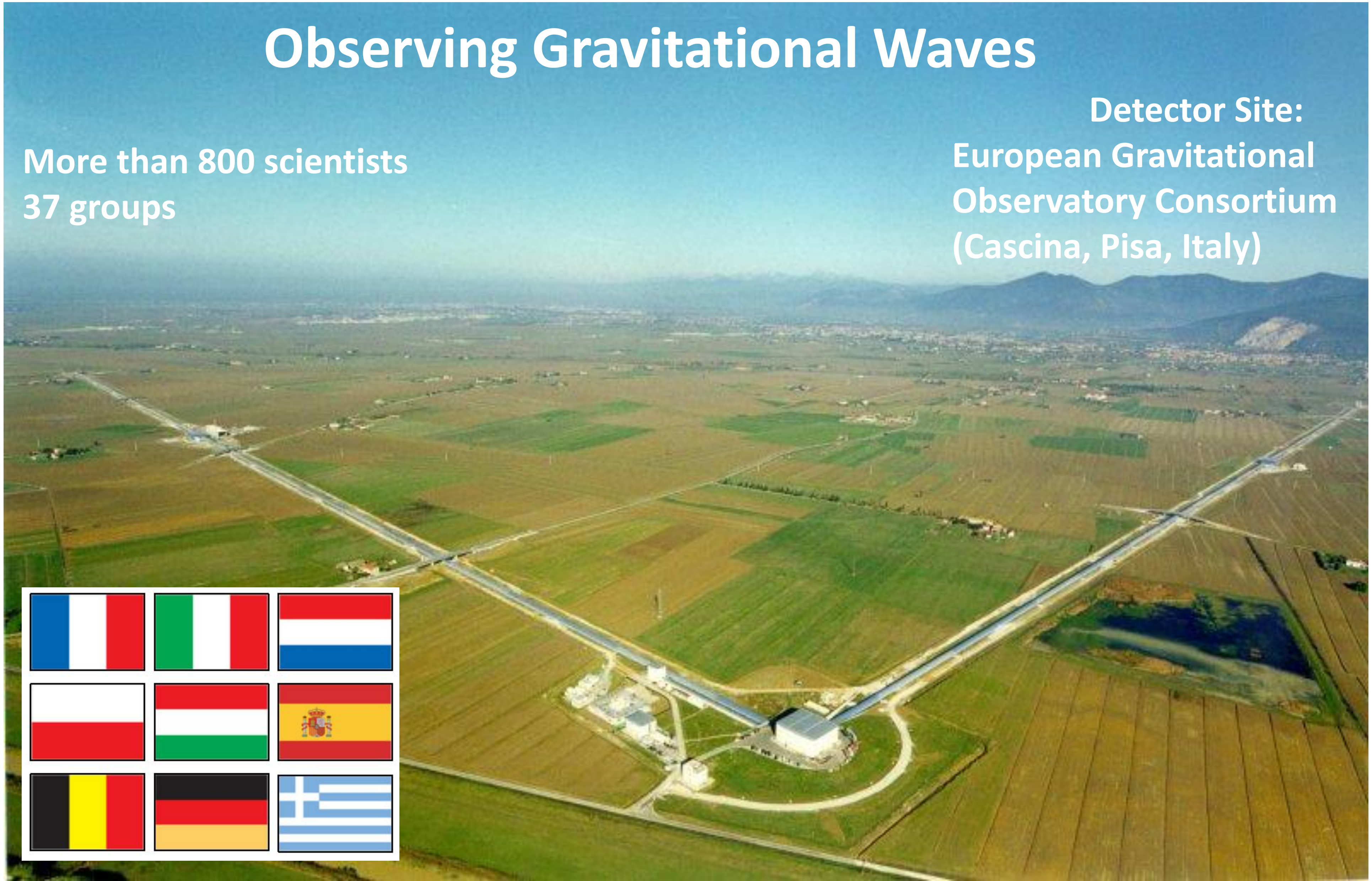
VIRGO



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 Virgo Group at TIFPA

Composition	FTE 6.3
Giacomo Baldi	0.2
Matteo Leonardi	0.4
Albino Perego	0.4
Antonio Perreca	0.4
Giovanni Prodi	0.7
Marco Zanatta	0.2 TBC
Andrea Miani	0.8
Paul Lagabbe	0.4 TBC
Sophie Bini	0.8
Alessandro Martini	1.0
Denis Nabari	1.0
Gianmarco Puleo	LM
Damiano Avi	
Roberto Graziola	

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

- **Virgo LIGO 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**

Virgo preventivi TIFPA 2025

Work in progress:

- Hardware: ~ 20 k (inventariabile + consumo)
  - control of optical matching beam-cavities
  - tailoring squeezed light beams
- Travel funds (excluding conferences): ~ 15 k
  - joint work with other LIGO-Virgo groups at their sites
  - topical f2f meetings when feasible and collaboration meetings
  - shifts at Virgo site: commissioning breaks and operation in O4
  - measures at synchrotron-FEL facilities

Da Settembre 2024 nuovo PA in DipFis: Giacomo Ciani

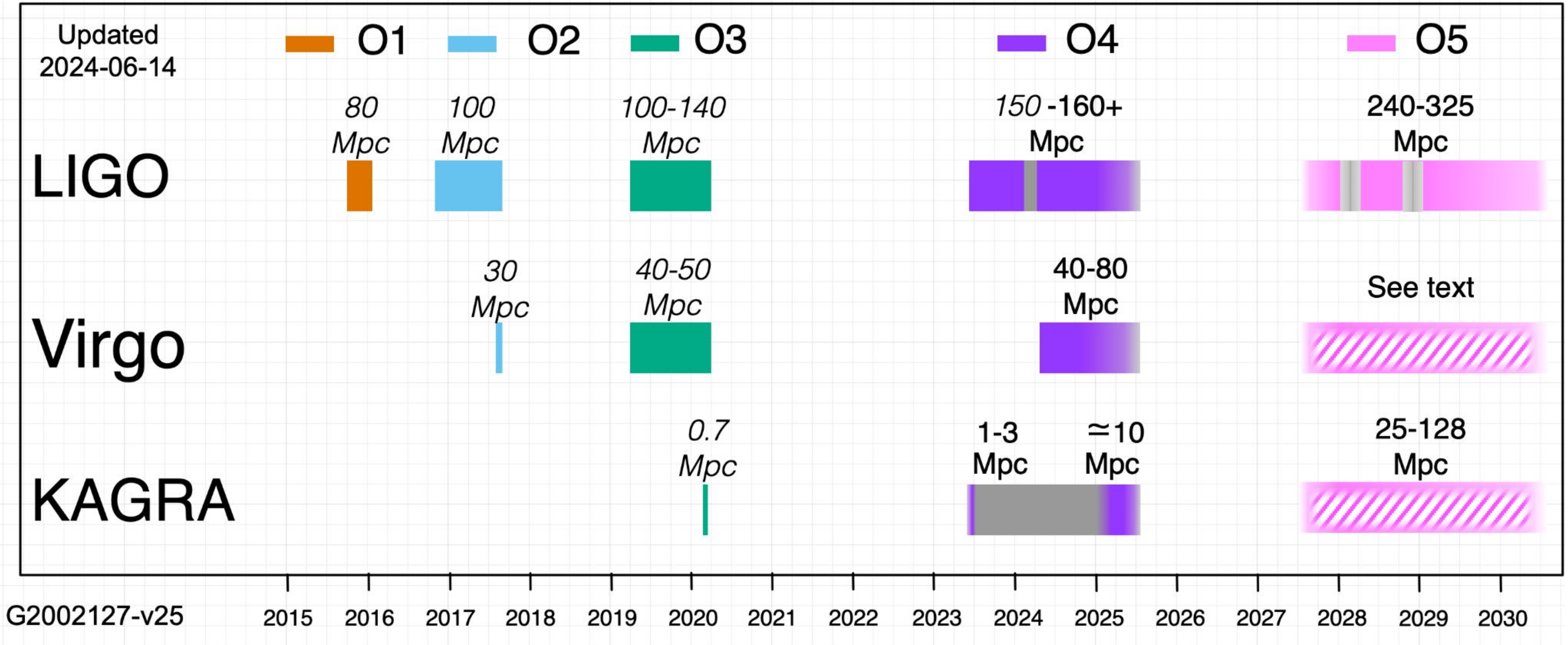
LIGO–Virgo **past** Gravitational Wave Surveys

- **Open data:**
- **LV** 10.1016/j.softx.2021.100658

  LV *arXiv:2302.03676 (2023).*

  http://www.gw-openscience.org

Observing plans and prospects
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

