Strategies to Follow-Up Gravitational Wave Transients with the Cherenkov Telescope Array

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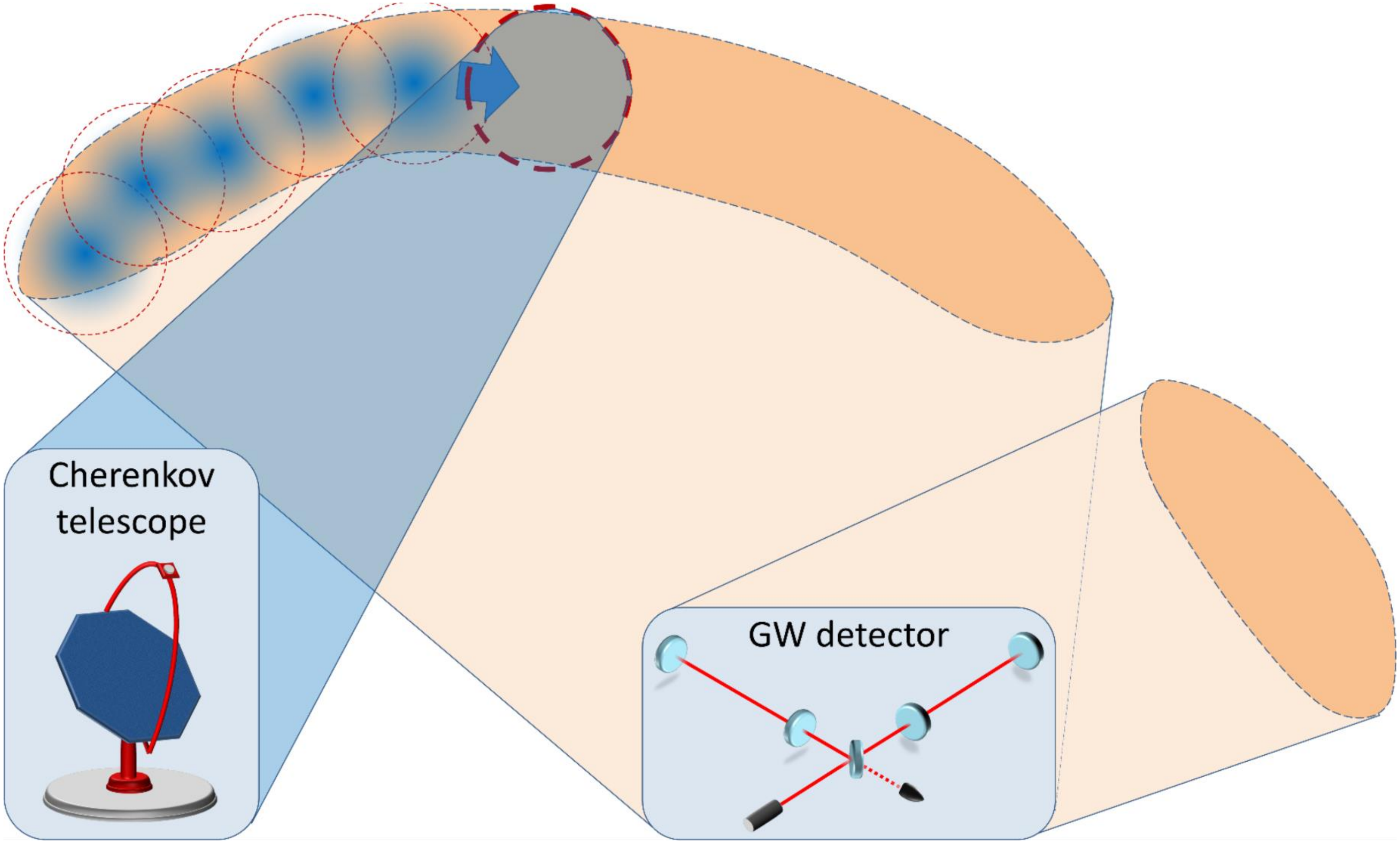
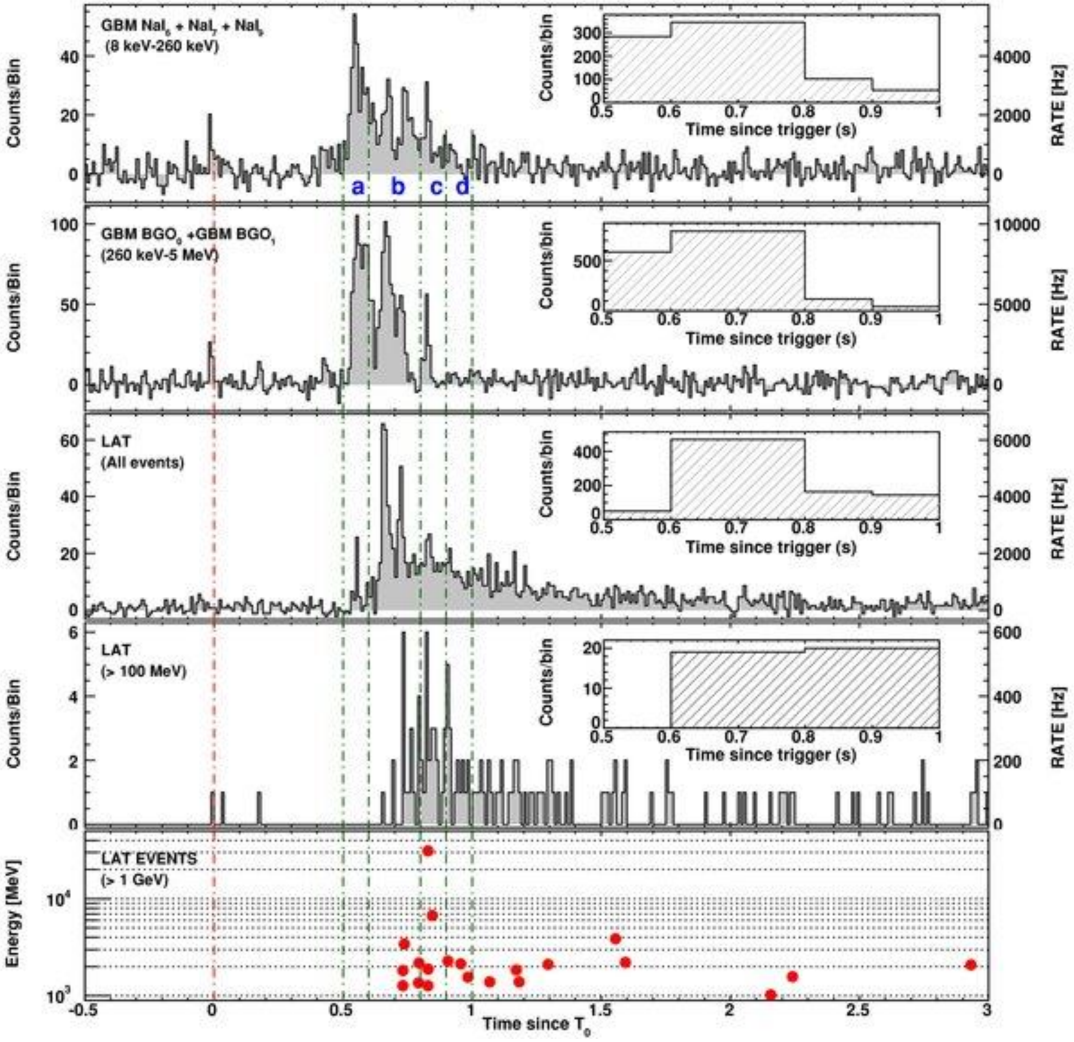
First Perugia Gravi-Gamma Wave Workshop
Rocca di Sant'Apollinare, May 16, 2019

