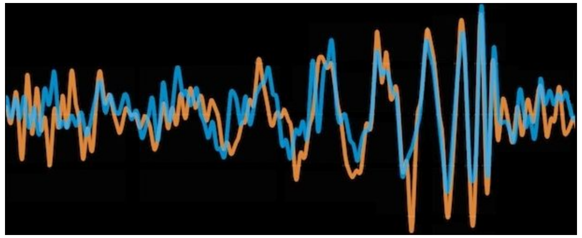
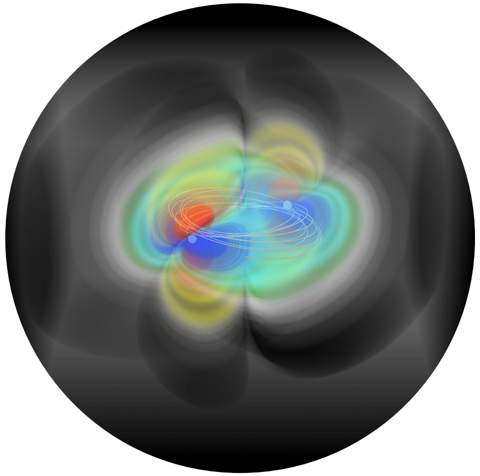
Update on gravitational wave signals in LIGO/Virgo

insights from a rapidly growing observational field





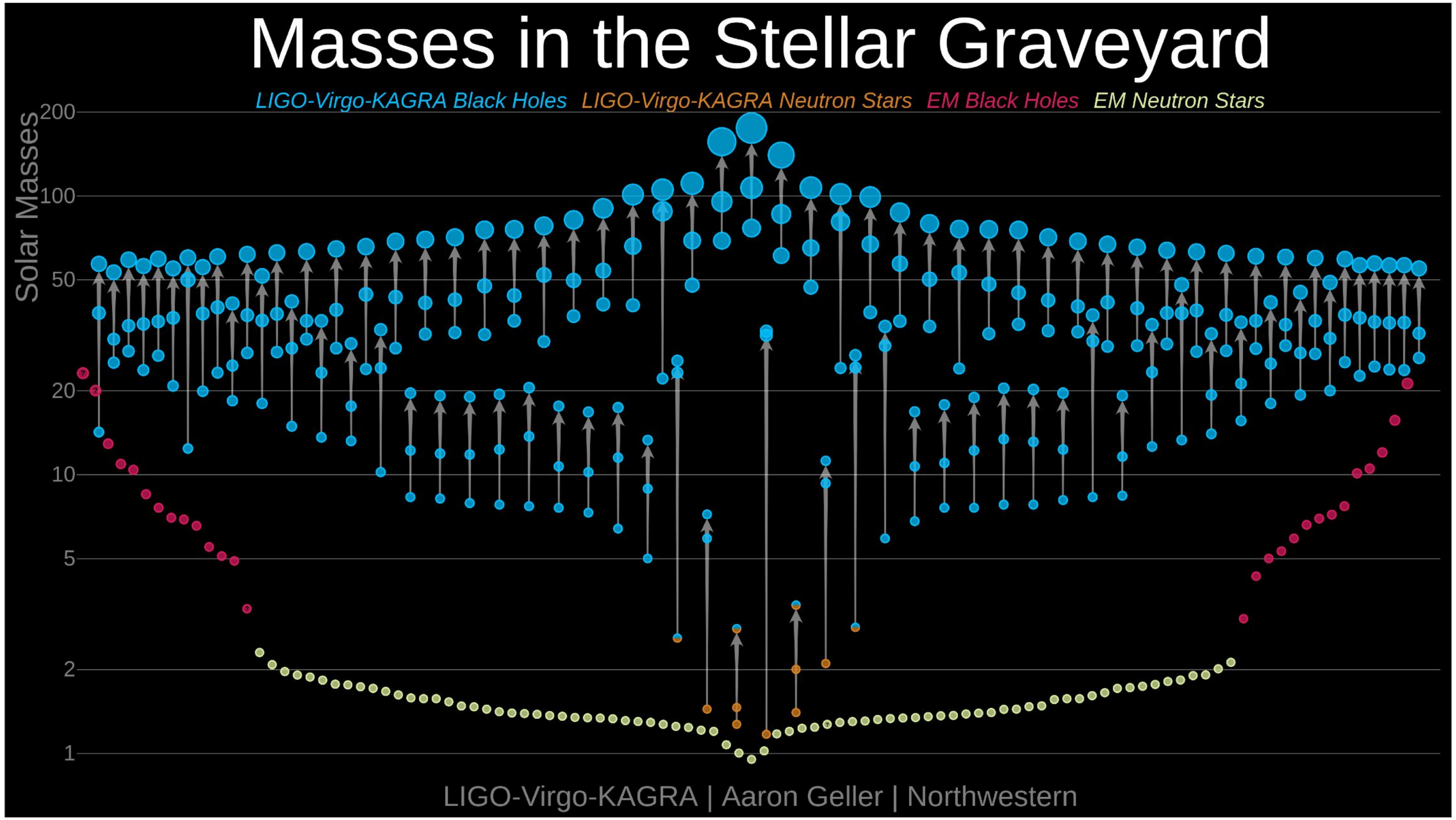
David Keitel, Marta Colleoni, Sascha Husa, Alicia Sintes
(Universitat de les Illes Balears)

Universitat de les Illes Balears | IAC3 Institute of Applied Computing & Community Code.

Dark World to Swampland 2021, 6th IBS-IFT-MultiDark Workshop, 2021-11-18

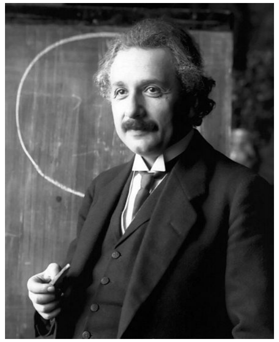
LIGO-G2102383-v1

6 years after the first detection, this is where we are:



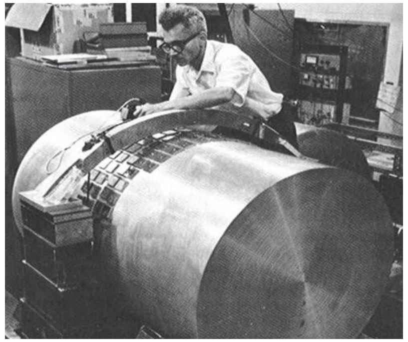
Gravitational Waves - the long road to observational reality

1915



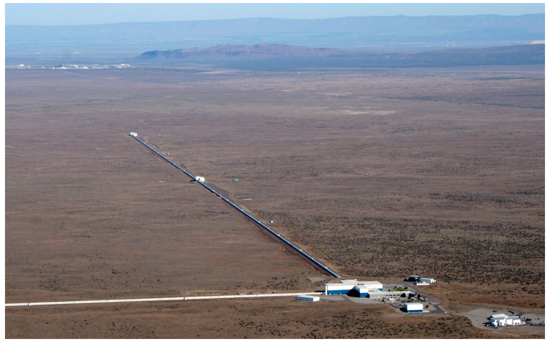
GR

1968



Weber bars

2002–2010



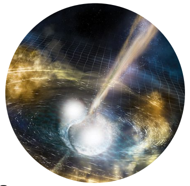
initial LIGO+Virgo operations

aLIGO upgrade

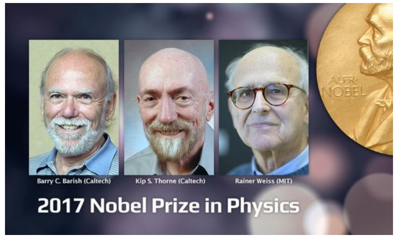
2015

first detection

2017



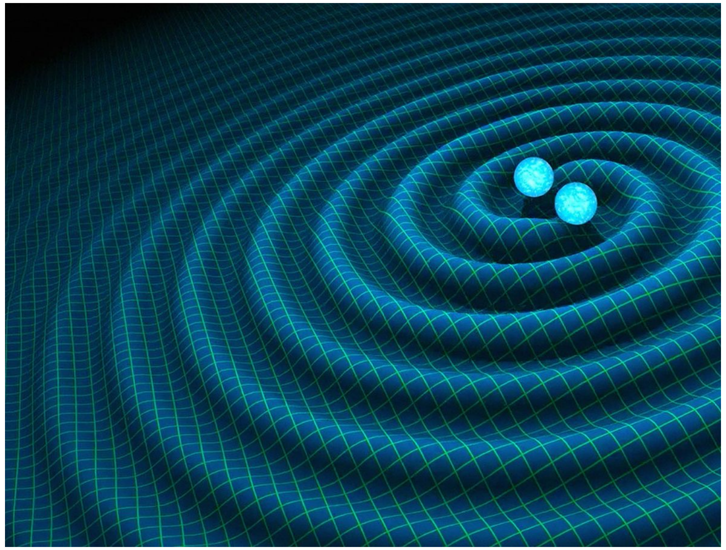
adVirgo joins multi-messenger



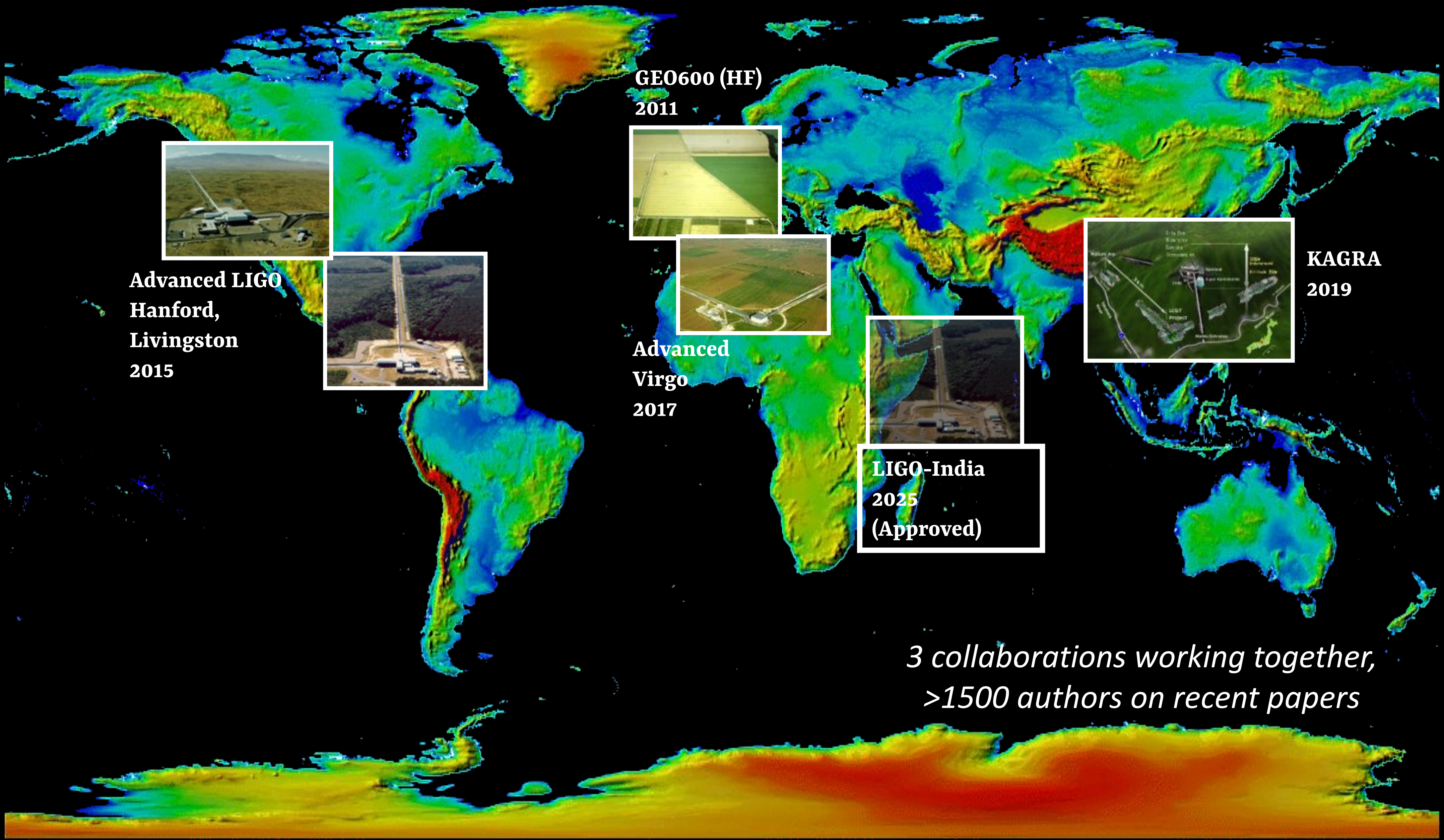
2021

90+ detections KAGRA joins

- general relativity: “Spacetime tells matter how to move, and matter tells spacetime how to curve.”
- time-varying quadrupolar mass distributions → propagating ripples in spacetime: GWs.
- spacetime is “a very stiff fabric” → only extreme astrophysical sources yield detectable GWs



The growing network of advanced GW detectors



LIGO-Virgo groups in Spain

Spanish GW community is growing, contributing to…

- both LIGO and Virgo collaborations
- future detectors
  (LISA, Einstein Telescope, ...)
- many theoretical, observational and instrumentation areas of GW science

LIGO Scientific Collaboration:

- Universitat de les Illes Balears (UIB)
- Instituto Galego de Física de Altas Enerxías (IGFAE)

Virgo Collaboration:

- Universitat de València (UV)
- Instituto de Ciencias del Cosmos, Universidad de Barcelona (ICCUB)
- Institut de Física d'Altes Energies (IFAE), Barcelona
- Instituto de Física Teórica (IFT), Universidad Autónoma de Madrid-CSIC

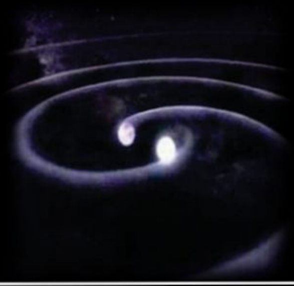
UIB Gravitational Physics Group

3 faculty (Sintes, Husa, Keitel),
4 post-docs, 6 PhD, 2 master and
4 undergrad students

- part of LSC, GEO, LISA, ET
  (A. Sintes founding member of the LSC in 1997)
- We focus on data analysis for GWs from binary black holes and neutron stars (including continuous waves), and the computational modeling needed to identify them.
- IMRPhenom models used for analysing all GW events so far, latest generation developed at UIB: XPHM and TPHM
- leadership on several LVC/LVK O3 projects: continuous waves, gravitational lensing, tests of GR

Recap on GW sources

- Compact Binary Coalescing systems *(CBC)*, well modeled waveforms –> numerical and analytical relativity, phenomenological models

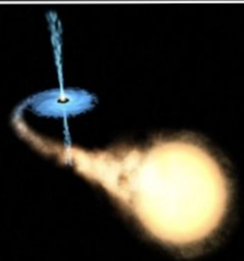


Two Black Holes (BHs) ✓2015
Two Neutron Stars (NSs) ✓2017
BH-NS ✓2020

- Supernovae, GRBs (*bursts*), unmodeled waveforms; short-duration GW events in coincidence with signals in electromagnetic (EM) radiation/neutrinos

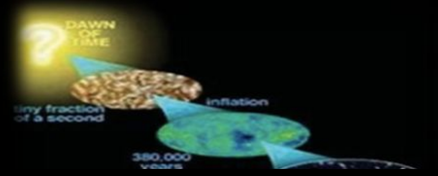
X

- Fast-spinning NSs in our galaxy (either <u>isolated</u> or in <u>binary systems</u>); monochromatic waves; modeled waveform



