CTAO
Cherenkov Telescope Array Observatory

Chasing Gravitational Waves with the Cherenkov Telescope Array Observatory

Main authors: Jarred Green, Lara Nava, Barbara Patricelli, Monica Seglar-Arroyo, Fabian Schüssler, Antonio Stamerra, for the CTAO-GW team (*on behalf of the CTAO-Consortium*)

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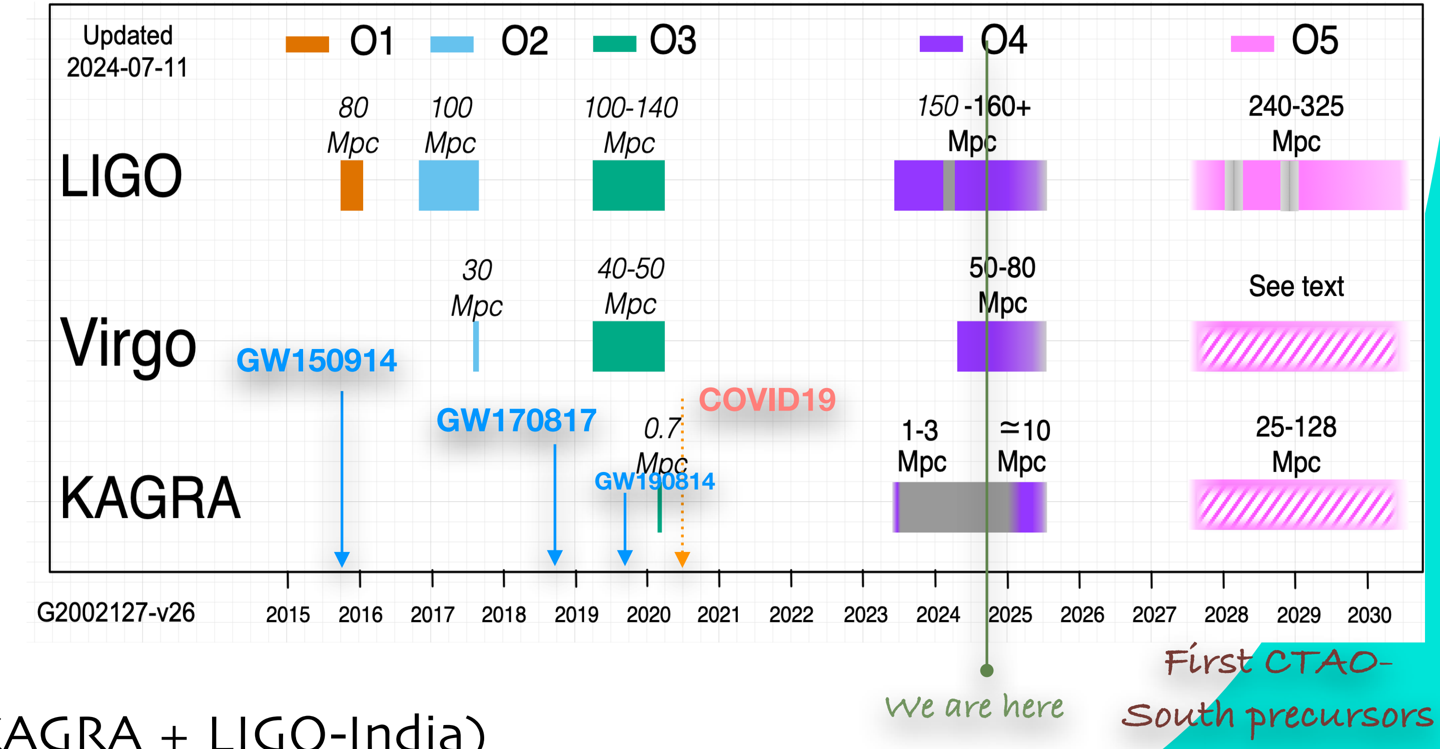
GW interferometers - scientific runs

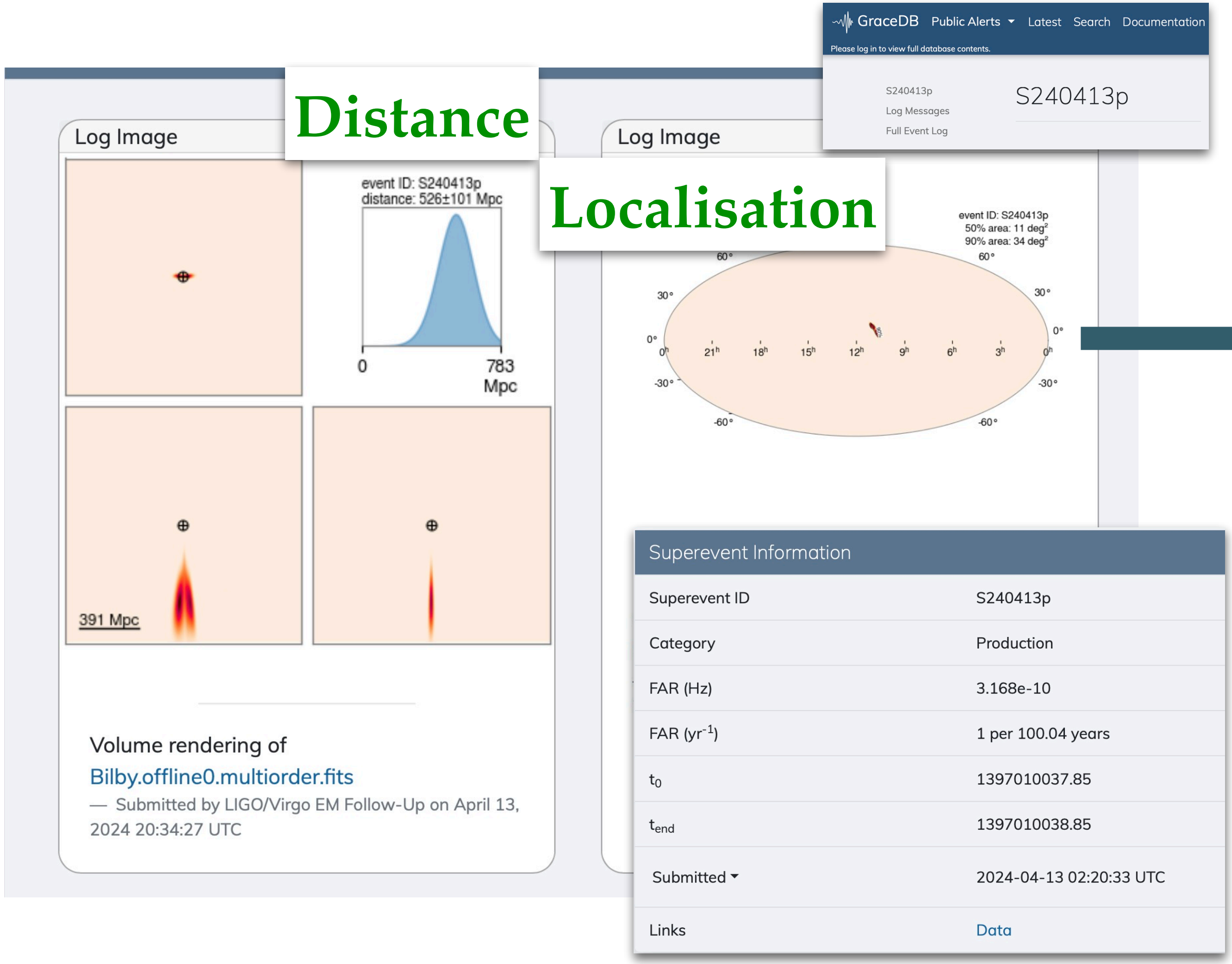
- Run 01 (2x LIGO)
  Sept 2015 - Jan. 2016
  First GW (BH-BH) event!
- Run 02 (LIGO + VIRGO)
  2016-2017; 6 months; Virgo: Aug. 2017
  First e.m. counterpart of BNS merger!
- Run 03 (LIGO + VIRGO) -advan. phase
  February 2019; 1 year - O3a / O3b
  First NS-BH events!
  March 27th: stop due to COVID19...
- Run O4 - (LIGO+VIRGO+KAGRA)
  Started 24 May 2023 until 2025, June 9th
- Run O5 - AdV+ phase (LIGO+VIRGO+KAGRA + LIGO-India)
  2027-2030

https://observing.docs.ligo.org/plan/



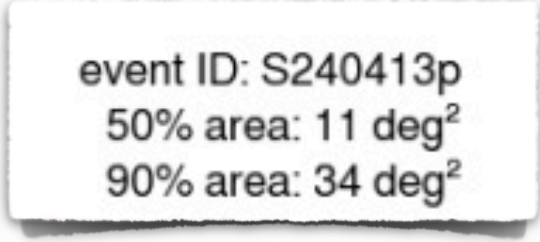
Run O5 matches the current CTAO timeline

GW interferometers - scientific runs



Superevent Information	
Superevent ID	S240413p
Category	Production
FAR (Hz)	3.168e-10
FAR (yr^{-1})	1 per 100.04 years
t_0	1397010037.85
t_{end}	1397010038.85
Submitted	2024-04-13 02:20:33 UTC
Links	Data

First significant event in O4b, including Virgo
April 13, 2024 - BBH @526 Mpc



CTAO array could cover most of the region with a single or a few pointings!

https://gracedb.ligo.org/superevents/S240413p/view/

GW e.m. counterparts

- Binary Neutron Star mergers (BNS) ➔ short GRB
  suggested (since Eichler+1989), expected (GRB050724) and observed (GW/GRB170817)
  - But 3 long GRBs were associated kilonova (GRB060614, GRB211227, GRB230307A) —> scenario not straightforward

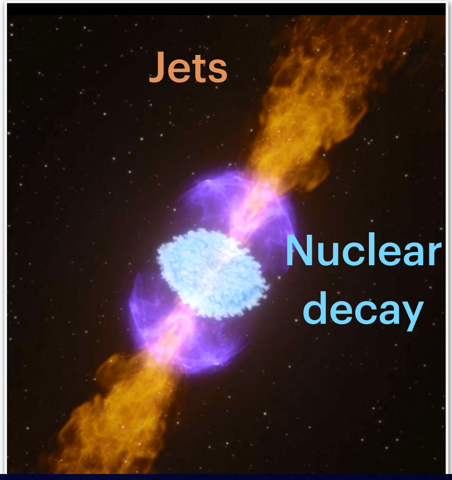
- Black Hole (BH)-NS ➔ short GRB ?
  e.g. Berger+2014, Barbieri+2020, Rossi+2019 e.g. GRBs 050509B, 061201.