Follow-up of GW Transients with CTA

Bartos et al. (2014) MNRAS 443, 738: ''CTA is well suited to follow up GW transients''



Multi-GeV Emission from Short GRBs



Ackermann et al. (2010):
Fermi observations of GRB090510

LAT emission observed up to ≈100 s

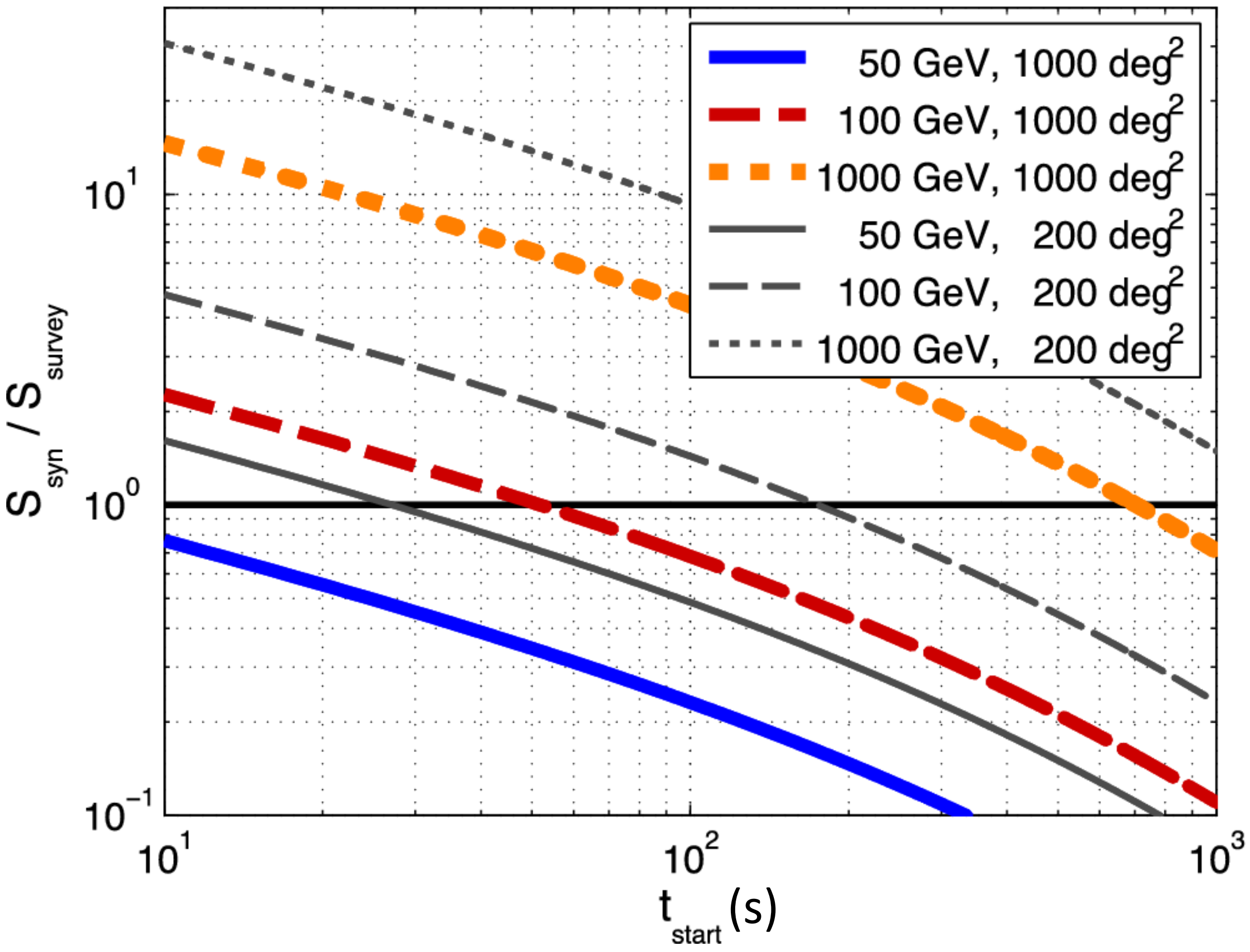
Short Gamma Ray Bursts (GRBs) thought to originate from compact binary mergers, expected to produce GWs

