

When and Where to Look: Optimizing CTAO Observations of Gravitational wave counterparts

Antonio Stamerra - Osservatorio Astronomico di Roma and ICSC (National Center for Supercomputing)
and the GW-team for the CTAO-Consortium



Finanziato
dall'Unione europea
NextGenerationE



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



ICSC
Centro Nazionale di Ricerca in HPC,
Big Data and Cloud Computing



The GW landscape

GW interferometers - scientific runs

- **Run o1 (2x LIGO)**

Sept 2015 - Jan. 2016

First GW (BH-BH) event!

- **Run o2 (LIGO + VIRGO)**

2016-2017; 6 months; Virgo: Aug. 2017

First e.m. counterpart of BNS merger!

- **Run o3 (LIGO + VIRGO) -advan. phase**

February 2019; 1 year - O3a / O3b

First NS-BH events!

March 27th: stop due to COVID19...

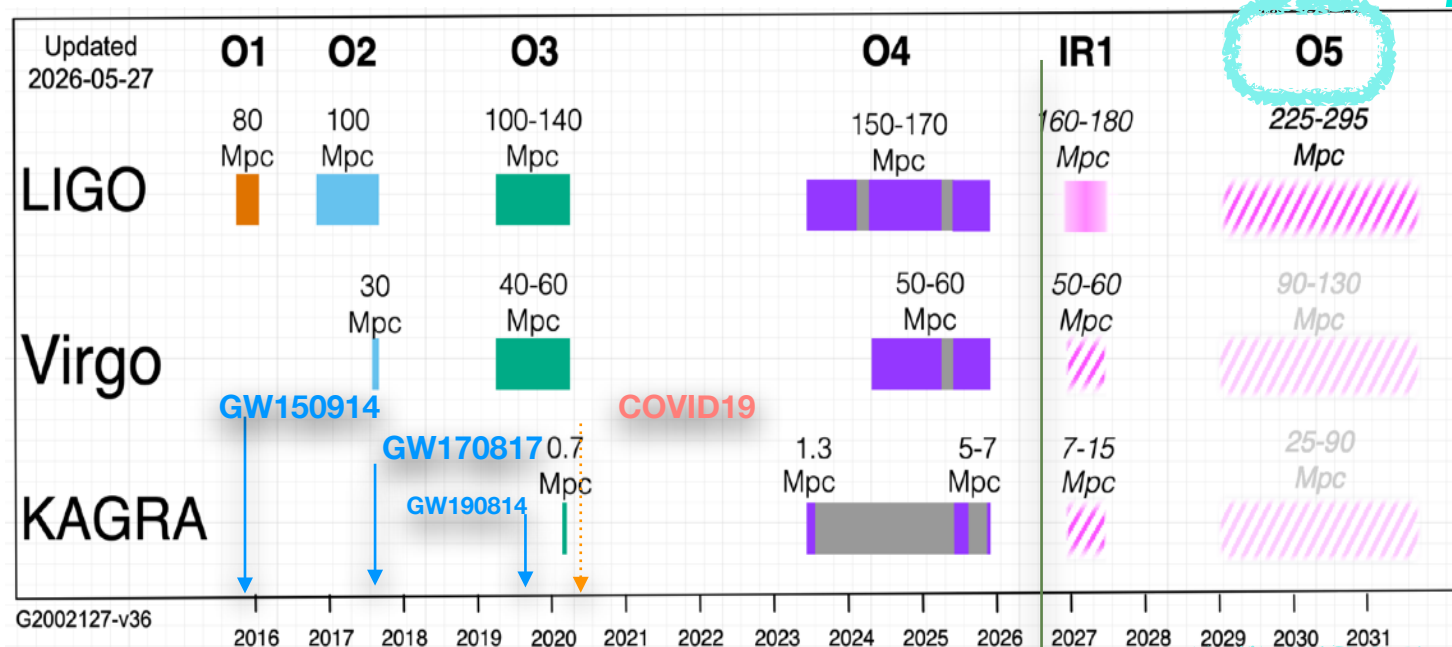
- **Run O4 - (LIGO+VIRGO+KAGRA)**

Started 24 May 2023 end Nov.2025 (additional IR1 end 2026)

- **Run O5 - AdV+ phase (LIGO+VIRGO+KAGRA + LIGO-India)**

2029-2031+

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

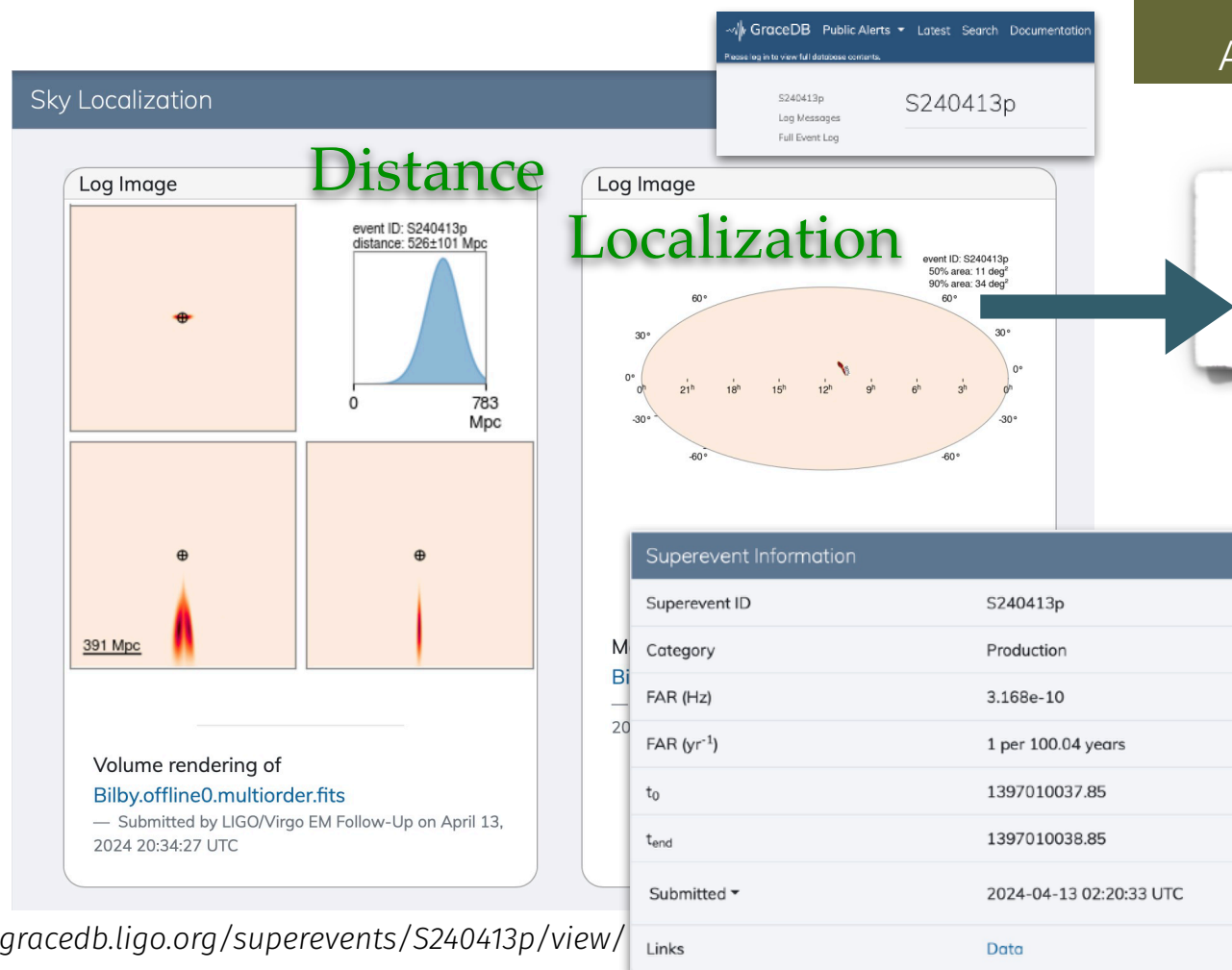


First CTAO-South precursors

Run O5 matches the current CTAO timeline

The era of gravitational waves: GW interferometers

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



event ID: S240413p
50% area: 11 deg²
90% area: 34 deg²

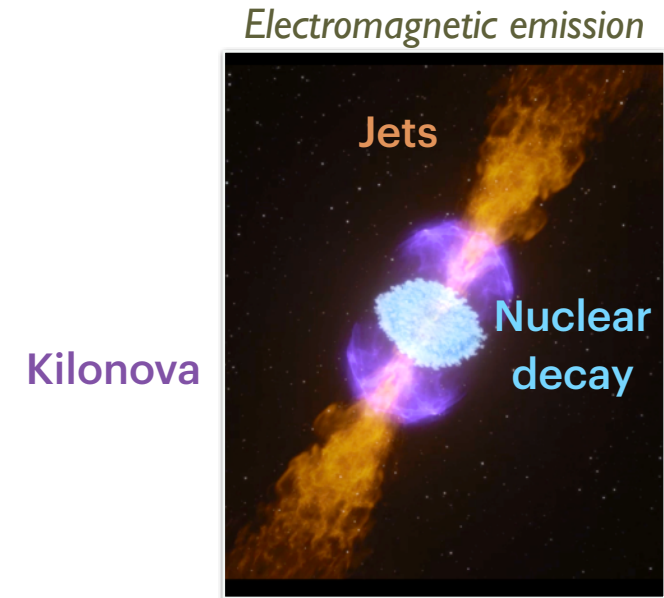
~10% of GW events in
O5 will have a similar
uncertainty area

For similar events, CTAO array
could cover most of the region
with a single or a few pointings!

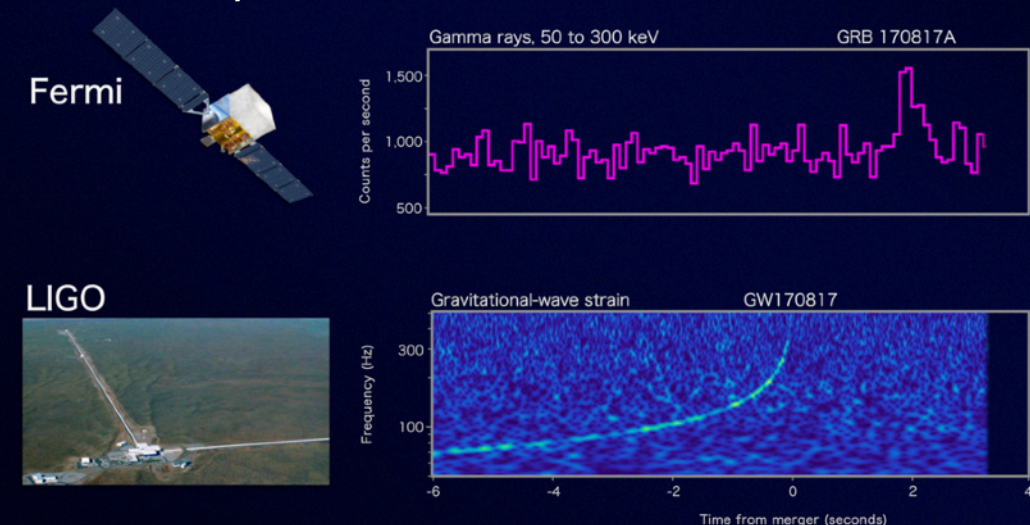
GW e.m. counterparts

- Binary Neutron Star mergers (BNS) → **short GRB**
suggested (since Eichler+1989), expected (GRBo50724) and observed (GW/GRB170817)
 - But 2 long GRBs were associated kilonova (GRBo60614, GRB211227) → scenario is not straightforward
- 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, Tagawa et al. 2023,...)
- SN collapse: long GRB ? (LIGO coll. 2014, LVC 2021)

What do we expect in the TeV band?

