LIGO

An Archival Search for Very-High-Energy Counterparts to Sub-Threshold Neutron-Star Merger Candidates

ICRC 2021

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on behalf of the VERITAS collaboration
and
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BARNARD

Outline

- Past
  - LIGO and BNS Mergers
  - EM Counterparts
    - Very-High-Energy
- Present
  - Sub-Threshold Searches in Archival VERITAS data
- Future
  - Potential to expand to:
    - Other IACTs
    - The Next-Generation: CTA

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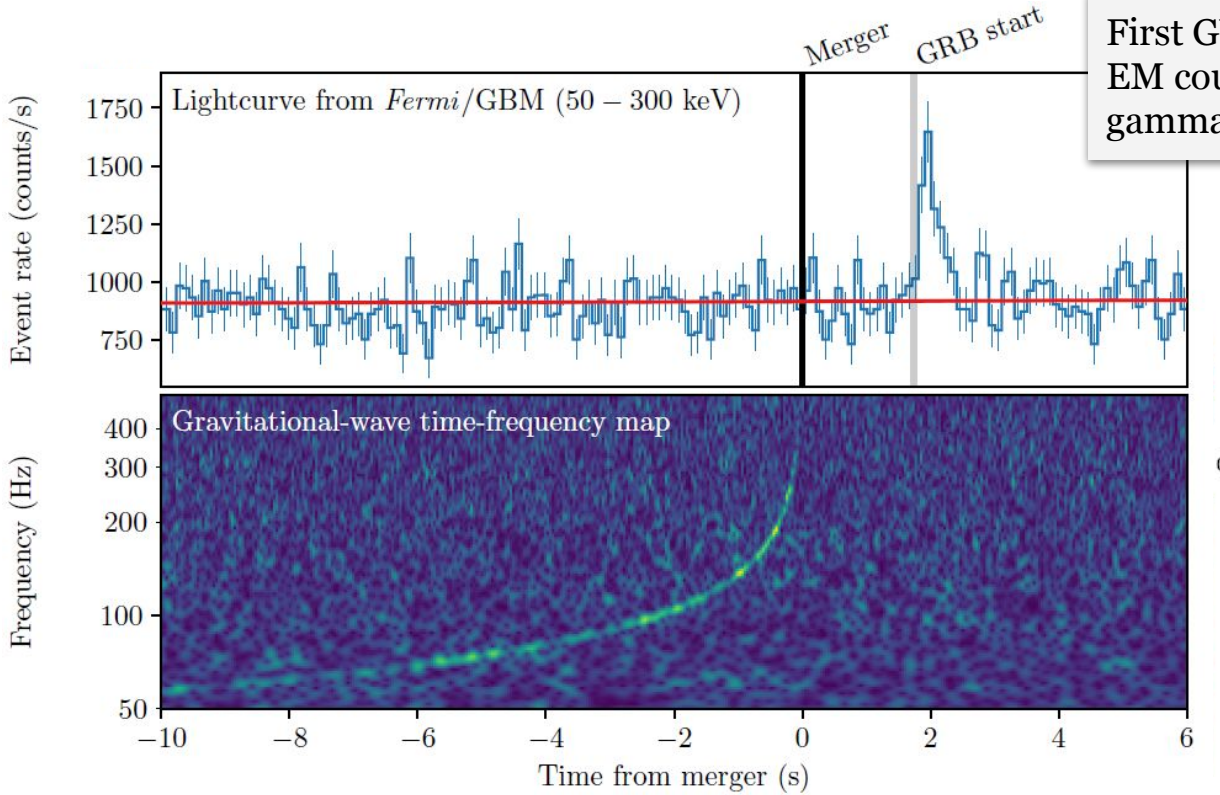
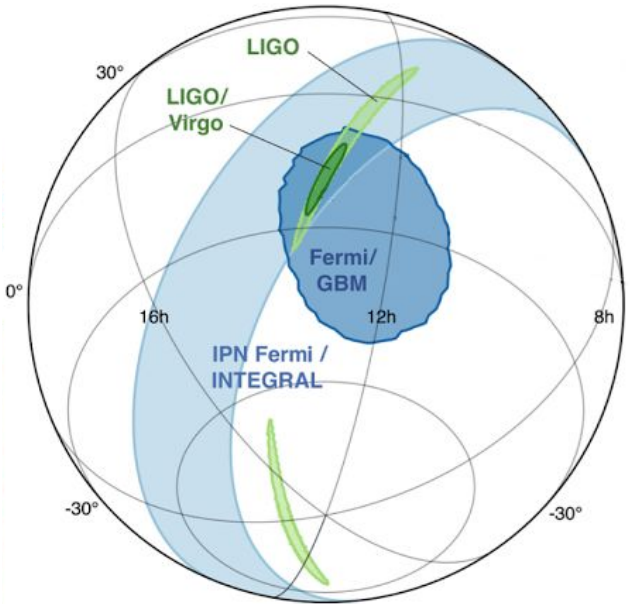
First BNS Merger Detections - GW 170817



