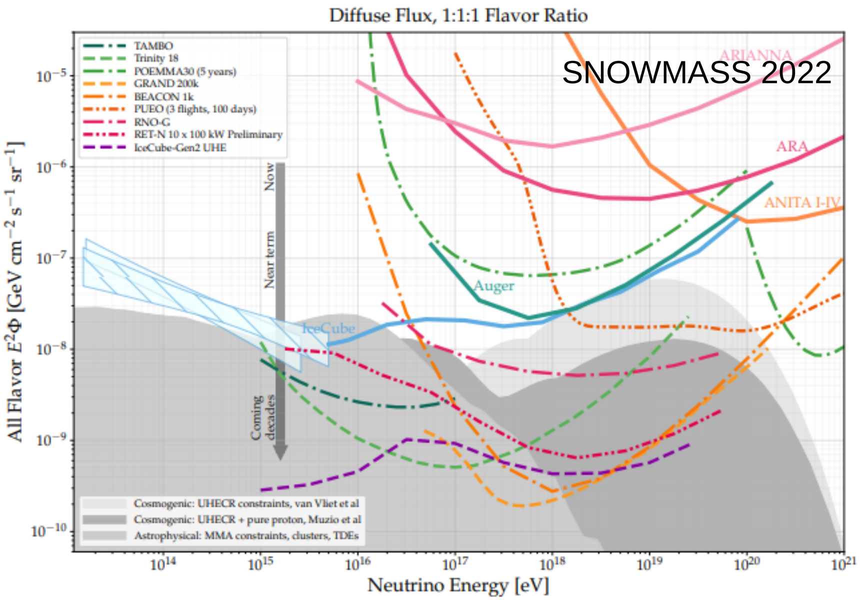
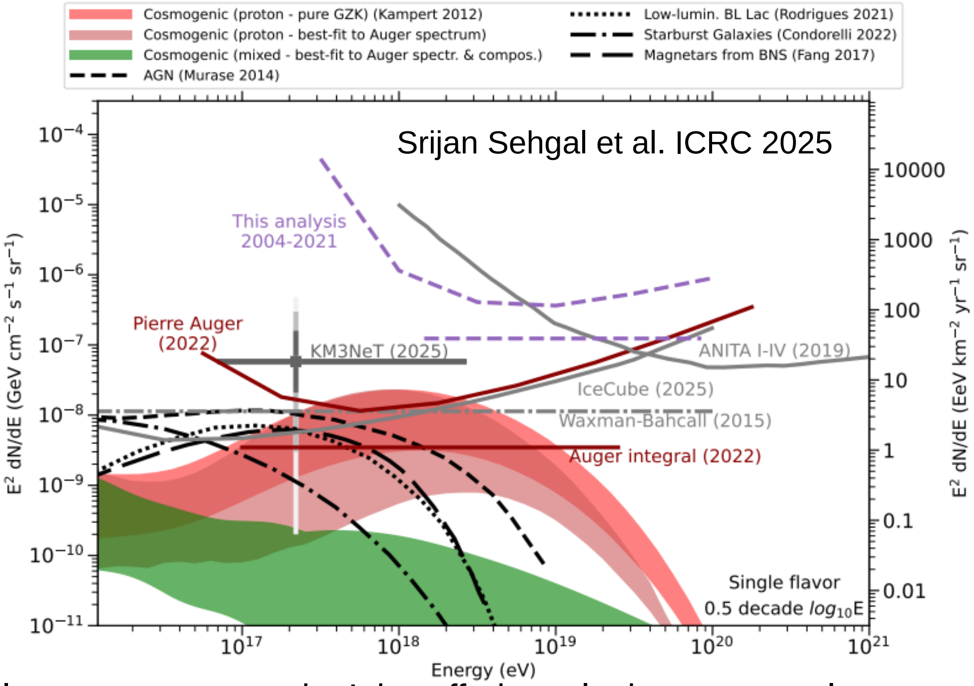
Overview of the Next-Generation Radio Detection Schemes for Ultra-High-Energy Neutrinos

Chao Zhang
Nanjing University

Workshop on Neutrinos and related
New Physics Research, NuPhyR
Zhuhai, 2025

State-of-the-art of UHE neutrino detection





IceCube has identified neutrinos at PeV energies, and faces financial pressure to upgrade. It is suffering a lot its poor angular resolution, but a 0.5° resolution has been obtained recently

KM3NeT has found event at 120 PeV, with expected neutrino energy around 220 PeV

AUGER has ruled out several neutrino models of cosmogenic neutrinos. It is now trying hard to detect inclined neutrino air shower by combining Radio and Surface detectors

GRANDprototype300 has found some CR candidates (self-trigger?), but it can not detect neutrino. Additionally, GRAND is facing great pressure due to its difficulty of deployment

ANITA has struggled a lot to identify the neutrino-like events they have discovered

...

New projects have been proposed

First, why Radio?

- Excellent resolution:

  angular: ~ 0.1°

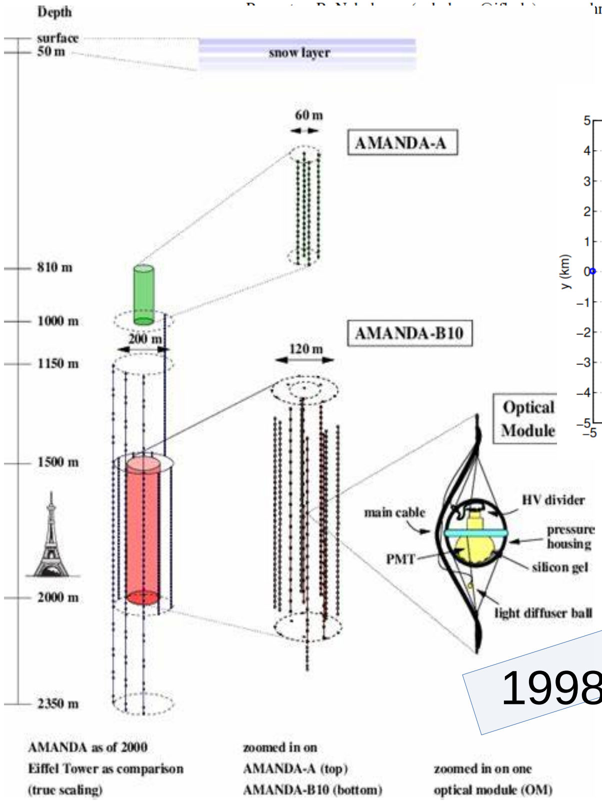
  Mass decomposition: X_{max} ~ 10 g/cm^2 or even better

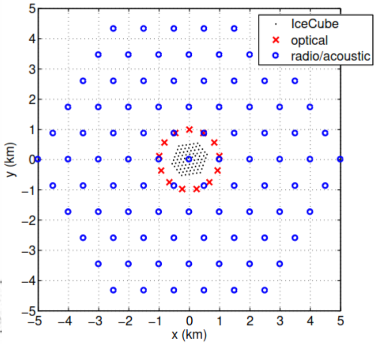
  Energy reconstruction: 10-20%
- 100% duty cycle
- Much lower cost
- Convenient to extend to large scale

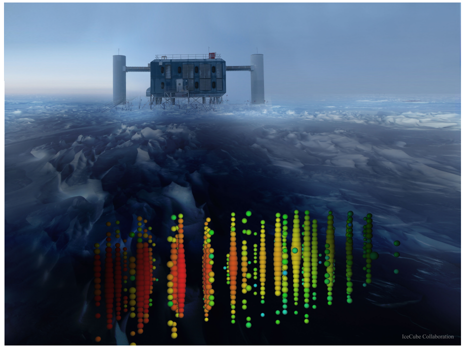
Example:
IceCube evolution in ~3 decades

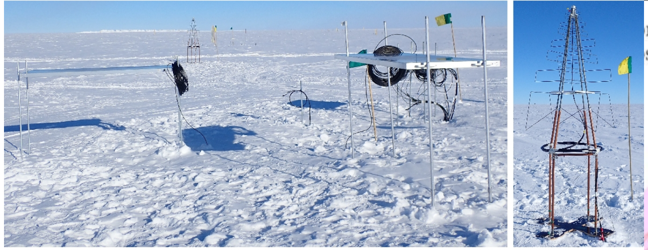
Simulation of a Hybrid Optical/Radio/Acoustic Extension to IceCube for EeV Neutrino Detection

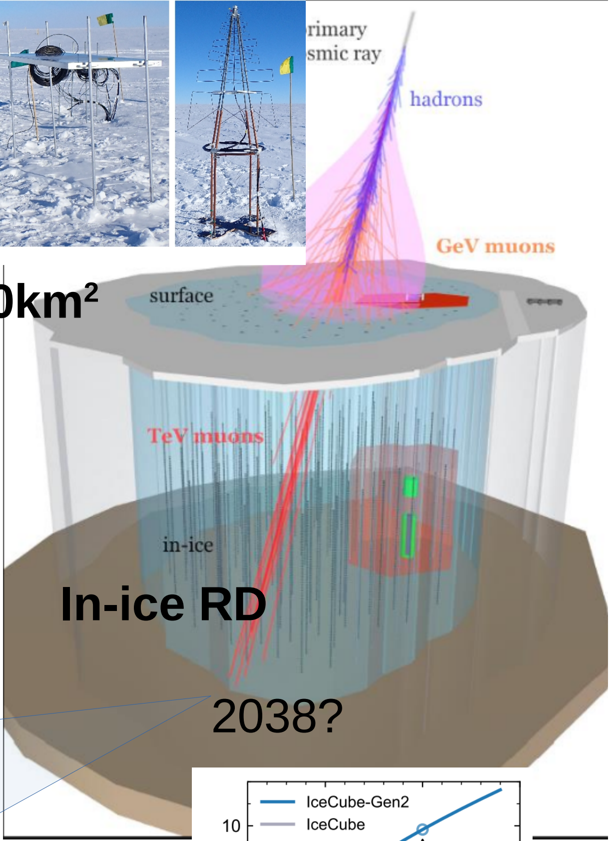
D. Besson[a], S. Böser[b], R. Nahnhauer[b], P.B. Price[c], and J. A. Vandenbroucke[c] for the IceCube Collaboration
(a) Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045-2151, USA
(b) DESY, D-15738 Zeuthen, Germany
(c) Dept. of Physics, University of California, Berkeley, CA 94720, USA











SD+RD 500km^2

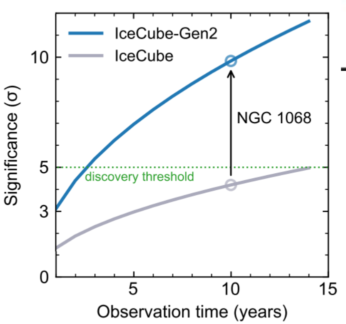
In-ice RD

2038?

2024

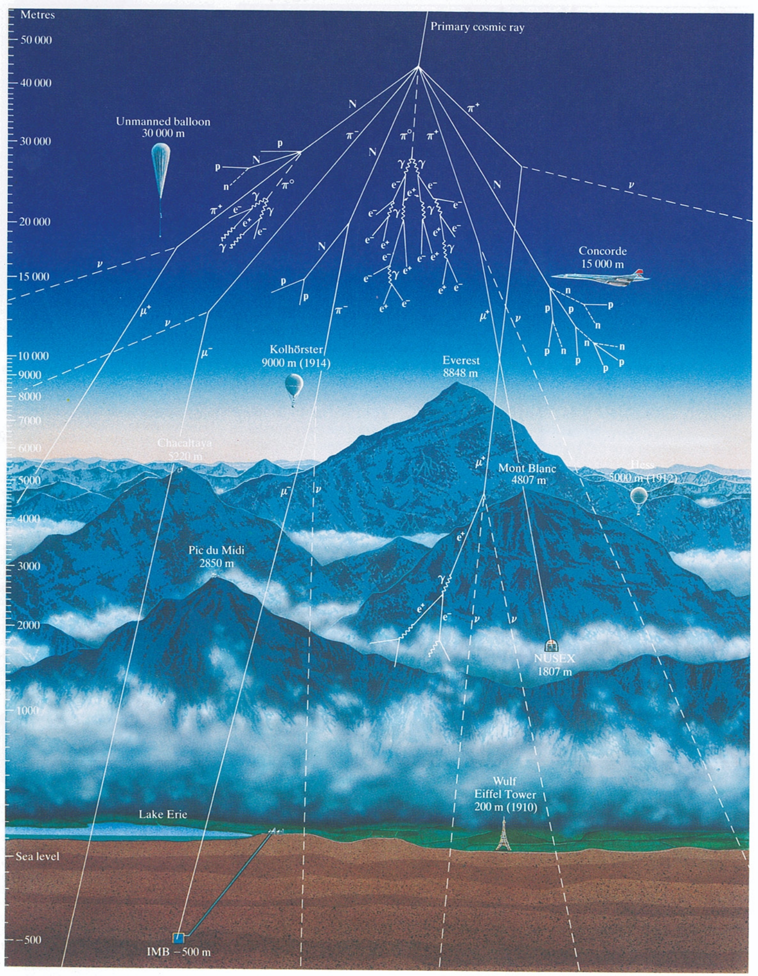
2005

1998

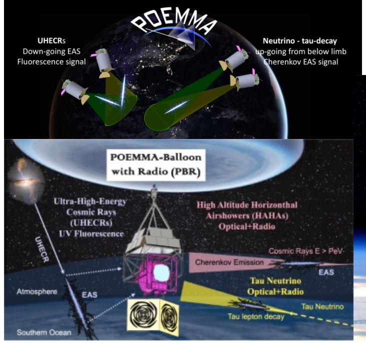


- Optical Cherenkov detection 10^{14} eV to 10^{18} eV.
- Radio efforts: neutrino fluxes > 10^{16} eV.
- Acoustic detection efforts are at an earlier stage

