The landscape of multi-messenger astrophysics with GWs

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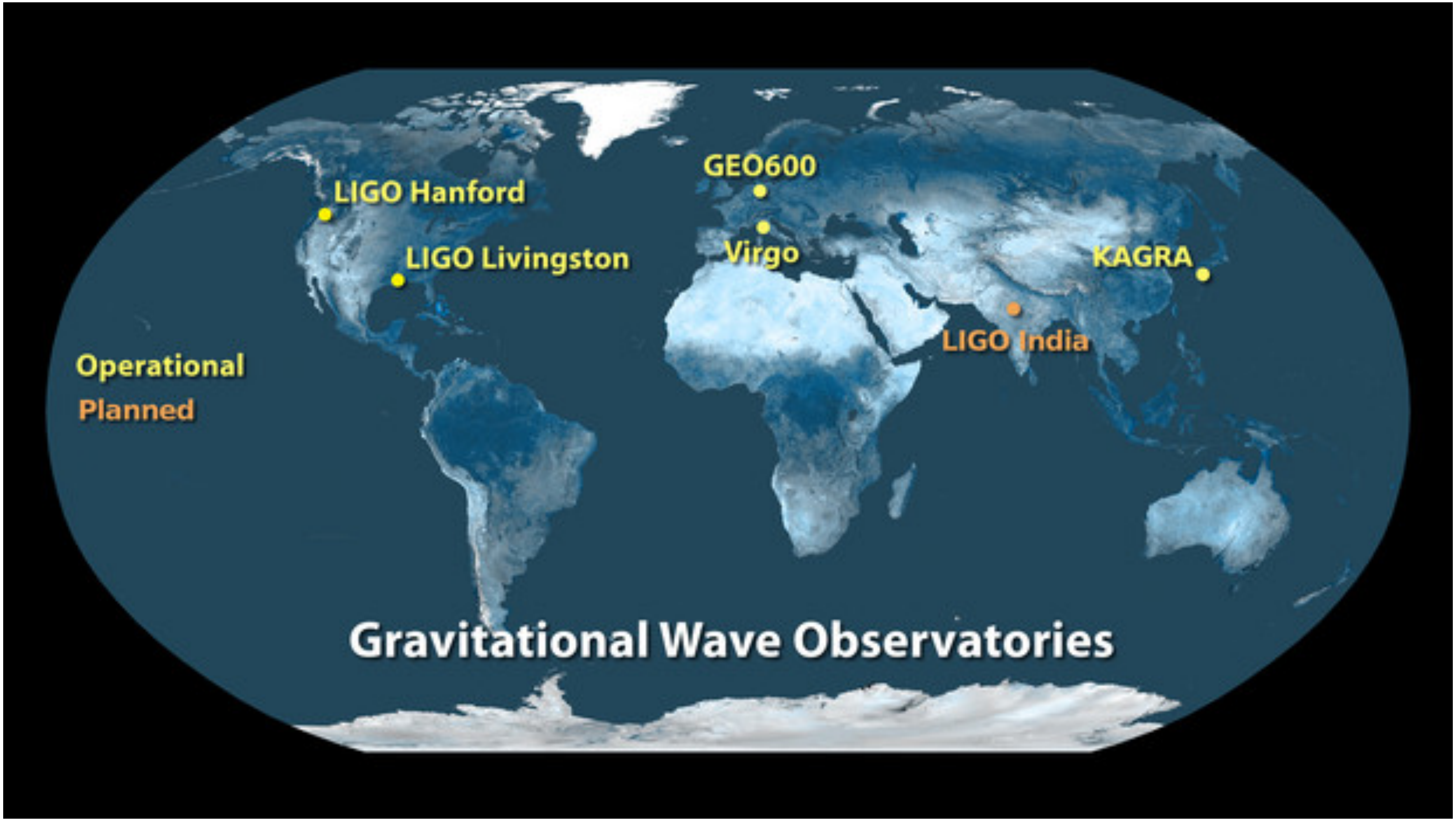
From 9 to 40: the SST telescopes and gamma-ray science with Astri and CTAO
Sexten, 23 July 2026

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

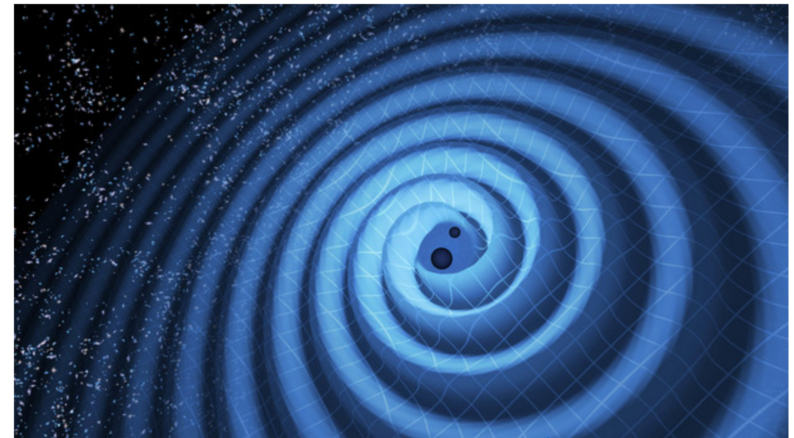
The Gravitational Wave (GW) astronomy era



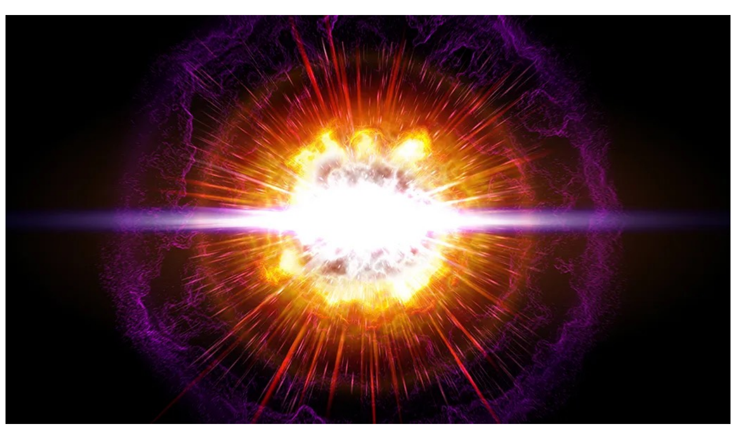
The 2nd generation GW detector network

High-frequency interferometers

Capable to probe high frequency emitters, such as stellar mass compact binary inspirals and core-collapse SNe



Accurate modelling
$E_{GW} \sim 10^{-2}\ M_{sun}c^2$



Difficult modelling
$E_{GW} \sim 10^{-11}\text{-}10^{-7}\ M_{sun}c^2$

Why is MM detection important?

GWs and photons provide complementary information about the physics of the source and its environment

GW:

- mass
- spin
- system orientation
- luminosity distance

- BH mass spectrum
- NS e.o.s.
- Compact object binary rates
- Compact objects formation and evolution

- Probe of progenitors, central engine and geometry
- Fundamental Physics
- Cosmology

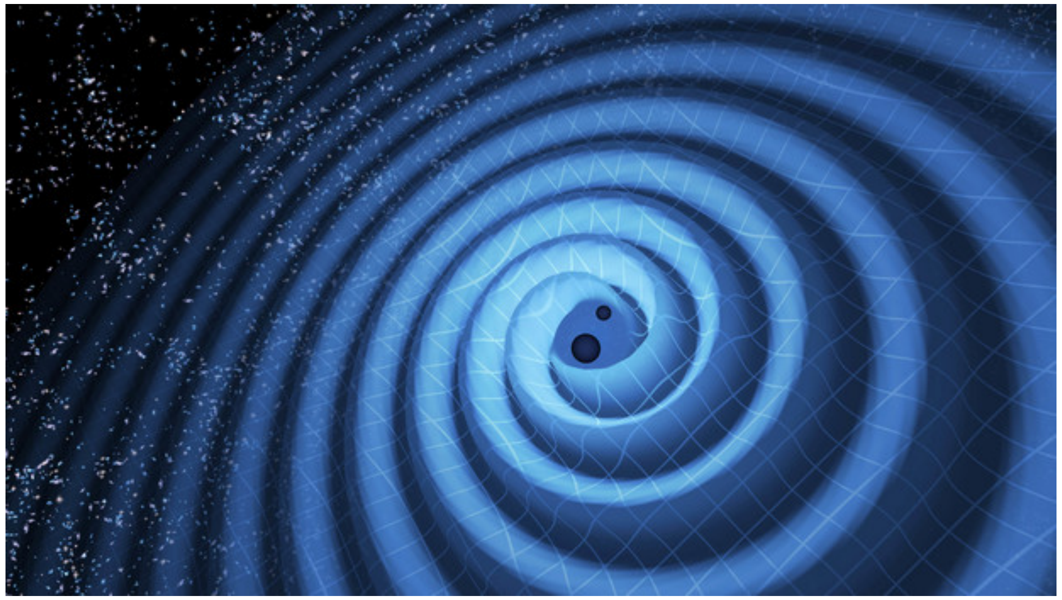
EM:

- precise (arcsec) sky localization
- host galaxy
- Redshift
- MW emission

- Environment
- Particle acceleration mechanisms
- Nucleosynthesis

When do we expect to have and EM counterpart?

BBH merger



Typically **not expected to produce bright EM signal** due to the absence of baryonic matter left outside the merger remnant (see however Loeb 2016, Perna et al. 2016, Janiuk et al. 2017, Seto & Muto 2011, Murase et al. 2016)

BNS or NSBH merger

Associated with EM transients such as:

- **Short gamma-ray burst** (from TeV to radio)
- **Kilonova** (UV-optical-IR)

1. Short gamma-ray bursts (SGRBs)

✓ diverse merging times:

➡mix of early and late type galaxies

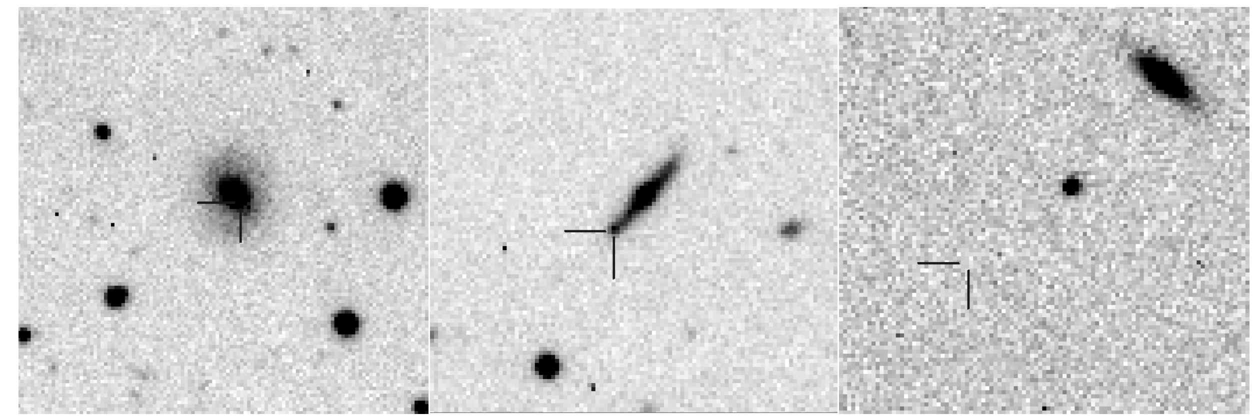
✓ kicks/migration from their birth sites:

➡offset

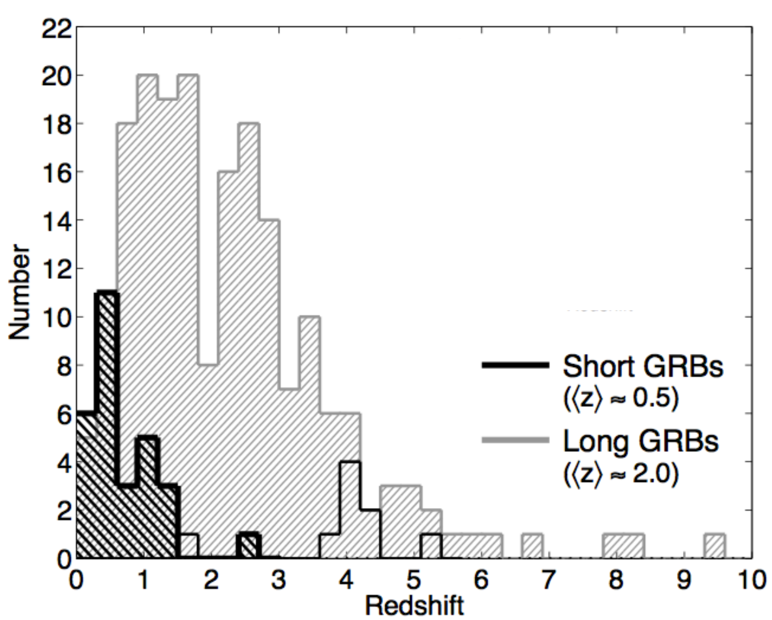
➡no correlation with UV light of their host galaxies