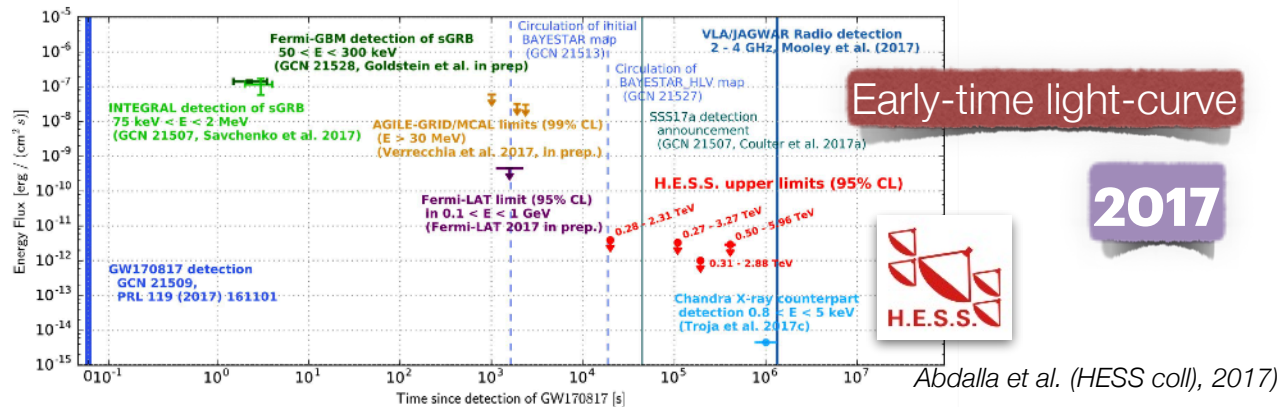


GRB170817/GW170817

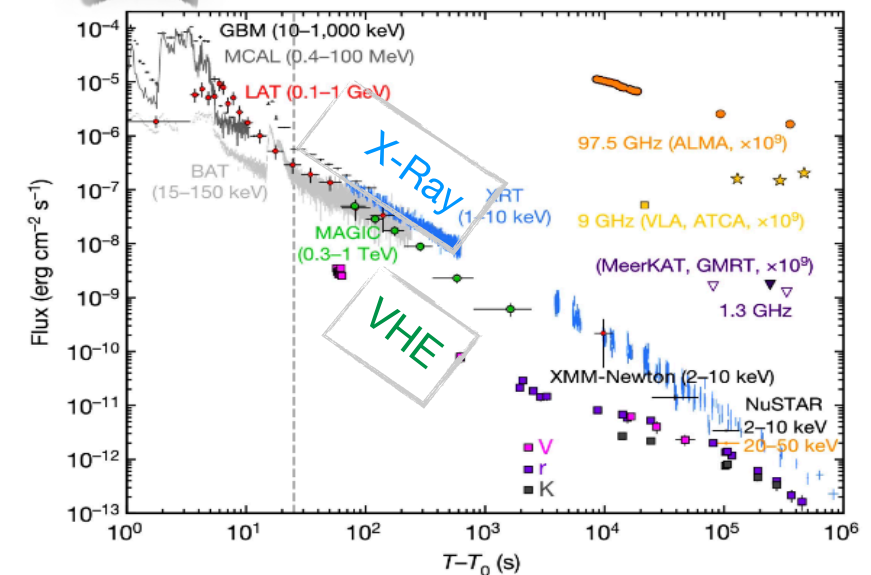
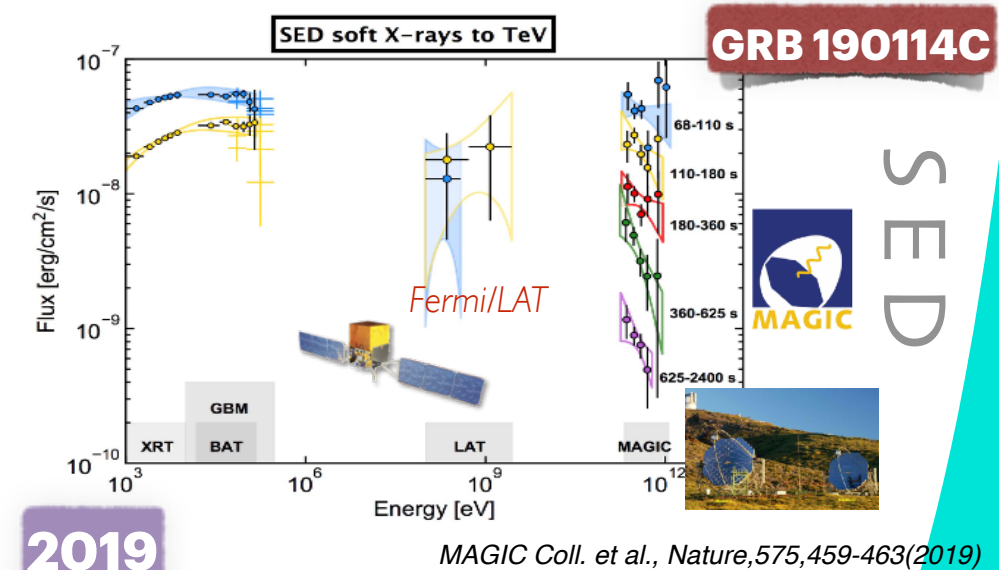


GWs and GRBs at TeV energies

- No detection of GeV-TeV emission from the counterpart of GW170817/GRB170817A.
- No detection at the maximum of the delayed emission (T0+200d)



- ★ Detection of the TeV (afterglow) emission from GRBs
- ✓ GRB engine accelerates photons up to TeV
Gamma rays up to 12 TeV from the GRB 221009A!
- ✓ Evidence of a second energetic GeV-TeV component
- ✓ Energy budget and time evolution similar to the optical-X-ray component: *TeV flux follows closely the X-ray flux*

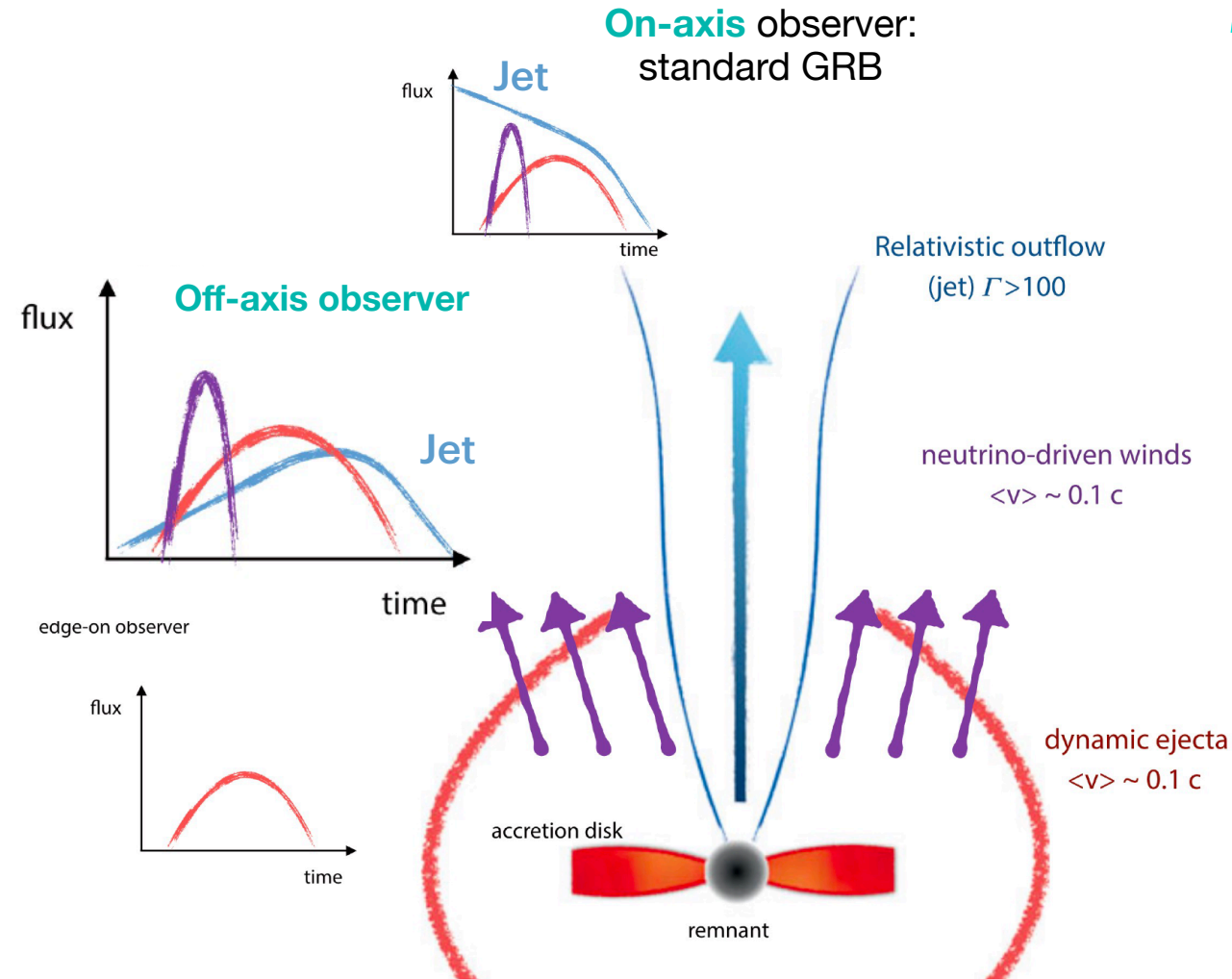


The Role of Off-axis Observations and structured Jet

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})