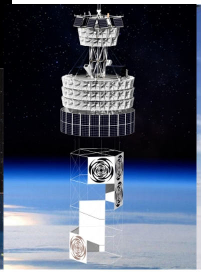
Ongoing radio projects
on earth



By Sebastián Martín Ruiz

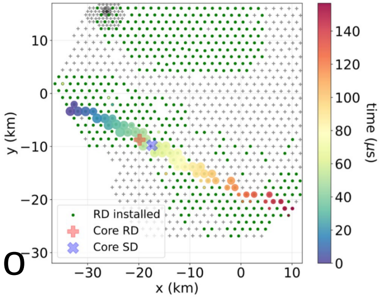


PUEO



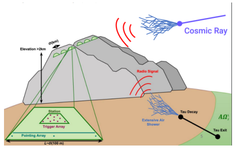
ANITA

AUGER Prime



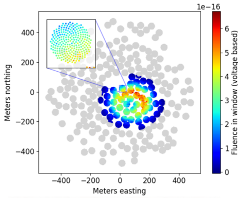
TAROGE

BEACON

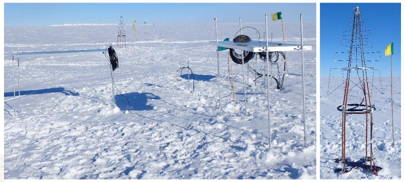


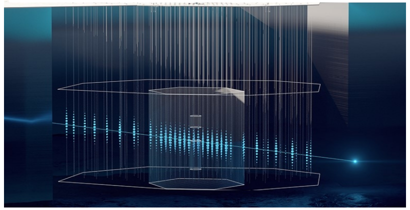
GRAND

SKA-Low

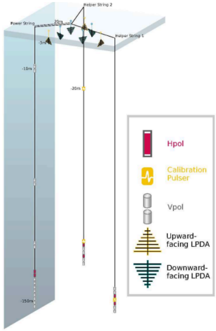


IceCube-Gen2 Radio





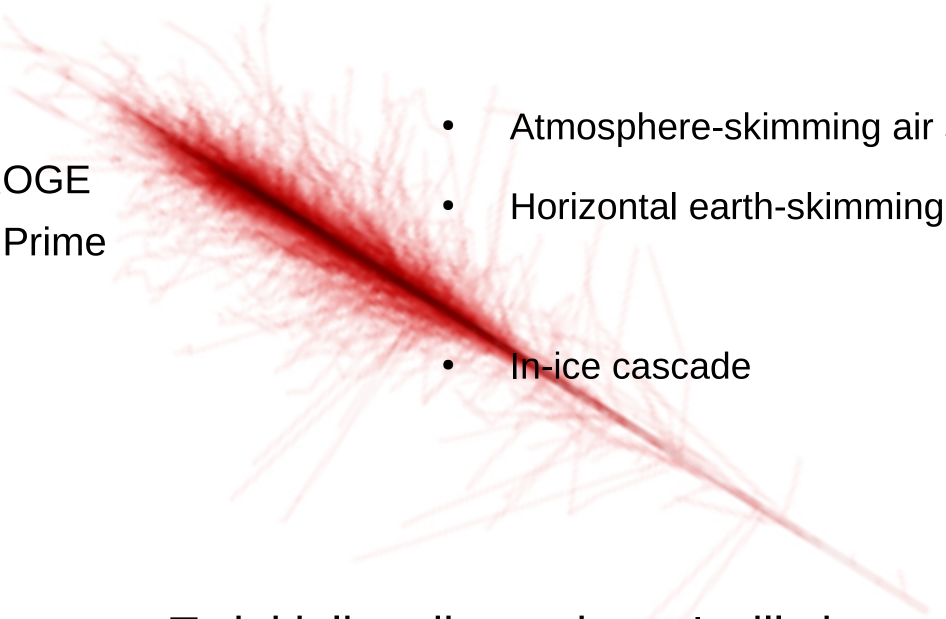
RNO-G



ANDIAMO

Radio experiments and air shower geometry

- High altitude：
  Radio + Optical: POEMMA
  Ballon-borne Radio: ANITA, PUEO
- Ground + mountain:
  Pure radio: BEACON, GRAND, TAROGE
  Radio + Cherenkov + e^+e^-: AUGER Prime
- In ice
  RNO-G, IceCube-Gen2, ARA.
  ...
- In permafrost（冻土层） ...
- On Moon, Jupiter...



- Upward-going air showers
- Atmosphere-skimming air showers
- Horizontal earth-skimming air showers
- In-ice cascade

To initialize discussions, I will show the recent achievements in several of these experiments.

Simulation and analyzing tools

Radio simulation tools

READY for neutrino air showers/cascades

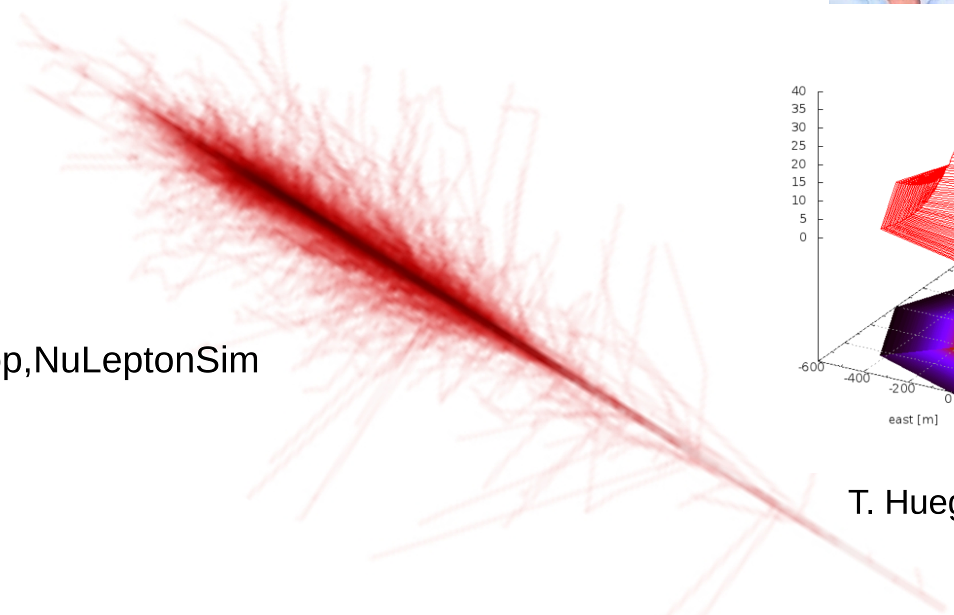
Macroscopic approach	**Microscopic approach**
EVA	ZHAireS-RASPASS
MGMR	**CORSIKA/CoREAS (>77550)**
	+ CORSIKA 8 Radio
SELFAS	nuRadioMC
	nuSpaceSim
	SMIET
	RadioMorphing

Other tools:

Tau generators:
NuTauSim,DANTON, nuPyProp,NuLeptonSim

Event reconstruction:
NuRadioReco, GRANDlib...

Electric field reconstruction:
Kewen's method



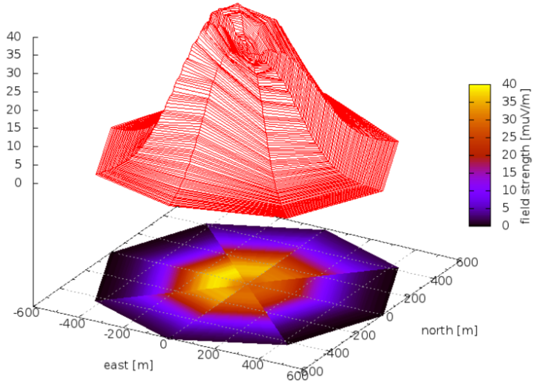
Radio emission from cosmic ray air showers

Monte Carlo simulations

T. Huege[1] and H. Falcke[1,2,3]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Radio Observatory, ASTRON, Dwingeloo, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands
[3] Adjunct Professor, Dept. of Astronomy, University of Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands

Received August 20, 2004; accepted October 10, 2004

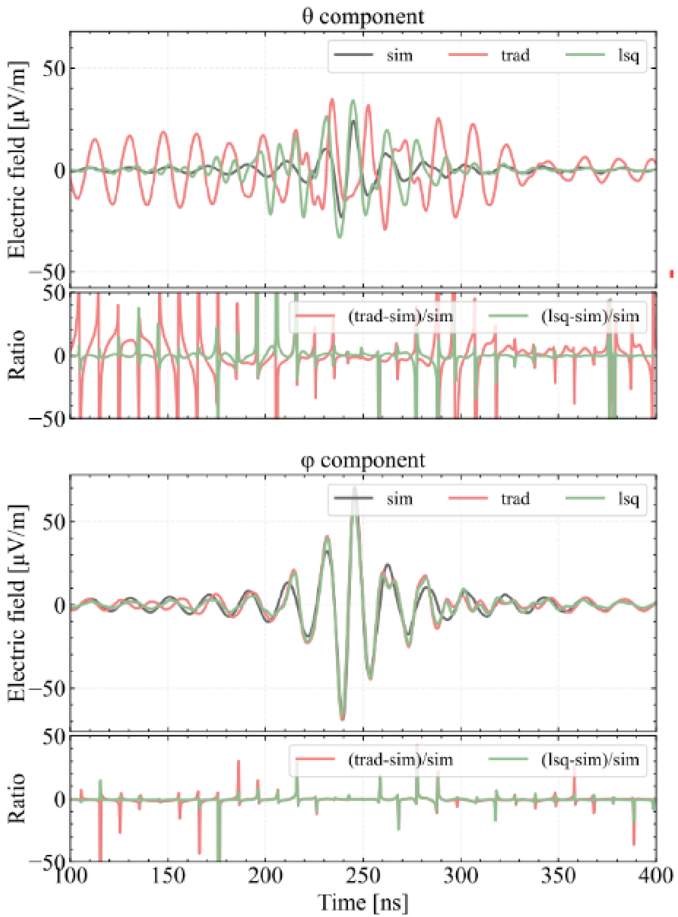


43 – 74 MHz

T. Huege et al., ARENA2012

Example: New Electric field reconstruction

(1st step in radio analysis)

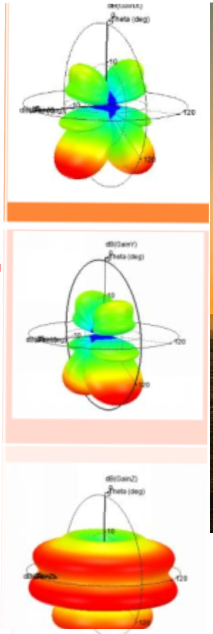


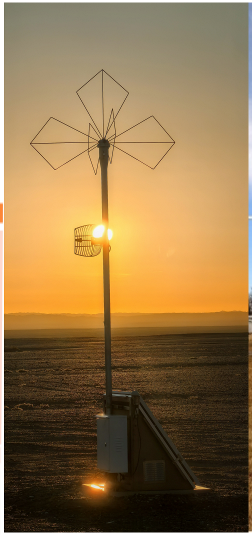
$$\begin{pmatrix} \mathcal{V}_1(f) \\ \mathcal{V}_2(f) \\ \cdots \\ \mathcal{V}_n(f) \end{pmatrix} = \begin{pmatrix} \mathcal{H}_1^\theta(f) & \mathcal{H}_1^\phi(f) \\ \mathcal{H}_2^\theta(f) & \mathcal{H}_2^\phi(f) \\ \cdots & \\ \mathcal{H}_n^\theta(f) & \mathcal{H}_n^\phi(f) \end{pmatrix} \begin{pmatrix} \mathcal{E}^\theta(f) \\ \mathcal{E}^\phi(f) \end{pmatrix}$$

+ Noise

tions is then solved for $\mathcal{E}^{\theta,\phi}$. Due to the typical noise contribution on measured waveforms, there is no perfect solution. Hence, we determine the electric field values

Christian Glaser et al.
Eur. Phys. J. C 2019



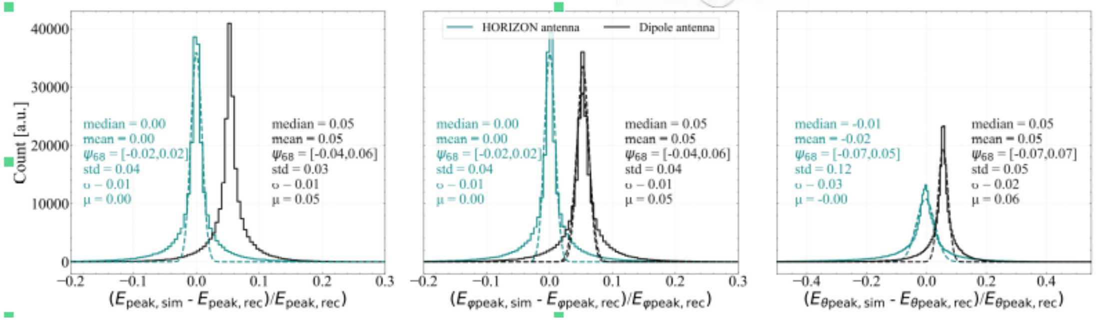


A generic analytical solution

$$\nabla_{\mathcal{E}}\chi^2 = -2(\mathcal{H}^T\sigma_V^{-1}\mathcal{V} - \mathcal{H}^T\sigma_V^{-1}\mathcal{H}\mathcal{E}) = 0$$

We get an analytical solution of electric field:

$$\mathcal{E} = (\mathcal{H}^T\sigma_V^{-1}\mathcal{H})^{-1}\mathcal{H}^T\sigma_V^{-1}\mathcal{V}$$



Kewen Zhang, Chao Zhang, Yi Zhang et al. JCAP 2025

This allows to extract radio signal of UHE particle from complicated bkg.