➡diversity of their environment

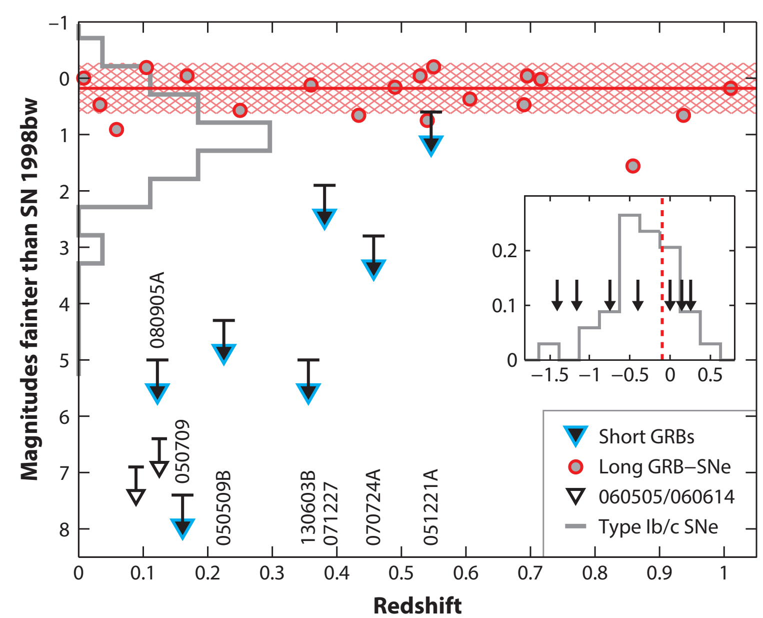
✓ no supernova associated



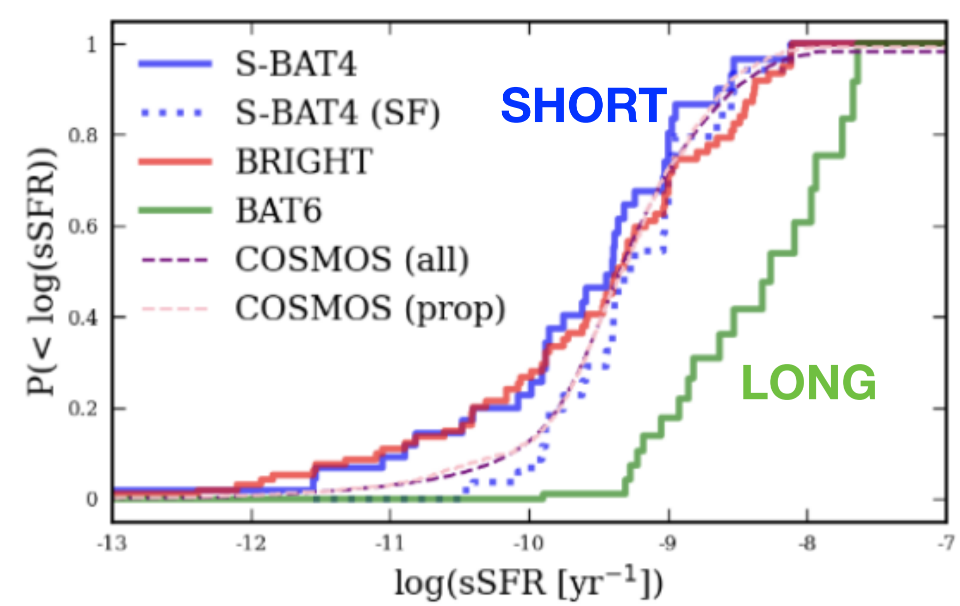
Redshift distribution



Limits of the SN mag in SGRBs compared to typical LGRB SNe



L and SGRBs sSFR compared to the COSMOS galaxies



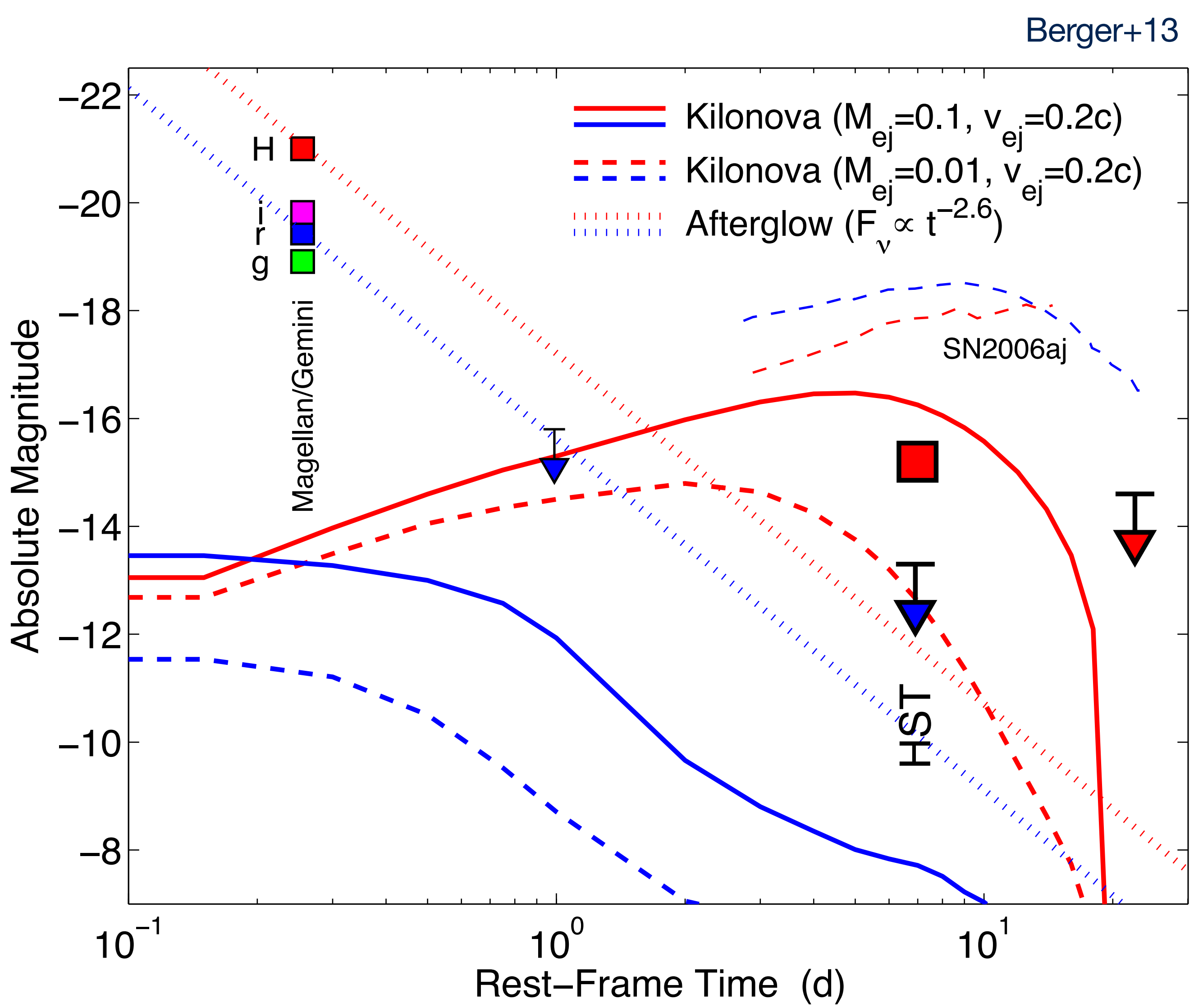
Credits: M.Ferro

Fong+13, Berger14, D'Avanzo15

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**



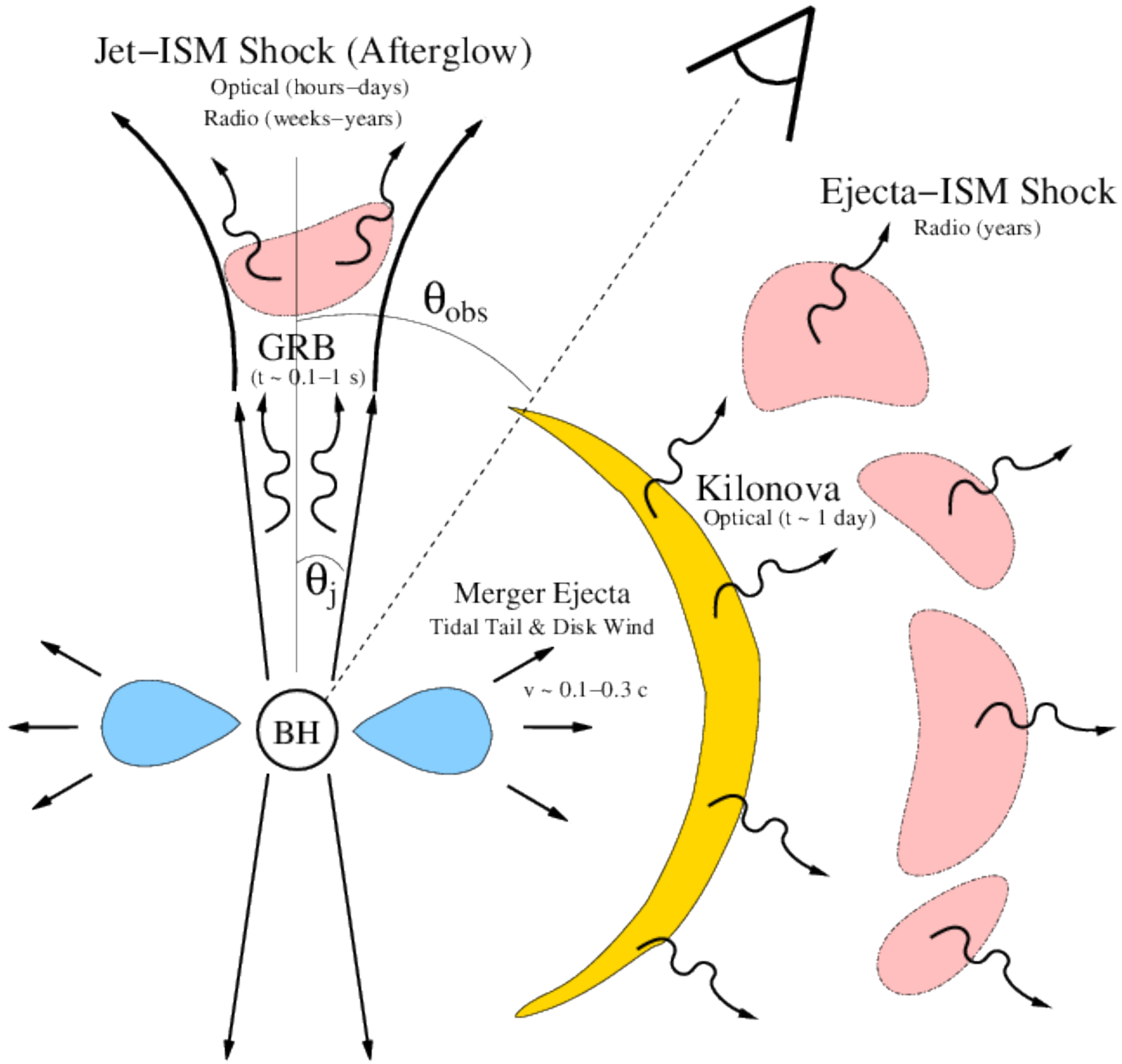
- large uncertainty in the composition of the materials leads to various expected colours, duration (a few days) and luminosities (~10^{40} erg/s)
- **previous observational evidences based on chromatic excesses in short GRB afterglows** (e.g. GRB 130603B, GRB 060614, GRB 050709)

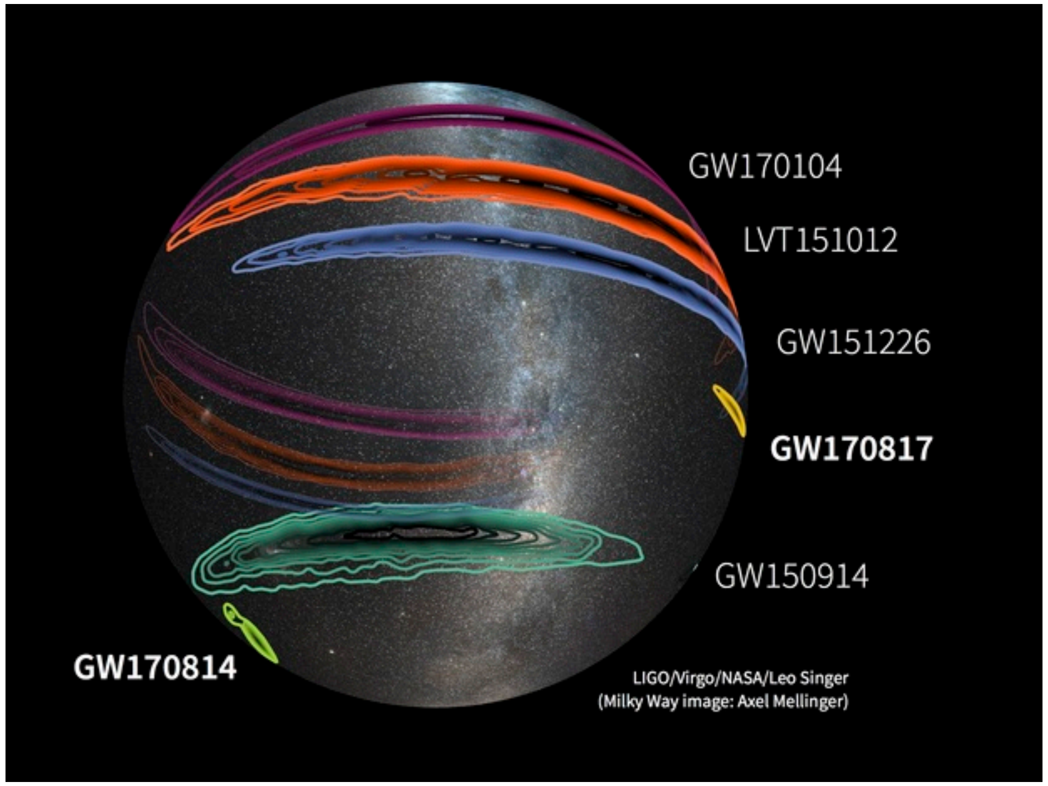
Fast evolving, multi-wavelength transients…

Short GRB:

- Prompt MeV emission (< 2 s)
- Multiwavelegth afterglow emission: TeV, GeV, X-ray, optical and radio (minutes, hours, days, months)

Kilonova: UV, optical and NIR (Hours, days)





… in large (100 deg) skymaps

Follow-up strategy

Need to cover huge sky maps (hundreds of square degrees)	Wide-field telescopes and/or galaxy-targeted searches	**WIDE**
Need to find and rank candidates	Dedicated strategies/pipelines	**FAST**
Need to characterize interesting candidates	Large area telescopes for photometry and spectroscopy of the candidates	**DEEP**

