Status and future perspectives of the European EM follow-up of GW sources

Maria Grazia Bernardini

INAF-OAB, Merate, Italy

GW6: Gravitational kHz waves - LIGO-Virgo-KAGRA @MG17
Pescara, 11 July 2024

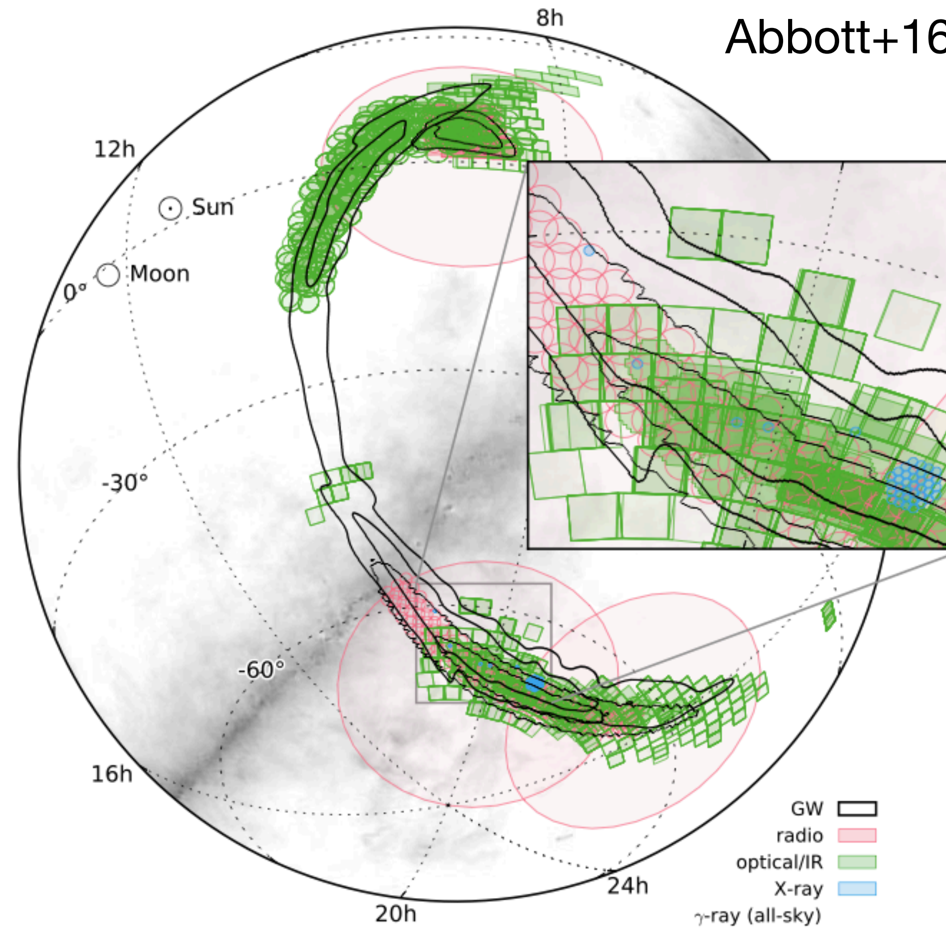
Credit: NSF/LIGO/Sonoma State University/ A. Simonnet

The dawn of the GW astronomy: GW 150914

Two possible strategies:

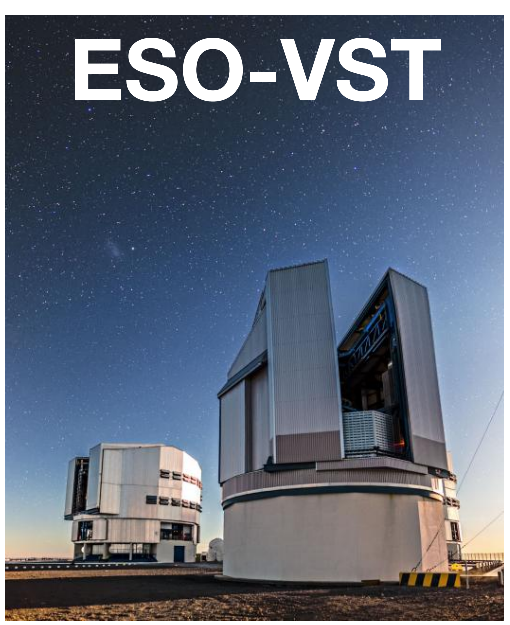
- targeted search
- **wide-field search** (skymap ~ **600 deg²**):
  - **FAST**: 23h after alert
  - **WIDE:** 90 deg^2 of large contained probability
  - **DEEP**: r_{lim}~22.5 mag

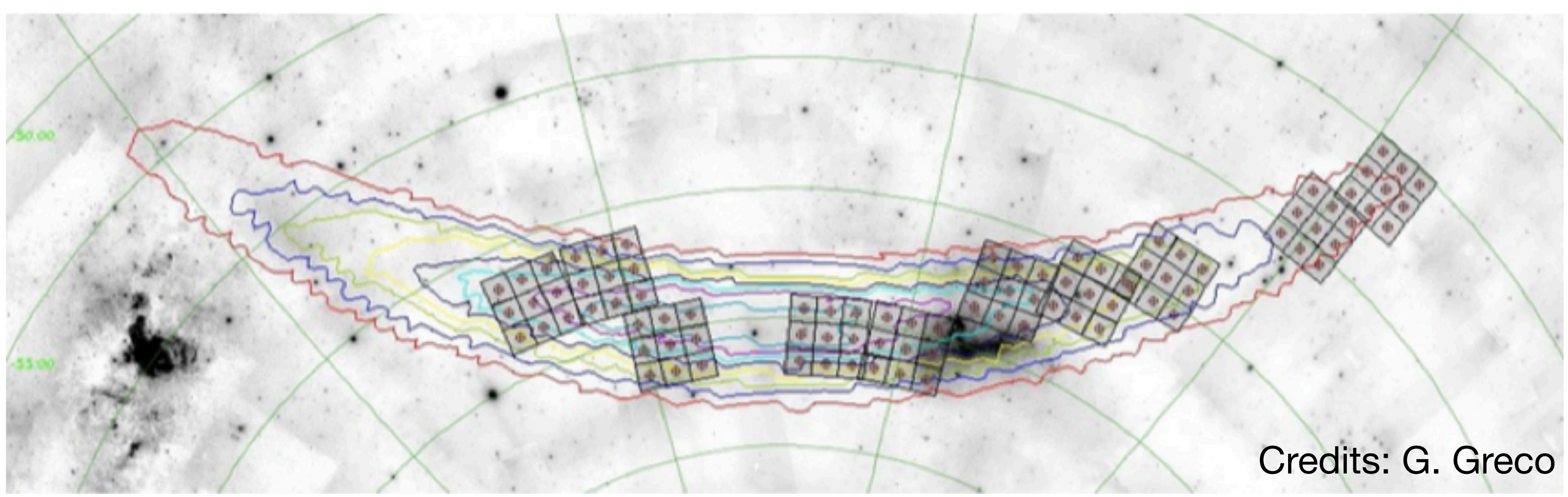
Brocato+17



Abbott+16

➡**no electromagnetic (EM) counterpart found (but none expected)**





Credits: G. Greco

When do we expect to have and EM counterpart?

BBH merger

Merger with at least one NS (BNS or NSBH)

1. Gamma-ray bursts (GRBs)

SGRBs:

merging of compact objects
(NS-NS or NS-BH)

✓ diverse merging times:

➡mix of early and late type galaxies

✓ kicks/migration from their birth sites:

➡offset

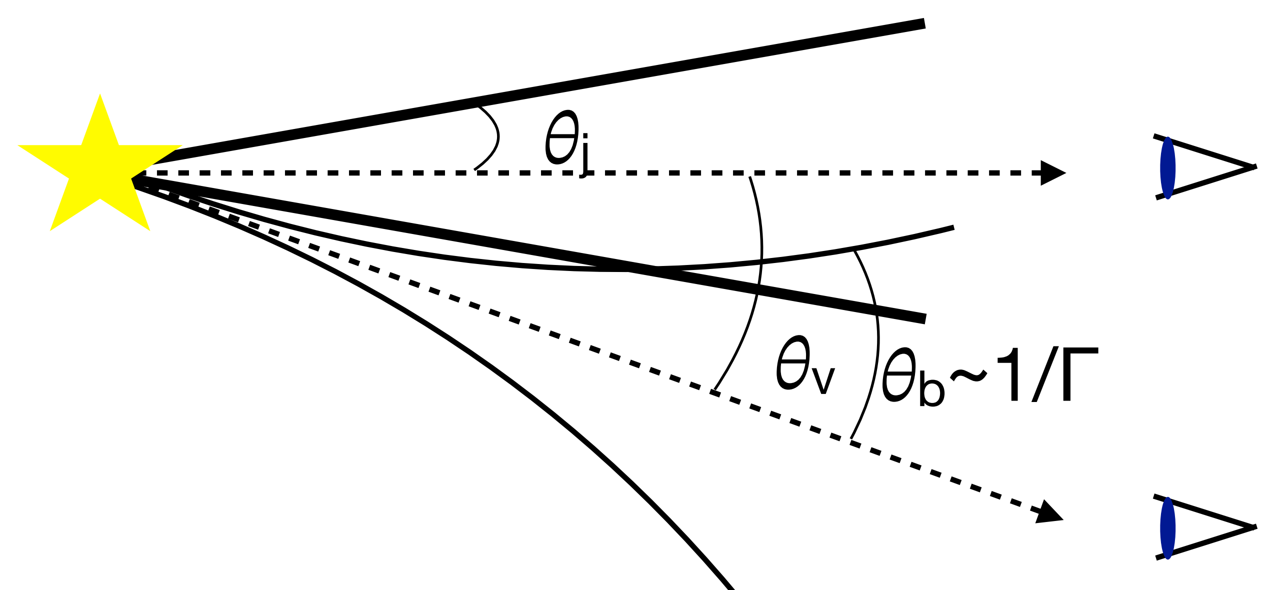
➡no correlation with UV light of their host galaxies

➡diversity of their environment

✓ no supernova associated

– Collimated emission, rare event

Typical jet angles for SGRBs:
θ_j ~5^o-15^o (Fong+15)



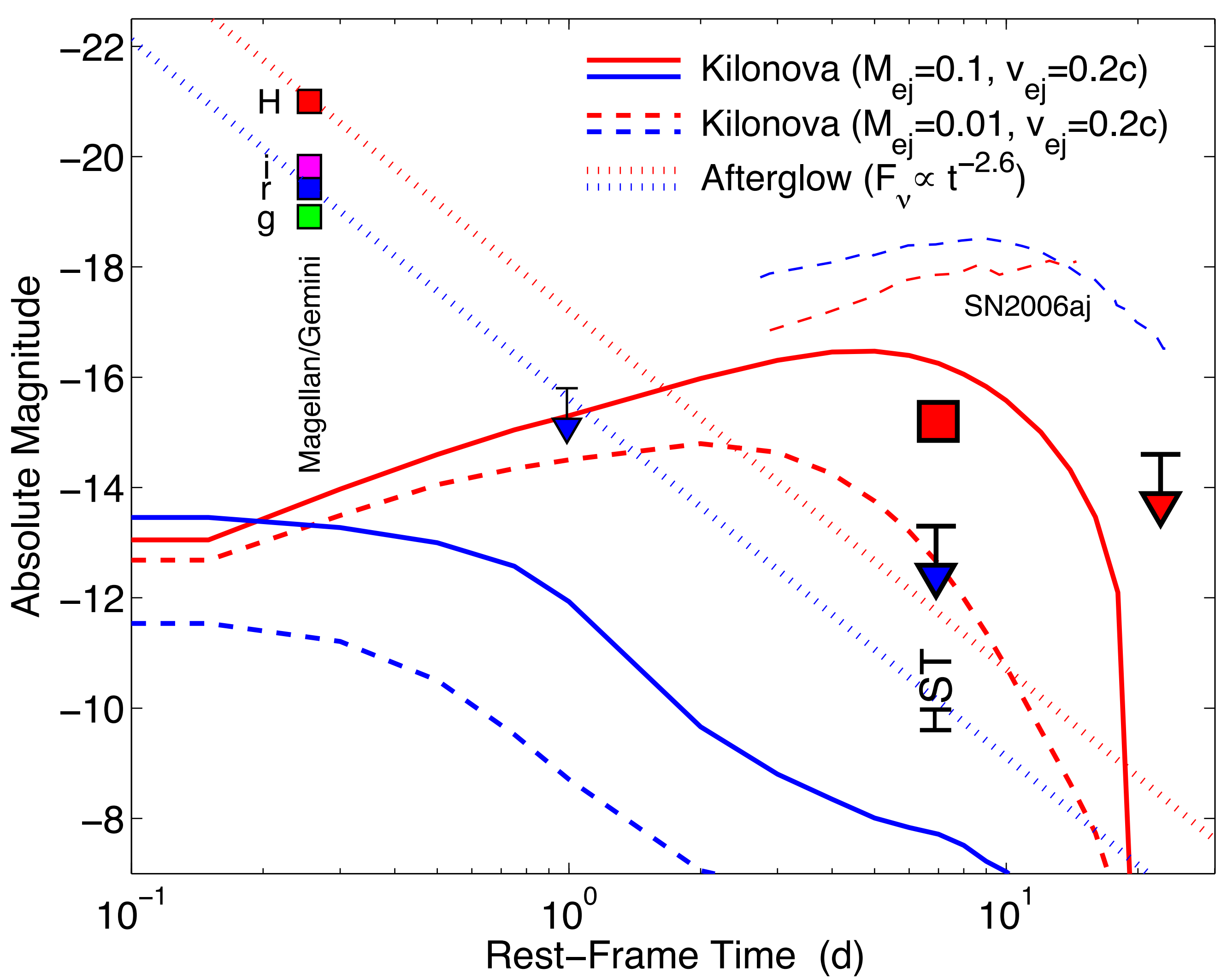
Fong+13, Berger14

2. Kilonova

Optical/infrared isotropic transient produced in the merger of two NSs, powered by radioactive decay of neutron-rich species synthesized in the merger

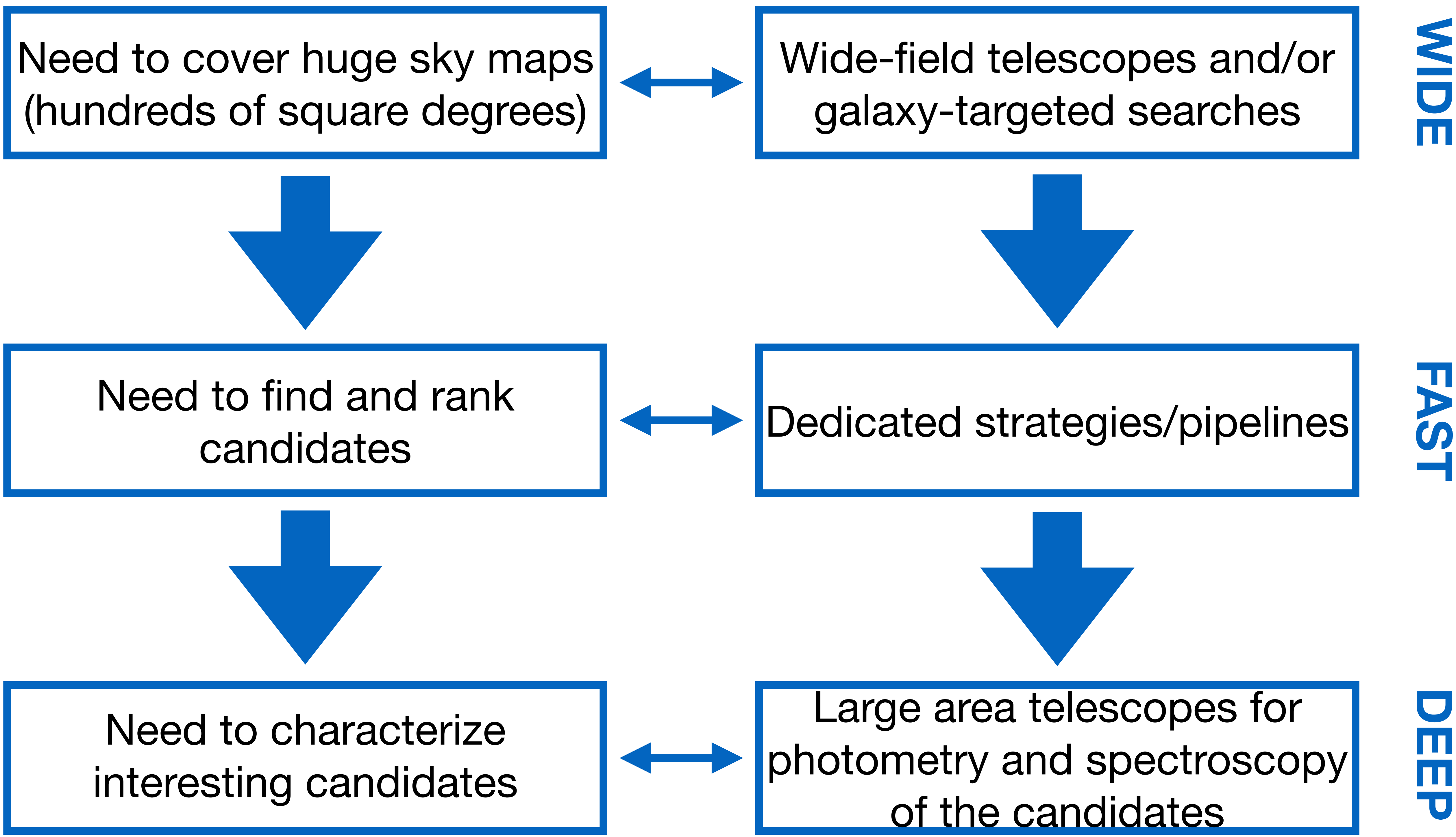
- 10^{-4}-10^{-2} M_{sun} of ejecta at high velocities (0.1-0.3 c) undergo rapid neutron capture (**r-processes**) leading to heavy elements
- **necessary to explain abundances of heavy elements**

