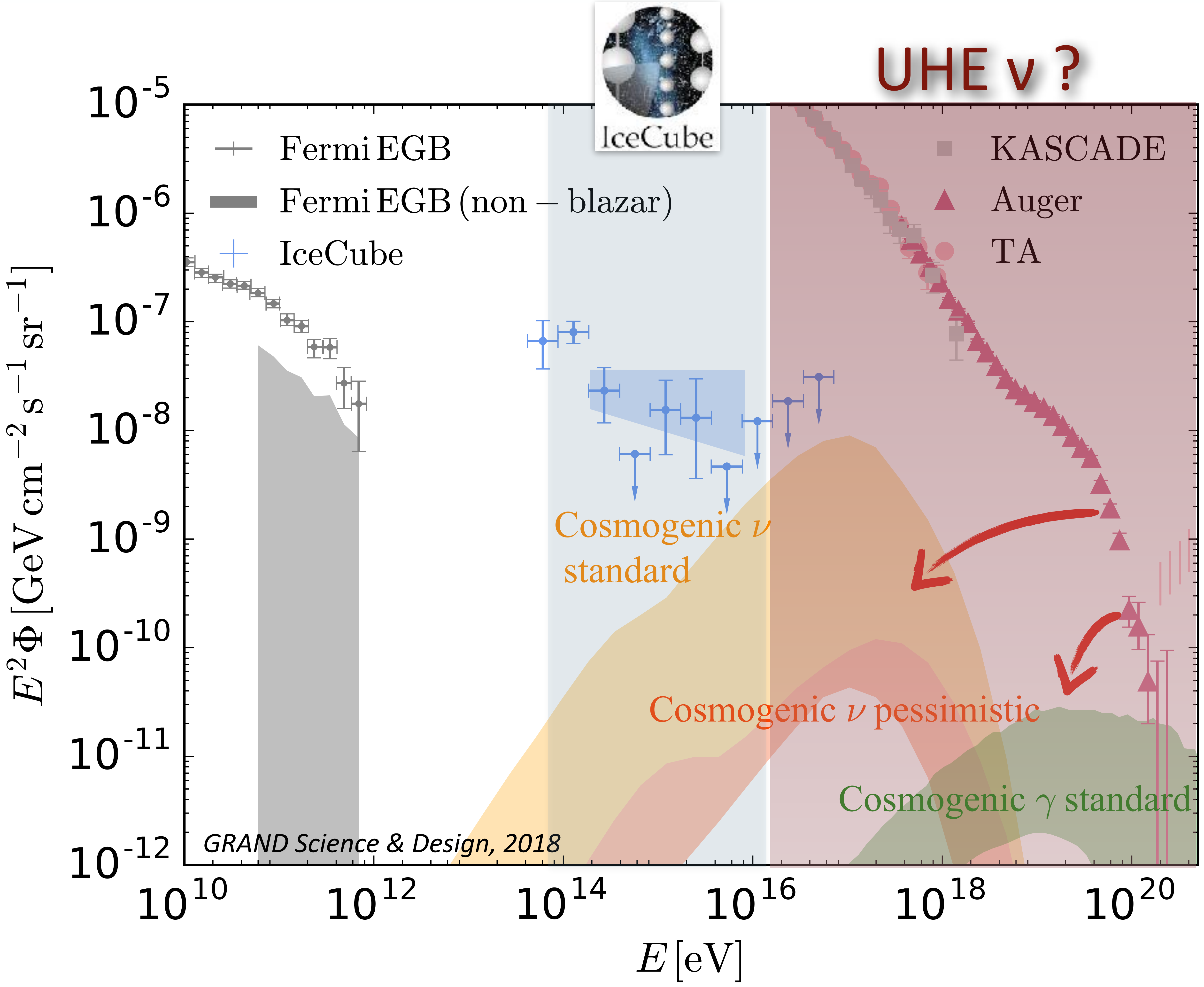
Observation Strategies for UHE neutrinos

Kumiko Kotera
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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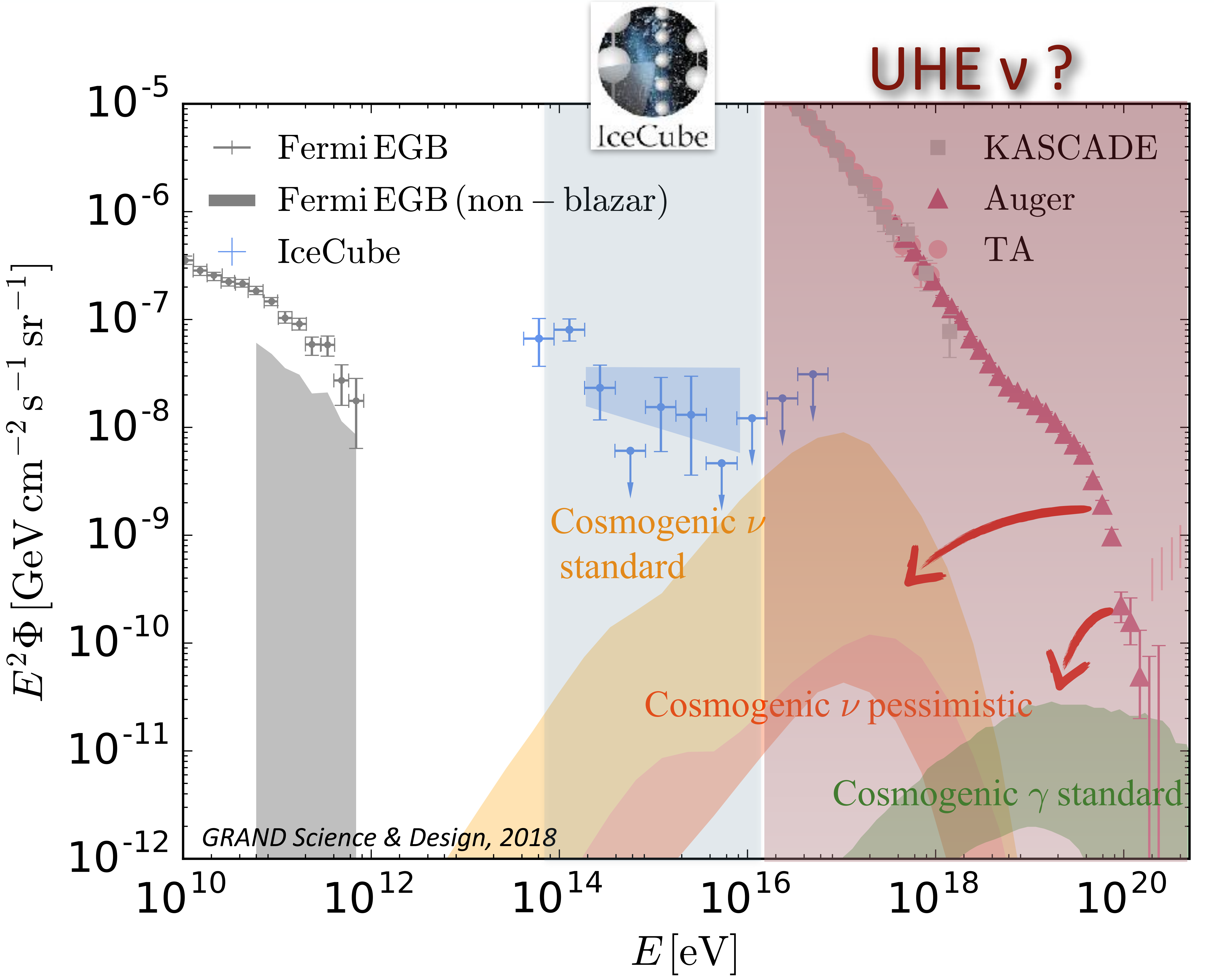

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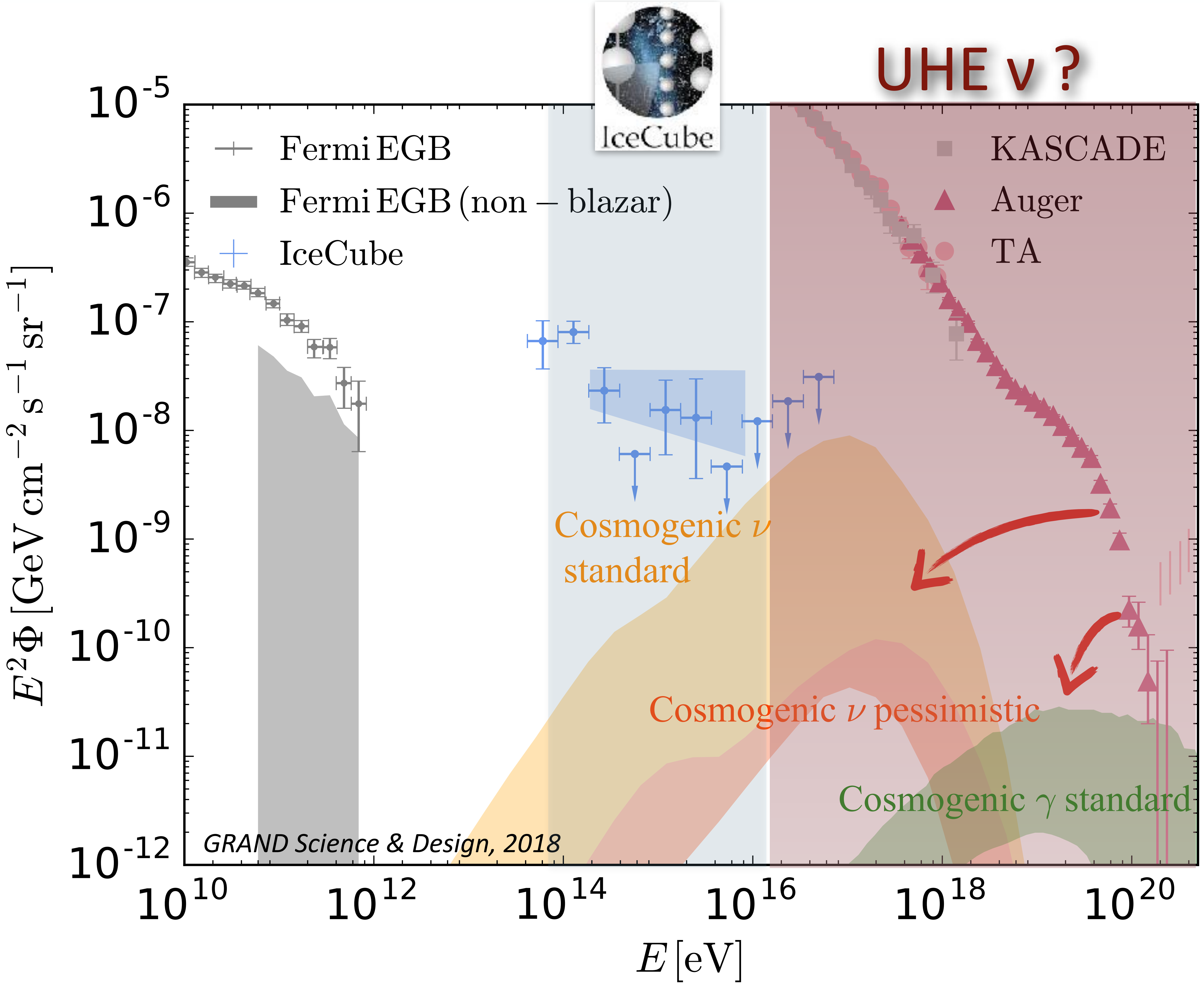

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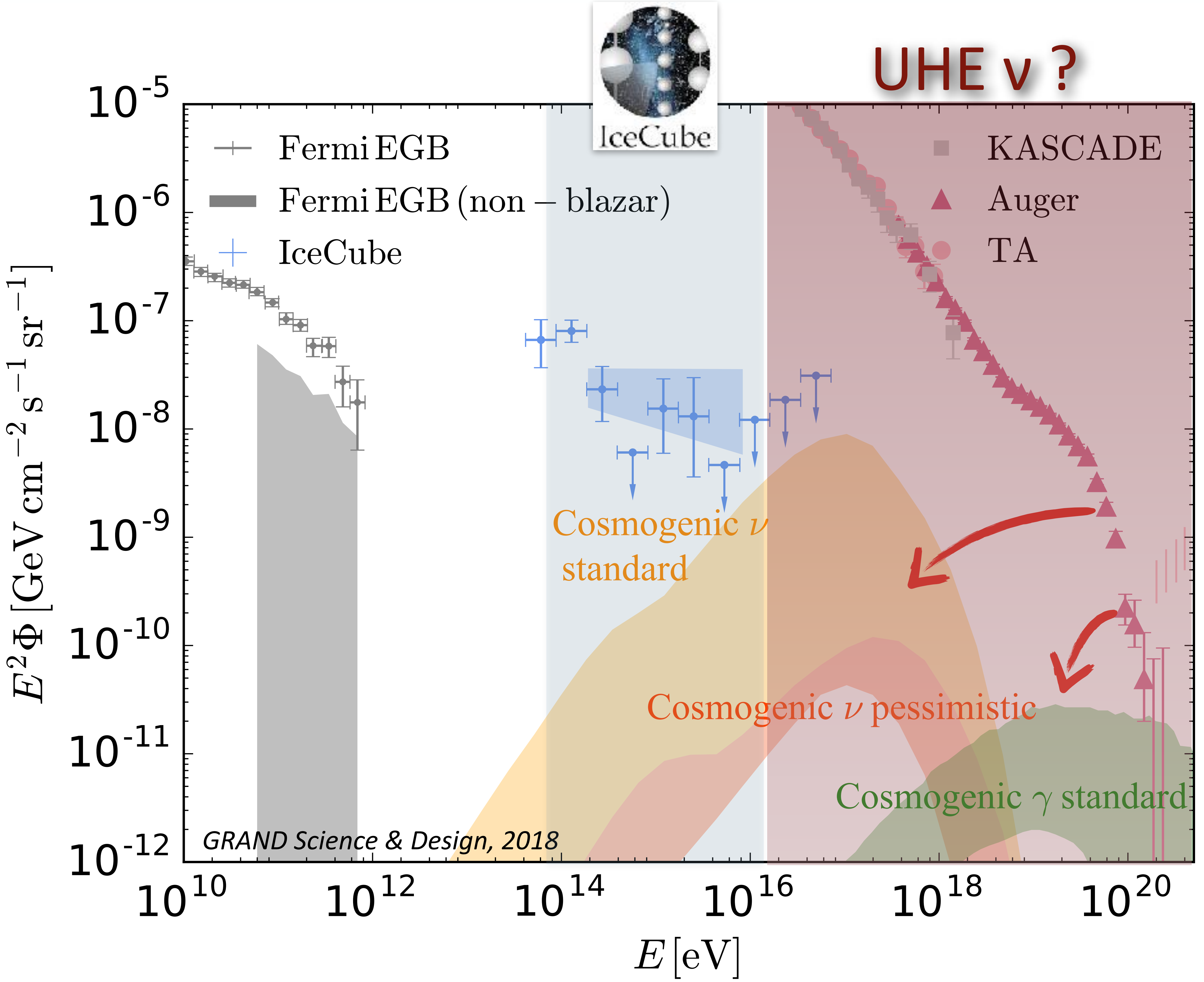

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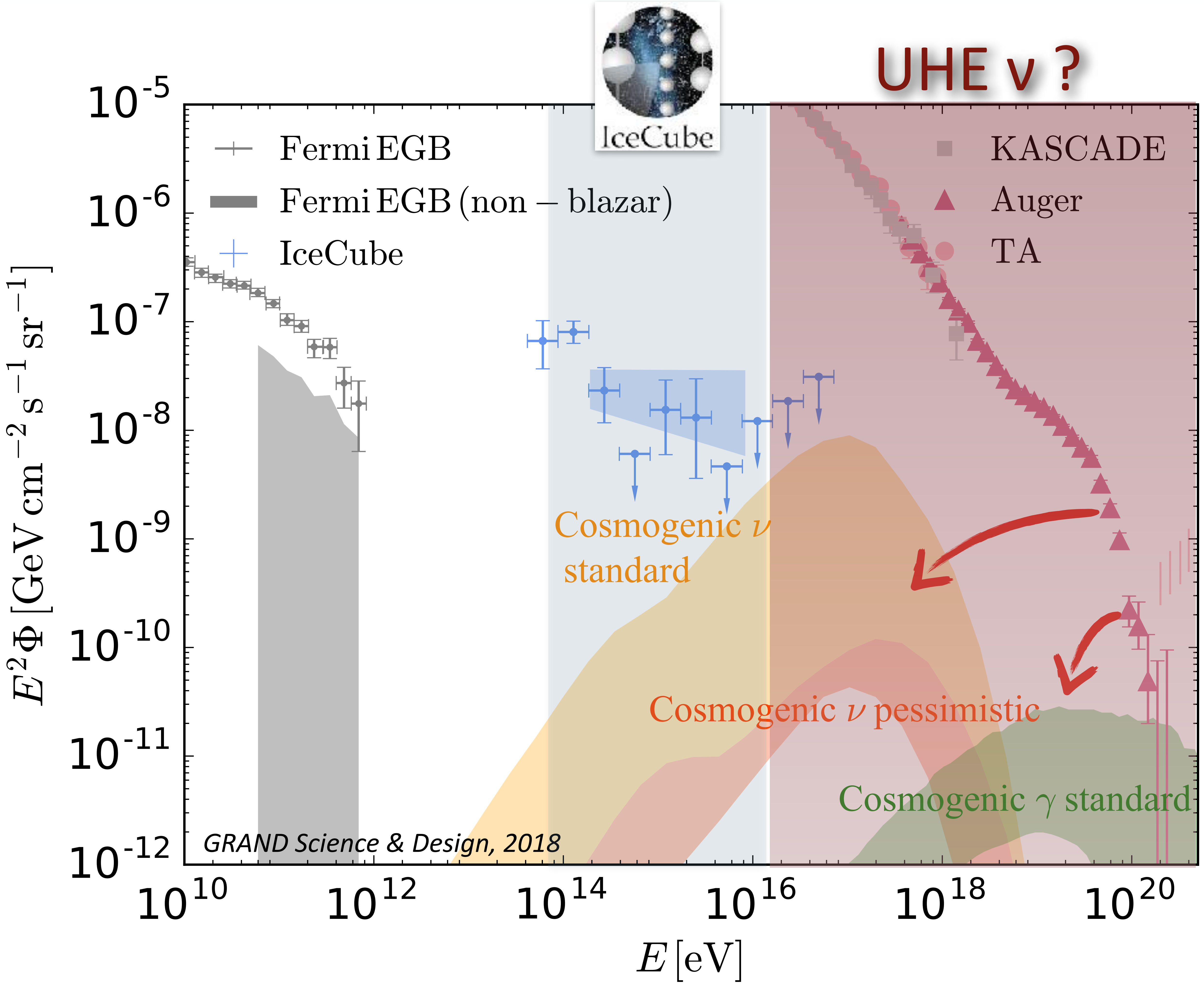