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)
S. Piranomonte

Science Board
M.G. Bernardini (PI)
M. Arca Sedda, M.T. Botticella, R. Ciolfi, S. Cristallo, F. D'Ammando, A. Melandri, A. Rossi, M. Pilia

WG4
RADIO FOLLOW-UP
M. Giroletti

WG5
HIGH ENERGY PROMPT & FOLLOW-UP
A. Bulgarelli

WG6
THEORY
M. Bulla

WG7
ARCHIVING & WEB
L. Nicastro

More than 100 scientists from 21 Institutes (INAF + Italian Universities and research institutes), born in 2013 specifically for the search and characterization of EM counterparts of GW candidate events detected by LVK from high energies to radio

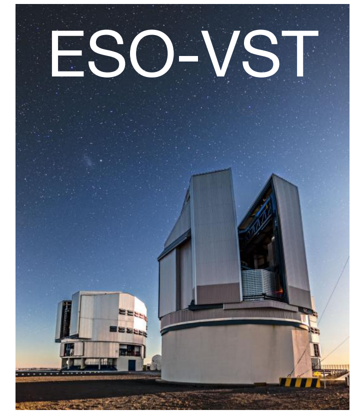
GRAWITA coll. meeting, Padova (2026)

GW 150914 : the dawn of the GW era

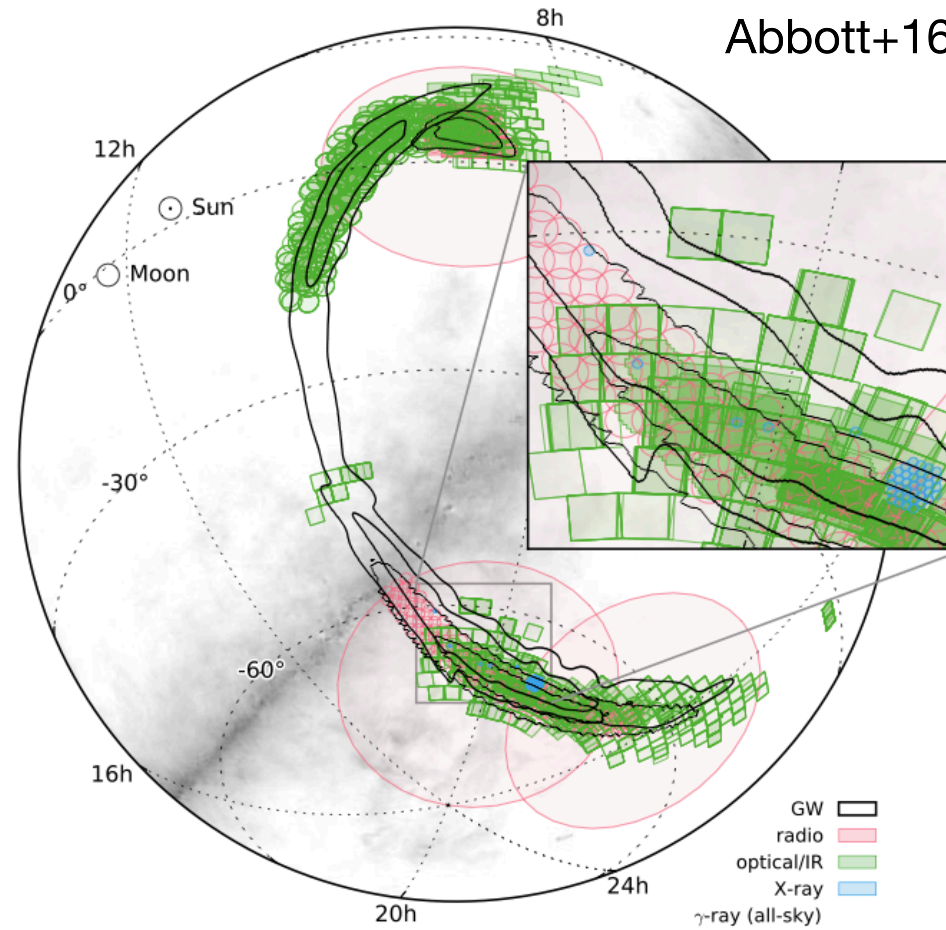
Wide-field search (skymap ~ **600 deg²**):

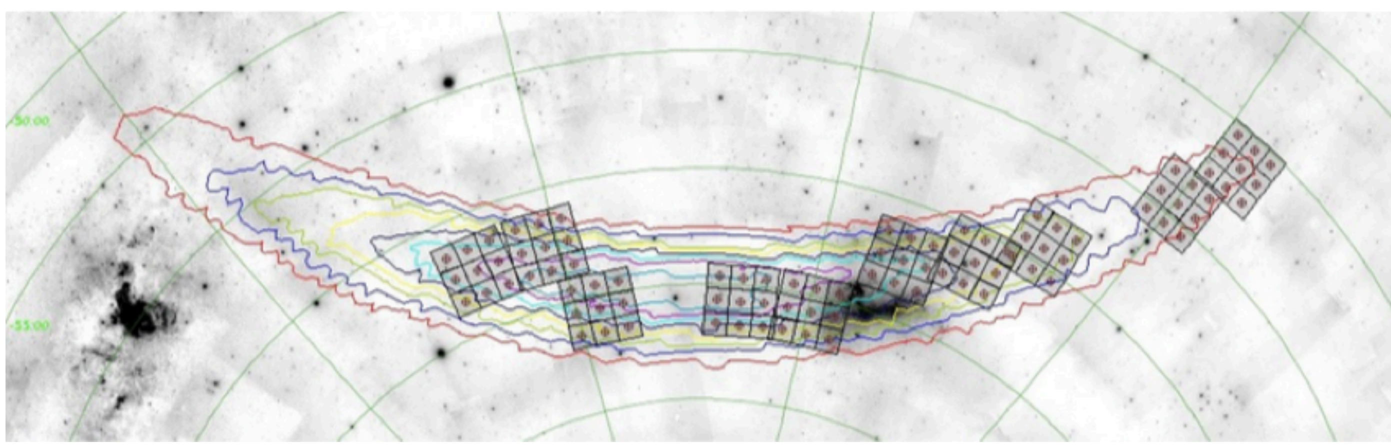
- **FAST**: 23h after alert
- **WIDE:** 90 deg² of large contained probability
- **DEEP**: r_{lim}~22.5 mag

➡**no electromagnetic (EM) counterpart found (but none expected since it was a BBH merger)**