Berger+13



- large uncertainty in the composition of the materials leads to various expected colours, duration (a few days) and luminosities (~10^{40} erg/s)
- **previous observational evidences based on chromatic excesses in short GRB afterglows** (e.g. GRB 130603B, GRB 060614, GRB 050709)

Follow-up strategy



GraWITA: the GRAWitational Inaf TeAm

WG1
24h/7d OPERATIONS

P. D'Avanzo

WG2
WIDE FIELD SEARCH

F. Getman

WG3
CHARACTERISATION AND FOLLOW-UP (Opt & NIR)

A. Melandri

Science Board
E. Brocato (PI)

M.G. Bernardini, M. Branchesi, E. Cappellaro, A. Grado, E. Palazzi, A. Possenti

WG4
RADIO FOLLOW-UP

M. Giroletti

WG5
HIGH ENERGY PROMPT & FOLLOW-UP

A. Bulgarelli

WG6
THEORY

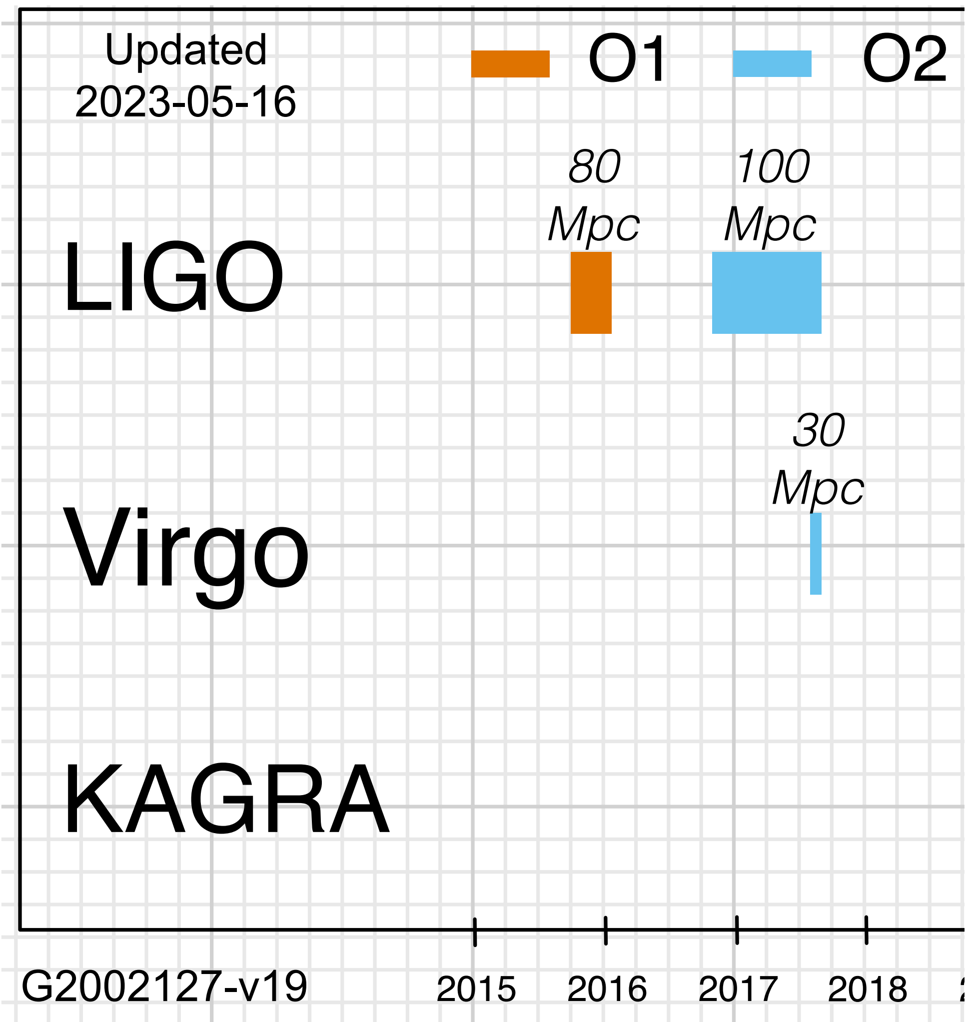
R. Ciolfi

WG7
ARCHIVING & WEB

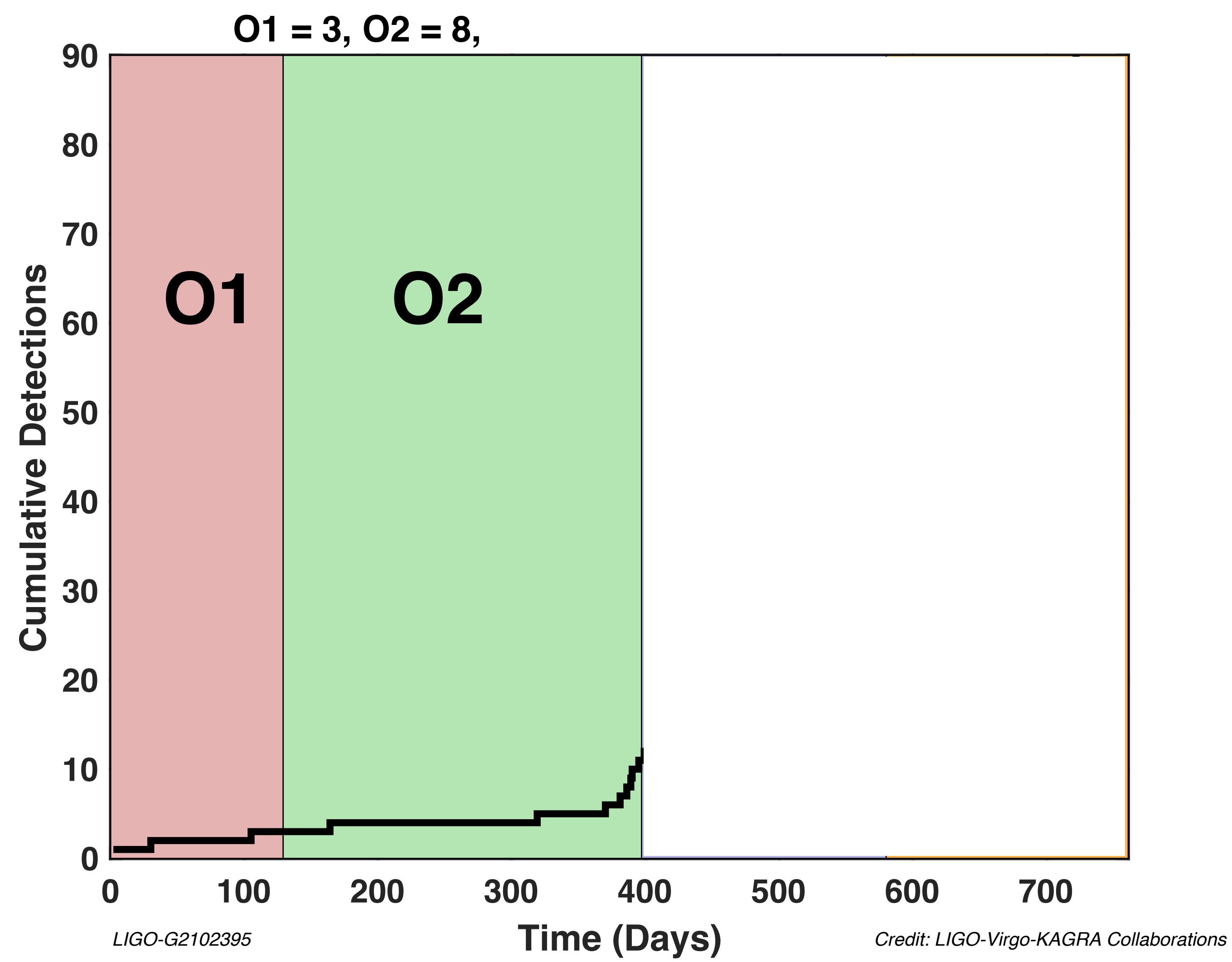
L. Nicastro

~ 100 scientists from 21 Institutes (INAF + Universities)
Active since O1
+
Coordination with AGILE, Fermi, INTEGRAL & Swift INAF research teams (Super-GRAWITA, since O3)

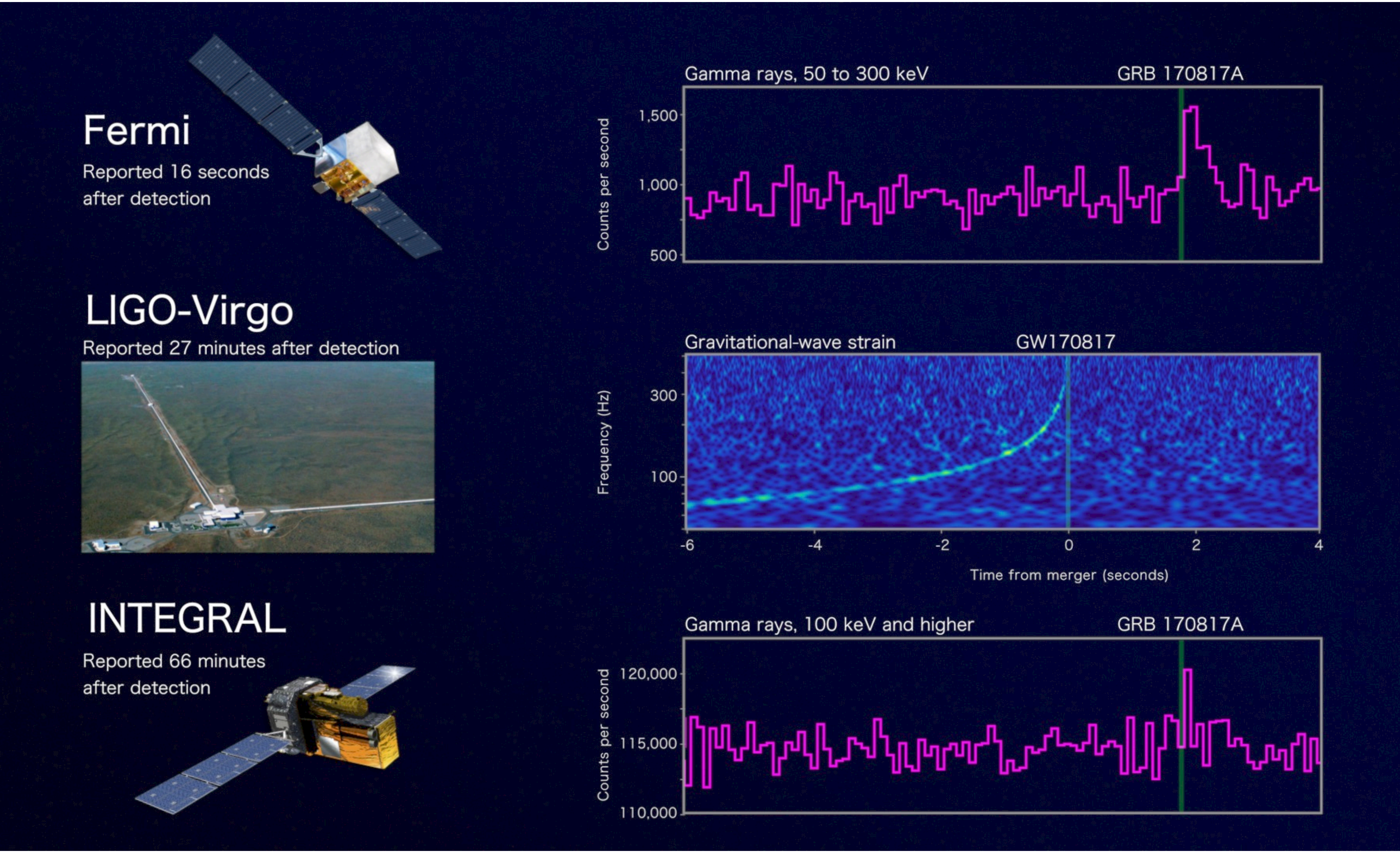
LVK observing runs: O1 and O2 (4+8 months)



- Alerts released via MoU
- Virgo joins during the last month
- 11 events (GWTC-1: 10 BBH, **1 BNS**)



