GRAND – BEACON
status & perspectives

Jaime Alvarez-Muñiz with input from many people

INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS (IGFAE)
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

GRAND Collaboration Meeting, Warsaw, 2 – 6 June 2025

GRAND-BEACON: an R&D project dubbed HERON
(Hybrid Elevated Radio Observatory for Neutrinos)

HERON

GRAND-BEACON could be a promising option for next phase of GRAND

- **Goal**: join main **strengths** of GRAND & BEACON prototypes to **alleviate intrinsic weaknesess** of each
  - **GRAND-Proto300** – autonomous radio detection, large area, sensitivity at high energy, RFI rejection, accurate reconstruction,...
  - **BEACON** – self-triggering phased array, low-energy threshold, accurate pointing, RFI masking,...
- **leveraging** the well-grounded technology developed for GP300 and BEACON prototypes
- **addressing common scientific, practical and technological challenges** (deployment, RFI noise mitigation strategies, self-triggering, time synchronization, simulations, reconstruction, etc...)

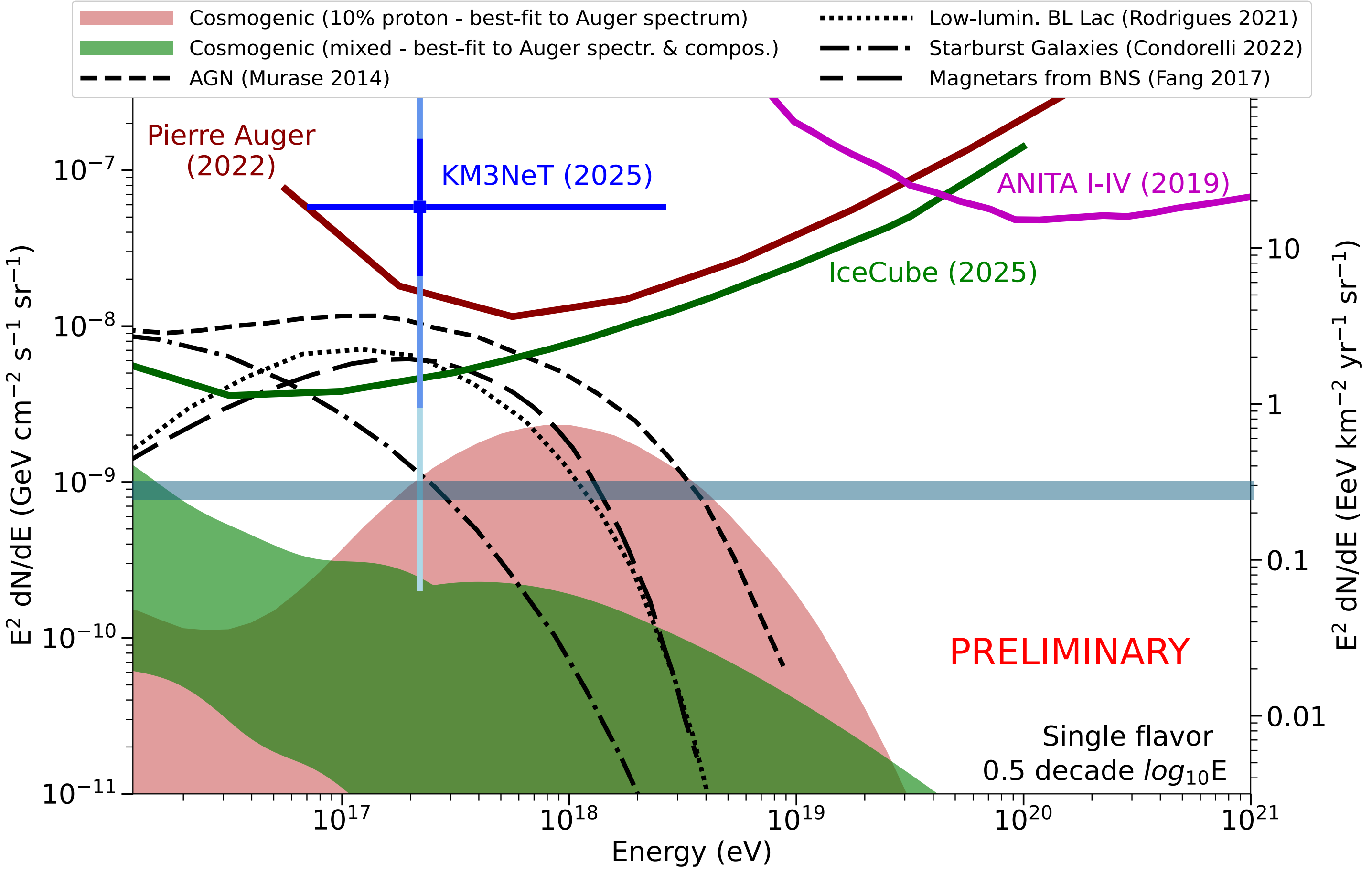
Science case: Neutrino detection

(see Kumiko's talk on Science - 2 June)

- low ***cosmogenic*** neutrino flux expected due to measured heavy-like UHECR composition with Pierre Auger Observatory: ~ 10% protons still possible
- target ***astrophysical*** (source) neutrinos peaking at $10^{17} - 10^{18}$ eV
  - Aim for **energy threshold ≲ 10^{17} eV**
  - Diffuse & **transient** fluxes expected: GRB, binary coalescence, magnetars, AGN, SBG,…
  - **Reach diffuse sensitivity**

  ≲ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} at 100 PeV
- Neutrinos (maybe) exist around 200 PeV!!

KM3NeT event



→ also, neutrino sources detected at sub-PeV

Galactic Plane & NG1068

How? You know how

(see Kumiko's introduction - 2 June)

- **General Strategy:** target quasi-horizontal showers from tau lepton decay after UHE tau neutrino interactions

- Monitor a **large area/volume** with **100% duty cycle** to compensate for low expected neutrino flux

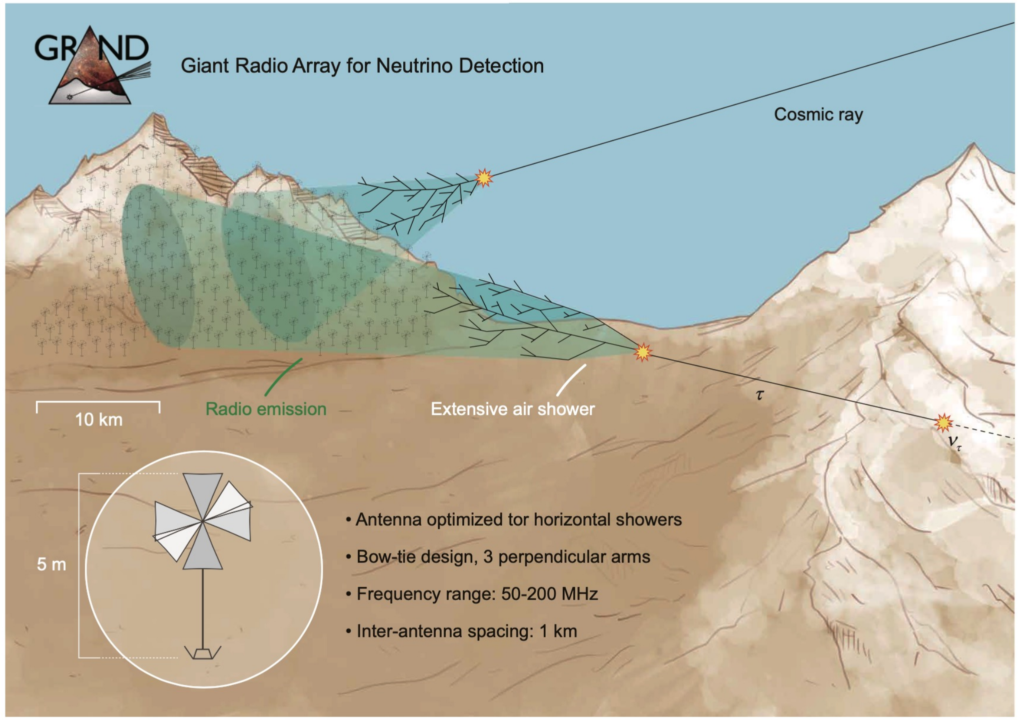
- Keep instrumentation **cost-effective** with **low-maintenance** detectors => radio detection with antennas

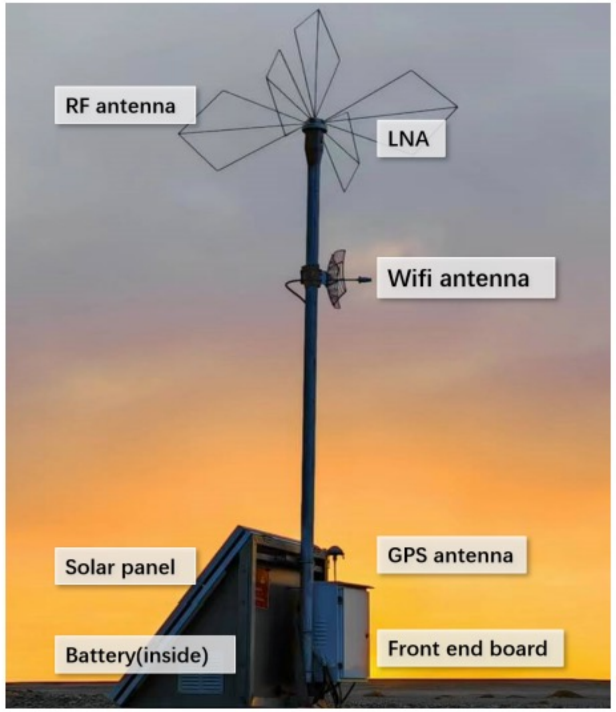
⇒ two *leading edge* concepts

- **high-altitude detector**: BEACON; PUEO;…
- **large-area antena array** : GRAND; Pierre Auger RD; RNO-G, IceCube Gen-2 radio;…

