Multi-messenger astrophysics: A perspective on past detections and future prospects

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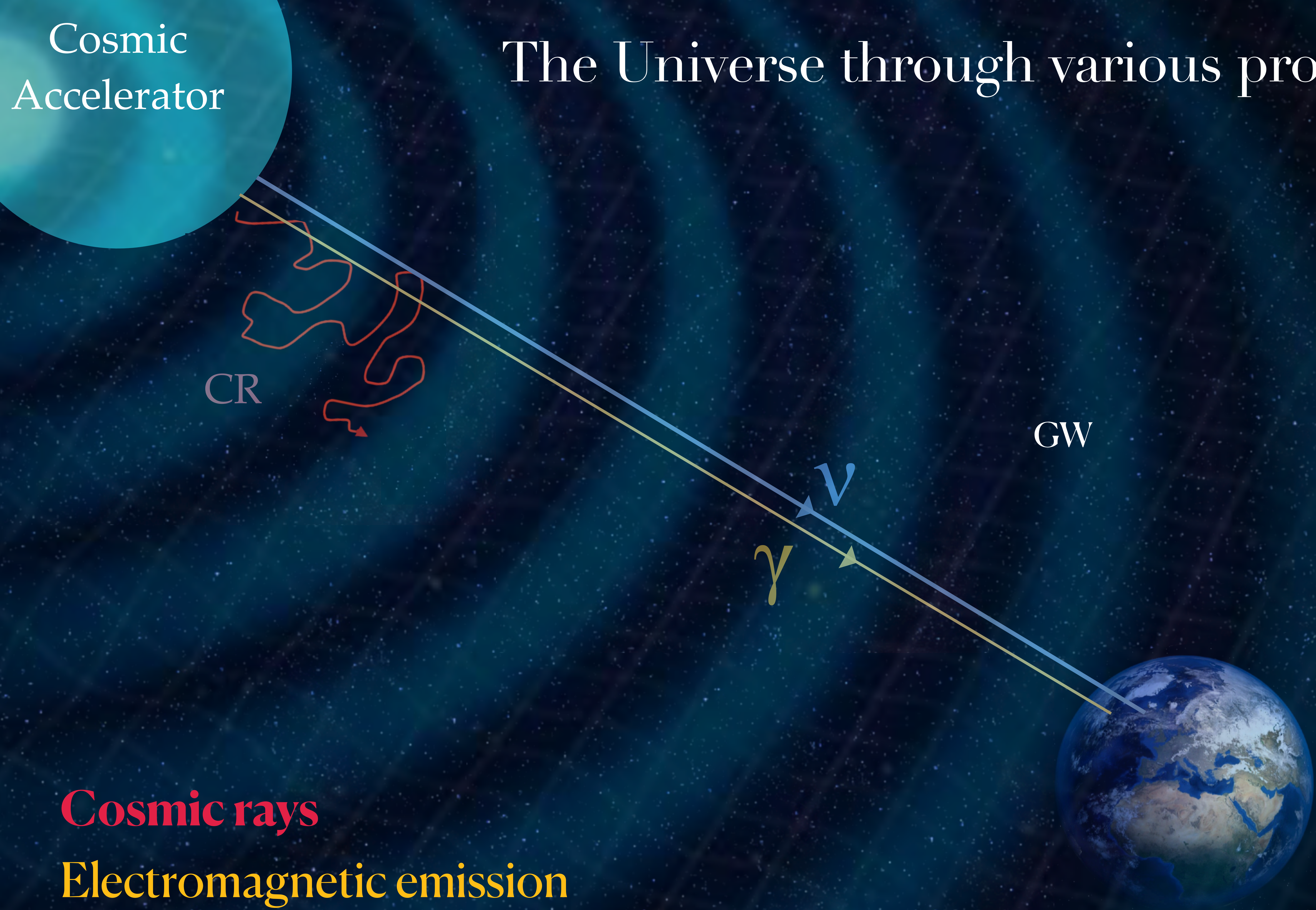
GW Iberian meeting
CIEMAT, Madrid
Tuesday 24, 2025

Image credit: NASA SVS

The Universe through various probes



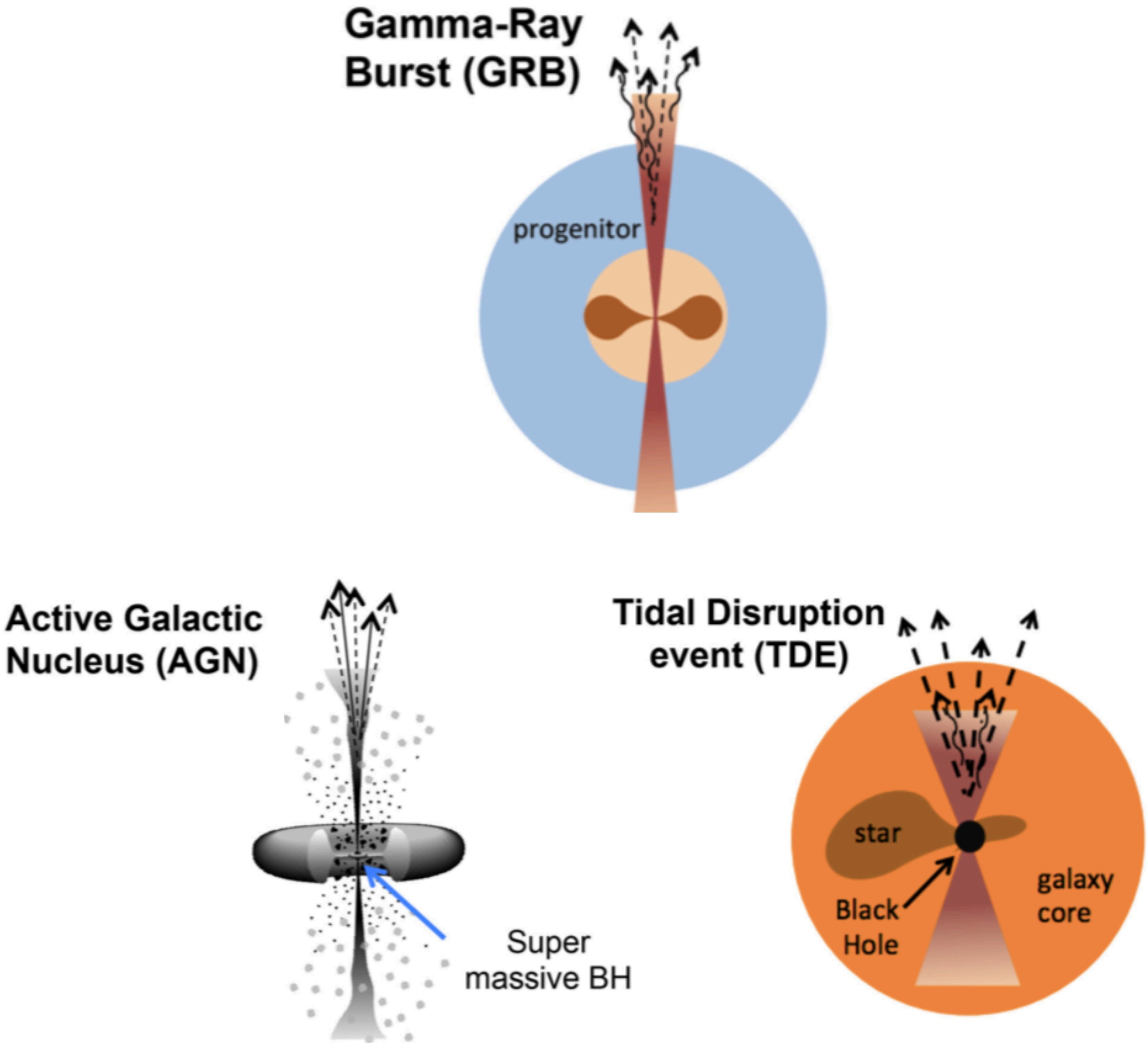
Cosmic rays

Electromagnetic emission

Neutrinos

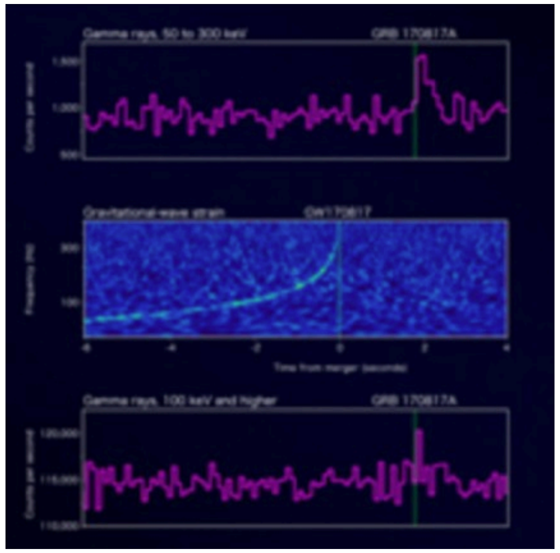
Gravitational Waves

The tip of the iceberg of the MM landscape*



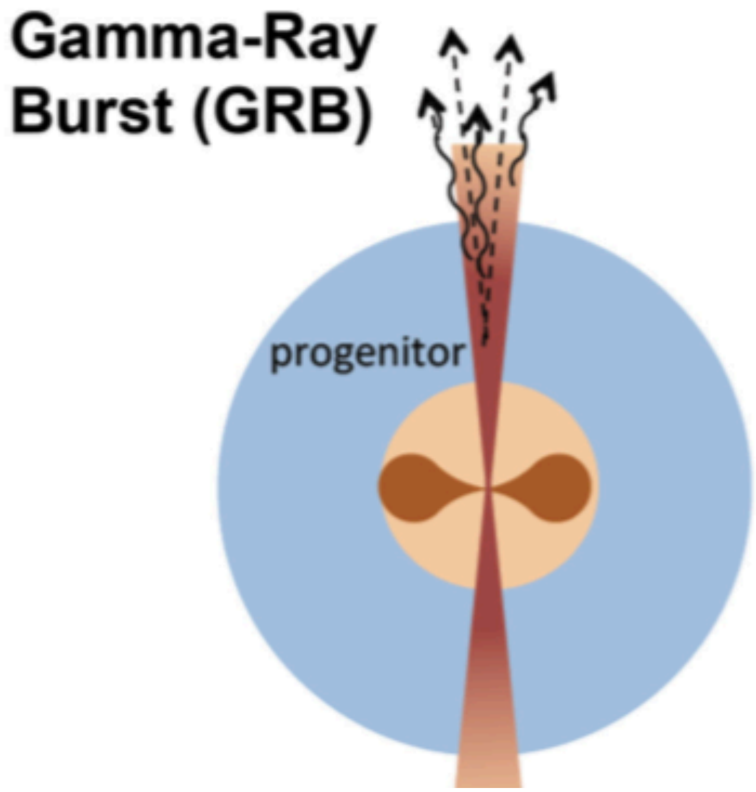
*simplified representation

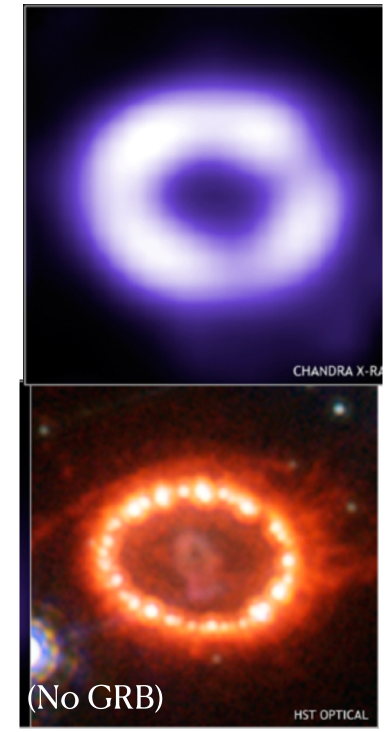
The tip of the iceberg of the MM landscape*



Abbott et al, 2017, ApJ 848, L13

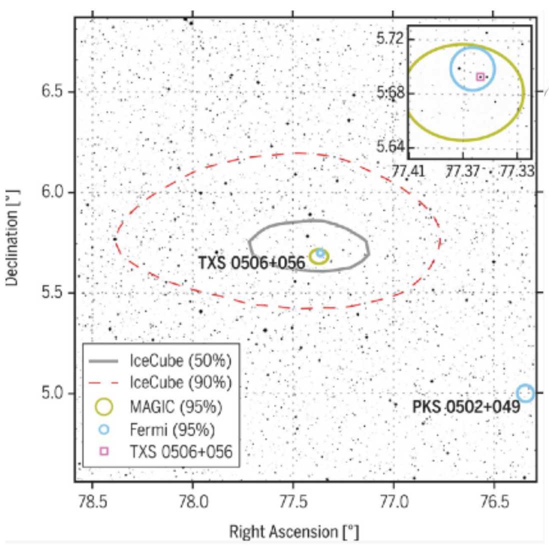
GW170817
GRB170817a





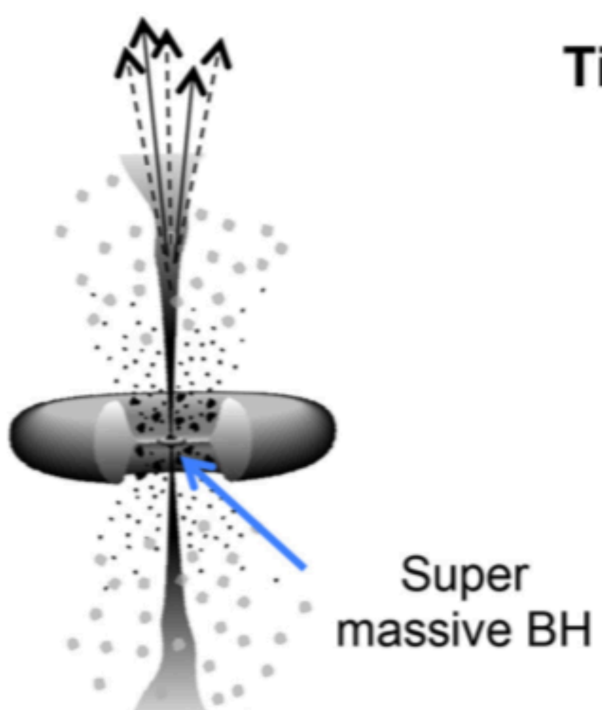
SN 1987A

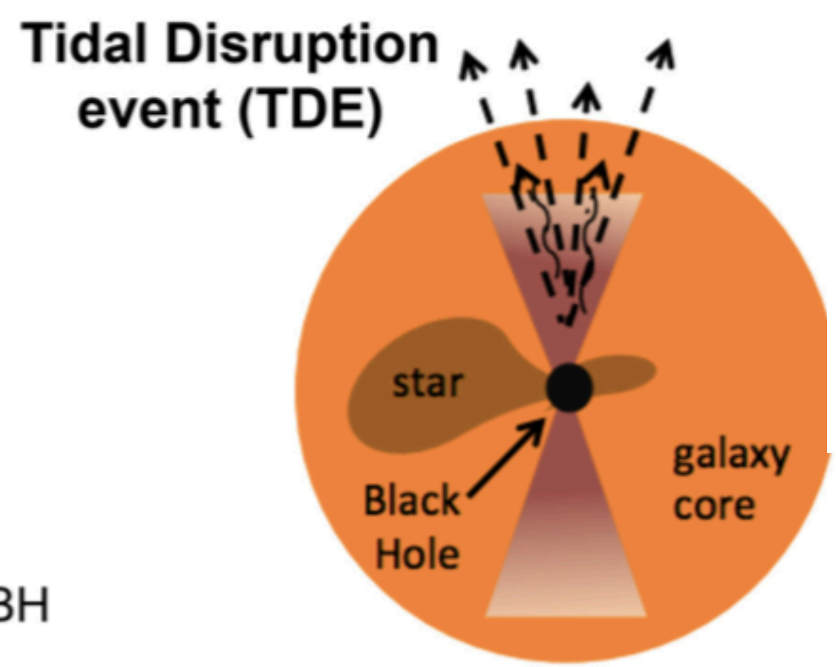
SuperK: Phys. Rev. Lett. 1988, **58**, 1490
HST evolution: J. Larsson *et al* 2019 *ApJ* **886** 147

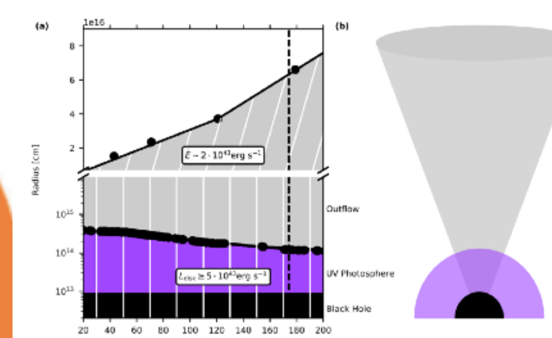


IC 170922A
TXS0506+056

Science, **361**,eaat1378(2018)



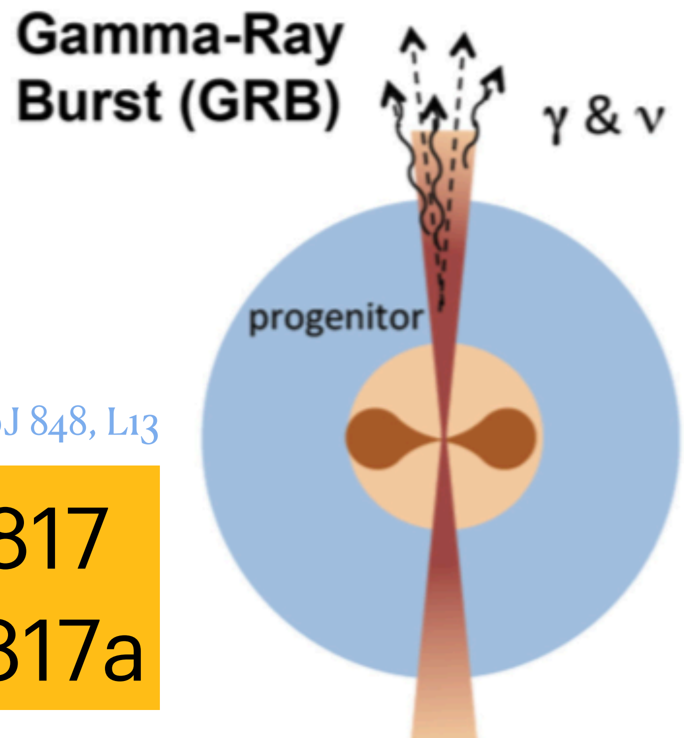




AT2019dsg
IC 191001A

Nature Astronomy , **5**, 510–518 (2021) *simplified representation

The tip of the iceberg of the MM landscape*



Abbott et al, 2017, ApJ 848, L13

GW170817
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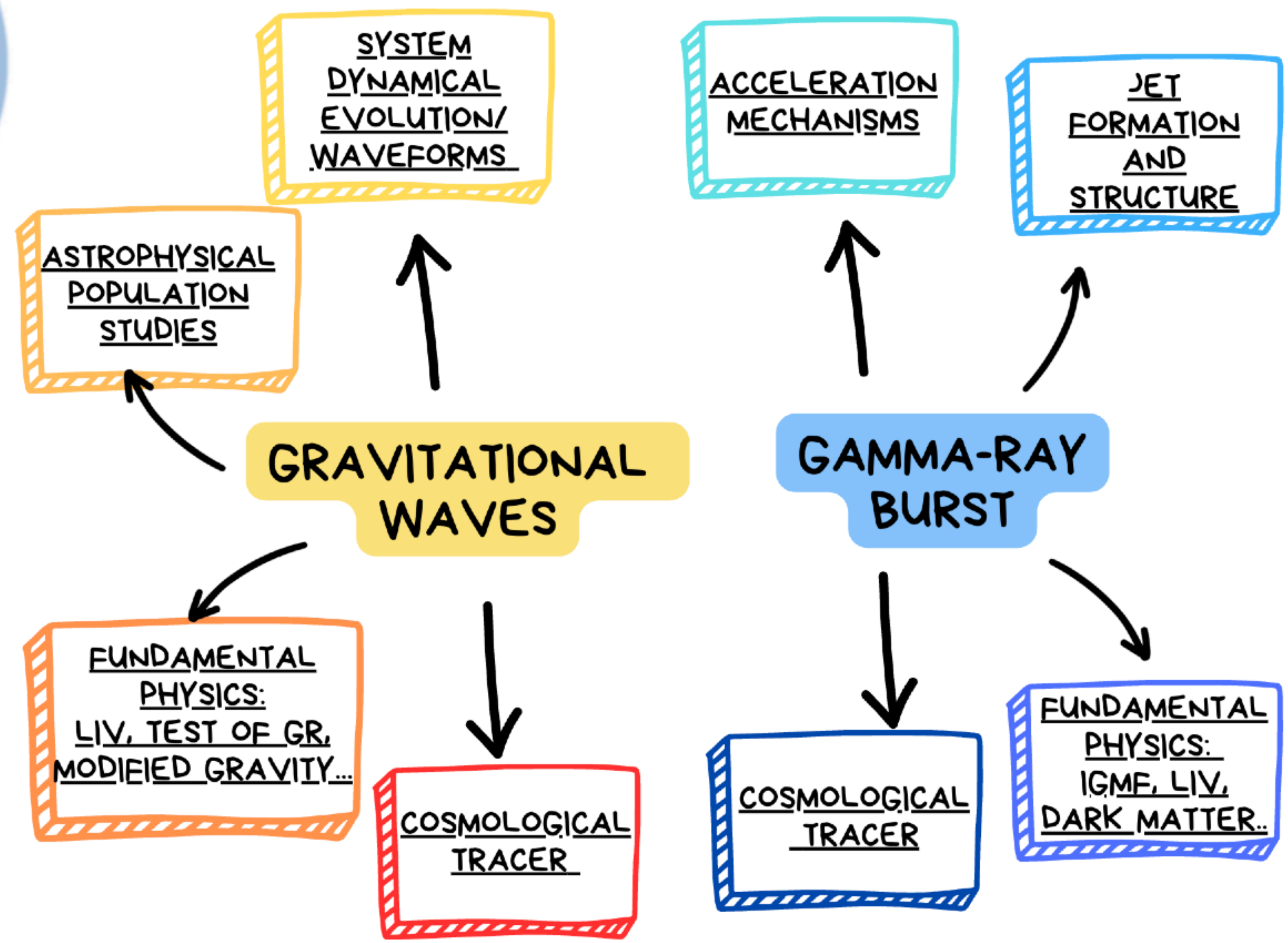
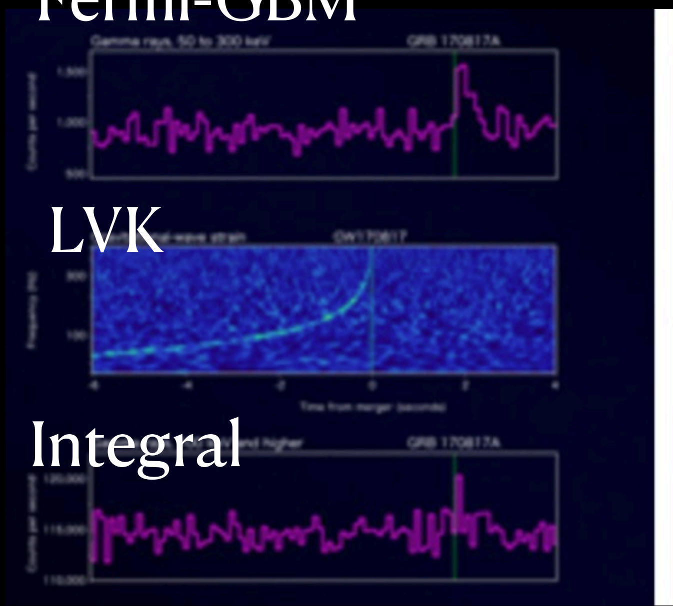
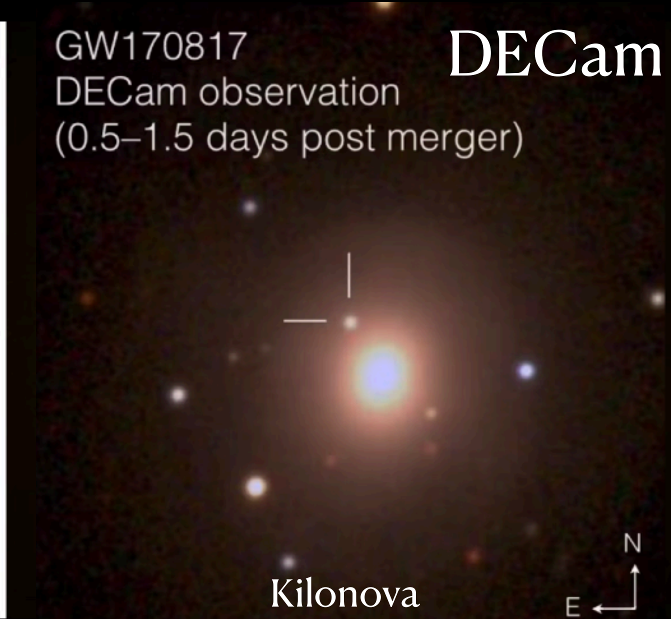


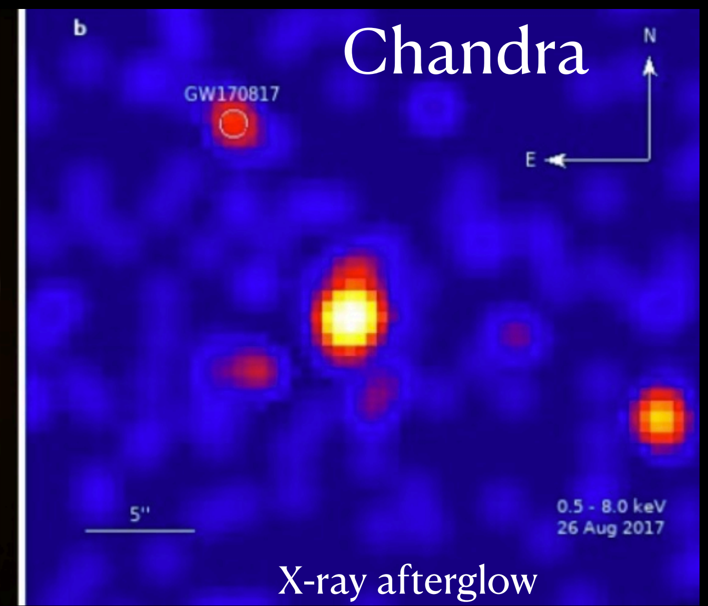
Specially, if detected!



