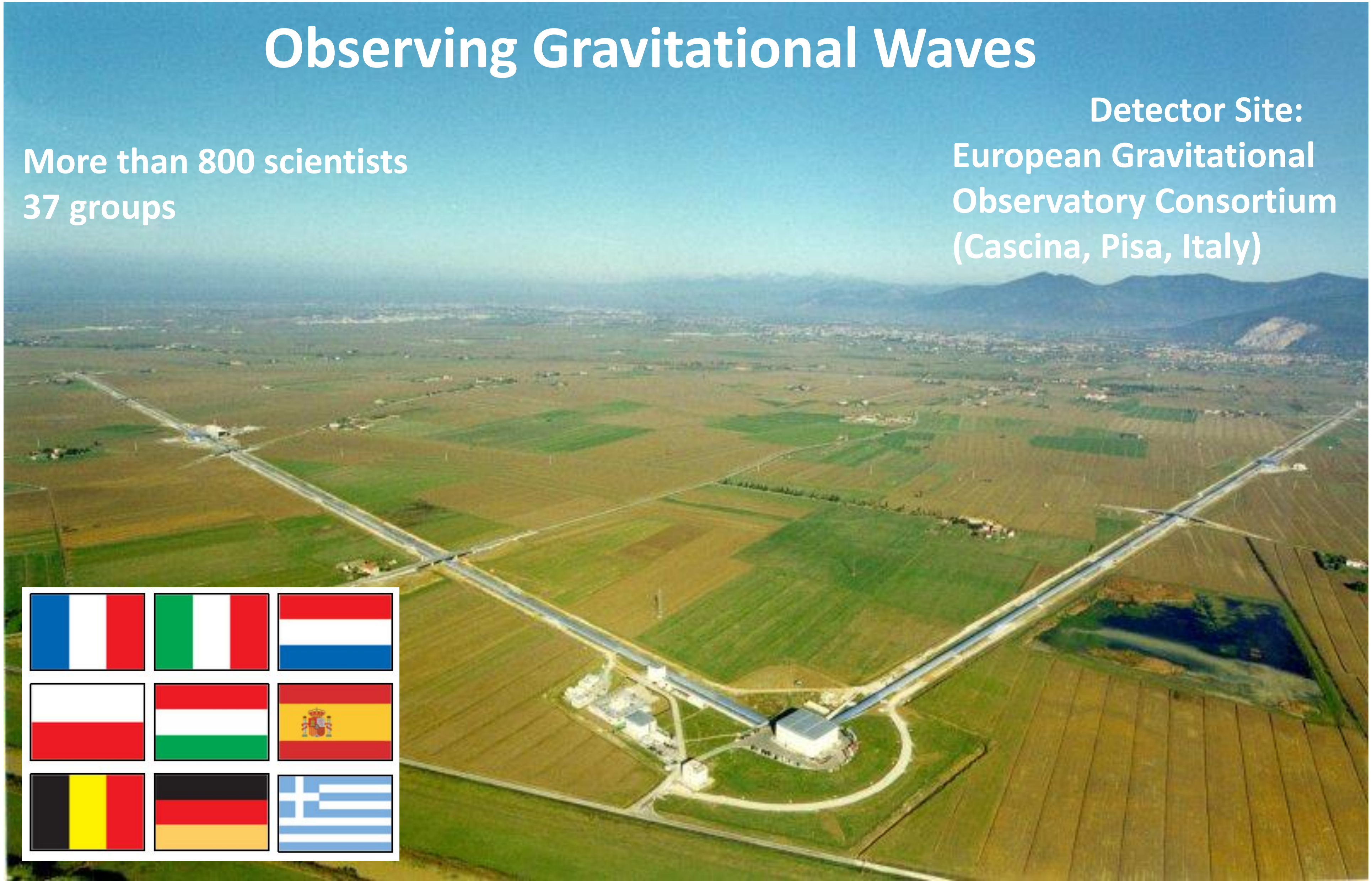
VIRGO



a large collaboration

LIGO & Virgo coordinating detector upgrades

Joined by **KAGRA collaboration (Japan)**

- joint strategies for observing runs and data analysis;
- prompt public alerts for multimessenger astronomy.
- Virgo detector joined current observing run O4 in March 2024, but with spectral sensitivity similar to O3
- Current observing run planned till Nov.2025

Virgo Group at TIFPA

Composition	FTE 3.7
Giacomo Baldi	0.2
Matteo Leonardi	0.3
Albino Perego	0.2
Antonio Perreca	-> June’25
Giovanni Prodi	0.7
Marco Zanatta	0.2
Andrea Miani	-> April’25
Paul Lagabbe	0.4
Sophie Bini	-> Aug’24
Alessandro Martini	1.0
Denis Nabari	0.7
Filippo Lusvardi	LM
Anna Cisamolo	LM
Damiano Avi	Technician

activities:

- **Virgo Detector upgrade and commissioning**
  - Mode Matching sensing for squeezed light injection
  - Quantum noise Reduction
- **R&D in instrument science**:
  - optical mode matching devices
    - optical actuators
    - Study of Mode Matching control loop
  - squeezed light sources
  - Internal friction in optical coatings

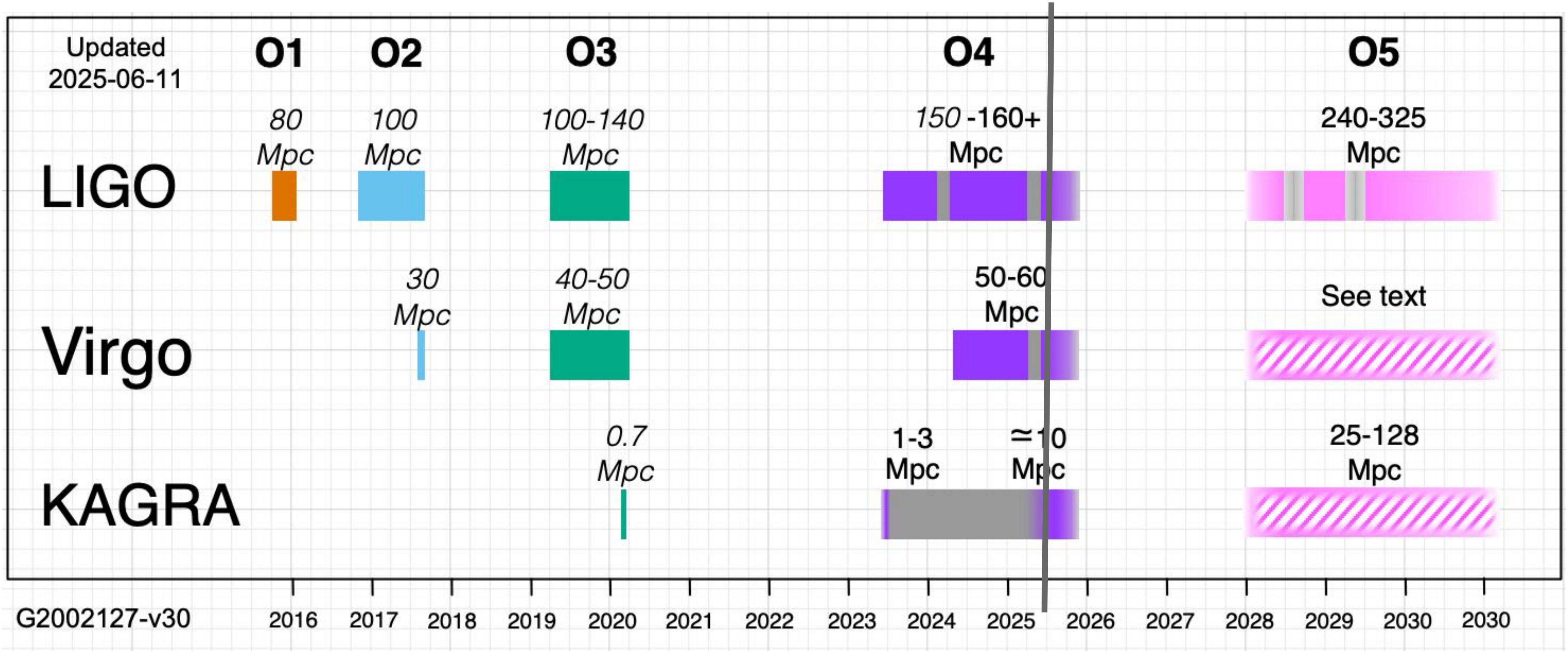
- **LIGO Virgo KAGRA observational science:** transient GWs
    - Detection: most general search for transients
    - Characterization of transients’ morphology
    - Fundamental properties of BHs and NSs
  - interpretation of NS observations
- **R&D in data analysis and modeling of GW sources**

R&D activities have large overlap with **Einstein Telescope**

LIGO–Virgo–KAGRA Gravitational Wave Surveys

- **Open data:**
- **LV** 10.1016/j.softx.2021.100658
  LV Abbott+ (2023) ApJS 267 29
  http://www.gw-openscience.org

Observing plans and prospects
https://observing.docs.ligo.org/plan/#
doi.org/10.1007/s41114-020-00026-9
LIGO-G2002127



