HERON
Hybrid Elevated Radio Observatory for Neutrinos

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INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS (IGFAE)

IGFAE Retreat
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European Research Council
Established by the European Commission

HERON

USC Universidade de Santiago de Compostela

Ministerio de Ciencia, Innovación y Universidades

Agencia Estatal de Investigación

Rede CIGUS
Centros de investigación do Sistema Universitario de Galicia

Cofinanciado por la Unión Europea

Fondos Europeos

Xacobeo 2027

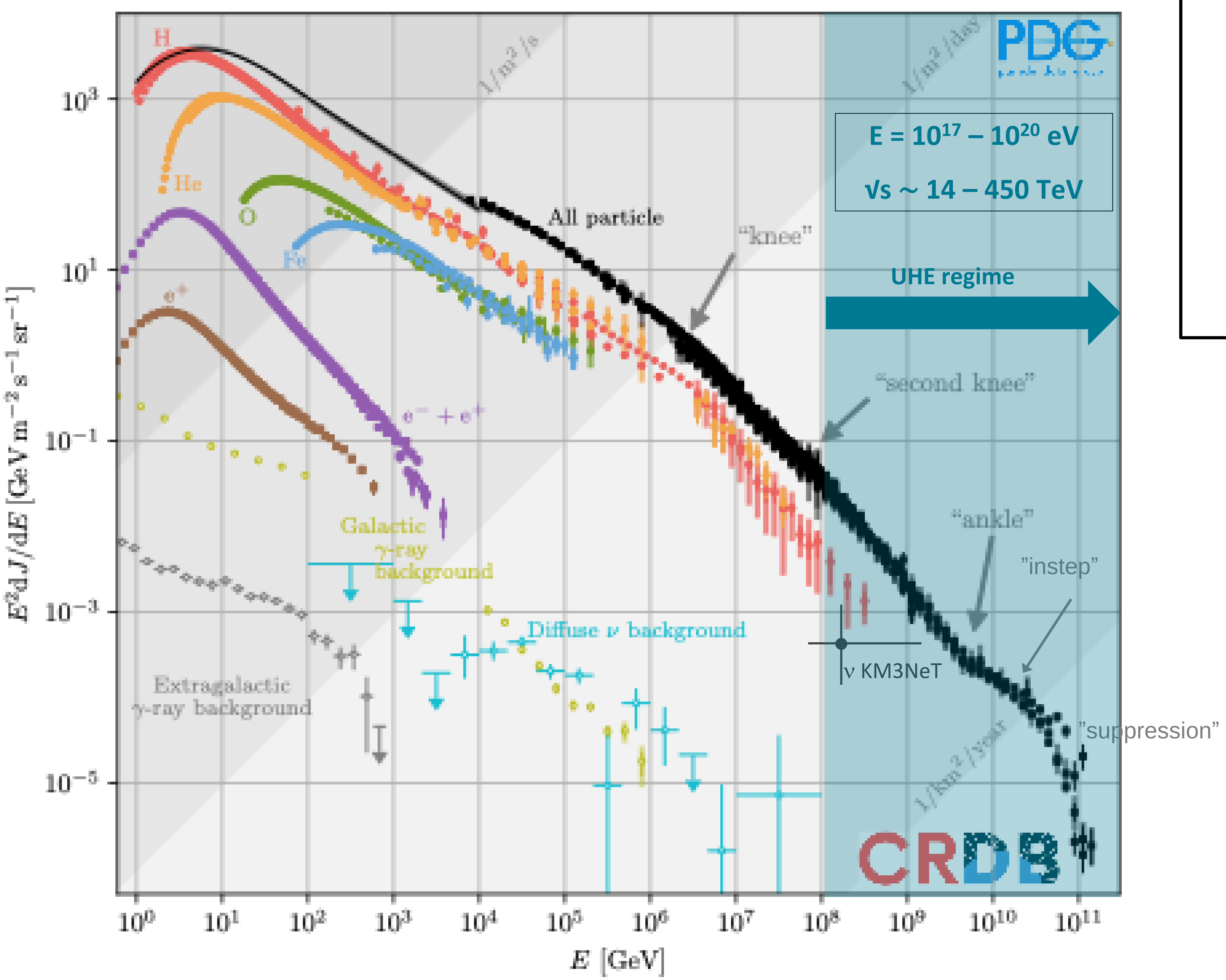
Image credit: DESY

HERON Science Case:
Enhance Multimessenger Astronomy at Ultra-High Energy with neutrinos

*Messengers are created by different astrophysical processes, and reveal **different & complementary information** about their sources.*

Energy spectrum of cosmic rays

J. A-M, Z. Cao, U.F. Katz, P. Mertsch, C. Spiering.
Chapter 30 "Cosmic Rays" Particle Data Group
PRD **110** (2024) 030001



at **E > 10^{15} eV** (**> 10^{18} eV**) the CR rate is

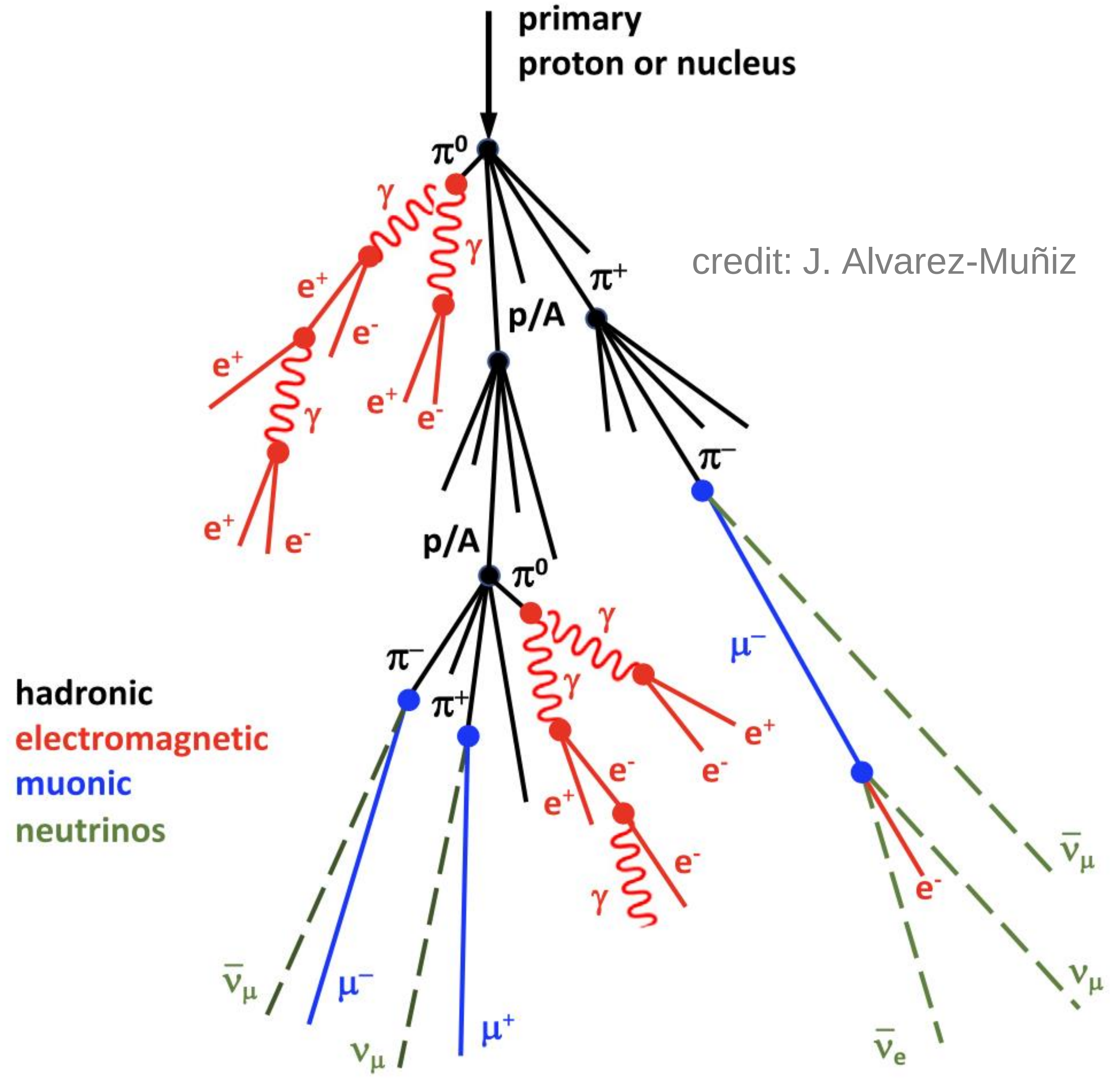
~ 1 particle per m^2 per year

(~ 1 particle per km^2 per year)

=> **indirect detection** of

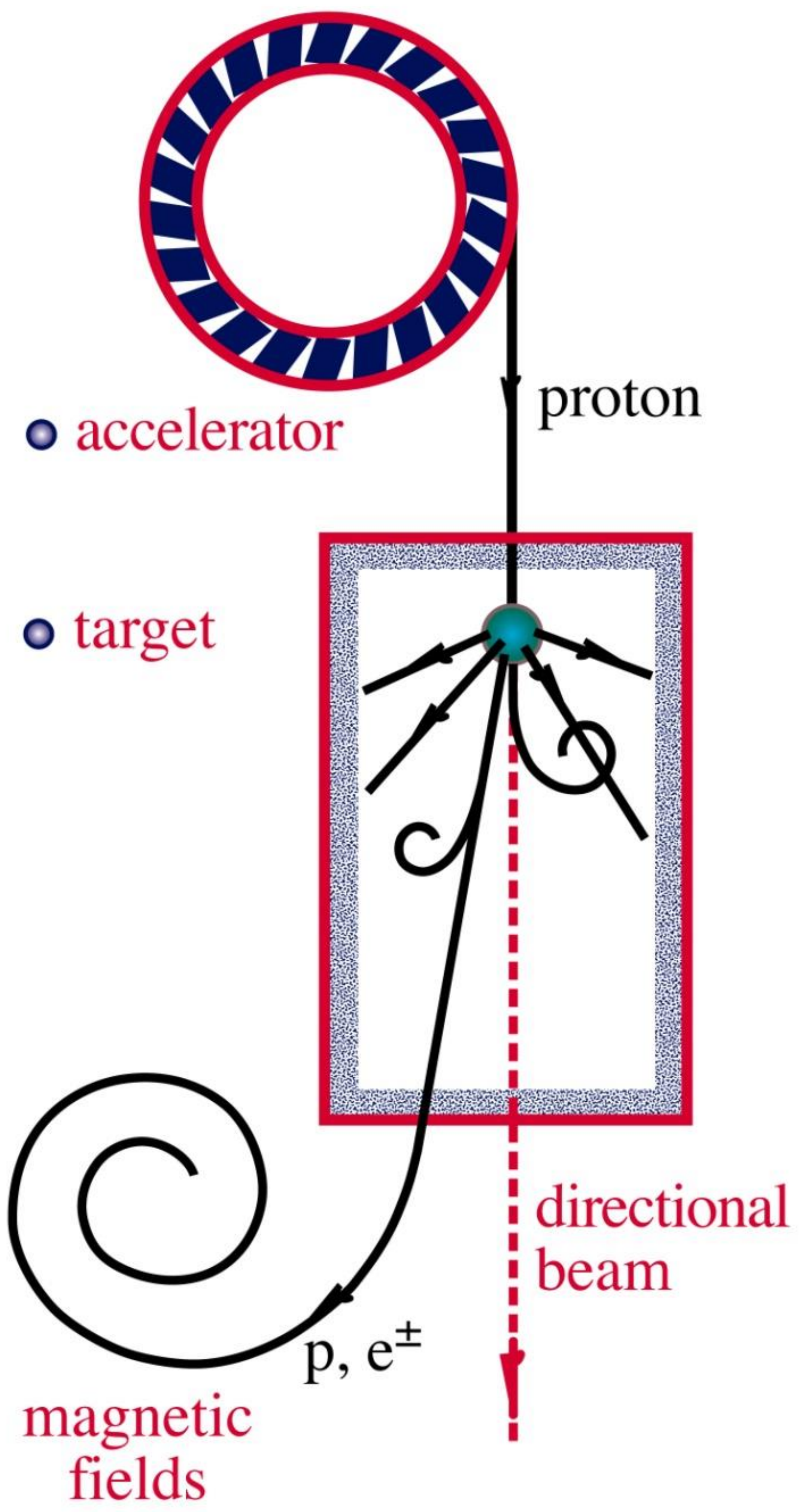
Extensive Air Showers with

particles, optical Cherenkov, radio emission



Neutrino beams: Heaven & Earth

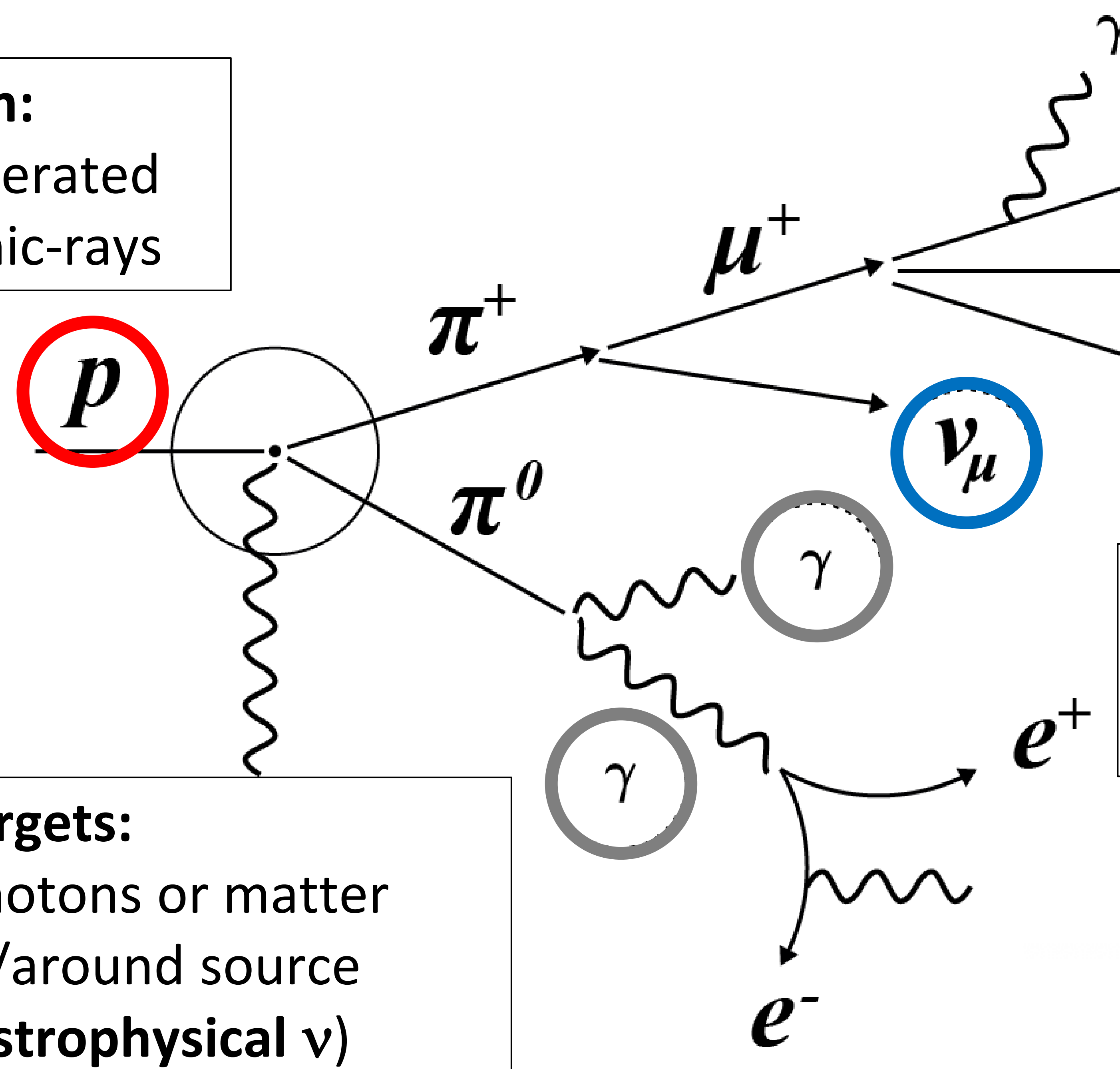
Earth



credit: Francis Halzen

"Standard model" of ν production

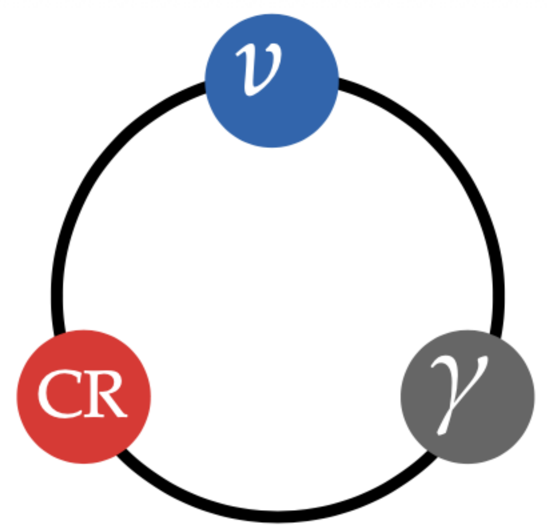
beam:
accelerated cosmic-rays



$\langle E_\nu \rangle \sim E_p/20$
mainly ν_μ & ν_e at production

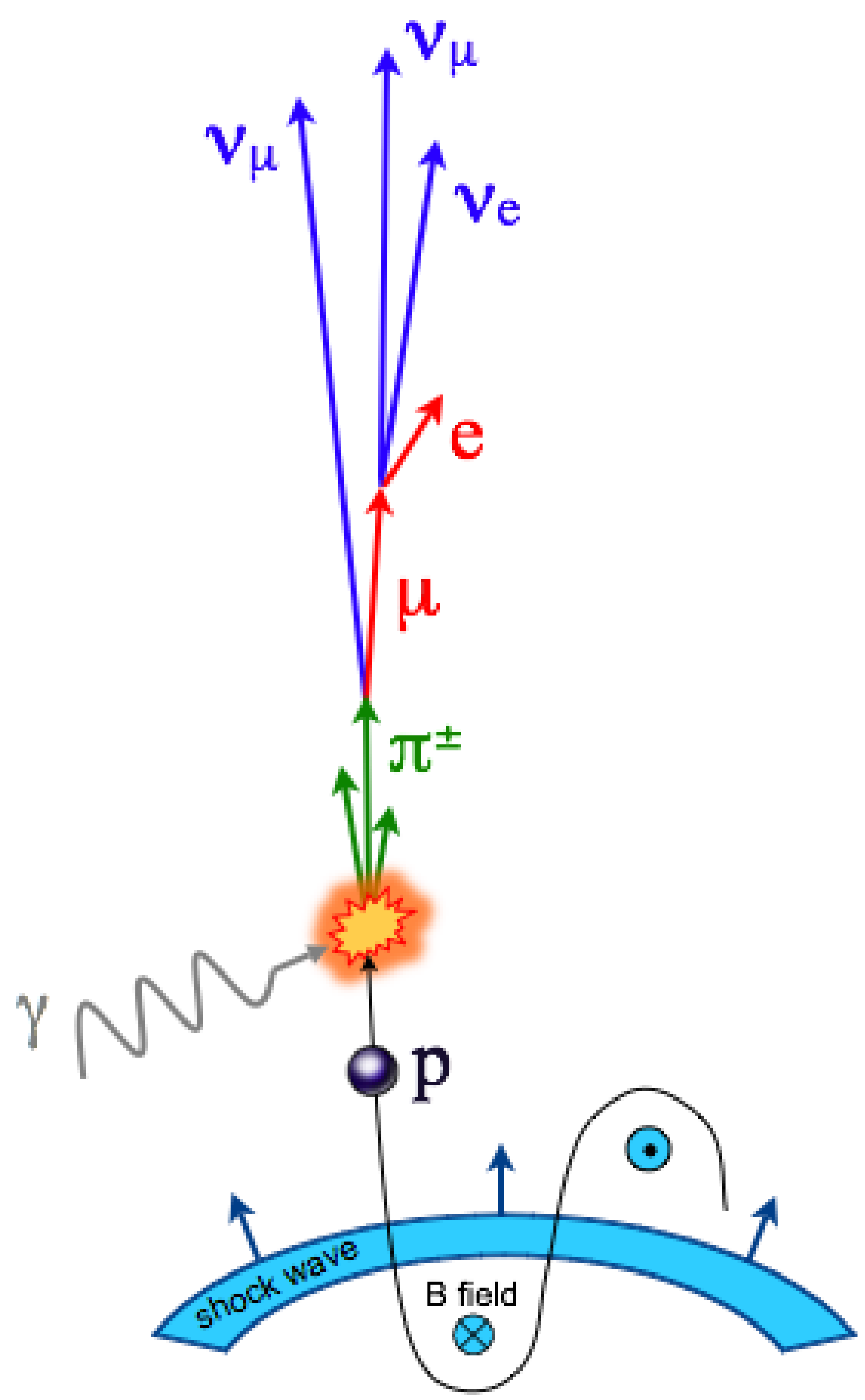
targets:
photons or matter in/around source (**astrophysical ν**)

CMB photons (**cosmogenic ν**)



Multi-Messenger connection

Heaven



credit: T, De Young

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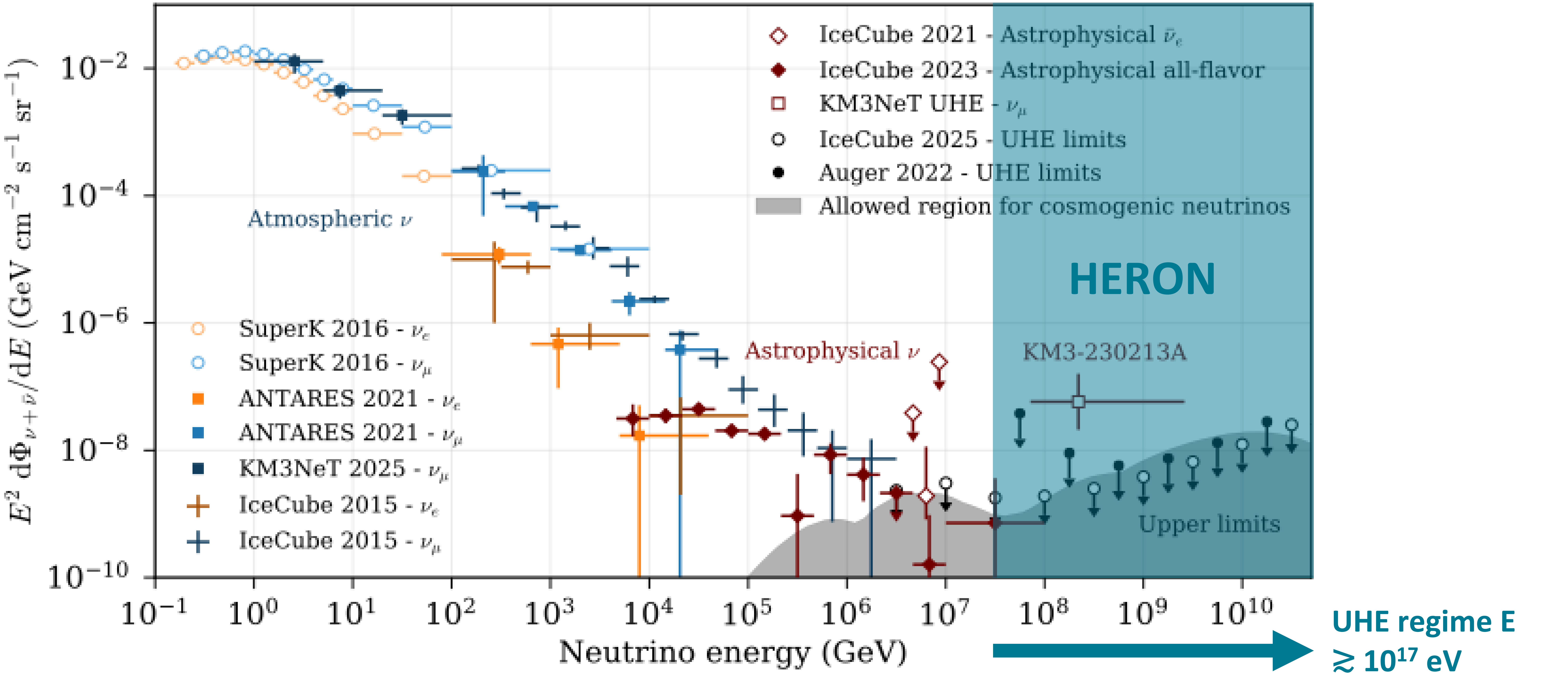
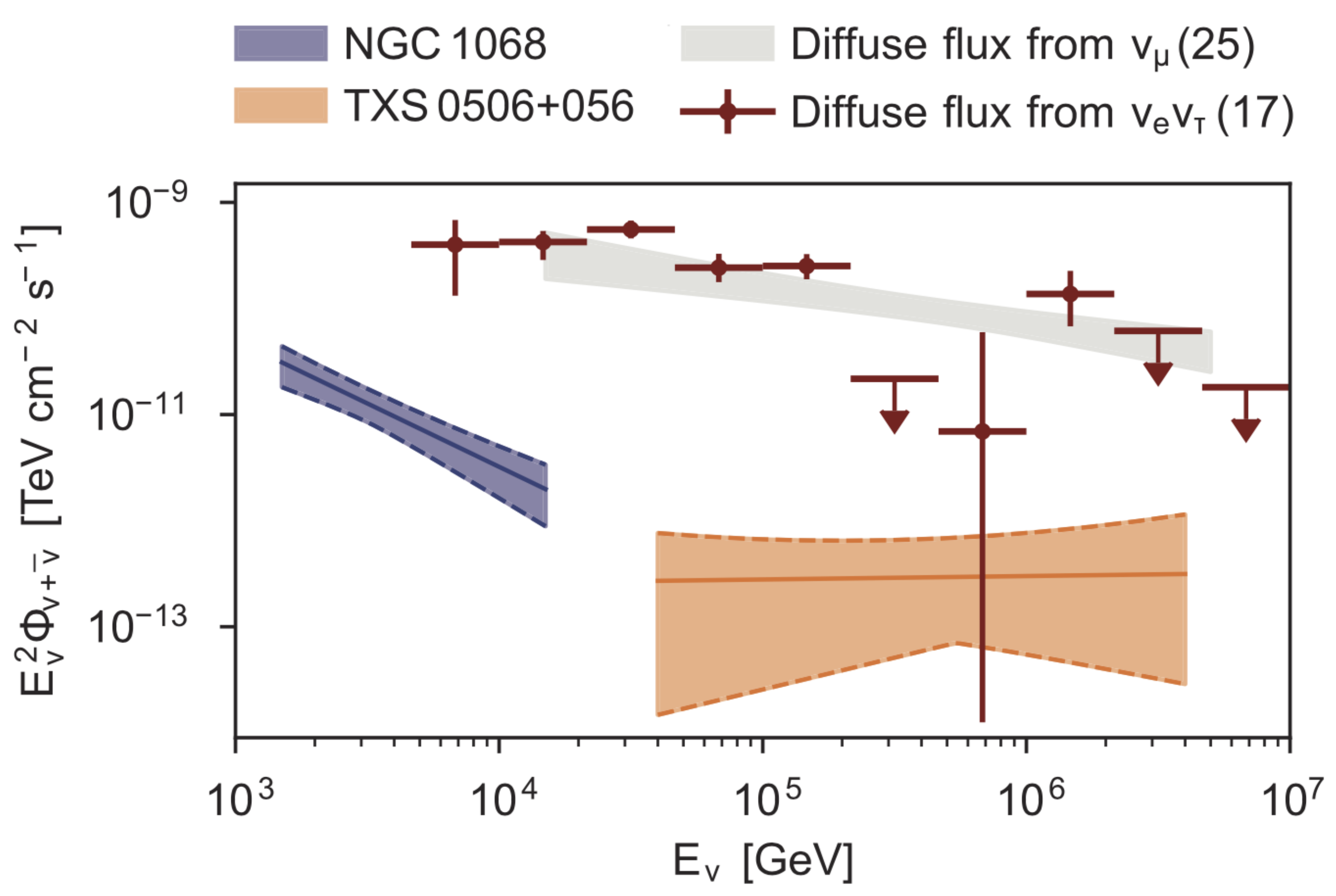
Energy spectrum of neutrinos



► energy range above $E_\nu \cong 10^{16} - 10^{17}$ eV is (almost) **uncharted territory**