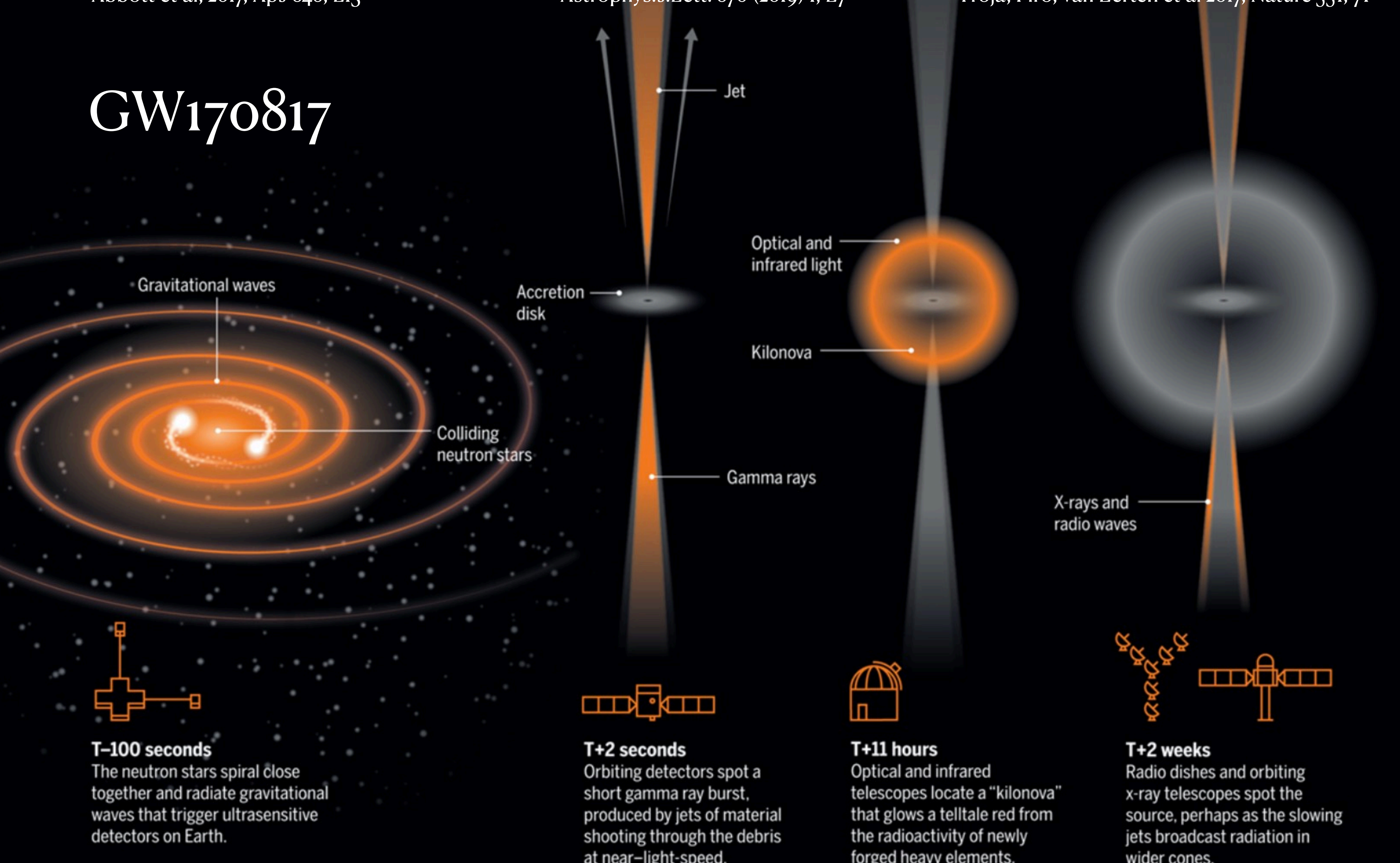
Abbott et al, 2017, ApJ 848, L13



Astrophys.J.Lett. 876 (2019) 1, L7



Troja, Piro, van Eerten et al 2017, Nature 551, 71



Impact:

- Astrophysical
- Fundamental
- Cosmological
- Nuclear

Tools:

- GCN (private at the time!)
- Strategy
- Proposals
- Reaction

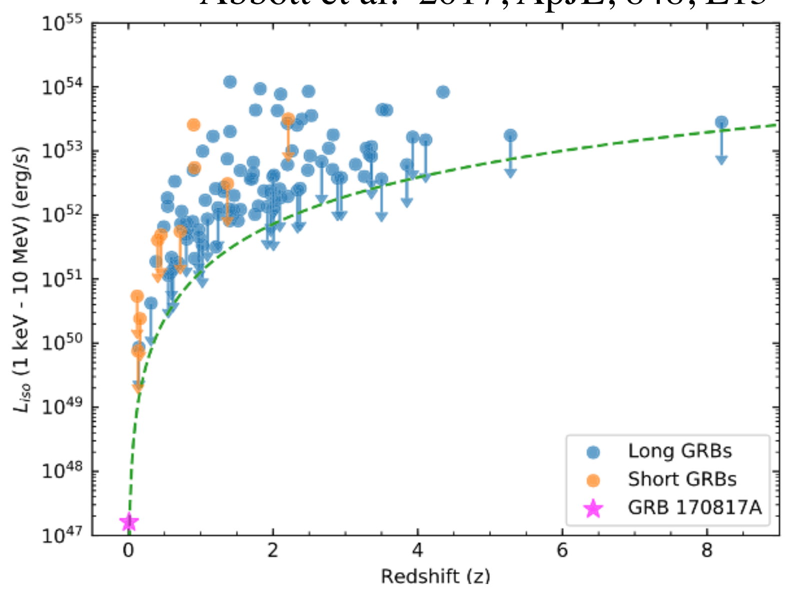
GW170817: not a *usual* sGRB

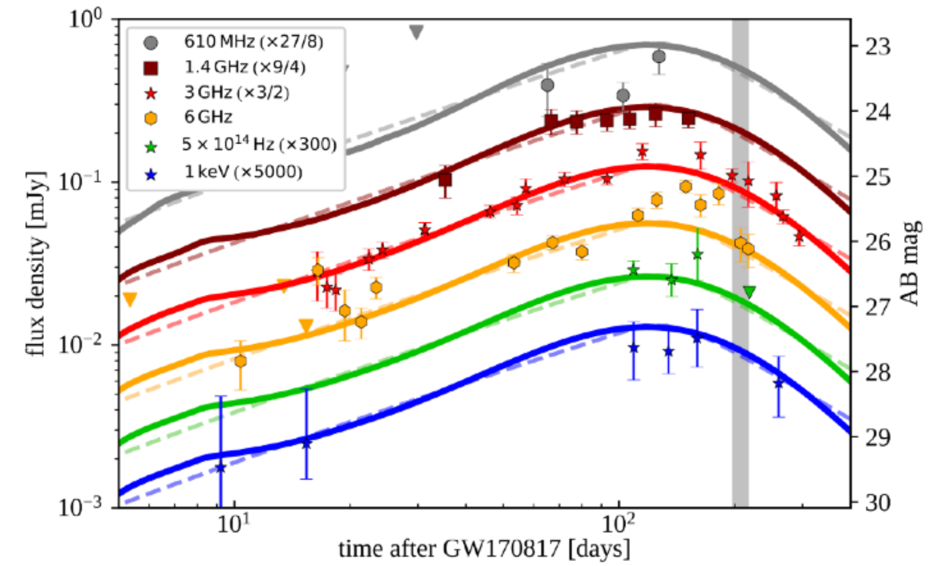
- Low luminosity Fermi-GBM GRB, ~ irrelevant without the gravitational wave detection

Ghirlanda et al. 2019 Science

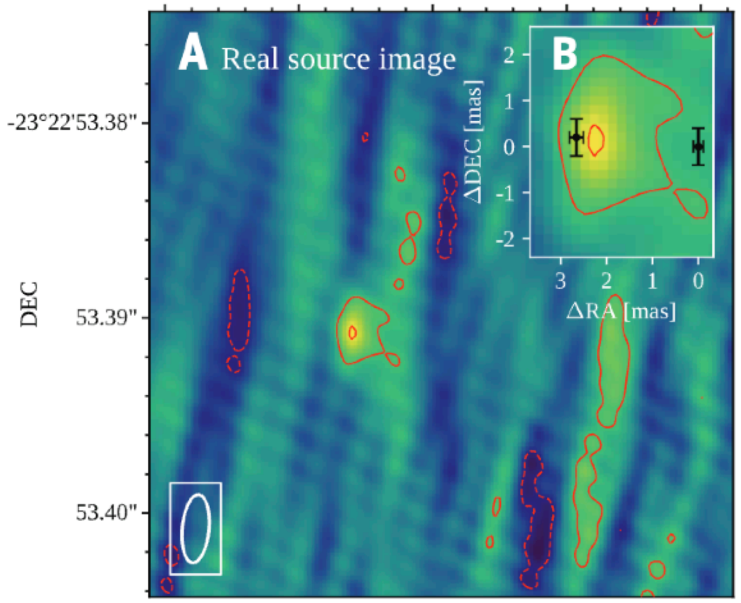
- Possible scenarios **hard to disentangle** :
  - Successful, structured jet
  - Isotropic cocoon: Unsuccessful jet chocked?

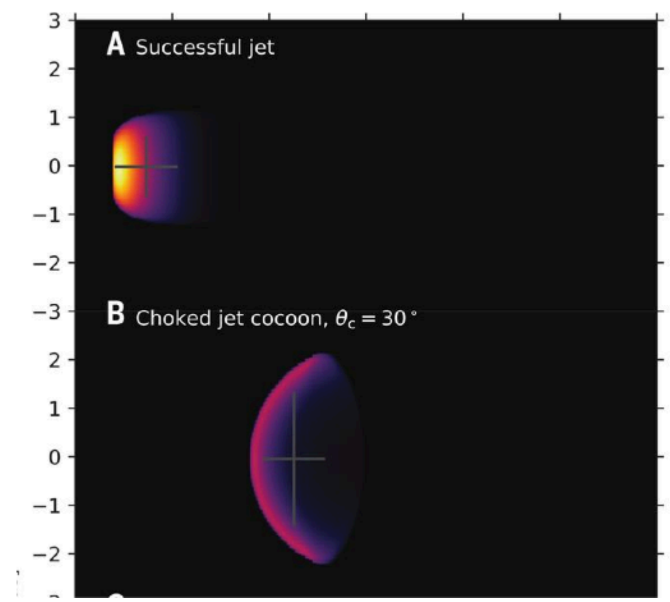
Abbott et al. 2017, ApJL, 848, L13





- **Peak at X-ray and radio ~ 155 days post-merger**: Interaction of off-axis jet with surrounding medium ?
- From radio measurements: Superluminal motion, found using very long baseline interferometry (VLBI),
- Constraints on the viewing angle (14–28 degrees), the opening angle of the jet core (<5 degrees)

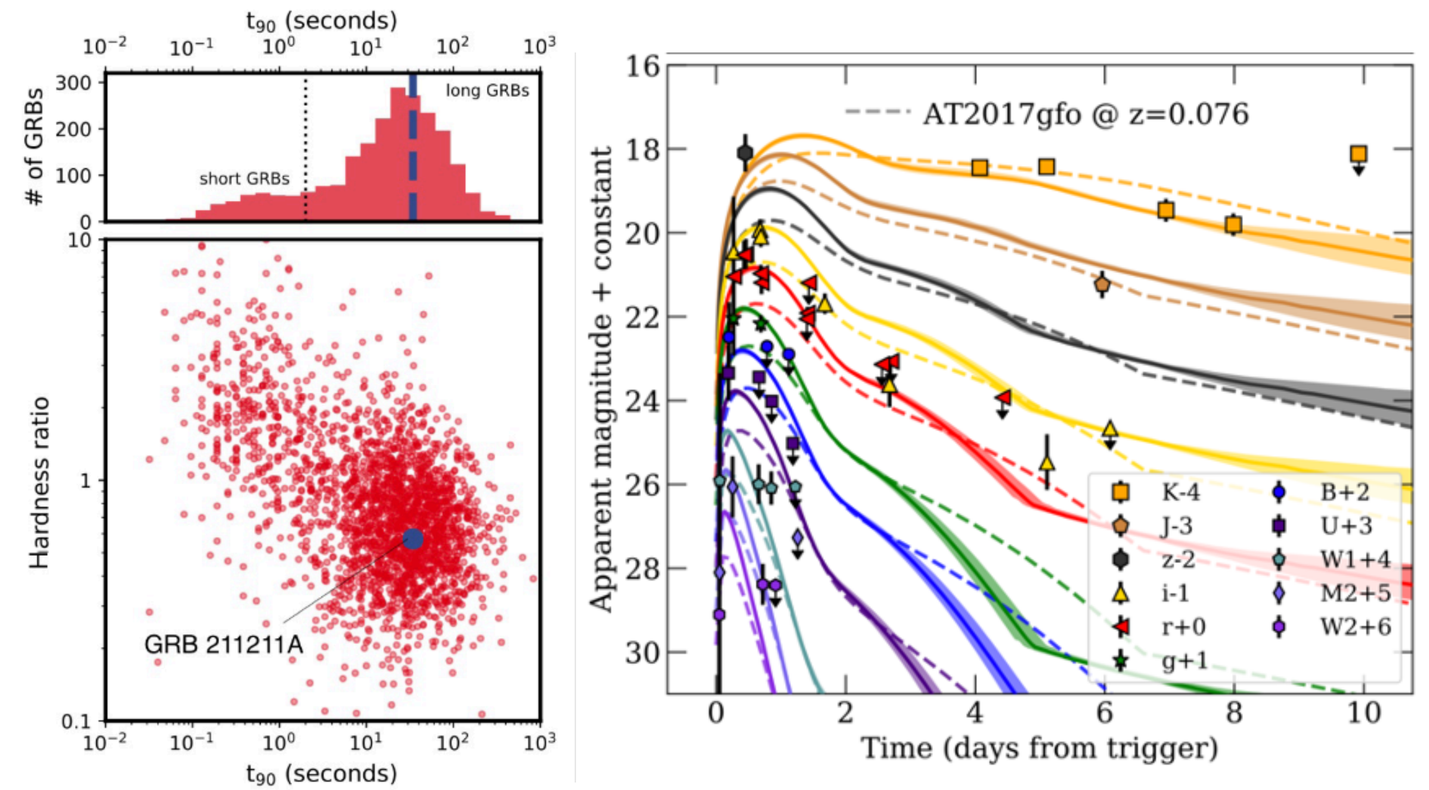




Ghirlanda et al. 2019 Science

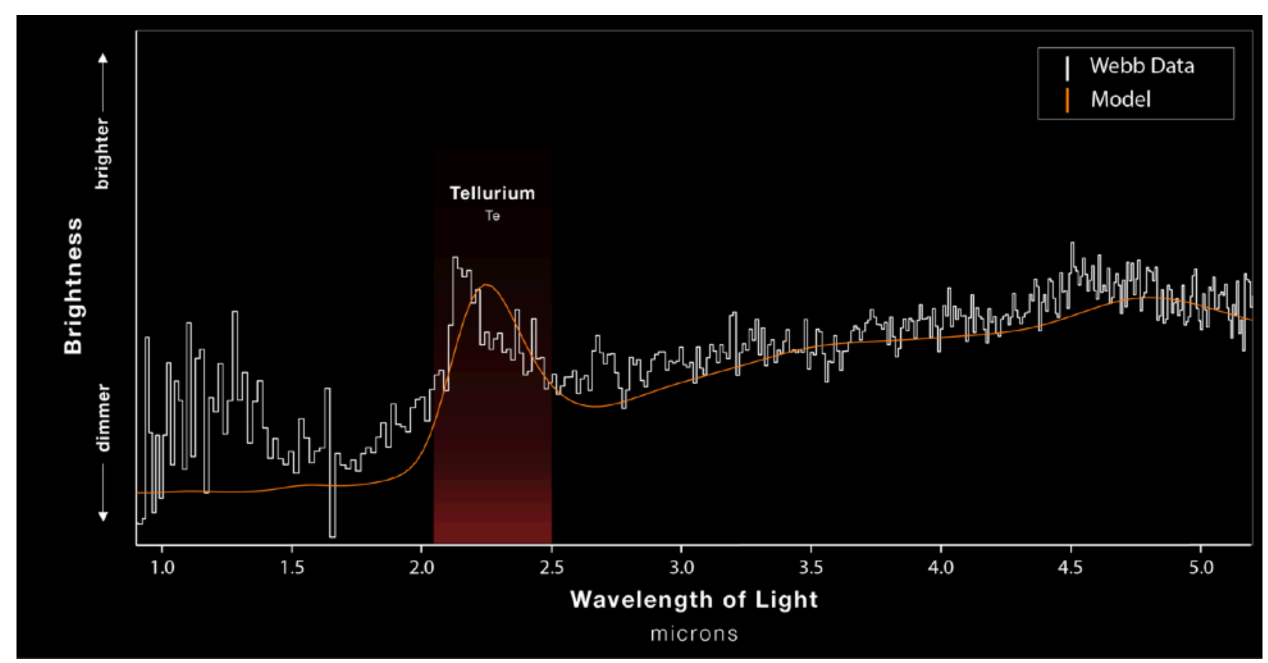
Are there other GW*-GRB-KN associations?

- GRB211211A: **Kilonova** Following a long GRB (Fermi-GBM) at 350 Mpc
- lGRB with precursor + Kilonova (similar luminosity, duration and color than GW170817)
- 1.4+1.3 M binary producing ≈ 0.02 M of ejecta
- ~GeV emission (Fermi-LAT) interpretation: KN photons up-scattered by electrons from low-power jets (Inverse Compton), Mei et al, Nature 612, 236–239 (2022)



Rastinejad, JC, et al, Nature 612.7939 (2022): 223-227.

- Very similarly in GRB230307A (Fermi-GBM)
  - second-highest gamma-ray fluence ever recorded
  - Long GRB with precursor: T90 of ~33 s
  - KN: Tellurium line seen by JWST!
  - Binary kicked from the host galaxy (from JWST)

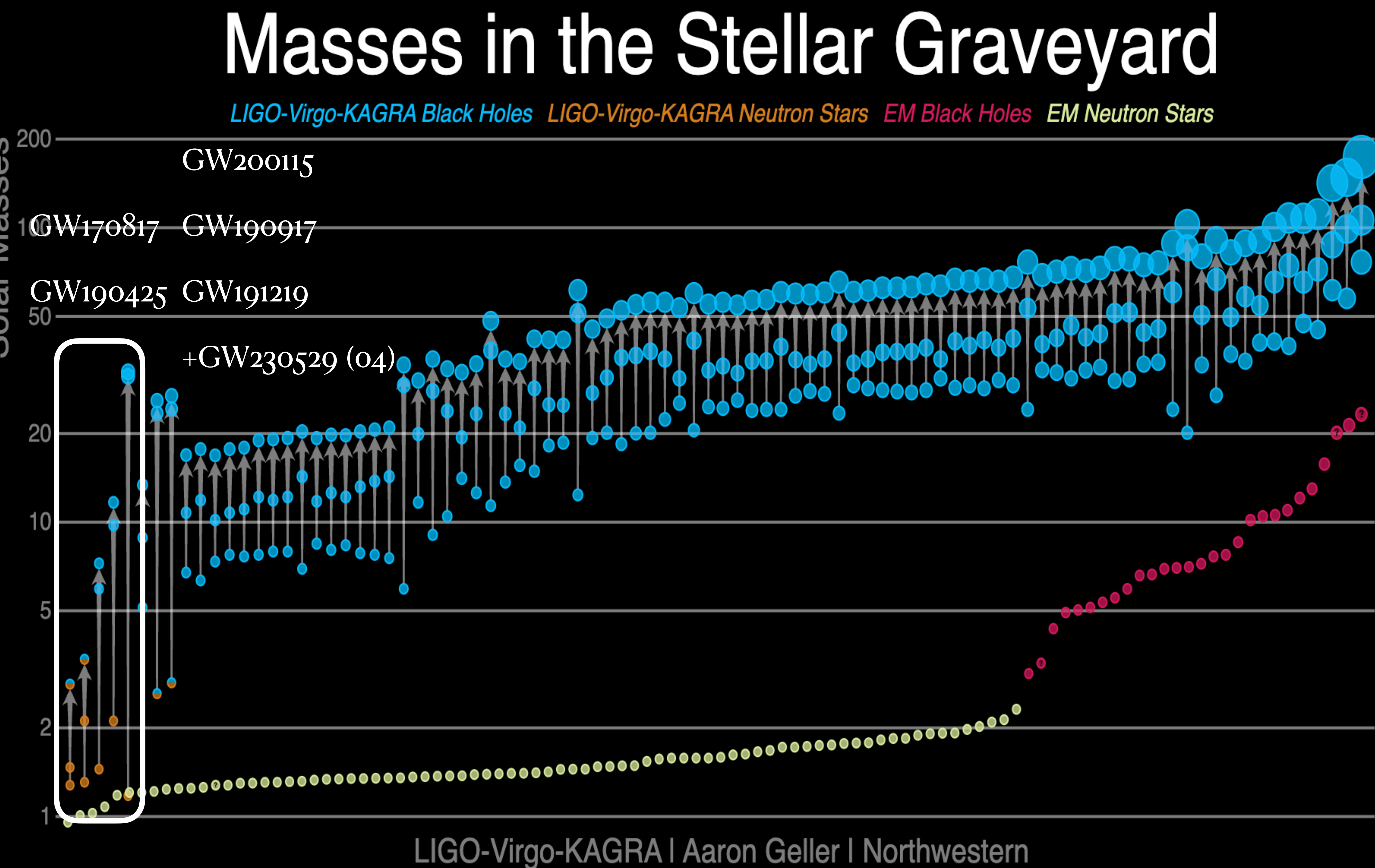


Levan et al, Nature, 626, (2024) 737–741

*No GW detection possible as ITF under commissioning towards O4

Other BNS and NSBHs ?