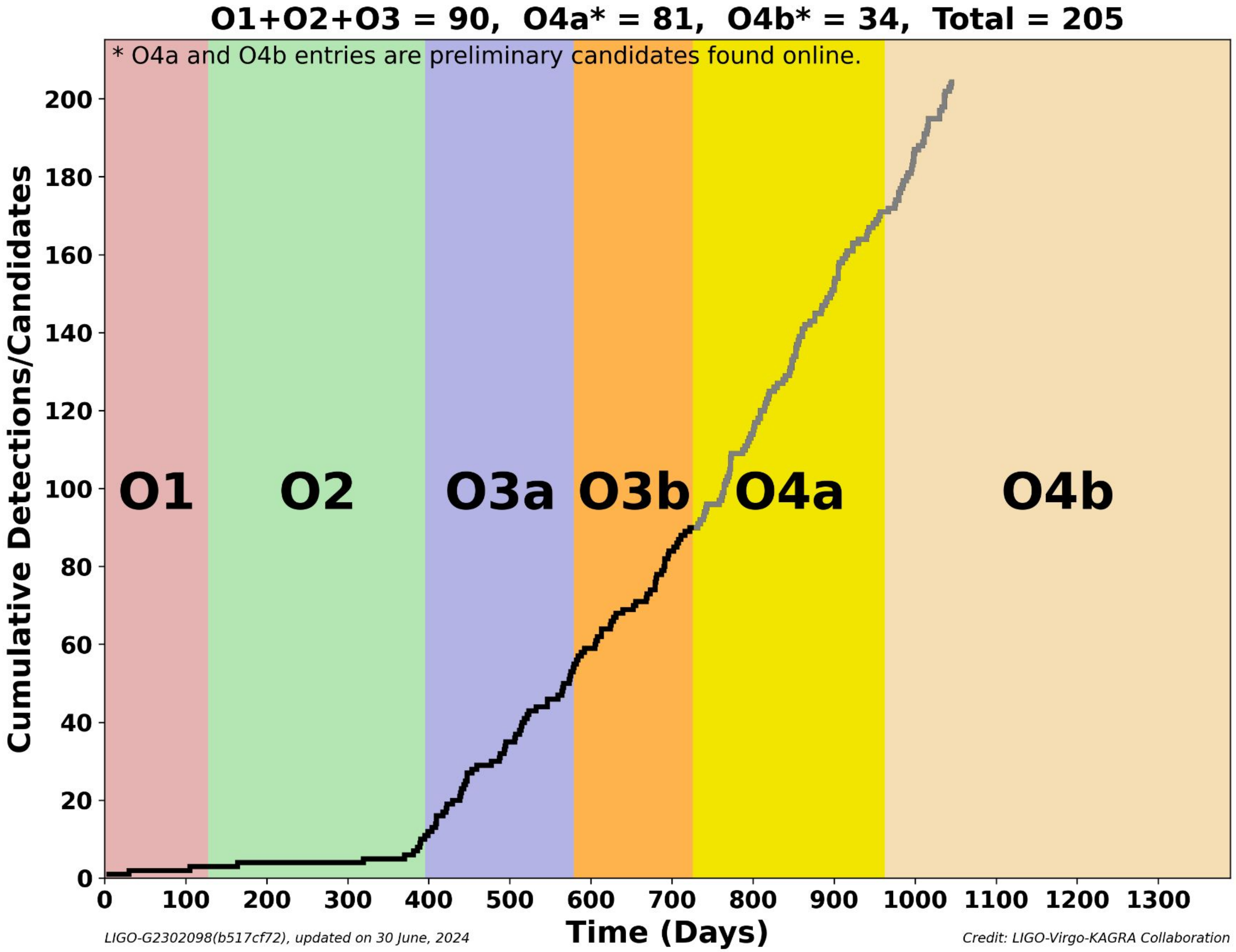
O4a: May 2023 - January 2024

LIGO operating; KAGRA operating for 1 month

O4b: April 2024 -> June '25

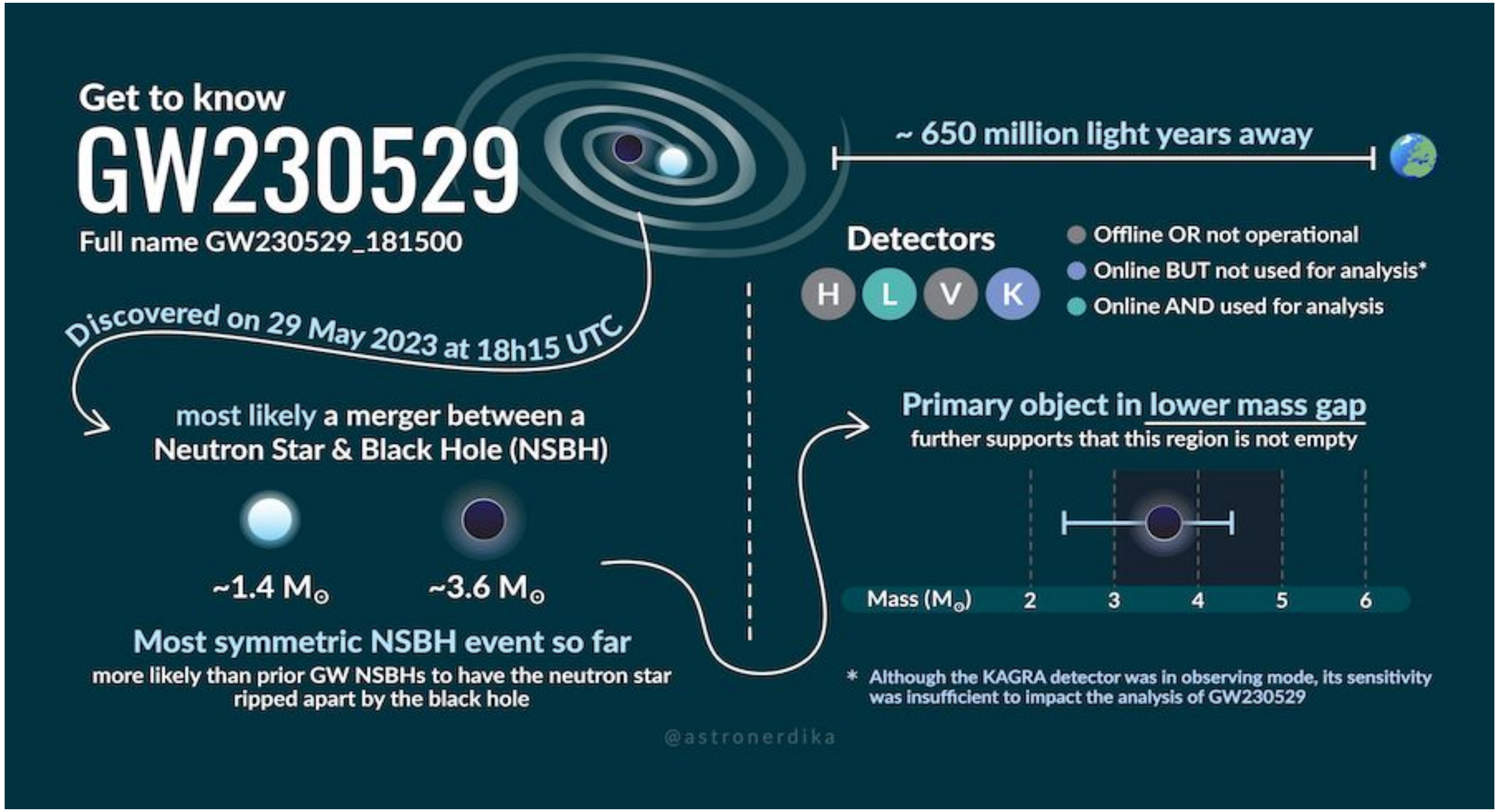
LIGO and Virgo operating;

KAGRA expected to join before the end of the run



Exceptional event in O4a:

Observation of Gravitational Waves from the Coalescence of a 2.5-4.5 M_sun Compact Object and a Neutron Star,
2404.04248



single detector

More interesting to Trento data analysis group:

public alert S231123cg
BBH

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

public alert S240422ed HLV detectors 259 deg^2
NSBH
No counterparts found

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

- Completed analysis of HL O4a data
- Writing the collaboration paper
- Starting offline analysis of O4b

Testing General Relativity and GW emission-propagation models with BBH mergers

- Unmodeled reconstruction of the GW waveform to test consistency with GR predictions
- Investigating the dynamicsof the BH horizon: our search for echoes in the post-merger included in the LVK "testing GR" plans

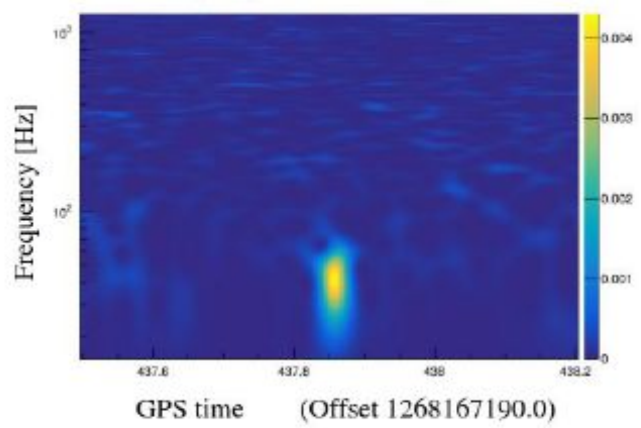
Improving Data Analysis methods

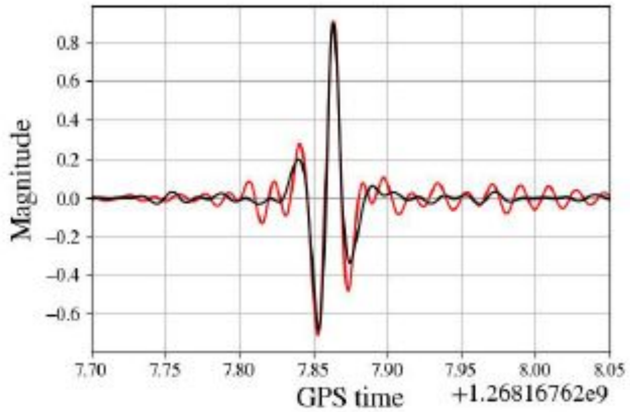
- fully exploiting Machine Learning in searches for GW bursts
- Developing data whitening procedures:
  Maximum Entropy Spectral Analysis: an application to gravitational waves data analysis,
  Martini et al., arXiv:2106.09499

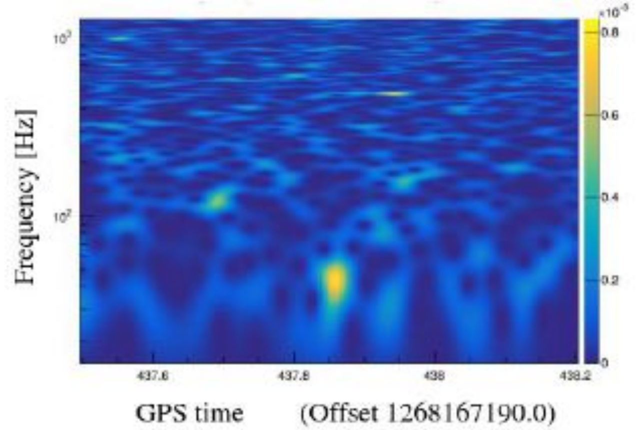
Searches for transient gravitational waves @ Trento