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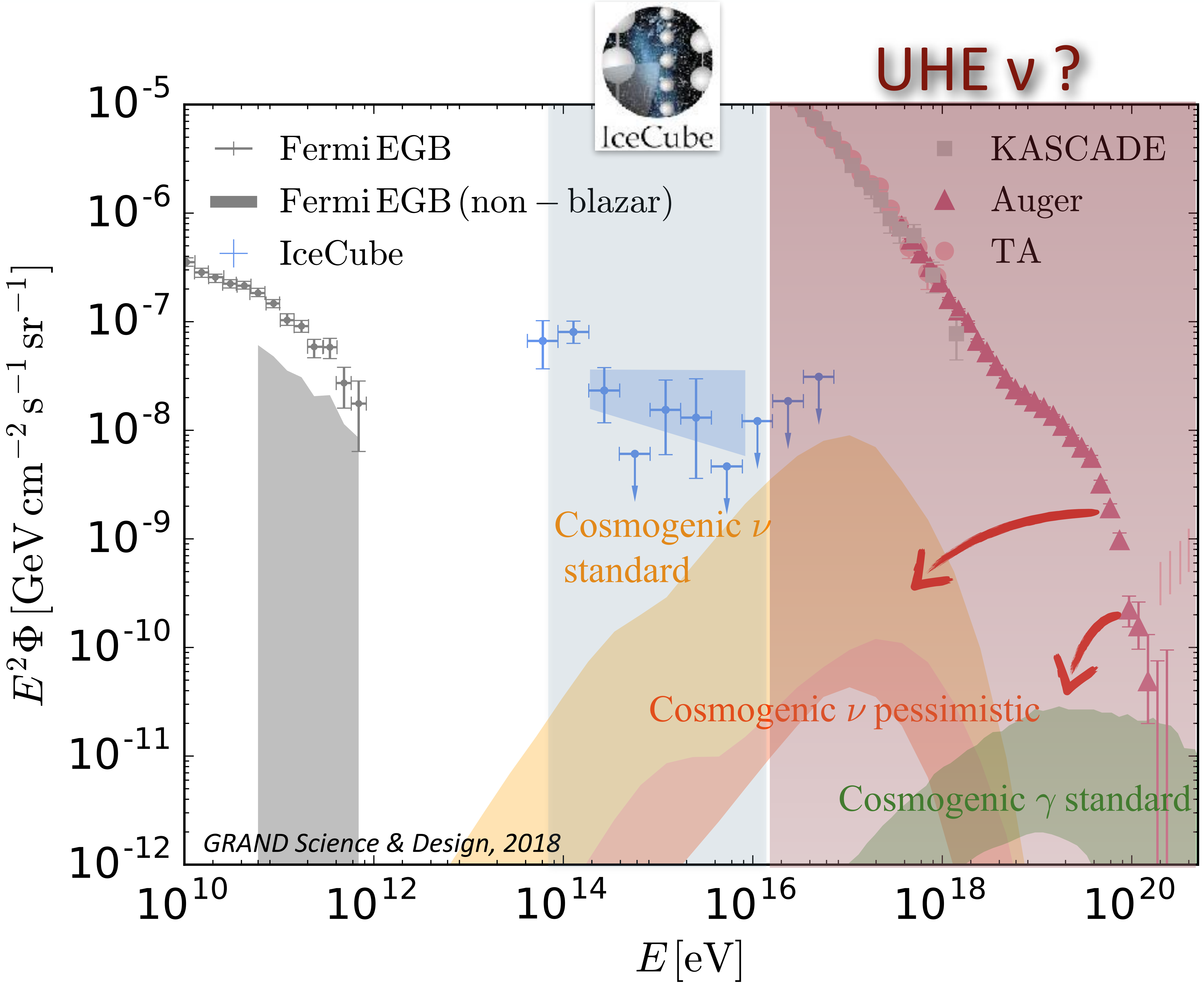

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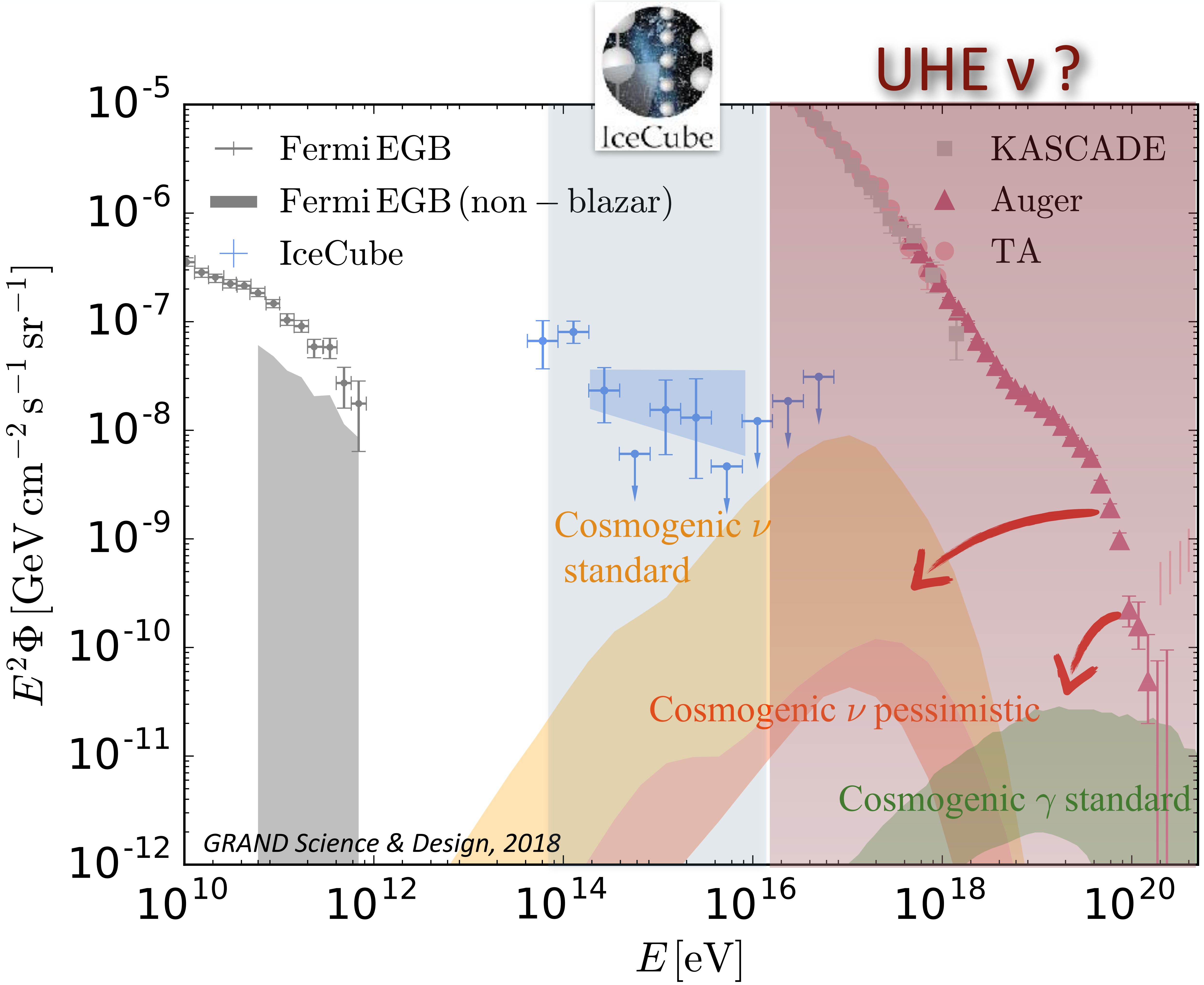

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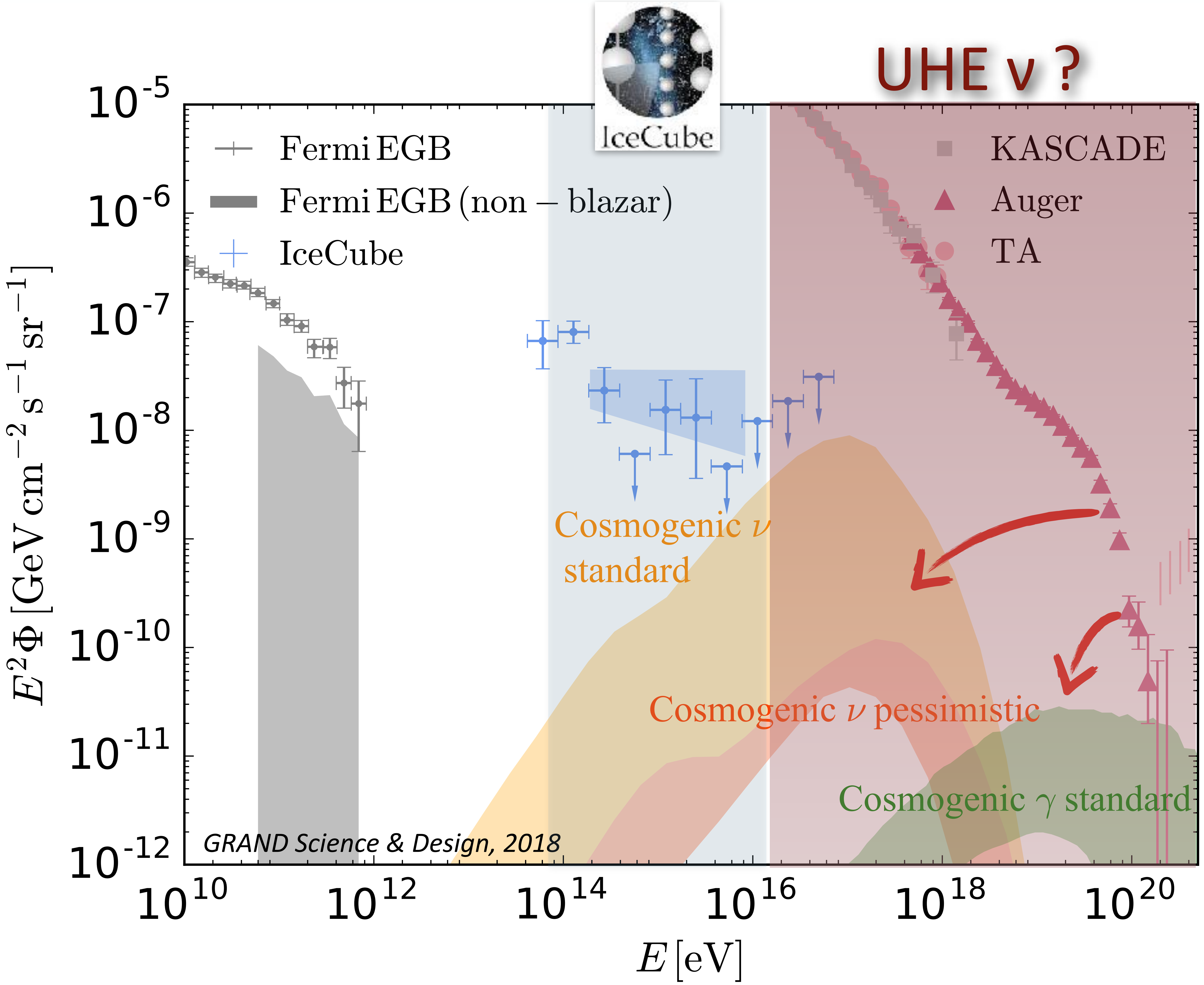

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4. Boom in MM + time domain astronomy: require specific strategies of observations & instrumental performances

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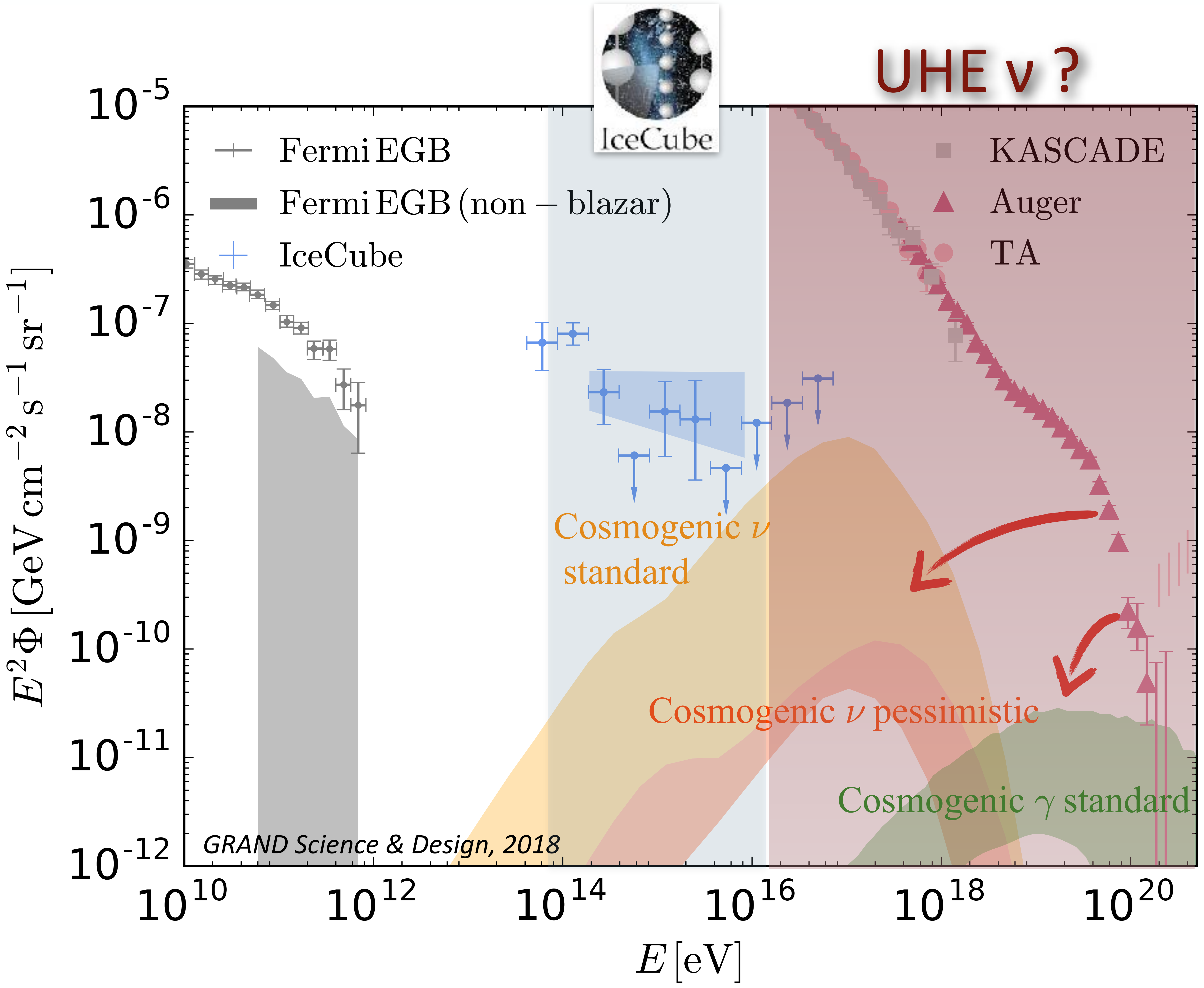

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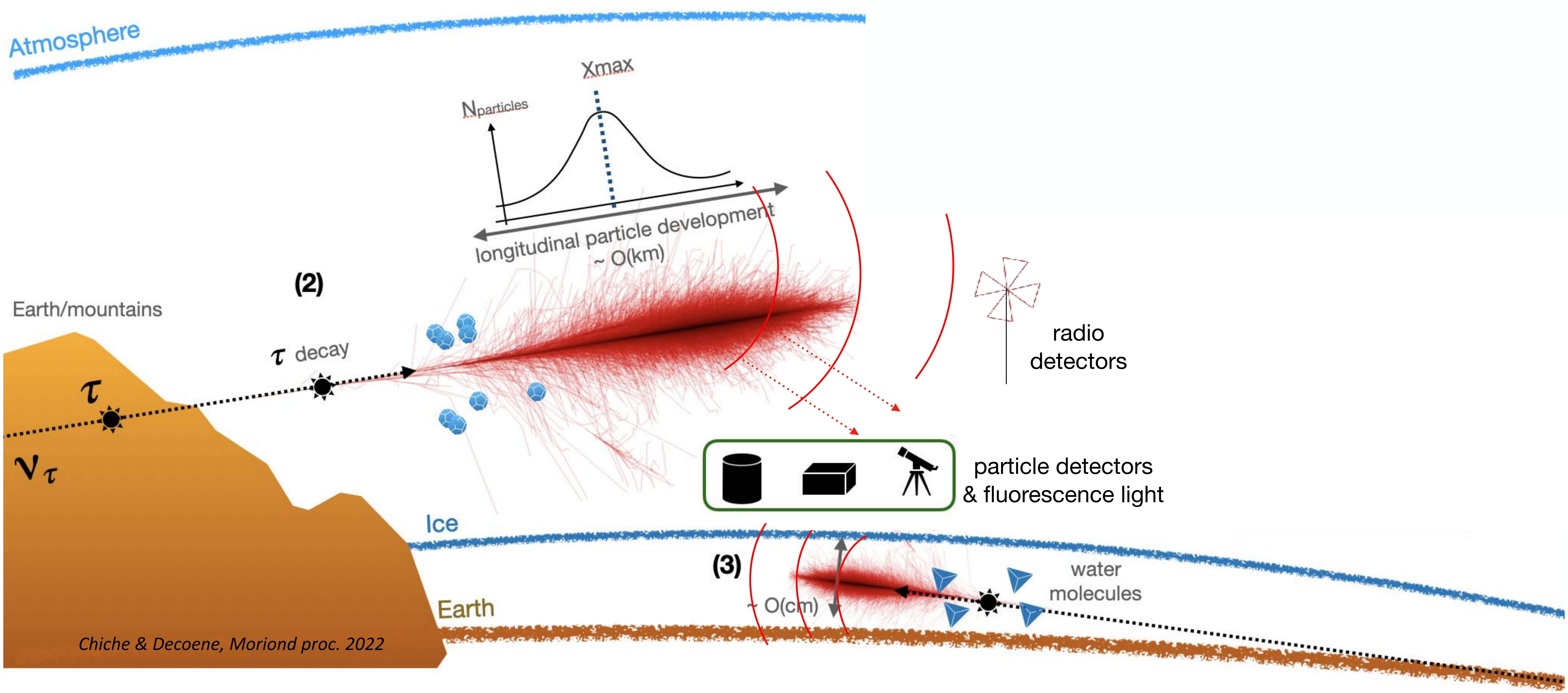
4.E **lesson from MM**: develop follow-up tools and