Radio Emission Mechanisms

Previous description of radio emissions in all the radio papers

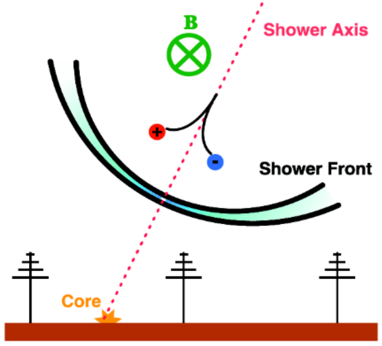
依靠这两个效应
首次精确解释
实验数据

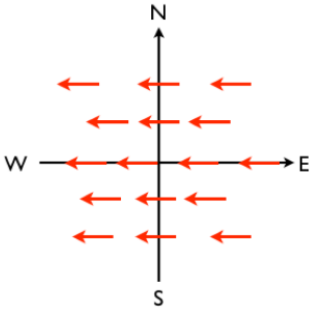
射电领域所有博士论
文第一章的经典描述

Geomagnetic

Transverse current

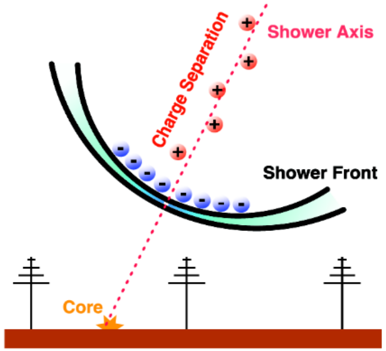
Dominates in
high air density

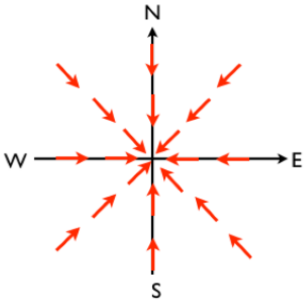




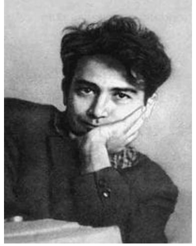
Askaryan

Dominates in
dense media





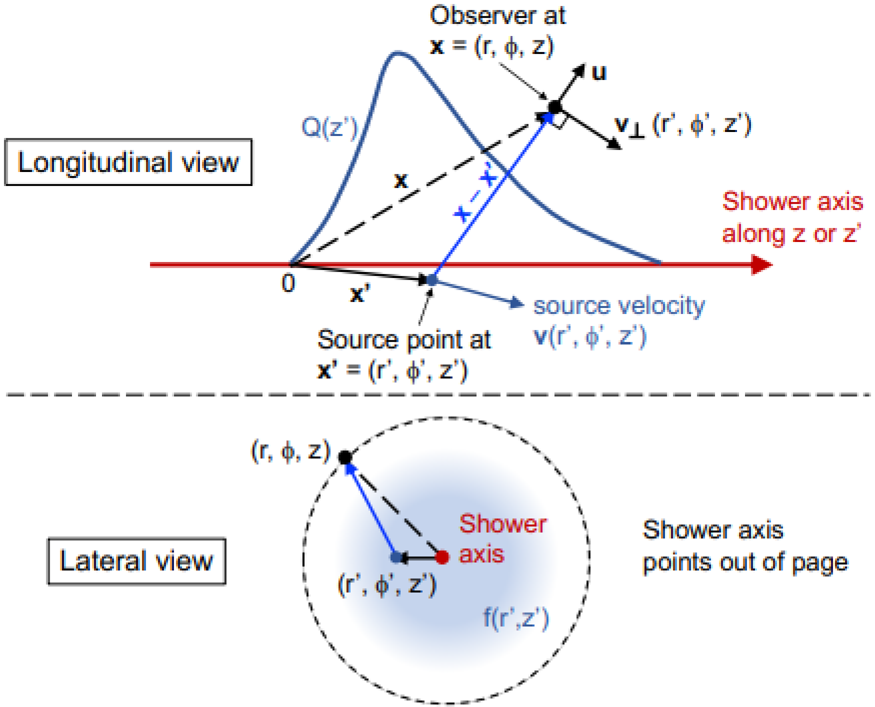
Askaryan Effect



1. In dense dielectric material
2. A negative charge asymmetry due to Compton scattering and positron annihilation.

- $v > v_c$
- When λ < 0.1 m, radiation destructively interferes.

When λ > 0.1 m, coherent radiation, the shower can be approximated as a point charge



Cherenkov Cone: $\theta = \arccos(1/n\beta)$

Broad band from 200 MHz to 1.2 GHz,

Detectable at peak frequency ~ 1 GHz

$$\mathbf{A}(\mathbf{x},t) = \frac{\mu}{4\pi}\int_{-\infty}^{\infty} dt' \int_{-\infty}^{\infty} dz' Q(z')\,\delta(z' - vt')$$
$$\int_0^{\infty} dr' r' \int_0^{2\pi} d\phi' f(r',z')\,\mathbf{v}_{\perp}(r',\phi',z')$$
$$\frac{\delta\left(n|\mathbf{x}-\mathbf{x}'|/c - (t-t')\right)}{|\mathbf{x}-\mathbf{x}'|},$$

SOVIET PHYSICS JETP VOLUME 14, NUMBER 2 FEBRUARY, 1962

EXCESS NEGATIVE CHARGE OF AN ELECTRON-PHOTON SHOWER AND ITS COHERENT RADIO EMISSION

G. A. ASKAR'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 24, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 616-618 (August, 1961)

We investigate the excess of electrons in an electron-photon shower. This excess is caused by annihilation of the positrons in flight and by the Compton and δ -electrons in the cascade. It is shown that at the maximum of the shower the excess may comprise ten percent of the total number of shower particles. The Cerenkov radiation from this excess charge in a dense medium is estimated. It is indicated that this radio emission from showers produced by high-energy accelerator particles or cosmic rays in blocks of dense matter can be recorded and used. The possibility of recording radio waves from penetrating particle showers in the moon's ground, by apparatus dropped on the lunar surface, and in underground layers on the Earth in which radio waves can propagate, is also noted.

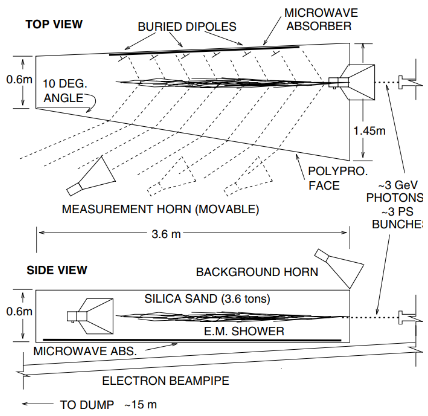
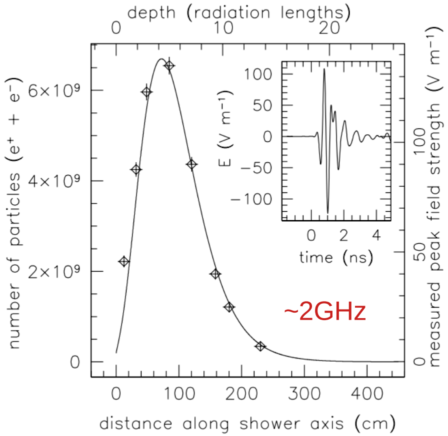


FIG. 1. Sectional views of the target geometry.



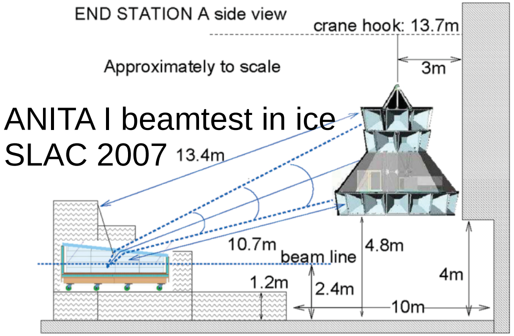
VOLUME 86, NUMBER 13 PHYSICAL REVIEW LETTERS 26 MARCH 2001

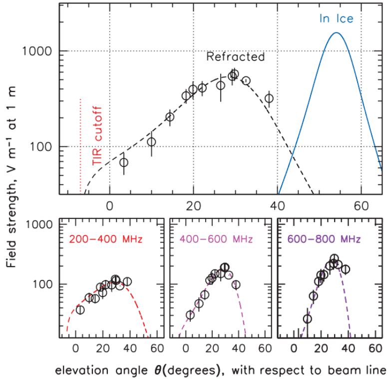
Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High-Energy Particle Cascades

David Saltzberg,[1] Peter Gorham,[2] Dieter Walz,[3] Clive Field,[3] Richard Iverson,[3] Allen Odian,[3] George Resch,[2] Paul Schoessow,[4] and Dawn Williams[1]

[1]Department of Physics and Astronomy, University of California, Los Angeles, California 90095
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109
[3]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
[4]Argonne National Laboratory, Argonne, Illinois 60439

(Received 2 November 2000)





PRL **99**, 171101 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

Observations of the Askaryan Effect in Ice

P. W. Gorham,[1] S. W. Barwick,[2] J. J. Beatty,[3] D. Z. Besson,[4] W. R. Binns,[5] C. Chen,[6] P. Chen,[6] J. M. Clem,[7] A. Connolly,[8] P. F. Dowkontt,[5] M. A. DuVernois,[9] R. C. Field,[6] D. Goldstein,[2] A. Goodhue,[8] C. Hast,[6] C. L. Hebert,[1] S. Hoover,[8] M. H. Israel,[5] J. Kowalski,[1] J. G. Learned,[1] K. M. Liewer,[10] J. T. Link,[1,11] E. Lusczek,[9] S. Matsuno,[1] B. Mercurio,[3] C. Miki,[1] P. Miočinović,[1] J. Nam,[2] C. J. Naudet,[10] J. Ng,[6] R. Nichol,[3] K. Palladino,[3] K. Reil,[6] A. Romero-Wolf,[1] M. Rosen,[1] L. Ruckman,[1] D. Saltzberg,[8] D. Seckel,[7] G. S. Varner,[1] D. Walz,[6] and F. Wu[2]

(ANITA Collaboration)

Radio detection timeline

2001
Evidence of
Askaryan
effect

ANITA
LOPES
LOFAR
ARIANNA
AERA
ARA
LOFAR
Tunka-RX
POEMMA
SKA-Low
GRAND
IceCube-Gen2
RNO-G
Beacon
PUEO
AUGERPrime

GNO
AURA
TREND
Yakutsk
CROME
TAROGE
MIDAS
AMBER
NuMoon
LORD
...

1911
HESS
(Cosmic
Ray)
(诺奖)

1946
Blackett （诺奖）
and Lovell
(First Radio
detection)

Manchester (UK),
Moscow (USSR),
Haverah Park (UK),
Medicina (Italy),
Penticton (Canada),
Chacaltaya (Bolivia),
...

1991
AGASA
首个低频
射电探测
实验

2005
LOPES
CODALEMA
(1st Precise Measurement!)

Absence of contribution from China

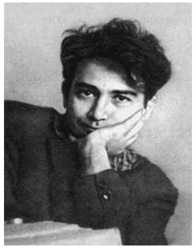
1894
Heltz
EM wave

1947
Magnetic
field effect
朱洪元
(Hung-yuan Tzu)

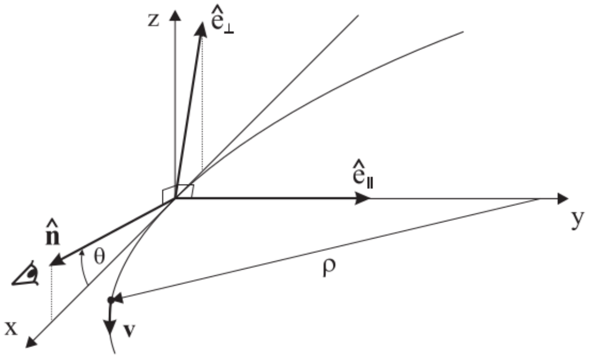
1962
Askaryan Effect (prediction)

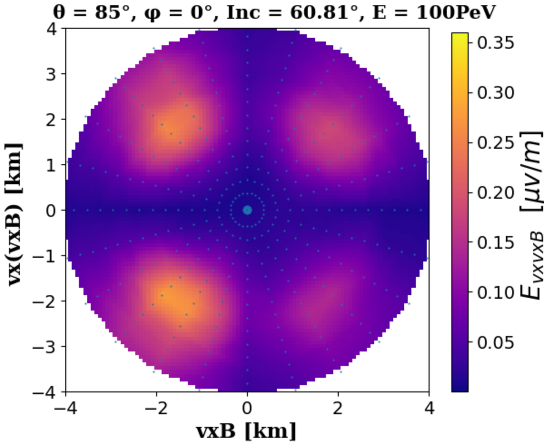
1965
D. Kahn
I. Lerche
Transverse current Effect
预测

No new theory



Synchrotron Radiation

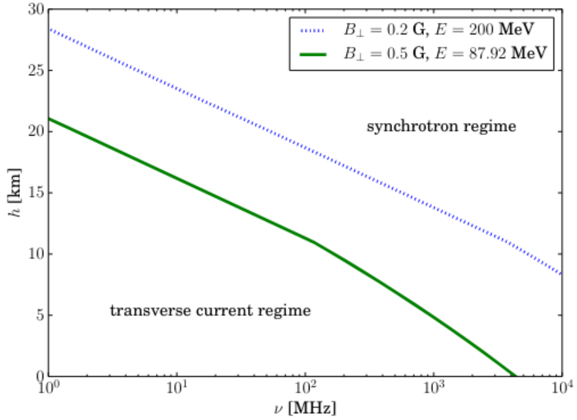




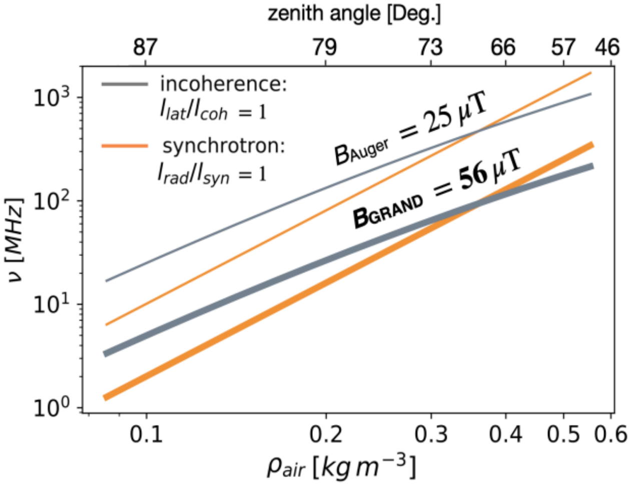
First evidence in CoREAS
(Chao Zhang. Tim Huege 2021)

1. Expected to be only in GHz.
2. Does not exist in vertical air showers (all the previous experiments).

3. Appears ~ 100 MHz in low air density + Strong B field (recent progress).
4. Need experimental evidence.



Clancy James PRD Jan. 2022



S.Chiche,C.Zhang et al. PRL 2024

A complete scenario of radio emission from air shower

Geomagnetic

Geosynchrotron-like

Dominates in low air density and strong B

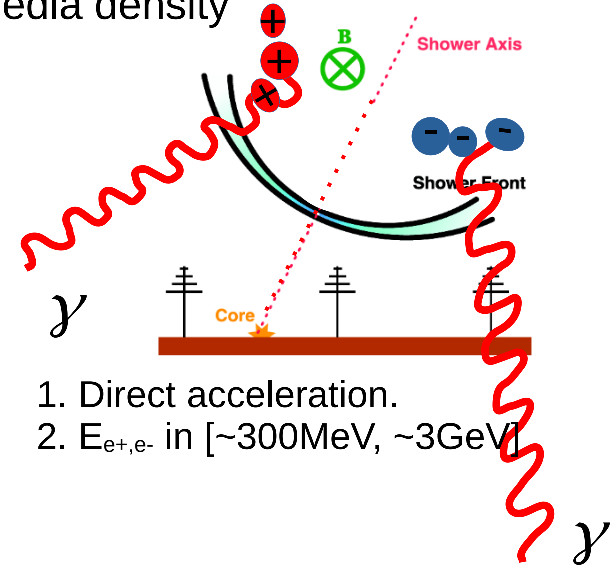
Transverse current

Dominates in high air density

Askaryan

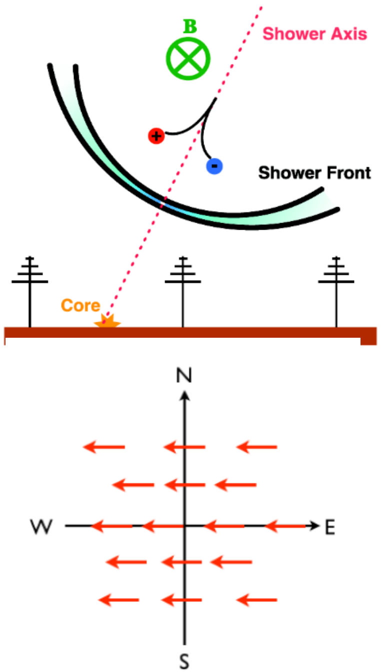
Dominates in dense media

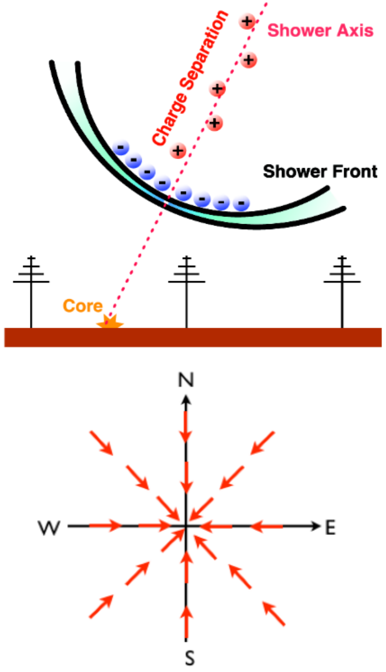
low media density → high media density



1. Direct acceleration.
2. $E_{e+,e-}$ in [~300MeV, ~3GeV]

第三种基本机制





For more details, See: S. Chiche, C. Zhang et al. PRL 2024

Radio Timeline

Experiments

1911 HESS
Cosmic Ray
（诺奖）

1946
Blackett
（诺奖）and
Lovell
First Radio
detection

- Manchester (UK),
  Moscow (USSR),
  Haverah Park (UK),
  Medicina (Italy),
  Penticton (Canada),
  Chacaltaya (Bolivia),
- etc

2002
Evidence of Askaryan effect

No progress
In experiments !