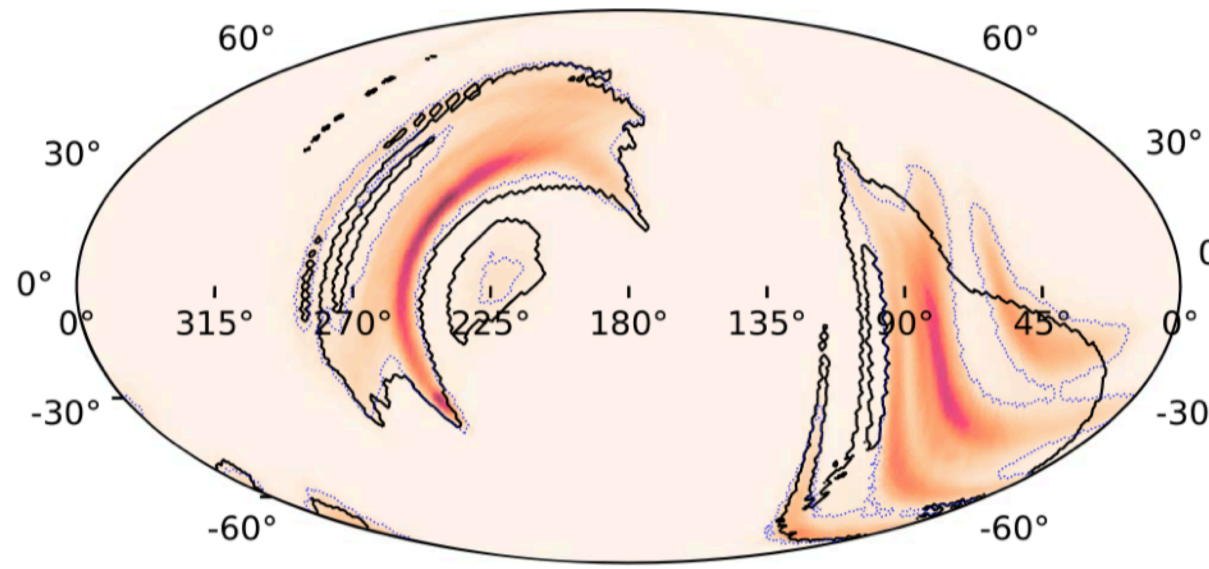
*GWTC-3



GW190425 : a second BNS detected by LVK:

ApJL 892 (2020) L3

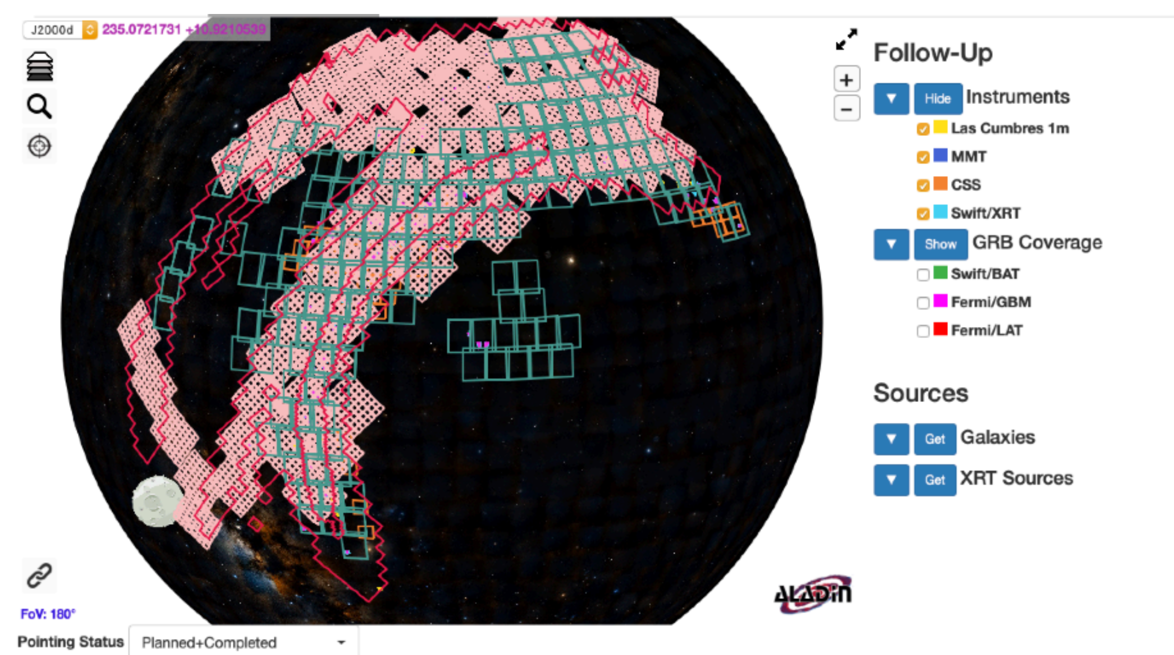
- LIGO-L + Virgo sky localisation:
  - very large region due to sensitivity differences
  - 5 sigma deviation from total mass and chirp mass of known galactic binaries (difficult to explain by isolated binary evolution)



$2.0^{+0.6}_{-0.3}M_\odot + 1.4^{+0.3}_{-0.3}M_\odot$ $d_L = 159^{+69}_{-72}$ Mpc

- Extensive campaign via GCN although **no counterpart was found**
  - Fermi satellite : 45.4% of localisation region occulted by the Earth
  - Poor constraints on the binary inclination: GRB-jet not oriented in our line of sight?
  - GRB170817A (40 Mpc) was **so faint that the same event wouldn't be detectable by Fermi-GBM at** ~75 Mpc and Swift/BAT at ~100 Mpc

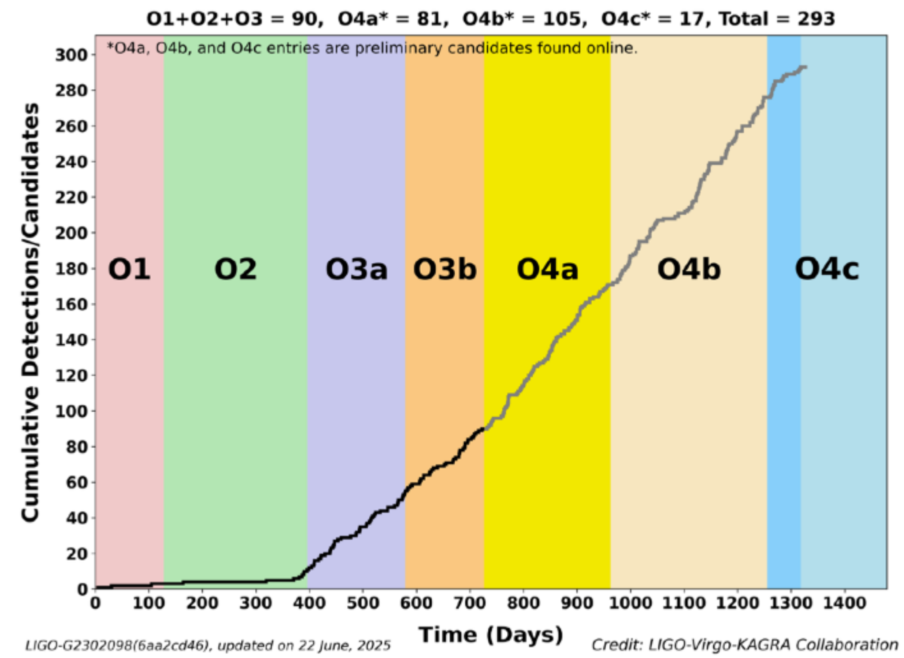
2225 tiles in this case!

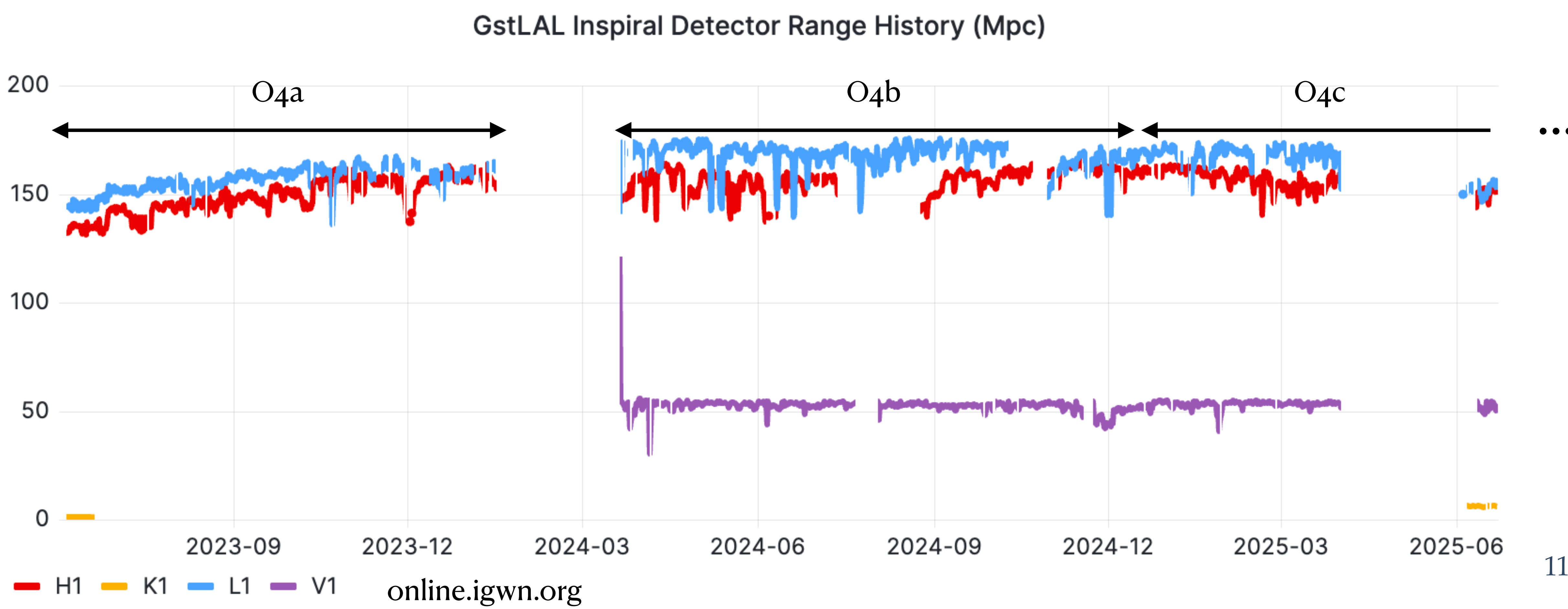


From http://treasuremap.space/

Observing run O4

- Started **May 24, 2023**, until **November 19, 2025**
- ~200 CBC candidates: detection BBH dominated
- ~5 NSBH, 1 BNS (FAR 4/yr, 15% terrestrial)
  - S240422ed (retracted)
  - Largest campaign on S250206dm with >8k pointings
  - **GW 241125n (BBH) +Swift-GUANO candidate!** GCN38308: only proposed EM candidate



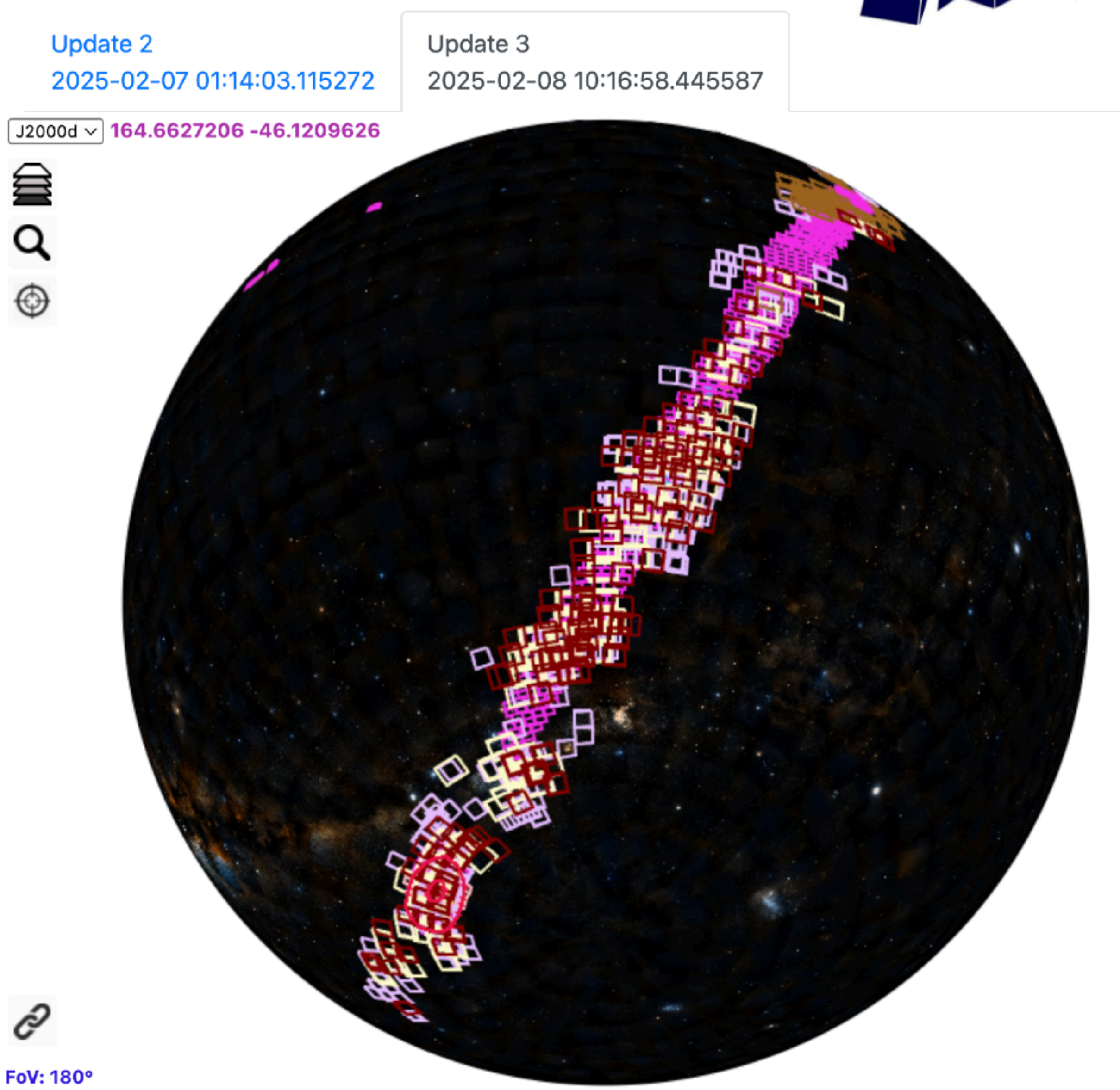


online.igwn.org

Tools Developed Through the Years

Treasure Map

treasuremap.space



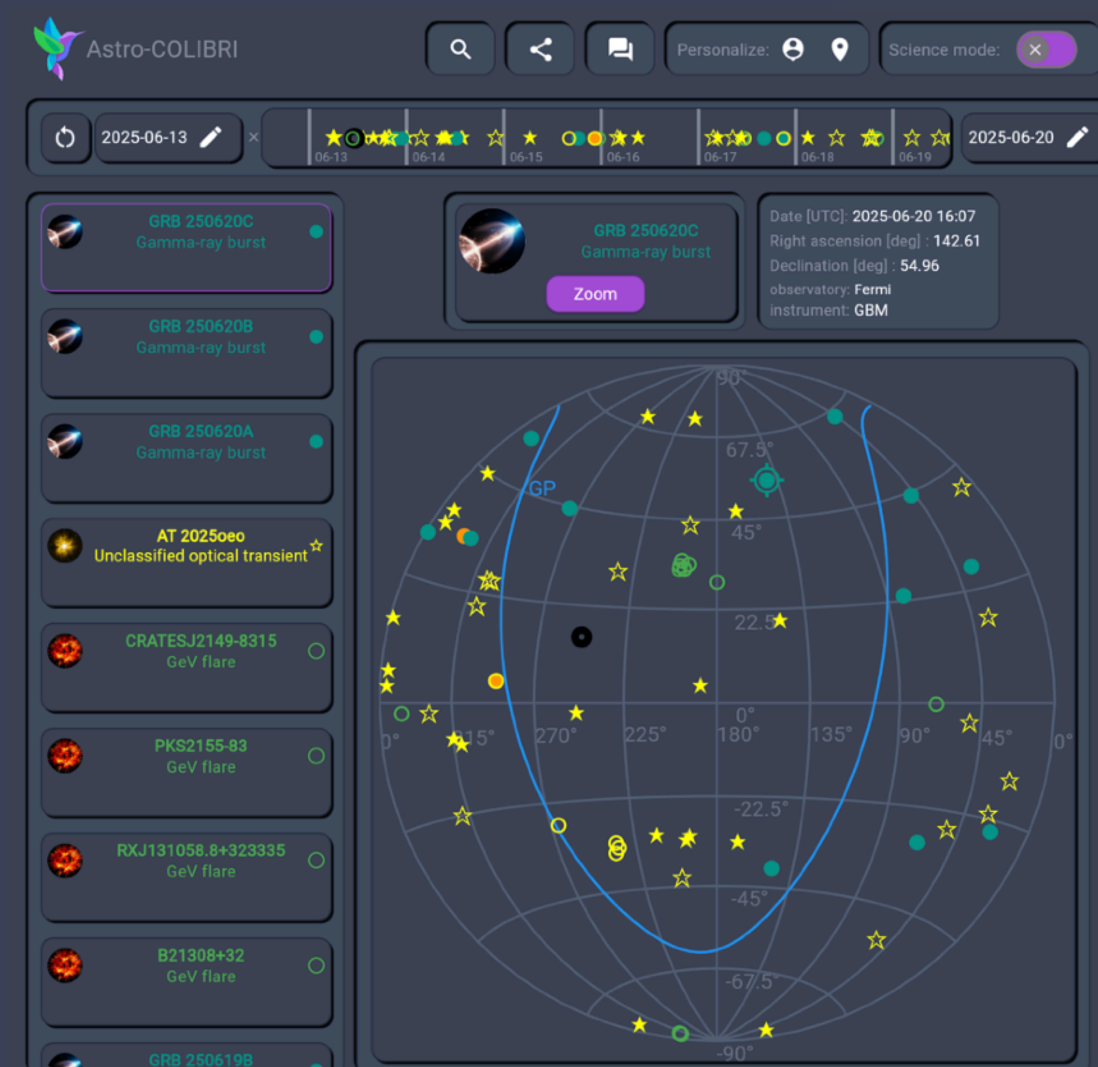
GW250206dm:

NSBH (55.0%) BNS: (37.3%) Mass Gap: (34.9%)

Distance (Mpc)373.42 +/- 104.18

Astro-COLIBRI

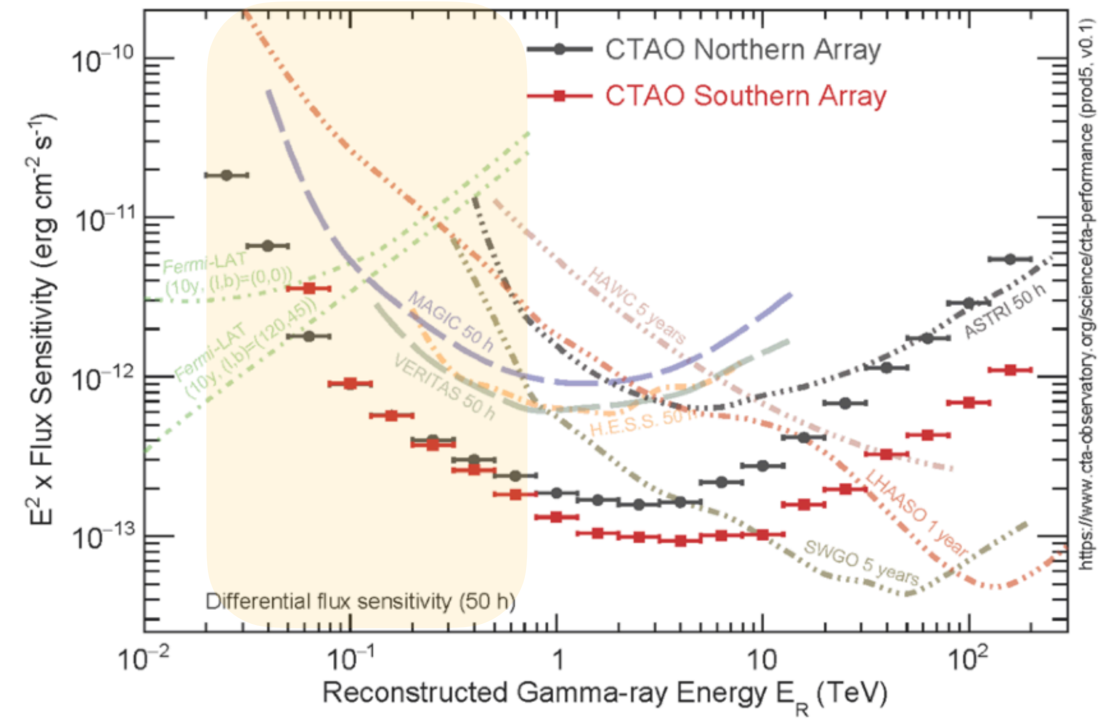
astro-colibri.com



The GeV-TeV energy range

Astrophysics at the GeV- TeV gamma-ray range:

- Cherenkov Telescopes: **MAGIC, HESS, VERITAS, CTAO**
- Water detectors: **HAWC, LHAASO**