GRAND: Giant Radio Array for Neutrino Detection

Proto300





GRAND (GP300)
HORIZON ANTENNA

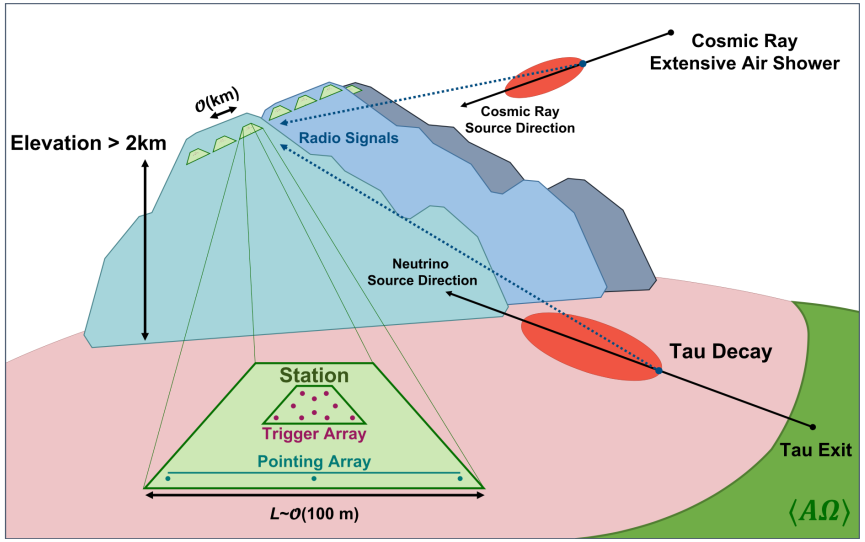
GRAND Collab. Science China Mechanics & Astronomy 63 (2020) 219501

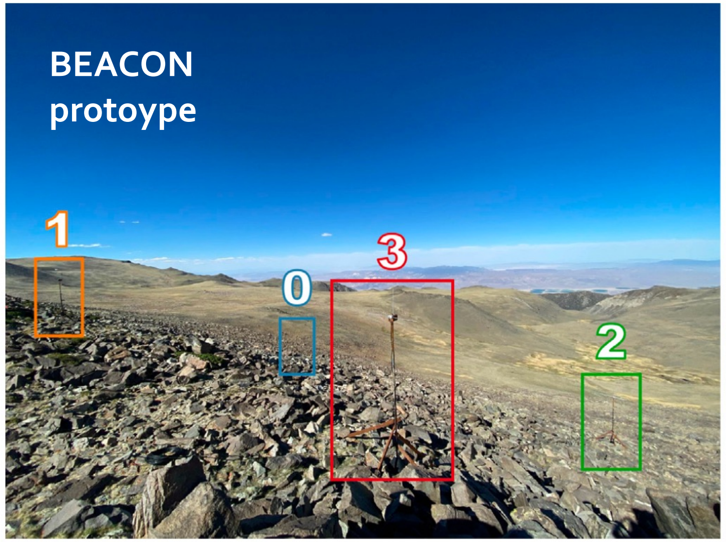
Large sparse autonomous antenna array *O*(1000's km²) with *O*(1 km) separation

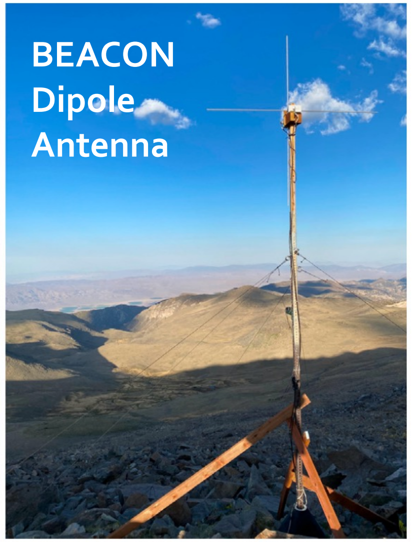
- **large coverage area** enhances sensitivity to particle fluxes at higher energies
- antenna design to improve sensitivity to **large zenith angles** (HORIZON ANTENNA)
- **long baselines** allow imaging of Cherenkov cone, accurate reconstruction (angular resolution), and RFI rejection. Timing synchronization with AERA-style beacons
- **~ 20-30 cosmic-ray candidates identified** with GP300 ! (3 with high confidence)

BEACON: Beam-forming Elevated Array for Cosmic Neutrinos

D. Southall et al. (BEACON). NIMA 1048 (2023) 167889





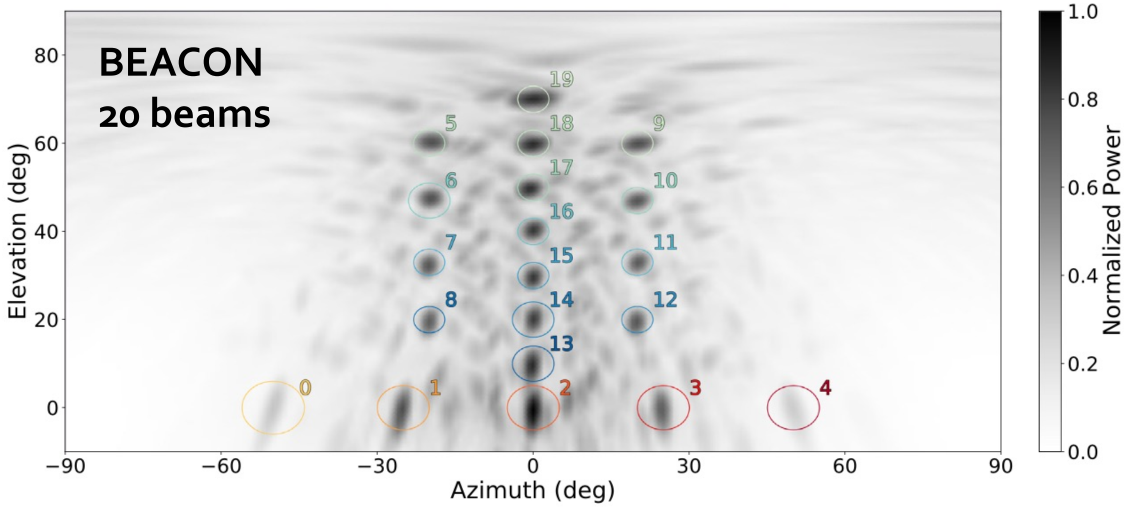


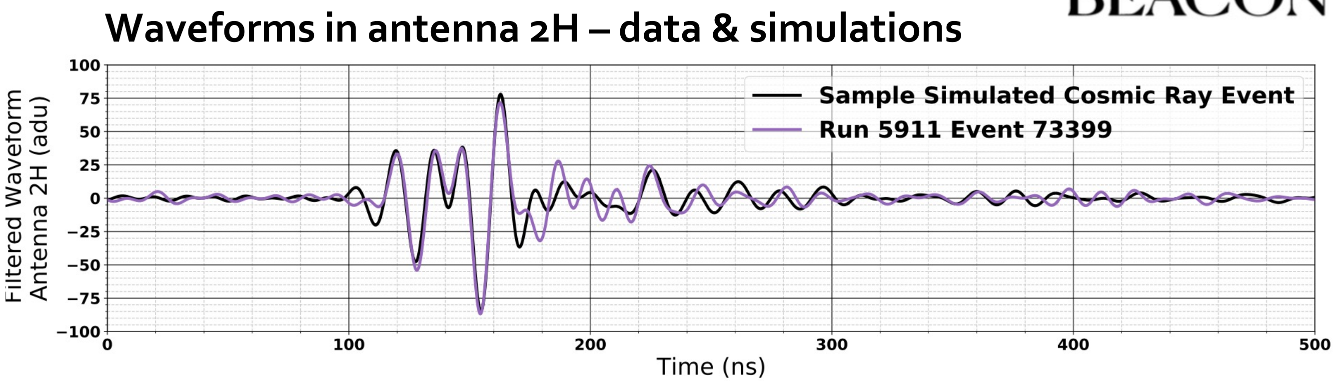
Compact autonomous arrays (stations) of O(10) antennas separated by O(few 10's m).

