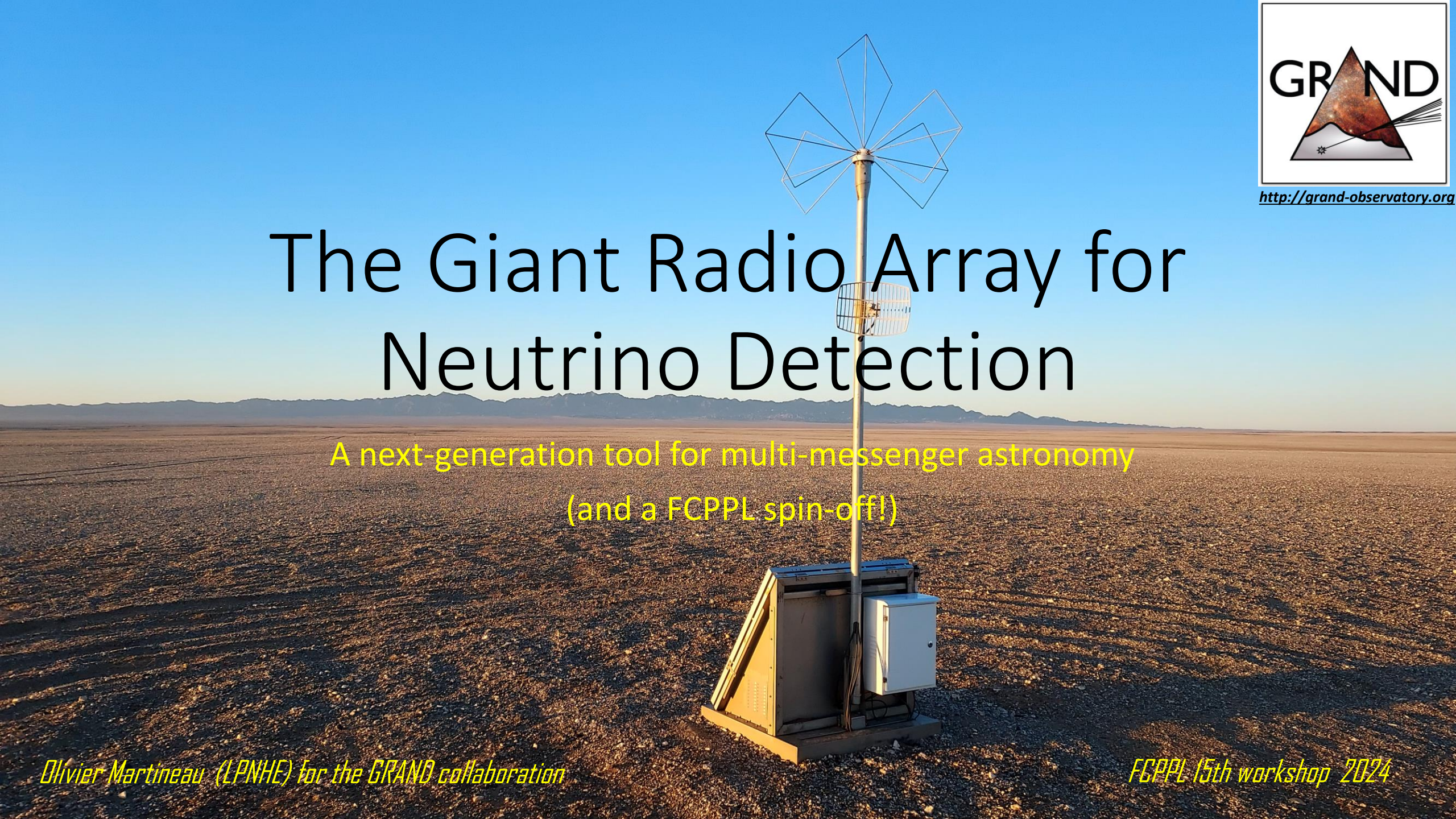


http://grand-observatory.org

The Giant Radio Array for Neutrino Detection

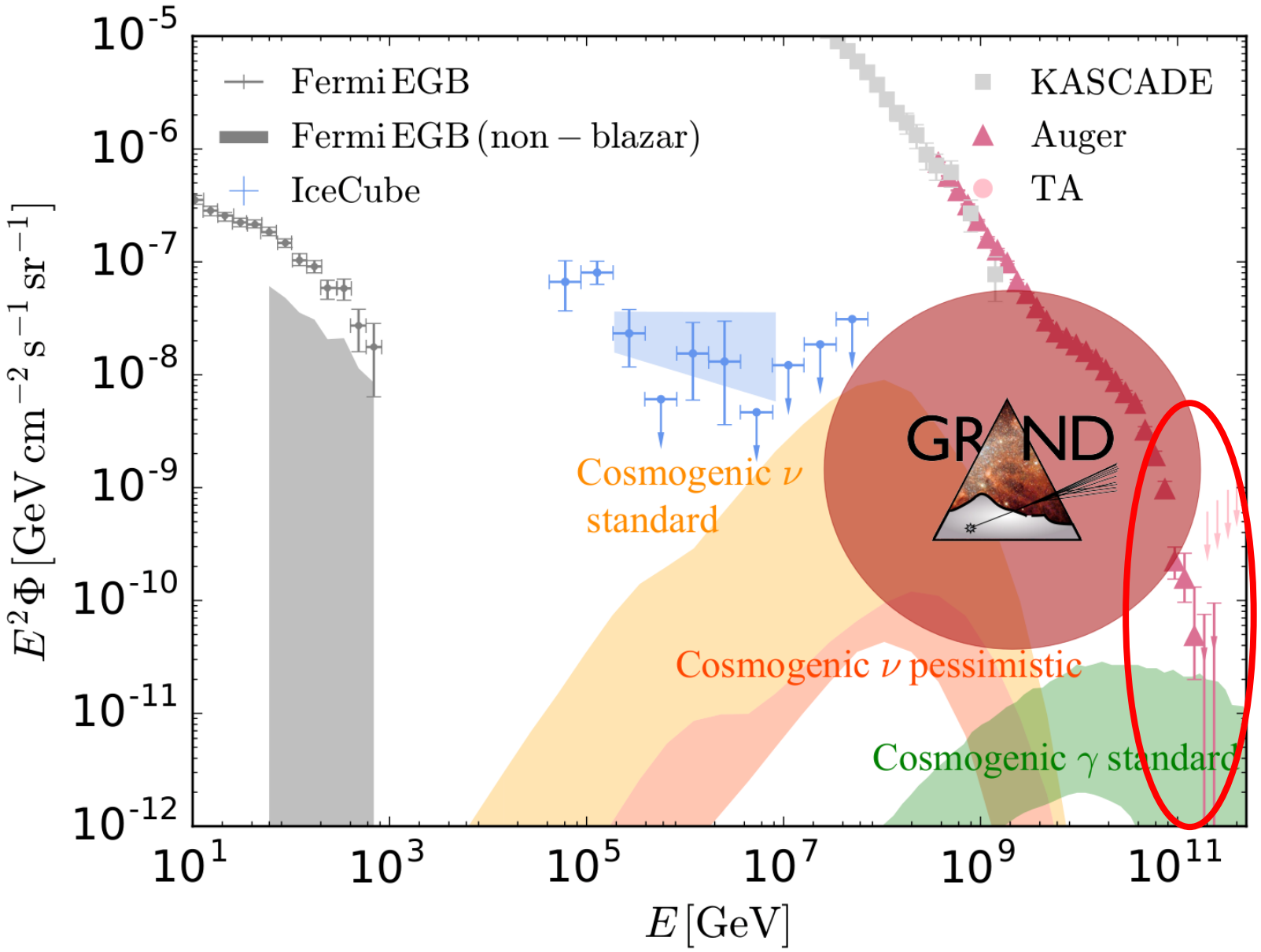
A next-generation tool for multi-messenger astronomy

(and a FCPPL spin-off!)

Olivier Martineau (LPNHE) for the GRAND collaboration

FCPPL 15th workshop 2024

The New Frontier of the cosmic landscape



UHECR sources still not know!
Challenges:
Charge + mixed composition
EAS physics…
UHE neutrinos as a powerfull indirect probe?

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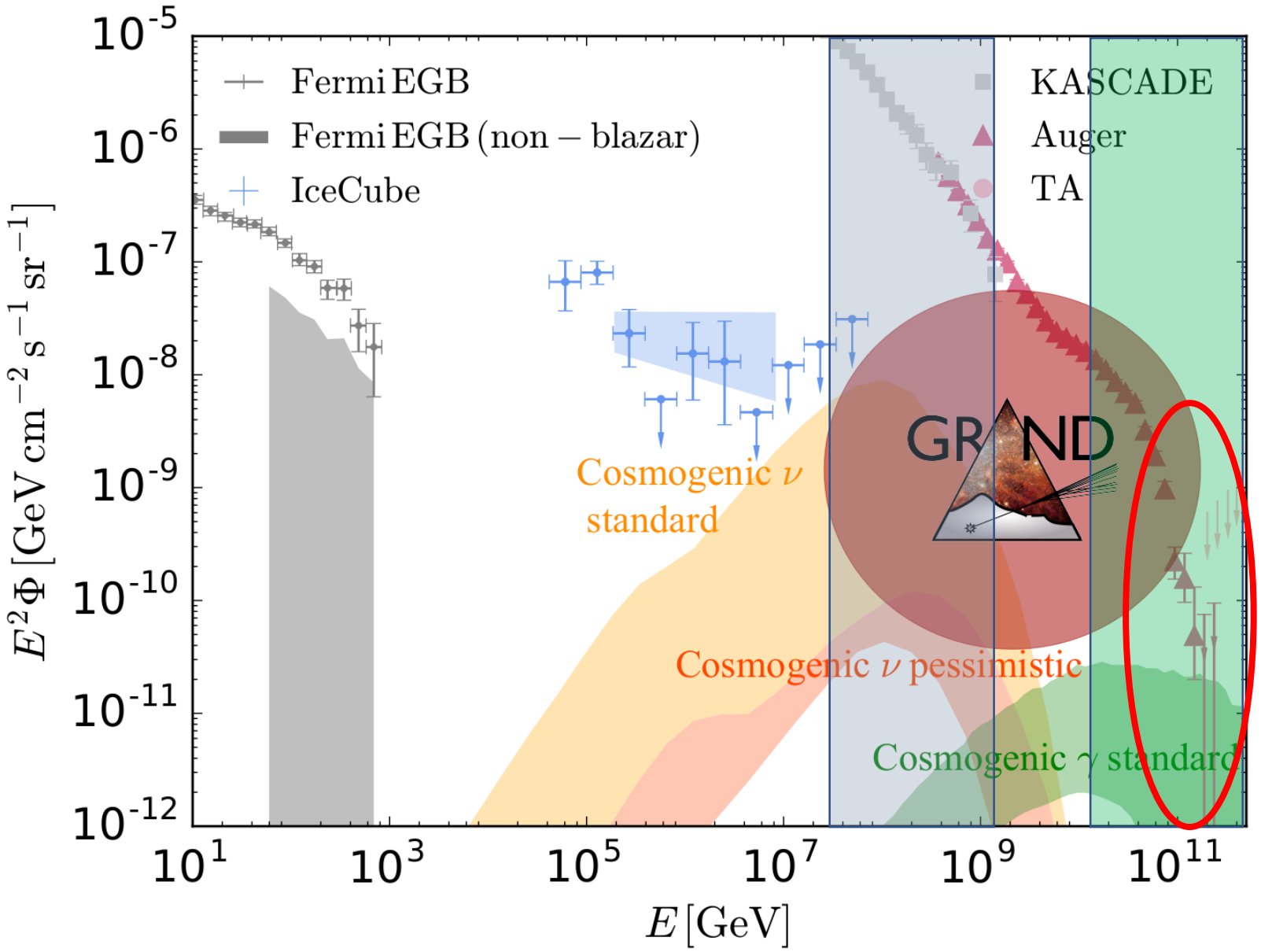

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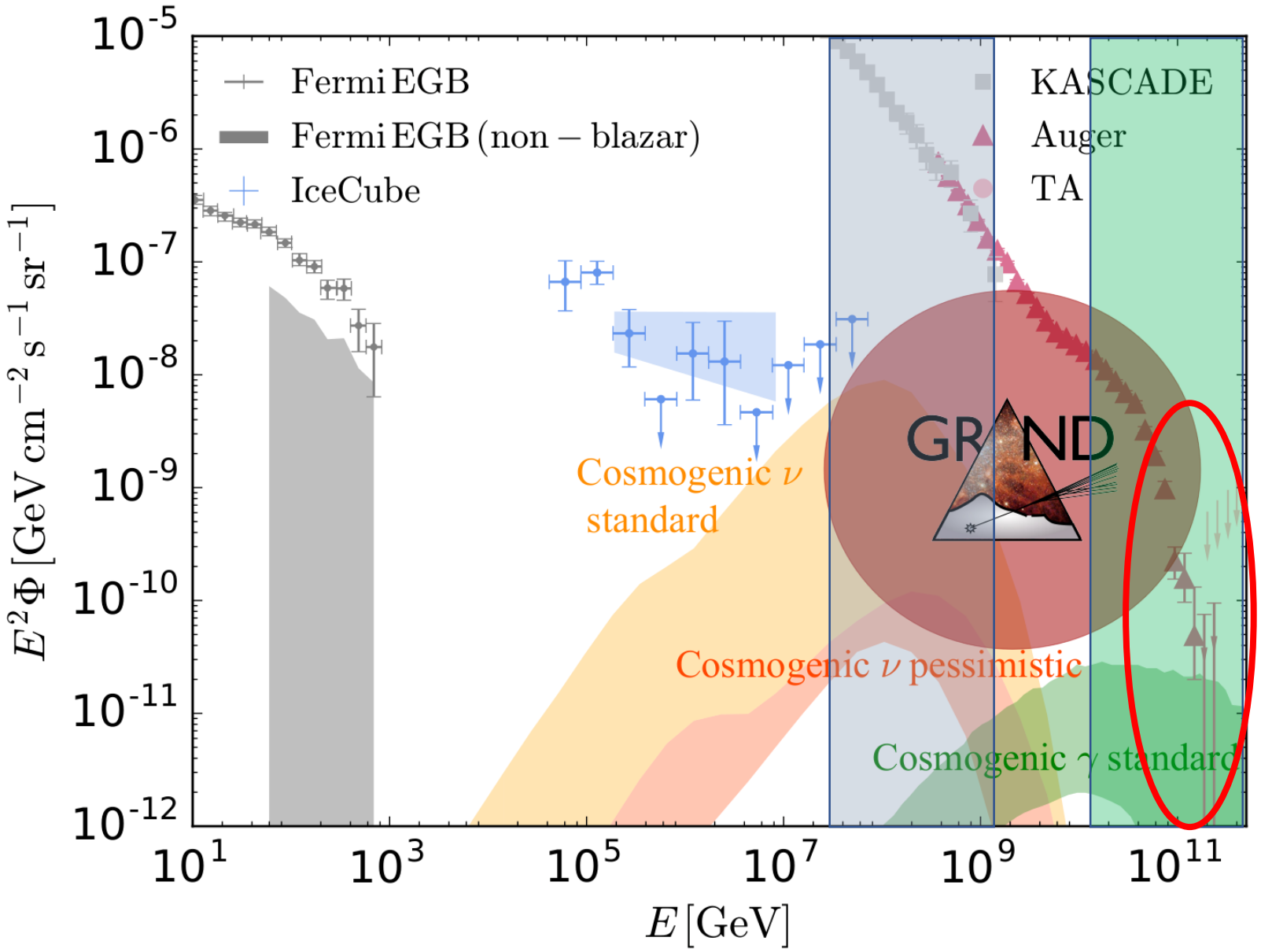

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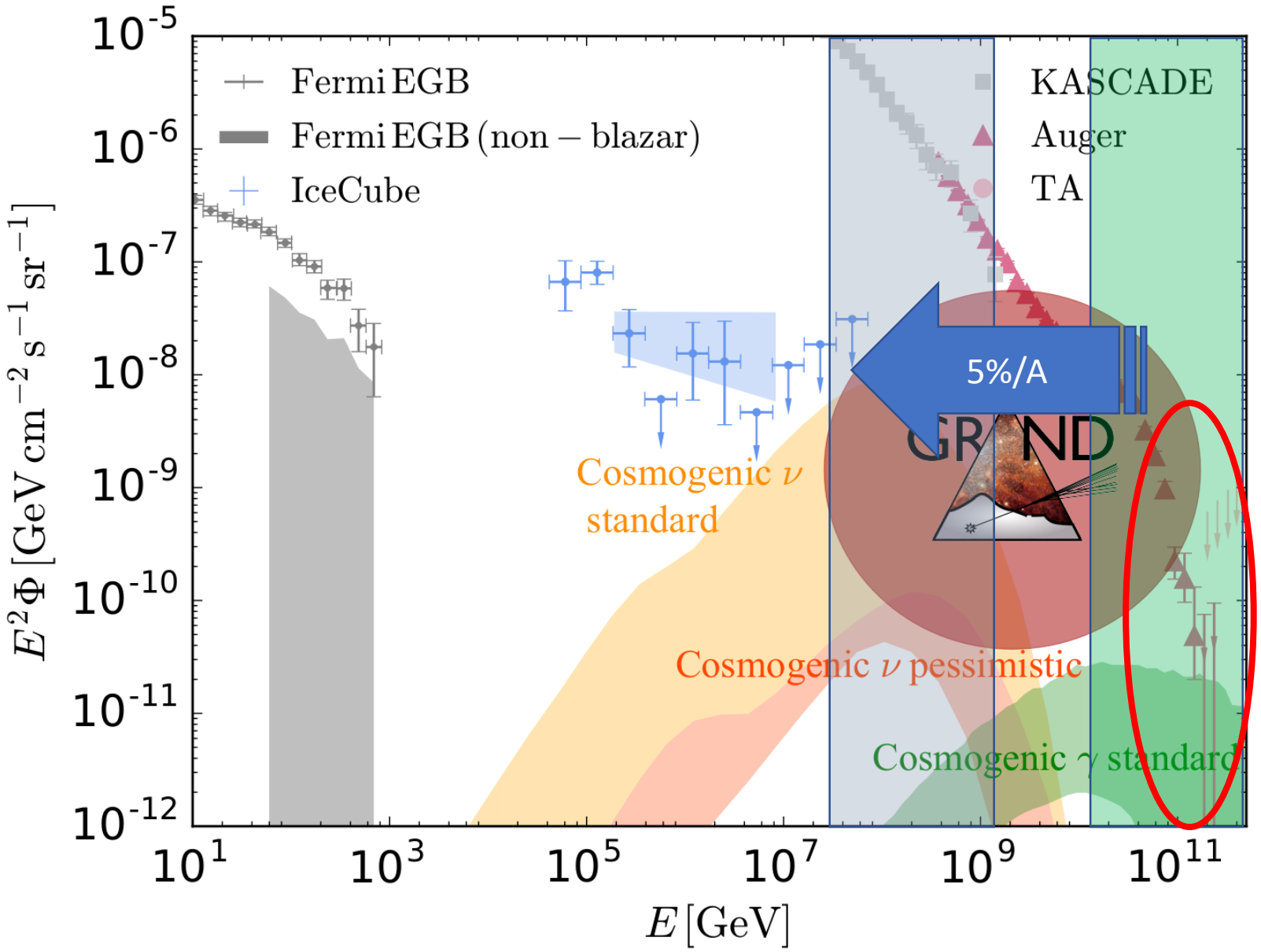

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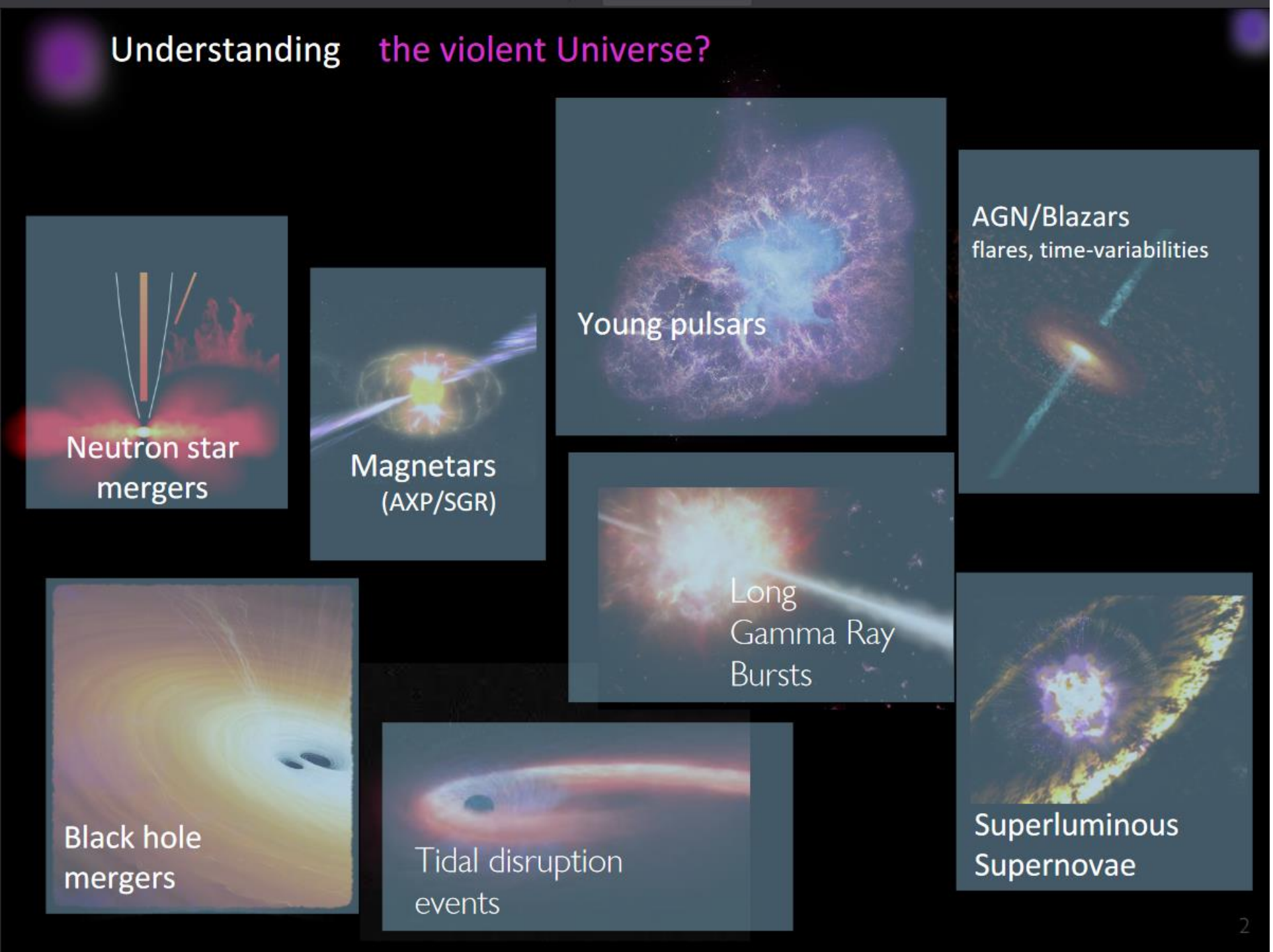
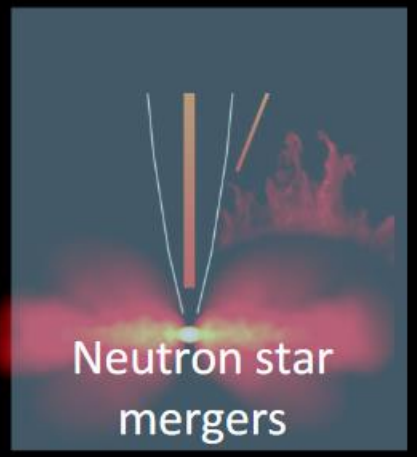
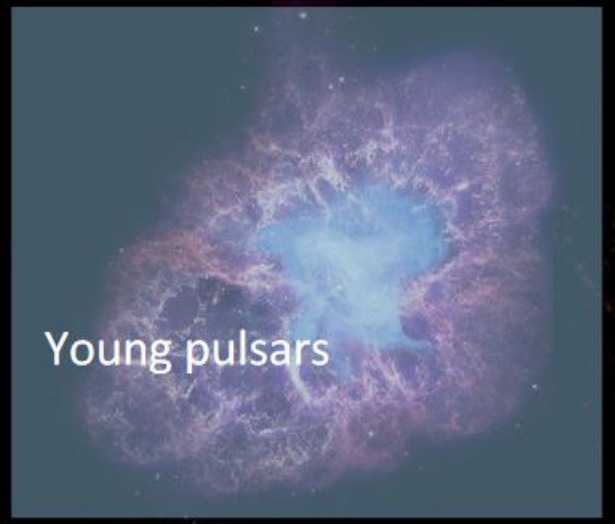


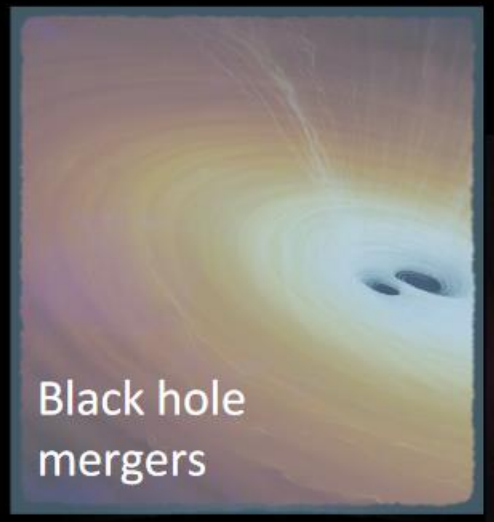
Slide by K. Kotera

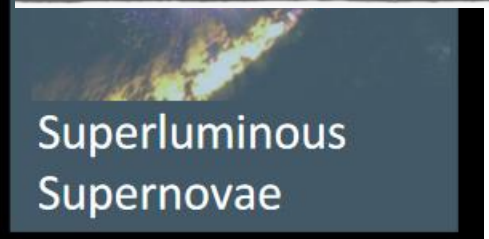
Understanding the violent Universe?

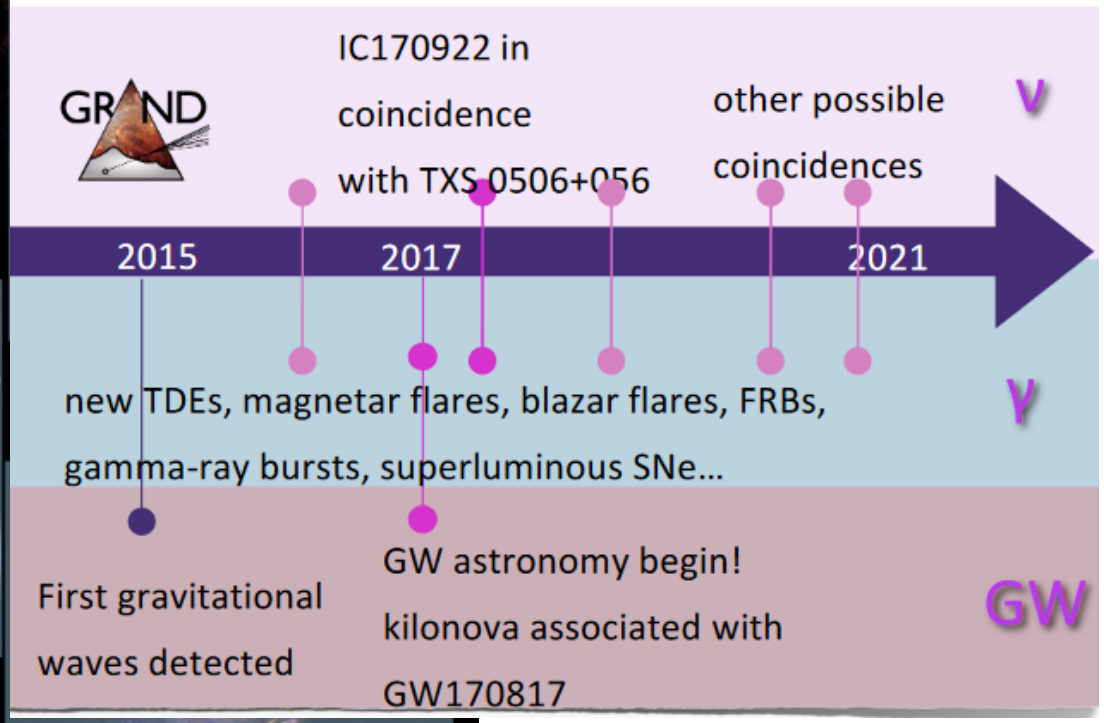




AGN/Blazars
flares, time-variabilities







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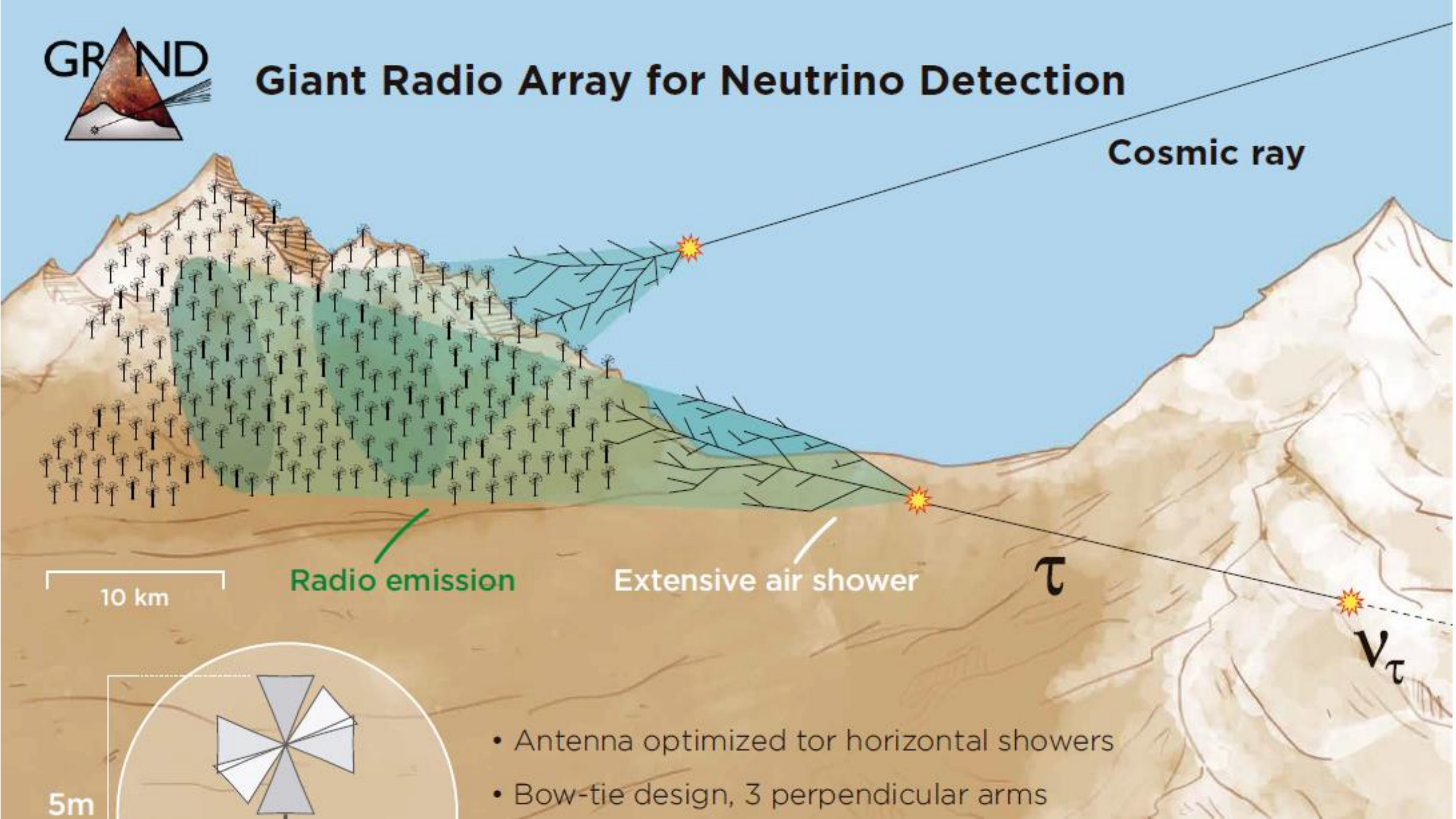
GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
Radio emission
Extensive air shower
τ
ν_τ
10 km
5m
• Antenna optimized tor horizontal showers
• Bow-tie design, 3 perpendicular arms

