Radio Detection of UHE neutrinos

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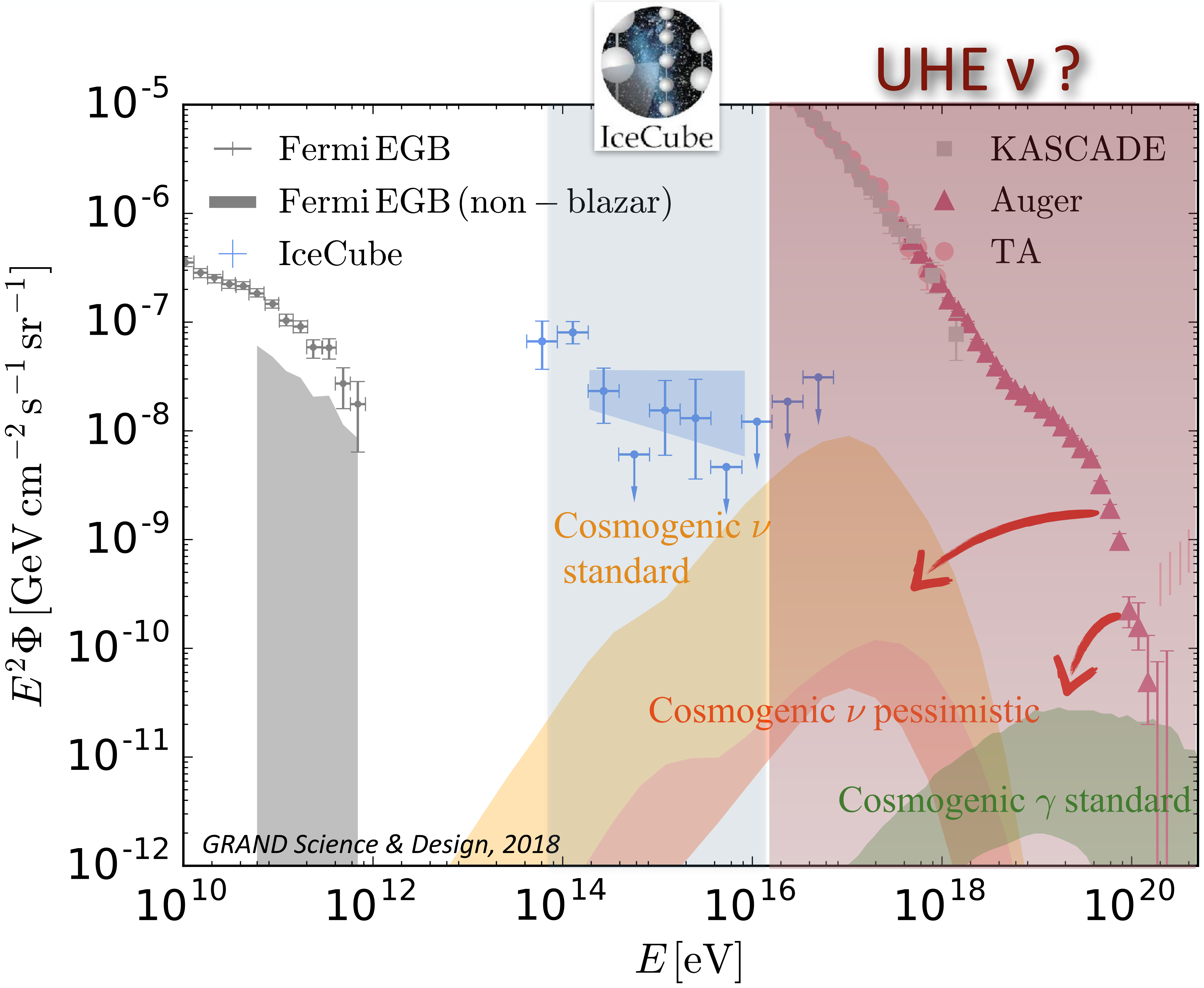
Institut d'Astrophysique de Paris - CNRS - Sorbonne Université
Vrije Universiteit Brussels

Detecting ultra-high-energy neutrinos – lessons learnt from experiments



A recent endeavor

- UHE neutrino search: ancillary science case of UHECR & HE neutrino experiments
- Recently: dedicated instruments ARIANNA, ARA, ANITA

Summary of recent progress

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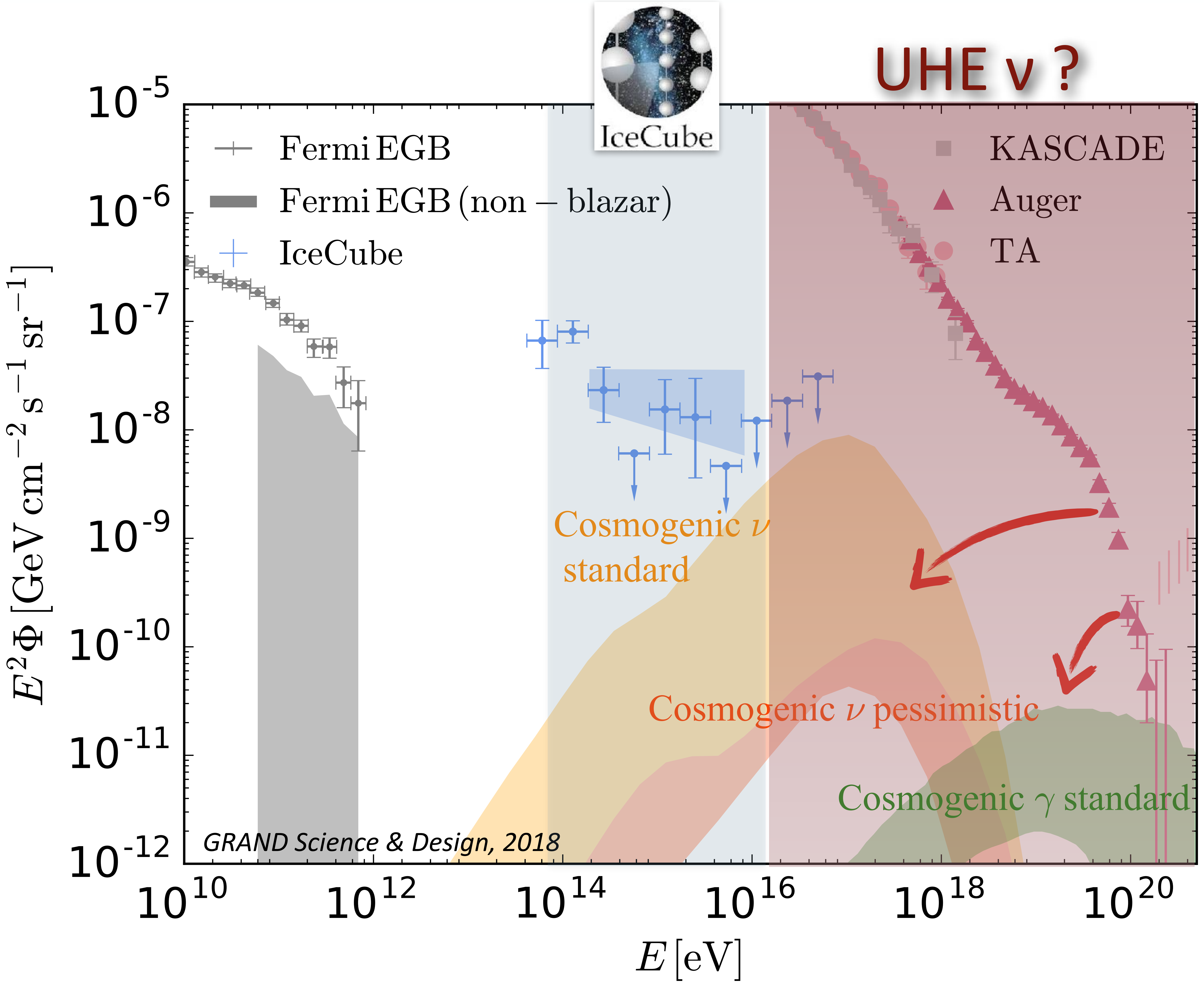

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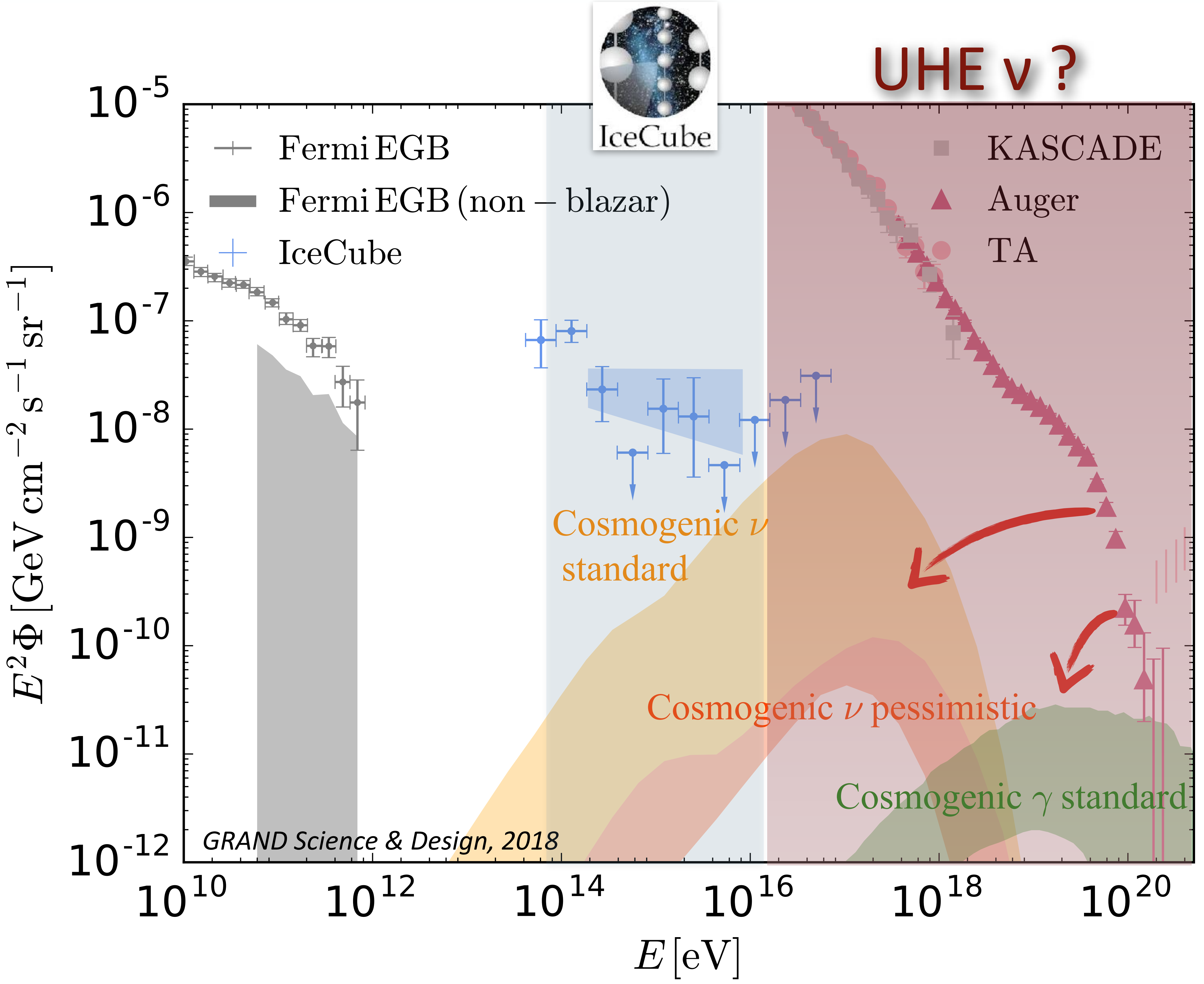

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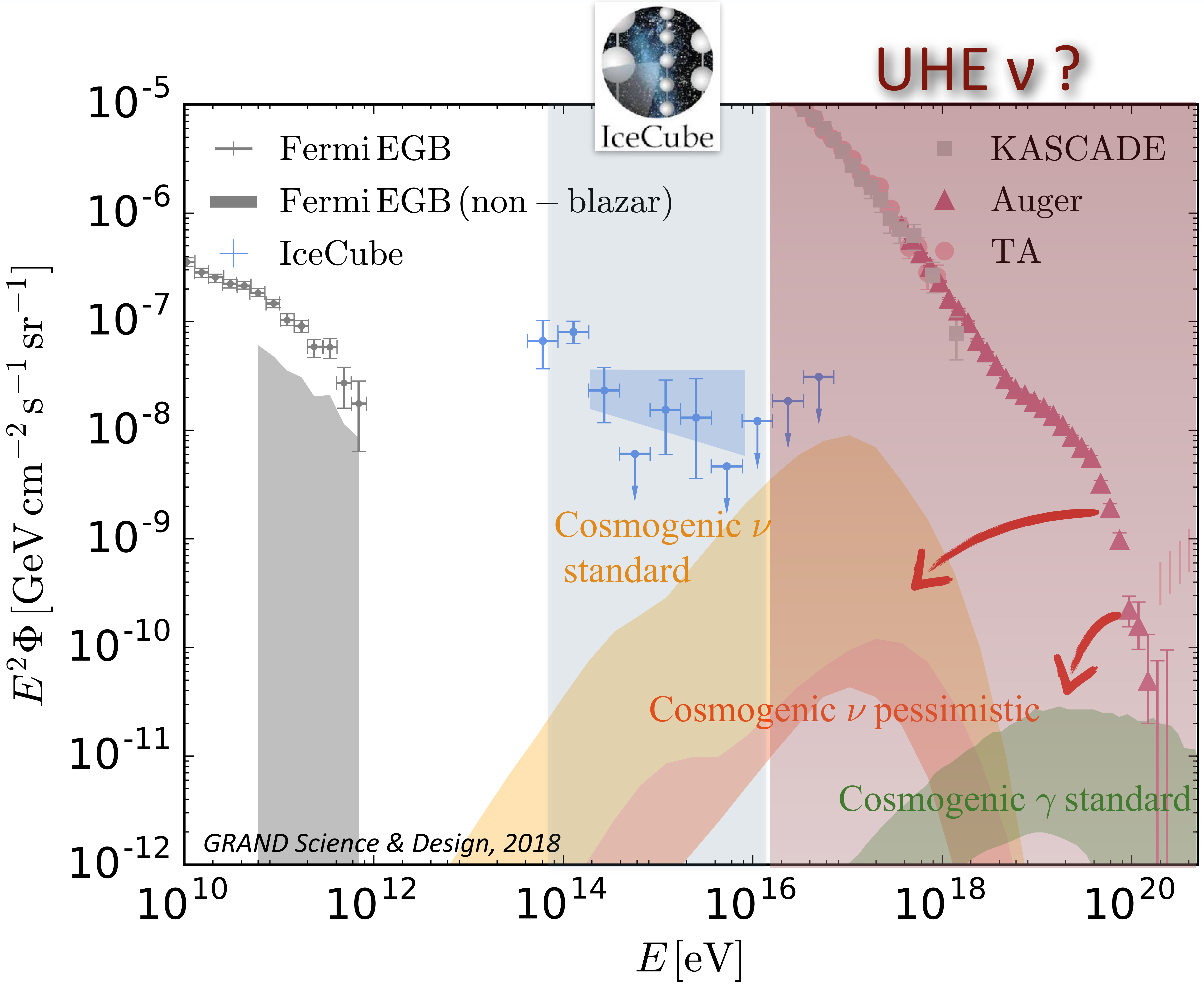

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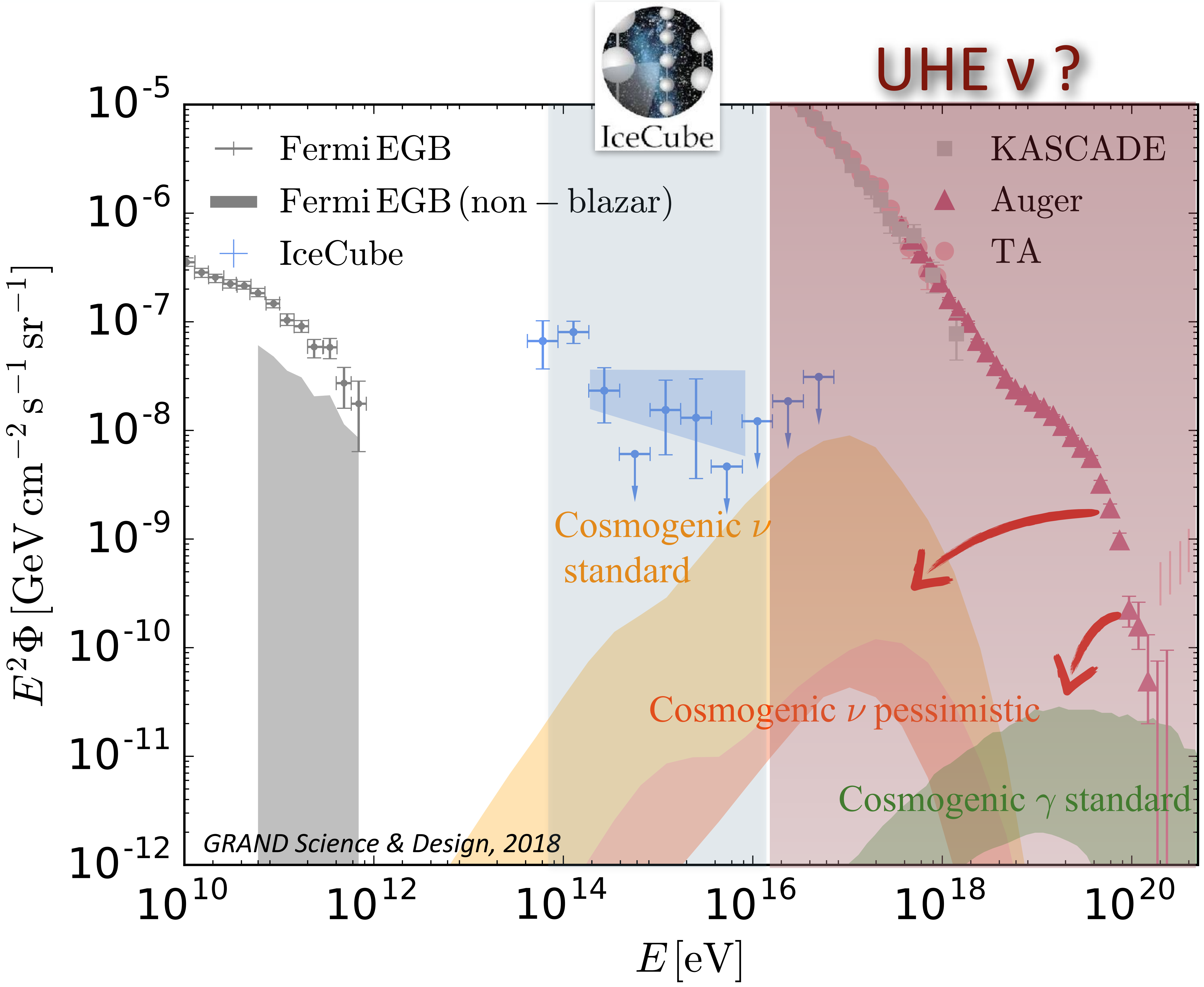

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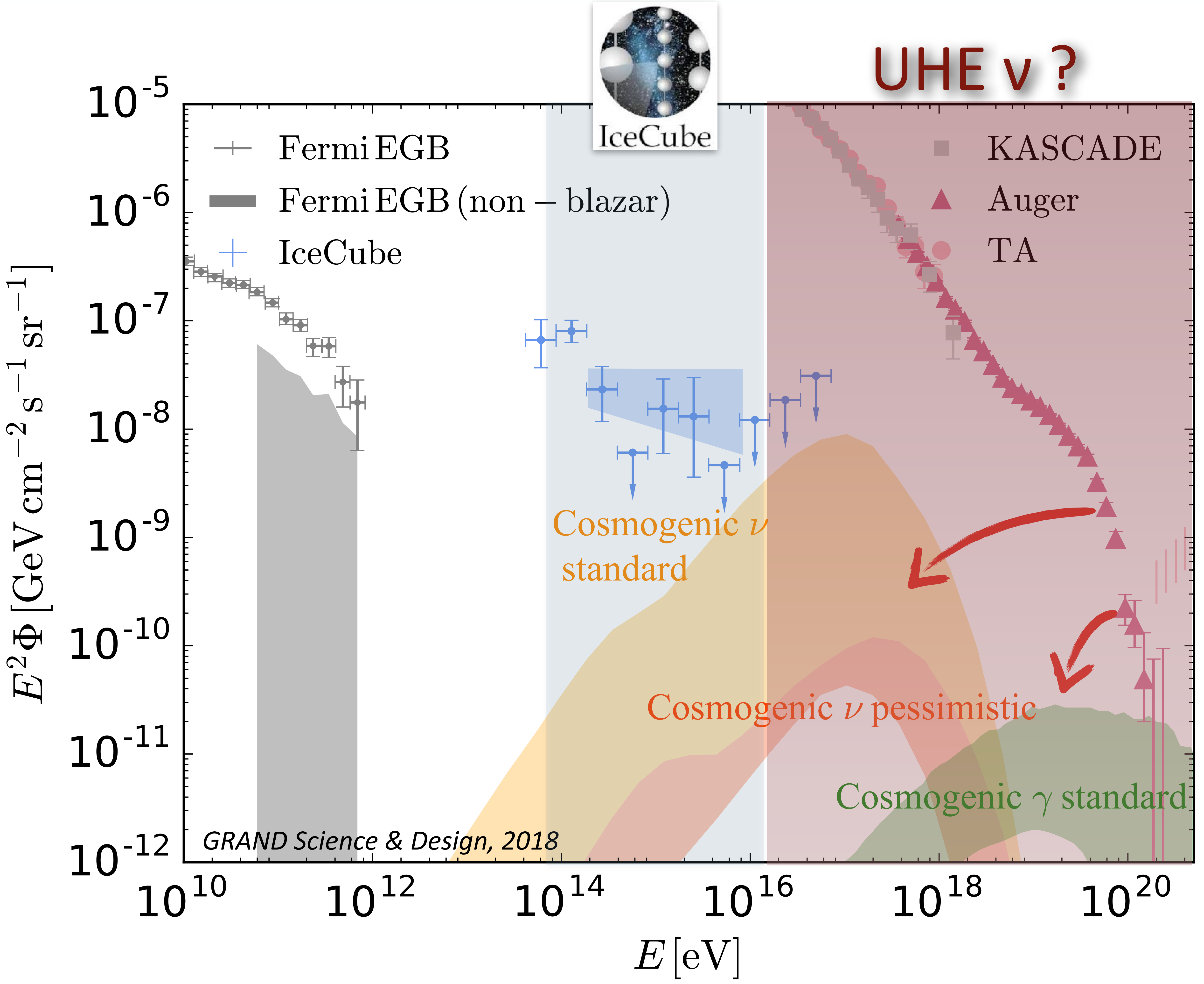

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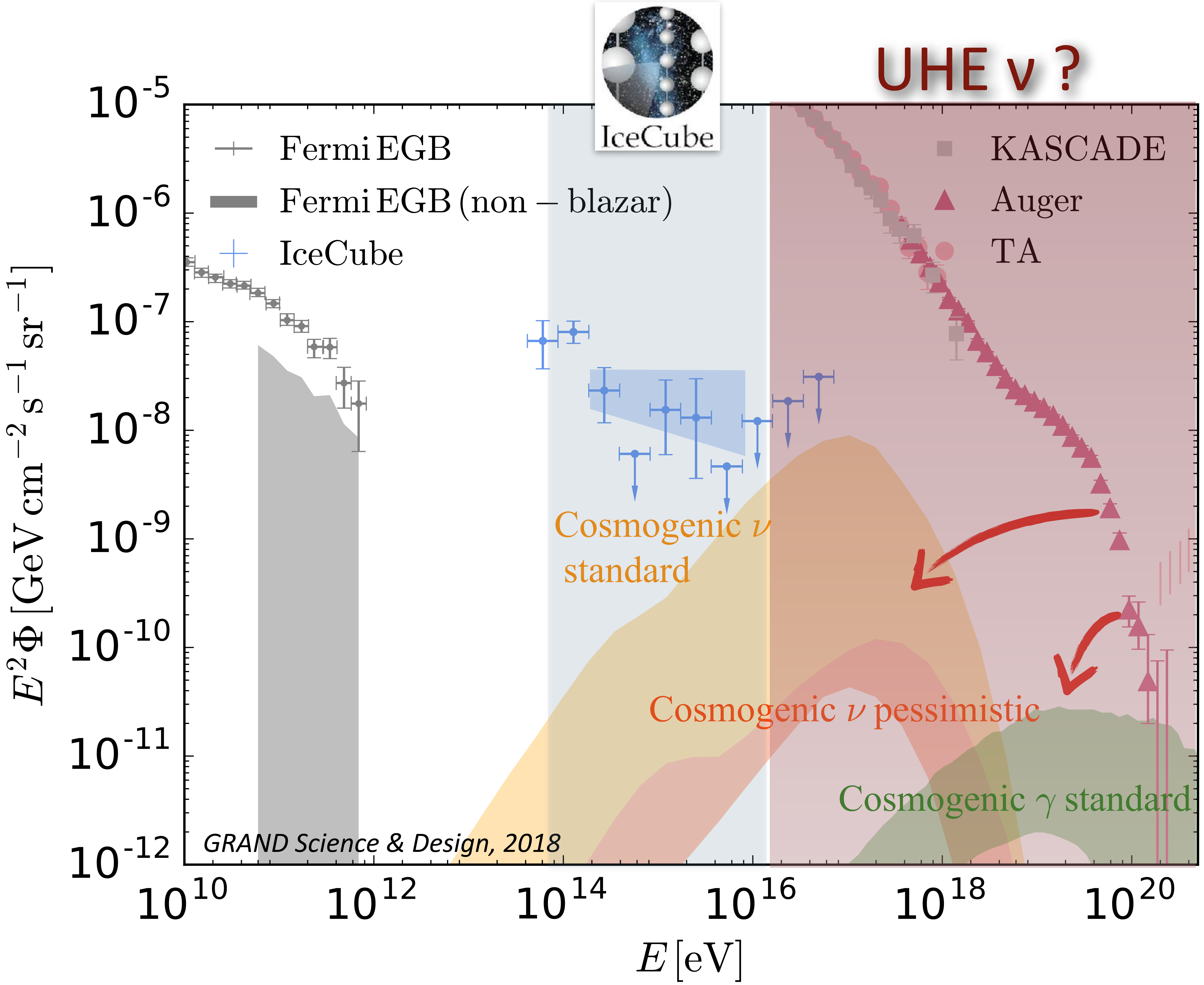

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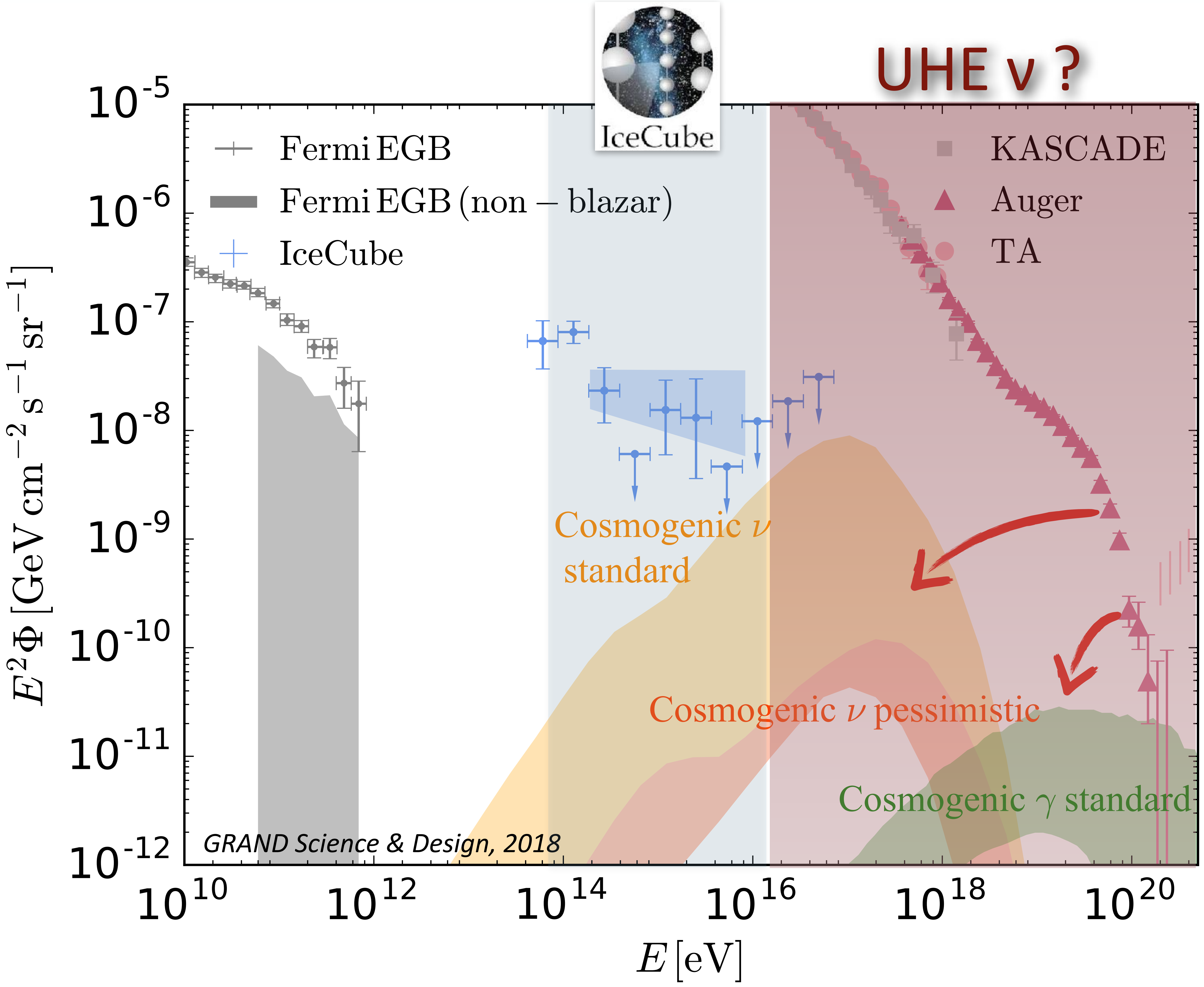

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4. Boom in MM + time domain astronomy: require specific strategies of observations & instrumental performances

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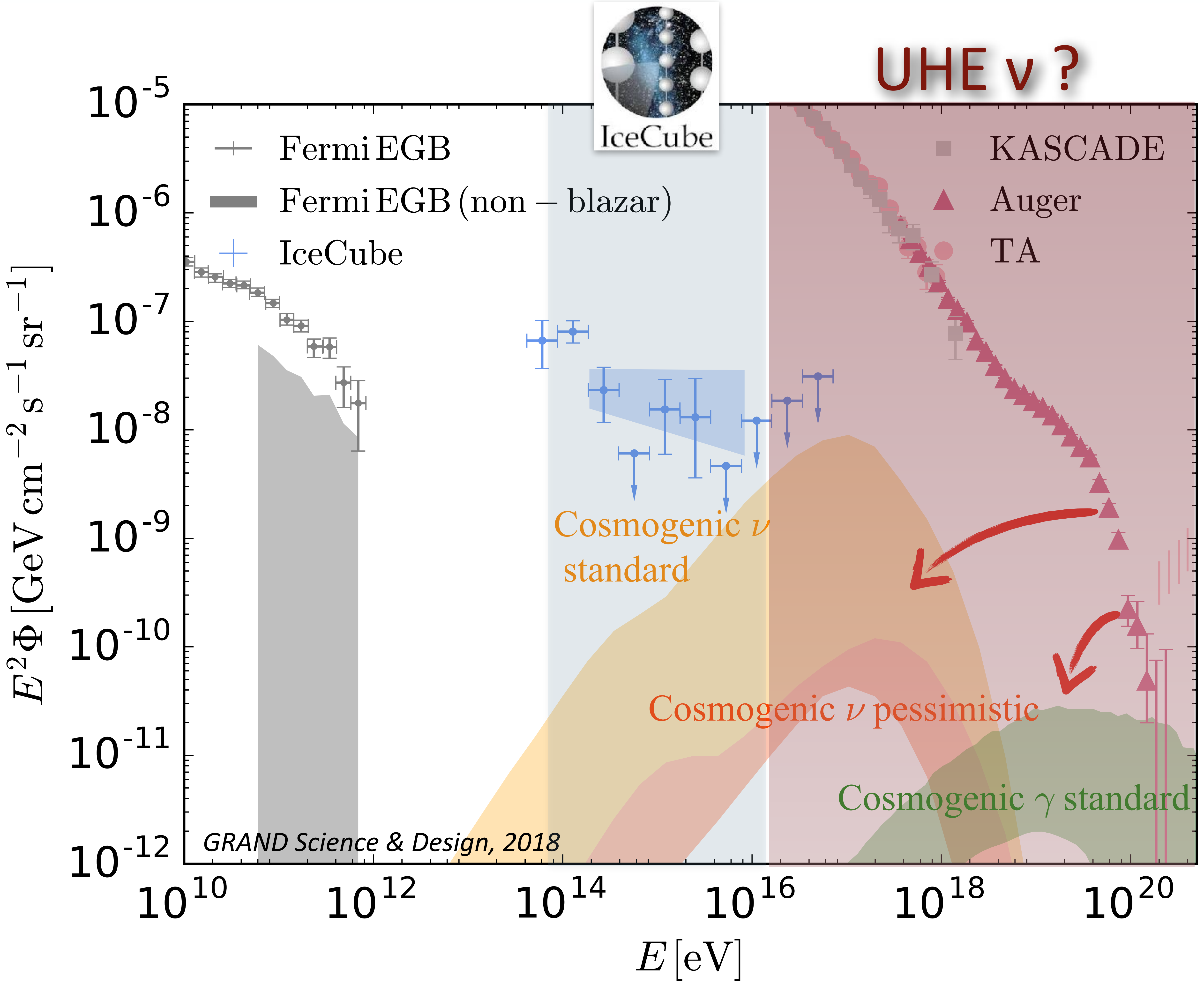

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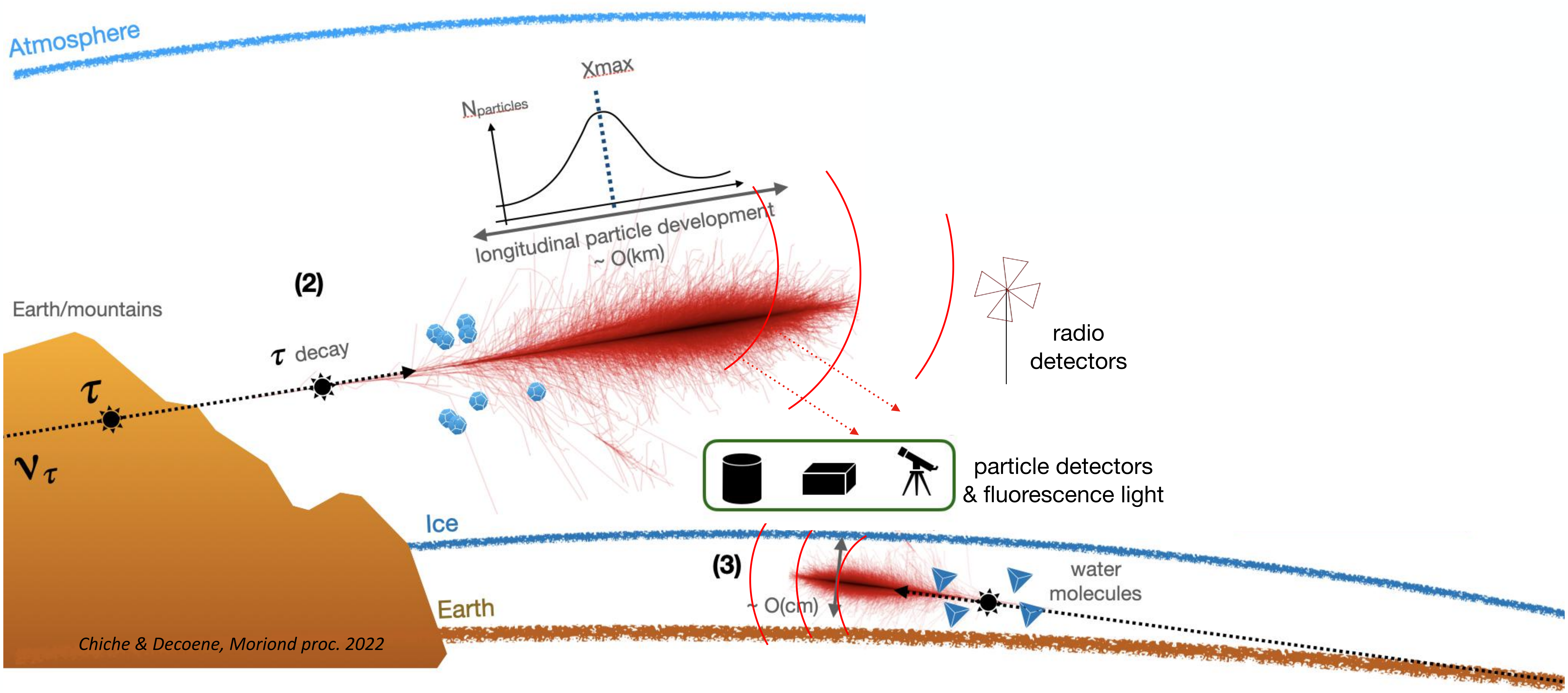
4.E st

lesson from MM: develop follow-up tools and integrate in a MM framework, enabling rapid response and alerts