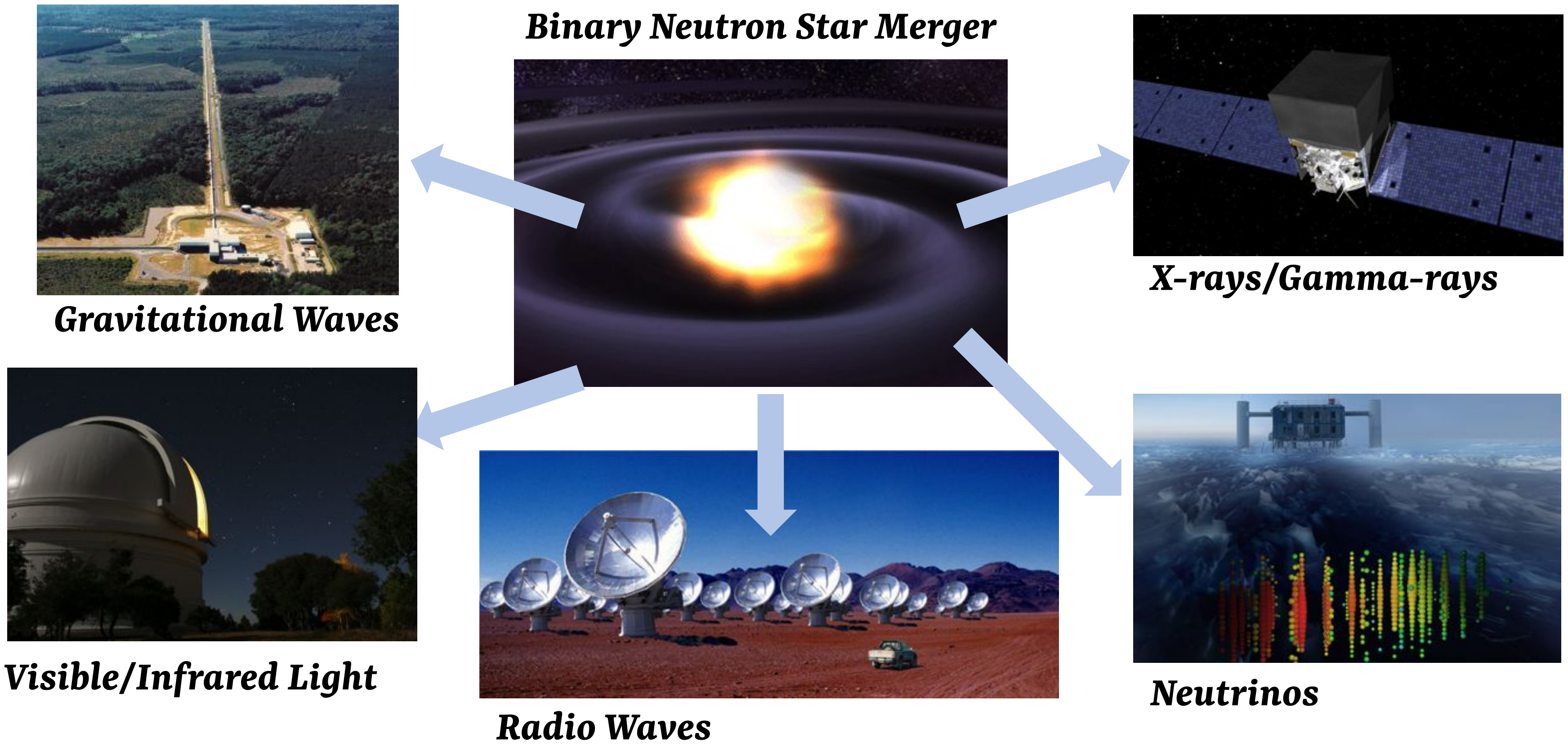
X X

- Cosmological GW (*stochastic background*); A background of primordial and/or astrophysical GWs; unmodeled waveform



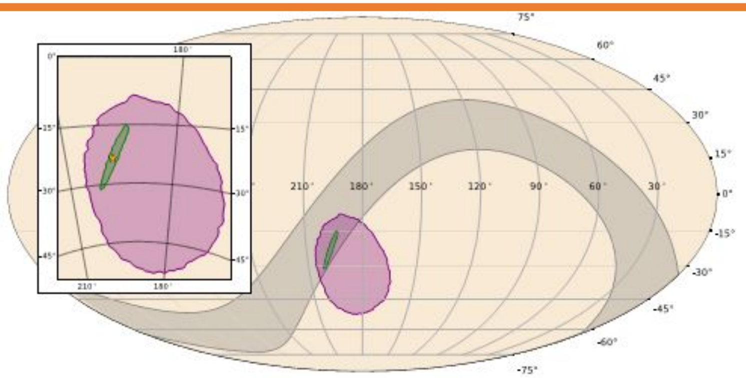
X

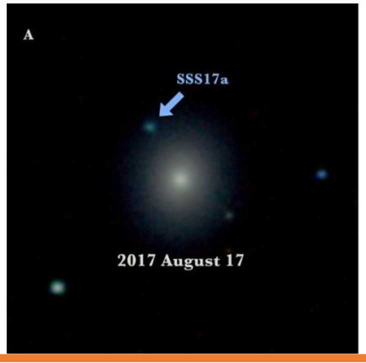
GWs and multi-messenger astronomy



GW170817 multi-messenger breakthrough

[LVC: PRL119,161101 / ApJL848:L13 / ApJL848:L12]





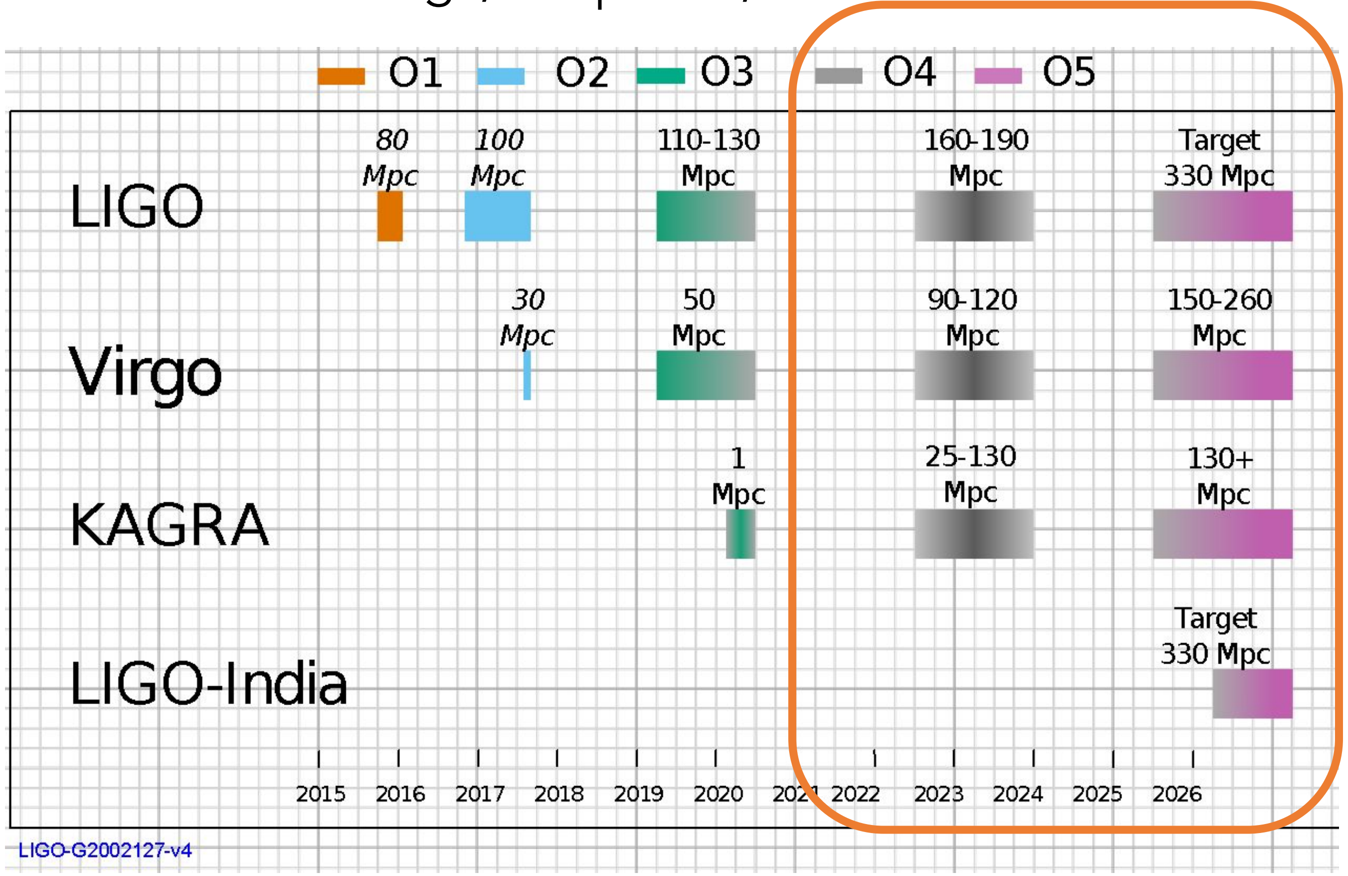
[Drout et al. 2017, Science 10.1126/science.aaq0049]

not the end of the road yet:

On-going Advanced LIGO+ ("A+")/adVirgo+ upgrades in two main steps:

O4: frequency-dependent squeezing, higher power

O5: improved mirror coatings, full power, …

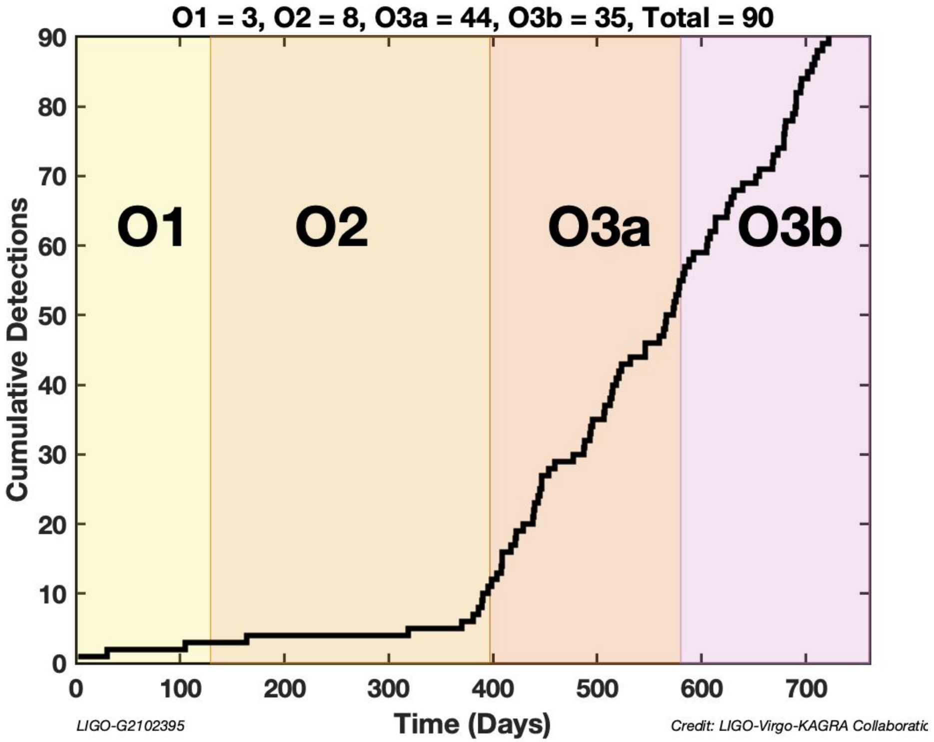


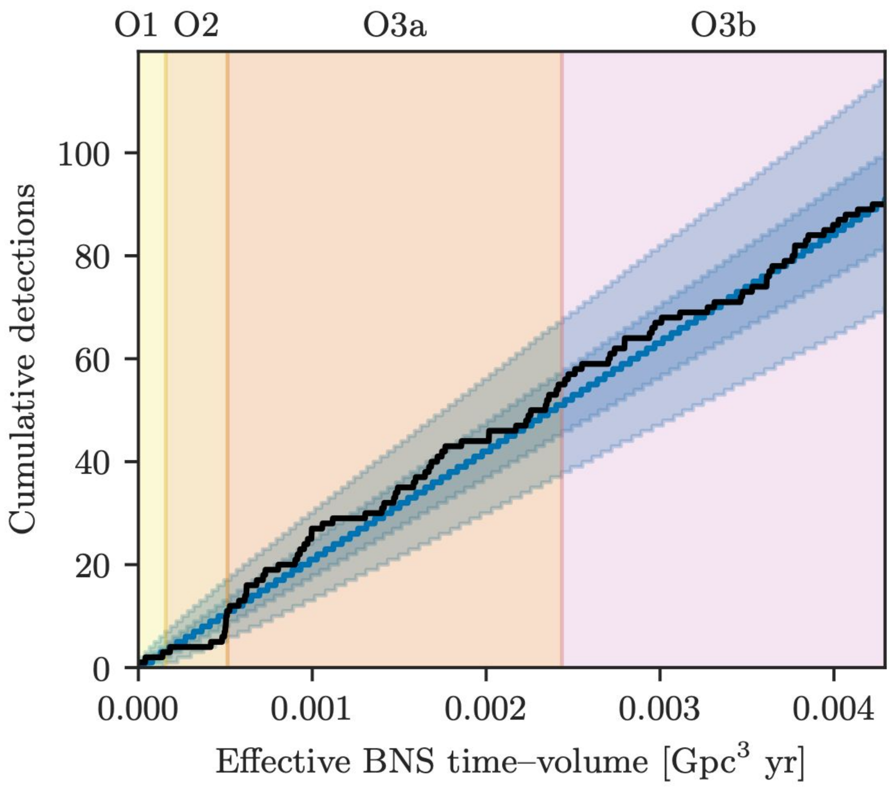
Latest update:
O4 start planned for December 2022.

Work in progress to define the "post-O5" timeline.

[LIGO-Virgo-KAGRA observing scenarios: LRR23,3 (2020)]

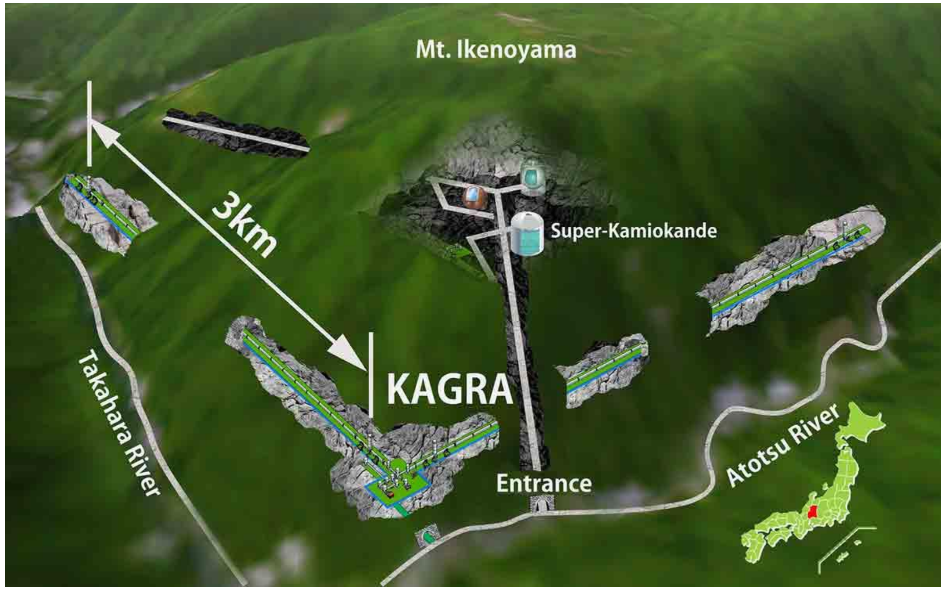
focus today: third Observing Run (O3)





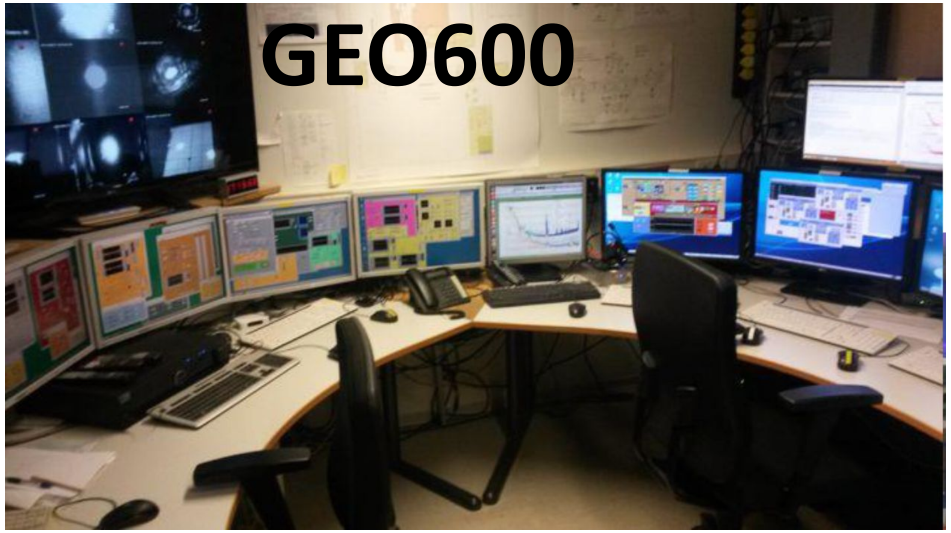
LVK: [arXiv:2111.03606](https://arxiv.org/abs/2111.03606)

O3GK (GEO–KAGRA joint run April 7-21, 2020)



