Simulating Cosmic Ray Air Shower Radio Emission for the Askaryan Radio Array

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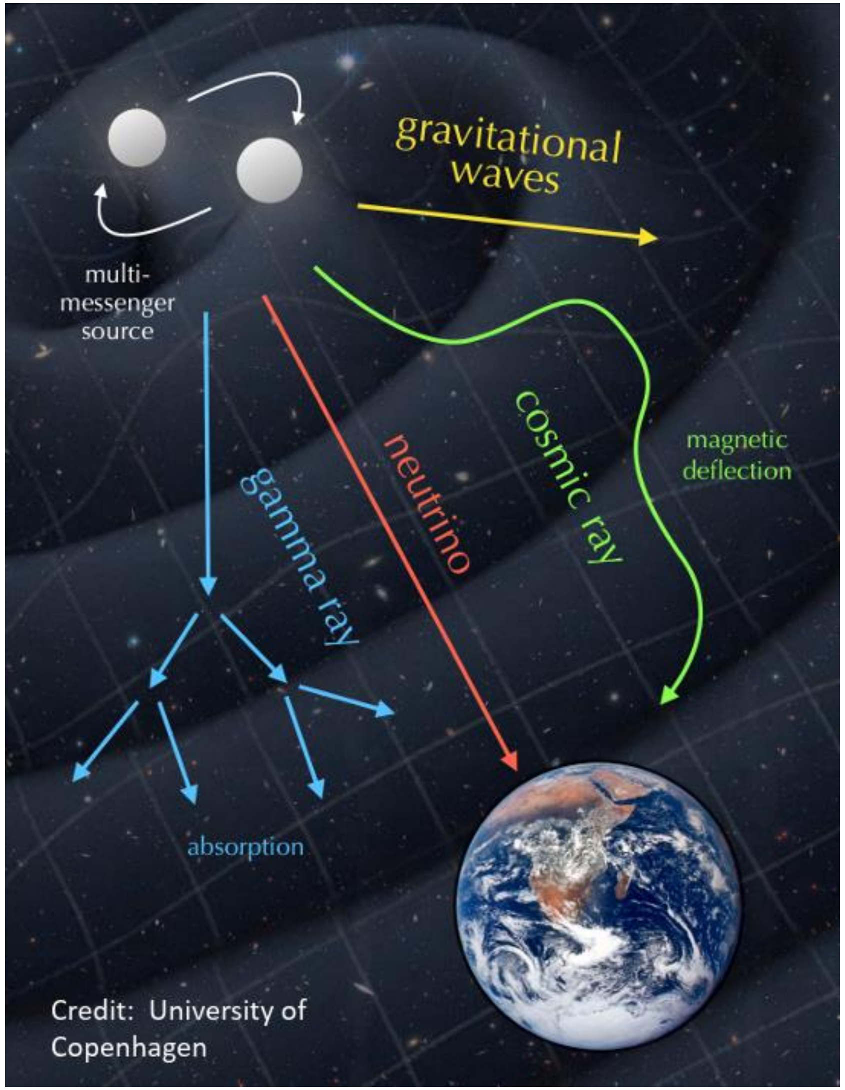
Multi-messenger Astronomy

Messengers :

- <u>*Gamma rays*</u> : Interact with ISM and within source
- <u>*Gravitational waves*</u> : Out of scope
- <u>*Cosmic Rays*</u> : Deflected by galactic/inter-galactic magnetic field
- <u>*Neutrinos*</u> : Only reliable particle to point at dense sources



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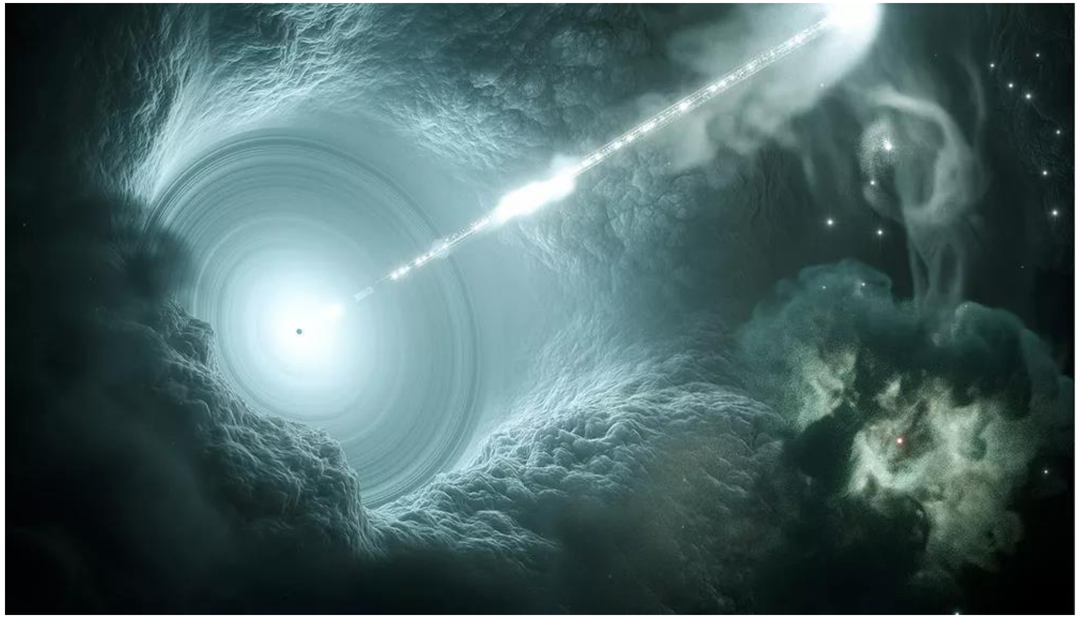
What we want to look at !

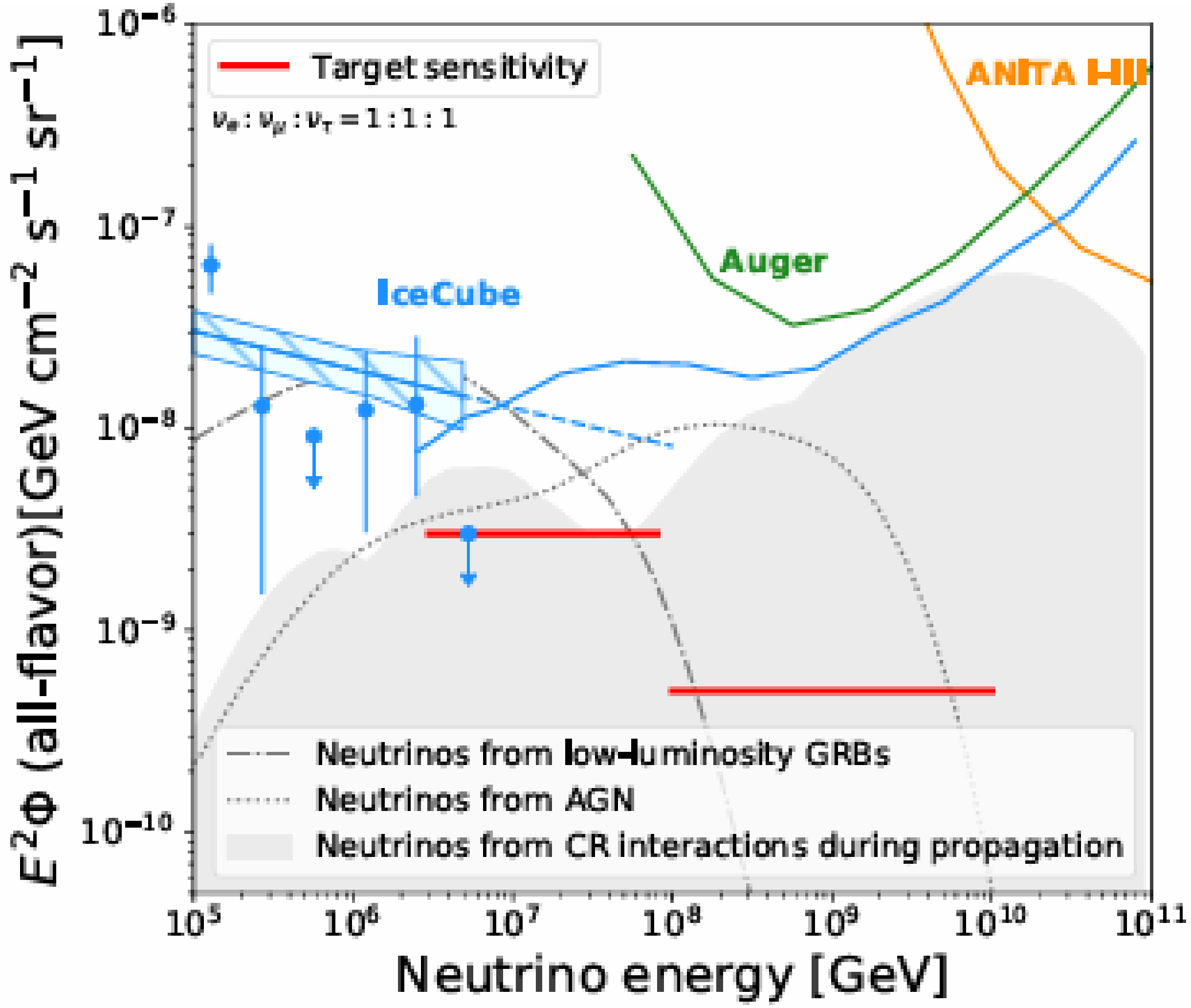


Neutrino flux

- IceCube observes astrophysical neutrino flux

- No event beyond $10^{16} eV$ observed yet

- Decreasing flux => Need for a larger detection volume



arXiv:1903.04334v2 [astro-ph.HE] 1 July 2019

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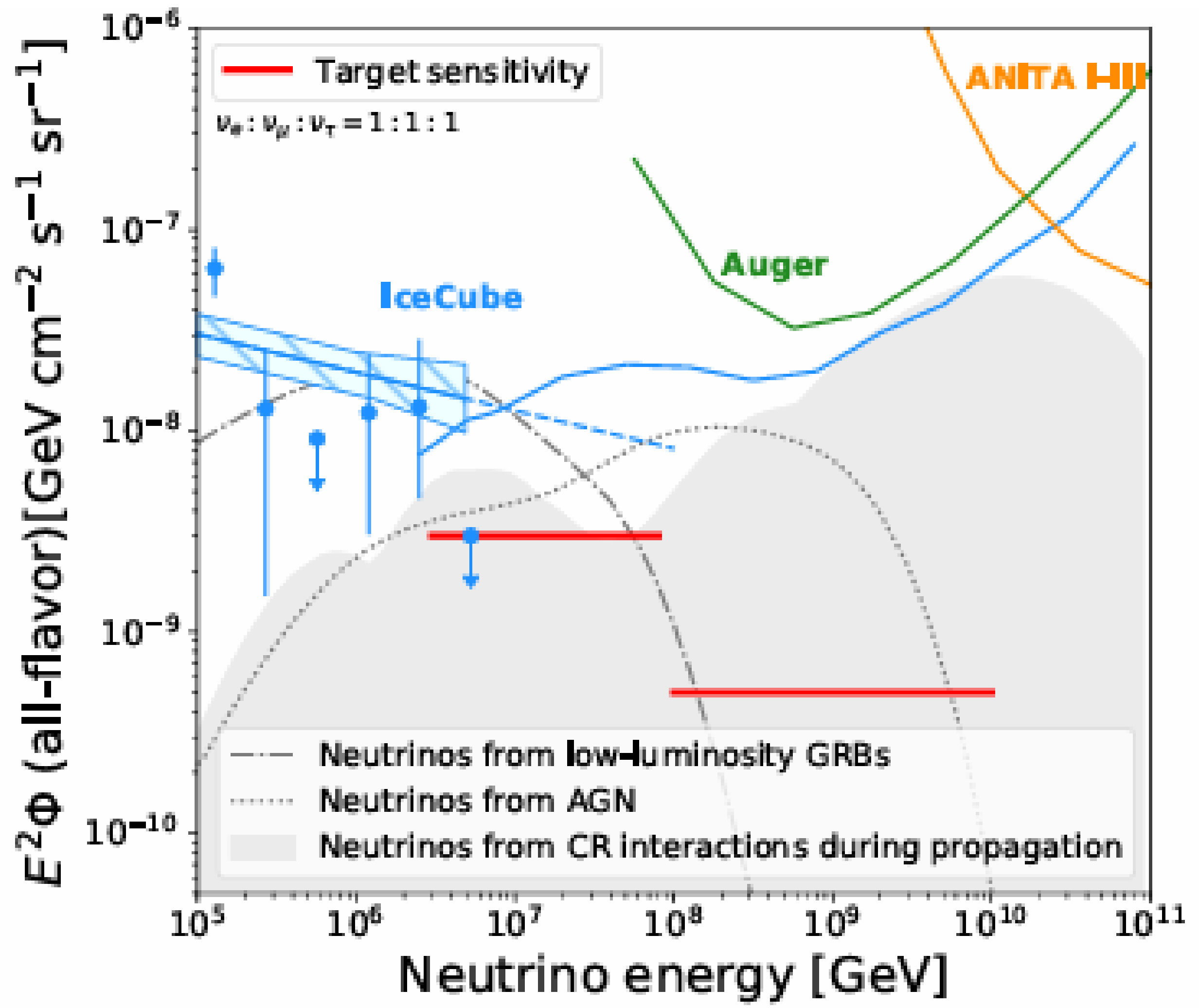
→ **Radio Detection Method**



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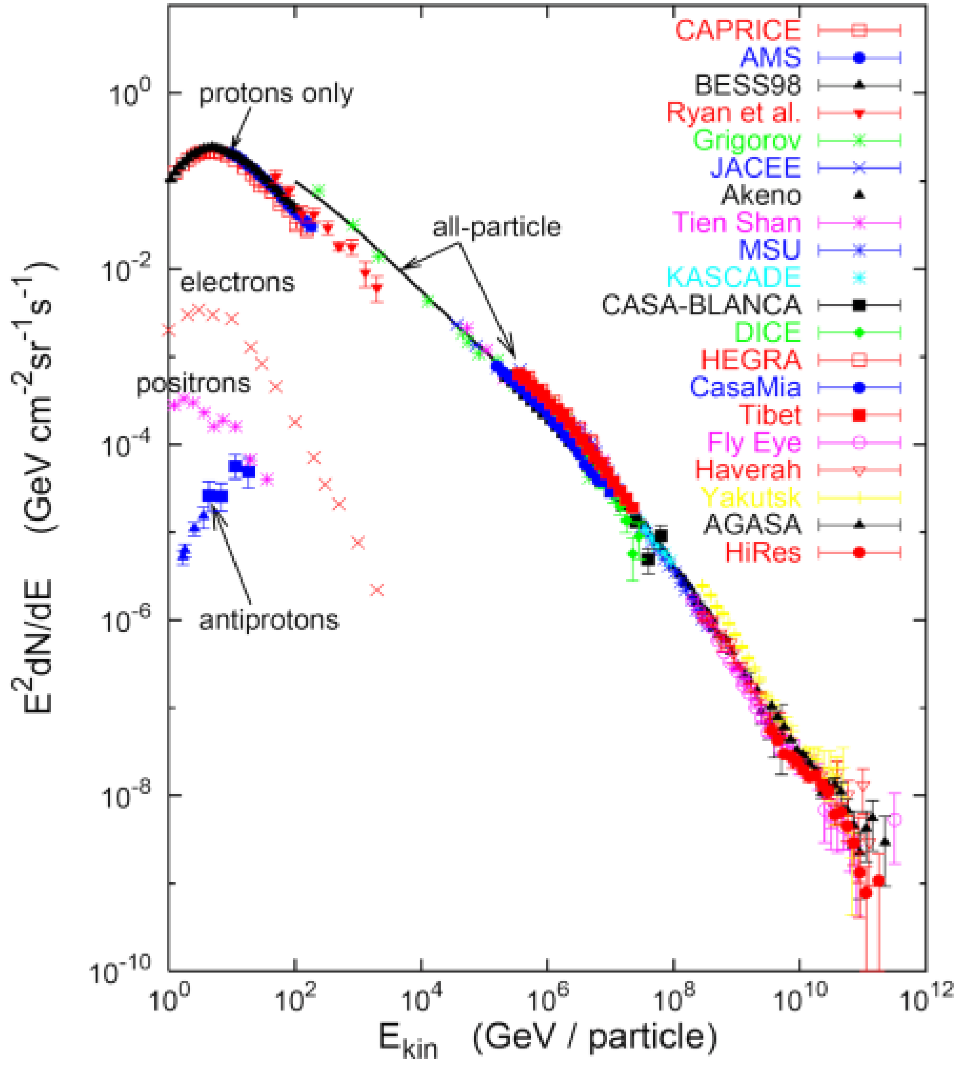
Why UHE neutrinos ?

