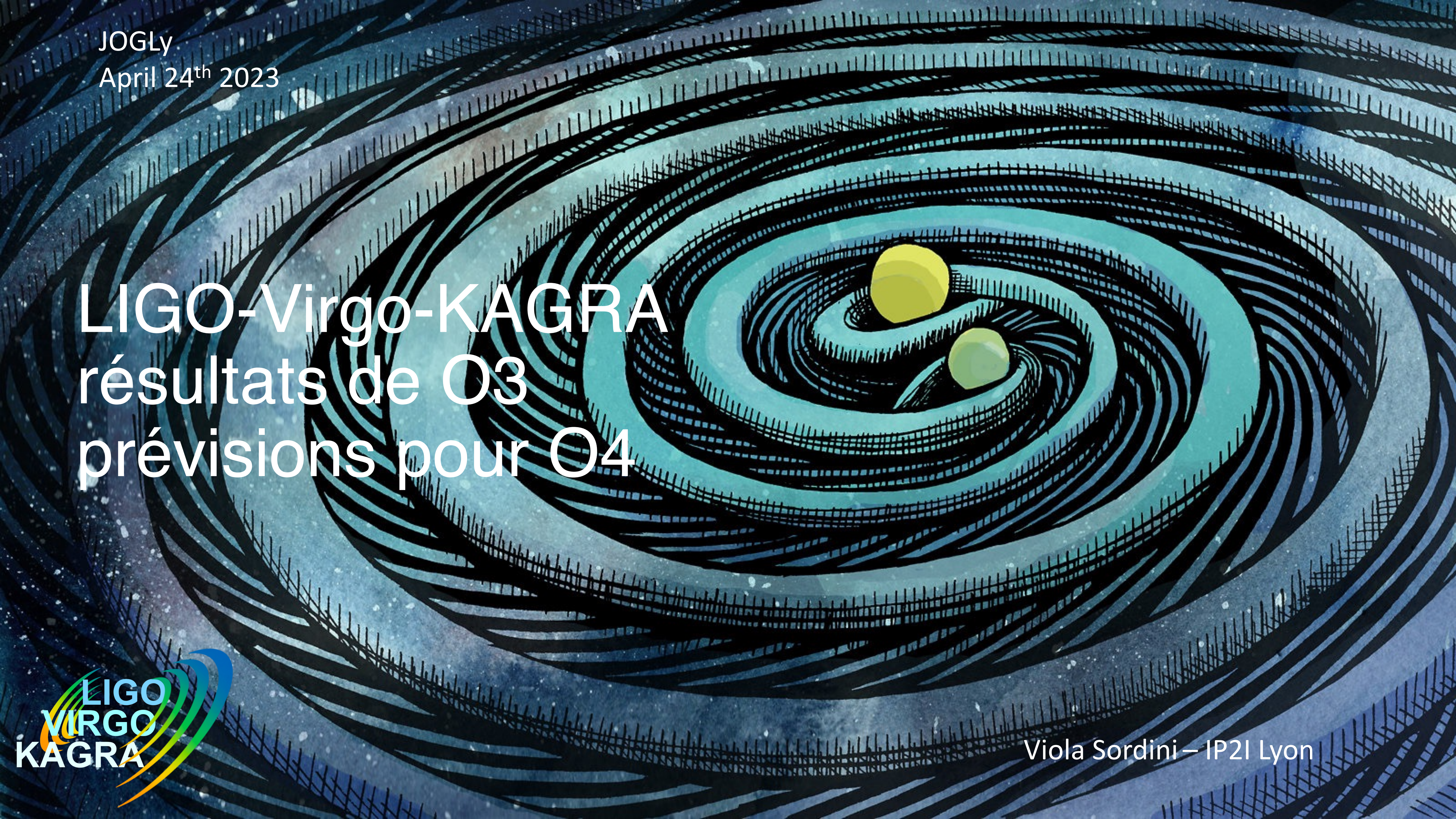


JOGLy
April 24th 2023

LIGO-Virgo-KAGRA résultats de O3 prévisions pour O4

Viola Sordini – IP2I Lyon

Outline for today

1. Introduction to GW and terrestrial interferometers for GW detection

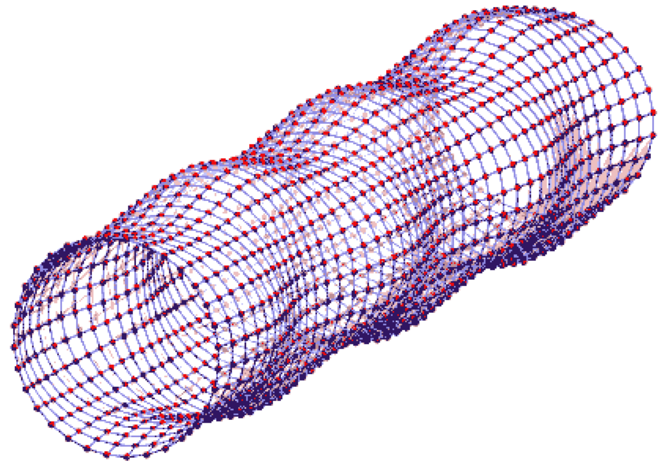
2. Focus on O3 (2019-2020) LIGO-Virgo(-KAGRA) results

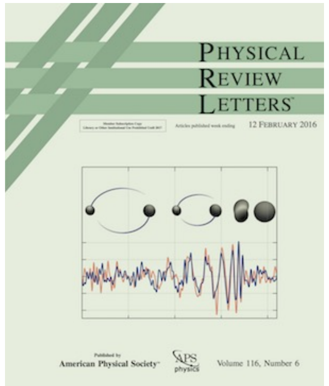
3. (in short) Prospects for O4 (2024-2026) and the future

Gravitational Waves

Ripples in the spacetime metric generated by the acceleration of masses, propagating at the speed of light

- GW cause the the space itself to stretch/compress
- Predicted by Einstein's General Relativity (1916) - first direct observation 2015 (LIGO)
- Probe gravity in unprecedented conditions, new messenger from the Universe
- Amplitude scales with the **inverse of the distance** from the source
- Possible sources of detectable GW are some of the most violent events in the Universe involving massive and compact objects in relativistic regime



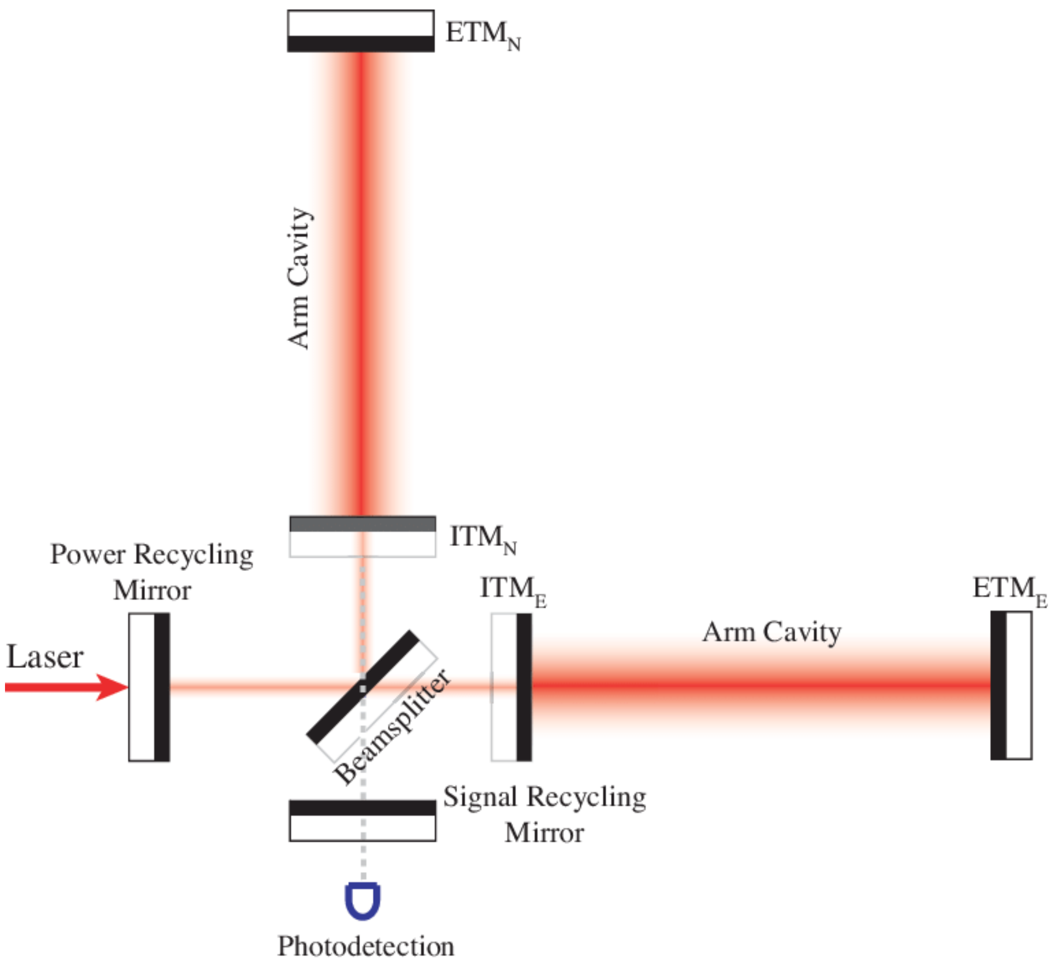


GW terrestrial detectors

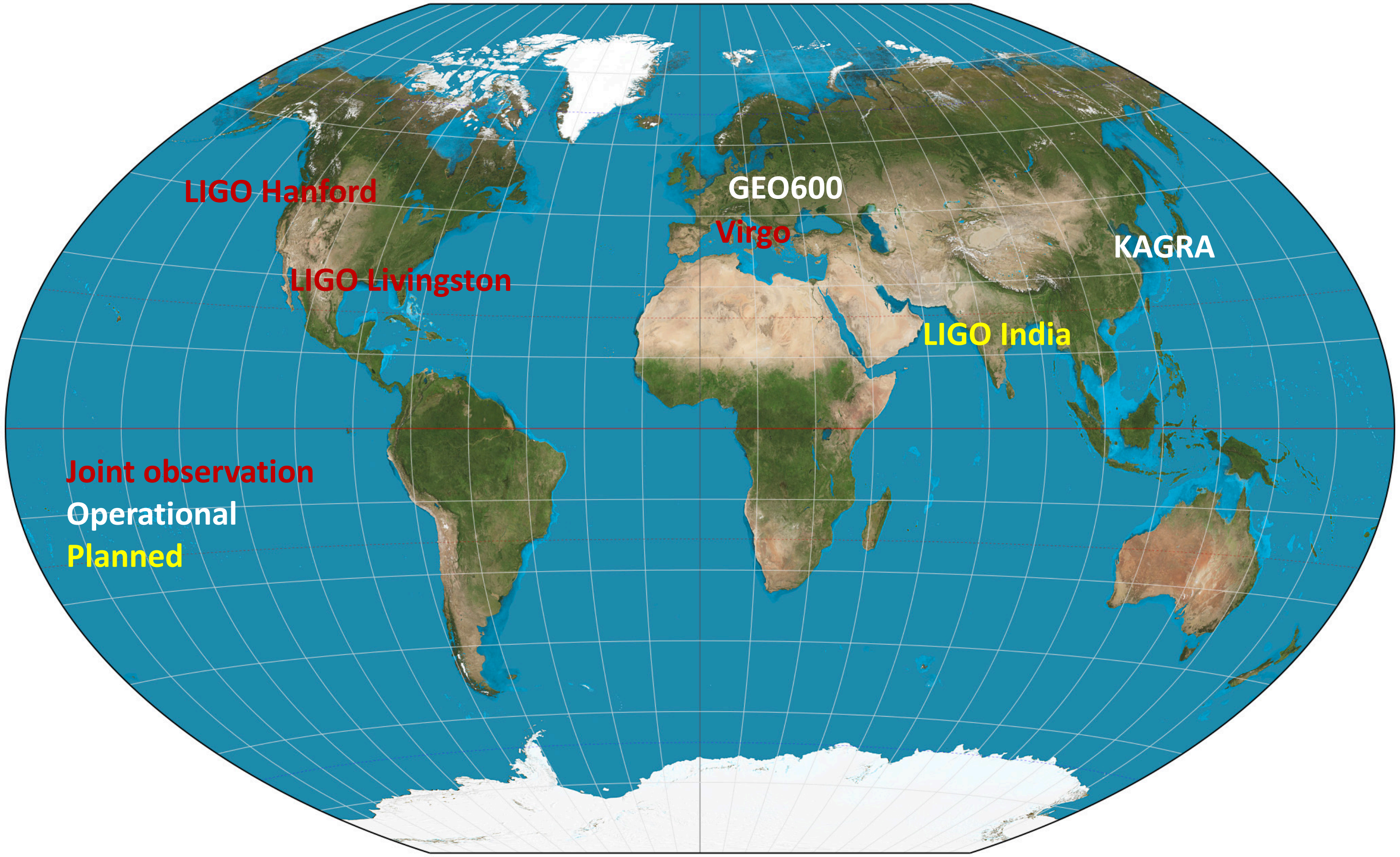
- Michelson interferometers with Fabry-Pérot cavities in the arms, operating on dark fringe
- Amplitude of gravitational waves $h \sim 10^{-21}$
- $\delta L = hL$ → km-long arms
- Observable: h(t) – “strain”

- 1970s first prototypes
- ~1990 LIGO and Virgo proposal

- Sensitive in the ~10Hz – ~1kHz frequency band
- Sky localisation thanks to different positions and orientations



International GW observatory Network - (IGWN)