At least some short GRBs emit GeV photons, with no clear sign of cutoff

E_{max} = 31 GeV

Prospects for Joint GW+CTA Detection

Detectability of joint GW+CTA short GRBs
for different cutoff energies and survey areas



$E_{kin} = 10^{51}$ erg
$D_L = 300$ Mpc
$T_{obs} = 1000$ s

t_{start} from the onset of the GRB ≡ merger of the compact binary

Delays:
GW alert ≈ min
CTA slewing ~ 30 s

Joint detection rate:
~ 0.03/yr

Bartos et al. (2014)

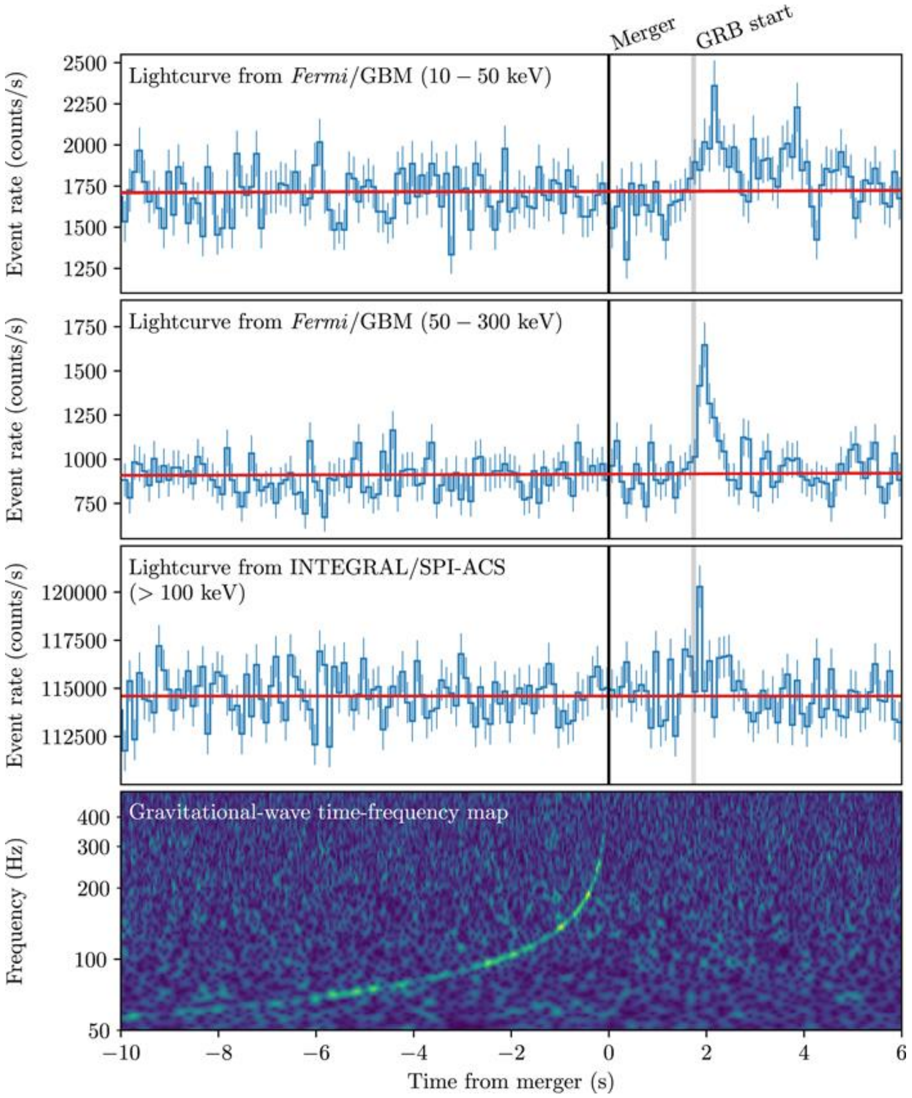
Strategies for the GW Follow-up with CTA

Bartos, TDG, Gair, Hendry, Heng, Humensky, S. Márka,
Z. Márka, Messenger, Mukherjee, Nieto, O’Brien, Santander
(2018) MNRAS 477, 639