- Cosmic ray flux extends to $> 10^{20}$ eV



Why UHE neutrinos ?

- Cosmic ray flux extends to $> 10^{20}$ eV
- UHE Neutrinos come from UHE cosmic rays:
  - From interaction within the source

$$p + p \rightarrow \begin{cases} p + p + \pi^0 & (2/3) \\ n + p + \pi^+ & (1/3) \end{cases} \tag{4}$$

Neutrons can then decay as:

$$n \rightarrow p + e^- + \nu_e \tag{5}$$

or interact like protons, but with a π^- production:

$$n + p \rightarrow \begin{cases} n + p + \pi^0 & (2/3) \\ p + p + \pi^- & (1/3) \end{cases} \tag{6}$$

These pions then decay as:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{7}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} \tag{8}$$

$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu} \tag{9}$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu \tag{10}$$

The proton–proton or neutron–proton interactions are dominant in opaque sources such as supernovae remnants because of the high quantity of matter. For sources featuring powerful electromagnetic emission, as Blazar jets for instance, radiation tends to dissipate the matter surrounding the source and proton–photon interactions become dominant:

$$p + \gamma \rightarrow p + \pi^0 \tag{11}$$

$$\pi^0 \rightarrow \gamma + \gamma \tag{12}$$

$$p + \gamma \rightarrow n + \pi^+ \tag{13}$$

The π^+ in Eq. 13 then decays as in Eqs. 7 and 8, while the π^0 decay shown in Eq. 12 is a source of high energy γ–rays that can be detected by the Fermi space telescope [12] for instance.

Why UHE neutrinos ?

- Cosmic ray flux extends to $> 10^{20}$ eV
- UHE Neutrinos come from UHE cosmic rays:
  - From interaction within the source
  - Or from interaction with CMB photons via GZK-effect

UHE neutrinos can also be produced during the propagation of the cosmic rays that managed to escape the source environment. Indeed, UHE cosmic rays can interact with CMB photons by the so-called GZK effect. This occurs for protons with energies above $10^{19.5}$ eV hitting the Δ^+ resonance:

$$p + \gamma \to \Delta^+ \to p + \pi^0 \quad (14)$$
$$\pi^0 \to \gamma + \gamma \quad (15)$$
$$p + \gamma \to \Delta^+ \to n + \pi^+ \quad (16)$$
$$\pi^+ \to \mu^+ + \nu_\mu \quad (17)$$
$$\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu} \quad (18)$$

Note that the delta resonance can also occur within sources but is not required there since both photons and protons can have a very high energy.

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Why UHE neutrinos ?

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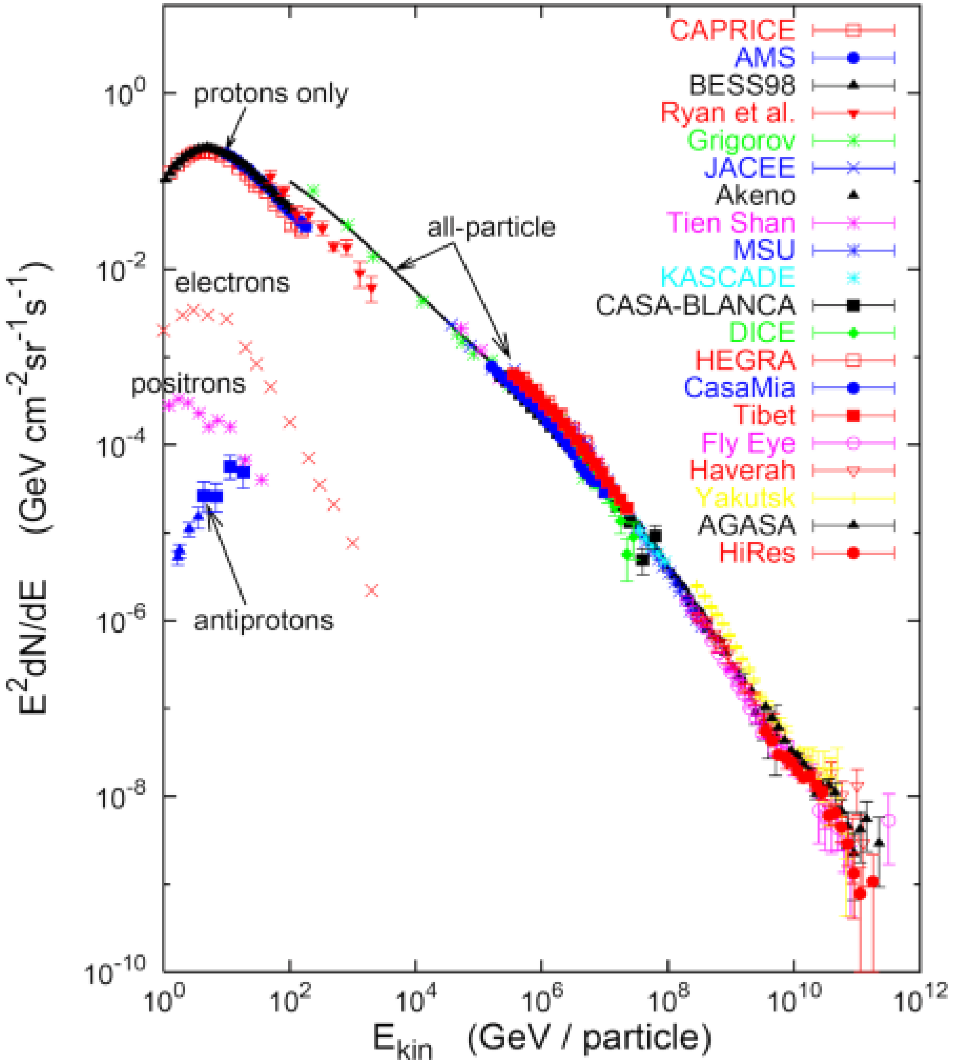
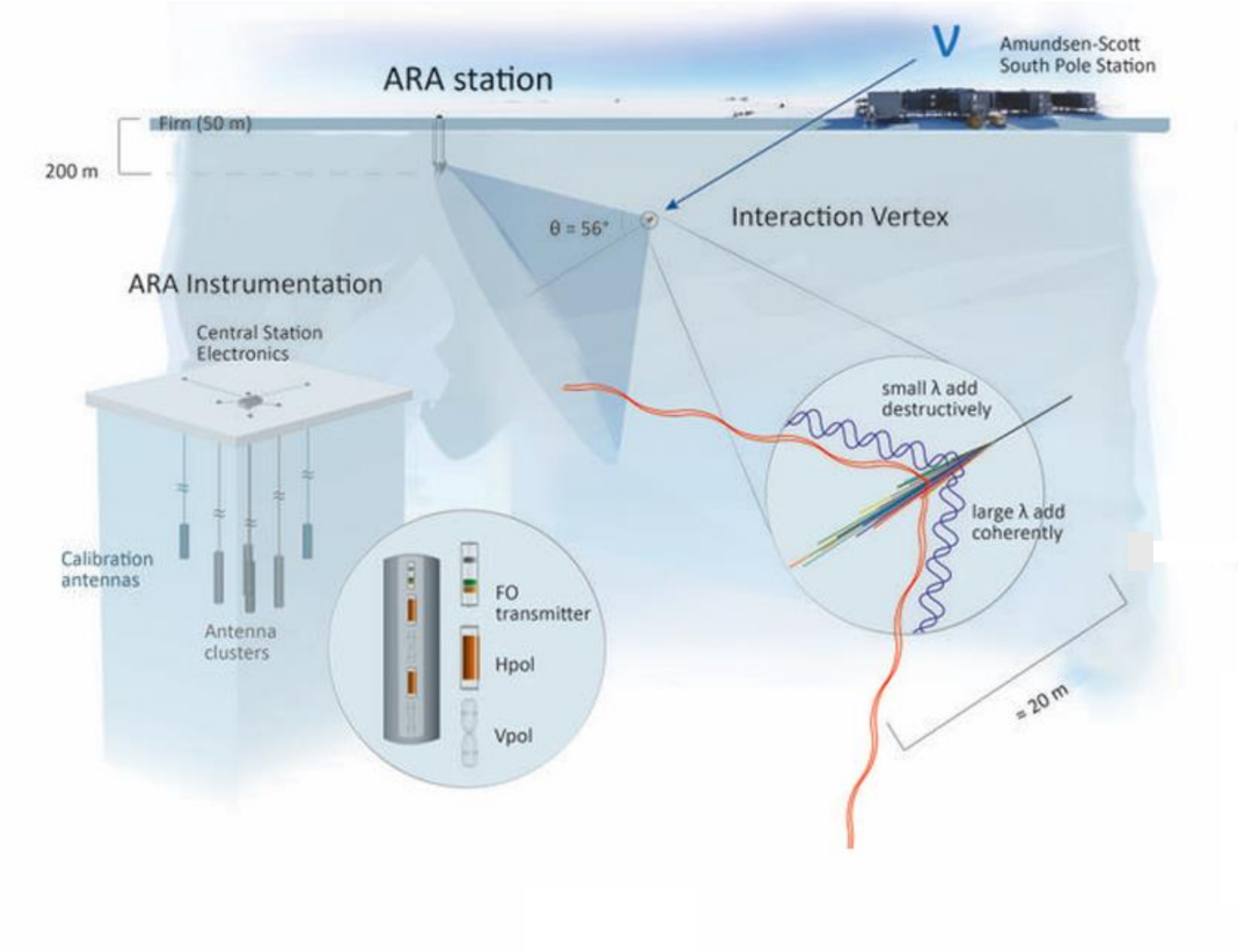
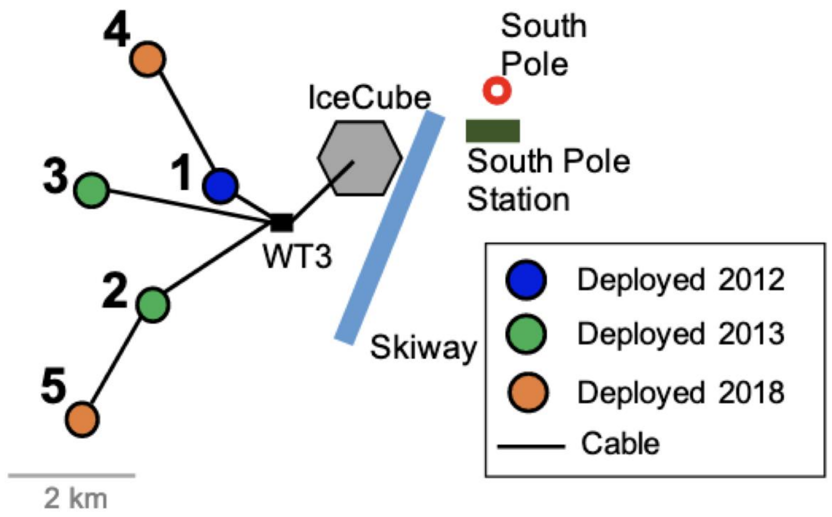
- UHE Neutrinos come from UHE cosmic rays:
  - From interaction within the source
  - Or from interaction with CMB photons via GZK-effect
- Neutrinos carry $\sim 5\%$ of the primary energy per nucleon
- Neutrinos flux should extend to $\sim 10^{19}$ eV
- If no UHE neutrino detection:
  - Set constraints on models of the sources
  - There is something we don't understand