First GW detection of a BNS merger. EM counterpart detected up to HE gamma rays (Abbott+ 2017 a & b)

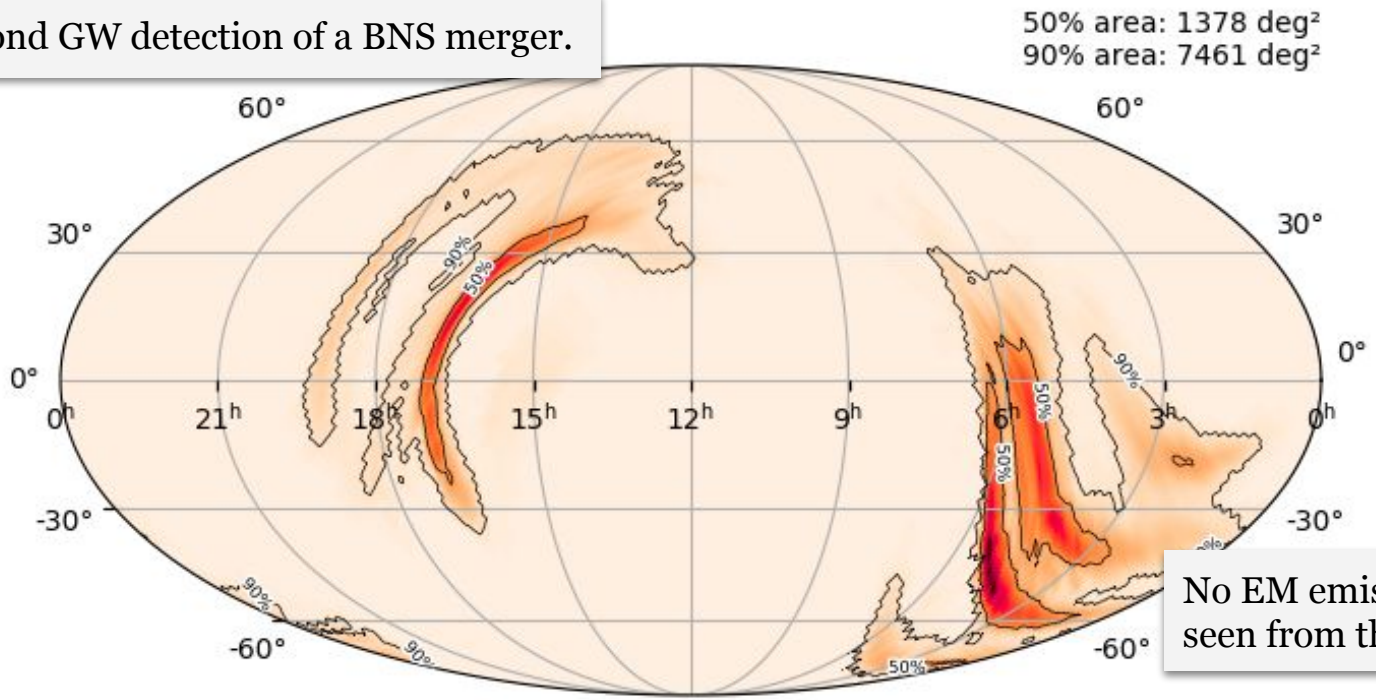


Adapted from Abbott+ 2017

http://maravelias.info/2017/12/a-short-talk-on-gw170817-at-uoc/

First BNS Merger Detections - GW 190425

Second GW detection of a BNS merger.

