Very high energy gamma-ray follow-up observations of gravitational waves

Monica SEGLAR-ARROYO

16th Marcel Grossman Conference

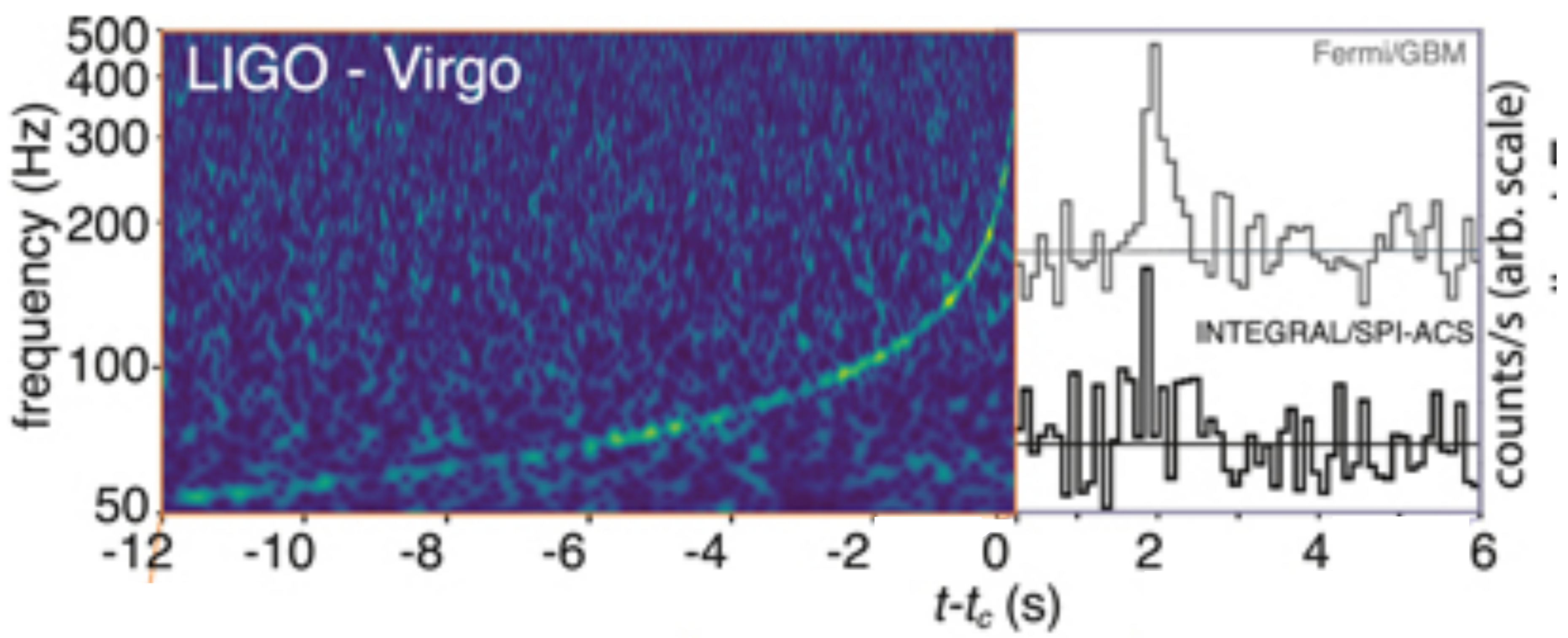
HE and VHE emission from GRBs session

5th July 2021

Credit: NASA's Goddard Space Flight Center/CI Lab

The Compact Binary Coalescences-Gamma Ray Burst connection

Abbott, B.P. et al (2017) ApJL 848, L12



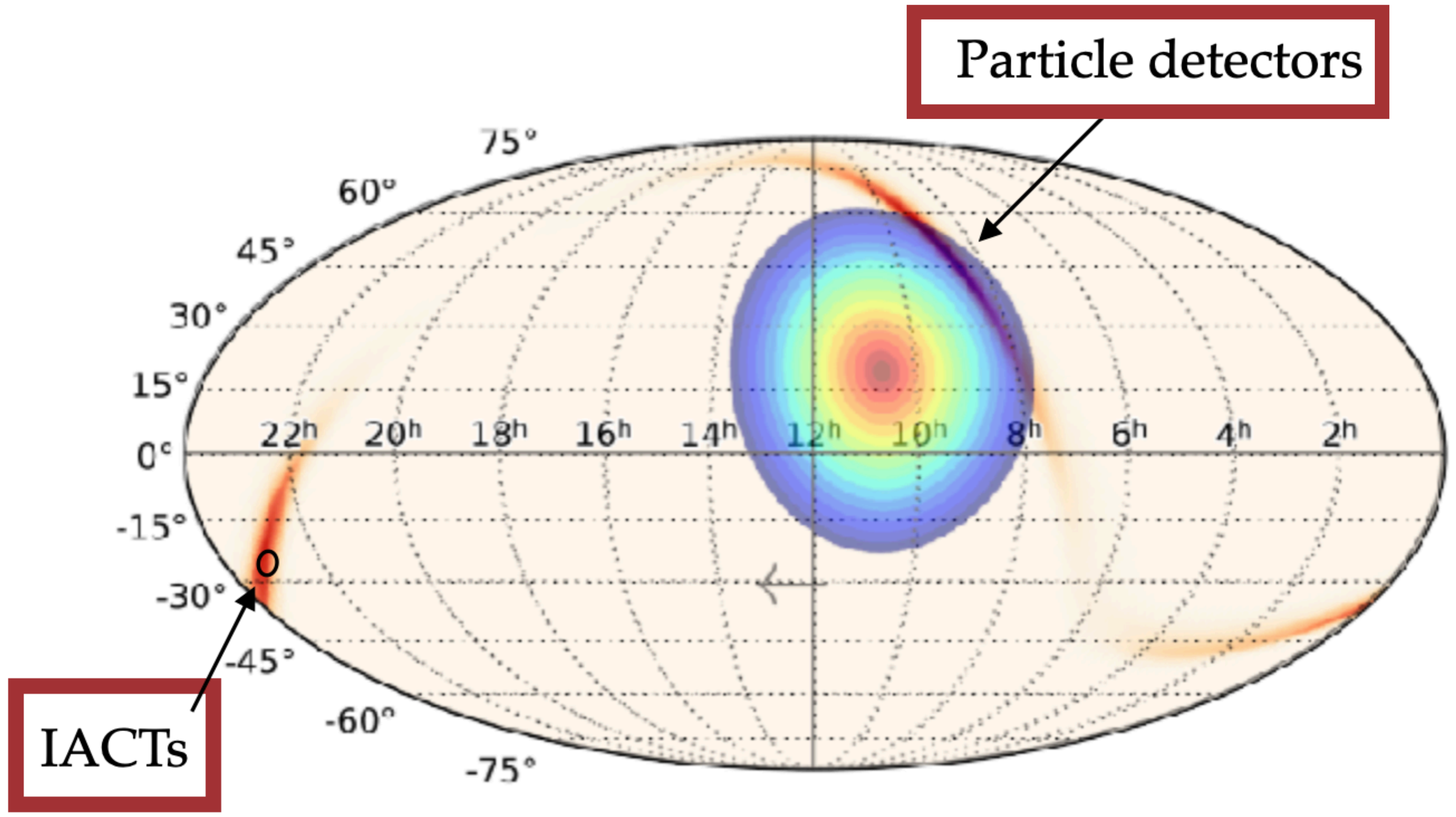
- Compact binary coalescences (CBC), proposed as progenitors of short GRBs (sGRBs)
- The unambiguous detection of **GW170817-GRB170817A** shows that at least **a subsample of sGRBs have BNS as progenitors.**
- GW170817-GRB170817A:
  - Closest+dimmest sGRB, $L_{ISO} \sim 10^{47}$ erg s^{-1}, $D_L \sim 40$ Mpc
  - Regarding HE/VHE emission:
    - No detection from Fermi-LAT: passing the South Atlantic Anomaly at the merger time, no significant detection at later times
    - H.E.S.S. and HAWC followed up the event: ULs on the VHE emission.
- The joint GW-GRB detections:
  - GW: properties of the binary system, i.e. mass, spins, eccentricity, inclinations, luminosity distances, rates..
  - GRB: sky localization, host galaxy identification, emission processes, acceleration mechanisms..

Challenges in GW-follow-ups associated to the detection technique

*Imaging Atmospheric Cherenkov Telescope

	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%

- Gravitational waves can have really large localization uncertainty regions from 10s to 1000s deg²



First VHE counterpart searches: Observation run O1 and O2

O1

GW151226 (BBH)

MAGIC

- 2nd BBH merger detected
- Localization ~1400 deg^2
- Manually selected regions
- Total of 2.6h, ~65.5h after the GW event

No significant excess found.

De Lotto, B. et al, 2016

HAWC

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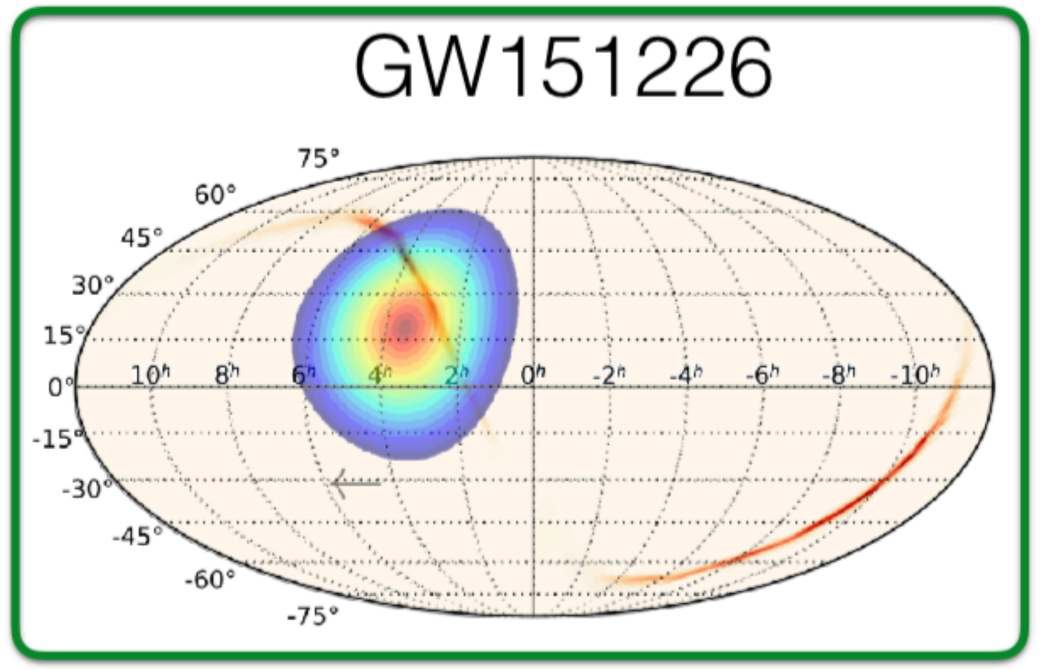


Martinez-Castellanos, I. et al, 2018

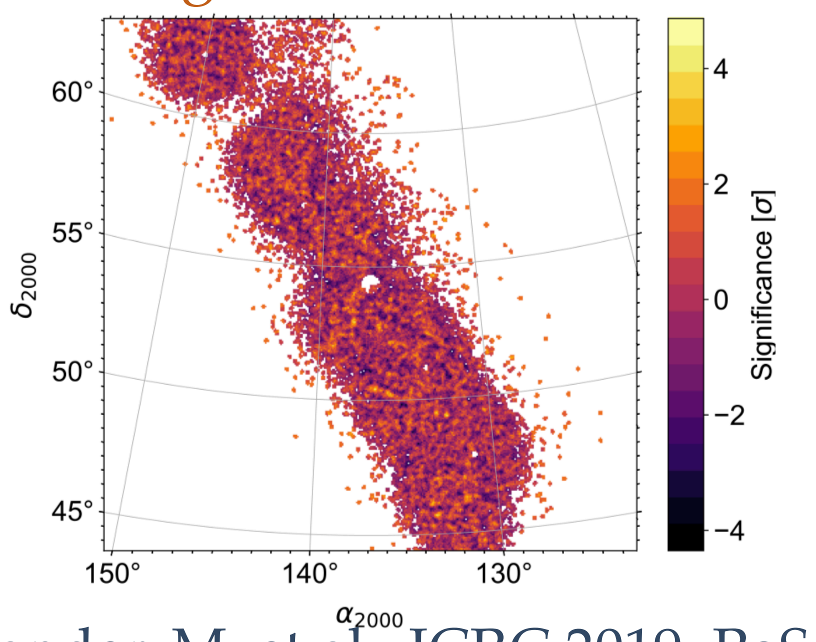
O2

GW170104 (BBH)

VERITAS

- 21h after the GW event
- 39 5-minute tiling pointings (~27% probability coverage)

No significant excess found.



Santander, M. et al., ICRC 2019, PoS 358

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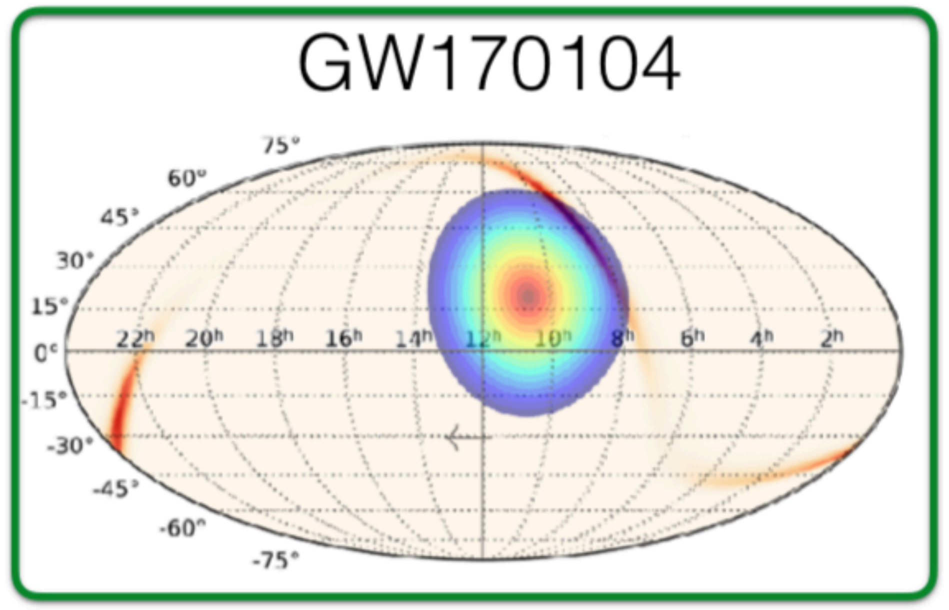
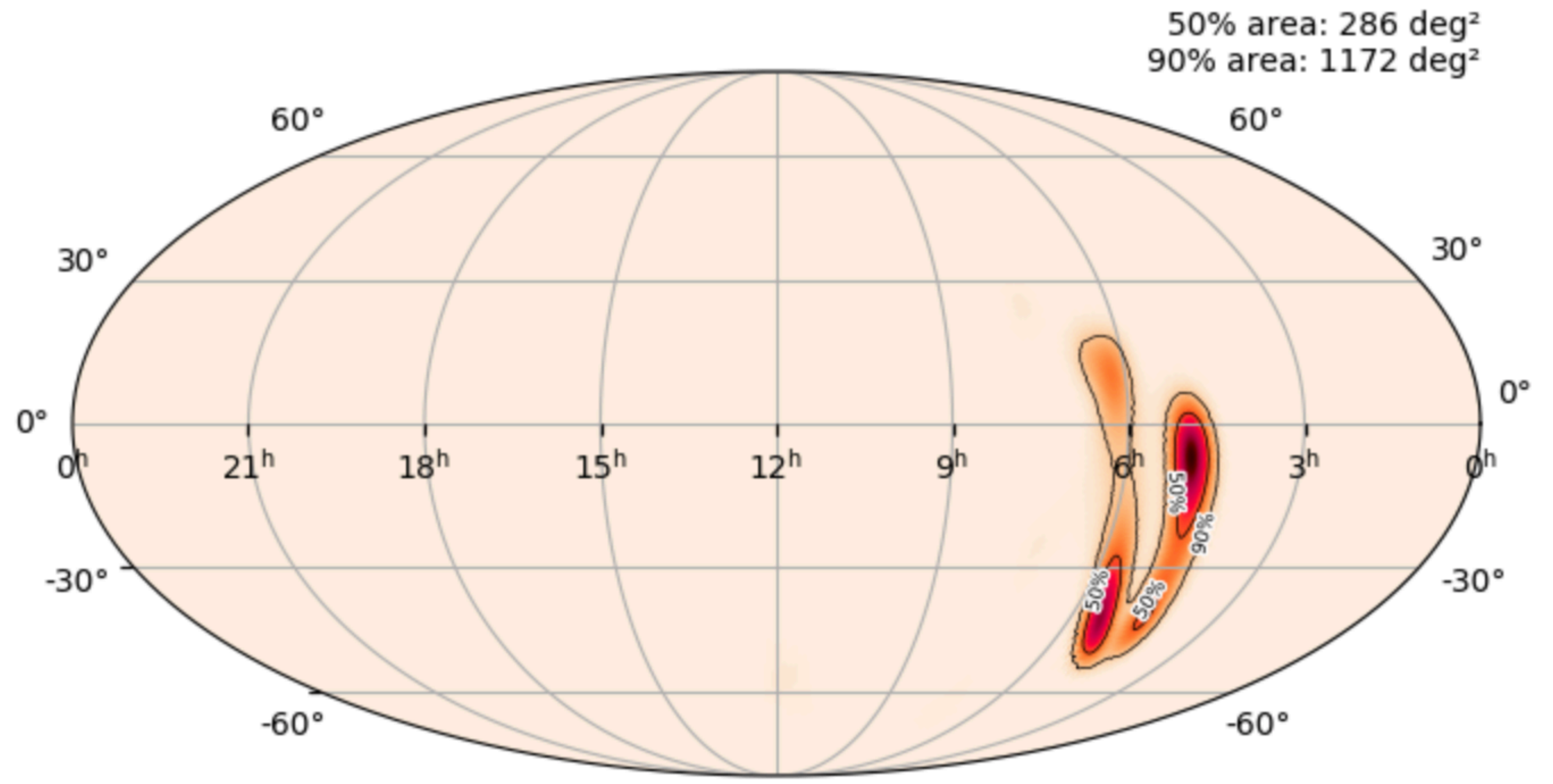