KAGRA in Japan: underground & cryogenic

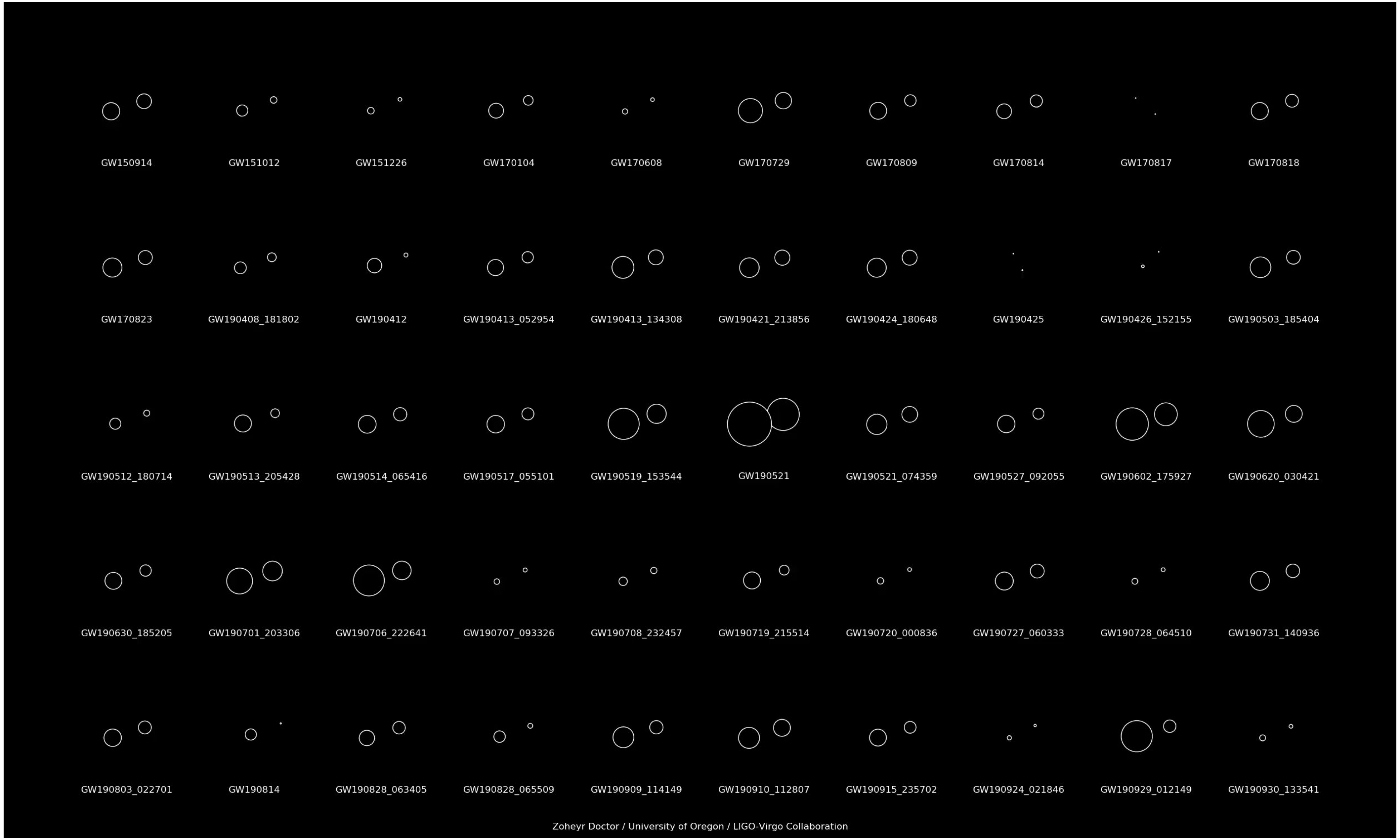
KAGRA achieved ~1 Mpc in March 2020, shortly after completing installation of the main interferometer components



GEO600 in Germany:
robust continuous operations even during the pandemic

Gravitational-Wave Transient Catalog, GWTC-2

Compact binary coalescences observed by LIGO &Virgo during the first half of the third observing run
[LVC PRX11,021053 (2021)](LVC PRX11,021053 (2021))



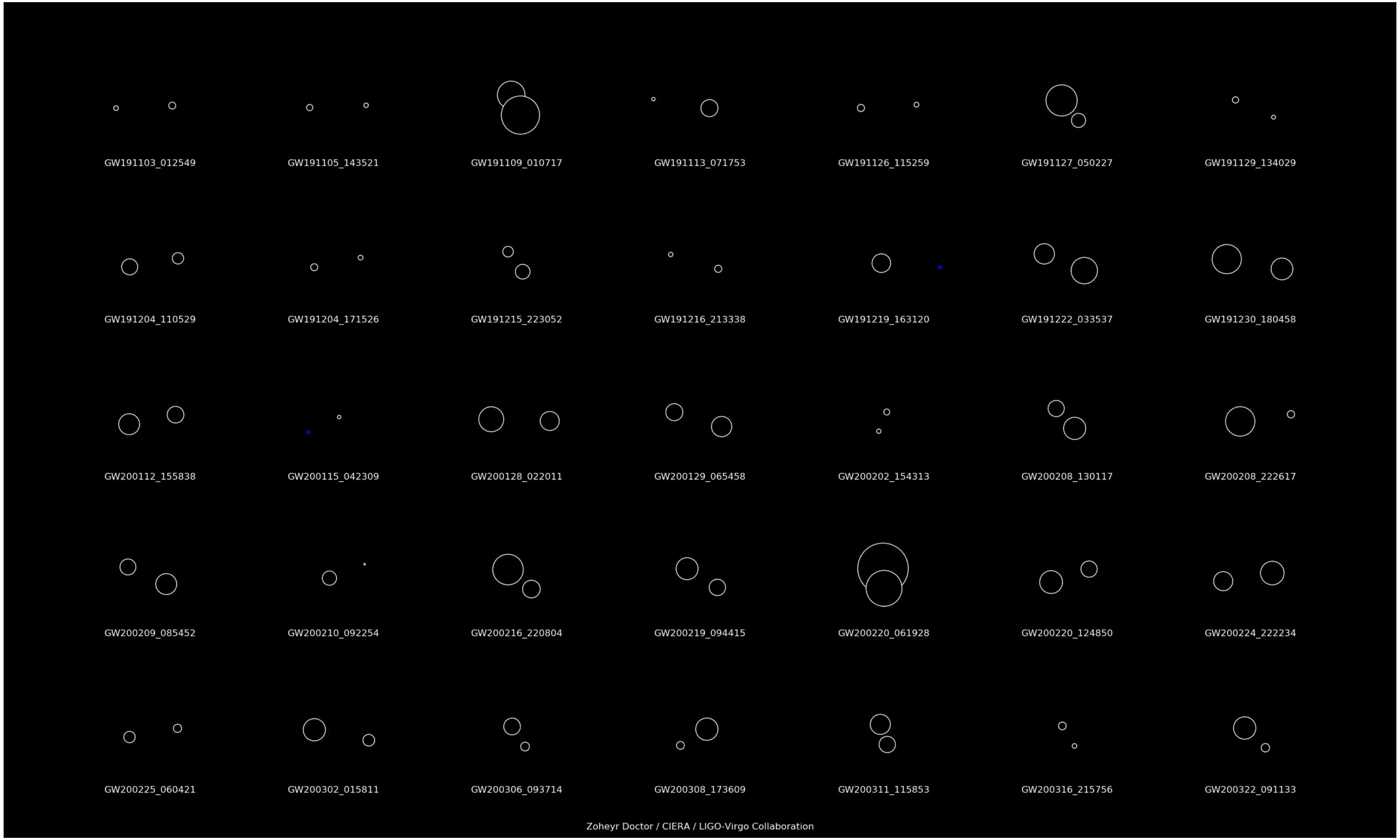
50 events total:

3 from O1
8 from O2
39 from O3a

(+8 in GWTC-2.1, arXiv:2108.01045)

Gravitational-Wave Transient Catalog, GWTC-3

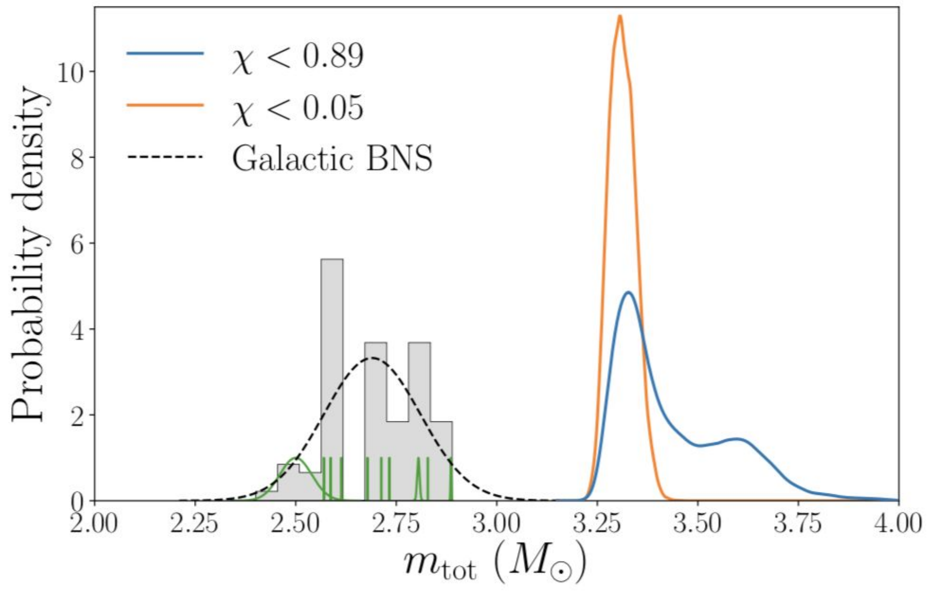
Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run
[LVK arXiv:2111.03606](https://arxiv.org/abs/2111.03606)



35 new events from O3b

highlights of O3a

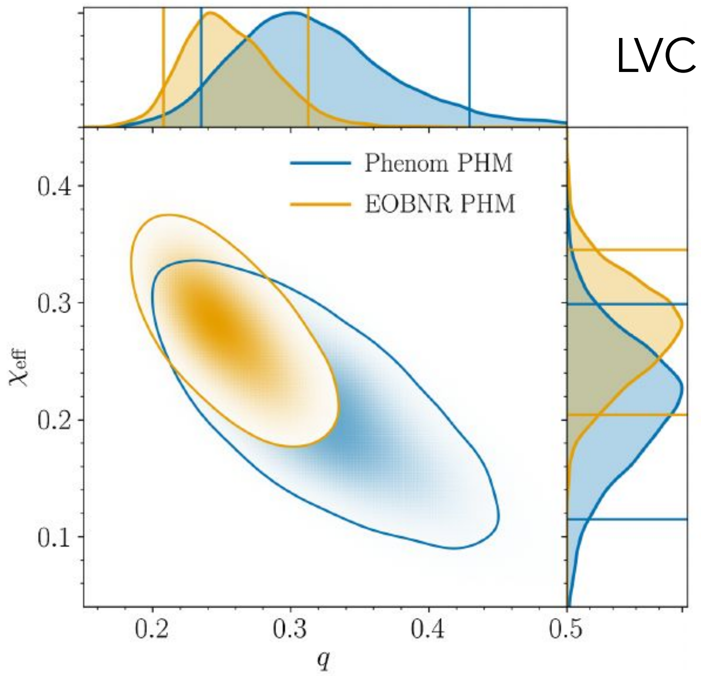
massive BNS: GW190425



LVC ApJL892:L3 (2020)

- both components in "normal" neutron star range
- total mass much higher than GW170817 or known galactic BNS
- 159^{+69}_{-72} Mpc distant
- no EM counterpart, post-merger signal, tidal constraints

unequal-mass BBH: GW190412

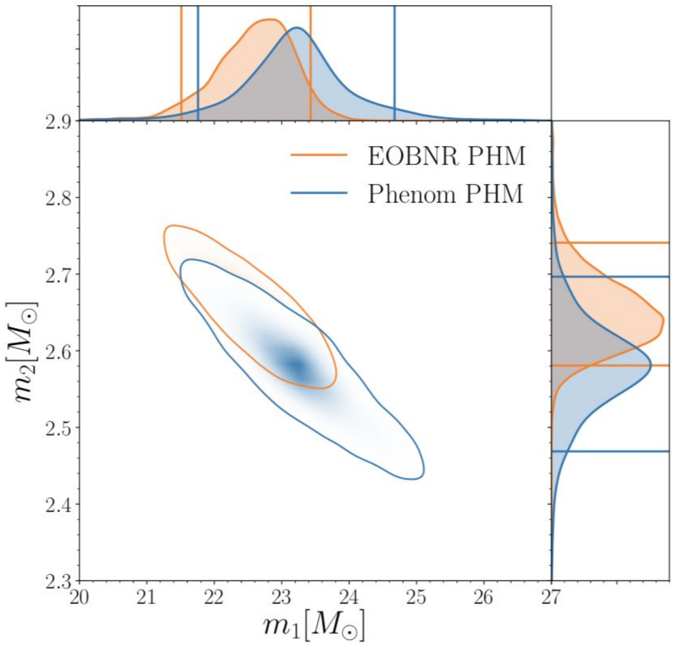


LVC PRD102,043015 (2020)

- asymmetric → strong higher GW multipoles
- other asymmetric detections since then, but this was the first clear one
- detailed reanalysis: Colleoni+ PRD103,024029 (2021)

highlights of O3a

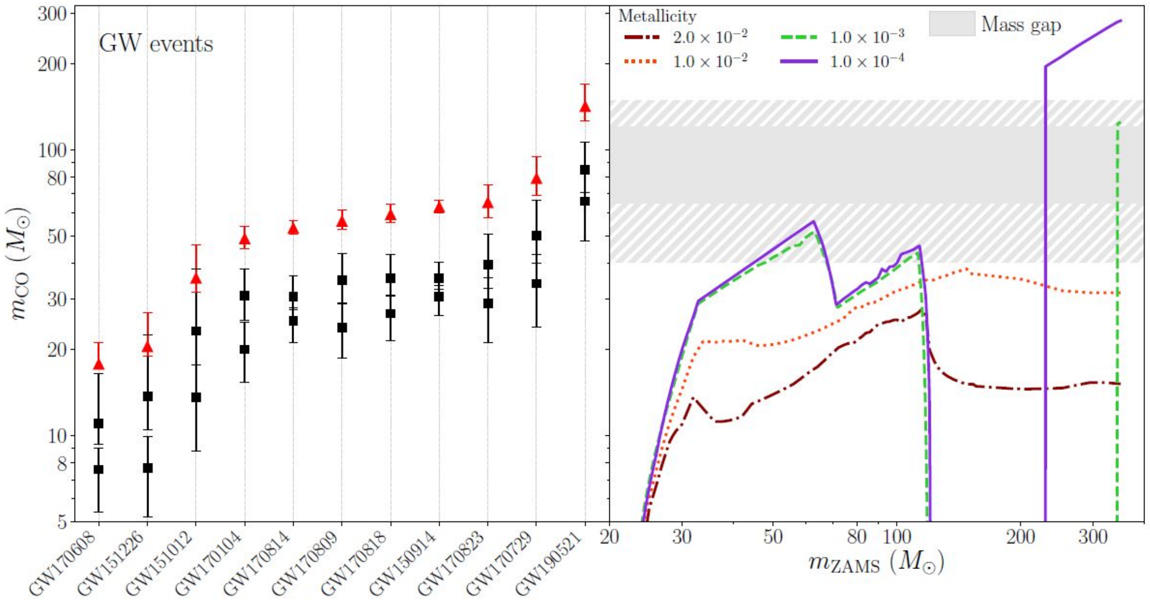
mystery merger: GW190814



LVC ApJL896:L44 (2020)

- mass ratio ~10:1; primary: normal BH
- secondary: either heaviest NS or lightest BH so far
- outlier to population analysis (1 similar O3b event)
- challenging for standard formation scenarios
- great for testing GR thanks to high mass ratio → strong higher multipoles

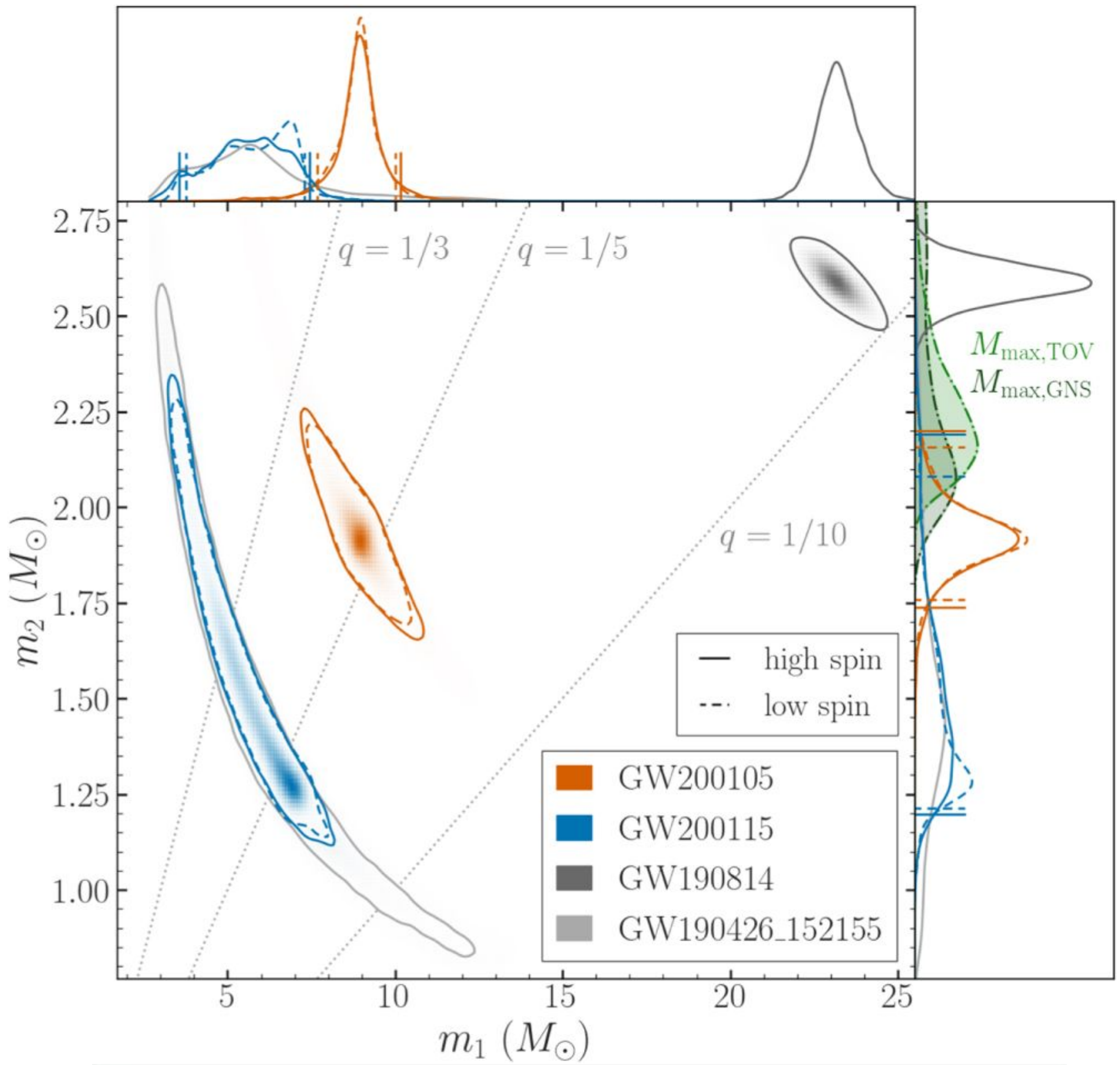
massive BBH: GW190521



LVC PRL125,101102 (2020) / ApJL900:L13 (2020)

