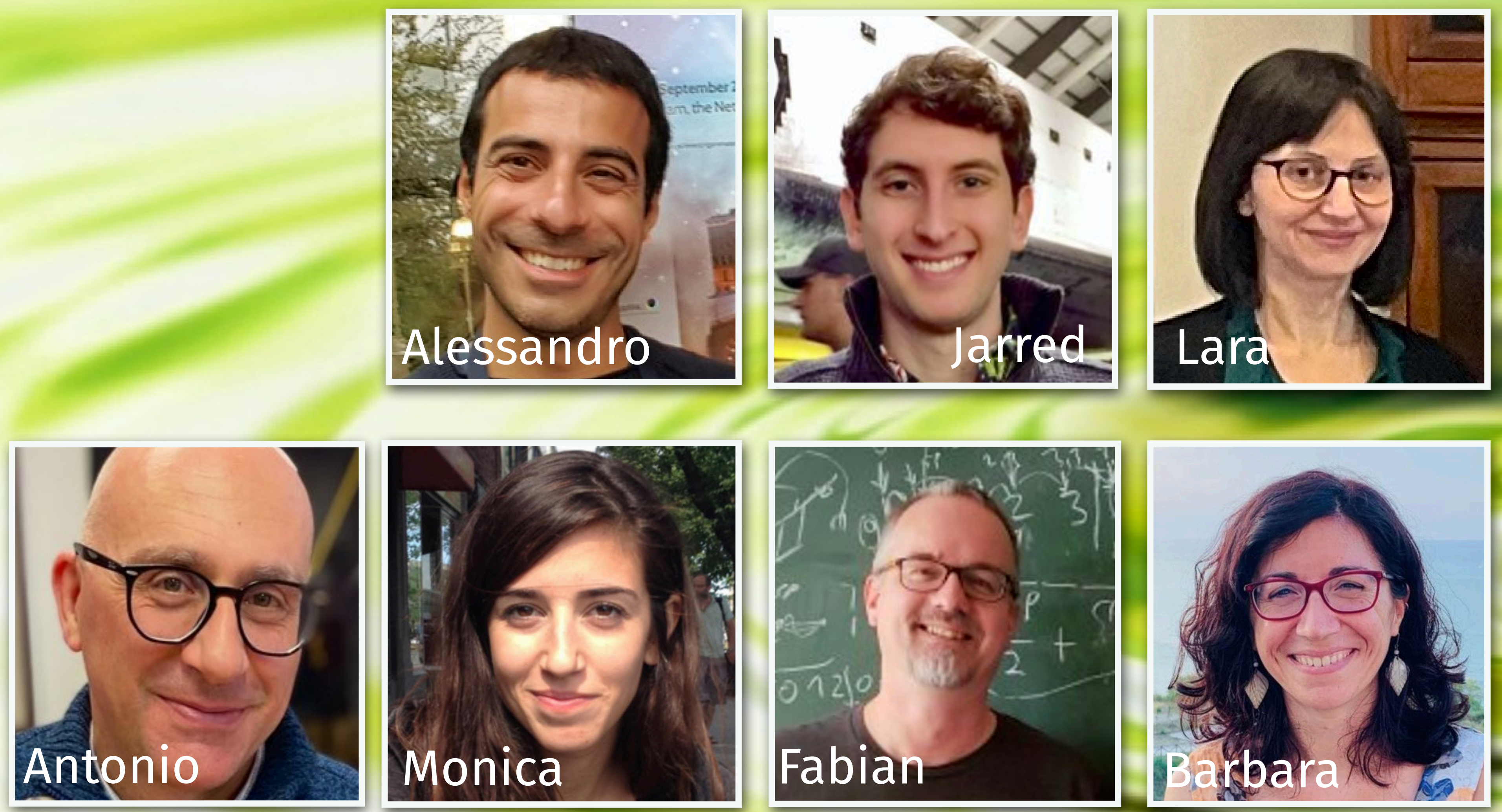
CTAO Symposium
Bologna - 15-17 April 2024

The Electromagnetic Follow-up of Gravitational Wave Events at TeV Energies with the CTA-Observatory

A. Carosi, J. Green, L. Nava, B. Patricelli, F. Schüssler, M. Seglar-Arroyo, A. Stamerra
for the CTAO-GW team (*on behalf of the CTAO Consortium*)



cherenkov telescope array

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

"We gratefully acknowledge financial support from the agencies and organisations listed here: www.cta-observatory.org/consortium_acknowledgments/"

The era of gravitational waves: GW interferometers

https://www.ligo.org/scientists/GWEMalerts.php

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

- Run 01 (2x LIGO)

  Sept 2015 - Jan. 2016

  First GW black-hole binary event!

- Run 02 (2x LIGO + VIRGO)

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

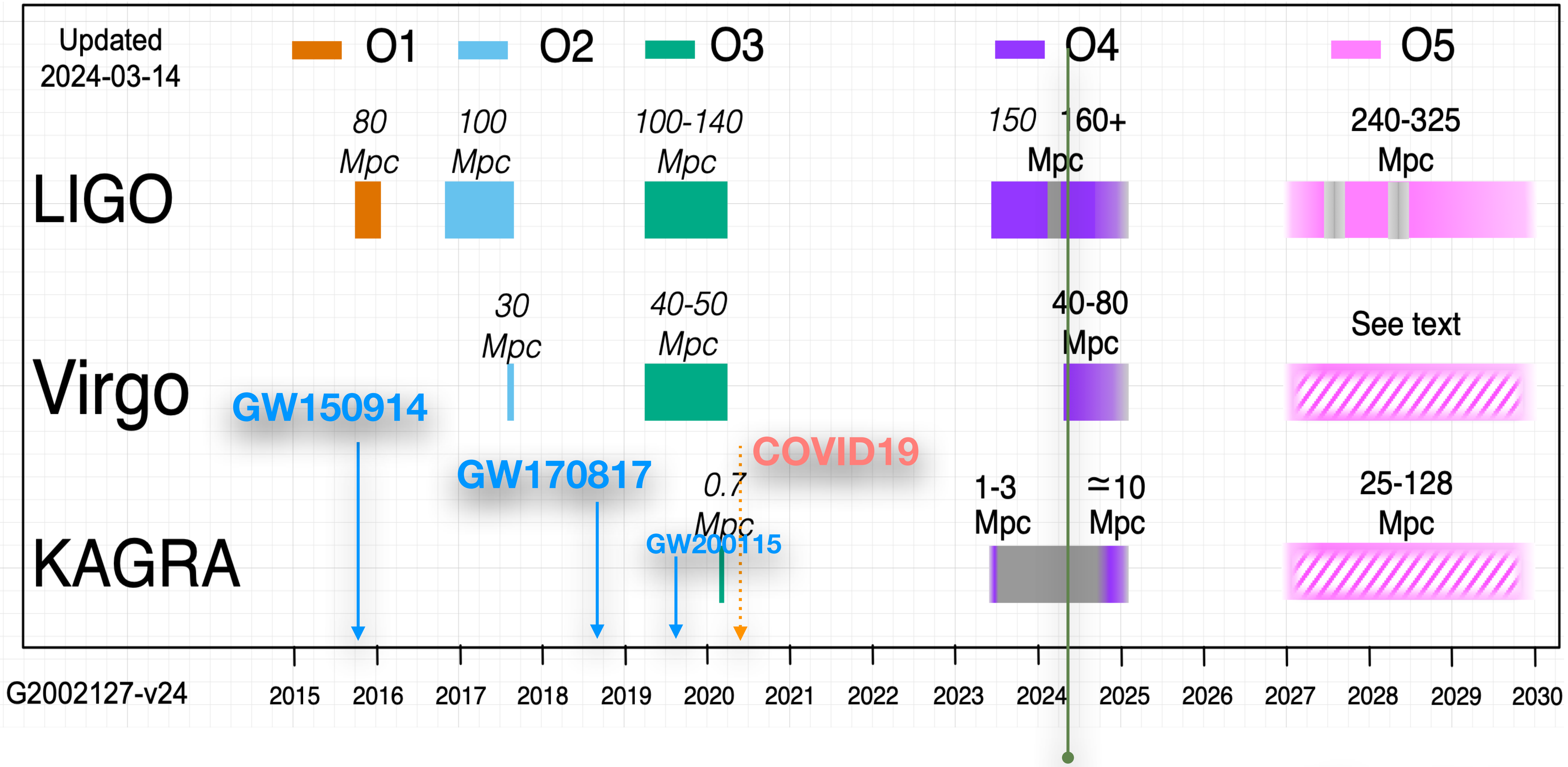
  First EM counterpart of binary neutron stars merger!

- Run 03 (2x LIGO+VIRGO+KAGRA)

  February 2019; 1 year - O3a / O3b

  First neutron star-black hole events!

  March 27th: stop due to COVID19...



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

  Started 24 May 2023 until February 2025

Since April 10, 2024 Virgo is online!

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

  2027-2030

Run O5 matches the current CTAO South timeline

The era of gravitational waves: GW interferometers

GraceDB Public Alerts Latest Search Documentation

Please log in to view full database contents.

S240413p
Log Messages
Full Event Log

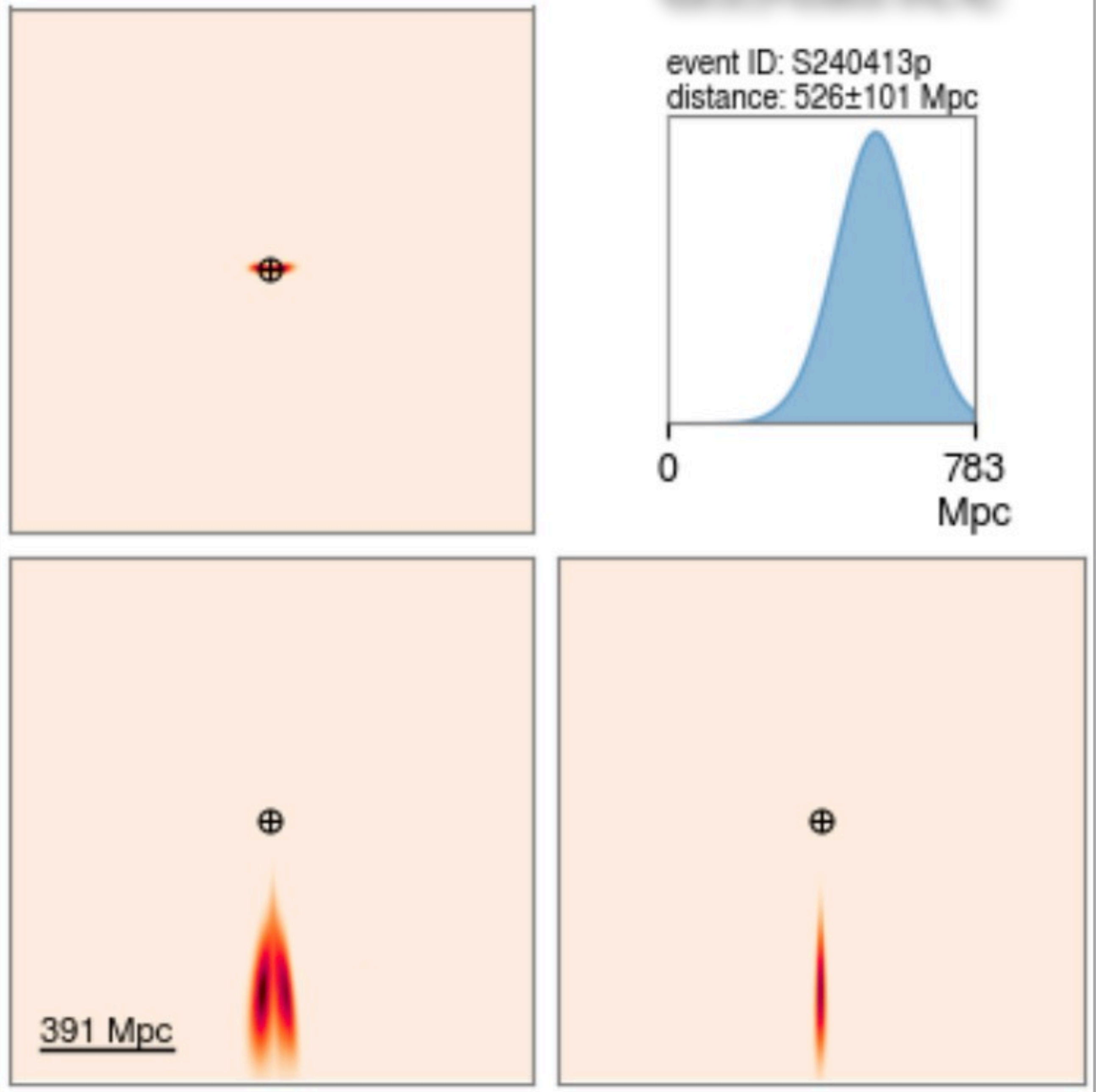
S240413p

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

Sky Localization

Log Image

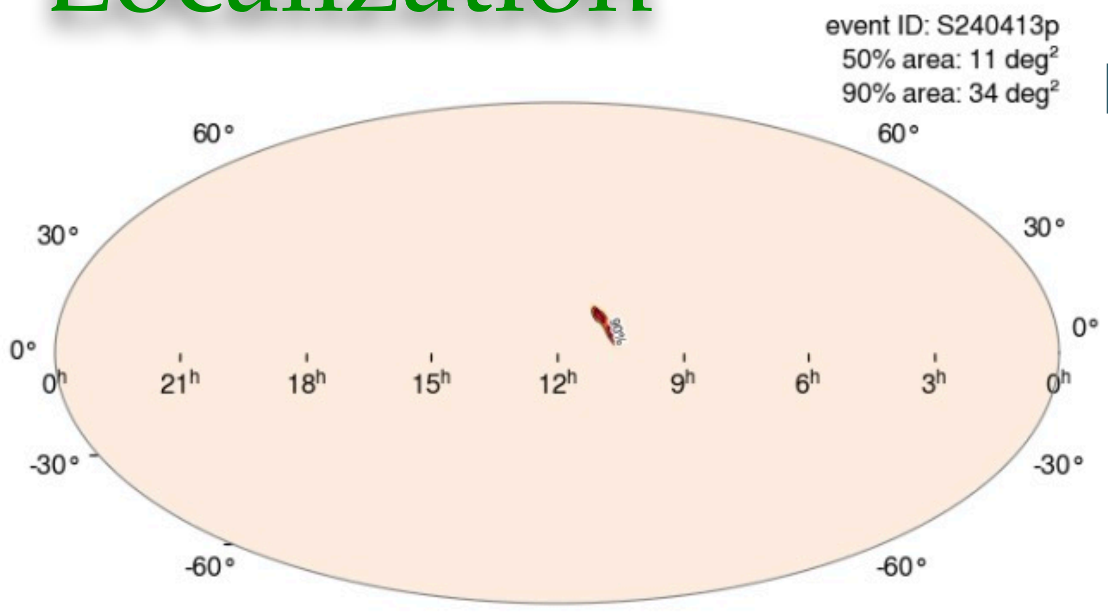
distance

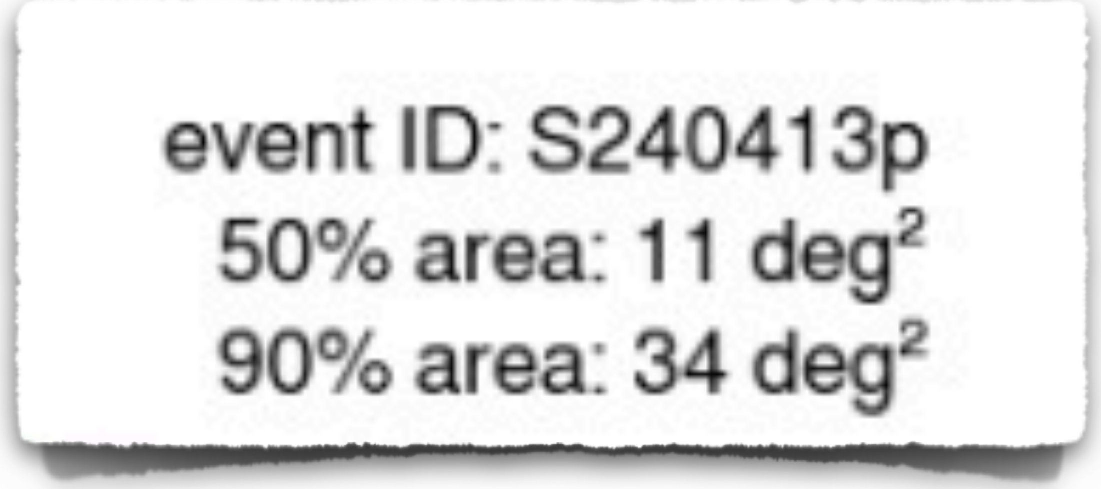


Volume rendering of
Bilby.offline0.multiorder.fits
— Submitted by LIGO/Virgo EM Follow-Up on April 13, 2024 20:34:27 UTC

Log Image

Localization





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

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

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

GW AND ELECTROMAGNETIC (EM) COUNTERPARTS

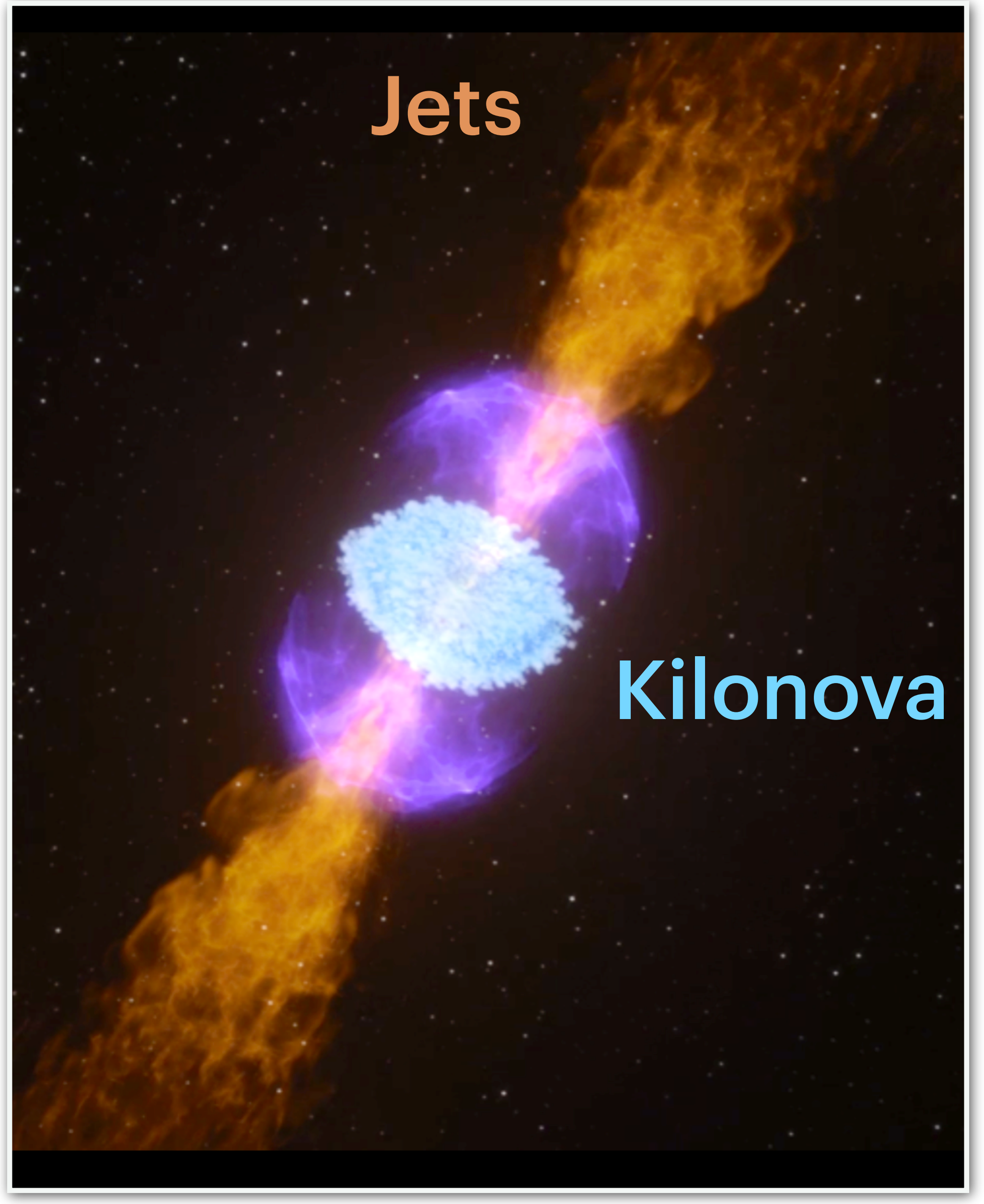
- Binary Neutron Star mergers (BNS) ➔ **short GRB**
  suggested (since Eichler+1989), expected (GRB050724) and observed (GW/GRB170817)
  - But 2 long GRBs were associated kilonova (GRB060614, GRB211227) —> scenario not straightforward

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

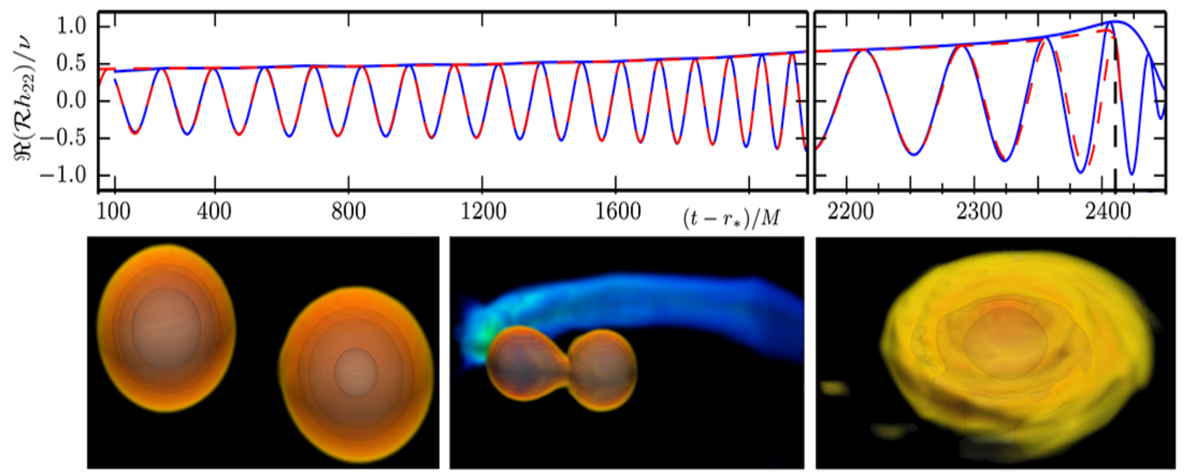
- BH-BH: **??** no EM emission expected
  (but Loeb+2016, Perna+2016, Murase+2016, Graham et al. 2020,…)