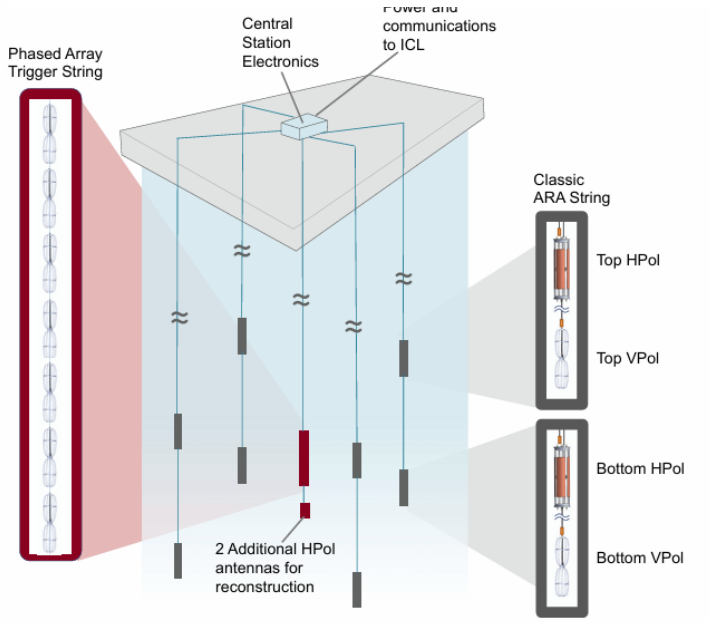


In-Ice Radio Detection Method

ARA







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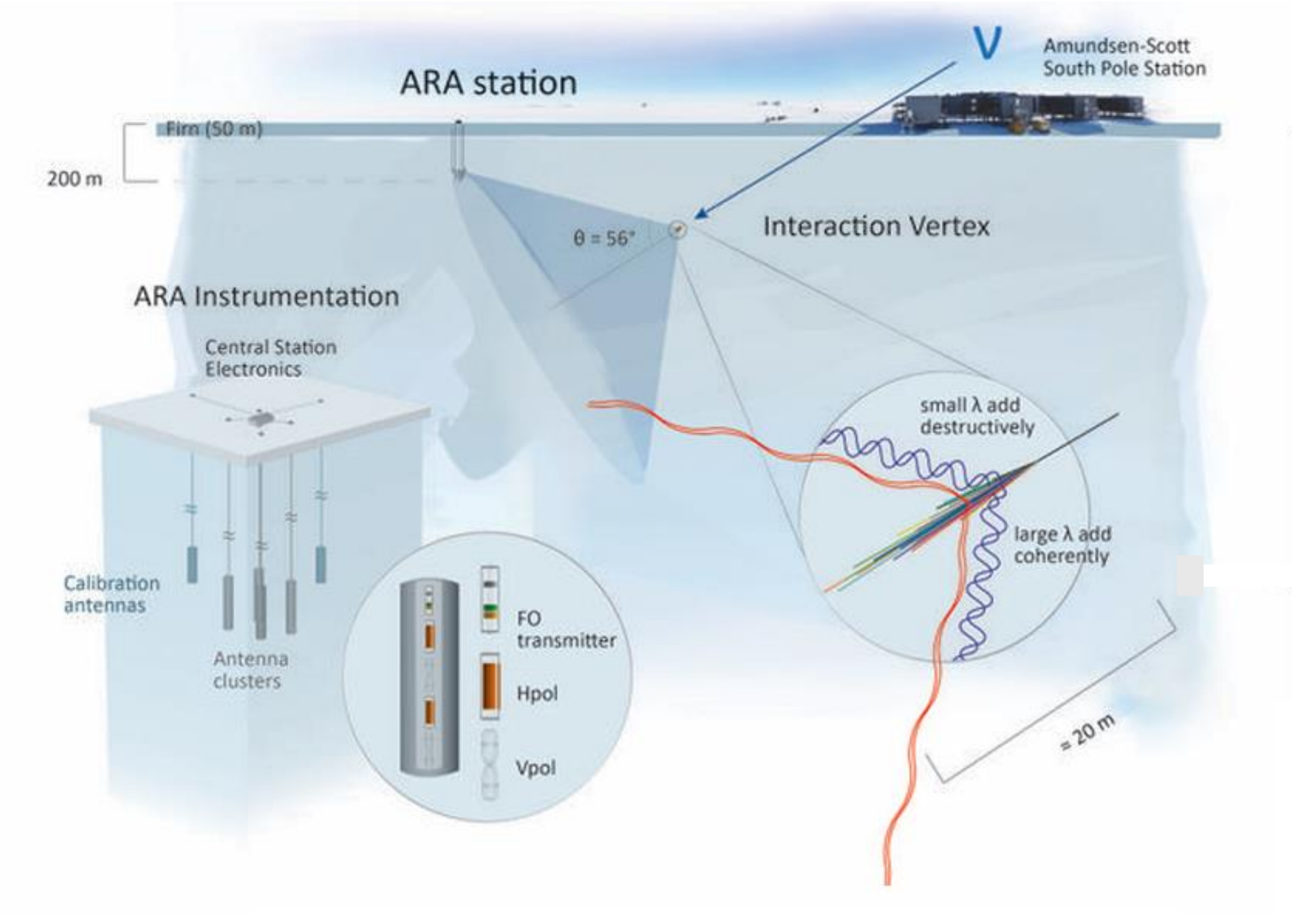
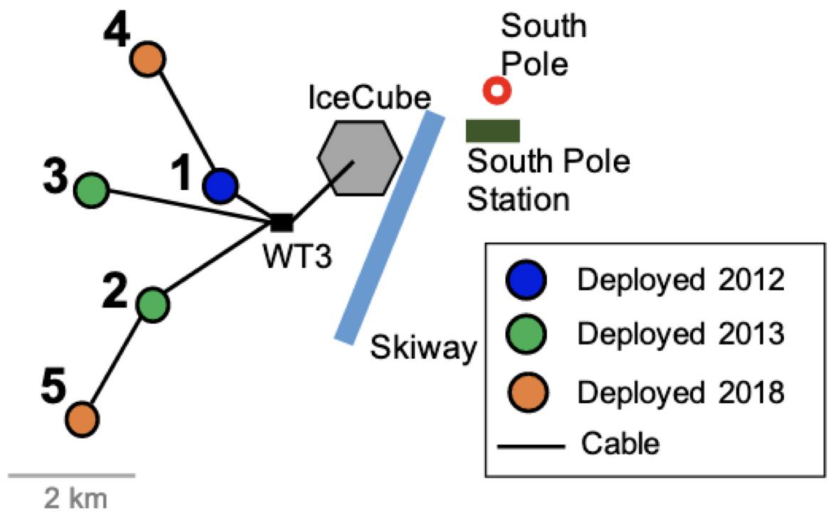
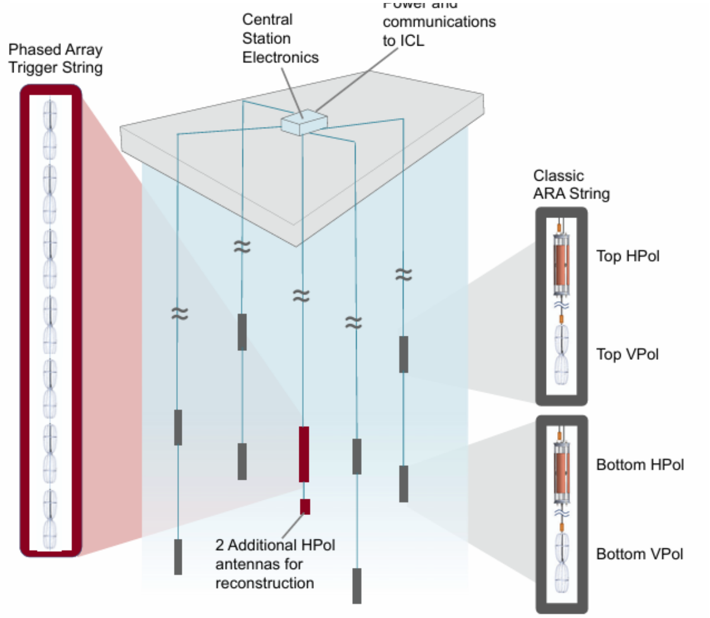


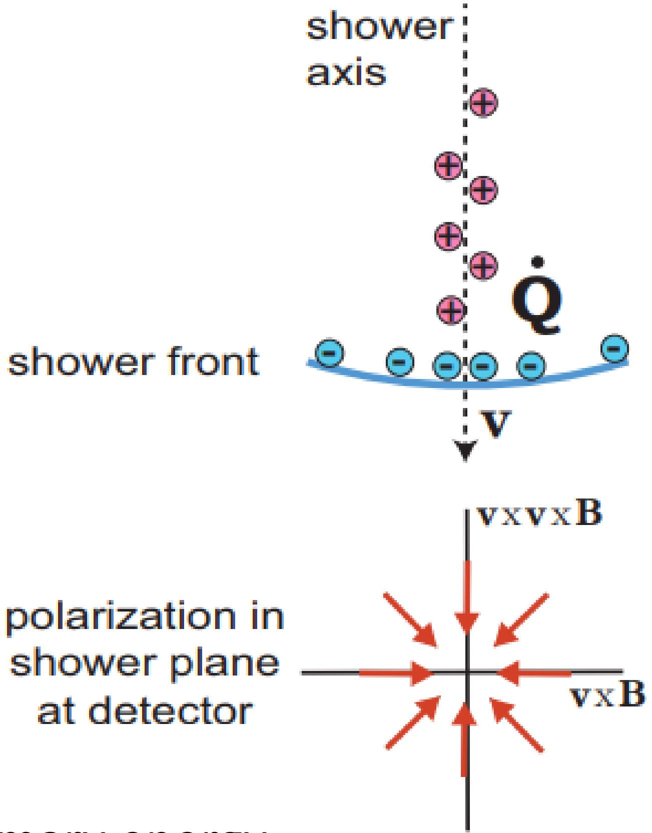




We look at skimming neutrinos !

Detection Principle

Askaryan effect



- $e^{+}_{cascade} + e^{-}_{media} \rightarrow \gamma + \gamma$
- $\gamma_{cascade} + X \rightarrow e^{-} + X^{+}$

➡ Development of a negative charge excess (20-30%)

Number of particles not constant ⇒ varying current

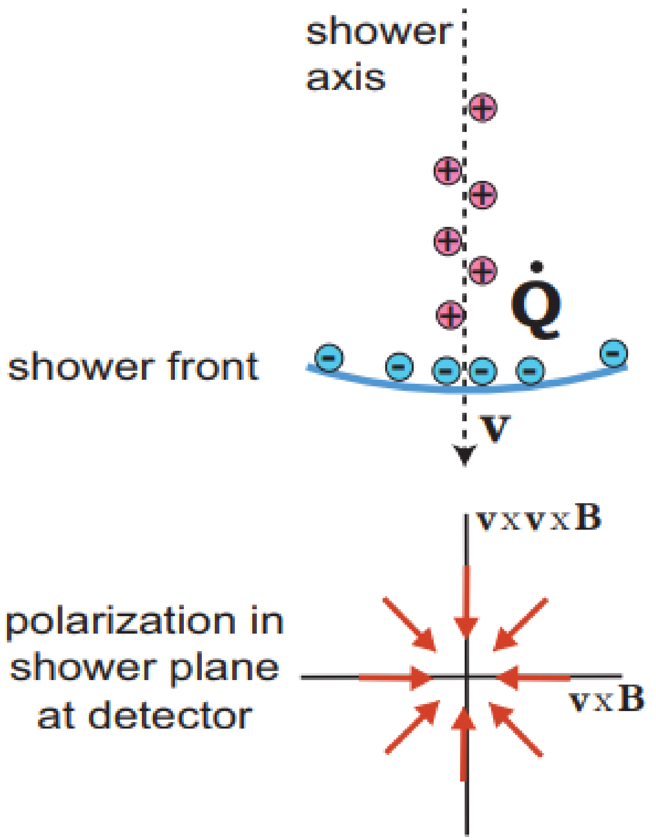
➡ Radio emission

Where the emission is coherent : Amplitude ∝ Number of emitters ∝ Primary energy

➡ Threshold for radio detection : $> 10^{16-16.5} eV$

Detection Principle

Askaryan effect



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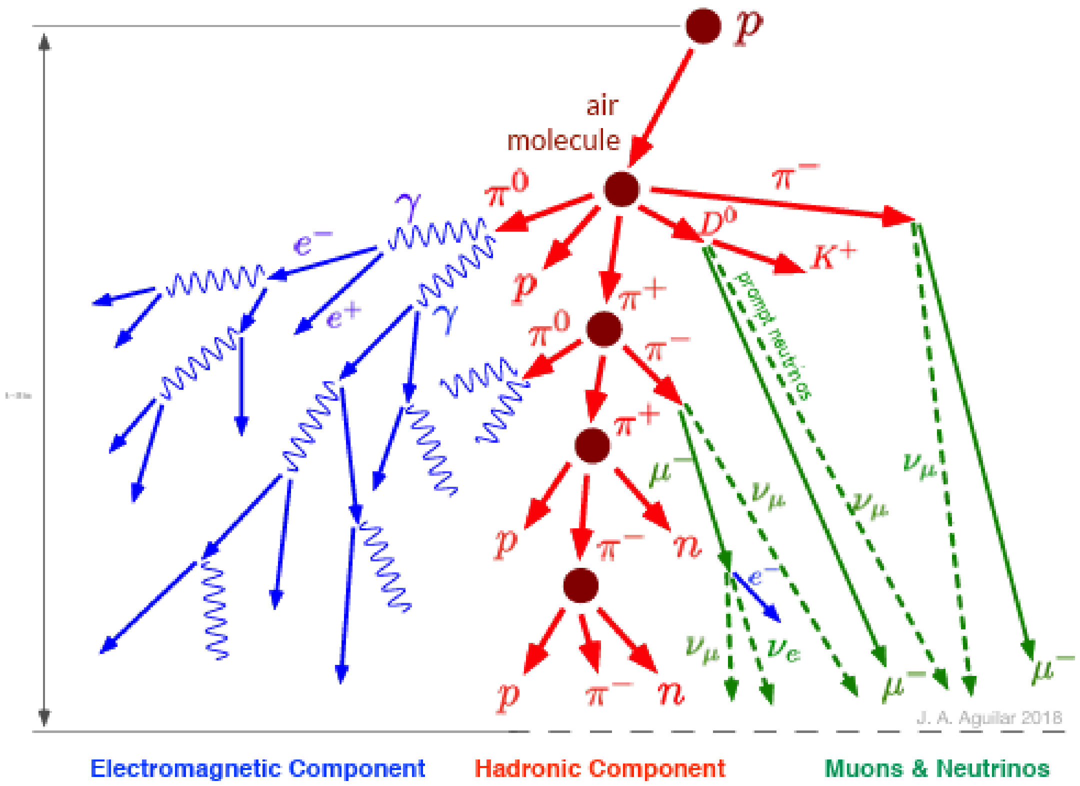
Problem: UHE-CR interactions in South-Pole ice produce an in-ice cascade that mimics the signal of a neutrino-induced cascade

Cosmic Ray Interactions in the Atmosphere

- Cosmic rays impacting nucleus in the atmosphere induce extensive air-showers with dimensions of typically 10 km height and a few kilometers large



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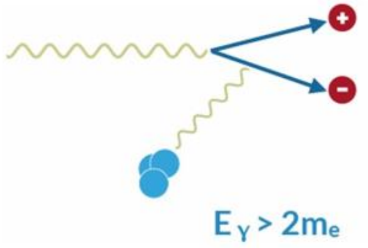

