Highlights from the results of the gravitational wave observing run O3 (so far!)

Monica Seglar-Arroyo on behalf of the Virgo Collaboration
L.A.P.P. Universite Savoie Mont-Blanc
ENIGMASS plenary meeting
28th October 2021

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).

General news from observing run O3

GWTC-2, Abbott, R., et al. *PRX* 11.2 (2021): 021053

- 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, 3 interferometers (ITF), during O3a:

Virgo	LIGO-L	LIGO-H
76%	76%	71%

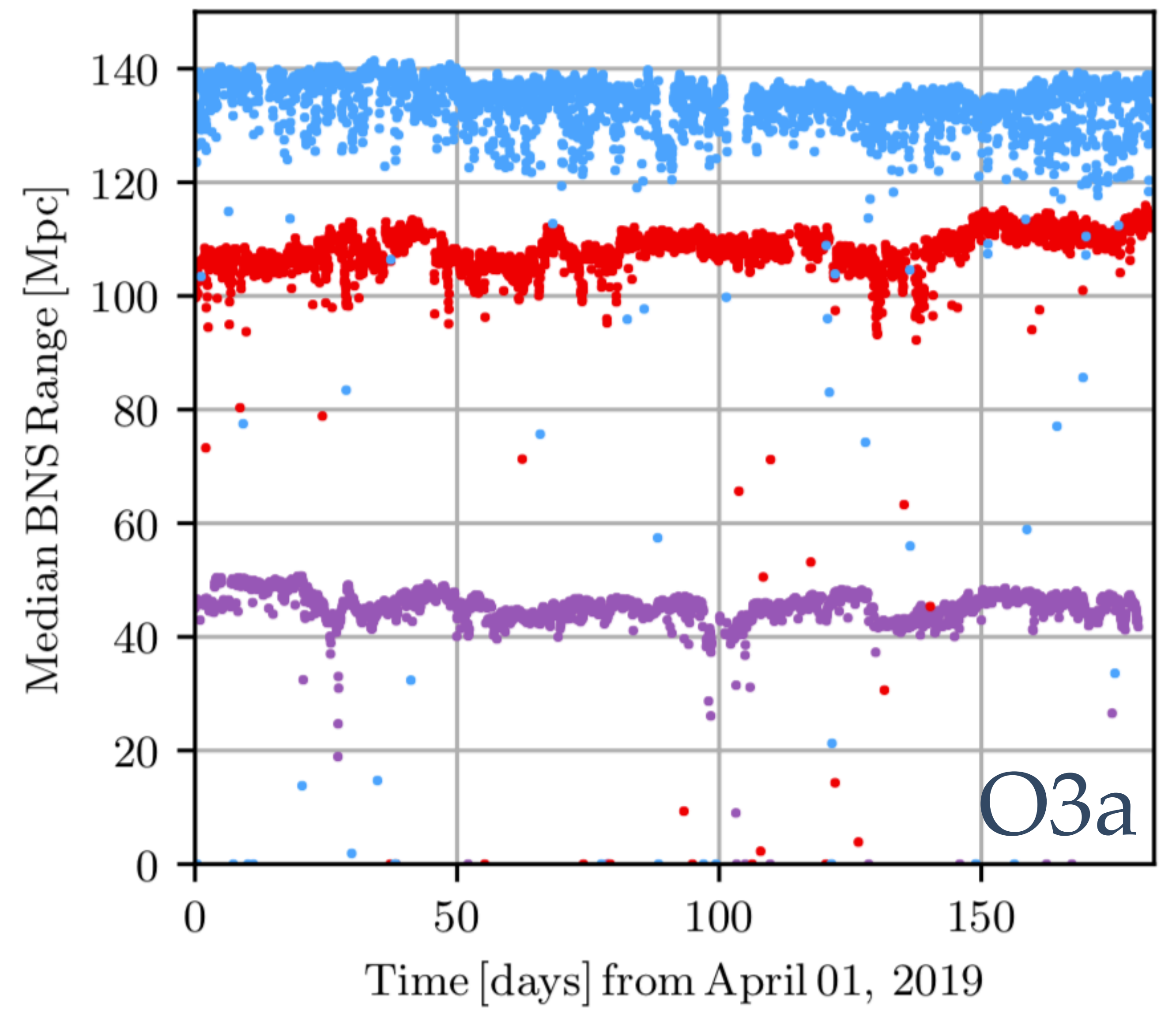
→

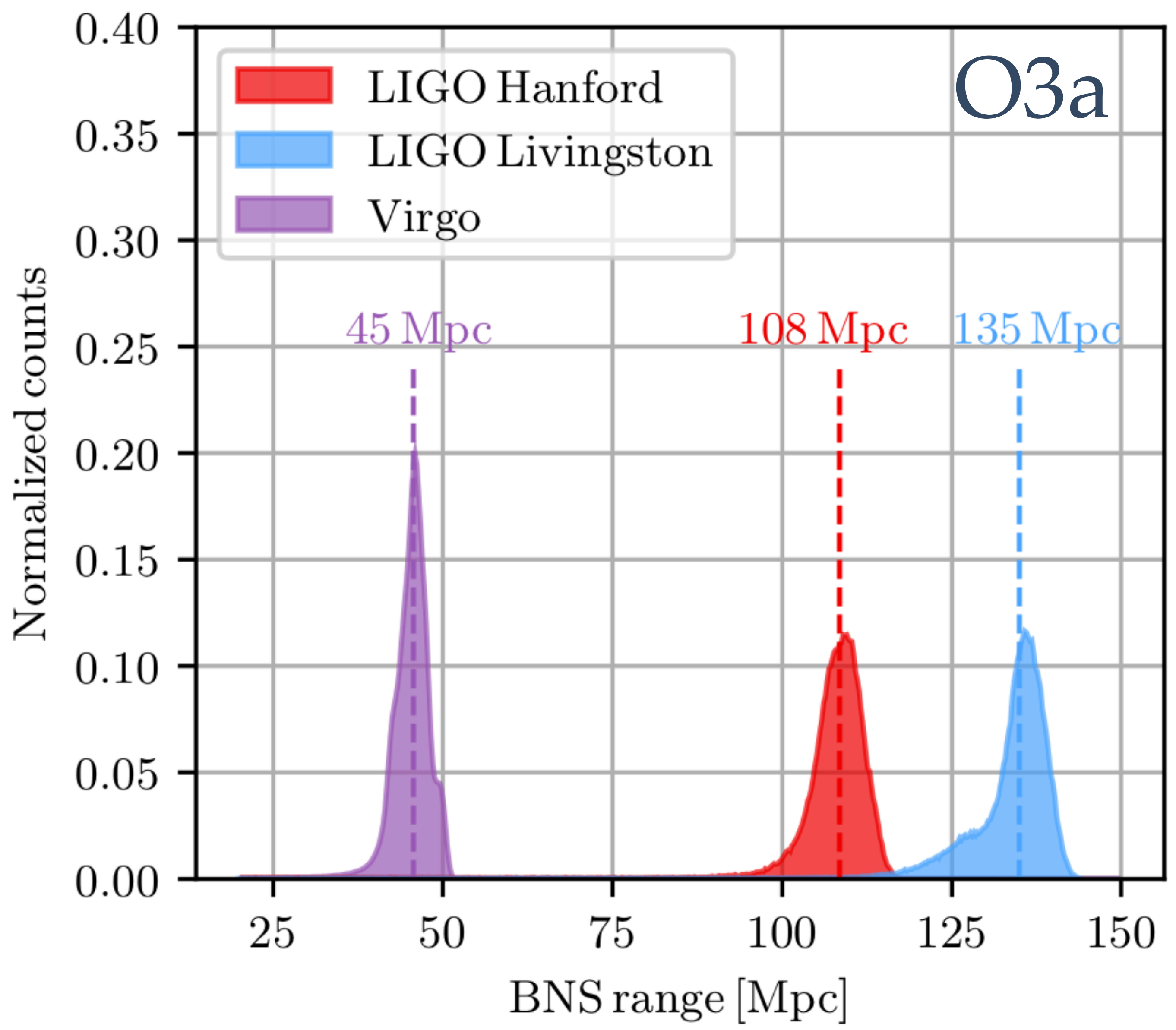
At least 1-ITF	At least 2-ITF	3-ITF
96.9%	81.9%	44.5%

- Alerts online: A total of 56 online candidates after 24 retractions in O3 (26 during O3a)
  - Distributed via **GCN Notices and Circulars**, in **gracedb.ligo.org** and via **Chirp App**
    - BBH(38), BNS(6), BH-NS (5), MassGap (4), Terrestrial(3) events

- **O3a data are public and O3b will be soon, check GWOSC** (https://www.gw-openscience.org)

Results in this talk from O3a, O3b results to come in the future!





Published results by LIGO-Virgo-KAGRA from 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

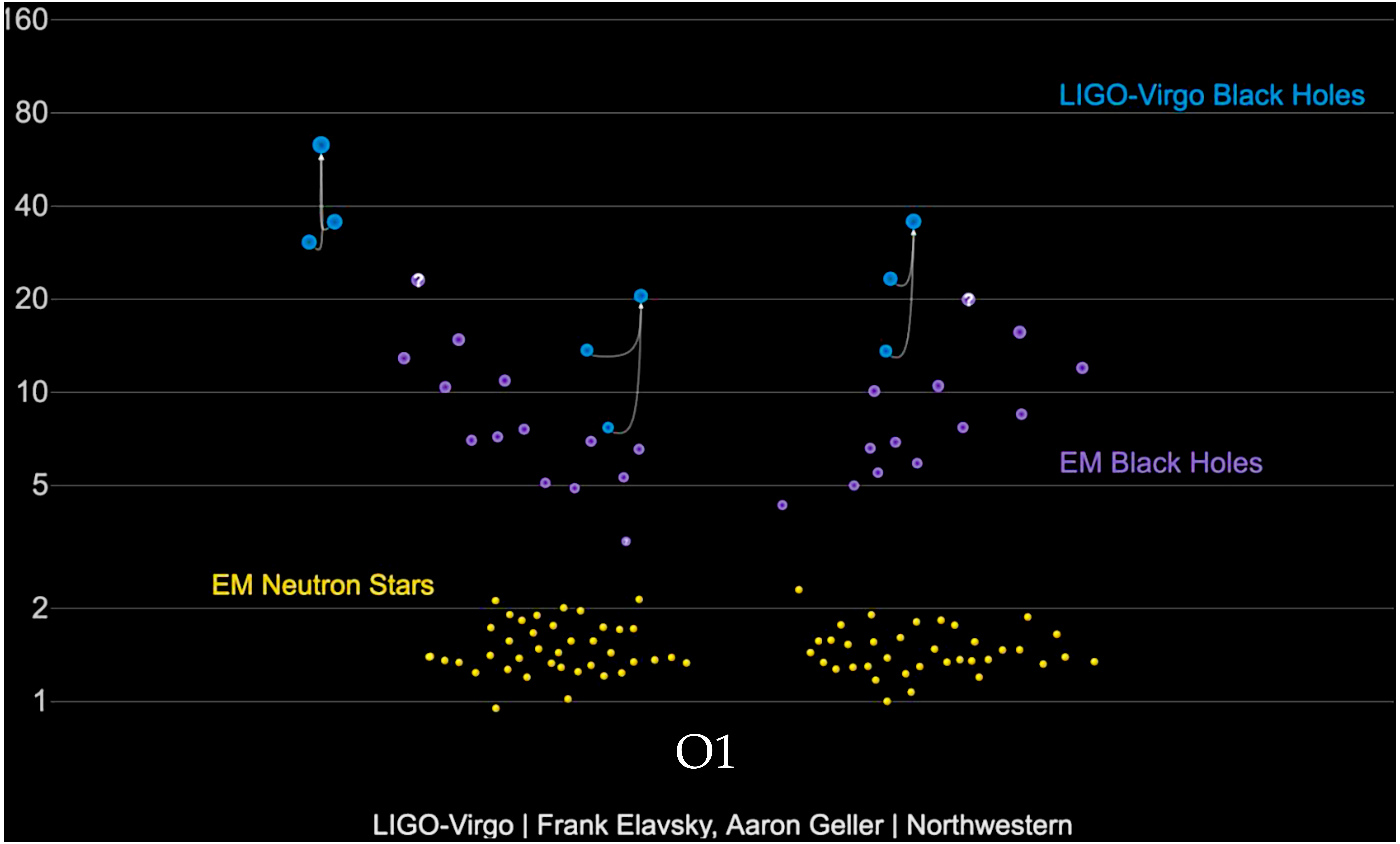
- Continuous waves
  - All-sky binaries (link)
  - All-sky isolated (link)
  - SN remnants (link)
  - Targeted J0537-6910 (link)
  - Accreting millisecond X-ray pulsars (link)
- Stochastic (gravitational-wave backgrounds)
  - O3 isotropic (link)
  - O3 anisotropic (link)

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)

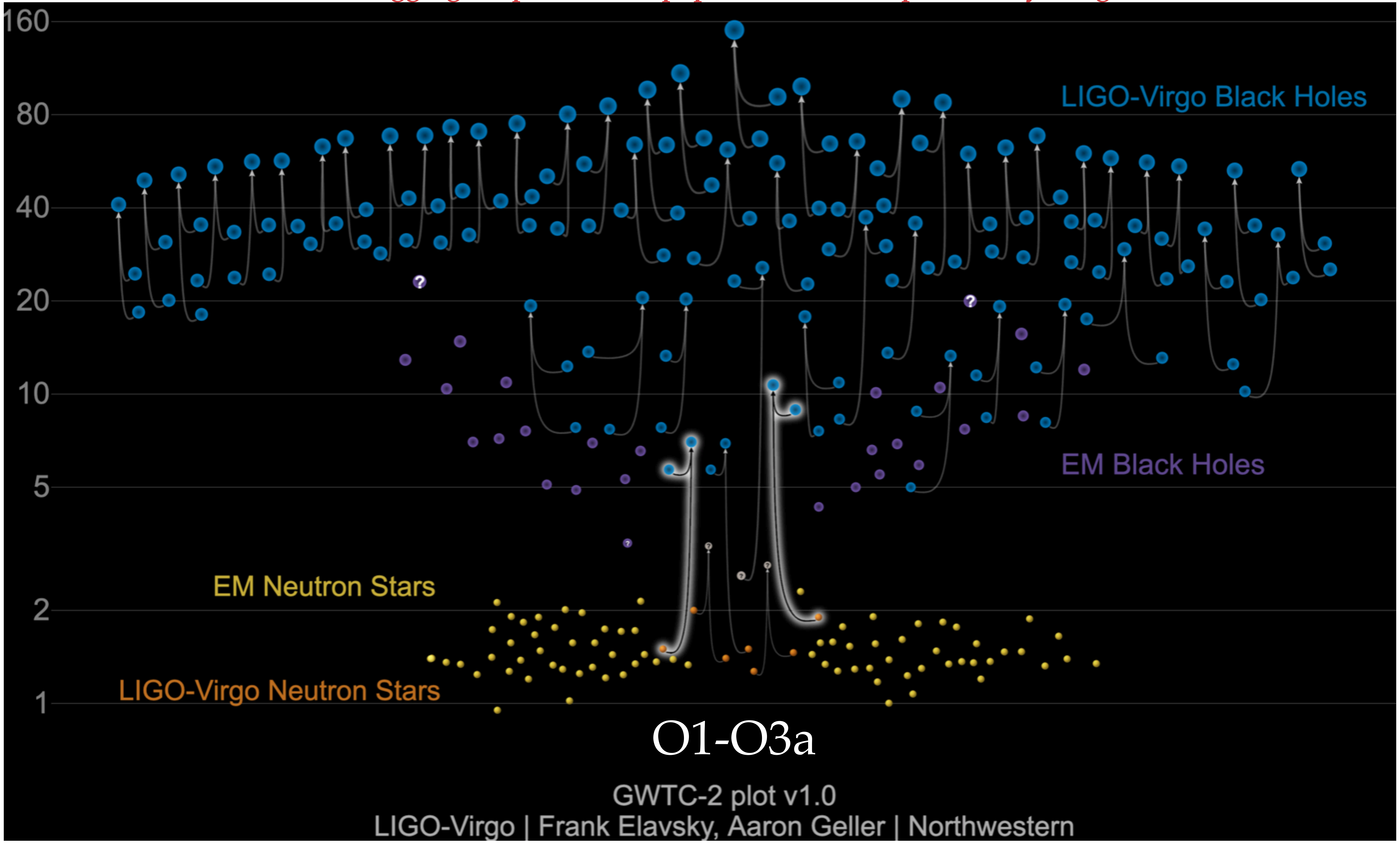
GW astronomy is here - LOTS of results in really different fields!