st integrate in a MM framework, enabling rapid response and alerts

Experimental perspectives

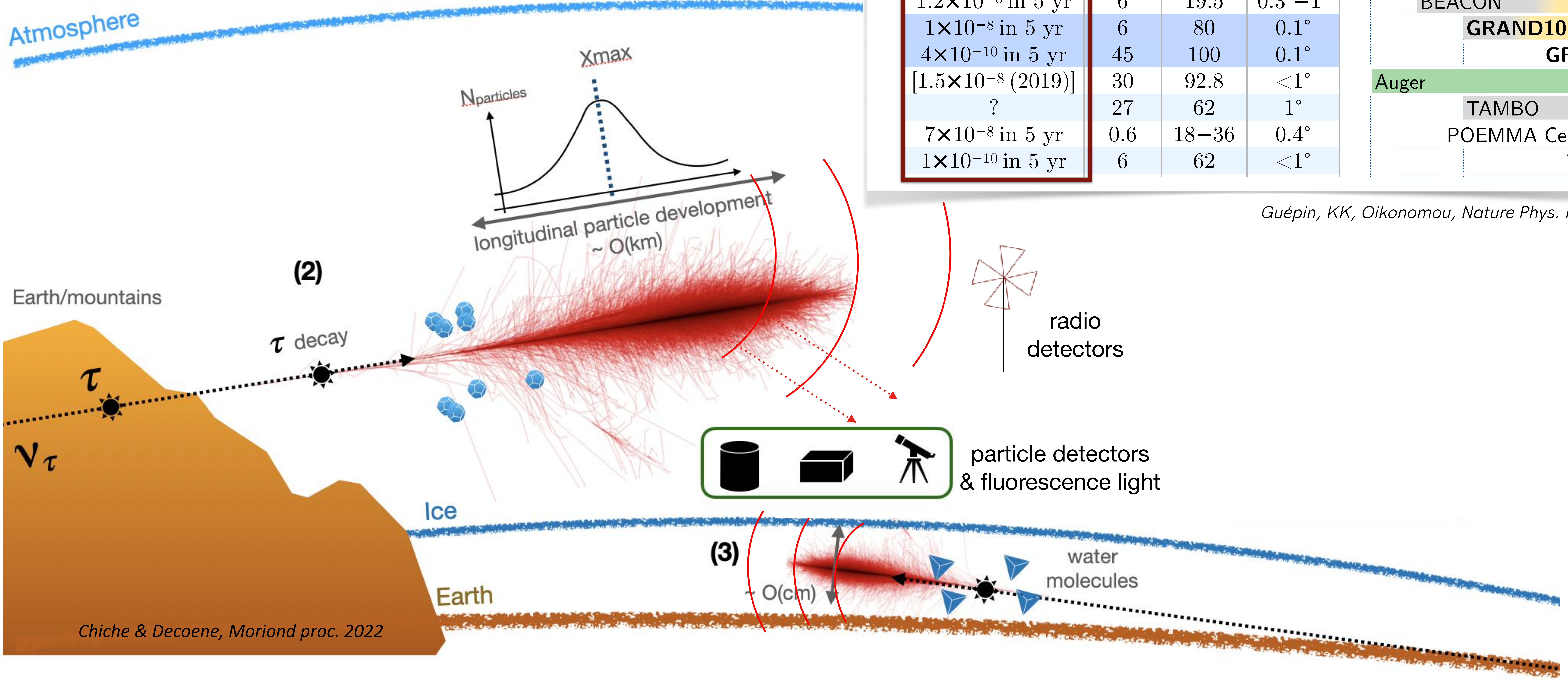


Chiche & Decoene, Moriond proc. 2022

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	$2°\times10°$	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	$2°\times10°$	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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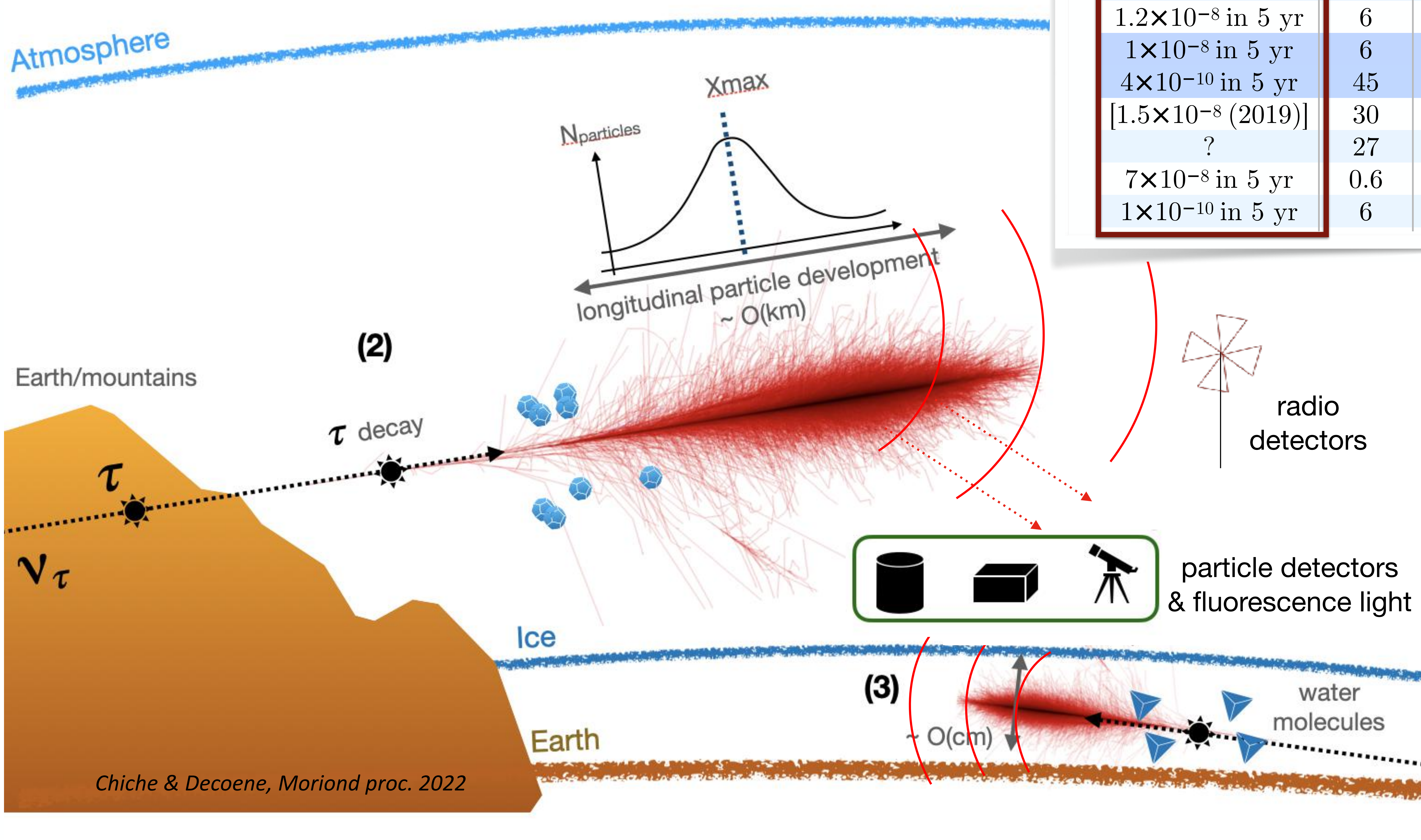

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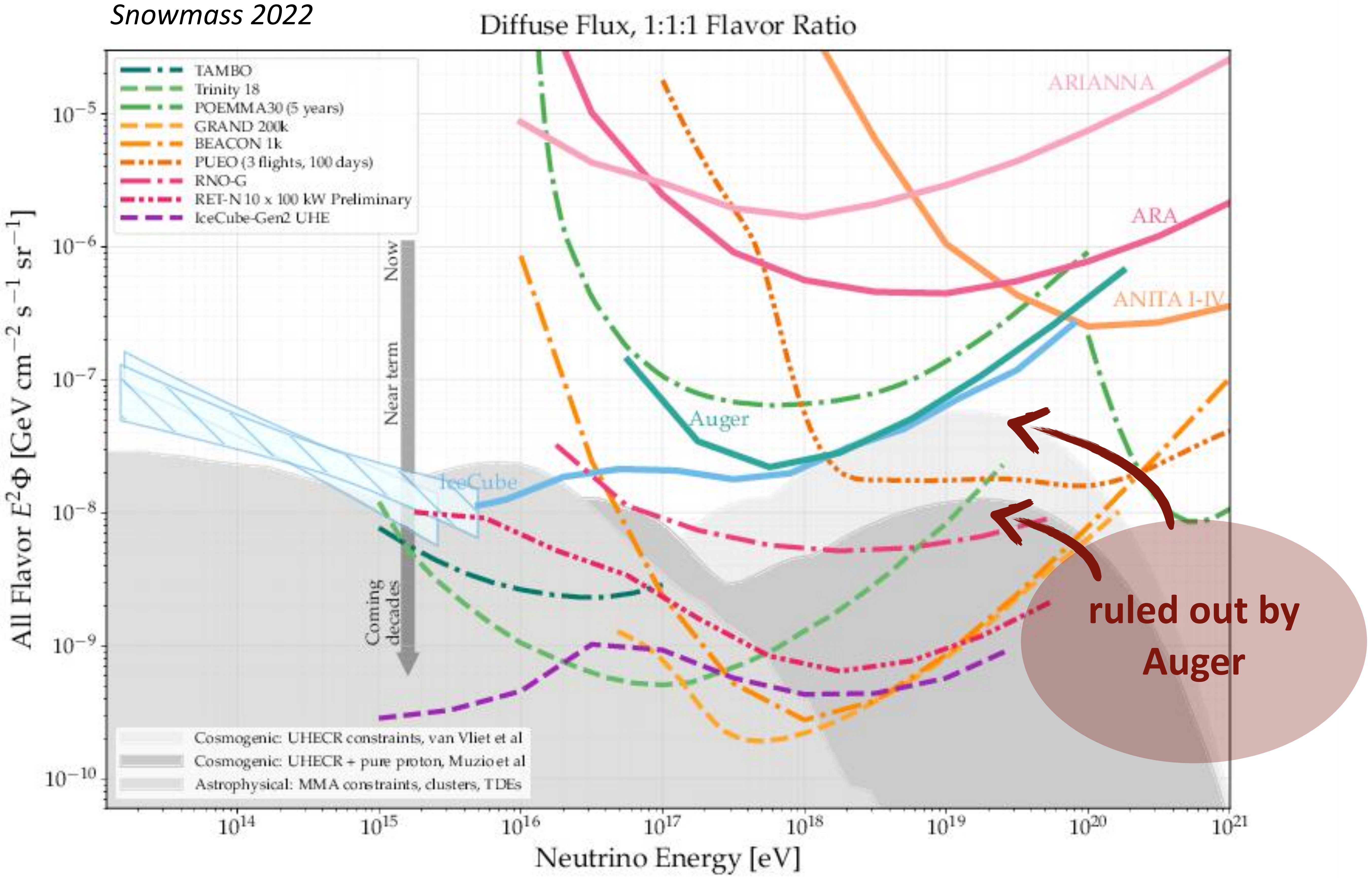
Future experiments target 10-yr integrated sensitivity to diffuse flux

$$\sim 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$
$$\text{above } 5\times10^{17}\,\mathrm{eV}$$

Diffuse UHE neutrino fluxes: readjusting our experimental perspectives

Snowmass 2022



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

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

- Promising astrophysical fluxes exist

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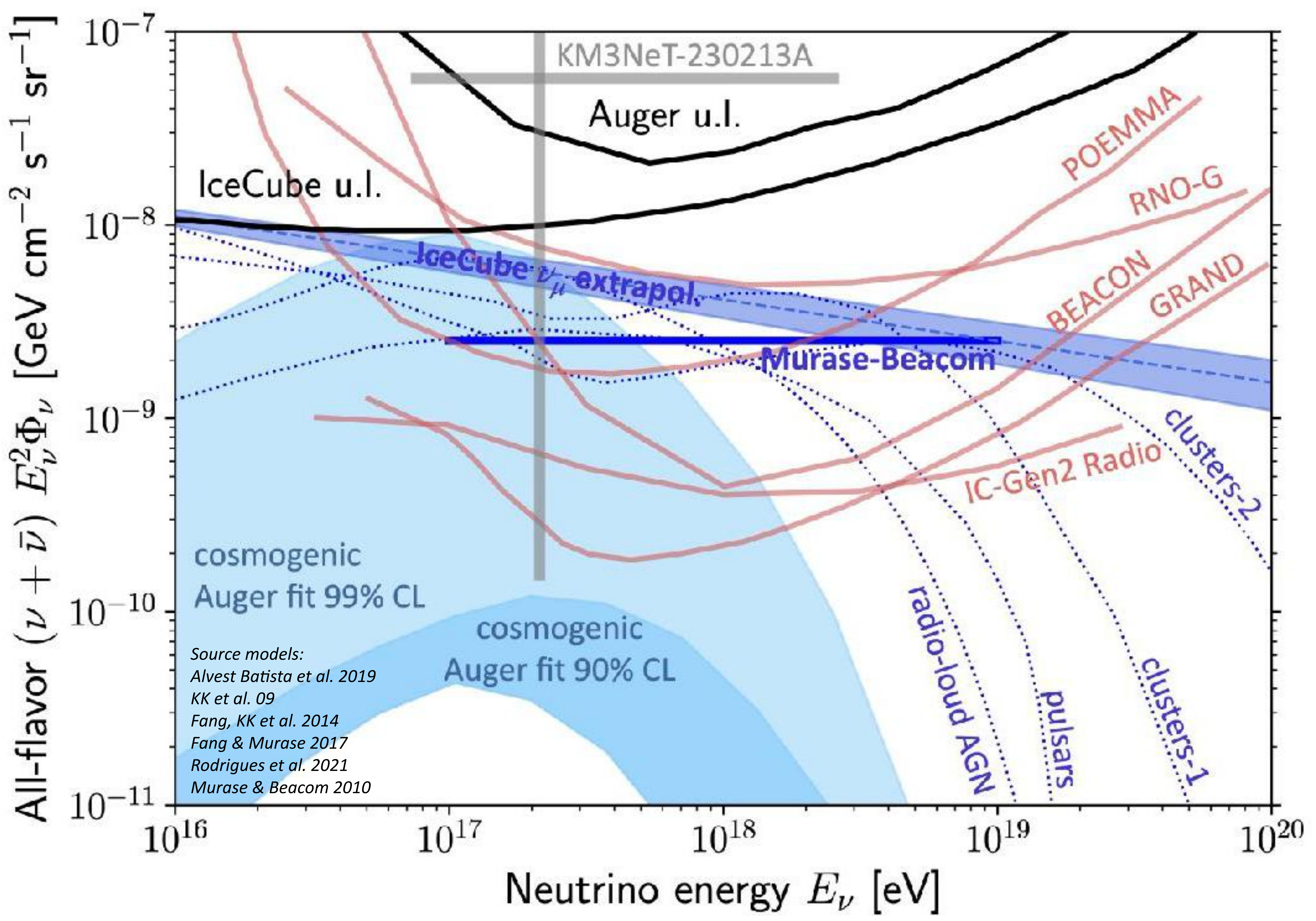

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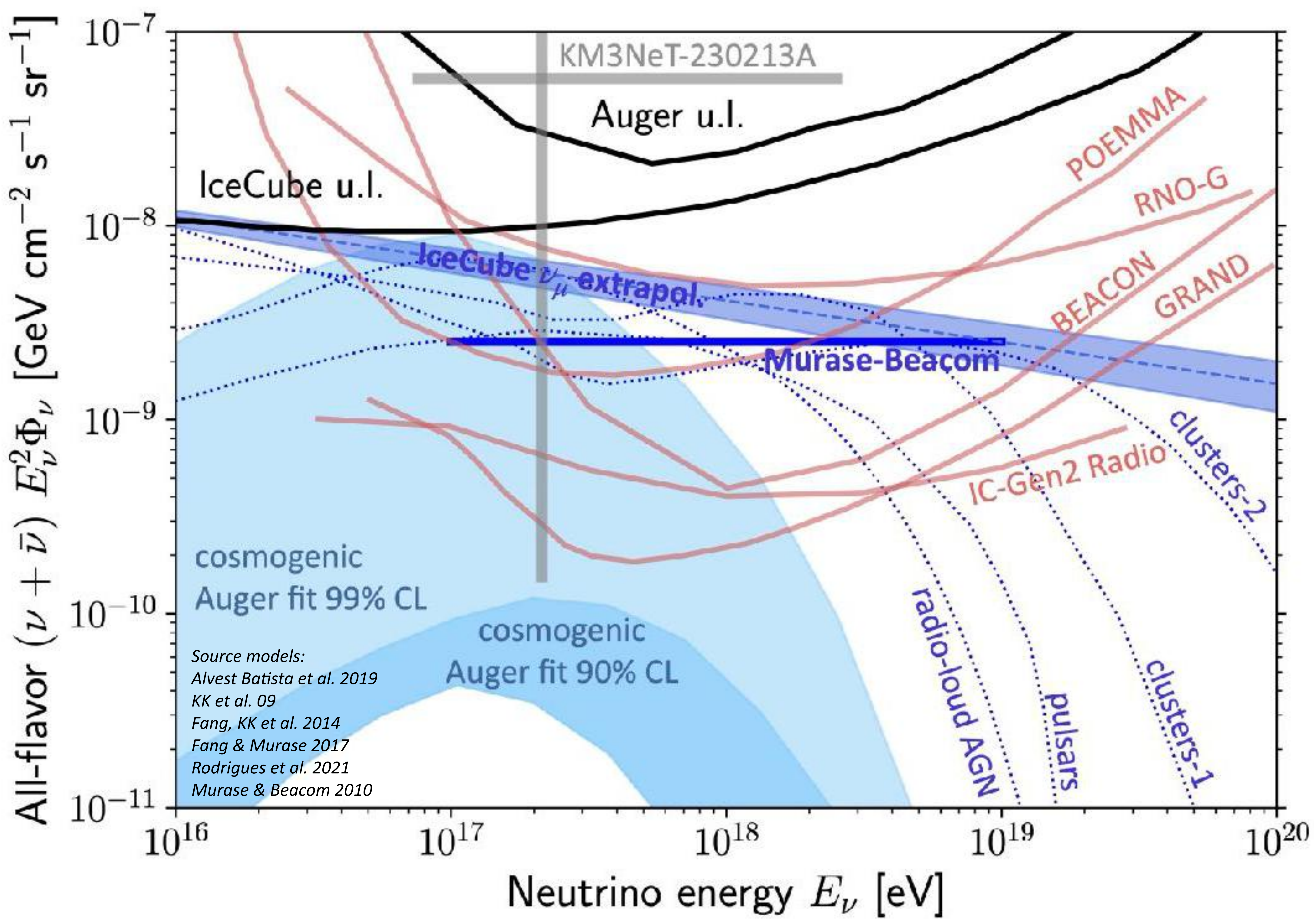

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- Promising astrophysical fluxes exist

- 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)