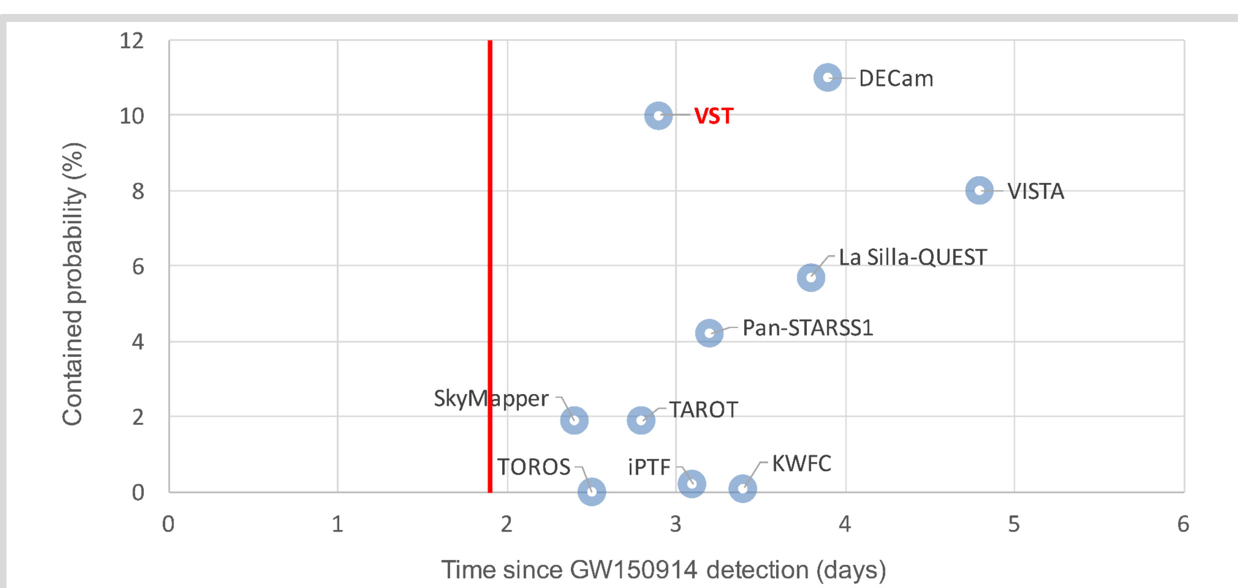


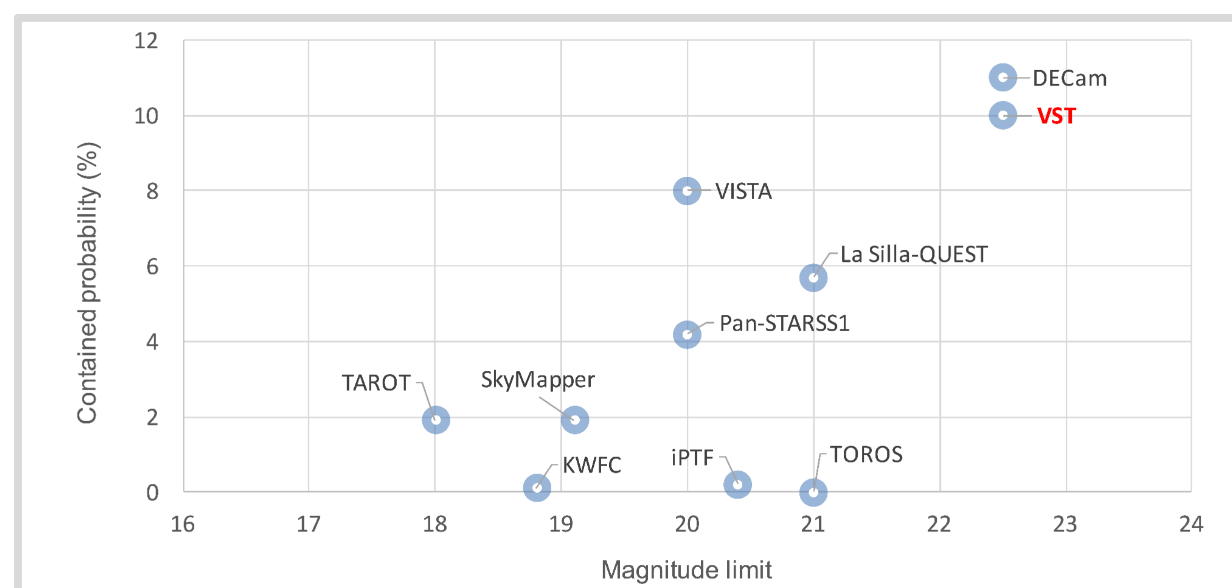
Abbott+16



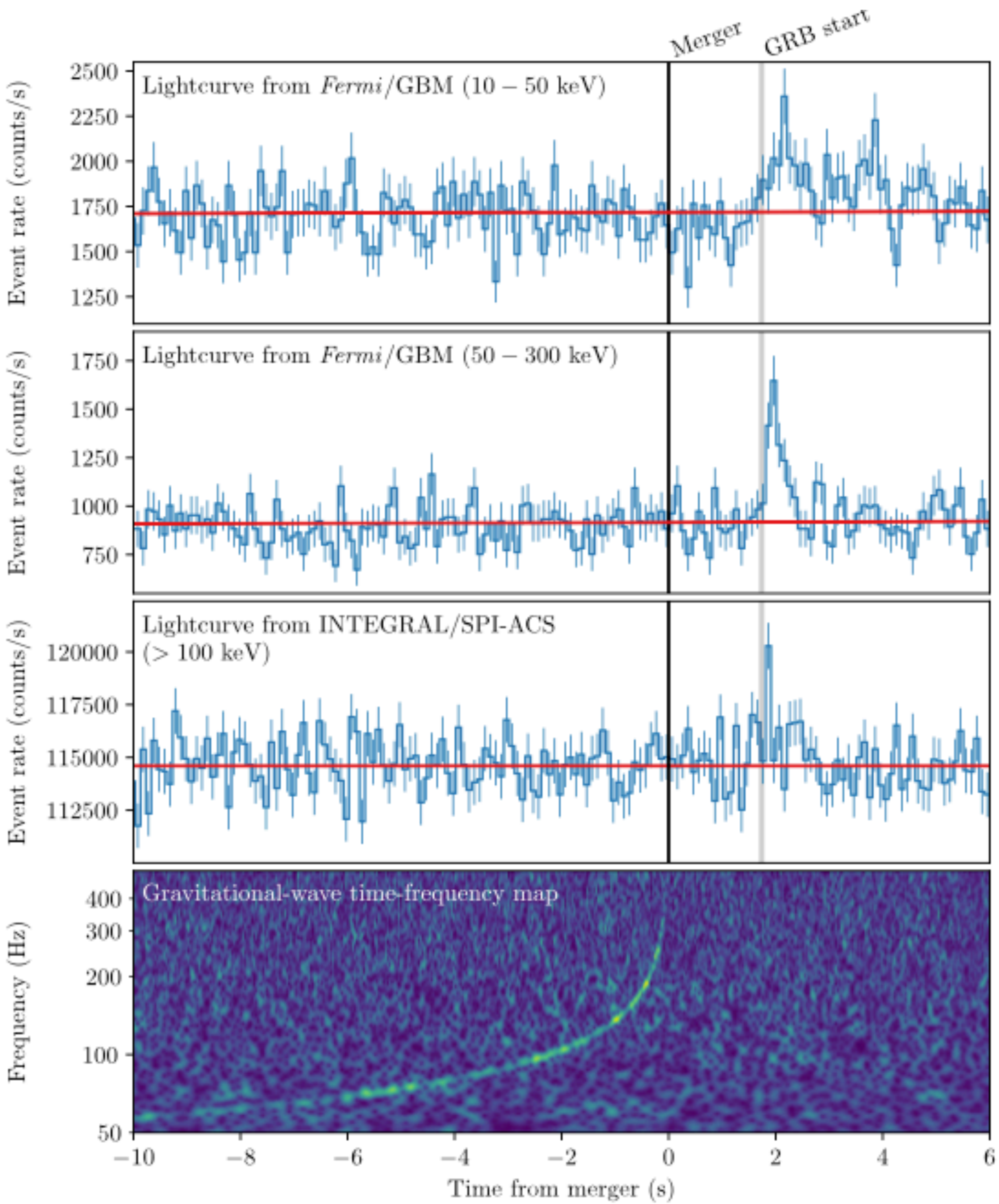


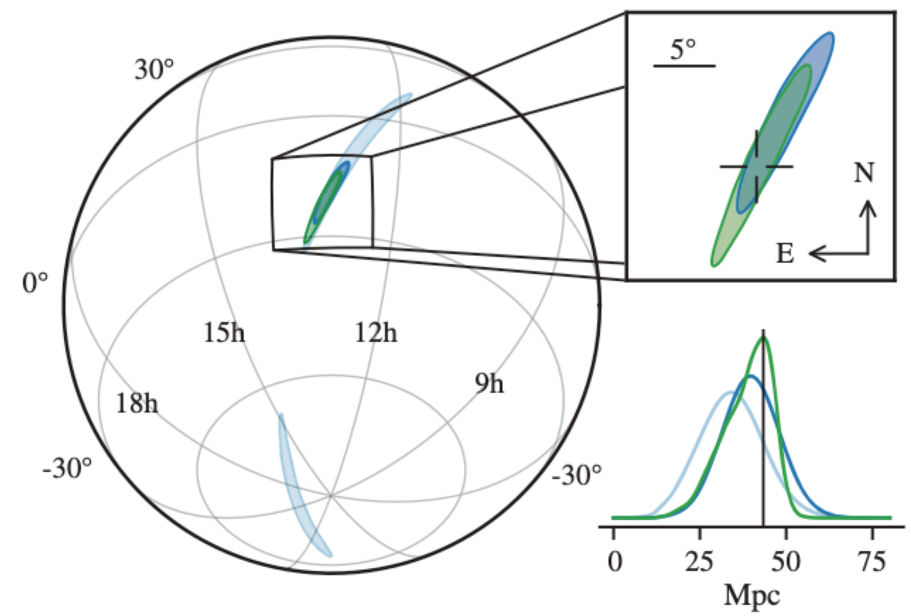
Brocato+17





GW 170817/GRB 170817A: the birth of MM astronomy with GW





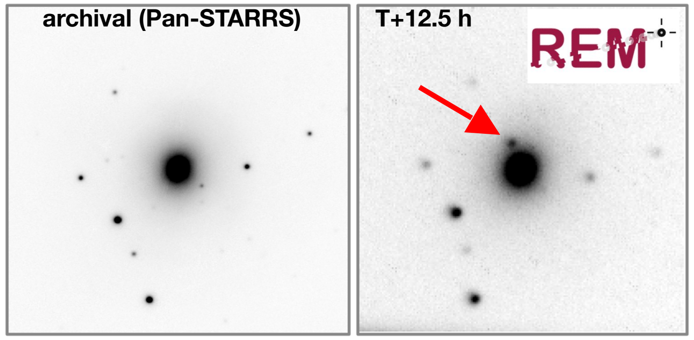
- On August 17, 2017: first observation of a **binary NS inspiral GW170817**
  - Distance: 40 Mpc
  - Rapid sky loc:
    190 deg2 (HL) -> 30 deg2 (HLV)
- Coincident detection of a short GRB from Fermi/GBM and INTEGRAL

➡**First MM detection with GWs**

➡**First proof that BNS mergers are progenitor of short GRBs**

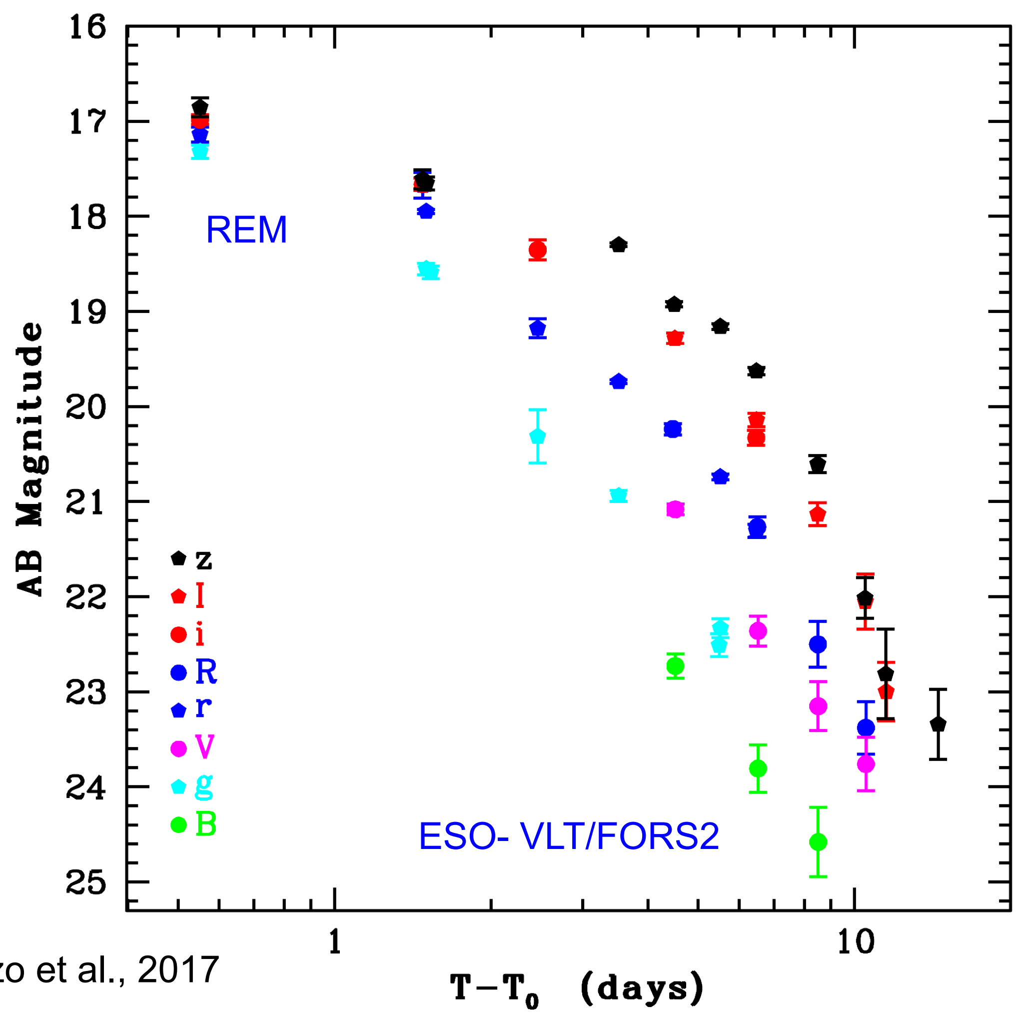
Abbott+17a,b; Goldstein+17; Savchenko+17

AT 2017gfo, the first spectroscopically identified kilonova



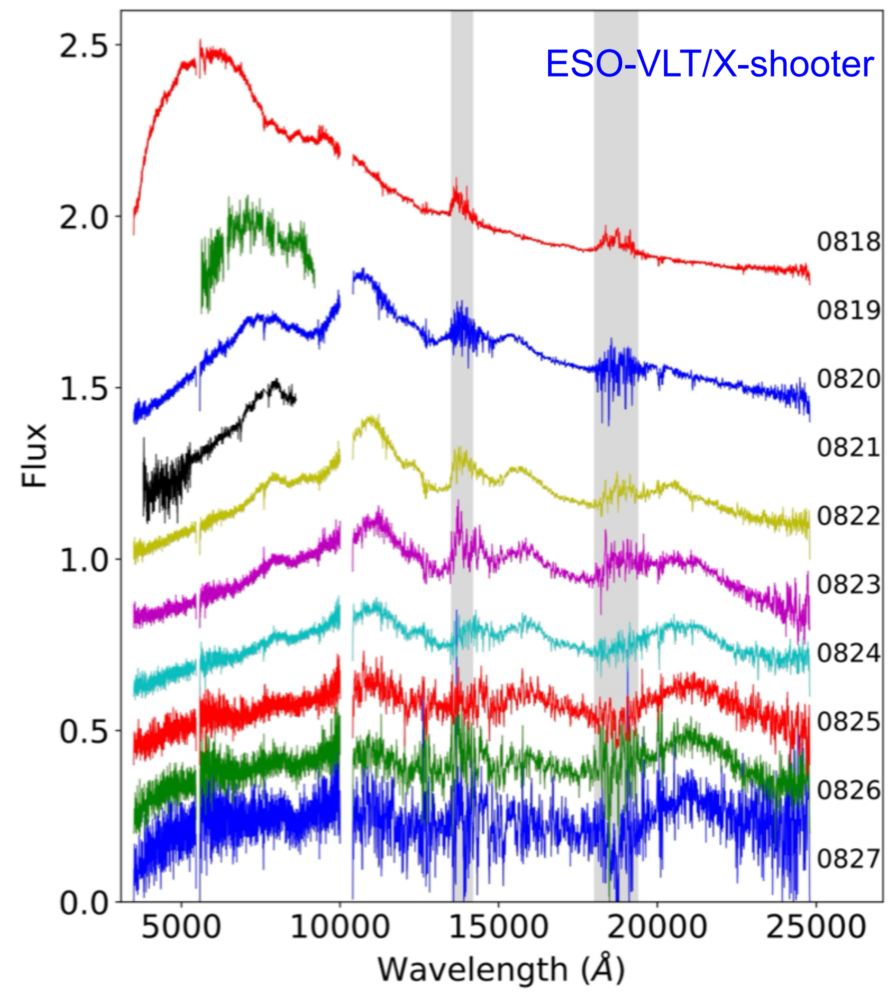
Pian, D'Avanzo+2017; Arcavi+17; Coulter+17; Evans+17; Lipunov+17; Smartt+17; Soares-Santos+17; Tanvir+17; Valenti+17, Lyman+17, Villar+17; Margutti & Chornock 21 and many many others

KN light curve



Pian, D'Avanzo et al., 2017

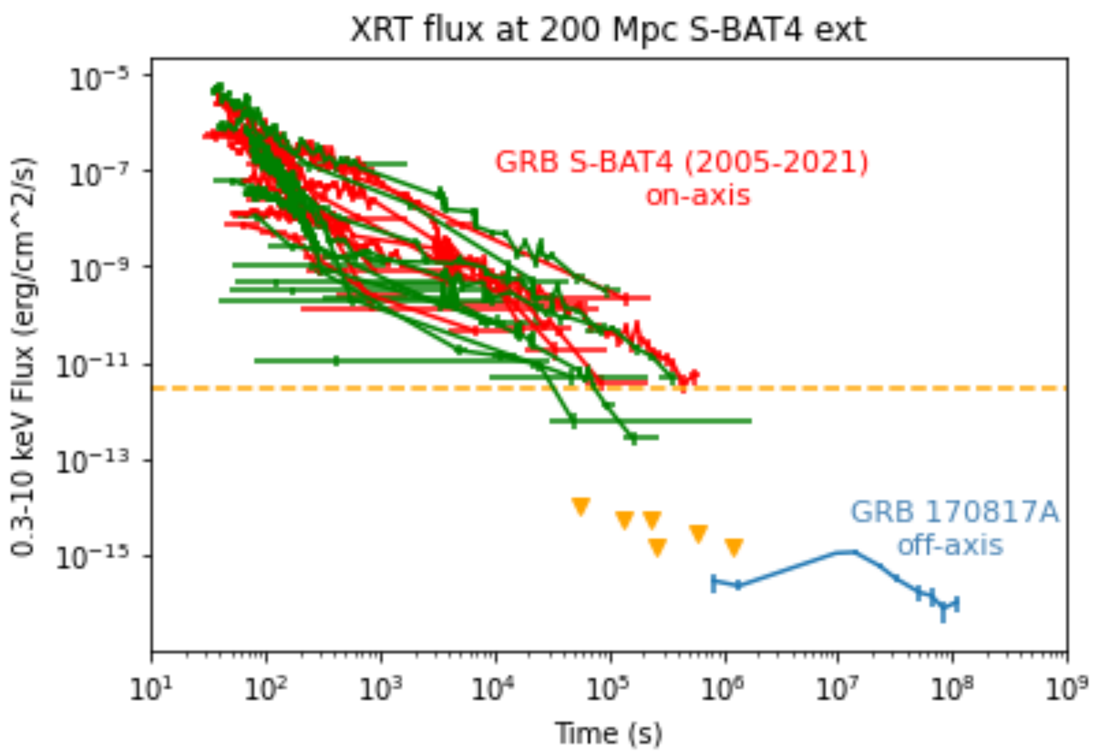
KN spectral sequence



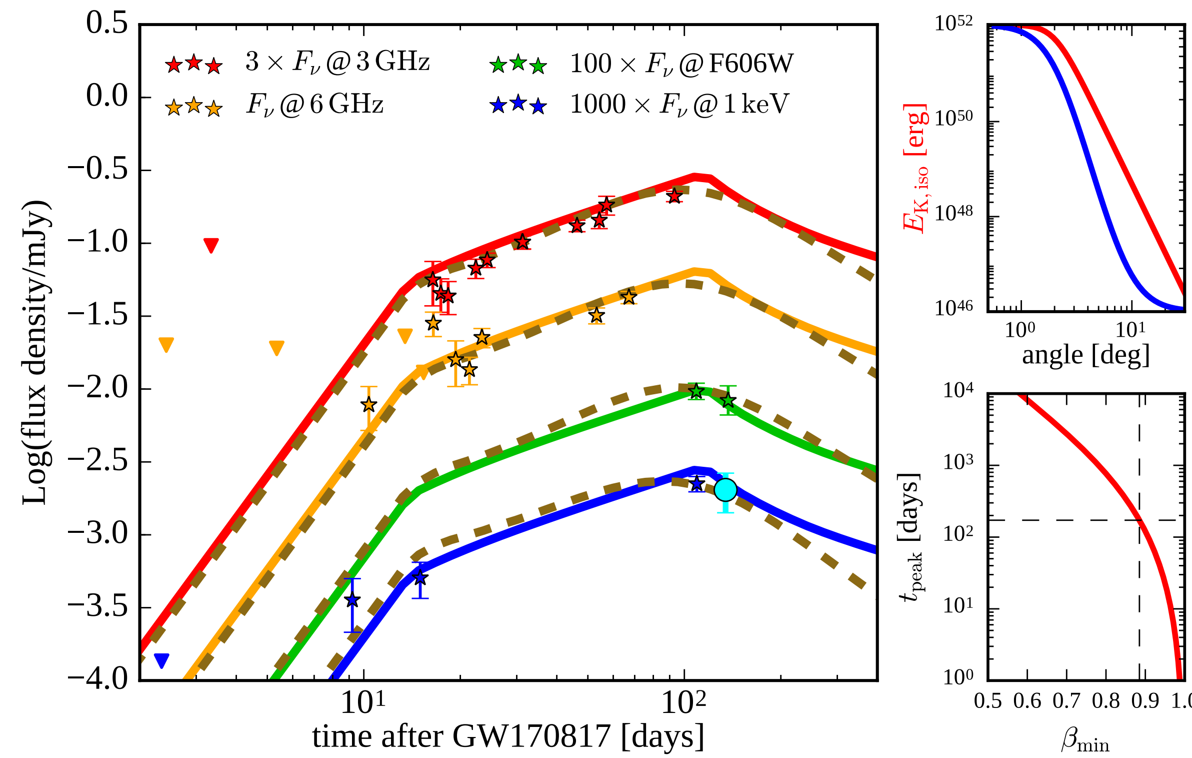
➡ First spectroscopic identification of a kilonova and evidence that BNS mergers can produce heavy r-process elements!