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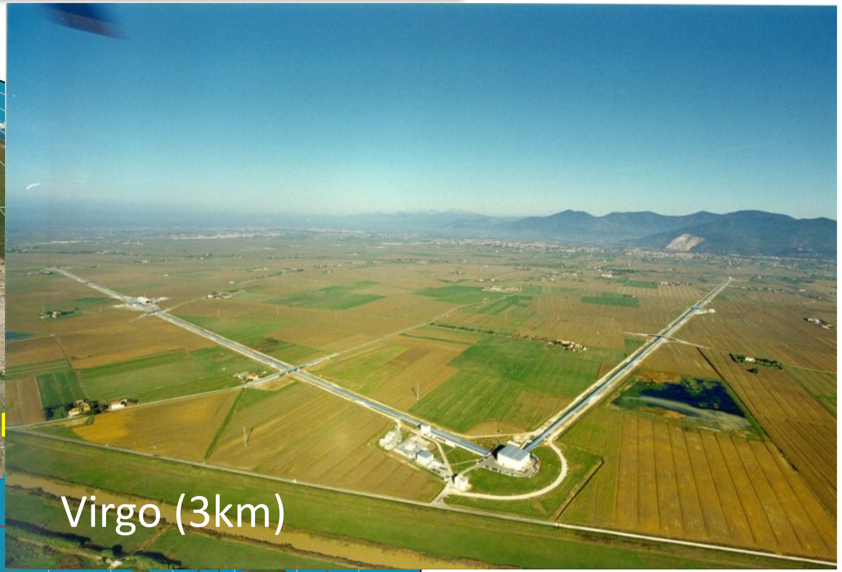
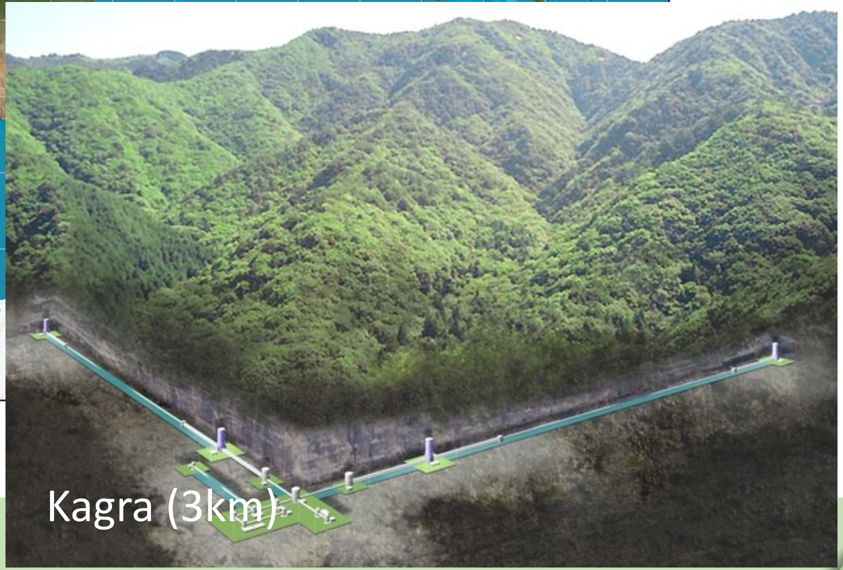
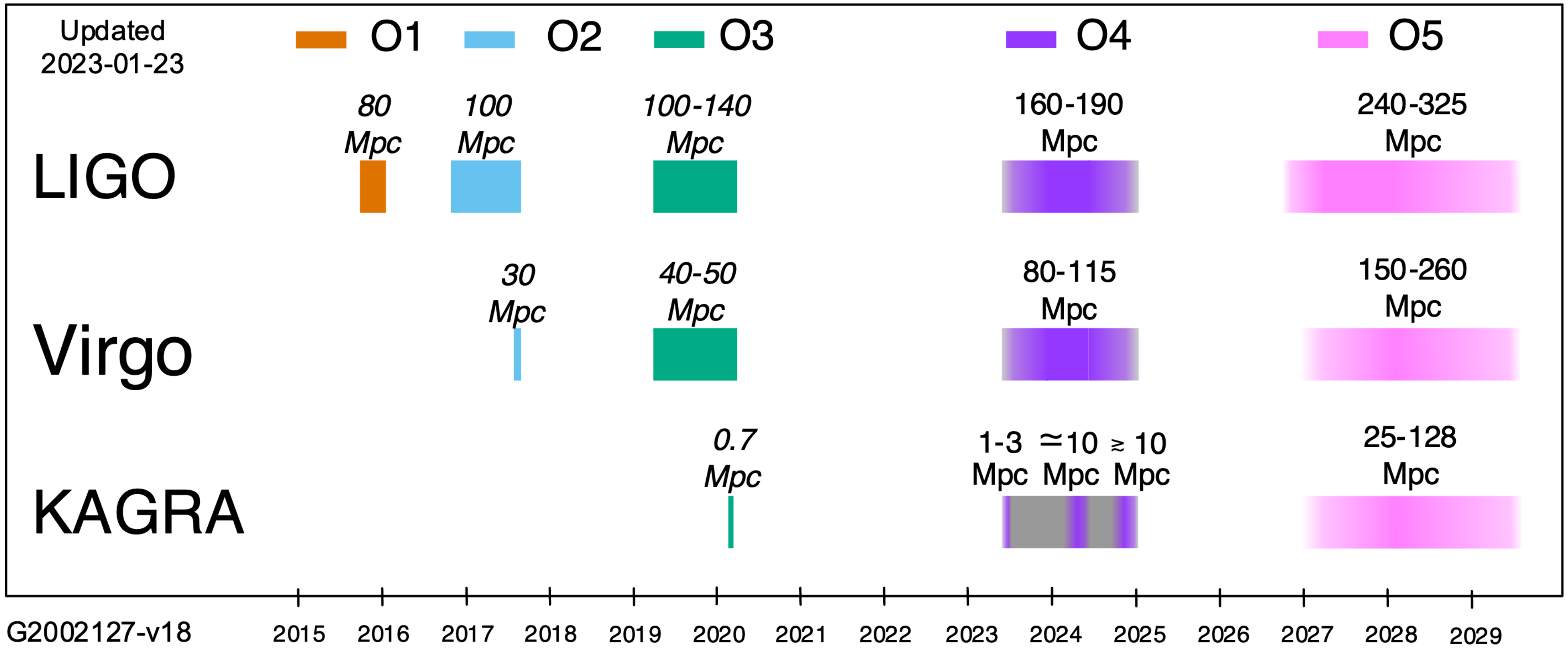


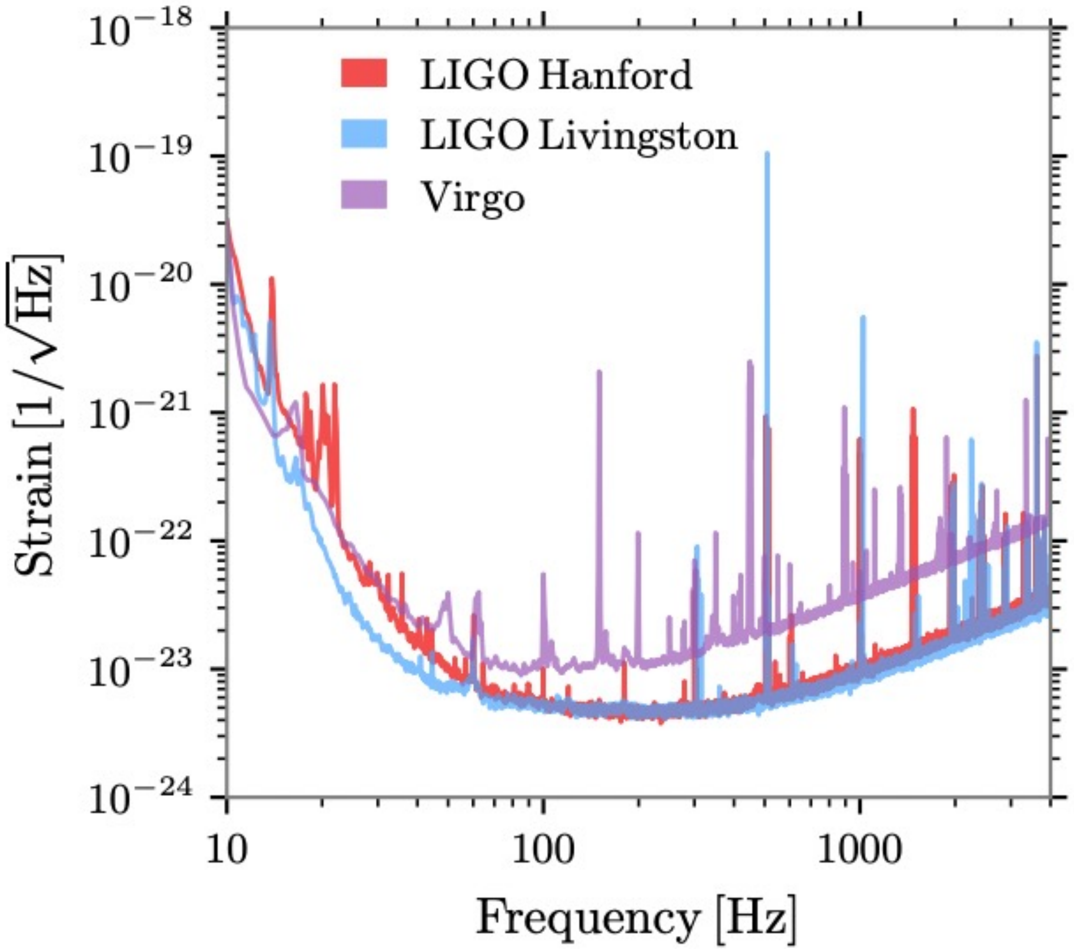


LIGO-Virgo(-KAGRA) observing runs



GW terrestrial detectors

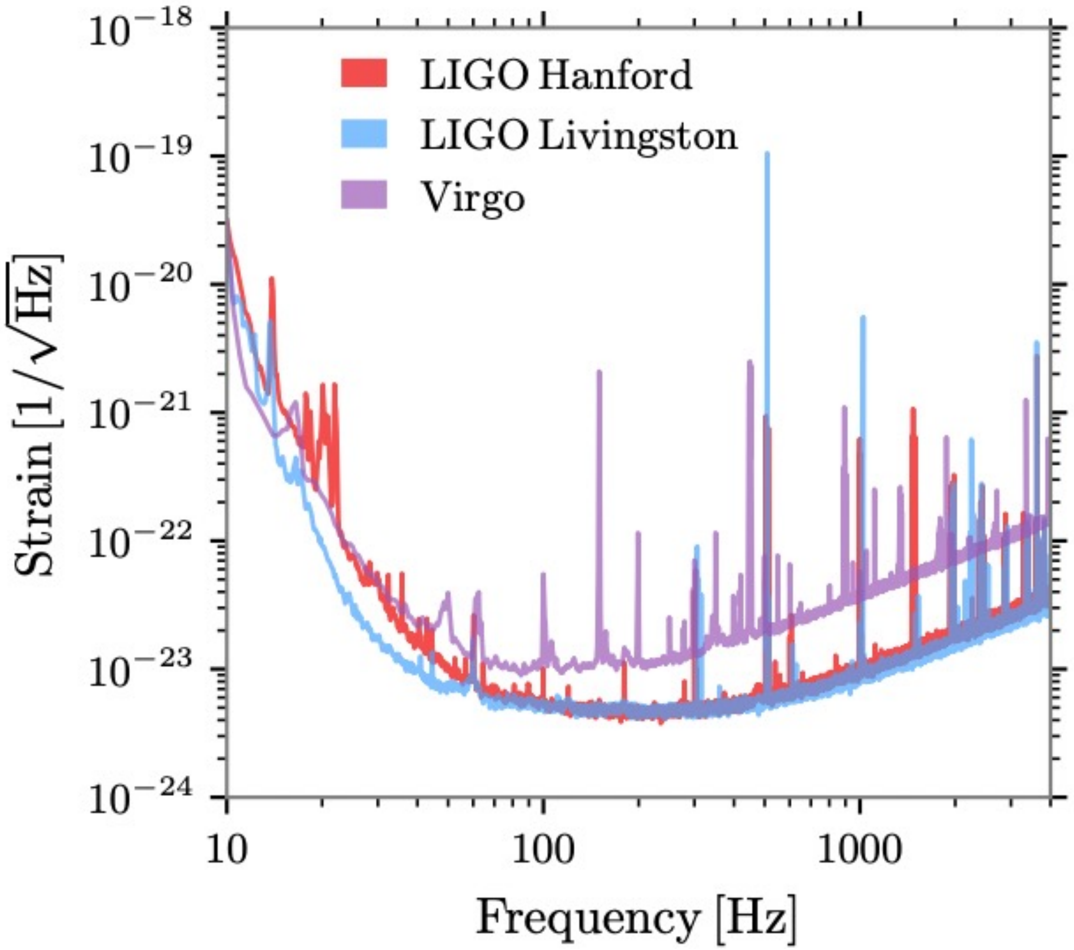
Power Spectral Density



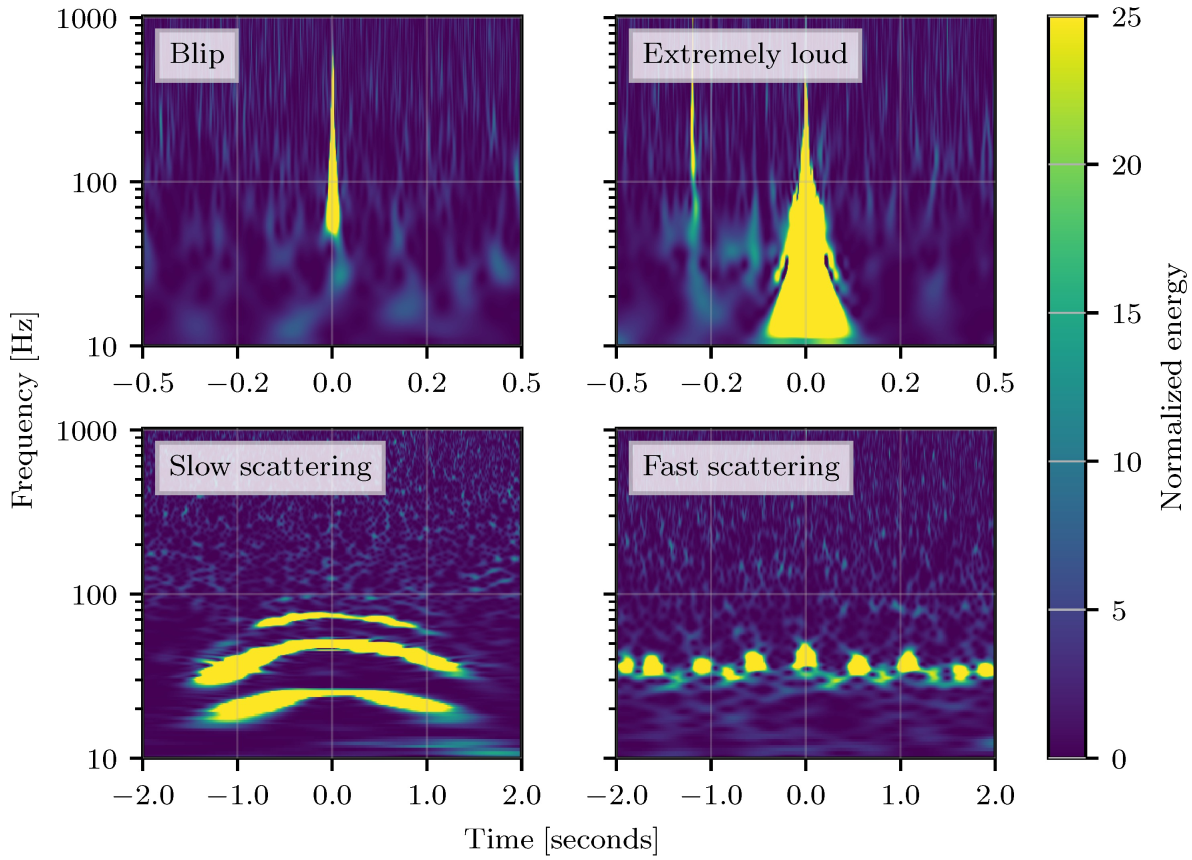
Several sources of noise affect different frequencies.
Tightly related to the detector, but also environment.
Detector design, technology, materials, commissioning..

GW terrestrial detectors

Power Spectral Density



And transient noise!