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

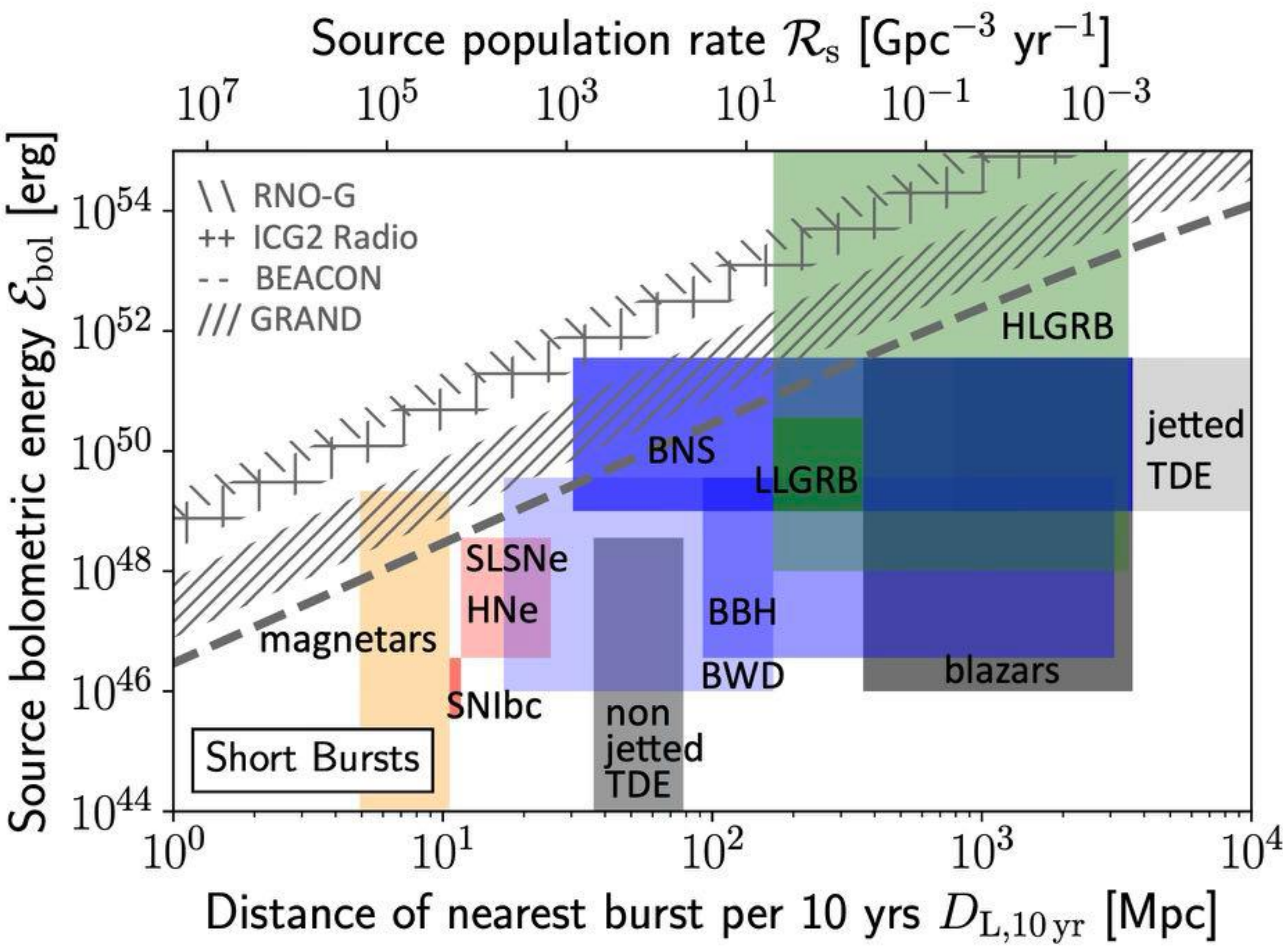
effective (energy-loss) photodisintegration optical depth < 1
here: source evolution factor f_z = 3

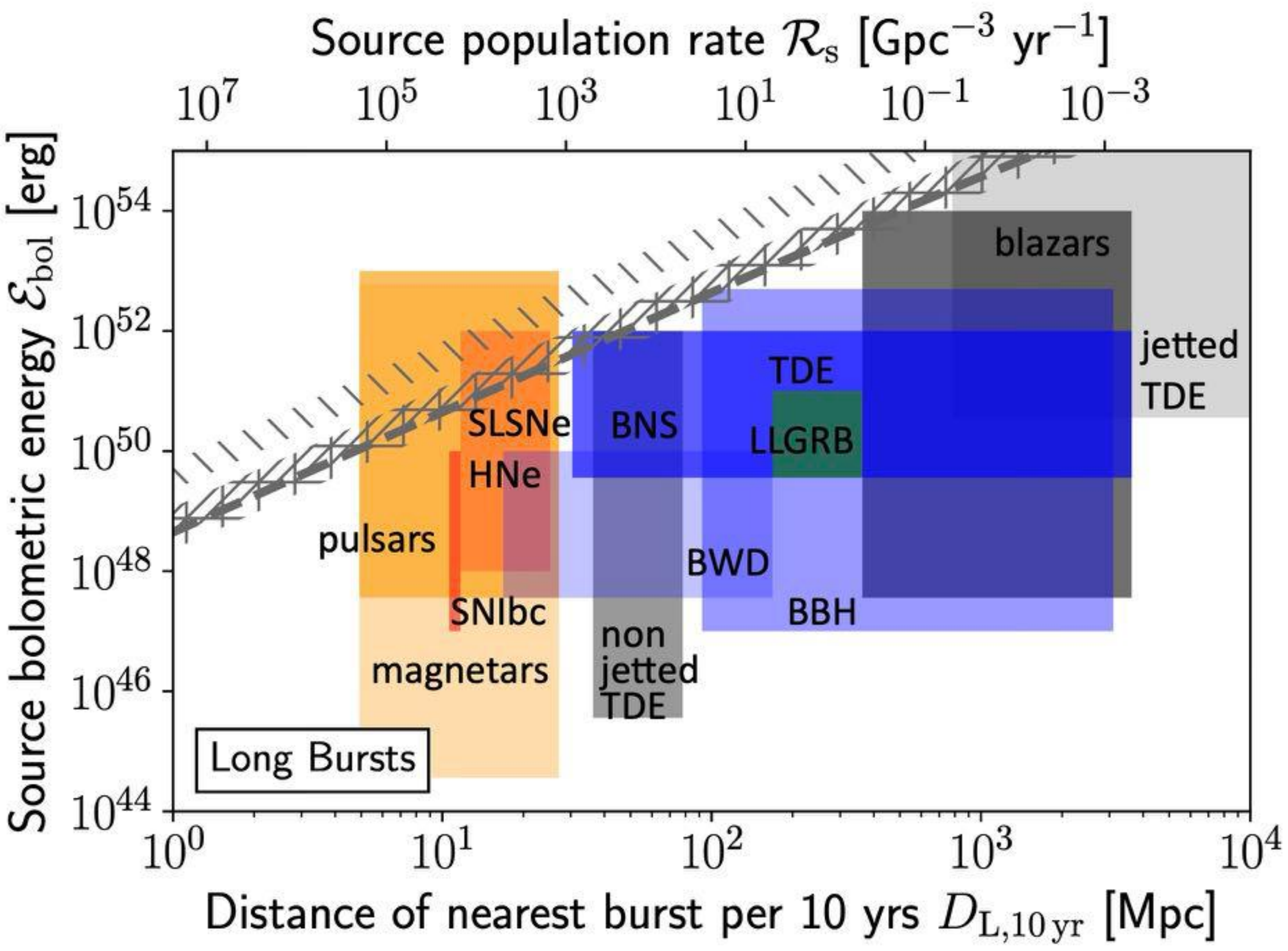
Detector reaching these limits in $10^{17\text{-}19}$ eV can strongly constrain source models.

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

KK, Mukhopadhyay, Alves Batista, Fox, Martineau-Huynh, Murase, Wissel, Zeolla, subm.

What astrophysical sources to aim for in the MM era?





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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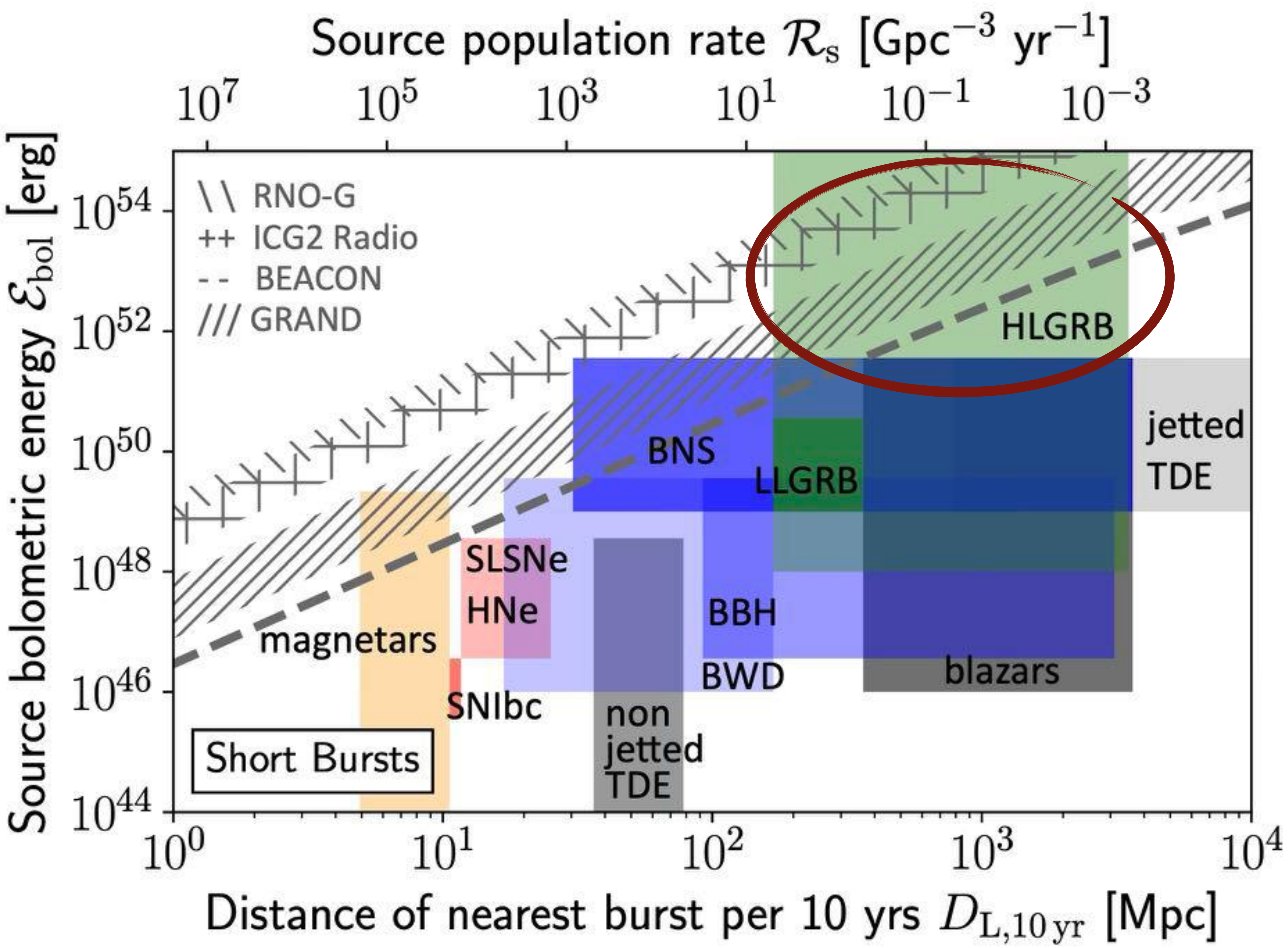

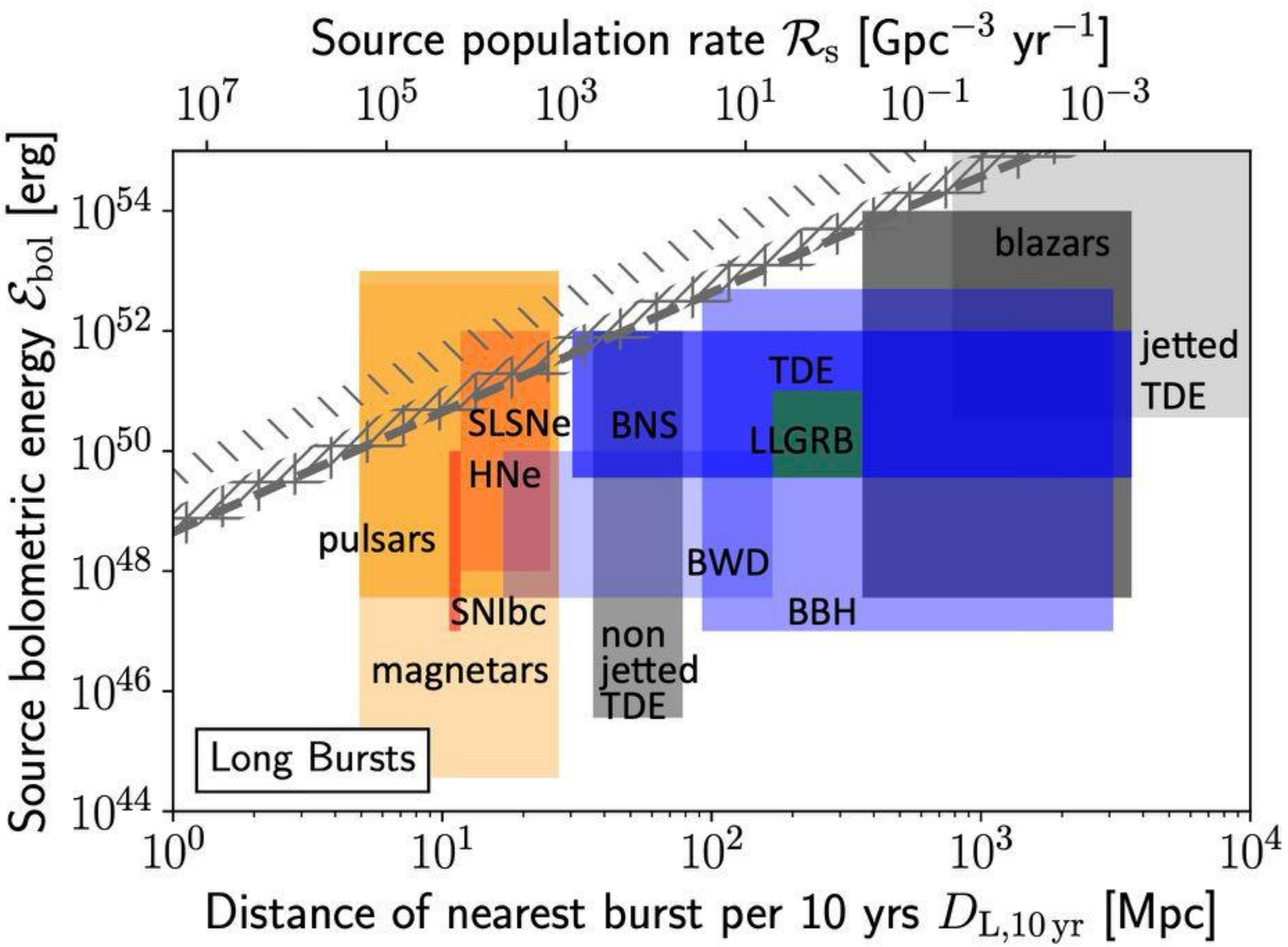

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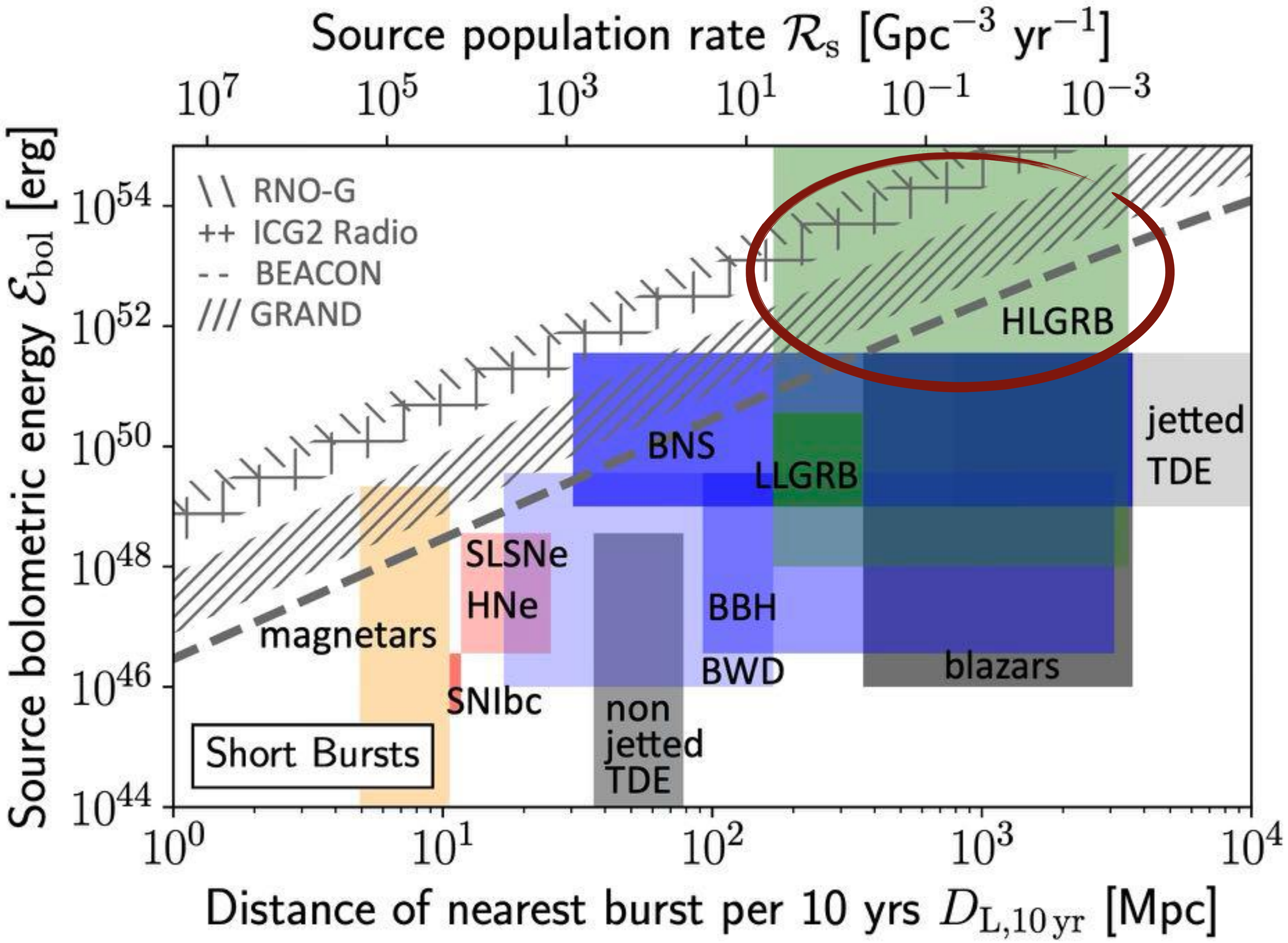