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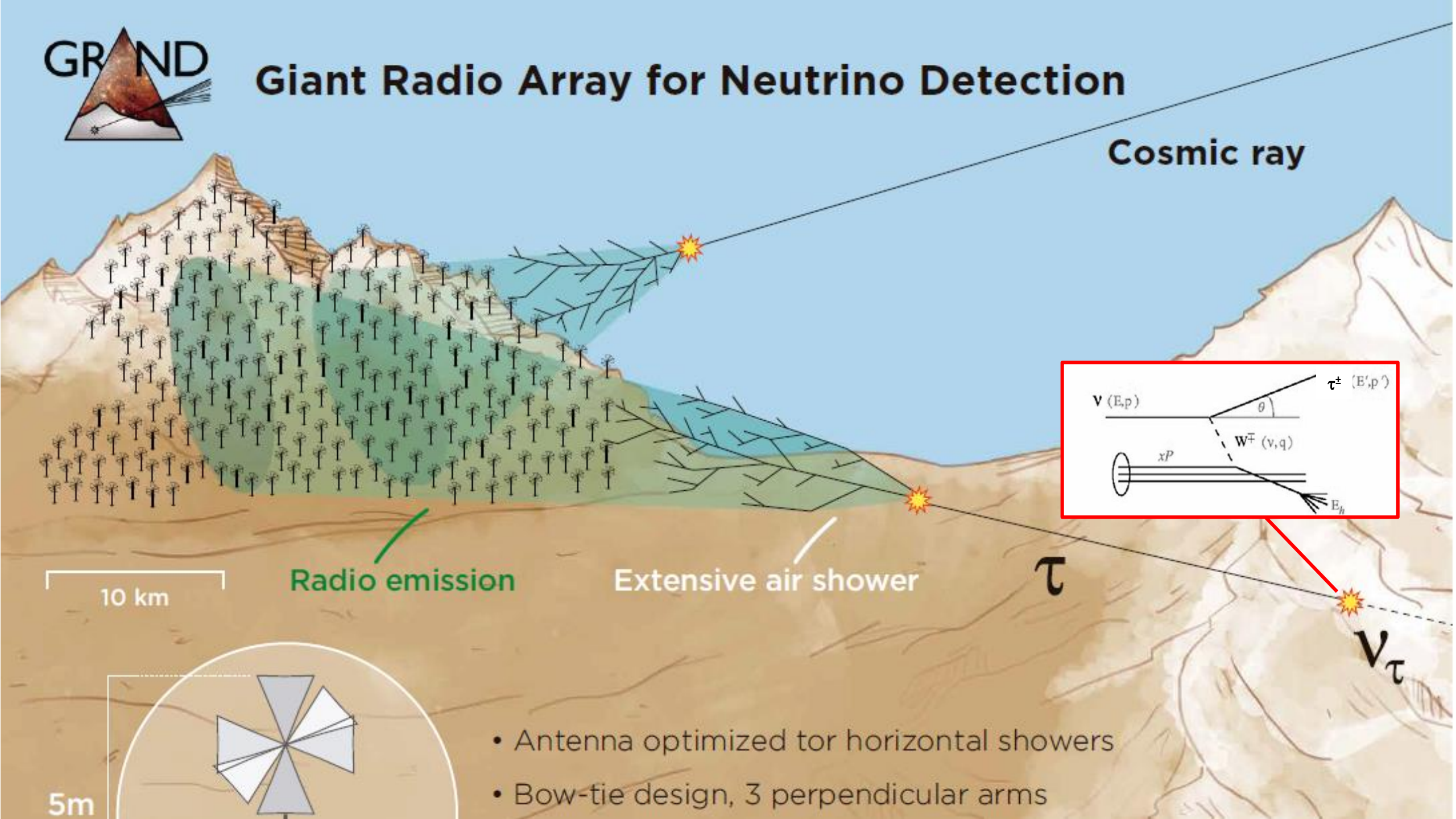

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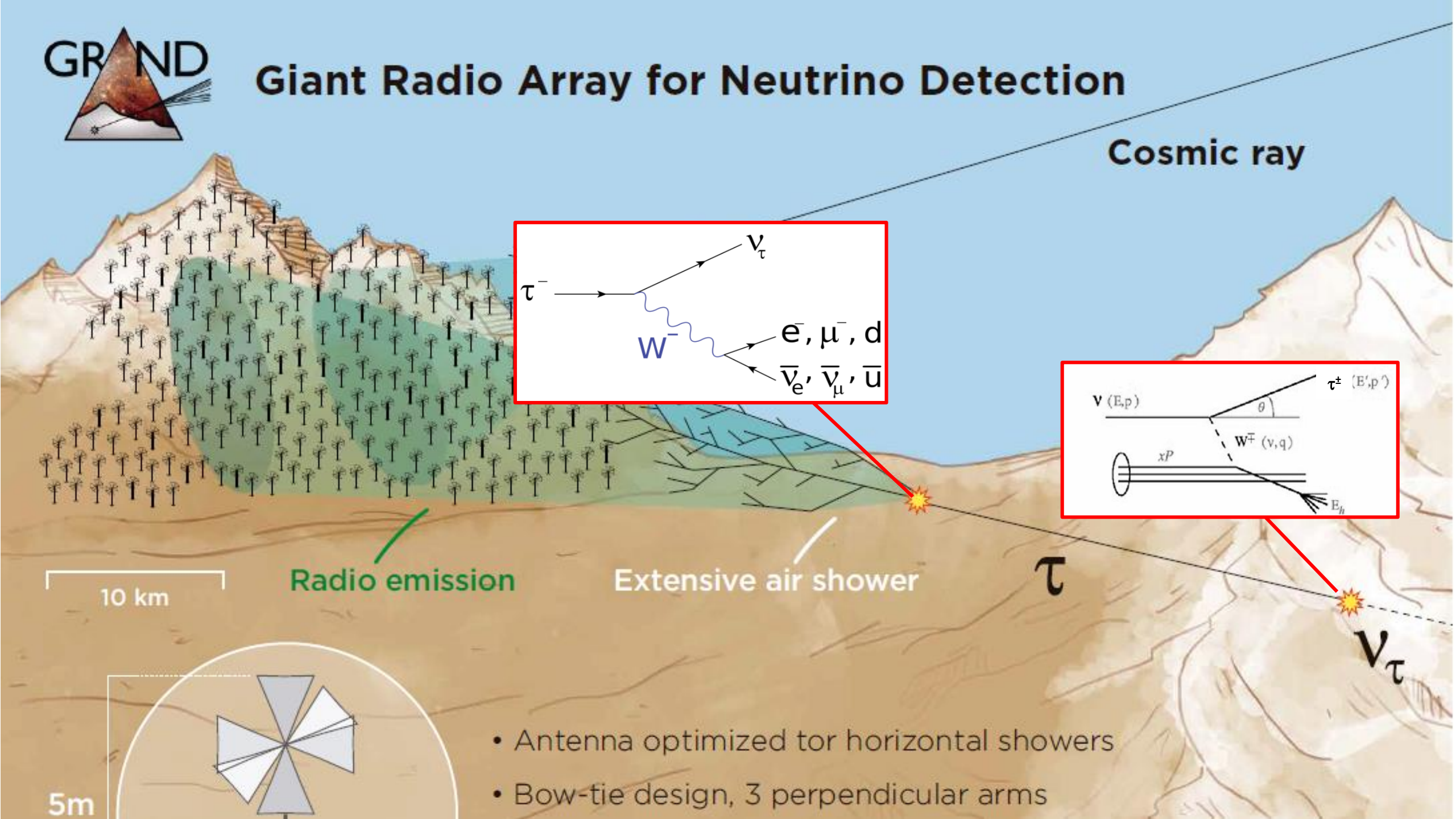

- Antenna optimized tor horizontal showers
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Why radio?

A LOFAR Low-Band Antenna

Why radio?

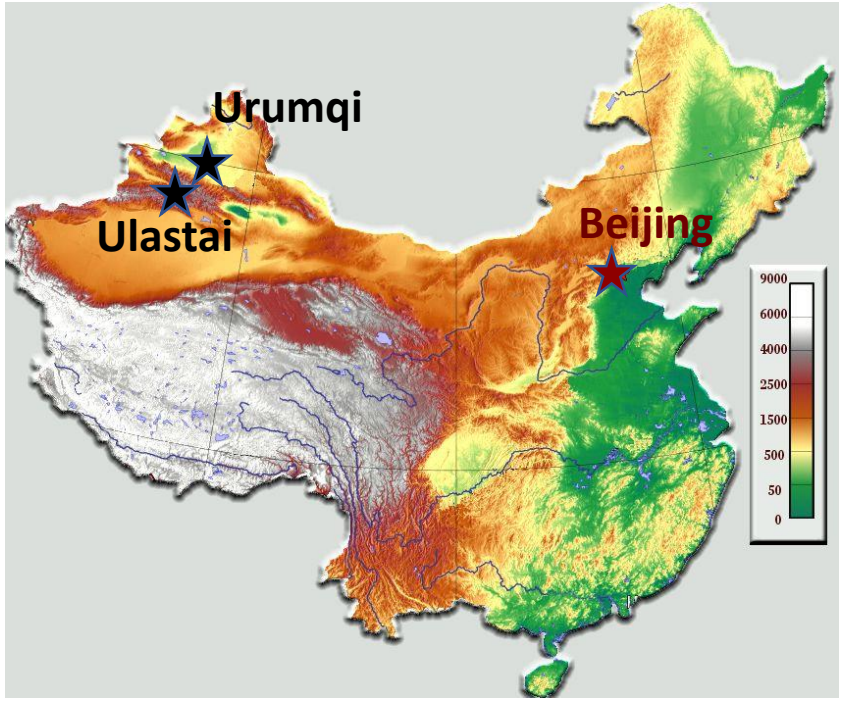
Because it is cheap!

➔ perfect for giant detectors

A LOFAR Low-Band Antenna

Air shower identification with TREND

- <u>50 antenna autonomous array deployed in XinJiang (2009-2013_2018)</u>
  - Important background rate despite remoteness BUT distinct signatures for EAS & background (event bursts, amplitude & polarization patterns)



On the 21CMA-TREND site, October 2008

D. Charrier et al., Astropart. Phys (2020)

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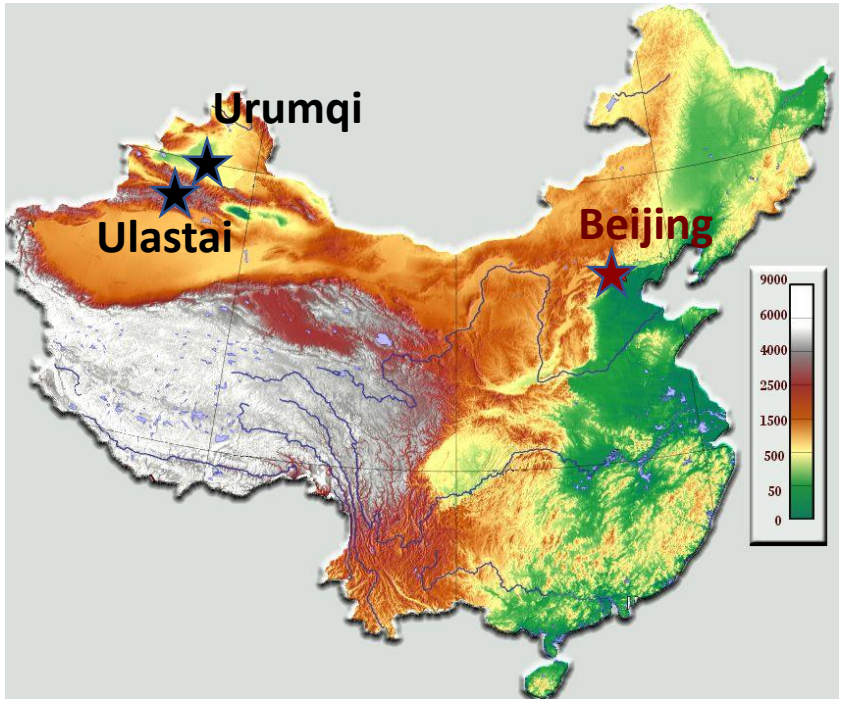
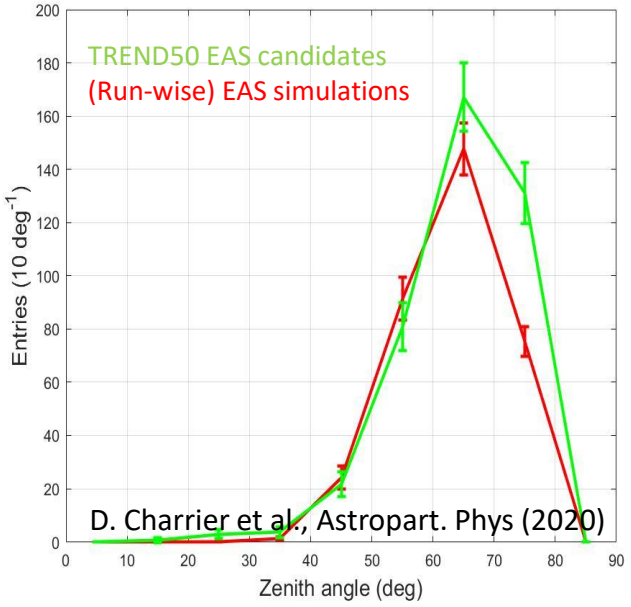
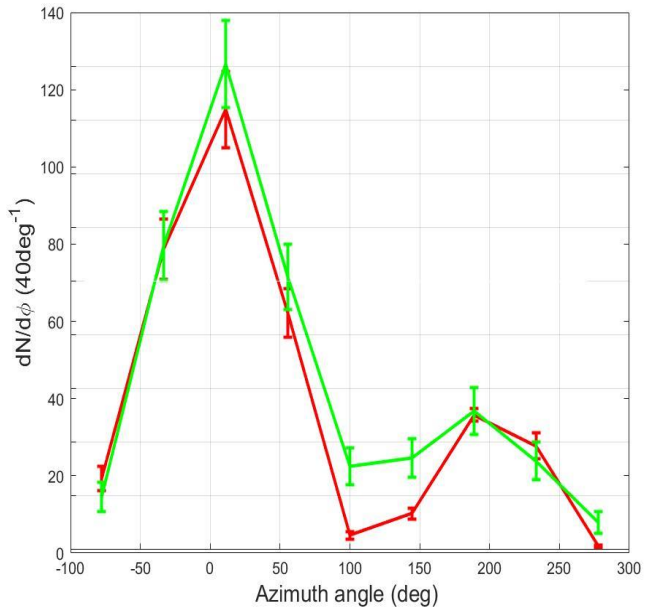


On the 21CMA-TREND site, October 2008

564 EAS candidates selected out of ~109 events. Estimate from simulations:
<u>EAS purity</u> = 80%. False positive prob. ~ 10^{-7} · <u>EAS det eff</u> ~3% (soft sel eff: 32%)





The GRAND Collaboration

16 Member & Associate Institutes represented at the Board

- Hellenic Open University (HOU)
- Institut d'astrophysique de Paris (IAP)
- Institute of Physics of the Czech Academy of Sciences (FZU)
- Inter-University Institute for High Energy at Vrije Universiteit Brussel (IIHE-VUB)
- Karlsruhe Institute of Technology (KIT)
- Laboratoire de Physique Nucléaire et des Hautes Energies (LPNHE)
- Laboratoire Univers et Particules de Montpellier (LUPM)
- Radboud University
- University of Warsaw

- Nanjing University
- National Astronomical Observatories, Chinese Academy of Sciences (NAOC)
- Purple Mountain Observatory (PMO)
- Xidian University

- Pennsylvania State University (PSU)
- San Francisco State University (SFSU)

- Universidade Federal do Rio de Janeiro (UFRJ)

119 members

14 countries: Argentina, Belgium, Brazil, China, Czech Republic, Denmark, France, Germany, Greece, Japan, Netherlands, Norway, Poland, USA

Co-spokespersons: K. Kotera (IAP), Wu XiangPing (NAOC) & O. Martineau (LPNHE)

Nanjing Collaboration Meeting @ Purple Mountain Observatory, May 2024

GRAND proposal (2018)

- Huge effort for end-to-end simulation

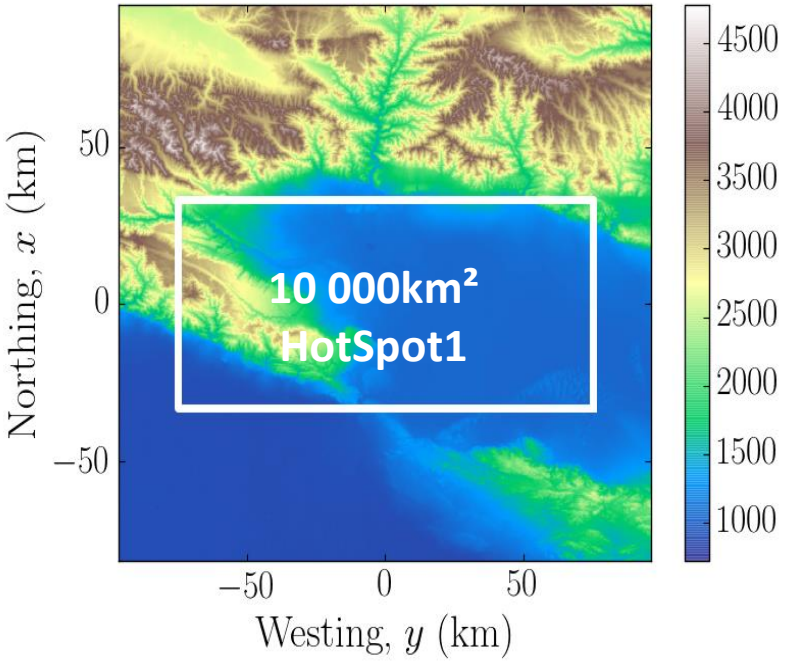
DANTON Niess & Martineau-Huynh arXiv:1810.01978

RadioMorphing Zilles et al. arXiv:1811.01750

on a 10000 antennas hotspot (GRAND10k)

➔Sensitivity in IceCube2015 range.

- **Go for x20!! ➔ Network of o(20) subarrays of o(10000) antennas with sparse density (1/km²) at various favorable locations around the world (« hotspots »)**
- Sensitivity of full array good enough for GRAND to detect cosmogenic neutrinos for standard hypothesis



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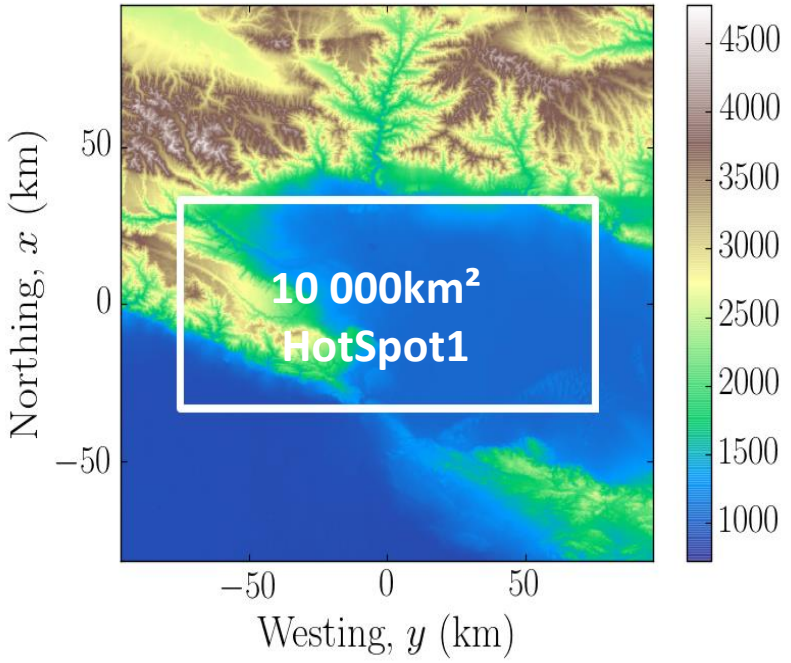
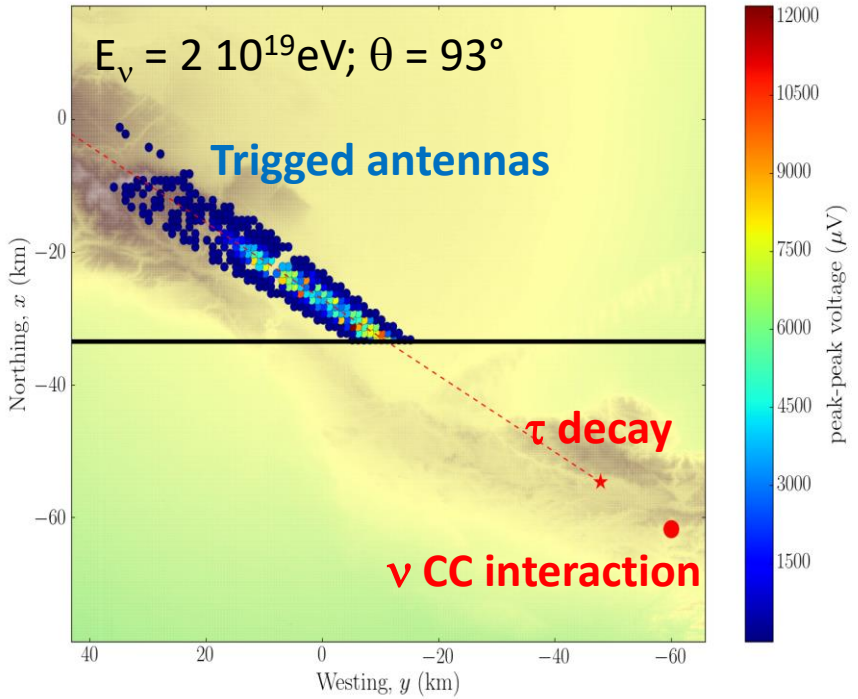


A simulated neutrino event in a GRAND hotspot



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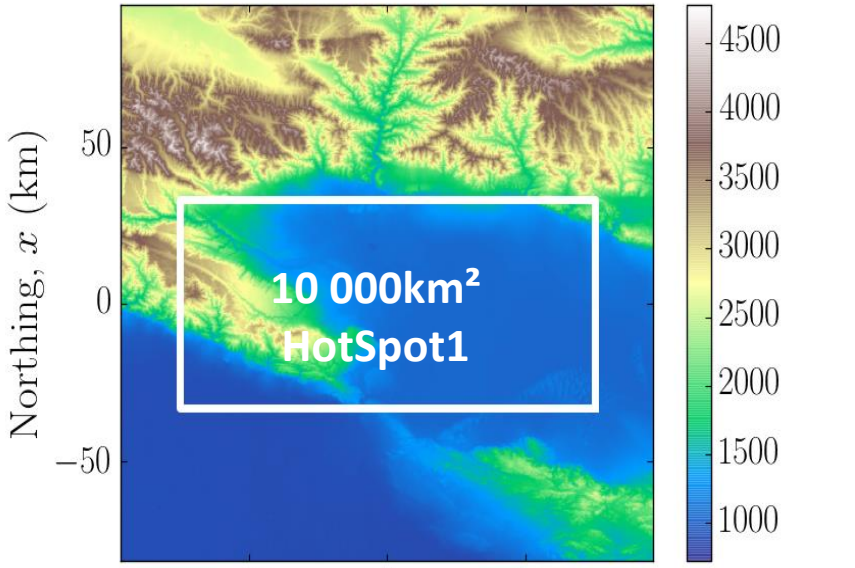

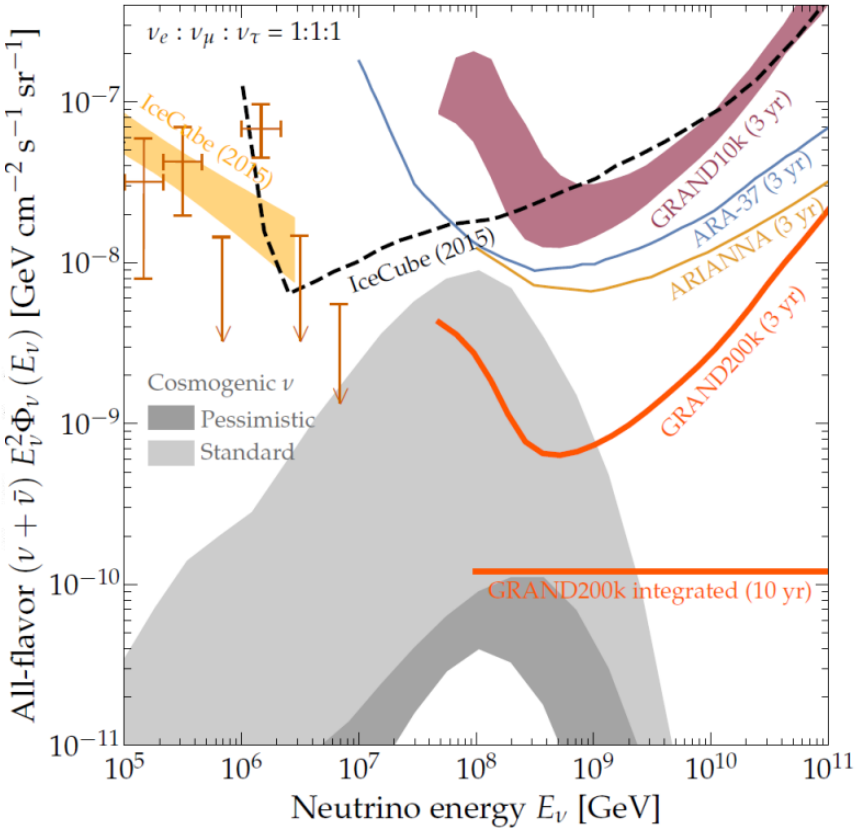

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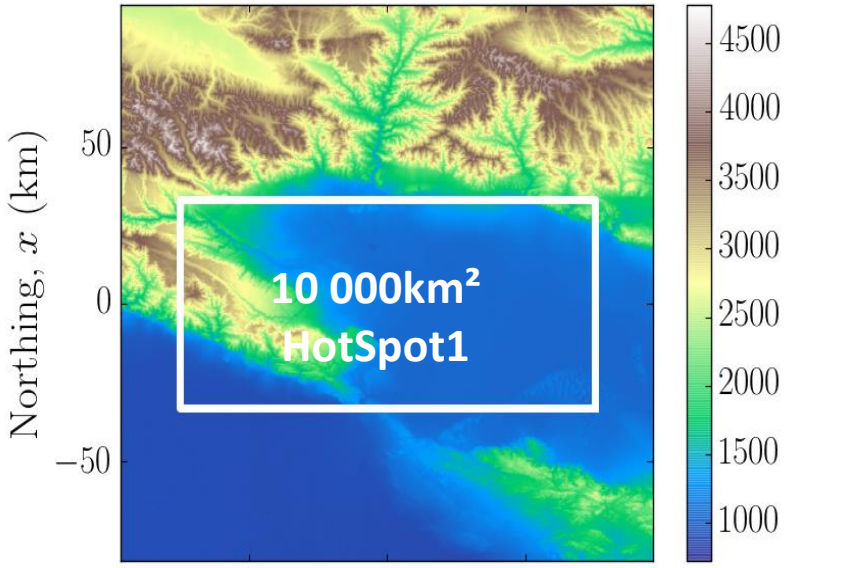

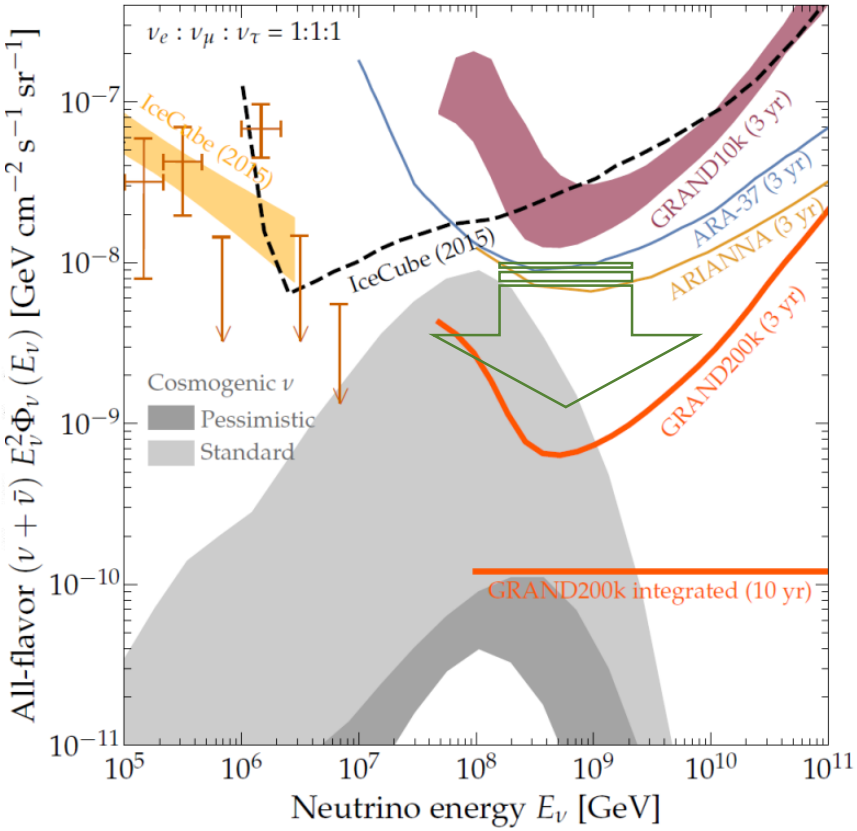

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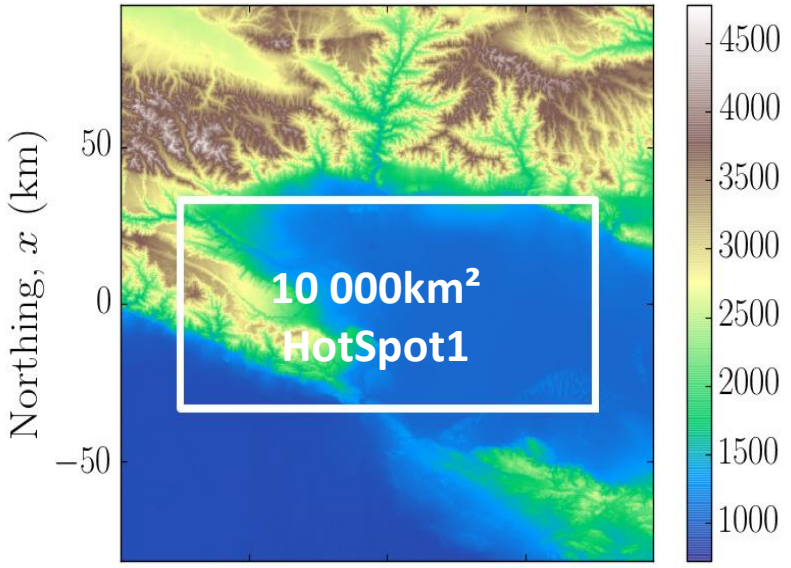