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

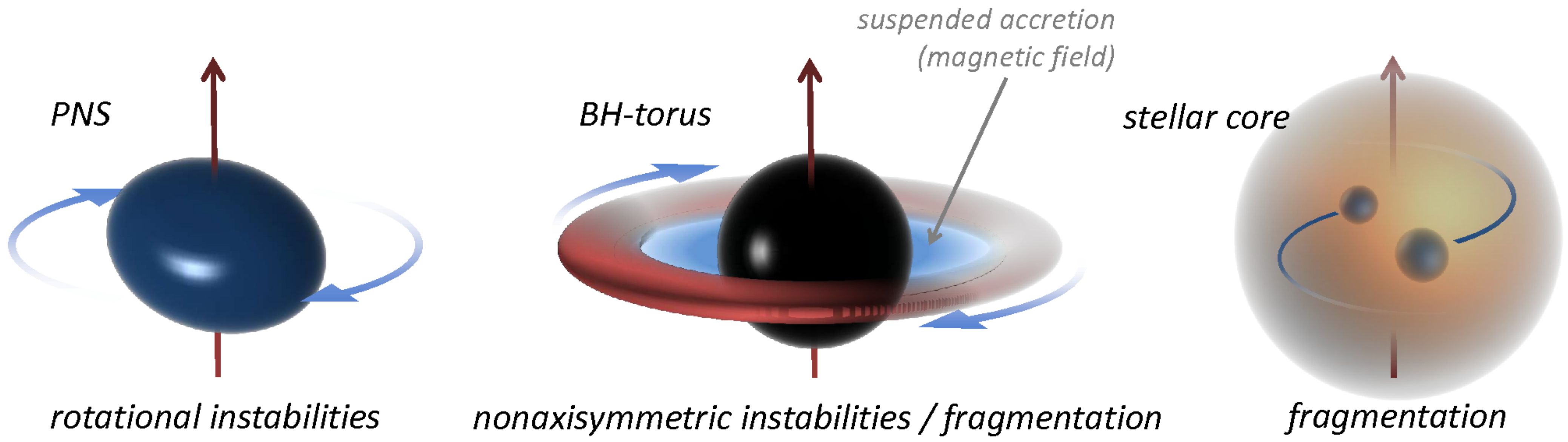
Electromagnetic emission



GW emission from merger



GW emission from asymmetric star collapse



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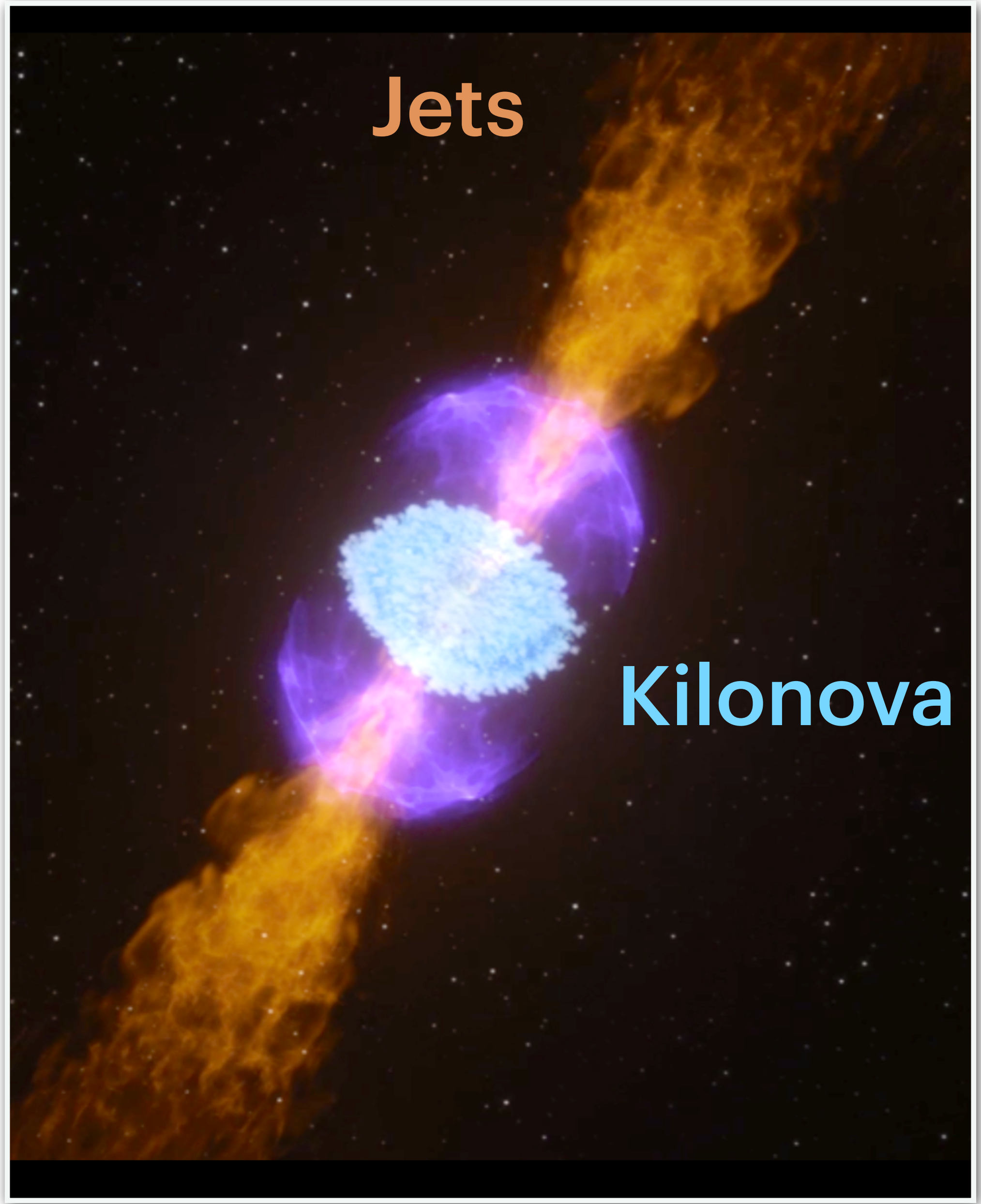
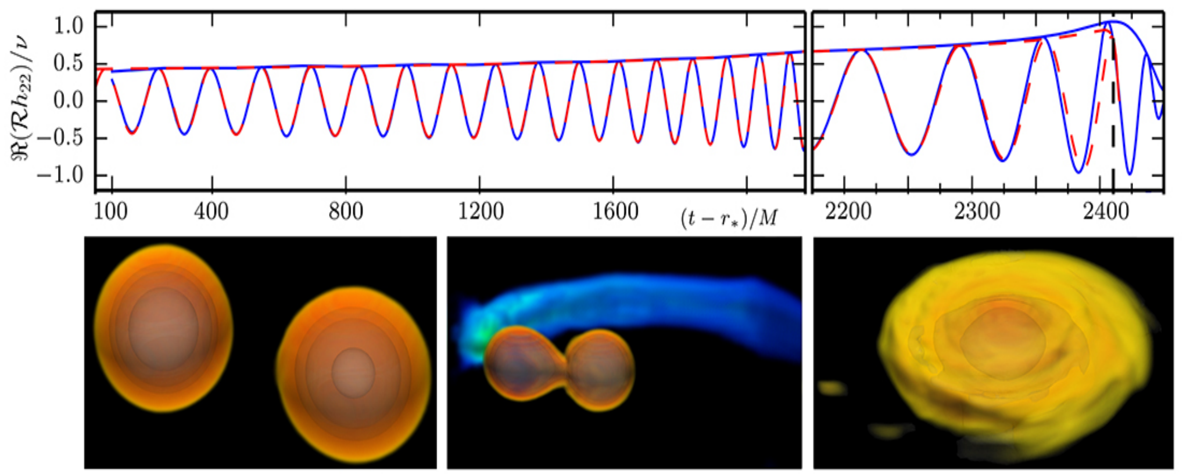
What do we expect in the TeV band?

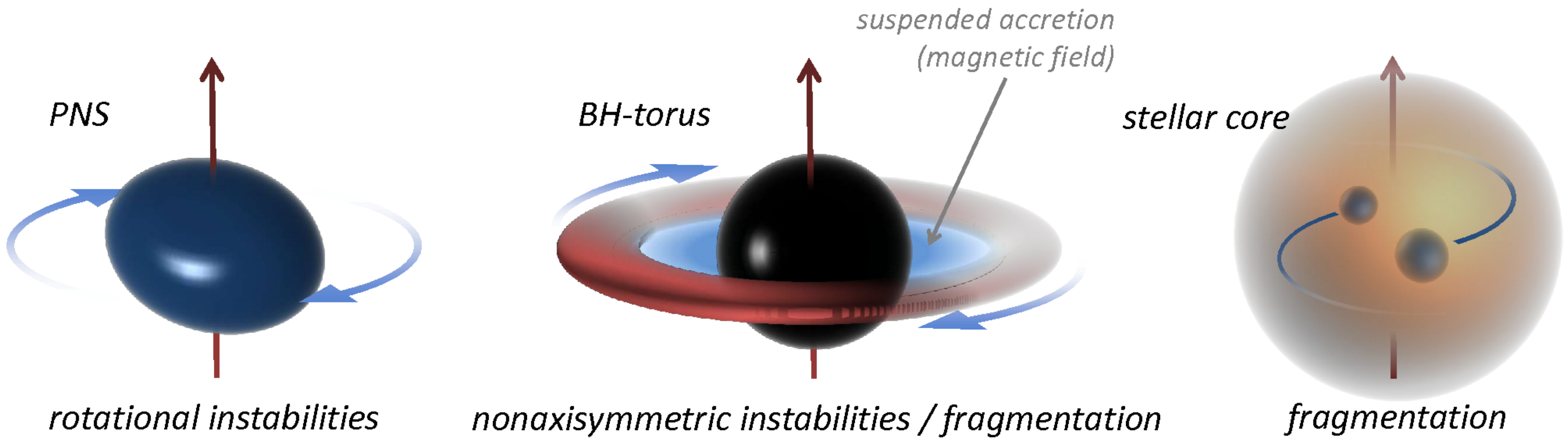
Electromagnetic emission



GW emission from merger

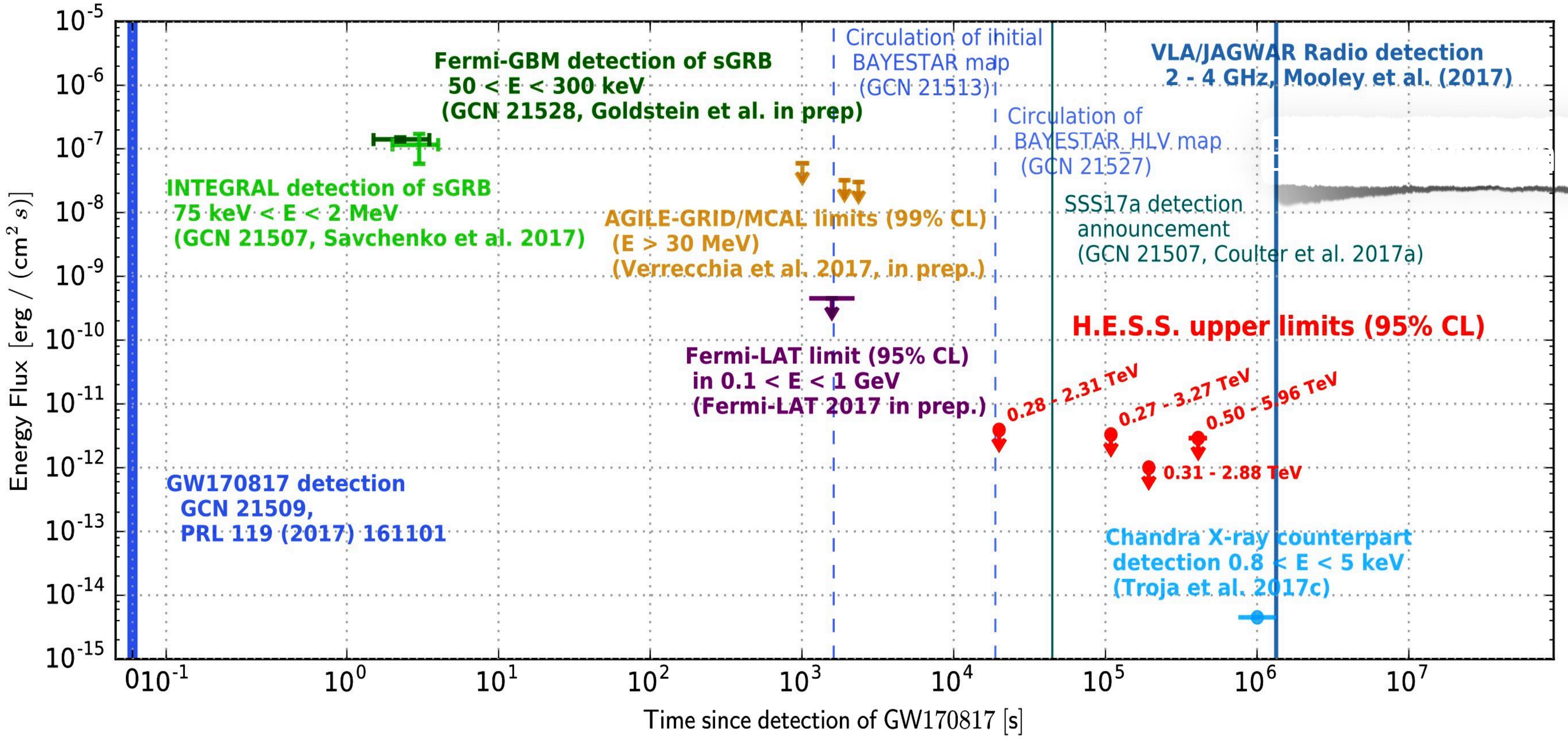


GW emission from asymmetric star collapse



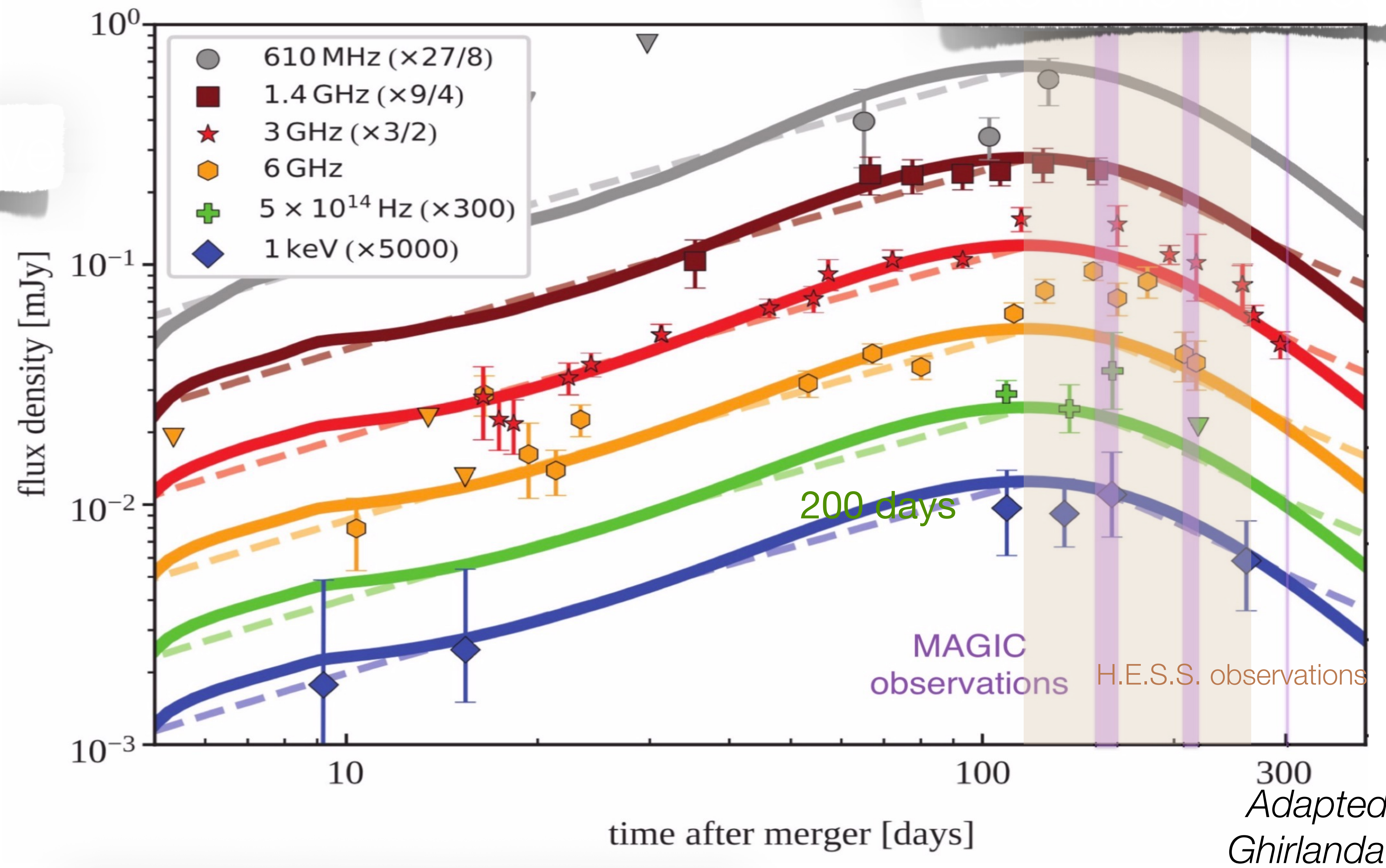
GWs and GRBs at TeV energies

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

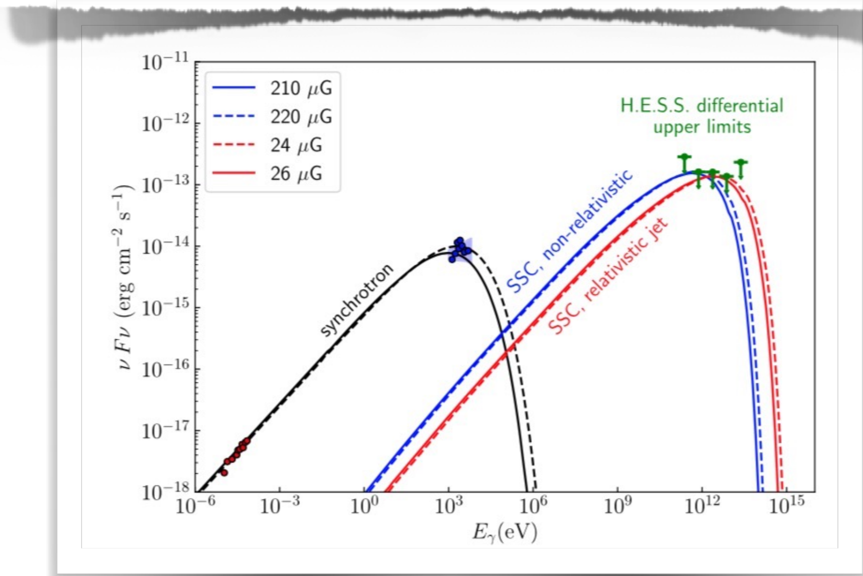


Abdalla et al. (HESS coll), 2017

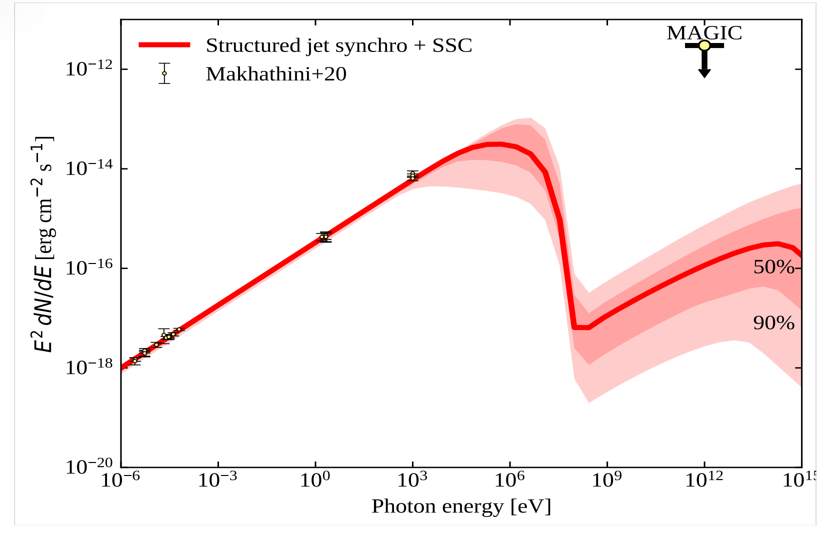
No detection at the maximum of the delayed emission