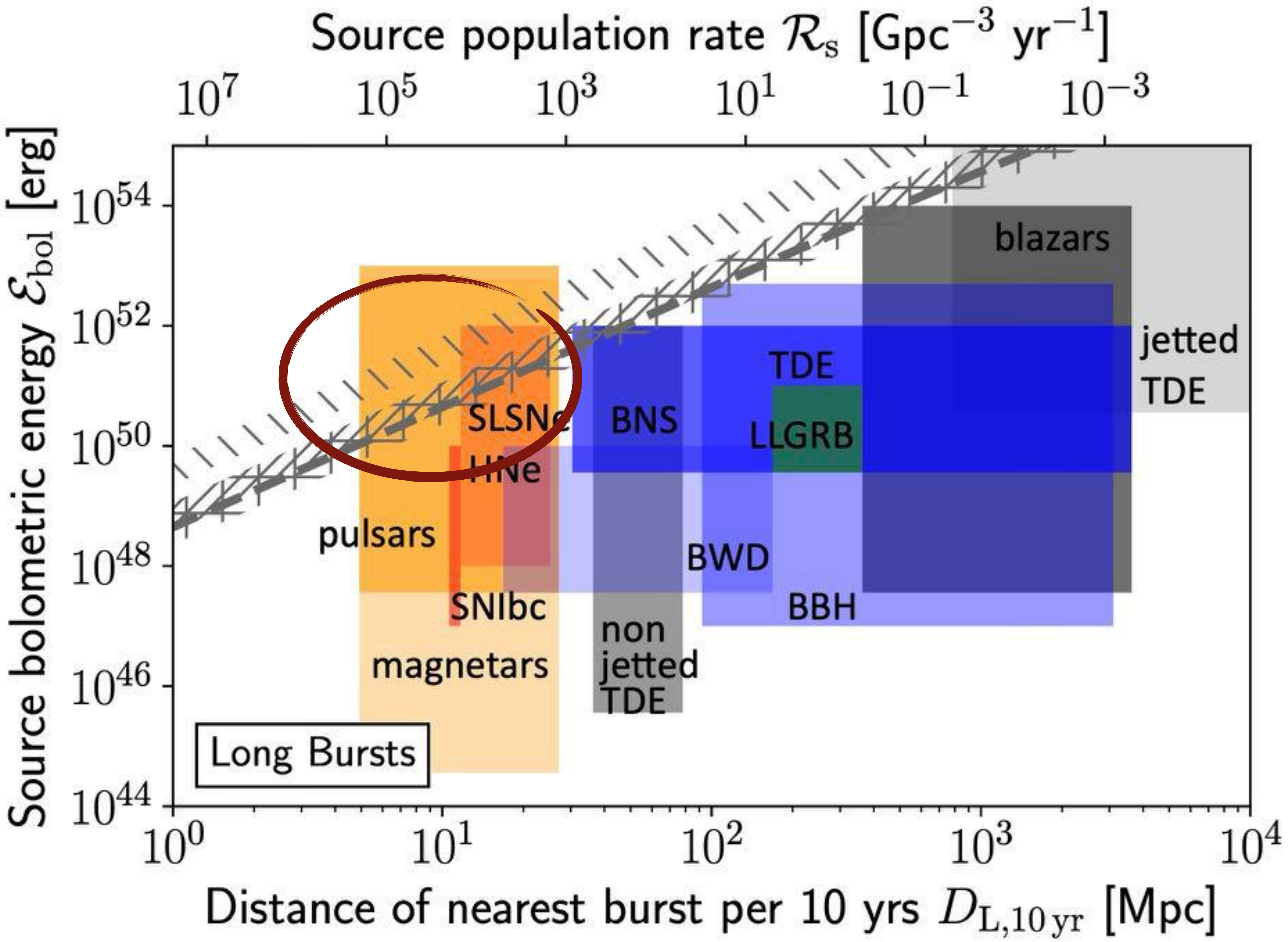

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Detectable: Local Group & nearby galaxies

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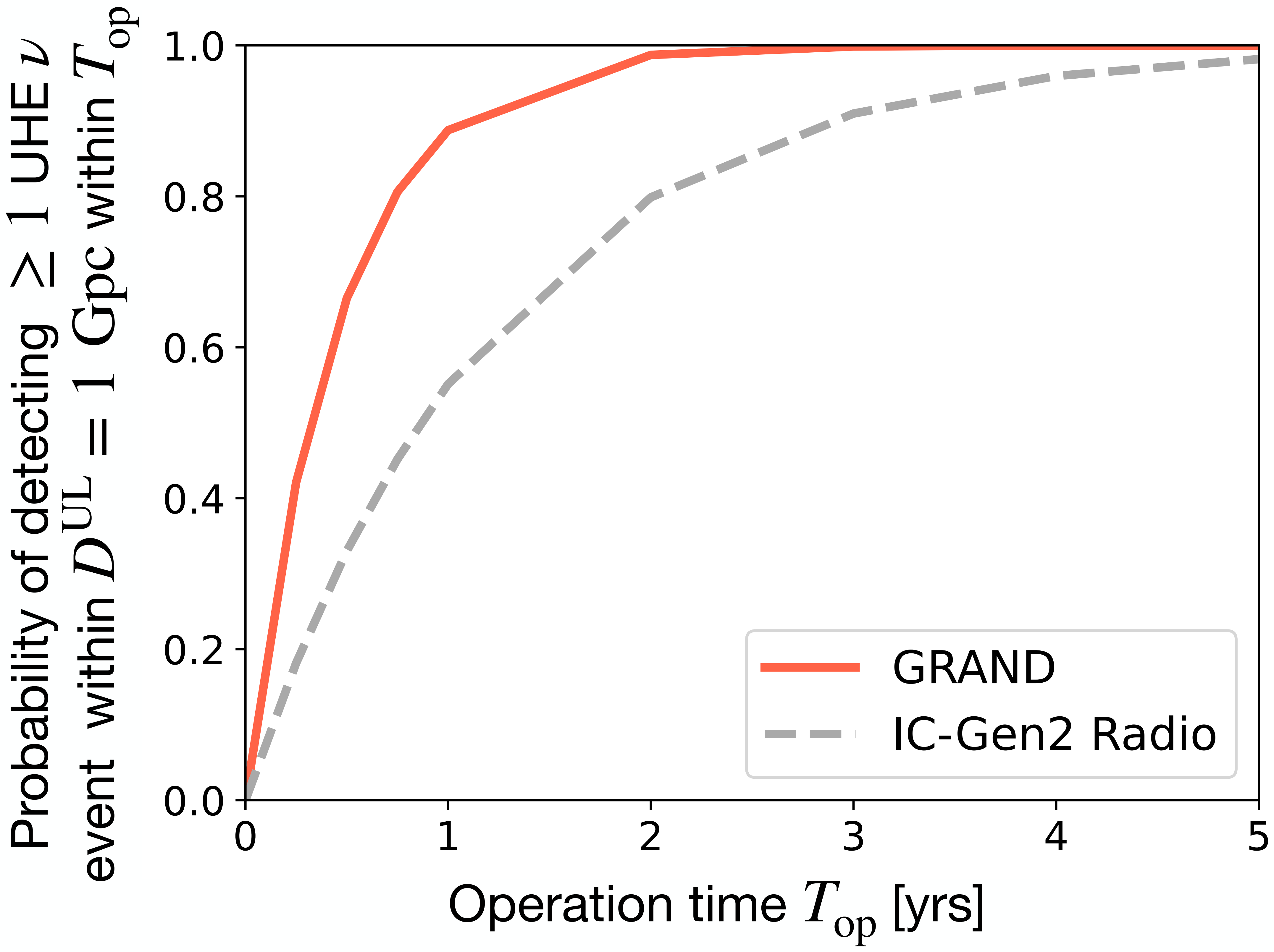
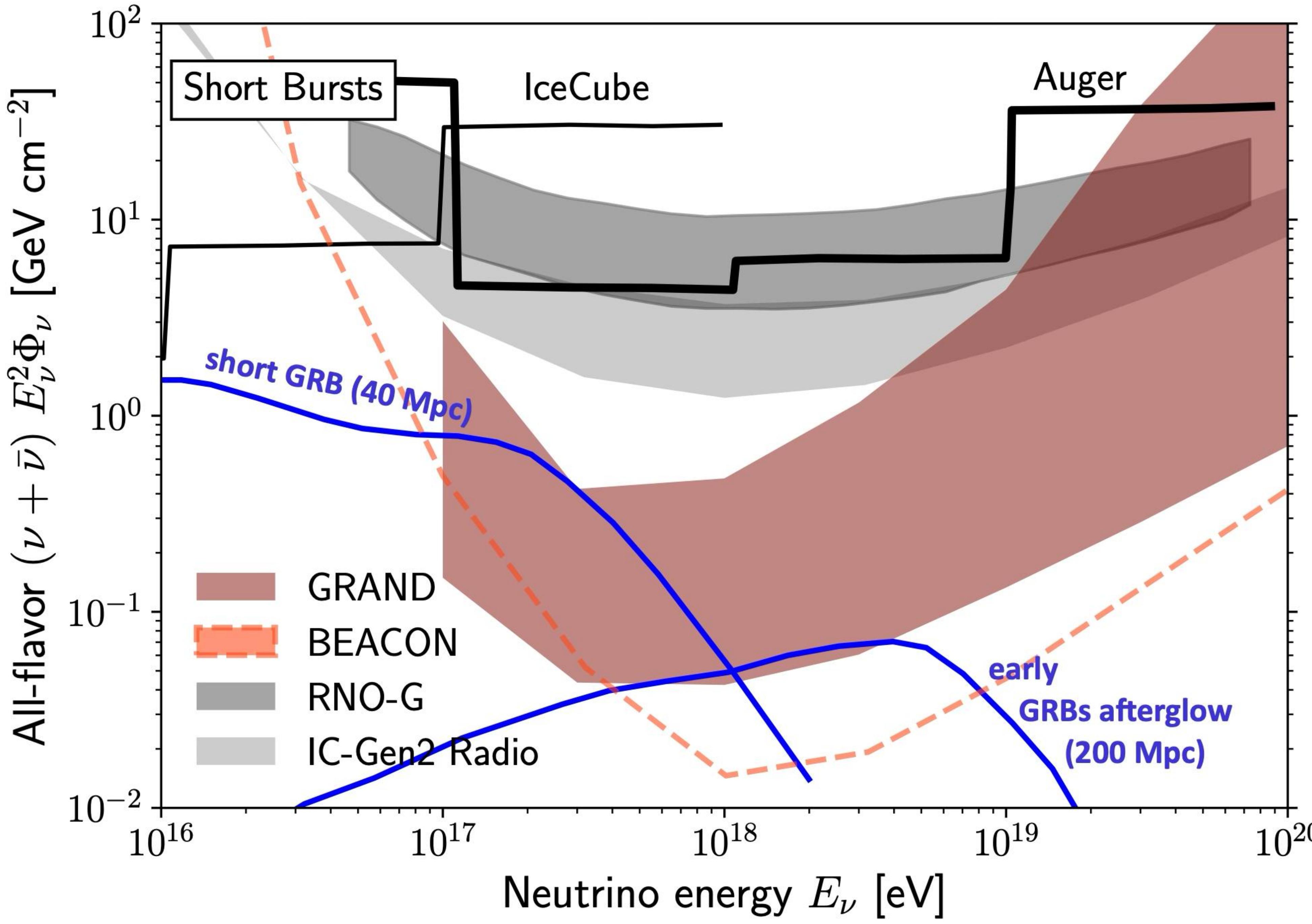
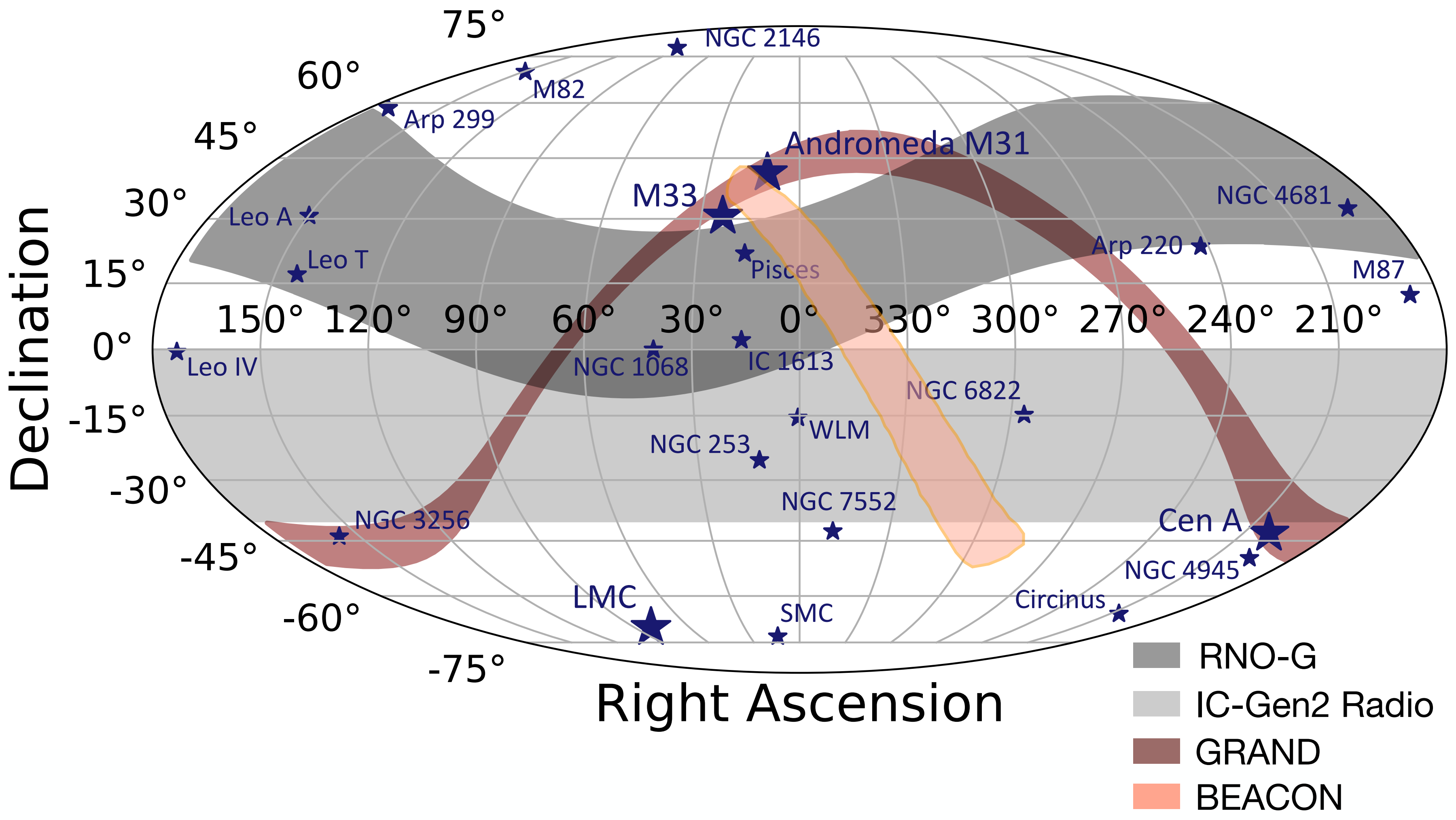
Astronomical observation strategies: Wide & Shallow vs. Deep & Narrow