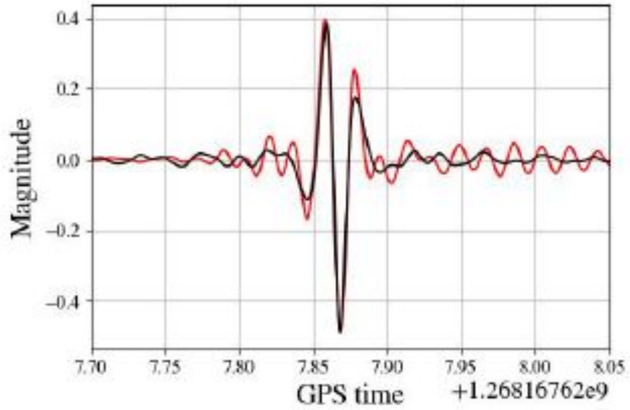
Search for hyperbolic encounters of compact objects in the third LIGO-Virgo-KAGRA observing run,

Bini et al. PRD 109 (2024) 042009









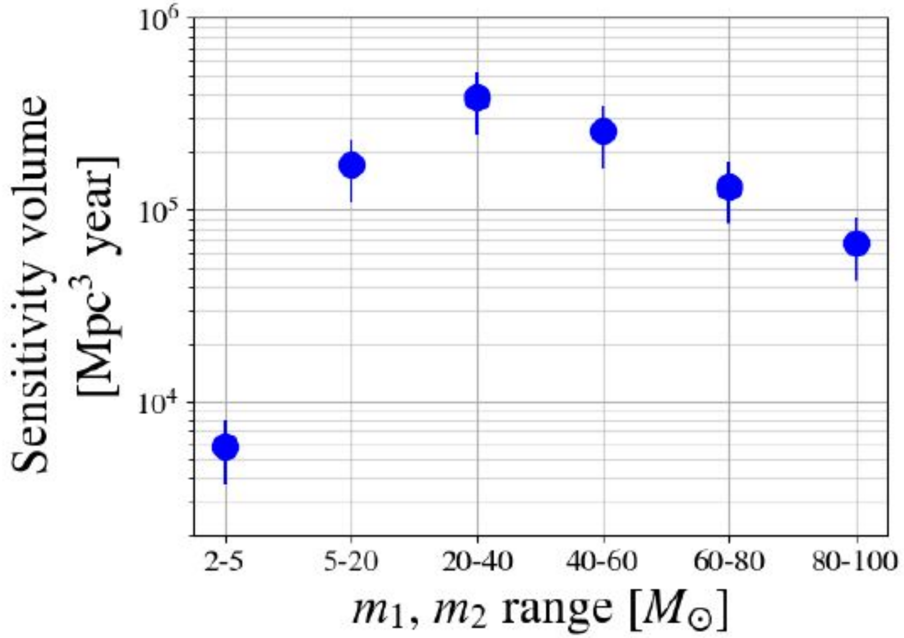


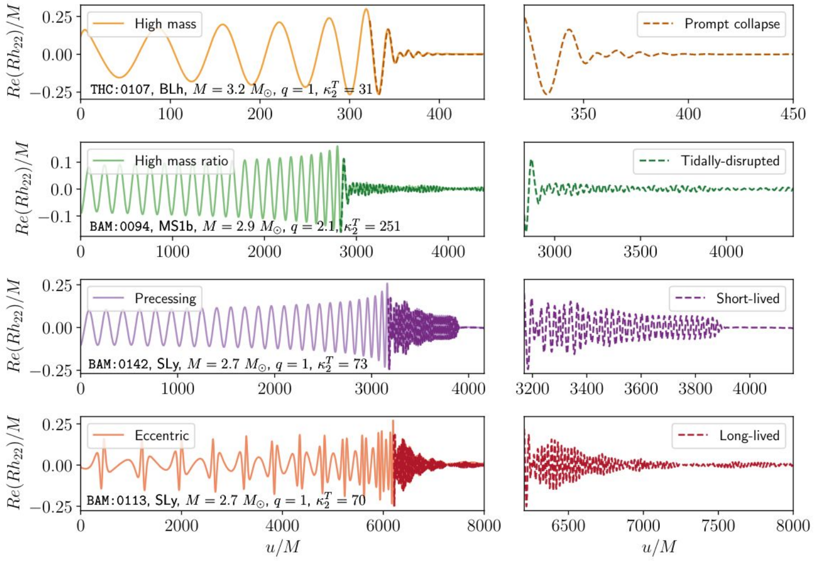
FIG. 4. Sensitivity spacetime volume $\langle VT \rangle$ for each mass range considering hyperbolic encounters simulations recovered by cWB with an iFAR > 10 years.

Progress in waveform modeling

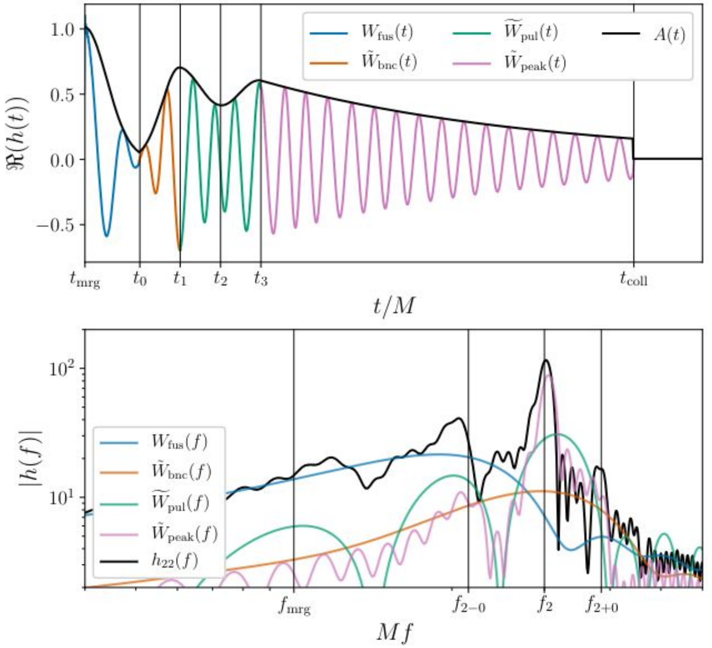
- second release of **CoRe database** for BNS mergers
  - Gonzales *et al* (2023) CQG
  - 254 different BNS configurations
  - 590 NR simulations
  - NS mass, mass-ratio, spin, eccentricity, 18 nuclear EoSs
- **NRPMw:** analytical model for **post-merger GWs** from BNS mergers
  - Breschi *et al* (2024) PRD
  - calibrated by 618 NR simulations
  - in frequency domain using a combination of Gaussian wavelets
  - EOSs-insensitive relations from NR data

A. Perego and A. Camilletti (unitn PhD, Teongrav), supporting research Activity from Jena U. Virgo group of S. Bernuzzi

Gonzales *et al* (2023) CQG



Breschi *et al.* (2024)PRD



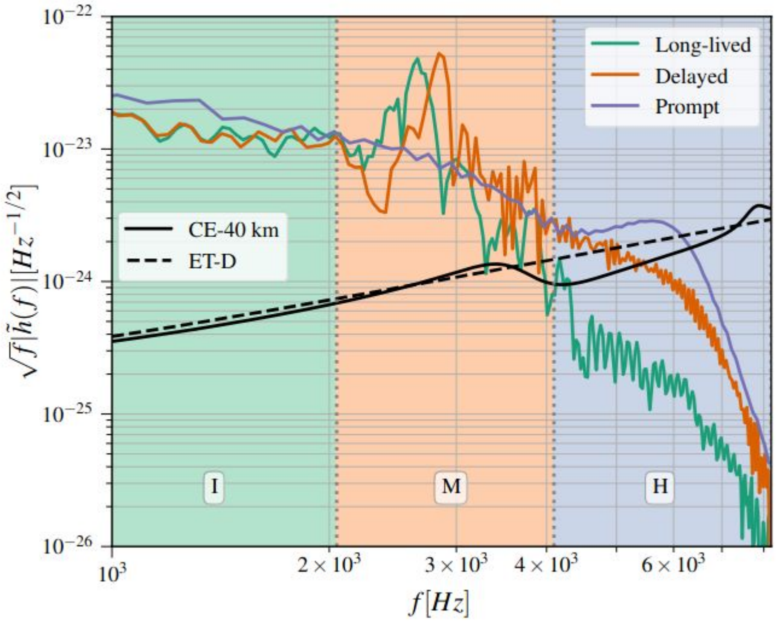
Prospects for GW observations

- prospects for **detection of prompt collapse** BNS mergers
  - Dahni *et al* (2024) PRD
  - quasi-normal ringdown for BHs from BNS mergers
  - power excess at high GW frequency for promptly collapsing BNS merger
- ringdown signal of BH formation in BNS mergers
  - Bandyopadhyay *et al* (2024) CQG
  - non-trivial dependence on binary mass ratio and tidal deformability
  - relevance: valuable GR test inspiral VS post-merger

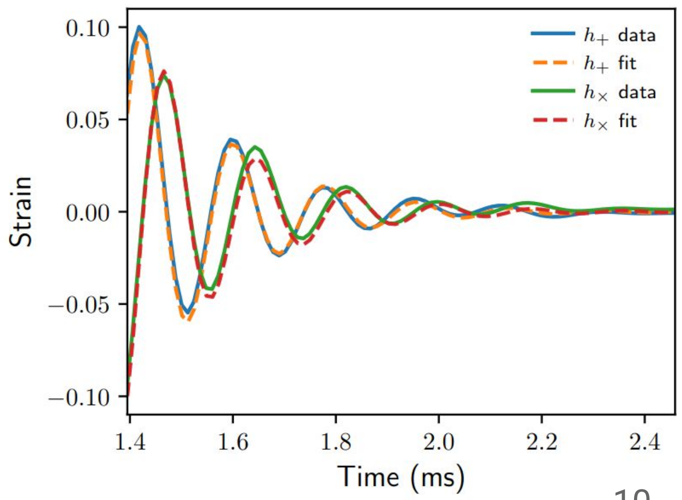
…mostly for ET and III generation telescopes…