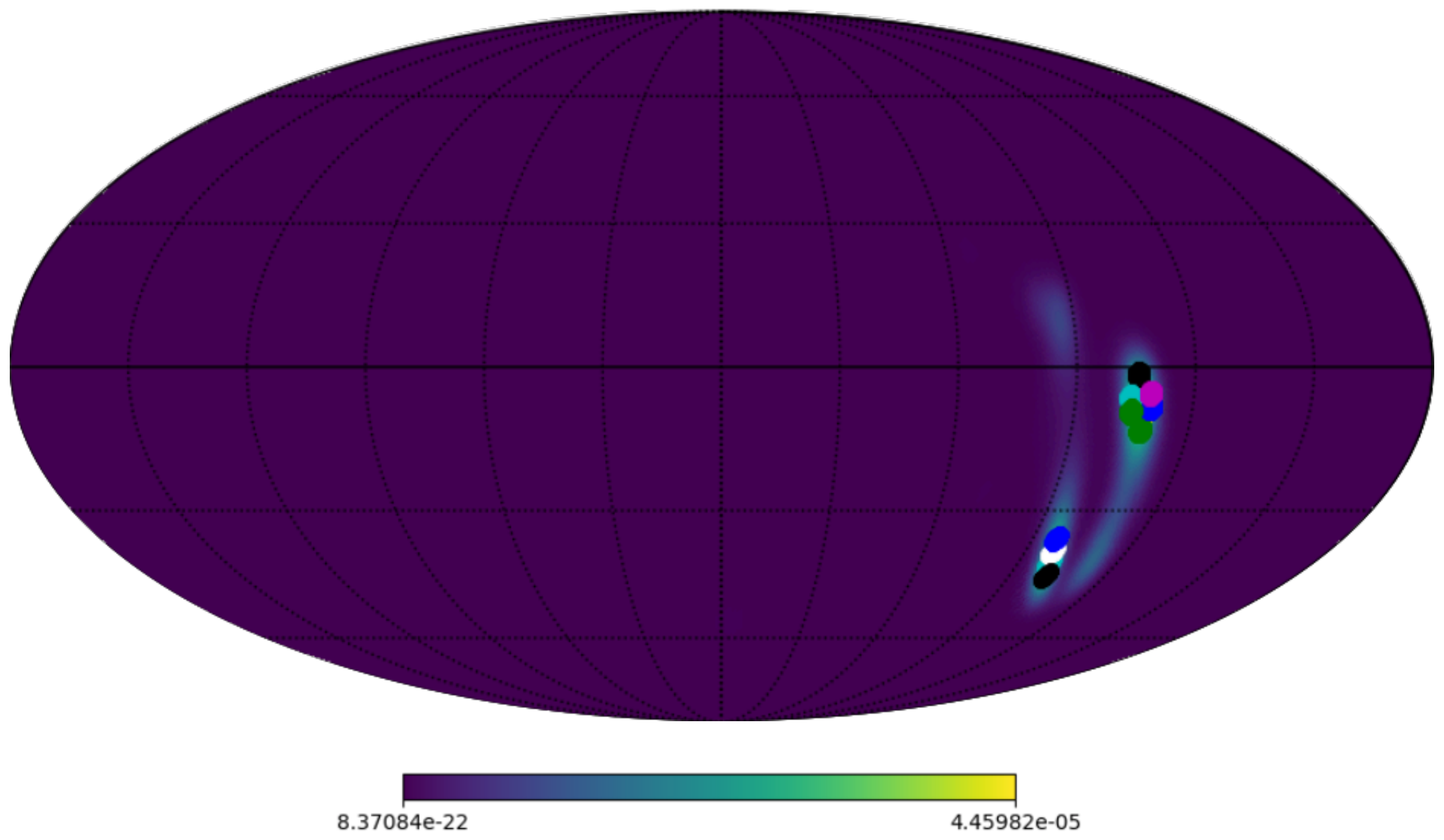
Martinez-Castellanos, I. et al, 2018

Observation strategy for IACTs to maximise the probability to cover the source

- Due to the large localization uncertainty regions, observation strategies are key to cover the source of GW with small/ mid-size telescopes

- Implementation for IACTs:
  - Dedicated observation scheduling algorithm selected depending on the parameters of the events (most probable source type, 3D uncertainty region)
  - Correlation of the 3-dimensional localization uncertainty region with galaxy catalogs
    - A probability of hosting the event is associated to each galaxy.





Seglar-Arroyo, M. & Schussler, F. Moriond VHEPU 2017 arXiv: 1705.10138
Ashkar, H. et al., JCAP 2021.03 (2021): 045 arXiv:2010.16172

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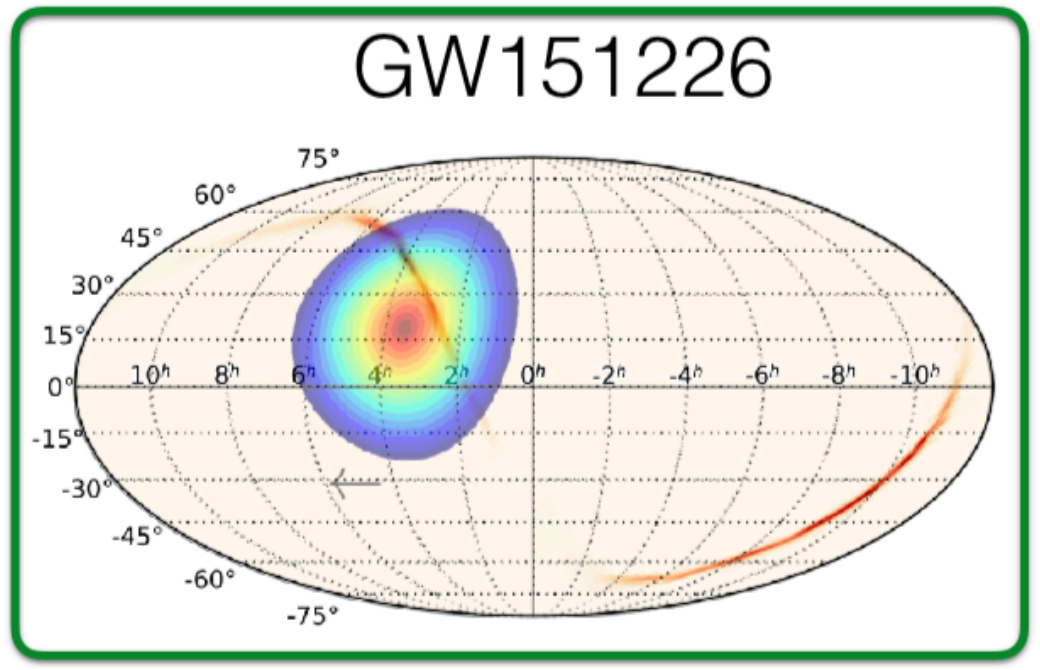

Martinez-Castellanos, I. et al, 2018

GW170104 (BBH) O2

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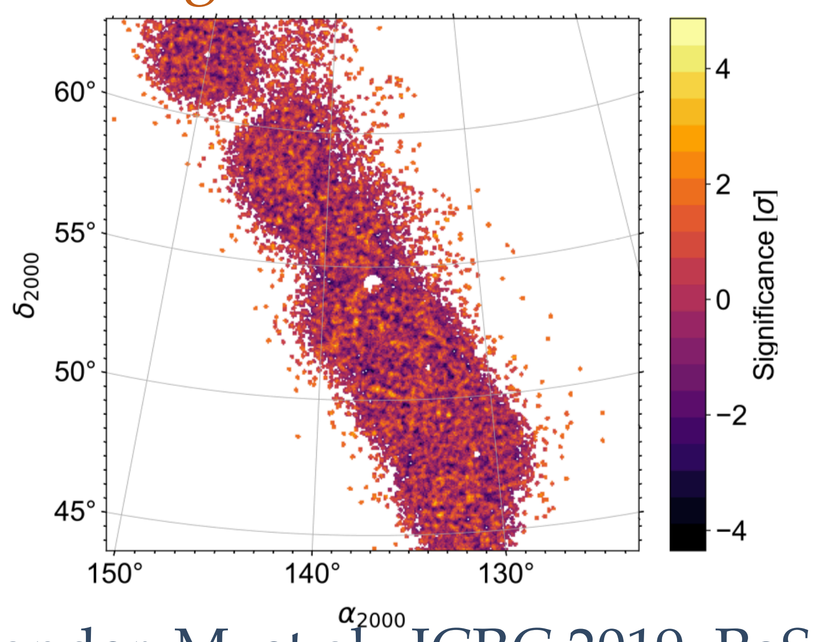
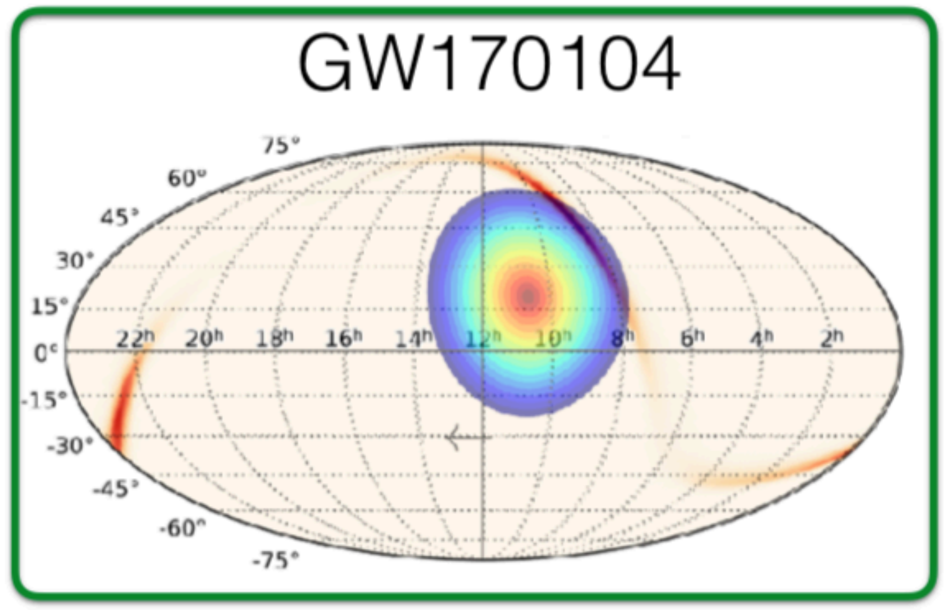


Santander, M. et al., ICRC 2019, PoS 358

HAWC

No significant excess found.



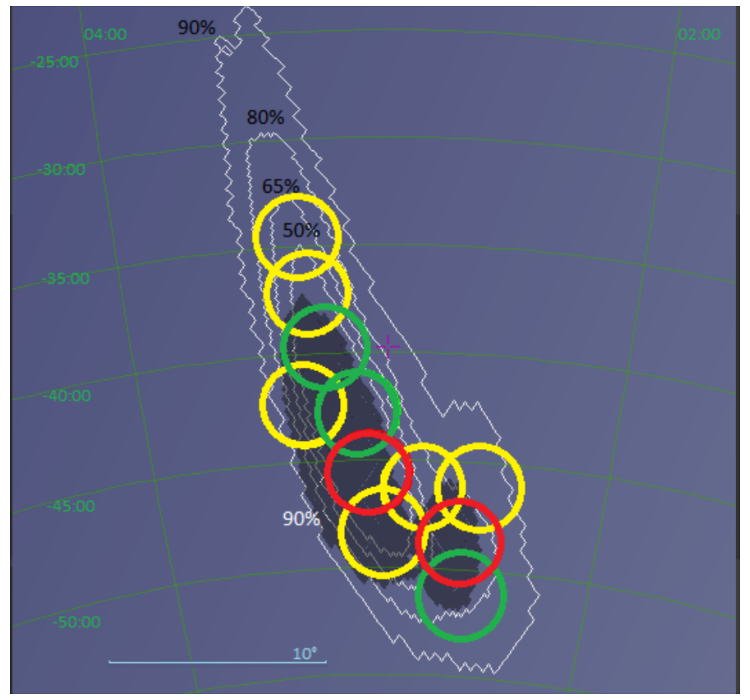
Martinez-Castellanos, I. et al, 2018

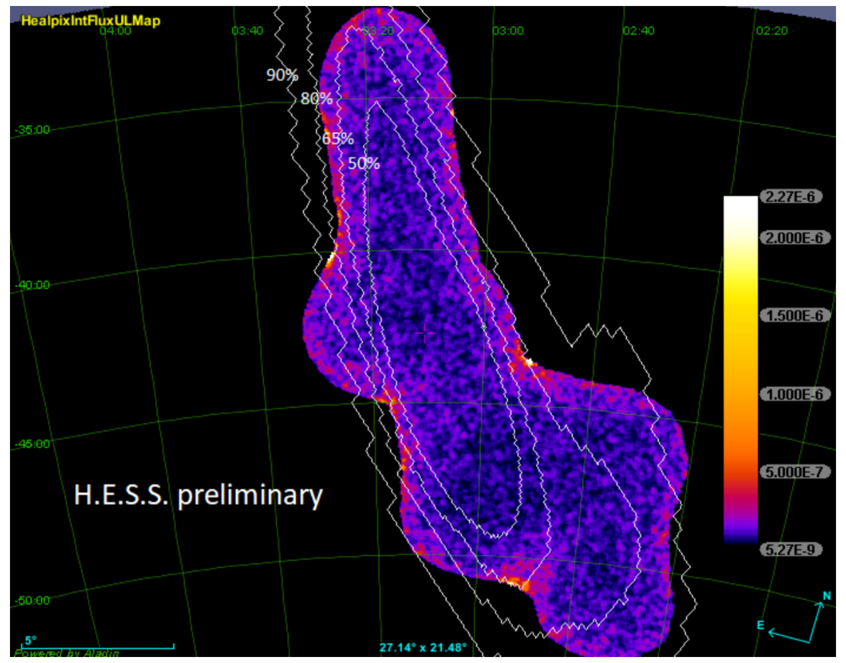
GW170814 (BBH) O2

H.E.S.S

- 3 IFO localisation: 60 deg^2
- First large probability coverage (~95%, 68% after analysis cuts)

No significant excess found.



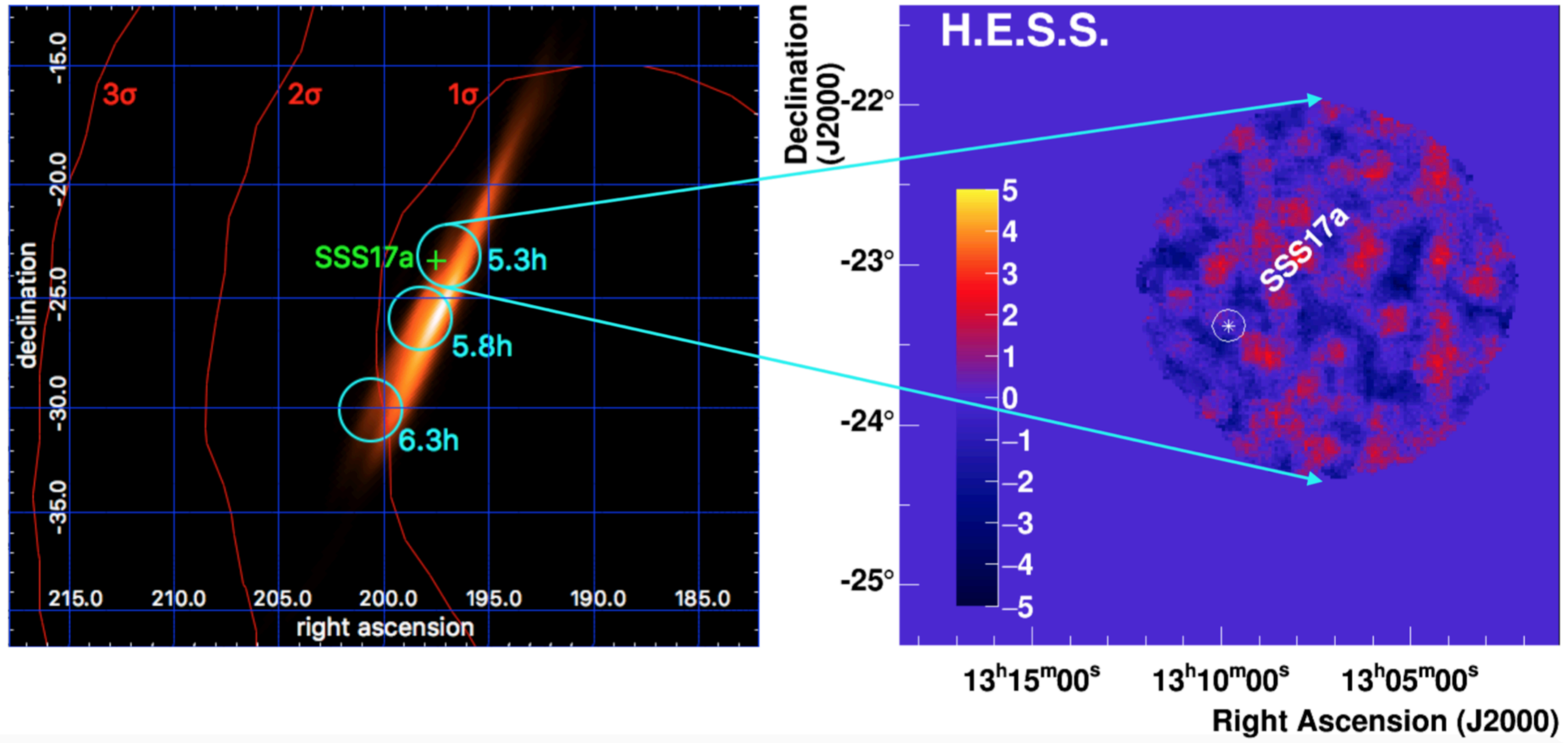


Ashkar, H. et al., 12th INTEGRAL conference, arXiV:1906.10426

O2: Prompt observations of GW170817 at VHE with H.E.S.S.