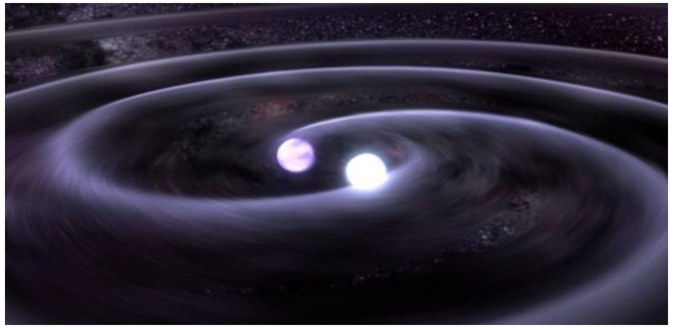


Detector caracterisation important part of data analysis

LIGO-Virgo-KAGRA physics program

Transient GW signals

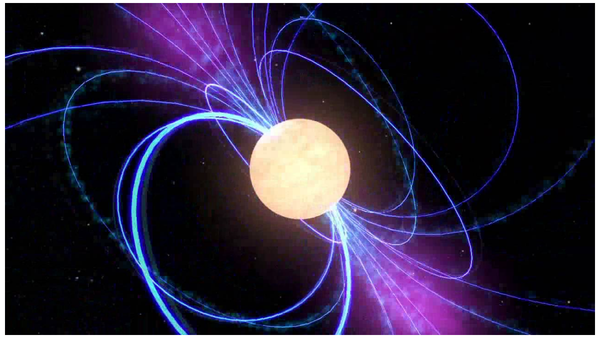
- Compact Binary Coalescences (CBC) – modelled



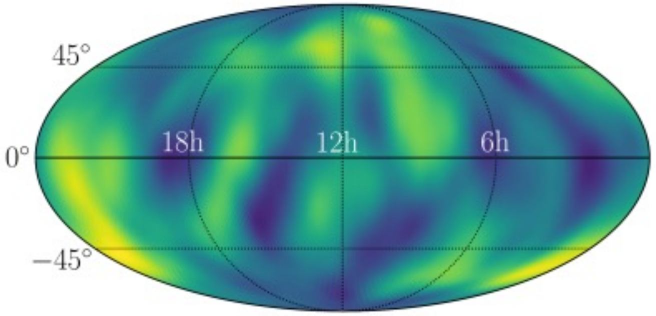
- Other “bursts”, e.g. supernovae - unmodelled

Longer duration GW signals

- Continuous emission from rotating neutron stars



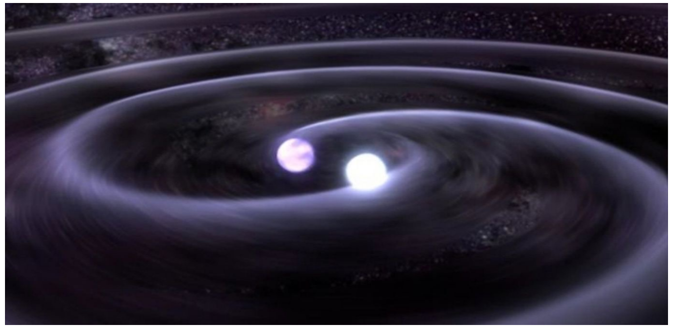
- Stochastic GW background



LIGO Virgo KAGRA physics program

Transient GW signals

- Compact Binary Coalescences (CBC) – modelled



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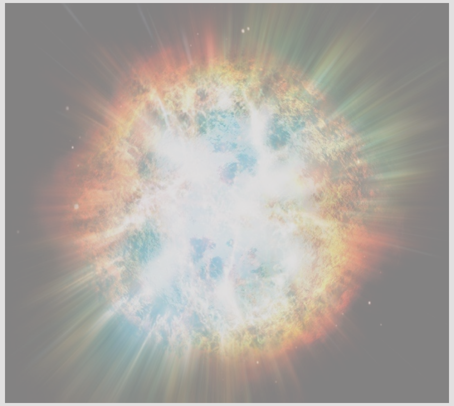


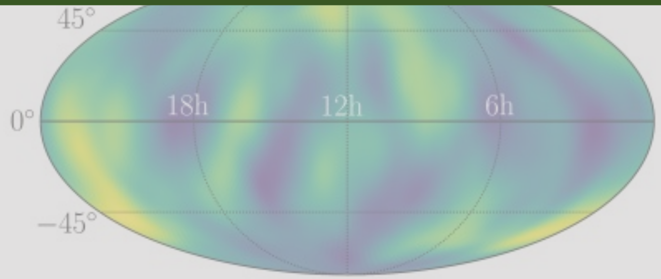
Lo

ars

Focus on CBC

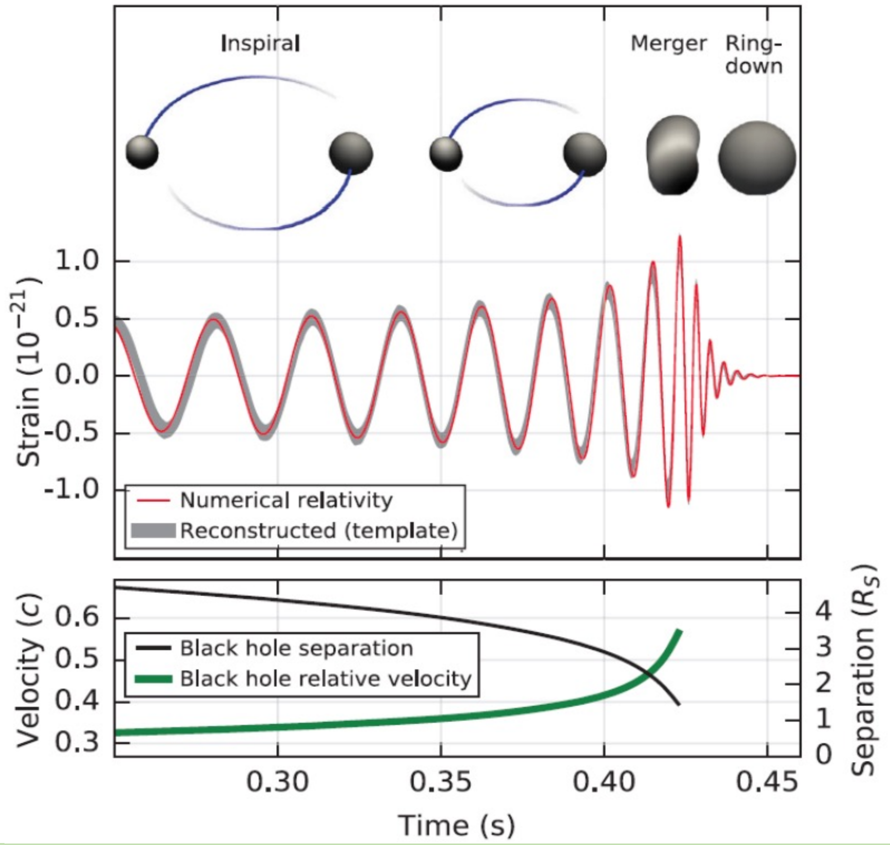
- Coalescences of compact objects (BH, NS)
- 2015: 1st BBH detection
- 2017: 1st BNS detection
- Observed ~100 events !

Will talk about other searches later on..



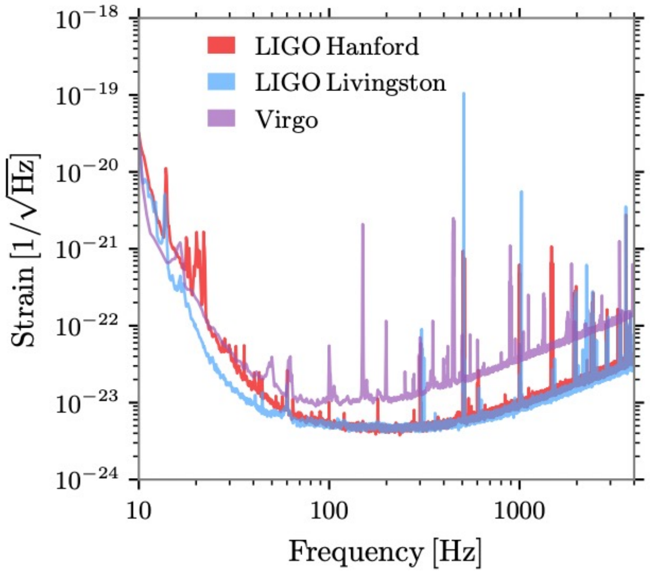
CBC detection – matched filtering

- Waveforms assume GR, analytical in inspiral phase (PN), numerical relativity for merger, perturbation theory for ringdown



Cross-correlation (in the Fourier space) of data with a bank of known CBC signals, weighted by the frequency-dependent noise.

- Naturally returns a Signal-to-Noise-Ratio (SNR)
- To be repeated for each template waveform!
- Typically use template banks

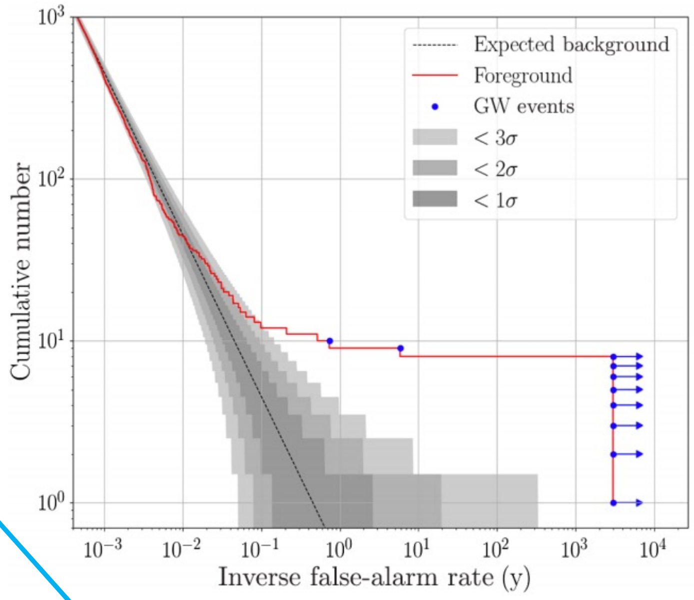


data — signal template — PSD

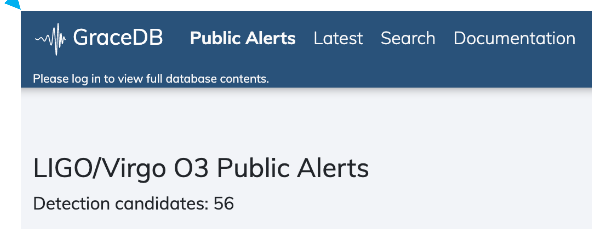
$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

Compact Binary Coalescences (CBC)

- From SNR, and knowledge of the background (that we take FROM DATA!) → associate a False Alarm Rate to our detection
- Probability of being of astrophysical origin (pastro) – depends on expected distributions of GW signals for different CBC sources

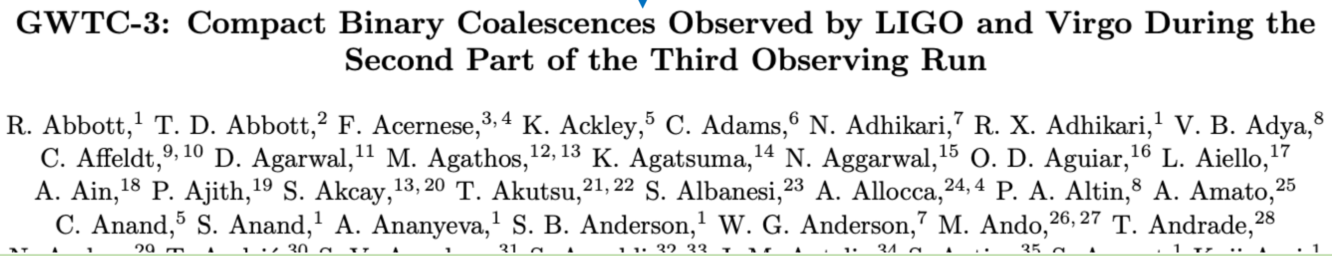


- CBC search analyses run **online** during data taking to issue alerts in case of interesting candidates



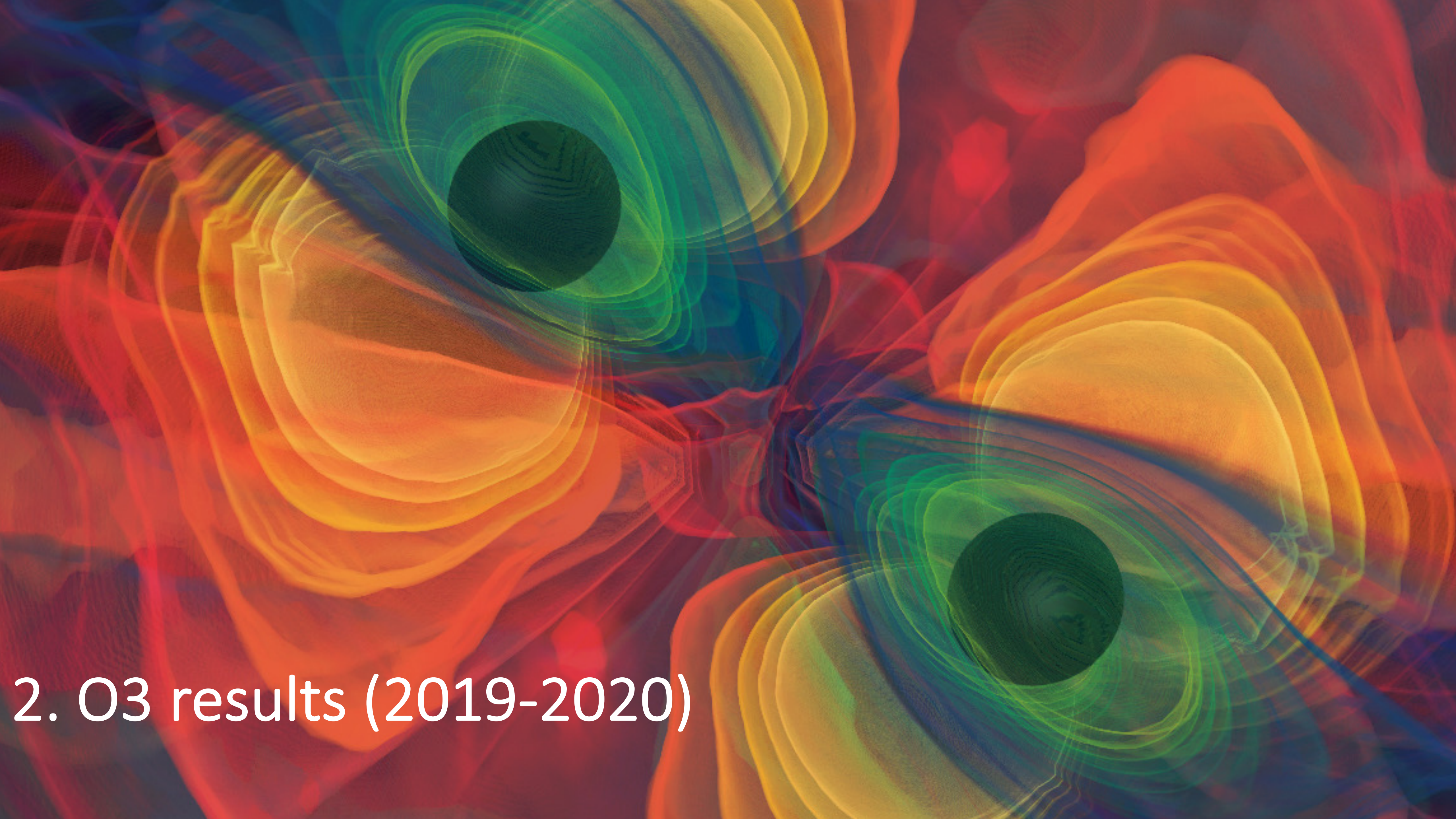
gracedb.ligo.org

- Searches are then run **offline** with relaxed selection cuts, calibrated data, better noise subtraction, data-quality etc → publications



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

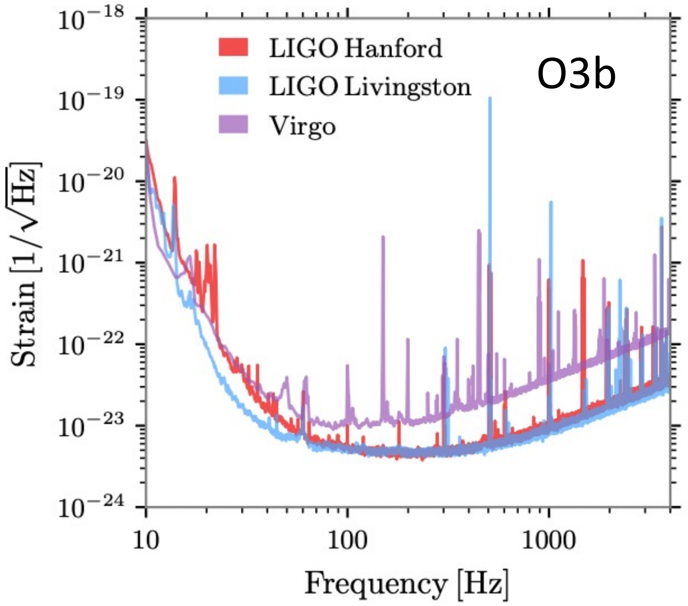
R. Abbott,[1] T. D. Abbott,[2] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] N. Adhikari,[7] R. X. Adhikari,[1] V. B. Adya,[8] C. Affeldt,[9,10] D. Agarwal,[11] M. Agathos,[12,13] K. Agatsuma,[14] N. Aggarwal,[15] O. D. Aguiar,[16] L. Aiello,[17] A. Ain,[18] P. Ajith,[19] S. Akcay,[13,20] T. Akutsu,[21,22] S. Albanesi,[23] A. Allocca,[24,4] P. A. Altin,[8] A. Amato,[25] C. Anand,[5] S. Anand,[1] A. Ananyeva,[1] S. B. Anderson,[1] W. G. Anderson,[7] M. Ando,[26,27] T. Andrade,[28]