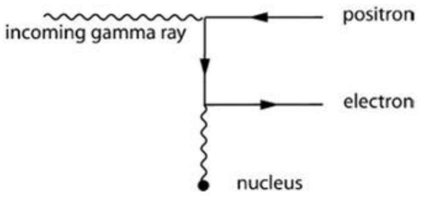

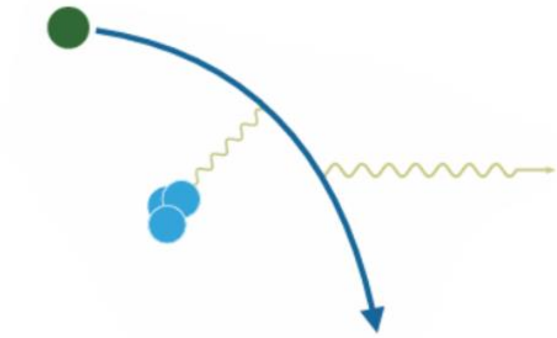

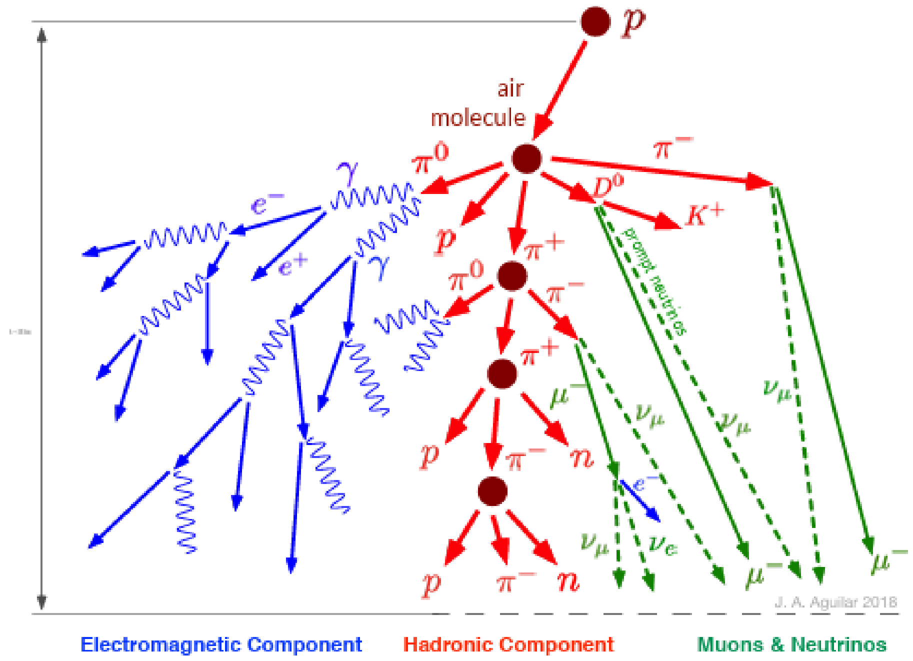

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  - Number of particle increases
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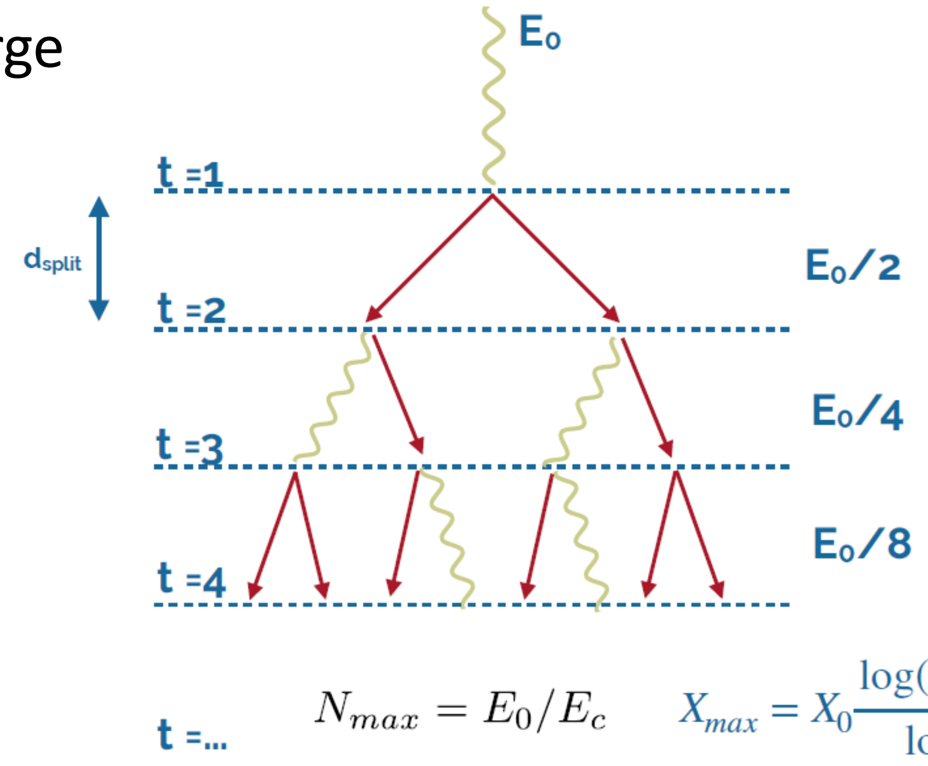

$$N_{max} = E_0/E_c \qquad X_{max} = X_0 \frac{\log(E_0/\epsilon_e)}{\log 2}$$

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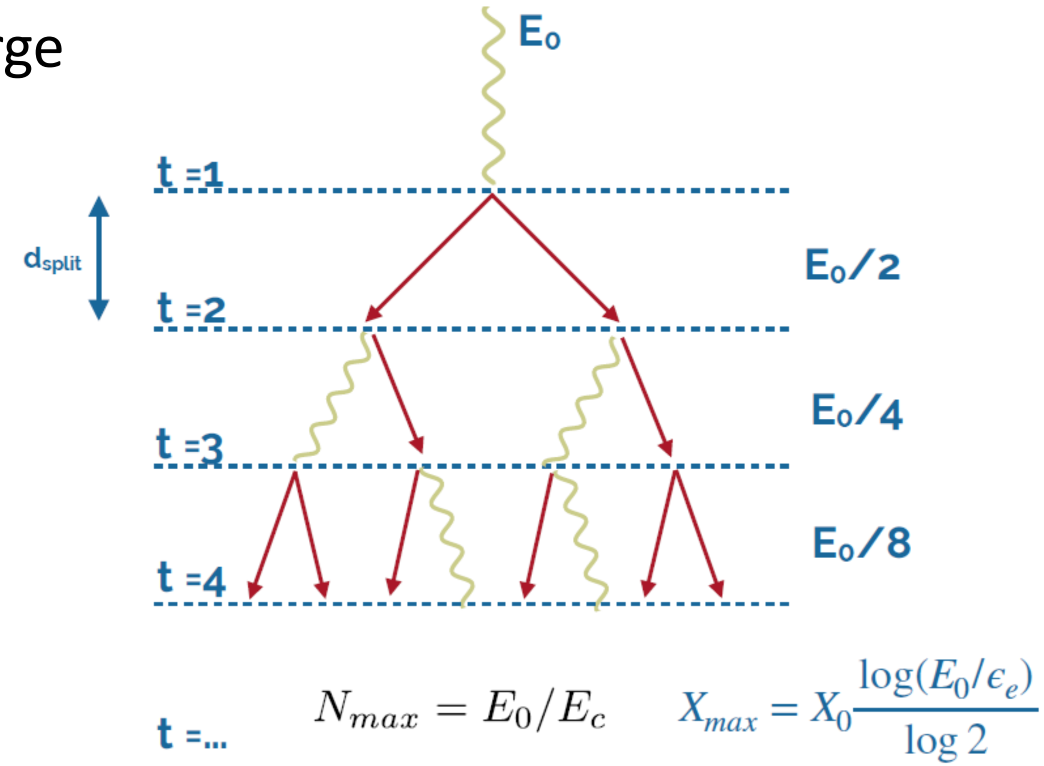
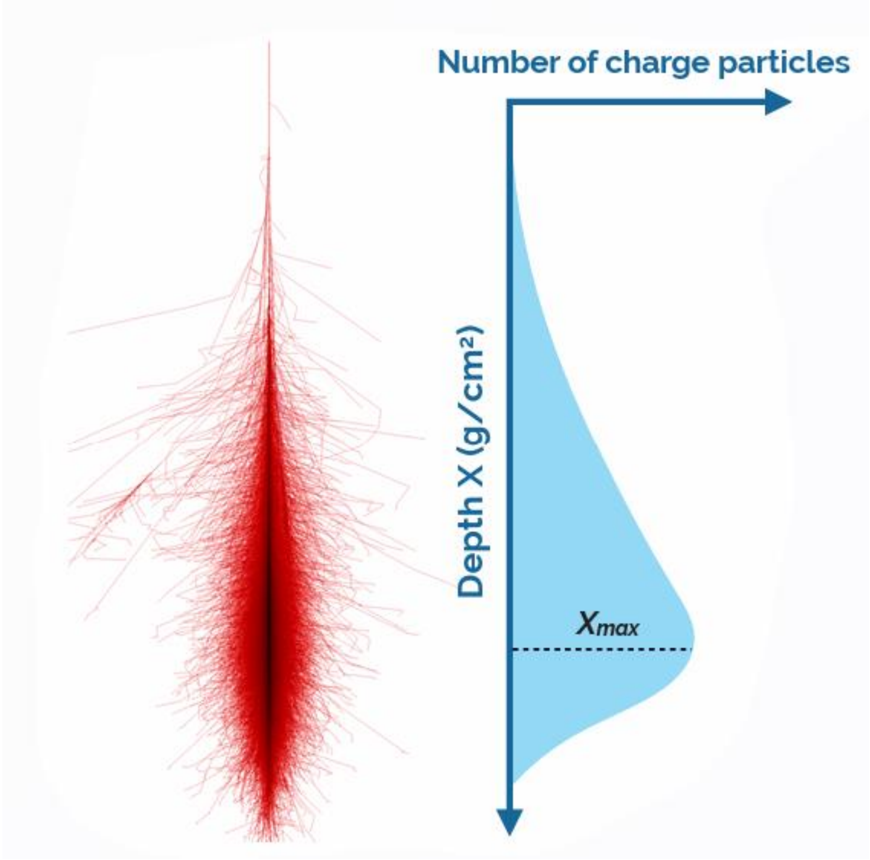
- Heitler Model:
  - Number of particle increases
  - Energy per particle decreases
- When energy/particle $< E_C$
  - Ionization energy loss dominates
  - The number of particles decreases



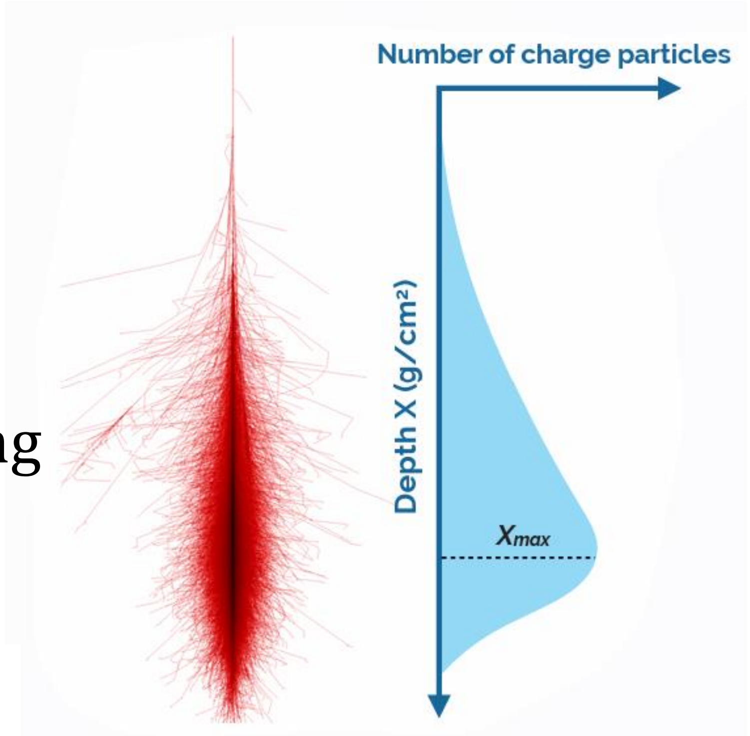
Cosmic Ray Interactions in the Atmosphere

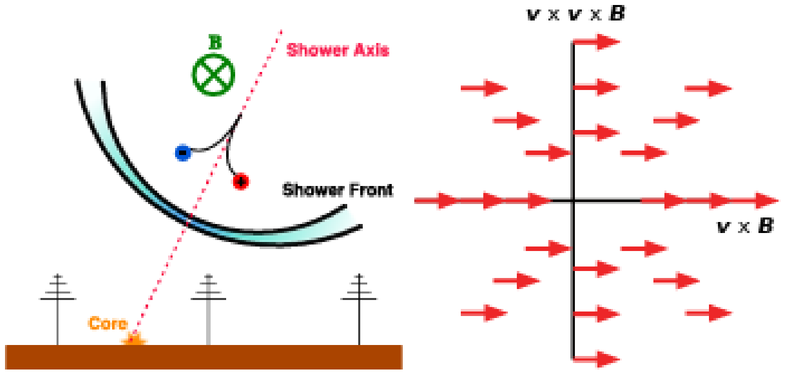
- The air-shower development reaches a maximum (X_{max})
- All the highest energy particles travel in nearly straight line very close from the shower axis

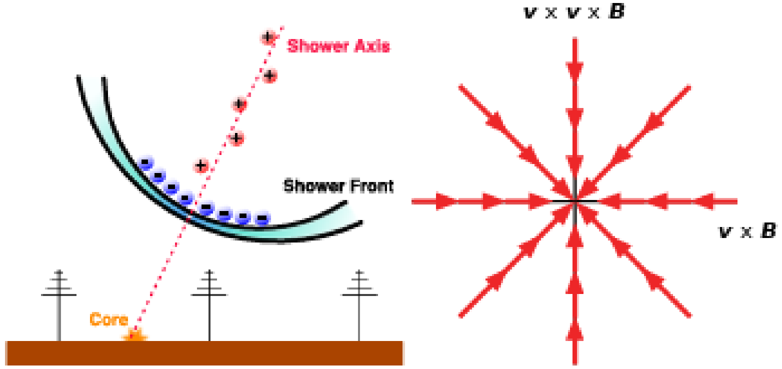


Cosmic Ray Interactions in the Atmosphere

- The air-shower development reaches a maximum (X_{max})
- All the highest energy particles travel in nearly straight line very close from the shower axis
- The very energy-dense central part of the shower radiates through Askaryan and Geomagnetic effects (Earth magnetic field deviate $e^-$and e^+ in opposite directions $\Rightarrow$ time-varying current)
- The emission is maximum at X_{max}