LIGO–Virgo–KAGRA **current** Gravitational Wave Survey

- **Observing run 4**

started on May 24, 2023

public alerts in low latency
https://gracedb.ligo.org

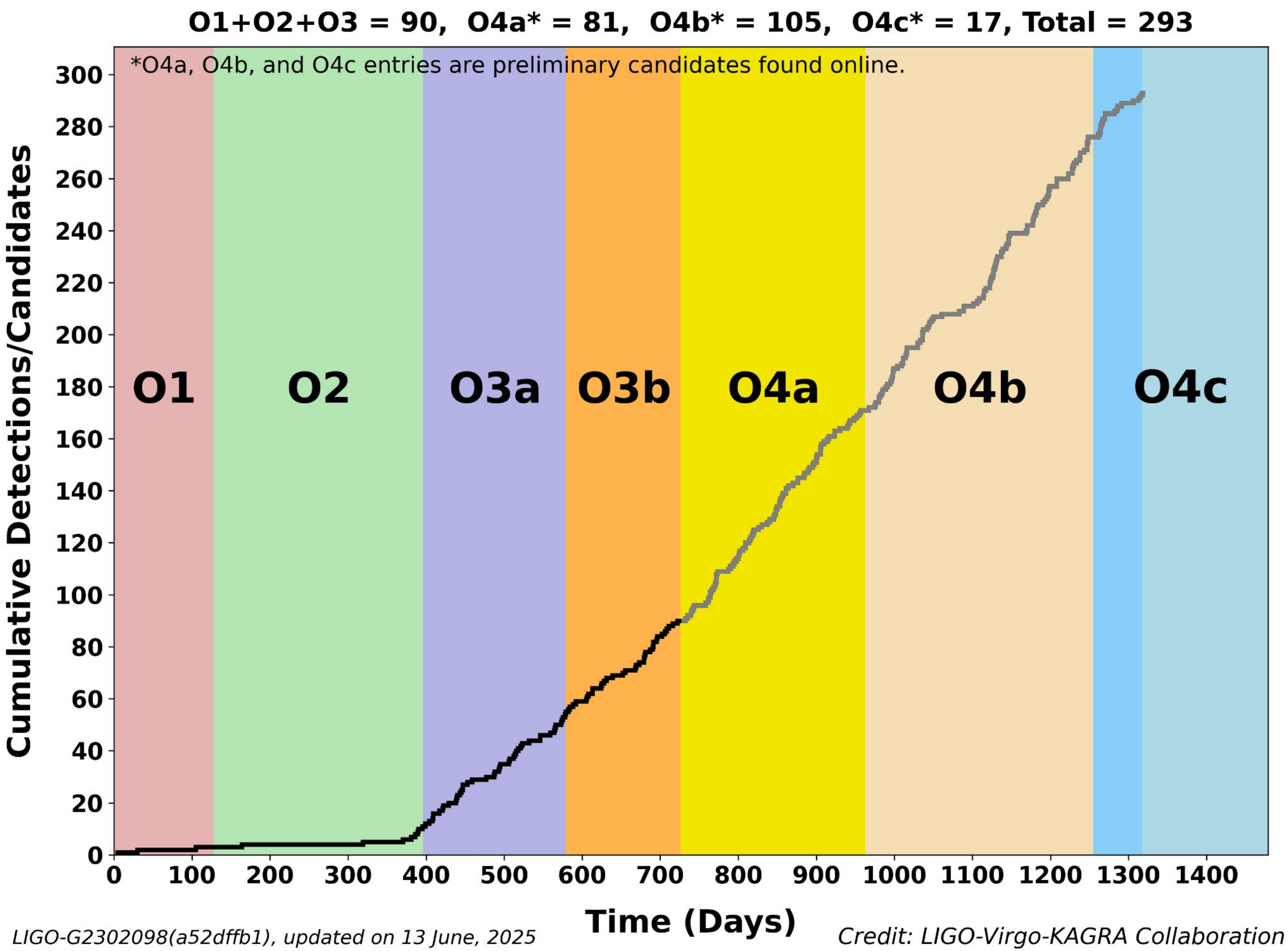
O4a: May 2023 - January 2024

LIGO operating; KAGRA operating for 1 month

O4b-c: April 2024 -> Nov. '25

LIGO and Virgo operating;

KAGRA expected to join before the end of the run

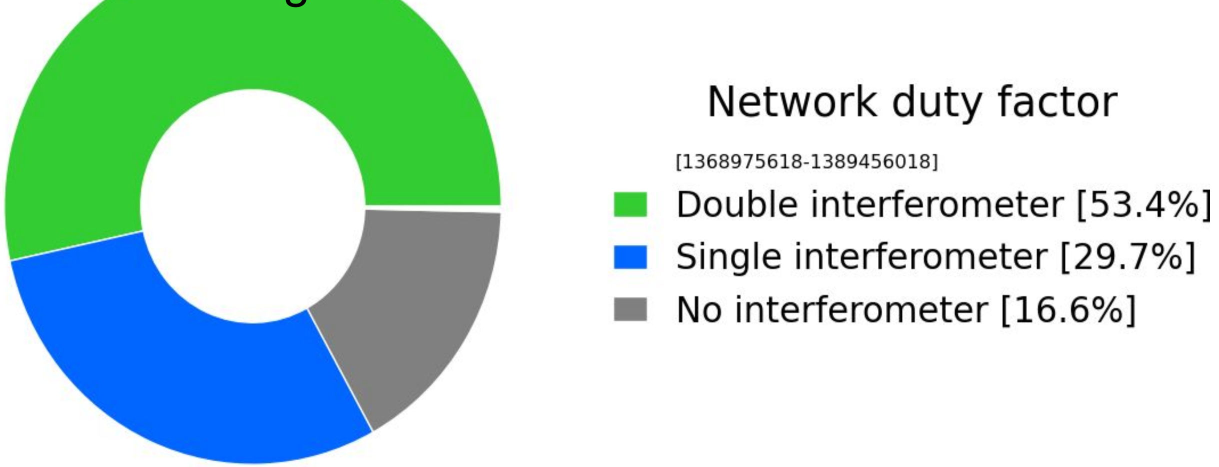


LIGO-G2302098(a52dffb1), updated on 13 June, 2025

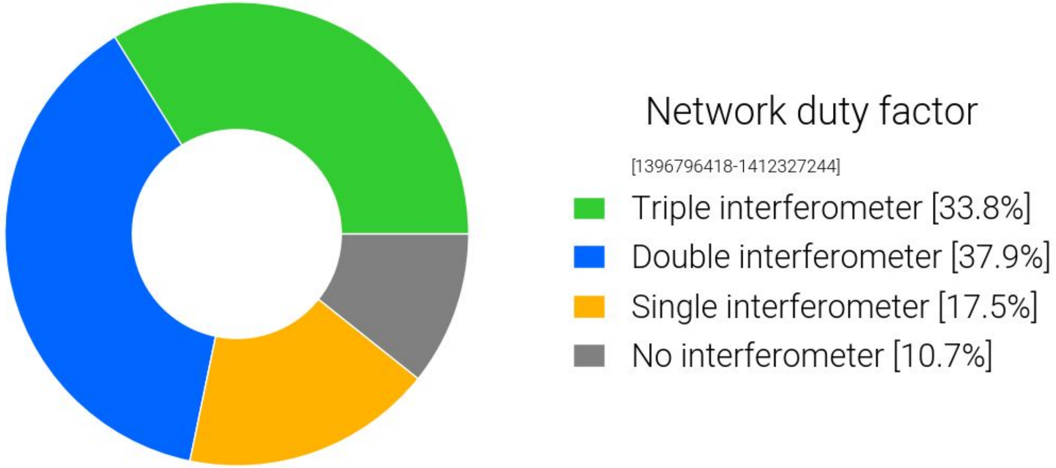
Credit: LIGO-Virgo-KAGRA Collaboration

O4 data

O4a (H1+L1) May 24, 2023 –Jan 16, 2024
Public release: Aug’25



O4b (H1+L1+V+K*) Apr 10, 2024 –Jan 28 2025



O4c (H1+L1+V1) Jan 28, 2025 –Nov 18, 2025
in progress

More interesting sources for Trento data analysis group:

- public alert S231123cg BBH
- VELA Pulsar glitch on April 29 2024, df/f ~10^-6

Searches for transient gravitational waves @ Trento

Pursuing the most general search for transient gravitational waves

- Agnostic method wrt the signal morphology
- Phase-coherent analysis of the detector network
- All-sky, all-time, full frequency-band survey

- finalizing the collaboration paper on HL O4a data
- ongoing offline analysis of O4b-c

Testing General Relativity with BBH mergers

- Unmodeled reconstruction of the GW waveform to test consistency with GR predictions
- Investigating the dynamics of the BH horizon: our search for echoes after the merger is part of the LVK "testing GR" papers

Improving Data Analysis methods

- fully exploiting Machine Learning in searches for GW bursts
- combining concurrent searches over different network configurations
- improving fidelity of signal reconstruction

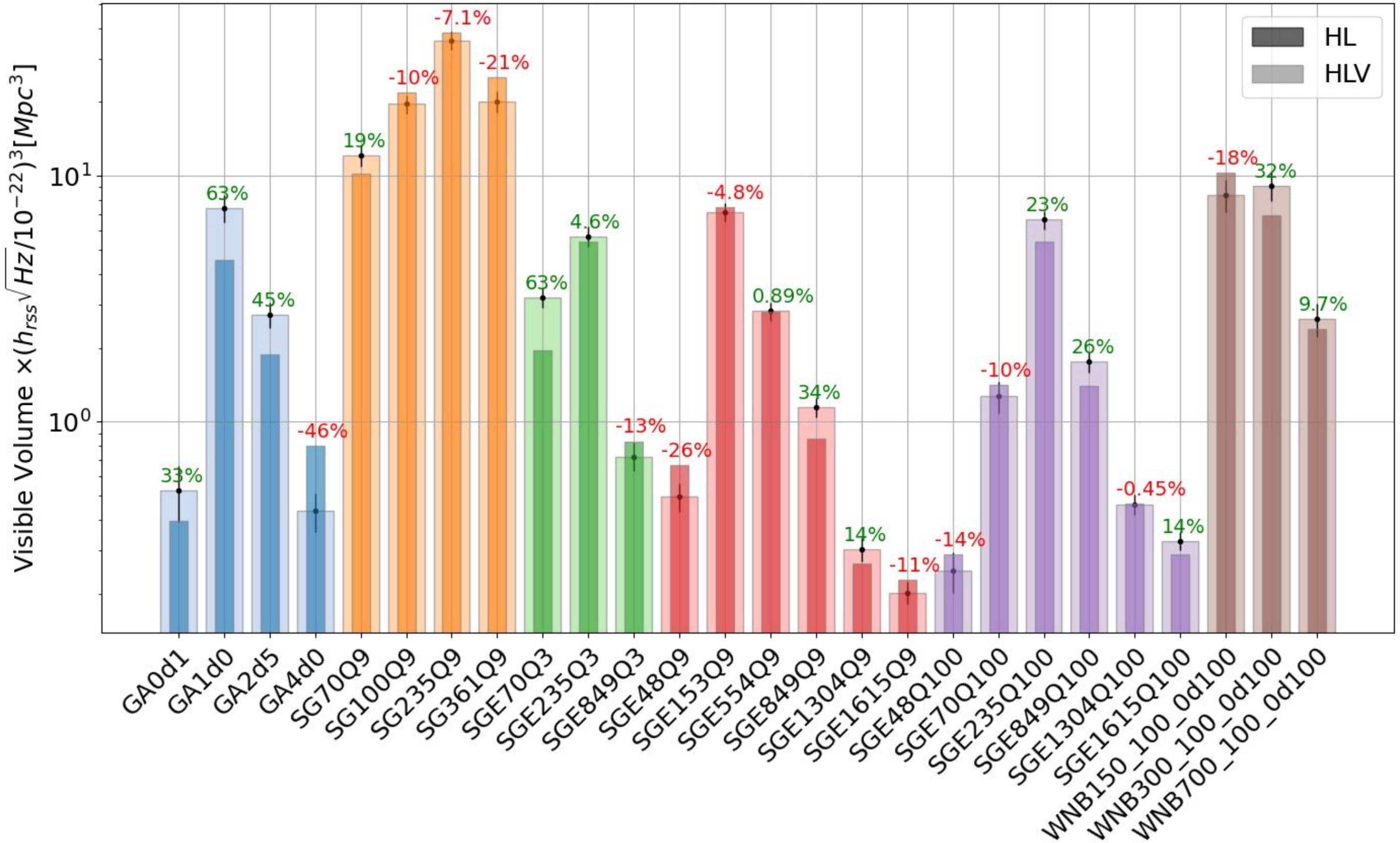
    data whitening procedures: Martini et al., Eur. Phys. J. C 84, 1023 (2024)