From O1 to GWTC-2: detected compact binary coalescenses



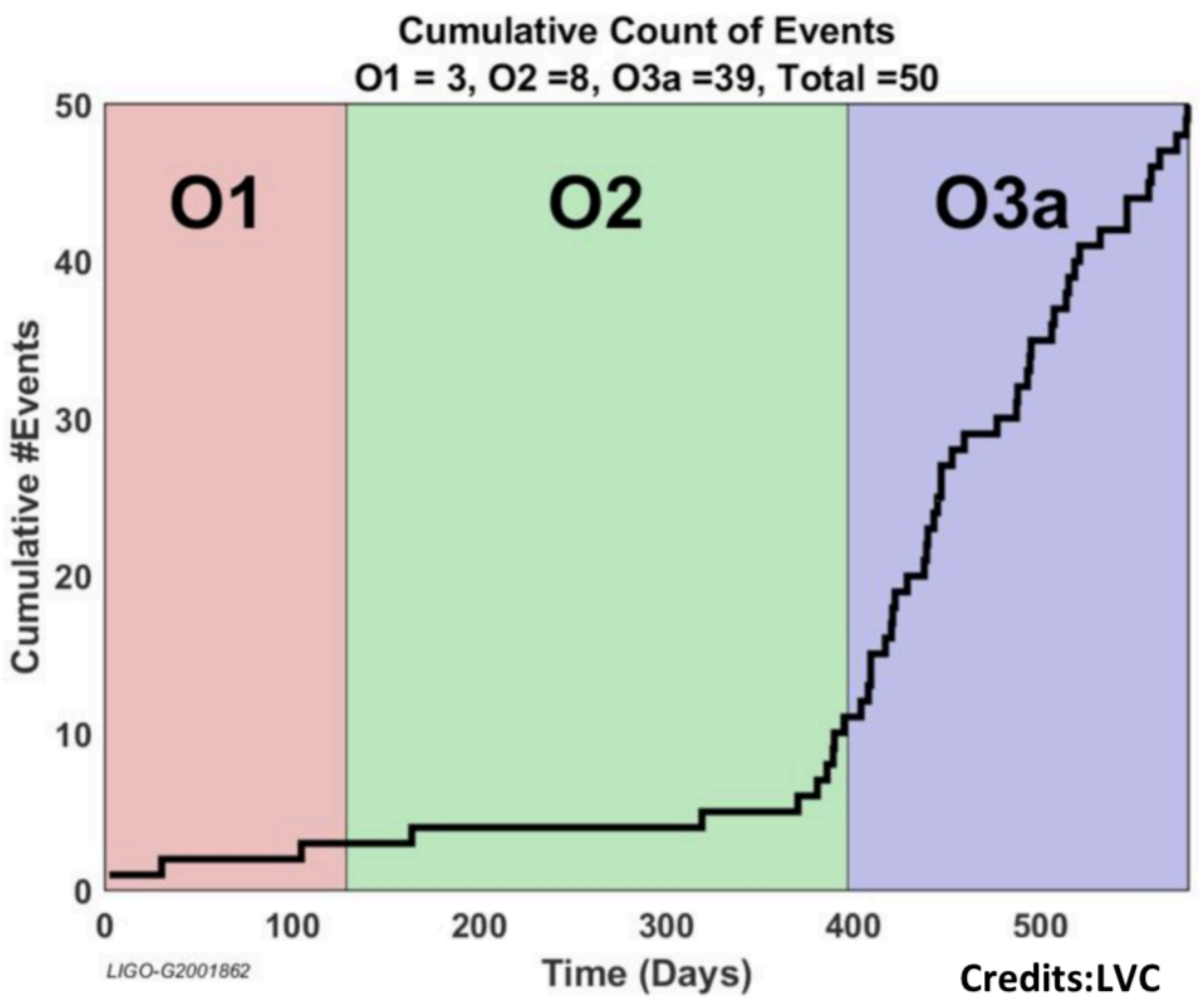
From O1 to GWTC-2: detected compact binary coalescenses

If O2 was marked by GW170817 and first joint LIGO-Virgo detections, O3 can be summarized as the observing run of an exploding number of CBC => digging deeper into the populations of compact binary mergers !



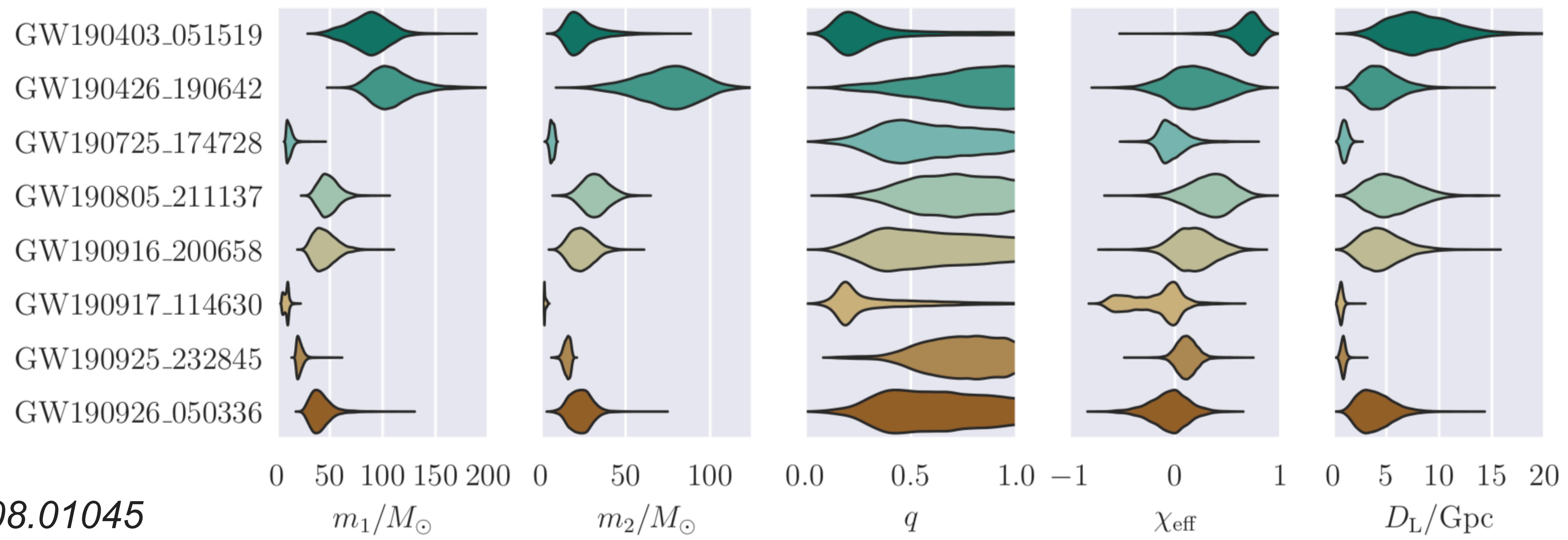
Catalog paper GWTC-2.1 (O3a)*

- Two Gravitational Wave Transient Catalogs (GWTC) for O3 with different FAR:
  - GWTC-2 => False Alarm Rate (FAR) 2/yr
    - Pipelines: cWB, GstLAL, PyCBC
    - Total of **39 candidates**
  - GWTC-2.1=> FAR 2/day + Improvements on calibration and data quality
    - Pipelines: GstLAL, PyCBC, **MBTA**
    - Total of **1201 candidates**: **44 high-probability events (p_{astro}>0.5, 8 new events, 3 excluded)**
    - **Interesting subset for joint sub-threshold searches with other catalogs of events.**



Phys. Rev. X 11, 021053 (2021)

- Dedicated source parameter estimation analysis using Bayesian inference algorithms
  - Use bank of waveform models
  - Constrains on e.g. m1, m2, mass ratio, effective inspiral spin, luminosity distance.



arXiv:2108.01045

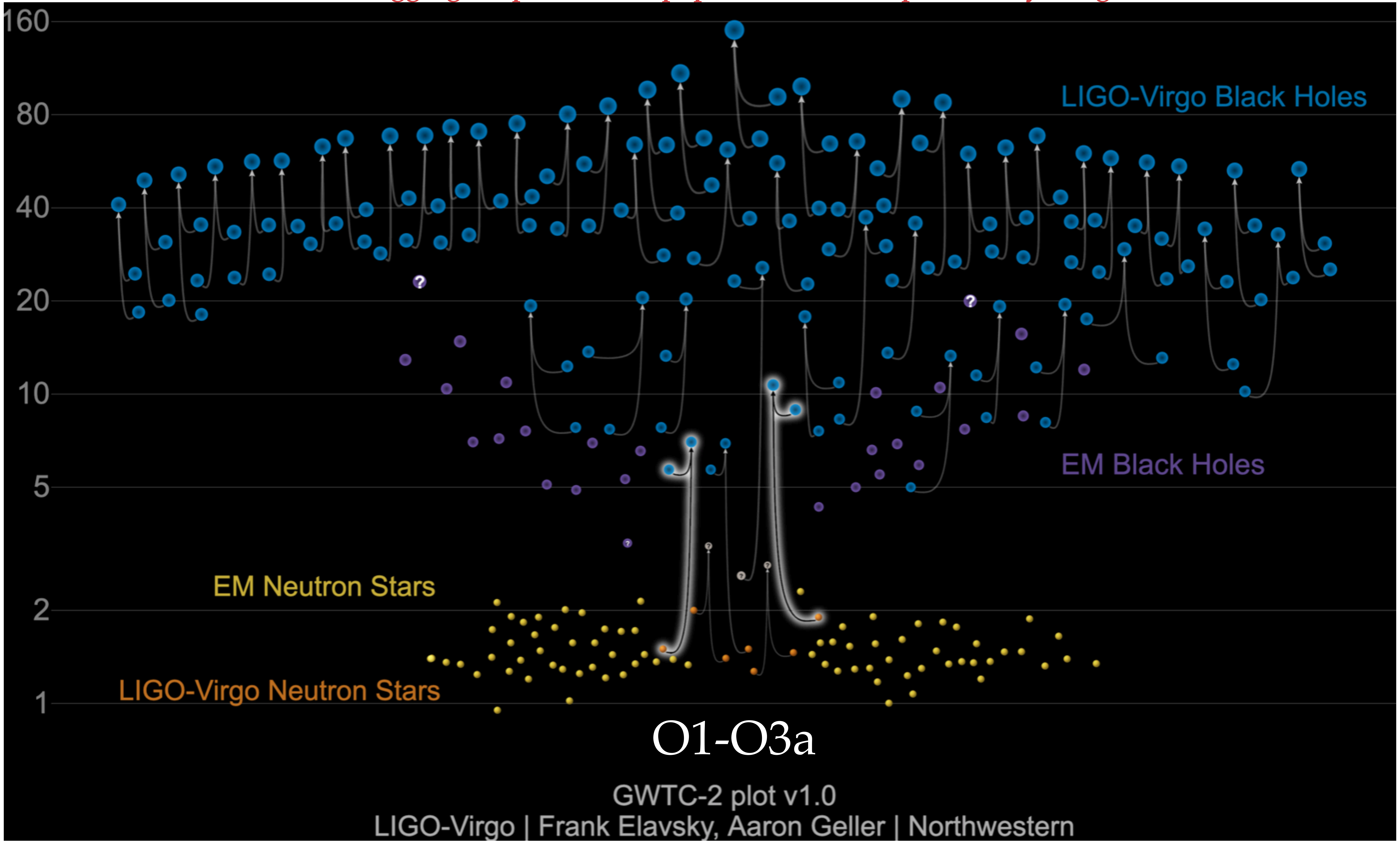
- Population paper: based on 47 CBC FAR < 1/yr (most significant ones)

R_{BBH}	R_{BNS}
$23.9^{+14.3}_{-8.6}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	$320^{+490}_{-240}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

ApJL **913** L7 (2021)

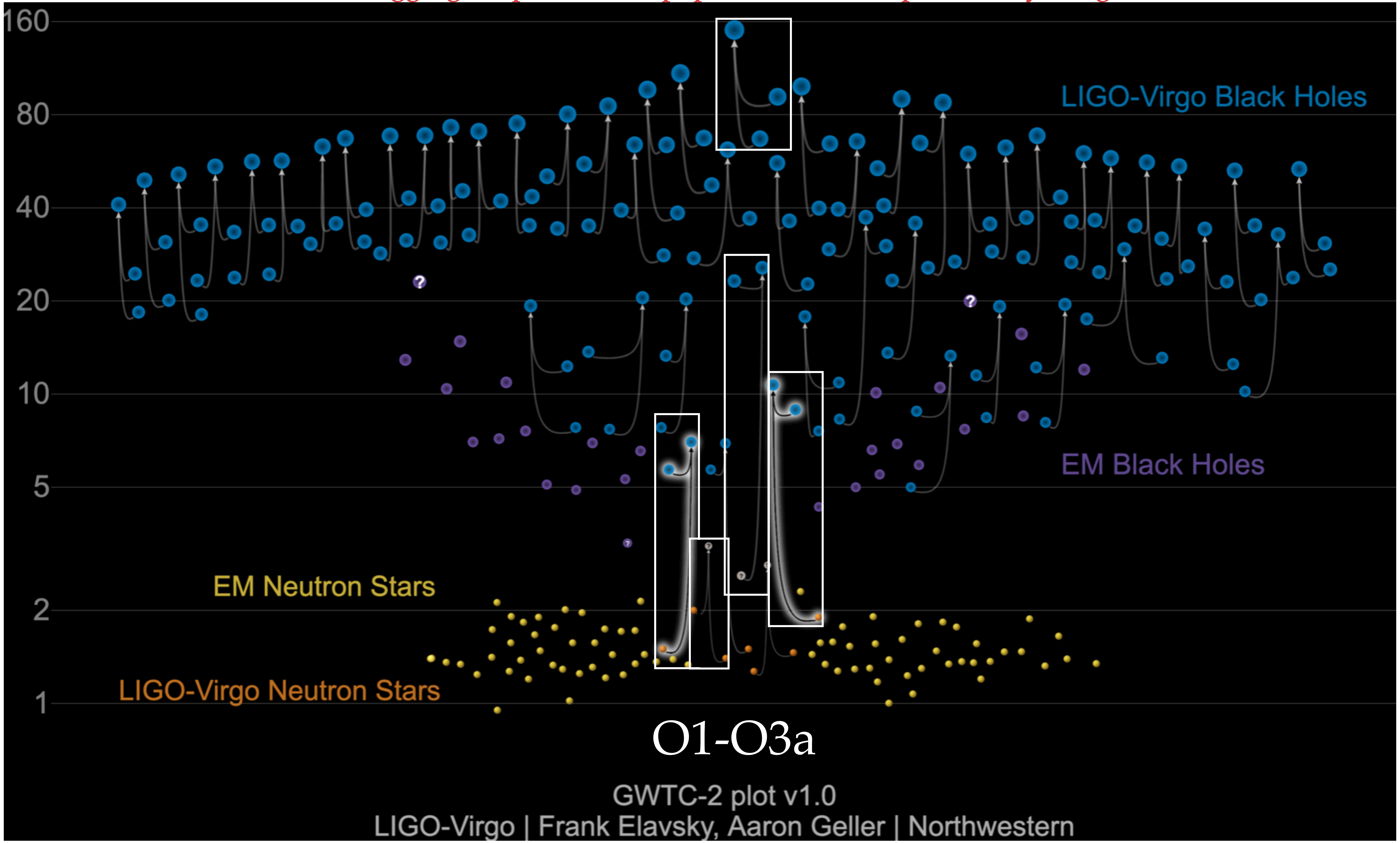
From O1 to GWTC-2: detected compact binary coalescenses

If O2 was marked by GW170817 and first joint LIGO-Virgo detections, O3 can be summarized as the observing run of an exploding number of CBC
=> digging deeper into the populations of compact binary mergers !



From O1 to GWTC-2: detected compact binary coalescenses

If O2 was marked by GW170817 and first joint LIGO-Virgo detections, O3 can be summarized as the observing run of an exploding number of CBC => digging deeper into the populations of compact binary mergers !