- ~ 7 Glyr distant (some O3b events further away)
- first detection of "intermediate mass" black hole (its remnant)
- at least one progenitor black hole (85 Msun) in pair instability supernova mass gap (50–120 Msun)
- challenging for standard formation scenarios
- could be e.g. a 2nd generation merger
- detailed reanalysis: Estellés+ arXiv:2105.06360 (ApJ accepted)

highlight of O3b: GW200105 & GW200115



	m_1	m_2
GW200105	$\sim 8.9\,M_\odot$	$\sim 1.9\,M_\odot$
GW200115	$\sim 5.7\,M_\odot$	$\sim 1.5\,M_\odot$

Observation of Gravitational Waves from Two Neutron Star-Black Hole Coalescences

LVK ApJL915:L5 (2021)

- first detections of neutron star – black hole systems
- no EM counterpart observed (as expected)
- luminosity distances 280 and 300 Mpc

- some of the most expensive parameter estimation runs done by UIB group on MareNostrum cluster

PHYSICAL REVIEW X **11,** 021053 (2021)

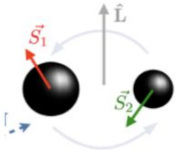
GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

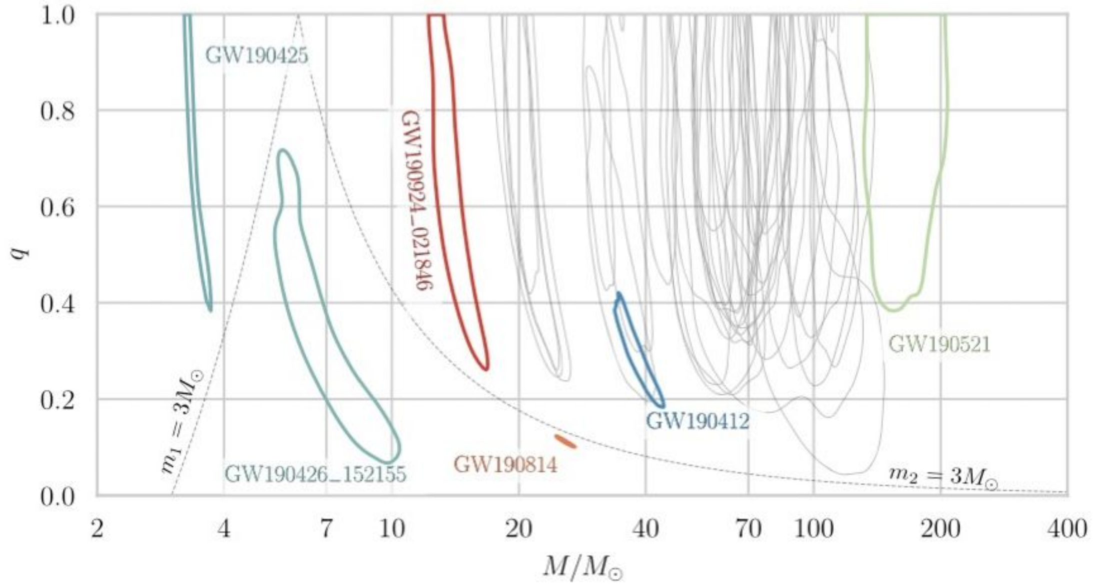
39 compact binary coalescences from O3a (FAR<1/2yr)

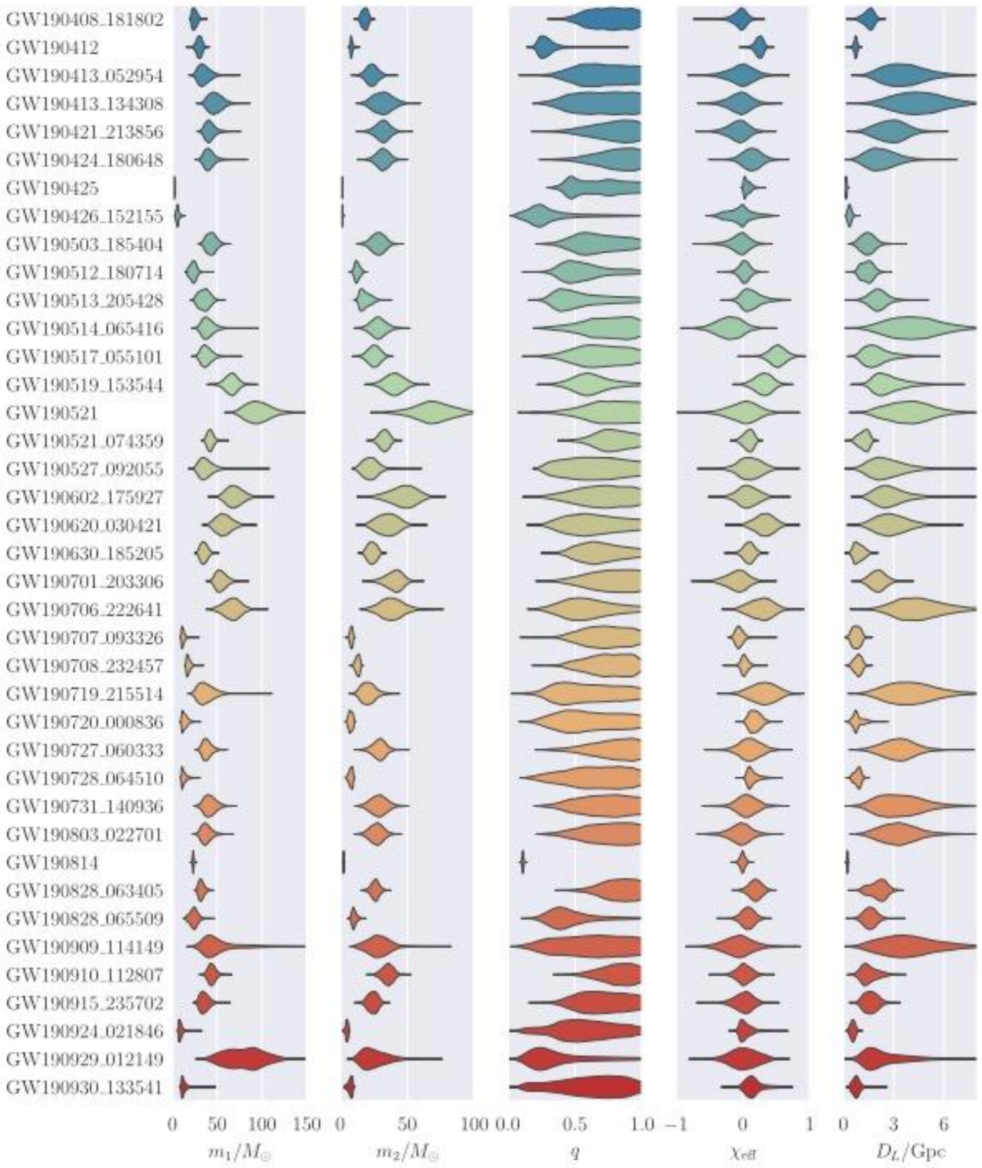
3x more than before, thanks to upgraded detectors, enhanced data quality and better searches.

- most events: binary black holes
- wide range of masses
- redshifts up to ~0.8
- spins:
  - key signatures for formation channels
  - some events with positive X_{eff}



$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$$





GWTC-2.1: Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run

LVC arxiv:2108.01045

- 8 new events that were not in GWTC-2 with probability of astrophysical origin $p_{astro} > 0.5$

Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	D_L (Gpc)	z	M_f ($M_\odot$)	χ_f	$\Delta\Omega$ (deg^2)
GW190403_051519	$110.5^{+30.6}_{-24.2}$	$36.3^{+14.4}_{-8.8}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.88}_{-3.99}$	$1.14^{+0.64}_{-0.49}$	$105.2^{+29.1}_{-24.1}$	$0.92^{+0.04}_{-0.11}$	5600
GW190426_190642	$184.4^{+41.7}_{-36.6}$	$77.1^{+19.4}_{-17.1}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$	$175.0^{+39.4}_{-34.3}$	$0.76^{+0.15}_{-0.15}$	8200
GW190725_174728	$18.2^{+4.2}_{-1.8}$	$7.4^{+0.6}_{-0.5}$	$11.5^{+6.2}_{-2.7}$	$6.4^{+2.0}_{-2.0}$	$-0.04^{+0.26}_{-0.14}$	$1.05^{+0.57}_{-0.46}$	$0.21^{+0.10}_{-0.09}$	$17.4^{+4.4}_{-1.8}$	$0.65^{+0.08}_{-0.07}$	2300
GW190805_211137	$80.1^{+22.5}_{-16.1}$	$33.5^{+10.1}_{-7.0}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.35^{+0.30}_{-0.36}$	$5.31^{+4.10}_{-2.95}$	$0.82^{+0.48}_{-0.40}$	$75.8^{+21.2}_{-15.3}$	$0.81^{+0.09}_{-0.15}$	3900
GW190916_200658	$68.9^{+21.0}_{-14.0}$	$27.3^{+9.3}_{-5.5}$	$44.3^{+21.2}_{-13.3}$	$23.9^{+12.7}_{-10.2}$	$0.18^{+0.33}_{-0.29}$	$4.46^{+3.79}_{-2.52}$	$0.71^{+0.46}_{-0.36}$	$65.7^{+19.8}_{-13.4}$	$0.73^{+0.14}_{-0.23}$	4500
GW190917_114630	$11.4^{+3.0}_{-2.9}$	$3.7^{+0.2}_{-0.2}$	$9.3^{+3.4}_{-4.4}$	$2.1^{+1.5}_{-0.5}$	$-0.11^{+0.24}_{-0.49}$	$0.72^{+0.34}_{-0.31}$	$0.15^{+0.06}_{-0.06}$	$11.2^{+3.0}_{-2.9}$	$0.42^{+0.12}_{-0.06}$	2100
GW190925_232845	$37.0^{+3.8}_{-2.6}$	$15.8^{+1.1}_{-1.0}$	$21.2^{+6.9}_{-3.1}$	$15.6^{+2.6}_{-3.6}$	$0.11^{+0.17}_{-0.14}$	$0.93^{+0.38}_{-0.35}$	$0.19^{+0.07}_{-0.07}$	$35.2^{+3.8}_{-2.4}$	$0.72^{+0.07}_{-0.06}$	1200
GW190926_050336	$62.9^{+22.7}_{-11.9}$	$25.6^{+8.8}_{-5.3}$	$39.8^{+20.6}_{-11.1}$	$23.2^{+10.8}_{-9.7}$	$-0.04^{+0.28}_{-0.33}$	$3.78^{+3.17}_{-2.00}$	$0.62^{+0.40}_{-0.29}$	$60.5^{+21.8}_{-11.6}$	$0.65^{+0.14}_{-0.19}$	2500

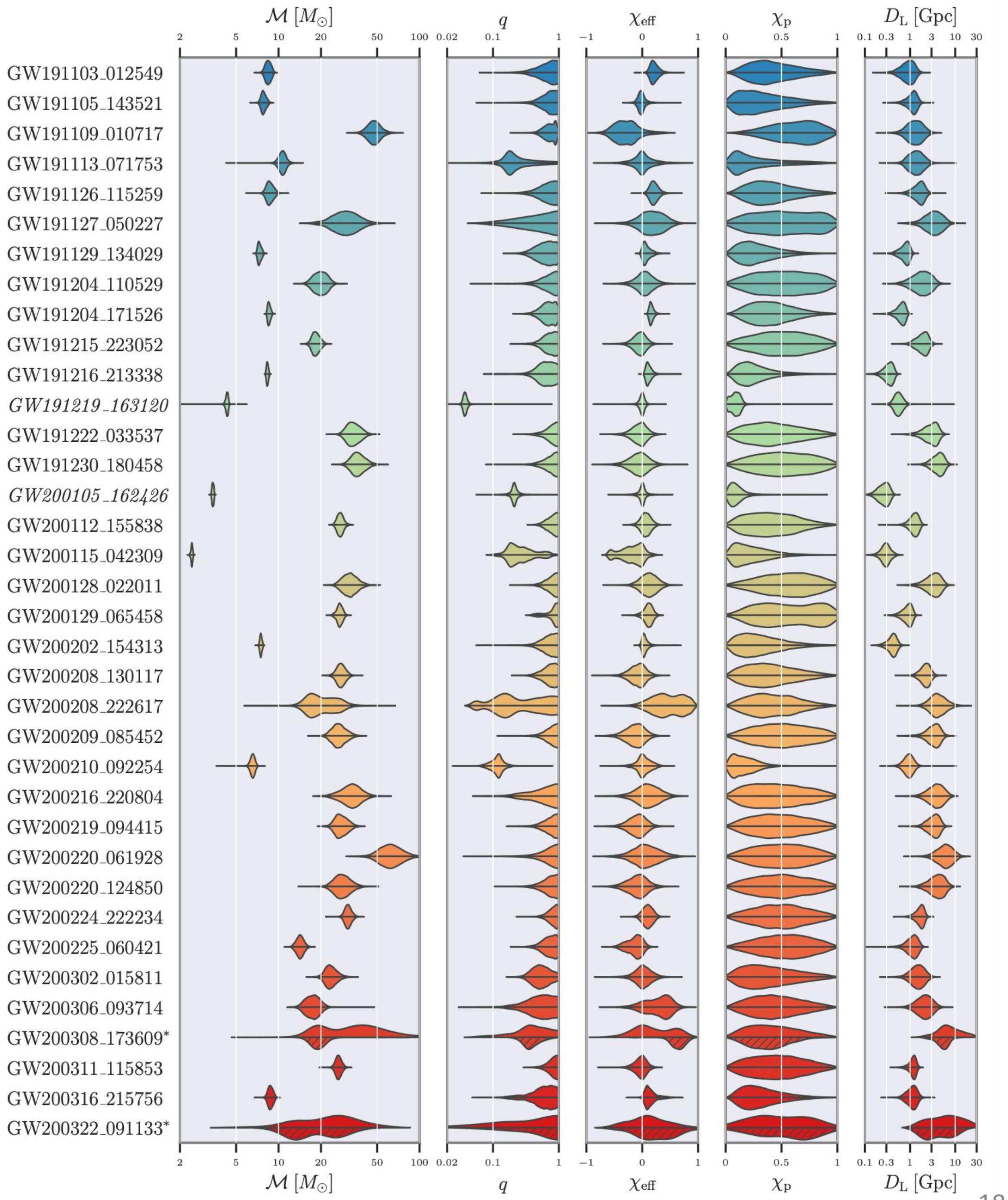
- 1201 marginal candidates passing a false-alarm rate threshold of 2 per day arXiv.org > gr-qc > arXiv:2111.03606

General Relativity and Quantum Cosmology

[Submitted on 5 Nov 2021]

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

- **<u>35 new events</u>** with p_{astro}>0.5
- again, mostly BBHs with similar masses and low spins
  - some more with unequal masses and/or nonzero spins
  - new high-mass events but not quite rivaling GW190521
  - approaching z~1
  - all analysed with multiple updated waveforms, including UIB's IMRPhenoMXPHM
- no BNS
- NSBHs:
  - GW200115_042309 still loud and clear
  - GW200105_162426 *not* included (p_{astro}<0.5) but still "candidate of interest"
  - GW191219_163120: some uncertainty in p_{astro}
  - GW200210_092254: borderline NSBH/BBH
  - We're *sure* we've found *some* of them, but they are tricky beasts to analyse and categorise!