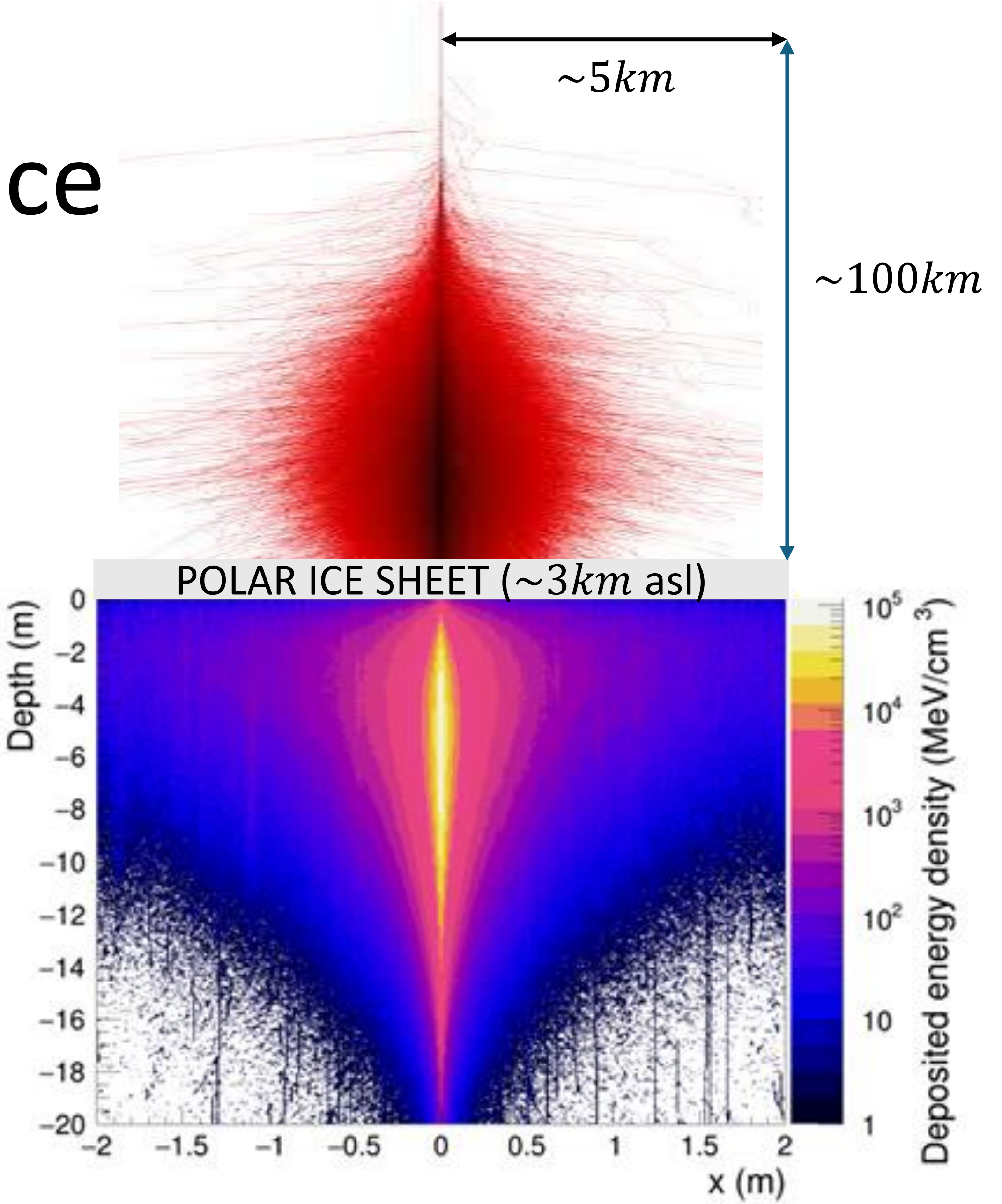






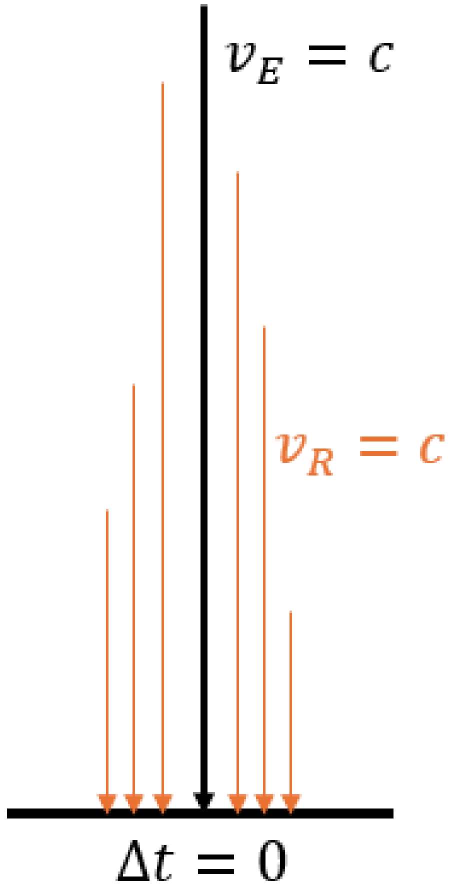
Air-shower Propagation in Ice

- When reaching the ground, the energy-dense core of the air-shower induces an in-ice cascade (thanks to the high altitude of the South-Pole ice sheet)
- Only the very high energy particles cascade in the ice
  - ⇒ small lateral extension (∼1m)
- Denser media
  - ⇒ shorter mean free path of particles
  - ⇒ vertical extension (∼20m)
- Radiates through Askaryan process
  - ⇒ very similar to a neutrino interacting in the ice



Coherence

- If the radiation from all those emitters has a negligible relative phase shift at a given frequency, the amplitudes will add up coherently to give a final signal whose amplitude is proportional to the number of emitters
- Achieved when the wavelength is larger than the emission region
- What matters is the projected length scale: $\Delta X = c\Delta T_{obs}$



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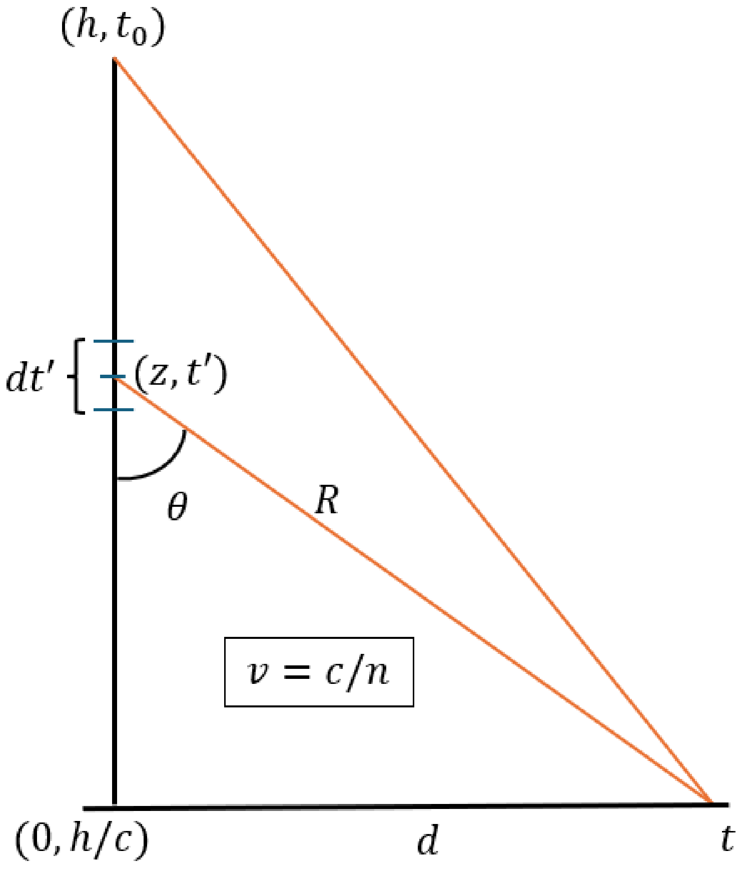
- What matters is the projected length scale: $\Delta X = c\Delta T_{obs}$
- The radiation travels at a speed: $v_R = \frac{c}{n} < c$
- The emitters travel at a speed: $v_E \sim c > v_R$
- Coherence is reached at a specific angle which is the Cherenkov angle of the media:

$$cos\theta = \frac{1}{n}$$

- $\theta \sim 1°$ in the air and $\theta \sim 56°$ in the ice



How to discriminate neutrino and cosmic rays?

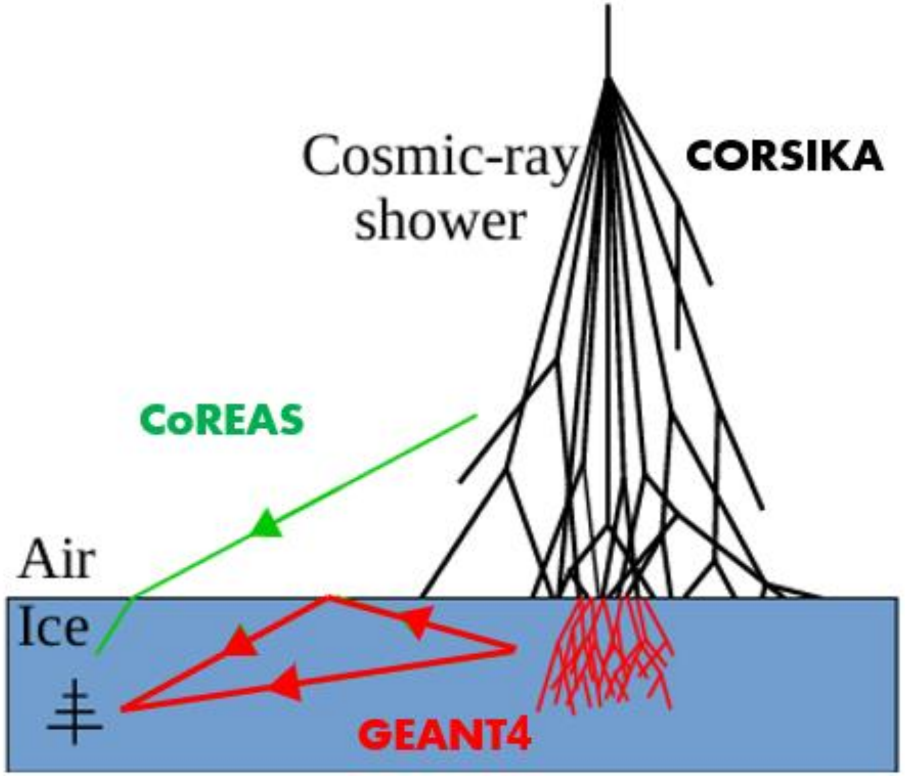
Need to understand the CR-induced signal !

- Build a library of simulated CR-induced waveforms
- Need to cover the phase space with as many simulations as possible
- Limited by CPU time consumption of the simulations :
  - Air-shower + in-air radio emission : ~ 5 days for a vertical shower at $10^{18} eV$ and 10 antennas
  - In-ice cascade + in-ice radio emission : ~ 1 week for a vertical shower at $10^{18} eV$ and 120 antennas

Simulation Framework : FAERIE

We need to simulate:

- The extensive air-shower (CORSIKA)
- The in-air radio emission and its propagation through the air-ice interface with complete ray-tracing (modified CoREAS)
- The in-ice particle cascade and its corresponding radio emission + ray-tracing (GEANT4)

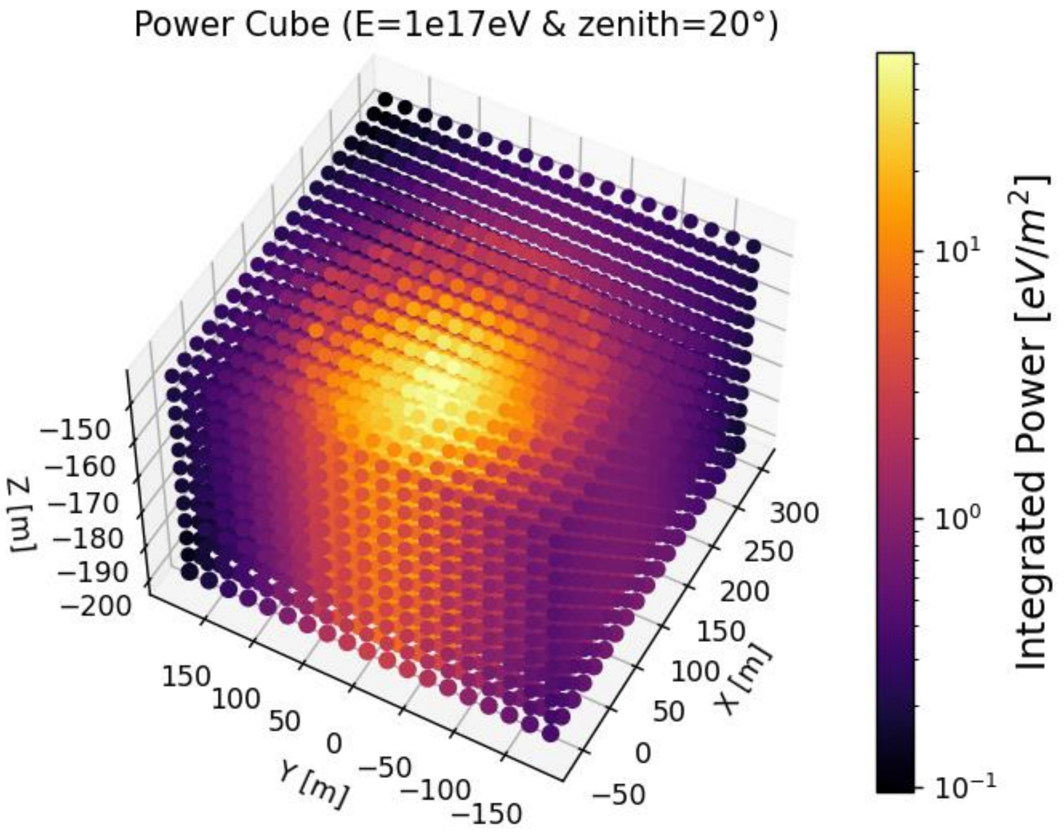


Outputs : $E_{x,y,z}(t)$ at each antenna position

$\text{Fluence}: \; P = \varepsilon_0 c \int dt\,(E_x^2 + E_y^2 + E_z^2)\;[eV/m^2]$

Cubic Antenna Grid

- 12 horizontal layers at different depths from -145 to -200 m (5 m vertical spacing)
- ~ 400 antennas per layer (20 m horizontal spacing)
- Need different grids depending on the zenith angle because of the increasing size of the footprint and its geometrical displacement