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



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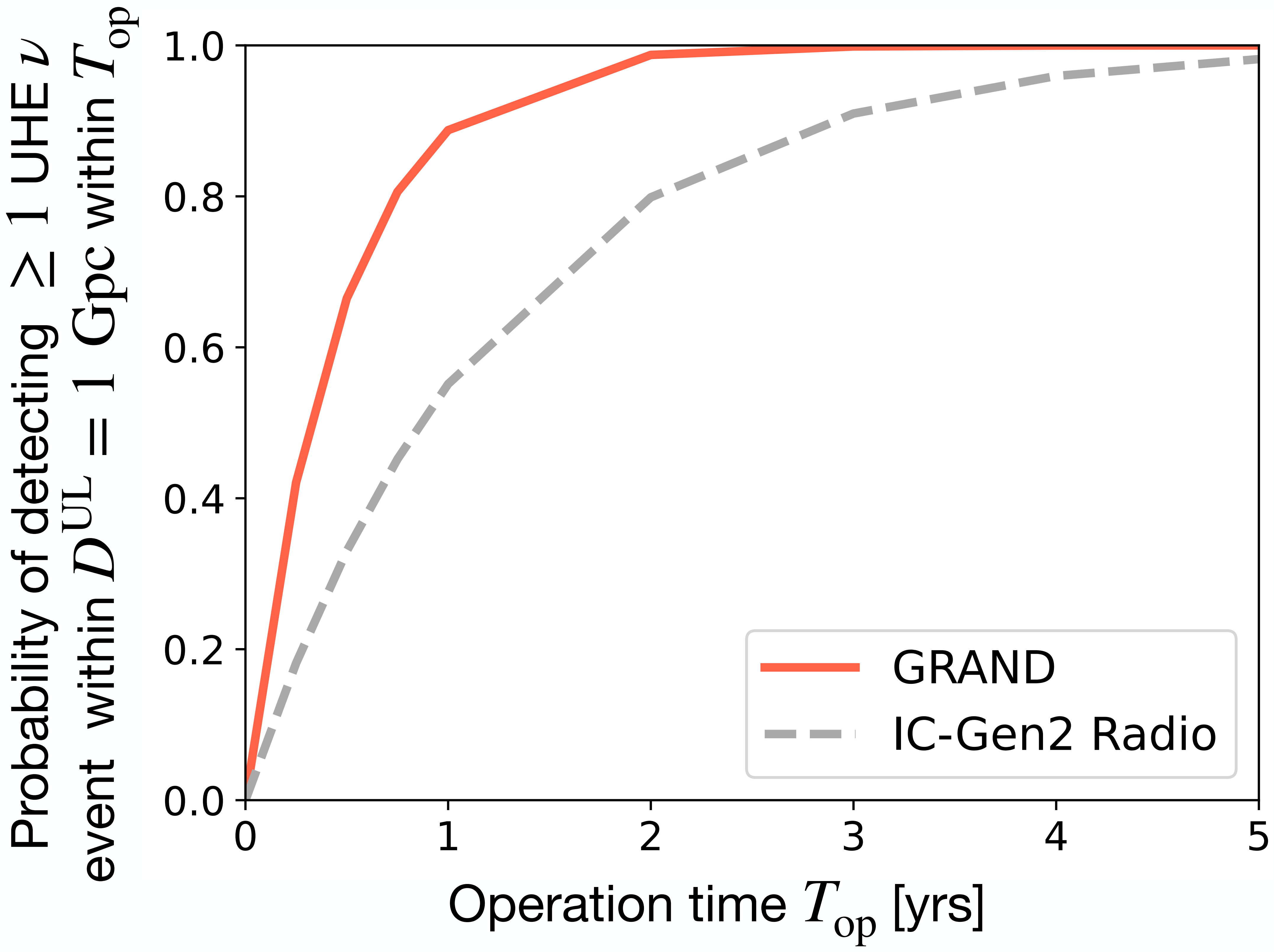
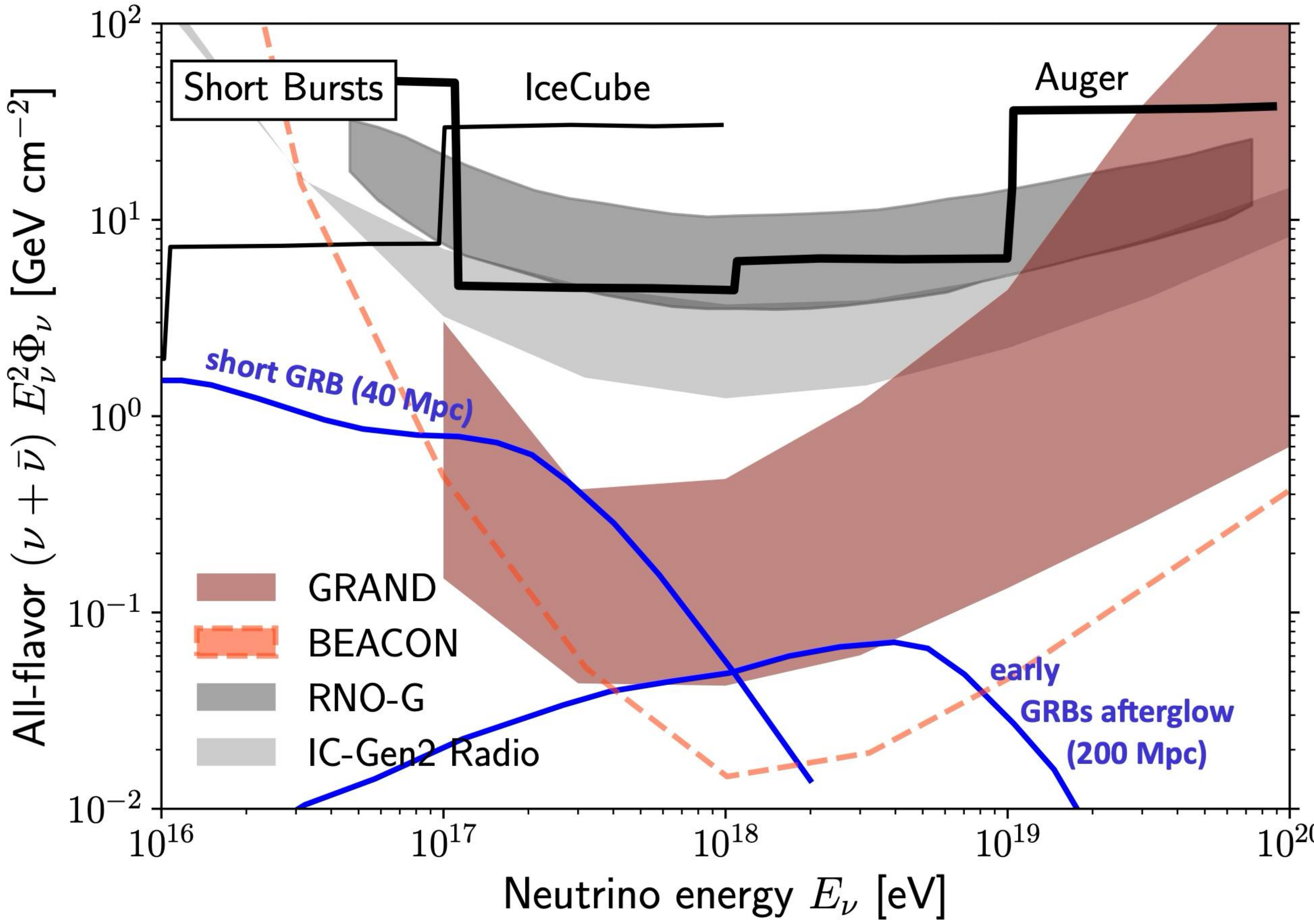
Astronomical observation strategies: Wide & Shallow vs. Deep & Narrow

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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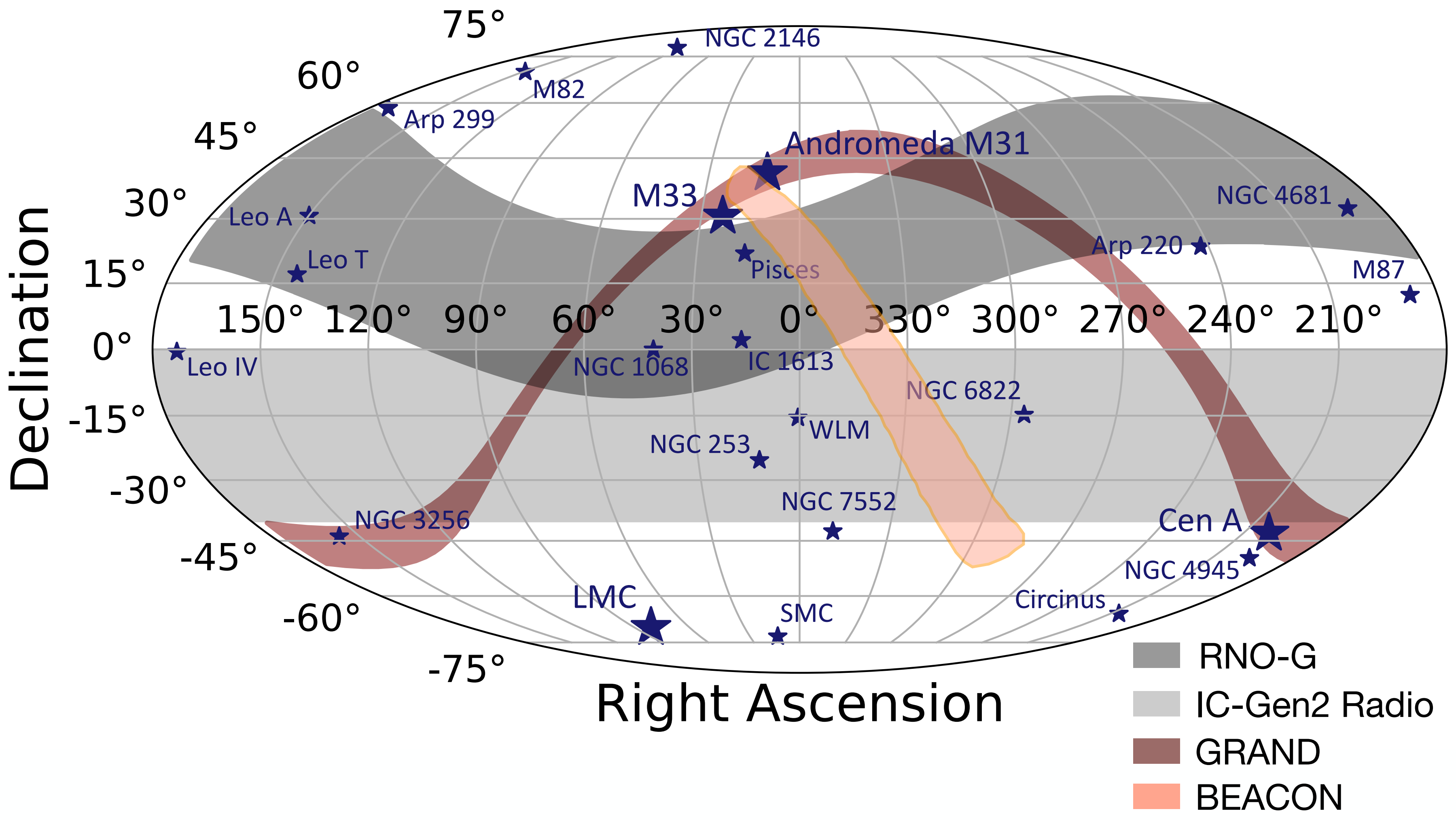

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Strategy for "long" bursts: increase daily field of view

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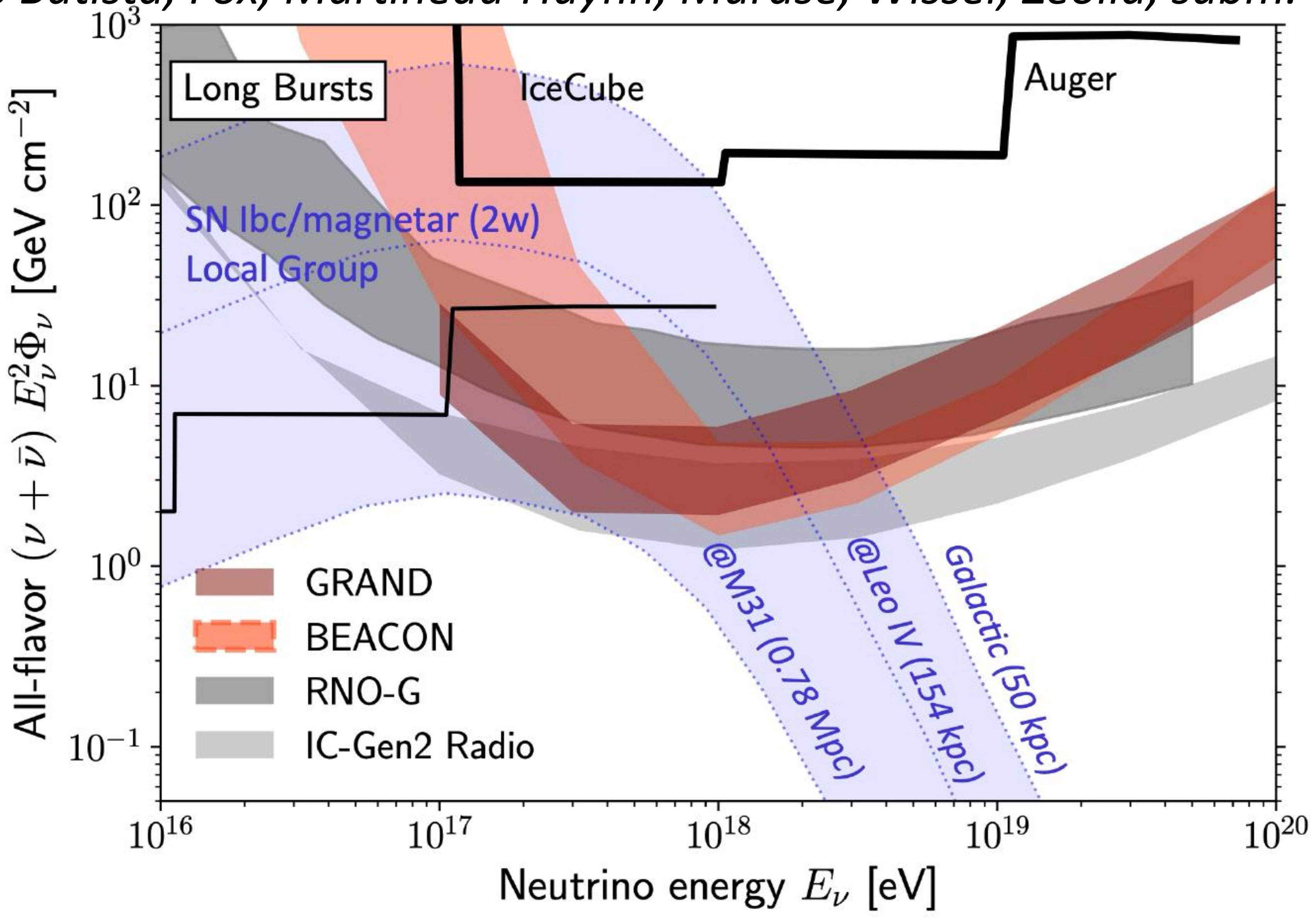
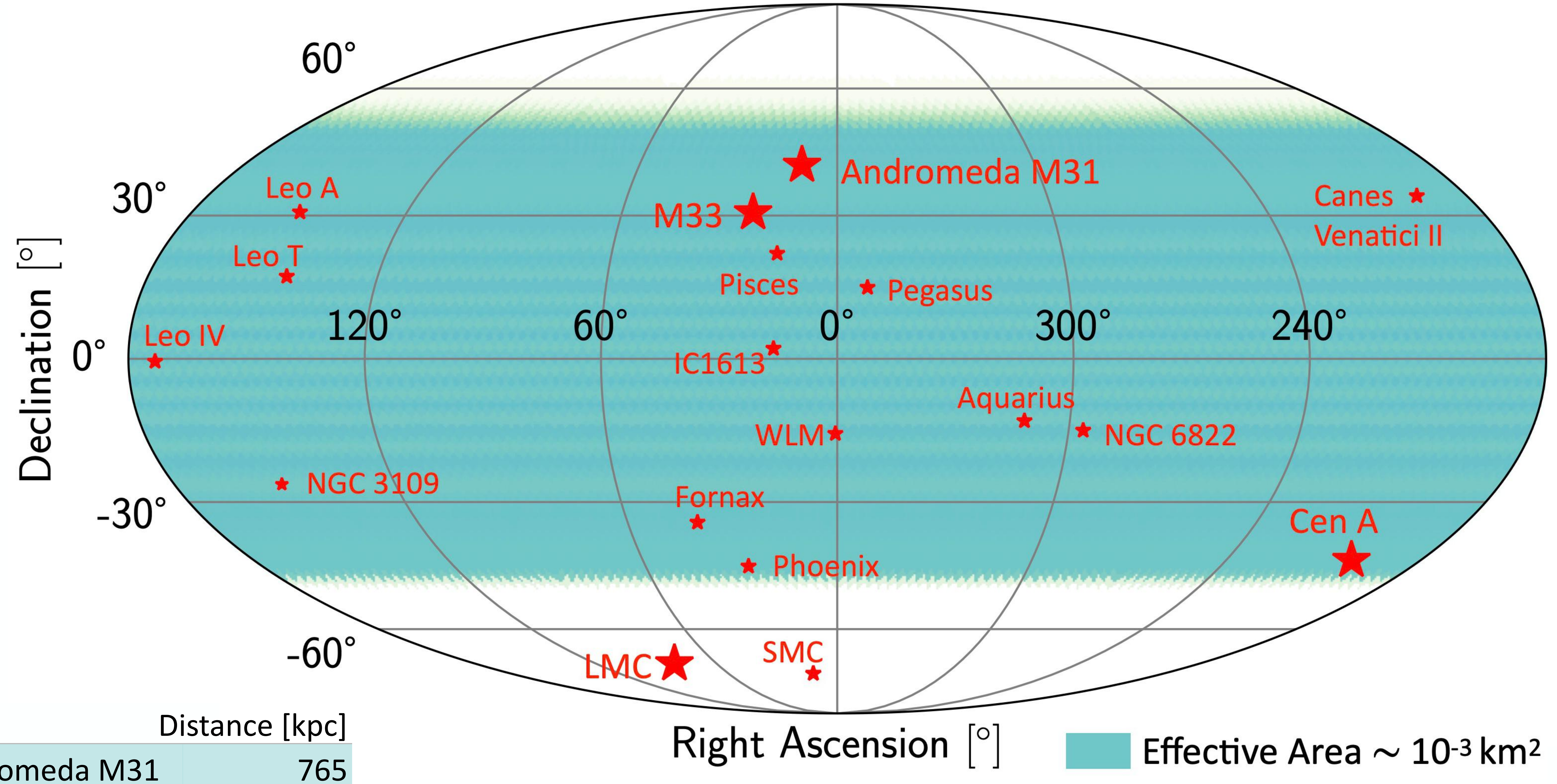


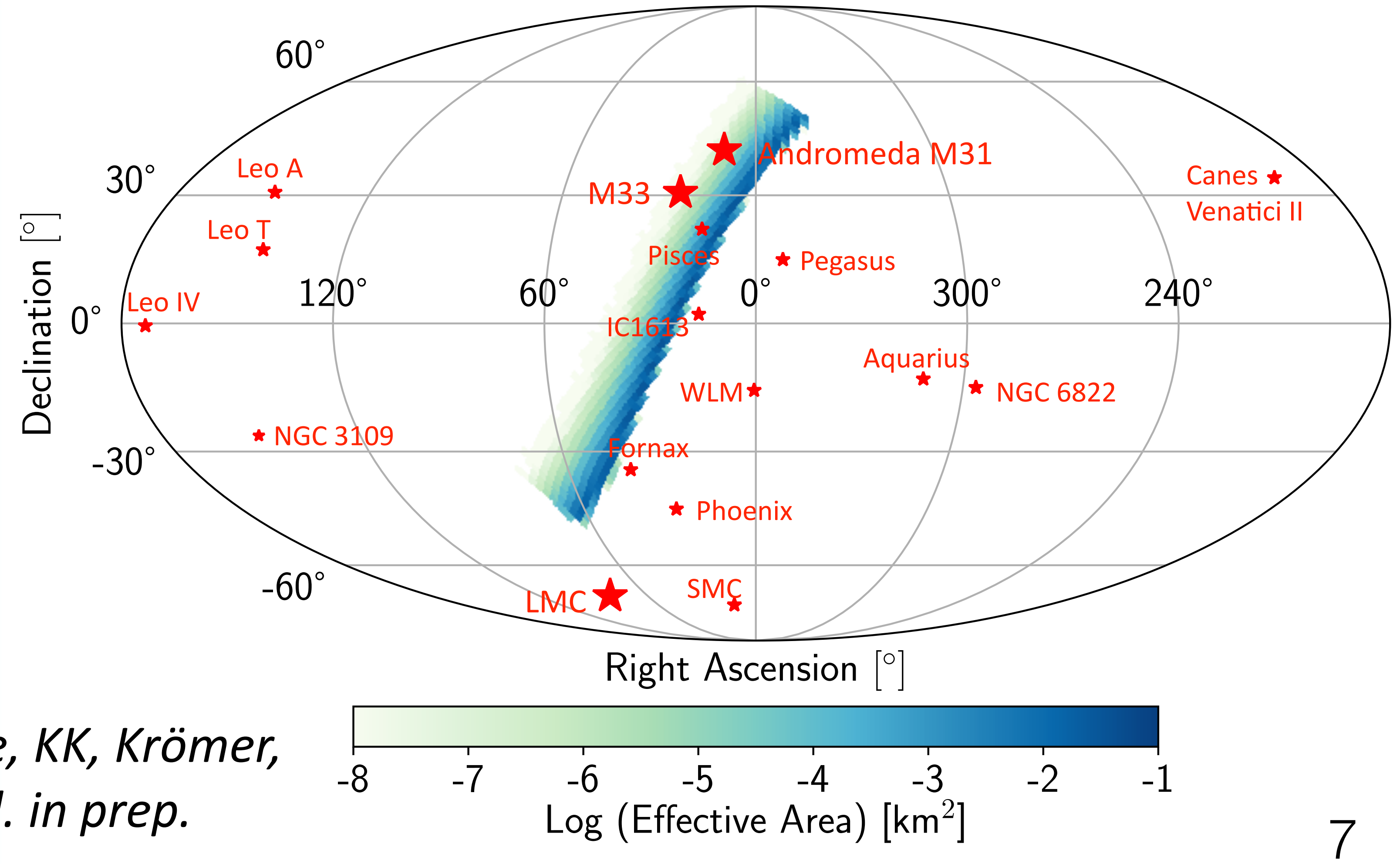


Daily FoV for HERON
(GRAND-BEACON hybrid)