2005
LOPES
CODALEMA
(1st precise measurement!)

ANITA
LOPES
LOFAR
ARIANNA
AERA
ARA
LOFAR
Tunka-RX
POEMMA
SKA-LOW
GRAND
IceCube-Gen2
RNO-G
Beacon
PUEO
AUGERPrime

GNO
AURA
TREND
Yakutsk
CROME
TAROGE
MIDAS
AMBER
NuMoon
LORD
...

Analog epoch

Digital epoch

Renaissance !

1894
Heltz
EM wave

1947
Magnetic field
effect

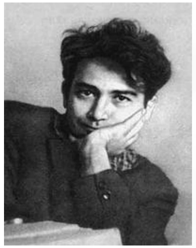
朱洪元 and
Blackett

1962
Askaryan Effect (prediction)

1965
D. Kahn
I. Lerche
Transverse current Effect (prediction)

No new theory !

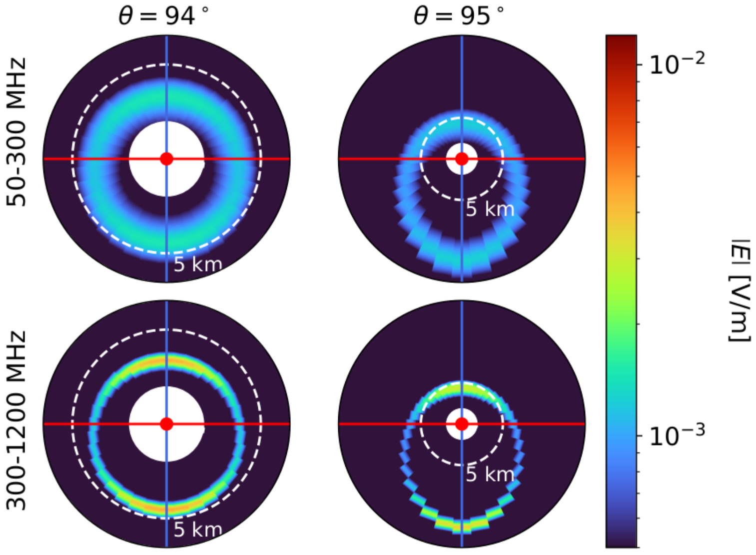
2021
Geosynchrotron radiation
地球同步辐射效应
(prediction)

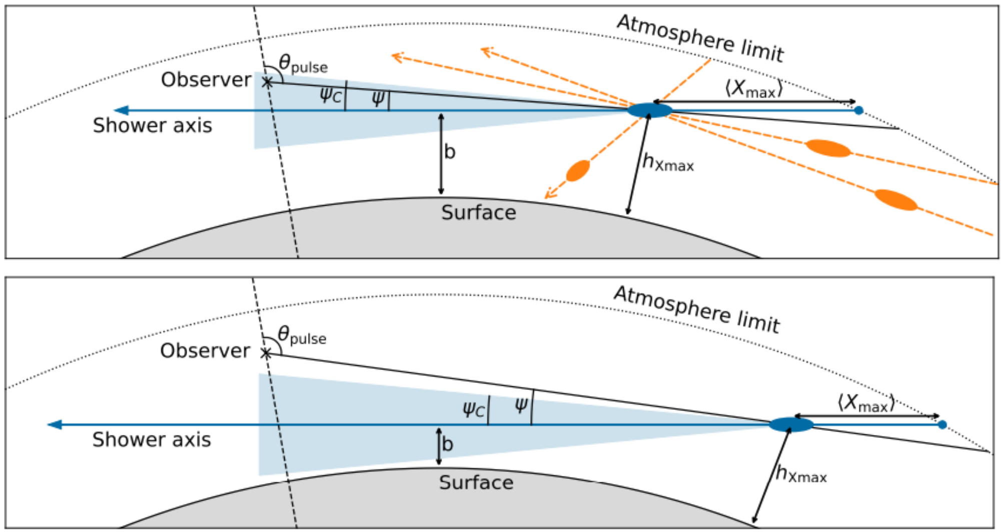


Mechanisms

17

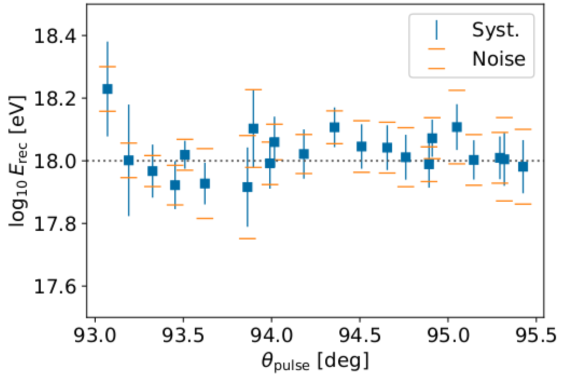
Impact of geosynchrotron radiation in atmosphere skimming air showers

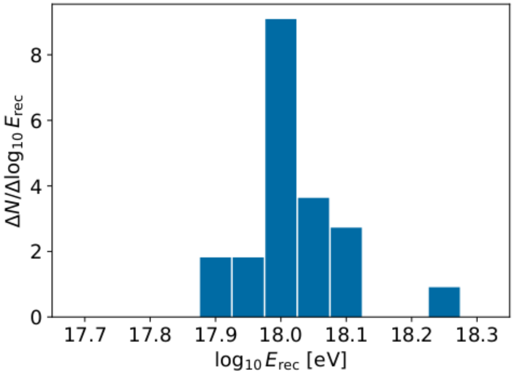




Refractive asymmetry radio core shifted from shower axis. Similar to the very inclined air showers in AUGER!

S. C.-Freire et al. ICRC 2025





Energy resolution: ~ 20%

Set the basis of energy reconstruction for PUEO, ANITA, and POEMMA-ballon with radio.

Another application in the energy reconstruction of inclined air showers

$$S^{\rho}_{\mathrm{RD}} = \frac{E_{\mathrm{rad}}}{a'(\rho_{X_{\max}})^2 + (1 - a'(\rho_{X_{\max}})^2)\sin^2\alpha \left(\frac{B_{\mathrm{Earth}}}{0.243\,\mathrm{G}}\right)^{1.8}} \frac{1}{(1 - p_0 + p_0 \exp[p_1(\rho_{X_{\max}} - \langle\rho\rangle)])^2} \tag{5.4}$$

with

$$a'(\rho_{X_{\max}}) = a(\rho_{X_{\max}})/(B_{\mathrm{Earth}}/0.243\,\mathrm{G})^{0.9} \tag{5.5}$$

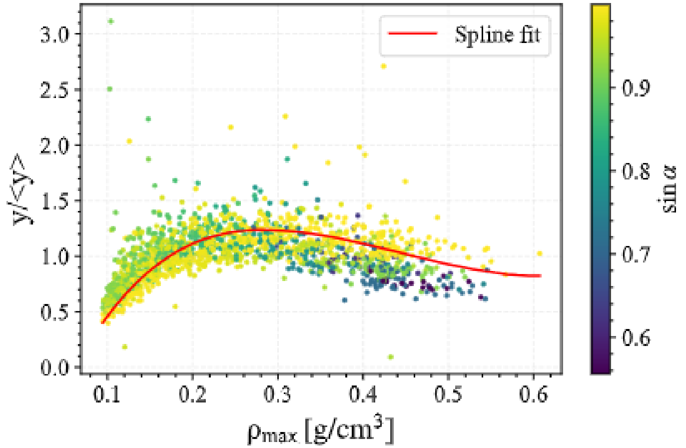
C. Glaser JCAP 2016

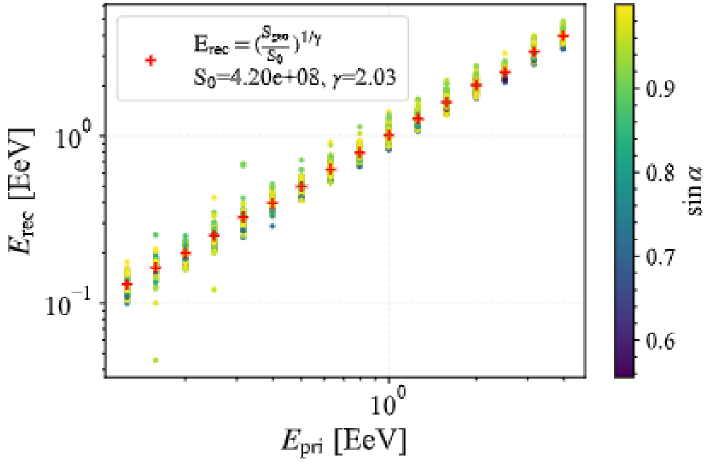
$$S_{\mathrm{geo}} = \frac{E_{\mathrm{geo}}}{\sin\alpha} \cdot \frac{1}{f(\rho_{\max})}$$

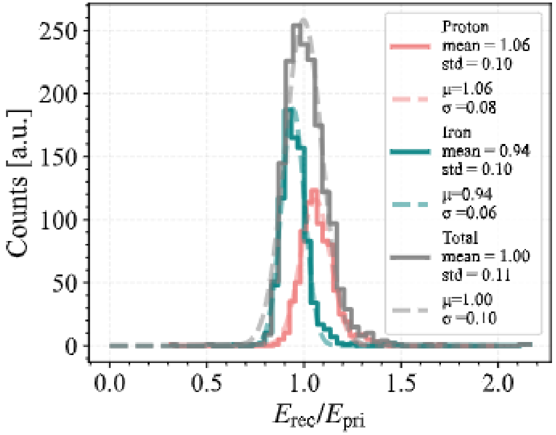
$$E_{\mathrm{rec}} = \left(\frac{S_{\mathrm{geo}}}{S_0}\right)^{1/\gamma}$$

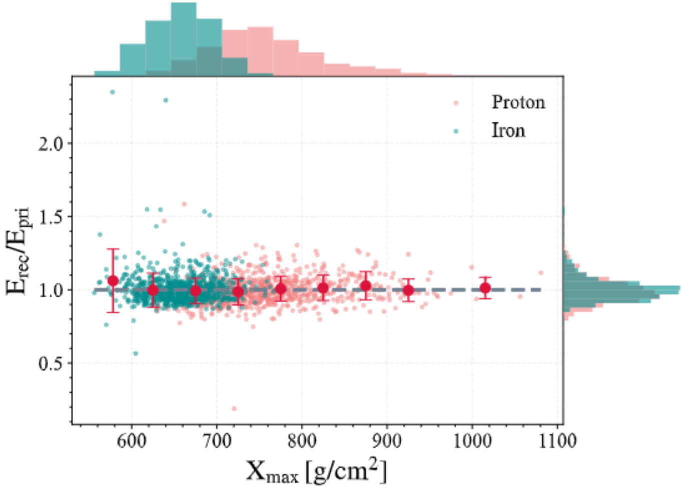
New air density Correction factor due to geosynchrotron radiation

