Gravitational waves in Virgo: transient-oriented overview of O3 results and the incoming O4 observing run

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L.A.P.P. Universite Savoie Mont-Blanc
1st Astro-COLIBRI Multi-Messenger Astrophysics Workshop
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Numerical relativity simulation of a BH-NS merger, where the NS is tidally disrupted by the BH (as GW200105, GW200115)
Modified from Deborah Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt University).

Gravitational waves

from www.einstein-online.info

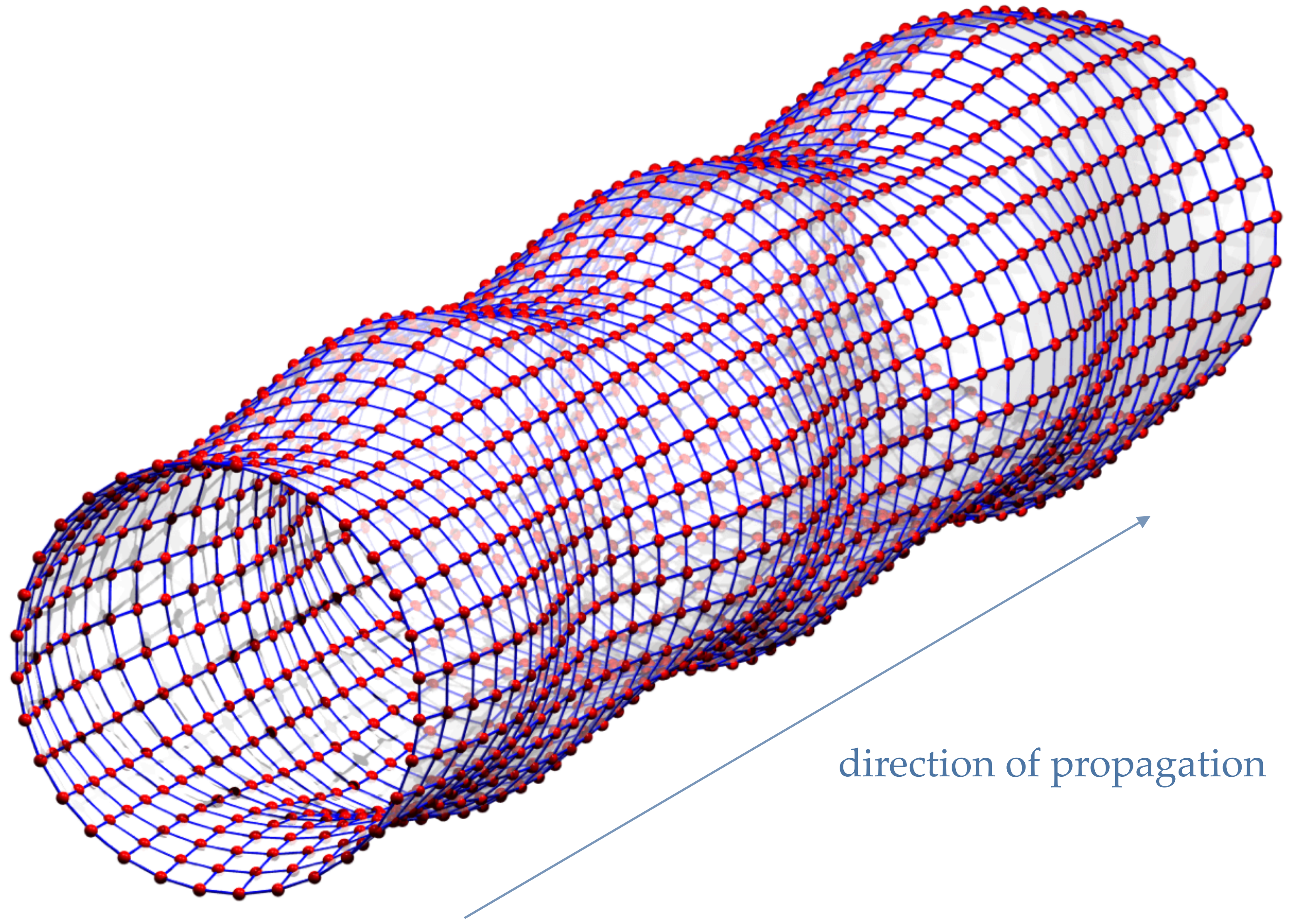
- *Ripples* of space-time produced by rapidly accelerating non-axisymmetric mass distributions. 2 polarizations (+, x)

- Its existence is a prediction of General Relativity (A. Einstein, 1916)

- First proof of their existencia via the study of the period of a binary pulsar PSR B1913+16 over ~15 years by Hulse and Taylor with the Arecibo telescope: loss of energy due to the emission of gravitational waves

- The strongest events disrupting space-time include coalescences of compact binaries e.g. black holes, neutron stars, but also supernova, pulsars

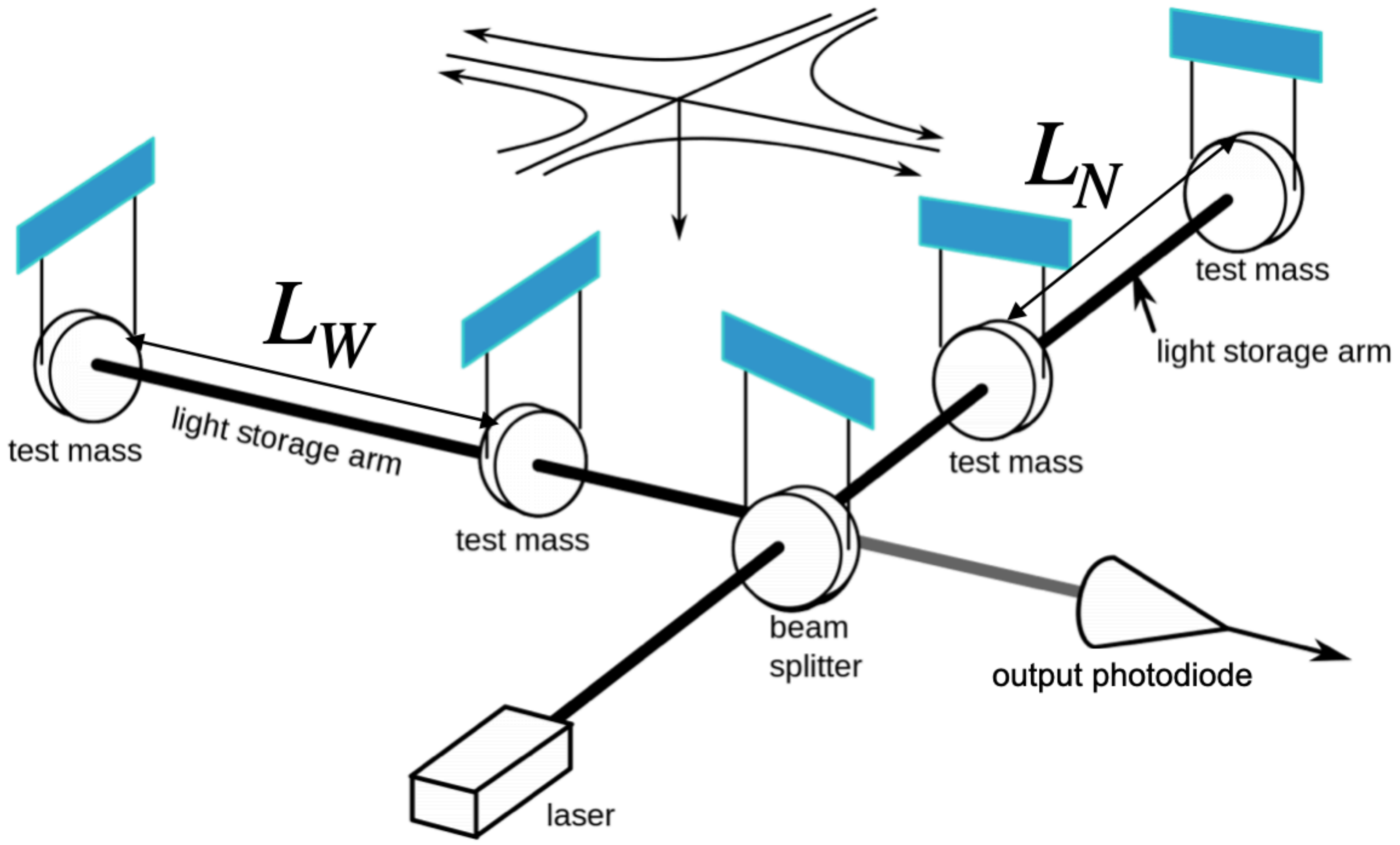
- A new window to the universe as the *fourth* messenger: GW170817



- In order to detect gravitational waves: <u>measure the relative displacement between tests masses</u>

Michelson Interferometers

- Really sensible instruments are needed: use optics!
  - The **length variations** produced by the passage of a GW are observed as **power variations** on the output photodiode
  - Optics are keep at precise locations so that that resonance is achieved

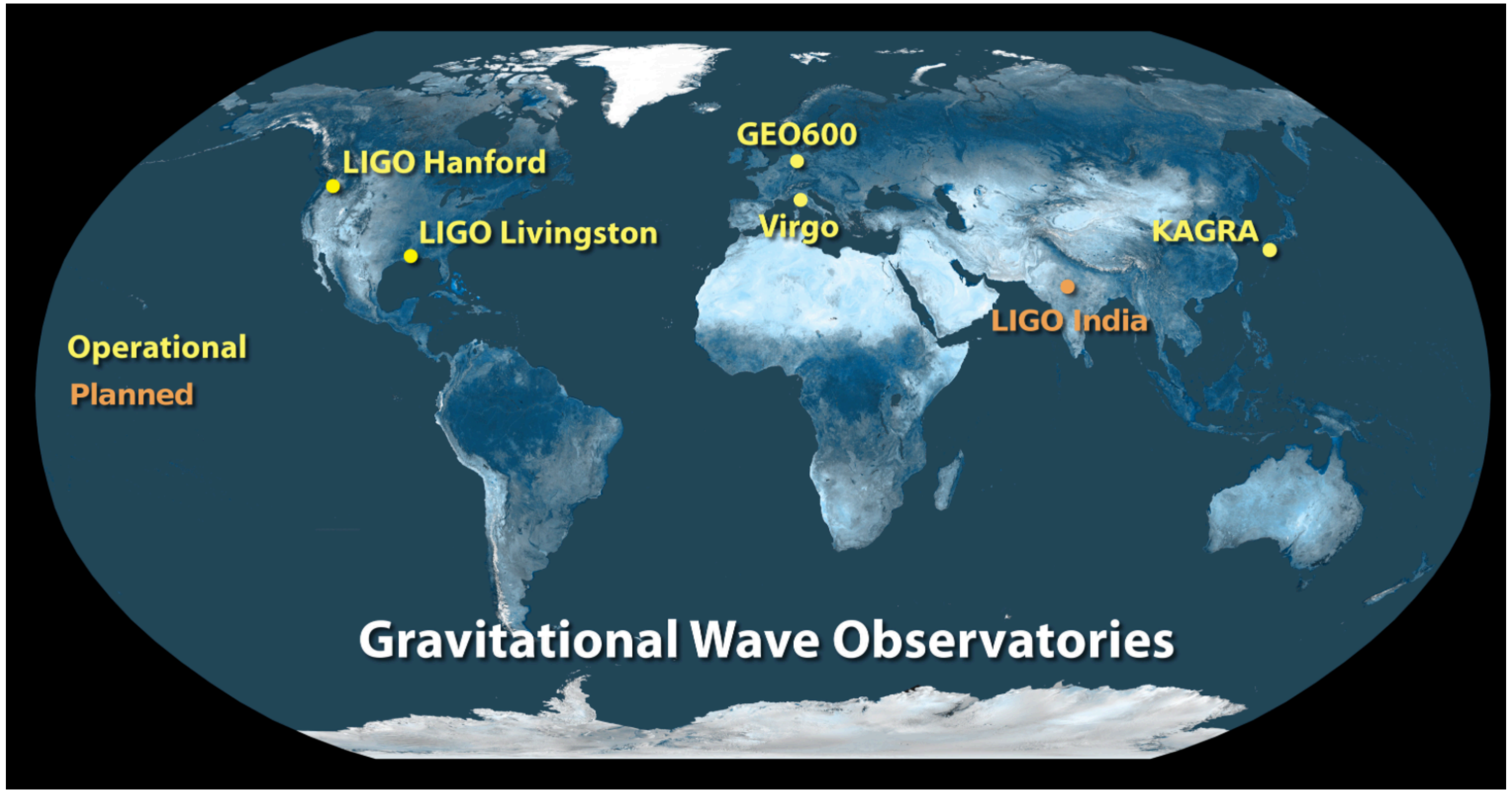


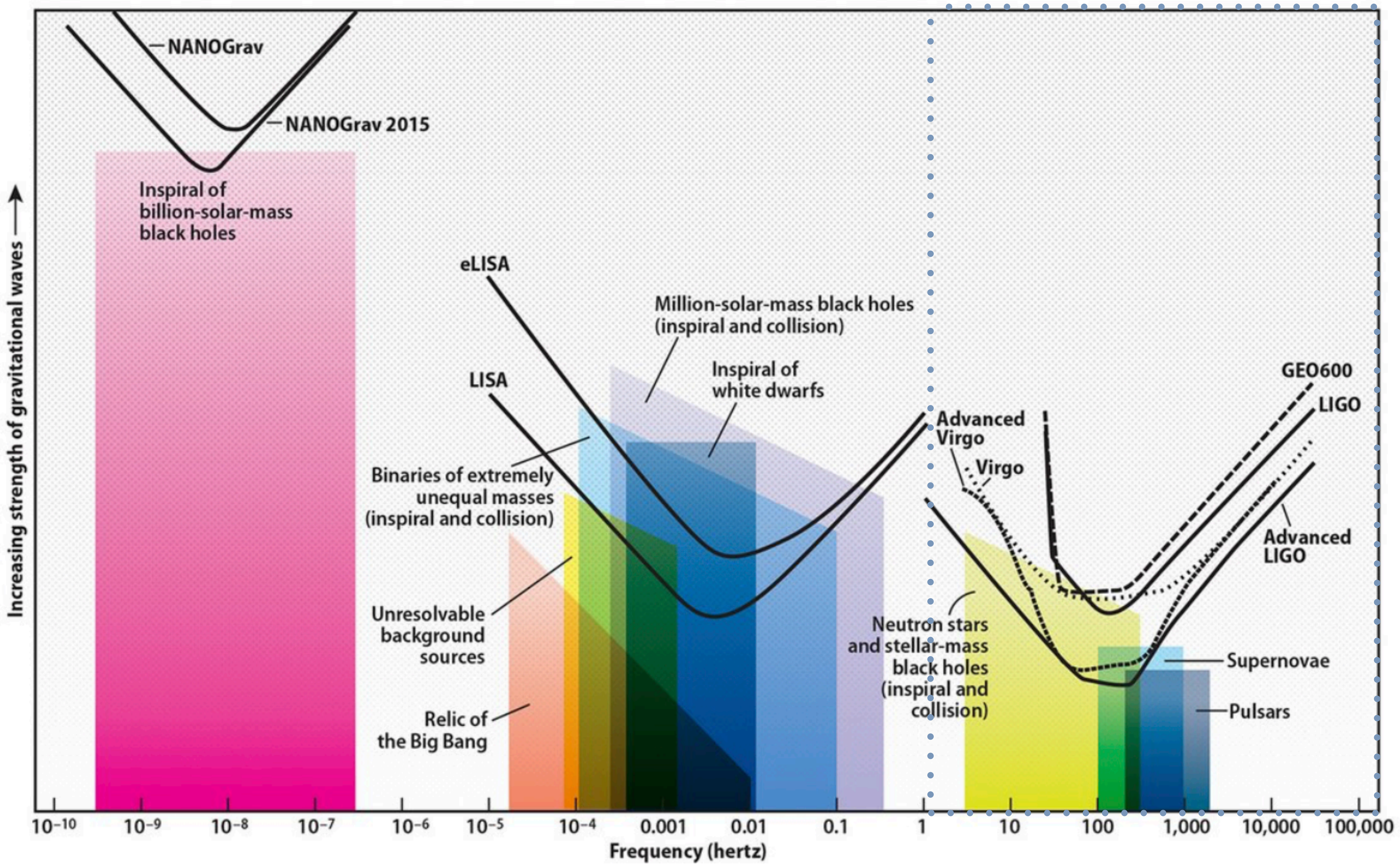
- The detector strain signal h(t) is the main observable of GW interferometers:
  - Relative change of the arm length in the interferometer

$$h = \frac{\Delta L}{L_0}$$

  - To detect e.g. compact binary coalescensces h ~10^{-21} with L_0~3km => $\Delta L \sim 10^{-18}$m

Wordwide network of 2nd generation GW interferometers





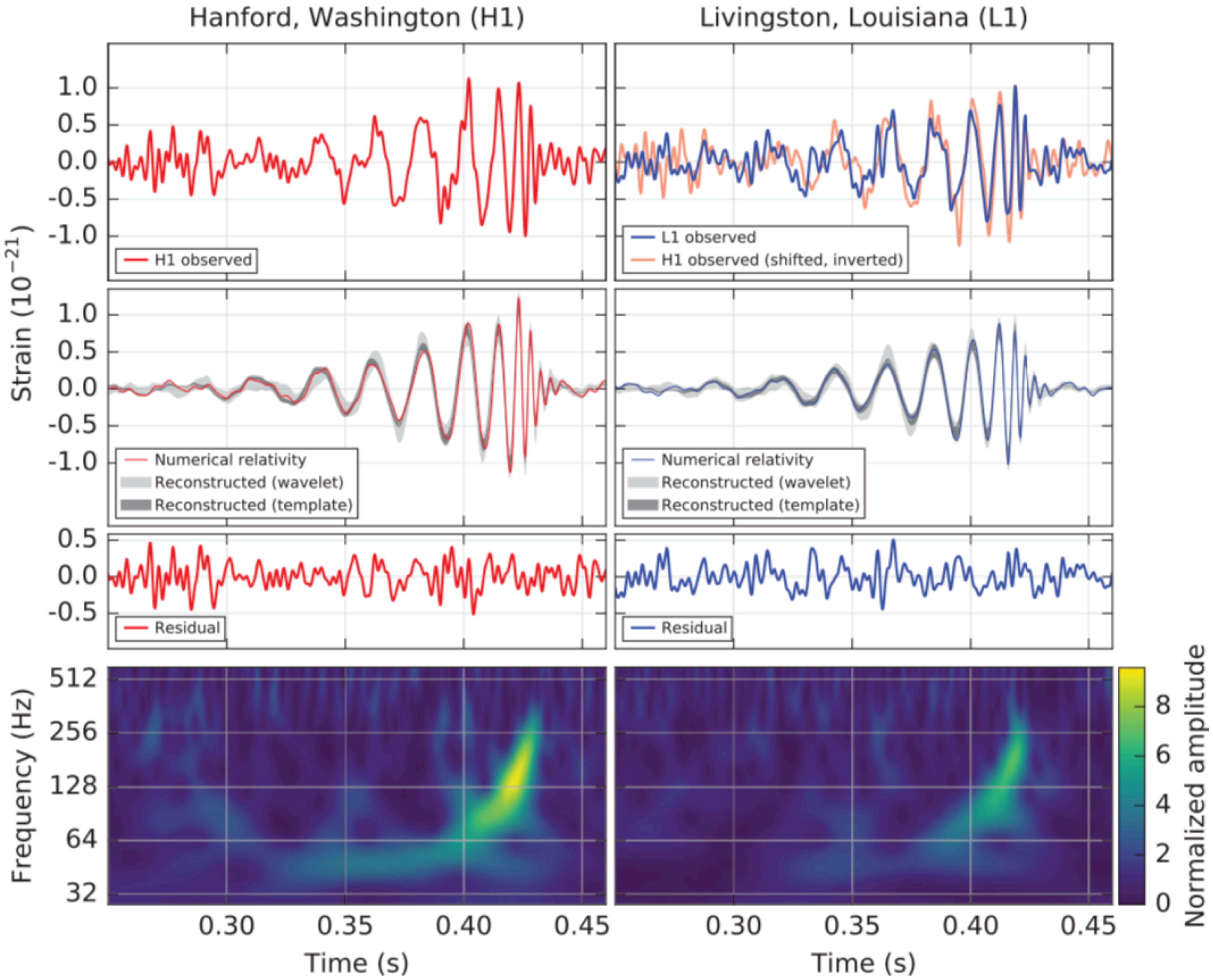
- KM-scale Advanced Michelson Interferometers: Technology is slightly different (e.g. underground ITF, criogenic mirrors, longer arms..)
- Joint observing runs of 2nd generation GW detectors:
  - After the strain h(t) is reconstructed and Data Quality assessed, ITF data are combined for astrophysical analysis.
  - Maximises VT, confidence on the detections, duty cycle and location accuracy via source triangulation

- Compact Binary Coalescences (neutron stars and stellar-mass BH)
- Supernovae
- Pulsars
- Stochastic backgrounds
- Tests of GR, Cosmology, H0, Standard Model

2015: first direct detection of gravitational waves

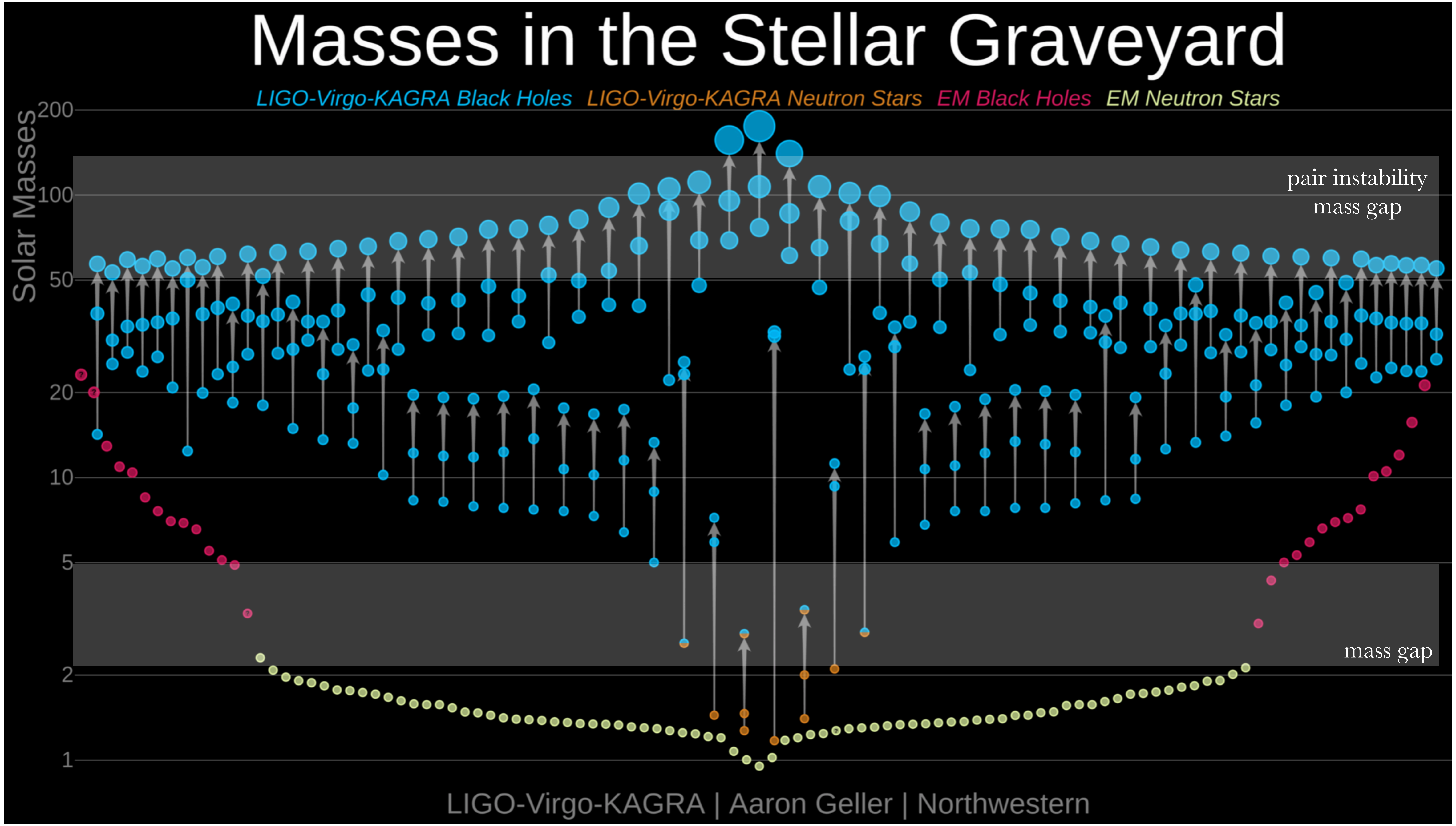
- The gravitational-wave event GW150914 observed by the LIGO (Hanford and Livingston) detectors
- September 14, 2015
- Binary black hole merger $36^{+5}_{-4} M_{\odot} + 29^{+4}_{-4} M_{\odot}$
- Luminosity distance: 410^{+160}_{-180} Mpc
- Sky localization: 600 sq.deg (90% credible region)
- False alarm probability < 2 × 10^{-7}

Physical Review Letters **116**, 061102 (2016)



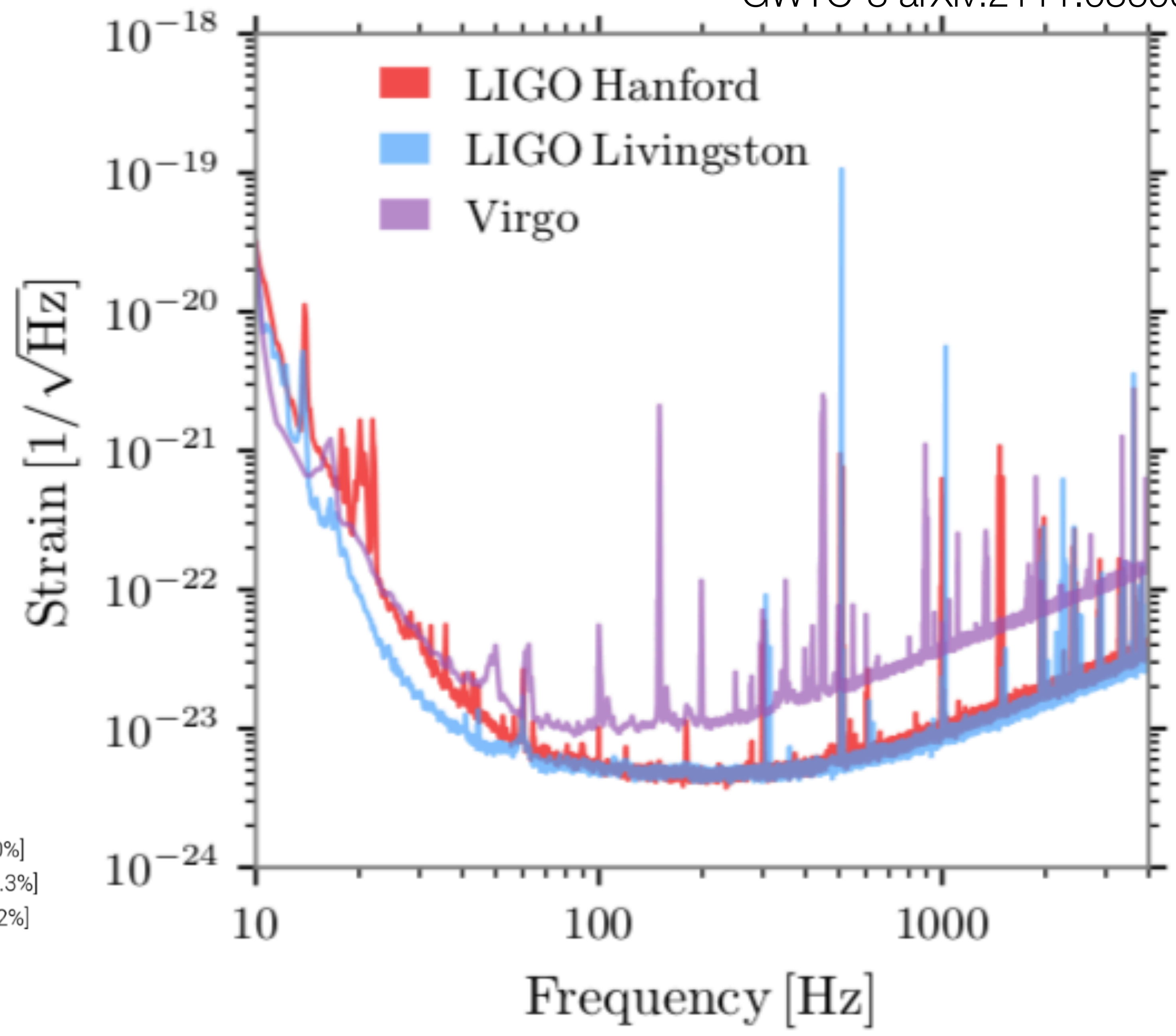
2020s: Gravitational Wave Transient Catalogs

O3 can be summarized as the observing run of an exploding number of compact binary mergers => GW astronomy is here, dig into population studies !