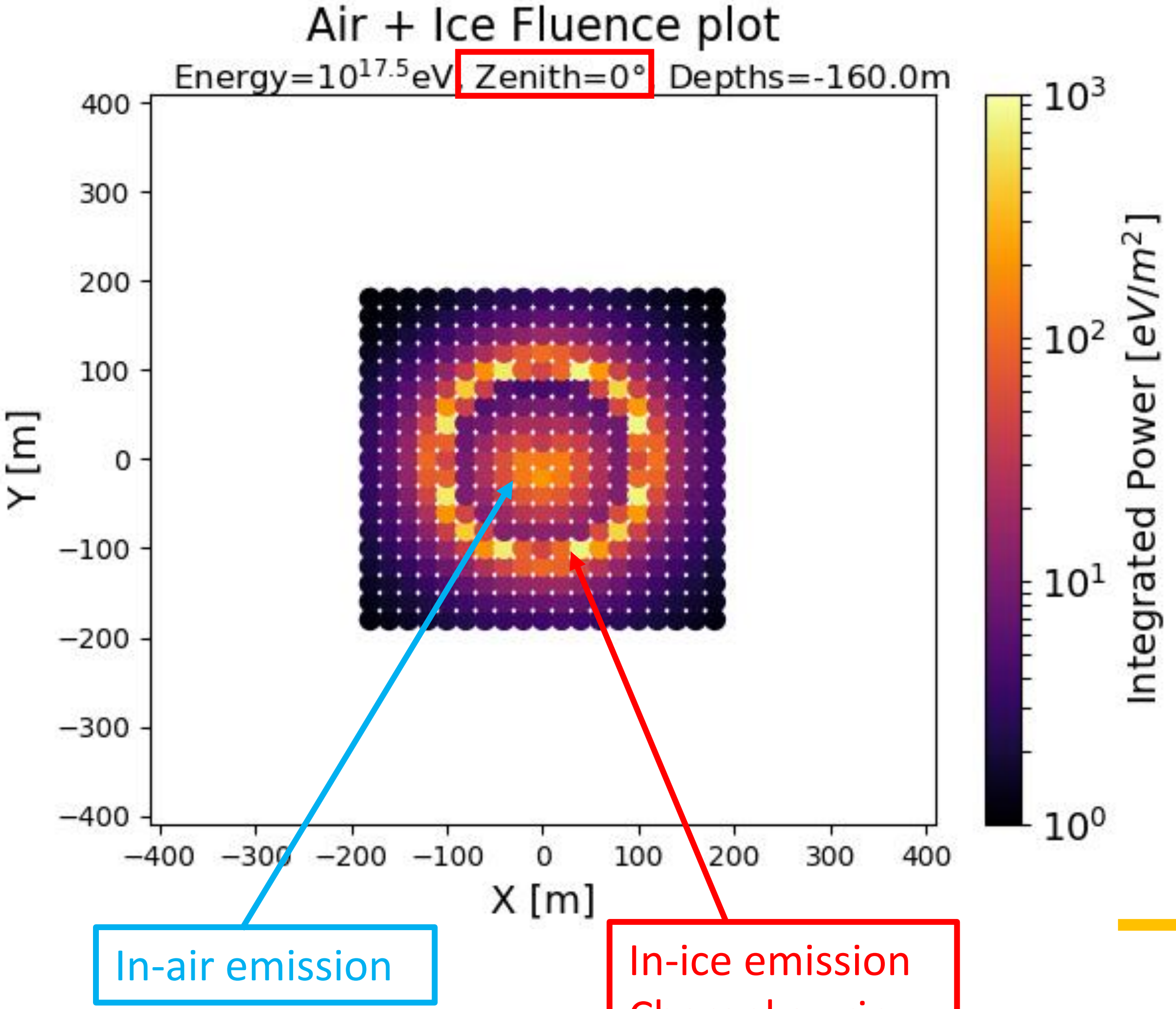


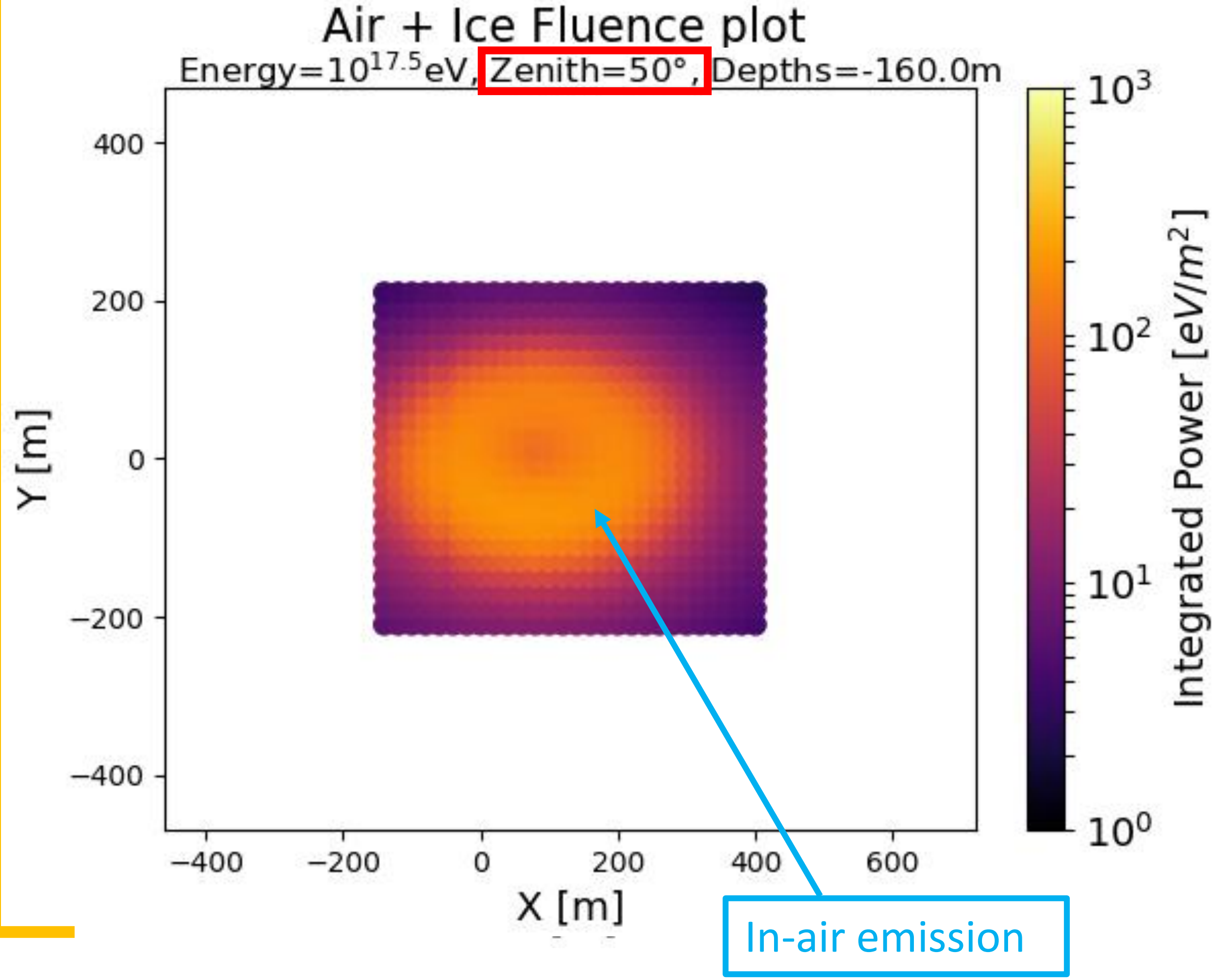
Simulation Parameters

- Primary type: only protons (to save time)
- Energy: $10^{16.5}, 10^{17}, 10^{17.5}, 10^{18} eV$
  - ➢Radio detection threshold $\sim 10^{16} eV$
  - ➢Model accuracy drops and computing time increase with energy
- Zenith: 0°, 10°, 20°, 30°, 40°, 50°
  - ➢Ice component negligible at zenith $> 60°$ because few particles hit the ice
  - ➢Flat Earth approximation
- Azimuth: 0° only
  - ➢cylindrical symmetry of the in-air radio emission due to vertical magnetic field lines in South-Pole)

Simulation results

Fluence : $P = \varepsilon_0 c \int dt\, (E_x^2 + E_y^2 + E_z^2)\ [eV/m^2]$





In-ice emission negligible because less particles hit the ice

What can we do with this library ?

1) Estimate the CR event rate in ARA
    - Starting point for any CR/neutrino analysis

2) Find the first CR detected by in-ice radio antennas
    - Simulate the antenna response to the electric fields (AraSim) to make a library of waveform templates, then use the library to develop analysis for CR searches

3) Build a CR-discriminant to remove the CR-background in ARA data

What can we do with that ?

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   - For future researches

3) Build a CR-discriminant to remove the CR-background in ARA data
   - For future researches

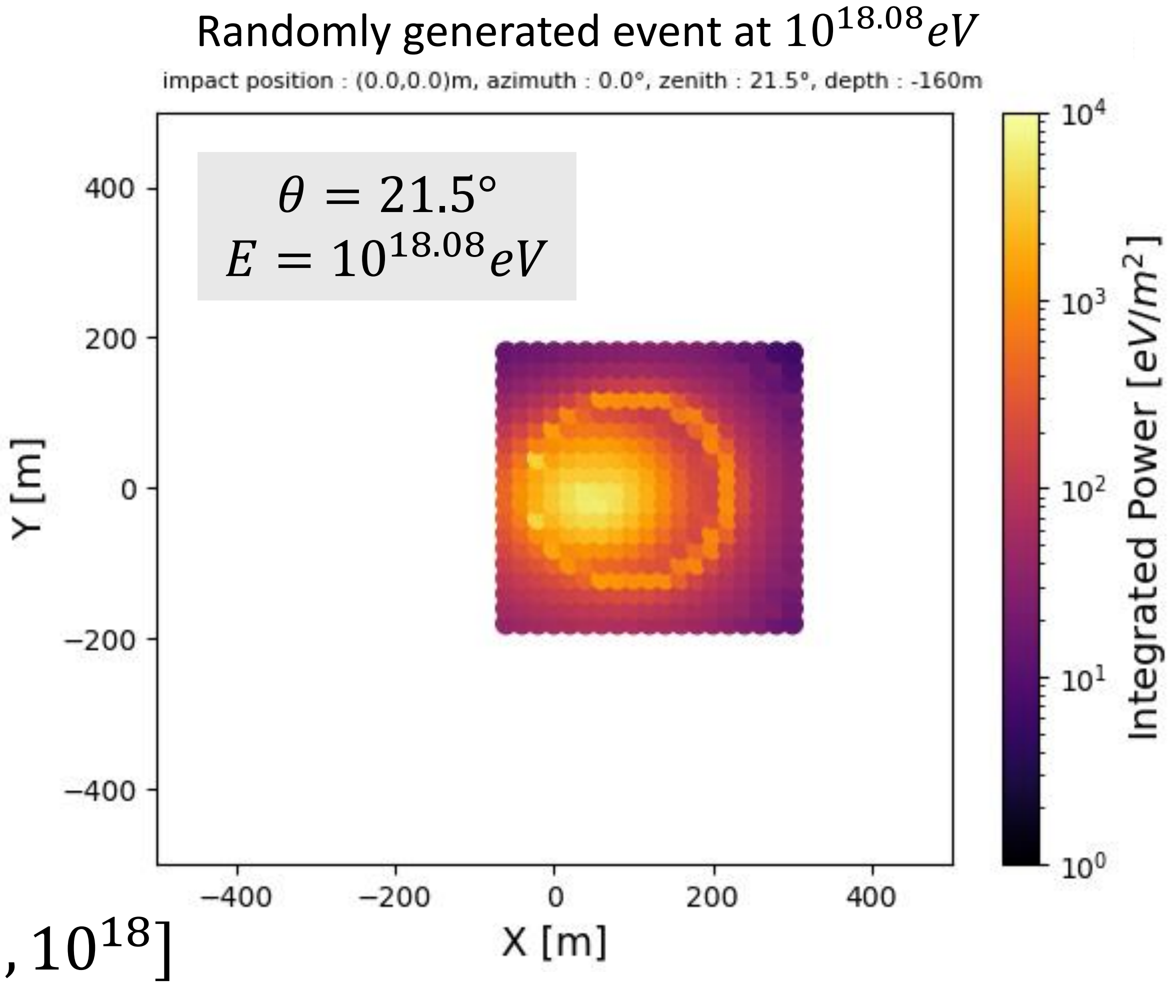
Estimate CR Event Rate

A. Generate random events

- Energy : $[10^{16.25}, 10^{18.25}]$ eV
- Impact position : x_{impact}, y_{impact} ∈ [-500,500] m
- Flat distribution in $\cos\theta$ ∈ [0,1]
- Only keep zenith angles between 0° and 55°
- Azimuth angle : Φ ∈ [0°,360°]

Estimate CR Event Rate

B. Find the closest event in library



If $0° < \theta < 5° \;\rightarrow zenith\ angle = 0°$

If $5° < \theta < 15° \;\rightarrow zenith\ angle = 10°$

…

If $45° < \theta < 55° \;\rightarrow zenith\ angle = 50°$

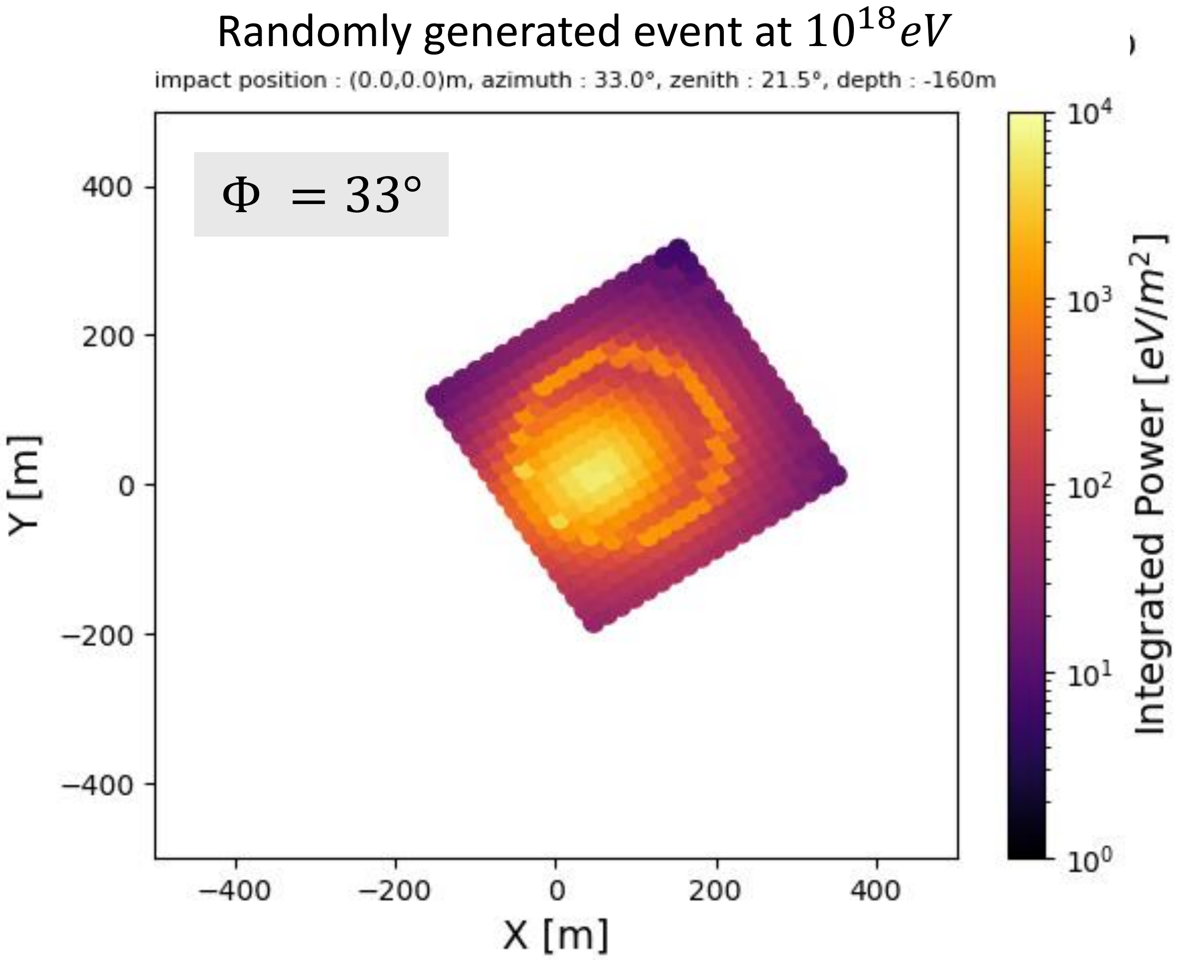
Same game with energy $[10^{16.5}, 10^{17}, 10^{17.5}, 10^{18}]$