Searches for transient gravitational waves @ Trento

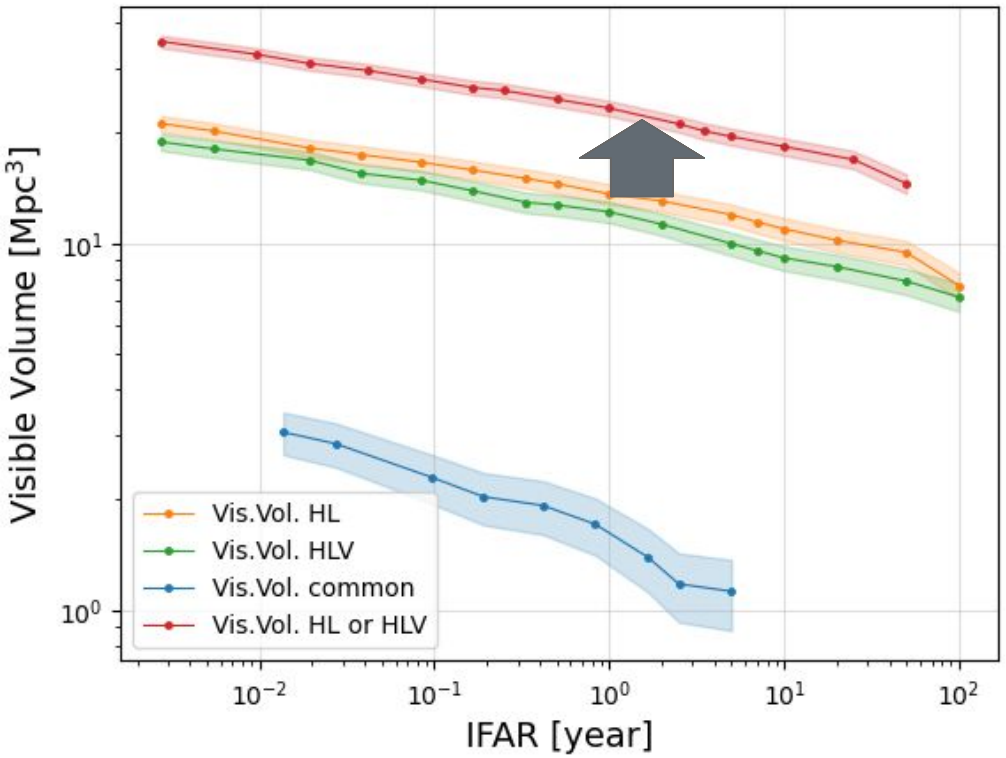
improving the exploitation of LVK data

Martini et al., in preparation, using latest public data of 3 detectors (O3)

Comparing HL and HLV searches:



Combining HL and HLV searches:



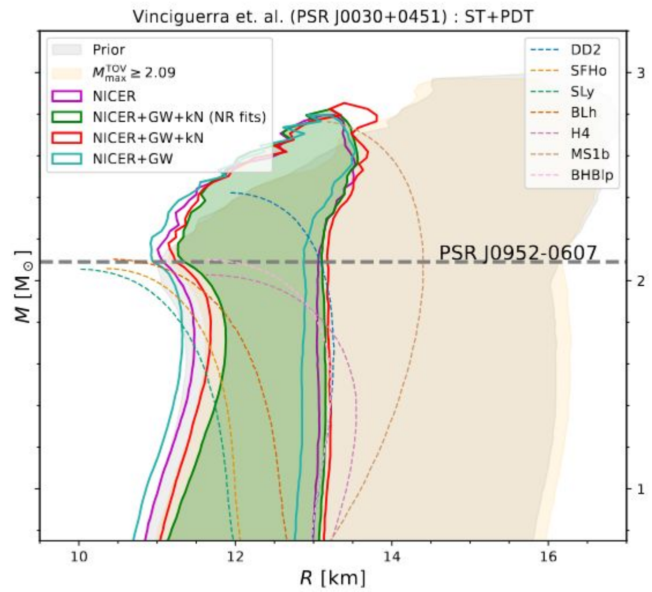
Progress in multimessenger astro with GWs

- Implementation of genuine GW+KN Bayesian analysis of GW170817 and its counterparts
  - Consistent inclusion of pulsar and NICER observations
  - robust constraints on NS radius, max mass, deformability and nuclear EOS

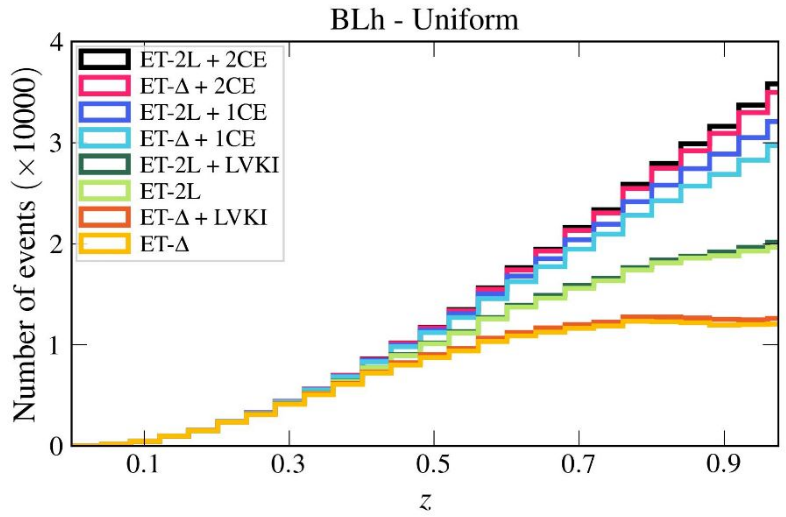
- In depth study of BNS merger multimessenger perspective using 3G detectors, LVK and Vera Rubin telescope
  - **10-100 GW+KN/year**
  - up to redshift 1
  - sensitive to BNS rate
  - insensitive to nuclear EoS and stellar population
  - modest contribution from LVK wrt ET or CE

A. Perego in connection also with Jena U. (Bernuzzi) and GSSI (Branchesi) Virgo groups

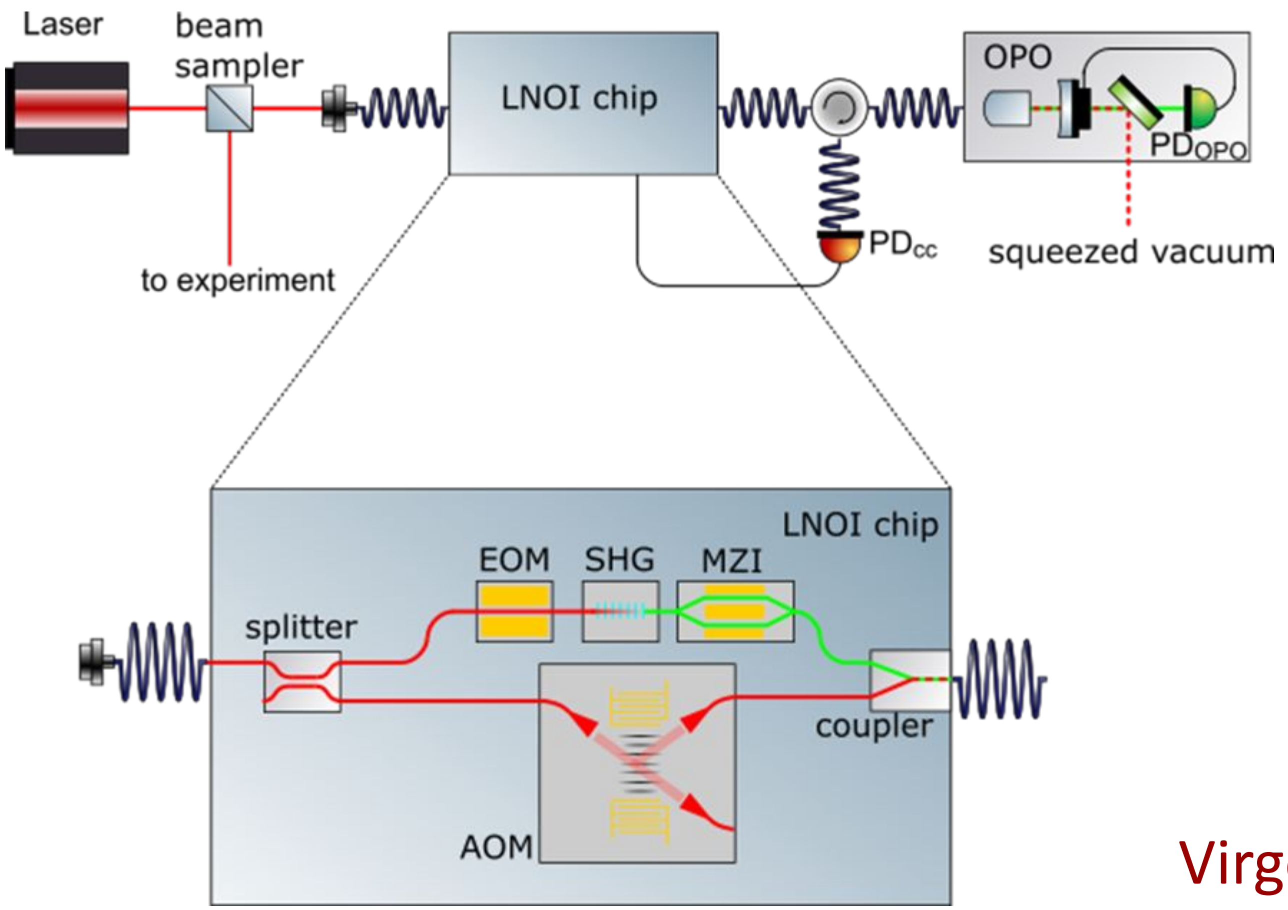
Breschi *et al* (2024) *PRD*



Loffredo *et al.* (2025) A&A



Integrated squeezed vacuum source for measurements beyond the quantum limit



Programma per Giovani Ricercatori "Rita Levi Montalcini" - Bando 2020 obtained by M. Leonardi.