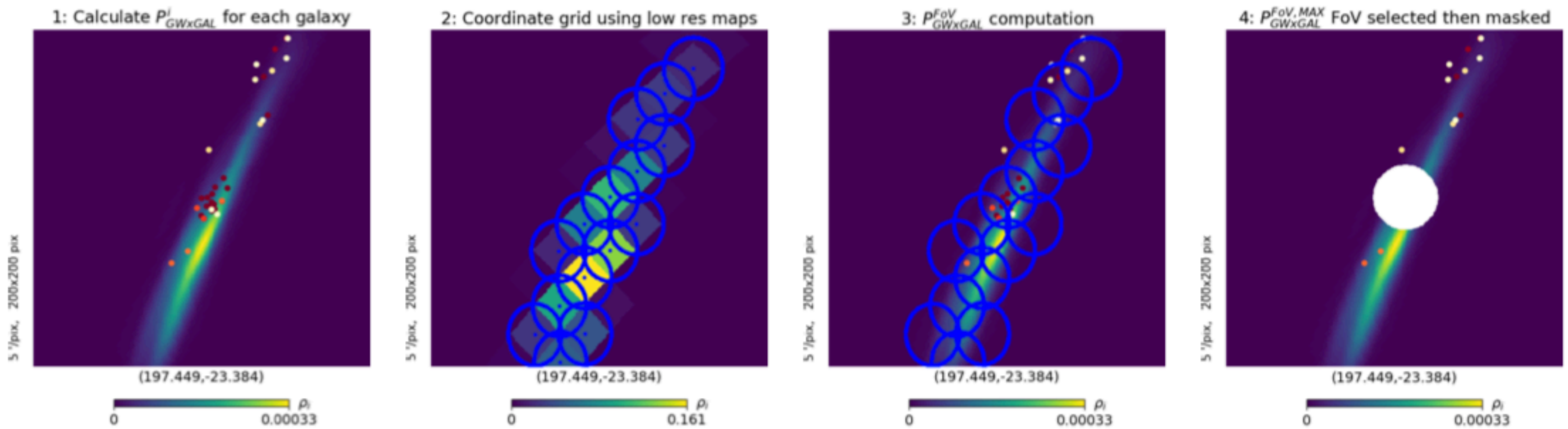
Currently observing

Under construction

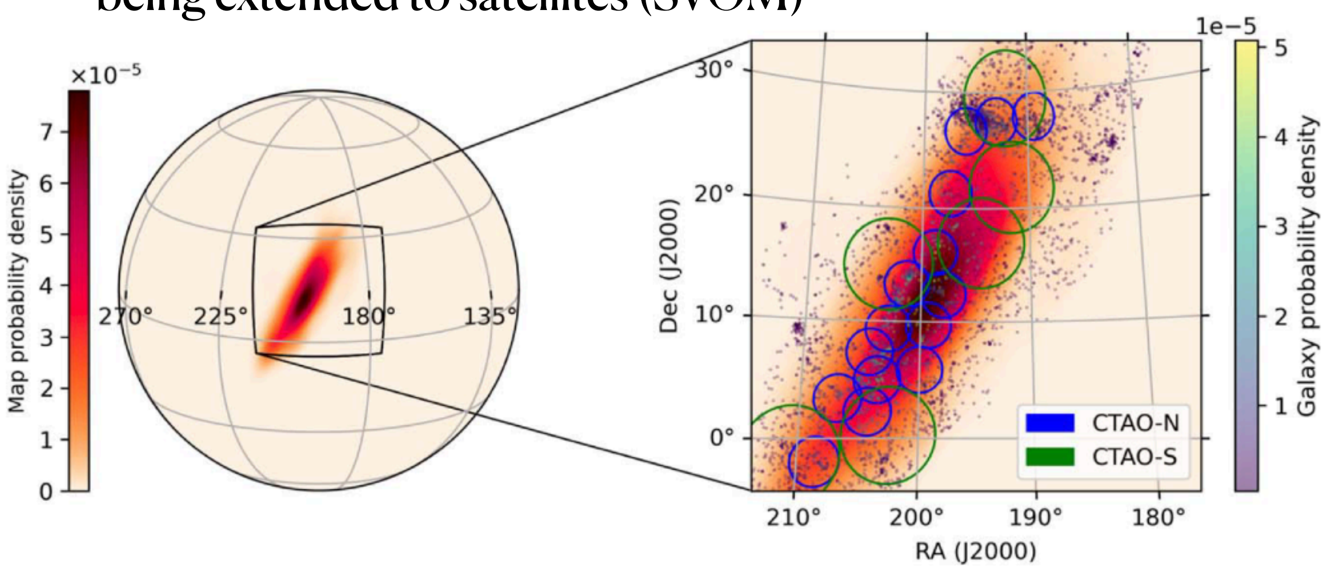
Mid-FoV challenges

- Mid-FoV as Imaging Atmospheric Telescopes have challenges to follow large sky localisations! ⟶ Scheduling algorithms
- tilepy: **flexible and modular python package: GNU3-licenced open-source, PyPI deployment**
- The basic ingredients: visibility, probability integration, galaxy catalogs, zenith angle optimisation

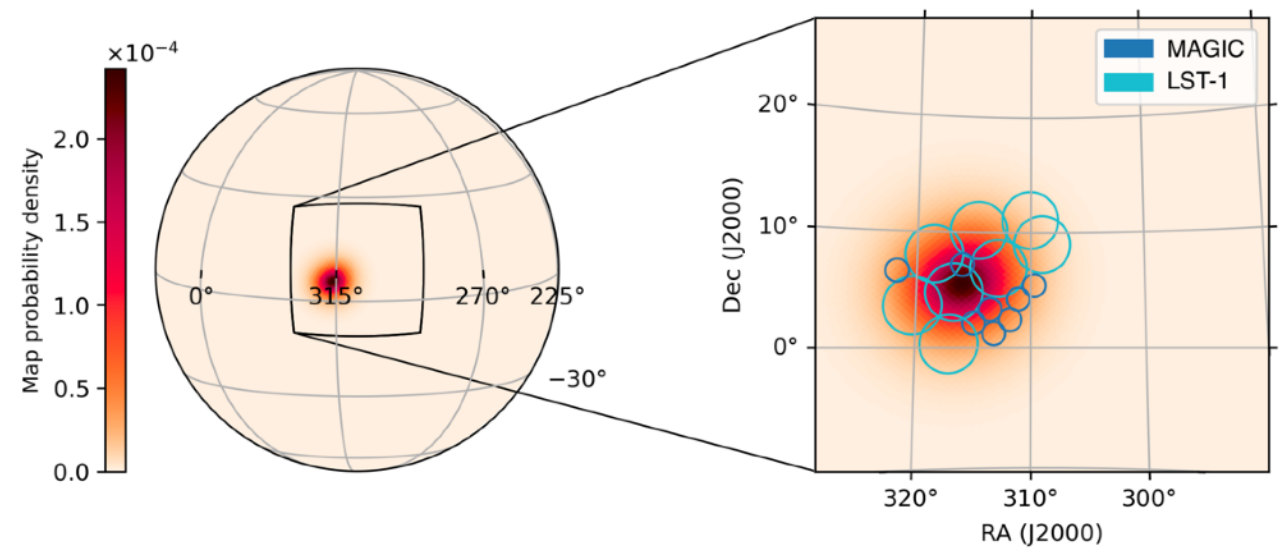
Ashkar, SA, et al, JCAP 03 (2021) 045



- Very powerful for coordination between observatories (used in the gamma-ray community: H.E.S.S.,LST, CTA-C, astro-Colibri, being extended to satellites (SVOM)

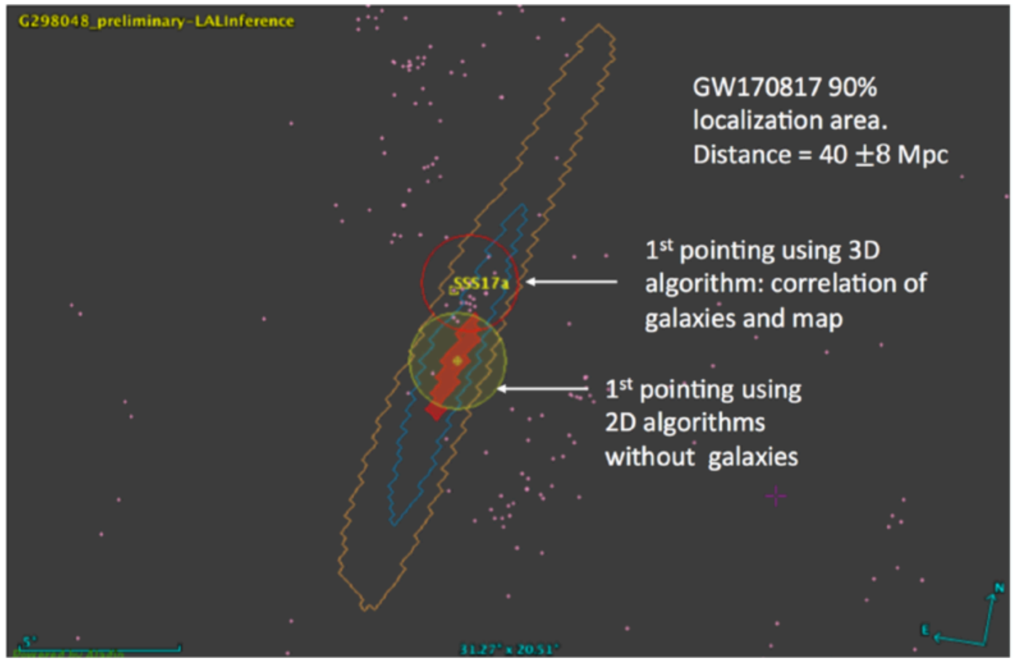


SA, Ashkar, Schussler, de Bony, Astrophys.J.Suppl. 274 (2024) 1, 1



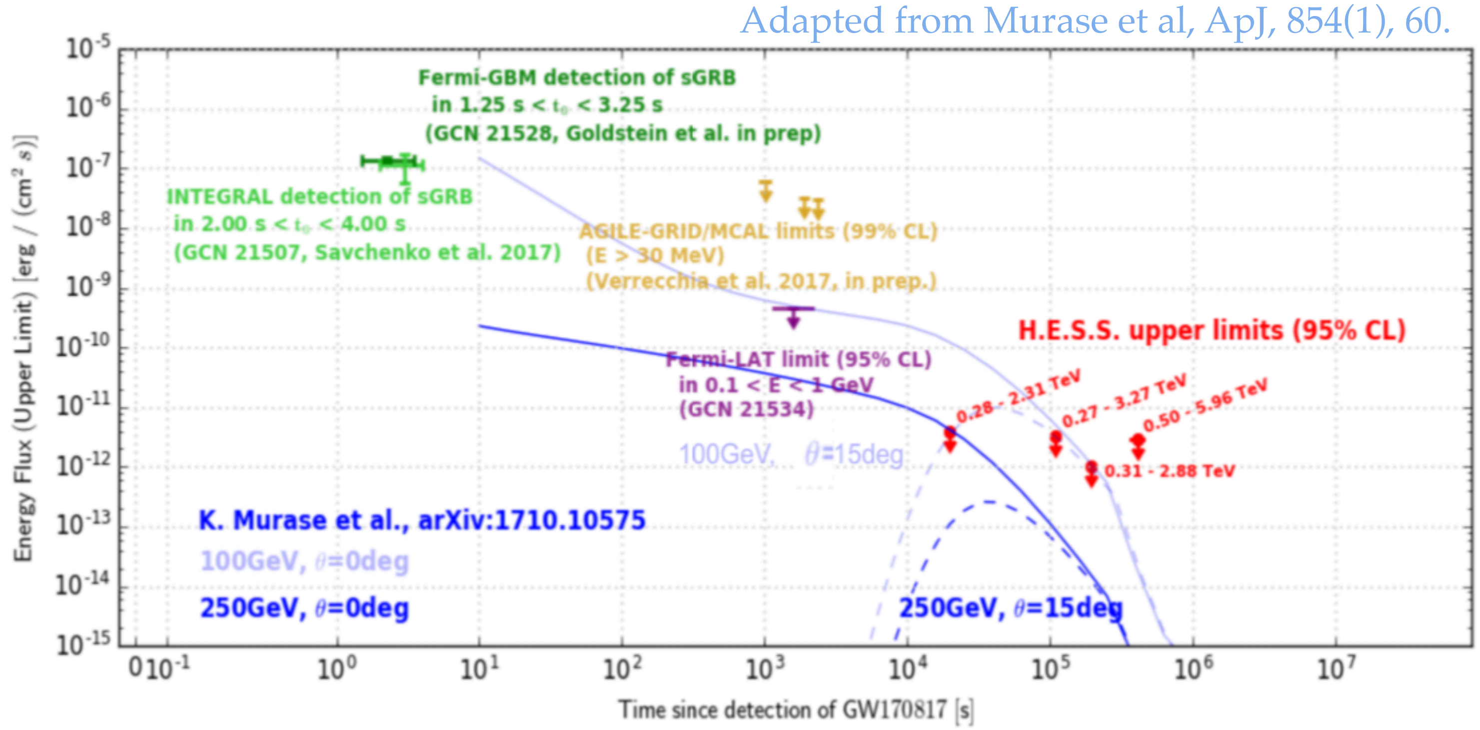
Seglar-Arroyo et al, PoS(ICRC2025), in prep

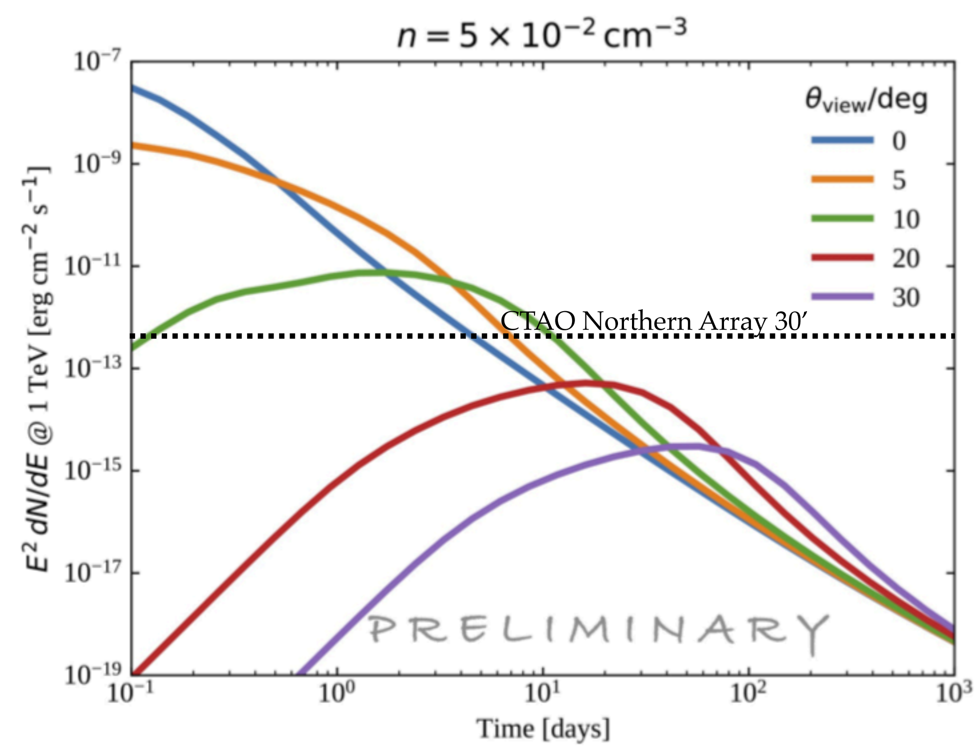
Gamma-ray results: GW170817 by H.E.S.S



- **H.E.S.S. was the first ground based instrument on target**
  - 5.3 hours after merger, 5' after LV GW skymap: 3 obs (17:59 - 19:30 UTC)
  - tilepy using Glade+ (MNRAS 514 (2022) 1, 1403-1411)
- No TeV emission was detected: upper limits derived (here external Inverse Compton in afterglow shock with X-ray photons)
- Conditions not favorable: low interstellar medium density n~10^{-4} cm^{-3} large viewing angle $\theta_V \sim 15 - 25$ deg . Detectable at peak for viewing angles $\theta_{view} < 10$ deg.

Adapted from Murase et al, ApJ, 854(1), 60.





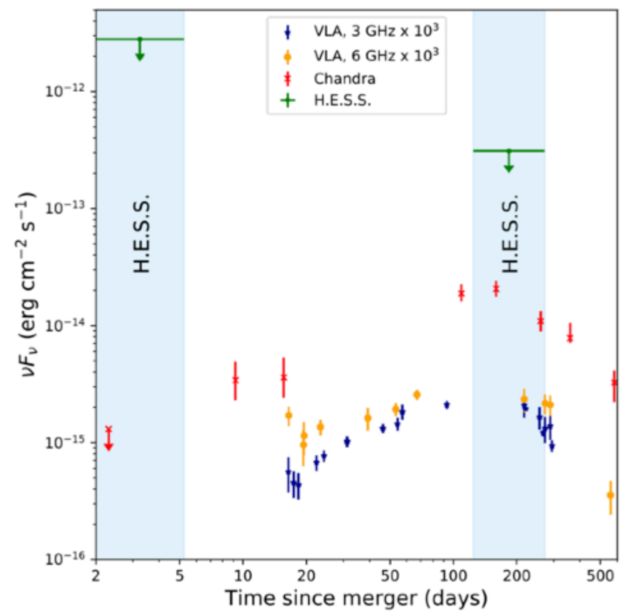
A. Stamerra, et al. *37th ICRC 2021*. Vol. 395.

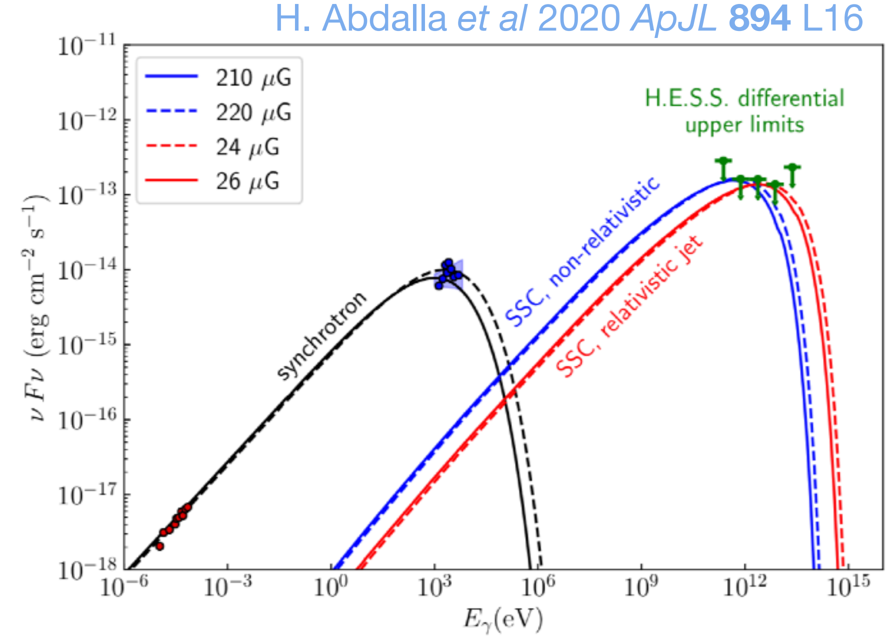
Gamma-rays emission from the remnant?

- Motivated by the non-thermal emission seen in radio and x-rays.
- Quite unclear gamma-ray expected emission though!

H. Abdalla *et al* 2020 *ApJL* **894** L16

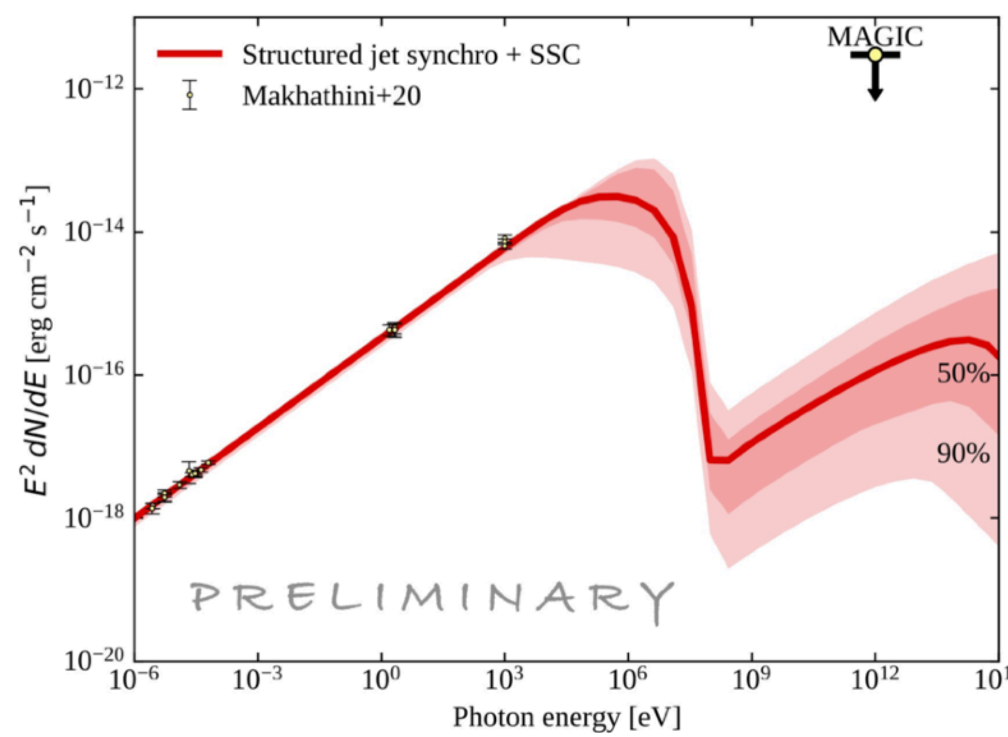
- H.E.S.S. (124 and 272 days after): ULs used to constrains the **minimum magnetic field** strength assuming the Synchrotron and Synchrotron Self-Compton emission at VHEs





- MAGIC (~ 9.5 h, January to June 2018): Constrains on **magnetic field from emission from the shock that arises as the structured jet sweeps the interstellar medium**

$$B(155\,\mathrm{d}) = 240^{+590}_{-140}\,\mu\mathrm{G}$$

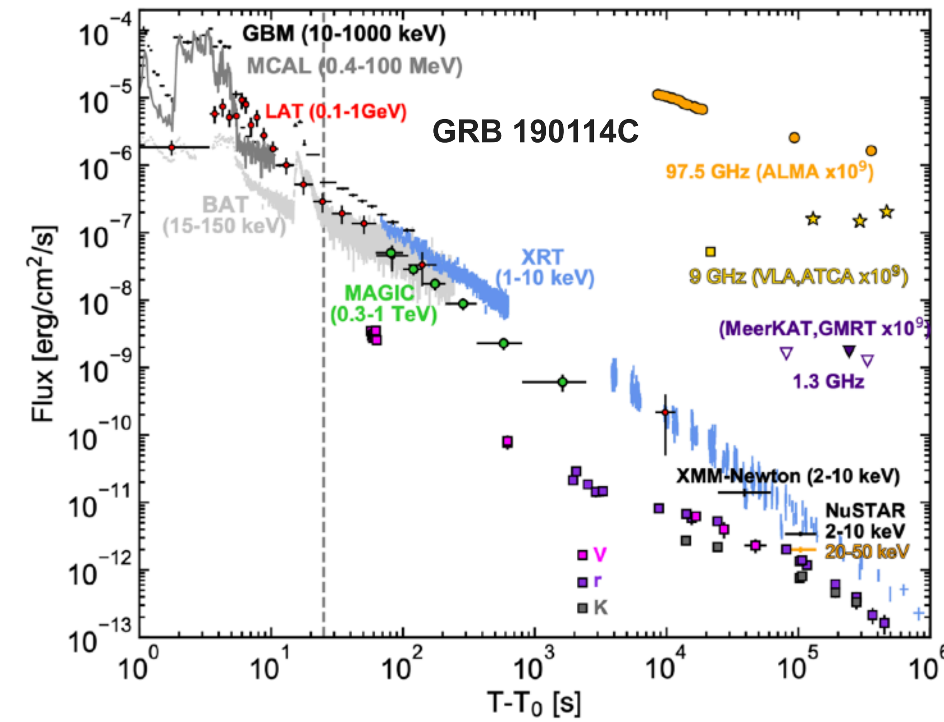


A. Stamerra, et al. *37th ICRC 2021*. Vol. 395. SISSA, 2021.

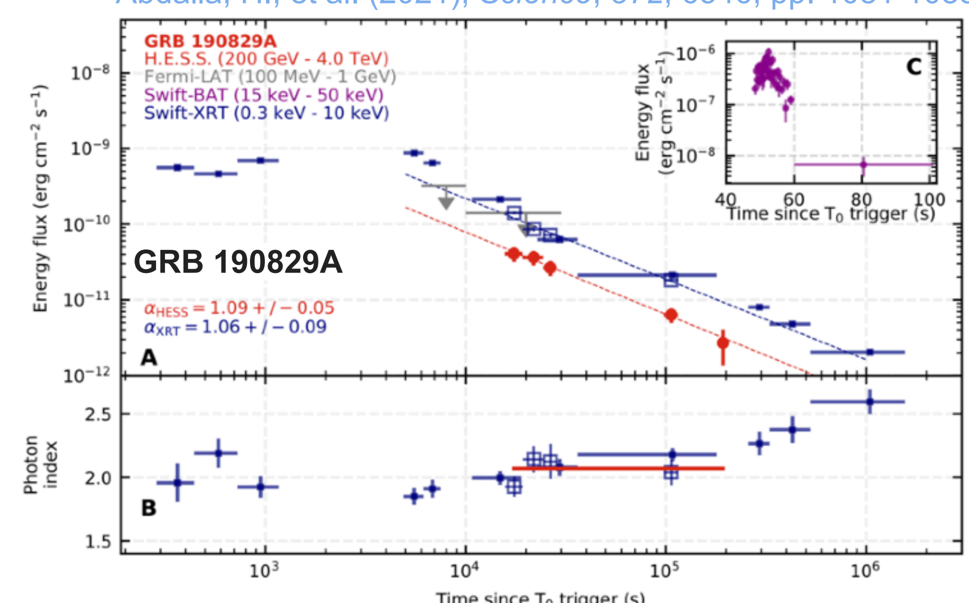
In the meantime…. First lGRBs detections of VHEgamma-ray emission