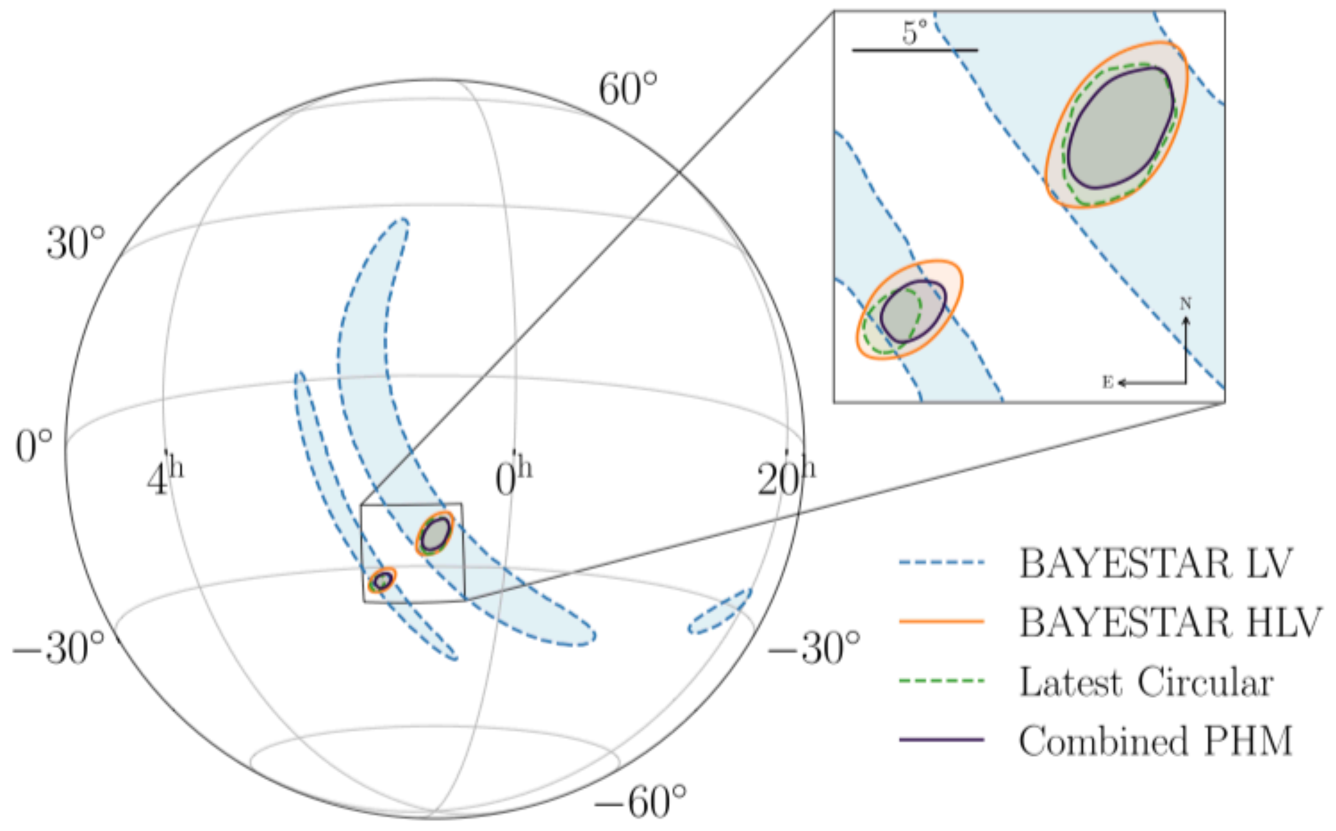
A largely asymmetric-mass system and an intermediate mass black hole

GW190814

ApJL **896** L44 (2020)

- $22.2 - 24.3 M_{\odot} + 2.50 - 2.67 M_{\odot}$ (classified as "Mass gap" event)
- Second mass in **the lower mass gap**, $2.5 - 5 M_{\odot}$ **between known NSs and BHs**, of the order of the remnant of GW170817
- SNR 25 (3ITF) - No EM or neutrino counterpart => consistent with mass ratio expectations
- Most **unequal mass ratio measured** yet:

  $0.112^{+0.008}_{-0.009}$ (average during O1 and O2 was $\simeq 0.9$)
- GW190814 poses a challenge for our understanding of the population of merging compact binaries i.e. order of magnitude less probable in isolated evolution scenarios, low metallicity needed in dynamical scenarios



GW190521

Phys. Rev. Lett. 125, 101102 (2020)

- 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** (IMBH, between stellar-mass $< 100 M_{\odot}$ and supermassive BH $> 10^5 M_{\odot}$) as **remnant**
  - Ongoing discussion on the binary formation: results point to a dynamical origin
- The **progenitor masses** seem to be in the **pair-instability mass gap** (~ 60-120 $M_{\odot}$, at which the supernova explotion leaves *no remnant*)
  - Ongoing discussion on BH formation: OK if accounting for uncertainties of the SN process

Phys. Rev. Lett. 124, 251102 (2020)

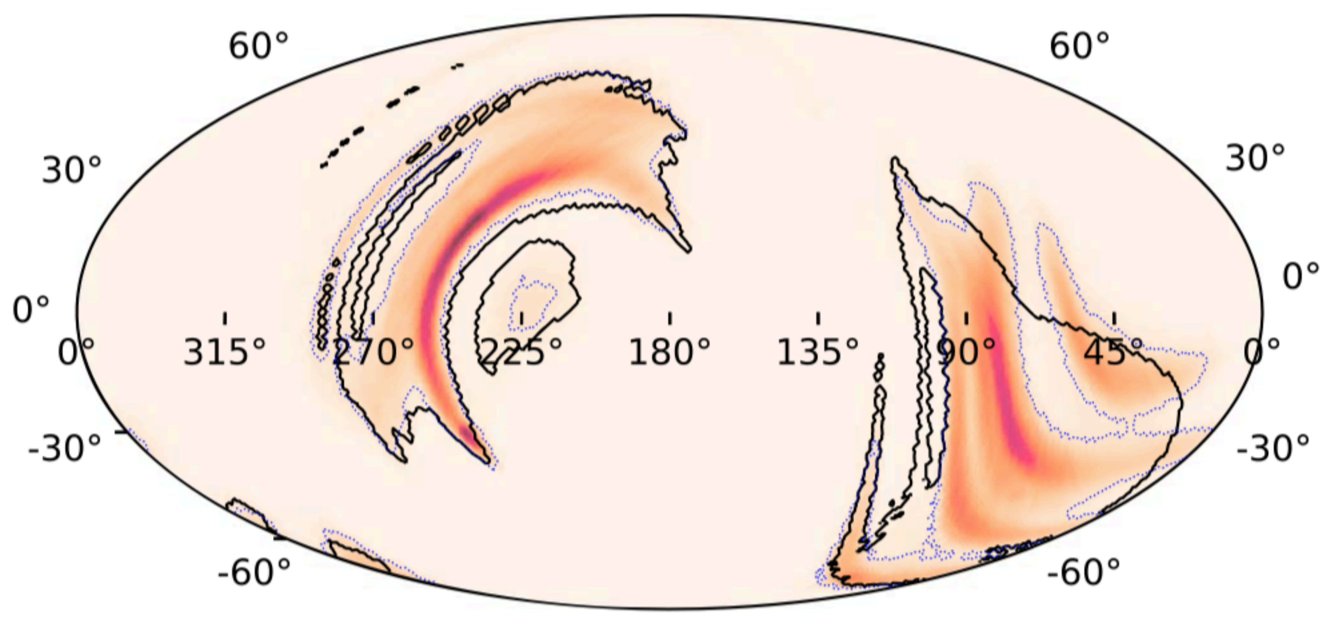
Candidate of optical EM-conterpart

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

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 $:3.4^{+0.3}_{-0.1} M_\odot$
  - **Assuming that it is a BNS:**
    - 5 sigma deviation from total mass and the chirp mass of known 10 galactic binaries expected to merge within Hubble Time
      - Difficult to be explained by the isolated binary evolution channels due to such high masses

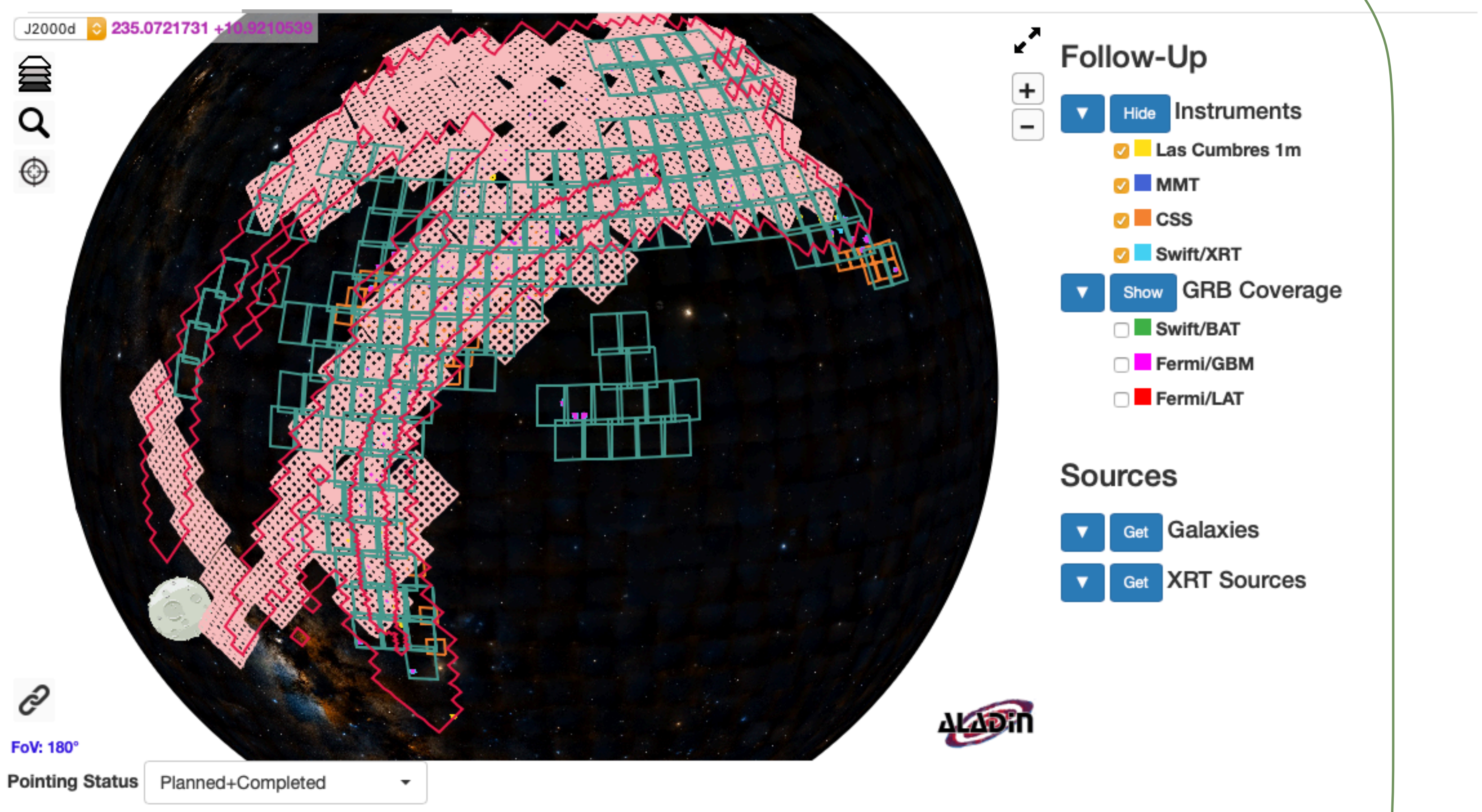
GW190425



$2.0^{+0.6}_{-0.3} M_\odot + 1.4^{+0.3}_{-0.3} M_\odot$ $d_L = 159^{+69}_{-72}$ 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
  - Poor constraints on the binary inclination: GRB-jet not oriented in our line of sight?
  - 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/

BH-NS systems: GW200105, GW200115

- Last of the CBC possible combinations detected in January 2020 (O3b): two NS-BH detected events!

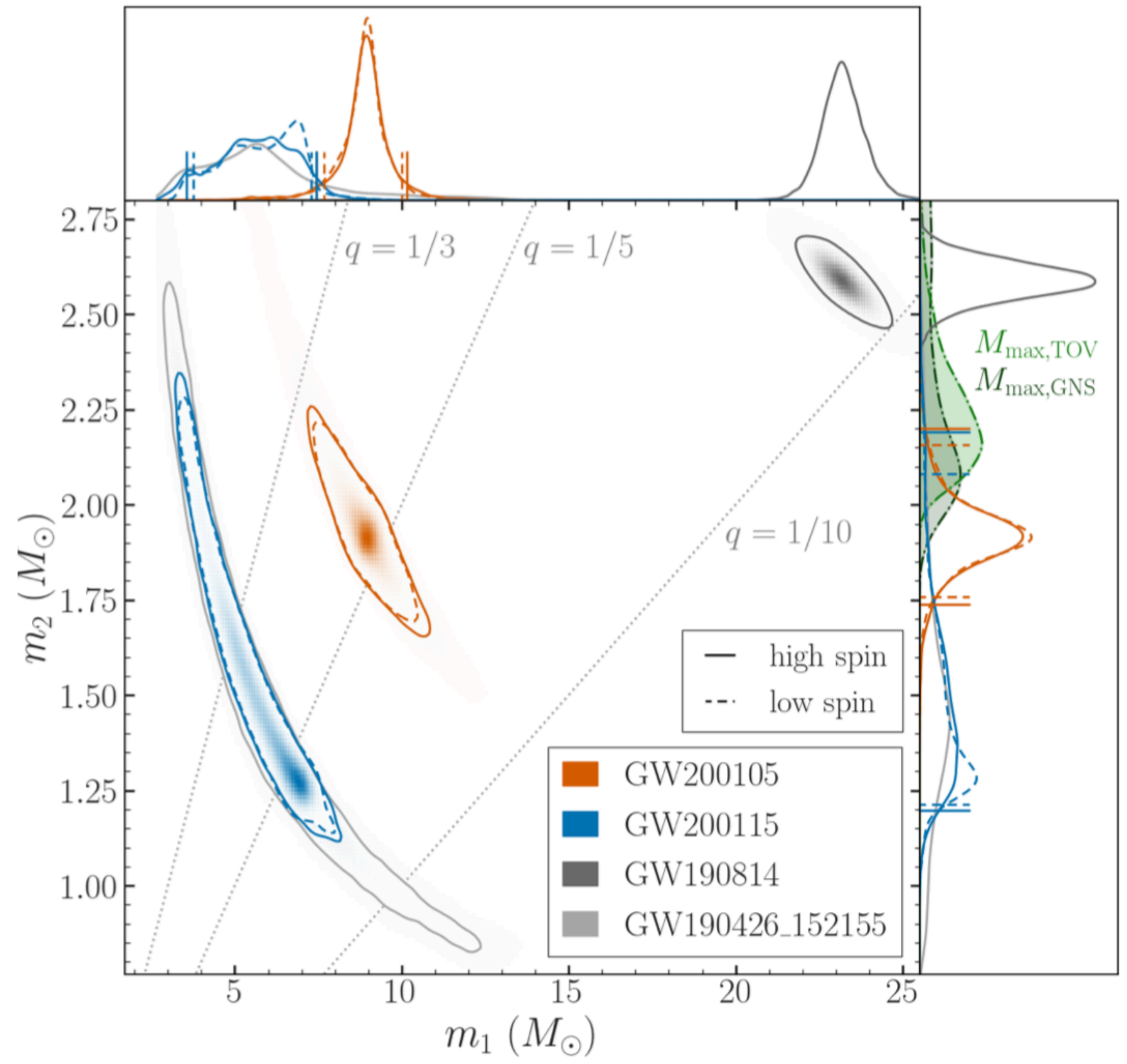
GW200105
- LL+Virgo
- $8.9^{+1.2}_{-1.5} M_\odot + 1.9^{+0.3}_{-0.2} M_\odot$
- $d_L = 280^{+110}_{-110}$ Mpc

GW200115
- LL, LH+Virgo
- $5.7^{+1.8}_{-2.1} M_\odot + 1.5^{+0.7}_{-0.3} M_\odot$
- $d_L = 300^{+150}_{-100}$ Mpc

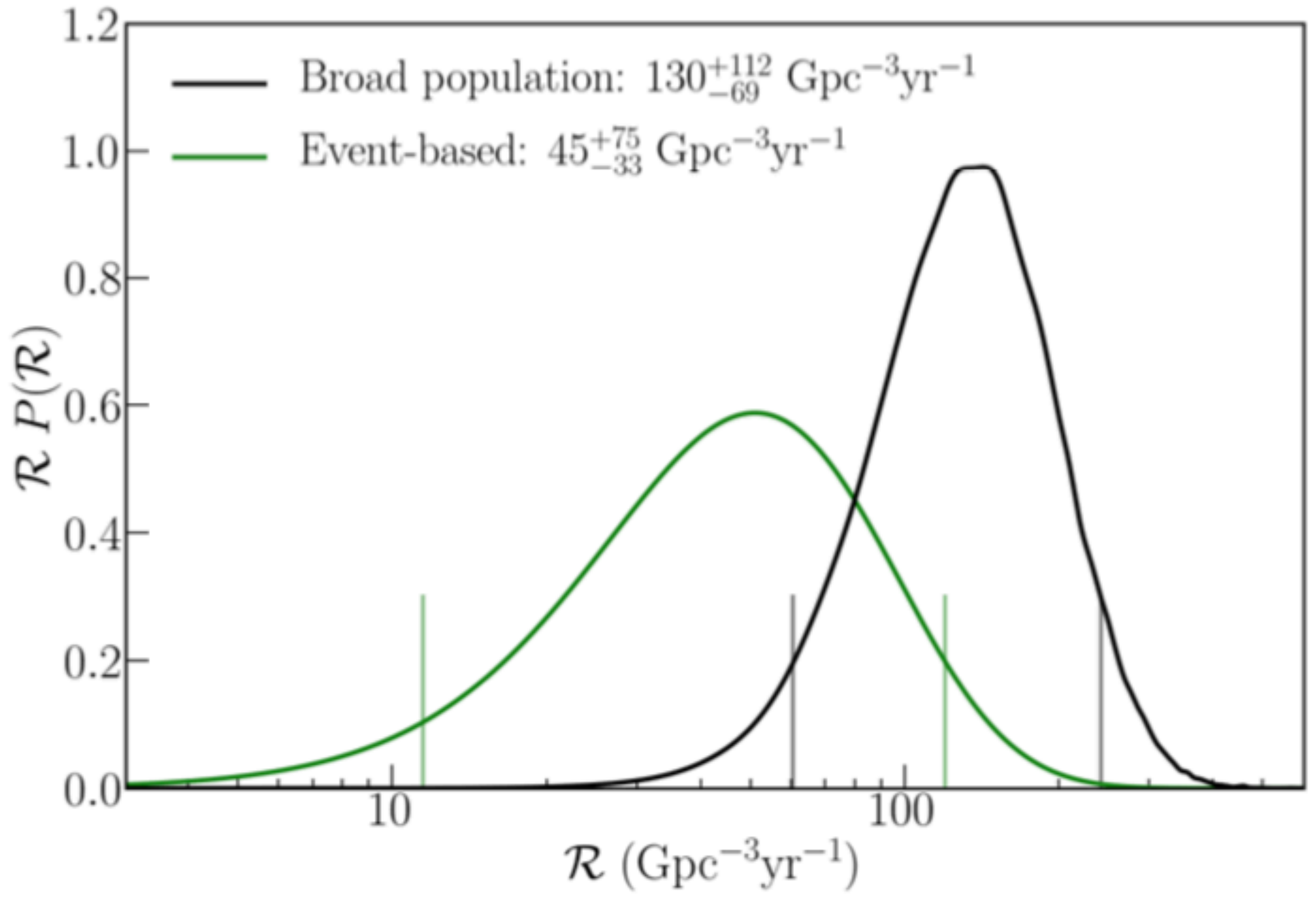
- The properties of the binaries are consistent with a NS-BH merger:
  - No imprint of tidal deformability in the GW (although their spins make that no tidal disruption is expected + SNR too low)
  - Mass of the less massive object consistent with maximum NS mass and known galactic NS
  - No EM counterpart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