- placed at **high prominence** O(few km) above horizon, **maximizing visible geometric area** available to a ground experiment
- **phasing** (delaying & summing) signals in antennas allows to construct **multiple beams** to enhance point-source sensitivity & directional masking of noise => **low-energy threshold**
- **existing prototype** (4-crossed dipoles) at 2.8 km prominence (White Mountains, California, USA)
- **deployment** on a rocky terrain: 33 kg rubber bases, wooden struts, and six guy-lines

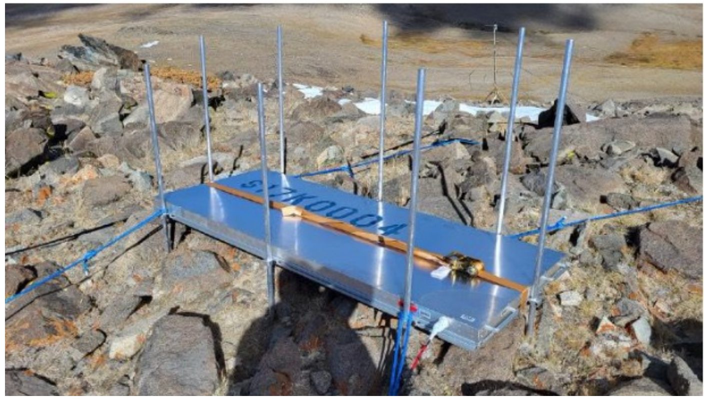
BEACON: Beam-forming Elevated Array for Cosmic Neutrinos

D. Southall et al. (BEACON). NIMA 1048 (2023) 167889





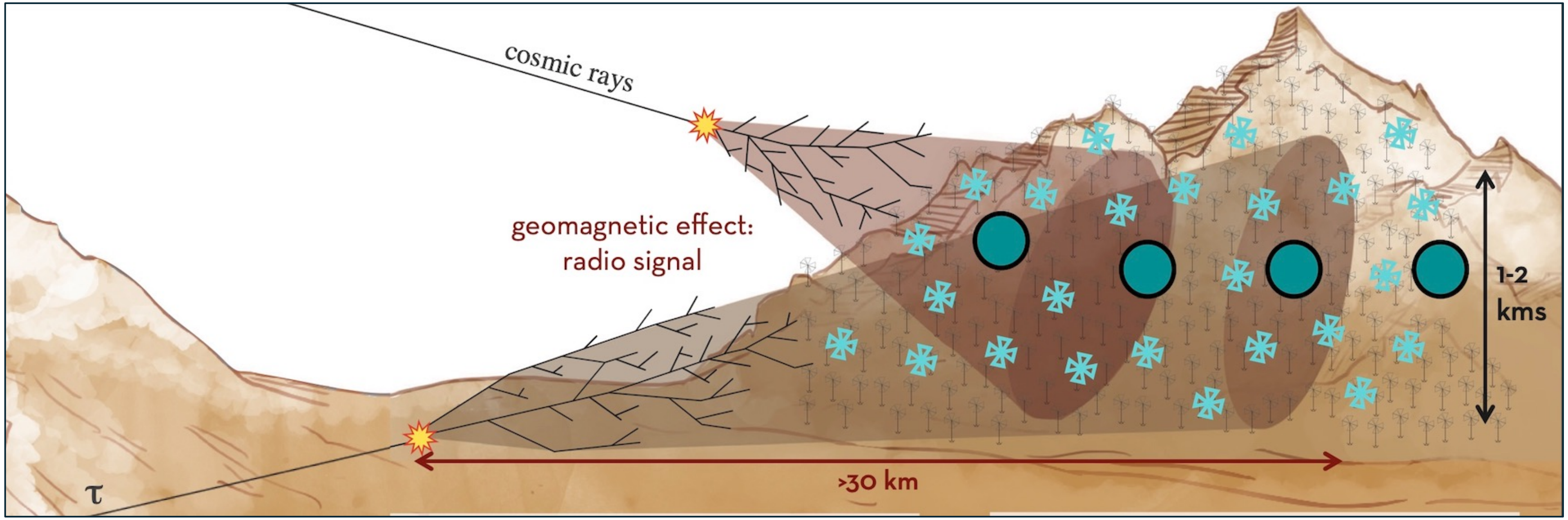
Scintillator at BEACON site



- validated phasing signals in antennas, constructing **multiple (20) beams** to enhance point-source sensitivity & directional masking of noise => **low-energy threshold**
- **self-triggering on impulsive signals** demonstrated on above horizon events: **Cosmic-Ray candidates identified**
- coincident **scintillator** and radio CR search in progress to optimize RF-only trigger + CR search

GRAND-BEACON concept (**HERON proposal**)

Hybrid **E**levated **R**adio **O**bservatory for **N**eutrinos

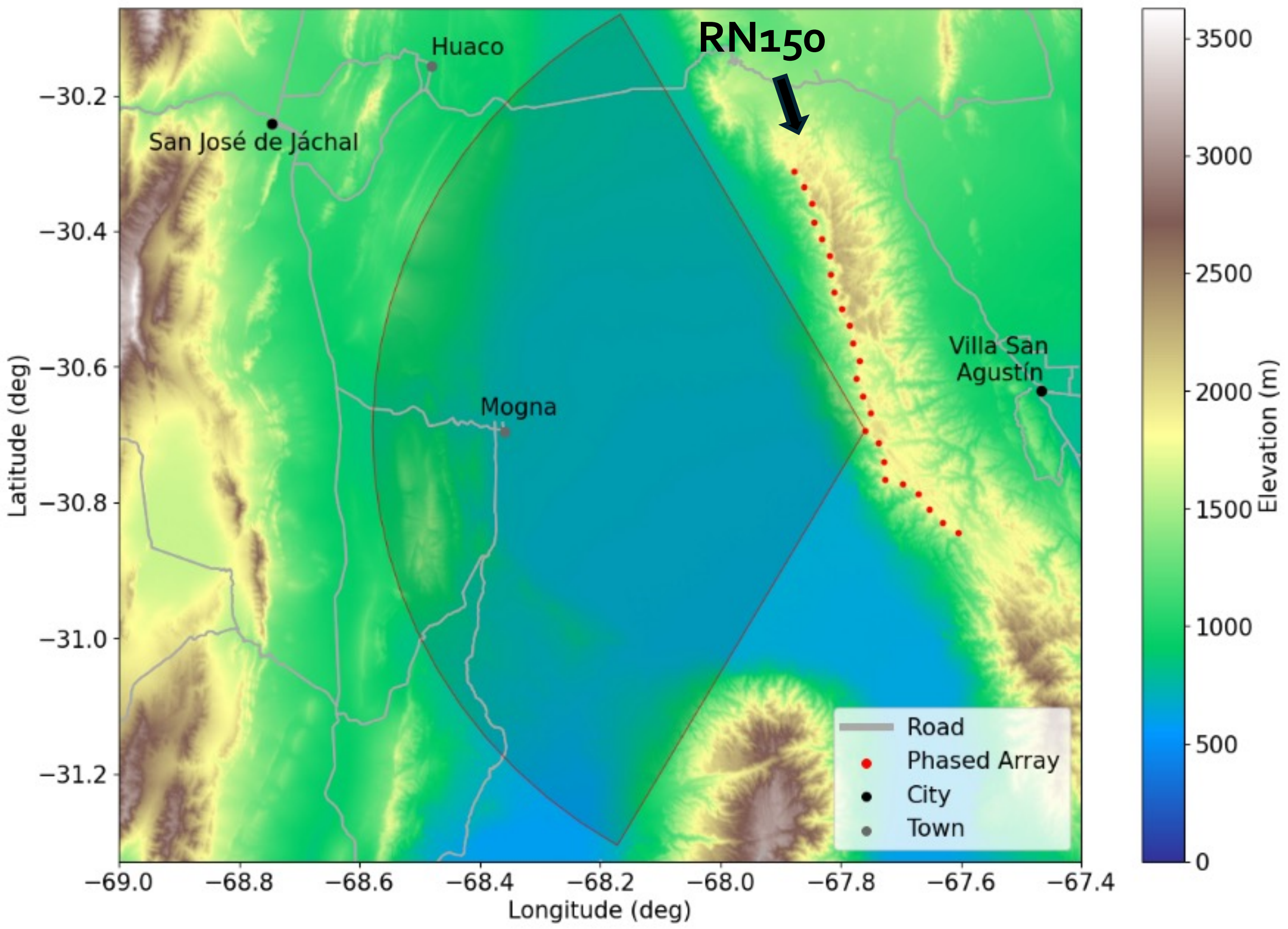


Compact phased arrays a la BEACON: Boost signal-to-noise ratio (SNR) by synchronizing signals & suppressing incoherent noise => Reduce energy threshold.

Can be tuned to point at or below the horizon for UHECR and neutrinos respectively.

Array of antennas a la GRAND: improve sensitivity at higher energies & high zenith angles, long baselines for reconstruction, RFI rejection.

