Searches for counterparts of Gravitational Waves with VHE gamma-ray observatories

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March 25, 2o18 , Groningen

Observing the VHE sky with gamma-rays

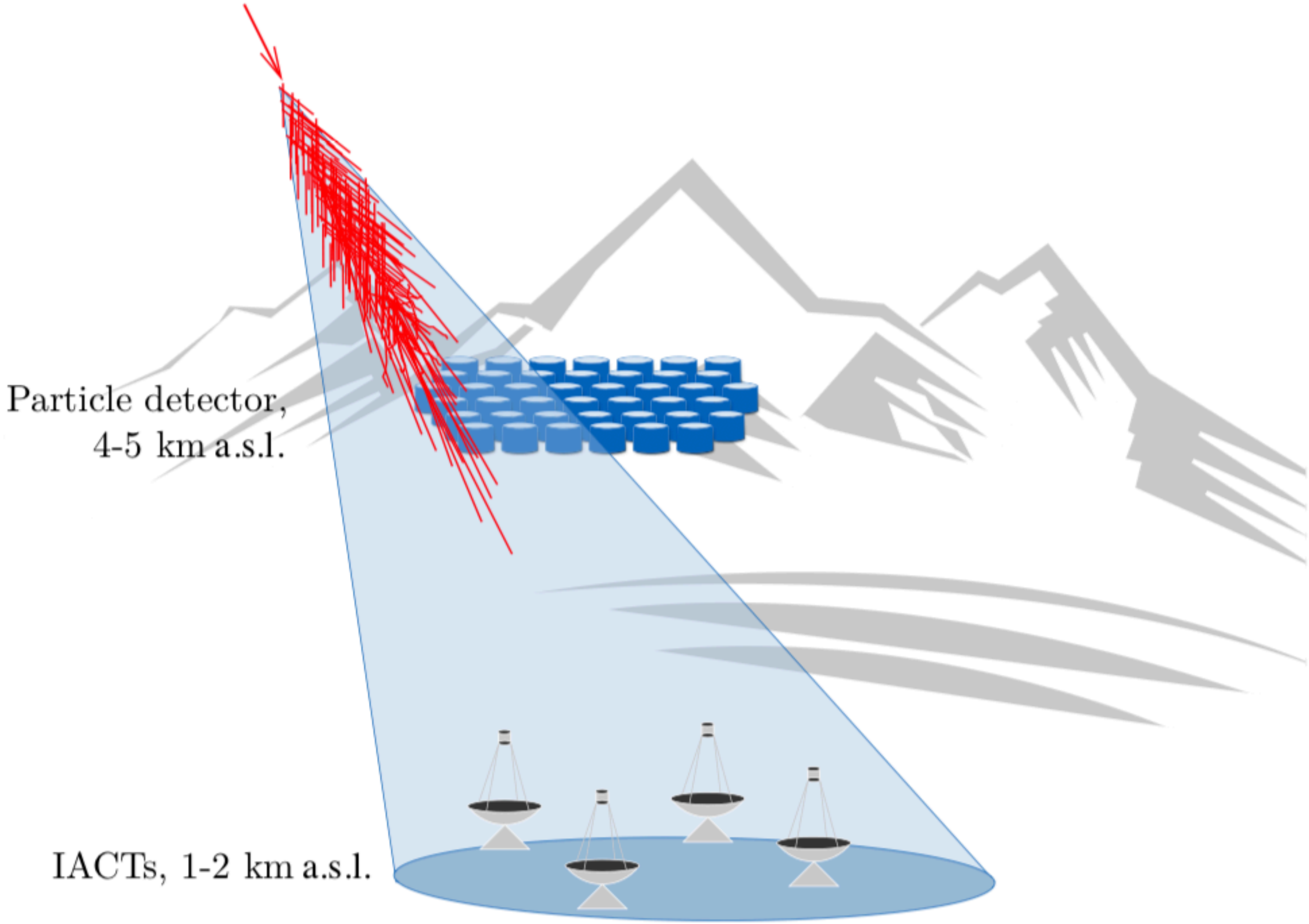


Figure from arXiv:1902.0842

Current instruments observing the VHE sky with gamma-rays

	IACT Arrays	Ground-particle Arrays
Field of view	3°–10°	90°
Duty cycle	10%–30%	>95%
Energy range	30 GeV – >100 TeV	∼500 GeV – >100 TeV
Angular resolution	0.05°–0.02°	0.4°–0.1°
Energy resolution	∼7%	60%–20%
Background rejection	>95%	90%–99.8%

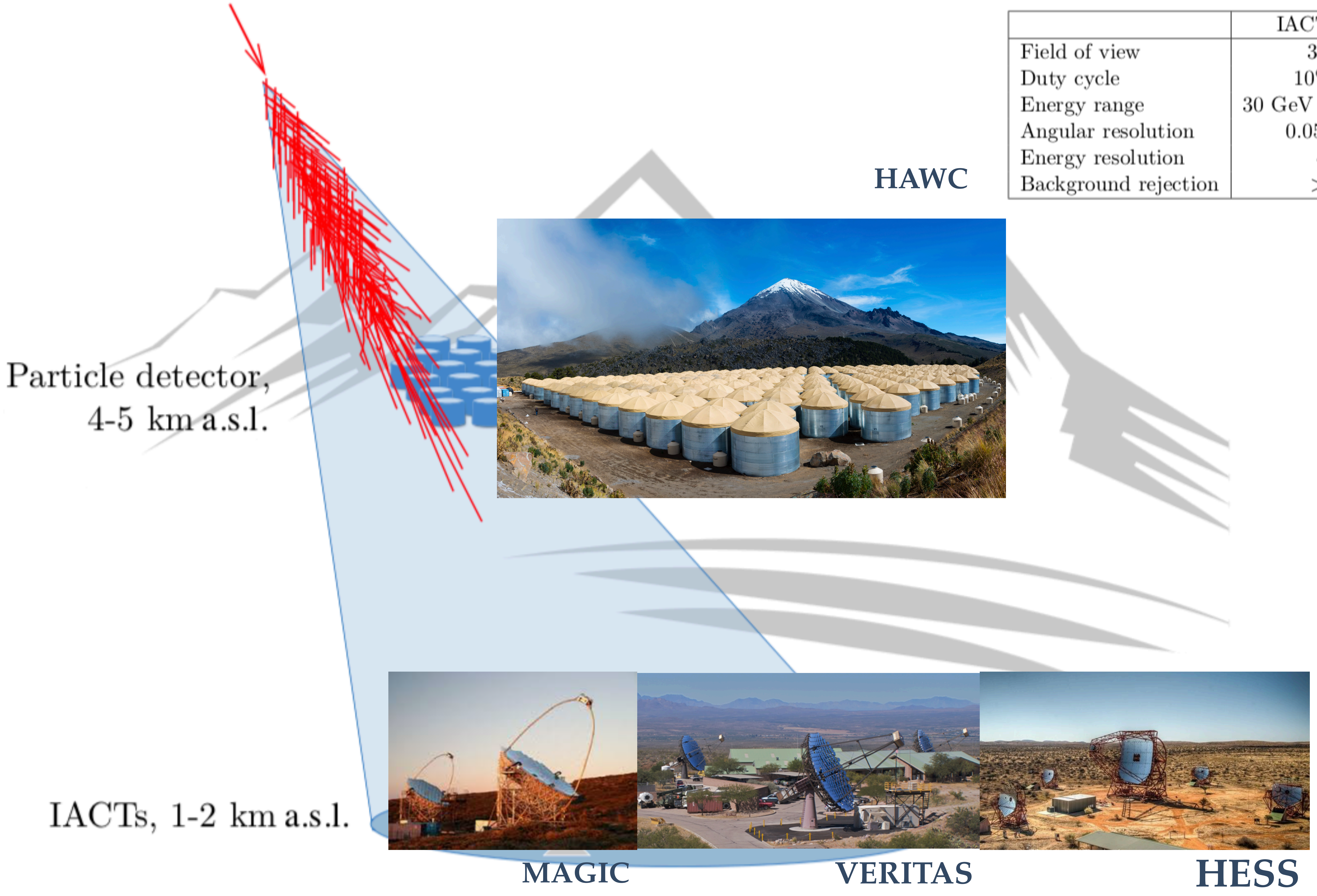
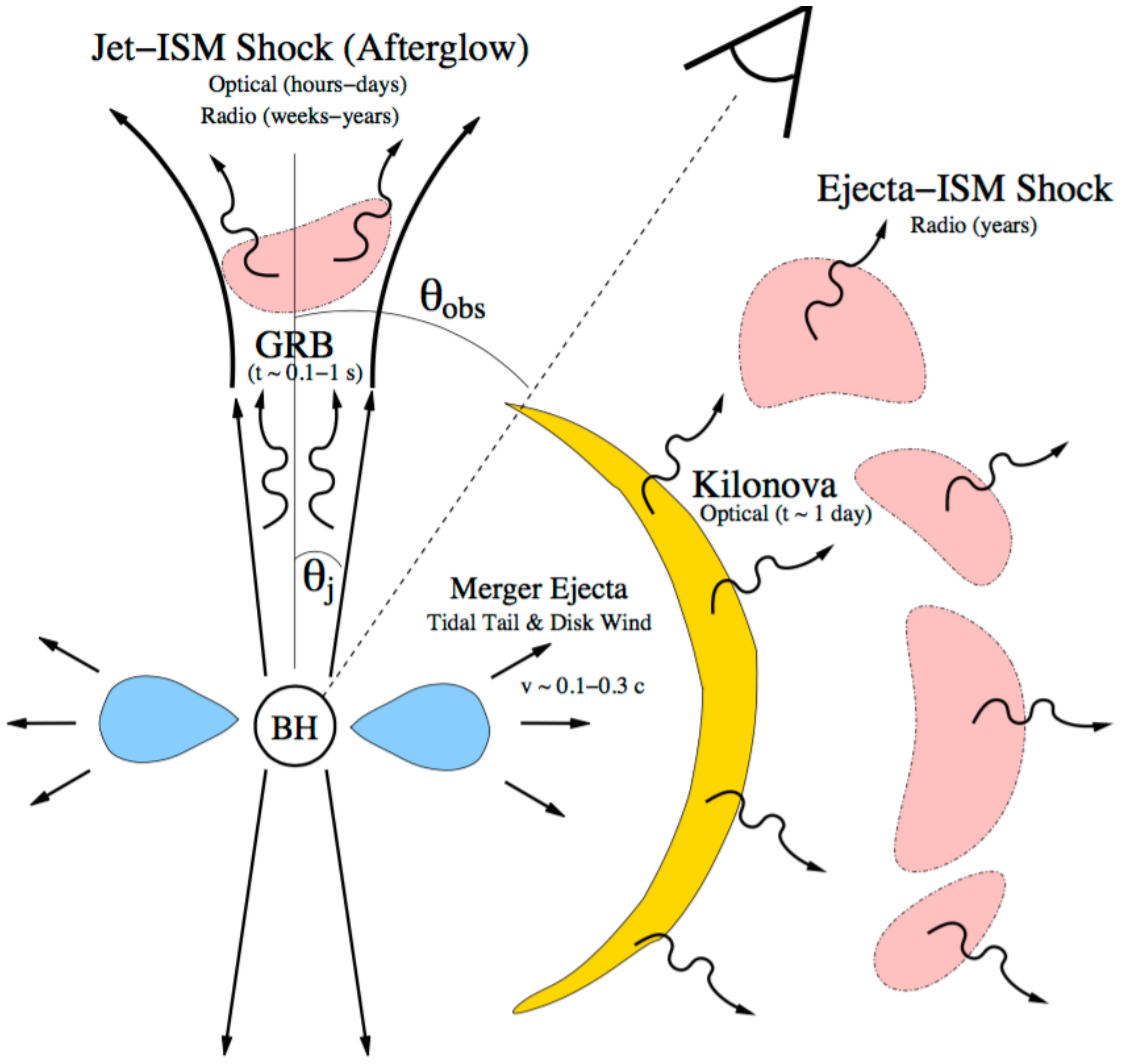


Figure from arXiv:1902.0842

Potential EM counterparts to NSNS/NSBH



Metzger and Berger, 2012

- Recently: First detection of a GRB by an IACT!

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
on ***15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

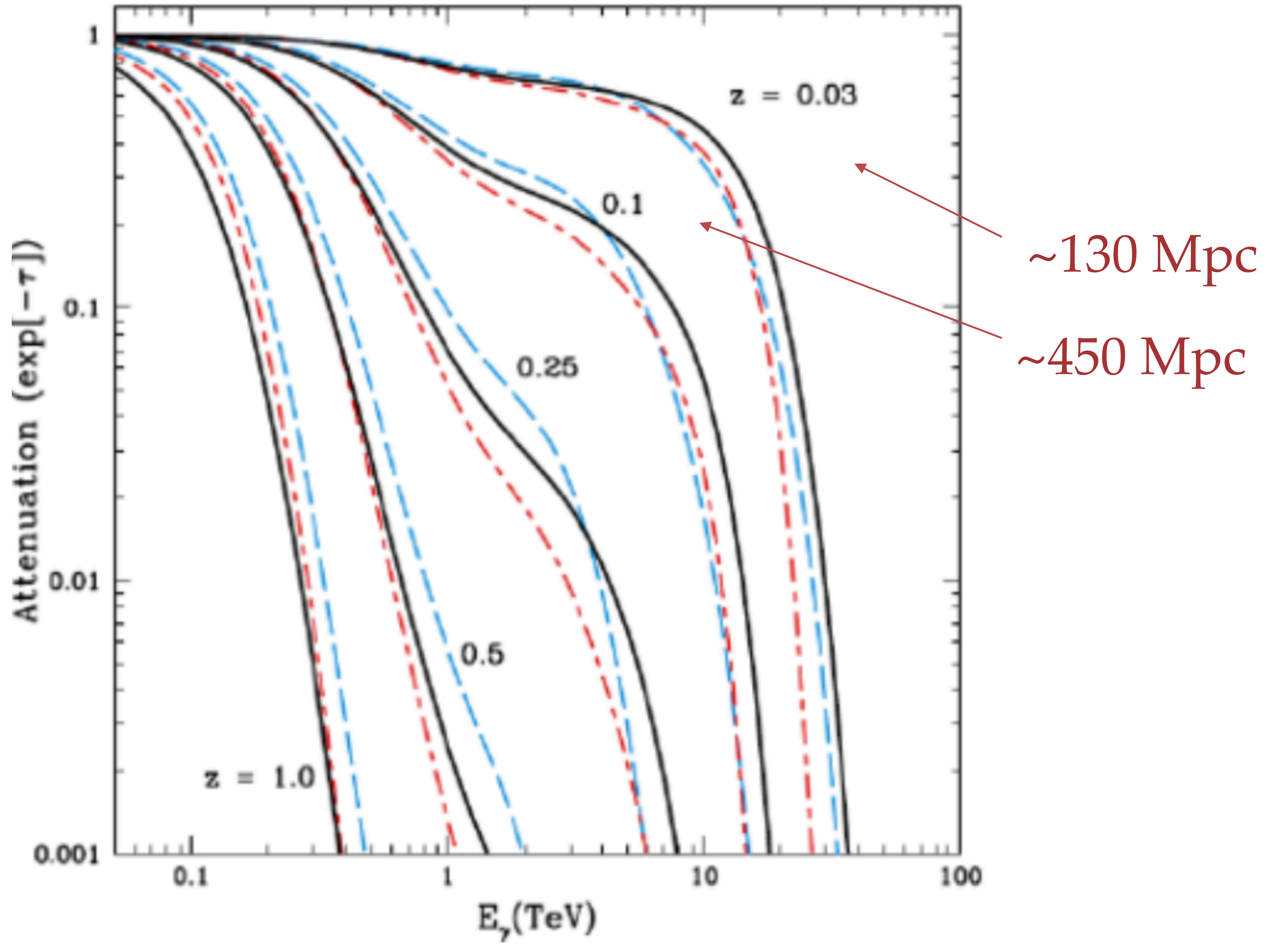
Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event,

Gravitational Wave Follow-up Challenges

- Attenuation of VHE emission is almost negligible at the expected BNS range, even at design sensitivities