Integrated squeezed vacuum source key components:

1. Lithium Niobate On Insulator (LNOI) chip
   - preparation and the stabilization of the signal to be sent to the OPO
2. Fibered Optical Parametric Oscillator (OPO)
   - Necessary to ensure high degree of purity of squeezed states

Virgo squeezed vacuum source:
contributions to parts (PLL of LASER sources, control sidebands)

Mode mismatch measurement and correction for Virgo

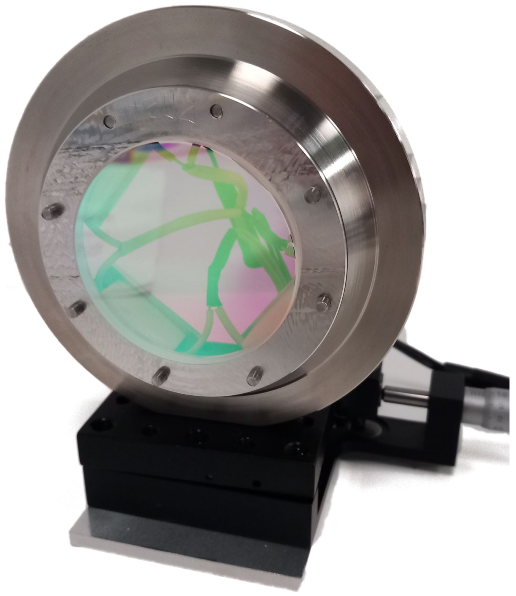
Mode-Mismatch measurement at 1064 nm:

- Measurement system already installed on EDB bench at Virgo to measure symmetrical mismatch
- One of the quadrant photodiode has been damaged→to be repaired

Mirror actuator, symmetrical only:

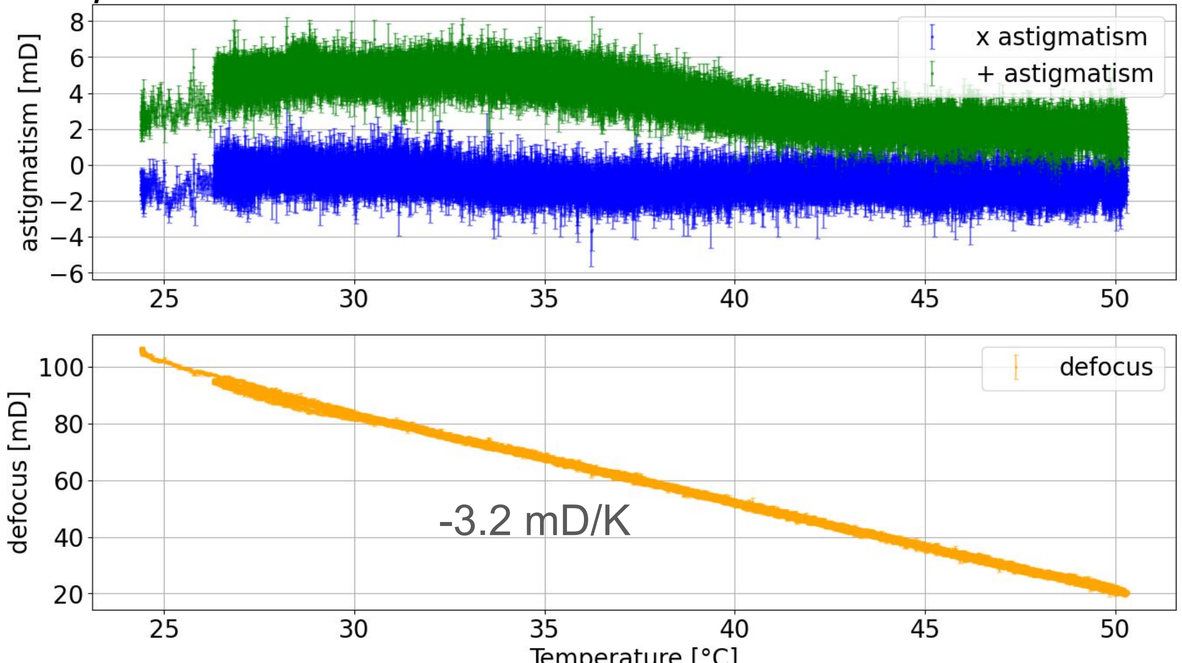
- Symmetrical actuator prototypes built and tested
- Mirror diopters measured as a function of temperature
- Temperature control system to be improved using Peltier cells
  - Thermal sink to be designed
- Adaptation of the mirror actuator to Virgo optical benches
  - To make it vacuum compatible
  - Use the right cable connectors
  - Installation of its DAQs and control software

(Future tasks)



Picture of the metallic symmetrical actuator

Diopter as function of temperature



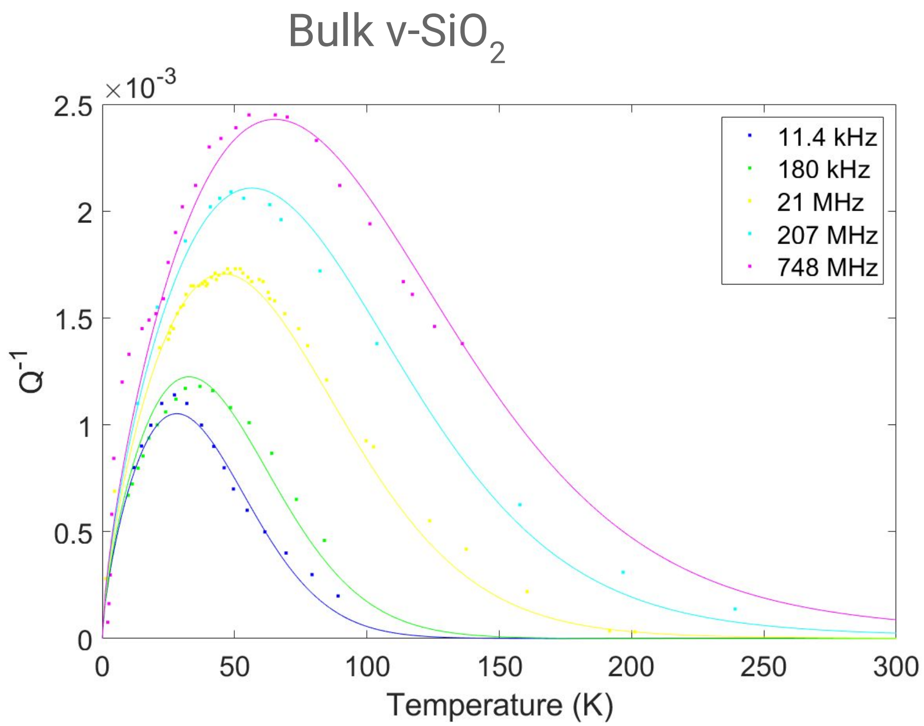
Activities on coatings – overview

PhD project of Denis Nabari
Giacomo Baldi
Matteo Leonardi
Marco Zanatta

Goals:

- Understand the microscopic origin of thermal noise
- Connect the thermal noise T and freq. dependence to physical parameters of the coating materials (density, elastic properties, microscopic structure)
- Choose the proper materials to minimize noise

Literature data on bulk glasses:



Internal friction data (i.e. inverse of mechanical quality factor) in the frequency range from ~ 100 Hz to ~ 1 GHz are well described by thermally activated relaxation processes (TARP)

Phenomenological model of unknown microscopic origin, whose parameters need to be adapted to data

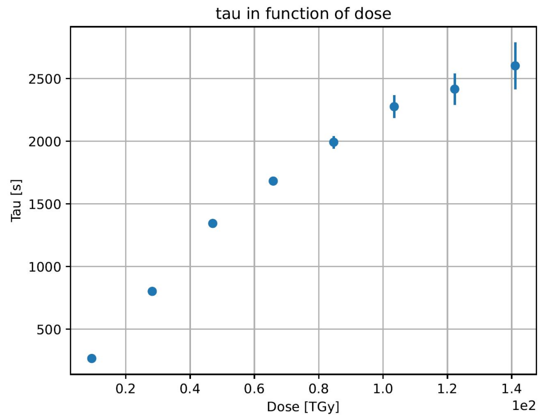
S. Caponi, A. Fontana, F. Rossi, G. Baldi, and E. Fabiani, Phys. Rev. B **76**, 092201 (2007).

G. Baldi *et al.*, Phil. Mag. **87**, 603-612 (2007).

Activities on coatings – ongoing

Research at synchrotron/FEL facilities

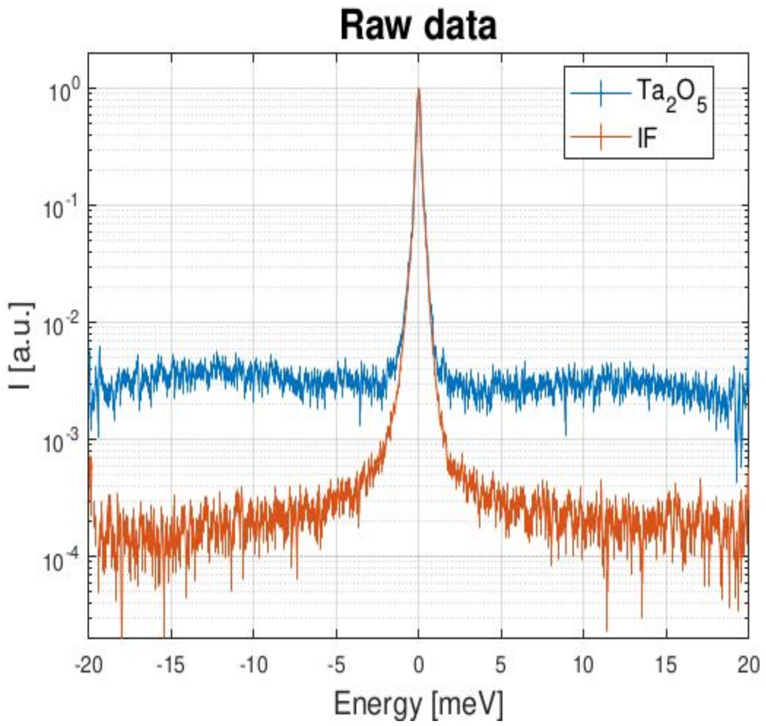
First results of XPCS on pure Ta_2O_5 at beamline ID10 @ ESRF (Grenoble)



-> information on the topology of the glass network
-> x-ray induced damage, information on defects and stability
(preliminary data, unpublished)

First results of IXS at ID14 @ESRF
(collaboration with M. Bazzan and M. Granata)