  - Event rate estimation:
    - Event-based estimates: assumming all NS-BH are like these two (lower limit)
    - Broad population estimates: these two+GW190814+large BH/NS mass range (upper limit)
    - Rates consistent with several formation scenarios: both isolated binary evolution and dynamical formation, either in young star cluster, AGN disks)

ApJL **915** L5 (2020)



Probability distribution for the NSBH merger rate density

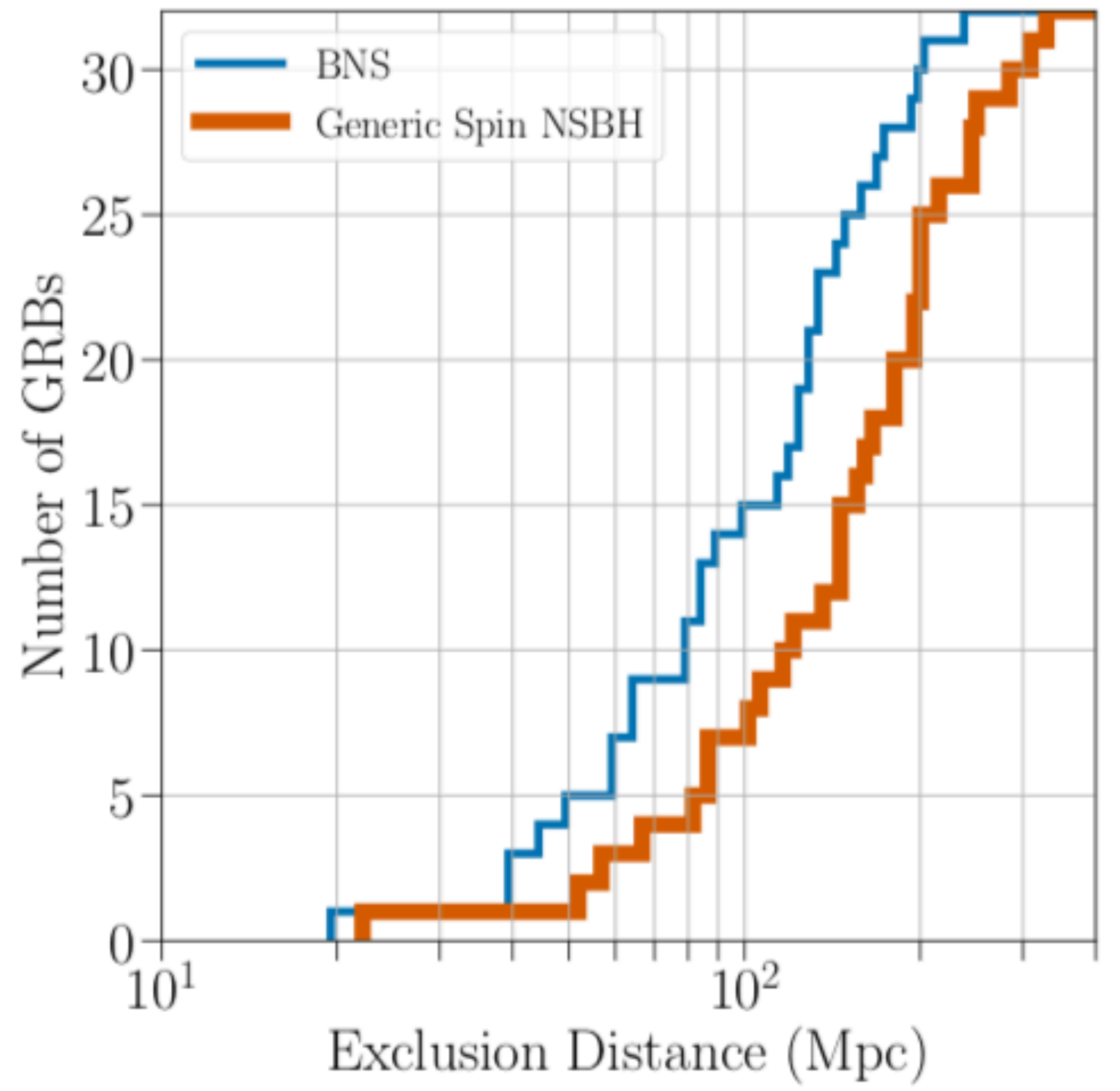


GRB follow-ups in O3a

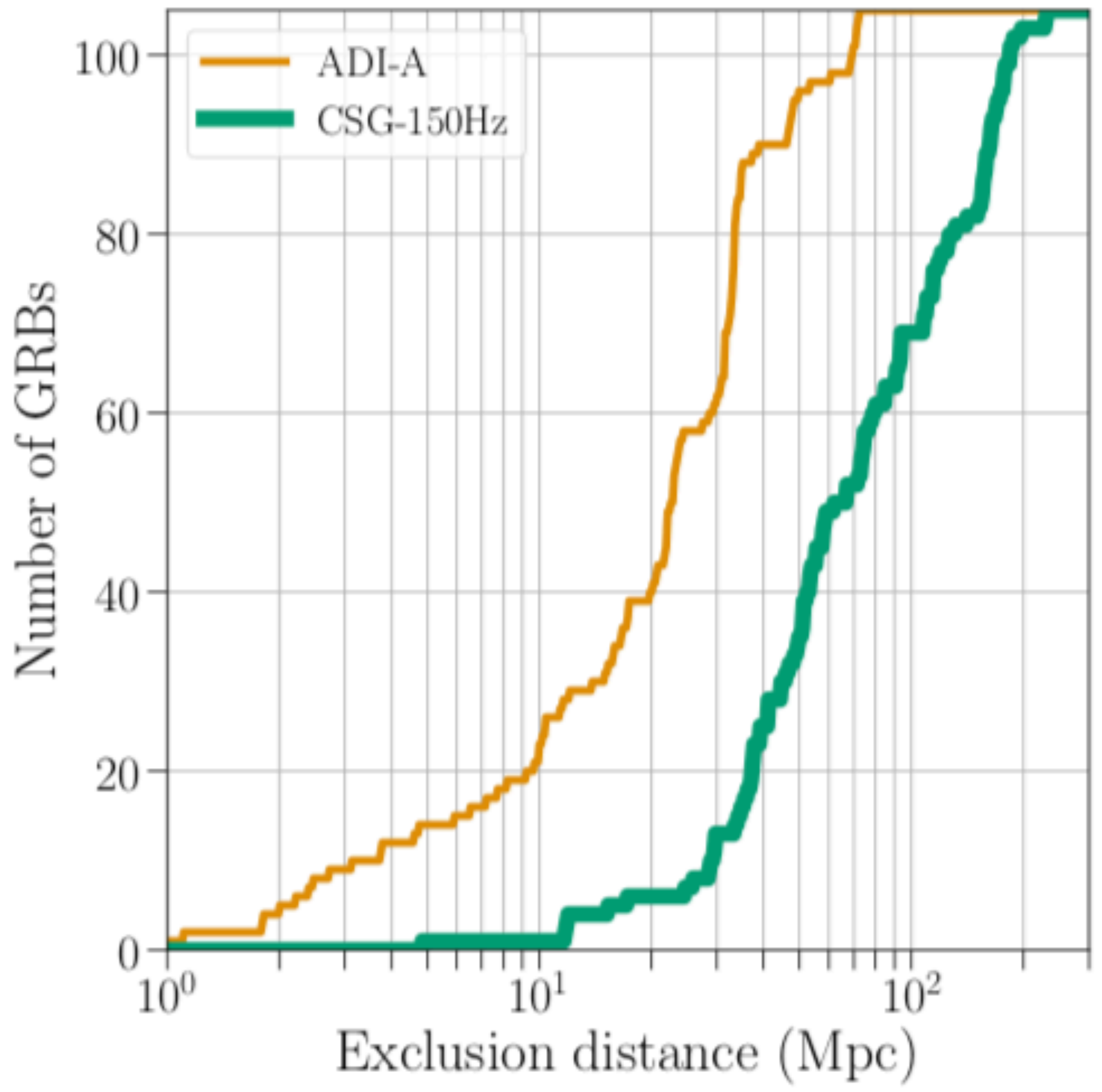
ApJL 915, 86 (2021)

- 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): **32 GRBs** analyzed (short+ambiguous)
    - Generic coherent GW transient search: all the sample, total of **105 GRBs** analyzed
      - Excess power that is coherent across the network of GW detectors + clusters in time-frequency power maps
  - **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

32 short and *ambiguous* GRBs (targeted search)



105 all sample of GRBs (generic search)



Modeled search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins	
D_{90} [Mpc]	119	160	231	
Unmodeled search (All GRBs)	**CSG 70 Hz**	**CSG 100 Hz**	**CSG 150 Hz**	**CSG 300 Hz**
D_{90} [Mpc]	146	104	73	28

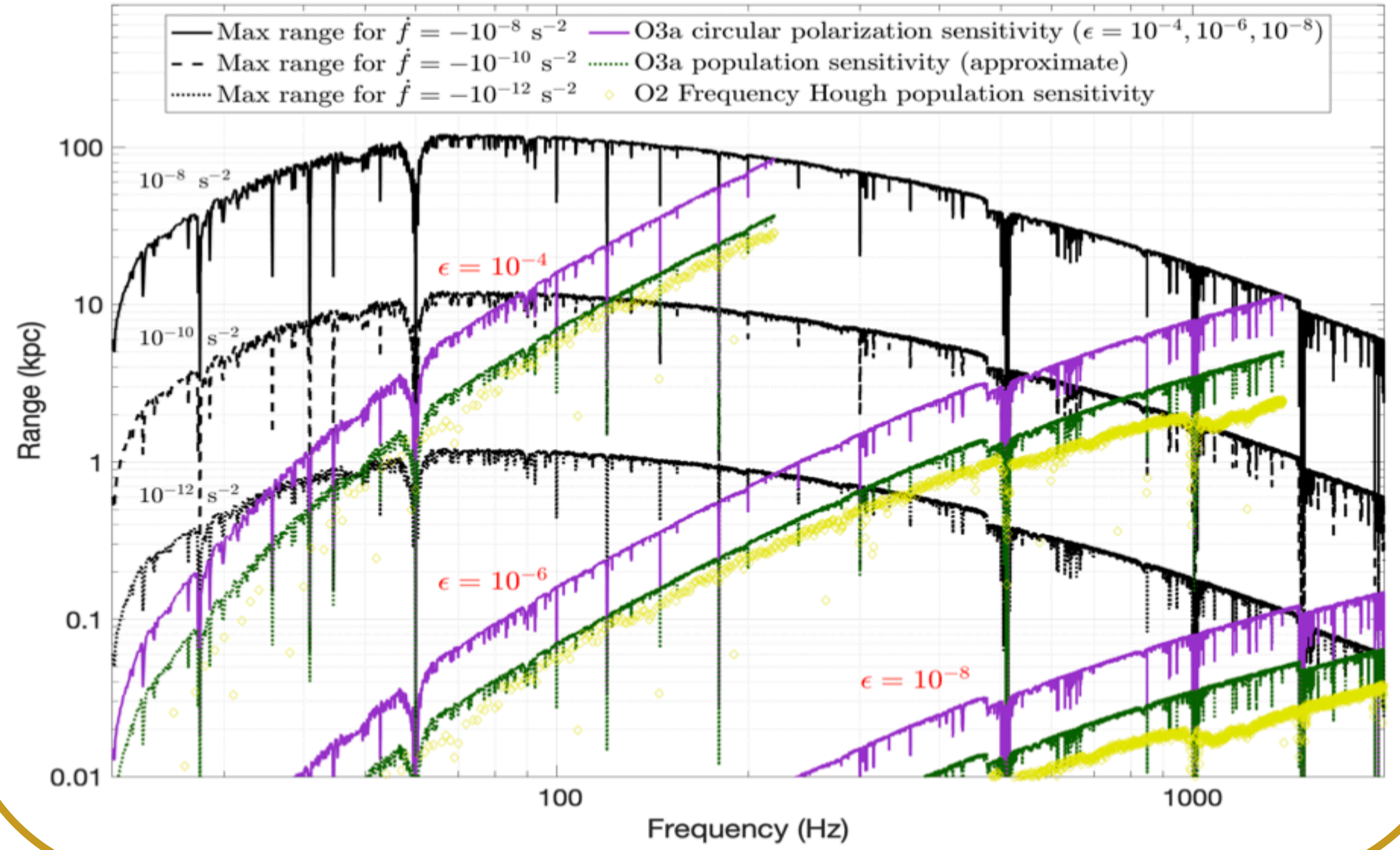
Unmodeled search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]	23	123	28	11	33

Continuous waves search

Phys. Rev. D 104, 082004 (2021)

All-sky isolated CW O3a

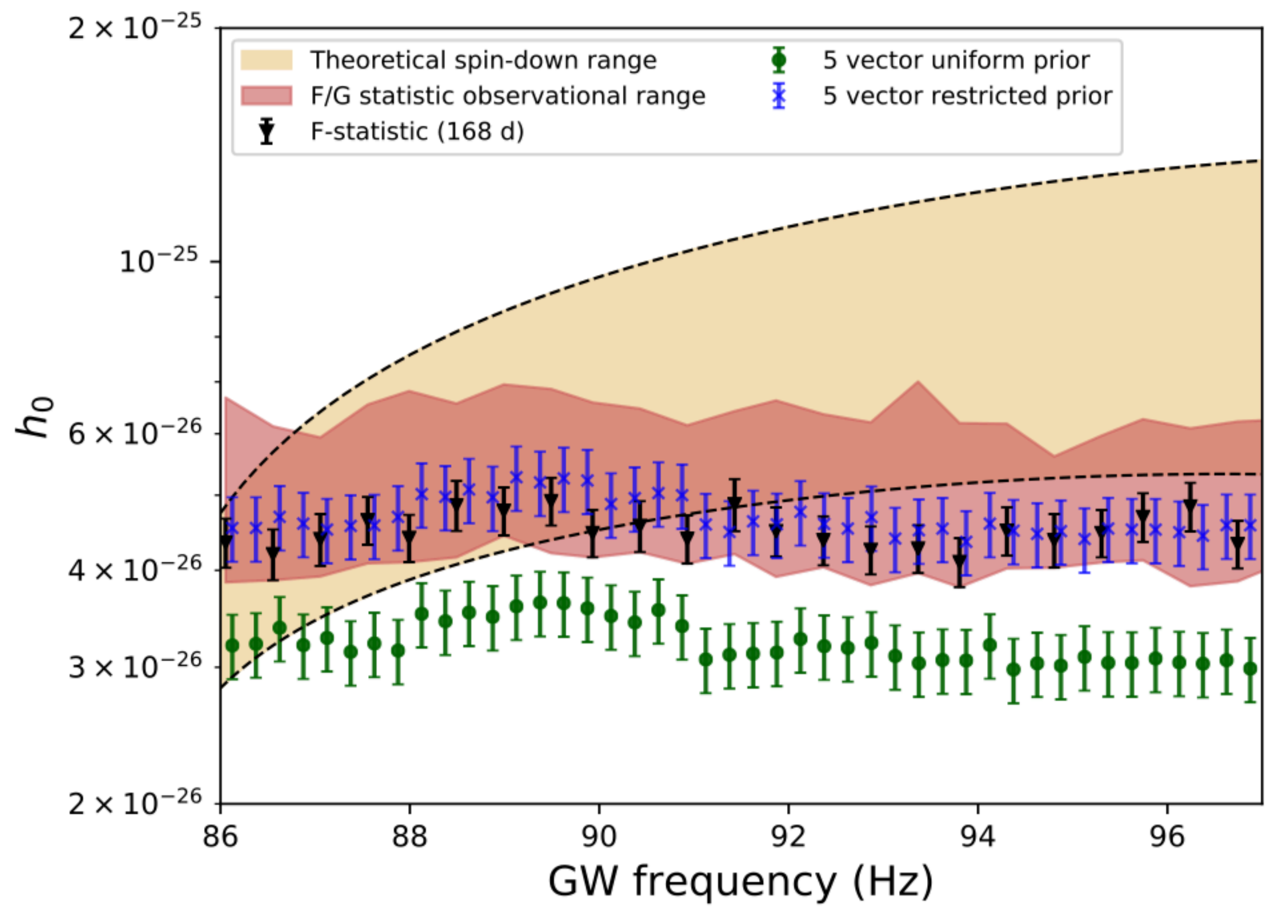
- Target: nearby, spinning, slightly non-axisymmetric isolated neutron stars **in the galaxy**
- Frequency band: 20-2000 Hz
- Frequency derivative band: [−1.0, +0.1] × 10^{-8}Hz/s
- **No periodic GW signal is observed.**
- Improvement on the set ULs specially due to the sensitivity improvement at high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