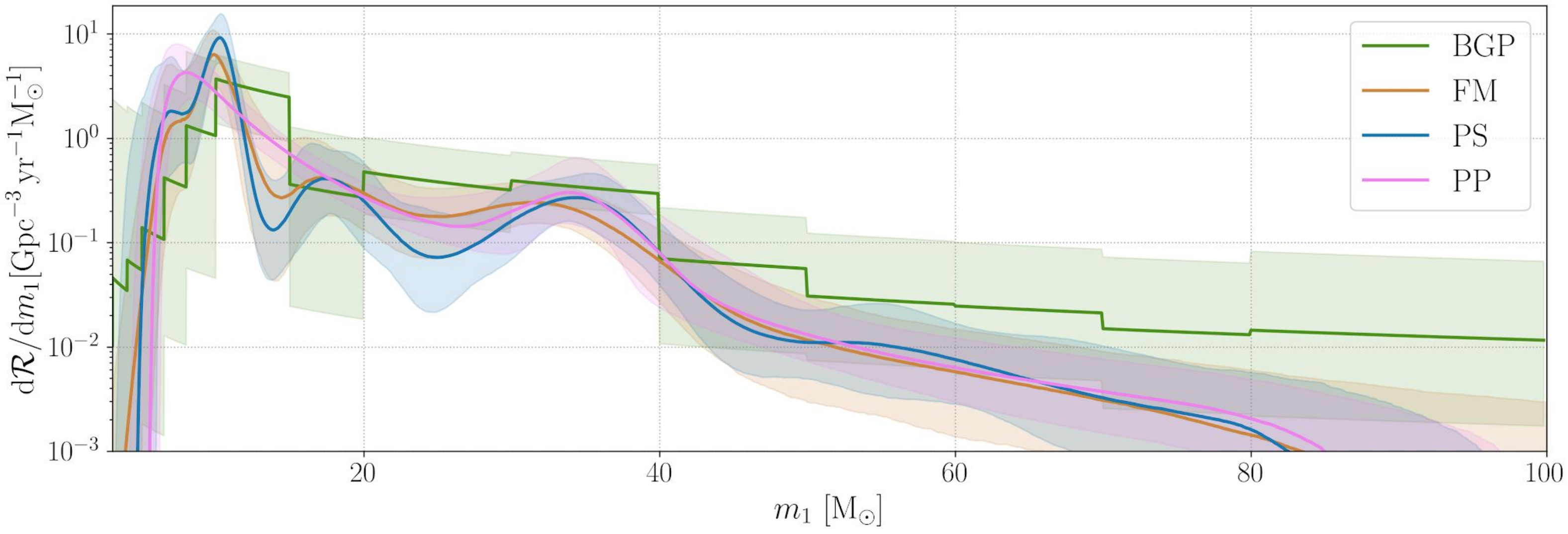
several events analysed by UIB group on MareNostrum cluster

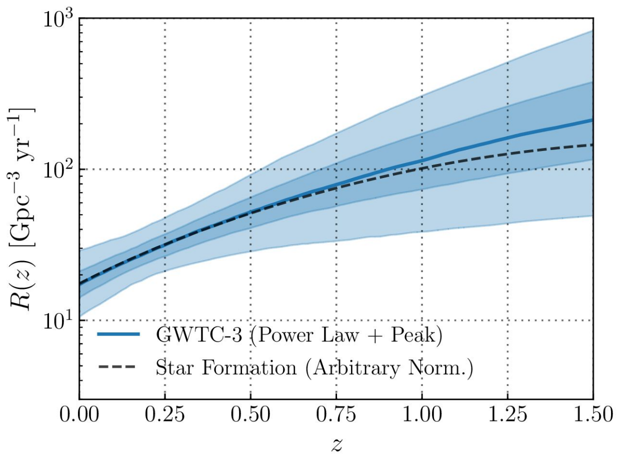
BBH, BNS, and NSBH population inference from GWTC-3 (O1,O2,O3a+O3b)

- In just 5 years we've come from a singular first detection to population astronomy.
- New paper supersedes previous results, e.g. ApJL913:L7 (2021).
- hierarchical Bayesian inference over various mass, spin and redshift distributions
- BBH population increasingly constrained, BNS and NSBH still very low number statistics

LVK arXiv:2111.03634

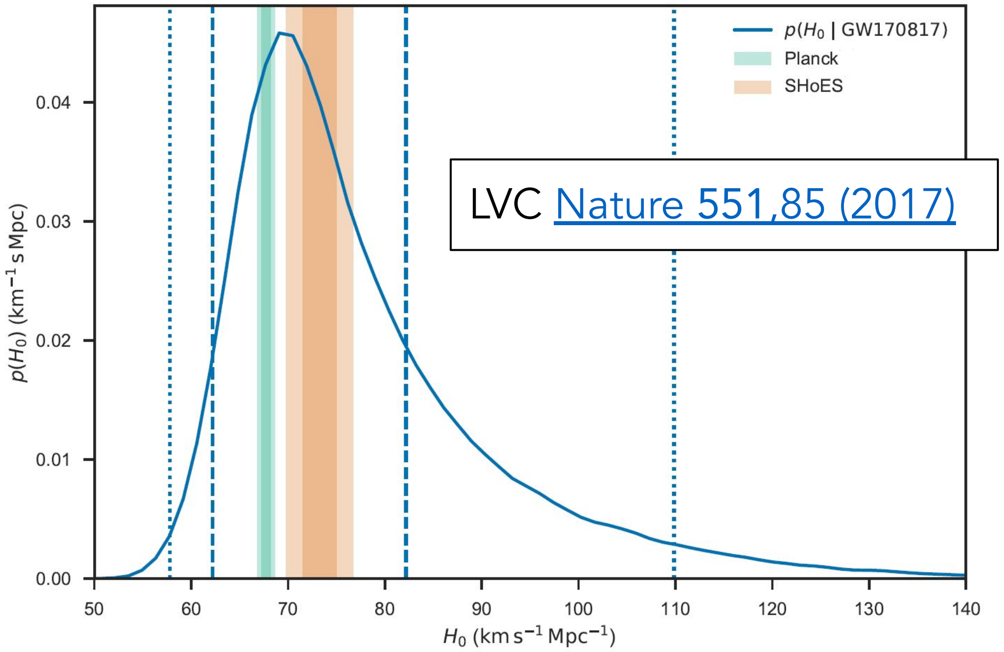
	BNS	NSBH	BBH	NS-Gap	BBH-gap	Full
	$m_1 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 50]M_\odot$	$m_1 \in [2.5, 100]M_\odot$	$m_1 \in [2.5, 5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$	$m_1 \in [1, 100]M_\odot$
	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [2.5, 100]M_\odot$	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [2.5, 5]M_\odot$	$m_2 \in [1, 100]M_\odot$
PDB (pair)	960^{+1700}_{-700}	59^{+81}_{-38}	25^{+10}_{-7}	41^{+69}_{-30}	$9.3^{+19.0}_{-7.6}$	1100^{+1700}_{-750}
PDB (ind)	250^{+640}_{-200}	170^{+150}_{-89}	22^{+9}_{-6}	29^{+55}_{-23}	10^{+15}_{-8}	470^{+830}_{-300}
MS	470^{+1400}_{-410}	57^{+120}_{-42}	42^{+88}_{-20}	$3.7^{+20}_{-3.4}$	$0.17^{+56}_{-0.16}$	650^{+1600}_{-460}
BGP	99^{+260}_{-86}	32^{+62}_{-25}	33^{+16}_{-10}	$2.1^{+33}_{-2.1}$	$5.1^{+12}_{-4.0}$	180^{+260}_{-110}
MERGED	13 – 1900	7.4 – 320	16 – 130	0.029 – 84	0.01 – 56	71 – 2200



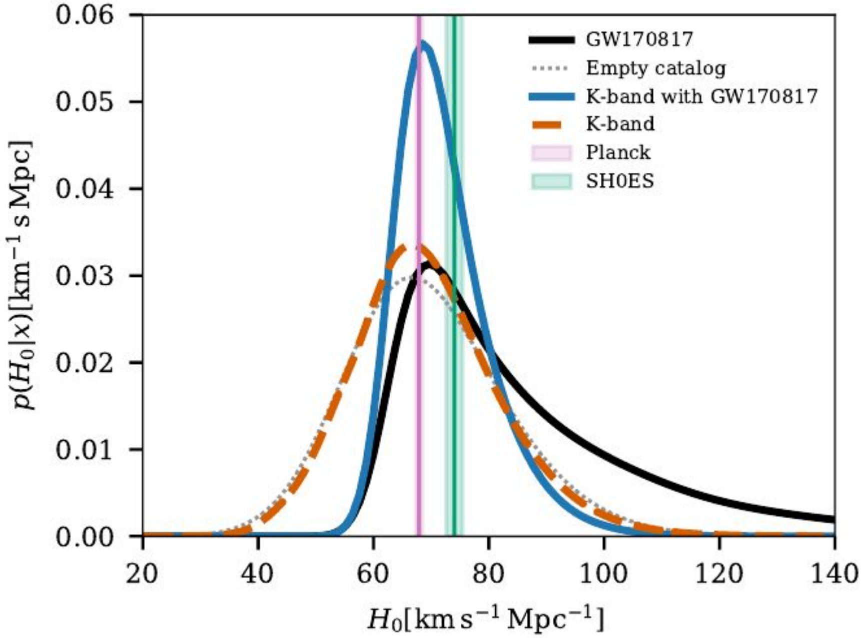


GW cosmology

- CBCs are "standard sirens": can measure luminosity distance directly from signal waveform
- distance *and* redshift → measure Hubble constant
- best constraints from "bright sirens" like GW170817 with electromagnetic counterpart for redshift
- statistical "dark sirens" approach for GWs without counterpart:
    - compare with galaxy catalogs
    - jointly infer cosmology with population model

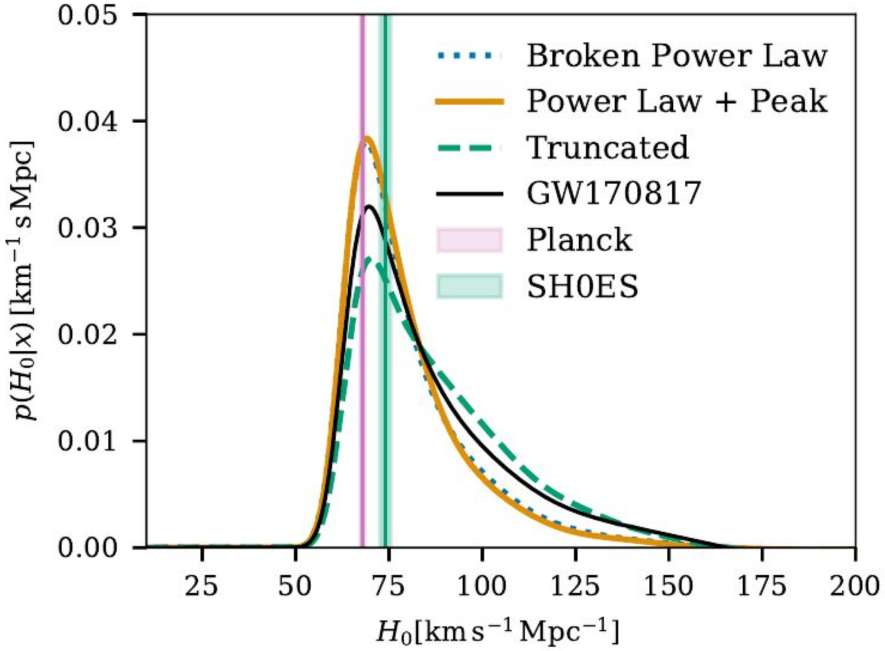


LVC Nature 551,85 (2017)

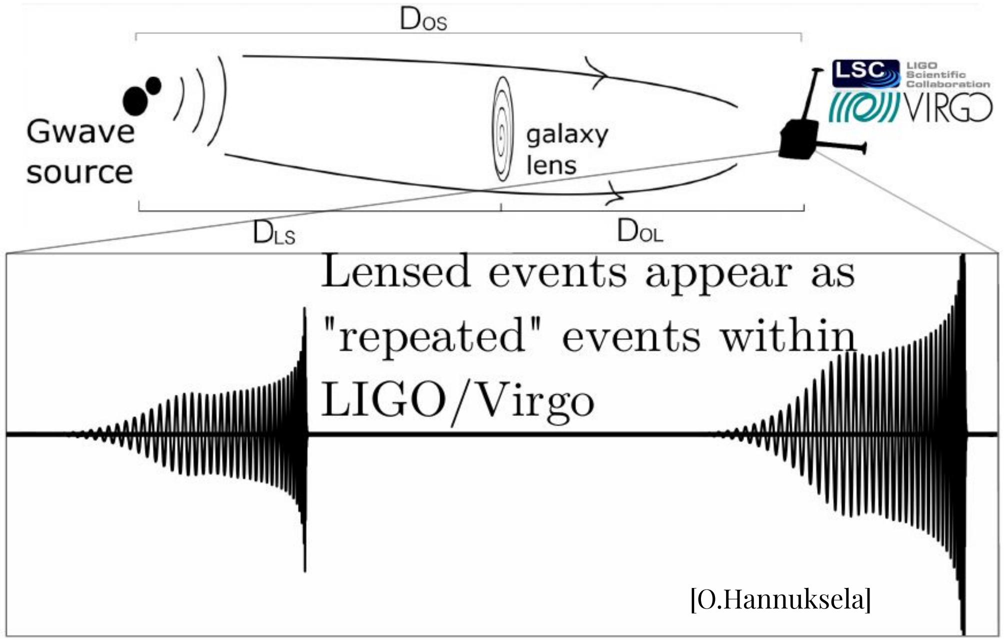


latest results based on GWTC-3 events:

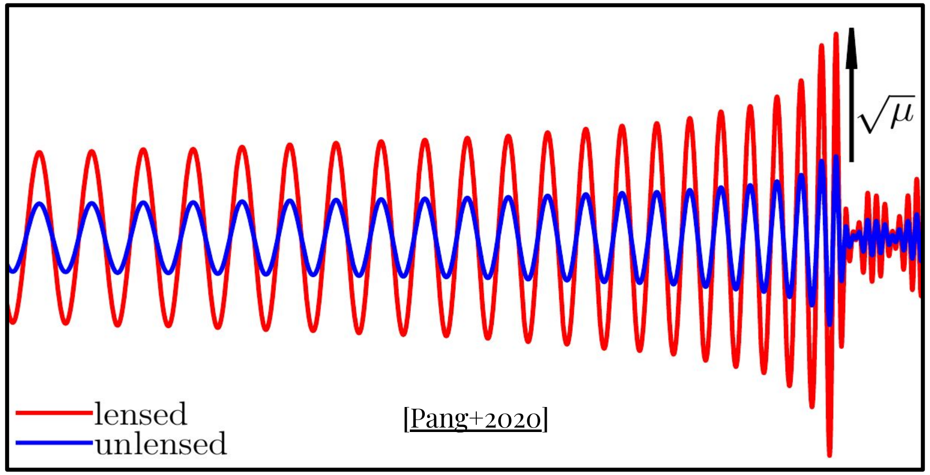
LVK arXiv:2111.03634



Are any of our detections gravitationally lensed?

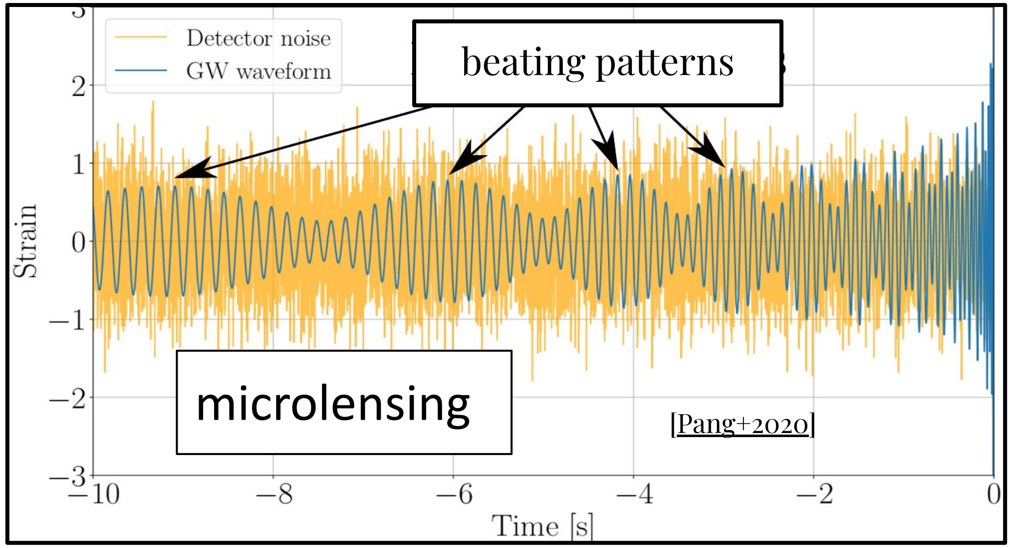


strong lensing



LVC arxiv:2105.06384

- search for magnification, multiple images, and microlensing signatures on O3a events
- no compelling evidence for gravitational lensing