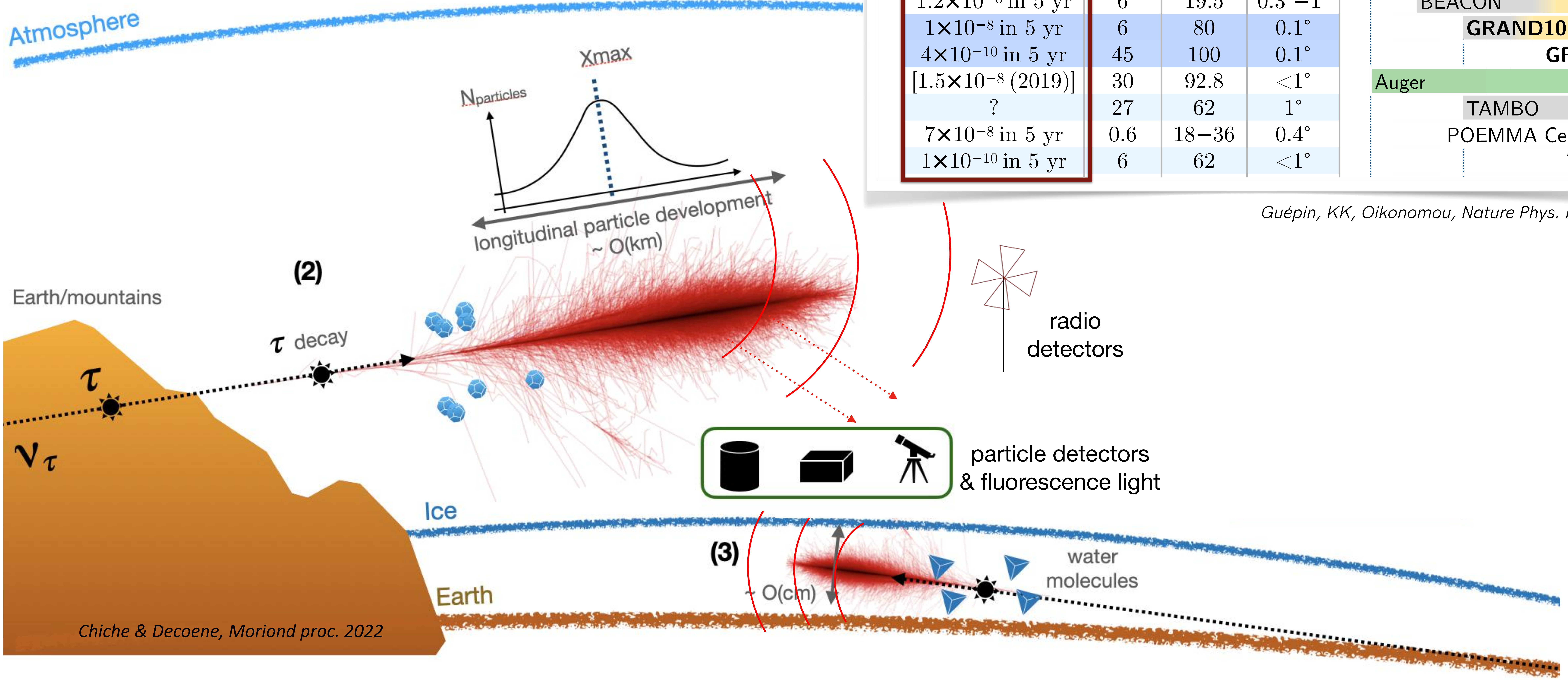
Experimental perspectives



Experimental perspectives

Diff. sens. lim. in GeV $cm^{-2}\,s^{-1}\,sr^{-1}$	iFoV in sky %	dFoV in sky %	ang. res.	2021 – 2025 – >2030
4.2×10^{-8} in 30 d	6	19	$<2.8°$	PUEO
3.6×10^{-9} (2030)	35	20	5°	ARA
1×10^{-8} in 5 yr	30	35	2°×10°	RNO-G
8×10^{-9} in 5 yr	50	>50	2.9–3.8°	ARIANNA-200
3×10^{-10} in 5 yr	50	>50	?	RET-N
4×10^{-10} in 5 yr	43	43	2°×10°	IceCube-Gen2 Radio
1.2×10^{-8} in 5 yr	6	19.5	0.3°–1°	BEACON
1×10^{-8} in 5 yr	6	80	0.1°	**GRAND10k**
4×10^{-10} in 5 yr	45	100	0.1°	**GRAND**
[1.5×10^{-8} (2019)]	30	92.8	<1°	Auger
?	27	62	1°	TAMBO
7×10^{-8} in 5 yr	0.6	18–36	0.4°	POEMMA Cerenkov
1×10^{-10} in 5 yr	6	62	<1°	Trinity

Guépin, KK, Oikonomou, Nature Phys. Rev. 2022



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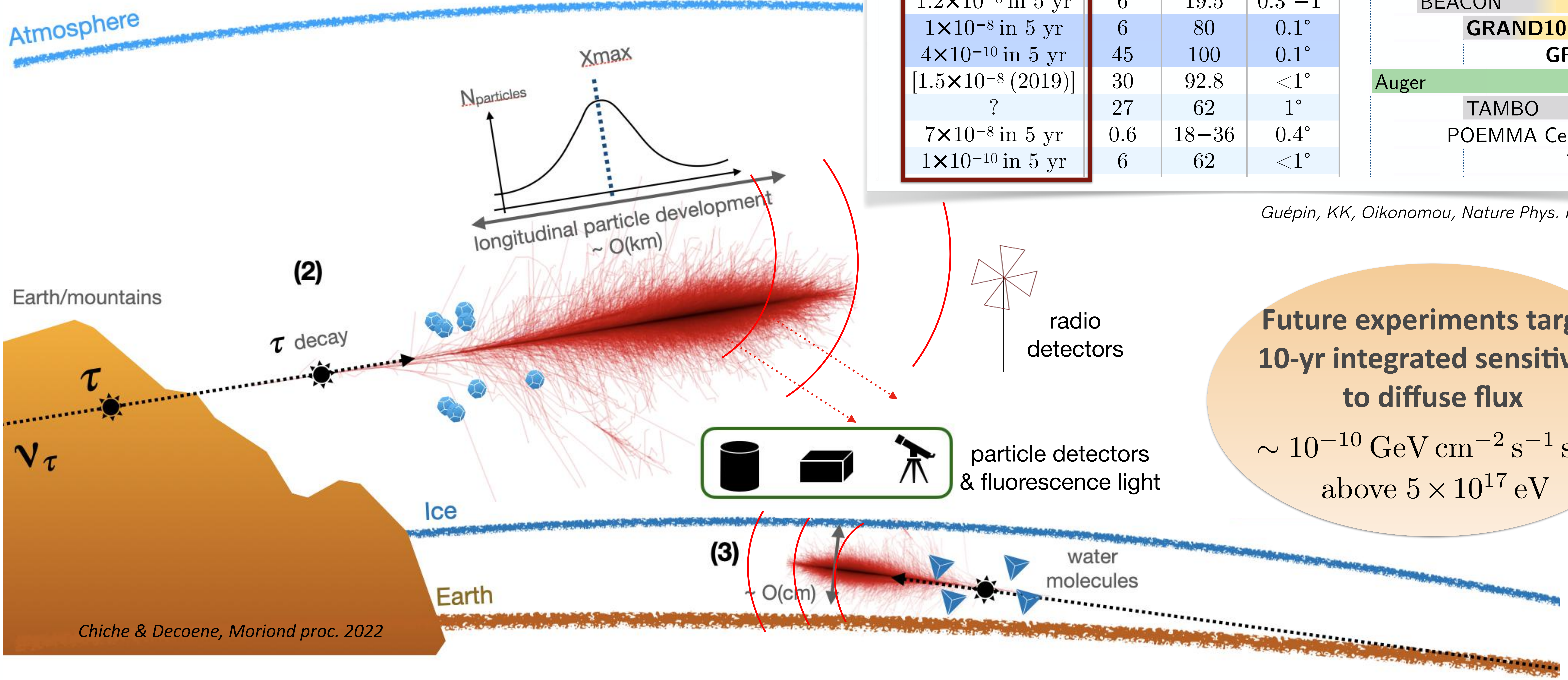


Chiche & Decoene, Moriond proc. 2022

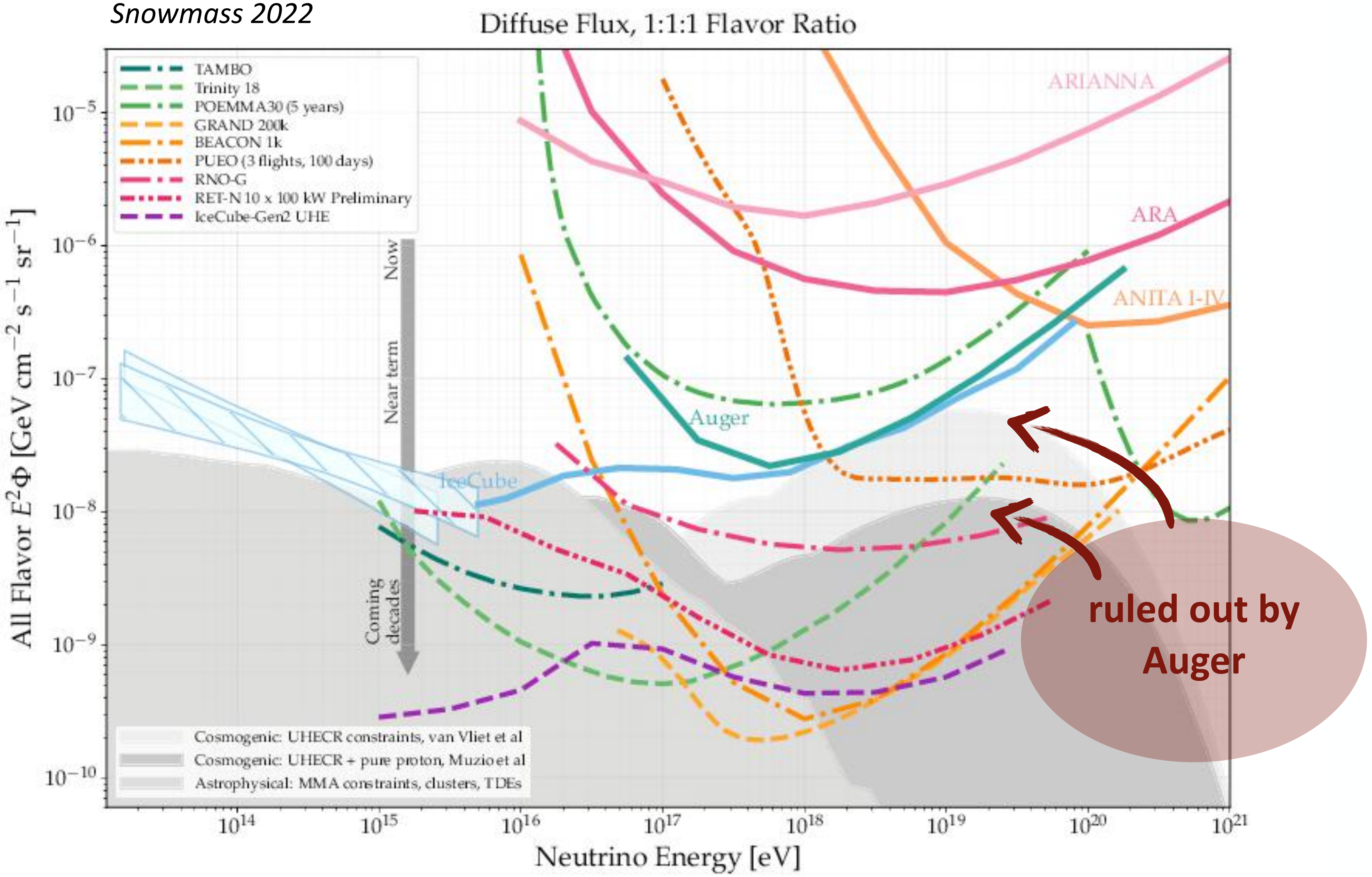
Future experiments target 10-yr integrated sensitivity to diffuse flux

$\sim 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$

above 5×10^{17} eV

Diffuse UHE neutrino fluxes: readjusting our experimental perspectives

Snowmass 2022



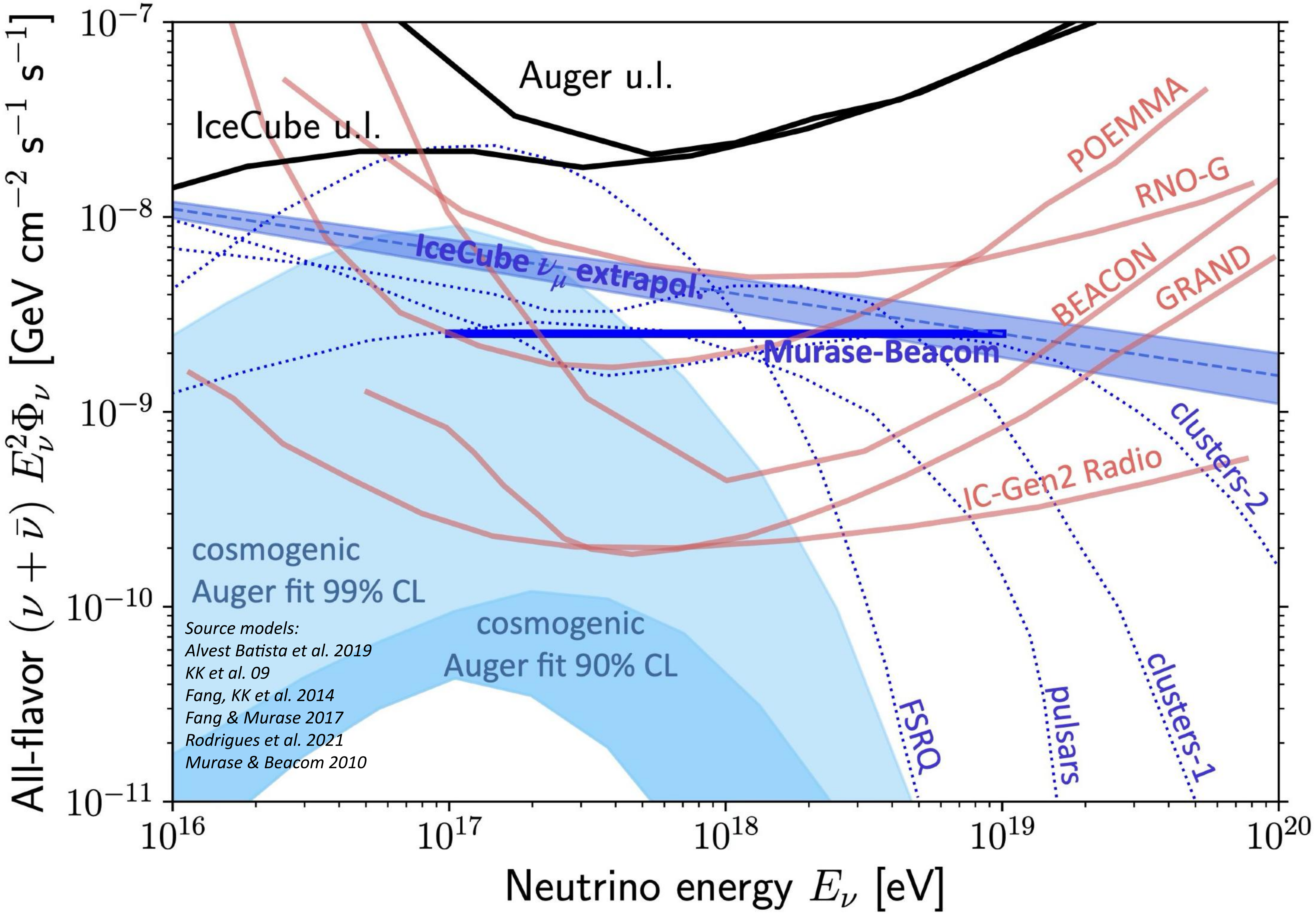
- Avoid presenting ruled out cosmogenic fluxes
- Auger constrains cosmogenic fluxes to below

$$\Phi_{\rm cosmo,max} \sim 10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\;,\;\; \text{at}\;\; 99\%\ \text{C.L.}$$

- Promising astrophysical fluxes exist

Diffuse UHE neutrino fluxes: readjusting our experimental perspectives

KK et al. in prep.



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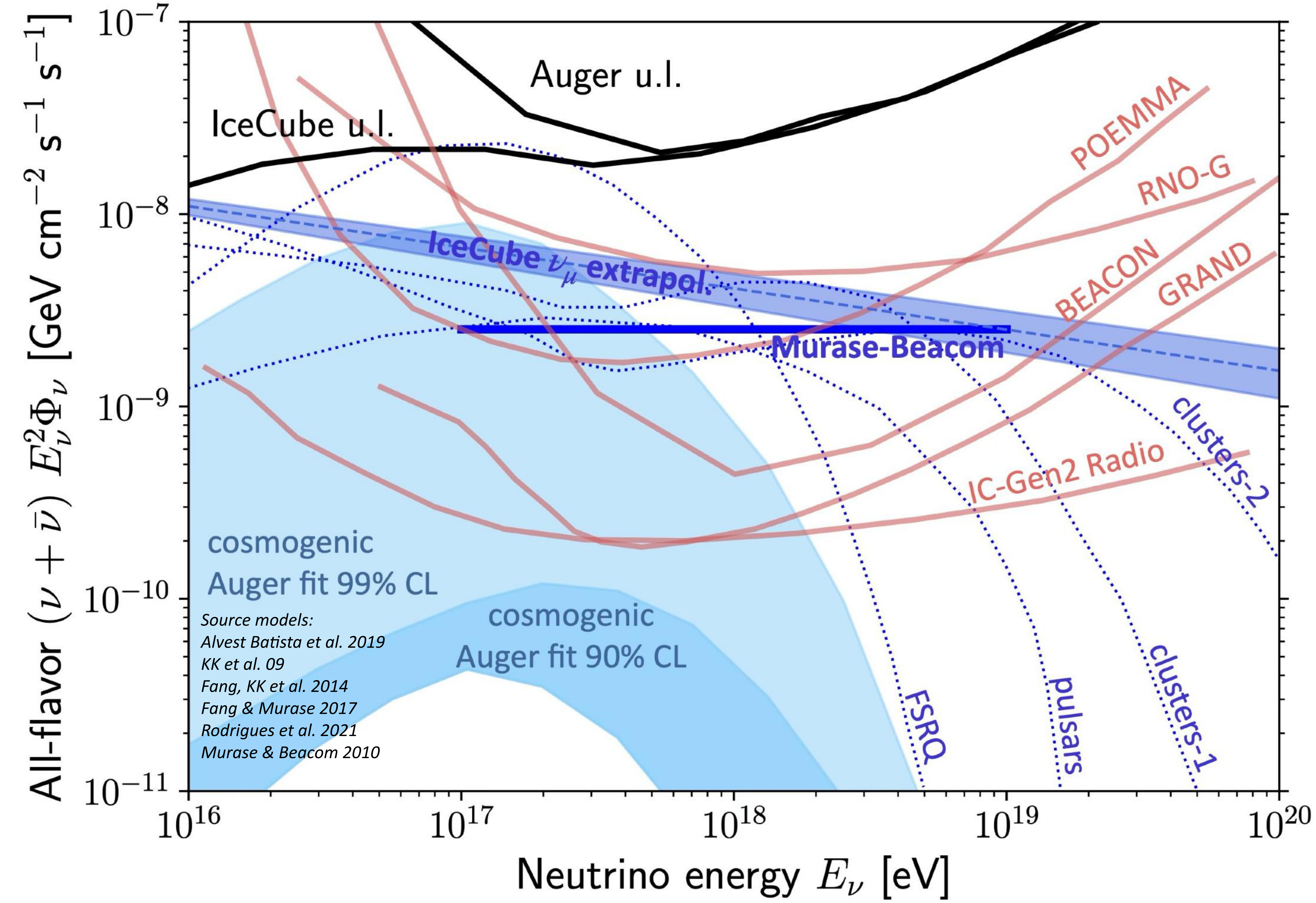

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- Promising astrophysical fluxes exist

- Which new "Waxman-Bahcall flux" to aim for at UHE?

IceCube extrapolation

$$E_\nu^2\Phi_\nu \sim 10^{-8}\,(E_\nu/10^{16}\,{\rm eV})^{-2.37}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Murase-Beacom (2010)

$$E_\nu^2\Phi_\nu \lesssim 8.4\times10^{-10} f_z (A/56)^{-0.21}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

effective (energy-loss) photodisintegration optical depth < 1
here: source evolution factor f_z = 3

Detector reaching these limits in $10^{17\text{-}19}$ eV can strongly constrain source models.

Whether they can do UHE neutrino astronomy requires to assess additional performances.

What astrophysical sources to aim for in the MM era?

KK et al. in prep.

Short bursts: stay in the instantaneous field of view (FoV) of the instrument (~30 min - 1 day)
Compare source fluences with instantaneous fluence sensitivities

Long bursts: any longer transients
Compare source fluences with daily averaged fluence sensitivities

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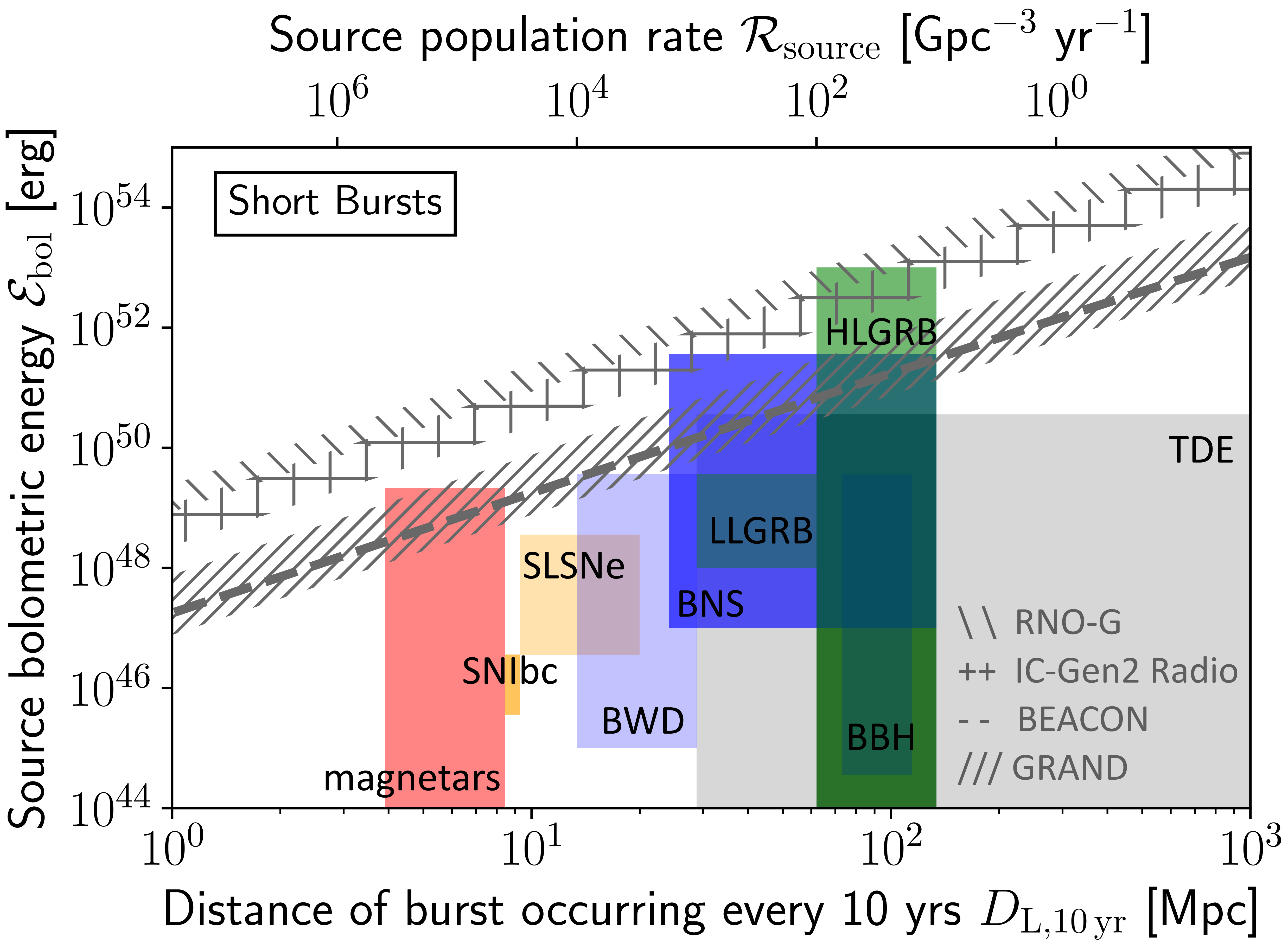

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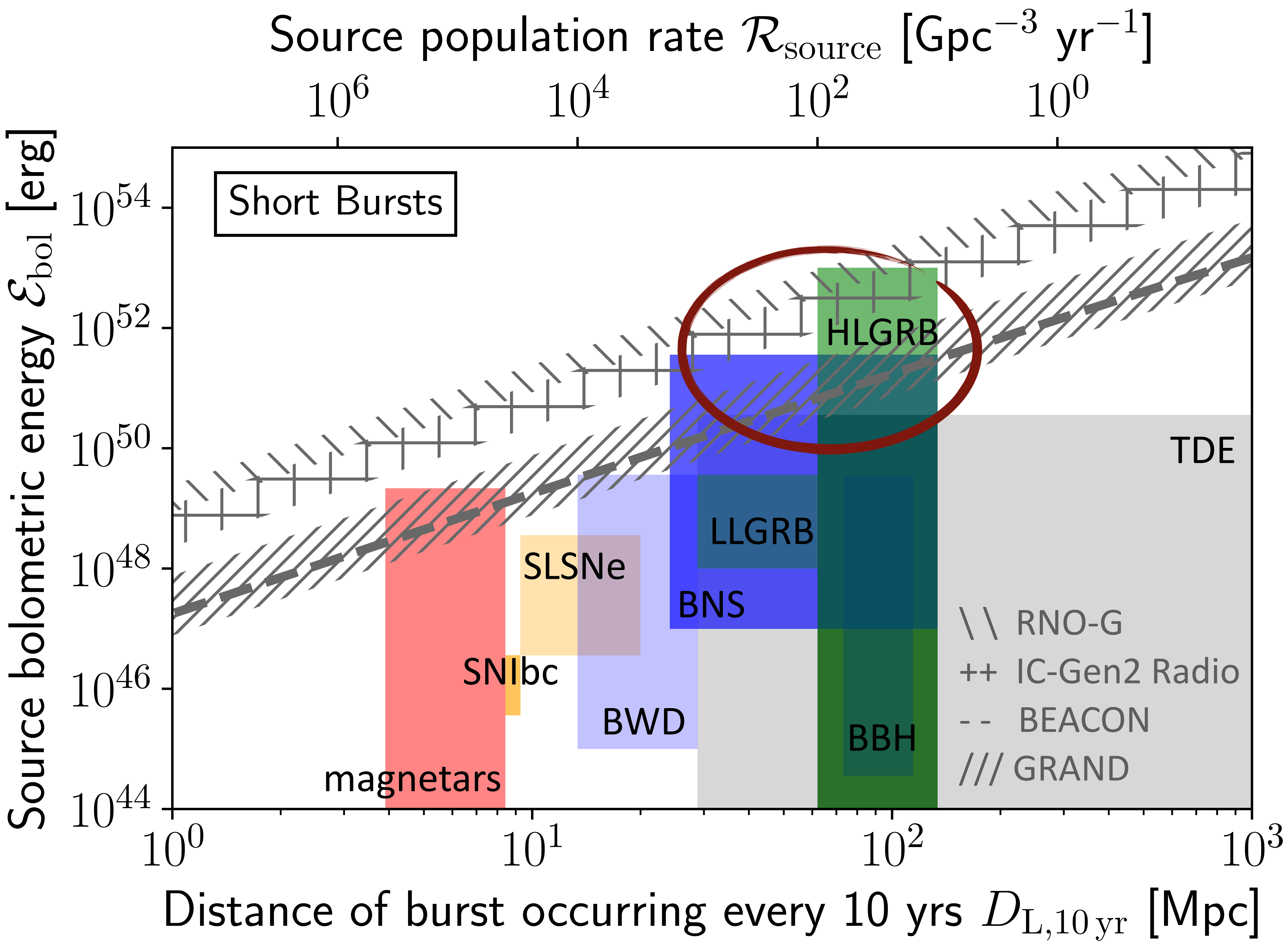

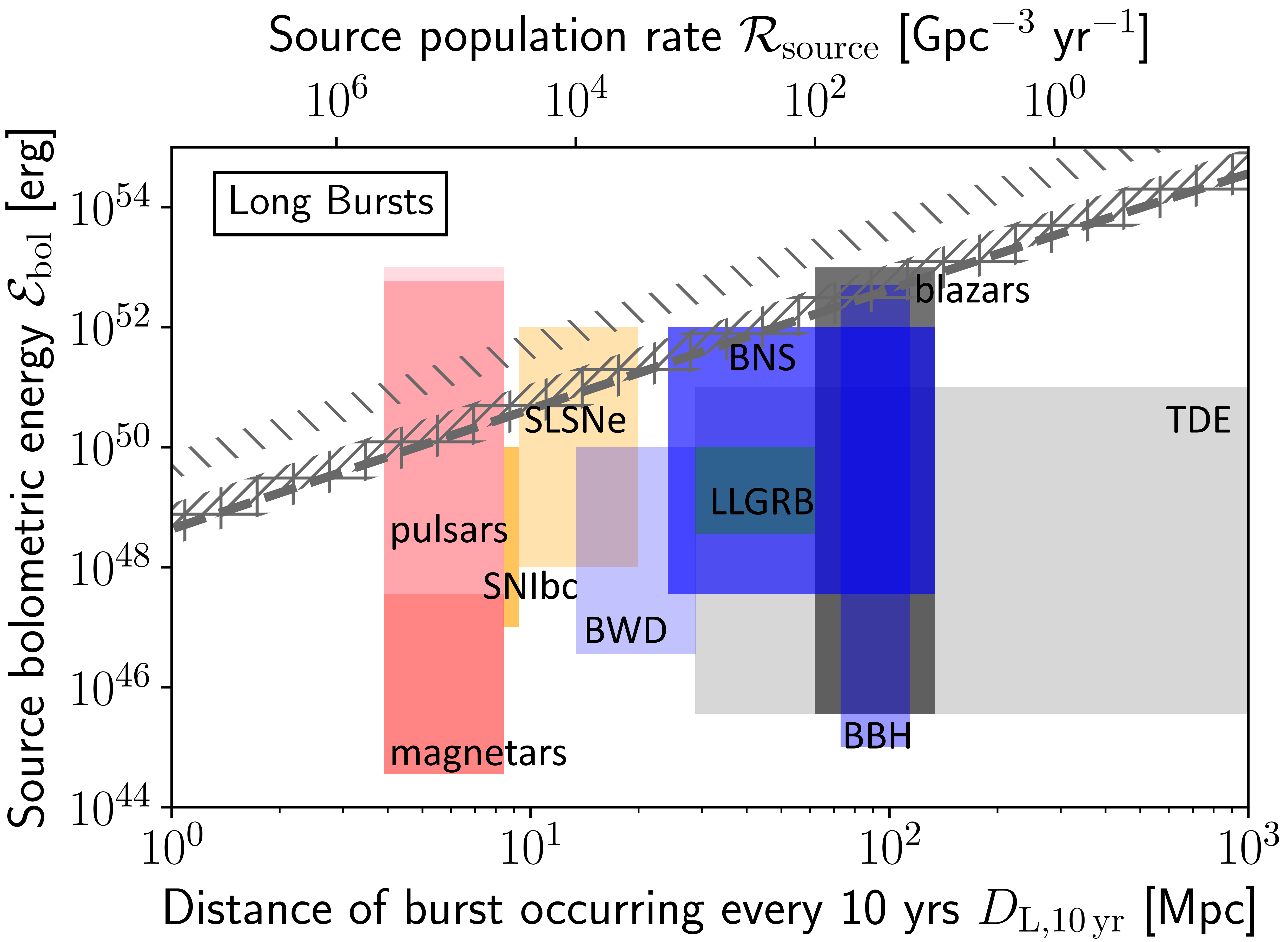

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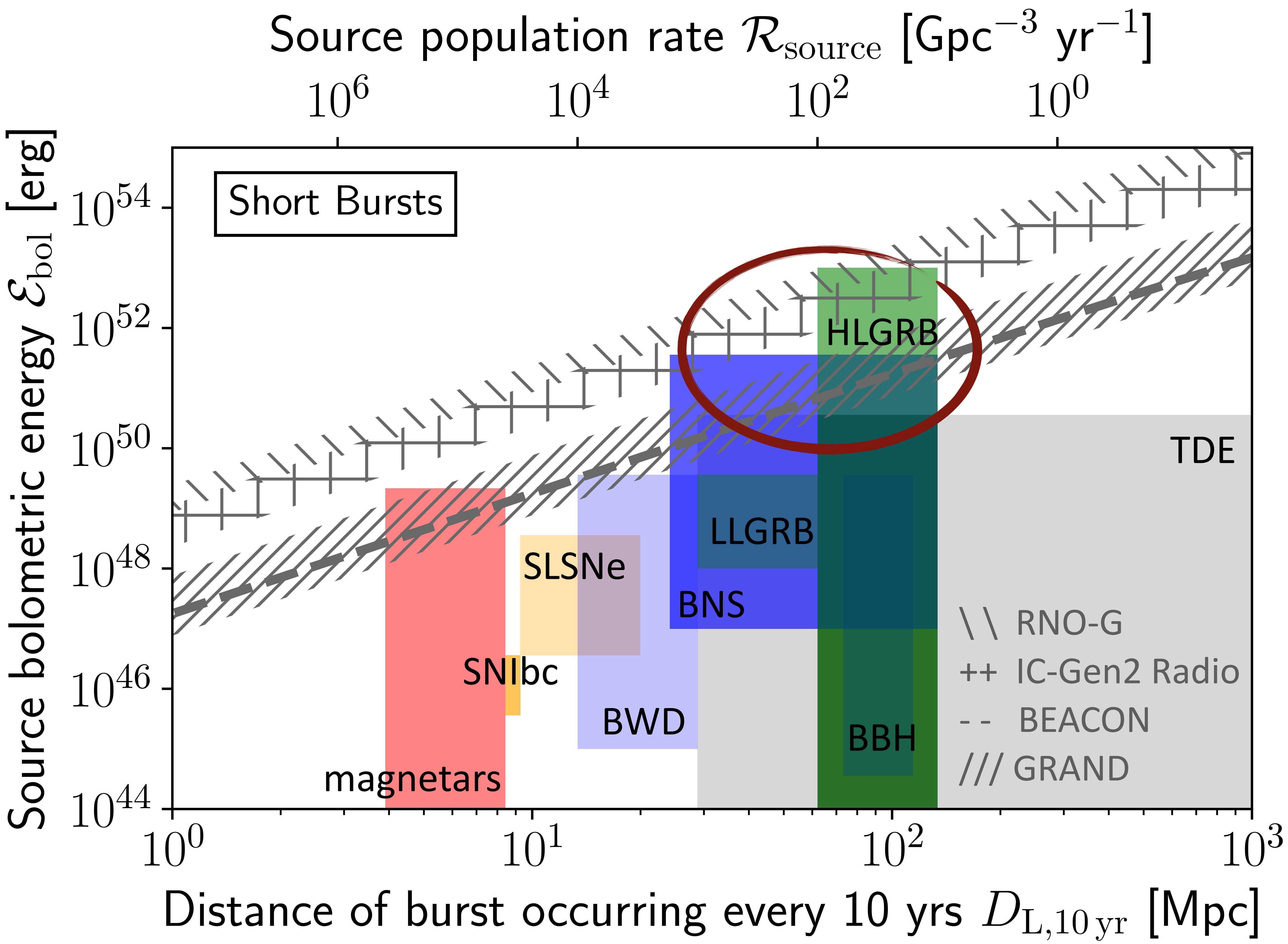