A. Perego, supporting research activity from Penn State's LIGO and ET groups, and from D. Radice (Penn State U.)

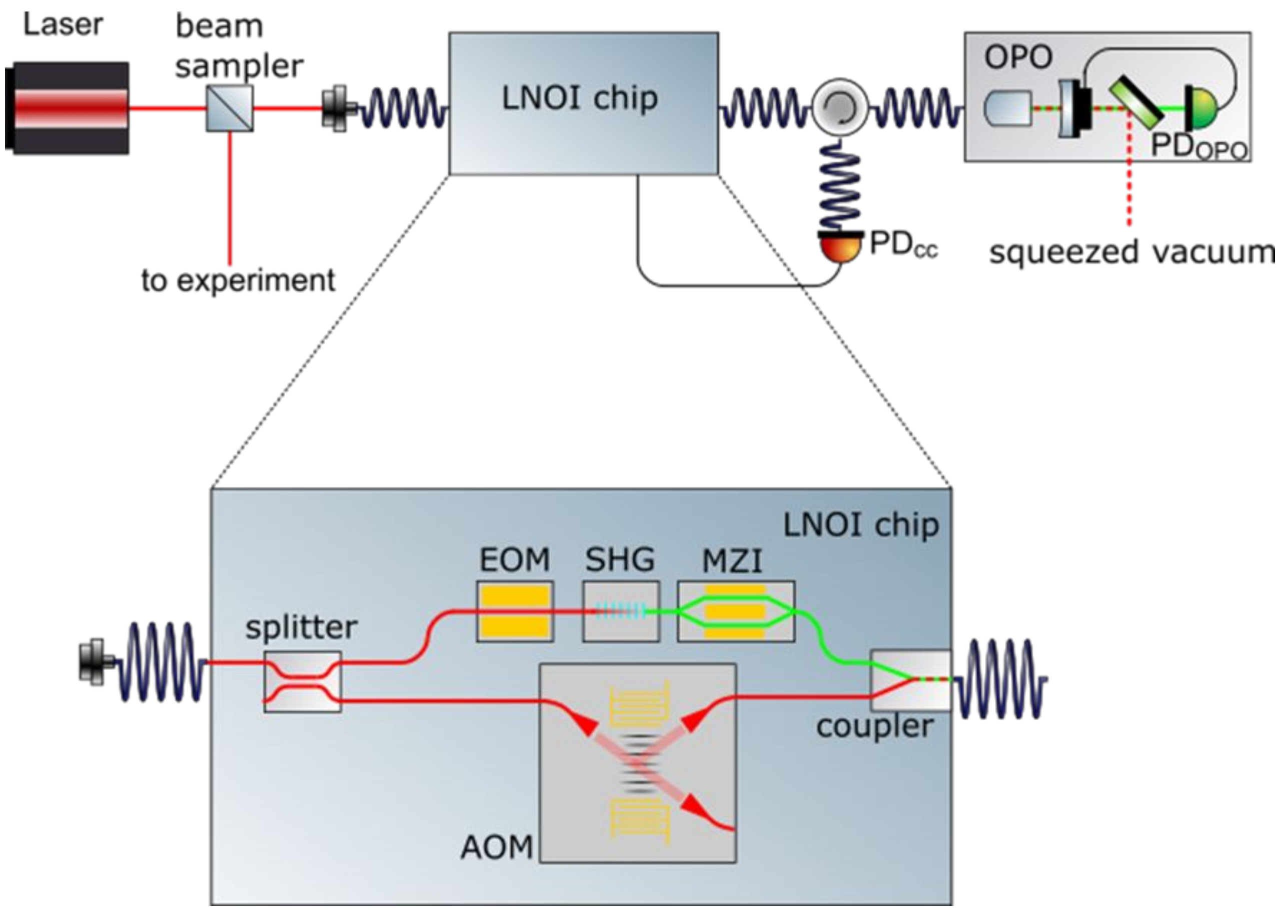
Dahni *et al* (2024) PRD



Bandyopadhyay *et al.* (2024)CQG



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

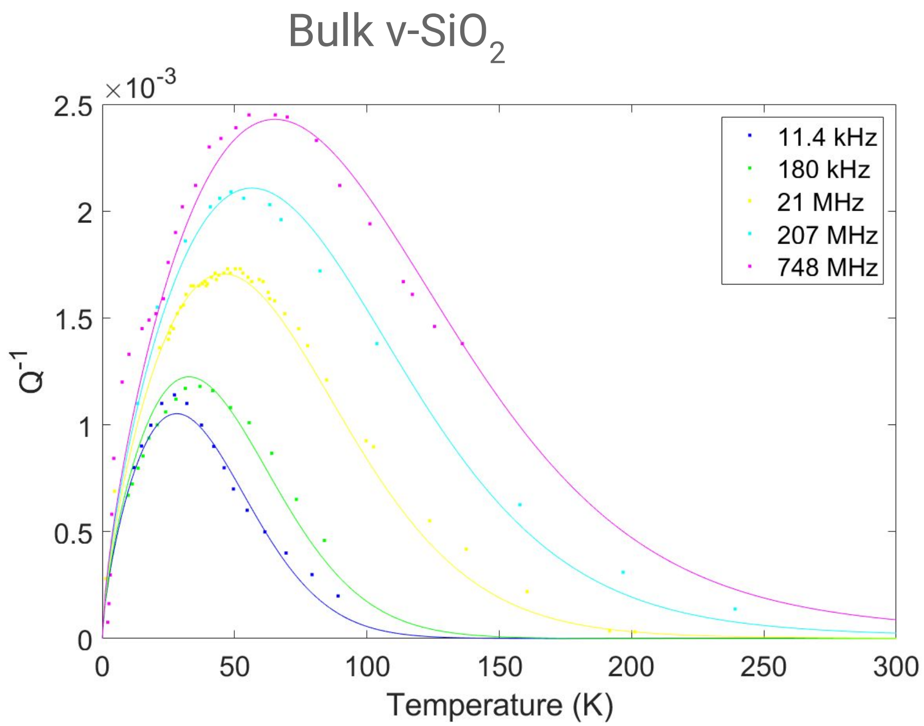
Activities on coatings – overview

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

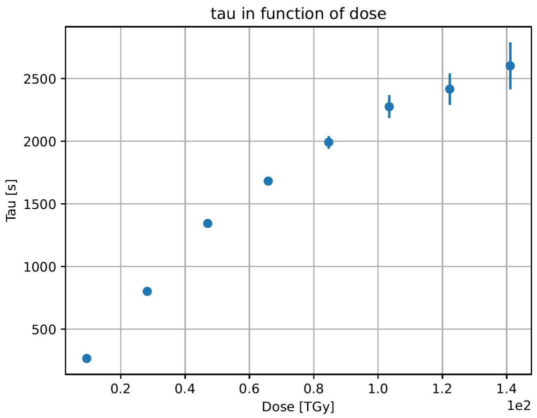
S. Caponi, A. Fontana, F. Rossi, G. Baldi, and E. Fabiani, Phys. Rev. B **76**, 092201 (2007).

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

Activities on coatings – ongoing

Research at synchrotron/FEL facilities

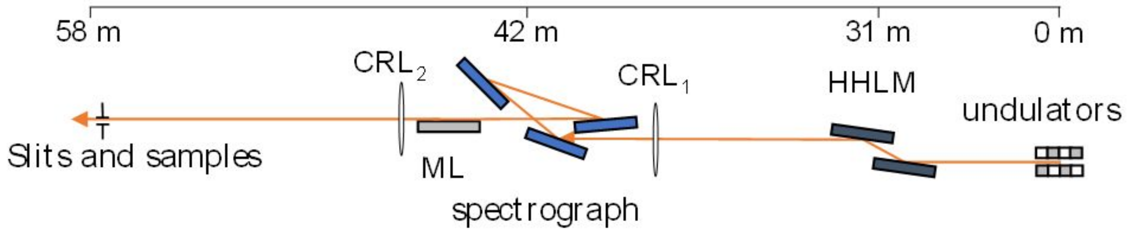
First results of XPCS on pure Ta_2O_5 at beamline ID10 @ ESRF (Grenoble)



-> information on the topology of the glass network (preliminary data, unpublished)

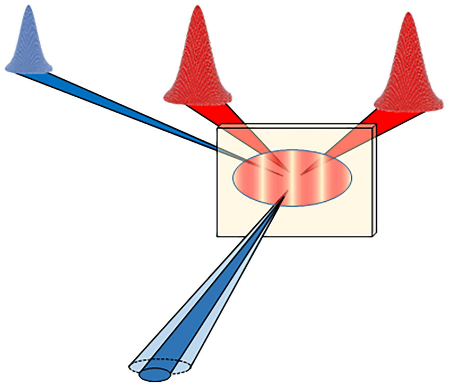
Beginning of September: Beamtime at ID14 @ESRF (collaboration with M. Bazzan and M. Granata)

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



Inelastic X-ray scattering at the new ID14 nuclear resonance beamline

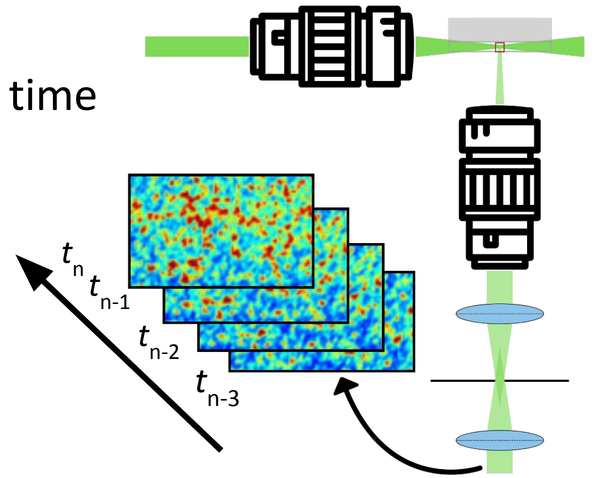
July: test experiment with optical transient grating spectroscopy (collaboration with A. Trapananti and F. Travasso)