Adapted from Ghirlanda+2019



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



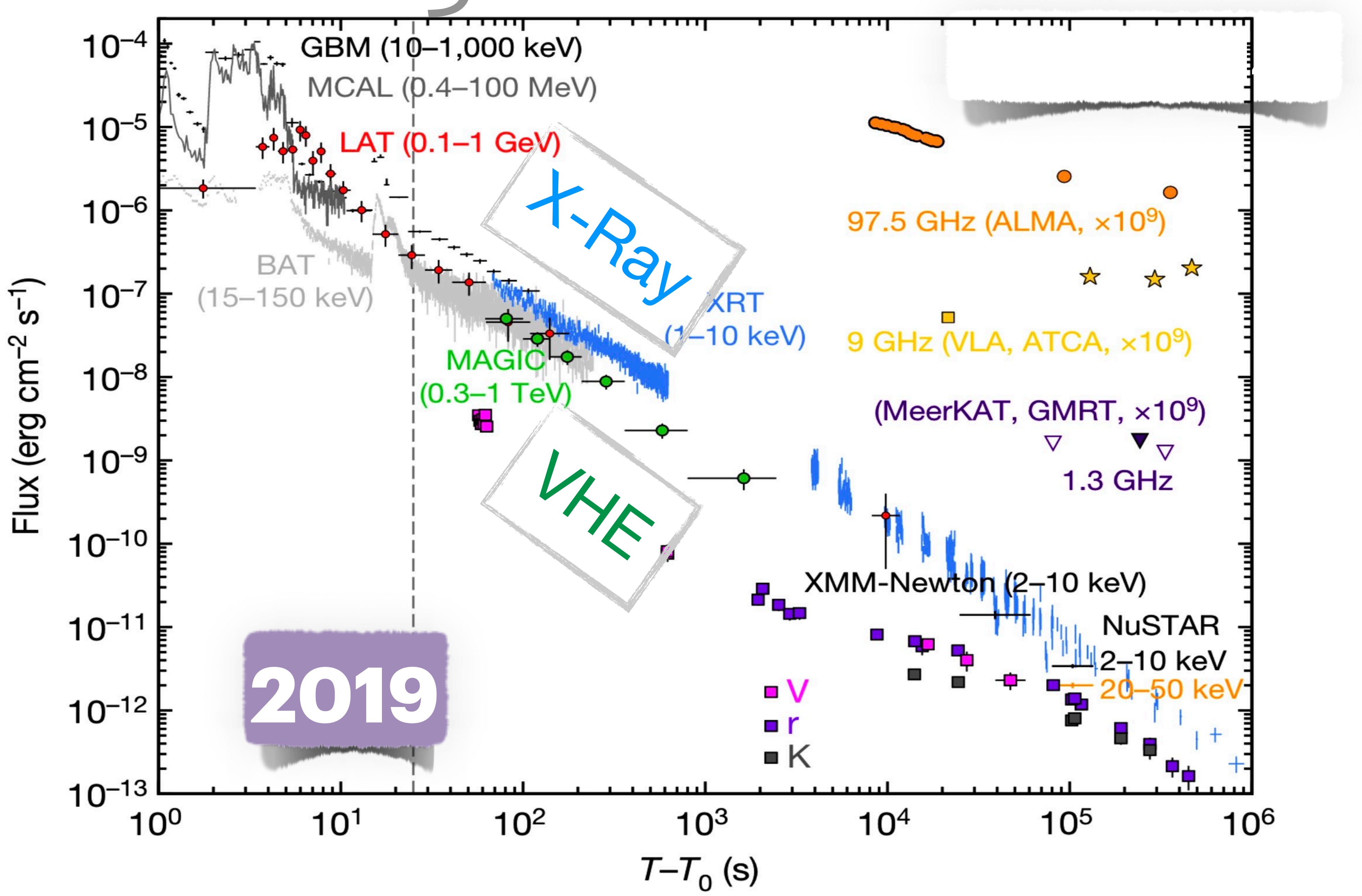
AS, Salafia O. S., et al. 2021a, PoS, 944

GWs and GRBs at TeV energies

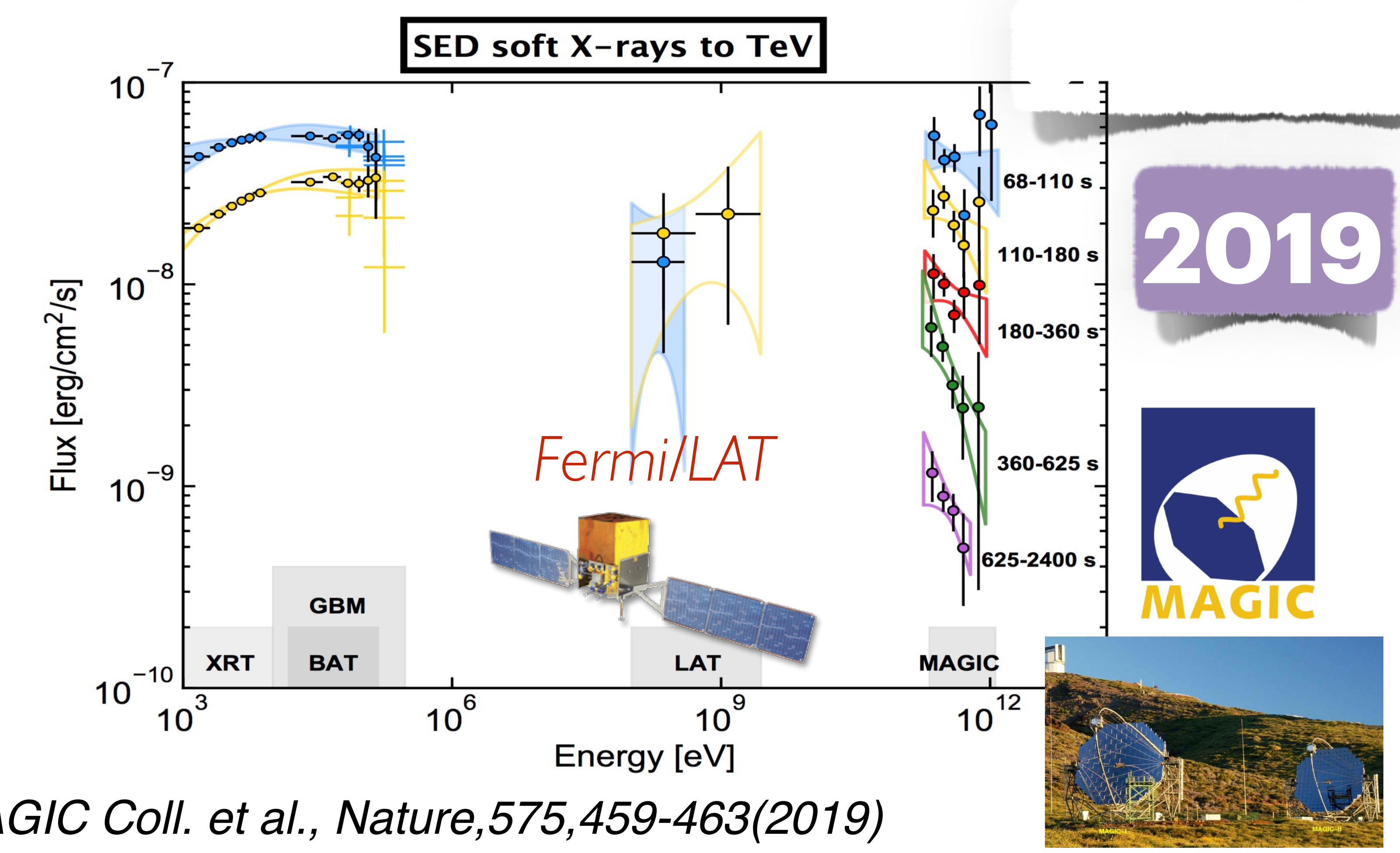
★ Detection of the TeV (afterglow) emission

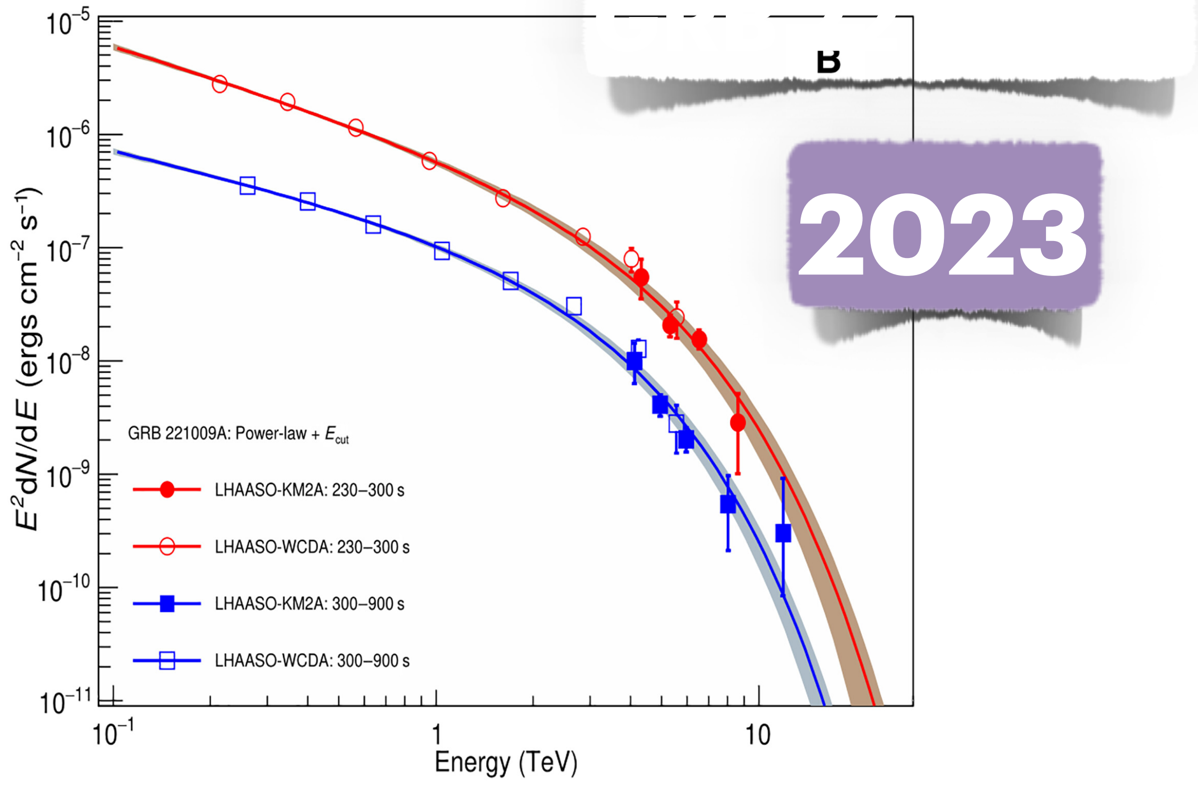
- ✓ GRB engine accelerates photons up to TeV
  - Gamma rays up to 12 TeV from the GRB 221009A!
- ✓ Evidence of a second energetic component
- ✓ Energy budget and time evolution similar to the optical-X-ray component: **TeV flux follows closely the X-ray flux**

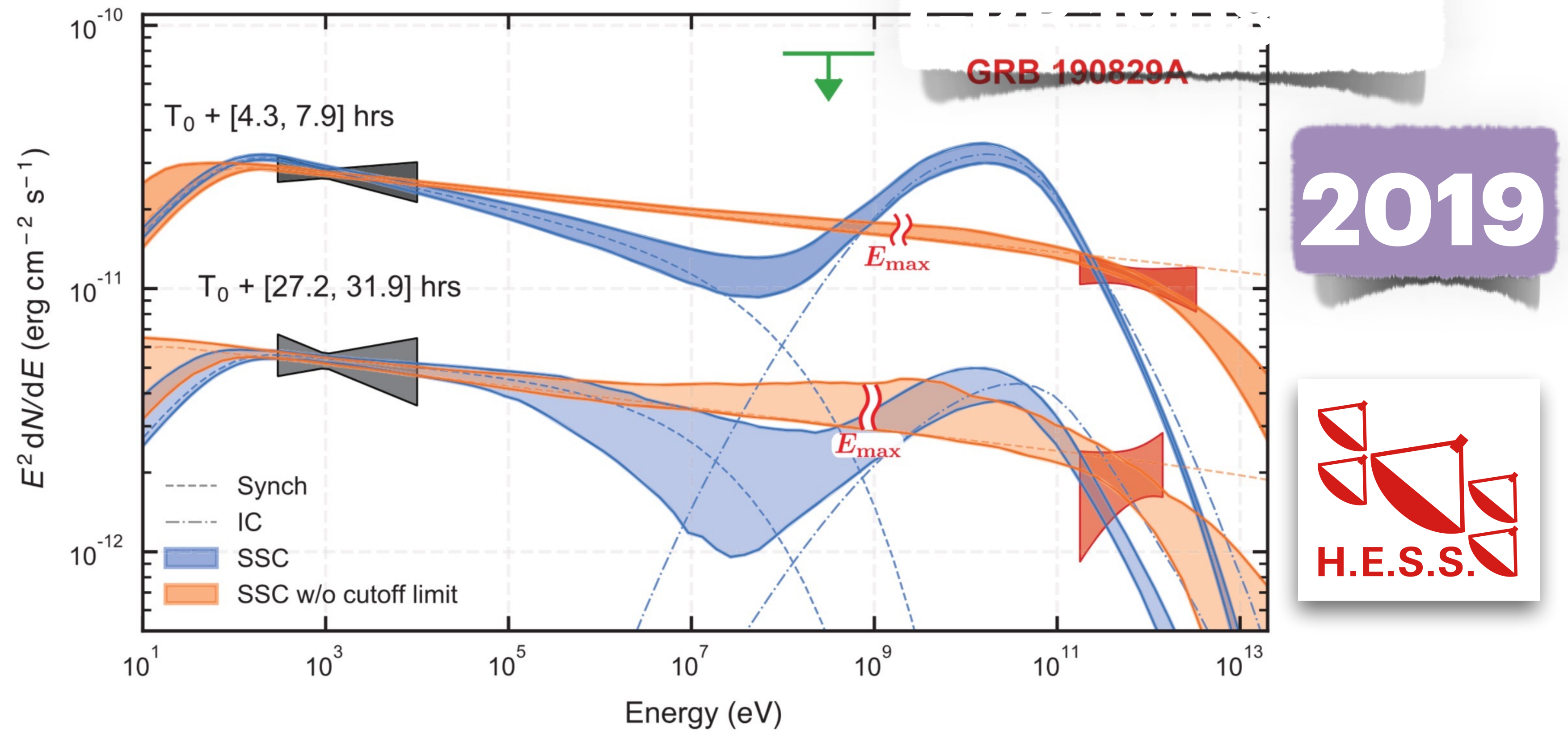
lightcurve



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)

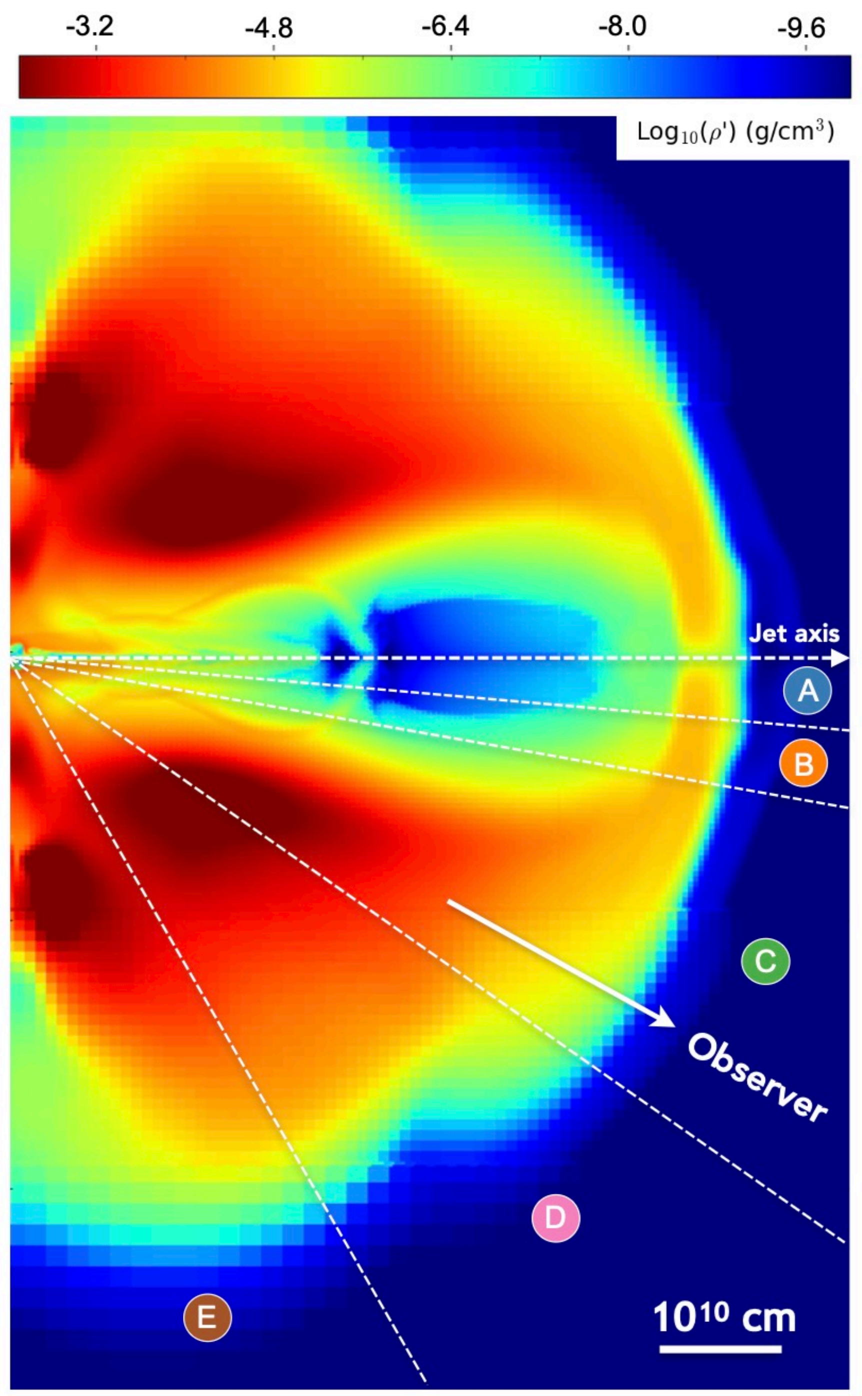
The Role of Off-axis Observations and structured Jet

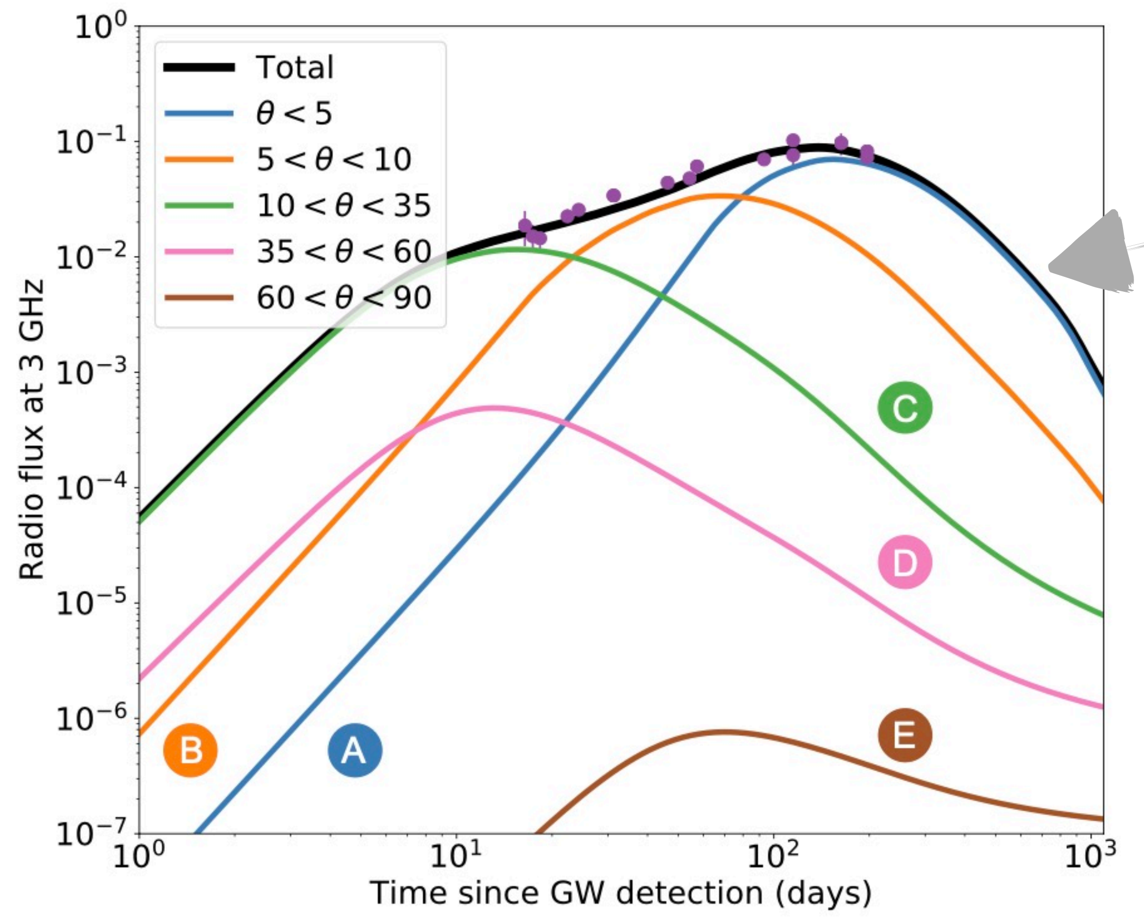
GeV-TeV emission is expected from the relativistic outflow (jets)

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

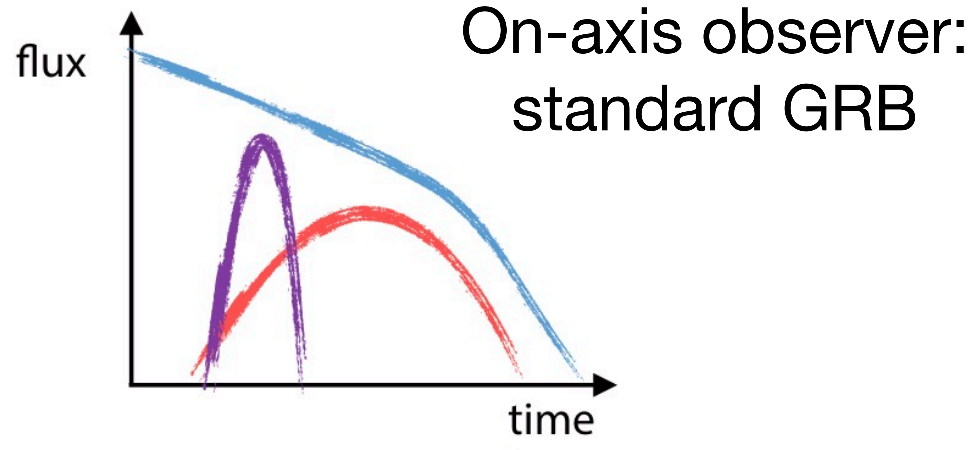
➡ intensity <u>weaker</u> 10^{-4} to 10^{-6} times than on-axis emission