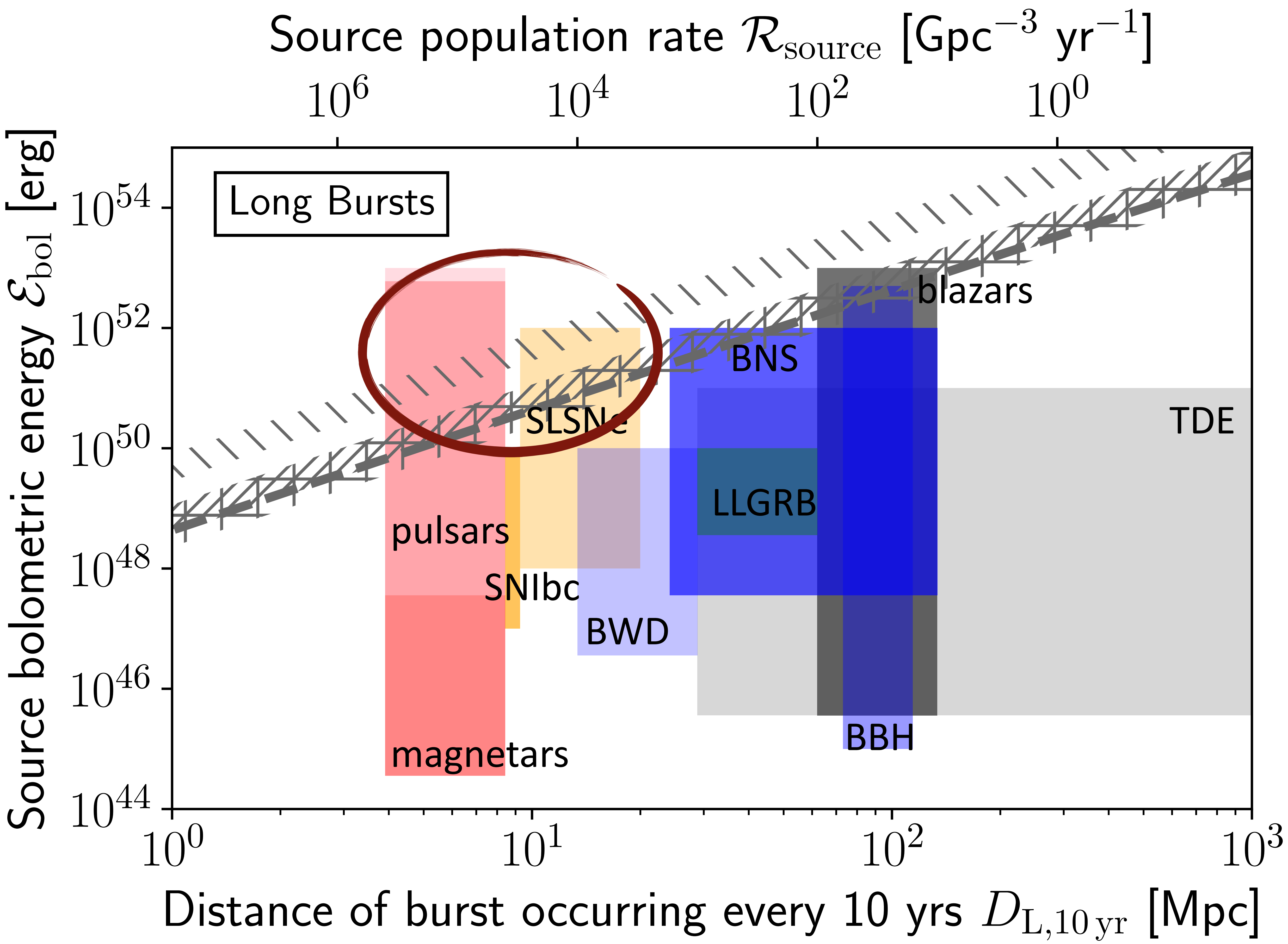

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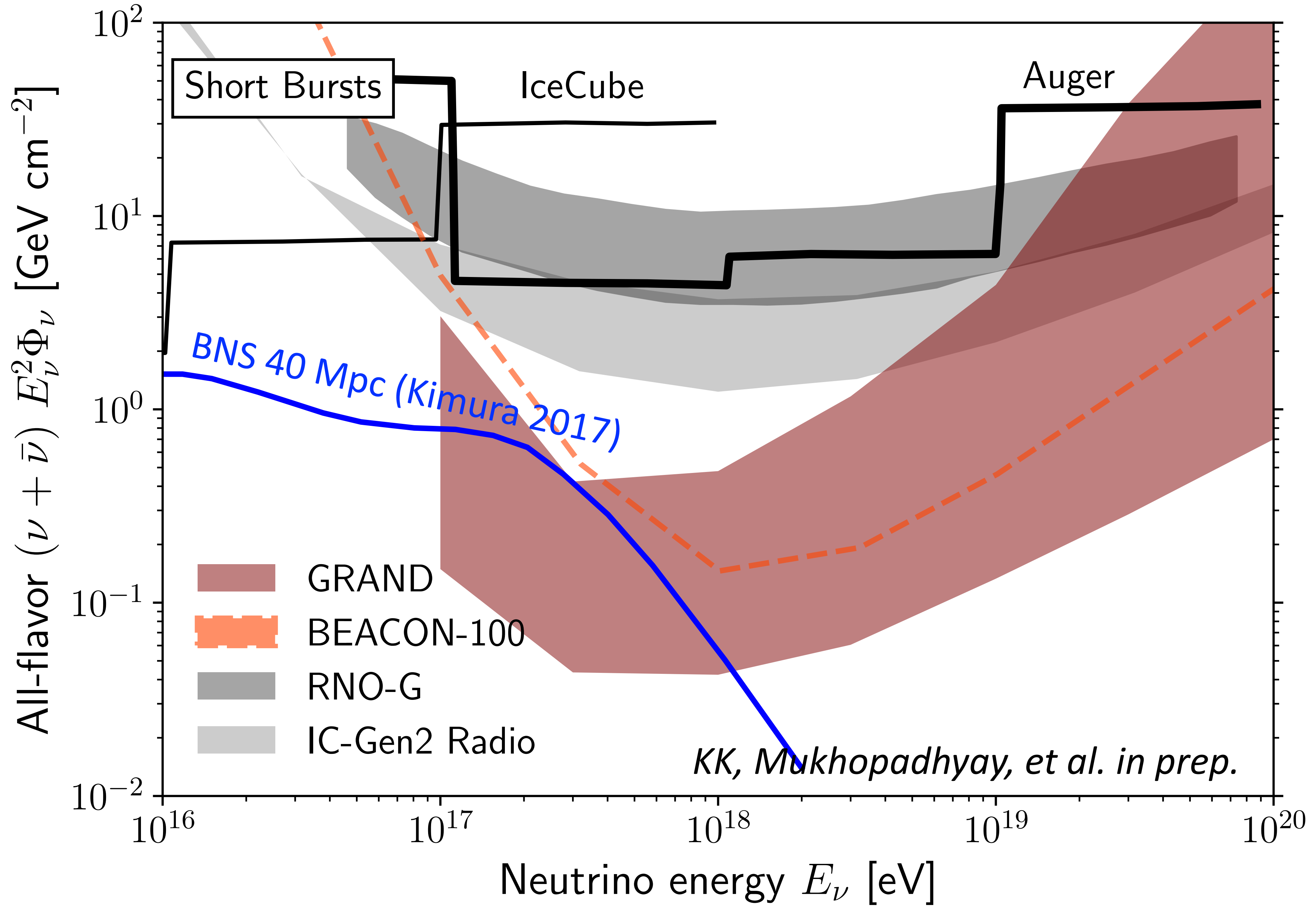
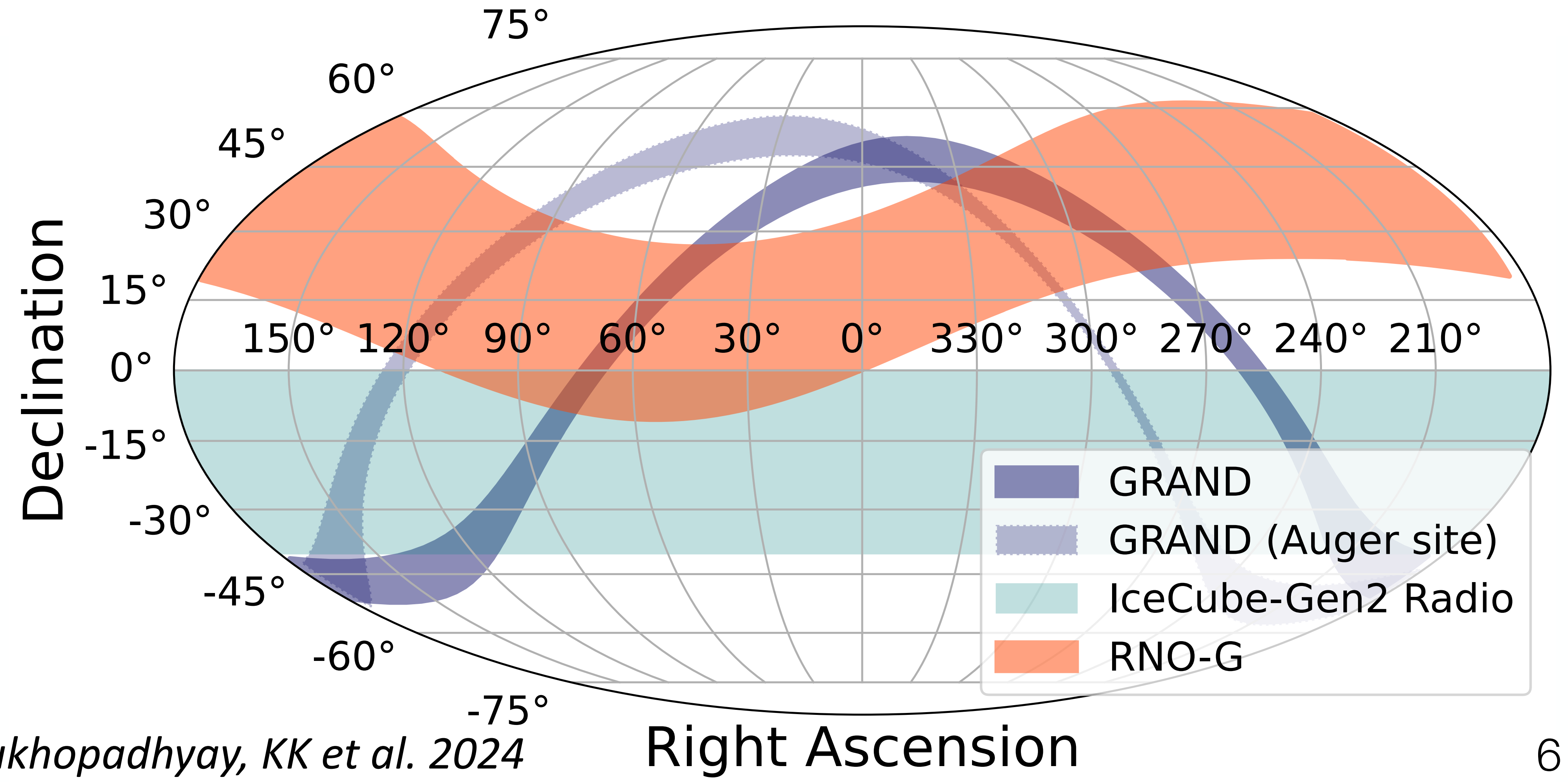
Detectable: Local Group & nearby galaxies

Astronomical observation strategies: Wide & Shallow vs. Deep & Narrow





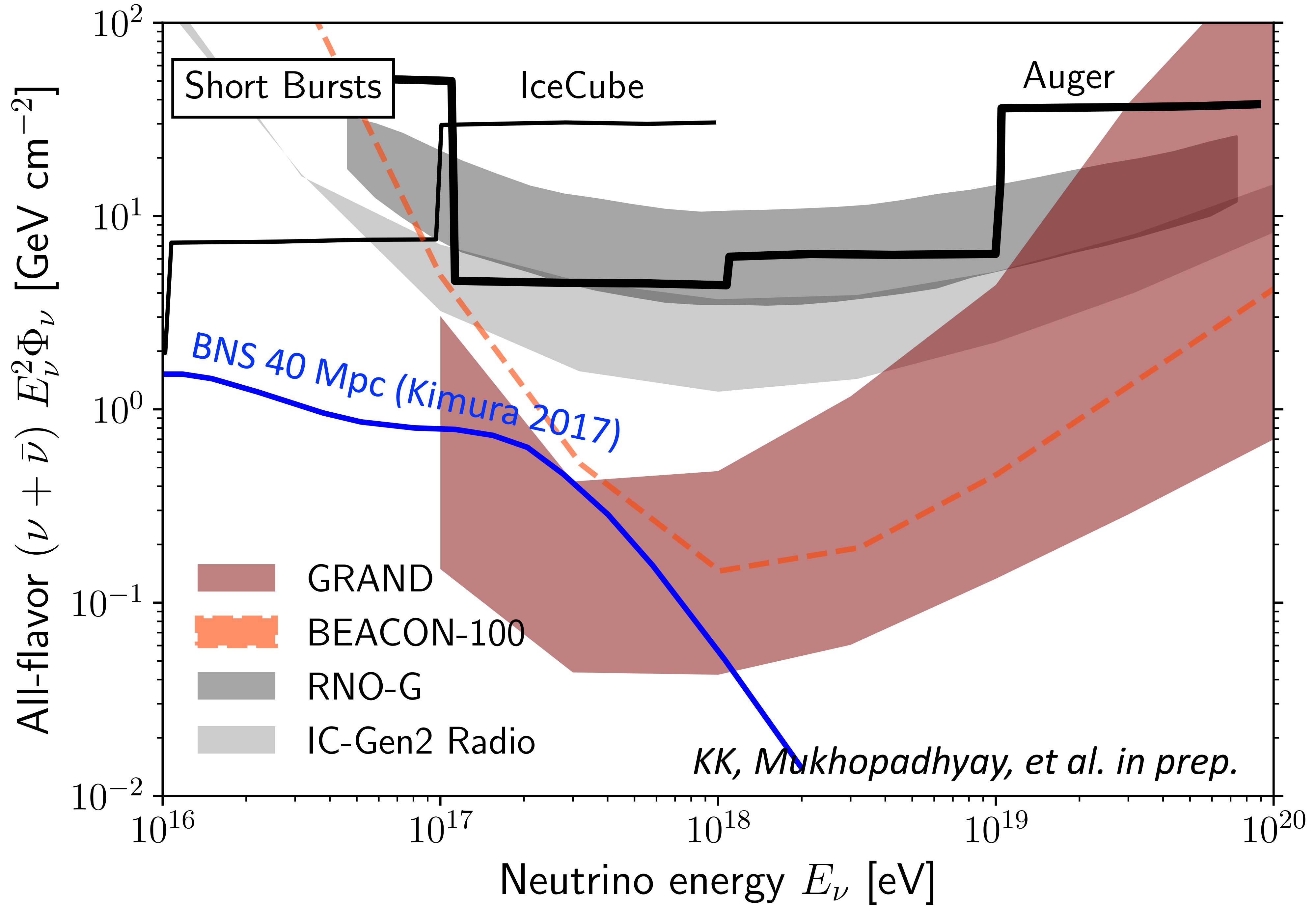
Mukhopadhyay, KK et al. 2024

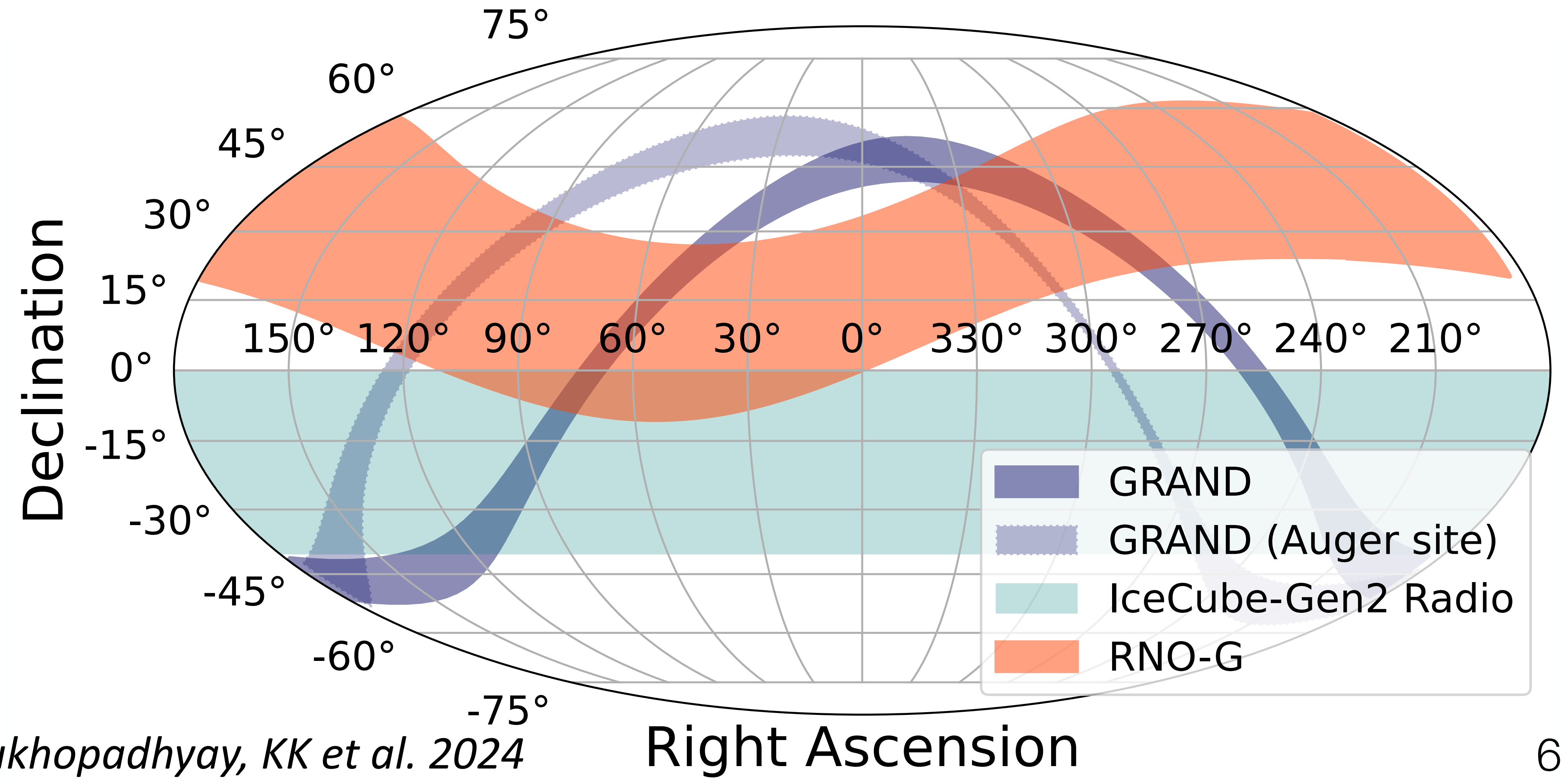
Volume (depth) —> dist³
Surface (FoV) —> dist²

Deep & Narrow observatories more powerful for UHE neutrino discovery of known targeted sources
Wide & Shallow: better suited for serendipitous all-sky searches

Astronomical observation strategies: Wide & Shallow vs. Deep & Narrow

CAUTION: updated IceCube-Gen2 Radio sensitivities:
~2 orders of magnitude discrepancy found for instantaneous fluence sensitivity *Guépin, KK, Oikonomou, Nat. Phys. Rev erratum*





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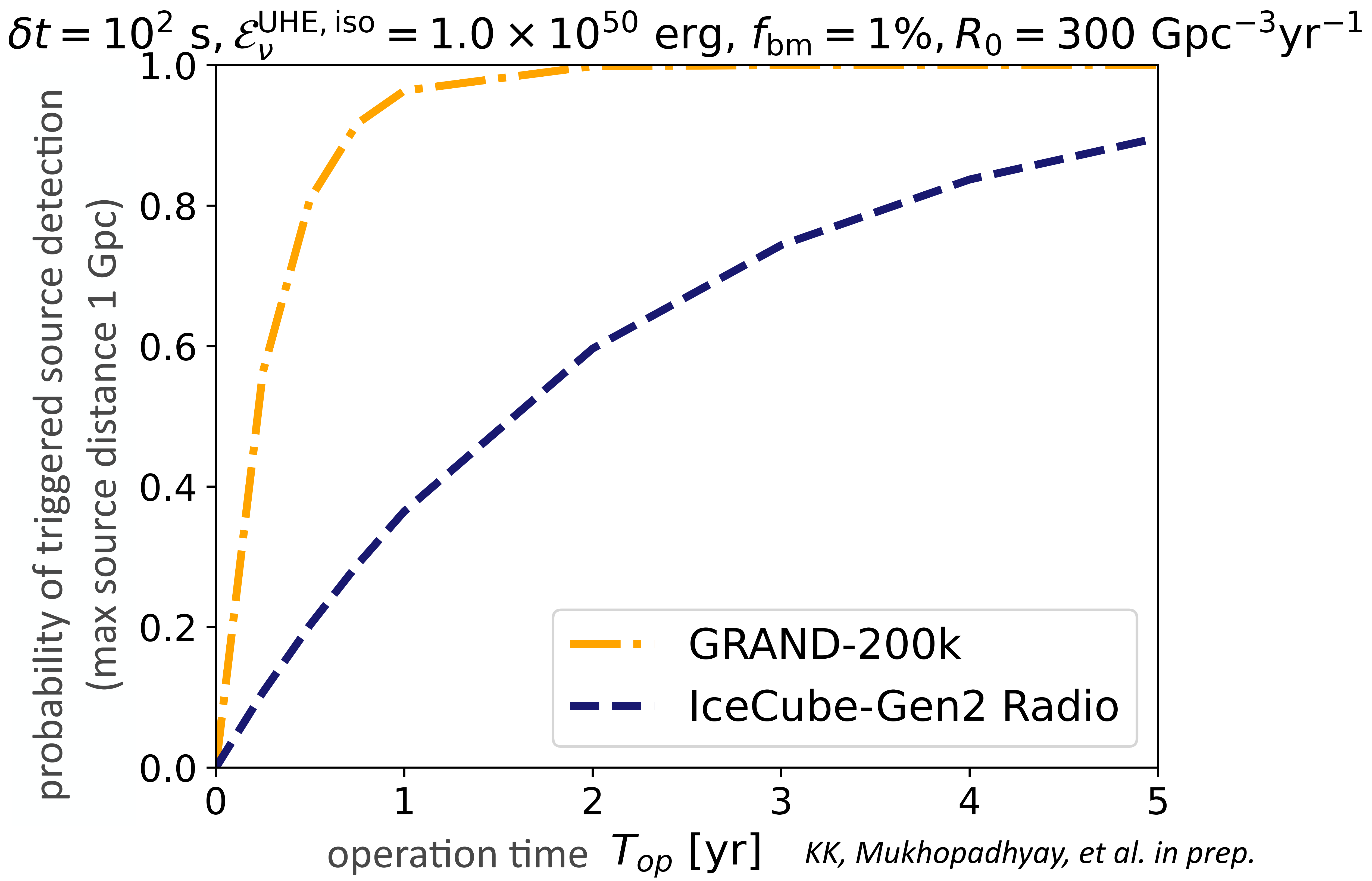

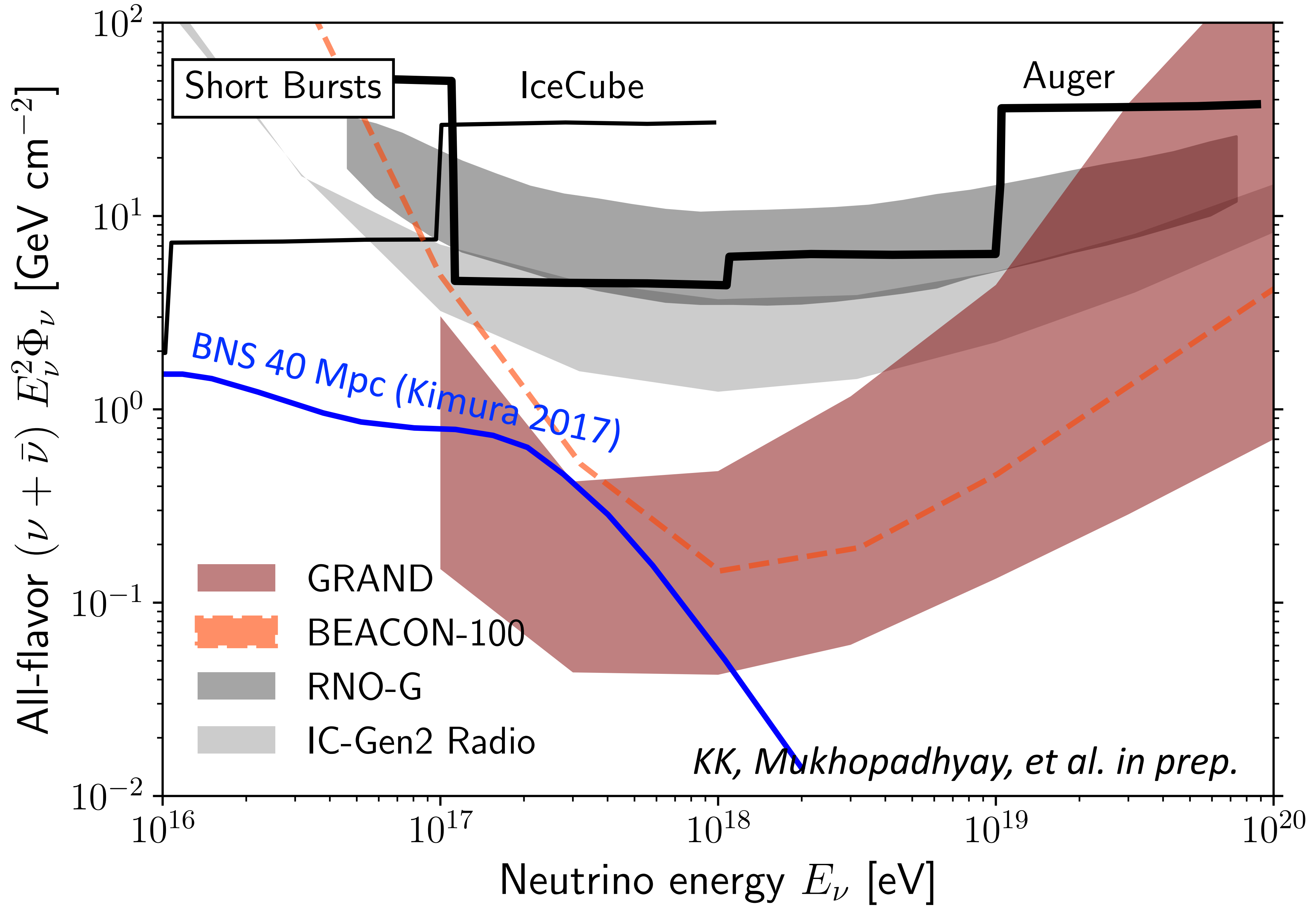

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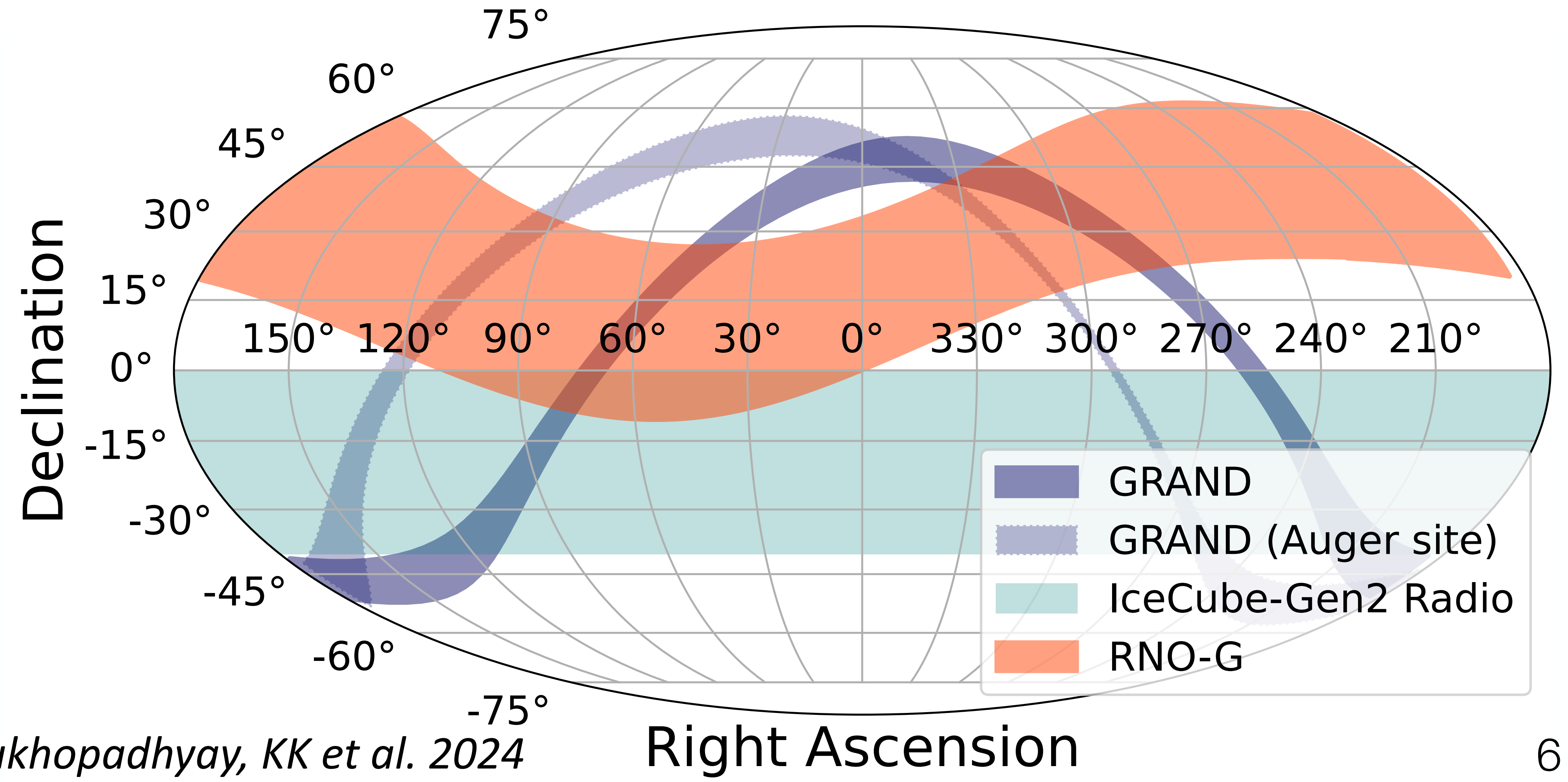
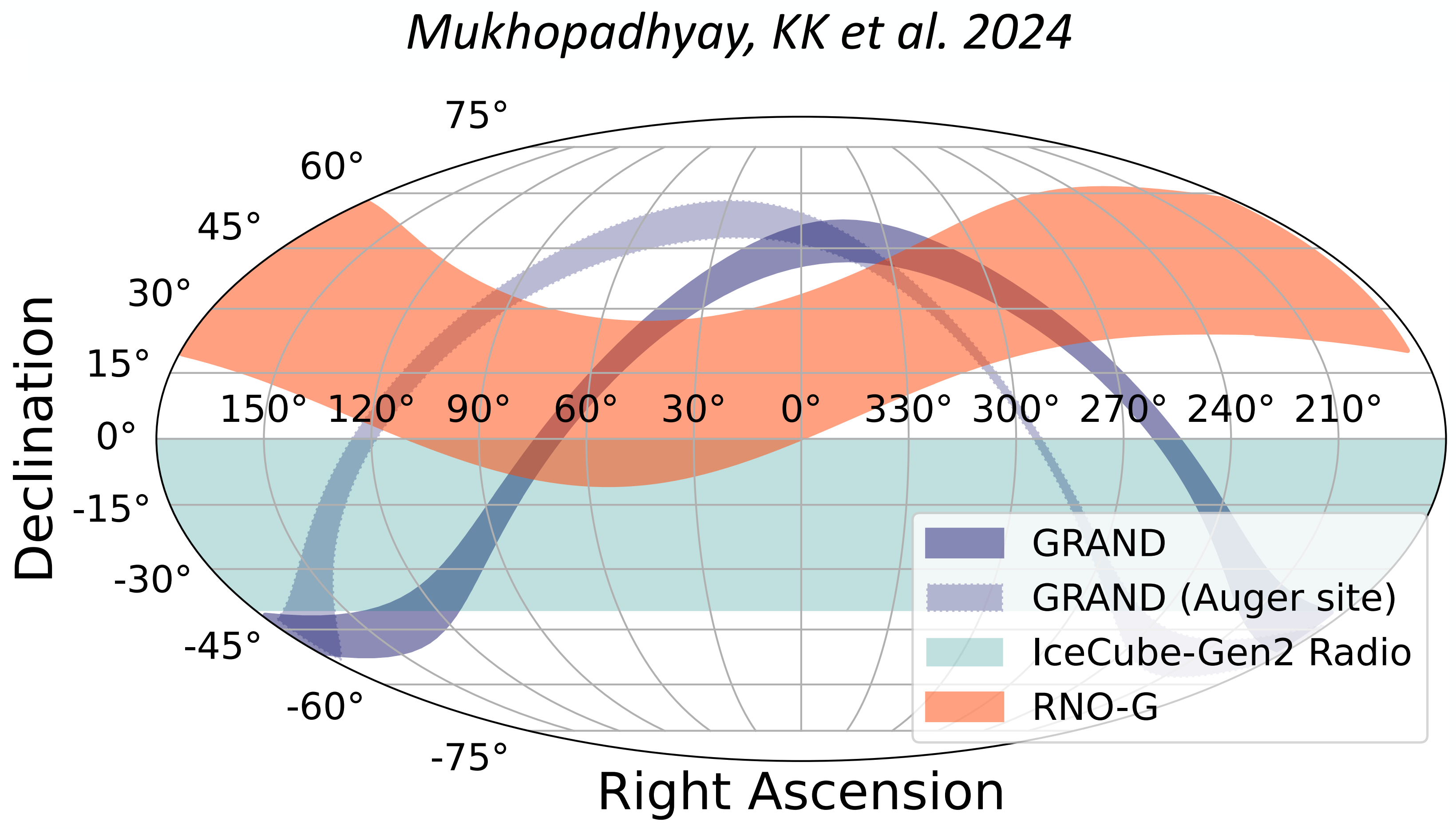
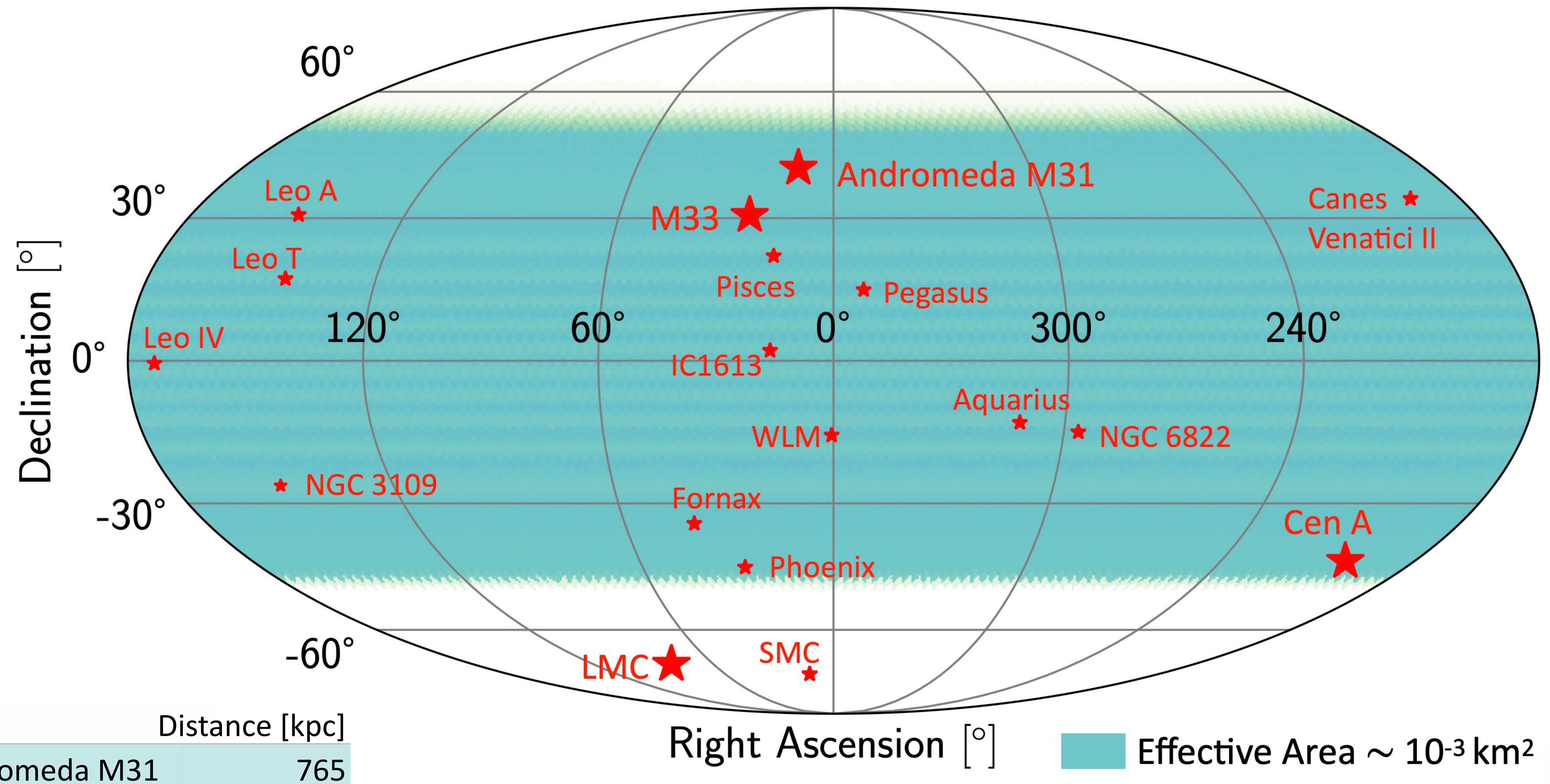