Recent discoveries in neutrino astronomy

- **first identified neutrino sources** at energies ≅ 10^{12} eV (NGC 1068) and ≅ 10^{14} — 10^{15} eV (TXS 0506+056)
- NO CANDIDATE SOURCES AT UHE



also Galactic Plane

&

Astrophysical ν flux

IceCube at E < 10^{16} eV

Origin unknown

IceCube

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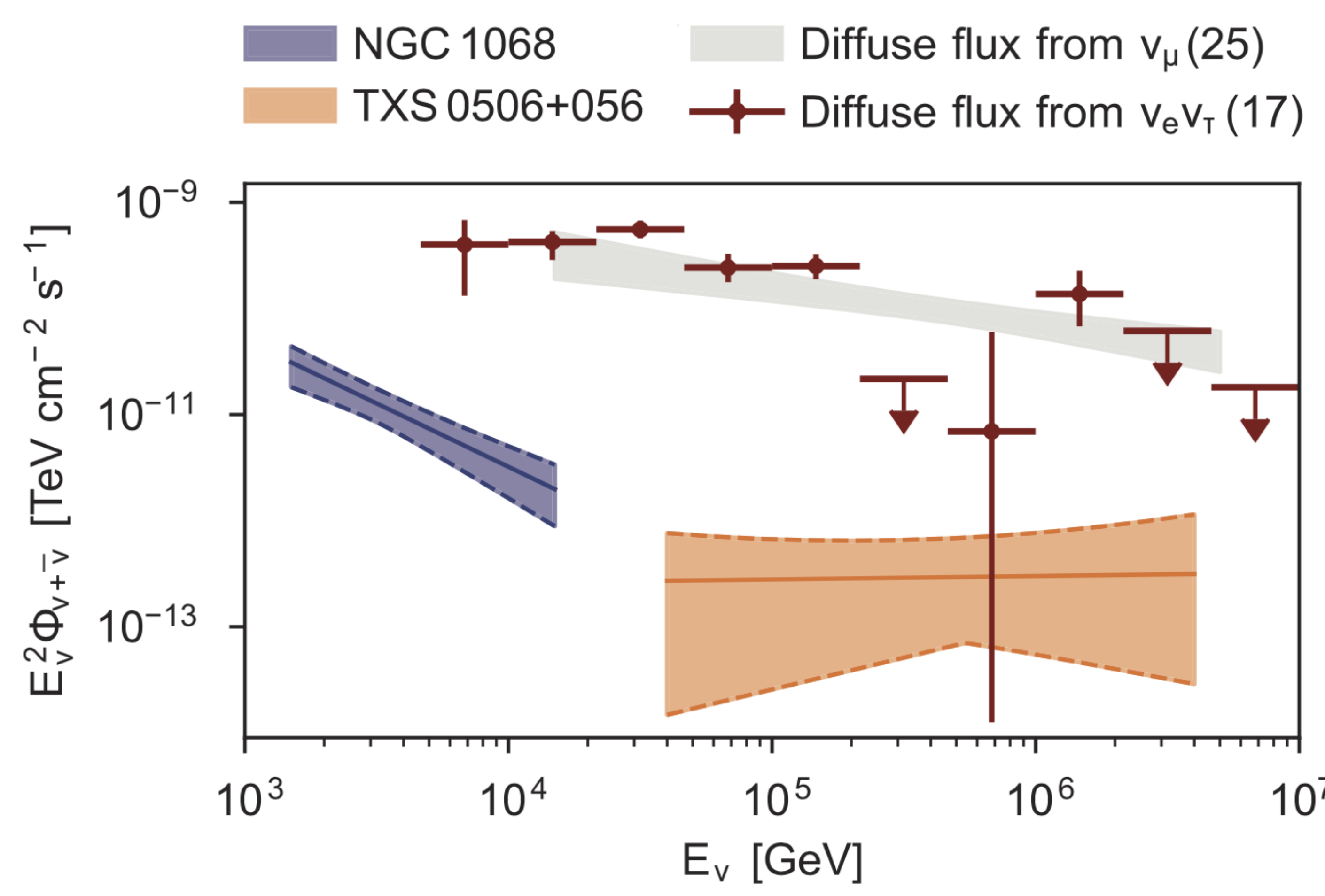
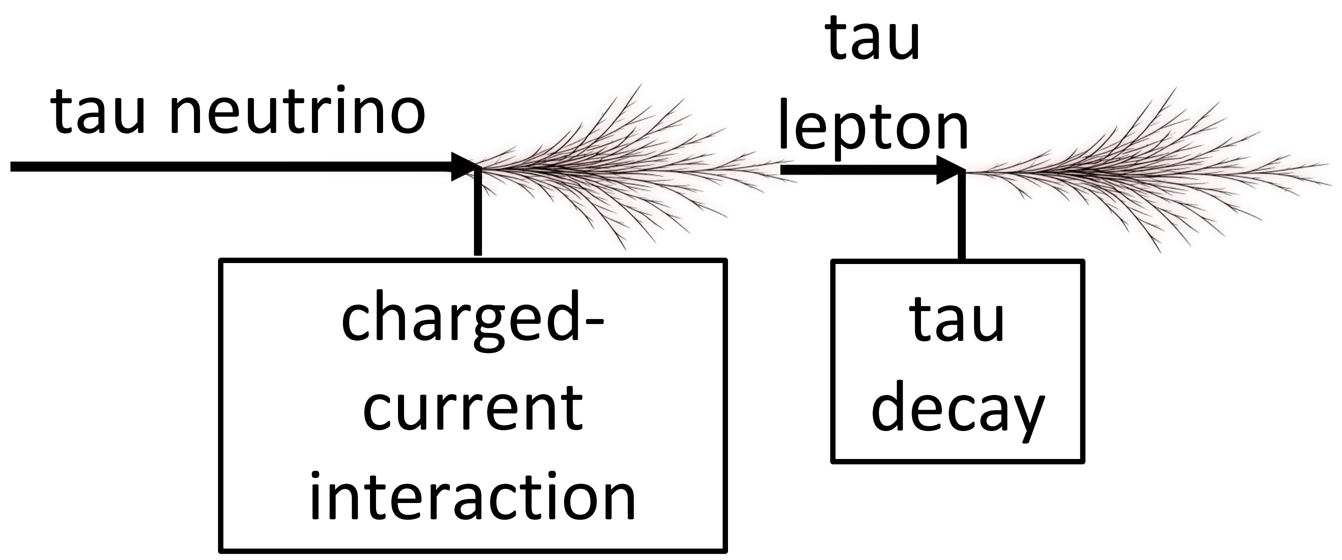
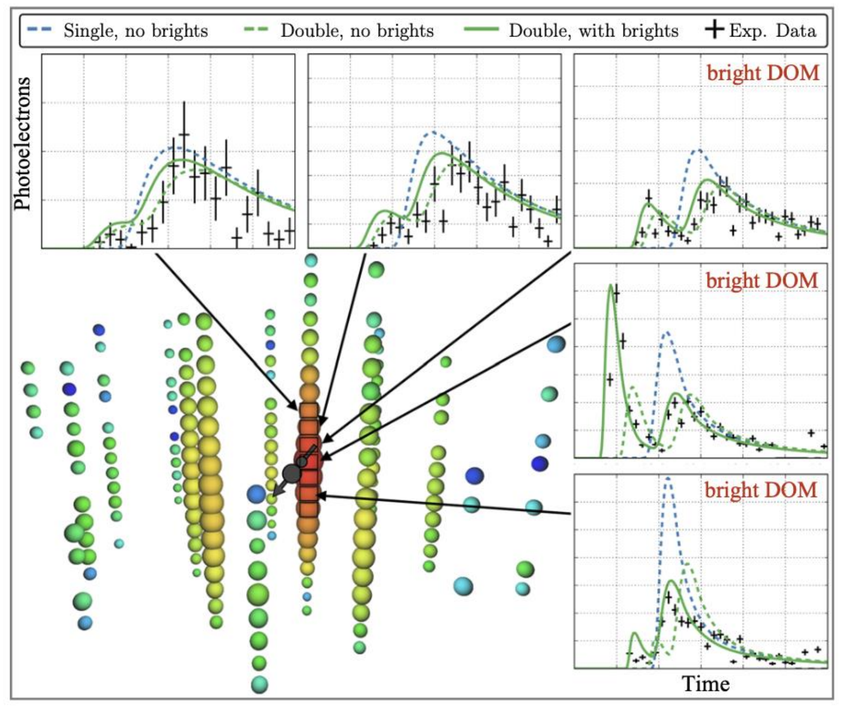


also Galactic Plane
&
Astrophysical ν flux
IceCube at $E < 10^{16}$ eV
Origin unknown

IceCube

- ▶ **7 tau neutrinos** identified in the cosmic flux. Median energy 2 x 10^{14} eV
- ▶ TAU NEUTRINOS EXIST IN COSMIC FLUX





"Double-Double"
a *double bang* tau neutrino candidate INSIDE IceCube

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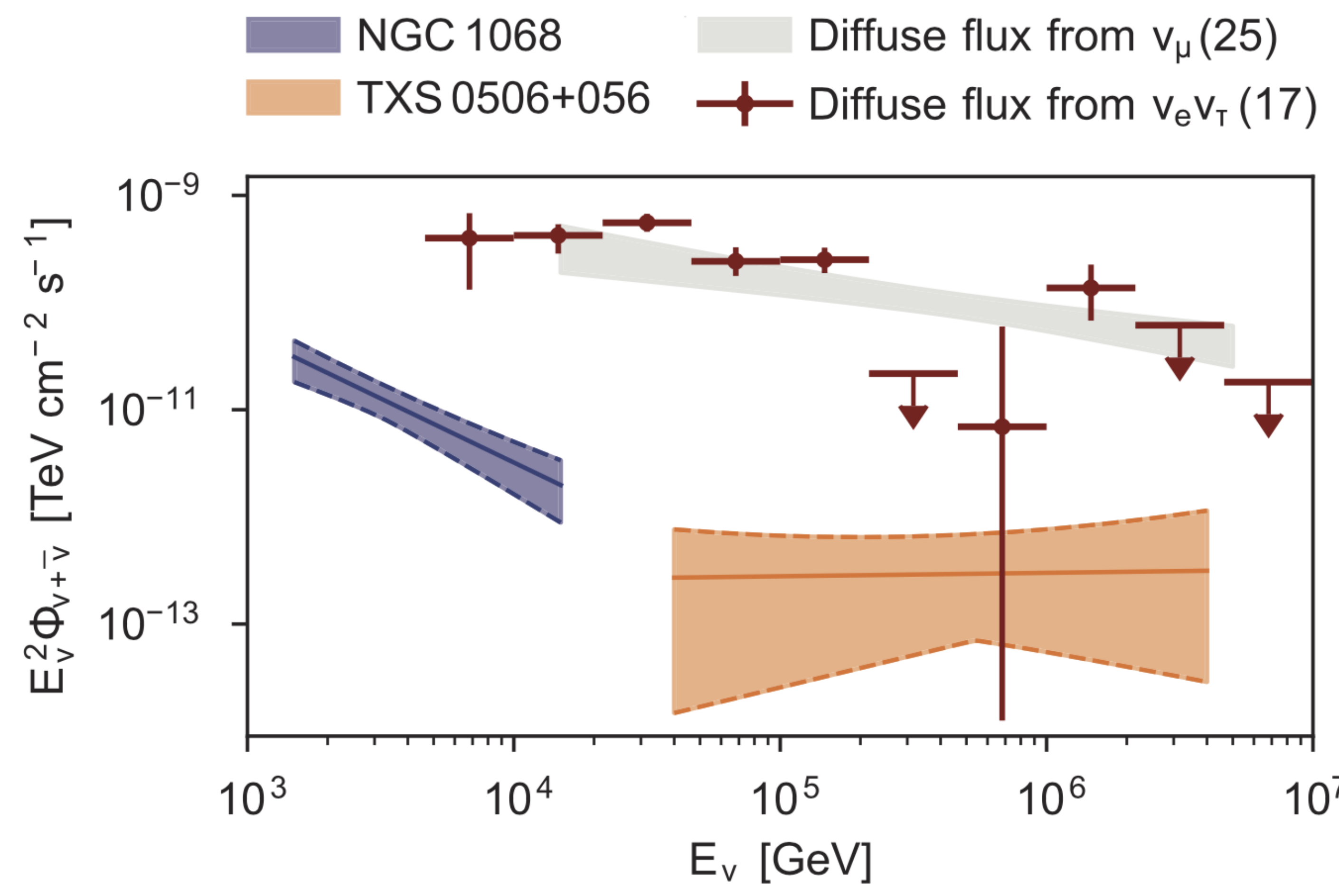

also Galactic Plane & Astrophysical ν flux IceCube at E < 10^{16} eV

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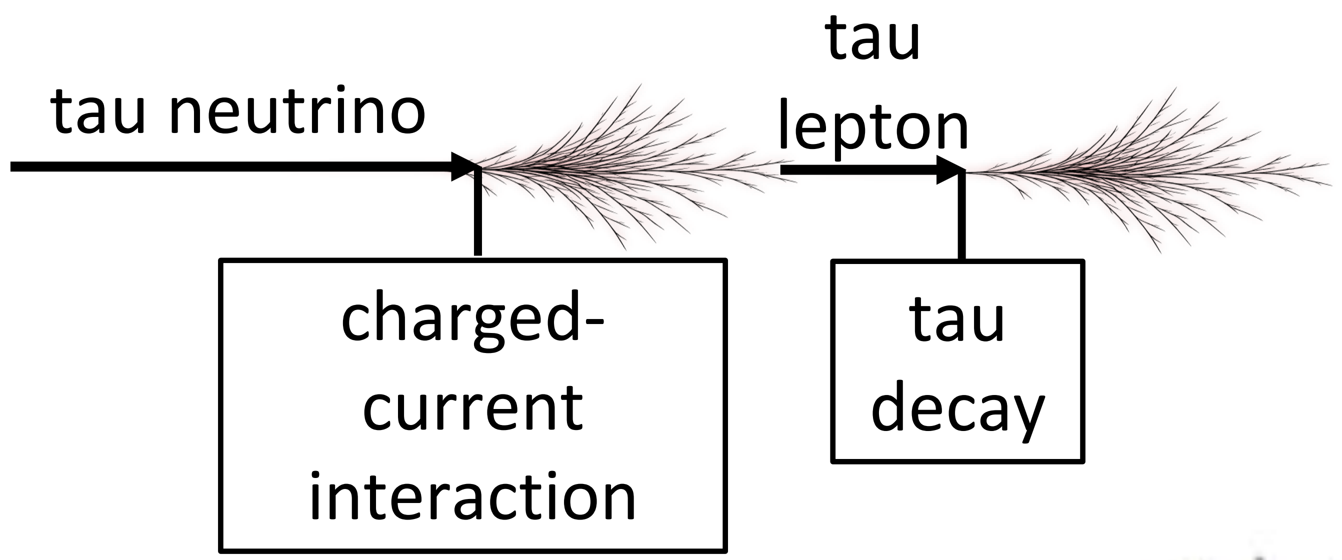

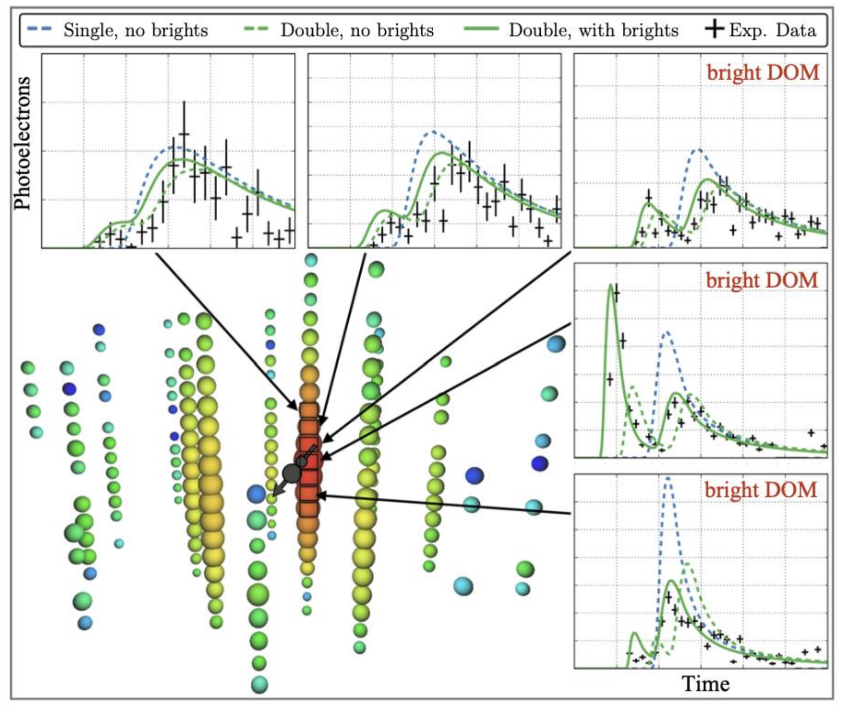

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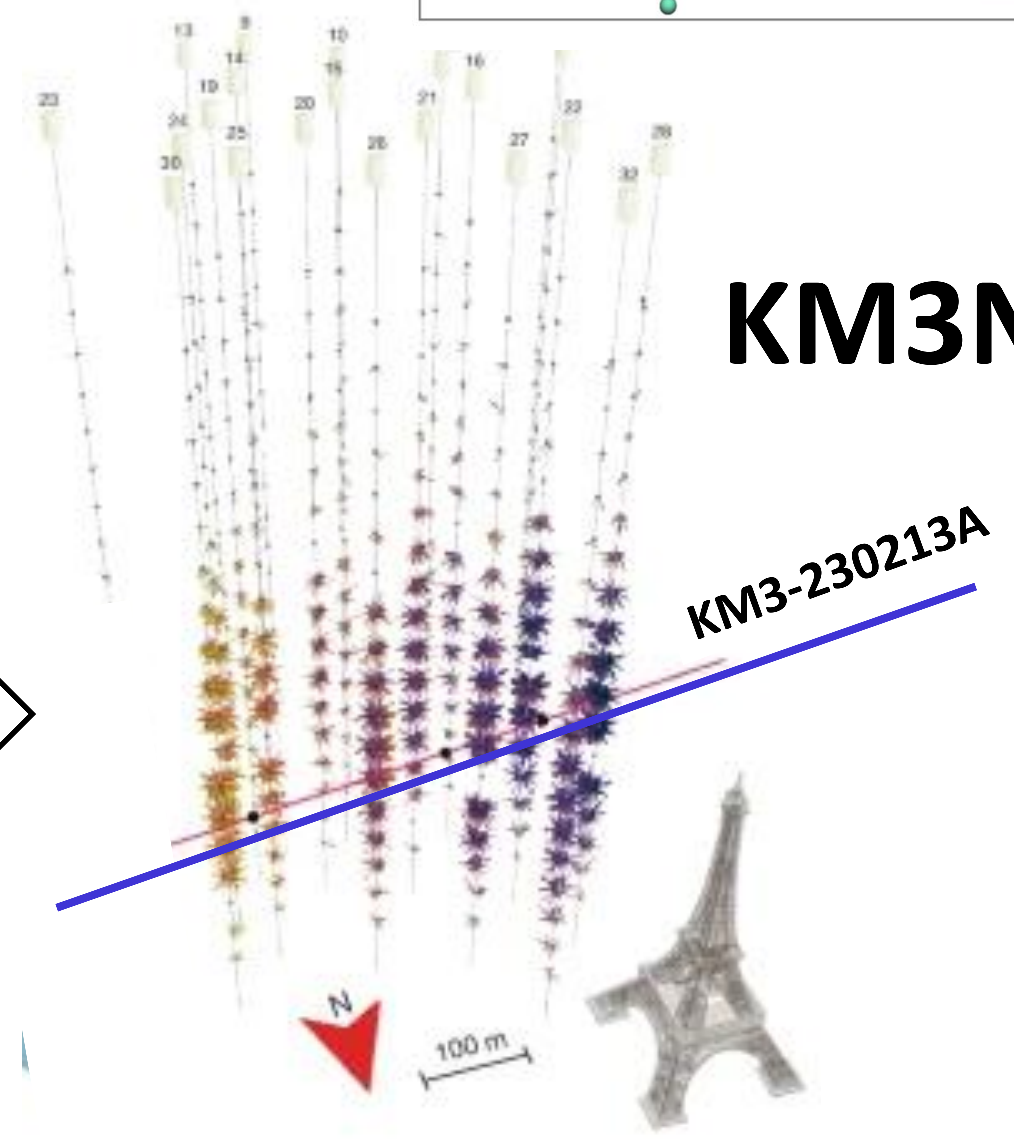
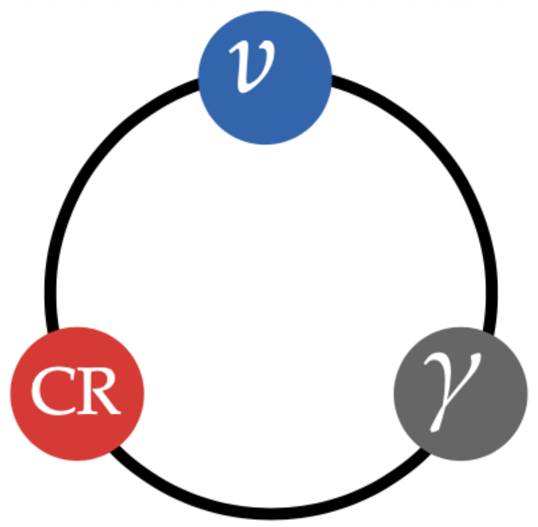
KM3NeT

- ▶ **highest energy neutrino candidate** estimated E_ν ≅ 1.1 x 10^{17} eV — 7.9 x 10^{17} eV source unknown (insufficient angular resolution)
- ▶ UHE COSMIC NEUTRINOS EXIST !!



Questions & Challenges at Ultrahigh Energy

- what are the **sources of UHE Cosmic Rays?**
- **acceleration mechanisms** that boost particles to extreme energies?
- **Multi-Messenger connection?**



- is there a population of **hidden sources** in the Universe opaque to radiation but not to neutrinos ?
- …

Challenges:
the "triple smallness" problem

- extremely **small flux of UHEν**
< 0.01 – 0.1 neutrinos/km²/year at E>10^{18} eV

- **small neutrino interaction probability**
mean free path at $E_\nu = 10^{18}$ eV
~ 650 km of rock

⇒ detection requires **large** instrumented target volumes or monitoring **large** areas

- but typically the **budget** is also **small**…

Hybrid Elevated Radio Observatory for Neutrinos (HERON)

Kumiko Kotera (IAP, CNRS, France)
Stephanie Wissel (Pennsylvania State University, USA)
Olivier Martineau (Sorbonne Université, France)
Jaime Alvarez-Muñiz (IGFAE, Univ. de Santiago de Compostela, España)
+ **Ingo Allekotte & Federico Sanchez** (partners in CNEA, Argentina)

Hybrid: phased antenna arrays + standalone antennas

Elevated: altitude & large extension enable broad viewing area for ν_τ interactions

Radio Observatory: ≅100% duty cycle, cost-efficient, robust, scalable

Neutrinos: the next frontier of Multimessenger Astronomy

A first-of-its-kind experimental concept

936 total antennas

HERON's Proofs-of-Concept

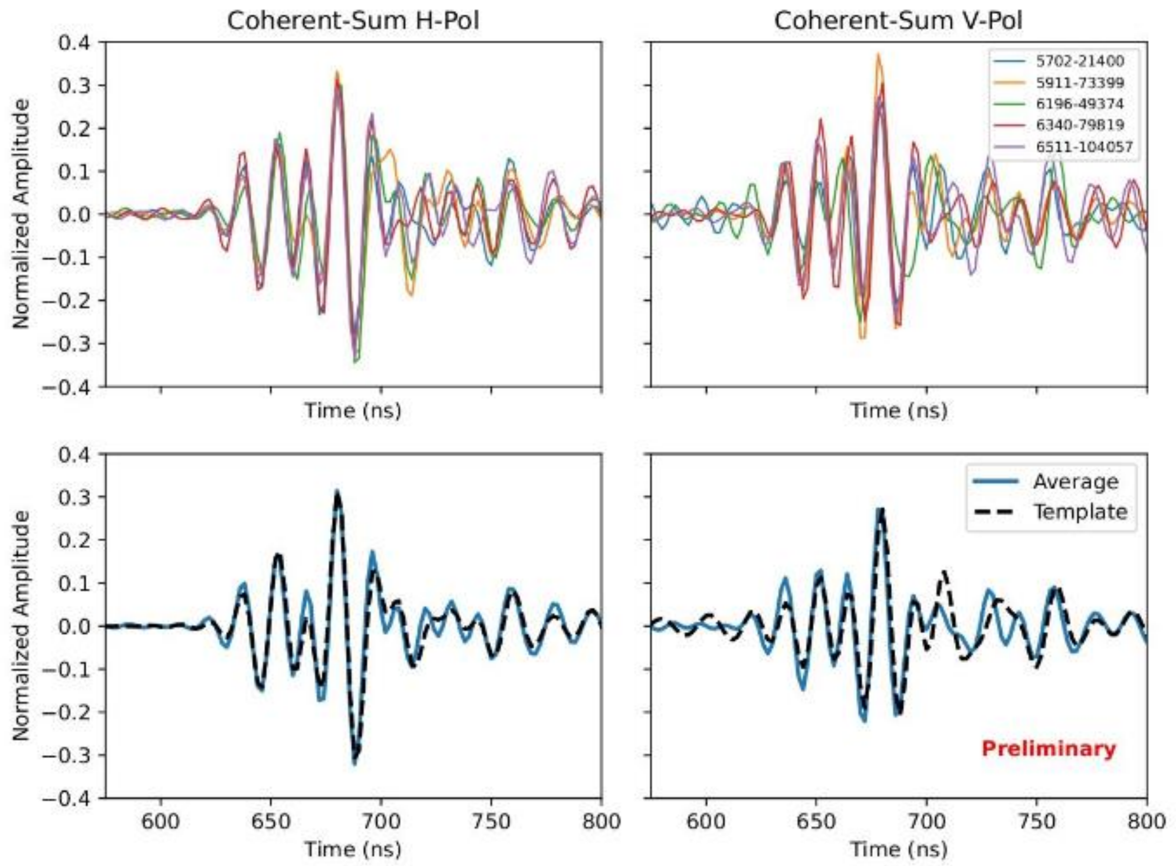
BEACON: Elevated phased arrays

Sensitivity at 10^{18} eV with a handful of antennas

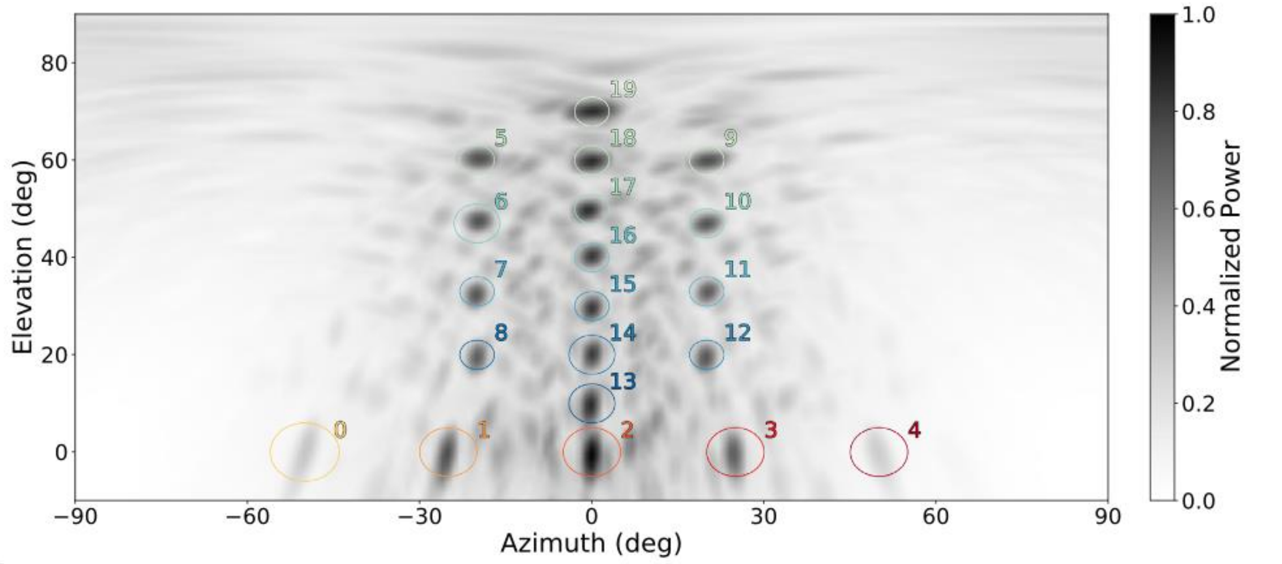
✦ **BEACON: cosmic-ray candidates**

5 radio-only; 10 coincident radio + scintillator

BEACON collab (ICRC2025)



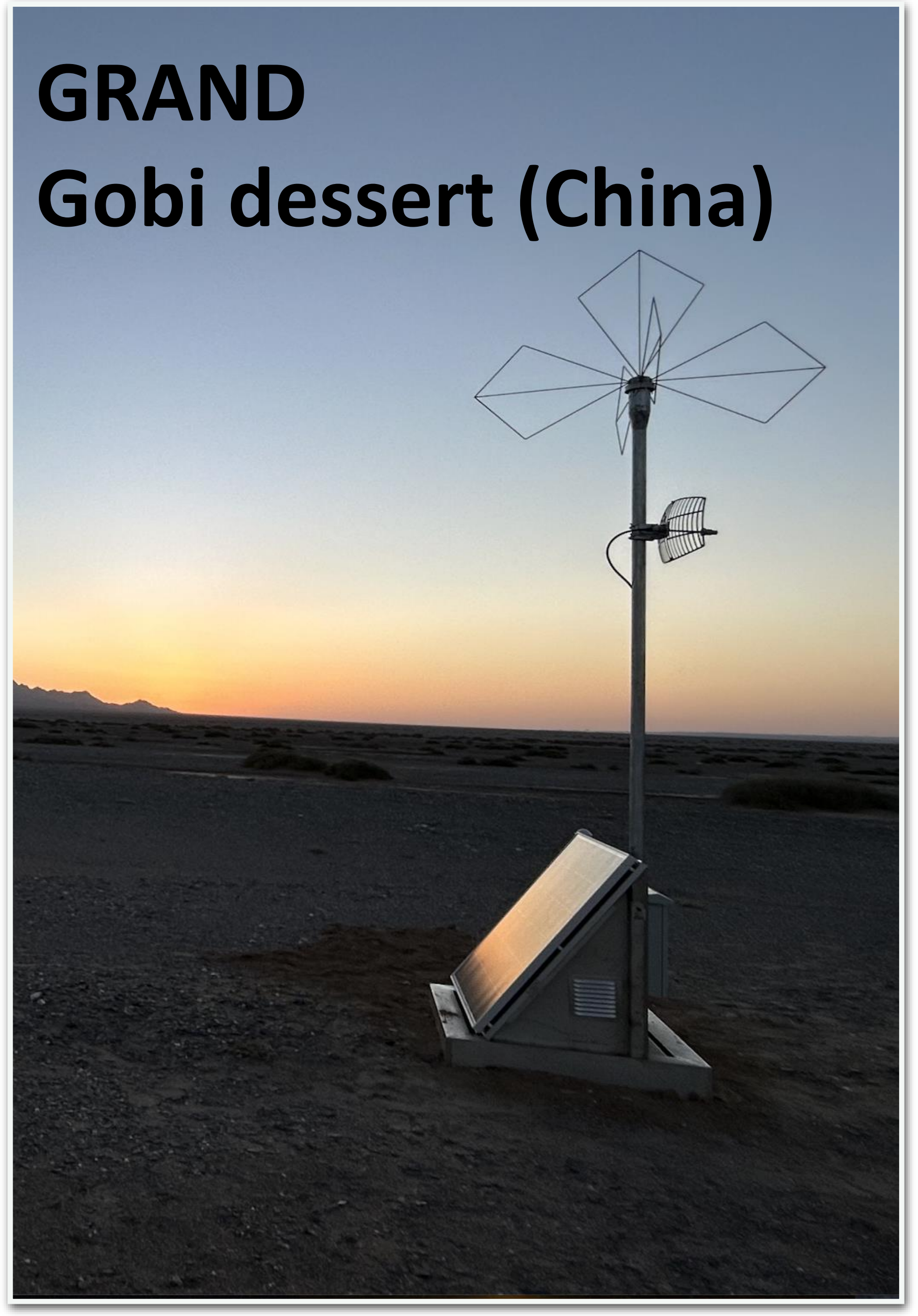
✦ **BEACON validated beamforming**



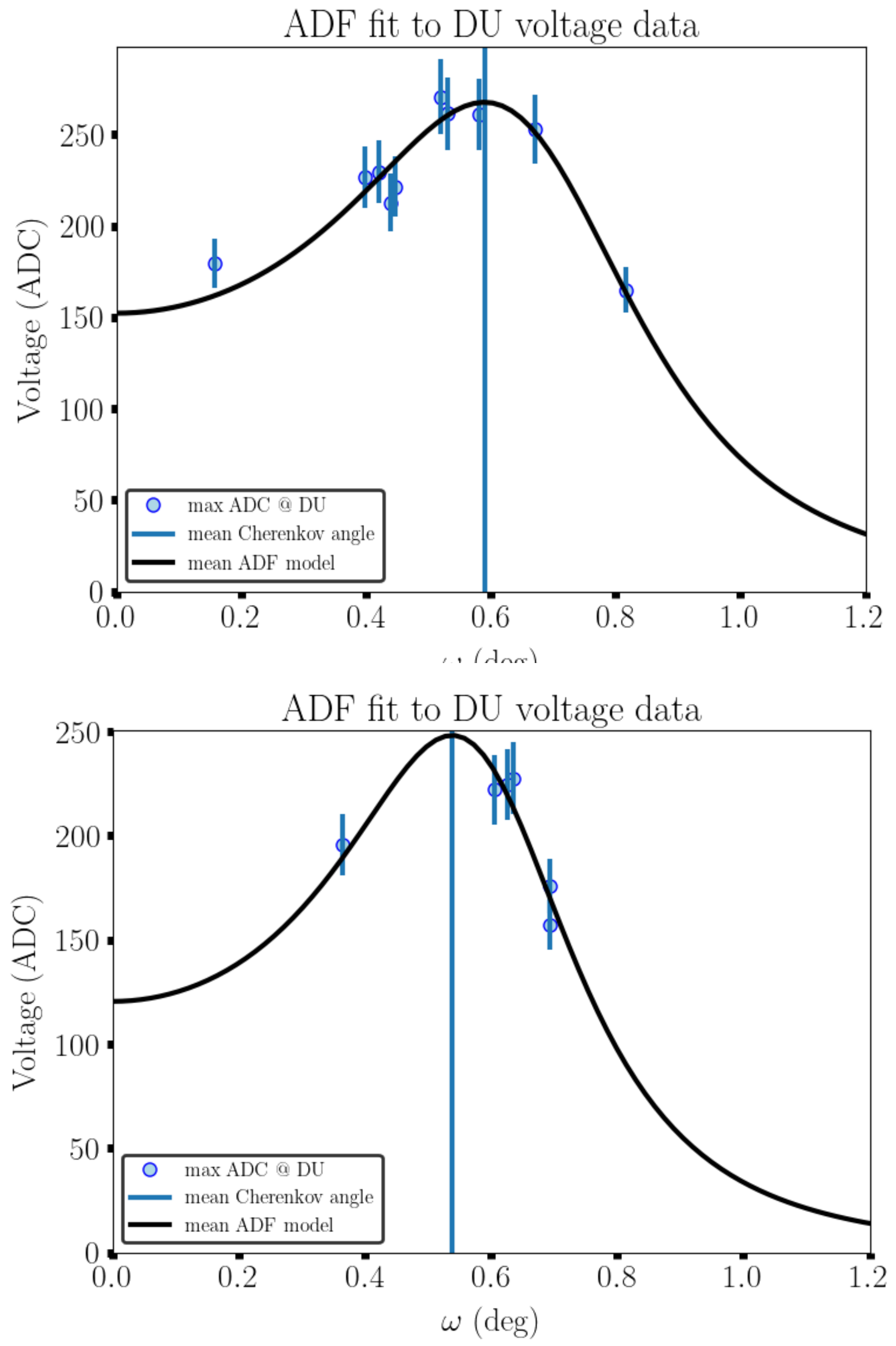
GRAND: Autonomous standalone antennas

Large area, precision pointing

✦ **GRAND Proto 300: 73 cosmic ray candidates**



GRAND collab (ICRC2025)