Pump - probe experiment to measure Q^{-1} in the frequency range 100 MHz - 1 GHz

Activities on coatings – future plans

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

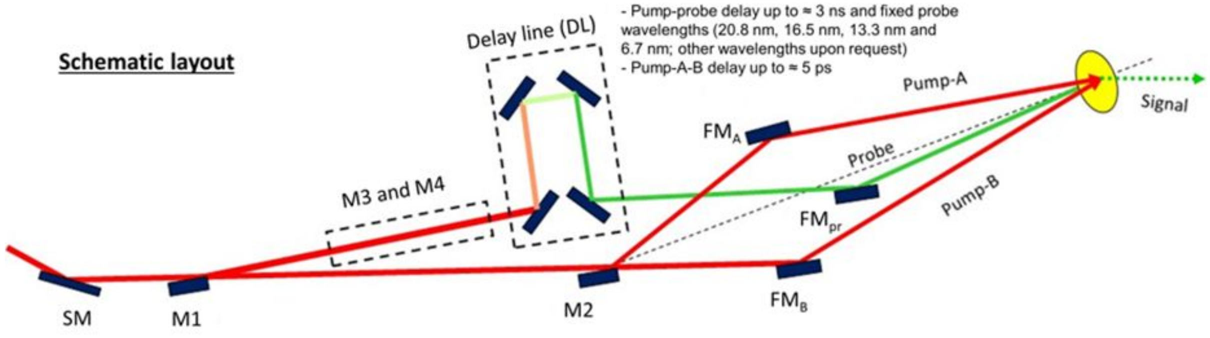


Need to update the existing setup with:

- 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. Proposal submitted to 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)

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

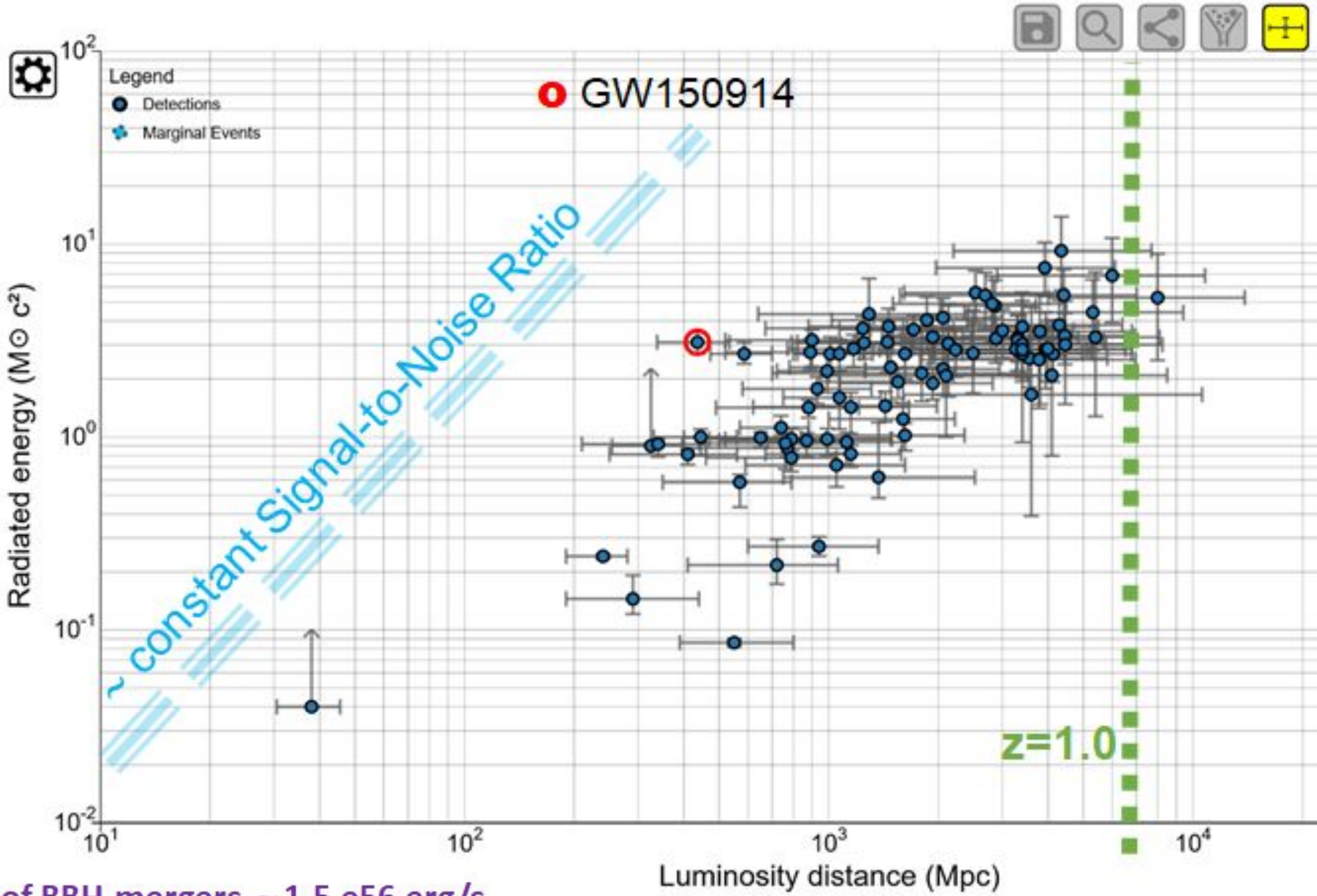
Radiated energy in GWs up to 10 solar masses