Goals:

1) Summarize the status, operations and prospects of GW detectors for the CTA community, and conversely
2) Outline the steps needed to carry out effective multi-messenger surveys and give specific recommendations to optimize this effort, before the start of joint observations

GW170817 – GRB170817A



Abbott et al. (2017), ApJ 848, L13

- The localization only with LIGO data determines an area of 190 deg^2
- Including Virgo signal, this area is reduced to 28 deg^2 (then to 16 deg^2 in Abbott et al. 2019)
- Source distance is 40 Mpc
- Unambiguous association of a short GRB with a Binary Neutron Star (BNS) merger
- Soft prompt emission extending only to ~1 MeV
- H.E.S.S. set some VHE upper limits at later times
- Associated kilonova observed at optical and infrared frequencies

New Considerations for the GW Follow-up with CTA

a) The GRB may be delayed by O(10^3 s) after the GW trigger
(Vietri & Stella 1998, Ciolfi & Siegel 2015)

b) Joint detection rate of ~ 0.03/yr should increase with off-axis events like GRB170817A (Abbott et al. 2017, Lazzati et al. 2017)
Higher rate (0.03 – 0.5 /yr) in Patricelli et al. (2018) JCAP 5, 56

c) Some long GRBs are associated with core collapse of massive stars, which may produce detectable GW emission before the GRB if the collapse is asymmetric enough (Kobayashi & Mészáros 2003, van Putten et al. 2004)

d) Fermi-GBM detected a weak (false-alarm probability of 2.9σ) transient 0.4 s after the Binary Black Hole (BBH) merger GW150914 (Connaughton et al. 2016)

e) AGILE found a weak (post-trial significance of 2.4 – 2.7σ) transient 0.46 s before the BBH merger GW170104 (Verrecchia et al. 2017), similar to the weak precursor of short GRB090510 (Abdo et al. 2009, Giuliani et al. 2010)

Sensitivity of GW Detectors in the CTA Era

- The new observational run (O3) of Advanced LIGO and Virgo started on April 1
- The BNS ranges are 110–140 and ~50 Mpc, respectively, and will reach ~190 and ~125 Mpc at final design (Abbott et al. 2018)
- During O3, about 10–20% of detected BNS mergers will be localized within 20 deg^2 with three interferometers in operation. When LIGO India (Iyer et al. 2011) will be added to the network, this value will reach ~70%.
- KAGRA detector (Somiya et al. 2012, Aso et al. 2013) may join LIGO and Virgo during O3, however its sensitivity may not be sufficient for a scientific contribution
- During O3, the expected detection rate of Binary Black Hole (BBH) mergers ranges from a few per month to a few per week. At design sensitivity, $\approx 10^2$ BBH detections per year are expected.
- The expected detection rate of BNS mergers during O3 is up to one per month, and may reach a few per month at design sensitivity
- There is still a lack of Neutron Star – Black Hole merger detections, however the first one may happen during O3
- We should be ready for a nearby Core-Collapse SuperNova during O3

Importance of Low-Latency Follow-up

- During the first two observational runs (O1 and O2) of Advanced LIGO and Virgo, GW candidates were shared rapidly to partner observatories
- Going forward, GW candidates will be shared at increasing rates and decreasing latency
- During O2, the False Alarm Rate (FAR) of shared triggers was set at 1/month. The future trigger rate will likely be higher than this.
- Follow-up observatories can select GW triggers based on different parameters, given in Open Public Alerts starting from O3:
  arrival time, source type, source distance, skymap, significance (FAR)
- For compact binary mergers, information on possible NS and remnant matter is also given, pointing out likely electromagnetically (EM) bright sources
- GW candidates can be identified with a latency of ~ 1 min
- During O1 and O2, a human data quality check introduced a ~30 min delay
- Given the expected short duration of Very High Energy (VHE) emission, CTA will need to rely on the earliest available reconstruction
- Later human data quality check may result in a retraction of the GW candidate