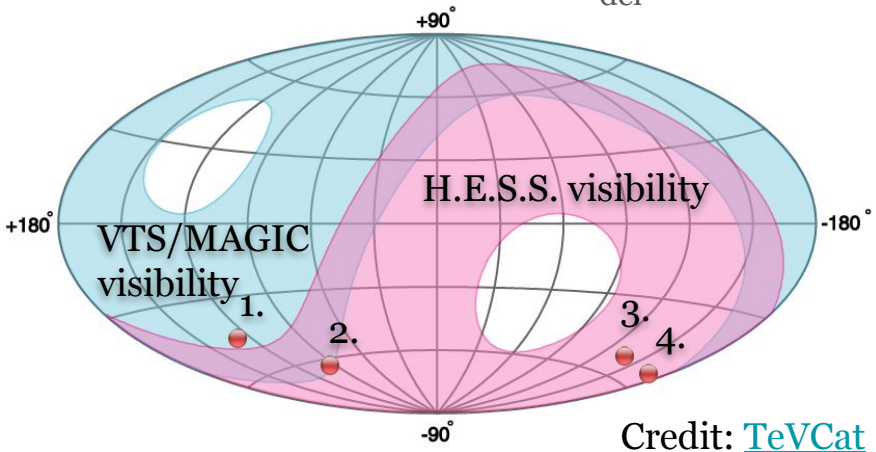


No EM emission was seen from this source.

https://cplberry.com/2020/01/06/gw190425/

GRBs with IACTs

- **Long GRBs have been detected** by current-generation IACTs:
  1. 201216C (MAGIC: t_{del}~ 57 s)
  2. 180720B (HESS: t_{del}~ 10 h)
  3. 190114C (MAGIC: t_{del}~ 50 s)
  4. 190829A (HESS: t_{del}~ 4.3 h)



Credit: TeVCat

- 3 σ hint of a **short GRB** at VHEs:
  - 160821B (MAGIC: **t_{del}~ 24 s**)

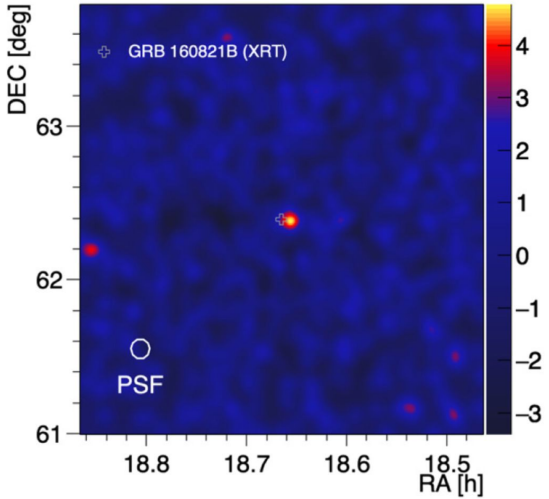


Figure 3. Sky map showing the excess significance (standard deviation, pre-trial) as measured by MAGIC for events above ~0.8 TeV. The white cross marks the position of GRB 160821B according to Swift-XRT. The PSF corresponding to 68% containment is depicted as a white circle in the left lower corner, with radius 0.045 deg.