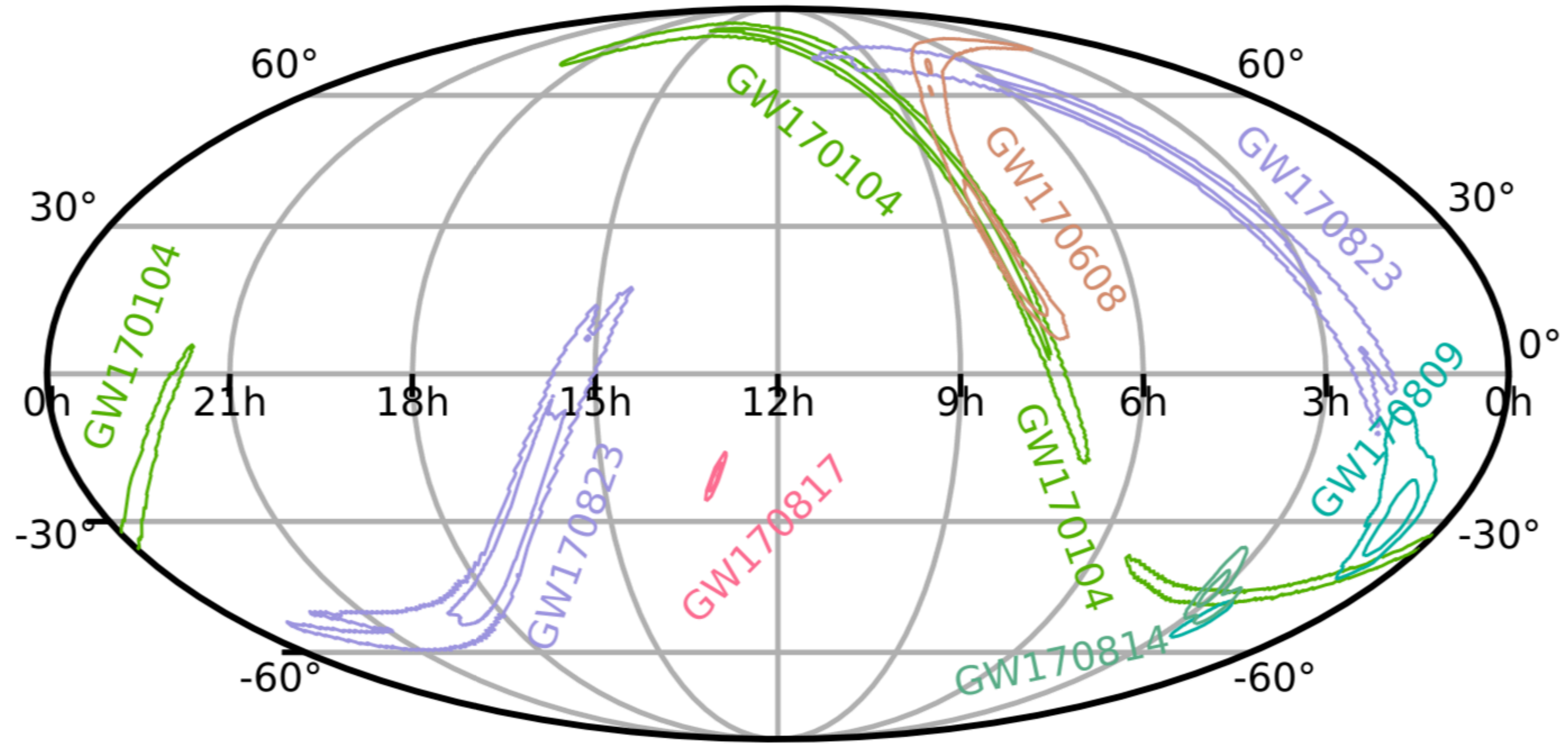
  * GW170817: z~0.009

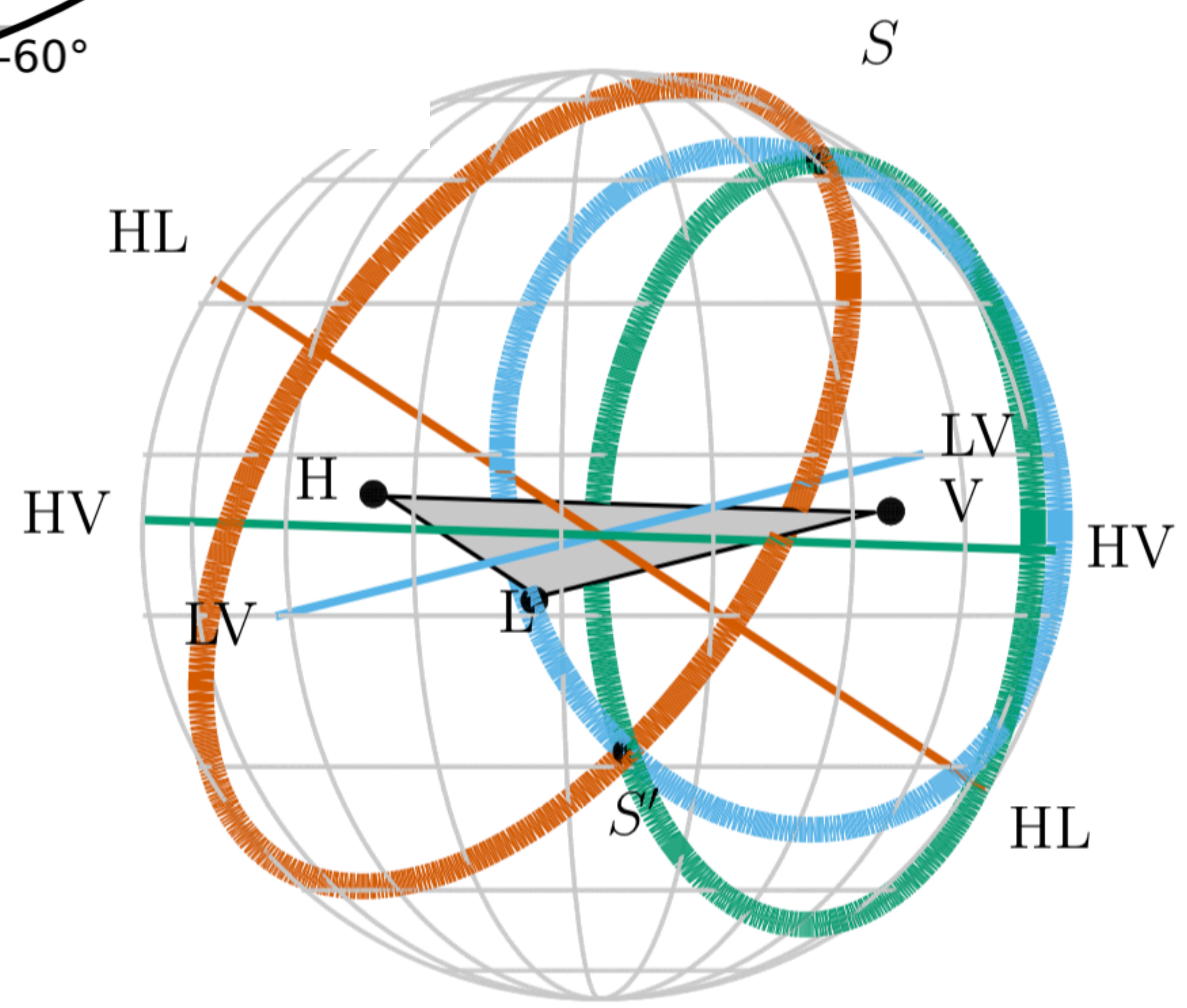


AIP Conference Proceedings. Vol. 1381. No. 1. AIP, 2011.

- GW sky localizations can cover large area in the sky due to the detection technique

50%-90% credible regions of sky localisations of confidently detected O2 GW events (from GWTC-1)





Abbott, B.P., Abbott, R., Abbott, T.D. et al. Living Rev Relativ (2018) 21: 3

GW Follow-up programs in IACTs : Prompt reactions

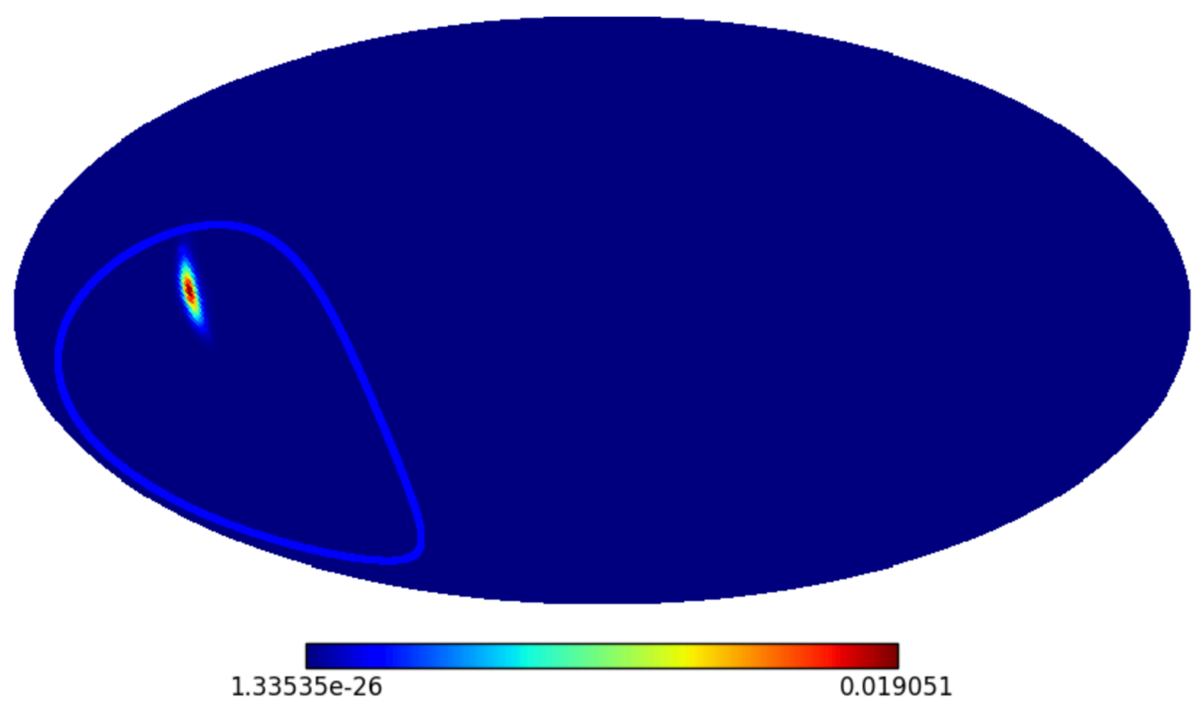
IACTS are specially challenged by their FoVs and observational constraints!

See C.Hoischen talk on 'The H.E.S.S. transients alert system'

GW Event

~minutes

A GW event is triggered. After reconstruction, the event is released as a Open Public Alert (OPAs)



Alert received

~seconds

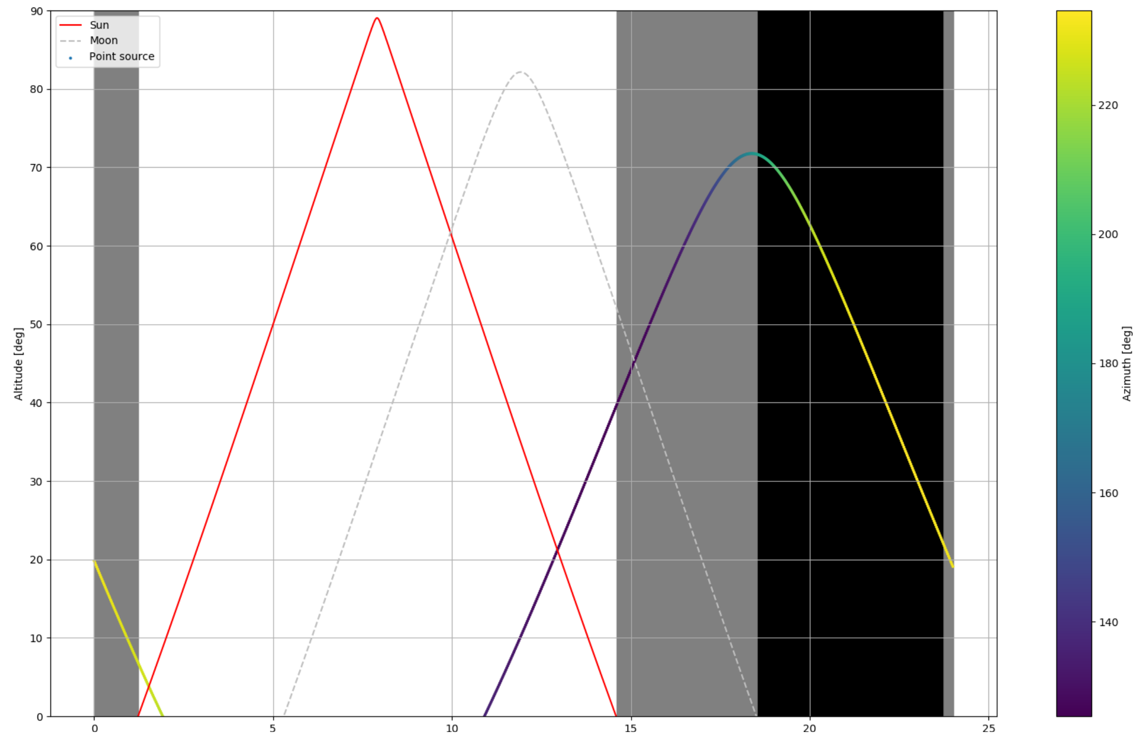
The GW alert received and parsed.

GW Scheduler

~10 x seconds

Observational constraints are considered
Tile the sky localization using different strategies.

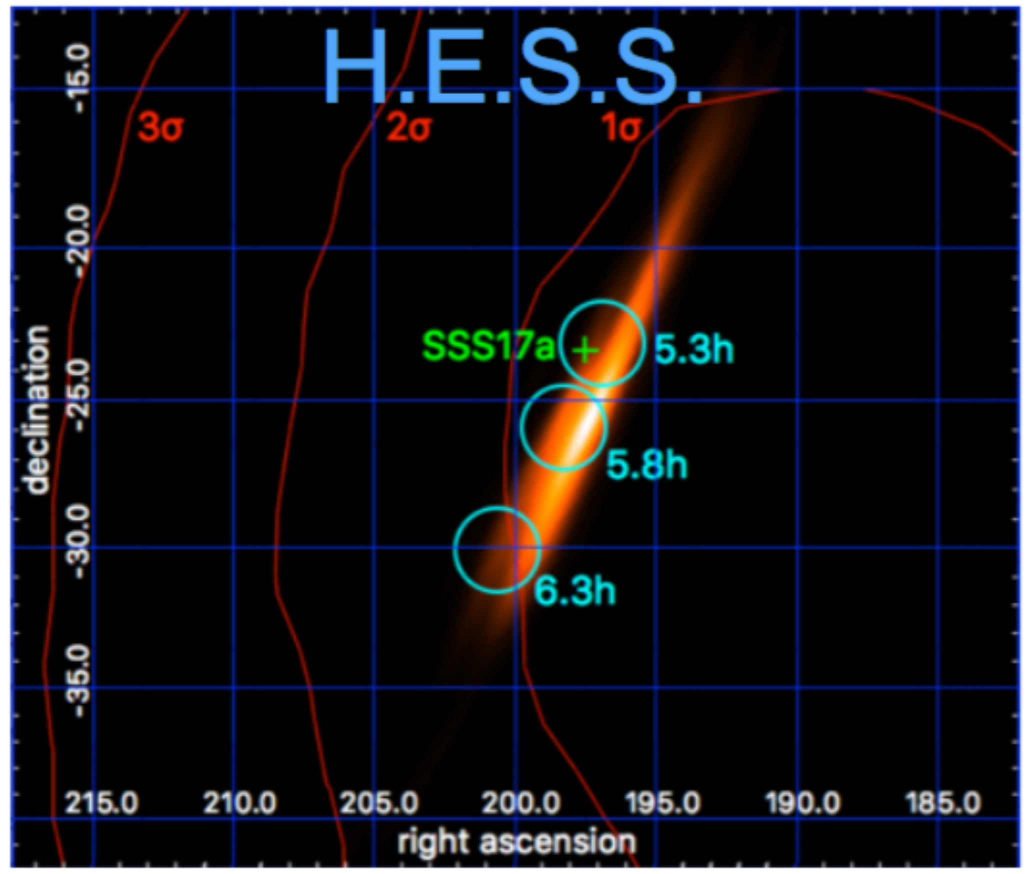
See H. Prokoph talk on 'MM Observations with H.E.S.S' for further info



Observation

Observation starts. The schedule is subject to further change if considered appropriate.

Total Time ~ minutes

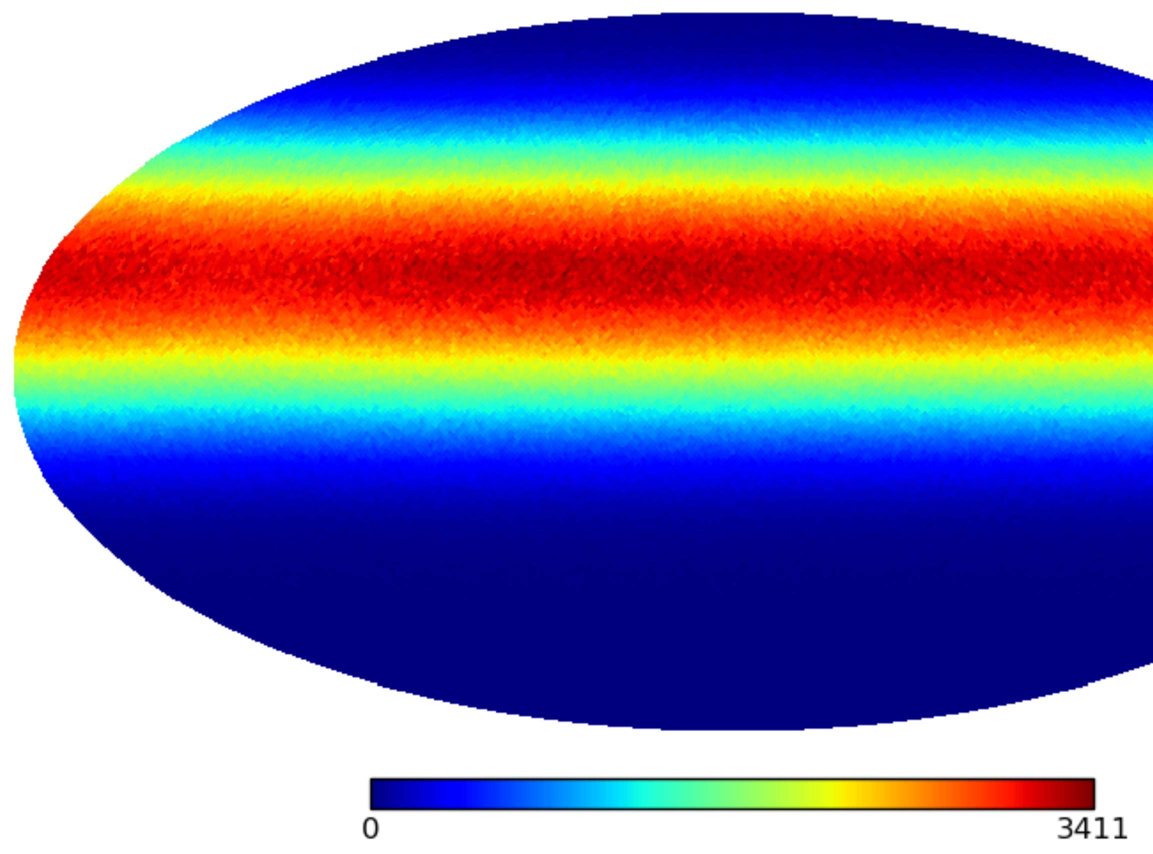


The ApJ Letters, 850:L22 (9pp)

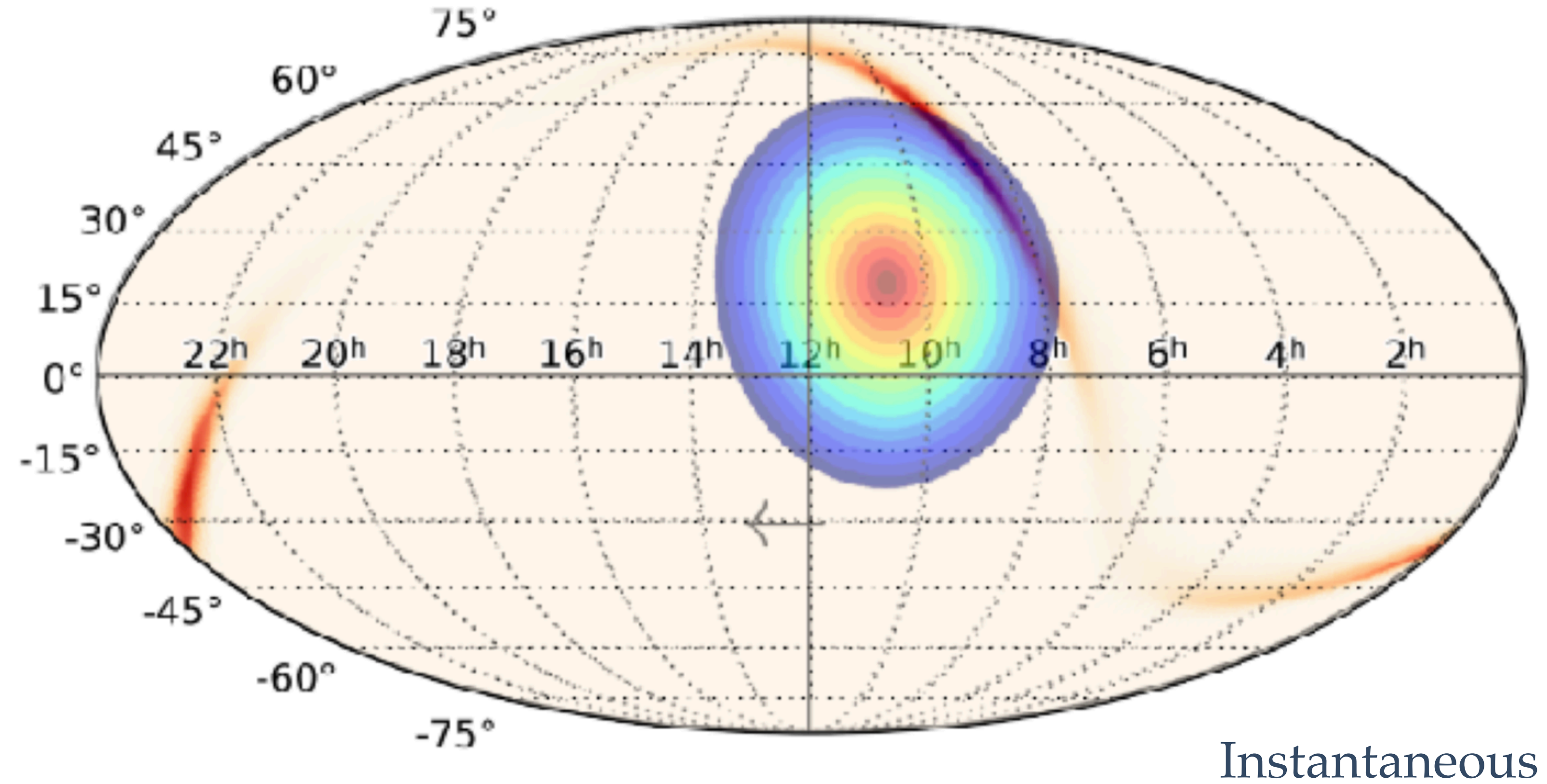
See M.Ribo Poster on 'MAGIC follow-up of GW events in O3'

GW Follow-up of Air Shower Arrays

- HAWC
  - Inst. FoV of 2sr (1/6 sky)
  - 95% uptime
  - Energy range: 0.1-100 TeV