Key Characteristics of CTA Telescopes

LST → Large-Sized Telescope

MST → Medium-Sized Telescope

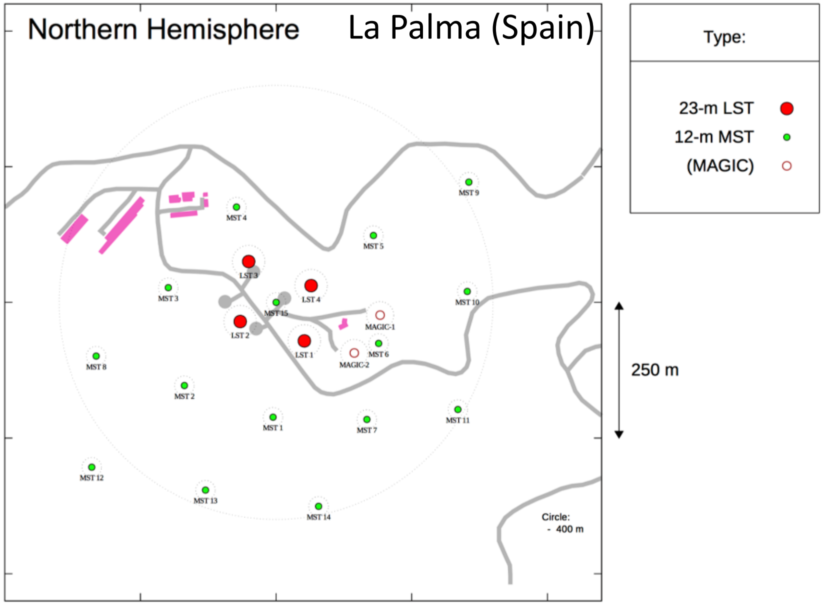
SST → Small-Sized Telescope

SCT → Schwarzschild-Couder Telescope
→ dual-mirror version of MST
with a 9.7 m primary mirror

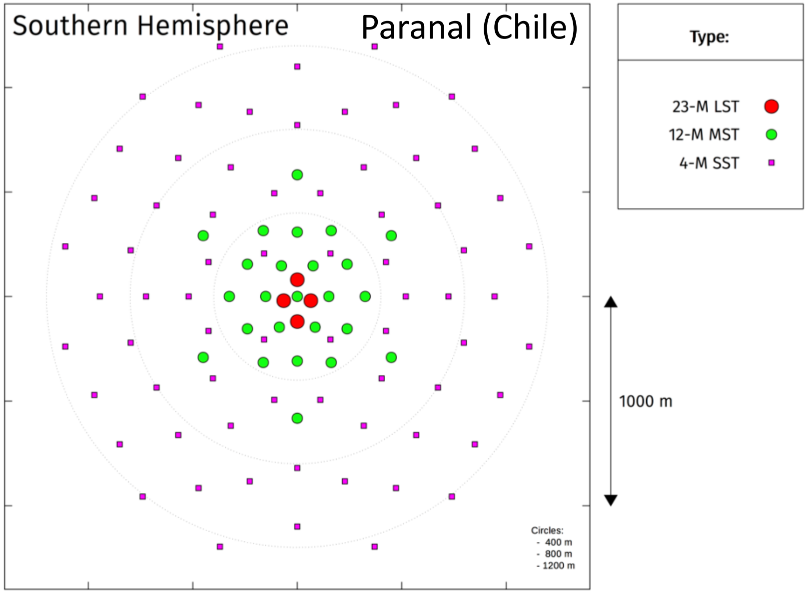
Telescope	Diameter	Energy Range	Angular Resolution	Field of View (FoV)	Slewing Time
LST	23 m	≤ 0.1 TeV	~ 0.25°	~ 5°	< 20 s
MST	12 m	0.1–10 TeV	~ 0.07°	~ 8°	< 90 s
SST	4 m	≥ 10 TeV	~ 0.03°	~ 10°	< 60 s

"Science with the Cherenkov Telescope Array" (book → arXiv:1709.07997)
+ www.cta-observatory.org