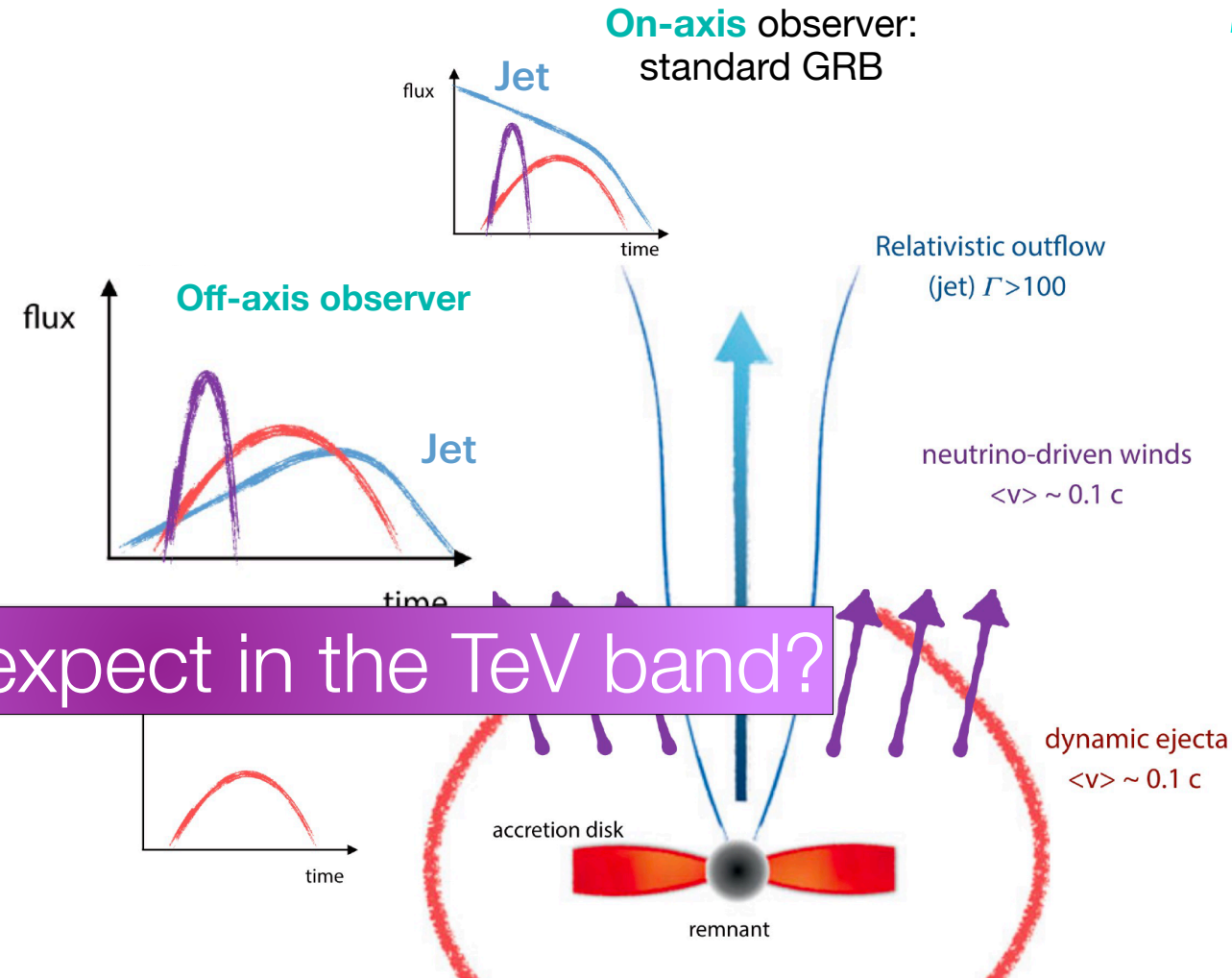


The Role of Off-axis Observations and structured Jet

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

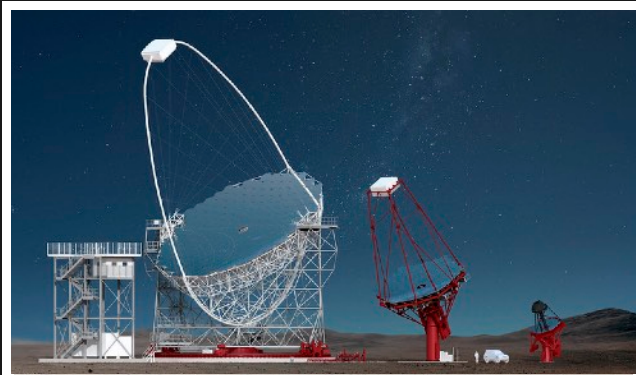
In GW-counterparts, the jet is seen preferentially **off-axis**: small Lorentz factor

- intensity weaker 10^{-4} to 10^{-6} times than on-axis emission
- light curve delayed (how depending on θ_{view})

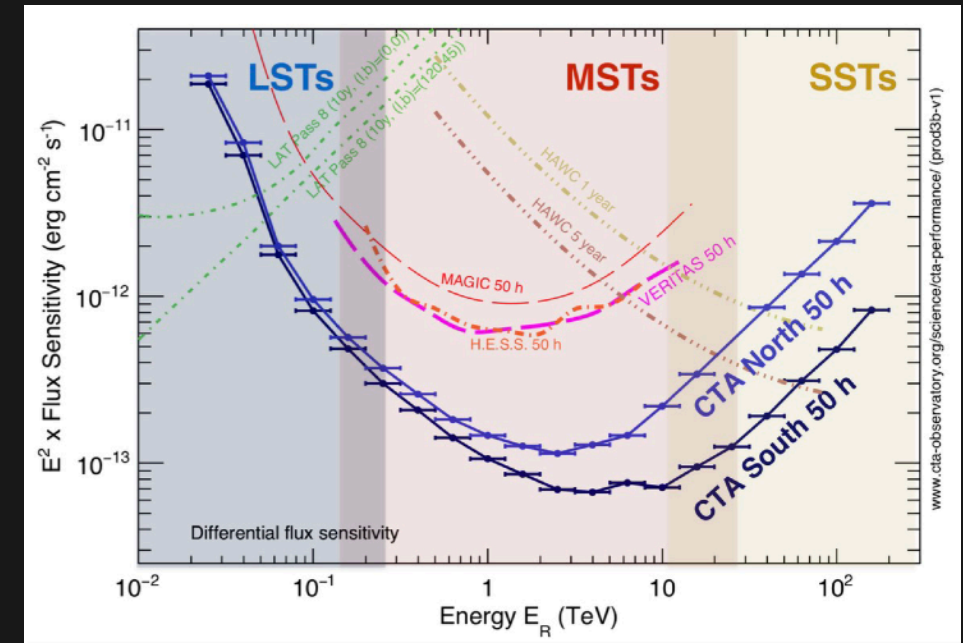
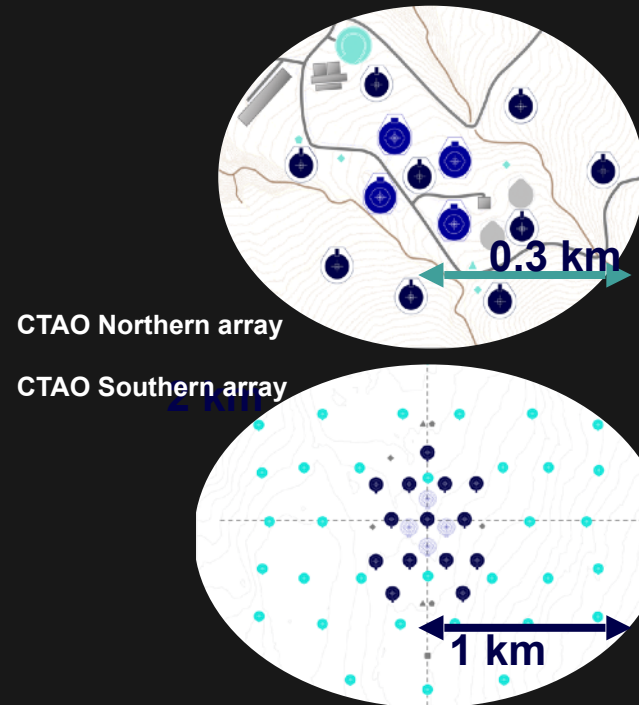


CTAO: a diverse array

- Extended energy range (20 GeV-300 TeV) with telescopes of 3 sizes.
- Improved sensitivity, up to 5-10 times than current IACTs.
- Improved angular resolution (3') and energy resolution (7% @1 TeV).



	LST	MST	SST
Mirror $\varnothing$	~23m	~11.5m	~4m
FoV	~4.3deg	~7.5deg	~9deg



CTAO

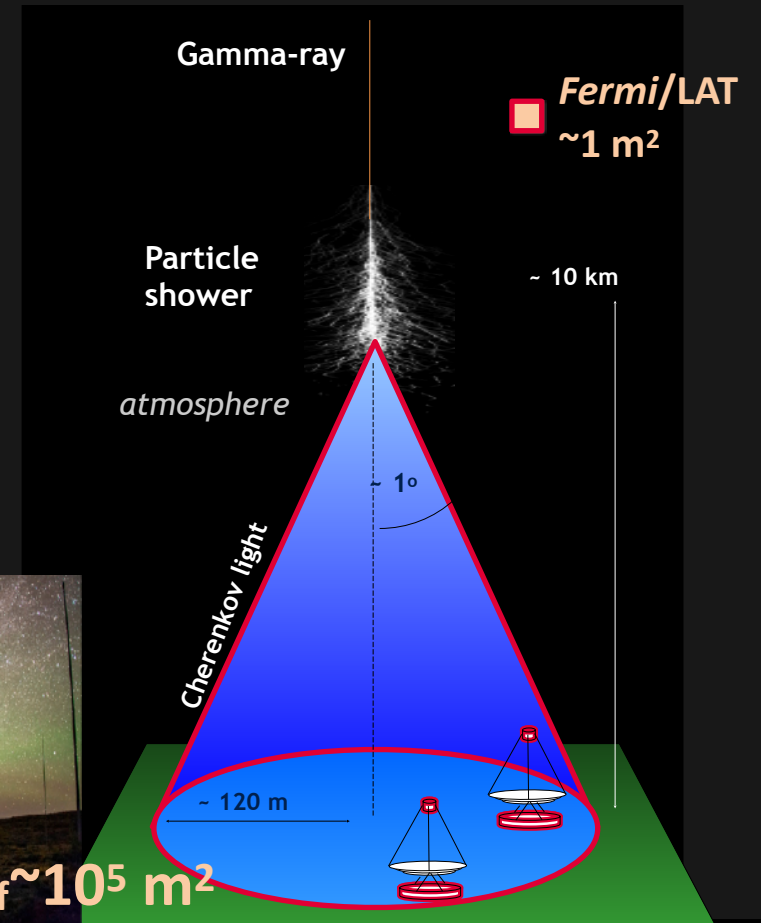
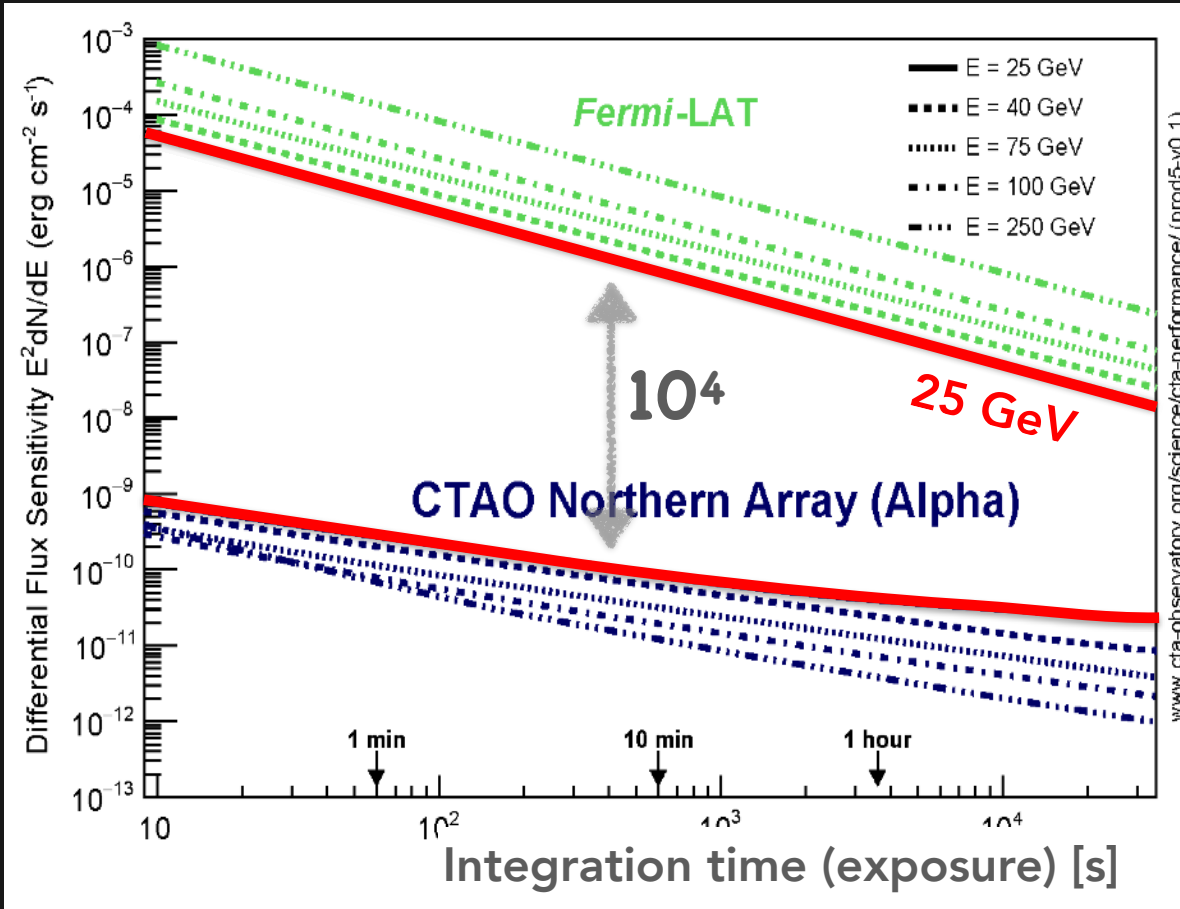
and transient source (e.g. GRBs)