GRB 170817A: proof of the jet structure

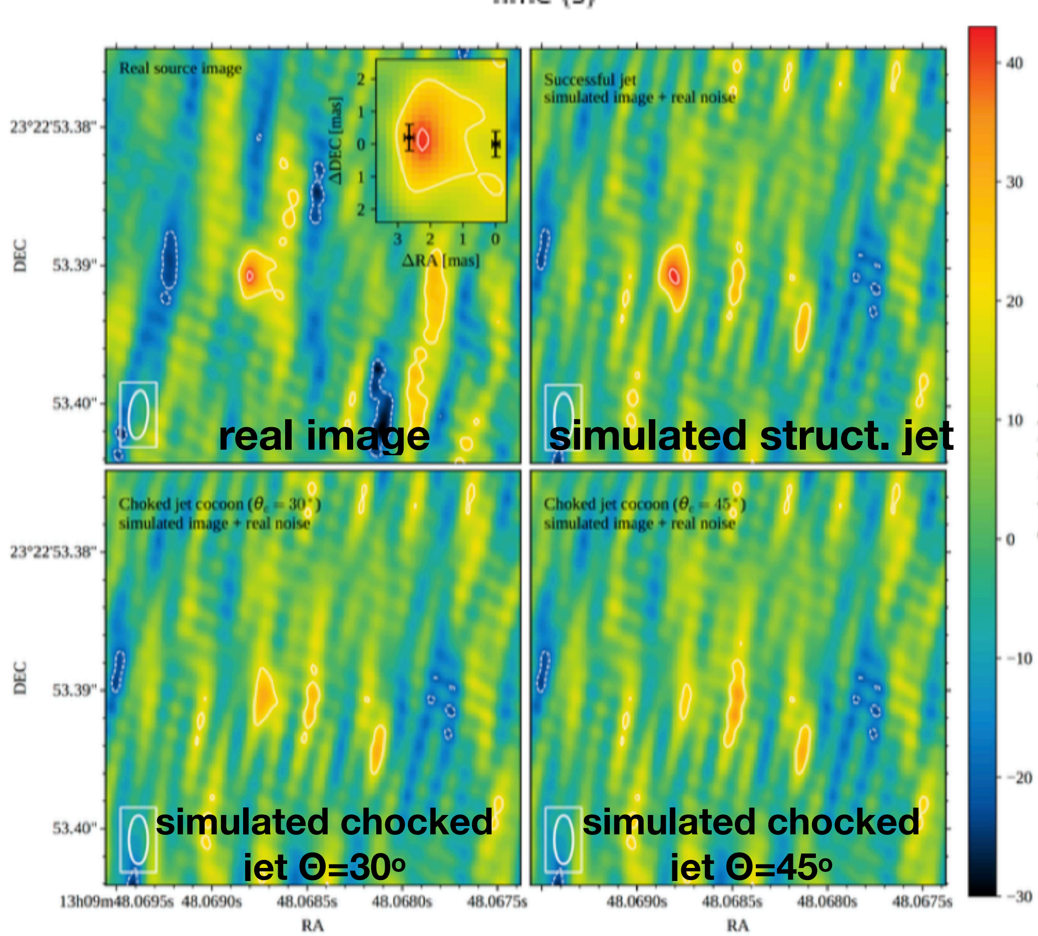
Alexander+17,18; D'Avanzo+18; Dobie+18; Fong+19; Haggard+17; Hallinan+17; Hajela+19; Margutti+17,18; Mooley+18a,b; Reasmi+18; Ruan+18; Troja+18a,b,19,20; Ghirlanda+19; Piro+19; Margutti & Chornock 21 and many many others



Credit: M. Dinatolo



D'Avanzo+18



Ghirlanda, Salafia+19

- 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

Towards a European collaboration for GW counterparts

www.pesto.org

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

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

www.grawita.inaf.it

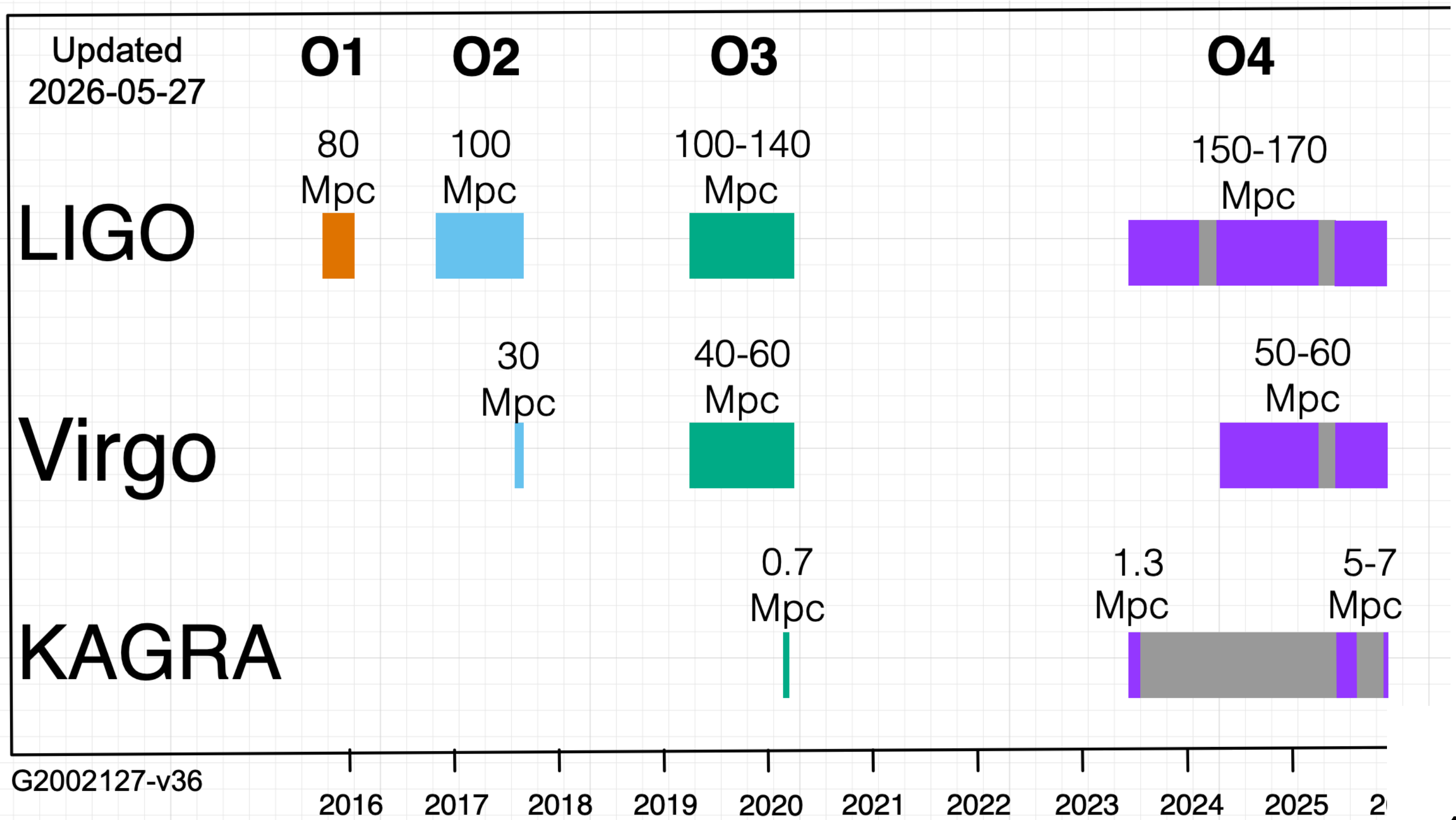
www.engrave-eso.org

<u>Governing Council</u>: M. Branchesi, E. Brocato, P. D'Avanzo, J. Hjorth, P. Jonker, E. Pian, S. Smartt, J. Sollerman, D. Steeghs, N. Tanvi
<u>Executive Committee</u>: M. Fraser, A. Levan, K. Maguire, D. Malesani, **O.S. Salafia**, S. Vergani
<u>WG leaders</u>: **M.G. Bernardini, M.T. Botticella, L. Izzo,** A. de Ugarte, S. Schulze, D. Young, **A. Perego,** J. Chen, **S. Piranomonte**

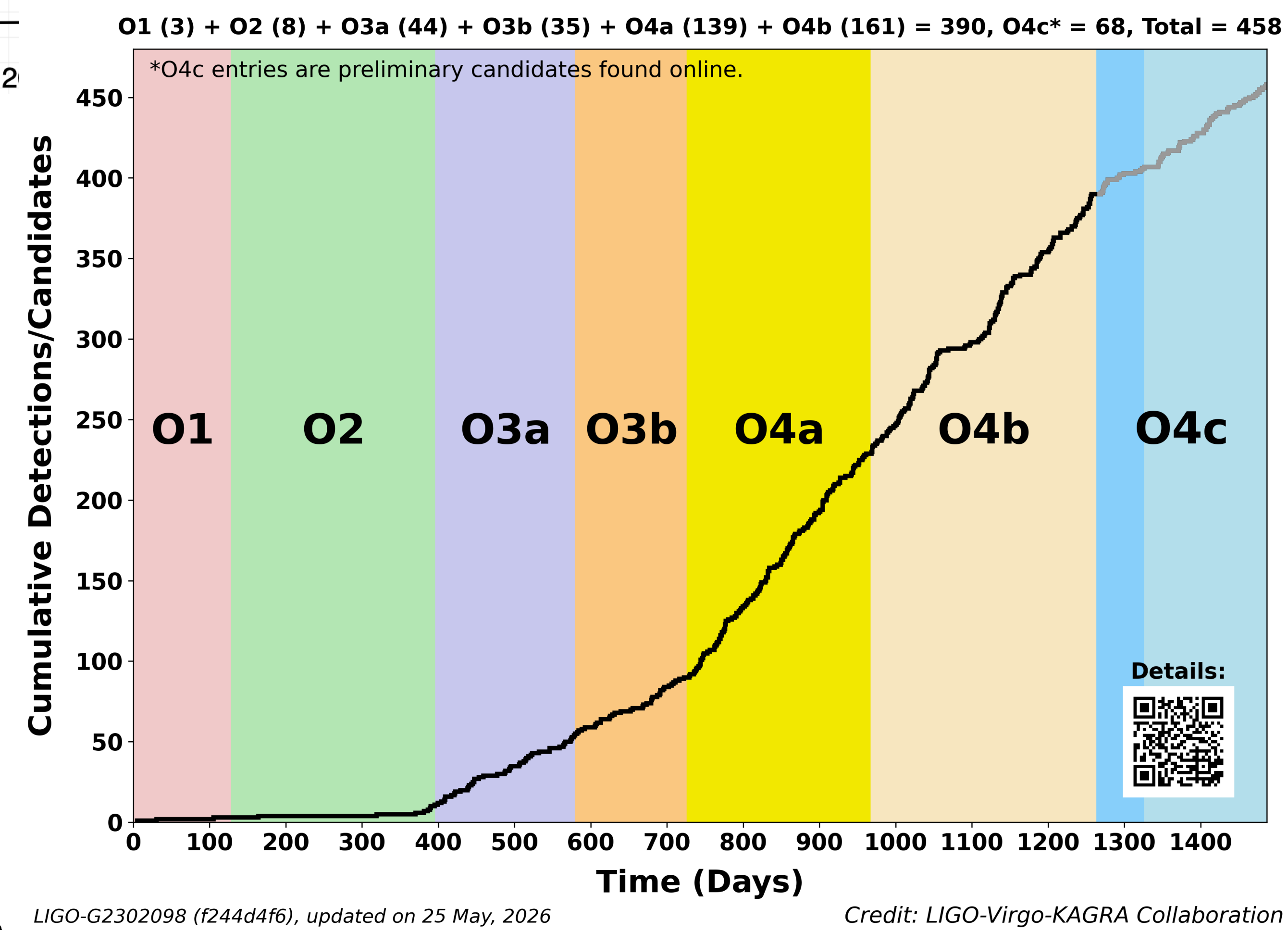
A collaboration of ~ 250 ESO scientists

- Approved programs during O3 and O4
- Time for EM counterparts **follow-up** on every useful **VLT** instrument + **ALMA, HST** and **JWST**

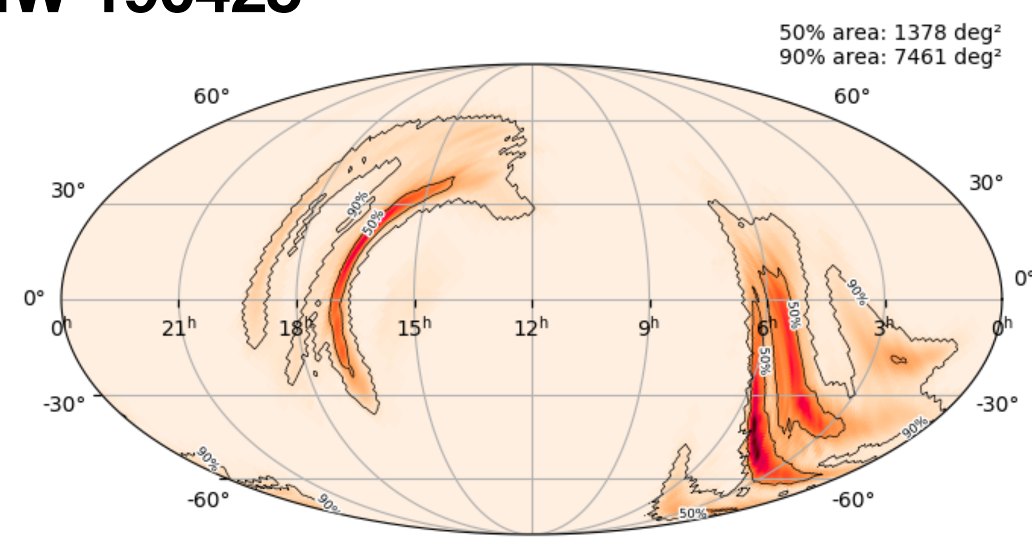
Where do we stand now?