	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

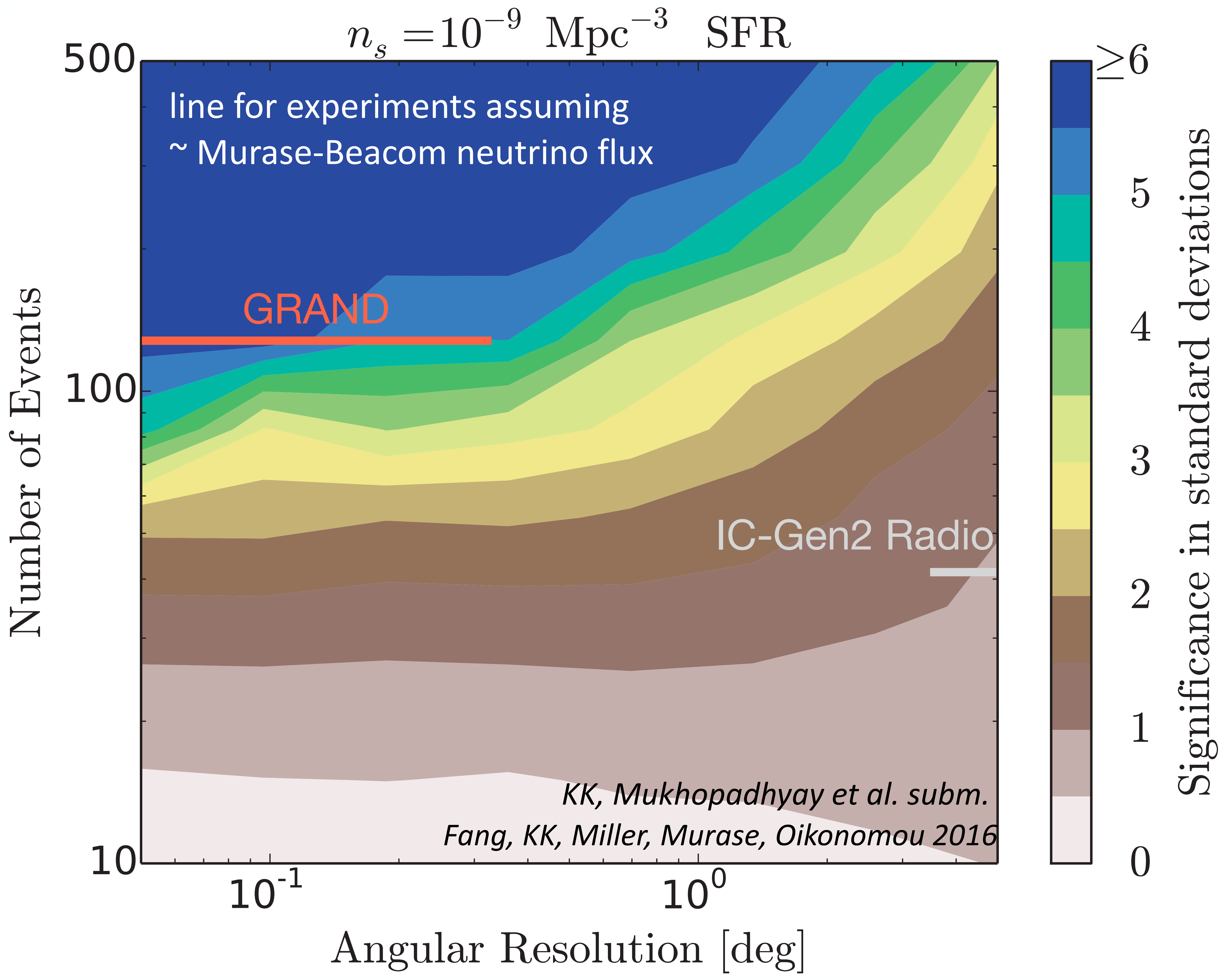
	Distance [kpc]
NGC 6822	500
Pegasus	920
Fornax	143
Canes Venatici II	522
Leo IV	154
Leo T	420

instantaneous FoV for HERON
(GRAND-BEACON hybrid)



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

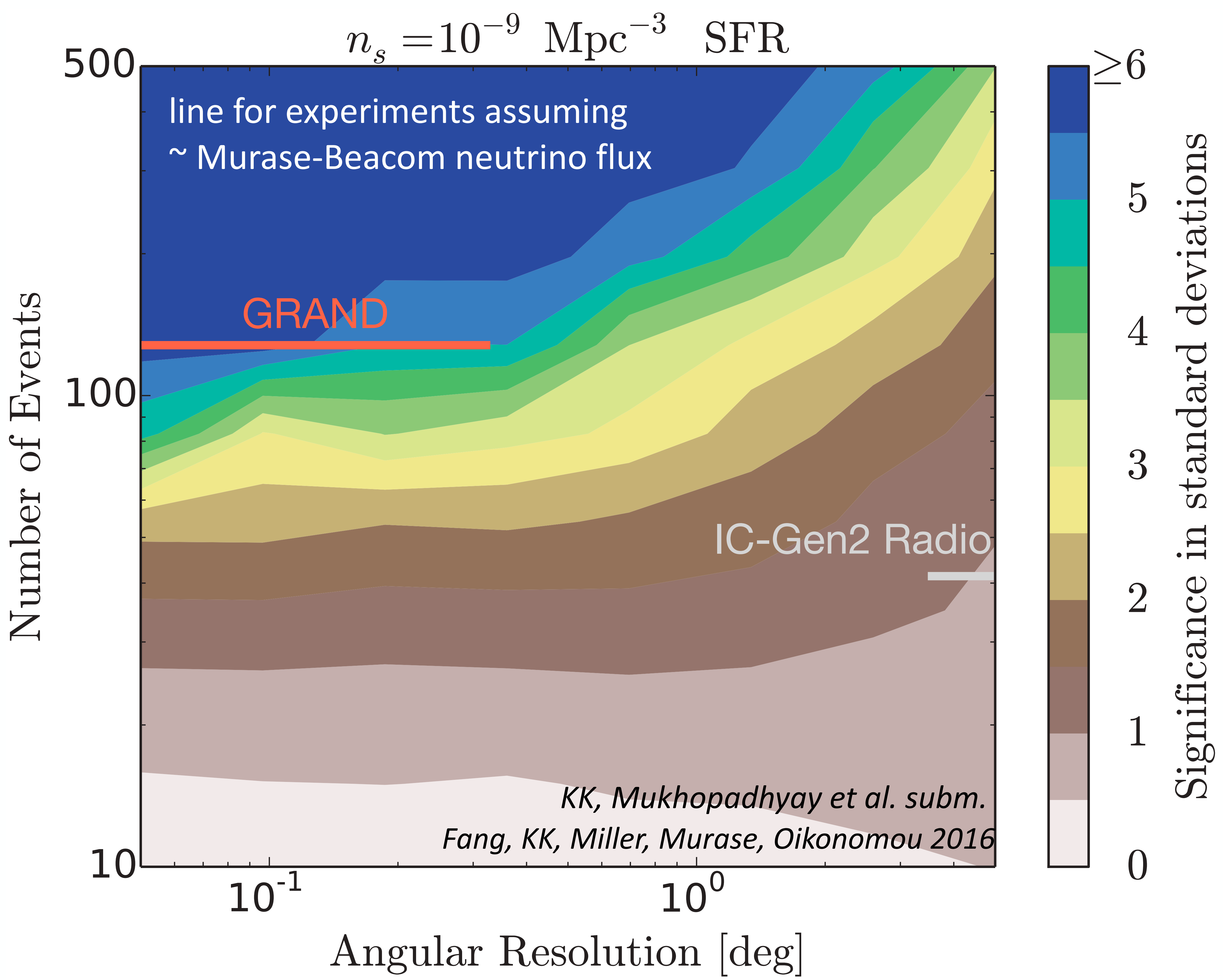
A necessary angular resolution



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

KK, Mukhopadhyay, Alves Batista, Fox, Martineau-Huynh, Murase, Wissel, Zeolla, subm.

Astrophysically motivated search for UHE neutrinos

Short rare & bright transients

- follow-up searches of EM / GW + stacking
- deep instruments with sub-degree angular res.

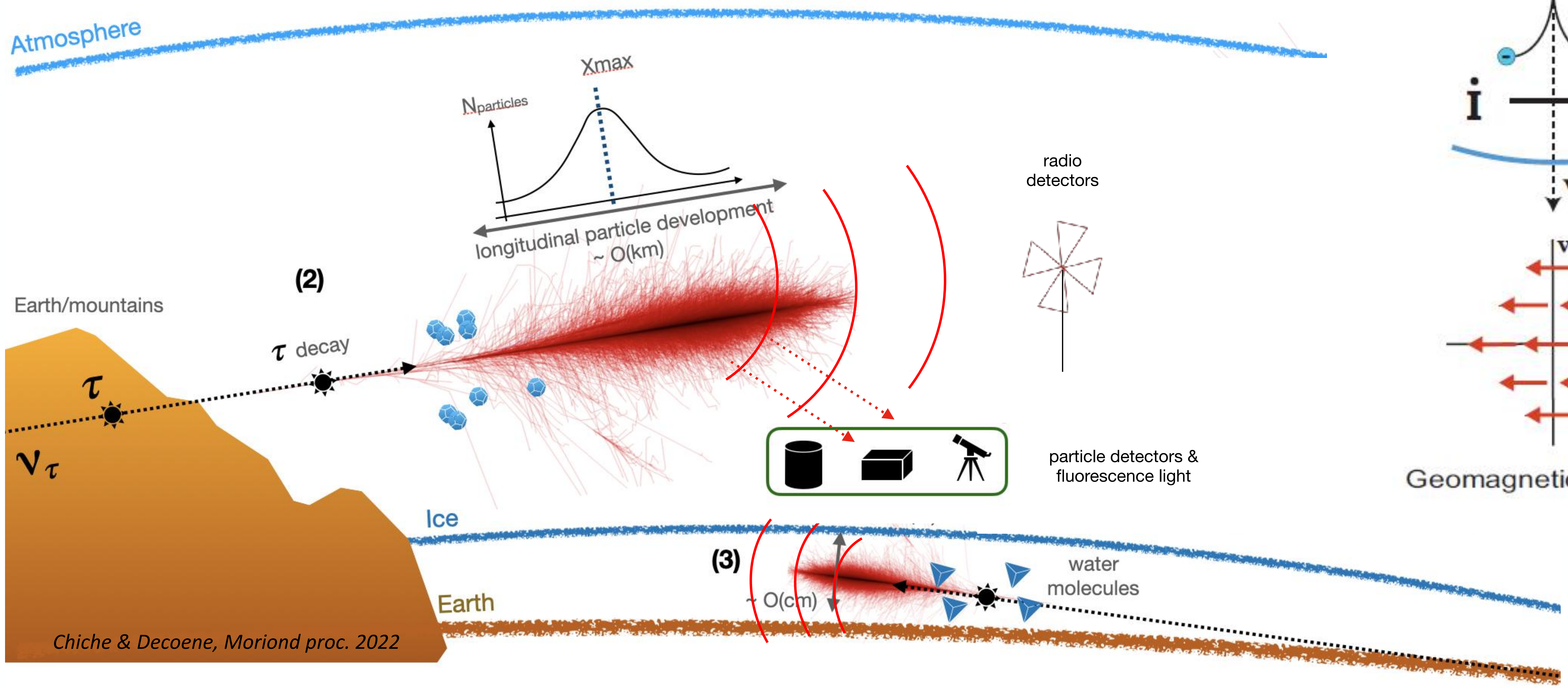
Nearby serendipitous sources

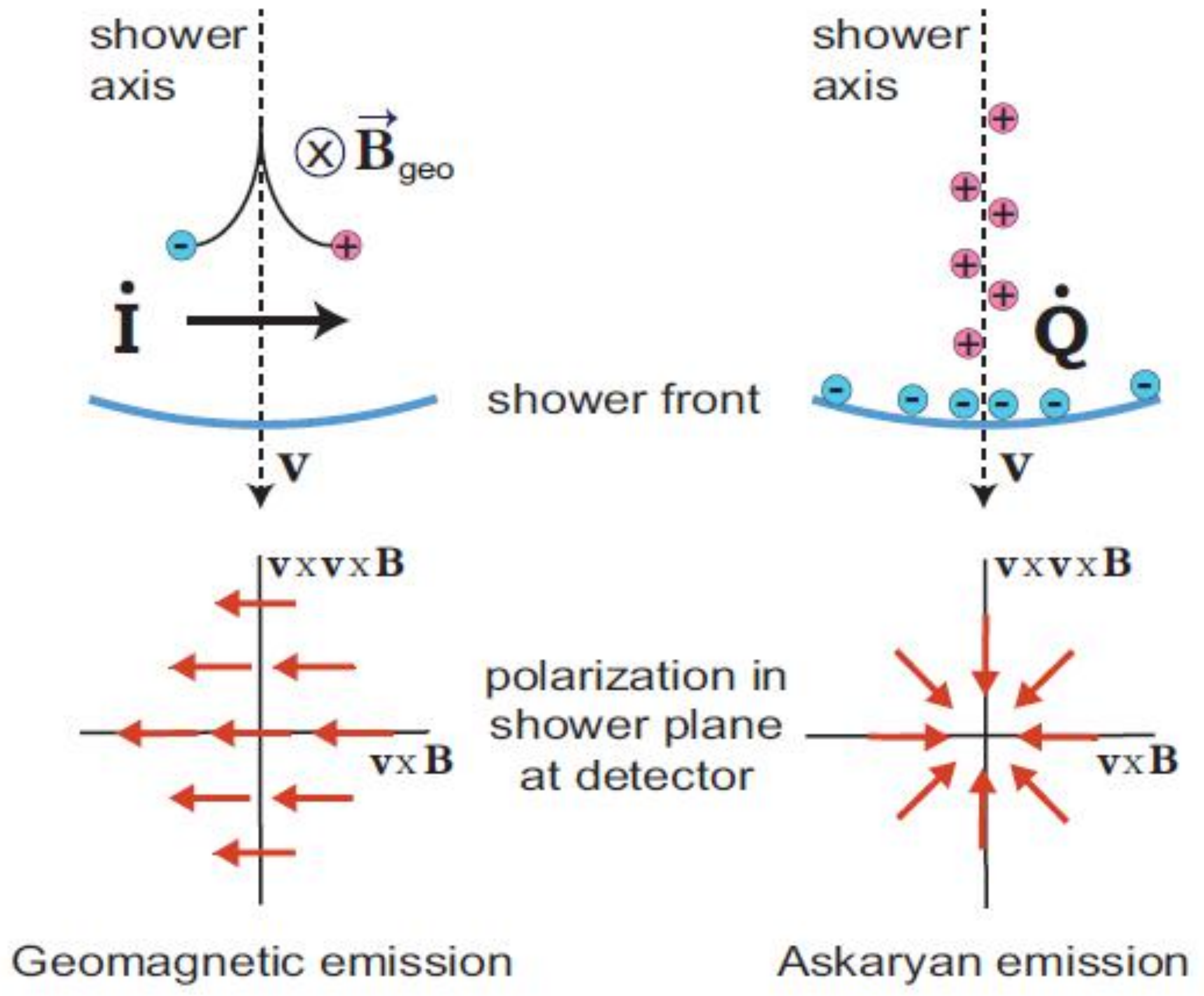
- long transients, well-identified
- both deep & narrow + wide & shallow instruments

What can we do to improve UHE neutrino detectability and the associated scientific output?

1. Improve the instantaneous sensitivity even at the cost of reduced instantaneous FoV (deep & narrow)
2. Improve the angular resolution down to sub-degree.
3. Build a catalog of sources in the Local Universe that instruments should have in their day-averaged FoV.
4. Follow-up these catalogued sources. For most UHE instruments that do not point and track source positions in the sky naturally, this requires to develop a designated data-taking/observation mode.
5. For narrow instruments: Widen the instantaneous FoV along right ascension, to increase sensitivity for long bursts.
6. Coordinate and optimize the location of detectors on the globe for best collective daily sky coverage.