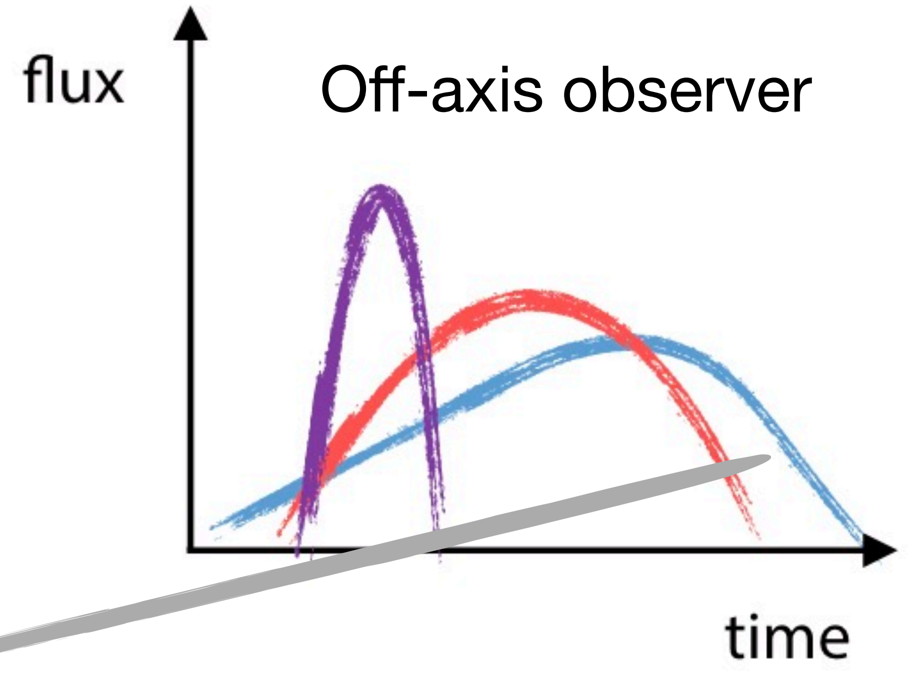
➡ light curve <u>delayed</u> (hours/days/months, depending on θ_{view})

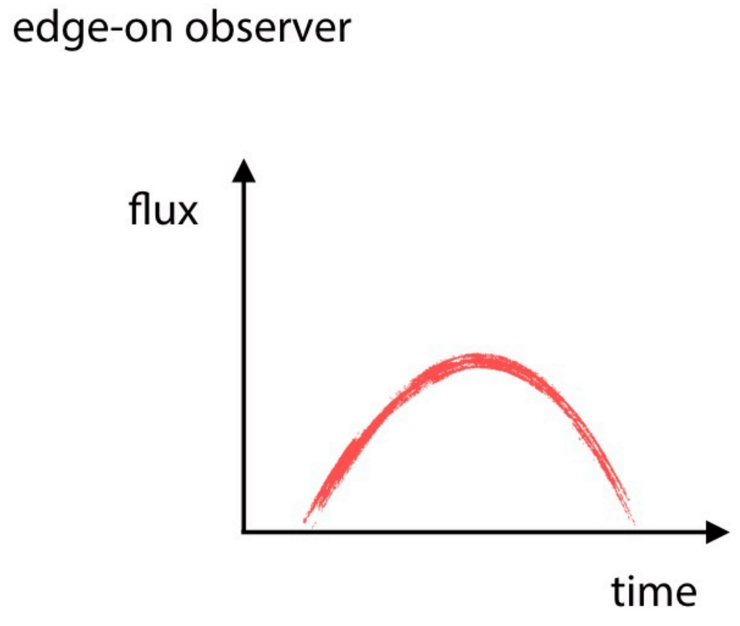


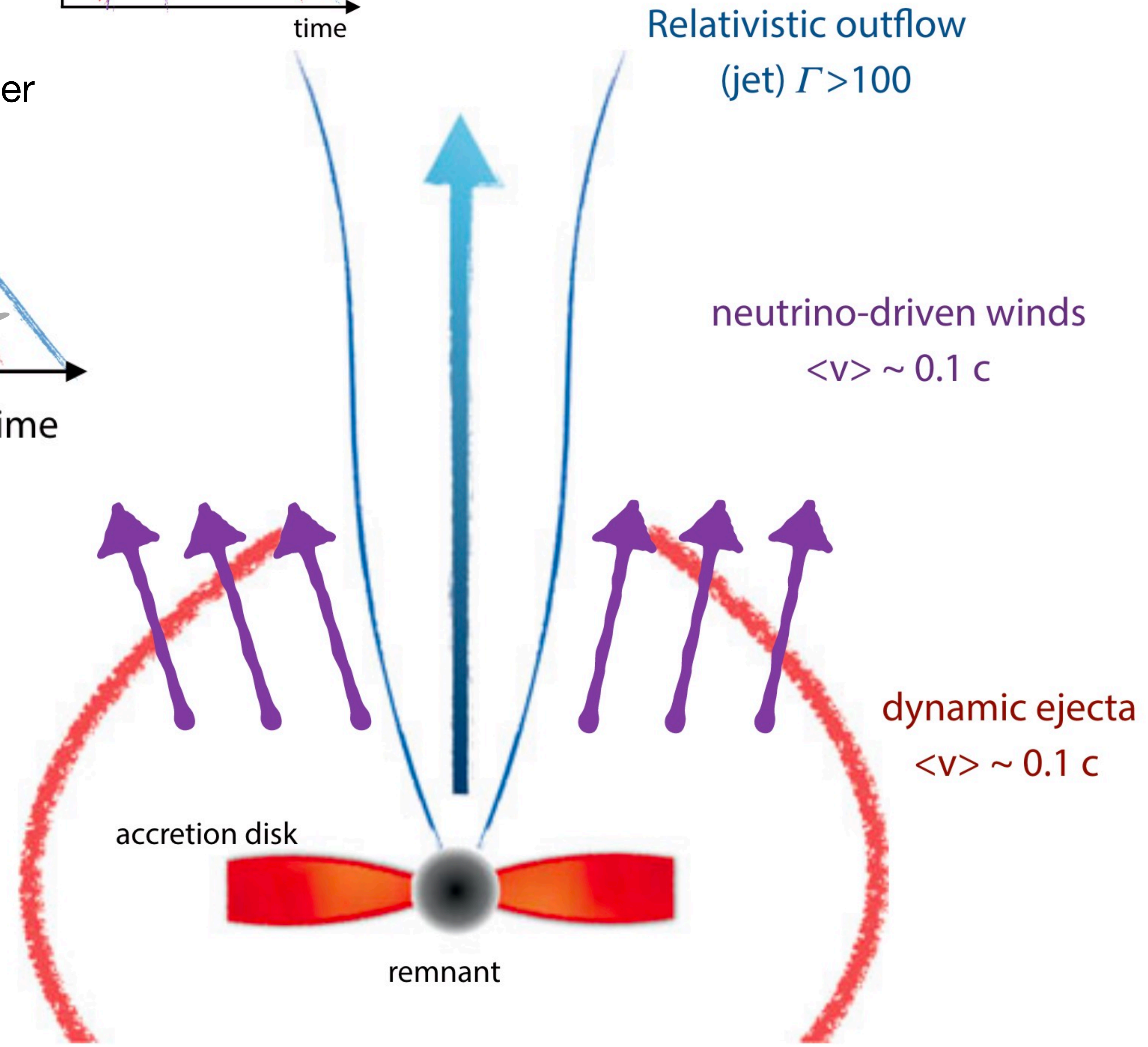


Hydrodynamical simulation of a short GRB (Lazzati+2018)









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

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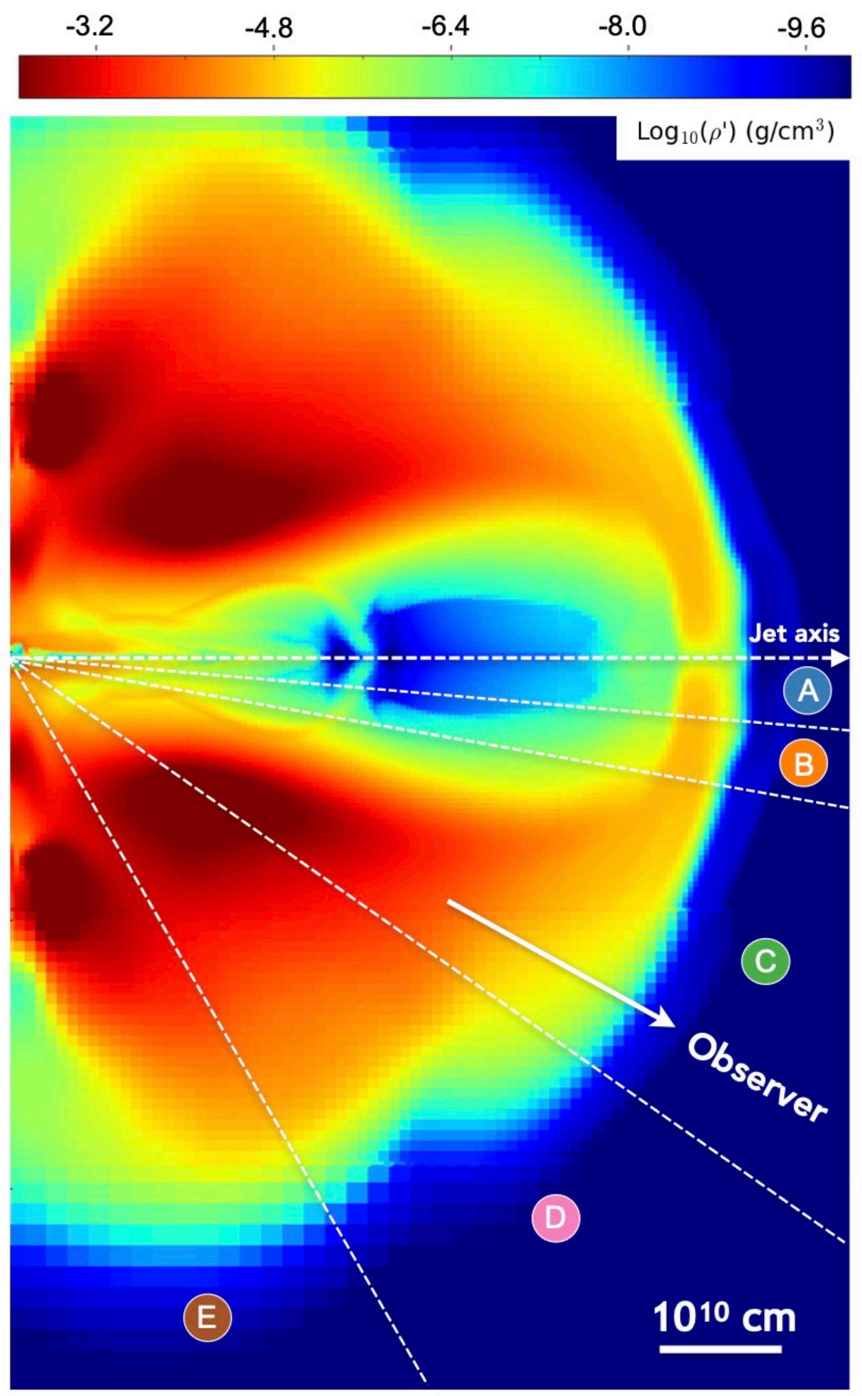

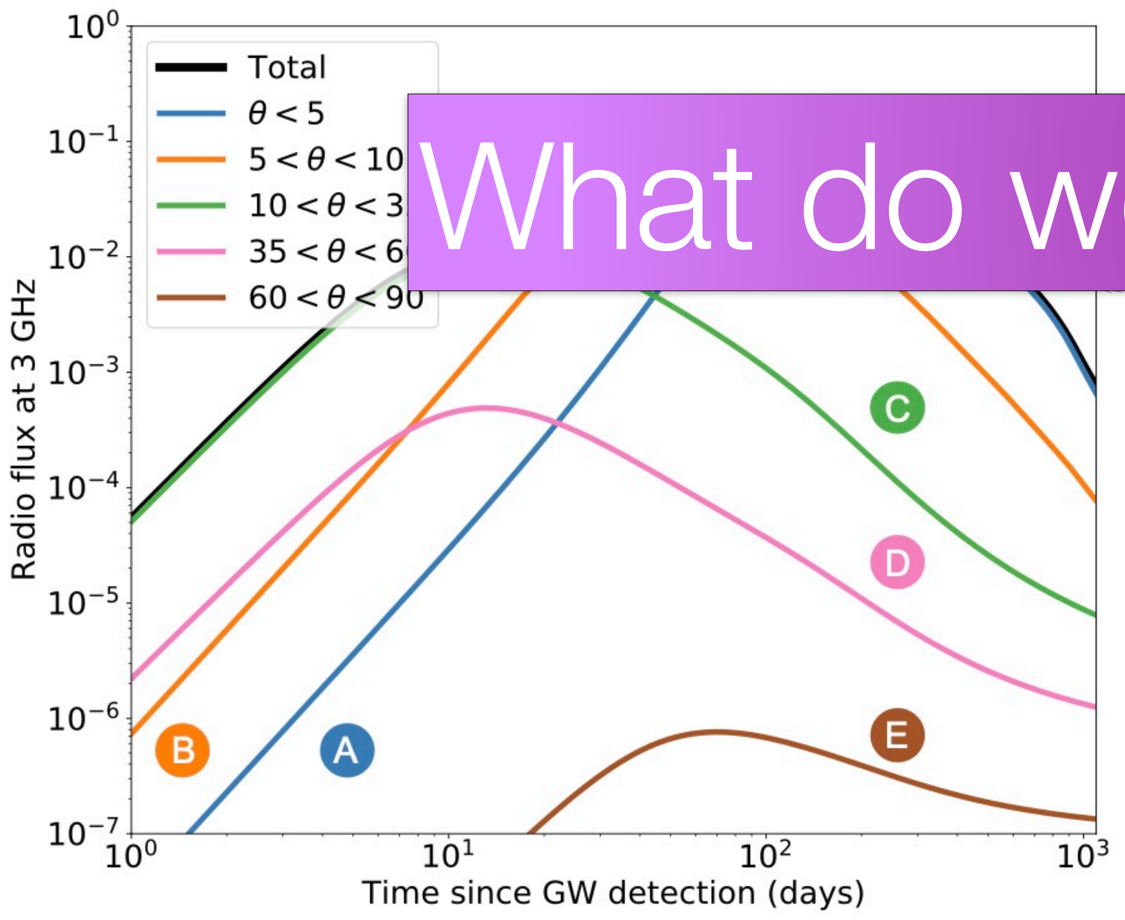

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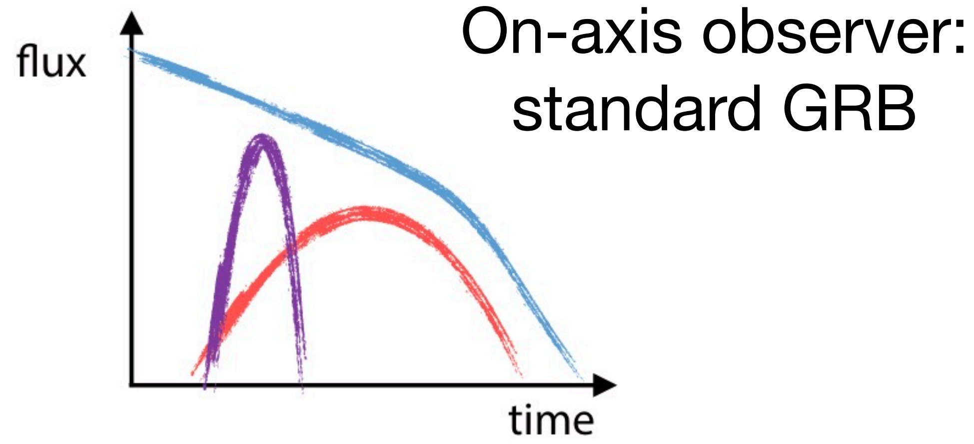
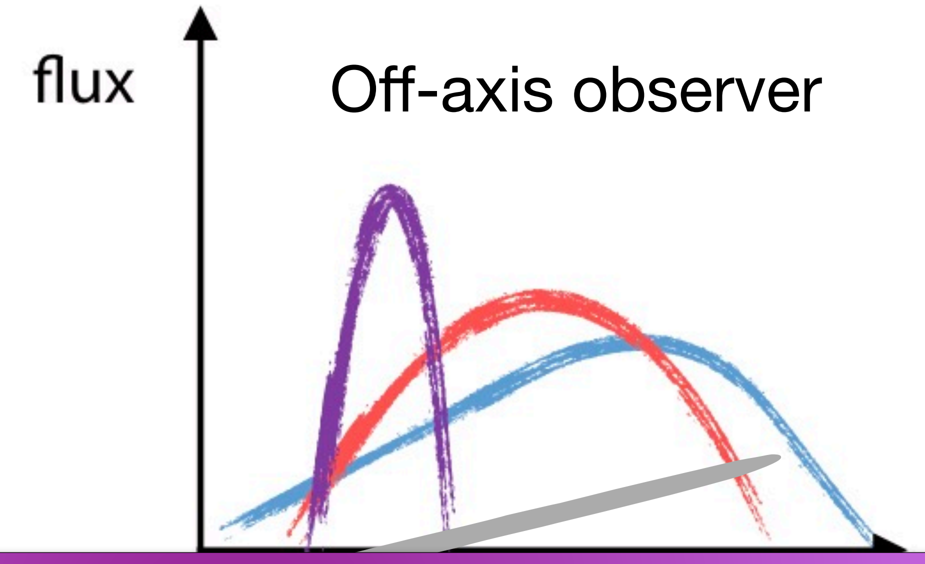
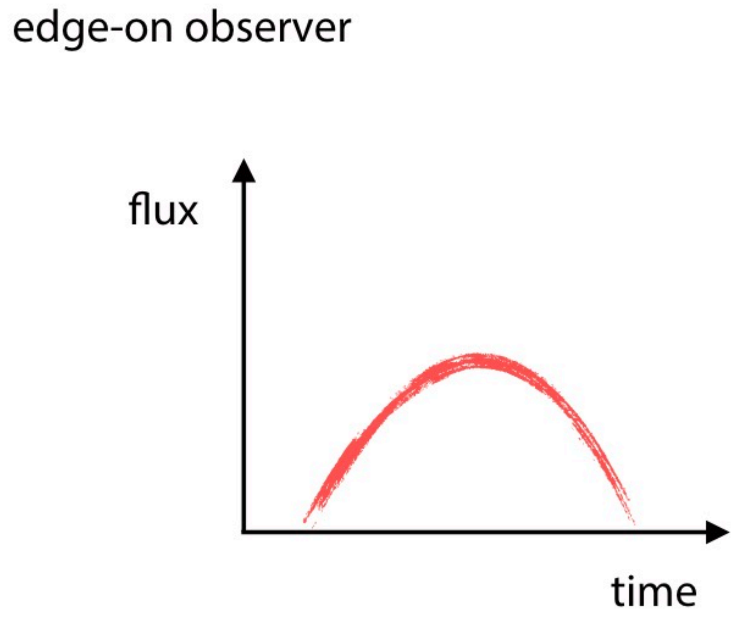
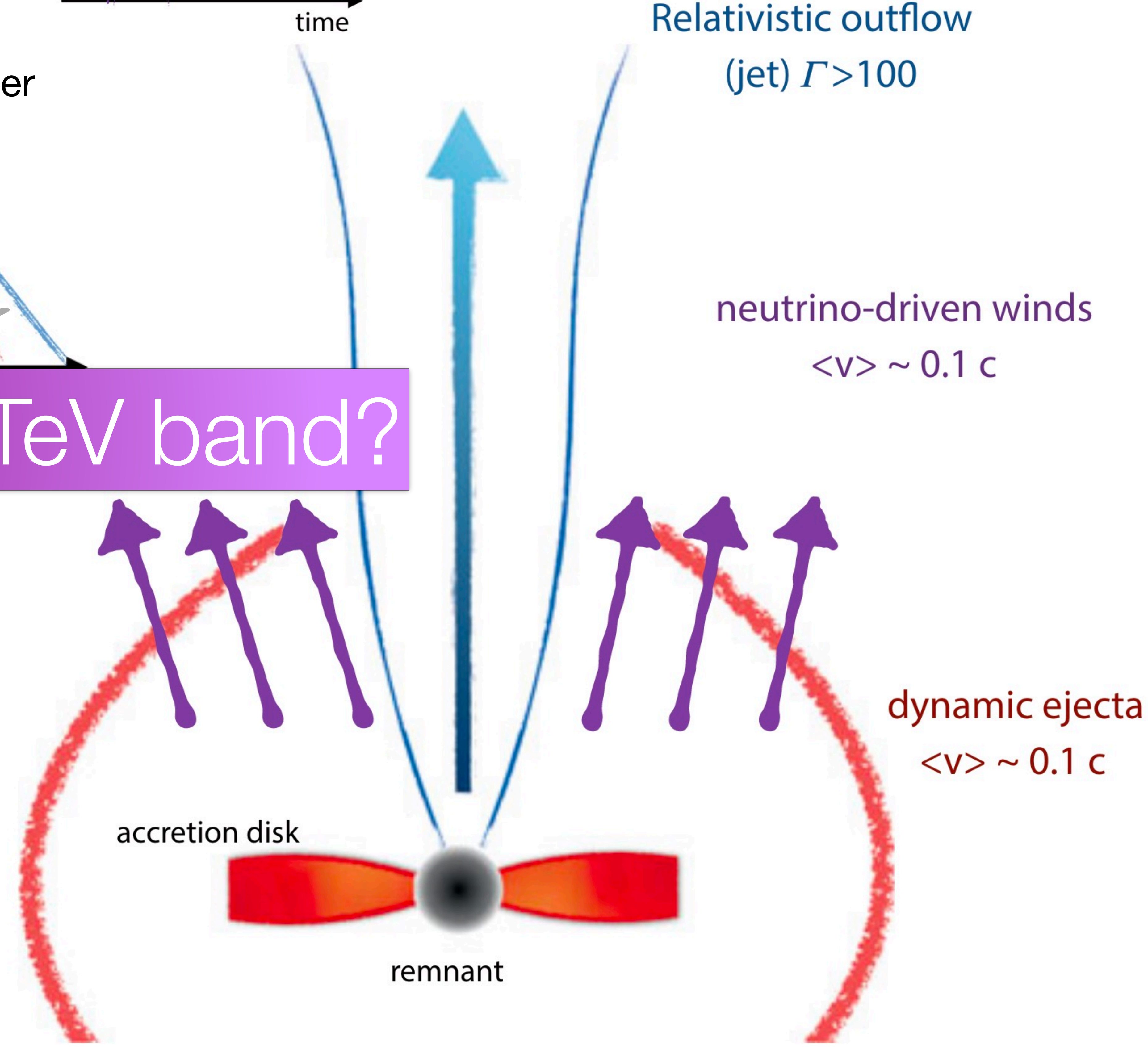




What do we expect in the TeV band?