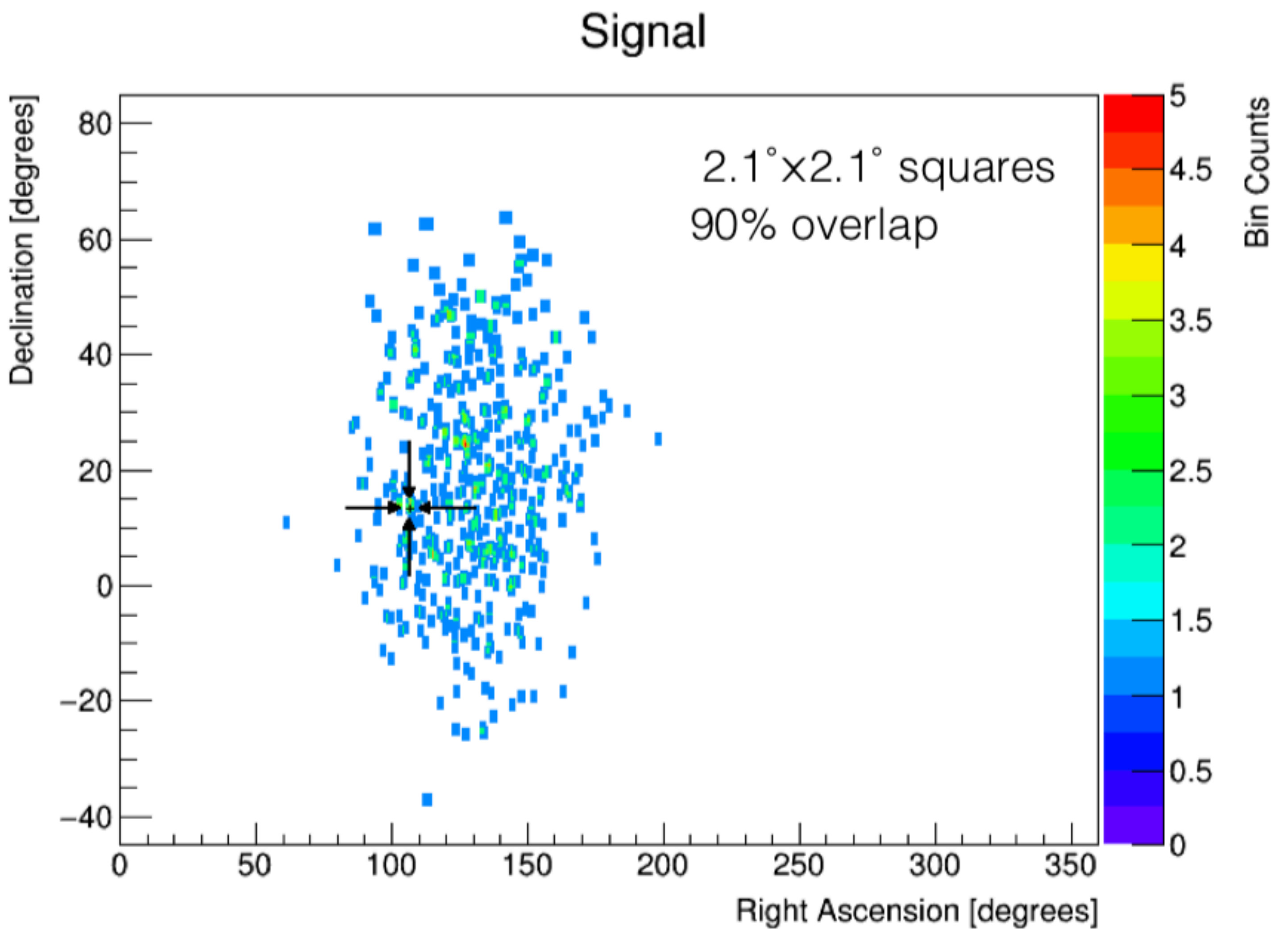


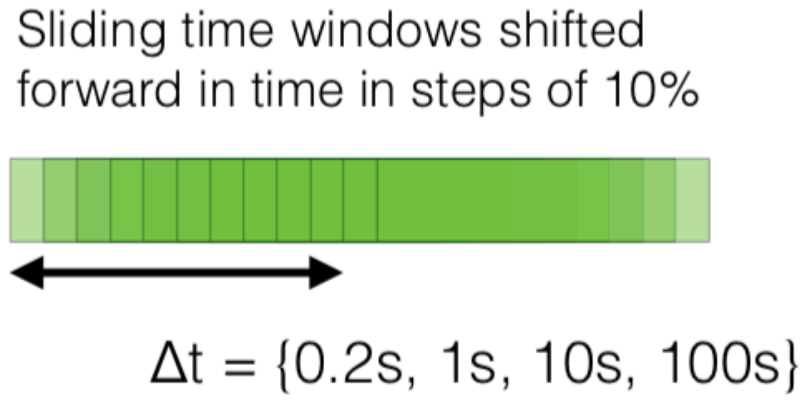
1 transit

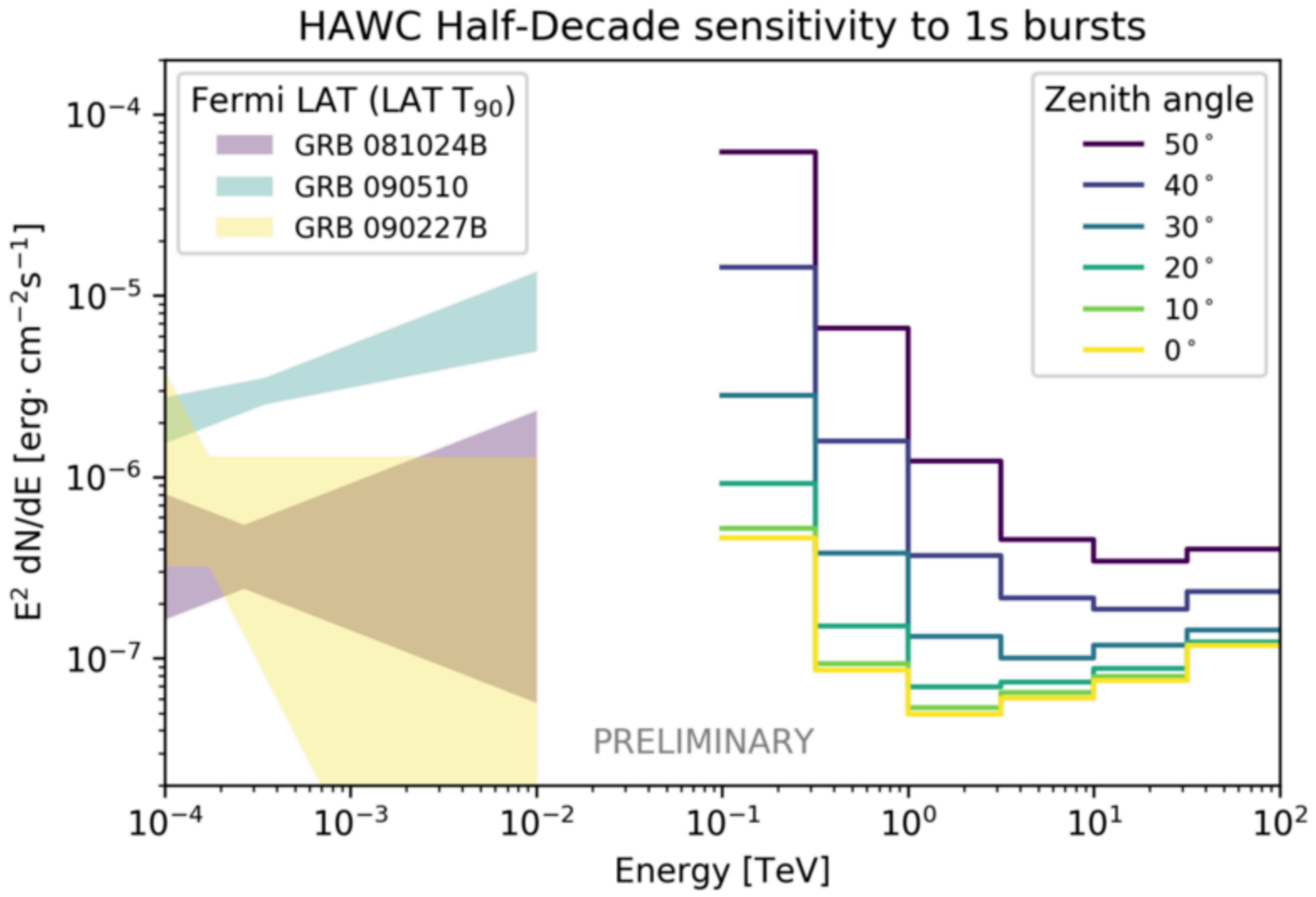


Instantaneous FoV

- Real time all-sky GRB search
  - Spatial grid 2.1°x2.1°
  - Temporal intervals: 0.1,1,10,100s
  - Sliding window of 10%







Wood, J. (2018) arXiv:1801.01550

TeV counterpart searches to Gravitational Waves

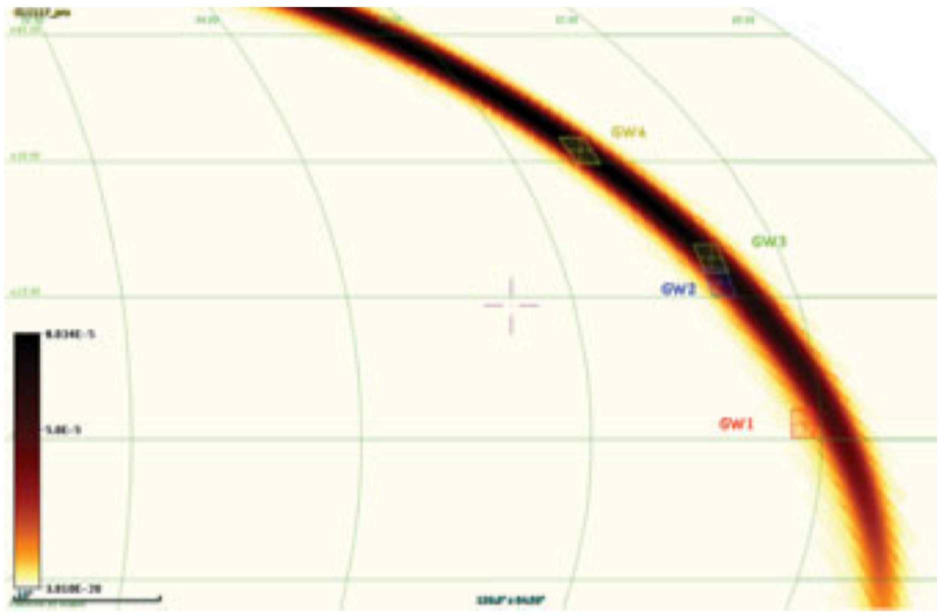
GW151226 (BBH)

MAGIC

O1

- 90% C.R. ~1400 deg^2
- Manually selected regions with info from EM follow-up group.
- Total of 2.6h, ~65.5after the GW event

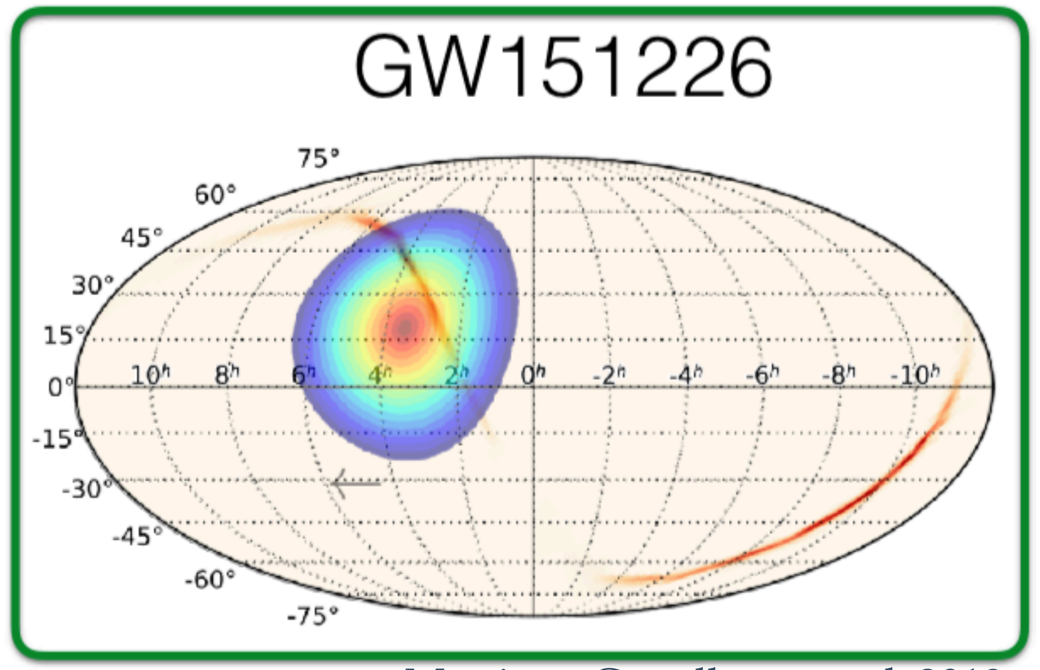
No significant excess found.



De Lotto, B., et al (2016)

HAWC

No significant excess found.



Martinez-Castellanos et al, 2018

GW170104 (BBH)

VERITAS

O2

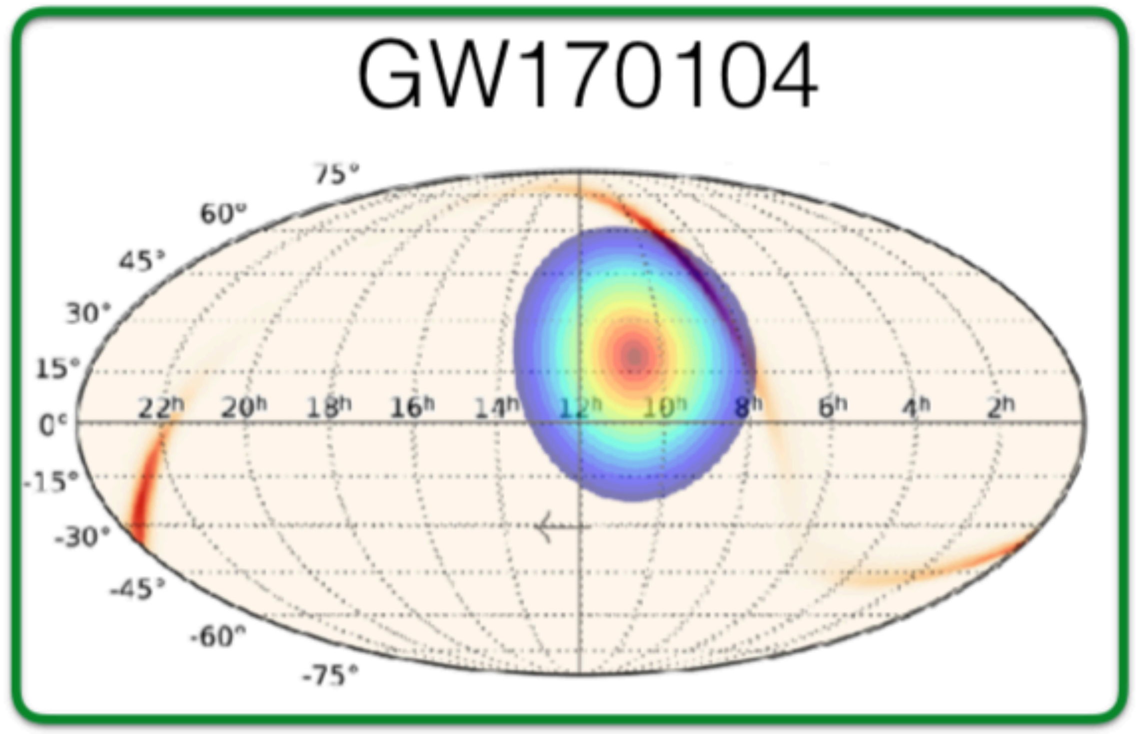
- 21 hours after the GW event
- 39 consecutive 5 minutes tiling pointings.
- 27% of the sky localization covered
- With better weather conditions, observation would have been sensitive to sources with a flux greater than 50% of the Crab Nebula above 100 GeV

No significant excess found.

GCN circular 21153

HAWC

No significant excess found.



Martinez-Castellanos et al, 2018

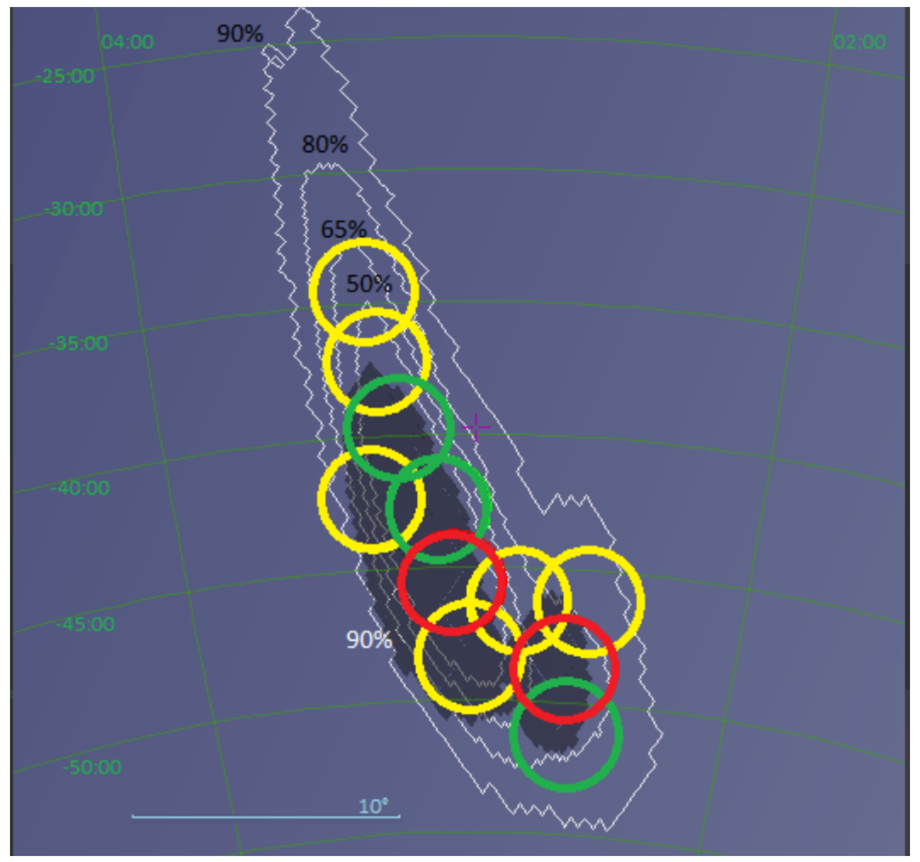
GW170814 (BBH)

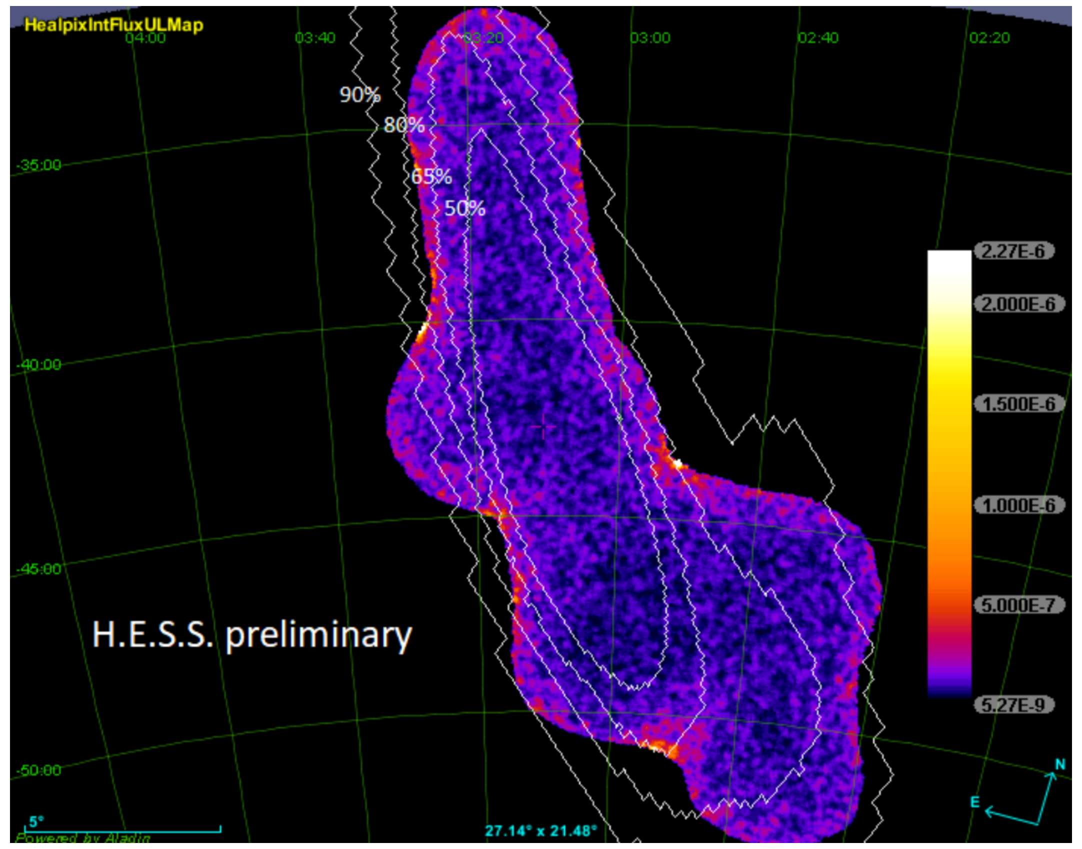
H.E.S.S

O2

- 3 IFO localisation: with V1, 60 deg^2
- 3 consecutive nights of observation covering the localization

No significant excess found.