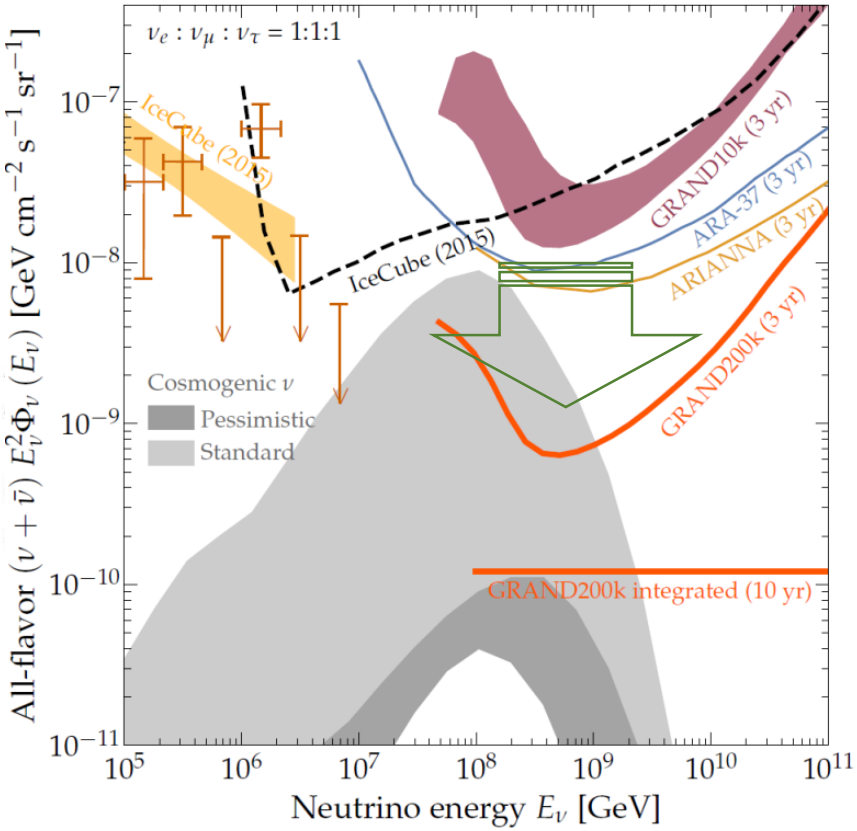

Alvarez-Muniz et al., The GRAND collab, Sci. China-Phys. Mech. Astron. 63, 219501 (2020) arXiv:1810.09994

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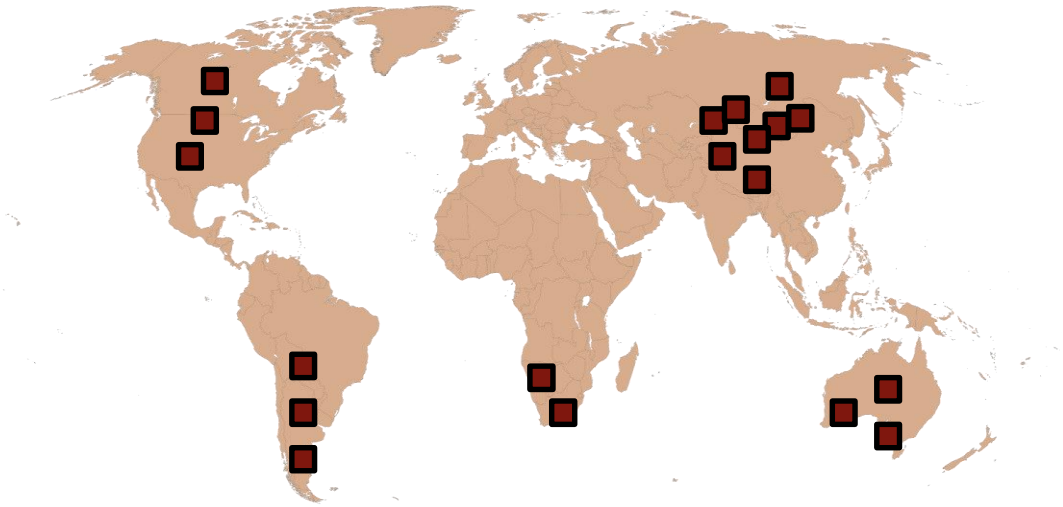

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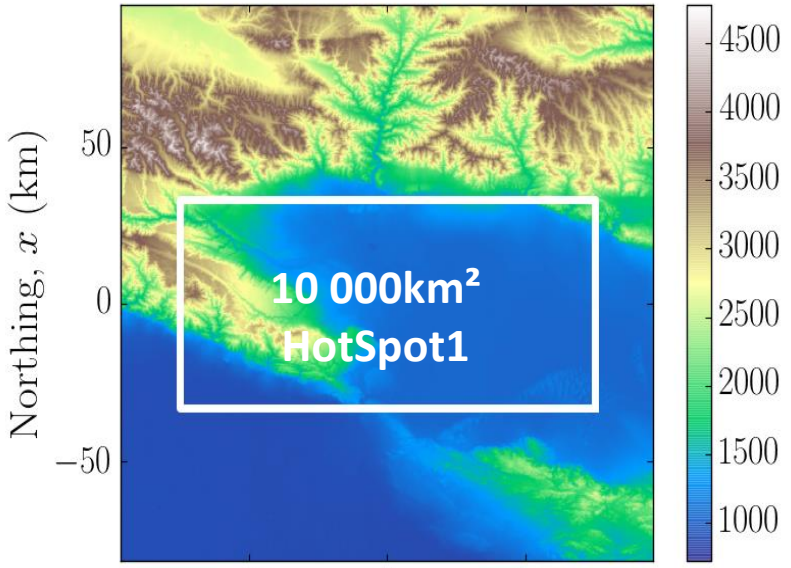
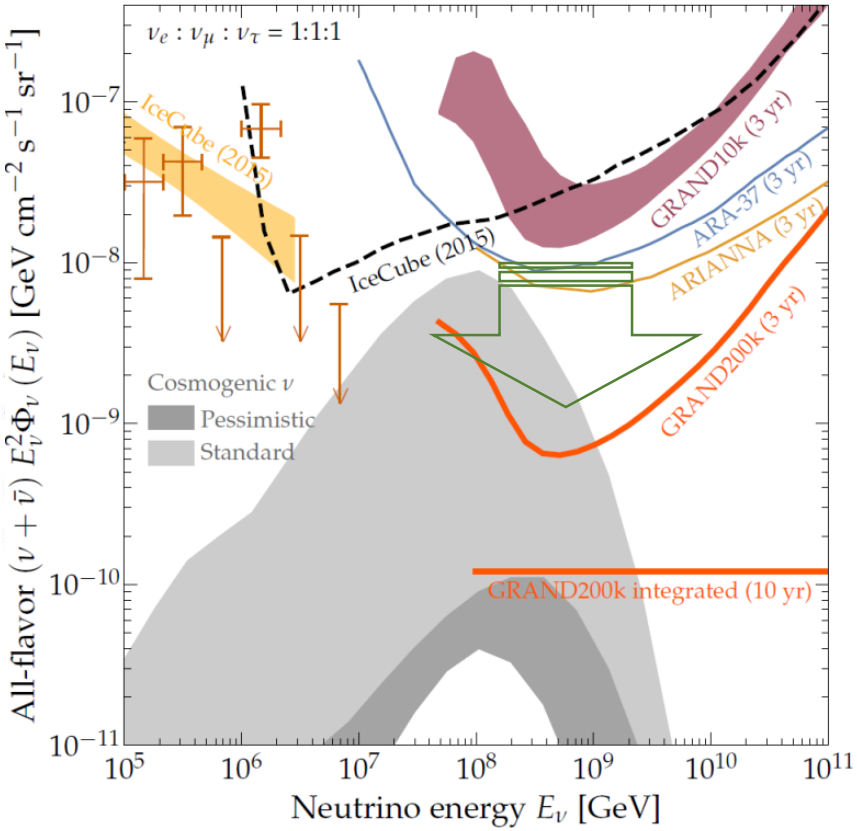
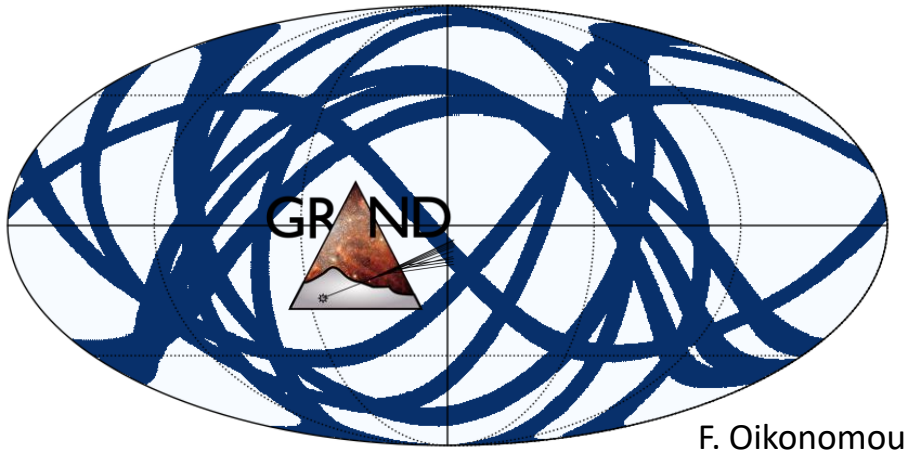




GRAND performances

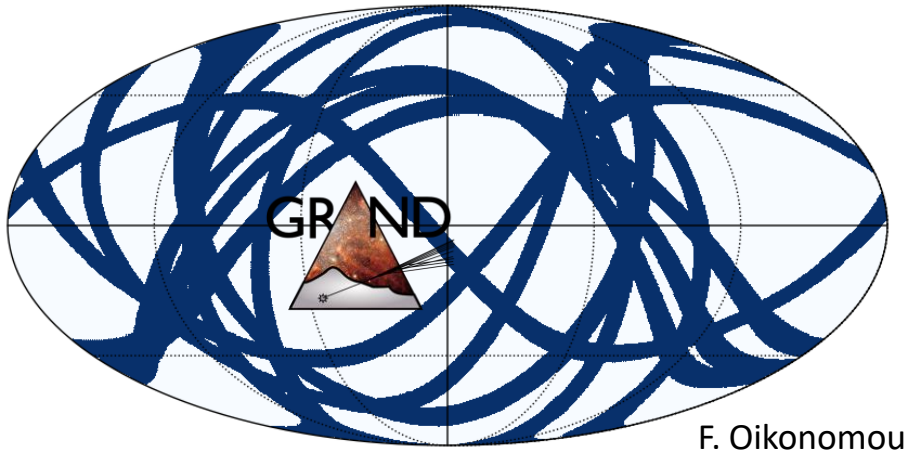


F. Oikonomou

instantaneous FoV: 45% of sky

(for 10 random* site locations between 40S and 60N)

GRAND performances



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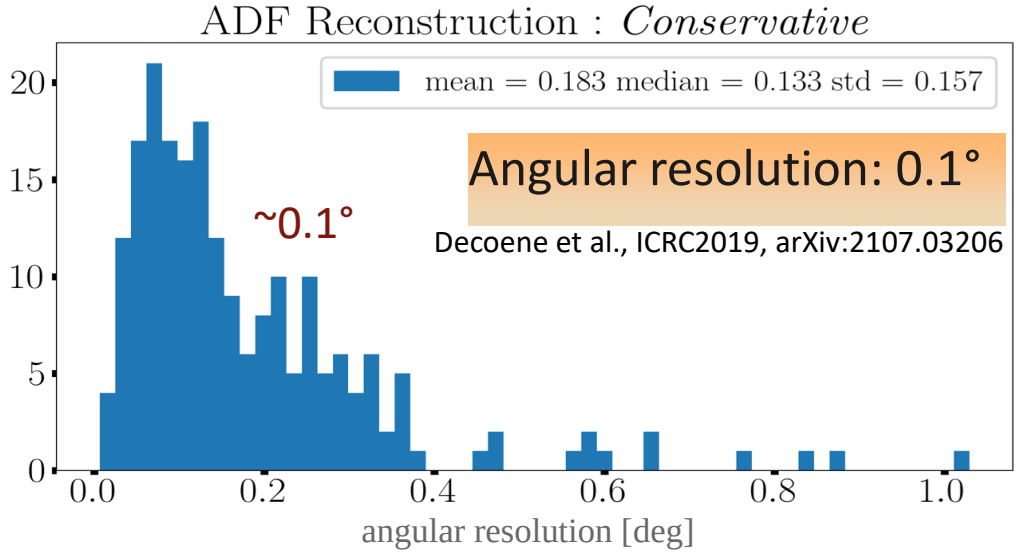

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PUEO	4.2×10^{-8} in 30 d	6	19	$<2.8°$
ARA	3.6×10^{-9} (2030)	35	20	5°
RNO-G	1×10^{-8} in 5 yr	30	35	$2°\times10°$
ARIANNA-200	8×10^{-9} in 5 yr	50	>50	$2.9–3.8°$
RET-N	3×10^{-10} in 5 yr	50	>50	?
IceCube-Gen2 Radio	4×10^{-10} in 5 yr	43	43	$2°\times10°$
BEACON	1.2×10^{-8} in 5 yr	6	19.5	$0.3°–1°$
GRAND10k	1×10^{-8} in 5 yr	6	80	0.1°
GRAND	4×10^{-10} in 5 yr	45	100	0.1°
Auger	$[1.5\times10^{-8}$ (2019)]	30	92.8	$<1°$
TAMBO	?	27	62	1°
POEMMA Cerenkov	7×10^{-8} in 5 yr	0.6	$18–36$	0.4°
Trinity	1×10^{-10} in 5 yr	6	62	$<1°$
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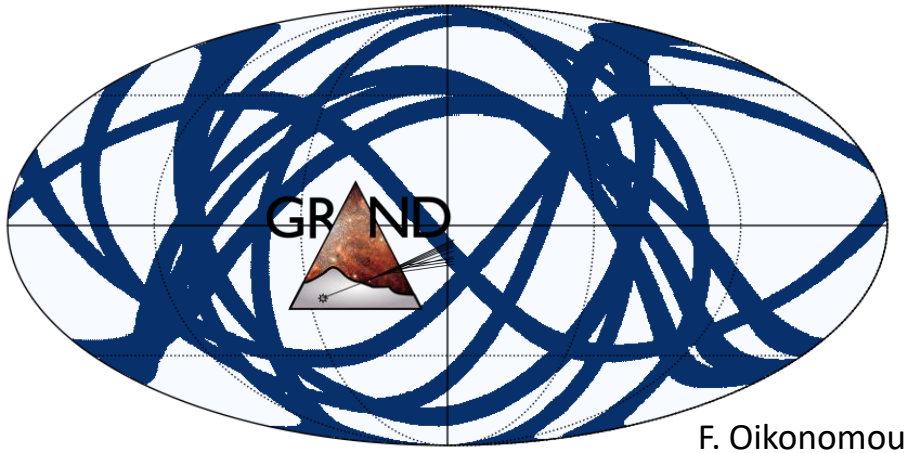
adapted from Guépin et al. Nature Phys. Rev. 2022

GRAND performances



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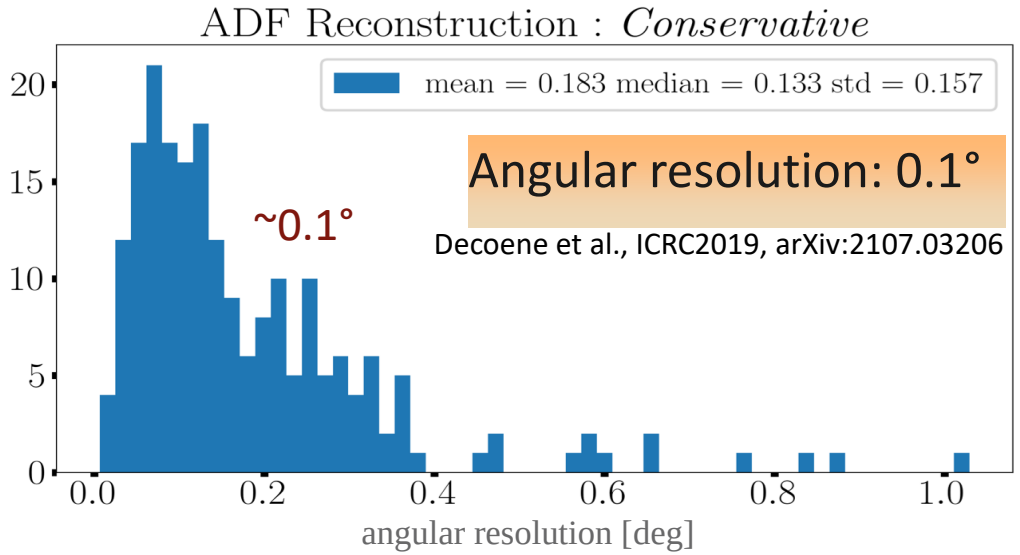

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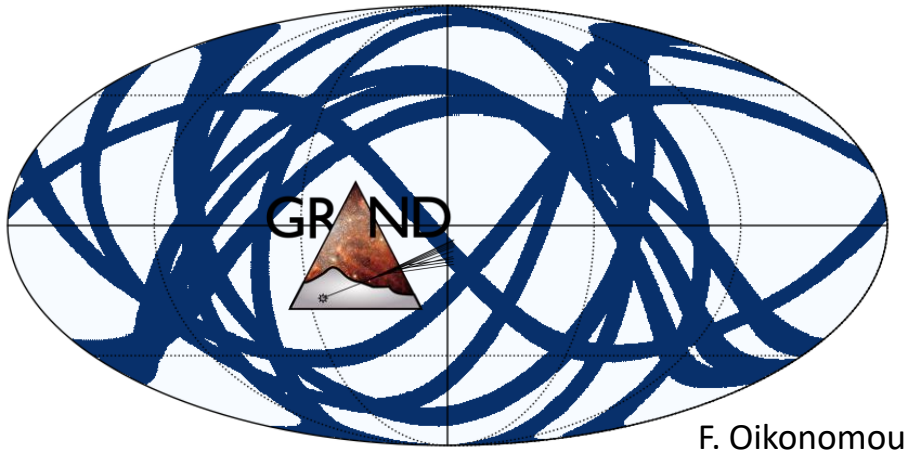

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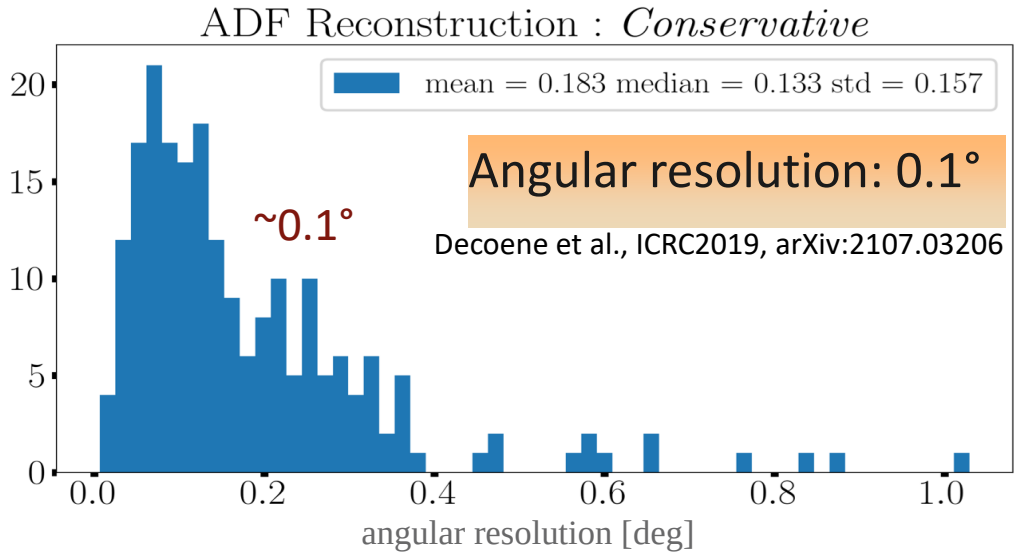

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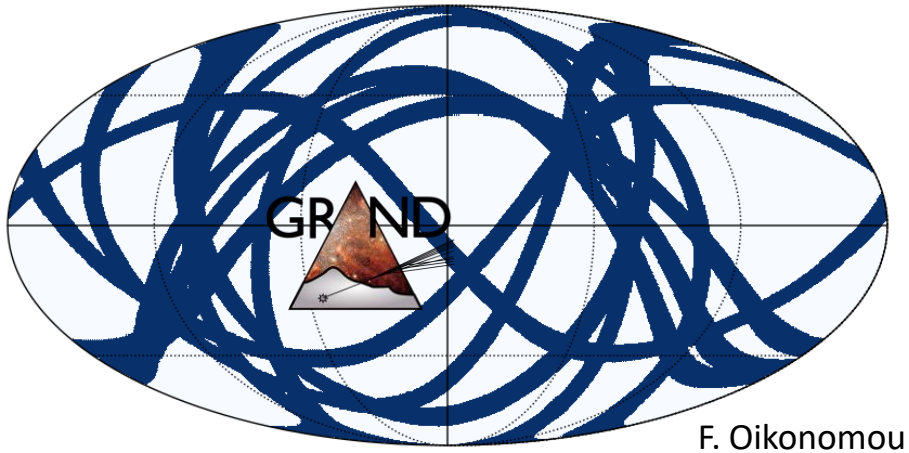
POEMMA Cerenkov	7×10^{-8} in 5 yr	0.6	18–36	0.4°
Trinity	1×10^{-10} in 5 yr	6	62	$<1°$
Ashra-NTA	2×10^{-10} in 5 yr	30	>50	0.1°

adapted from Guépin et al. Nature Phys. Rev. 2022

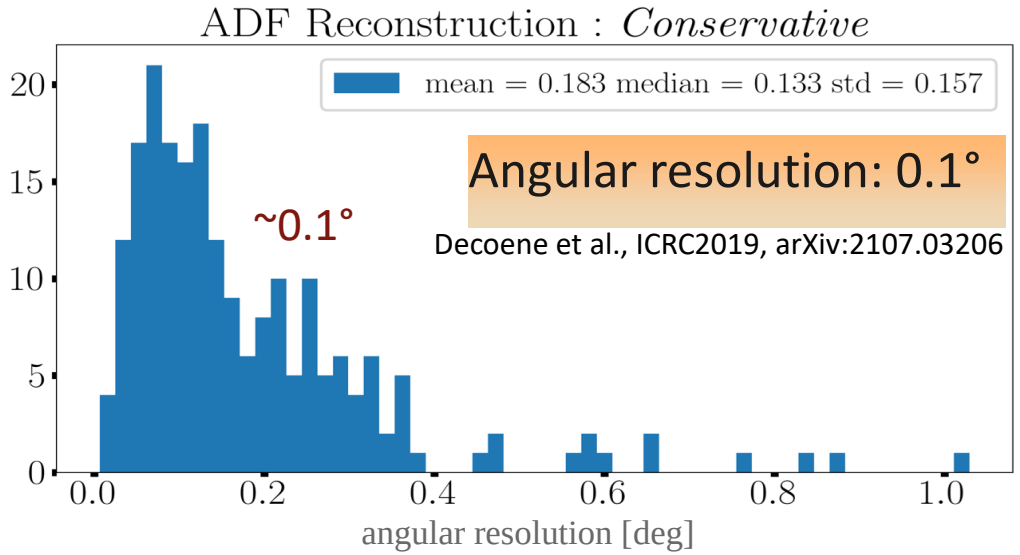
GRAND performances



F. Oikonomou

instantaneous FoV: 45% of sky

(for 10 random* site locations between 40S and 60N)



2021 / 2025 / >2030	Diff. sens. lim. in GeV cm^{-2} s^{-1} sr^{-1}	iFoV in sky %	dFoV in sky %	ang. res.
PUEO	4.2×10^{-8} in 30 d	6	19	$<2.8°$
ARA	3.6×10^{-9} (2030)	35	20	5°
RNO-G	1×10^{-8} in 5 yr	30	35	$2°\times10°$
ARIANNA-200	8×10^{-9} in 5 yr	50	>50	$2.9–3.8°$
RET-N	3×10^{-10} in 5 yr	50	>50	?
IceCube-Gen2 Radio	4×10^{-10} in 5 yr	43	43	$2°\times10°$
BEACON	1.2×10^{-8} in 5 yr	6	19.5	$0.3°–1°$
GRAND10k	1×10^{-8} in 5 yr	6	80	0.1°
GRAND	4×10^{-10} in 5 yr	45	100	0.1°
Auger	$[1.5\times10^{-8}$ (2019)]	30	92.8	$<1°$
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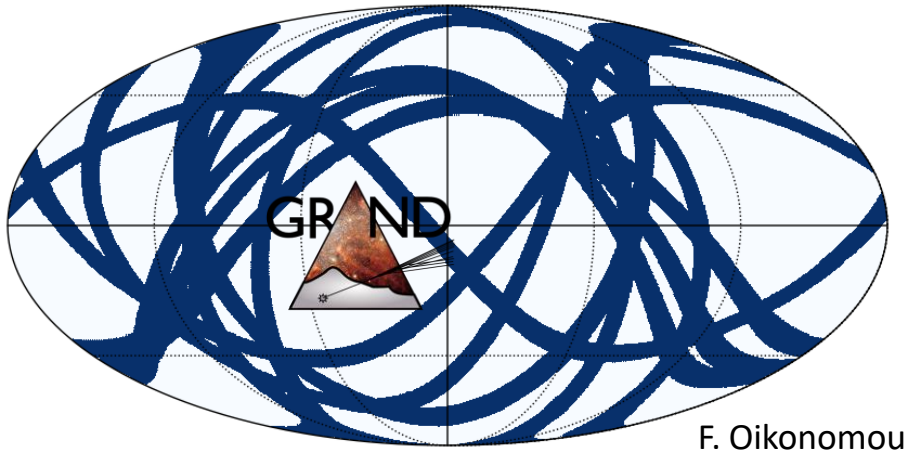

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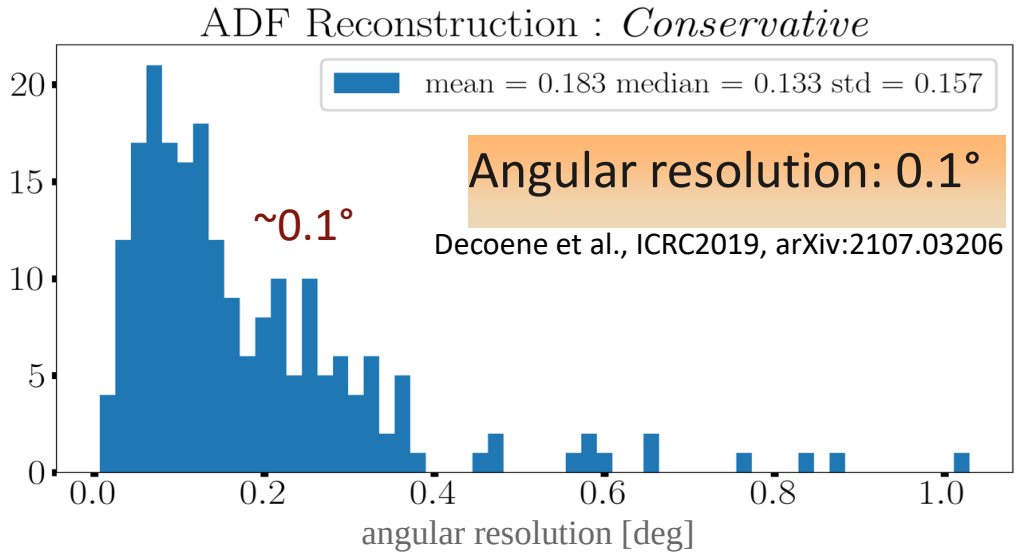

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GRAND is the most competitive proposal for the detection of UHE neutrinos

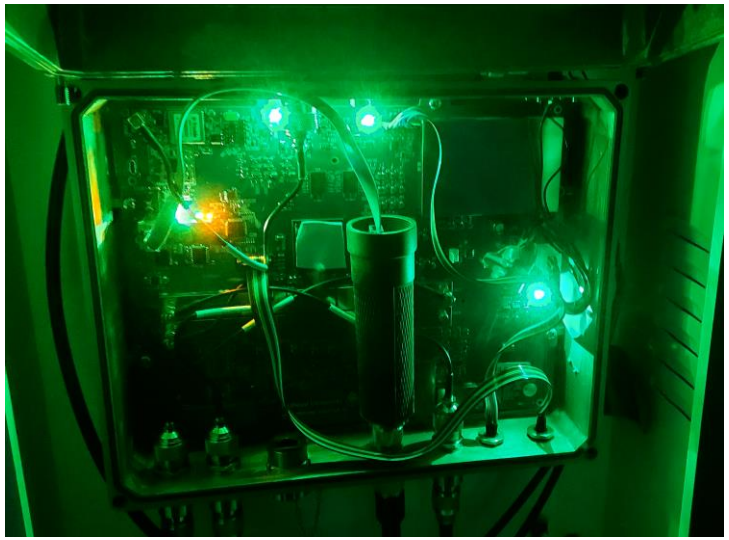
A staged approach with self-standing pathfinders

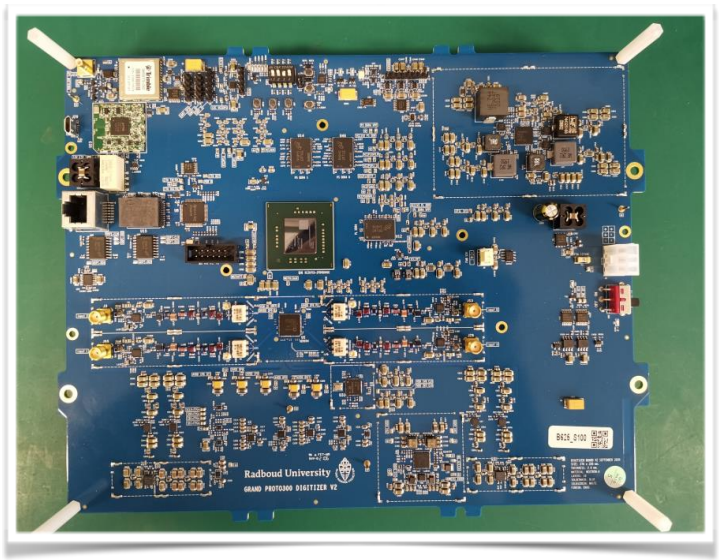
	GRANDProtos	GRAND10k	GRAND200k
	2023	2028	203x
Goals	**autonomous radio detection of very inclined air-showers** Cosmic rays $10^{16.5\text{-}18}$ eV • Galactic/extragalactic transition • muon problem • radio transients	**1st GRAND sub-array** • discovery of EeV neutrinos for optimistic fluxes • radio transients (FRBs!)	sensitive all-sky detector **Neutrino astronomy!**
Setup	• **GRANDProto300**: 300 antennas over 200 km² • GRAND@Auger: 10 antennas for cross-calibration • GRAND@Nançay: 4 antennas for trigger testing	• 2 detectors of 5-10k antennas each in each hemisphere: GRAND-North (China) and GRAND-South (Argentina?)	• 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • on different continents
Budget	2 M€ 100 antennas produced Funded by China + ANR-DFG NUTRIG (France- Germany) + Radboud University	13 M€ 1500€/unit	300M€ in total 500€/unit to be divided between participating countries