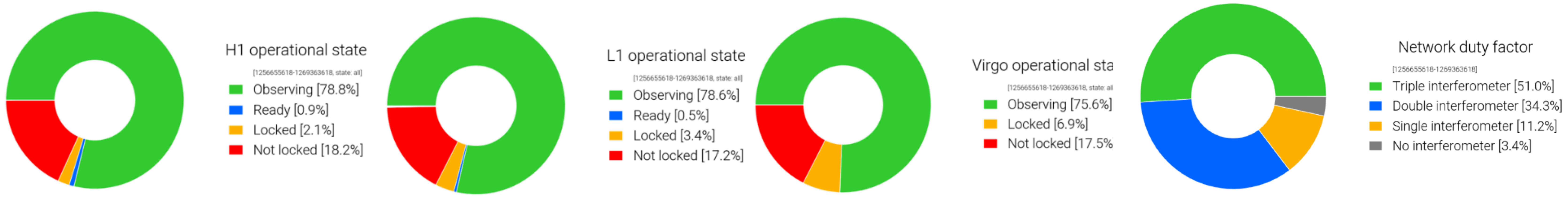


Observing run O3

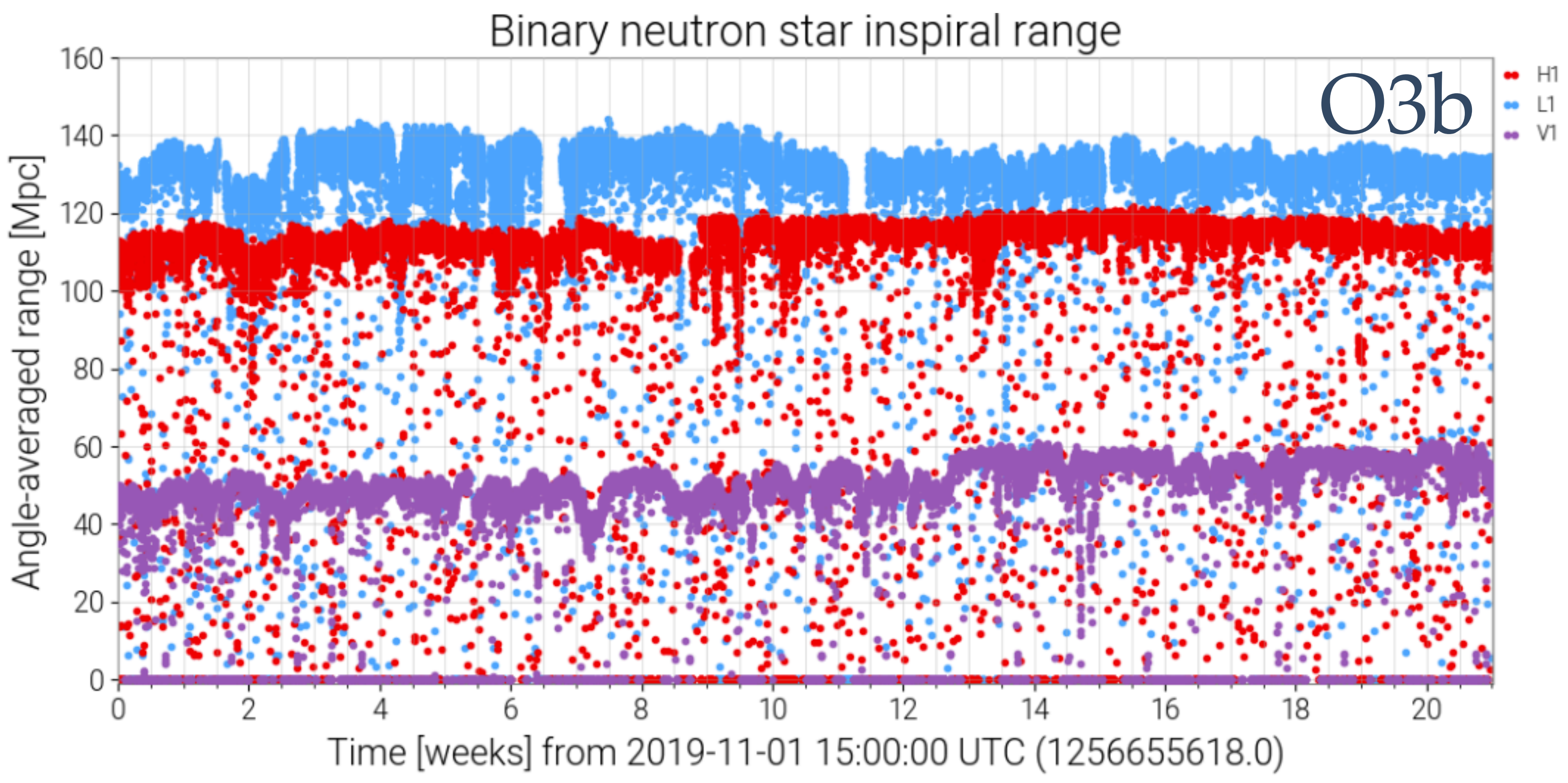
GWTC-3 arXiv:2111.03606



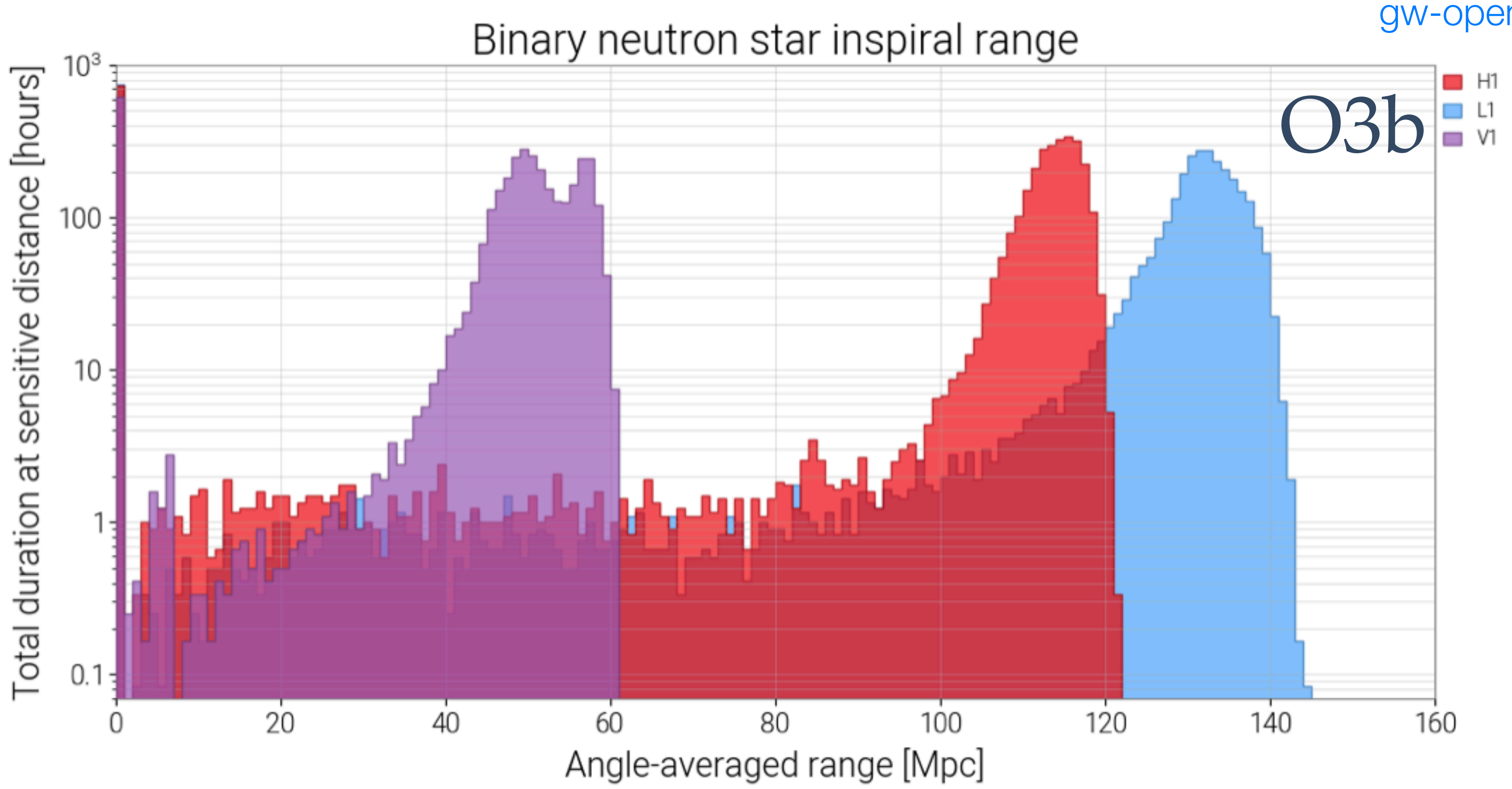
- A little less than a year of observations due to Covid-19
  - O3a: 6 months=> 2019 April 1 – 2019 October 1
  - O3b: ~ 5 months=> 2019 November 1 – 2020 March 27
- Duty cycle of the GW network:



- Alerts online: A total of 56 online candidates after 24 retractions in O3
  - BBH(38), BNS(6), BH-NS (5), MassGap (4), Terrestrial(3) events



gw-openscience.org



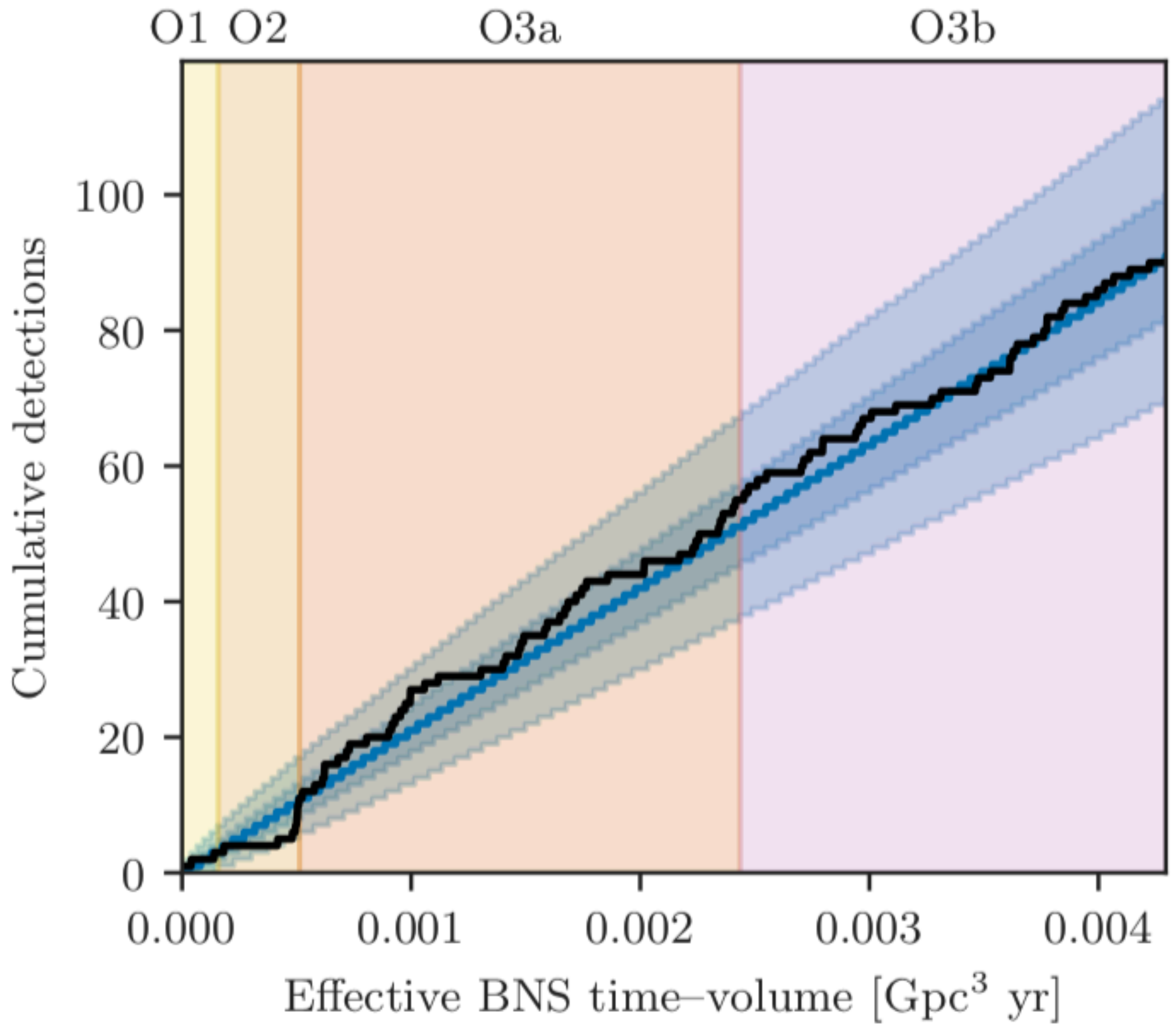
Catalog paper GWTC-3

ArXiV:*2111.03606*

- Gravitational Wave Transient Catalogs (GWTC) include detected compact binaries coalescences during a observing run for a certain FAR
  - Separated papers for specially insteresting events
- In GWTC-3: FAR< 2yr-1 + <u>at least one of the pipelines</u> with p_{astro}>0.5
- Four offline search pipelines (burst+match filtering techniques).

Name	Inst.	cWB			GstLAL			MBTA			PyCBC-broad			PyCBC-BBH		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW191103_012549	HL	–	–	–	–	–	–	*27*	*9.0*	*0.13*	4.8	9.3	0.77	0.46	9.3	0.94
GW191105_143521	HLV	–	–	–	*24*	*10.0*	*0.07*	0.14	10.7	> 0.99	0.012	9.8	> 0.99	0.036	9.8	> 0.99

- Total of 90 events: ~86 BBH, ~1 BNS, ~3 BH-NS
  - GWTC-3 adds 35 events
  - Previously there was GWTC-1 (O1+O2), GWTC-2 (O3a), GWTC-2.1 (O3a)
- Source parameter estimated using Bayesian inference algorithms include
  - m1, m2, mass ratio, effective inspiral spin, luminosity distance.



Populations of BBH, BHNS, BNS

ArXiV:*2111.03634*

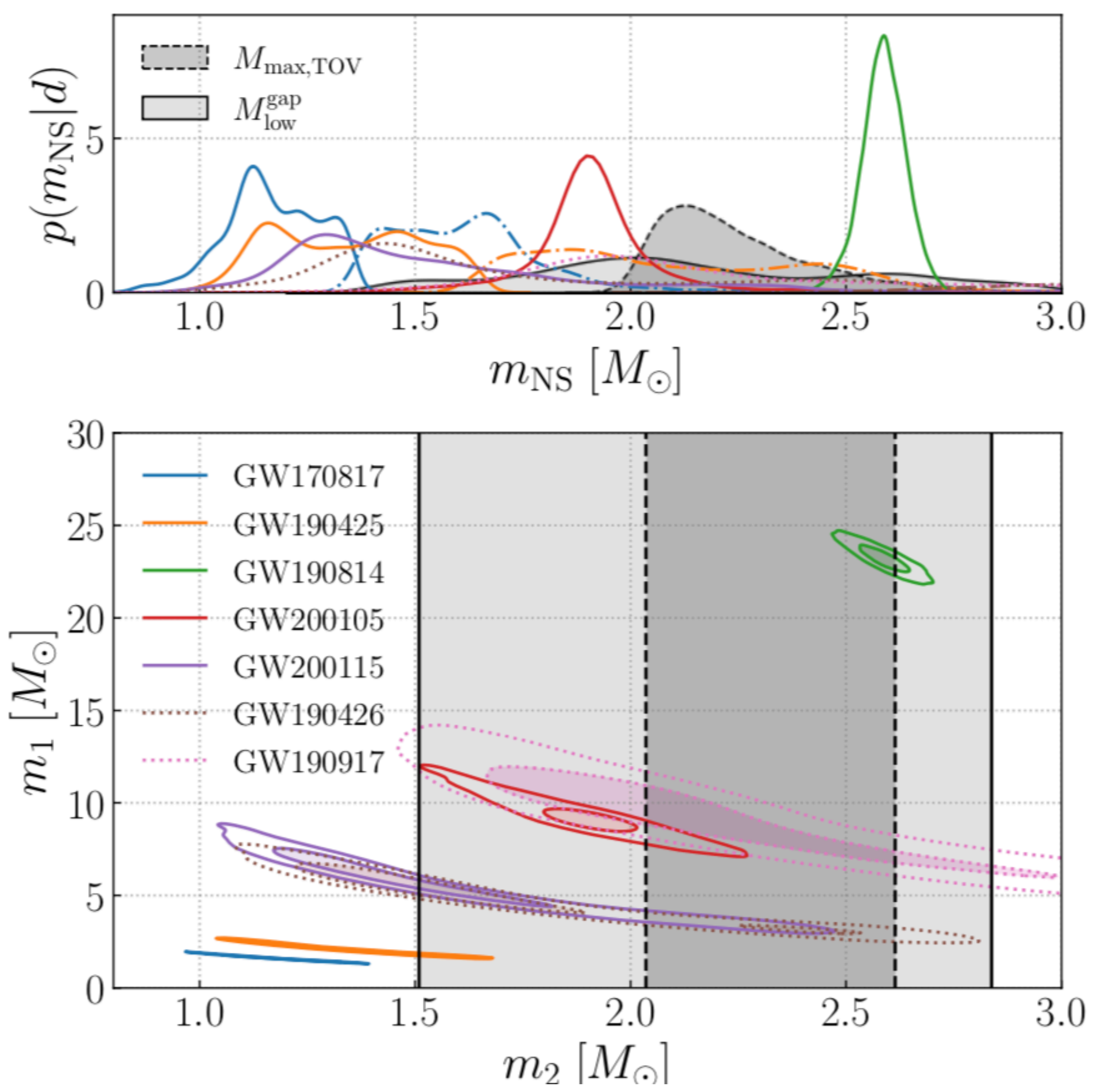
- High purity events selected for populations studies
    - 67 compact binary mergers detected (FAR <0.25 yr^{-1}, <1 yr^{-1} if BBH)

- Maximum mass of NS population is consistent with constraints for equation of state and Galactic pulsars

- BBH populations among catalogs are consistent when comparing mass distributions+mass ratio

    - No clear identification of a upper mass cut-off in BH mass
    - Two features in the primary mass distribution 11 $M_\odot$ and 34 $M_\odot$

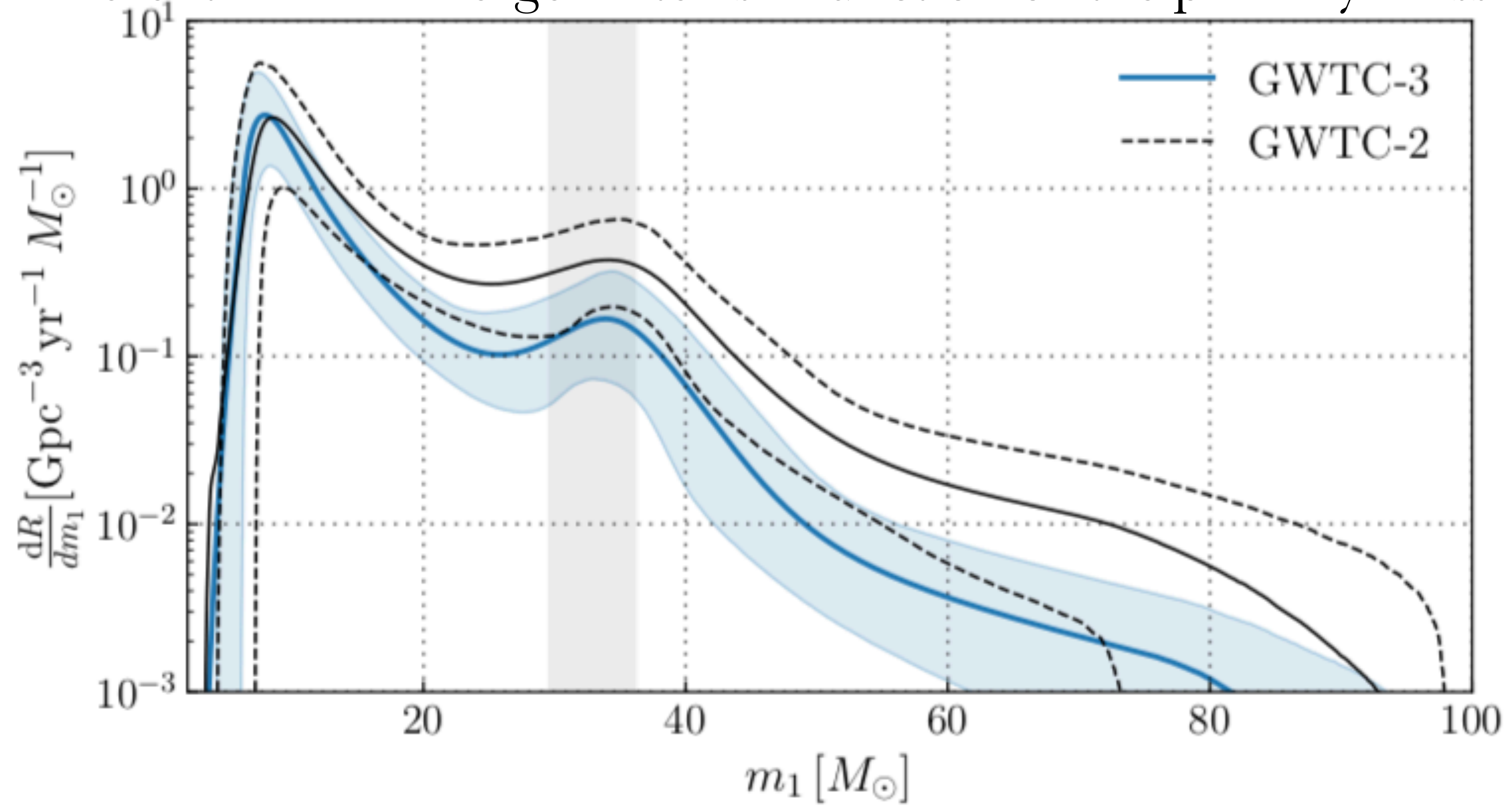
Masses for events with at least one candidate *neutron star*



Derived merger rates in $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ from the union of the 90% credible intervals of the three main models

	BNS	NSBH	BBH	NS-Gap	BBH-gap	Full
	$m_1 \in [1, 2.5] M_\odot$	$m_1 \in [2.5, 50] M_\odot$	$m_1 \in [2.5, 100] M_\odot$	$m_1 \in [2.5, 5] M_\odot$	$m_1 \in [2.5, 100] M_\odot$	$m_1 \in [1, 100] M_\odot$
	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 100] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 5] M_\odot$	$m_2 \in [1, 100] M_\odot$
MERGED	10 – 1700	7.8 – 140	16 – 61	0.02 – 39	9.4×10^{-5} – 25	72 – 1800

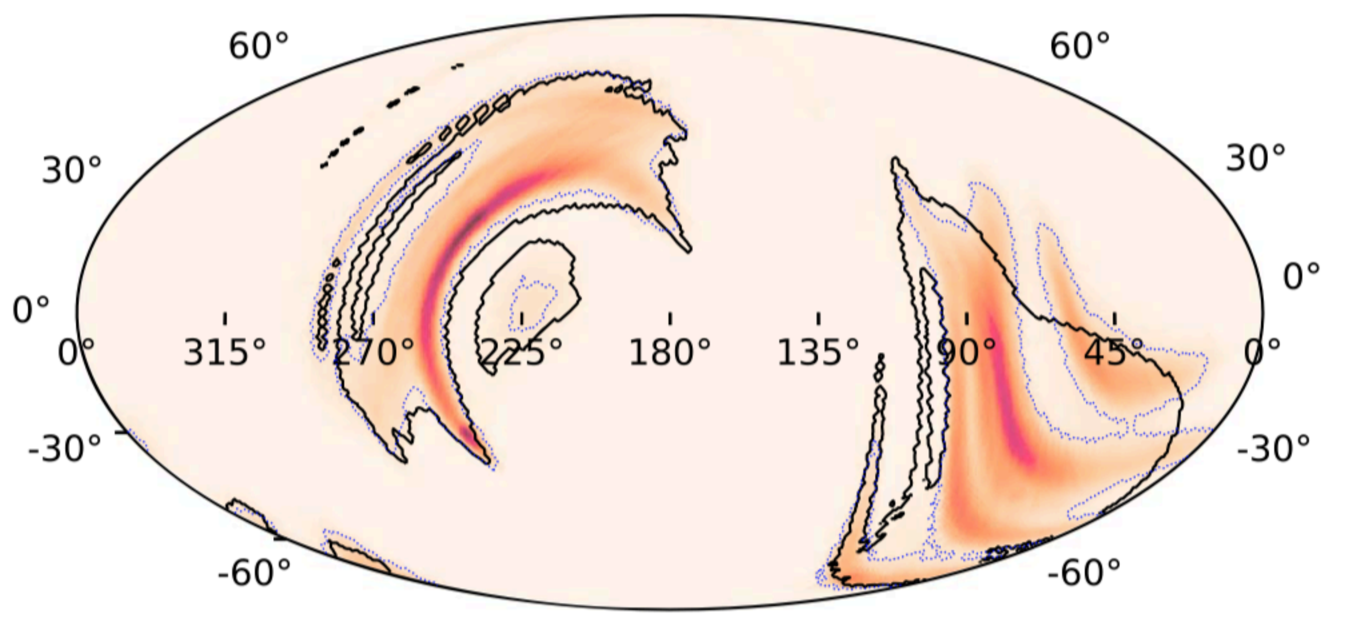
Differential BBH merger rate as a function of the primary mass



BNS GW190425 and multi-messenger follow-up campaign

- NS-NS candidates: GW190425
  - LIGO-L + Virgo: large localization region **>8000deg²** due to the combination of two detectors with largely different sensitivities
  - Chirp mass :$1.44^{+0.02}_{-0.02} M_\odot$, Total mass :$3.4^{+0.3}_{-0.1} M_\odot$
  - Total mass significantly larger than any other know BNS
    - 5 sigma deviation from total mass and the chirp mass of known 10 galactic binaries expected to merge within Hubble Time

