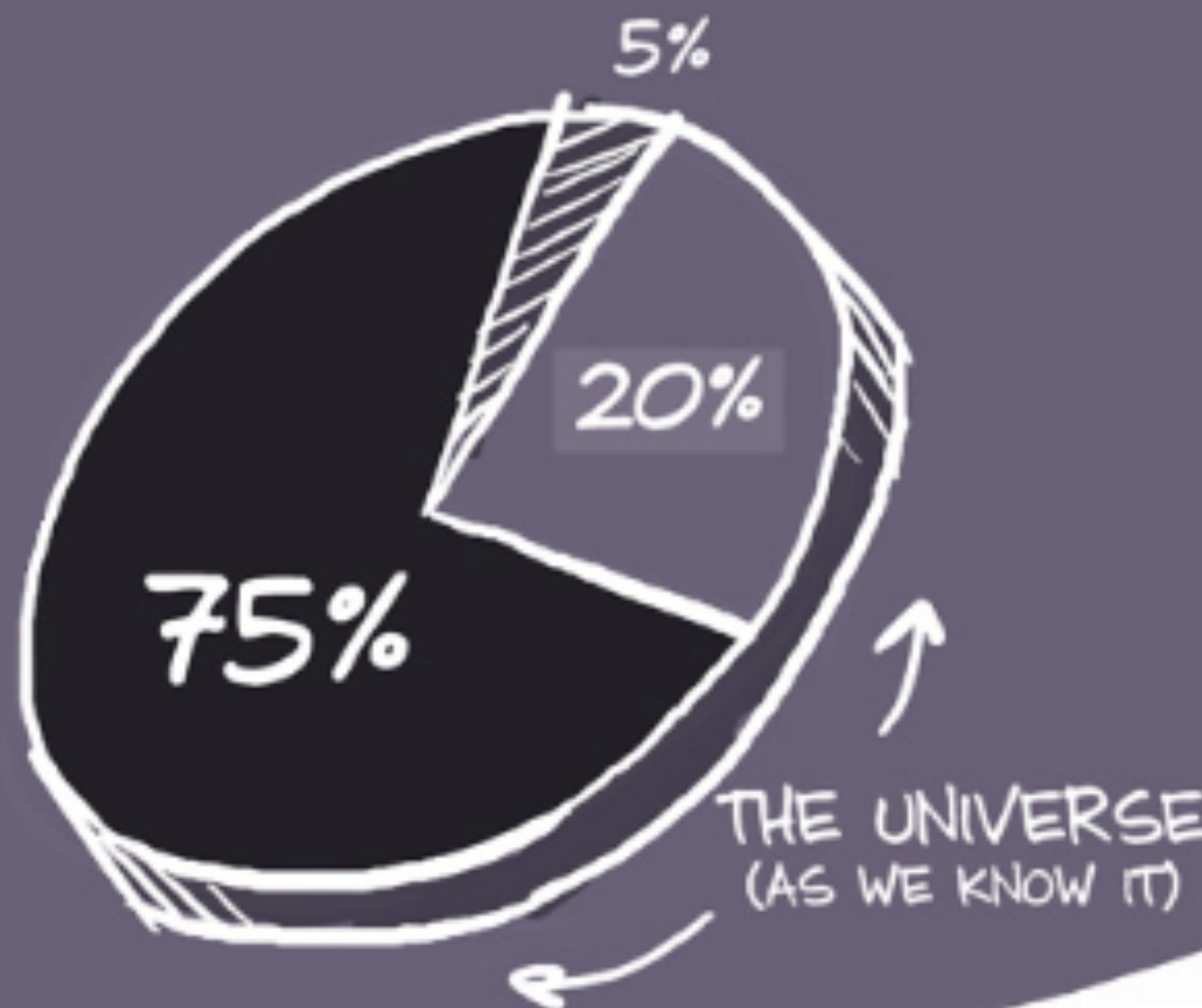
arXiv:1410.2895

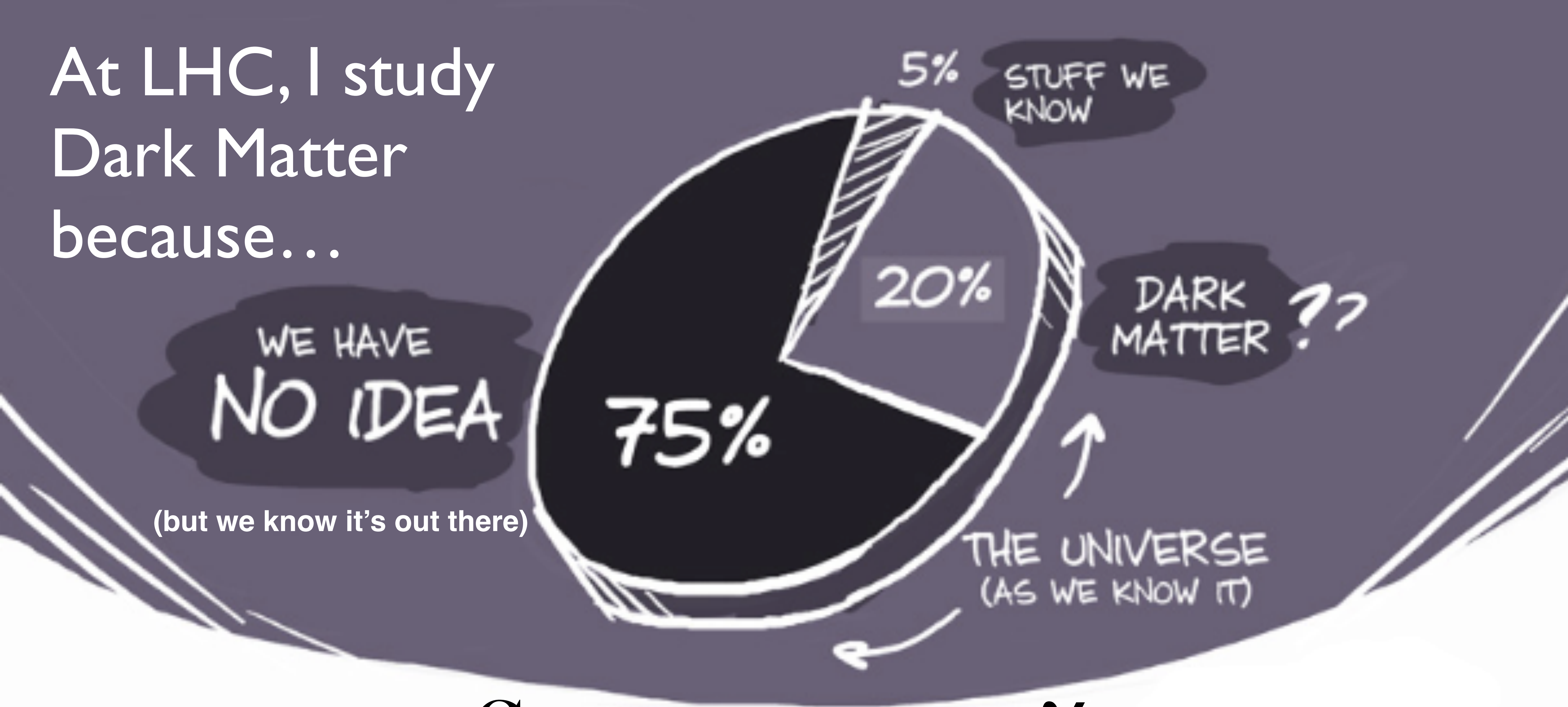
So then,

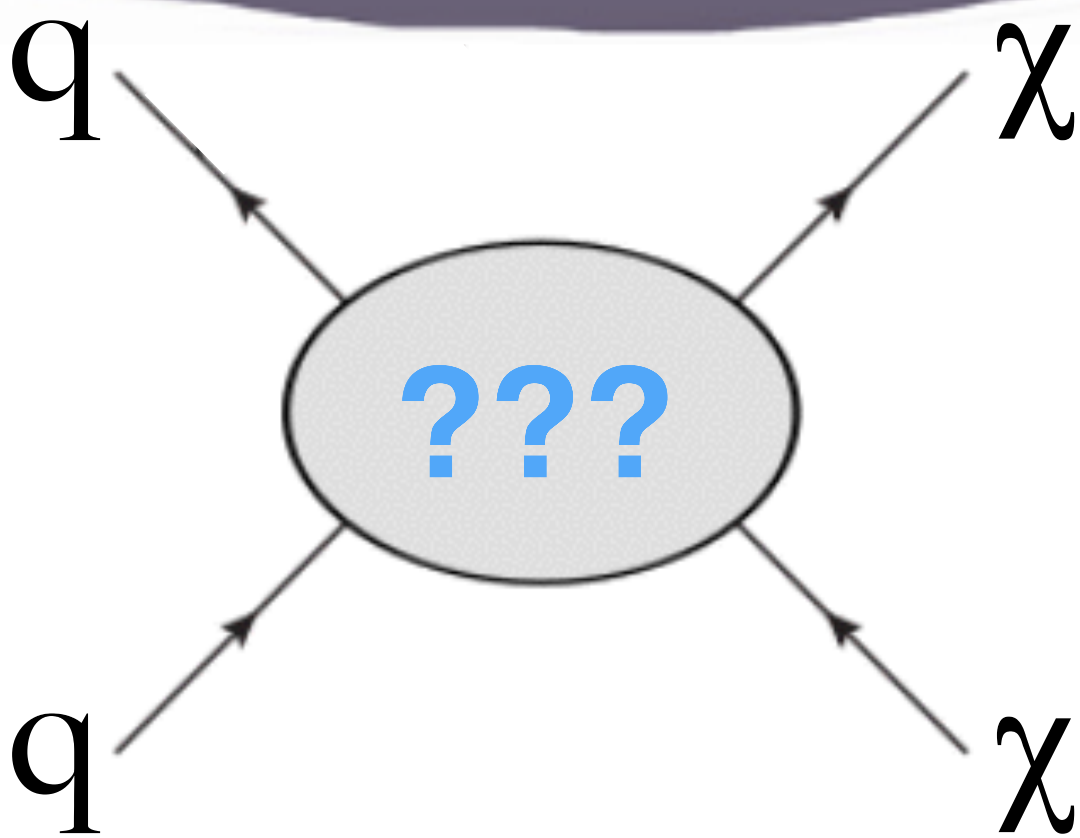
Why Comic Rays?

At LHC, I study Dark Matter because…

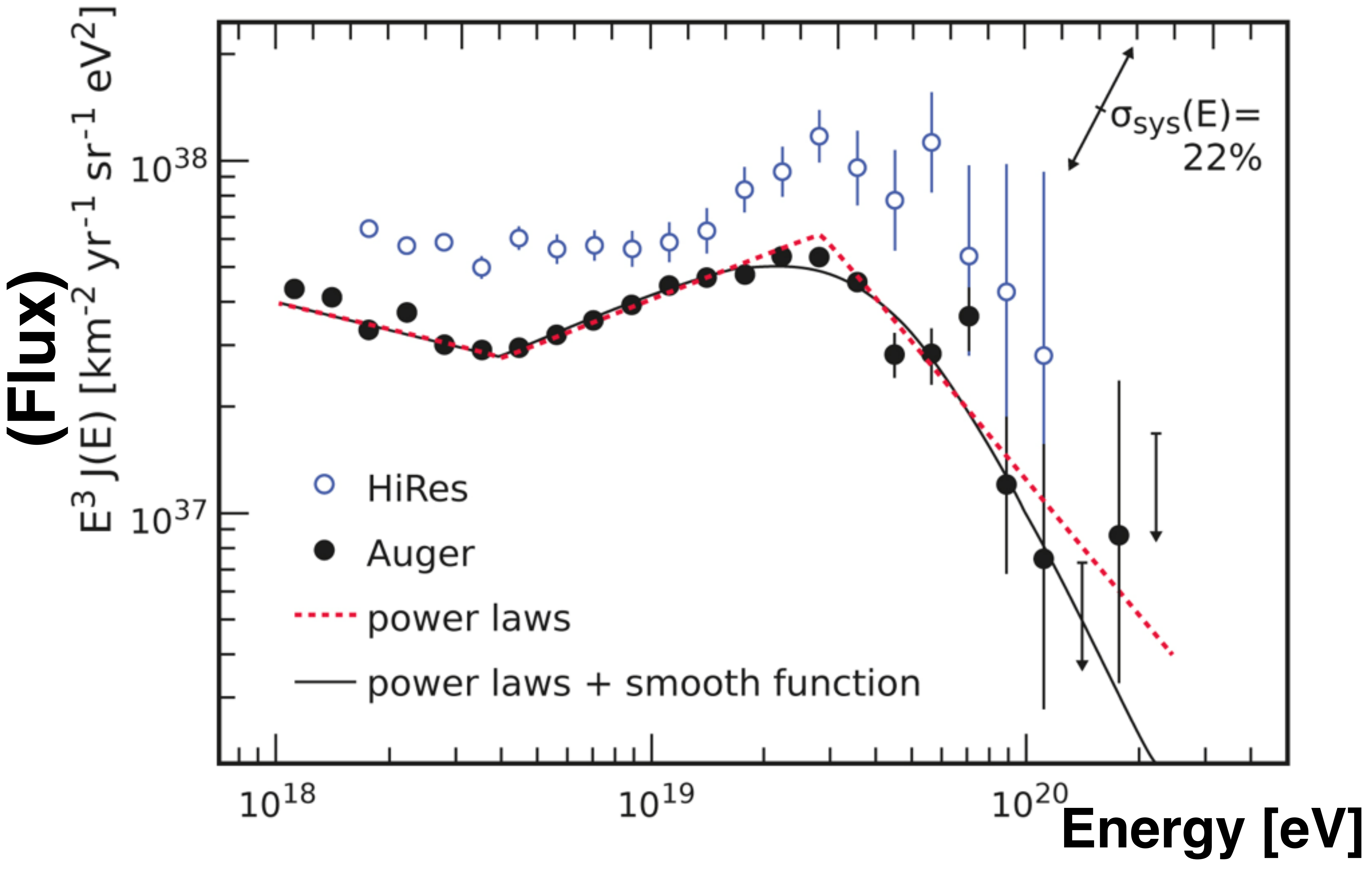


At LHC, I study Dark Matter because…



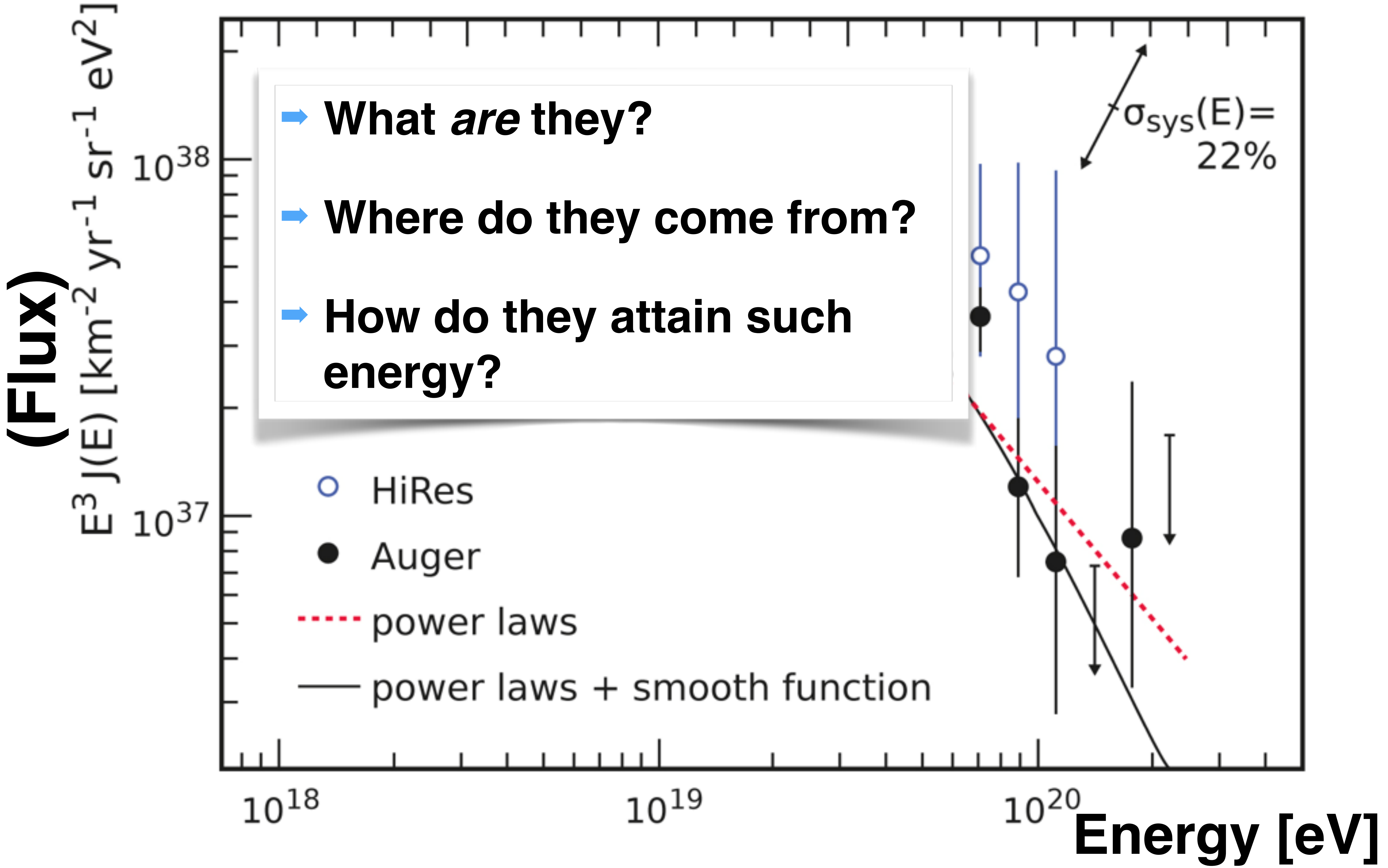


CR's are Mysterious

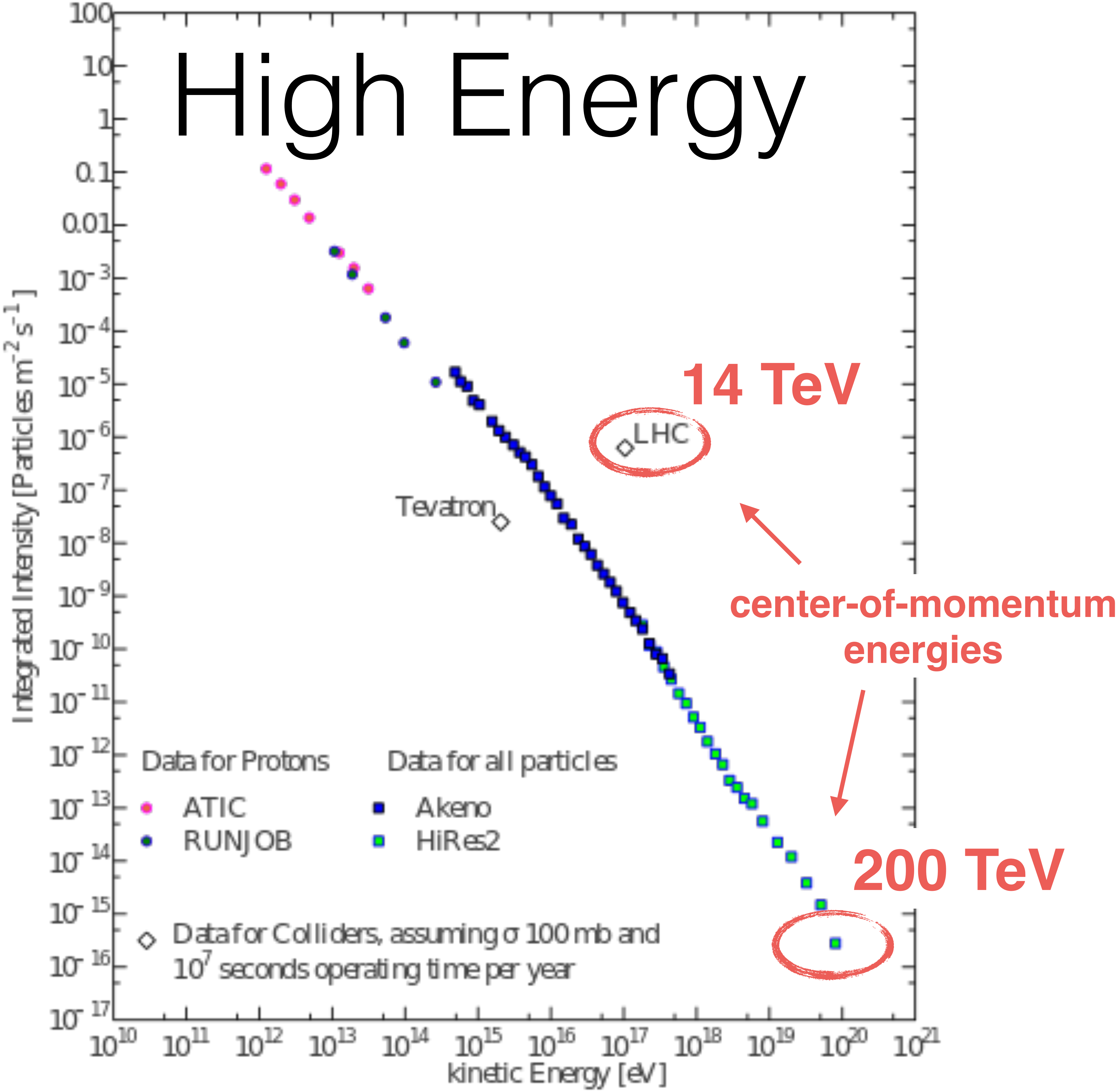


CR’s are Mysterious

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

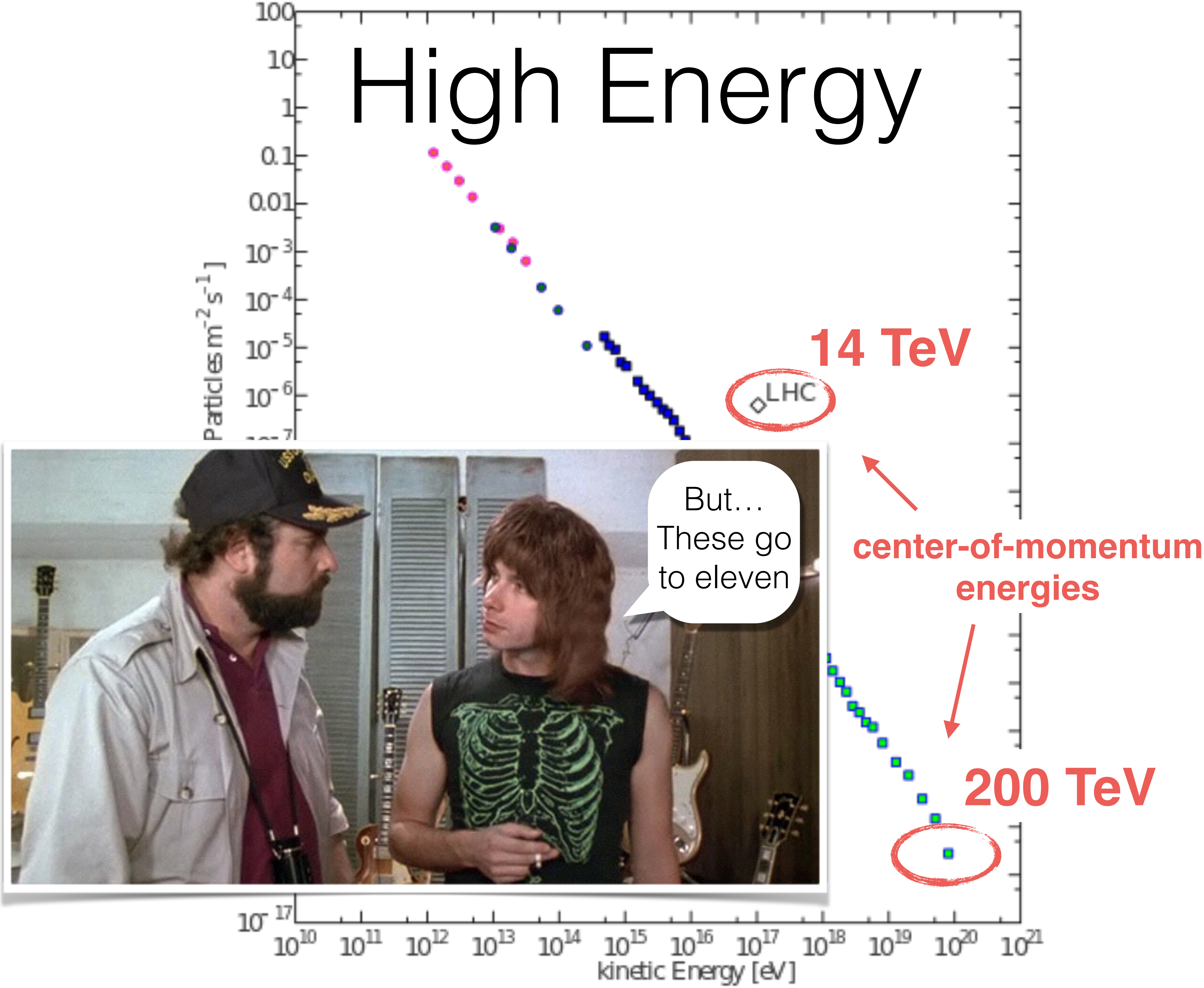


High Energy



14 TeV
LHC
Tevatron
center-of-momentum energies
200 TeV
Data for Protons
ATIC
RUNJOB
Data for all particles
Akeno
HiRes2
Data for Colliders, assuming σ 100 mb and 10^7 seconds operating time per year
Integrated Intensity [Particles $m^{-2} s^{-1}$]
kinetic Energy [eV]

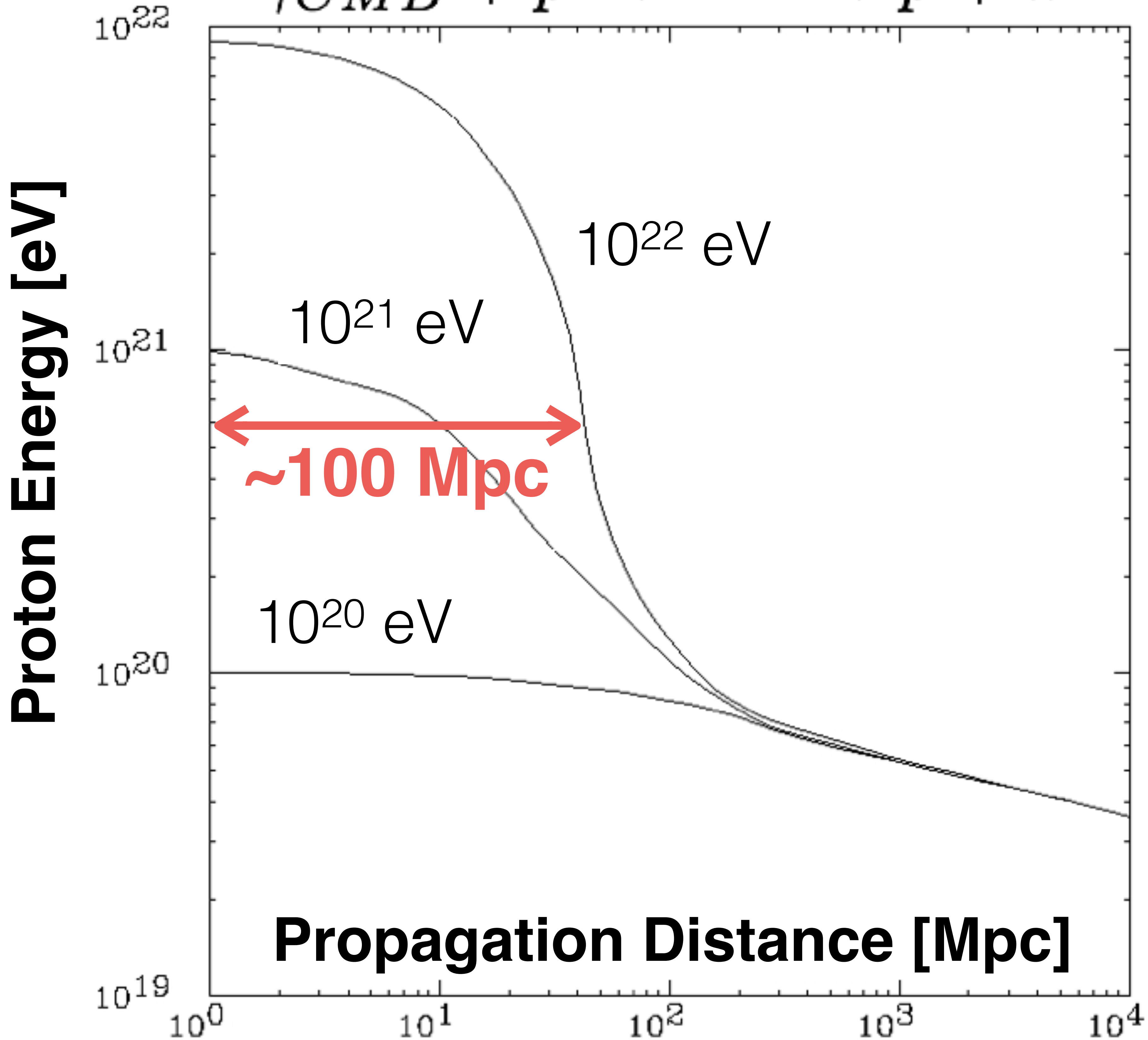
High Energy



Particles m^-2 s^-1]
100
10
1
0.1
0.01
10^-3
10^-4
10^-5
10^-6
10^-17
LHC
14 TeV
center-of-momentum energies
200 TeV
But…
These go
to eleven
10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21
kinetic Energy [eV]

