Chasing the Electromagnetic Counterpart of Gravitational Waves with VHE gamma-ray observatories

M. Seglar-Arroyo, A. Carosi, J. Green, L. Nava, B. Patricelli, F. Schüssler, A. Stamerra on behalf of the CTA Consortium

Postdoctoral researcher

IFAE, Barcelona (Spain)

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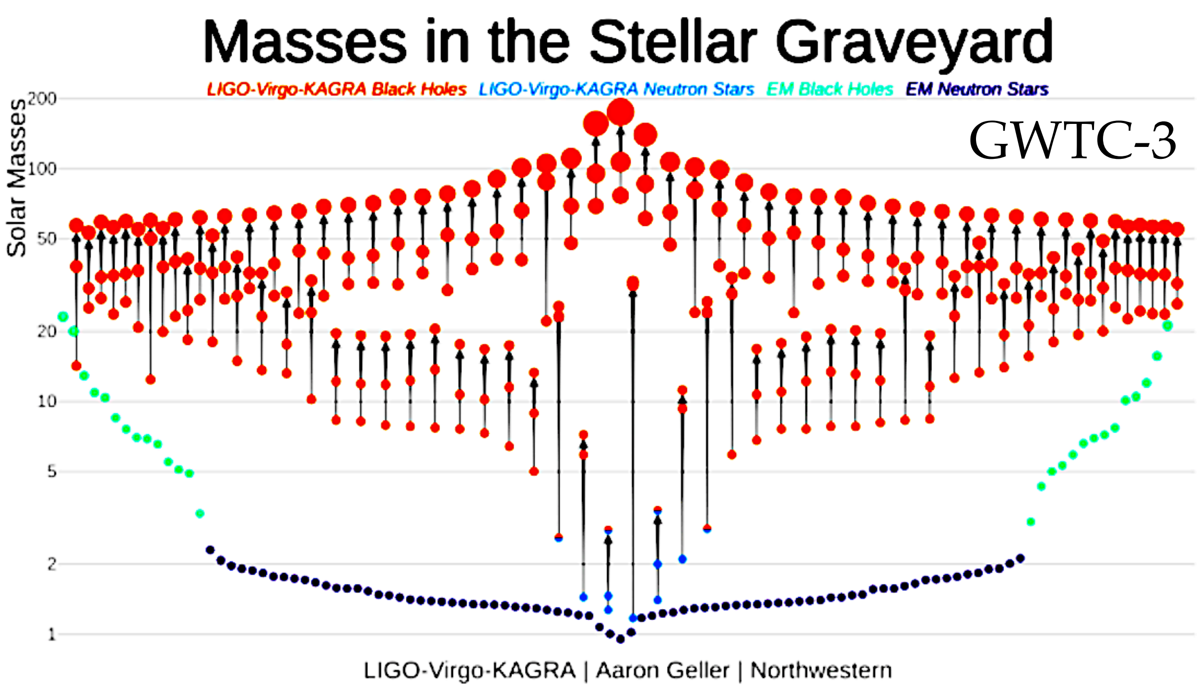
The gravitational wave sky and the gamma sky

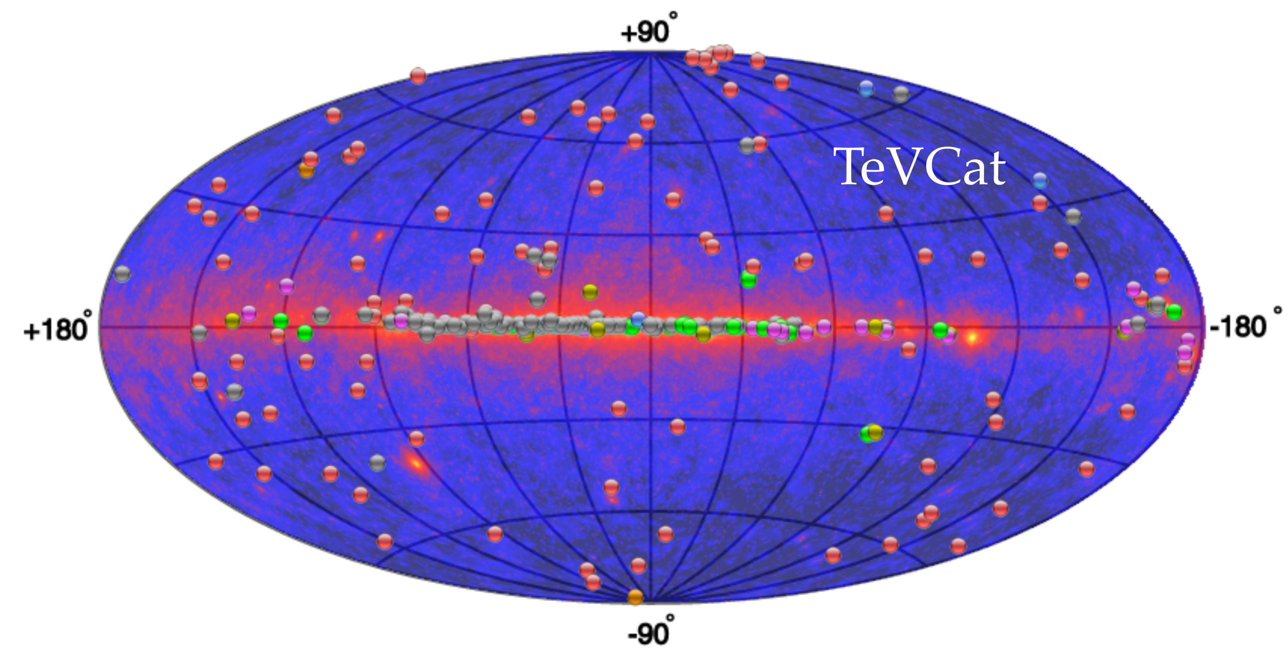
- Several dozen of compact binaries have been detected via GW since 2015



- Dynamics: masses, spins, equation of state…
- Fundamental physics: H0, deviations from GR, astrophysical population studies..

- Since the first VHE experiments, ~ 170 gamma-ray sources have been detected, including 5 gamma-ray bursts

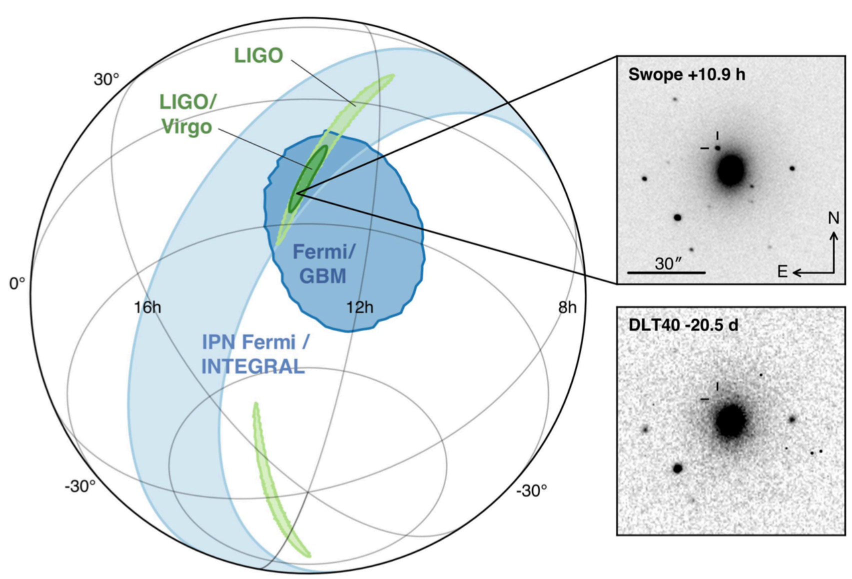
very-high-energy gamma-ray sky

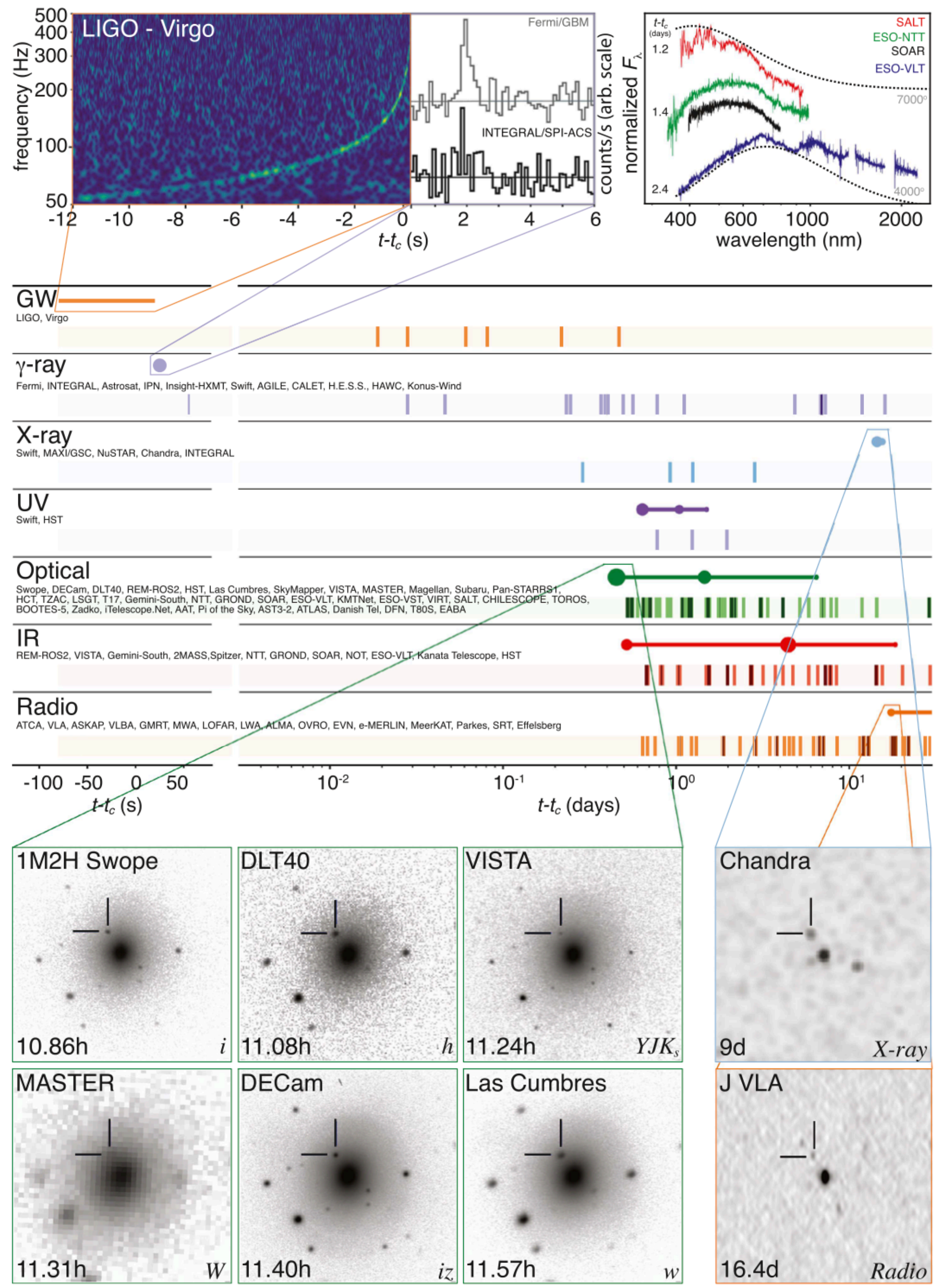


- Energetics of the source: radiation mechanisms, acceleration processes in shock waves, variability, Lorentz Invariance Violation, dark matter searches…
- Hints on the environment: interactions with interstellar medium, jet formation…

GW170817: largest observation campaign to date

- BNS observed by LHV 17th of August, 2017
- Proved the value of searching for counterparts!
- Implications in many fields:
    - First BNS merger ever detected
    - Proved that BNS are progenitors of sGRB
    - Host galaxy identified!
    - UV, optical and NIR: rapid neutron capture process in radioactive decay
    - Put constraints in NS EoS
    - Structured jet oriented $\sim 20^{\circ}$ from the line of sight (VLBI)
    - H0, ...