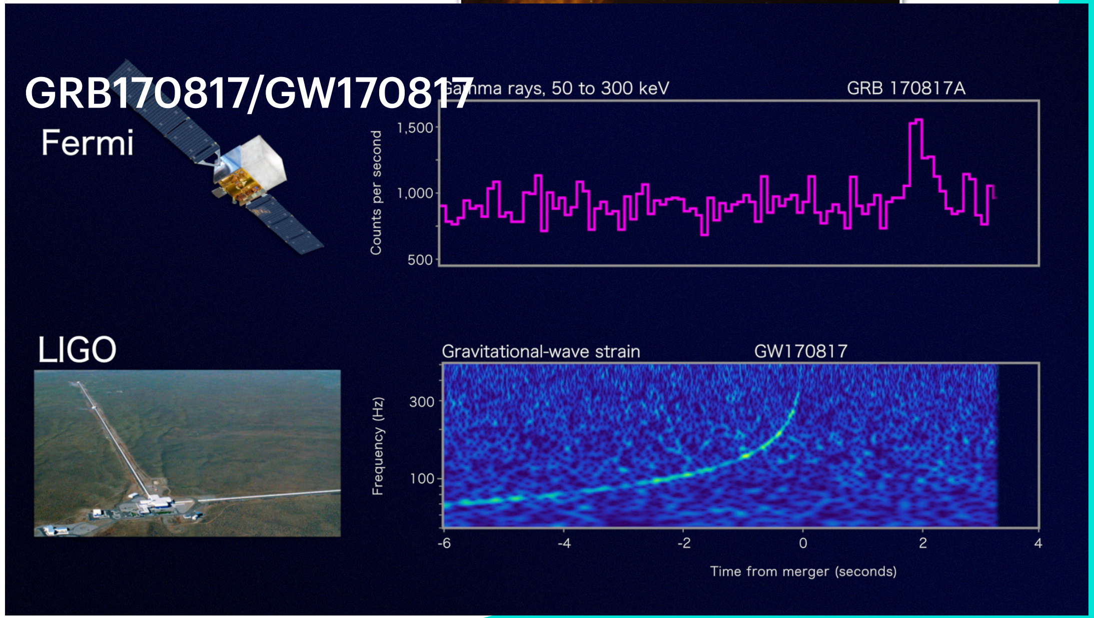
- BH-BH: ?? no EM emission expected
  (but Loeb+2016, Perna+2016, Murase+2016, Graham et al. 2020,…)

- SN collapse: long GRB ? (LIGO coll. 2014, LVC 2021)

What do we expect in the TeV band?

Electromagnetic emission

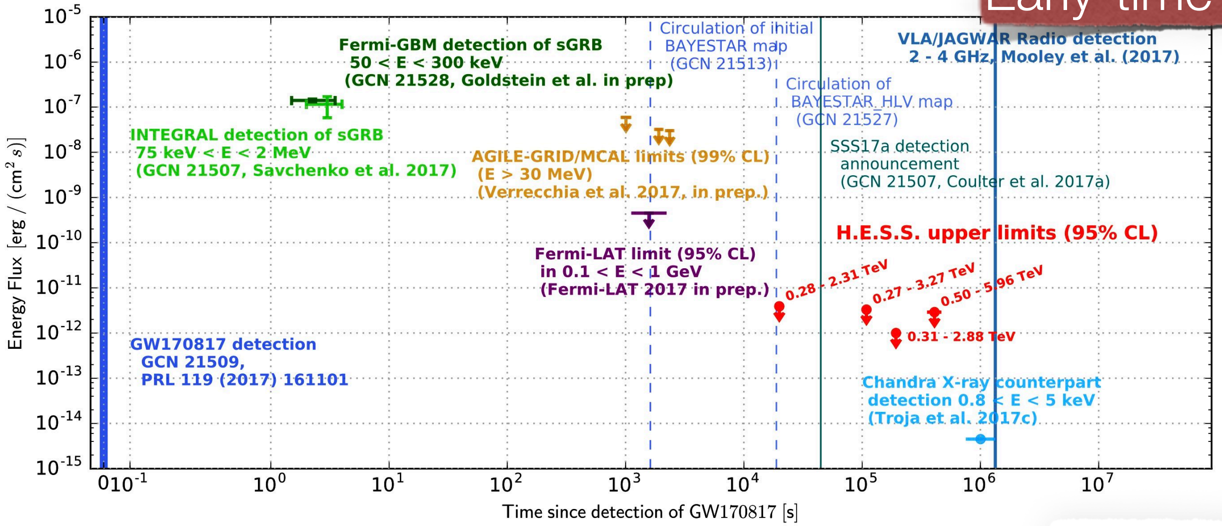




GWs and GRBs at TeV energies

No detection of GeV-TeV emission from the counterpart of GW170817/GRB170817A

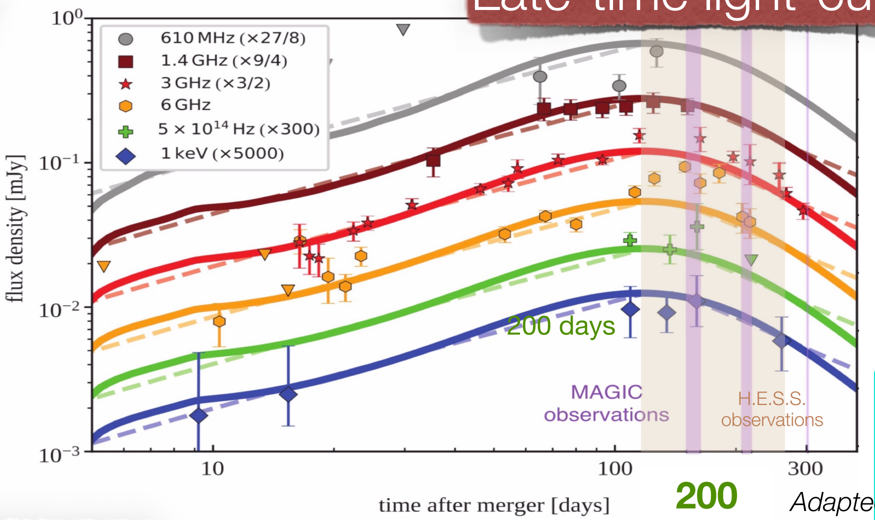
Early-time light-curve



Abdalla et al. (HESS coll), 2017

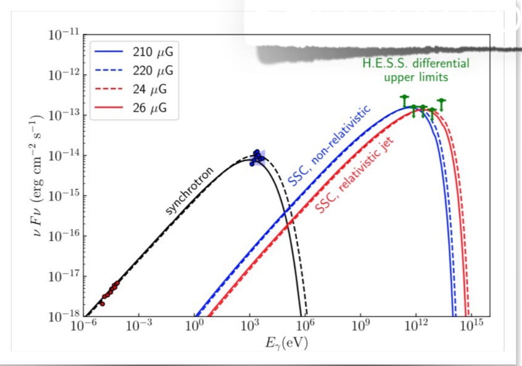
No detection at the maximum of the delayed emission

Late-time light-curve

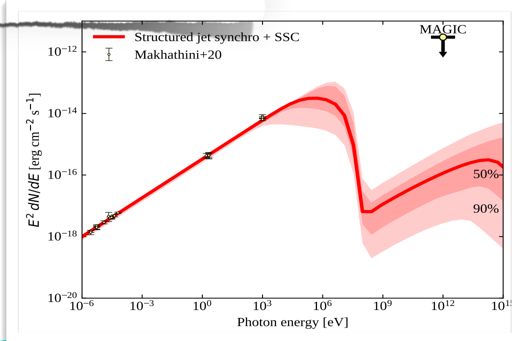


200 days

Adapted from Ghirlanda+2019



H.E.S.S. coll., 2020 ApJL, 894



AS, Salafia O. S., et al. 2021a, PoS, 944

GWs and GRBs at TeV energies

★Detection of the TeV (afterglow) emission

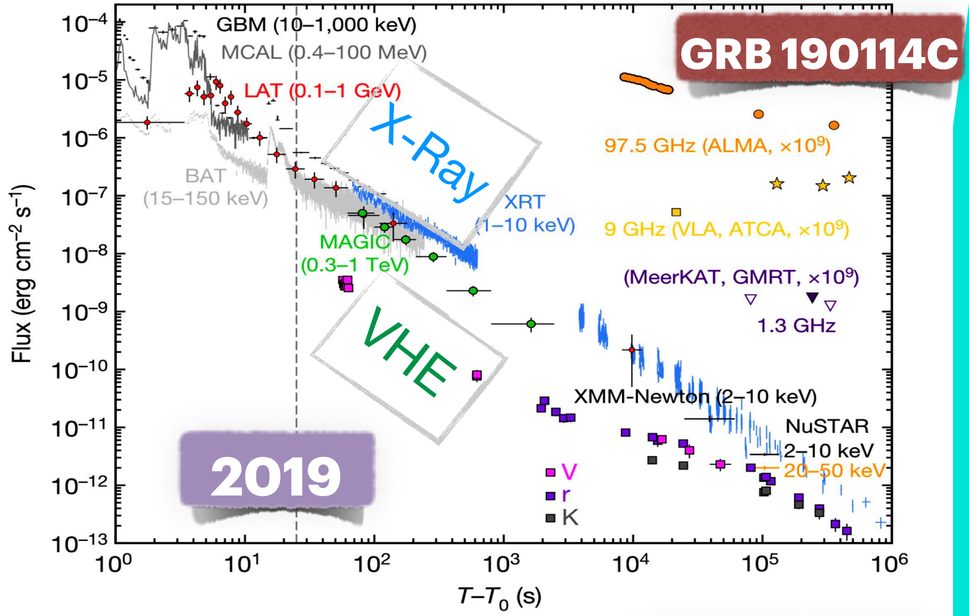
✓GRB engine accelerates photons up to TeV

Gamma rays up to 12 TeV from the GRB 221009A!

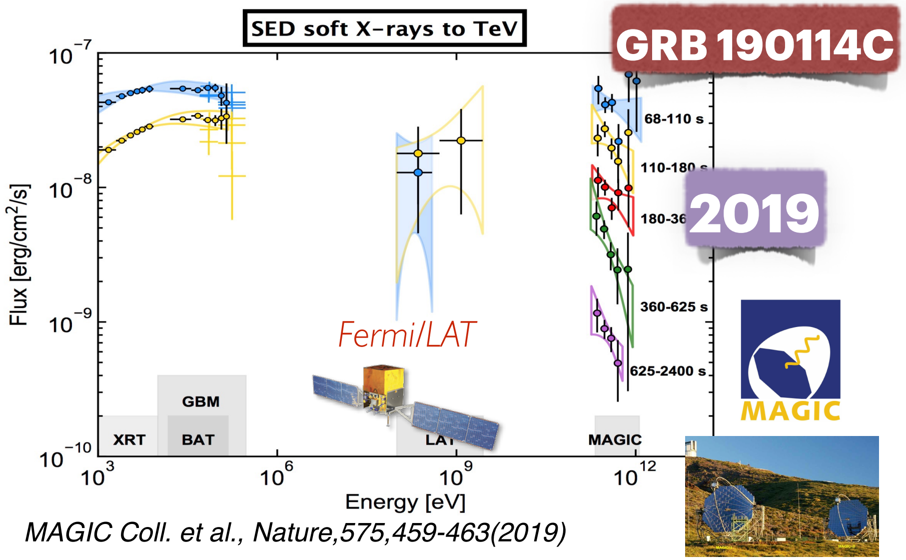
✓Evidence of a second energetic component

✓Energy budget and time evolution similar to the optical-X-ray component: *TeV flux follows closely the X-ray flux*