GW 170817/GRB 170817A

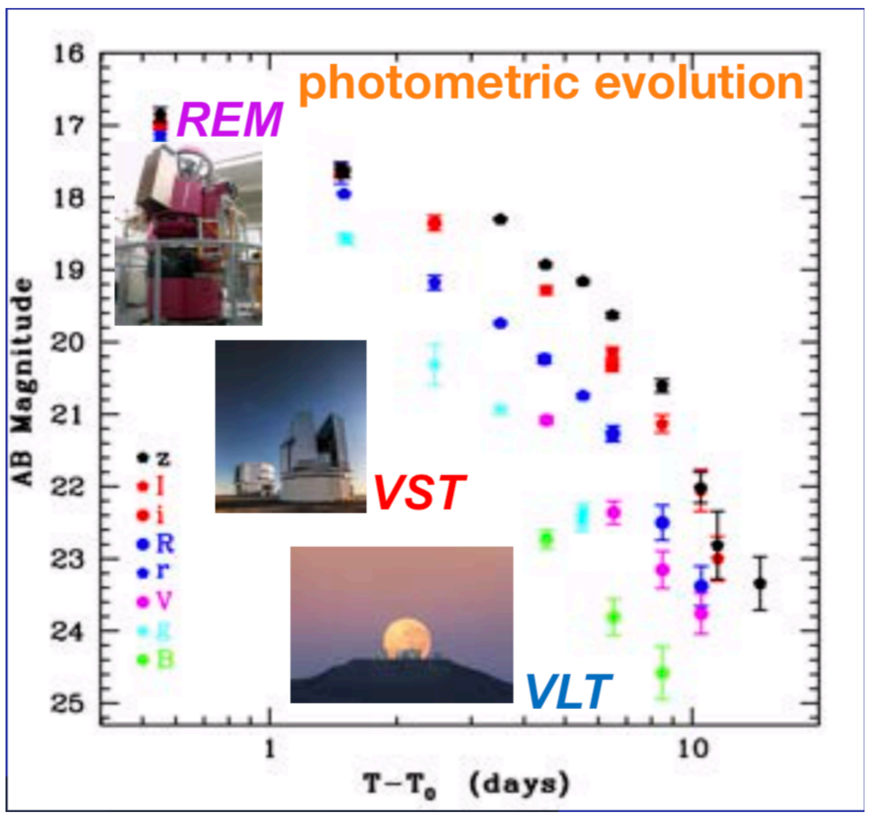


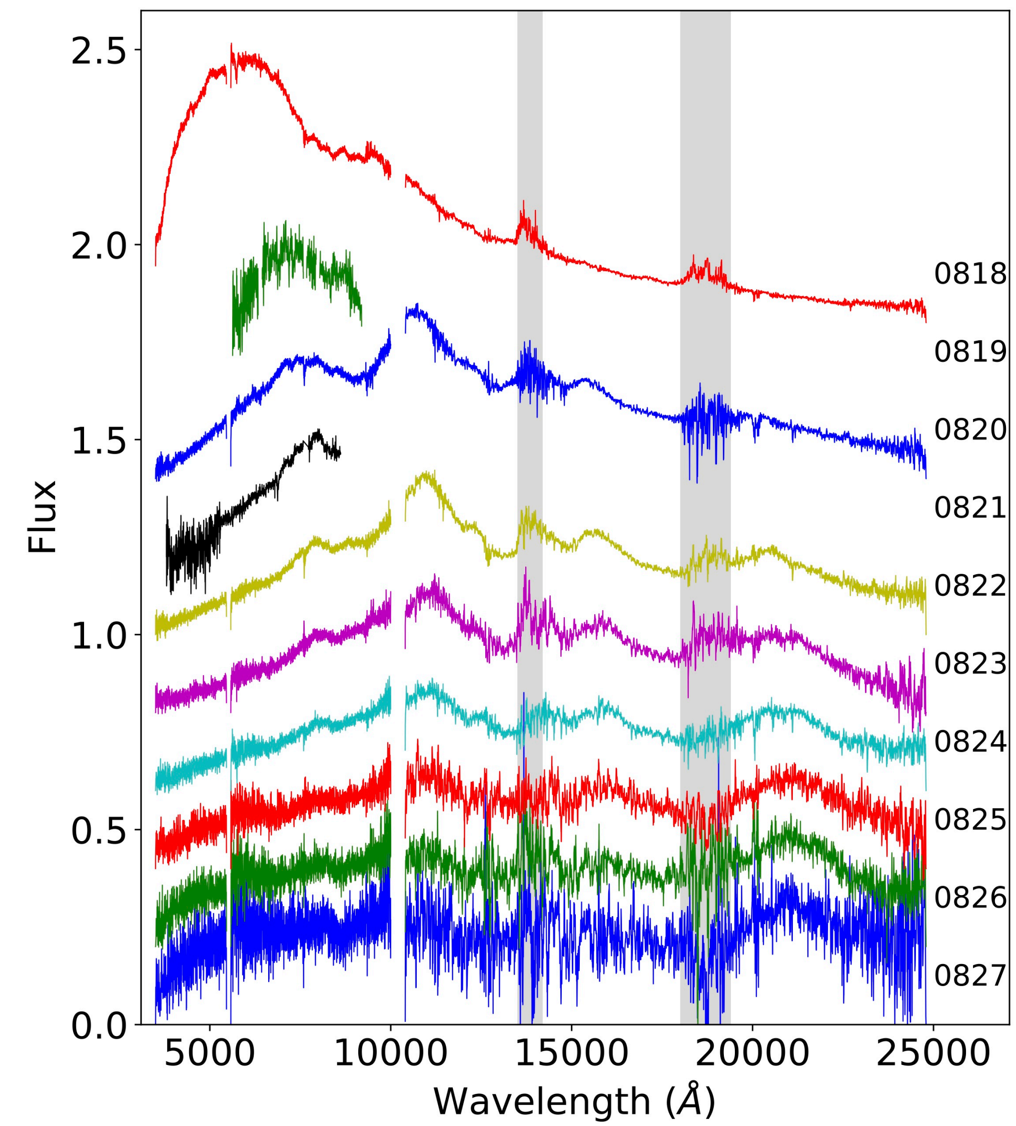
Abbott+17; Goldstein+17; Savchenko+17

AT 2017gfo, the first spectroscopically identified kilonova

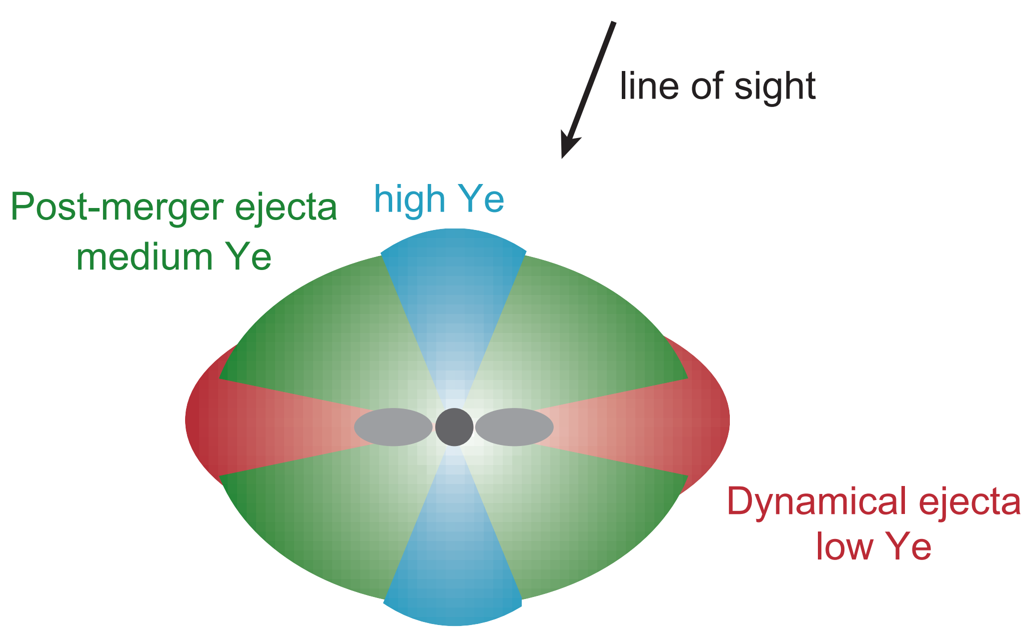
Pian, D'Avanzo+2017; Arcavi+17; Coulter+17; Evans+17; Lipunov+17; Smartt+17; Soares-Santos+17; Tanvir+17; Valenti+17, Lyman+17, Villar+17 and many many others

KN light curve





KN spectral sequence

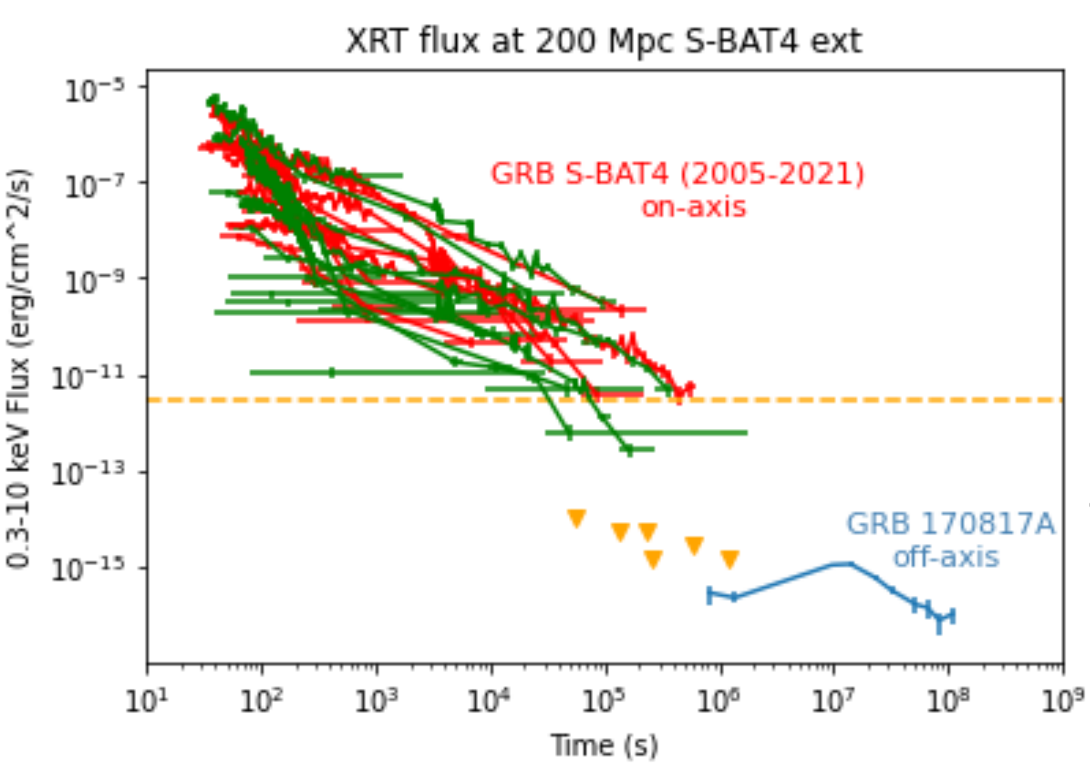


Three components kilonova model (with different velocity, mass and composition of the ejecta): 0.03-0.05 M_{sun} ejected mass, fast moving dynamical ejecta (0.2c) + slower wind (0.05c)

Tanaka+17

GRB 170817A: proof of the jet structure

Alexander+17,18; D'Avanzo+18; Dobie+18; Fong+19; Haggard+17; Hallinan+17; Hajela+19; Margutti+17,18; Mooley+18a,b; Reasmi+18; Ruan+18; Troja+18a,b,19,20; Ghirlanda+19; Piro+19; Margutti & Chornock 21 and many many others



Credit: M. Dinatolo (undergrad. Student)

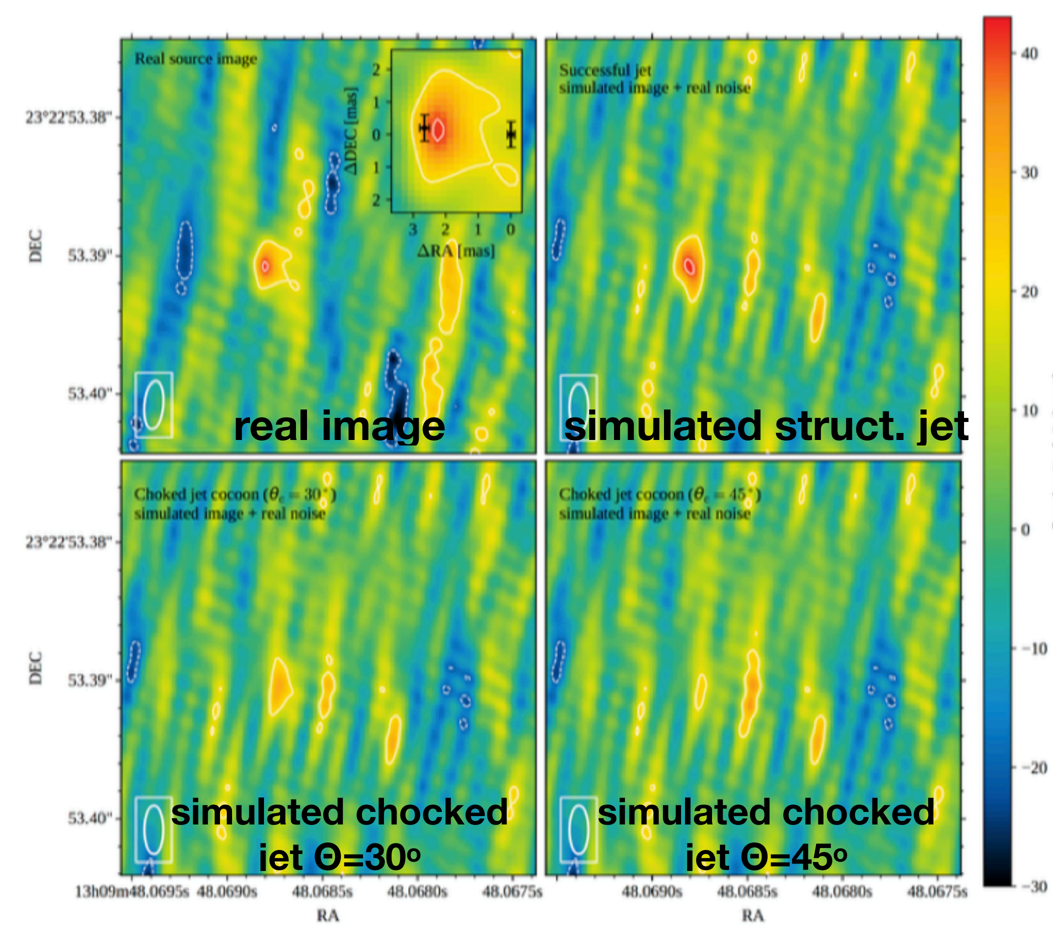
- X-ray and radio emission non detected until 9 days and peaking at ~100 days

➡**First GRB seen off-axis**

- Evidence of proper motion and measure of the source size with **VLBI** Ghirlanda+19, Mooley+18

➡**Final proof of the structured jet scenario**

Structured jet: relativistic core with $\theta_{jet} < 5$ deg and $\theta_{view} \sim 20$ deg



Ghirlanda, Salafia, ..,Bernardini+19

The birth of multi-messenger Astronomy with GWs

GW 170717 / GRB 170817A / AT2017gfo results:

- Definition and consolidation of successful follow-up strategies
- First GW EM counterpart (at all wavelengths)
- First unambiguous observational evidence for a kilonova
- Evidence for kilonovae as a heavy elements factory
- "Smoking gun" for short GRB progenitors
- Clues on short GRB outflow geometry and properties: first evidence for a structured jet
- Direct EM distance determination (cosmology)

Still a number of open issues:

- What about BH-NS EM counterparts?
- What is the origin of the blue KN component?
- Are KNe associated to every short GRB?
- How to unveil the nature of the NS-NS remnant?

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Search and follow-up European teams

www.pesto.org

www.star.le.ac.uk/nrt3/VINROUGE/

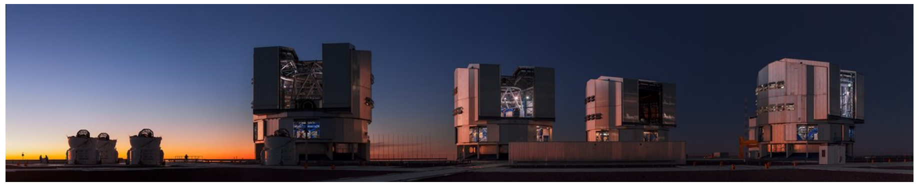
The **G**W **O**ptical **T**ransient **O**bserver **GOTO**
www.goto-observatory.org

www.grawita.inaf.it

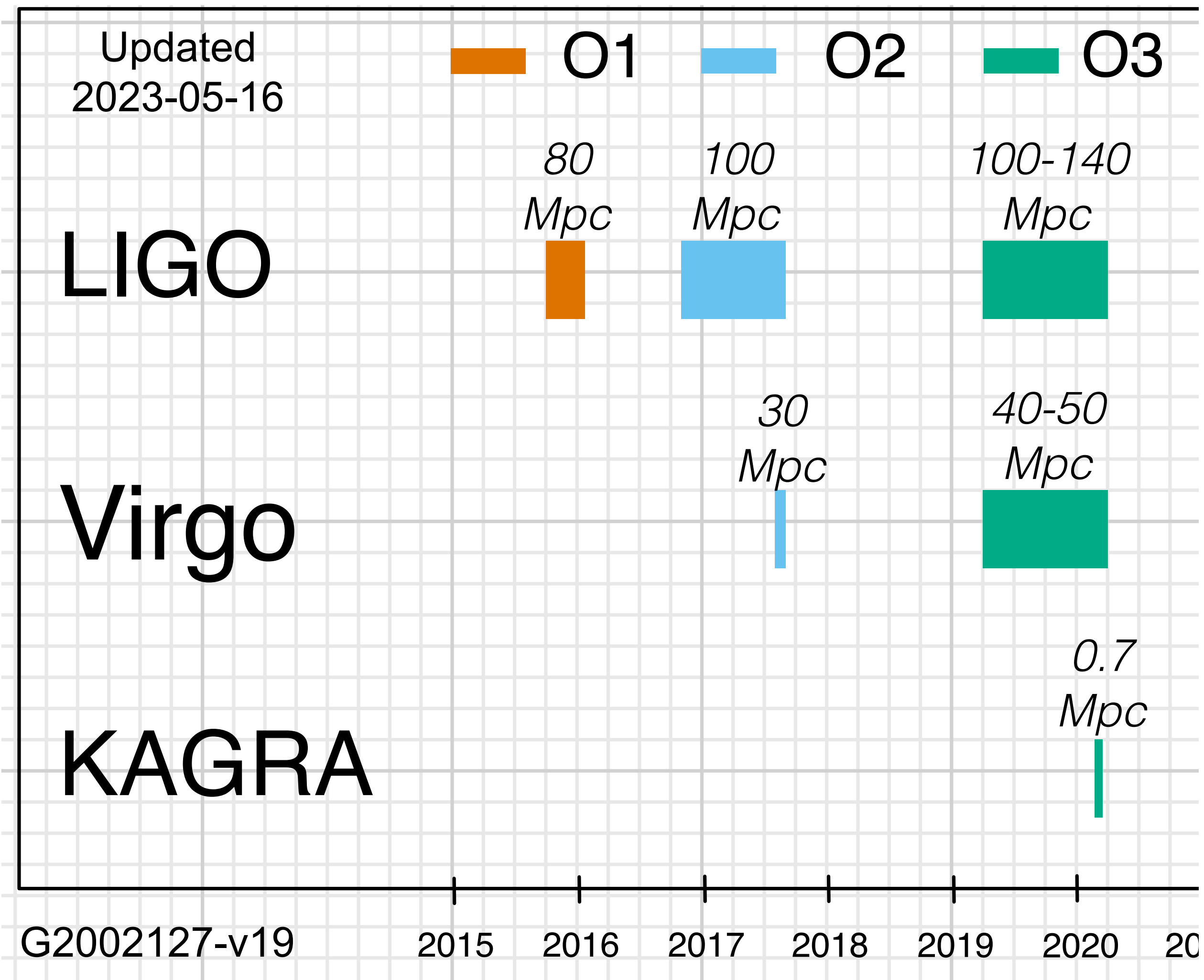
www.engrave-eso.org

Governing Council: M. Branchesi, E. Brocato, P. D'Avanzo, J. Hjorth, P. Jonker, E. Pian, S. Smartt, J. Sollerman, D. Steeghs, N. Tanvir (Chair).
Executive Committee: M. Fraser, A. Levan (Chair), K. Maguire, D. Malesani, O.S. Salafia, S. Vergani.

A collaboration of ~ 200 ESO scientists
Approved programs during O3 and O4. Time for EM counterparts **follow-up** on every useful **VLT** instrument + **ALMA, radio, HST** and **JWST**.