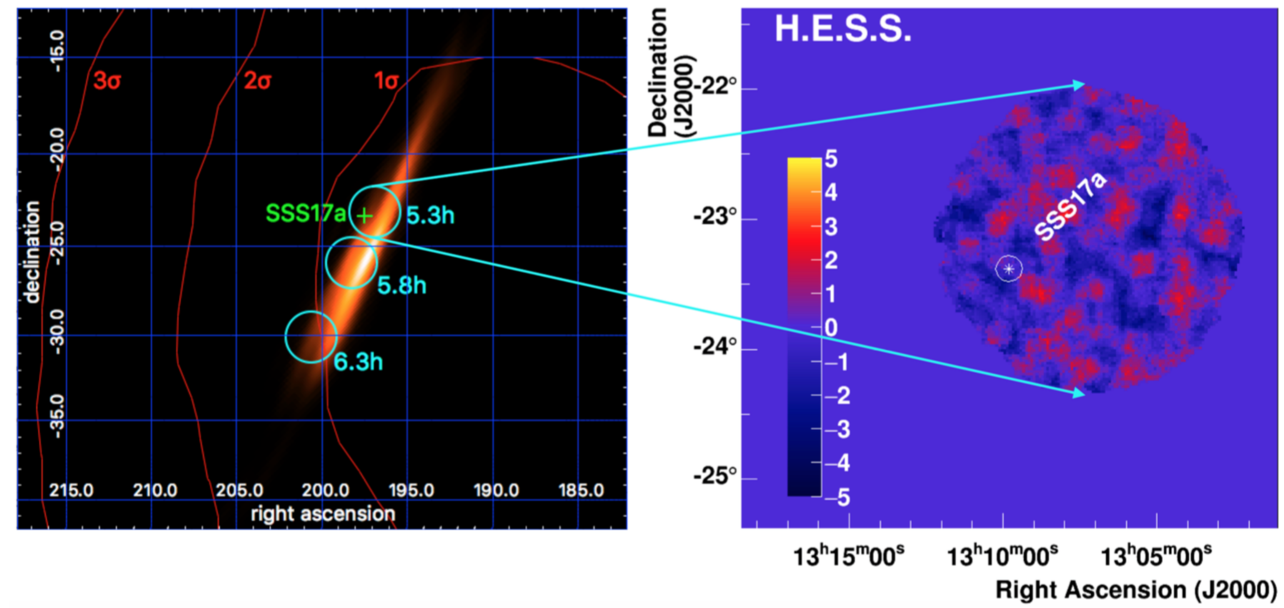


Multi-messenger Observations of a Binary Neutron Star Merger, Abbott, B. P., et al, ApJ, 848:L12 (59pp), 2017

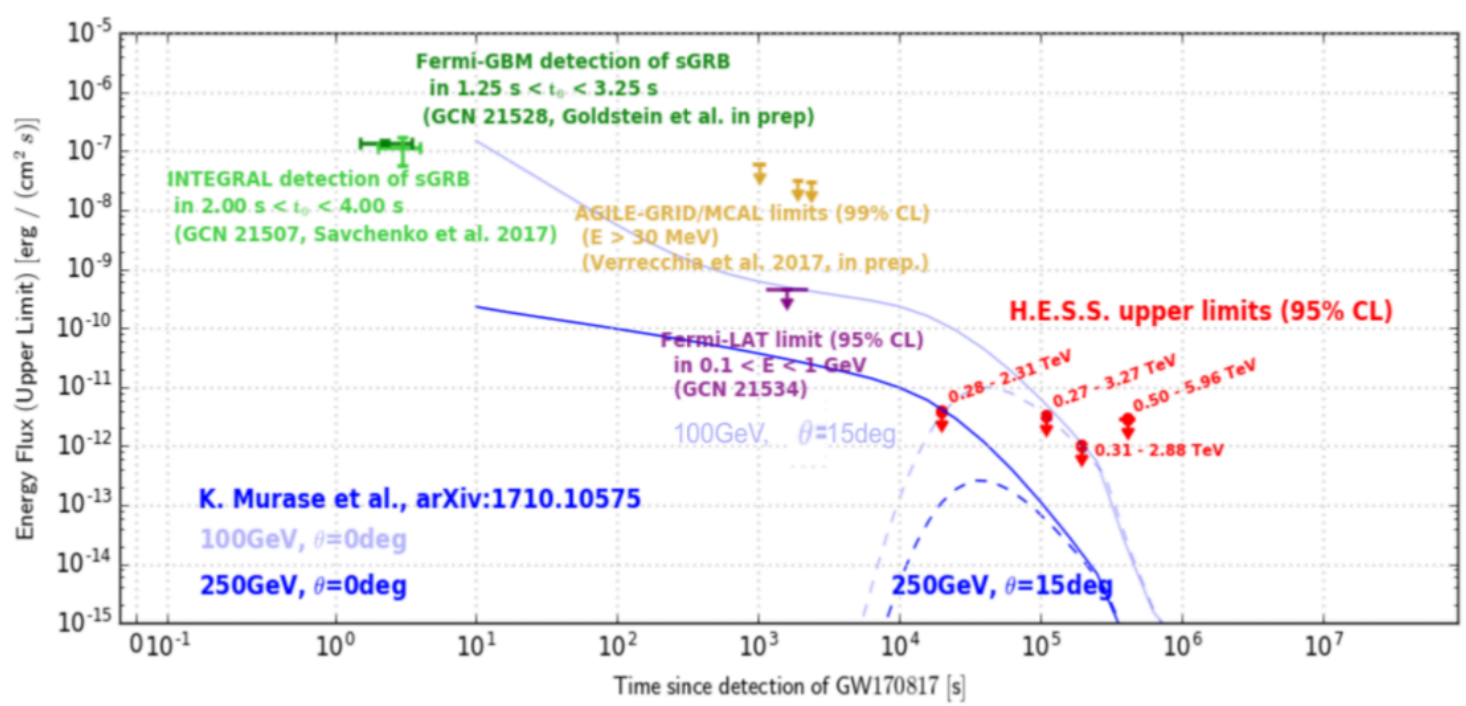
GW-sGRB at VHE: Rapid observations of GW170817

- **H.E.S.S. was the first ground based instrument on target**
  - 3 tiling observations from 17:59 - 19:30 UTC (1st before the discovery of the optical transient SSS17a)
  - 56 % of the GW uncertainty region covered (1.5° radius FoV)
- No TeV emission was detected: upper limits derived

Abdalla, H, MSA, et al., The Astrophysical Journal Letters, 850(2), L22

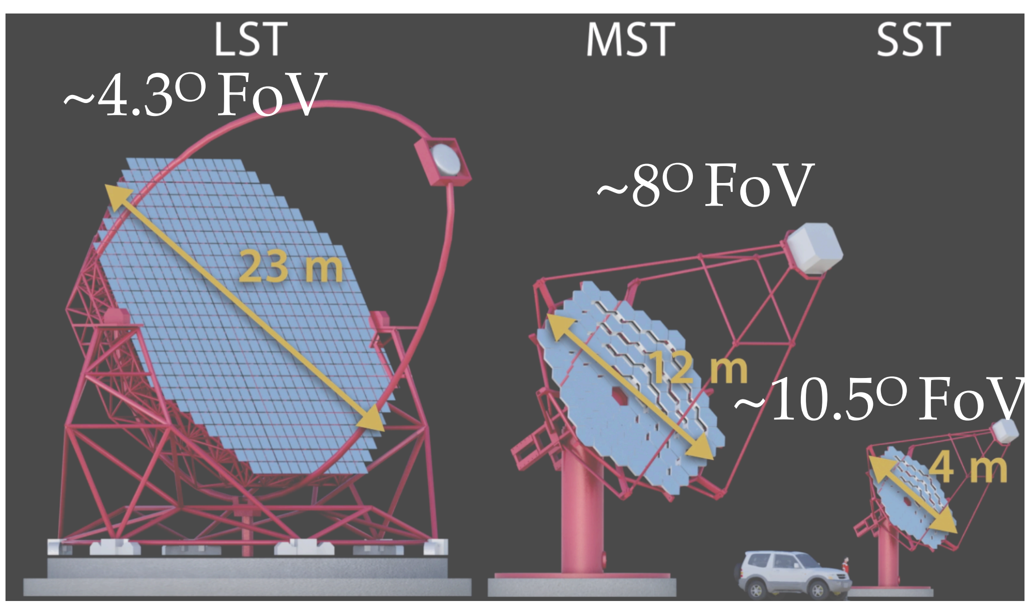


- 5 days of monitoring until the source was no longer in the H.E.S.S. FoV
  - Constraints on the VHE emission from external Inverse Compton in afterglow shock with X-ray photons

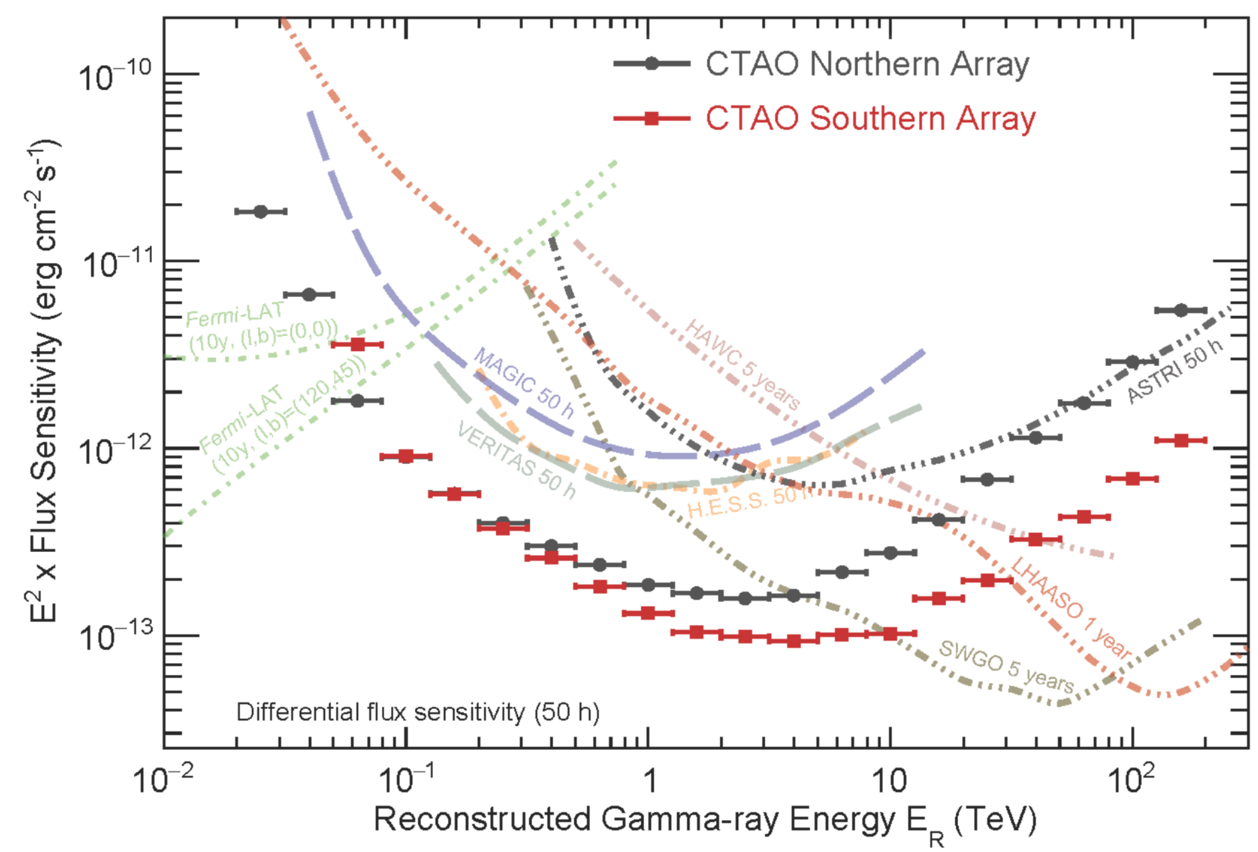


CTAO: the Cherenkov Telescope Array Observatory

- Next generation of Cherenkov Telescopes observing the sky from ~10s of GeVs up to ~100s of TeVs
- Two arrays of various types of telescopes: CTA North (La Palma), CTA South (Chile)
  - Large-Sized Telescopes, Medium-Sized Telescopes, Small-Sized Telescopes
  - LST: suited for short time-scale transients follow-up and high-redshift sources
    - Large effective area=> Low energy-threshold
    - Fast repositioning (~20 s for 180°)
    - LST-1 telescope currently in its **commissioning phase** on La Palma, Canary Islands
  - MST: slower repositioning although larger FoV!