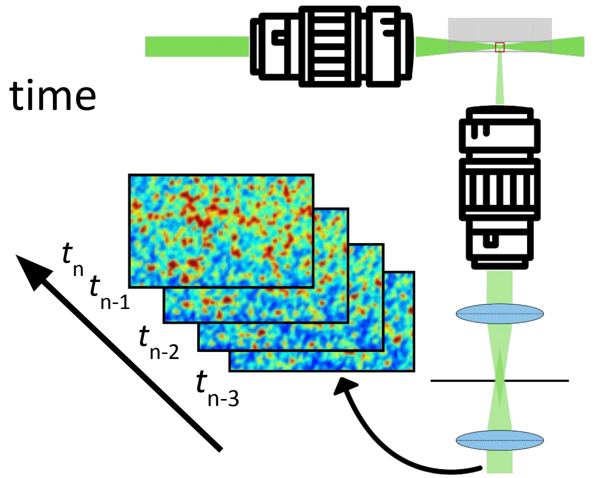
-> Relaxation processes in pure Ta_2O_5 at frequencies > 10 GHz



Preliminary data, unpublished

Activities on coatings – future plans

1. Measurement of the quasielastic light scattering signal using laser-based photo-correlation spectroscopy

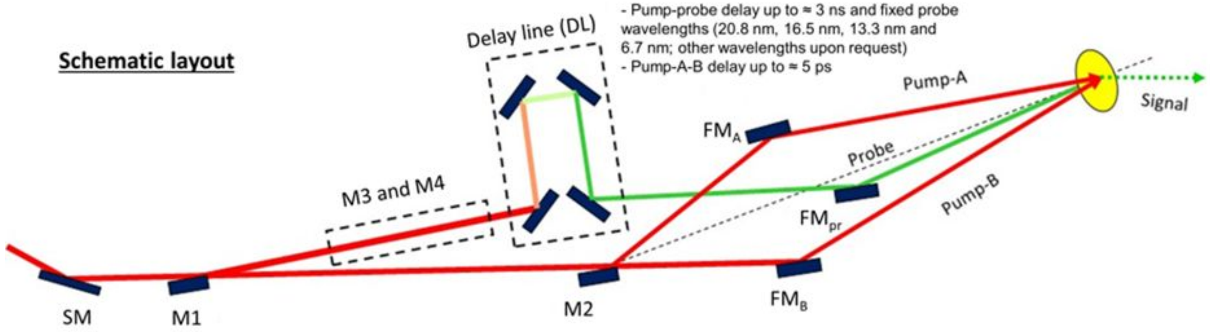


Need to update the existing setup with:

- Dedicated focusing and collection optics
- Micromanipulator
- New hardware correlator for longer acquisition times (~ few hours)
- Ray-tracing of the optical setup with a confocal design

2. Experiment planned in December at FERMI-FEL in Trieste for beamtime at EIS-TIMER (collaboration with A. Trapananti and F. Travasso)

Transient grating spectroscopy in the deep UV. Feasibility already tested.



D. Fainozzi *et al.*, APL Mater. **12**, 051122 (2024)

Virgo preventivi TIFPA 2025

Work in progress:

- Hardware: TBD (inventariabile + consumo)
  - control of optical matching beam-cavities
  - components for the Virgo squeezed light source
  - measurement of the quasielastic light scattering in optical coatings

- Travel funds (excluding conferences): ~ 22 k
  - joint work with other LIGO-Virgo groups
  - topical f2f meetings when feasible and collaboration meetings
  - measures at synchrotron-FEL facilities

SPARES

N

LIGO-Virgo **past** observations' highlights

catalog.cardiffgravity.org

Yet to detect emissions different from Compact Binary Coalescences

90 confirmed detections of Compact Binary Coalescences

"…expect ~ 10% of false alarms"

+ marginal and subthreshold candidates

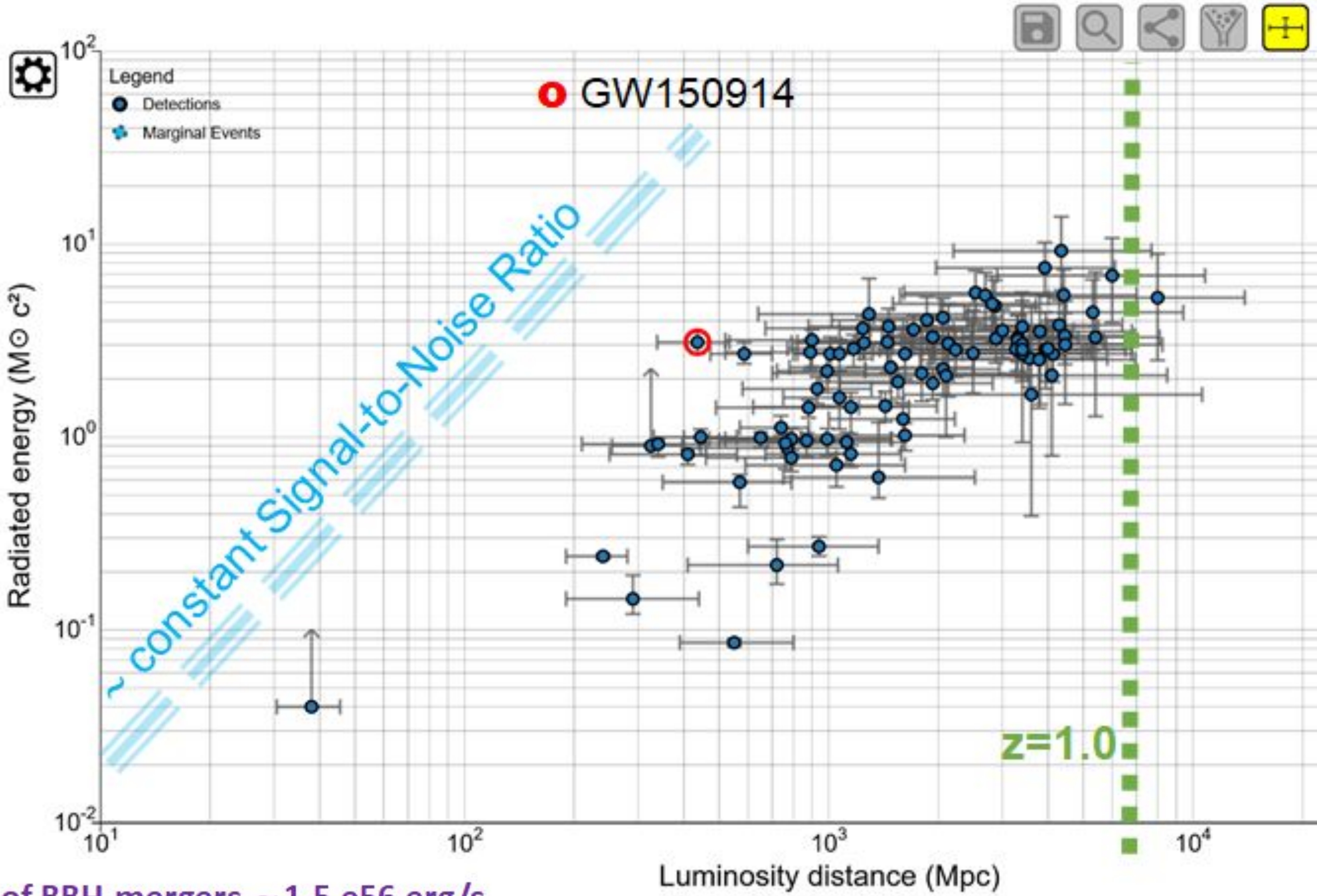
Radiated energy in GWs up to 10 solar masses

Distances up to z=1

GW Transient Catalogs:

GWTC-3 arxiv:2111.03606

GWTC-2.1 arxiv:2108.01045



Peak luminosity of BBH mergers ~1-5 e56 erg/s

~1e-3 of the upper limit set by GR (~Planck Luminosity)