Radio detection as a cost-effective technique





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

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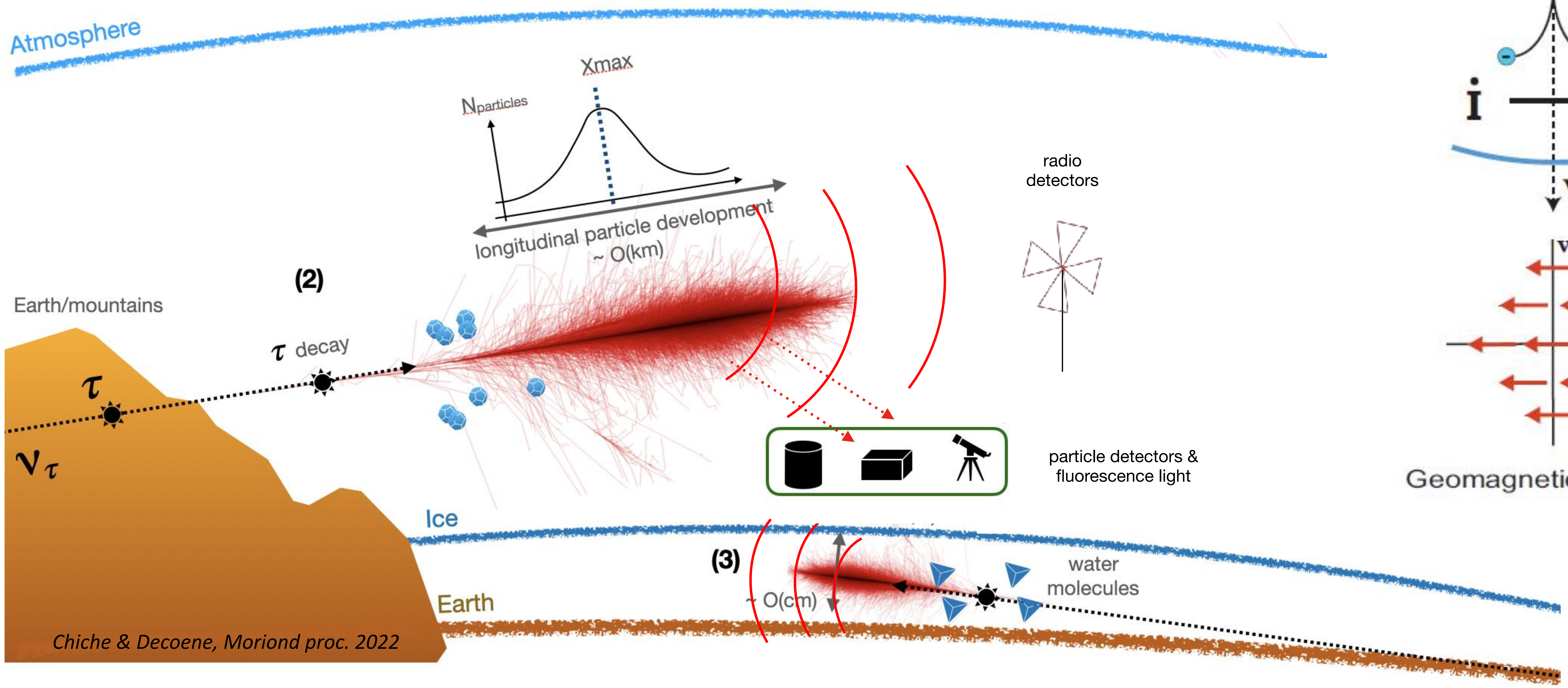

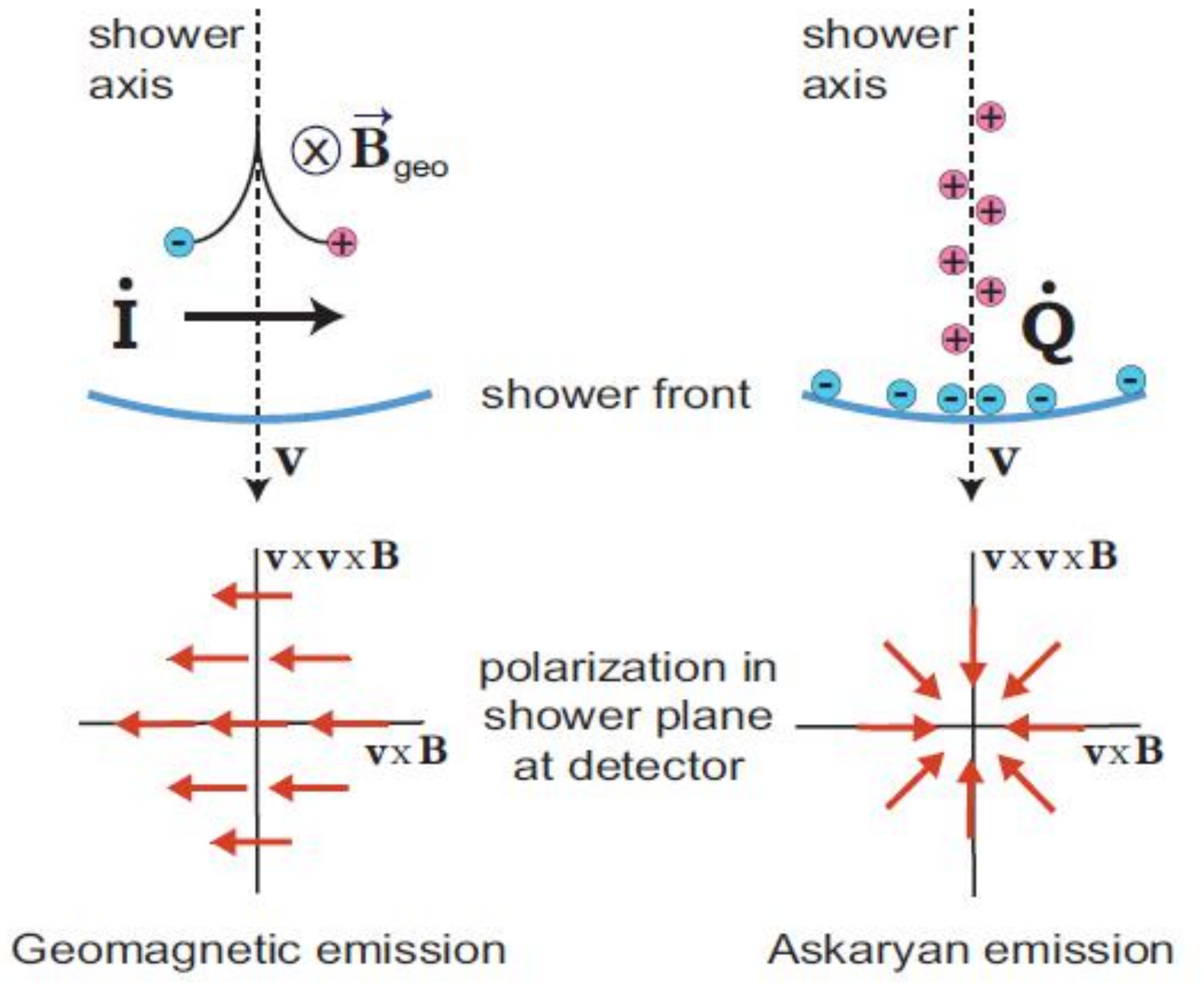

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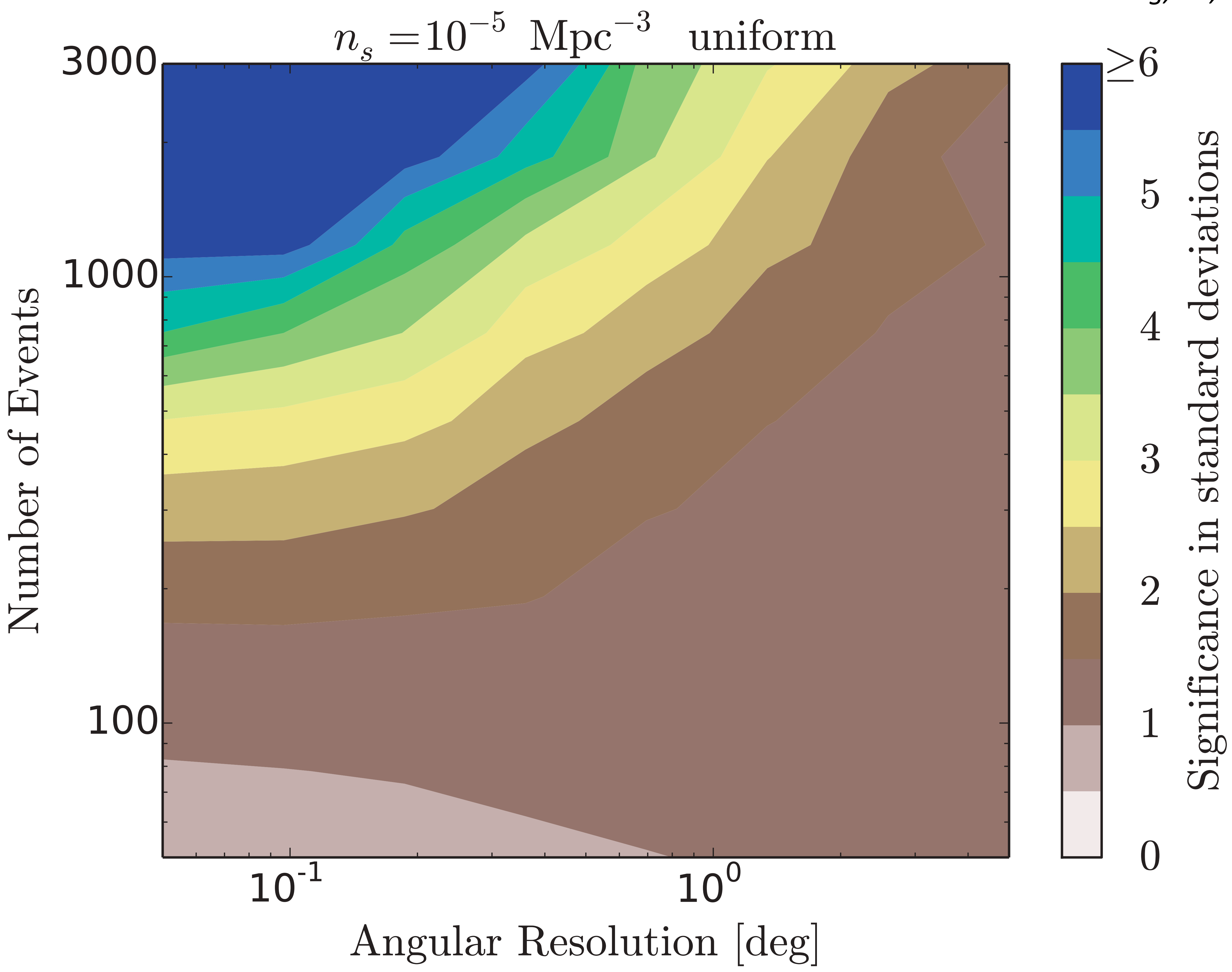
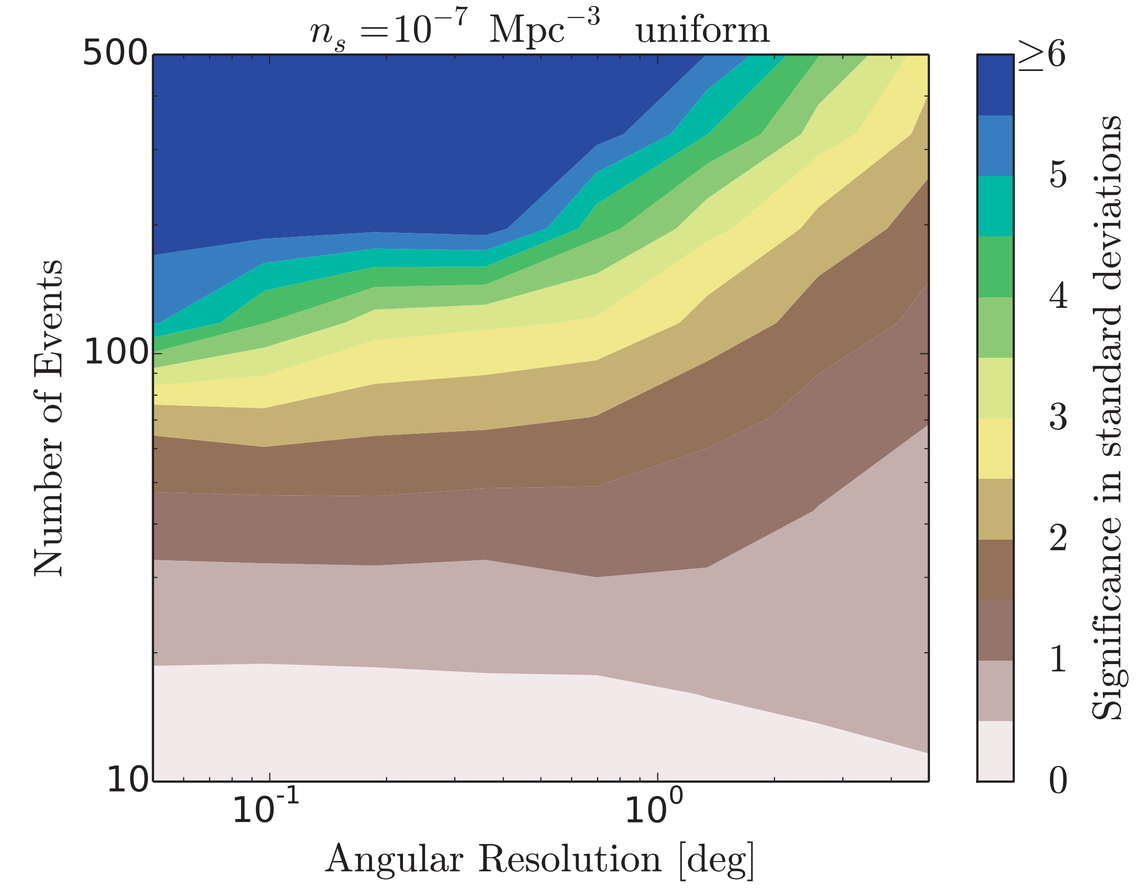
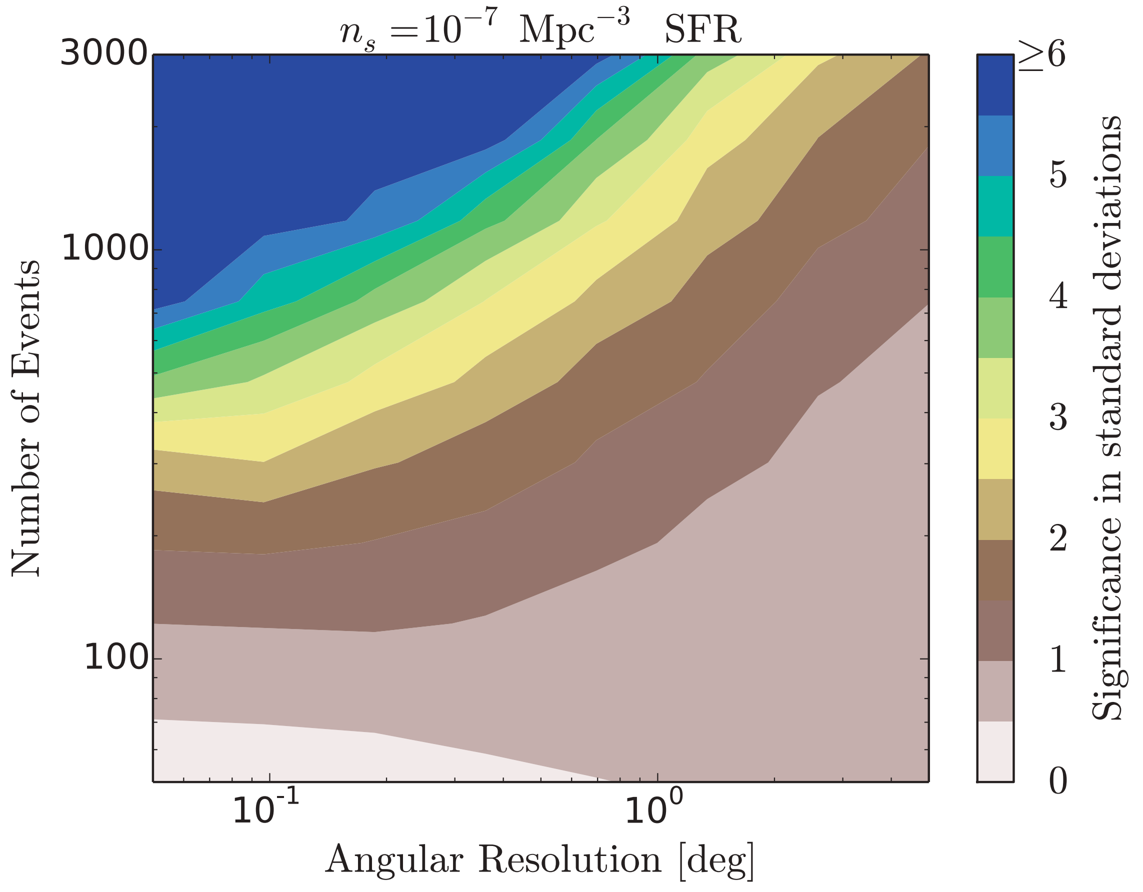
Performances	instantaneous sensitivity	daily aver. sensitivity	iFoV	dFoV	angular resolution
in-ice	+ wide & shallow	++	**+++** wide & shallow	++ no gain by Earth rotation if South Pole	+ reconstruction of polarization difficult
in-air	**+++** deep & narrow	++ equivalent as experiments tuned to diffuse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


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

Fang, KK, Miller, Murase, Oikonomou 2016







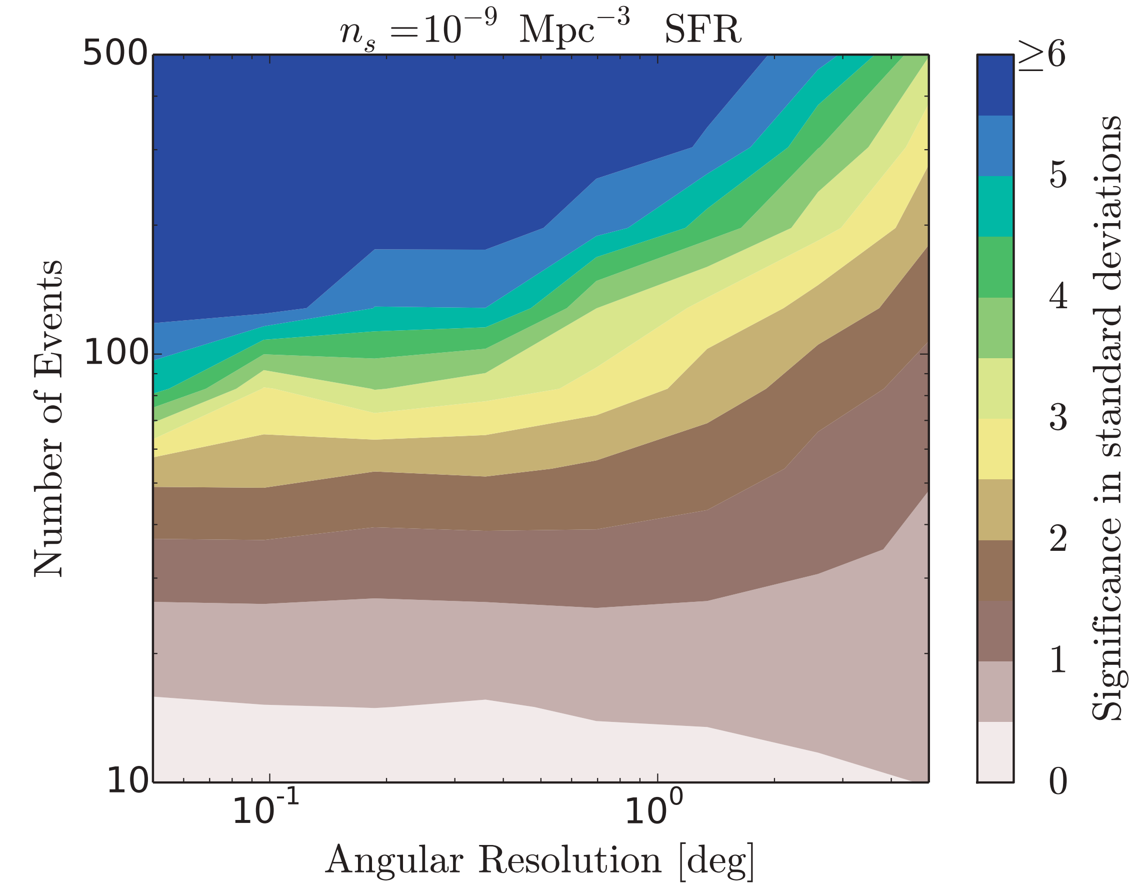


Figure 1. Significance of detection of point sources of UHE neutrinos by experiments with various angular resolutions and numbers of detected events. The color coding corresponds to the confidence level to reject an isotropic background using the statistical method from Ref. [65]. We assume that all 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 $\sim 0.1^\circ$ 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.