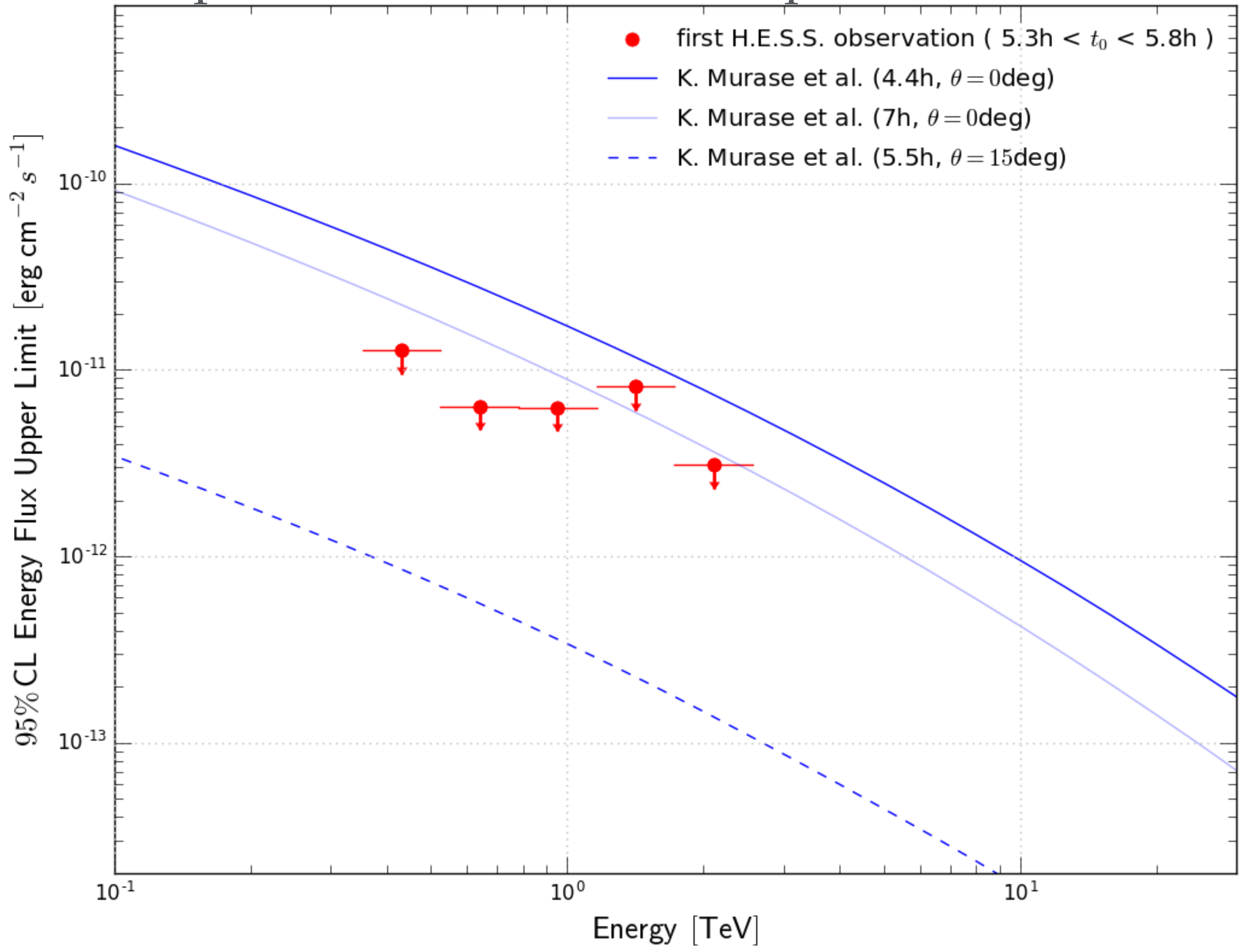
Abdalla et al, ApJL, 850:L22 (9pp)

- First ground-based pointing instrument on target
  - 5.3h after the signal GW170817 from the BNS merger
  - 5 minutes after the update of the GW skymap (LHV reconstruction)
  - Succesful coverage of the source in first observations thanks to the use of galaxy catalogs



- 5 days of monitoring until the source was no longer in the H.E.S.S. FoV
  - Constraints on the VHE emission from external Inverse Compton in afterglow shock with X-ray photons

Adapted from Murase et al, ApJ, 854(1), 60.



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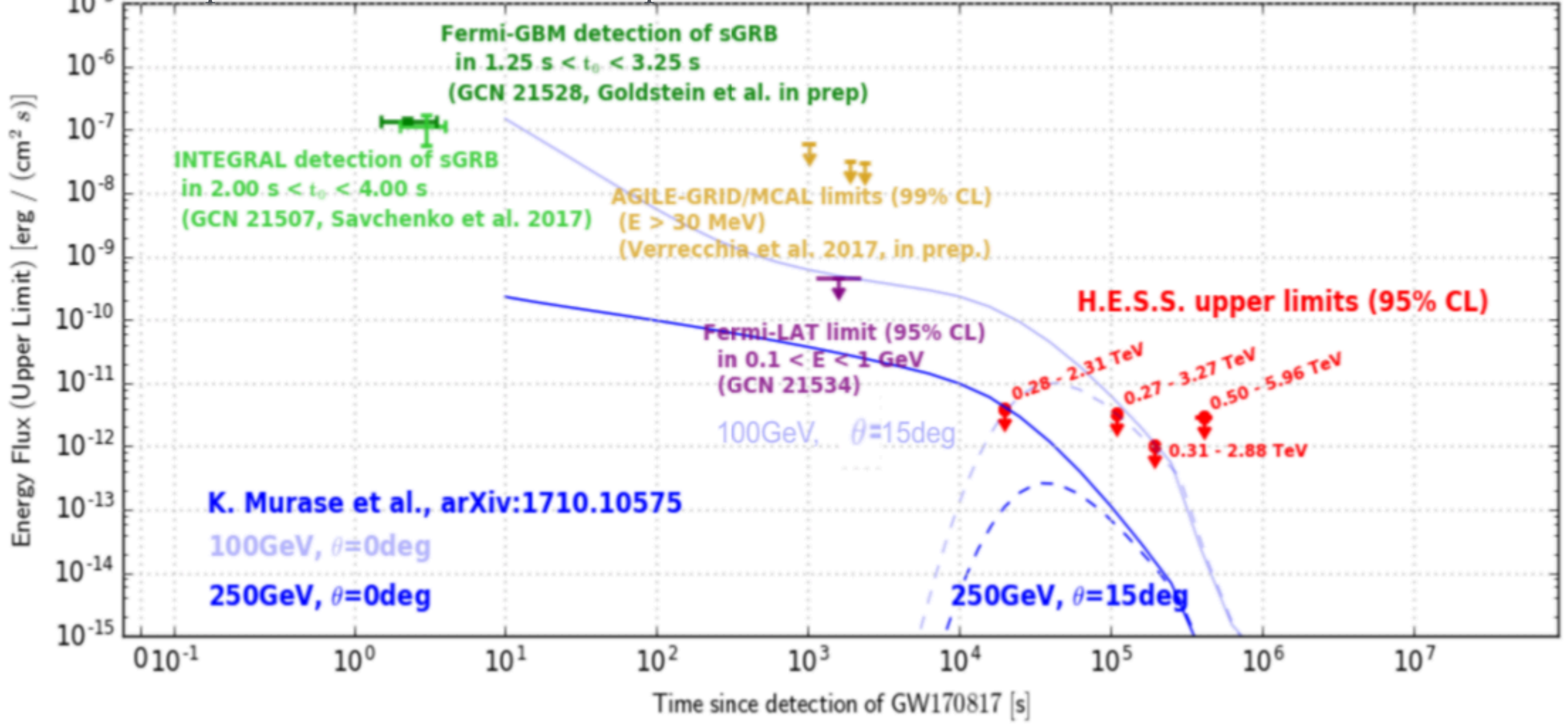
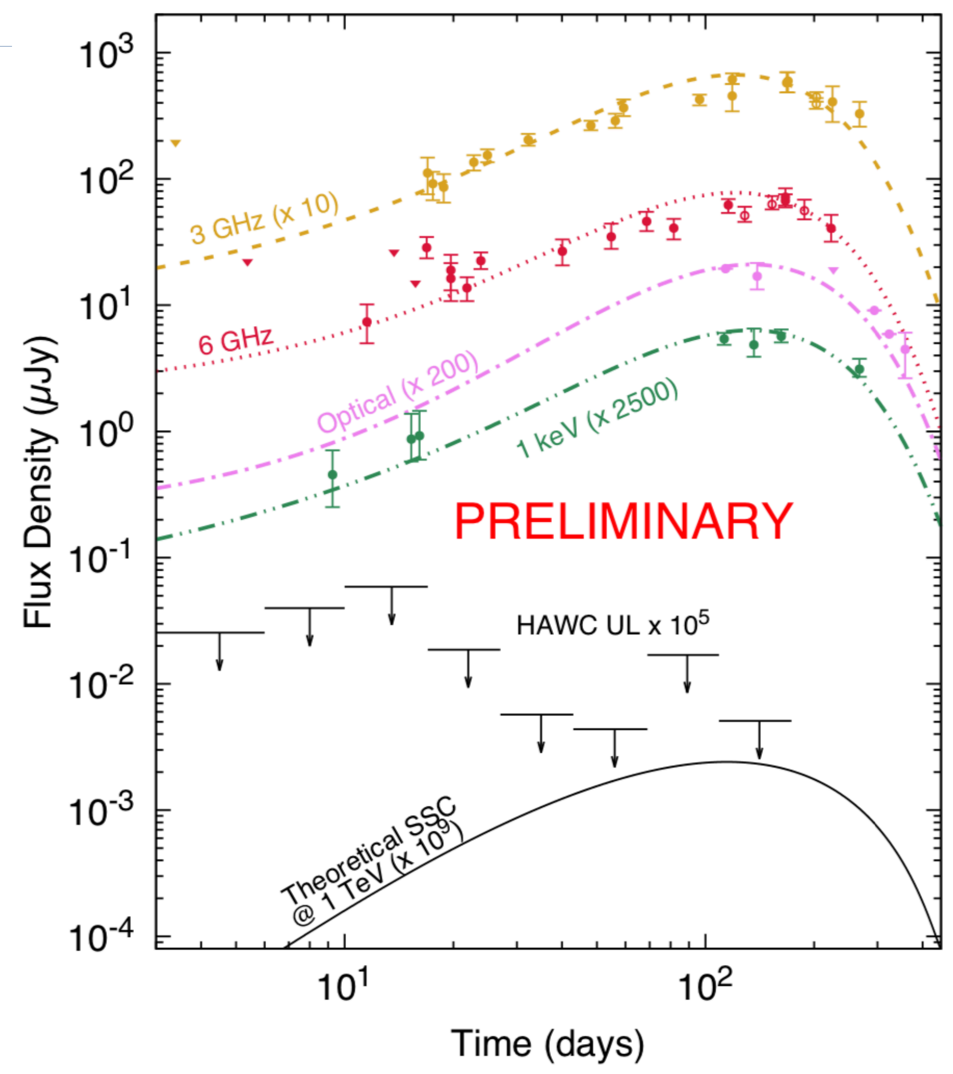


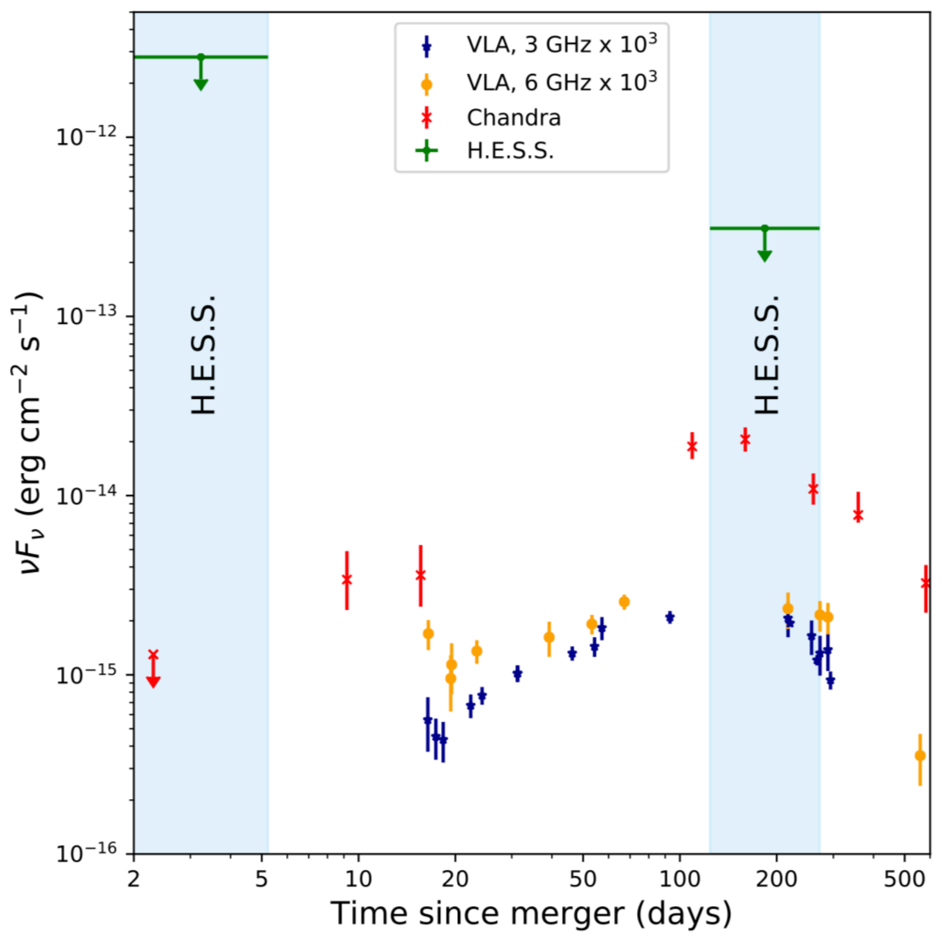
O2: More observations of GW170817 at VHE

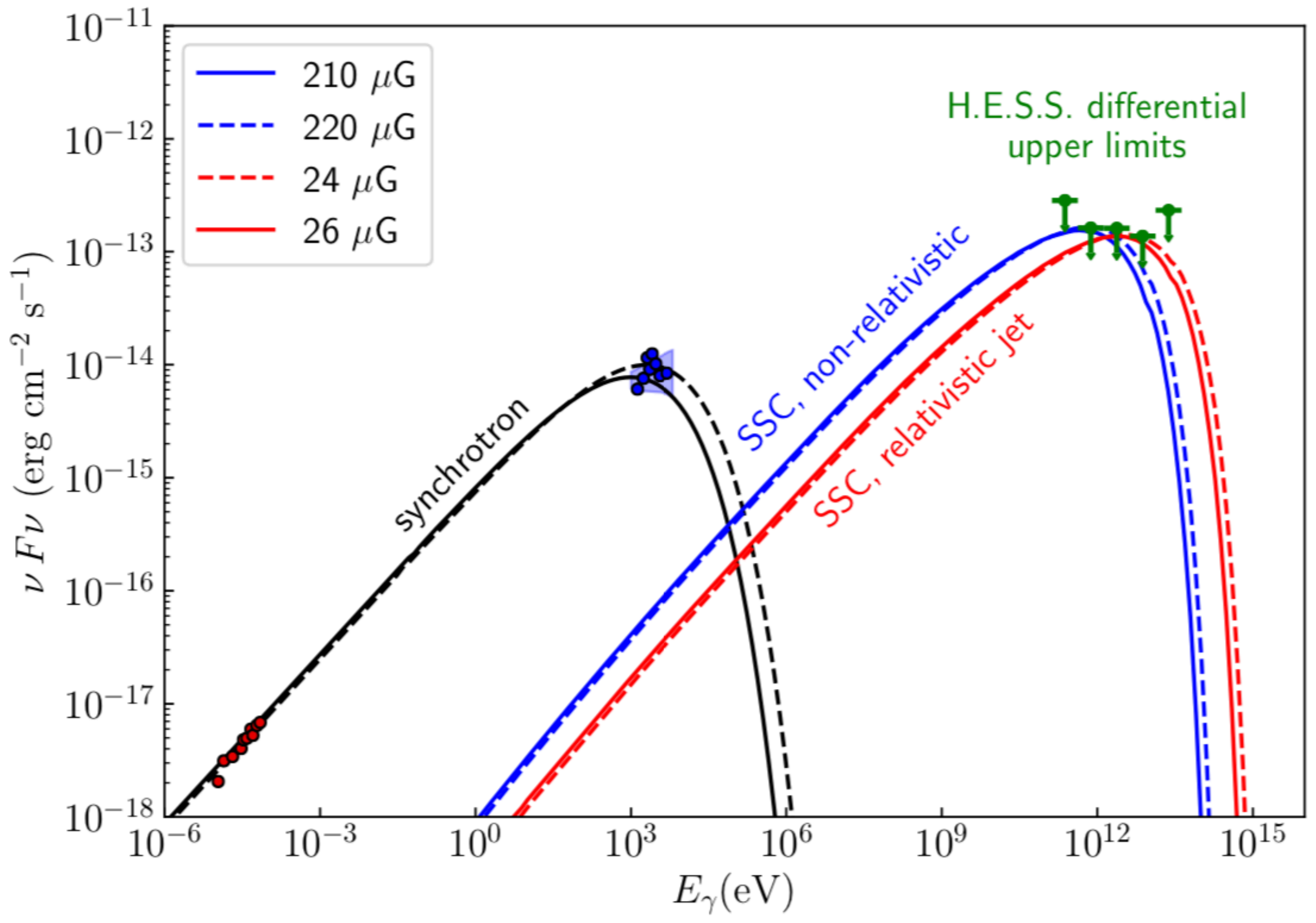
- HAWC follow-up observations
  - Short term: GW170817 entered in FoV 8h after merger, for 2.03h.
    - No signicant emission was detected, ULs: 1.5×10^{-8} erg cm^{-2} s^{-1} (100GeV - 1 TeV)
  - Long term: Flux limits derived above 40 TeV over 9 consecutive logarithmic time windows.



Galván, A. et al., ICRC2019. Vol. 36. 2019.
Martinez-Castellano, I et al. ICRC 2019, arXiv:1908.06122

- H.E.S.S. long-term follow-up observations
  - Observation campaign during the peak at X-ray and radio
  - Constraining the magnetic field by connecting the synchrotron and SSC emission



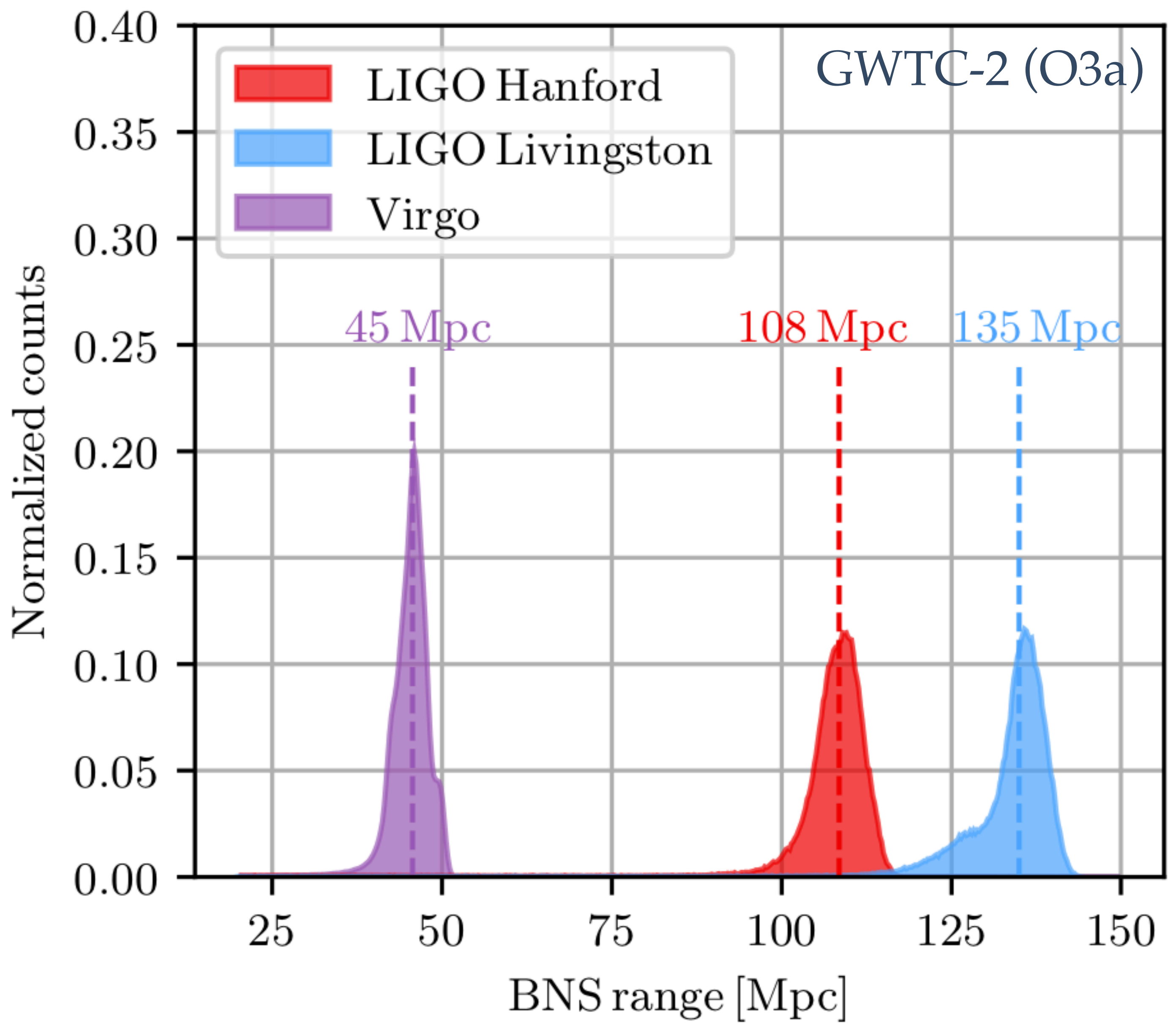


Abdalla, H., et al., *ApJL* 894.2 (2020): L16.