LIGO-Virgo **past** observations' highlights

catalog.cardiffgravity.org

Yet to detect emissions different from Compact Binary Coalescences

90 confirmed detections of Compact Binary Coalescences

\+ marginal and subthreshold candidates

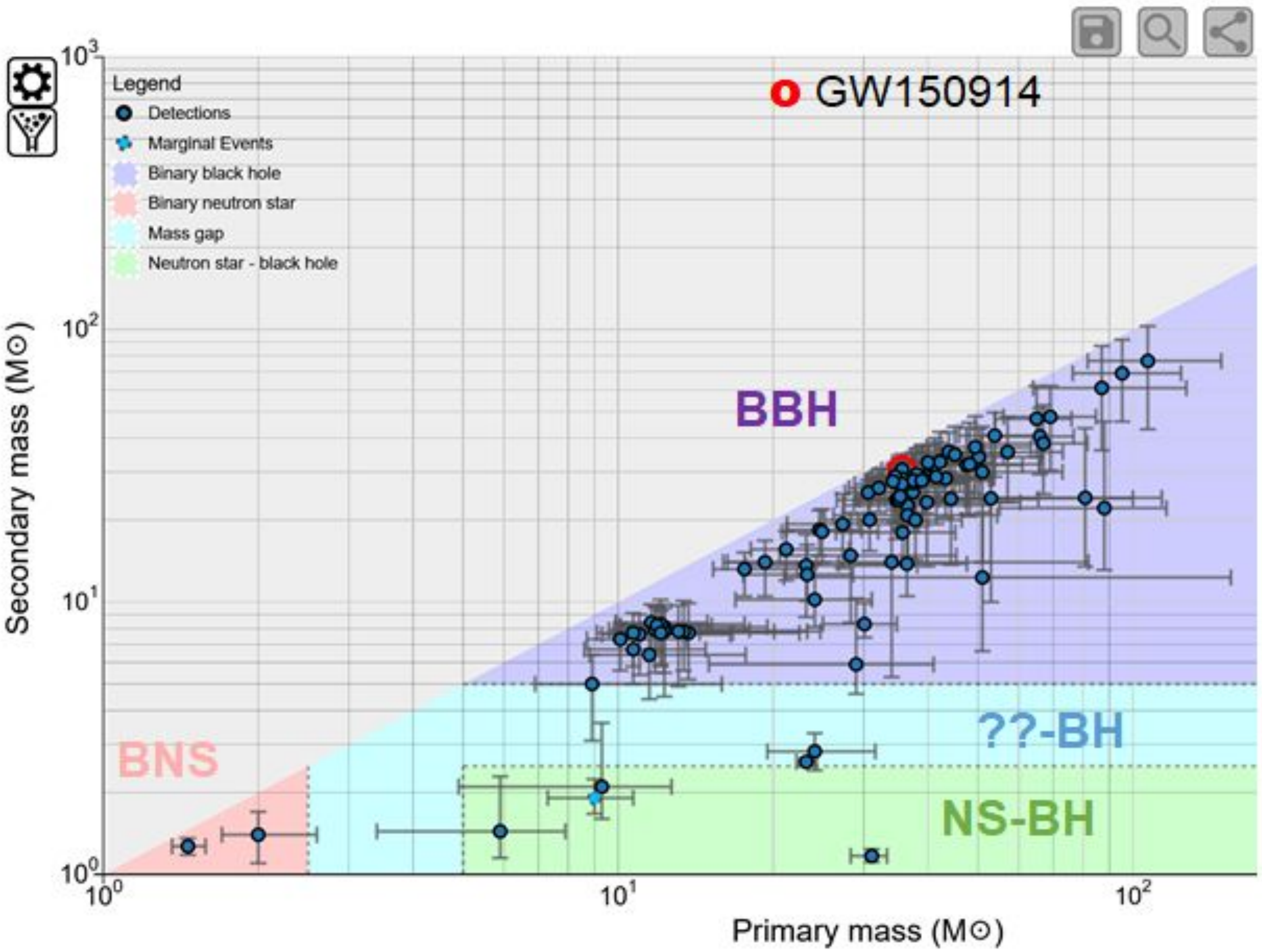
mostly binary BH mergers

2 Binary Neutron Star mergers

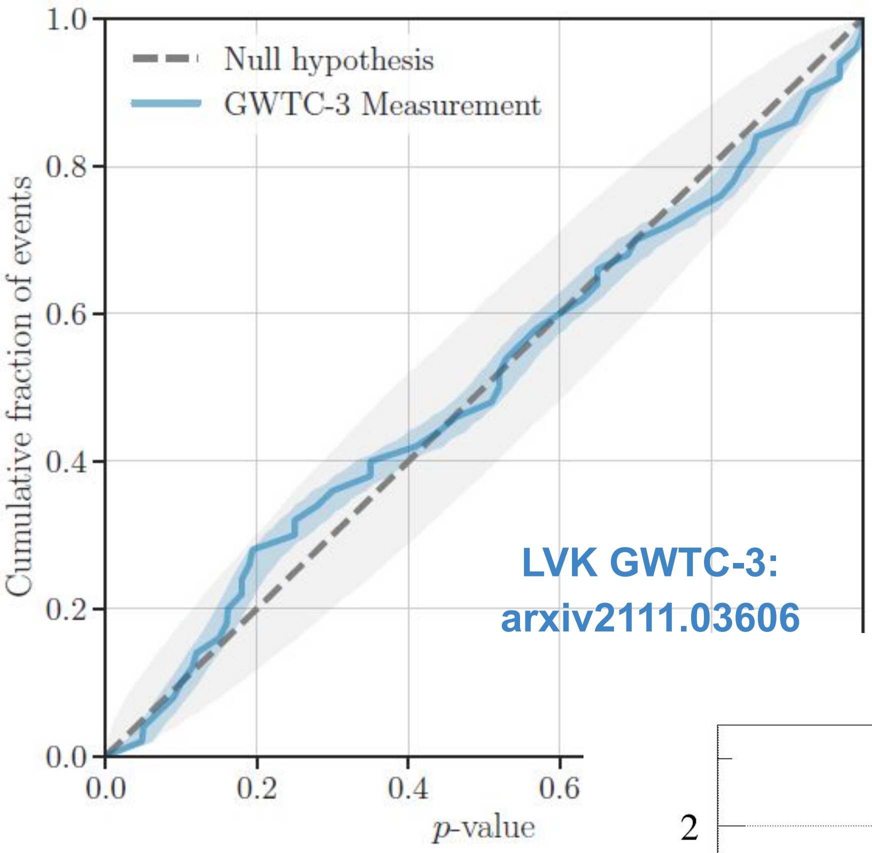
3 NS-BH mergers

2 ??-BH: ambiguous lighter object in-between known NS and BH mass ranges

3 intermediate mass BH

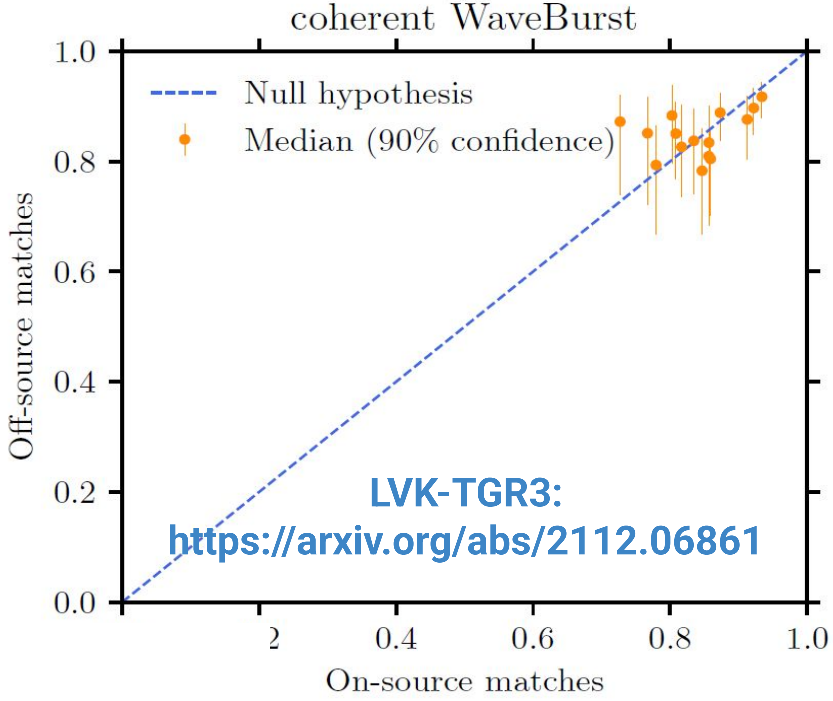


Unmodeled reconstruction vs GR models

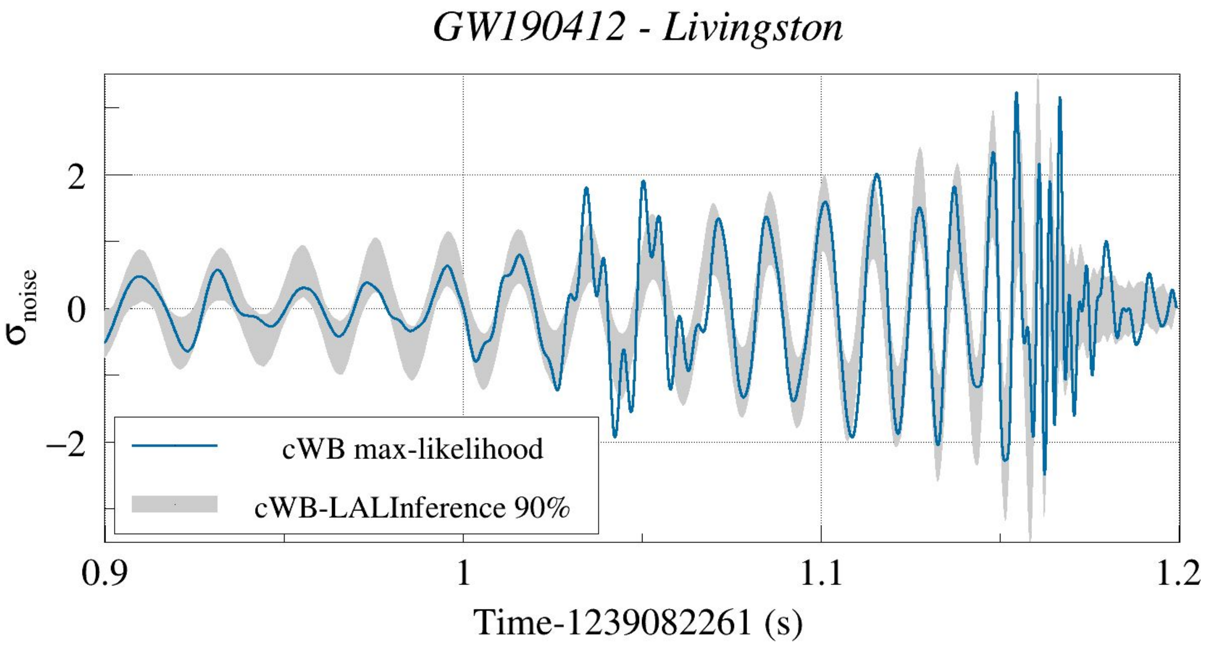


LVK GWTC-3:
arxiv2111.03606

check of consistency between preferred signal model and our data-driven agnostic reconstruction