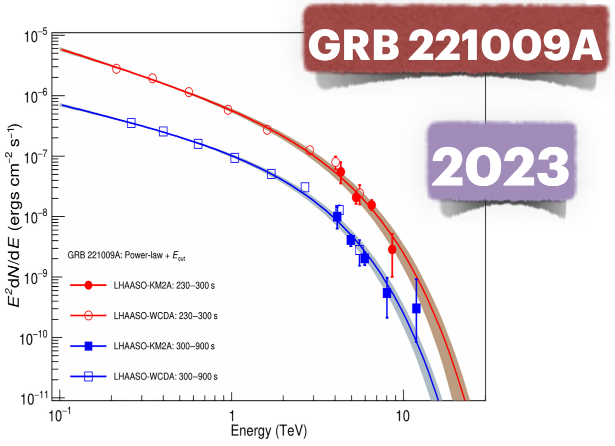
lightcurve



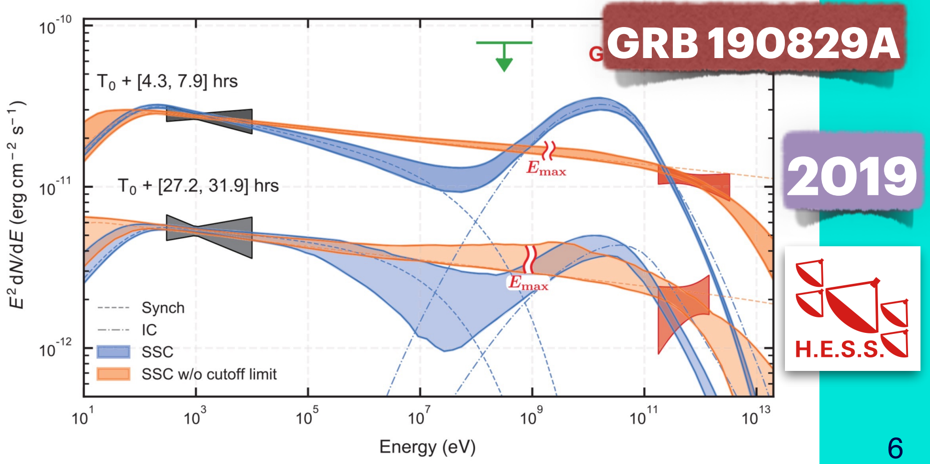
S E D



MAGIC Coll. et al., Nature,575,459-463(2019)



LHAASO Coll. et al., Science,9,46 (2023)



H.E.S.S. Coll., Science, 372 (2021)

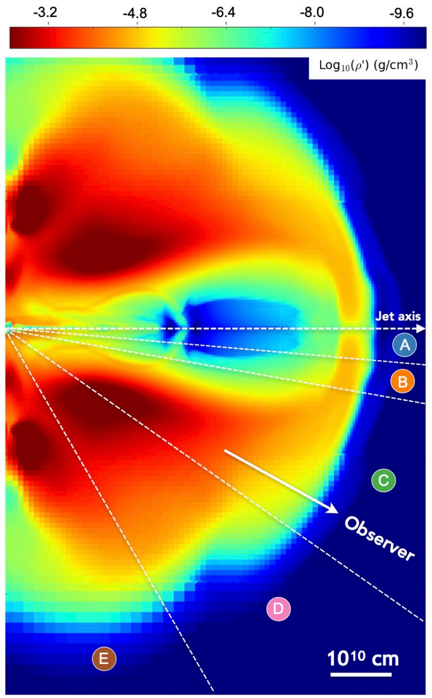
The Role of Off-axis Observations and structured Jet

GeV-TeV emission is expected from the relativistic outflow (jets)

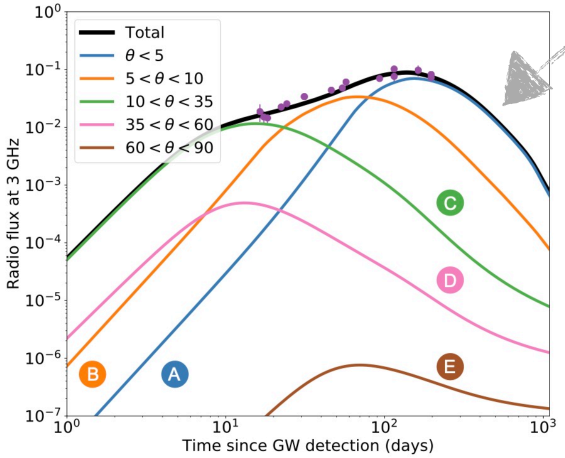
In GW-counterparts, the jet is seen preferentially **off-axis:** small Lorentz factor

➡️ intensity weaker 10^{-4} to 10^{-6} times than on-axis emission

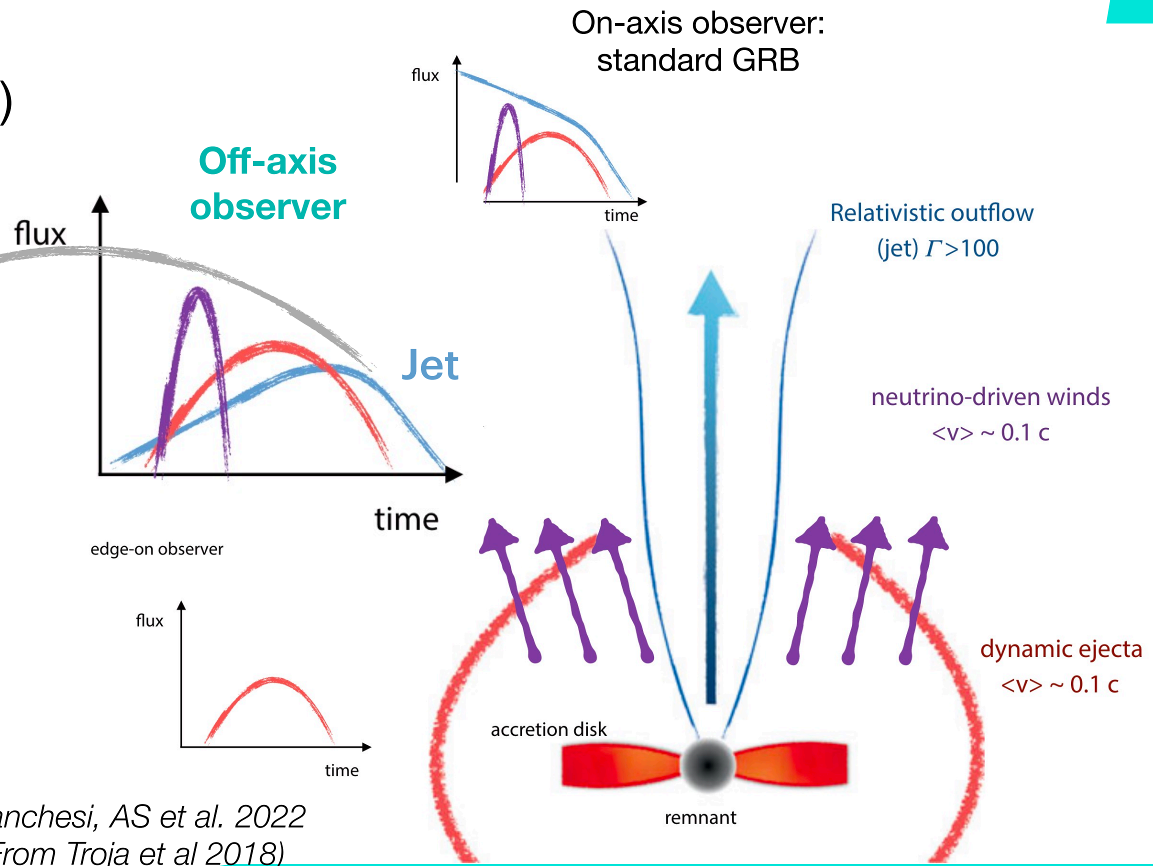
➡️ light curve delayed (hours/days/months, depending on θ_{view})



Off-axis observer and STRUCTURED JET



Hydrodynamical simulation of a short GRB (Lazzati+2018)



Branchesi, AS et al. 2022 (From Troja et al 2018)

The Role of Off-axis Observations and structured Jet

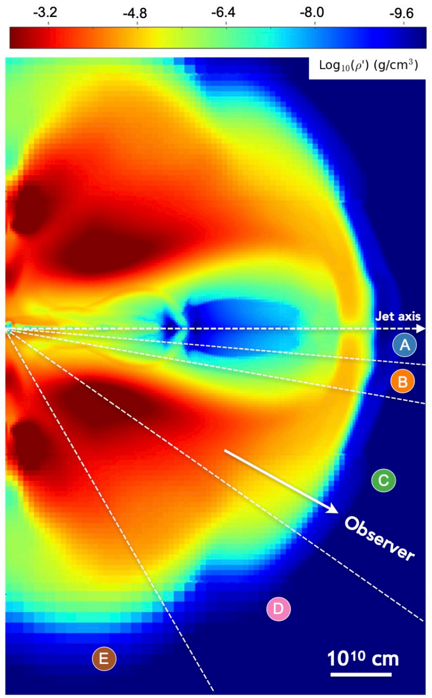
GeV-TeV emission is expected from the relativistic outflow (jets)

In GW-counterparts, the jet is seen preferentially **off-axis:** small Lorentz factor

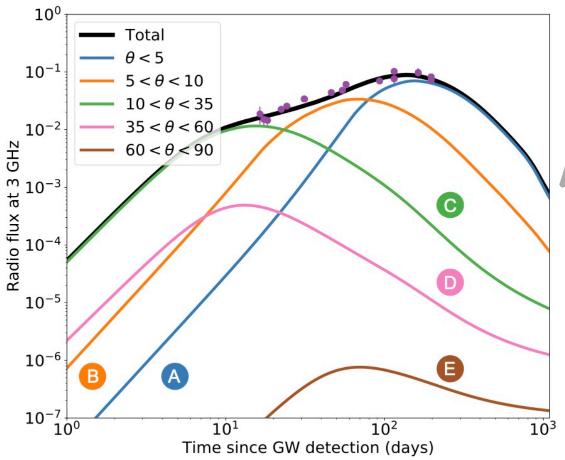
➡️ intensity <u>weaker</u> 10^{-4} to 10^{-6} times than on-axis emission

➡️ light curve <u>delayed</u> (hours/days/months, depending on θ_{view})