arXiv:2104.14417

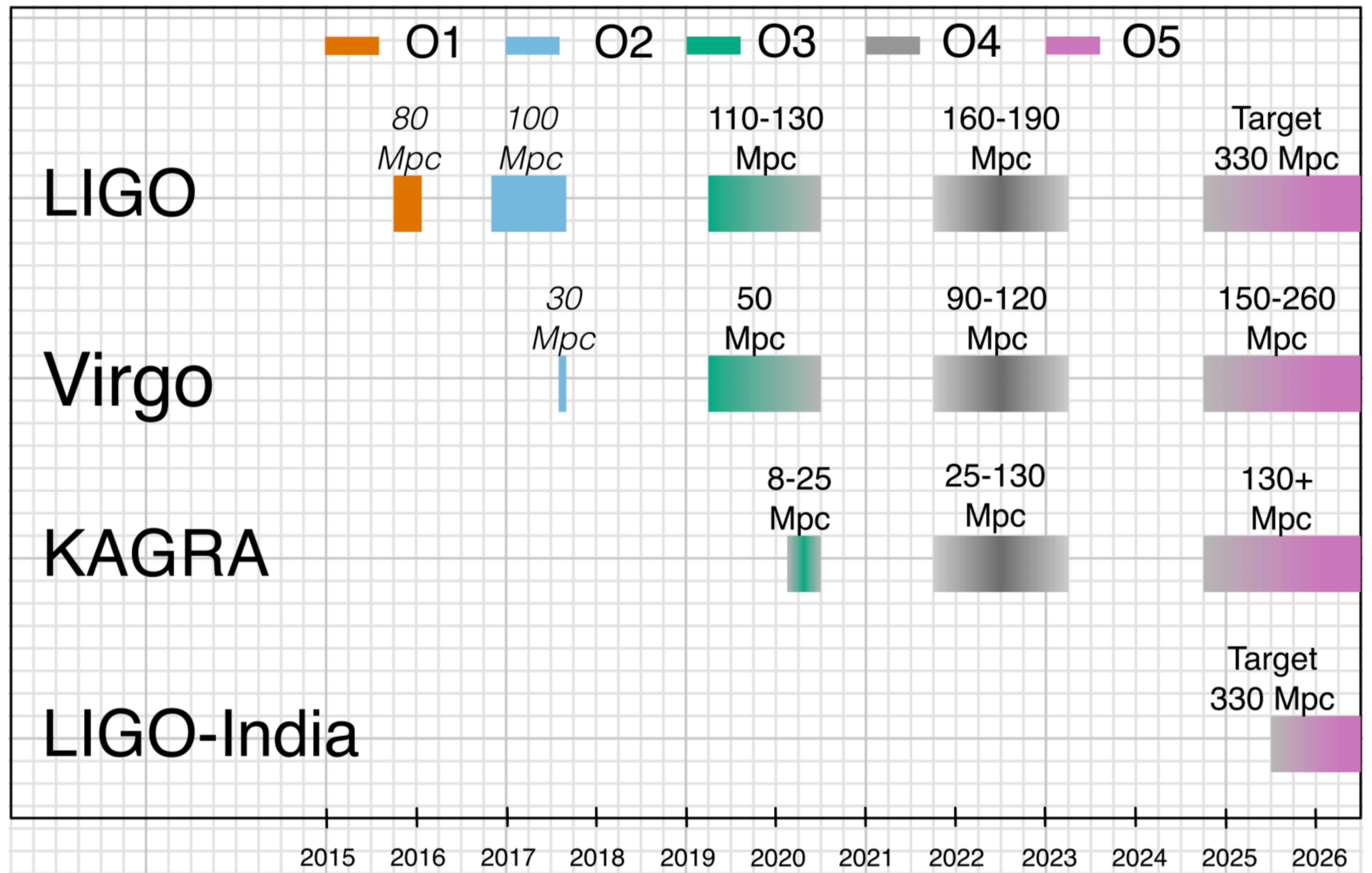
Targeted J0537-6910 pulsar O3

- 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



Towards observing run O4

- The **Observing run O4 will not start before June 2022** and will go on for a **full year**
- Main news on the status of the commissioning towards phase I of AdV+ upgrade
  - 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)
  - Ongoing: Reach stable lock, adjusting frequency dependent squeezing, noise hunting and mitigation, optical characterization, etc.



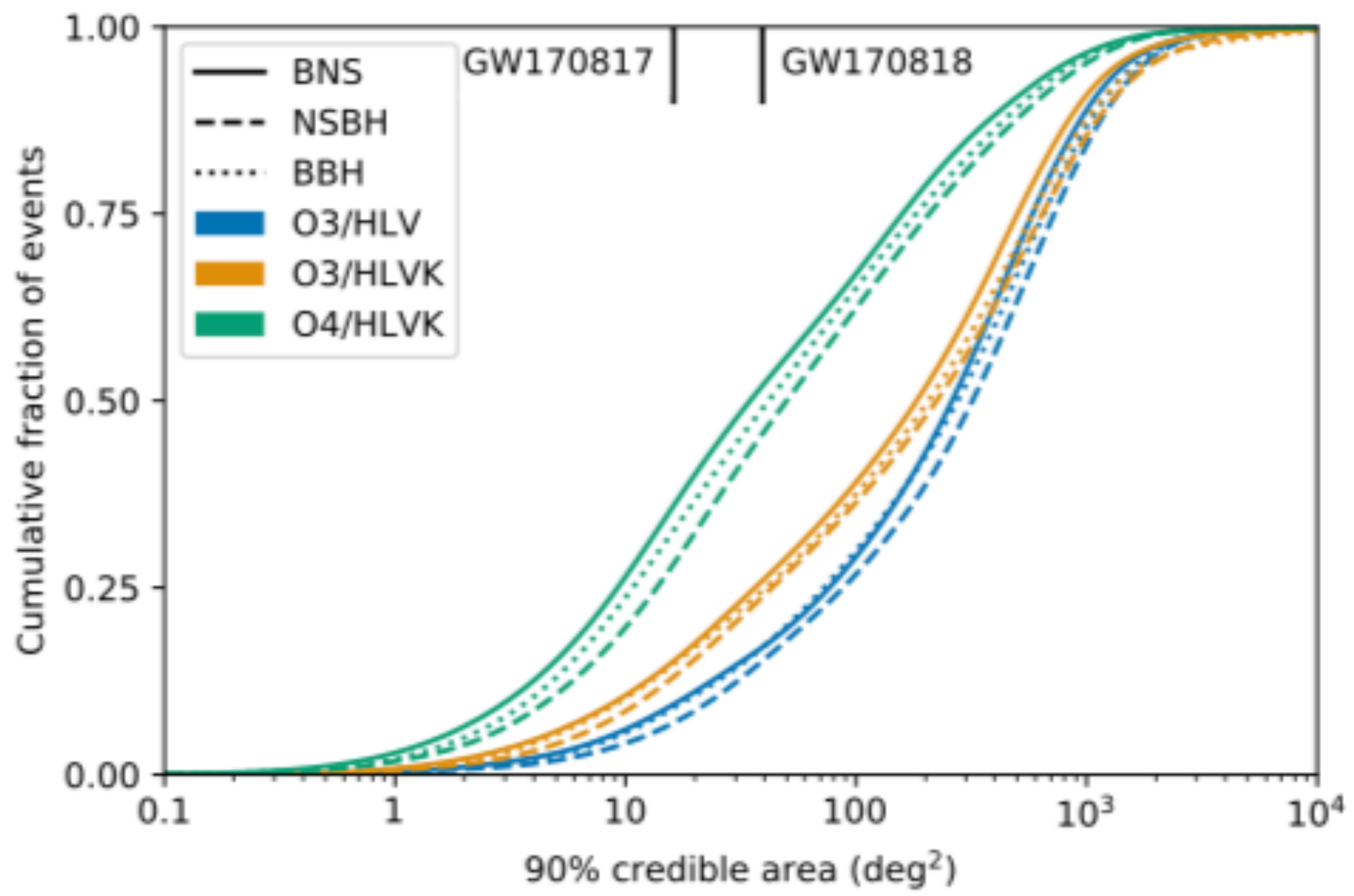
Expectations for O4

- From GW side: 4 ITF network
  - Increase of the horizon, 10x search volume O3
    - 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}

Living Rev Relativ 23, 3 (2020)

- MWL follow-ups: Mature strategies set up to follow-up GW
  - Comunity gets together via e.g. GCN, coordination of observations via TreasureMap
  - Synergies between large and small FoV telescopes
    - Monitoring the sky (e.g. Fermi-GBM) vs. Observation strategies in small+mid FoV telescopes e.g. LST, H.E.S.S., optical telescopes, networks of telescopes as GRANDMA/GROWTH…

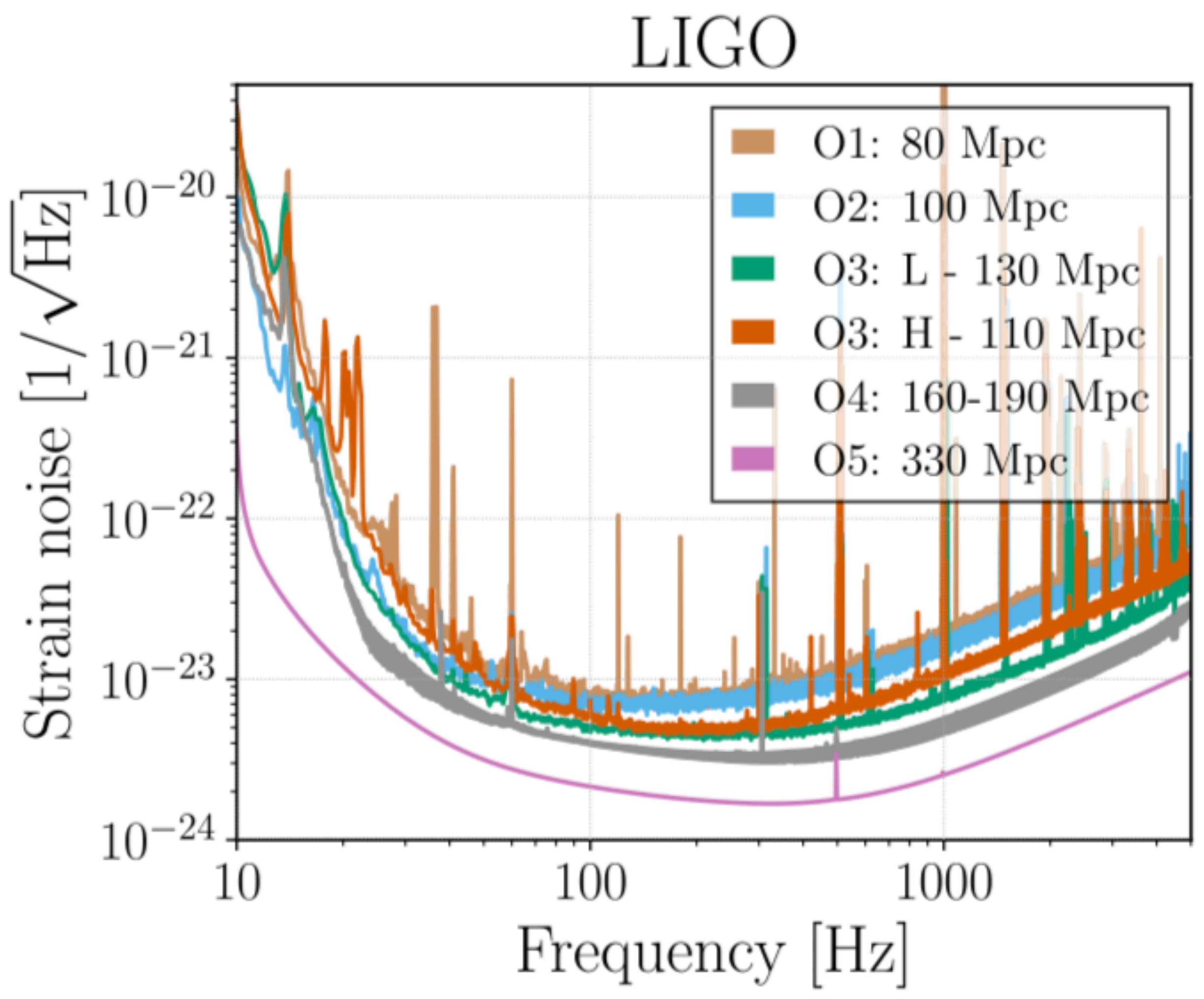


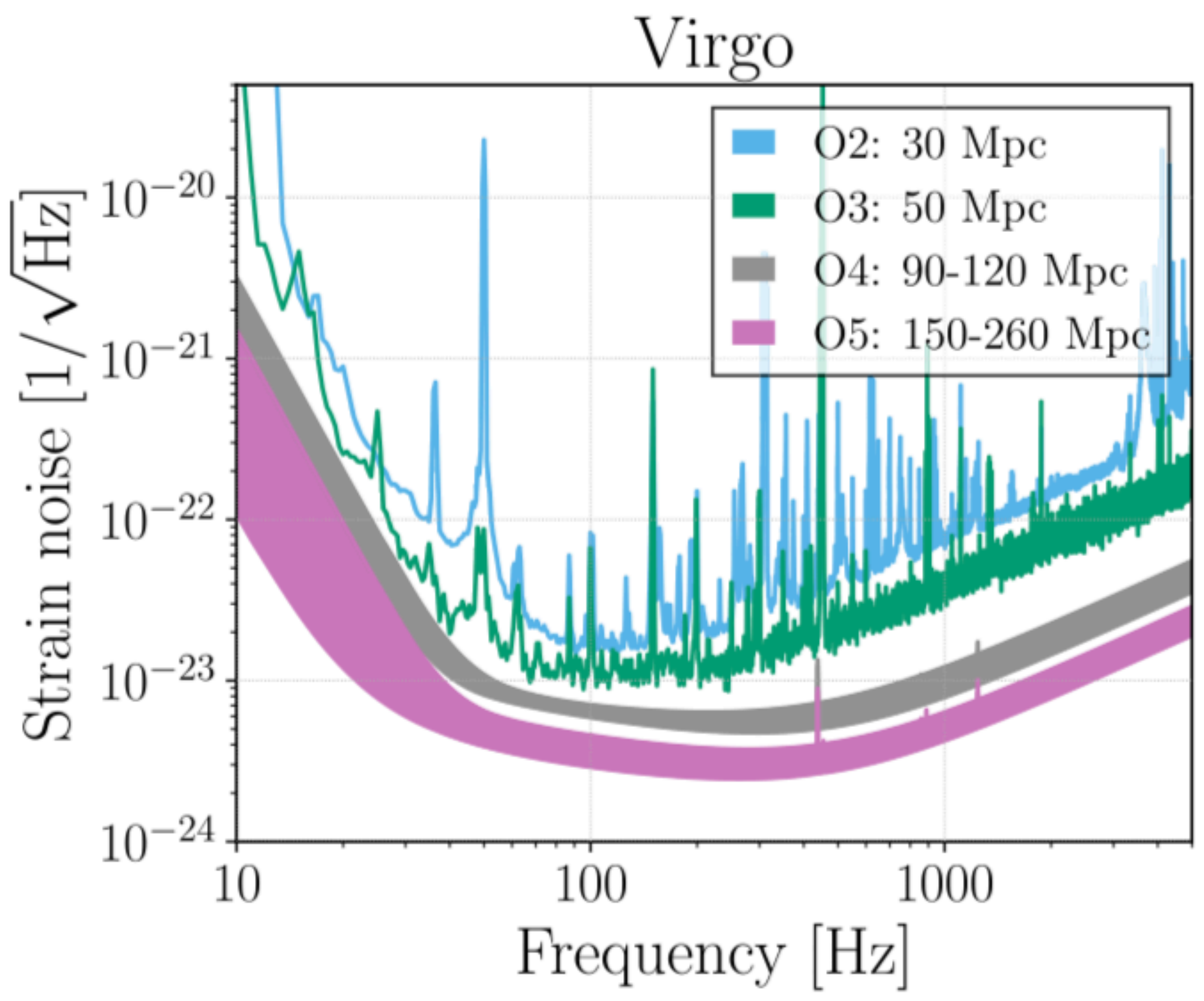
Stay tuned!