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

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

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

Simulation of BNS mergers
and GW signal in local universe

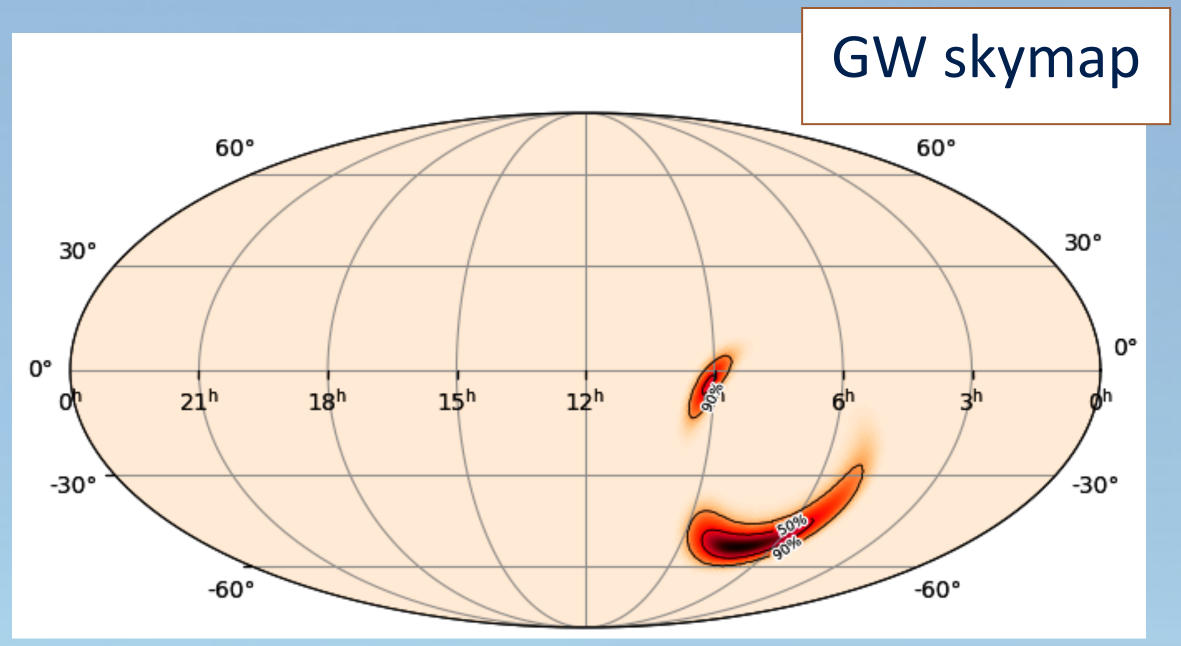
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

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

Observation optimisation and scheduler
CTAO observing strategy

B. Patricelli et al., 2022

The GW-TeV and CTAO simulation chain



- 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

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Simulation of CTAO response
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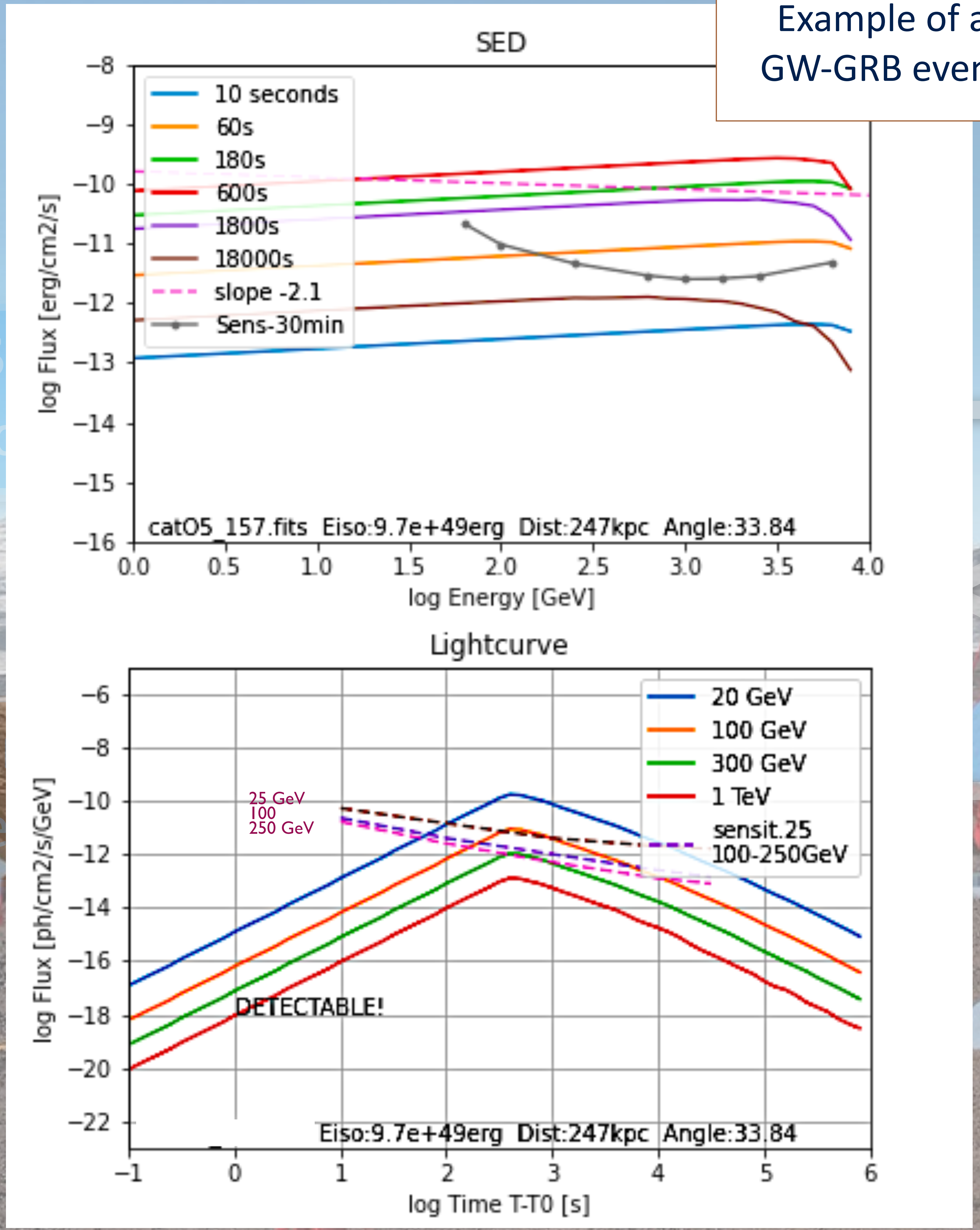
The GW-TeV and CTAO simulation chain

Example of a GW-GRB event

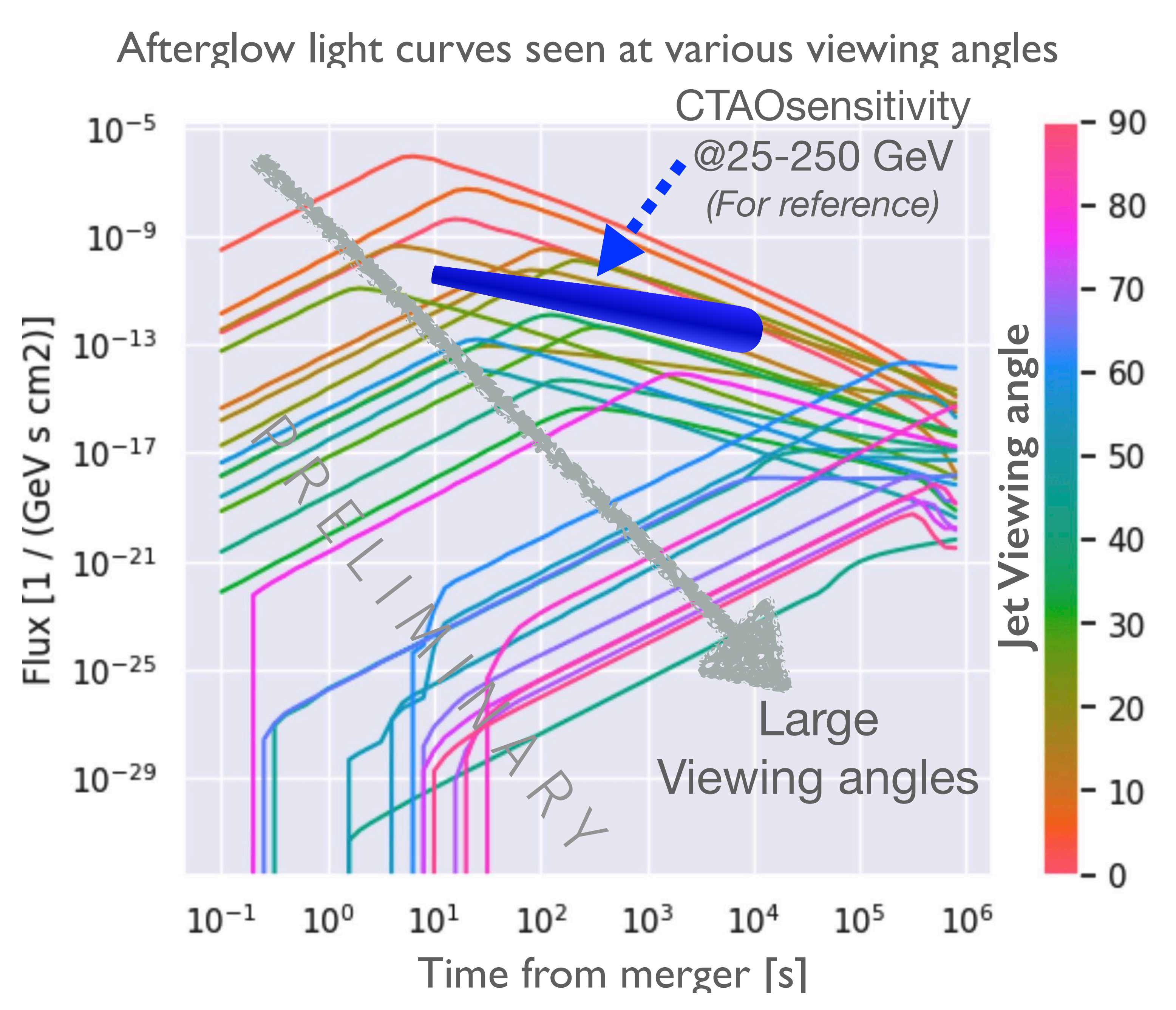


Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

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

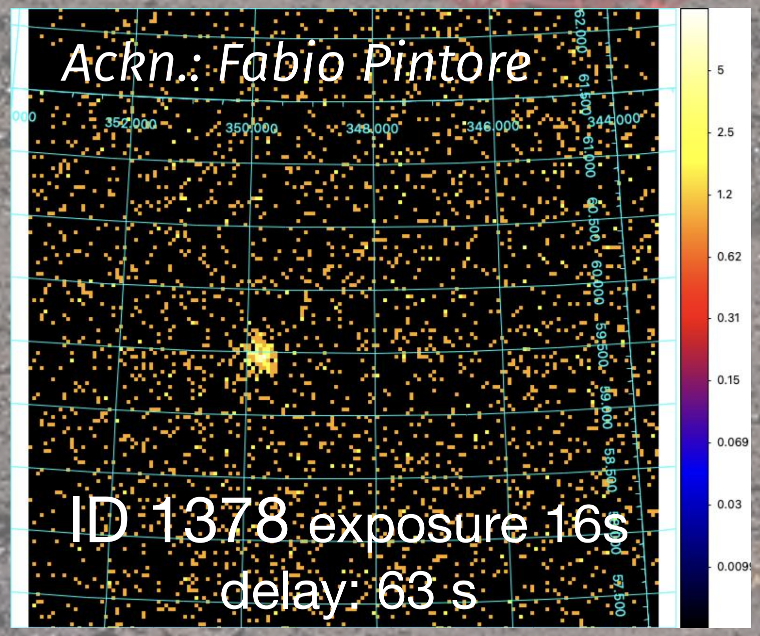


- Optimised follow-up strategy for detection: the exposure is tuned to detect the source (*Patricelli et al. 2018*).
- Realistic observing conditions for CTAO are considered (*Seglar-Arroyo et al. 2019*)
- The Scheduler iterates on the best visible positions. If the true source position is covered, by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

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

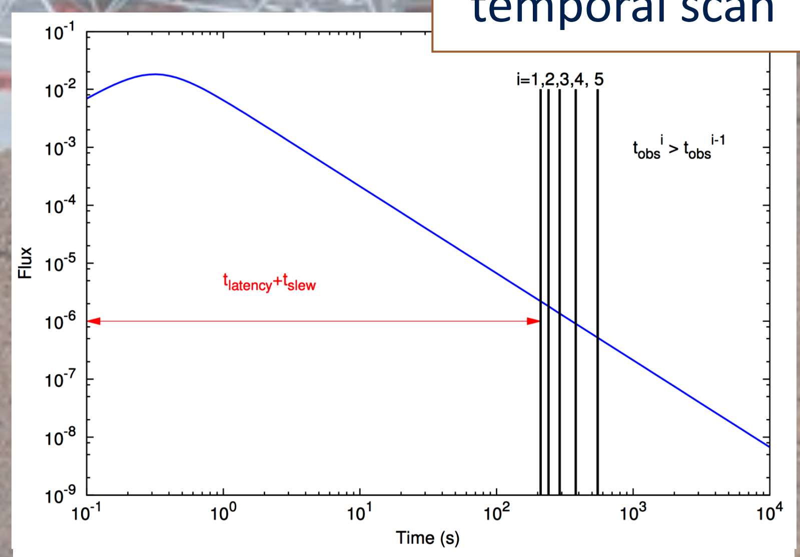
Observation optimisation and scheduler
CTAO observing strategy

* **IRF: Instrument Response Function**



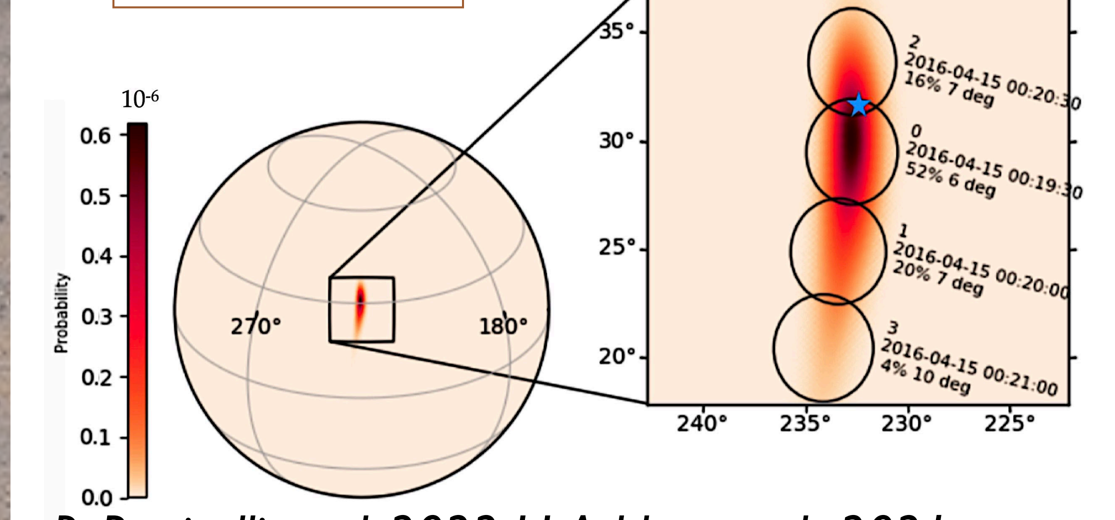
- Computation of CTAO sensitivity tailored on the GW-GRB models, including EBL absorption
- CTAO Alpha configuration

temporal scan



B. Patricelli et al., 2018.

CTAOtiling



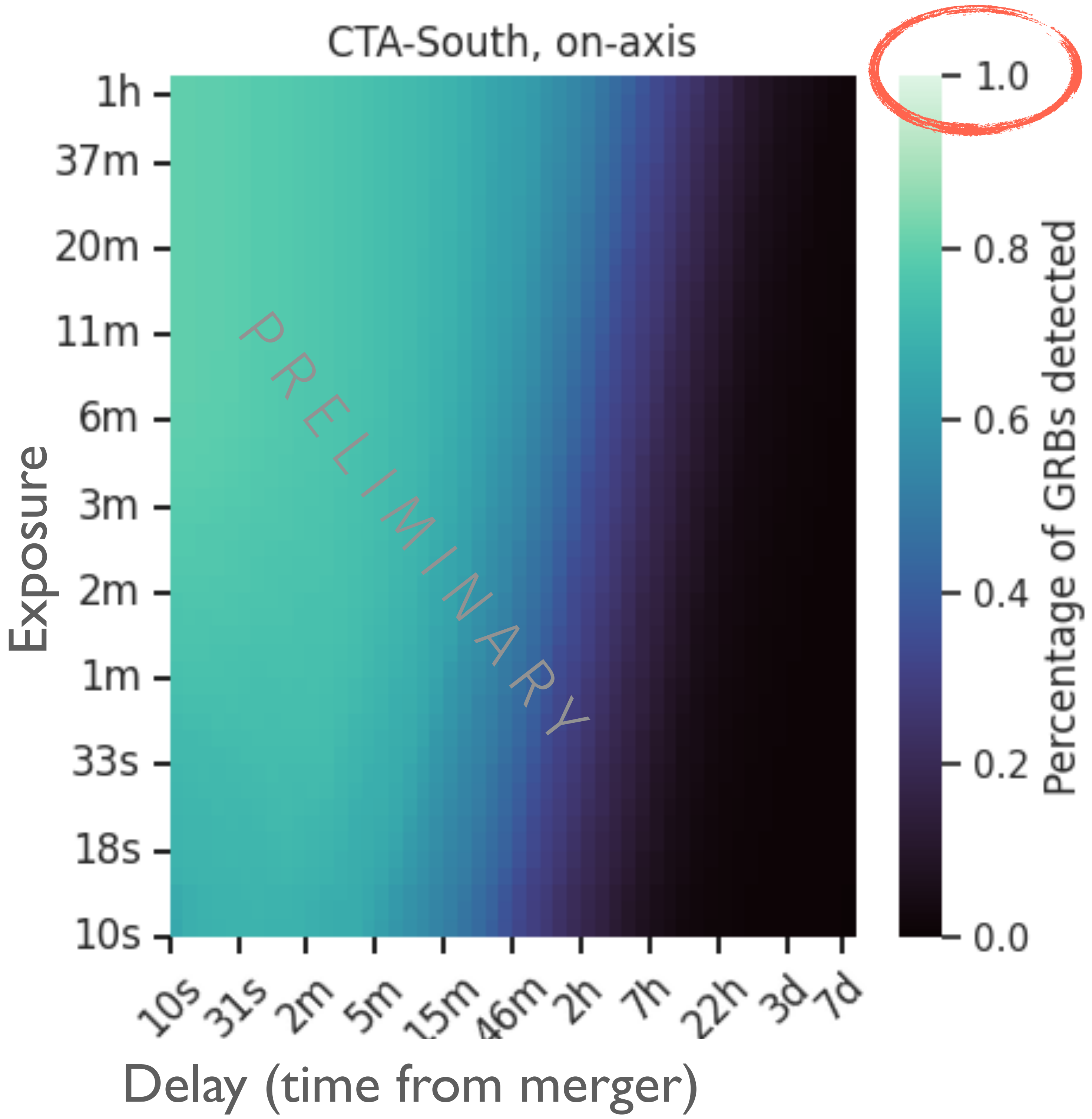
B. Patricelli et al. 2022 H. Ashkar et al., 2021

First preliminary results - 1. detectability

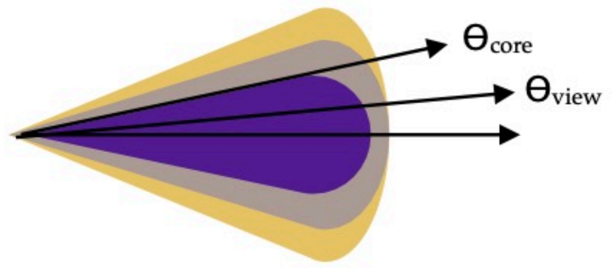
- Detection expectations by CTAO as a function of delay and exposure
- Based on the 2307 simulated GW-GRBs and the CTAO sensitivity (Alpha configuration)

t_0 ~30 sec, ~ 75% detections with $T_{exp} \leq$ 1 min.

t_0 ~10 min ~ 60% detections with T_{exp} ~ 1 min.