Observation run O3: consolidation of gravitational wave astronomy

- A (little less than a) year of observations due to Covid-19 (April 2019 - end March 2020)

- A total of 56 online detection candidates after 24 retractions (gracedb.ligo.org)
  - Several possible source probability: BBH(38), BNS(6), BH-NS (5), MassGap (4), Terrestrial(3) events
  - No electromagnetic counterpart associated+confirmed to any of these events



- Some results from O3 :
  - Catalog papers GWTC-2 (O3a): 39 candidates (extra 13 compared to online searches) — Abbott, R., et al. *PRX* 11.2 (2021): 021053
  - Binary systems with largely asymmetric masses: GW190412, GW190814 — Abbott, R., et al., *PRD* 102.4 (2020): 043015; Abbott, R., et al. ApJL 896.2 (2020): L44
  - NS-NS candidates: GW190425 (Total Mass ~3.4 $M_\odot$) — Abbott, R., et al., *ApJL 892.1 (2020): L3*
  - Intermediate-mass black holes (IMBHs): GW190521(Total Mass of 150$M_\odot$) — Abbott, R., et al., PRL 125.10 (2020): 101102
  - Recent publication : first two BH-NS systems: GW200105 (8.9+1.9 $M_\odot$), GW200115 (5.7+1.5 $M_\odot$) — Abbott et al. ApJL, 915 (2021), L5

O3: observations of IACTs

MAGIC

- Semi-automatic strategy, with two cases of interest:
  - Follow-up of well localized GW (~ 10° at 90% CL) with good observation conditions
  - Follow-up of identified transients by other facilities and shared through GCN & ATels

Miceli, D. et al. ICRC 2019, arXiv:1909.03971.

VERITAS

- Observation strategy consisting on short exposures of 5 minutes, using the Greedy Traveling Salesman algorithm

GW ID	Delay [hrs]	Compact binary coalescence type	Prob. covered	VERITAS obs. [hrs]
S190412m	24.1	BBH:> 99%	~ 50%	3.1
S190425z	1.3	BNS:> 99%	~ 2%	0.9
S190426c	17.6	NSBH:60%, MG: 25%, BNS:15%	~ 20%	2.5
S190707q	20.3	BBH:> 99%	~ 30%	3.0

Santander, M. et al., ICRC 2019, PoS 358

H.E.S.S.

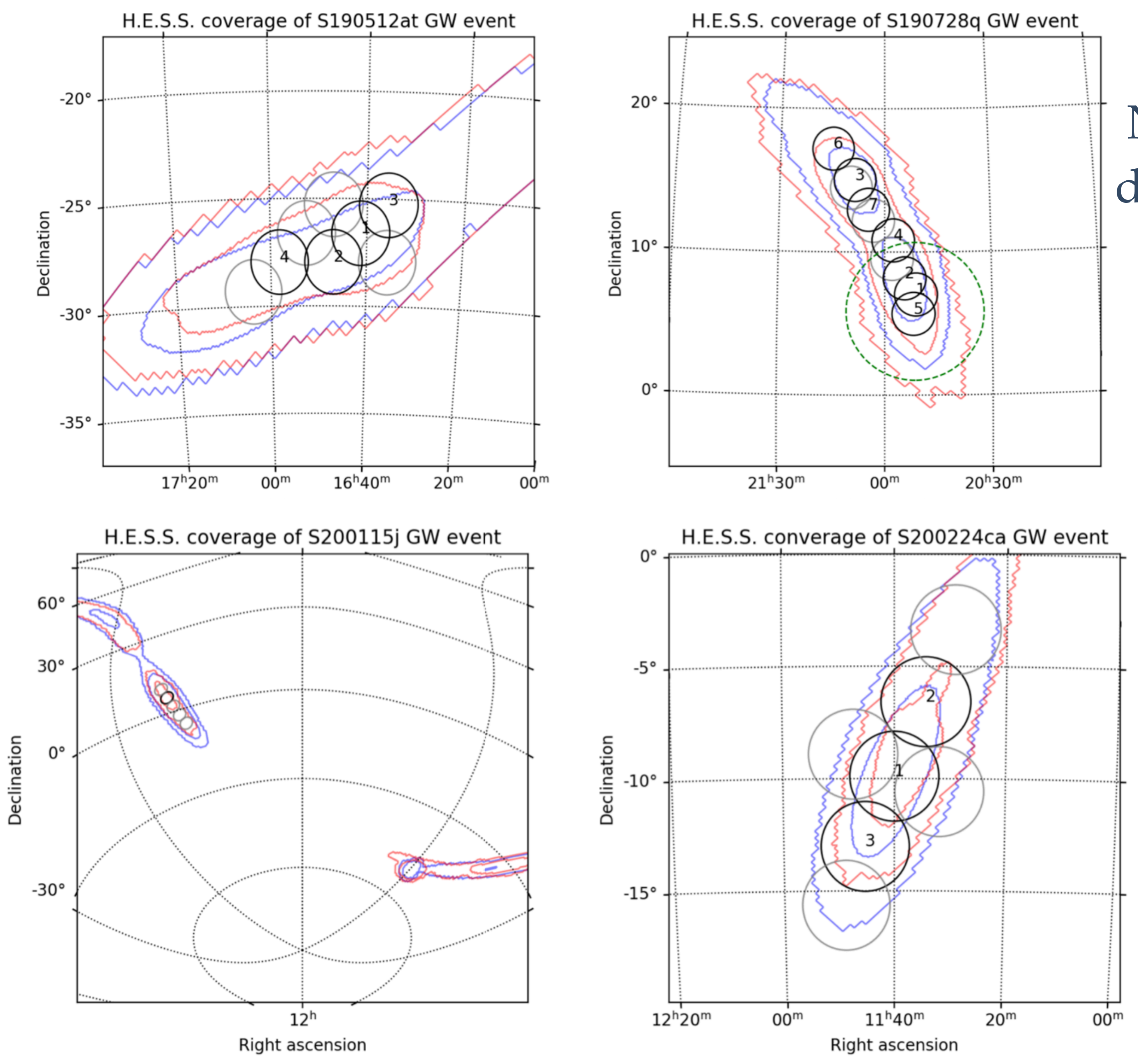
- Automatic response with scheduling algorithms which maximise the total probability covered with observations
  - Use of galaxy catalogs

BBH
Favorable zenith angle
$P_{covered}$ ~21%

BBH
Neutrino alerts during the same day
$P_{covered}$ ~64 %

NSBH
Bad weather
$P_{covered}$ ~2.4% / 25%

BBH
Bad weather
$P_{covered}$ ~70%



Ashkar, H. et al., (2020), JCAP, 2021.03 (2021): 045.

O3: observations with particle detectors

HAWC

- Automated, low-latency response search of clusters of gamma-rays in the field-of view **(~2 sr)** during the entire O3 run
  - Timescales (0.3 -100s), in steps of 20%

- Follow-up of all the events during O3 in the instrument's FoV
  - Issue GCN Circulars with the results of these analysis, even if no candidate is found.
  - Special focus on events whose progenitor contains NS
  - **No significant emission detected in any of these searches**
    - Analysed the 25% (S190425z), 28% (S190426c) and 4% (S190510g)
    - S191216ap BBH (99%): Subthreshold trigger (4.6 sigma pre-trials, 10 s search) found (GCN #26472)
      - IceCube neutrino in coincidence
      - Cross-match with galaxy catalogs to look for candidates => Follow-up by MASTER, Subaru, VLA…
      - No candidate was identified in other wavelengths

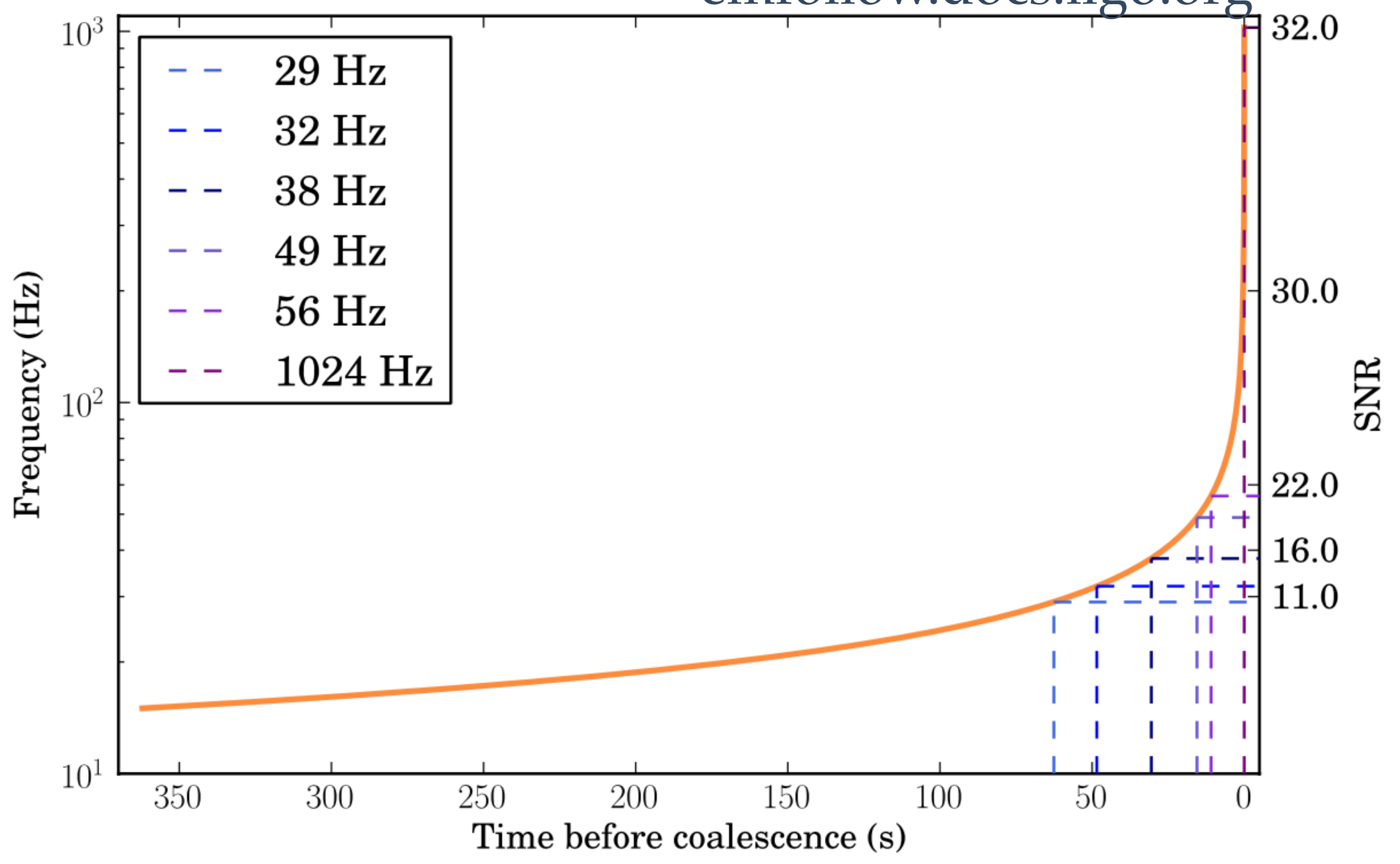
Martinez-Castellanos, I et al. ICRC 2019, arXiv:1908.06122

The HLVK observing run O4

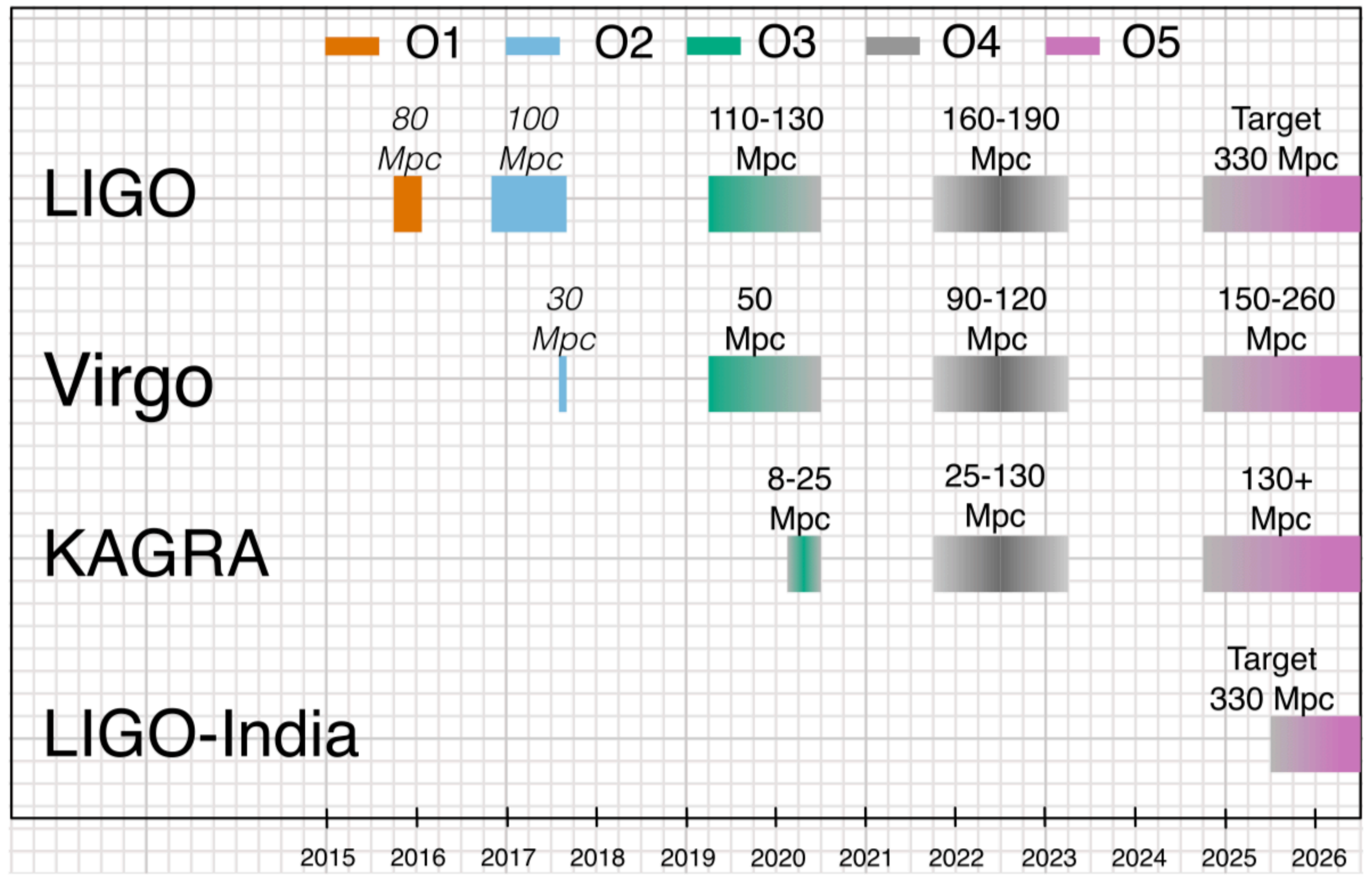
- Next observing run of Virgo-LIGO-Kagra is O4
  - Planned to start not before June 2022
  - 1-year observing run

- Substantial improvement in the sensitivity yield to:
  - Increase of the horizon -> Number of detection
  - Larger signal-to-noise ratio for closer events
    - Better localization
    - Accumulate large part of the signal before the merger => Early Warning alerts

emfollow.docs.ligo.org



The time evolution of the gravitational-wave frequency and the cumulative SNR for a GW170817-like BNS system.