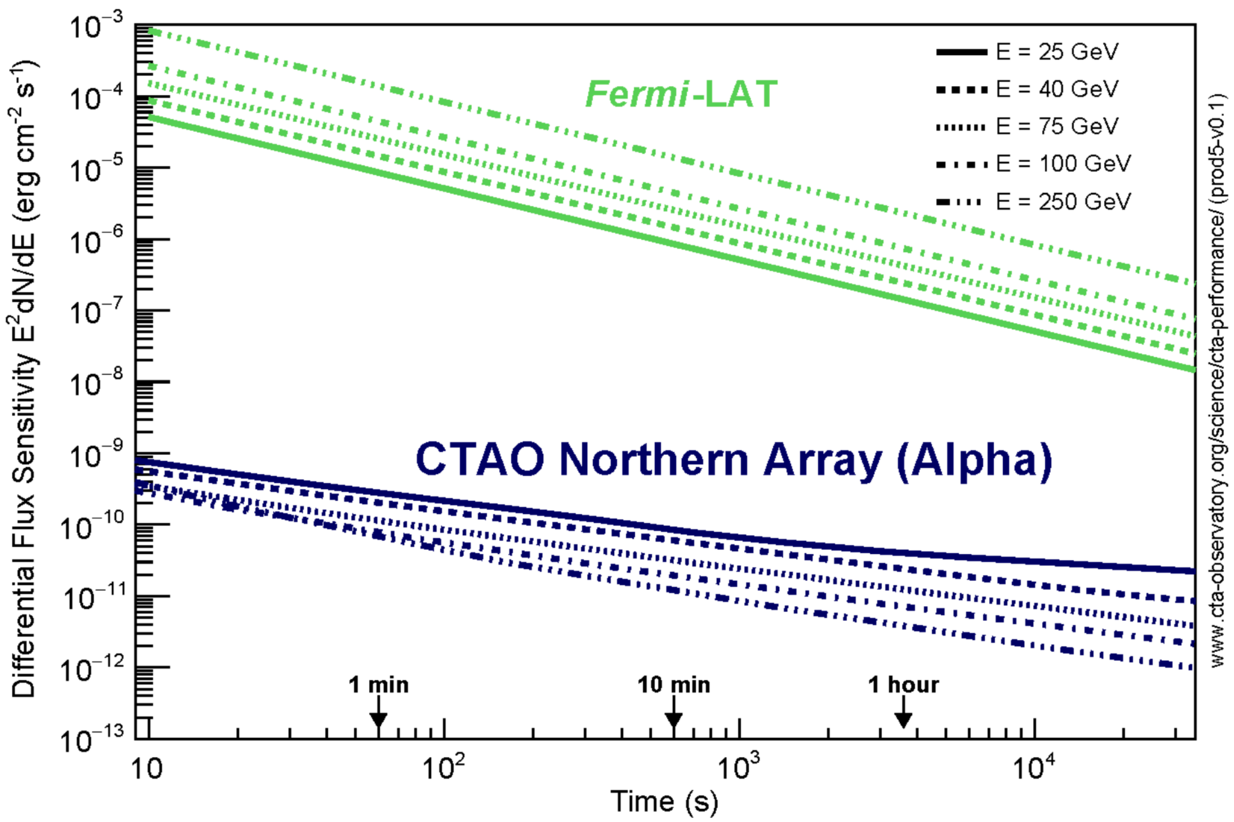
20-150 GeV 150 GeV-5 TeV 5-300 TeV

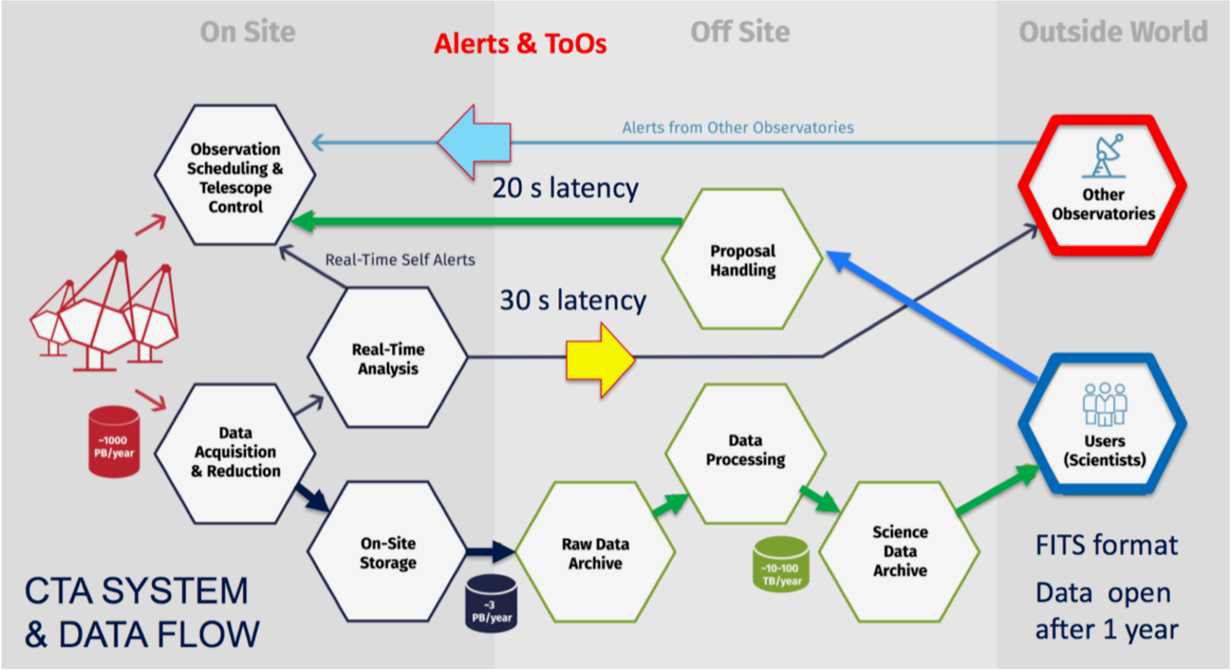


CTAO: the Cherenkov Telescope Array Observatory

Combination of hardware and software of improvements in CTAO, key for **transient physics**:

- High sensitivity in short scale exposures at ~GeV energies: Large effective area (~10^5 m^2) compared to satellites as Fermi-LAT (~1 m^2)
- Low latency response assured by the **Science Alert Generation (SAG)** system in charge of the real time data analysis
- Goals:
  - Data reconstruction, data quality monitoring, science monitoring and real-time alert issuing with **latencies ~20s**
  - Flexible capability, including **observations with sub-arrays**

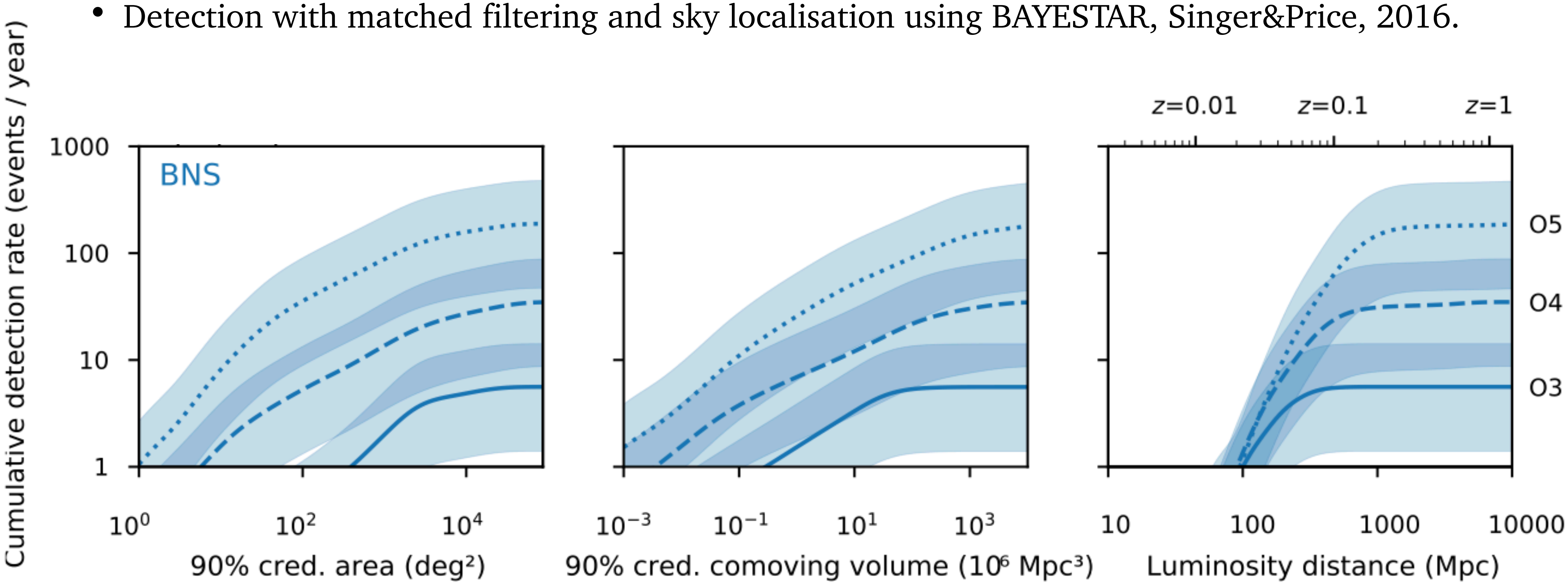




Bulgarelli, A. et al.,The Science Alert Generation system of the CTA Observatory, PoS(ICRC2021)937 cta-observatory.org

Gravitational waves simulations from O5 and O6

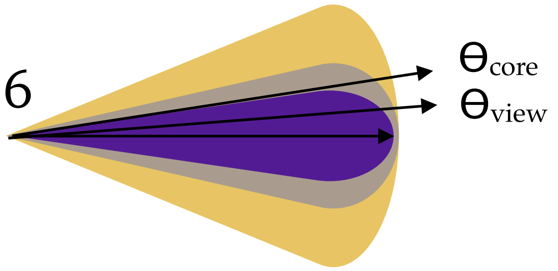
- Gravitational wave catalog from Petrov, P et al., *Astrophys.J.* 924 (2022) 2, 54 (full set of simulations in Zenodo, Singer 2021b,c,d,e)
- GW detector sensitivities from Abbott et al. 2020b, 70% duty cicle per interferometer
  - 4 interferometers in O5 (LHVK): 2 aLIGO 330Mpc, AdV 150–260Mpc. KAGRA∼130Mpc
  - 5 interferometers in O6 (LHVKI): 3 aLIGO 330Mpc, AdV 150–260Mpc and KAGRA∼130+Mpc
- ∼2300 (8160) simulated compact binaries for O5 (O6), isotropically distributed, with realistic astrophysical distributions of masses, spins, distances, and sky locations.
- Detection with matched filtering and sky localisation using BAYESTAR, Singer&Price, 2016.