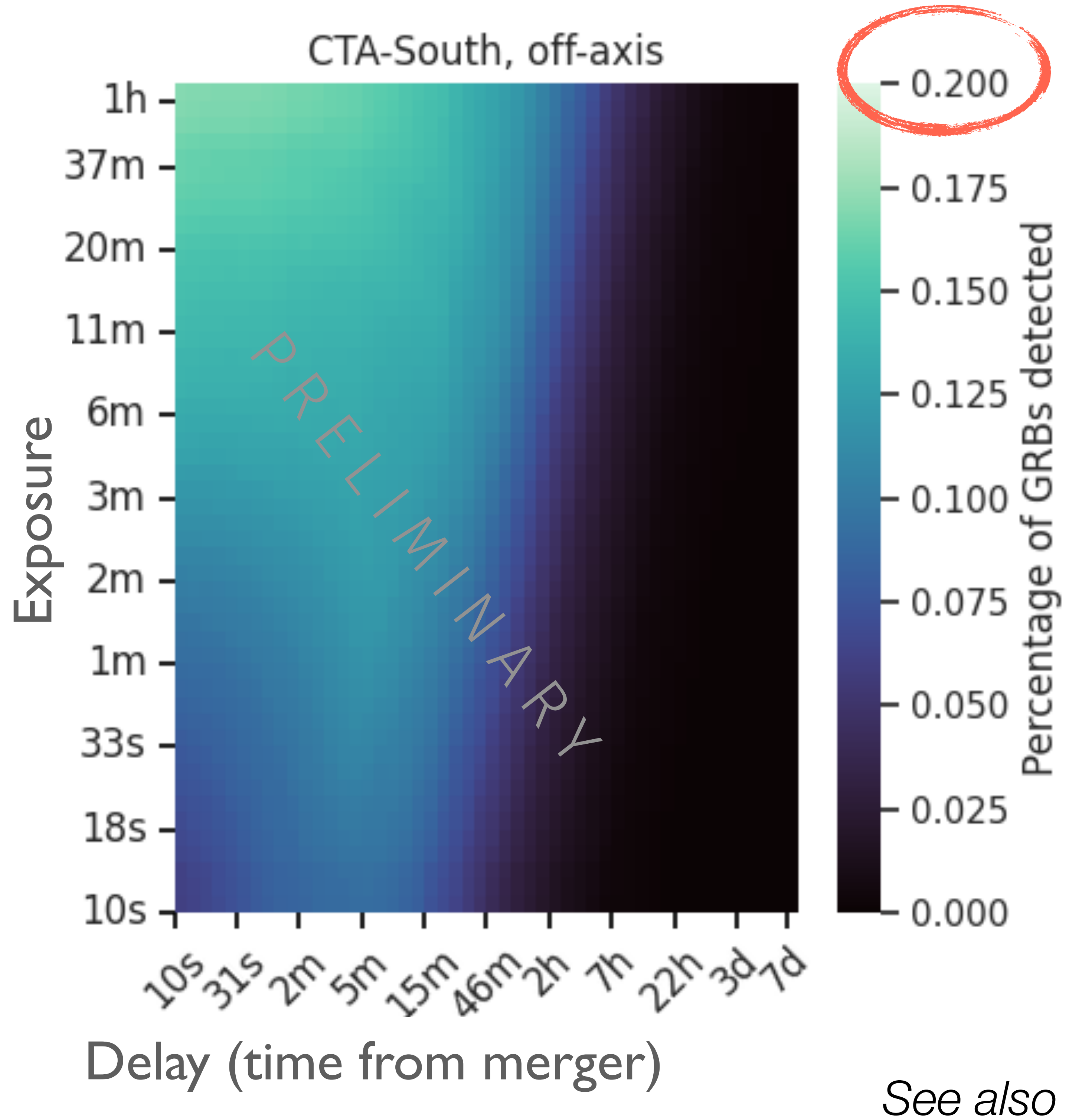


Events seen on-axis (13%, $\Theta_{view} < \Theta_{core}$)

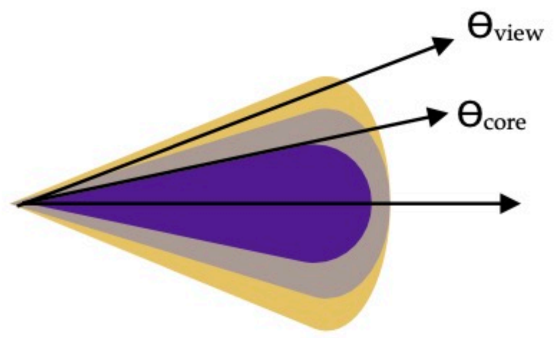


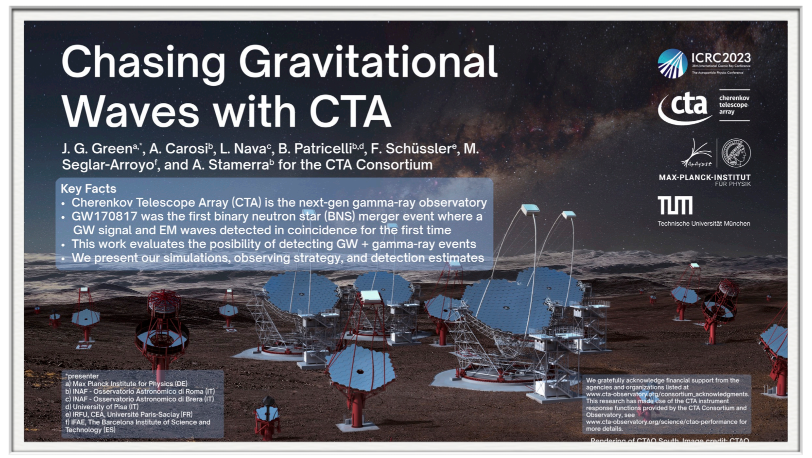
t_0 ~ 30 sec, ~ 10% detections with $T_{exp} \leq$ 1 min.

t_0 ~ 10 min ~ 10% detections with T_{exp} ~ 1 min.



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



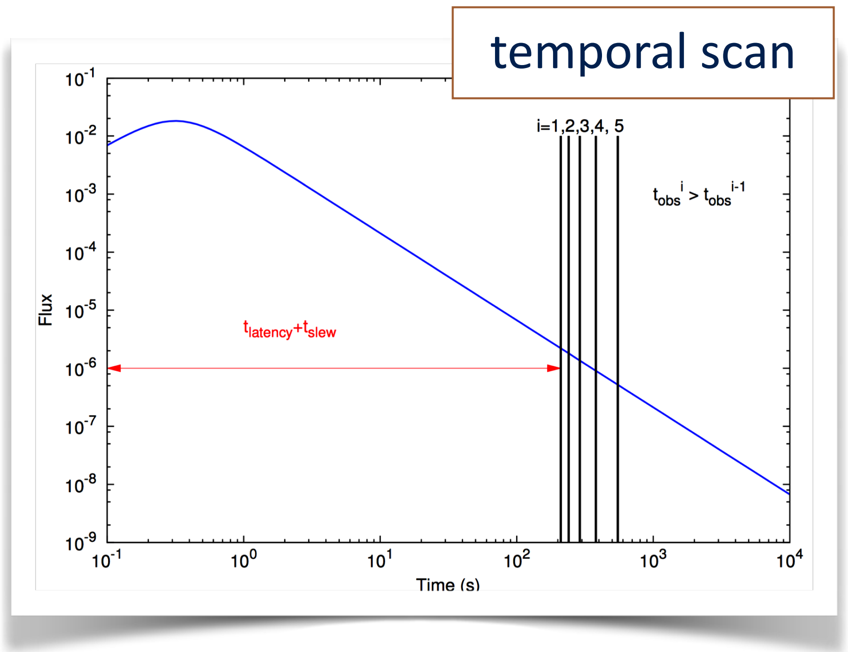


See also Jarred Green et al. 2023 (ICRC2023)

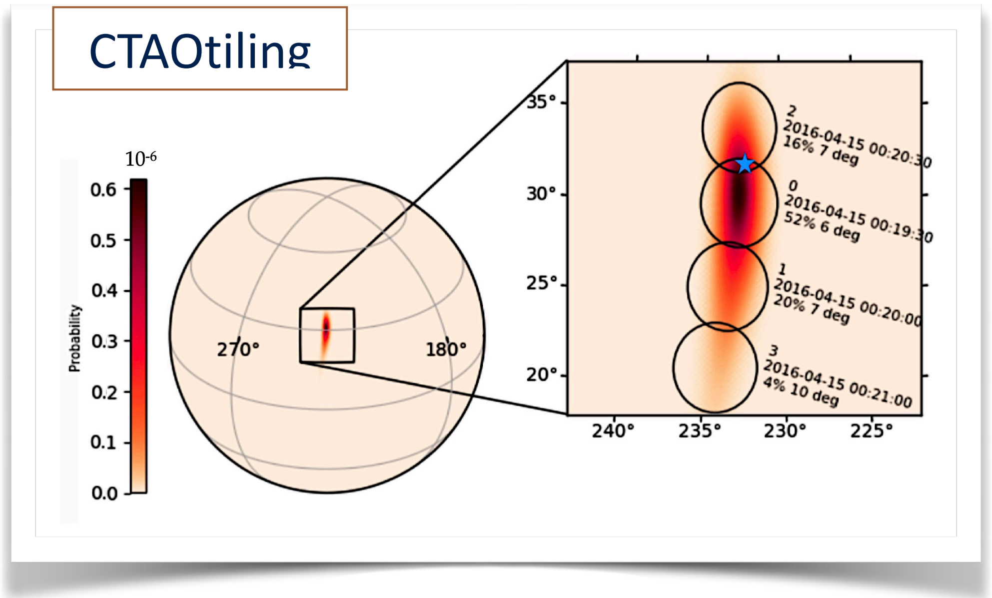
- Followed up GW-GRB events: **8% of the total population**
- **4.5%** of follow-ups covered the **true location of the source**
- on-axis events: 18% followed up; 10% covered the true location
- off-axis events: 7% followed up; 4% covered the true location

PRELIMINARY

temporal scan



CTAOtiling



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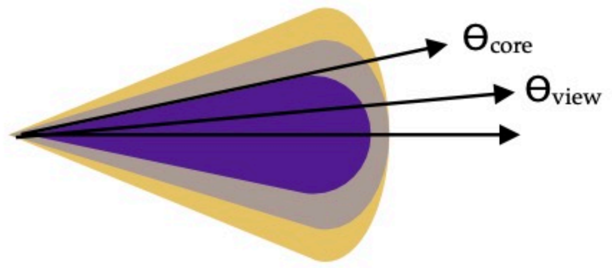

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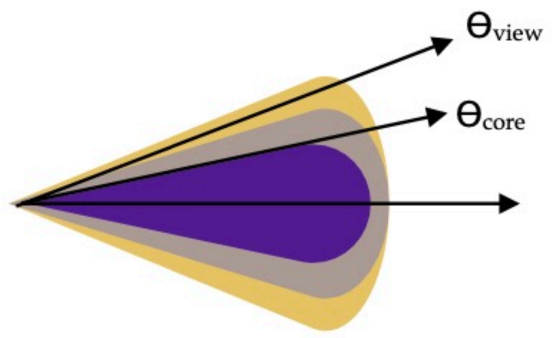
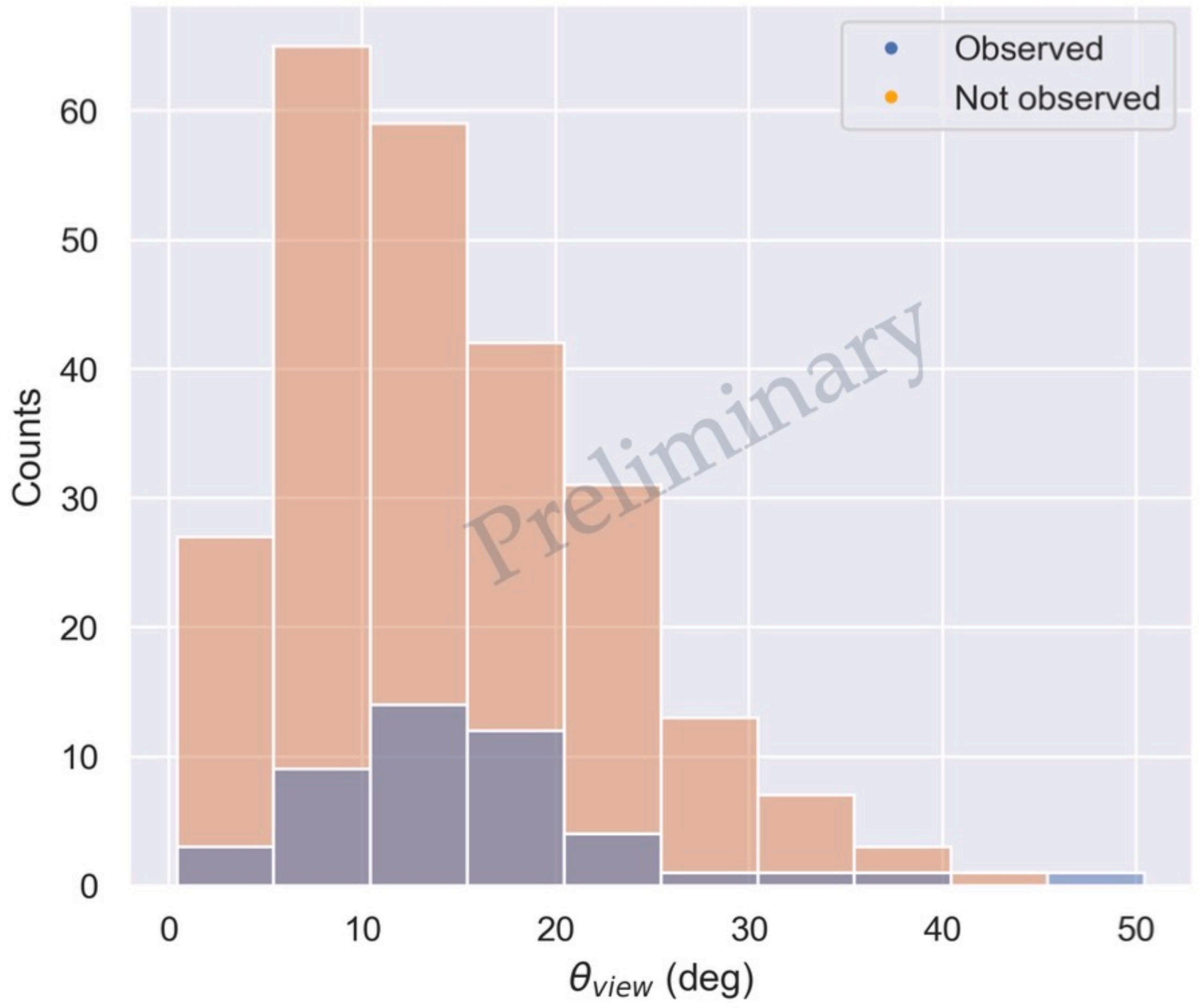
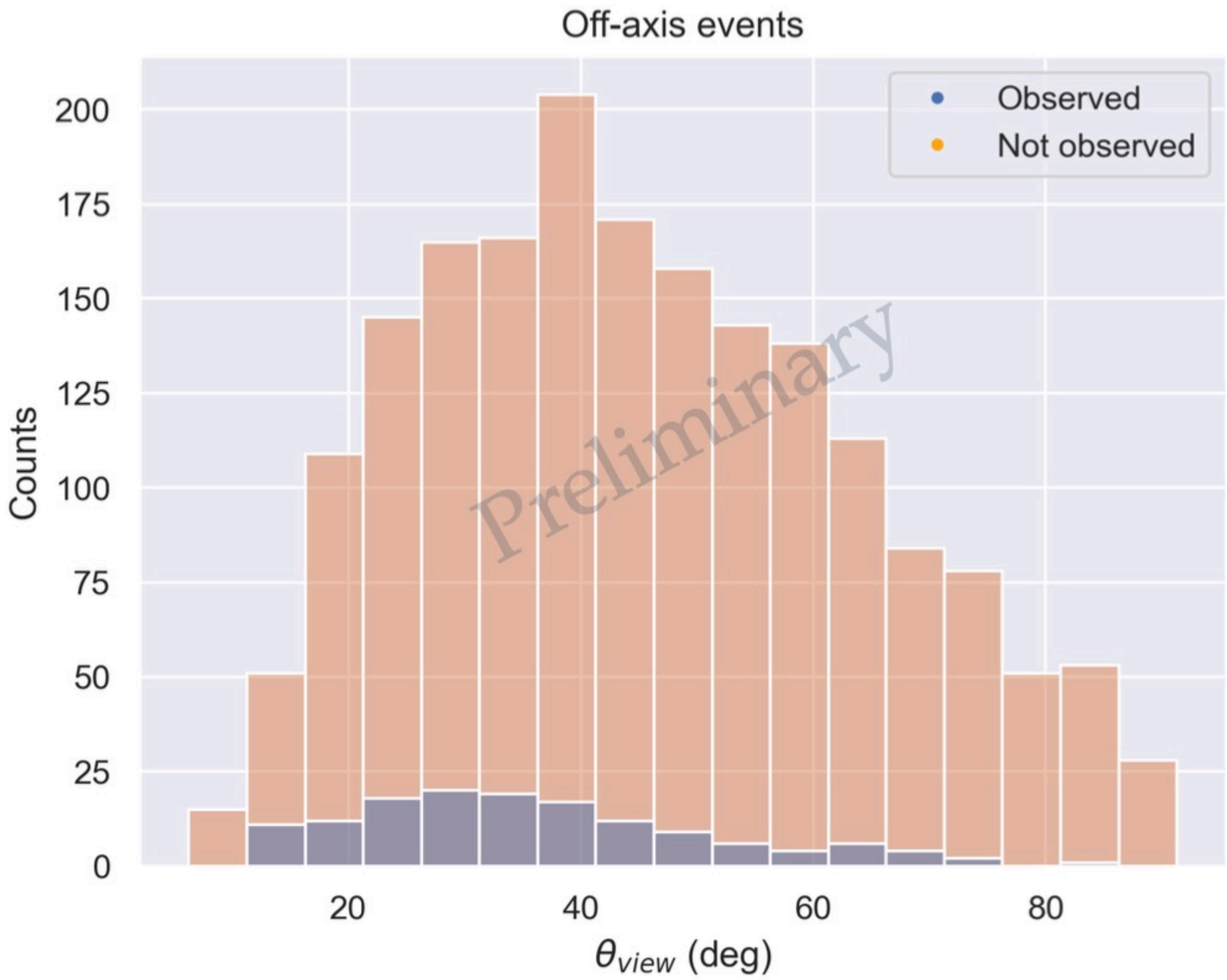
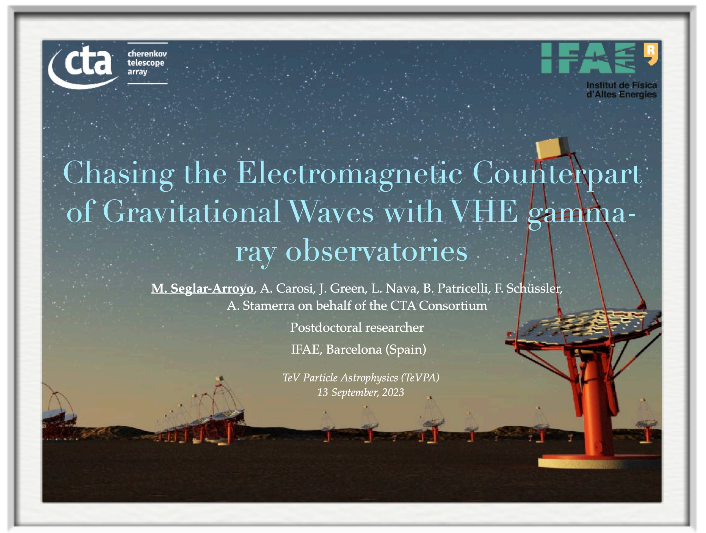






Realistic observing conditions for CTAO are considered (duty cycle, visibility).

No subarrays, and only North or South array



See also Monica Seglar-Arroyo et al. 2023 (TeVPa2023)

GW Follow-ups with CTAO: A Summary

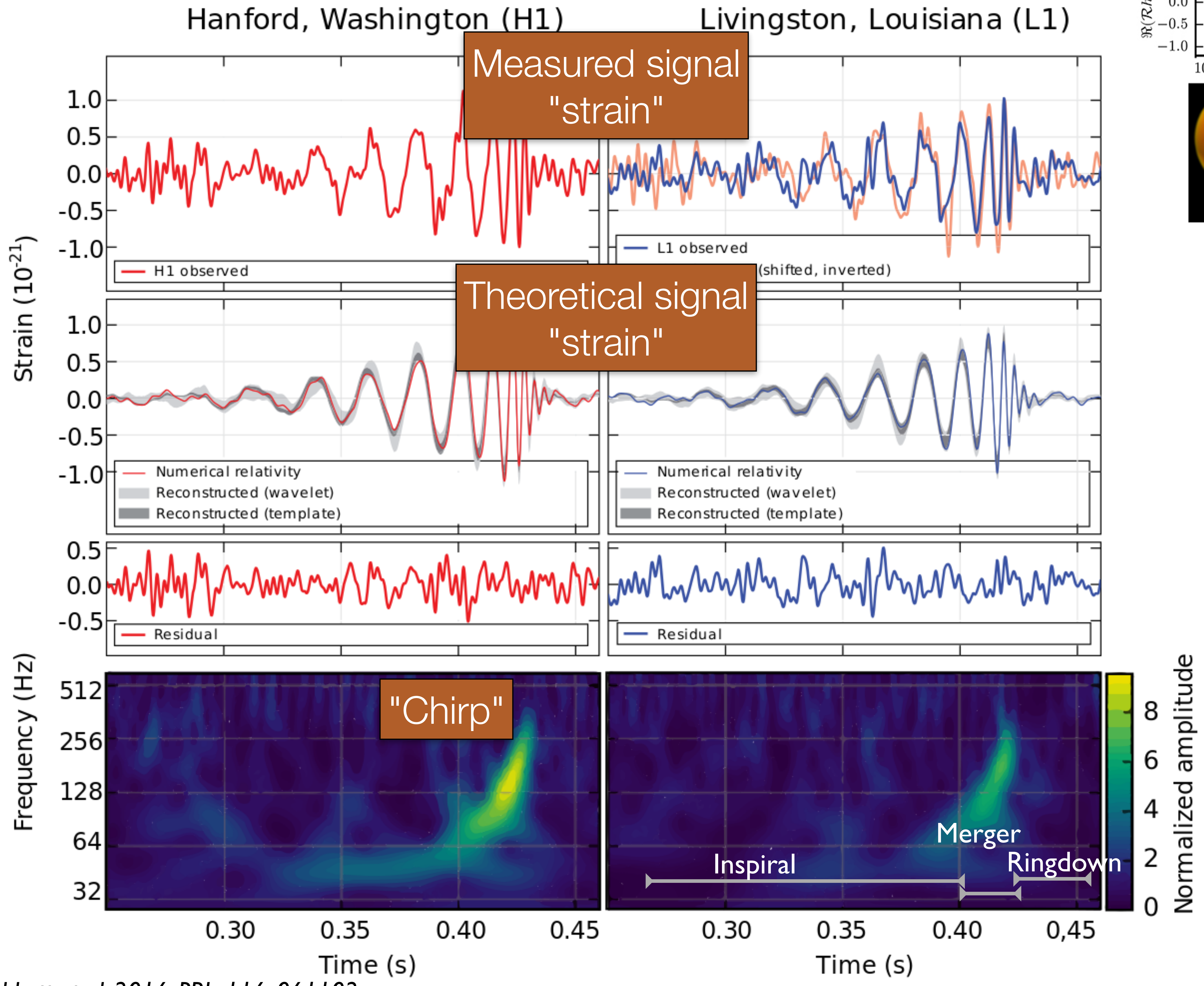
- ✓ A new GW and TeV-GRB landscape emerged ➟ **an expanded CTAO's science program**
- ✓ Plethora of GW triggers expected ➟ **Observing strategies and optimised follow-up observations required**
- ✓ Groundwork laid with GW-GRB simulation chain for BNS during the LIGO-Virgo-KAGRA scientific run O5 (2027-2030)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

CTAO-N and CTAO-S are key player in the transients and GW follow-ups!