- **No detection until 2018 , despite the many efforts!**
- Puzzling scenario due to **diversity of detections**. Emission models: Synchrotron/Synchrotron Self Compton/ Inverse Compton
    - GRB 190114C : **early afterglow, short-lasting (~57 s after, for ~15 mins)**, bright (E_{iso} ~10^{53} erg). Inverse Compton
    - GRB 180720B: **deep afterglow (~10 h after, for 2h)**, bright (E_{iso} ~10^{53} erg). Synchrotron Self Compton
    - GRB 190829A: **deep long-lasting (~days!) afterglow**, dimmer (E_{iso} ~10^{50} erg): Synchrotron/Synchrotron Self Compton
    - Also GRB 201216C (**z=1.1**, MNRAS 527, 3, 2024, 5856–5867), GRB 160821B (3 sigma sGRB)

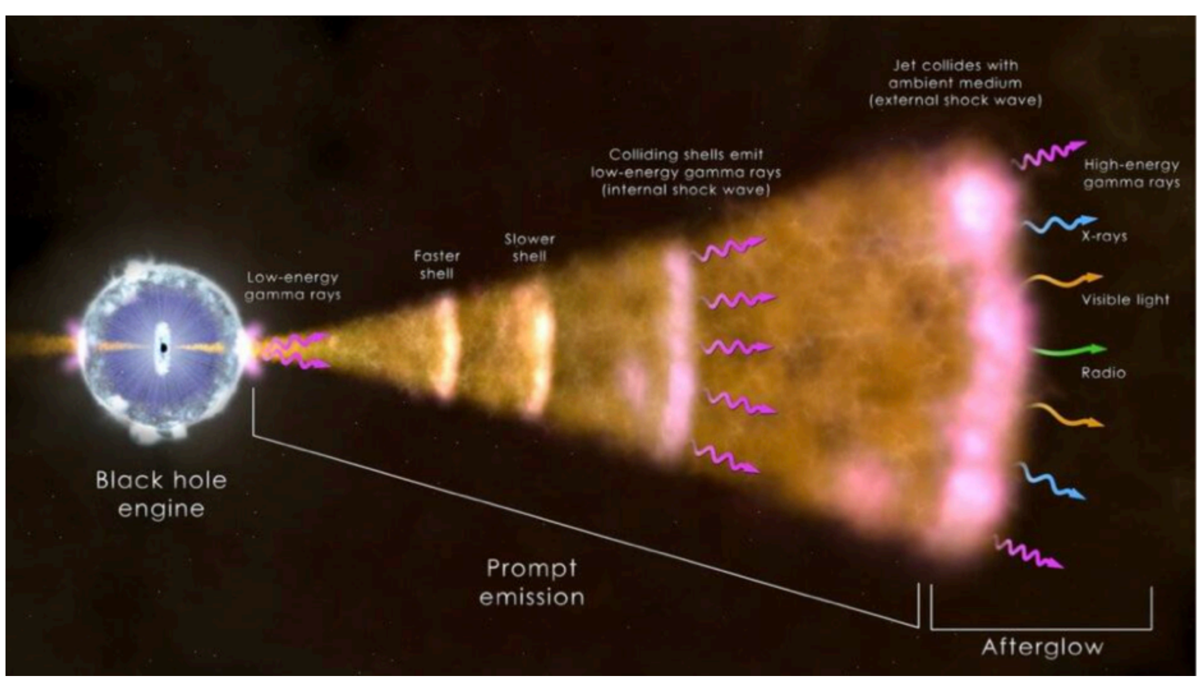
MAGIC Collaboration (2019), *Nature*, *575*, 455.



Abdalla, H., et al. (2021), *Science*, *372*, 6546, pp. 1081-1085

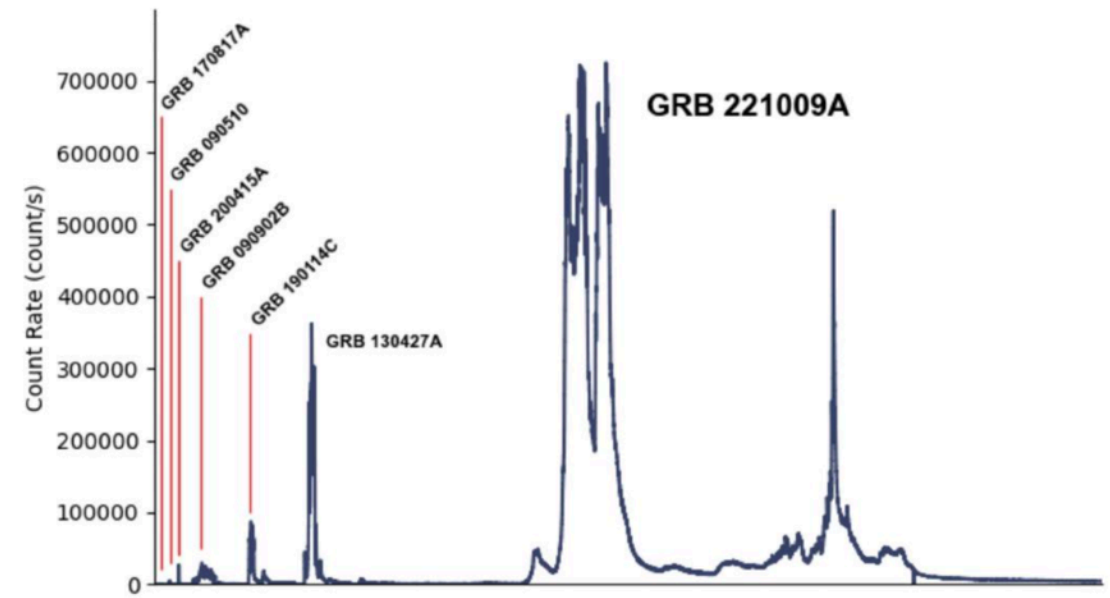


56 hours



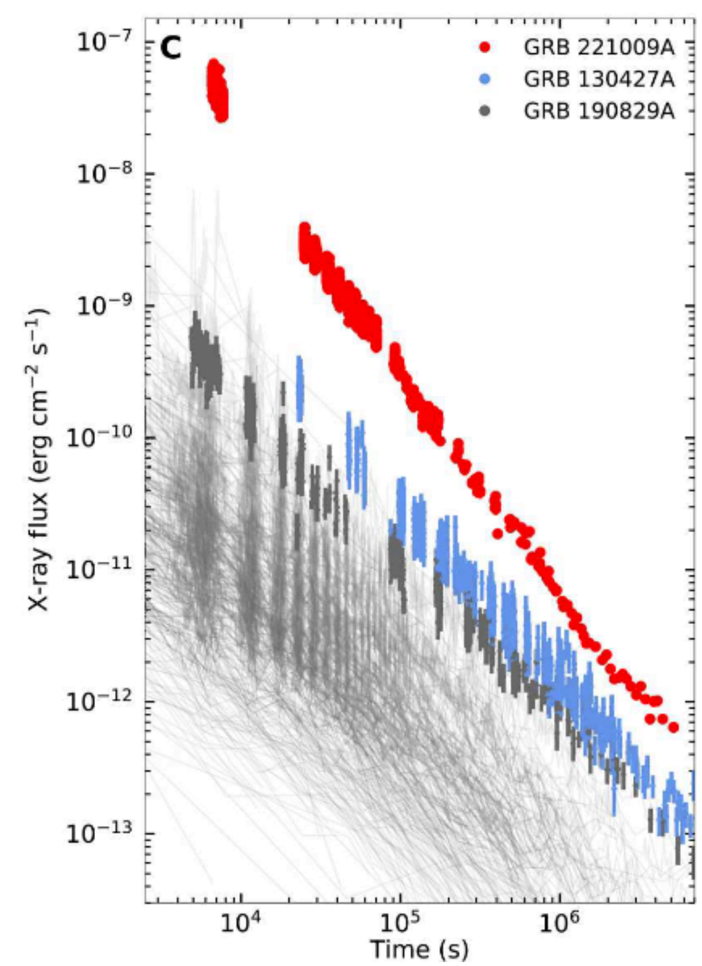
Brightest of All Times GRB

- GRB 221009A: Brightest gamma-ray burst to date (rate: 1 per 10k years)
- Very close (z=0.15) and bright (Eiso ~ 2×10^{54} erg)
- Most extensive long GRB campaign to date
- Fermi -LAT suffered from a strong pile-up at early times (bulk started ~200s after Fermi-GBM trigger pulse). During the prompt phase that lasted for more than 600 s, a photon of 99.3GeV was detected at T0 + 240 s, while a photon of 400GeV was detected at T0 + ~9 h in the afterglow phase.
- LHAASO: detected!
    - 200GeV-7TeV by WCDA @250 sigma
    - 3TeV-13 TeV by KM2A from T0+[230, 900] s => emission >10TeV, synchrotron radiation of UHE protons (reverse shock)
- Bad luck/ good luck for IACTs: moon break. Active effort to observe ASAP



Credit: A. Goldstein (USRA)

O'Connor et al., A.*Sci. Adv.***9**,eadi1405(2023)

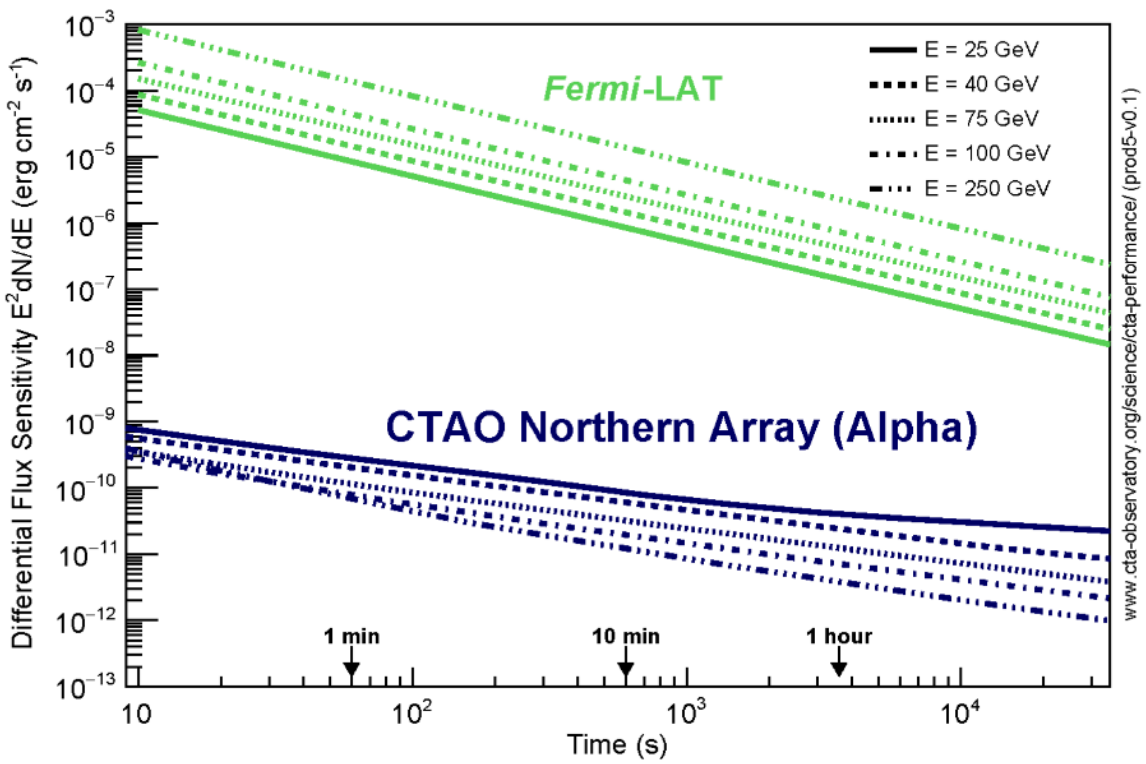


The first telescope of CTAO: LST-1

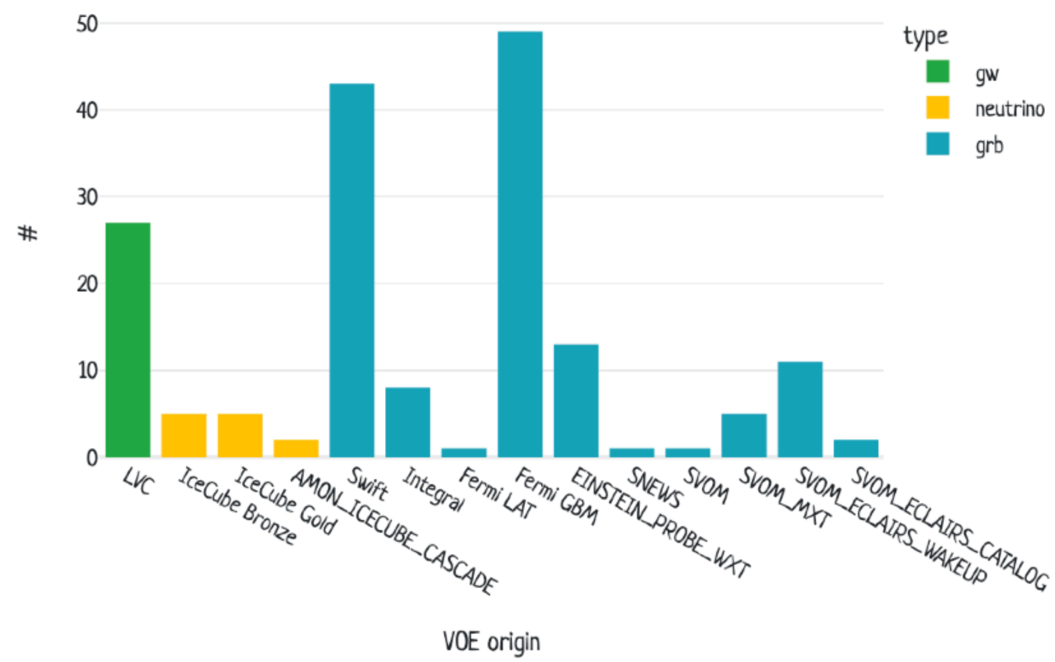
First telescope of CTAO: the **Large-Sized Telescope-1**

- large reflective surface, enabling the detection of faint Cherenkov flashes from electromagnetic cascades of gamma rays down to 20 GeV
- 4.5 deg field-of-view (FoV): coverage of broad sky regions
- light design of the telescope structure: fast slewing (180 deg / 20 s)

..... i.e. a transient catcher machine

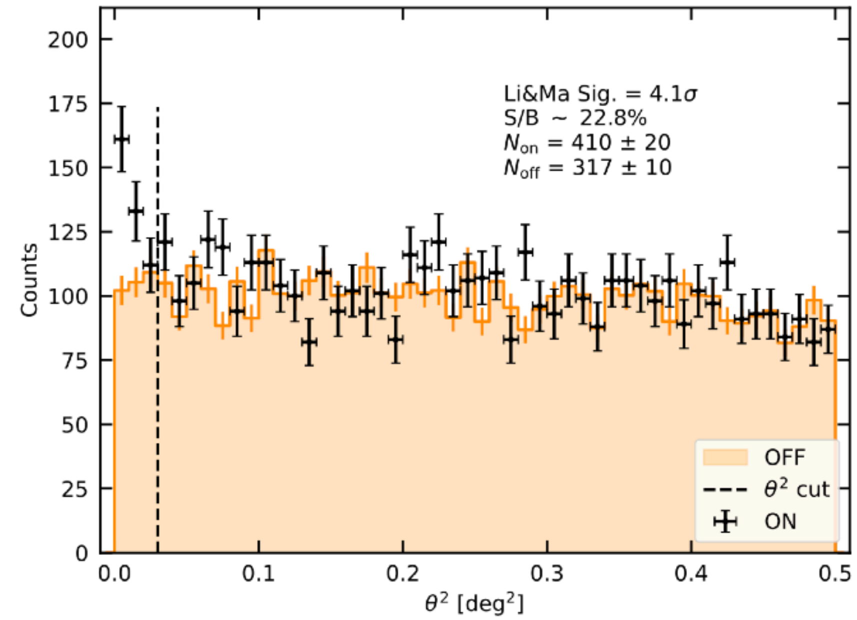


- Very rich transient program covering **GW, GRB, neutrino, TDEs, FRBs, galactic novas**
- Handles automatically alerts in the order of ~ 10s seconds-min
- GW program: all LVK alerts (for now CBC and Burst)
  - Based on probabilities released (no mass info :()
- Differently depending on 90% C.R. localisation: Wobble, extended coverage



LST-1 observations of GRB221009A

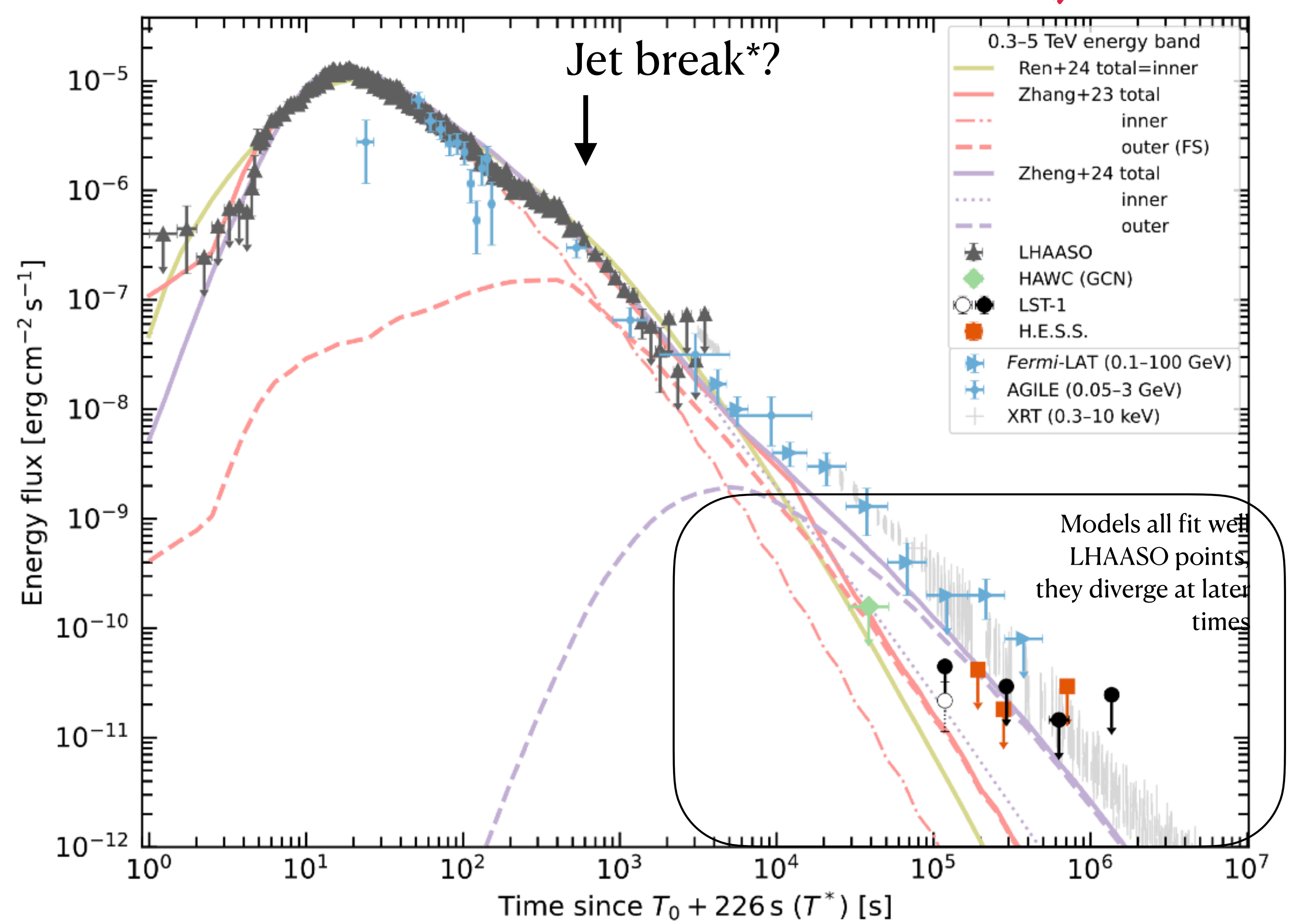
- LST observations: earliest observations by an IACT on this GRB (To+1,33days, 20-day campaign) => **4.1 sigma in first run**
- LHAASO really unveils onset of afterglow emission (~first hour). Great HE coverage by AGILE+Fermi-LAT (up to 105s)
- *Jet break*: Jet propagates through the progenitor star and interacts with stellar material. Jet slowing down enough that its radiation is no longer narrowly beamed (~0.6deg)—the jet widens. We see more than one emitting region
- Strongest evidence of structure jets in lGRBs (vs. top hat)
- Similarities: Circumburst medium same, narrow jet, **emission from forward shock of the inner jet: X-rays (synchrotron), VHE (SSC)** Differences: **emission region** at later times, large differences in microphysical parameter choice



Ren +24

Zhang+23

Zheng+24



Aguasca, Terauchi, SA, Inoue et al., accepted in ApJ Letters

Prospects on CTAO detectability of sGRBs from BNS mergers during O5

Goals:

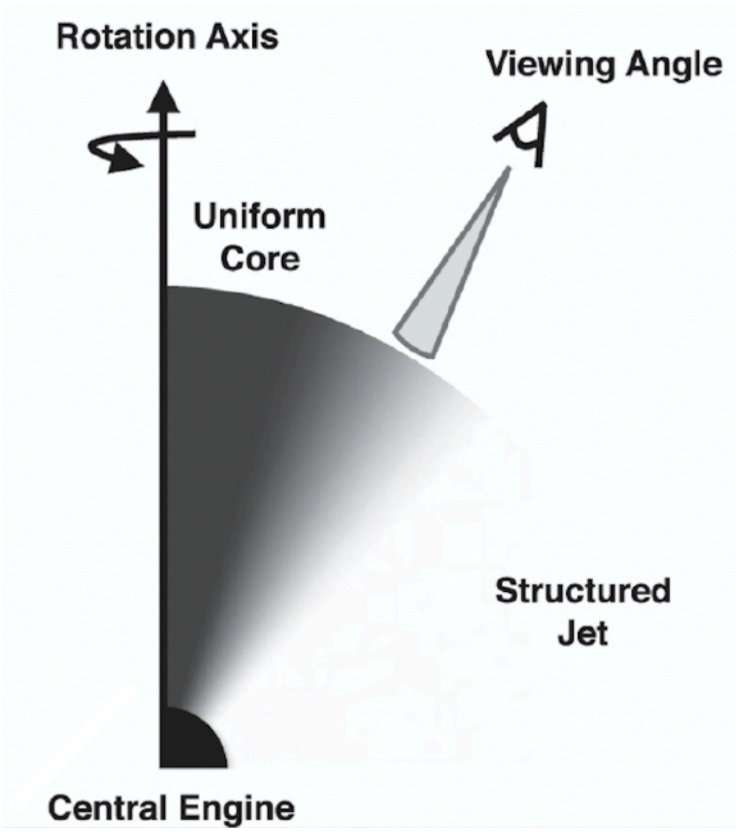
- sGRBs detections using state of the art considerations

- Investigate the best way to detect these sGRBs **linked to GW detections** (~poorly localised source).

- **GW: O5 simulated** (Petrov, P et al., *Astrophys.J.* 924 (2022) 2, 54,)
  - Homogeneous and isotropic distribution
  - 3D BAYESTAR localization

- GRBs: Phenomenological set of short GRB simulations
  - Assume that **all launch** a jet.