✦ **GRAND@Auger: 1 coincident candidate GRAND+Auger**

HERON: a transformative discovery project

European Research Council
Established by the European Commission

HERON

What? (goals)

- ❑ launch ultra-high-energy neutrino astronomy
- ❑ probe the most extreme phenomena in the Universe in an uncharted energy range with neutrinos
- ❑ find the sources of the highest energy particles

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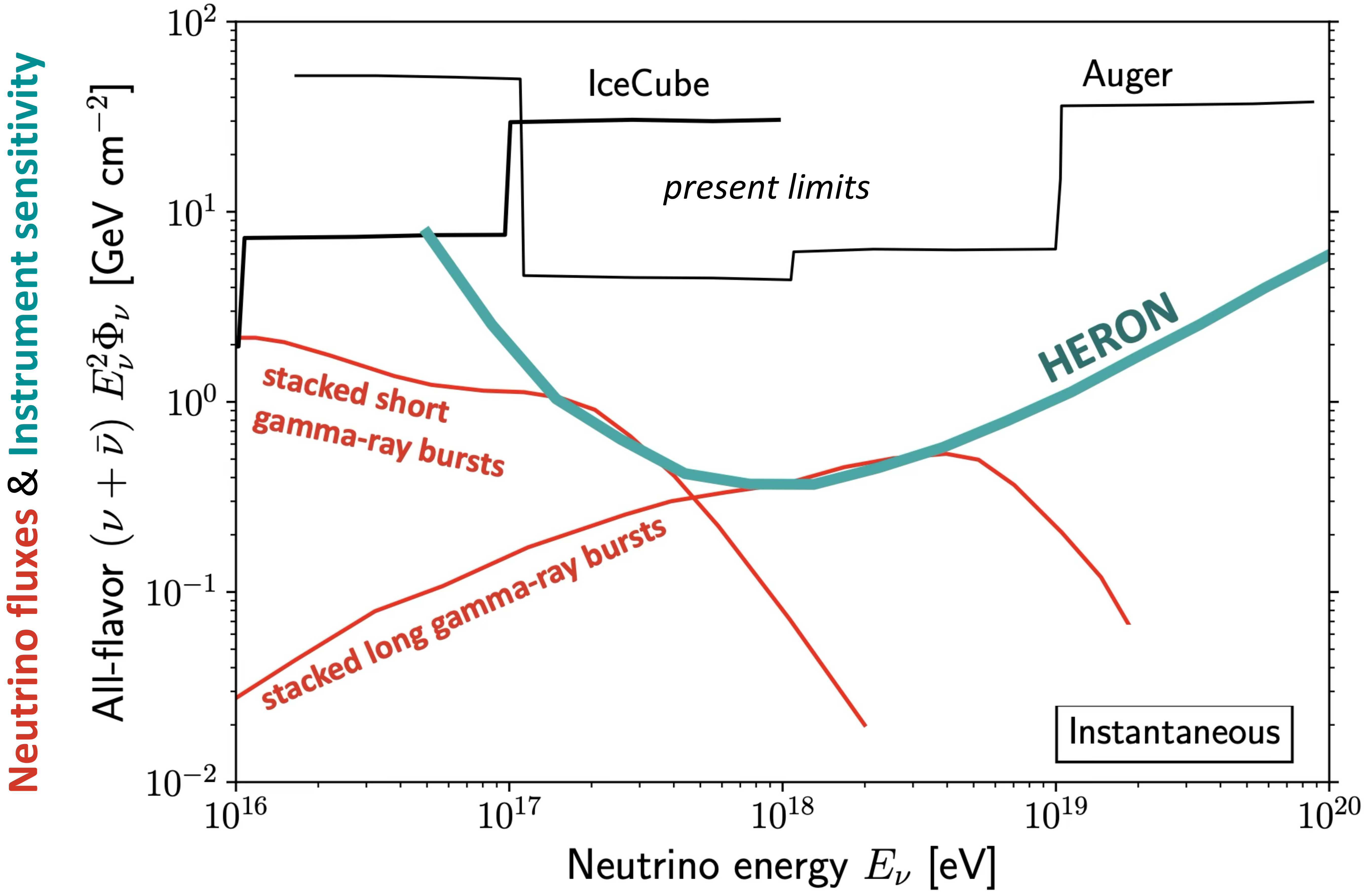
How?

Design, build and operate **HERON**

- ❑ aim for neutrinos E $\gtrapprox 10^{17}$ eV
- ❑ 10 x sensitivity of current experiments
- ❑ sub-degree angular resolution
- ❑ focus on likely neutrino sources (transients)
- ❑ "deep" view of the Universe



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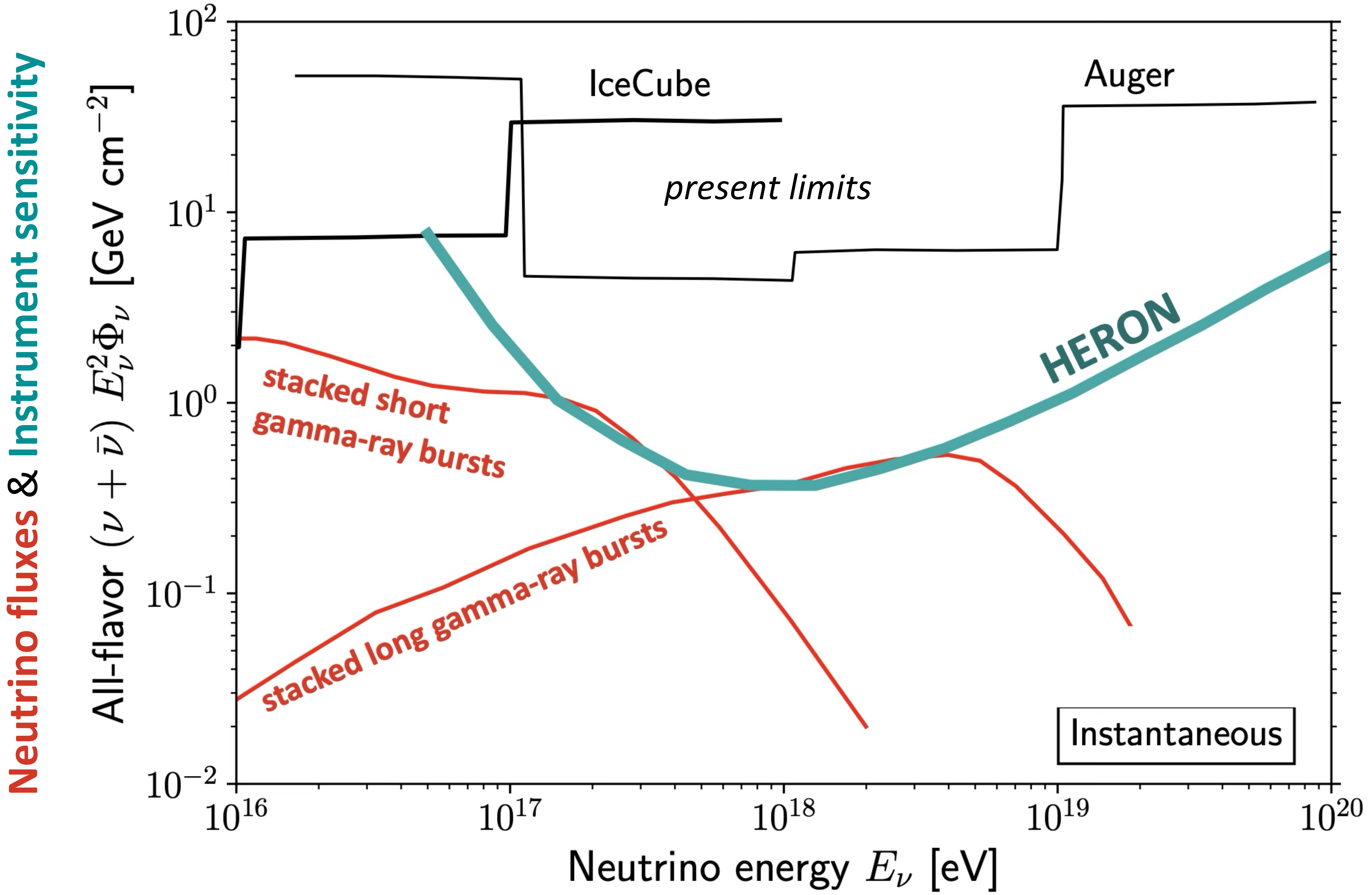
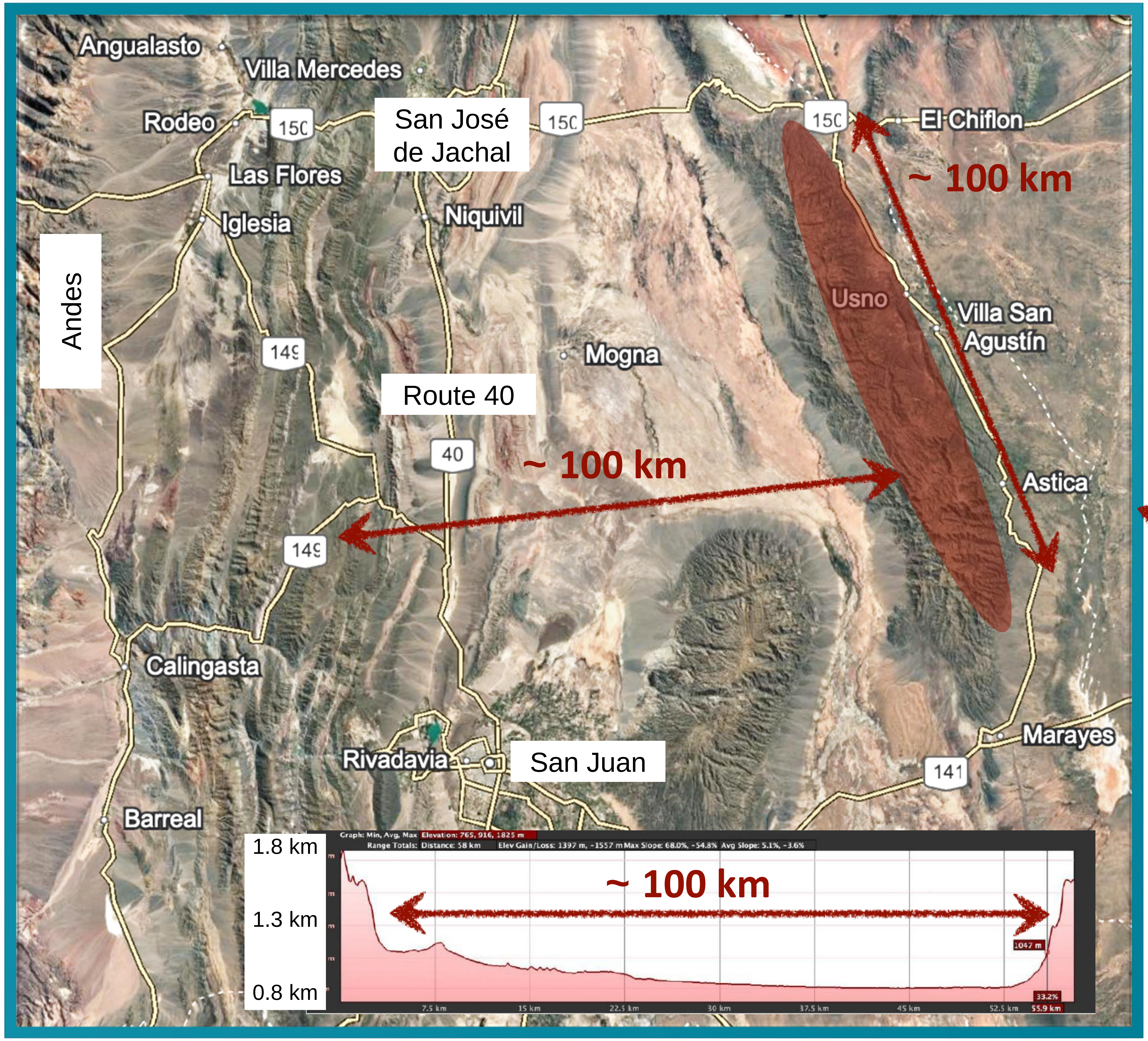


Why now?

- ❑ MM astronomy eagerly awaits UHE neutrinos, but current experiments are too small
- ❑ no short-term plan for a more sensitive experiment (GRAND 200k, IceCube-Gen2 Radio, in 10+ years)

Where? Preliminary preferred site



Jáchal Department,

San Juan province, Argentina

Latitude -30.5º

Leveraging a unique topography

- ❑ valley at 0.8 km above-sea-level, ~ 100 km wide, between two ridges extending over ~100 km north-south
- ❑ largely unpopulated area, low radio noise

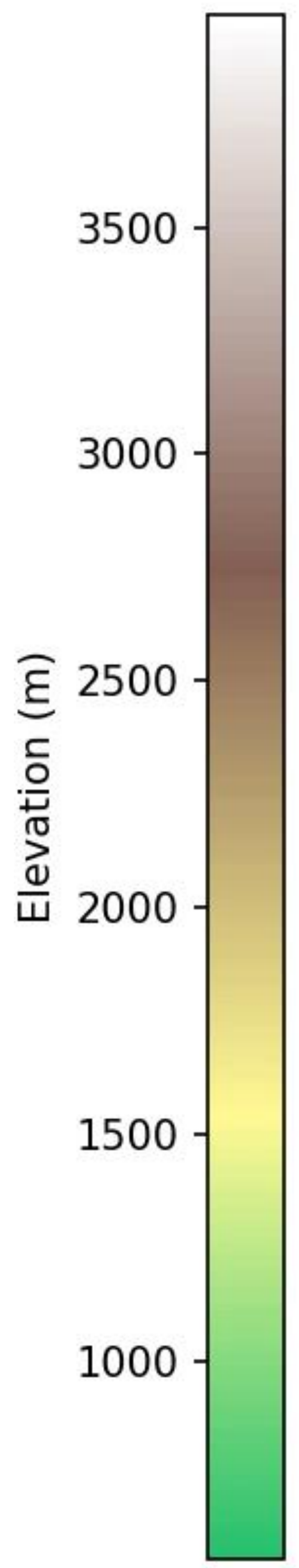
Observational strategy:

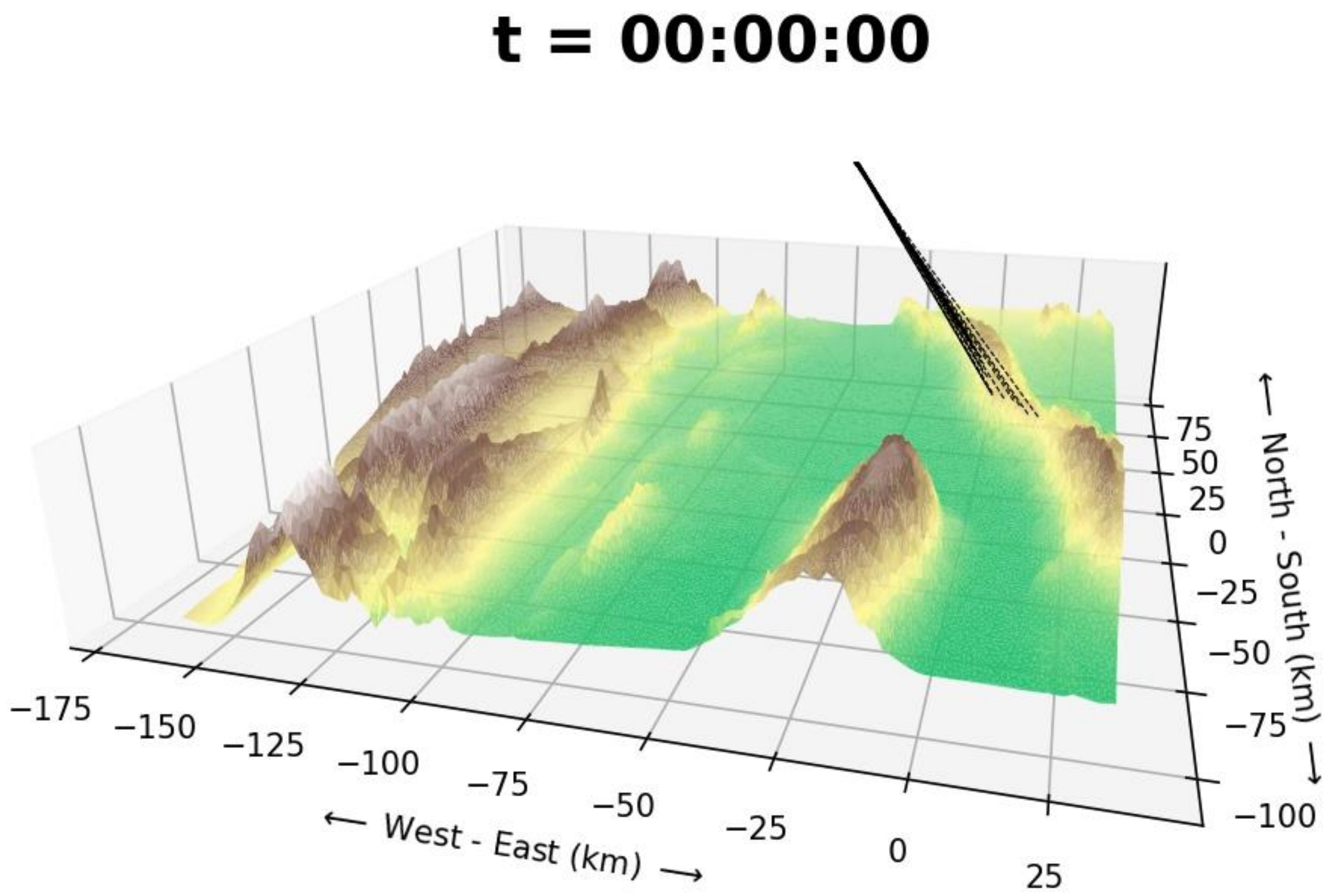
*use **astrophysical & multimessenger information** to target likely neutrino sources as they set below horizon*

credit: Andrew Zeolla, IAP-Paris

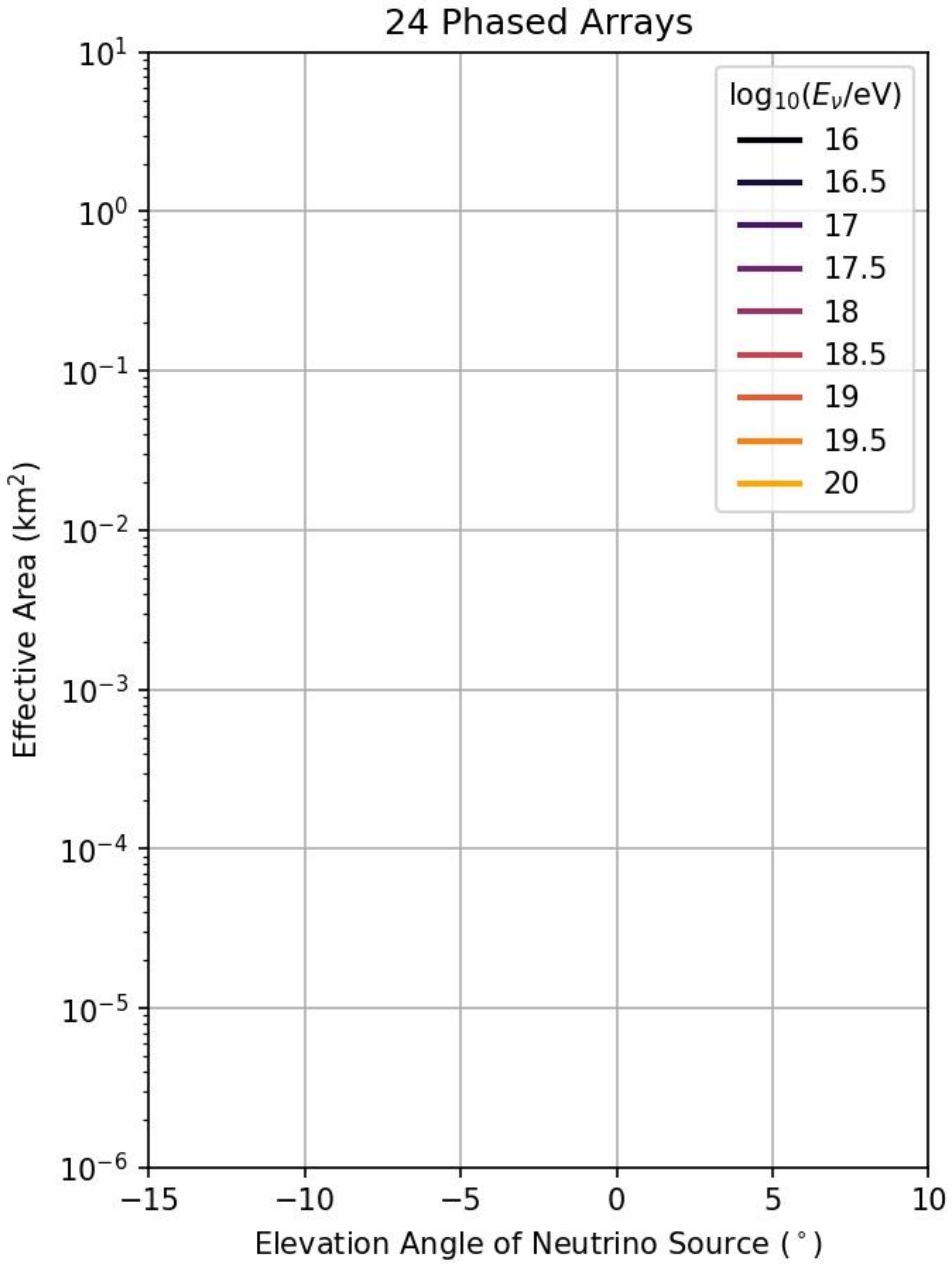
ν source:

declination $= 0^\circ$, Right Ascension $= 0^\circ$





Red = Area from which we expect tau leptons to emerge (within 3° cone extended toward targeted source)

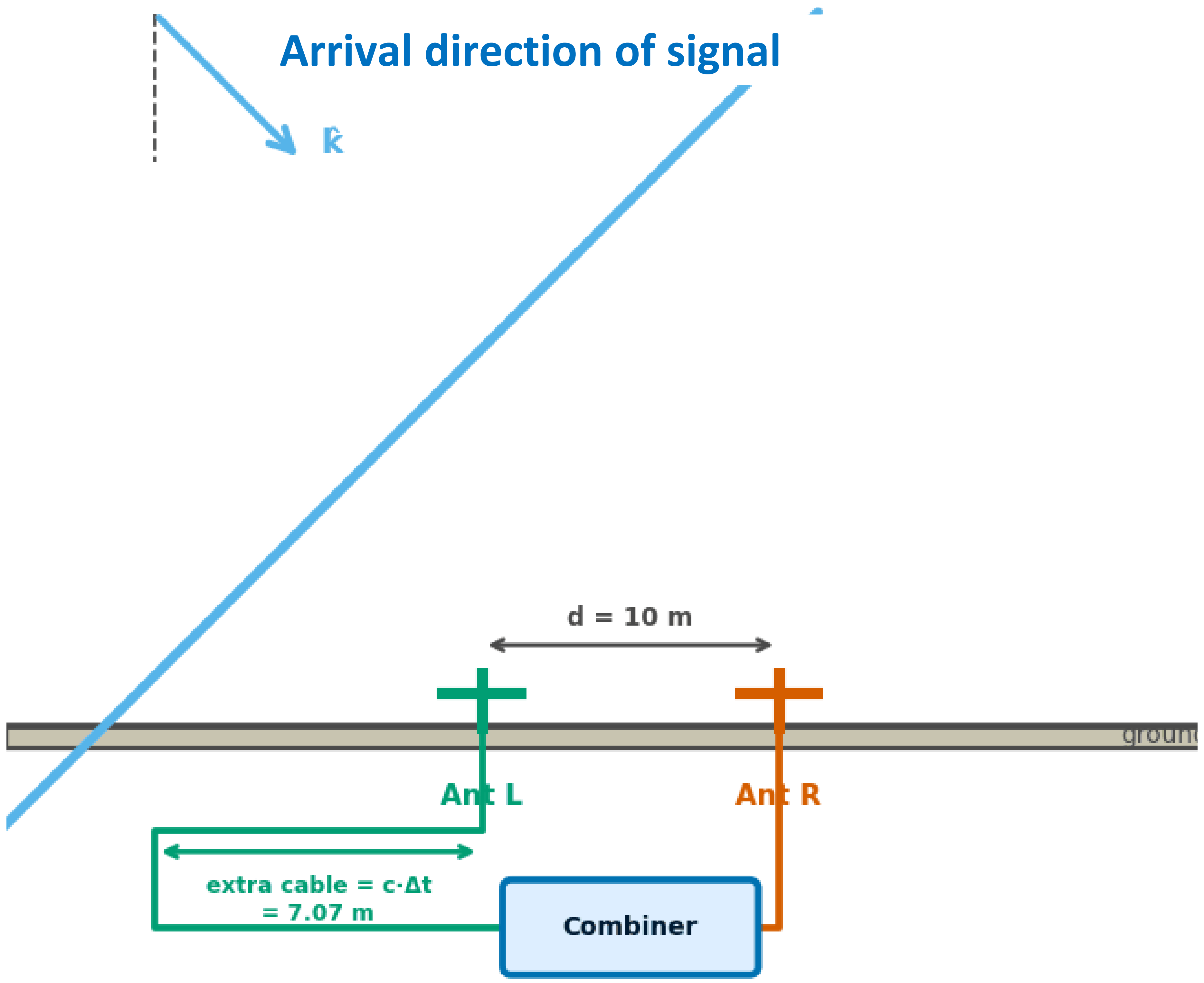


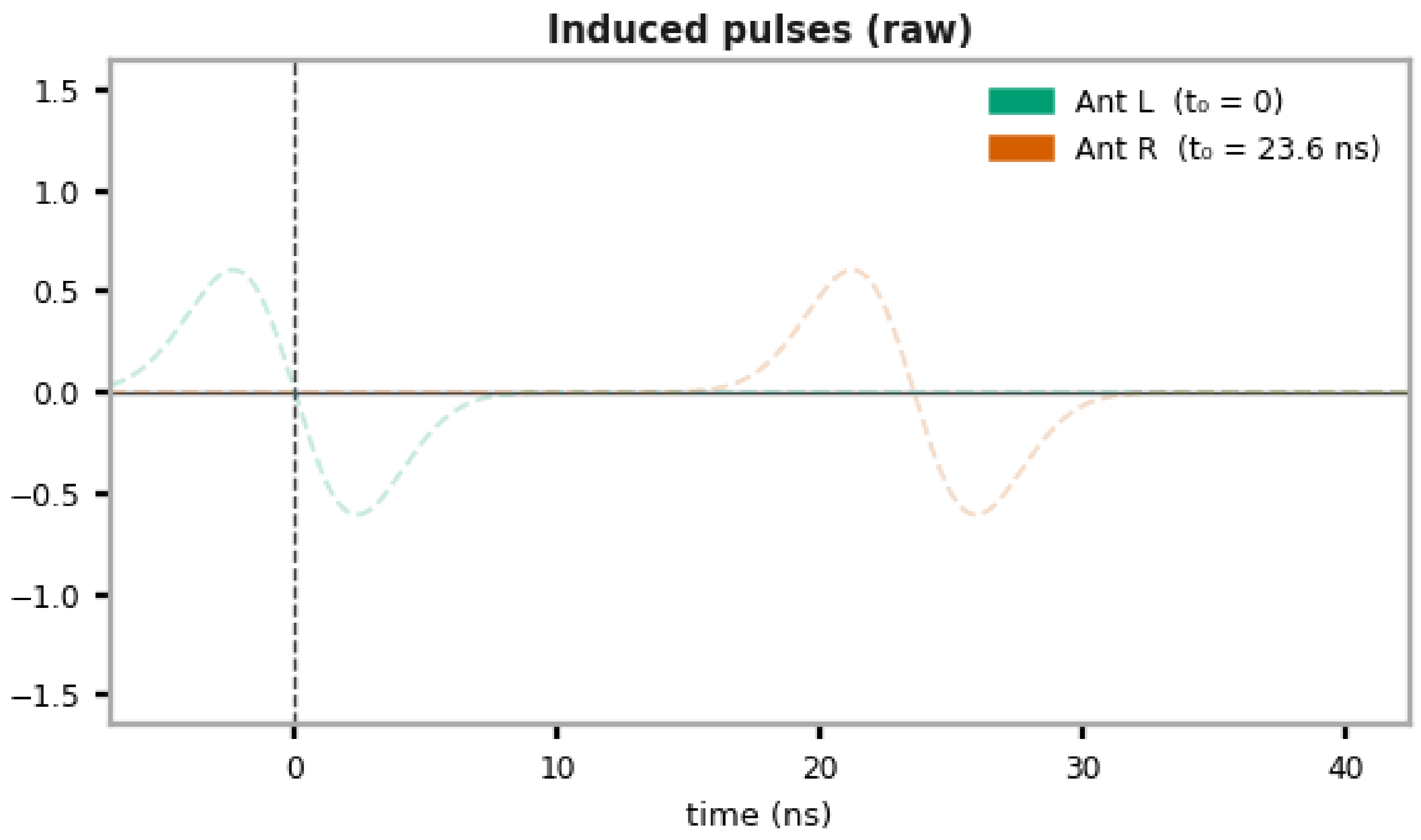
Observational strategy

The concept of a phased array:

Phased-Array Receiver: 2 antennas d=10m. Plane wave arriving at 45º

Powered by Claude AI





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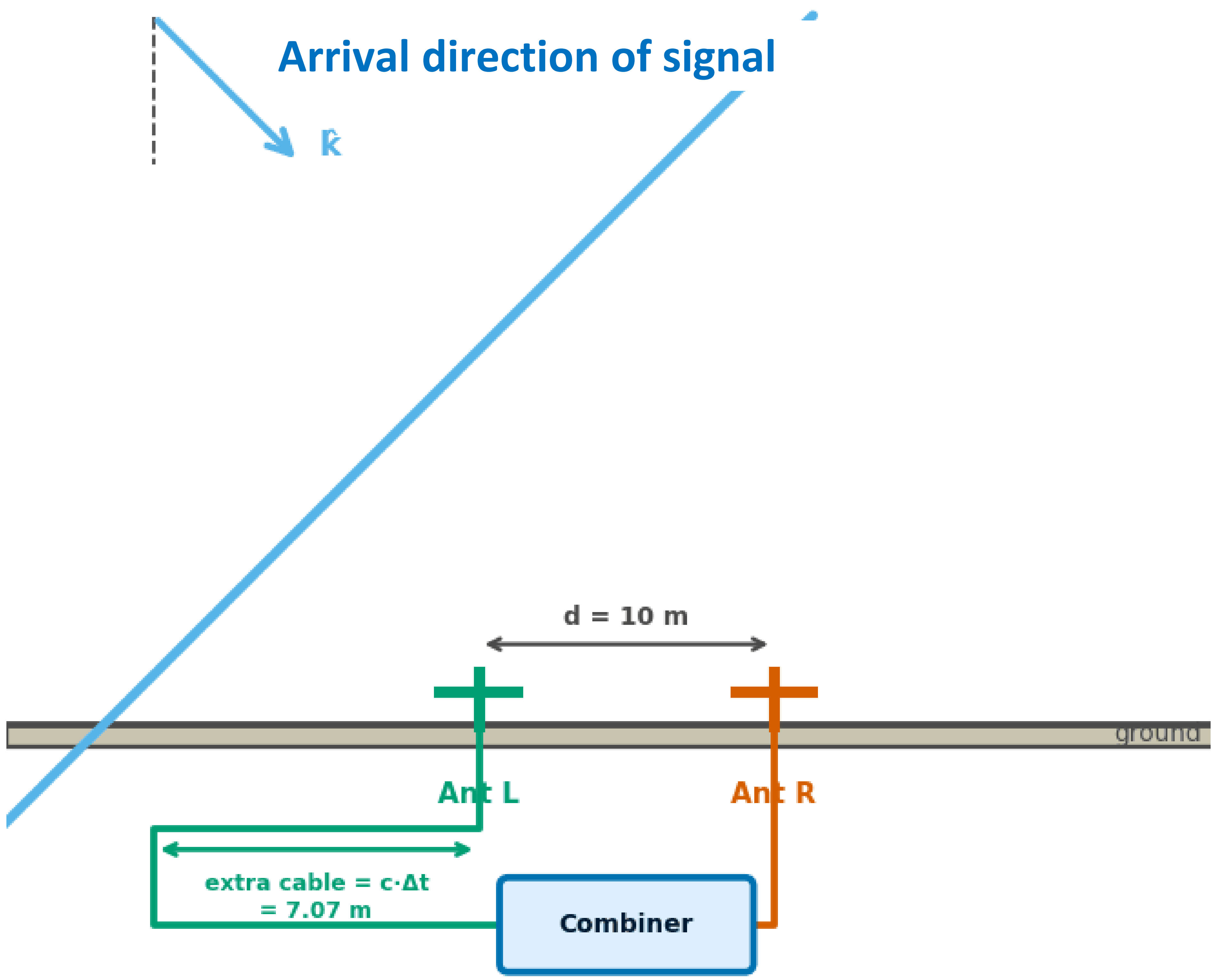
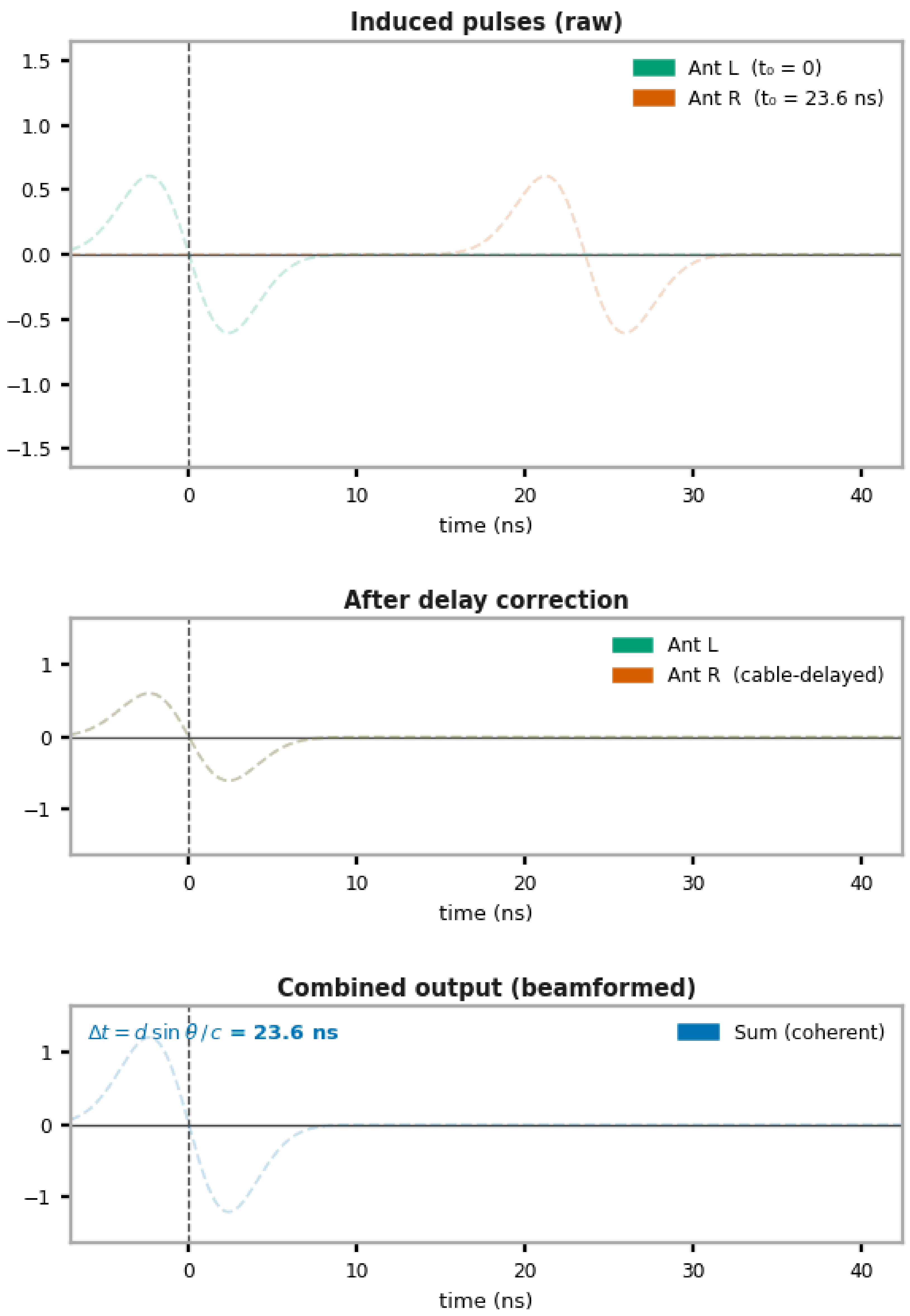
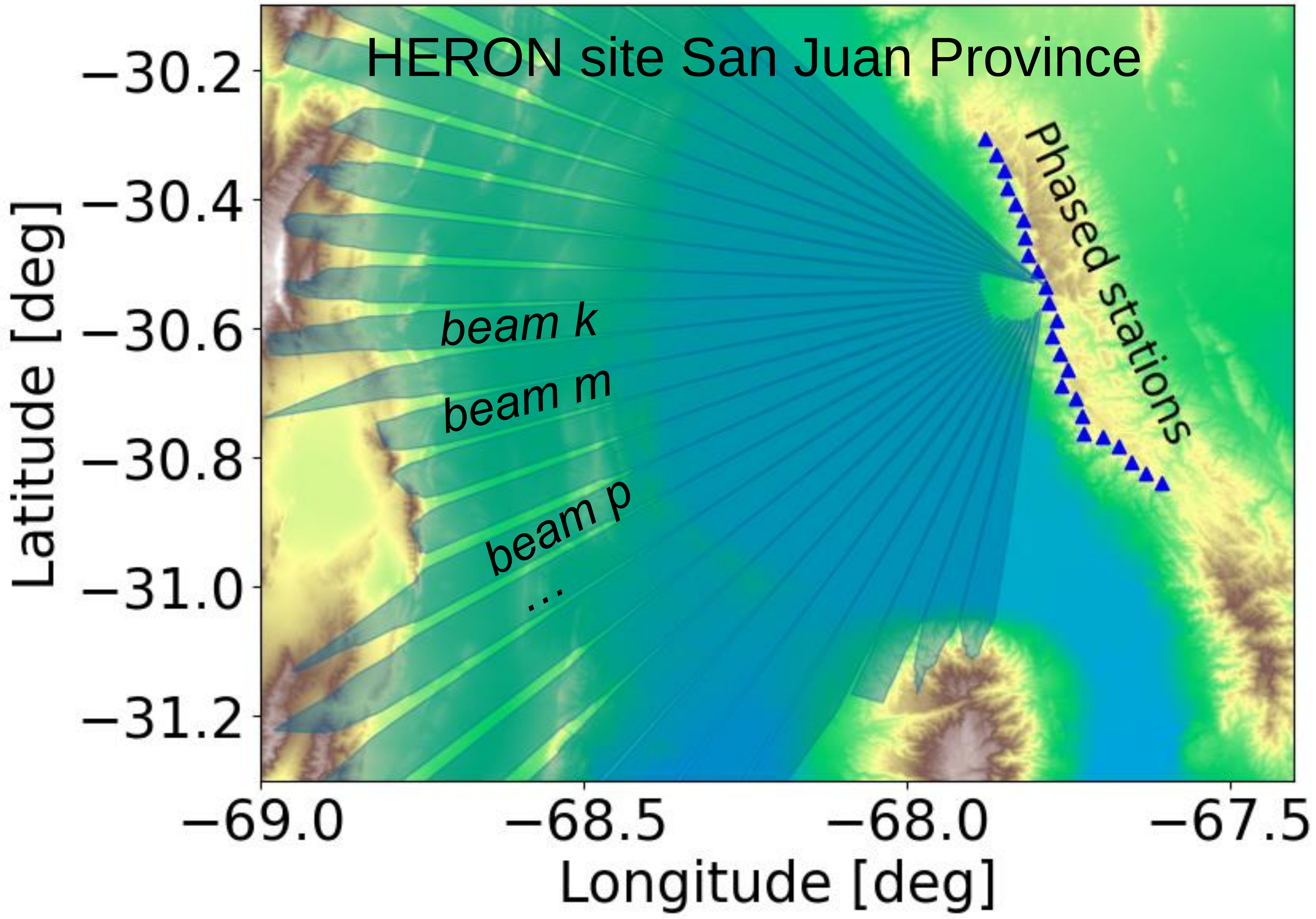


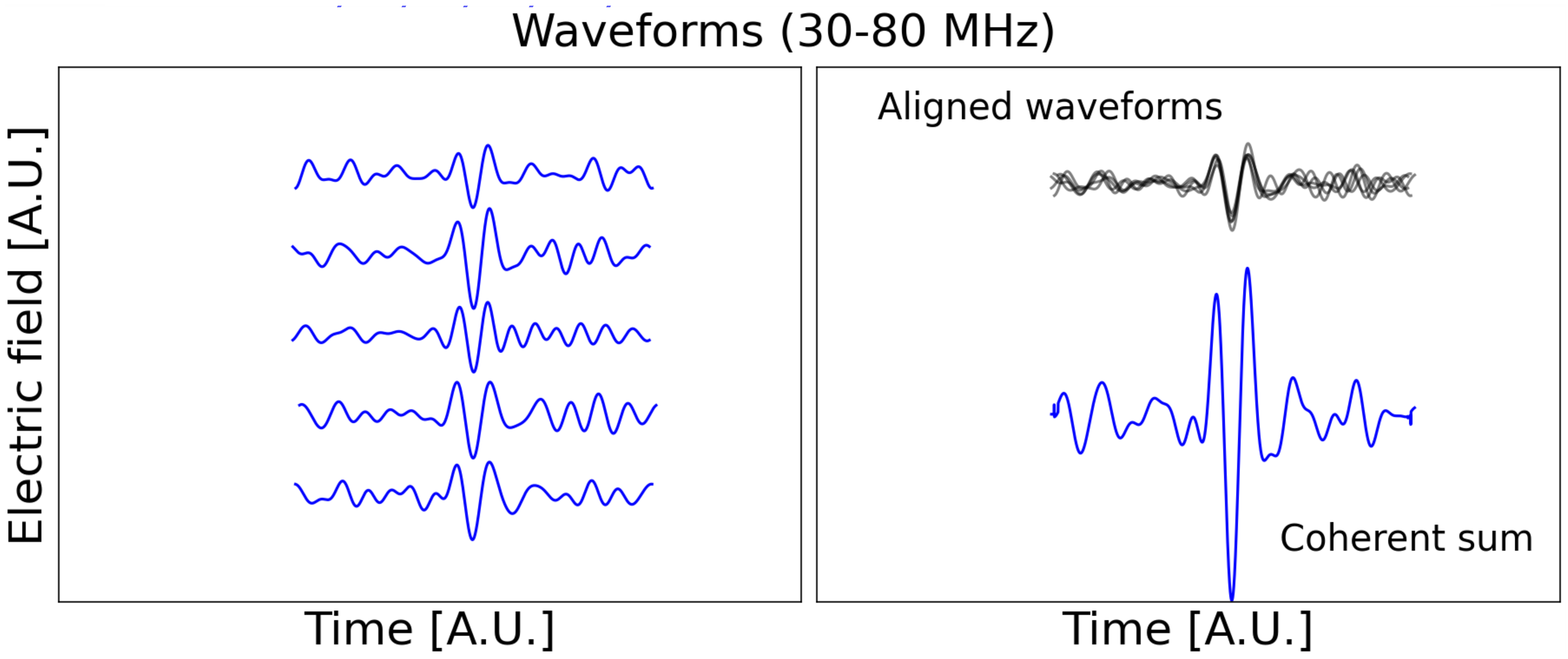


waves **add constructively in one direction after time-delaying**

a ”beam” has been formed

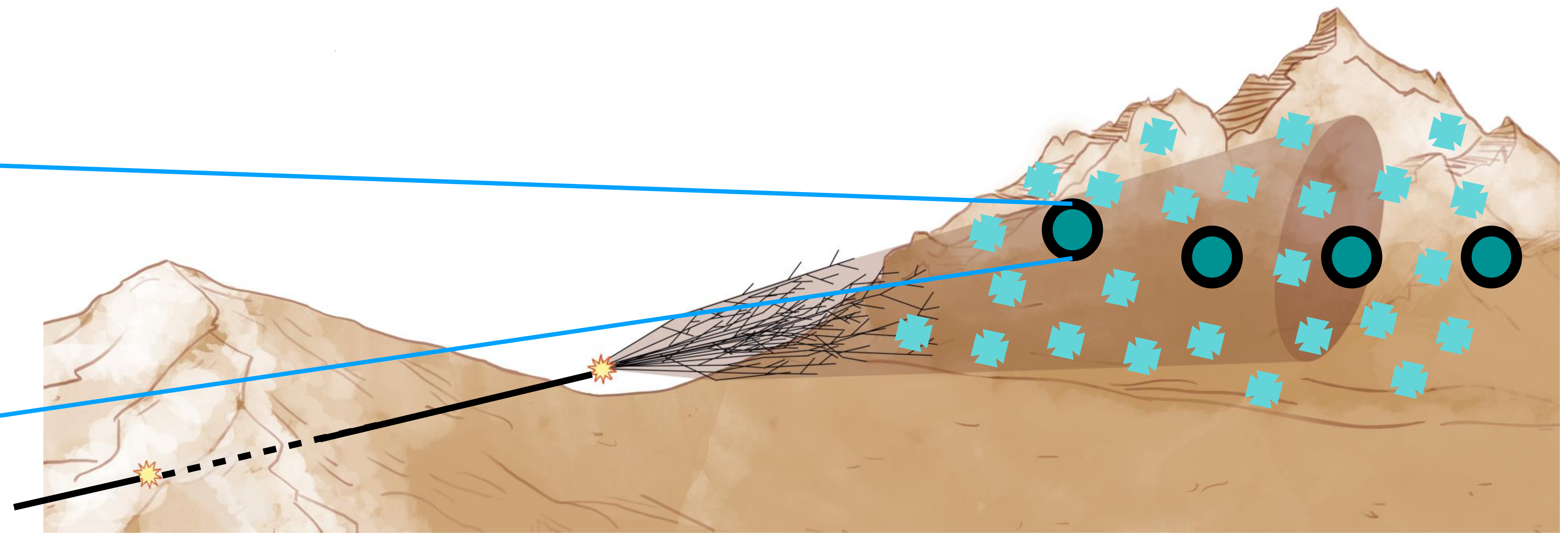
Observational strategy:





credit: Sergio Cabana-Freire, IGFAE-USC

- ❑ *Digitally **synthesize observation beams** which cover a gigantic area in the mountains and valley where tau leptons are more likely to emerge*

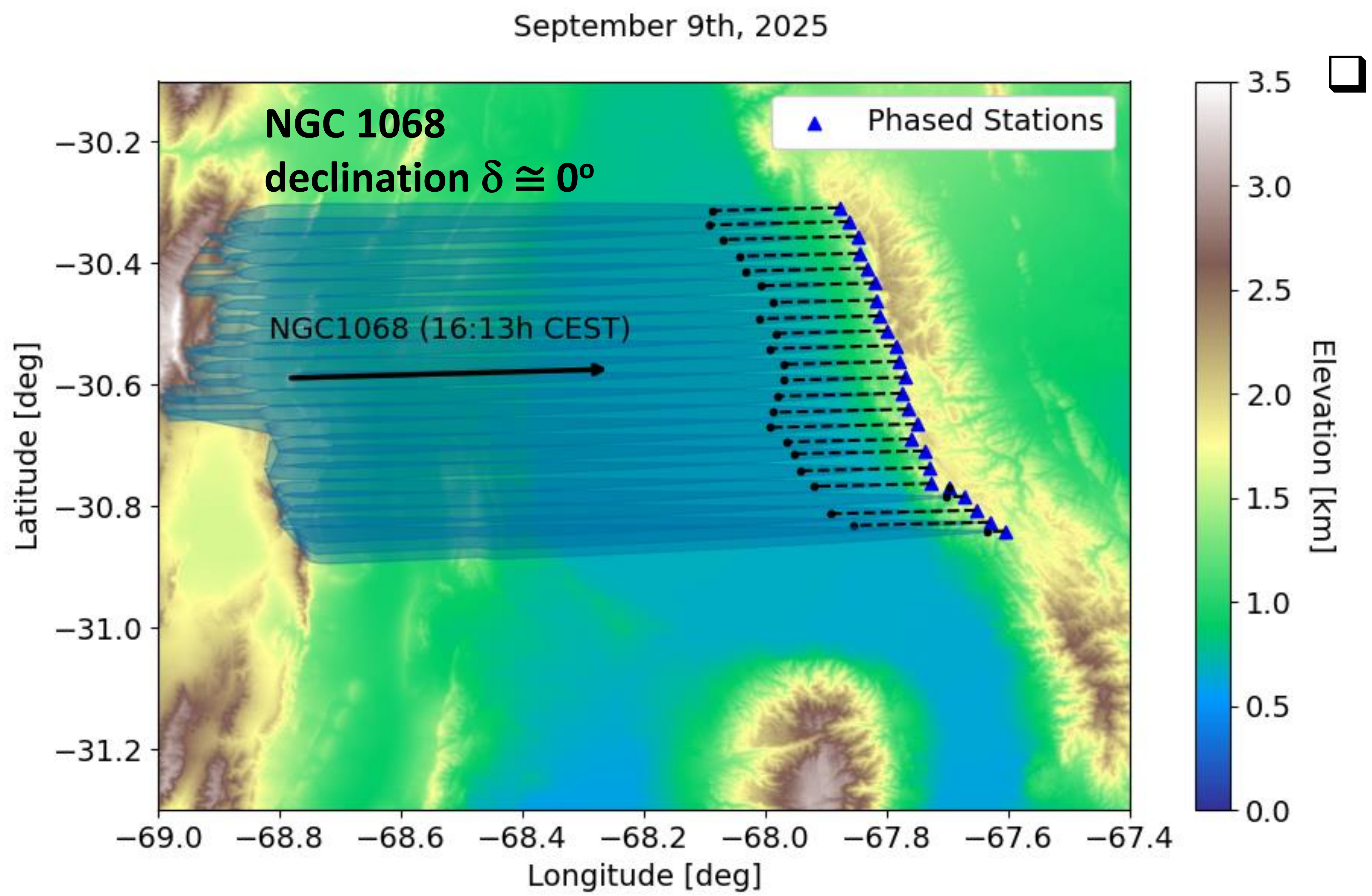


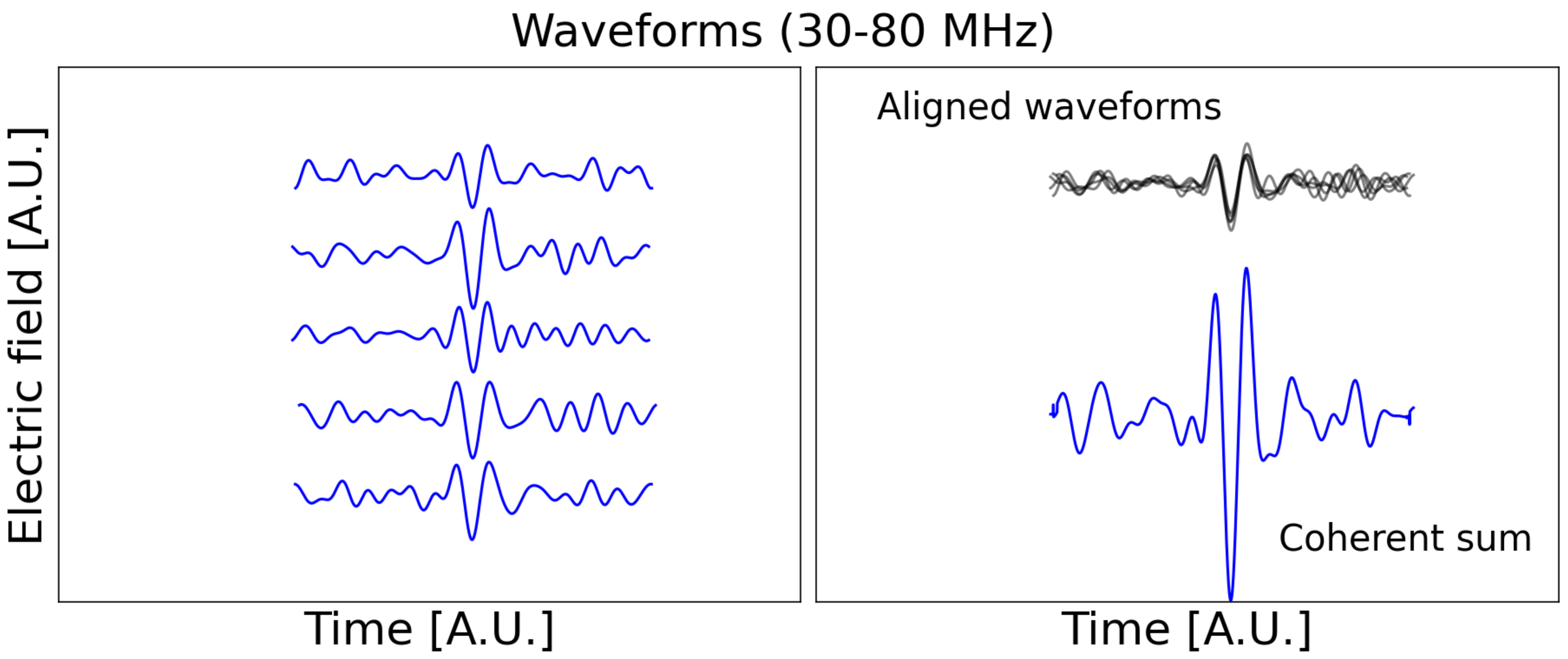
Beamforming for triggering of transient radio signals

Phased arrays:

- ❑ signal to noise ~ √N   (N = 24 antennas)
- ❑ *low-energy threshold*
- ❑ *dynamic beamforming suppresses noisy regions & enhances directional sensitivity*

Observational strategy:





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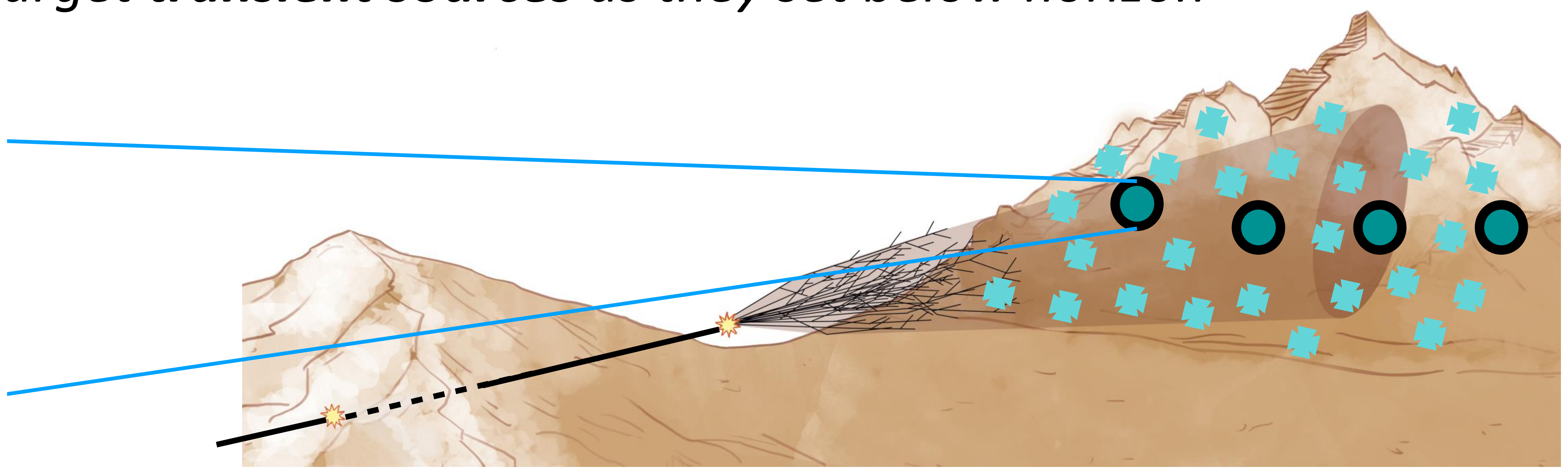
- *Target **transient sources** as they set below horizon*