- Overall, 458 candidates discovered so far (GWTC-5 + O4c): mostly BBHs, a few are NS-BH binaries or mass gap systems and **two are possible BNS (GW 170817 and GW 190425)**
- No further unambiguous EM counterpart detected so far

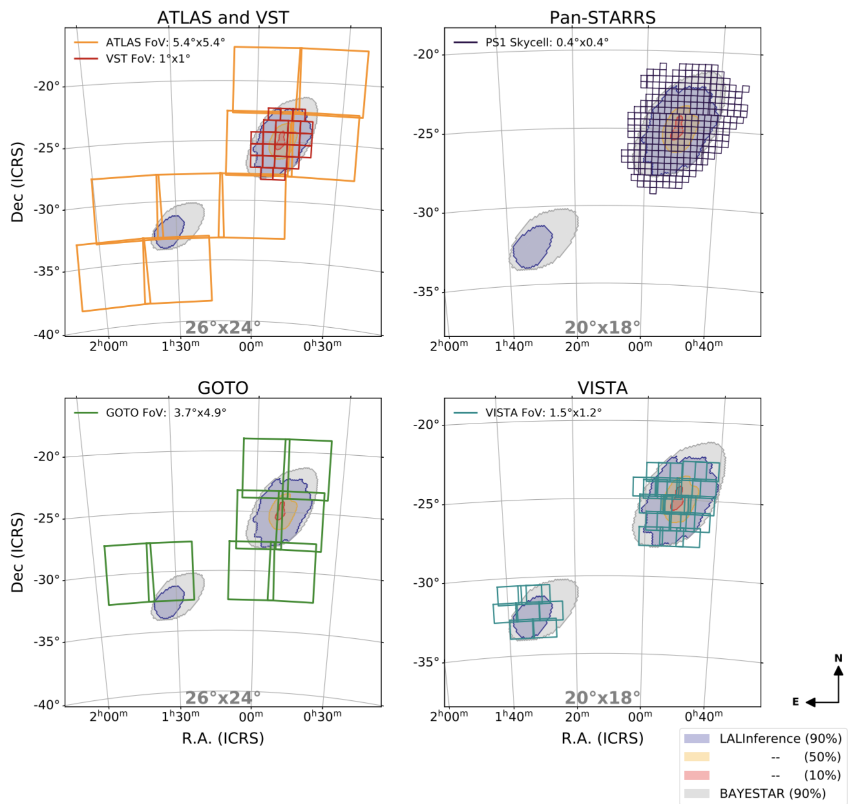


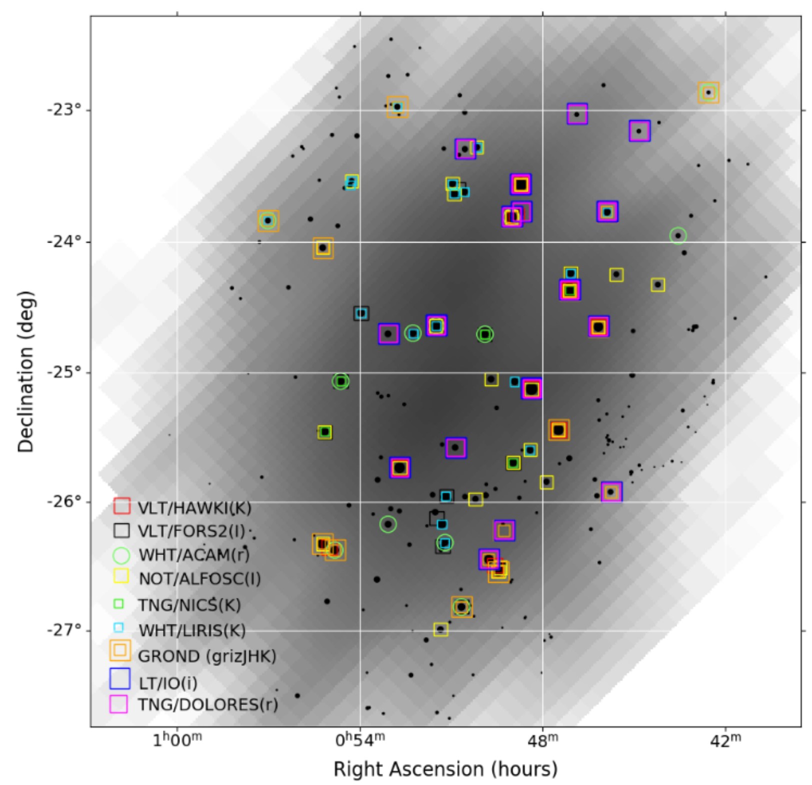
GW 190425



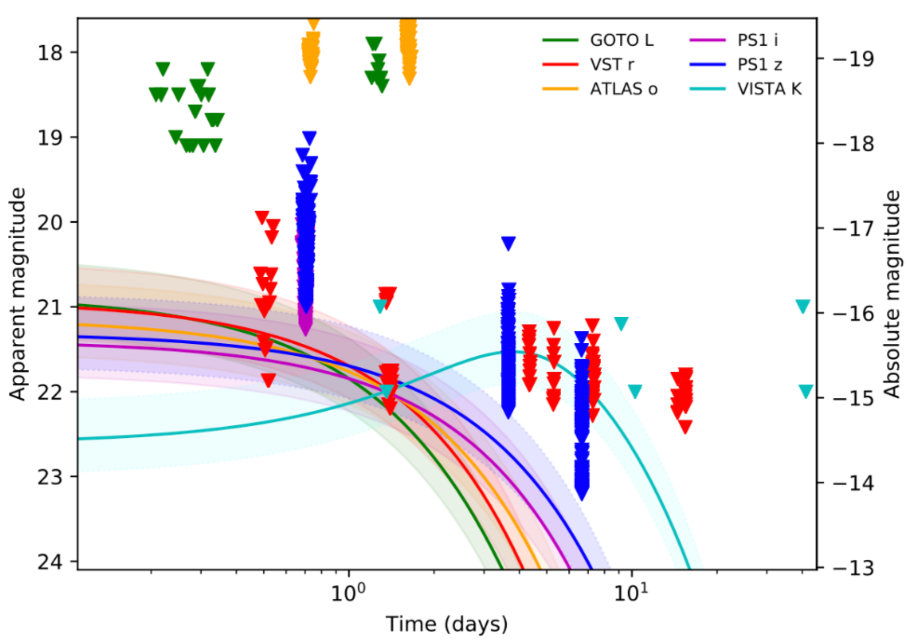
Constraints on the optical-NIR emission associated to GW 190814

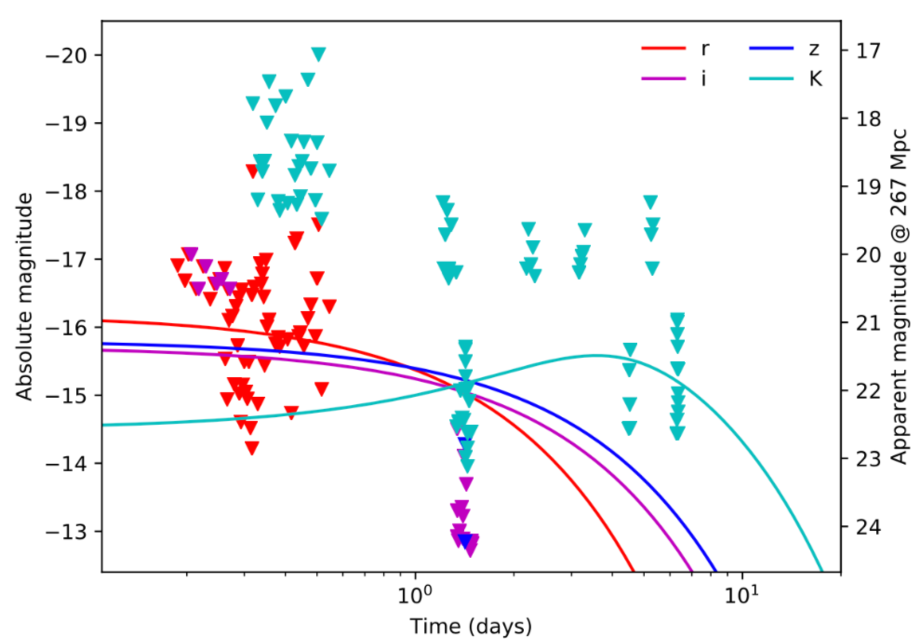
Asymmetric system of ambiguous nature, possibly a NS-BH merger