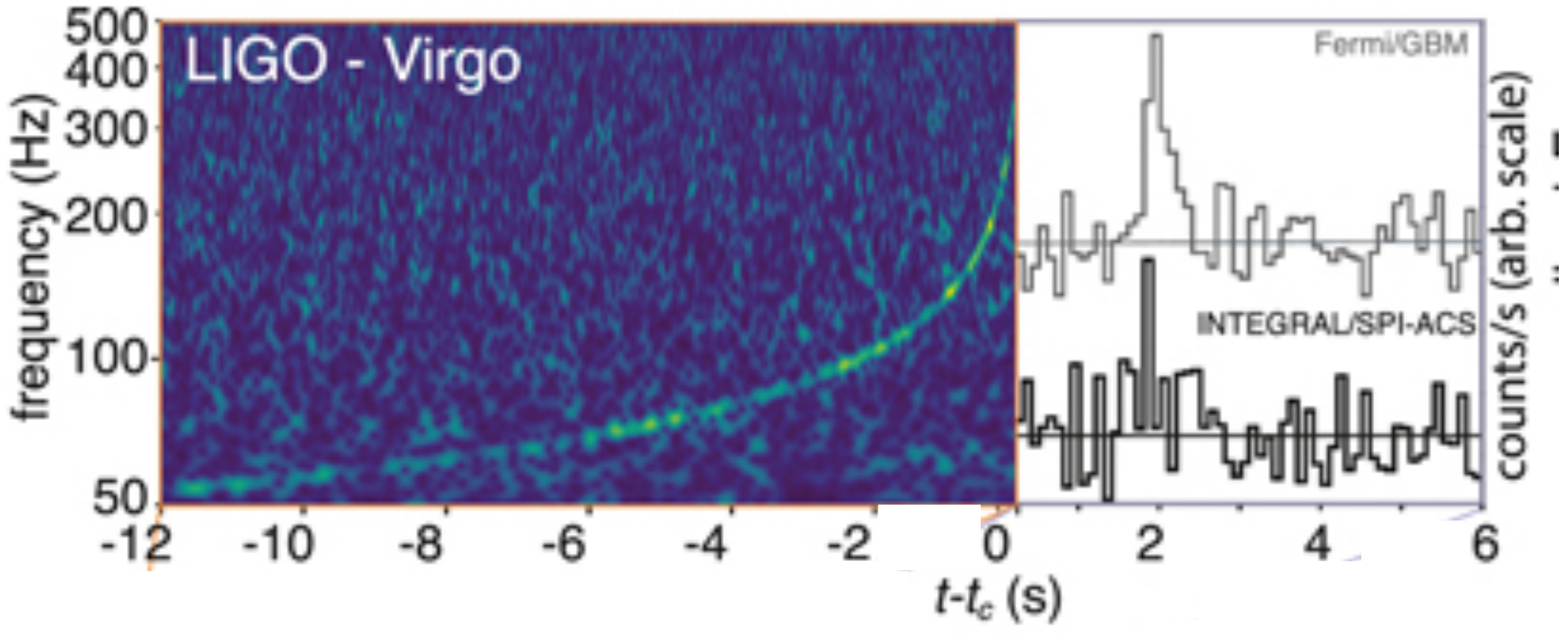
MS et al,TeVPa 2018

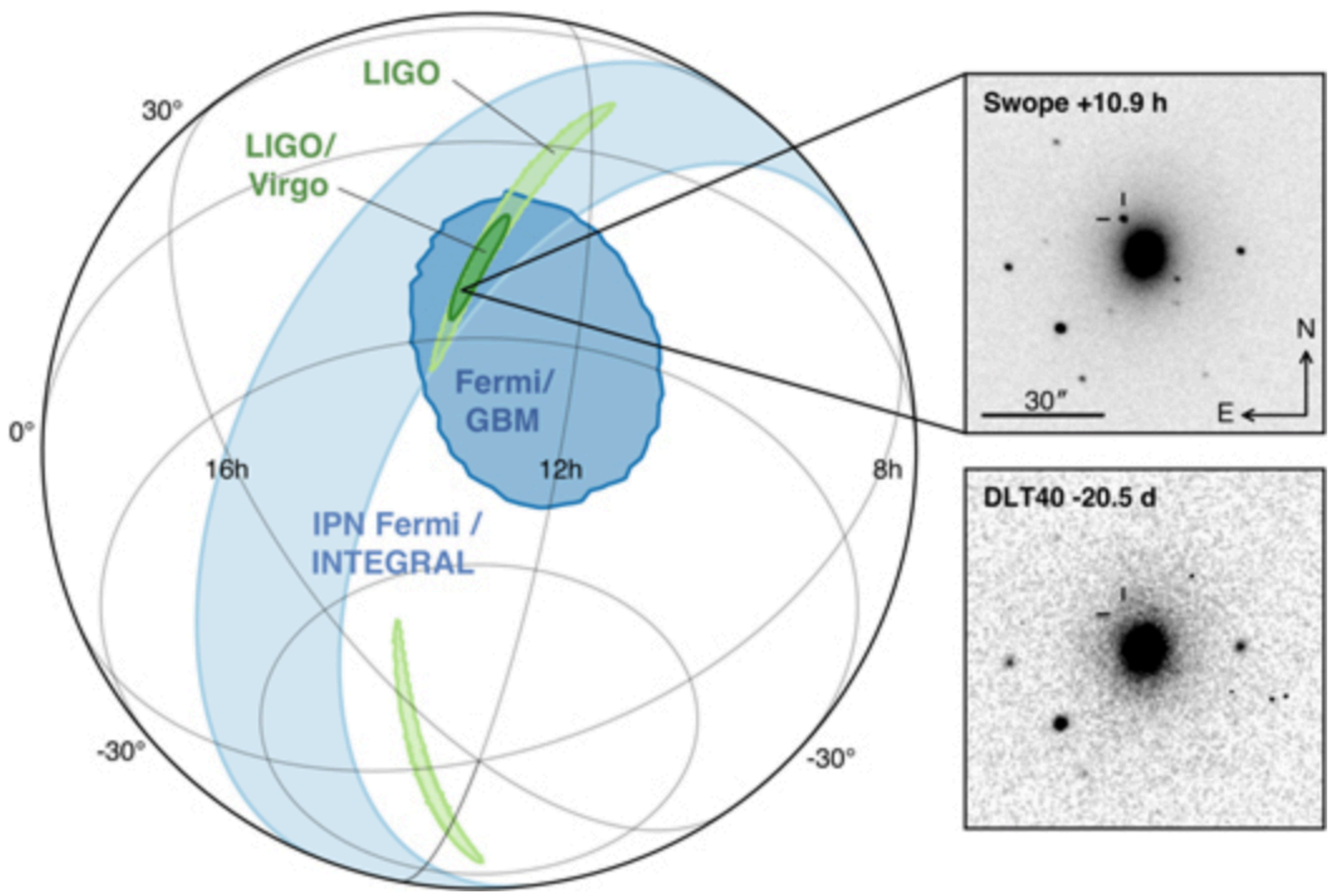
GeV-TeV counterpart searches to Gravitational Waves

- GW170817/ GRB170817A
  - First observation of BNS+sGRB
  - Through multi-messenger efforts, the source could be identified!
  - Counterpart located in galaxy NGC 4993
  - First evidence of a population of NS-NS mergers responsible for sGRBS
- Further details: Astrophys. J. Lett 848.2 (2017): L12.

What was observed in VHE?

O2

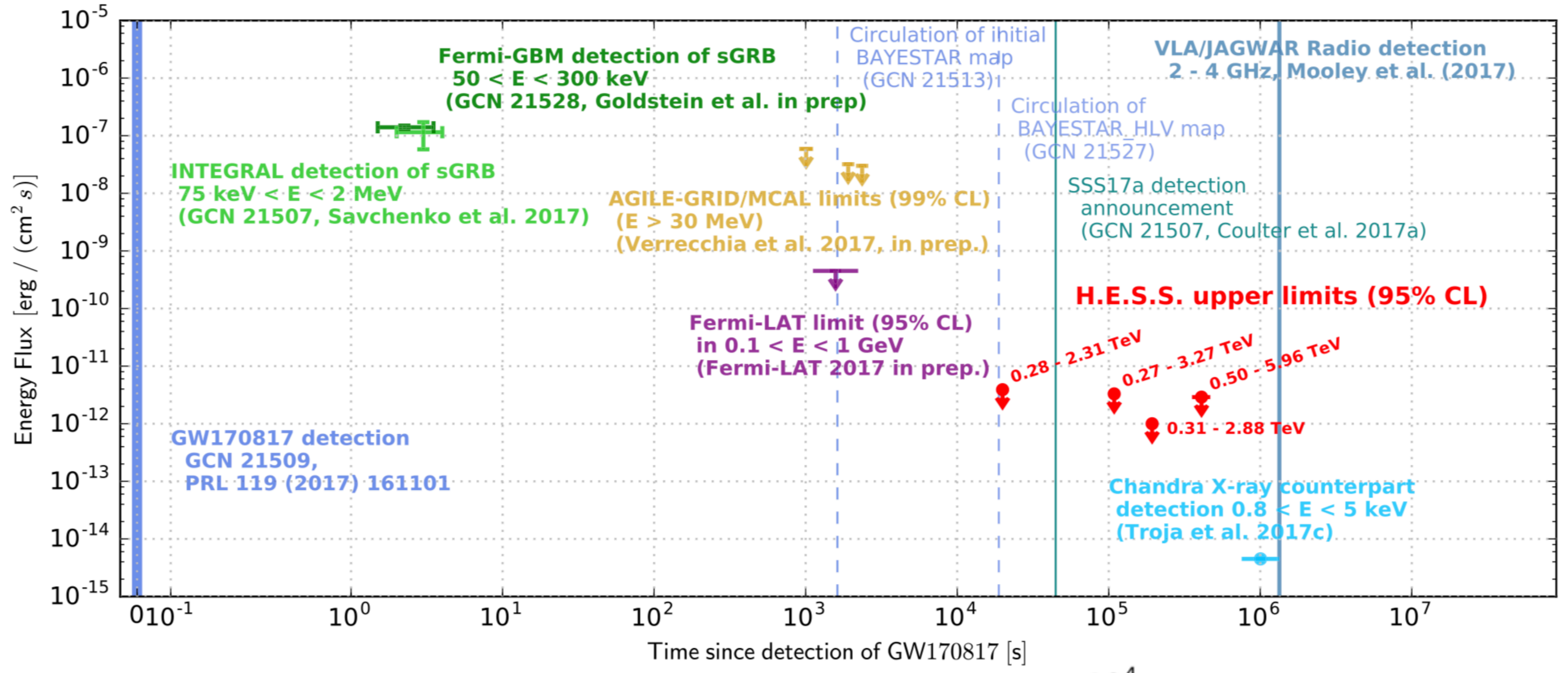


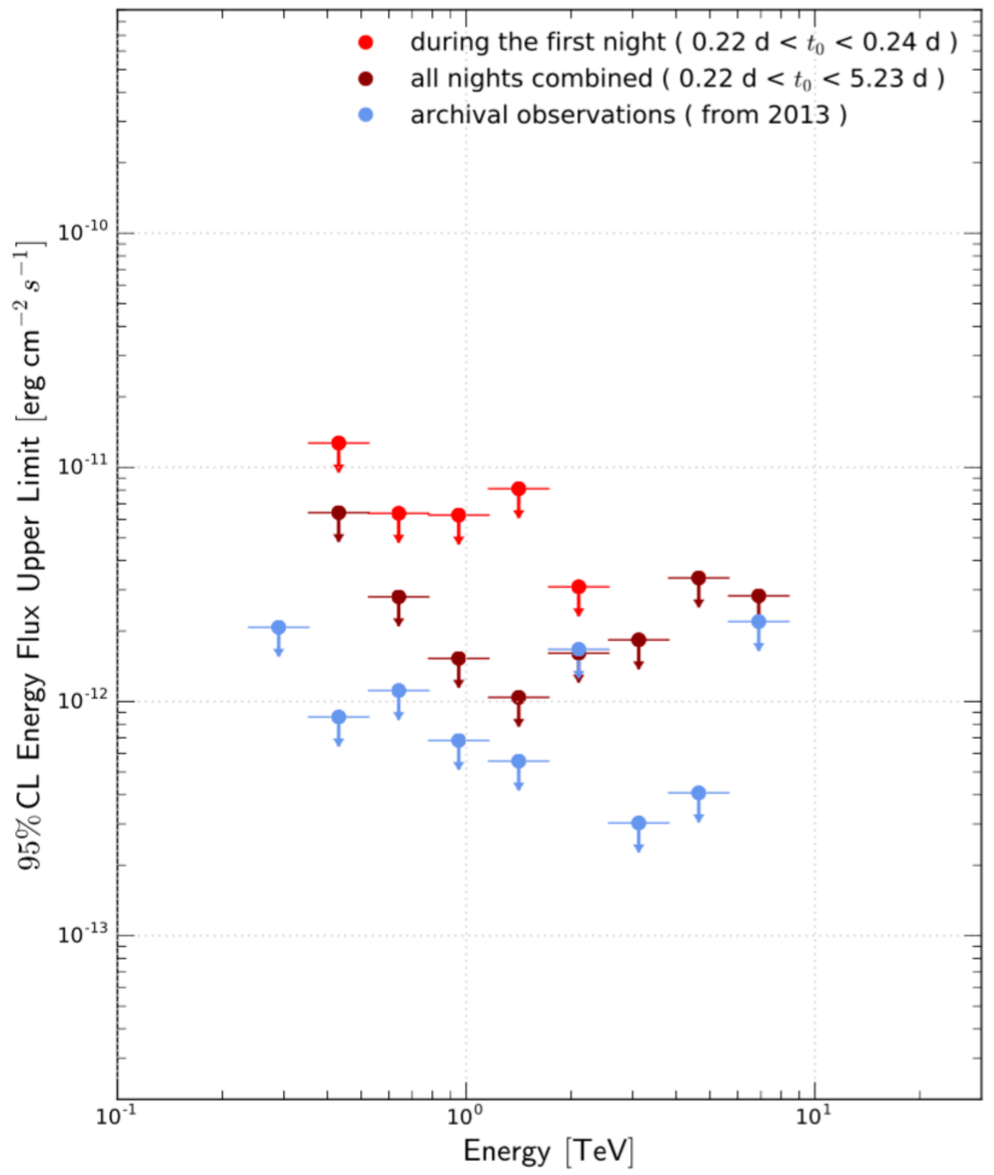


GW170817 follow-up in IACTs

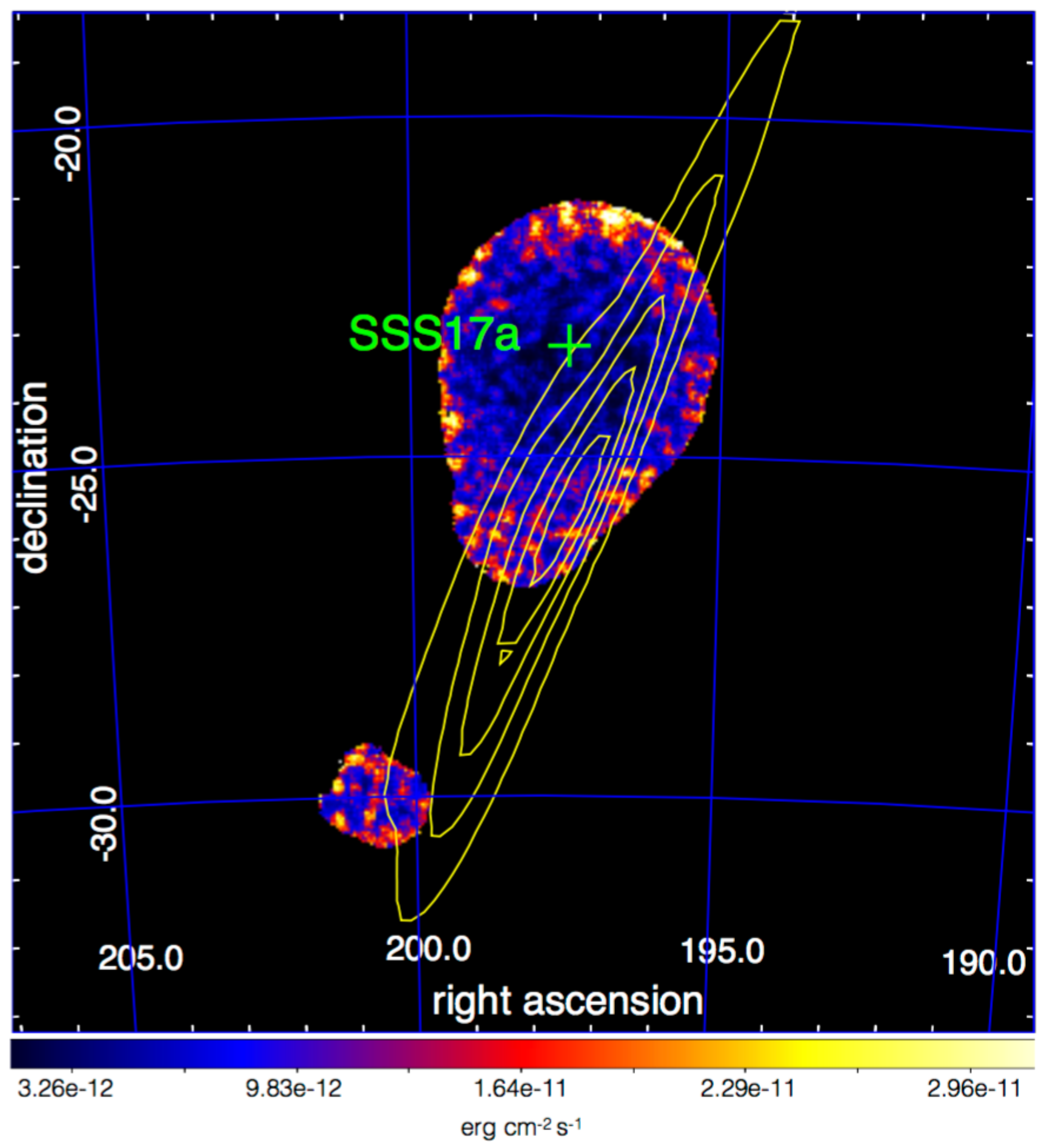
HESS prompt observations of GW170817

- First ground based instrument on target! 5.3 hours after merger
  - 5 minutes after the update of the GW skymap (LV reconstruction)