Location



Jáchai Department, San Juan province, Argentina. Latitude -30.5º

Ideal topography:

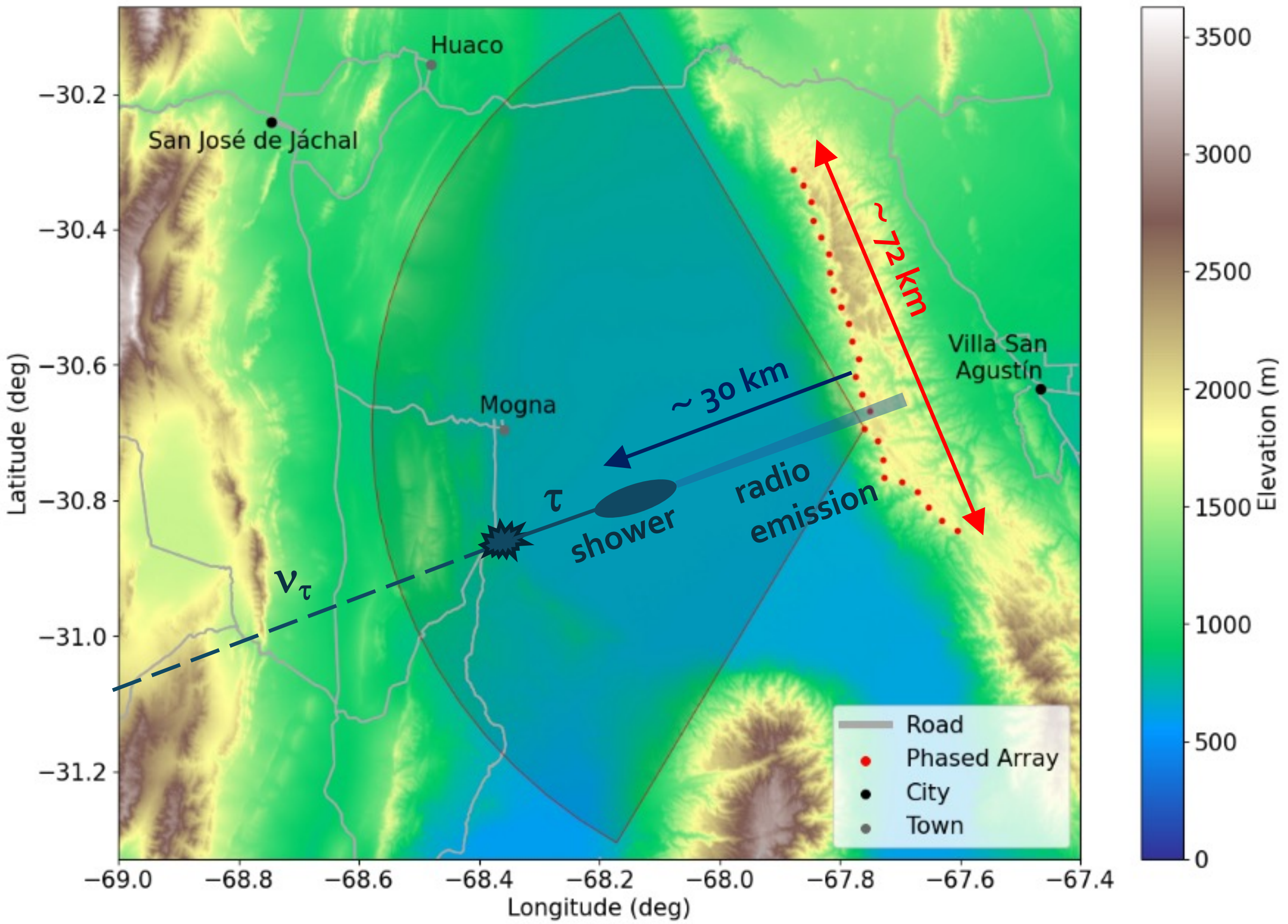
valley at altitude 0.8 – 1.4 km between 2 km ridges running North-South of width 60-80 km, 100 km length

(Ingo Allekotte, CNEA – next talk)

→ Survey of RFI at site planned

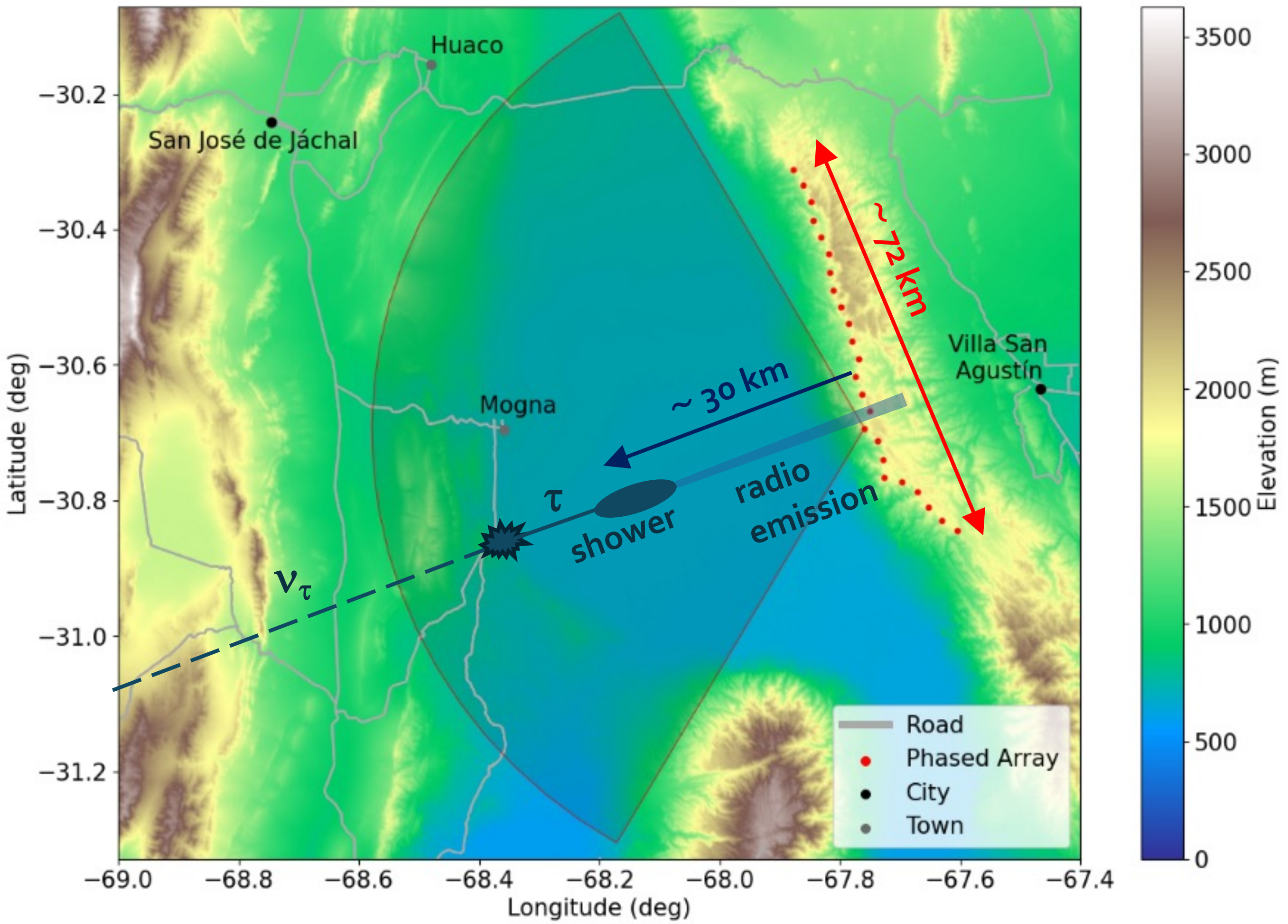
View from Route **RN150** (Google maps)

Baseline, not optimized design: layout & antennas



- **24 Phased stations** along mountain ridge
  - ~ 1 km altitude, 3 km apart => 72 km
  - each station with 24 high-gain dual polarized 30-80 MHz elevated antennas (< 200 m spacing)

Baseline, not optimized design: layout & antennas

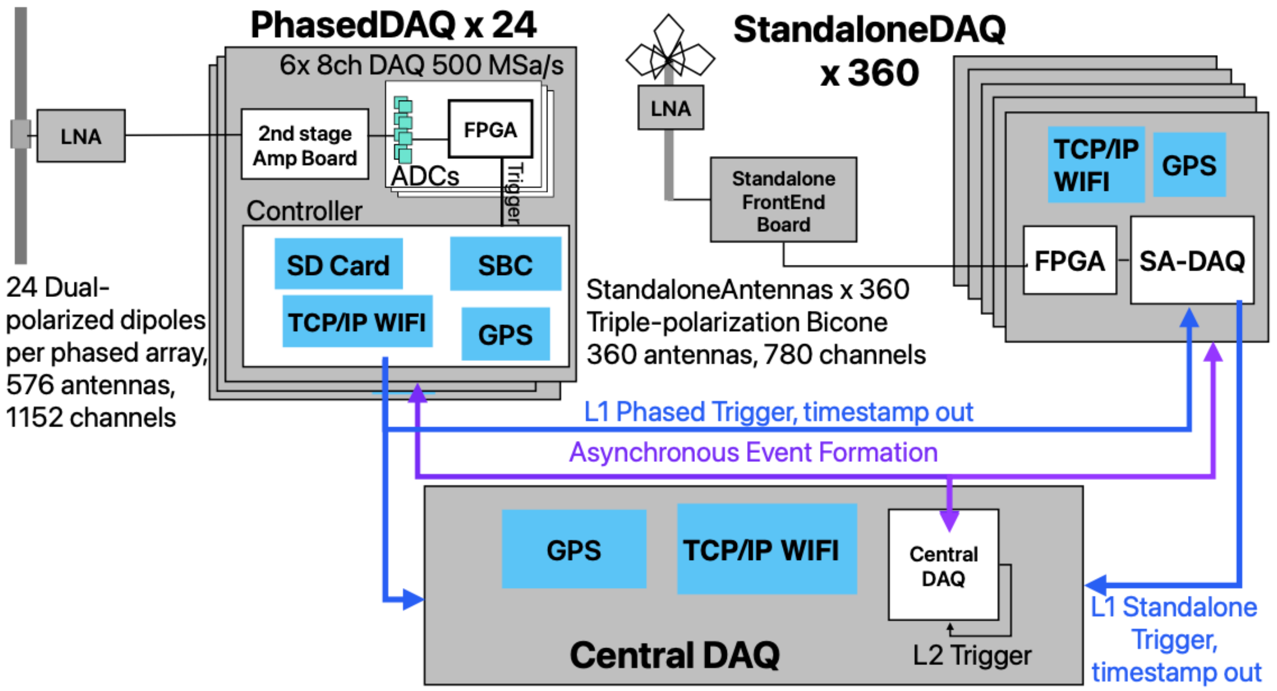


Total number of antennas = 936

- **24 Phased stations** along mountain ridge
  - ~ 1 km altitude, 3 km apart => 72 km
  - each station with 24 high-gain, dual polarized 30-80 MHz elevated antennas (<200 m spacing)
- **Outrigger autonomous array**
  - 15 sparse antennas per phased station, use triple-polarized bicone GRAND elevated 50 – 200 MHz (**HORIZON ANTENNA**)
  - evenly spaced around each phased station between 0.5 -1.5 km altitude
  - can trigger autonomously or can be triggered by phase array – low signals extracted from noise