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

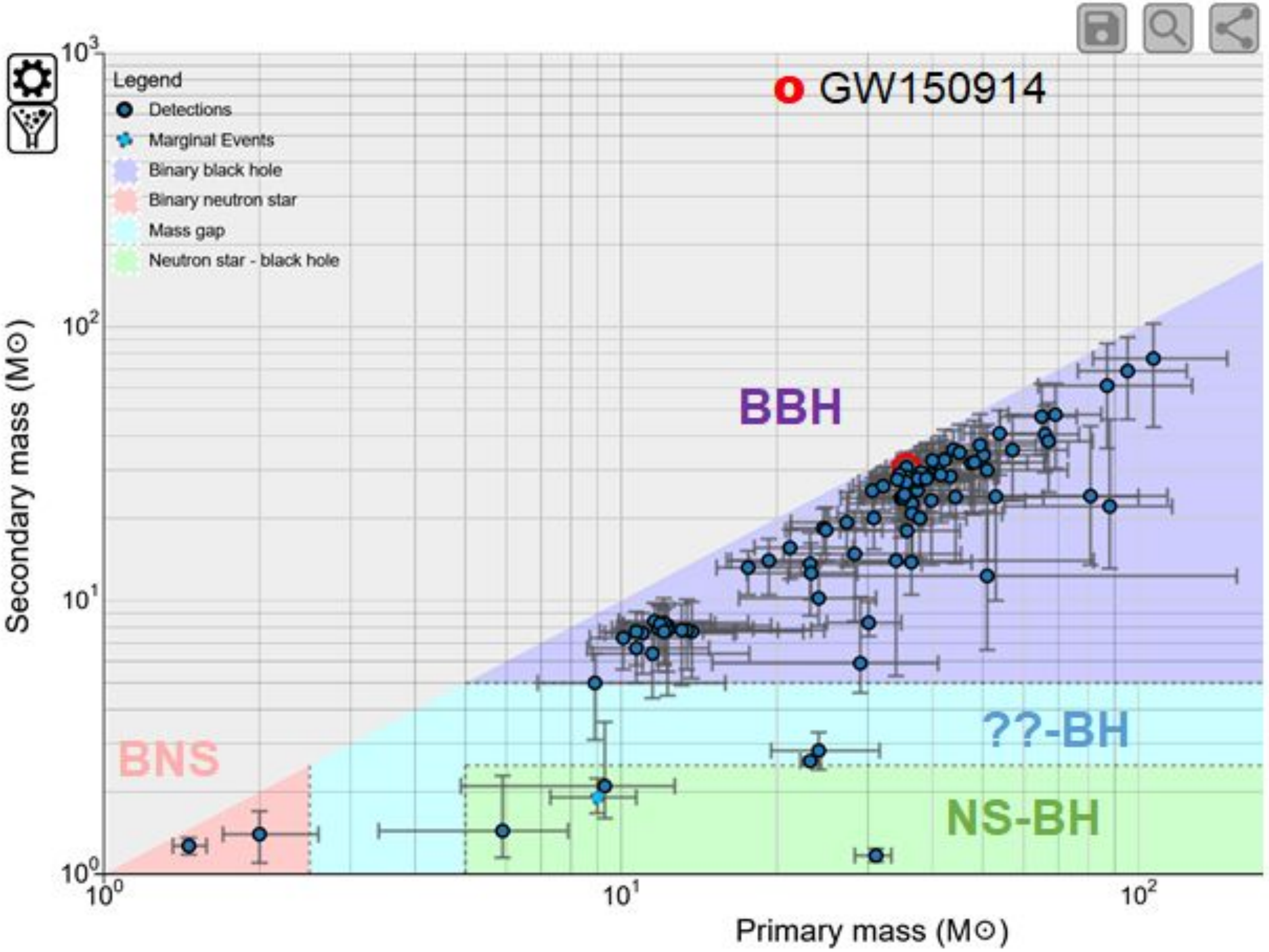
mostly binary BH mergers

2 Binary Neutron Star mergers

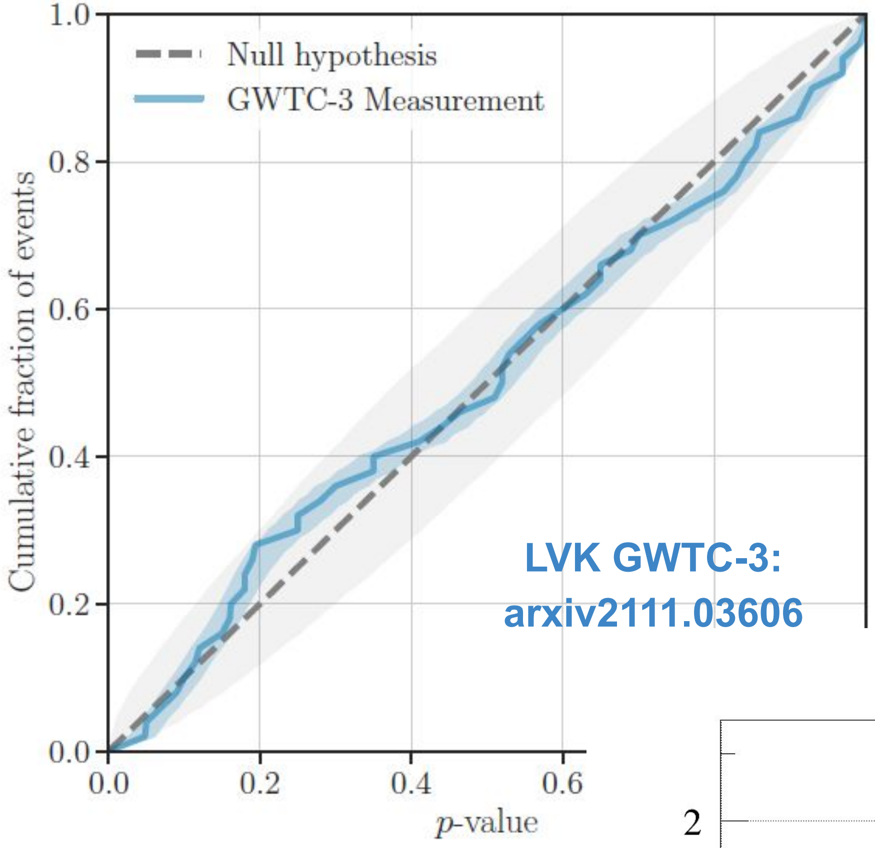
3 NS-BH mergers

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

3 intermediate mass BH

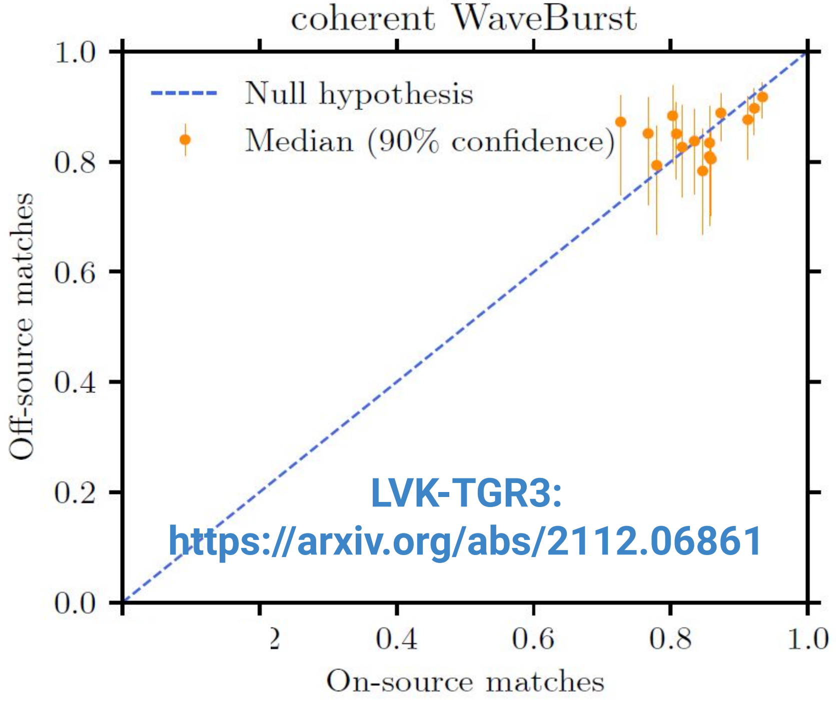


Unmodeled reconstruction vs GR models

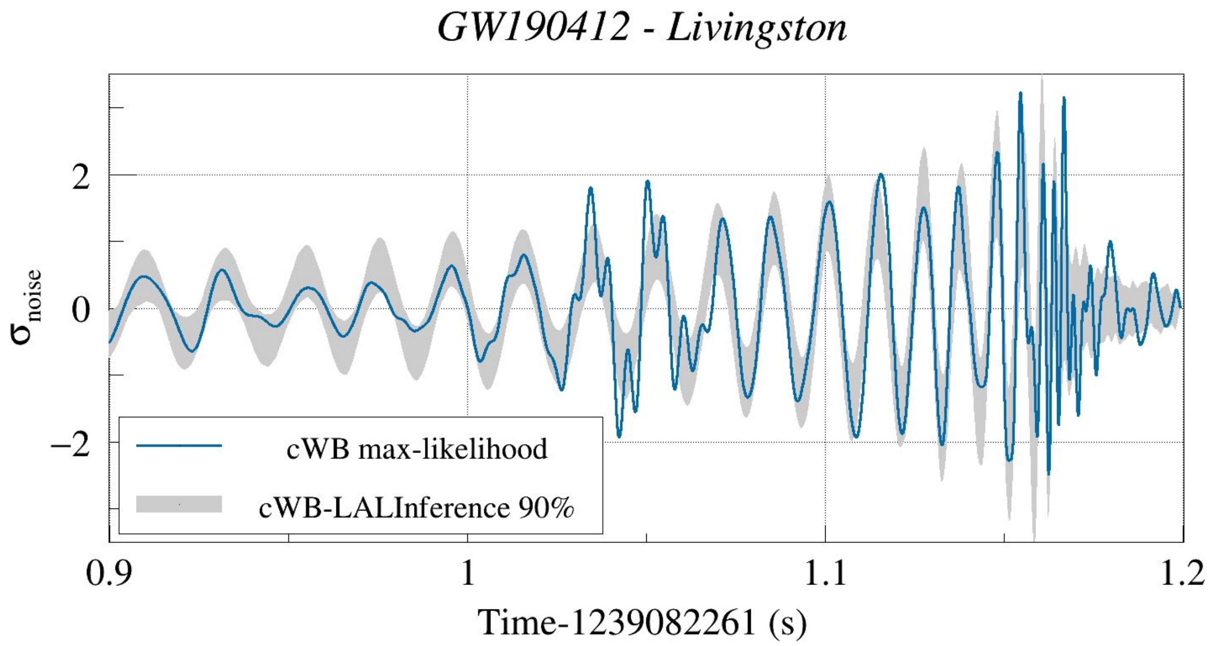


LVK GWTC-3:
arxiv2111.03606

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

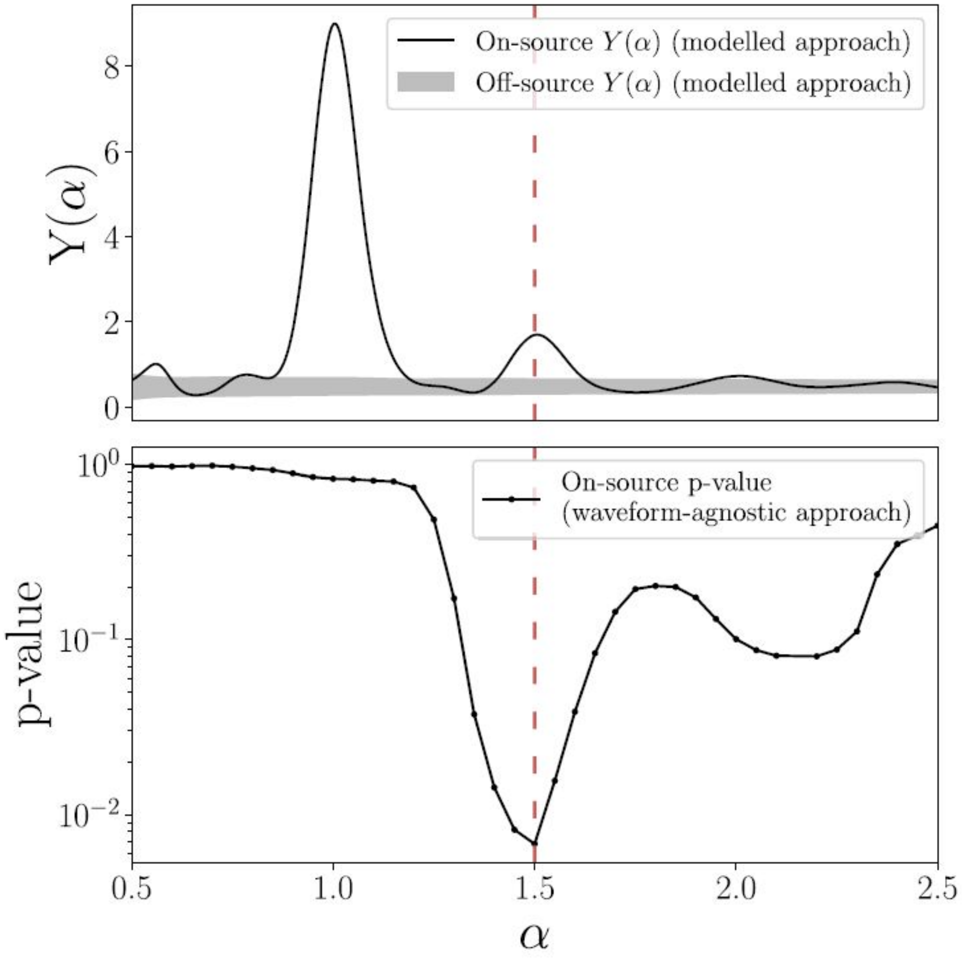


LVK-TGR3:
https://arxiv.org/abs/2112.06861

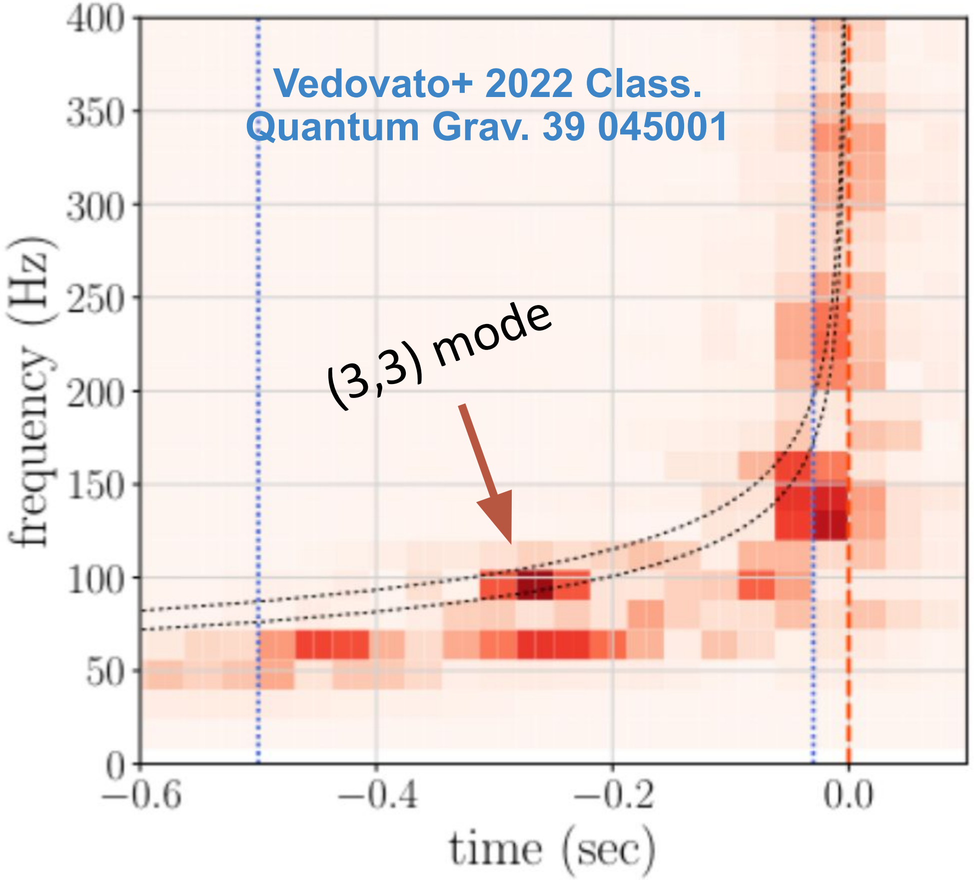


Unmodeled reconstruction vs GR models

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

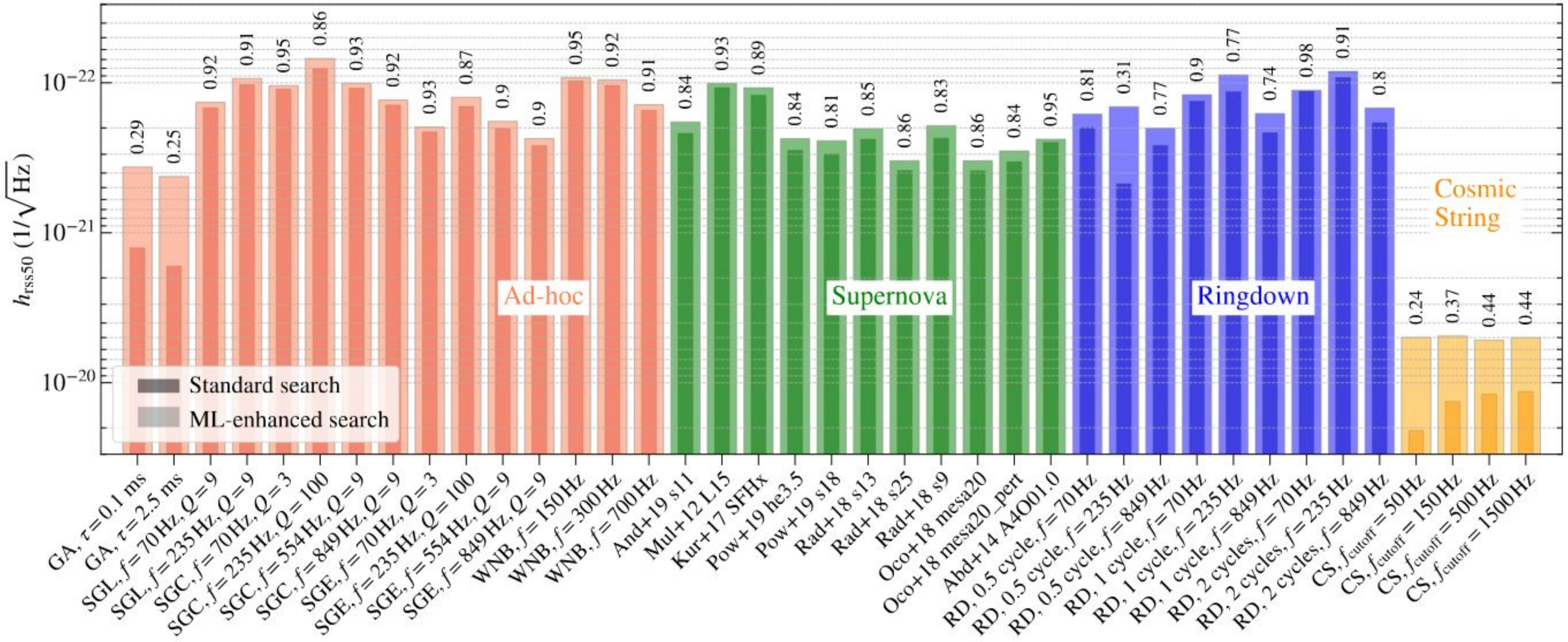


FIG. 2: Resulting h_{rss50} achieved with cWB with standard post-production veto procedure (darker colors) and with ML-enhanced cWB (lighter colors) for the HL network on