Kewen Zhang, C. Zhang et al.
Arxiv: 2507.17266



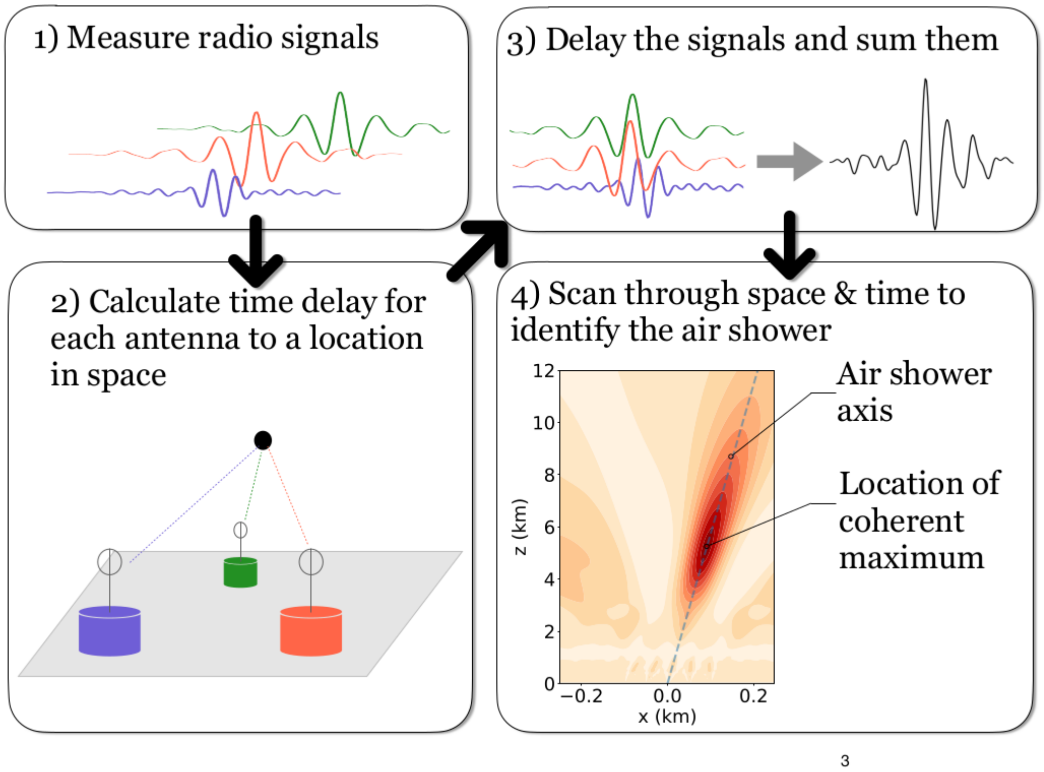


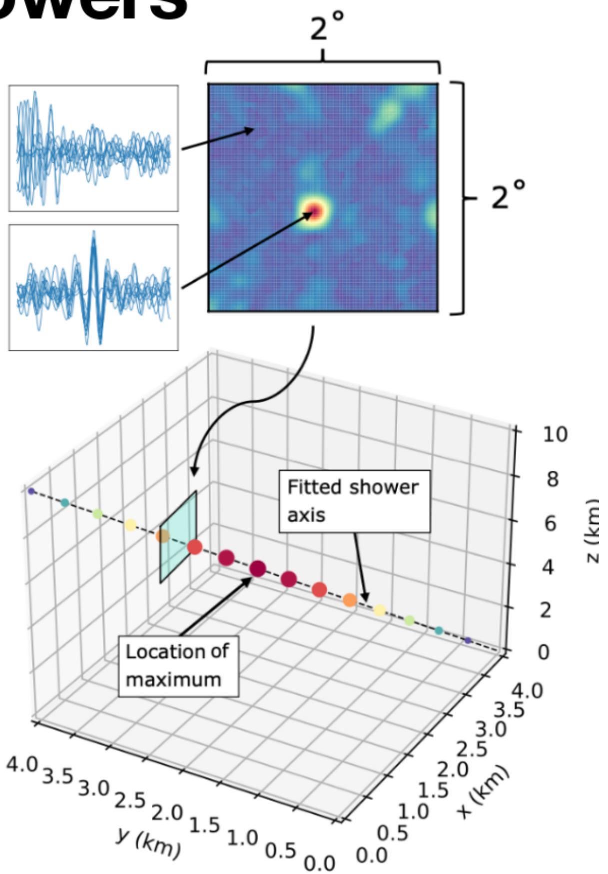




Interferometric Beamforming and other triggering techniques

Inteferometry applied to air showers



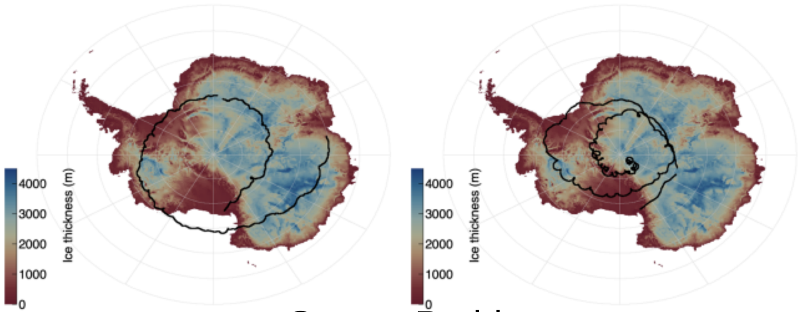


Pim van Dillen et al. ICRC 2025

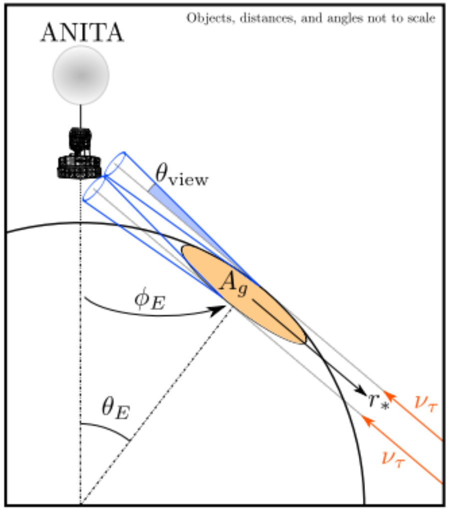
Beamforming:
Increase SNR by a factor of $\sqrt{N_{antenna}}$, decrease significantly the energy threshold

5148 inclined air showers observed on AERA @AUGER

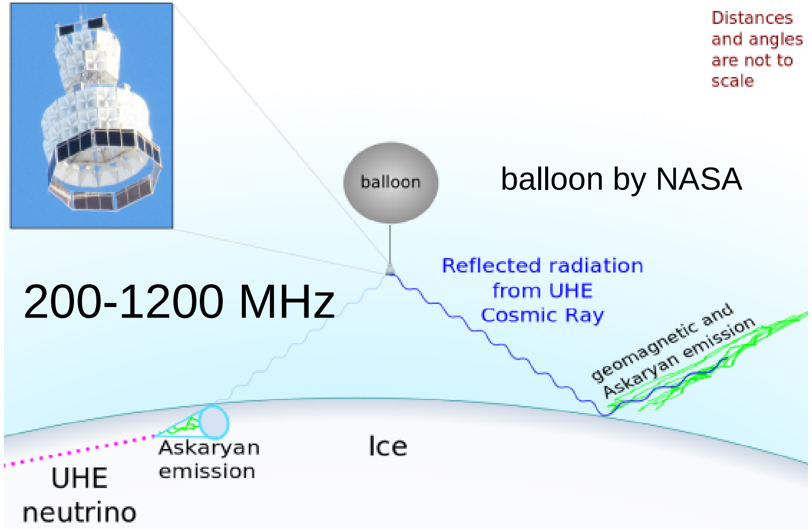
ANITA



Steven Prohira
Arxiv: 1903.11043

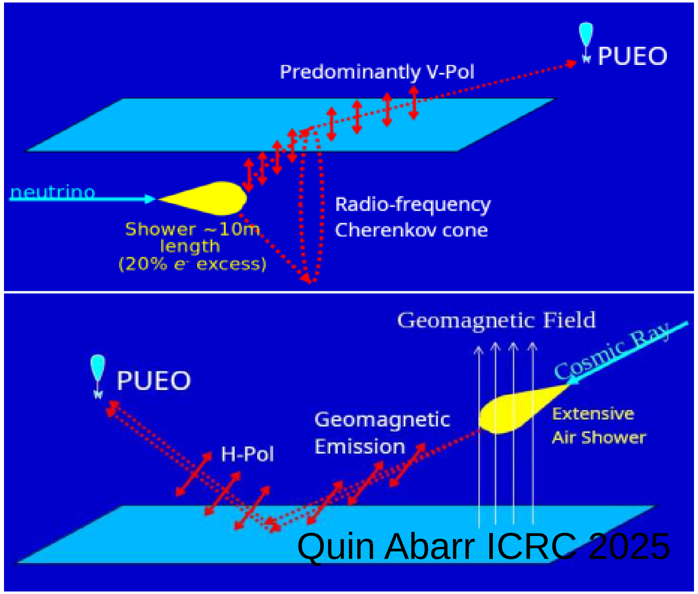


Arxiv: 2112.07069



Astropart. Phys. 77 (2016) 32-43

To detect neutrinos through the Askaryan effect in ice
To detect cosmic rays through geomagnetic effect

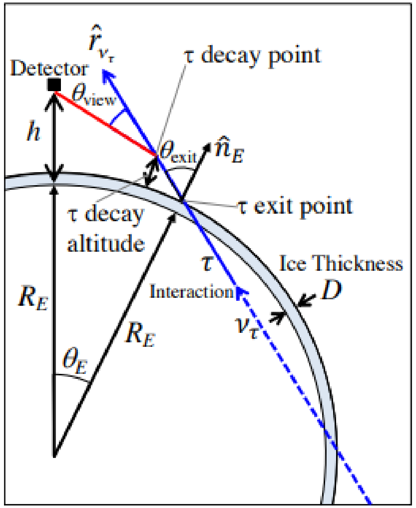


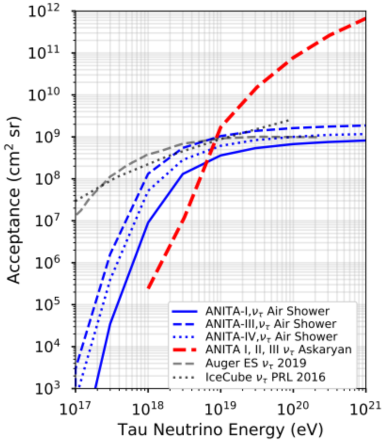
Quin Abarr ICRC 2025

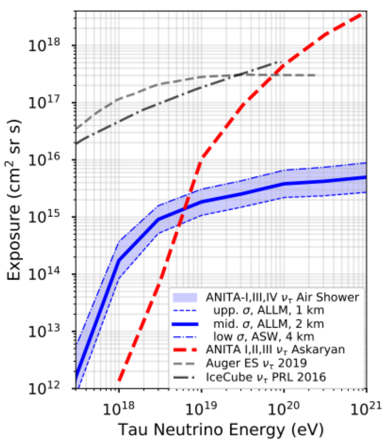
Radio signal:
Vertically polarized
 for neutrino

Horizontally polarized
For CR.

Complicated noise sources:
galactic+solar+k T_{ice}
Anthropogenic
(satellite or ground-based activities)
Electronic noise.







Stephanie Wissel, ICRC 2019

Arxiv:1903.11043

FEATURED IN PHYSICS | EDITORS' SUGGESTION

Observation of an Unusual Upward-Going Cosmic-Ray-like Event in the Third Flight of ANITA

P. W. Gorham[1], B. Rotter[1], P. Allison[2], O. Banerjee[2], L. Batten[3], J. J. Beatty[2], K. Bechtol[4], K. Belov[5], D. Z. Besson[6,7] *et al.*

Show more

Phys. Rev. Lett. **121**, 161102 – **Published 18 October, 2018**

DOI: https://doi.org/10.1103/PhysRevLett.121.161102

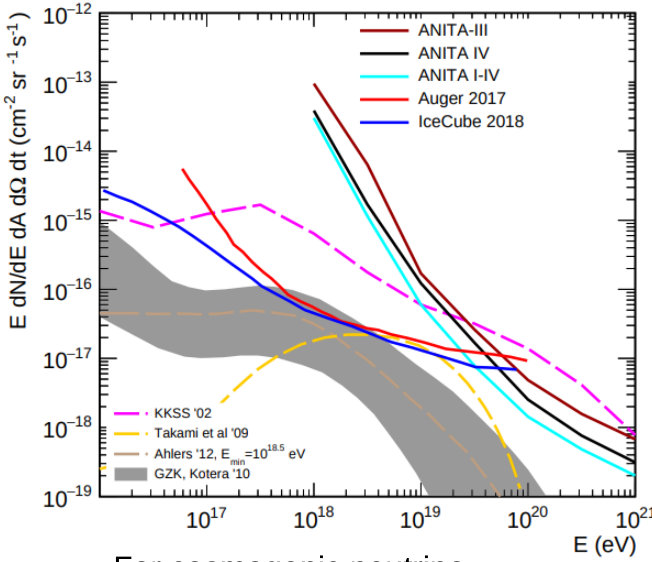
Characteristics of Four Upward-Pointing Cosmic-Ray-like Events Observed with ANITA

P. W. Gorham[1], J. Nam[2], A. Romero-Wolf[3], S. Hoover[4], P. Allison[5,6], O. Banerjee[5], J. J. Beatty[5,6], K. Belov[3], D. Z. Besson[7] *et al.* (ANITA Collaboration)

Show more

Phys. Rev. Lett. **117**, 071101 – **Published 8 August, 2016**

DOI: https://doi.org/10.1103/PhysRevLett.117.071101



For cosmogenic neutrino

L. Cremonesi et al. JINST 2019

Hard to identify:

~~1.an isotropic flux of tau neutrinos~~

~~2. sterile neutrinos and other feebly interacting particles~~

~~3. DM explanation~~

…

6 upward-going events discovered. None of them identified as neutrino

Flight (year)	Elevation angle	Shower energy
ANITA-I (2006)	-27.4° ± 0.3°	0.6 ± 0.4 EeV
ANITA-III (2014)	-35.0° ± 0.3°	0.56 $^{+0.3}_{-0.2}$ EeV
ANITA-IV (2016)	-6.17° ± 0.21°	1.5 ± 0.7 EeV
	-6.71° ± 0.20°	0.9 ± 0.5 EeV
~1° below horizon	-6.73° ± 0.20°	0.8 ± 0.3 EeV
	-6.12° ± 0.10°	3.9 ± 2.5 EeV

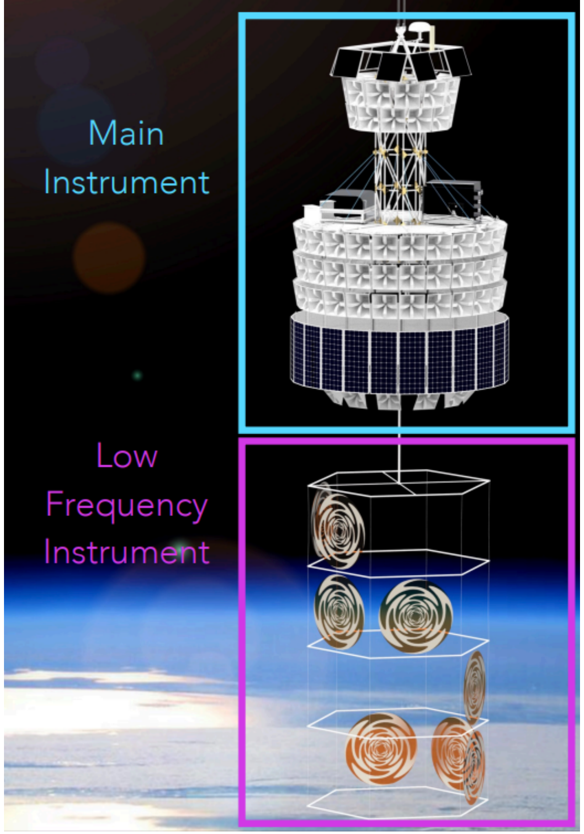
Summarized by Shih-Hao Wang

PUEO

Successor of ANITA

NASA program
To detect neutrino with E> 1EeV

2π acceptance
Phased-array trigger
Navigation system
Power system – omni PV
RF enclosure for all electronics （-80dB）
StarLink



96 antennas, 300-1200 MHz
8 antennas, 50-500 MHz

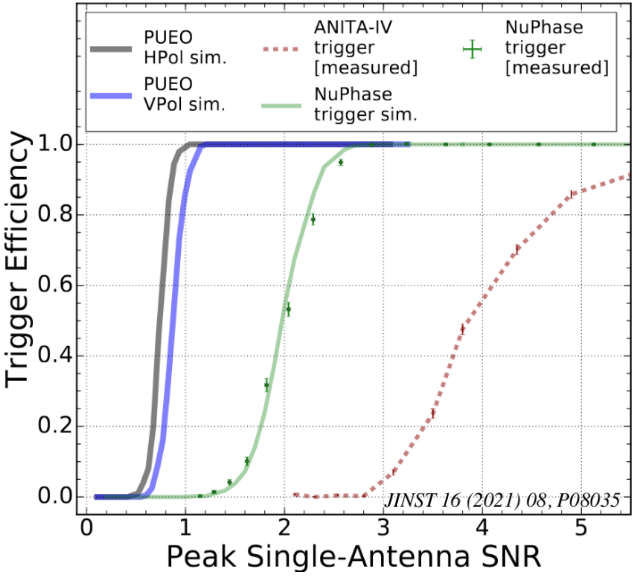
New achievements:

i) antenna size reduced by factor of ~2, so double number of antennas, and doubled collecting area at ~300 MHz.