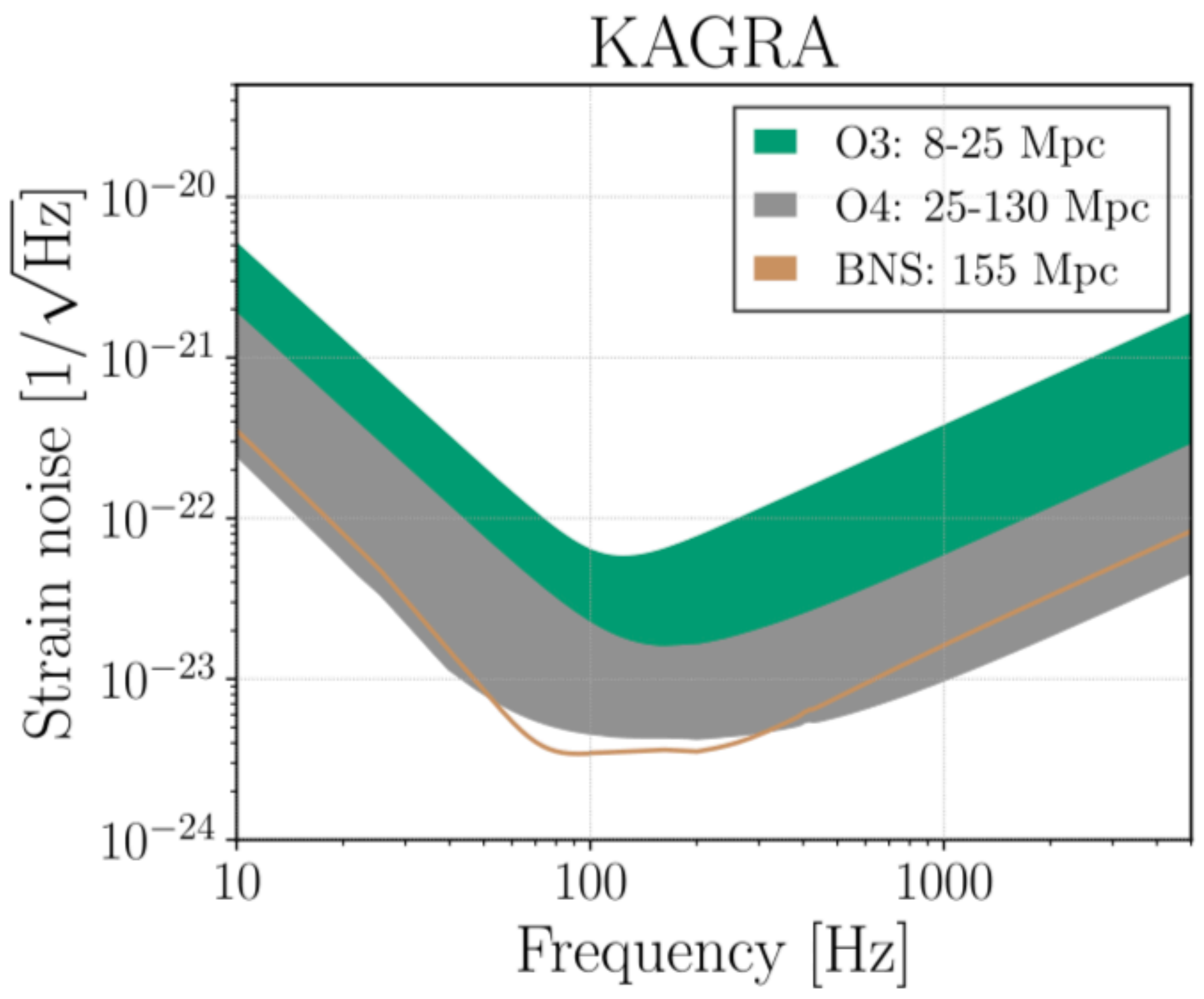
Thanks for your attention!

Back-up slides

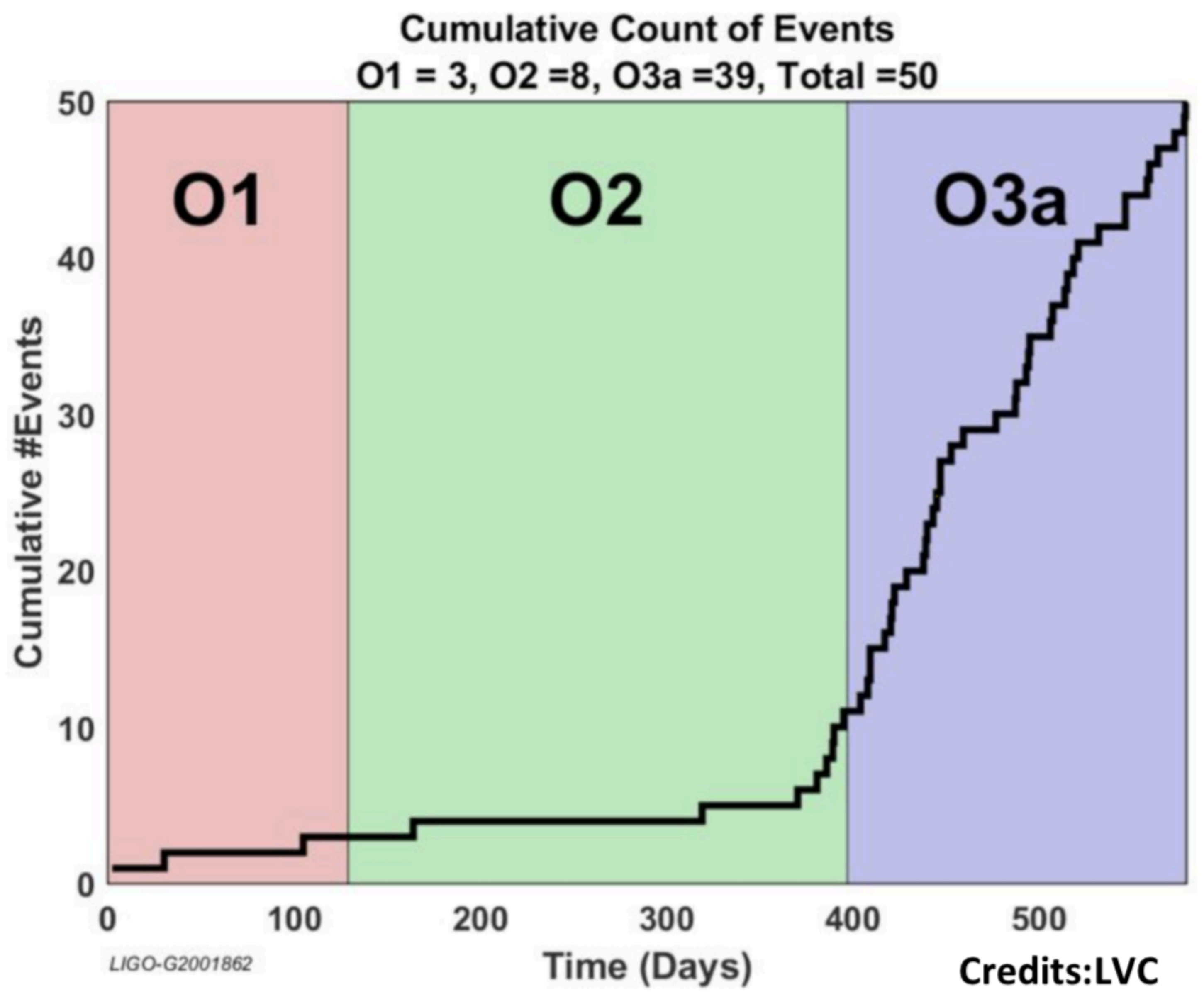
Sensitivity vs. Observing run

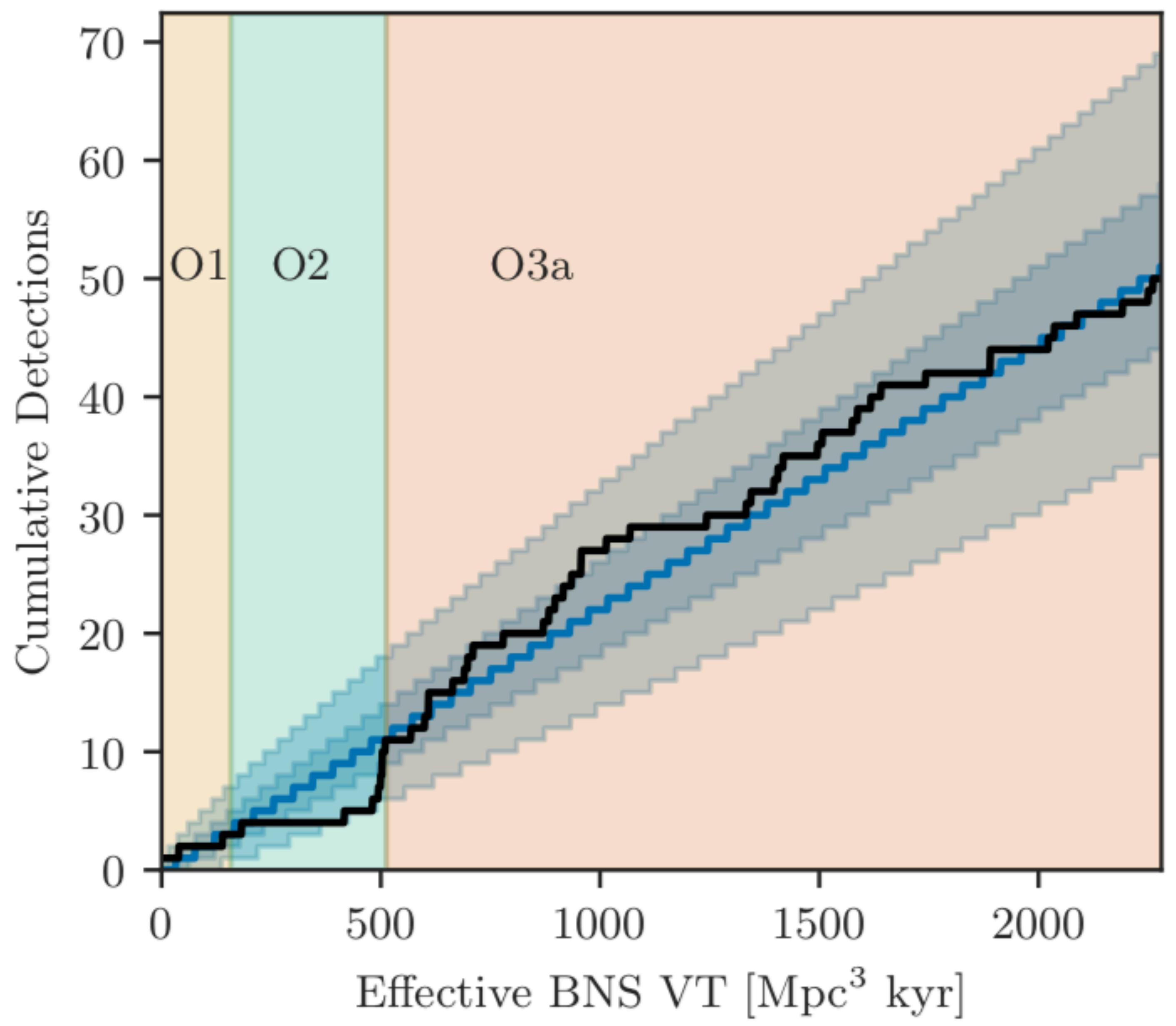


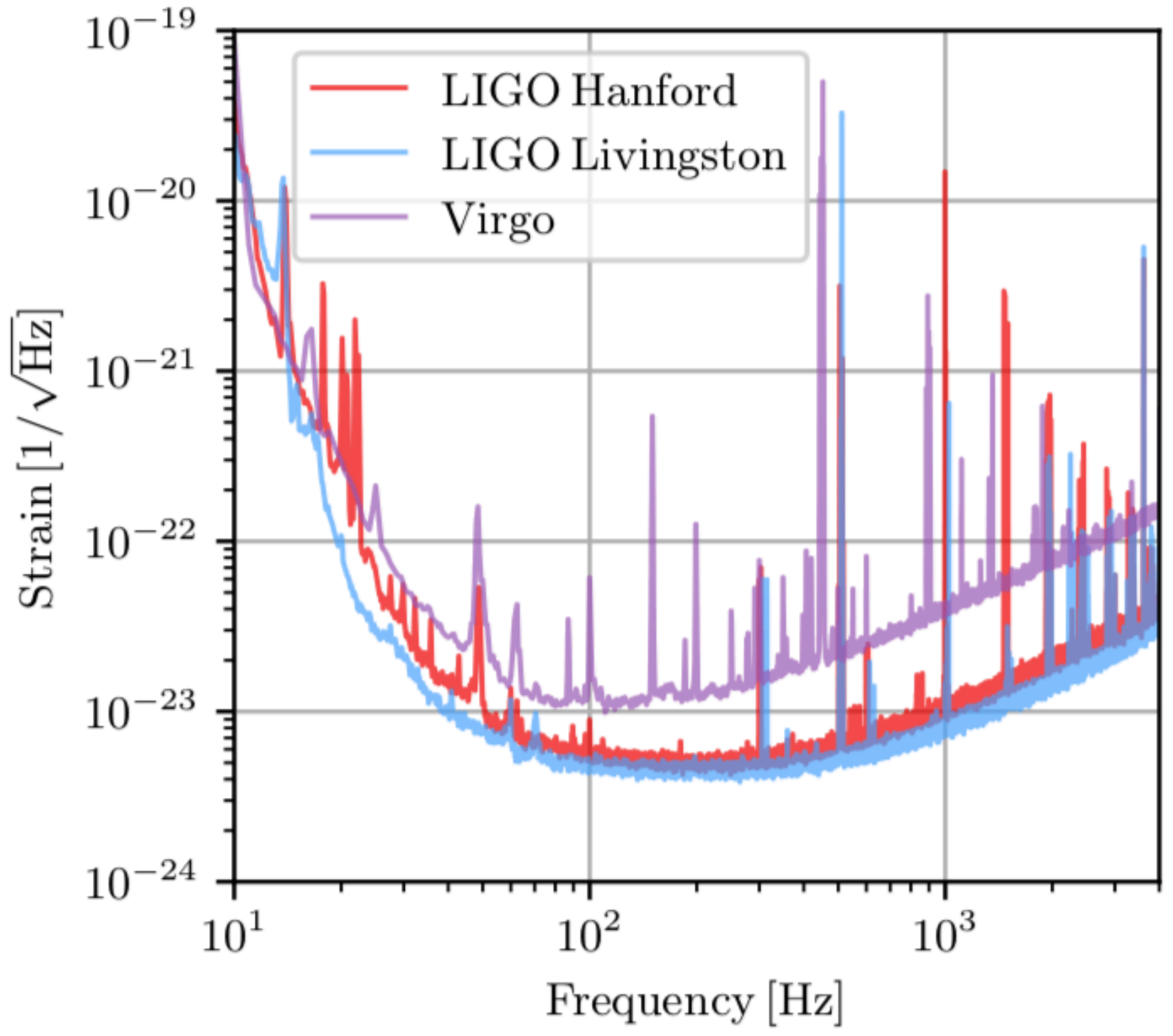




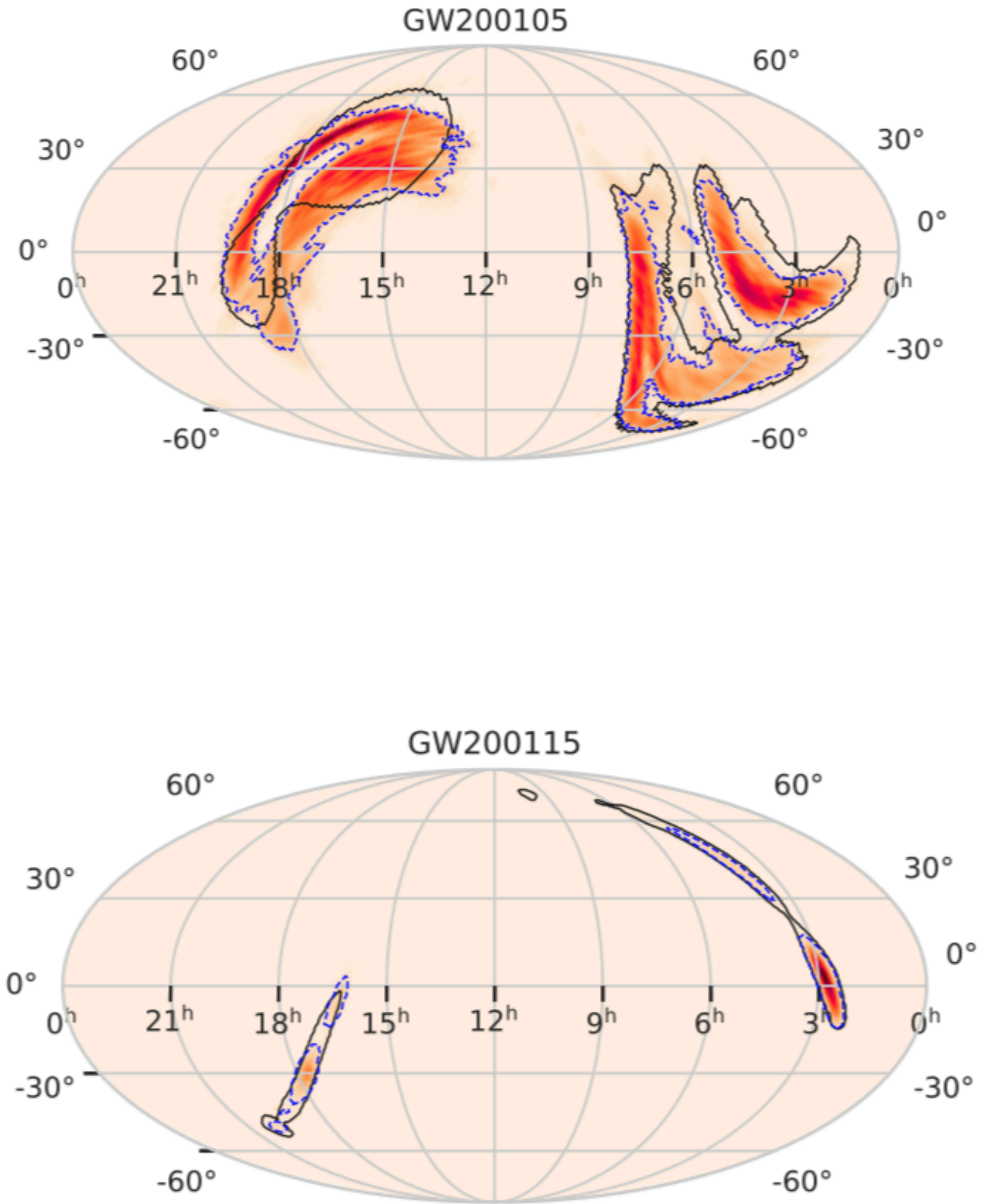
CBC vs. Time, CBC vs. Volume-Time, Sensitivity during O3a