full O3 and at iFAR$\geq$ 100 years. The waveforms reported are a subset of those listed in Table I: ad-hoc signals ordered according 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

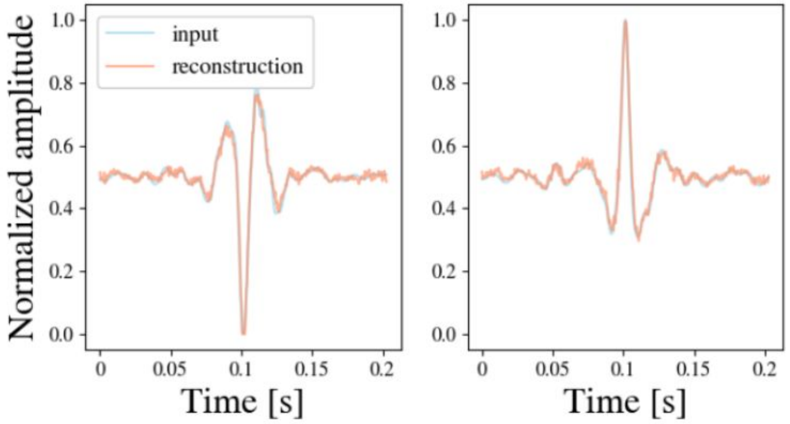


Figure 2. Two examples of blip time-series according to the GravitySpy classification detected by cWB in LIGO Hanford. In blue the autoencoder inputs x_i, that are cWB reconstructed waveforms windowed and normalized as described in Section 4.2). In orange the autoencoder reconstructions $g_D(f_E(x_i))$.

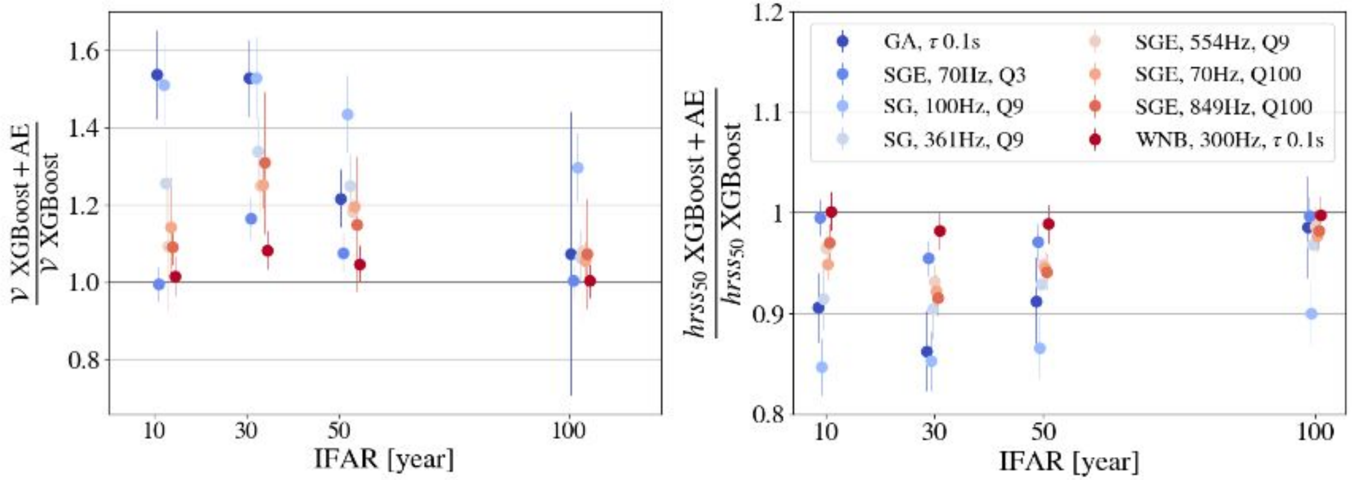


Figure 5. Ratio between the sensitivity volume $\mathcal{V}$ (left) and h_{rss50} (right) obtained including the autoencoder (`XGBoost + AE`) and without using it (`XGBoost`), at different IFAR thresholds (10, 30, 50, 100 years) for a subset of ad-hoc waveforms (data points are slightly shifted around 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