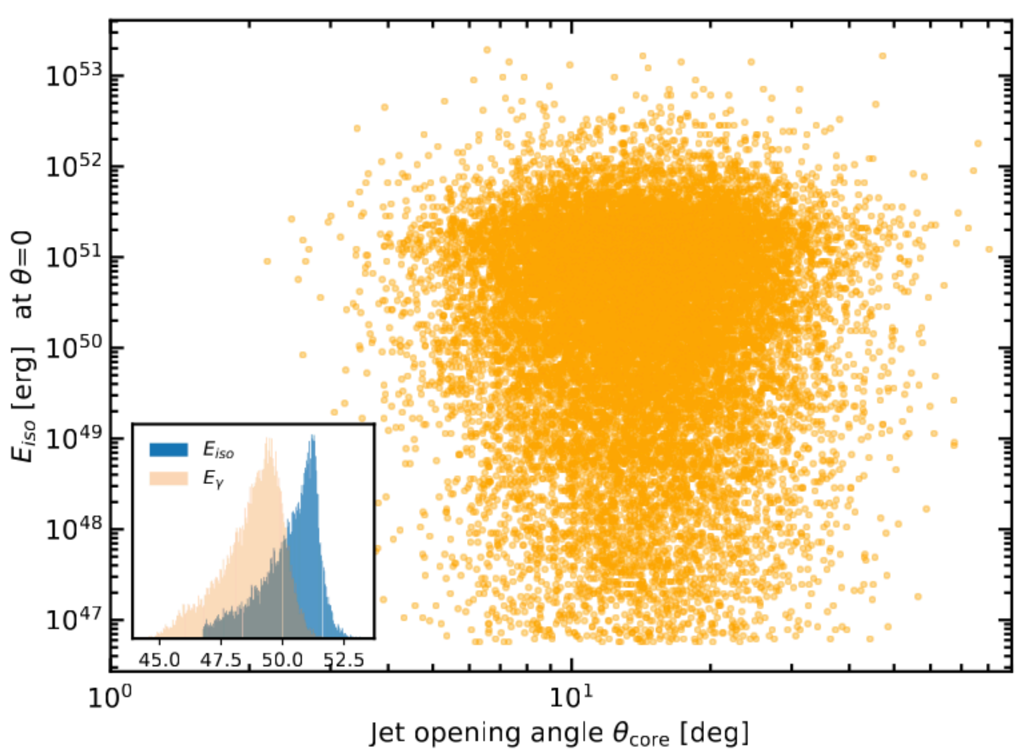
Petrov, P et al., *Astrophys.J.* 924 (2022) 2, 54

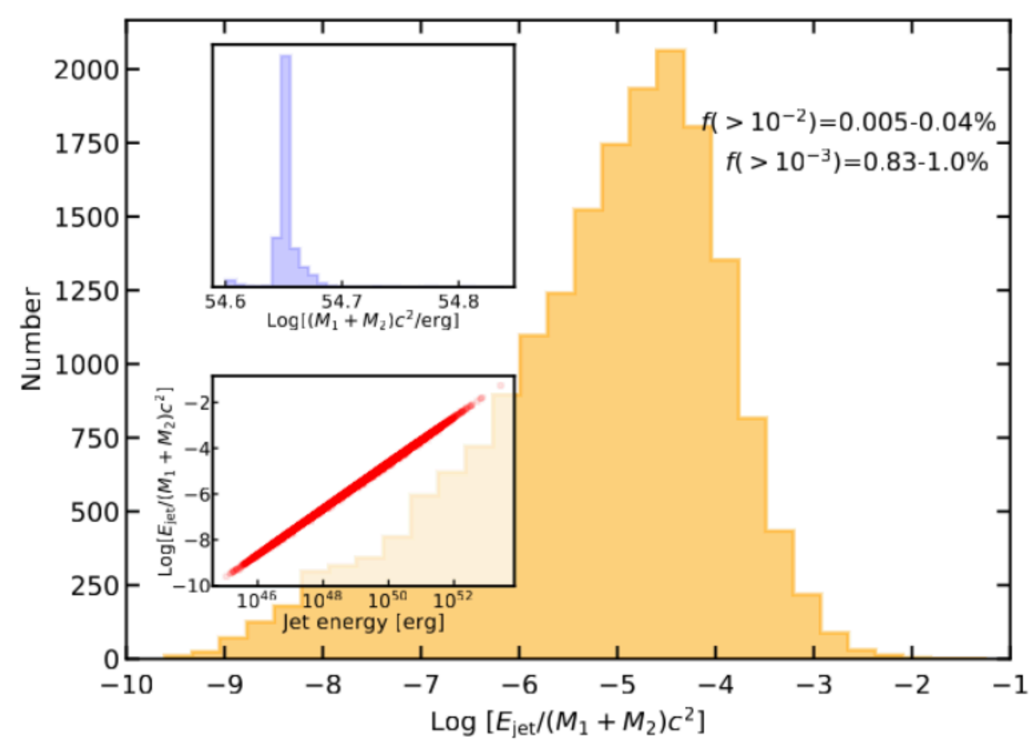
The sGRB emission at VHE energies

- Phenomenological set of short GRB simulations, assuming that all launch a jet. Link via distance, **viewing angle** between the jet axis and the mass of the BNS
- Built based on sGRB detections in X-rays, GRB detections at TeVs and flux upper limits by IACTs.
- **E_{iso}** randomly extracted from distribution in Ghirlanda et al. A&A, 594:A84, Oct 2016



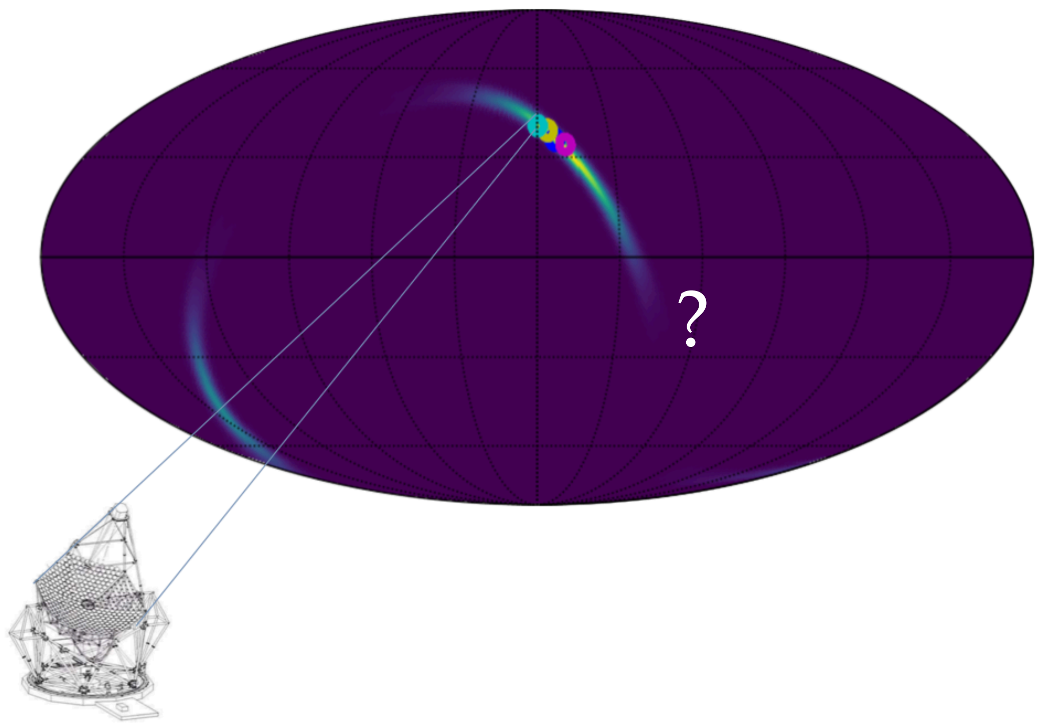
- **Jet opening angle of the core entered** around 14deg (ARA&A , 52:43–105, 2014.)
- **Lightcurve**: temporal decay and luminosity at TeV similar to that in soft X-ray band.
- **Spectrum**: Power-law with photon index of -2.2. Density of the external medium ∼0.1cm^{-3}
- **Jet structure:** Gaussian distribution for energy and Lorentz factor





The main challenges of GW with IACTs

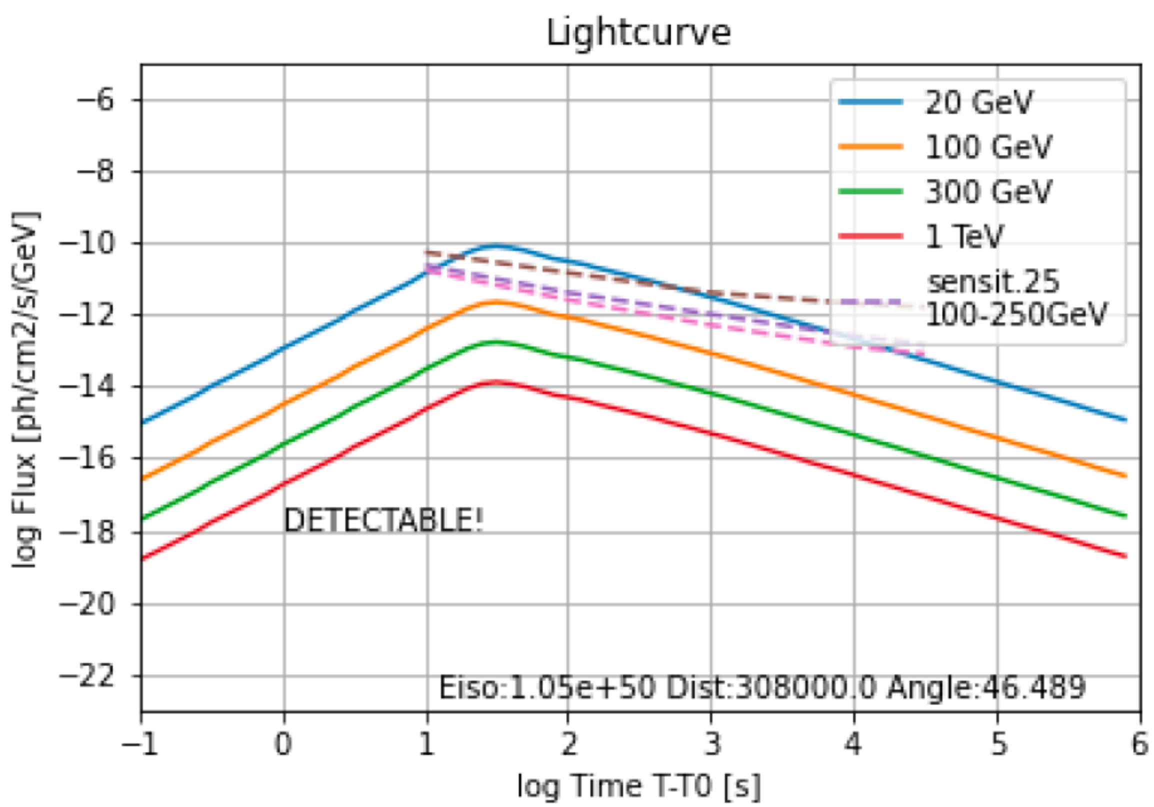
- **Low duty cicle due to visibility condition**
  - Sun: Astronomical darkness
  - Moon: consider moon phase, distance moon-source, moon elevation
- **Spatial challenge: GW localisation have large uncertainty regions 10-1000 deg^2**
  - Mid-FoV telescope: tiling strategy needed
- **Temporal challenge**: evolution of the transient emission:
  - Most followed approach based on the emission observed by Fermi-LAT: **rapid reponse**
  - **Recent long GRB detections at VHE pointing towards more complex scenarios**
    - Detections in the **early afterglow** (MAGIC GRB 190114C), **deep afterglow** (H.E.S.S. GRB 180720B,~tens of hours) and **very deep afterglow** (H.E.S.S. GRB 190829A, ~days)
    - LHAASO GRB221009A: **brightest GRB in X-rays and gamma-rays in 55 years**, no detection of the prompt phase at TeV energies, but several minutes after