Big effective area  **photon statistics**

Low energy threshold (~ 50 GeV)

Repositioning speed ~7 deg/s; *automatic* repointing

Observations in moon-time





13

KLAMMBACHALM (MALGA)

NEMESALM (MALGA)

A / NEGERDÖRFL

V / SEXTEN - SESTO

S / JGIO - PENDIO

AUMAH

S - MO SO

1h V
2h S

The CTAO path to GWs

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

Optimise the observing strategy

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

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, expos.)

CTAO FLASHPOINT

Chasing Echoes: How the CTAO Plans to Detect Gamma-Ray Signals from Binary Neutron Stars

CTAO
4,409 followers

May 29, 2026

Written by CTAO Consortium members: Jarred J. Green, MPI, Max-Planck-Institut für Physik; Lara Nava, INAF - Osservatorio Astronomico di Brera; Barbara Patricelli, INAF - Osservatorio Astronomico di Roma; Monica Seglar-Arroyo, Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB; Fabian Schuessler, IRFU, CEA, Université Paris-Saclay; and Antonio Stamerra, INAF - Osservatorio Astronomico di Roma.

THE ASTROPHYSICAL JOURNAL, 1004:46 (26pp), 2026 June 10

© 2026. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS

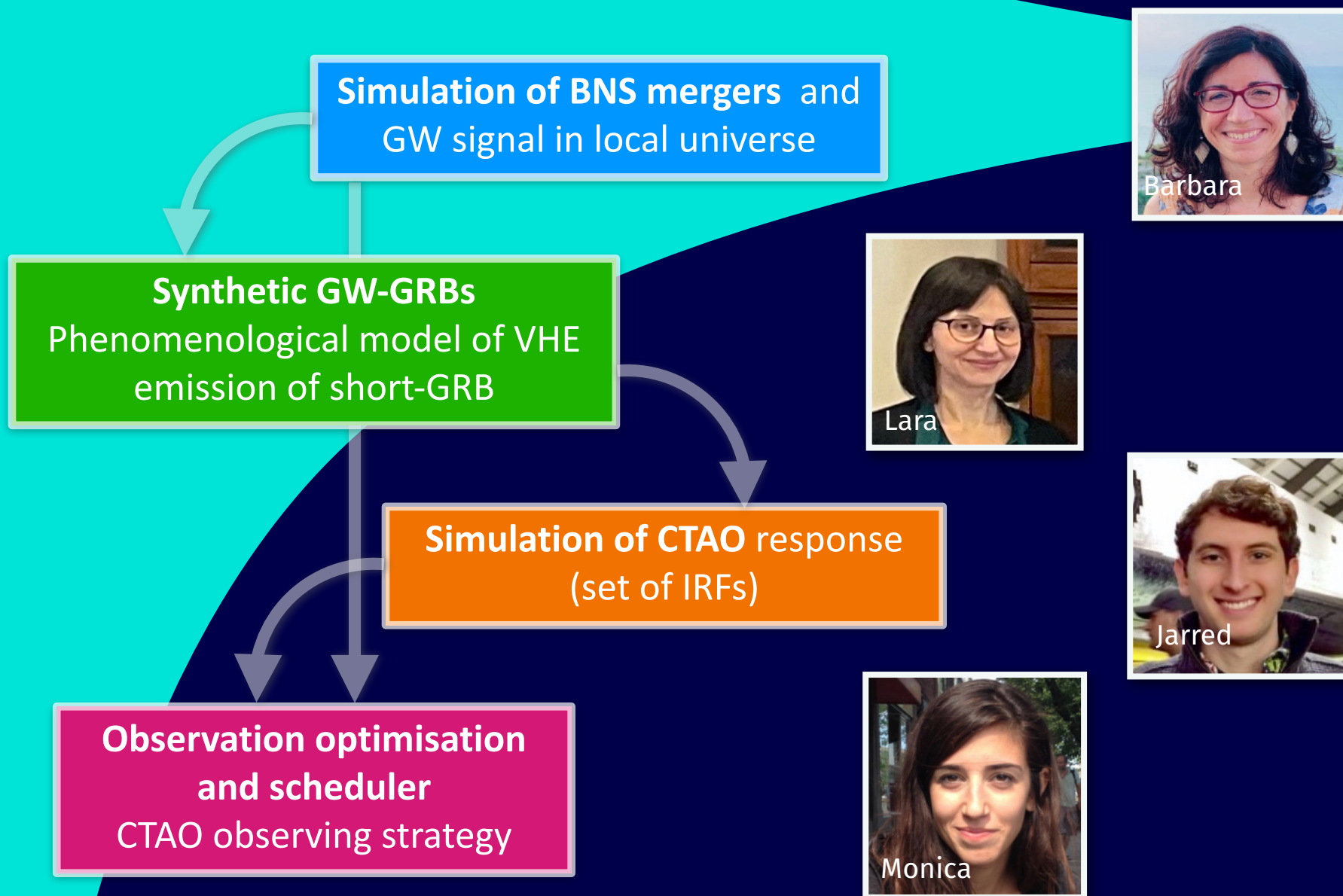
<https://doi.org/10.3847/1538-4357/ae658c>

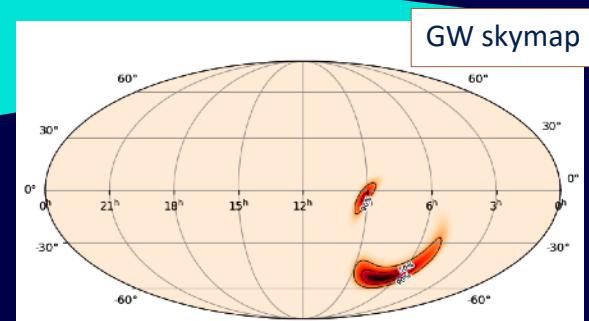
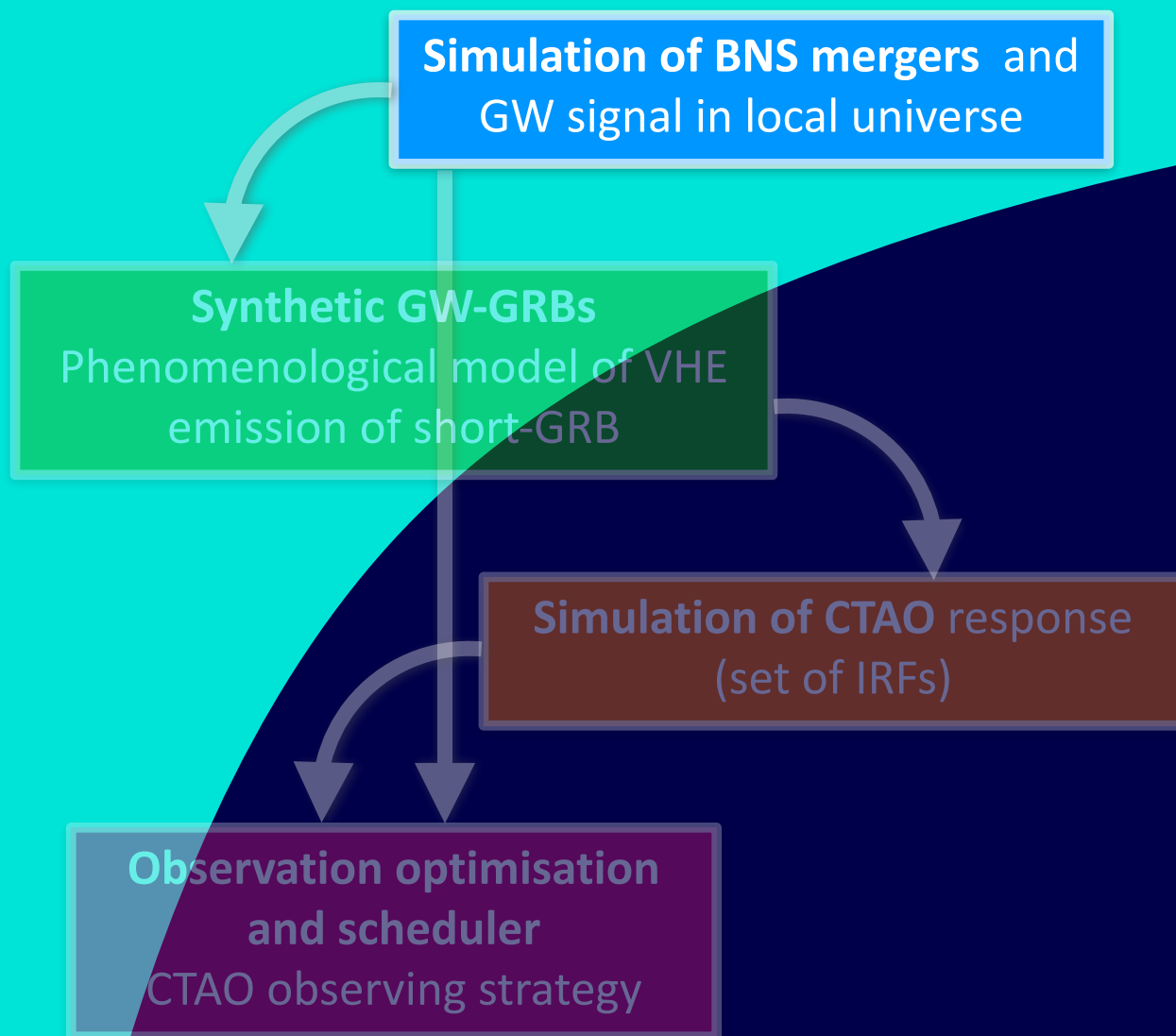


Chasing Gamma-Ray Signals from Binary Neutron Star Coalescences with the Cherenkov Telescope Array: Prospects and Observing Strategies

