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Supplementary information

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High-energy neutrino transients and the future of multi-messenger astronomy

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2021 2025 >2030	Minimum energy	Peak energy	Differential sensitivity limit [u.l.]	iFoV	dFoV	ang. res.	ν alert types, *examples*
ANITA	0.1 EeV	100 EeV	[2.4×10^{-7} GeV cm^{-2} s^{-1} sr^{-1} in 24 d]	6% [7°×360°]	19% [26°×360°]	2.8°	-
PUEO	0.1 EeV	20 EeV	4.2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 30 d	6 %	20 %	<2.8°	-
ARA	10 PeV	1−3 EeV	3.6×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} by 2030	35 %	35 %	5°	-
RNO-G	50 PeV	1 EeV	5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	30% [45°×360°]	>50%	2°×10°	*planned*
ARIANNA-200	30 PeV	1 EeV	4×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	50 %	>50%	2.9−3.8°	*GCN, AMON*
BEACON	30 PeV	1 EeV	6×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	6 %	19.5%	0.3°−1°	*planned*
Auger	50 PeV	0.3−1 EeV	[1.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 2019]	30 %	92.8%	<1°	no alerts, AMON
POEMMA Cerenkov	10 PeV	0.5 EeV	3.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	0.6 %	18−36%	0.4°	*planned*
fluorescence	10 EeV	100 EeV	1.5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	?	?	1°	*planned*
GRAND	50 PeV	0.4 EeV	2×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	45 %	100 %	0.1°	*planned*
IceCube-Gen2 Radio	10 PeV	0.3 EeV	2×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	43% [55°×360°]	43% [55°×360°]	2°×10°	*planned*
Ashra-NTA	1 PeV	0.1 EeV	10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	25% [30°×360°]	>80%	0.1°	*planned*
Trinity	0.1 PeV	0.1 EeV	5×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	6% [7°×360°]	62 %	<1°	*planned*
TAMBO	0.3 PeV	10 PeV	?	27 %	62 %	1°	*planned*
RET-N	10 PeV	0.1 EeV	1.5×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr	50 %	>50%	?	*planned*
ANTARES up(cascade)	20 GeV(1 TeV)	50(100) TeV	[2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 11 yr] (up+casc.)	50%(100%)	75%(100%)	0.3-0.4°(3°)	ν_μ only: GCN, AMON
IceCube up(cascade)	300 GeV	100 TeV	[1.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 3 yr] (up+casc.)	54%(100%)	54%(100%)	0.4°(10°)	GCN, AMON, SNEWs
IceCube-Gen2 up(cascade)	5 TeV	300 TeV	2×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in < 90 d (up+casc.)	54%(100%)	54%(100%)	0.3°(10°)	*GCN, AMON, SNEWs*
KM3Net ARCA up(cascade)	100 GeV(1 TeV)	100(100) TeV	5.8×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} in 1.5(1 yr)	50%(100%)	75%(100%)	0.1°(1.5°)	*GCN, AMON*
Baikal-GVD up(cascade)	100 GeV(1 TeV)	100(100) TeV	(5.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 10 yr)	50%(100%)	72%(100%)	<1°(4.5°)	*private MoU, GCN*
P-ONE up(cascade)	1 TeV	100 TeV	1.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} in 2 yr	50%(100%)	73%(100%)	0.1°(1−3°)	*planned*

Table 1. Indicative experimental characteristics of current and future neutrino detectors targeting energies above (light blue band) and below (dark blue band) 10 PeV. The left-hand side of the table indicates the timeline of each instrument (green: current, yellow: up-coming, gray: under construction). The following columns from left to right reference the minimum neutrino energy, the peak energy where the differential sensitivity is best, the differential sensitivity to diffuse neutrino flux [or measured flux or measured upper limits in brackets], the instantaneous (iFoV, FoV field of view) and daily averaged (dFoV) fields of view in sky percentage and in square degrees in brackets, and the angular resolution. The final column provides information on alert programs set up or planned to be set up (in italics) by the instrument. For instruments targeting < 10 PeV energies, the numbers in parenthesis are for 'cascade events' (see main text for definition), and the others for muon tracks, unless otherwise indicated. Question marks indicate the yet unknown values for up-coming experiments. References are given in the main text.