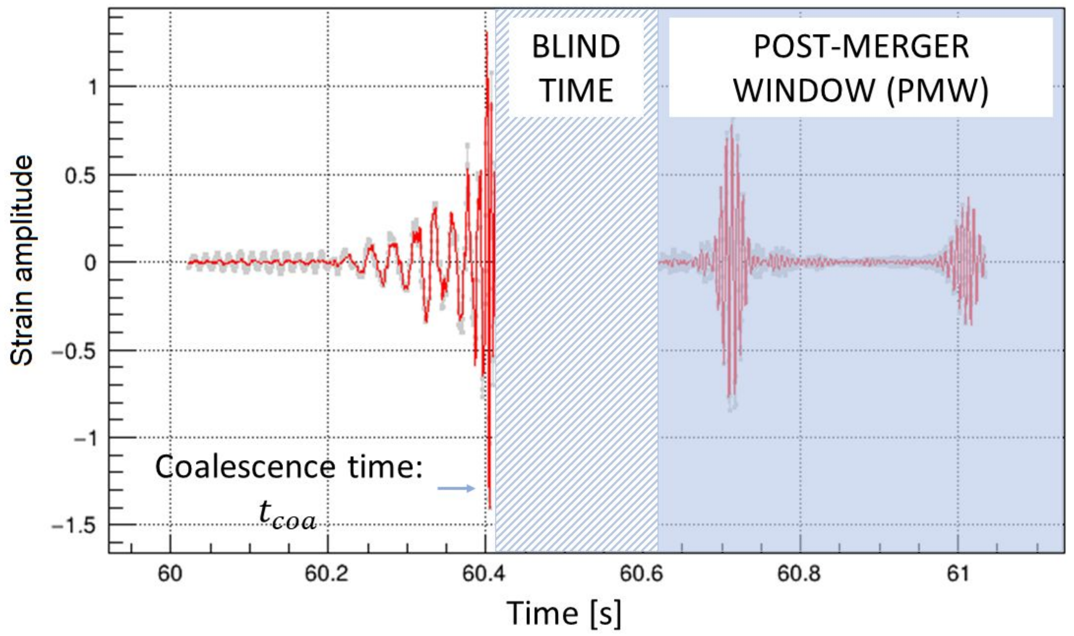
Echoes: repeated GWs pulses, after merger of binary of compact objects, ONLY IF remnant IS NOT a GR BH.

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

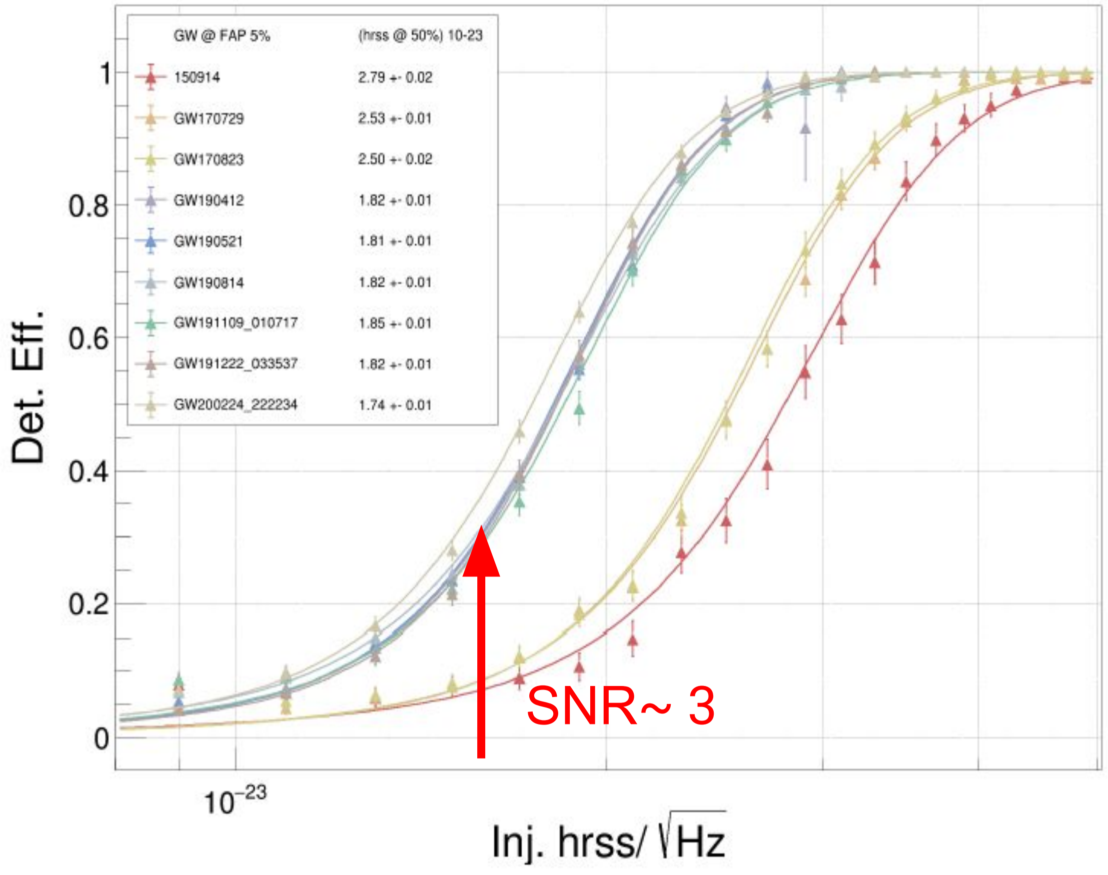


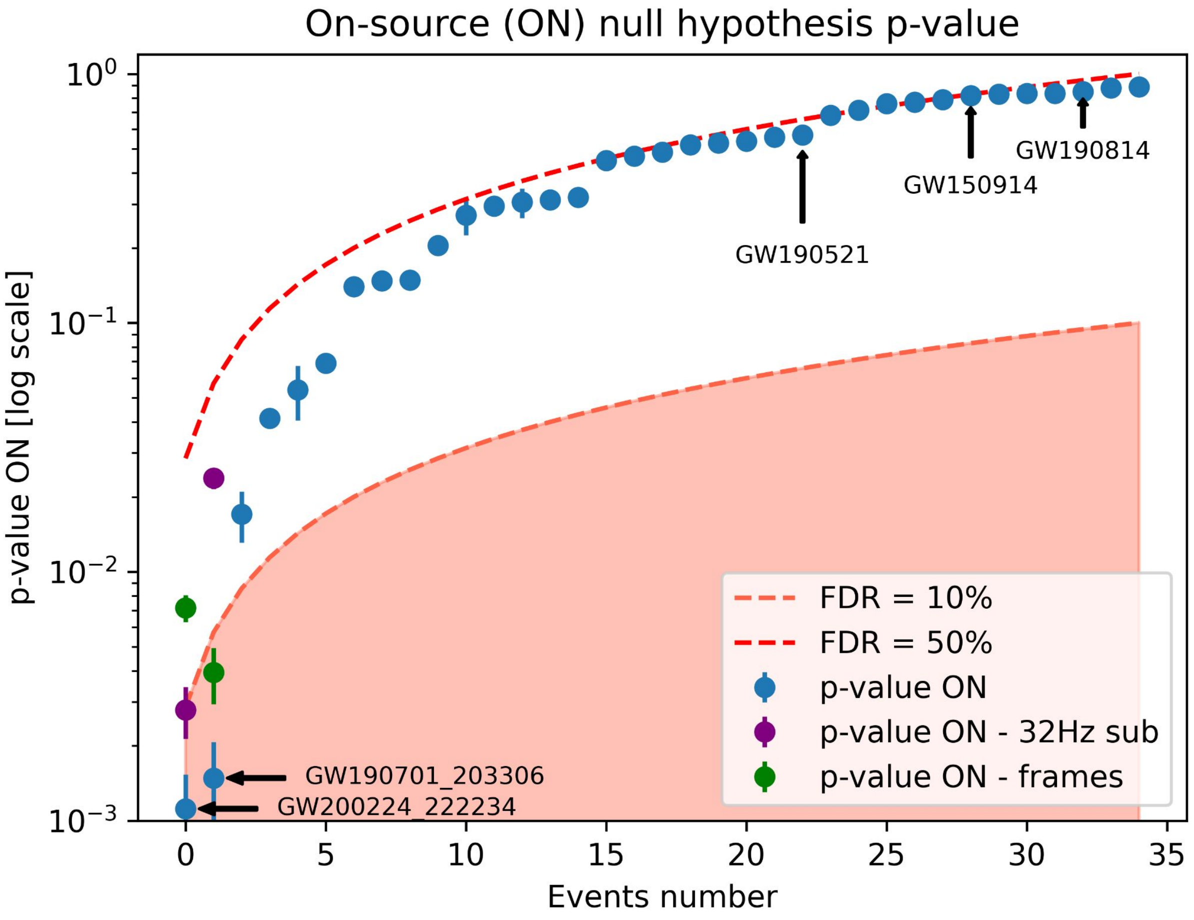
Andrea Miani's PhD thesis

A.Miani et al , arXiv:2302.12158

Searches for Black Hole mimickers: post-merger echoes

RESULTS





+

morphological reconstruction of subtreshold signals