CTA Layouts and Expected Performance

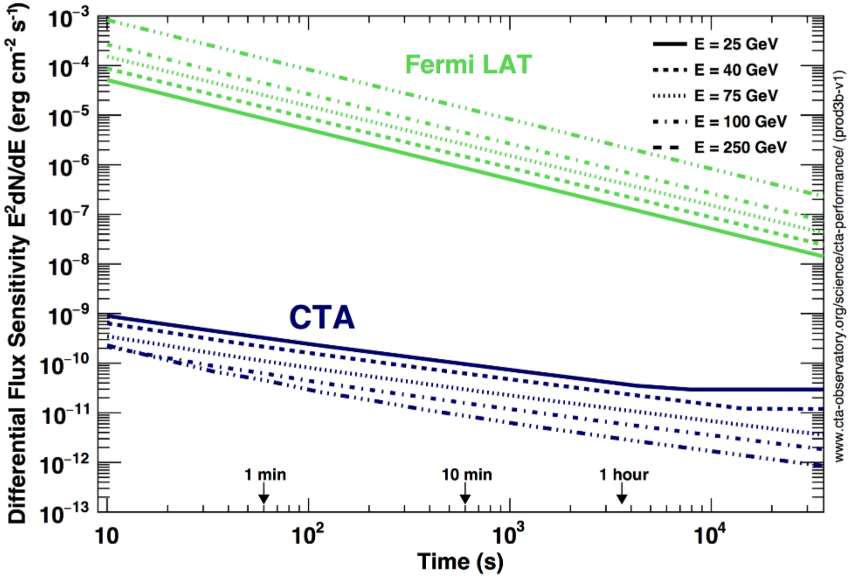


4 LS4 LSTs, 15 MSTs



4 LSTs, 25 MSTs, 70 SSTs

www.cta-observatory.org



LST prototype inaugurated on La Palma in October 2018, near the two MAGIC telescopes

SSTs will be deployed only in the South to enhance observations of the Galactic plane

Sensitivity vs observation time for zenith angle ~20°

Follow-up of Transient Sources with CTA

- Within the CTA Key Science Project on Transients, those associated with GWs are the highest priority targets
- The observation time devoted to follow up GW transients will range from a maximum of 20 hr/yr/site, before array completion, to 5-10 hr/yr/site with the full array
- “Divergent” pointing mode may reduce the time required to tile a large localization area at a given sensitivity
- Real Time Analysis (RTA) can identify transient sources and automatically issue an alert within 30 s
- Follow-up of GW transients during dark time with zenith angles $< 70°$ for 2 hr each, adding exposure time in case of detection
- Operation even during bright moonlight thanks to SiPM technology
- Possible operation of the LST prototype in coincidence with the two close MAGIC telescopes, which recently discovered the first TeV emission from a GRB → GRB190114C (Atel #12390, GCN 23701), long GRB, $t_{start} = 50$ s

"Science with the Cherenkov Telescope Array" (book → arXiv:1709.07997)

Previous Strategies with Cherenkov Telescopes

- H.E.S.S., MAGIC and VERITAS followed up GW transients searching for VHE gamma-ray emission as stipulated in Memoranda of Understanding with the LIGO/Virgo Collaboration during O1 and O2
- MAGIC followed up the BBH merger GW151226 (Carosi et al. 2017), manually selecting four pointings (average exposure 42 min) based on visibility, overlap with existing catalogues, observations of other telescopes. No source was detected.
- VERITAS followed up the 50-solar-mass BBH merger GW170104 at redshift 0.2 (GCN Circ. 21153), tiling the Northern fraction of the localization map with 39 pointings (~5 min each).

  The sensitivity reported was 0.5 Crab at E > 100 GeV.
- H.E.S.S. followed up the BNS merger GW170817 (Abdalla et al. 2017), starting 5.3 hr after the event. Its observational strategy included folding the localization map with a galaxy catalogue and prioritization of targets according to sky distribution and observational constraints. The first of the observed regions included the location of the EM counterpart.