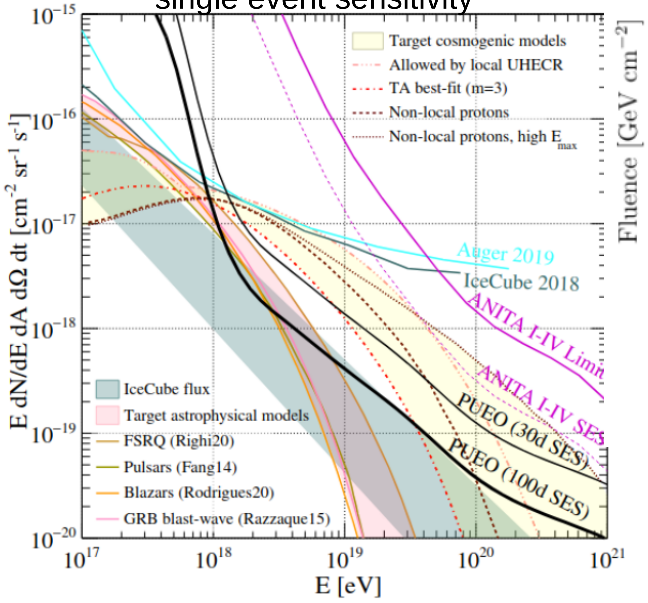
ii) adding low frequency antennas

iii) **interferometric phased array**, beamforming, improve SNR by a factor of 5, better trigger efficiency.

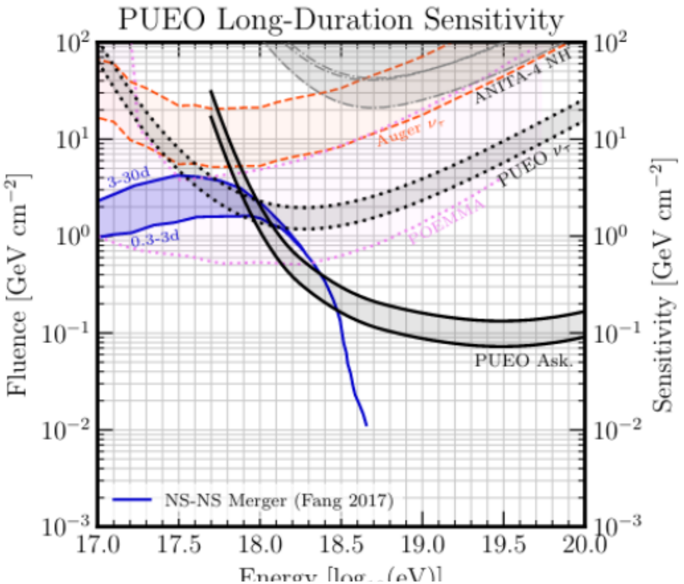
PUEO

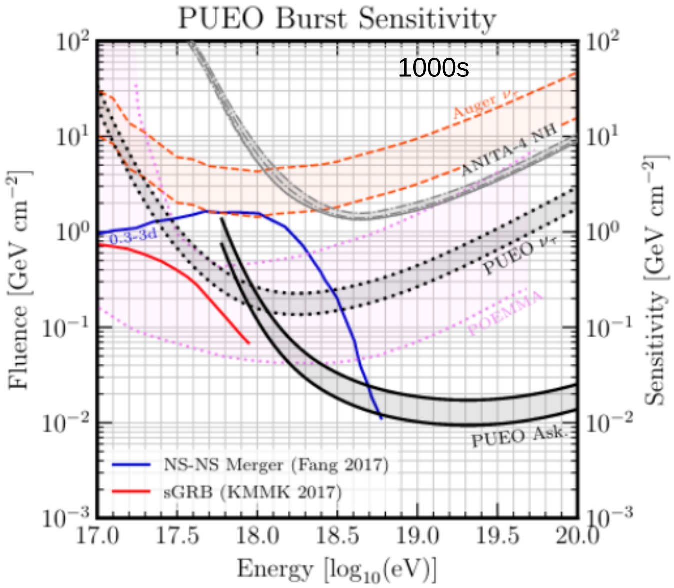


single event sensitivity



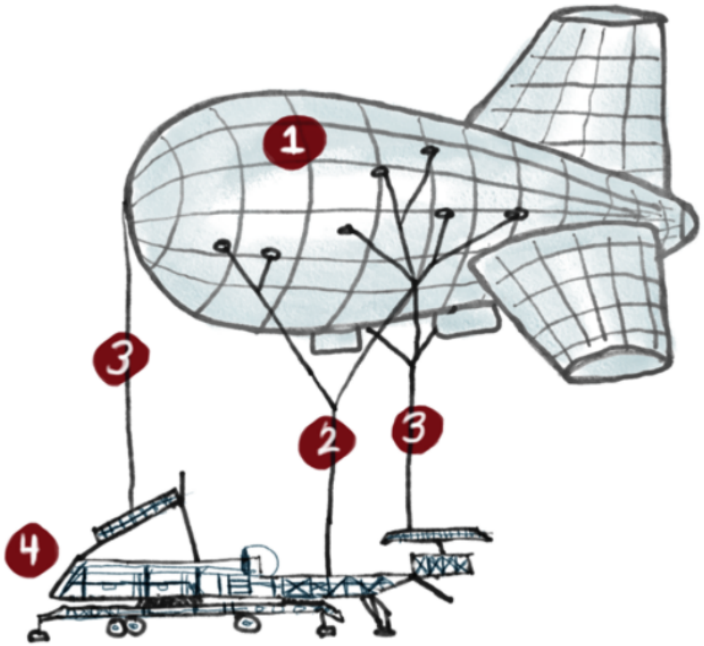
PUEO Collaboration white paper, JINST 2021





- Better triggering efficiency and sensitivities
- Long duration payload （60 days）
- Prepared to fly for 30 days, expecting lunch in December 2025
- 50 TB of data to be collected.

New idea：　Tethered Balloons



R. Scrandis, C. Deaconu, ARENA 2024

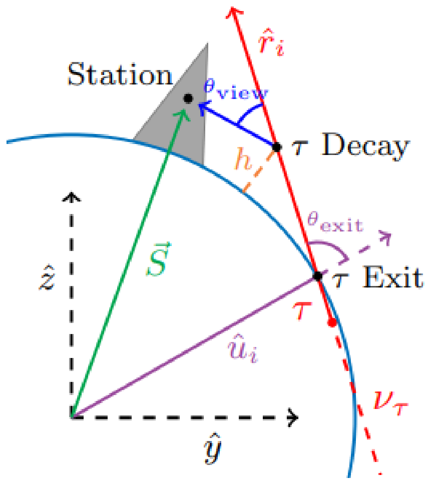
Altitude at 300m-20km
Carry ~300kg or less
Can be fixed from the ground, easy to mitigate the background noise, convenient to move and reuse.
Easily powered from the ground...

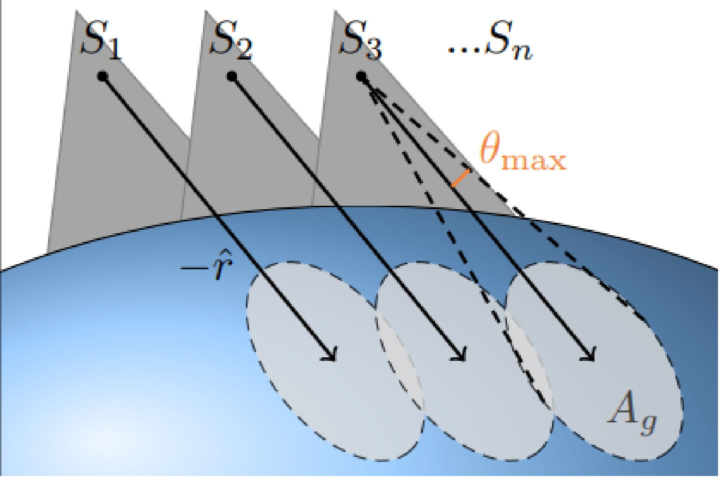
Much longer exposure time than ANITA, PUEO...
Much larger aperture than GRAND, IceCube and BEACON.

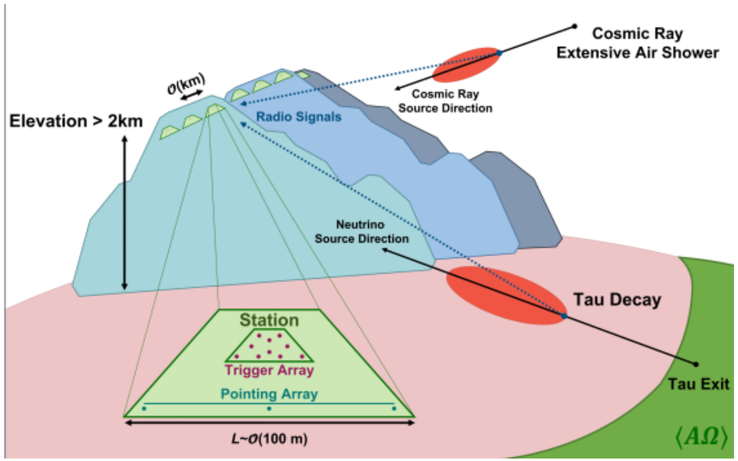
Cost effective: several thousands euros per flight.
Higher cost if at high altitude.

BEACON

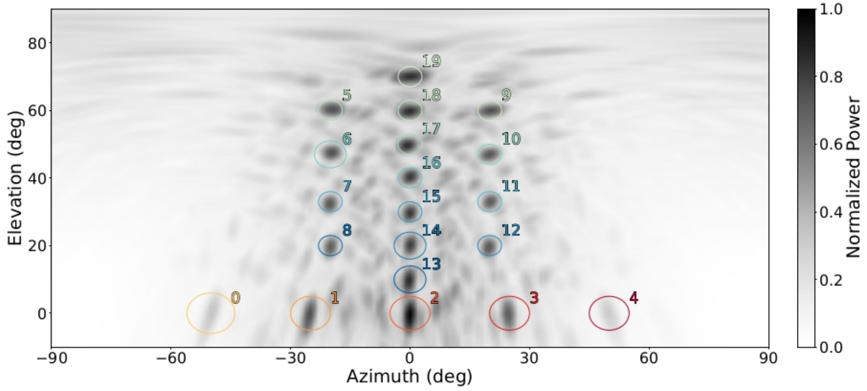
Phased array of antennas

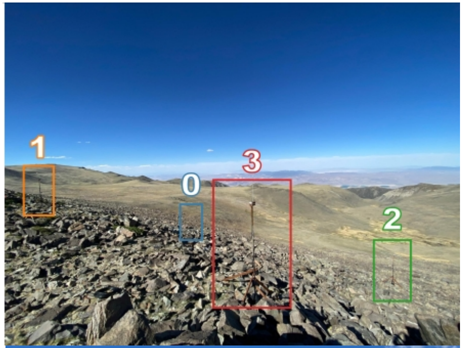






D. Southall et al. 2023.

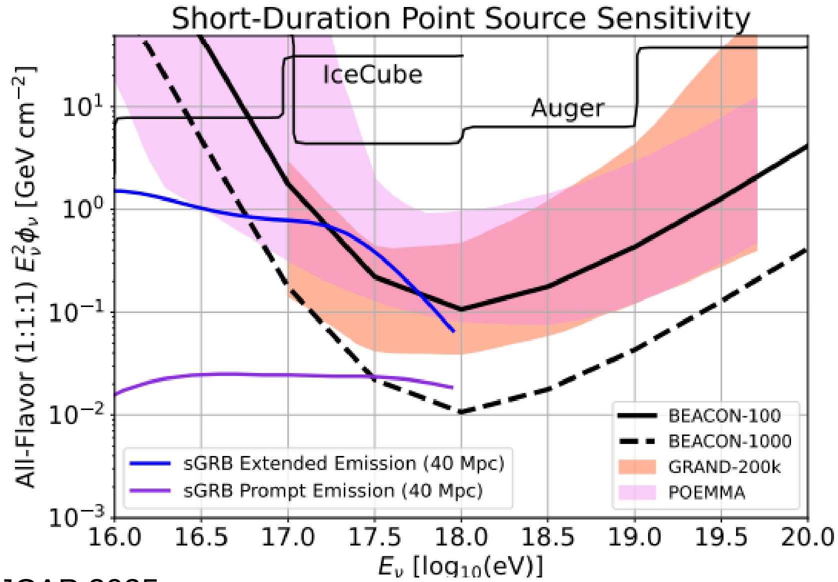




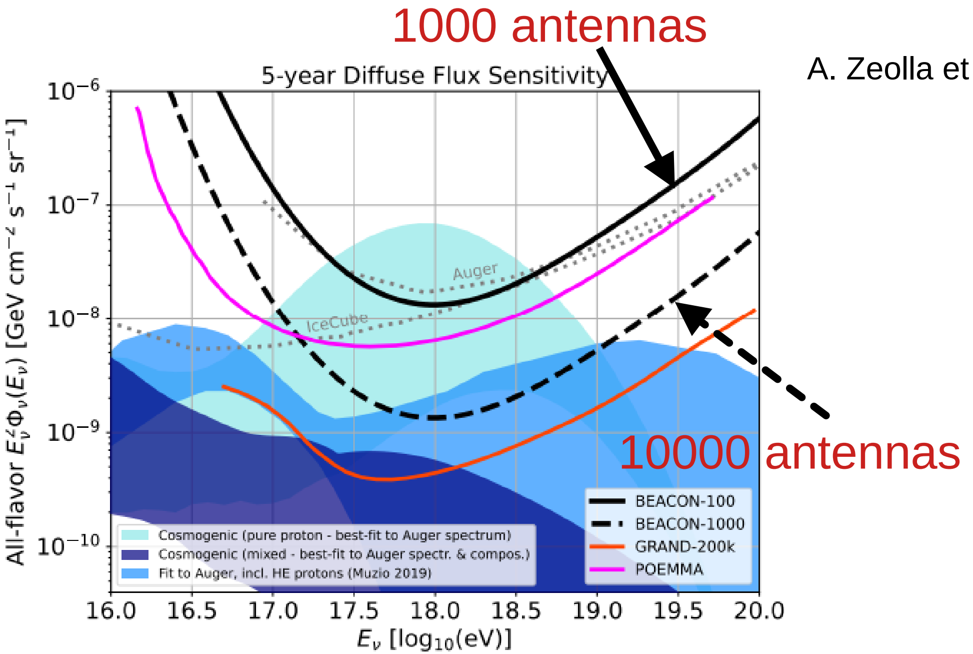
Sensitivity of BEACON

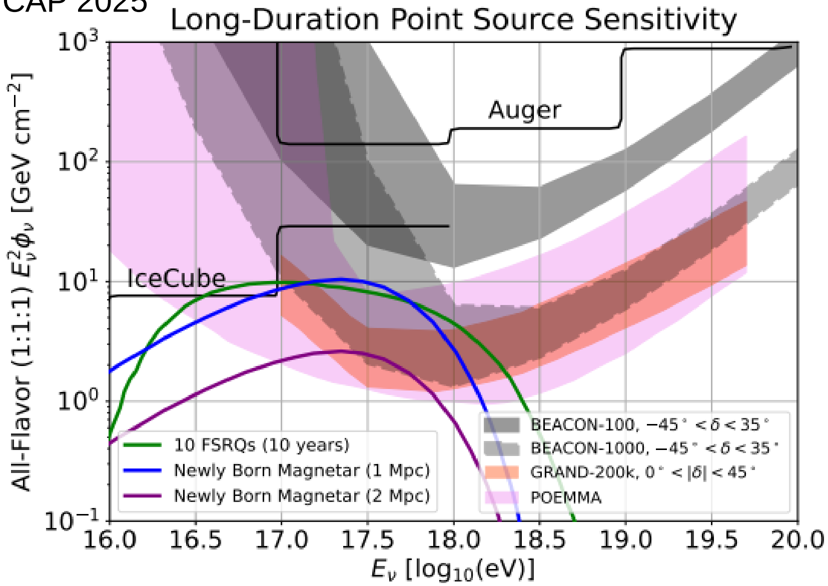
Excellent sensitivity
Very cost effective