lensing results from O3b (GWTC-3): stay tuned

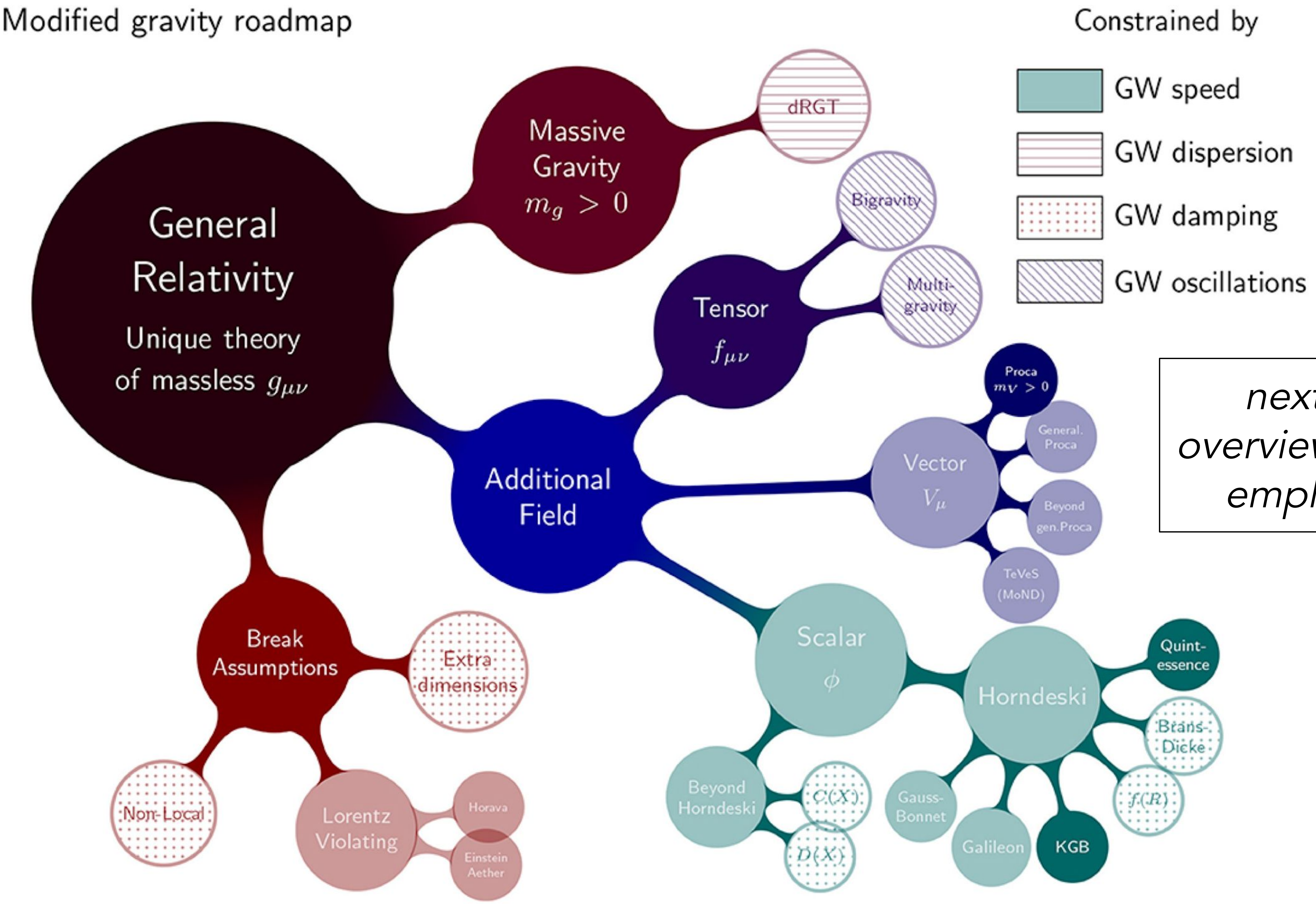
Search for deviations from general relativity

Learning about gravity with LIGO and Virgo – results from first half of O3 (GWTC-2)
LVC PRD103,122002 (2021)

Observations

- Residuals from best-fit waveforms consistent with noise ✓
- Consistency of parameters inferred from inspiral and merger-ringdown phases ✓
- No evidence for deviations from the PN coefficients predicted by GR ✓
- Consistency with no dispersion of GWs and massless graviton ✓
- BH spin-induced quadrupole moments are consistent with their Kerr values ✓
- Ringdown frequencies and damping times consistent with GR ✓
- No detection of echoes ✓
- No evidence for pure scalar or pure vector polarizations ✓
- New bound on mass of graviton: $m_g \leq 1.76 \times 10^{-23} \mathrm{eV/c^2}$

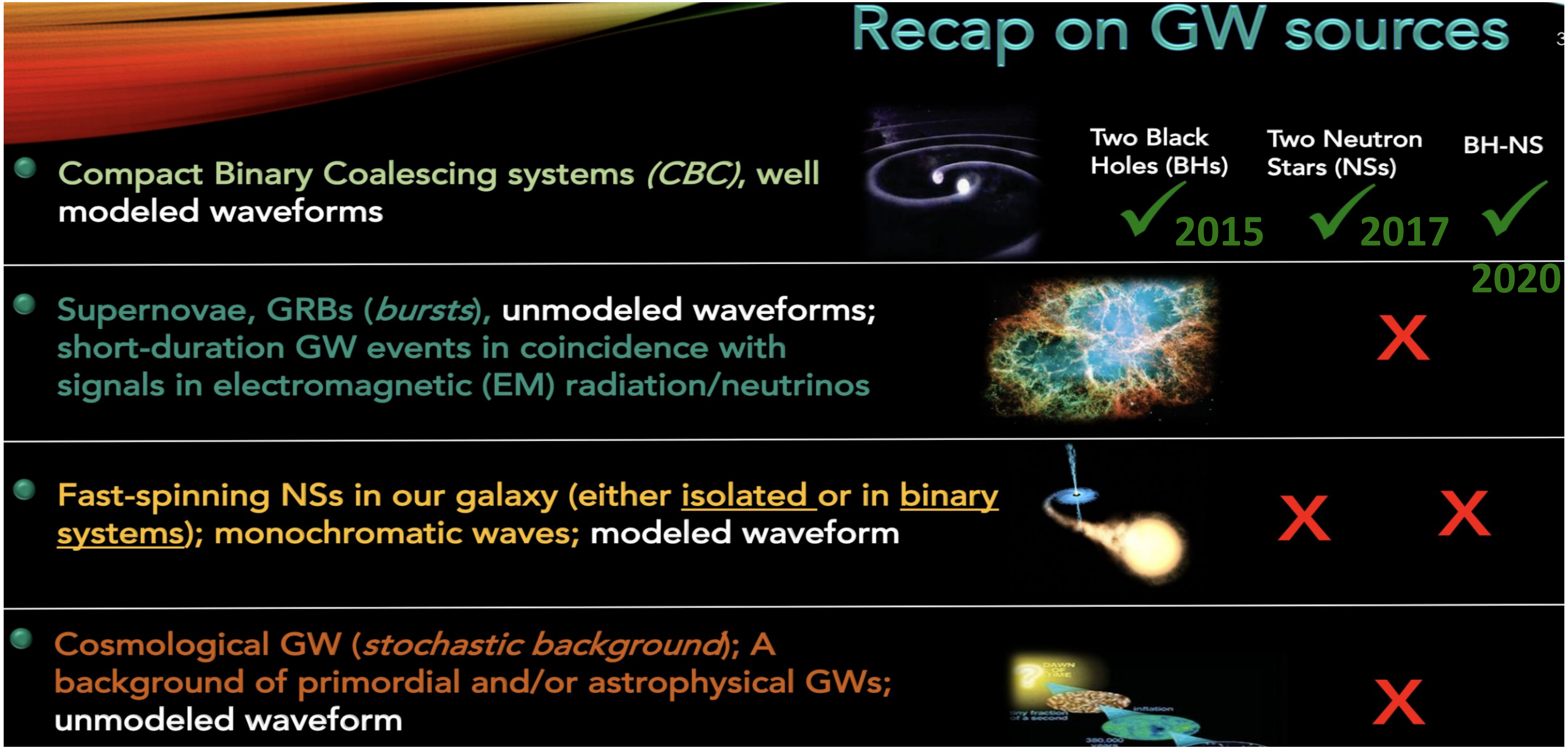
testing-GR results from O3b (GWTC-3): stay tuned



next few slides: overview of some tests employed by LVK

Ezquiaga & Zumalacárregui 18

other LVC/LVK searches:
GWs beyond compact binary coalescence

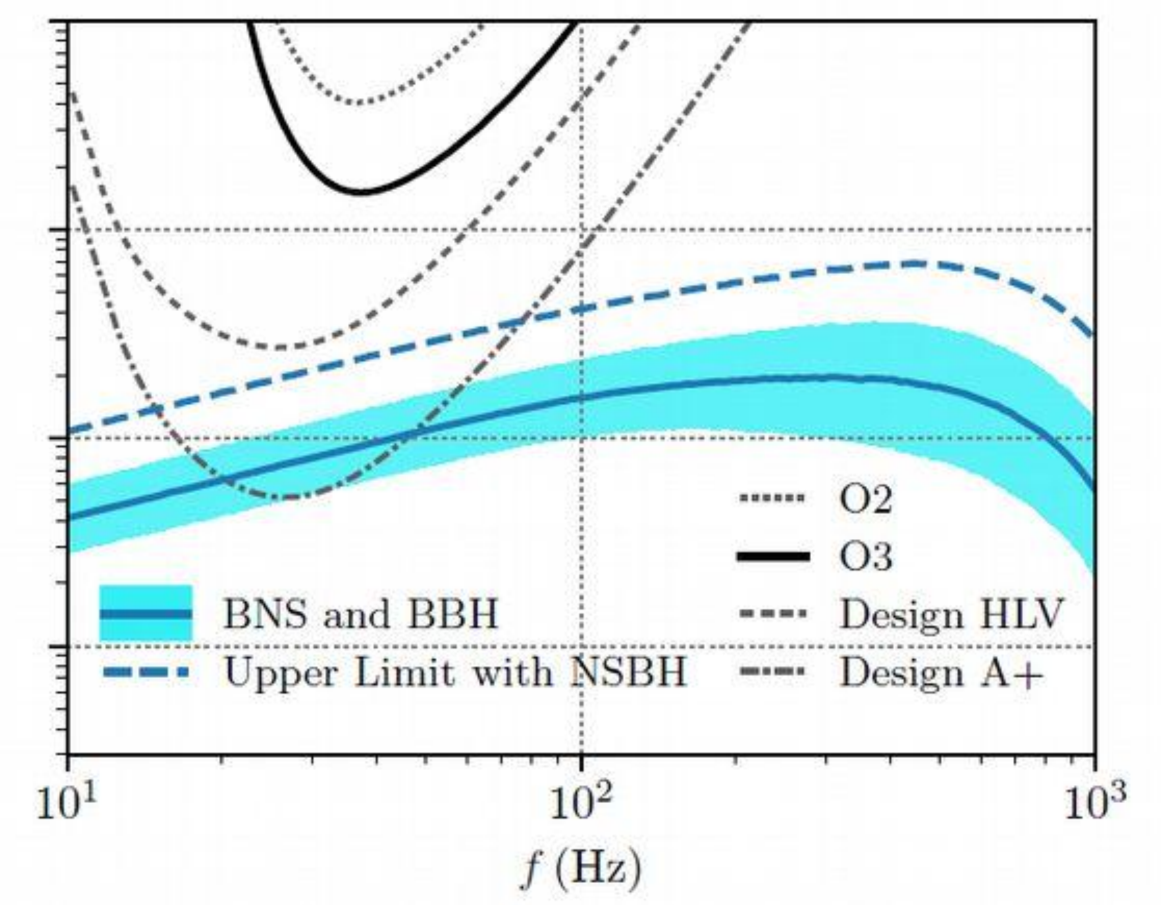


Searches for stochastic GW backgrounds

PRD104,022004 (2021) / PRD104,022005 (2021) / PRL126,241102 (2021) / arXiv:2110.09834

Searches for astrophysical and cosmological backgrounds, isotropic or directional; for cosmic strings, and any unmodelled long-duration signals:

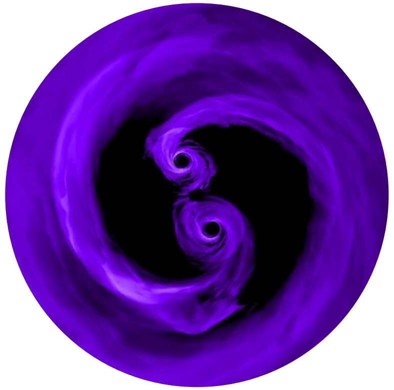
- so far no significant evidence
- O3 upper limits much improved, e.g. factor ~6 below previous bounds for a flat isotropic background
- cosmological backgrounds: probes of early universe high-energy physics



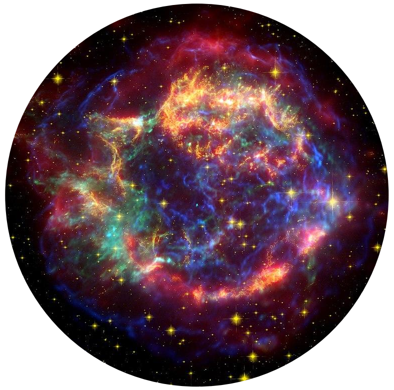
Isotropic background search: fiducial model predictions for the GWB from BBHs, BNSs, and NSBHs, along with current and projected sensitivity curves

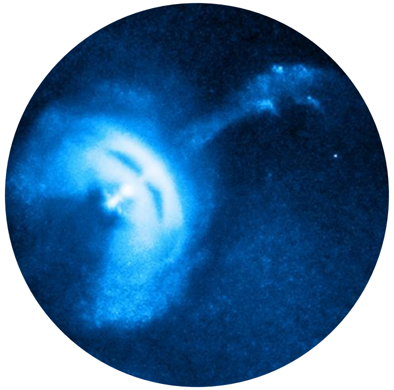
unmodelled bursts of GWs

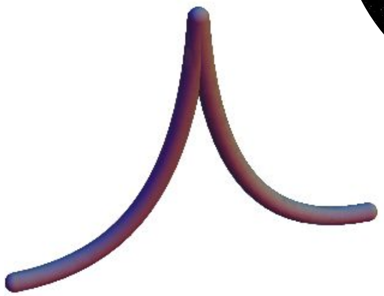
- Could include BBHs, allowing for deviations from standard waveform models.

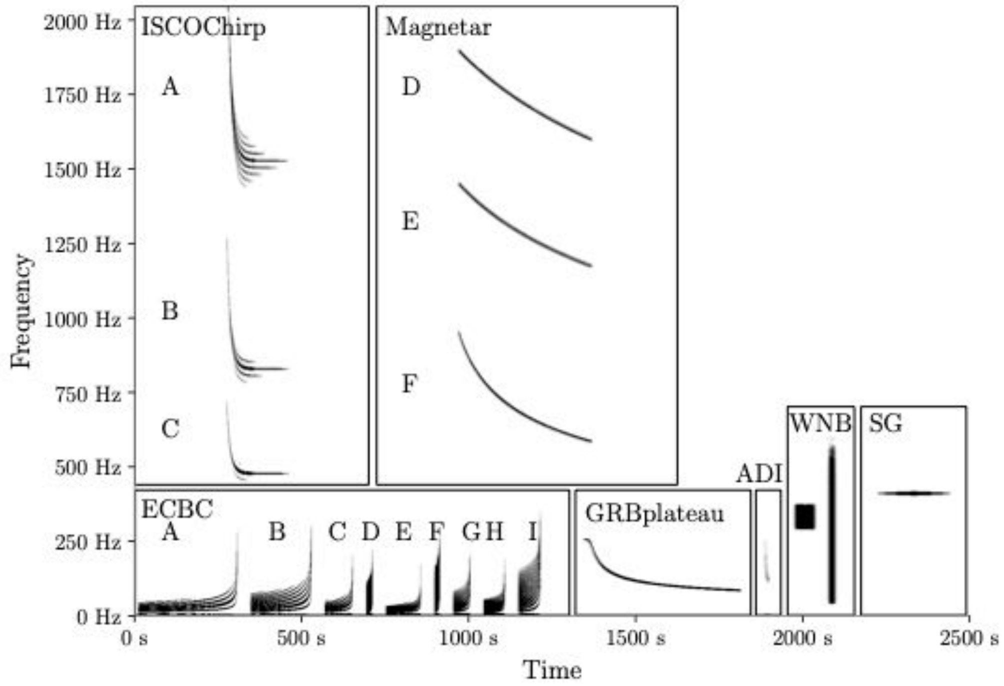


- other types of sources: CCSNe, cosmic strings, pulsar glitches, …









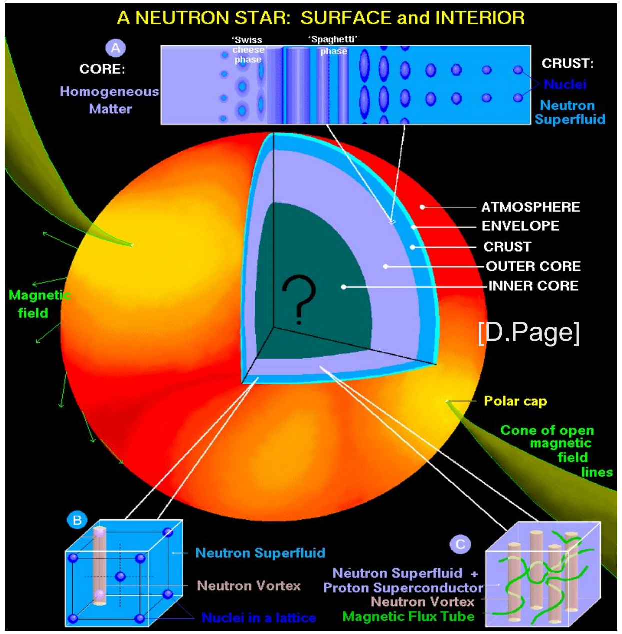
LVK O3 searches so far:

- short transients (<1s) arXiv:2107.03701
- long transients (<1000s) PRD104,102001 (2021)
- IMBH binaries arXiv:2105.15120
- cosmic strings PRL126,241102 (2021)

- No new candidates found apart from CBC sources.