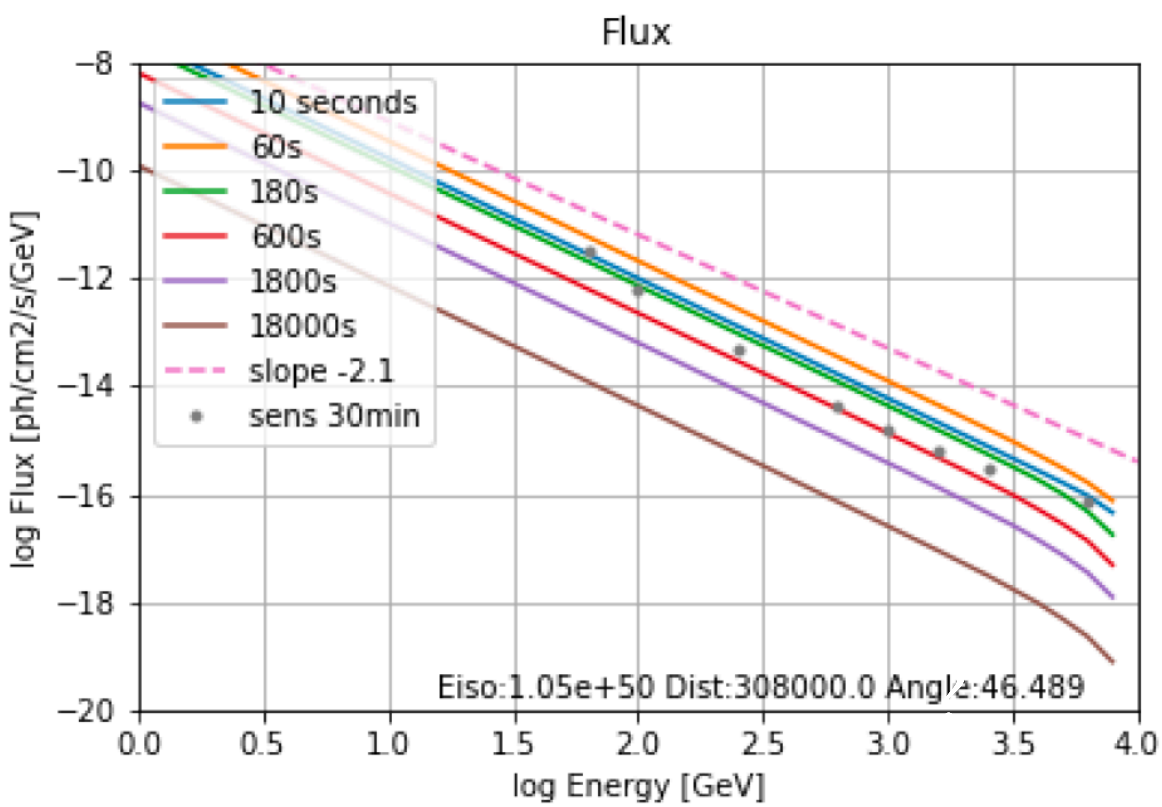


Temporal challenge: observation strategy to catch the VHE emission

- There is a set delays from the **detection of the source** to the observations by **the telescope**:
  - GW detection, distribution (GCN), reception, telescope slewing

- We study the detection probability considering the evolution of the source:
  - the delay (t_0)
  - the exposure (t_{exp})

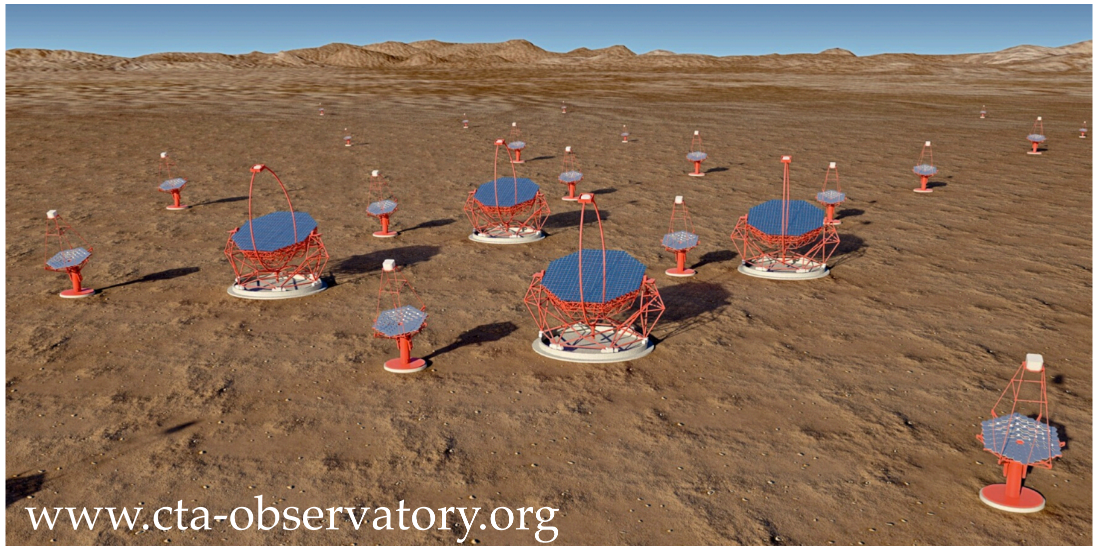




➡ **Definition of rapid follow-up vs. mid-latency follow-ups**

First prospects of joint GRB-GW detections

- **Configuration of the results presented here :**
  - ~2300 BNS+GRB simulations with O5 sensitivities
    - GRB with Extragalactic Background Light absorption taken into account
  - CTAO *alpha* configuration
    - CTAO Northern Array: 4 LST and 9 MST (area covered by the array of telescopes: ~0.25 km^2)
    - CTAO Southern Array: 14 MST and 37 SST (area covered by the array of telescopes: ~3 km^2)



Expectations for a well localised sGRB

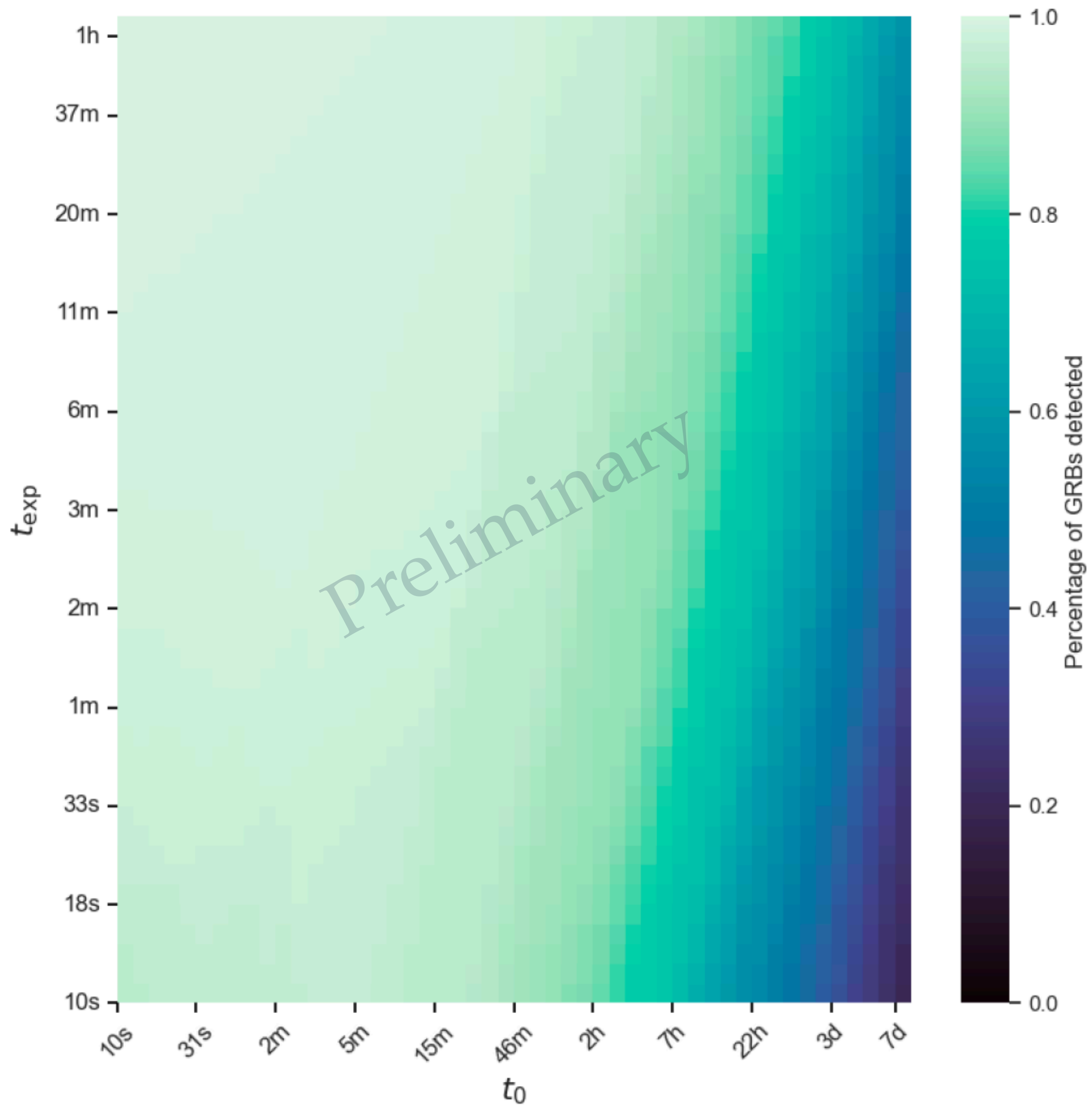
- First results for the detection expectations by CTA if the source was **well localised**

$t_0 \sim 30$ sec: ~ 99 % detections with $T_{exp} \leq 1$ minute

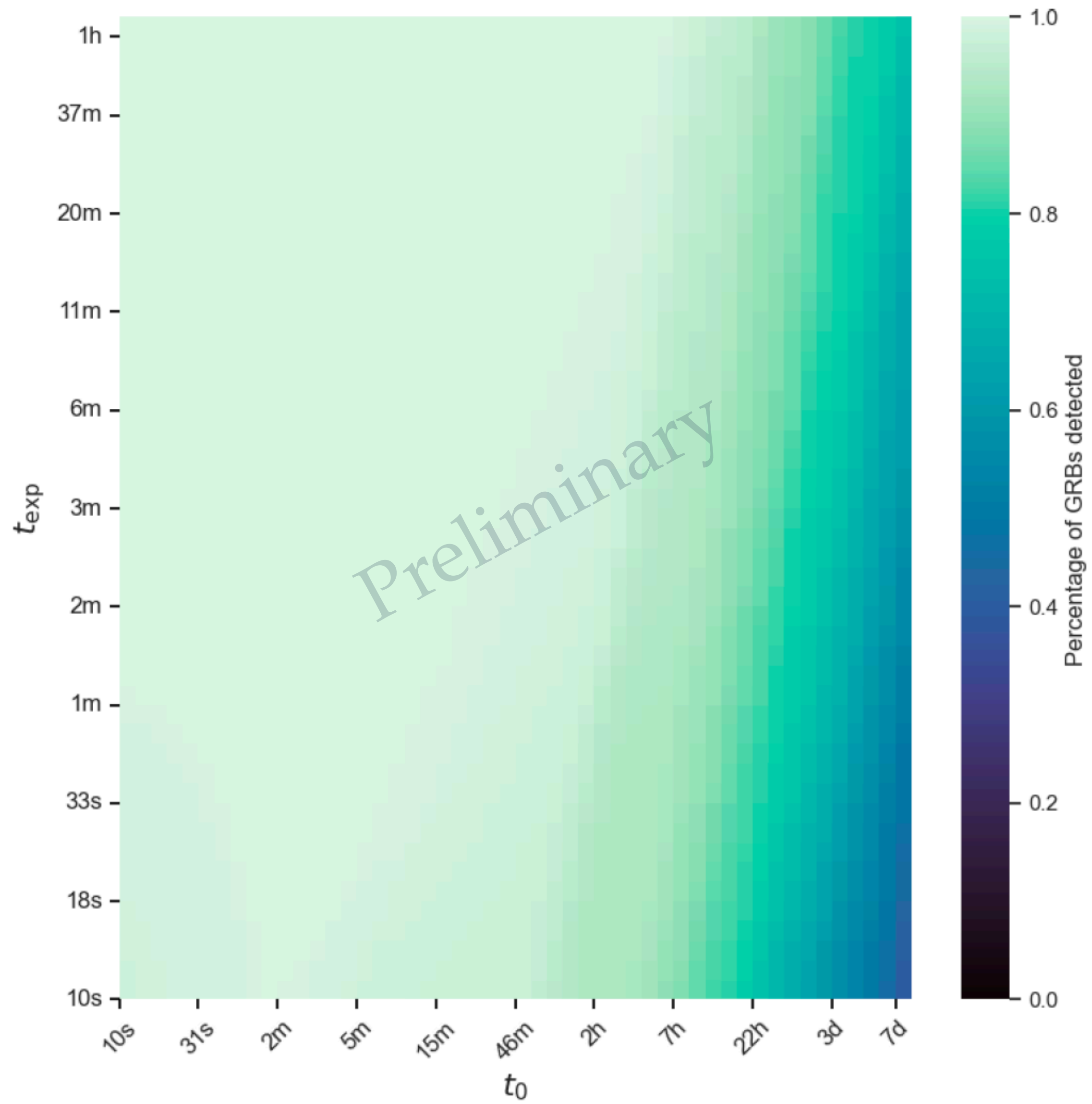
$t_0 \sim 10$ min: ~ 98 % detections with $T_{exp} \sim 1$ minute