GRANDProto300 & other prototypes: experimental setup

The HorizonAntenna:
3 butterfly arms + LNAs

WiFi antenna connected to bullet





50-200MHz analog filtering,
Electronics:
500MSPS sampling
FPGA+CPU
Bullet WiFi data transfert

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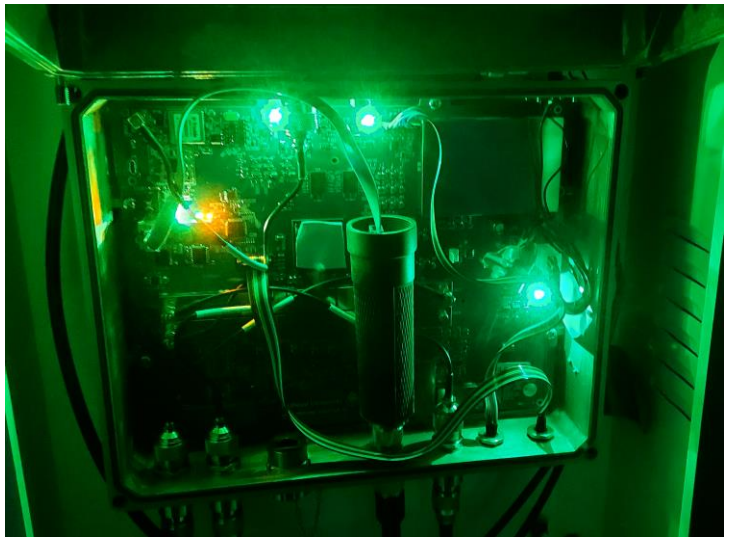
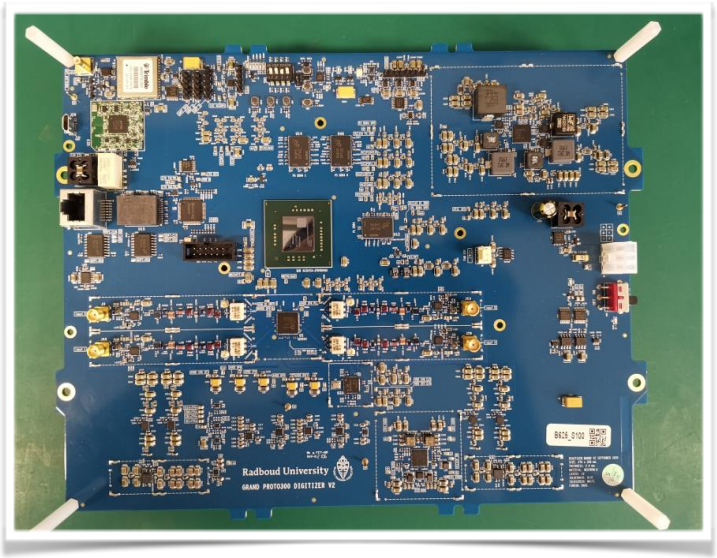
Deployed Feb 2023





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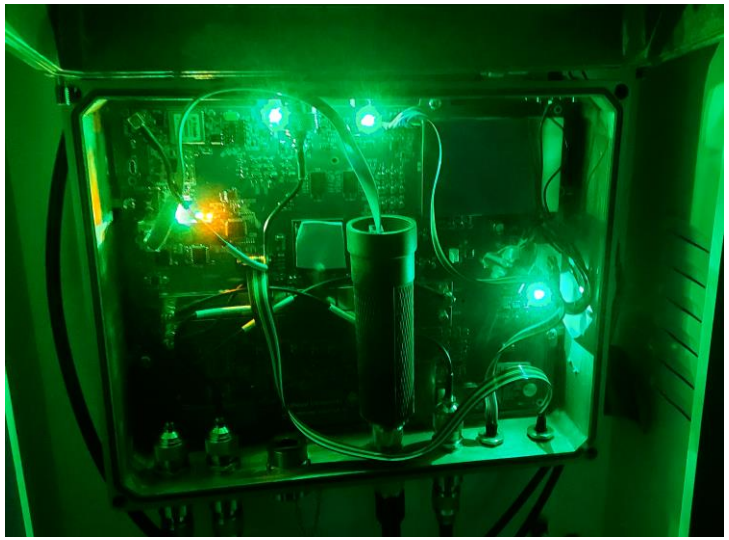

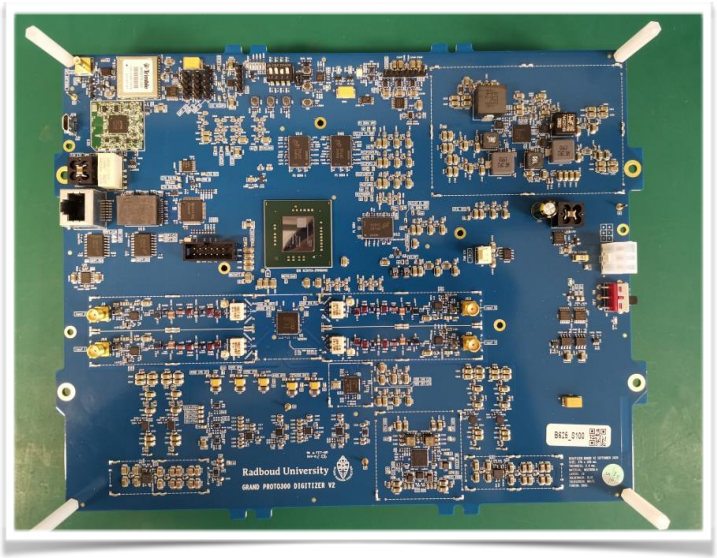

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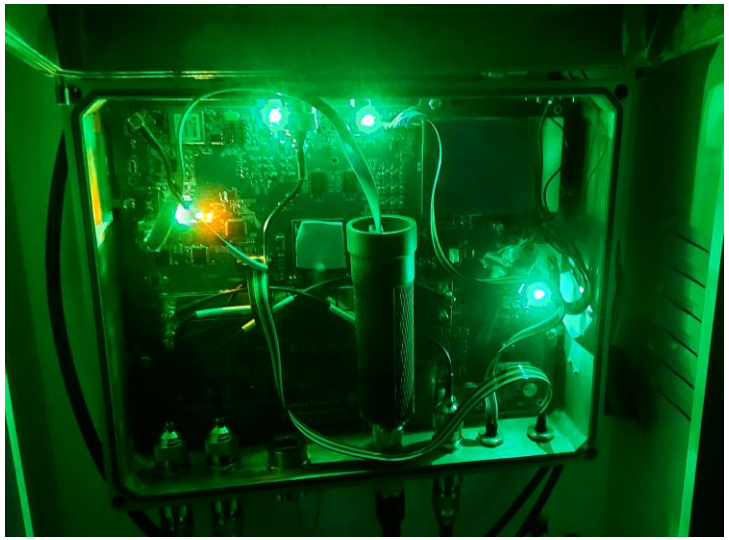
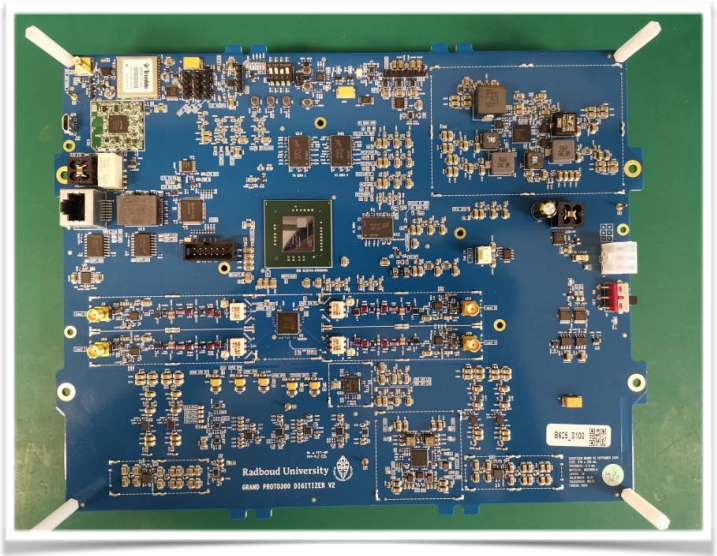
Deployment of 4 antennas in Nançay radio observatory (France) for trigger test (LPNHE)

Deployed Oct 2022





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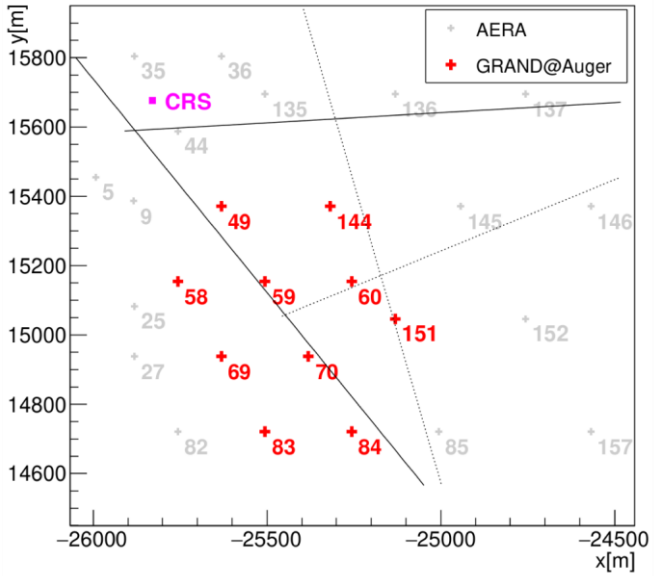
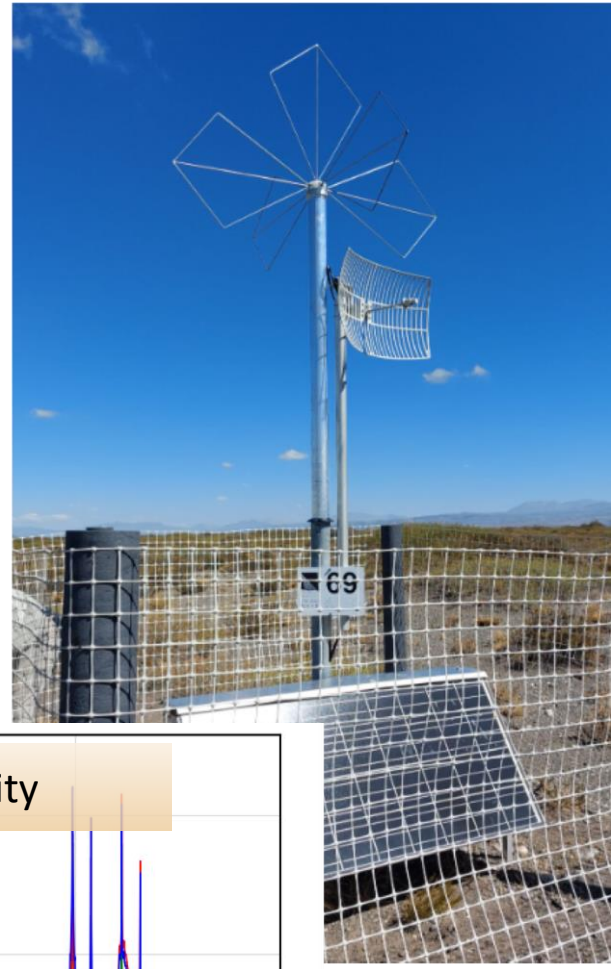
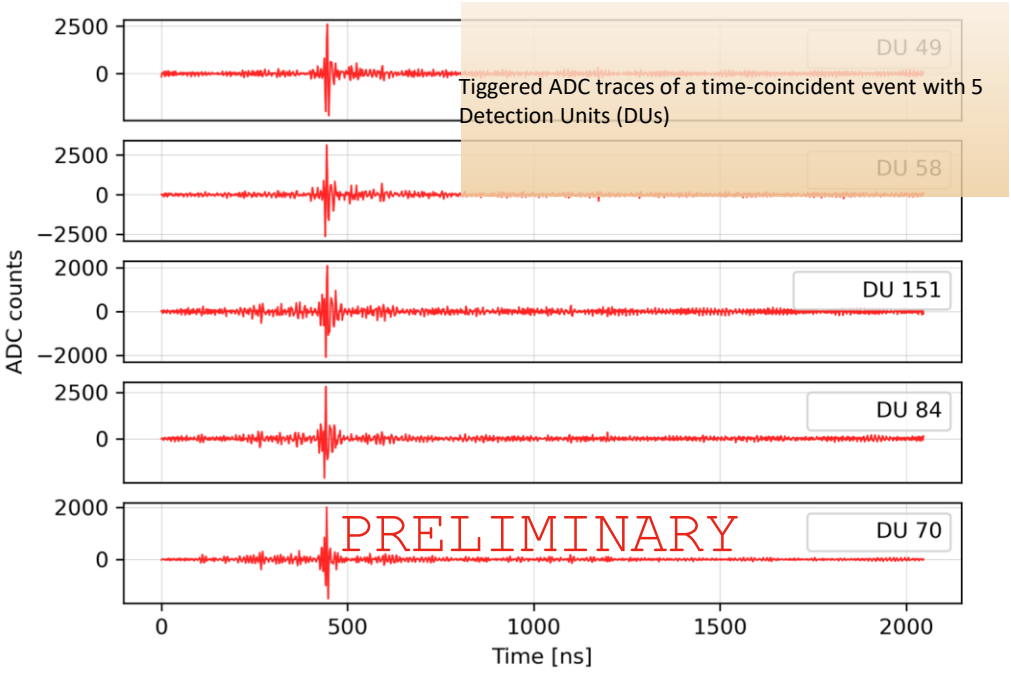
Prototypes: GRAND@Auger

GRAND Coll. in prep.

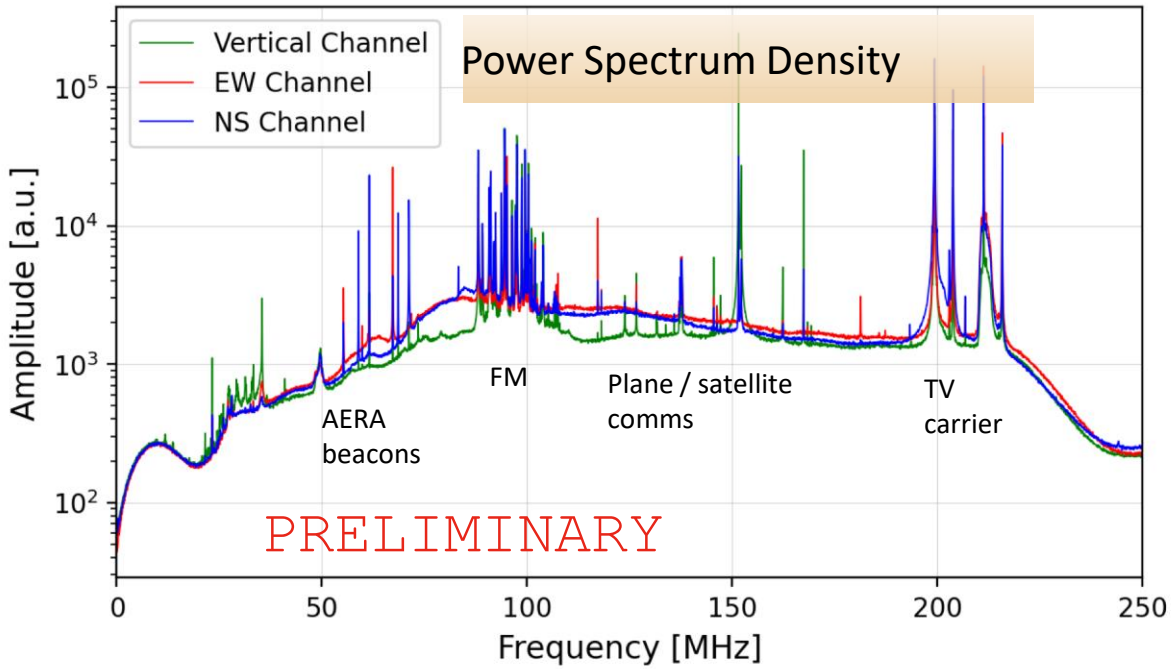


- Cross-calibration with Auger detectors
  1 coincident event/day expected
- 10 antennas deployed
  Auger mechanical structure + infrastructure
- Hardware tests: set-up stability
- Firmware tests, trigger / transient detection

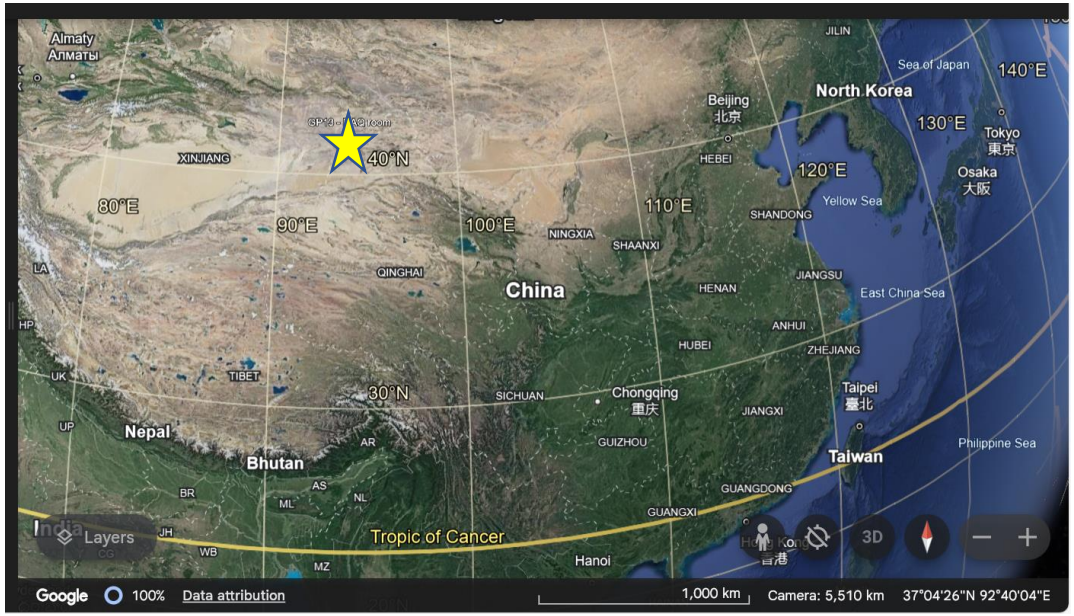




Tiggered ADC traces of a time-coincident event with 5 Detection Units (DUs)



GRANDProto300 in Xiao Dushan



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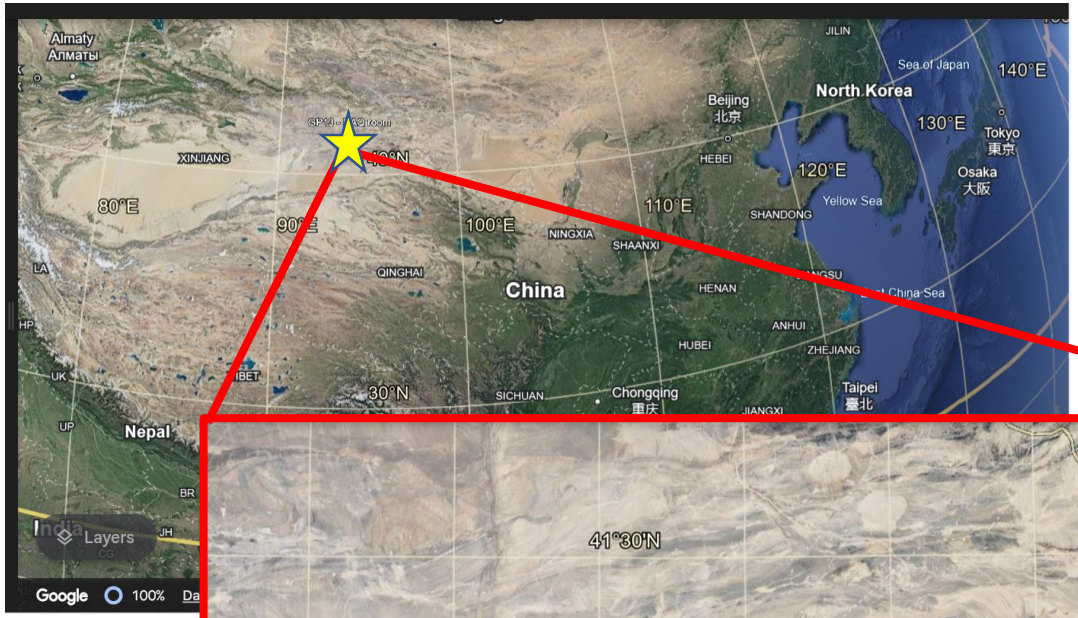

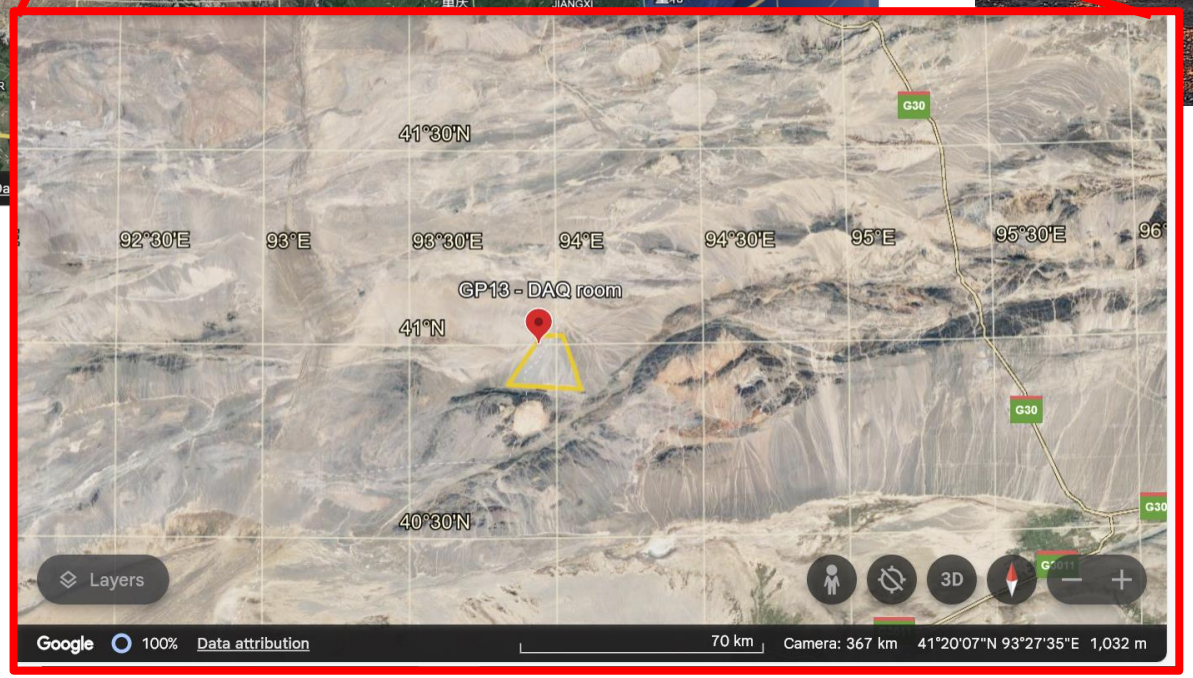

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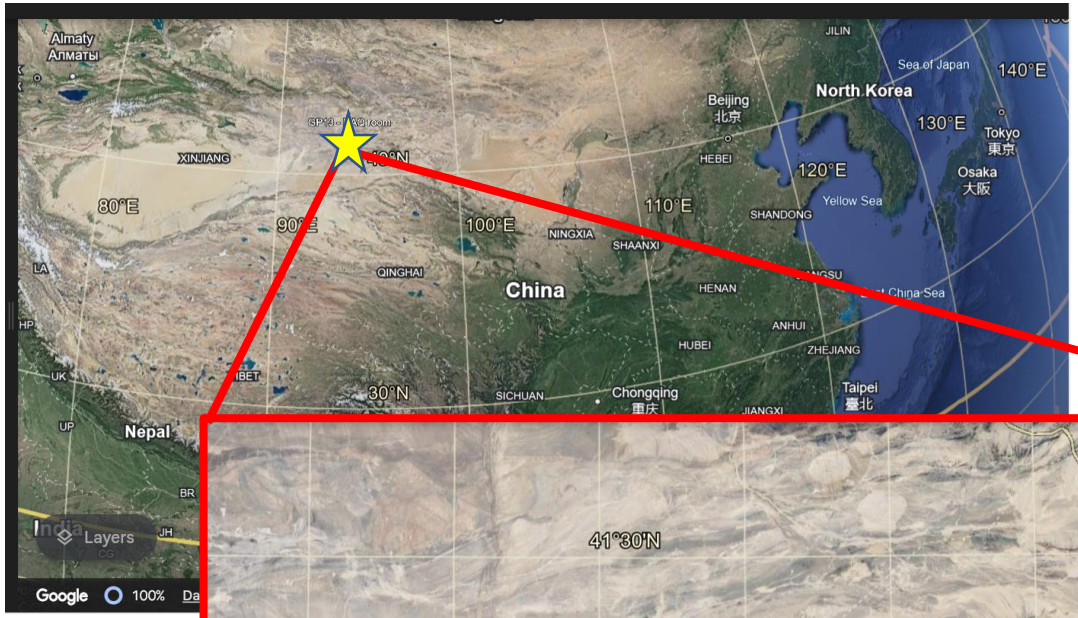

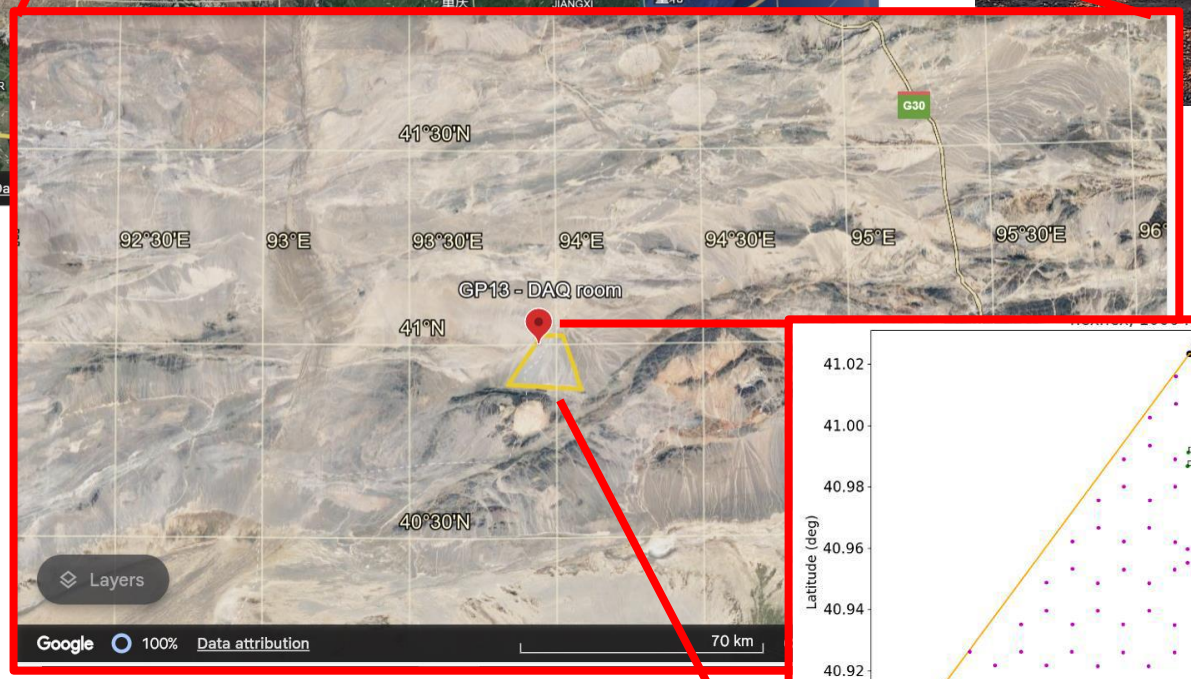

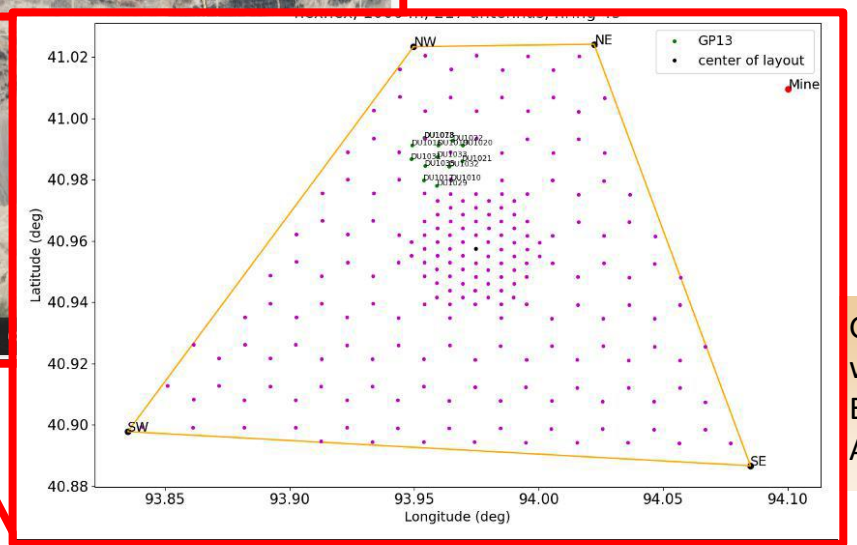

GP300: 300 antennas, 200km², 1km step size with denser infill (TBC)
Erange = $10^{16.5}$-10^{18}eV
Approved by authorities

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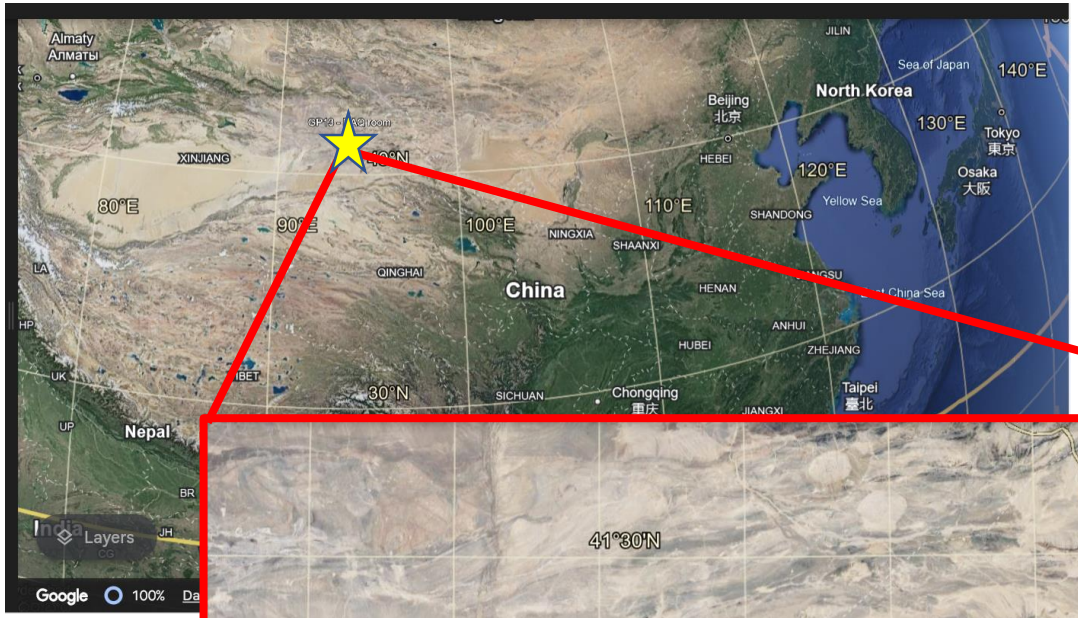