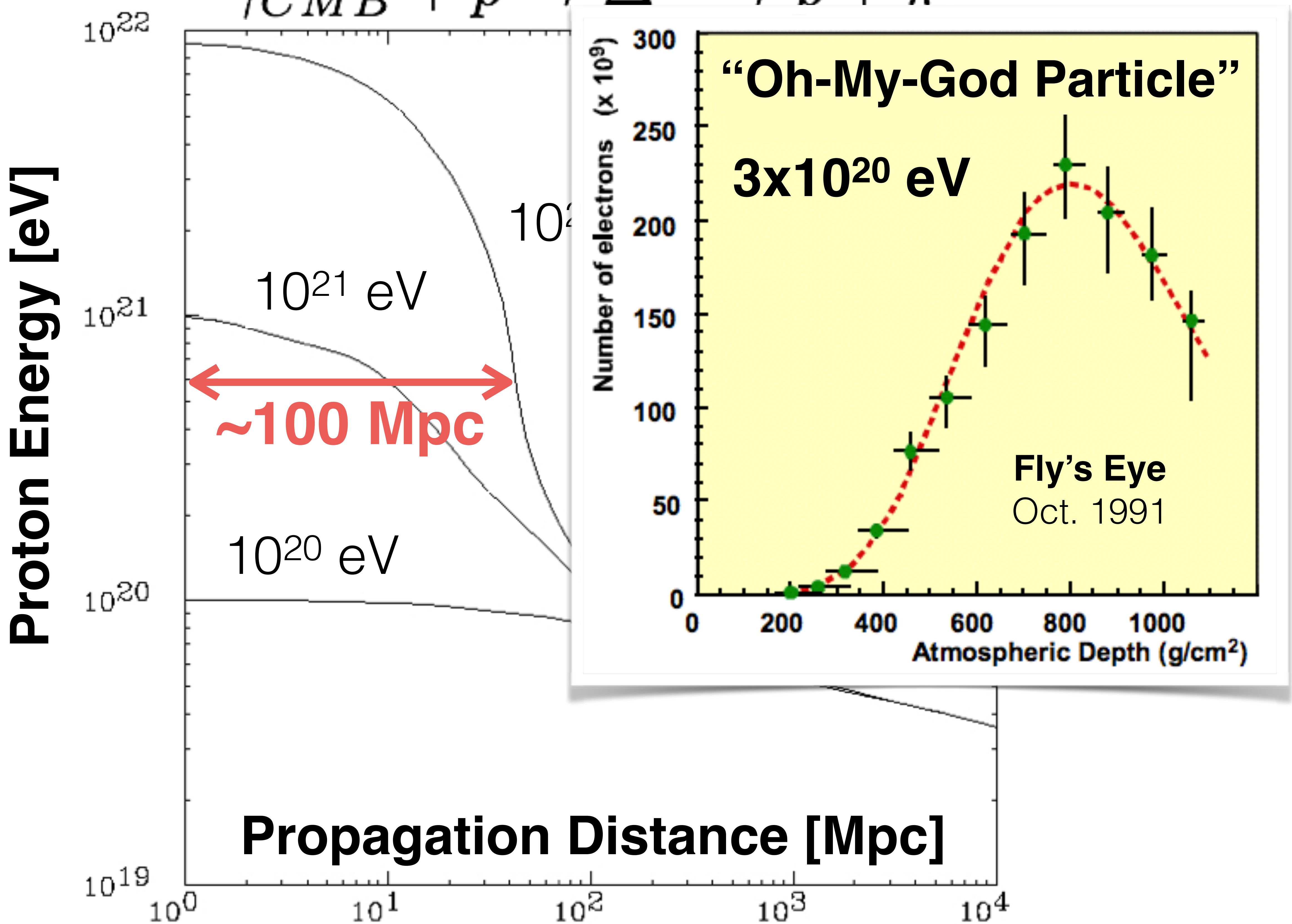
GZK Limit

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

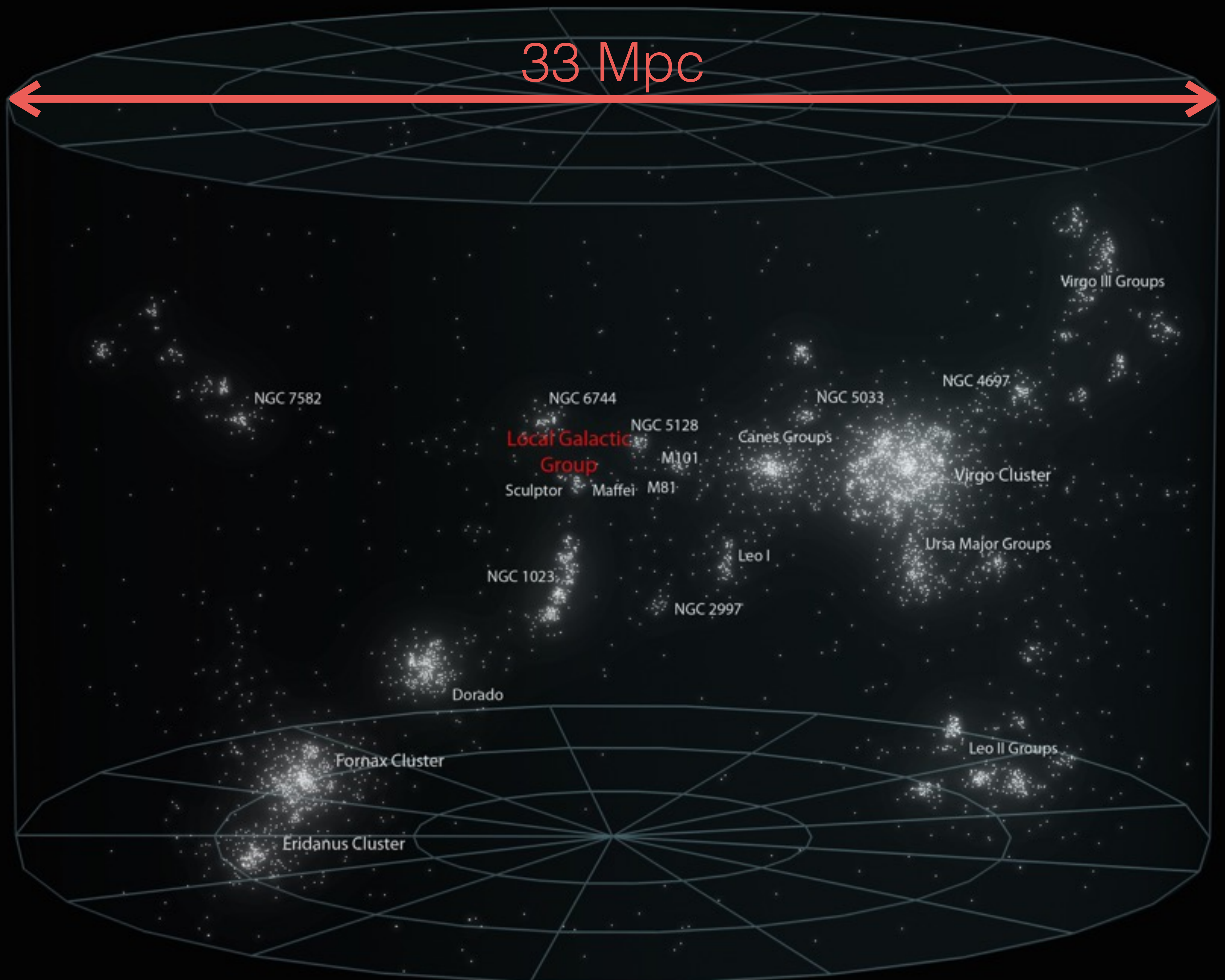


GZK Limit

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

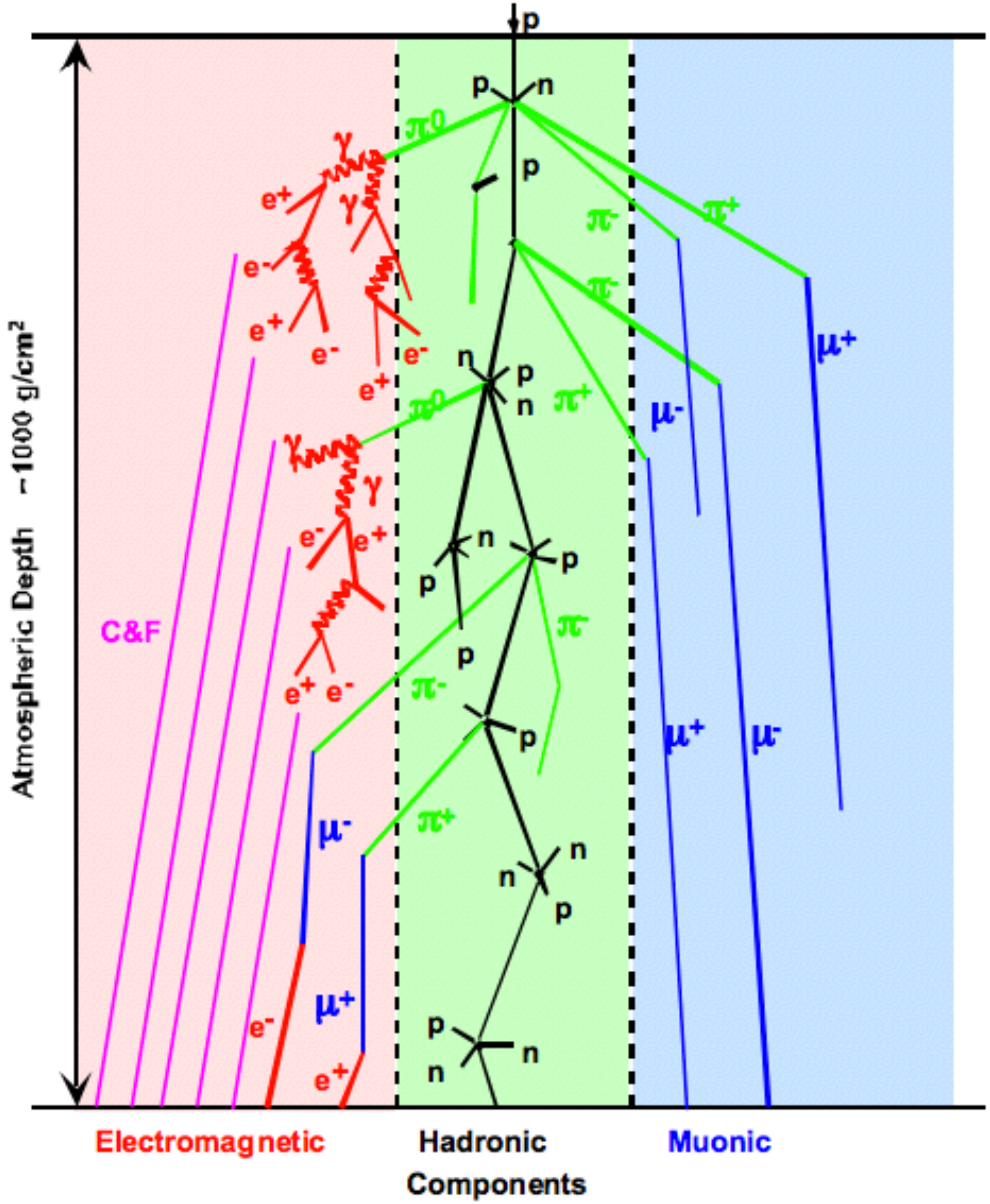


Virgo Supercluster

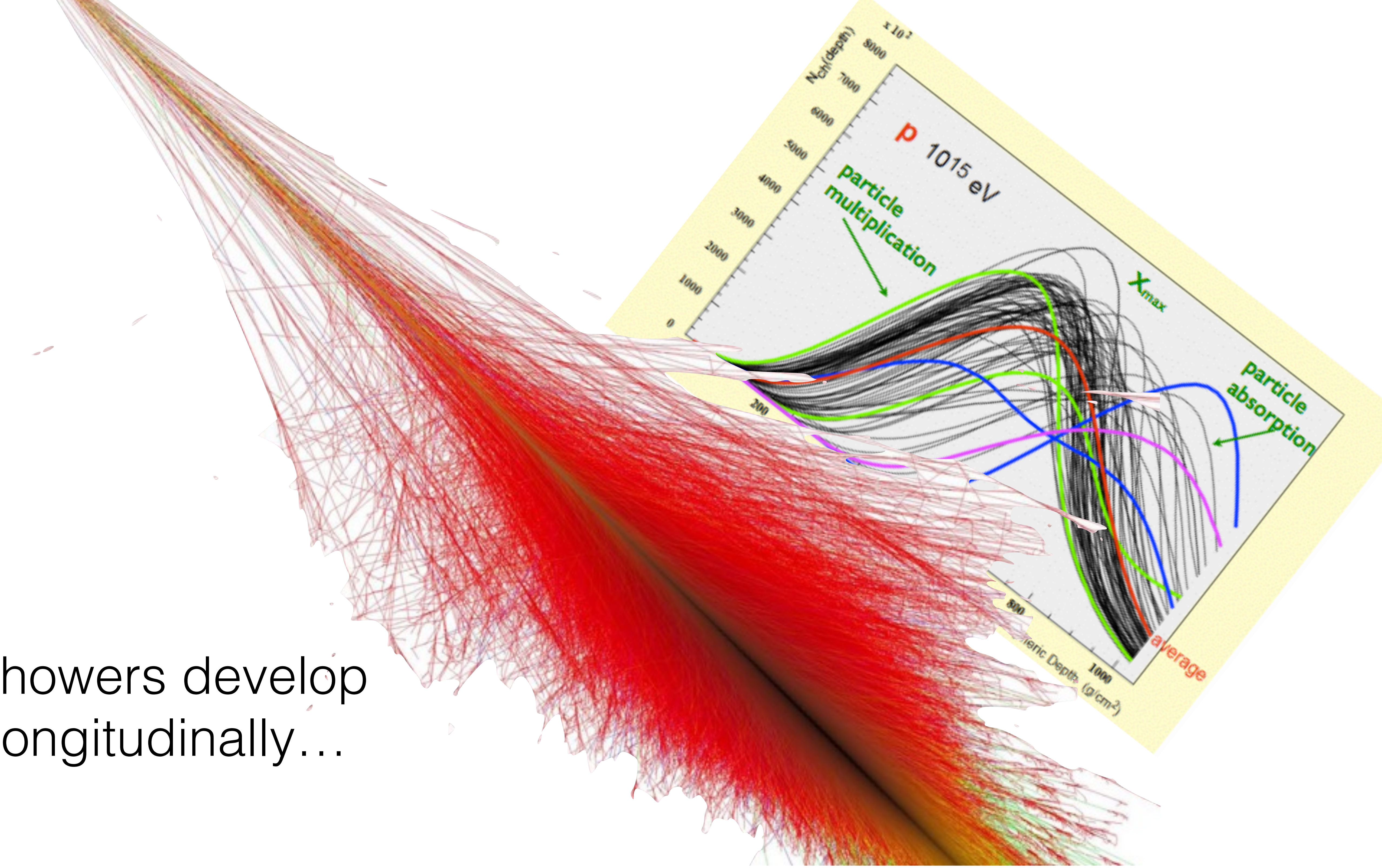


Extensive Air Showers

Air Showers

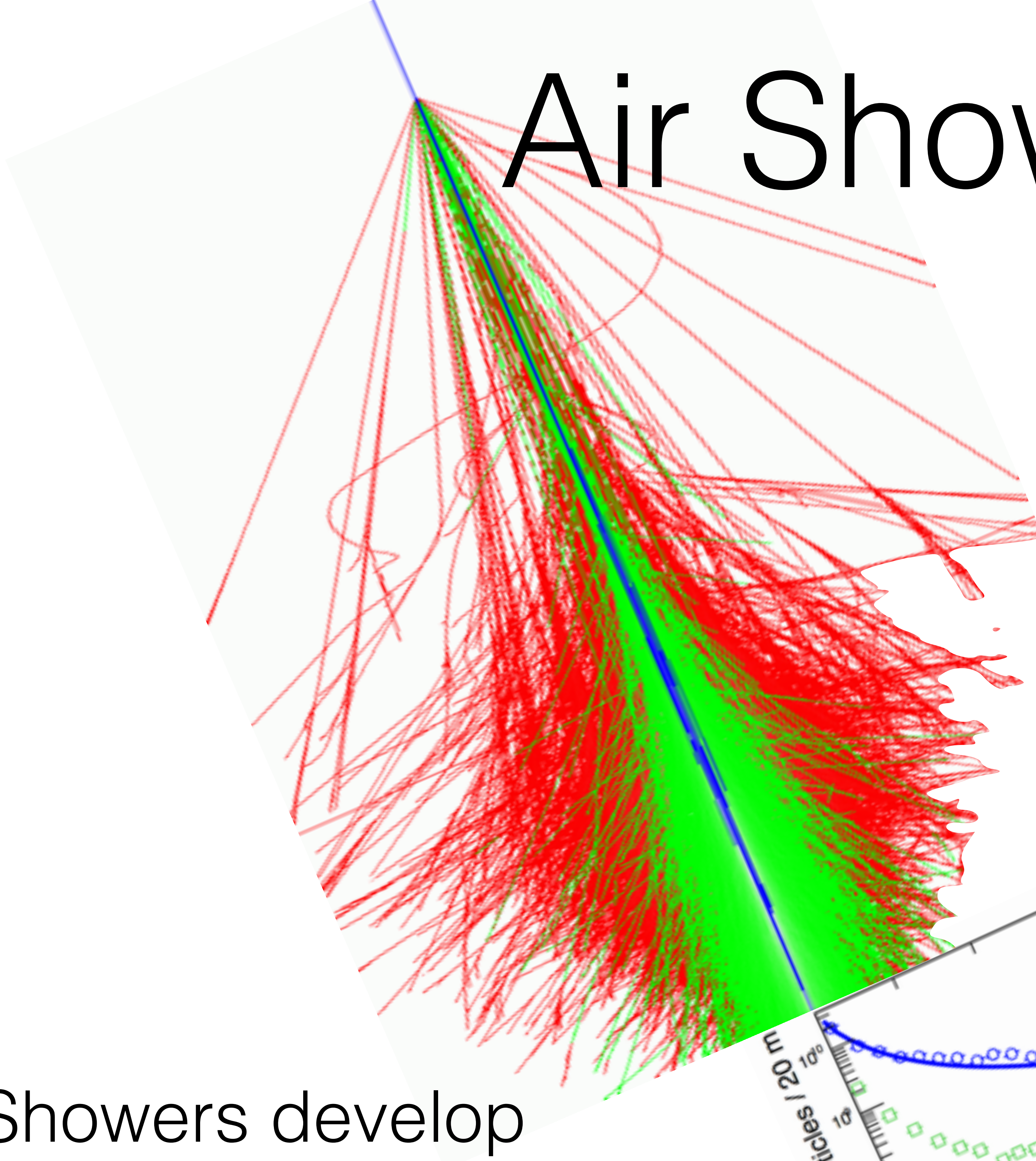

p
p
n
π0
γ
p
e+
γ
π-
π+
e-
π-
e+
e-
e-
n
p
μ+
e+
n
π0
π+
μ-
γ
γ
e-
e+
n
p
p
p
π-
C&F
e+
e-
p
π-
p
μ+
μ-
μ-
π+
n
n
p
μ+
e-
p
e+
n
n
Atmospheric Depth ~1000 g/cm²
Electromagnetic
Hadronic
Muonic
Components

Air Showers



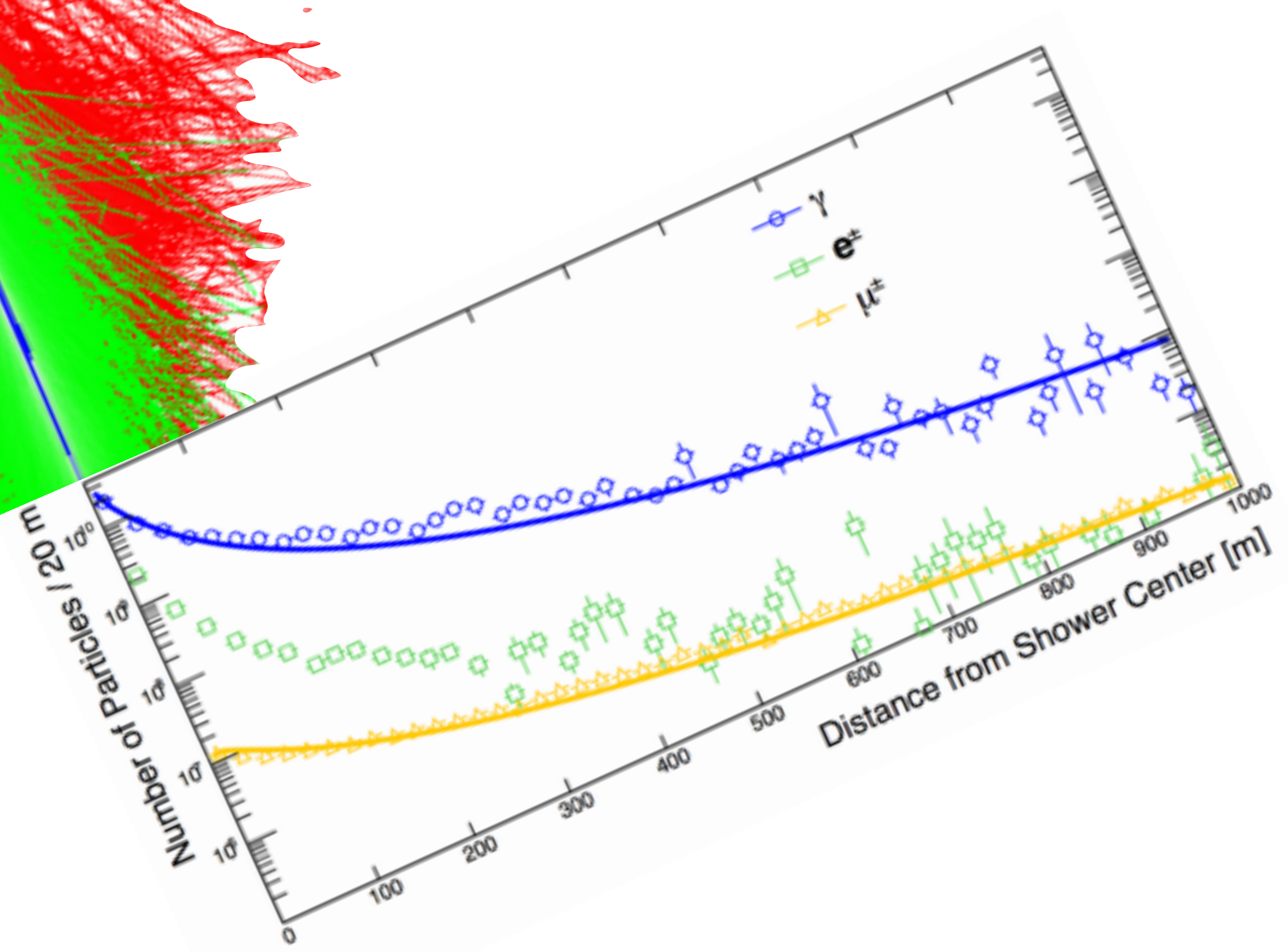
Showers develop longitudinally…

Air Showers

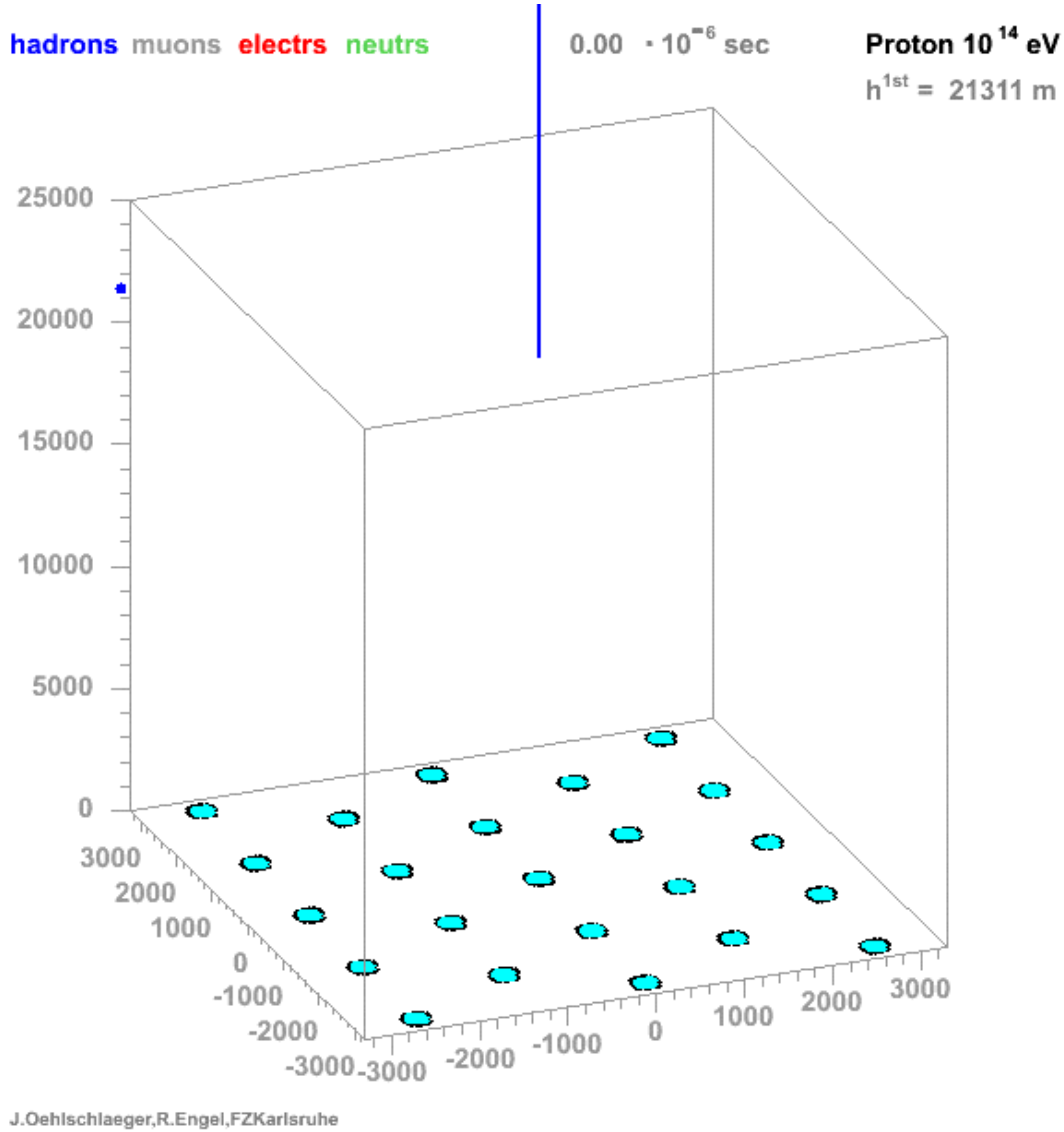


Showers develop longitudinally…

… and laterally



Air Showers

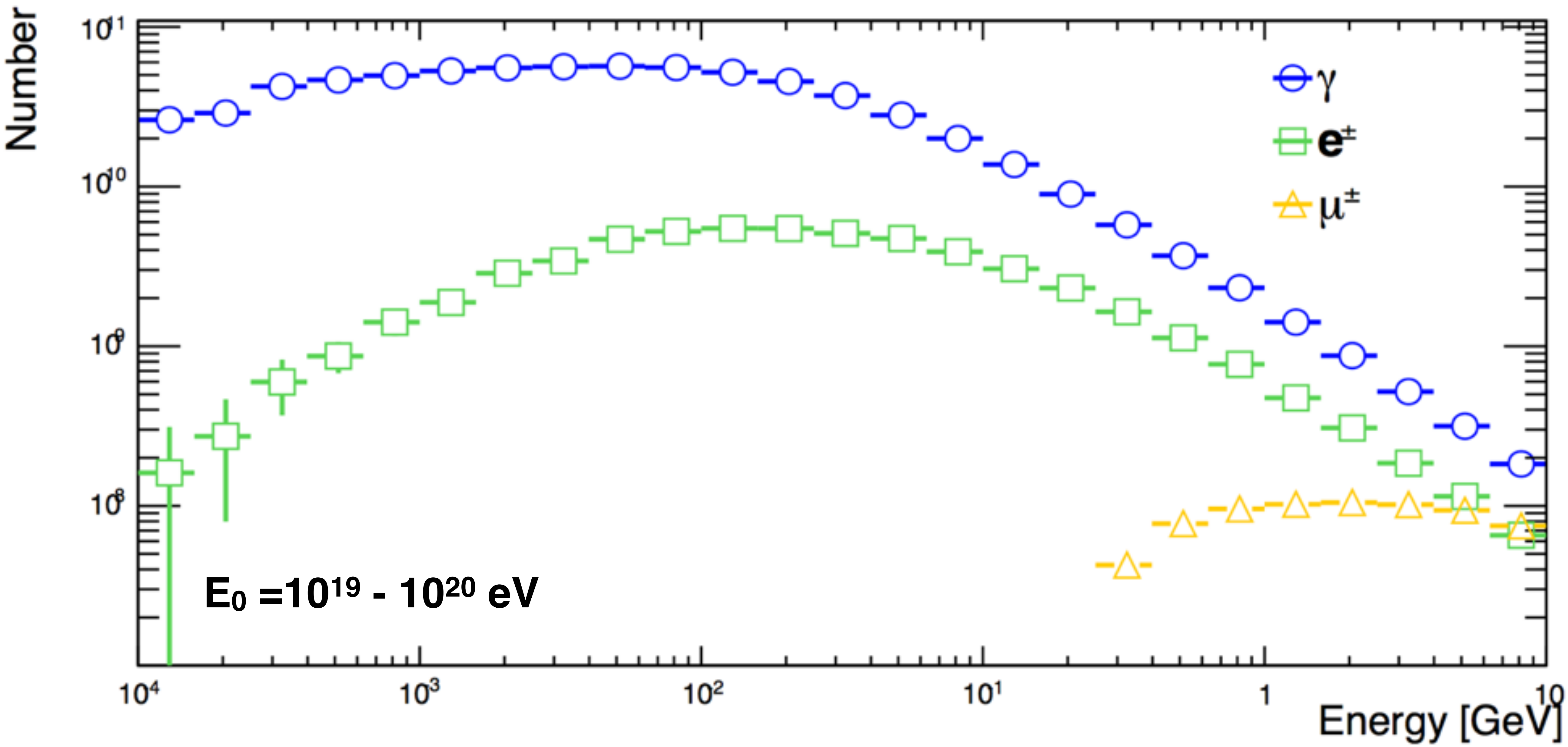


hadrons muons electrs neutrs
0.00 · 10⁻⁶ sec
Proton 10 14 eV
h1st = 21311 m
25000
20000
15000
10000
5000
0
3000
2000
1000
0
-1000
-2000
-3000
-3000
-2000
-1000
0
1000
2000
3000
J.Oehlschlaeger,R.Engel,FZKarlsruhe