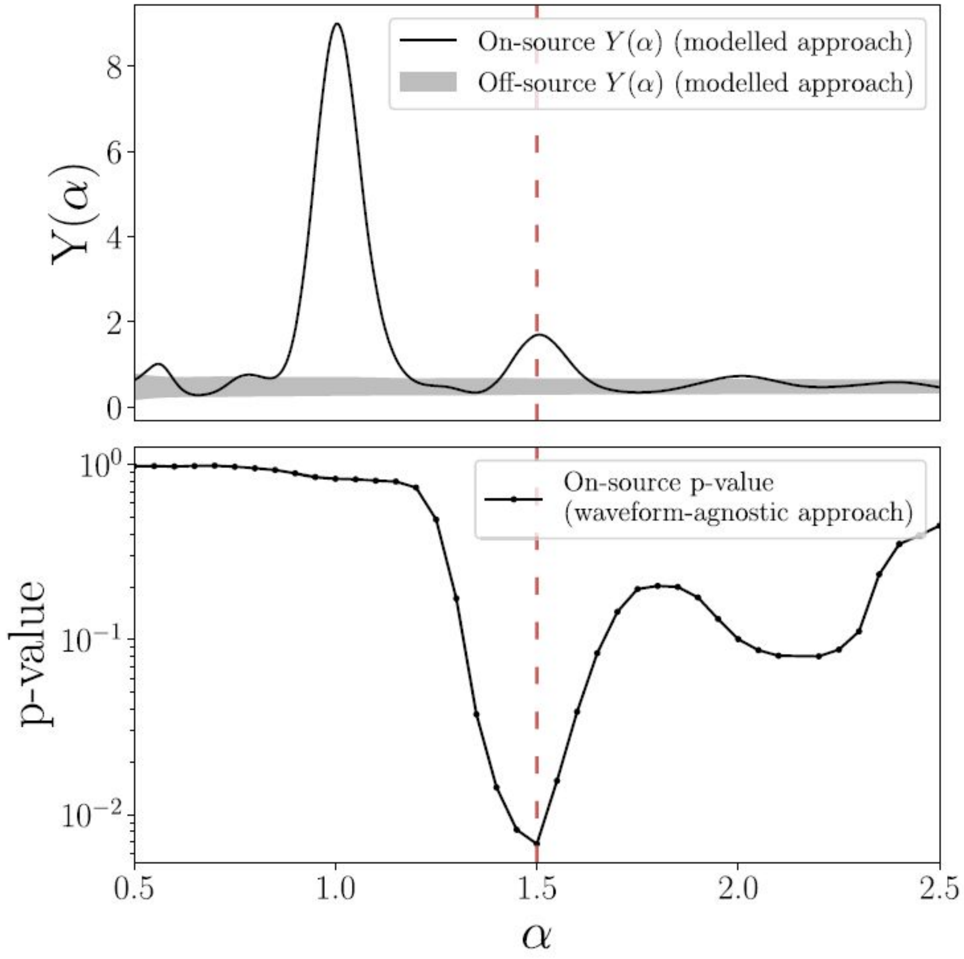


LVK-TGR3:
https://arxiv.org/abs/2112.06861

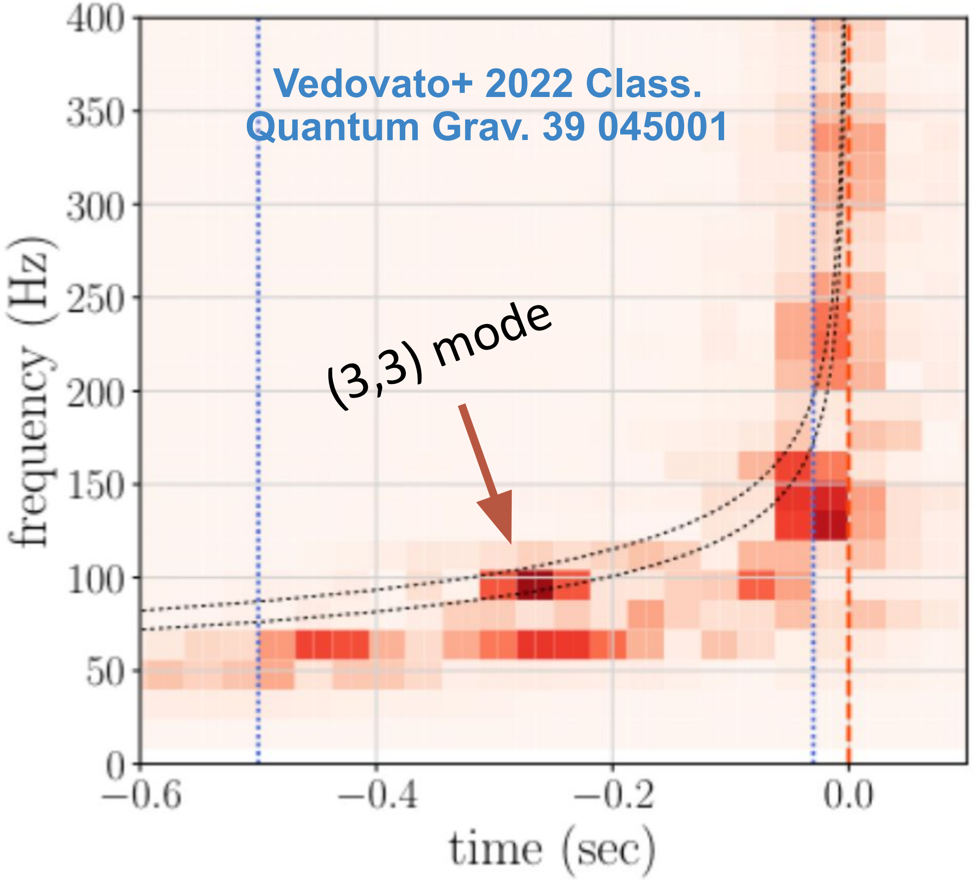


Unmodeled reconstruction vs GR models

Characterization of the signal waveform and detection of weak features



LVK GW190814: APJ896L44



Detection of l=3, |m|=3 higher order multipole in the inspiral of GW190814 at 1.5 * freq. of quadrupolar mode

Improving the most general search for GW transients

- Discrimination from noise
- Characterization of event properties

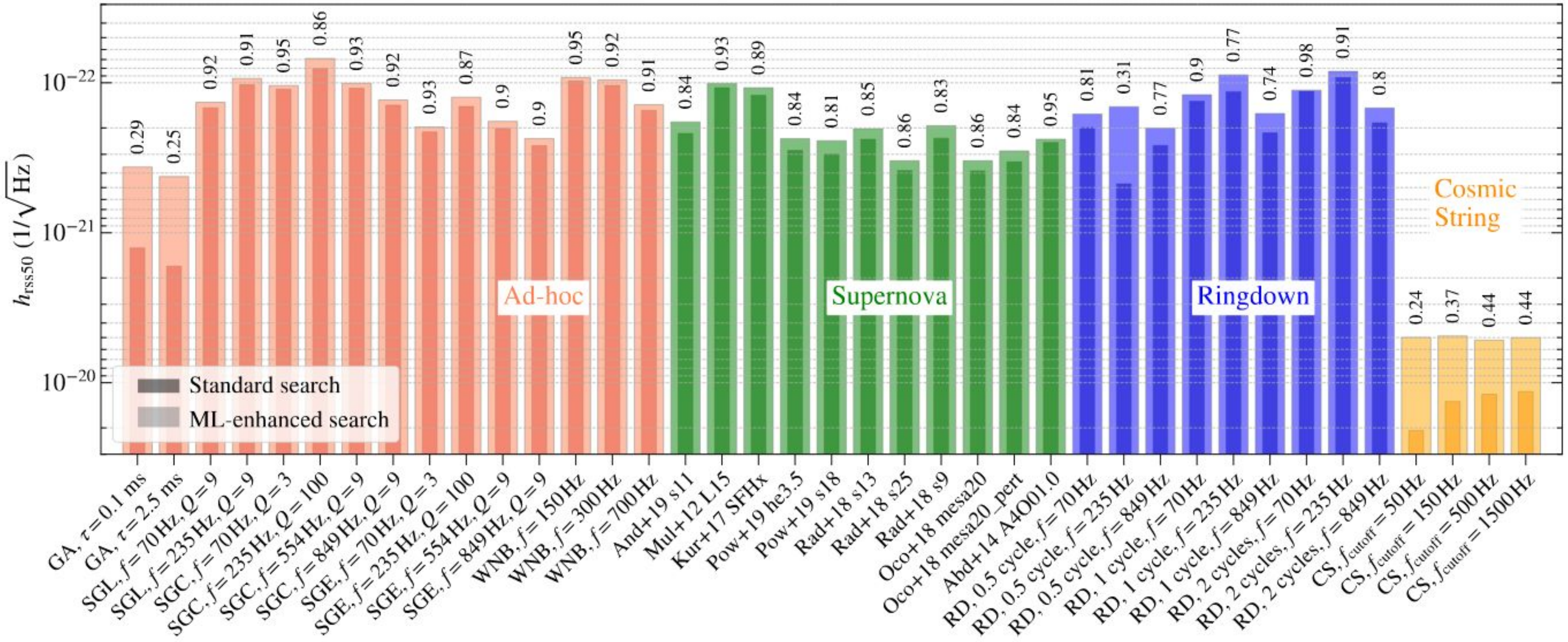


FIG. 2: Resulting h_{rss50} achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB (lighter colors) for the HL network on full O3 and at iFAR$\geq$ 100 years. The waveforms reported are a subset of those listed in Table I: ad-hoc signals ordered according to central frequency (red), core-collapse supernovae (green), ringdown waveforms (blue), and cosmic strings (yellow). The values on the top show the reduction factor on h_{rss50} with respect to the standard search; h_{rss50} ordinate scale decreases going upwards.

Szczepańczyk, M. J., Salemi, F., Bini, S., et al. (2022).
All-sky search for gravitational-wave bursts in the third Advanced LIGO-Virgo run with coherent WaveBurst enhanced by Machine Learning.
Phys. Rev. D 107, 062002 (2023) https://doi.org/10.1103/PhysRevD.107.062002

Improving glitch discrimination

An autoencoder neural network learns transient noises morphologies from GW time-series.

→

Improving sensitivity to generic GW transients and binary black hole mergers

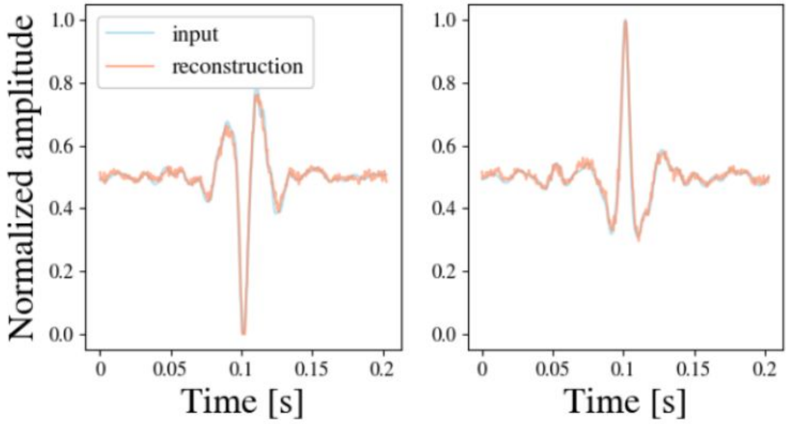


Figure 2. Two examples of blip time-series according to the GravitySpy classification detected by cWB in LIGO Hanford. In blue the autoencoder inputs x_i, that are cWB reconstructed waveforms windowed and normalized as described in Section 4.2). In orange the autoencoder reconstructions $g_D(f_E(x_i))$.

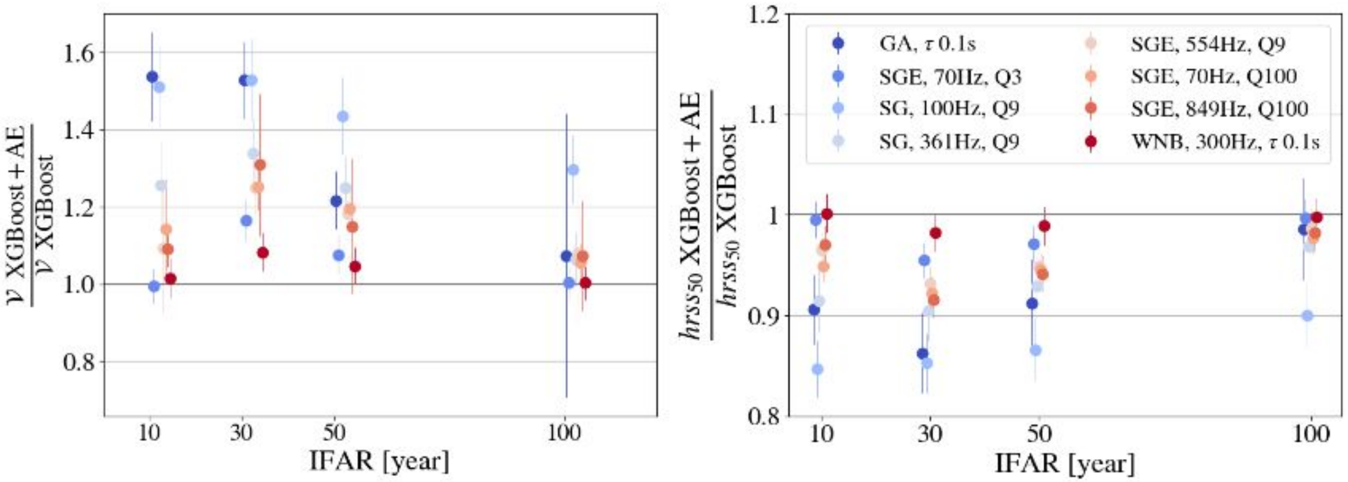


Figure 5. Ratio between the sensitivity volume $\mathcal{V}$ (left) and h_{rss50} (right) obtained including the autoencoder (`XGBoost + AE`) and without using it (`XGBoost`), at different IFAR thresholds (10, 30, 50, 100 years) for a subset of ad-hoc waveforms (data points are slightly shifted around the IFAR thresholds to avoid overlaps).The ad-hoc waveforms are: Gaussian Pulse (GA) characterized by the duration τ, then Sine Gaussian (SG) characterized by central frequency f, and the quality factor Q and White Noise Burst (WNB) with bandwidth Δf, duration τ and lower frequency bound f.