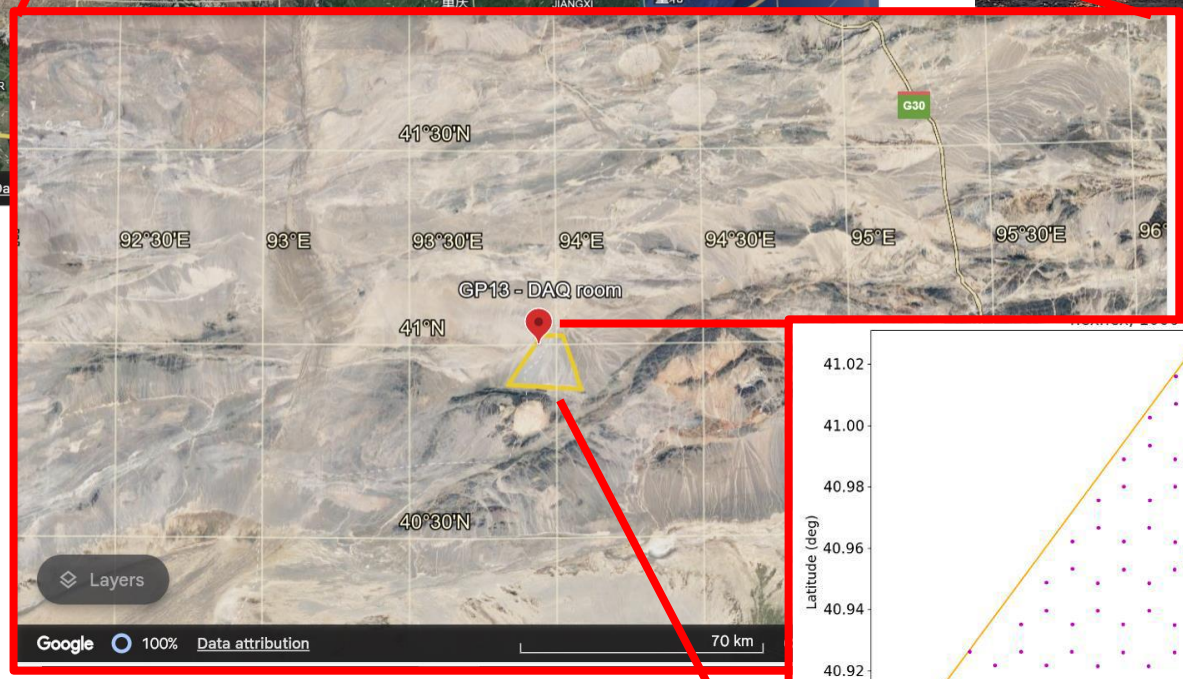

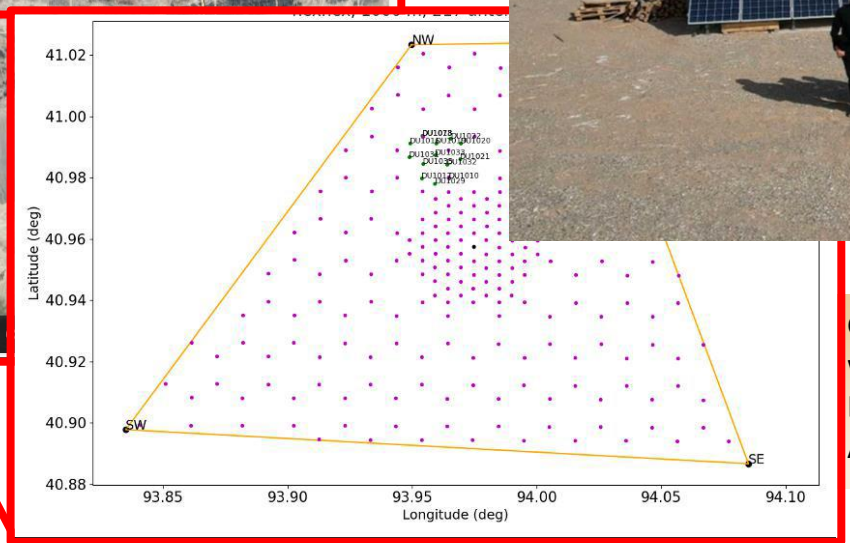

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  - Control of radio self-emission ➔ OK
  - Trigger / transient pulse detection ➔ OK
  - Data collection efficiency/ setup stability ➔ In progress
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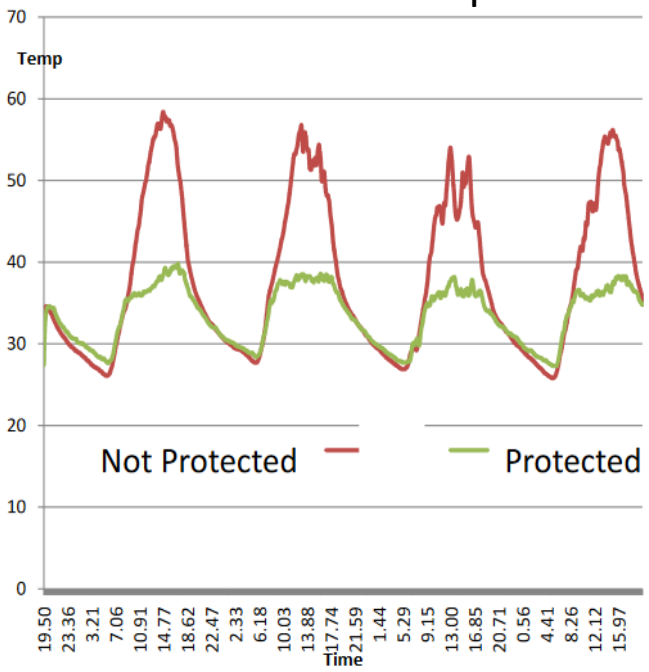
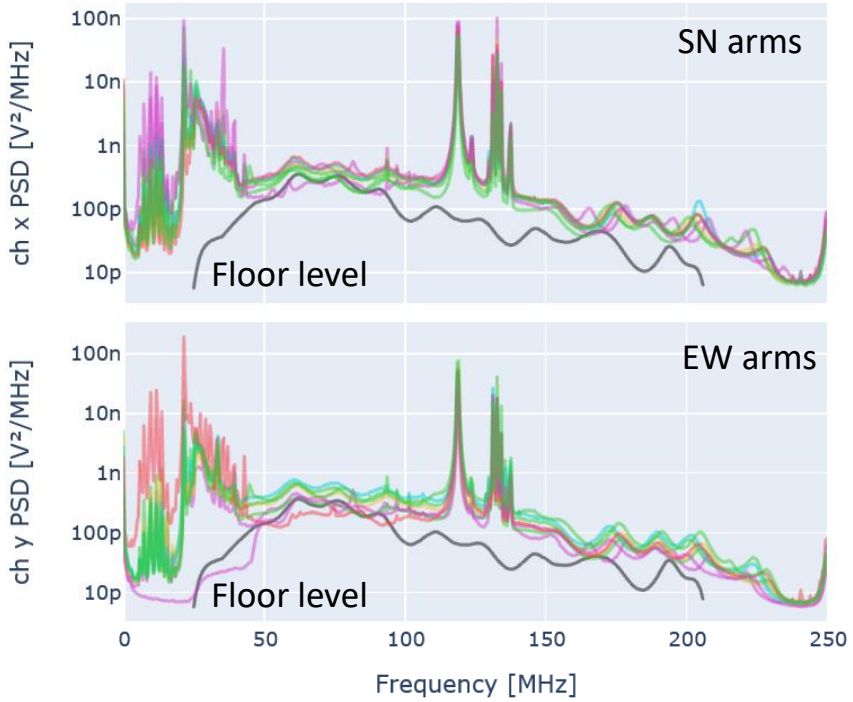


GP13 average frequency spectra for Feb 2024



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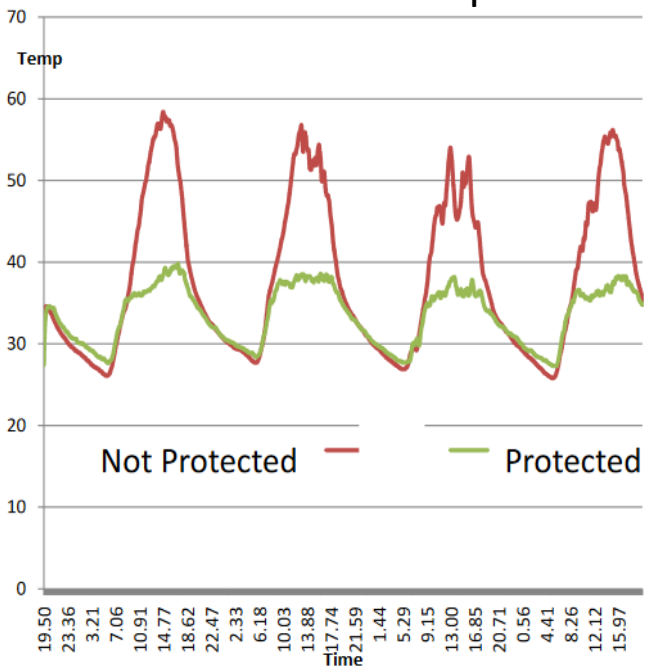

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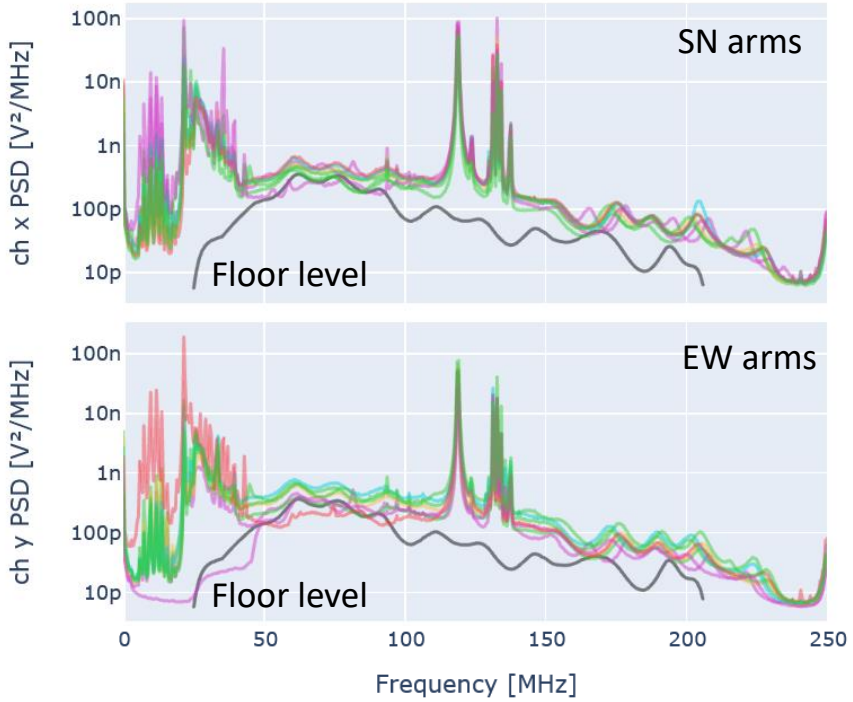

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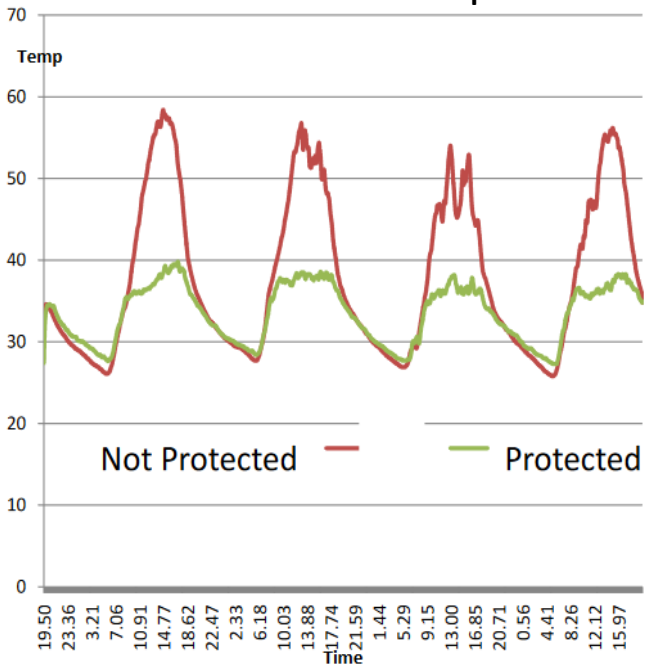

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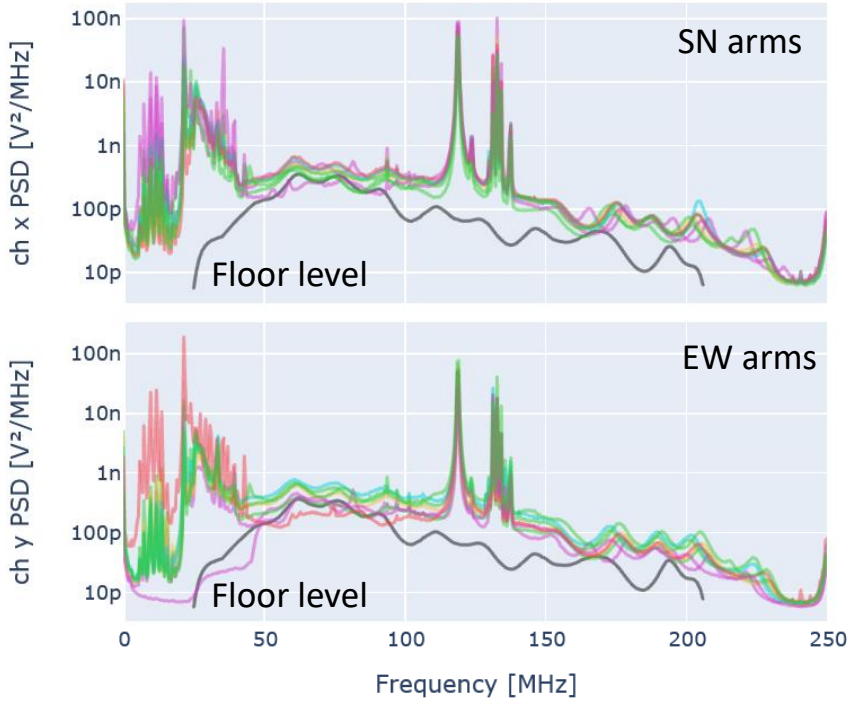
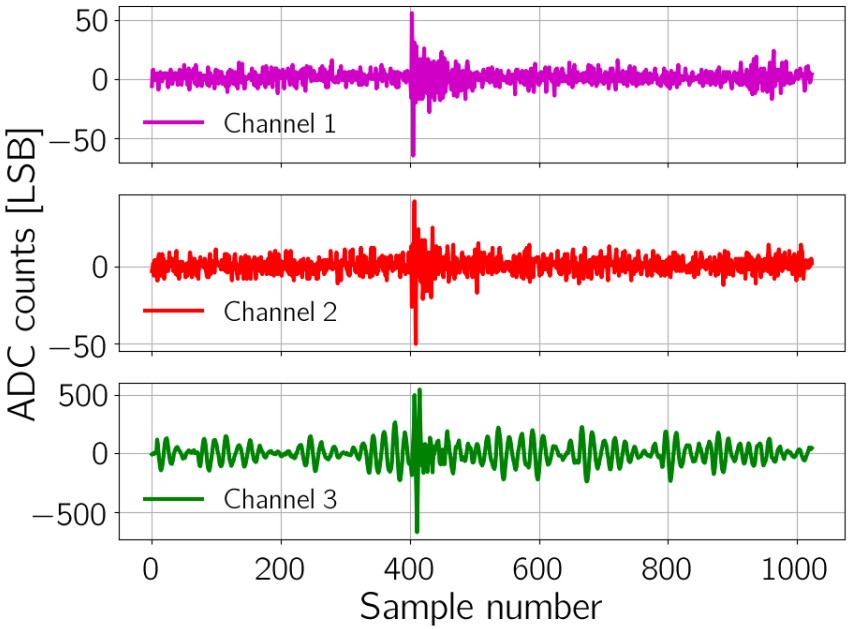


Example of a transiant pulse



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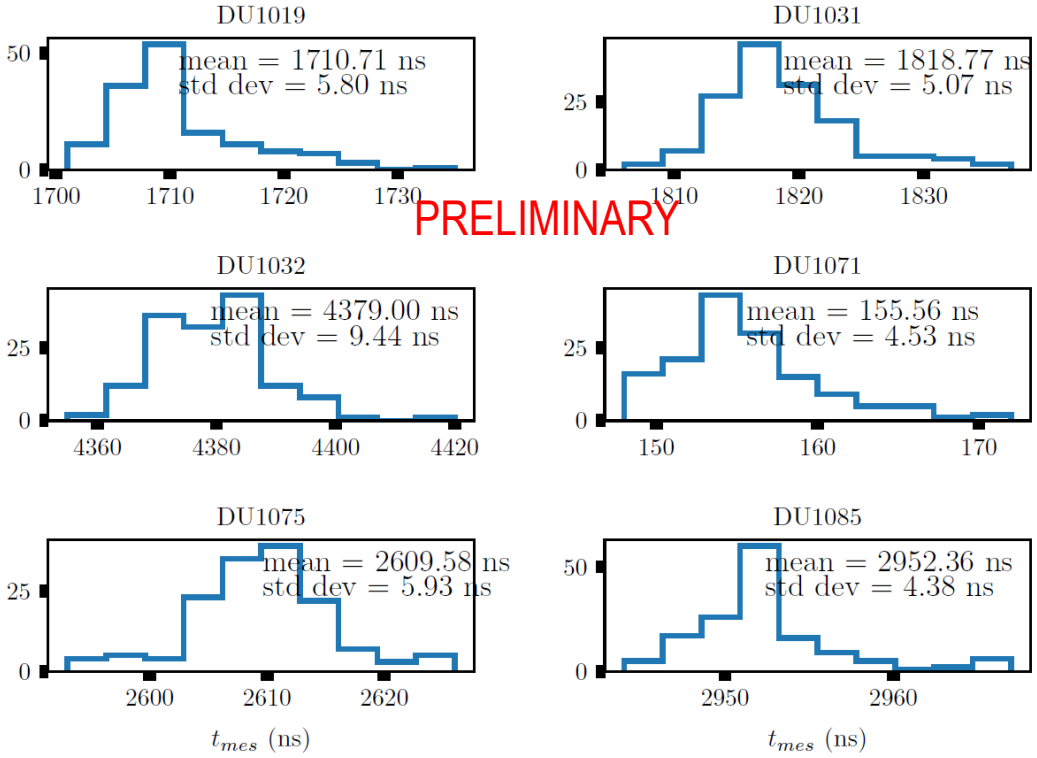
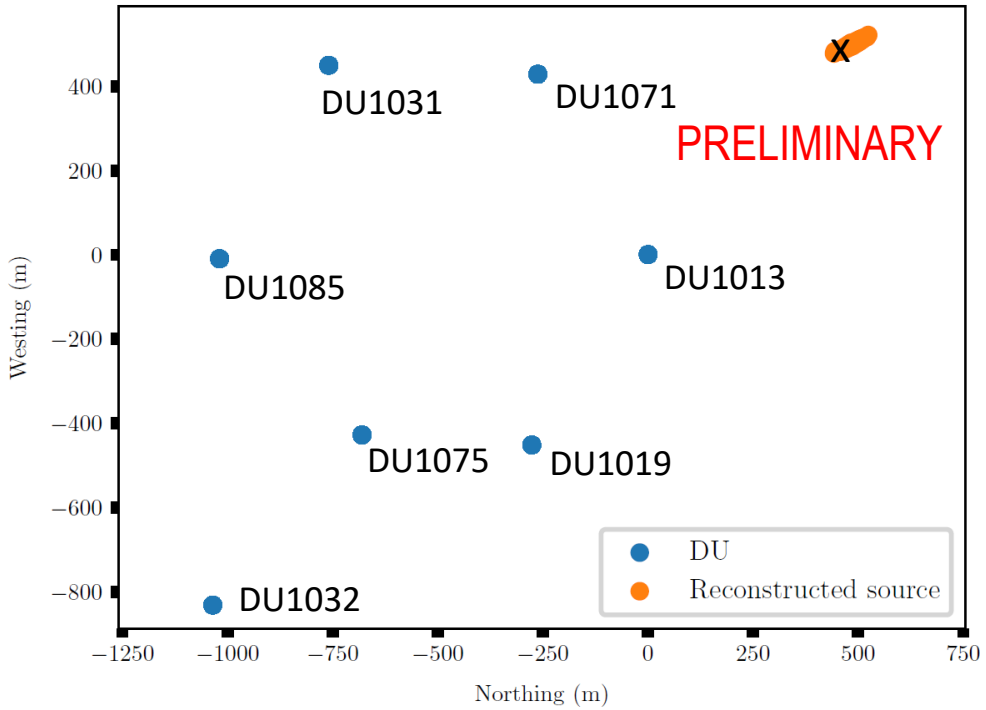
- Trigger, timing & reconstruction validation
  - Done with beacon source
  - **Timing resolution ~5ns** allows for ~10m resolution on source position
- Next steps:
  - **Deployment of 70 more units** in second half 2024
  - First air showers early 2025? ☺
  - **Then plenty of physics!**





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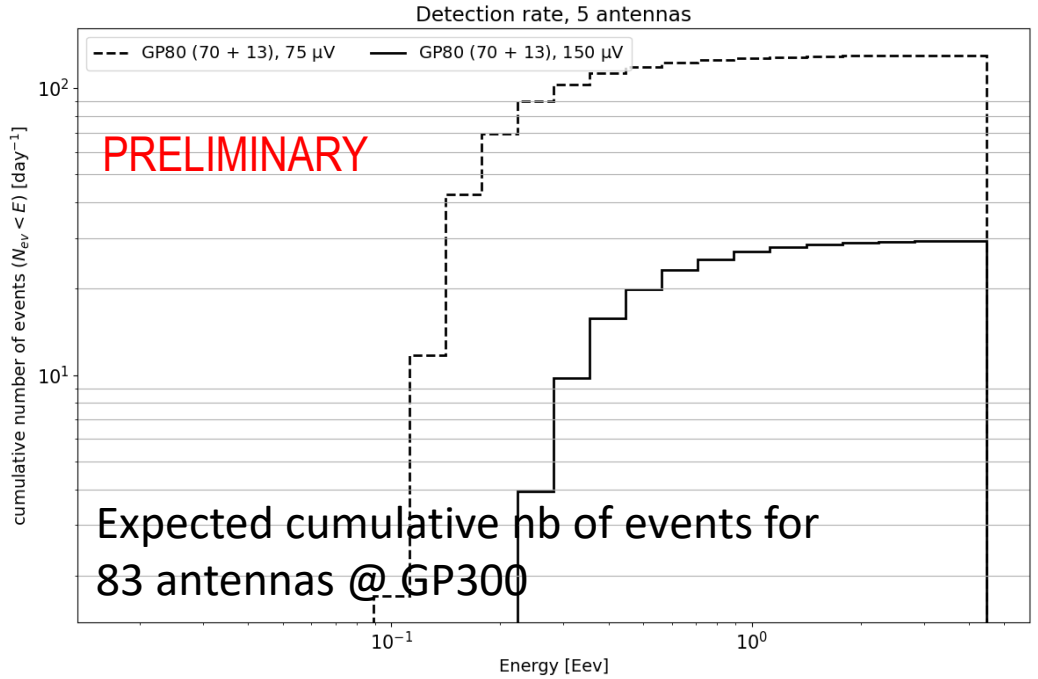
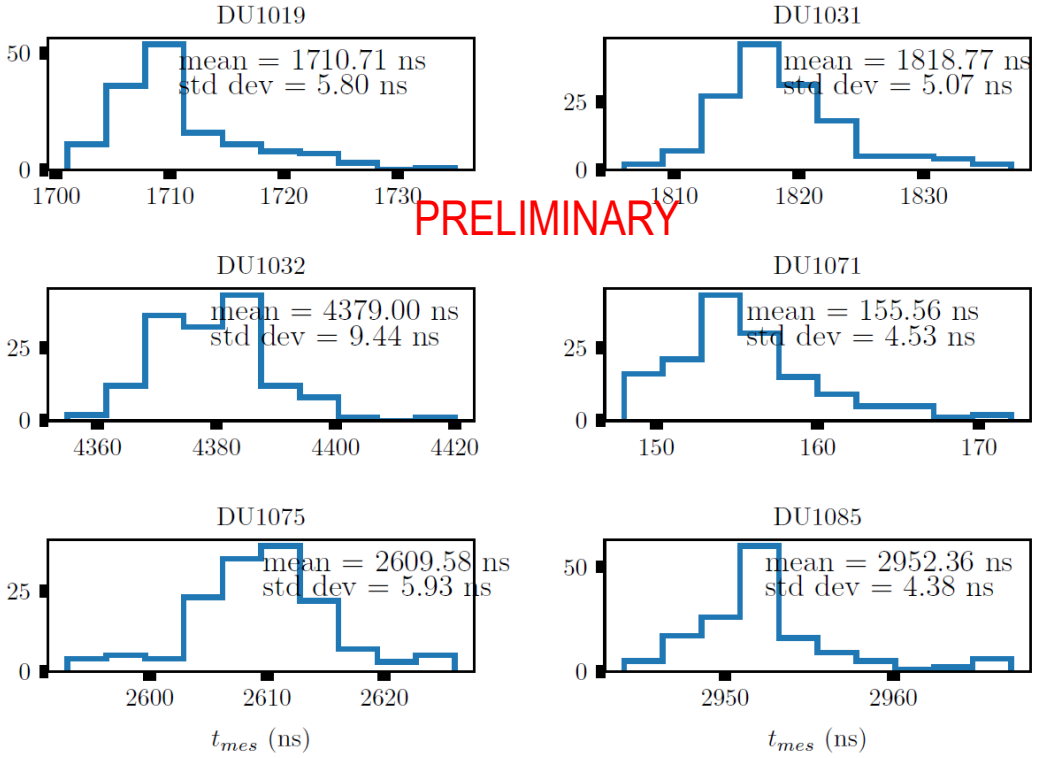
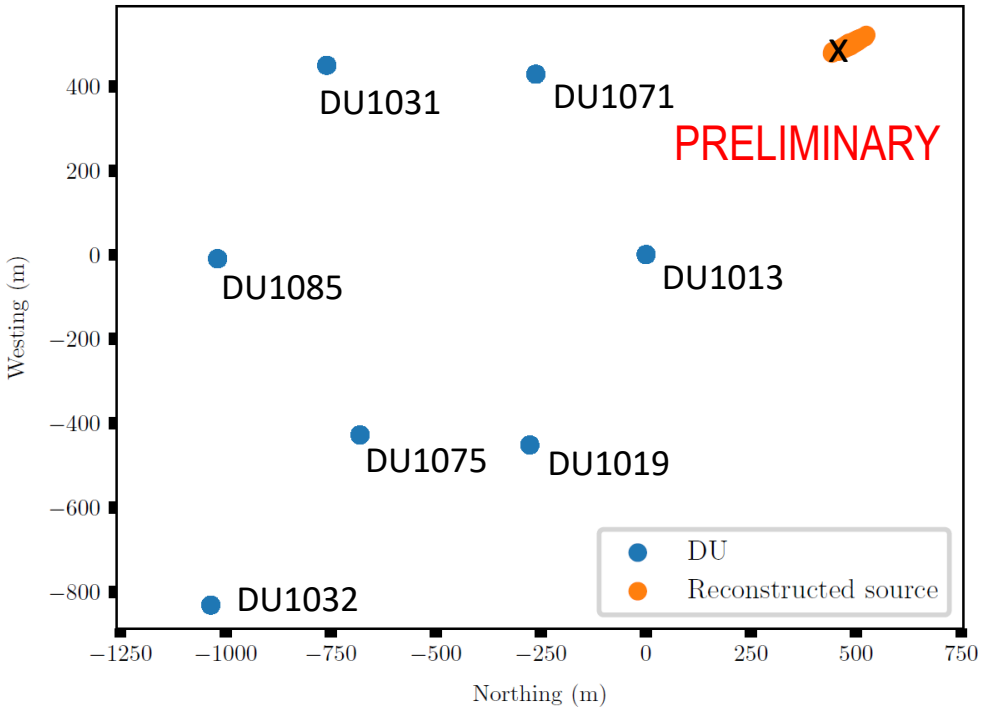
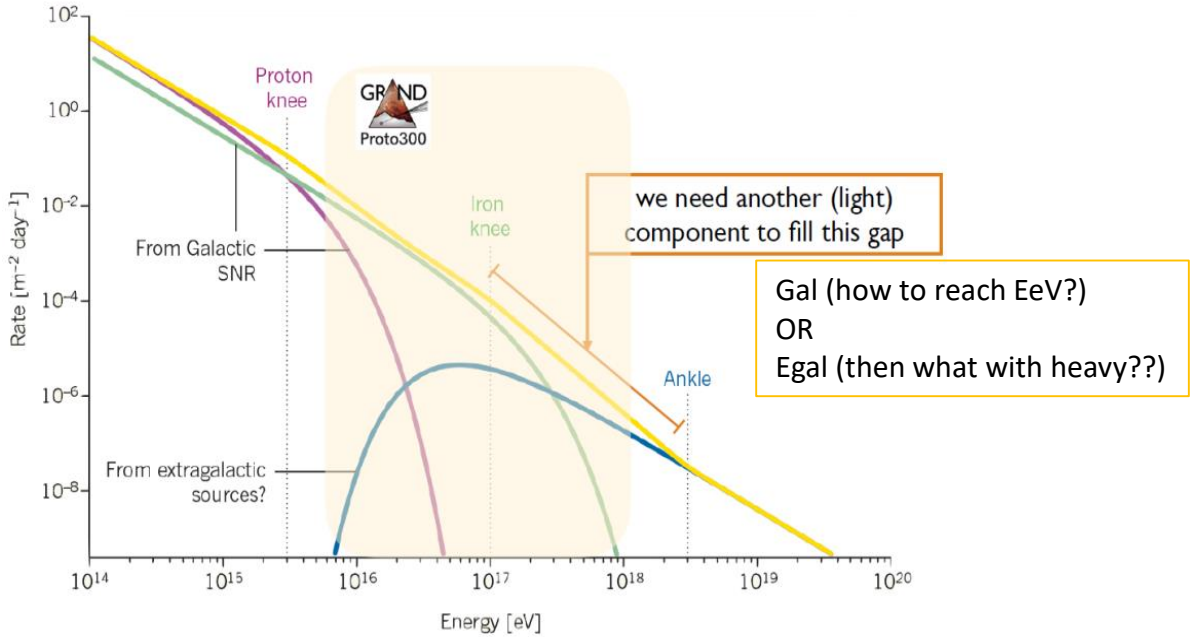