- Link via distance, **viewing angle** between the jet axis and the mass of the BNS
  - **Viewing angle** given by the orbital inclination of the binary
  - **Jet core angle :** from sGRB distribution, ~14deg (A&A , 52:43–105, 2014.)
  - EBL- absorbed GRB spectrum

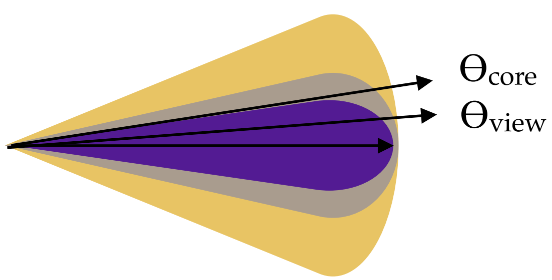


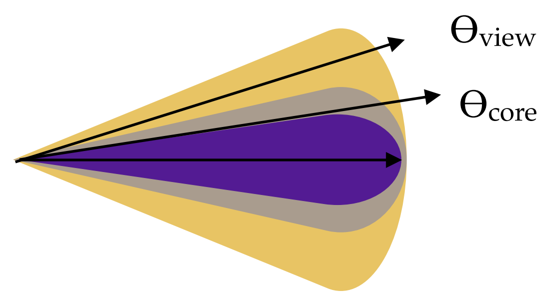
- E_{iso} from short GRB distribution in Ghirlanda et al. A&A, 594:A84, Oct 2016
- **Lightcurve**: temporal decay and luminosity at TeV similar to that in soft X-ray band.
- **Spectrum**: Power-law with photon index of -2.2. External medium ~0.1cm^{-3}

Green, Patricelli, SAm et al. 2024, PoS (ICRC2023) 1534
Seglar-Arroyo, M. et al.. 35th ICRC, PoS790, 2019

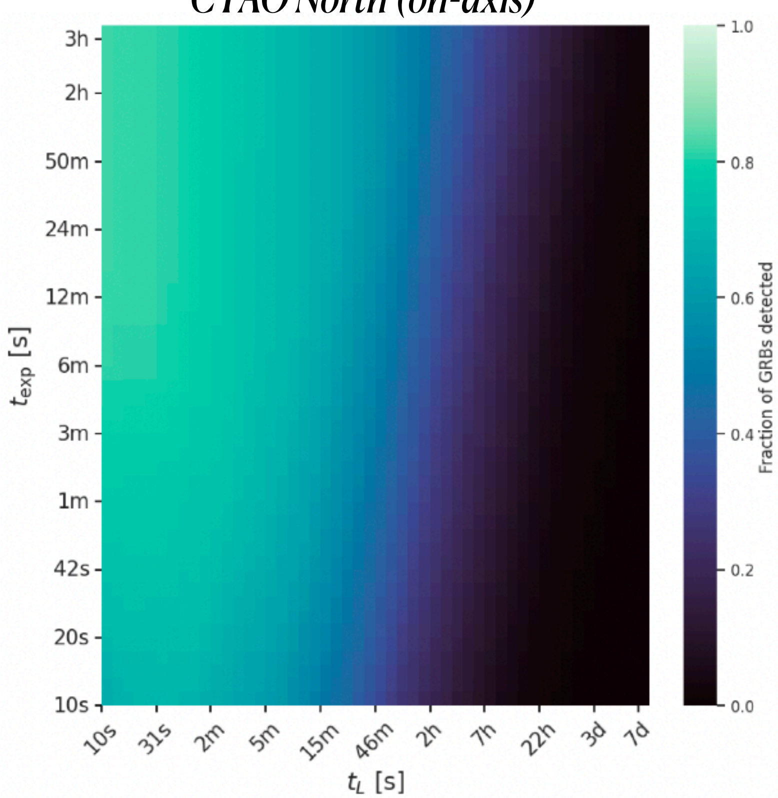
Prospects on CTAO detectability of sGRBs from BNS mergers during O5

- Short GRB detectability study: **fraction of GRBs detected depending on exposure and delay**
- IRFs used (latest official): CTAO alpha configuration (CTA- N: 4 LST and 9 MST, CTAO-S: 14 MST and 37 SST)
- First results
  - **Delays**: Results indicate that the turning point is for **~15-45 minutes in on-axis/off-axis events**
  - **Exposure**: detections are achieved in a large number of cases with short exposures ~10 s
- Main differences ON-axis/OFF-axis : **off axis detection not directly at ~seconds of delays, detectability notably decreases**

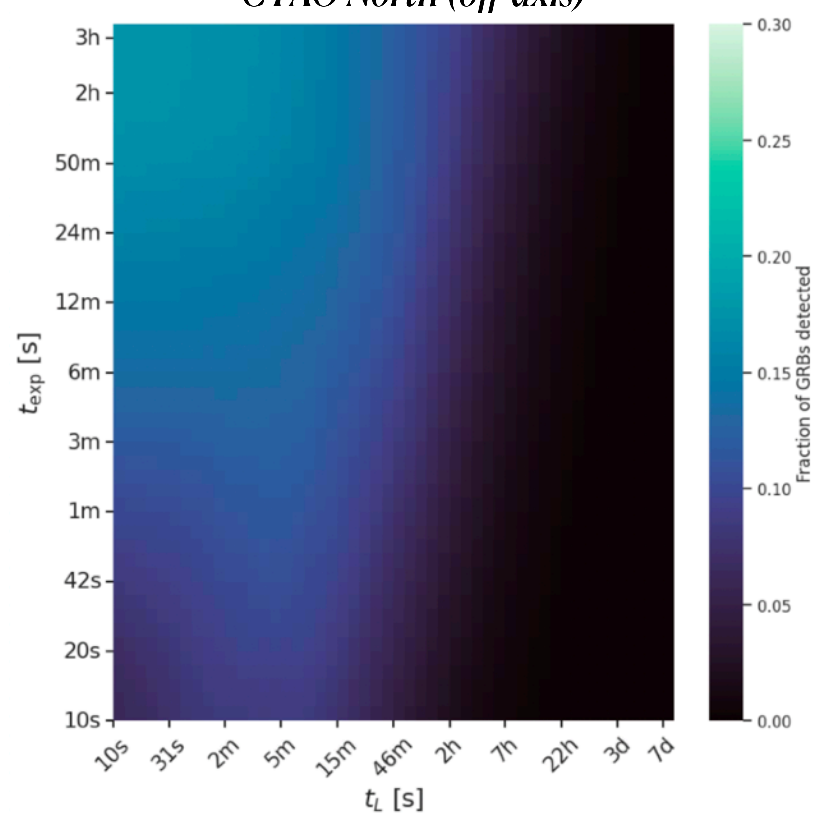


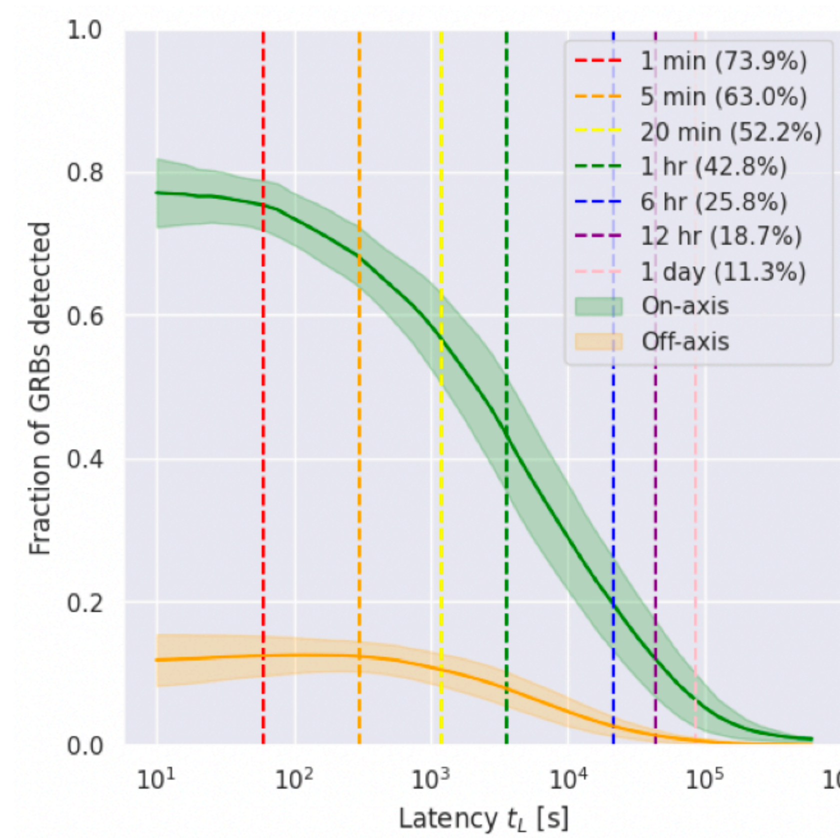


CTAO North (on-axis)



CTAO North (off-axis)



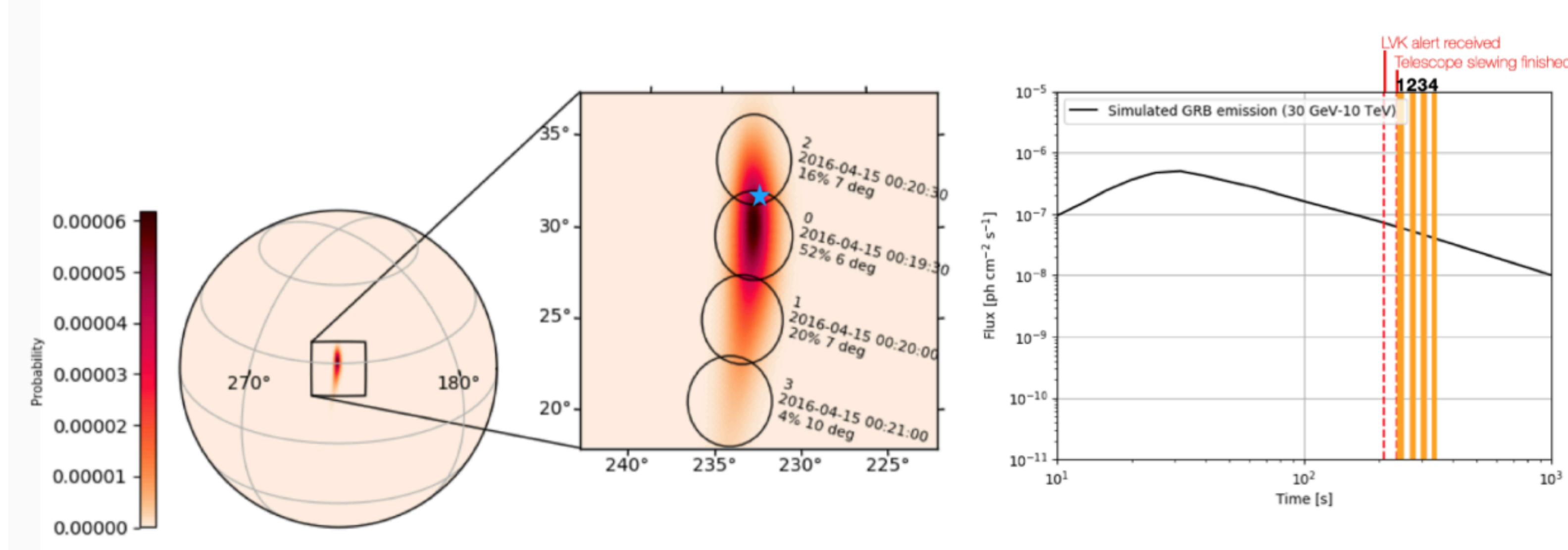


SA, Patricelli, Green, Stamerra, Schussler, (CTA Consortium paper), in prep

Prospects on CTAO detectability of sGRBs from BNS mergers during O5

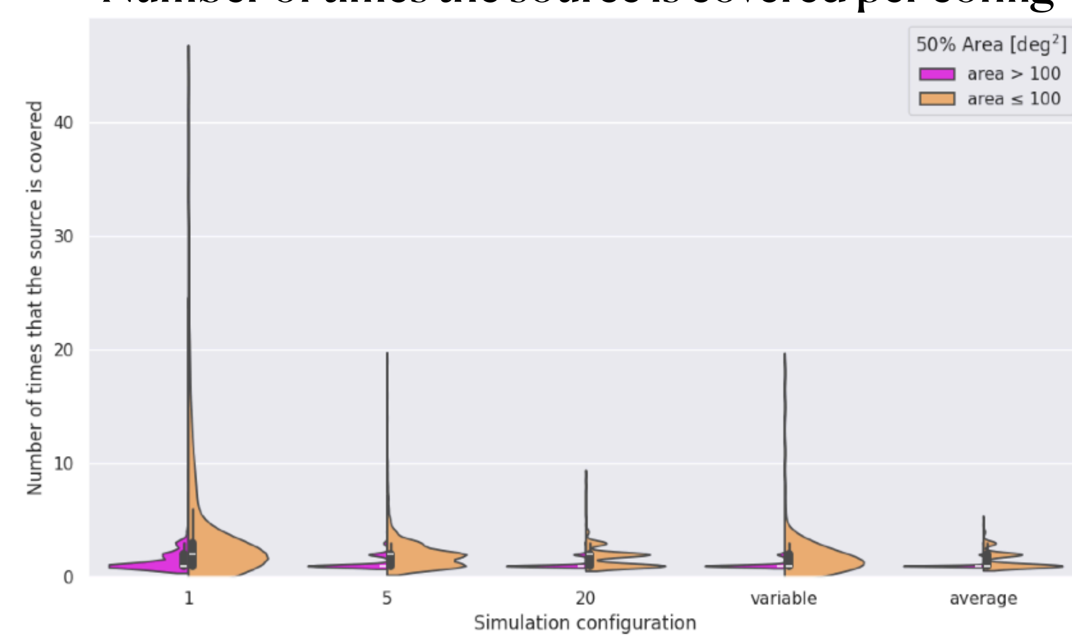
- **Observation strategy for the follow-up campaign**
  - Fixed window: Comparison of 1', 5', 20': Fast campaigns covering large regions versus usual IACT exposures
  - Variable window (1): Average LC among all the GRBs: is useful to have some information on the evolution?
  - Variable window (2): Tailored exposure per each GRB, so that the exposure is the one required for 5sigma detection

$$\int_{t_L}^{t_L+T_{EXP}} F(t)dt = F^{S}_{5\sigma}(T_{exp})$$



- Preliminary results for variable window (2, implies detection if covered)
  - 8% are followed , **5% cover and detect the source**
  - Focusing on viewing angle:
    - On- axis: 18% followed, **10% cover+detect the source**
    - Off-axis: 7% followed, **4% cover+detect the source**

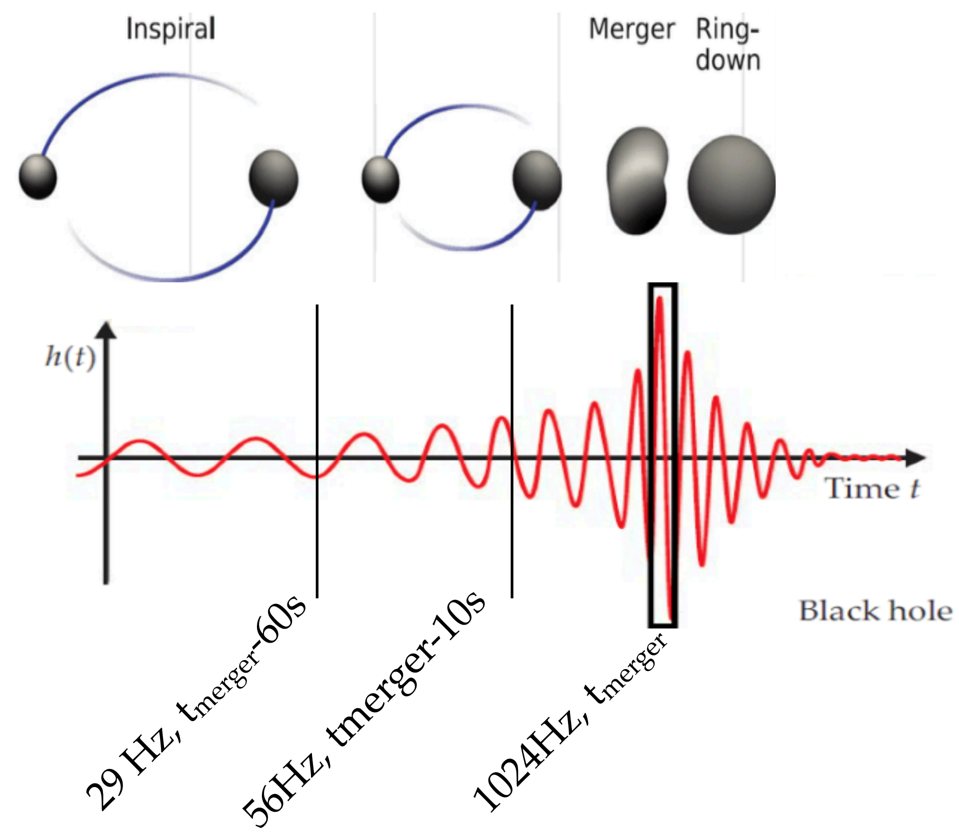
Number of times the source is covered per config

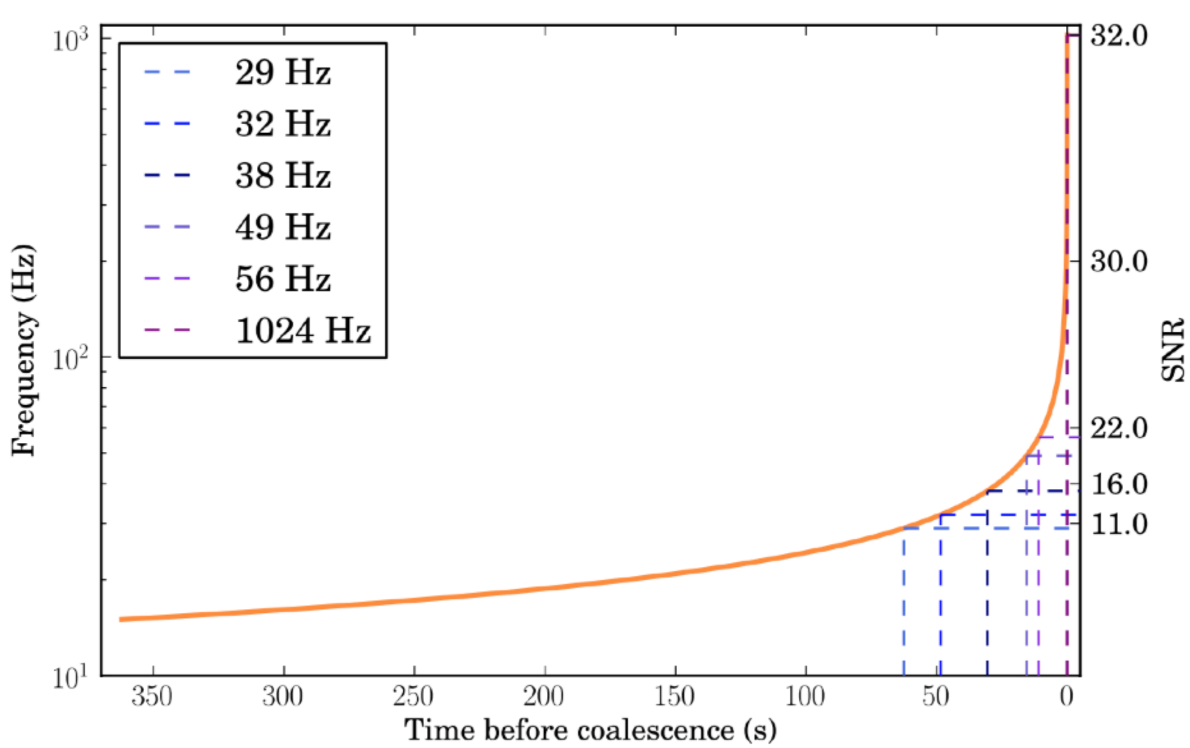


SA, Patricelli, Green, Stamerra, Schussler, (CTA Consortium paper), in prep

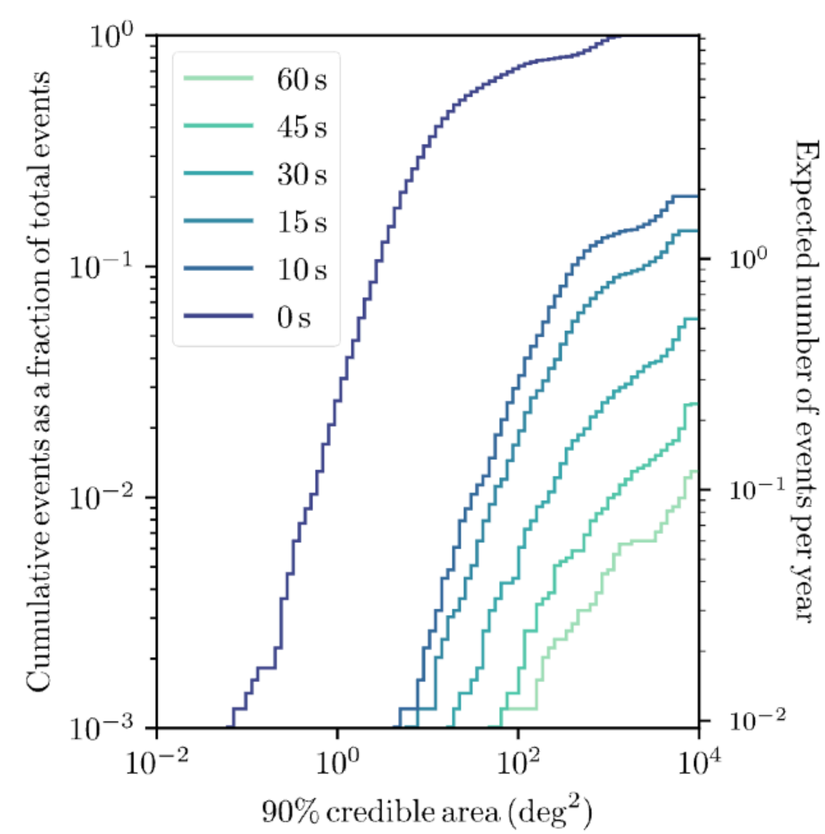
The role of Early Warning alerts

- Key ingredient to catch GRBs !!
- Pre-merger alerts: send the alert **BEFORE** the merger
  - In observing run O4 (for the first time)
  - Observing run O5 *2026-2028: ~3 BNS/year, 10 s prior to merger with localizations of 100 deg²* (Magee et al. 2021)
- All LVK CBC pipelines are able to produce EW alerts for BNS
- Drawbacks: localisation accuracy **<u>not yet</u> at the desired level**





The time evolution of the gravitational-wave frequency and the cumulative SNR for a GW170817-like BNS system.