S. Abe¹, J. Abhir², A. Abhishek³, F. Acero^{4,5}, A. Acharyya⁶, R. Adam^{7,8}, A. Aguasca-Cabot⁹, I. Agudo¹⁰, I. Albanese¹¹, J. Alfaro¹², C. Alispach¹³, R. Alves Batista¹⁴, E. Amato¹⁵, G. Ambrosi¹⁶, D. Ambrosino^{17,18}, E. Ambrosino¹⁹, L. Angel^{20,21}, C. Aramo¹⁷, A. Arbet Engel²², C. Arcaro²³, C. Arzoumanian²⁴, T. T. H. Arzoumanian²⁵







Gravitational wave catalogue of simulated binary neutron star (BNS) mergers from *Petrov et al. 2022 for O5*

Simulation of BNS mergers and
GW signal in local universe

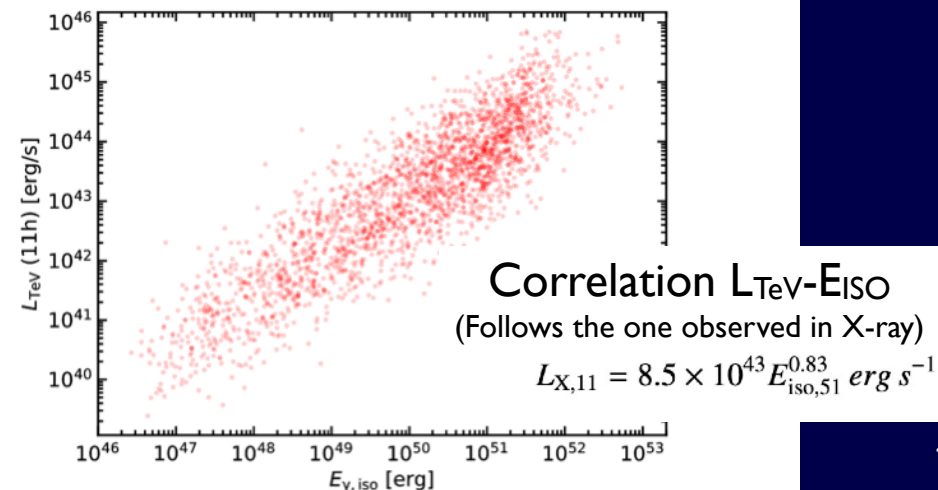
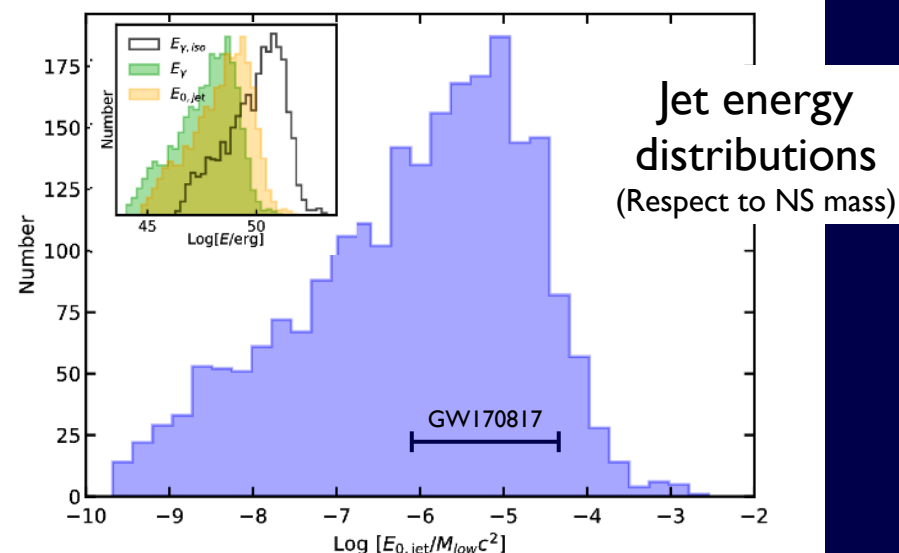
Synthetic GW-GRBs

Phenomenological model of VHE
emission of short-GRB

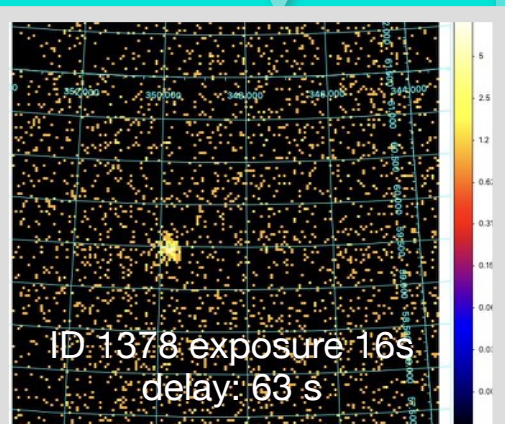
Phenomenological simulation of afterglow emission from
short GRBs and long-TeV-GRBs

- **Jet opening angle** inferred from short-GRBs seen on-axis, average: $\sim 14^\circ$
- **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 $\sim 0.1 \text{ cm}^{-3}$
- **Jet structure**: Gaussian distribution for both energy and Lorentz factor

Consistency checks



Simulation of BNS mergers and
GW signal in local universe



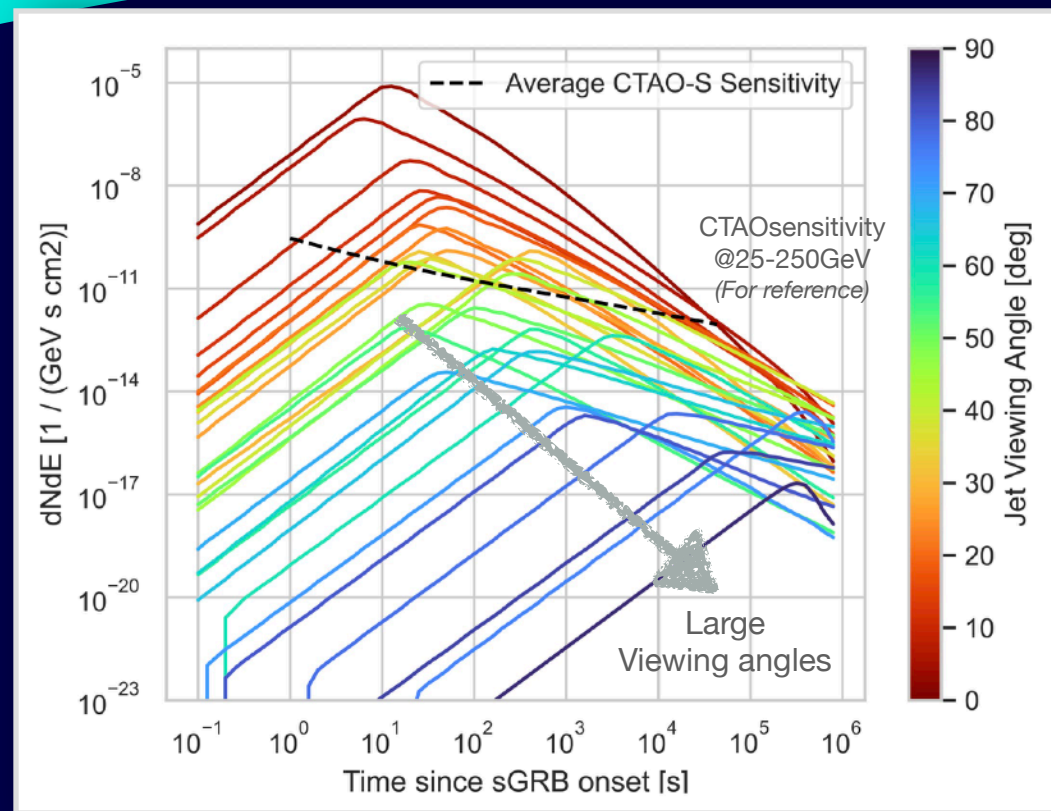
V-GRBs
model of VHE
short-GRB

Simulation of CTAO response
(set of IRFs*)

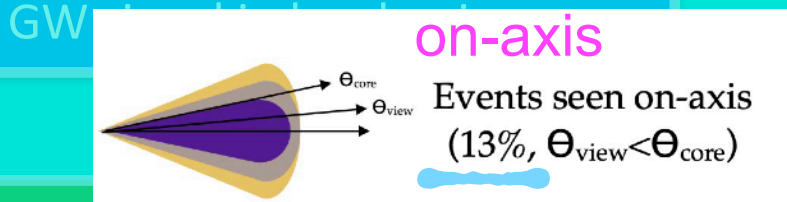
* IRF: Instrument
Response Function

Observation optimisation
and scheduler
CTAO observing strategy

Credits: Fabio Pintore,
gammapy



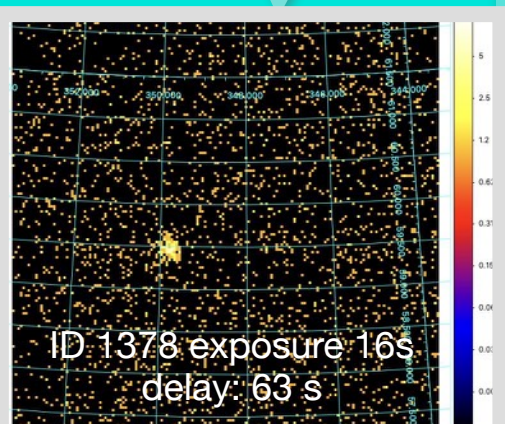
Simulation of BNS mergers and GW



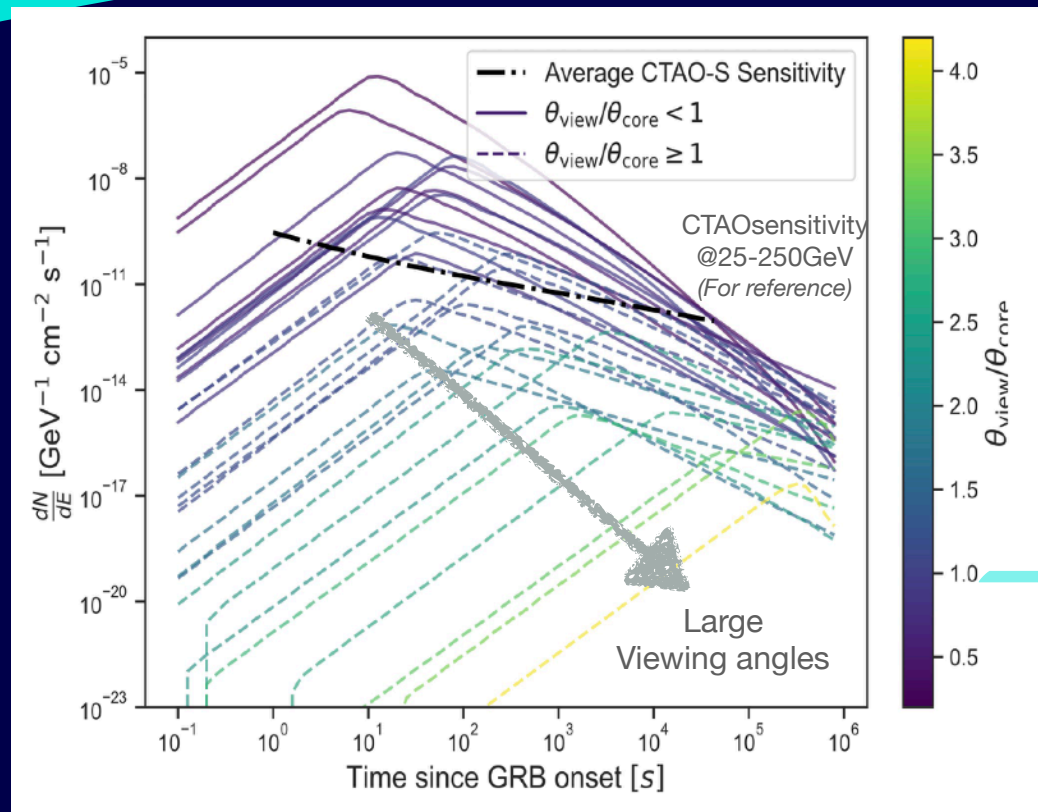
Simulation of CTAO response
(set of IRFs*)