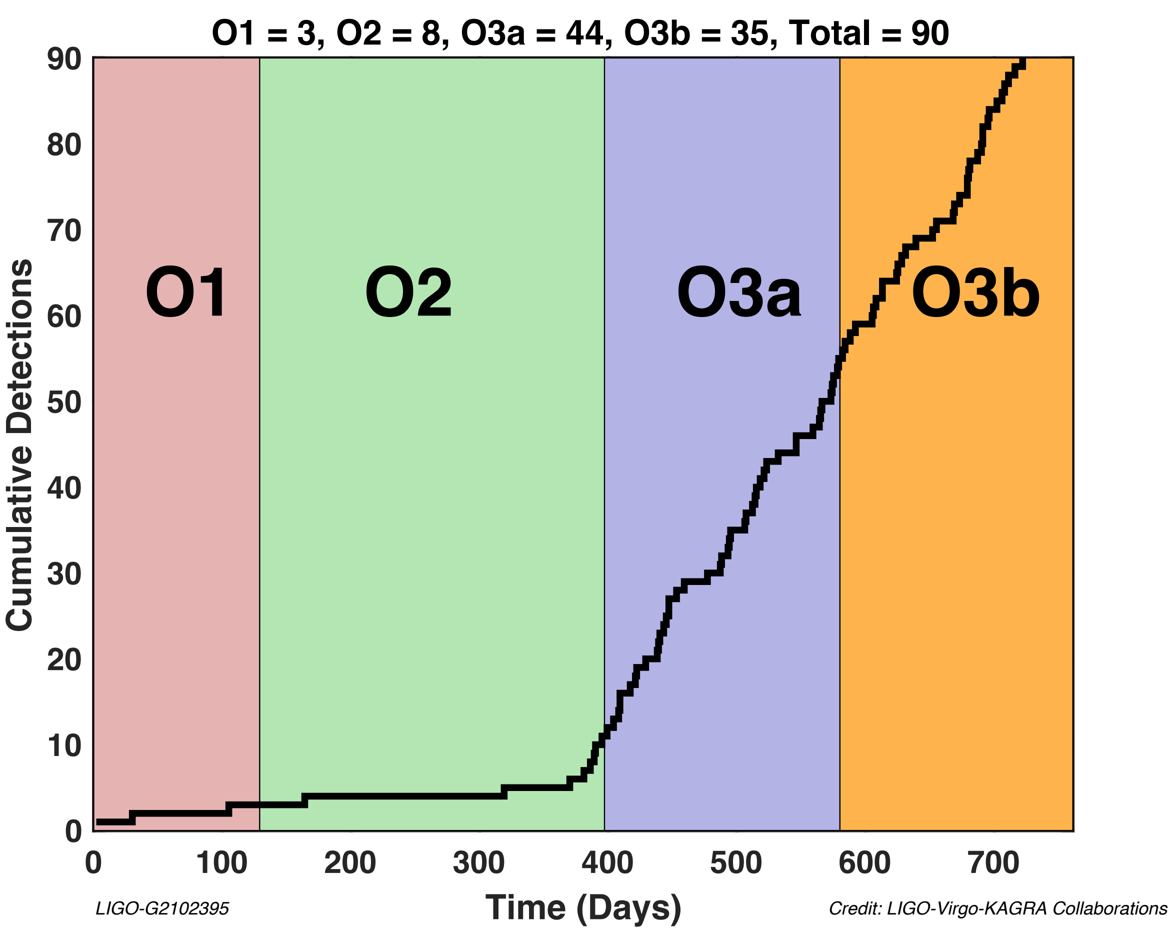


LVK observing runs: O3 (12 months)



- Improved sensitivity, volume increased
- Alerts publicly released
- 3 detectors
- Two sub-runs of 6 months, interrupted after 10 month due to COVID19 pandemics

- Overall, 90 candidates discovered (GWTC-3): mostly BBHs, some are NS-BH binaries and one BNS



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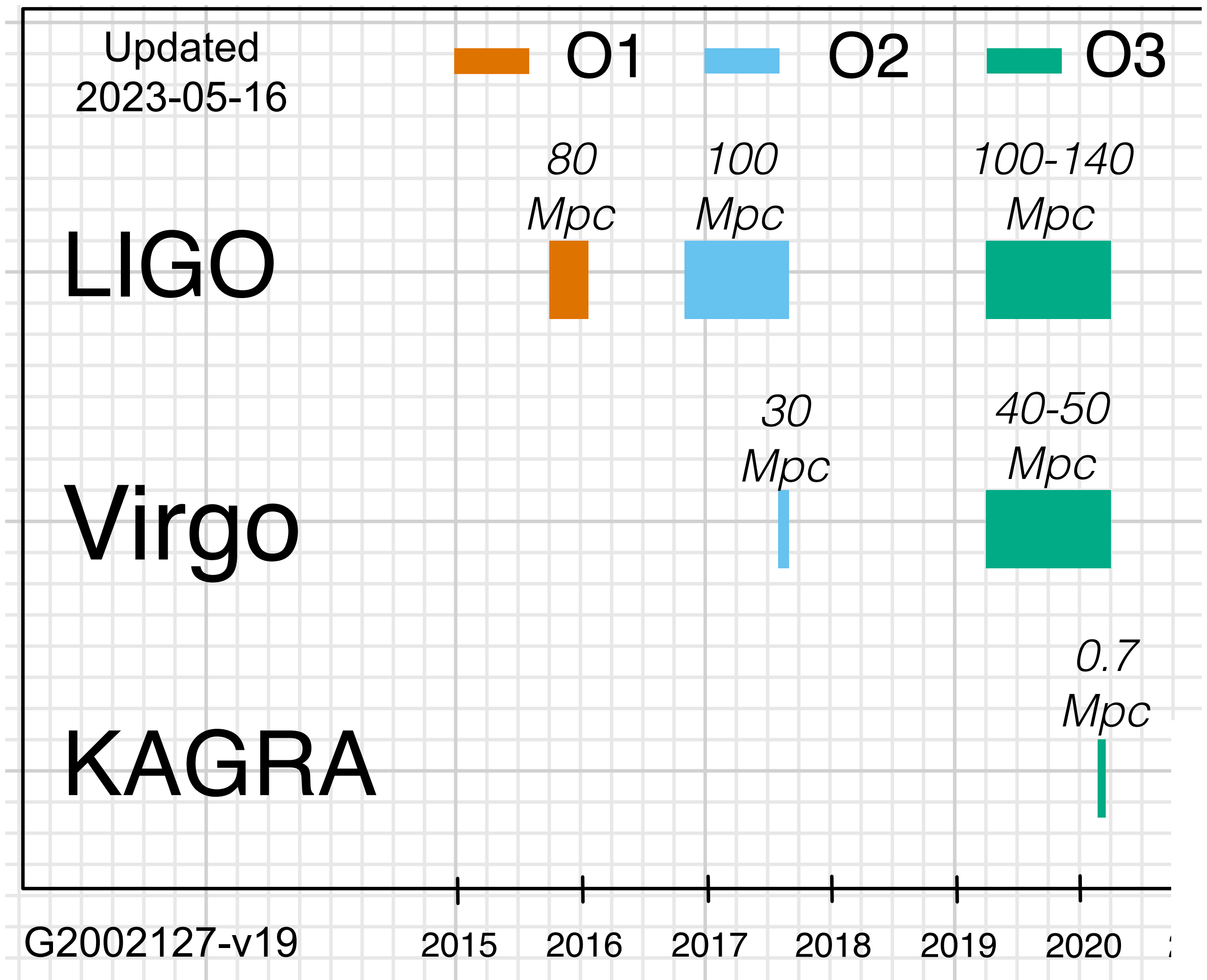

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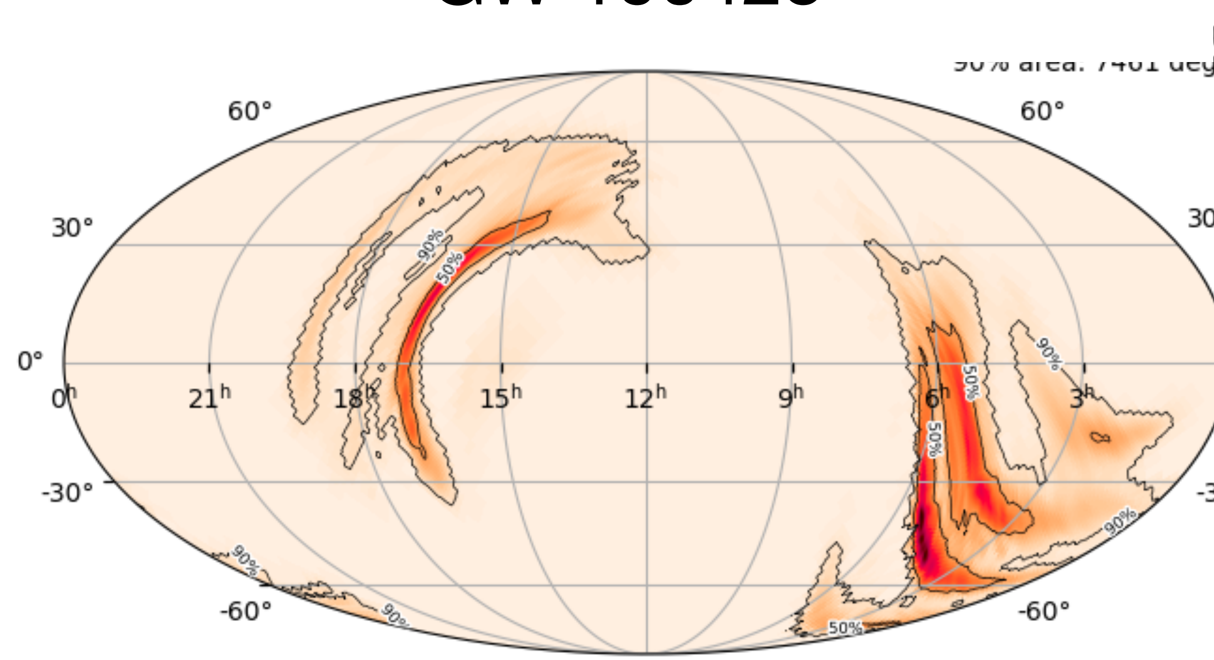
- Overall, 90 candidates discovered (GWTC-3): mostly BBHs, some are NS-BH binaries and **one BNS (GW 190425)**
- No EM counterpart detected

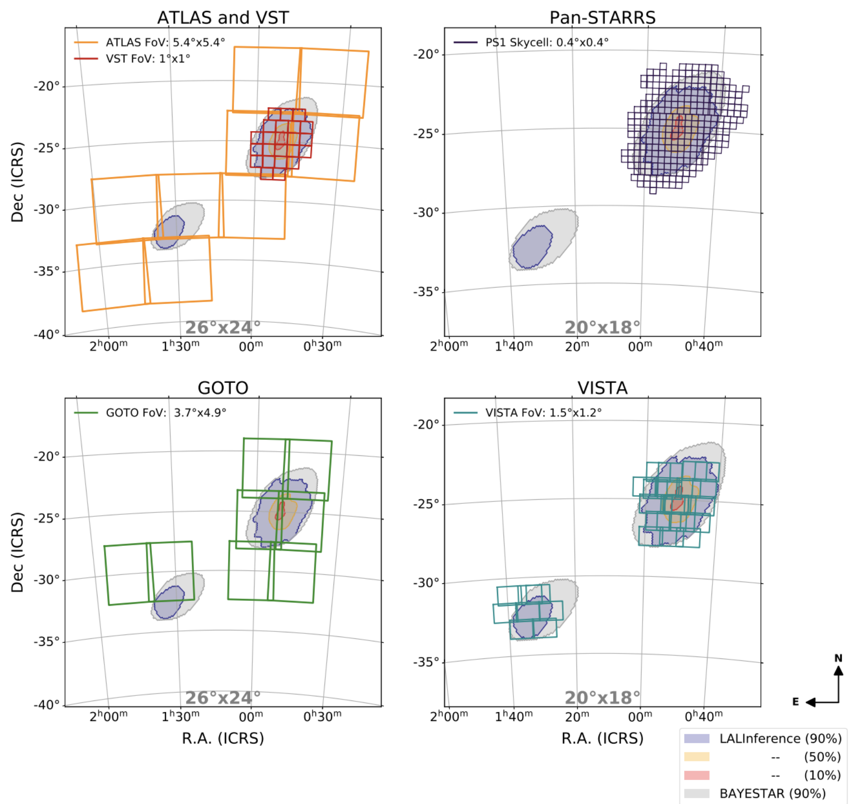
GW 190425

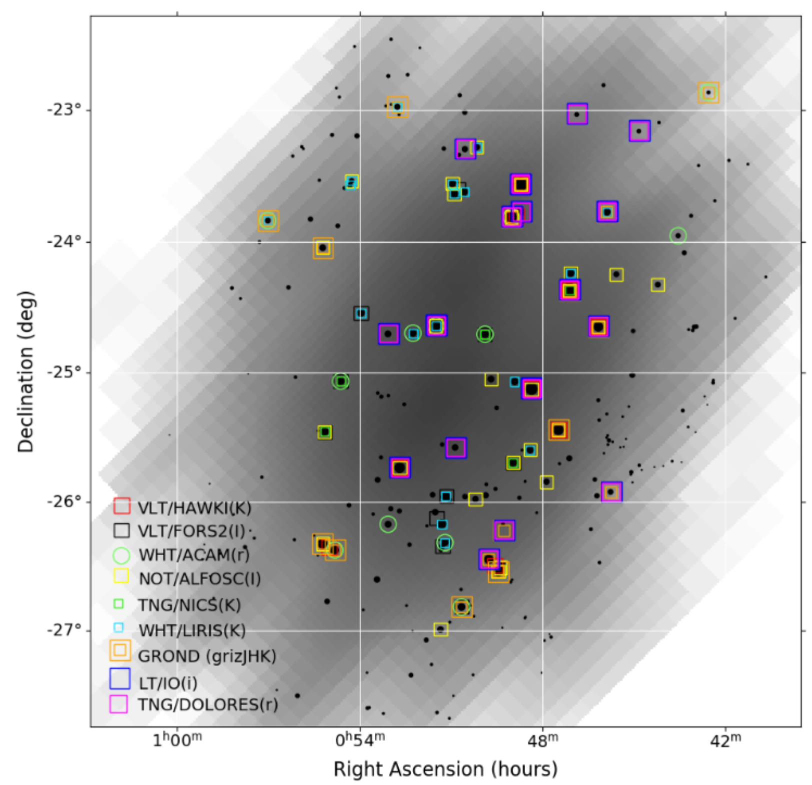


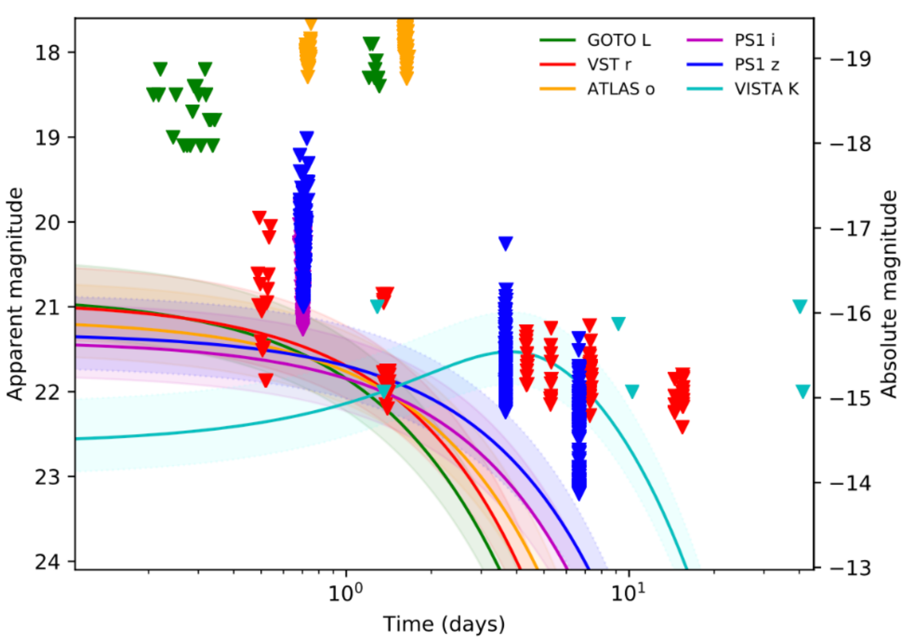
See Hosseinzadeh+19

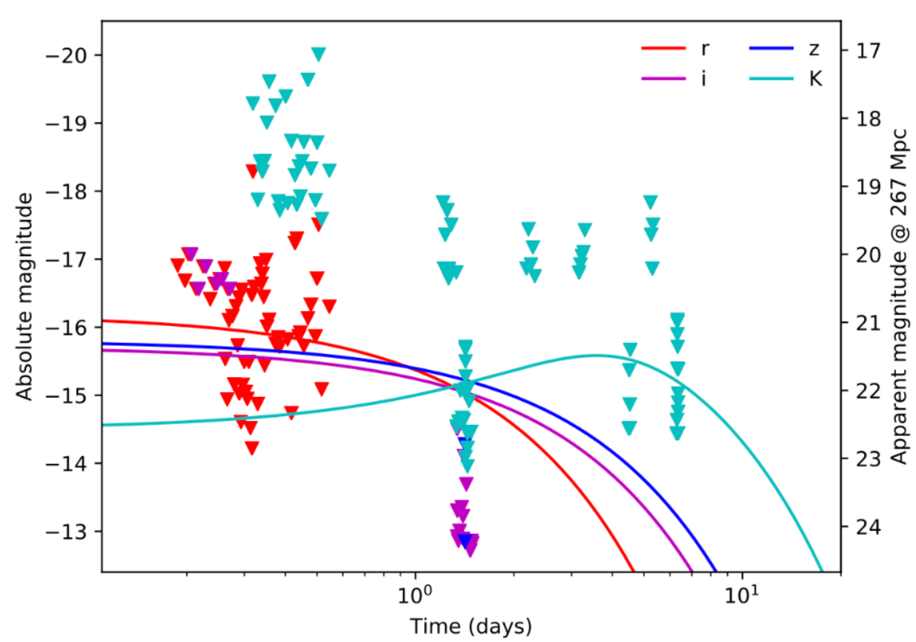
Constraints on the optical-NIR emission associated to GW 190814