Particle Content

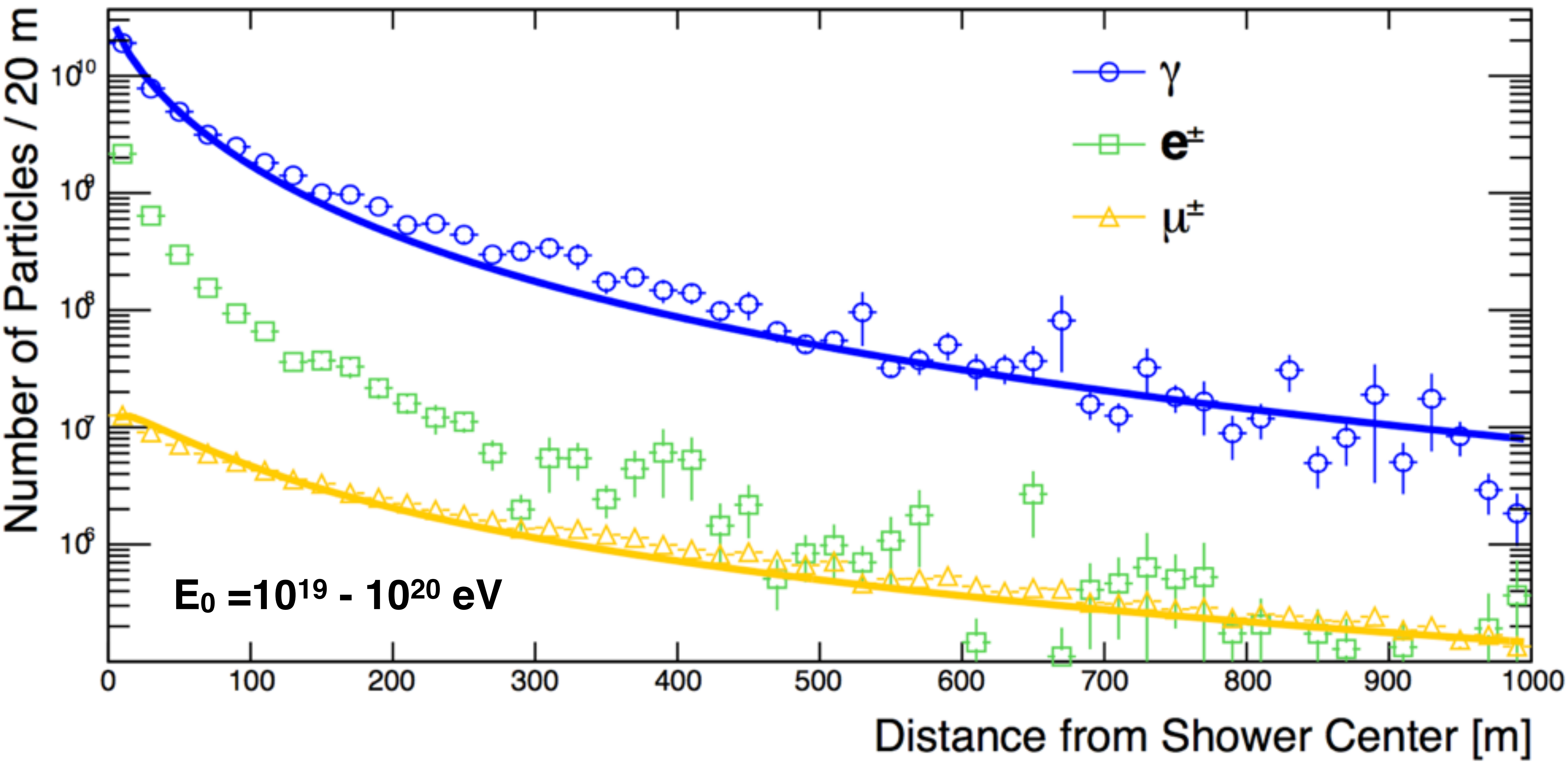
≥MeV **gammas**/**e±**

≥GeV **muons**



Particle Content

Tremendous densities
near shower core

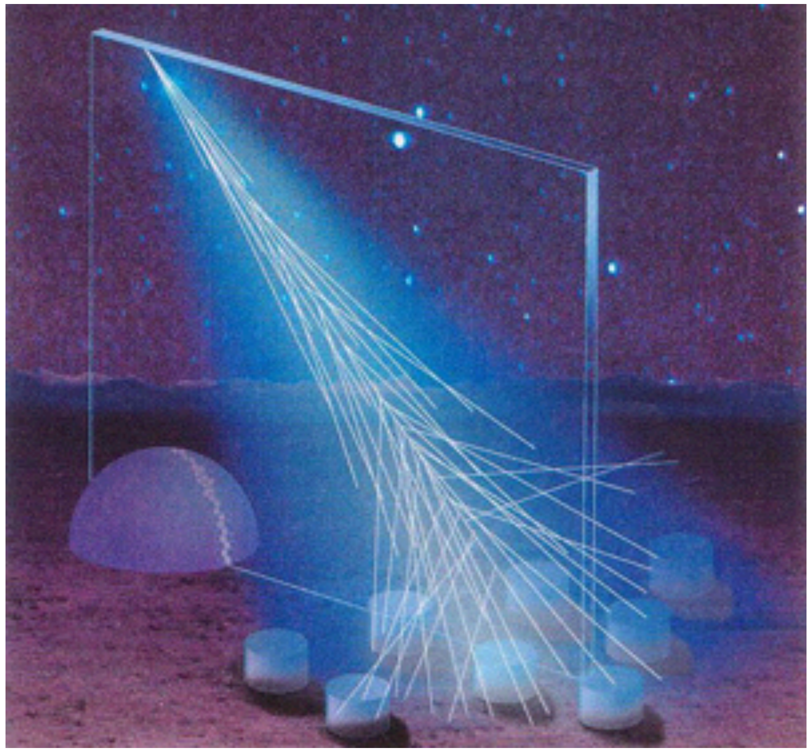


Detecting Cosmic Rays

Detection Techniques

Ways to detect air showers:

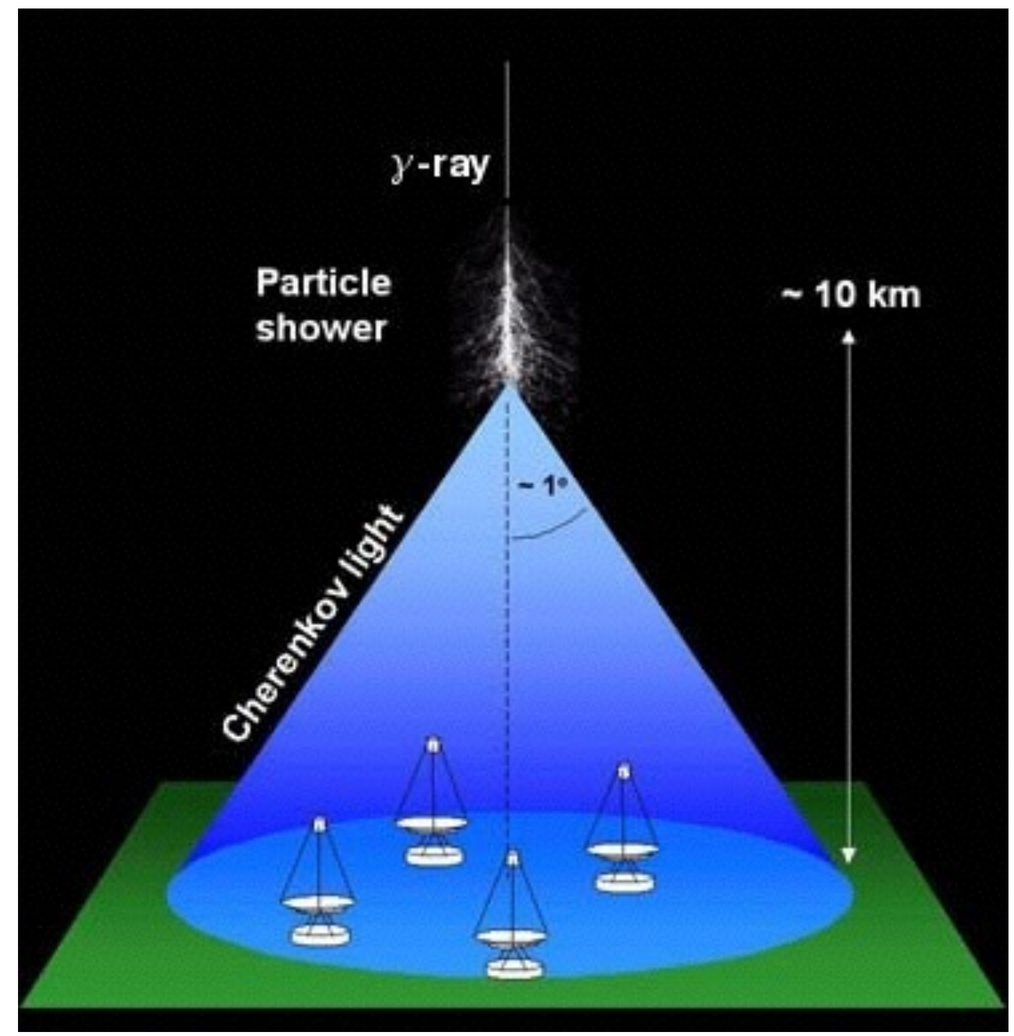
➡ Atmospheric fluorescence



Detection Techniques

Ways to detect air showers:

- ➡ Atmospheric fluorescence
- ➡ Cherenkov telescopes



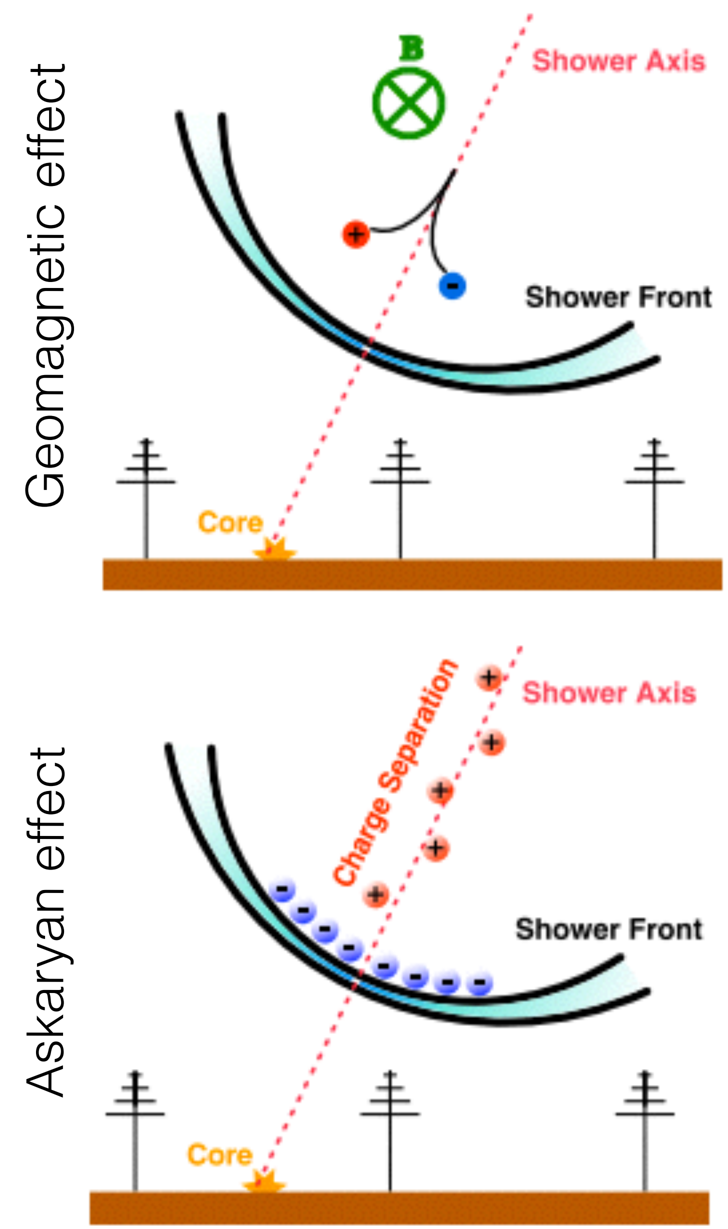
Detection Techniques

Ways to detect air showers:

➡ Atmospheric fluorescence

➡ Cherenkov telescopes

➡ Radio frequency



Detection Techniques

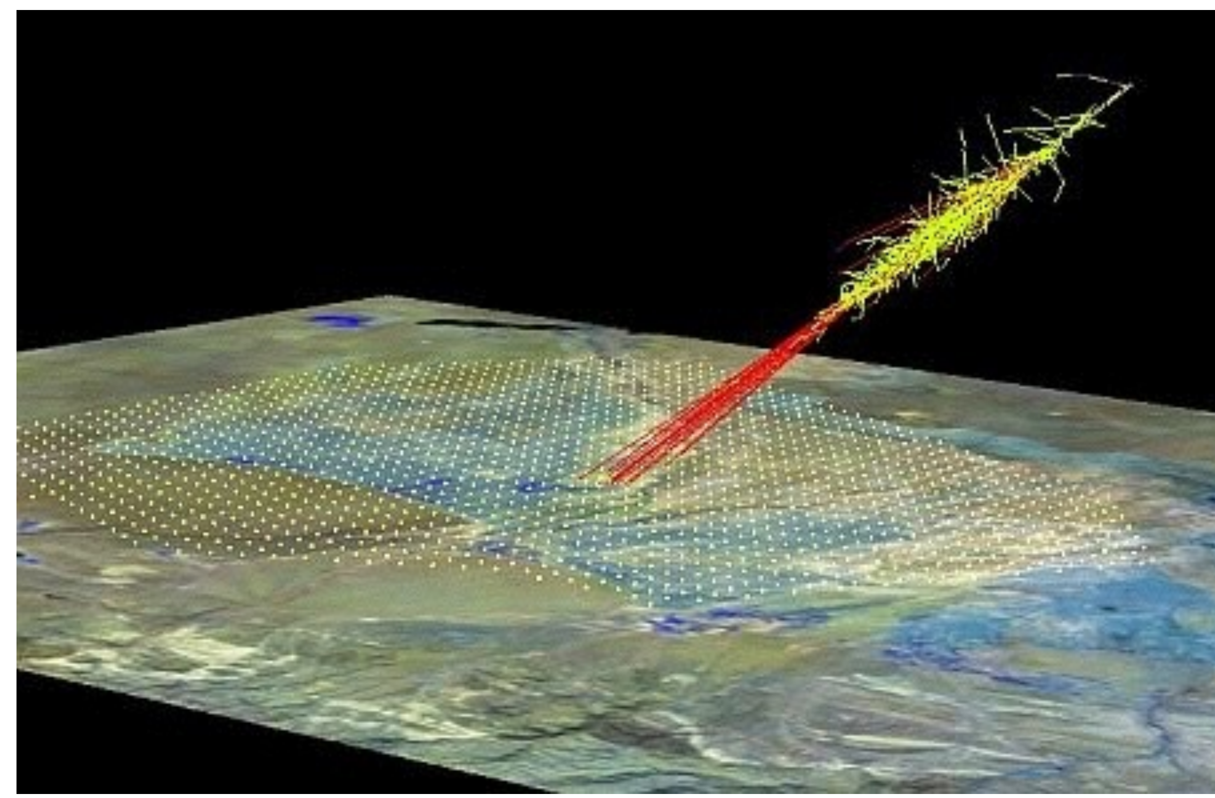
Ways to detect air showers:

➡ Atmospheric fluorescence

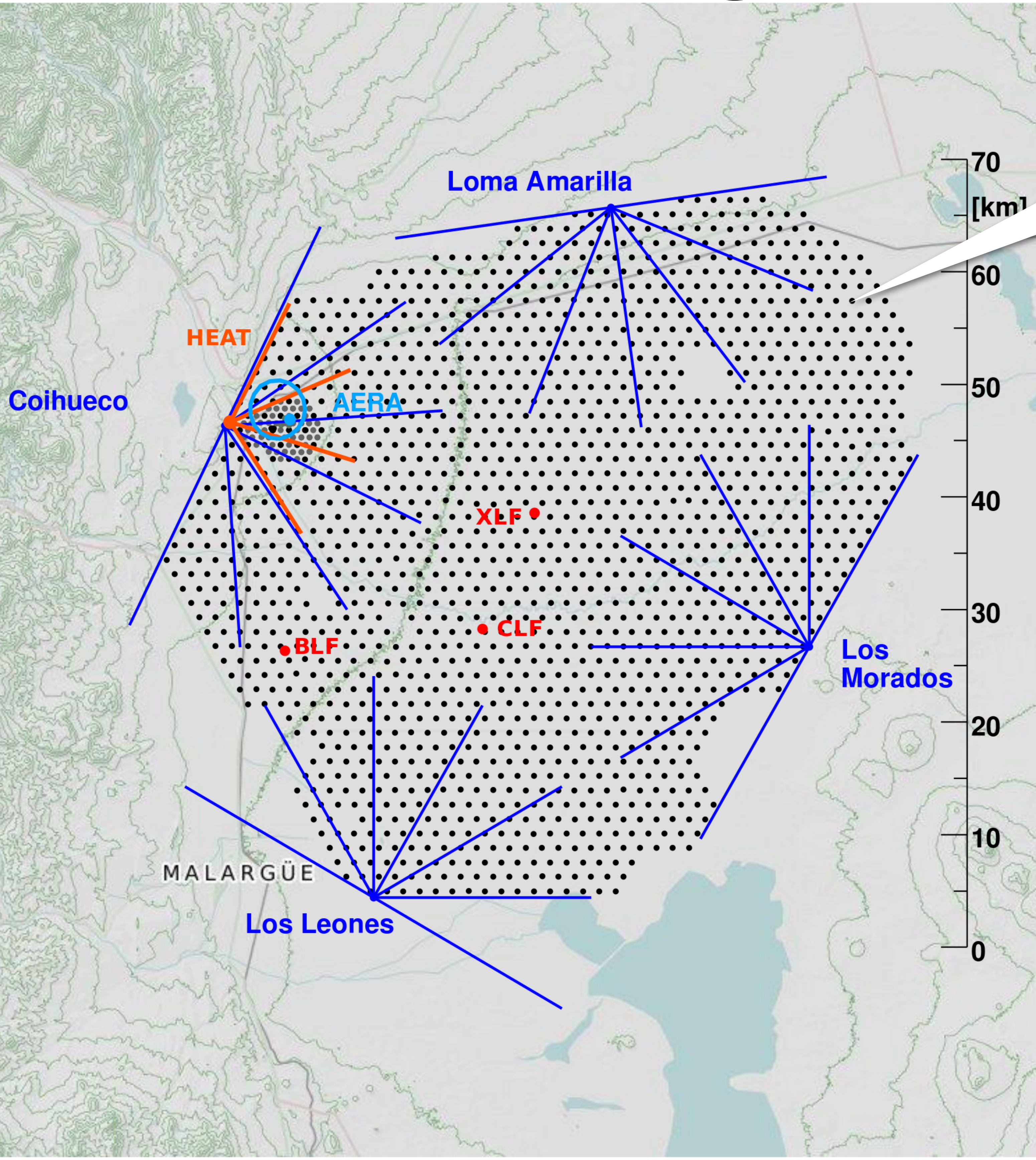
➡ Cherenkov telescopes

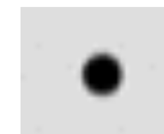
➡ Radio frequency

➡ **Ground arrays**



Pierre Auger Observatory





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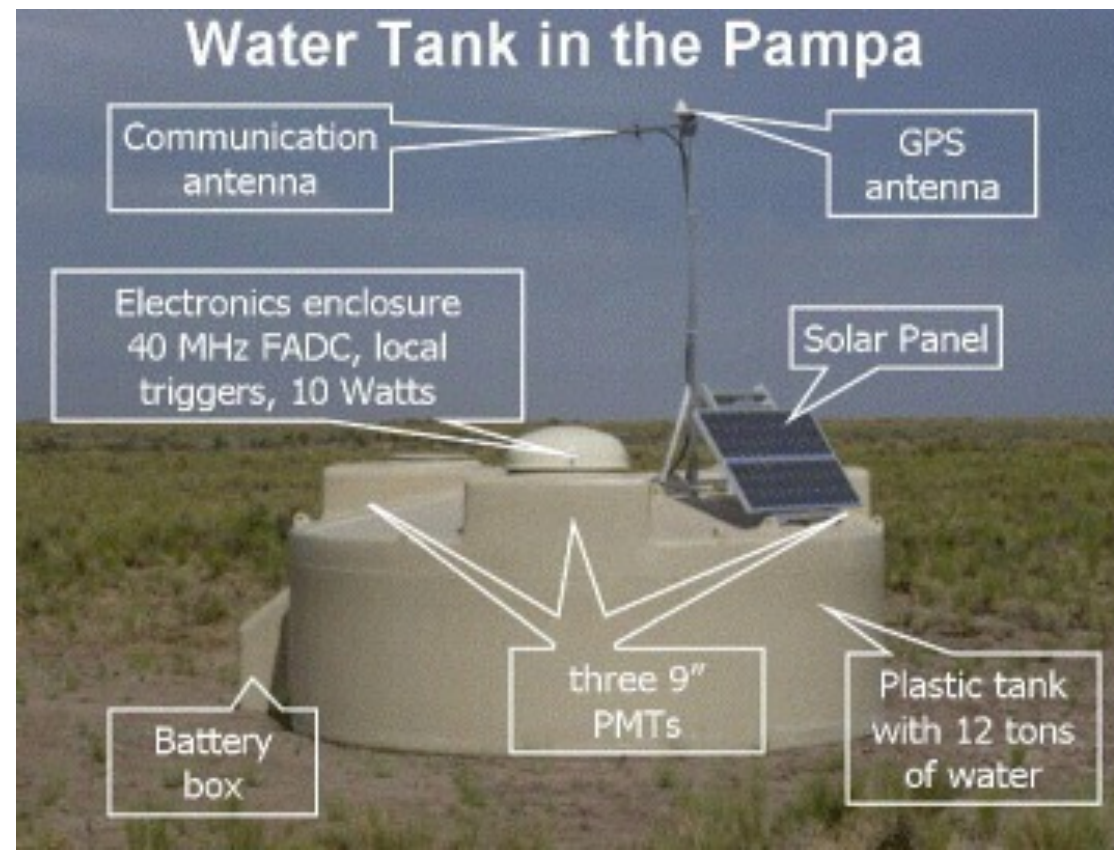
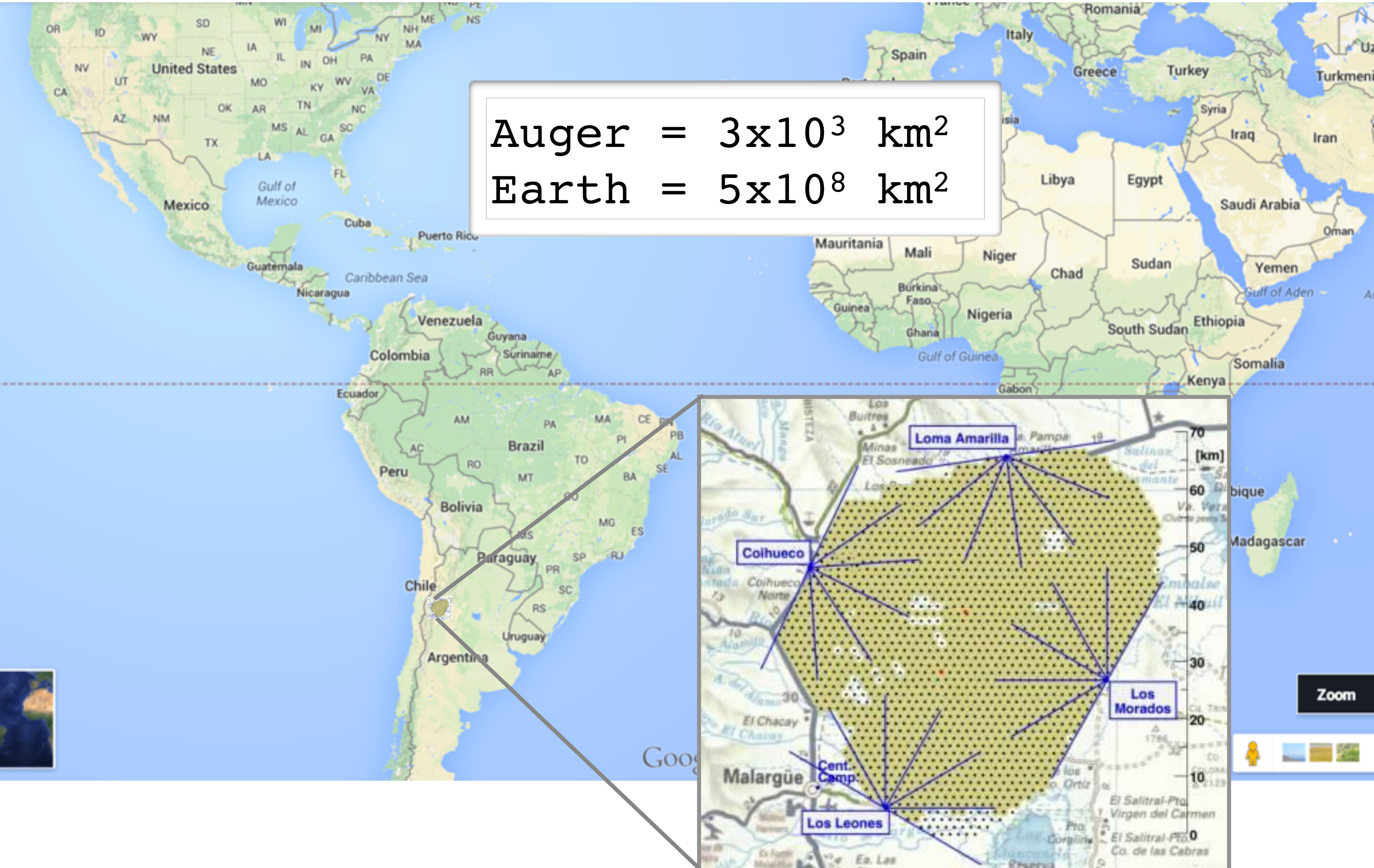


1600 Cherenkov tanks

3000 km²

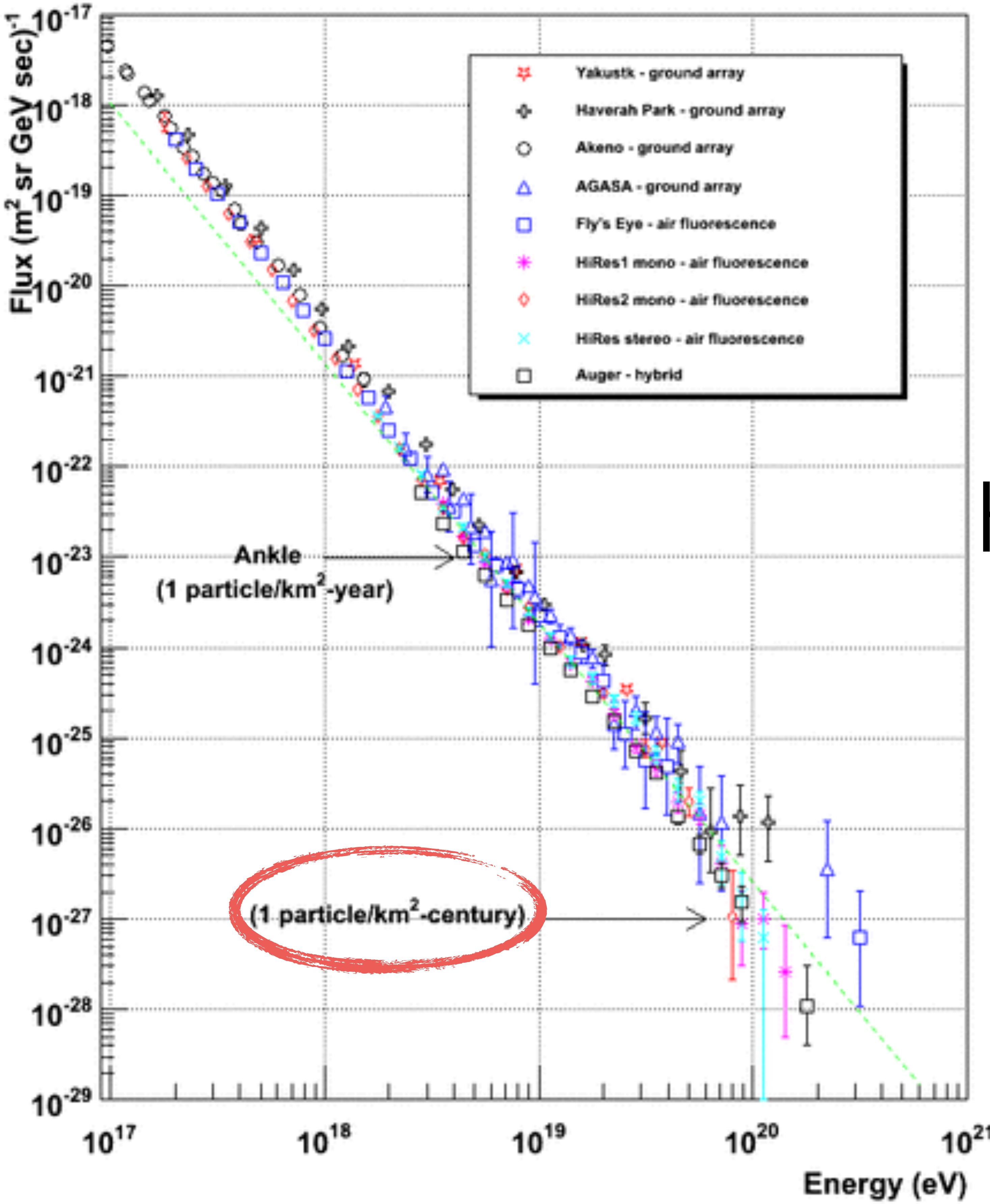
Pierre Auger Observatory

Pierre Auger Observatory



$$\text{Auger} = 3\text{x}10^3\ \text{km}^2$$
$$\text{Earth} = 5\text{x}10^8\ \text{km}^2$$

Rare Events



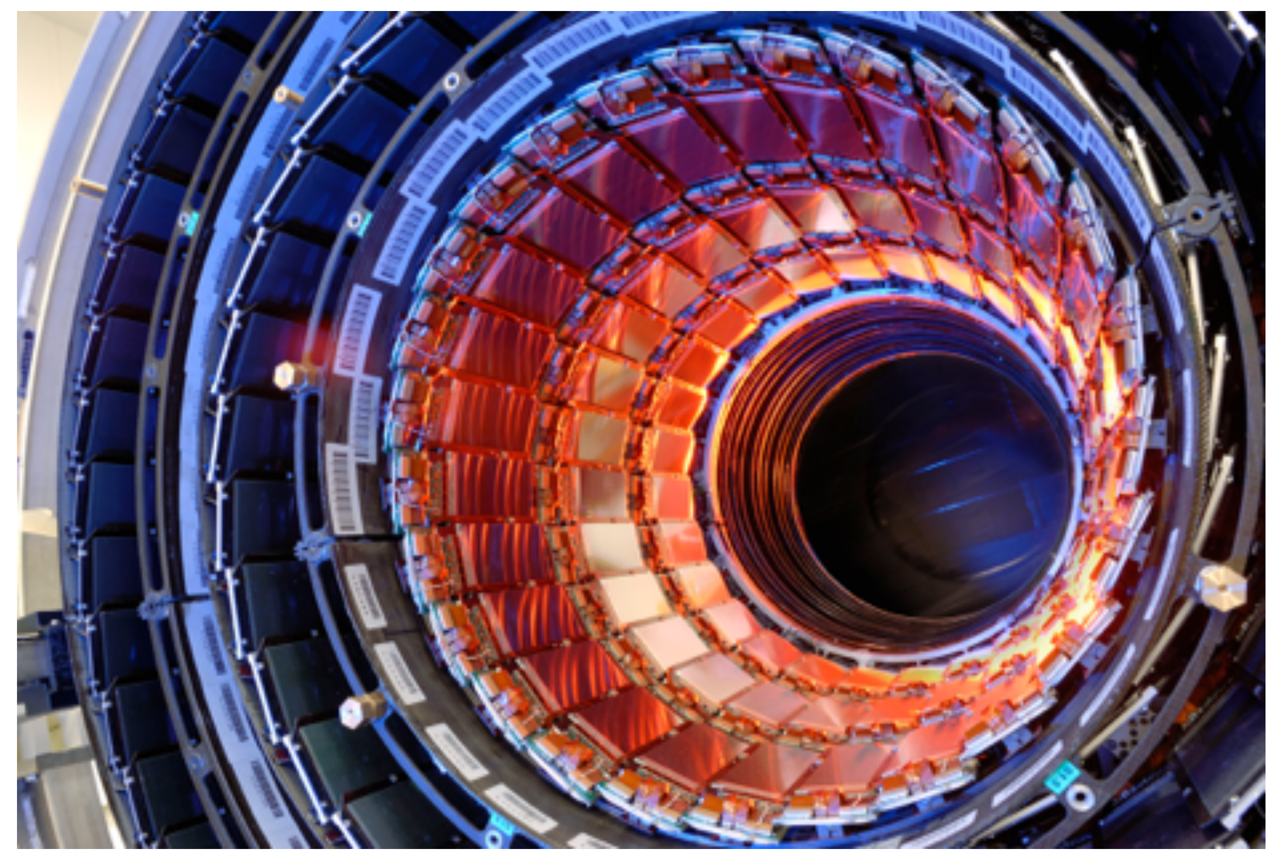
How can we cover **more ground?**

Smartphones!