* IRF: Instrument
Response Function

Observation optimisation
and scheduler
CTAO observing strategy



Credit: Fabio Pintore,
gammapy



Simulation of BNS mergers and
GW signal in local universe

Synthetic GW-GRBs

Phenomenological model of VHE
emission of short-GRB

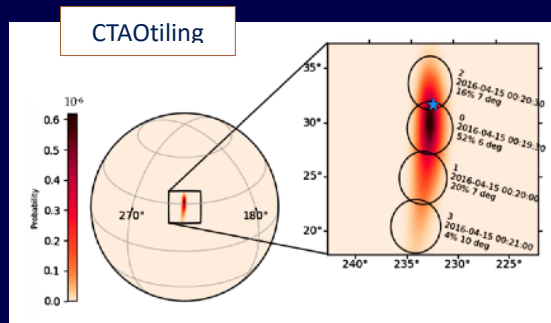
Simulation of CTA
(set of IRFs)

Observation optimisation
and scheduler
CTAO observing strategy

- Realistic observing conditions for CTAO are considered (*Seglar-Arroyo et al. 2019*)
- Based on Tilepy code (*M. Seglar-Arroyo et al. - APJS - 2024*)

Observing strategy:

- *Optimal*: Scheduler iterates on the best visible positions, with increasing, sensitivity-dependent, exposures. If the true source position is covered, by construction, it is detected.
- *Fixed*: Tiling with fixed exposures (1, 5, 20 min)



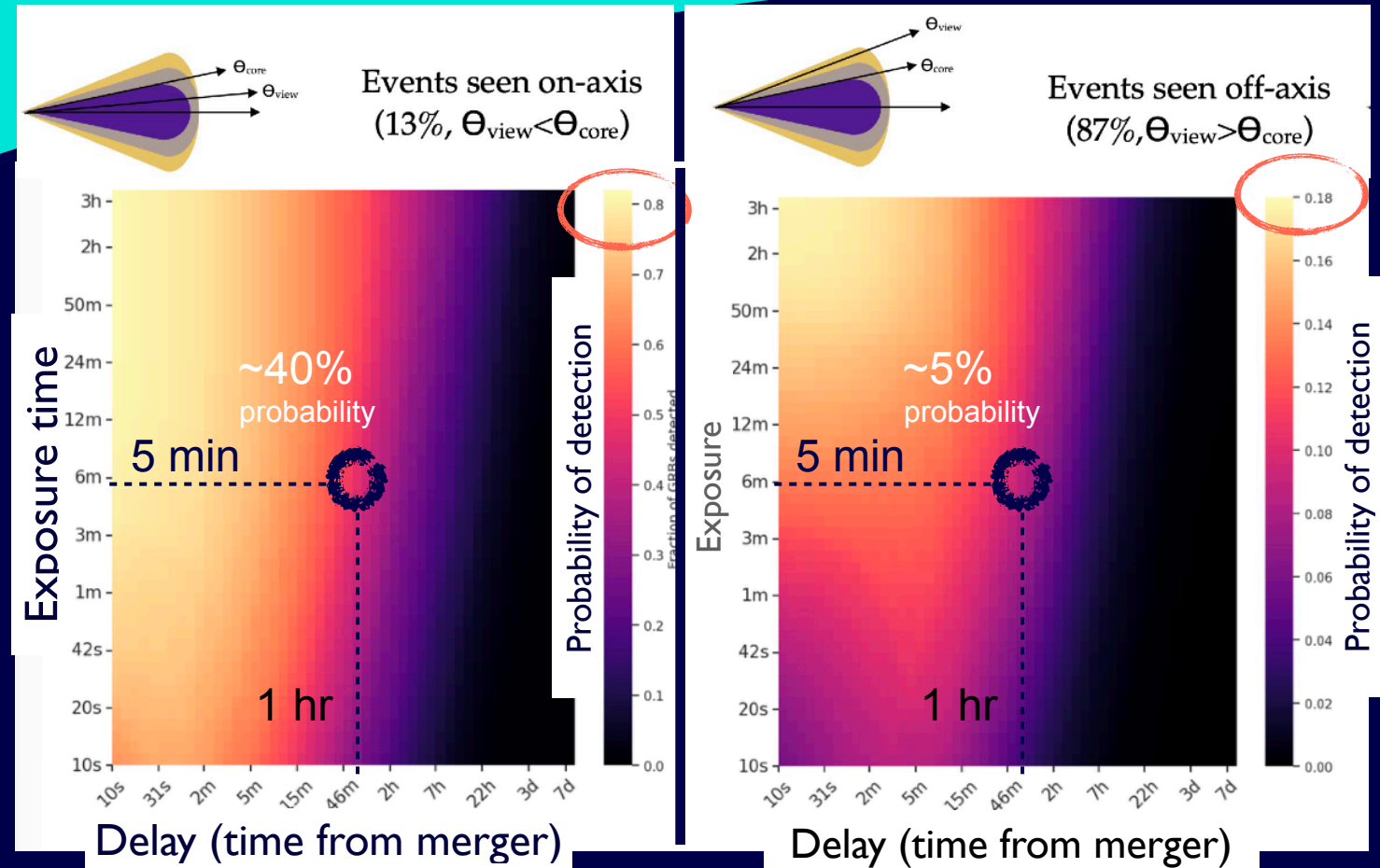
Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

Optimise the observing strategy

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

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

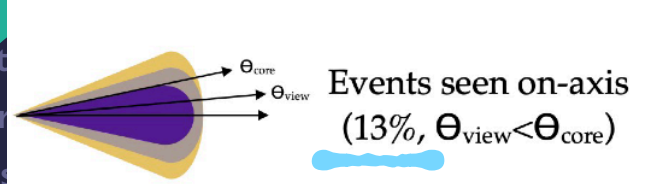
- ✦ Physical parameters (luminosity, jet opening angles and jet orientation, spectral slope)
- ✦ Observational parameters (time delays, exposures)



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

Optimise the observing strategy

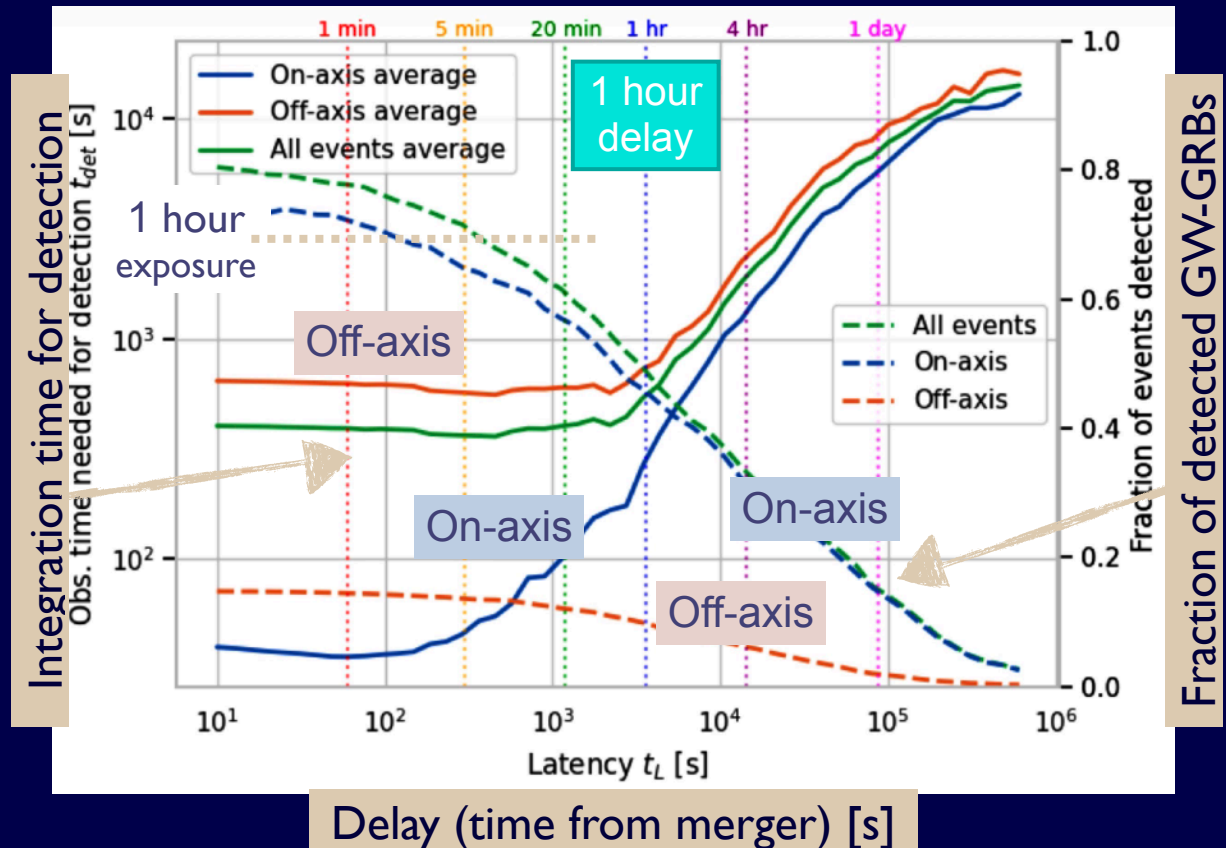
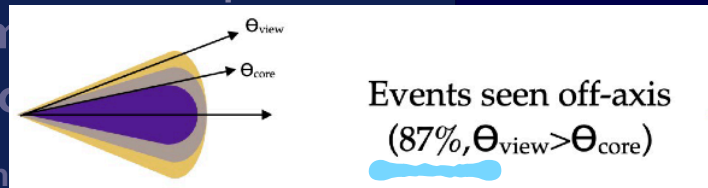
- Maximise the detection rate
- Maximise the physical interest
- Evaluate the amount of observations



Explore the parameter space

GW-GRBs detection

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



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

Optimise the observing strategy

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

$$\text{Rate}_{\text{CTAO-GW}} = \text{Rate}_{\text{BNS}} * \chi_{\text{jet}}^{\text{BNS}} * \text{detecProb}_{\text{LVK(O5)}} * \text{detecProb}_{\text{CTAO}}$$