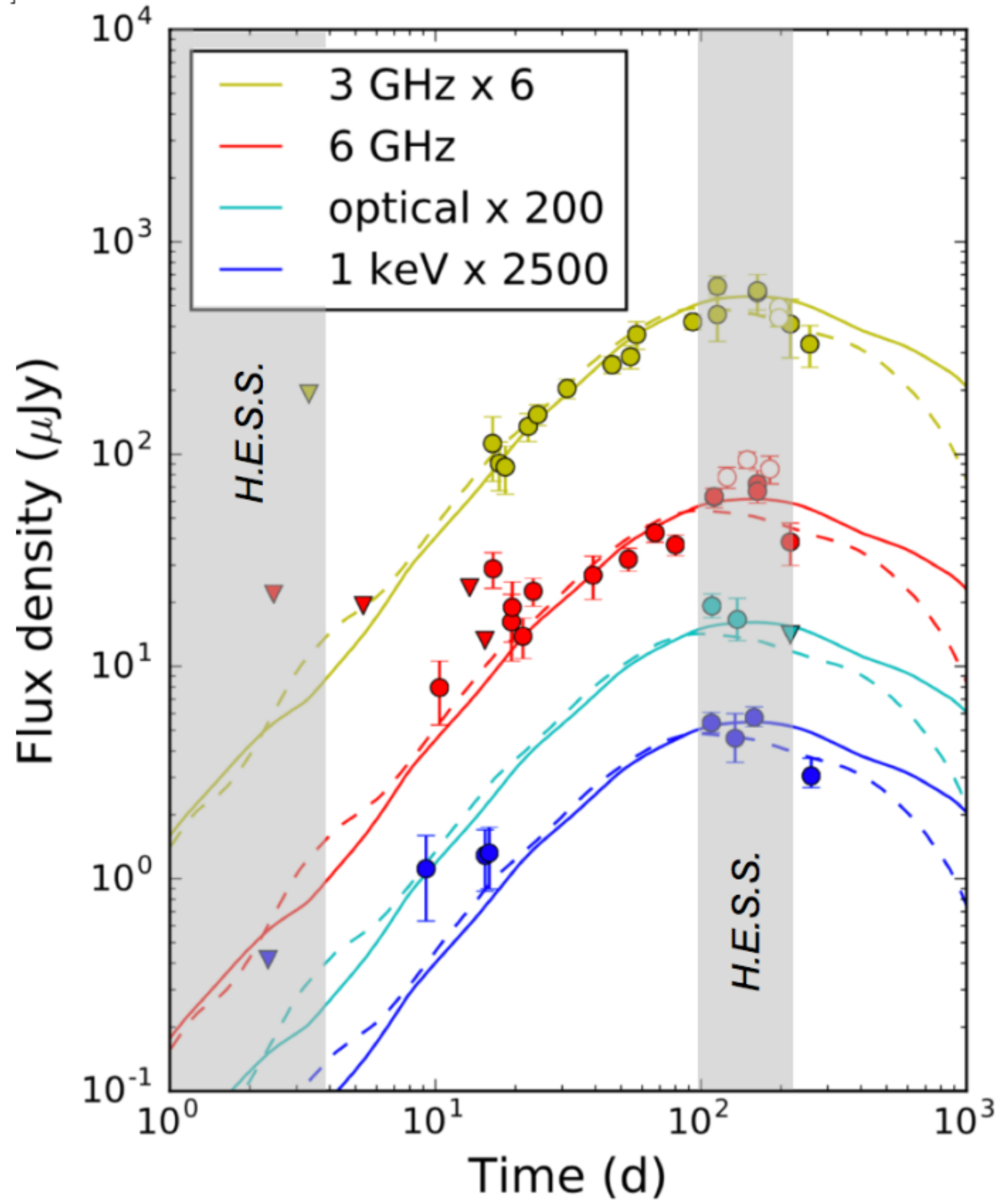
(a) SSS17a: H.E.S.S. limits



(b) GW170817: H.E.S.S. flux limit map

Long term follow-up:

- H.E.S.S. observations campaign covering the peak of X-ray / radio emission from December till May
- Analysis in progress



Alexander et al. (2018)

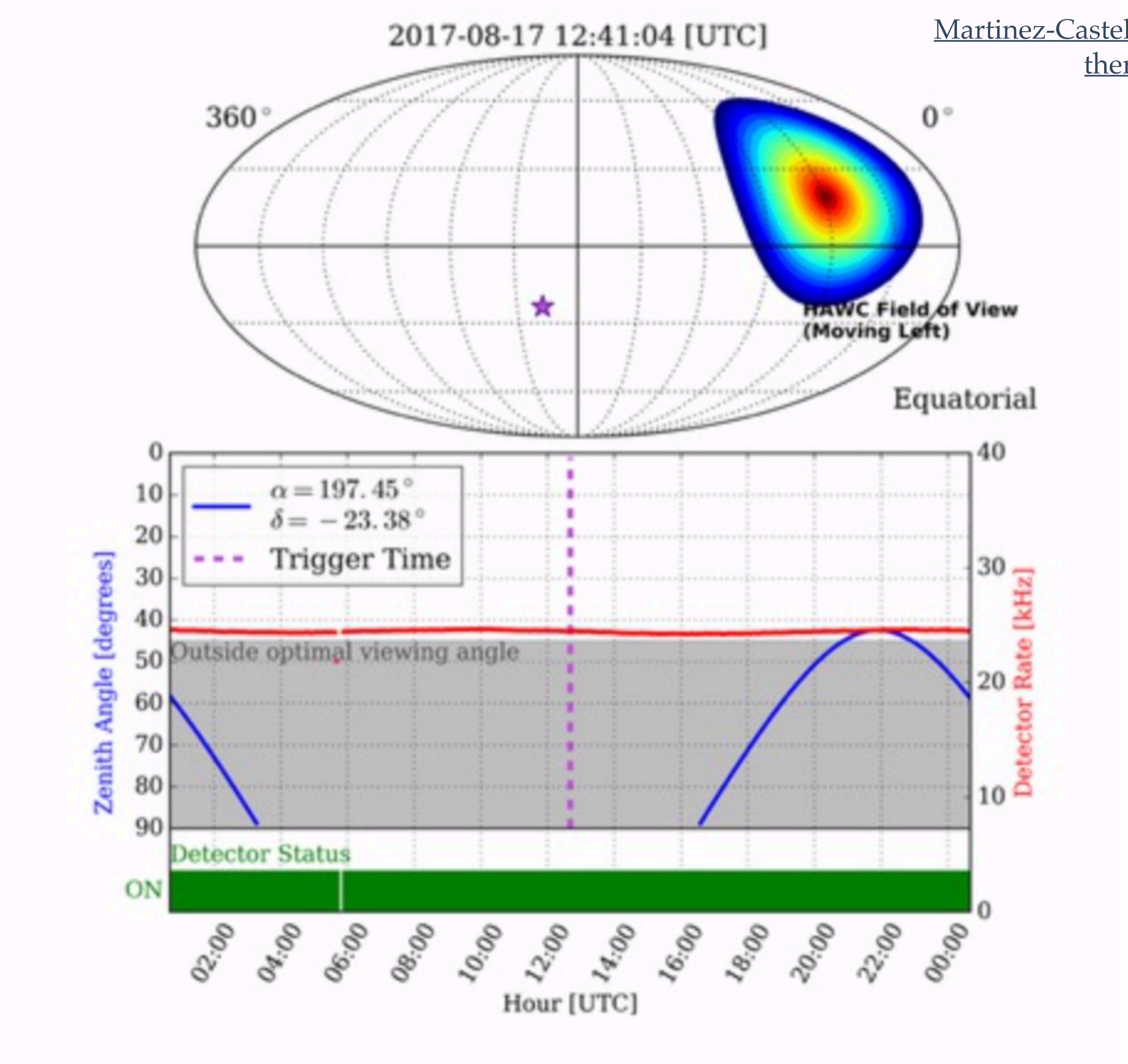
The Astrophysical Journal Letters, 850:L22 (9pp)

GW170817 follow-up in Air Shower Arrays

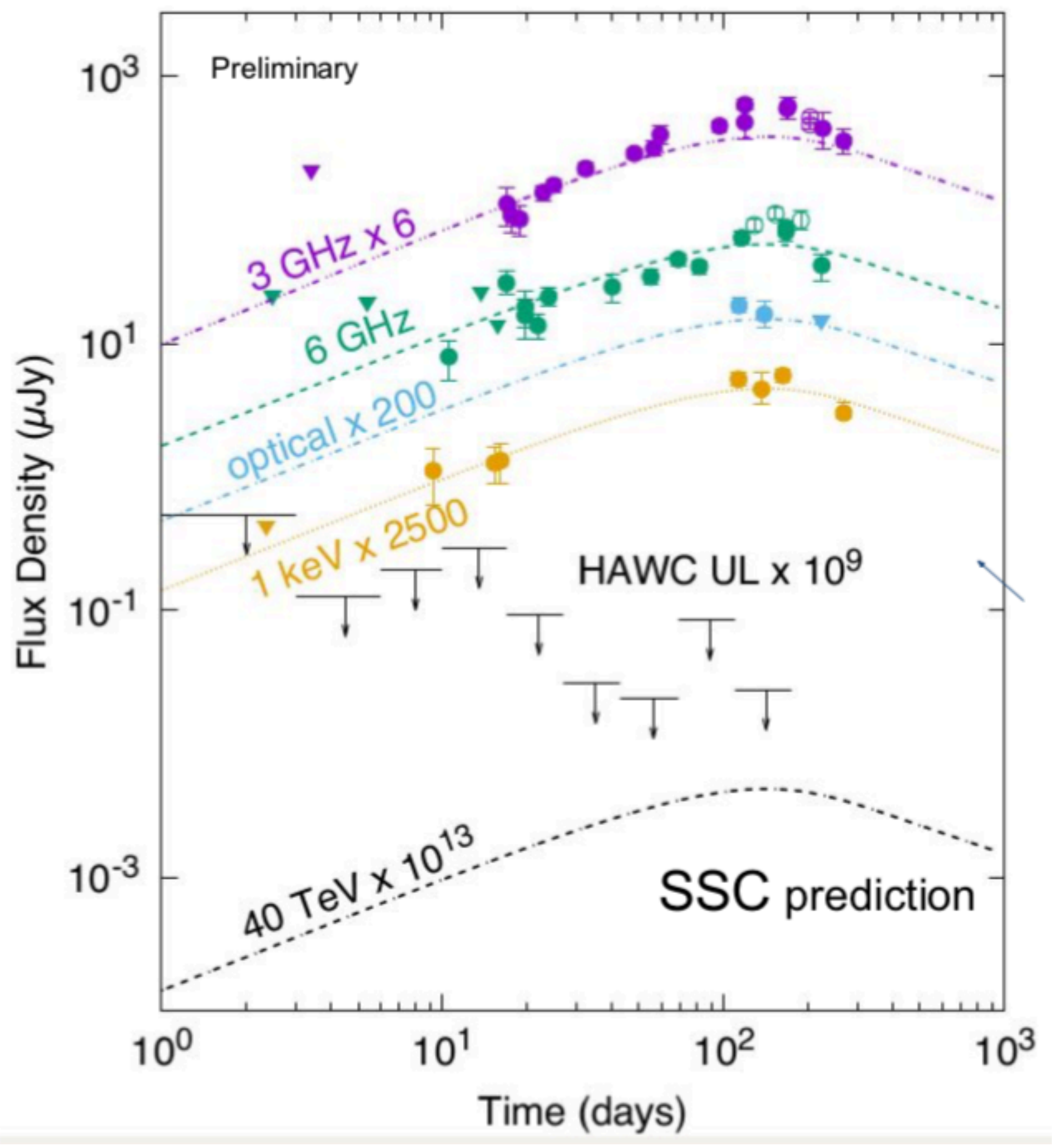
HAWC prompt observations of GW170817

- Source localization enter the HAWC FoV 9 hours after merger: observed for 2.03 h
- Localization at high zenith angles:
  - High energy threshold
  - Poor sensitivity
- 90 C.I upper limit between 4-100 TeV of 1.7 x 10^{-10}erg cm^{-2} s^{-1}

Martinez-Castellanos et al, Monitoring the non-thermal Universe, 2018



HAWC long term follow-up observations of GW170817



- Flux limits derived above 40 TeV over 9 consecutive logarithmic time windows.
- The limits are above the VHE flux expected for SSC from the external shock.

Dichiara et al, TeVPA 2018

Prospects

Starting April 2019!

O3!

- Number of estimated detections grow with the cube of the improvement on the BNS range!

Epoch		2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration		4 months	9 months	12 months	(per year)	(per year)
Expected BNS range/Mpc	LIGO	40–80	80–120	120–170	190	190
	Virgo	–	20–65	65–85	65–115	125
	KAGRA	–	–	–	–	140
Estimated BNS detections		0.05–1	0.2–4.5	1–50	4–80	11–180
Actual BNS detections		0	1	– ?	–	–

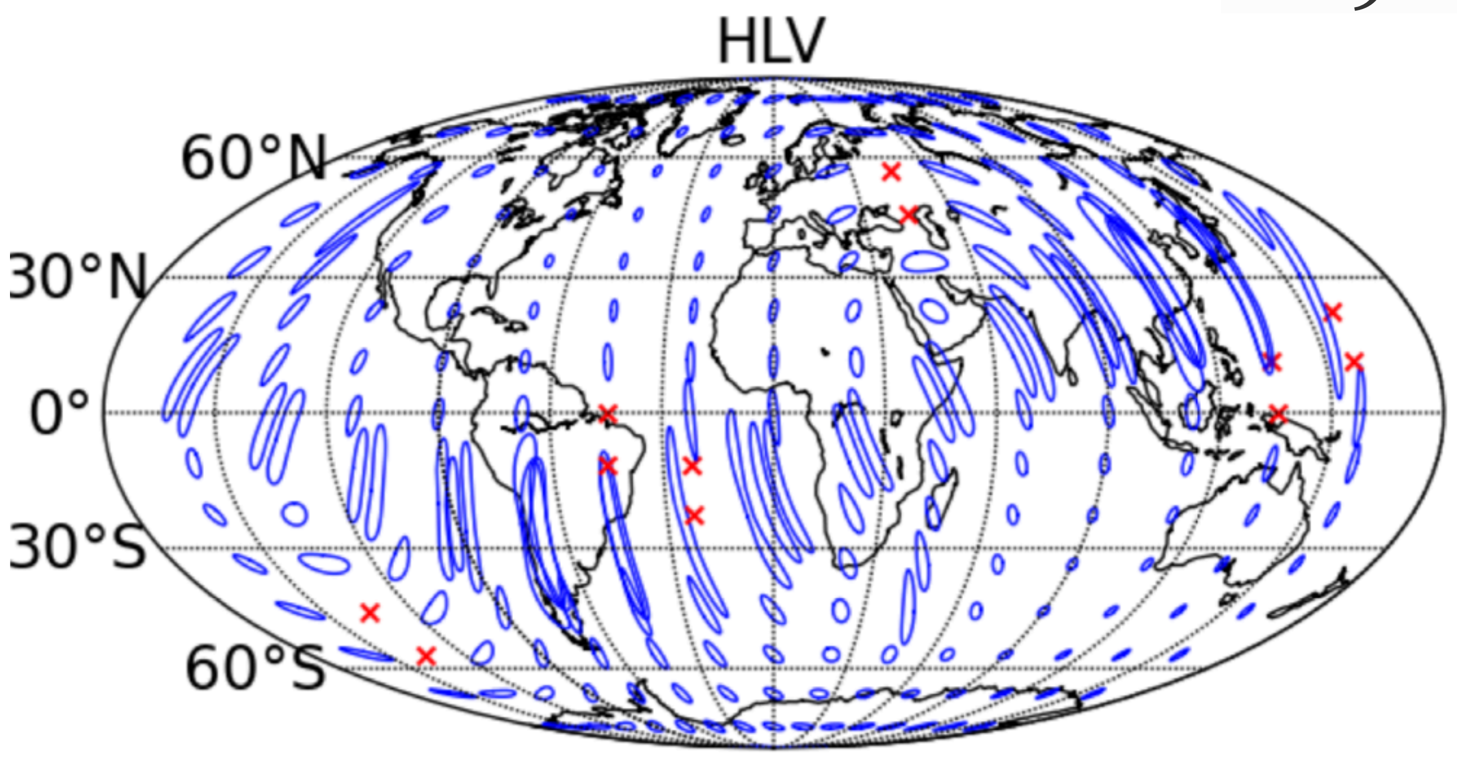
Abbott, B.P., Abbott, R., Abbott, T.D. et al. Living Rev Relativ (2018) 21: 3

- Sky localization will get smaller when approaching design sensitivity

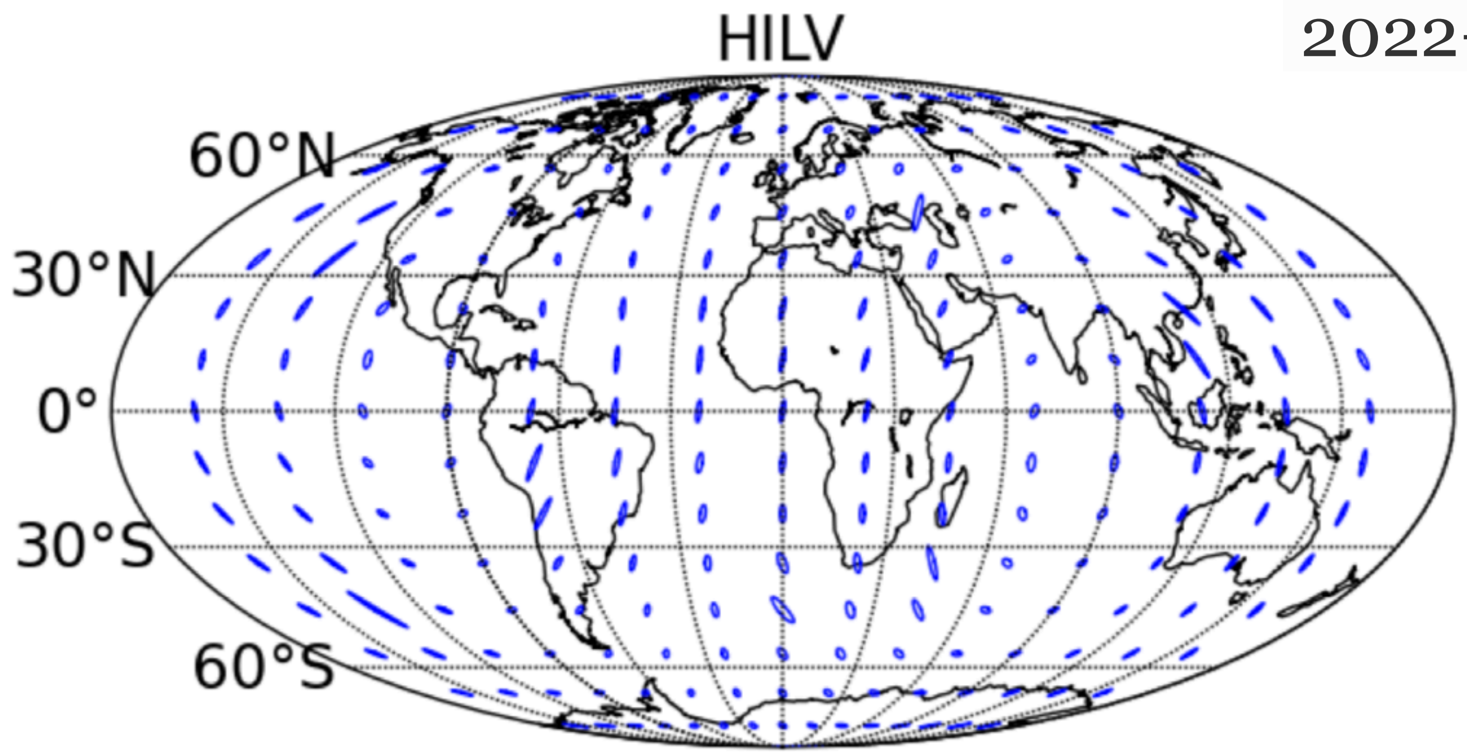
Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
90% CR	% within	5 deg^2	< 1	1–5	1–4	3–7	23–30
		20 deg^2	< 1	7–14	12–21	14–22	65–73
	Median/deg^2		460–530*	230–320	120–180	110–180	9–12