Asymmetric system of ambiguous nature, possibly a NS-BH merger









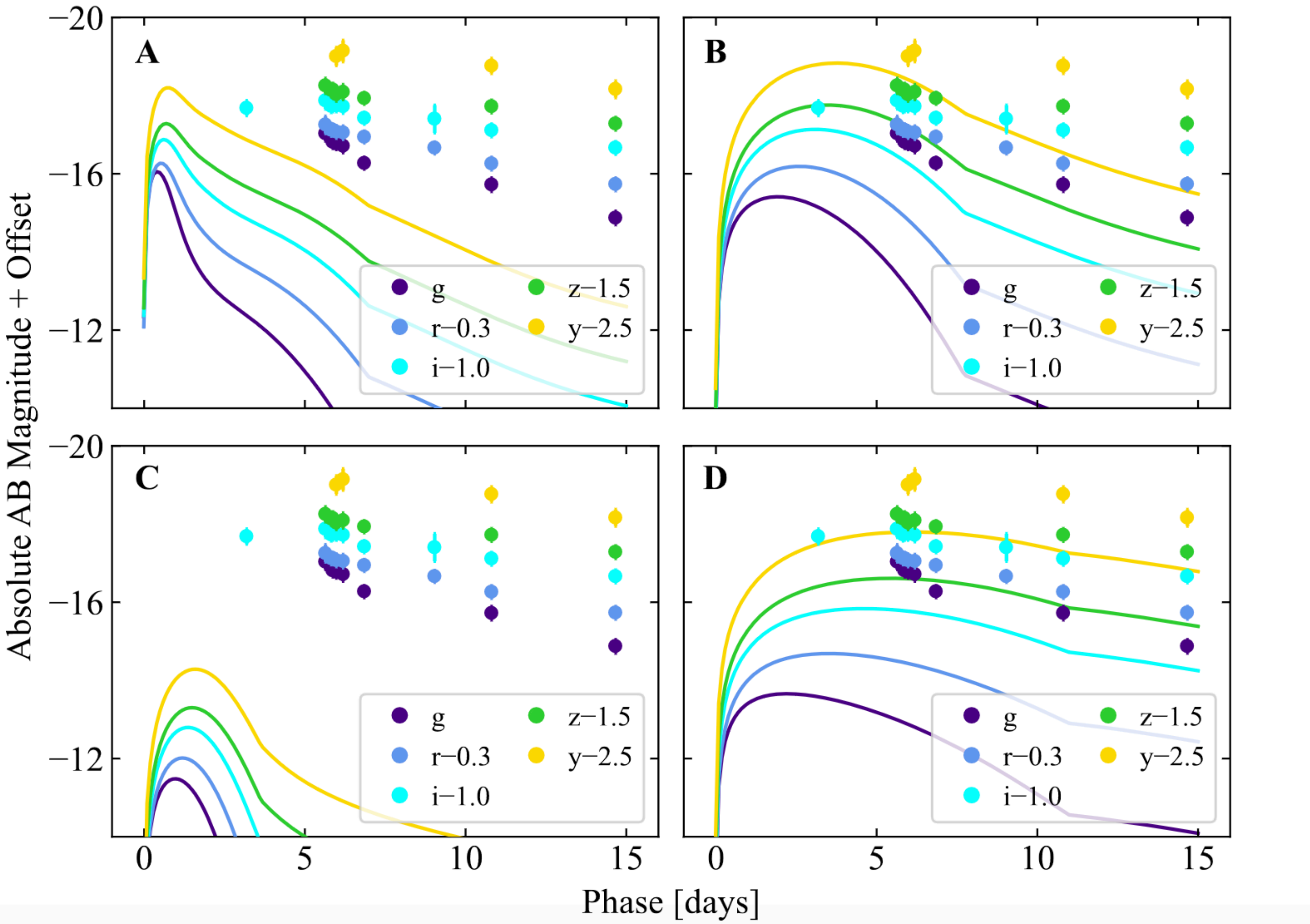
- Both skymap and galaxy target searches performed
- 27 transients detected
- No EM counterpart of the GW event identified
- Limits to a possible kilonova emission associated to this event, high ejecta mass excluded

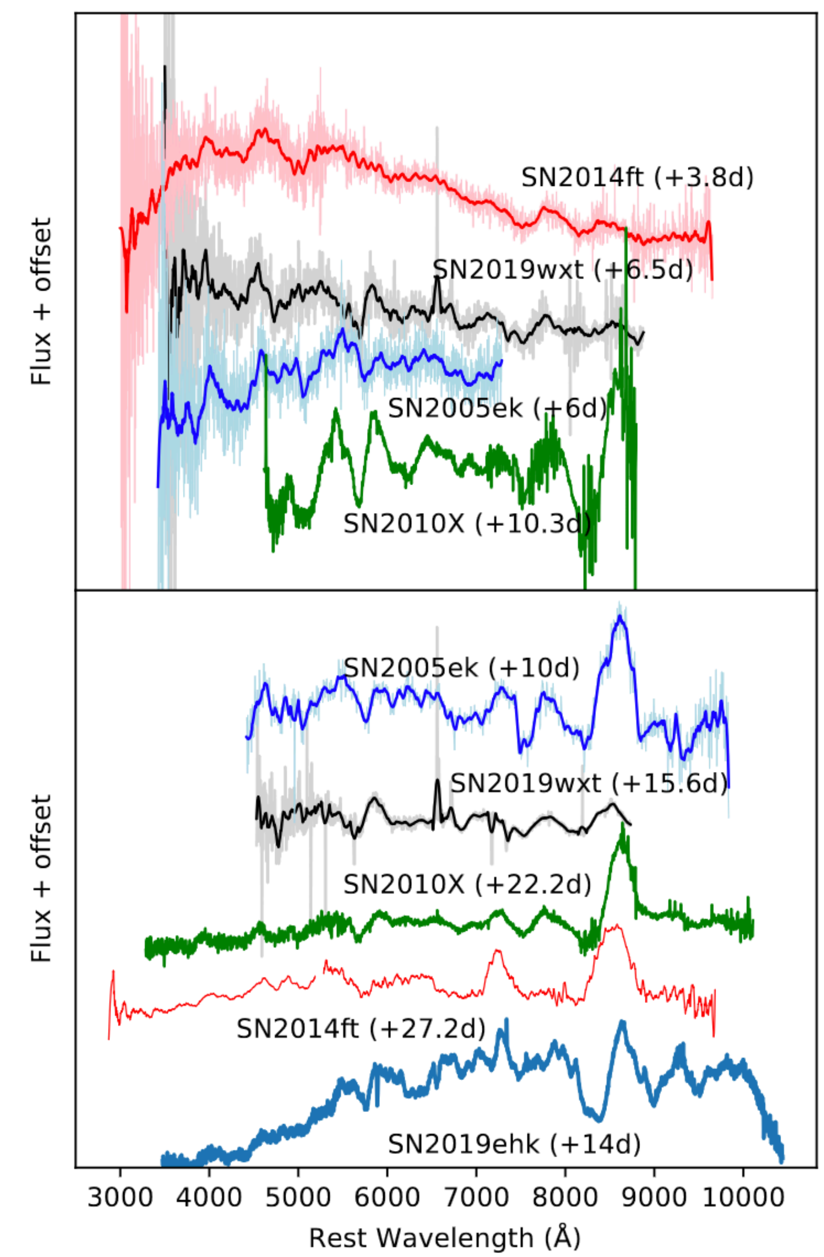
The ENGRAVE Collaboration, Ackley et al., 2020

See also Gomez+19, Andreoni+19

Panning for gold but finding helium

Ultra-stripped SN 2019wxt discovered when looking for counterparts of the GW candidate event S191213g (possible BNS, eventually not confirmed as real event)

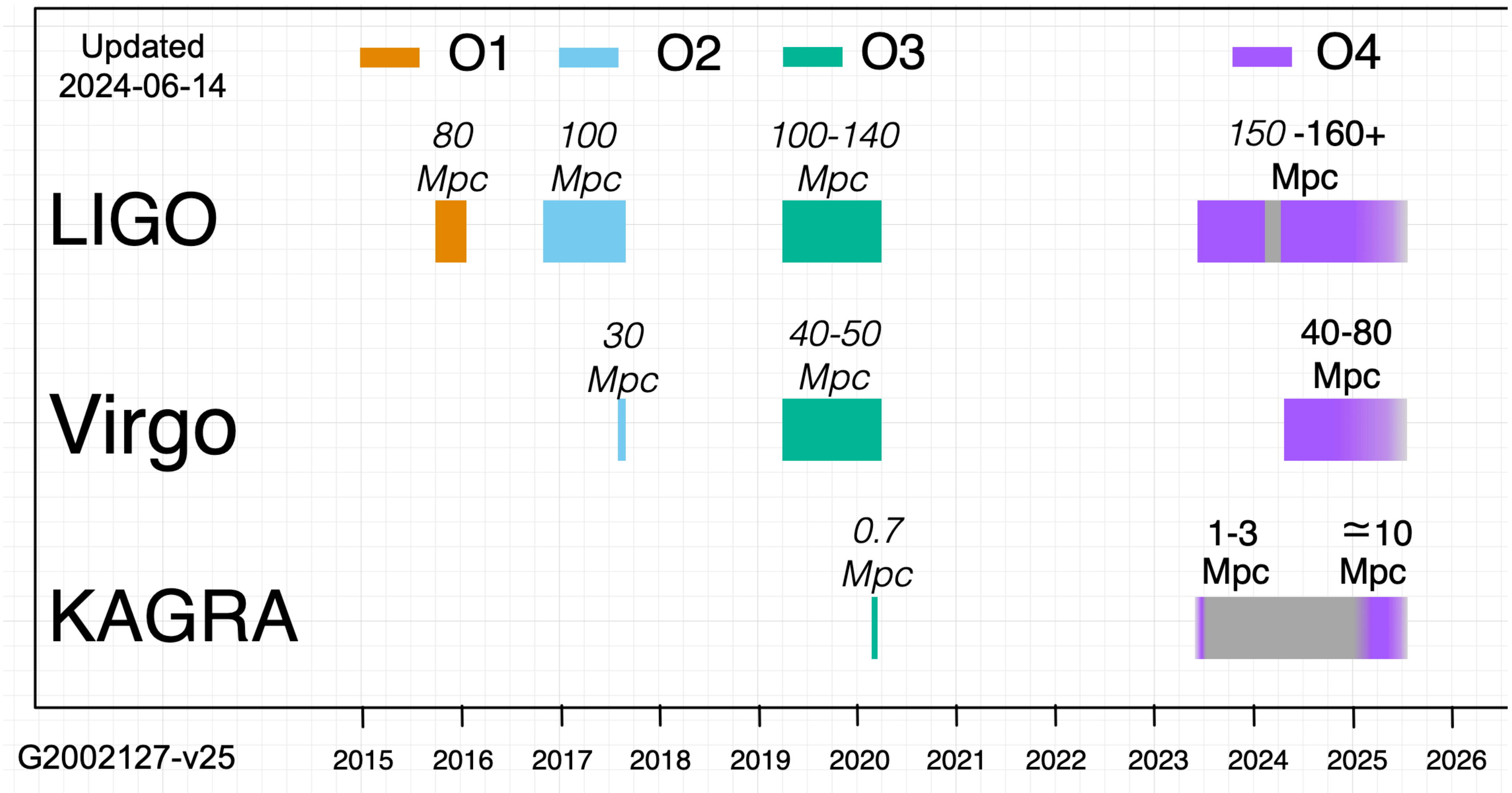




Not a KN, but a peculiar SN

The ENGRAVE Collaboration, Agudo et al., 2023

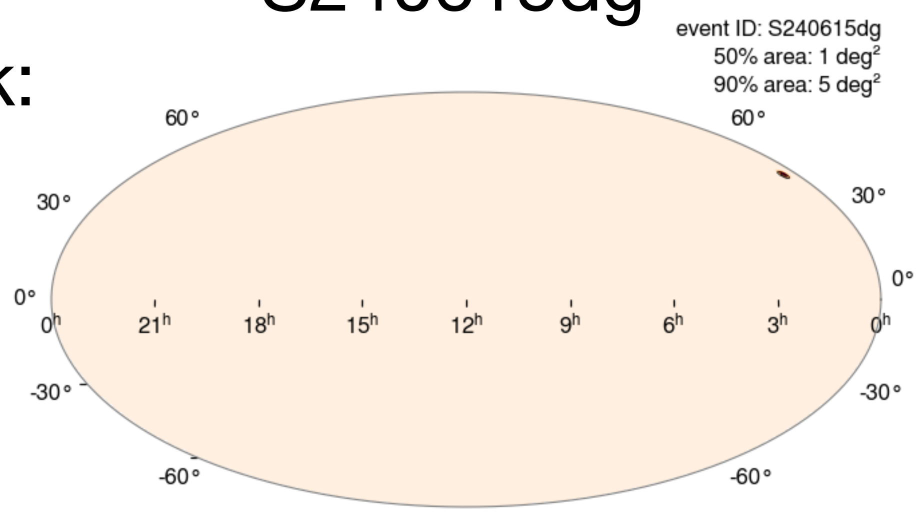
The current observing run: O4



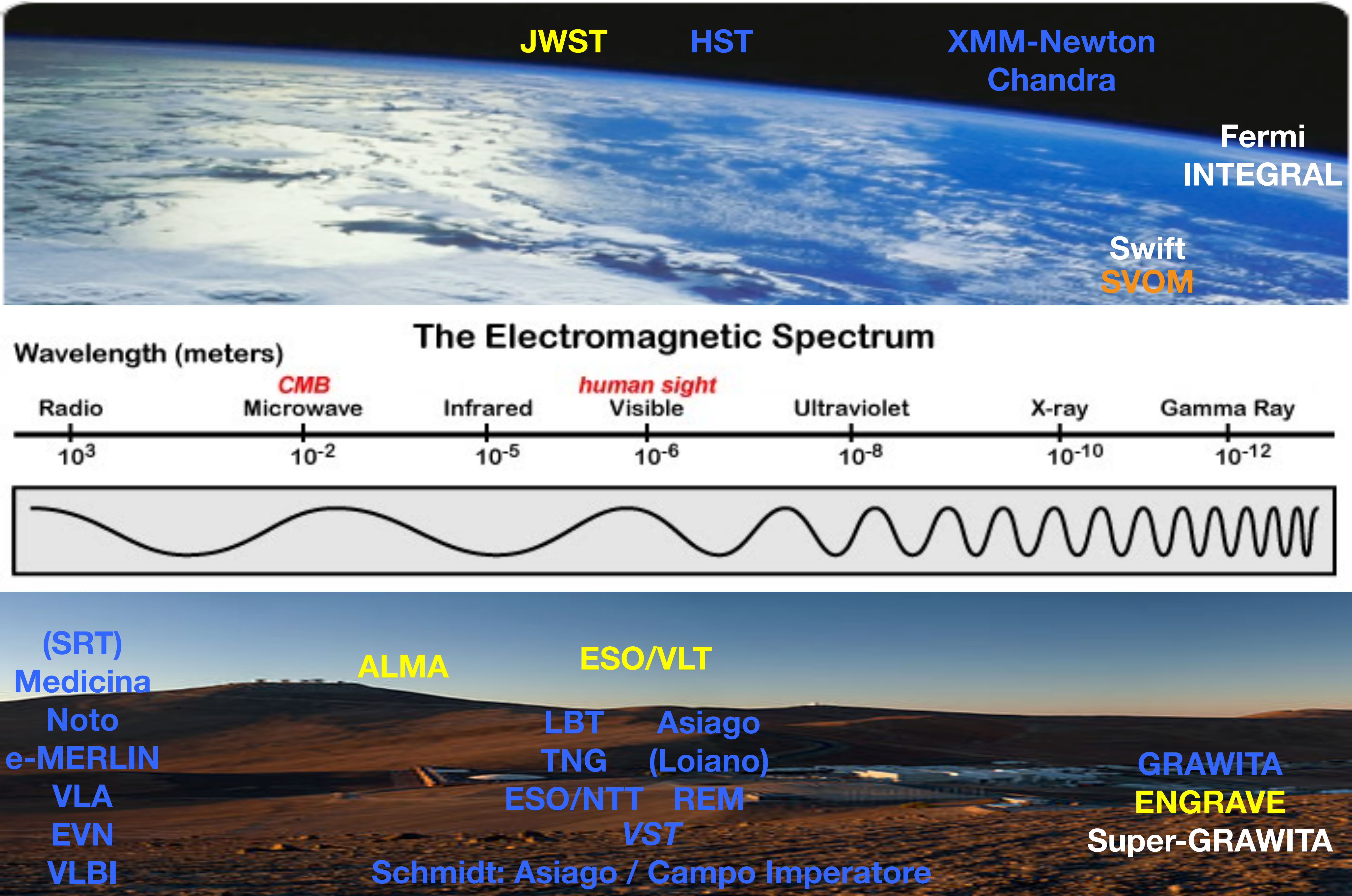
O4 run just started (24th of May, 2023), for a duration of 20 months with one engineering break:

- Much larger observable volume
- Lower threshold for public alerts
- Virgo joined recently, improving significantly the localization (~5-10 deg²)

S240615dg

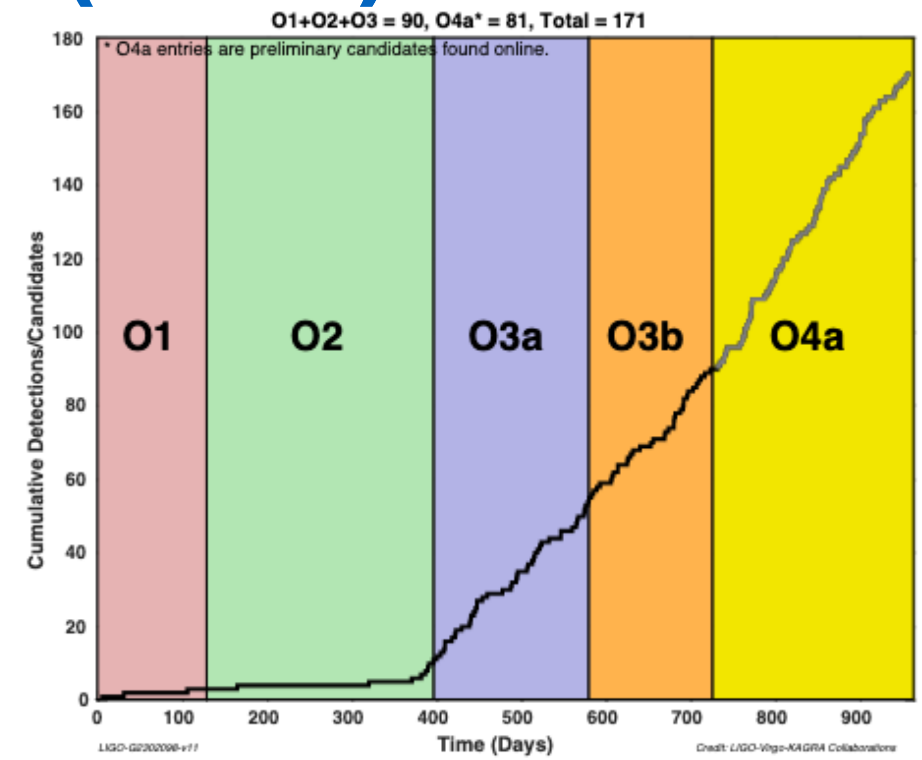


Follow-up facilities for O4

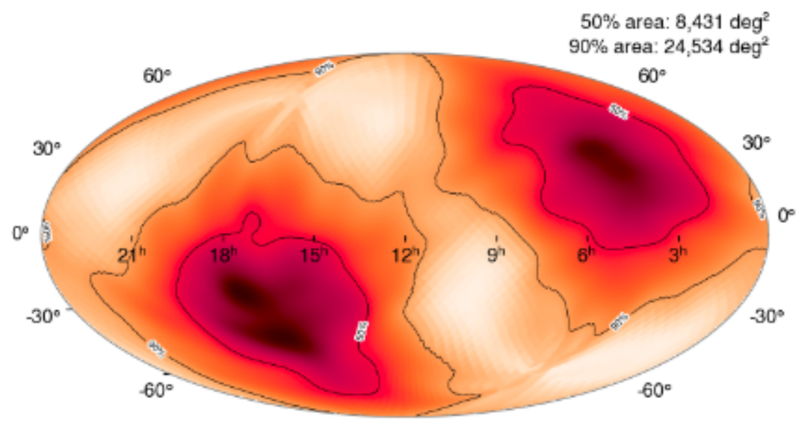


Significant events in O4 (so far)

O4a (8 months): 81 significant candidates, no BNS, 2 possible NSBH



GW 230529: merger of a **NS with a BH** in the mass gap

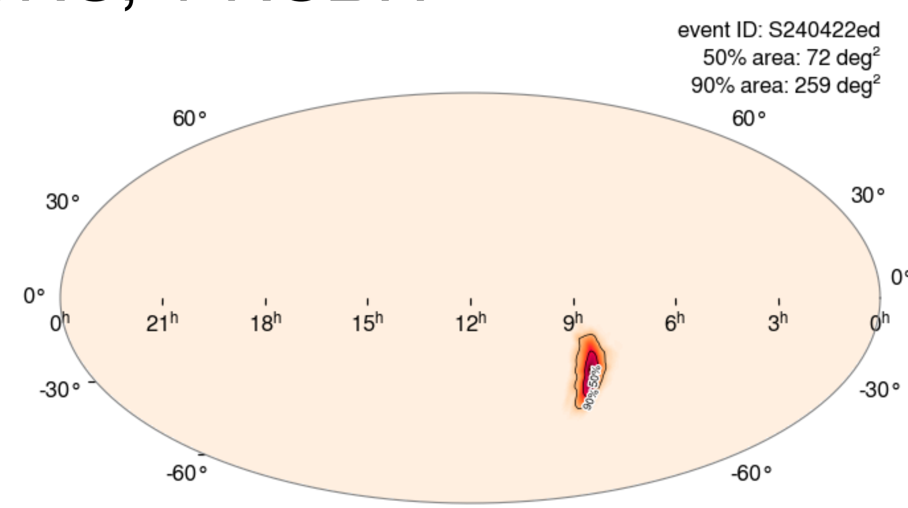


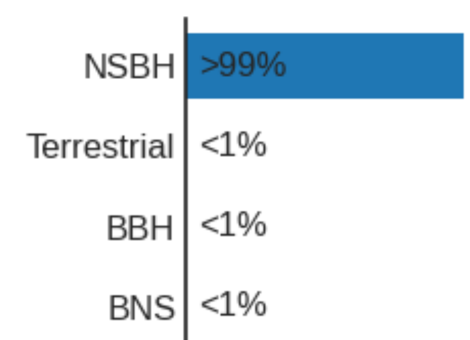
O4b: 27 significant detection candidate, no BNS, 1 NSBH

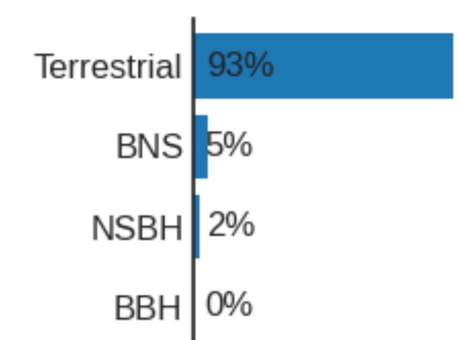
S240422ed: candidate **NSBH** with high probability of being "**EM bright**"

- Possibly not an astrophysical event
- ENGRAVE followed-up several candidates reported by searching facilities

➡ No EM counterpart found

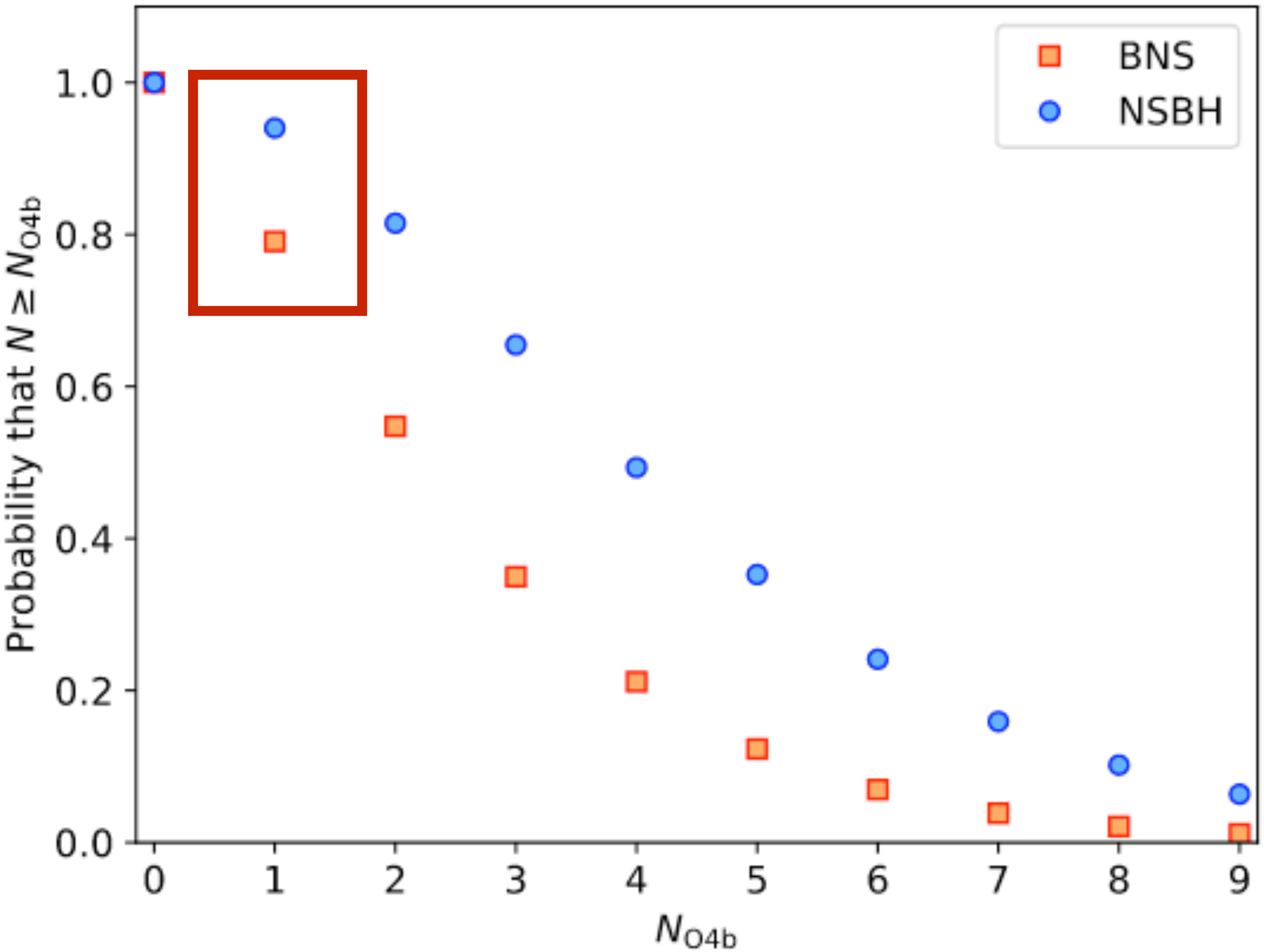






Probability of having a BNS or NSBH in O4b

How likely the detection of at least one such source is in the remainder of O4?

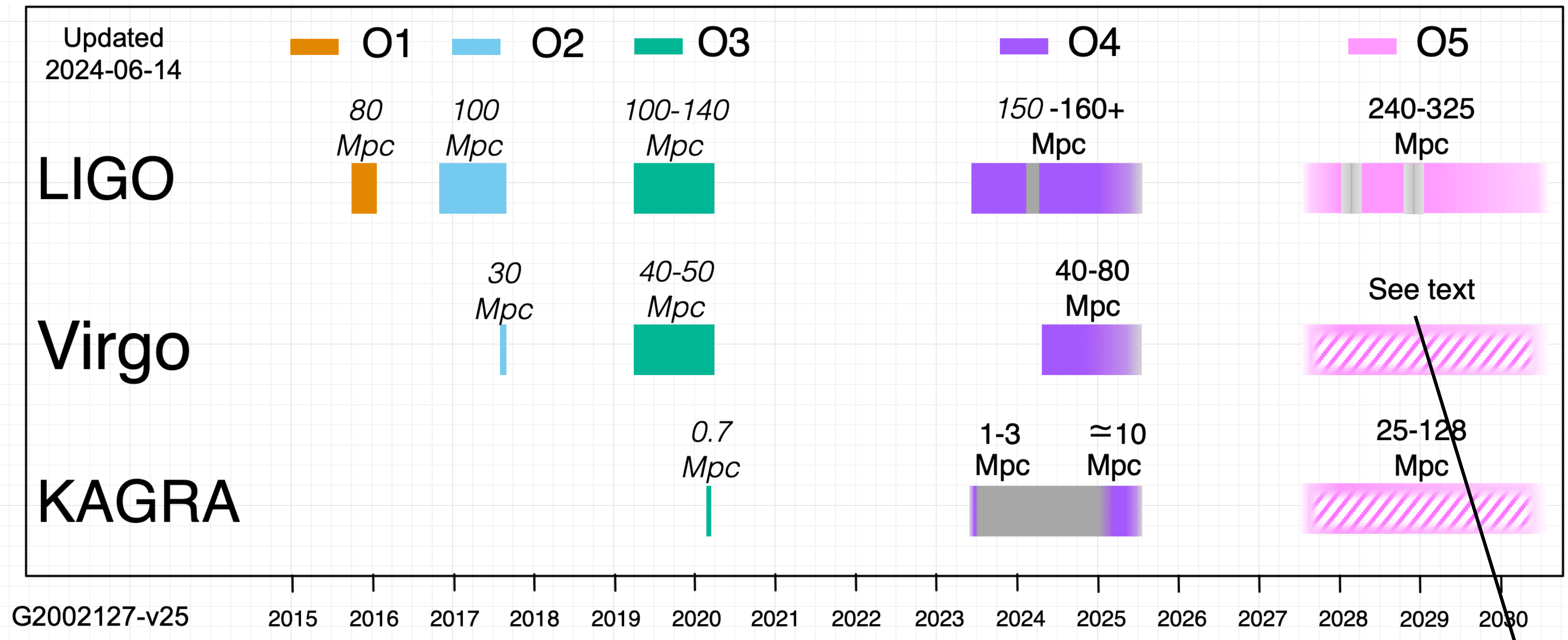


- **Probability of having at least one BNS is ~73%**
- **Probability of having at least one NSBH is ~94%**

https://emfollow.docs.ligo.org/userguide/capabilities.html

The near future: O5

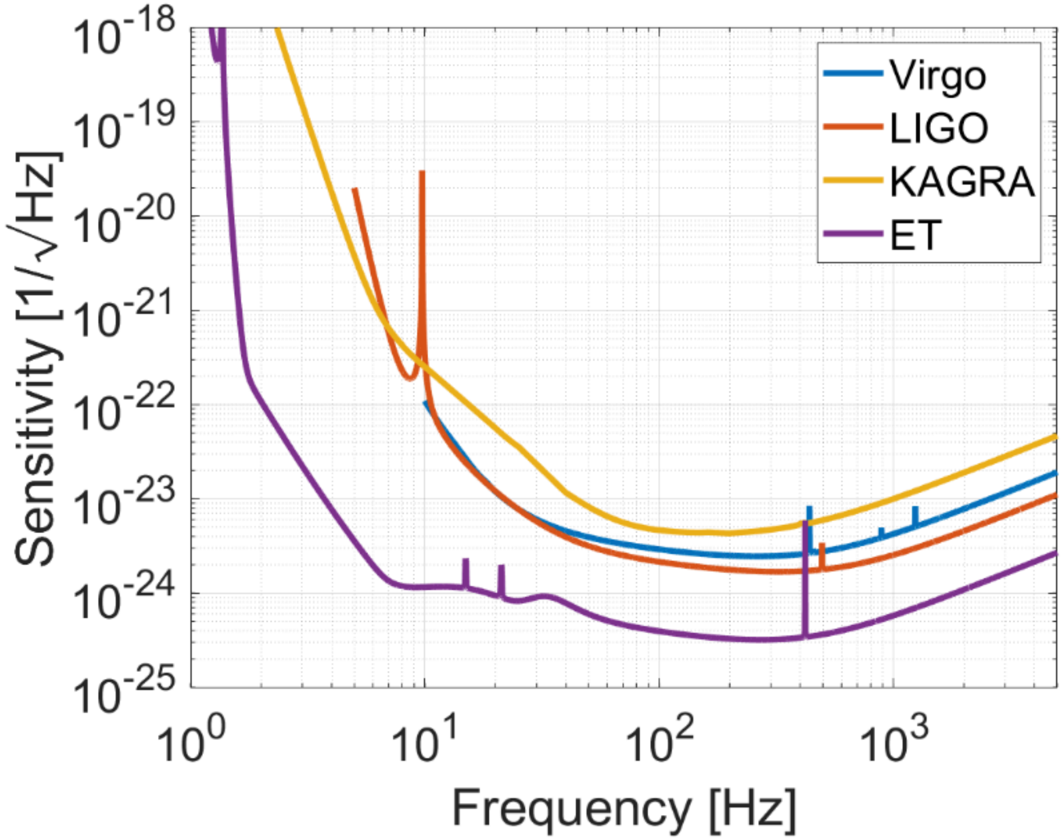
https://observing.docs.ligo.org/plan/



- Fifth observing run planned to start in a few years
- Sensitivity further improved