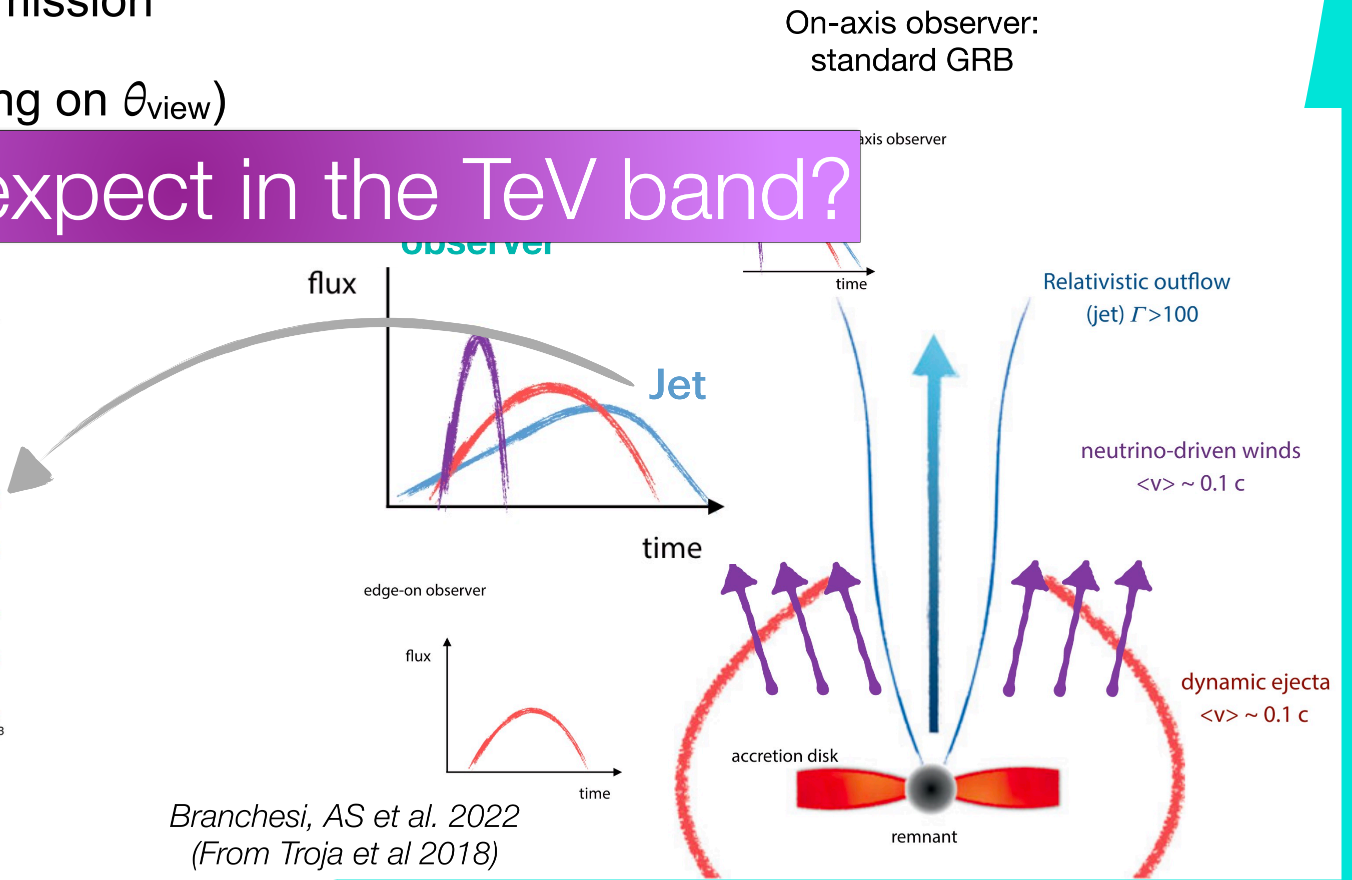
What do we expect in the TeV band?



STRUCTURED JET

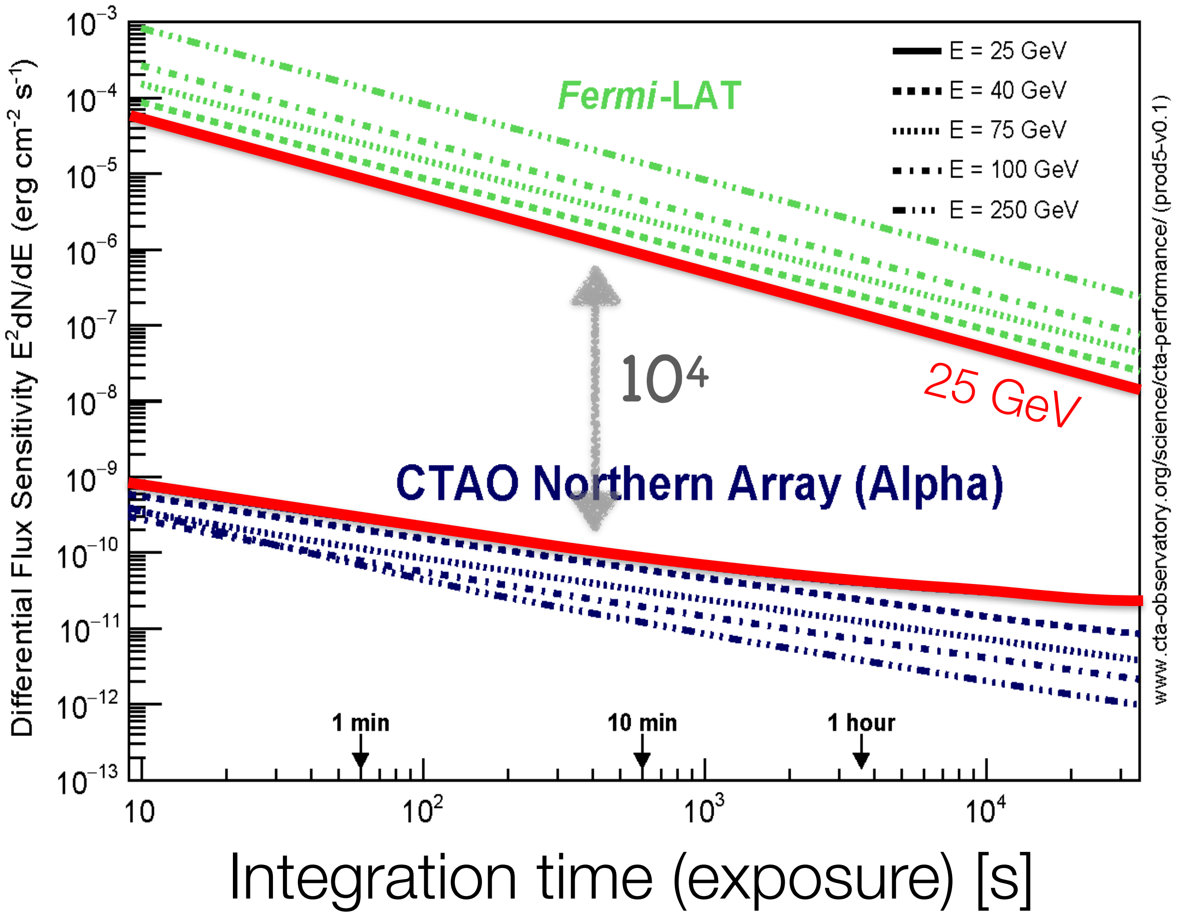


Hydrodynamical simulation of a short GRB (Lazzati+2018)

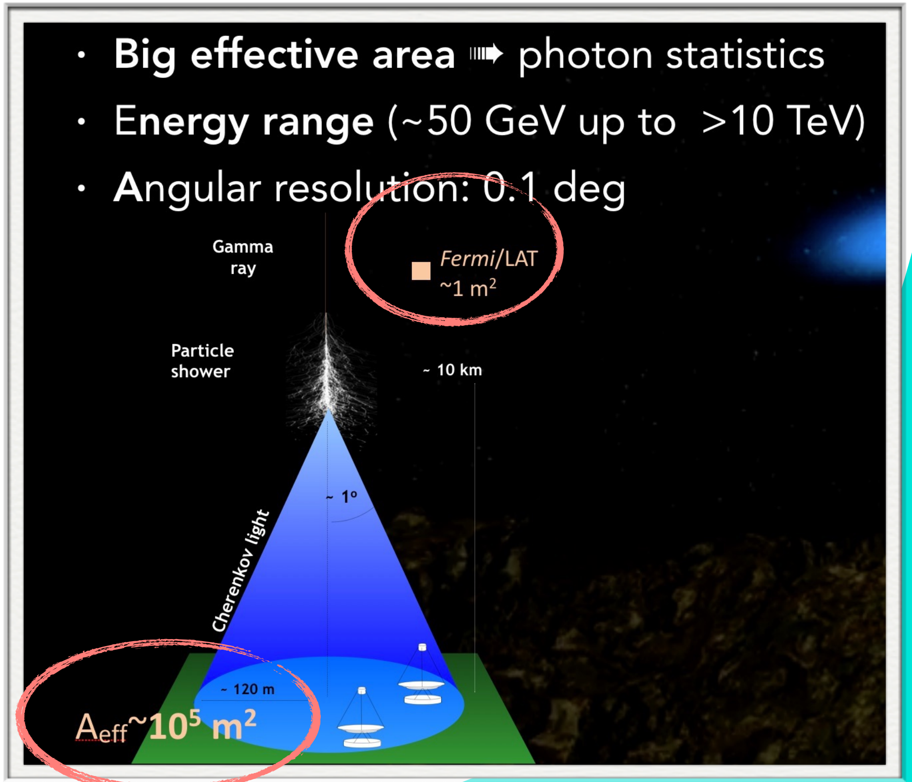


Branchesi, AS et al. 2022
(From Troja et al 2018)

CTAO performances: Sensitivity to transient and flaring sources



Extended "spectral arm leverage"
High statistics (=precision) on flares

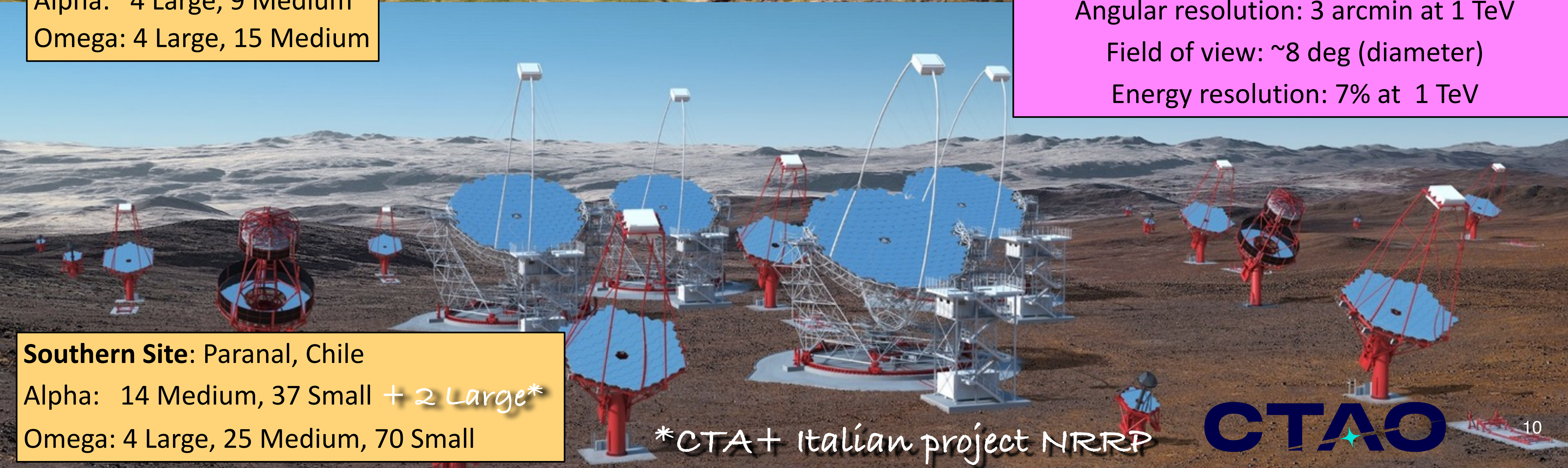


The Cherenkov Telescope Array Observatory

Northern site: La Palma
Alpha: 4 Large, 9 Medium
Omega: 4 Large, 15 Medium

CTA in a nutshell

Energy range: 20 GeV to 300 TeV
Sensitivity improvement: ×5 to ×20 (~mCrab)
Angular resolution: 3 arcmin at 1 TeV
Field of view: ~8 deg (diameter)
Energy resolution: 7% at 1 TeV