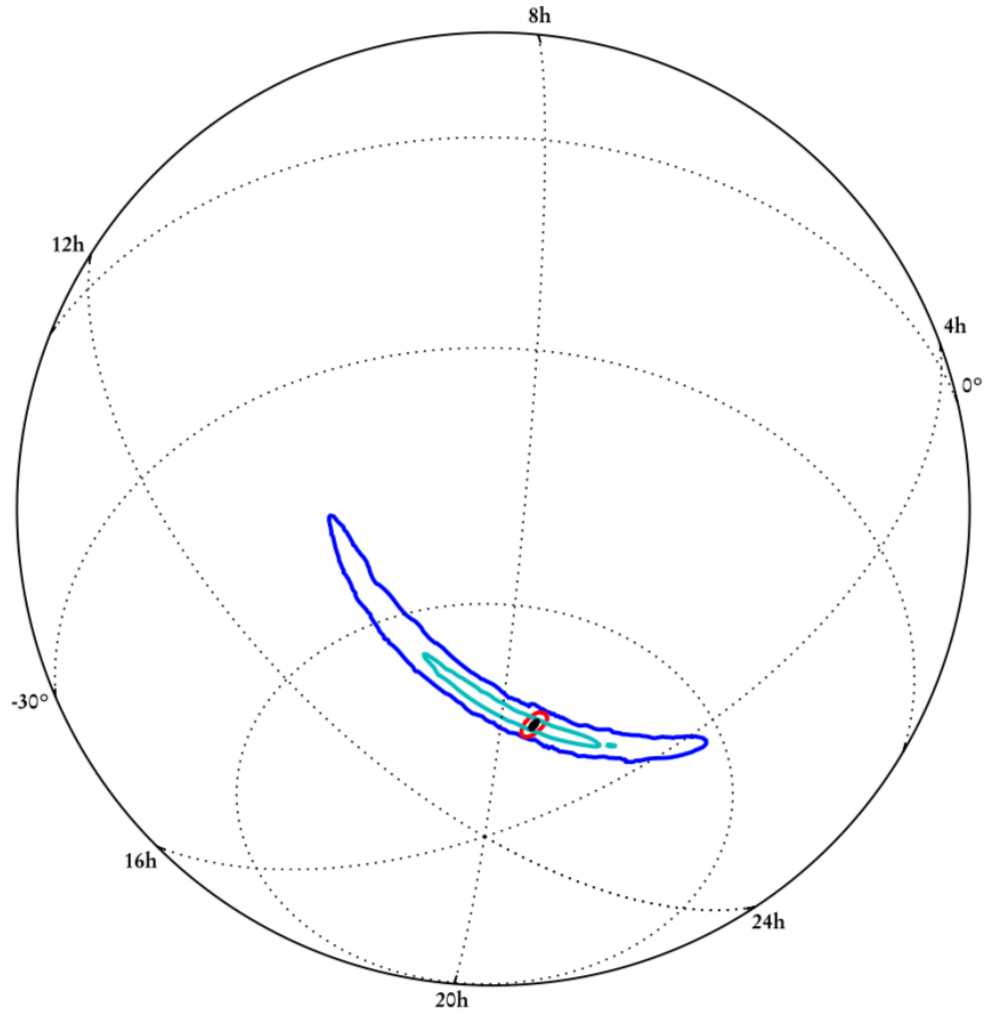
★ O1 two-detector network
★ LIGO at design sensitivity
★ 3 IFO at sensitivity O2 (expected)
★ 3 IFO at design sensitivity *

2019+



2022+

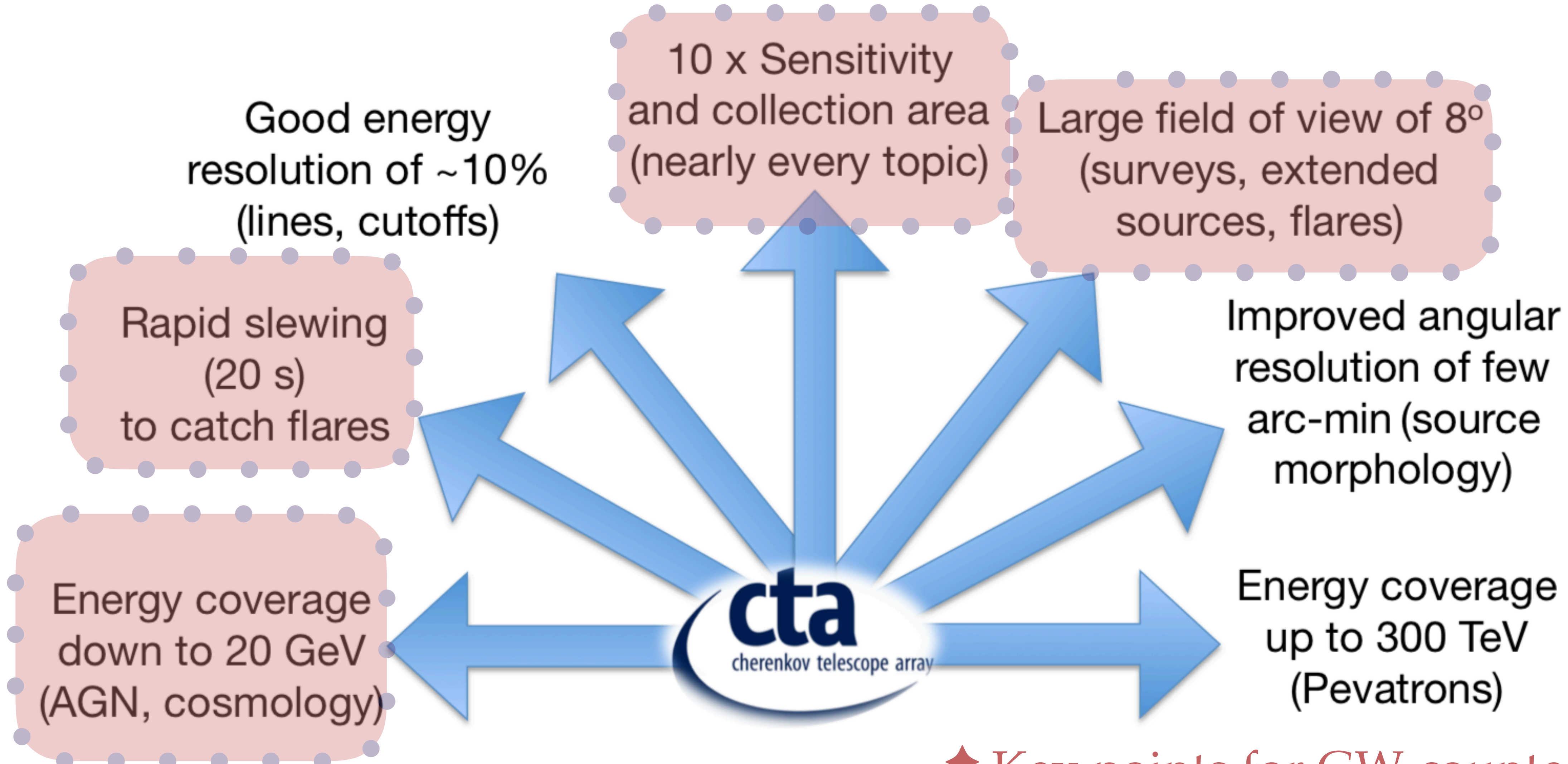


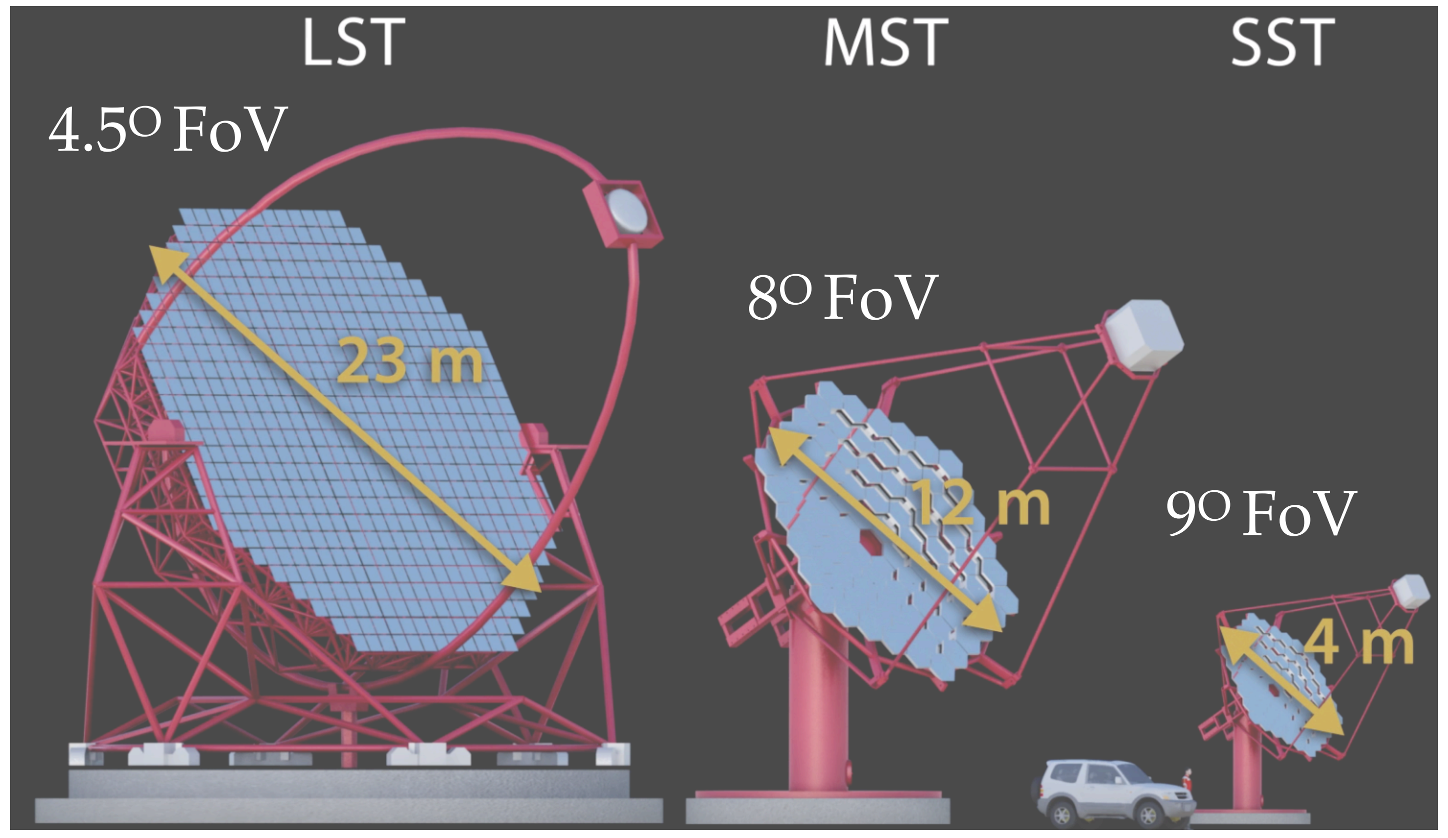


Abbott et al. 2016, Living Reviews in Relativity, 19

*face-on binary BNS system at 160 Mpc

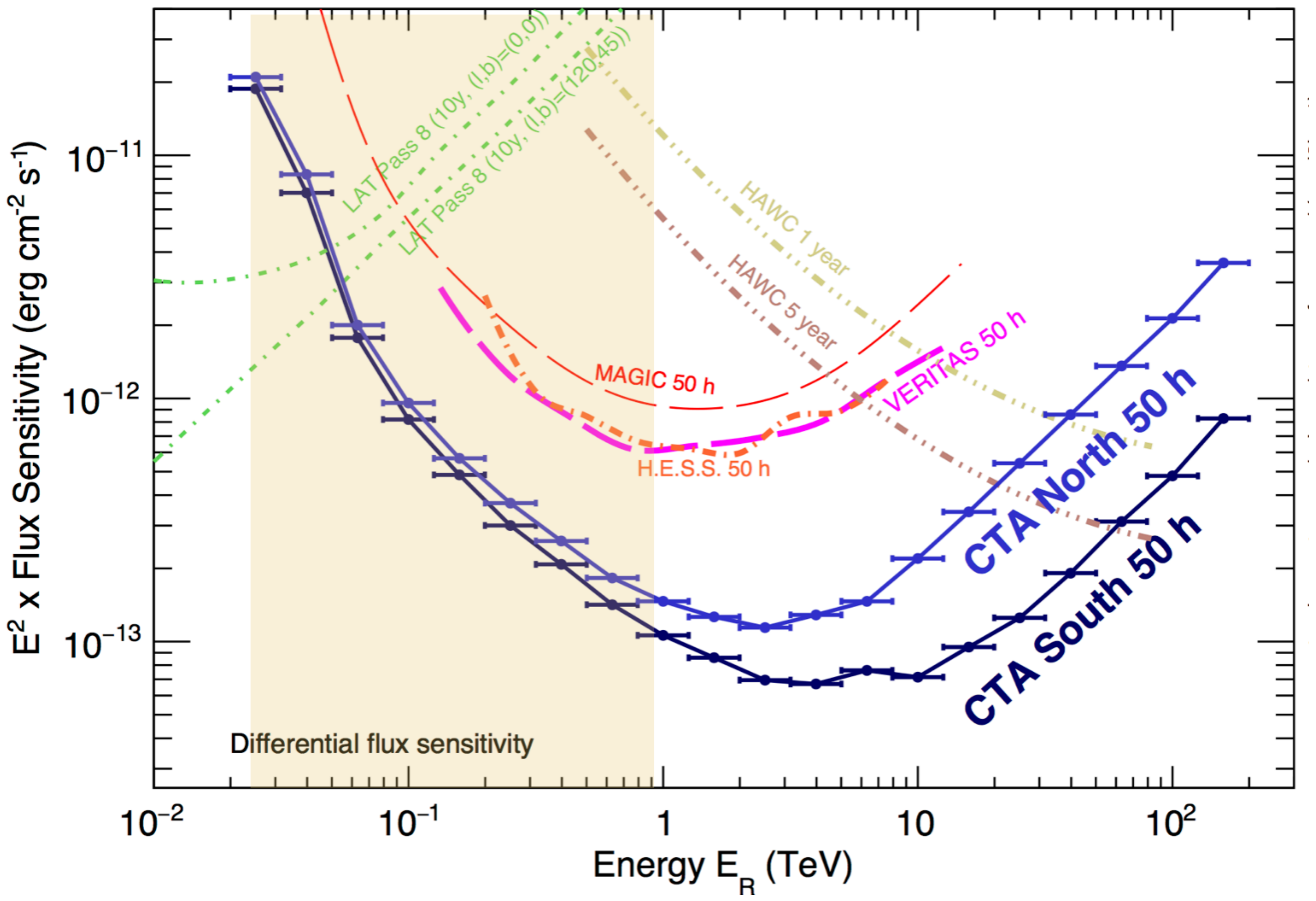
Next generation IACTs: CTA

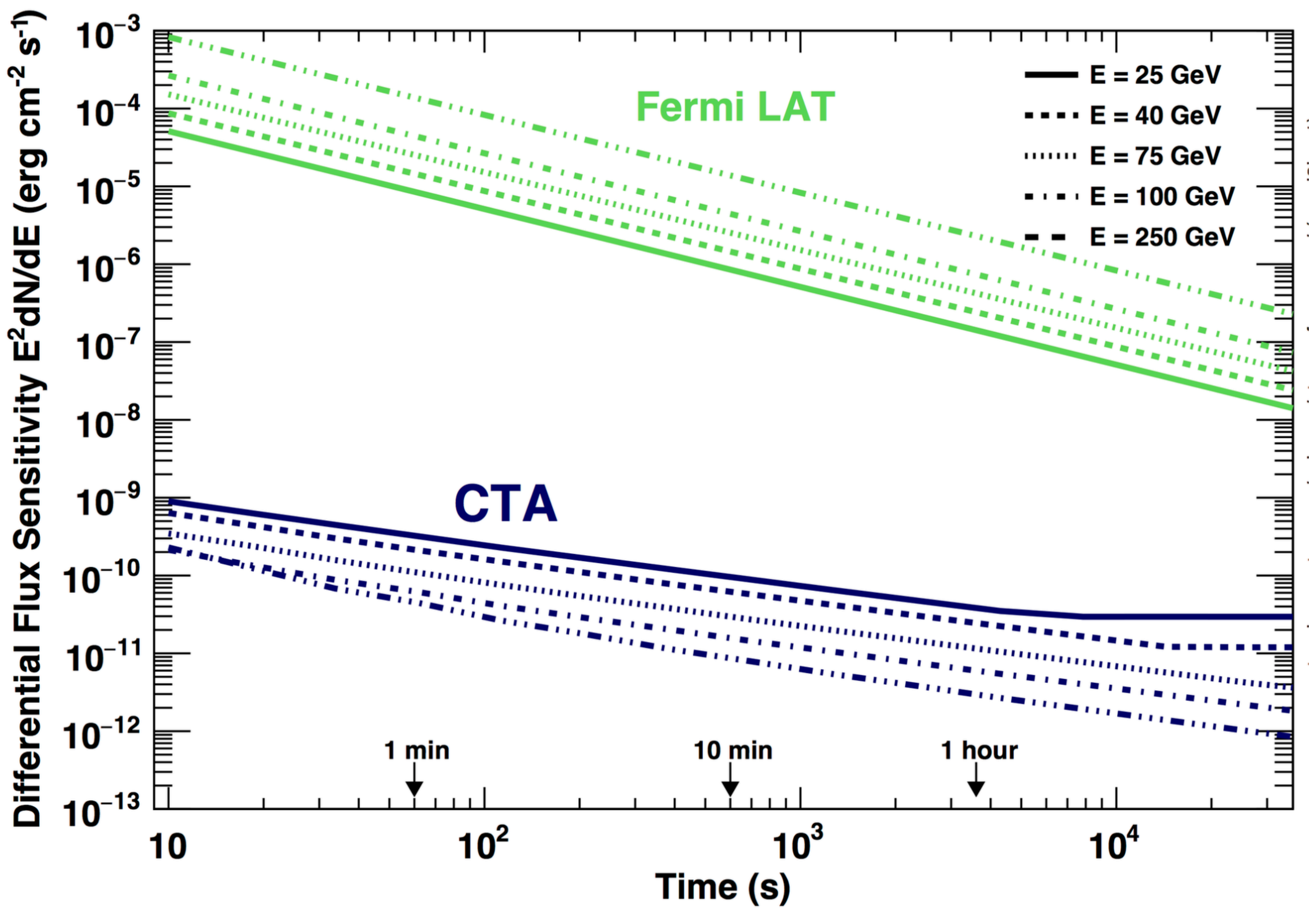




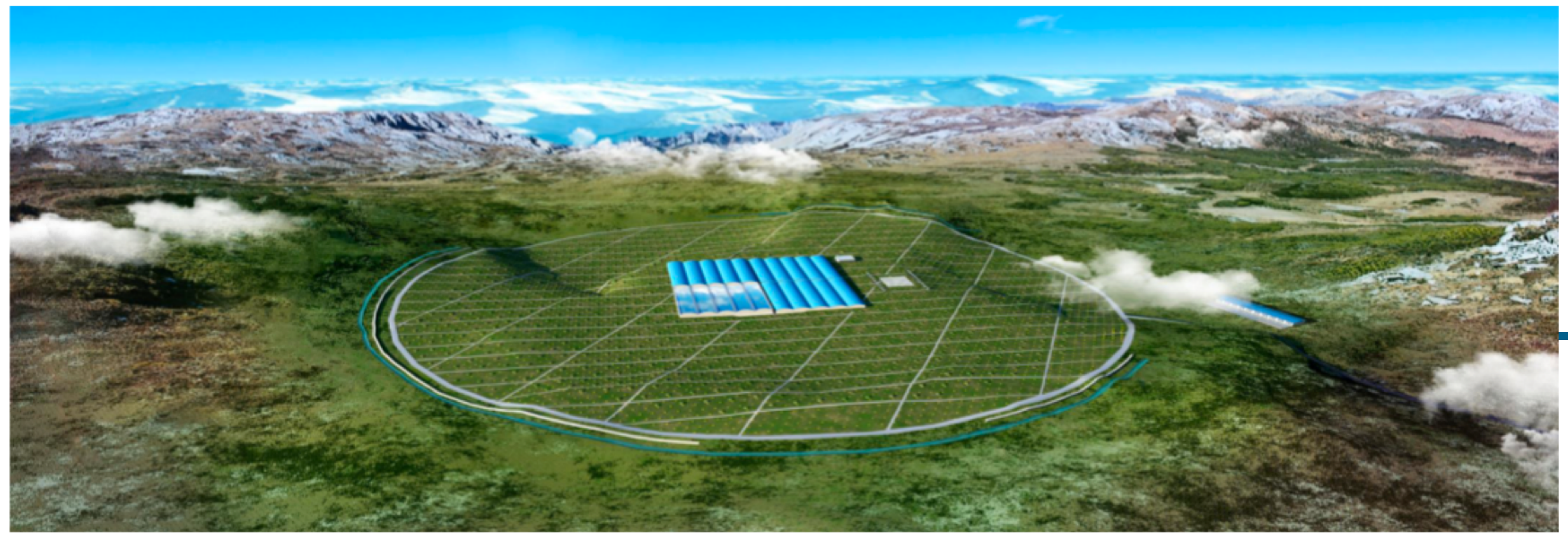
20-200 GeV 0.1-10 TeV 5-300 TeV

✦ Key points for GW counterpart searches!