Mukhopadhyay, KK et al. 2024

Strategy for "long" bursts: increase daily field of view



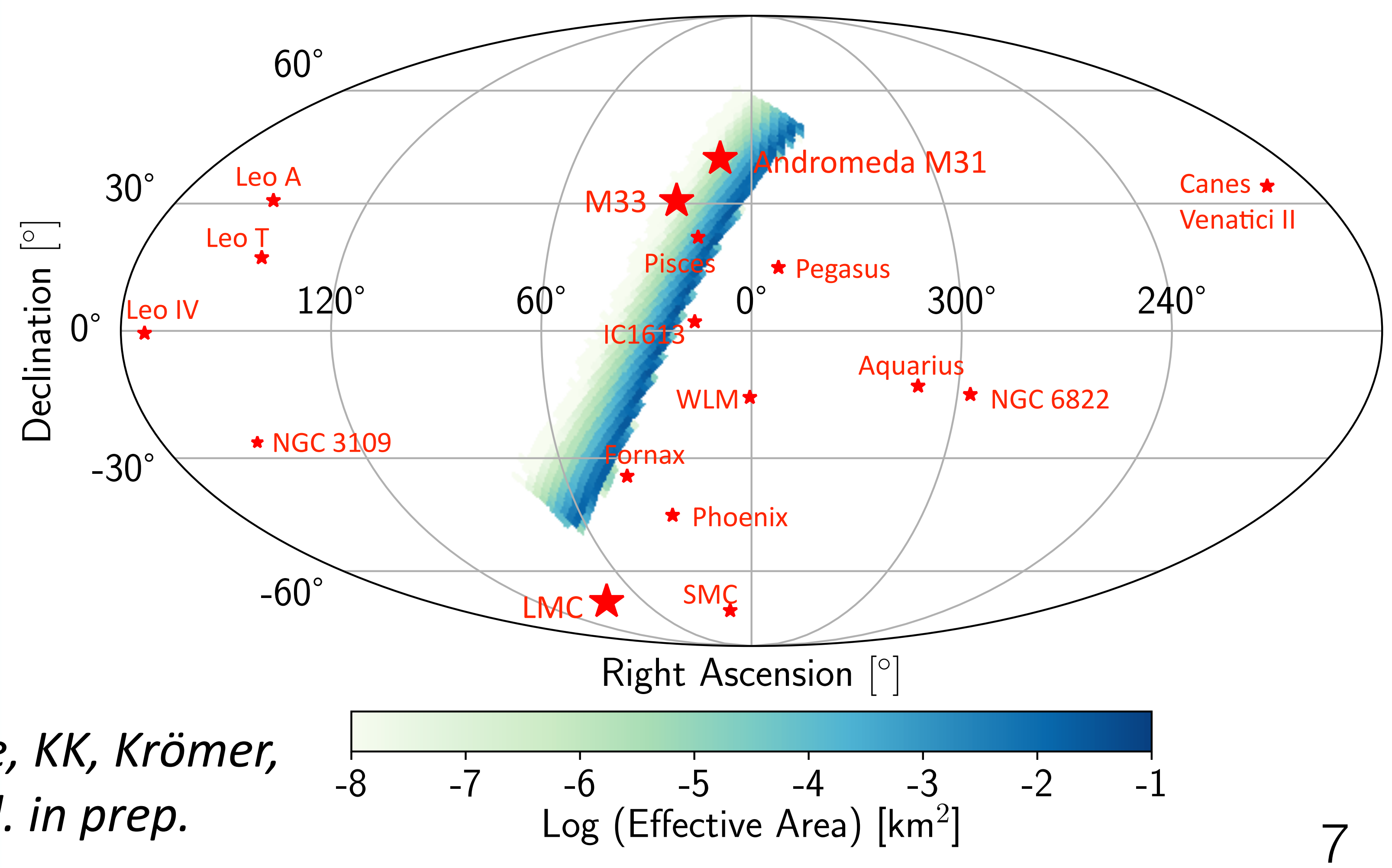


Daily FoV for HERON

(GRAND-BEACON hybrid)

instantaneous FoV for HERON

(GRAND-BEACON hybrid)

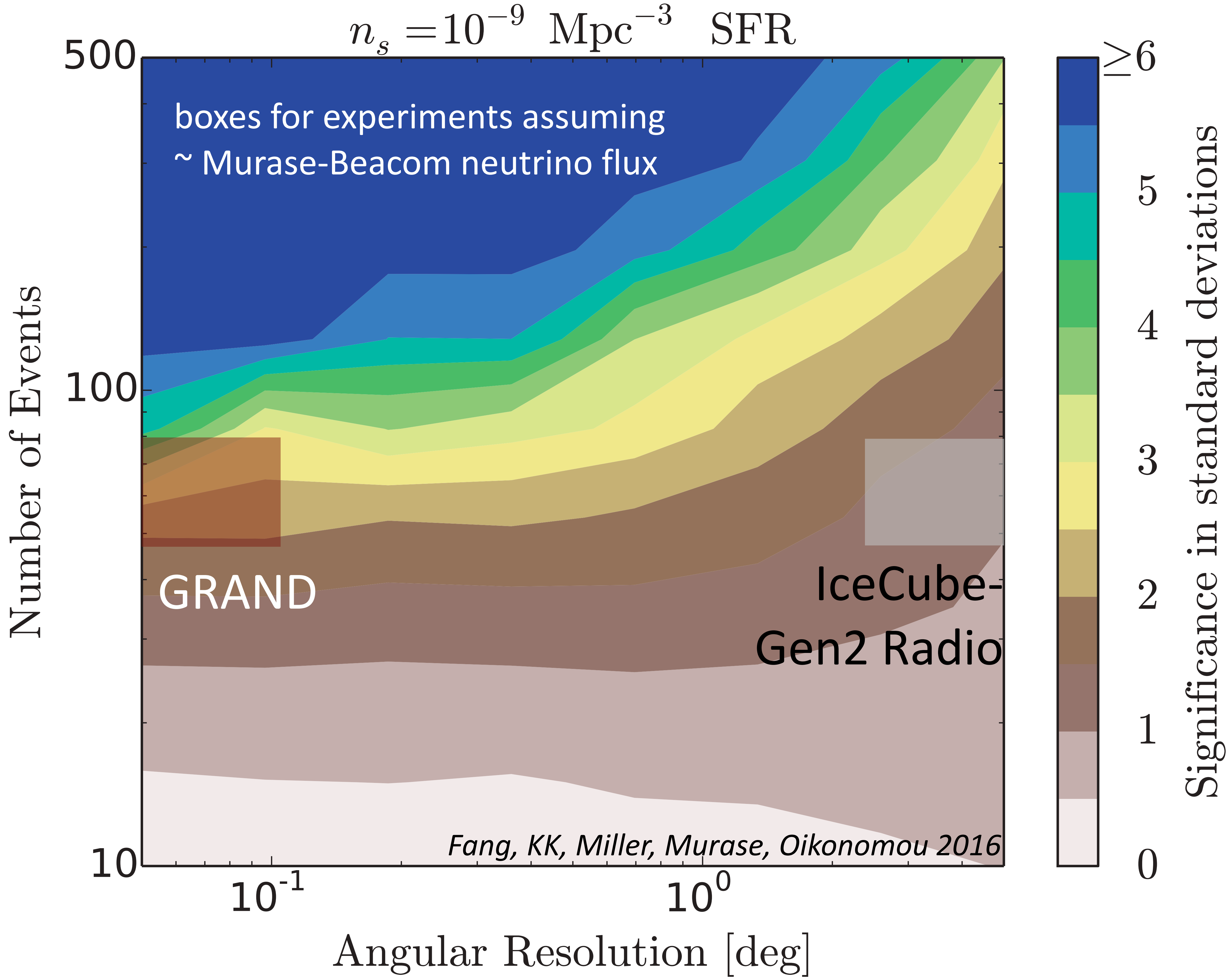


	Distance [kpc]
Andromeda M31	765
M33	970
LMC	50
NGC 3109	1333
WLM	930
SMC	620
Pisces	769
IC1613	730
Phoenix	440
Leo A	790
Aquarius	980

	Distance [kpc]
NGC 6822	500
Pegasus	920
Fornax	143
Canes Venatici II	522
Leo IV	154
Leo T	420

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

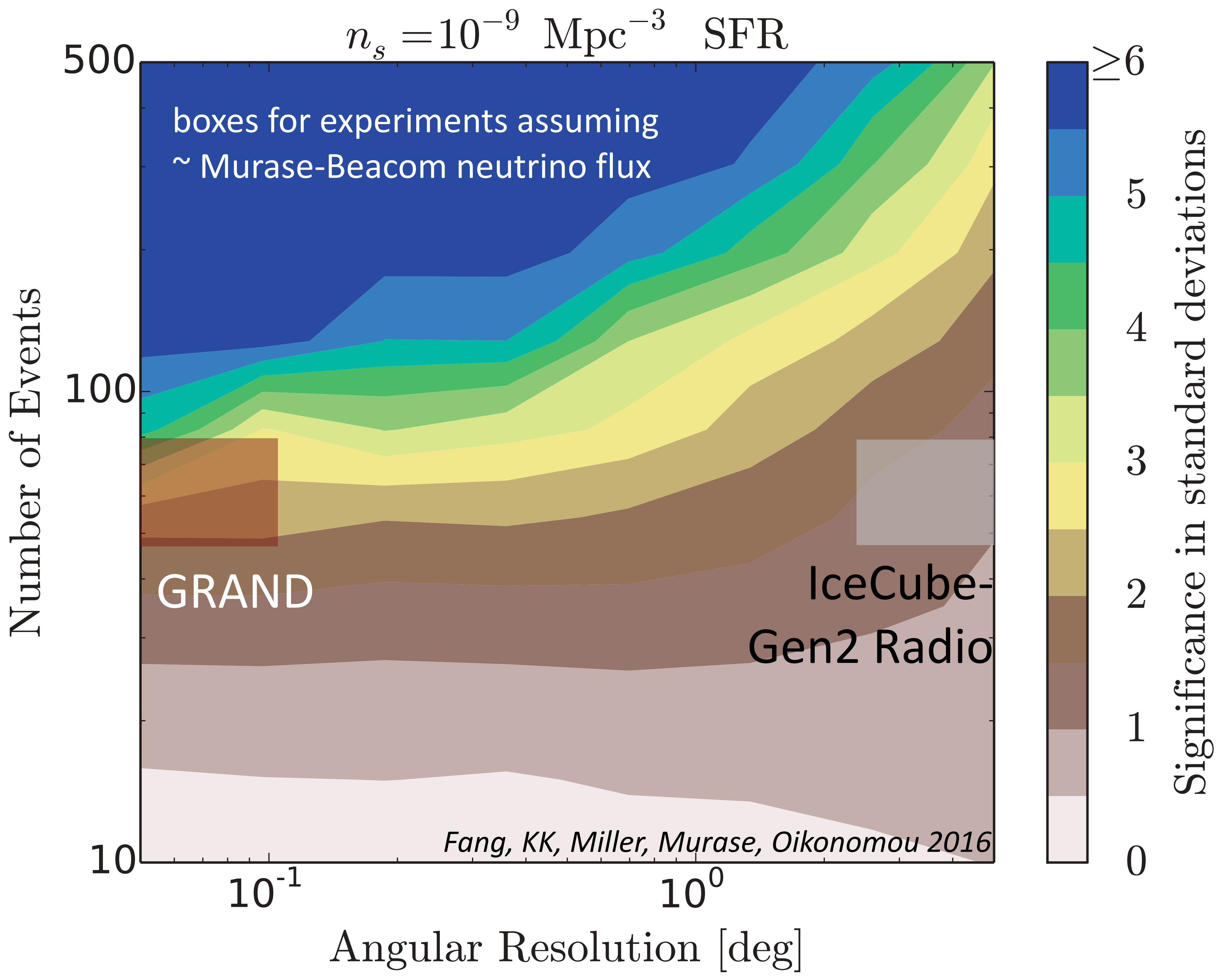
A necessary angular resolution



Can we identify a point-source out of a diffuse neutrino sky?

Yes, if we can collect ~100 events with sub-degree angular resolution…

A necessary angular resolution



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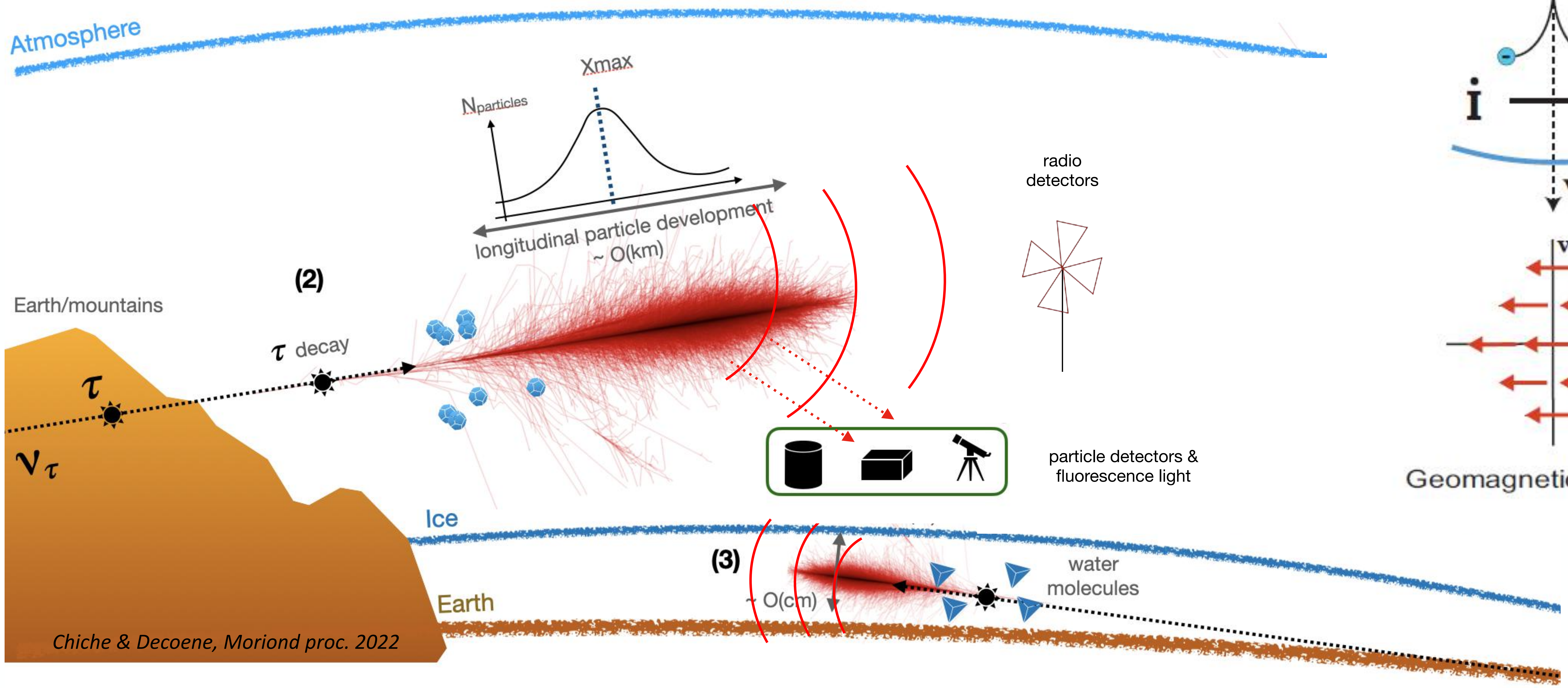
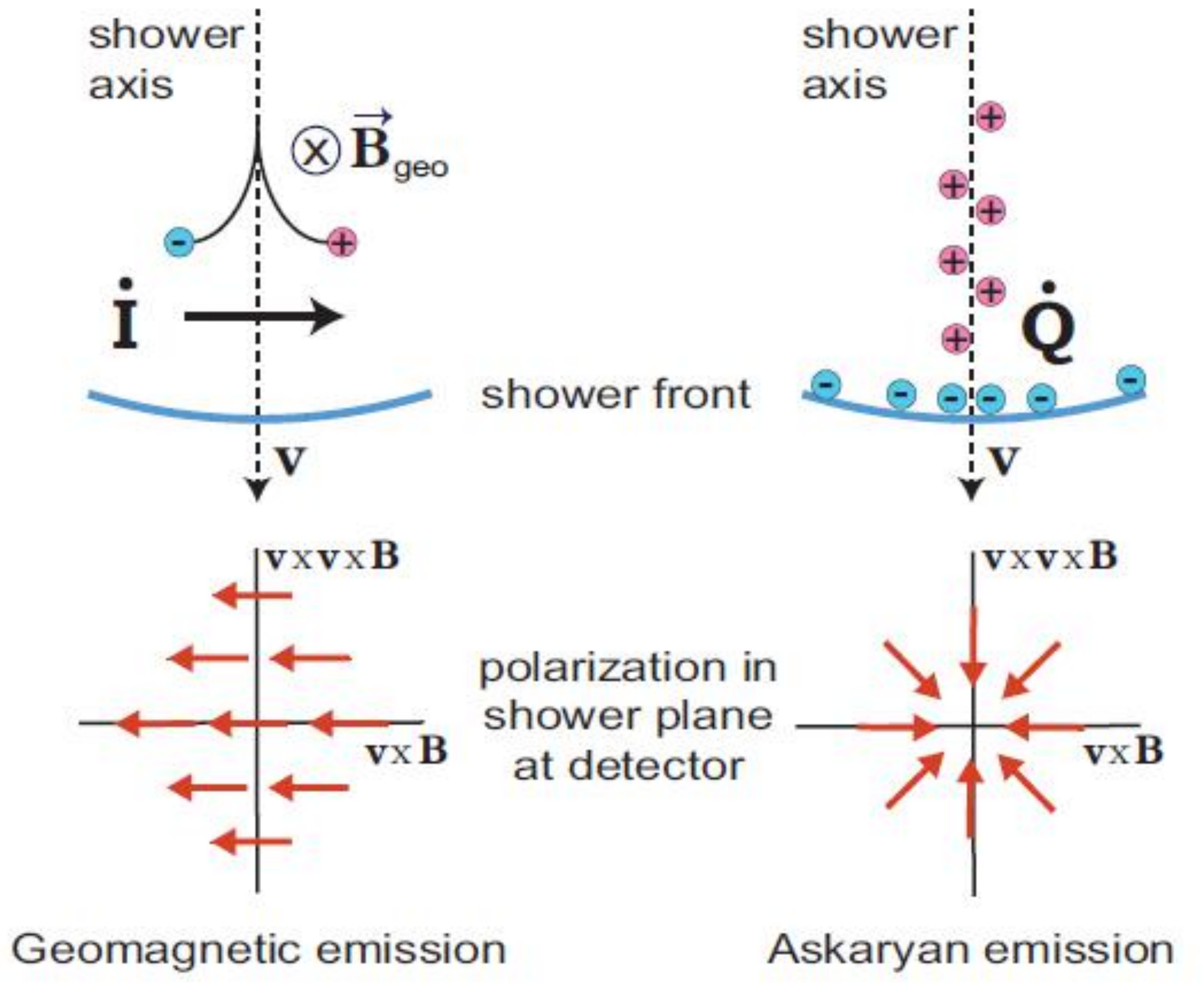
- development of MM-networks, EM instruments —> false associations will be common
- skim interesting events + narrow down search area —> requires angular resolution

	2021 2025 >2030	FoV	ang. res.
gamma	LHAASO	2 sr	0.3°
	CTA	10–20°	< 0.15°
	HAWC	2 sr	0.1°
	H.E.S.S.	5°	0.1°
	MAGIC	3.5°	0.07°
	VERITAS	3.5°	0.1°
	Fermi LAT	2.4 sr	0.15°
	GBM	9 sr	10°
	INTEGRAL IBIS	64 deg²	0.2°
	SPI-ACS	4π	-
X	XMM-Newton	0.5°	6"
	Athena-WFI	0.4 deg²	< 5"
multi	Swift BAT	1.4 sr	0.4°
	XRT	0.1 deg²	18"
	UVOT	0.1 deg²	2.5"
	SVOM ECLAIRs	2 sr	< 0.2°
	MXT	1 deg²	13"
	VT	0.2 deg²	< 1"
IR/optical/UV	ASAS-SN	72 deg²	7.8"
	ATLAS	29 deg²	2"
	Pan-STARRS	14 deg²	1.0–1.3"
	ZTF	47 deg²	2"
	Vera Rubin Obs. (LSST)	9.6 deg²	0.7"
	MASTER-II(VWF)	8(400) deg²	1.9" (22")
	TAROT	4 deg²	3.5"
	GEMINI (GMOS)	30.23'²	0.07"/pix
	GTC (OSIRIS)	0.02 deg²	0.127"/pix
	Keck (LRIS)	46.8'²	0.135"/pix
	VLT (X-shooter)	2.2'²	0.173"/pix
radio	VLA	0.16 deg²	0.12"
	MWA	610 deg²	0.9'
	SKA1(2)-MID	1(10) deg²	0.04°–0.7°

Guépin, KK, Oikonomou, Nature Phys. Rev. 2022

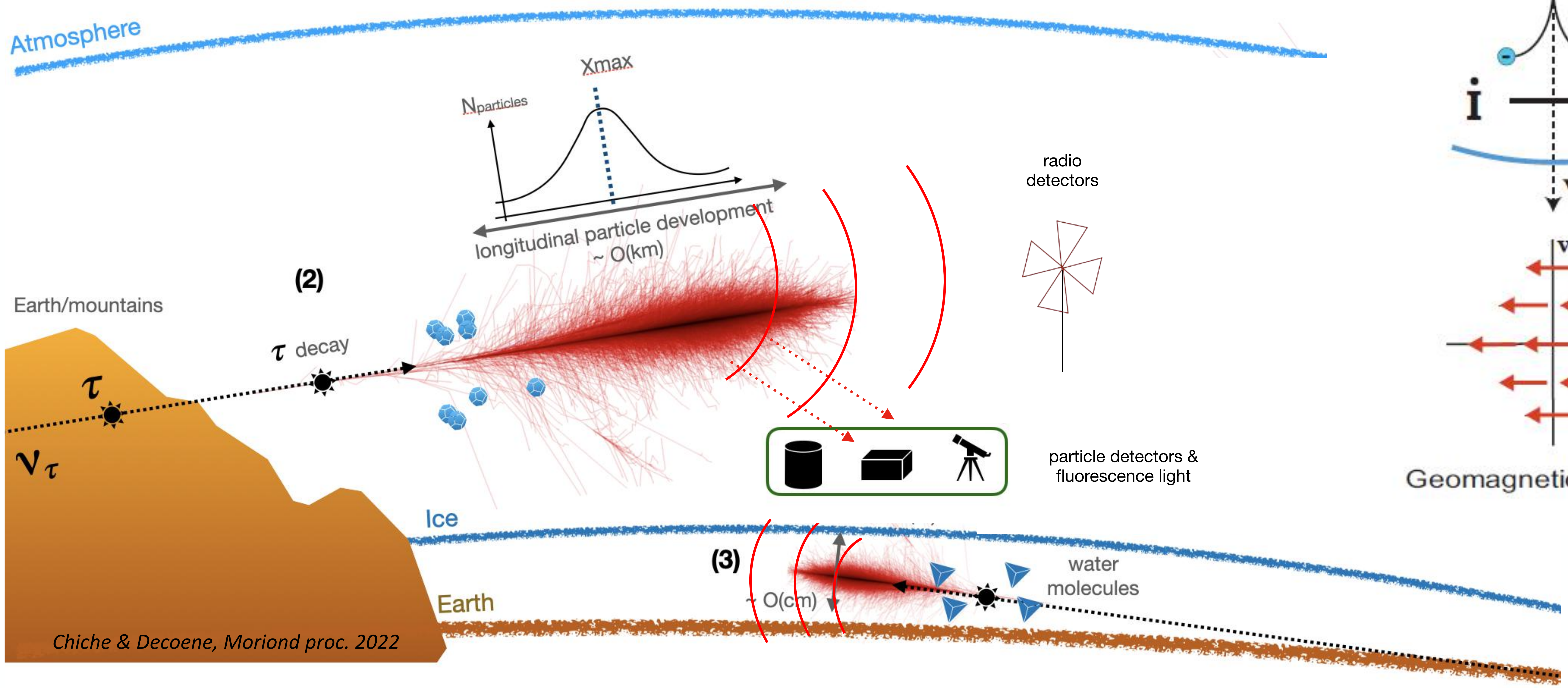
Radio detection as a cost-effective technique

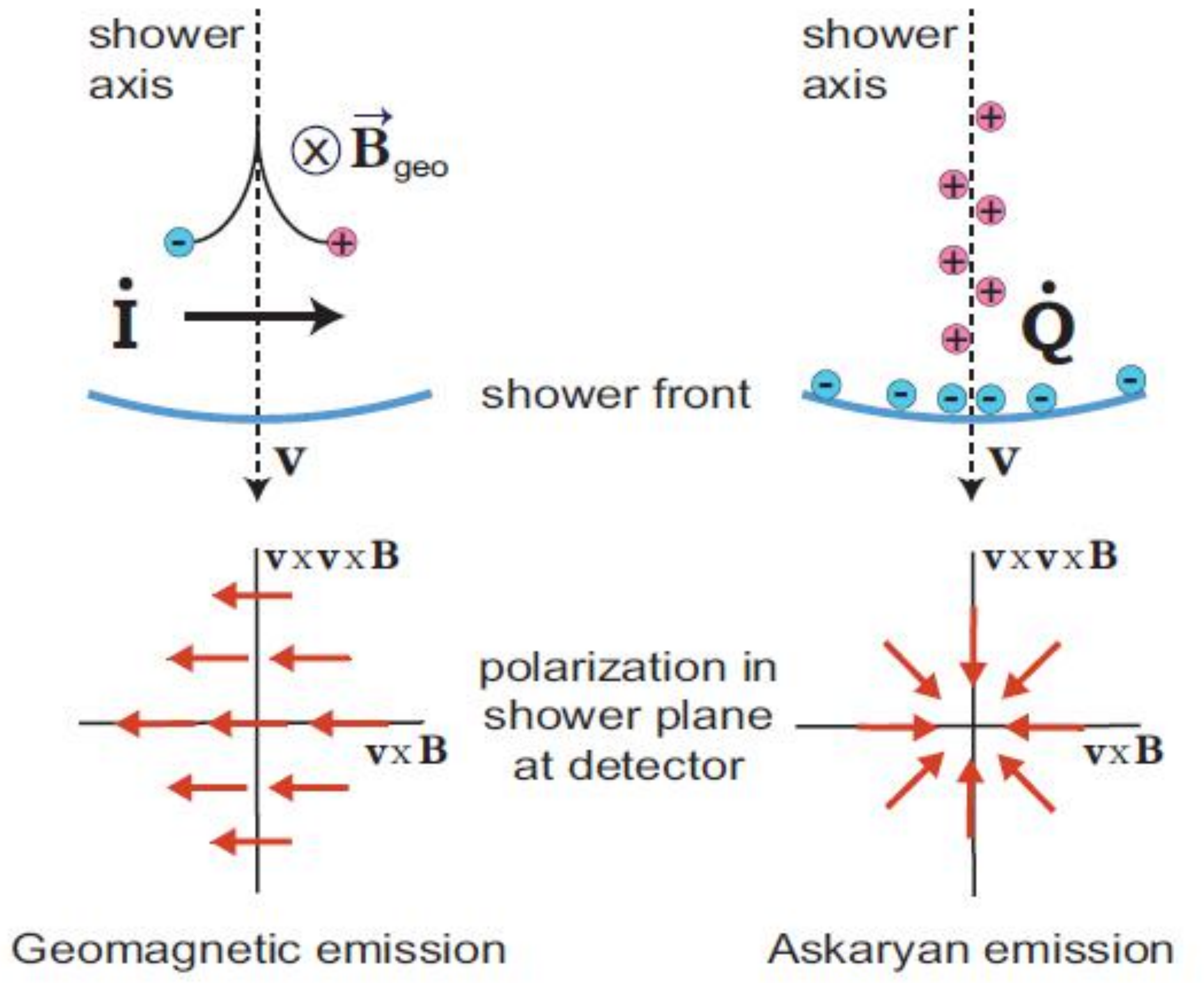




- Radio antennas: cheap, robust, scalable
- 100% duty cycle
- benchmarked technique
  in-ice & in-air for specific configurations

Radio detection as a cost-effective technique





- Radio antennas: cheap, robust, scalable
- 100% duty cycle
- benchmarked technique
  in-ice & in-air for specific configurations

Performances	instantaneous sensitivity	daily aver. sensitivity	iFoV	dFoV	angular resolution
in-ice	+ wide & shallow	++	**+++** wide & shallow	++ no gain by Earth rotation if South Pole	+ reconstruction of polarization difficult
in-air	**+++** deep & narrow	++ equivalent as experiments tuned to diffuse flux	+ deep & narrow	**+++**	**+++** large footprints

Challenges of radio-detection

A good radio detector?

by Abby Vieregg
GRAND-BEACON Workshop
PSU, Jan. 2024

- antenna collecting area (number & gain of antennas)
- trigger threshold (reducing system noise, smart triggering and noise rejection)
- collecting enough information so that events can be separated from background in analysis

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Deployment over large/challenging areas

- quiet site identification + geopolitics
- logistical challenges

Complexity & efficiency trade-off

- Number of channels
- Phasing or not
- Low noise system
- Robust for desert/ice environments & temperature fluctuations
- Simple deployment for large numbers

Reconstruction of shower parameters

- Different physics, asymmetries, ground reflections… for very inclined air-showers, in-ice propagation
- New reconstruction methods to develop & test

RFI discrimination & autonomous triggering on radio signals

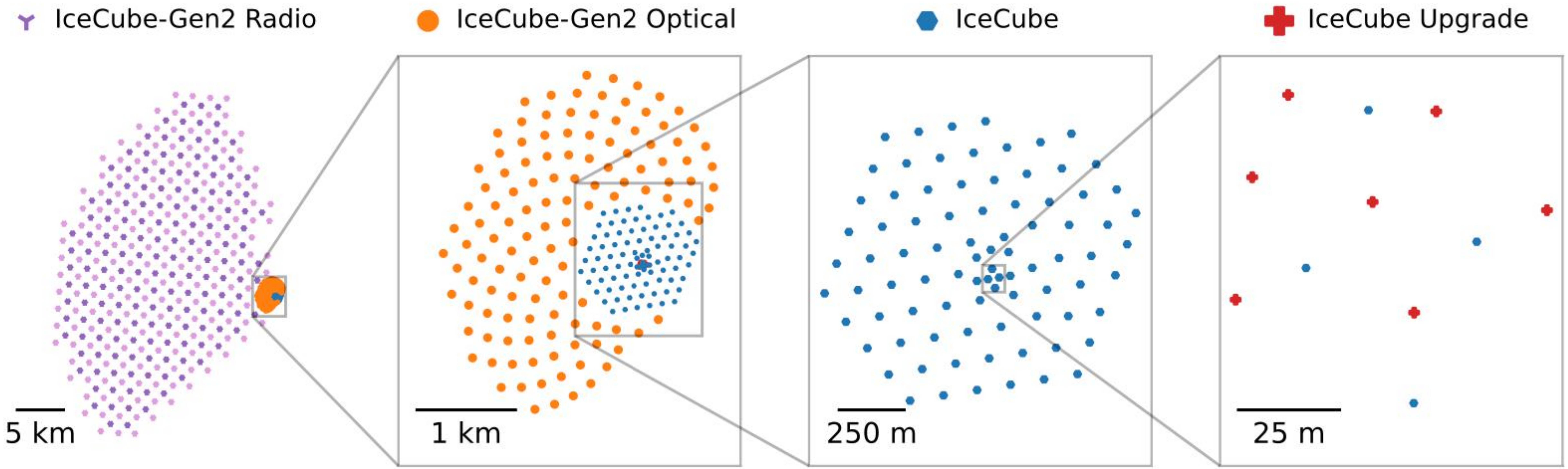
- Ultra-dominant noise: ideal quiet sites
- New electronics necessary: high sampling rate & autonomous triggering
- Identification of signals & denoising methods
- Previous successful efforts in other contexts: ANITA, TREND

Data volume & transfer: low-rate, low-power

- Huge data volume (currently on GRAND prototype ~10 kBy/trigger)
- Online treatment to reduce stored information (trigger time, amplitude, polar…)

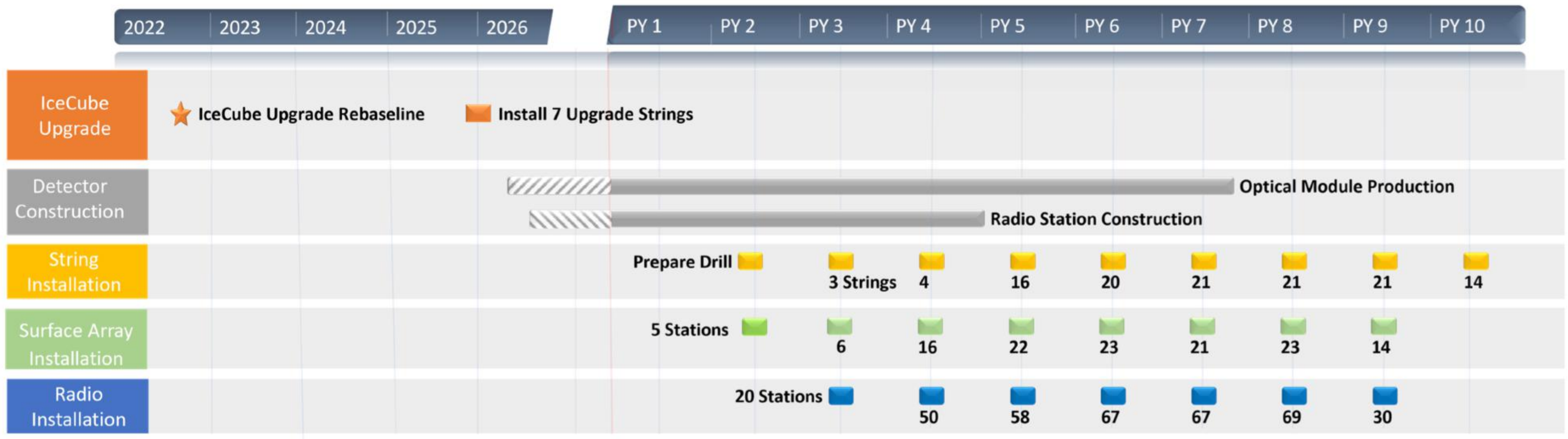
IceCube-Gen2 Radio

Slide by Stephanie Wissel



- 169 hybrid stations, 1.75 km spacing on square
- 192 shallow stations, interspersed 1.24 km spacing

IceCube-Gen2 Collaboration TDR



- IceCube-Upgrade expected completion 2026; NSF fully committed to support it
- TDR details a 10-year project plan for building the full experiment
- South Pole infrastructure to be upgraded in over the next ten years