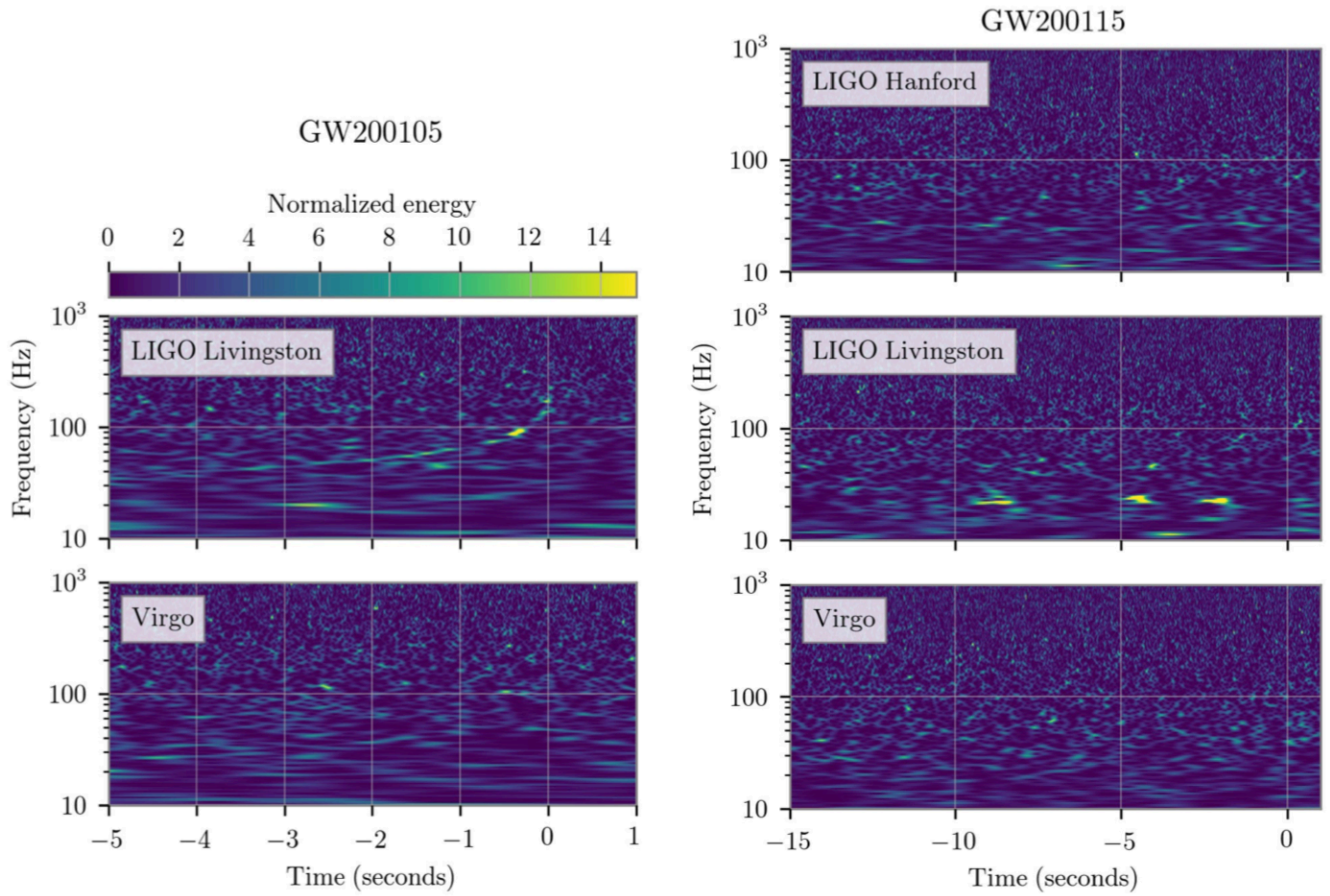






Skymaps of the BH-NS mergers





Test of GR using the GWTC catalog

Phys. Rev. D 103, 122002 (2021)

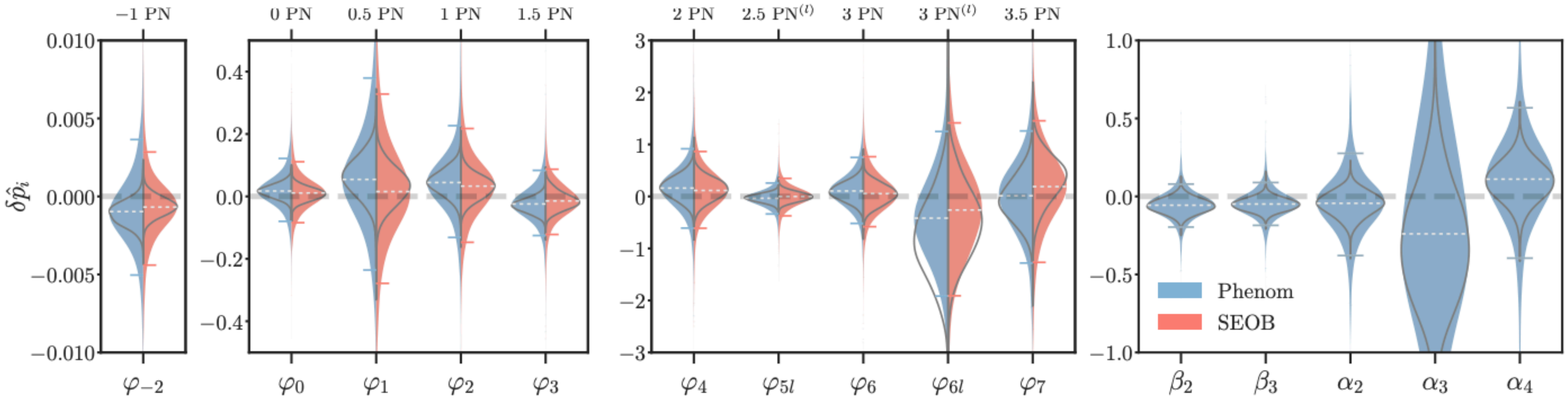
- Evaluation of the consistency of the data with predictions from the theory.
  - Residuals from the best-fit waveform are consistent with detector noise.

- Parametrized modifications to the waveform by varying post-Newtonian and phenomenological coefficients.
  - improving past constraints by factors of ~2.
  - Consistency with Kerr black holes when we specifically target signatures of the spin-induced quadrupole moment.

- Constraints on Lorentz-violating coefficients improved by a factor of ~2.6 and bound the mass of the graviton to mg ≤ 1.76 × 10−23 eV / c 2 with 90% credibility.

- Measurements of the ringdown frequencies and damping times: constraining fractional deviations away from the Kerr frequency. No evidence for postmerger echoes.

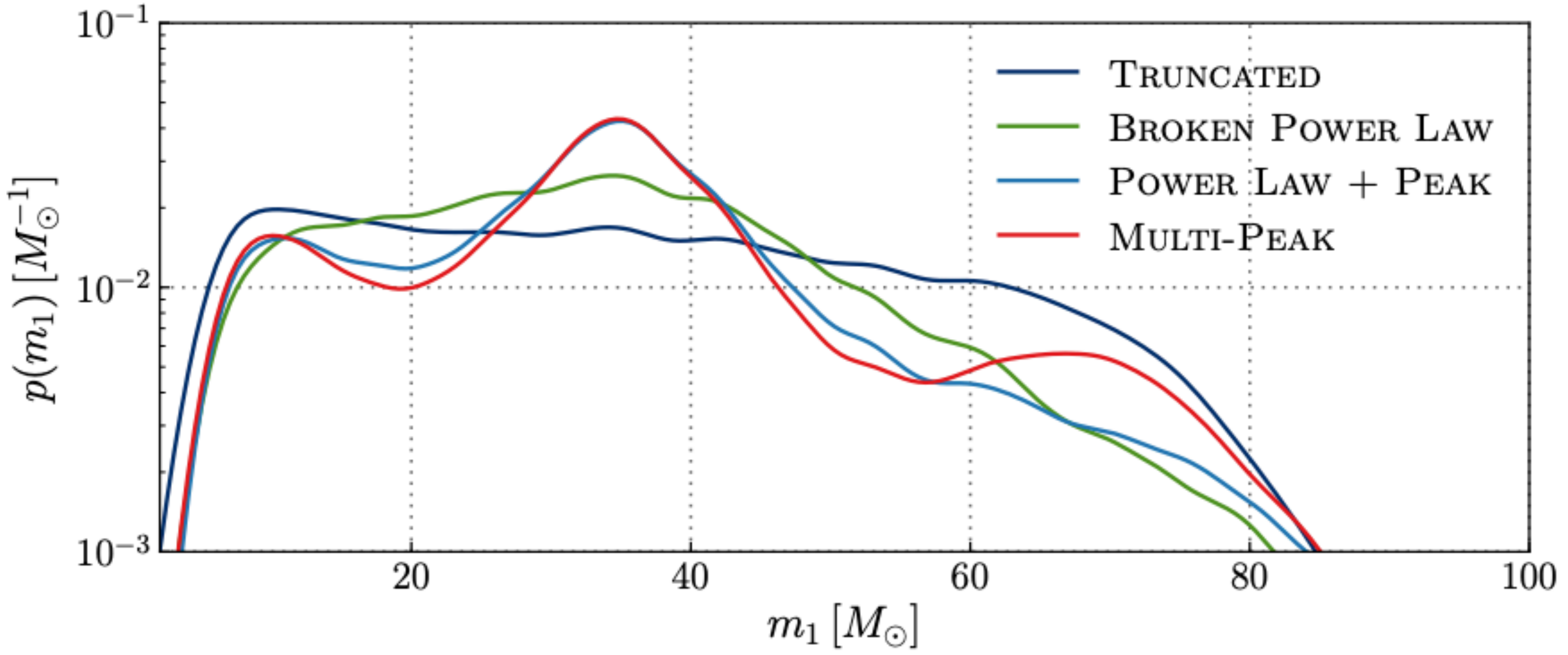
- Also, asses the validity of general relativity based on collections of events analyzed jointly.
  - No evidence for new physics beyond general relativity.

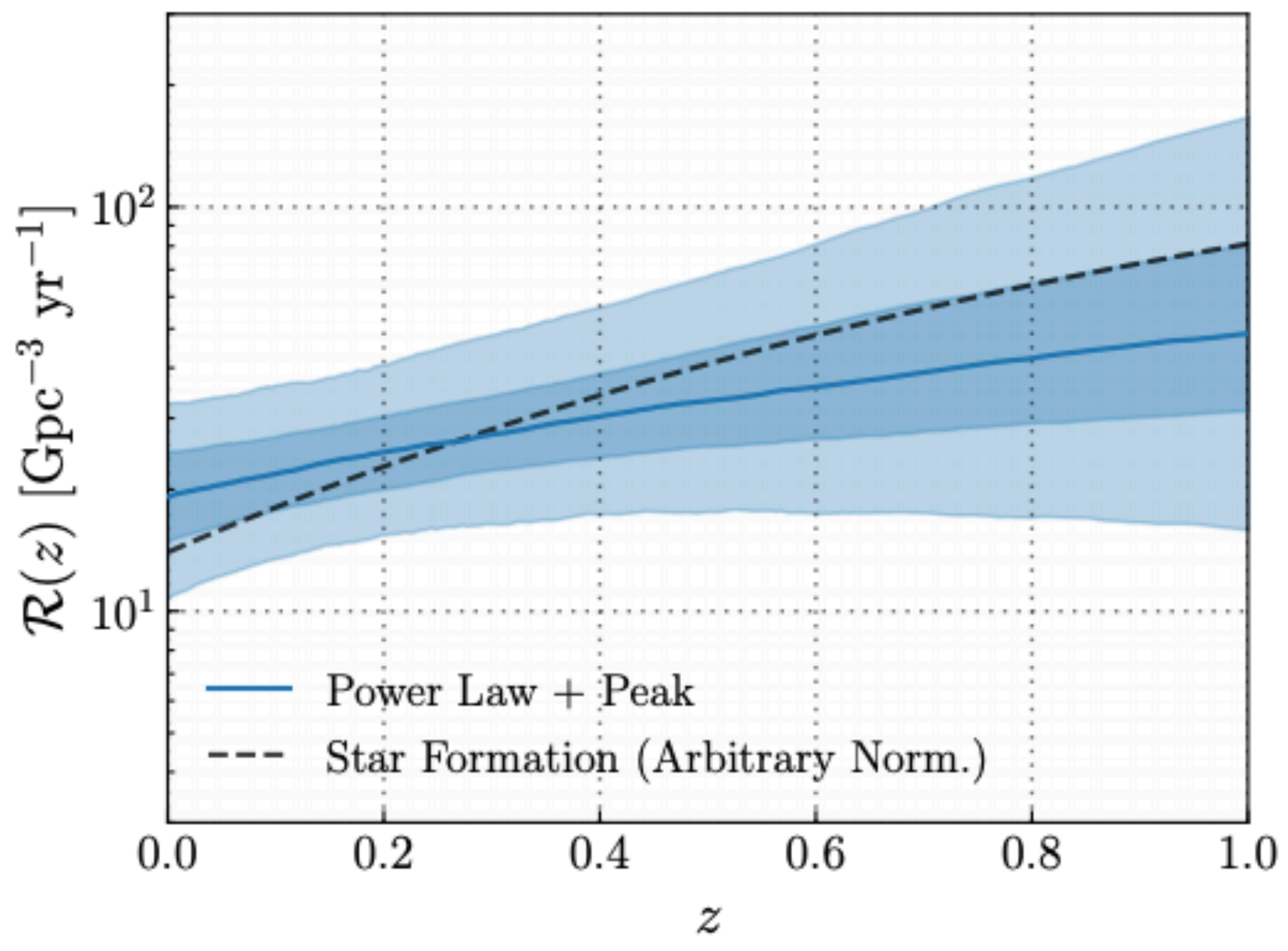


Rates of BBH, BHNS, BNS and prospects

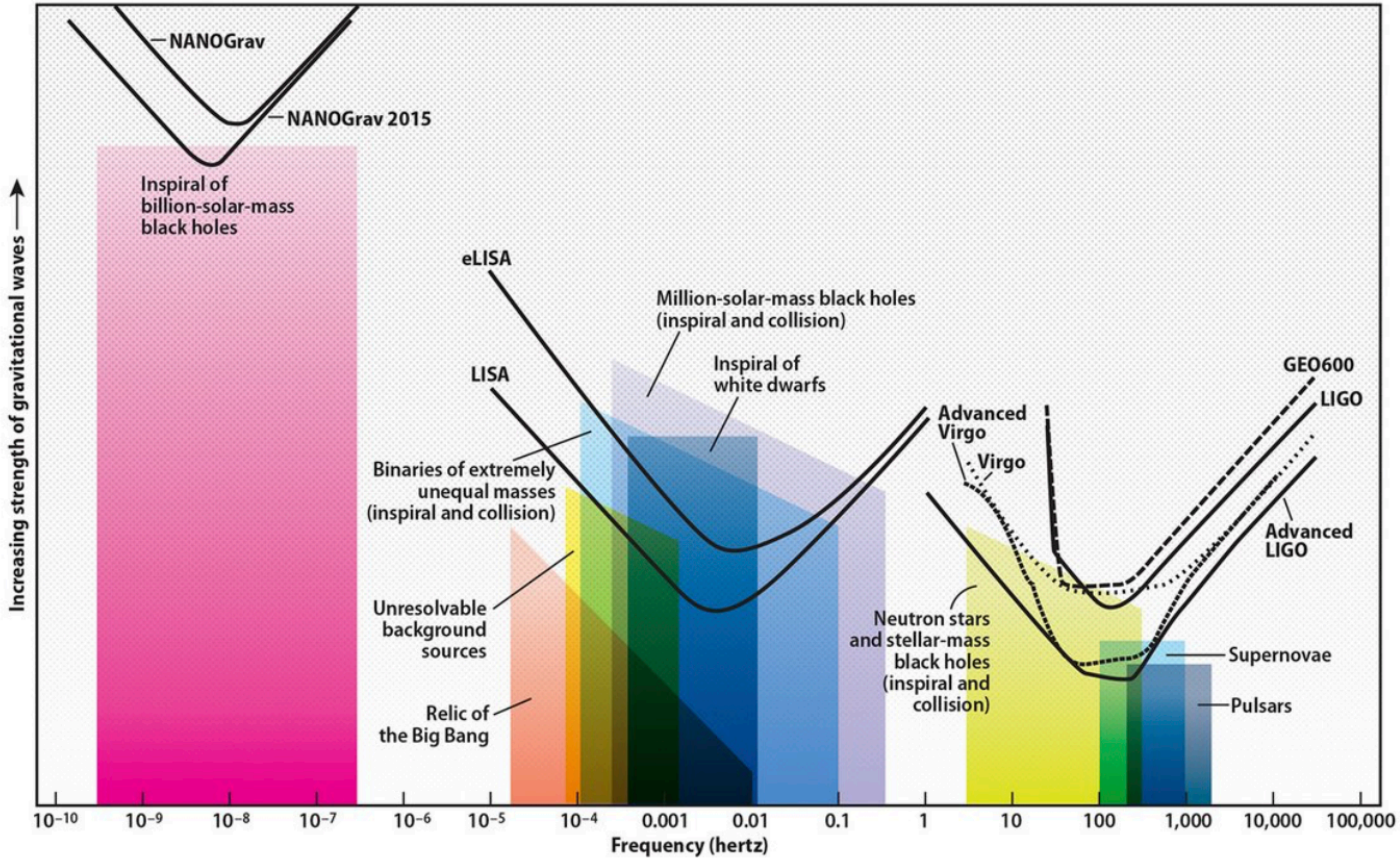
ApJL **913** L7 (2021)

- 47 compact binary mergers detected with a false-alarm rate <1 yr−1 in GWTC-2.
- We observe several characteristics of the merging binary black hole (BBH) population not discernible until now.
  - Primary mass spectrum contains structure beyond a power-law with a sharp high-mass cut-off: more consistent with a broken power law+break, power law + Gaussian feature, several peaks?
  - A fraction of BBH systems have component spins misaligned with the orbital angular momentum, giving rise to precession of the orbital plane.
    - 12% to 44% of BBH systems have spins tilted by more than 90◦=> formation by dynamical interaction?
  - BBH rate likely increases with redshift (85% credibility), but not faster than the star-formation rate (86% credibility)
  - Recent exceptional events in the context of our population models: the **asymmetric masses of GW190412** and the **high component masses of GW190521** are consistent with our models, but **the low secondary mass of GW190814 makes it an outlier**.
- Merger rates: $R_{BBH} = 23.9^{+14.3}_{-8.6}$ Gpc−3 yr−1 for BBH and $R_{BNS} = 320^{+490}_{-240}$ Gpc−3 yr−1 for binary neutron stars.