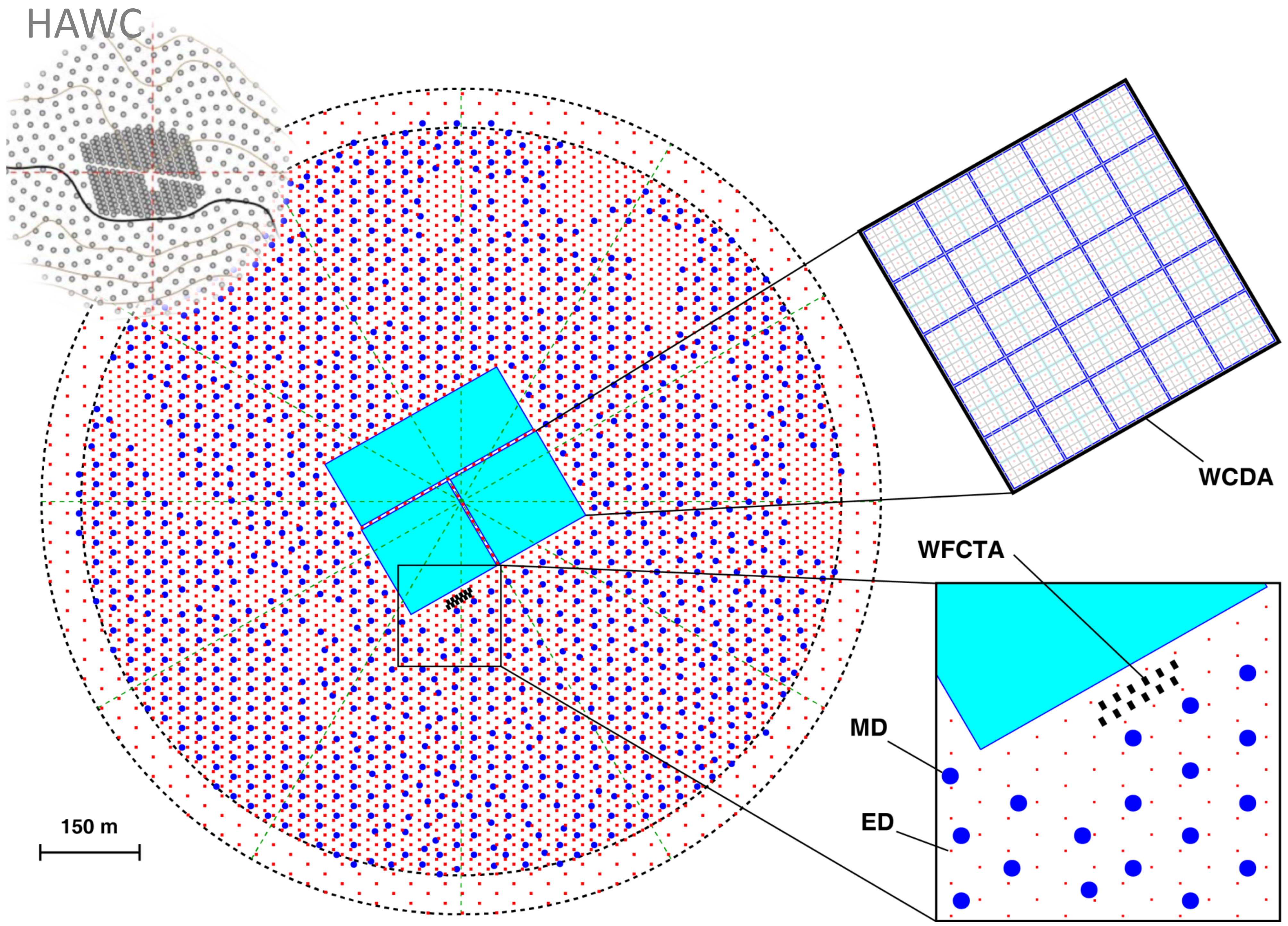


Next generation combined: Large High Altitude Air Shower Observatory (LHAASO)



LHAASO*

Sichuan, China, 4410 m asl

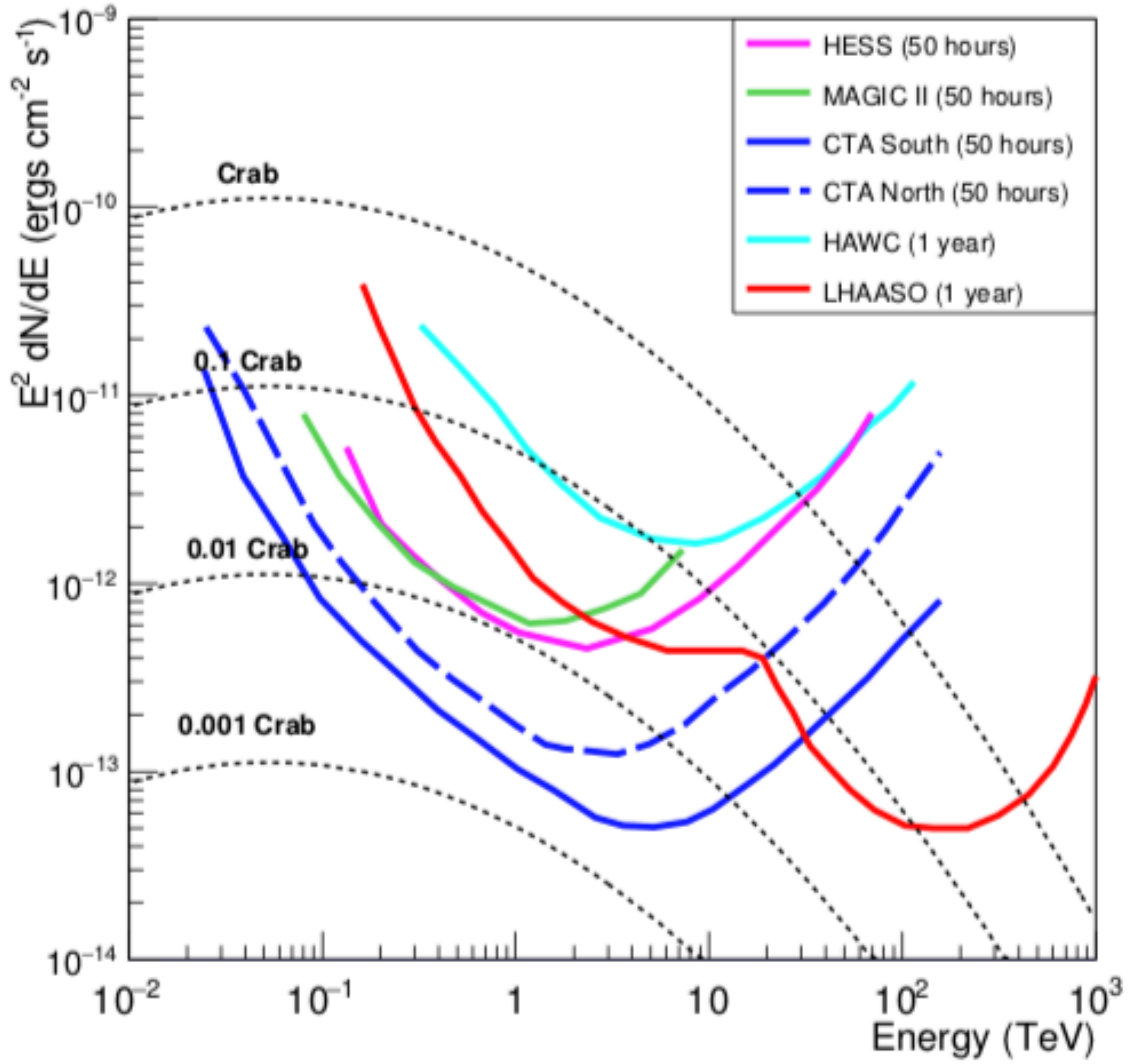


5195 Scintillators
- 1 m^2 each
- 15 m spacing

1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes



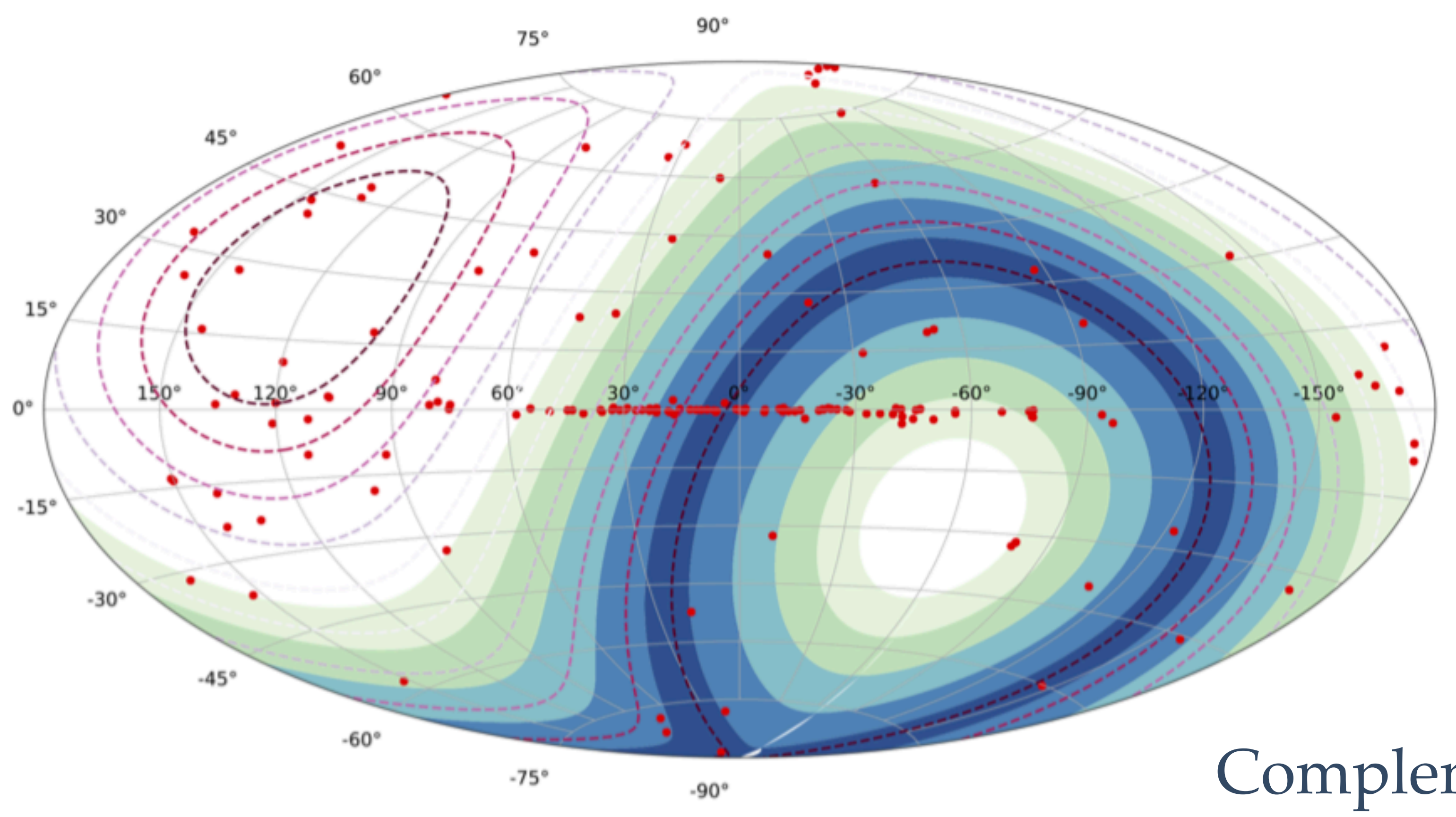
Nuclear Physics B Proceedings Supplement 00 (2016) 1–8

* Completion of LHAASO construction expected for 2020

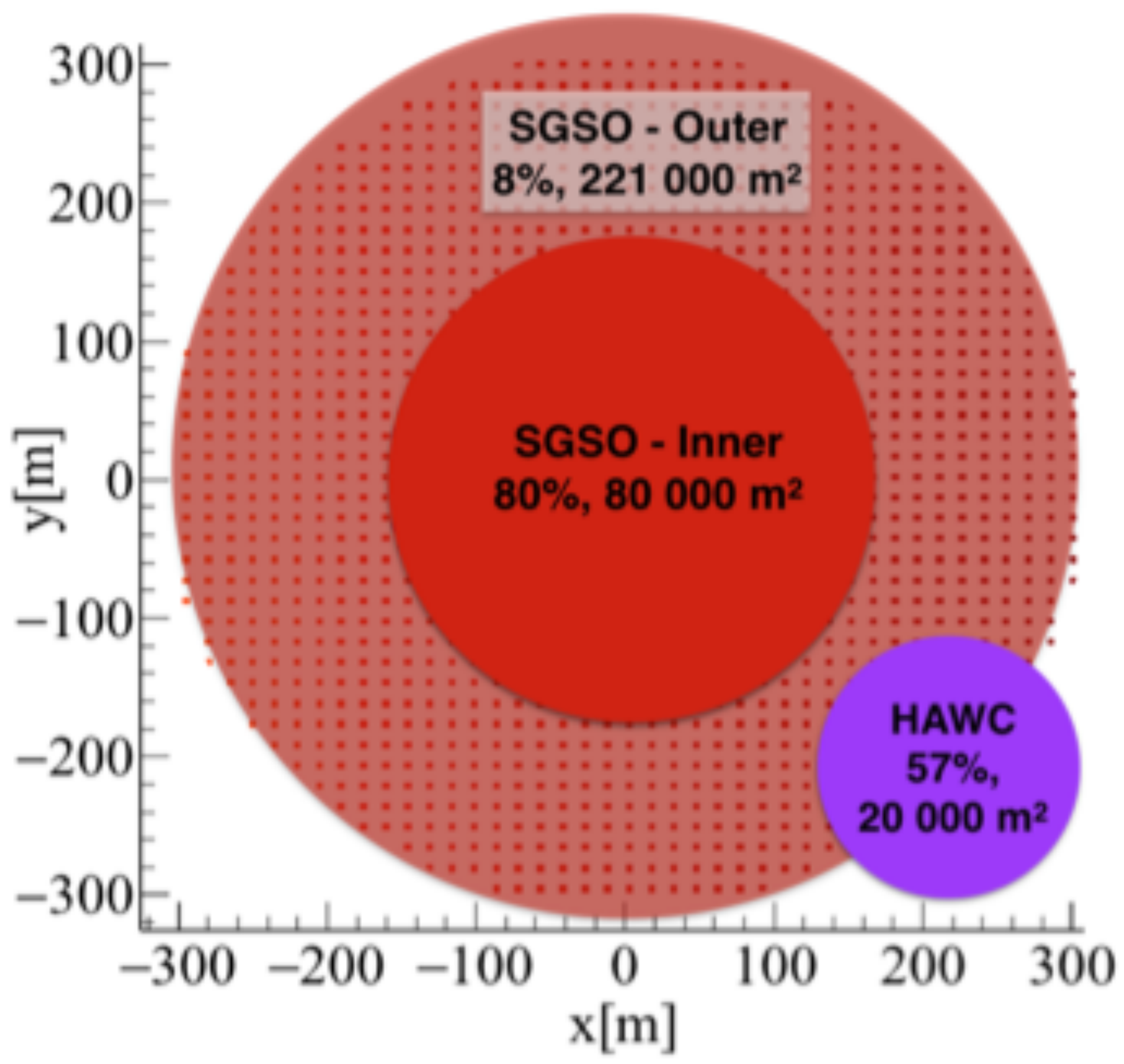
Next generation wide FoV projects: SGSO

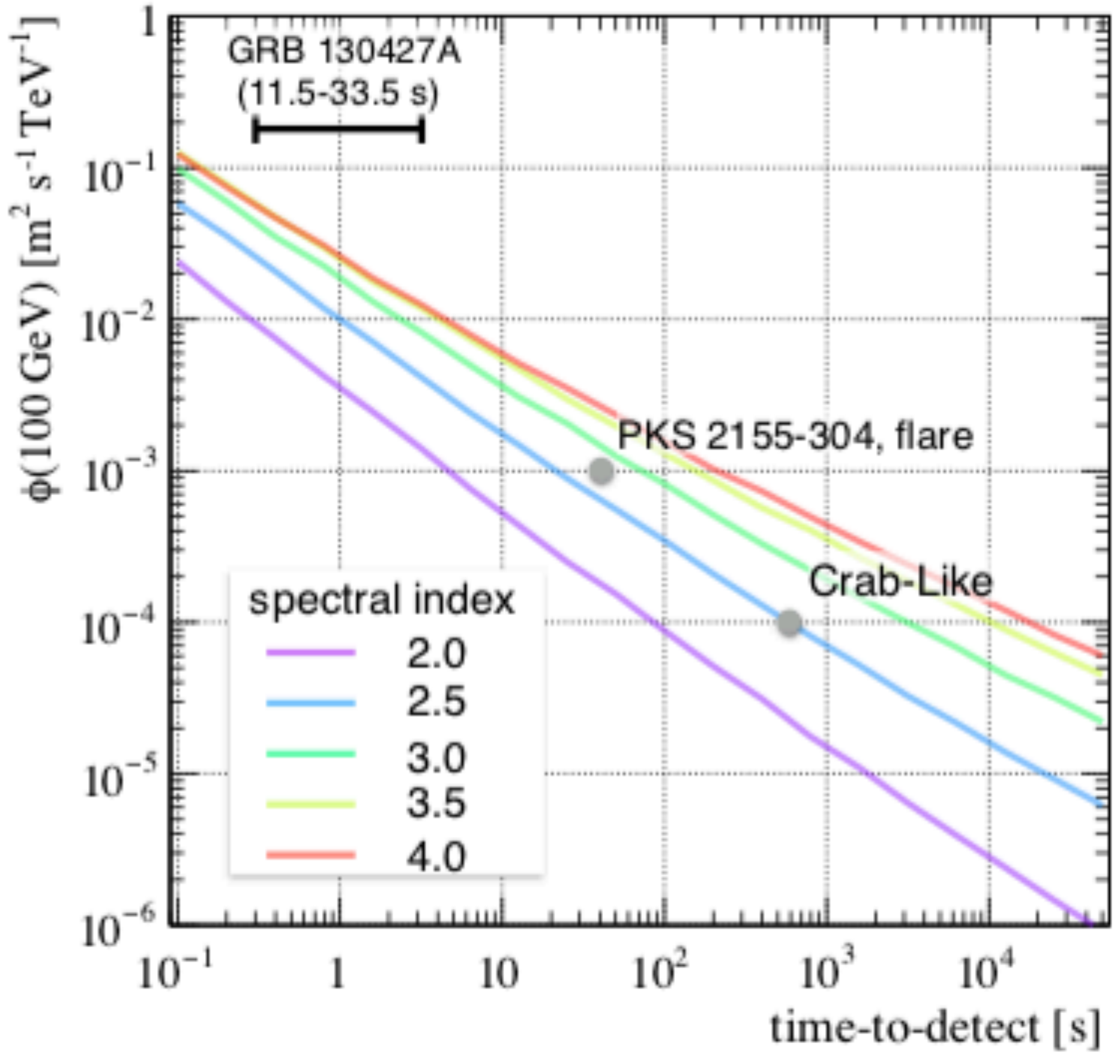
- BASIC IDEA: higher, larger, denser!
  - 5000 m. a.s.l.
  - Southern sky
  - Sparse Array: 1000 units covering 221.000 m²
  - Dense array: 4000 units covering 80.000 m²