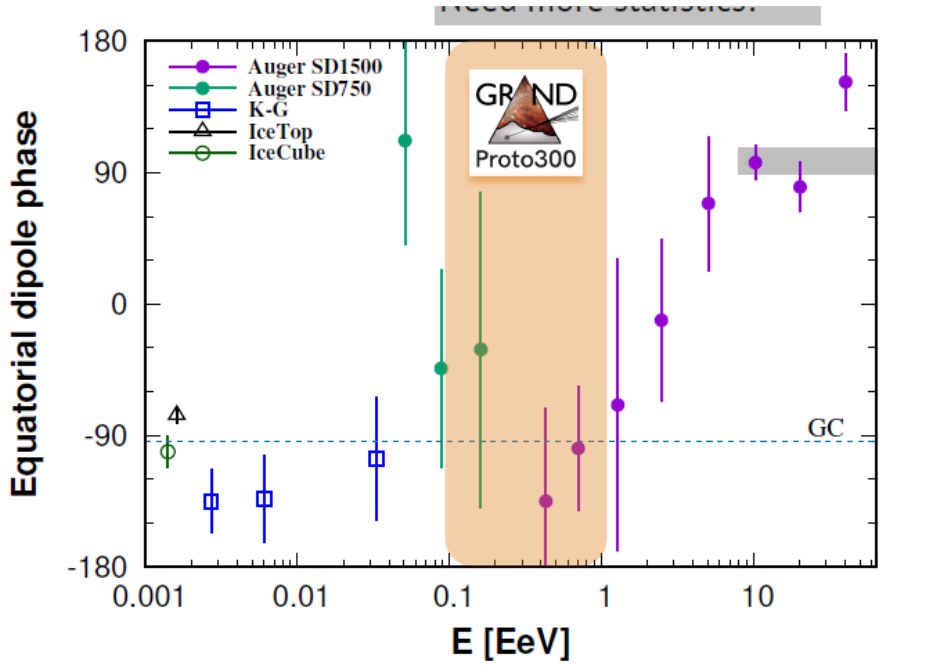




Gal-EGal transition

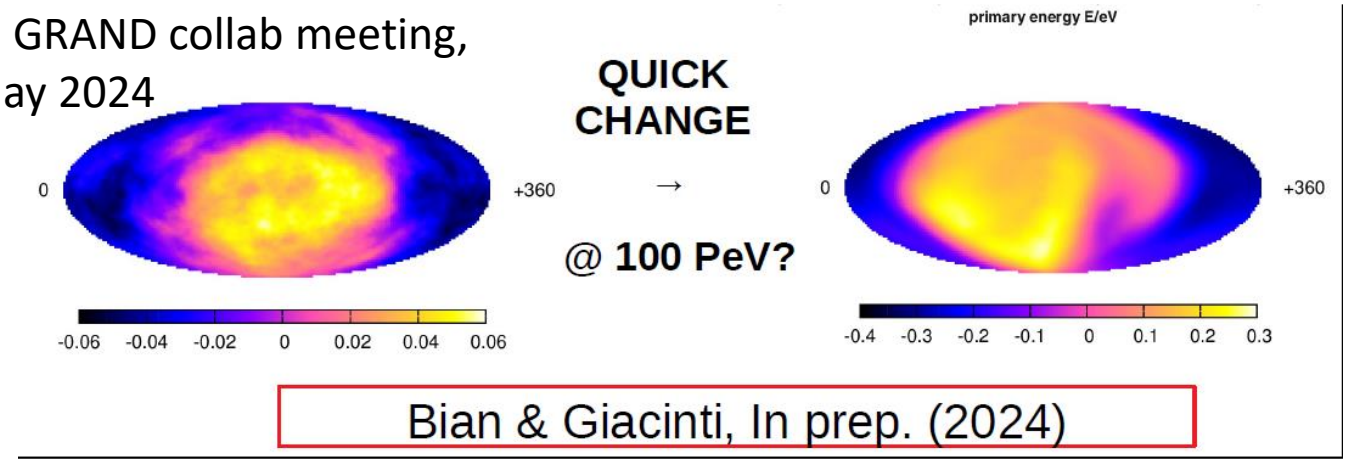


Plots by R. Batista



Snowmass White Paper. arXiv:2205.05845

G. Giacinti, GRAND collab meeting, Nanjing, May 2024



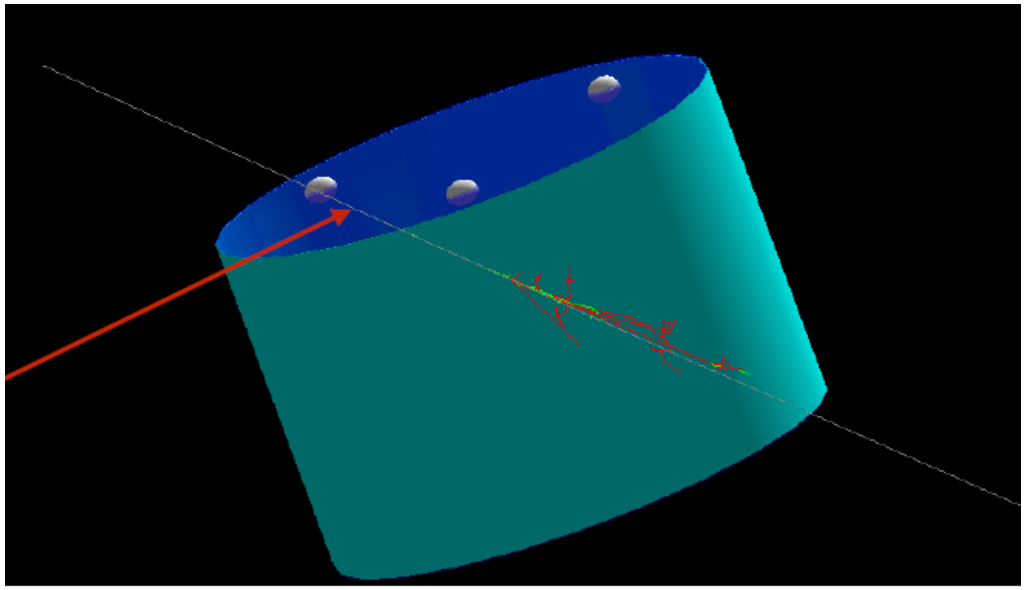
GP300 excellent angular resolution (~0.1°) & large statistics (100 of EAS/day) may be decisive!

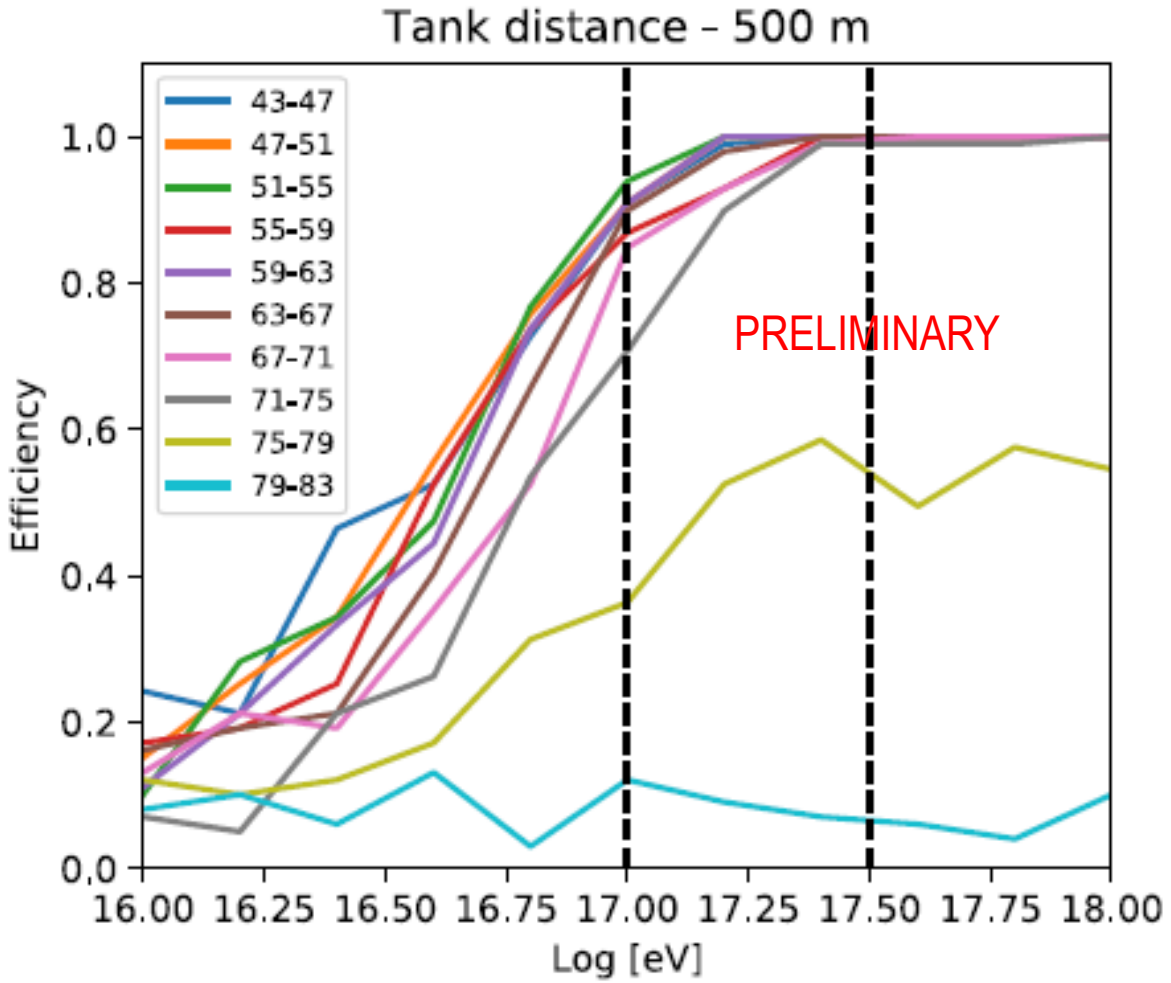
Physics with GP300?

- Completing the GP300 radio detector with an (independant) particle detector array (after 2025)?
  - Simulations assuming 300 tanks *a la* AUGER

(B. Zhang, Penn State)

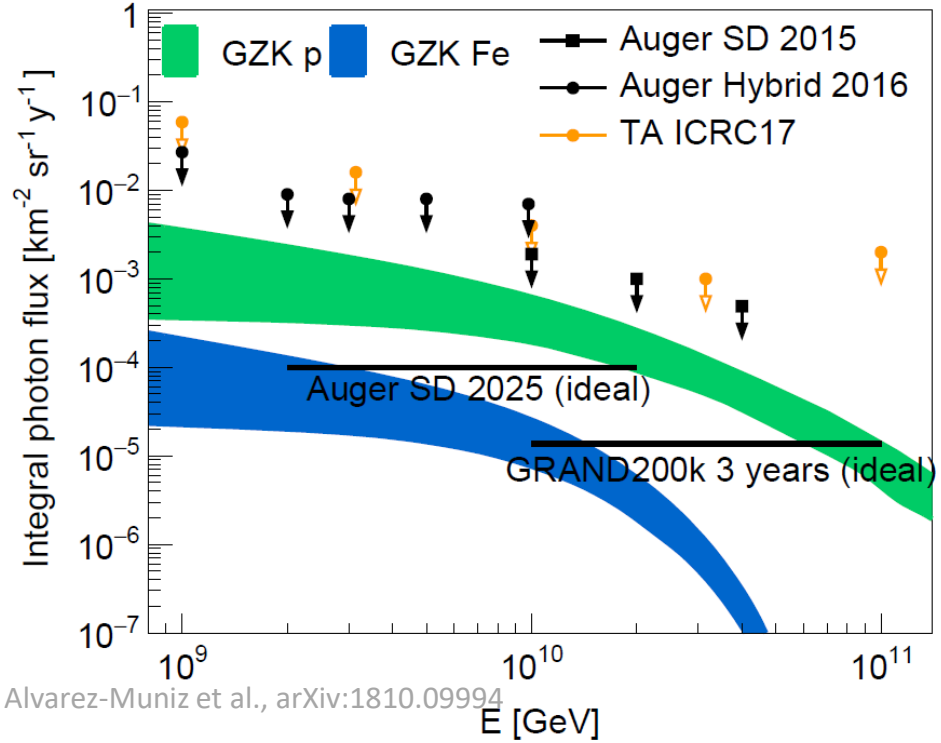
➔ **ε>20% for E>10^{16}eV & θ<75° ☺**



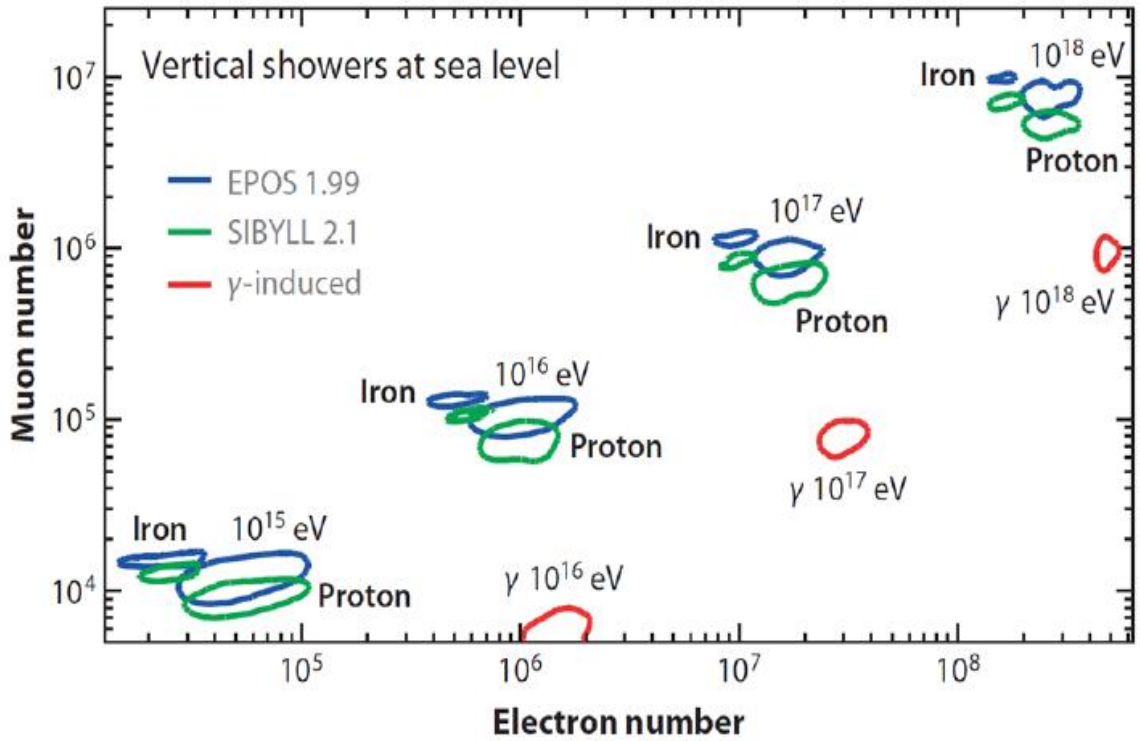


Gamma ray astronomy

- GP300: very clean separation of hadronic/γ primaries with ground array
- Later stages: large effective area may allow to reach sensitivity comparable to (better than?) Auger in the 10^{17} -10^{18} eV range.



Alvarez-Muniz et al., arXiv:1810.09994



Engel et al., Annual Rev of Nuclear and Part. Science 61, 467 (2011)

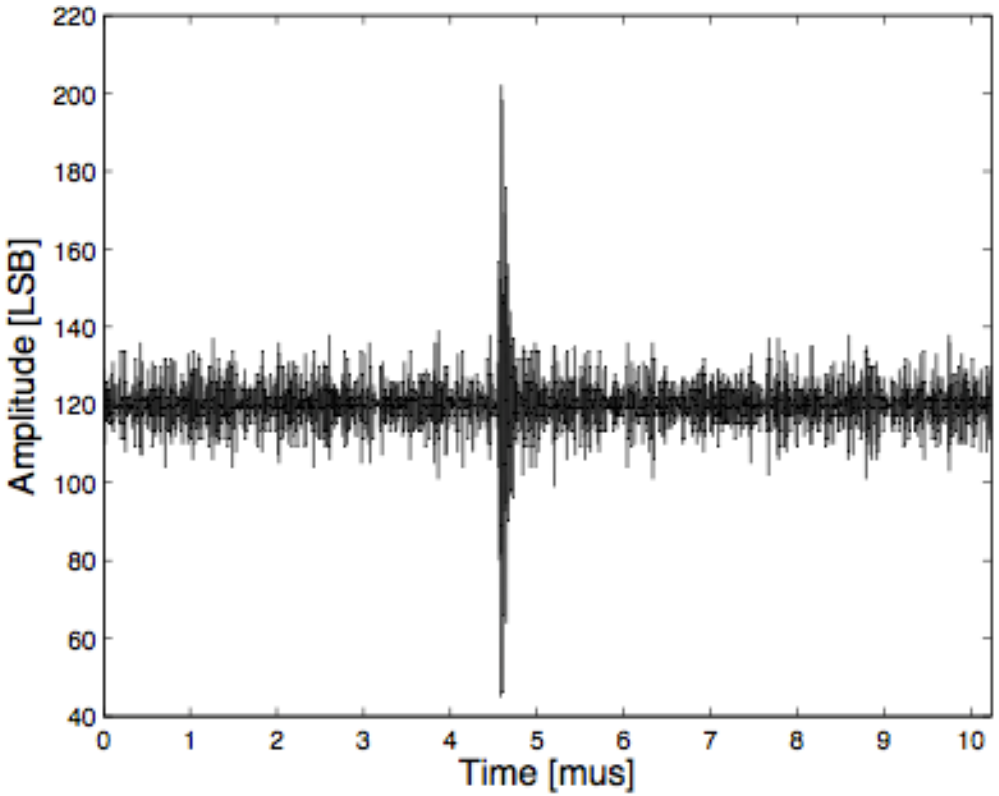
➔ Probe for cosmogenic γ

➔ UHE gamma ray astronomy???

New trigger methods for autonomous radio arrays

- At present (including GP300), only standard methods for triggering:
  - L1 @ unit level: (mostly) signal-over-threshold
  - L2 @ DAQ level: select causal coincs between L1s (GPS timetags)
  - Full time trace collected

A TREND event



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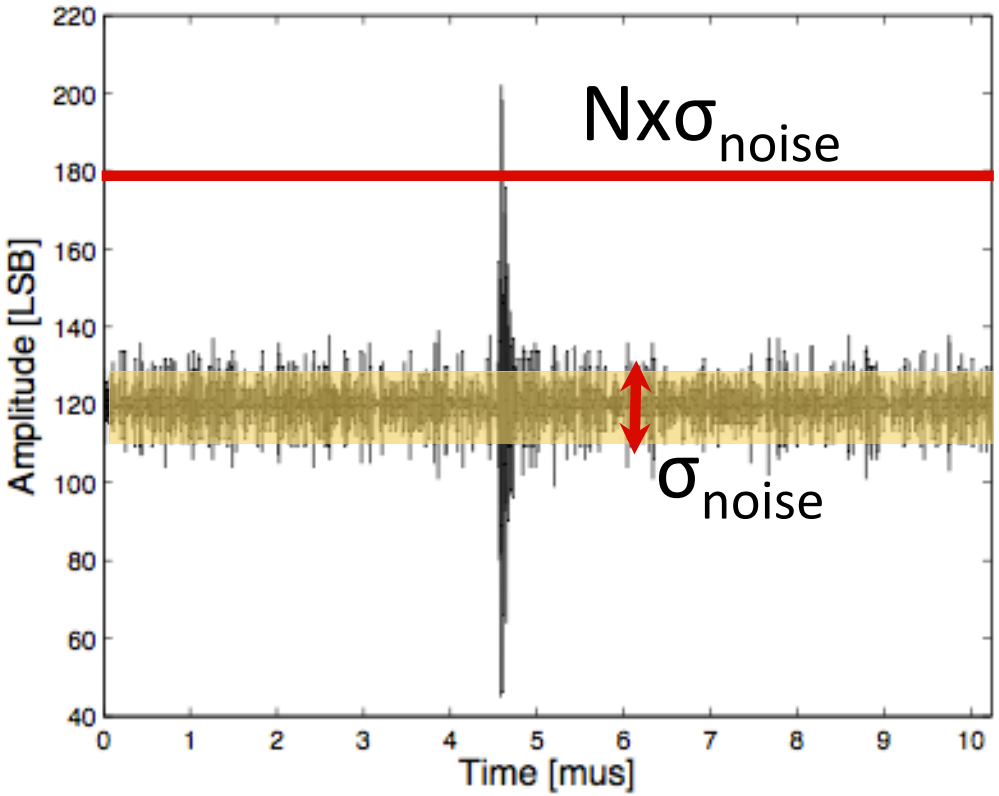

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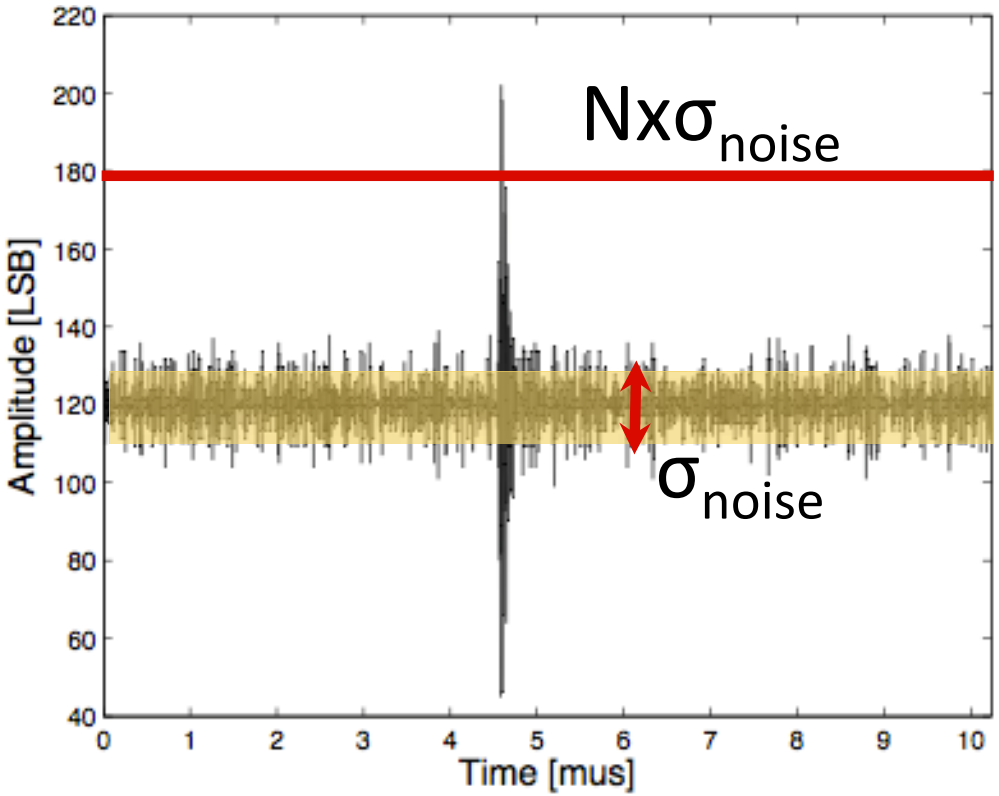

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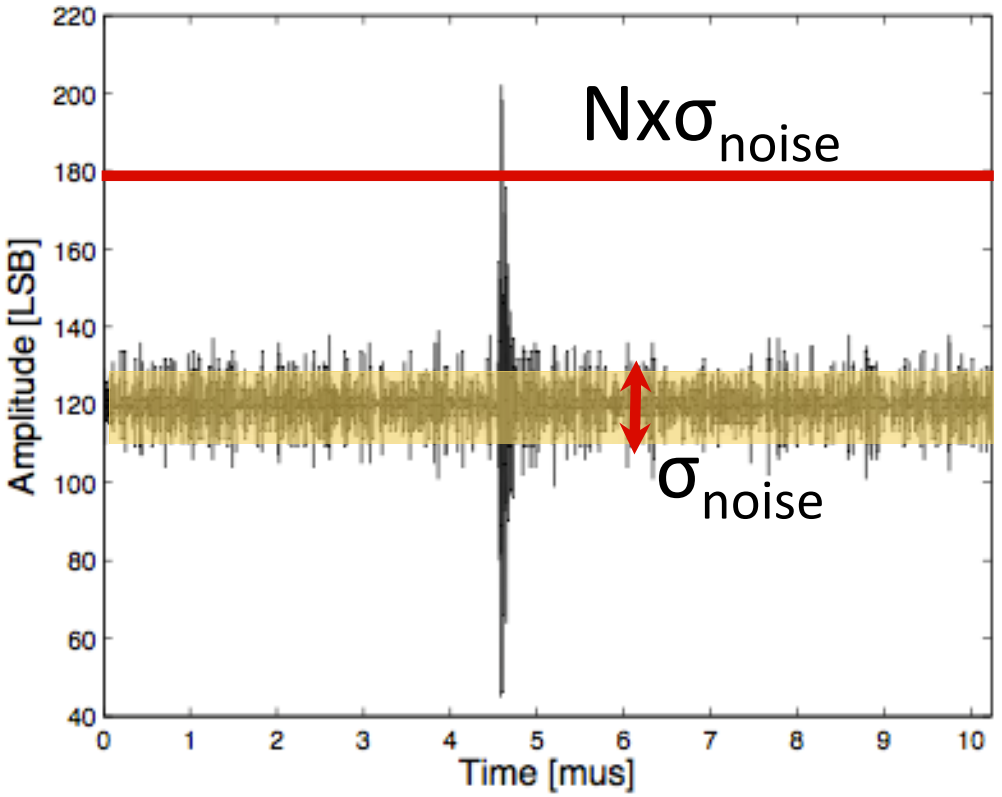

GP300: large volumes of data ➔ Large bandwidth needed ➔ WiFi ➔ High cost, high power consumption, low range

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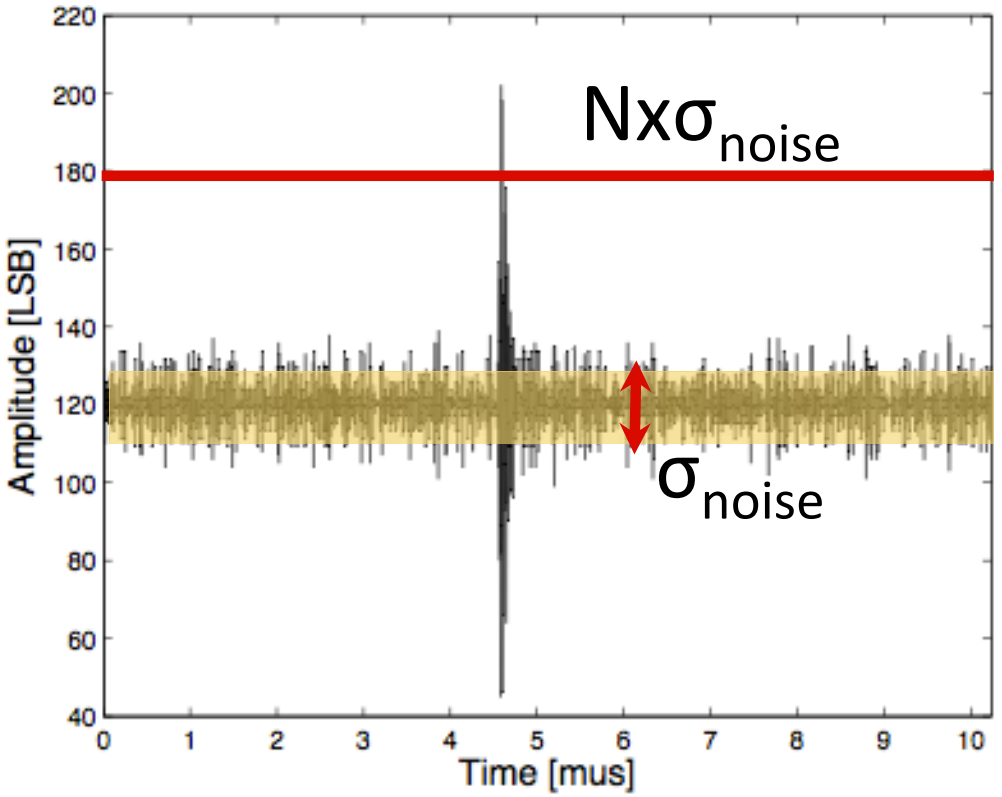

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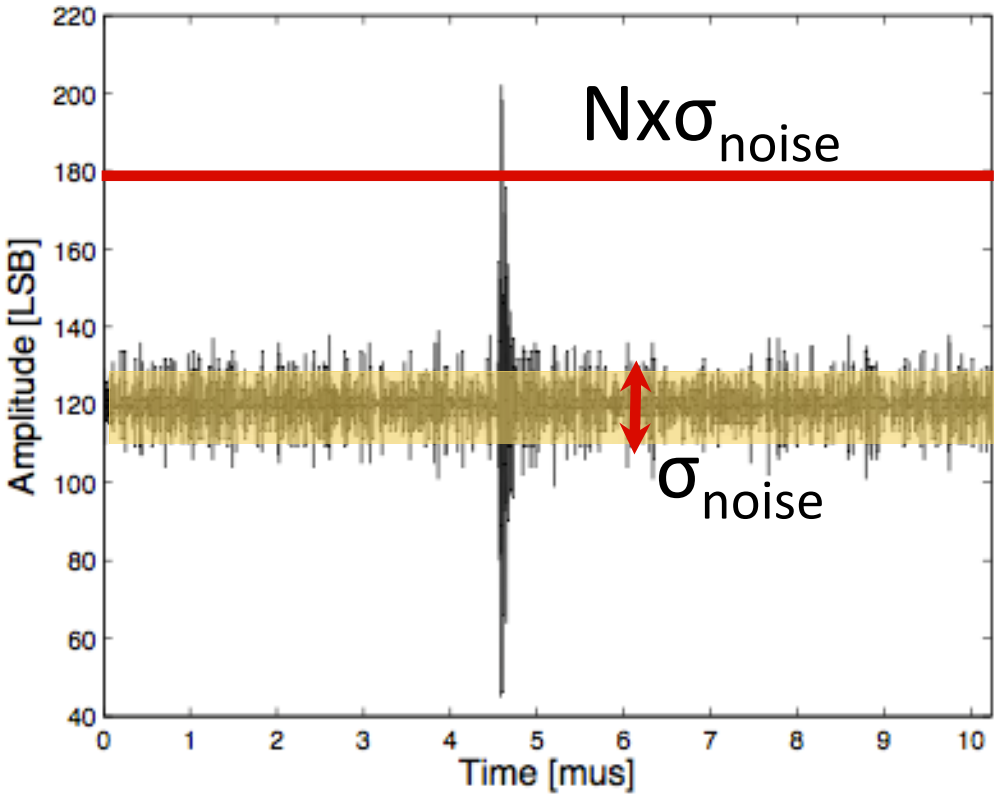

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NUTRIG (*LPNHE + IAP + KIT) ANR+DFG funded

- L1 trigger (LPNHE lead)
  - Developing innovative methods for
    - Signal identification (ie fighting against transient noise) ➔ improve purity
    - Signal extraction (ie fighting against stationnary noise) ➔ improve threshold
  - Specific constraints:
    - Online treatment (ie faster that data rate)
    - « Frugality »: low power & limited CPU
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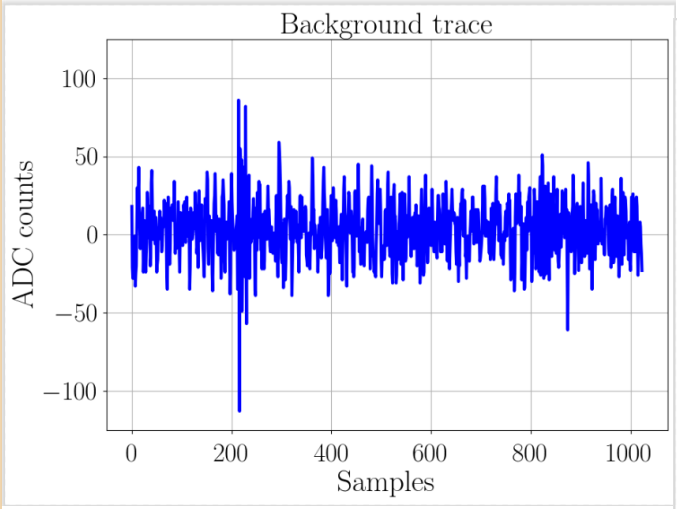
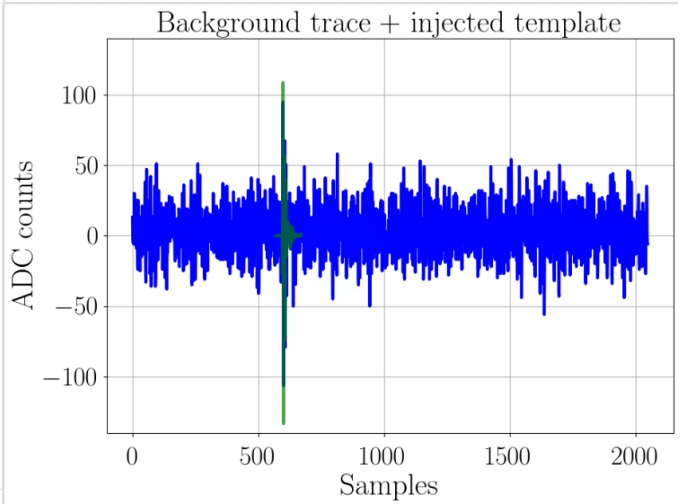
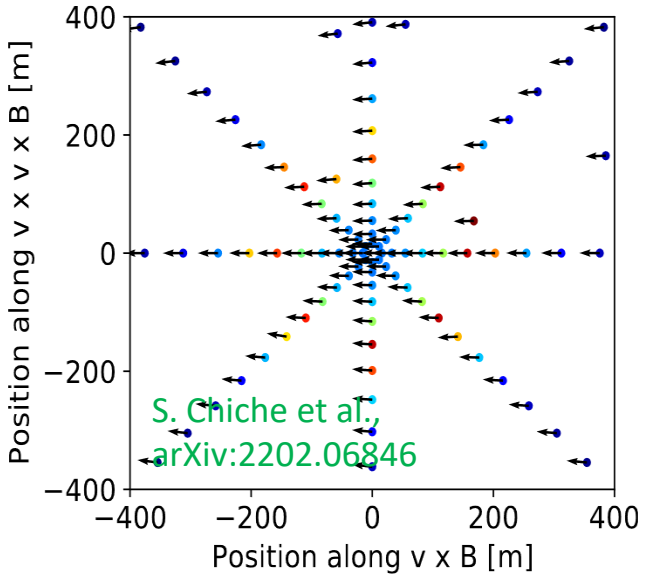
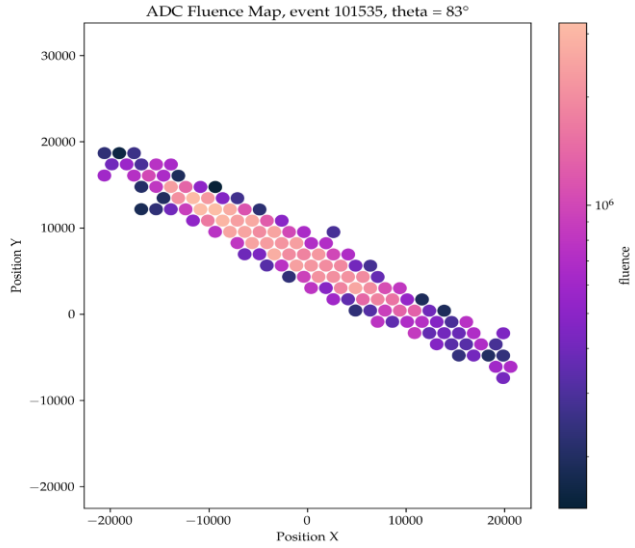
  - Optimize balance between data volume and quality using offline (blind) analysis based on reduced info.