Southern Site: Paranal, Chile
Alpha: 14 Medium, 37 Small + 2 Large*
Omega: 4 Large, 25 Medium, 70 Small

*CTA+ Italian project NRRP

CTAO

A Dedicated Study on the CTAO's Prospects on GW Follow-ups

CTAO

G O A L S

Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

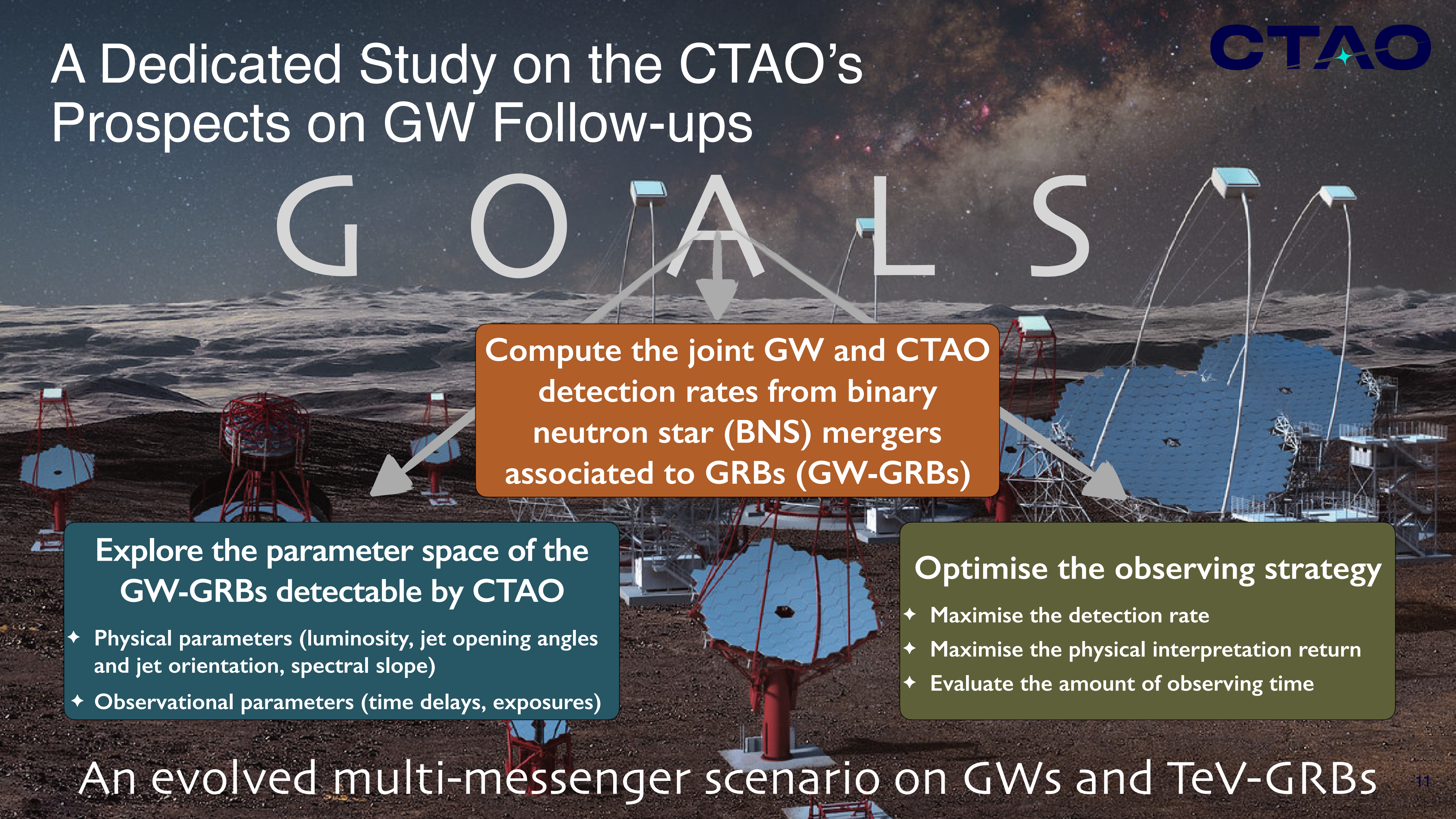
Explore the parameter space of the GW-GRBs detectable by CTAO

- Physical parameters (luminosity, jet opening angles and jet orientation, spectral slope)
- Observational parameters (time delays, exposures)

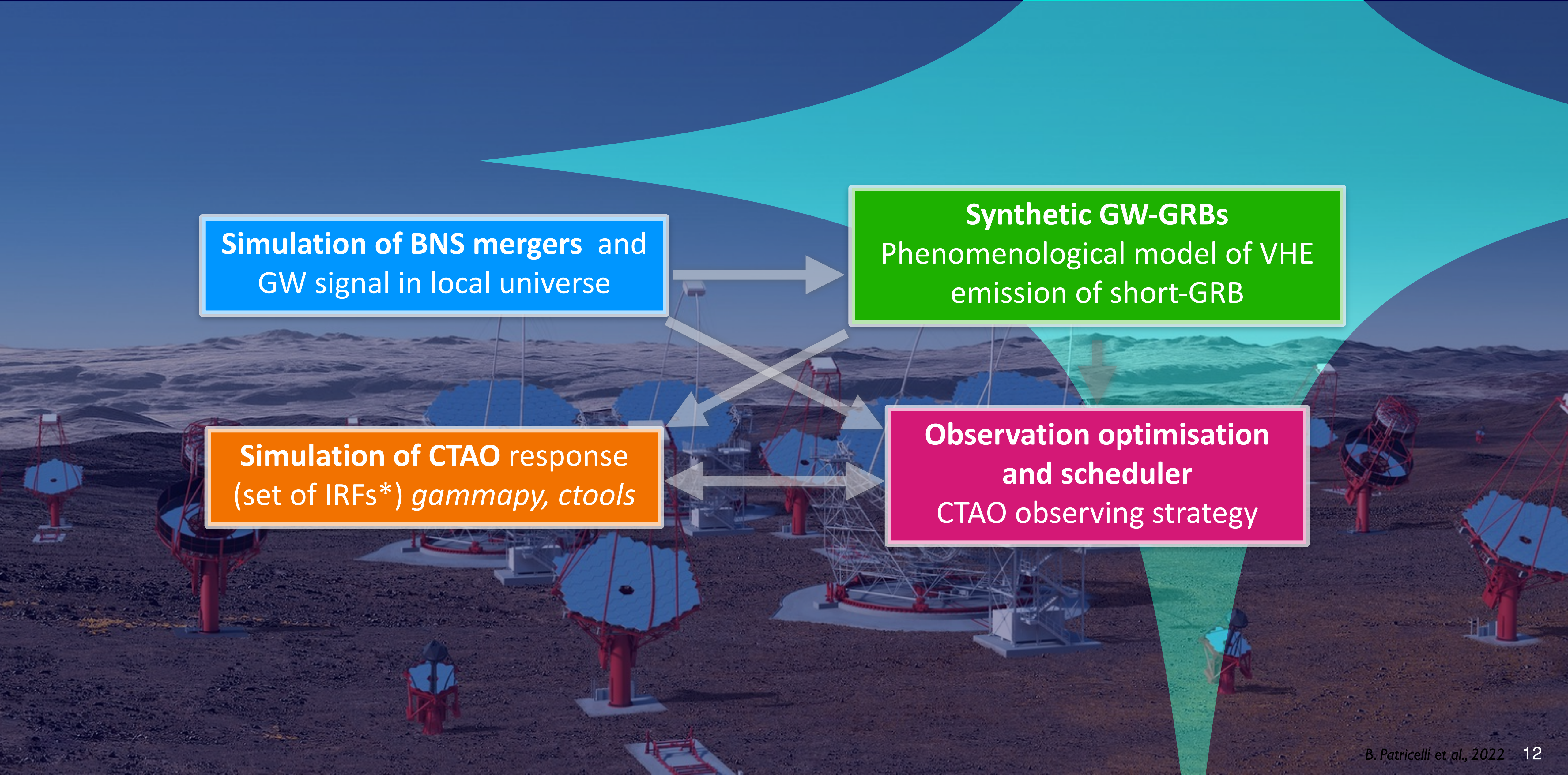
Optimise the observing strategy

- Maximise the detection rate
- Maximise the physical interpretation return
- Evaluate the amount of observing time

An evolved multi-messenger scenario on GWs and TeV-GRBs



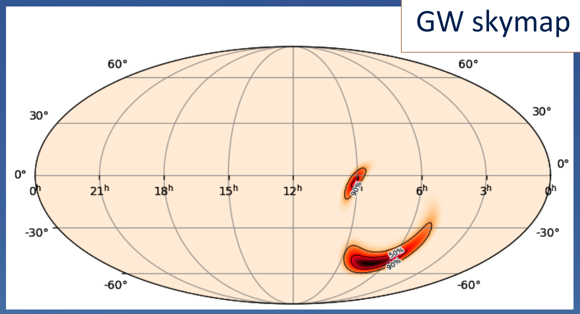
The GW-TeV and CTAO simulation chain



B. Patricelli et al., 2022

THE GW-TEV AND CTAO SIMULATION CHAIN

CTAO



GW skymap

- Gravitational wave catalogue of simulated binary neutron star (BNS) mergers from *Petrov et al. 2022 for O5 (O6)*
- ~2300 (8160) compact binaries in O5 (O6*) *detected*