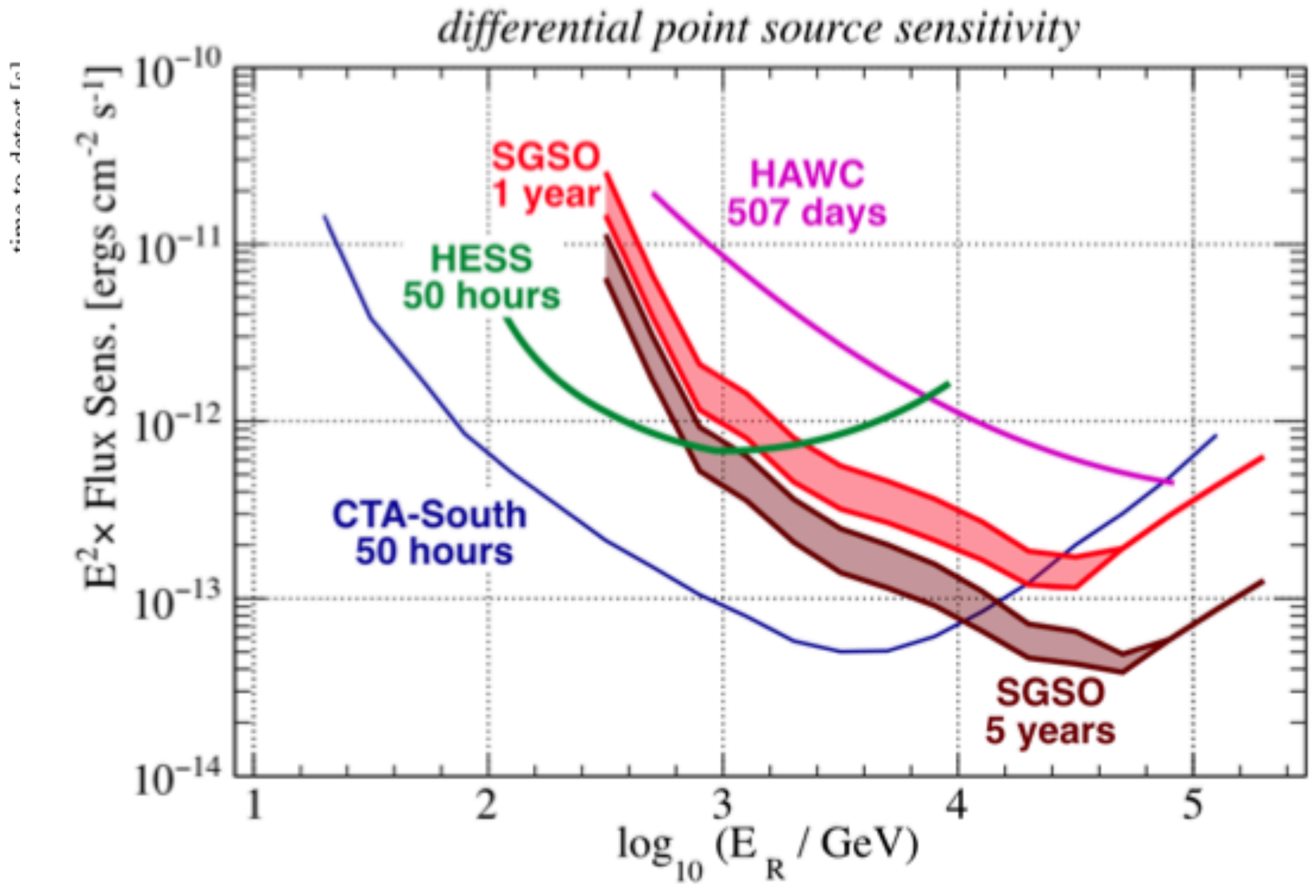
- Goal: Order of magnitude higher sensitivity than current generation instruments like HAWC



Complementarity between HAWC/LHAASO and SGSO.



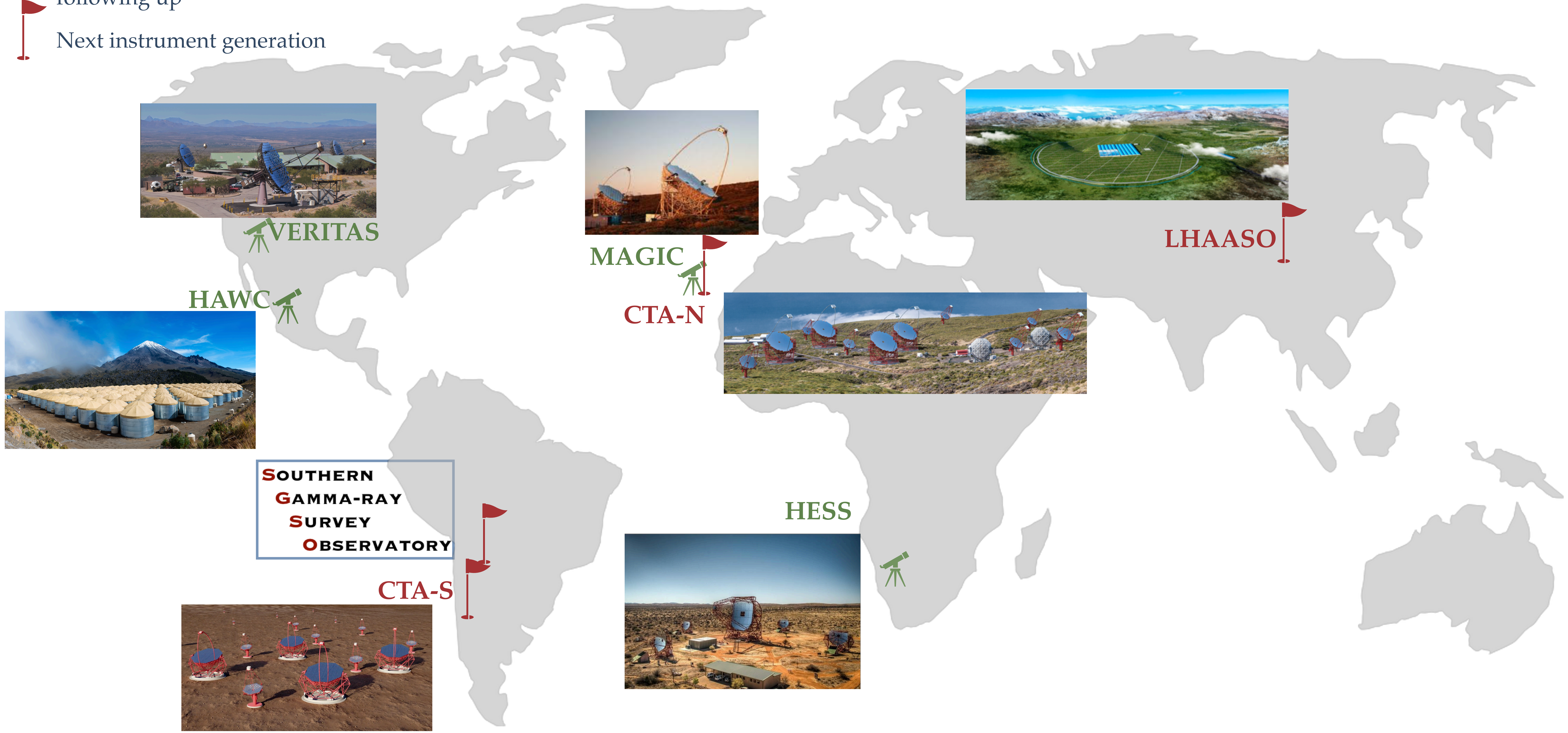




Prospects

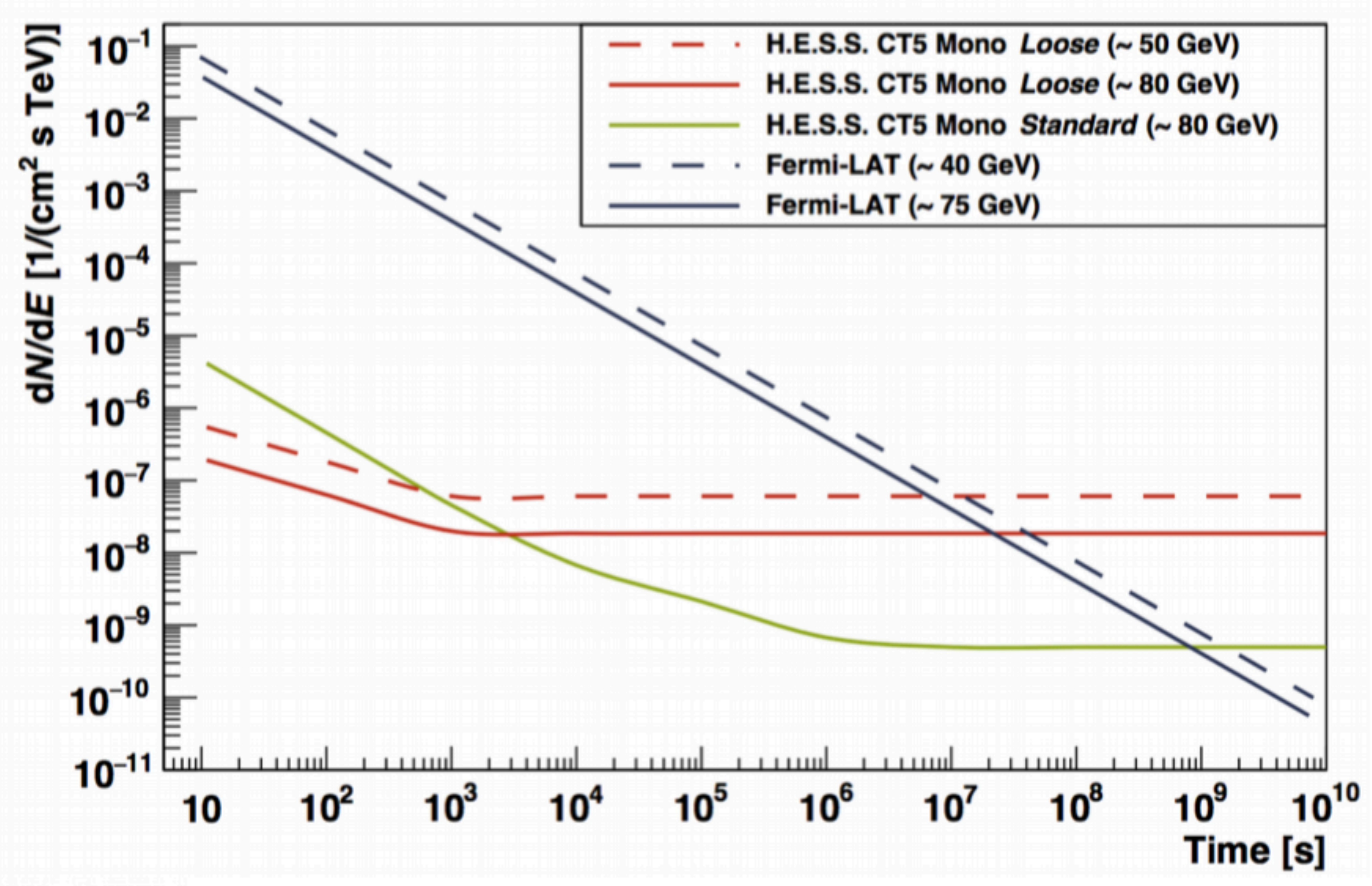
Near future (O3): VHE following up

Next instrument generation

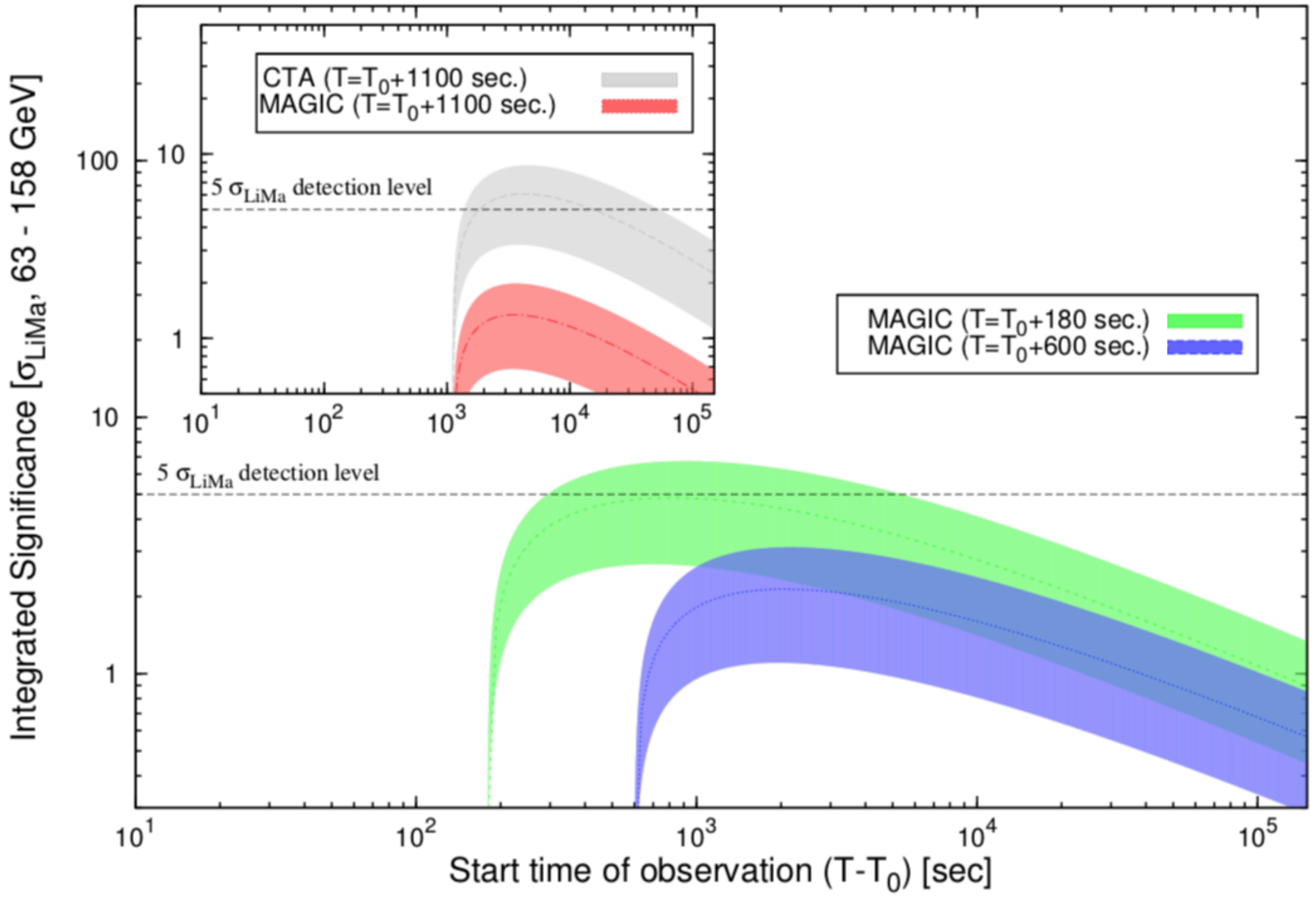


Back up

Sensitivity vs. time in current IACTs



Holler, M. et al, ICRC 2015



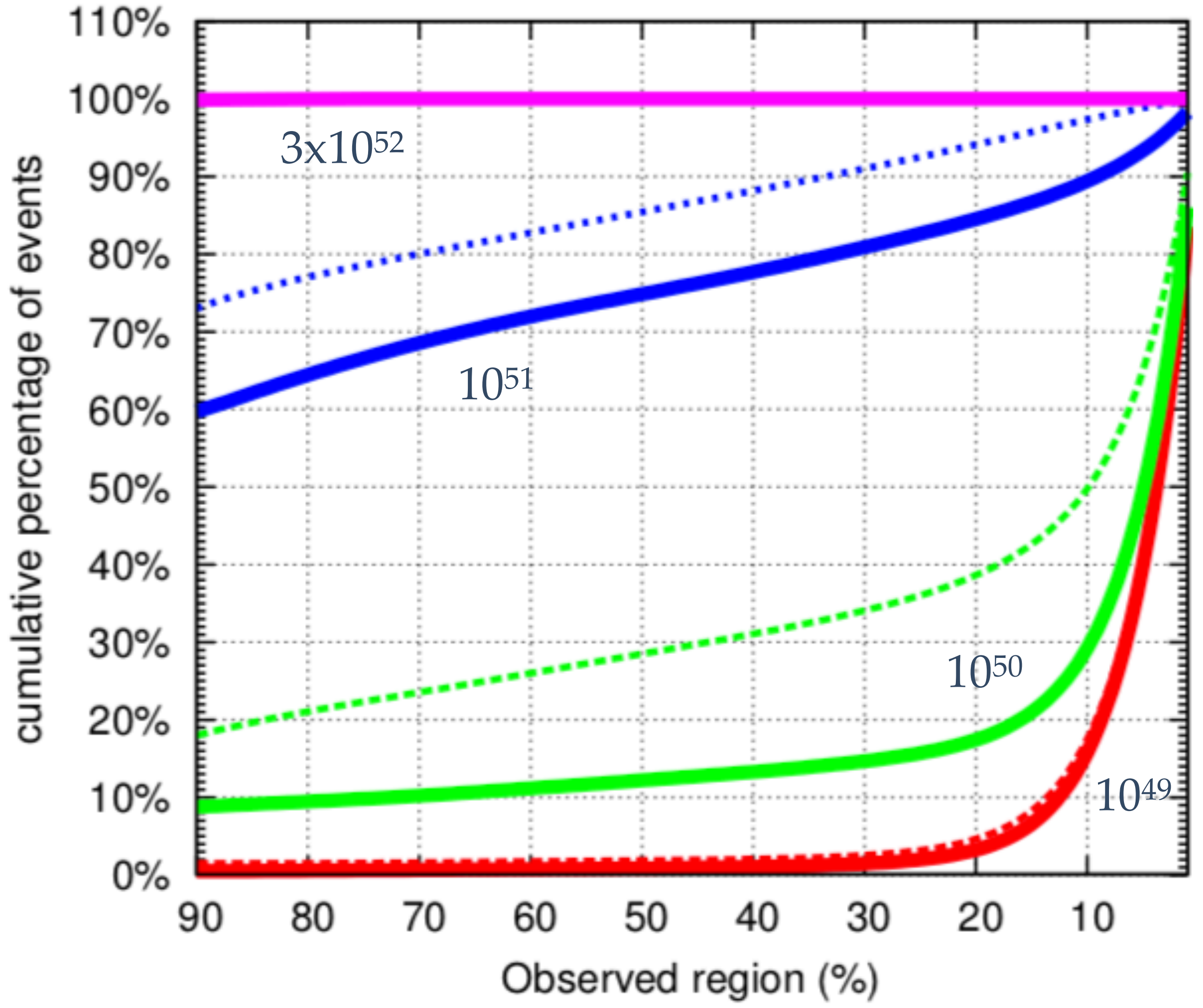
Aleksic et al. (2014)

CTA: Prospects on GW Follow-ups

- Sensitivity simulations:
  - **GWCosmos** simulations for the source location and GW sky localisation
  - GRB 090510 as prototype as it should VHE extended emission
  - On axis GRB 10º
  - Assume power-law + cutoff at 30 GeV and 100 GeV
  - Pointing duration =ΔT for 5σ detection at t_i

E_{iso} (ergs)	cut-off (GeV)	% of events Obs. region = 90%	% of events Obs. region ≥ 50%
10^{49}	30	< 1	< 1
	100	1.5	1.9
10^{50}	30	8.8	12.2
	100	18.0	28.8
10^{51}	30	59.7	74.5
	100	73.0	85.1
3.5×10^{52}	30	99.9	100
	100	99.9	100

- Prospects



E_{iso} (ergs)	cut-off (GeV)	EM and GW (yr^{-1})
10^{49}	30	$< 10^{-3}$
	100	0.001
10^{50}	30	0.01
	100	0.03
10^{51}	30	0.06
	100	0.07
3.5×10^{52}	30	0.08
	100	0.08

- Extra factors may come from
  - Considering moonlight observations (~**2**)
  - Higher NS-NS merger rates (~**6**)
  - Sub-arrays definition
  - Use of galaxy distribution

Patricelli et al. 2018, JCAP, 5, 56