entry date and the target sensitivity are unclear

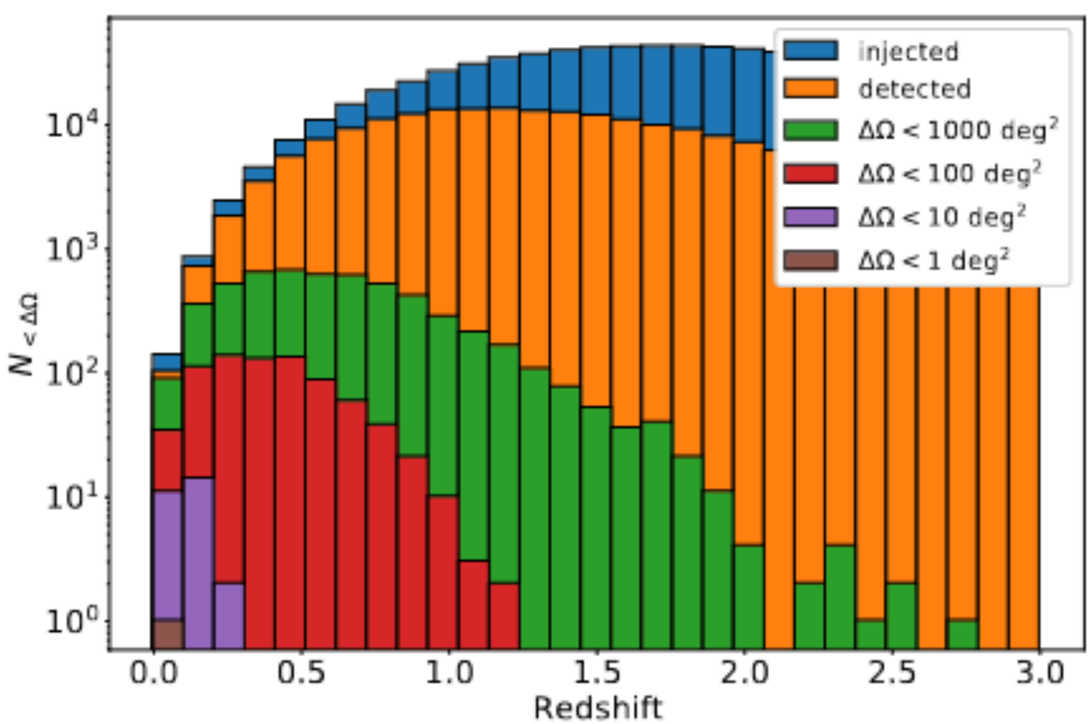
The 3rd generation: Einstein Telescope in Europe and Cosmic Explorer in US



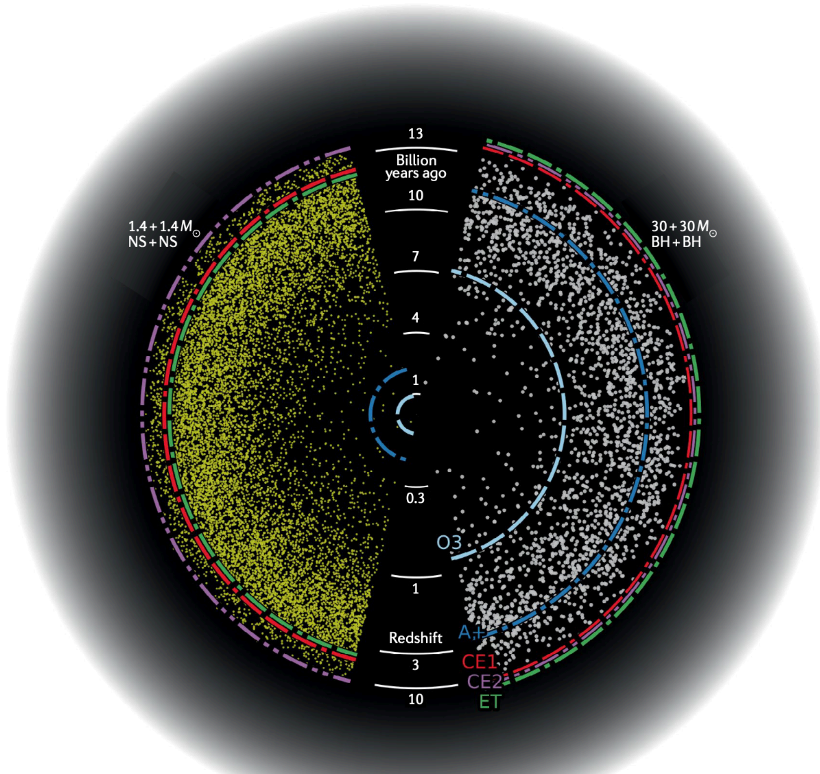
- 10 times more sensitive than 2G detectors (10^3 times larger volumes)
- Wider frequencies (lower freq.)

➡ Higher redshift accessible:

- Study BNS/NSBH along the cosmic history
- Increase of the detection rate
- Better parameter estimation



Branchesi et al., 2023 JCAP



Bailes et al., 2021 Nature

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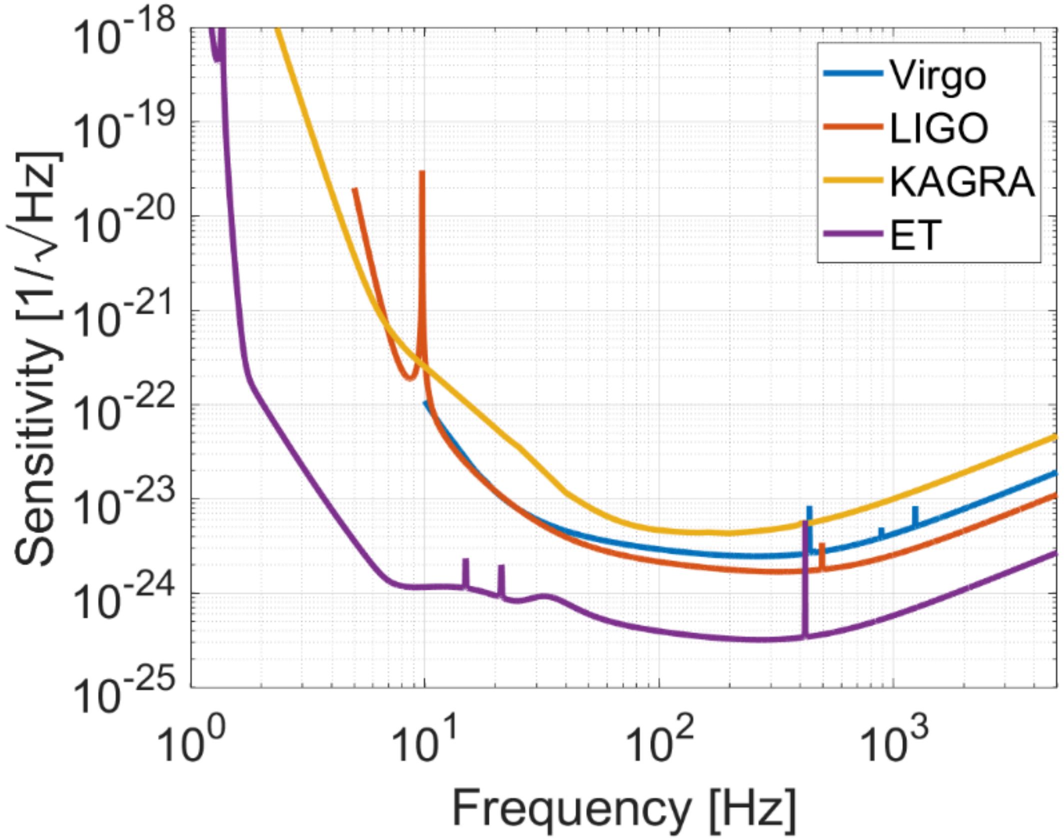

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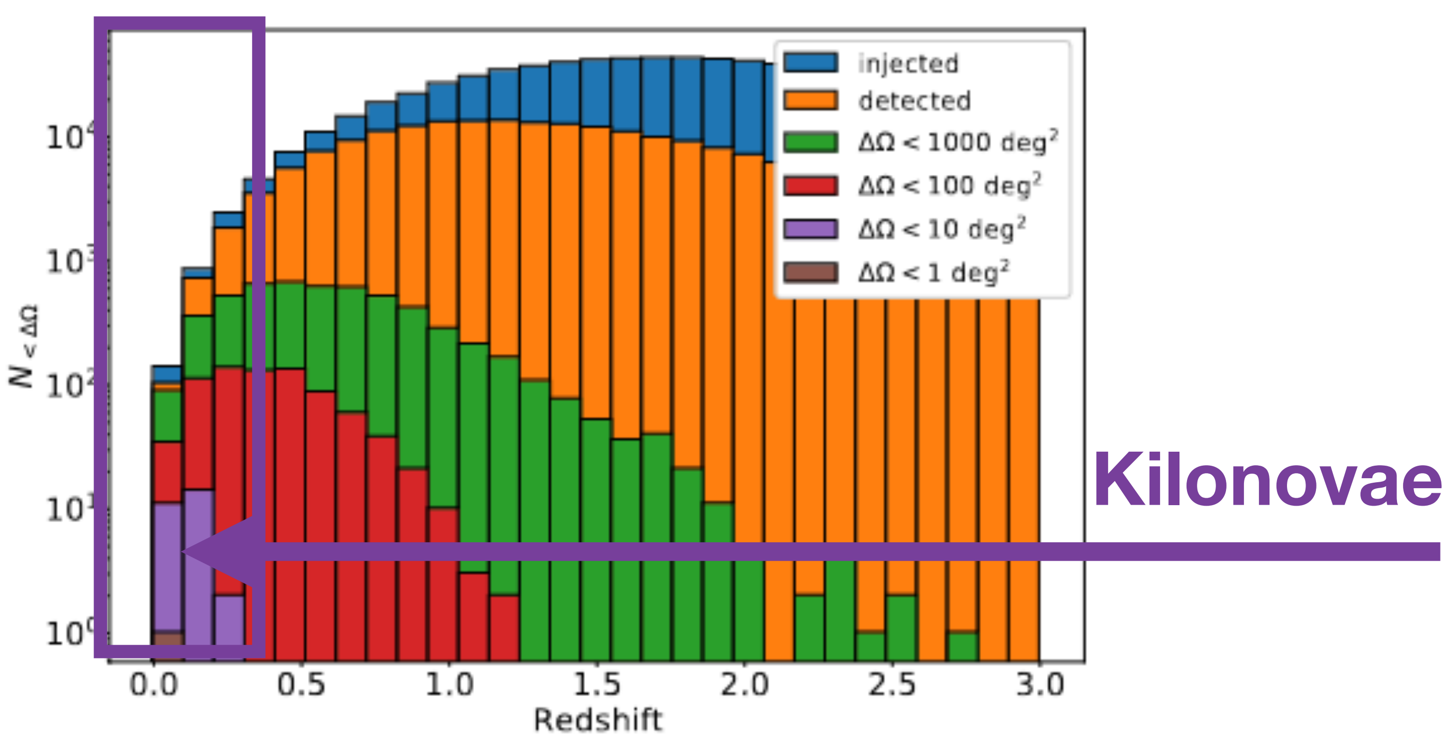

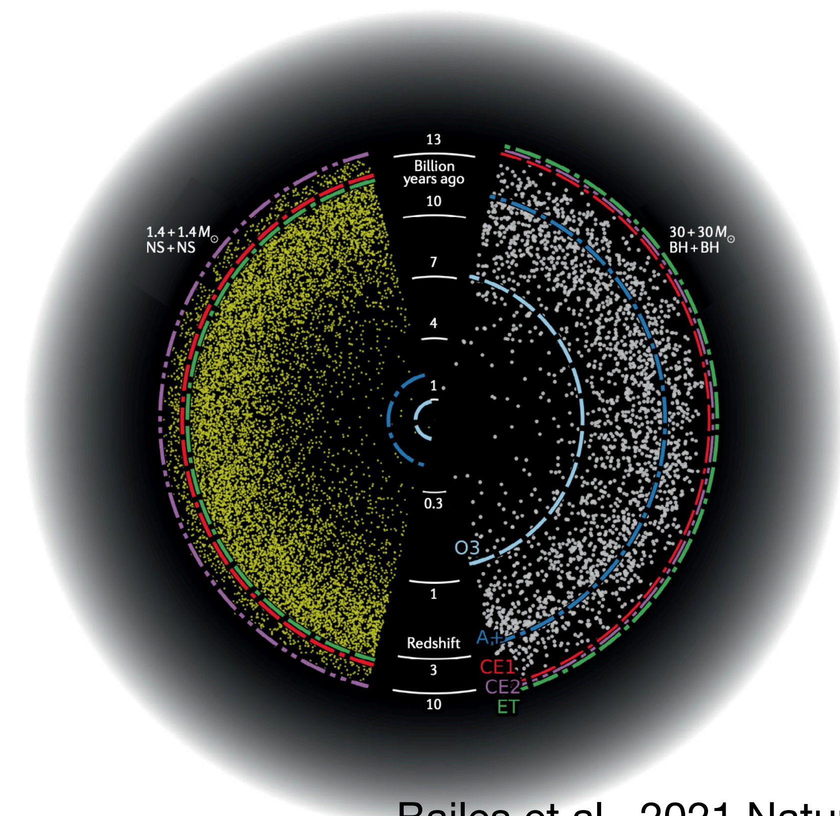

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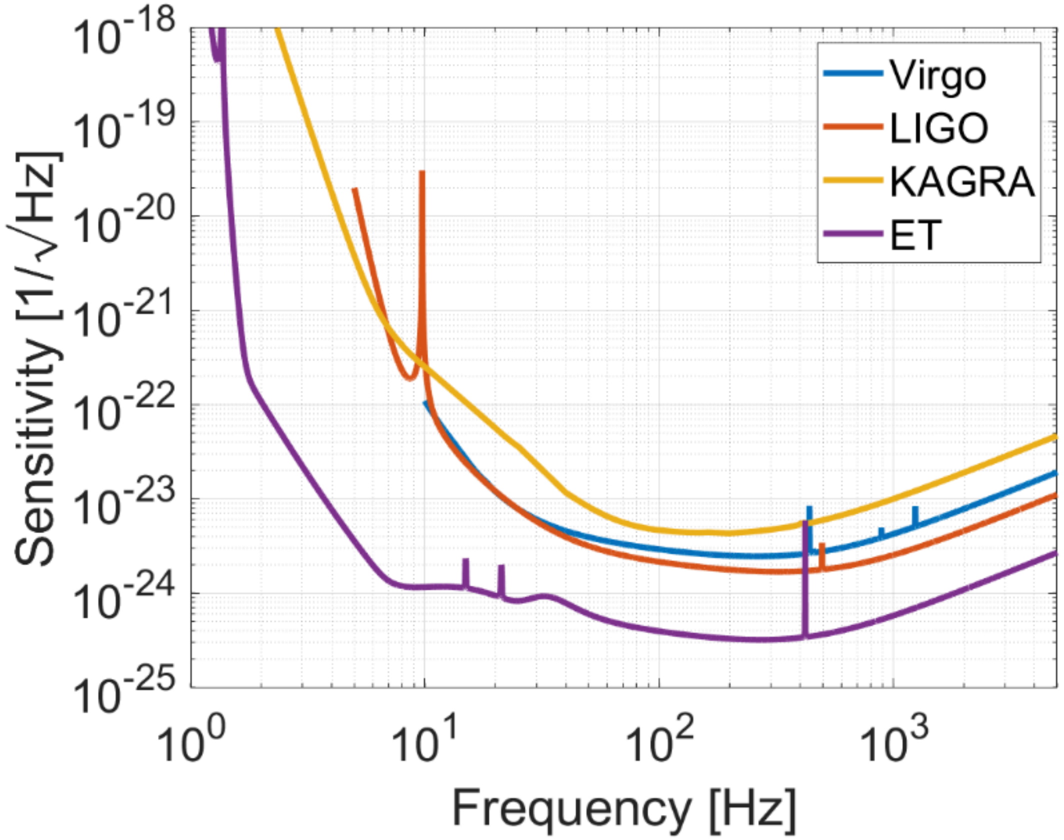