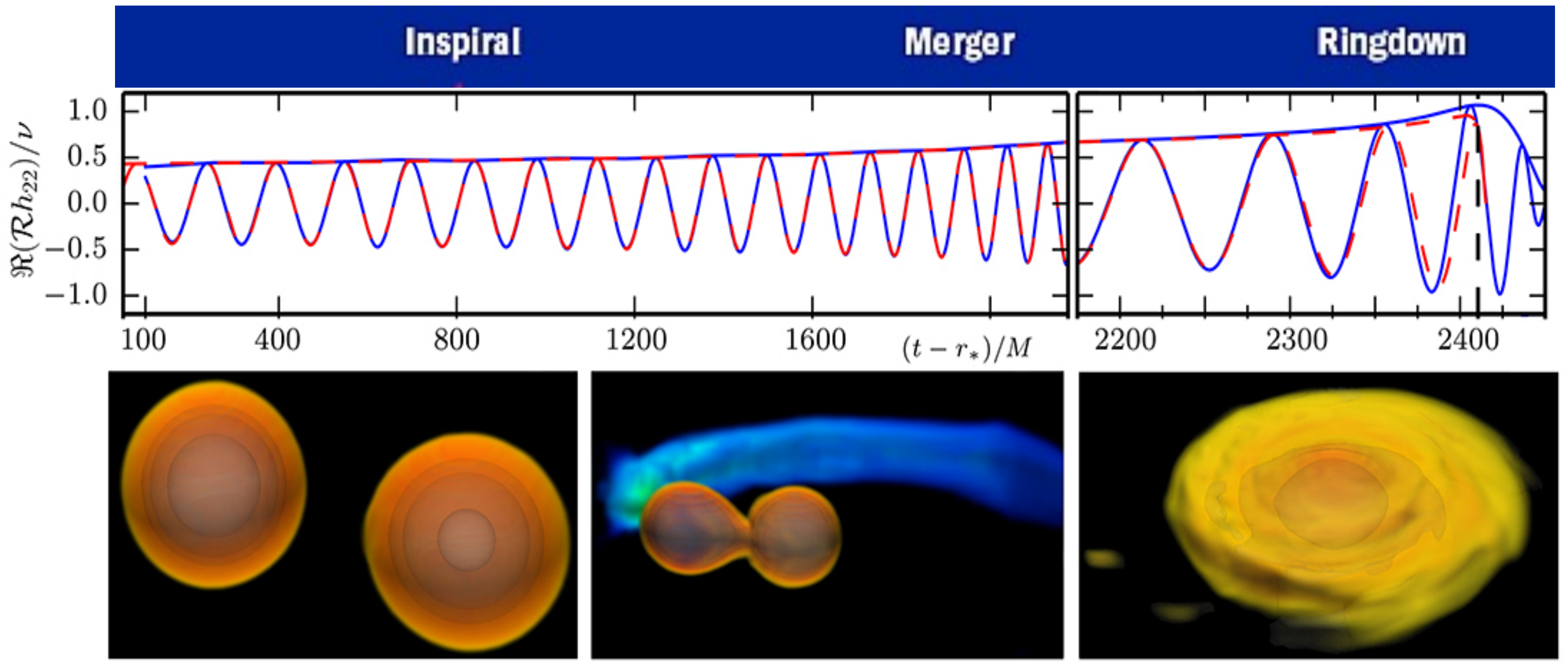
➡ Further effort will be devoted to the search of counterparts of binary black-hole and black hole-neutron stars mergers detected by the new generation of GW interferometers, like the Einstein Telescope and Cosmic Explorer

The era of gravitational waves

GW150914 (BBH)



Abbott et al. 2016, PRL, 116, 061102



Scheme of merging of a binary compact system and GW emission

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

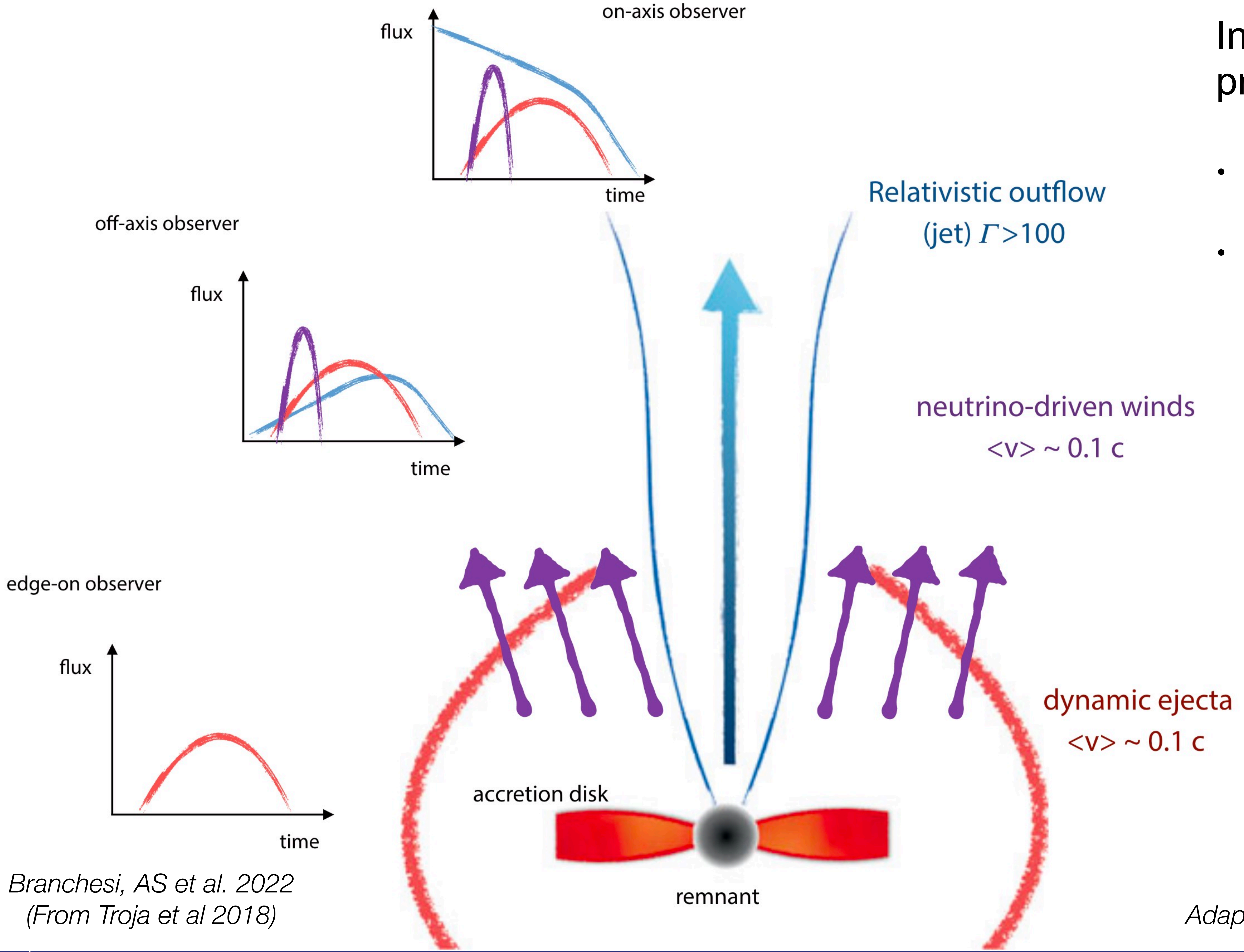
mass; strain; distance; frequency "chirp"

Plus other parameters: Spin, orientation, mass ratio, nature of progenitor, localization…

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

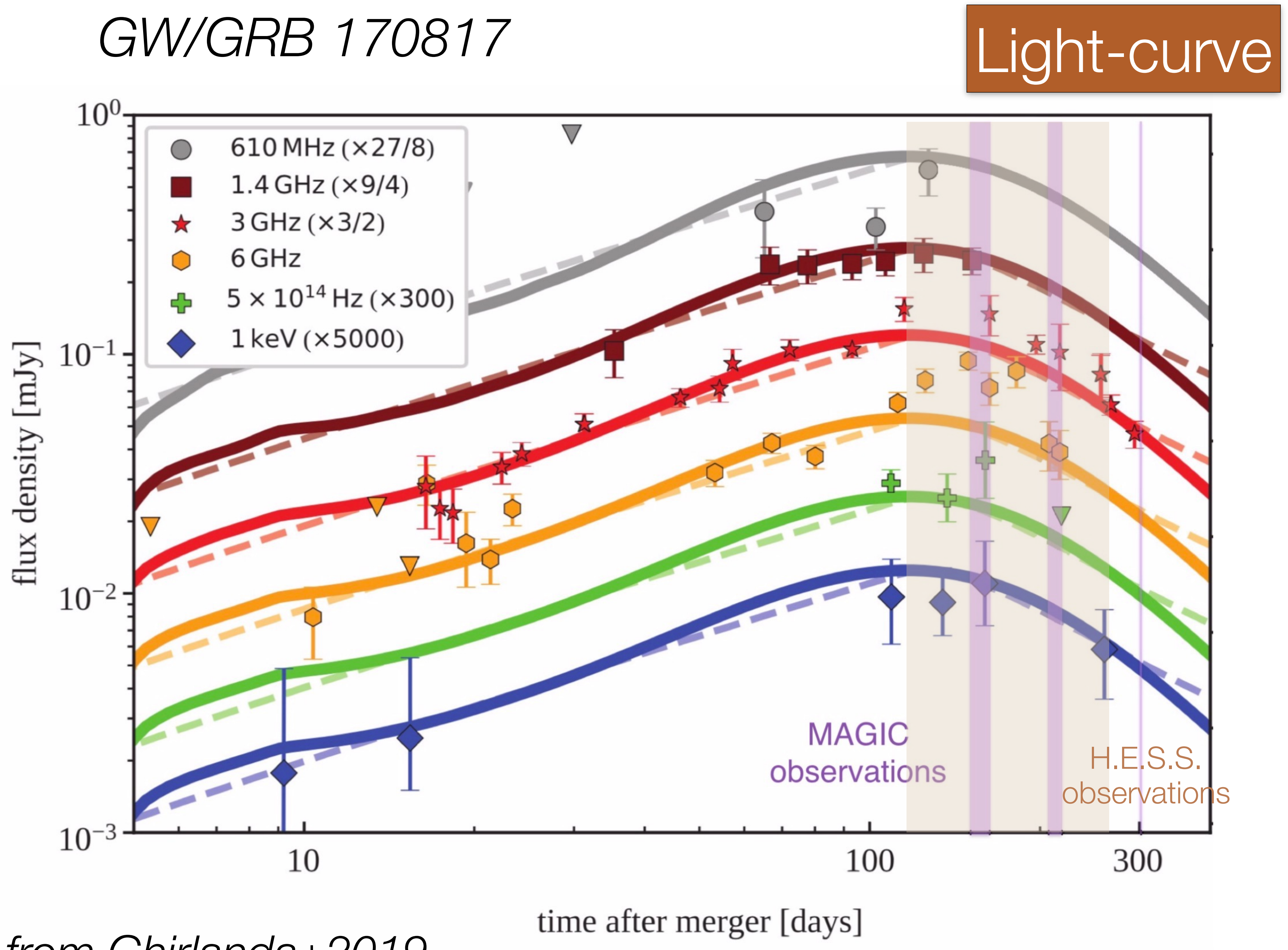
In GW-counterparts, the jet is seen preferentially **off-axis:** Γ~a few

- intensity <u>weaker</u> $10^{-4,-6}$
- light curve <u>Delayed</u> (hours-days-months, depending on θ_{view})



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

GW/GRB 170817



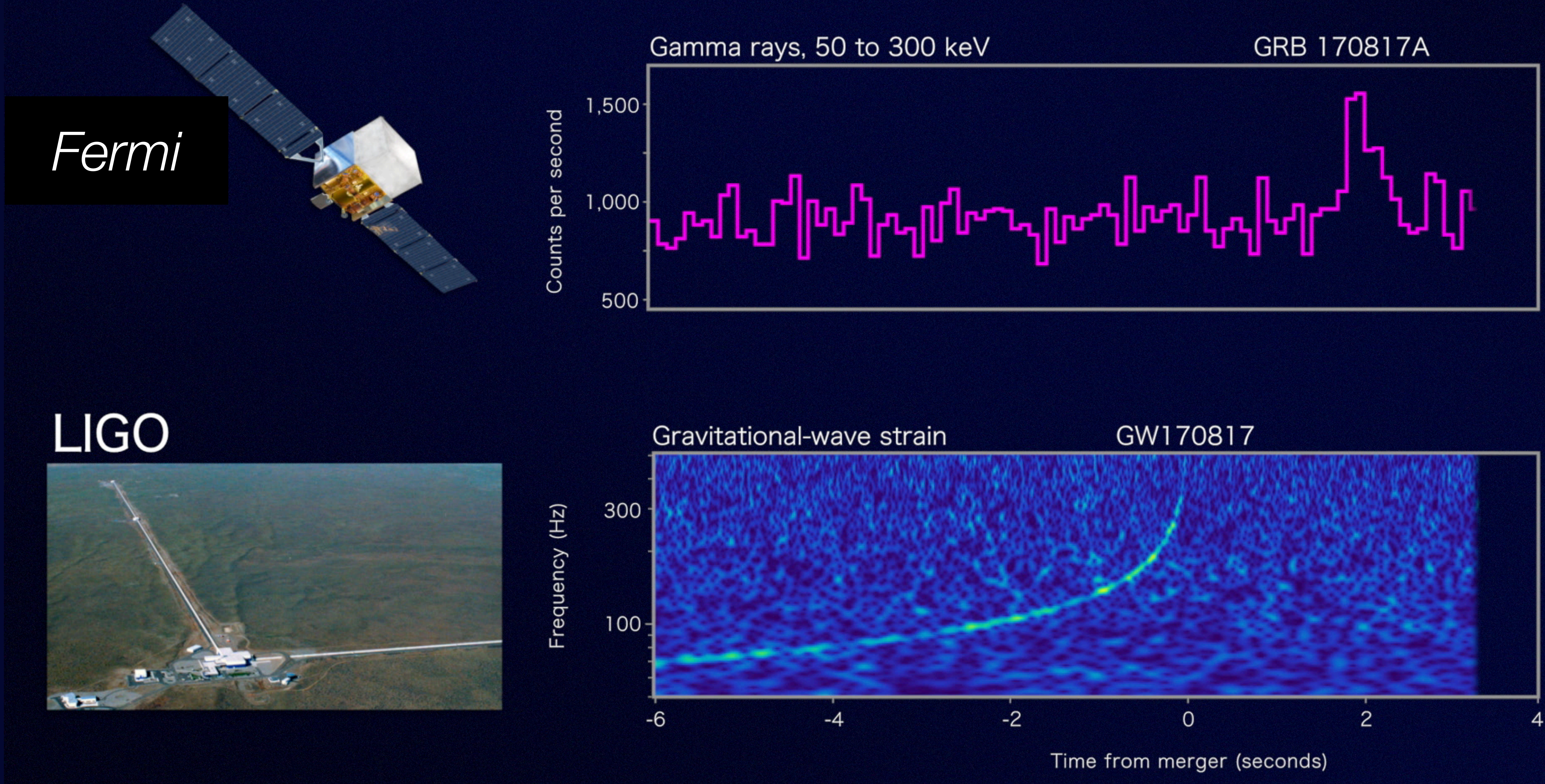
Adapted from Ghirlanda+2019

Association GW-Electromagnetic (EM) counterpart: GW170817/GRB170817A

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

1.7 s delay

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



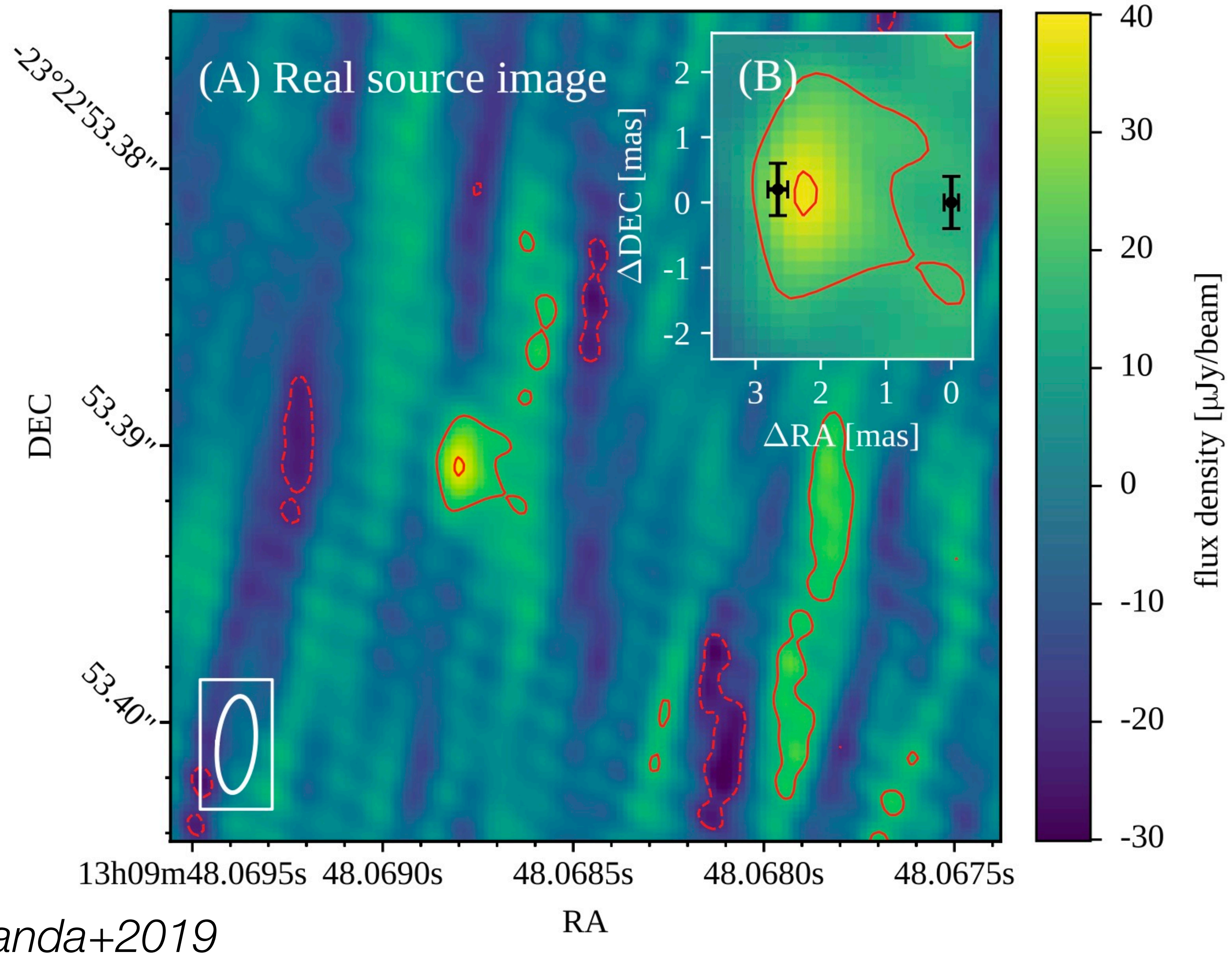
Abbott et al. 2017, ApJL, 848, L13

The Role of Off-axis Observations and structured Jet

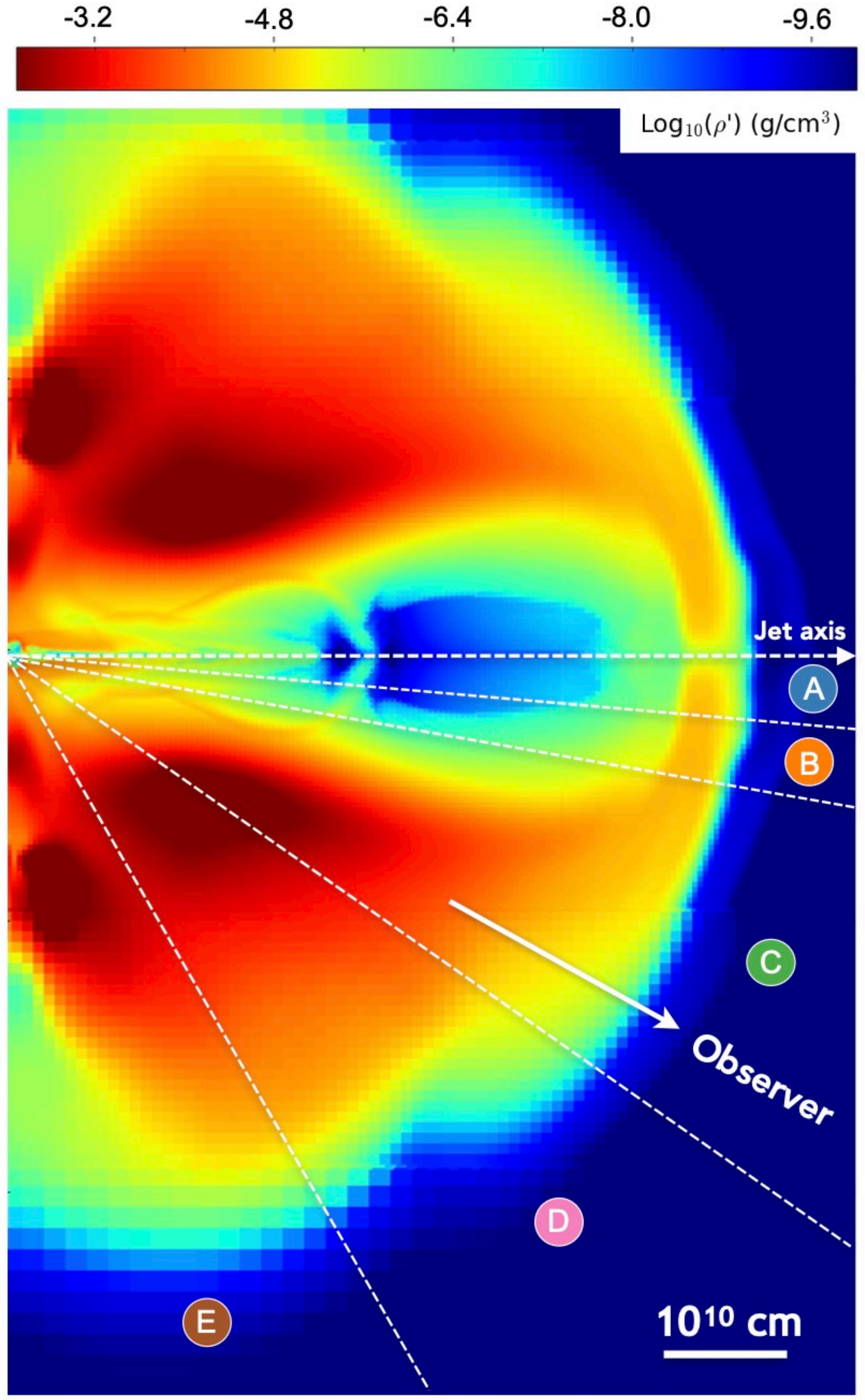
Theoretical models (e.g. GRMHD simulations) predict a structured jet; confirmed by observations