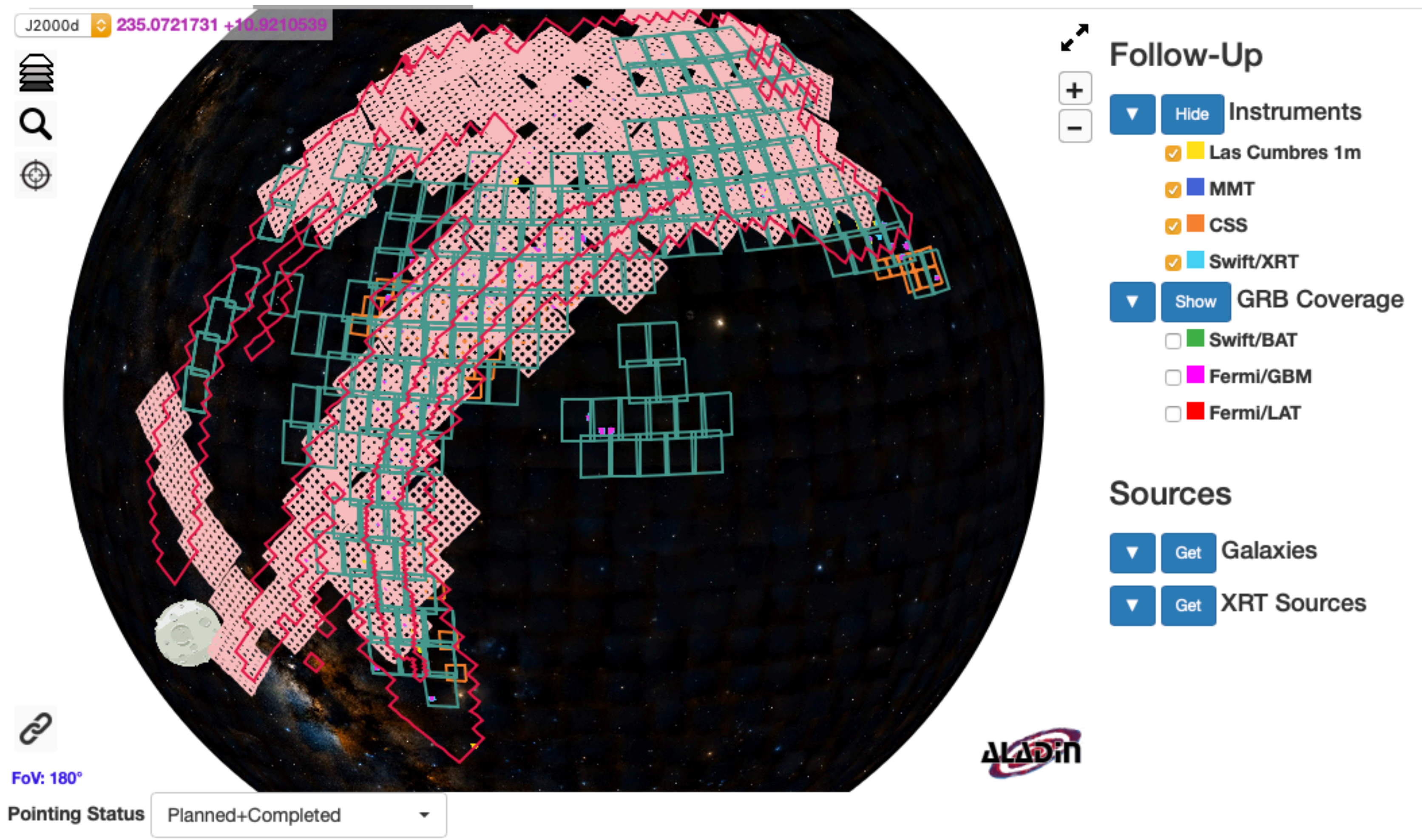
GW190425



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

ApJL 892 (2020) L3

- Most promising online alert sent during O3 due to the masses of the binary
- Really challenging follow-up campaign
- Extensive campaign via GCN although **no counterpart was found**
  - Fermi satellite : 45.4% of localization region oculted by the Earth
  - Relevant coverage of INTEGRAL and KONUS-Wind
  - 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



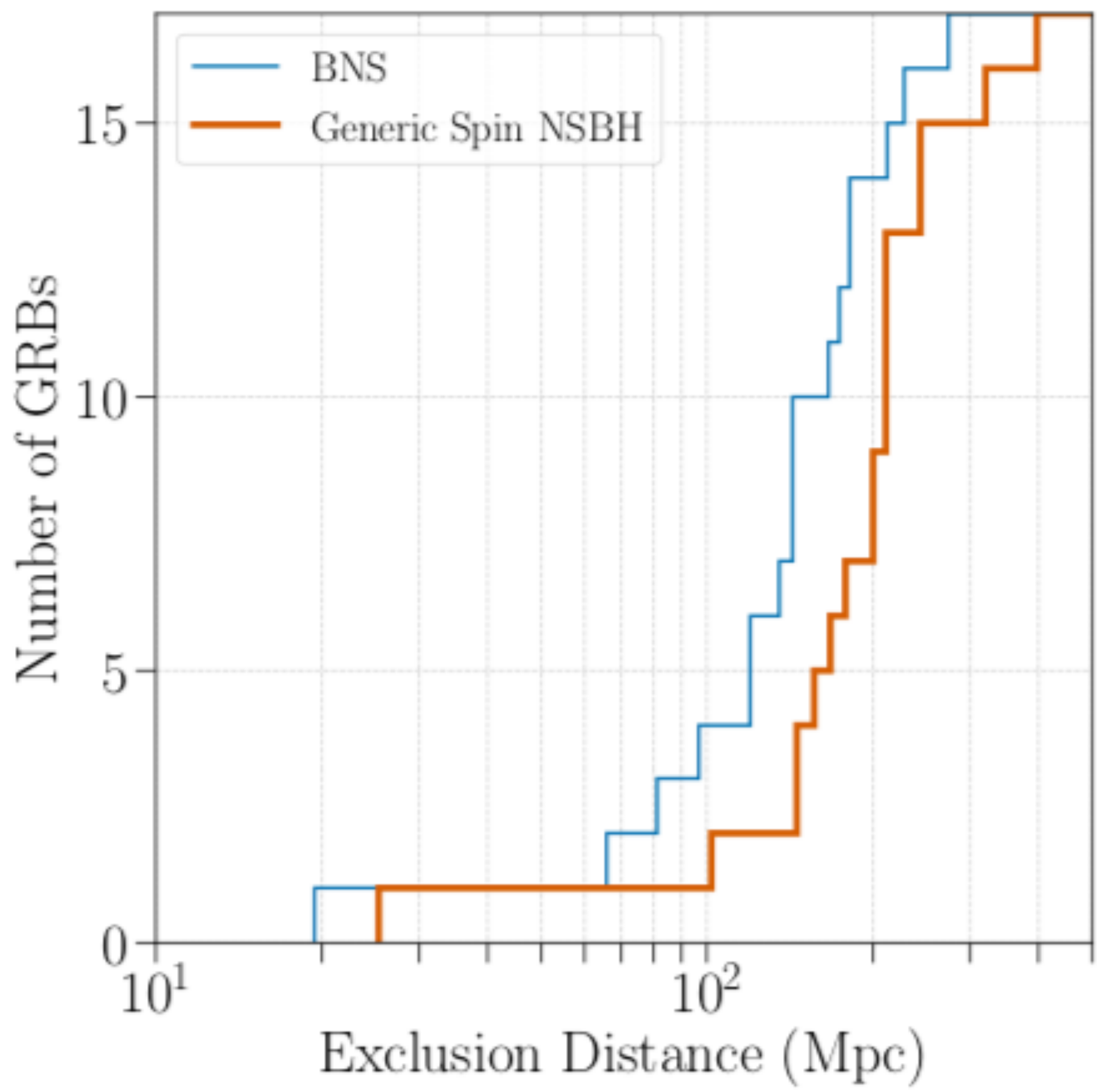
GW-follow up of GW190425 from http://treasuremap.space/

GRB follow-ups in O3b

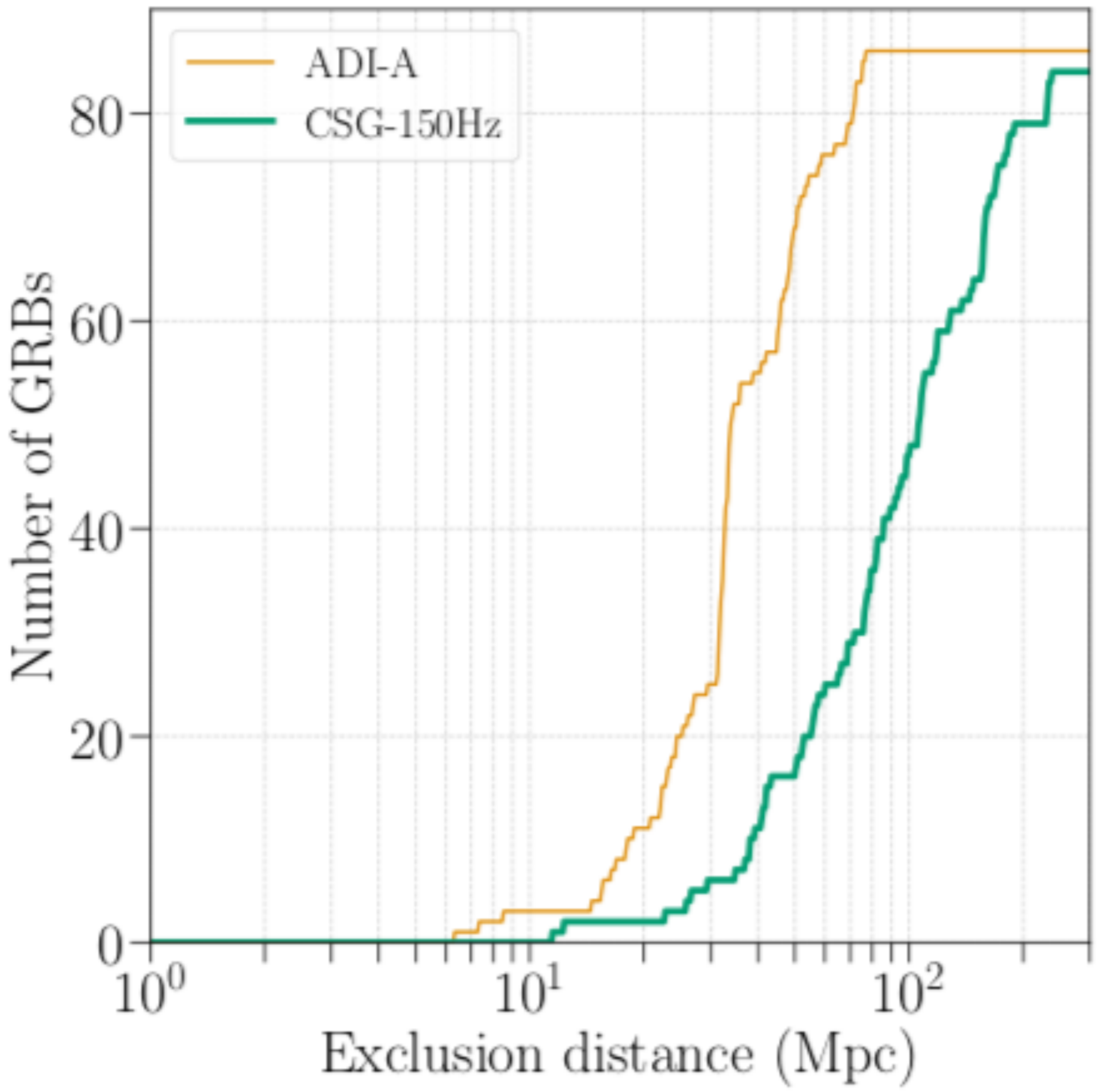
arXiv:2111.03608

- Search of GW signals associated with GRB detected by Fermi and Swift satellites (GCN + catalogs)
  - GRBs classified of short, long, ambiguous based on their T_{90} => note that none of the ones analysed have distance information
  - Two type of searches:
    - Targeted GW search (using BNS/NSBH waveform templates): **17 GRBs** analyzed (short+ambiguous)
    - Generic coherent GW transient search: all the sample, total of **86 GRBs** analyzed
  - **No significant detection associated with the GRBs (<2 sigma) => obtain 90% exclusion distance from simulations**
    - Several source types investigated in simulations: BNS, NSBH, accretion disk instabilities (ADI), circular sine-gaussian (CSG)
      - Order of magnitude of difference on the exclusion distance due to wide range of models used

17 short and *ambiguous* GRBs (targeted search)



86 all sample of GRBs (generic search)



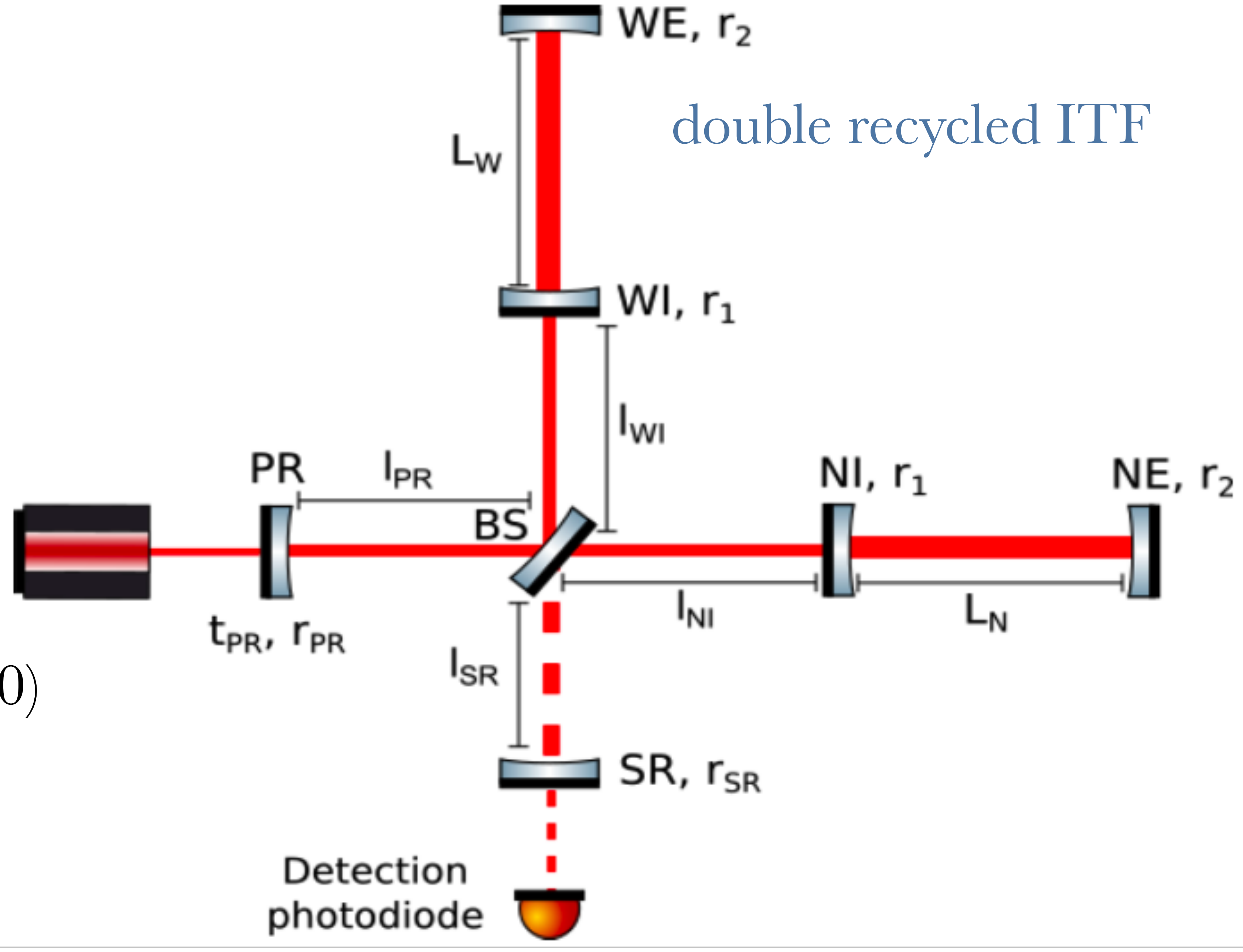
Modeled search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins
D_{90} [Mpc]	149	207	257

Generic transient search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} [Mpc]	166	126	92	42

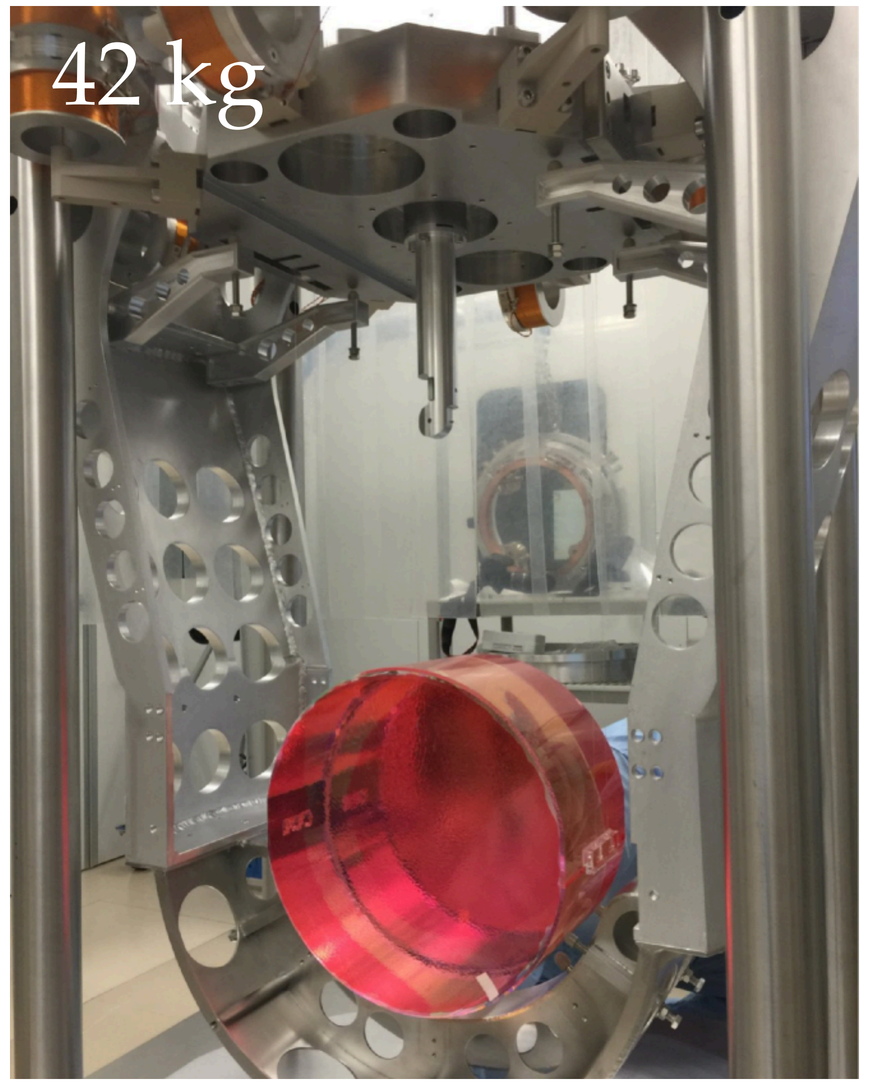
Generic transient search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]	34	140	54	22	52

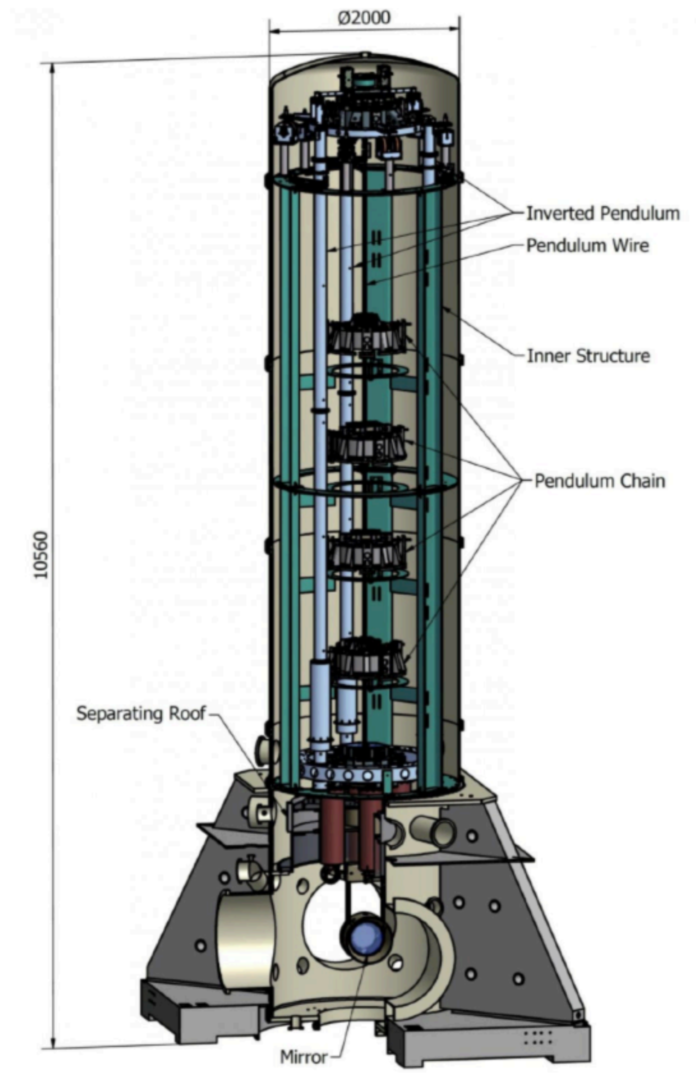
Gravitational Wave Interferometers: AdVirgo+ phase I

- 2nd generation GW interferometers are complex machines
  - Suspended optics for attenuation of horizontal seismic vibrations
  - Control loops up to ~kHz frequencies
  - System under vaccum at ~10^{-12} atm
  - High power of input laser (for O4: 33 W, target: 40W)
  - Frequency dependent squeezing to reduce quantum noise

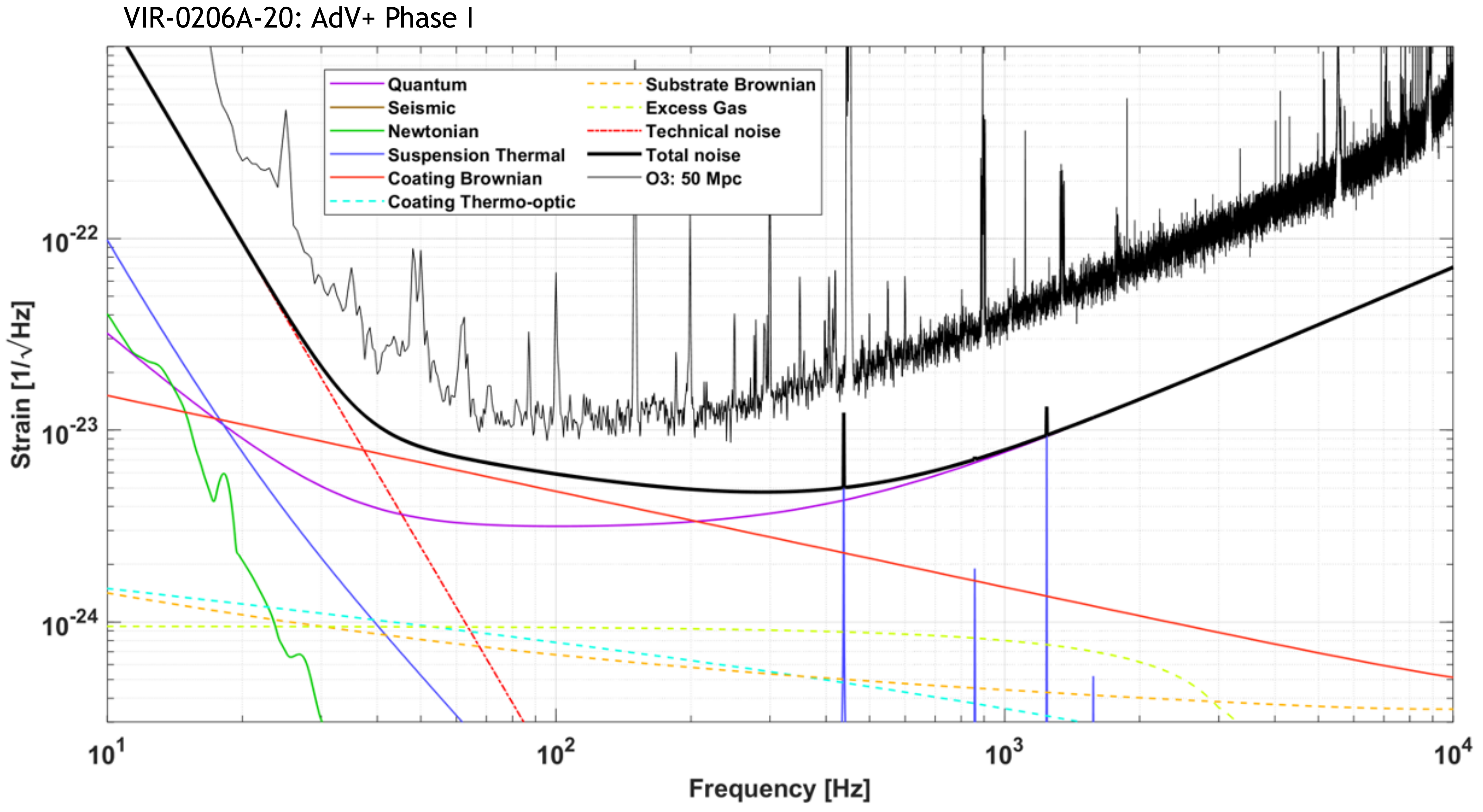


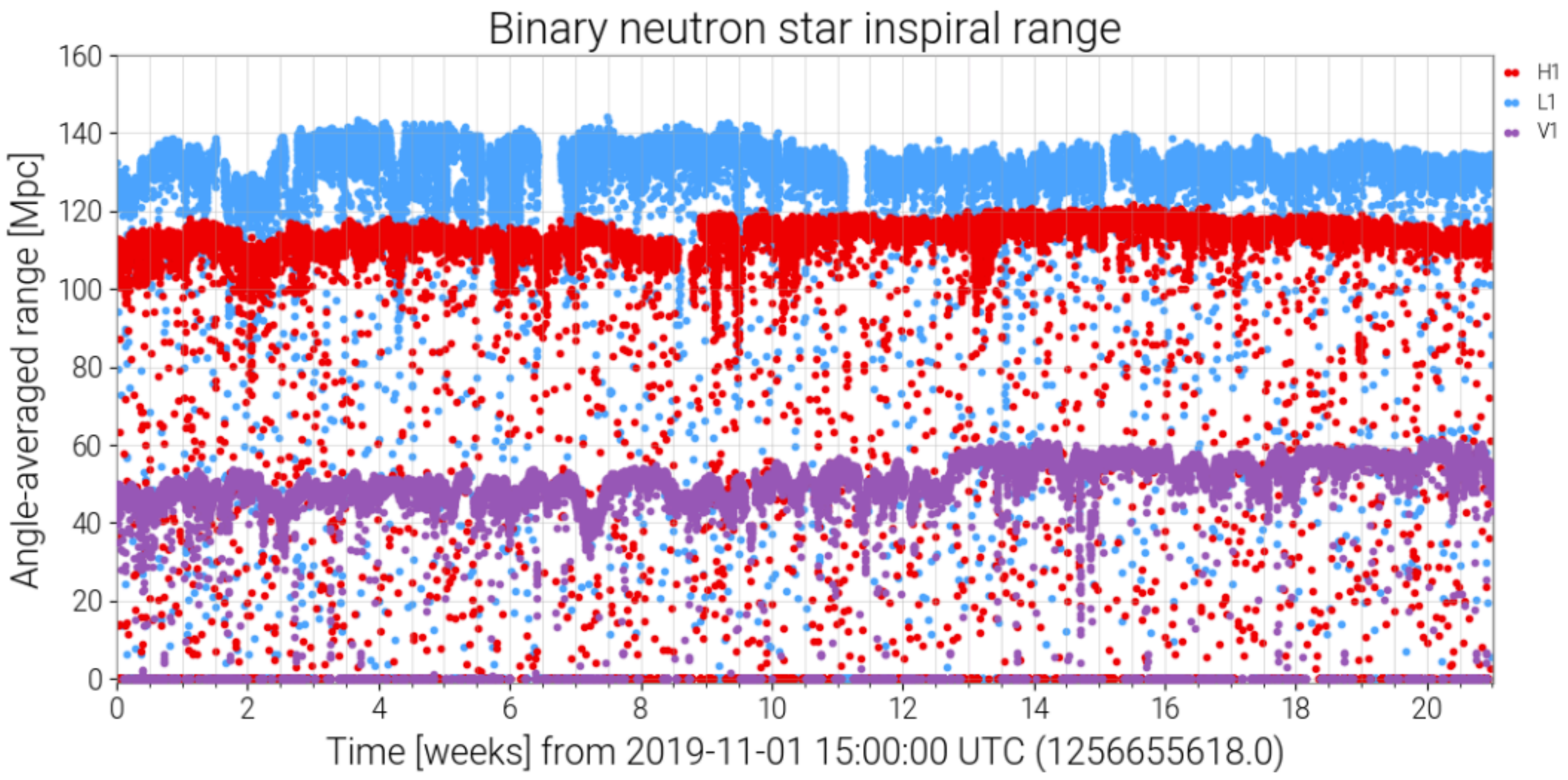
- Sensitivity is improved by adding further optical cavities to a simple Michelson Interferometer
  - Fabry-Perot Cavities between Input and End tests masses: increase optical path (finesse~400)
  - Input Mode Cleaner: laser beam is stabilized and high-order modes are cleaned
  - Output Mode Cleaner: clean the output beam
  - Power recycling cavity: increases the power circulating by recycling beam reflected back
  - Signal recycling cavity: enhances the signal before it reaches the detection photodiode