2021 2025 >2030	Band Width	Differential sensitivity limit	FoV	ang. res.	slew [survey] speed	resp. delay	ν foll. rate [% alerts] *examples*
LHAASO	100 GeV−1 PeV	5×10^{-14} erg cm^{-2} s^{-1} in 1 yr	2 sr	0.3°	[2/3 sky/day]	-	?
CTA	20 GeV−300 TeV	6×10^{-14} erg cm^{-2} s^{-1} in 50 h	10−20°	$<$ 0.15°	180°/20 s	20 s	20 h/yr (2016)
HAWC	100 GeV−100 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 1 yr	2 sr	0.1°	[2/3 sky/day]	-	[90% IC Gold alerts]
H.E.S.S.	30 GeV−100 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 50 h	5°	0.1°	10°/min	60 s	60−70 h/yr
MAGIC	50 GeV−50 TeV	9×10^{-13} erg cm^{-2} s^{-1} in 50 h	3.5°	0.07°	7°/s	20 s	60 h/yr, 15% ToO
VERITAS	85 GeV−30 TeV	6×10^{-13} erg cm^{-2} s^{-1} in 50 h	3.5°	0.1°	1°/s	90 s	45 h/yr
Fermi LAT	20 MeV−300 GeV	5×10^{-13} erg cm^{-2} s^{-1} in 10 yr	2.4 sr	0.15°	[all-sky/3 h]	4−5 h	[100% IC alerts]
GBM	10 keV−25 MeV	2 ph cm^{-2} s^{-1} in 1 s	9 sr	10°	[all-sky/1 h]	5−6 h	[60% IC alerts]
INTEGRAL IBIS	15 keV−10 MeV	1.2×10^{-12} erg cm^{-2} s^{-1} in 10^3 s	64 deg^2	0.2°	0.2°/s	min	[all ANTARES
SPI-ACS	100 keV−2 MeV	10^{-3} ph cm^{-2} s^{-1} MeV^{-1} in 10^6 s	4π	-	-	min	and GCN IC alerts]
XMM-Newton	0.2−12 keV	10^{-15} erg cm^{-2} s^{-1} in 10^6 s	0.5°	6”	90°/h	few h	*PKS 1502+106, Kloppo*
Athena-WFI	0.1−15 keV	3×10^{-16} erg cm^{-2} s^{-1} in 10^5 s	0.4 deg^2	$<$ 5”	1°/min	4 h	[5 ToO/month]
Swift BAT	15−150 keV	6×10^{-10} erg cm^{-2} s^{-1} in 2000 s	1.4 sr	0.4°			
XRT	0.2−10 keV	5×10^{-13} erg cm^{-2} s^{-1} in 10^4 s	0.1 deg^2	18”	1°/s	min−h	50% ToO
UVOT	0.16−0.62 μm	19 mag in 300 s	0.1 deg^2	2.5”			
SVOM ECLAIRs	4−150 keV	7.2×10^{-10} erg cm^{-2} s^{-1} in 10^3 s	2 sr	$<$ 0.2°			first 3 yrs:
MXT	0.2−10 keV	2×10^{-12} erg cm^{-2} s^{-1} in 3000 s	1 deg^2	13”	45°/5 min	min−h	15% ToO
VT	0.4−1 μm	22.5 mag in 300 s	0.2 deg^2	$<$ 1”			then: 40% ToO
ASAS-SN	380−555 nm	19.5 mag in 30 min	72 deg^2	7.8”	[vis. sky/days]	min−day	[70−80% all IC GCN alerts]
ATLAS	420−975 nm	19.7 mag in 30 s	29 deg^2	2”	[4×vis. sky/day]	45 s	[no ν alert yet]
Pan-STARRS	400−900 nm	23.1 mag in 904 s	14 deg^2	1.0−1.3”	[vis. sky/week]	h−day	[6 follow ups]
ZTF	400−650 nm	21.0 mag in 300 s	47 deg^2	2”	[vis. sky/2 days]	h−day	[74% IC Gold alerts]
Vera Rubin Obs. (LSST)	0.3−1 μm	24.5 mag in 30 s	9.6 deg^2	0.7”	[100 deg^2/5 min]	-	-
MASTER-II(VWF)	400−800 nm	19(12) mag in 1 min(5 s)	8(400) deg^2	1.9” (22”)	30°/s(8°/s)	min−h	[99% GCN neutrino alerts]
TAROT	350−980 nm	18.5 mag in 180 s	4 deg^2	3.5”	50°/s	s−day	$<$3% obs. time [70% GCN alerts]
GEMINI (GMOS)	0.36−1.03 μm, spec	25 mag in 2.5 days	30.23’^{2}	0.07”/pix	obj./2 min	20 min	*SN PTF12csy*
GTC (OSIRIS)	0.365−1.05 μm, spec	27 mag in 1 h	0.02 deg^2	0.127”/pix	obj./min	min	*TXS 0506+056*
Keck (LRIS)	0.32−1 μm, spec	23 mag in 20 s	46.8’^{2}	0.135”/pix	1.5°/s	h	*SN PTF12csy*
VLT (X-shooter)	0.3−2.4 μm, spec	23 mag in 60−120 s	2.2’^{2}	0.173”/pix	obj./5 min	30 s	*TXS 0506+056, IC190331A*
VLA	1−50 GHz	186 μJy in 1 min	0.16 deg^2	0.12”	[20 deg^2/h]	days	*TXS 0506+056, ANTARES events*
MWA	80−300 MHz	4.6 mJy at 1 s	610 deg^2	0.9’	obj./8 s	6−40 s	[30% IC Gold, $>$30% ANTARES]
SKA1(2)-MID	350 MHz−15.3 GHz	2(0.1) μJy in 1 h	1(10) deg^2	0.04°−0.7°	?	1 s	?

Table 2. Indicative experimental characteristics of a non-exhaustive list of actual or potential neutrino follow-up electromagnetic instruments. The left-hand side of the table indicates the timeline of each instrument (green for current and yellow for upcoming). Unclear termination dates are indicated with a fading gradient. The following columns from left to right reference the band width (characterized by either energy, wavelength or frequency range, depending on conventions), the differential sensitivity limit (definition depends on the type of instrument, see the main text), the field of view (FoV), the angular resolution, the slew speed and survey speed in brakets, the response delay to a neutrino or ToO alert. The final column provides elements of the neutrino or target of opportunity (ToO) follow-up program of each facility, with a neutrino alert follow up rate (“ν foll. rate”, in hour/year) when available, percentage or number of neutrinos followed in brackets, and specific followed source or event names in italics. Question marks indicate the yet unknown values for upcoming experiments. References are given in the main text.