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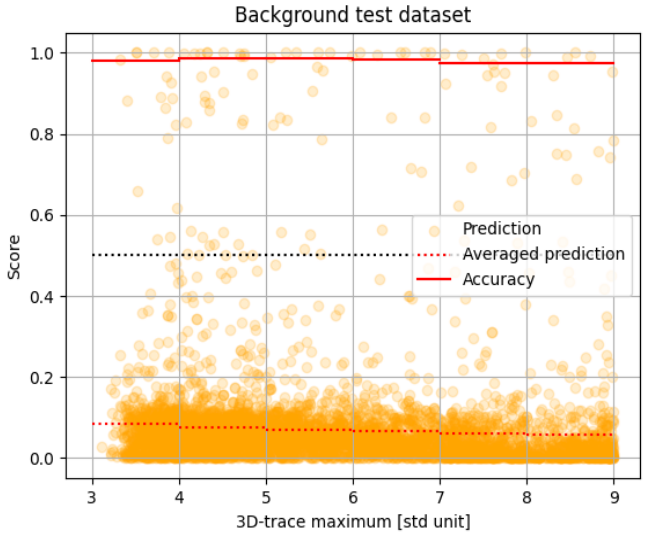
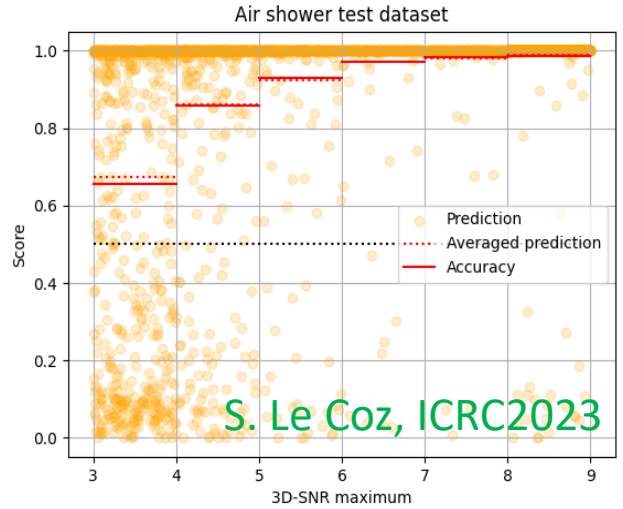
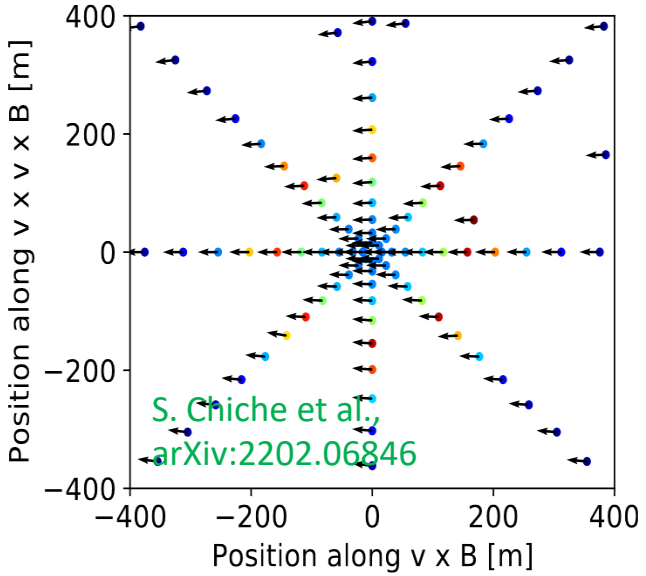
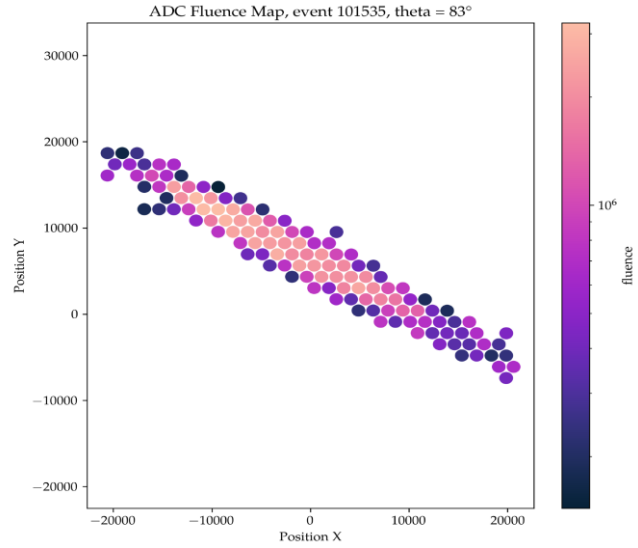
Machine Learning (CNN) classification

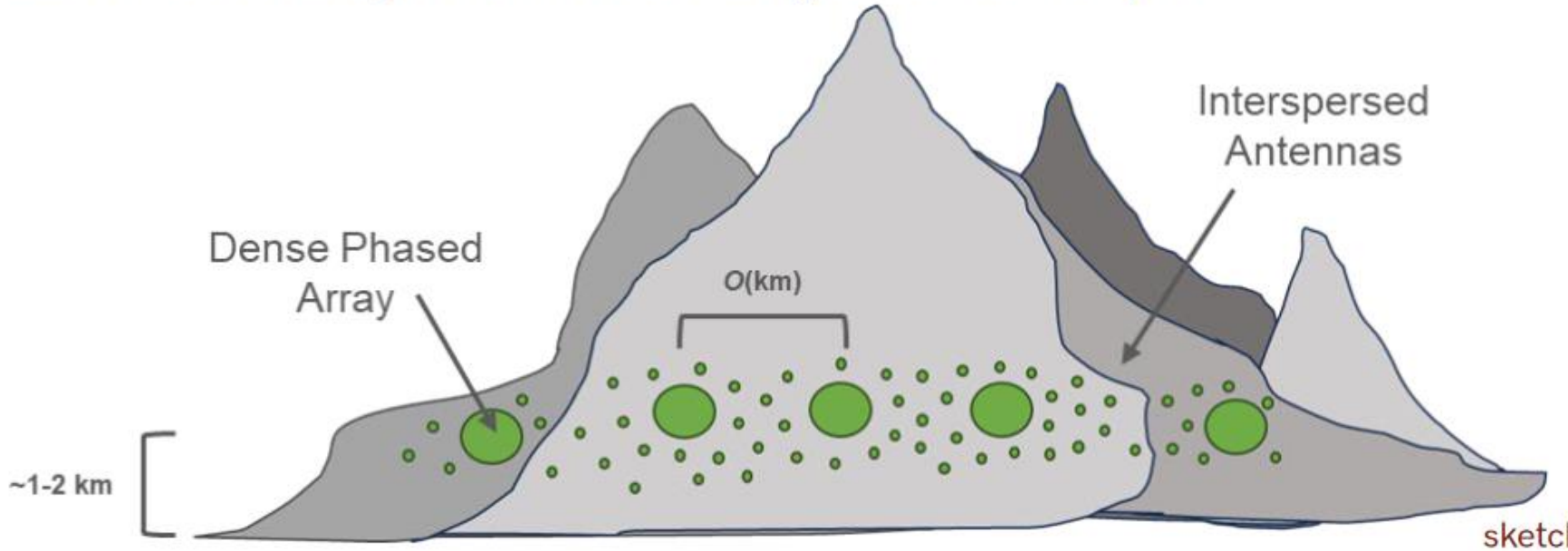








GRAND-BEACON: exploration of a hybrid concept



sketch by Andrew Zeolla
GRAND Analysis Forum Meeting - May 2024

- **BEACON-type: phased stations**
  low energy threshold for triggering
- **GRAND-type: interspersed antennas**
  autonomous trigger + also triggered externally by phased stations,
  use offline interferometry (via reference beacon transmitter), for reconstruction + RFI rejection
- **High gain antennas** design for individual antennas, focused at the horizon, mostly low frequencies (30-80 MHz), for minimal energy threshold —> to be developed within general GRAND framework
- **~1000m elevation**
  for aperture + sensitivity at low-energies

K. Kotera, GRAND collab meeting, Nanjing 2024
S; Wiessel, ARENA workshop, Chicago 2024

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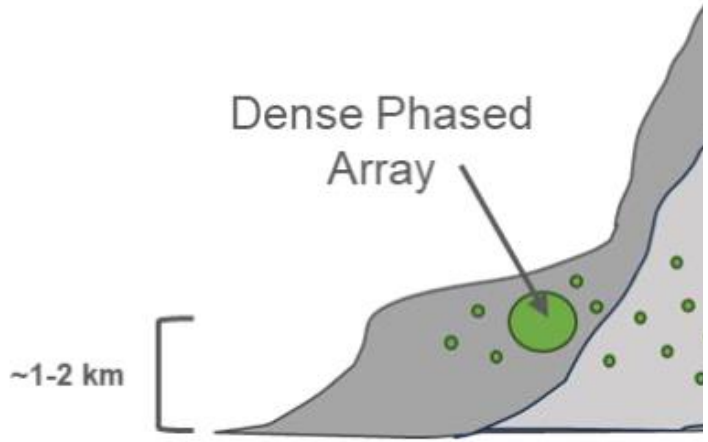

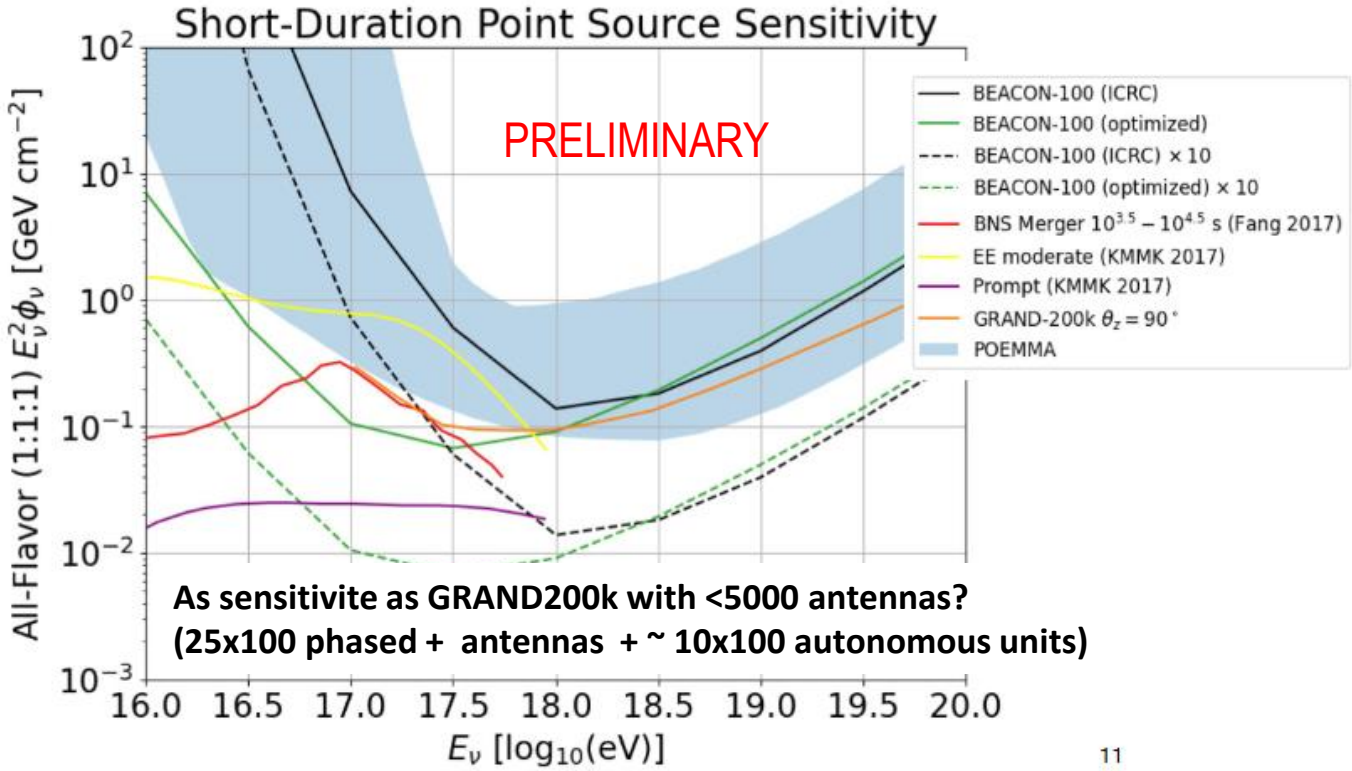

As sensitivite as GRAND200k with <5000 antennas?
(25x100 phased + antennas + ~ 10x100 autonomous units)

11

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GRAND: a great technological challenge, a rich science case

UHE neutrinos

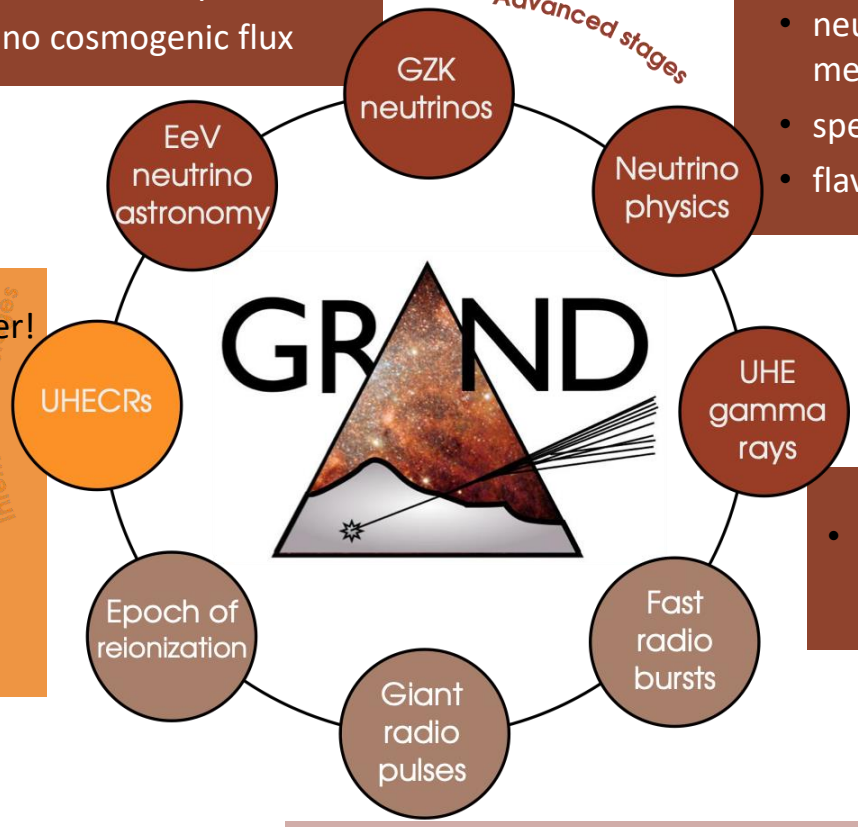
- UHE neutrino astronomy
- UHE neutrino cosmogenic flux

neutrino physics

- neutrino cross-section measurements
- spectral, angular distortions
- flavor ratios

UHECR, hadronic physics

- 20-80 times the exposure of Auger!
- GRANDProto300: transition from Galactic/extragalactic
- hadronic physics: muon discrepancy, UHECR mass composition, p-air cross-section

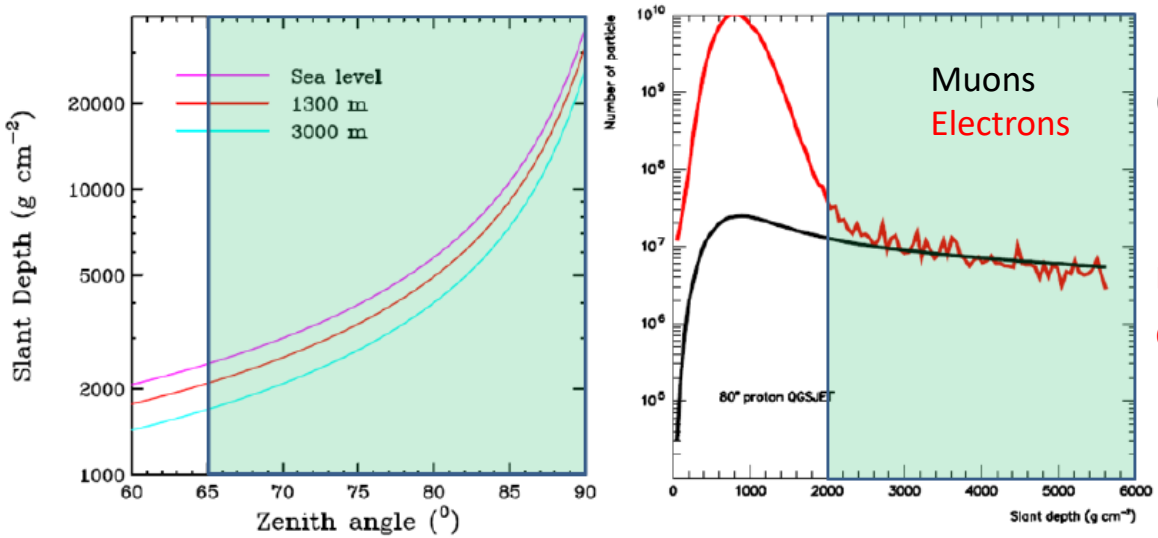


UHE gamma rays

- competitive with Auger at GRANDProto300 stage

radio-astronomy in a novel way

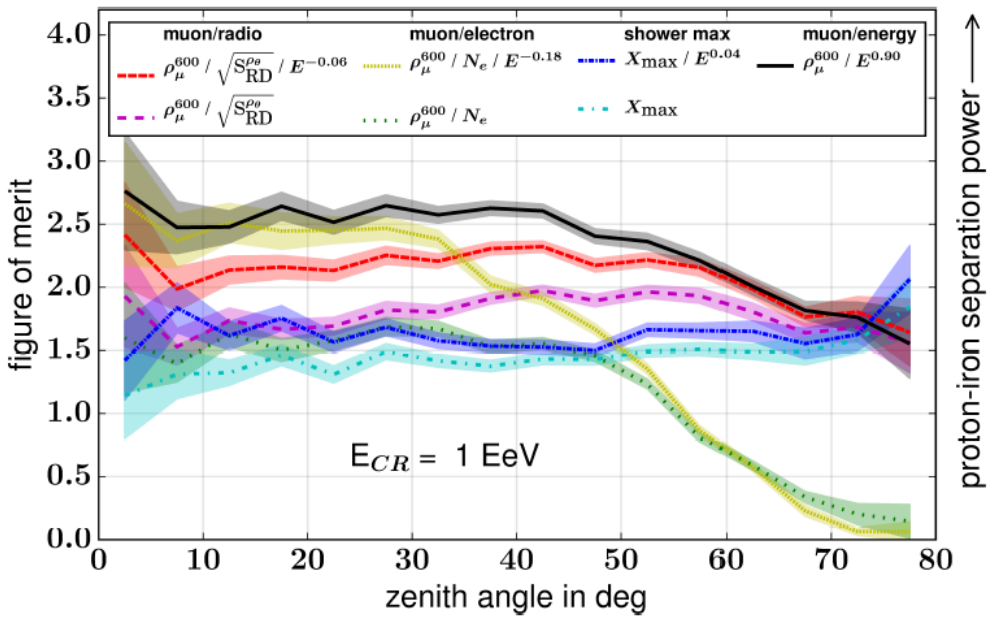
- unphased integration of signals: an almost full-sky survey of radio signals
- can detect FRBs and Giant Radio pulses of the Crab already at the GRANDProto300 stage



Zas, New Journal of Physics 7, 1302013130 (2005).

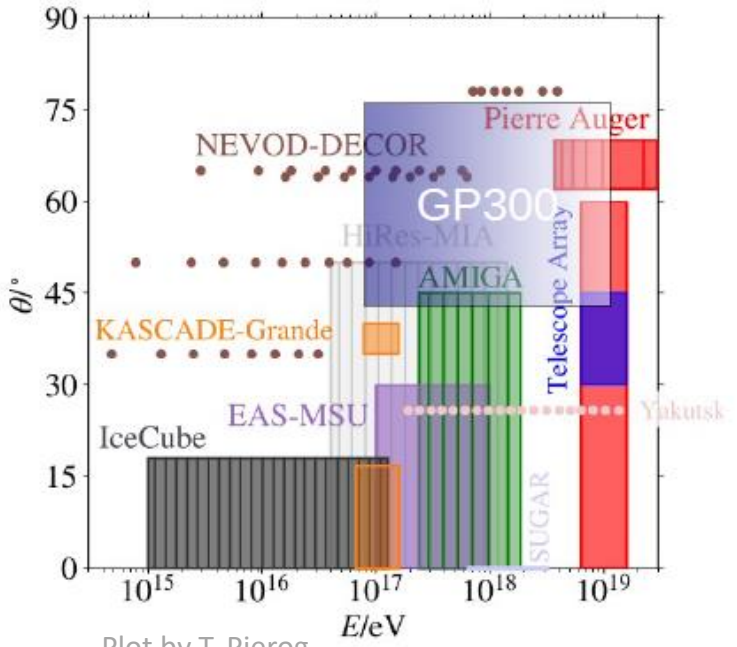
Only muons reach ground for θ>65°

➔ **Independent shower-by-shower measurement of EAS muonic and electronic components**



Holt et al, arXiv:1905.01409v1

Improved handle for primary determination

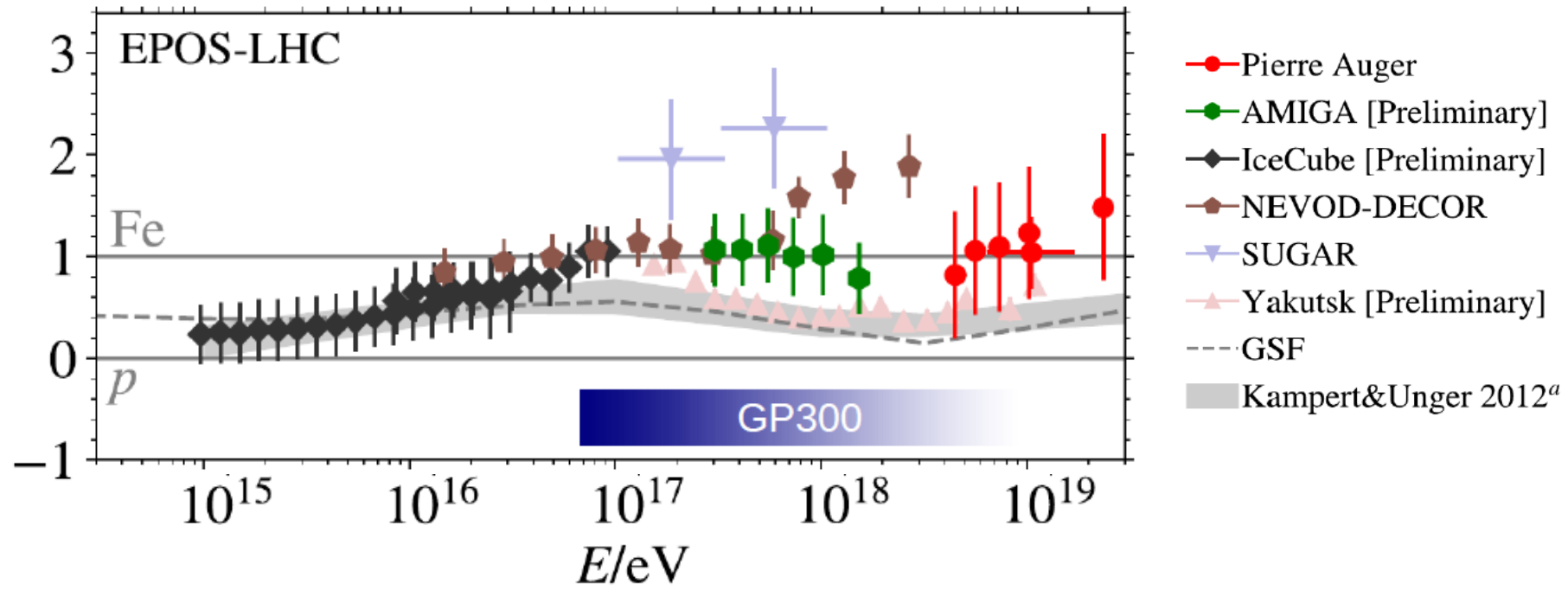


Plot by T. Pierog

Little-explored (E, θ) range

Insight on muon deficit in sims?

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

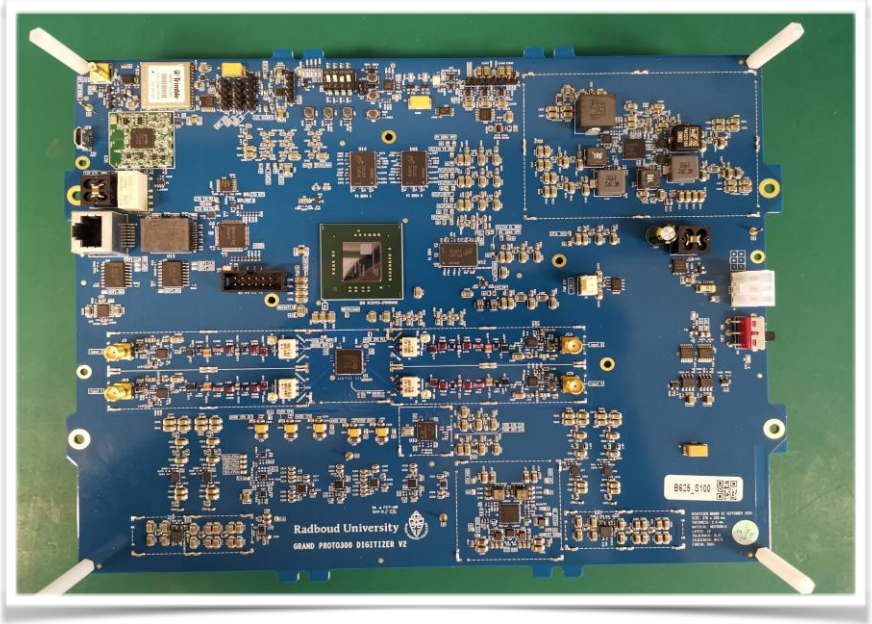


WHISP working group, EPJ Web Conf. 210 (2019) 02004 - arXiv:1902.08124

However:

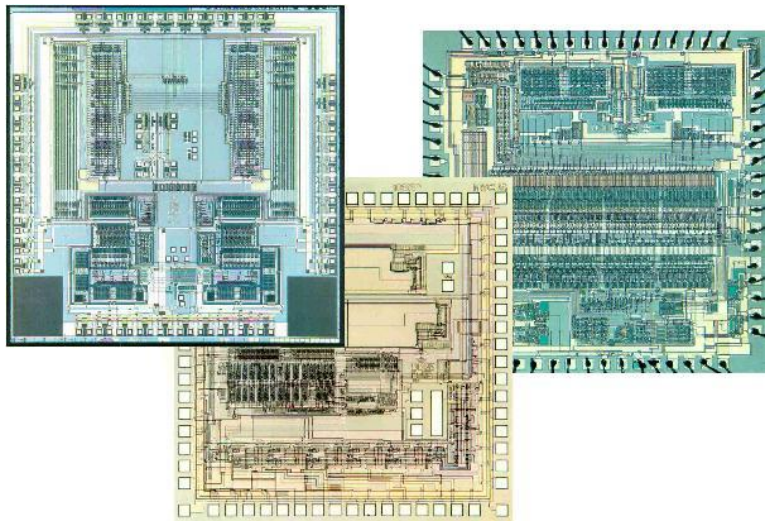
- Significant progress in understanding/comparing data in the last 3 years
- Upcoming data from AMIGA and IceCube/Top could clarify the situation

Physics at industrial scale (GRAND200k)



PCB + discrete componants:
amplifier, ADC, FPGA, comms.