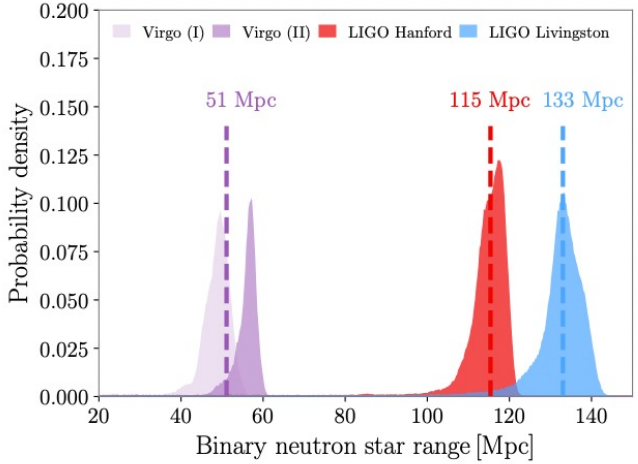


2. O3 results (2019-2020)

O3 data taking

- O3a : 1st April 2019 – 1st October 2019
- O3b : 1st November 2019 – 27th March 2020
- Duty cycle (O3b) ~76-79% for each detector, for an effective observation time during O3 of
  - 319 days – (at least) one detector
  - 264 days – (at least) two detectors
  - 156 days – three detectors
- BNS range wrt O2 : x1.5-1.7
- A lot of work of detector characterization, noise understanding/subtraction, data quality optimization (LIGO, Virgo)
- April 2021 O3a data public release
- November 2021 O3b data public release





A GW transient catalog anatomy

IP2I
R. Chierici, M. Lethuillier, E. Nitoglia, A. Ouzriat, V. Sordini

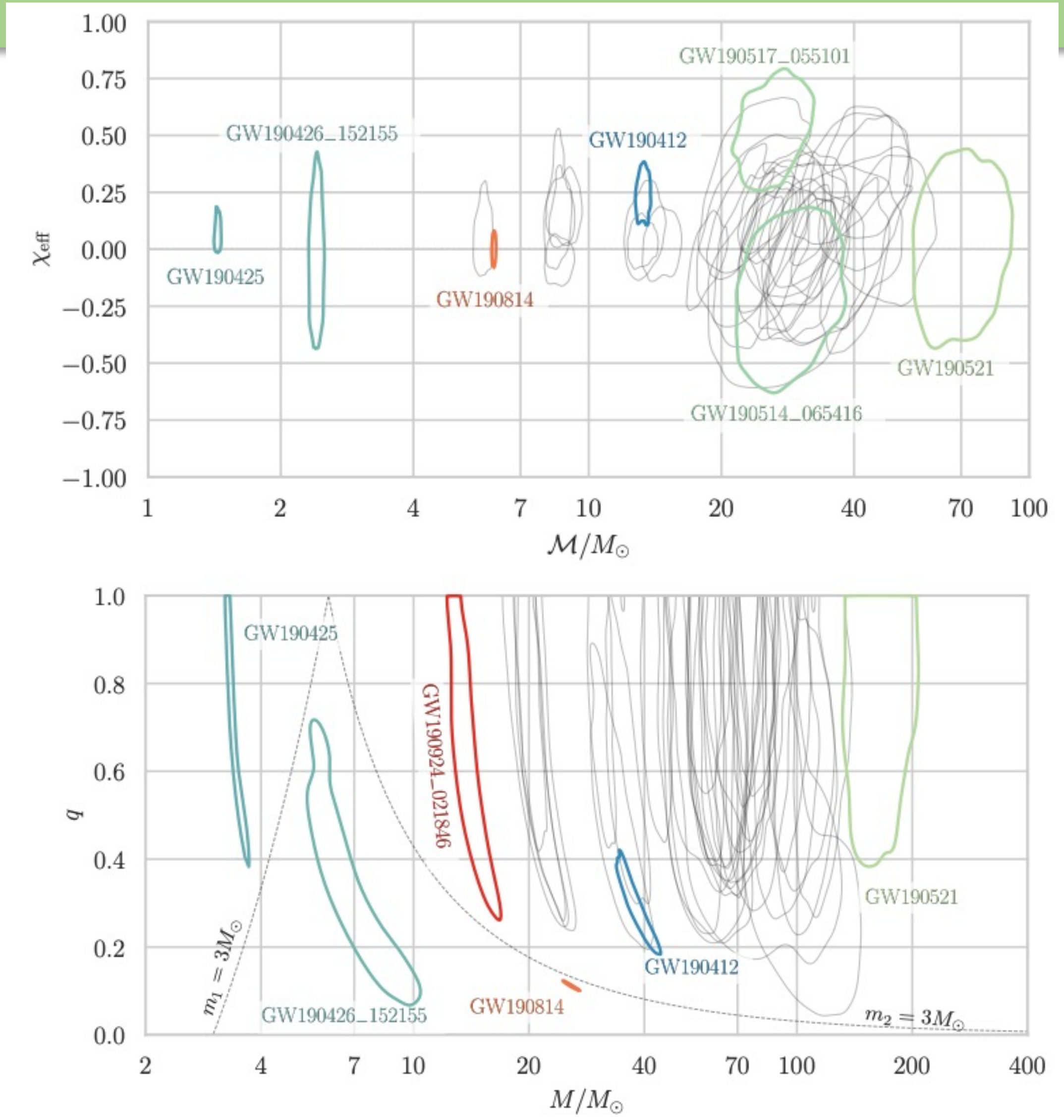
- List of events
- Significance as estimated by the several analyses

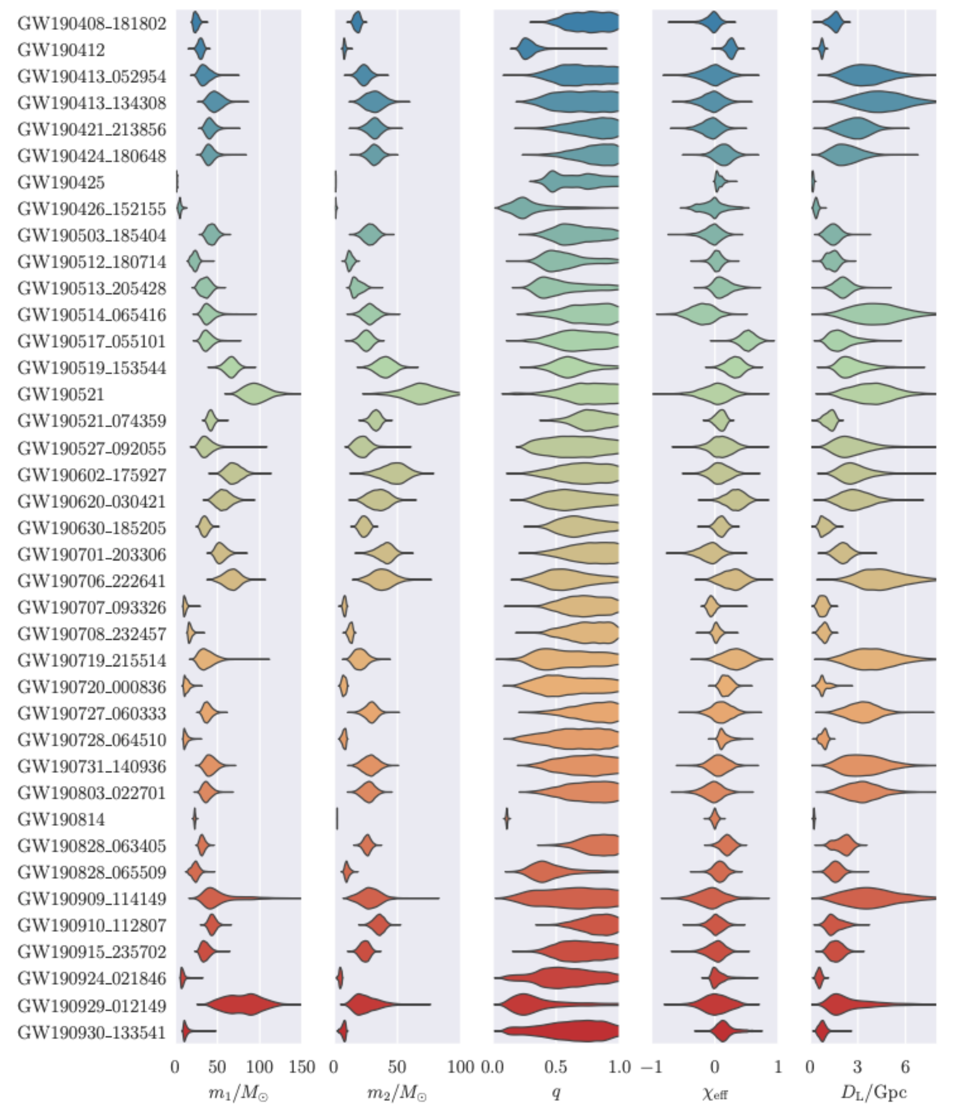
Name	Inst.	cWB			GstLAL			MBTA			PyCBC-broad			PyCBC-BBH		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW191103_012549	HL	–	–	–	–	–	–	*27*	*9.0*	*0.13*	4.8	9.3	0.77	0.46	9.3	0.94
GW191105_143521	HLV	–	–	–	*24*	*10.0*	*0.07*	0.14	10.7	> 0.99	0.012	9.8	> 0.99	0.036	9.8	> 0.99
GW191109_010717	HL	< 0.0011	15.6	> 0.99	0.0010	15.8	> 0.99	1.8×10^{-4}	15.2	> 0.99	0.096	13.2	> 0.99	0.047	14.4	> 0.99

- Data around each candidate is analysed again to determine astrophysical sources properties (masses, spins, localisation..)
- Obtained with expensive Bayesian inference algorithms (parameter estimation)
- Noise assumed to be Gaussian, stationary, and uncorrelated between detectors
- Multiple waveform models (different modelling techniques, including different physical effects), different samplers
- If at least one component with $m < 3M_{sun}$ → waveforms with matter effects

Sources Parameters Estimation

See talk by Jean-François





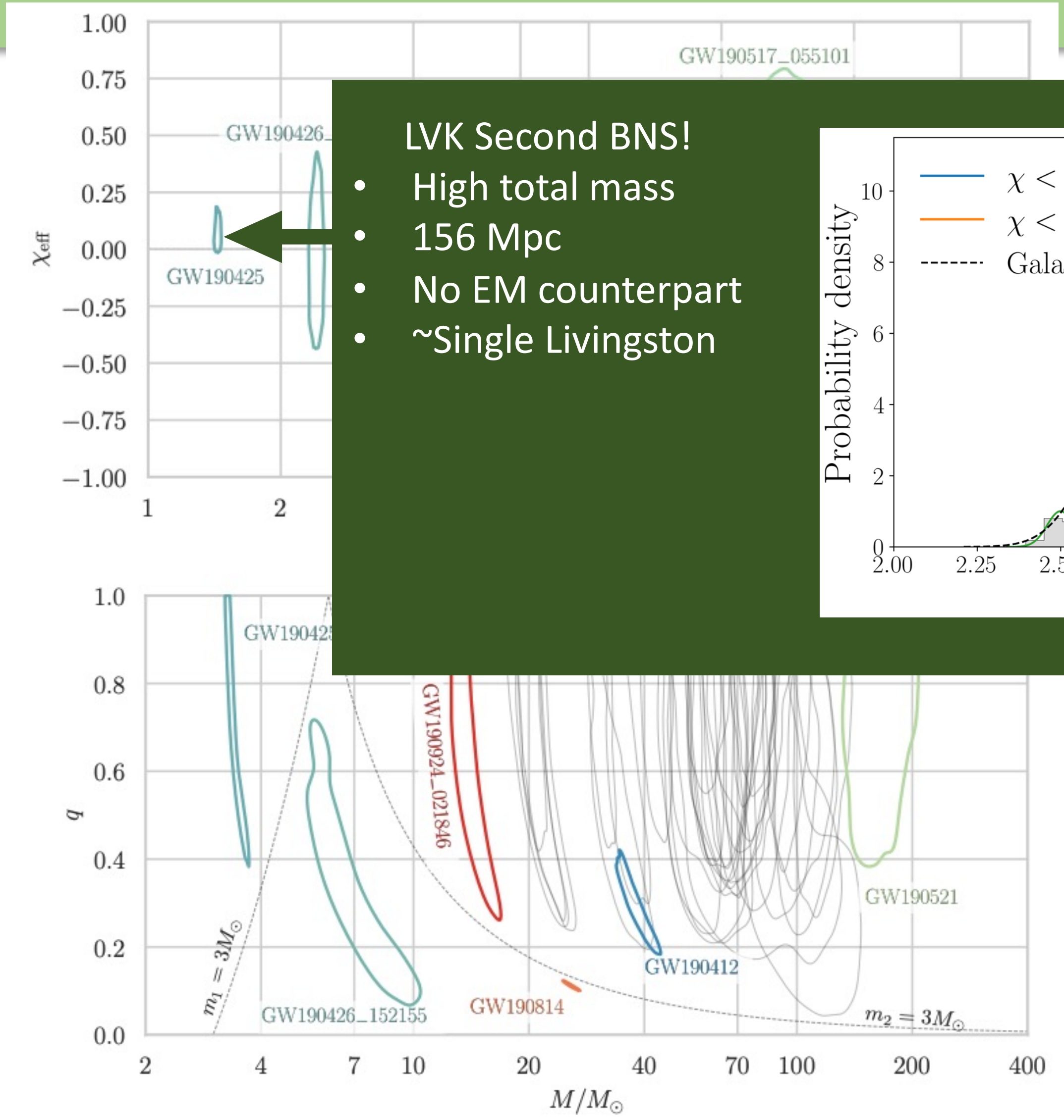
NB
O3 observations described in several catalog papers (O3a: GWTC-2, 2.1 O3b: GWTC-3)

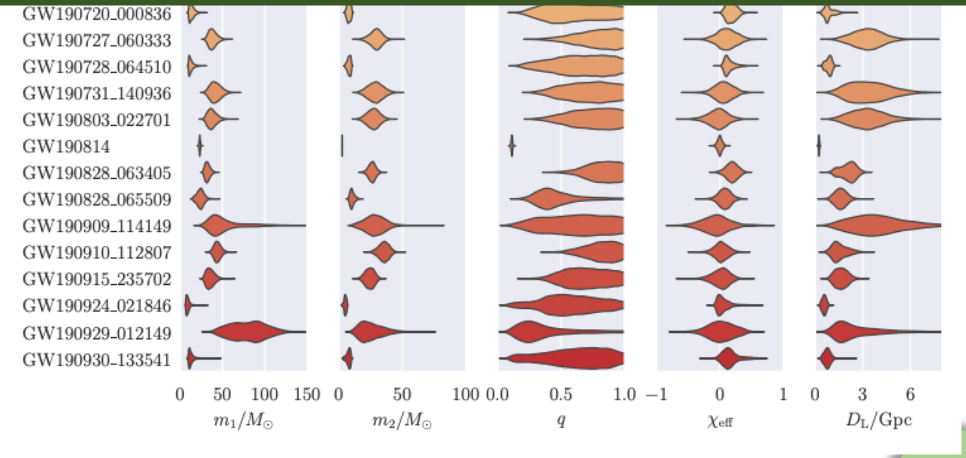
Plot here taken from GWTC-2

IP2I
J-F Coupechoux,
R. Chierici,
V. Sordini

+ Dedicated IMBH search (GW190521+2 marginal candidates) - A&A 659, A84 (2022) (arXiv)

Sources Parameters Estimation





NB

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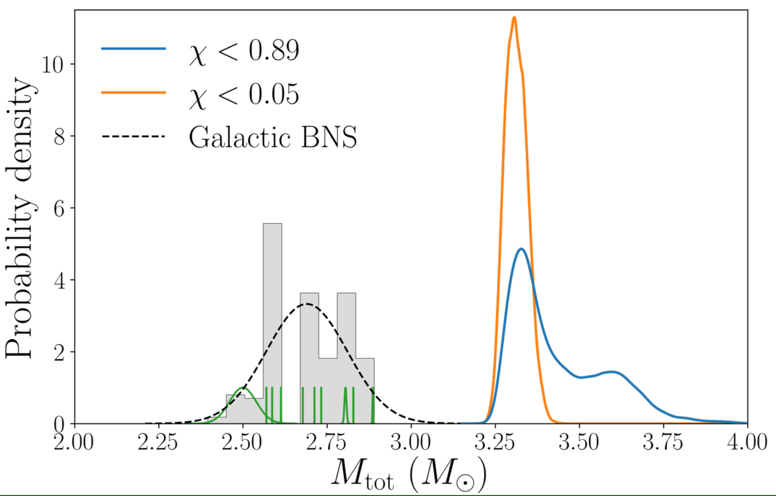
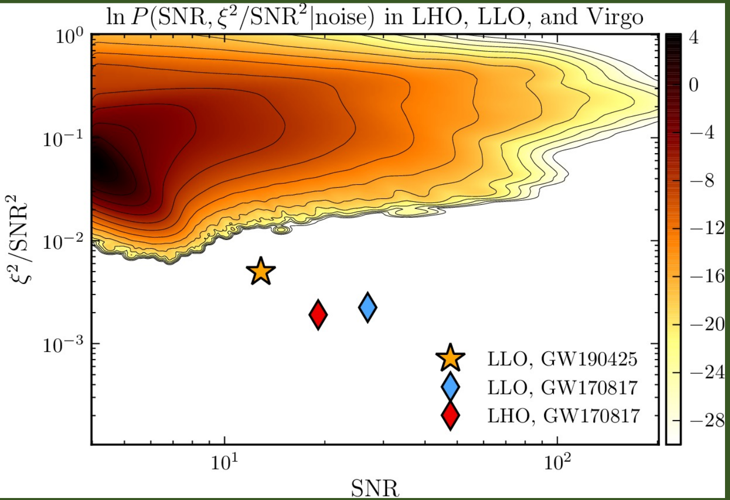
LVK Second BNS!