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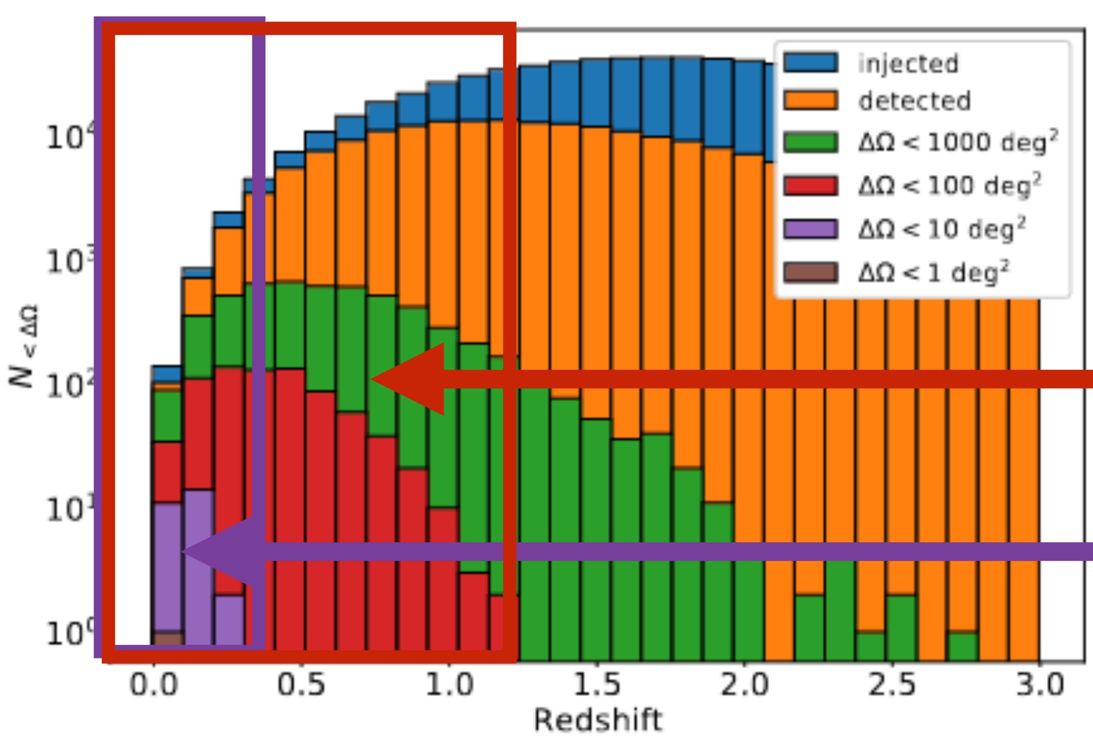
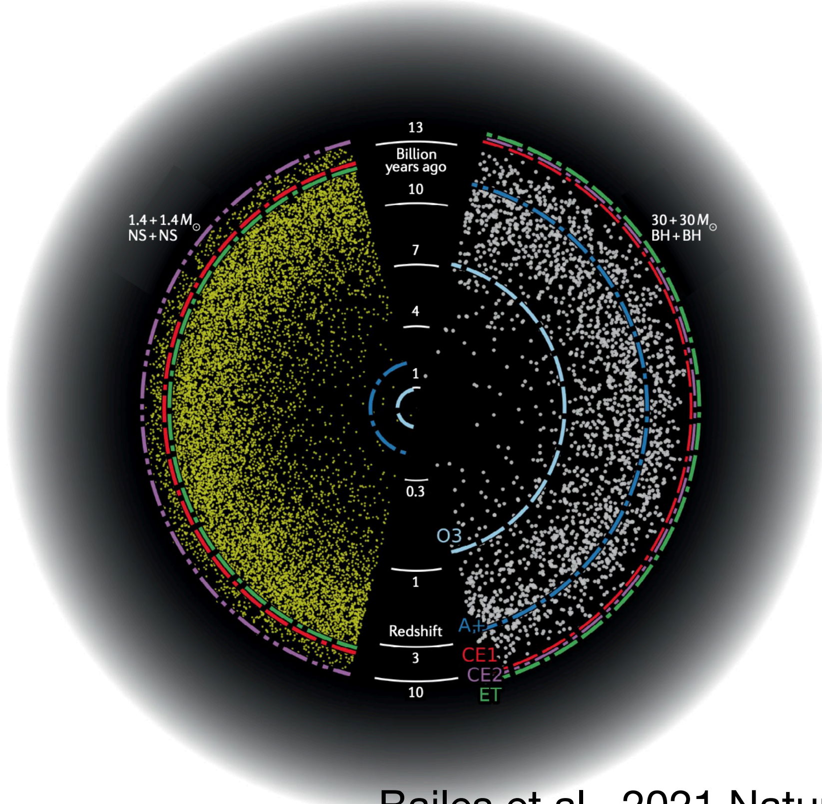


Short GRBs

Kilonovae

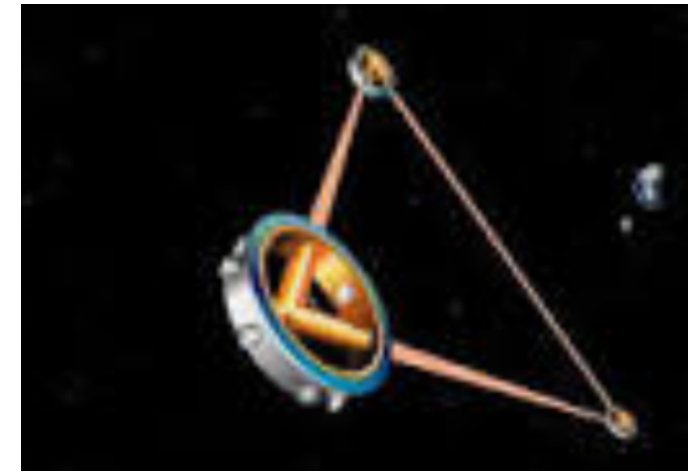
Branchesi et al., 2023 JCAP

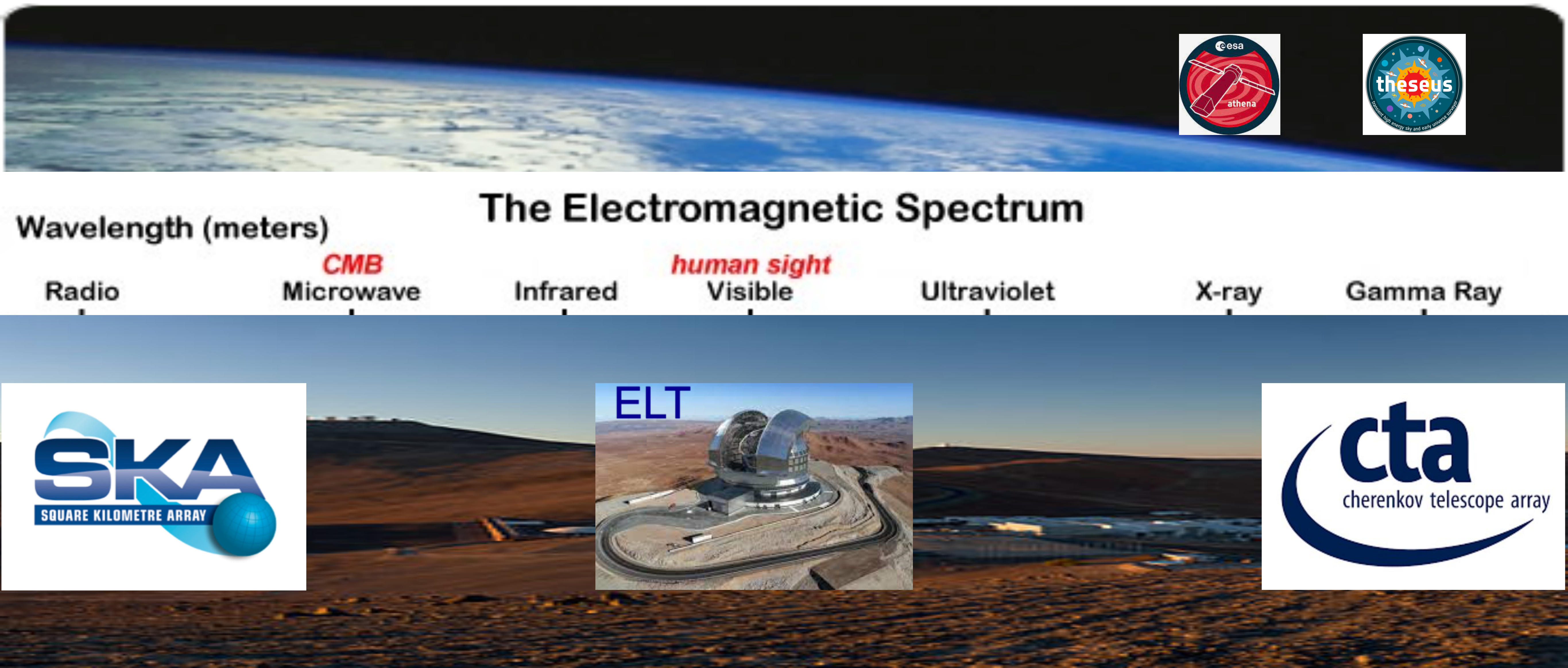


Bailes et al., 2021 Nature

The future is even brighter and louder!

ET EINSTEIN TELESCOPE





Conclusions

- GW 170817/GRB 170817A/AT 2017gfo marks the **birth of multi-messenger astronomy with GWs:**
  - ➡ smoking gun for SGRB progenitors
  - ➡ first direct detection of a kilonova (and it looks exactly like it should be!)
  - ➡ first off-axis GRB and constraints on the outflow geometry

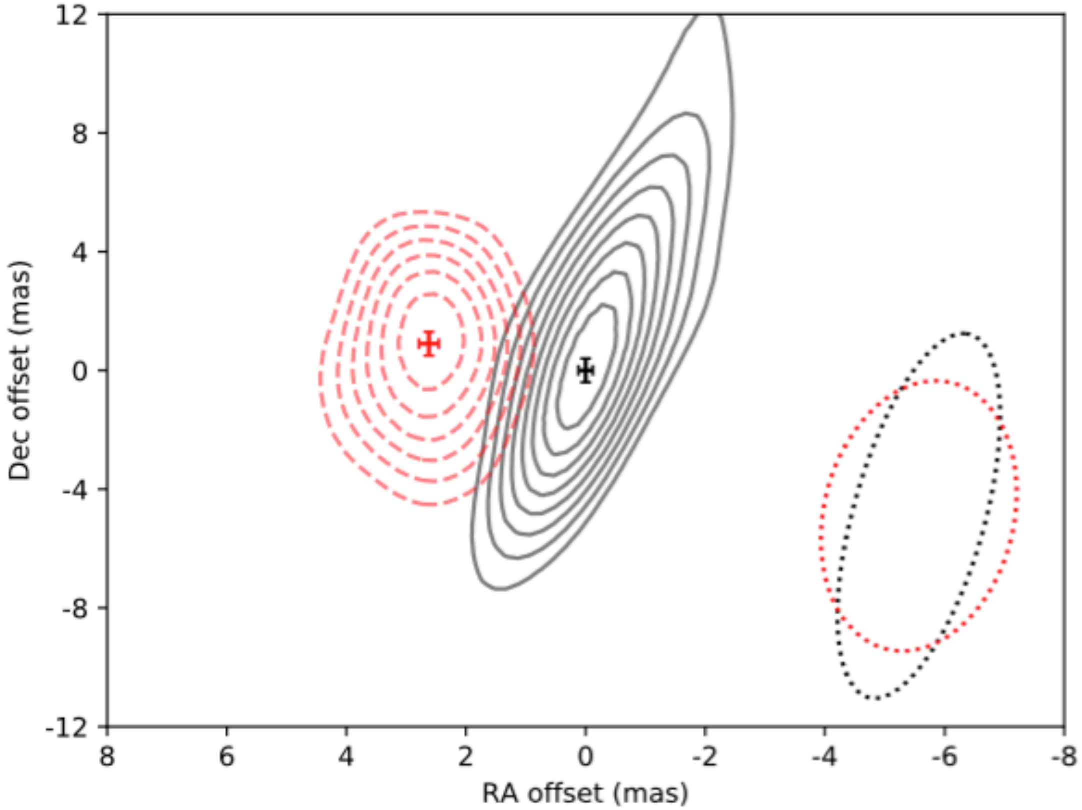
- Impressive observational campaign that required years of preparation, **experience with GRBs and SNe crucial** (astrophysical understanding of the targets and observational strategies)

- Yet a unicum, but we are confident about the rest of the O4 campaign with the contribution of Virgo to the network (**small error regions** are essentials)

- To perform successful observational campaigns:
  - **Broad range expertise** needed (observational-multiwavelength and multi messenger, theoretical)
  - **Coordinated observational effort** would be beneficial (e.g. Treasure Map https://treasuremap.space/)
  - Synergic network of **big, medium and small facilities** crucial (+**space**!!)

Backup slides

GRB 170817A: evidence for a structured jet



Mooley+18

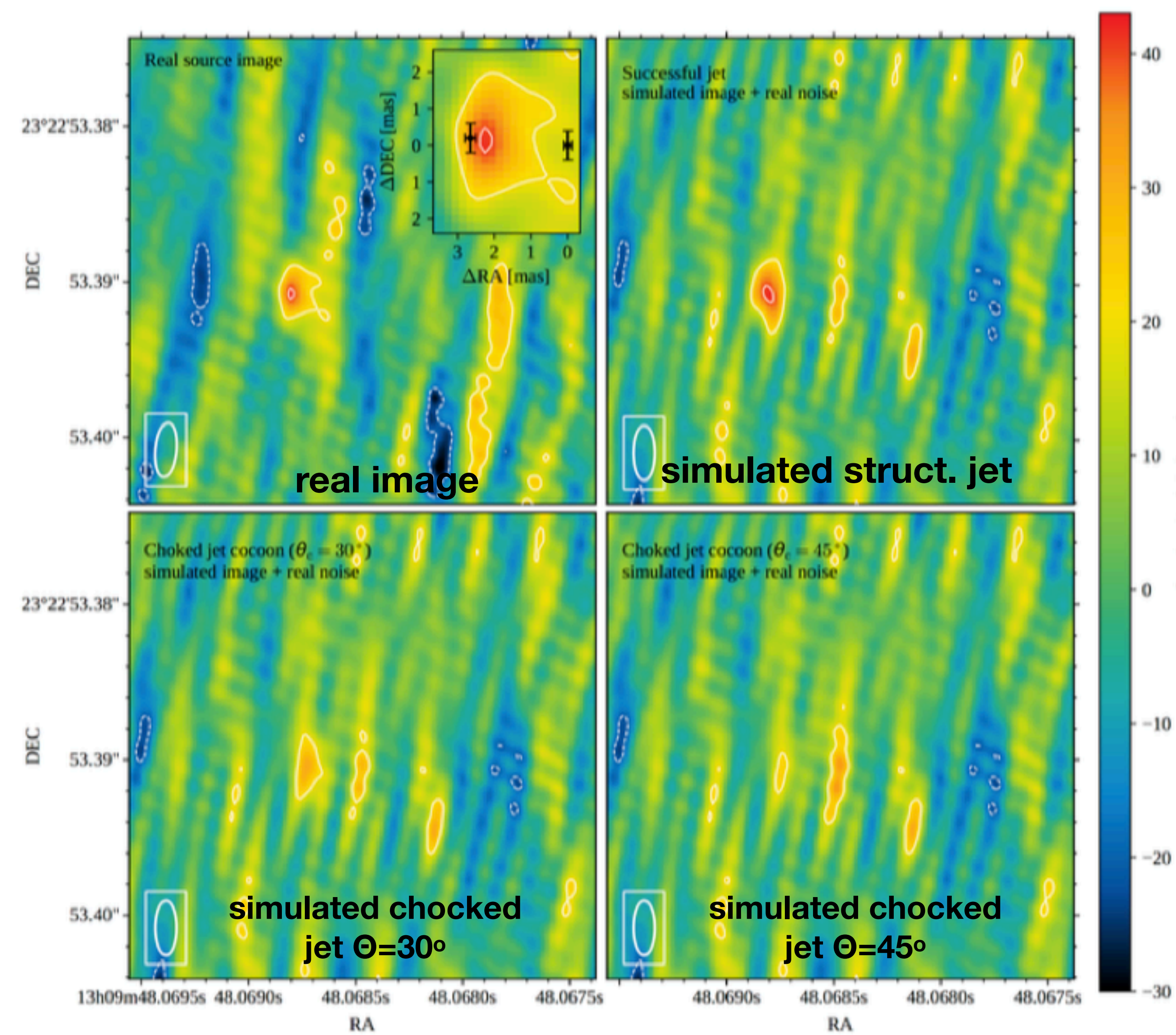
- Evidence for a proper (superluminal, v/c=4.1+/-0.5) motion with **VLBI** data (75 and 230 days) Mooley+18

  ➡**Support the structured jet scenario**

- Measure of the source size <2 mas with **VLBI** data (207 days) Ghirlanda+19

  ➡**Final proof of the structured jet scenario**

Ghirlanda,..,MGB+19



Structured jet: relativistic core with $\theta_{jet} < 5$ deg and $\theta_{view} \sim 20$ deg