Simulation of BNS mergers and GW signal in local universe

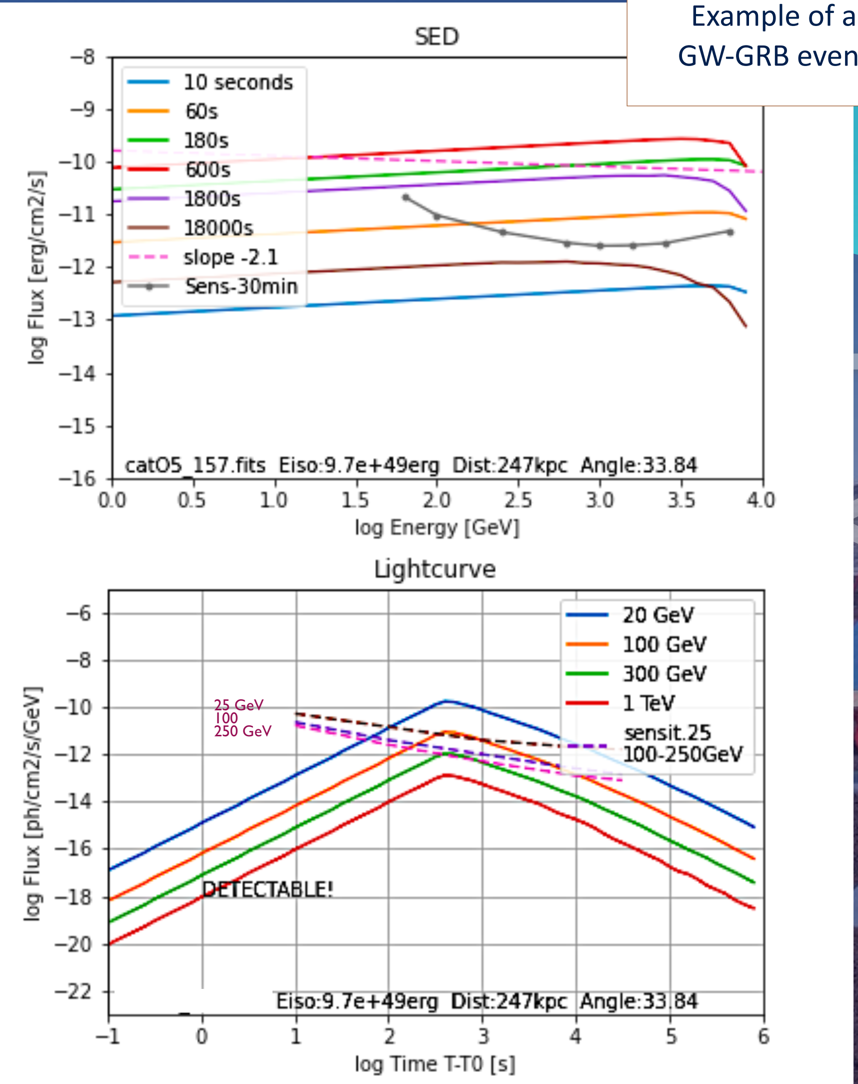
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTAO response
(set of IRFs*) *gammapy, ctools*

Observation optimisation and scheduler
CTAO observing strategy

★ O6 will have same sensitivity as O5 with the addition of LIGO-India

THE GW-TEV AND CTAO SIMULATION CHAIN



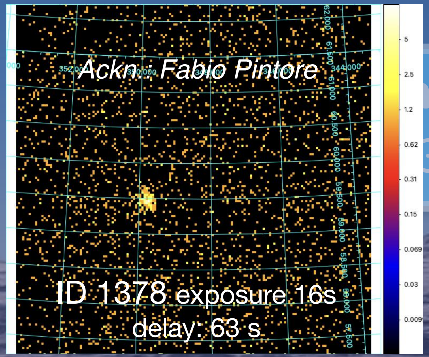
Example of a GW-GRB event

Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Phenomenological simulation of afterglow emission from short GRBs, built on short-GRB detections, GRB detections at TeV energies and flux upper limits by IACTs and X-ray observations

- **Jet opening angle** inferred from short-GRBs seen on-axis, average:~14deg
- **Viewing angle** from the inclination of the BNS
- **Lightcurve**: follows deceleration phase + similar temporal decay as in X-rays
- **Spectrum**: Photon index ~-2; Density of the external medium ~0.1 cm^{-3}
- **Jet structure:** Gaussian distribution for both energy and Lorentz factor

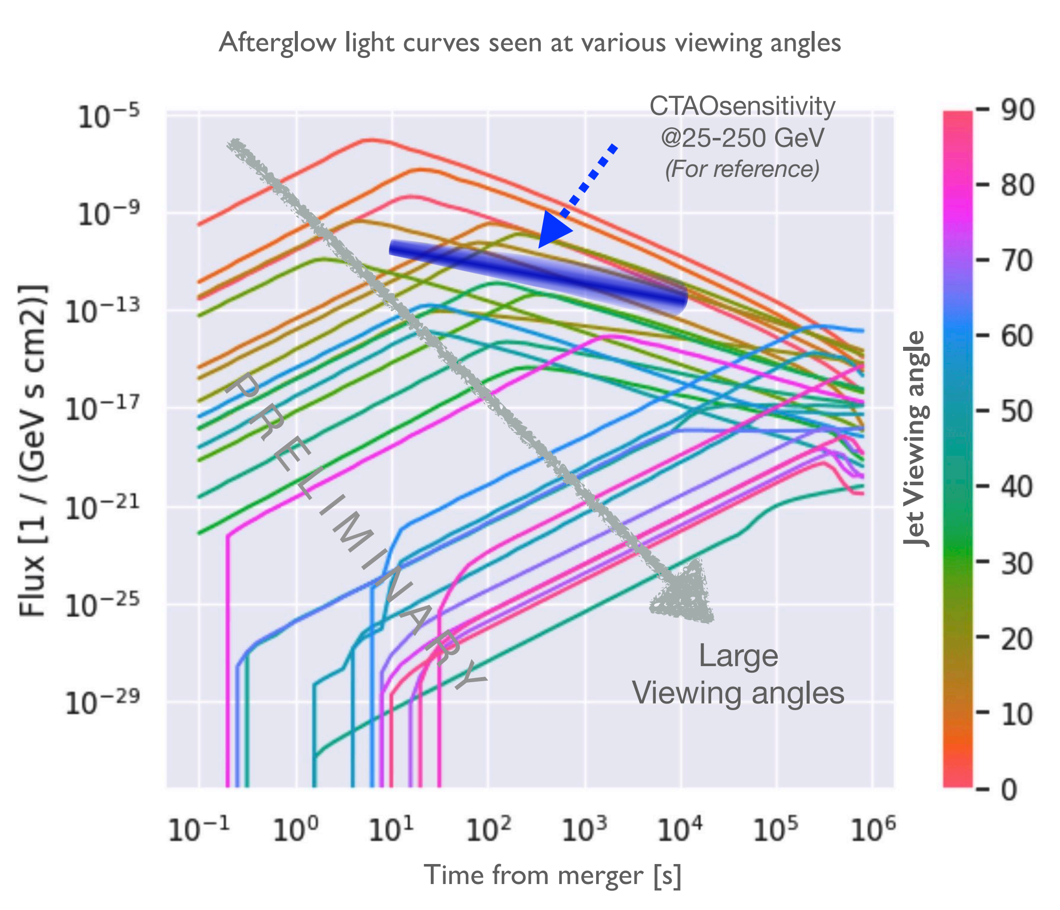
The GW-TeV and CTAO simulation chain



- Computation of CTAO sensitivity tailored on the GW-GRB models, including EBL absorption
- CTAO Alpha configuration

Simulation of CTAO response (set of IRFs*) *gammapy, ctools*

* **IRF: Instrument Response Function**



First preliminary results - 1. detectability

Simulation of CTAO response (set of IRFs*) *gammapy, ctools*

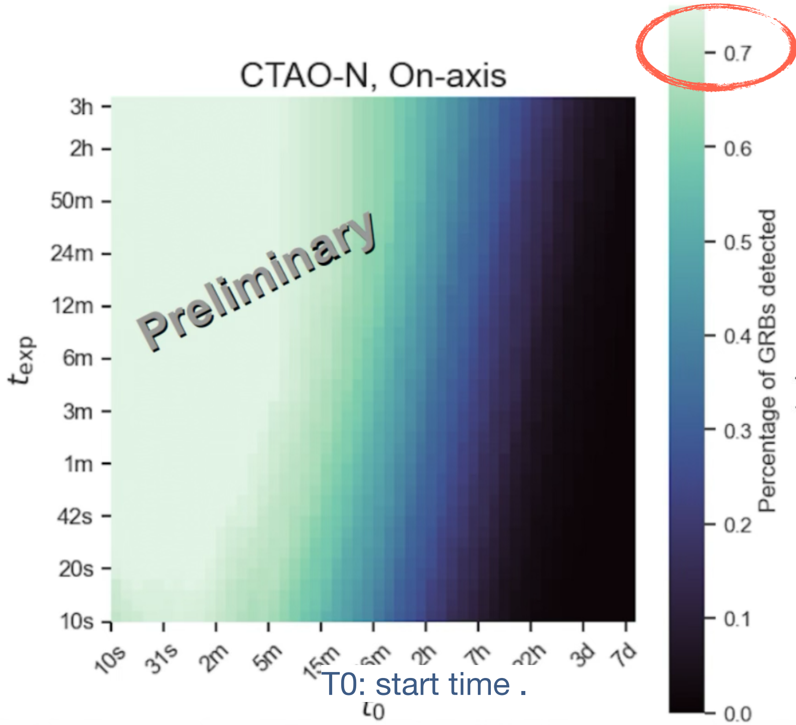
- Detection expectations by CTAO as a function of delay and exposure
- Based on the 2307 simulated GW-GRBs and the CTAO sensitivity (Alpha configuration)

t_0 ~30 sec, ~ 80% detections with T_{exp} ~ 5 min.

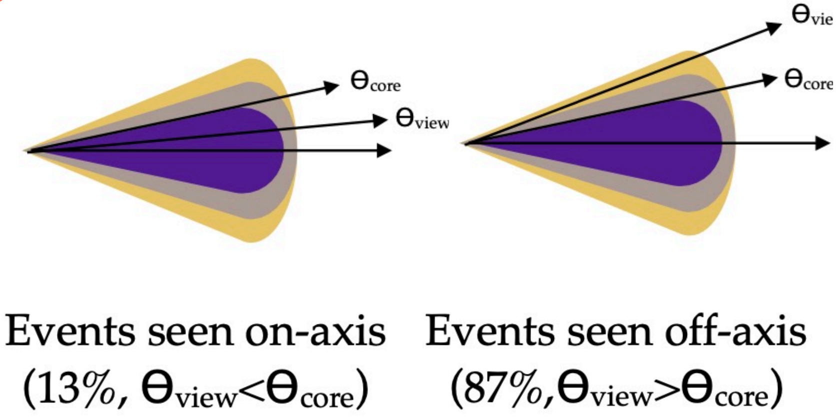
t_0 ~10 min ~ 69% detections with T_{exp} ~ 10 min.

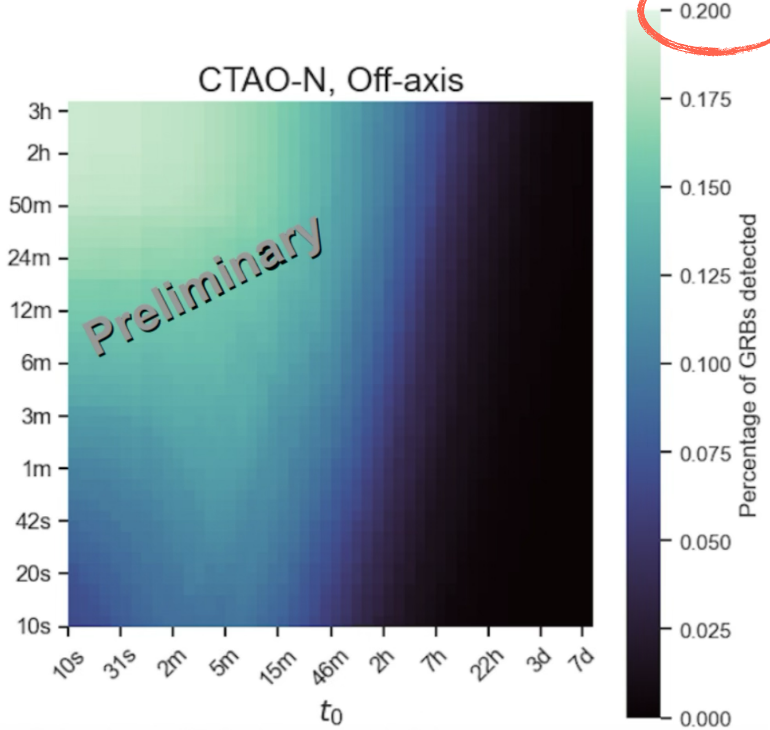
t_0 ~ 30 sec, ~ 13% detections with T_{exp} ~ 5 min.

t_0 ~ 10 min ~ 14% detections with T_{exp} ~ 10 min.