- Cost ~3000 € /board
- Consomption~ 15W
- Reliability?



ASIC

- Cost ~ 10M$ ➔ few 10$ /board
- Consomption < 1W
- Reliability ☺

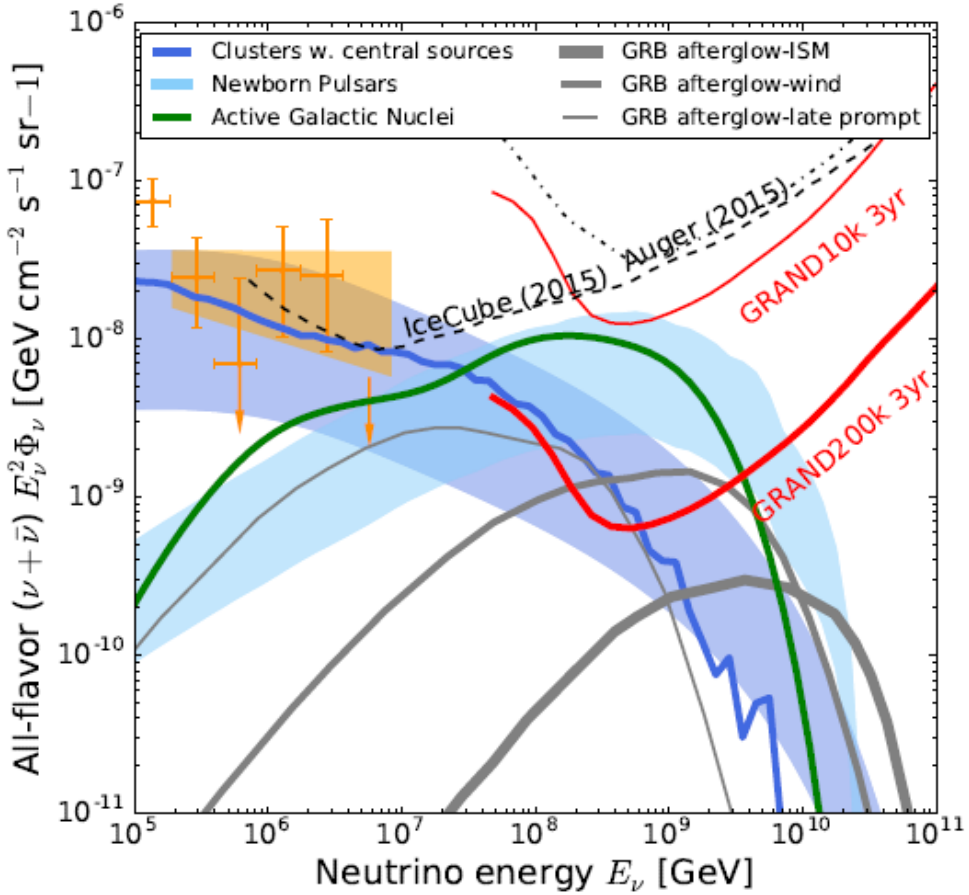


FIG. 5. Predicted neutrino flux from different classes of astrophysical sources, compared to upper limits on UHE neutrinos from IceCube [36] and Auger [16], and projected 3-year sensitivity of GRAND10k and GRAND200k (Sections V C and V D). Several source classes can account for the observed UHECR spectrum: galaxy clusters with central sources [37, 38], fast-spinning newborn pulsars [39], active galactic nuclei [40], and afterglows of gamma-ray bursts [41].

[37] K. Murase, S. Inoue, and S. Nagataki, ApJ **689**, L105 (2008), arXiv:0805.0104.

[38] K. Fang and K. Murase, Nature Phys. **14**, 396 (2018), arXiv:1704.00015 [astro-ph.HE].

[39] K. Fang, K. Kotera, K. Murase, and A. V. Olinto, Phys. Rev. D **90**, 103005 (2014), arXiv:1311.2044 [astro-ph.HE].

[40] K. Murase, (2015), arXiv:1511.01590 [astro-ph.HE].

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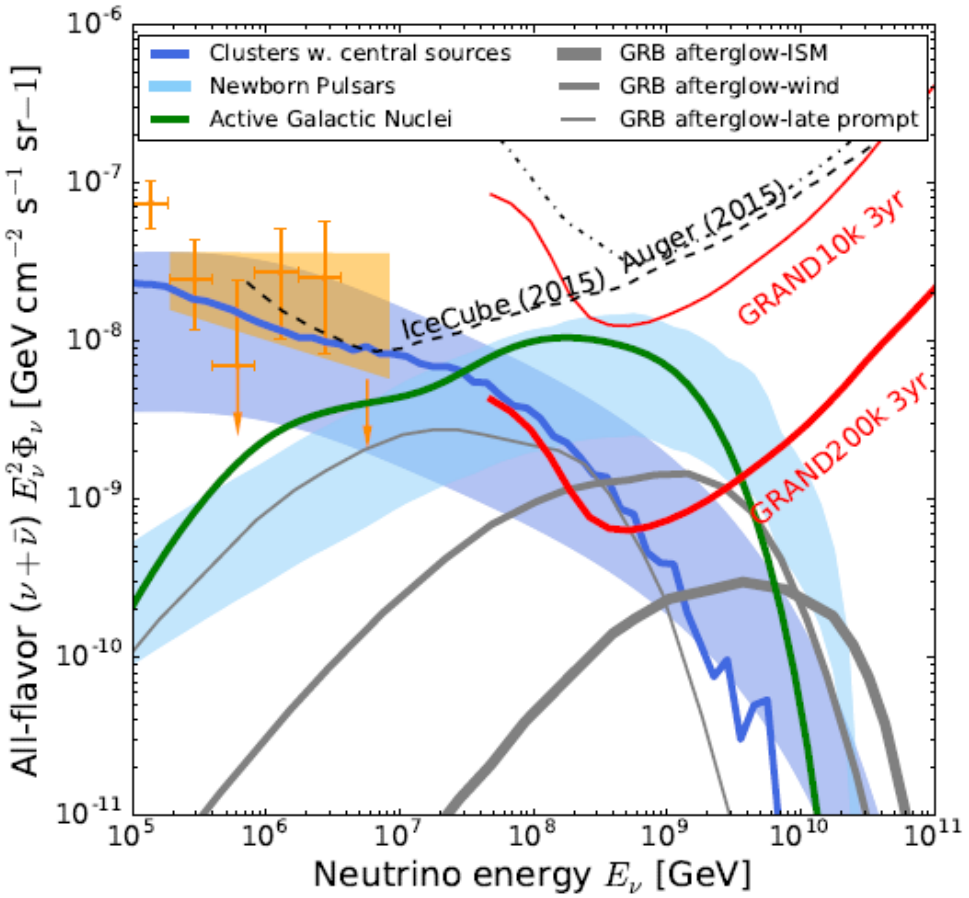

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Alvarez-Muniz et al.,
The GRAND collab,
Sci. China-Phys. Mech. Astron. 63, 219501 (2020)
arXiv:1810.09994

[37] K. Murase, S. Inoue, and S. Nagataki, ApJ **689**, L105 (2008), arXiv:0805.0104.
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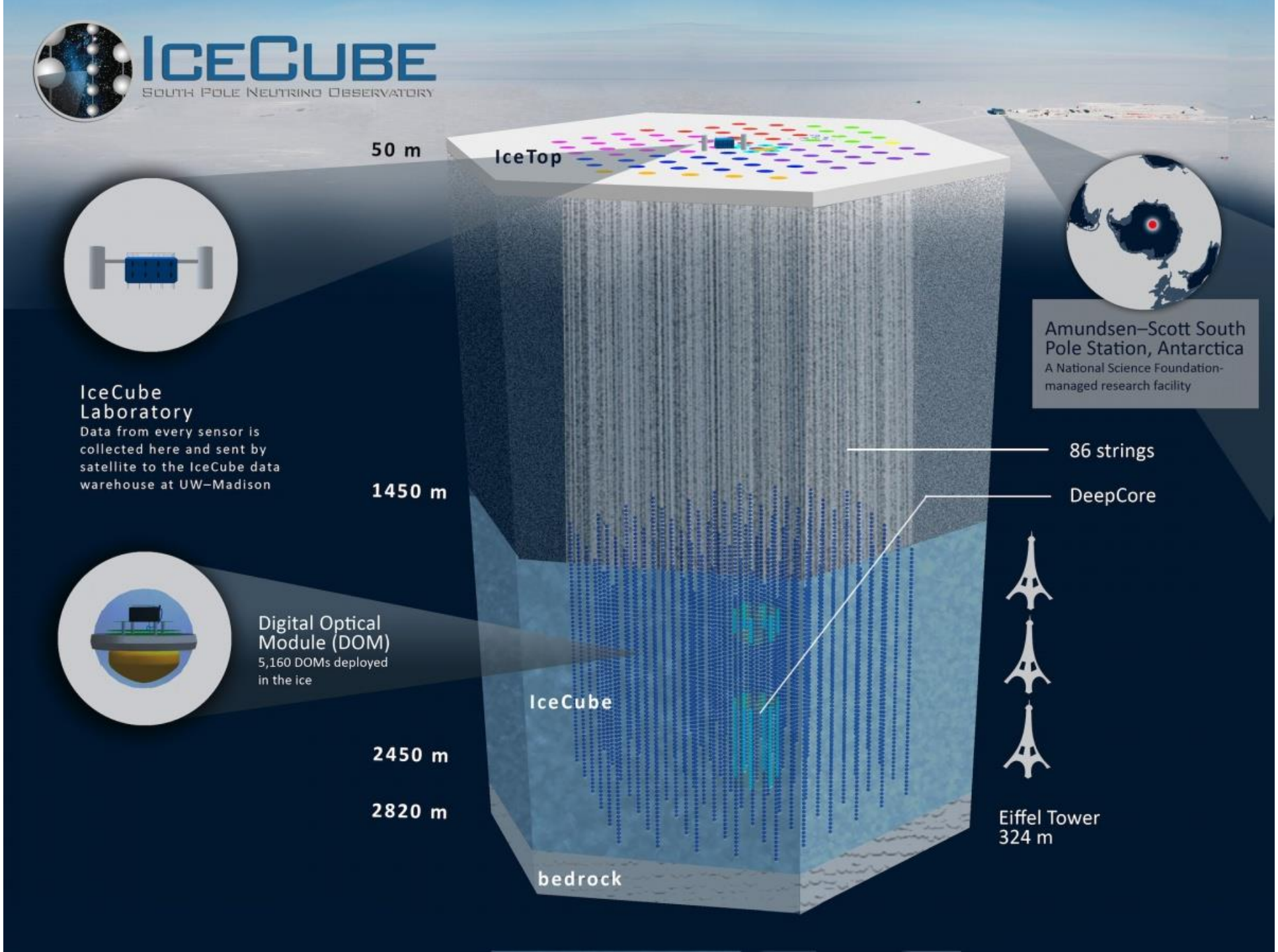
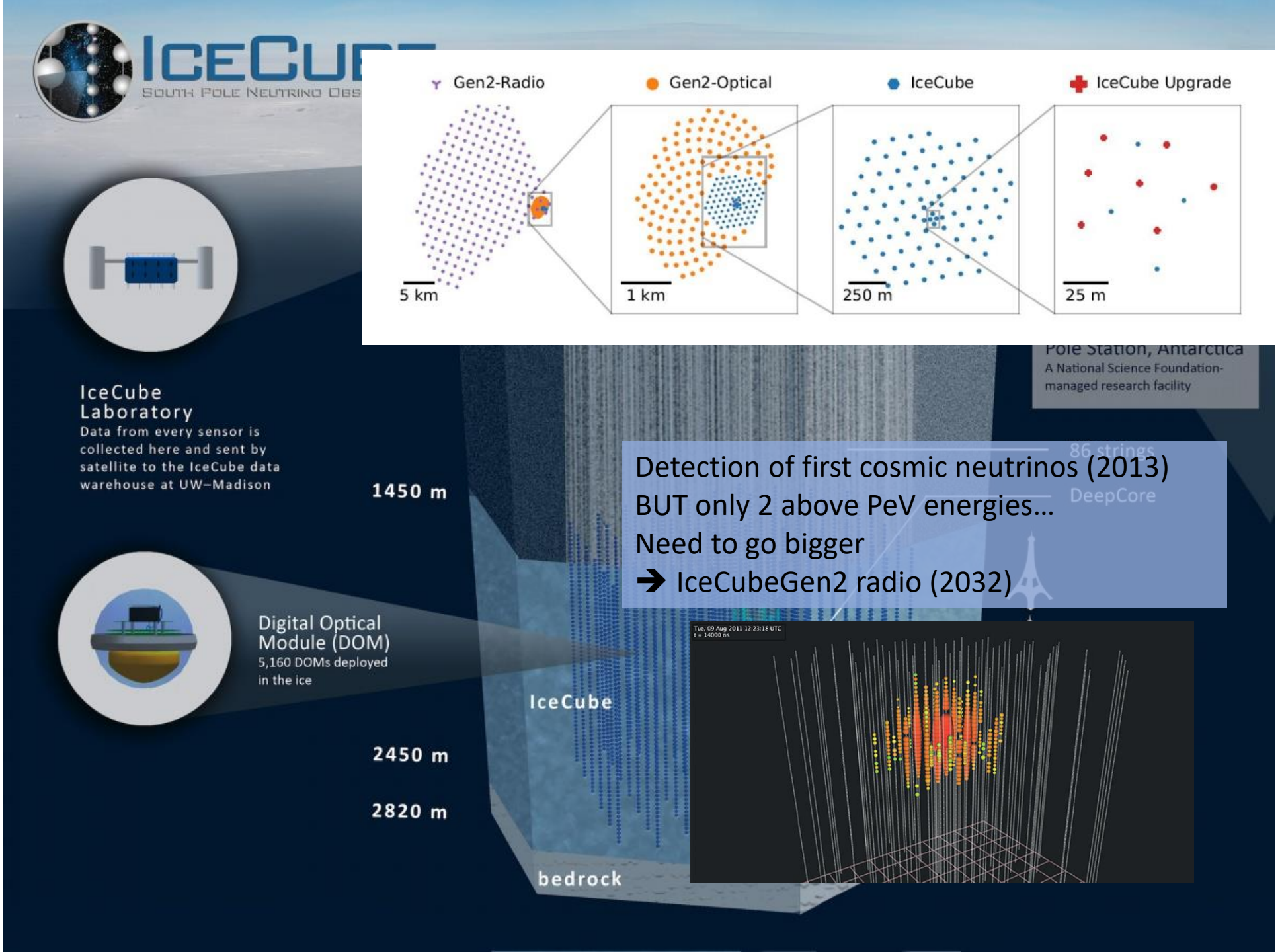
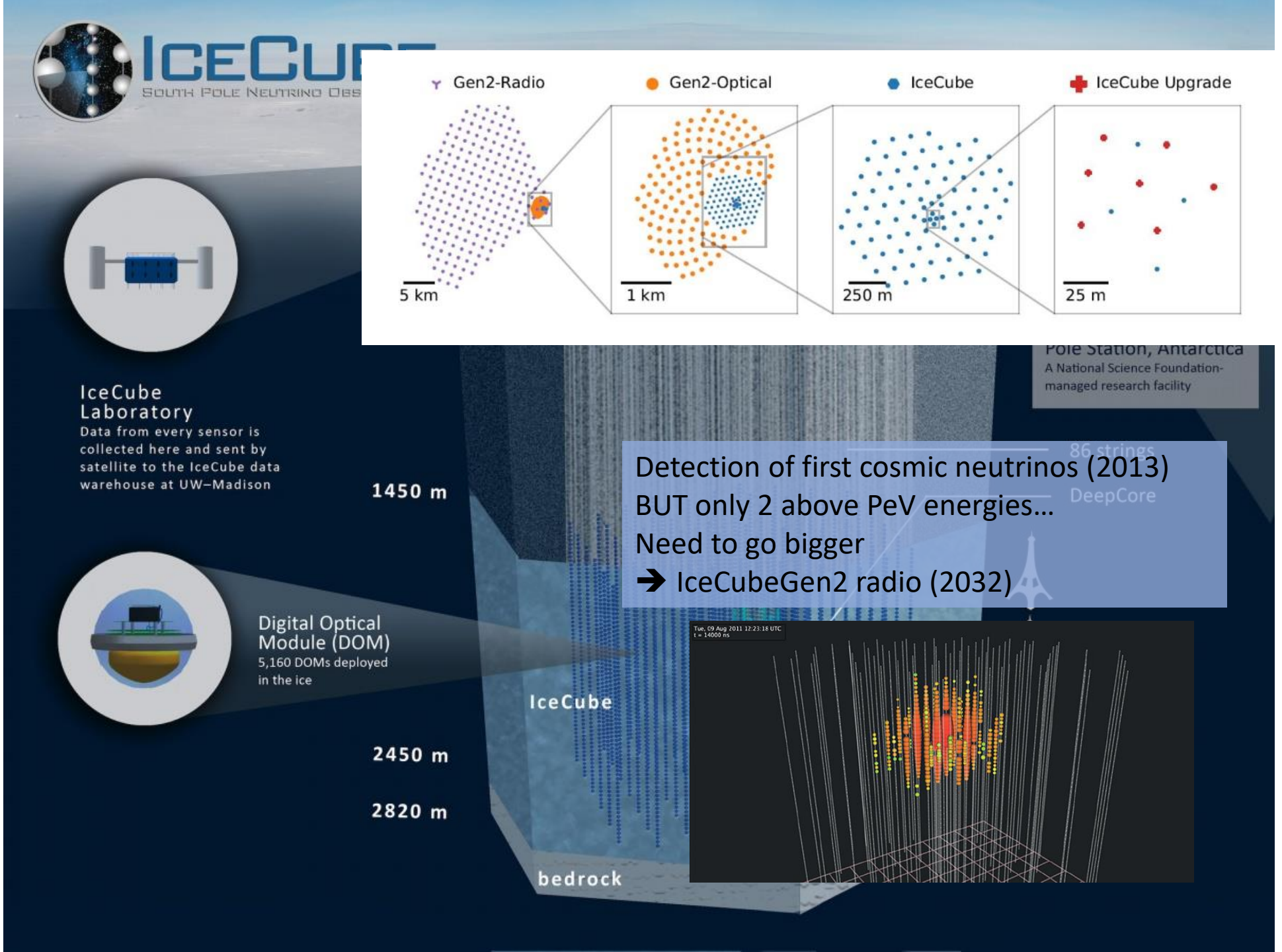

IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
Eiffel Tower
324 m



Detection of first cosmic neutrinos (2013)
BUT only 2 above PeV energies…
Need to go bigger
➔ IceCubeGen2 radio (2032)



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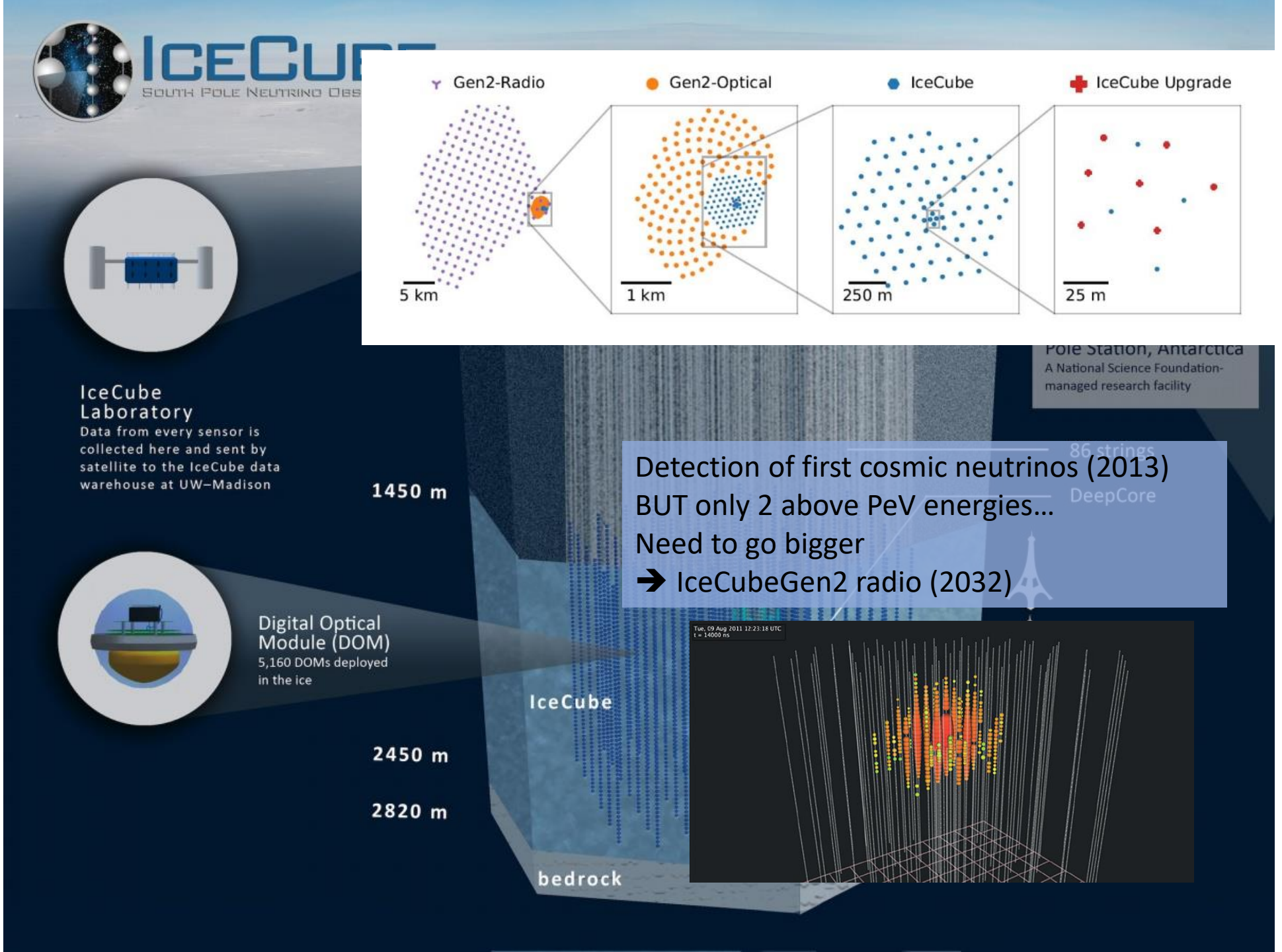

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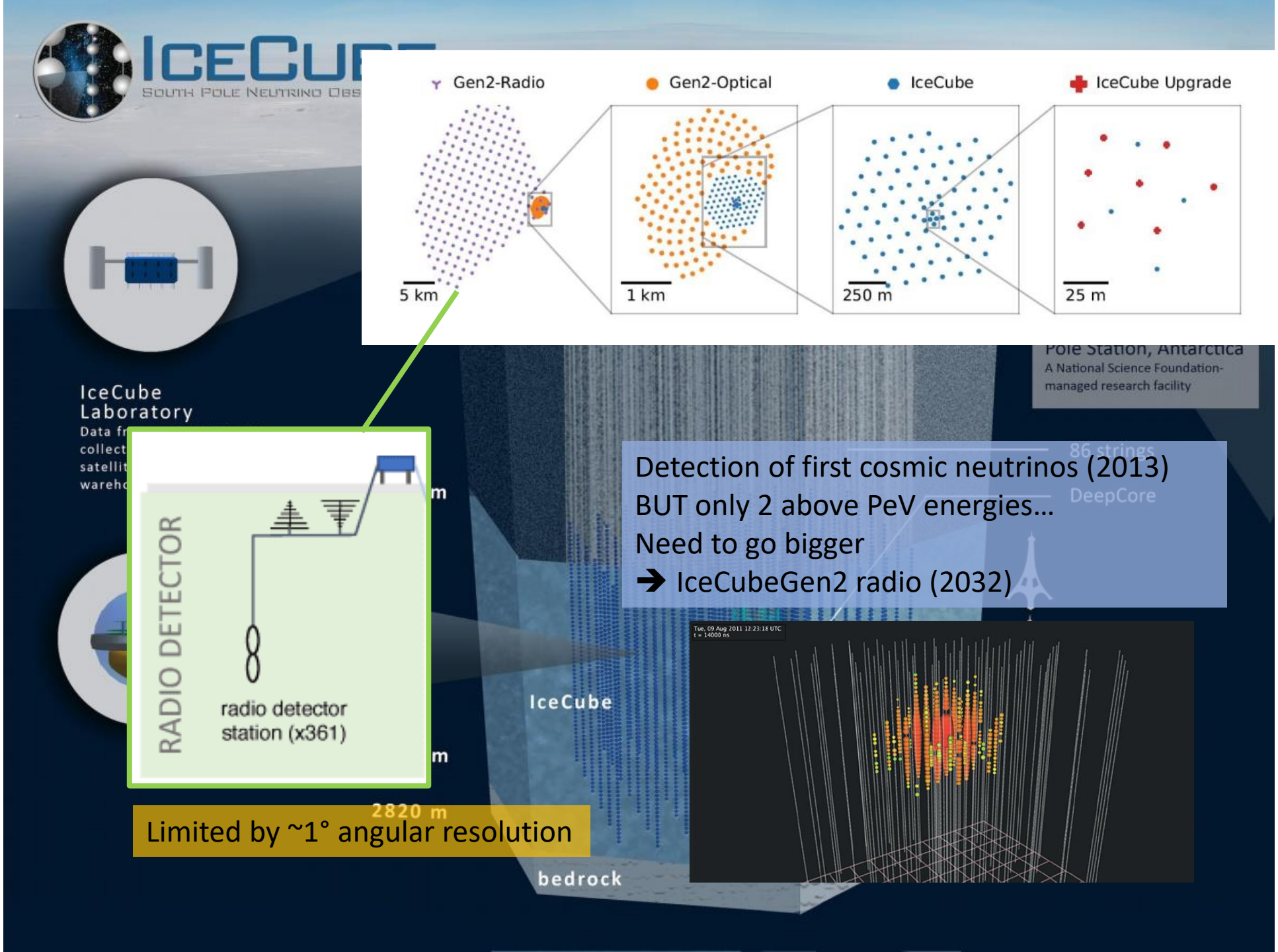
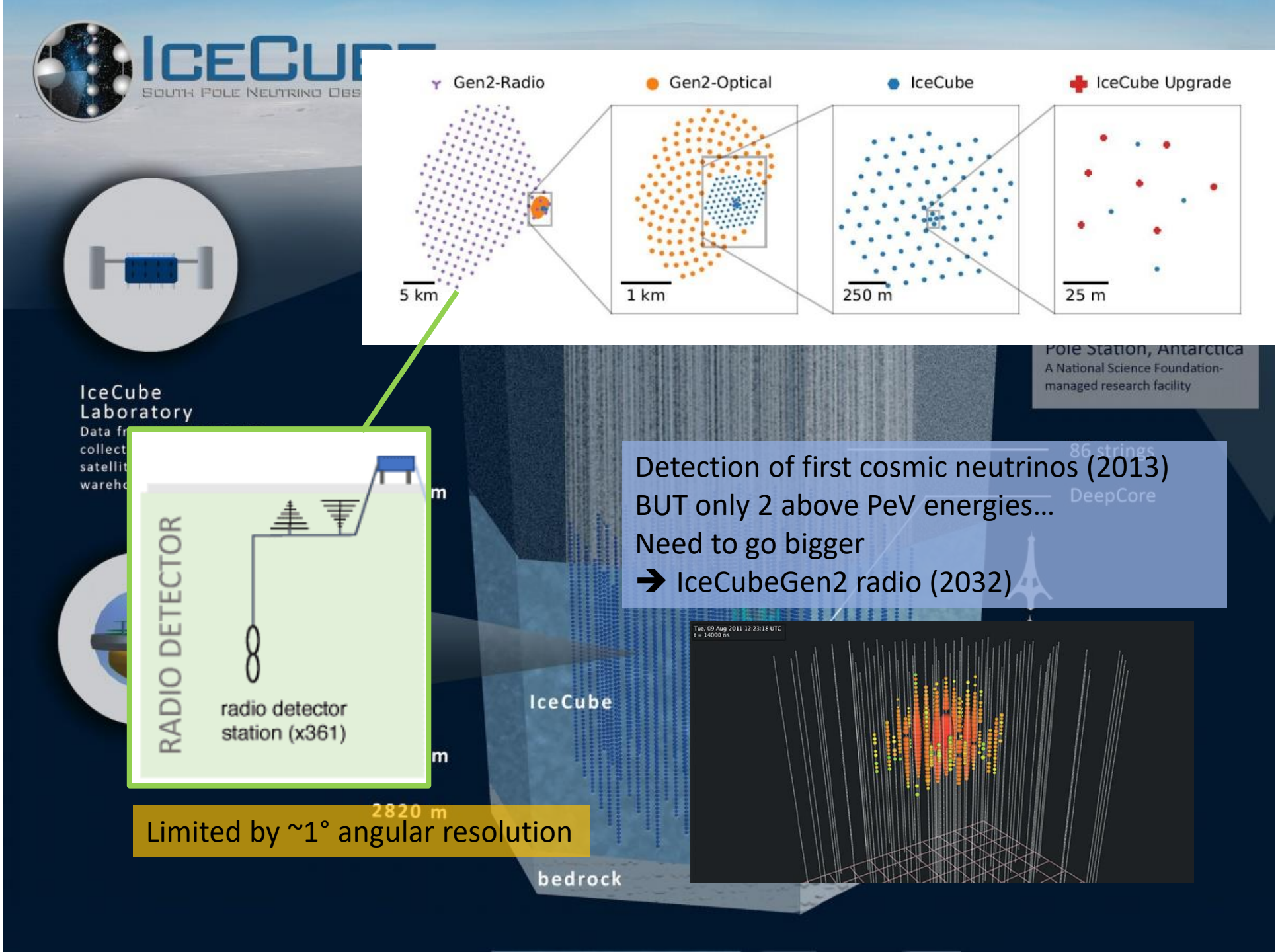

IceCube
South Pole Neutrino Obs
Gen2-Radio
Gen2-Optical
IceCube
IceCube Upgrade
5 km
1 km
250 m
25 m
IceCube Laboratory
Data fr
collect
satellit
wareh
Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
RADIO DETECTOR
radio detector station (x361)
m
m
2820 m
IceCube
bedrock
Detection of first cosmic neutrinos (2013)
BUT only 2 above PeV energies…
Need to go bigger
➔ IceCubeGen2 radio (2032)
Limited by ~1° angular resolution


IceCube
South Pole Neutrino Obs
Gen2-Radio
Gen2-Optical
IceCube
IceCube Upgrade
5 km
1 km
250 m
25 m
IceCube Laboratory
Data fr
collect
satellit
wareh
Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
RADIO DETECTOR
radio detector station (x361)
m
m
2820 m
IceCube
bedrock
Detection of first cosmic neutrinos (2013)
BUT only 2 above PeV energies…
Need to go bigger
➔ IceCubeGen2 radio (2032)
Limited by ~1° angular resolution