Acciari+ 2020

Sub-threshold motivation

- LIGO had 103 sub-threshold binary neutron star (BNS) merger candidates in their first observing run (O1) (Magee+ 2019)
  - Given local BNS merger rate of $\mathcal{R} \approx 100$ - 4000 $\mathrm{Gpc^{-3}\ yr^{-1}}$ at 90% confidence (nominal value of 1000 $\mathrm{Gpc^{-3}\ yr^{-1}}$ adopted) and estimated O1 sub-threshold search sensitivity $\langle VT \rangle = 6.7 \times 10^5\ \mathrm{Mpc^3\ yr}$
    - Expect that $\mathcal{R} \times \langle VT \rangle = 0.67^{+2.0}_{-0.60}$ of these candidates are **real gravitational wave signals**
  - Despite contamination fraction being very high, motivates possibility to correlate real events with other messenger signals

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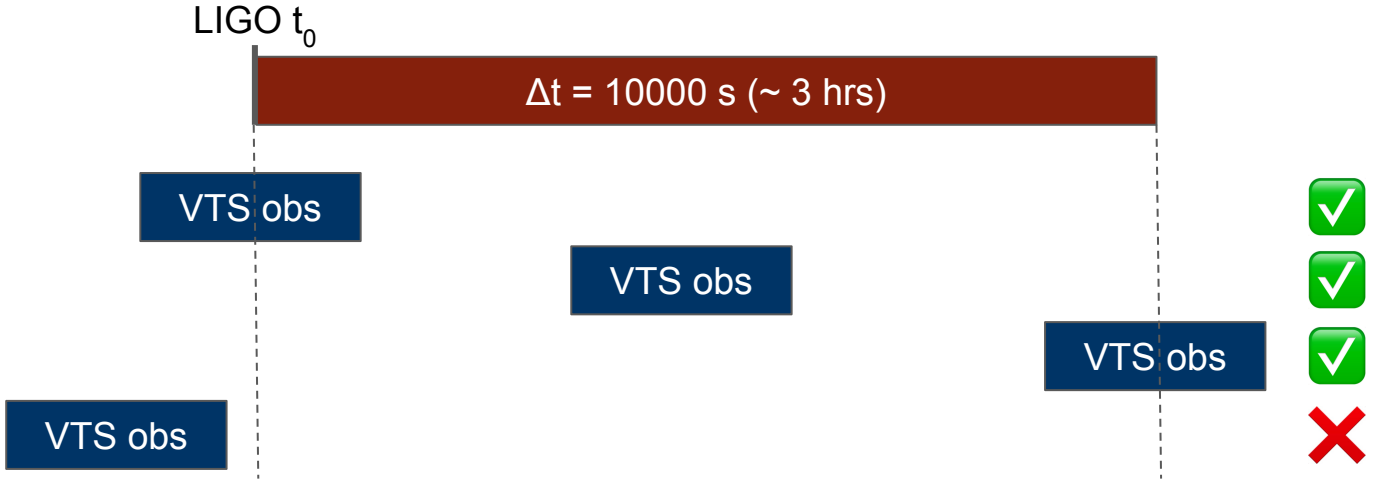
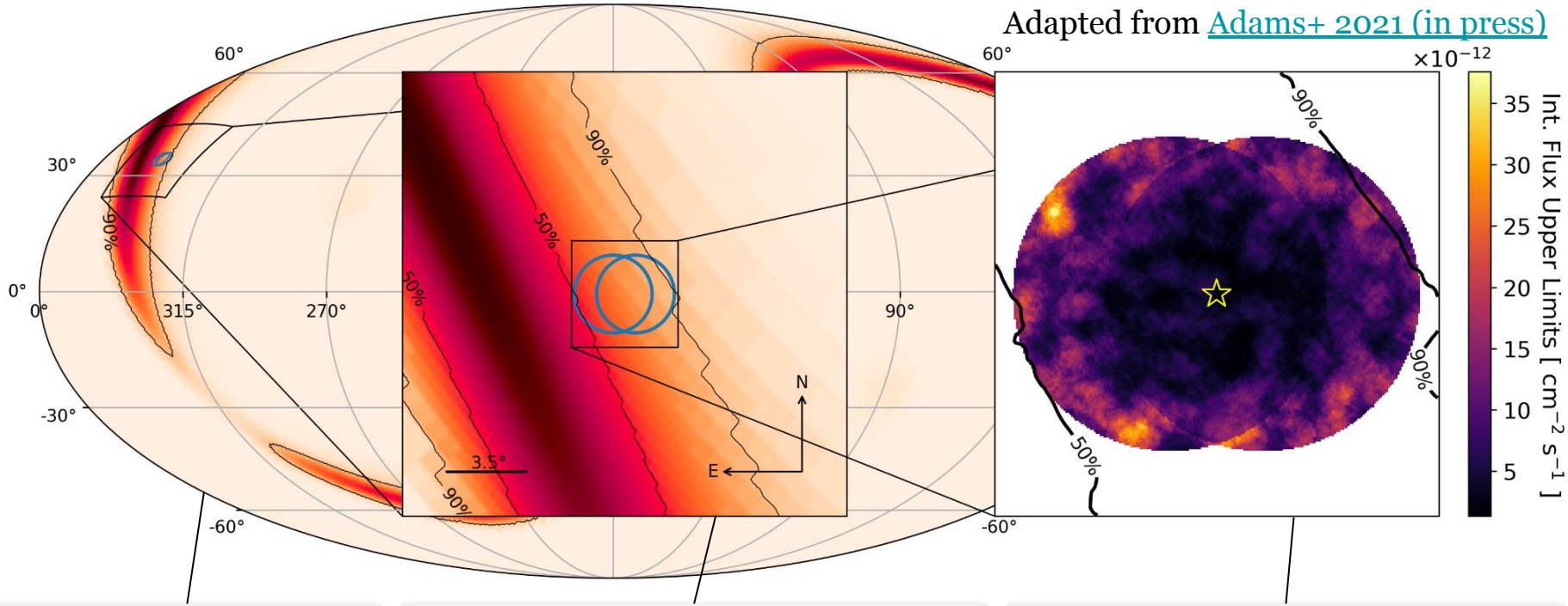
Coincidence Algorithm