Smartphones are:
(tiny) Particle Detectors

Camera Sensor

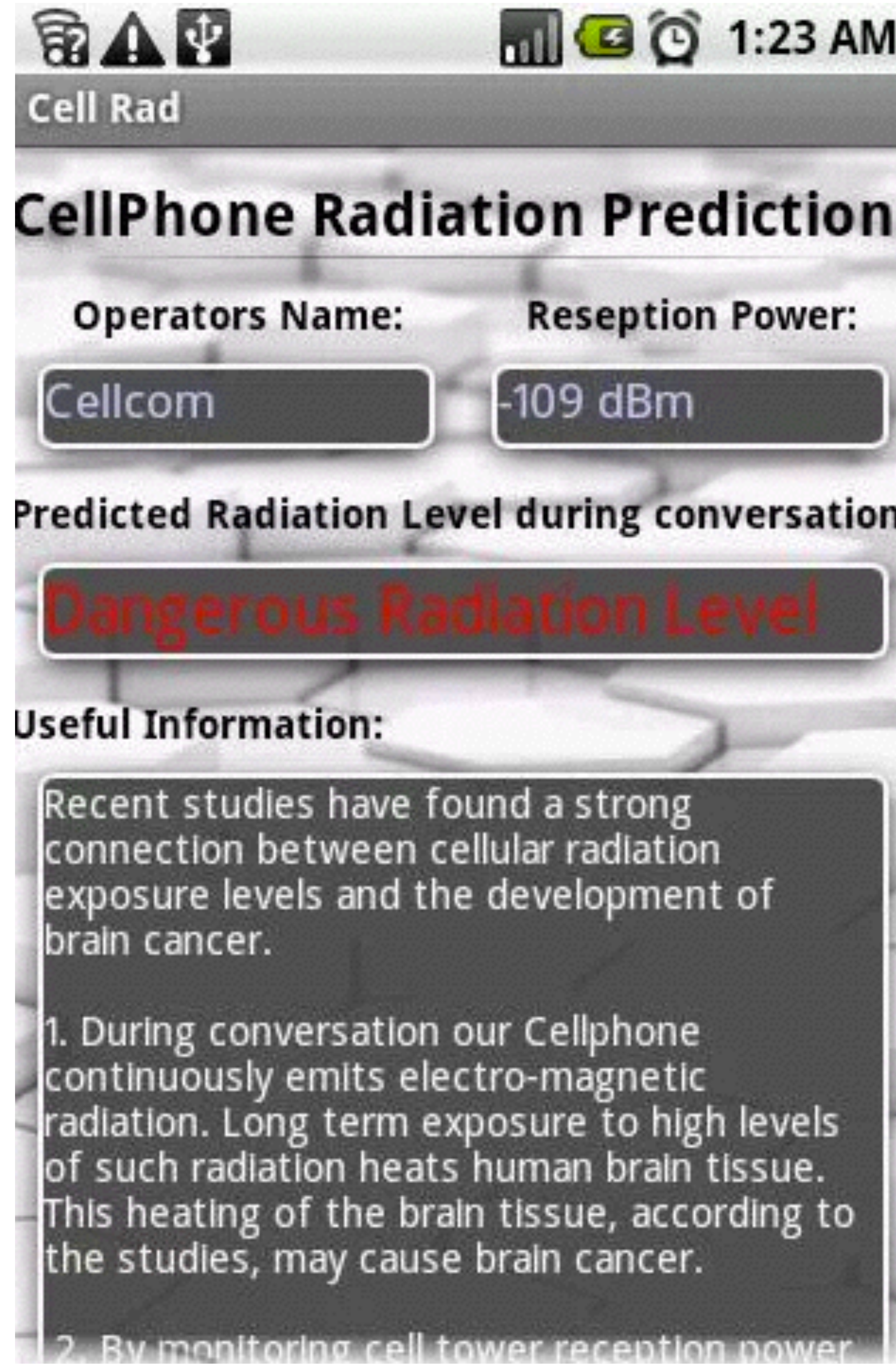
=



(Active area: ~0.3 cm^2)

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

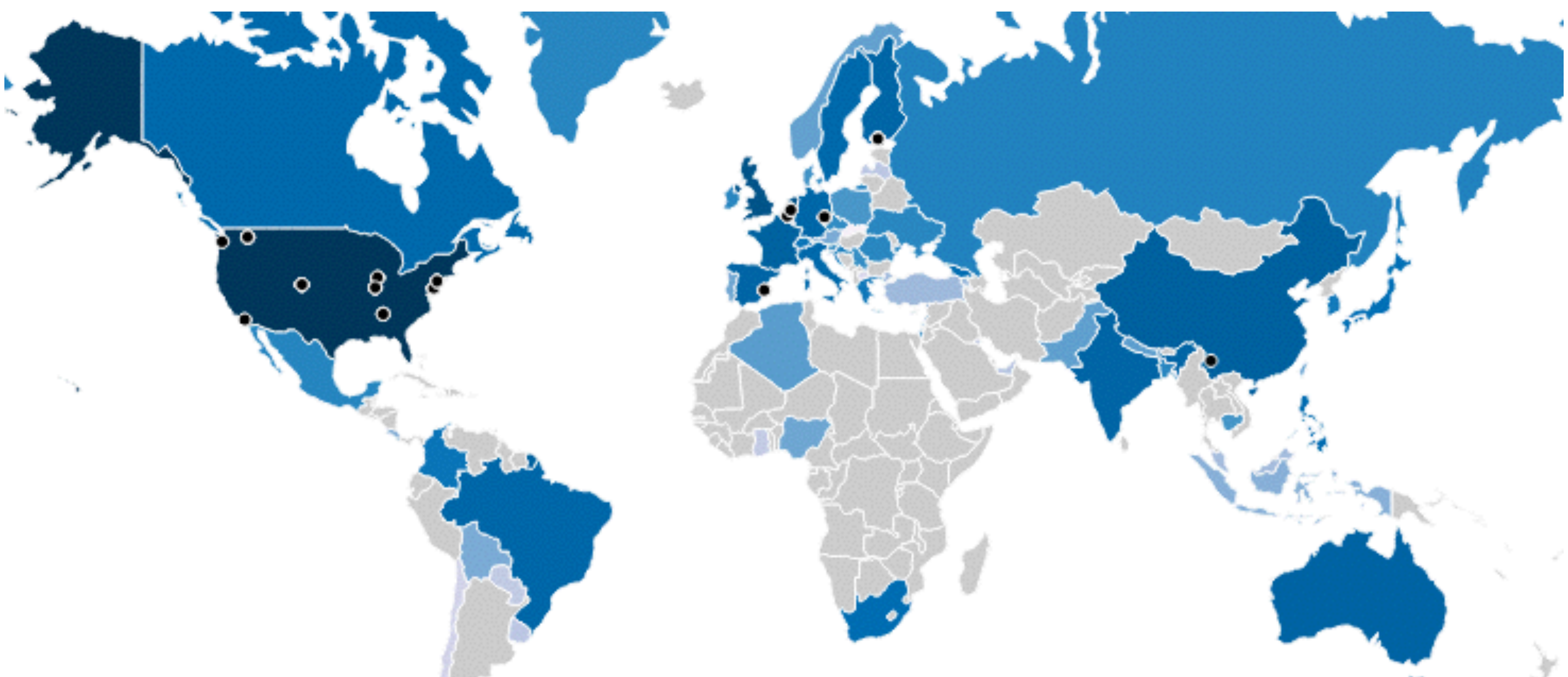
But:

it’s not enough to simply *observe particles…*

Our goal: *network* a large number of smartphones into a **worldwide observatory**!

CRAYFIS

cosmic rays found in smartphones



CRAYFIS

cosmic rays found in smartphones

Whiteson
Shimmin
Strong
Brodie
Goddard
Porter
Sandy

NYU

Cranmer

Яндекс
Yandex

Ustyuzhanin
+2 masters st.

UCDAVIS
UNIVERSITY OF CALIFORNIA

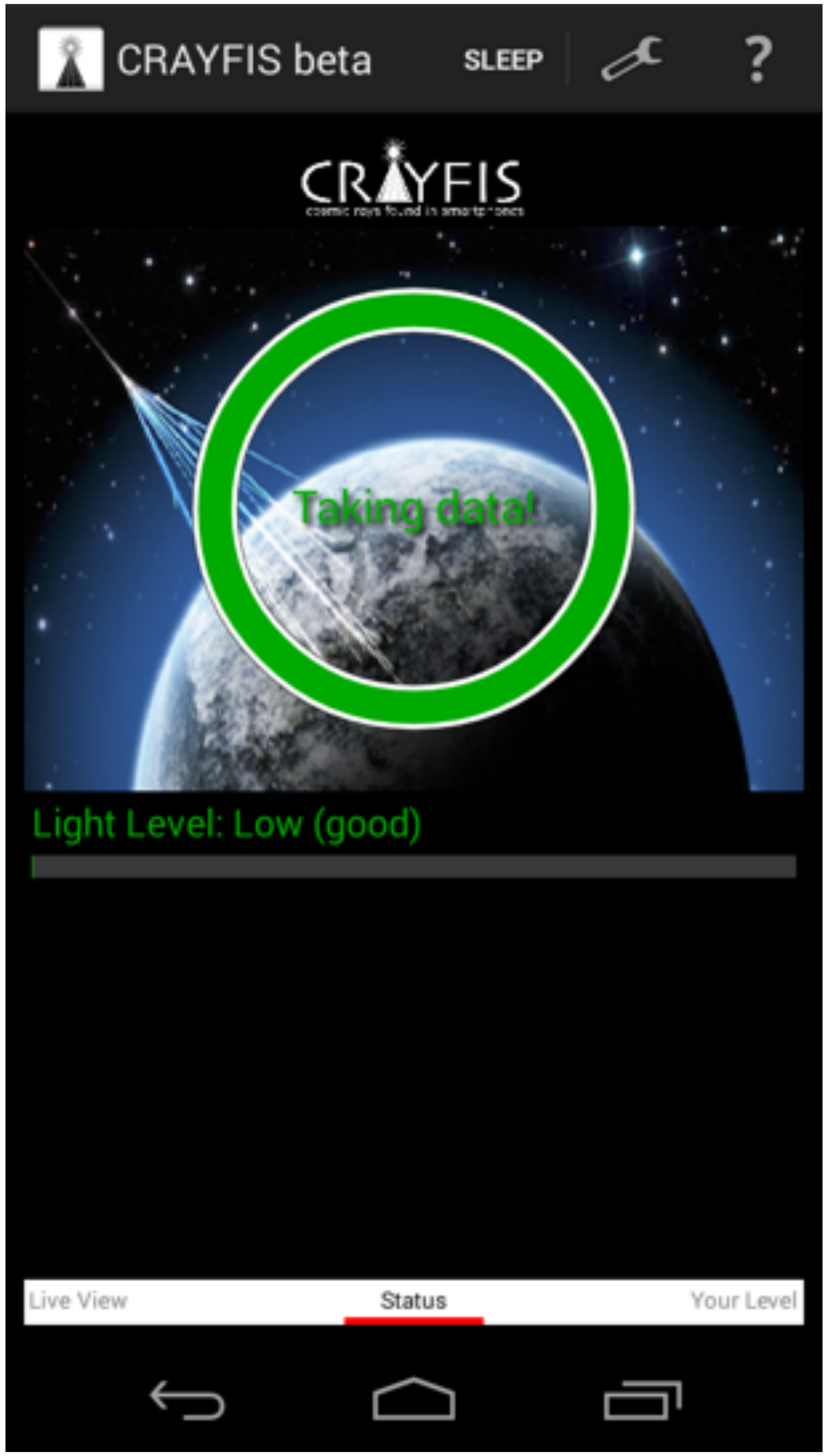
Mulhearn
Burns
Buonacarsi

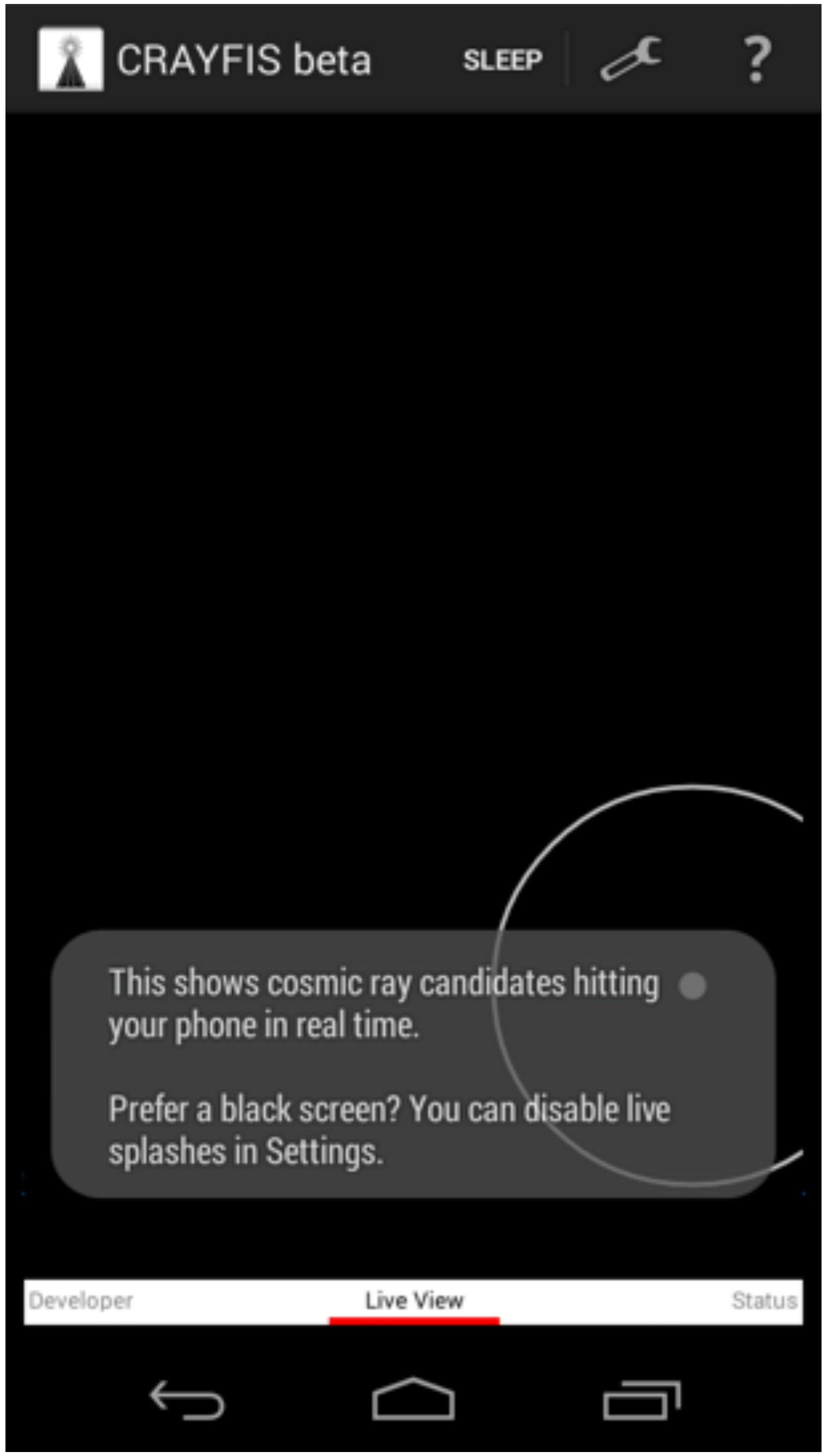
NAOC

Deng

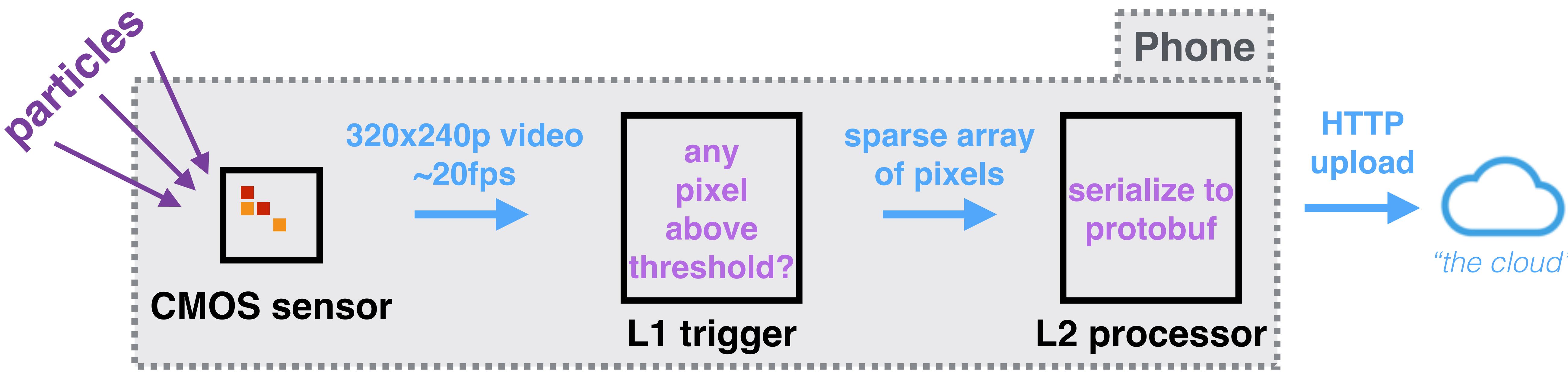
powered by amazon web services

The App (android)