Figures of merit of an observing run





https://www.gw-openscience.org/detector_status/O3b/

- The sensivity curve: results of improvements in the ITF and the limitations from various noise sources

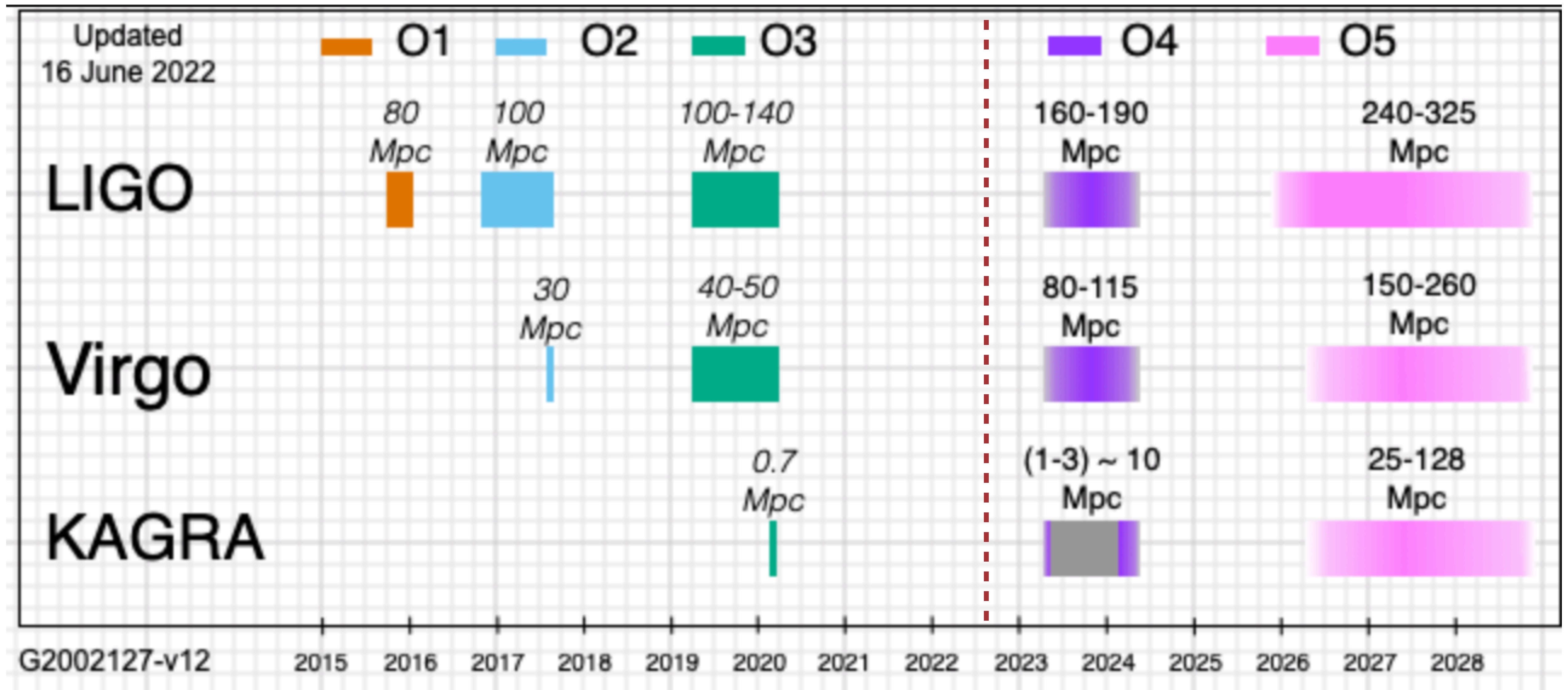
- BNS Inspiral range: gives a relative understanding of the interferometers performance
- Defined for a binary of 1.4+1.4 solar masses seen on-axis, optimally located (ITF zenith) seeing at SNR=8, then weighted by a factor 2.26 to considers directional sensitivity and source orientation
- BNS inspiral frequency band expected (~Hz to hundred Hz)
- Note that BBH are observed up to way larger distances!

Observing run O4

- The Observing run O4 will not start before March 2023
    - one-year run with a one-month break for maintenance

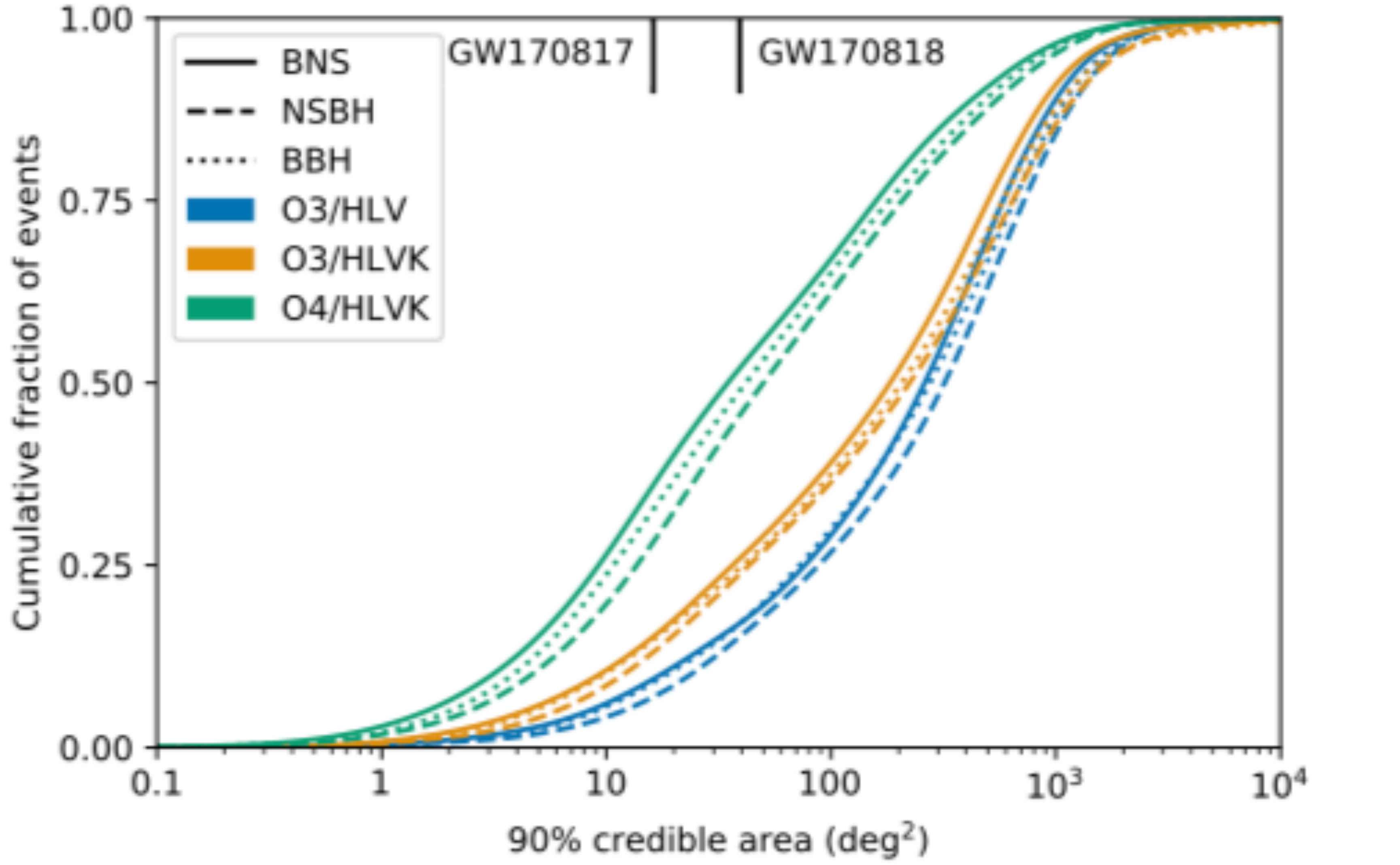
<u>Expectations for O4</u>

- 4 ITF network with different sensitivities
- Increase of the horizon
    - Number of detections ~ horizon^3
- Increase in number of detection (~1 BBH/day), better localized

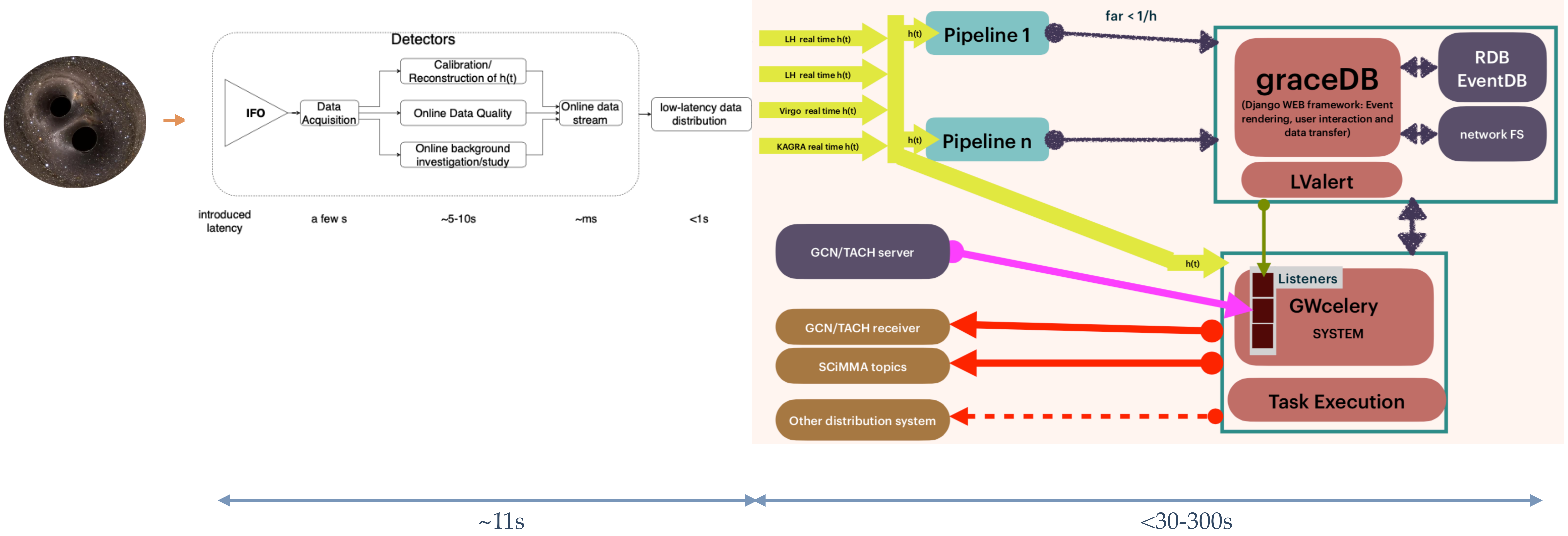


Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

Living Rev Relativ 23, 3 (2020)



Gravitational wave alert distribution in O4

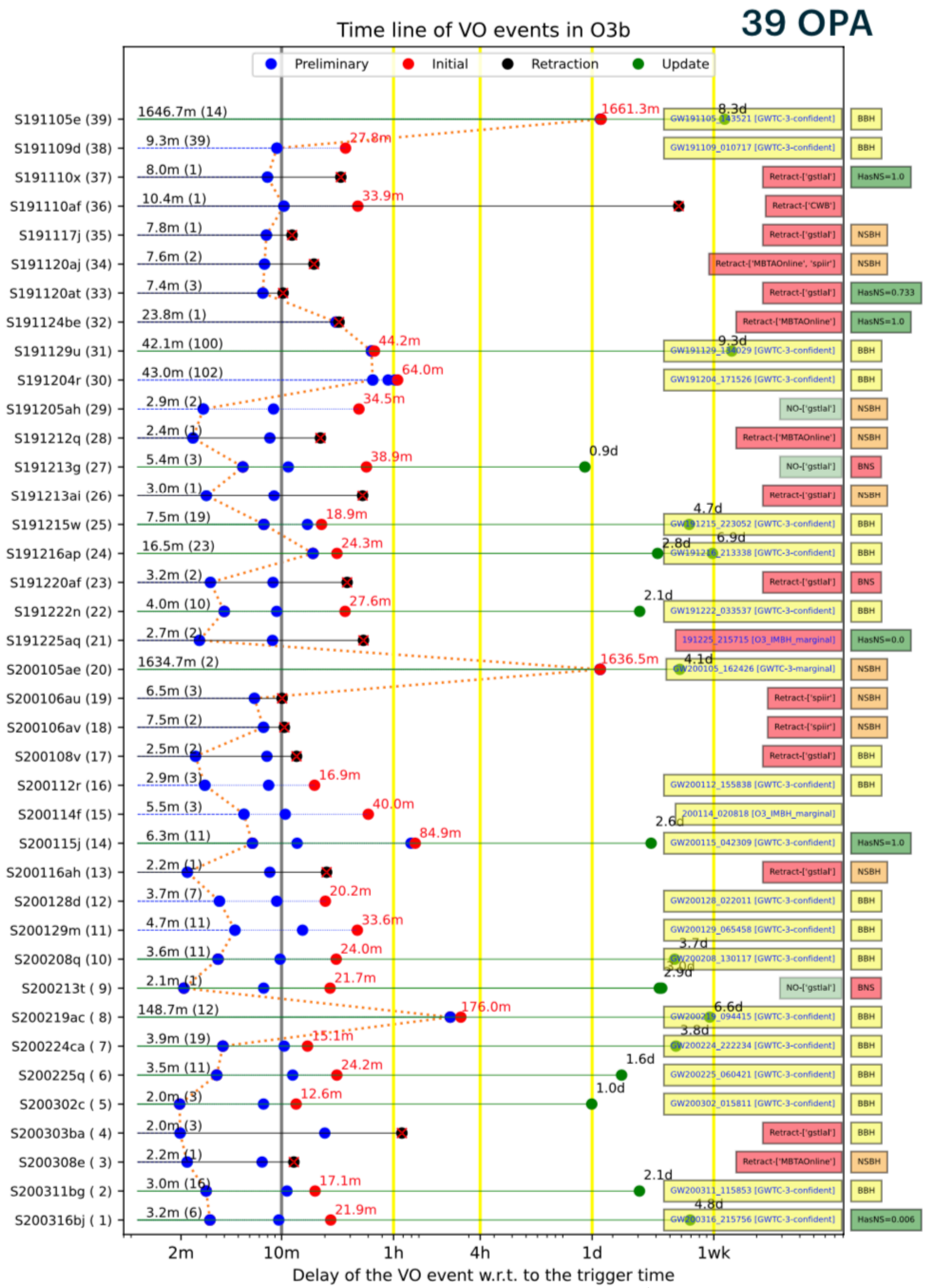


- Embedded multi-messenger analysis: spatial- and temporal-coincident, asigns a false alarm rate to the coincidence.
  - RAVEN: online pipeline search between GW events with alerts for gamma-ray bursts (GRBs) and galactic supernova alerts (SNEWS)
  - LLAMA: online search pipeline combining IceCube High Energy Neutrino (HEN) triggers

from LVK Town Hall Telecon

Open public GW alerts (OPA)

- The Open Public Alerts are triggered by online pipelines
- Several type of alerts during O3: preliminary, initial, update, retraction
- Offline analysis of the data may find further events or discard others
  - Some events in GWTC did not trigger online pipelines !
- 80 OPA during O3
  - 23 retraction: 1 retraction is now a marginal detection
  - 43 are confident detections
  - 4 are marginal detections
  - 9 not it catalog neither retracted



from R. De Pietri

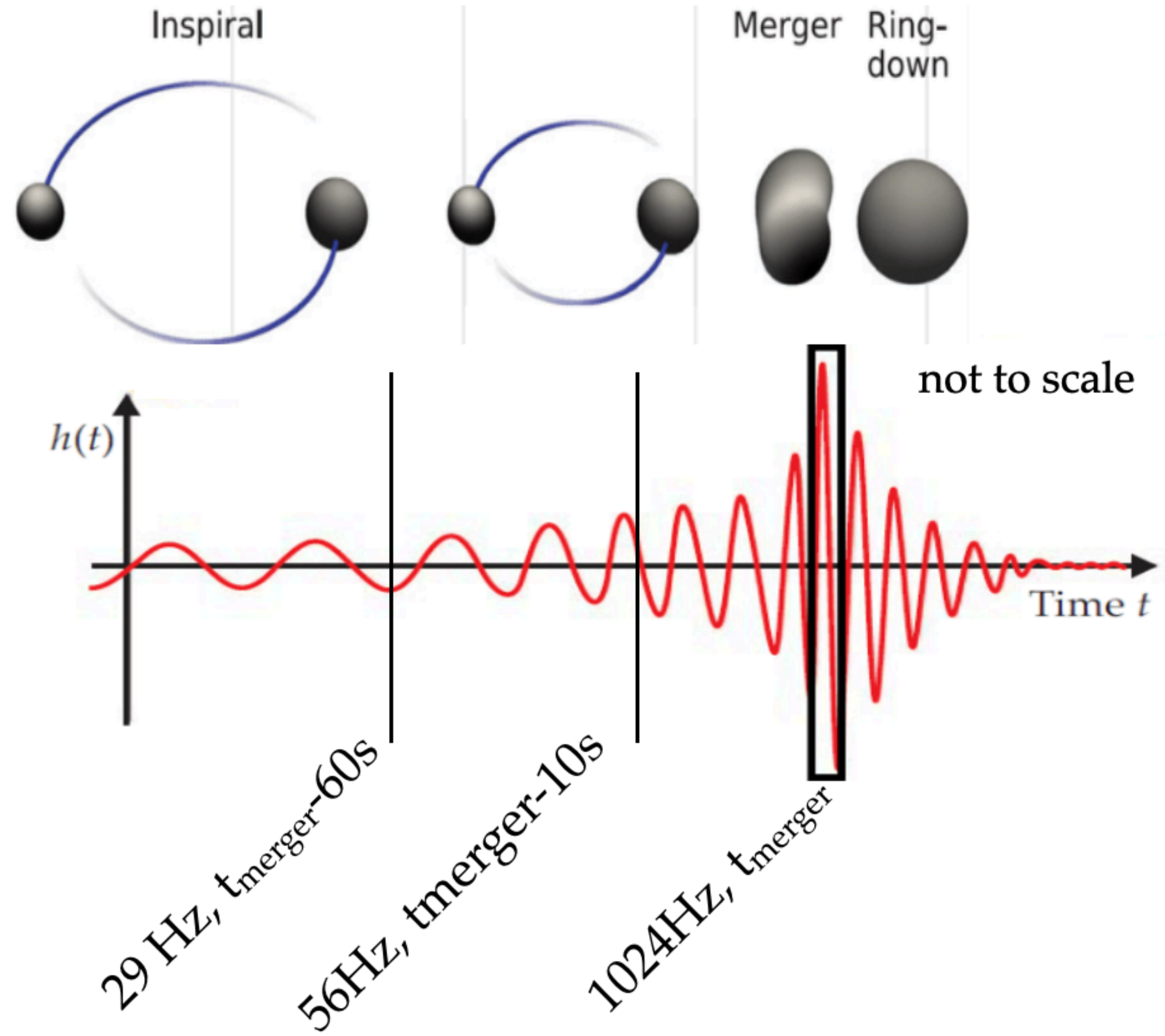
Early warning alerts and low-latency pipelines

- The signal of BNS evolves in frequency in the ITF sensitive band for hundreds of seconds
  - Enough SNR can be accumulated for best-case scenario BNS mergers (close, face-on oriented)
  - Pre-merger alerts: send the alert **BEFORE** the merger

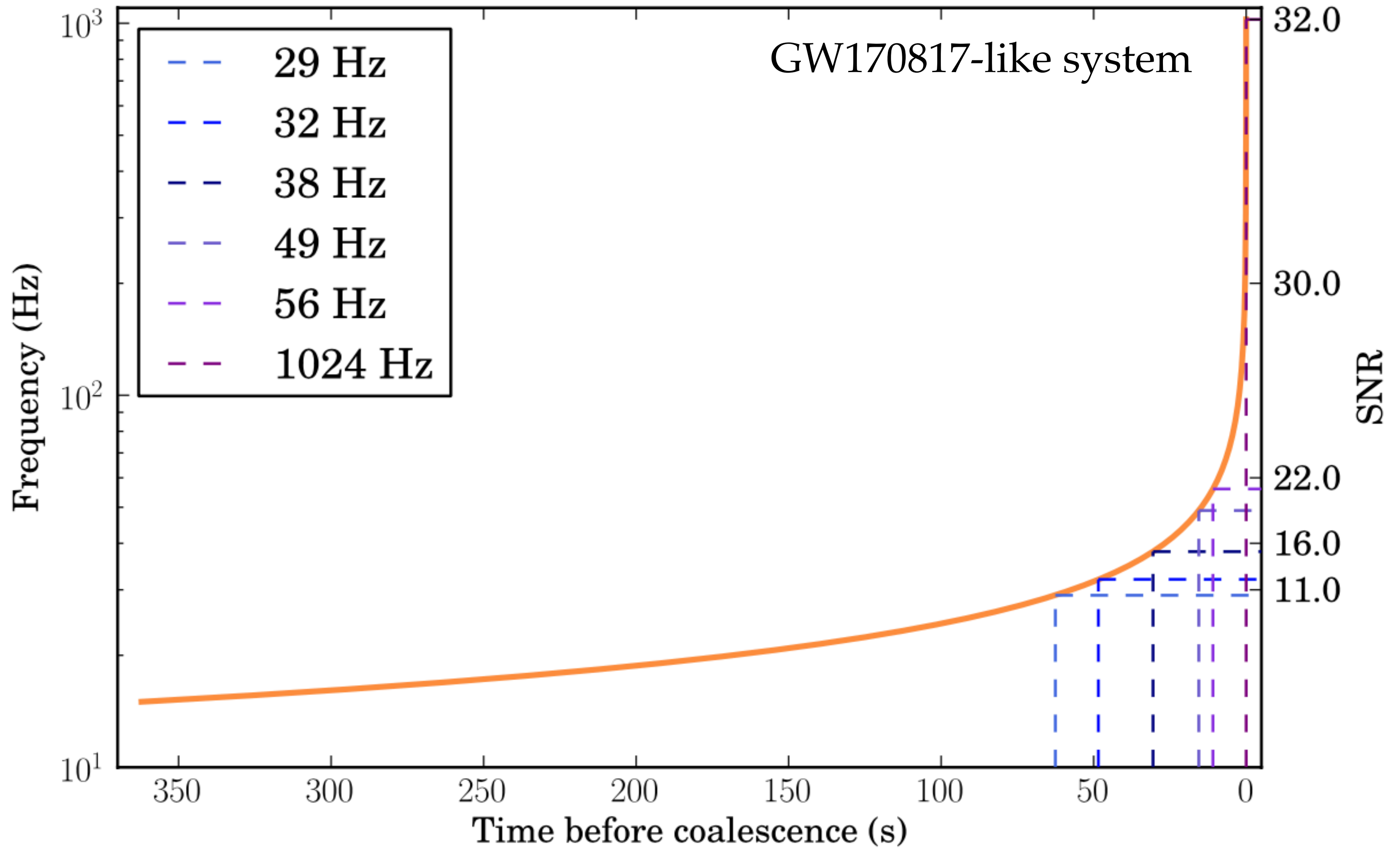
- Optimisations ongoing in the whole GW detection pipeline
  - Data acquisition, calibration, data quality, analysis pipelines…

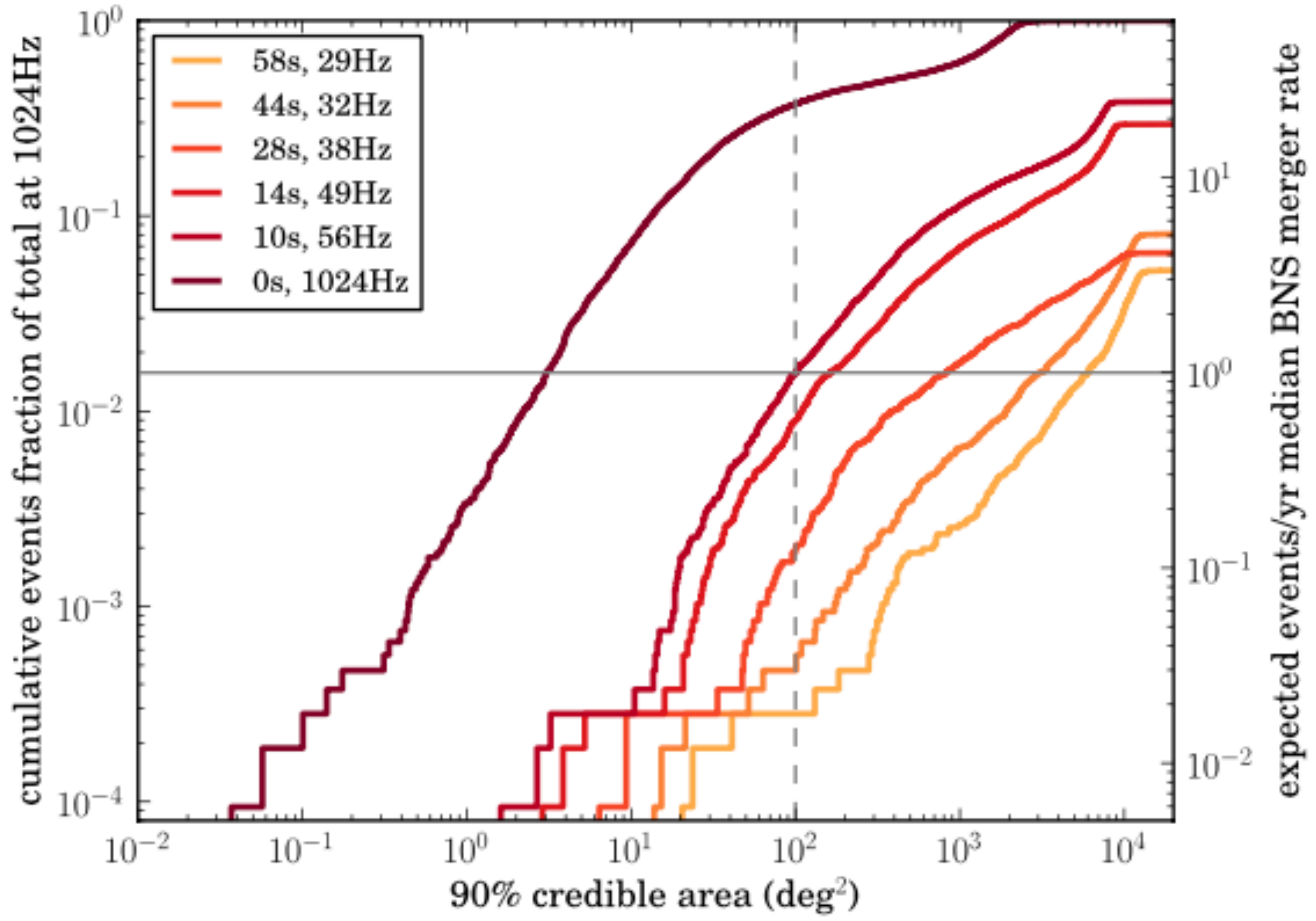
- To be online for Observing run O4
  - Observing run O5 *2026-2028: ~3 BNS/ year, 10 s prior to merger with localizations of 100 deg²* (Magee et al. 2021)