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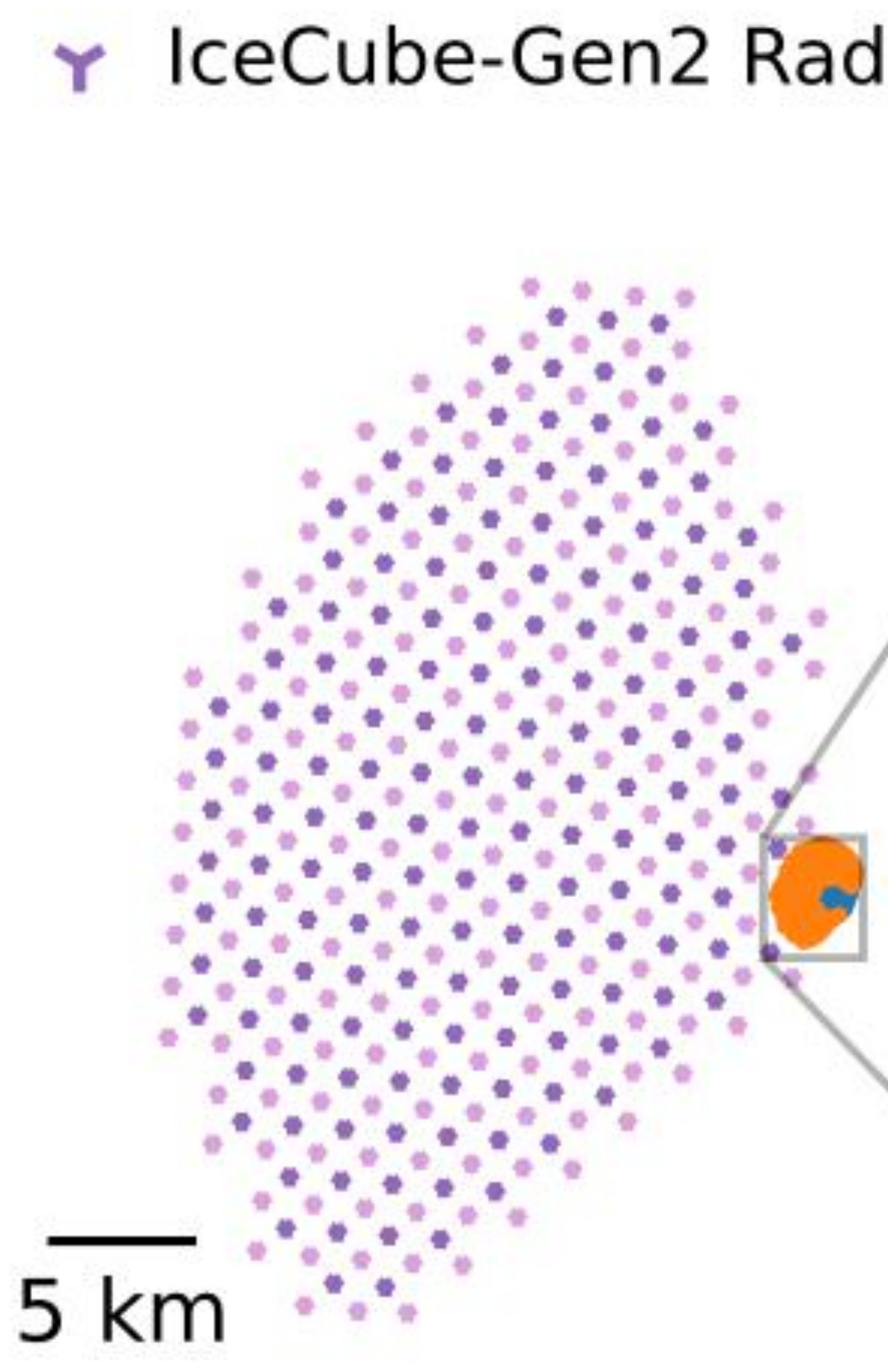
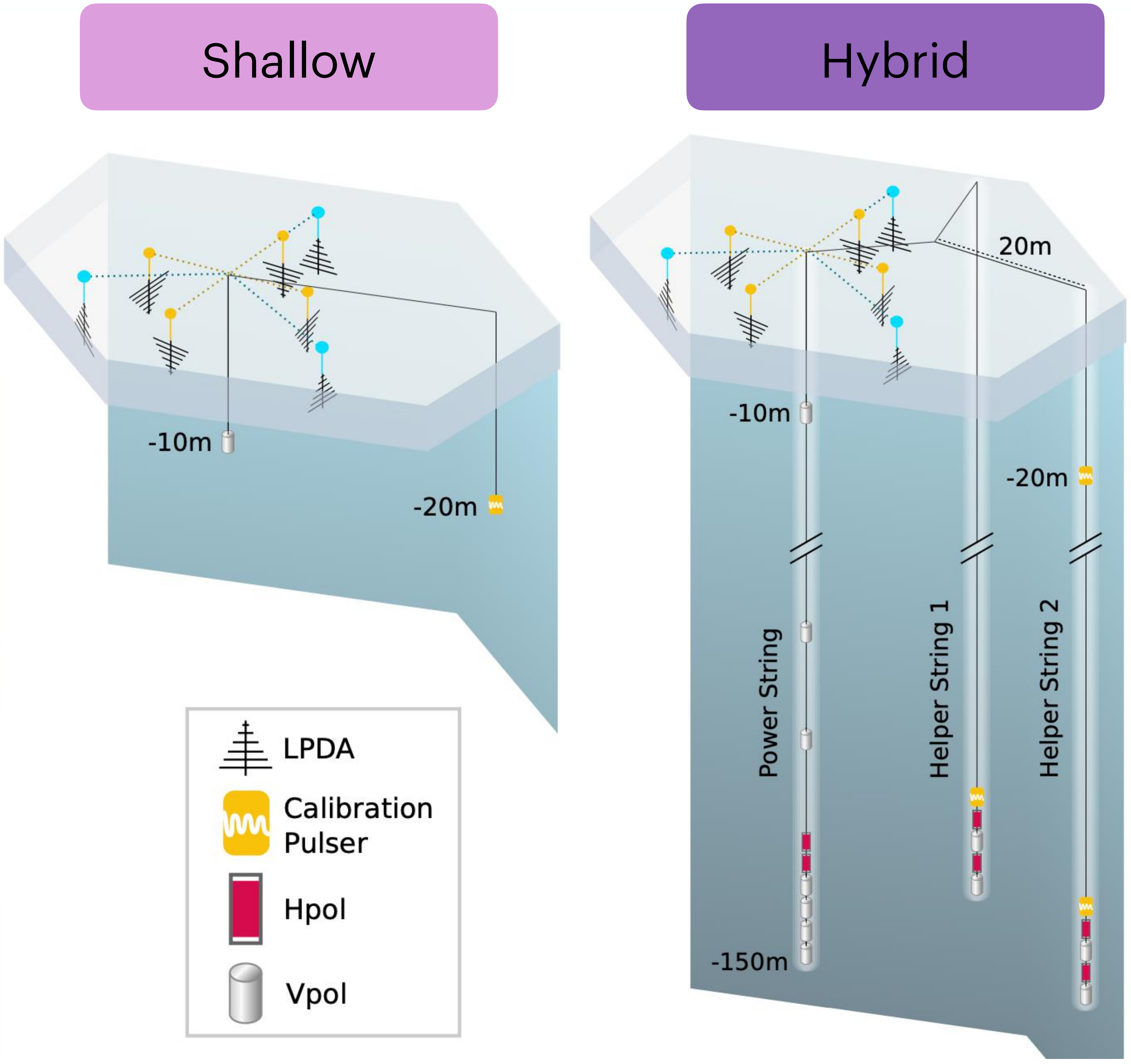


- Radio Array covers 500 km² to achieve sensitivity at ultrahigh energies
- Robust discovery-level instrument
  that combines shallow and deep antennas to mitigate against systematics with two approaches



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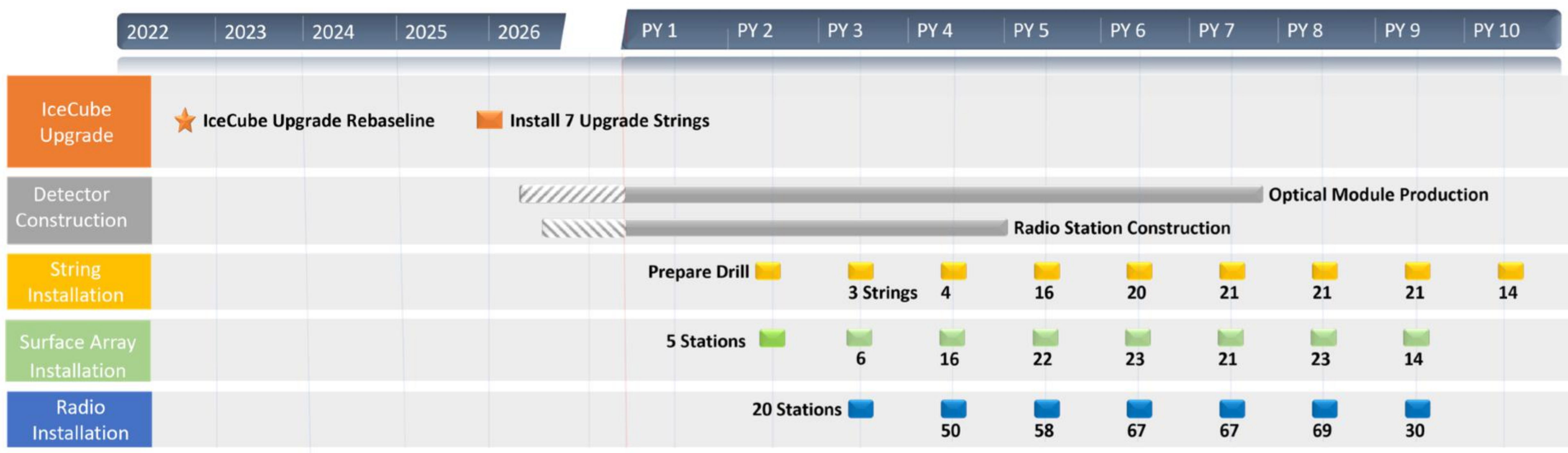

RNO-G

Instrument Status

- Upgrades to drill underway → will be focus of 2025 field season
- RNO-G-7 instrument characterized (arXiv:2411.12922) and several ice studies
  - Excellent agreement in detector model
  - Trigger modeling and upgrades underway
  - New all-digital designs under production
- Solar flares observed that can calibrate the array using global timing (arXiv:2404.14995)
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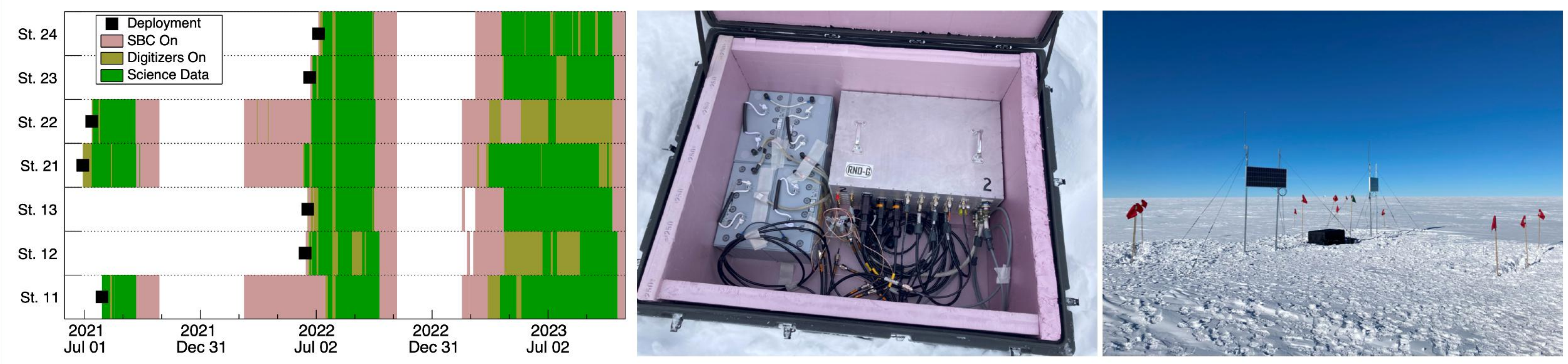

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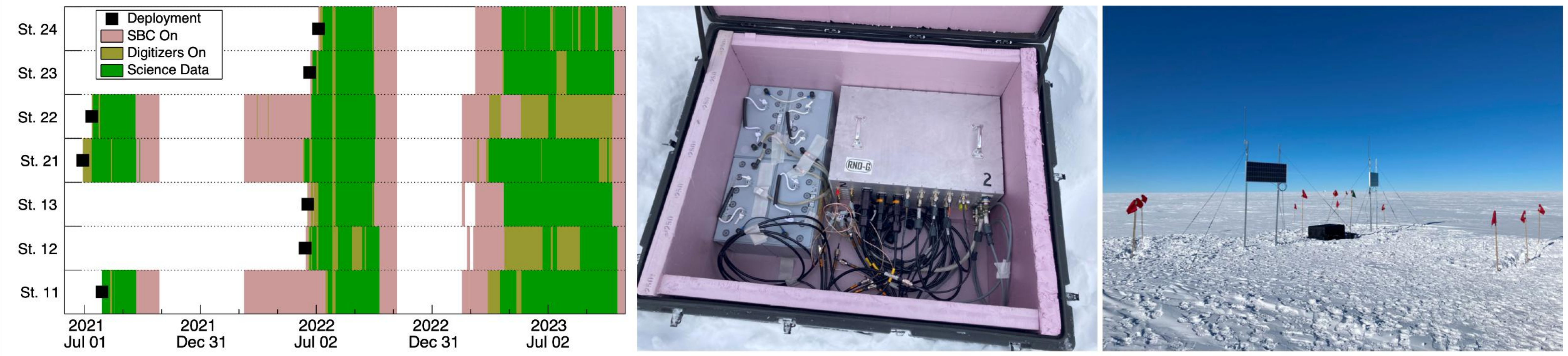

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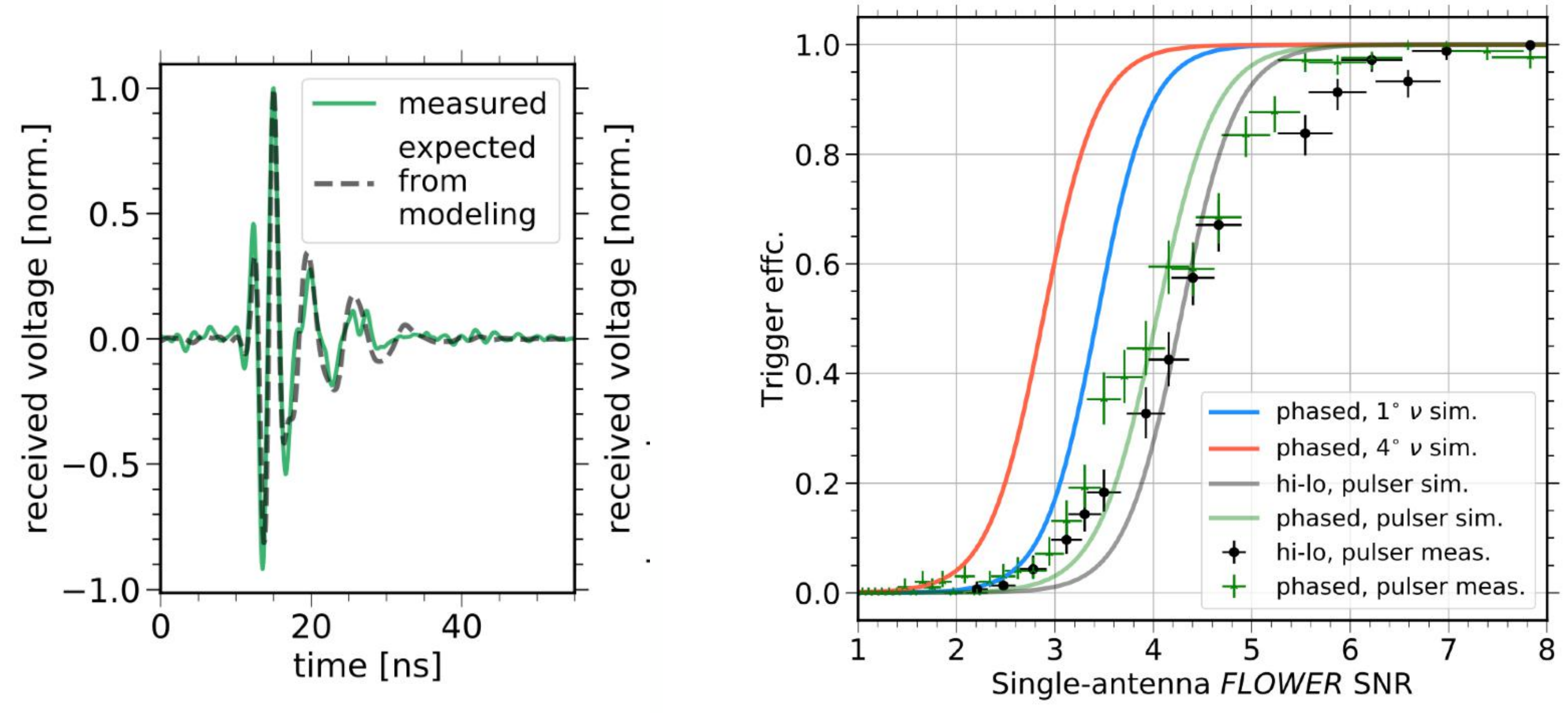

	TRIGGER	50% EFFC [SNR]
pulser	hi-lo	4.3
ν 1°	hi-lo	4.3
ν 4°	hi-lo	4.1
pulser	phased	4.0
ν 1°	phased	3.4
ν 4°	phased	2.9

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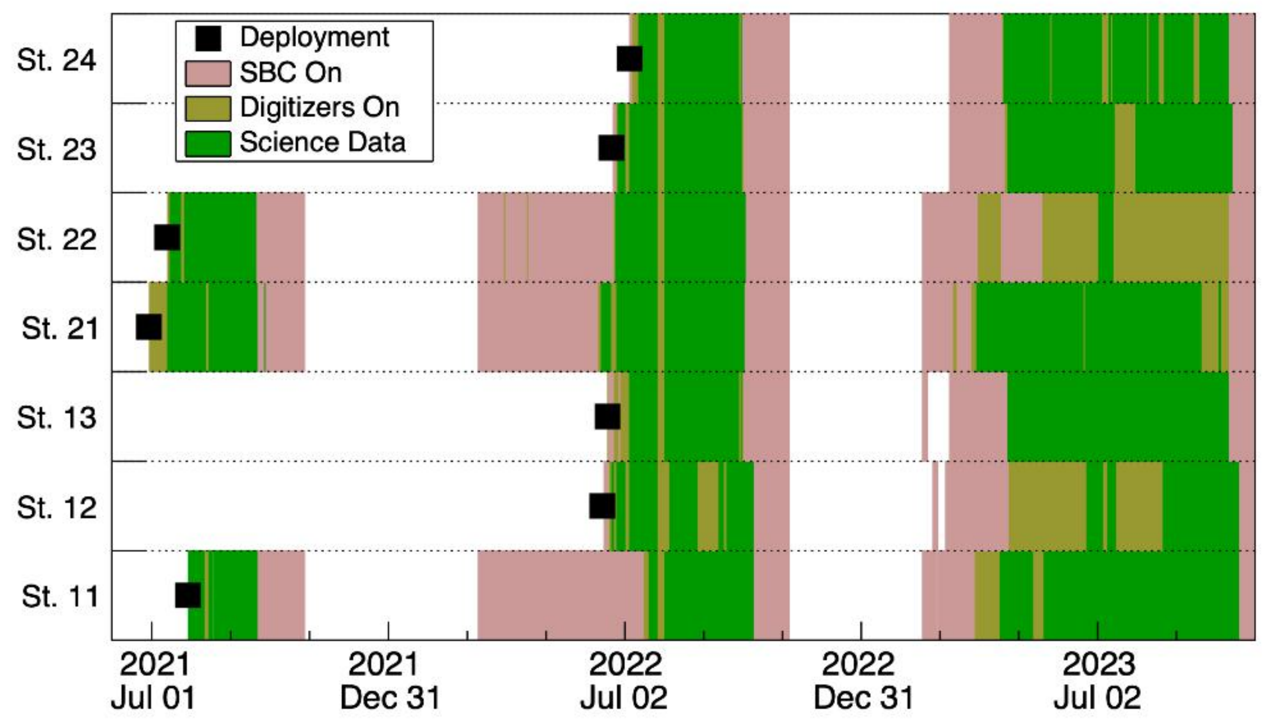

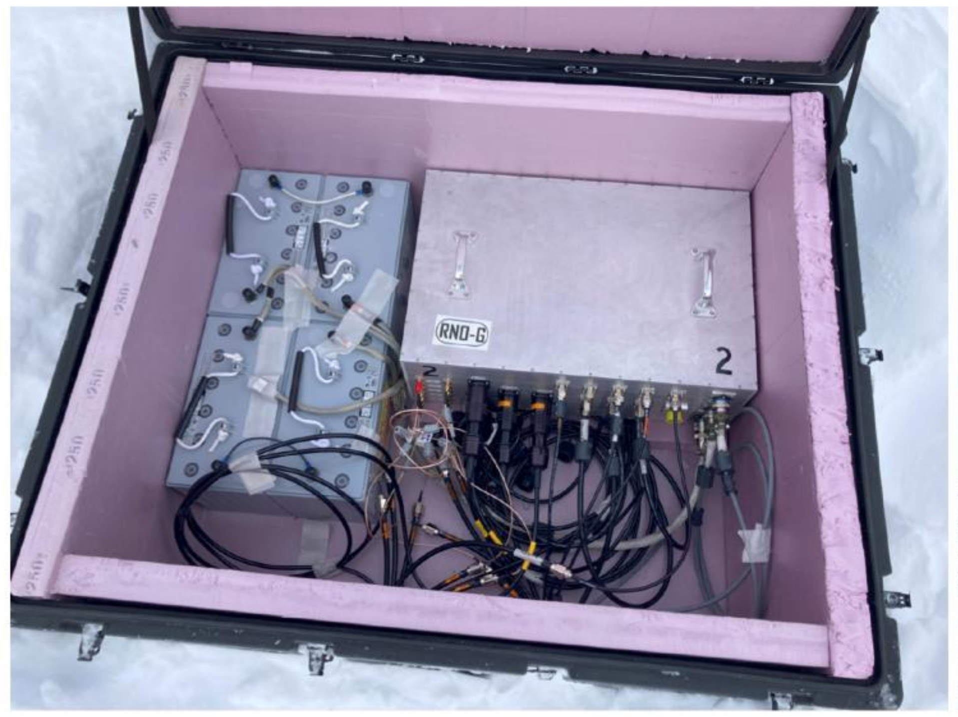

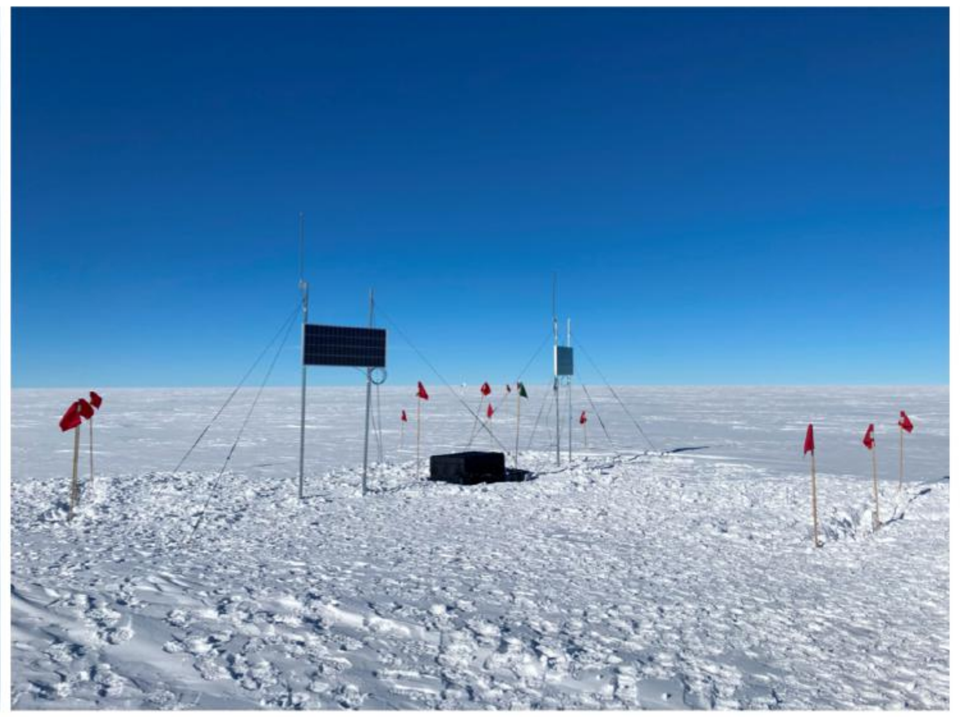

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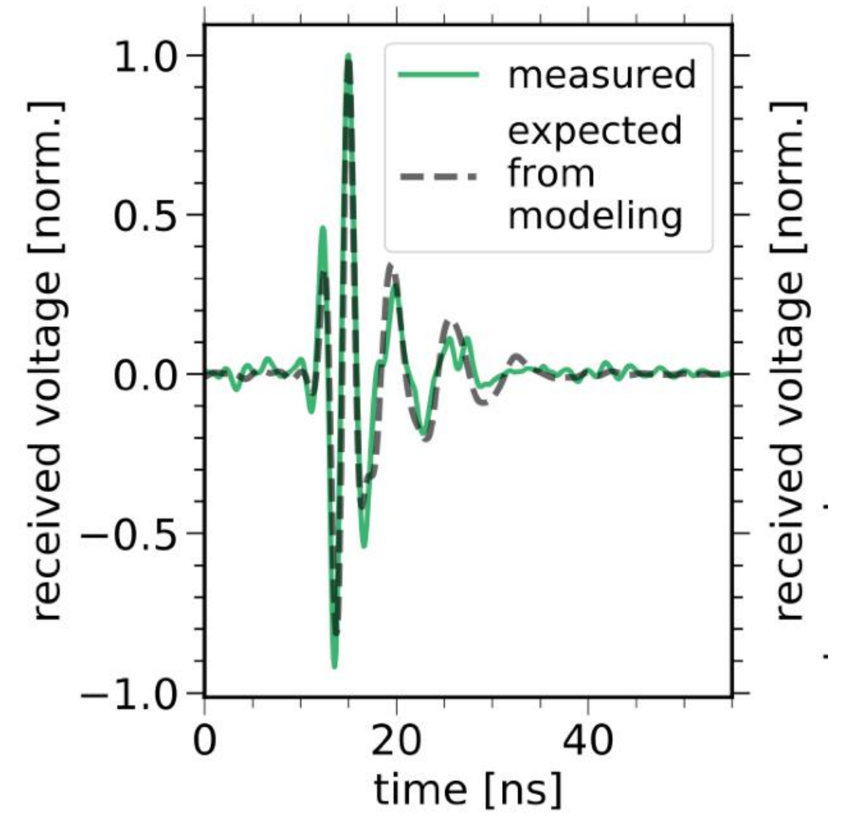

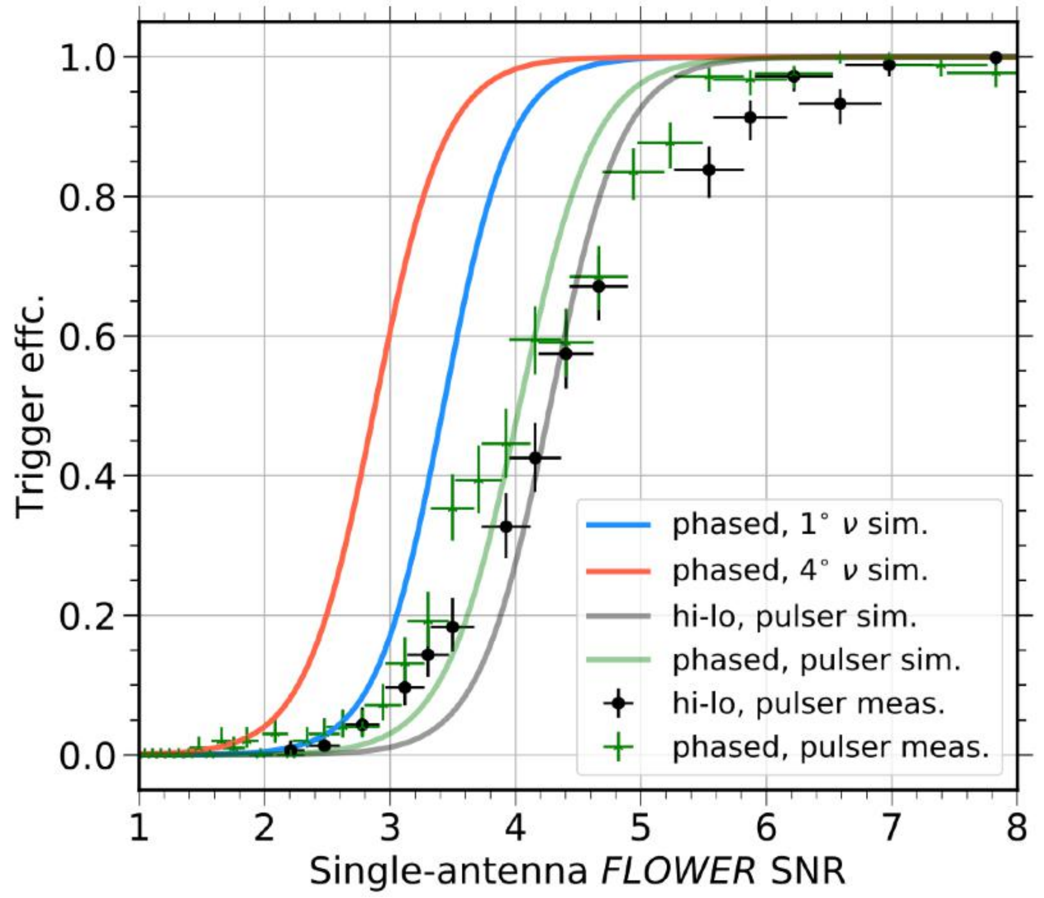

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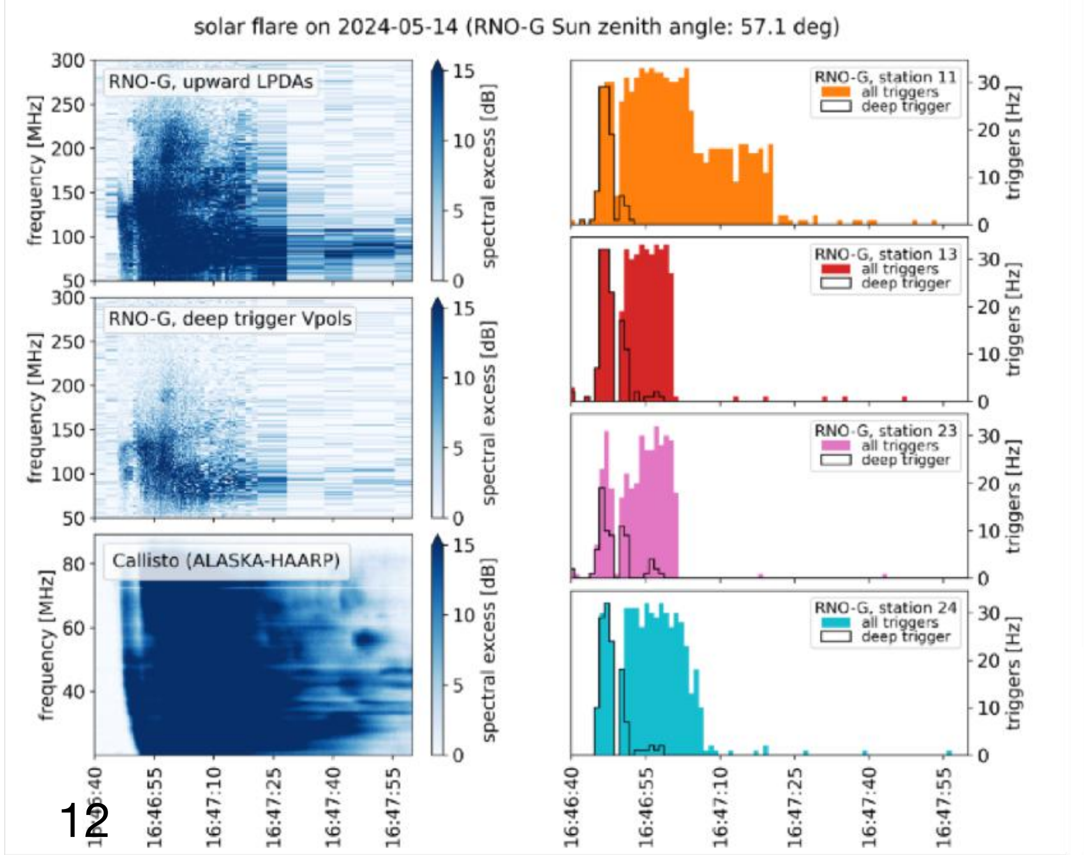

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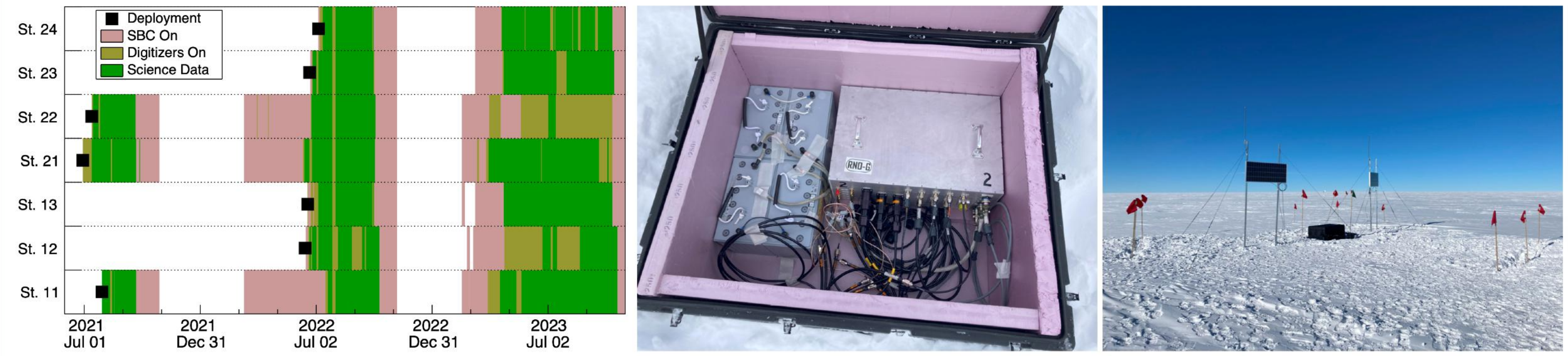

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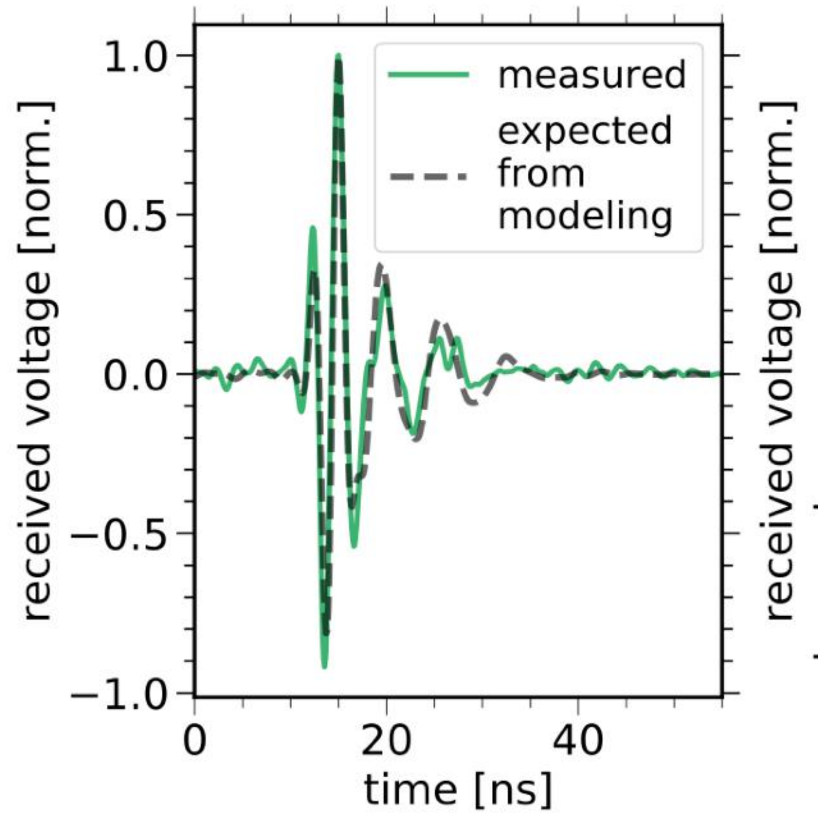

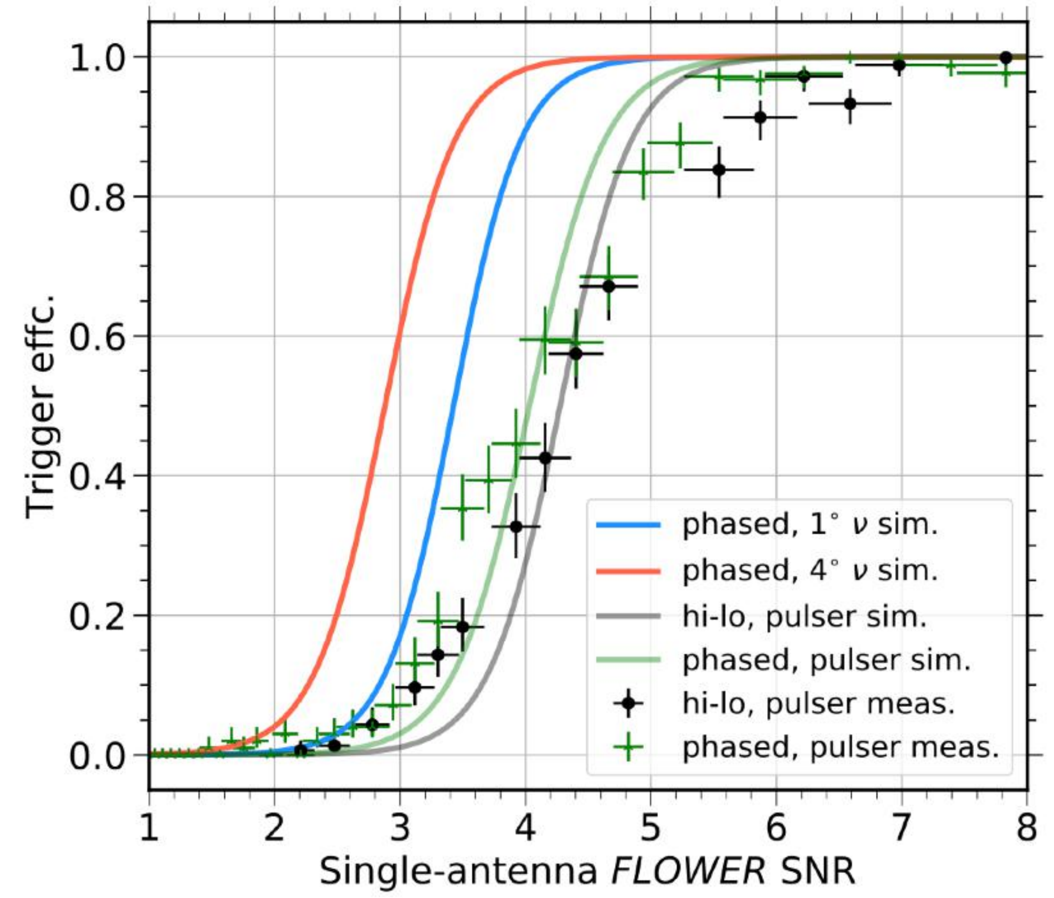

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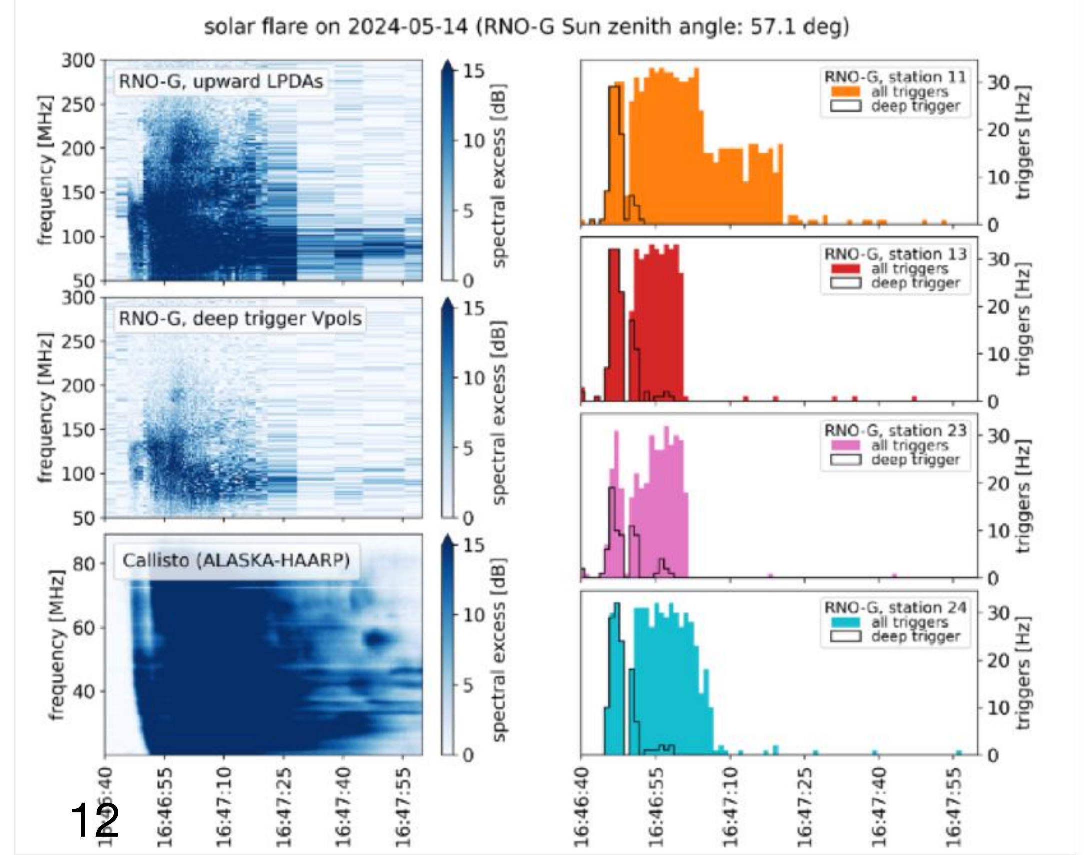