T0: start time .





The GW-TeV and CTAO simulation chain

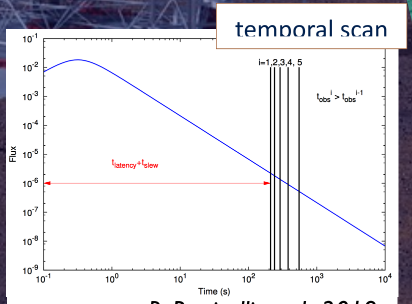
- Optimised follow-up strategy for detection: the exposure is tuned to detect the source (*Patricelli et al. 2018*).
- Realistic observing conditions for CTAO are considered (*Seglar-Arroyo et al. 2019*)
- The Scheduler iterates on the best visible positions. If the true source position is covered, by construction, it is detected.
- Based on Tilepy code (*M. Seglar-Arroyo et al. - APJS - 2024*)

Simulation of B
GW signal in

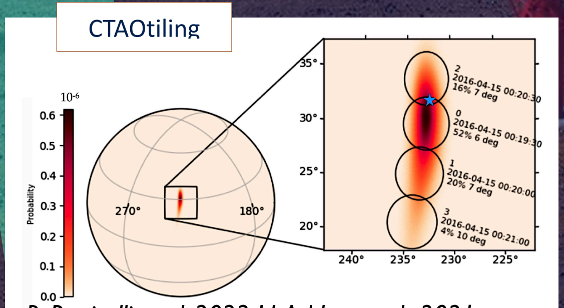
Simulation of CTAO response
(set of IRFs*) *gammapy, ctools*

tilepy
M. Seglar-Arroyo et al. - APJS - 2024

Observation optimisation and scheduler
CTAO observing strategy



B. Patricelli et al., 2018.



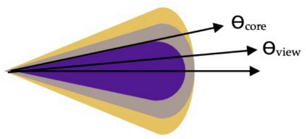
B. Patricelli et al. 2022 H.Ashkar et al., 2021

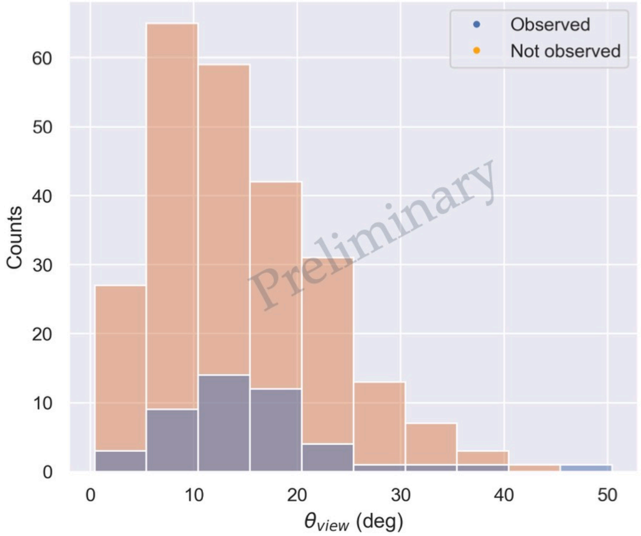
First preliminary results -
2. Realistic follow-ups and detections

Observation optimisation and scheduler
CTAO observing strategy

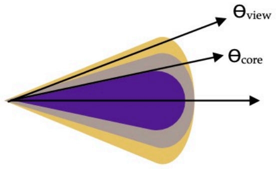
- Followed up GW-GRB events: 8% of the total population
- 4.5% of follow-ups covered the true location of the source
- on-axis events: 18% followed up; 10% covered the true location
- off-axis events: 7% followed up; 4% covered the true location

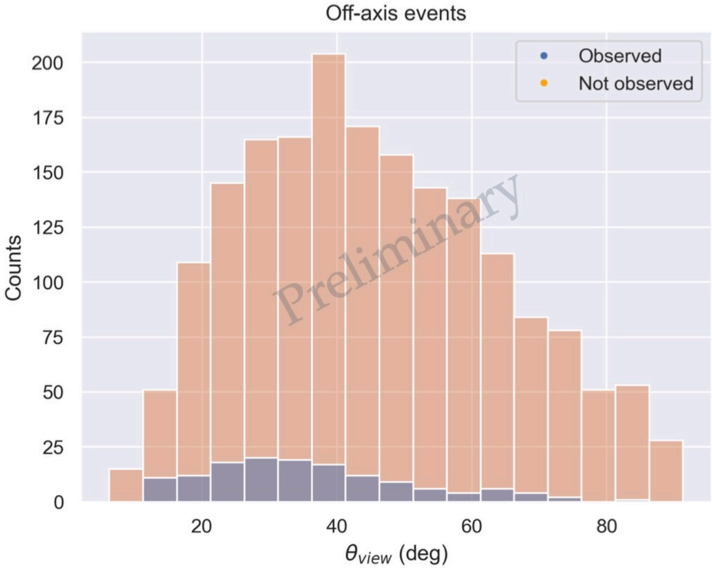
Events seen on-axis
(13%, $\theta_{view}<\theta_{core}$)





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





Realistic observing conditions for CTAO are considered (duty cycle, visibility).

No subarrays, and only North or South array

GW Follow-ups with CTAO

- ✓ A new GW and TeV-GRB landscape emerged ➟ **an expanded CTAO's science program**
- ✓ Plethora of GW triggers expected ➟ **Observing strategies and optimised follow-up observations required**
- ✓ Groundwork laid with **GW-GRB simulation chain for BNS during the LIGO-Virgo-KAGRA scientific run O5** (2027-2030)

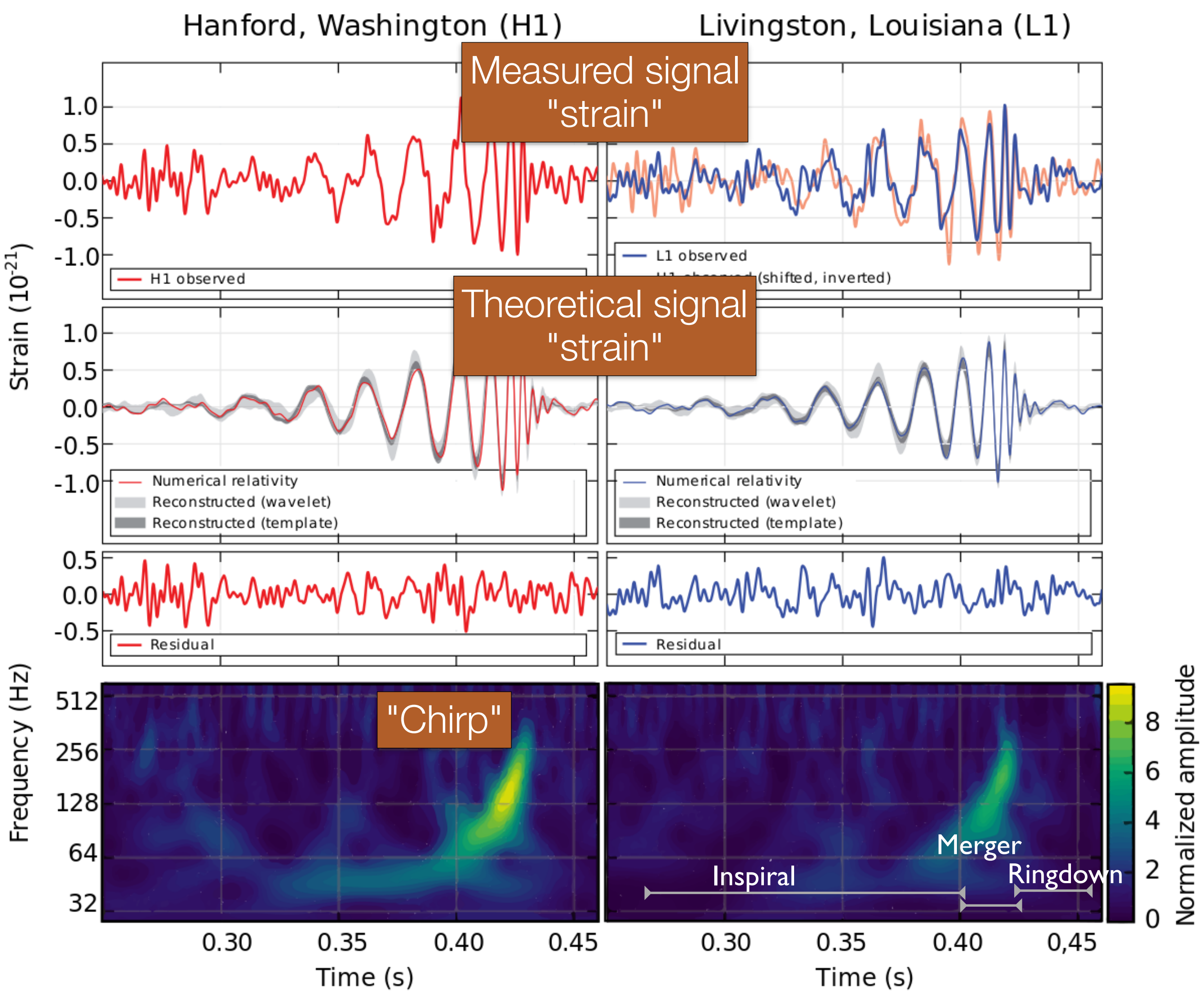
- ✱ CTAO key player in the transients and GW follow-ups!
- ✱ Further effort on prospects of CTAO with the new generation of GW interferometers, like the Einstein Telescope and Cosmic Explorer

Backup

CTAO

The era of gravitational waves

GW150914 (BBH)



Einstein equation $$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

Perturbation: "strain" $$h \sim \frac{2G}{c^4} \ddot{Q} \frac{1}{D_L}$$

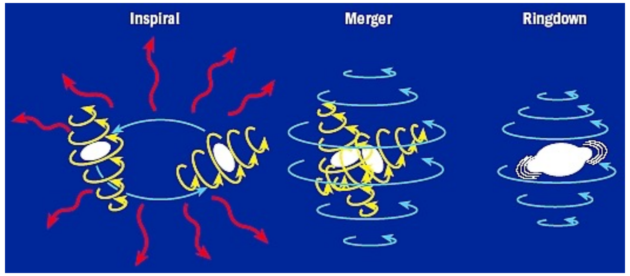
strain, quadrupole, distance

Solution $$h = \frac{G}{c^2} \frac{M_c}{D} \left(\frac{G}{c^3} \pi f M_c \right)^{2/3}$$