- High total mass
- 156 Mpc
- No EM counterpart
- ~Single Livingston





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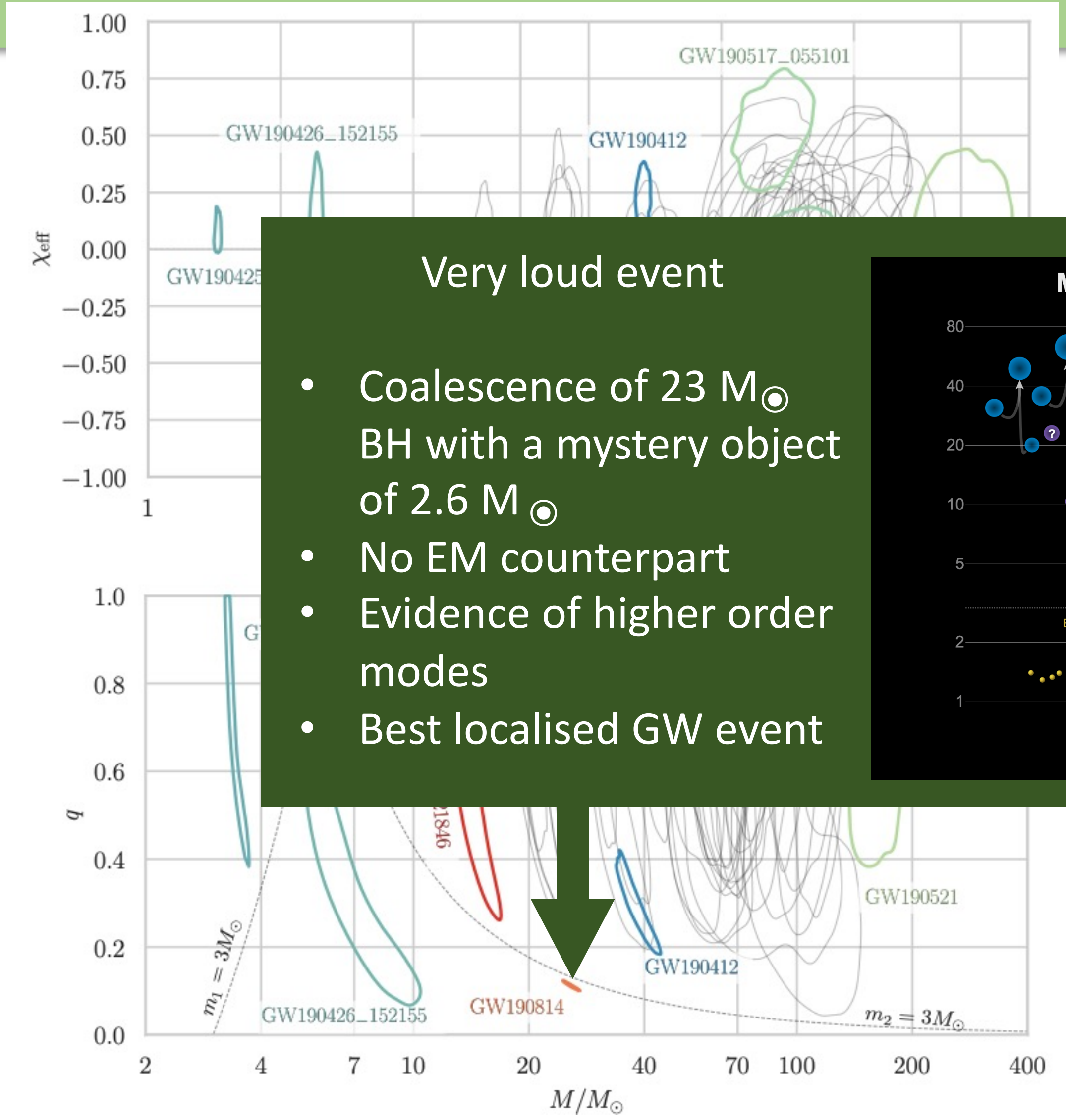
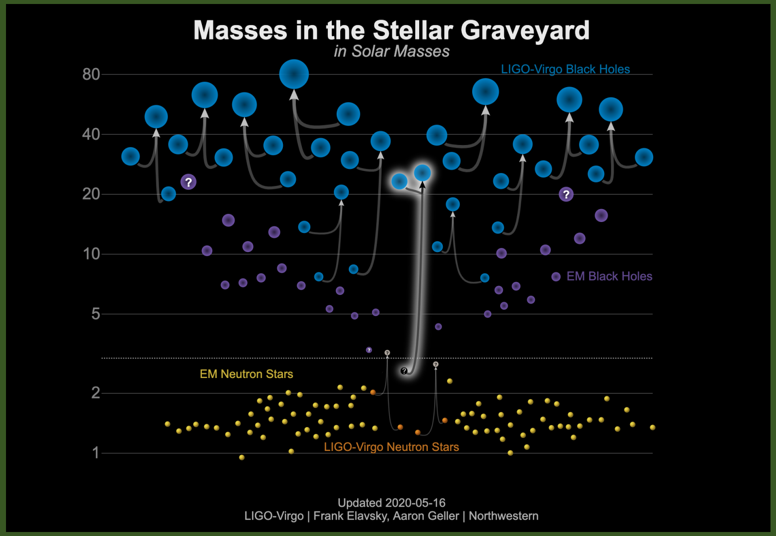
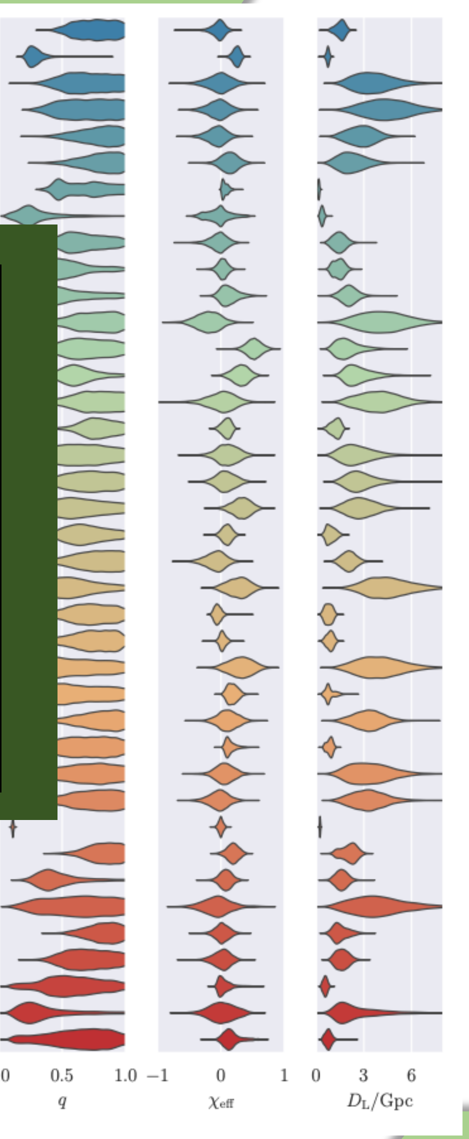


Very loud event

- Coalescence of 23 M⊙ BH with a mystery object of 2.6 M⊙
- No EM counterpart
- Evidence of higher order modes
- Best localised GW event





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Plot here taken from GWTC-2

+ Dedicated IMBH search (GW190521+2 marginal candidates) - A&A 659, A84 (2022) (arXiv)

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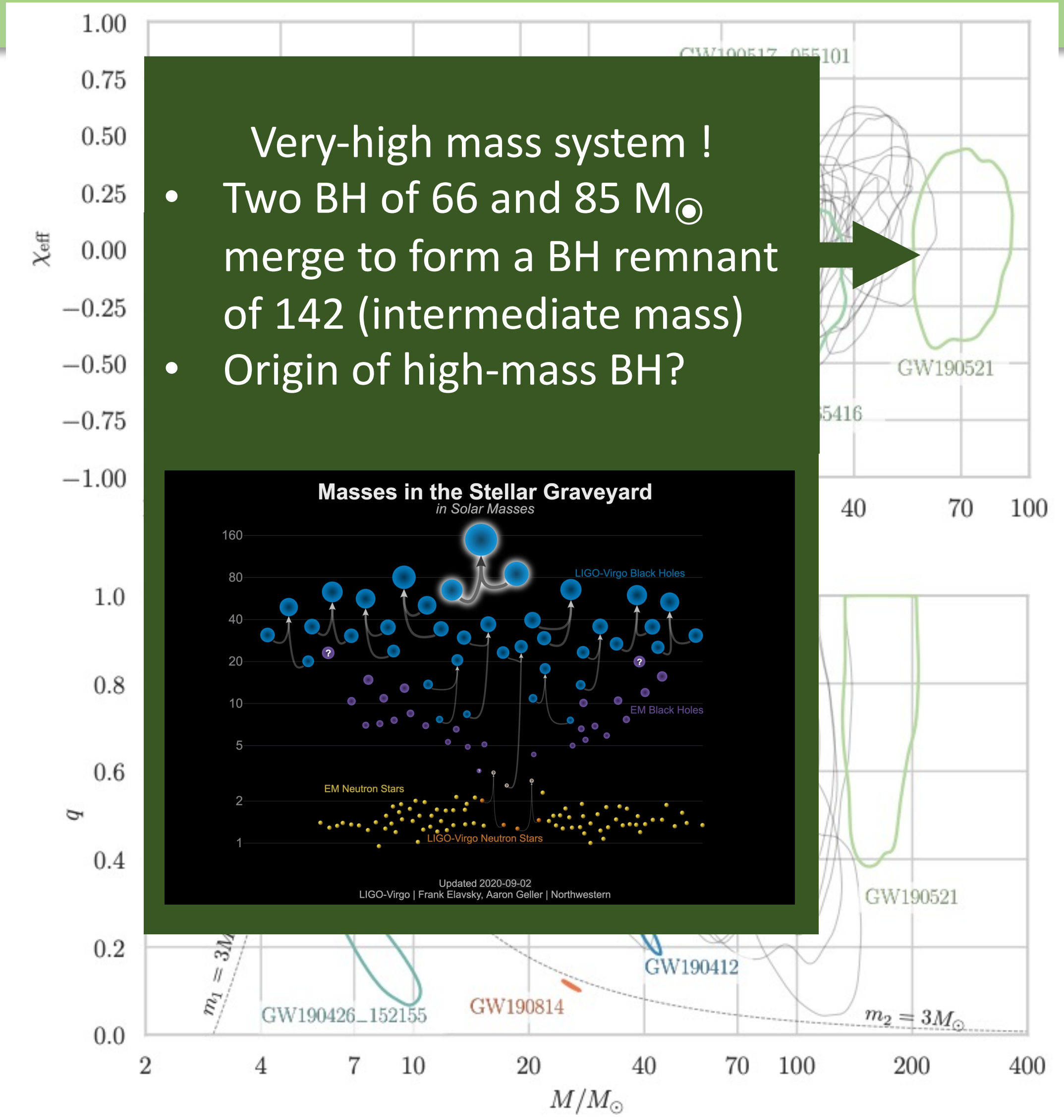
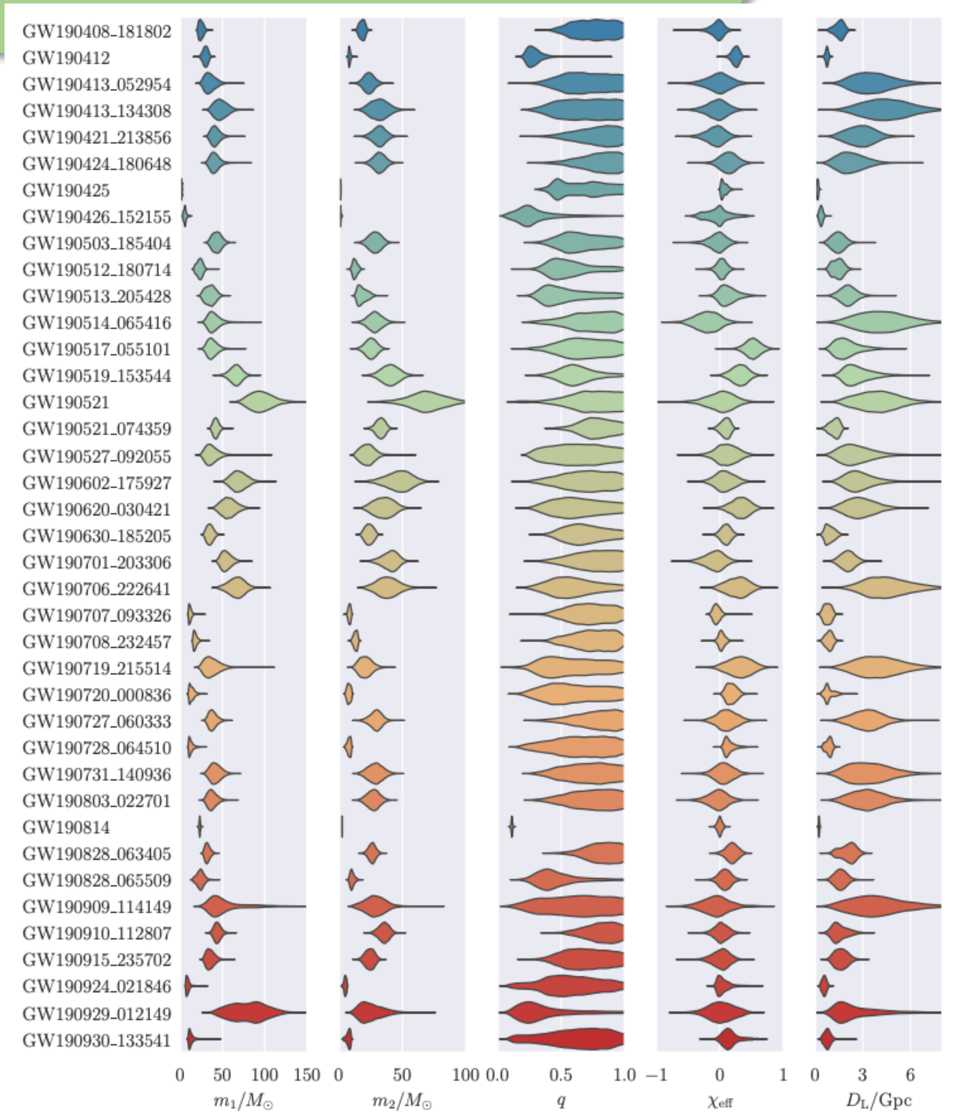


Very-high mass system !