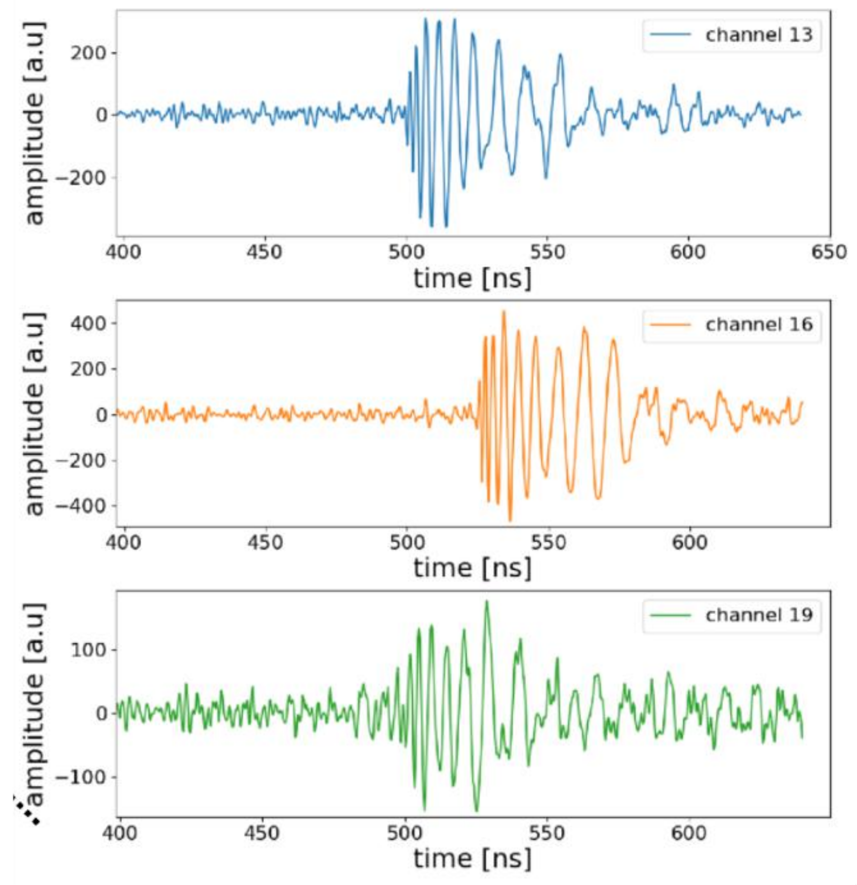

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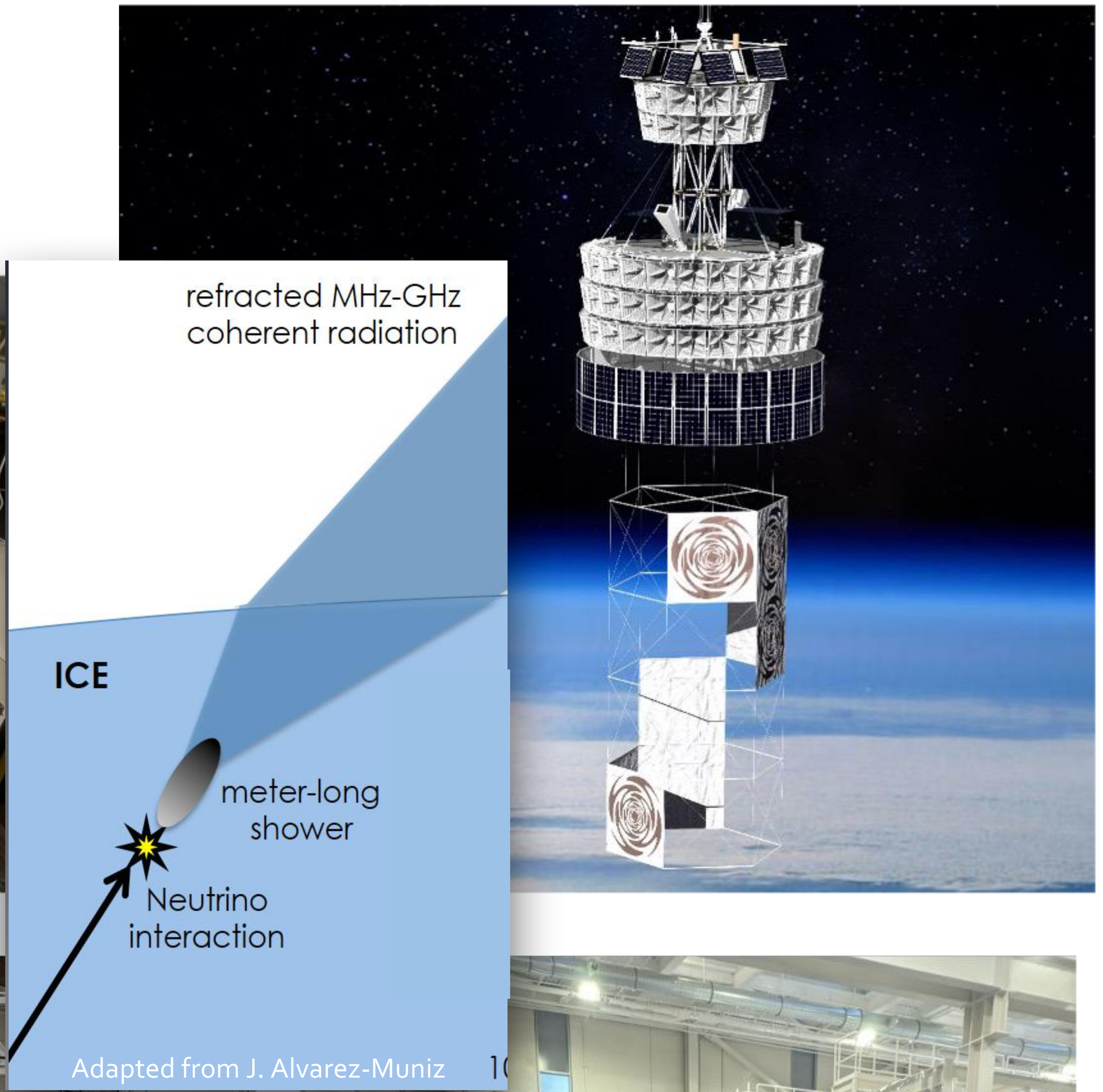
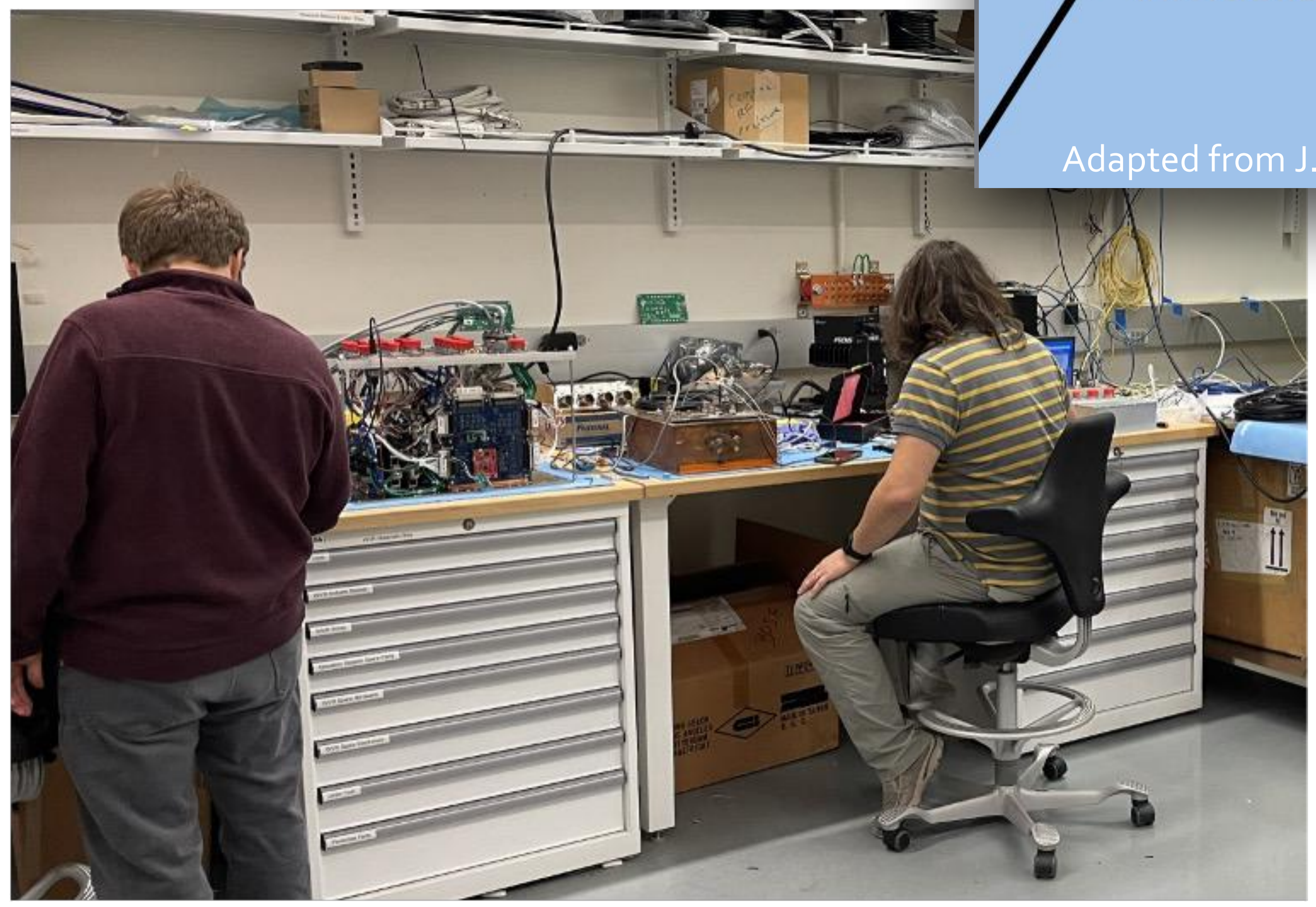
The Payload for Ultrahigh Energy Observations (PUEO)

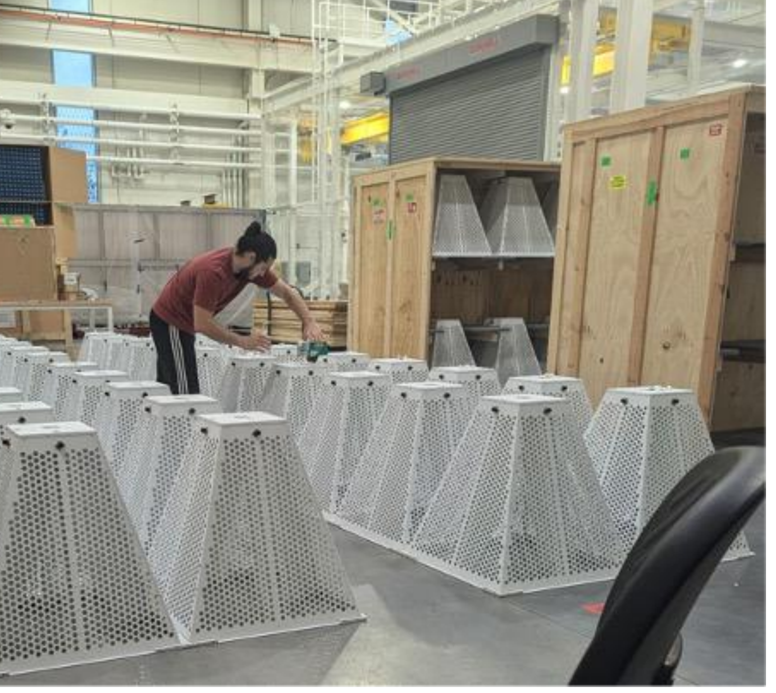
- PUEO is a NASA Pioneers mission, scheduled for launch on a Long Duration Balloon in Antarctica in December 2025.
- PUEO subsystems are being assembled; instrument integration begins in Chicago in December (next month!)
- PUEO targets the highest energy neutrinos through the in-ice Askaryan and air shower channels.

PUEO Instrument:

- 192-RF-Channel Main Instrument (MI), 16-channel Low Frequency Instrument (LFI)
- 16-antenna, dual-polarization beamforming trigger
- Triply redundant 128 TB onboard data storage
- Suite of navigation instruments
- Housekeeping/environment sensor system
- In-flight calibration from the ground and from a suite of hand-launched HiCal payloads.







POEMMA* Balloon with Radio (PBR)

*Probe Of Extreme Multi-Messenger Astrophysics

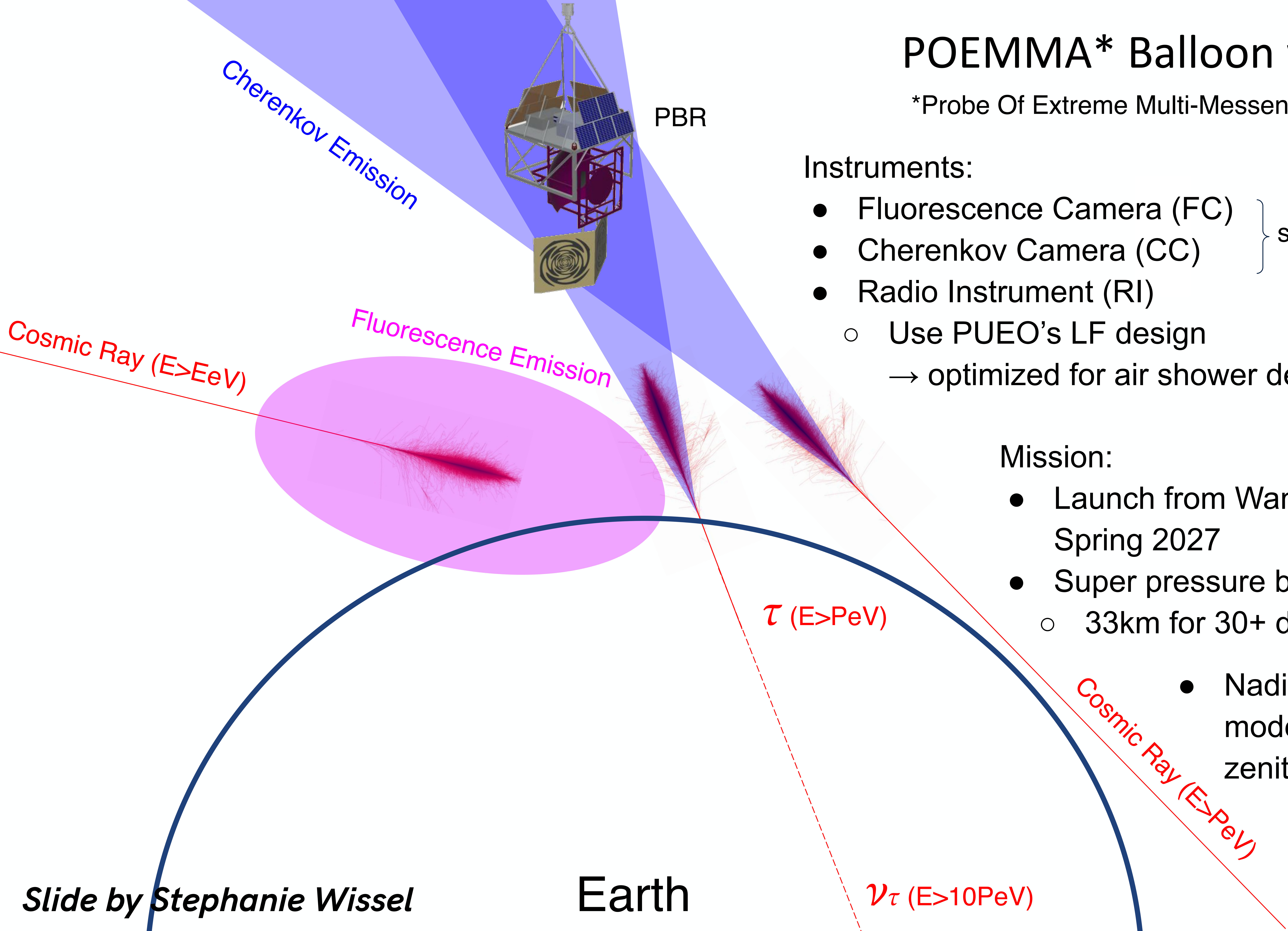
Instruments:

- Fluorescence Camera (FC)
- Cherenkov Camera (CC)
- Radio Instrument (RI)
  - Use PUEO's LF design → optimized for air shower detection

(FC and CC: share a focal surface)

Mission:

- Launch from Wanaka, NZ in Spring 2027
- Super pressure balloon flight
  - 33km for 30+ days
- Nadir/horizon operation modes using azimuth and zenith rotations



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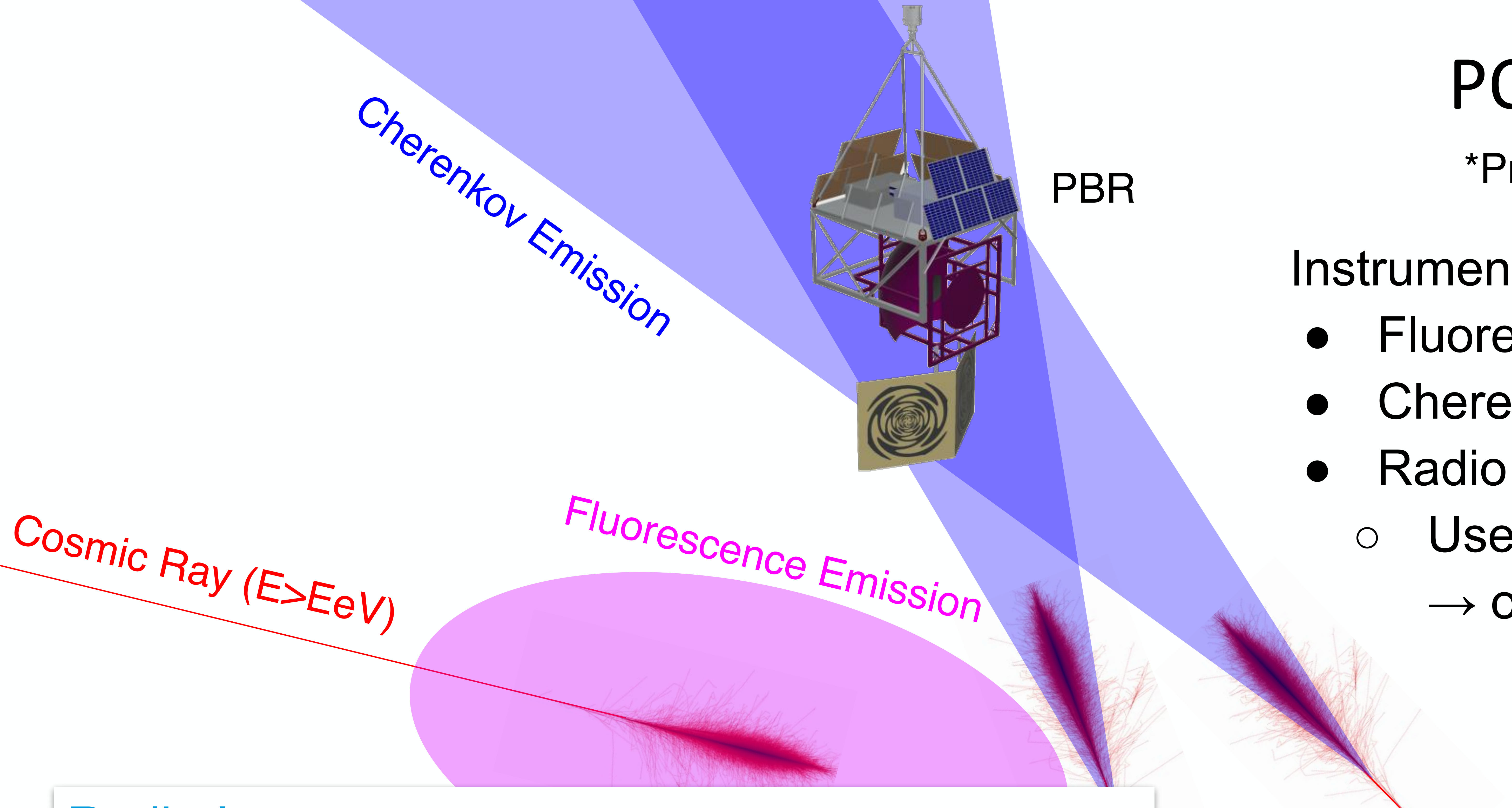

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Radio Instrument

- Two 2m x 2m dual polarized antennas, below payload, based on the design of PUEO's low frequency instrument
  - Bandwidth: 50-500MHz
  - 60° x 60° single antenna FoV
  - Beamforming allows for zenith reconstruction + lowered thresholds
- Two triggering methods via RFSoC:
  - Forced (coincident) trigger with Cherenkov camera (E~PeV)
  - Daytime radio-only trigger (E~EeV)
- Effort to measure and mitigate RFI from remainder of payload underway

Slide by Stephanie Wissel

BEACON Prototype

Goal → Validate full instrument neutrino sensitivity
How → Verify cosmic ray (CR) air shower radio flux

Recent Progress

- 2021 prototype CR search demonstrates capabilities to RF self-trigger on impulsive events (D. Southall)
- RF-only CR search improvements in progress (A. Zeolla) combing CNN classifier with spatiotemporal clustering and denoising
- 2023 upgrades introduced independent scintillator array
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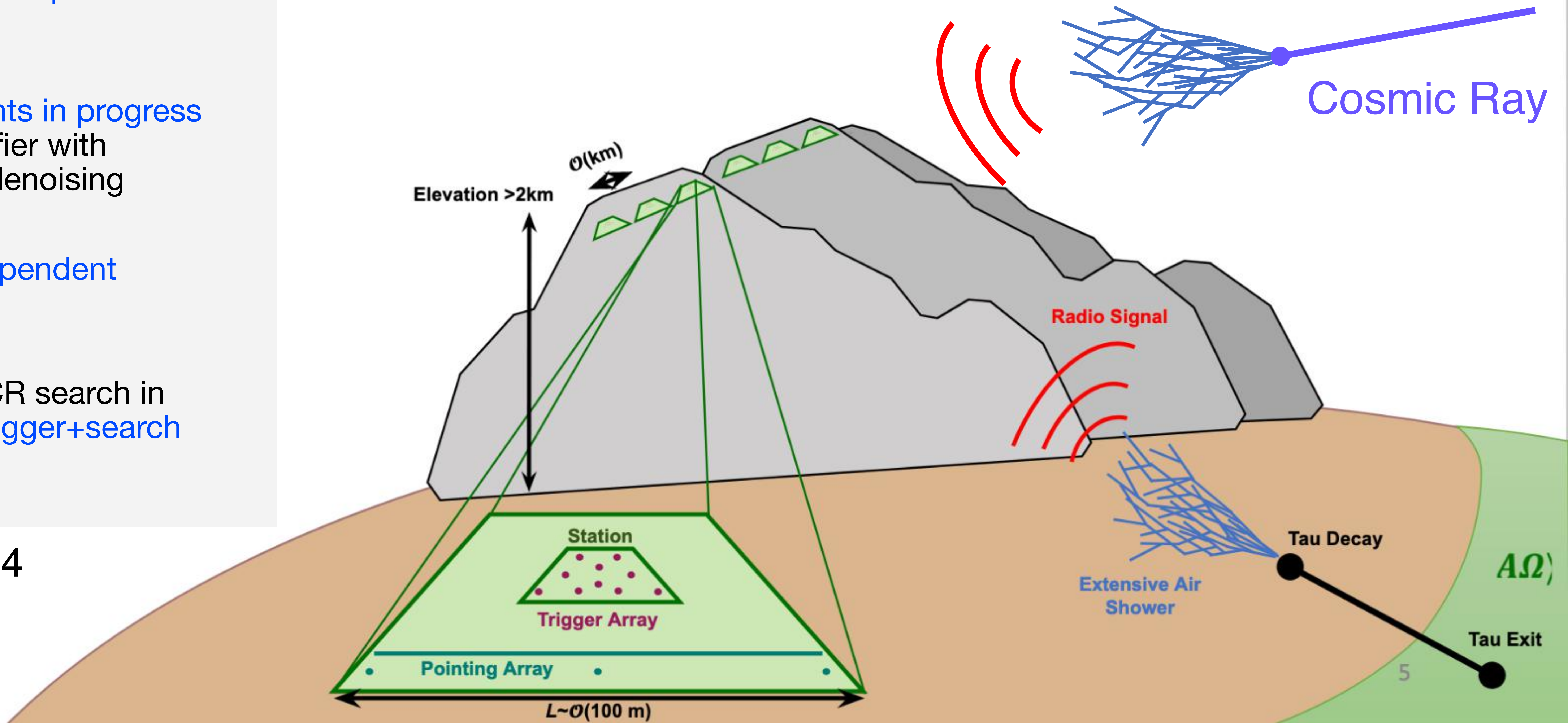
Z. Martin ARENA 2024



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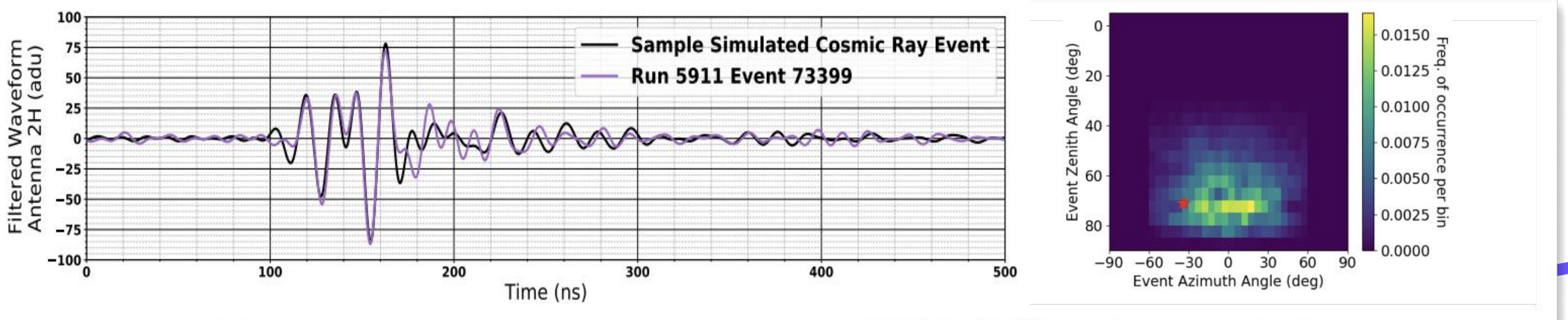
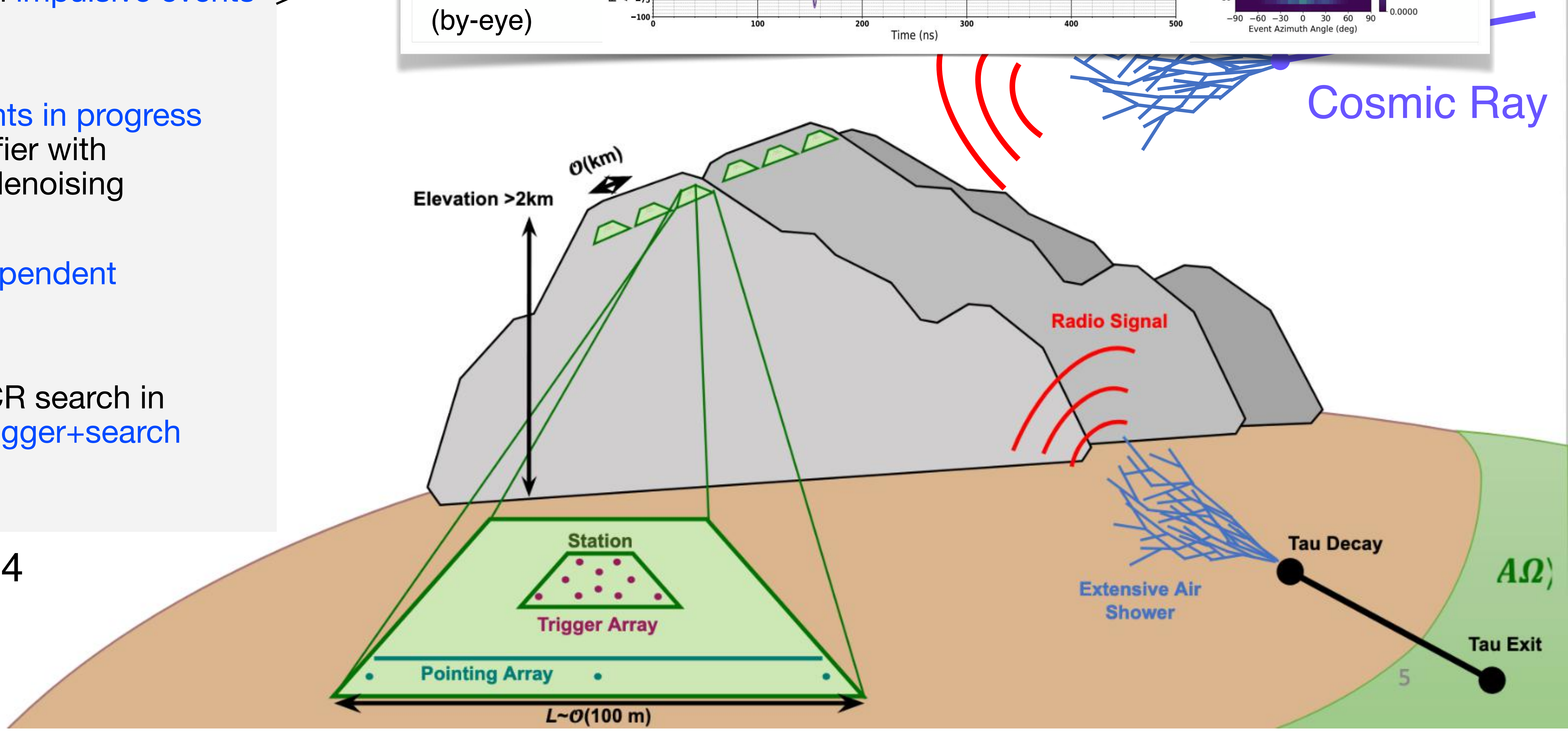
Cosmic-ray candidate event identified (by-eye)

Compared to expected geometry





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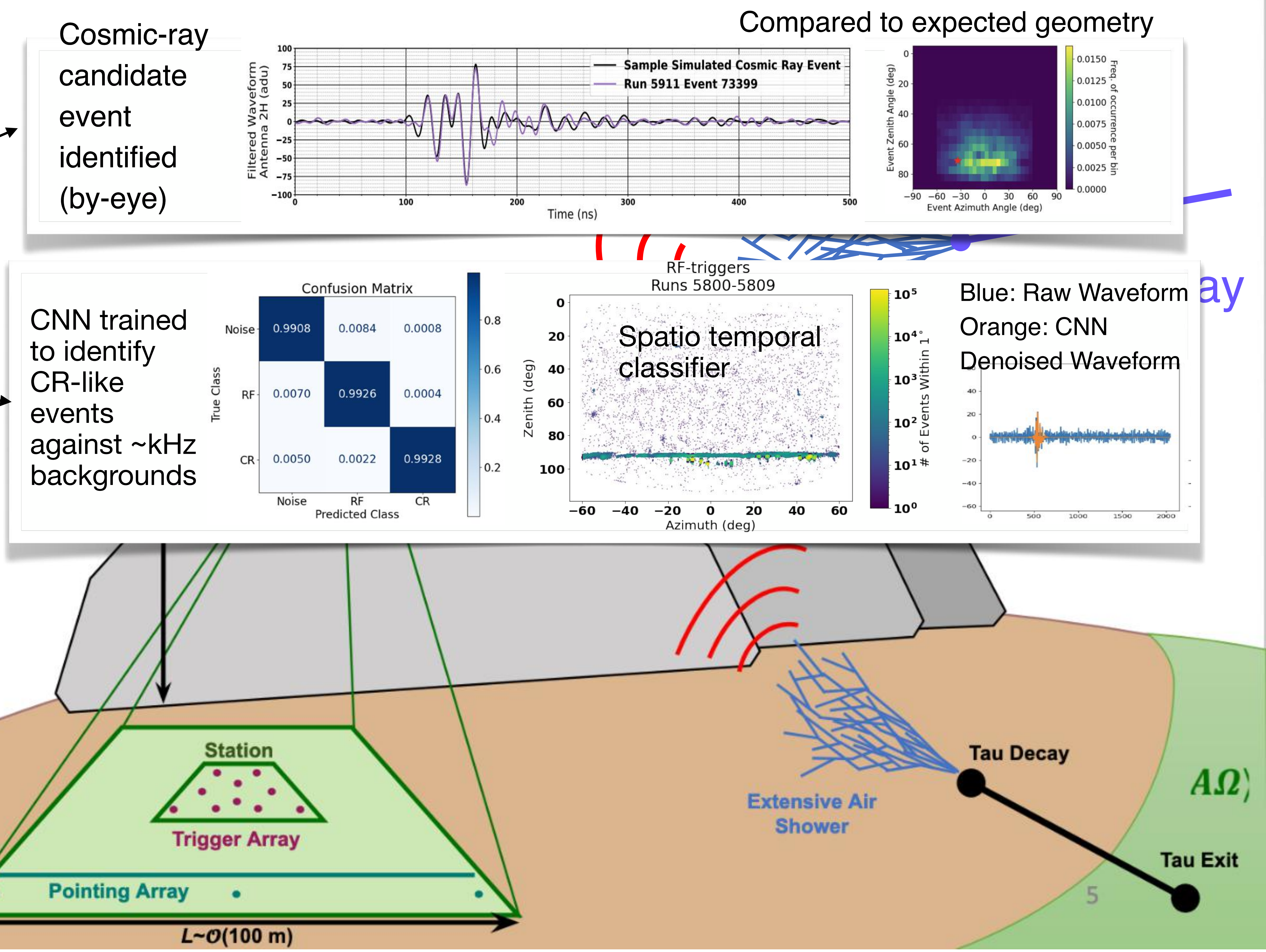