- Identify VERITAS observations that are:
  - Spatially coincident with the 90% credible region of a sub-threshold BNS merger candidate
  - Temporally coincident with a pre-defined coincidence window around a LIGO subthreshold measurement.



Sub-threshold examples

Adapted from Adams+ 2021 (in press)



Initially, 103 sub-thresh candidates from aLIGO O1 (Magee+ 2019).

7 with VERITAS observing in spatial and temporal coincidence - 0.04% probability of observing a true merger.

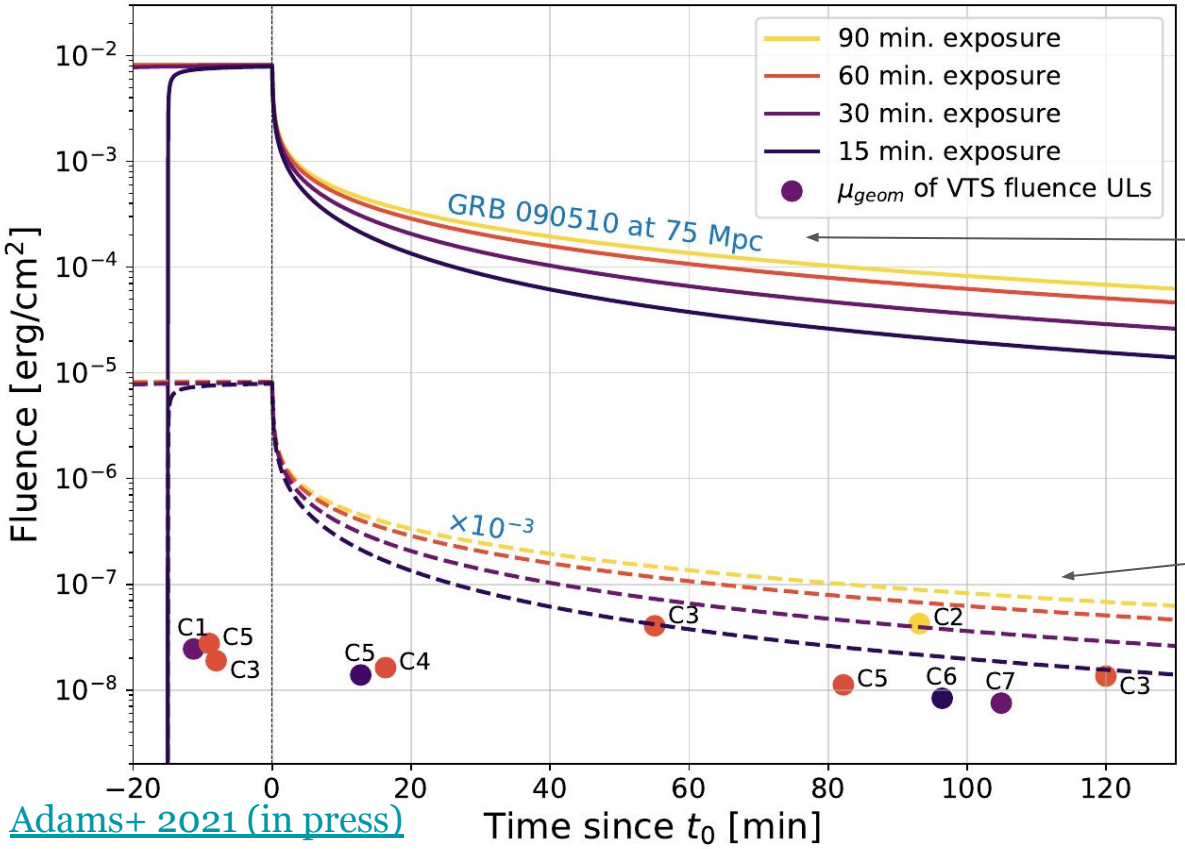
No significant excesses in 11 coinc. sets of VERITAS obs; we place upper limits on the integral flux.

Results

Candidate Label	LIGO BNS Candidate Event ID	LIGO				VERITAS		
		FAR (yr^{-1})	S/N	p-astro (10^{-3})	Area (deg^2)	t_{first}	t_{coinc}	Coverage Probability
C1	2015Oct12T02:40:22.39	142.27	8.42	3.82	2321	-0:11:17	0:18:53	0.22%
$C2^L$	2015Oct24T09:03:52.00	7.52	9.69	79.6	24218	1:33:08	1:11:08	0.06%
$C3^H$	2015Nov17T06:34:02.07	7.52	8.84	181	24221	-0:08:02	2:37:43	0.18%
C4	2015Dec04T01:53:39.14	225.02	9.09	2.5	2909	0:16:20	1:00:00	0.19%
$C5^L$	2015Dec06T06:50:38.17	77.45	7.72	6.64	24264	-0:09:02	2:10:18	0.15%
C6	2015Dec09T07:25:24.68	141.65	7.85	3.84	2606	1:36:25	0:15:00	0.03%
C7	2016Jan02T02:47:29.35	356.13	7.51	1.63	3487	1:44:55	0:30:00	0.18%

Adams+ 2021 (in press)

Results



Compare fluence to GRB model (Bartos et al. 2014 & 2019) at the O1 BNS merger range.

Constrain any VHE counterparts in VERITAS FoV at time of observation for emission similar to model prediction.

Adams+ 2021 (in press)