- Two BH of 66 and 85 M⊙ merge to form a BH remnant of 142 (intermediate mass)
- Origin of high-mass BH?



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+ Dedicated IMBH search (GW190521+2 marginal candidates) - A&A 659, A84 (2022) (arXiv)

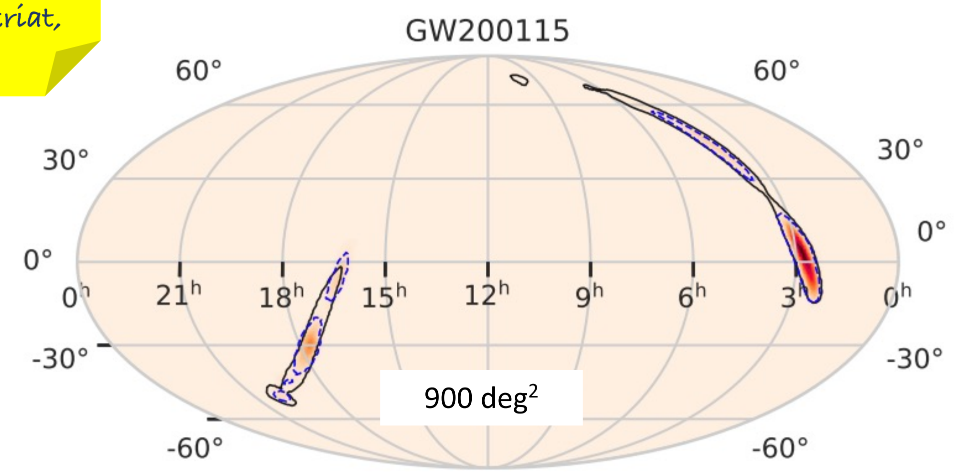
NSBH discovery

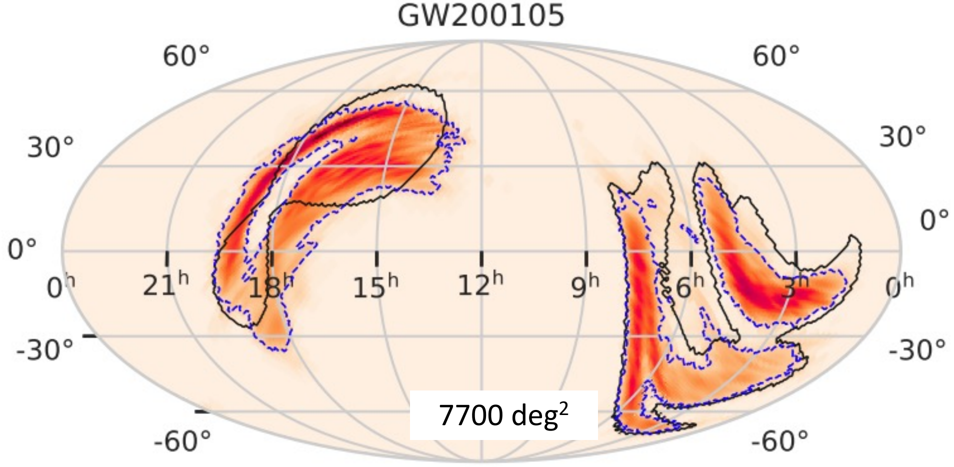
ApJL, 915, L5 (2021)
(arXiv)

IP21
R. Chierici, M. Lethuillier,
E. Nitoglia, A. Ouzriat,
V. Sordini

- No EM counterpart to date
- GW200115 - HL(V) coincidence, (best) FAR $10^{-5}yr^{-1}$
- GW200105 - Single-detector (L) event, FAR $(1/2.8)yr^{-1}$
- Secondary objects masses consistent with limits for NS masses (for non-rotating NS and Galactic NS)
- No evidence of tidal effects or precession
- GW200115 BH spin negatively aligned with respect to the orbital angular momentum, no formation process is excluded.
- Lensing excluded by non-overlapping posteriors

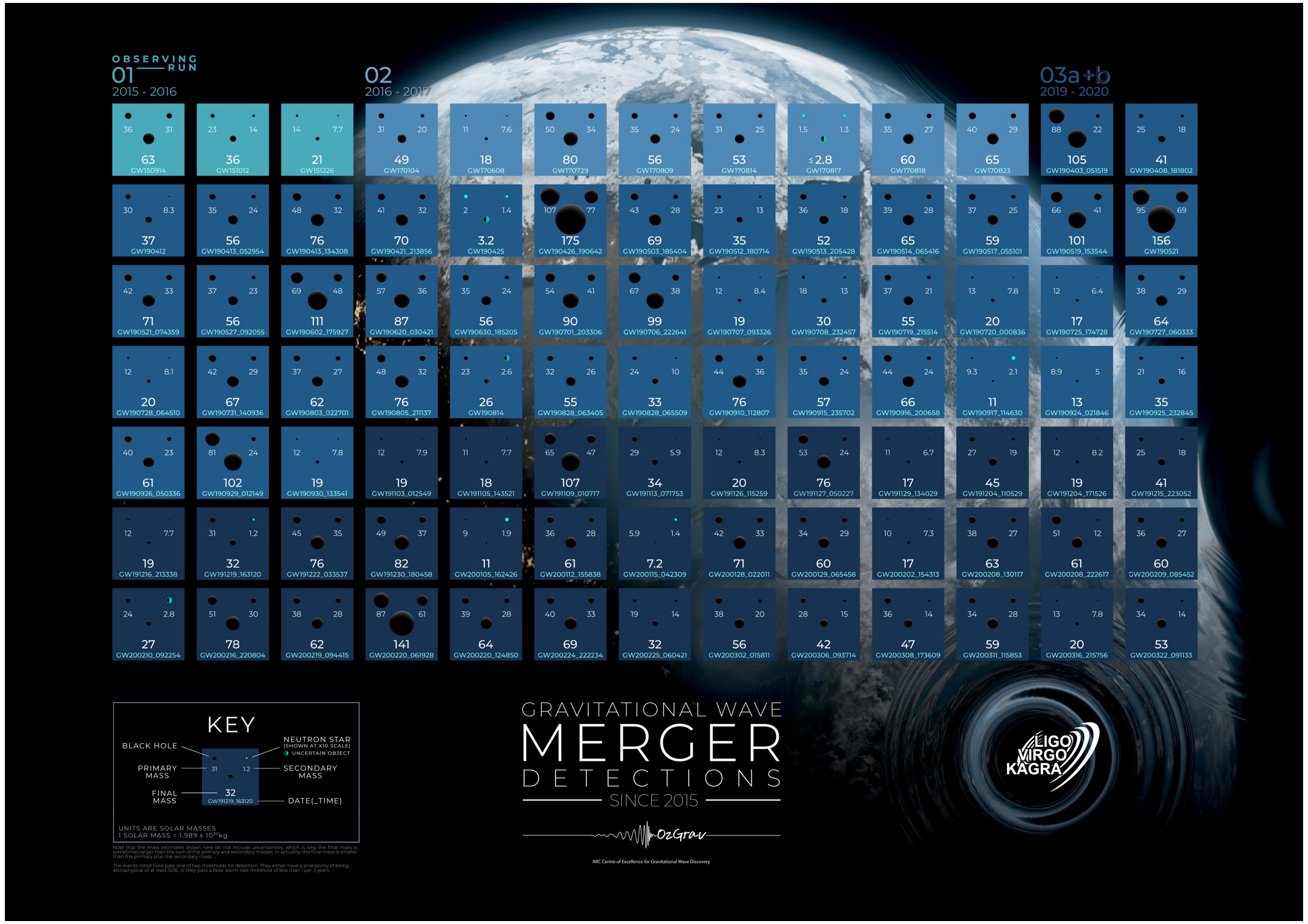
Event		GstLAL	MBTA	PyCBC	SPIIR
GW200105	low-latency	13.9	13.3	13.2*	13.2
	offline	13.9	13.4	13.1*	–
GW200115	low-latency	11.4	11.4	11.3	11.0
	offline	11.6	11.2	10.8*	–

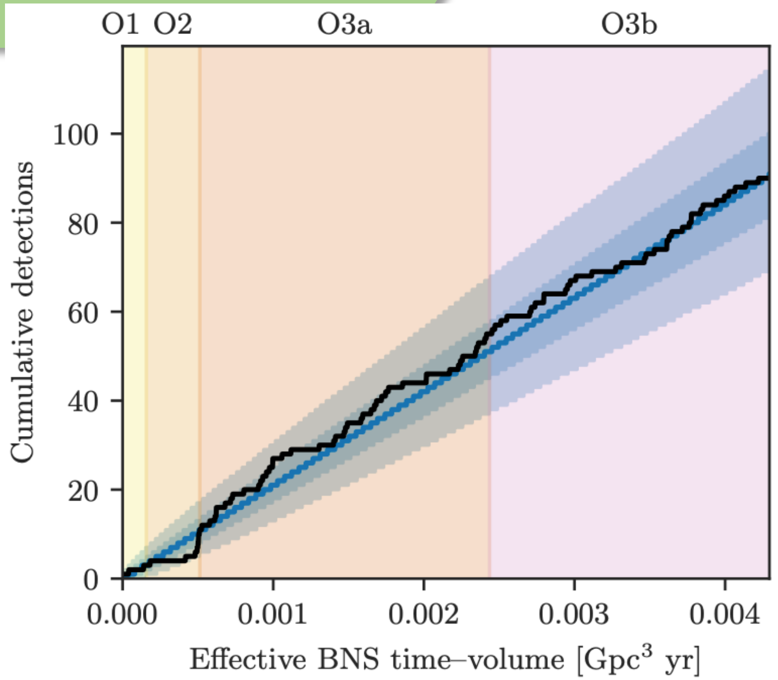




Implications of the CBC observations

- CBC detections have become a routine for GW astronomy !





- An input to several studies
  - Astrophysical populations studies
  - Tests of General Relativity
  - Cosmology
  - Targeted searches (GRBs, FRBs..)
  - Lensing signatures searches

Rates and populations

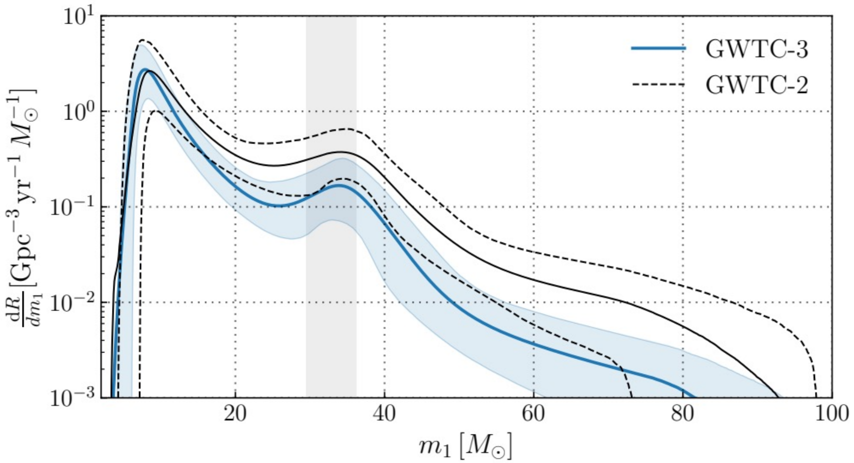
O3a ApJL **913** L7 (2021) (arXiv)

O3b (arXiv)

Population properties of compact objects based on 67 CBC from GWTC-3 (FAR<0.25/yr)

- Mass distribution of NS in binaries, different from galactic NS (peak at 1.35 Msun)
- Merger rates depend on models assumed for masses (Power Law + Dip + Break, Binned Gaussian process, Multi source), spins.
- New insight on BH population properties
    - Mass distribution has a substructure.
    - Evidence of spin precession, hints of dynamical formation (negative effective spins)
    - R_{BBH} z evolution consistent with one of star formation rate

	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)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$	19^{+28}_{-13}	$9.3^{+15.7}_{-7.2}$	240^{+270}_{-140}
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	770^{+1030}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
MERGED	10 – 1700	7.8 – 140	16 – 61	0.02 – 39	9.4×10^{-5} – 25	72 – 1800

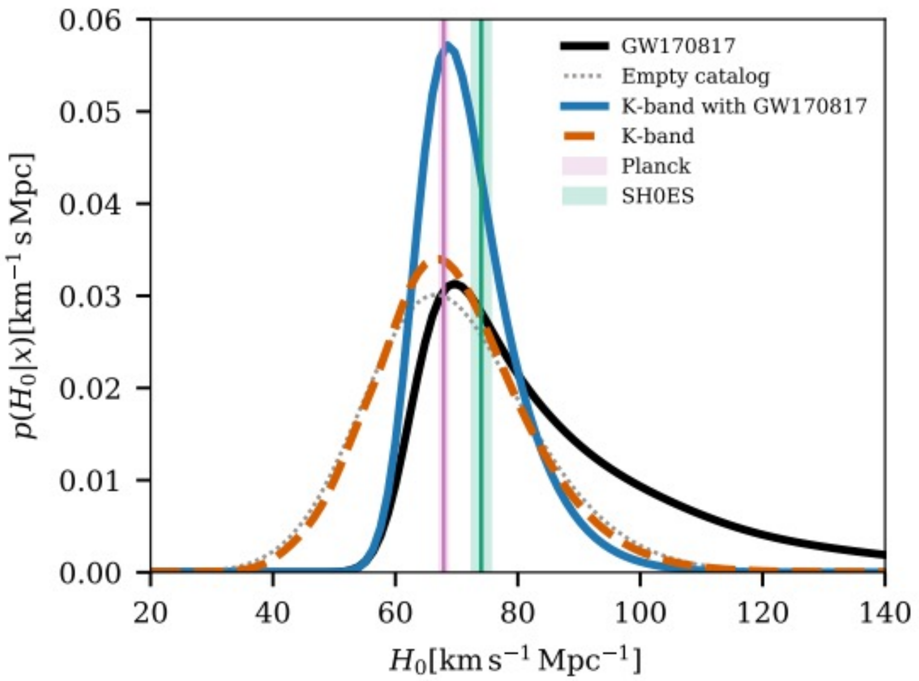


Cosmology with CBC

(arXiv, accepted by ApJ)

See talk by Grégoire

- Based on 47 highly significant (FAR<0.25yr-1, SNR>11) CBC observations: 42 BBH, 2 BNS, 2NSBH, GW190814
- GW detection → measurement of luminosity distance
- Different methods to constrain H_0
  - (Redshift information from EM counterpart - only for GW170817)
  - Infer the cosmological parameters using statistical galaxy catalog information (use population for out of catalog)
  - Jointly fitting the cosmological parameters and the source population properties of BBHs

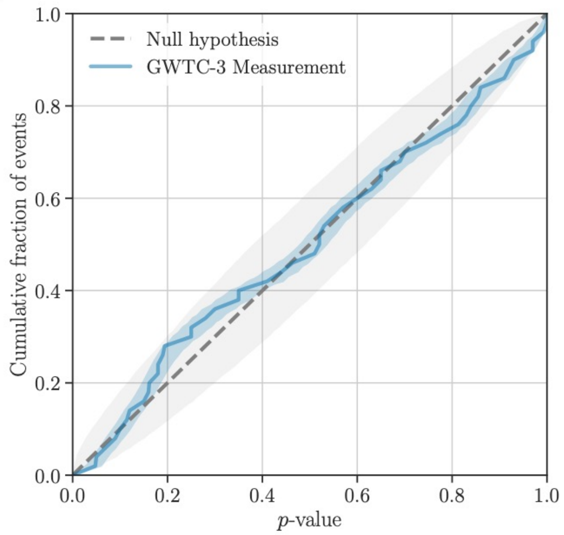


…eagerly waiting for new BNSs with EM counterpart!