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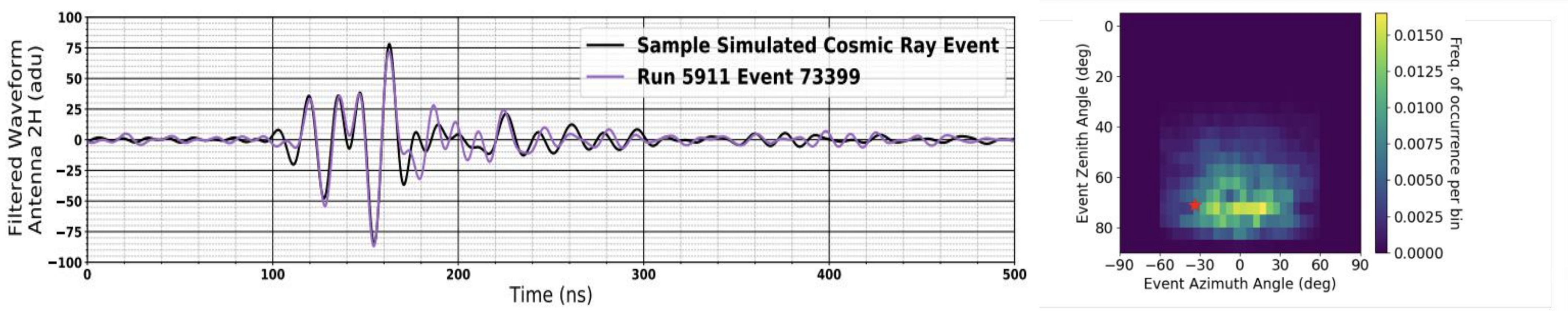
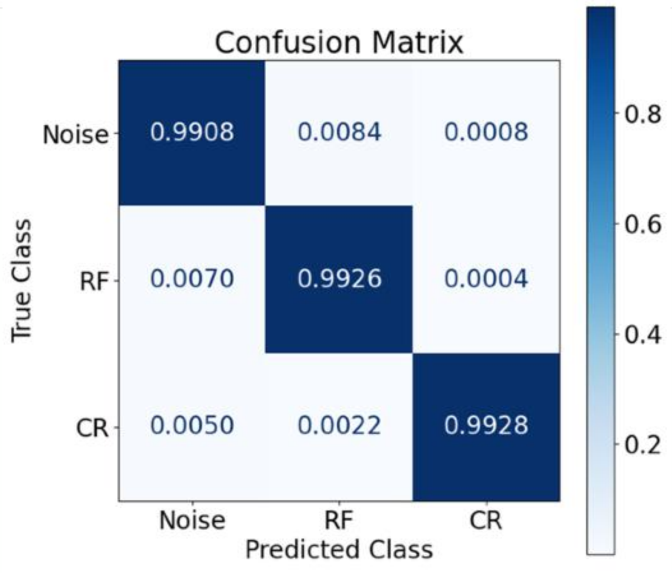
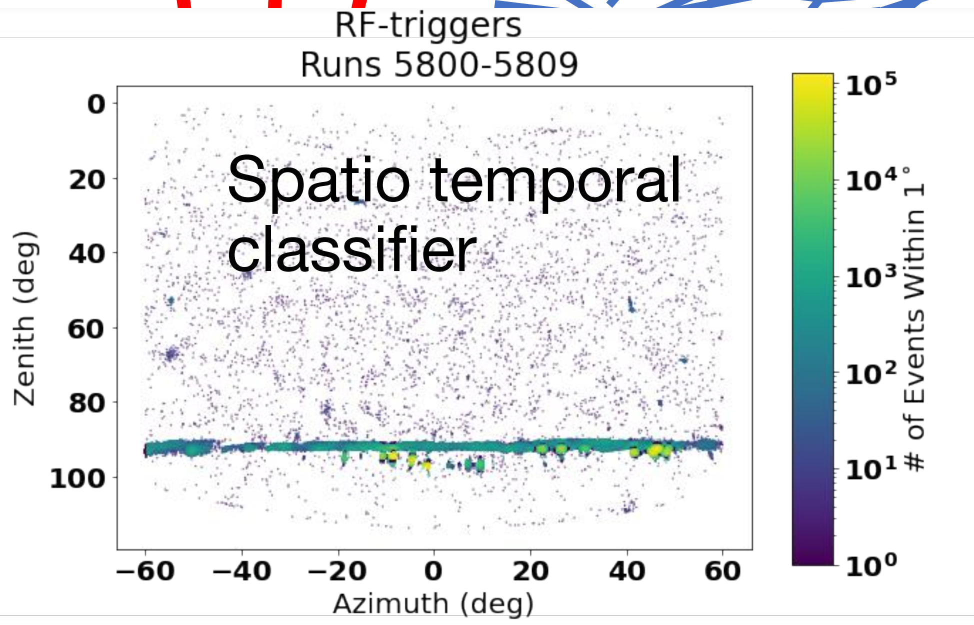
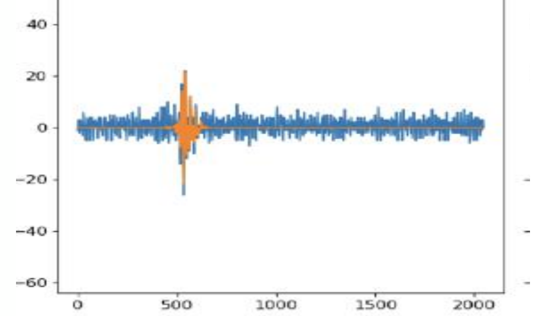


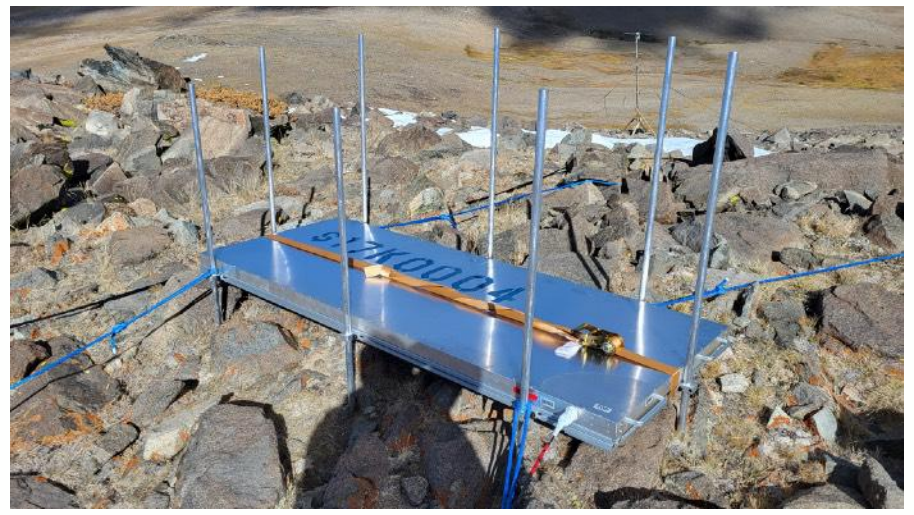
CNN trained to identify CR-like events against ~kHz backgrounds



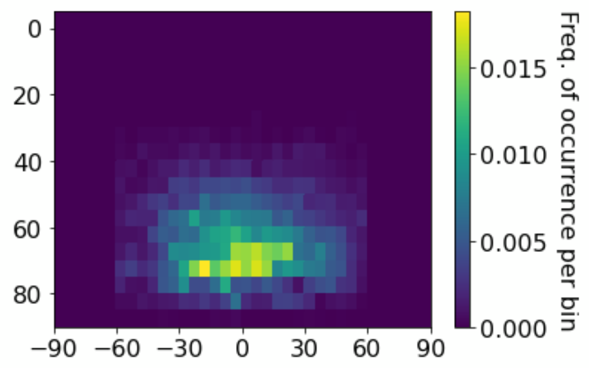


Blue: Raw Waveform
Orange: CNN Denoised Waveform

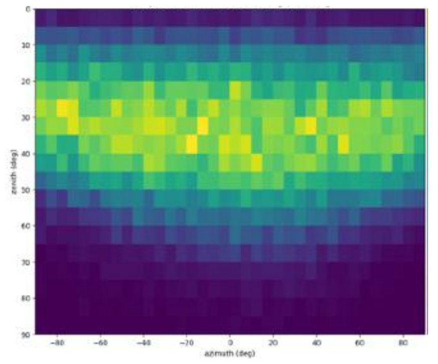


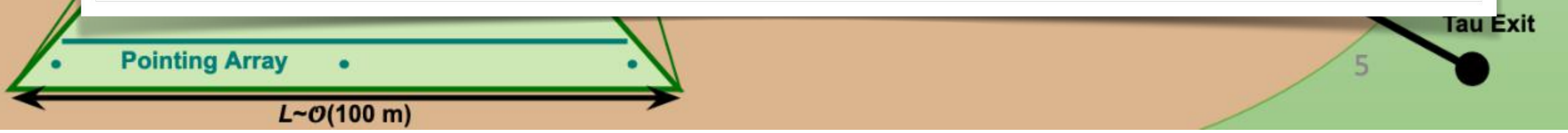


Simulated RF Event Distribution



Preliminary Scintillator Event Distribution





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GRAND & Prototypes

GRAND Coll. arXiv:2409.0295

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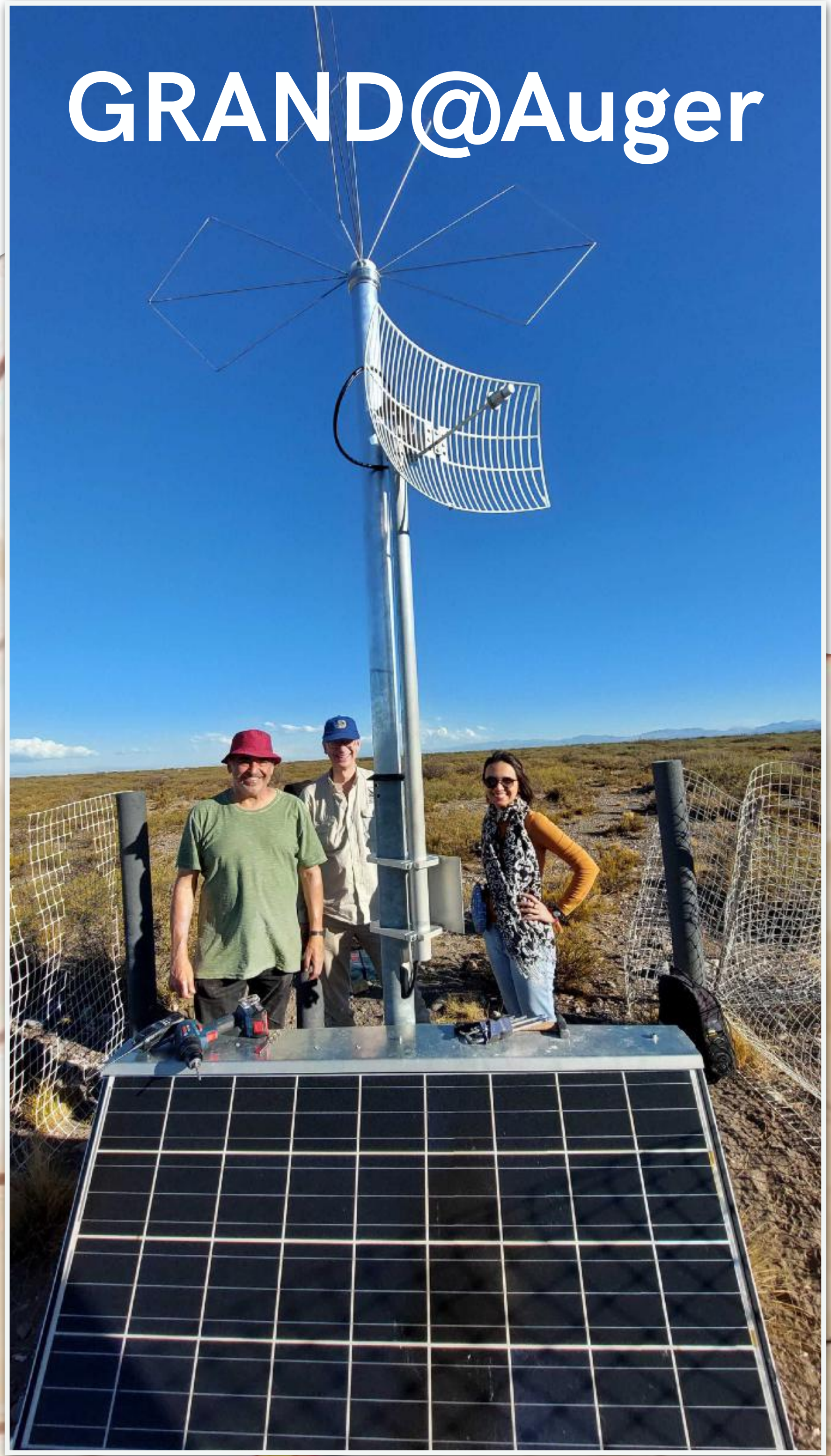

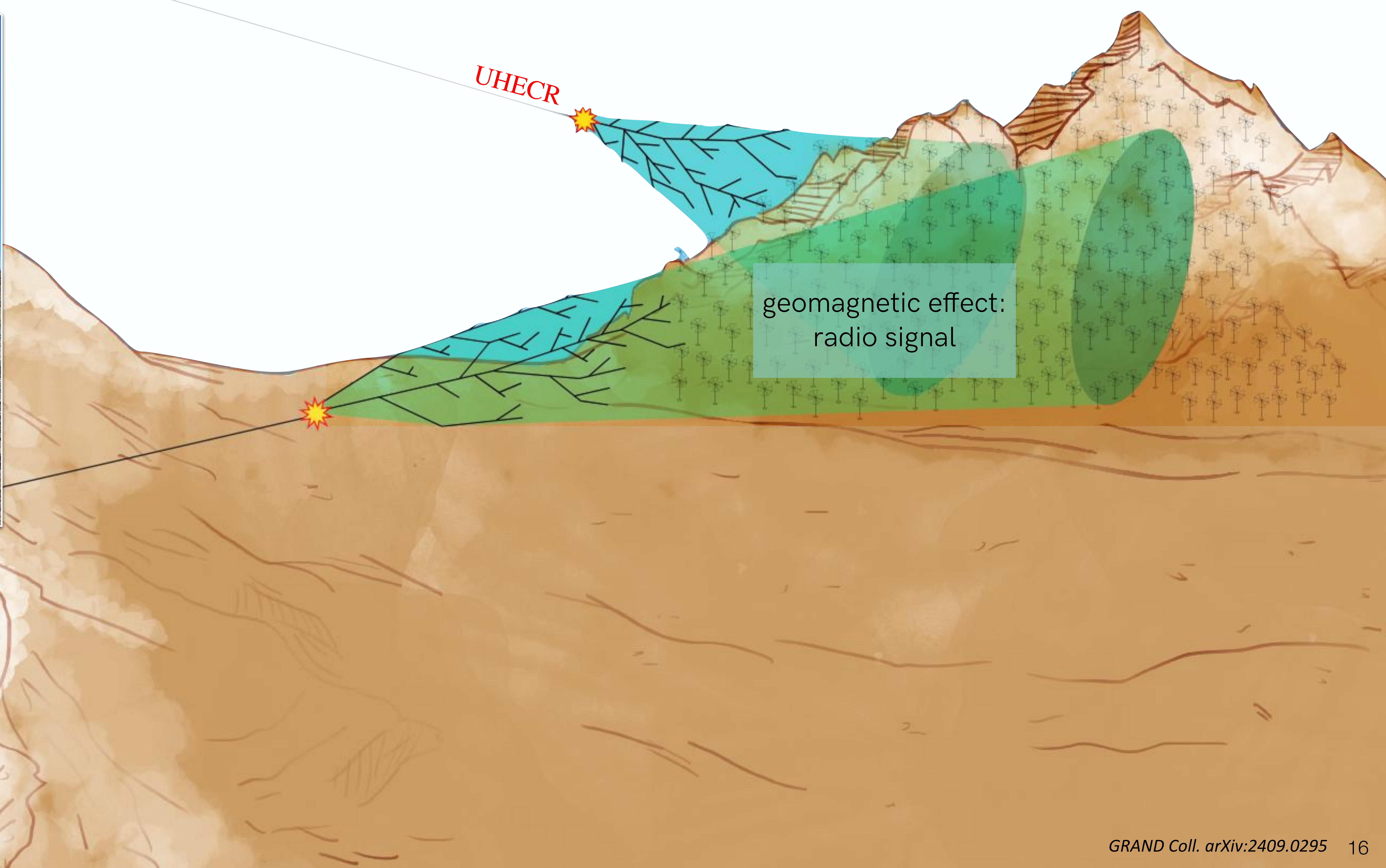

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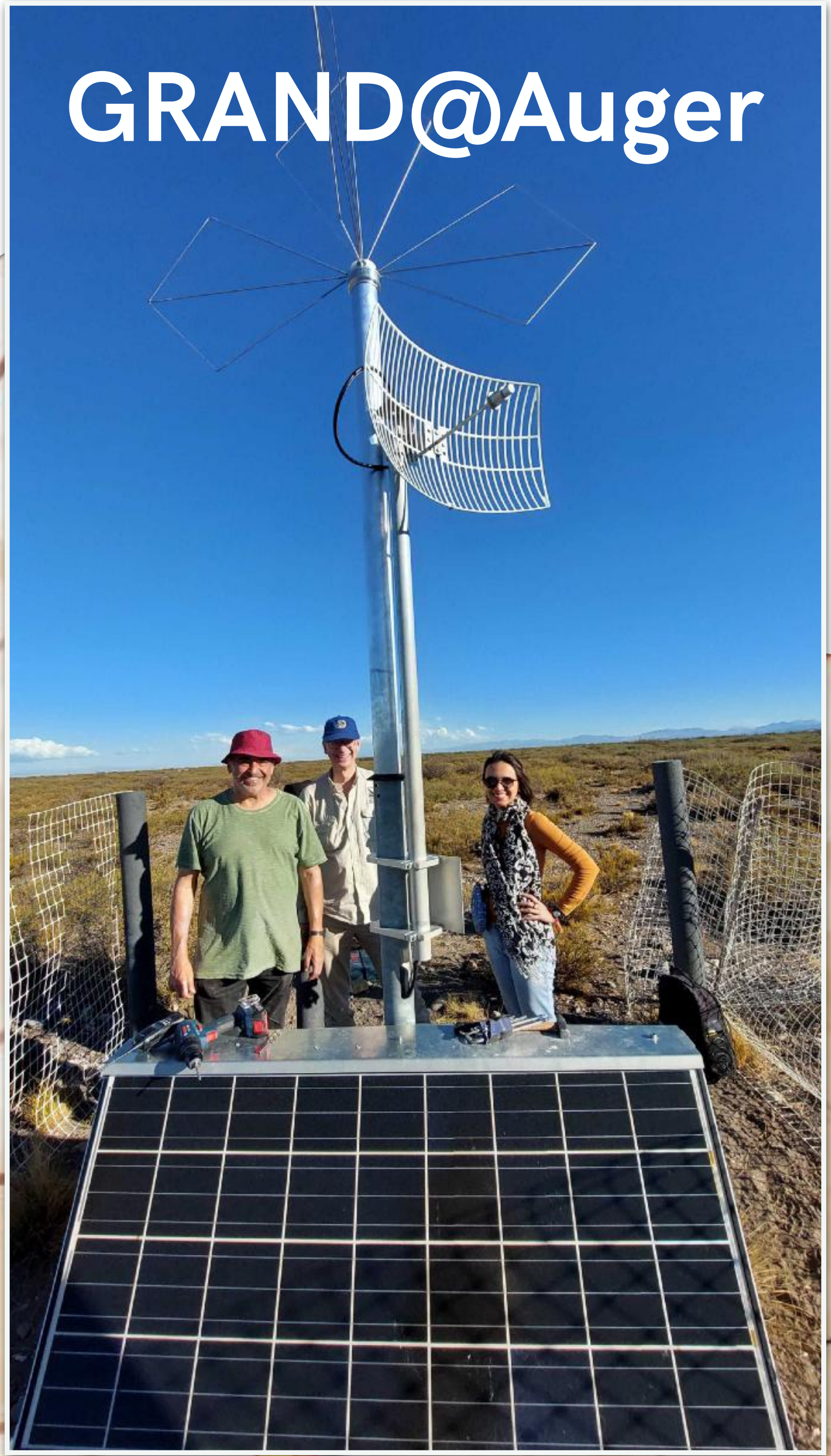

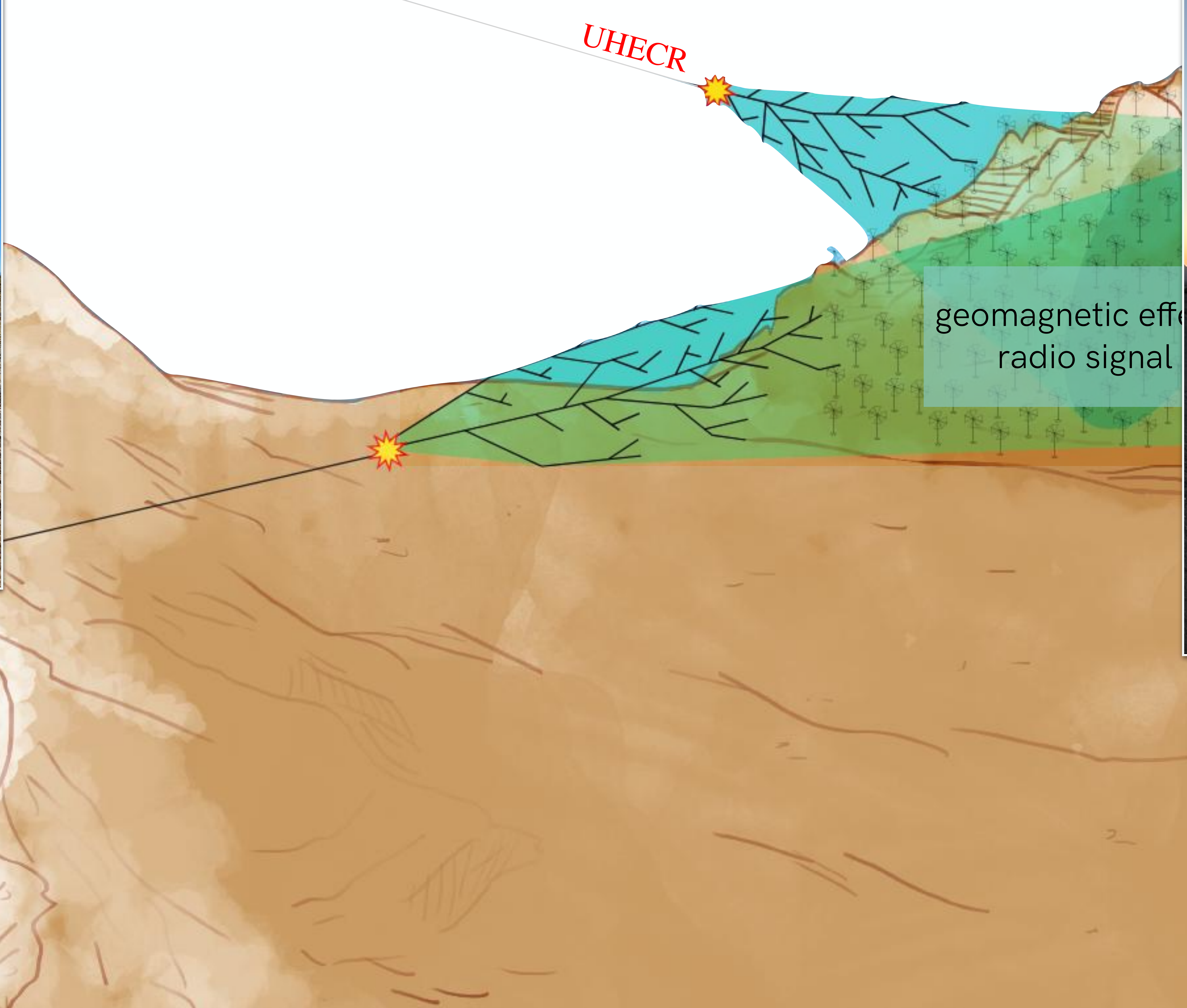

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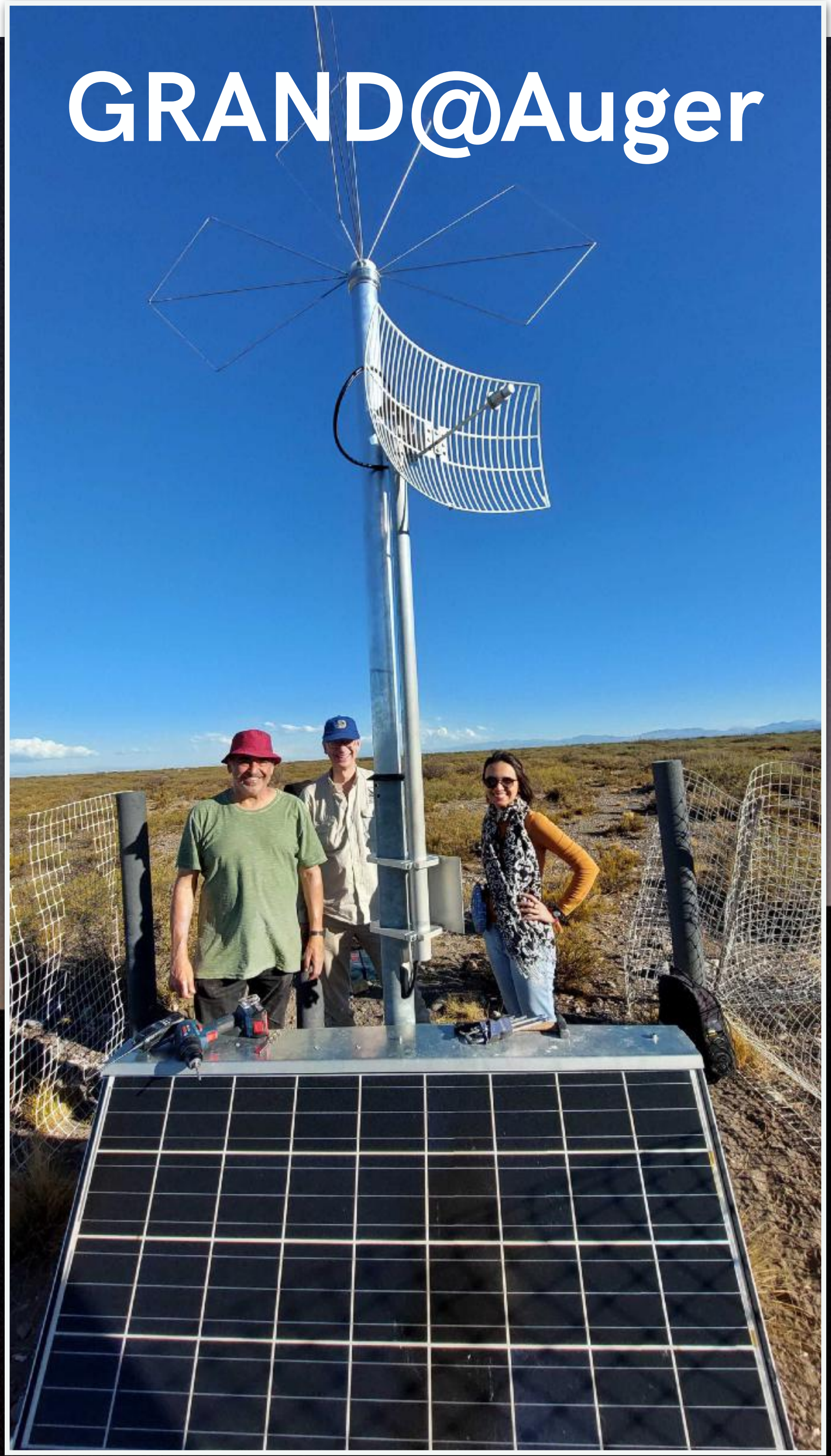

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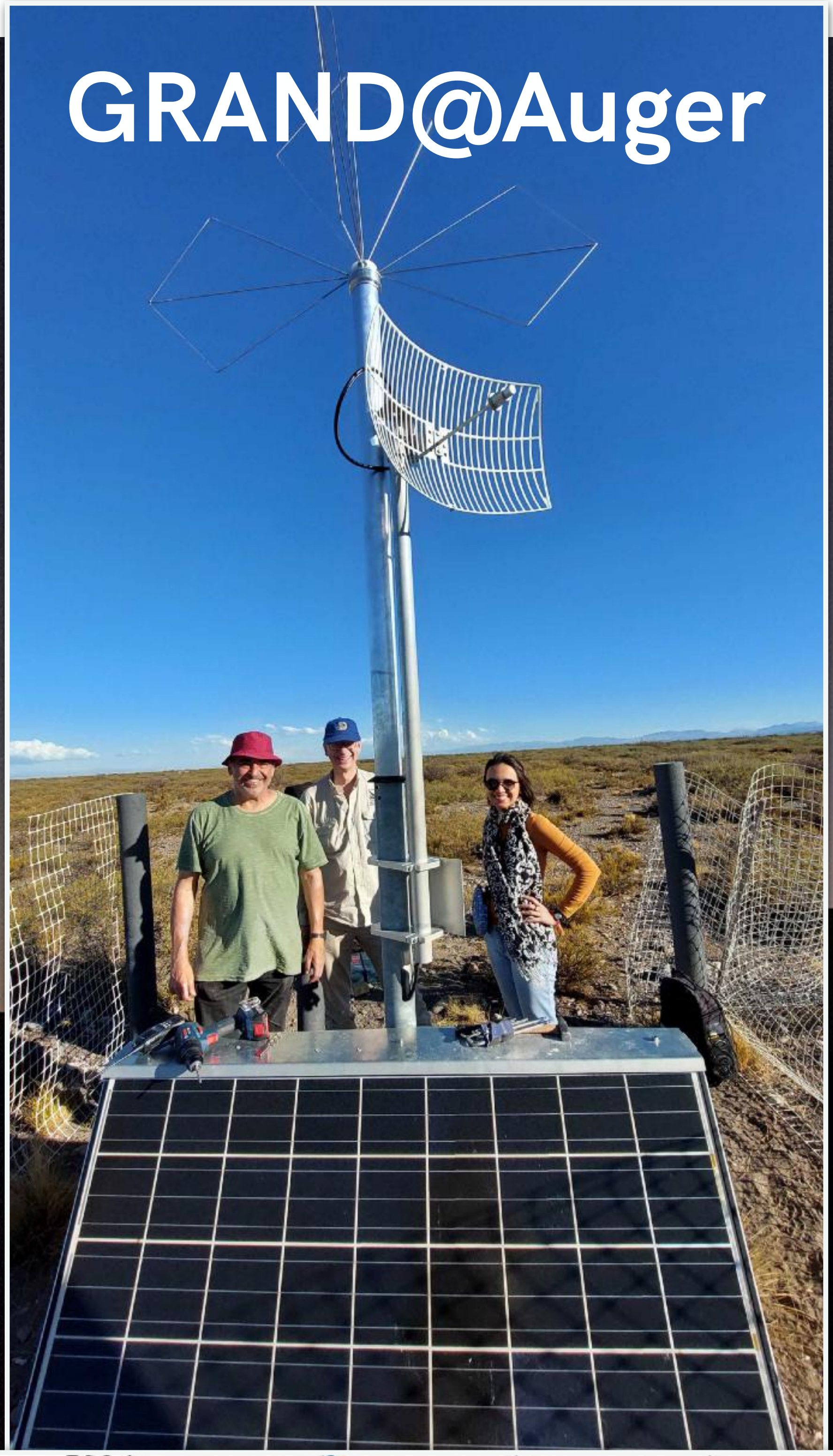
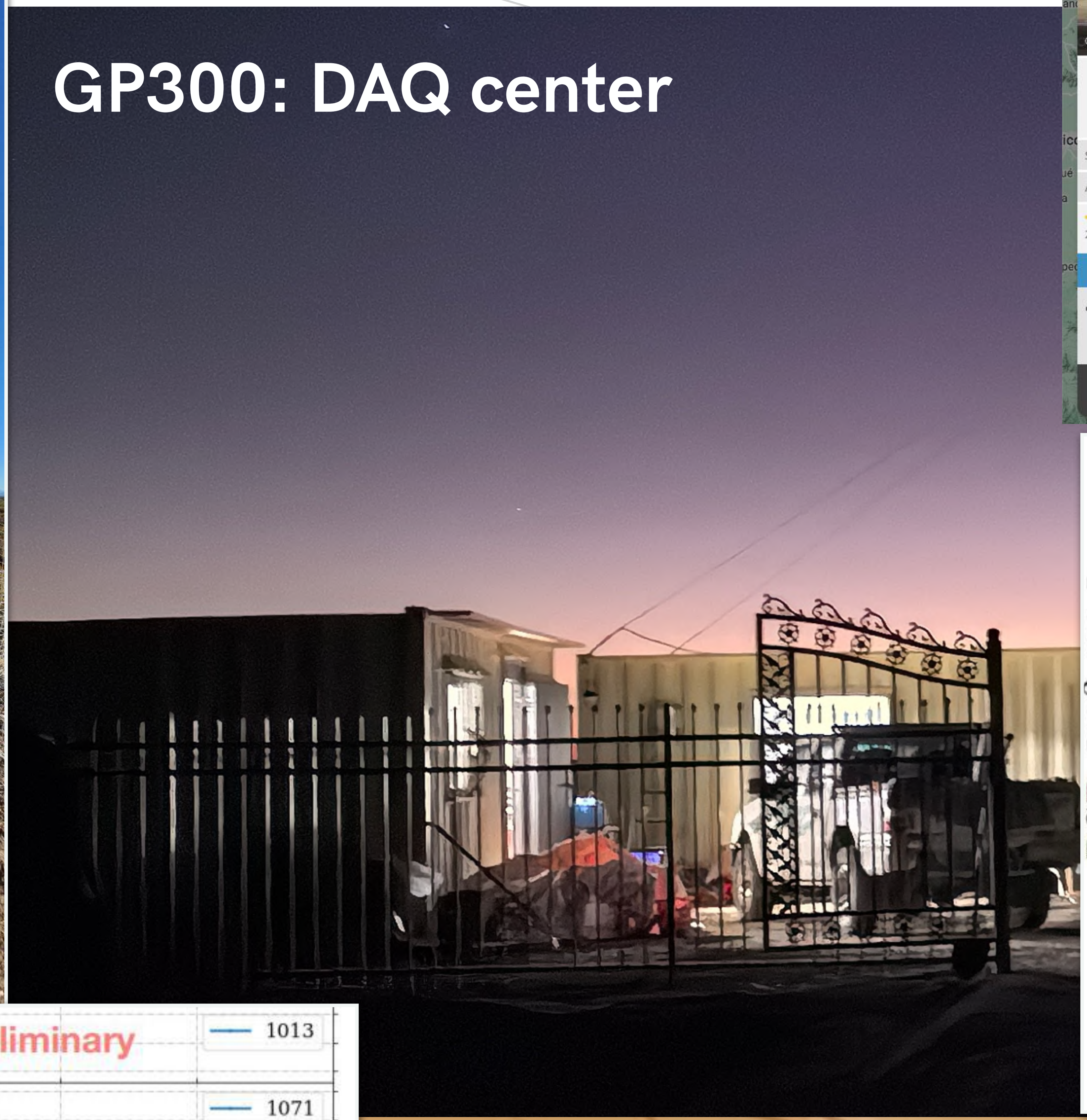
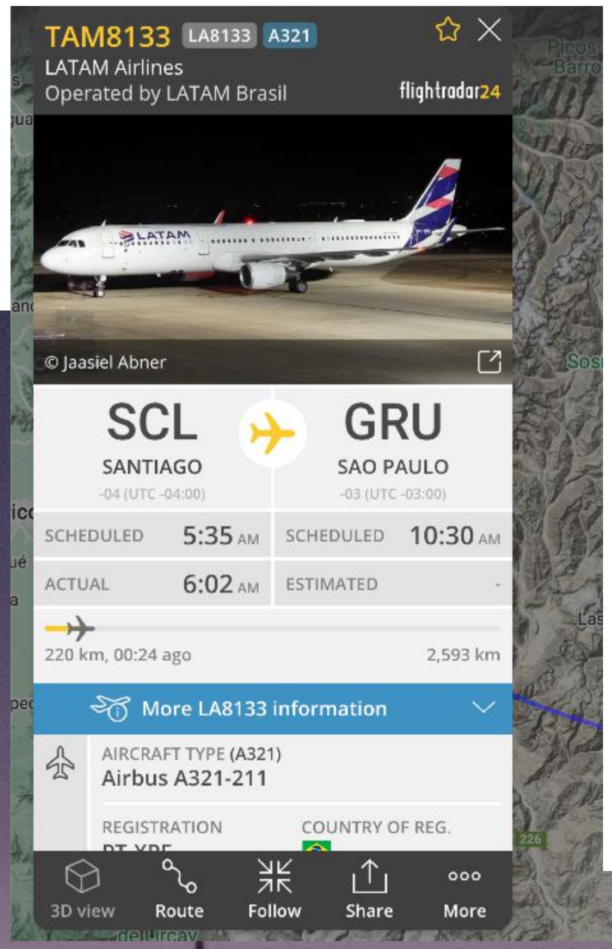
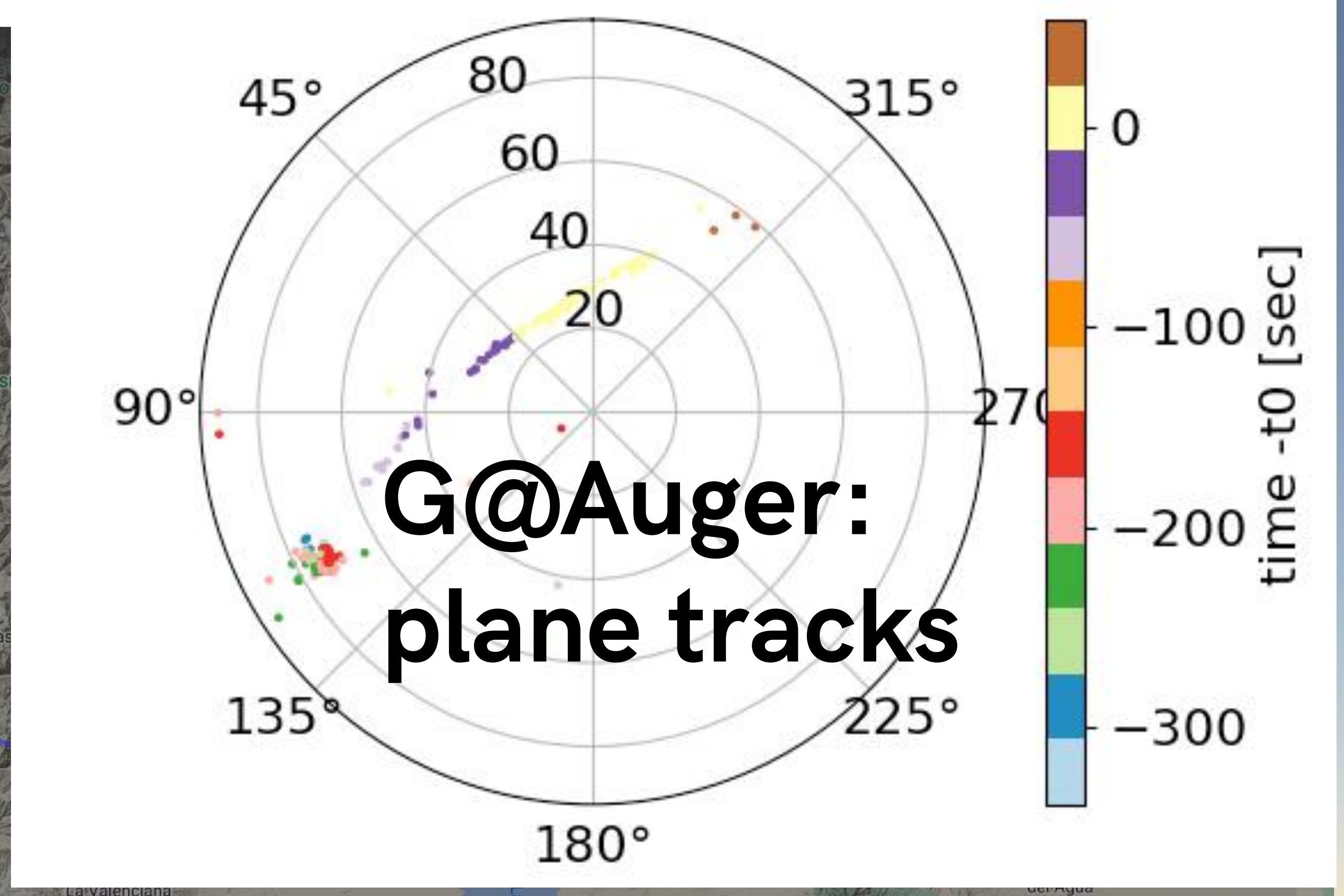
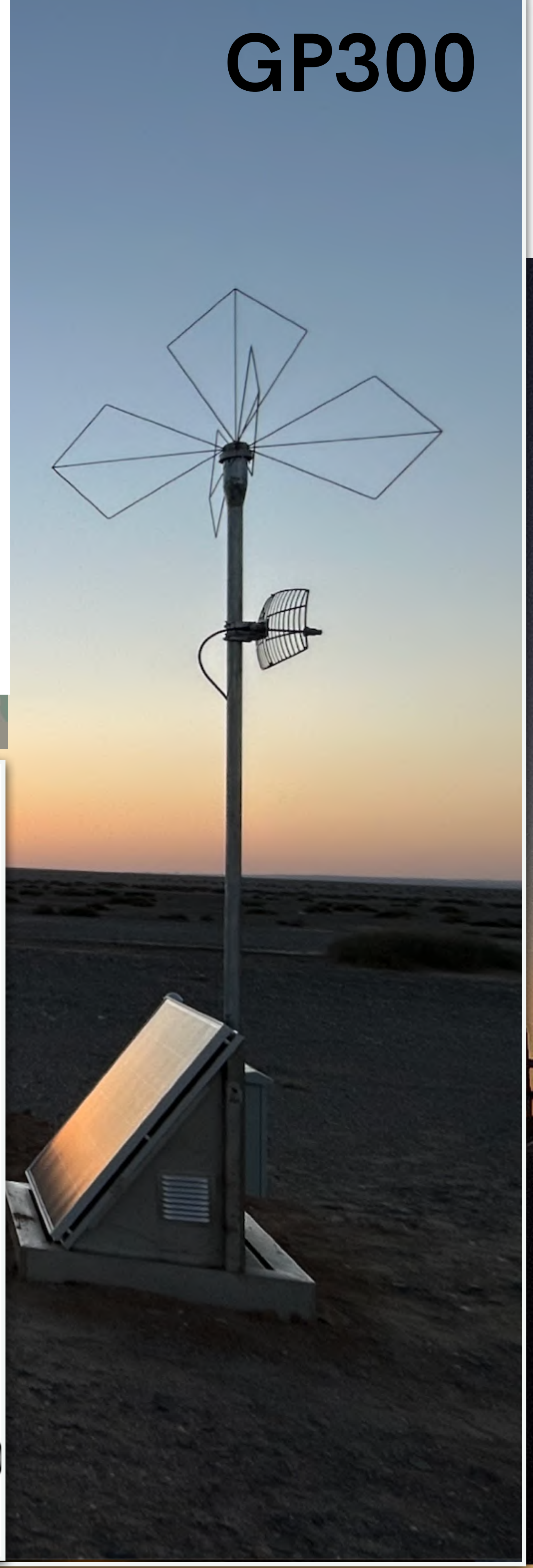
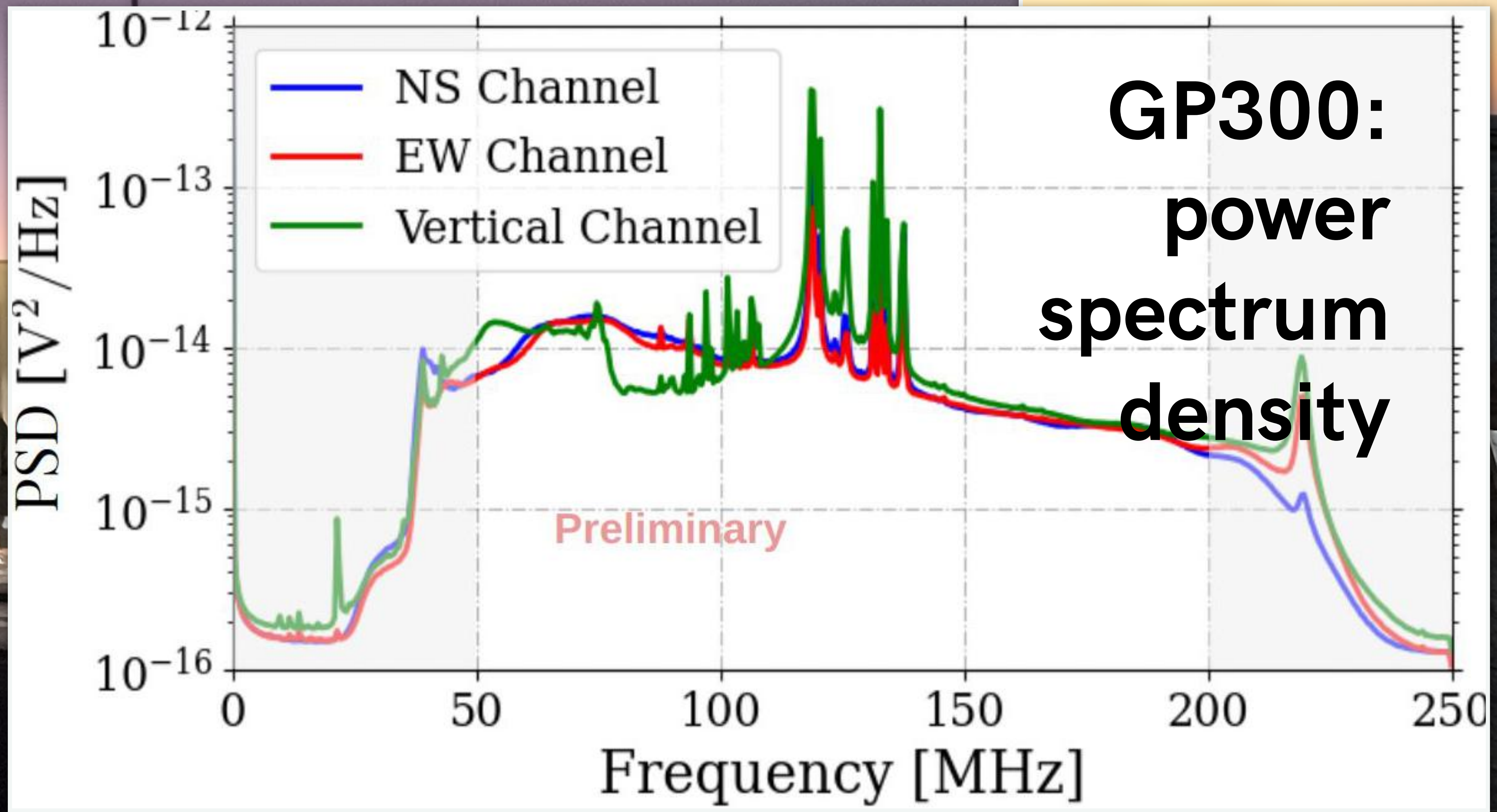