Baseline, not optimized design: DAQ & trigger

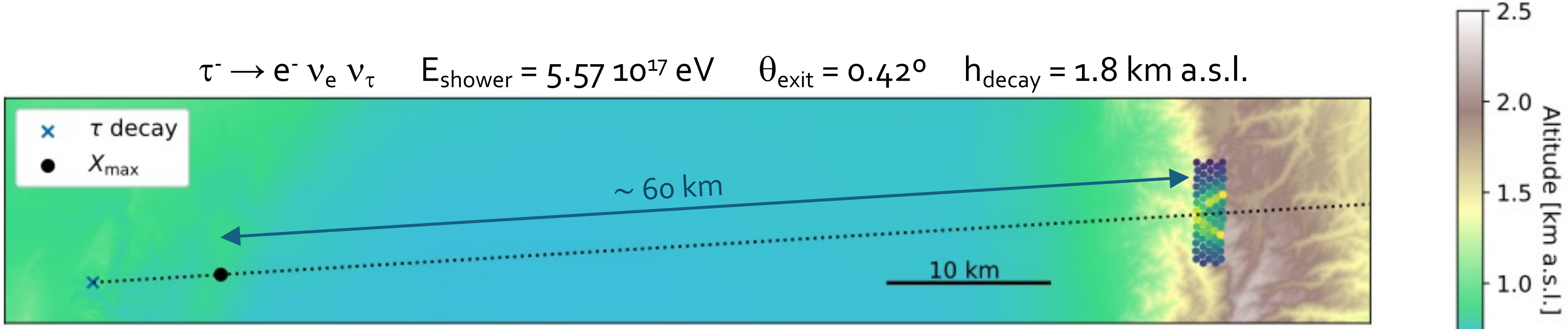
- **48-channel PhasedDAQ per station**, synchronized to **nanosecond precision** with **standalone antennas** via 3 beacons.
- Central **master DAQ**
- **Phased-array triggers** detect impulsive, linearly polarized signals (vertical & horizontal) from air showers
- Triggers are distributed to **45 nearby standalone antennas**:
  - **15 closest antennas** via direct communication
  - **30 others** via central DAQ and neighboring phased arrays
- **Standalone antennas** can also self-trigger similarly to **GRAND concept**
- **Advanced algorithms** may enable detection of **low SNR signals**



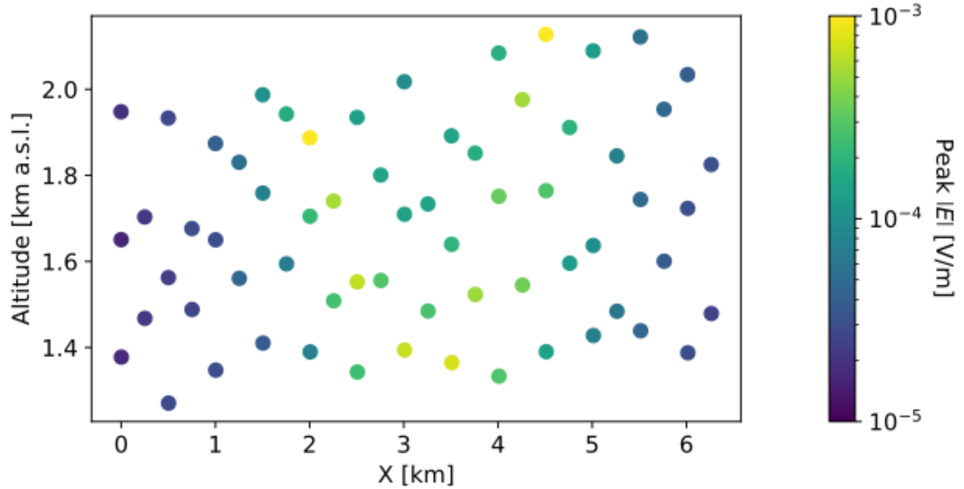
Simulations: showers & radio emission

- performed with ZHAireS – RASPASS
- look-up tables of horizontal events for phased (next slide) and outrigger array performance evaluation
- sims. of radio emission from τ-induced horizontal showers on dense array at ~ 1 km above San Juan valley

$\tau^- \rightarrow e^- \nu_e \nu_\tau$ E_{shower} = 5.57 10^{17} eV θ_{exit} = 0.42° h_{decay} = 1.8 km a.s.l.



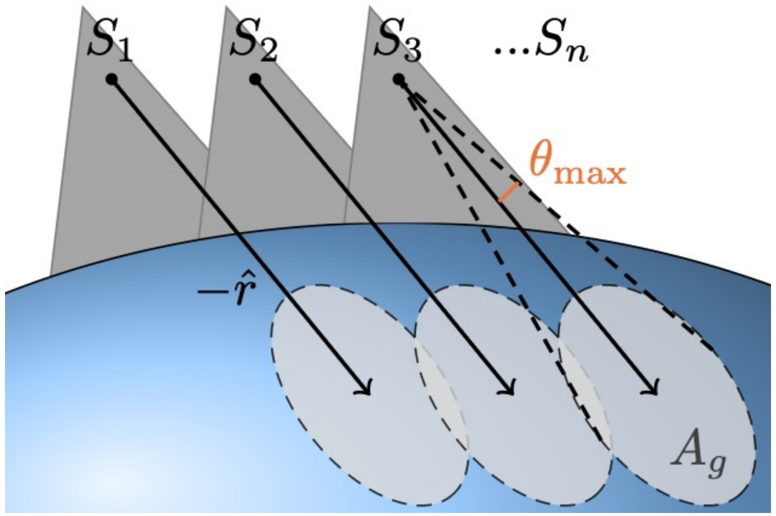
Sergio Cabana-Freire, IGFAE-USC



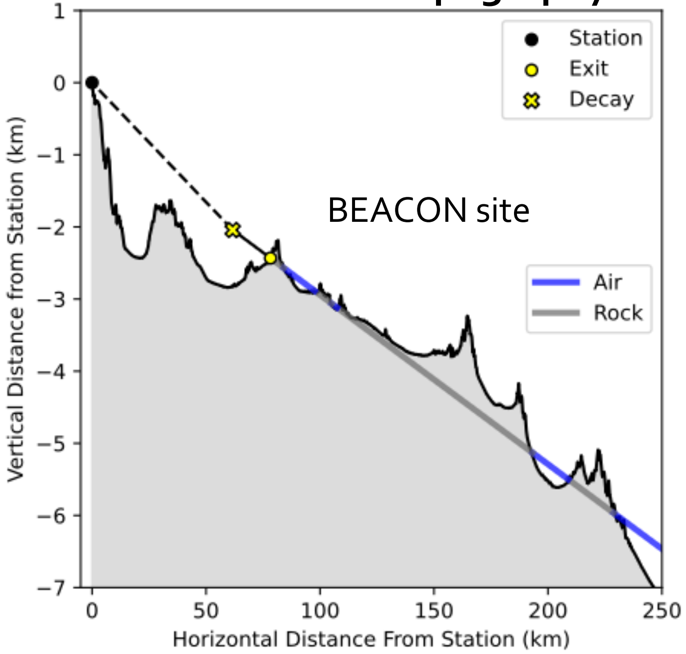
Simulations: Performance of phased array

- evaluated using **M**ultiple **A**ntenna **AR**rays on **MO**untains **T**au **S**ensitivity (**MARMOTS**) tool
  Andrew Zeolla, PSU, see talk later
- MARMOTS can calculate effective area of any number & configuration of elevated phased arrays
- branch of MARMOTS to account for site **topography**
- allows optimizing elevation, number of stations and antennas per station, layout,…

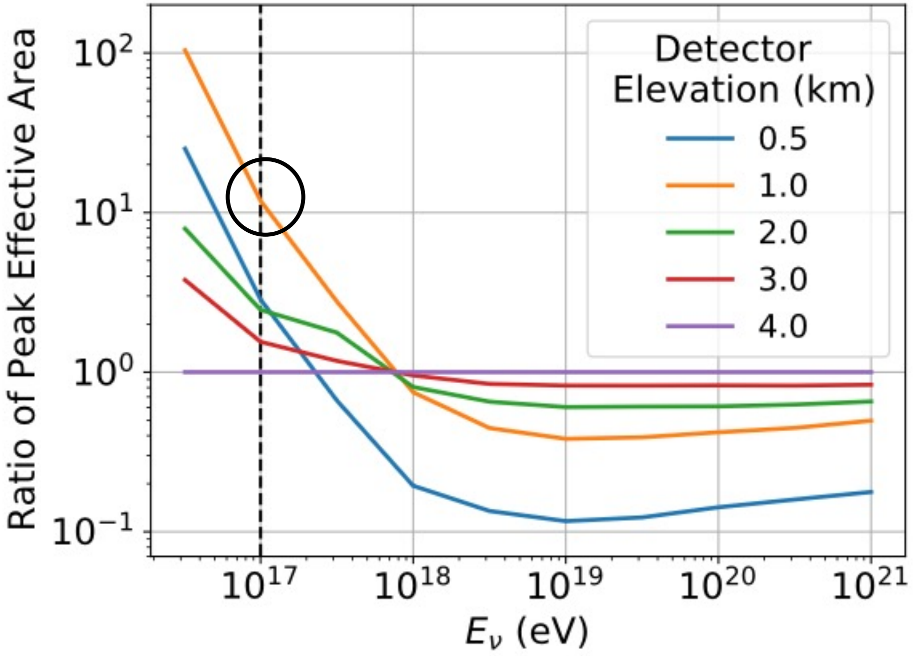
MARMOTS



MARMOTS with topography



Phased array **peak effective area** at different elevation (normalized to that at 4 km)