Estimate CR Event Rate

C. Rotate it along the azimuth

$$x' = x \times cos\varphi\ - y \times sin\varphi$$

$$y' = x \times sin\varphi + y \times cos\varphi$$



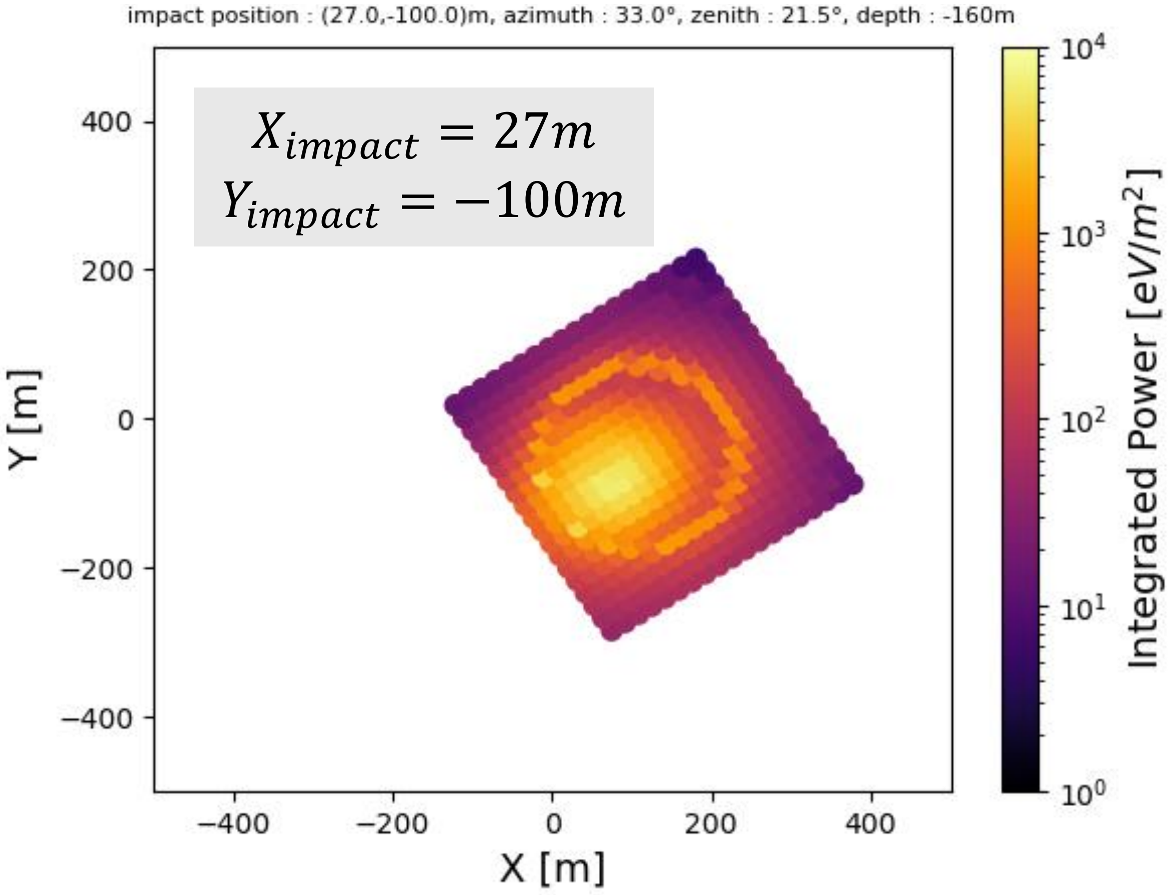
Estimate CR Event Rate

D. Shift it along X_{impact}, Y_{impact}

$$x' = x \times cos\varphi \; - y \times sin\varphi + x_{impact}$$

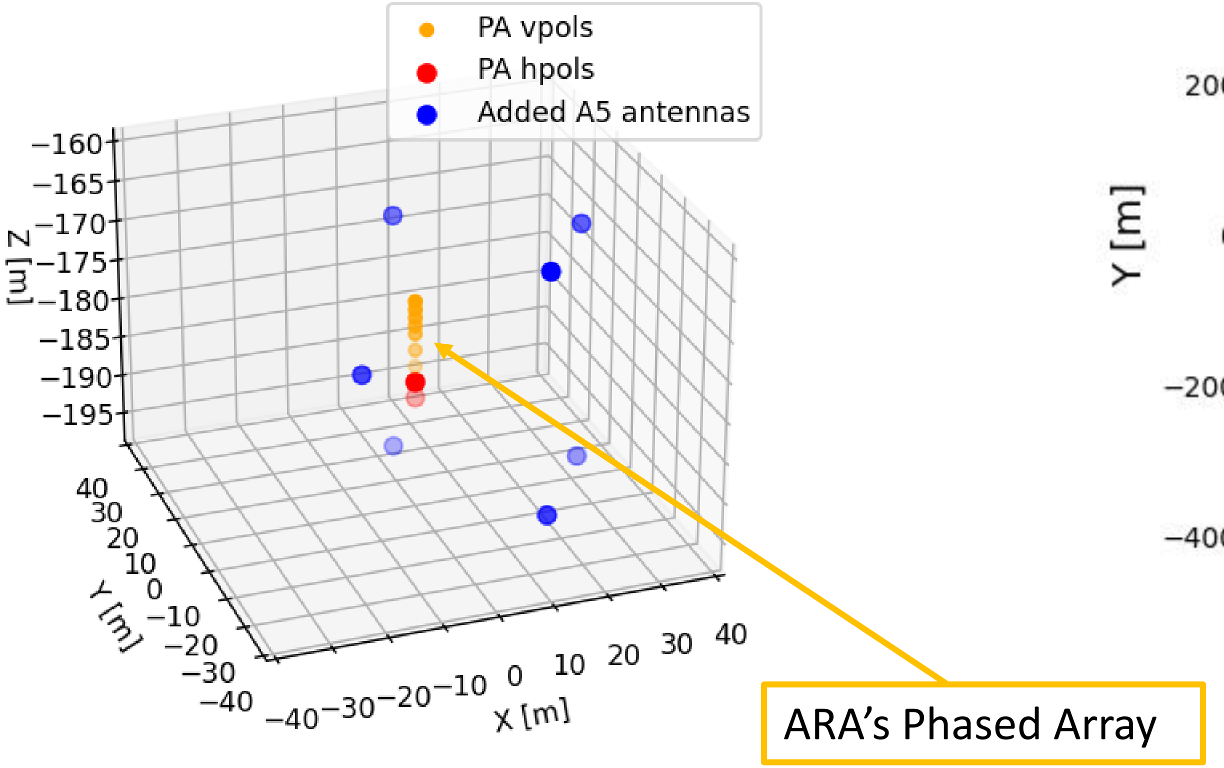
$$y' = x \times sin\varphi + y \times cos\varphi + y_{impact}$$

Randomly generated event at $10^{18}eV$



Estimate CR Event Rate

E. Add an ARA station



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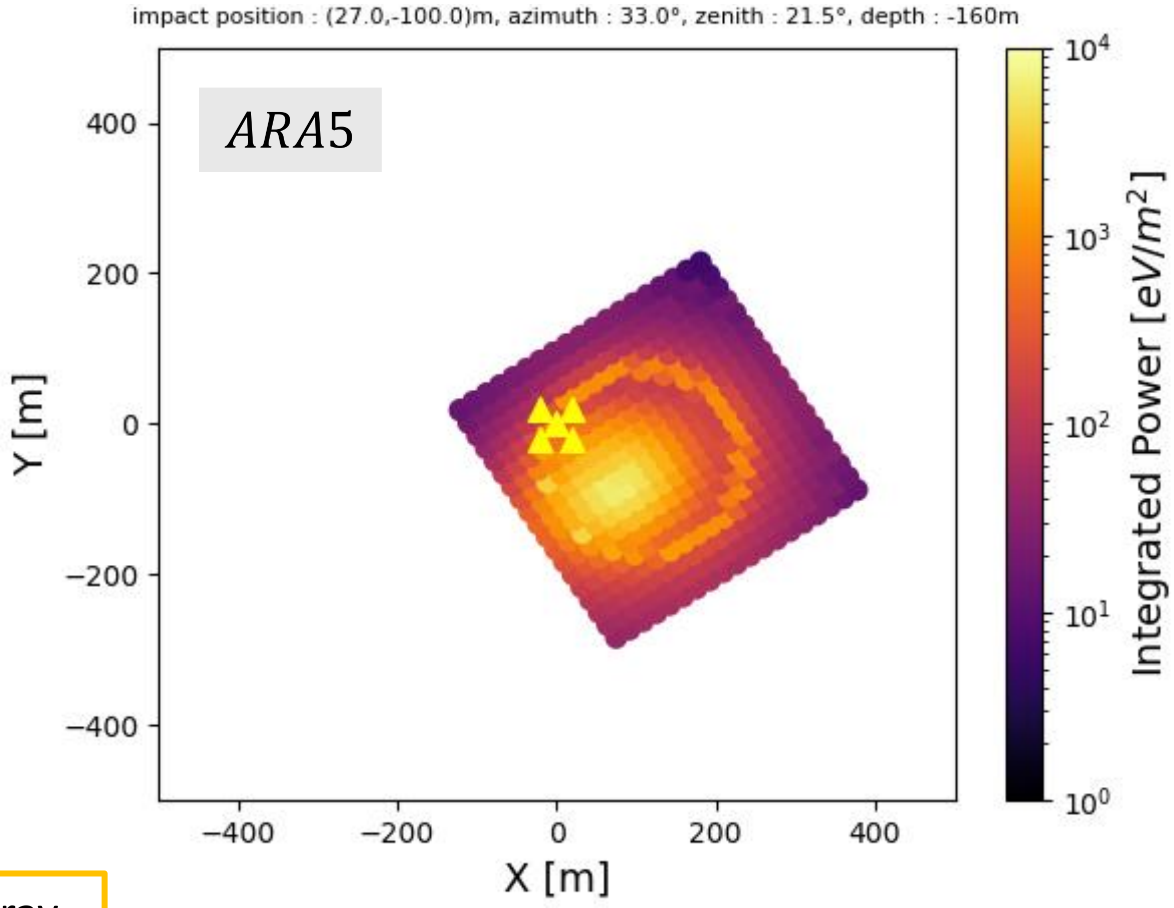
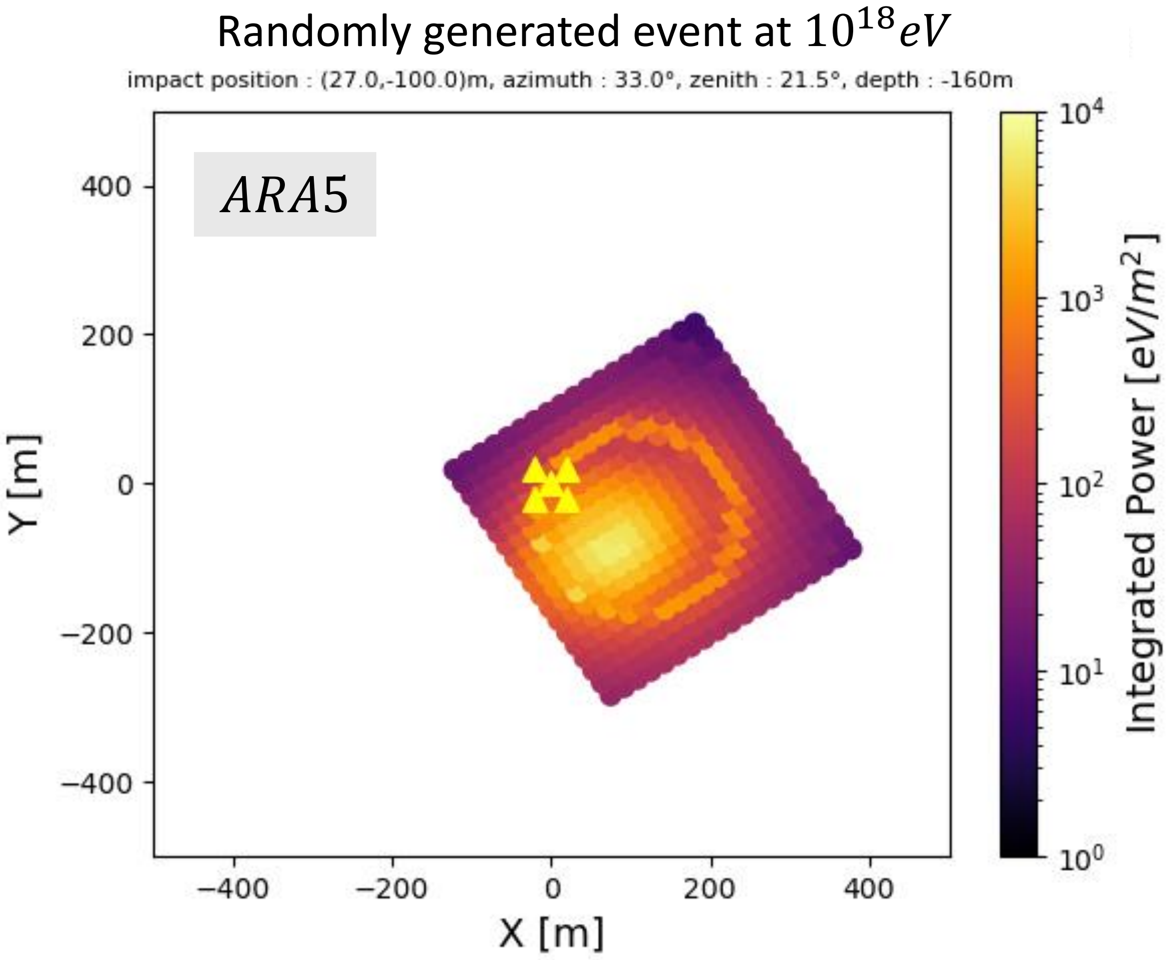


Estimate CR Event Rate

F. Implement trigger condition

Station triggers if SNR>6 !

=> Need to simulate the antenna response with noise (AraSim)

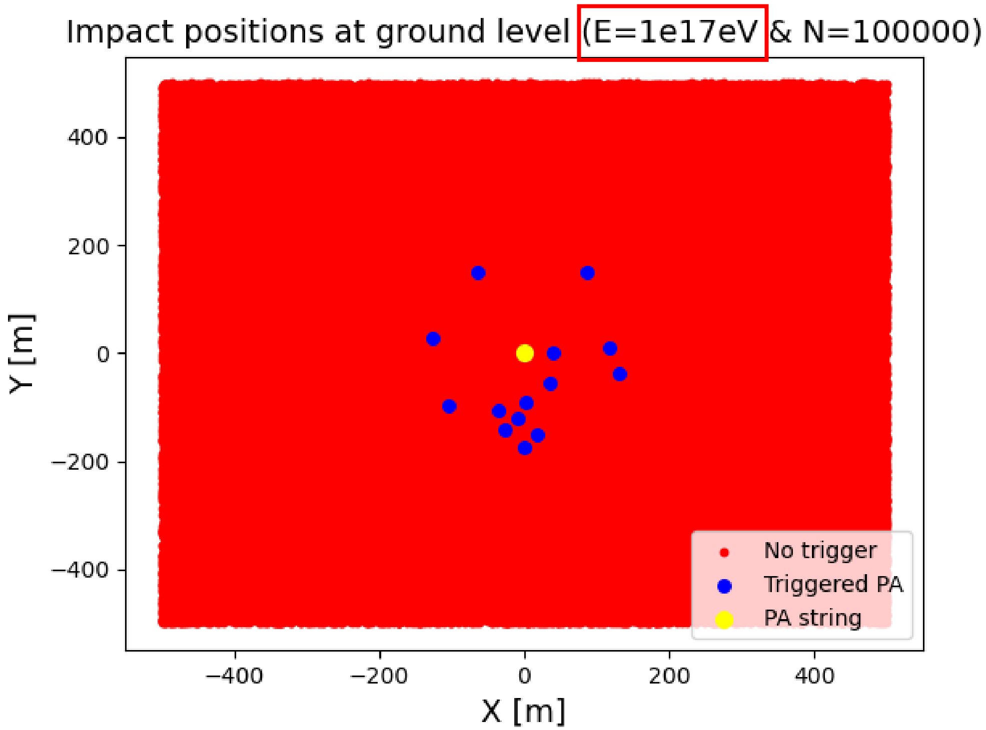


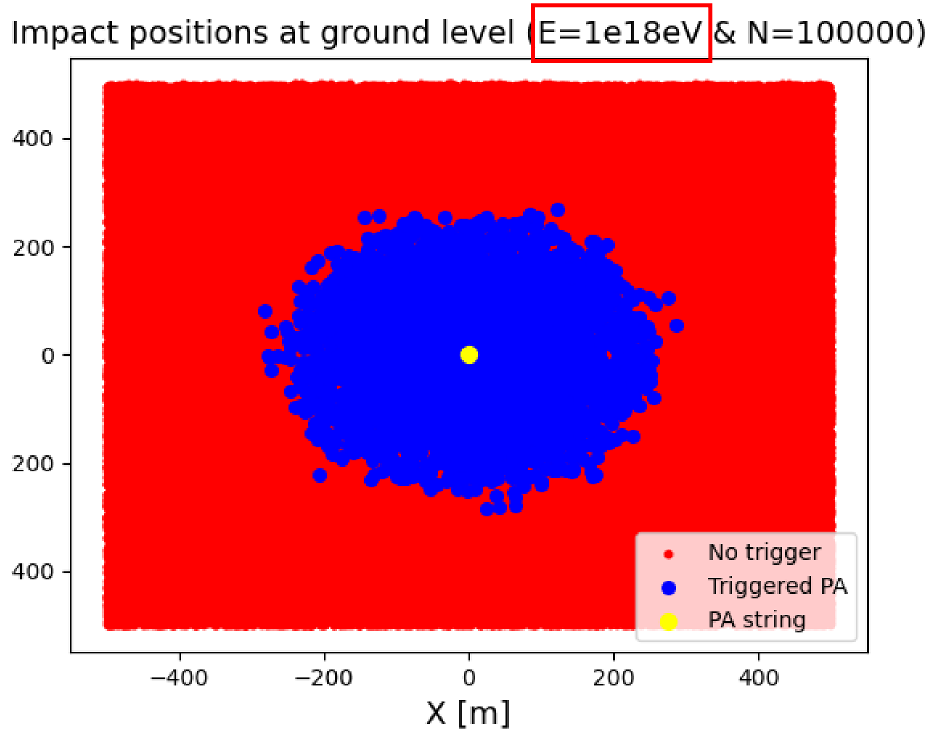
Results: shower impact position on ground