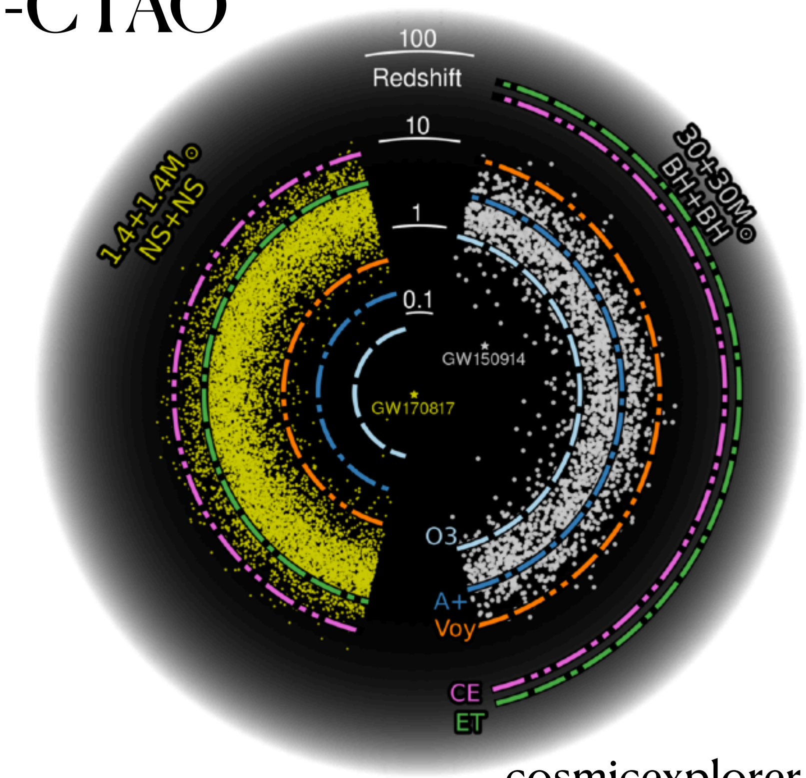


Magee et al, *Astrophys.J.Lett.* 910:L21 (7pp), 2021

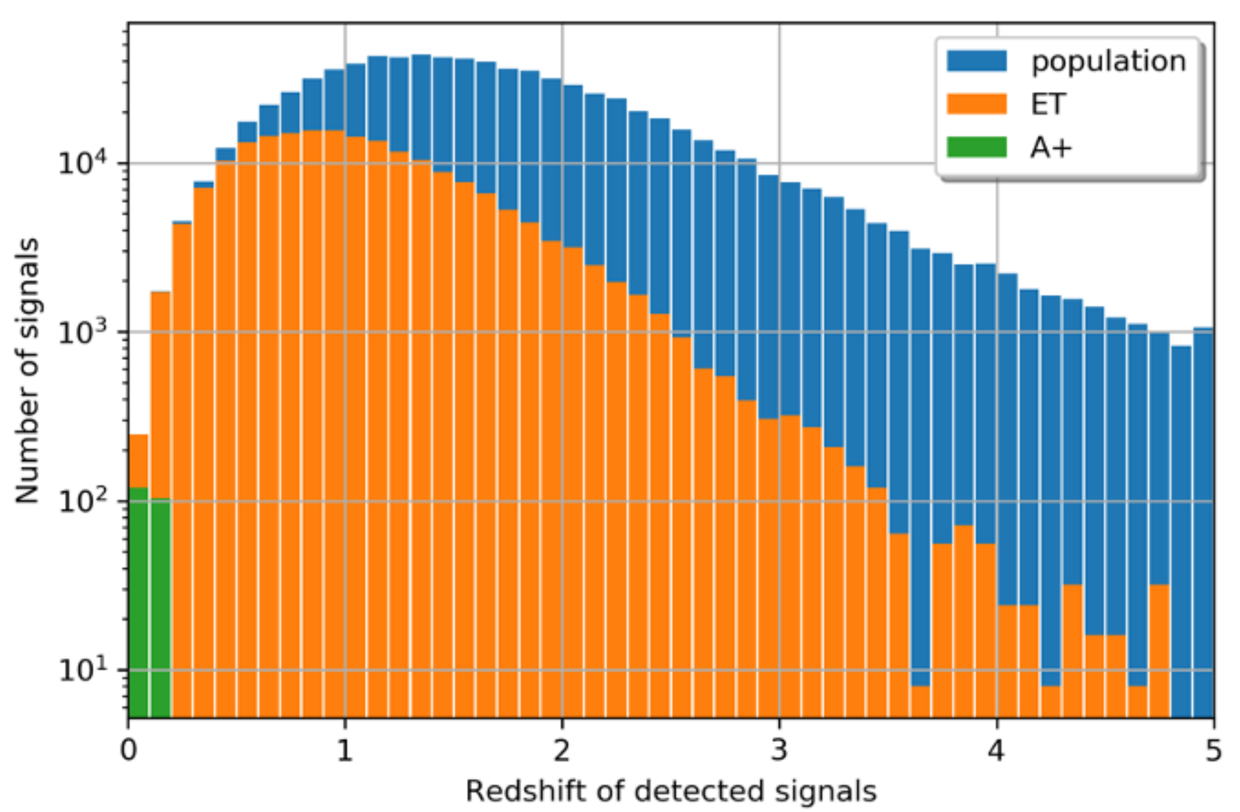
Detections in the future years with ET-CTAO

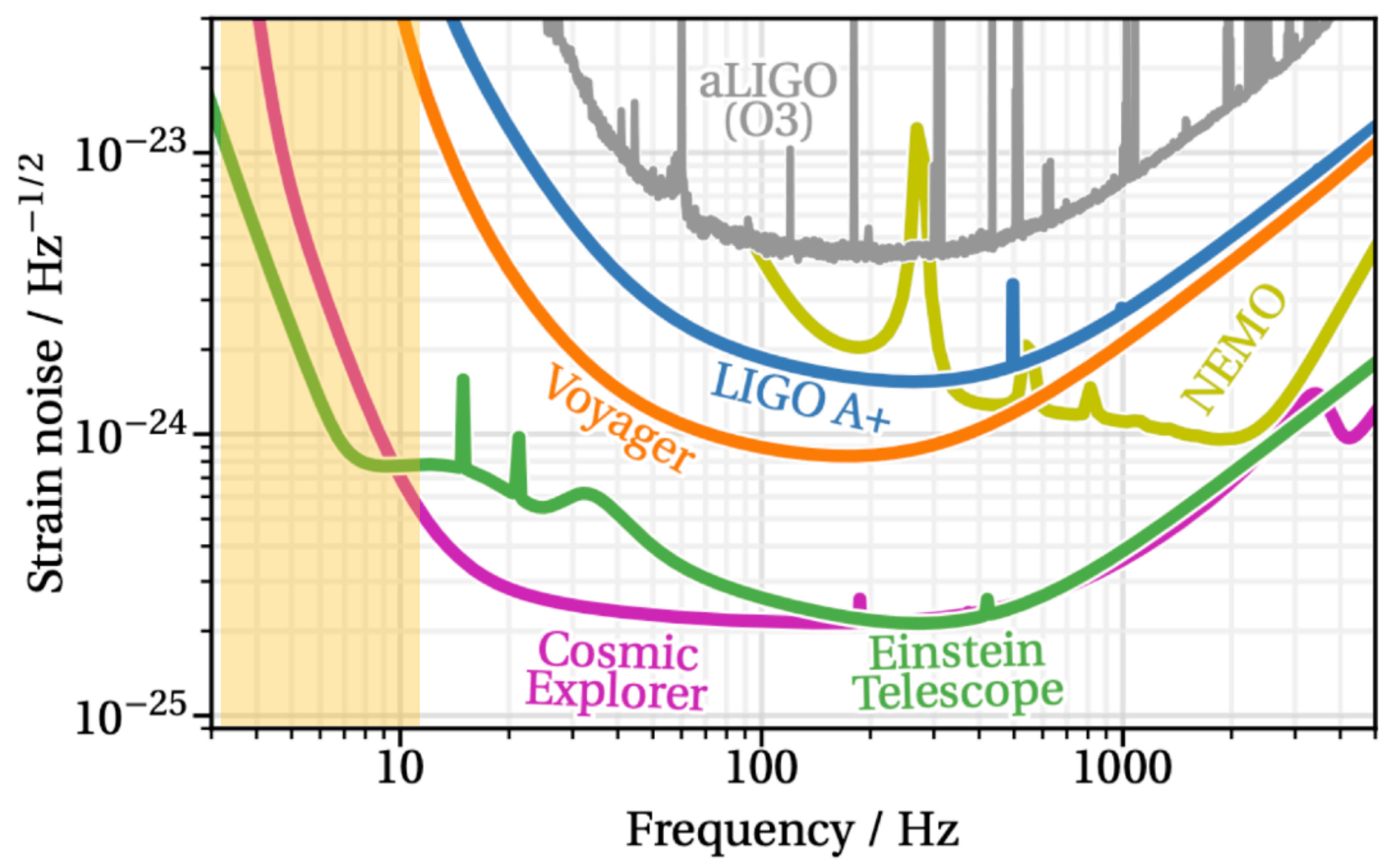
The 3G interferometers: Cosmic Explorer and Einstein Telescope will open an entire new window

- Broader frequency range, OoM sensitivity improvement
- Detections **get boosted** as CBC population peak is reached (z~2)
- Better sensitivity to **BNS during their inspiring phase if 3Gen secures <10Hz!**



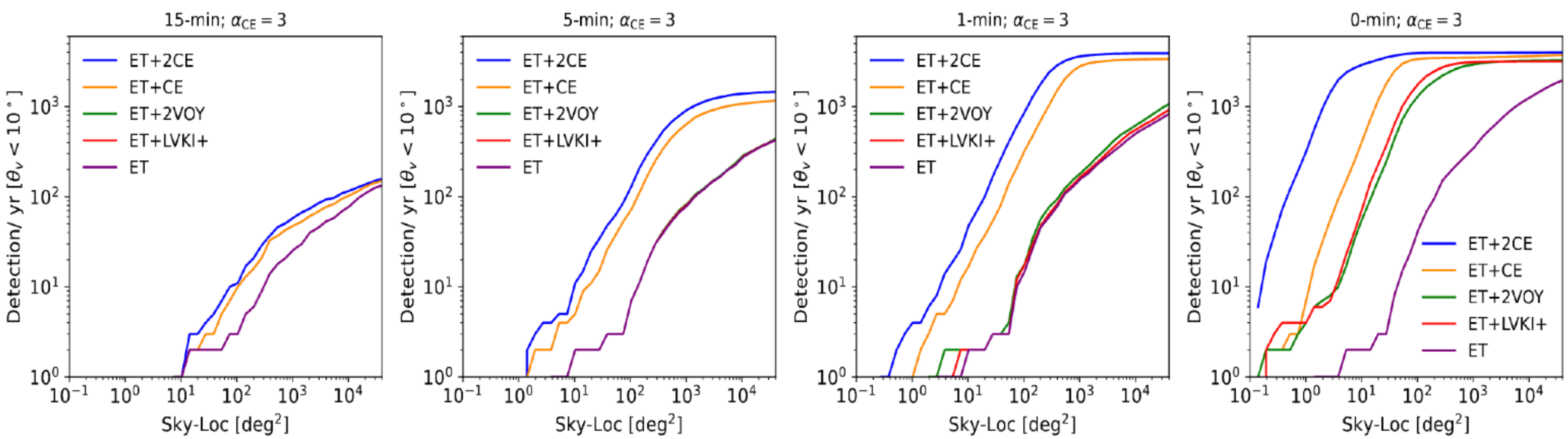
cosmicexplorer.org



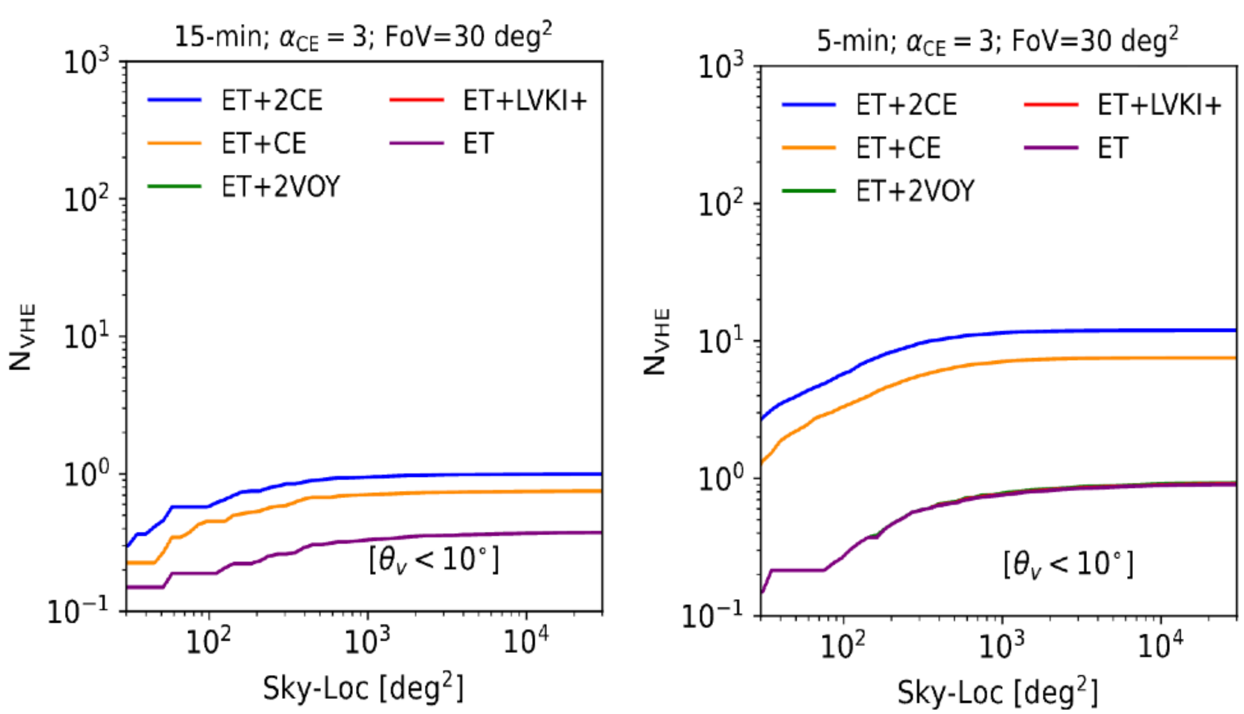


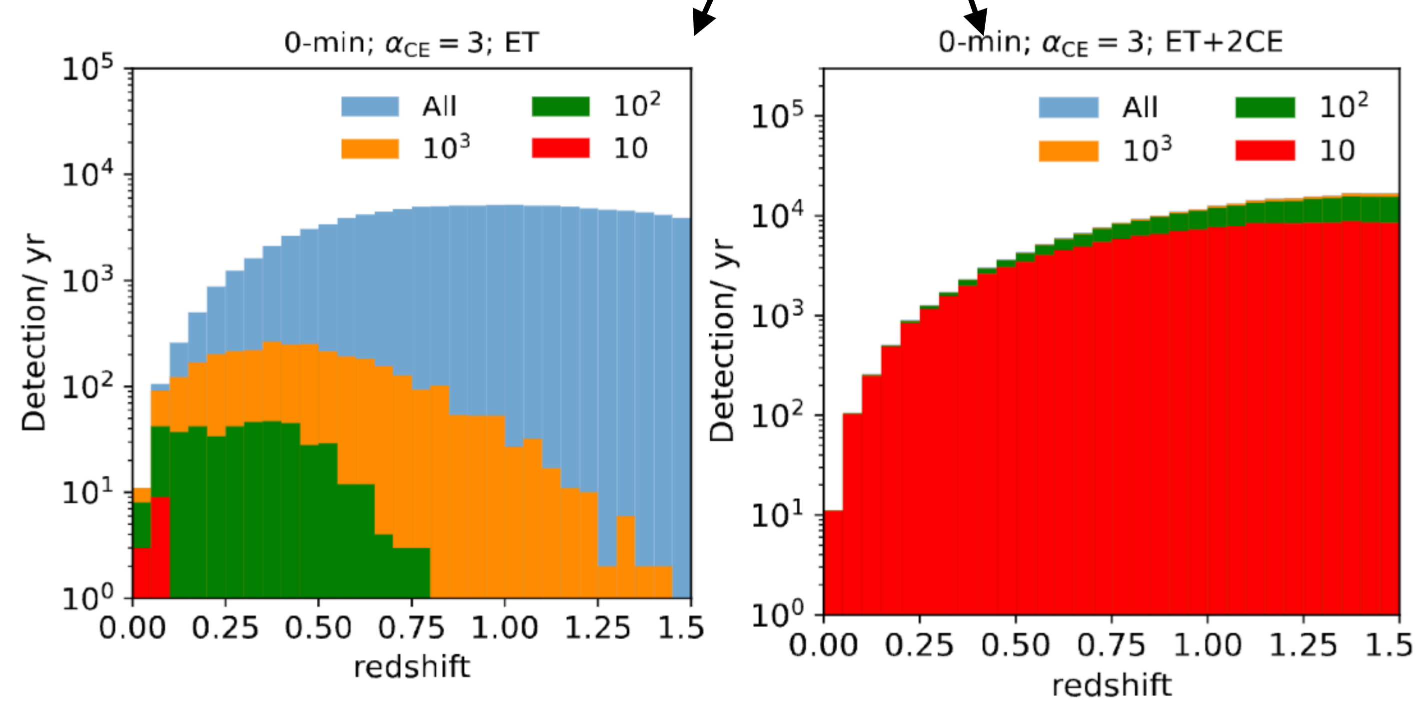
Detections in the future years with ET-CTAO

The prospects if we consider EW detections: **observation could start as soon as t-to= -15 min**



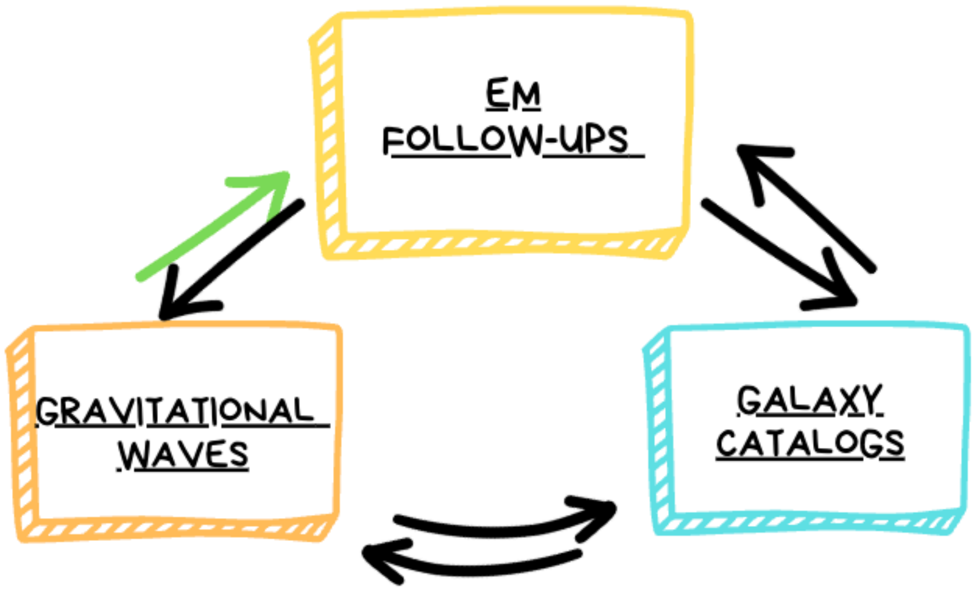
- Results with various ITF configurations + CTAO (~LST coverage, ~MST coverage)
  - Further opportunities considering CTAO sub-arrays, or divergent pointing





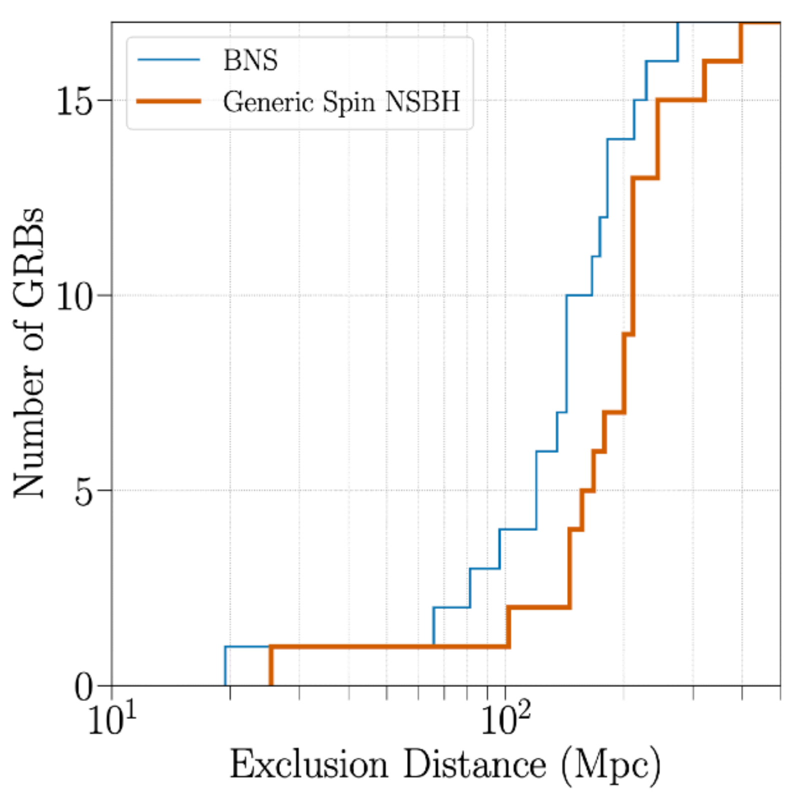
Banerjee, B., et al.: A&A 678, A126 (2023)

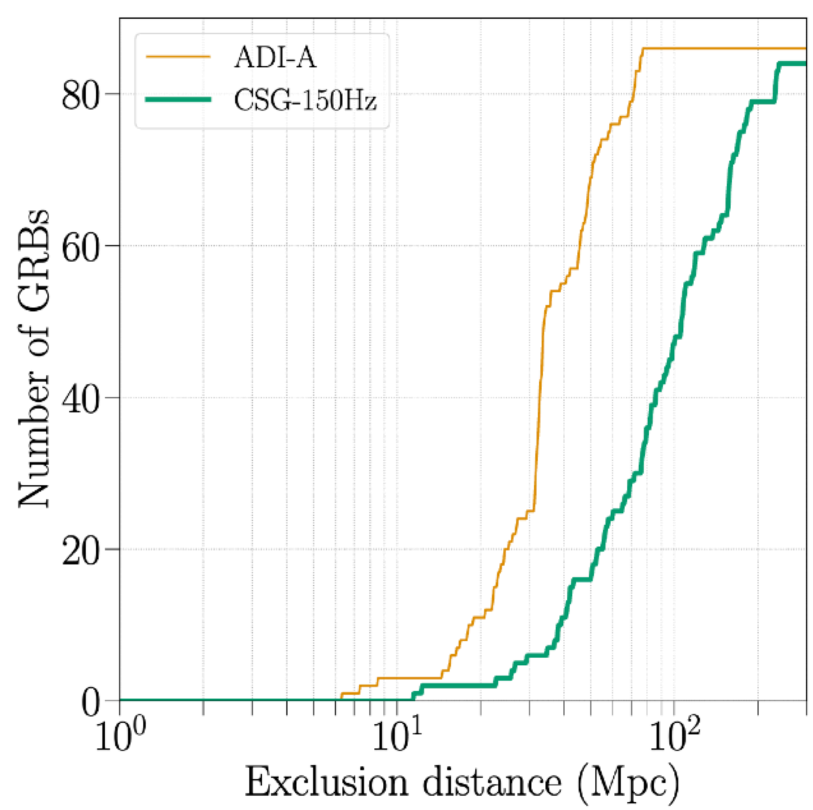
Counterpart of GRB searches in GW (GWTC-3 results)