$t_0 \sim 1$ day: ~ 80-85 % detections with $T_{exp} \sim 1$ h

$t_0 \sim 3$ days: ~ 65-70 % detections with $T_{exp} \sim 1$ h



(c) CTA North, $\theta_{view} < 10°$



(a) CTA South, $\theta_{view} < 10°$

Expectations for a well localised sGRB

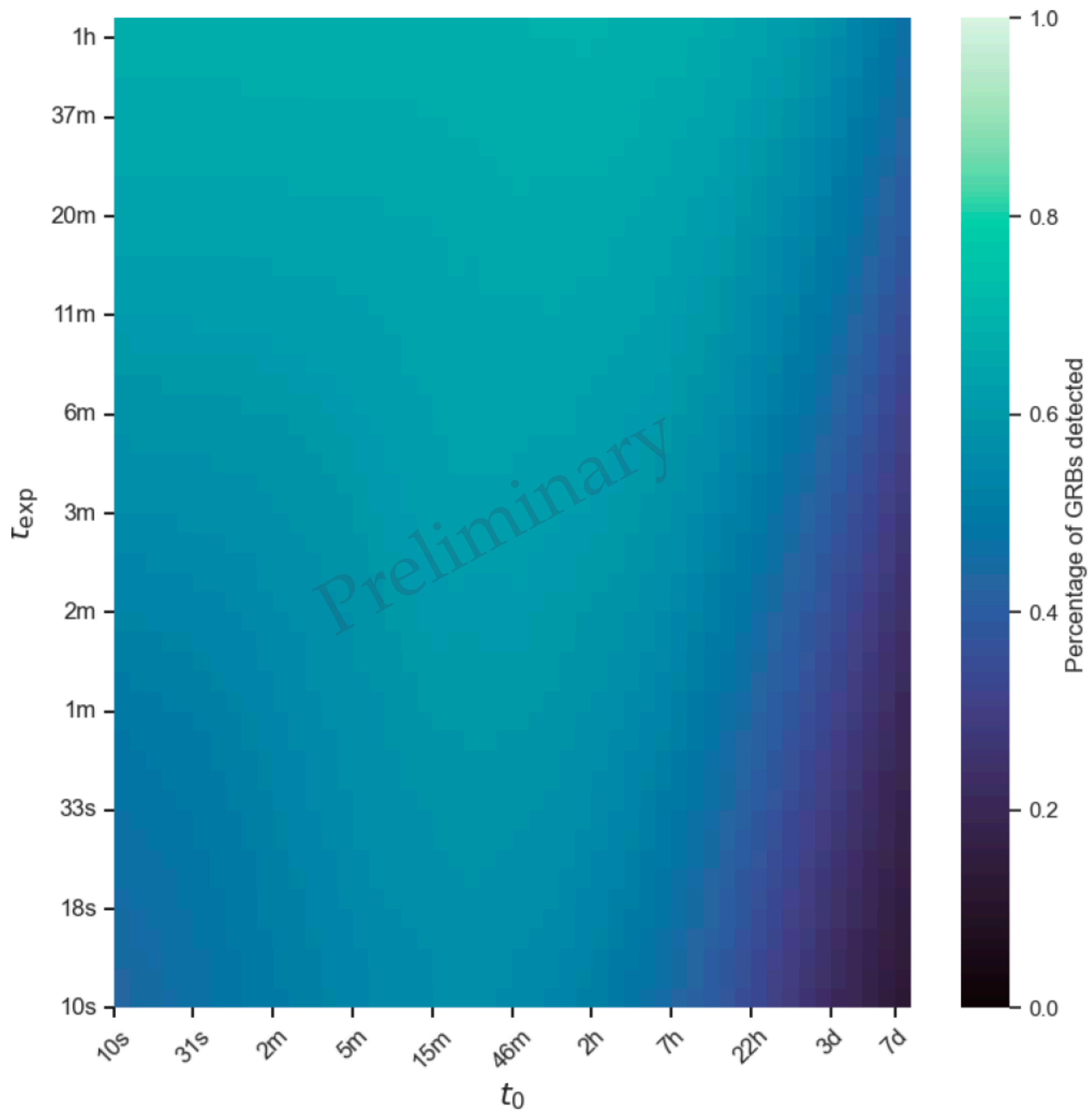
- First results for the detection expectations by CTA if the source was **well localised**

$t_0 \sim 30$ sec: $\sim$ 50-60% detections with $T_{exp} \sim 1$ min

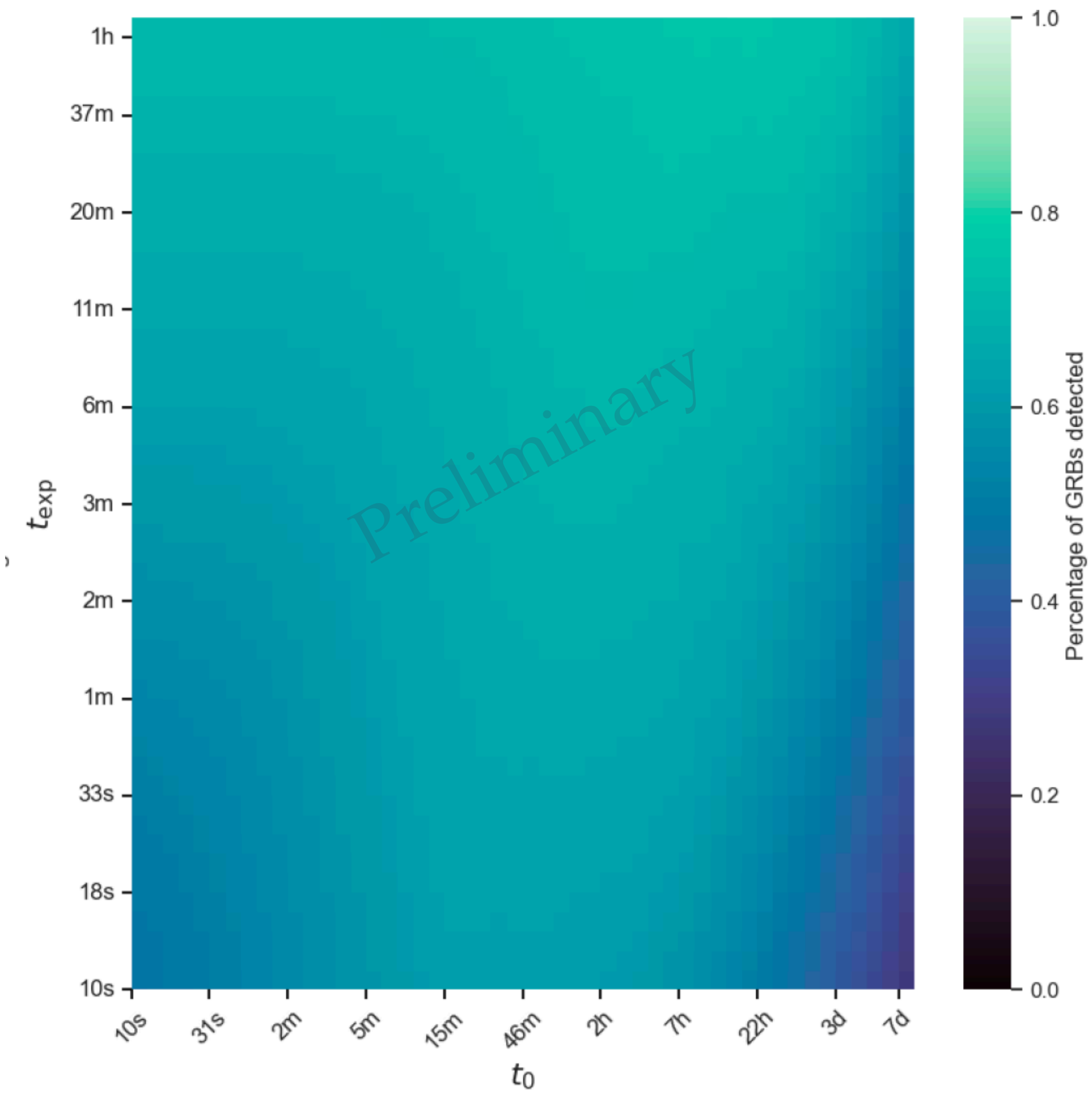
$t_0 \sim 10$ min: $\sim$ 50-60% detections with $T_{exp} \sim 10$ min

$t_0 \sim 1$ day: $\sim$ 50-70 % detections with $T_{exp} \sim 1$ h

$t_0 \sim 3$ days: $\sim$ 40-65% detections with $T_{exp} \sim 1$ h



(d) CTA North, $\theta_{view} < 45°$



(b) CTA South, $\theta_{view} < 45°$

Tackling the spatial challenge: tilepy

- Python-based algorithm specific derived to scan large sky regions
  - Further details later today in this session!

- The strategy is optimised as:
  - Consideration of visibility conditions (Moon, Sun)
  - Lower energy threshold are preferred - low zenith angle conditions are favoured
  - Exposure needed to detect the source is computed for each zenith angle, as a step of the coordinate selection, using the observatory IRFs and GRB physics are used
  - Maximisation of the probability region covered per pointing

- **Configuration of the results presented here:**
  - Latency to send the GW: 3 minutes
  - Slewing time: 30 s (as for LSTs)
  - Sequential follow-up with **one** CTAO site, selected from the largest probability pixel
  - 2 nights of follow-up
  - 2.5 degree FoV radius (as for LSTs)

Ashkar, H., MSA, et al., (2020), JCAP2021, 2021.03: 045
MSA, Schüssler, F. Moriond VHEPU 2017, PoS 167-174.