Limited angular resolution (0.5-1°),
large systematic uncertainty (1-2°)



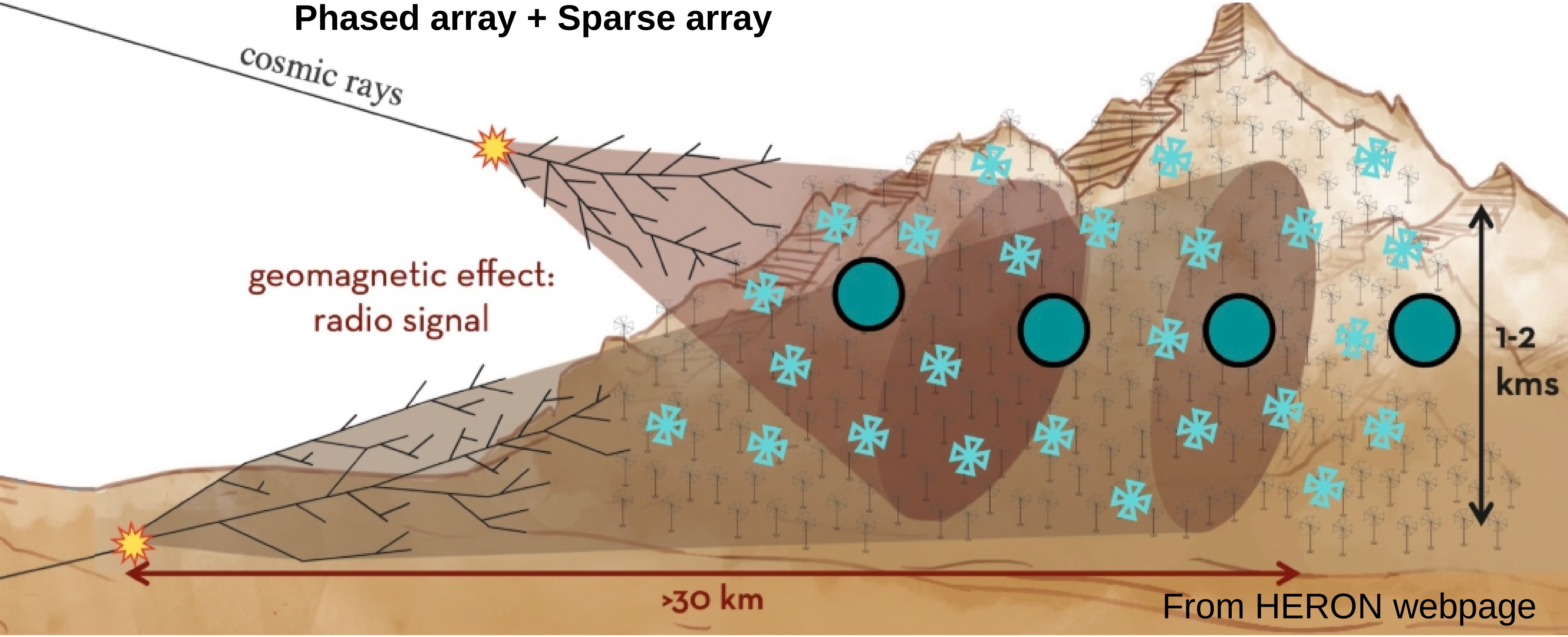
A. Zeolla et al. JCAP 2025





HERON = BEACON + GRAND

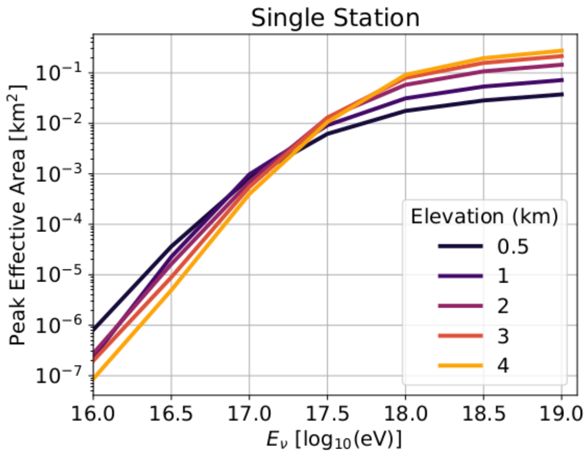
Phased array + Sparse array

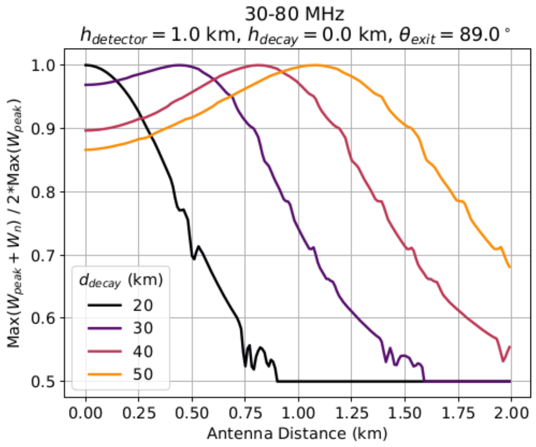


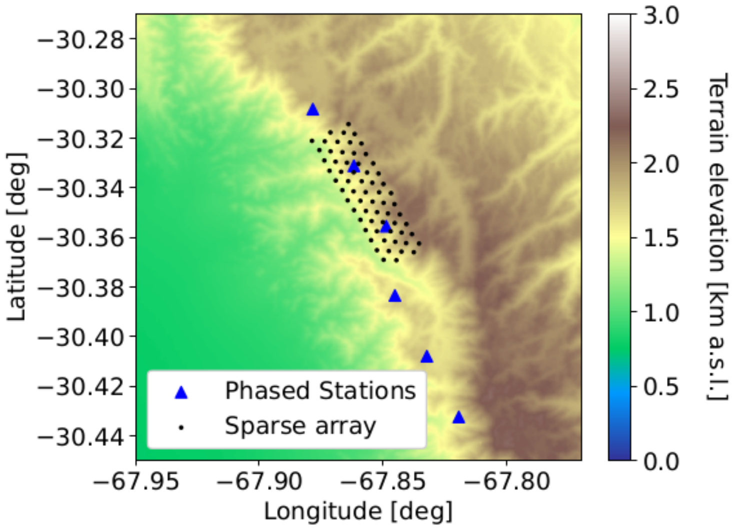
From HERON webpage

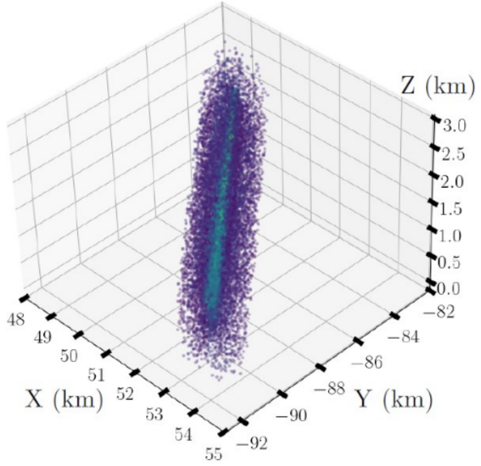
HERON

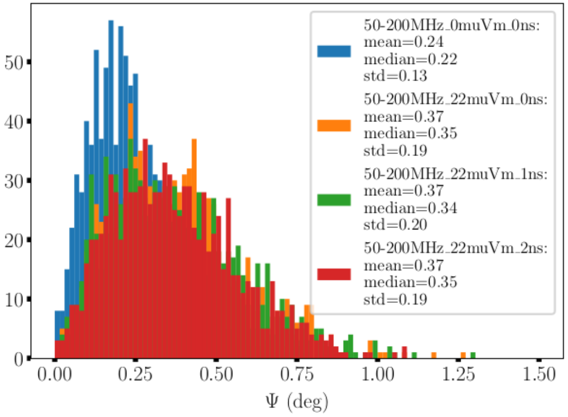
24*(24+25)= 936 Antennas
ERC funding (14 M€) approved recently









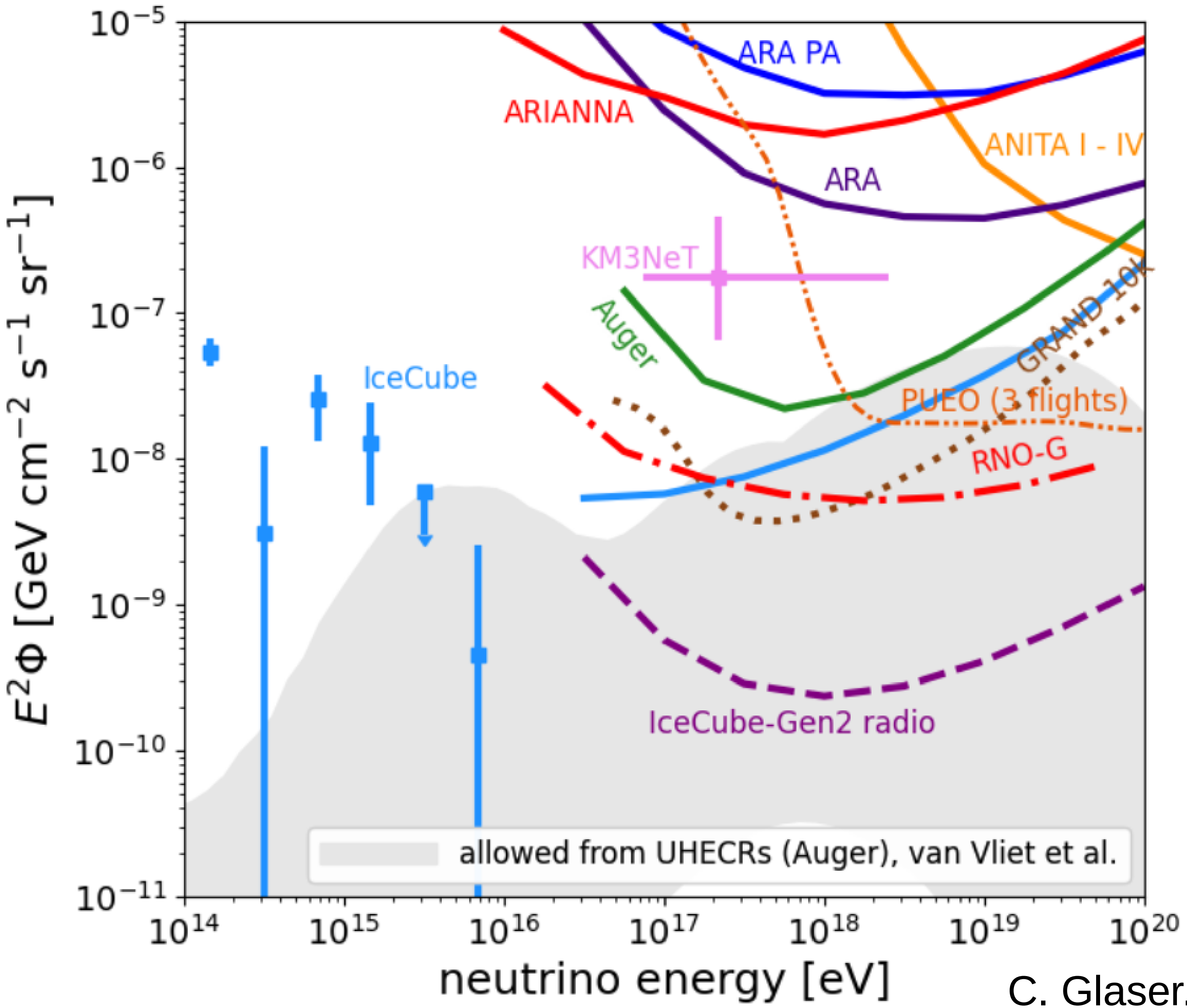


Andrew Zeolla ICRC 2025

Angular resolution: 0.4°

ML or DL

or differential programming ...



Deep-Learning or Differential Programming for
"Trigger and Reconstruction"
to increase
- detection rate
- angular resolution
- energy resolution
- Flavor Sensitivity

NuRadioOpt:
ν-N cross section: 5X
Neutrino flux: 5X
Point source: 3X
...

C. Glaser. ICRC 2025

Summary

- As the most cost-effective option in UHE neutrino detection, Radio detection is advancing rapidly in recent years in

  simulation, mechanisms, layout/site, trigger, reconstruction...