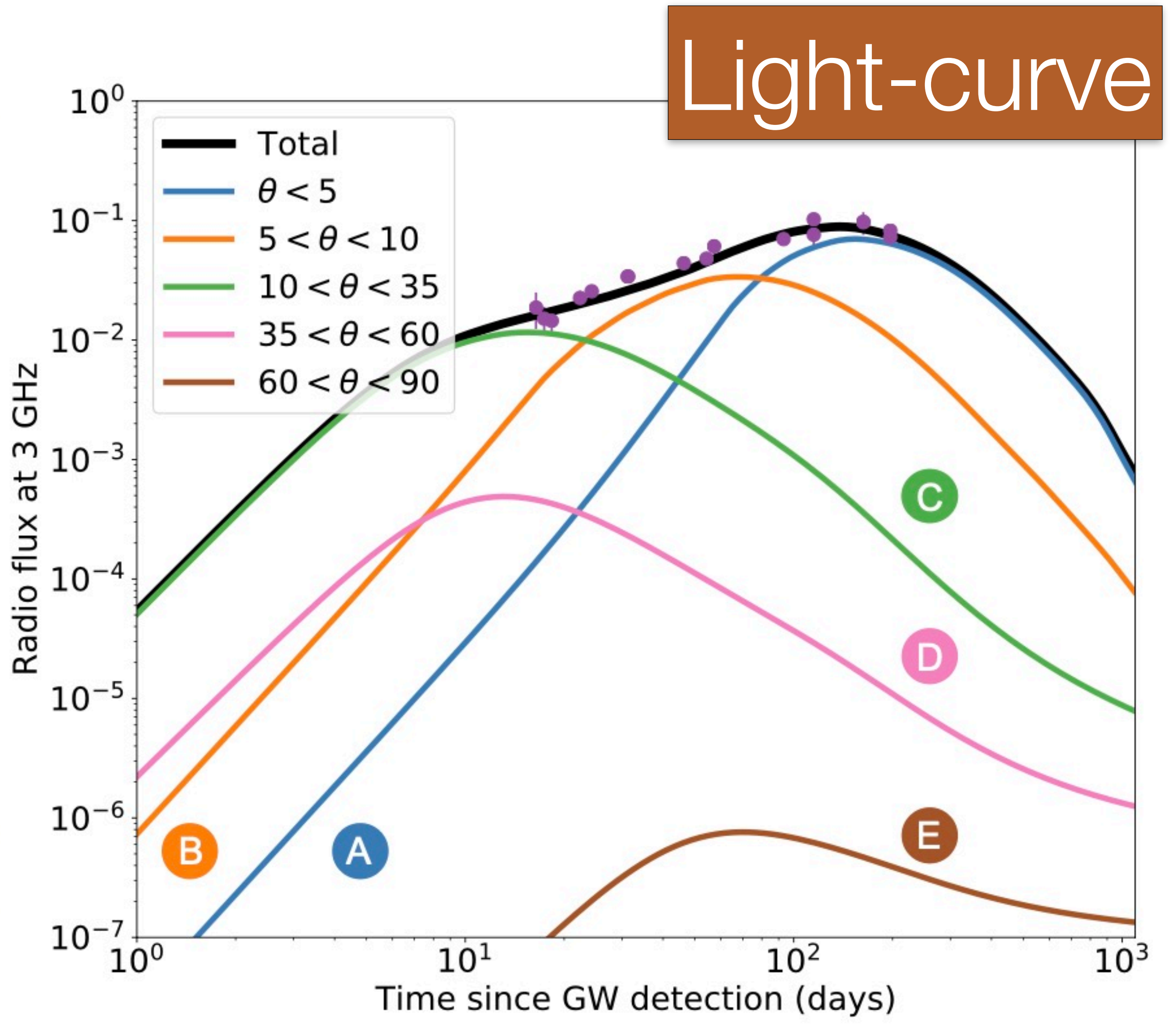
Radio images of GRB170817/GW170817A
207 d after merger

Showing a compact emission with a large displacement,
indication of a jet successfully breaking out the ejecta



Ghirlanda+2019

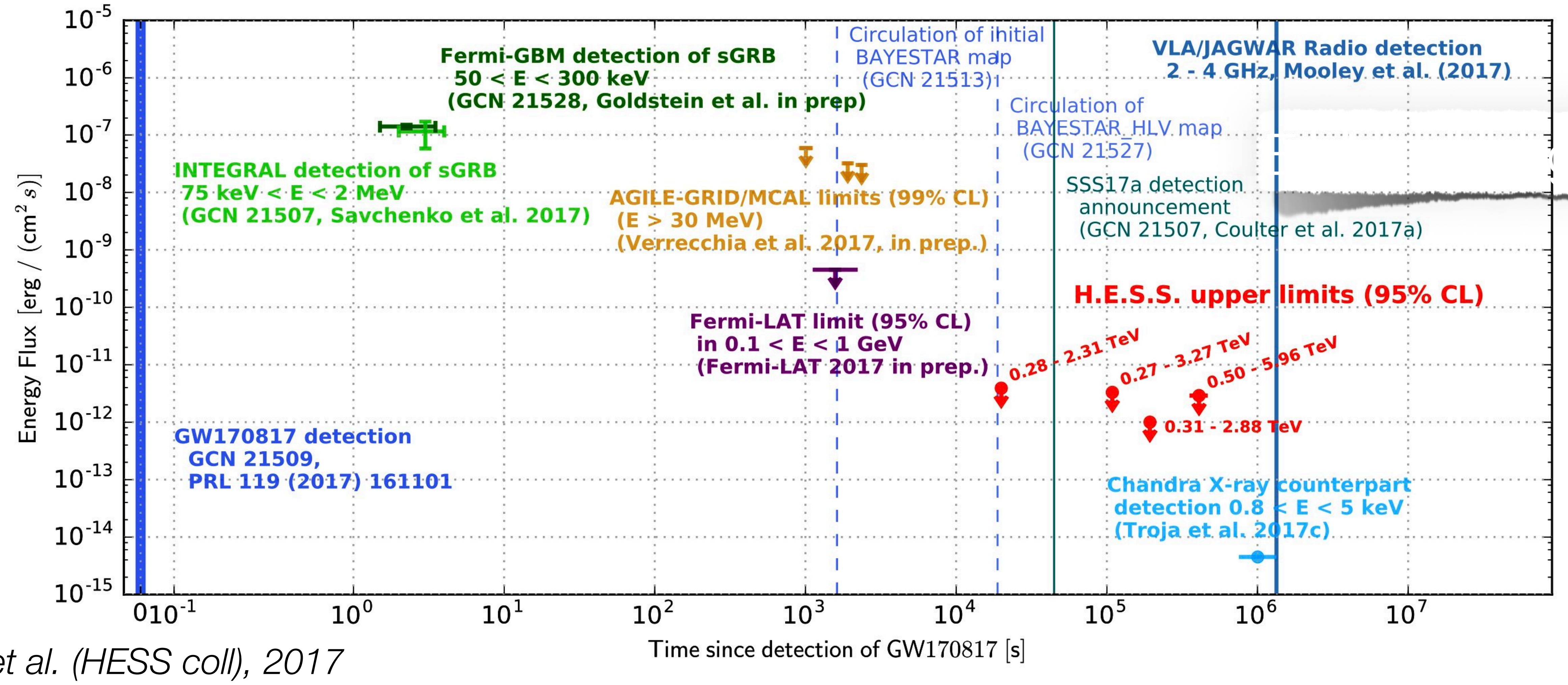




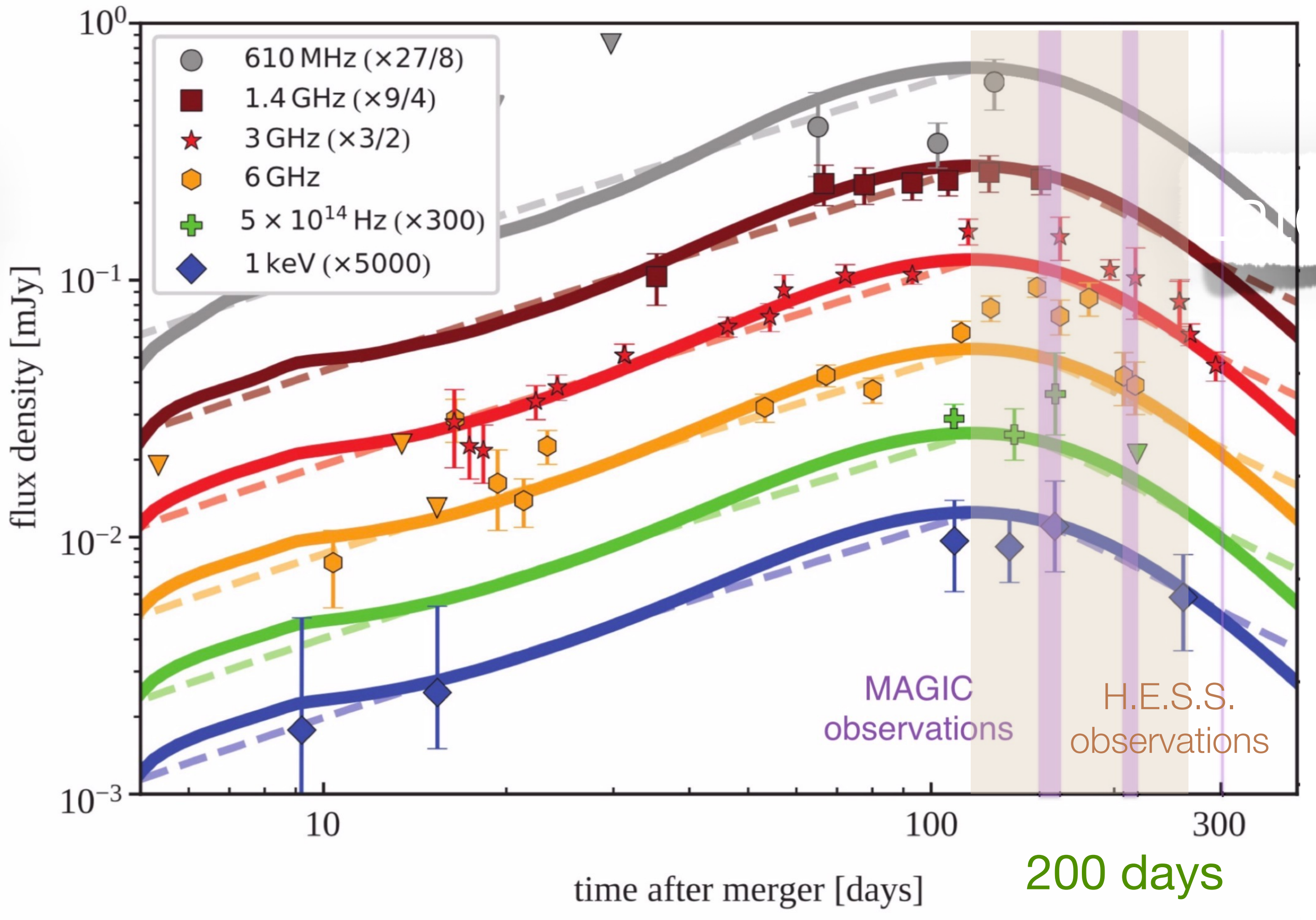
Hydrodynamical simulation of a short GRB (Lazzati+2018)

GWs and GRBs at TeV energies

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



Abdalla et al. (HESS coll), 2017

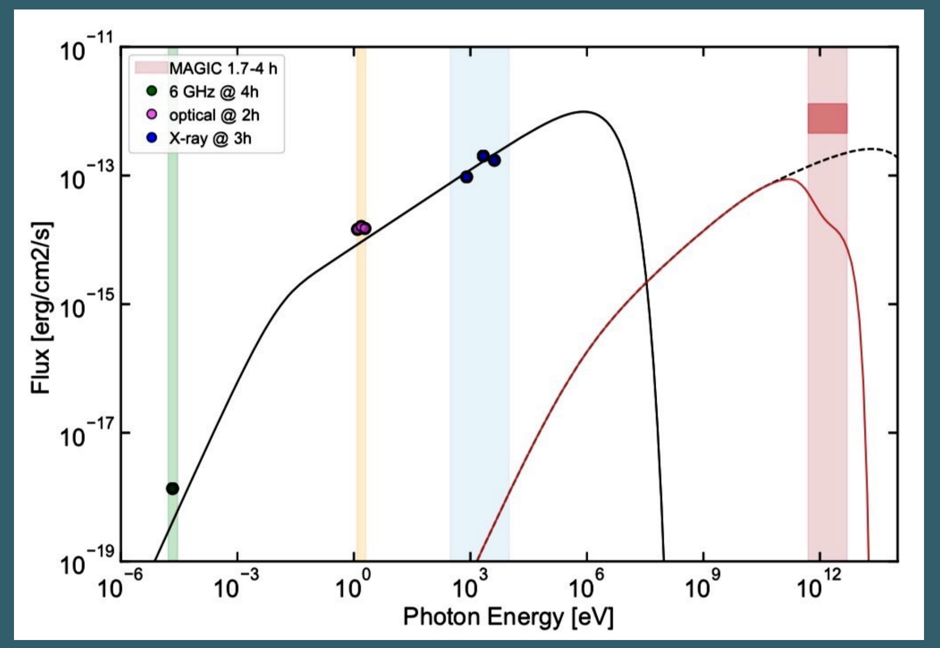


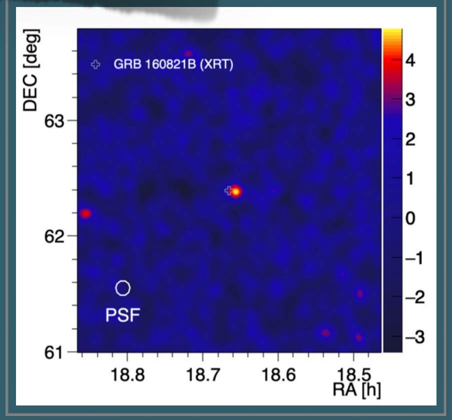
Adapted from Ghirlanda+2019

- No detection at the maximum of the delayed emission

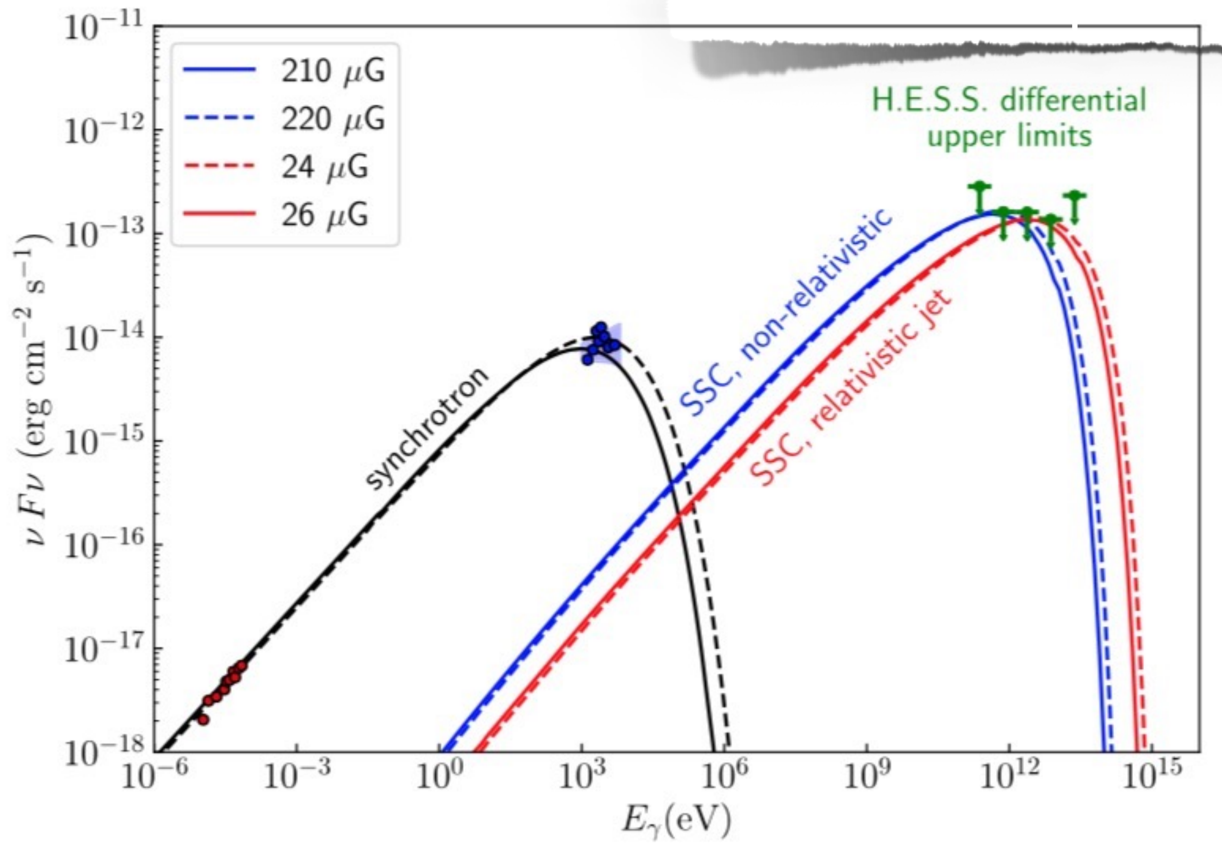
Short GRB 160821B

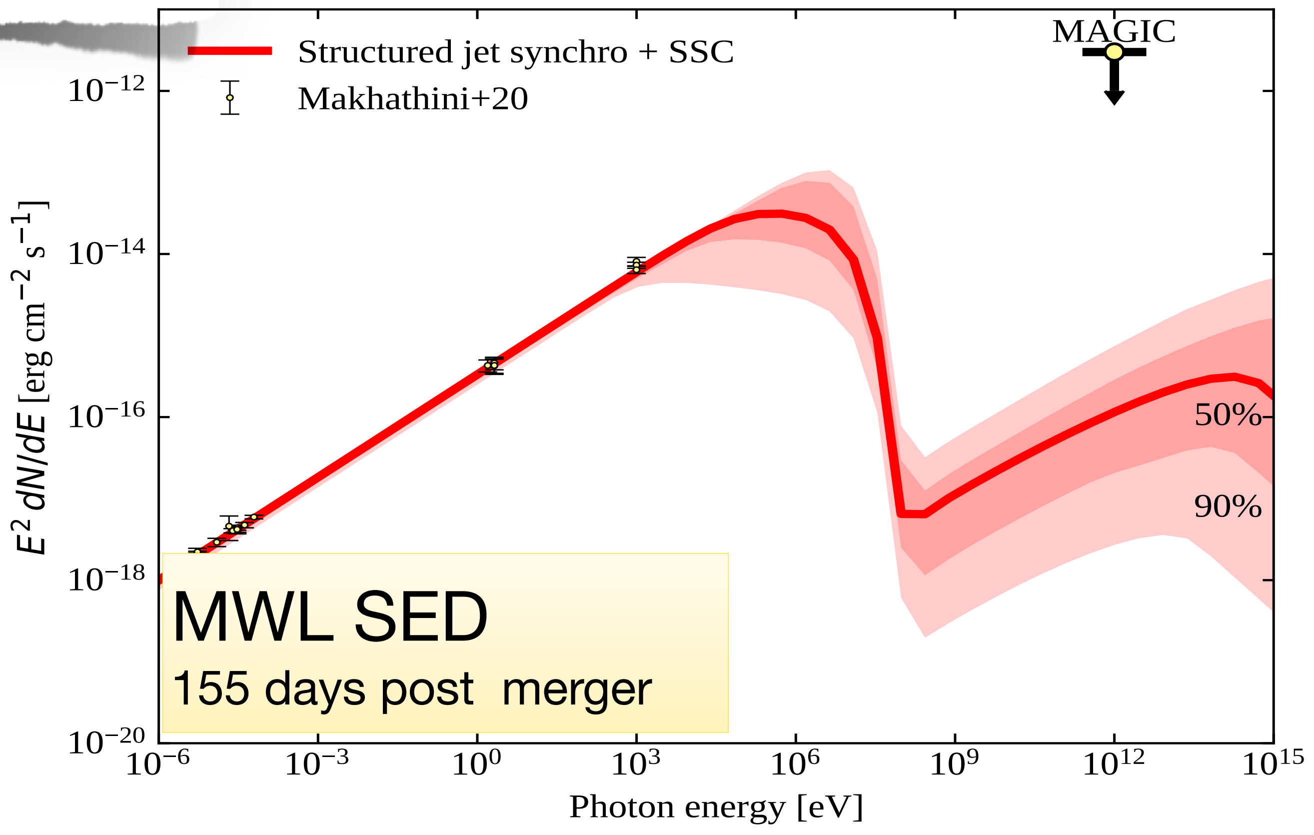
SED





Hint 3σ MAGIC





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

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