A. Zeolla et al. (BEACON) submitted to JCAP. arXiv: 2504.13271

Performance: field-of-view & sensitivity

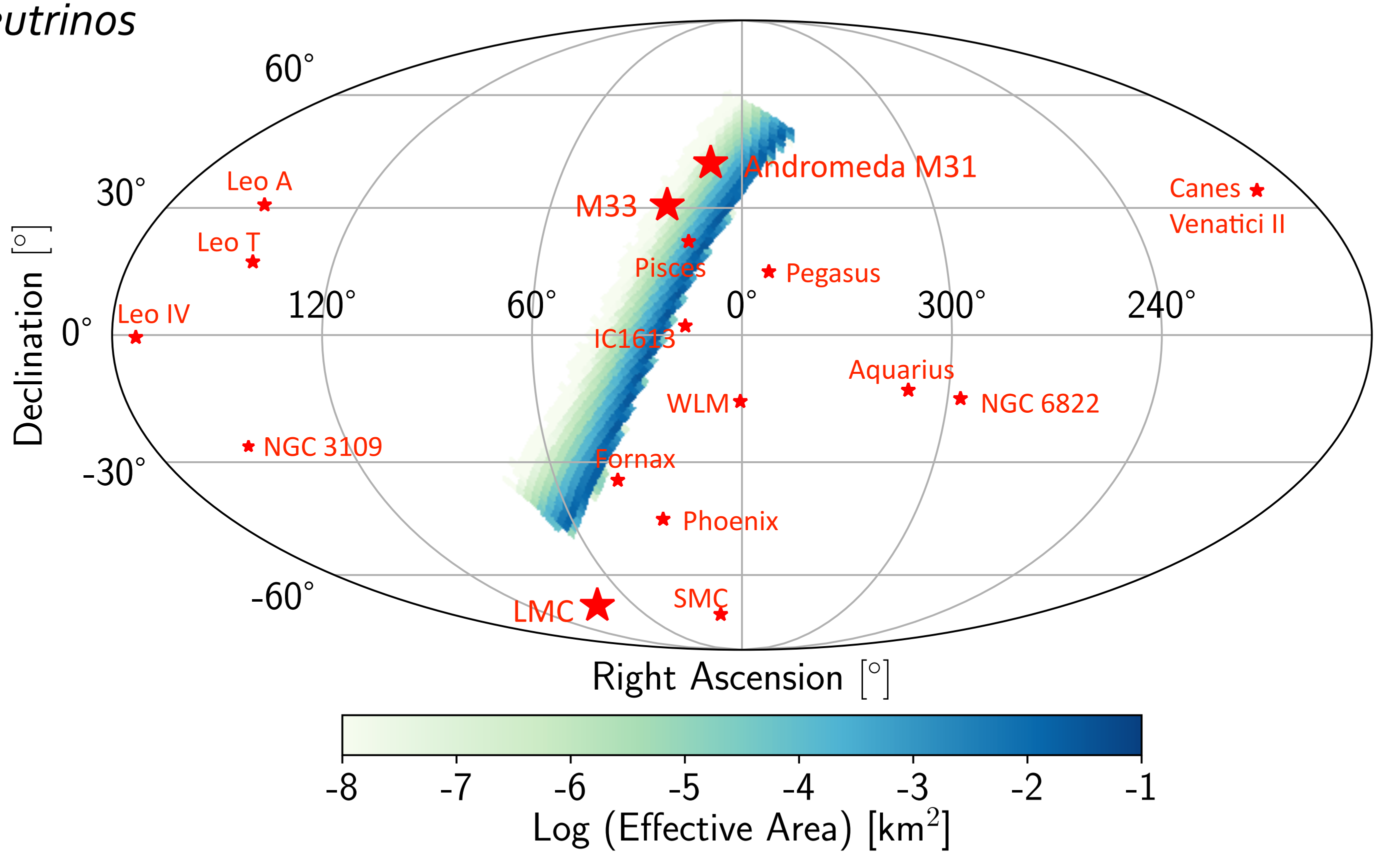
HERON

Deep & Narrow observational strategy

uses astrophysical & multimessenger information to target most likely sources & populations that could emit neutrinos

- covering 6% of the sky instantaneously with **large peak effective areas** for transient sources: ~ 10 times Auger or IceCube
- target discovery in 5 – 10 years

Instantaneous field-of-view



Allekotte, Alvarez Muñiz, Benoit-Lévy, Decoene, Huege, Kotera, Krömer, Martineau, Niess, Sanchez, Tueros, Wissel, Zeolla et al. in prep.

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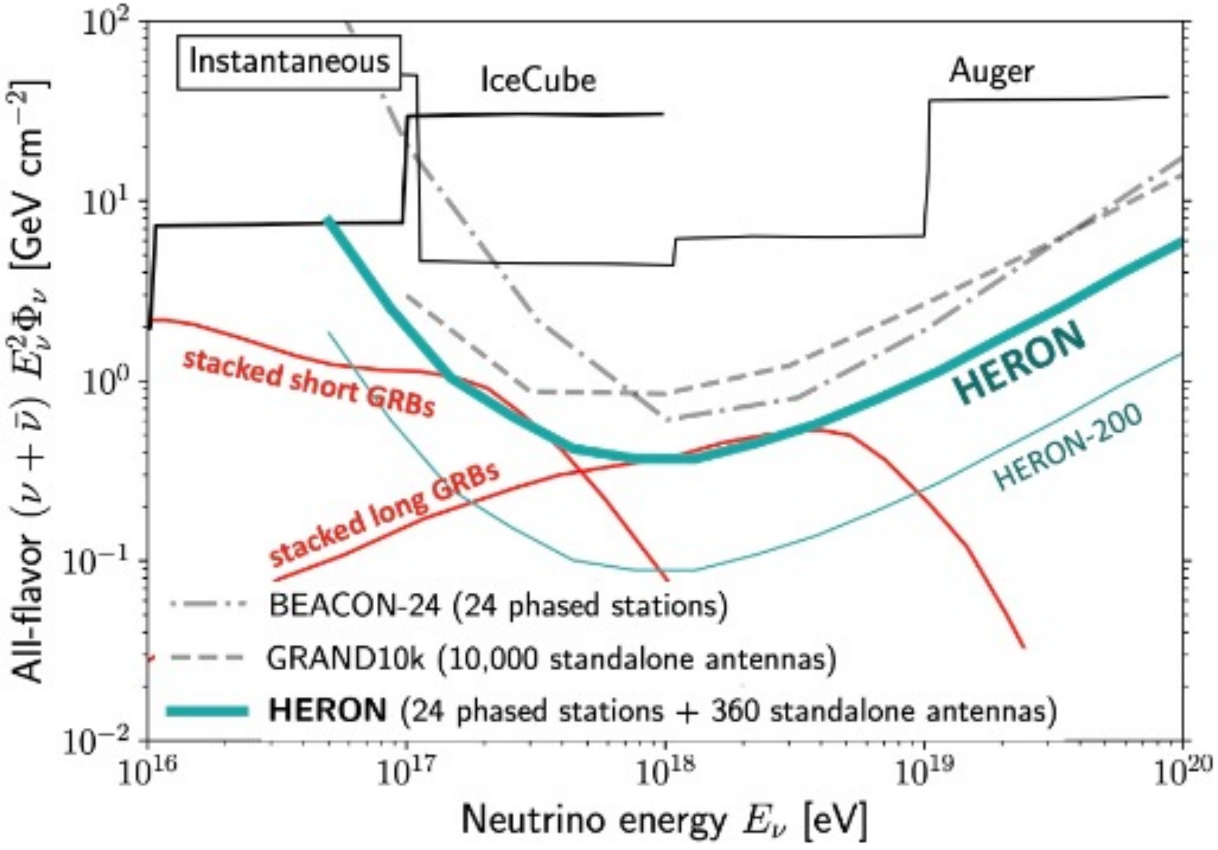