- Caviats: precision vs. latency



emfollow.docs.ligo.org



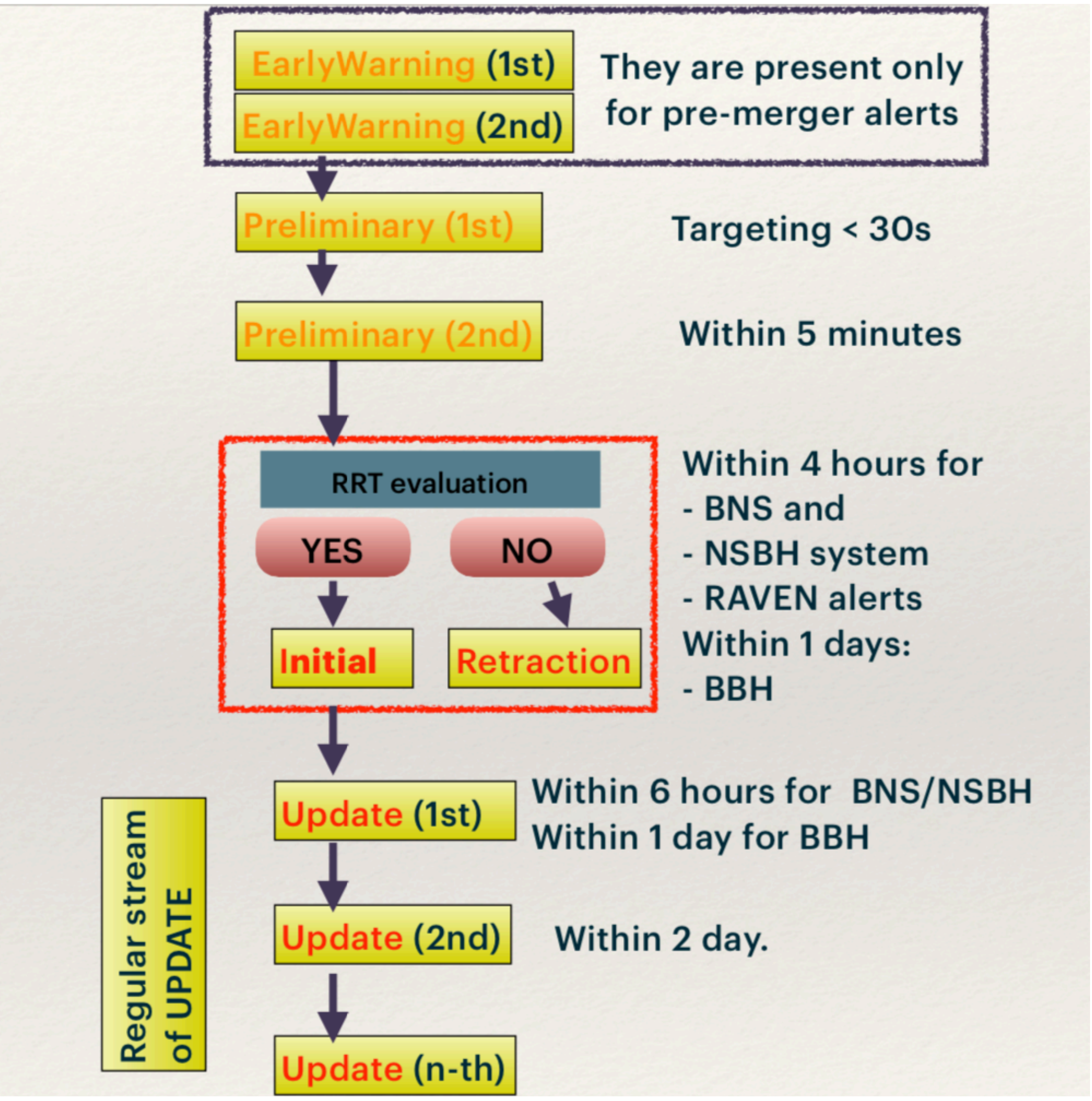


Preliminary workflow of OPAs in O4

- Monthly updates on alerts are given in **Open LVK Town Hall telecons**: https://wiki.gw-astronomy.org/OpenLVEM/
  - Next telecon: Oct 20, 2022 at 14:00 UTC

- (1st) EarlyWarning (fully automatic)
  [It is under consideration to send the first one without localization information. Need your feedback if this is useful if the MDC study show that this may reduce latency of > 2s]
- (2nd….3rd….) EarlyWarning (fully automatic) alert as new localization are available.
- (1st) Preliminary (fully automatic) alert (targeting < 30s).
- (2nd) Preliminary alert (fully automatic) after search is completed by all the pipelines with updated localization (targeting < 3 minutes).
- A (**3rd…n-th**) Preliminary will be published in case of improved localization before Rapide Response Team (RRT) validation.

- RRT meeting and a human/rapid-PE evaluation typically within 4 hours for BNS or 1 day for vanilla BBH.
- An Initial/Update or Retraction alert will be sent. An Initial/Update alert can contain improved localization and source classification.
- Update alerts will be sent when improved PE results are available.



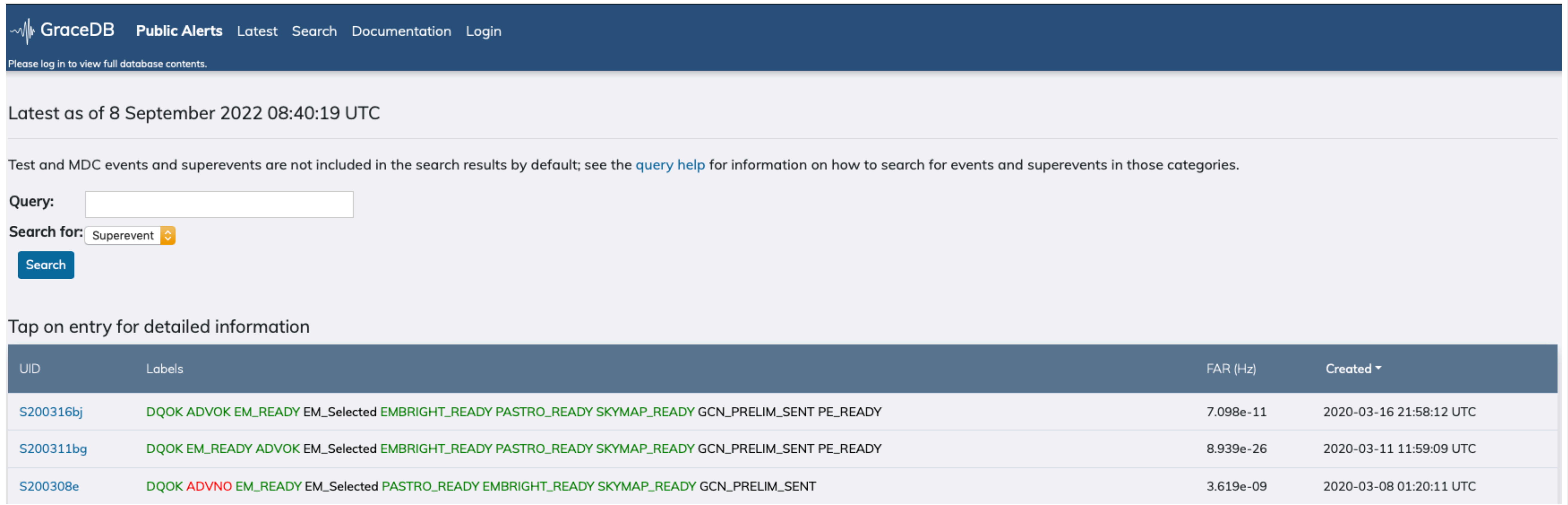
from Low-Latency Update at LVK Town Hall Telecon (22/09/2022)

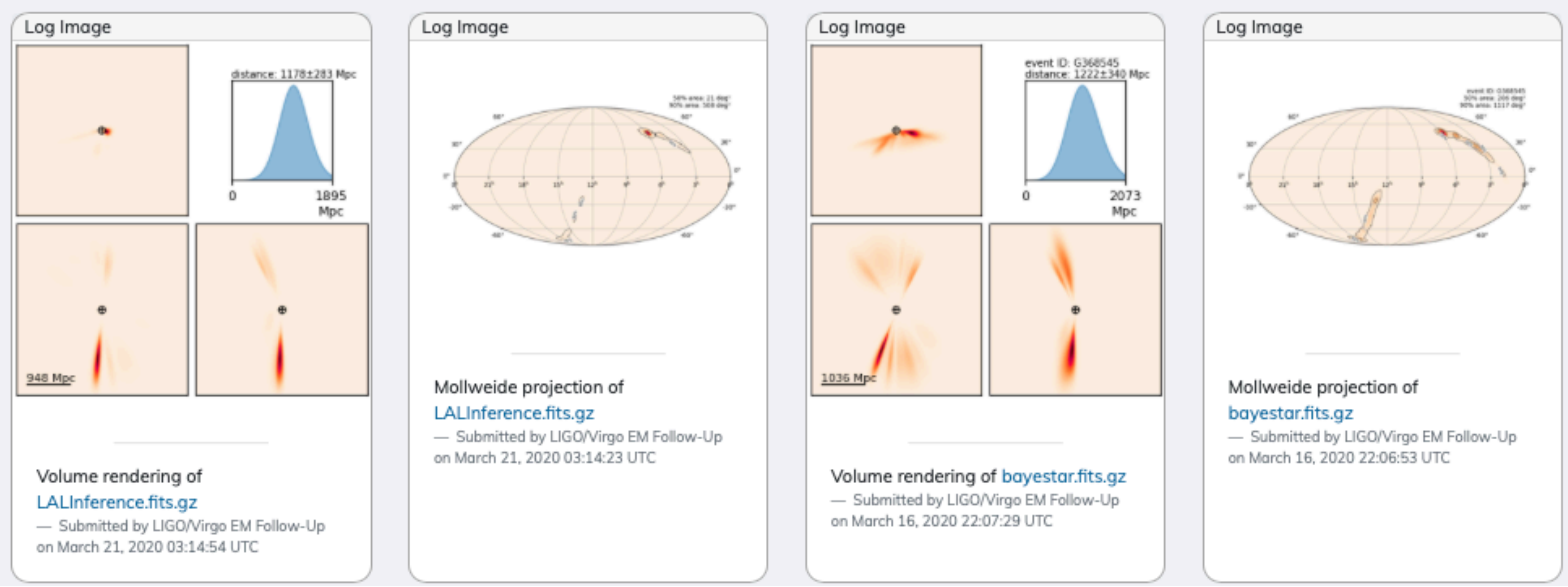
- Multiple distribution channels: GCN and Kafka-based via GCN and SCIMMA
- Key info: Two HEALpix formats: multiorder.fits and fits.gz (in GraceDB, for legacy), p-astro, and quantities HasNS, HasRemnant
- Mock Data Challenge ongoing to test pipelines: OPA may be distributed as well (under discussion)
- User Guide expected in ~November

Where to find data?

Preferred Event Information	
Group	CBC
Pipeline	gstlal
Search	AllSky
Instruments	H1,L1,V1
Event Time	1268431094.157
Submitted	2020-03-16 21:58:26 UTC

- GraceDB
  - High-level data uploaded by analysis pipelines
  - Skymaps, ITF that provides data, event time, search, type (em_bright, p_astro)
  - Files available include .xml, .png, .json, multiorder.fits and .fits





- GWOSC: Gravitational Wave Open Science Center https://www.gw-openscience.org
  - Strain h(t) data passing quality cuts available from all LVKG interferometers
  - LVK policy is that data become public in chunks of 3 months, 12 months after they were taken: O3 strain data are public
  - Tutorials and software for GW data analysis available (e.g. parameter estimation with Bilby, LALsuite, GWpy)

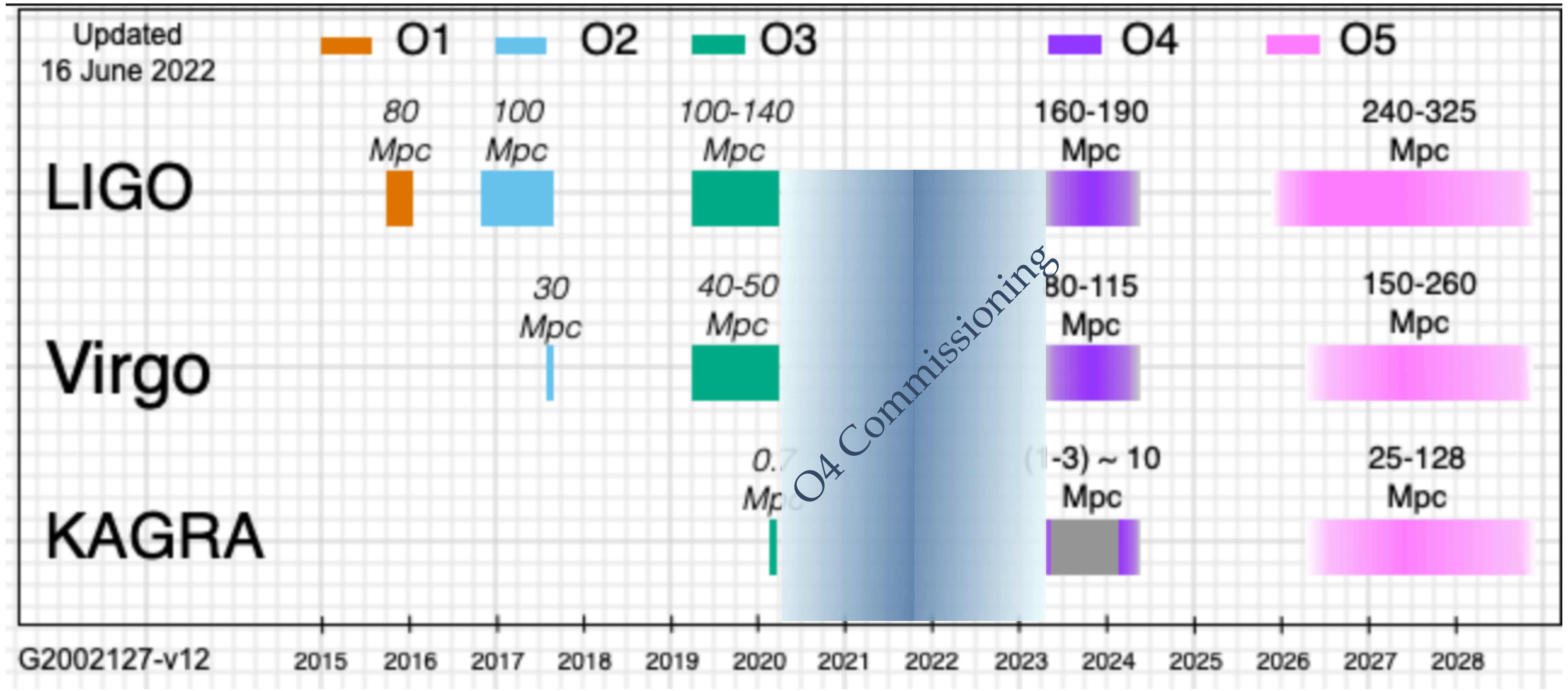
What's next towards O4?

- O4 Commisioning:
  - ~2 years of installation and control of upgrades
  - A new ITF to be commisioned
  - Problems along the way may delay the start of the run
    - Lock of the interferometer at 40 W punctually achieved (target power for O4) with limited power in arms (currently at 33 W to control the thermal compensation system)
    - Recent case: Radius of Curvature of PR and SR mirror done for 125W, makes cavities unstable at 33W
      => Required the installation of a Central Heating Radius of Curvature Correction

- Roadmap of O4 commissioning:
  - Robust lock adquisition to have a high duty cycle
  - Optical characterization of the interferometer
  - Noise hunting activities to assess and reduce technical and environmental noises that are known to couple to h, i.e. pollute the signal

- Close coordination between LVK

- Observing run O4 will start in March 2023
  - Engineering run a month before O4



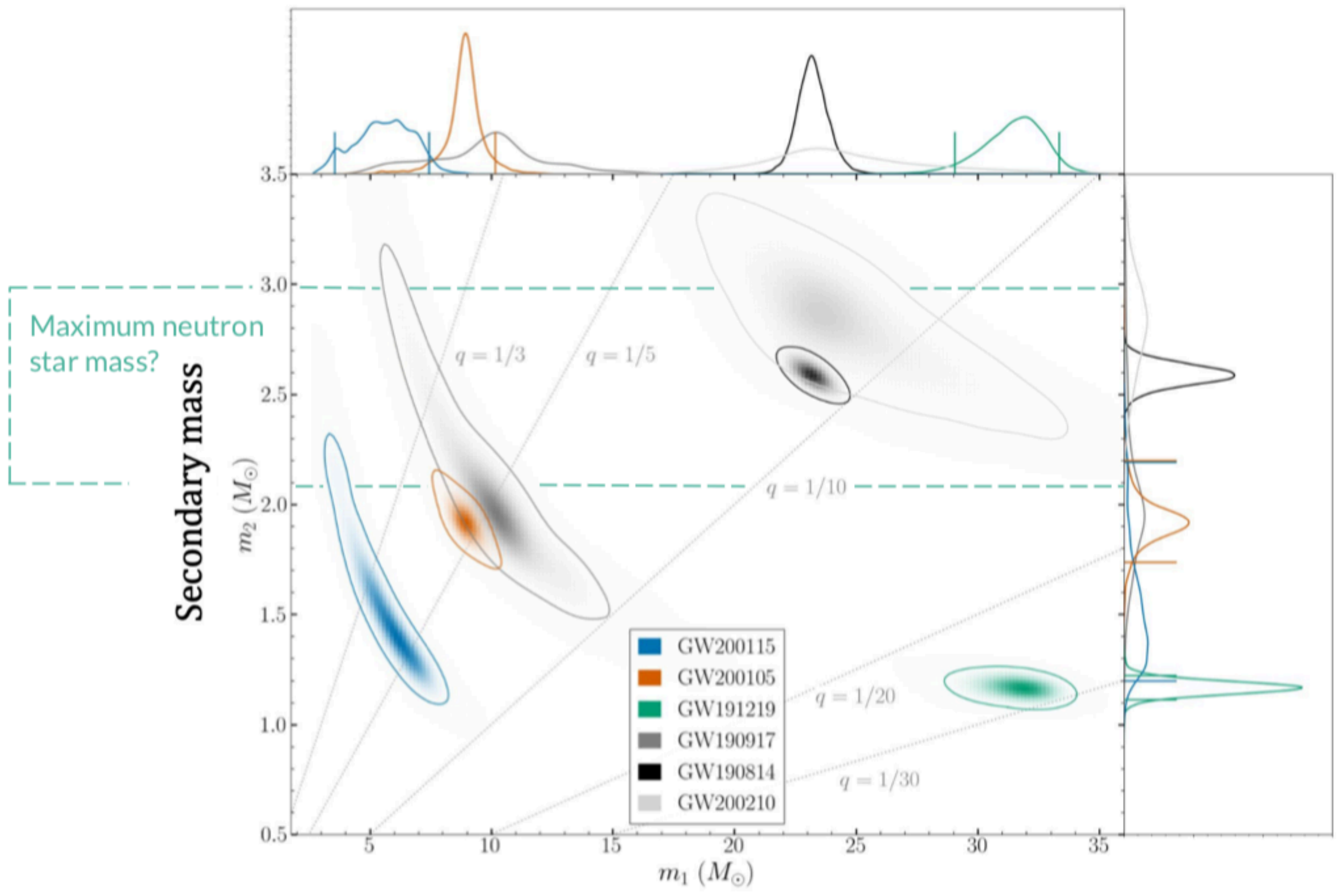
Thanks for your attention!

Back-up slides

BH-NS systems: GW200105, GW200115, GW191219

- Several events are consistent with NS-BHs pairs
- Grey events: secondary mass that may be a BH or a NS
- The properties of the binaries are consistent with a NS-BH merger:
  - No imprint of tidal deformability in the GW (although their spins make that no tidal disruption is expected + SNR too low)
  - Mass of the less massive object consistent with maximum NS mass and known galactic NS
  - No EM counterpart observed

NSBH candidates

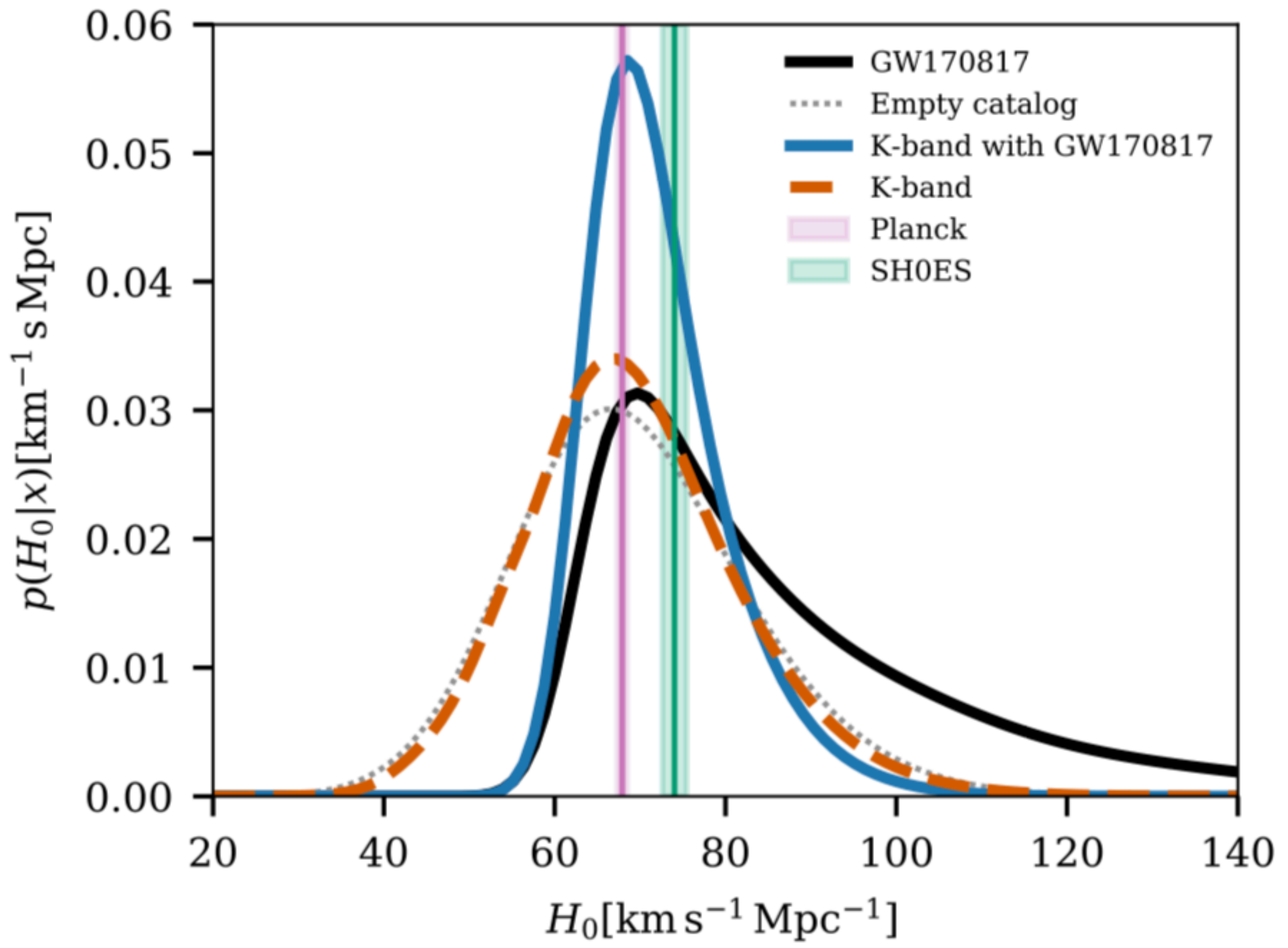


[LVK 2021]

H0 measurement & constrains on GR

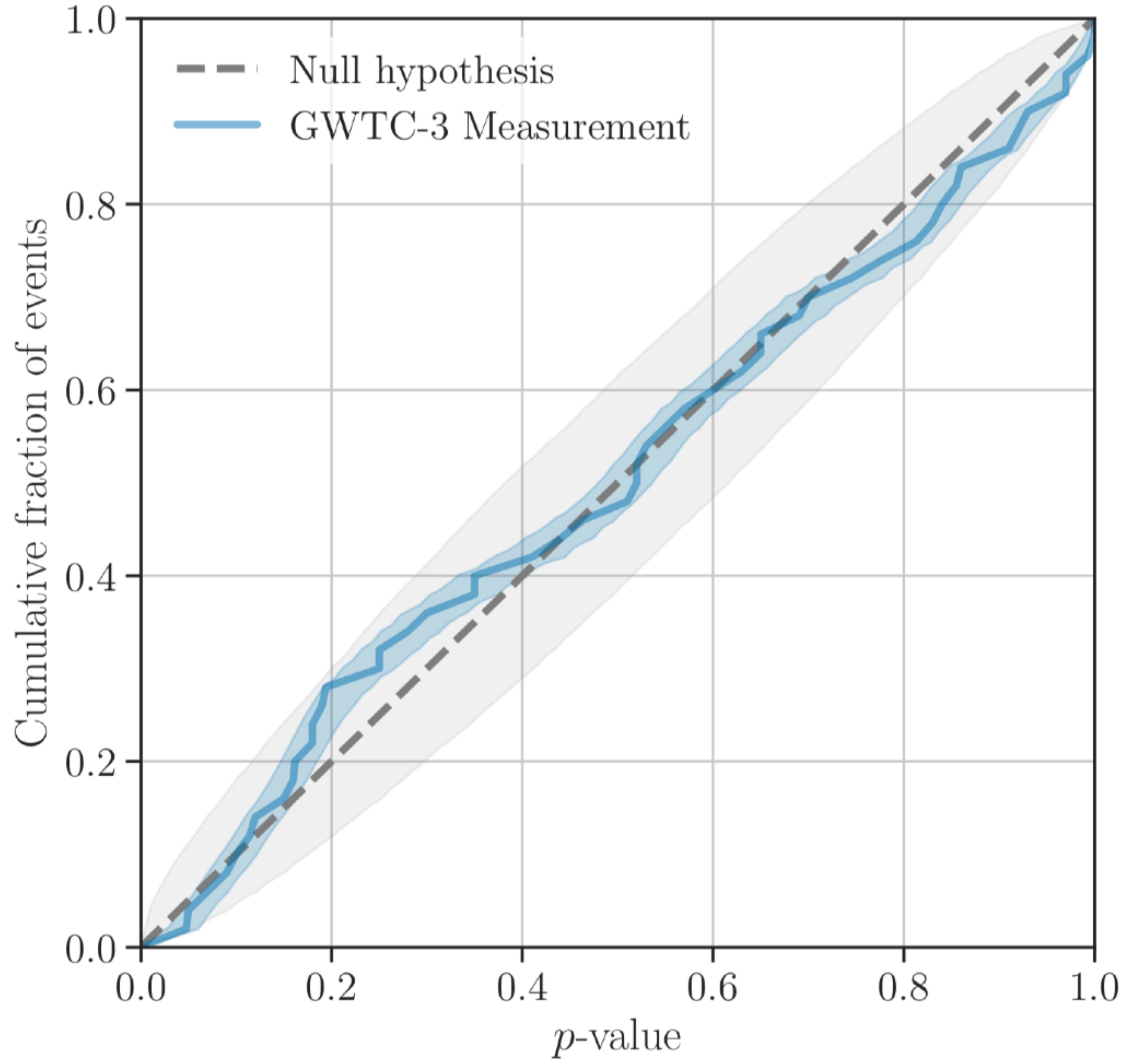
arXiv:2111.03604

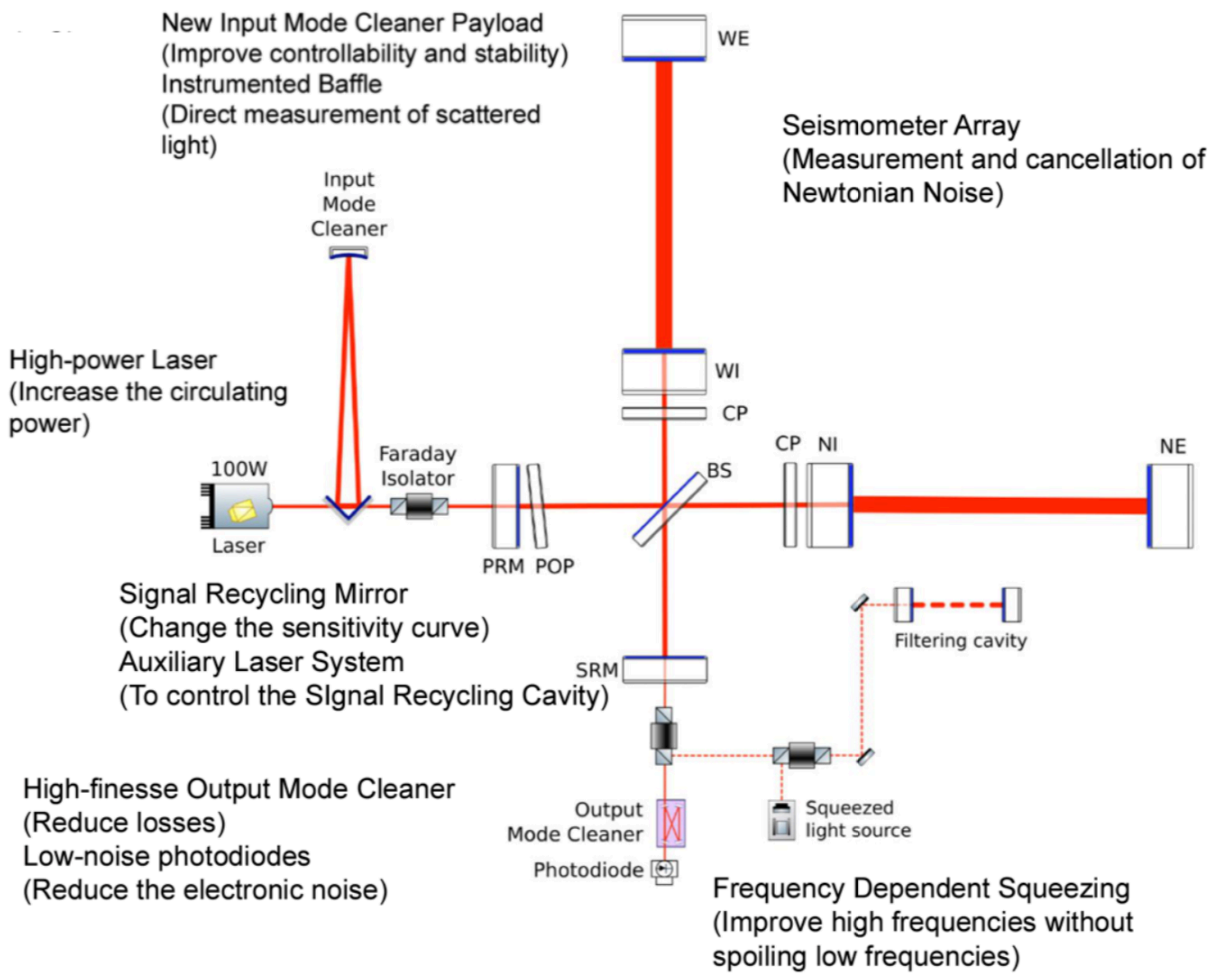
- Cosmology: Hubble constant H_0 estimations
  - *Dark sirens*: 47 sources of GWTC3 + GW170817 (most constraining)
    - Two method:
      - Joint of the cosmological parameters and the source population properties of BBHs
      - Fix source population properties, and infer- ring the cosmological parameters using a galaxy catalog (GLADE+)
    - Second method yields to $H_0 = 68^{+8}_{-6}\,\mathrm{km\,s^{-1}Mpc^{-1}}$