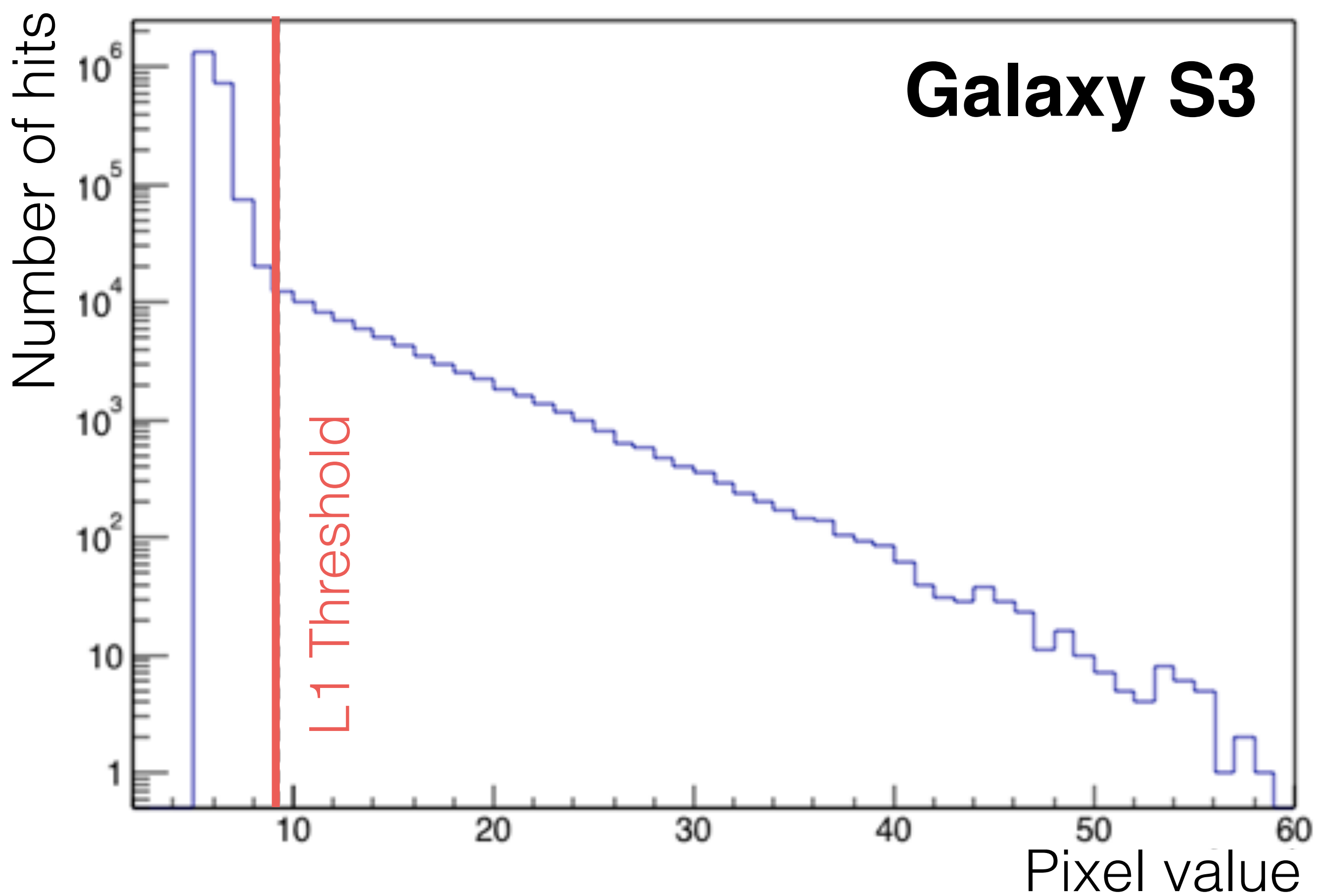


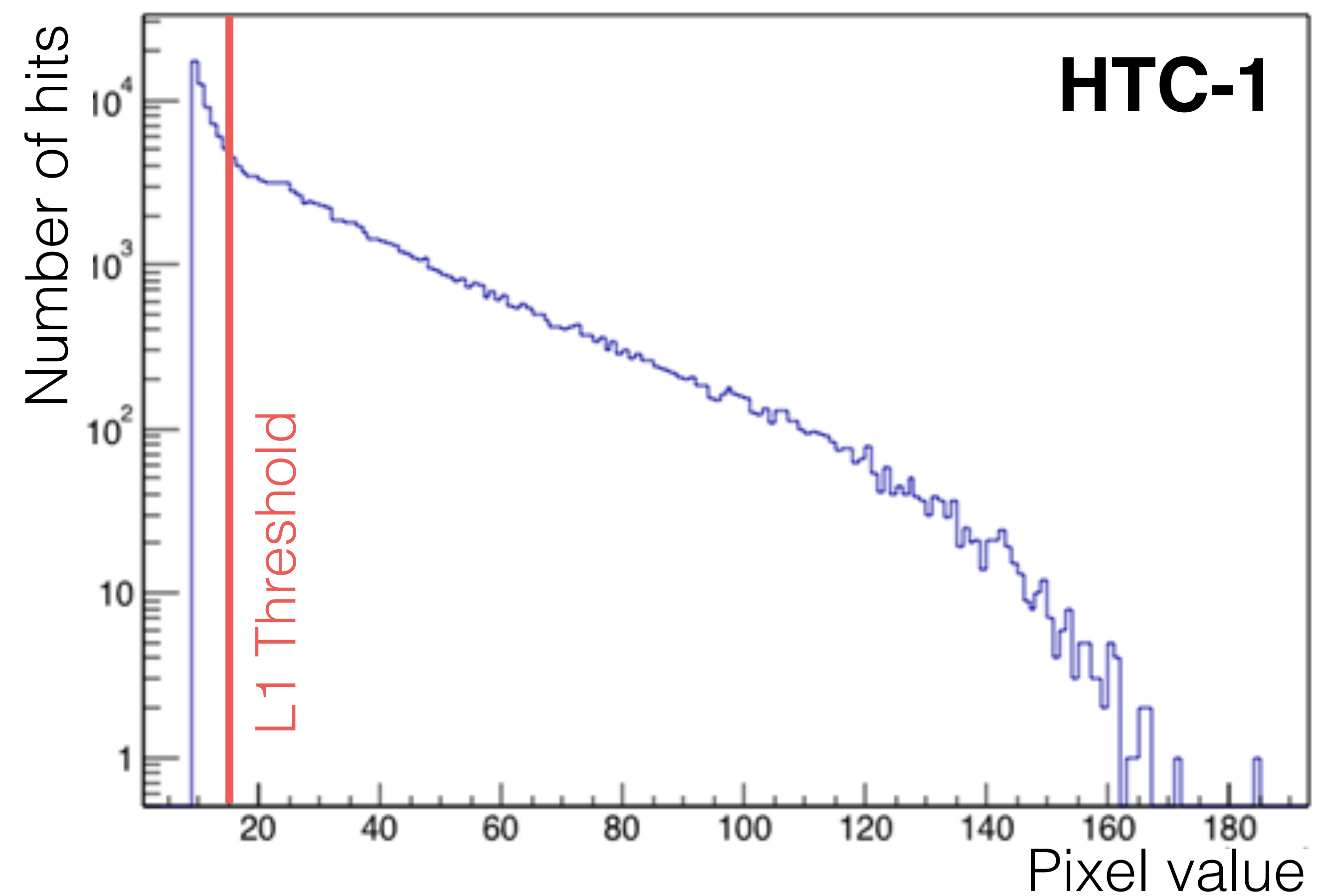
The App: Internals



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

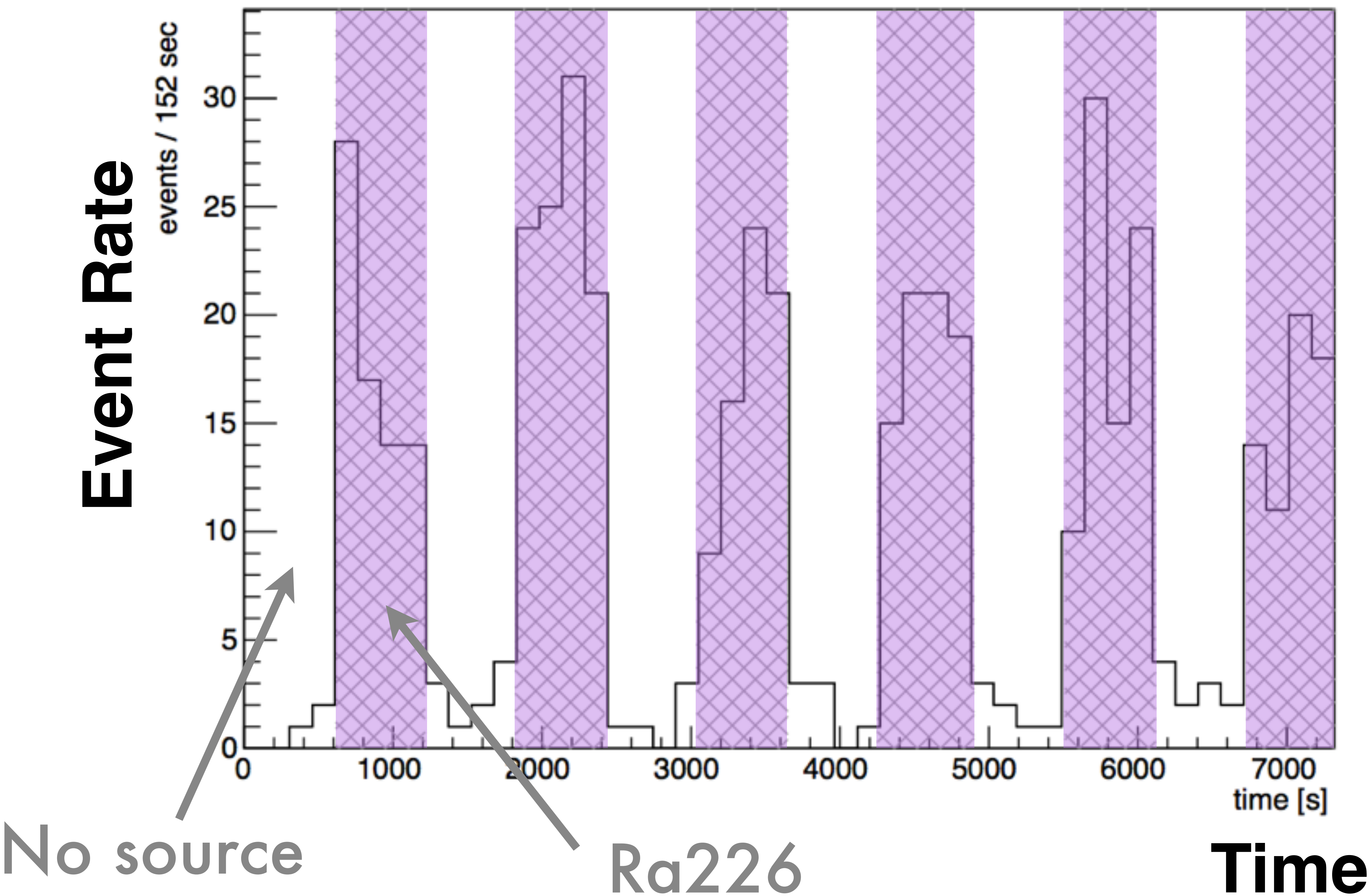
Trigger Calibration



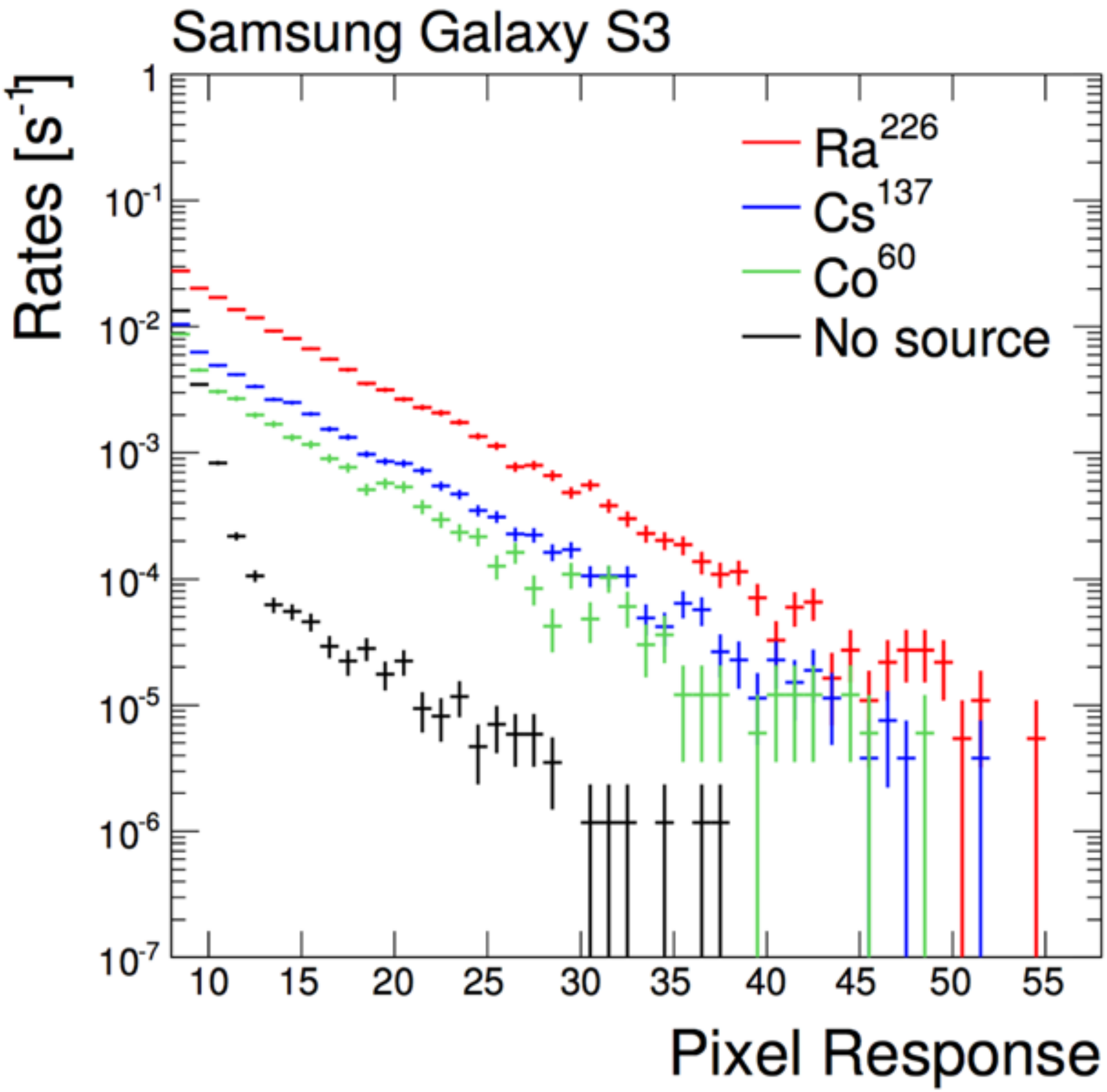


Set **trigger threshold** to maintain
average event rate of ~0.1Hz

Photon Sensitivity



Photon Sensitivity

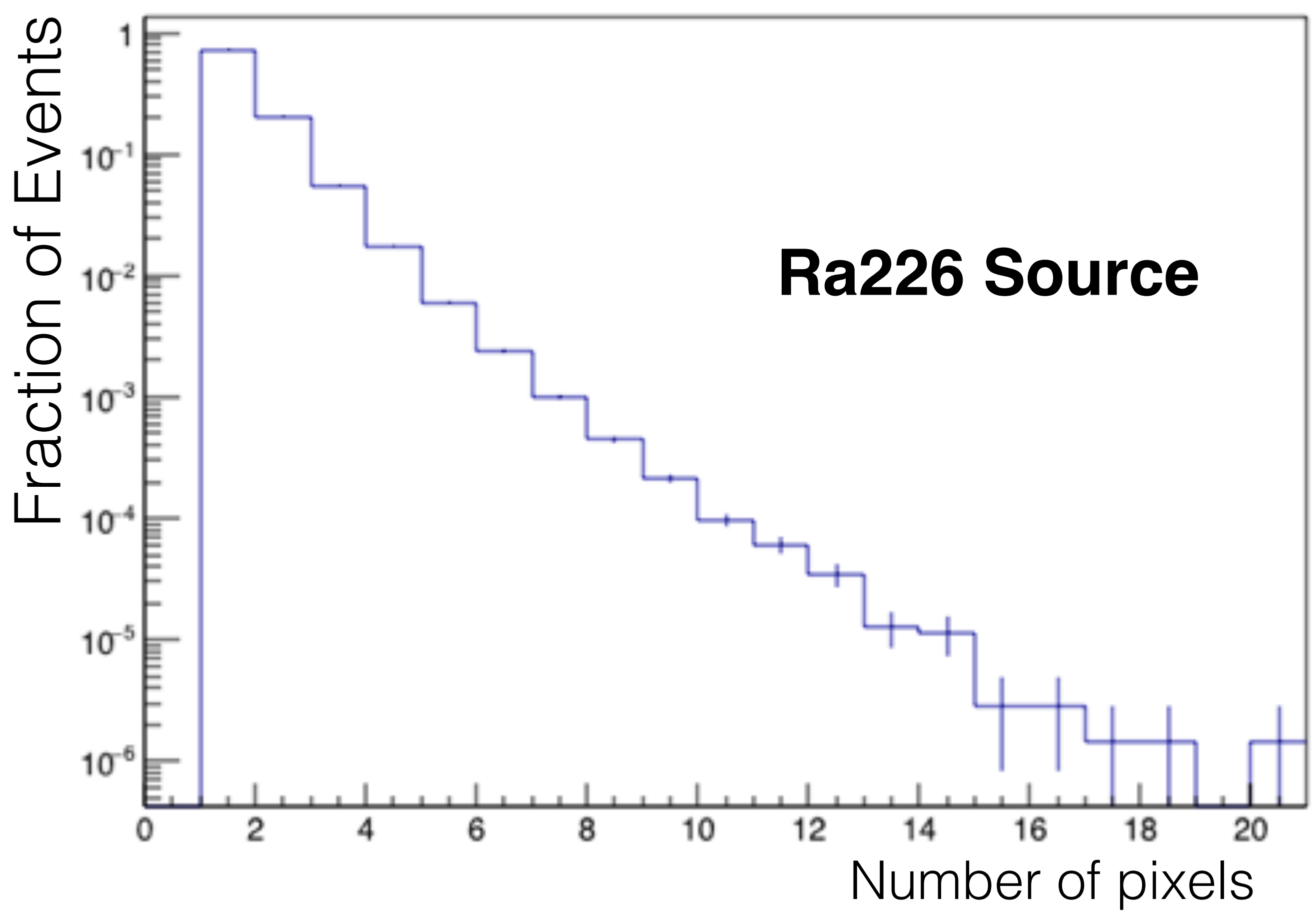


Sources w/ varying activity, energy:

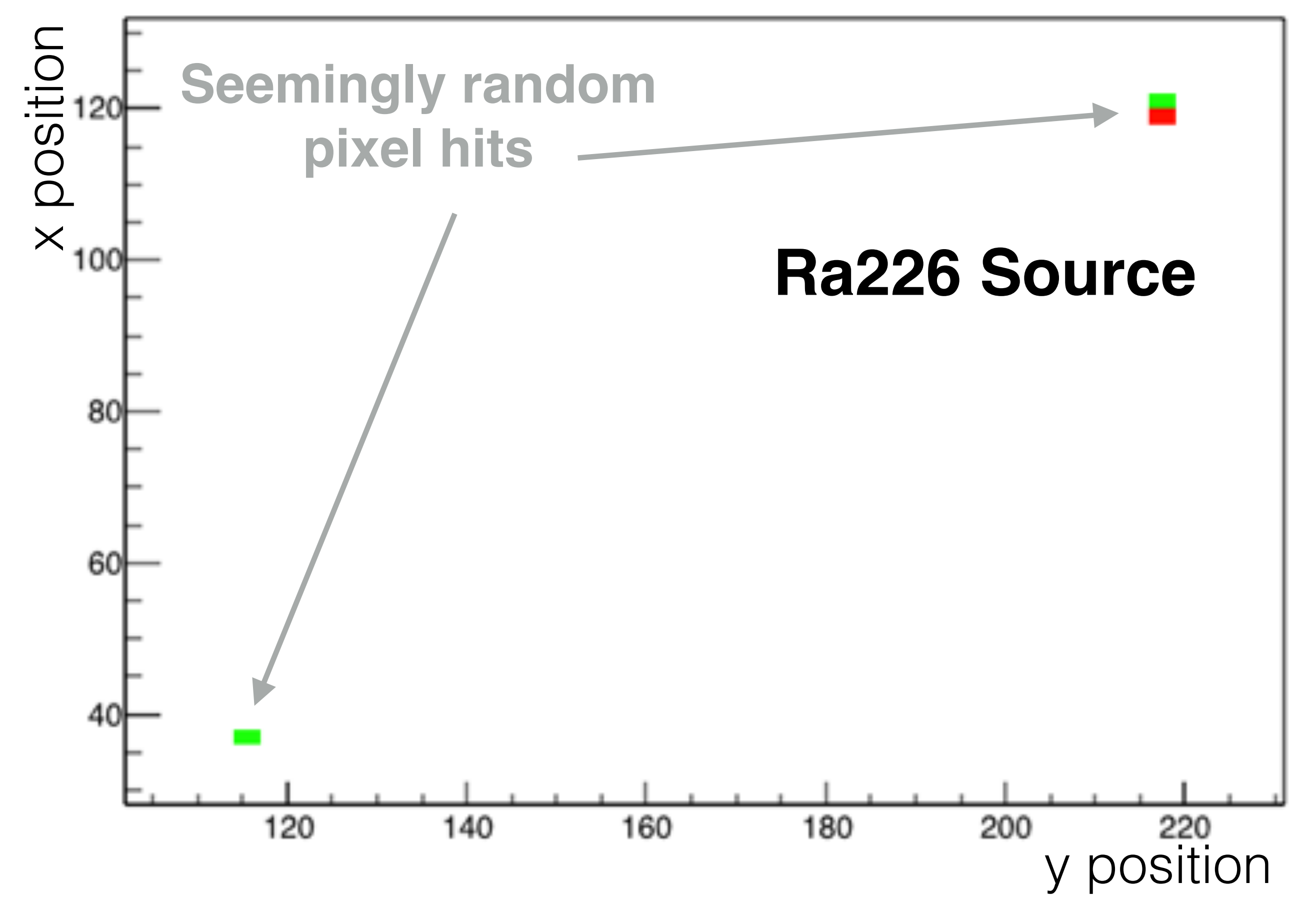
Ra226: ~180-600 keV
Cs137: 700 keV
Co60: 1.1/1.3 MeV

What do Photons *Look* Like?

Usually: a single pixel high above threshold



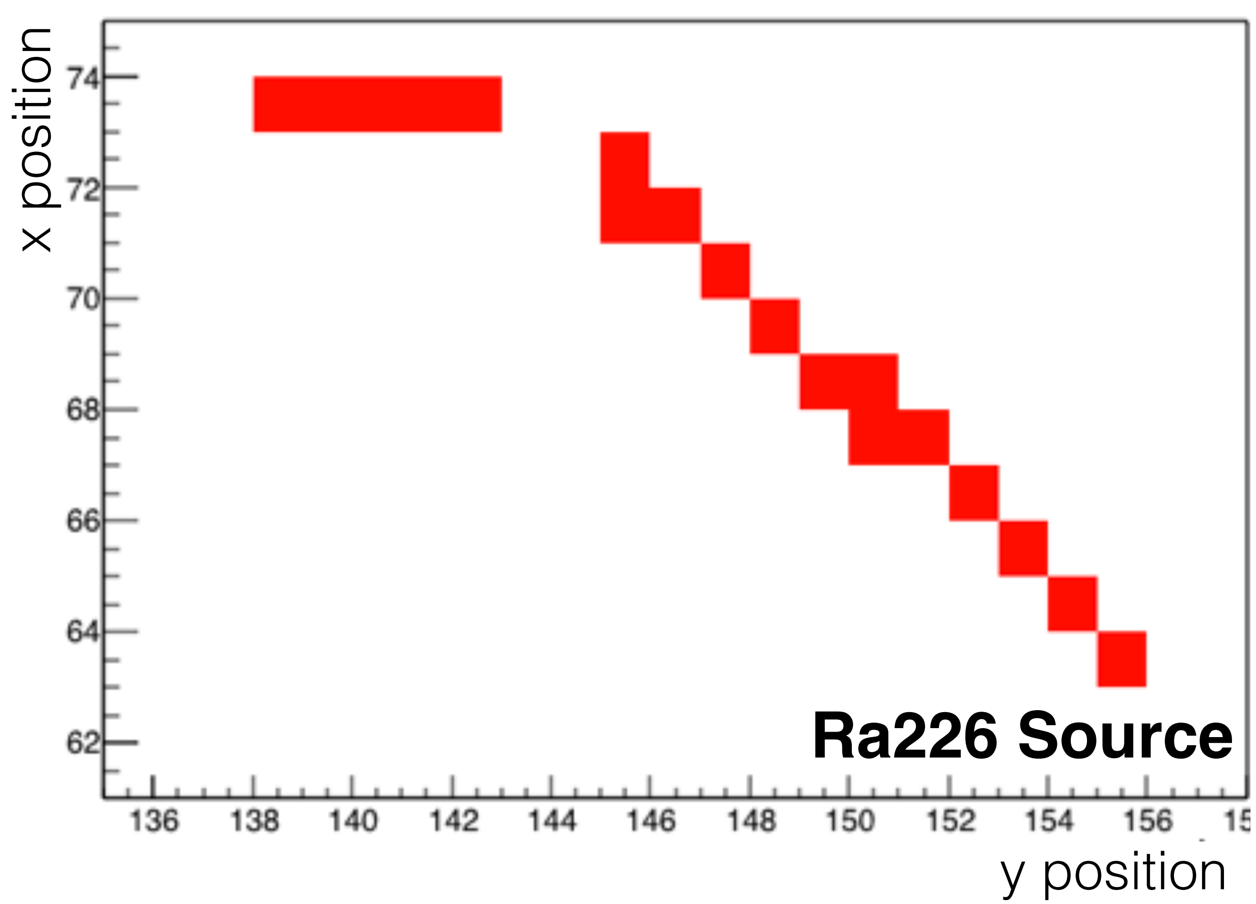
Pixels from one event



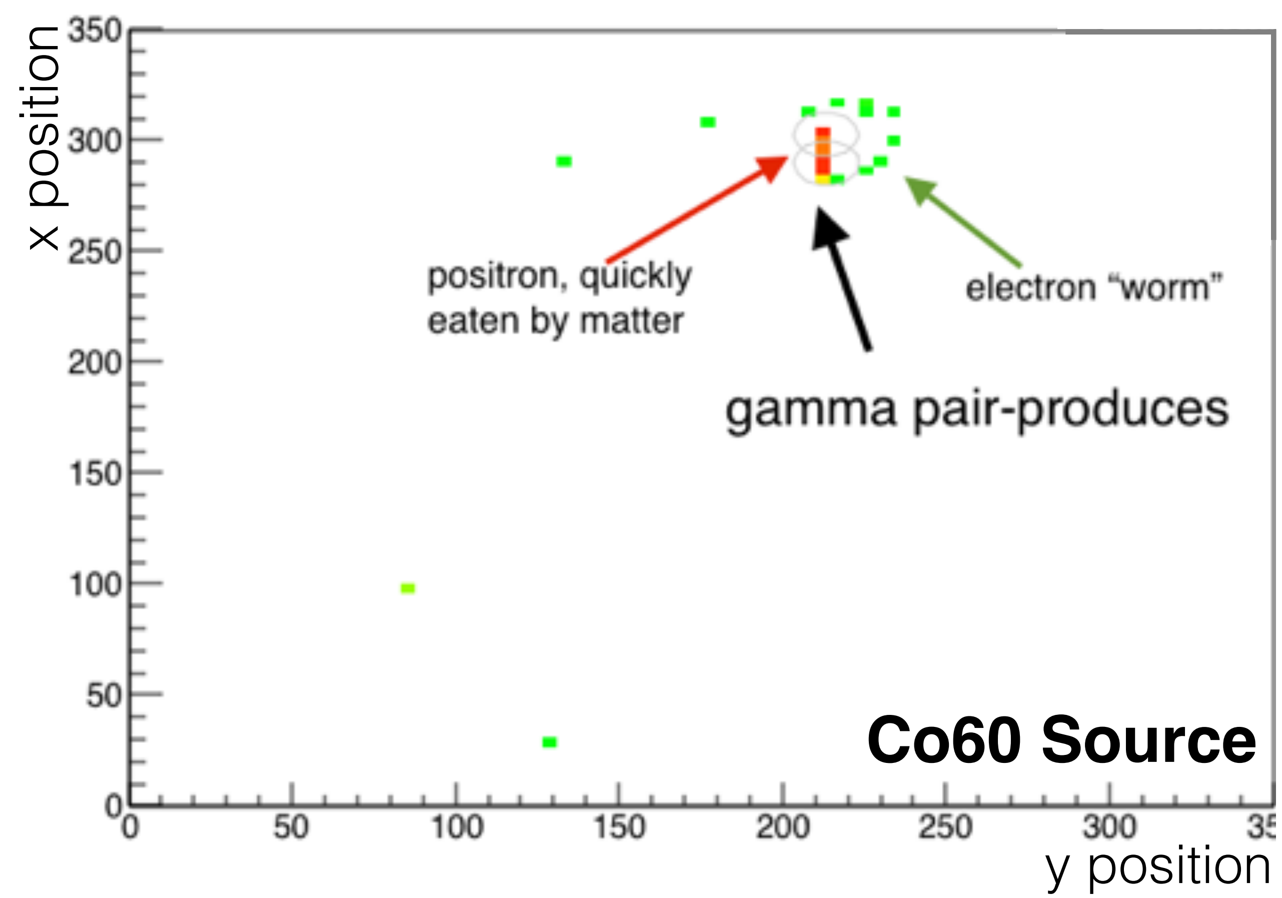
What do Photons *Look* Like?

Sometimes we get interesting tracks:

Pixels from one event



Pixels from one event



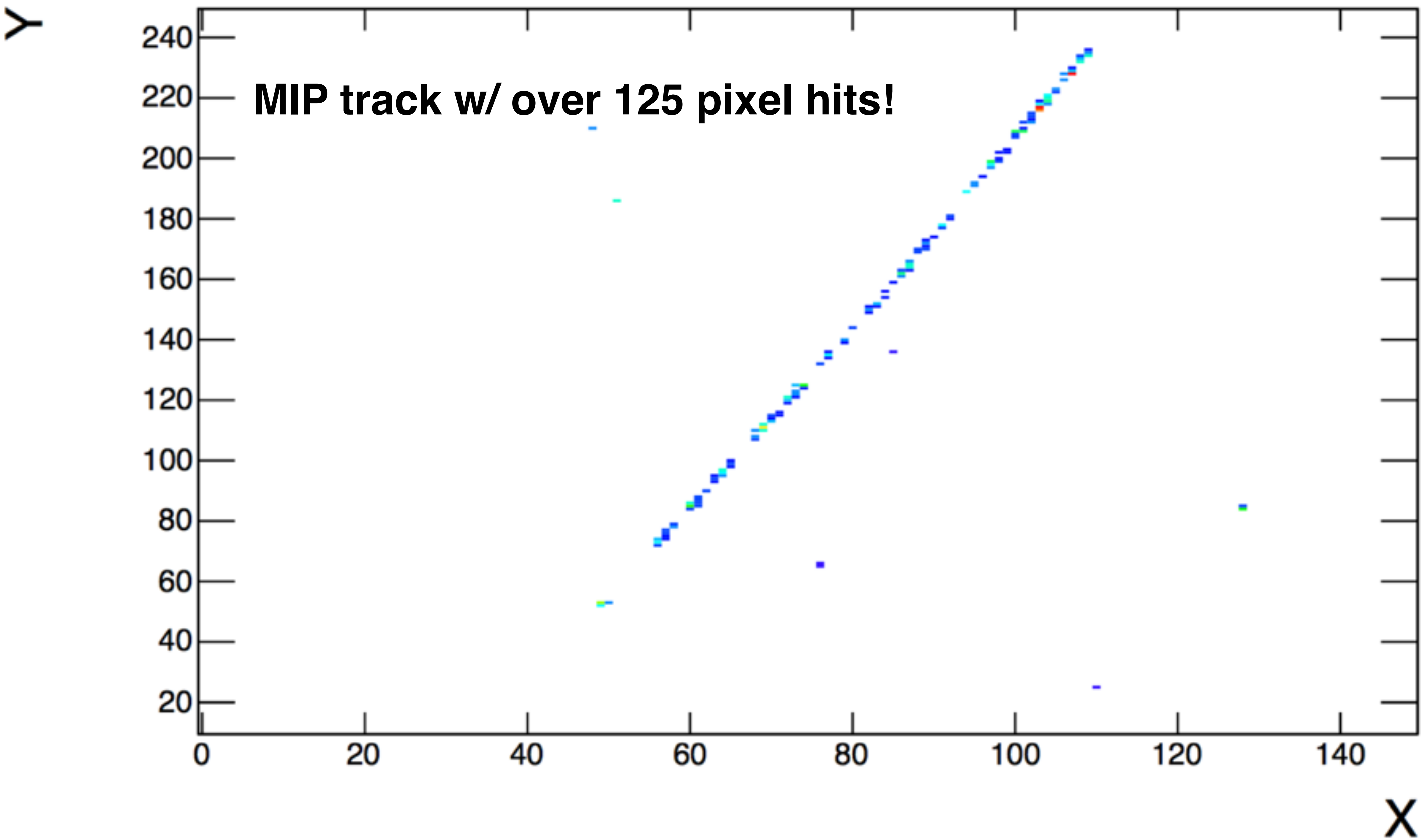
Muon Sensitivity

So far, no muon sources available…

Muon Sensitivity

Get them for free from the sky!

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



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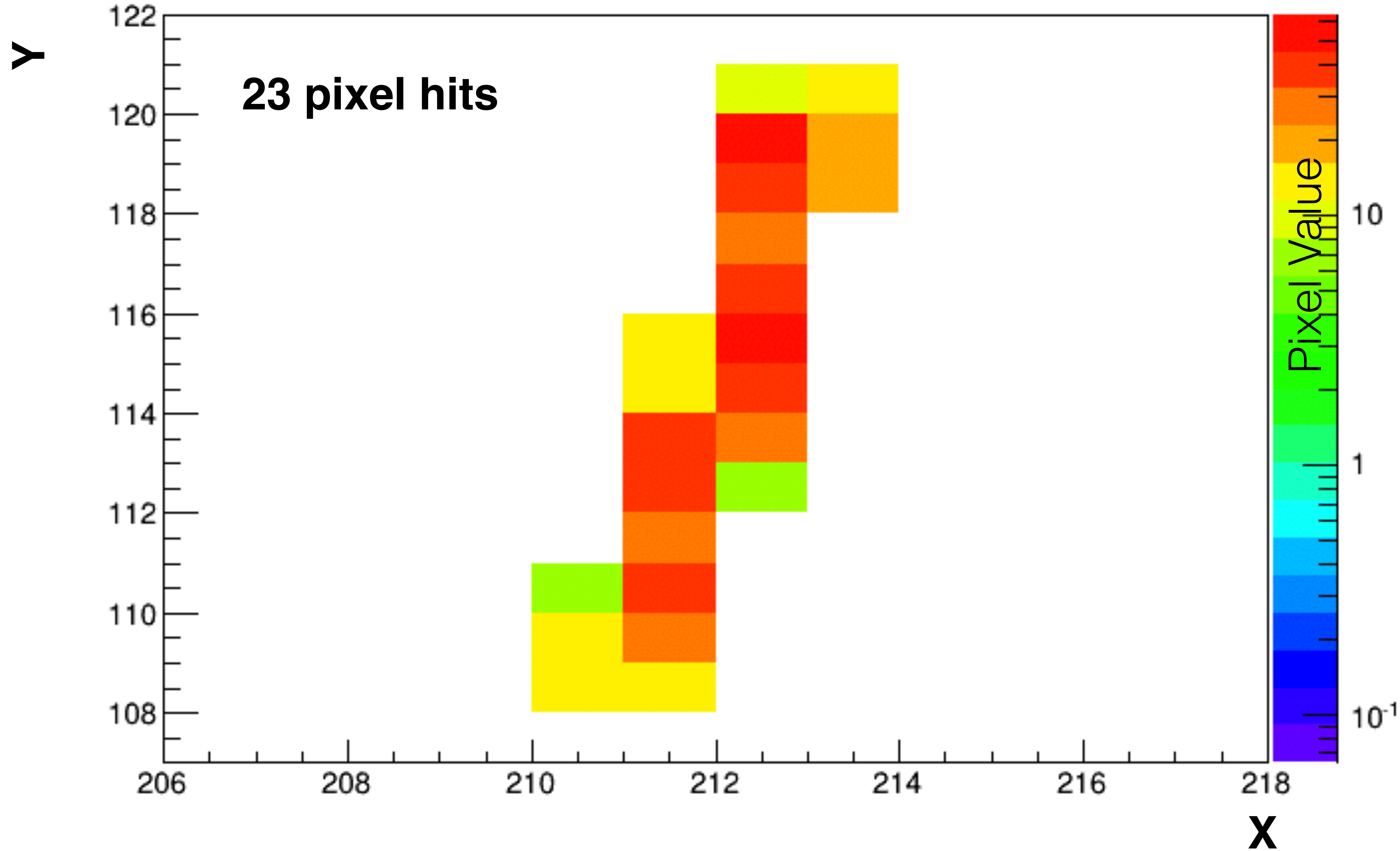
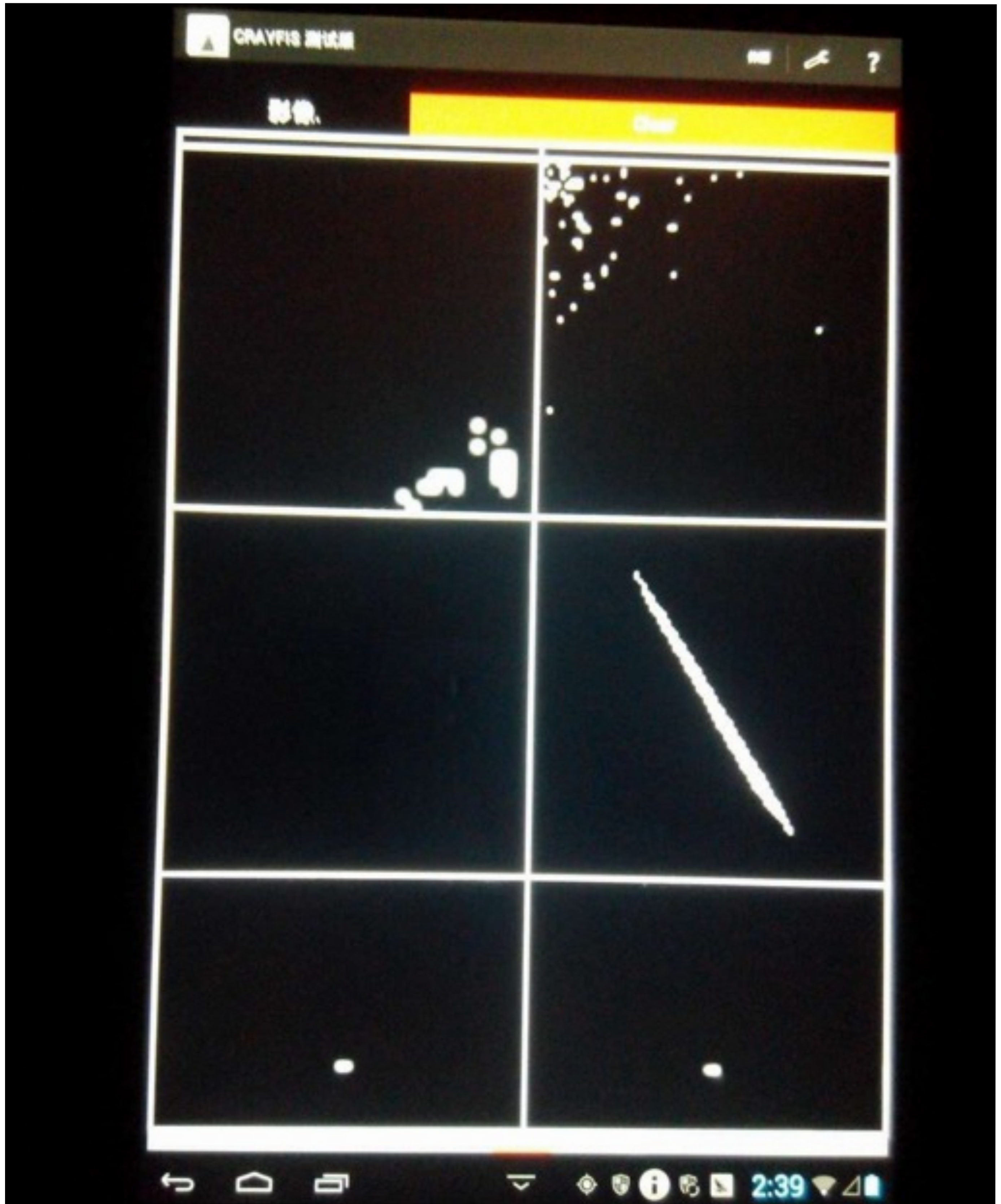
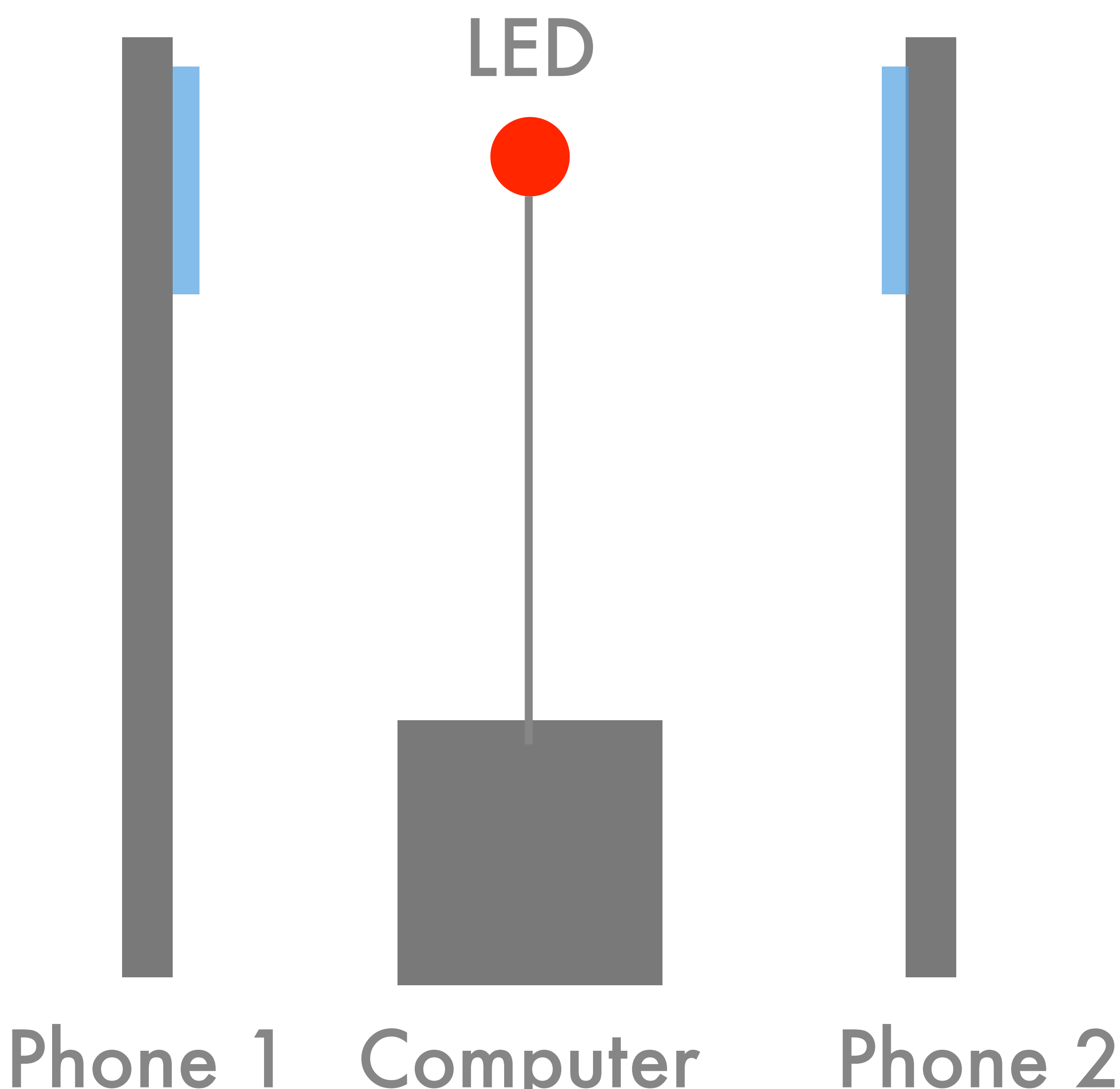