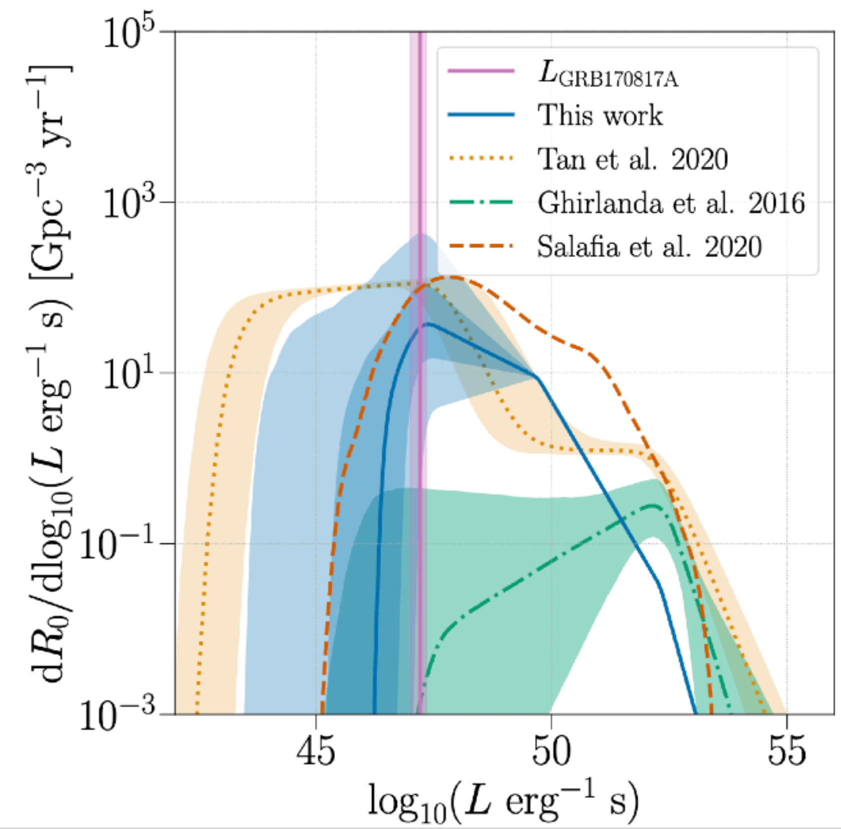


- GRBs Detected by Fermi and Swift During the LIGO-Virgo Run **O3b (Fermi GBM & Swift BAT)**
  - 86 GRBs=>search: accretion disk instability, circular sine–Gaussian@ 150Hz
  - 17 sGRB/ambiguous GRBs => search BNS/NSBH matched-filtering
- No significant identification, still compatible with expected rate (0.07–1.80 yr Fermi-GBM + GW) => exclusion distance derived
- Put constraints on the **GRB population** from the lack of detections

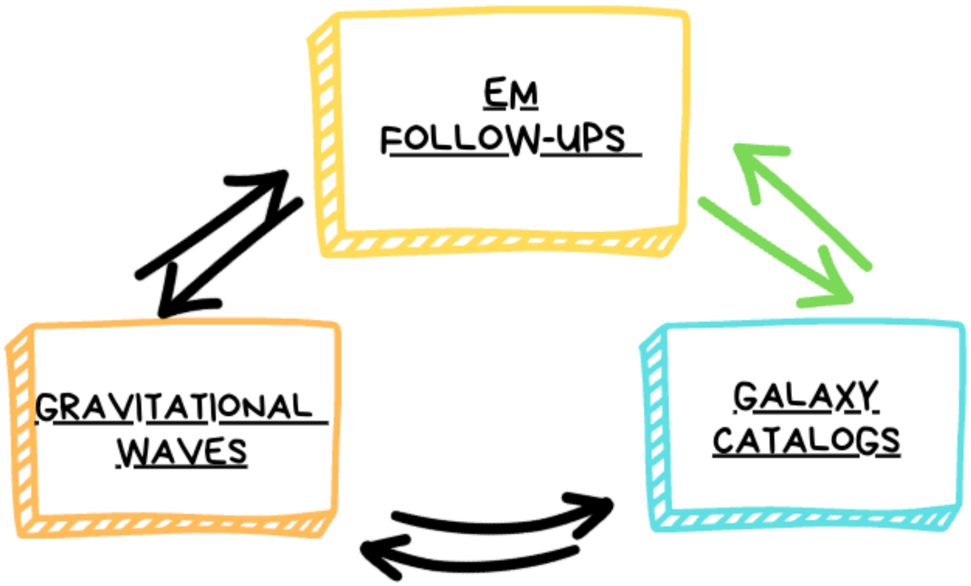
ApJ. 928 (2022) 2, 186







Using Galaxy Catalog info in Counterpart Searches

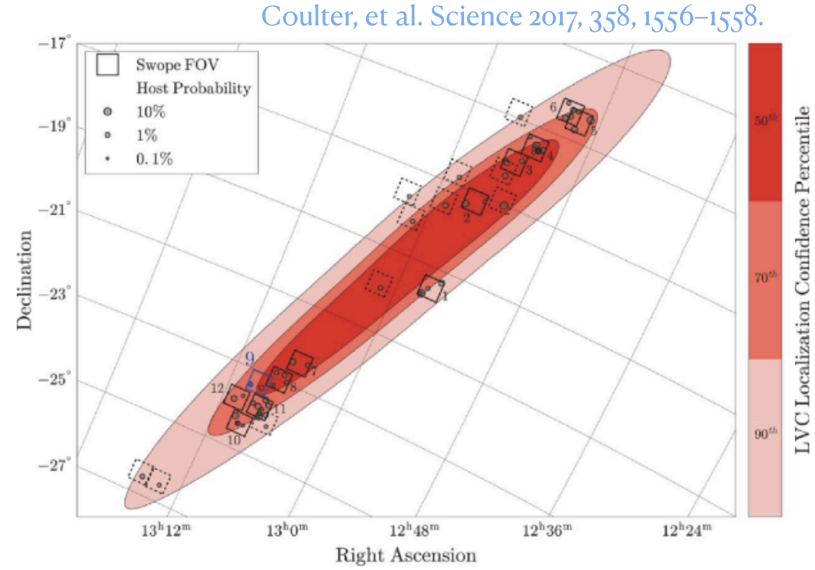


- Using galaxy catalog in **BNS**
  => source found!

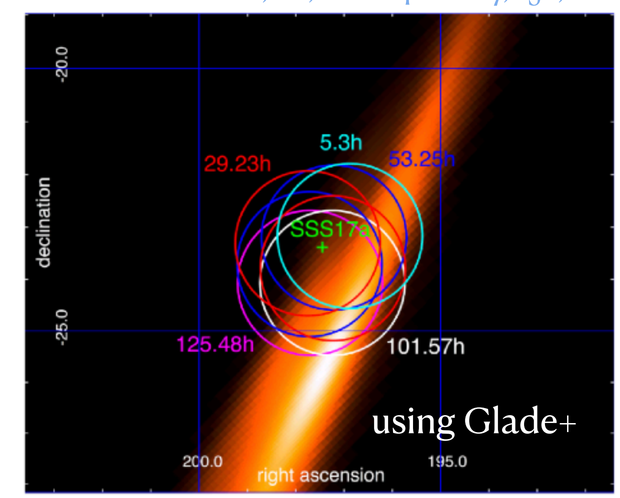
$$\frac{dP}{dV} = \rho_i \frac{N_{pix}}{4\pi} \frac{\hat{N}_i}{\sqrt{2\pi}\hat{\sigma}_i} \exp\left[-\frac{(r-\hat{\mu}_i)^2}{2\hat{\sigma}_i^2}\right]$$

Singer, et al., *ApJL* 829.1 (2016): L15

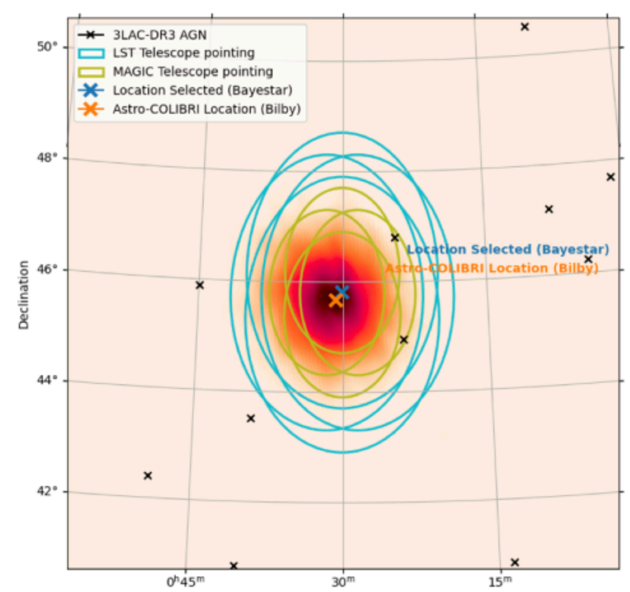
Coulter, et al. Science 2017, 358, 1556–1558.



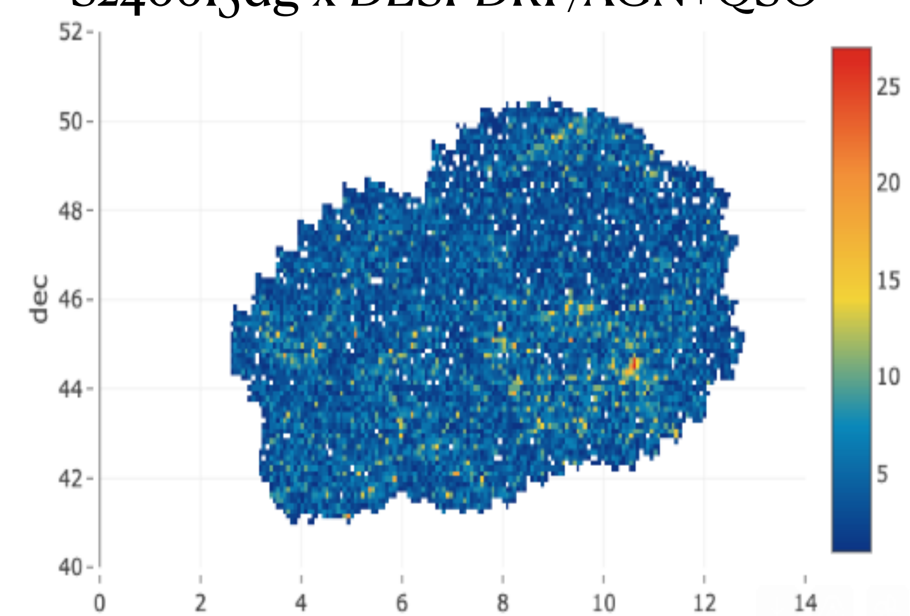
Abdalla, SA, et al. ApJL 2017, 850, L22



- Using galaxy catalog in **BBH and NSBH: Completeness of galaxy catalogs gets increasingly relevant!** NSBH >> Mpc scales, BBHs at Gpc!
  - The LST-1 + MAGIC campaign on S240615dg during O4: sub-deg 90% C.R. BBH
  - EM emission from BBH in AGNs? Kicked remnants? Claims by ZTF in the past S190521 (PRL 124.25 (2020): 251102) ZTF19abanrhr: AGN J124942.3+344929 at z = 0.438

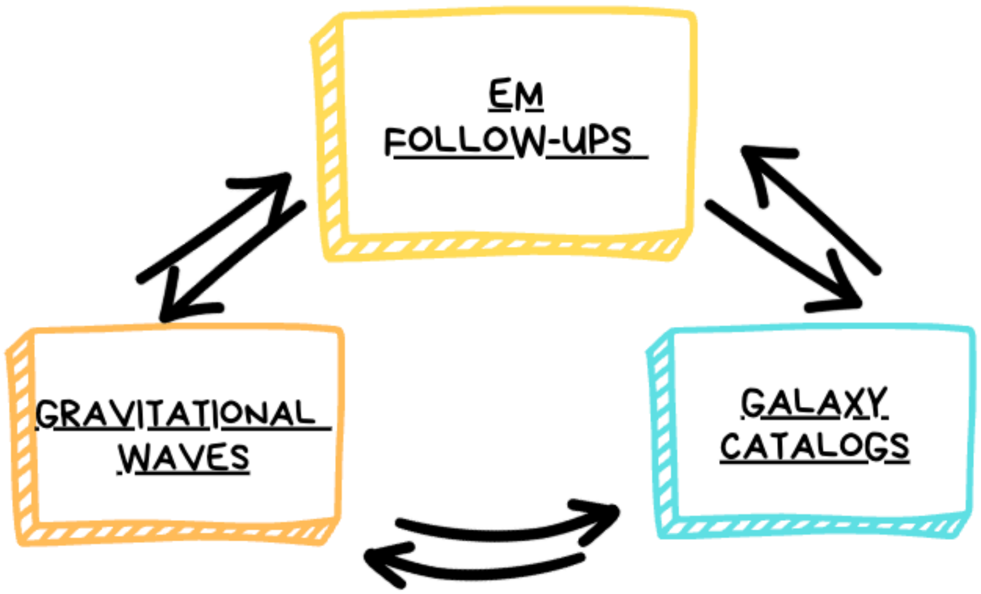


S240615dg x DESI-DR1 /AGN+QSO



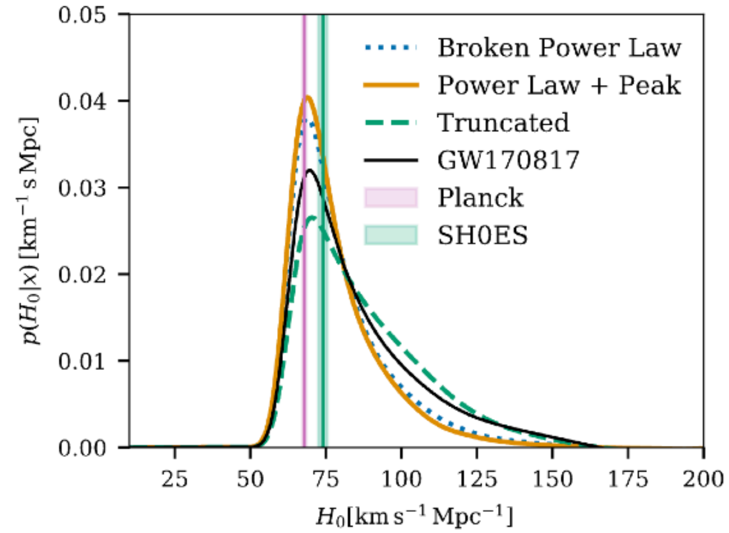
Jimenez, J., MSA, et al, in prep

Galaxy catalogs and Gravitational Waves (+EM)



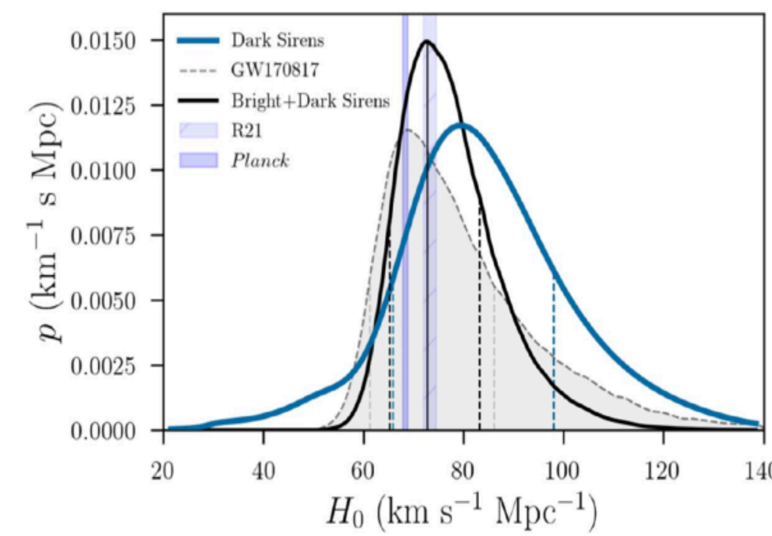
- GW+Galaxy catalogs are used for cosmology using bright sirens, dark sirens (and spectral sirens)

Hubble constant with GWTC-3



ApJ 949 (2023) 2, 76

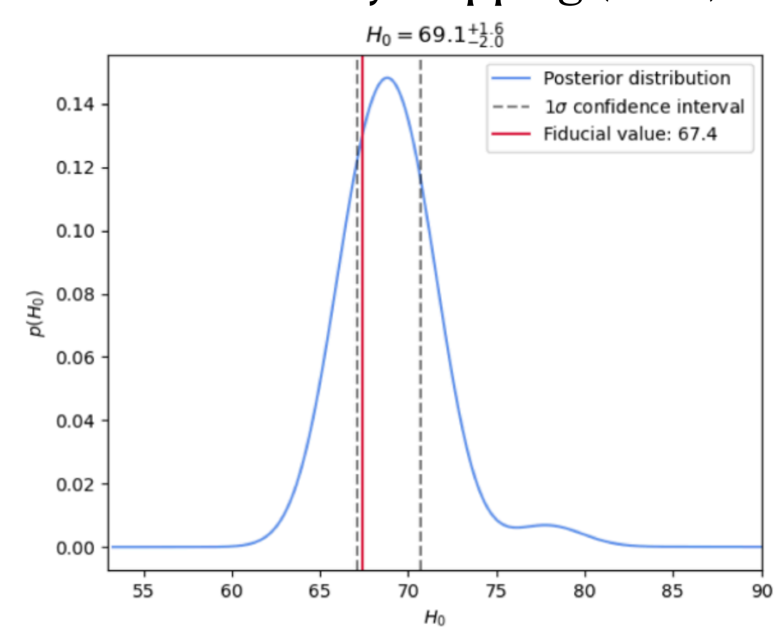
From DESI-DR1



Palmese, ApJ 943:56 (12pp), 2023

- **Other probes complementary to galaxy catalogs?**
- Line Intensity Mapping as an emerging approach
  - HI : 21 cm hyperfine line emission from neutral hydrogen
  - Tracer of large -scale sctructure, connected to the distribution of CBCs host galaxies
- See Nanadoumgar-Lacroze, D. et al, PoS Moriond 2025 for first results using MeerKat simulations +GWTC3 -like BBHs

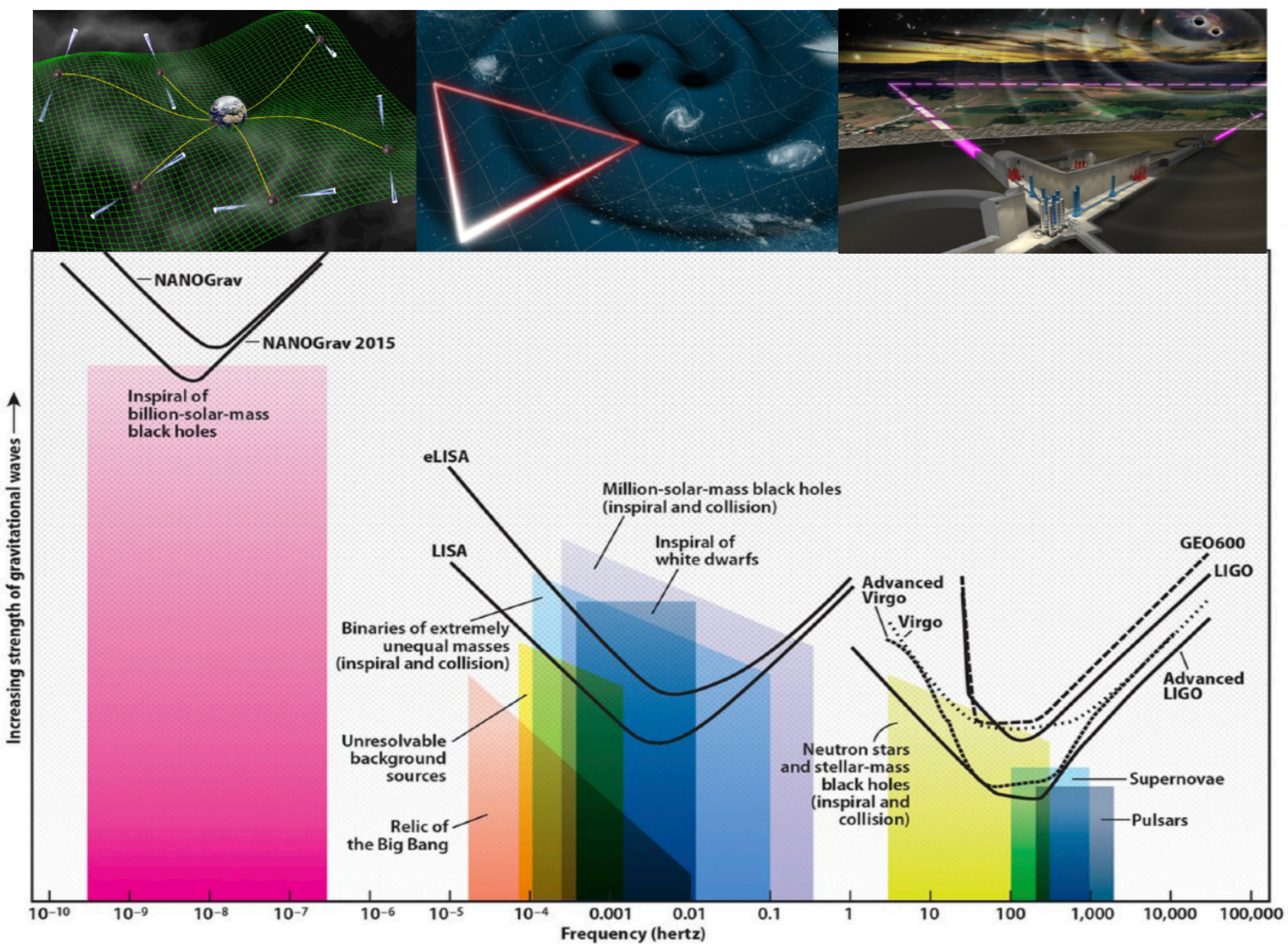
HI intensity mapping (21cm)

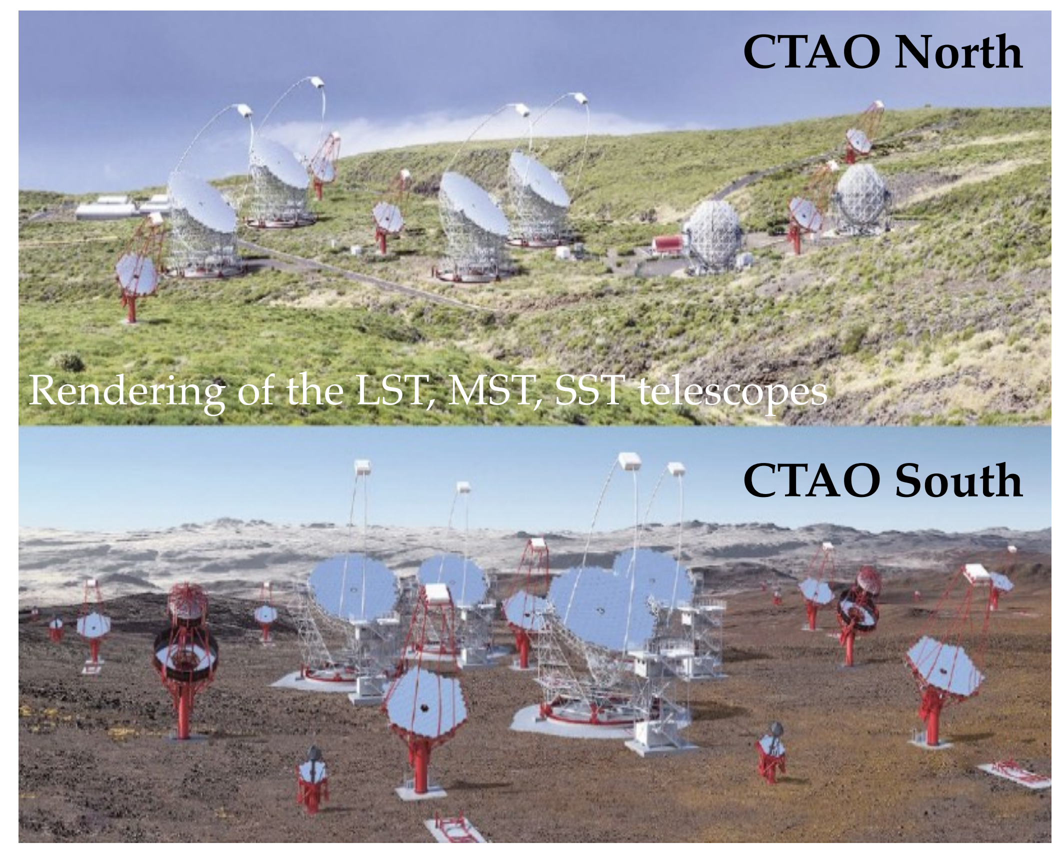


Nanadoumgar-Lacroze, D. et al, PoS Moriond 2025

The future ahead of us

- **The field is just at a starting stage!**
- >10 Hz: Observing Run O5 expected to start in ~2-3 years. ET site selection soonish?
- < 10Hz: gw- electromagnetic **multi messenger stage is set for other GW frequencies**
  - LISA-EM: galactic binaries, EMRI,/ TDEs /AGN flares?
- Gamma ray sky with CTAO: ~mCrab sensitivities, reach of z~2-4 thanks to the LSTs





Back-up