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HERON

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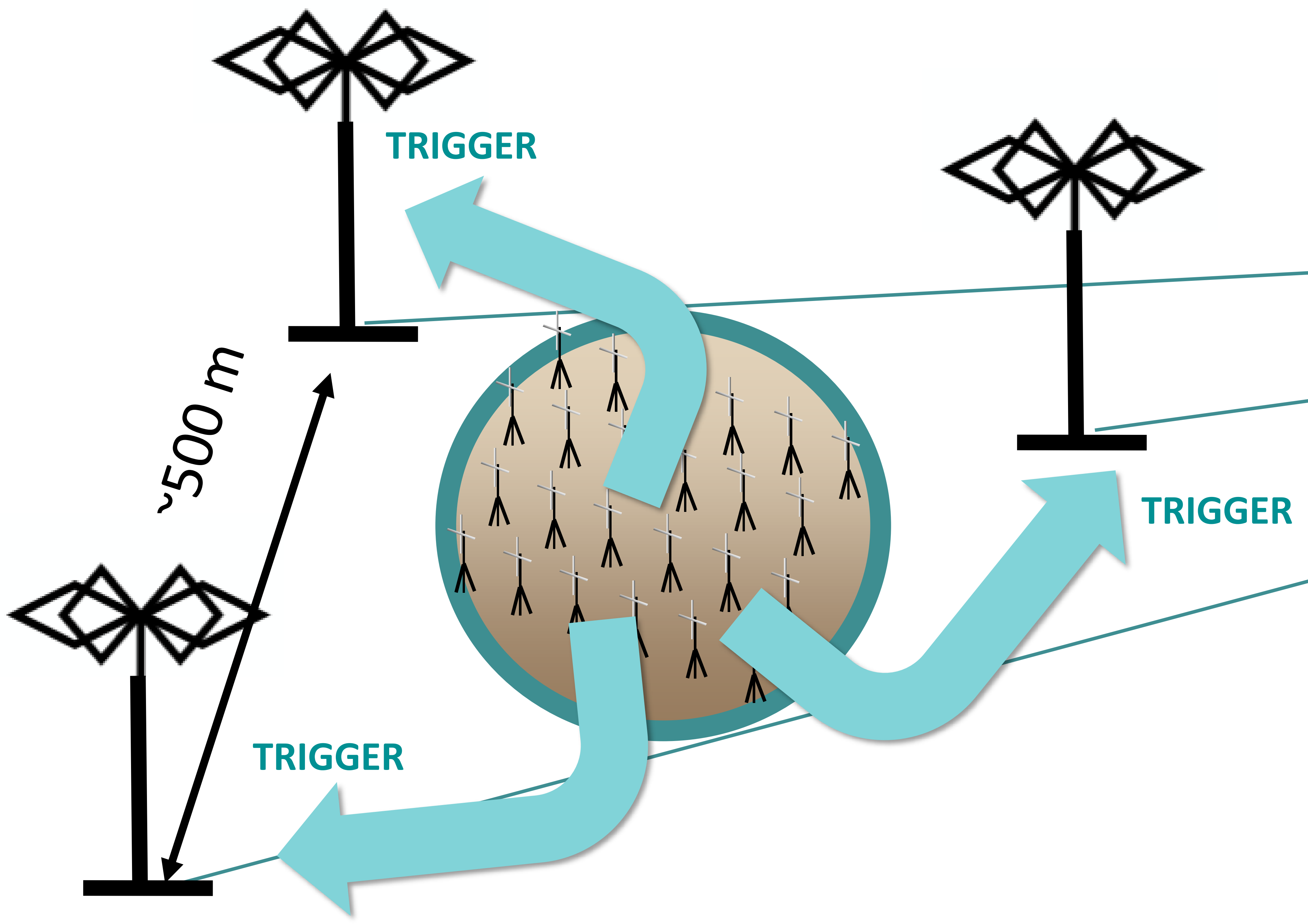
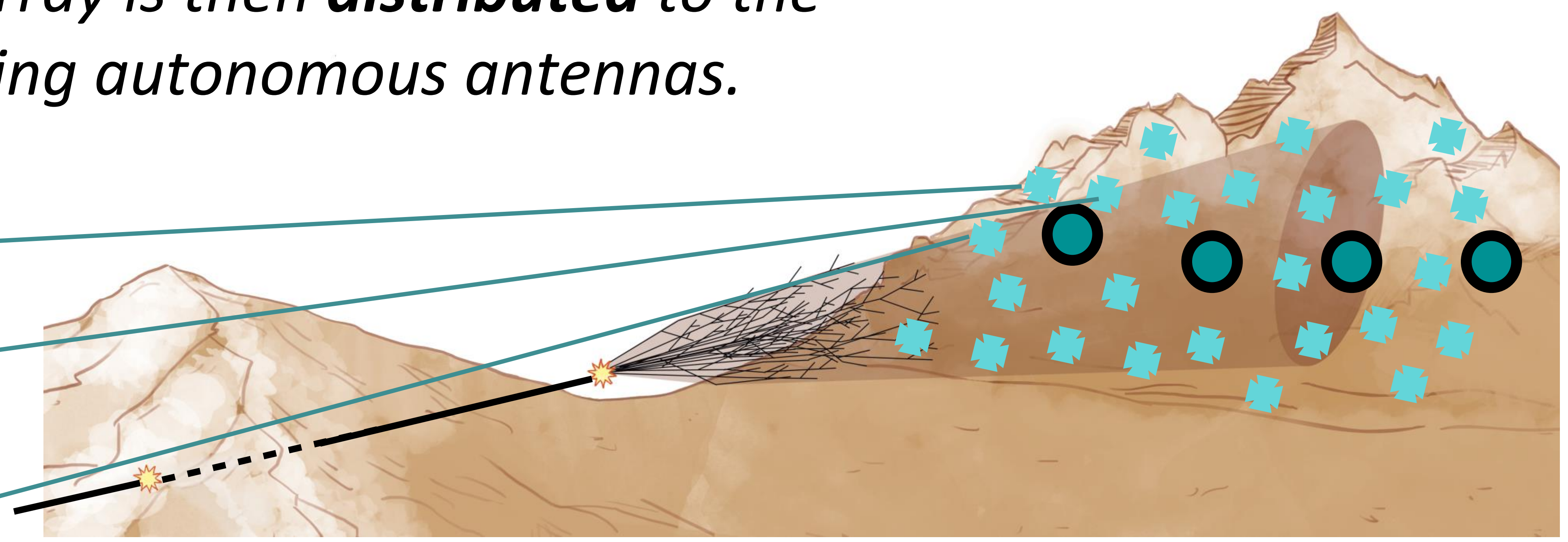


Real novelty of HERON:

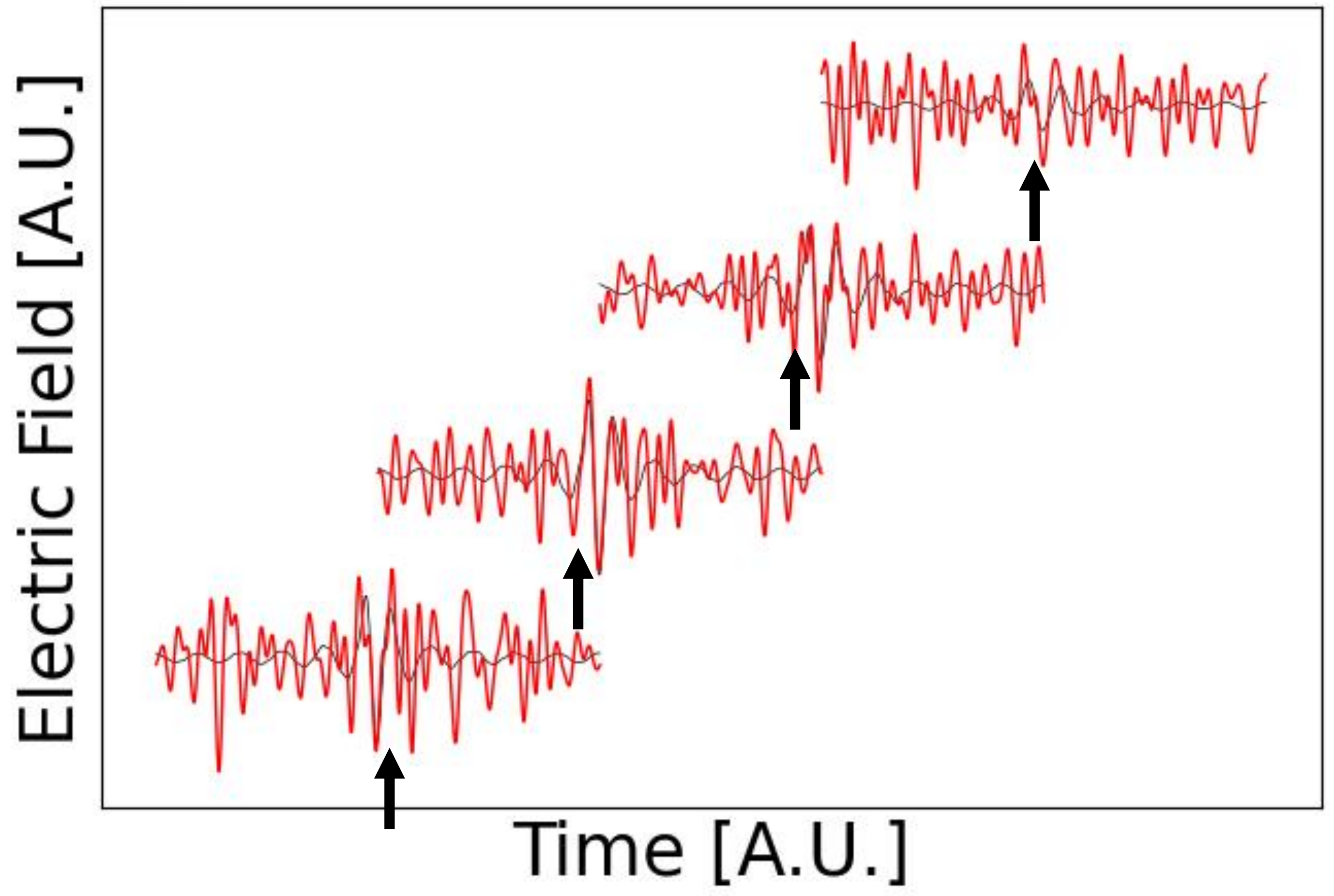
*The low-threshold **trigger** provided by the phased array is then **distributed** to the neighboring autonomous antennas.*



Beamforming for reconstruction of transient radio signals

Standalone antennas:
- ❑ receive triggers from phased arrays to find signals otherwise not detectable
- ❑ can also self-trigger
- ❑ veto noise (Radio Freq. Interference, RFI)

standalone individual signals



*Standalone antennas record μs-long time traces around the **time when the radio wave is expected to hit them**.*

Observational strategy:

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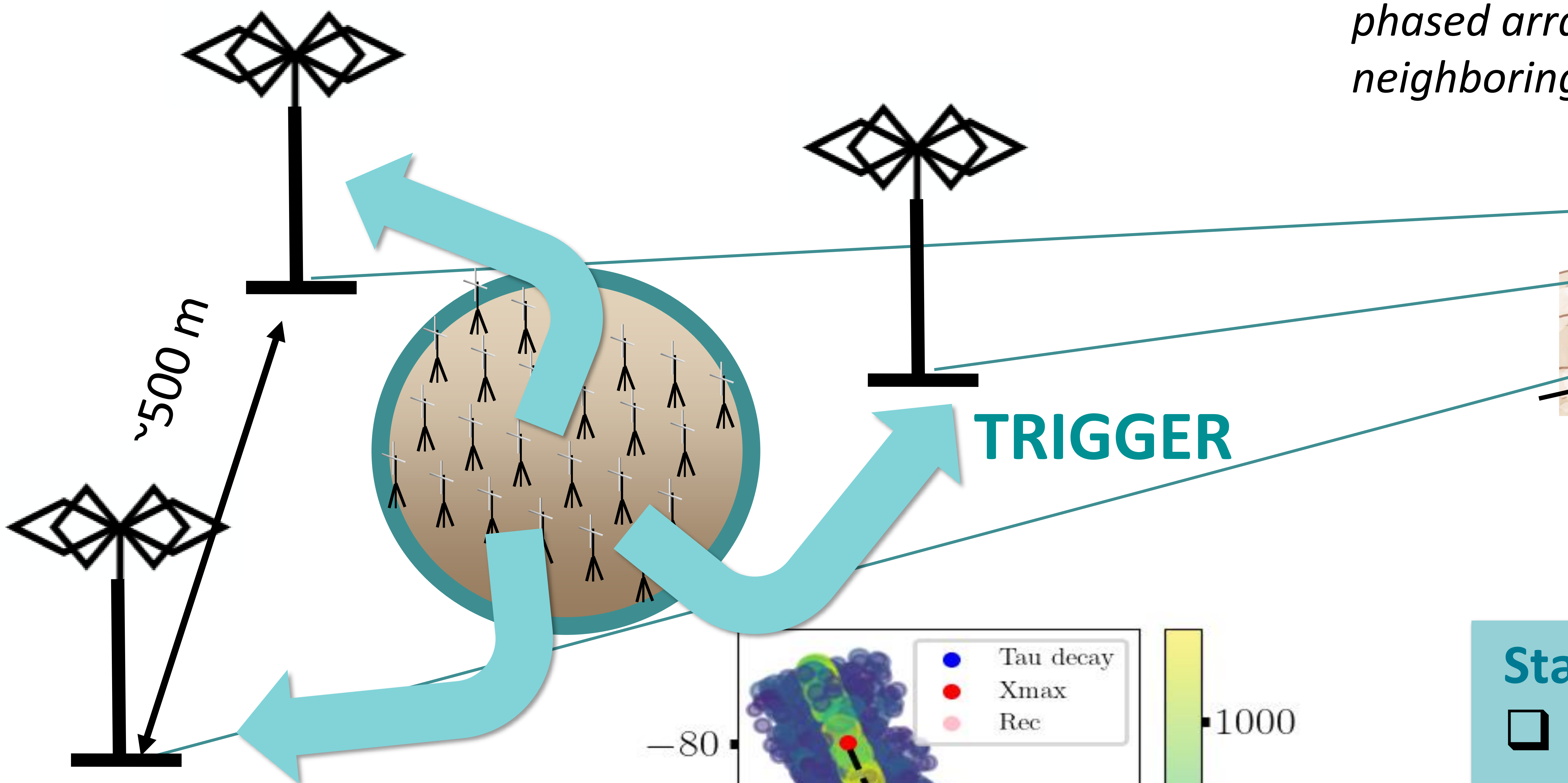

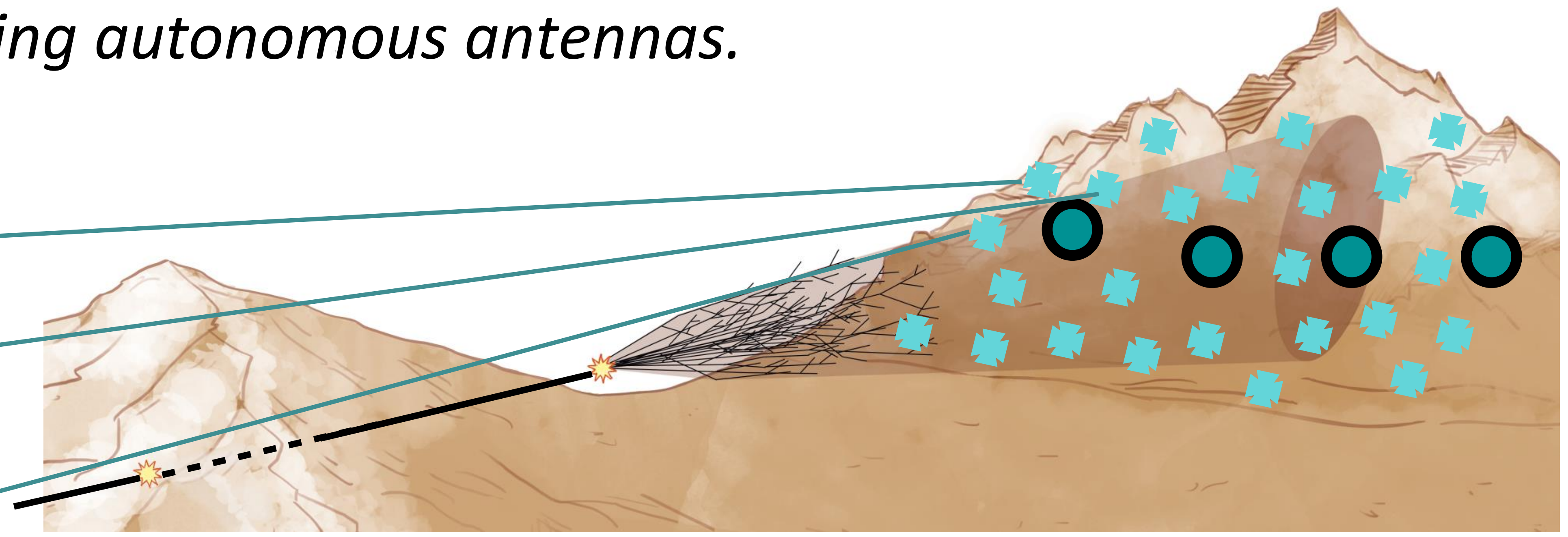

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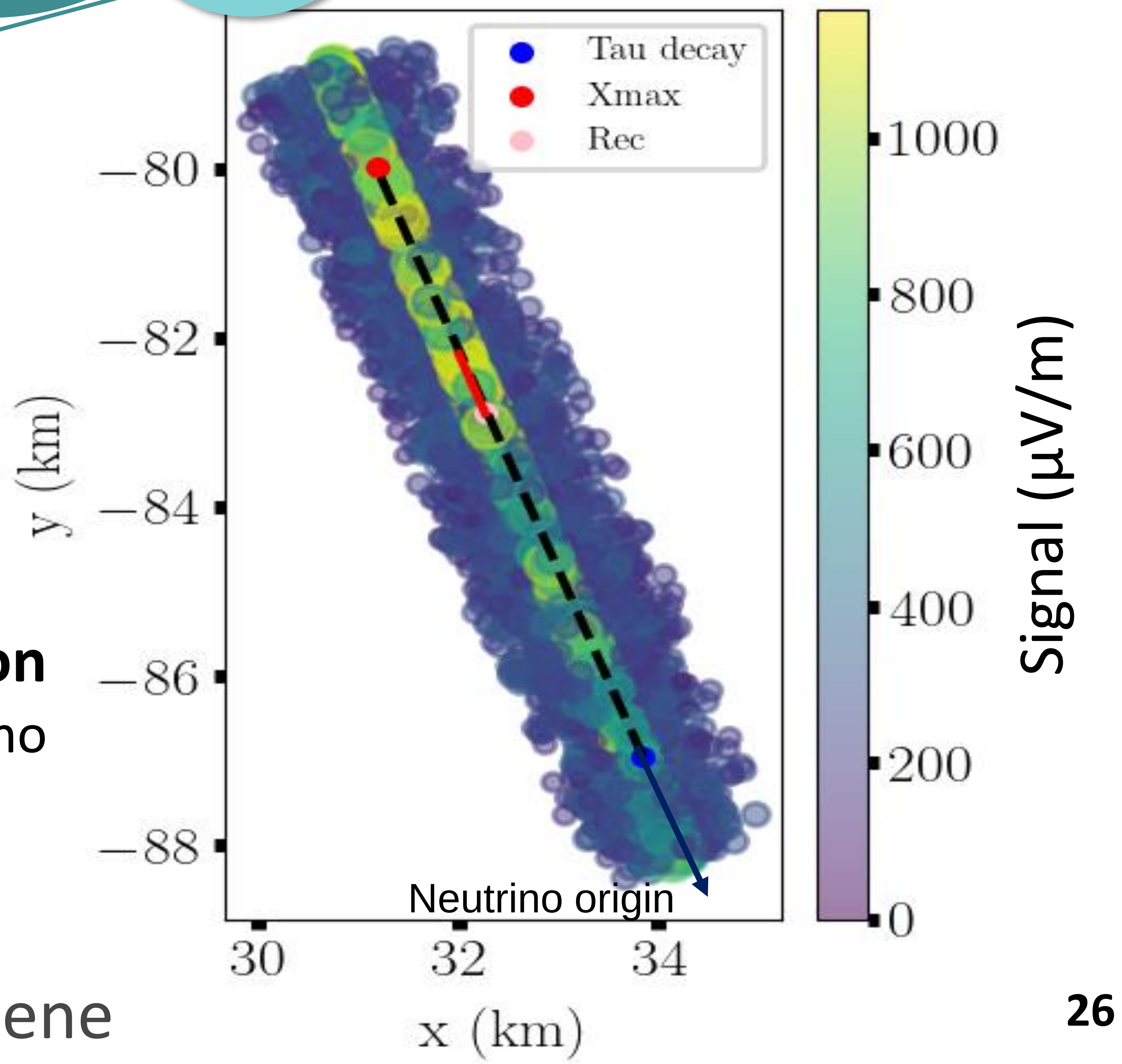
Standalone antennas (offline):

- ❑ 3D interferometric map of the air shower
- ❑ *excellent direction reconstruction ($\sigma < 0.4°$)*
- ❑ *reconstruction of distance to shower*

⇒ Neutrino astronomy



HERON simulation
of a 10^{18} eV neutrino

credit: A. Ferriere, V. Decoene

Building HERON *Requires:*
ERC-SyG funding + Synergetic team

European Research Council
Established by the European Commission

HERON

- Which astrophysical sources to point? — K. Kotera
- Which signal to search for? — J. Alvarez-Muñiz
- How to build phased stations? — S. Wissel
- How to build standalone antennas? — O. Martineau
- Where and how to deploy? — Argentina

instrument design & optimization

trigger, timing, communication

multi-messenger framework

data analysis

HERON

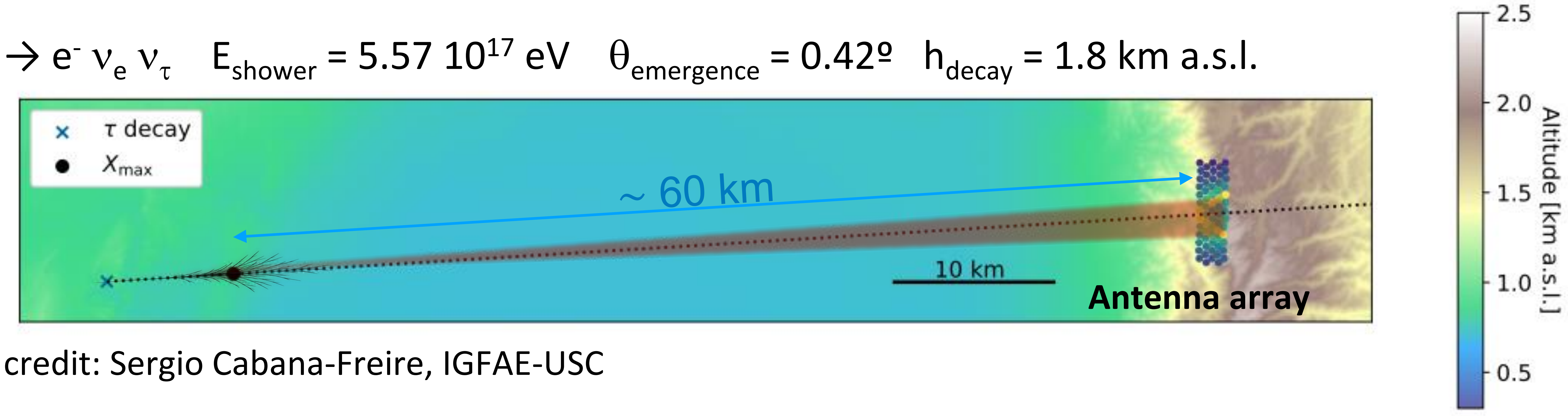
ν

New Window on the Extreme Universe

Simulations

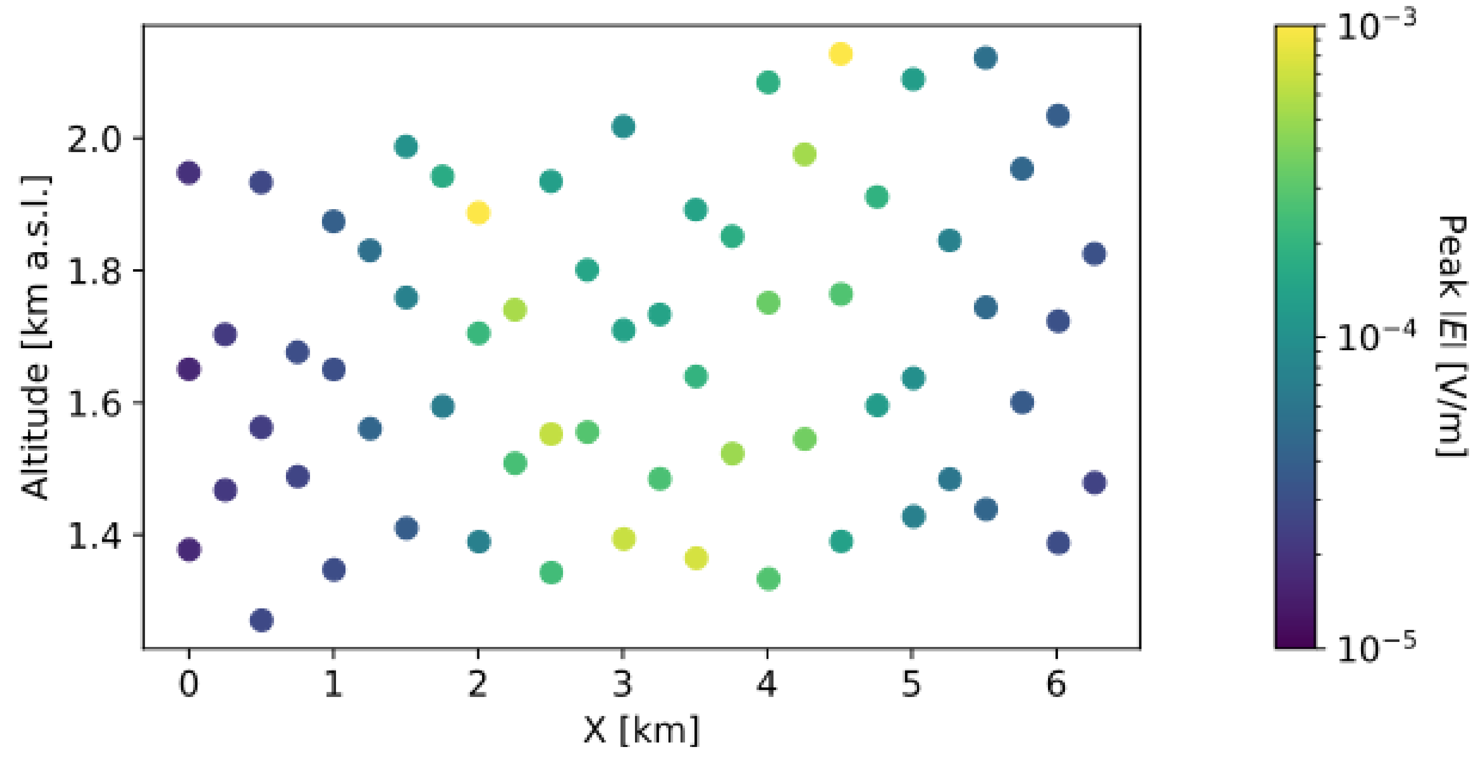
performed with ZHAireS – RASPASS

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



credit: Sergio Cabana-Freire, IGFAE-USC

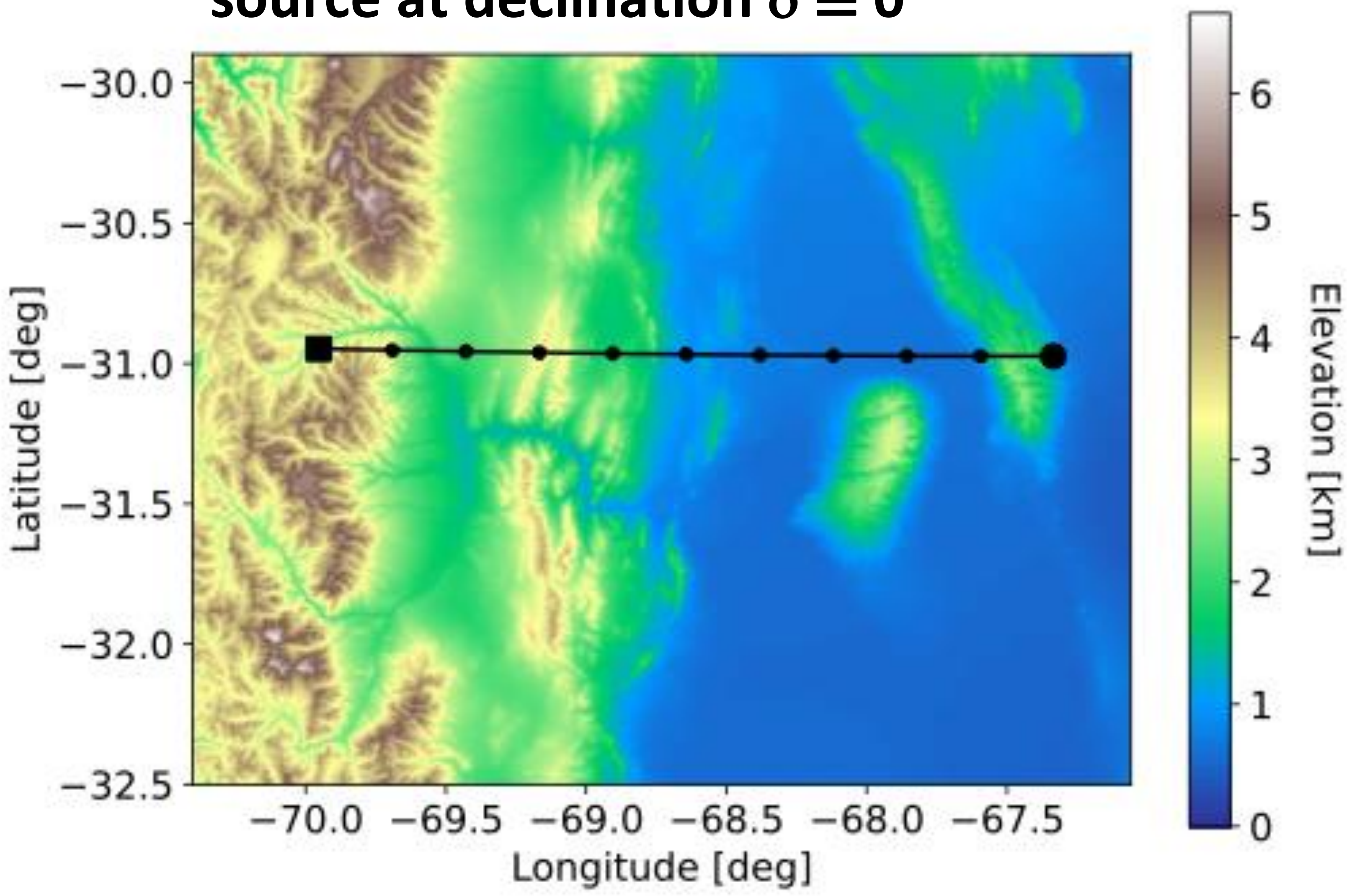
Peak electric field (ZHAireS)

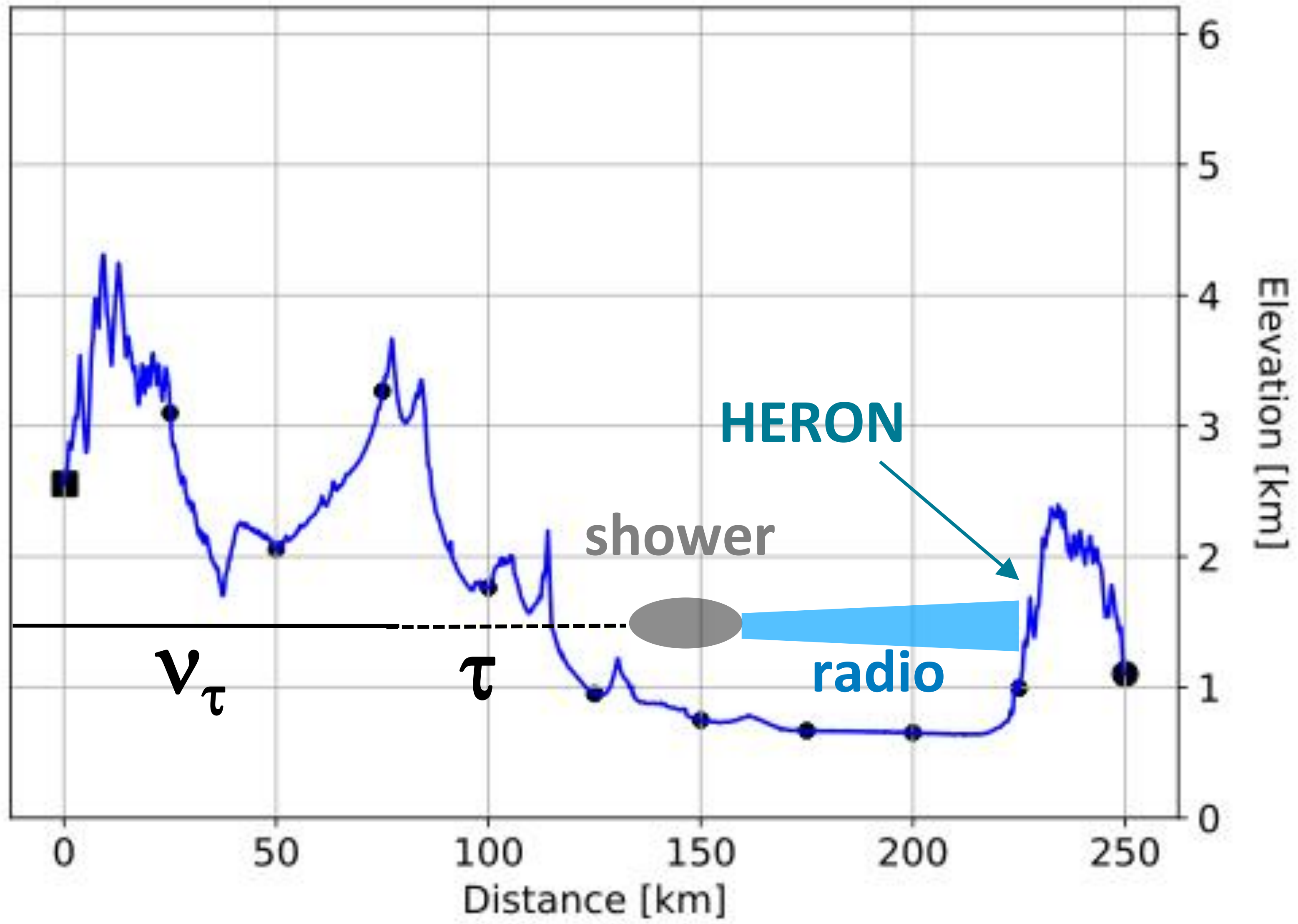


Simulations:

- estimate sensitivity of site(s) vs ν_τ energy, accounting for topography, declination of sources,…
- optimize parameters of both phased & standalone arrays
- …

source at declination $\delta \cong 0^o$





Topography in simulations

INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS

HERON

credit: Maria Durán de las Heras, IGFAE-USC

Plan of Work

We have begun site surveying

We are here. Grant agreement with EU expected to be signed in June 2026

Prototyping, Site Surveys & First Deployments

Validate trigger & time sync.