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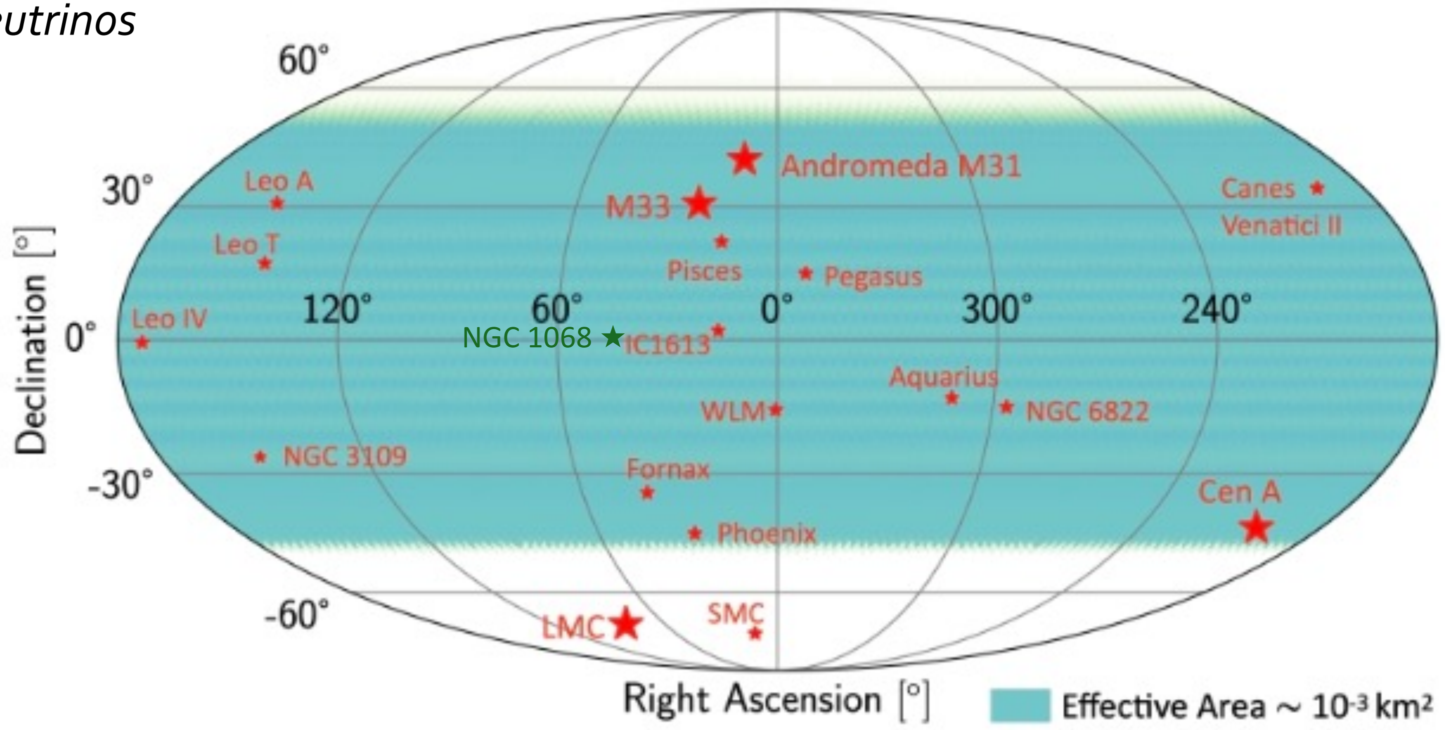
- but also with wide daily field-of-view covering ~ 70% of the sky

Daily-averaged field-of-view



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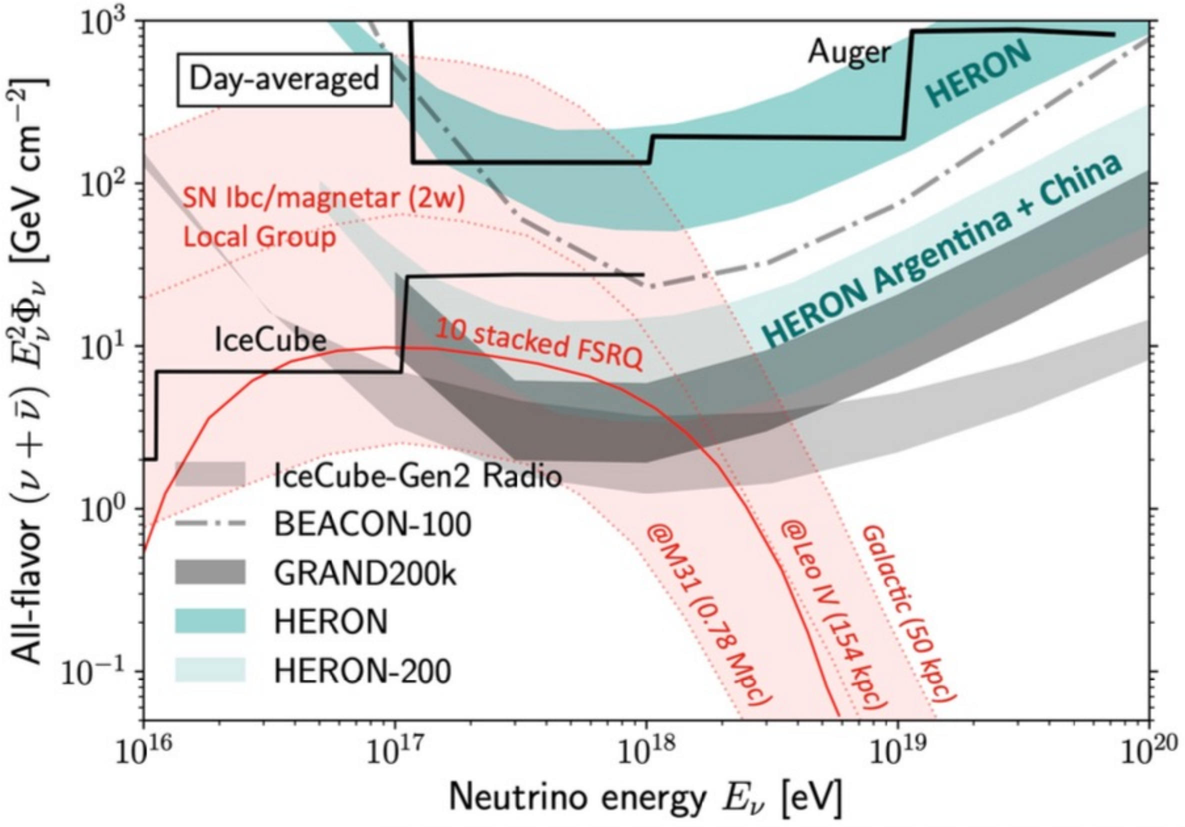
- target discovery in 5 – 10 years
- but also with wide daily field-of-view covering ~ 70% of the sky
- sensitivity to Galactic & local group sources

Daily-averaged field-of-view



Allekotte, Alvarez Muñiz, Benoit-Lévy, Decoene, Huege, Kotera, Krömer, Martineau, Niess, Sanchez, Tueros, Wissel, Zeolla et al. in prep.

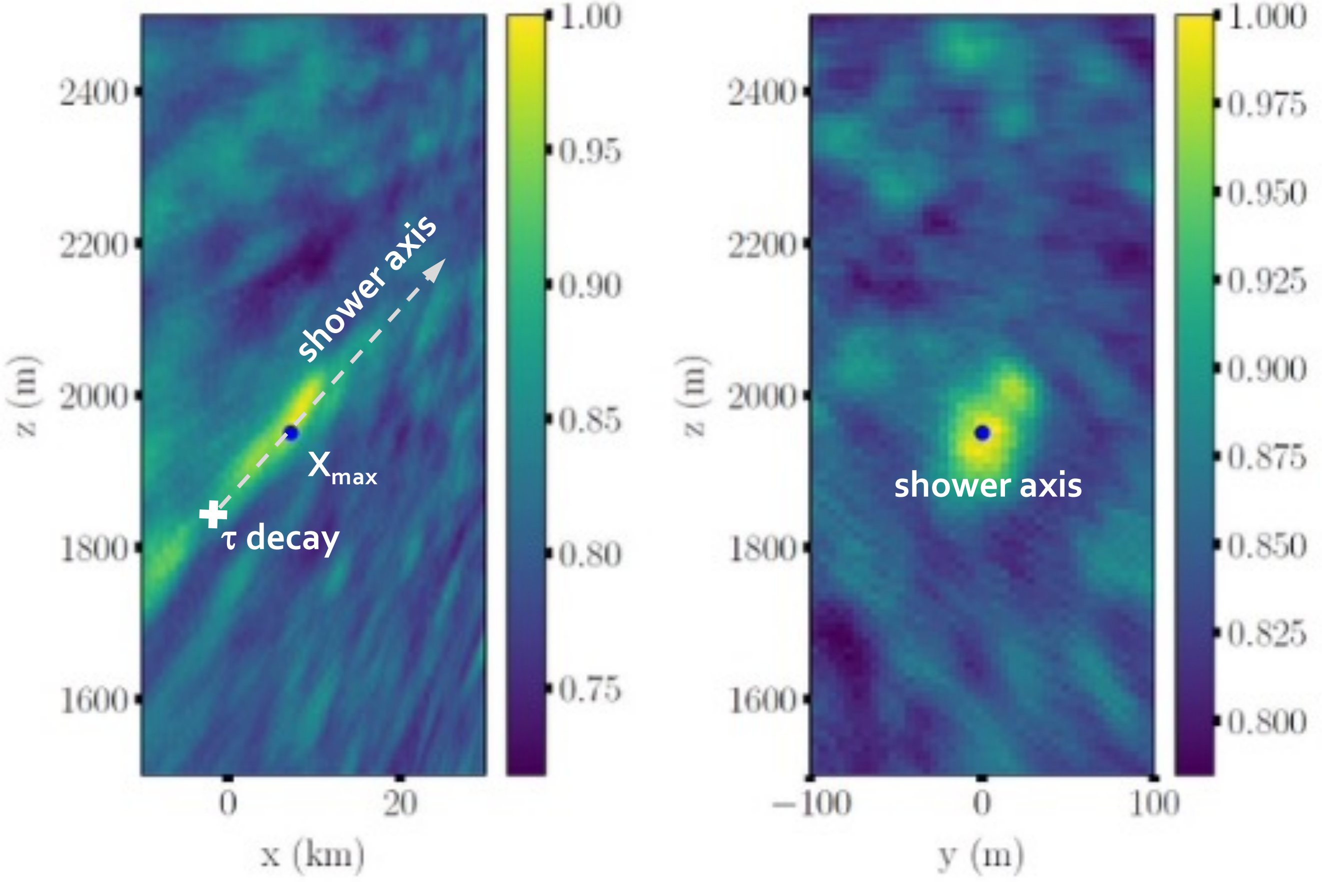
Performance:
quasi-horizontal event reconstruction with standalone array