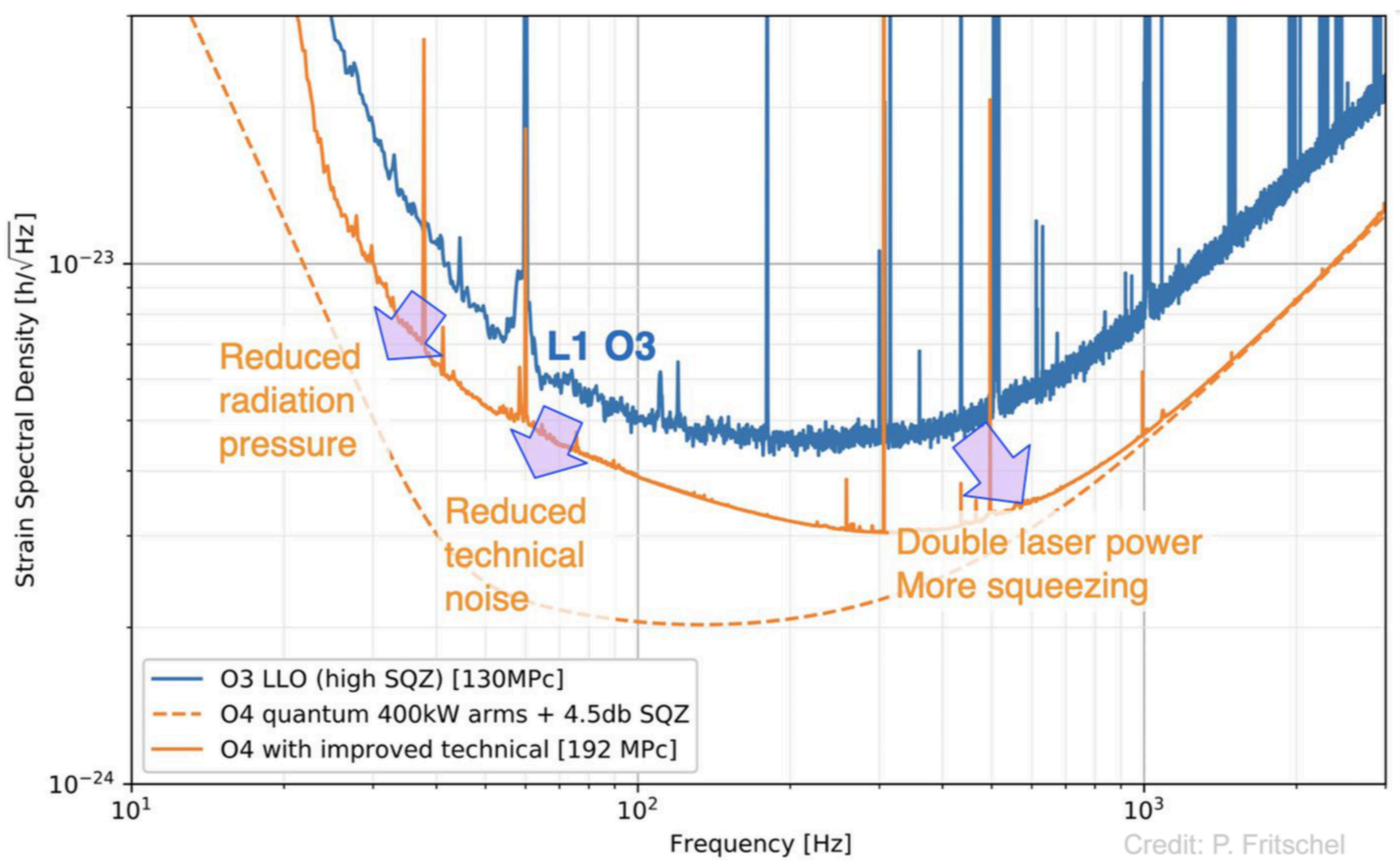


arXiv:2112.06861

- Constraints on General Relativity:
  - Model waveforms constructed from GW: add small modification
  - Various tests include:
    - Consistency of residuals fron GR with detector noise
    - Inspiral phase, modified GR, GW echoes…
  - No evidence for deviations from GW so far



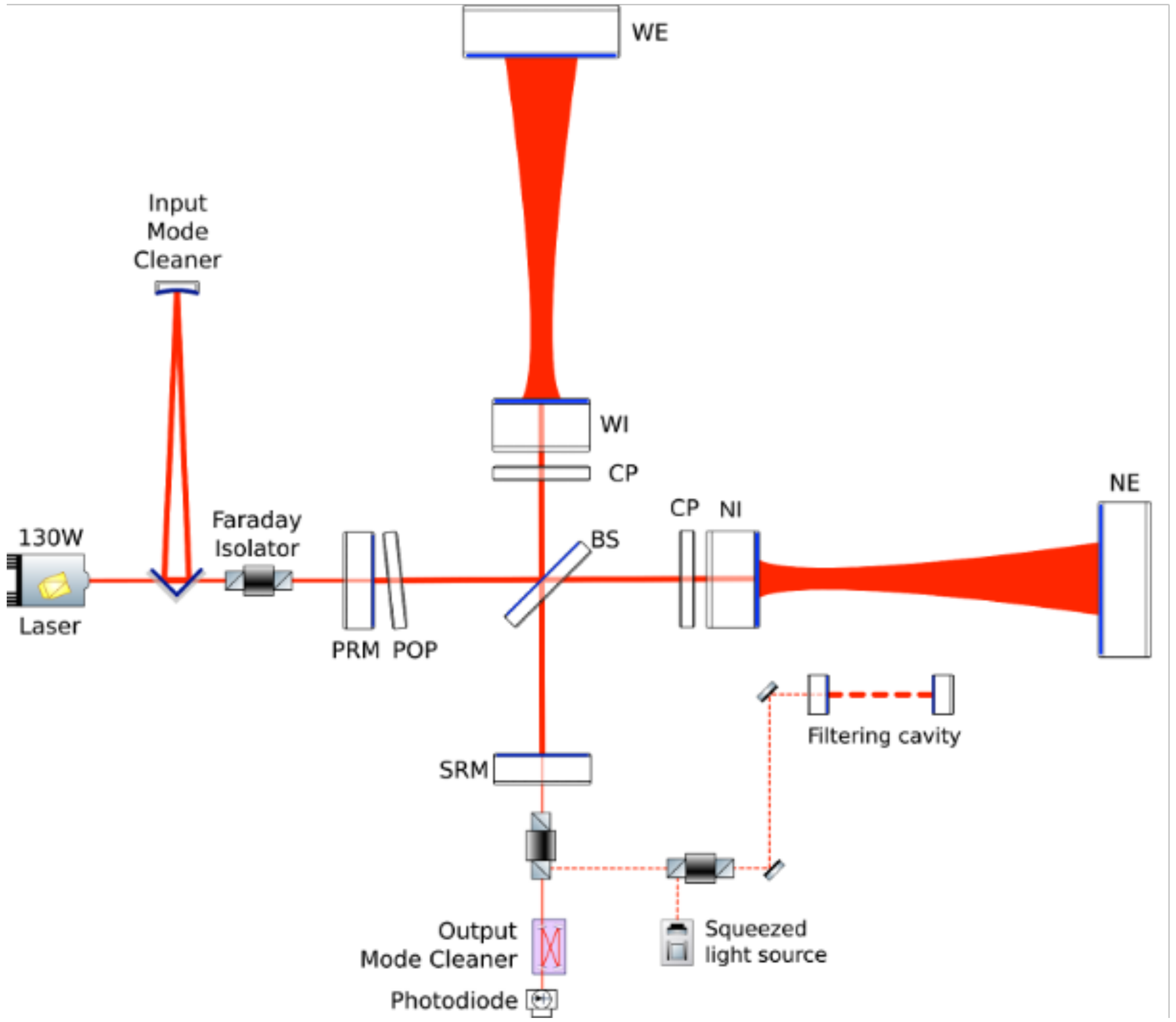




from V. Fafone

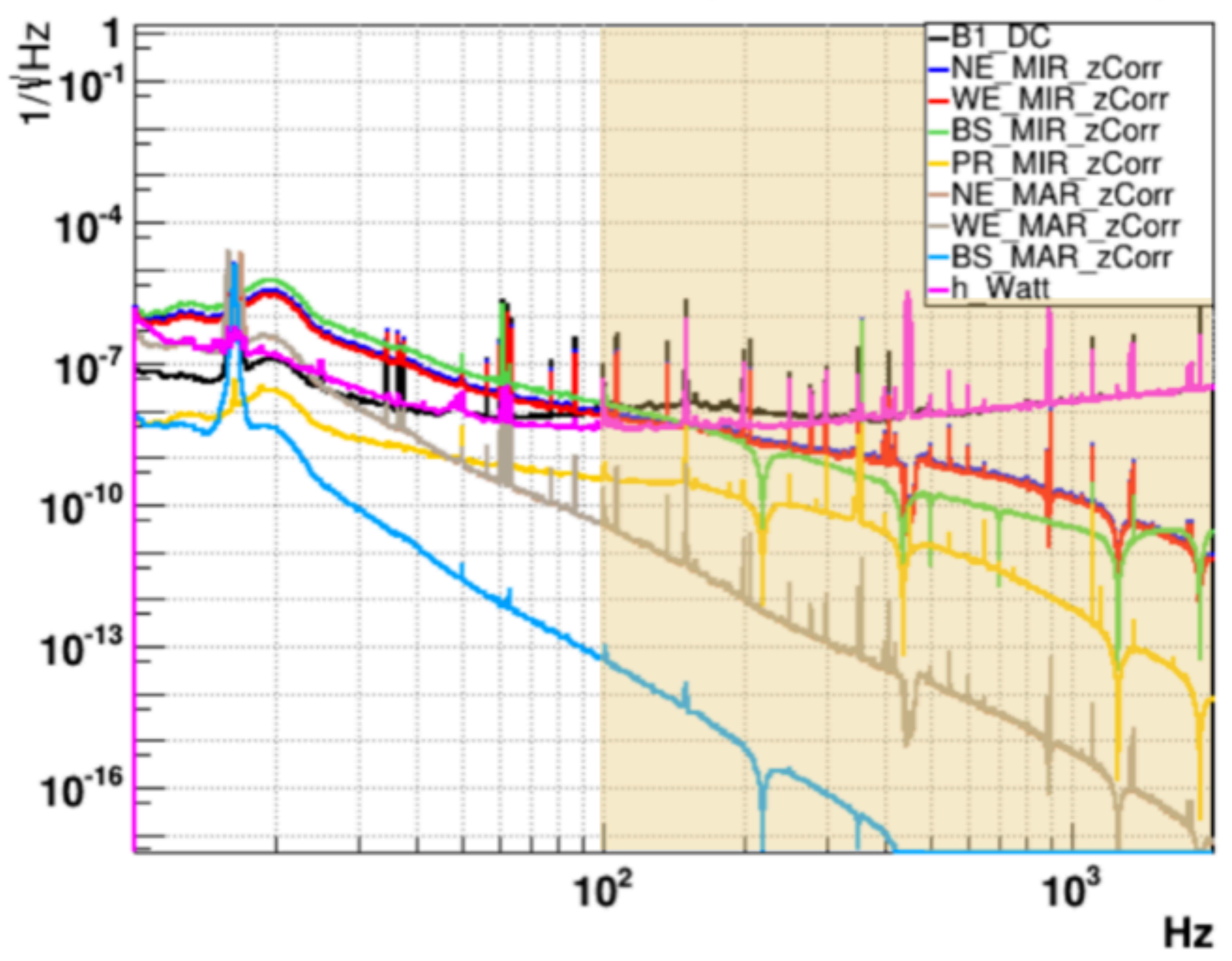
Advanced Virgo+: phase II

- Larger beams on end tests masses
  - Reduce thermal noise (6cm =>10 cm)
- Change end mirrors: larger mass
  - Adapt the mirrors to the larger beam size and the radiation pressure
  - 40 kg=> 100 kg, 33 cm=> 55 cm diameter
- Improvements in mirror coating
- Increase laser power (40 W=> 80 W)



Key aspects of h(t) reconstruction

Breakdown of the control signals in h(t) during O3



- The ITF is controlled via control loops to be kept on a working point to optimize the sensitivity

- The control loops dominate the output signals between 10Hz -100Hz => part of the GW signal is in the control signals

Calibration-reconstruction connection

$$\mathcal{E}(f) = S(f)\Big[\sum_i O_i(f)\cdot(\Delta L_{mir,i}(f) + \Delta L_{mar,i}(f)) + O_{ITF}(f)\cdot h(f)\cdot L_0\Big]$$

- The ITF needs to be calibrated:
  - Response of the mirror/marionettes to the EM actuators used in longitudinal control: A_{MIR} and A_{MAR} [m/V]
  - Readout electronics of the output photodiode *S*
  - ITF optical response function O_{ITF}

- The accuracy of the calibration of the ITFs impacts astrophysical results :
  - Absolute calibration of the GW network
    - Impact on the luminosity distance estimation, e.g. determination of the Hubble constant

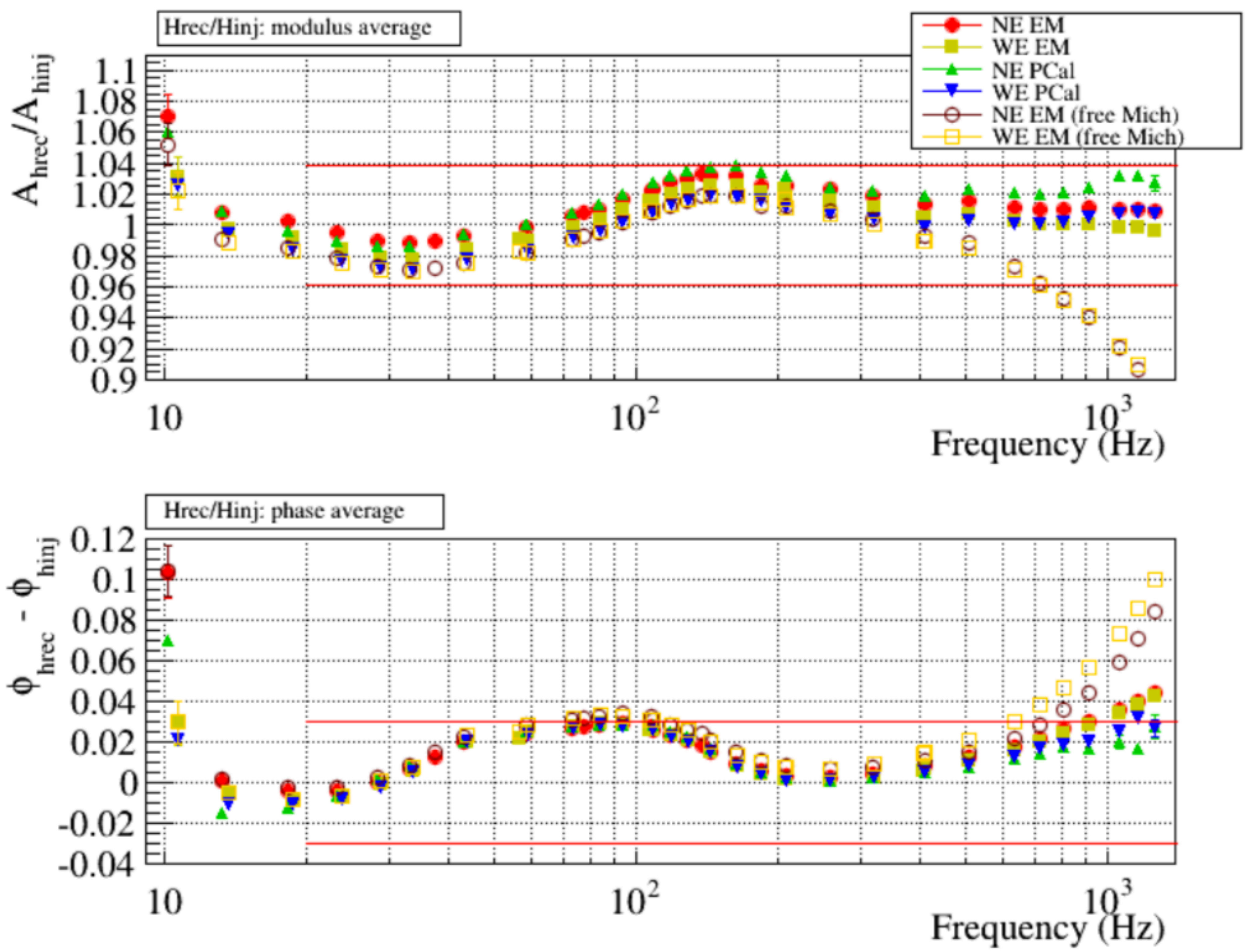
  - Relative calibration between ITFs
    - Impact on the accuracy of the timing of GW network, e.g. sky localization of a source => key in counterpart searches

h(t) uncertainties

The h(t) uncertainties are computed as conservative, frequency-independent symmetric uncertainties from:

- ✦ **Systematic errors** from the actuator models
- ✦ Using h_{rec}/ h_{inj}:
  - ✦ **Frequency-dependent bias observed** in averaged h_{rec}/ h_{inj} TF from weekly monitoring
  - ✦ **Shorter scale variations** observed during the h_{rec}/ h_{inj} monitoring (the largest between weekly and continuous)
- ✦ Uncertainties on the sensing and timing

Average of weekly h_{rec}/ h_{inj} TF for O3a (statistical)



Conservative h(t) uncertainties during O3

In the band 20Hz-2kHz:

± 5 % in amplitude
± 35 mrad
±10 μs

(!) Warning: larger error at 46-51 Hz in O3b

Published results by LIGO-Virgo-KAGRA from O3a/O3 data (a non-exhaustive list)

Compact binary coalescenses and bursts

- Catalog papers GWTC-X (GWTC-2, GWTC-2.1)
- Sub-solar mass search (link)
- All-sky intermediate mass black holes search (link)
- O3a rates and populations (link)
- Burst searches (link)
- GRB searches (follow-ups) (link)

Continuos waves/stochastic

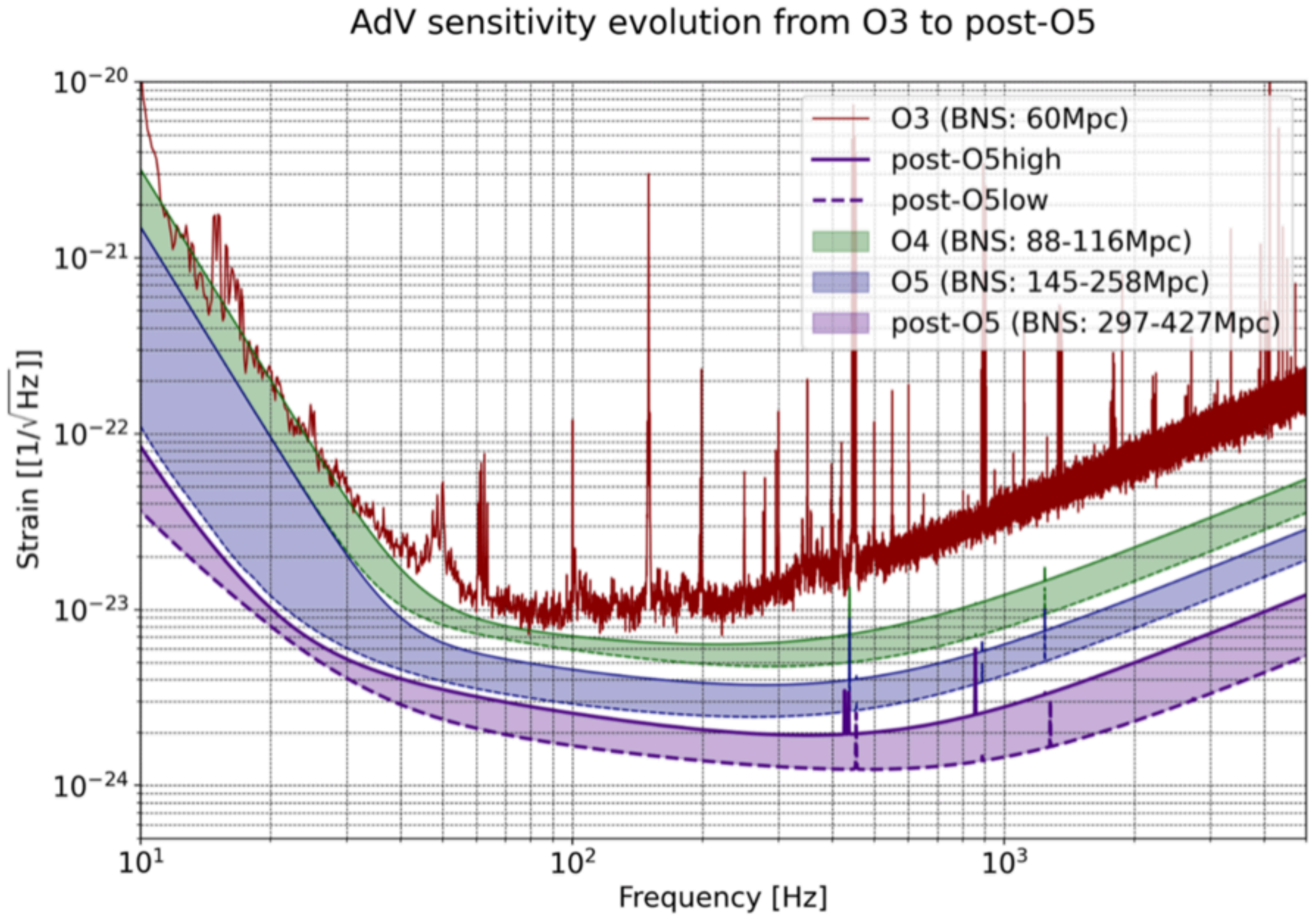
- Continuous waves
  - All-sky binaries (link)
  - All-sky isolated (link)
  - SN remnants (link)
  - Targeted J0537-6910 (link)
  - Accreting millisecond X-ray pulsars (link)
- Stochastic (gravitational-wave backgrounds)
  - O3 isotropic (link)
  - O3 anisotropic (link)

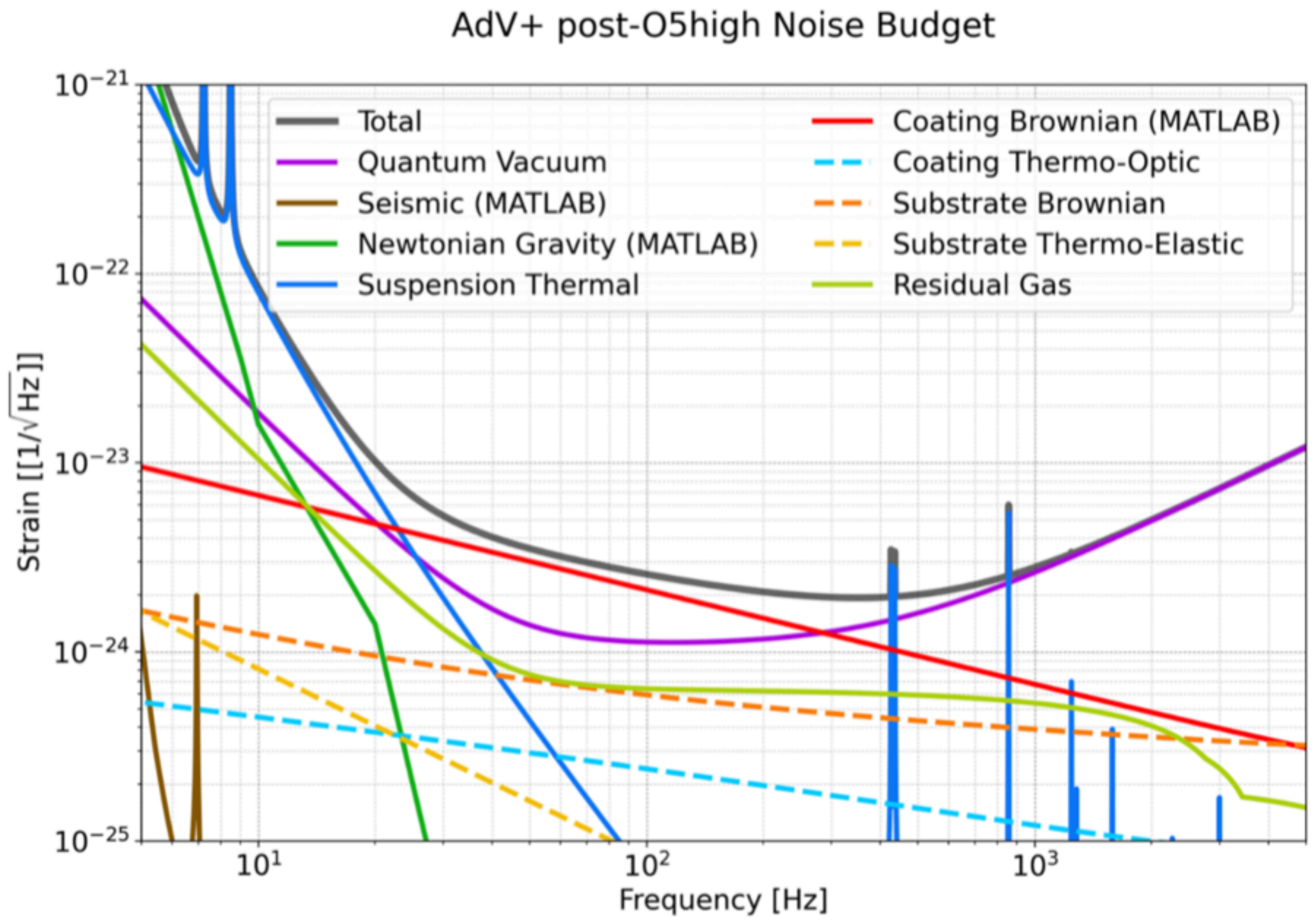
Cosmology and beyond *standard* model

- Test of general relativity (link)
- H0 determination (link)
- GW lensing (link)
- All-sky cosmic strings (link)
- Dark photon and dark matter (link)

GW astronomy is here - LOTS of results in really different fields!