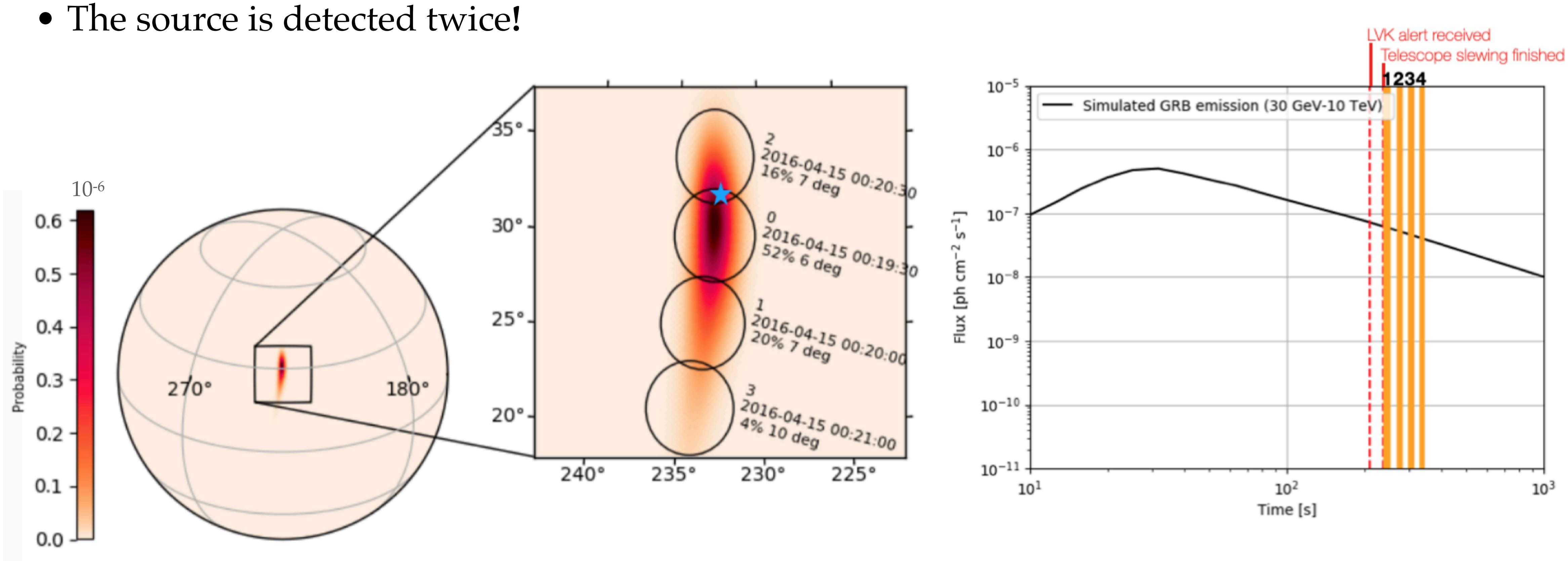
Example of a full simulated GW follow-up

- Optimised follow-up strategy is that where **the exposure is optimal to detect the source.**

- We consider each observing conditions to derive the exposure (via corresponding IRFs per site and zenith angle) to obtain 5 sigma detection: defined as:

$$\int_{t_0}^{t_0+T_{\rm exp}} F(t)dt \geq F^{s}_{5\sigma}(T_{\rm exp}),$$

- Example: BNS merger, $E_{iso} \sim 10^{50}$ erg, 3 minutes to receive the alert, 30s for the slewing
  - Scheduled observations cover **~90%** of the localisation uncertainty region (~40 deg^2) in **2 min**
  - The source is detected twice!

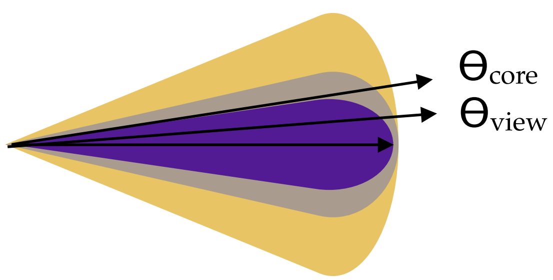


Patricelli, B., MSA et al.. 36th ICRC2021, PoS998, 2021

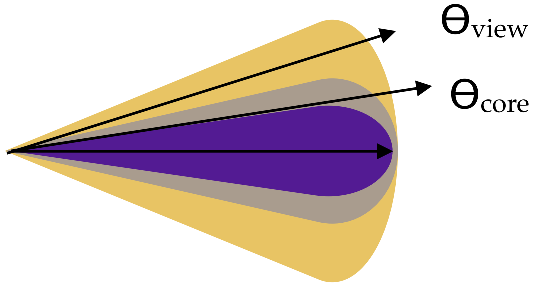
First prospects of joint GRB-GW detections

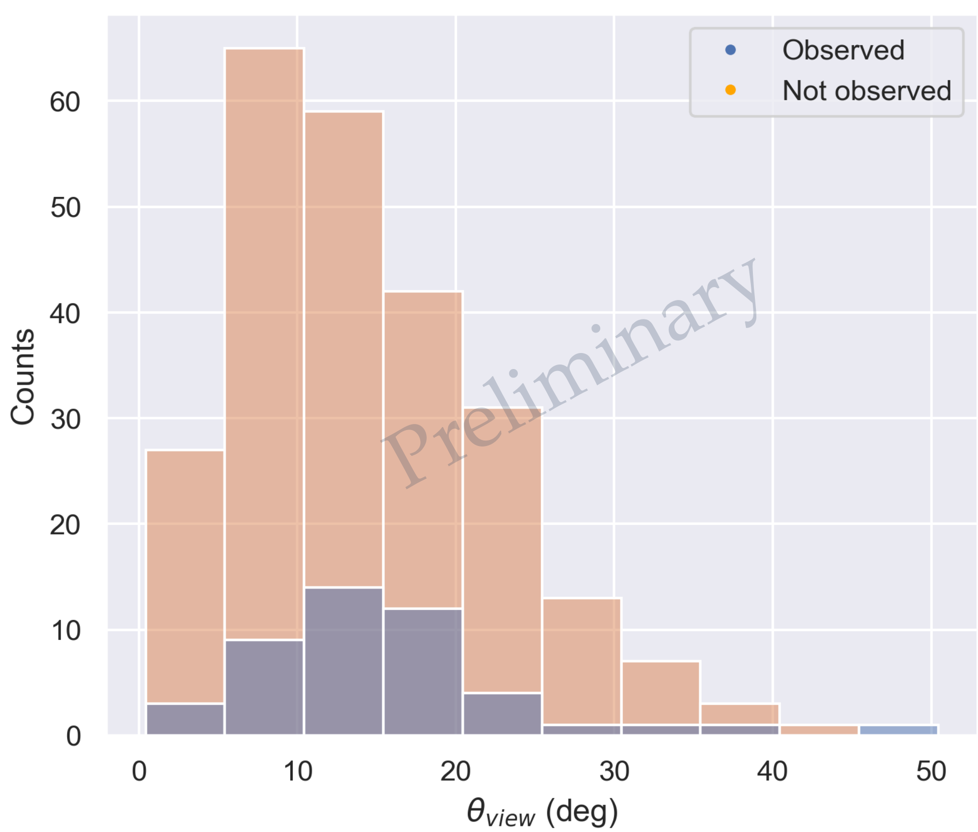
- The total number of followed up GW-GRB events: **8% of the total population**
- **4.5%** of cover the **true location of the source**
  - $\sim 8^{+9}_{-5}$/year detections in O5, using number of public alerts in emfollow.docs.ligo.org
- Focusing on the viewing angle:
  - on-axis events: **18%** are followed up and **10%** covered the true location of the source
  - off-axis events: **7%** are followed up and **4%** covered the true location of the source

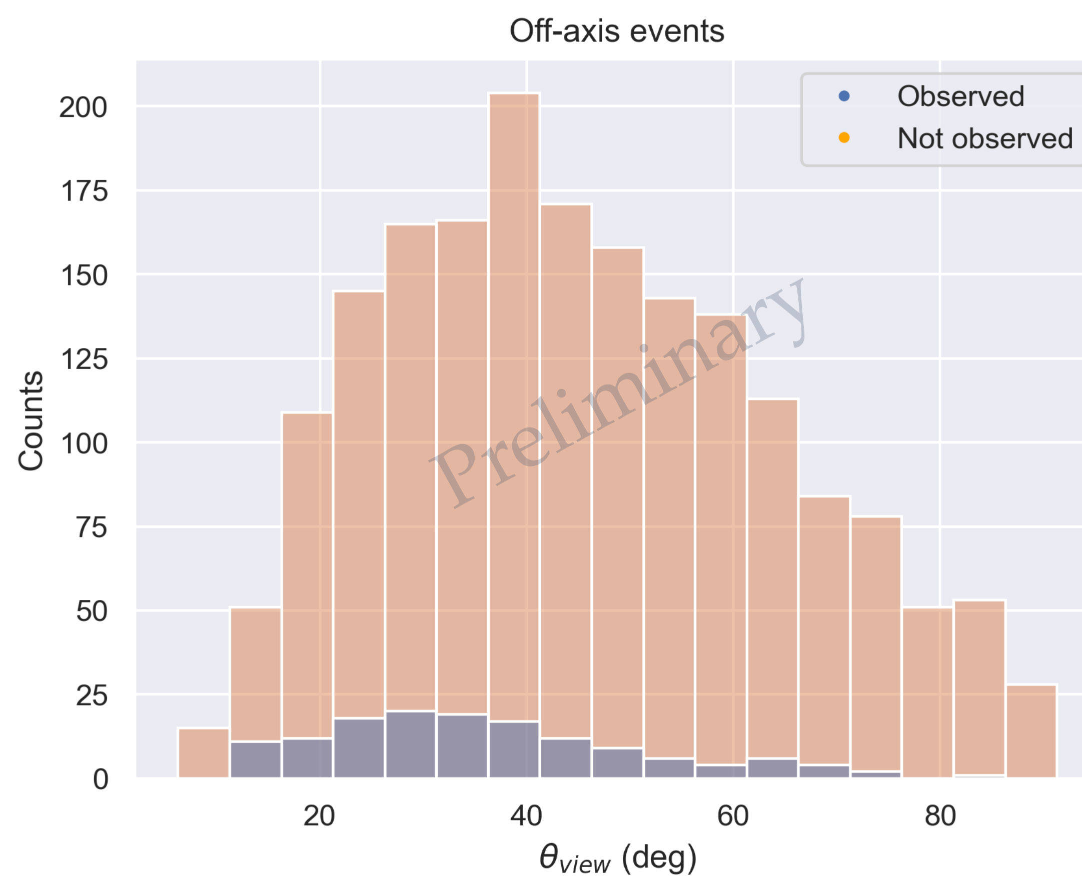
Events seen on-axis
(13%, $\Theta_{view} < \Theta_{core}$)



Events seen off-axis
(87%, $\Theta_{view} > \Theta_{core}$)