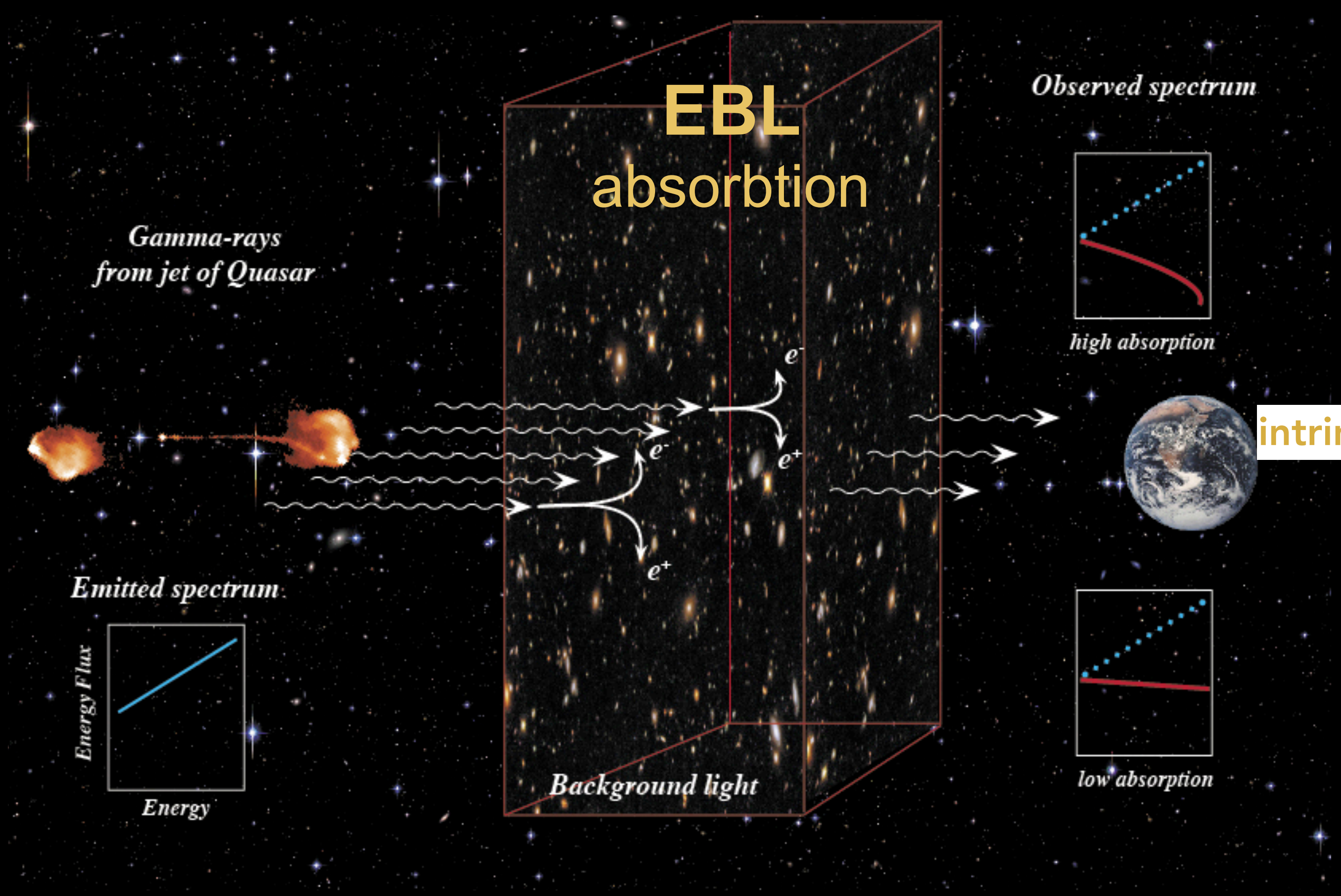
strain, mass, distance, frequency "chirp"

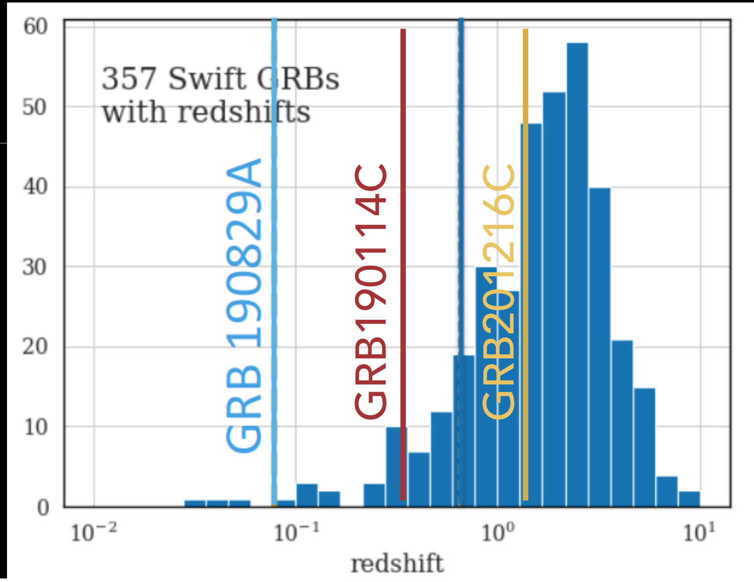
Plus other parameters: Spin, orientation, mass ratio…

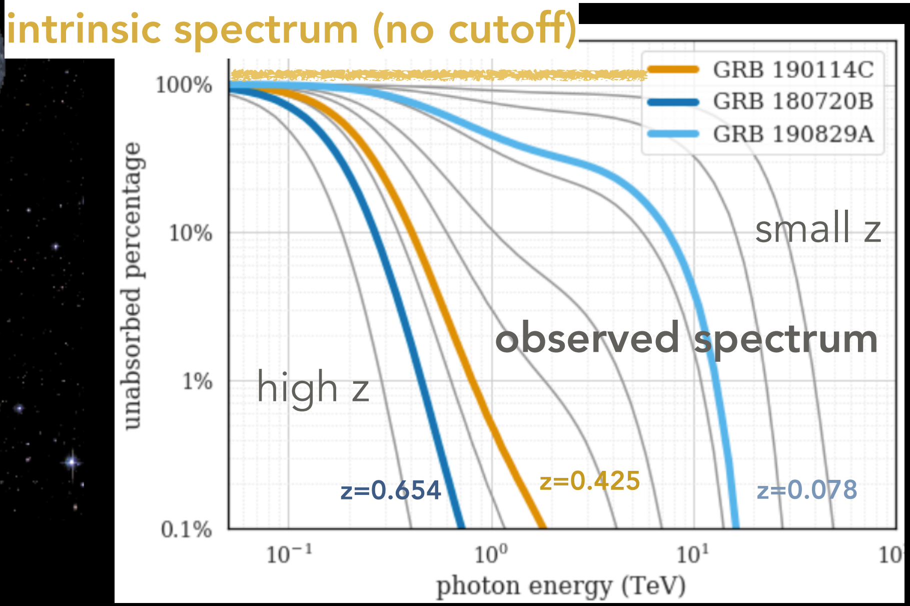
The GW emission from a binary compact system (BBH, BNS, NS-BH)



TeV Transients with IACTs





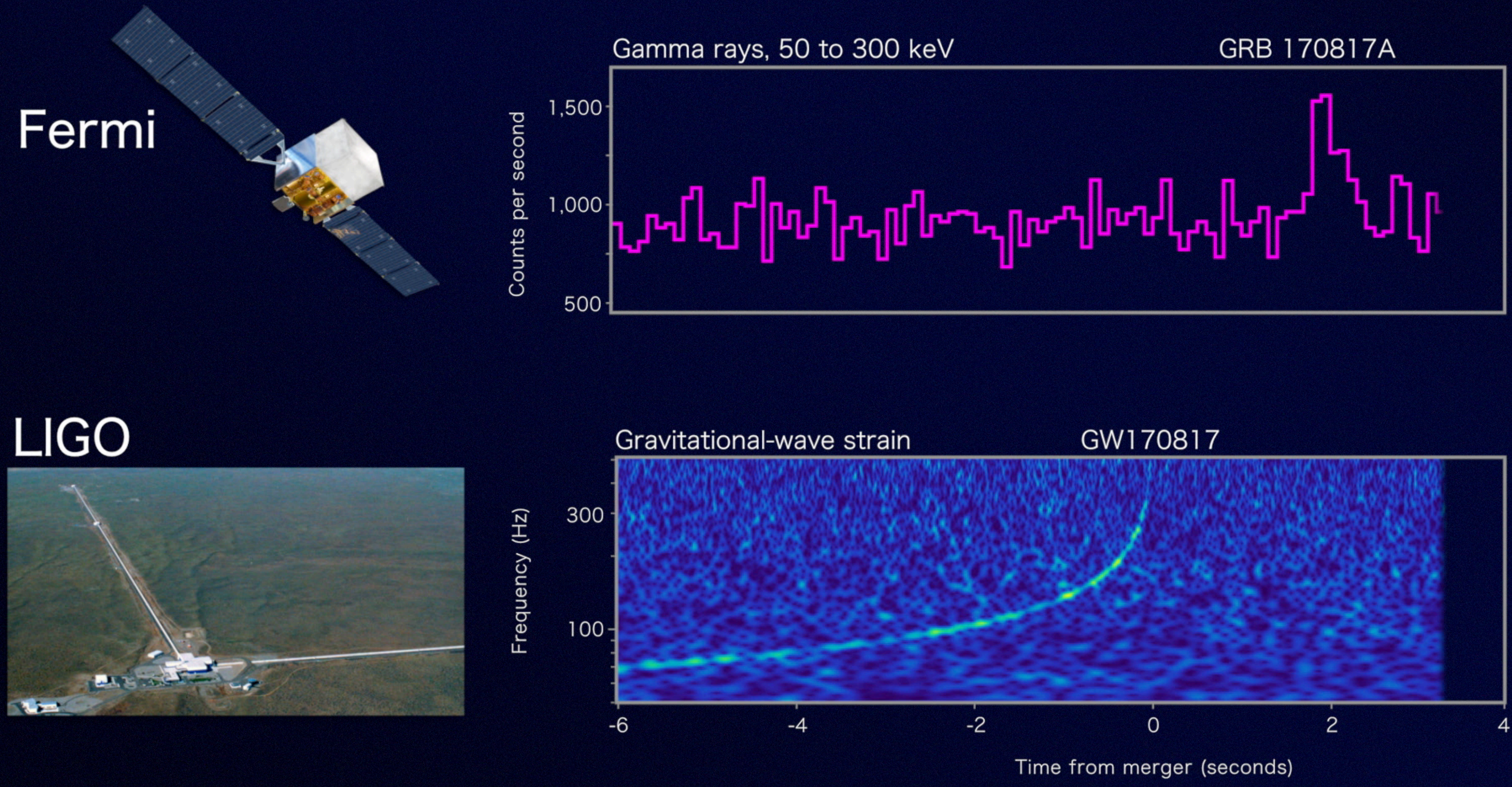


Association GW-e.m. counterpart: GW170817/GRB170817

1.7 s delay

L_{iso} ~5x10^{46} erg/s

"At 12:41:06.47 UT on 17 August 2017, the Fermi Gamma-Ray Burst Monitor triggered and located GRB 170817A (trigger 524666471 / 170817529).



TeV instruments in operation