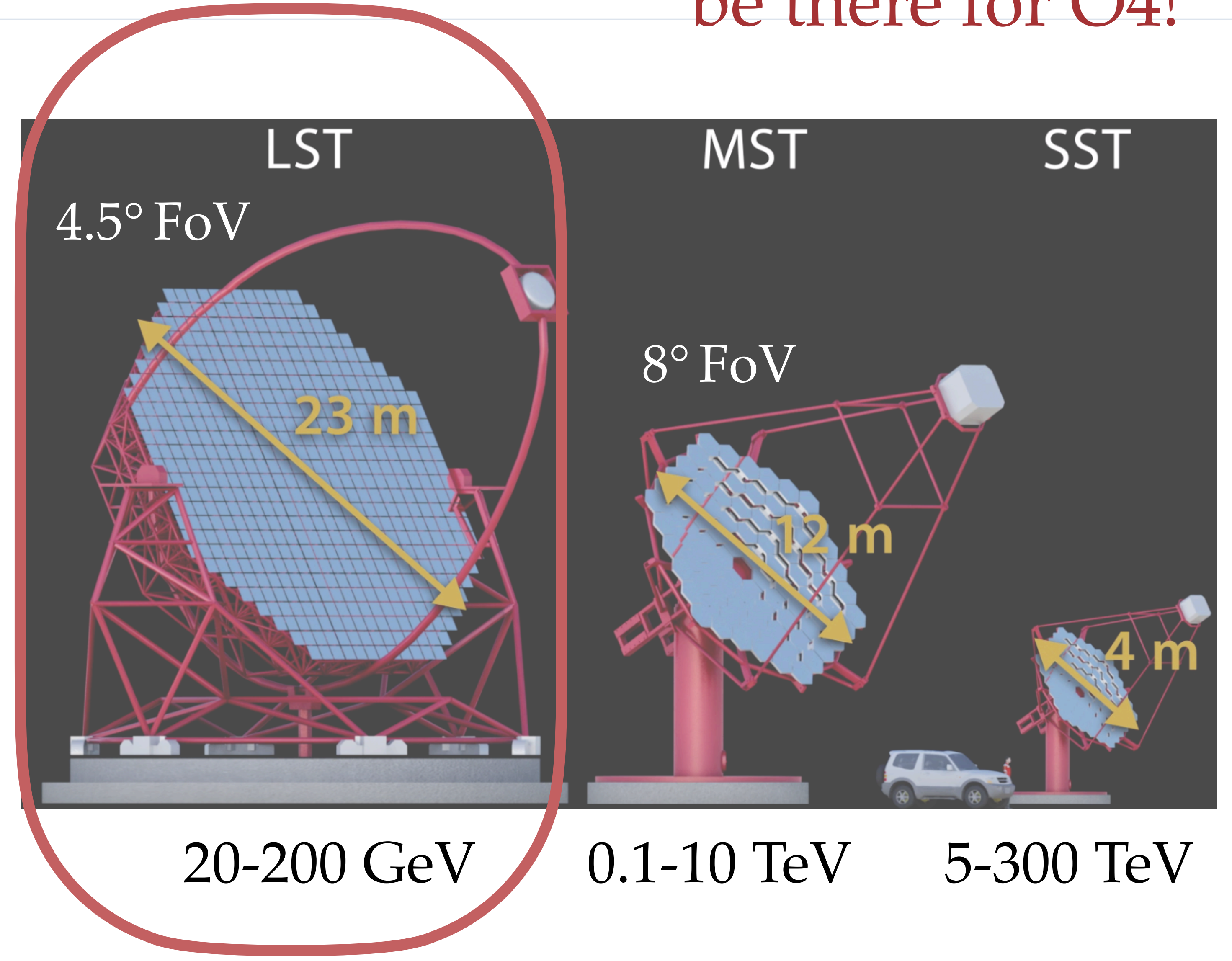
Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
Observation run	Network	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

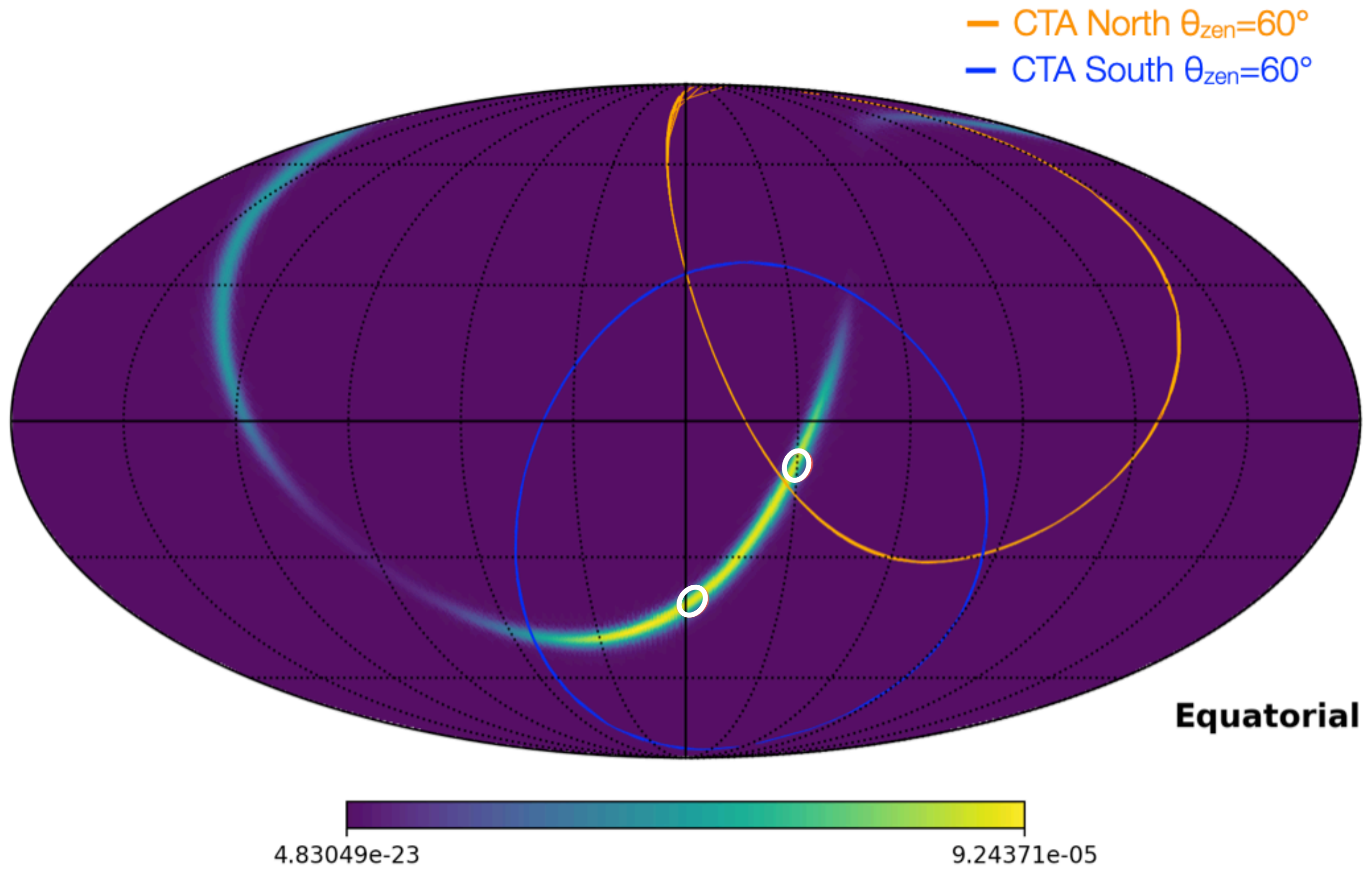
Abbott, B. P., et al.. 23.1 (2020): 1-69.

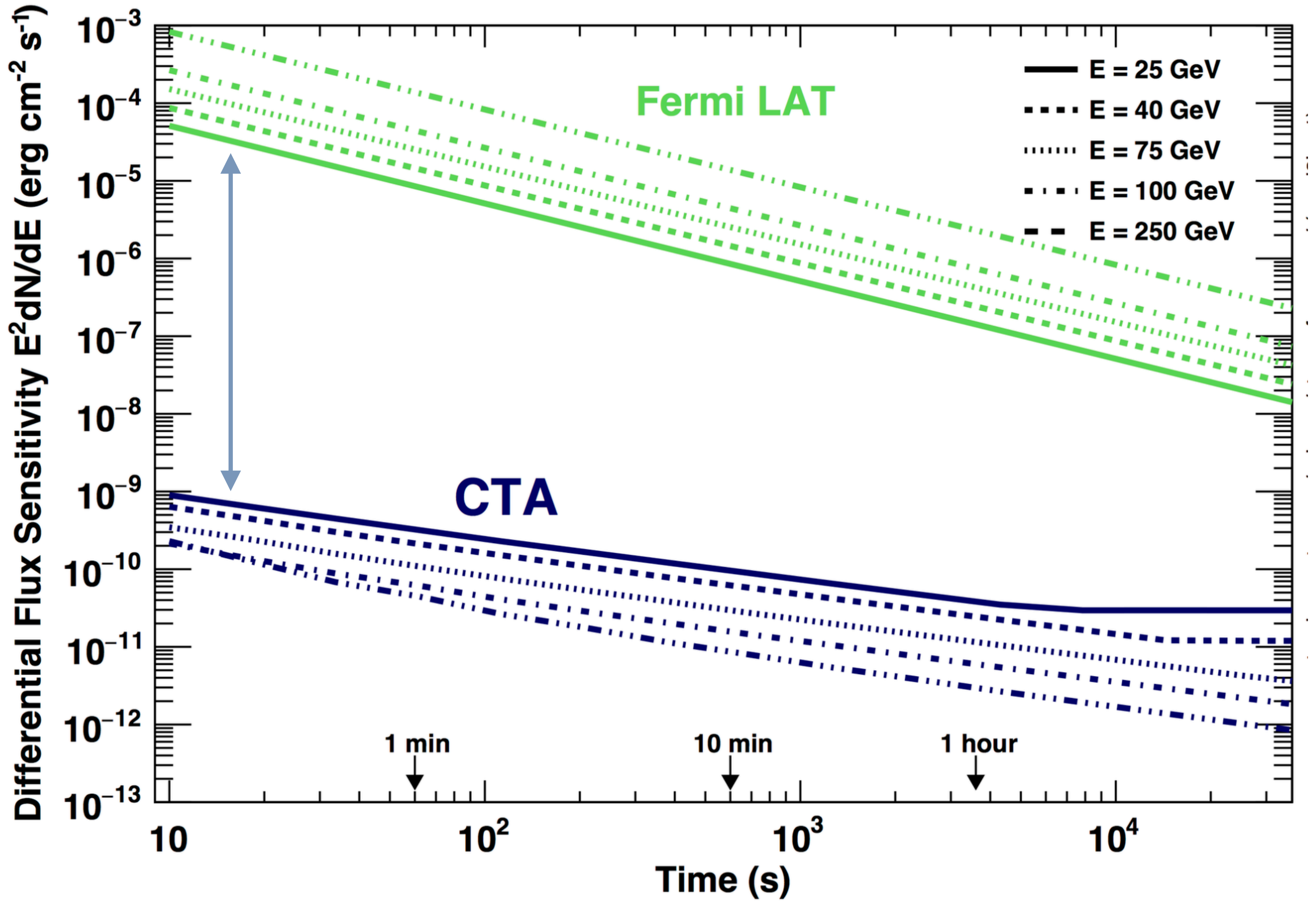
Next generation IACT: The Cherenkov Telescope Array

LST-1 currently taking data, will be there for O4!

- Key points on GW counterpart searches of CTA
  - 5-10x sensitivity and collection area
  - Large FoV of 8°
  - Rapid slewing of the telescopes (~20 s)
  - Energy coverage down to ~20 GeV and up to ~300 TeV
  - Two-hemisphere coverage thanks to North-South sites







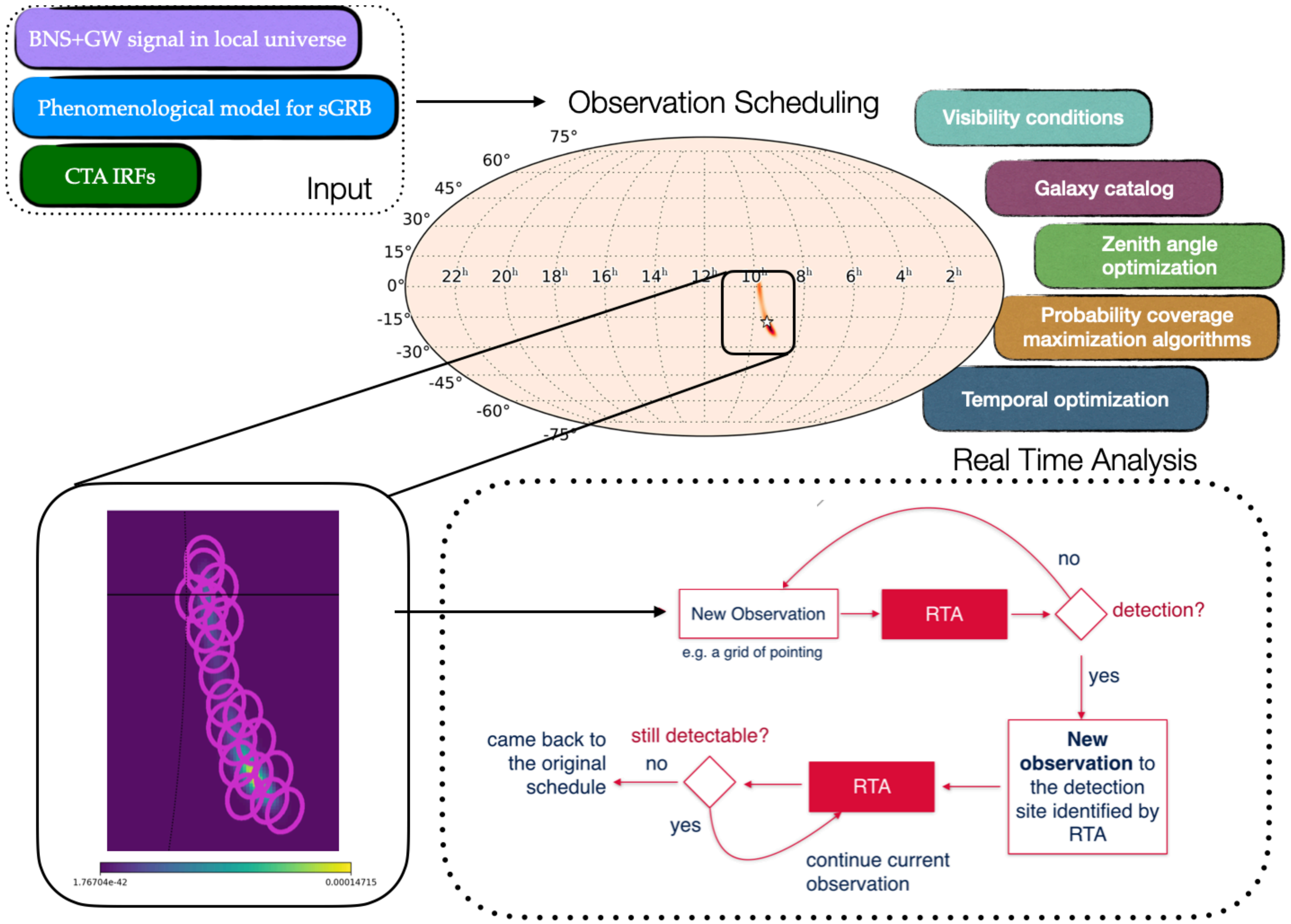
Gravitational Wave follow-up with CTA

- First studies on the detectability of joint sGRB-GW at VHE:
  - Bartos, I., et al. , *MNRAS* 443.1 (2014): 738-749 +MNRAS 477 (2018) 639-647
    - *CTA may be capable of efficiently detecting late-time high-energy gamma-ray emission from short GRBs*
    - Survey mode+GRB090510-like source+300Mpc, Syn+IC
    - Joint rate of ~**0.03 yr-1**
  - Patricelli B. et al., JCAP 05 (2016) 056 + JCAP 05 (2018) 056
    - Exposure is chosen as the time needed to get 5 sigma post-trials signal

$$\int_{T_j}^{T_j+t_j^{obs}} F(t)dt \geq F_s(t_j^{obs});$$

    - Survey mode+ GRB 090510-like source to 30/100 GeV
    - Joint rate of ~**0.001-0.08 yr-1** ($E_{iso}10^{49}$-10^{52} erg, 100 GeV cut-off)

- Detailed simulations of joint GRB-GW detections ongoing:
  - Study the prospects for joint GRB-GW detections with CTA
  - Optimize observation strategy



Seglar-Arroyo, M. et al.. 36th ICRC, PoS790, 2019
Patricelli et al. ICRC 2021
CTA consortium, in preparation

Conclusions

- Really exciting times ahead for joint detections of GW-sGRB
- First proof of the connection BNS-sGRB with GW170817-GRB170817A
- GW network will improve their sensitivity in the coming years: O4, O5, post-O5, Einstein Telescope/Cosmic explorer…
  - Crucial impact on number of events and localization uncertainty regions
- Gamma-ray observatories, current and future generations:
  - Implementation of optimized observation strategies in **IACTs**, large sky coverage in **ground particle arrays**.
  - Short-term and long-term GW follow-up campaigns in place
- Recent detections at VHE gamma-ray from GRB by H.E.S.S. and MAGIC are a major milestone in GRB physics
  - First three detections of lGRBs GRB180720A, GRB190114C, GRB190829A and hint of sGRB detection of GRB160821B
  - Promising expectations for GRB detection in the future with IACTs and particle detectors.
- Lots of open questions about the VHE GRB emission in sGRB/lGRB **being tackled**!
  - Emission mechanisms, progenitors, physics of the jet, particle acceleration…

Stay tuned!

Thanks!

Back-up

Early Warning alerts

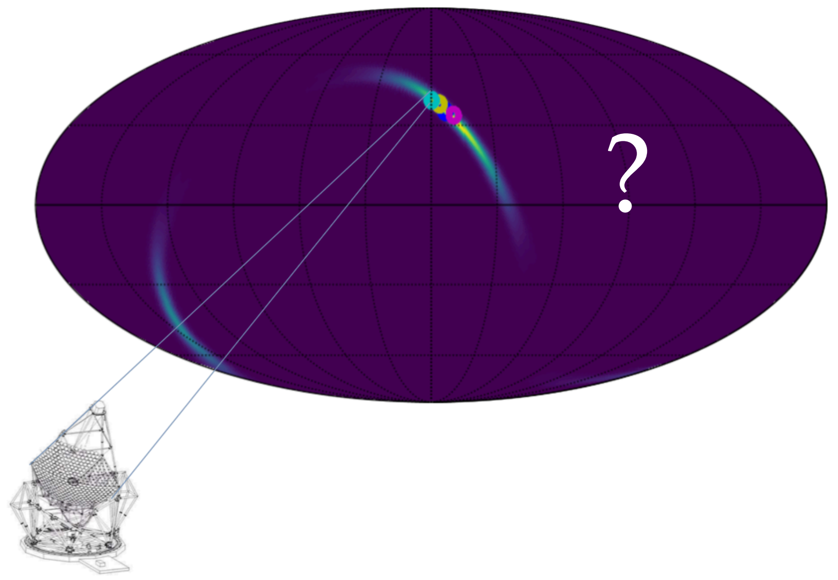
- Shorten to its minimum the latency between the various steps of the chain, before the alert is sent.
- System under commissioning during O4 => The progress on shortening the latency for early warning alerts in the different steps of the chain may be used for 'standard' alerts in the future
- Caviats: end of the inspiral contributes a lot to the SNR. These last seconds are key to cross-match h(t) signal seen in different IFO
  - Big impart in localization

- Expectation:
  - only 5-30% will be amenable for sending early warning alerts.
  - At 60 s before merger, **one event per year** is expected to be localized to within 400 deg^2.
  - At 30 seconds before merger, at least **one event per year** is expected to be localized to within 40 deg^2 and **~4 events per year** are expected to be localized to within 400 deg^2.
  - By 10 seconds before merger, **~10 events per year** are expected to be localized to within 400 deg^2.