- Both wide field 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



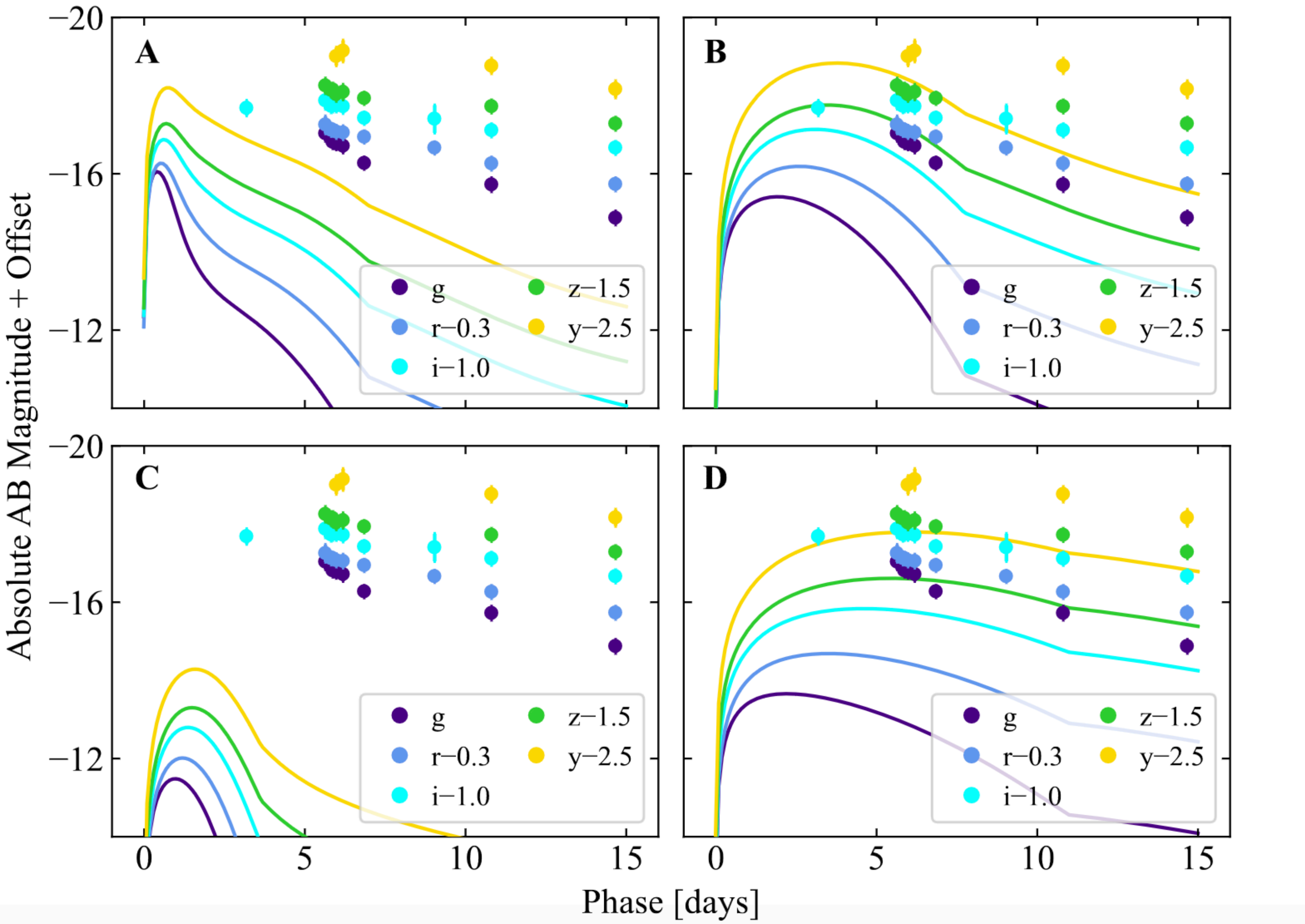


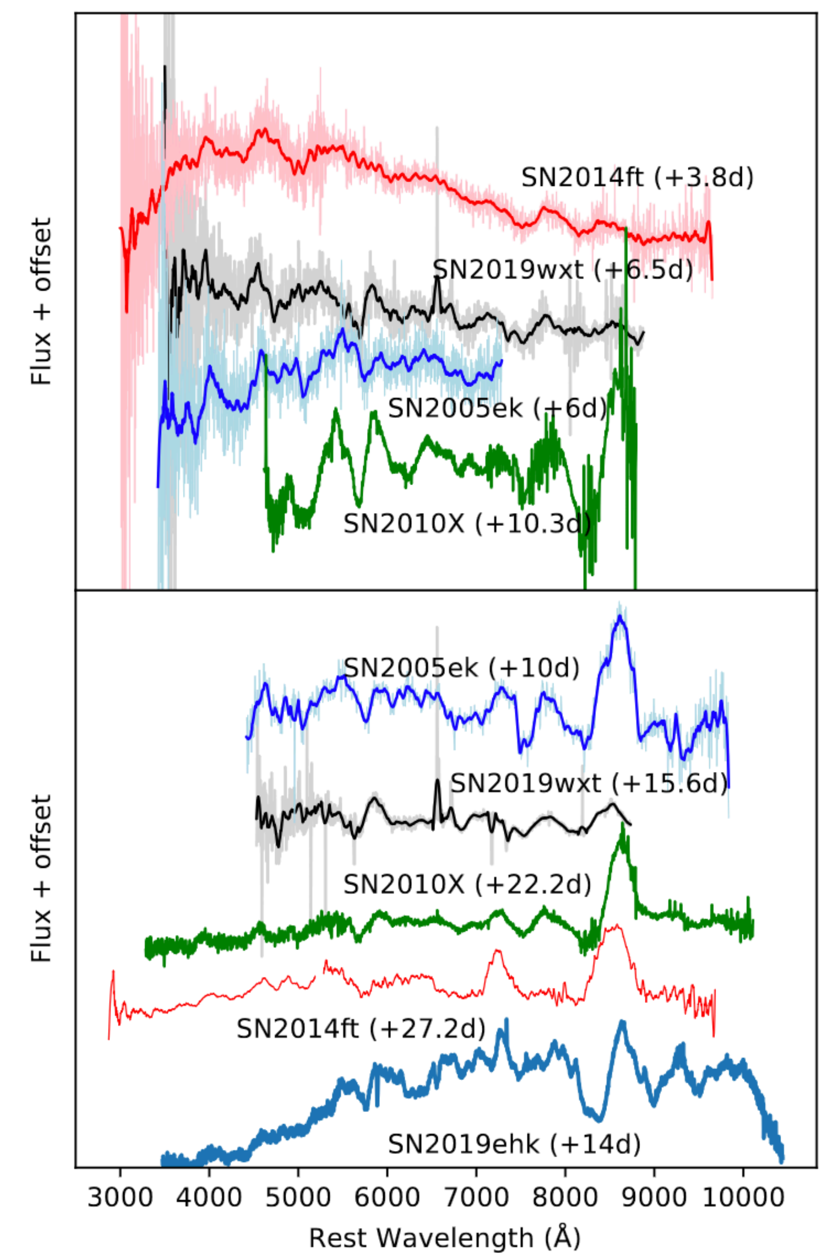
The ENGRAVE Collaboration, Ackley et al., 2020

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)



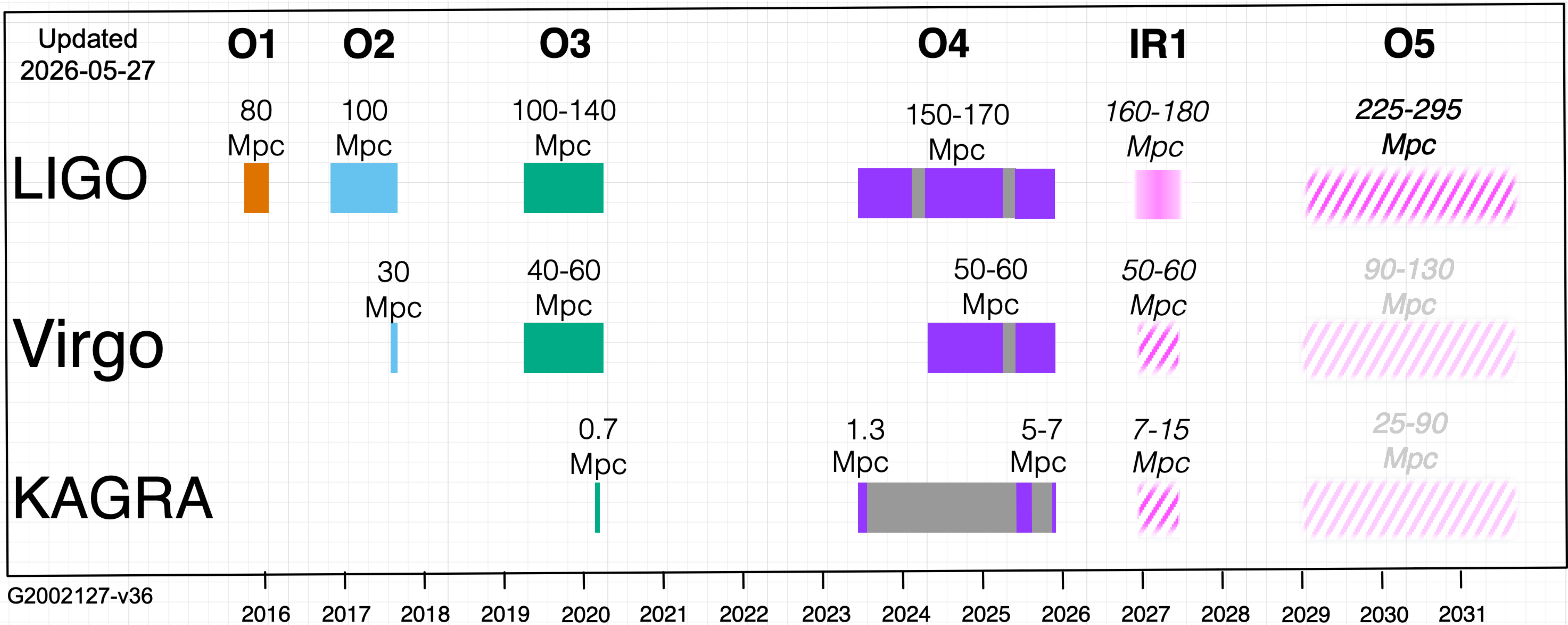


Not a KN, but a peculiar SN

The ENGRAVE Collaboration, Agudo et al., 2023

The near future

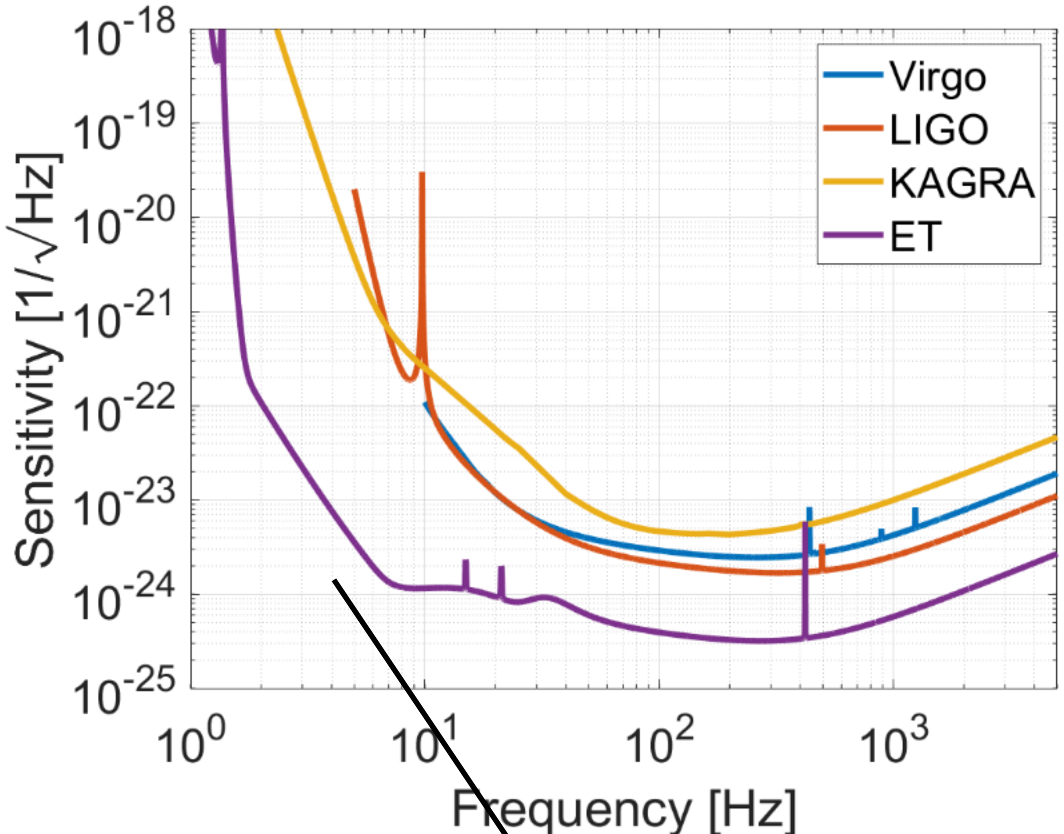
https://observing.docs.ligo.org/plan/

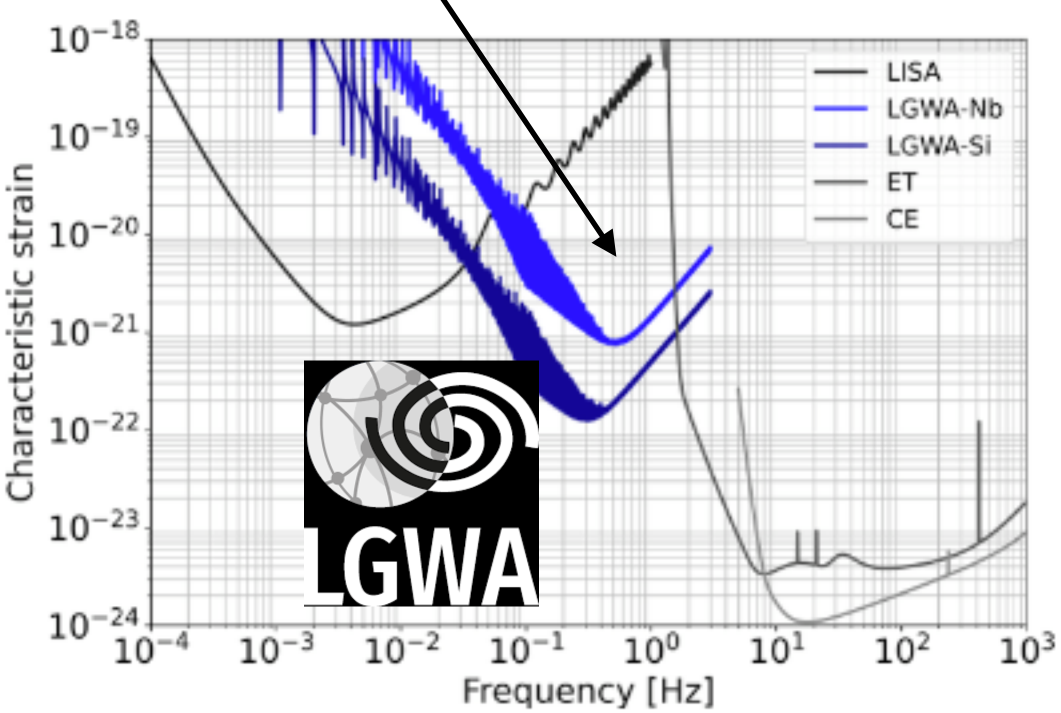


- **Intermediate run 1 (IR1)** announced for the **late 2026**: both LIGO detectors will be observing in IR1. Virgo will join but with possible interruptions for maintenance and upgrade, and KAGRA will join as available
- Plans and timeline for the O5 are being refined

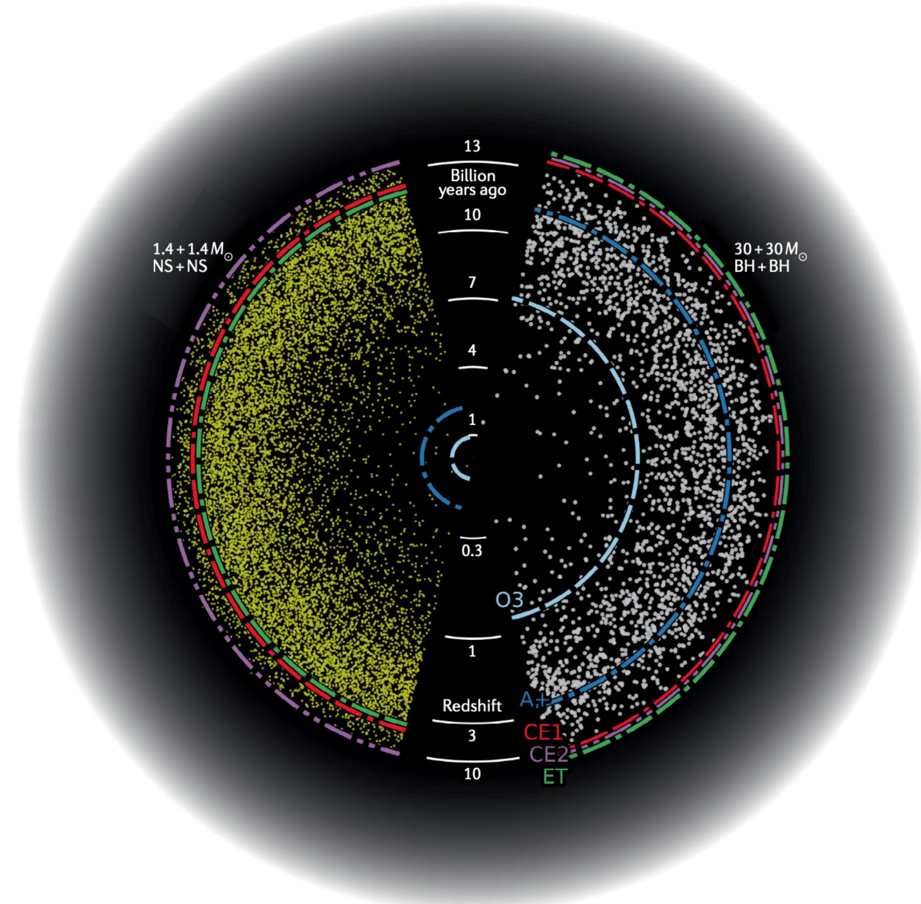
The 3rd generation: Einstein Telescope (ET)