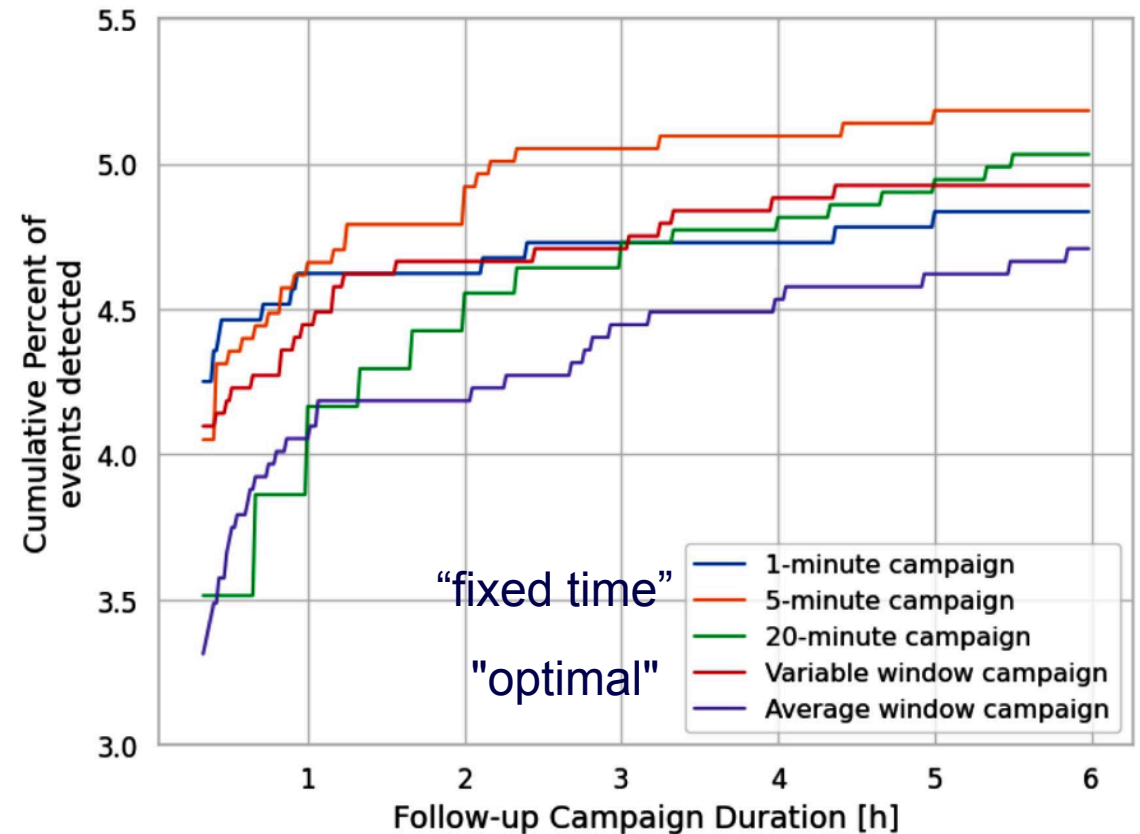
40(+115-35) Gpc⁻³ yr⁻¹
Based on O3-04 (GWTC-5.0)

??
BNS producing
jets (10-50%??)

This work
~5%

$\text{Rate}_{\text{BNS}} * \text{detecProb}_{\text{LVK(O5)}} \sim 190^{+410}_{-130}$ Petrov+2022 Too optimistic!

Detection rate



~5% of the sampled BNS mergers are detectable.
Expected yearly rate depends greatly on the
BNS rate (largely uncertain!)

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

SAG system
(science alert generation
aka “real-time analysis”)

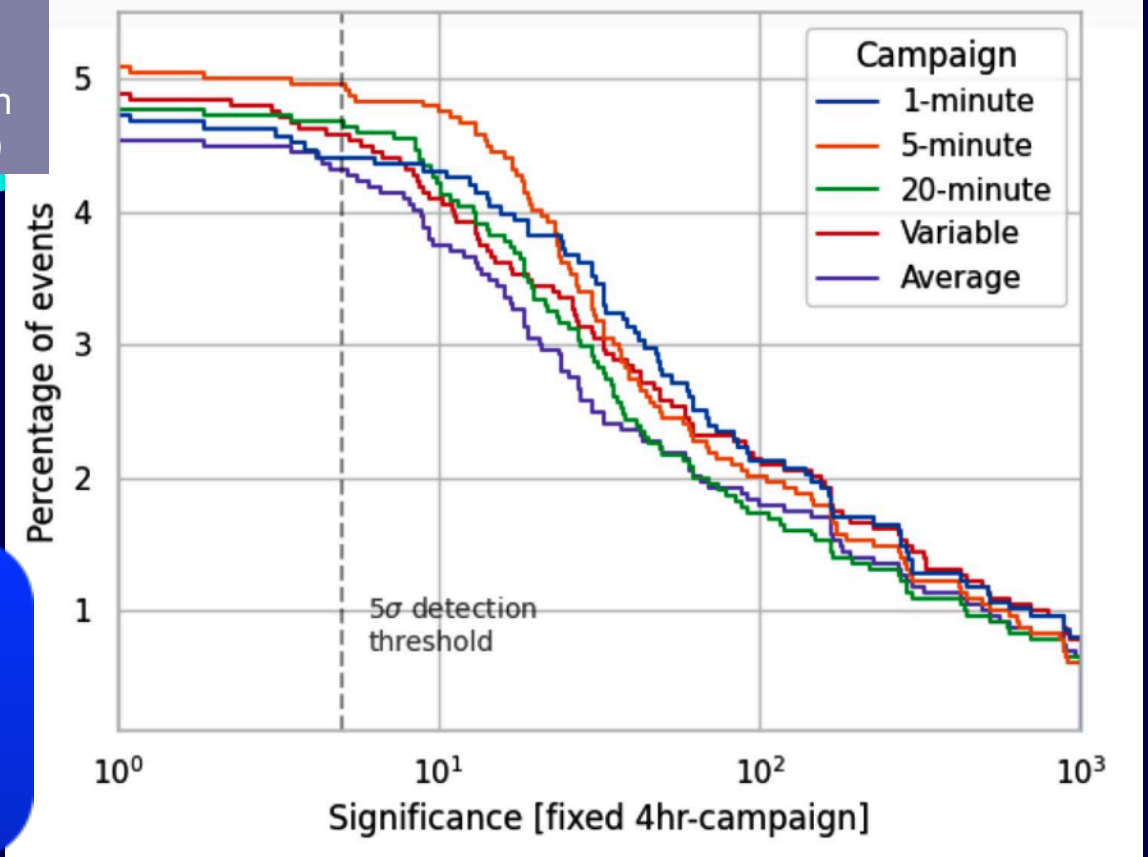
Optimise the observing strategy

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

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

- ✦ Physical parameters (luminosity, jet opening angles and jet orientation) and other (GW area, distance)
- ✦ Observational parameters (time delays, exposures)

Science
needs
sigmas!



~5% of the sampled BNS mergers are detectable.
Expected yearly rate depends greatly on the
BNS rate (largely uncertain!)

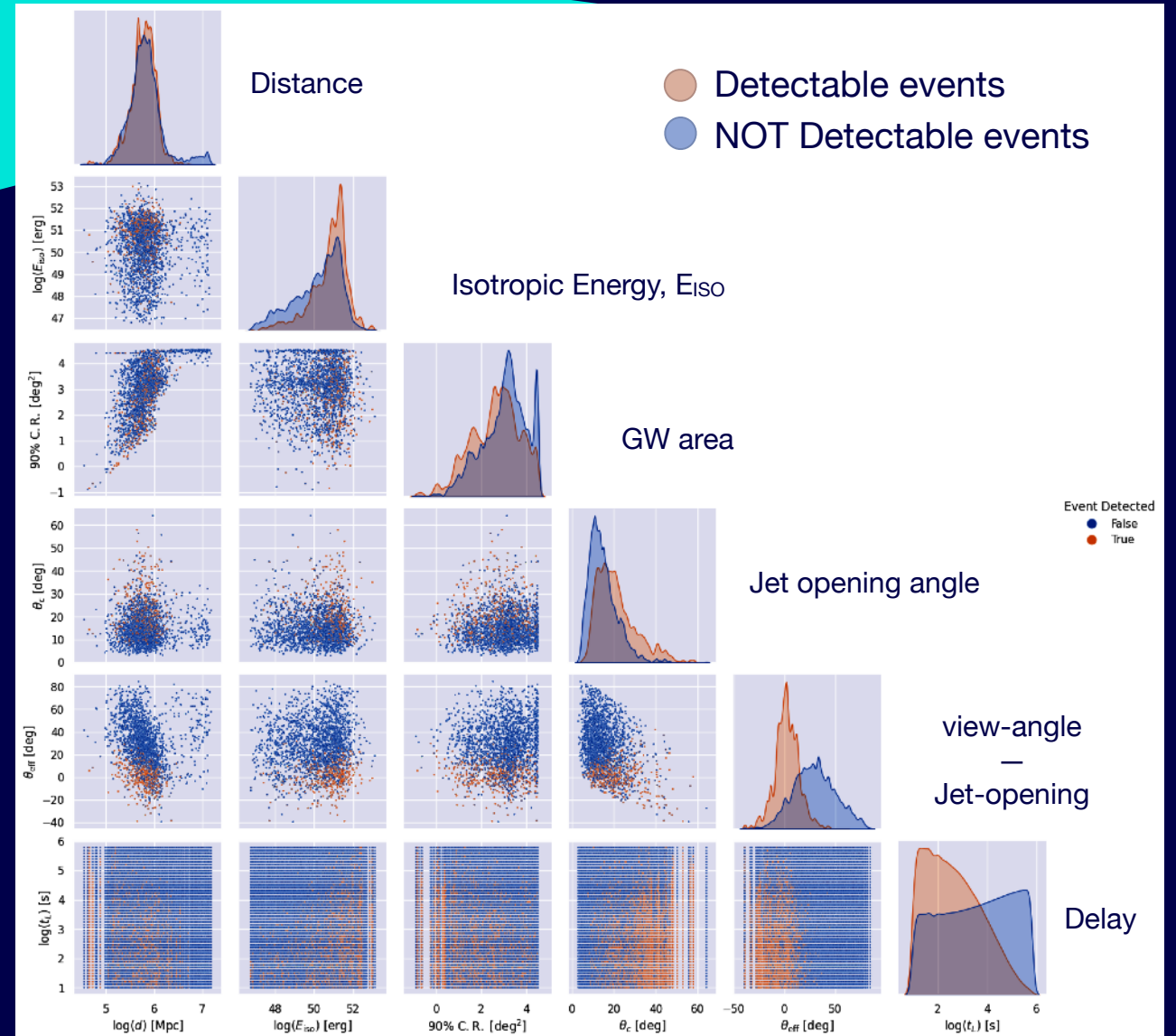
Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

Optimise the observing strategy

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

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

- ✦ Physical parameters (luminosity, jet opening angles and jet orientation) and other (GW area, distance)
- ✦ Observational parameters (time delays, exposures)



GW FOLLOW-UPS WITH CTAO

✓ This Groundwork was laid with **GW-GRB simulation chain for BNS during the LIGO-Virgo-KAGRA scientific run O5 (2027-2030)**, motivated by:

- ✧ A new GW and TeV-GRB landscape has emerged $\Rightarrow$ **an expanded CTAO's science program.**
- ✧ A plethora of GW triggers expected $\Rightarrow$ **requiring optimised observing strategies and follow-up observations.**

✓ **Explore the potential of CTAO** with the next-generation of GW interferometers, like the Einstein Telescope, post-O5 LVK, for new science cases, and different and new CTAO configurations (divergent mode, subarrays).



Podcast



CTAO-consortium
paper:

<https://iopscience.iop.org/article/10.3847/1538-4357/ae658c>

THE ASTROPHYSICAL JOURNAL, 1004:46 (26pp), 2026 June 10

<https://doi.org/10.3847/1538-4357/ae658c>

© 2026. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS



Chasing Gamma-Ray Signals from Binary Neutron Star Coalescences with the Cherenkov Telescope Array: Prospects and Observing Strategies

- Do all GRB exhibits a second high-energy component (Gev-TeV)?