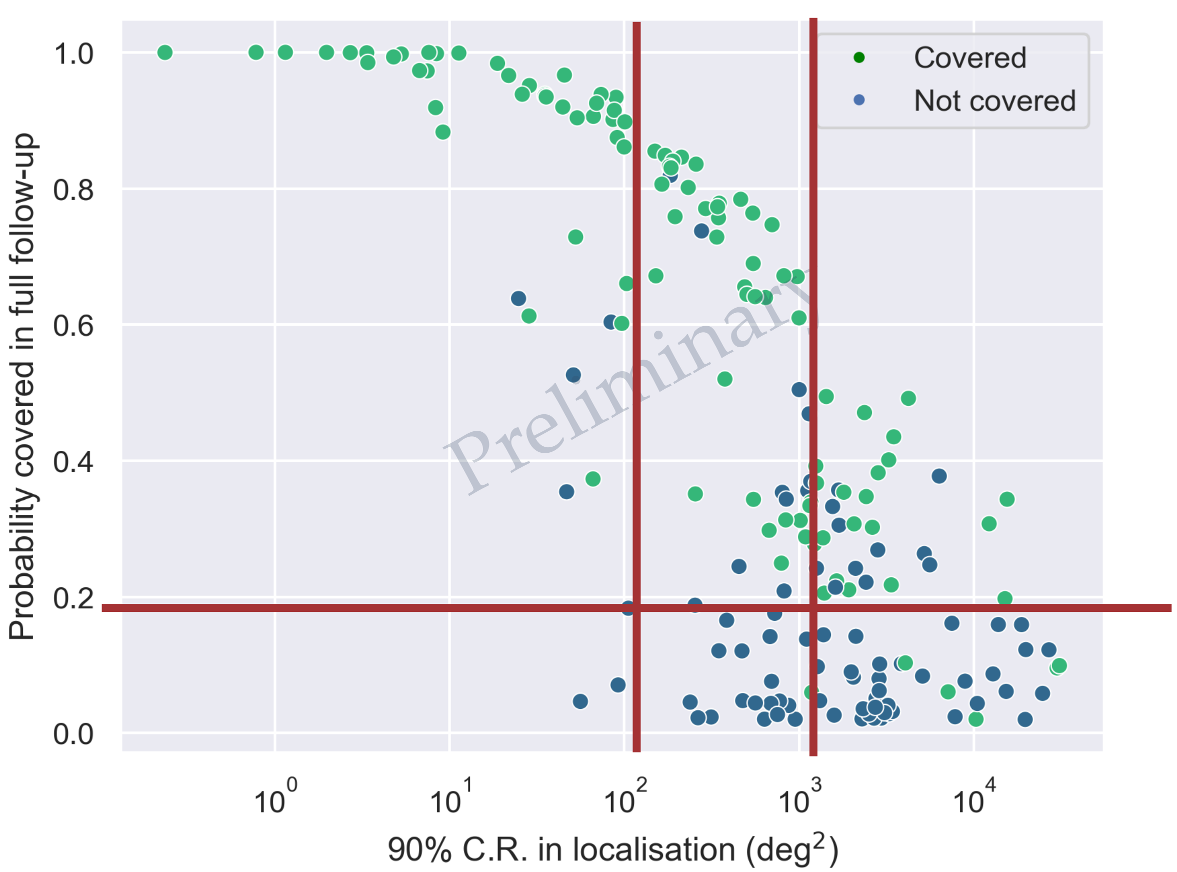


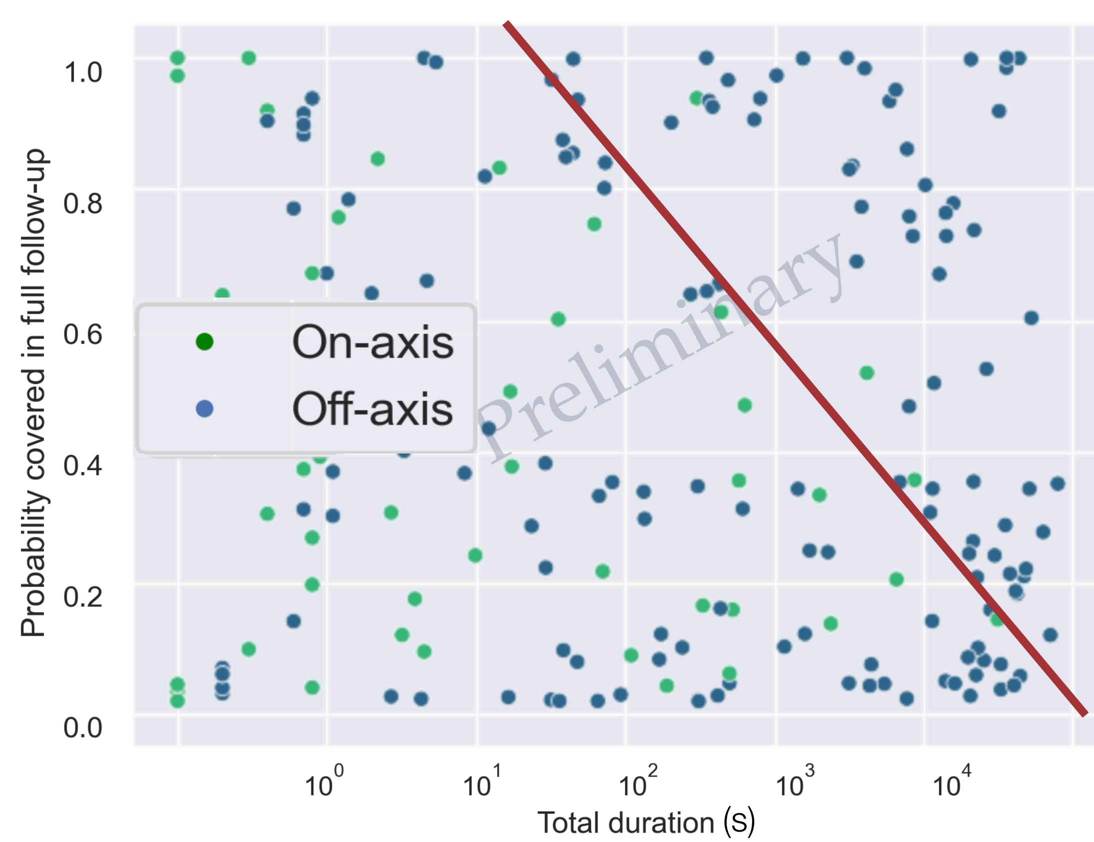


GW coverage in the follow-up observation

- Preliminary identification of the most convenient strategies: subset of followed events
- If observations are possible, we have a big chance of detecting the source for **covered probabilities >20%**
- Efficiency of the follow-up is **~0.9 (0.6)** for areas **<100 (1000)deg²**
- Large coverage and detections are possible even for **long follow-ups**
- Note that the source is covered more than once in many cases!

➡ More results coming soon!





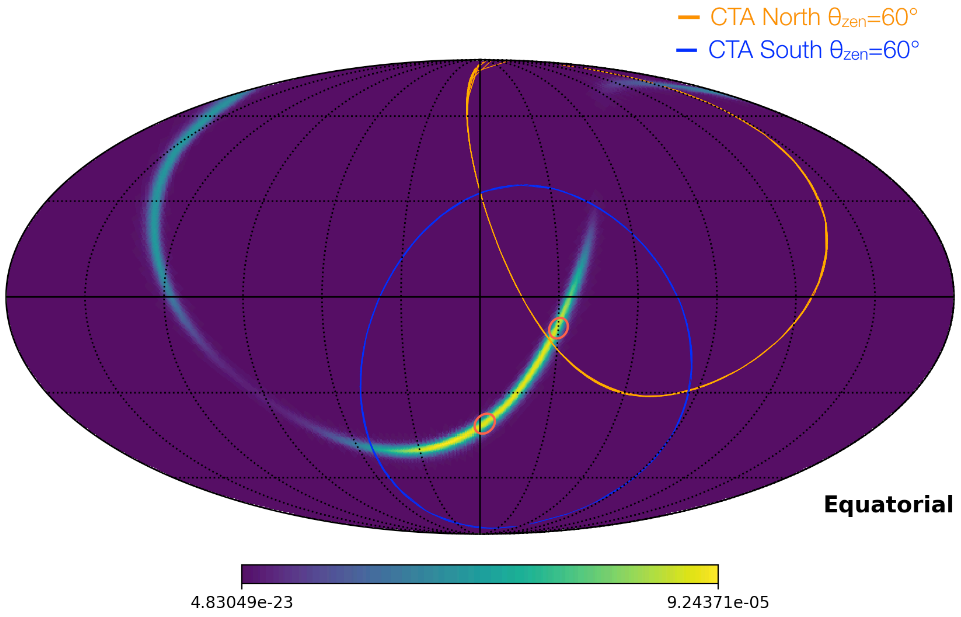
First conclusions and next studies

- Multi-messenger campaigns are very mature and robust (GCN, treasureHunt..)

- What have we learned so far:
  - Counterpart detection makes a big difference! (O2 vs. O3 case)
  - O2/O3/O4 so far: GW170817 was probably a golden event ?

- Observing run O4: LST-1 is following gravitational wave alerts in a fully automatic mode, endorsed by real-time analysis

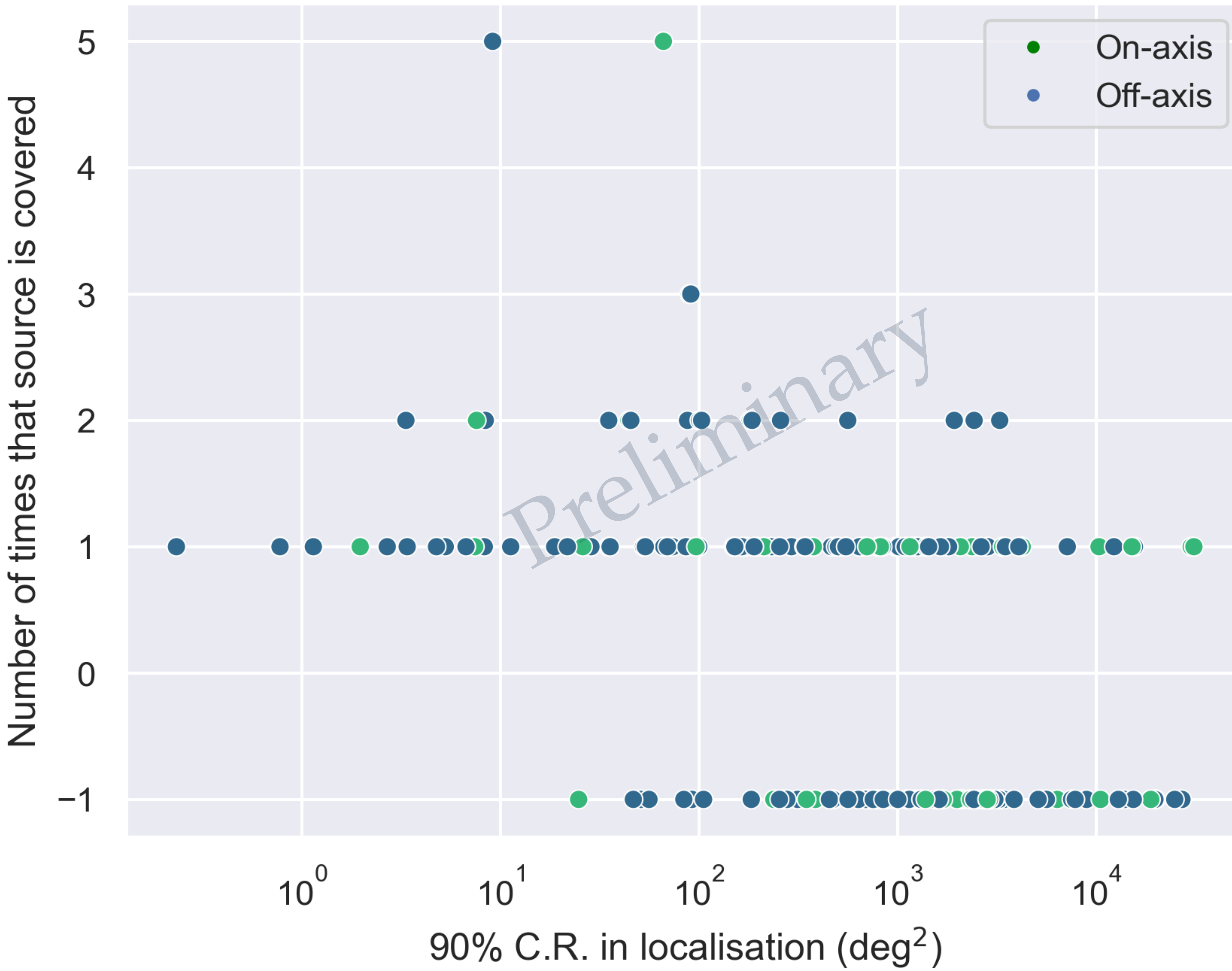
- Observing run O5-O6: First prospects for CTAO are very promising!
  - **Stay tuned for the full set of results!**
  - **Several strategies under study**
    - Fixed exposure vs. flexible time-windows
    - Sub-array strategy: maximise coverage in low-latency response but worsening of sensitivity
    - Early warning alerts oriented strategies



Thanks for your attention!

Back-up slides

Number of times the source is covered



Probability covered in full follow-up
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1
10^2
10^3
10^4
90% C.R. in localisation (deg^2)
On-axis
Off-axis
Preliminary