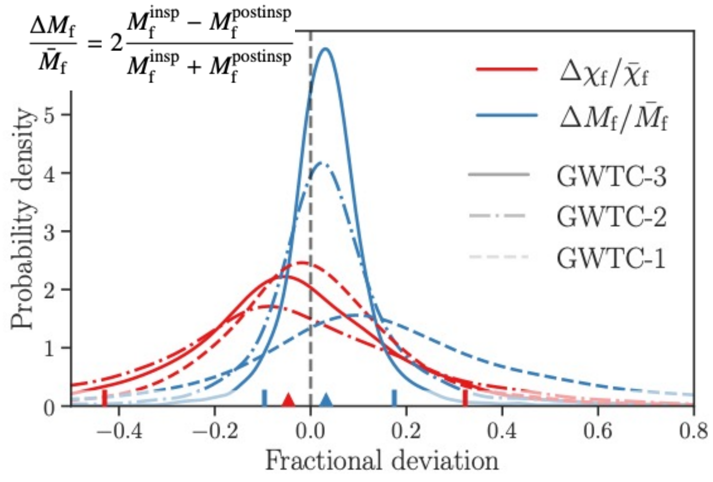
IP2I
S. Perries,
G. Pierra

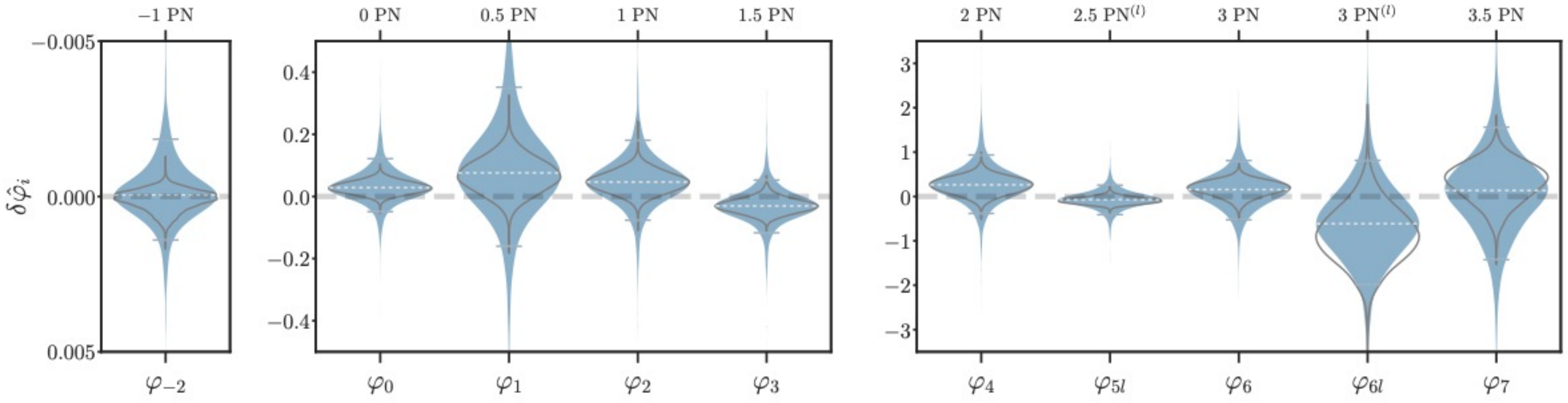
Tests of GR with CBC

Phys. Rev. D 103 122002 (2021) (arXiv) (arXiv)



- Tests of GR using 47 CBC from GWTC-2 + 15 from GWTC-3 (FAR<10^{-3}/yr) - no evidence for new physics beyond general relativity. Using a large variety of waveform approximants
- Residual tests from remnant coherent power in network data after subtraction of candidates
- Inspiral-merger-ringdown consistency checks (mass and spin of remnant BBH)
- Generic modifications to waveforms (varying post-Newtonian and phenomenological coefficients) → constraints ~2x stronger than previous
- Gravitational-wave dispersion (null in GR) → constraints on Lorentz-violating coefficients, graviton mass $m_g \leq 1.27 \times 10^{-23}$ eV/c2 @90%CL
- Data consistent with tensorial polarization, no deviation from Kerr BH, no post-merger echoes





+ Searches for gravitational lensing signatures (2021 ApJ 923 14 arXiv + arXiv)

O3 Sub-solar mass

IP21
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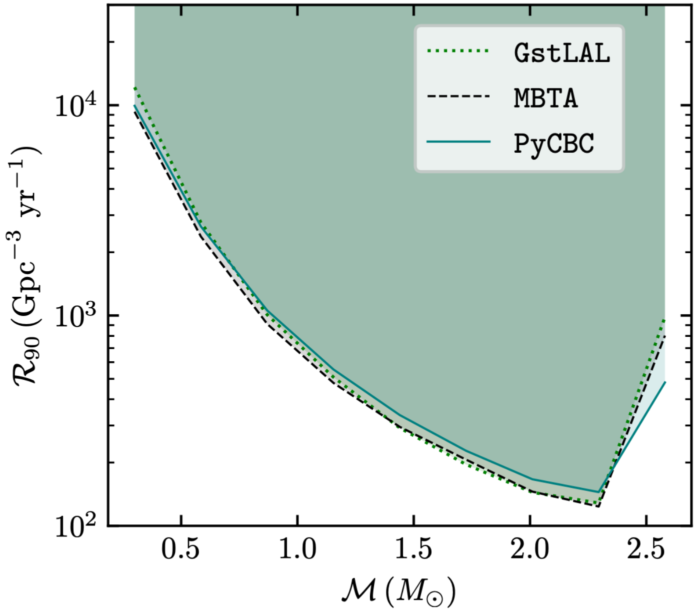
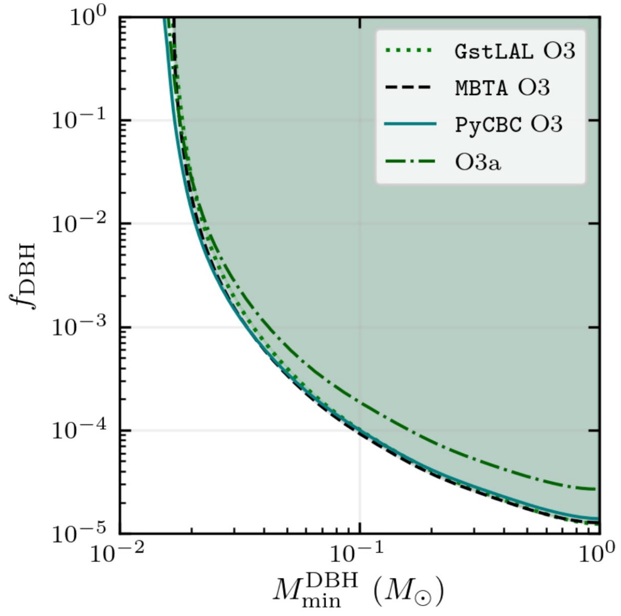
V. Sordini

(MNRAS)

$$0.2 < m_1 < 10 \quad 0.2 < m_2 < 1$$
$$0.1 < \frac{m_2}{m_1} < 1$$
$$|\chi_i| < 0.1(0.9) \text{ if } m_i < 0.5 \text{ (otherwise)}$$

- Sub-solar compact objects predicted by many models
  - Primordial Black Holes (BHs) from overdensities in early Universe
  - Dissipative Dark Matter (DM)
  - BH from DM accumulation in NS cores
- No observation → constraint on the merger rate. Interpretation in two models





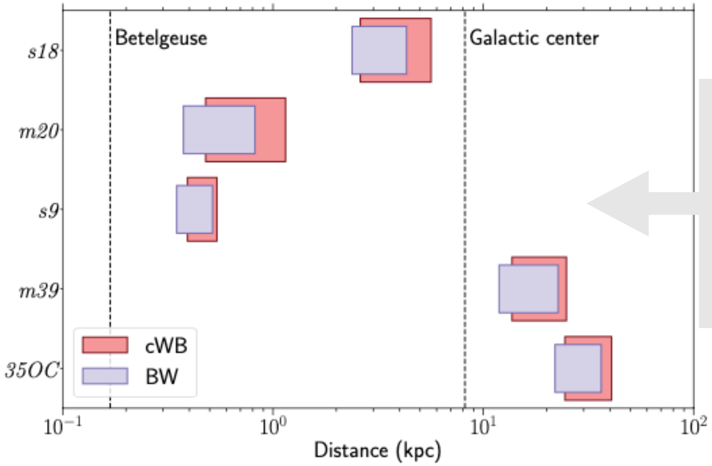
Dissipative DM model (two dark fermions + 1 massless dark photon)

- Power-law distribution for BH masses (unknown cutoff M_{min})
- Upper limit (function of M_{min}) on the fraction of DM that ends up in BH
- Lowest upper limit : f_{DBH}<0.0012% (M_{min} = 1$M_\odot$)

O3 Search for short GW bursts

Phys. Rev. D 104, 122004 (arXiv)

- Transient [ms-s] GW signals in [24–4096] Hz, no assumption on signal morphology
- Two independent analyses look for excesses of signal power in time - frequency (**Coherent WaveBurst** and **BayesWaves** as a followup on interesting times)
- **No GW detection (iFAR>100 yr) beyond the CBC ones**, sensitivity studies based on simulations
  - Generic signal morphologies: sine-Gaussian wavelets (SG), Gaussian pulses (GA), and band-limited white-noise bursts (WNB).
  - CCSNe: different models (s18, m10, s9, m39, 35OC)
  - Constraints on pulsar glitches



Distances at which [10%-50%] efficiency is reached.

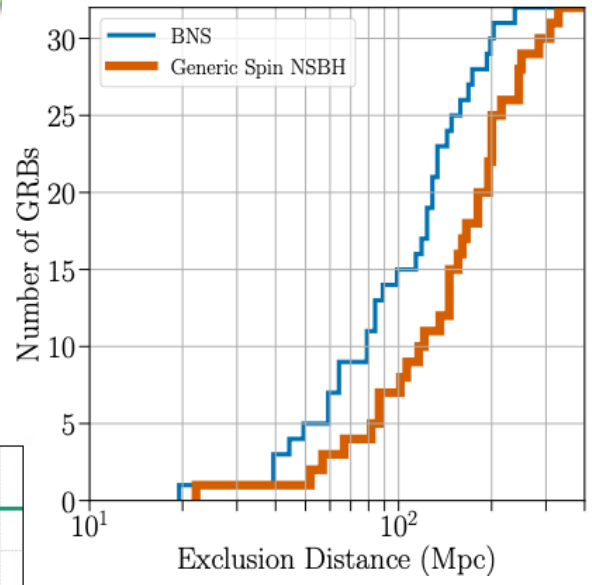
No confident candidate for long-duration bursts - Phys. Rev. D 104, 102001 (arXiv)

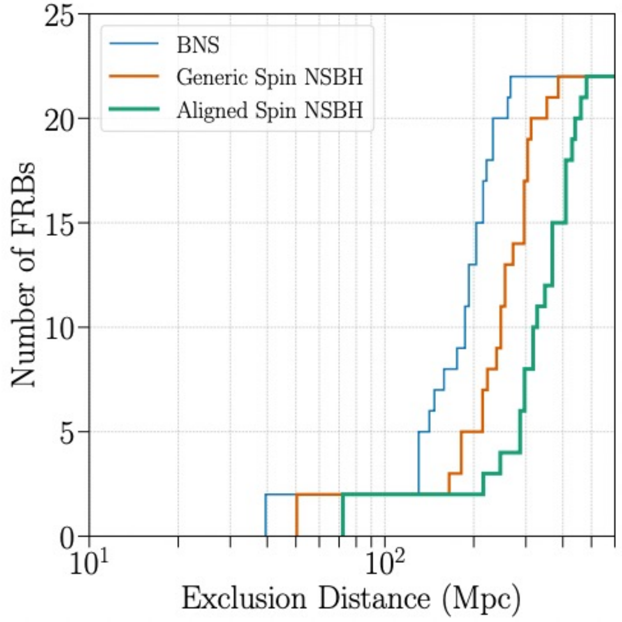
Triggered searches (GRB, FRB)

ApJ. 915, 86 (2021) (arXiv)
ApJ 928 186 (2022) (arXiv)
(arXiv)

Search for GW transient associated with GRB (Fermi/Swift) during O3a and O3b or FRB(CHIME/FRB), during O3a

- 105(86) GRB analysed (X-Pipeline) + BNS/NSBH specific search (PyGRB) for 32(17) short ones in O3a(O3b)
- 34 non-repeating FRBs, 11 repeated bursts from the closest 3 repeating sources (FRB 20180916B, FRB 20180814A and FRB20190303A)
- Searches for unmodelled ans modeled associated GW signals
- No GW signal associated to a GRB or FRB. Sensitivity determined on simulation. Exclusion distance.





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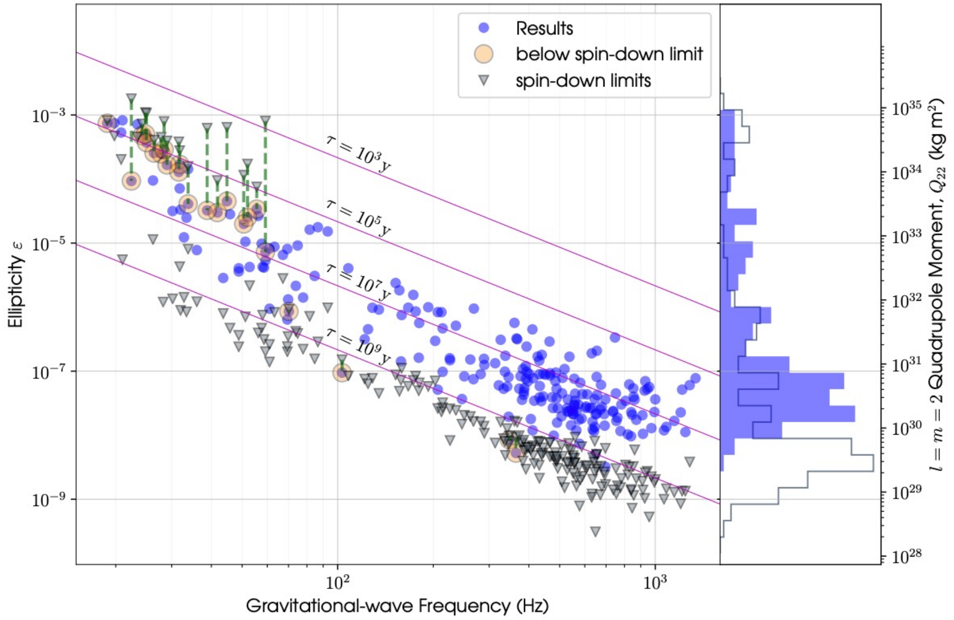
Not only transient !