- Is this component significant or even dominant, as observed in GRB 190114C? Under what conditions?
- What is the connection between this emission and the GRB progenitor or its environment?
- Is SSC the dominant emission mechanism? What roles do external Compton, pure synchrotron, or hadronic processes play?
- Next observational breakthrough: unambiguous TeV detection from short-GRB! GW (BNS)! NS-BH and BBH still uncharted territory...
- Which observational strategies in the TeV band are best suited for detecting GW counterparts?

TeV observations can:

- ✓ Clarify the structure of the environment (density, winds)
- ✓ Better constrain SED modeling and parameters
- ✓ Identify/discard dominant emission processes in afterglow
- ✓ Identify and shed light on the prompt emission physics.

Constraints on the VHE counterpart of two binary black hole mergers observed by the MAGIC and CTAO LST-1 telescopes

<https://arxiv.org/abs/2607.19972>



Simulation of BNS mergers and
GW signal in local universe

Synthetic GW-GRBs

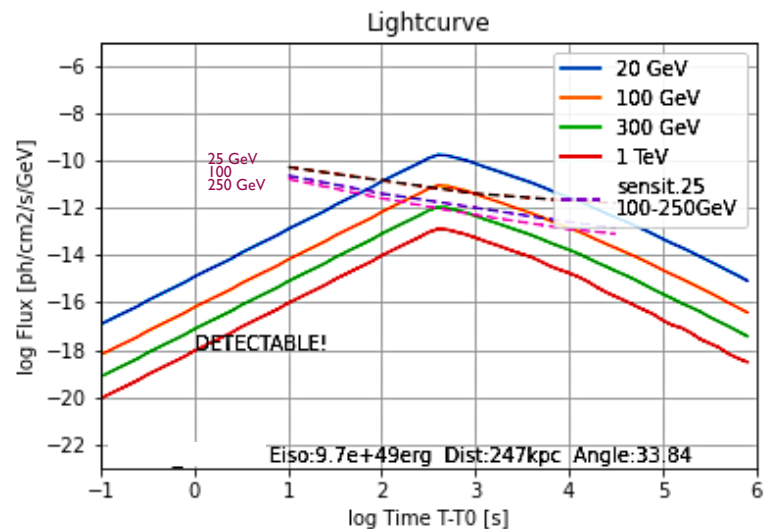
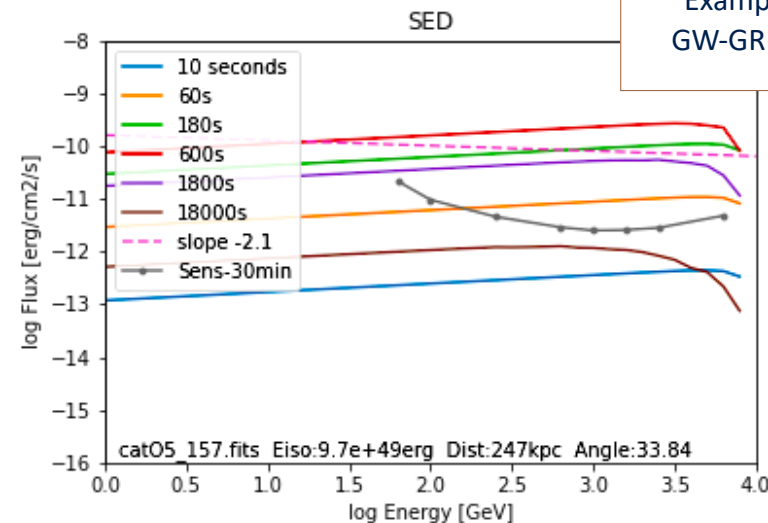
Phenomenological model of VHE
emission of short-GRB

Phenomenological simulation of afterglow emission from
short GRBs.

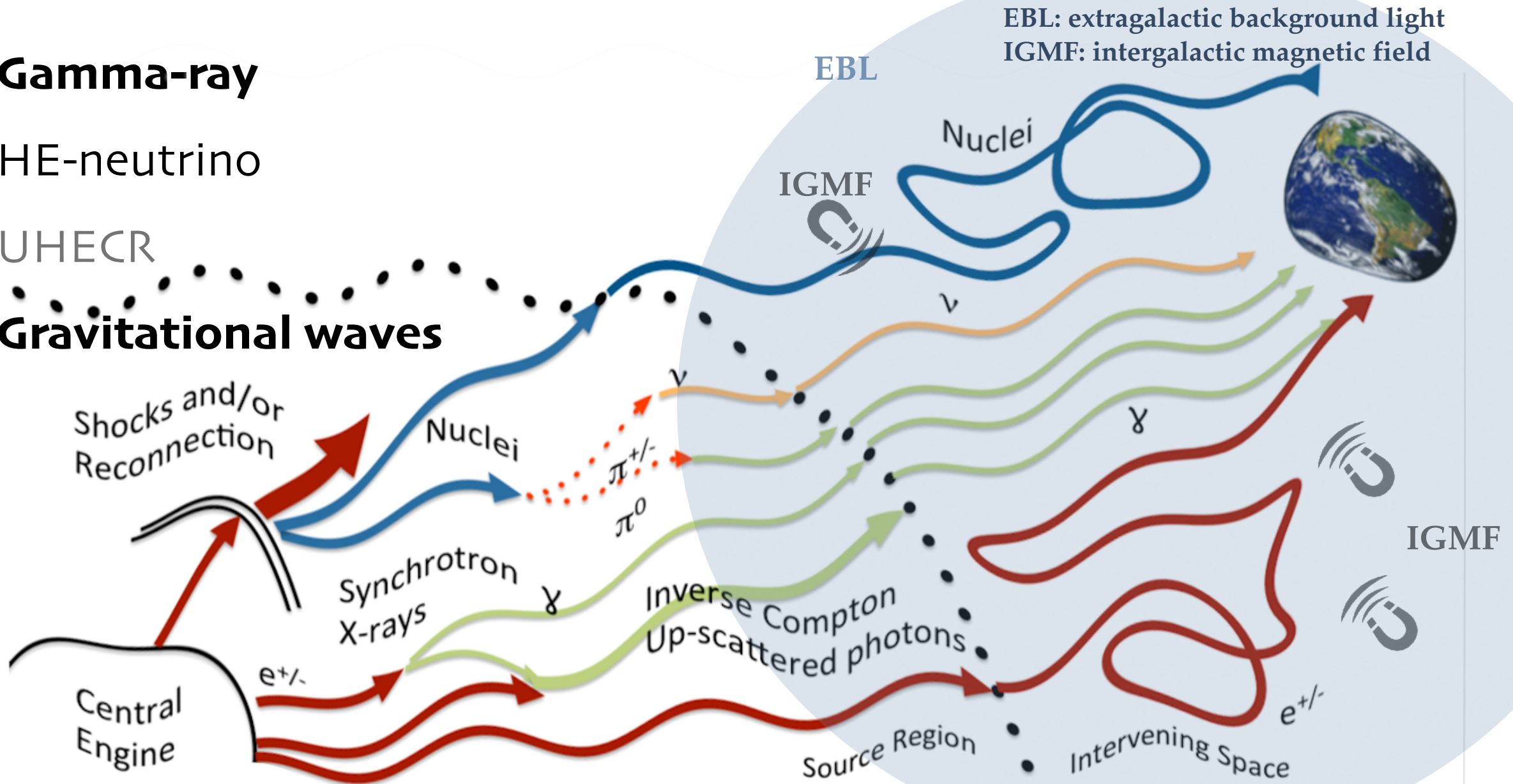
- **Jet opening angle** inferred from short-GRBs seen on-axis, average: $\sim 14^\circ$
- **Viewing angle** from the inclination of the BNS
- **Lightcurve**: follows deceleration phase + similar temporal decay as in X-rays
- **Spectrum**: Photon index ~ -2 ; Density of the external medium $\sim 0.1 \text{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

CTAO observing strategy

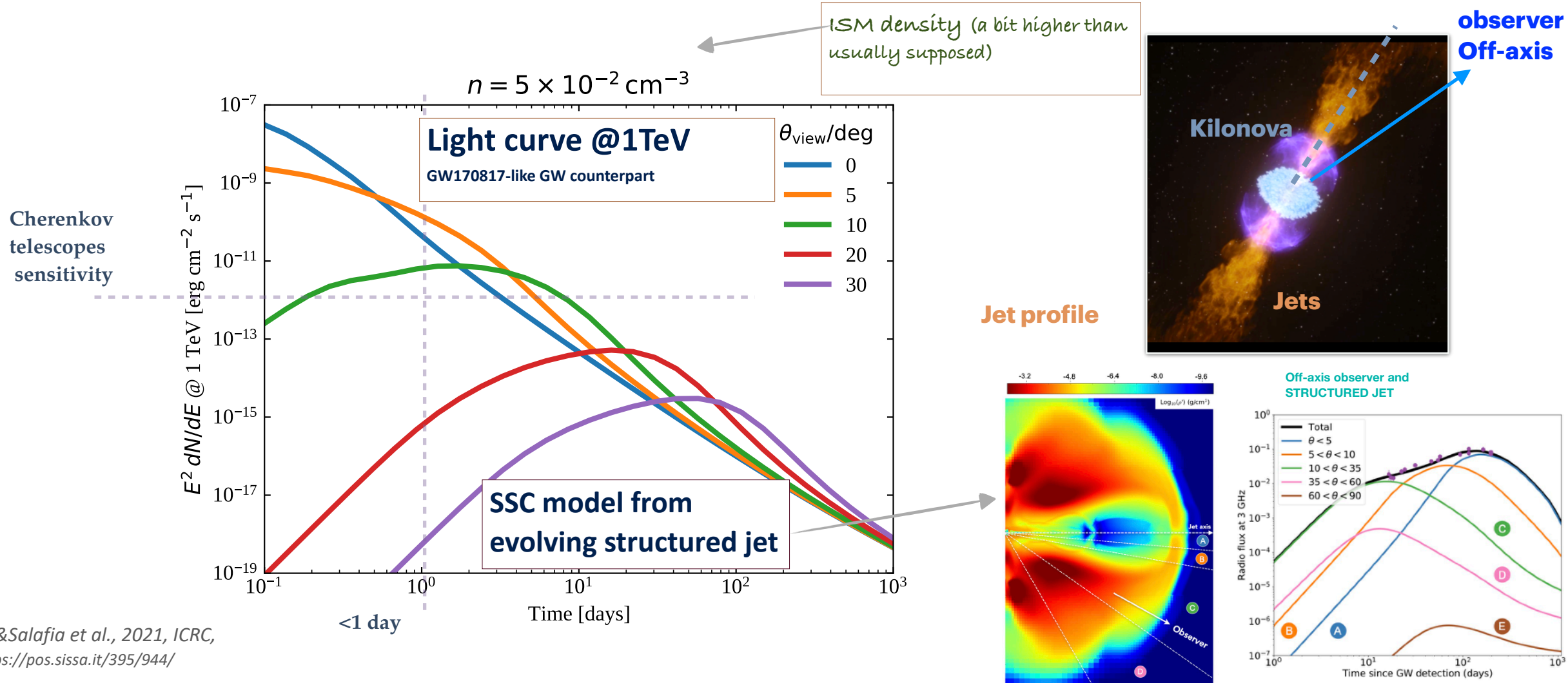
Example of a
GW-GRB event



- **Gamma-ray**
- HE-neutrino
- UHECR
- **Gravitational waves**



TeV emission from GW counterparts: an off-axis GRB



AS&Salafia et al., 2021, ICRC,
<https://pos.sissa.it/395/944/>

How can we increase the chances to detect TeV emission from GW counterparts?