Prospects and noise limitations





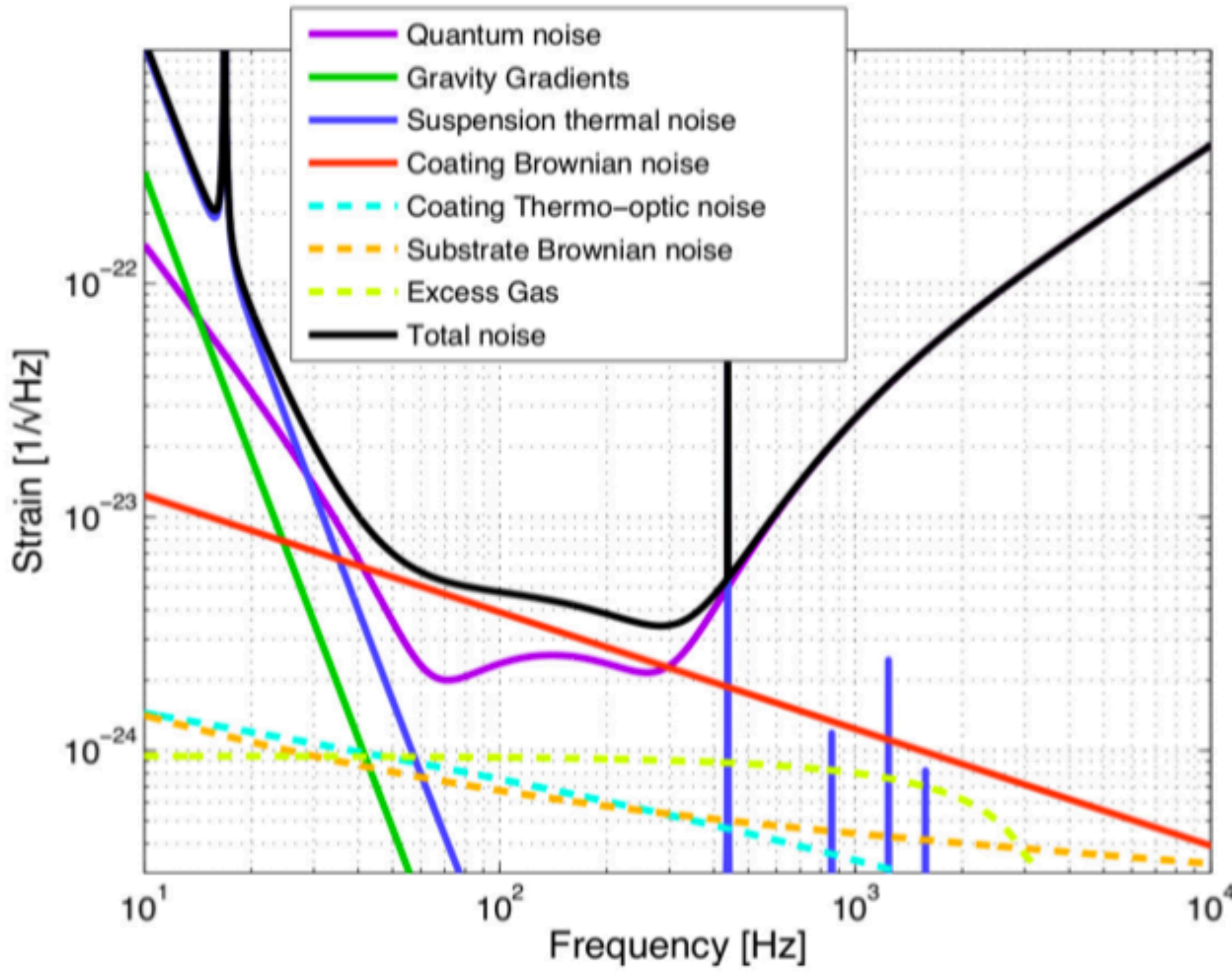
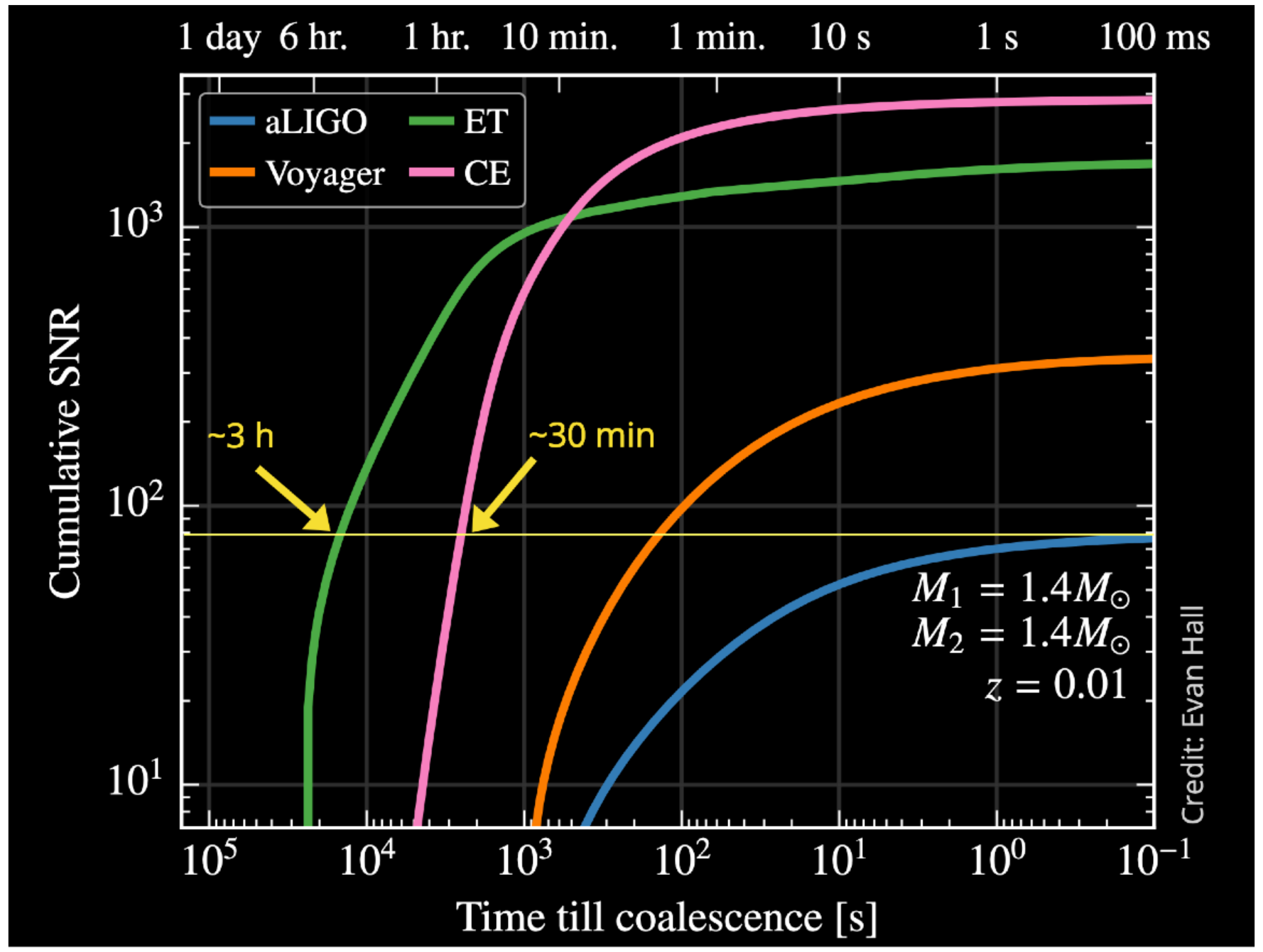


FIGURE 2.5: Sensitivity curve of the Advanced Virgo detector for its Dual Recycling configuration with 125 W of input power. The contributions from the main limiting noises are also shown [14].

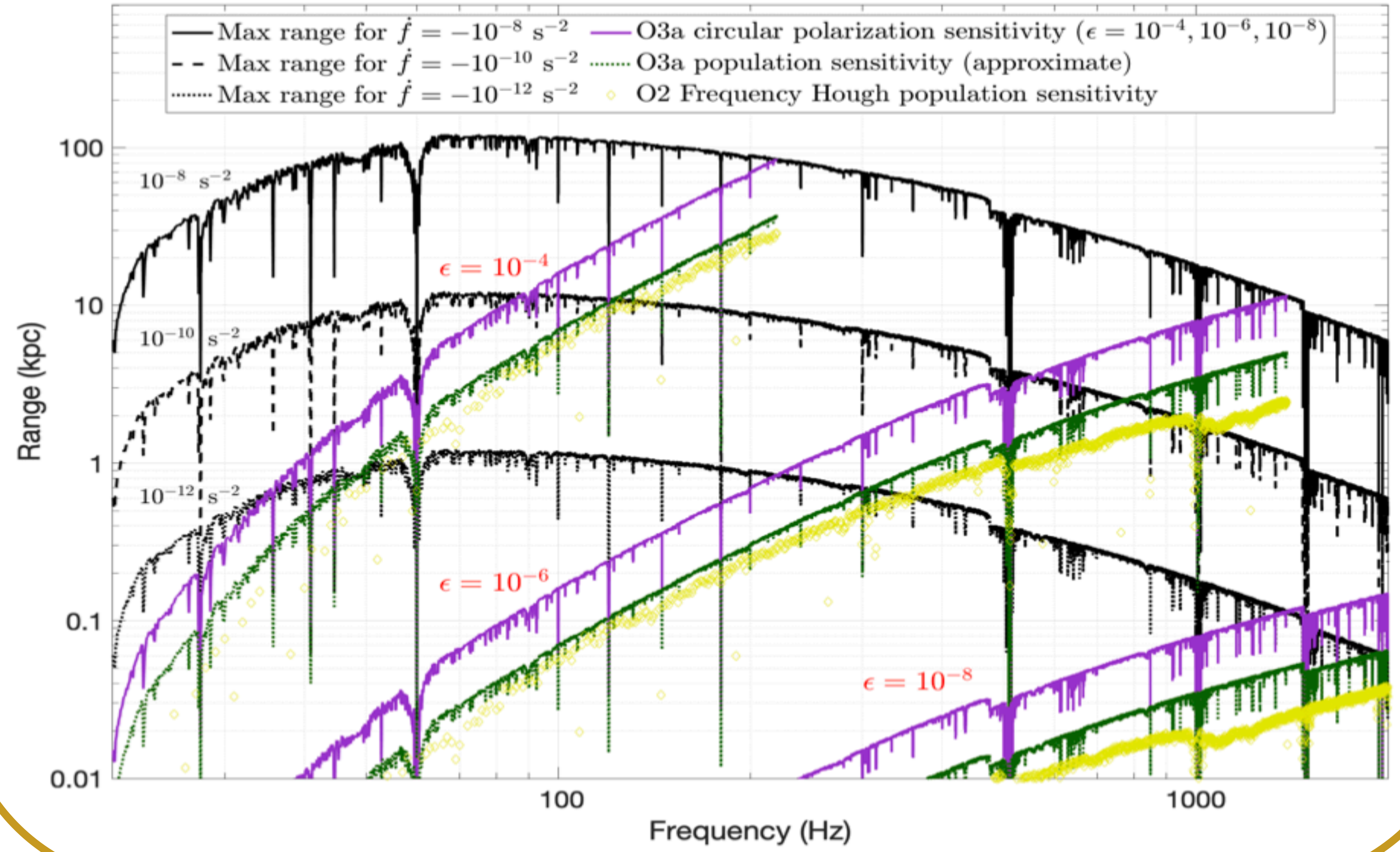


Continuous waves search

Phys. Rev. D 104, 082004 (2021)

All-sky isolated CW O3a

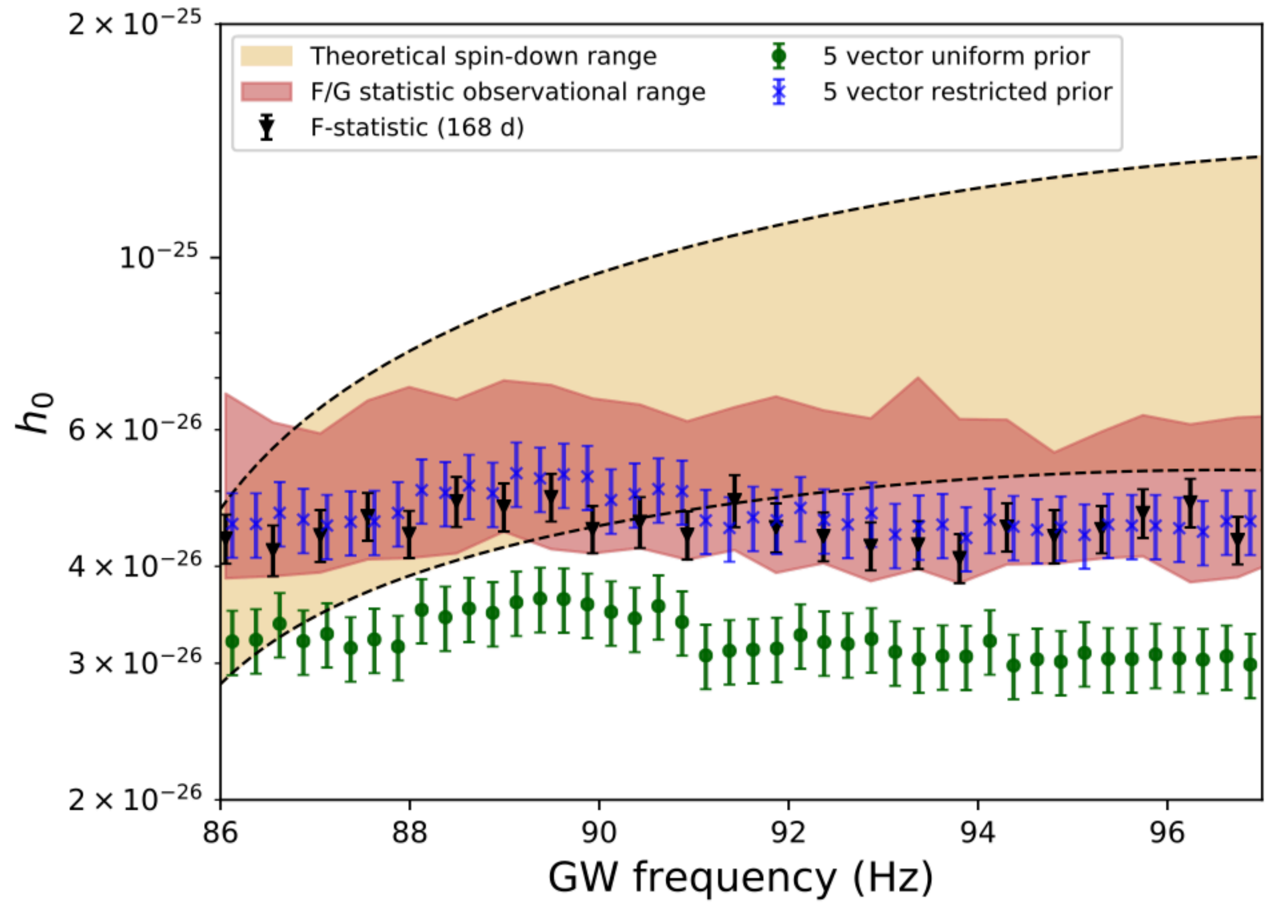
- Target: nearby, spinning, slightly non-axisymmetric isolated neutron stars **in the galaxy**
- Frequency band: 20-2000 Hz
- Frequency derivative band: $[-1.0, +0.1] \times 10^{-8}$ Hz/s
- **No periodic GW signal is observed.**
- Improvement on the set ULs specially due to the sensitivity improvement at high frequencies from LIGO quantum squeezing



arXiv:2104.14417

Targeted J0537-6910 pulsar O3

- Target: young (1-5kyrs) energetic X-ray pulsar spinning at 62 Hz, at 49.6 kpc
- Glitchy behaviour with sudden increase of spin frequency every ~100 days
- GW emission due to r-mode oscillations may play an inportant role in its evolution => Search for emission between glitches
- **No signal detected in the band 86-97 Hz** where signal is expected from theoretical predictions.
  - Stringent upper limits on GW amplitude h0(f) on r-mode driven spin-down of the pulsar



Largely asymmetric-mass systems and intermediate mass black holes

GW190412

- BBH merger: $\sim 30M_\odot + \sim 8M_\odot$
- SNR 19 (3 ITF)
- Asymmetric masses, which are an order of magnitude less probable than near equal mass binaries in canonical isolated binary evolution, but consistent with detections so far
- The asymmetric components may point to the formation of the binary in a lower metalicity environment where higher rates of these are expected.

GW190521

- BBH merger: $\sim 85^{+21}_{-14}M_\odot + \sim 66^{+17}_{-18}M_\odot => 142^{+28}_{-16}M_\odot$
- SNR 14.7 (3 ITF)
- First (and only, so far) observed intermediate mass black hole (in O1-O3 data) => indicates formation channel for IMBH
- IMBH are between stellar-mass ($< 100M_\odot$)and supermassive BH ($> 10^5 M_\odot$)
- The progenitor masses seem to be in the pair-instability mass gap (at which SN are expected to explode and leave no trace) => discussion in the community ongoing

GW190814

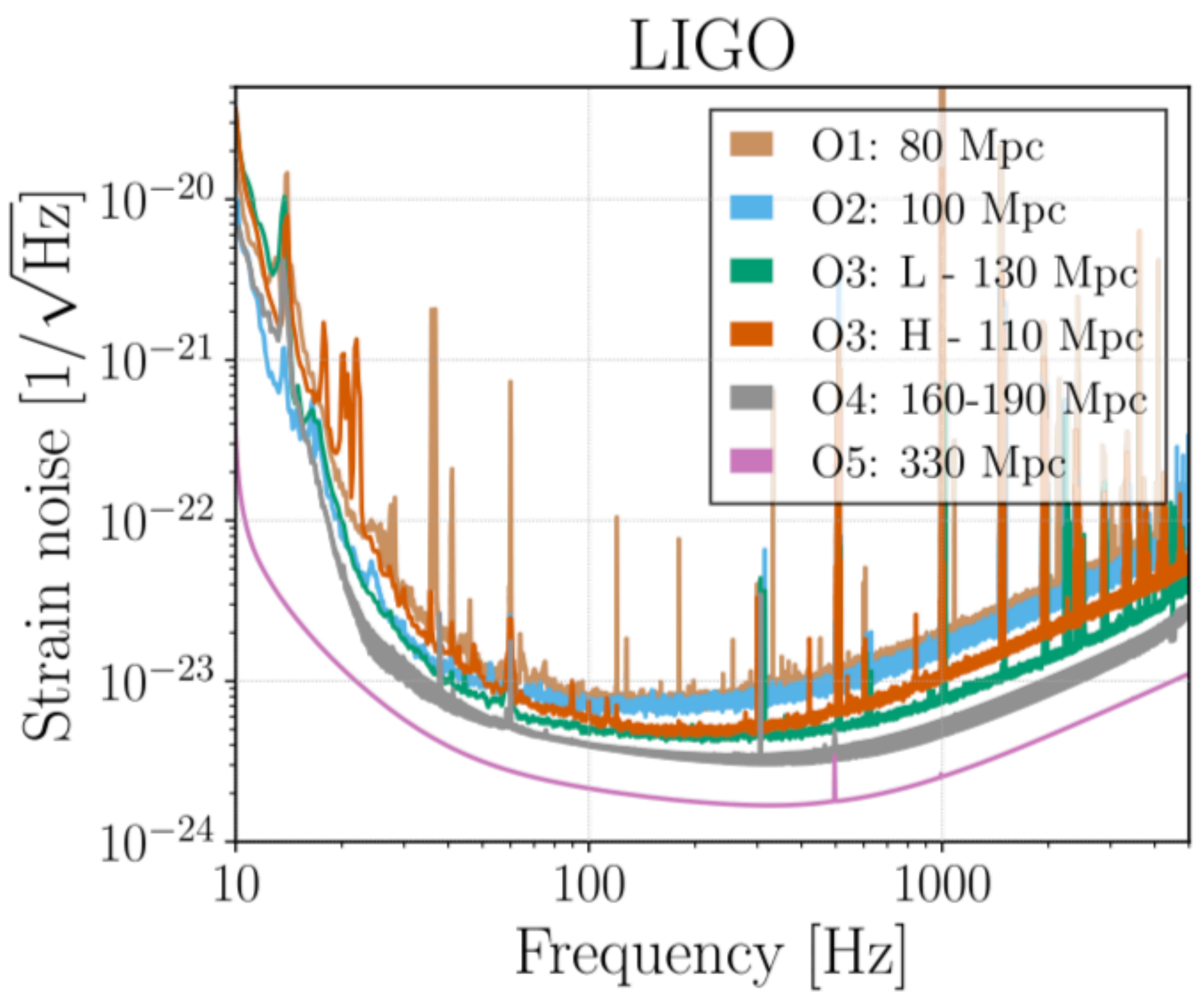
- $22.2 - 24.3M_\odot + 2.50 - 2.67M_\odot$ (second mass in the lower mass gap, $2.5 - 5M_\odot$ between known NSs and BHs, of the order of the remnant of GW170817)
- SNR 25 (3ITF) - No EM counterpart.
- Most unequal mass ratio measured yet:
  $0.112^{+0.008}_{-0.009}$(average during O1 and O2 was $\simeq 0.9$)
- This mass ratio => Several possible formation channels, unlikely formed in globular clusters (outliers in the population prediction)
- Mass ratio+ component masses+ merger rate
  - Challenges model of formation and mass distribution of CBC

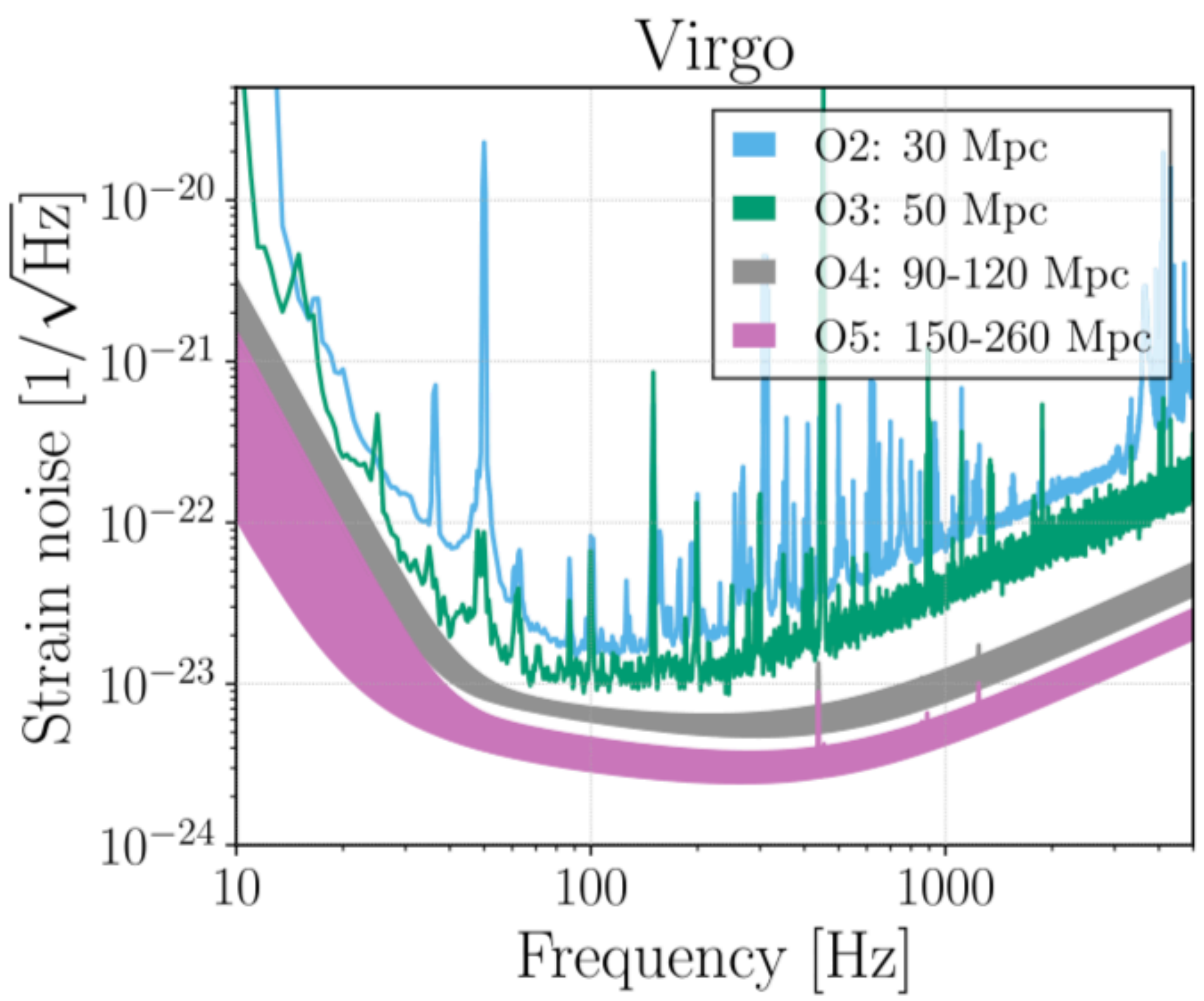
→

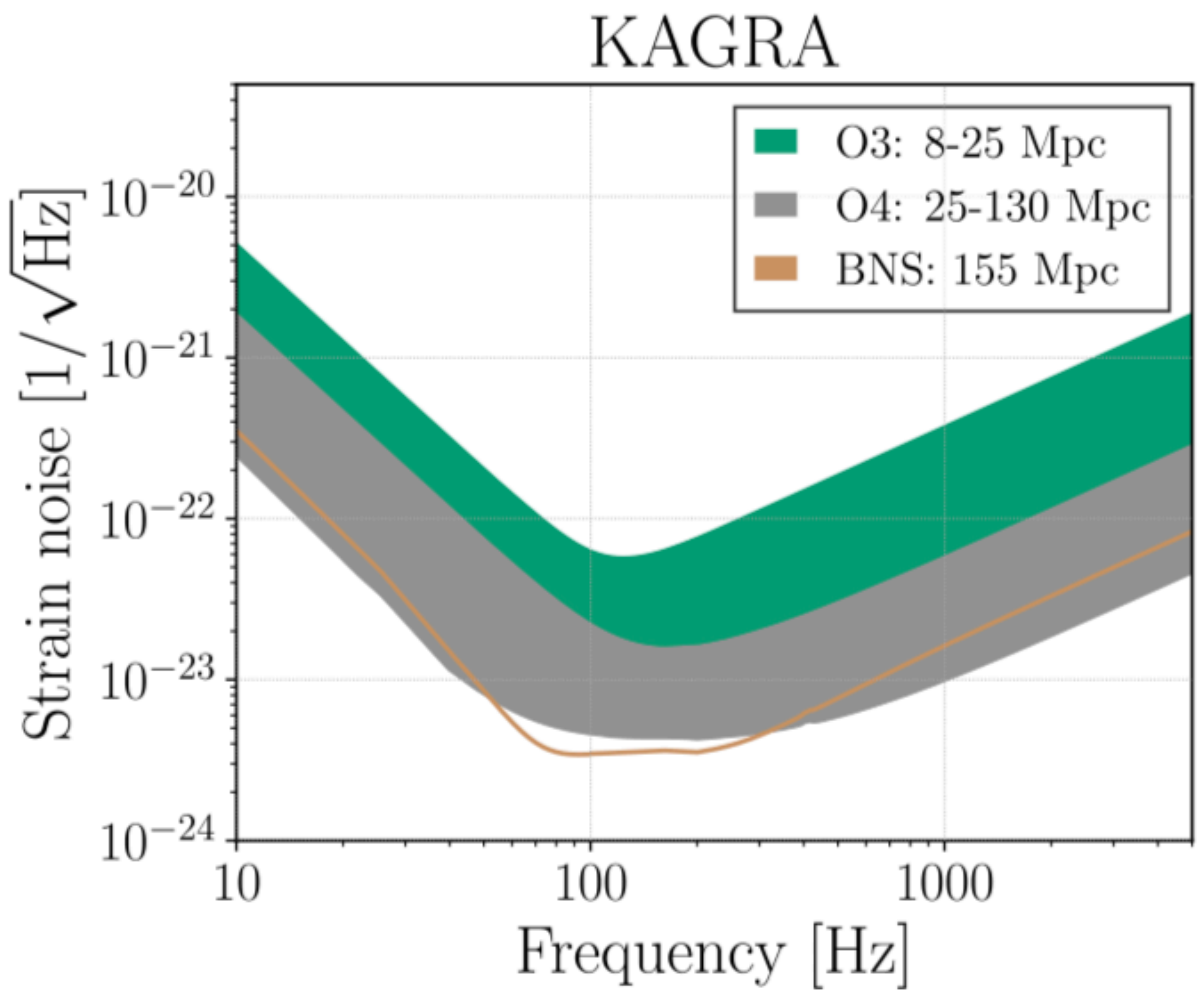
Candidate optical EM-conterpart

- Zwicky Transient Facility (ZTF)
  - 48% of the sky localization covered
  - ZTF19abanrhr: AGN J124942.3+344929 at z = 0.438
  - Mechanism: kicked BBH merger in the accretion disk of an active galactic nucleu