<table>
<tr><th>Final SNR</th><th>11</th><th>18</th><th>25</th></tr>
<tr><td>Distance</td><td>250 Mpc</td><td>210 Mpc</td><td>160 Mpc</td></tr>
<tr><td>Frequency</td><td colspan="3">Localization accuracy (90% credible area)</td></tr>
<tr><td>29 Hz</td><td rowspan="3">Not detected</td><td rowspan="2">Not detected</td><td>12000 deg²</td></tr>
<tr><td>32 Hz</td><td>10000 deg²</td></tr>
<tr><td>38 Hz</td><td>9200 deg²</td><td>8200 deg²</td></tr>
<tr><td>49 Hz</td><td>2300 deg²</td><td>1000 deg²</td><td>730 deg²</td></tr>
<tr><td>56 Hz</td><td>1000 deg²</td><td>700 deg²</td><td>250 deg²</td></tr>
<tr><td>1024 Hz</td><td>10 deg²</td><td>31 deg²</td><td>5.4 deg²</td></tr>
</table>

https://emfollow.docs.ligo.org/userguide/early_warning.html

Probability selection algorithms



- 2D Algorithm: 2D localization uncertainty region is considered

One-pixel algorithm

Select individual high-probability **pixels** of the GW sky map

Pixels-in-FoV algorithm

Integrate the localization uncertainty in FoV region and select the highest in the ranking

$$P^{\mathrm{FoV}}_{\mathrm{GW}} = \int_0^{FoV_{\mathrm{H.E.S.S.}}} \rho_i d\rho_i$$

- 3D Algorithm: 3D posterior 'GW x galaxy' probability distribution is considered

One-galaxy algorithm

Select individual high-probability **galaxies**

Galaxies-in-FoV algorithm

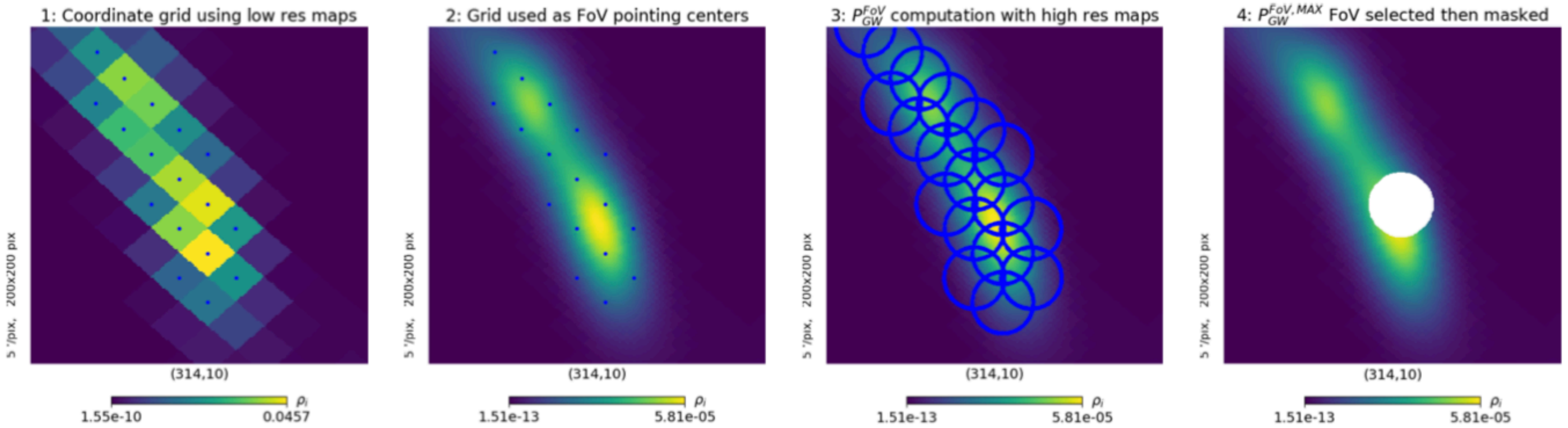
Integrate the 3D posterior 'GW x galaxy' probability distribution in FoV region and select the highest in the ranking

$$P^{\mathrm{FoV}}_{\mathrm{GWxGAL}} = \int_0^{FoV_{\mathrm{H.E.S.S.}}} P^{i}_{\mathrm{GWxGAL}} dP_{\mathrm{GWxGAL}}$$

The selection of regions of probability is iterative => Each region of probability defines an observation
The total pointing pattern defines the coverage of the observations

Ashkar, H. et al., JCAP 2021.03 (2021): 045 arXiv:2010.16172

Gravitational waves follow-up performance paper



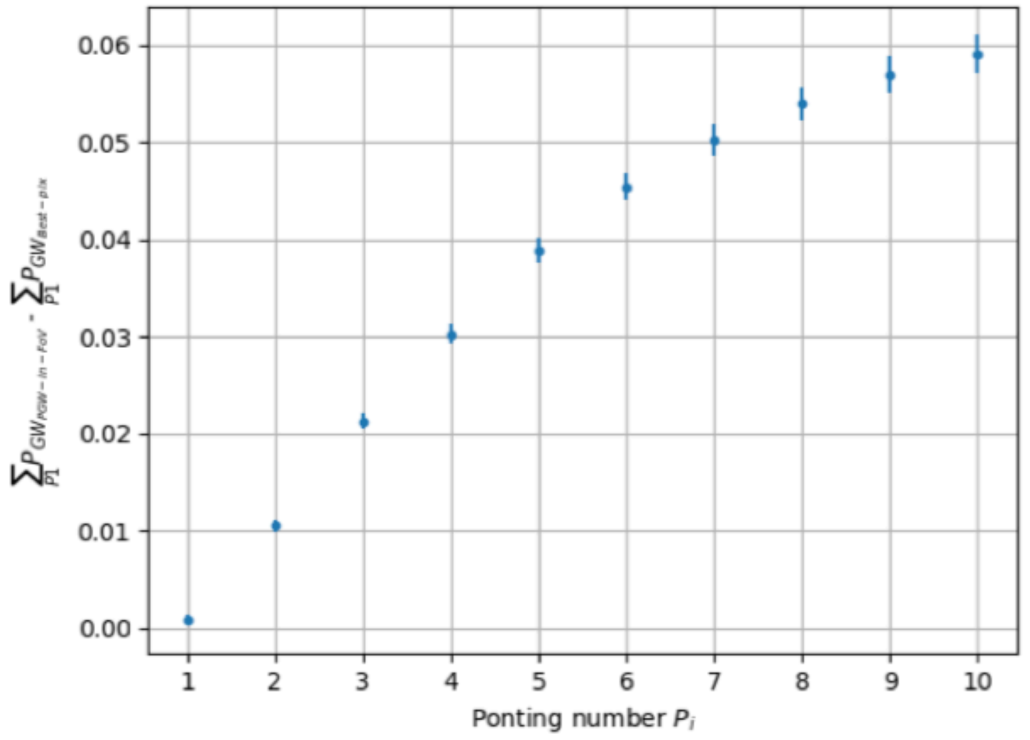


Figure 5. Difference of the cumulative P_{GW} per pointing between `PGW-in-FoV` and `Best-pixel`

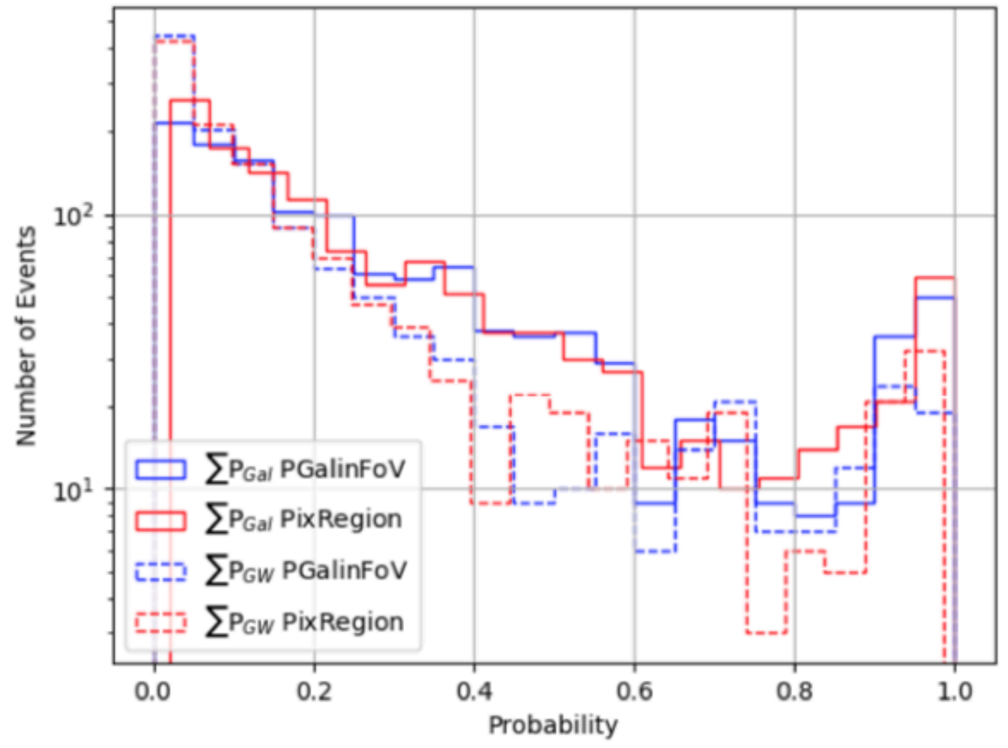


Figure 6. Total P_{GAL} and P_{GW} simulated coverage distributions for `PGalinFoV` and `PGalinFoV-PixRegion`.

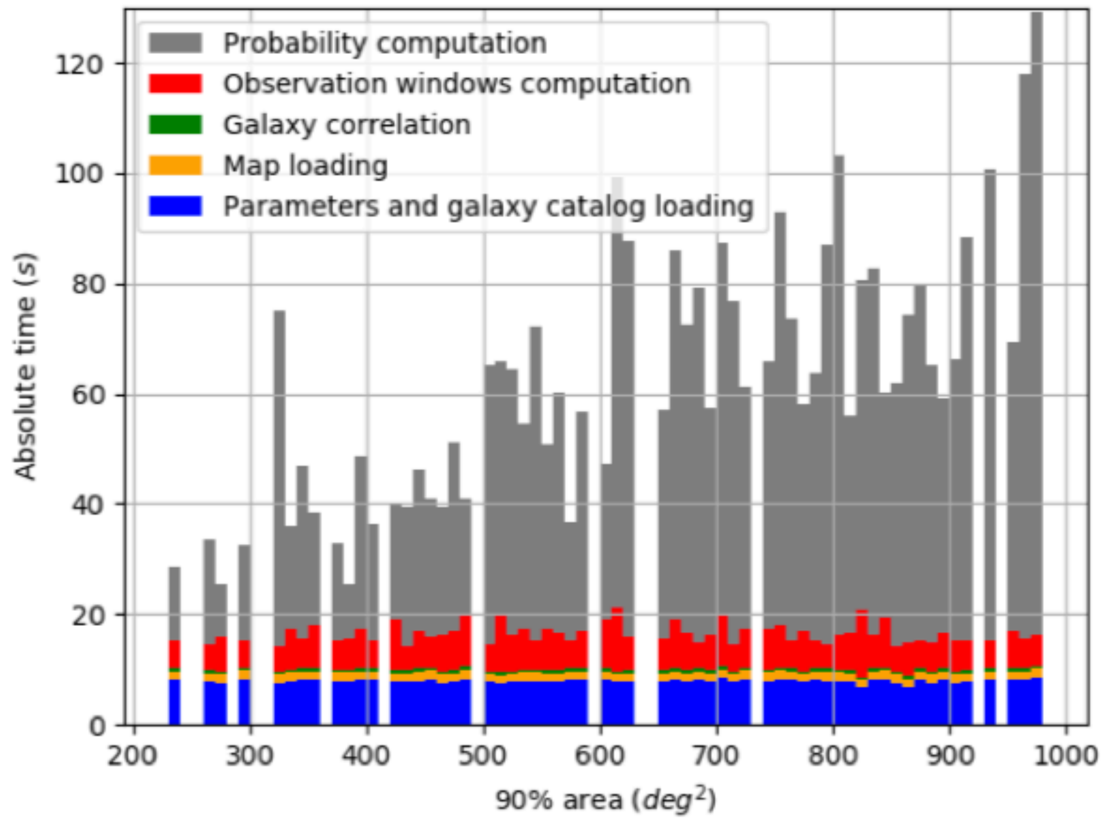
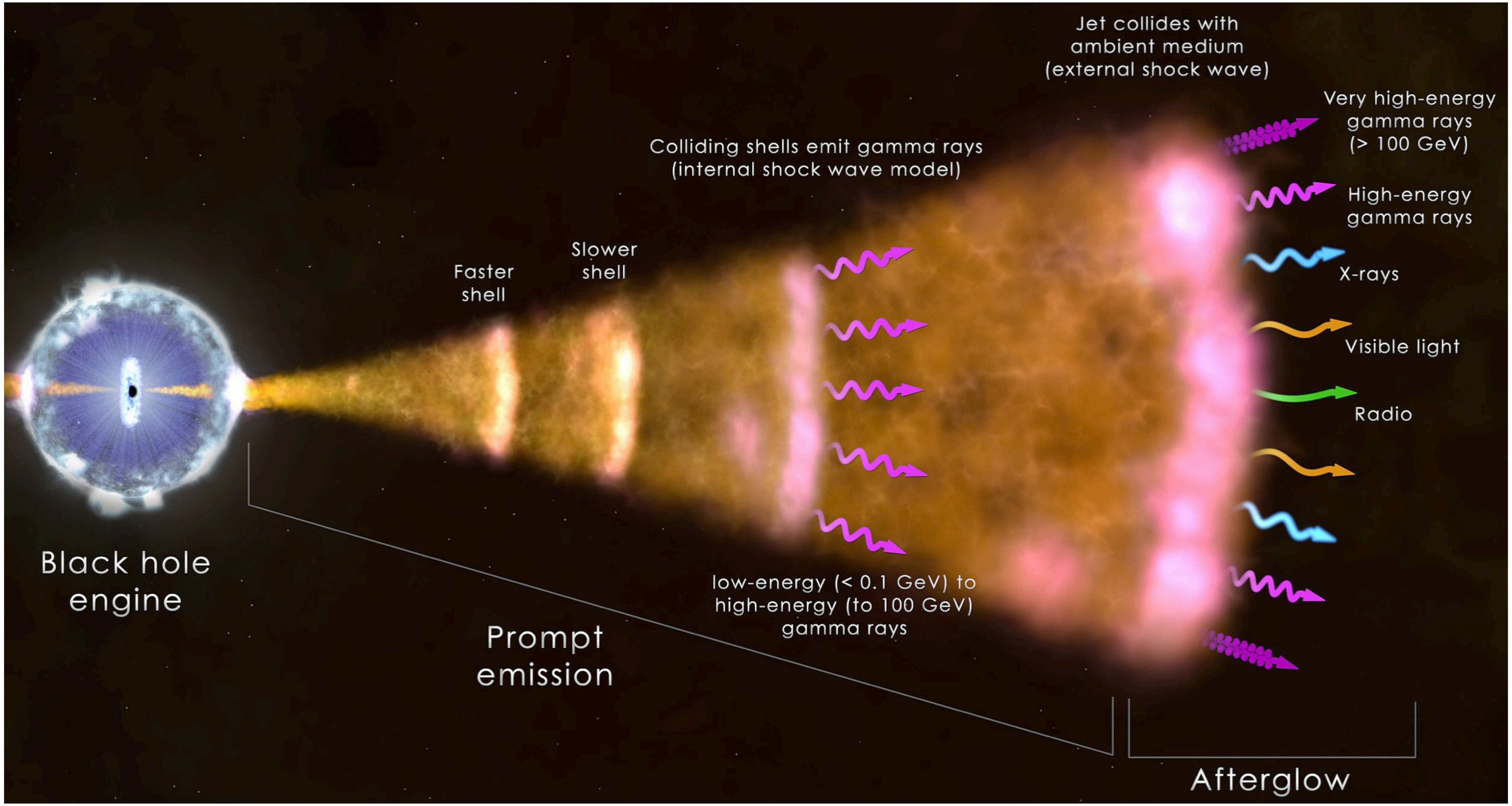


Figure 8. Absolute time for the computation of each step of the PGalinFov algorithm for N_{side} = 512 maps up to an area of 1000 deg^2.