- combining *classic* **Cherenkov cone mapping** on array with *novel* **interferometric reconstruction** to determine shower parameters

- **3D mapping of emitting region of air shower**: beamforming standalone antenna signals assuming point source & shifting signals by propagation time from source
  - accurate reconstruction of shower direction & position of maximum development, sub-degree angular resolution down to E < 10^{17} eV
  - essential for CR/ν discrimination

- **note**: reconstruction can only improve when combining standalone antenna signals with (stronger) signals from phased array

3D mapping of emitting region of τ-induced air shower



(see Valentin Decoene & Arsene Ferriere talk next)

GRAND - BEACON
ongoing work

- **design optimization**:
  - layout
  - antenna design, frequency range, gain (for phased & standalone arrays)
  - optimize beams of phased array, study phasing efficiency
- **computing voltage** for antennas
- **measurements of sky noise** when pointing at ground, need to conduct RFI site-survey
- **advanced algorithms** to extract **low SNR signals** in standalone antennas triggered by phased array
- **reconstruction performance** on low-threshold signals from standalone & phased array
- evaluate impact of **topography**
- **…**

Institutions (alphabetical per country) involved/expressed interest in GRAND-BEACON R&D

- CNEA (Argentina) – I. Allekotte, F. Sanchez, …
- Inst. Física de La Plata (Argentina) - **M. Tueros**
- Xidian Univ. (China) **– Pengfei Zhang**
- PMO (China) **– Zhang Yi**
- Institute of Physics, Czech Academy of Sciences (Czech Republic) – **M. Bohacova**
- IAP, Paris (France) – **K. Kotera, R. Alves-Batista**, **P. Minodier**
- LPNHE, Paris (France) – **O. Martineau**
- Université Paris-Saclay, CEA, List (France) - **A. Benoit-Lévy, A. Ferrière**
- Lab. Univers et Particules Montpellier (France) – **C. Guepin**
- SUBATECH, Nantes (France) - **V. Decoene**
- Univ. Clermont Ferrand (France) – **V. Niess**
- Univ. of the Aegean (Greece) – **A. Leisos, G. Vittakis**
- Hellenic Open University, Pátrai (Greece) – **S. Nonis**
- IGFAE, Univ. Santiago (Spain) - **J. Alvarez-Muñiz**, **S. Cabana-Freire**
- Penn State Univ. (USA) – **S. Wissel**, **A. Zeolla**, **K. Murase**

GRAND
BEACON
GRAND & BEACON

collaborators welcome!

Current funding opportunities

- **Synergy Grant ERC** 14M€ for 6 yrs – submitted Nov. 2024
  - requested funds for all equipment, deployment costs and personnel
  - passed Phase 1 → Phase 2 decision before 15 Aug. 2025 → Phase 3 (interview in Brussels) 8-12 Sept. 2025
  - Final decision – before 27 Oct. 2025
- **Kavli foundation** (USA) start-up 10k$ + next step 14k$ – submitted Jan. 2025
- **CNRS Intl. Research Network** (France) 75 k€ for 5 yrs – to be submitted June 2025
- **ANR (French National Research Agency) - MRSEI** (France) 35k€ for 2 yrs
  - support to apply to European programmes
- **CNRS - AMORCE** (France) 10k€ for 1 yr
  - support for development of European coordinated research projects
- **Oportunius program, Xunta de Galicia** (Spain) 50k€ for 2 yrs
  - support for improving ERC projects (if Phase2 passed)
- Argentina *in kind* – local support from San Juan Province

GRAND - BEACON

final remark

HERON ***builds on the proven technologies*** developed with the GRAND and BEACON prototypes, while ***contributing to a landscape of scientific, practical, and technological challenges*** **shared by these and other projects**.

HERON also aims to create a fertile ground for synergies, learning, and productive feedback.

New collaborators are warmly invited to join!

Backup

GRAND + BEACON
conclusions & ongoing work

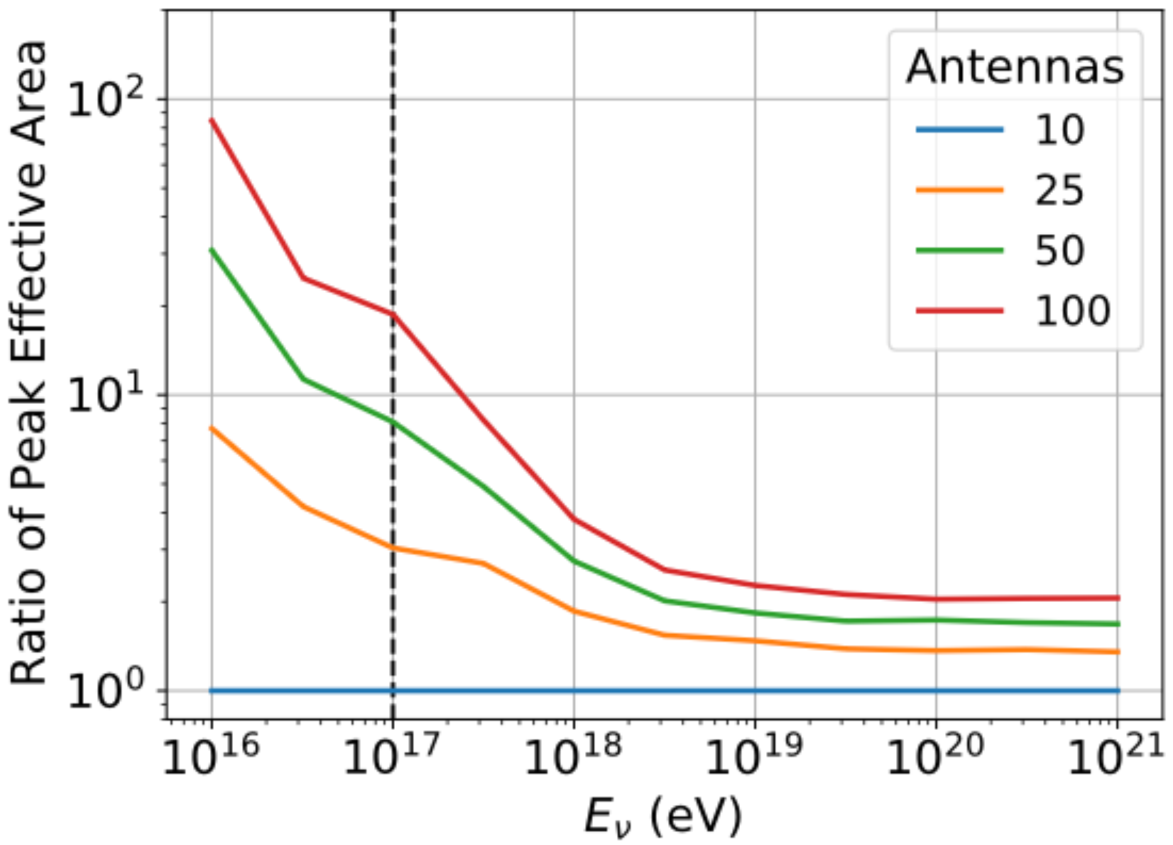
HERON

- **combined approach resulting in an ambitious and groundbreaking hybrid design:**
  - **phased arrays for low thresholds & directional masking of noise with phasing**
  - **sparse autonomous antennas for reconstruction, CR/nu discrimination, noise rejection & additional effective area at high energies**
    - 10 times instantaneous sensitivity of current approaches; sub-degree angular resolution; wide daily field of view; connected to the worldwide network of MM observatories: follow-up & sending alerts
  - target discovery in 5 – 10 years
  - given its **scalability** it could be possible to **extend HERON**, further improving its design, to produce (a maybe even larger) distributed observatory

- **work for immediate future:**
  - **design optimization**: layout, antenna design & frequency range, antenna beams, gain…
  - **reconstruction performance** on low-threshold signals from standalone & phased array
  - impact of **topography**
  - **measurements of sky noise** when pointing at ground, need to conduct RFI site-survey

Simulations: Performance of phased array

- Increasing number of antennas included in phased array increases peak effective area
- 24 antennas for the nominal design: factor 3 more sensitive than 10, and feasible to install practically.
- Effective area linear with gain of phased array (log of)
- Beams will be tuned to cover the full annulus at horizon. Number of beams needed scales with beam gain.



R&D on antennas

T. Huege and O. Krömer, JINST 19 (2024) P11022

Rhombic antenna: very promising in the 30 – 80 MHz band

- mechanically very **simple**
- **narrow beam at a low elevation above the horizon** – tilt for sensitivity below horizon or use mountain slope
- horizontally and vertical polarized versions both with narrow beam in azimuthal direction of ~ 20° – 60° half-power width
- relatively **insensitive to ground conditions**