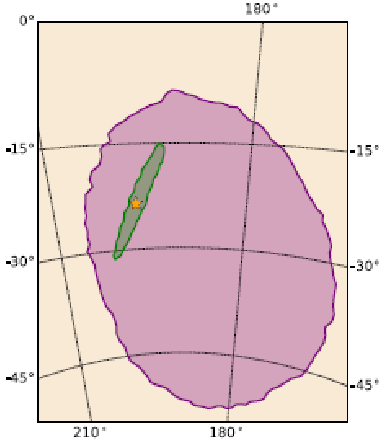
  Upper limits were set between 0.28 and 8.55 TeV.

LIGO/Virgo Alerts for the Follow-up

The LIGO/Virgo alert process results in the publication of an alert via the Gamma-ray Coordinates Network (GCN), as for GRBs

Considering the case of GW170817:

- the event was recorded 6 min after the merger (Abbott et al. 2017)
- the GCN alert was sent ~35 min later, due to human intervention
- a LIGO/Virgo skymap of ~30 deg^2 (90% c.l.) was distributed 5 hr after the merger
- this GW skymap identified a region smaller than the Fermi-GBM skymap for GRB170817A (distributed 14 s after detection, Goldstein et al. 2017), allowing the discovery of the optical transient and the identification of the host galaxy
- partner observatories scanned the GRB localization region until the improved GW localization became available
- the Swope Telescope, even though small, discovered the optical counterpart by targeting galaxies within the GW skymap (Coulter et al. 2017)



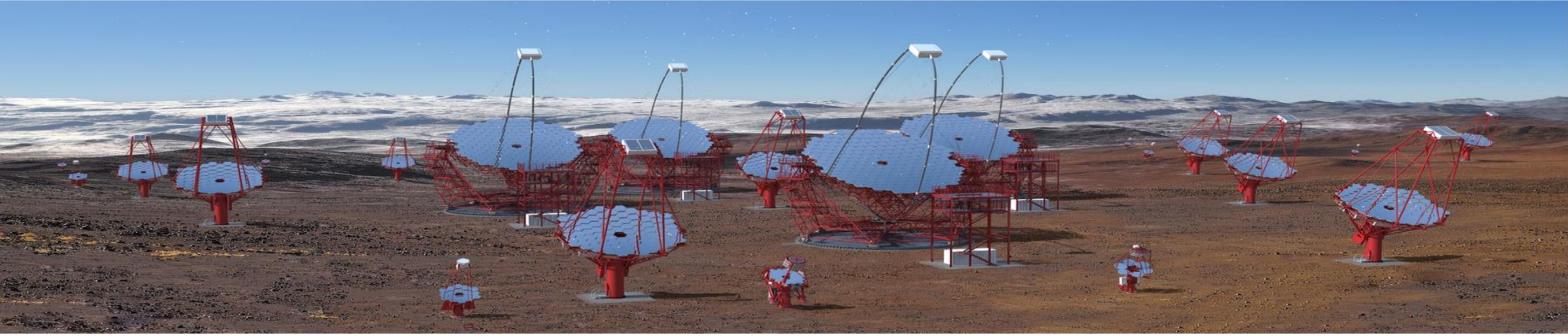
Abbott et al. (2017)

Conclusions

Important directions to maximize the GW follow-up potential of CTA:

1) Low-latency (≈min) GW alerts are critical, full automation is required. Tolerance for FAR higher than 1/month if $T_{obs} \approx 1000$ s.
2) Even a single LST telescope may detect a VHE transient at ≈ 100 Mpc
3) Due to CTA large FoV (multi-deg^2 with some sensitivity degradation off axis) and few VHE transients, there is no need for galaxy catalogs
4) Most GW candidates can be followed up (not all BBH mergers), assuming $T_{obs} = 1000$ s per event and a dedicated time ~10 hr/yr/site
5) Deeper (preferably longer) observation of promising GW events, maybe guided by a prompt result of the RTA
6) Multi-messenger (GRBs, neutrinos) follow-up also to refine pointing
7) Multi-messenger alert, with better localization (≈0.1°) of the GW transient, to other follow-up observatories

Getting Ready for Joint GW/CTA Observations



Maybe starting from 2019