Science data starts

24 Phased Stations / 360 Standalone Antenna Deployment

Largest UHE tau neutrino detector in the world with best sensitivity to short transients

Design & Optimization Phase

Maximize effective area

We have begun optimization simulations & already made significant progress

Cosmic Ray Search:

First large scale radio-only CR spectrum & composition

Target of Opportunity Neutrino Pipeline Online

First UHE neutrino instrument that responds to alerts *rapidly. Possible discovery.*

Stacked GRB Neutrino Searches

Discovery of UHE neutrinos or significant constraints on jetted transients

Team of technicians, engineers, postdocs, students... and PIs

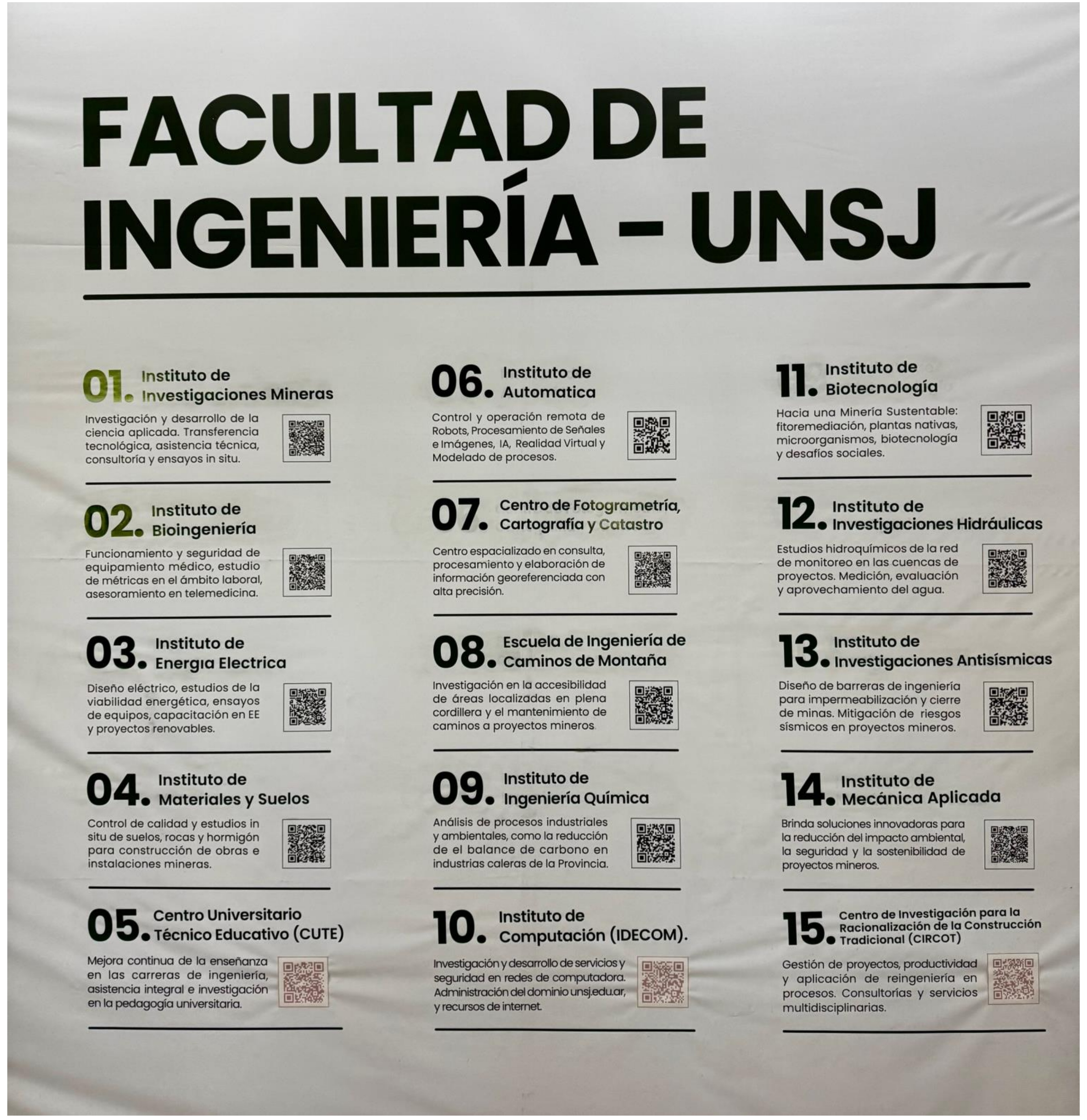
San Juan Province, Argentina, 29 March 2026

Meeting at Universidad Nacional de San Juan University (UNSJ) Faculty of Engineering

San Juan, Argentina, 30 March 2026

Faculty members, local authorities, members of funding agencies and HERON PIs

Institutes at Faculty of Engineering UNSJ:
01. mining research / 04. materials & soils /
07. cartography / 08. mountain tracks /
14. applied mechanics / ...



Conclusions

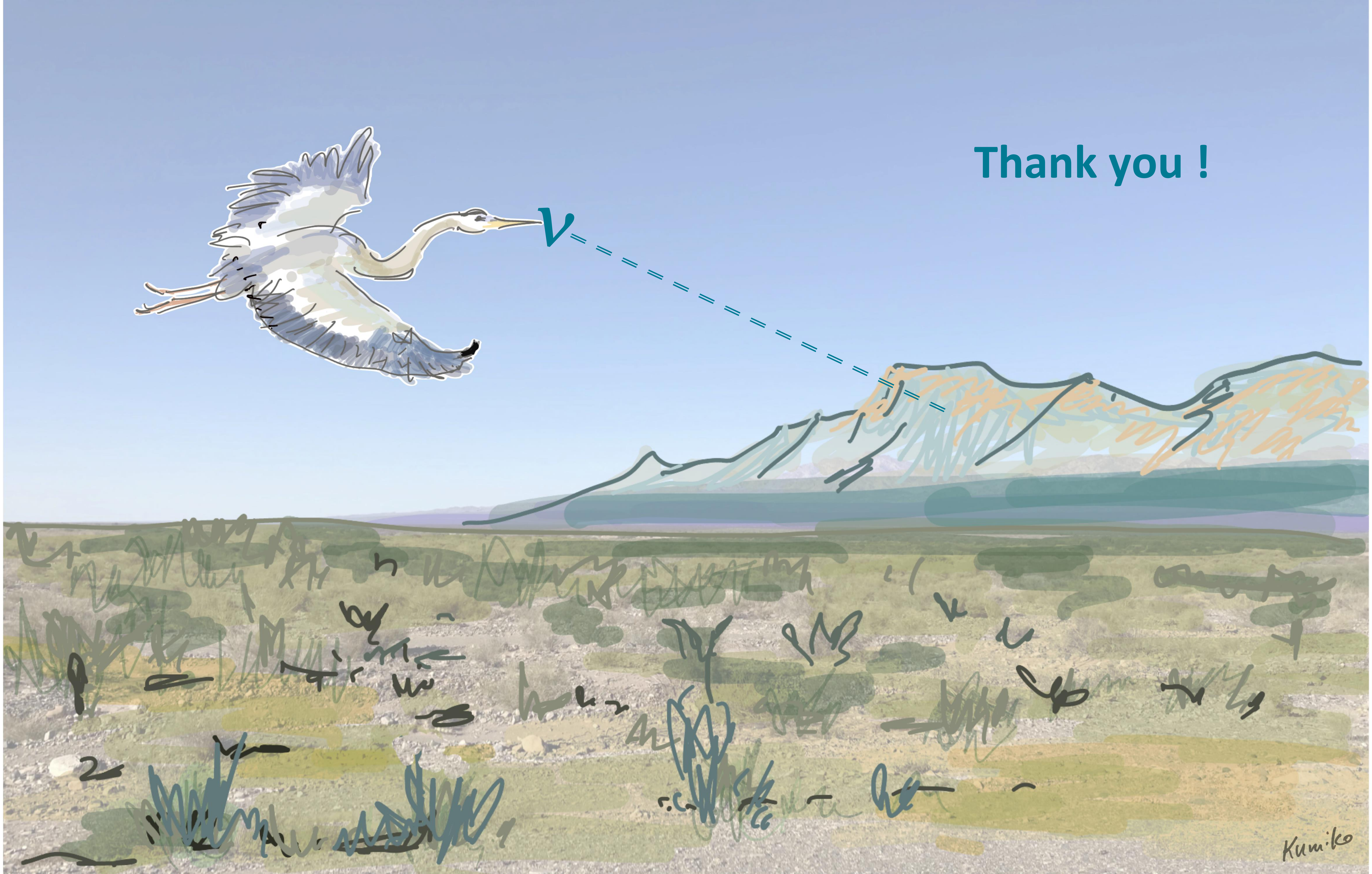
- **HERON bridges the gap** between current experiments and future large-scale projects

- With a large instantaneous effective area and an excellent pointing resolution, **HERON** has the **best sensitivity to transient sources** across a broad view of the sky.

- **HERON** will be incorporated into the broader network of **multi-messenger** observatories

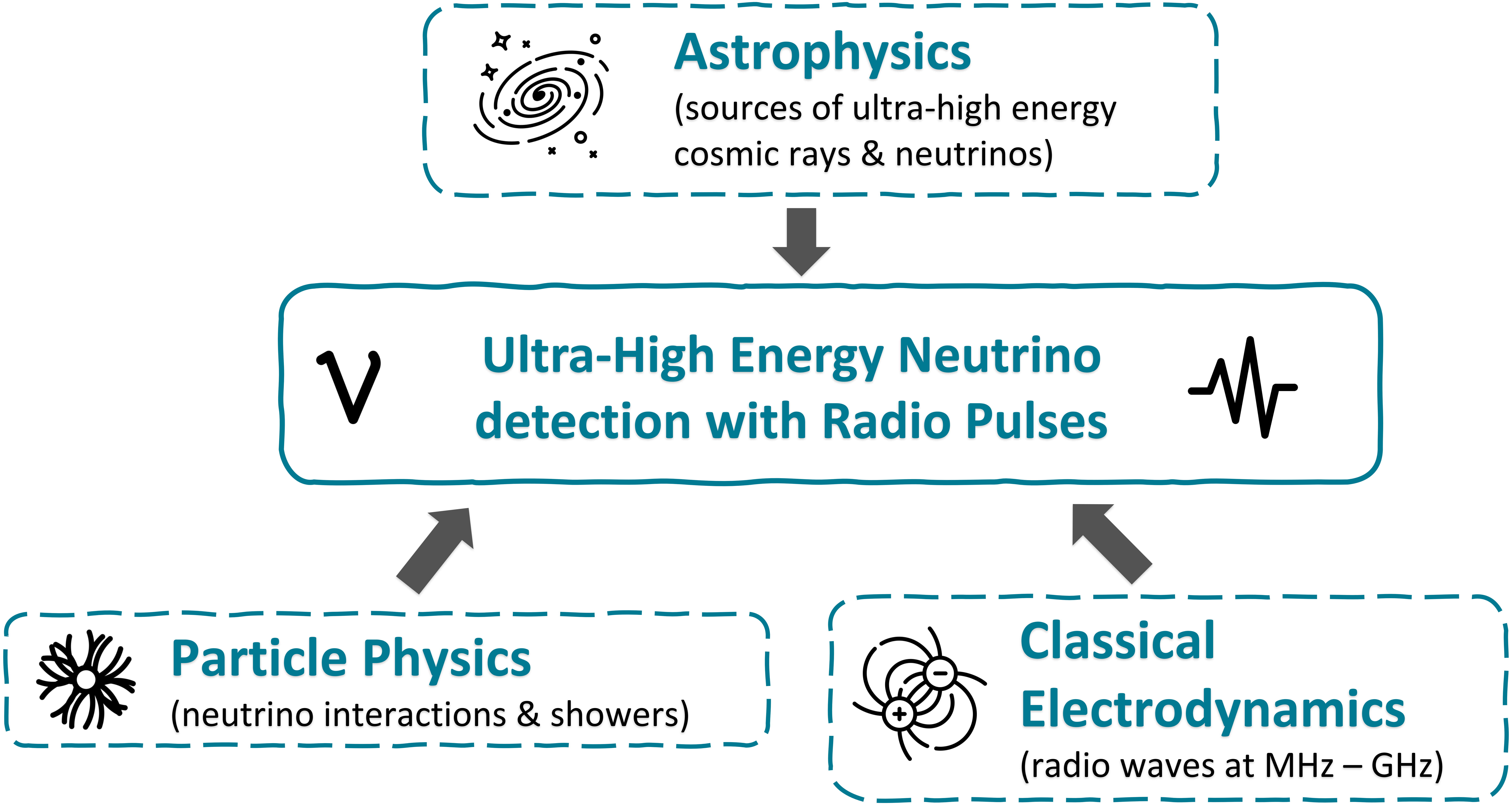
HERON

With a handful or more neutrinos,
we will transform multimessenger astrophysics



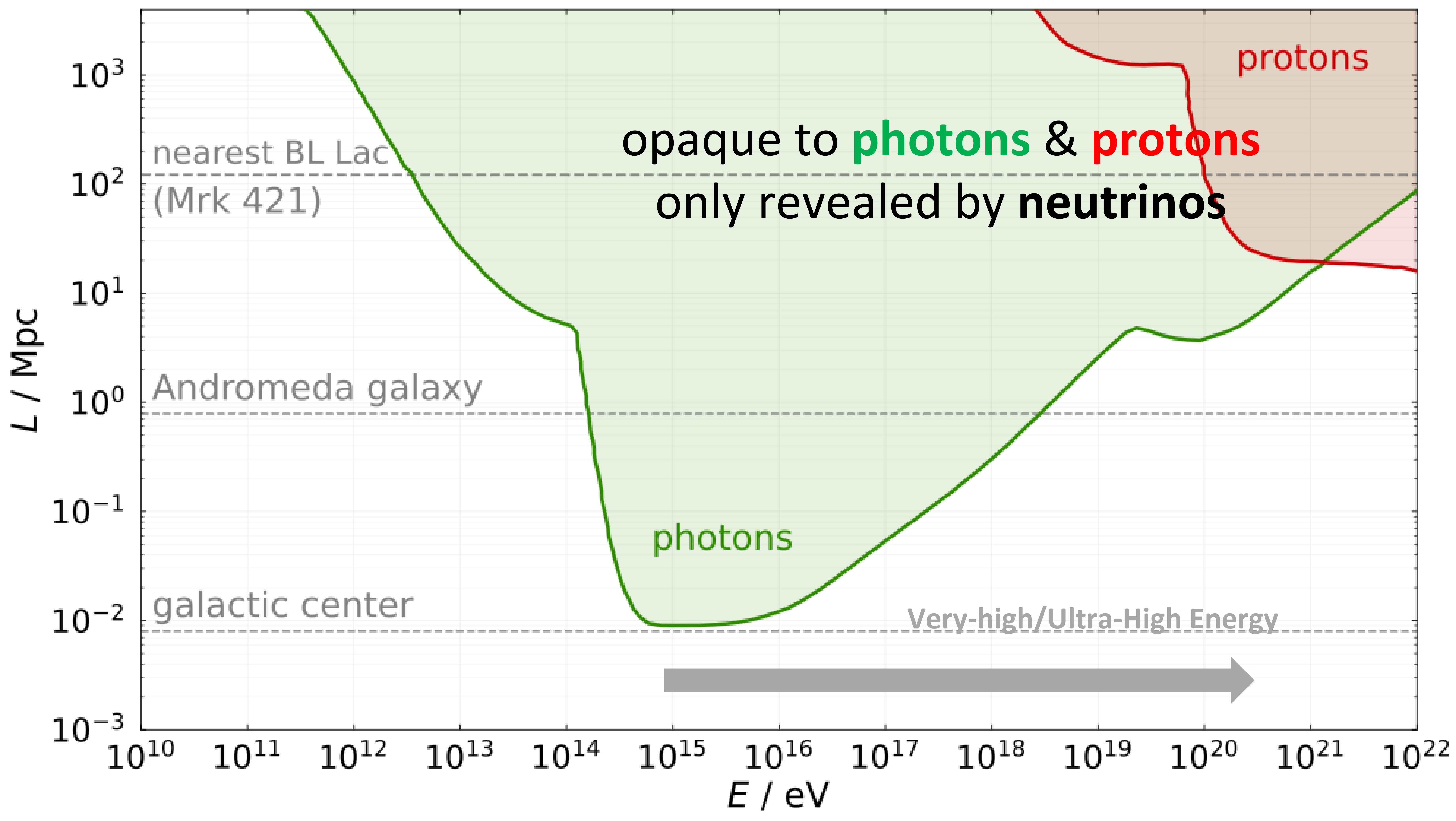
HERON

Additional slides


Astrophysics
(sources of ultra-high energy cosmic rays & neutrinos)
Ultra-High Energy Neutrino detection with Radio Pulses
ν
Particle Physics
(neutrino interactions & showers)
Classical Electrodynamics
(radio waves at MHz – GHz)

Neutrino: the best messenger at high energy

Attenuation distance in the Universe vs particle energy for protons & photons



- ▶ **a large fraction of the Universe is opaque to photons,** especially above ~ 10^{15} eV
- ▶ **cosmic rays** can probe large volumes of Universe **but are deflected by magnetic fields**
  → do not directly reveal their sources
- ▶ **neutrinos are unique messengers** of the high-energy, high-redshift Universe

The tau-neutrino “Earth-Skimming” air-shower channel

▶ most promising channel for UHE neutrino detection

Site survey

HERON

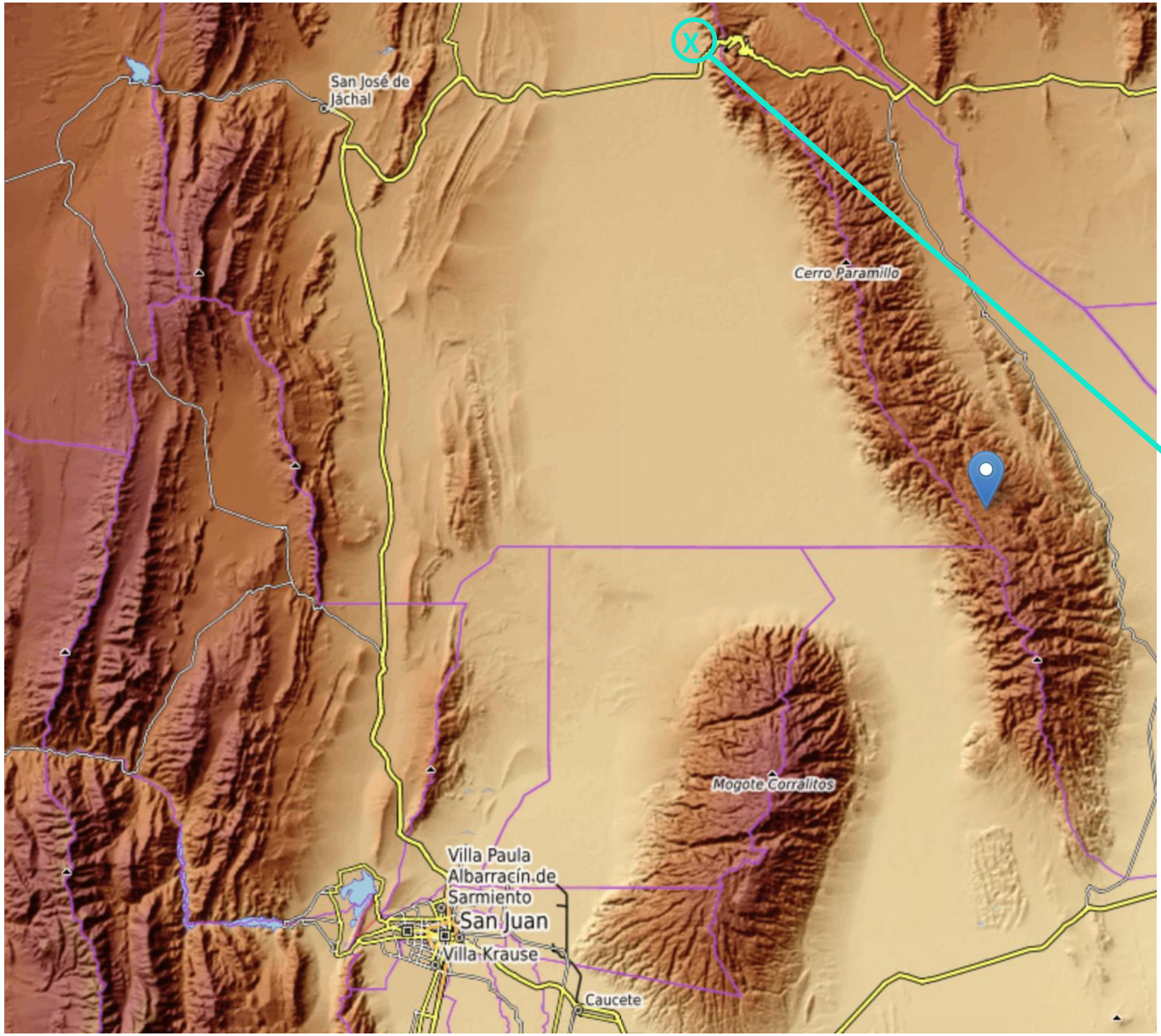
San Juan Province, Argentina, 25-29 March 2026

Jáchal Department,

San Juan province, Argentina

Latitude -30.5º

Site survey



Jáchal Department,

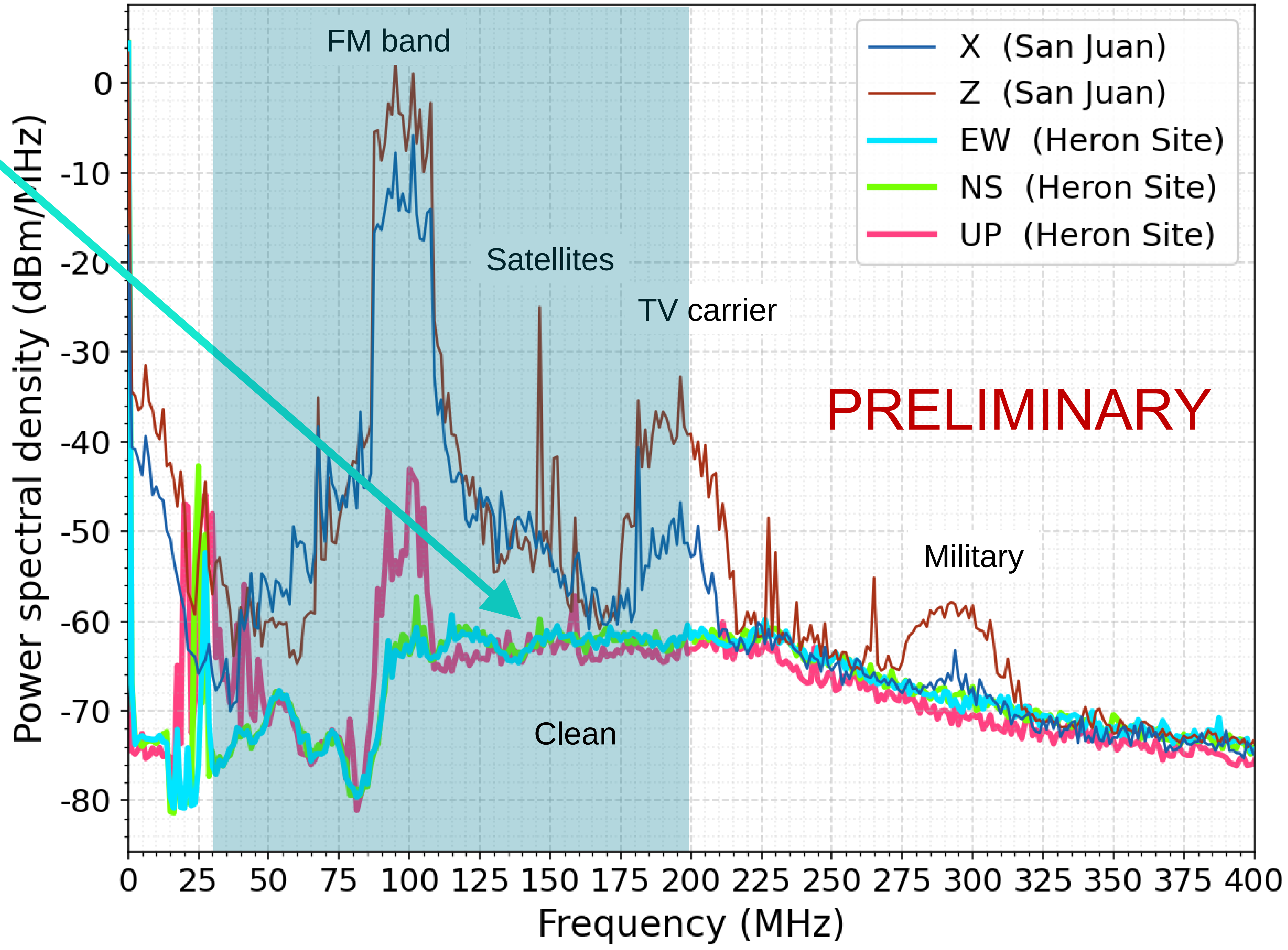
San Juan province, Argentina

Latitude -30.5º

Low-noise environment

comparison of HERON Site to San Juan suburbs

26 March 2026



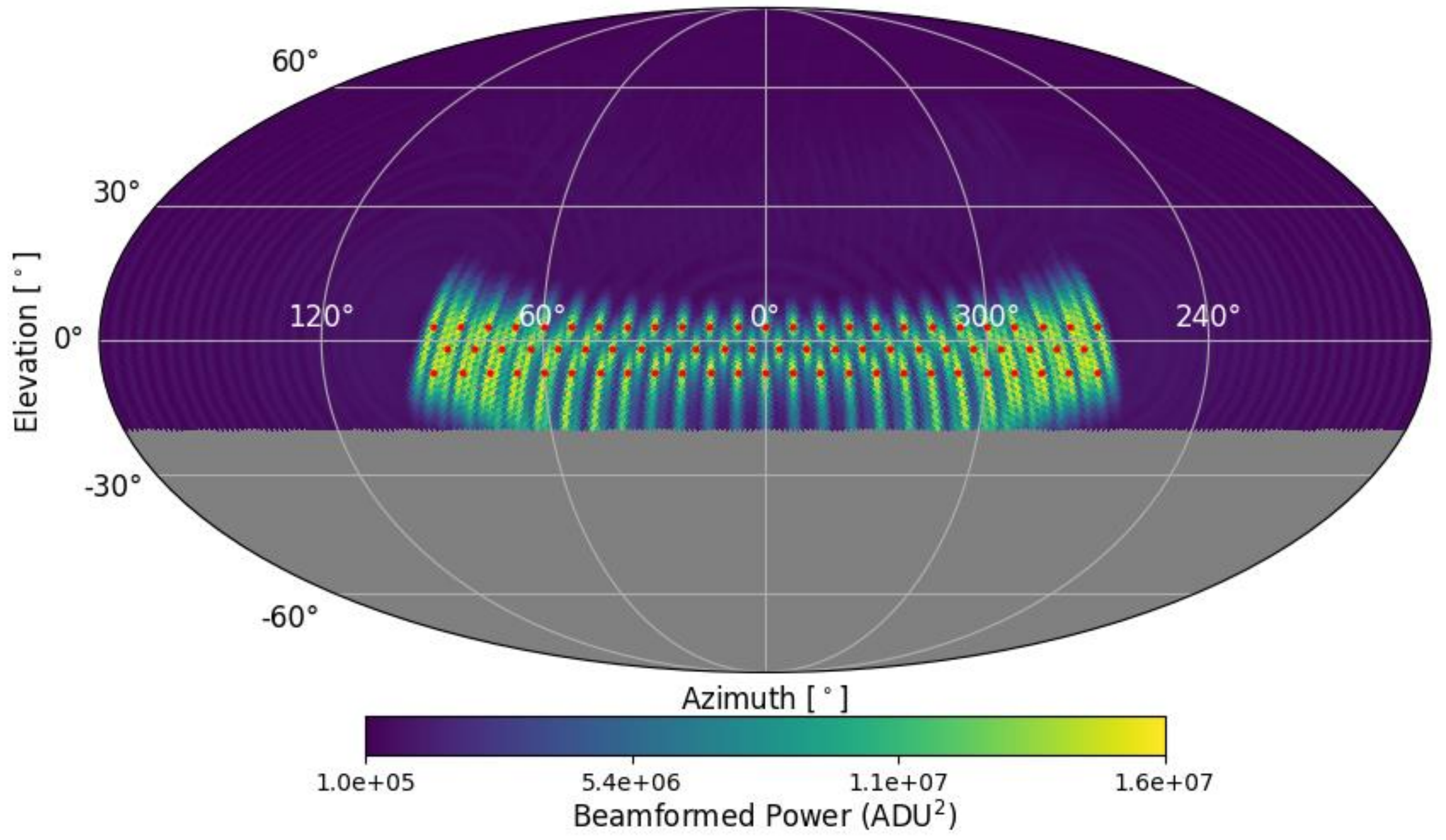
Observational strategy:

*use **astrophysical & multimessenger information** to target likely neutrino sources as they set below horizon*

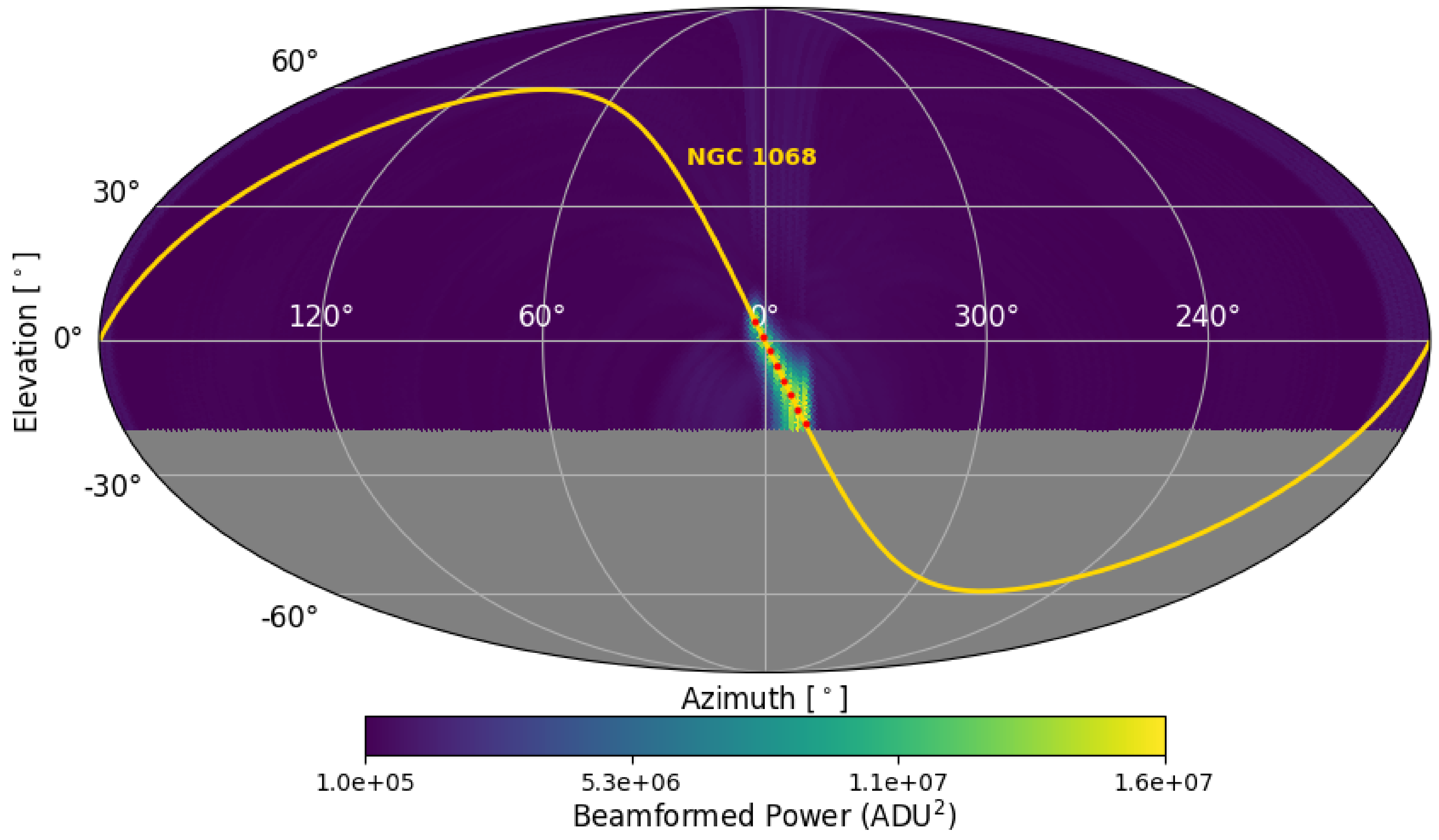
- HERON's beams will typically be distributed along the horizon
- If a target of opportunity is identified, beams can be assigned along its path

credit: Andrew Zeolla, IAP-Paris

74 beams covering horizon:

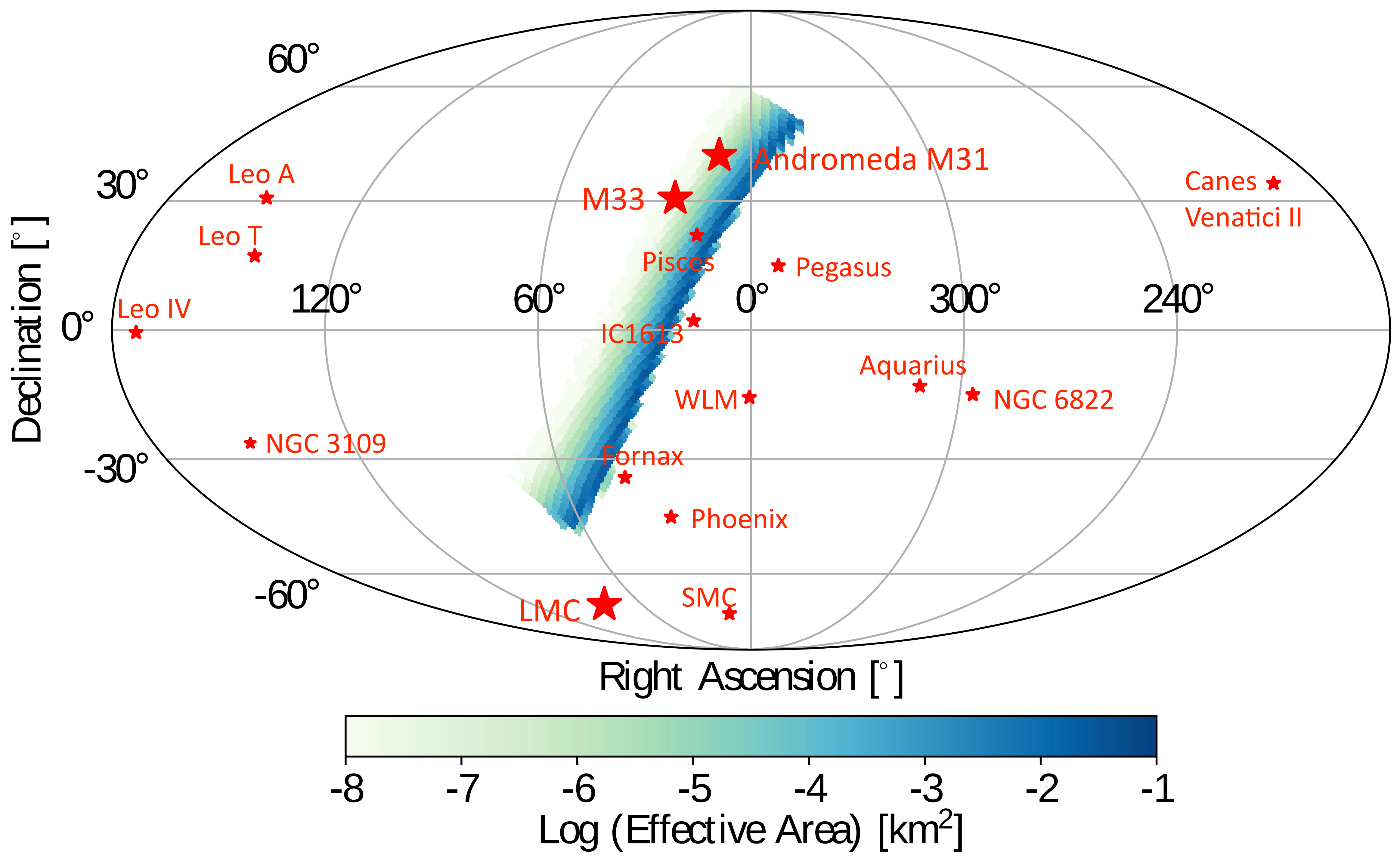


8 beams tracking NGC 1068:

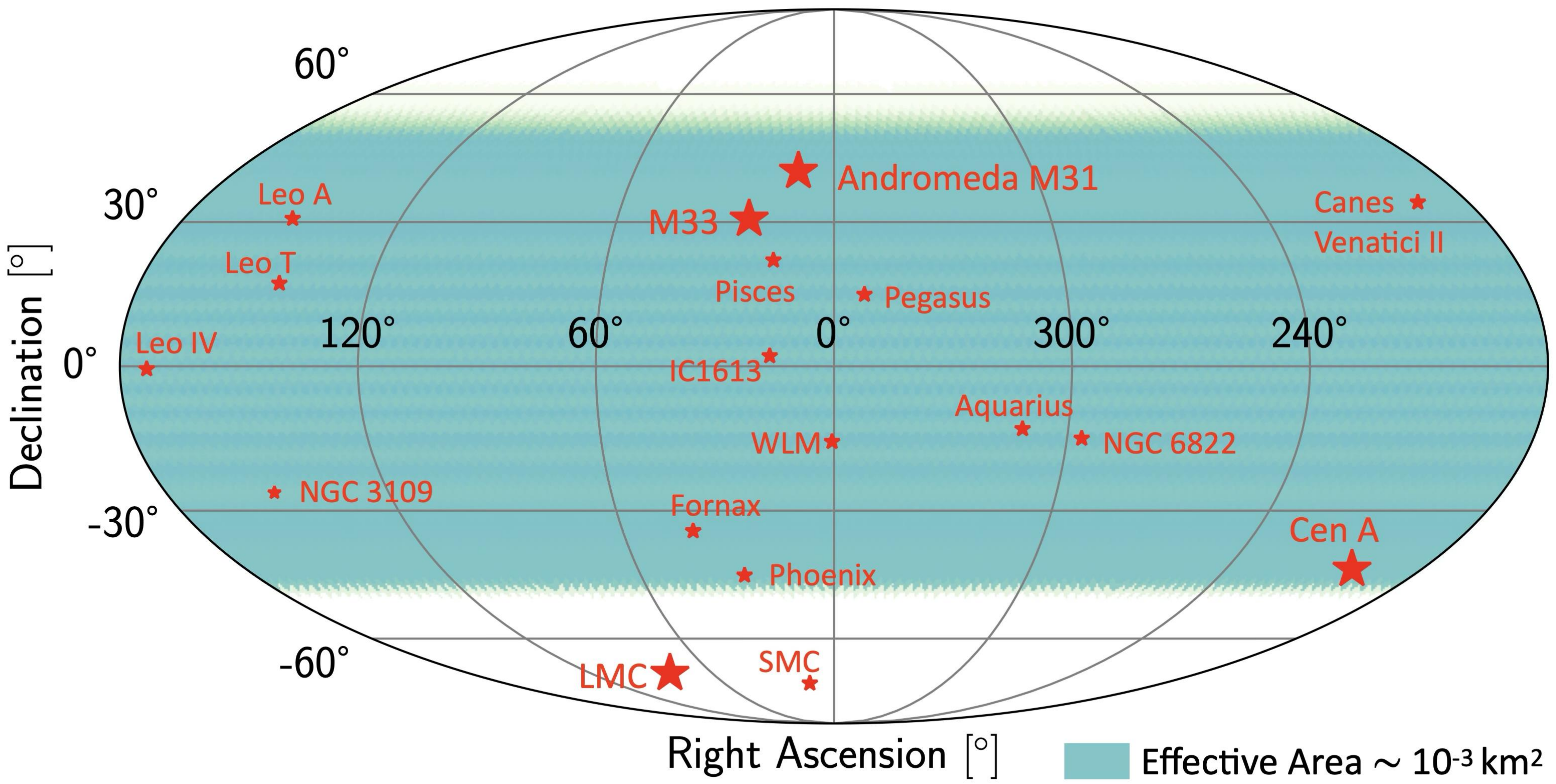


How much of the sky can HERON view?

≅ 6% of sky instantaneously

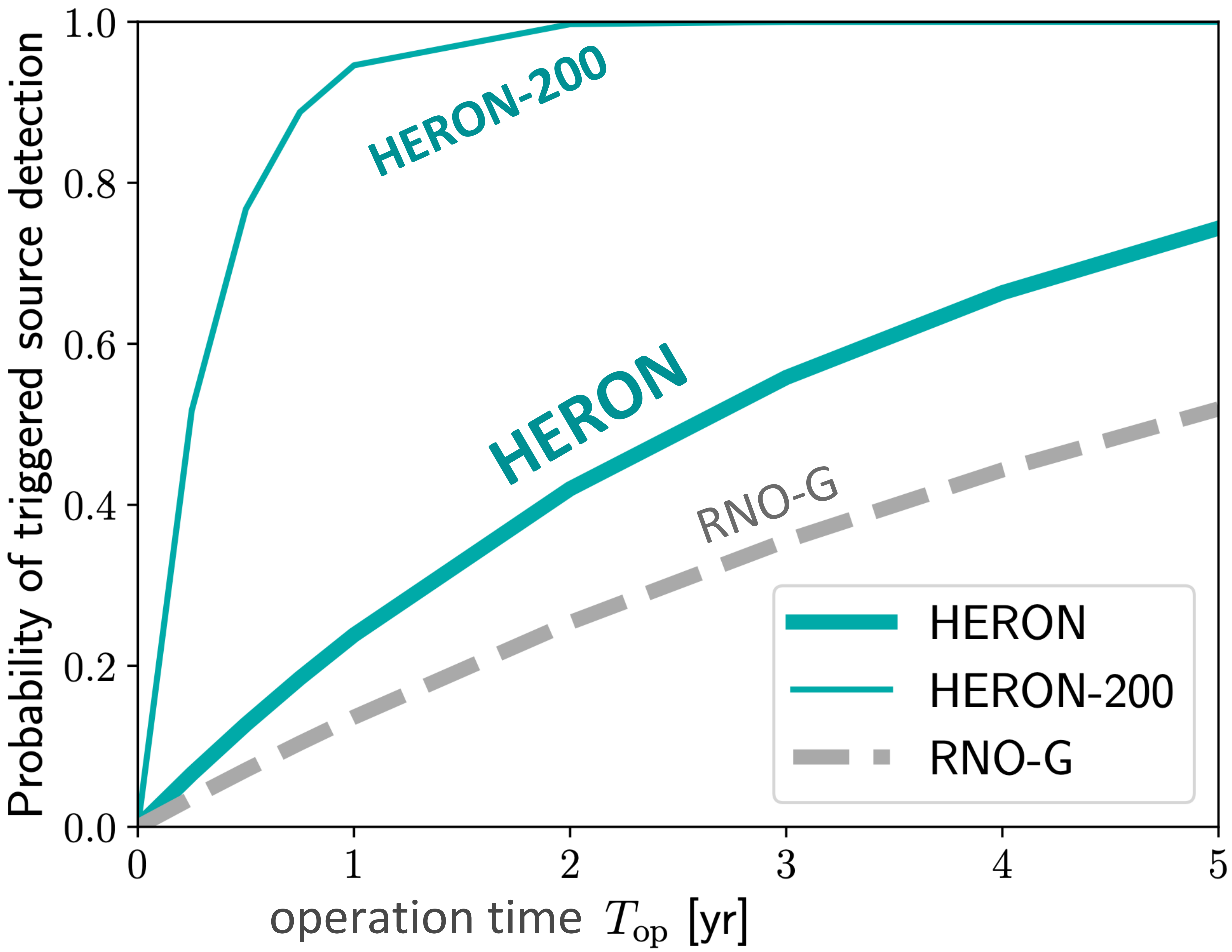


≅ 70% of sky each day



HERON performances to detect UHE neutrino sources

typical parameters for binary neutron star mergers



~100% probability in 2 years

75% probability of source detection within 1 Gpc in 5 years

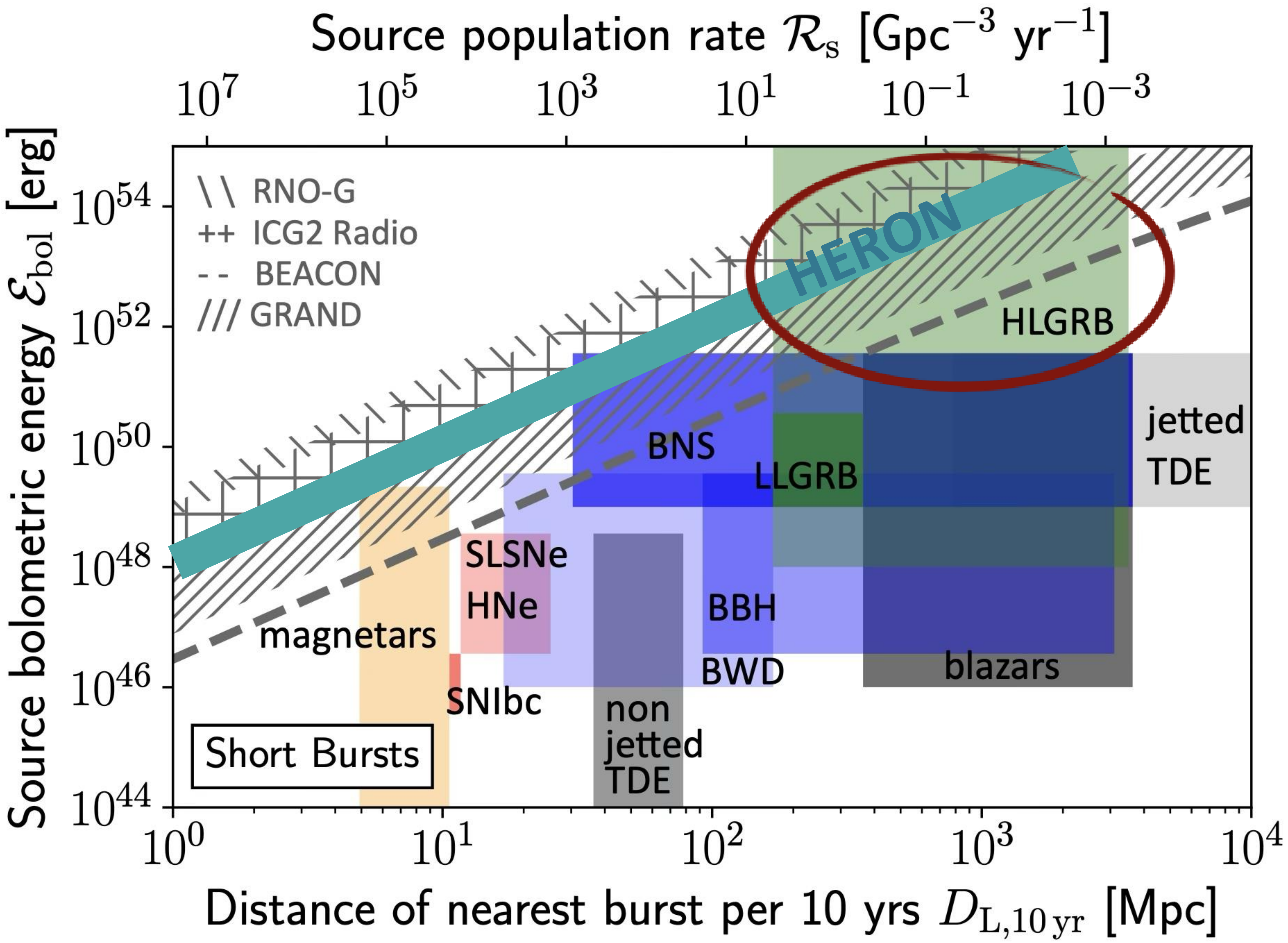
For longer bursts: SNIbc/magnetar types of superluminous supernovae can be detected in the Local Universe. Occurrence rate: 1 per 10 to 600 years.

KK, Mukhopadhyay, Murase, Alves Batista, Fox, OM, SW, Zeolla, subm.

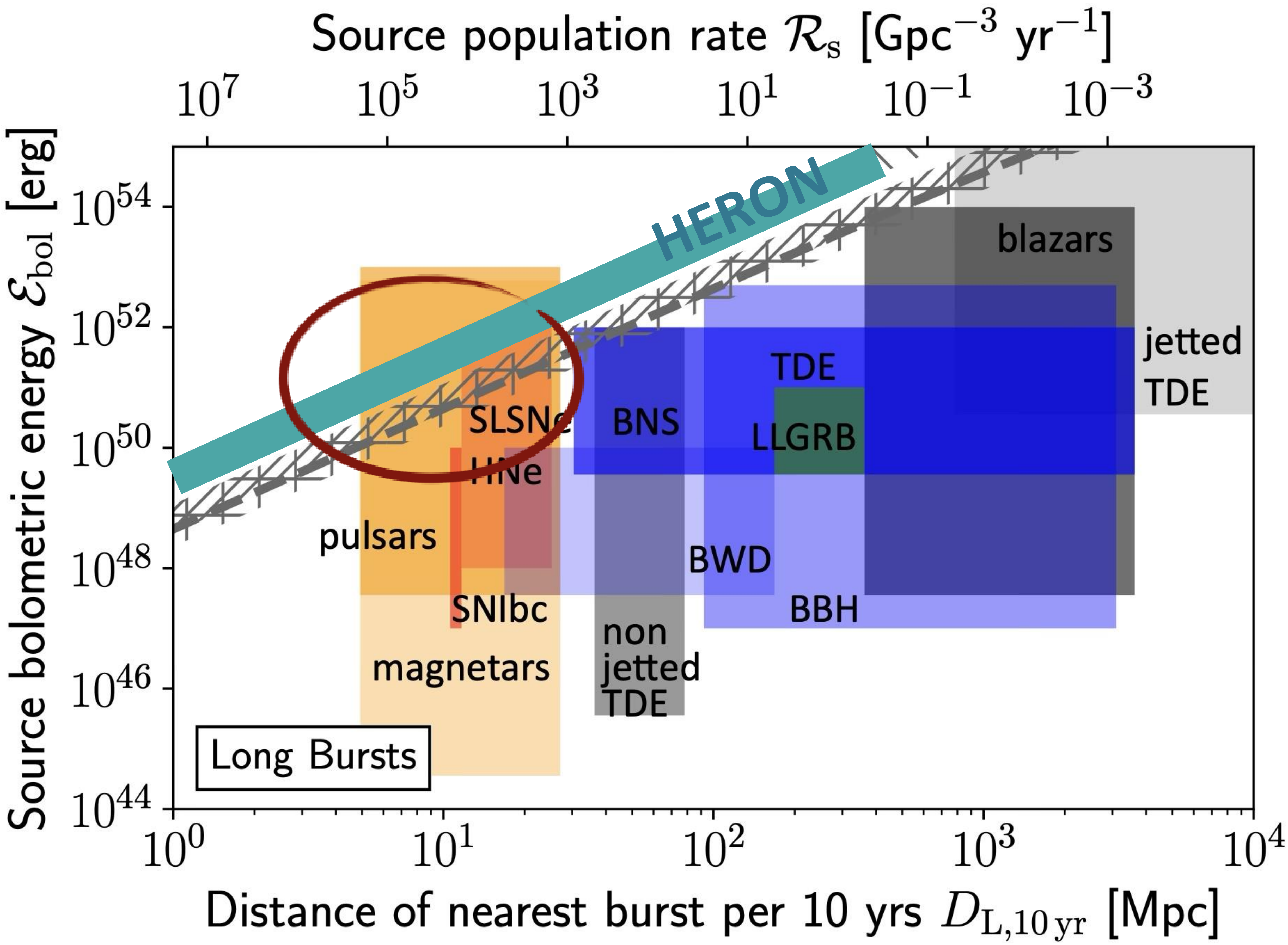
$\delta t = 10^2$ s, $\mathcal{E}_\nu^{\rm UHE,\,iso} = 3.0 \times 10^{50}$ erg, $f_{\rm bm} = 1\%$, $R_0 = 300$ Gpc^{-3}yr^{-1}

What astrophysical sources to aim for in the multi-messenger era?

KK, Mukhopadhyay, Murase, Alves Batista, Fox, **OM**, **SW**, Zeolla, subm.



Short bursts: stay in the instantaneous field of view (FoV) of the instrument (~30 min - 1 day)

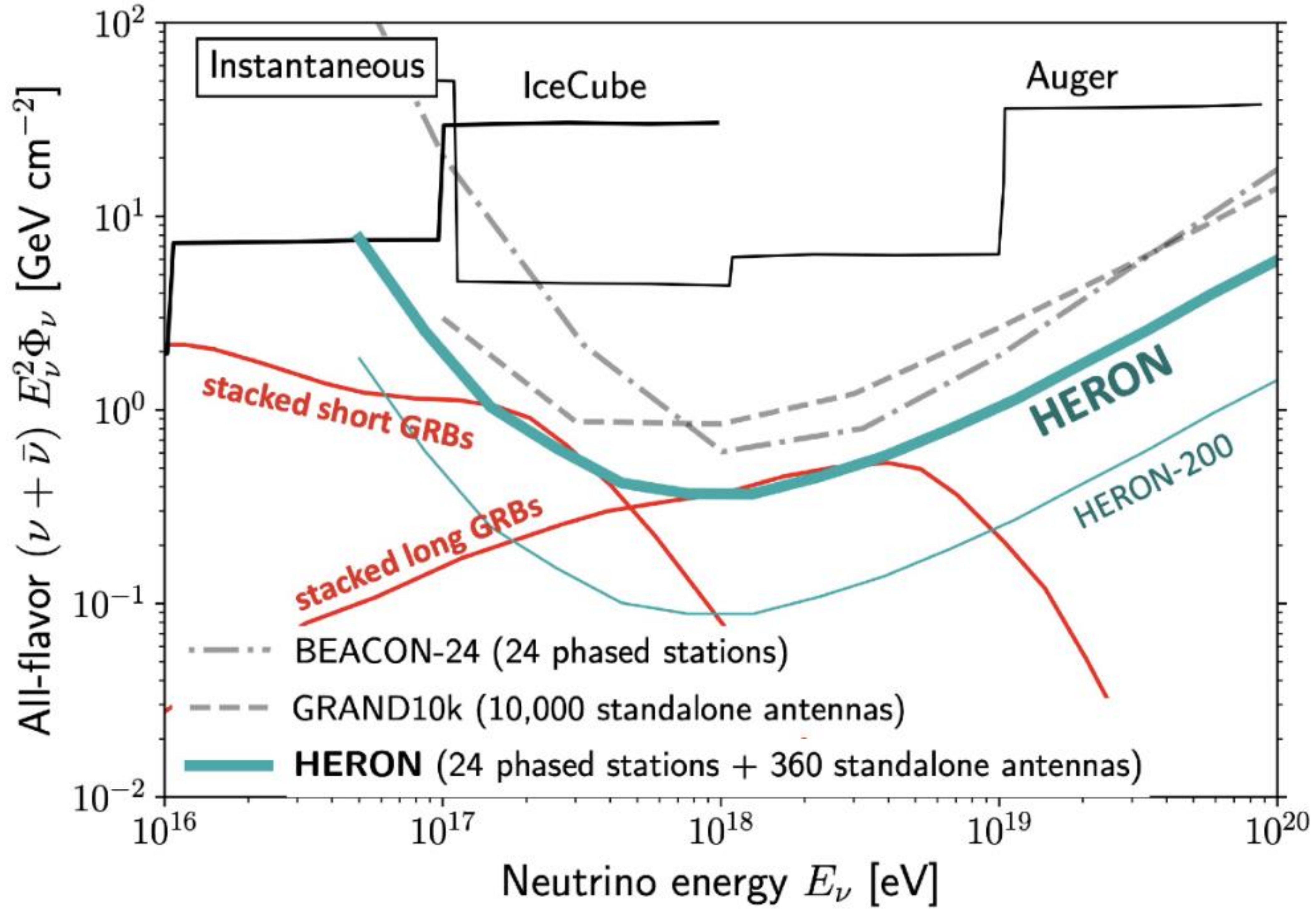


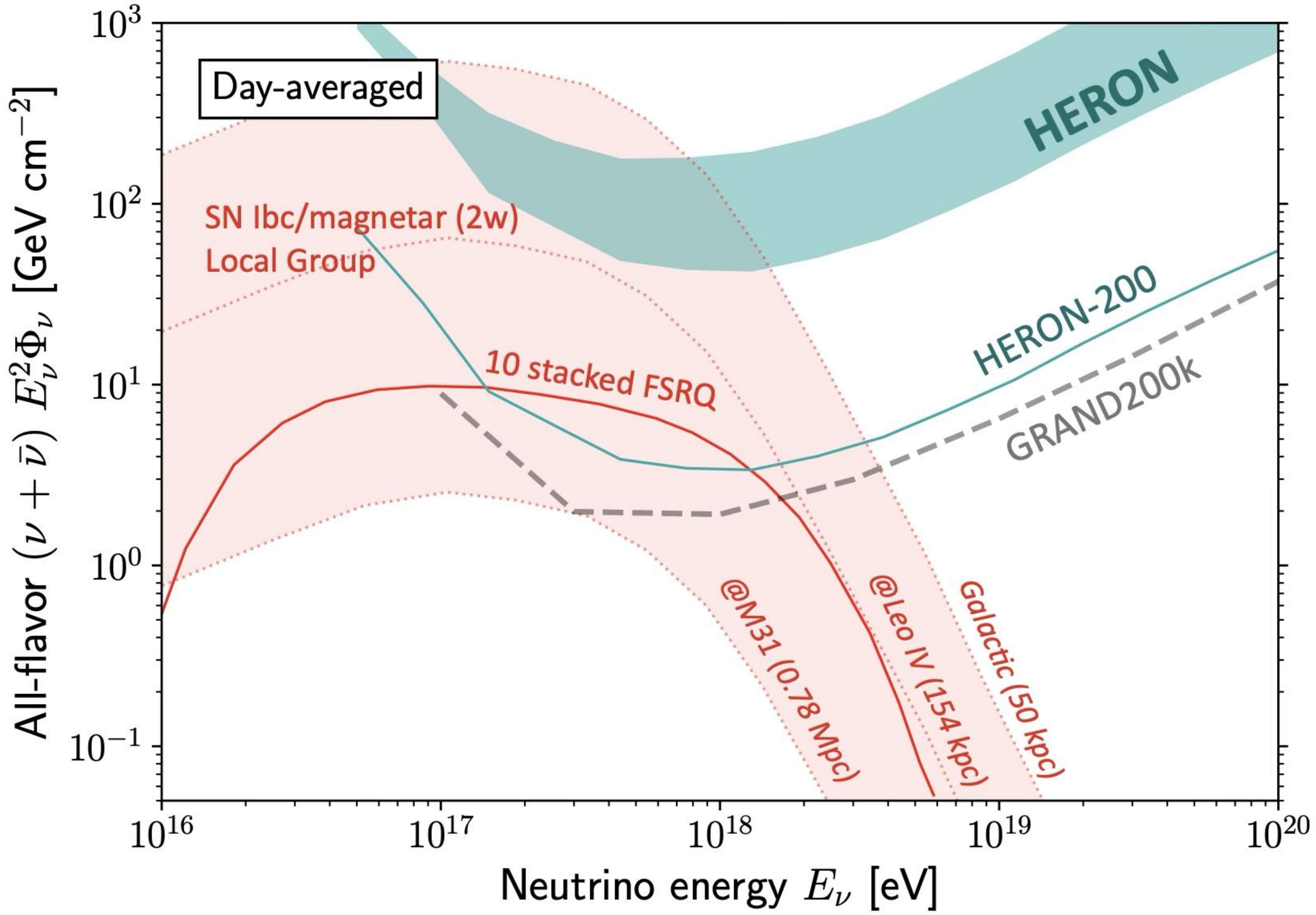
Short bursts: stay in the instantaneous field of view (FoV) of the instrument (~30 min - 1 day)