Muon Sensitivity



Timing

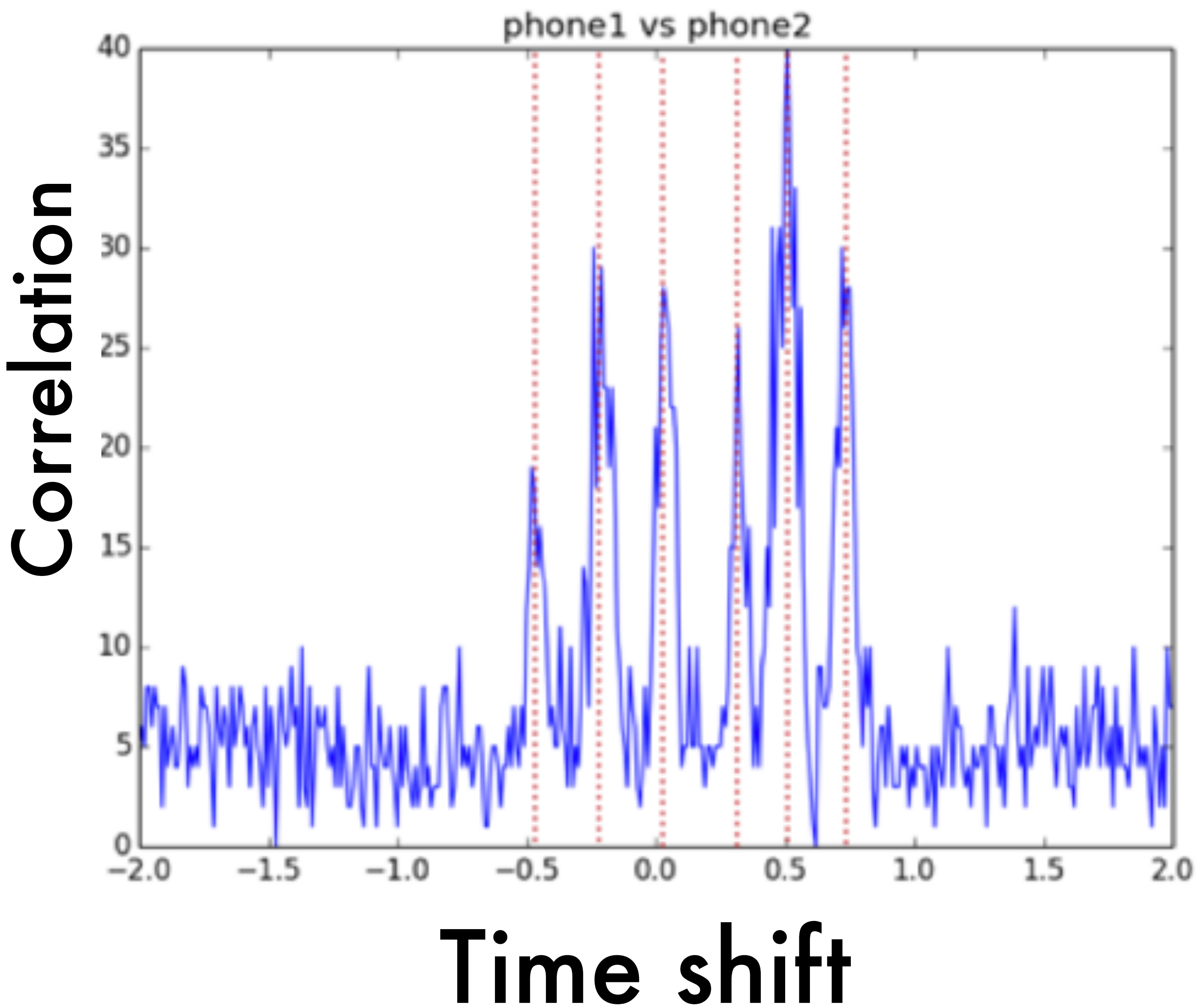
For measuring **coincident hits**



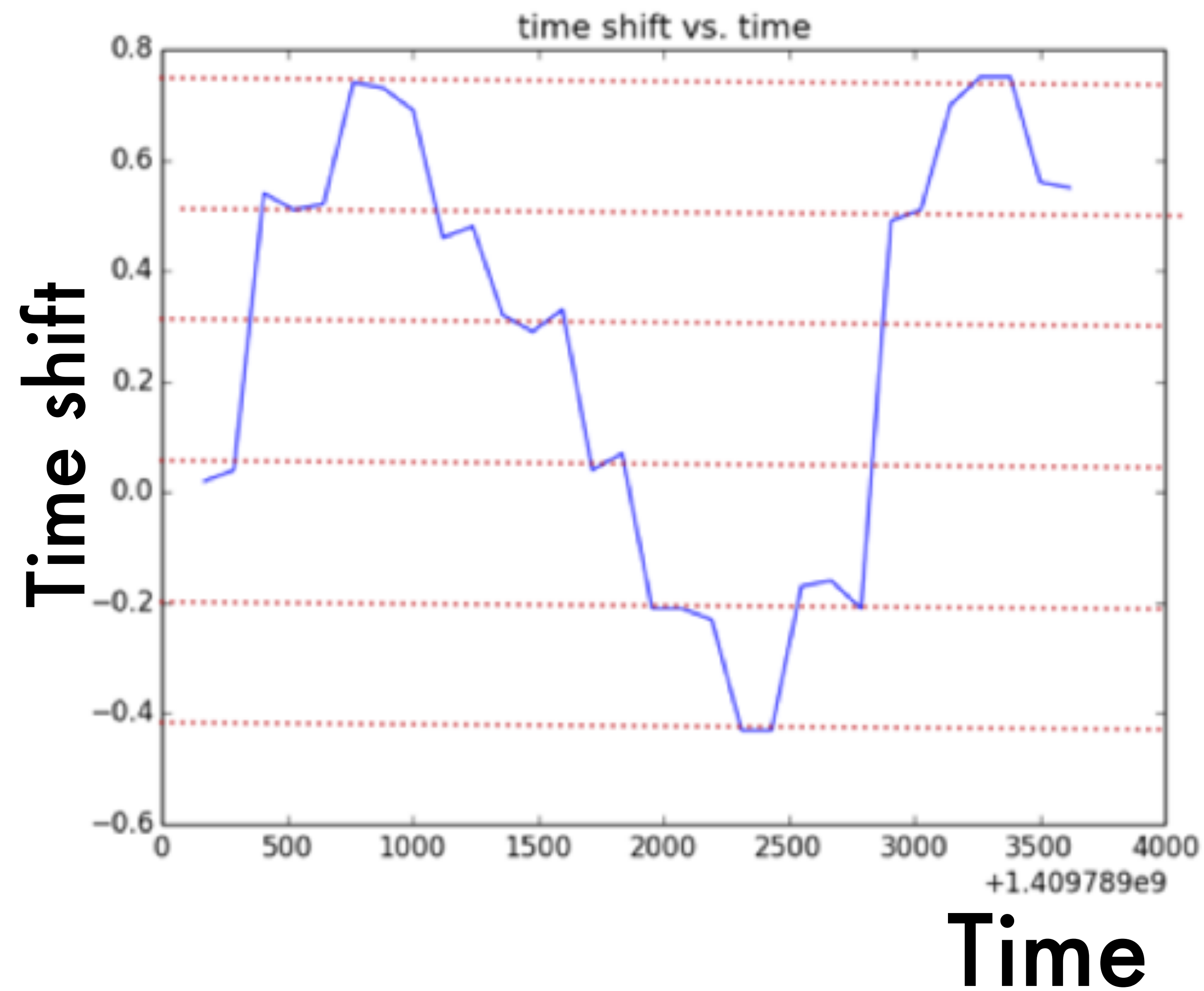
Timing test

Random blinking LED
Measure capture time
on two phones.

Timing



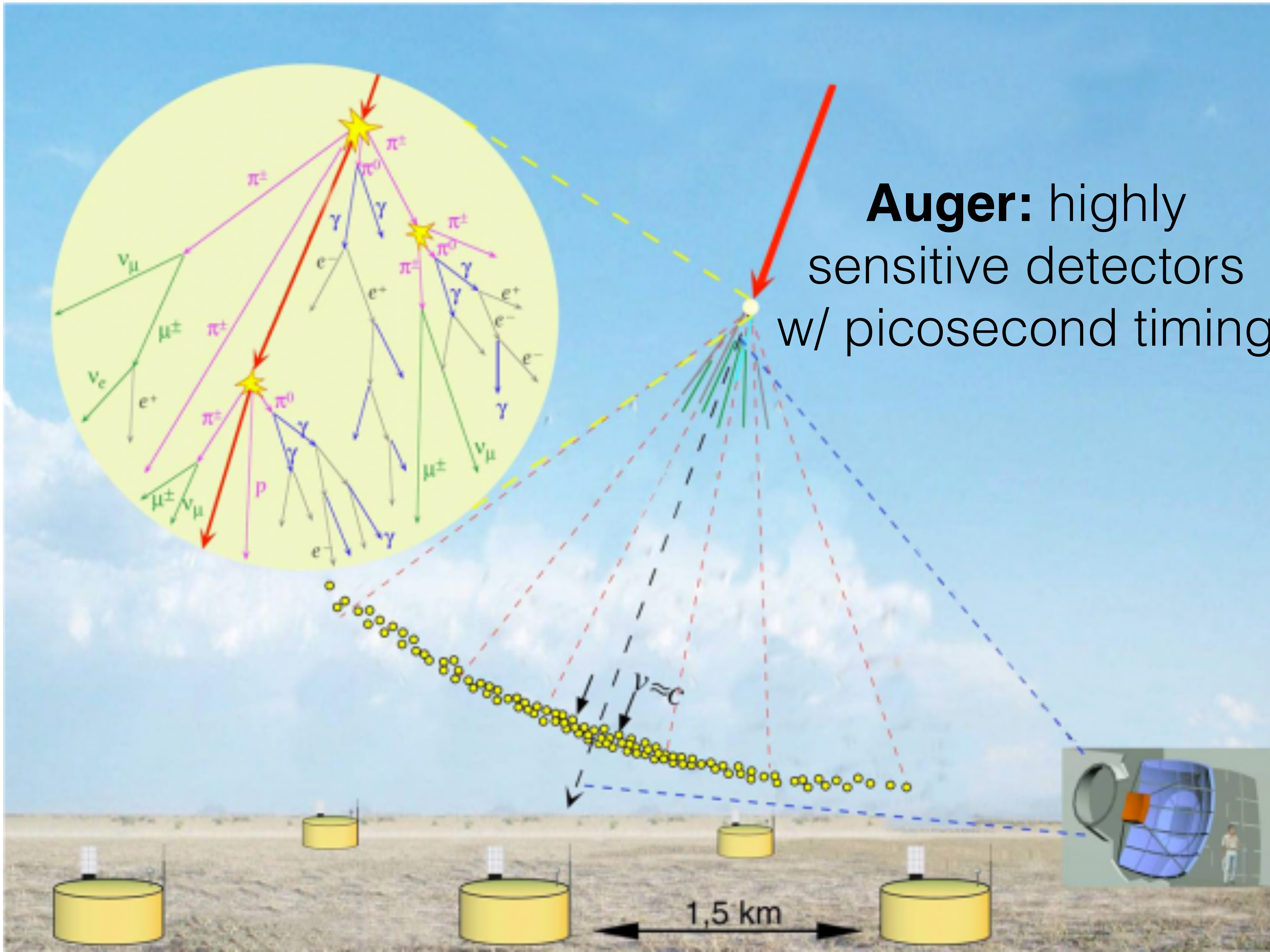
phone1 vs phone2
Correlation
40
35
30
25
20
15
10
5
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Time shift



time shift vs. time
Time shift
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
500
1000
1500
2000
2500
3000
3500
4000
+1.409789e9
Time

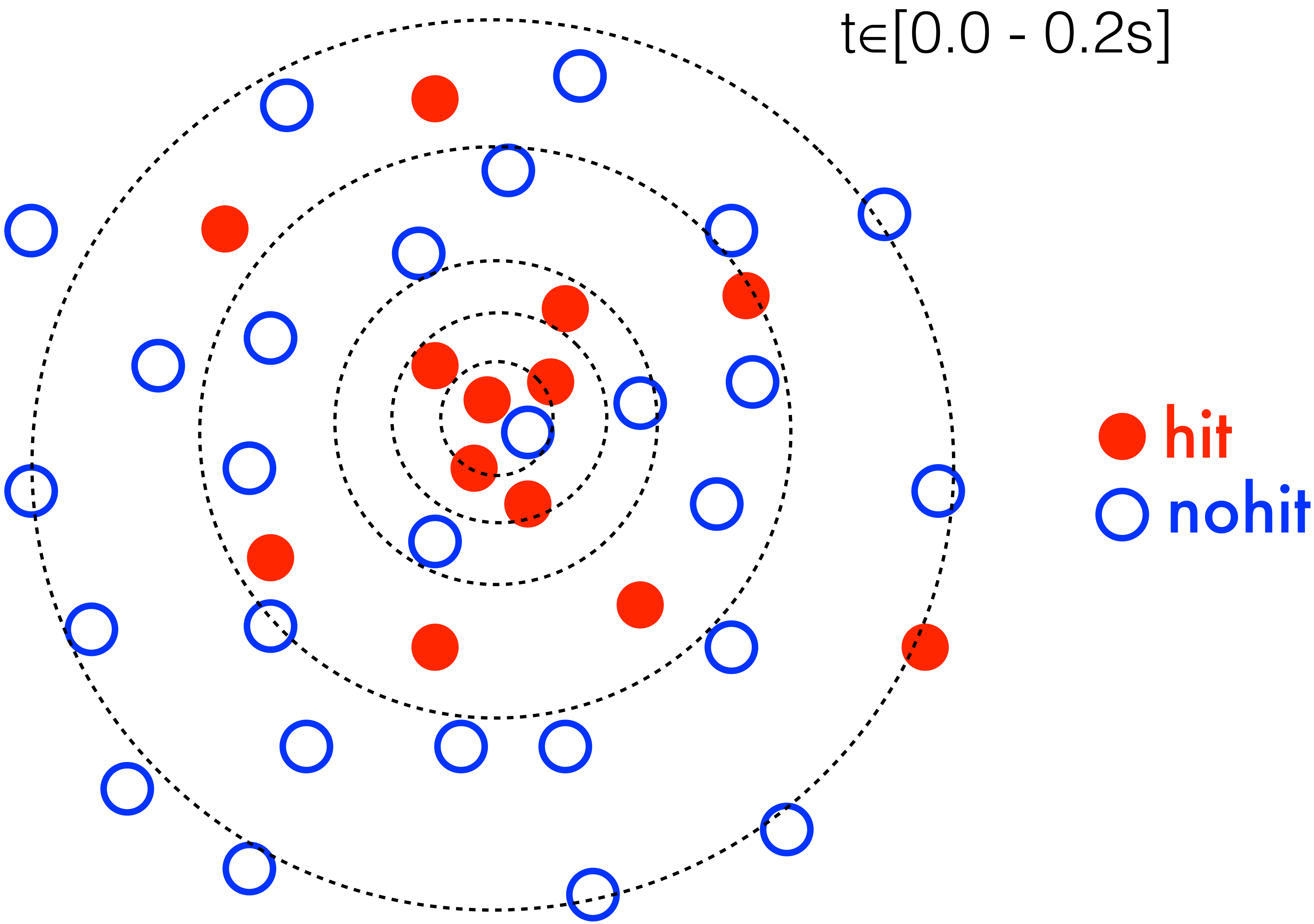
Putting it All Together

Shower Reconstruction

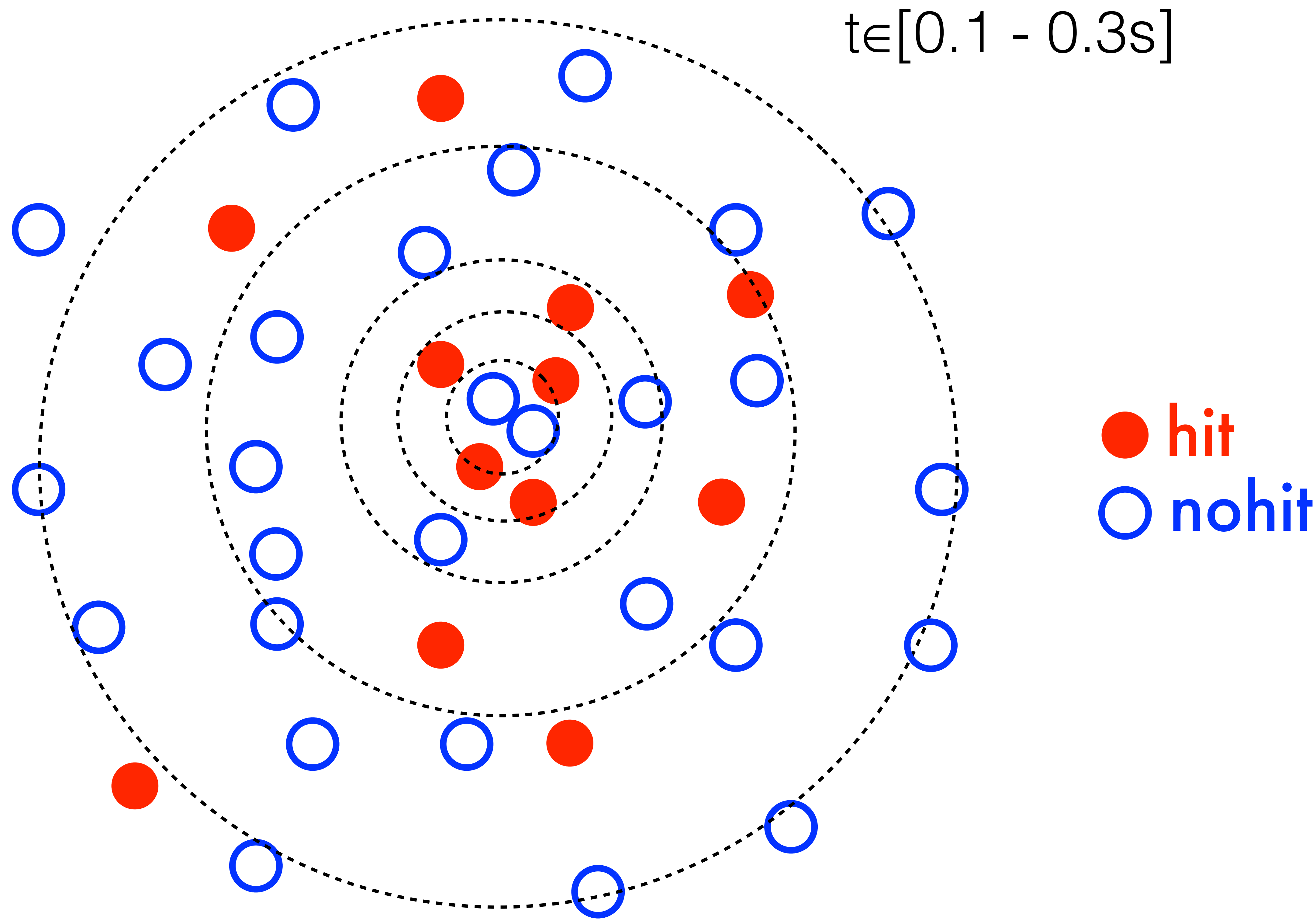


Auger: highly sensitive detectors w/ picosecond timing

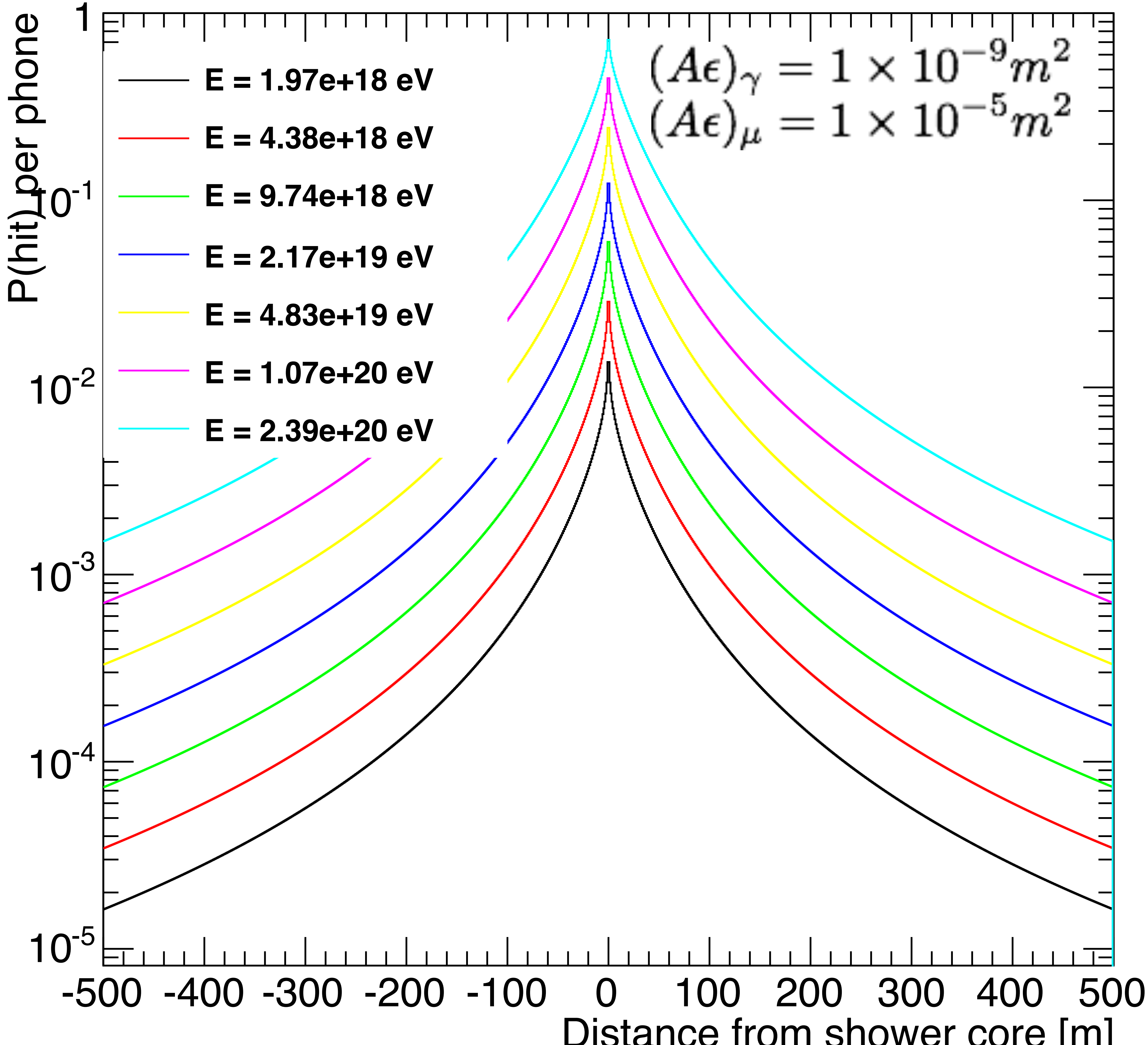
Shower Reconstruction



Shower Reconstruction



Probability of Hit

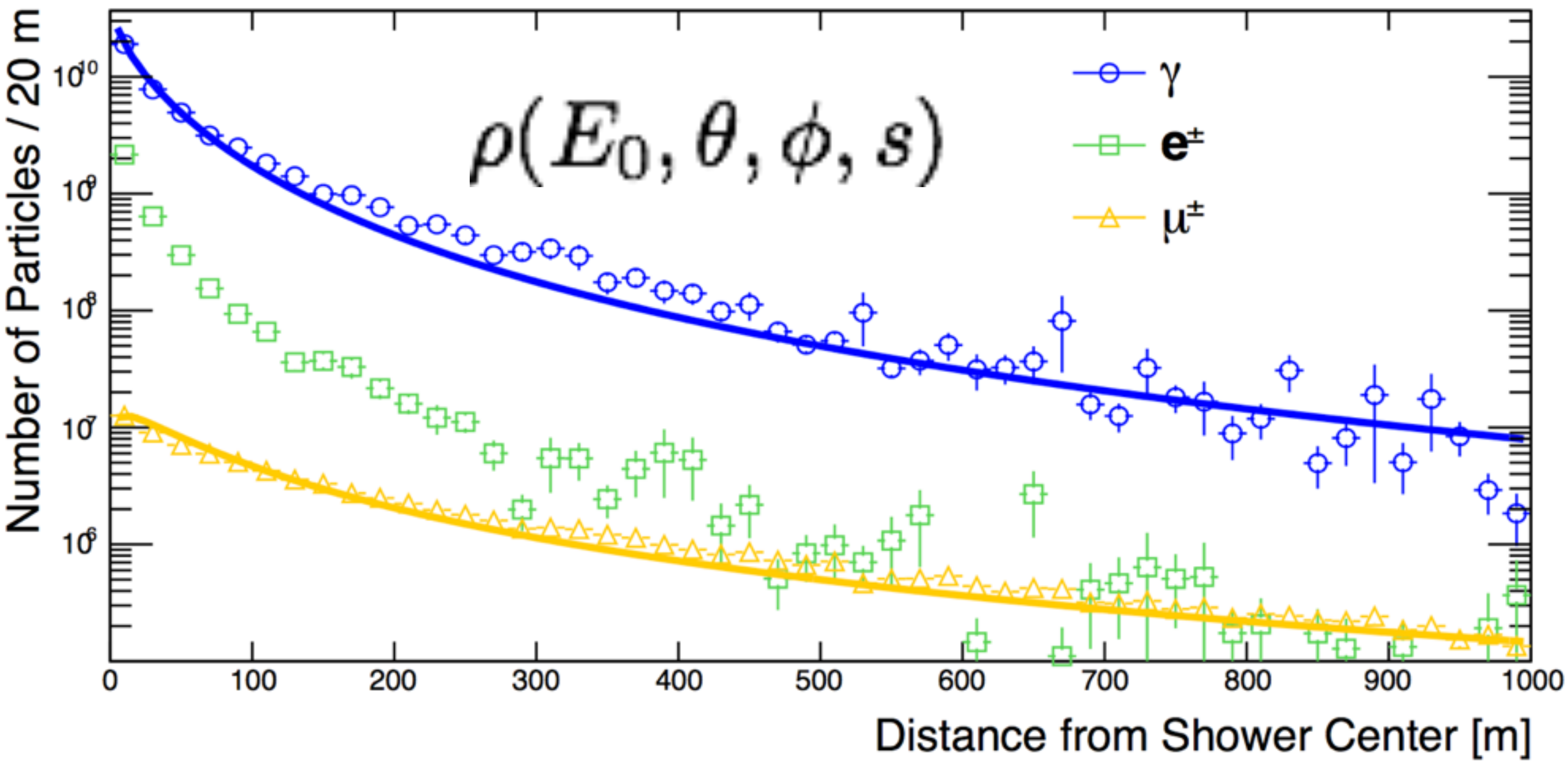


Likelihood

During a shower event, the expected number of particle hits is:

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

A — active area
ϵ — detection eff.
ρ — LDF [particles/m^2]
η — noise term



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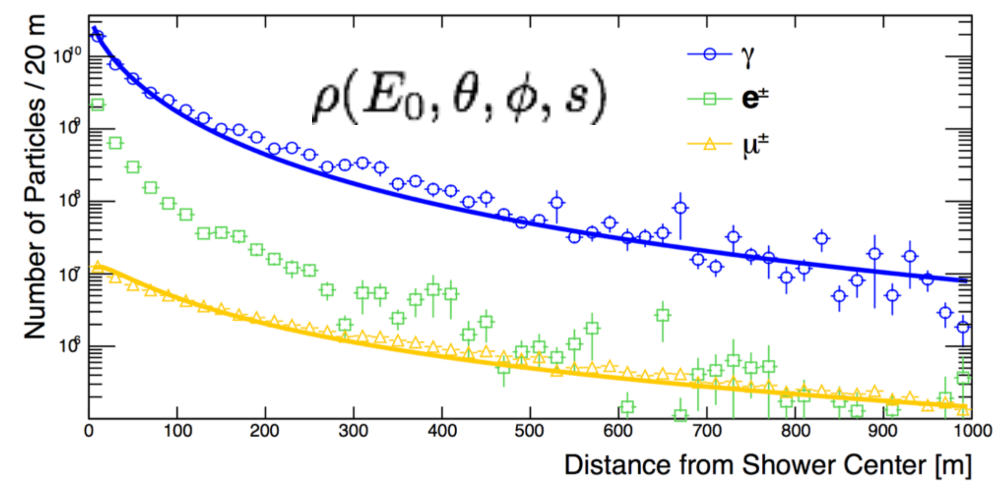
η — noise term

Probability of seeing nothing:

$$P_0(x, y) = e^{-\lambda}$$



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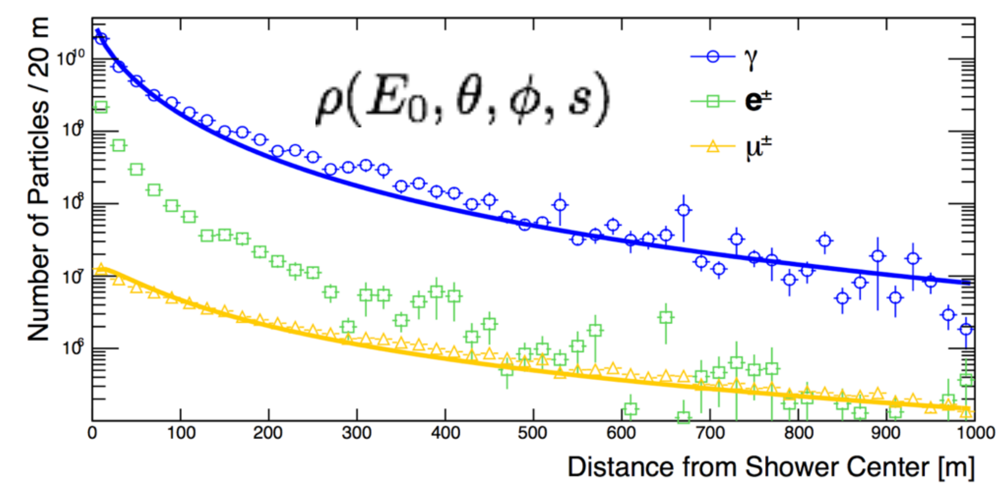
Probability of seeing nothing:

$$P_0(x, y) = e^{-\lambda}$$



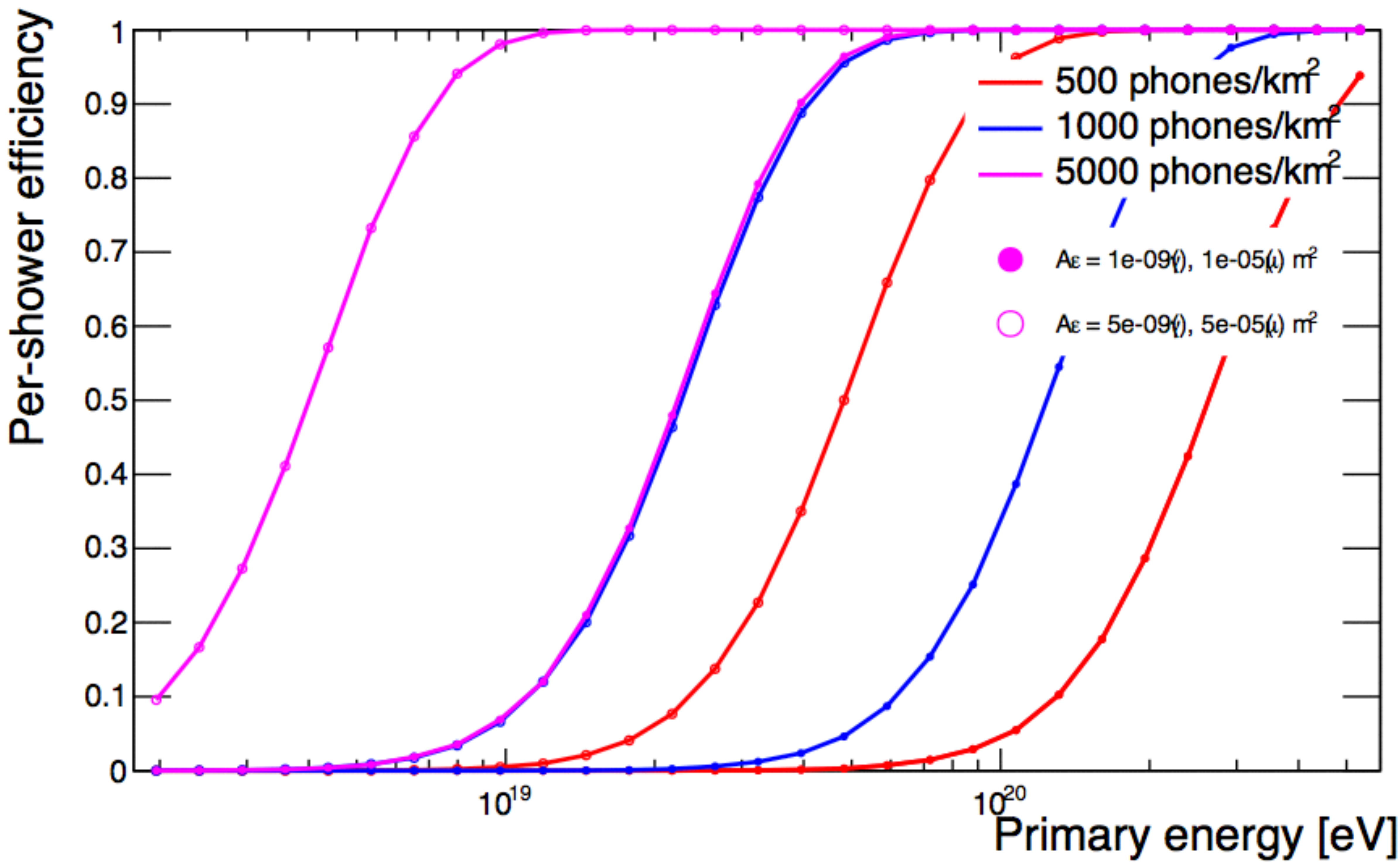
Likelihood function, given phones that were / weren't hit:

$$L(E_0, \theta, \phi, s) = \underbrace{\prod_i P_0(x_i, y_i)}_{\text{no hit}} \underbrace{\prod_j (1 - P_0(x_j, y_j))}_{\text{hit}}$$

Shower Reco Efficiency

Sensitive only at the very highest energies

(those are the interesting ones!)



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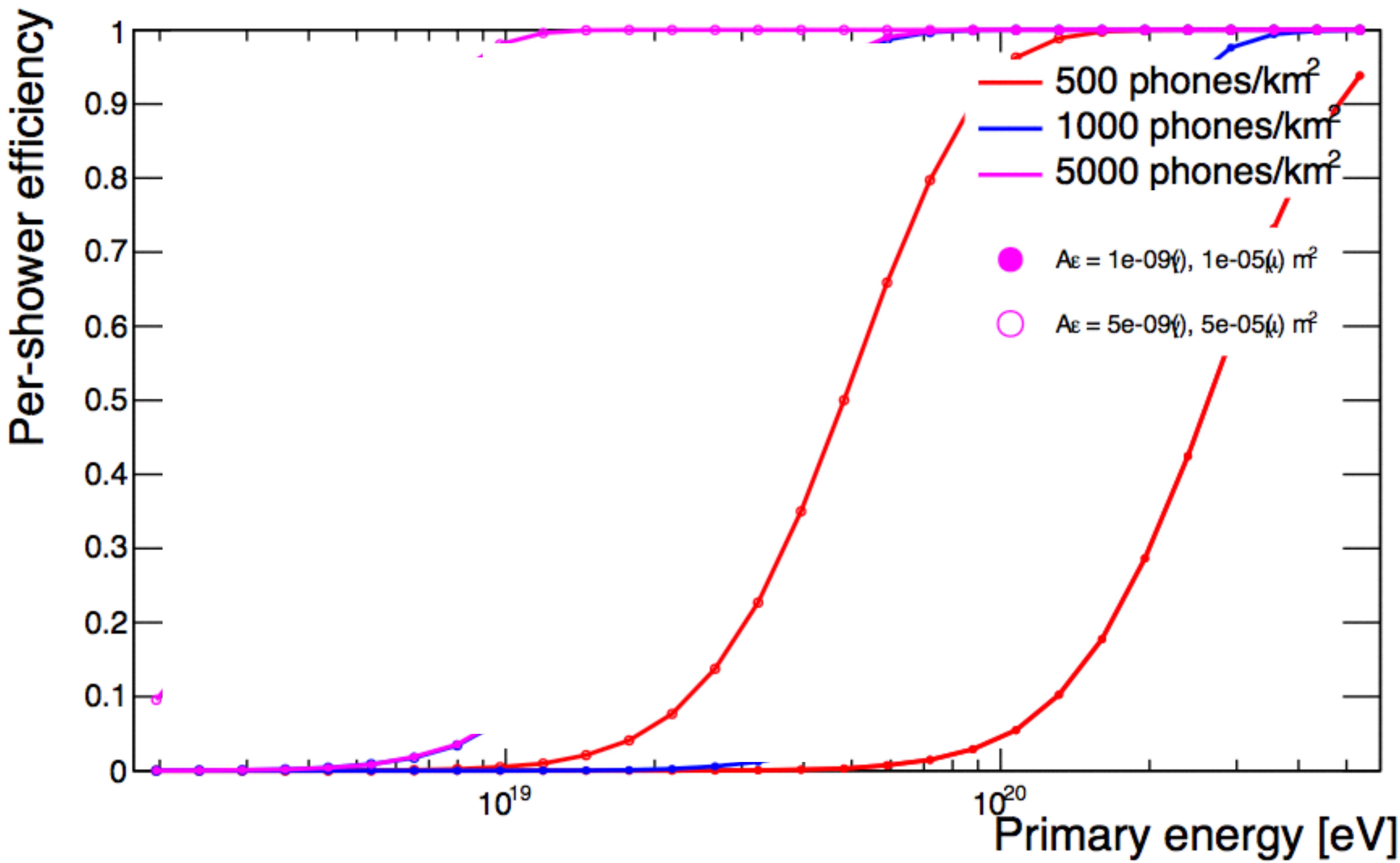
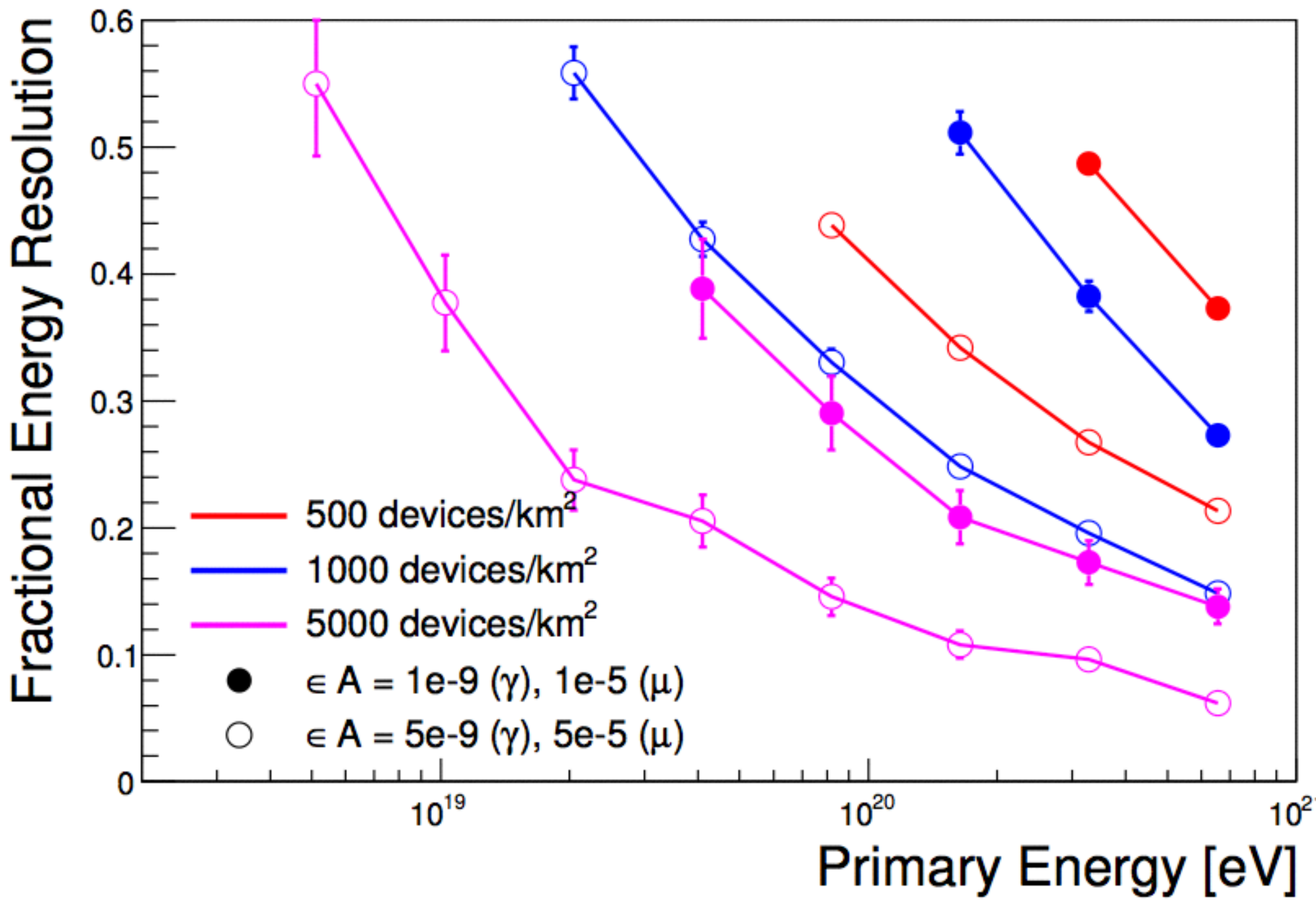


Energy Resolution

Higher energy → more hits → better measurement



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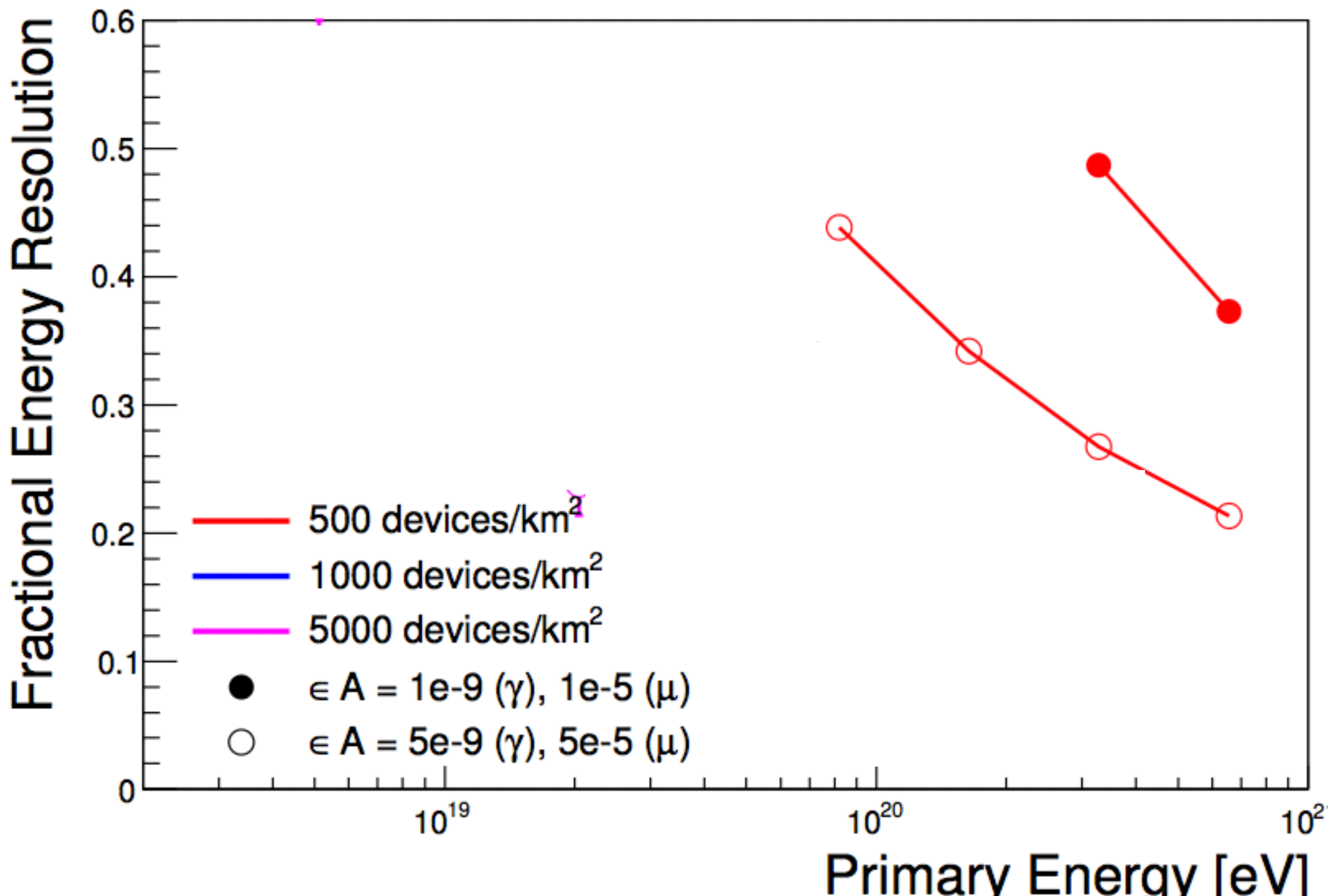
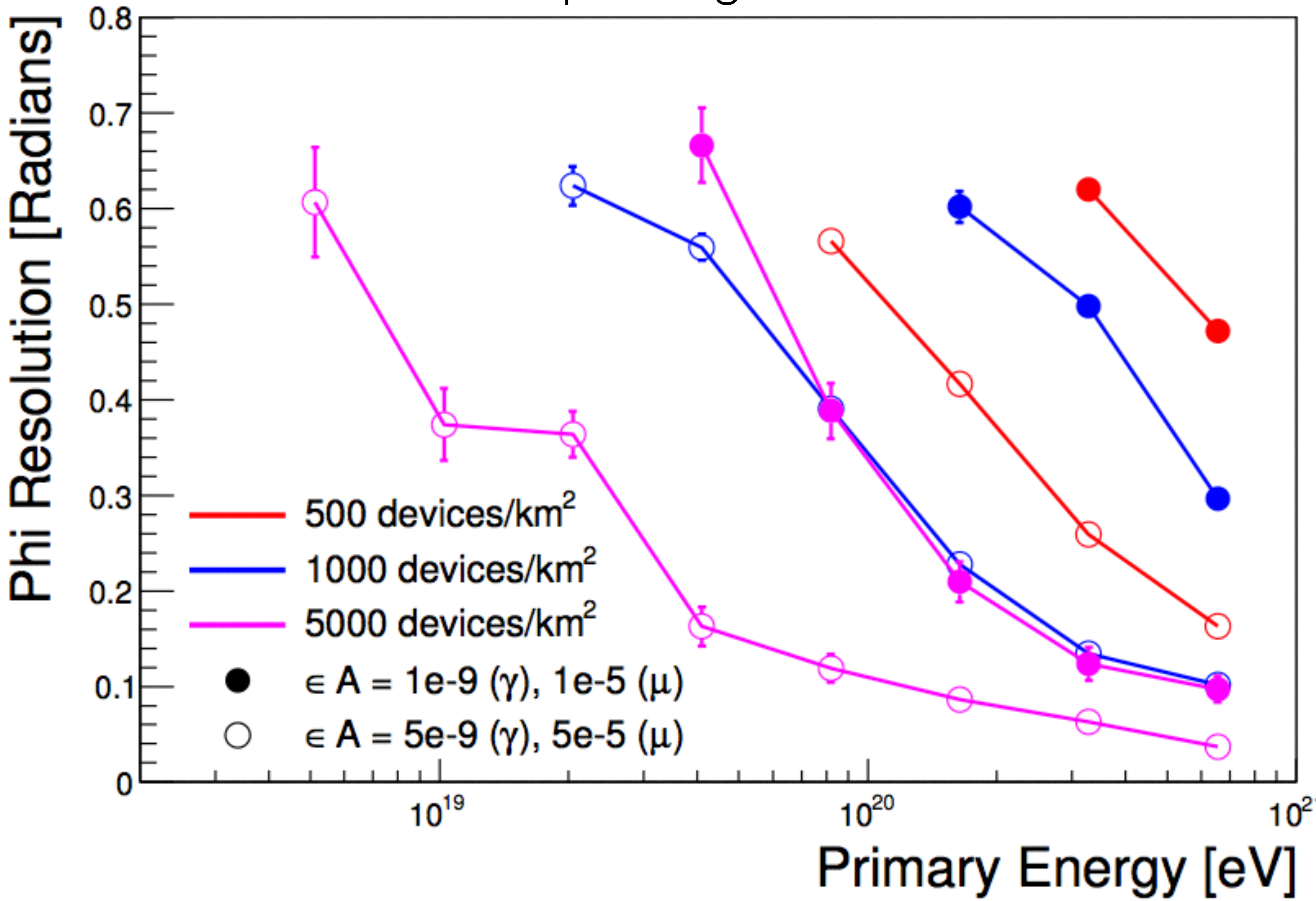
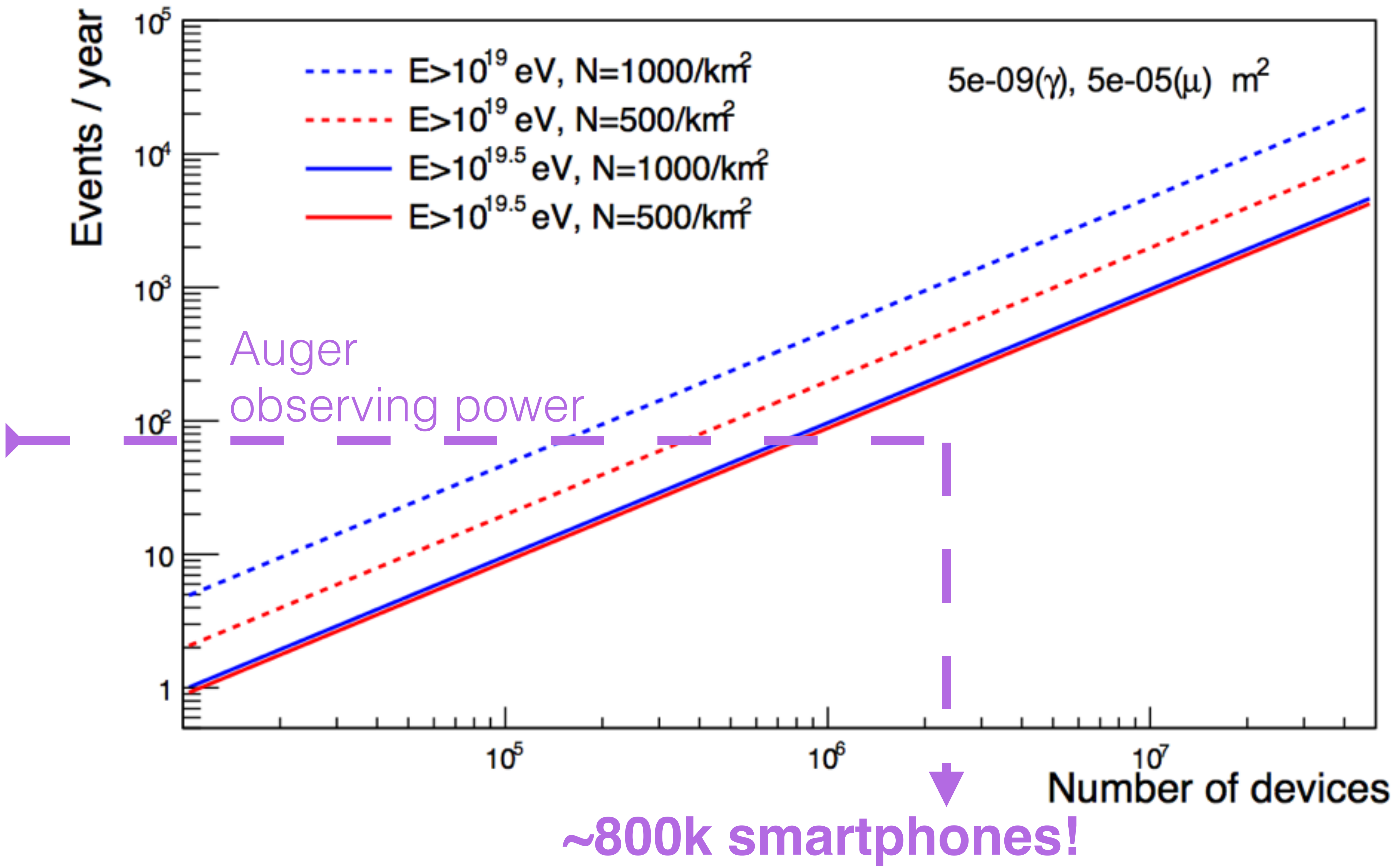


Angular Resolution

Except in the most optimistic scenario,
almost no pointing information.