- Early O3 all-sky binaries CW - Phys. Rev. D 103, 064017 arXiv
- Full O3 targeted J0537-6910 CW - 2021 ApJ 922 71 arXiv
- Full O3 PSR J0537-6910 pulsar r-mode CW - 2021 ApJ 922 71 arXiv
- O3 SN remnants CW 2021 ApJ 921 80 arXiv, Phys. Rev. D 105, 082005 arXiv
- O3 all-sky isolated CW – (early Phys. Rev. D 104, 082004 arXiv), arXiv
- O3 twenty AMXPs CW - Phys. Rev. D 105, 022002 arXiv
- Full O3 BH boson cloud CW - Phys. Rev. D 105, 102001 arXiv
- Early O3 Cas A / Vela Jr CW - Phys. Rev. D 105, 082005 arXiv
- O3 isotropic stochastic - Phys. Rev. D 100, 061101(R) arXiv
- O3 anisotropic stochastic - Phys. Rev. D 104, 022005 arXiv
- O3 all-sky cosmic strings search - Phys. Rev. Lett. 126, 241102 arXiv
- O3 constraints on dark photon and dark matter - Phys. Rev. D 105, 063030 arXiv

GW from known pulsars

(arXiv, ApJ **935** 1 2022)

- Targeted search for continuous GW from 236 pulsars (O2+O3) with frequency>10Hz
- The GW emission assumed to follow the phase evolution from EM observations (radio and X-ray : CHIME, Mount Pleasant,Lovell, MeerKAT, NICER, Molonglo)
- No evidence of GW → 95%CL limits on strain amplitude, pulsars ellipticity ε.
- 23 have strain amplitudes lower than spin-down limits (for 9 of them for the first time).
  → Constraints on NS EoS
- No evidence of additional polarisation (Brans-Dicke, beyond GR)



Stochastic gravitational wave background

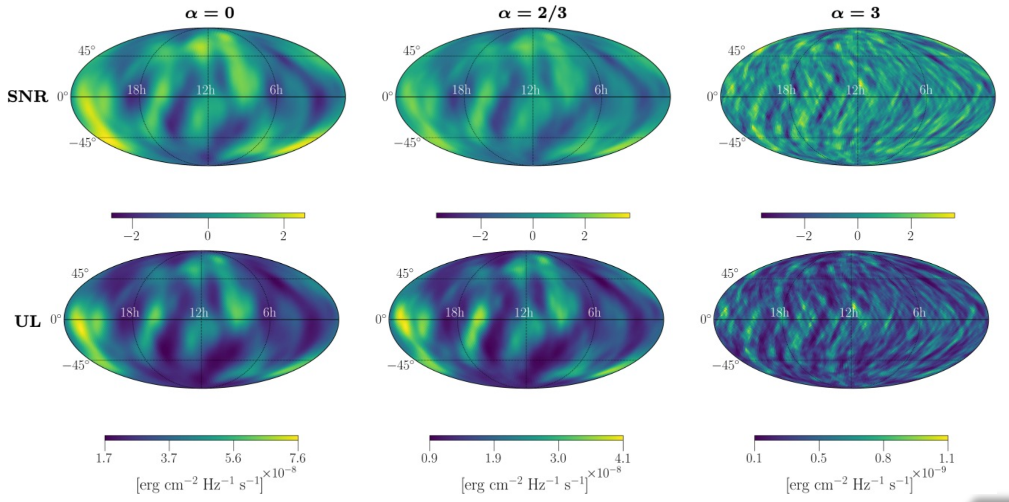
Isotropic SGWB (including Virgo for the first time) (Phys. Rev. D 100, 061101(R) arXiv)

- Results consistent with uncorrelated noise --> dimensionless energy density Ω_{GW}
- $\Omega_{GW} \leq 5.8 \times 10^{-9}$ @95% (flat in frequence)
- At design sensitivity, SGWB+CBC may yield stronger constraints on the merger rate of binary black holes at z~2 wrt CBC alone

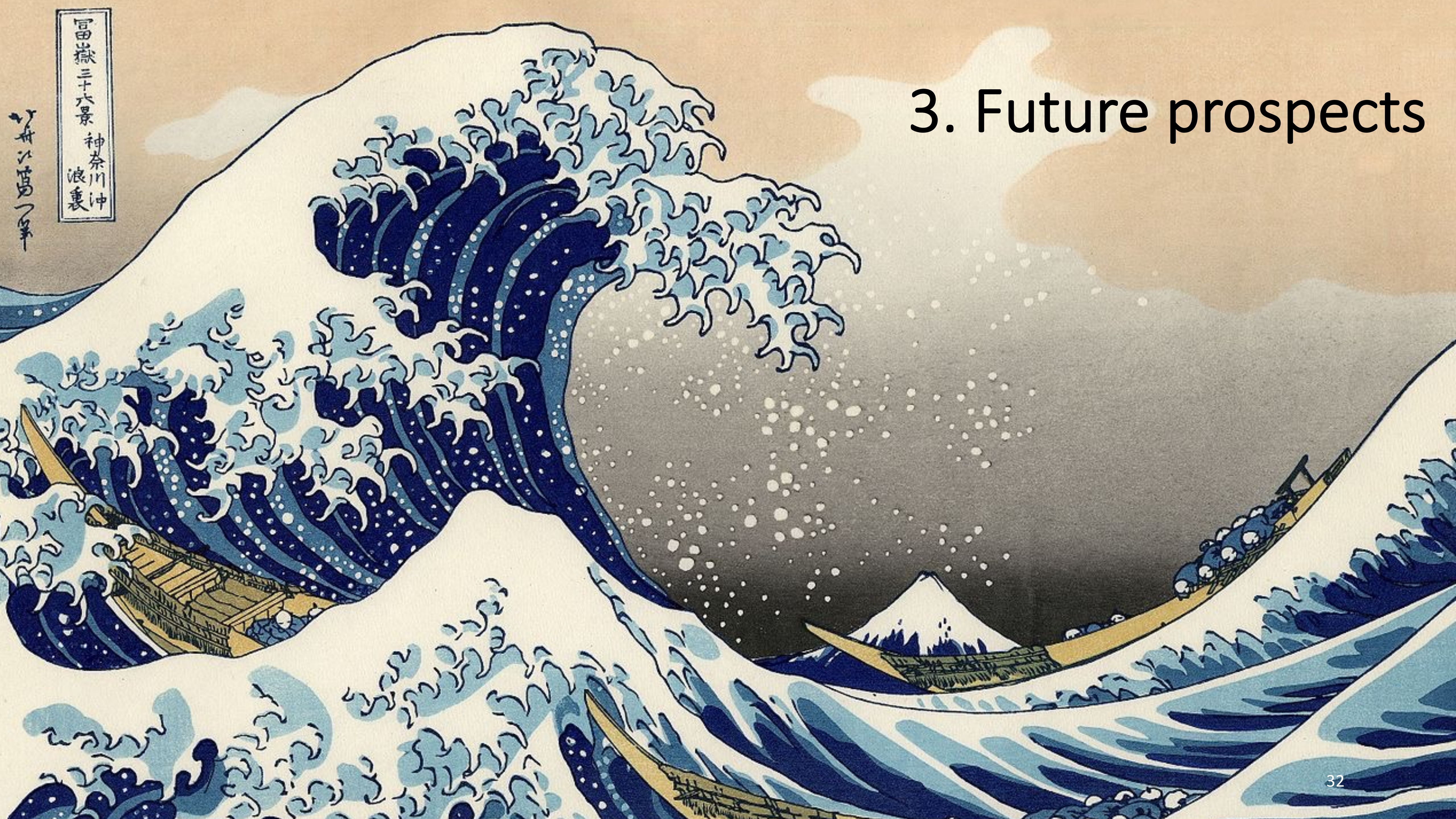
Anisotropic SGWB (anisotropies from astrophysical nearby sources) (Phys. Rev. D 104, 022005 - arXiv)

- Cosmological component possible (signals from inflationary period of early Universe, phase transition, PBH..), with different angular distributions for different models
- Analyses rely on cross-correlation

SNR maps consistent with Gaussian noise → upper limits on gravitational-wave energy flux from different sky directions

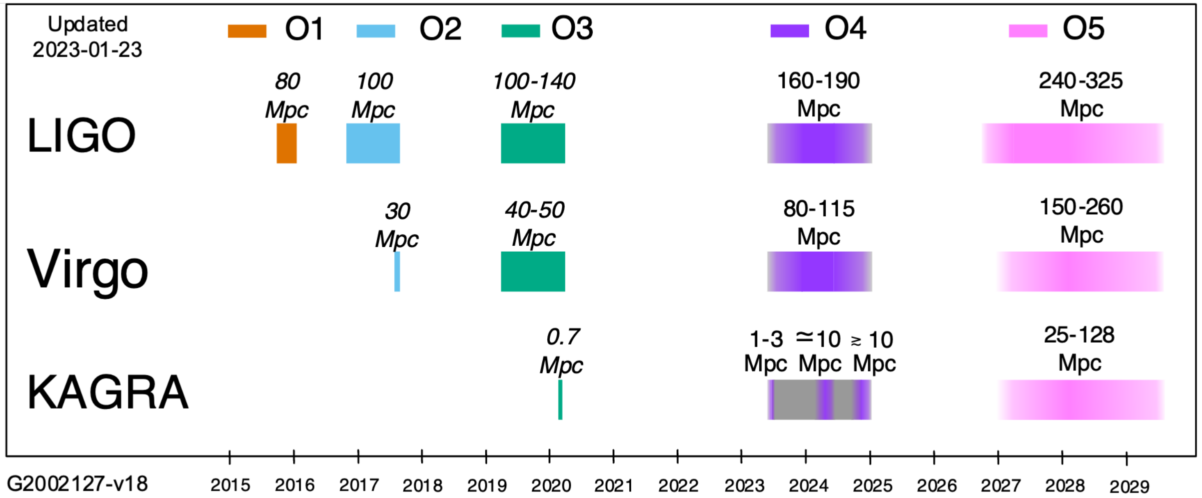


3. Future prospects



A look at the future – O4

- O4 starts **May 24th**, engineering run starts **this Wednesday !**
- 18 (+2) months, better sensitivities
- First 9 months data released August 2025, second 9 months data released May 2026
- LIGO improved optical squeezing, increased laser power
- Virgo improved optical squeezing, new signal recycling, increase of laser power.
- O4 target sensitivity ~met for LIGO, Virgo is still struggling



A look at the future – O4

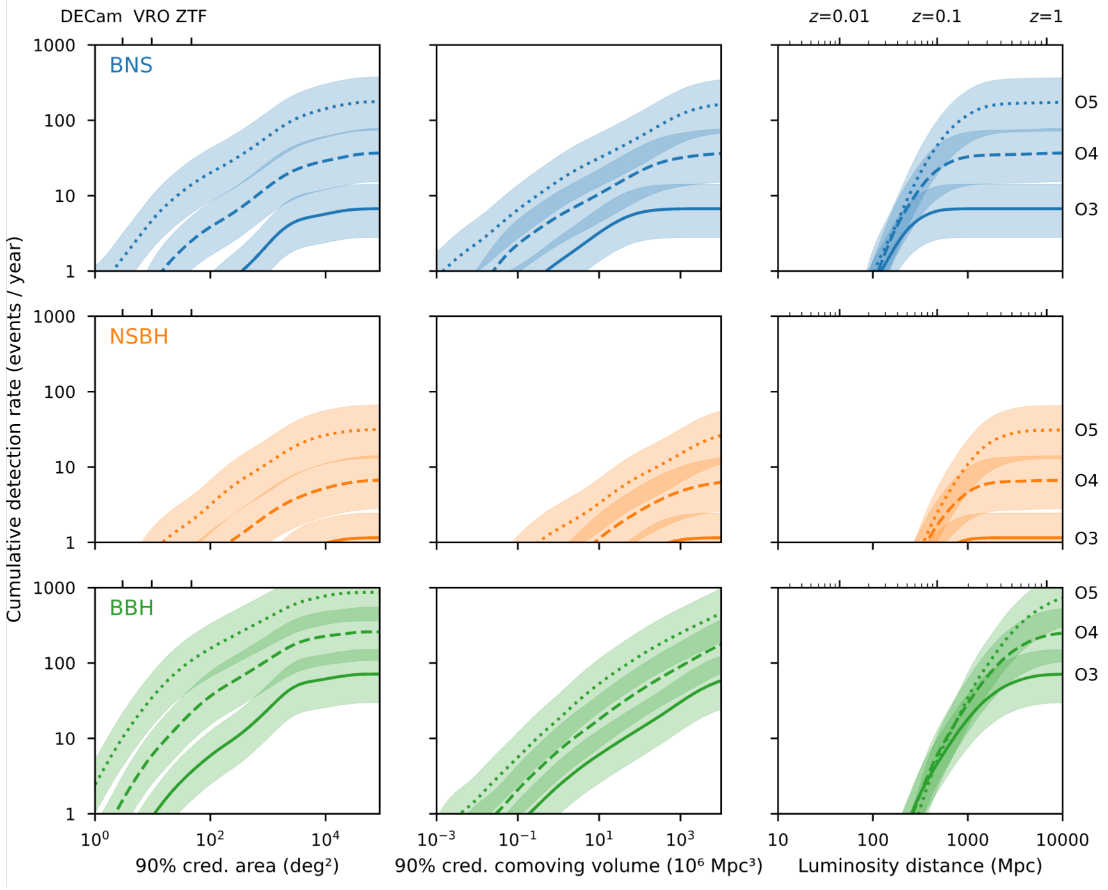
See talk by Nicolas

Assumptions:
- Design sensitivities
- Network SNR >8
- Merger rate (Gpc^{-3} yr^{-1}) from GWTC3

BNS	NSBH	BBH
$m_1 \in [1, 2.5] M_\odot$	$m_1 \in [2.5, 50] M_\odot$	$m_1 \in [2.5, 100] M_\odot$
$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 100] M_\odot$
170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$

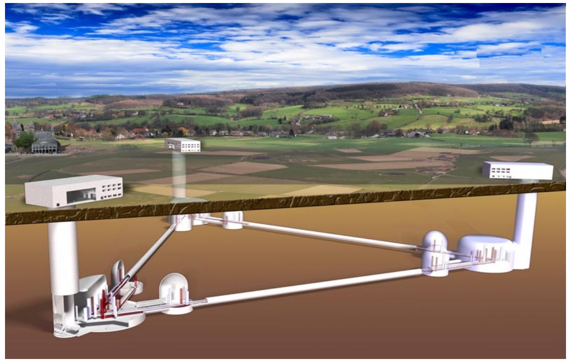
	BNS	NSBH	BBH
Annual number of public alerts	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
Median luminosity distance (Mpc)	398^{+15}_{-14}	770^{+67}_{-70}	2685^{+53}_{-40}
Median 90% credible area (deg^2)	1860^{+250}_{-170}	2140^{+480}_{-530}	1428^{+60}_{-55}

More details here

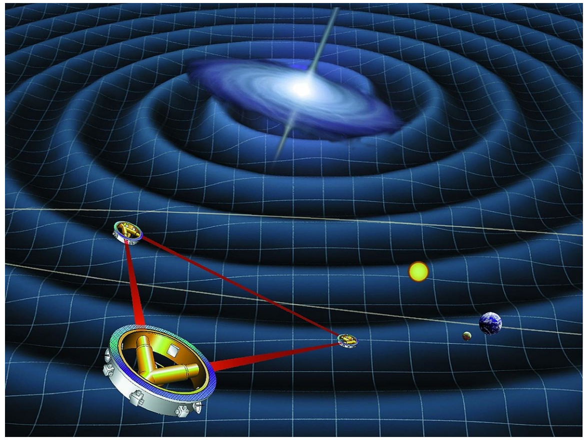


A look at the future – beyond O4

- Future generation ground-based detectors (~2035?)
  - Einstein Telescope (Europe) – see talk by Patrice
  - Cosmic Explorer (USA)
  - → better sensitivity, lower noise, signal-dominated data



- LISA space-based interferometer (launch ~2037)
  - Sensitivity to events involving super-massive BH (lower frequencies)



Useful links

- Follow latest news on ligo.org, OpenLVKEM
- Follow the alerts (gracedb.ligo.org, usersguide)
- Help identifying glitches (gravity spy)
- Gravitational Wave Open Science Center (GWOSC)
- Learn more about GW science following an Open Data workshop (May 15-17 @IP2I)
- Public data
  - Check out the LVK detections here
  - Analyse yourself the bulk data here

Conclusions

O3 (2019-2020) big success and change of gear for the LIGO-Virgo-KAGRA collaborations

- Many varied scientific results
  - 90 high-probability CBC candidates since first detection
  - Unfortunately only one EM counterpart observed until now (GW170817)
  - Constraints on sources populations and rates, tests of GR, cosmology
  - Searches performed for (non-CBC) bursts, CW emission, SGWB, DM..
  - Although no evidence (other than CBC) for the moment, sensible improvements in constraints

- GW astronomy is entering the era of statistics accumulation
- GW remain a newcomer among the Universe messengers – still room for unexpected !

In the future

- Larger interferometers networks, more data
- New observatories on earth and in space
- Exciting science !