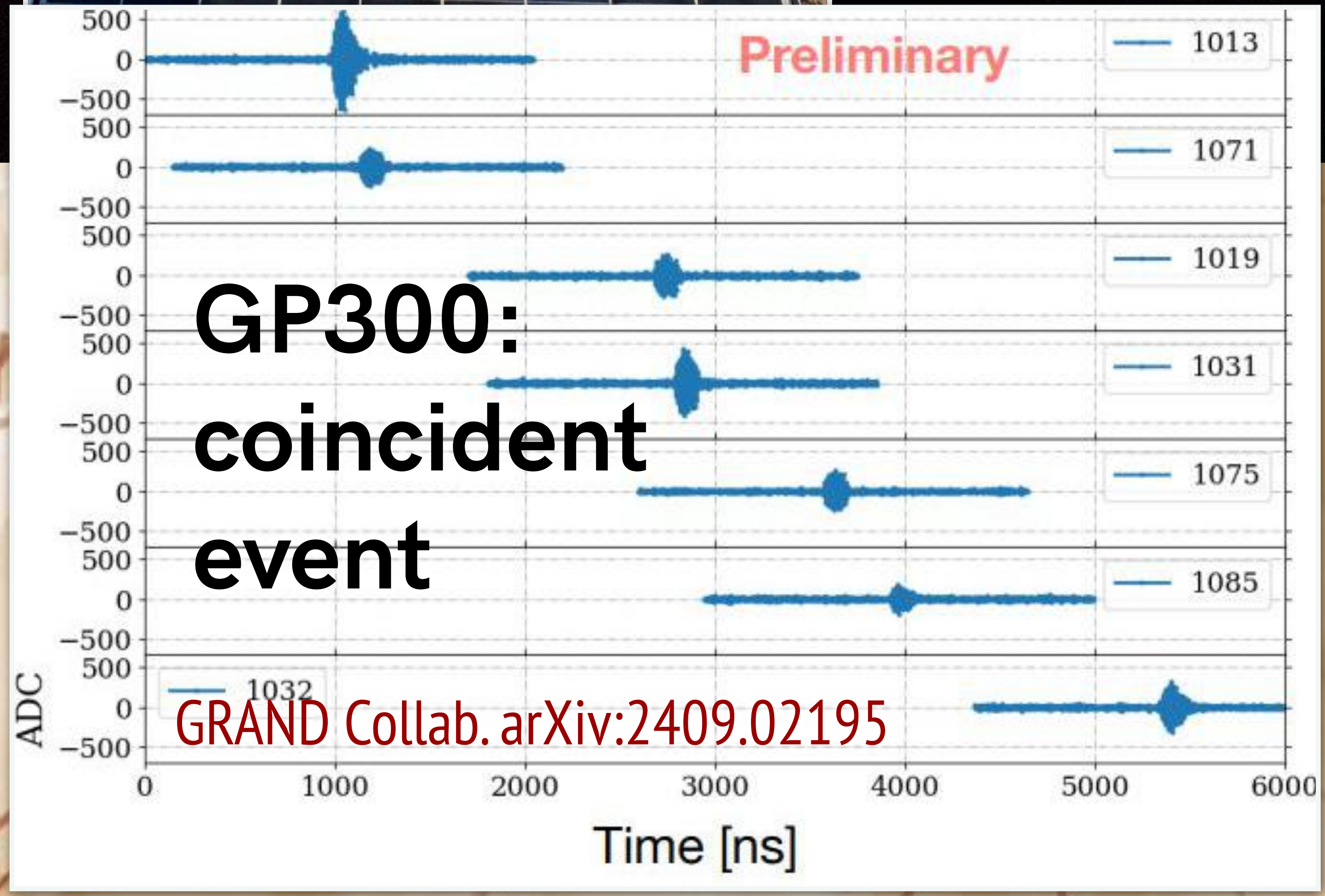






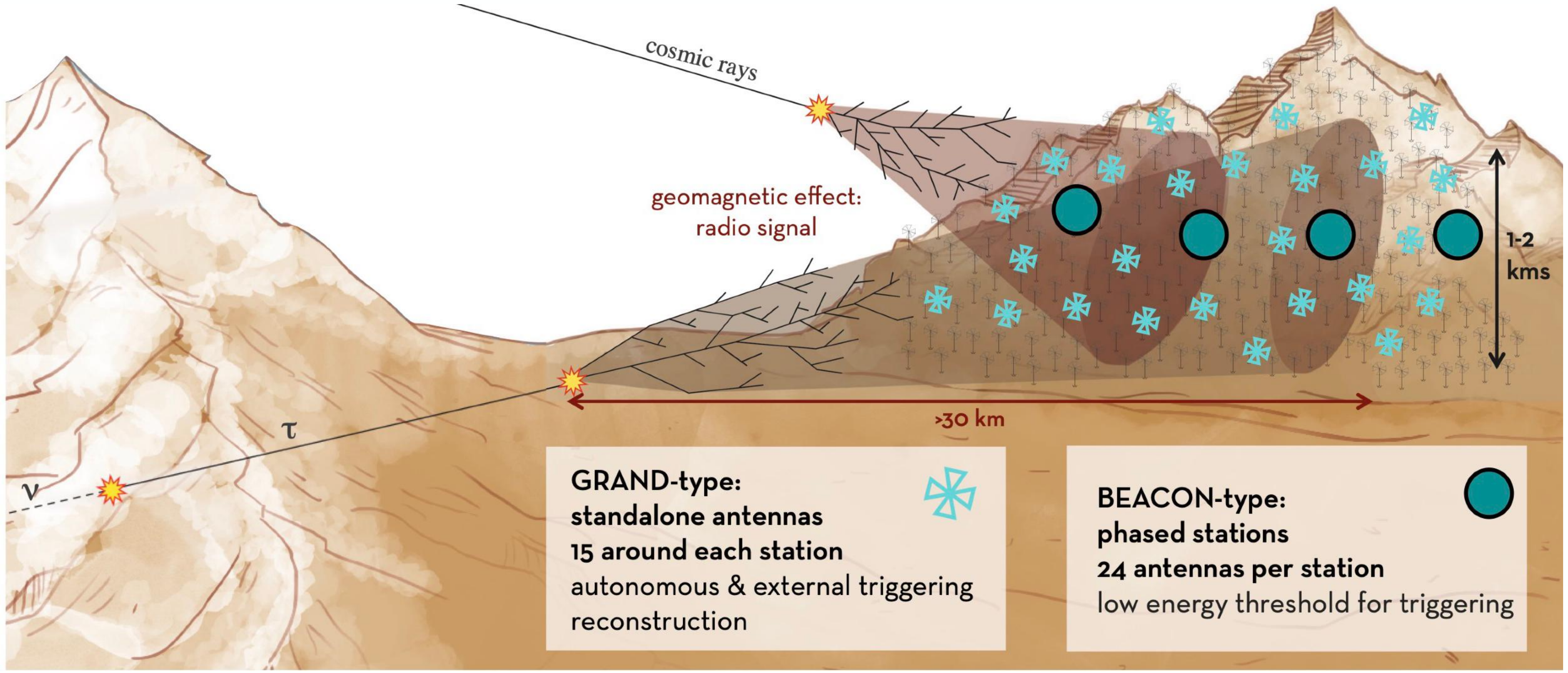




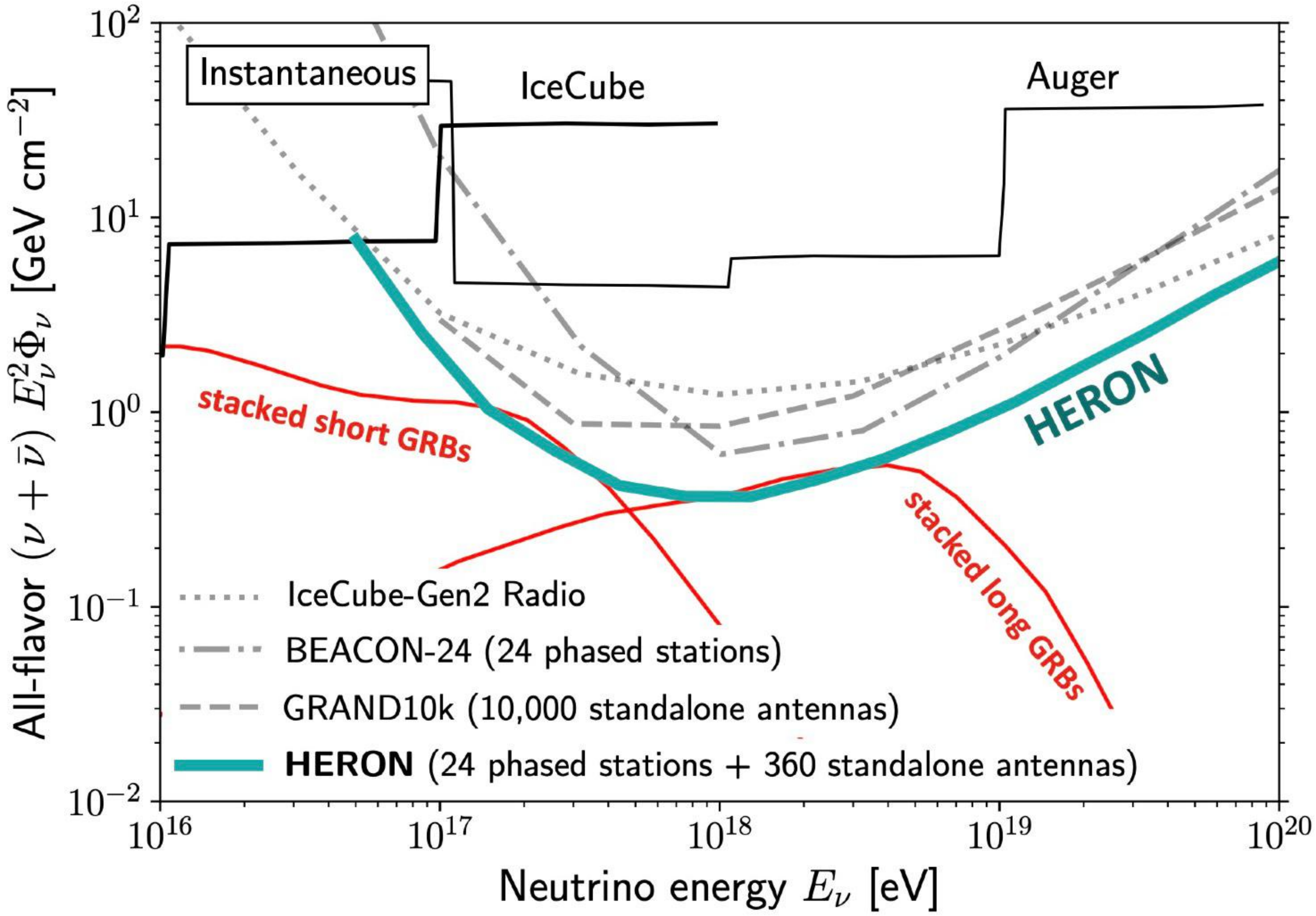


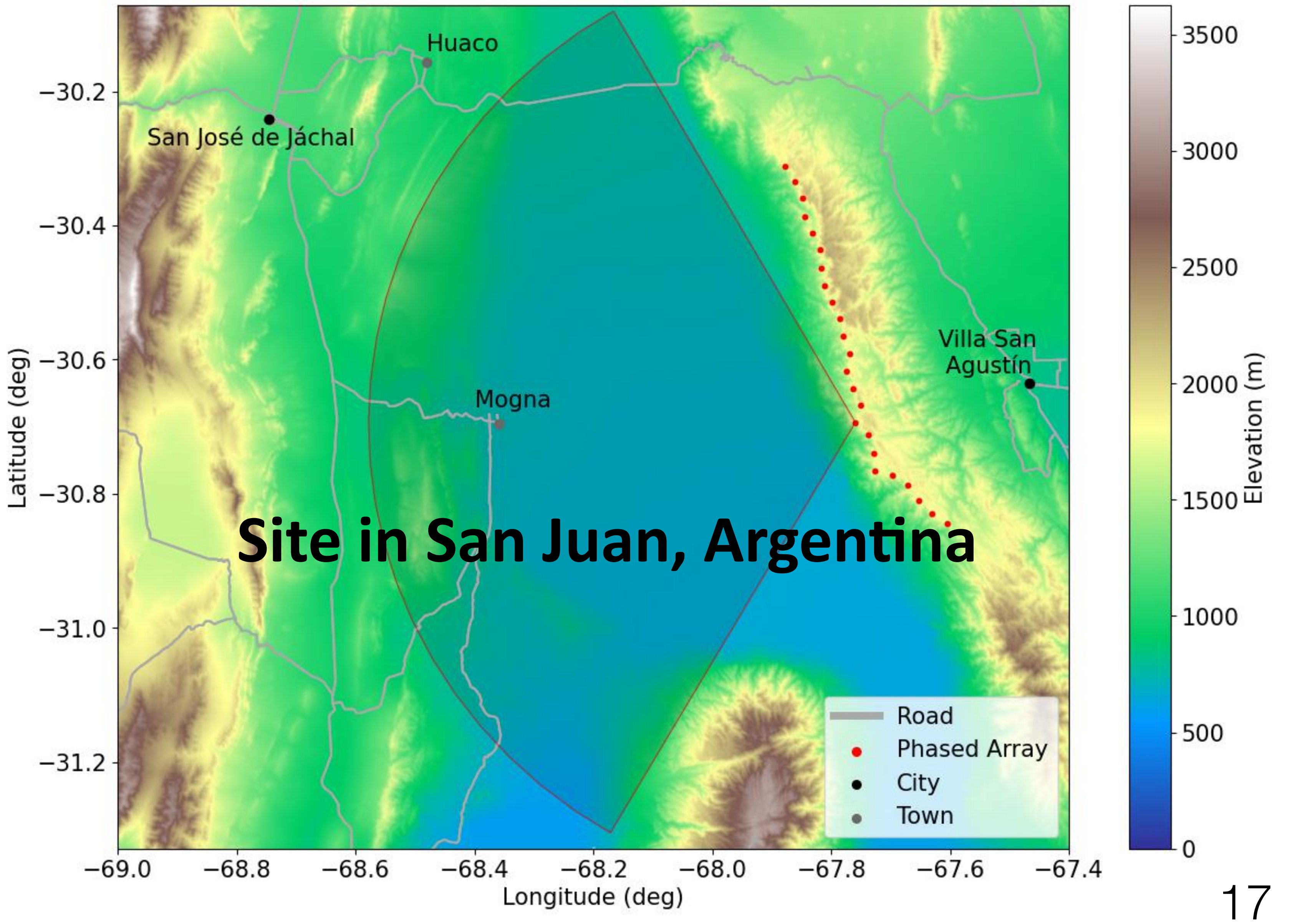
GRAND Coll. arXiv:2409.0295

Hybrid Elevated Radio Observatory for Neutrinos (HERON)



A discovery instrument!





- **24 phased stations** ("BEACON-type" in the figure below) : **70 km linear along mountain**
  each station contains: 24 compact radio antennas (3 m high, 1 m² of footprint on ground)
  station surface: ~100 m² each
  altitude 1000 m
  separation between stations: ~ 3 km
- **360 standalone antennas** ("GRAND-type" in the figure below) **at altitudes between 500 m and 1500**
  3m high, 1 square meter of footprint on ground)


2024
2026
2030+
RADIO DETECTION OF UHE NEUTRINOS
BALLOON
IN-AIR
IN-ICE
POEMMA
planned launch
PUEO
self-triggered
phased
pathfinders in commissioning
PIERRE AUGER OBSERVATORY
BEACON
GRAND
Proto300
HERON
RNO-G
Radio Neutrino Observatory - Greenland
RET
ICECUBE GEN2

Fang, KK, Miller, Murase, Oikonomou 2016

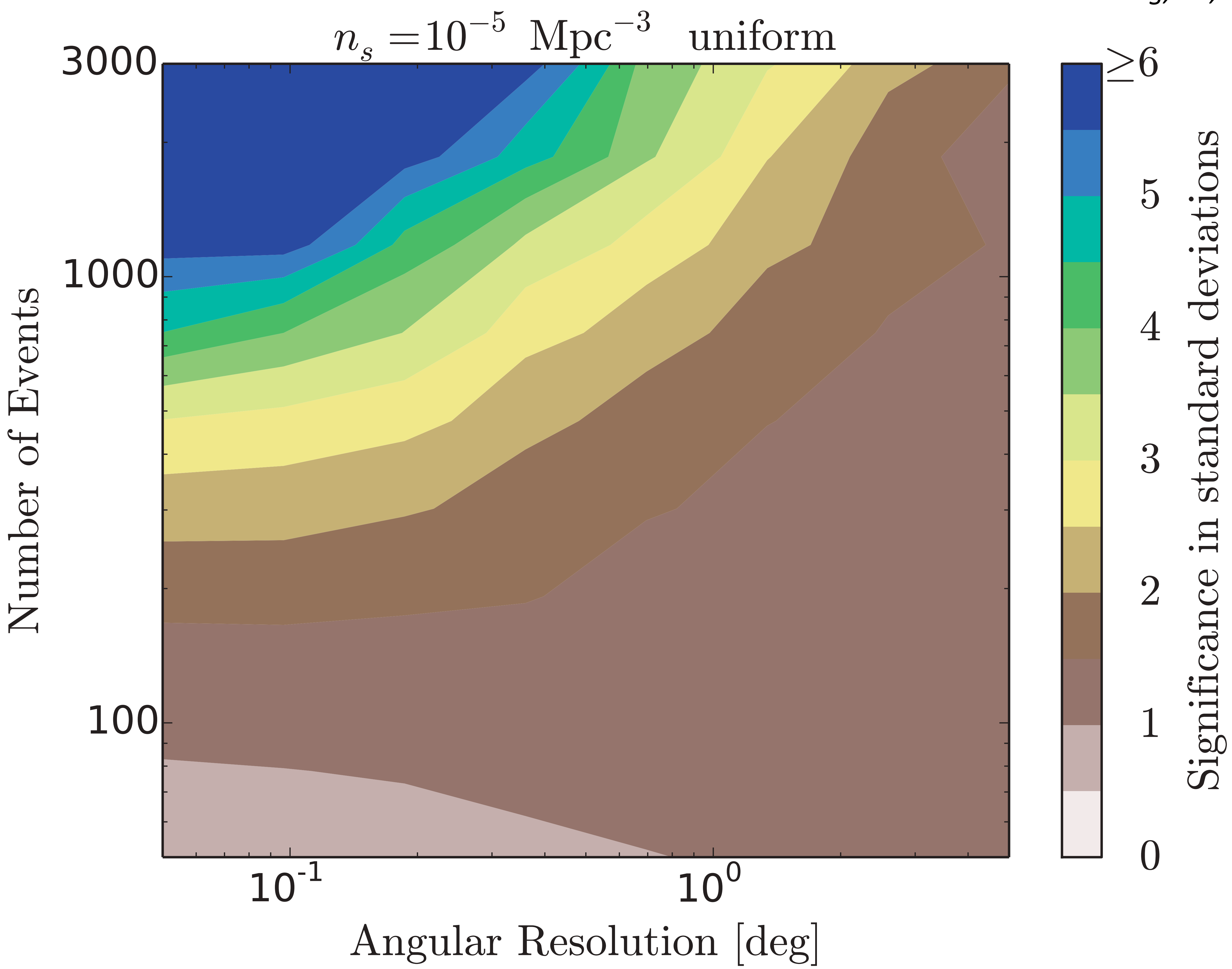
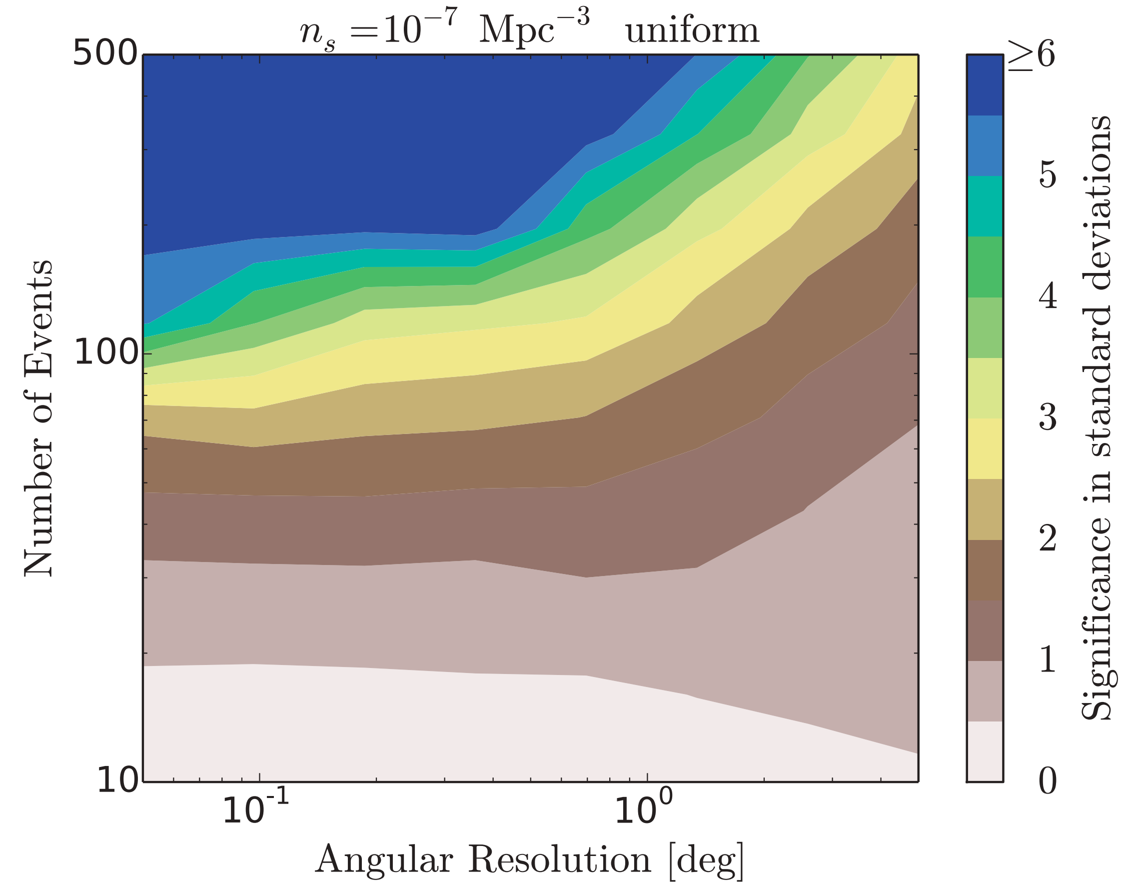
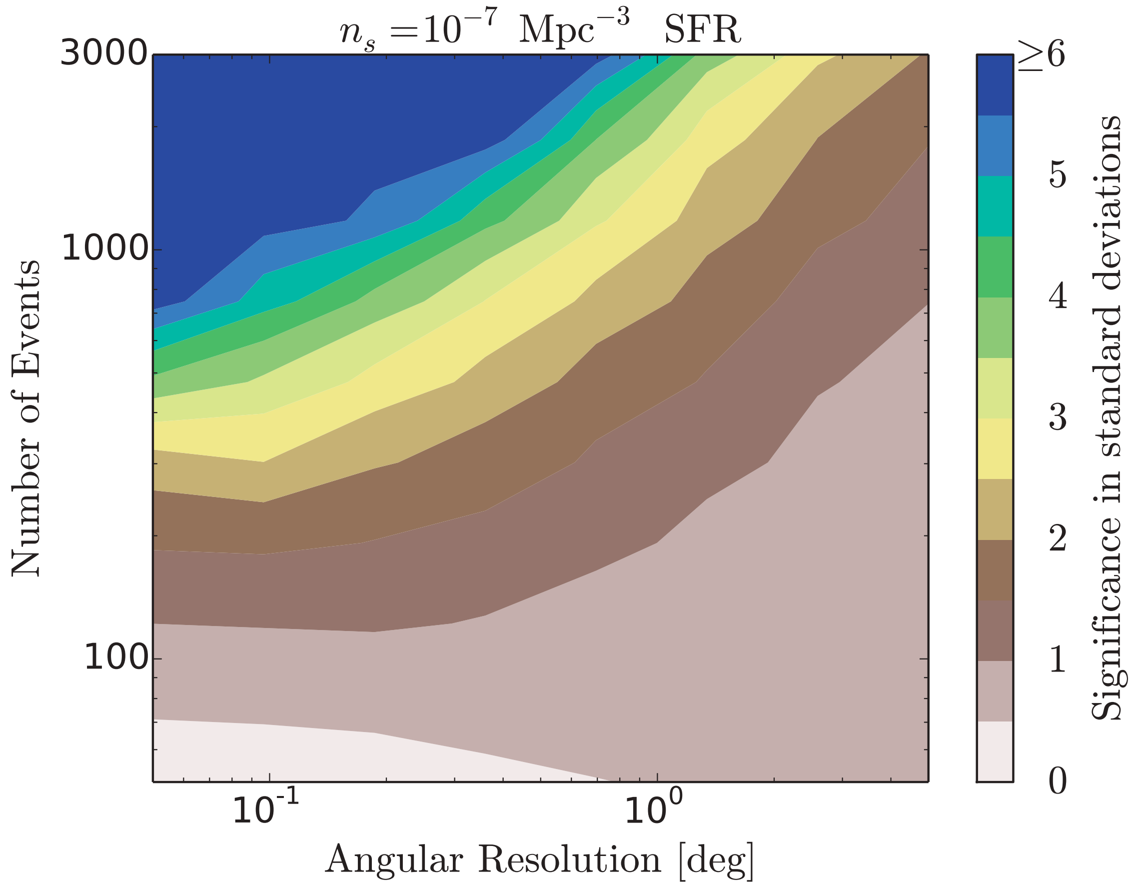
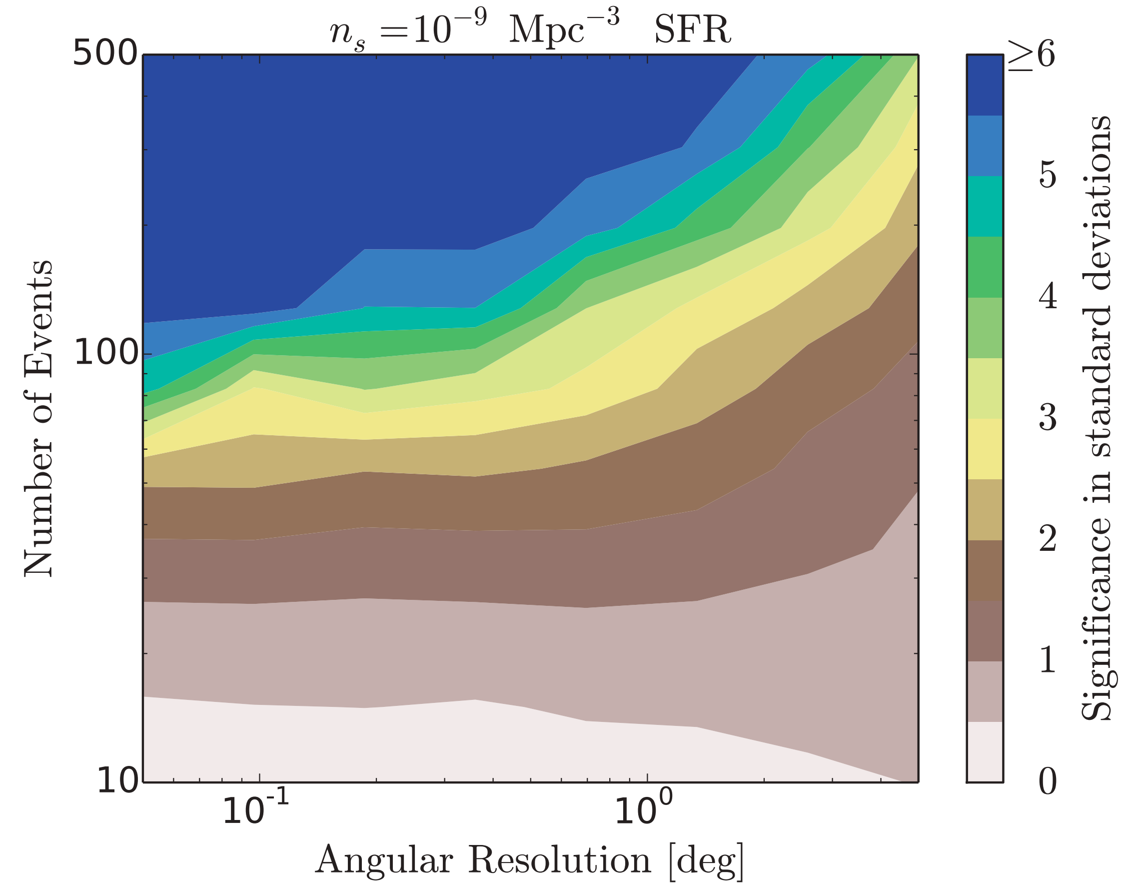


Figure 1. Significance of detection of point sources of UHE neutrinos by experiments with various angular resolutions and numbers of detected events. The color coding corresponds to the confidence level to reject an isotropic background using the statistical method from Ref. [65]. We assume that all of the sources have the same luminosity, and that the sources follow a uniform distribution with a number density $10^{-5}\,\mathrm{Mpc}^{-3}$ up to 2 Gpc (case I). With this source number density, ~ 1000 events and $\sim 0.1°$ angular resolution are needed to reach a 5σ detection of point sources. In the above calculation, $f_{\rm cov} = 1$ is used; fewer events are required *in the field of view* if $f_{\rm cov}$ is smaller.







KK, Mukhopadhyay, et al. in prep.