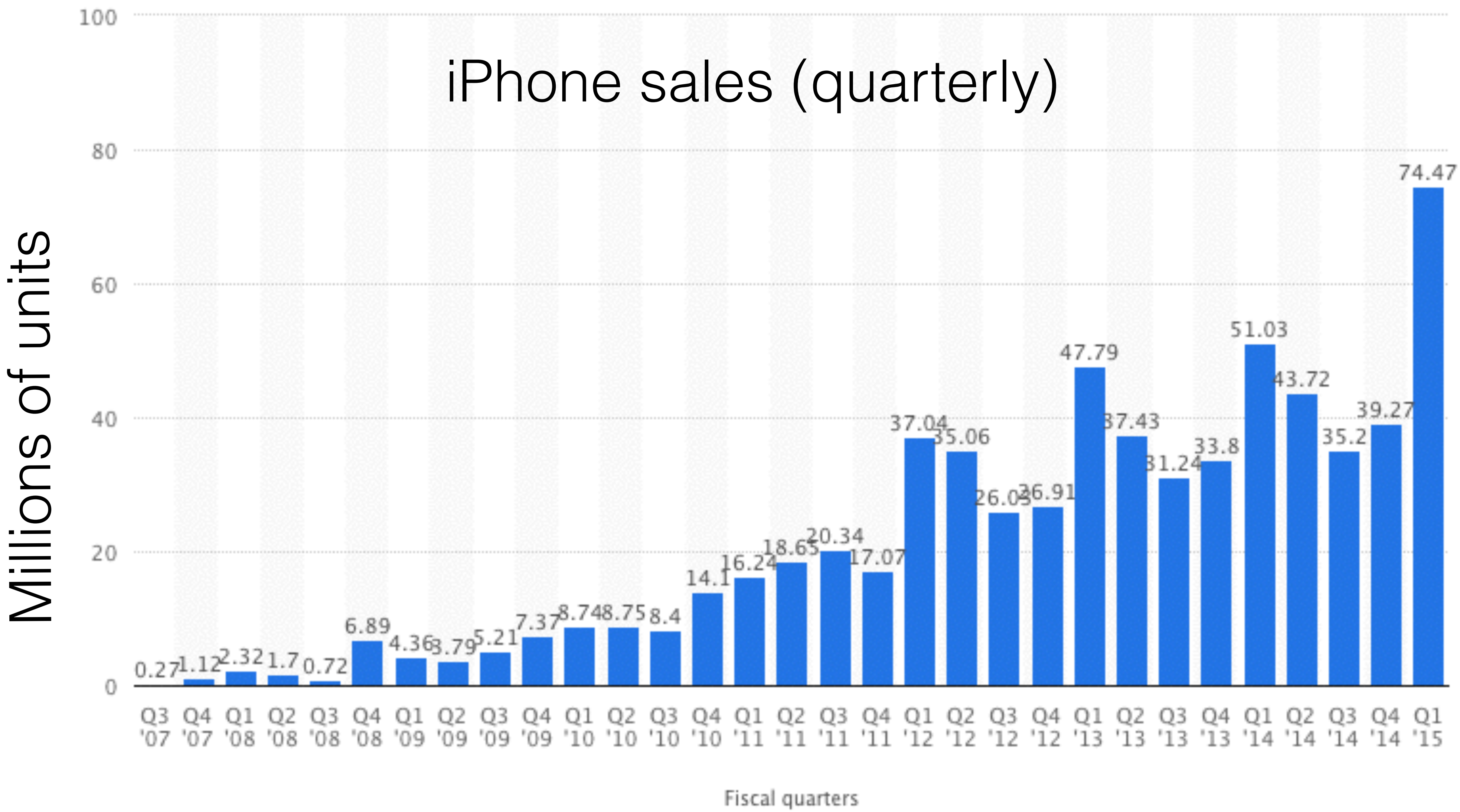


Keeping up with Auger

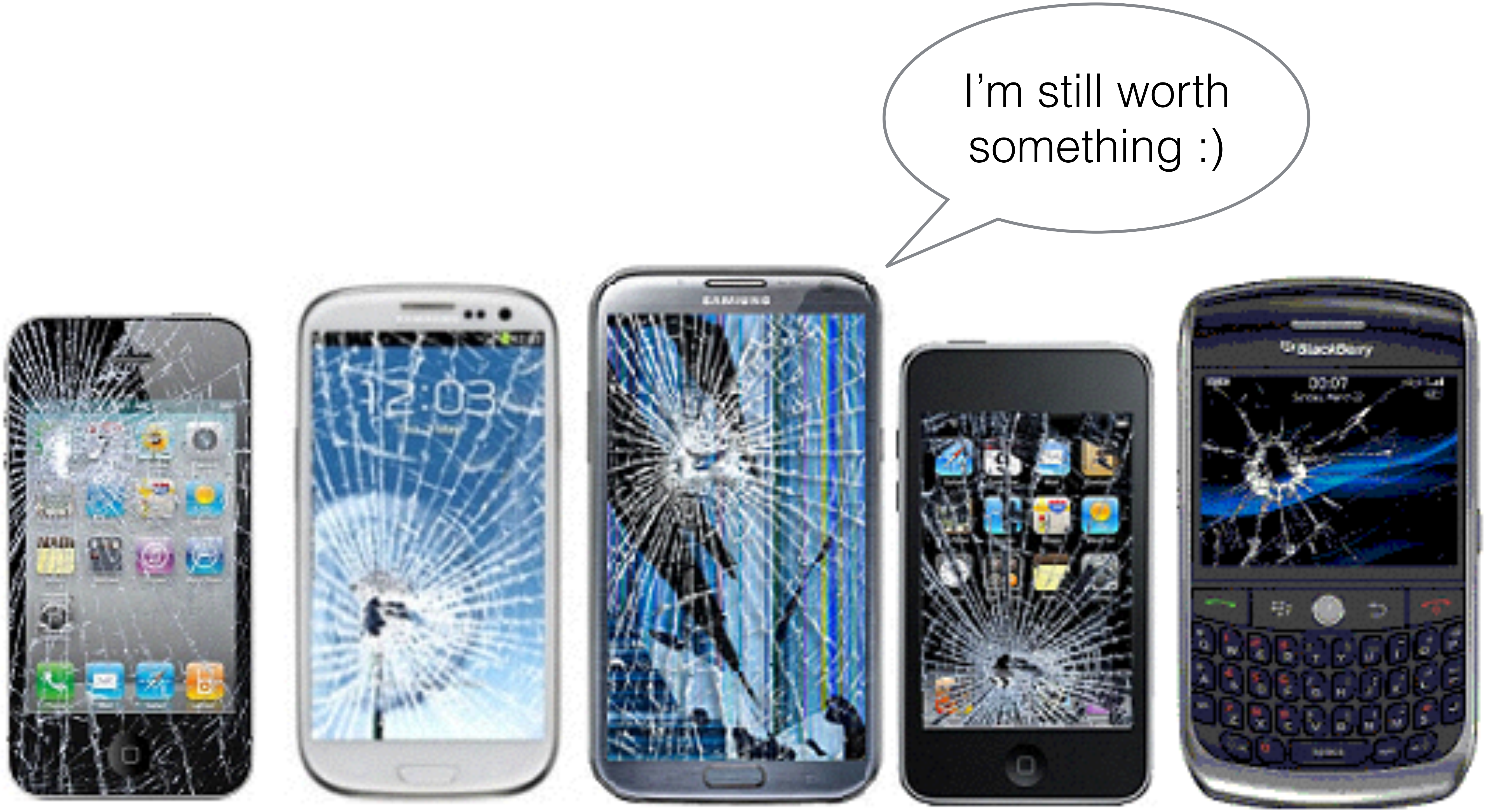


800k phones?!

- ➡ Over a **billion** smartphone users in the world
- ➡ Initial media response netted over 50k signups




12:03
SAMSUNG
BlackBerry
00:07


I’m still worth
something :)

To Summarize

- ➡ Phones *can* see muons and gamma rays

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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

IP[y]: Notebook craftExample (unsaved changes)

Save Reload Publish About

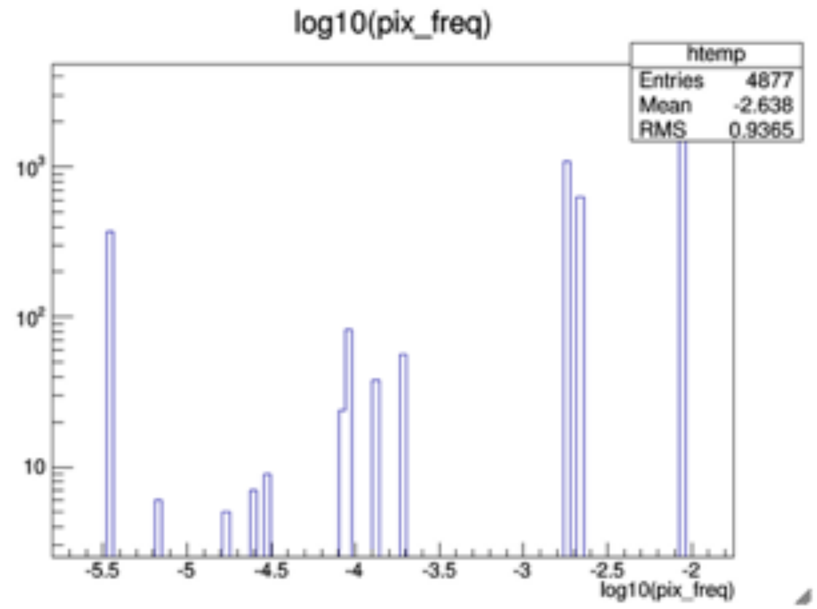
File Edit View Insert Cell Kernel Help

Code Cell Toolbar: None

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

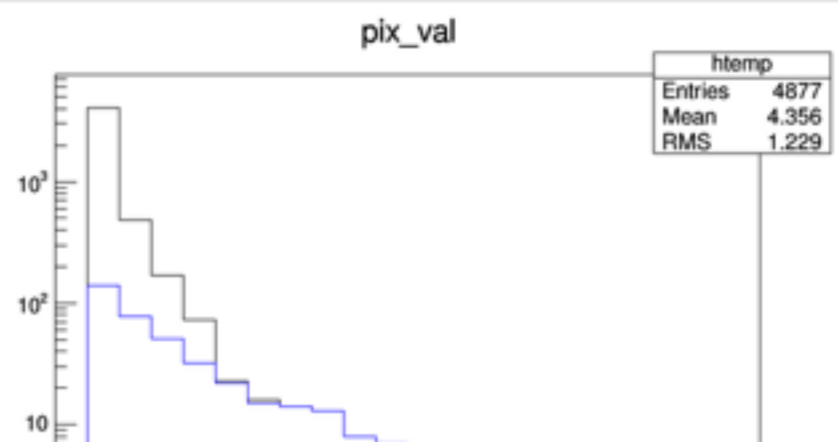
293825

Out[6]:



In [7]:
```python
# 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]:



Going Beyond

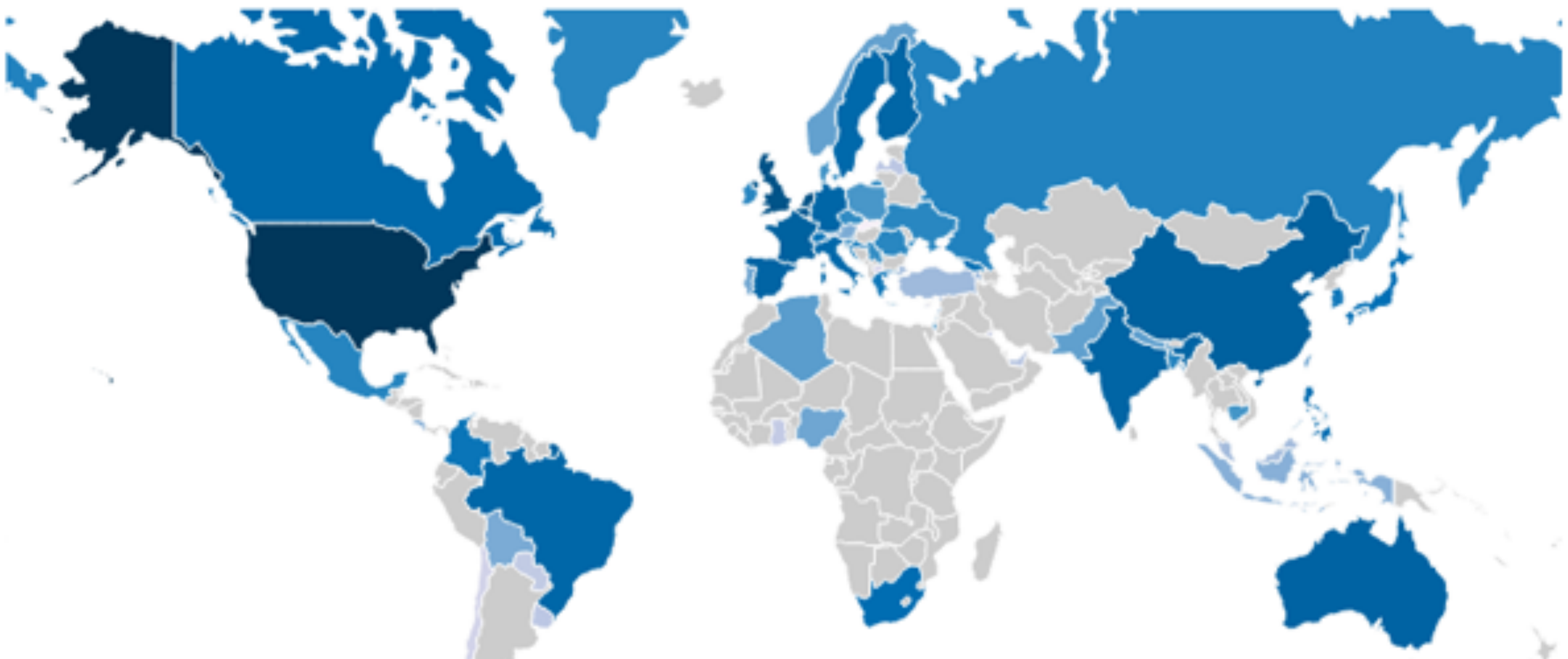
Users own the data!

CRAYFIS | Cosmic RAYs Found In Smartphones | Project ▾ | Welcome, crayfis! | My Devices | Logout

CRAYFIS
cosmic rays found in smartphones

Total Exposure	Unique Devices	Candidate Hits
7 years, 201 days, 18 hours	662	11,428,600

Network Map



National Ranking

Rank	Country	Score
1	USA	65,536,712
2	NLD	10,256,765
3	GBR	9,611,524
4	BEL	6,163,009
5	CHN	2,796,829
6	FRA	2,631,734
7	AUS	2,371,036
8	ESP	2,108,252
9	IND	2,071,819
10	FIN	1,947,809

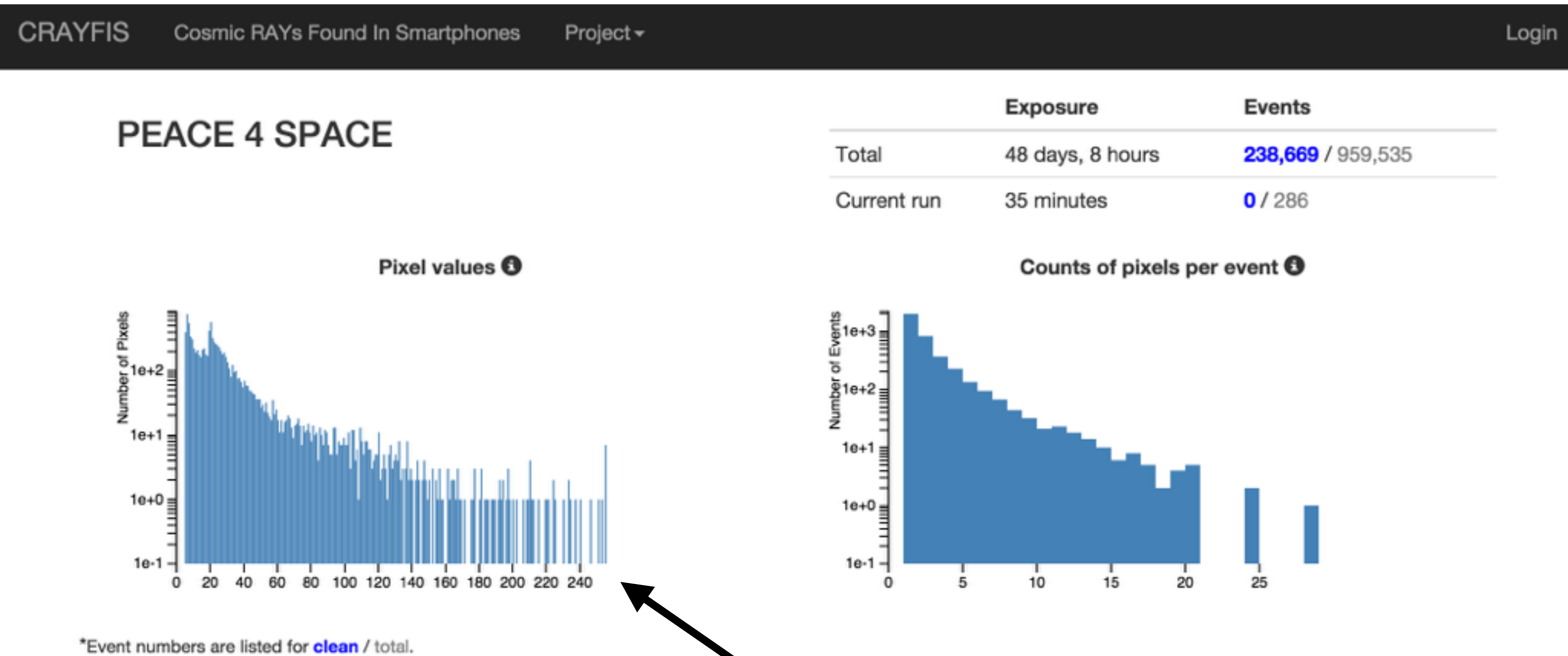
Top Users

Rank	Username	Score
1	Coleslaw	10,967,700
2	crayfis_ucd	9,129,341
3	dwhiteson	7,612,199

Top Devices

Rank	Codename	Owner	Score
1	PEACE 4 SPACE	hansmex	4,014,498
2	Galaxy Proclaim	Coleslaw	3,803,978
3	BESTPHONEEVER	dwhiteson	3,732,130

Going Beyond

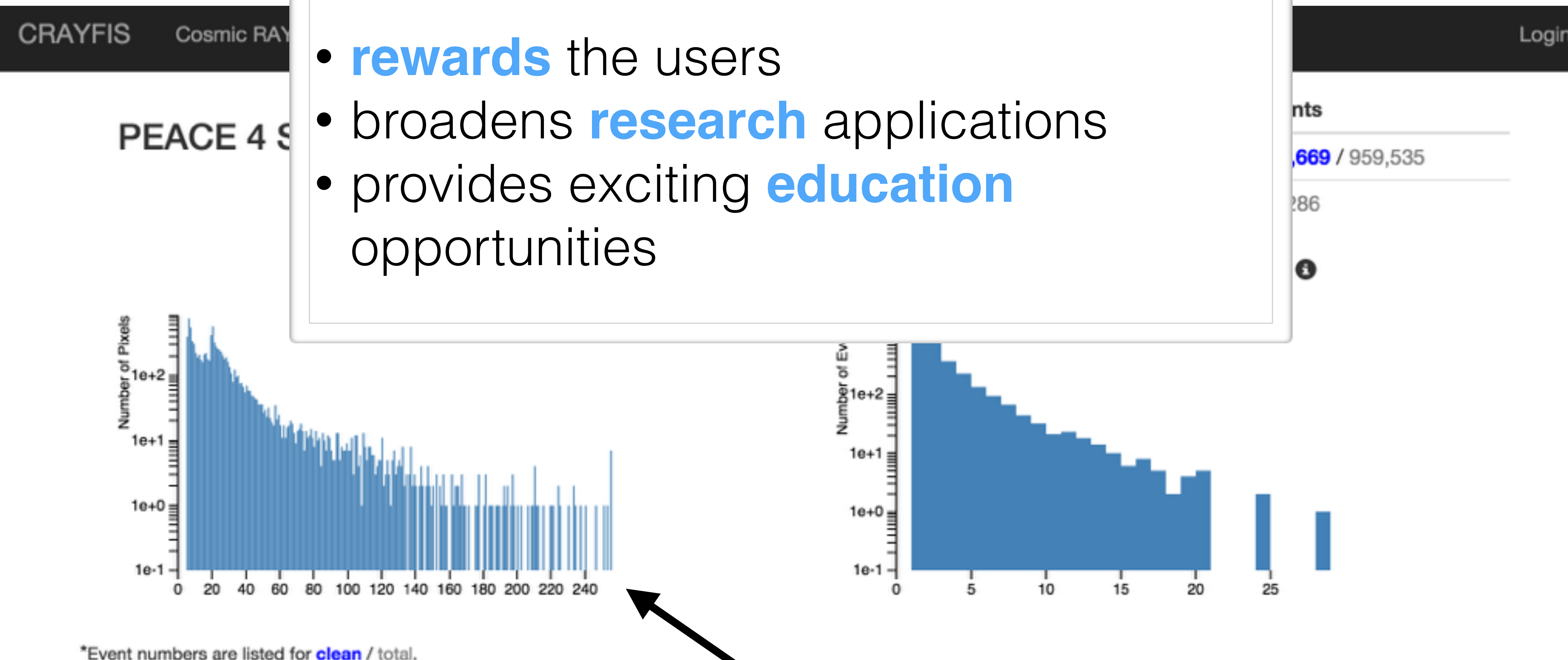


Live plots from each device!

Going Beyond

Opening the data to the community:

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



Live plots from each device!

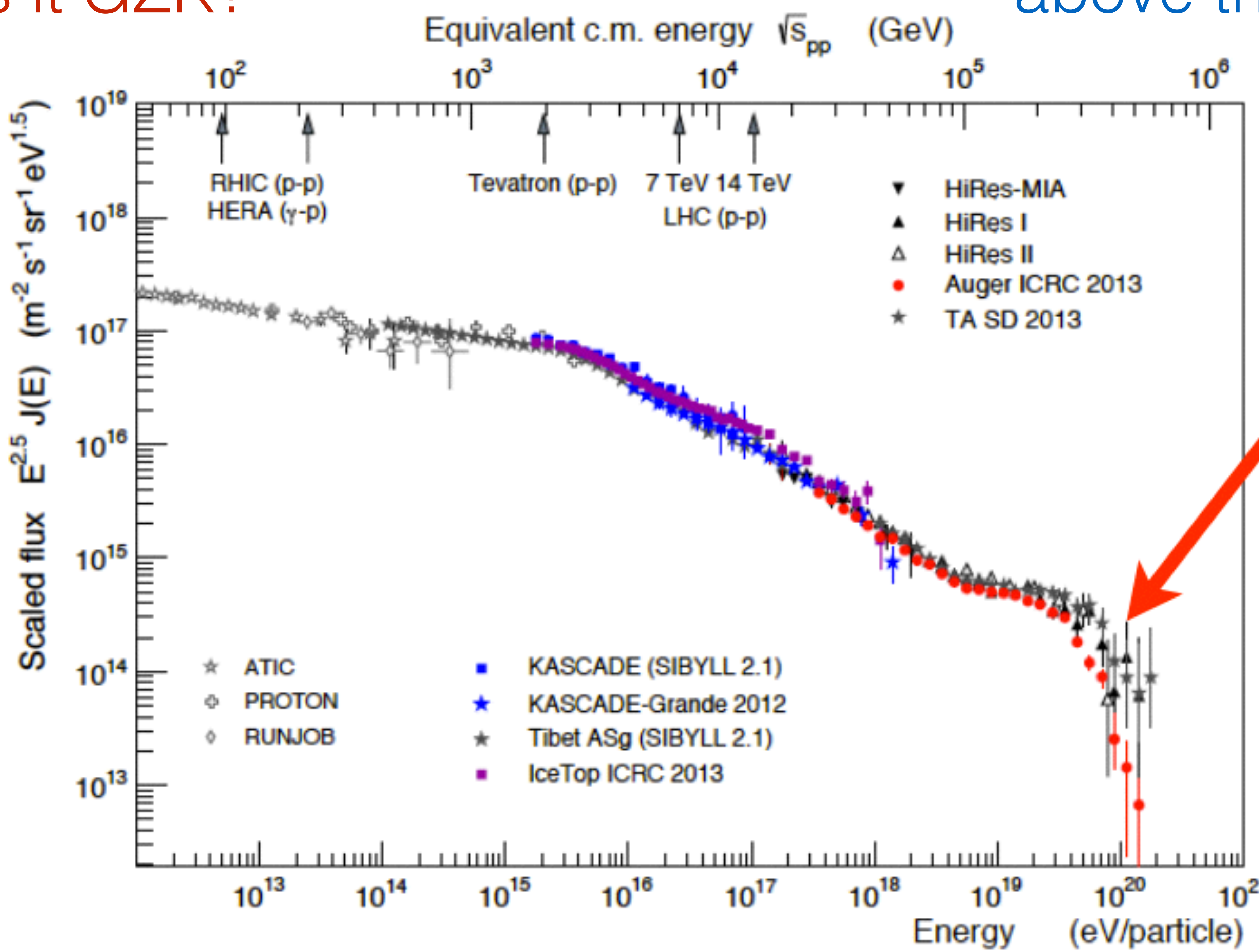
The End

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

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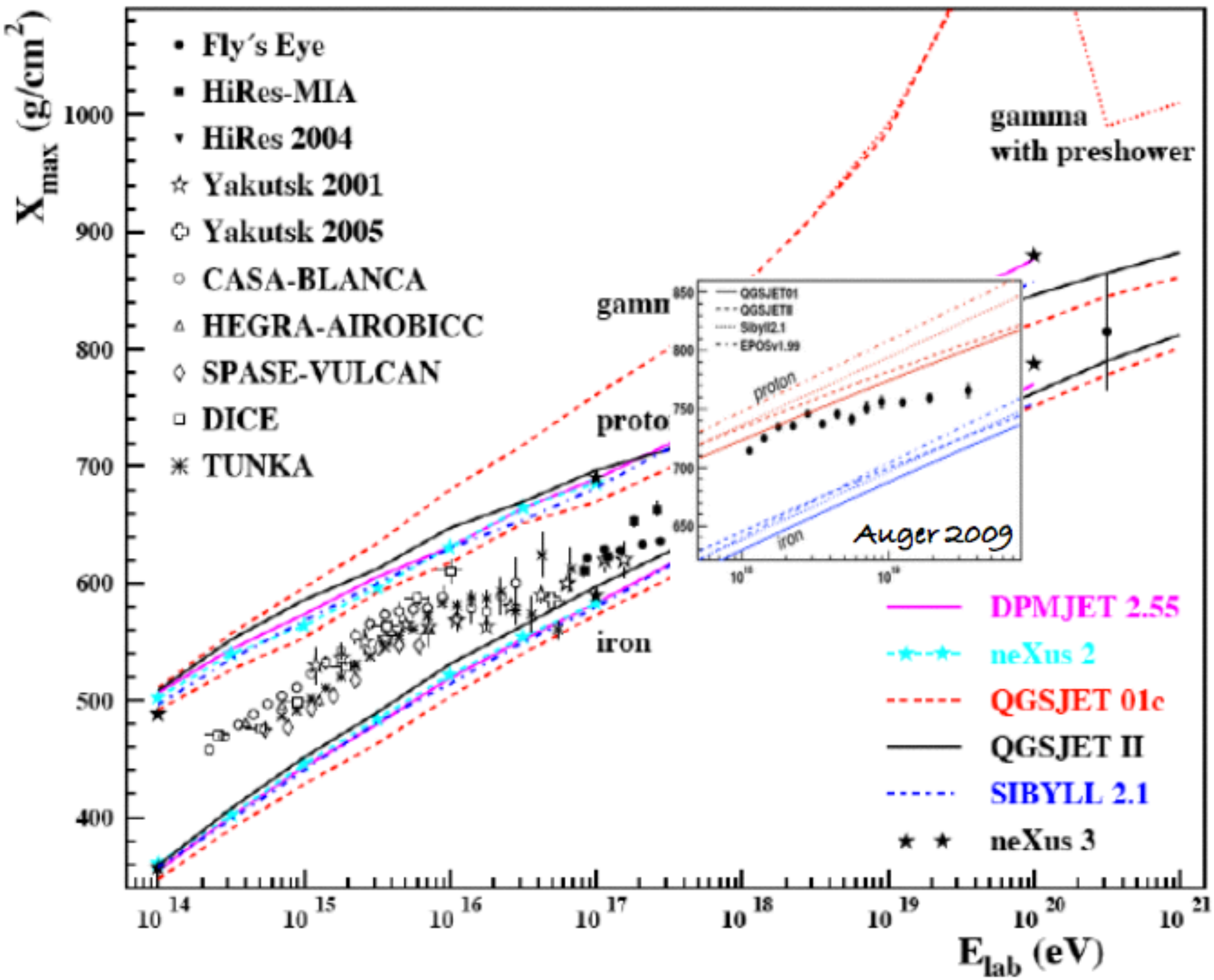
what **are** the UHECR's *made of*?

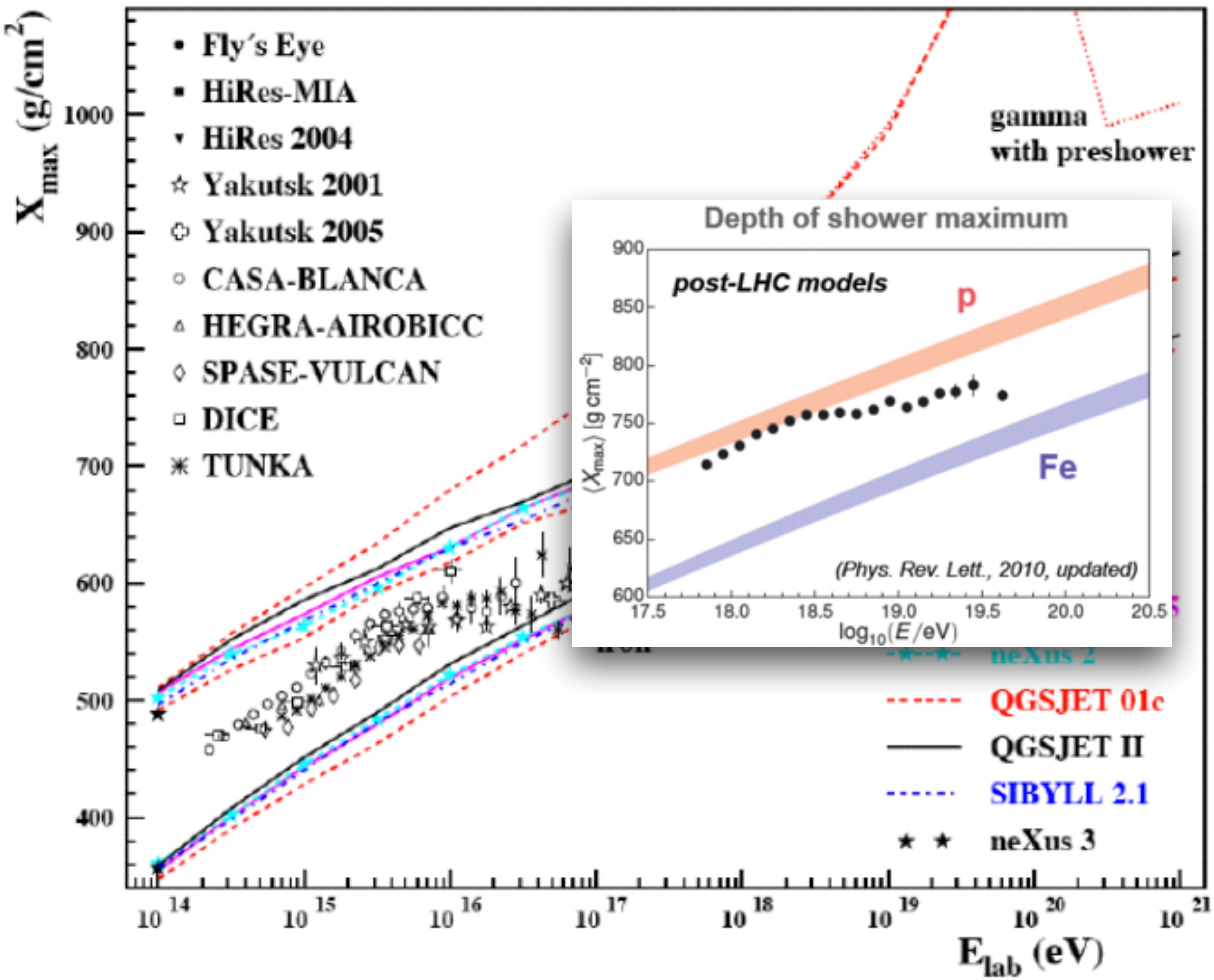
The short answer: probably protons or iron nuclei.

Primary Composition



Hadronic physics dictates the atmospheric depth of the shower maximum

Primary Composition



Hadronic physics dictates the atmospheric depth of the shower maximum