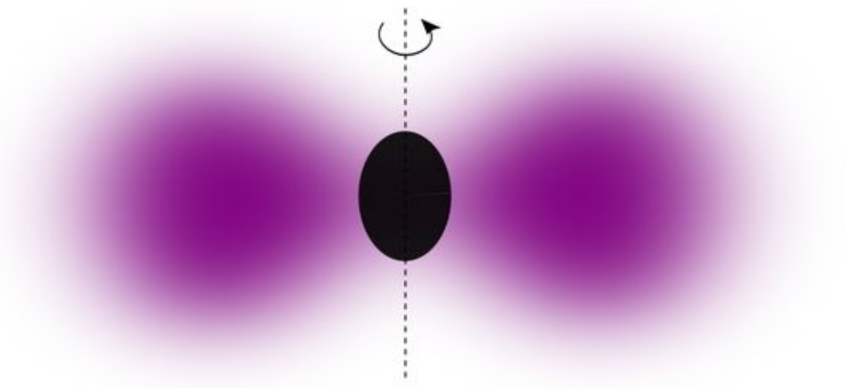
Continuous Gravitational Waves

- prime targets: neutron stars, probing high-density QCD
- expected signals extremely weak, but can integrate over long time



$$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

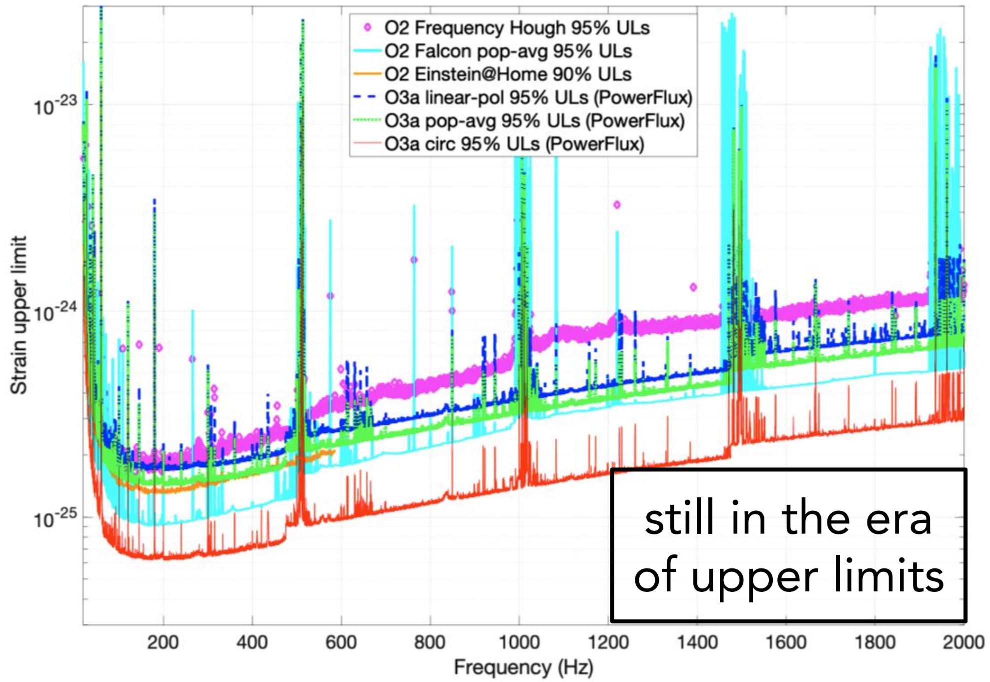
- also: boson clouds around spinning BHs



[KIPAC Stanford / X.Huang / M. Baryakhtar]

LVC/LVK O3 searches so far, no detections:

- targeted searches for Crab, Vela, MSPs ApJL902:L21 (2020)
- J0537-6190 ApJL913:L27 (2021), arxiv:2104.14417
- supernova remnants ApJ921:80 (2021)
- all-sky search for isolated NSs arXiv:2107.00600
- all-sky search for NSs in binaries PRD103,064017 (2021)
- AMXPs arXiv:2109.09255

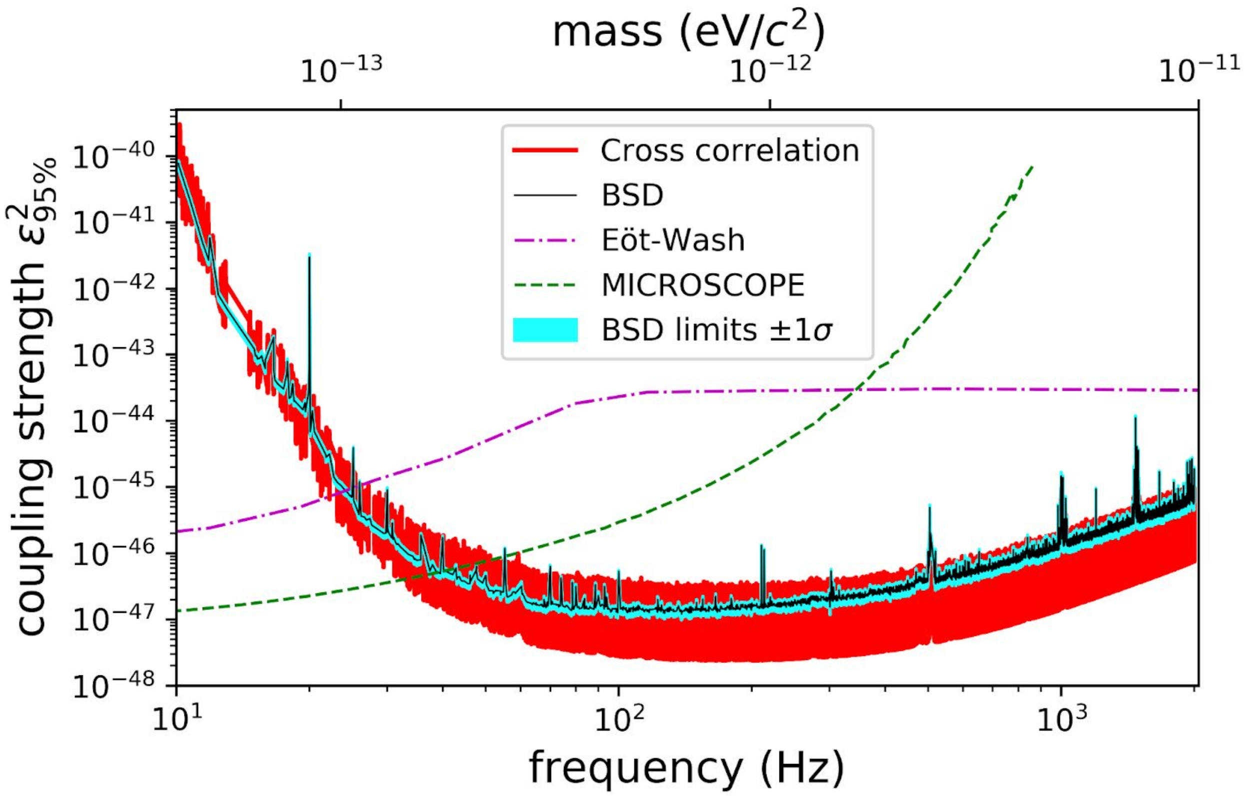


still in the era of upper limits

CWs and fundamental physics: constraints on dark photon dark matter using O3

LVK arxiv:2105.13085

- Dark matter could interact directly with detector mirrors via dark photons.
- monochromatic signals, frequency depending on particle mass.
- explored dark photon mass range: $10^{-14} – 10^{-11}$ eV/c^2
- improvement of O(100) w.r.t. dark matter direct detection experiments in the range [2 – 4] 10^{-13} eV/c^2

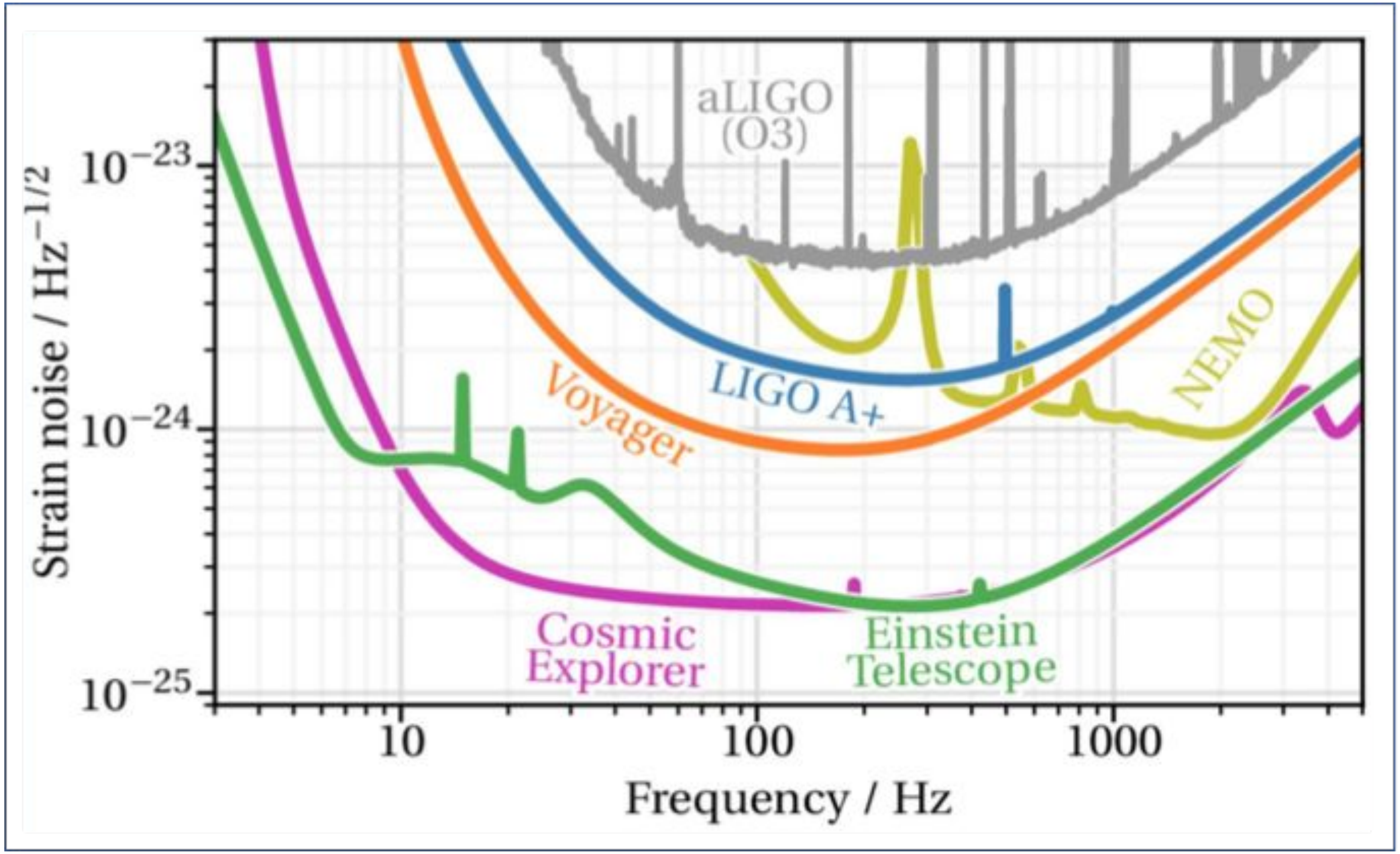


open data from all of O1, O2, O3:

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

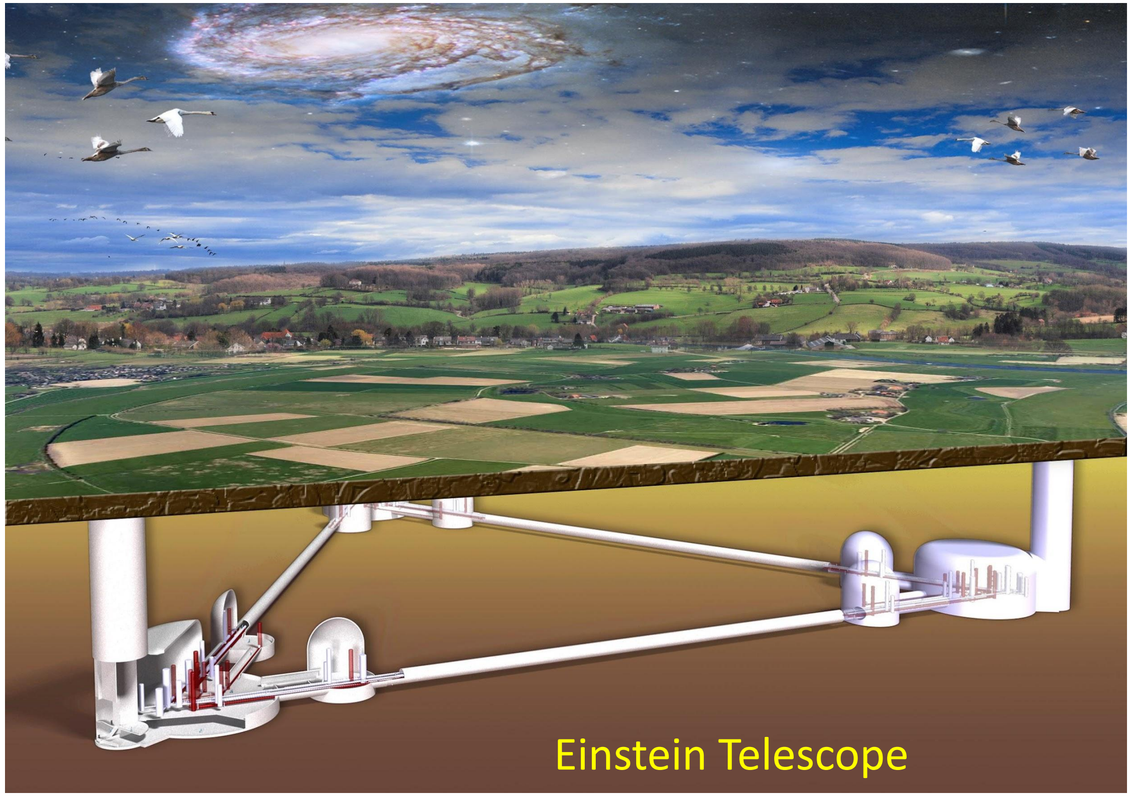
- bulk data download
- per-event 1-hour time-series data
- pointers to papers, data behind figures, posterior samples, …
- pointers to analysis codes
- workshop materials

What does the future hold?



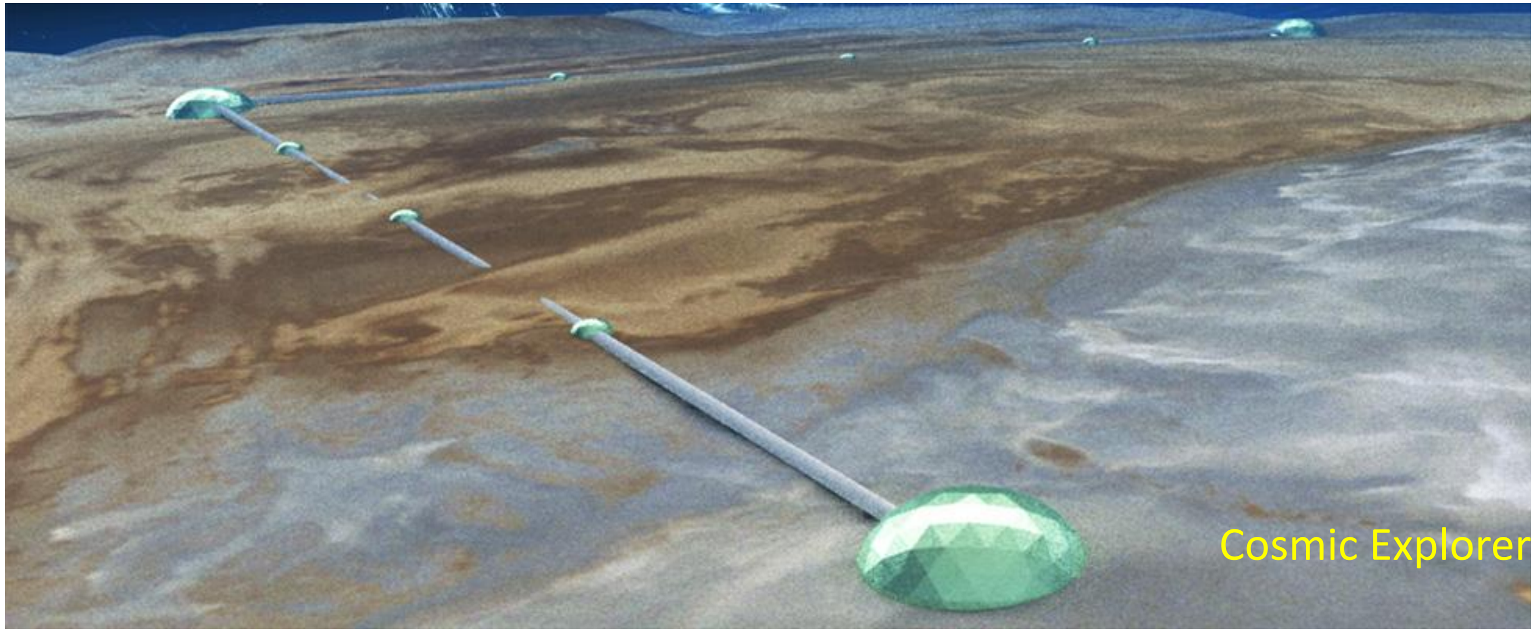
second-generation instruments (2G) → next-generation instruments (3G)