Ashkar, H. et al., JCAP 2021.03 (2021): 045 arXiv:2010.16172

GRB emission

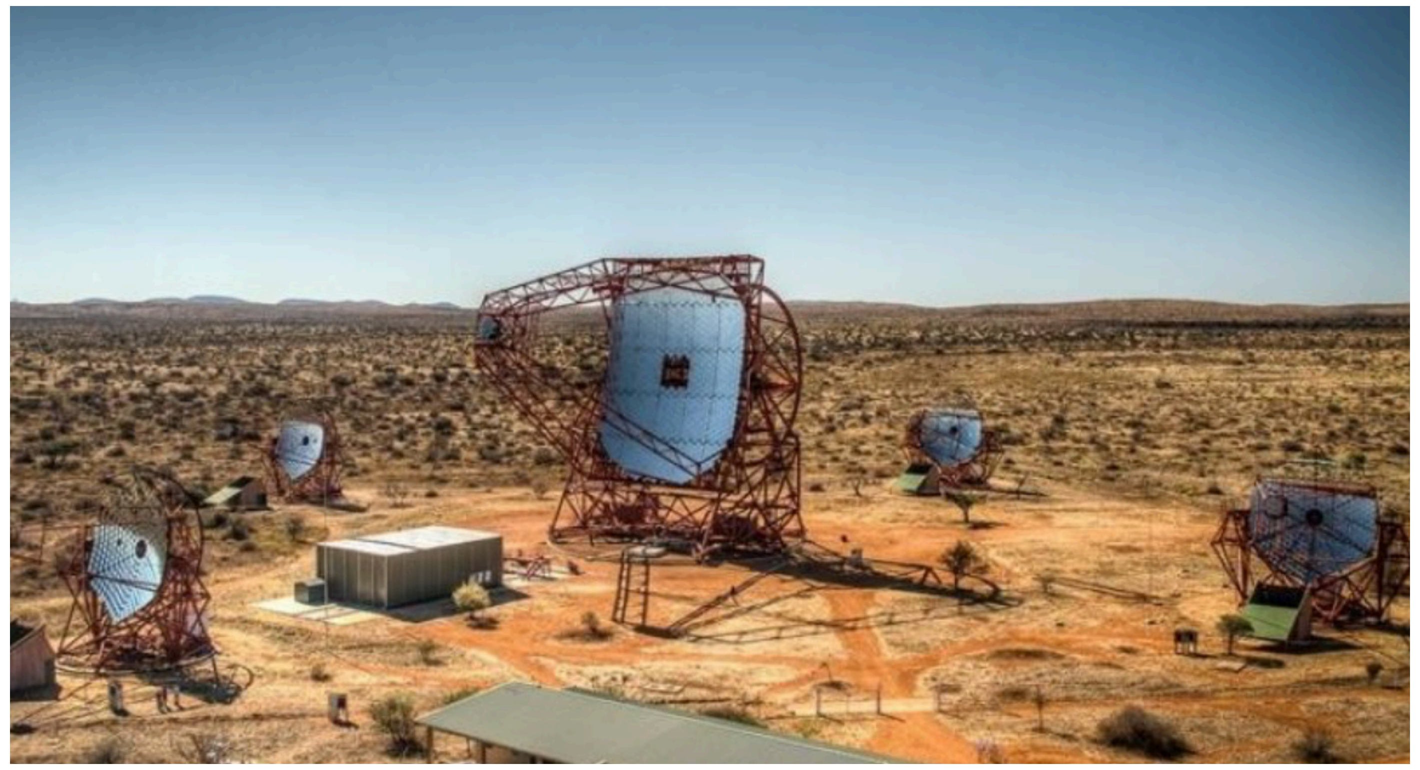


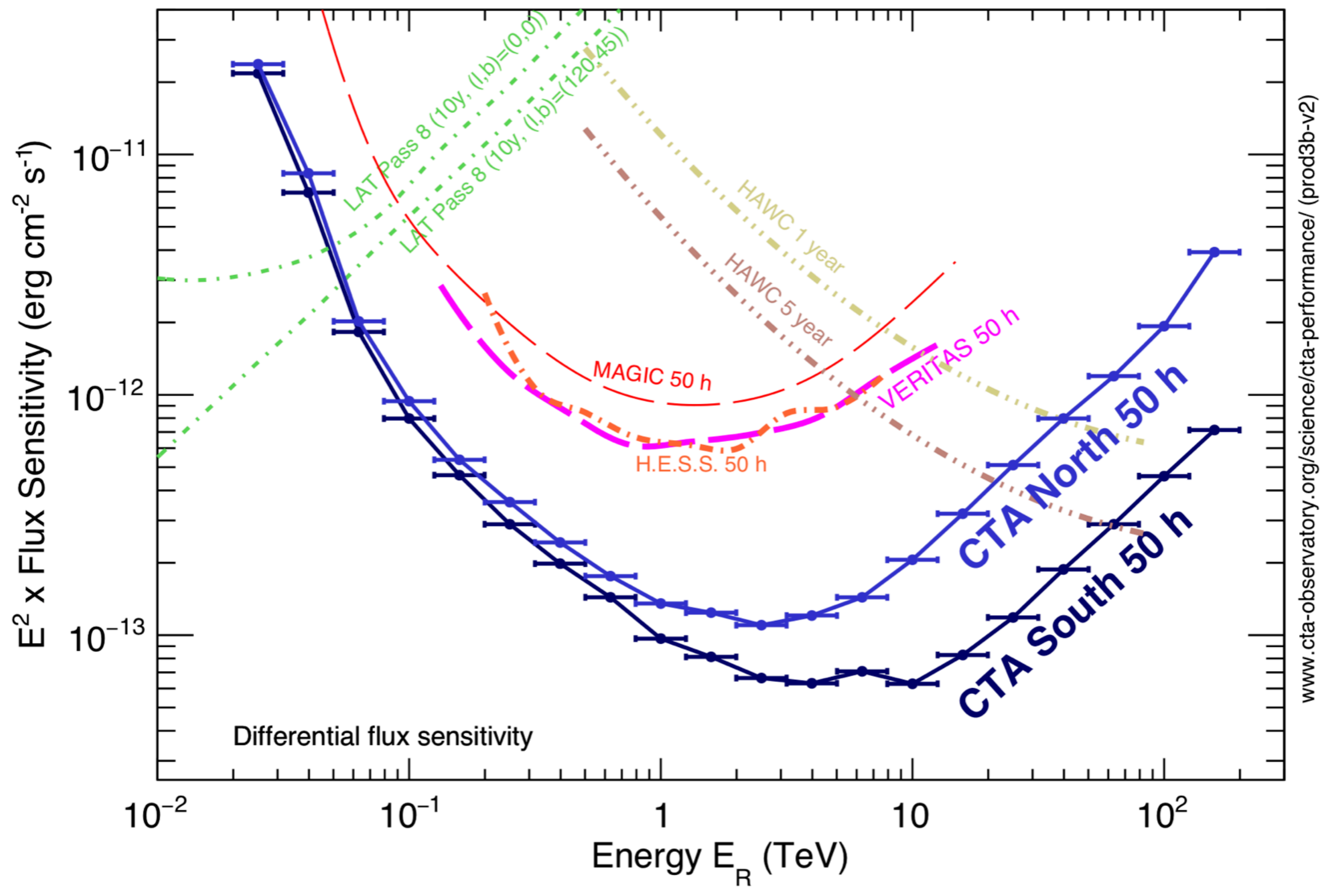
IACTs

MAGIC

VERITAS

HESS

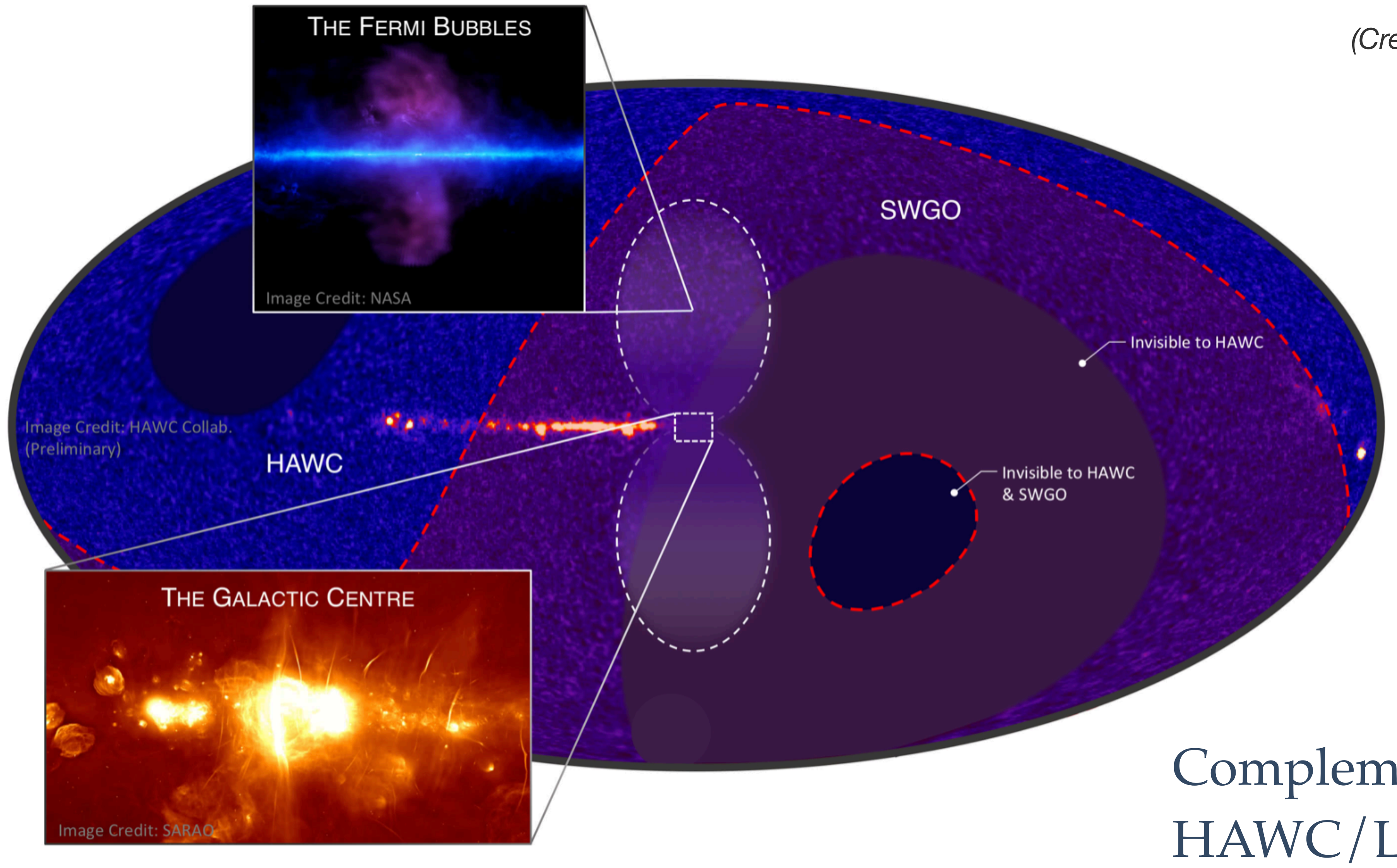




	IACT Arrays
Field of view	3°–10°
Duty cycle	10%–30%
Energy range	30 GeV – >100 TeV
Angular resolution	0.05°–0.02°
Energy resolution	∼7%
Background rejection	>95%

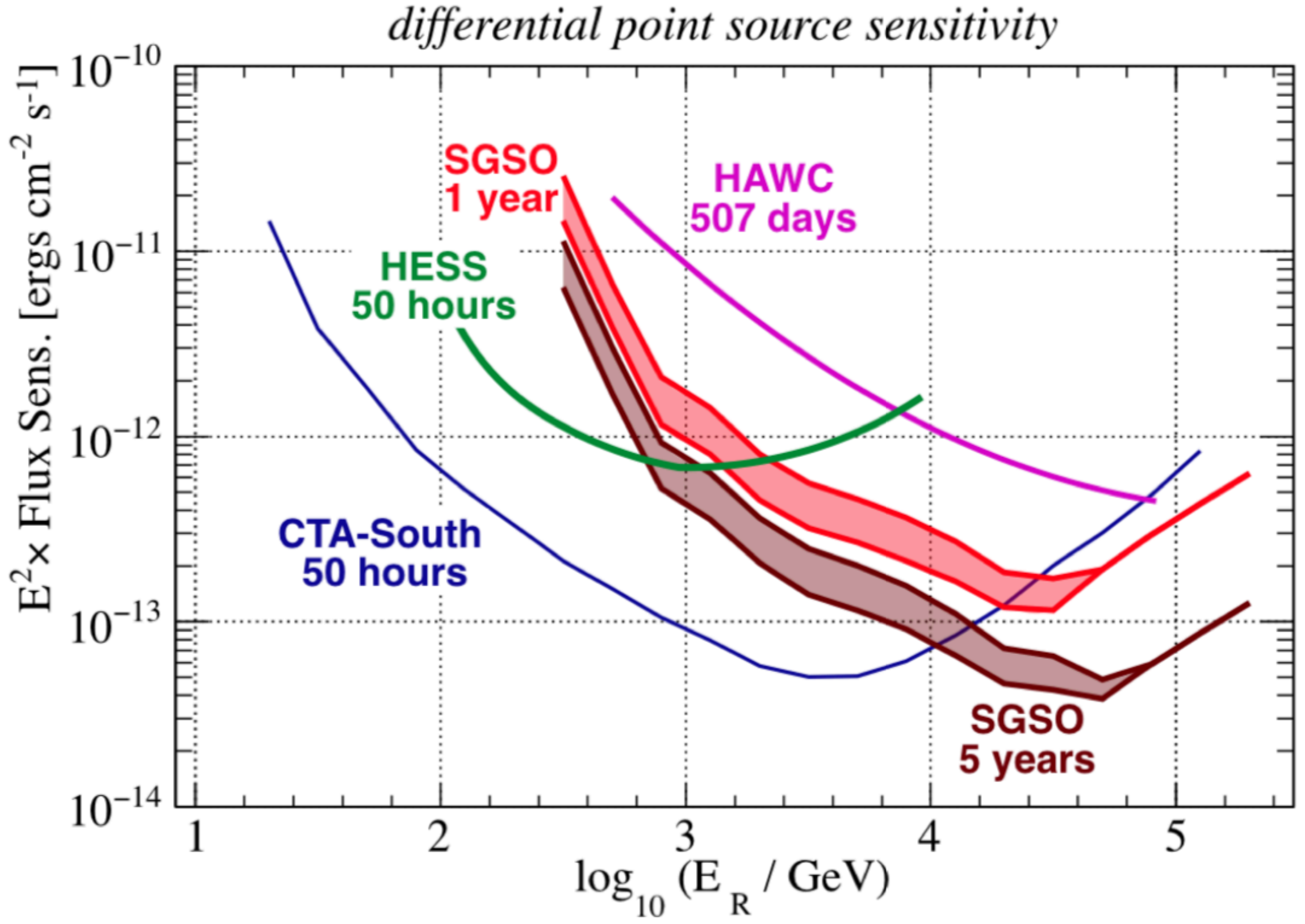
HAWC/SWGO

- HAWC:
  - Design: 300 water Cherenkov tanks 4 PMTs/tank + 350 smaller tanks
  - Inst. FoV of 2sr (1/6 sky)
  - 95% uptime
  - Energy range: 0.1-100 TeV



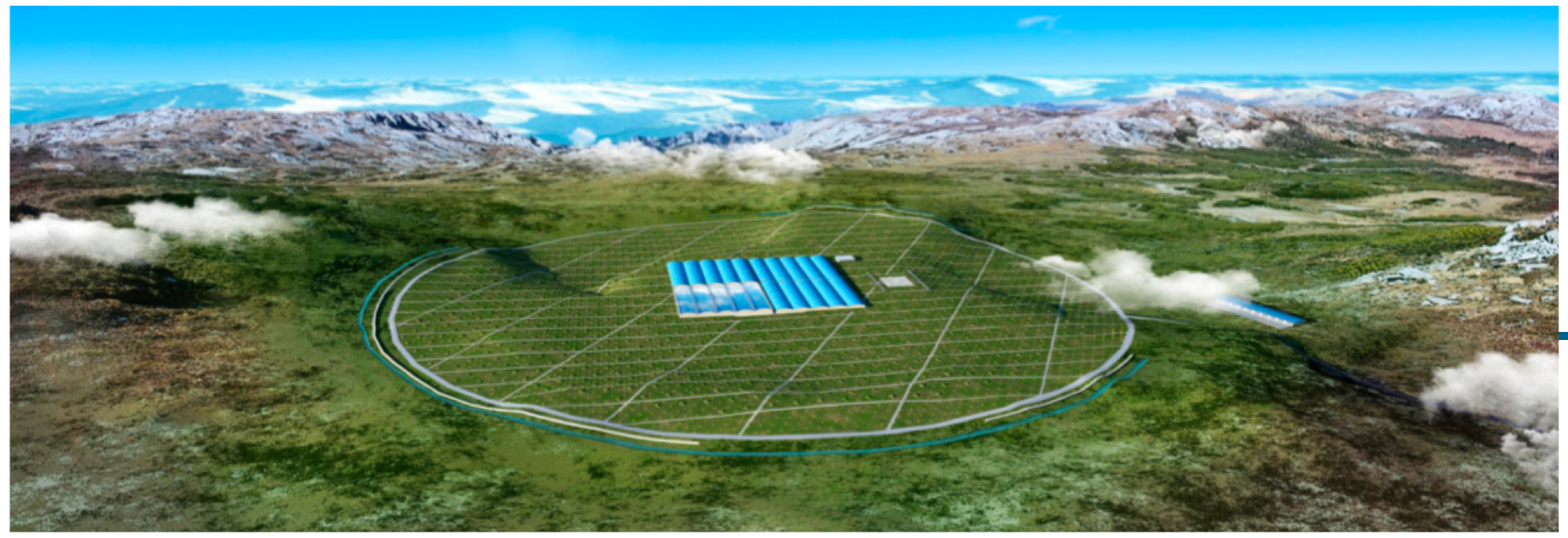
(Credit: Richard White, MPIK)

Complementarity between HAWC/LHAASO and SWGO.



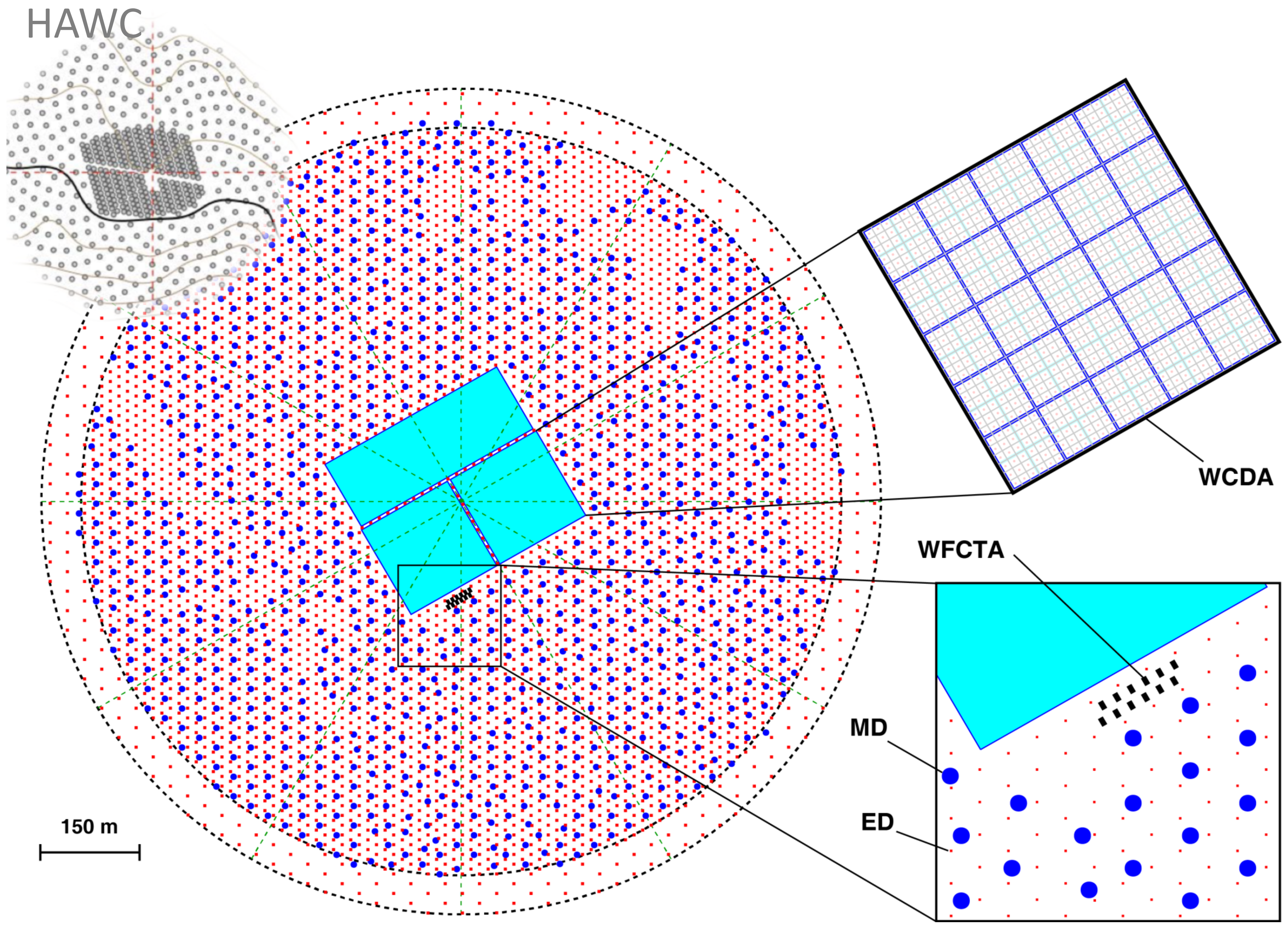
- SWGO: higher, larger, denser!
  - 5000 m. a.s.l.
  - Southern sky
  - Sparse Array: 1000 units covering 221.000 m^2
  - Dense array: 4000 units covering 80.000 m^2