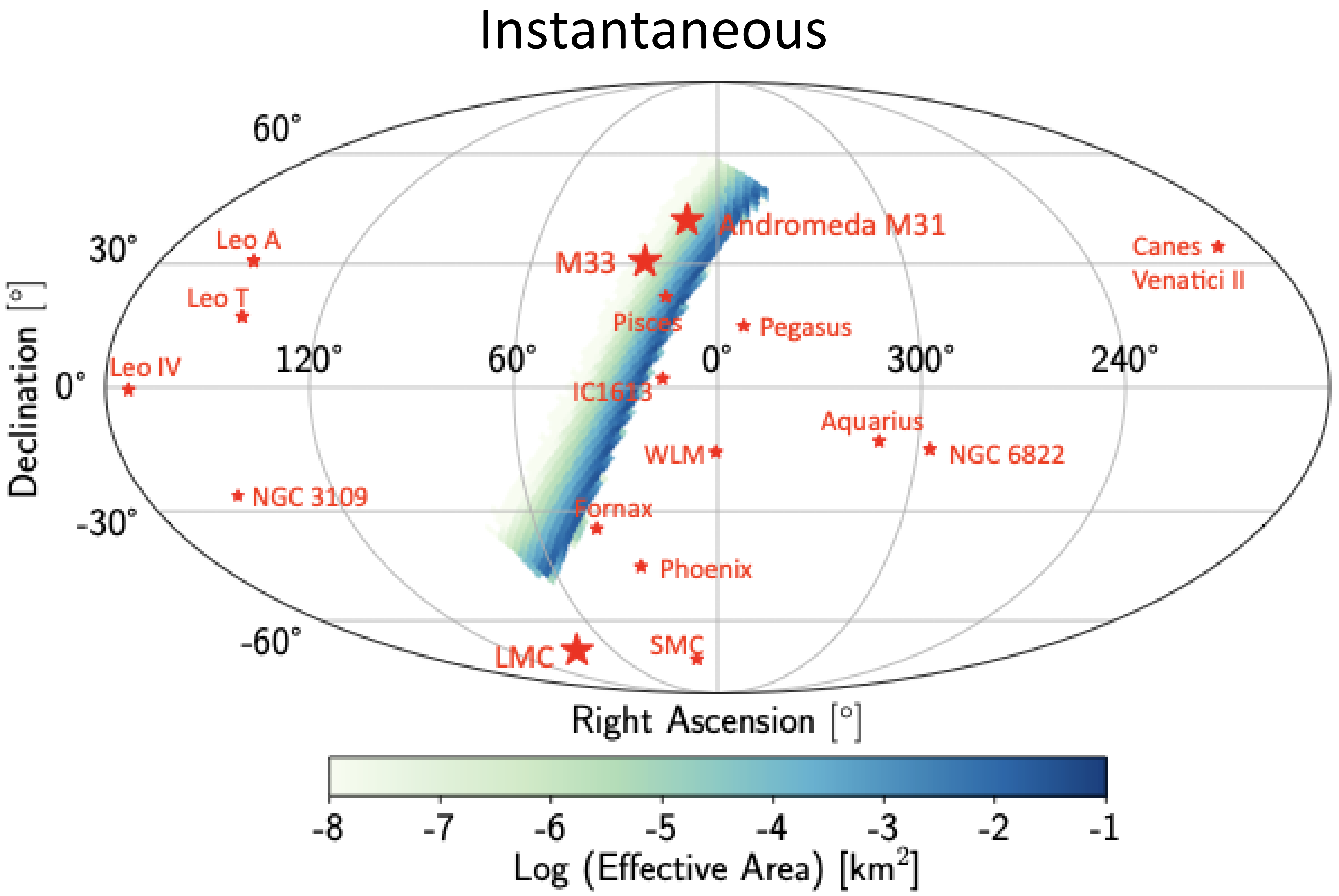
Long bursts: any longer transients

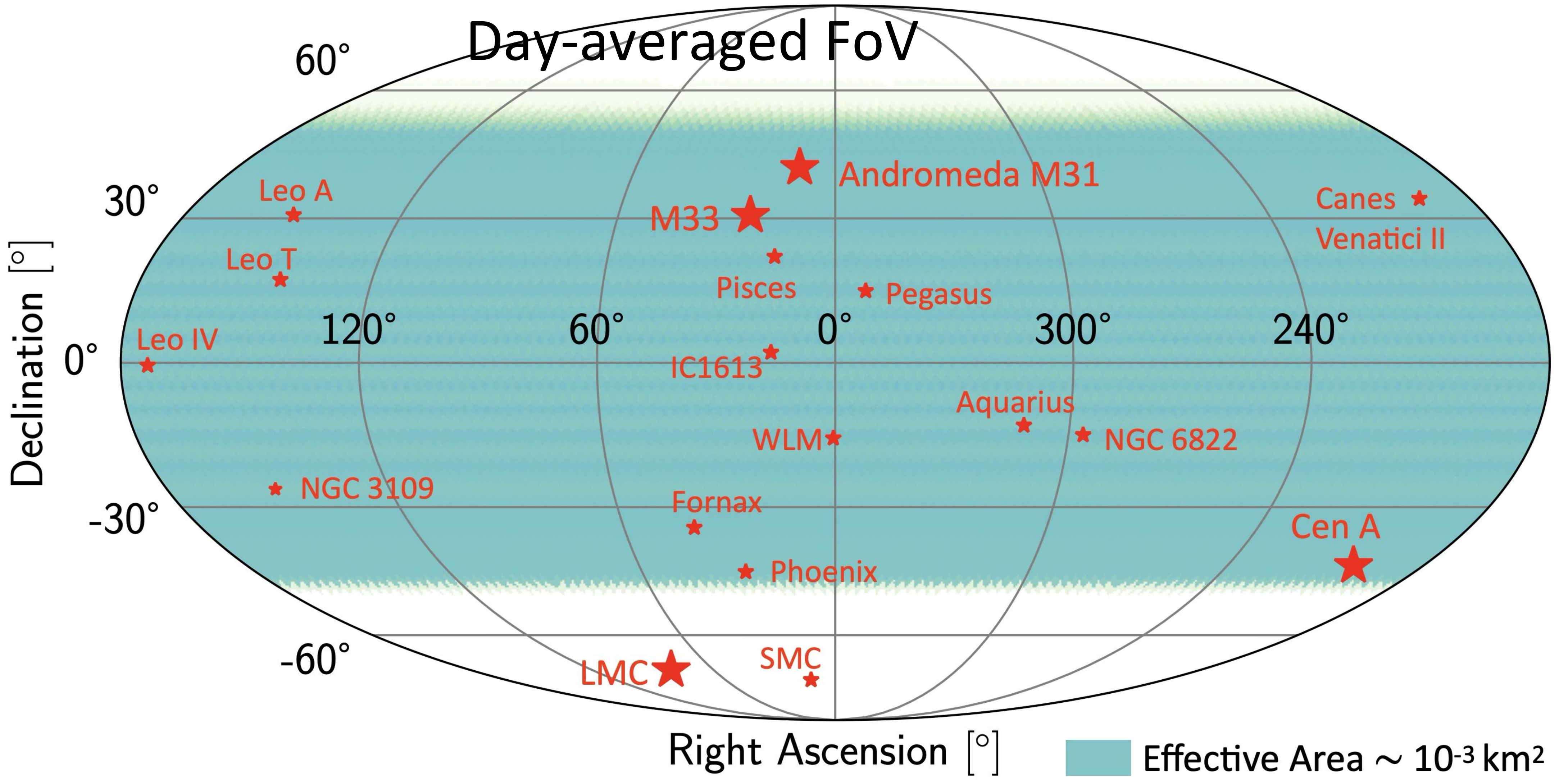
Detectable: Bright rare (distant) sources

Detectable: Local Group & nearby galaxies


Instantaneous
IceCube
Auger
stacked short GRBs
stacked long GRBs
HERON
HERON-200
BEACON-24 (24 phased stations)
GRAND10k (10,000 standalone antennas)
HERON (24 phased stations + 360 standalone antennas)
All-flavor $(\nu + \bar{\nu})$ $E_\nu^2 \Phi_\nu$ [GeV cm^{-2}]
Neutrino energy E_ν [eV]


Day-averaged
HERON
SN Ibc/magnetar (2w)
Local Group
10 stacked FSRQ
HERON-200
GRAND200k
@M31 (0.78 Mpc)
@Leo IV (154 kpc)
Galactic (50 kpc)
All-flavor $(\nu + \bar{\nu})$ $E_\nu^2 \Phi_\nu$ [GeV cm^{-2}]
Neutrino energy E_ν [eV]


Instantaneous
Andromeda M31
M33
Pisces
Pegasus
IC1613
WLM
Fornax
Phoenix
LMC
SMC
Leo A
Leo T
Leo IV
NGC 3109
Aquarius
NGC 6822
Canes
Venatici II
Declination [°]
Right Ascension [°]
Log (Effective Area) [km^2]


Day-averaged FoV
Andromeda M31
M33
Pisces
Pegasus
IC1613
WLM
Fornax
Phoenix
LMC
SMC
Cen A
Leo A
Leo T
Leo IV
NGC 3109
Aquarius
NGC 6822
Canes
Venatici II
Declination [°]
Right Ascension [°]
Effective Area ~ 10^{-3} km^2

3D mapping of showers

- Simulation data data set on HERON topography (Neutrinos, E in 2 10^{16} – 2 10^{18}eV)

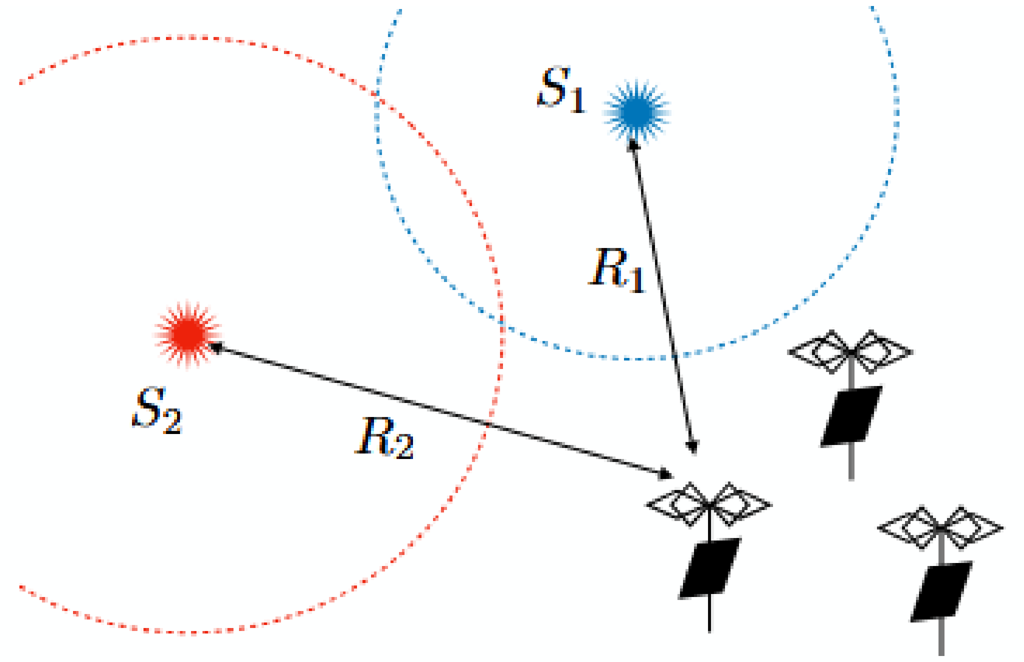
➔ Efield at positions of HERON autonomous antennas

- (Estimated) Galactic noise added to simulated Efield signals (σ = 20μV/m)
- Beamforming treatment following Schoorlemer & Carvalho, Eur. Phys. J.

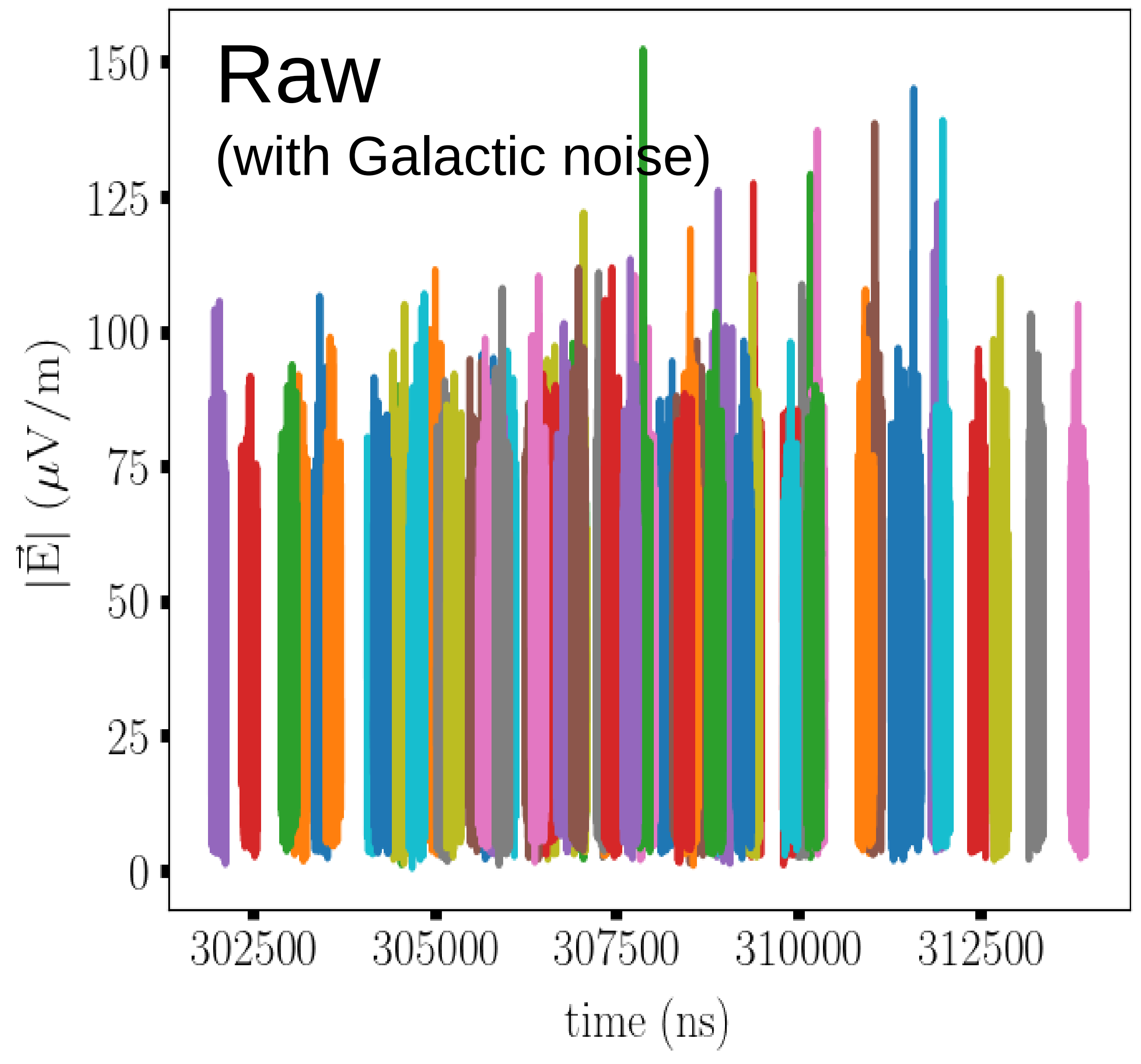
Time delay $\frac{c}{n}\delta t = R$

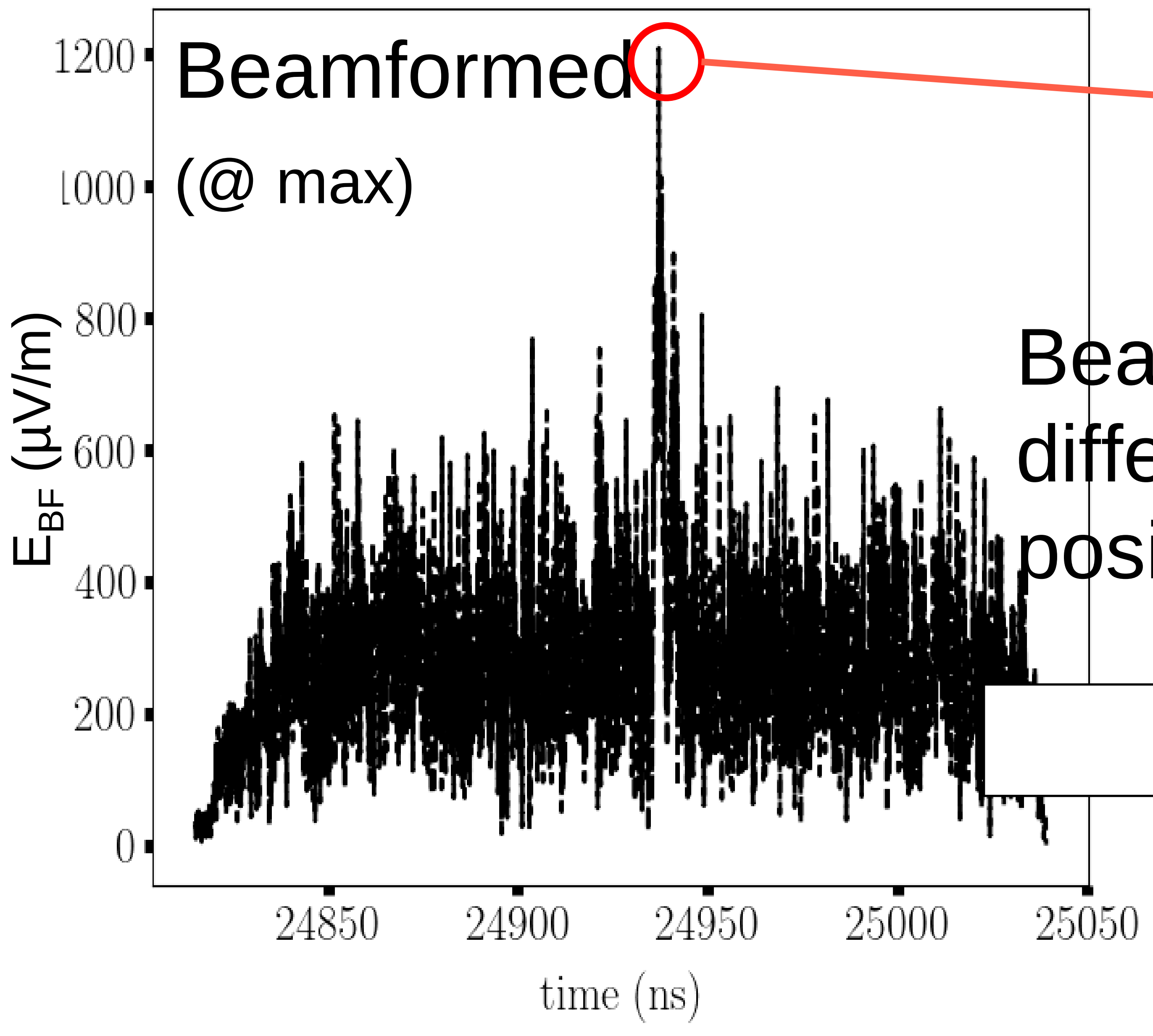
"Phasing" $\vec{E}(t) \to \vec{E}(t - \delta t)$

"Beamforming" $\vec{E}_{\mathrm{BF}} = \sum_i \vec{E}_i(t - \delta t_i)$

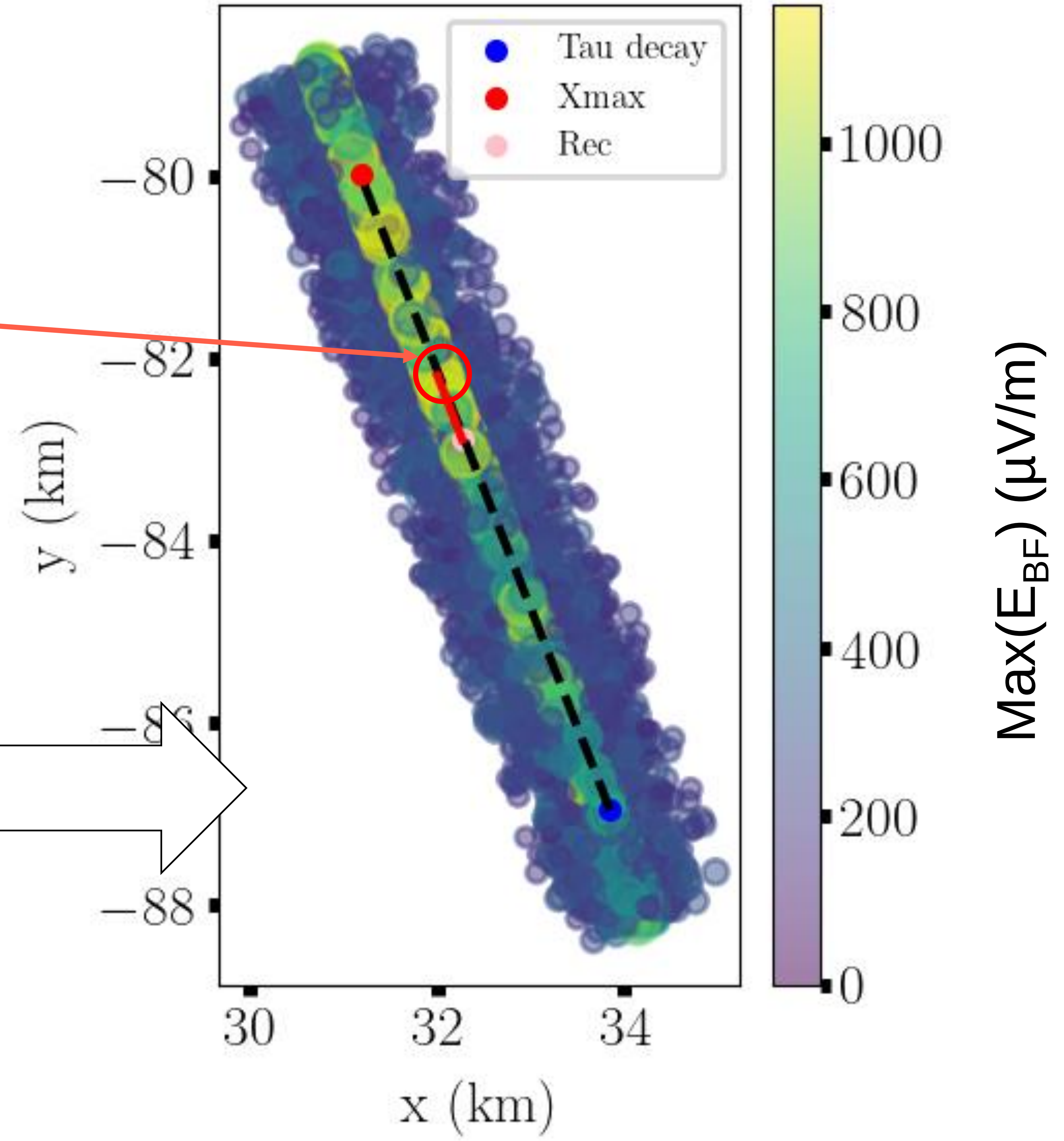


Simulation: E_ν = 1.2 10^{18} eV / E_τ = 10^{18} eV





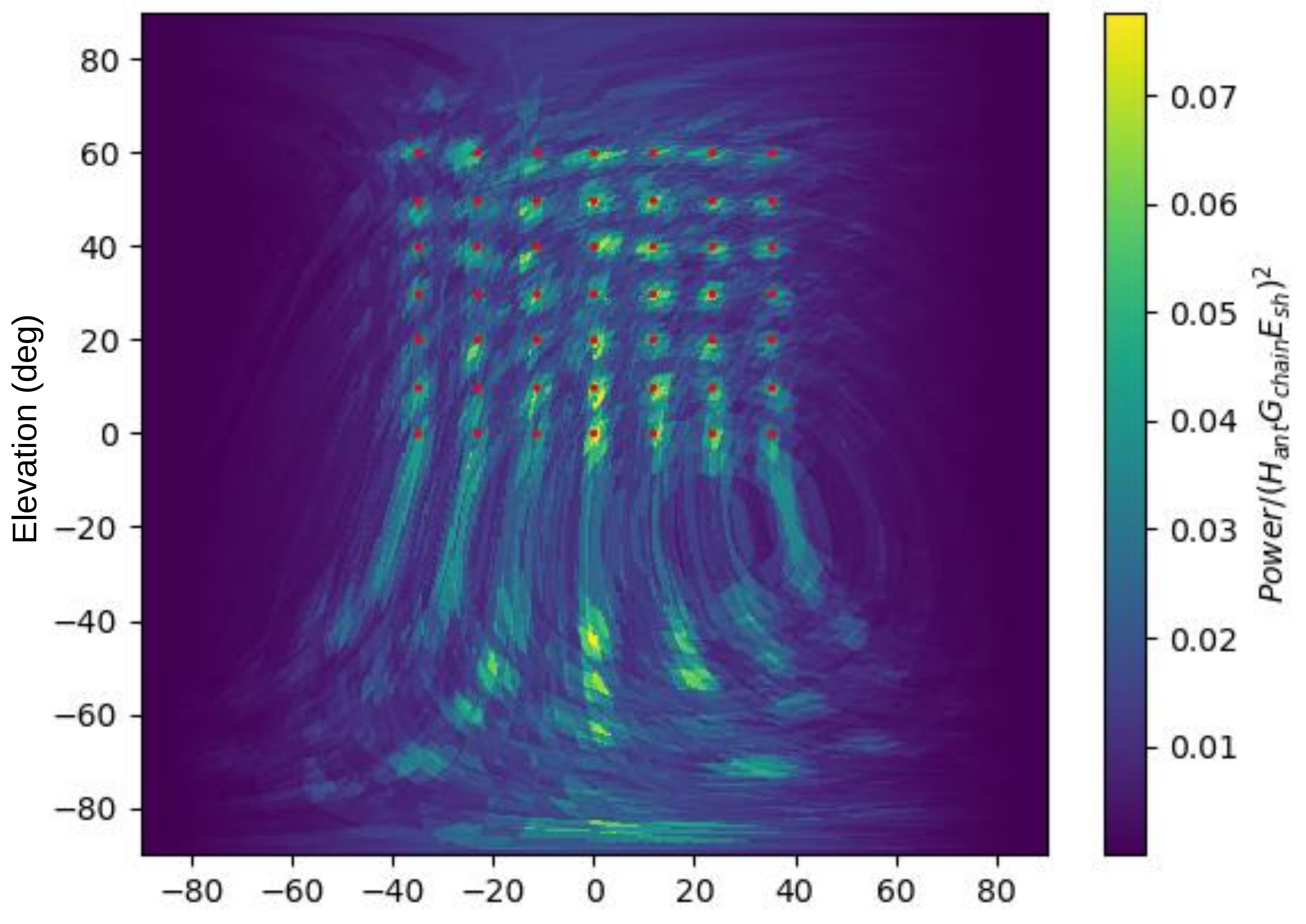
Beamforming for different test positions in space



Beams in the Trigger

- Beam width $\delta\theta \sim \frac{c}{L\,\Delta f\,(SNR)}$
- BEACON prototype (Spartan7) with 6 antennas & 42 beams with a beamwidth of 10°
- HERON beamwidth: 5°
- Requires 108 beams to cover 15° zenith angle range centered at the horizon and 180° FOV per station
- With 3 FPGAs per station, fits within budget (max 126) with margin for additional above and below horizon beams for calibration

Beams programmed into the BEACON prototype



Azimuth (deg)