part of Sophie Bini's PhD thesis

S. Bini *et al* 2023 *Class. Quantum Grav.* **40** 135008
10.1088/1361-6382/acd981

Searches for Black Hole mimickers: post-merger echoes

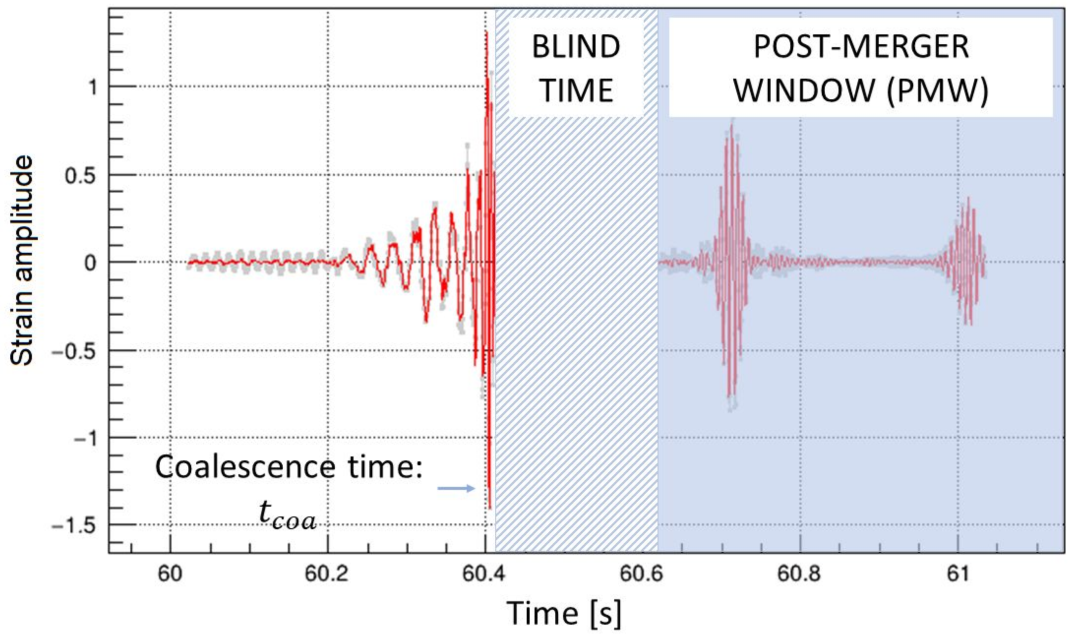
Echoes: repeated GWs pulses, after merger of binary of compact objects, ONLY IF remnant IS NOT a GR BH.

General method to search for weak GW features…

- **any exotic properties of matter at extreme densities (exotic compact objects)** ?
- **Solution of the BH information paradox ?**
- violations of the no-hair theorem for Black Holes ?

- not limited to GW echo signals
  - extendable to any post-merger features
  - morphological reconstruction
    - detector noise characterisation

Simulated Echoes

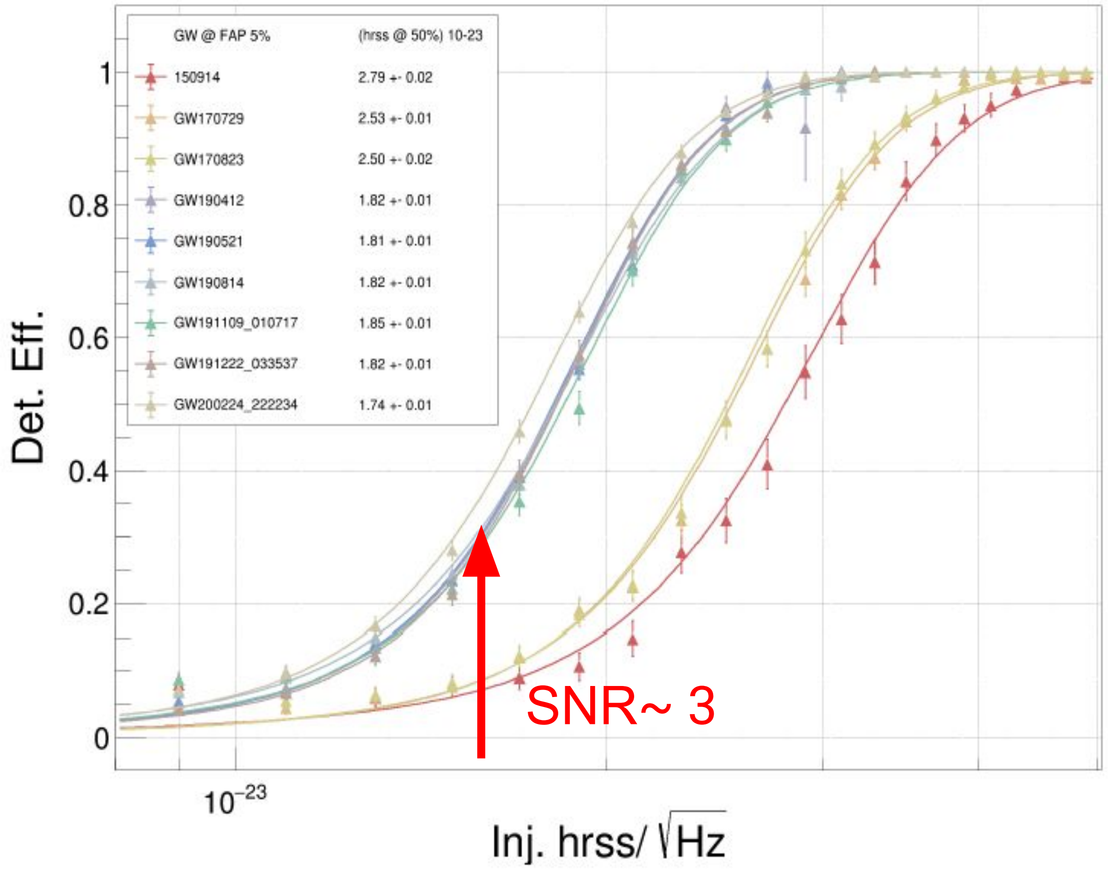


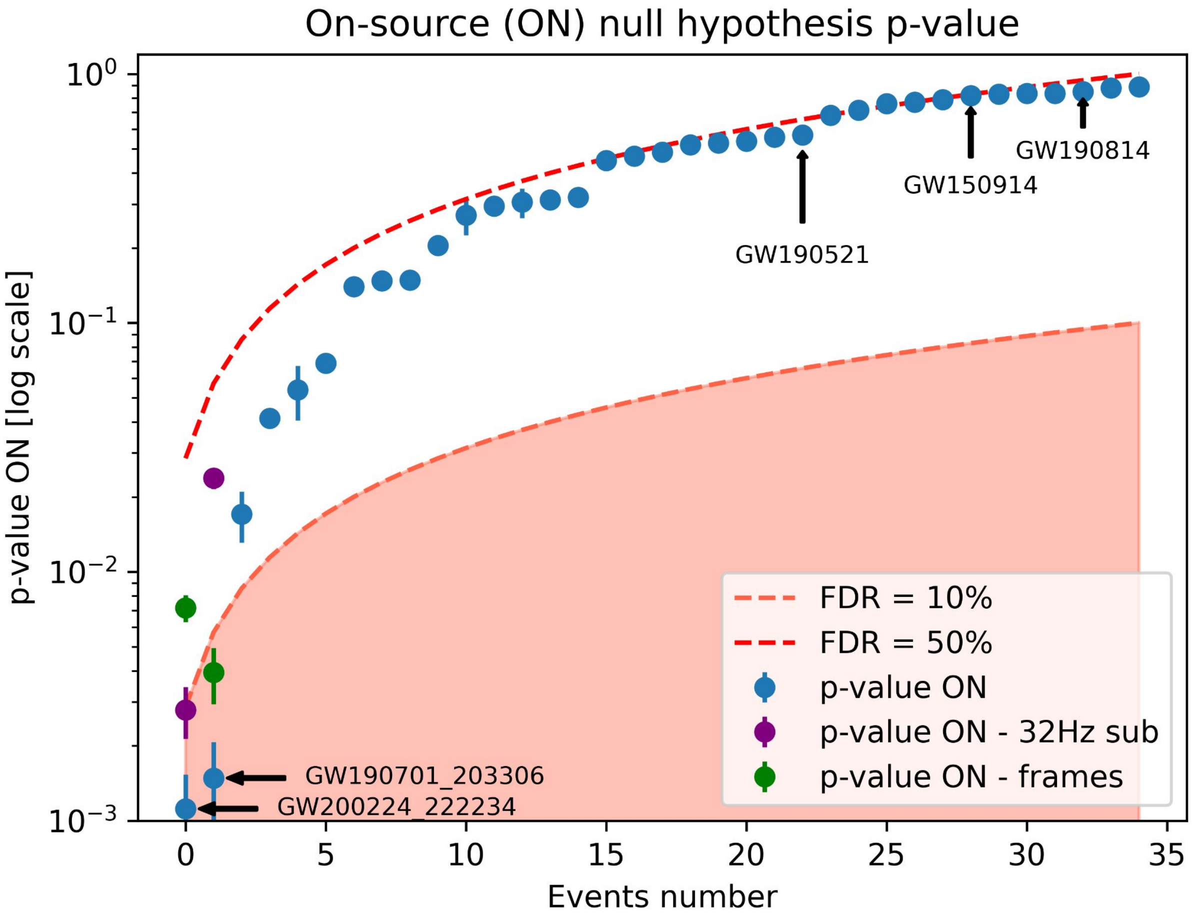
Andrea Miani's PhD thesis

A.Miani et al , arXiv:2302.12158

Searches for Black Hole mimickers: post–merger echoes

RESULTS





+

morphological reconstruction of subtreshold signals