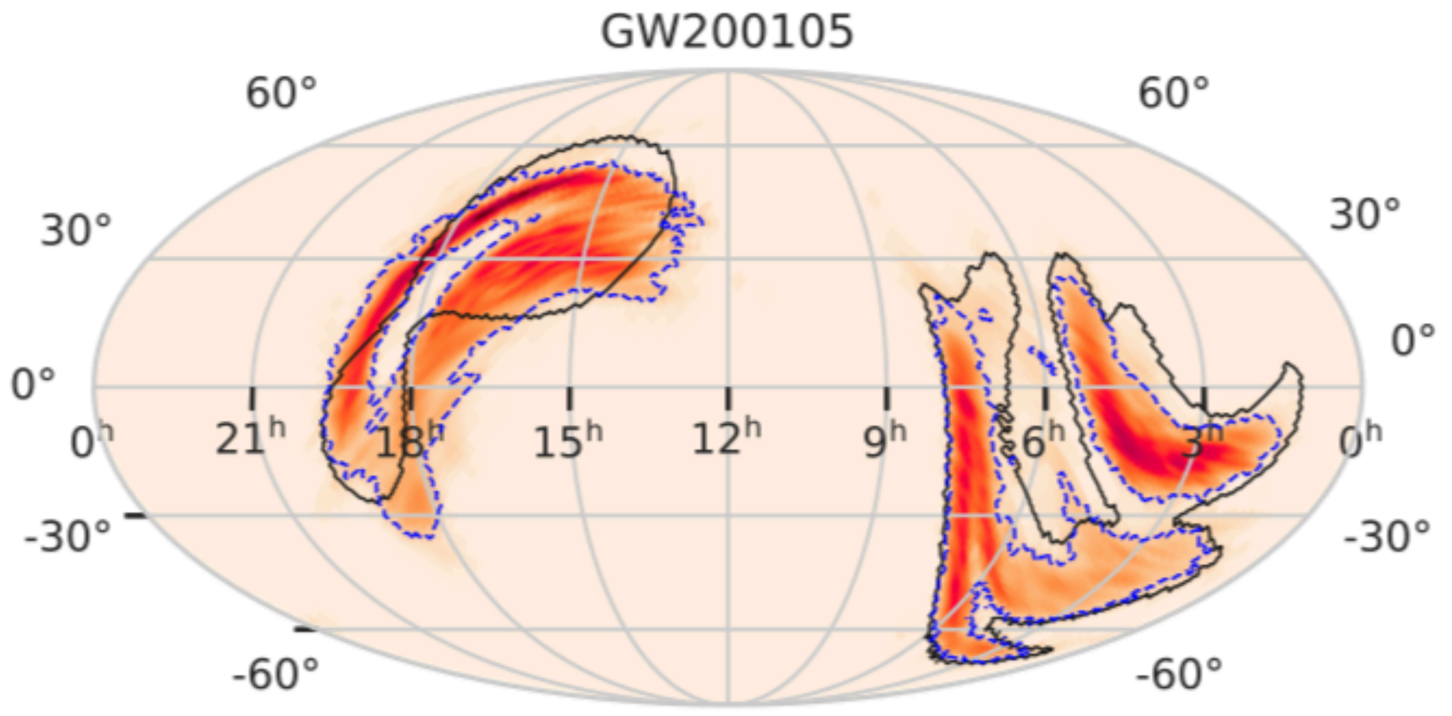
Sensitivity vs. Observing run

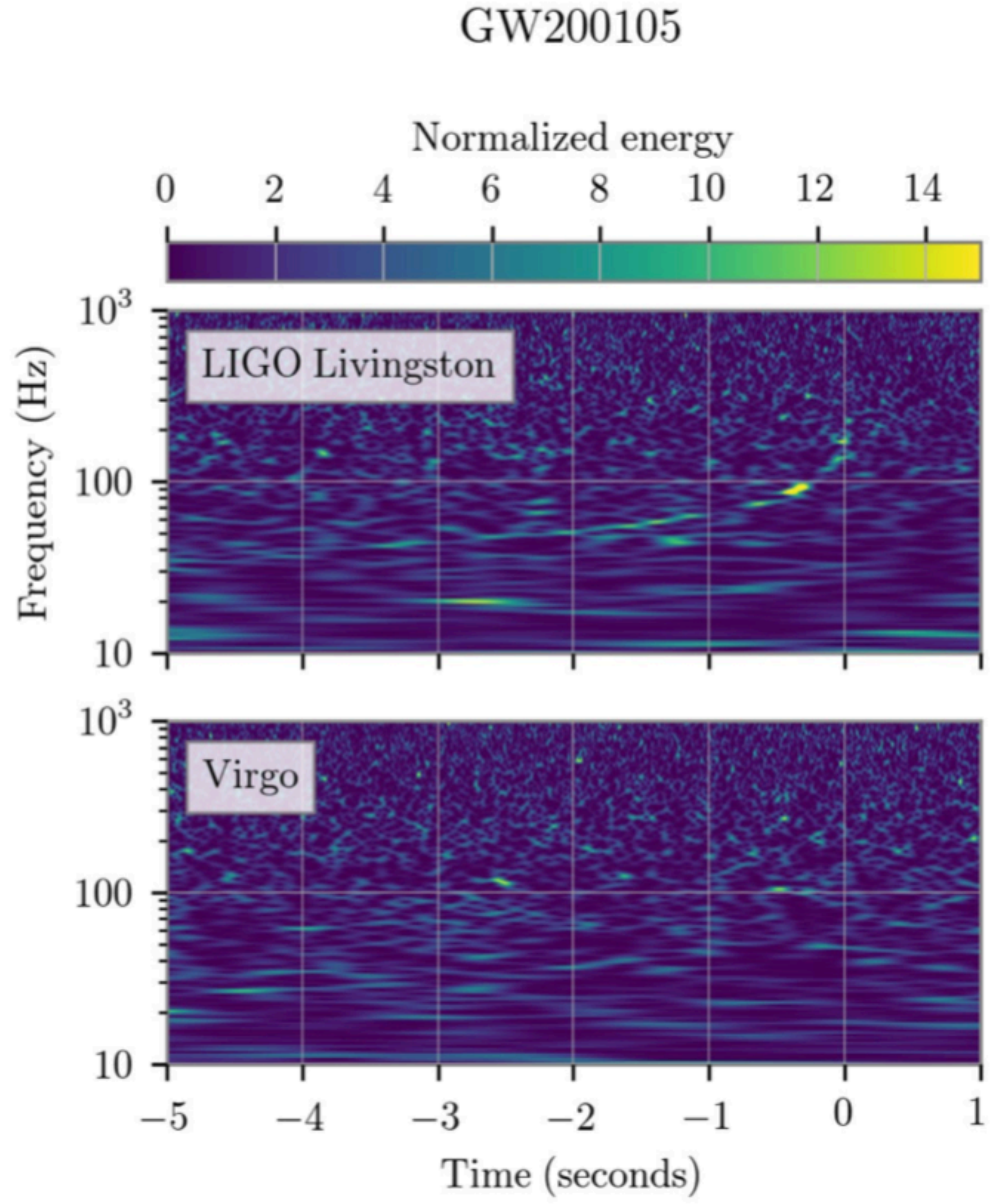


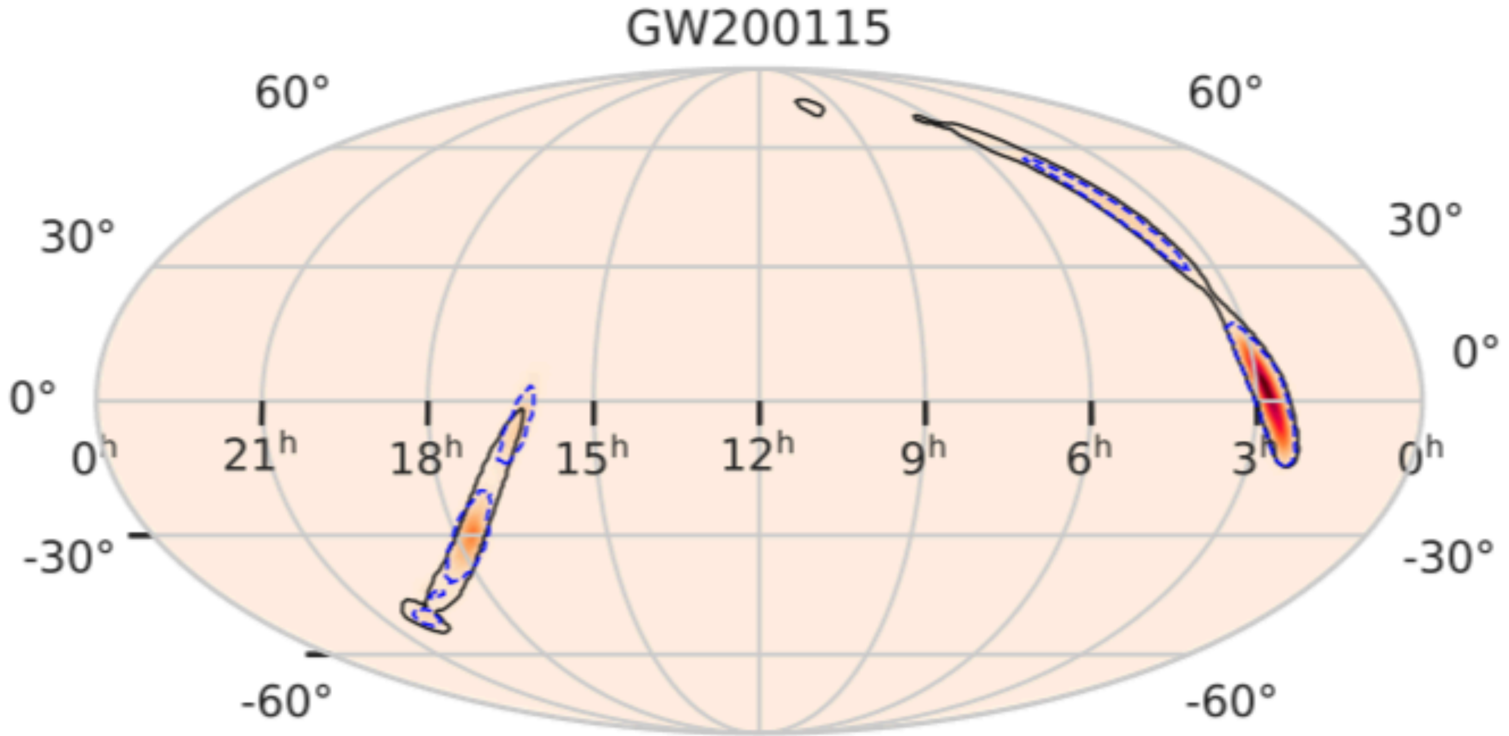


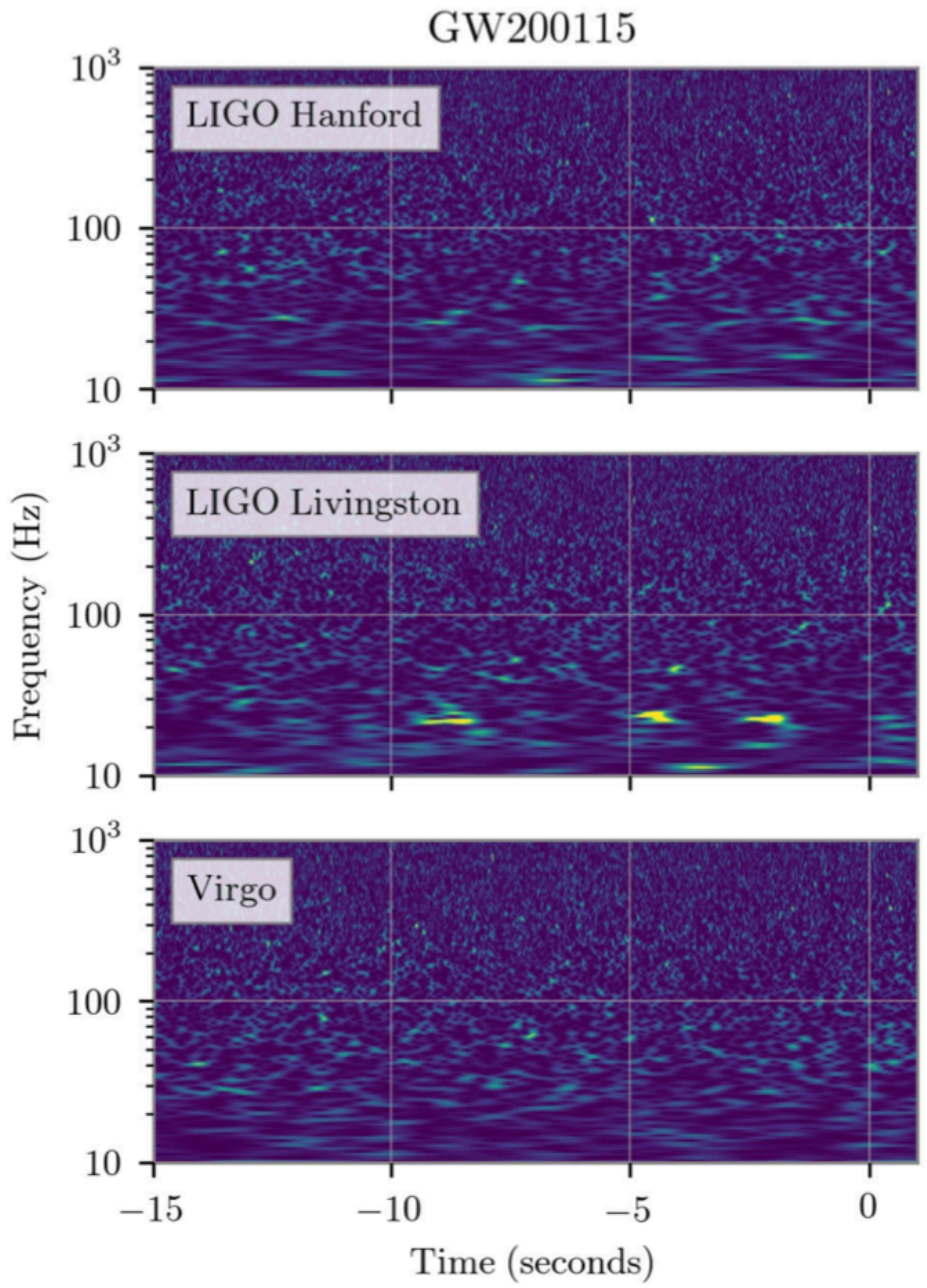


Skymaps of the BH-NS mergers

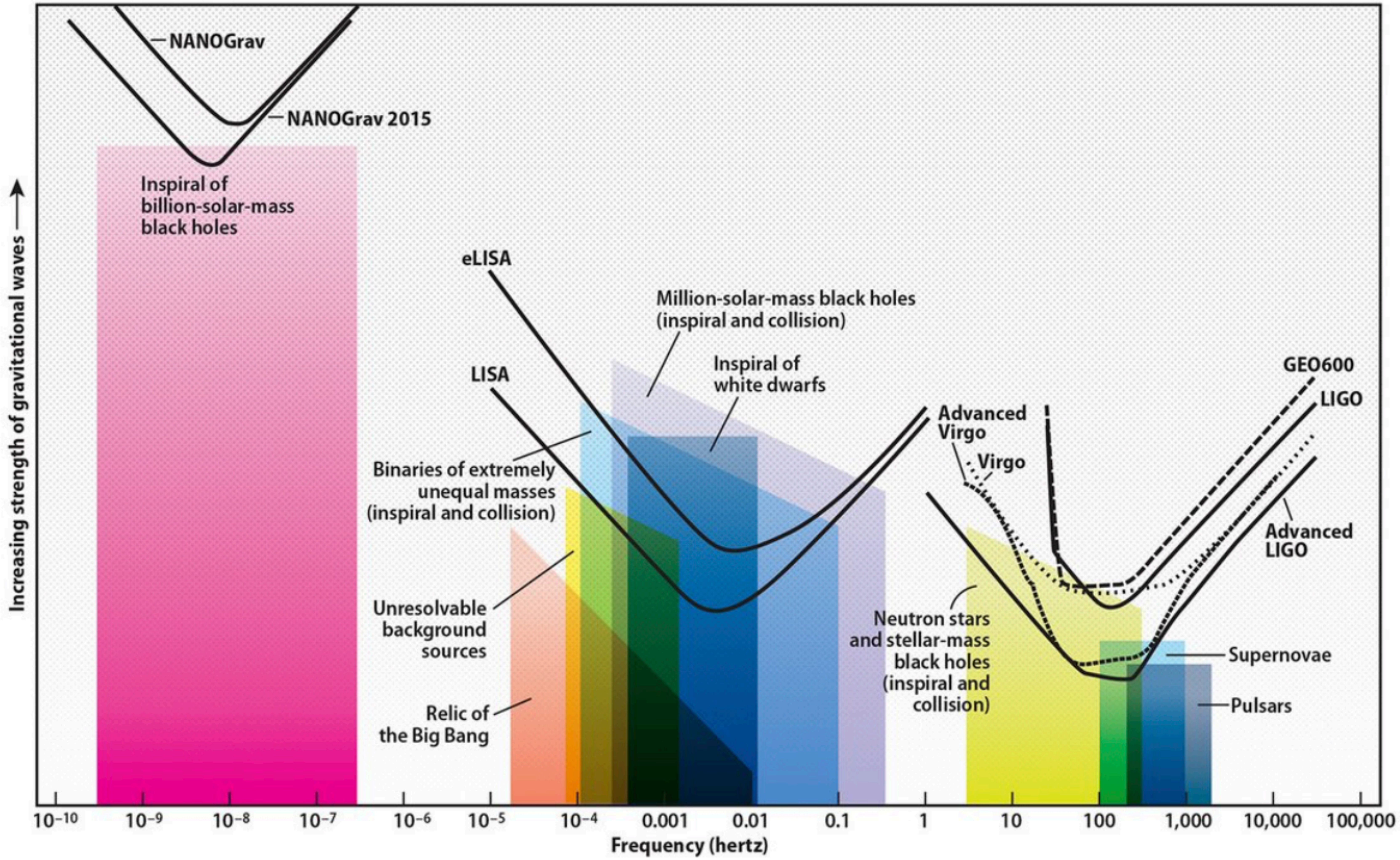








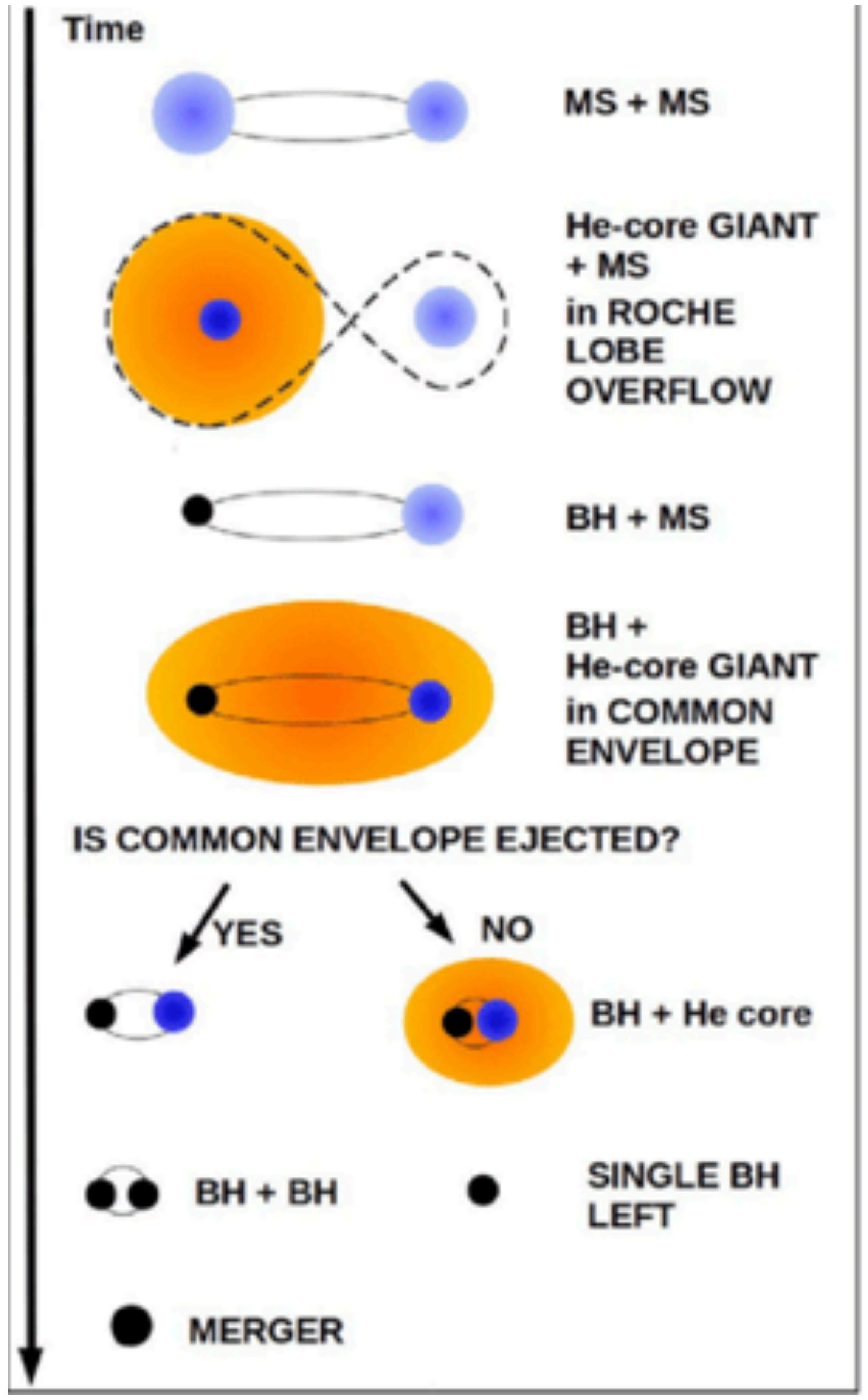
Sensitivity current vs. future experiments



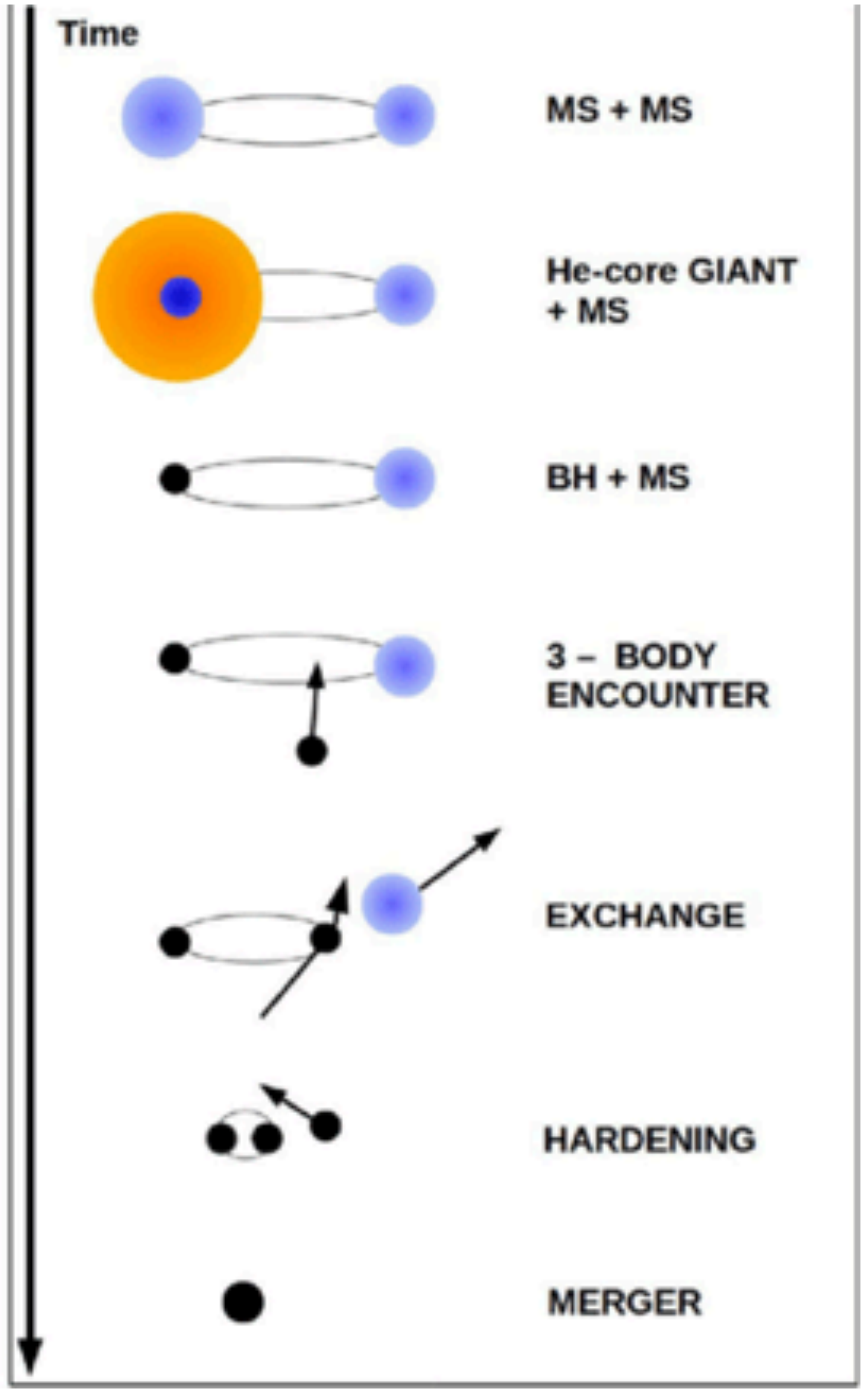
M. Mapelli, *Frontiers in Astronomy and Space Sciences*, 2020, 7: 38.

Formation channels

Isolated BBH formation through common envelope: two stars form from same cloud and evolve into two compact objects gravitationally bound



Dynamical BBH formation in stellar clusters



More in the last LVK Townhall meeting

We will continue feeding the GCN classic stream of VO using the standard “legacy” channel

We will feed alerts in json format to GCN kafka brocker.

We will distribute OPA alert using SCiMMA kafka broker.

We are considering to provide streaming alert to other distribution system (on request).