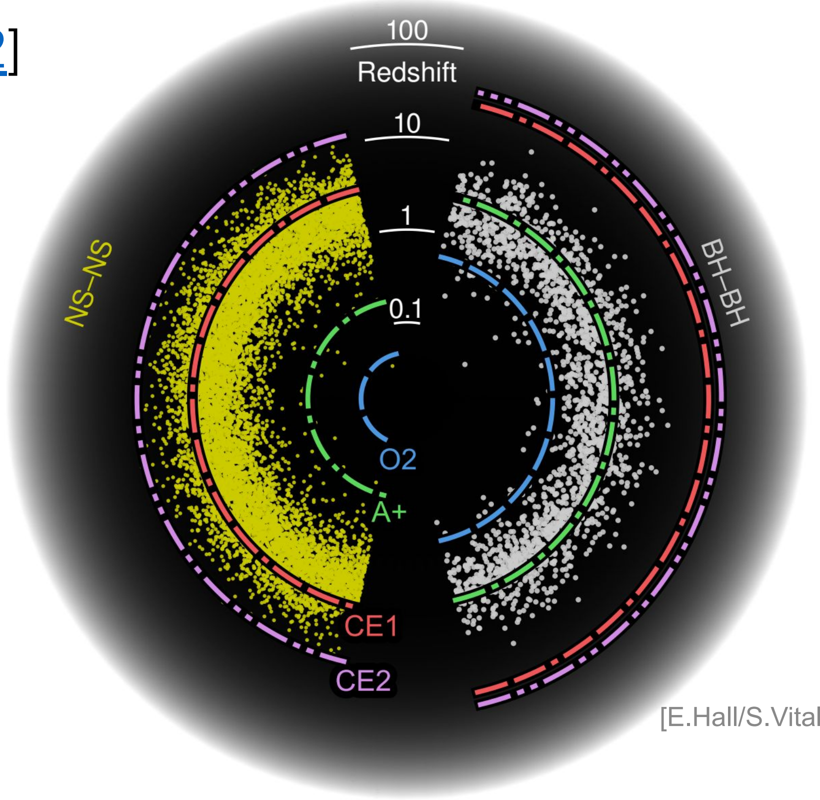
third-generation GW detectors



Einstein Telescope placed on Europe's ESFRI Roadmap on 2021-06-30
ET Consortium Agreement signed by 41 institutions, coordinated by INFN and Nikhef

Cosmic Explorer conceptual design study submitted to NSF in the USA
[arXiv:2109.09882]



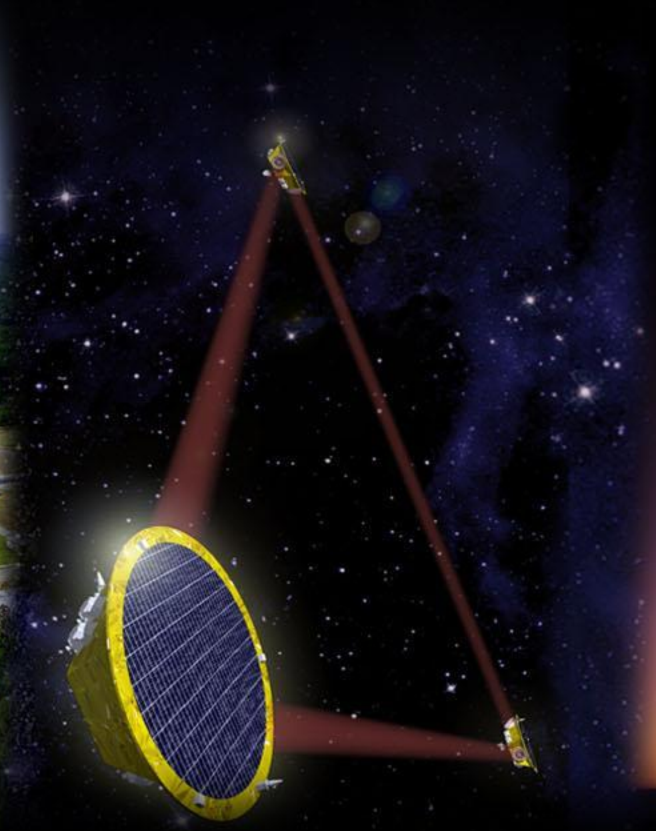


[E.Hall/S.Vitale/MIT]

Gravitational Wave Periods

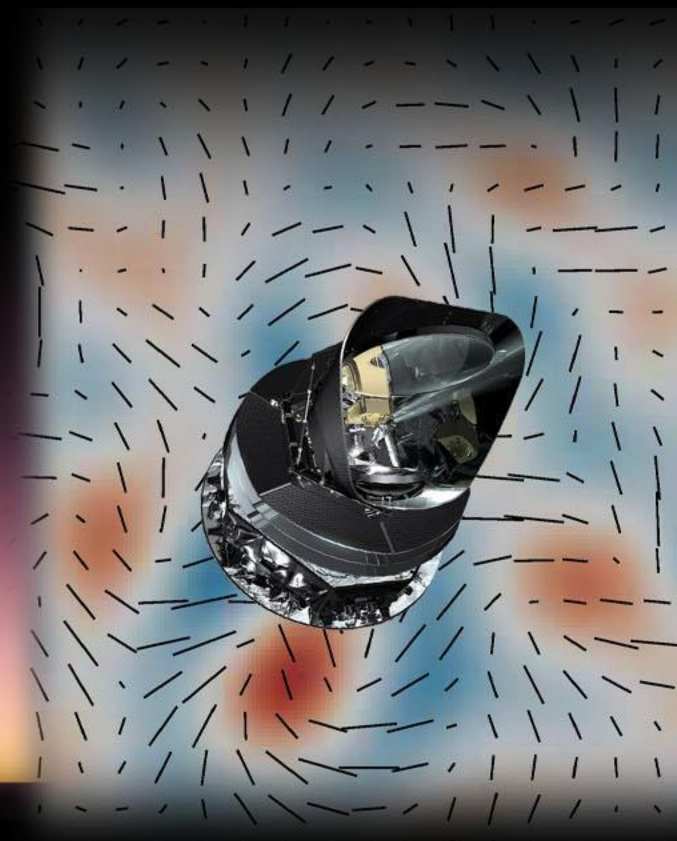
Milliseconds

Minutes to Hours



Years to Decades

Billions of Years



LISA, PTAs and CMB observations complement ground-based GW detectors at longer wavelengths

Summary and Outlook

- O3 detector sensitivities significantly better than O1/O2
- as of last week, 90 detections published; many BBHs, some BNS and NS-BH
- waveform modelling is crucial for these results, and at UIB we are at the forefront of it

- For a quick overview of all LVC/LVK papers, see our **Science Summaries** available in multiple languages: https://www.ligo.org/science/outreach.php
- **O1, O2 & O3a+b bulk data** have been released: https://www.gw-openscience.org/data/

- O4 currently planned to start December 2022
- If you'd like to receive alerts about new GW detections in O4, see the **Public Alerts User Guide** https://emfollow.docs.ligo.org/userguide/ and the app from chirp.sr.bham.ac.uk

- Firm plans for 3G (third-generation) ground-based GW detectors + LISA; funding committed for ET+LISA!
- Order-of-magnitude better strain sensitivities are feasible, and the science case is very strong.

Acknowledgments

D. Keitel is supported by the Spanish Ministry of Science and Innovation (ref. BEAGAL 18/00148) and cofinanced by the Universitat de les Illes Balears. This work is supported by European Union FEDER funds; the Spanish Ministry of Science and Innovation and the Spanish Agencia Estatal de Investigación grants PID2019-106416GB-I00/MCIN/AEI/10.13039/501100011033, RED2018-102661-T, RED2018-102573-E, FPA2017-90566-REDC; the Comunitat Autònoma de les Illes Balears through the Direcció General de Política Universitària i Recerca with funds from the Tourist Stay Tax Law ITS 2017-006 (PRD2018/24); the Conselleria de Fons Europeus, Universitat i Cultura del Govern de les Illes Balears; the Generalitat Valenciana (PROMETEO/2019/071); and EU COST Actions CA18108, CA17137, CA16214, and CA16104.

See https://dcc.ligo.org/P2100218/public for LVK acknowledgments.

BACKUP SLIDES

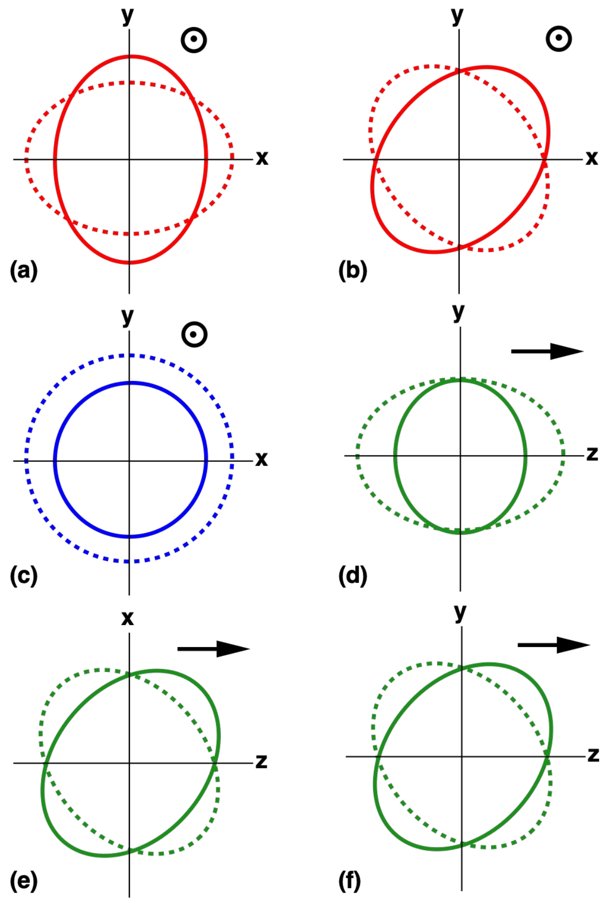
Polarization tests

- GR predicts only two tensorial polarizations of GWs
- generic metric theories of gravity can have up to 6 polarisation modes:
  2 tensor, 2 vector, 2 scalar
- Null-stream approach: create combinations of data outputs which should be consistent with noise under a given polarization hypothesis (Gürsel&Tinto 89, Chatterji+ 06)

- Typically, M+1 detectors needed to constrain M polarization modes independently
  —> LIGO India and KAGRA will be key additions!

- Waveform-agnostic approaches suggested to test mixed polarizations (Chatziioannou + 21, Wong + 21)

Gravitational–Wave Polarization



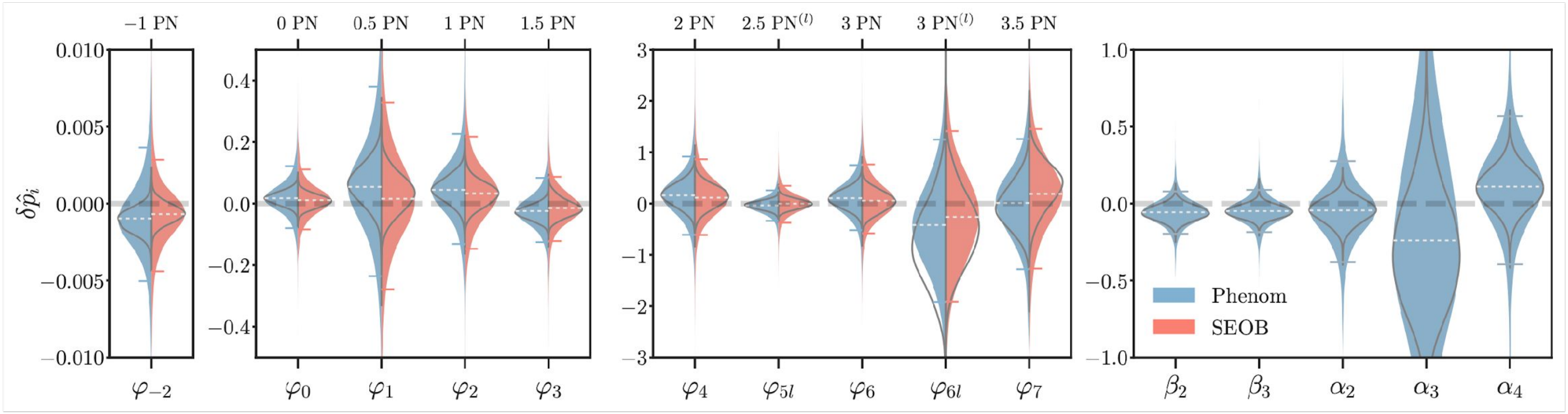
Will, Living Rev. Relativity 17 (2014)

Credit: LIGO-Caltech

Credit: IUCAA

parametrised tests of deviations from GR

- Scarcity of explicit waveforms for specific alternative theories of gravity
- Introduce generic deviations in the inspiral and merger-ringdown phase of BBH waveform models developed under regular GR (Phenom and SEOB model families)
- Coefficients are individually perturbed: not a realistic model of beyond GR waveforms but useful for null tests



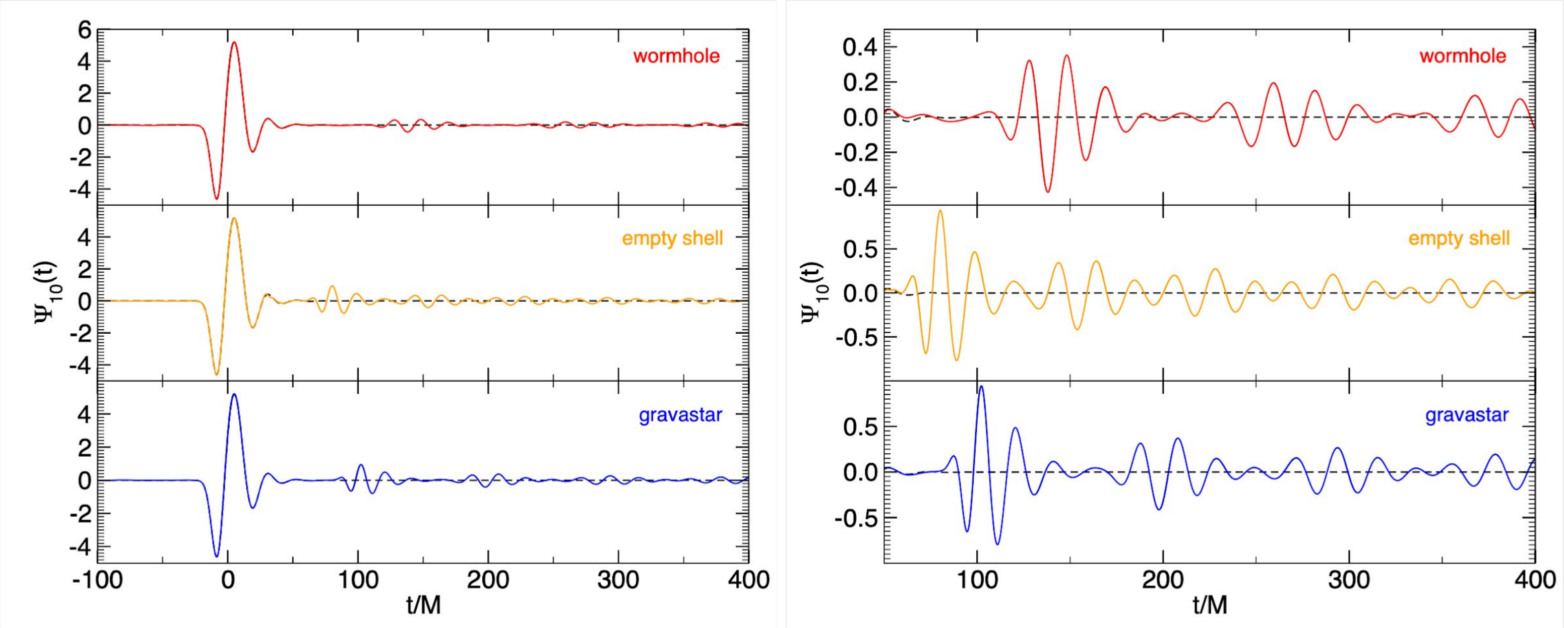
LVC [PRD103,122002 (2021)]
(GWTC-2 events)

echoes from ECOs

- dark particles are hard to detect, but could be easier in the strong-field regime of compact objects
- mergers involving ECOs could be a probe for their existence, non-GR modes could be excited
- If no horizon, then modes can get trapped between potential barrier and light ring and slowly leak out, producing pulses of radiation absent in a true BBH merger.
- can be modelled either in waveform-agnostic way or by adding a "train" of pulses to a BBH template

TABLE X. Results of search for GW echoes. A positive value of the log Bayes factor $\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$ indicates a preference for the IMRE model over the IMR model, while a negative value of the log Bayes factor suggests instead a preference for the IMR model over the IMRE model.

Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$	Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		



Cardoso et al Phys.Rev.D 94 (2016)

LVC PRD103,122002 (2021)
(GWTC-2 events)