Trigger Map (N=100.000)

Blue if triggered

Red if not





Results: Trigger Efficiency

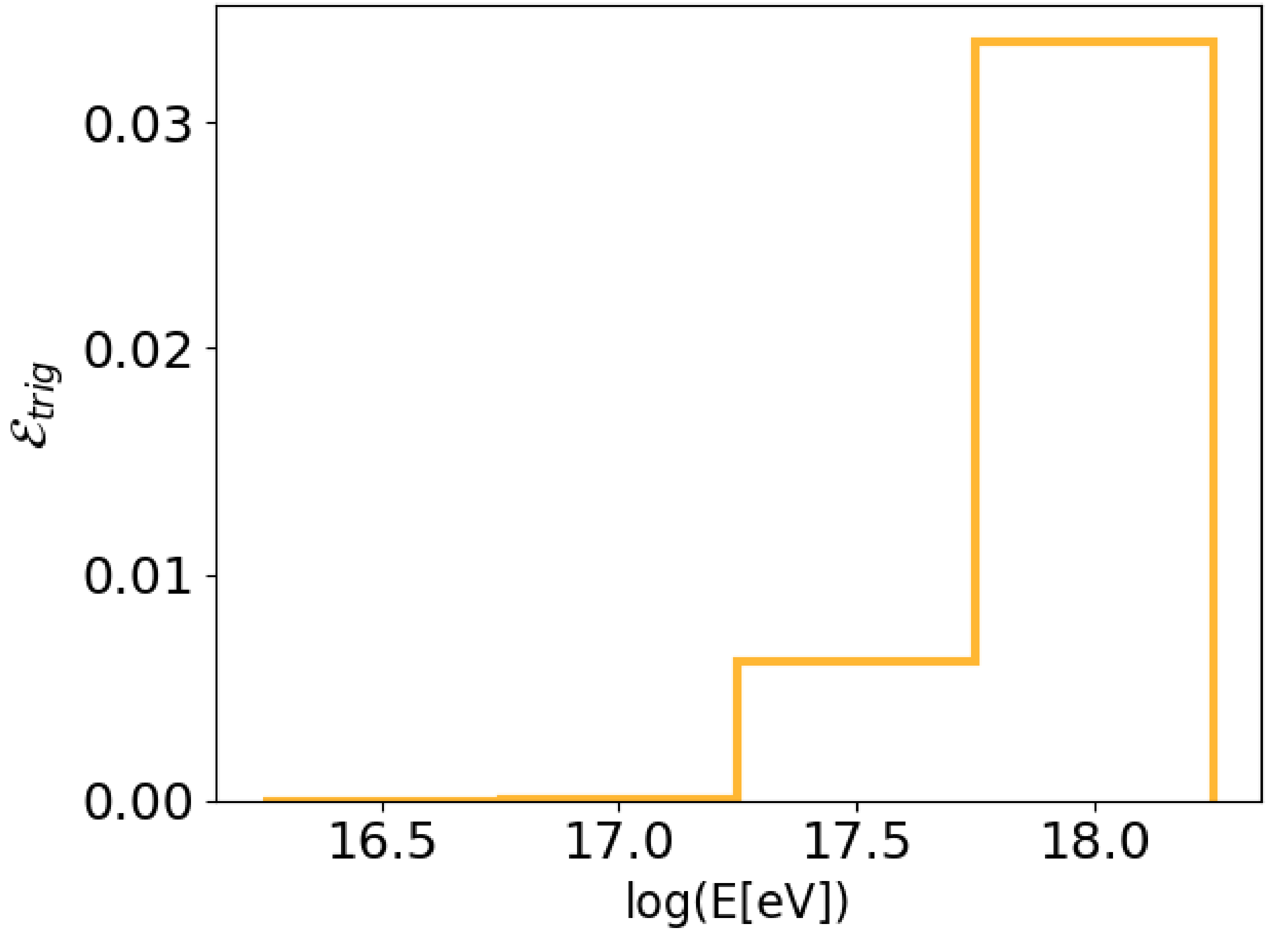
$$T_{eff} = \frac{N_{trig}}{N_{tot}} \times \cos\theta$$

Geometrical effect:
At non-zero zenith angle, the projected surface area is less than the actual simulated area by a factor cos(theta)

Event rate:

$$N = \int T_{eff} \times F \, dE \int dA \, d\Omega \, dt$$

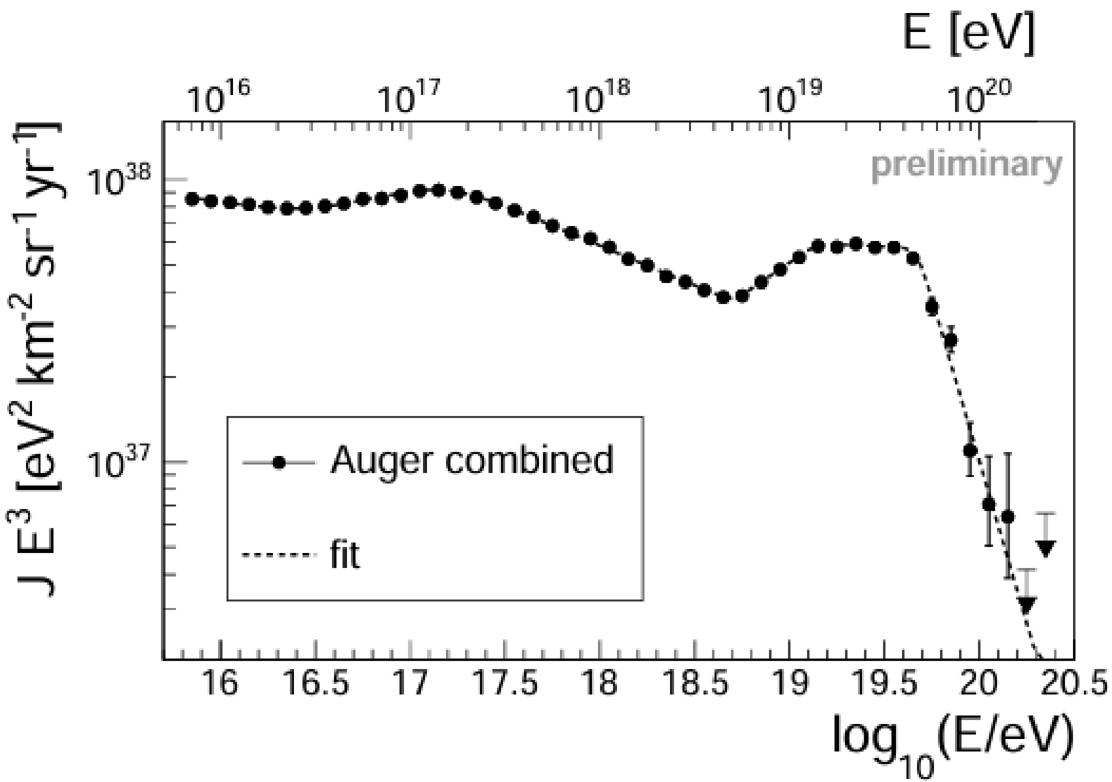
Flux!

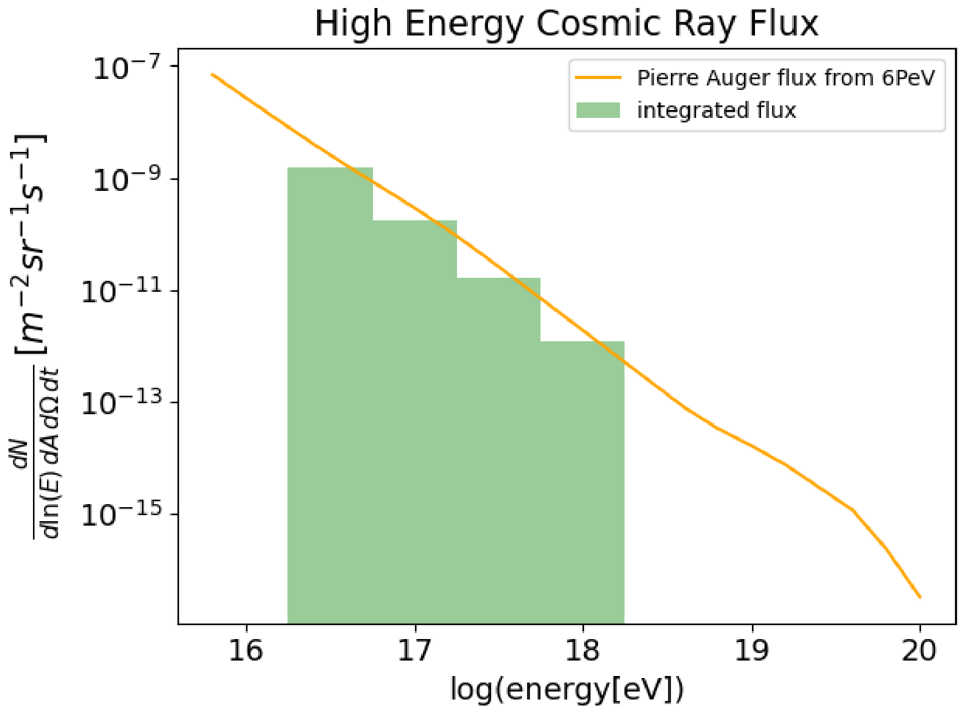


Estimate CR Event Rate

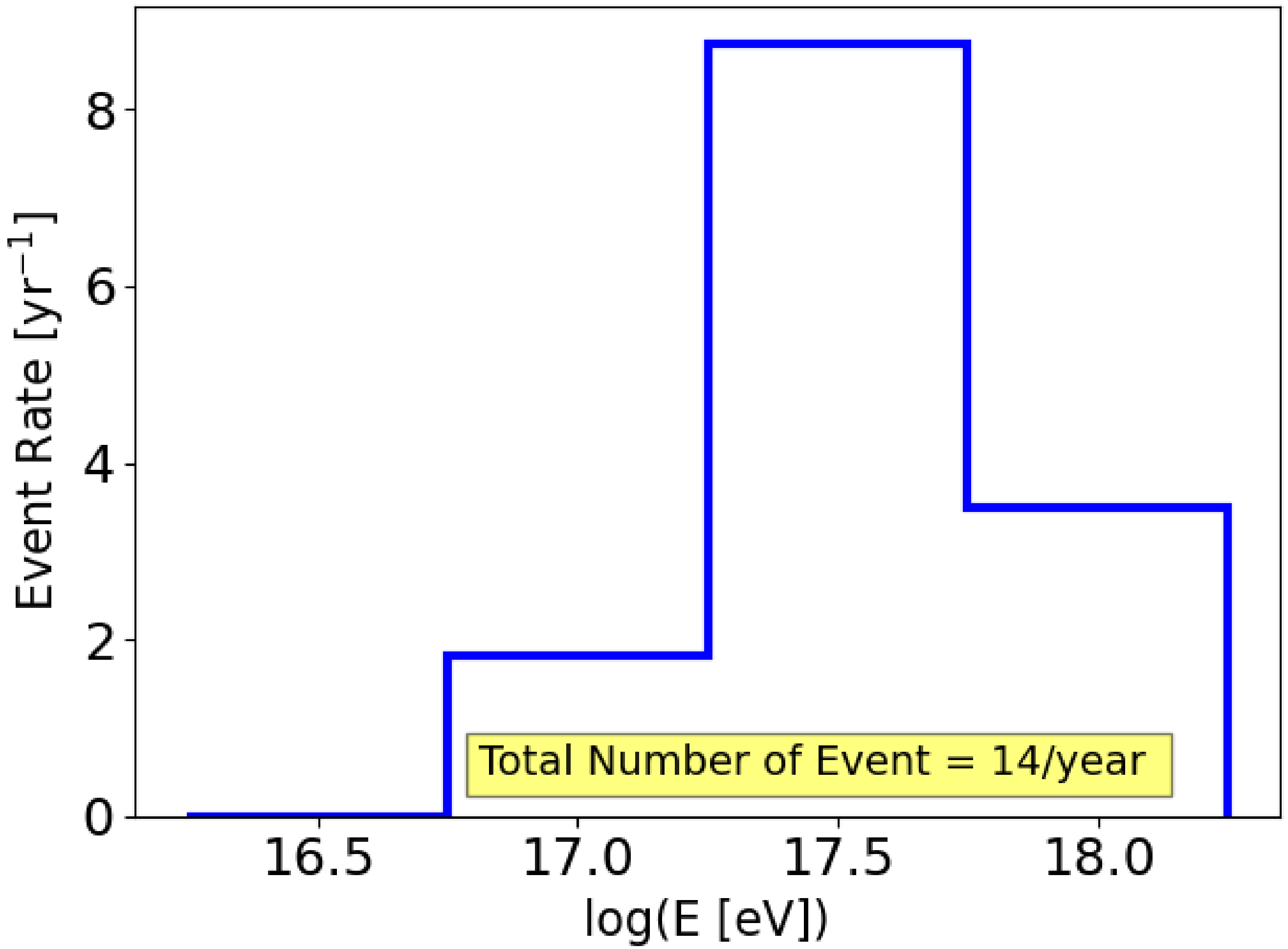
H. Integrate the CR flux over energy bins

Analytical flux function from a Pierre Auger paper : *PoS(ICRC2021)324*





Results



Event Rate [yr^{-1}]
8
6
4
2
0
16.5
17.0
17.5
18.0
log(E [eV])
Total Number of Event = 14/year

Conclusion

- ❖ Cosmic-Ray searches in ARA have been difficult due to the lack of CR simulations in ARA – we are now in a position where we can simulate an ARA station response to CR events with different parameters (just need to plug simulation results in AraSim)
- ❖ 14 CR events per year expected in ARA data
- ❖ We can now try to build a CR-discriminant and look for a cosmic ray signal in ARA.