- These provide

  much better sensitivity

  improved angular resolution

  at much lower cost

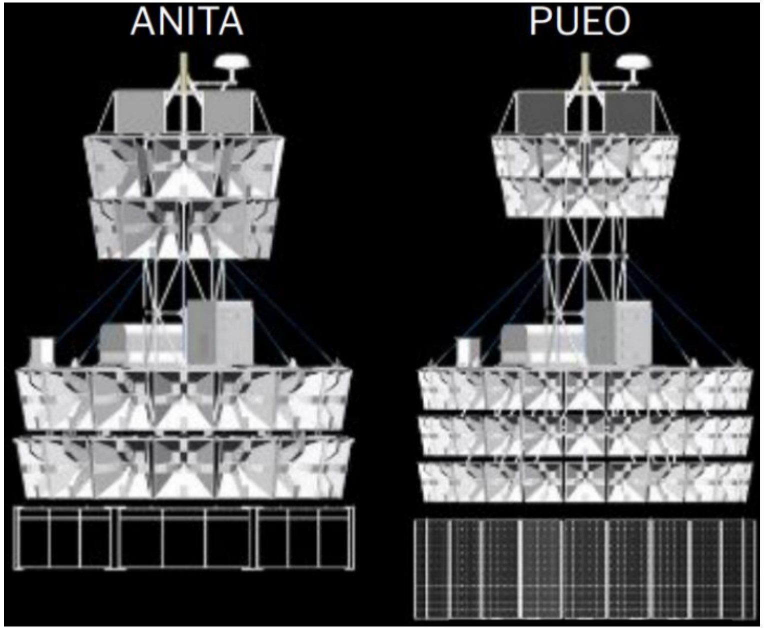
→ indicating still a large improvement space for the schemes of

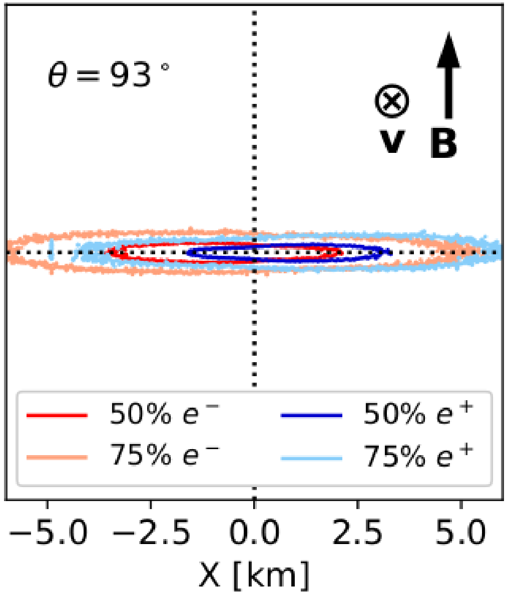
next-generation experiments

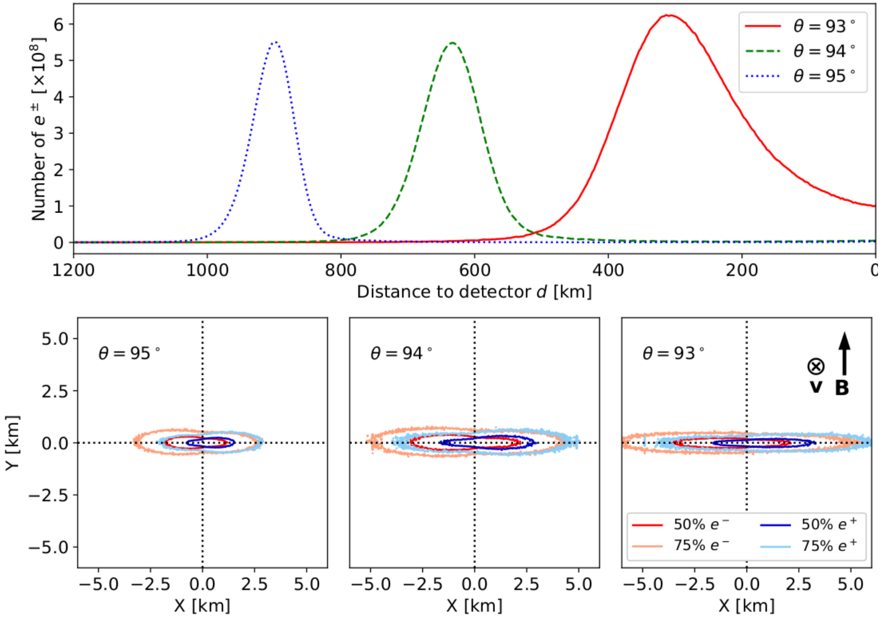
- To be continued

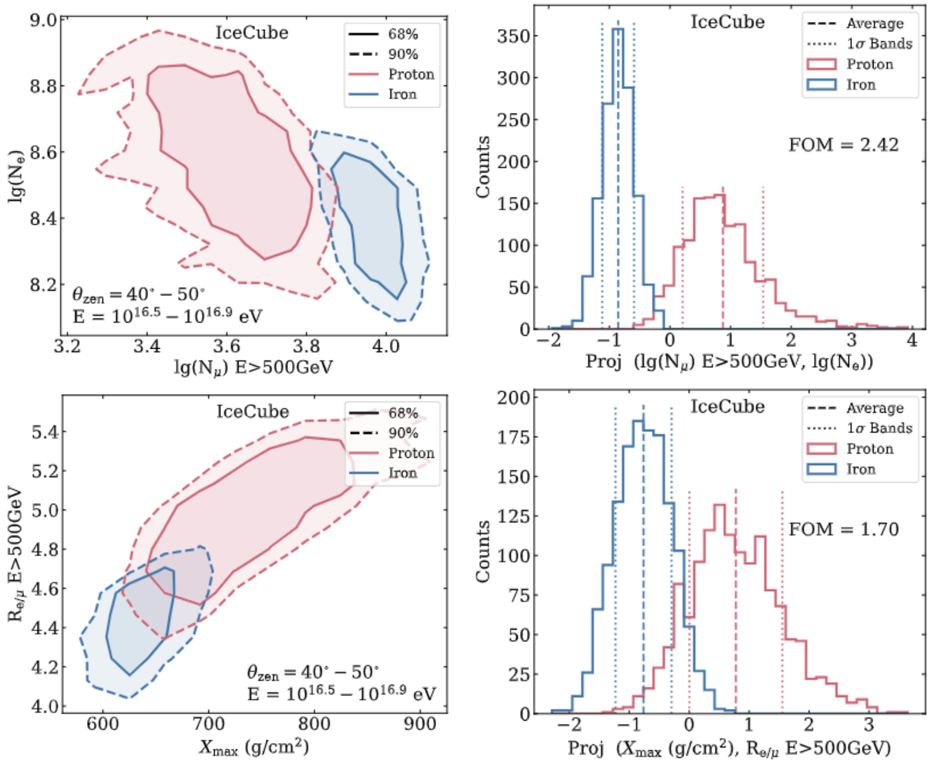
Thanks a lot!

Back up



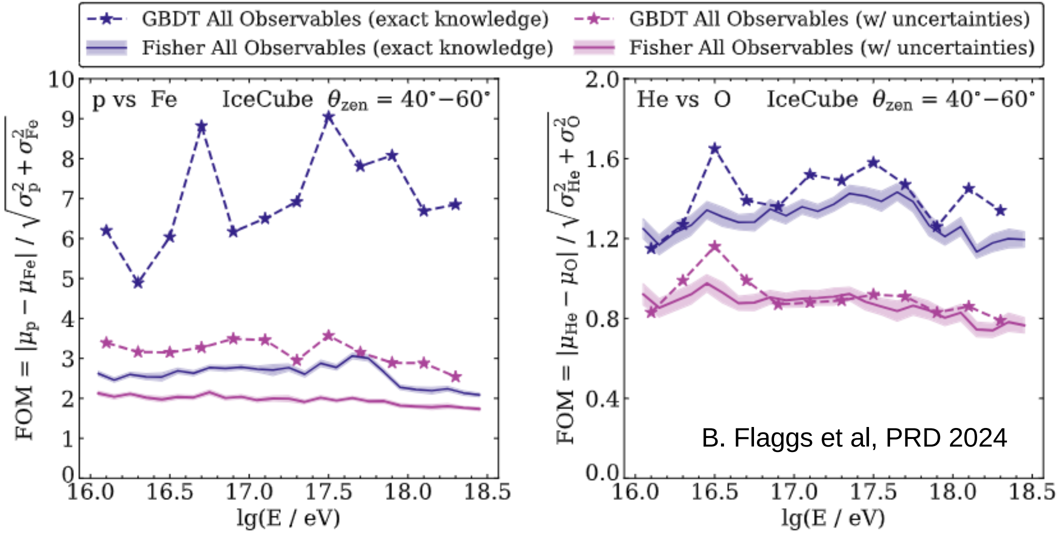

θ = 93°
v
B
50% e⁻
75% e⁻
50% e⁺
75% e⁺
−5.0
−2.5
0.0
2.5
5.0
X [km]


Number of e± [×10⁸]
Distance to detector d [km]
θ = 93°
θ = 94°
θ = 95°
1200
1000
800
600
400
200
Y [km]
X [km]
θ = 95°
θ = 94°
θ = 93°
v
B
50% e⁻
75% e⁻
50% e⁺
75% e⁺



B. Flaggs et al, PRD 2024

N_e+N_μ better than X_{max} + N_μ

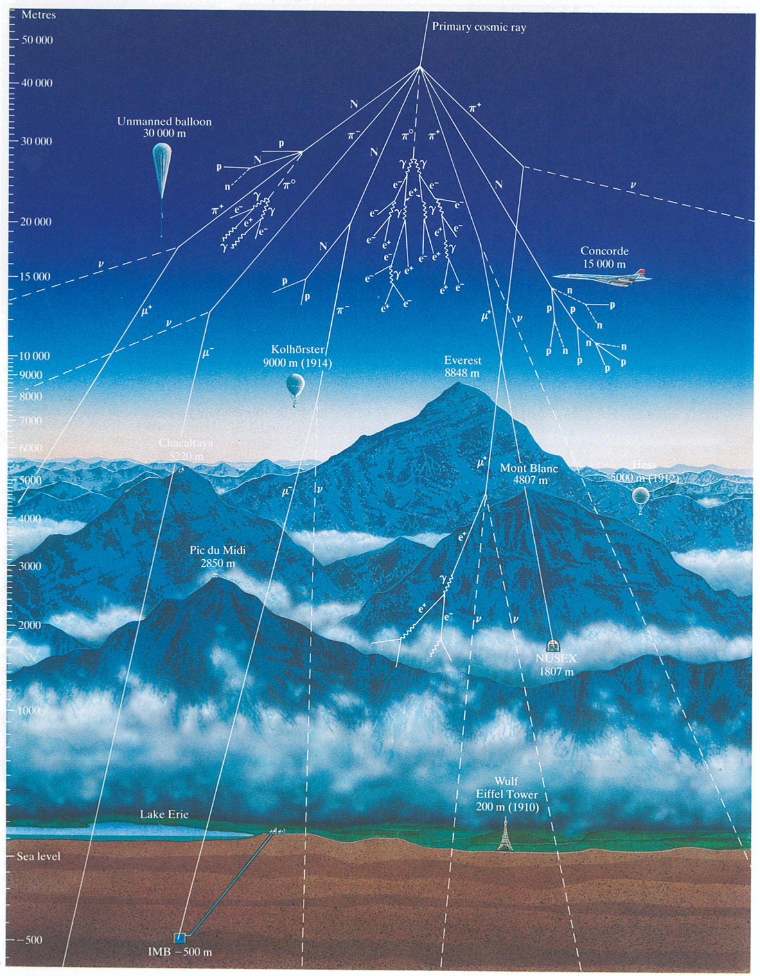


GBDT (Ensemble Learning) better than Fisher discrimination in event-by-event separation.

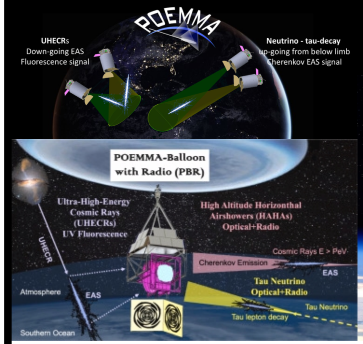
Cosmic ray in IceCube-Gen2
mass decomposition method in the next-generation experiments: X_{max} + N_μ + N_e.

Example: combination of radio and muon detection in IceCube-Gen2, which requires X_{max} better than 20 g/cm^2 + good N_μ resolution.

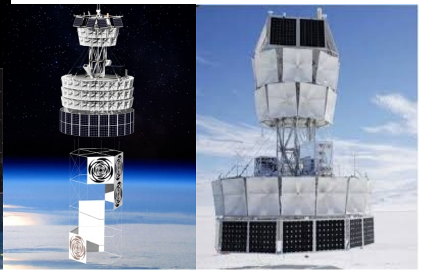
This analysis is limited in zenith < 60° (IceCube) and 65° (AUGER radio).



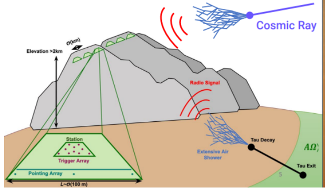
By Sebastián Martín Ruiz



PUEO ANITA

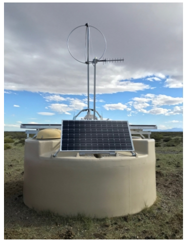


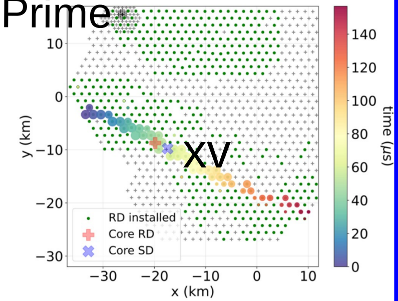
BEACON

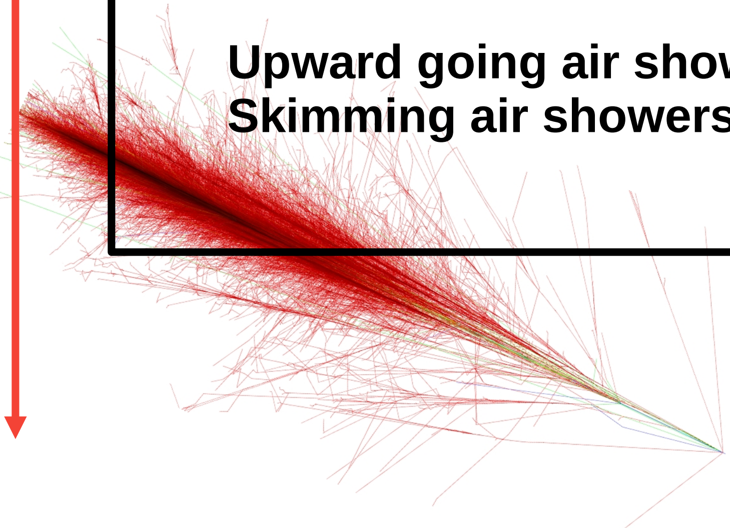


GRAND

AUGER Prime







Upward going air showers
Skimming air showers

Very inclined and Skimming
air showers

Ongoing radio projects
on earth