Branchesi et al., 2023 JCAP





ET blue book (2026)
LGWA science white paper (2023)



Bailes et al., 2021 Nature

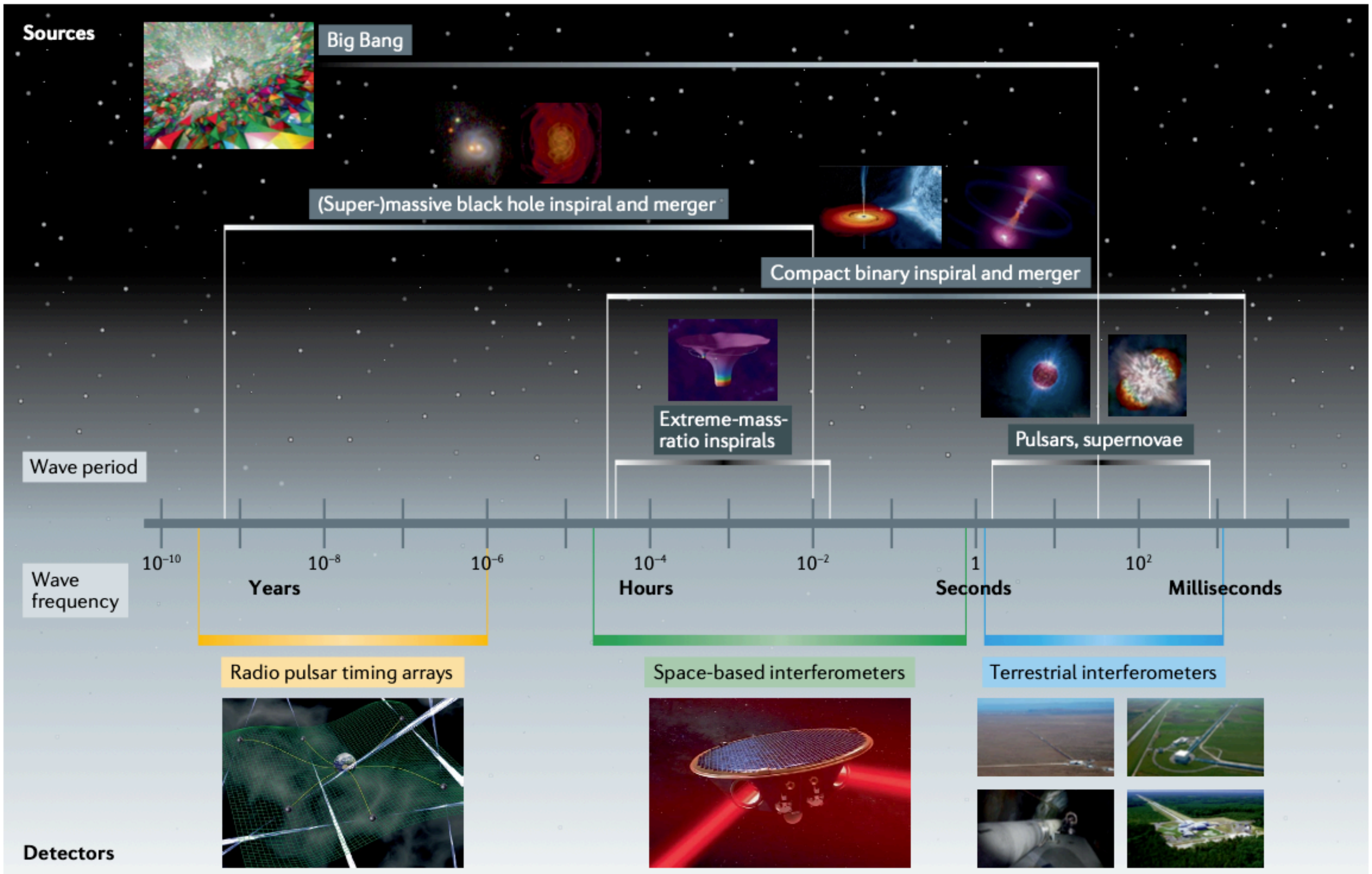
- 10 times more sensitive than 2G detectors (10^3 times larger volumes)
- Wider frequencies (lower freq.)

➡ Higher redshift accessible:

- Study BNS/NSBH along the cosmic history
- Increase of the detection rate
- Better parameter estimation
- Early warning alerts (+LGWA)

The MM landscape

Not only from ground: new ranges of mass accessible (and new physics to probe)



The GW physics and astronomy in the 2020s and 2030s, Nat.Rev. (2021)

Where do we stand?

- GW 170817/GRB 170817A/AT 2017gfo marks the **birth of multi-messenger astronomy with GWs:**
  - ✓Definition and consolidation of successful follow-up strategies
  - ✓First GW EM counterpart (at all wavelengths)
  - ✓First unambiguous observational evidence for a kilonova
  - ✓Evidence for KNe 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)

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

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

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- **Still a number of open issues:**
  - What about NSBH counterparts?
  - What is the origin of the blue KN component?
  - Are all BNS mergers associated to a short GRB?
  - How to unveil the nature of the BNS remnant?
  - **Do binary mergers have a VHE counterpart?**
    - GRBs are detected at TeV energies (D. Miceli & A. Carosi's talks)
    - IACTs f.o.v. increasing and optimised follow up strategies (A. Stamerra's talk)

    ➡ **Great perspectives with both Astri and CTAO**

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Einstein Telescope:
- Routinely detect GW associated to short GRBs
- Early warning alerts help in reducing the latency for follow-up (e.g. Banerjee+23)

Where do we go?

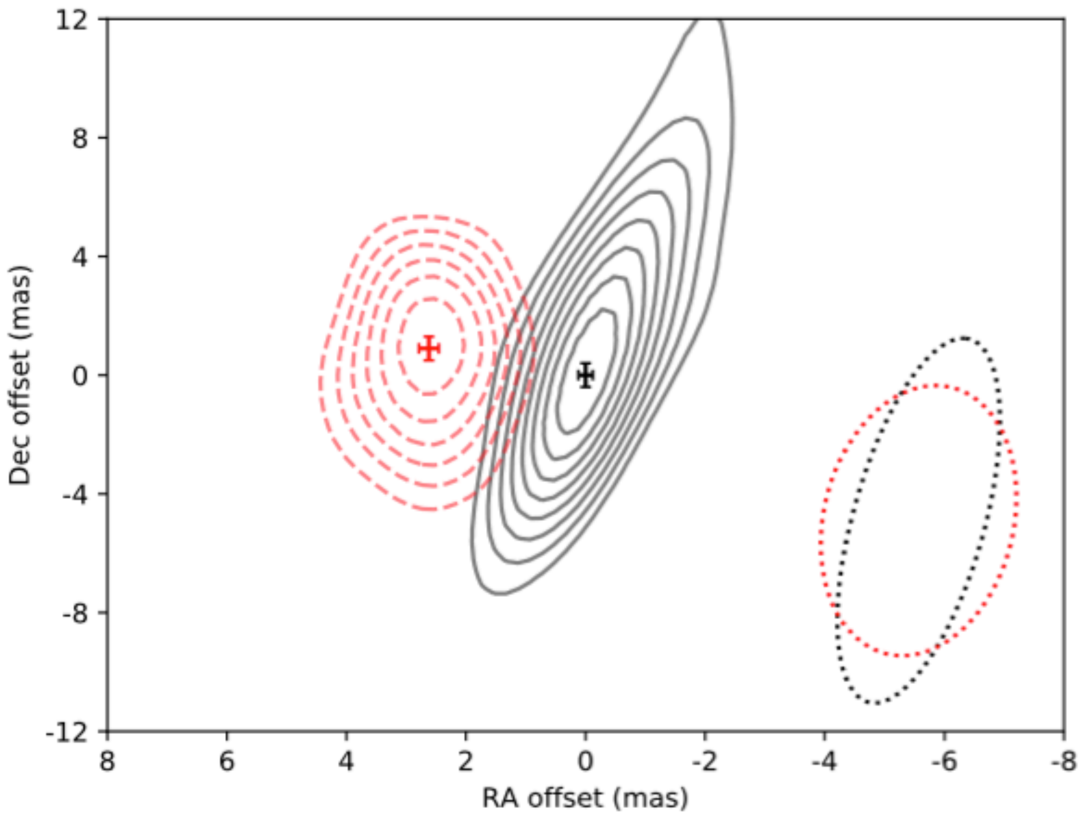
- **Trigger & alert generation:**
  GW, neutrino detectors, high-energy satellites (?), and wide-field optical and radio surveys (e.g. Rubin, SKA) issue real-time alerts for transient and multi-messenger events.

- **Rapid localisation and identification:**
  Networks of high energy/UV/optical/IR and radio facilities – from 1–4 m class telescopes to VLT/ELT, SKA, ngVLA, CTAO and future GW/neutrino detectors – rapidly refine positions, associate host galaxies and obtain first-epoch spectra.

- **Classification and physical characterisation:**
  High-throughput spectroscopy and IFUs, combined with high-resolution imaging, deliver ejecta velocities, composition, energetics and environmental diagnostics.

Backup slides

GRB 170817A: evidence for a structured jet



Mooley+18

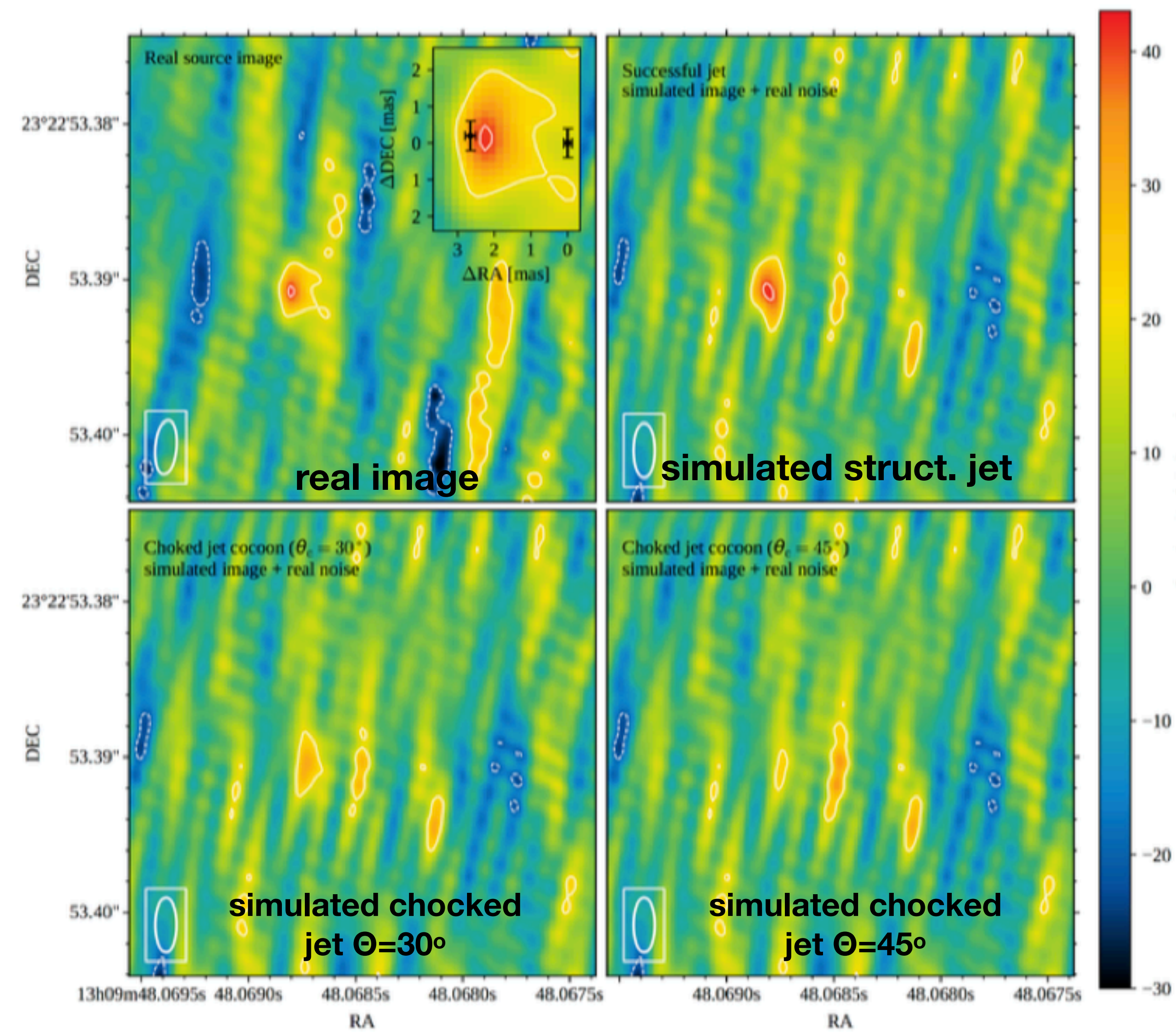
- Evidence for a proper (superluminal, v/c=4.1+/-0.5) motion with **VLBI** data (75 and 230 days) Mooley+18

➡**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