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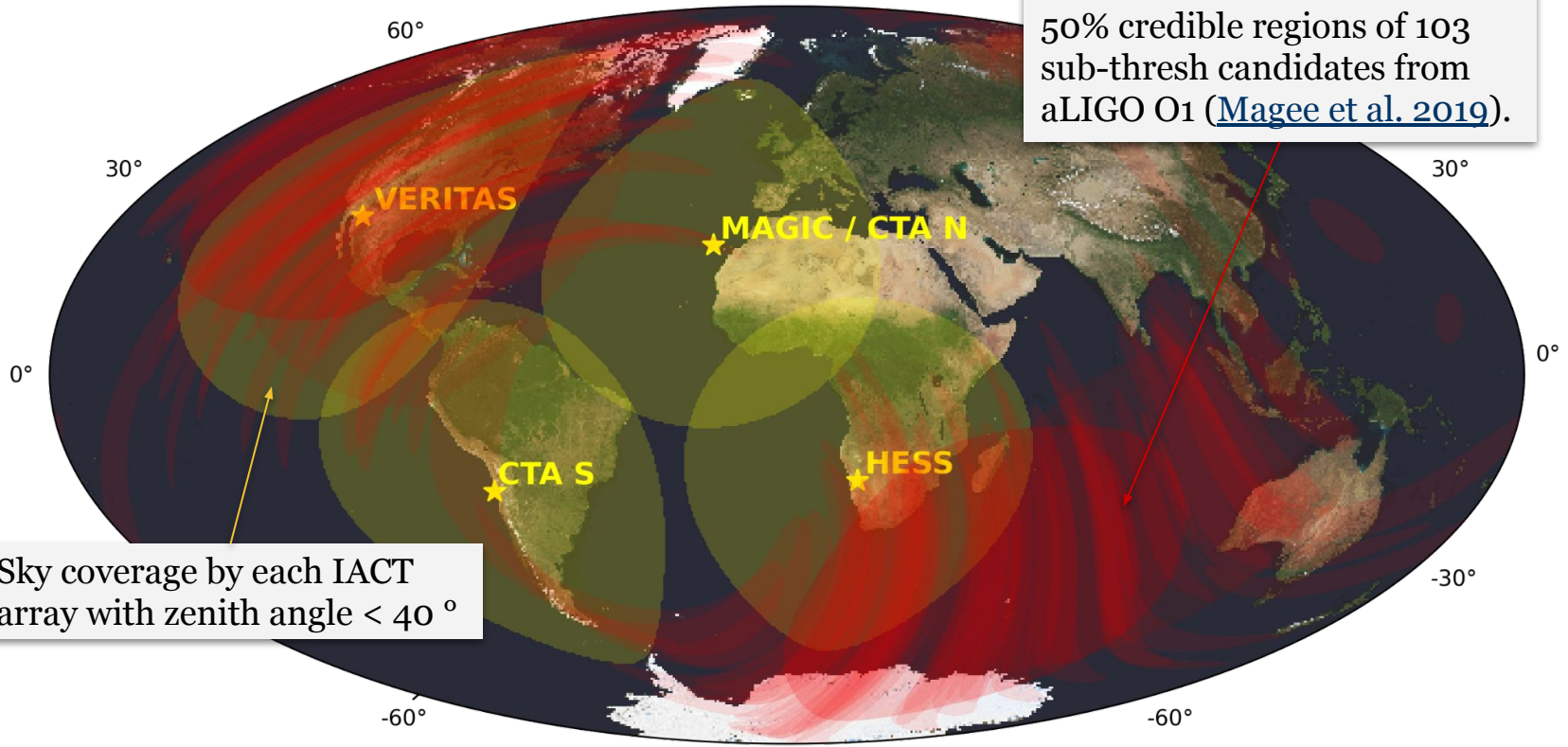
Moving forward



50% credible regions of 103 sub-thresh candidates from aLIGO O1 (Magee et al. 2019).

Sky coverage by each IACT array with zenith angle < 40 °

Outlook

- Current-generation IACTs
  - **≳ 70** additional coincident VERITAS observations predicted in aLIGO O2/O3 (Adams+ 2021, in press)
    - Without a detection, enough coincident observations has potential to constrain VHE emission (need a LOT of observations - participation of H.E.S.S. and MAGIC would help bridge the gap)
  - **MoUs for near real-time alerts** would provide additional opportunities
    - Minimal operational burden
      - Can adjust pre-defined observing schedules to maximize overlap with candidates
- Future prospects
  - Factor of **5-to-16 improvement** in FoV area with CTA over VERITAS
    - CTA era also includes O4/O5 → **vastly expanded sensitive area**

Thank You