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



LHAASO*

Sichuan, China, 4410 m asl

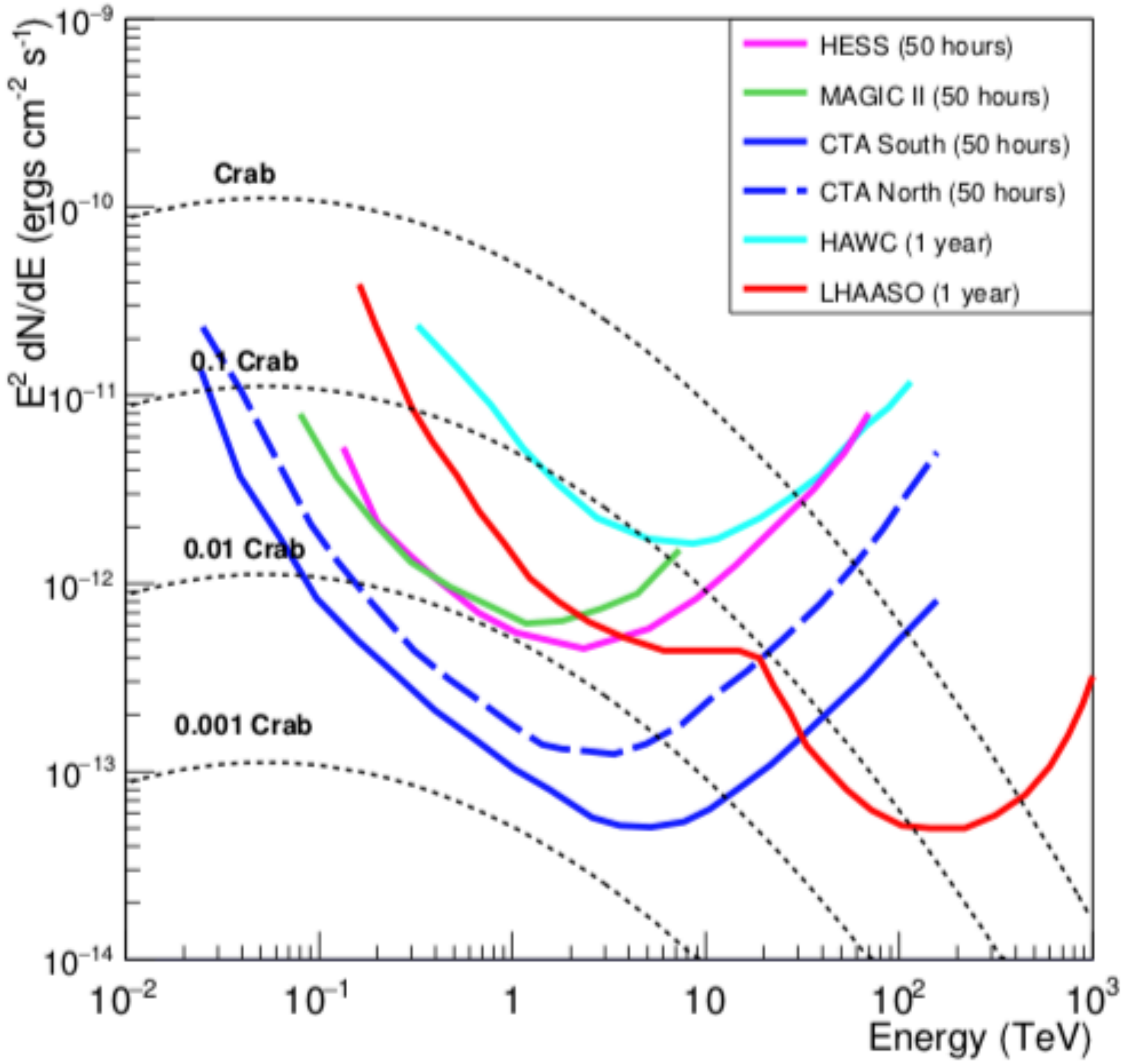


5195 Scintillators
- 1 m² each
- 15 m spacing

1171 Muon Detectors
- 36 m² each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m² each

12 Wide Field Cherenkov Telescopes



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

* Completion of LHAASO construction expected for 2020

Different approaches in joint GW-GRB simulations (1/3)

- Bartos, I., et al. , *MNRAS* 443.1 (2014): 738-749 +MNRAS 477 (2018) 639-647
  - GRB emission as a GRB090510-like source+
    - Use temporal decay and spectral index + Distance= 300Mpc
    - Tstart= 100 s, Tend= 1000s

    - Synchrotron emission by a shocked electron population with power-law index $p = 2.5$
      - Cut-off at 0.1 and 1 TeV.

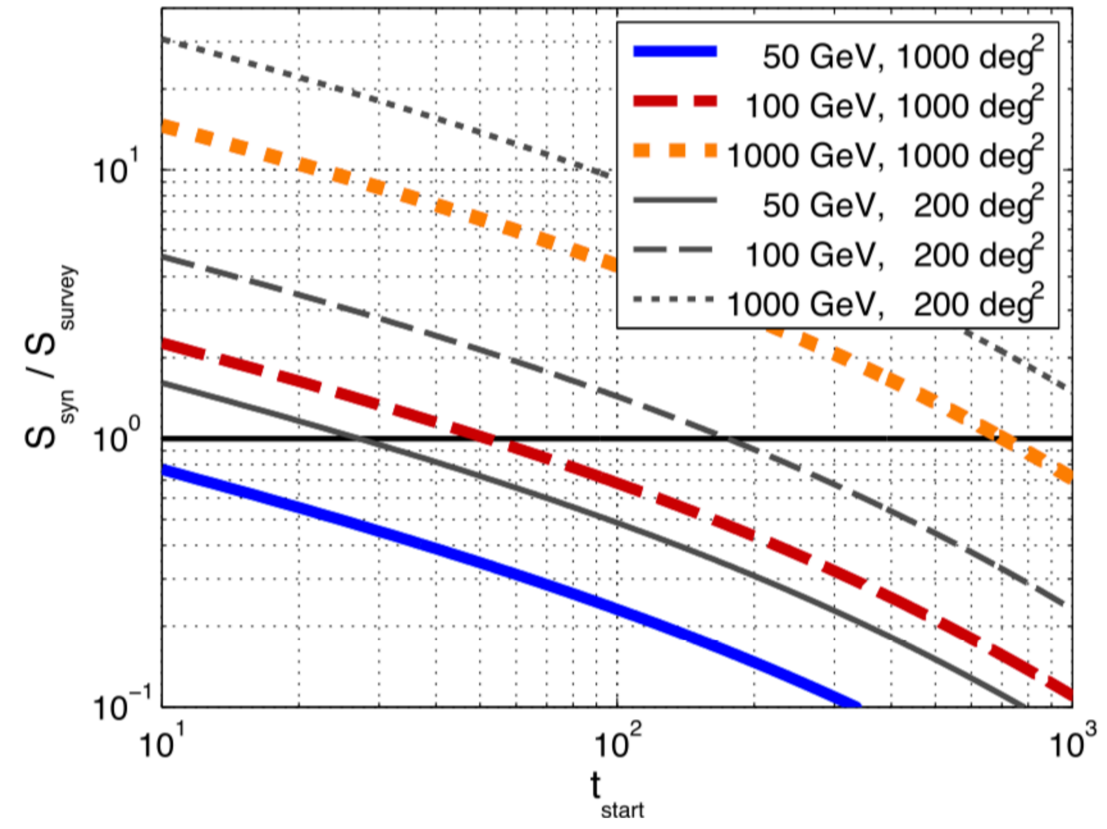
    - SSC emission considered for realistic choise of the parameters n, ε_B (fraction of energy in magnetic fields), ε_e(fraction of energy carried by electrons, E_{kin}(kinetic energy), and electron population power-law index p to describe the synchrotron component and calculate the SSC flux

    - Late rebrightening due to a SSC fordward shock SSC emission in a refreshed shock OR continuous injection

- Scheduler: Survey mode

- About GRB090510 (Abdo et al. 2009).
  - LAT emission from the energetic GRB 090510 10^{53} erg, observed for up to ~200 s
  - z = 0.9 highest photot at 30 GeV
  - temporal index: $\alpha = -1.38$

Detectability as ratio between fluence assuming synchrotron emission vs. sensitivity CTA in survey mode



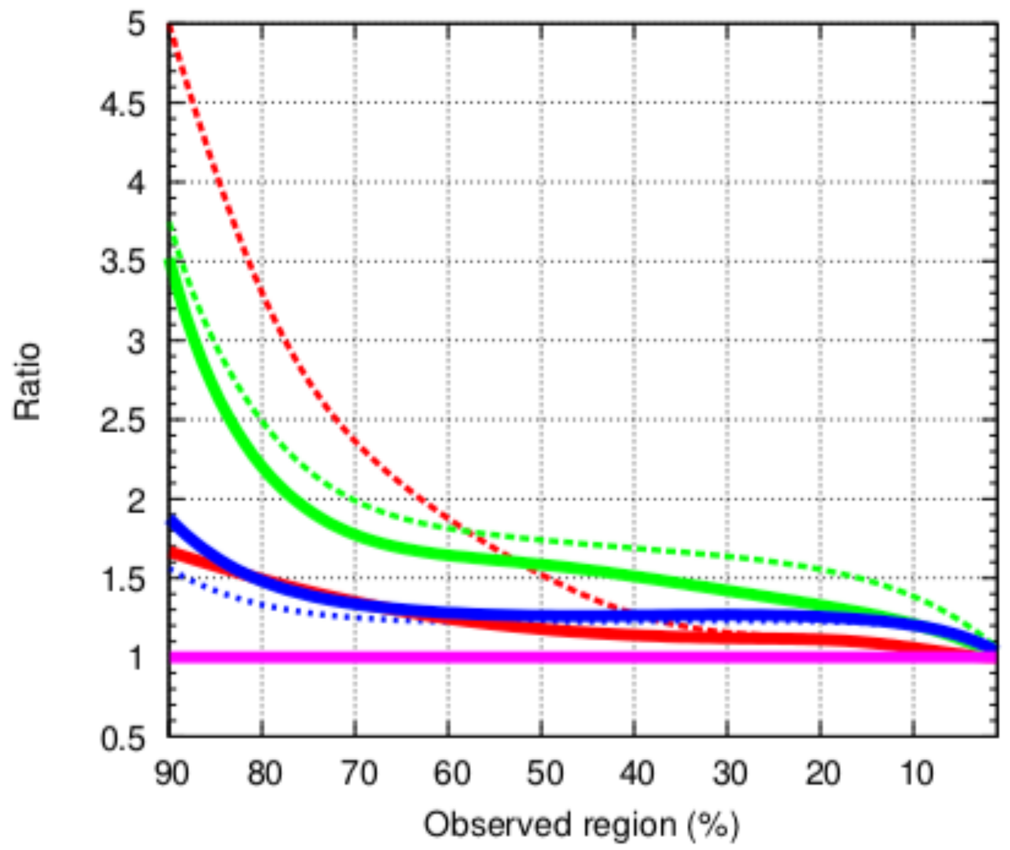
E_{cutoff} (energy cutoff)	50 GeV	100 GeV	1 TeV
S_{det} (CTA) (10^{-9} erg cm^{-2})	80	23	2
S_{survey} (CTA - survey; 1000 deg^2)	800	230	20
S_{survey} (CTA - survey; 200 deg^2)	360	100	9
S_{syn} (GRB 090510-like; D_L = 5.8 Gpc)	50	40	20
S_{syn} (GRB 090510-like; D_L = 300 Mpc)	33 000	28 000	16 000
S_{syn} ($E_{kin} = 10^{51}$ erg; D_L = 300 Mpc)	190	160	90
S_{syn} ($E_{kin} = 10^{51}$ erg; D_L = 300 Mpc; t_{start} = 30 s)	360	310	170
S_{syn} ($E_{kin} = 10^{51}$ erg; D_L = 300 Mpc; $t_{start} = 10^3$ s)	30	25	14
S_{ssc} ($n = 10^{-1}$ cm^{-3})	4400	5300	3700
S_{ssc} ($n = 10^{-3}$ cm^{-3})	20	40	70

Table 1. Fluence values for different emission and detection scenarios presented in the text, in units of 10^{-9} erg cm^{-2}, for different emission cutoff energies E_{cutoff}. CTA-detectable fluences for single pointing and survey mode (S_{det}, S_{survey}) are shown for 1000 s duration, and for 1000 deg^2 as well as 200 deg^2 observable sky area in the case of the survey mode (see Section 4.1). These detection fluences are calculated conservatively from the differential sensitivity of CTA (see text). For the fluence of synchrotron emission (S_{syn}), we take the parameters of GRB 090510, and an observation starting at t_{start} = 100 s after the binary merger and lasting for $t_{duration}$ = 1000 s, except for the parameters stated explicitly in the table. For the fluence of SSC emission (S_{ssc}), we consider isotropic-equivalent GRB energy $E_{kin} = 10^{51}$ erg, an observation with t_{start} = 100 s and $t_{duration}$ = 1000 s, and circumburst number density n stated in the table.

Different approaches in joint GW-GRB simulations (2/3)

- Patricelli B. et al., JCAP 05 (2018) 056 + JCAP 05 (2018) 056
  - GW: GWCosmos
    - Montecarlo simulation pipeline: BNS +detection by GW interferometers.
    - 830 Gpc-3yr-1
    - Local Universe up to 500 Mpc
  - GRB emission as a GRB090510-like source til 30/100 GeV
    - A power-law with exponential cut-off spectrum
    - Spectral index β=-2.1 and two different values for the cut-off energy: 30 GeV and 100 GeV.
    - Correction on the redshift + isotropic energy
    - No limit on the duration (since probably Fermi-LAT is a experimental biased)
  - Exposure of CTA:10000 seconds as max
  - Scheduler: Survey mode + exposure obtained as time needed to get 5 sigma post-trials

Ratio between the CTA coverage with consecutive observations estimated with the strategy proposed in this work and using a constant observing time for each field.

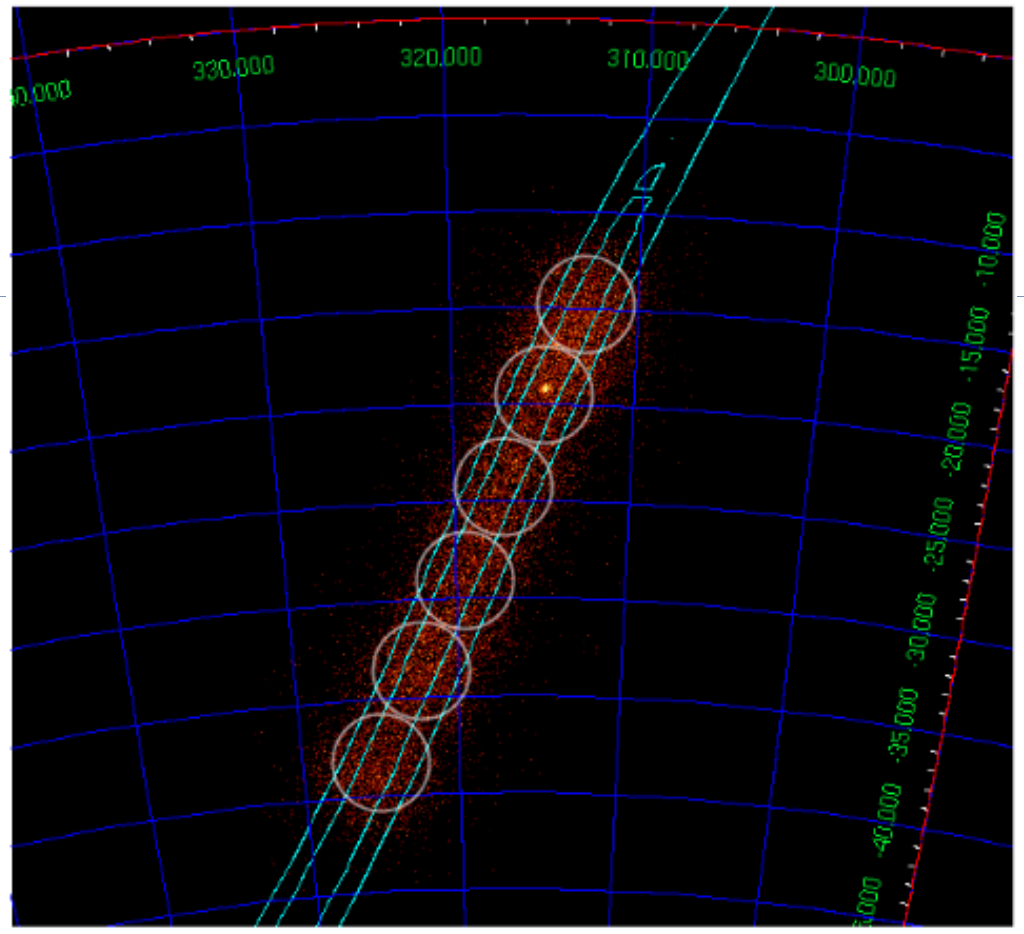


3.5 10^{52} erg (magenta), 10^{51} erg (blue), 10^{50} erg (green) and 10^{49} erg (red); the dotted (solid) lines refer to a cut-off energy of 100 GeV (30 GeV)

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

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

Different approaches in joint GW-GRB simulations (3/3)



- Seglar-Arroyo, M. et al.. 36th ICRC, PoS790, 2019
  - GW: GWCosmos
  - GRB: Purely phenomenological approach based on observations of Fermi-LAT GRBs.
  - Randomly associate Eiso from the intrinsic distribution inferred for short GRBs.
  - The 0.1-10GeV luminosity as a function of time, based on LAT GRBs, and in particular in GRB090510.
  - During the initial phase of the afterglow emission (before deceleration) the flux is assumed to be proportional to t2 (as expected for homogeneous medium); the afterglow onset is fixed at tpeak = 3s; during the deceleration phase the luminosity decreases as t-1.4.
  - To normalize the light curve, we use the correlation found in a sample of 10 LAT GRBs, including also GRB 090510.
  - Power law with photon index -2.1 and normalization derived from the integrated luminosity 0.1-10 GeV, extrapolated up to 10 TeV.
  - Consider the viewing angle and apply a correction assuming a homogeneous jet.
  - Scheduler, following :
    - Seglar-Arroyo, M. & Schussler, F. Moriond VHEPU 2017 arXiv: 1705.10138
    - Ashkar, H. et al., JCAP 2021.03 (2021): 045 arXiv:2010.16172
  - Updates@ ICRC 2021