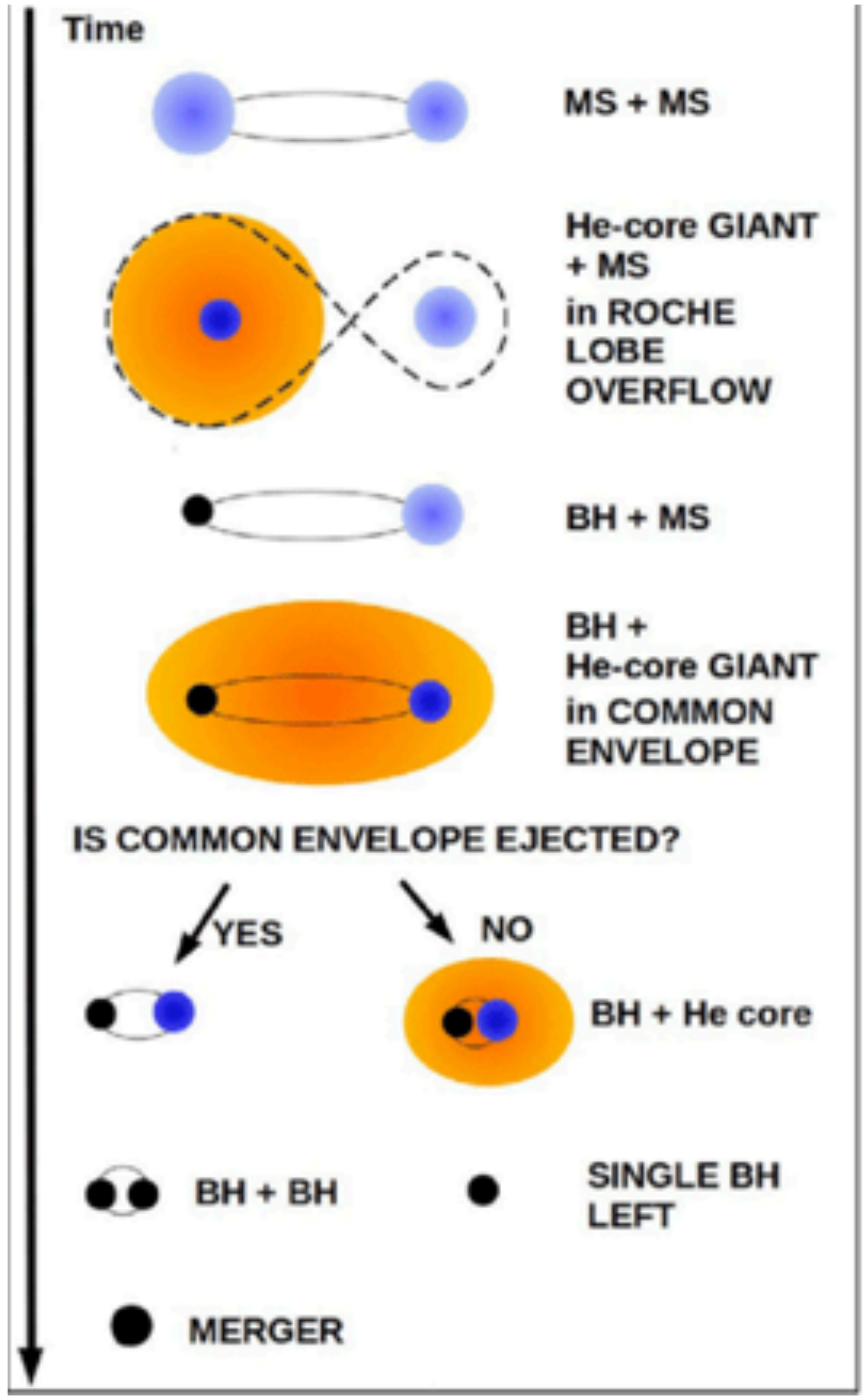
Sensitivity current vs. future experiments



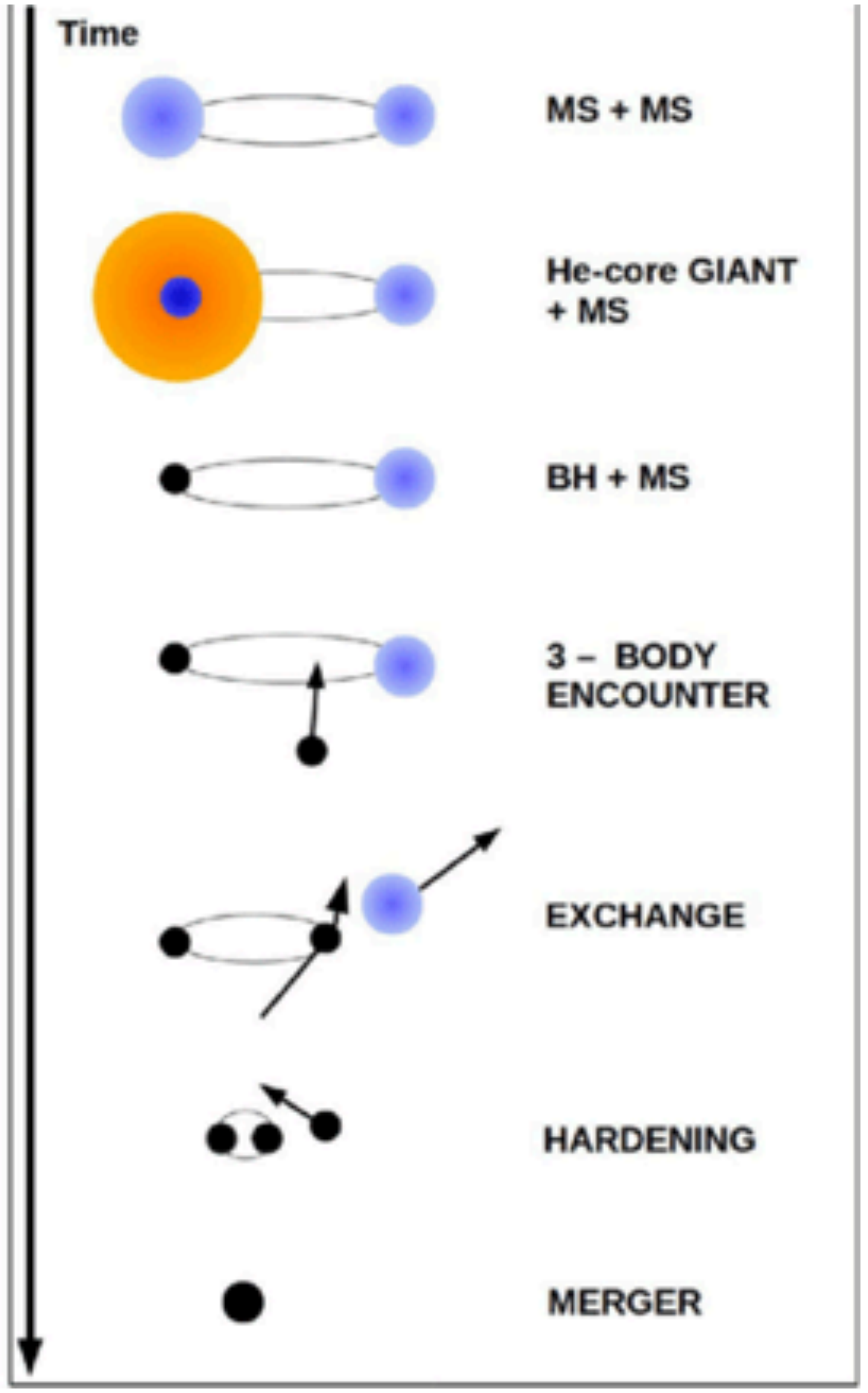
M. Mapelli, *Frontiers in Astronomy and Space Sciences*, 2020, 7: 38.

Formation channels

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



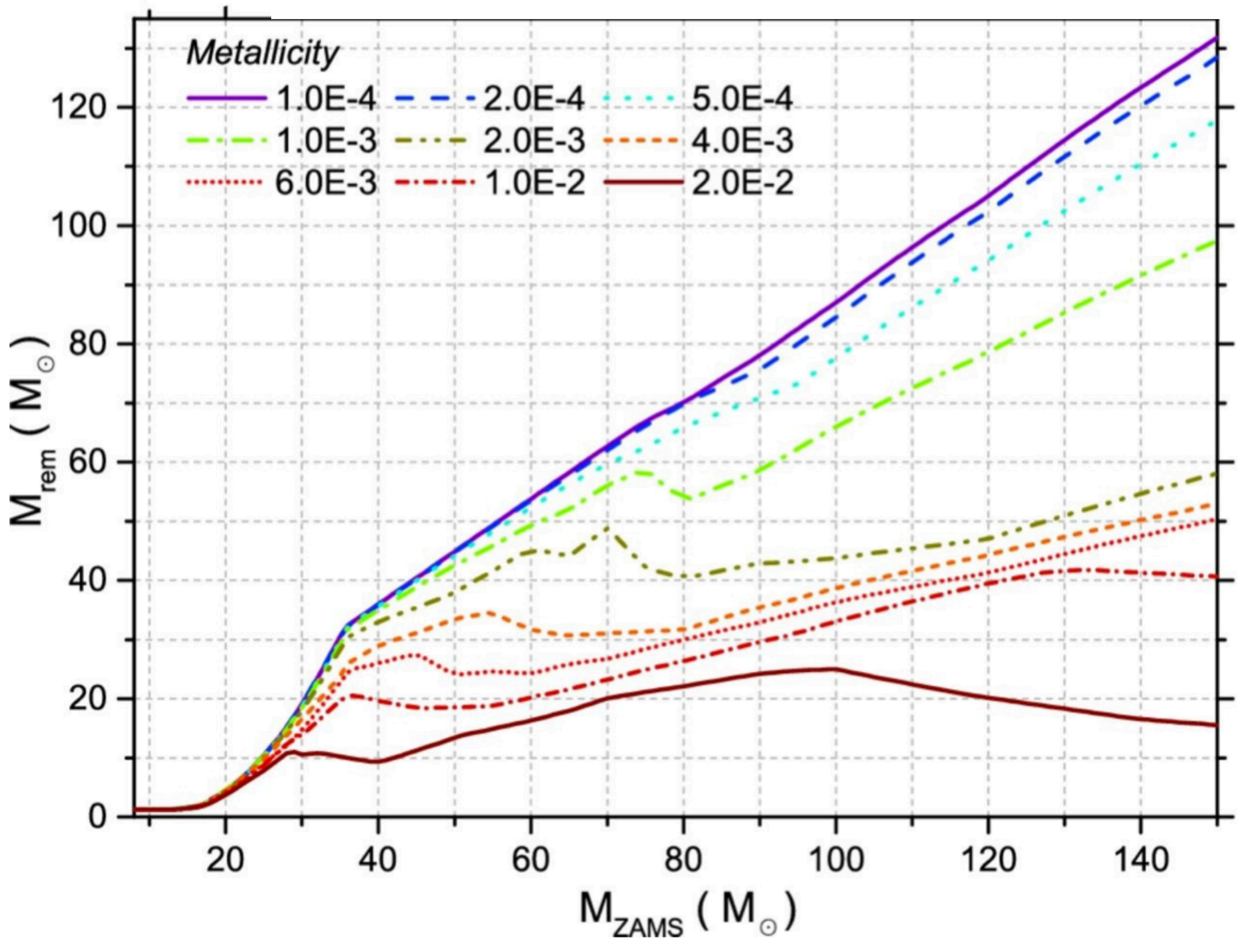
Dynamical BBH formation in stellar clusters



BH mass spectra and pair-instability gap

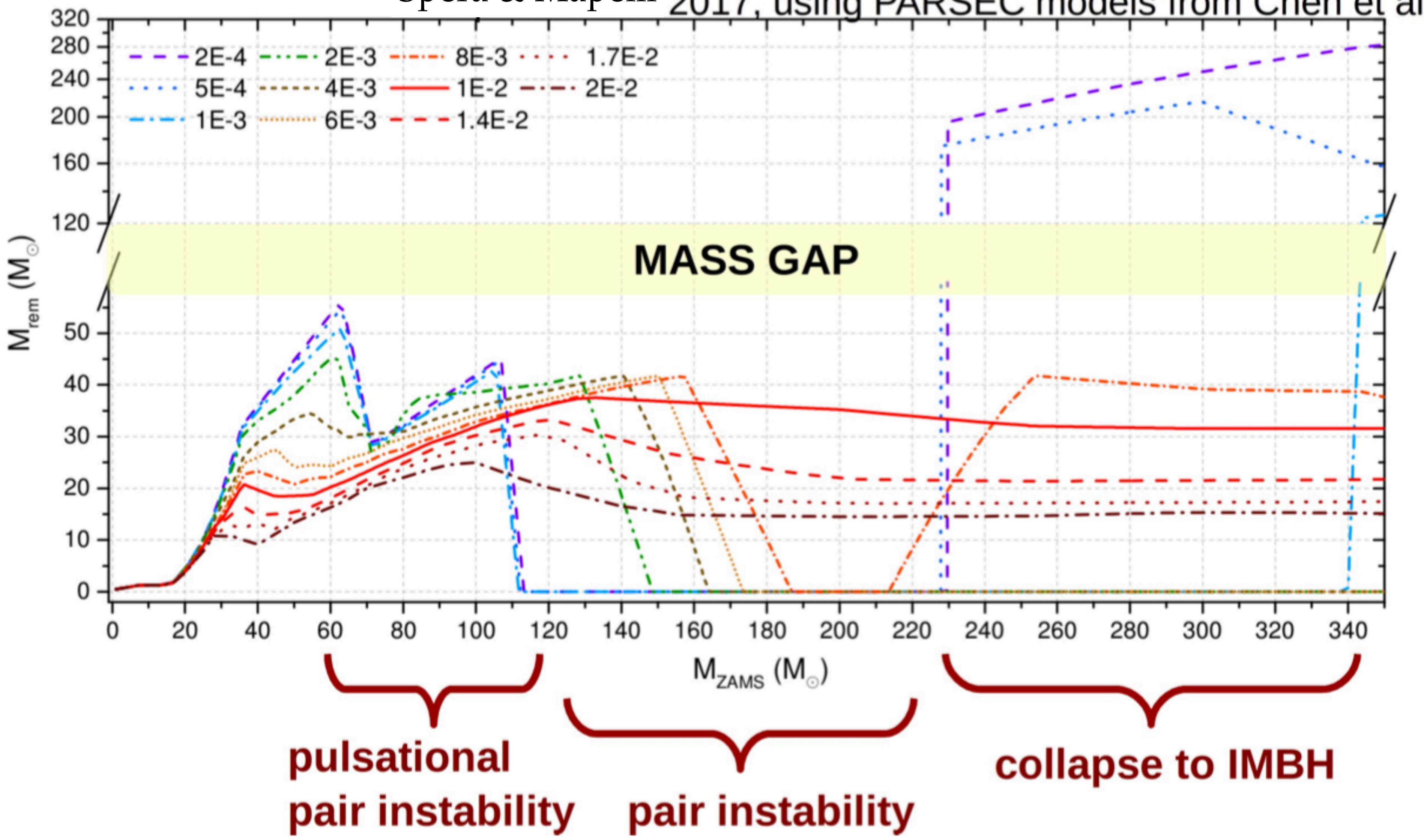
Main uncertainties of that mass gap due to uncertainties in nuclear reaction rates, uncertainties on the collapse of the residual hydrogen envelope and on the role of stellar rotation

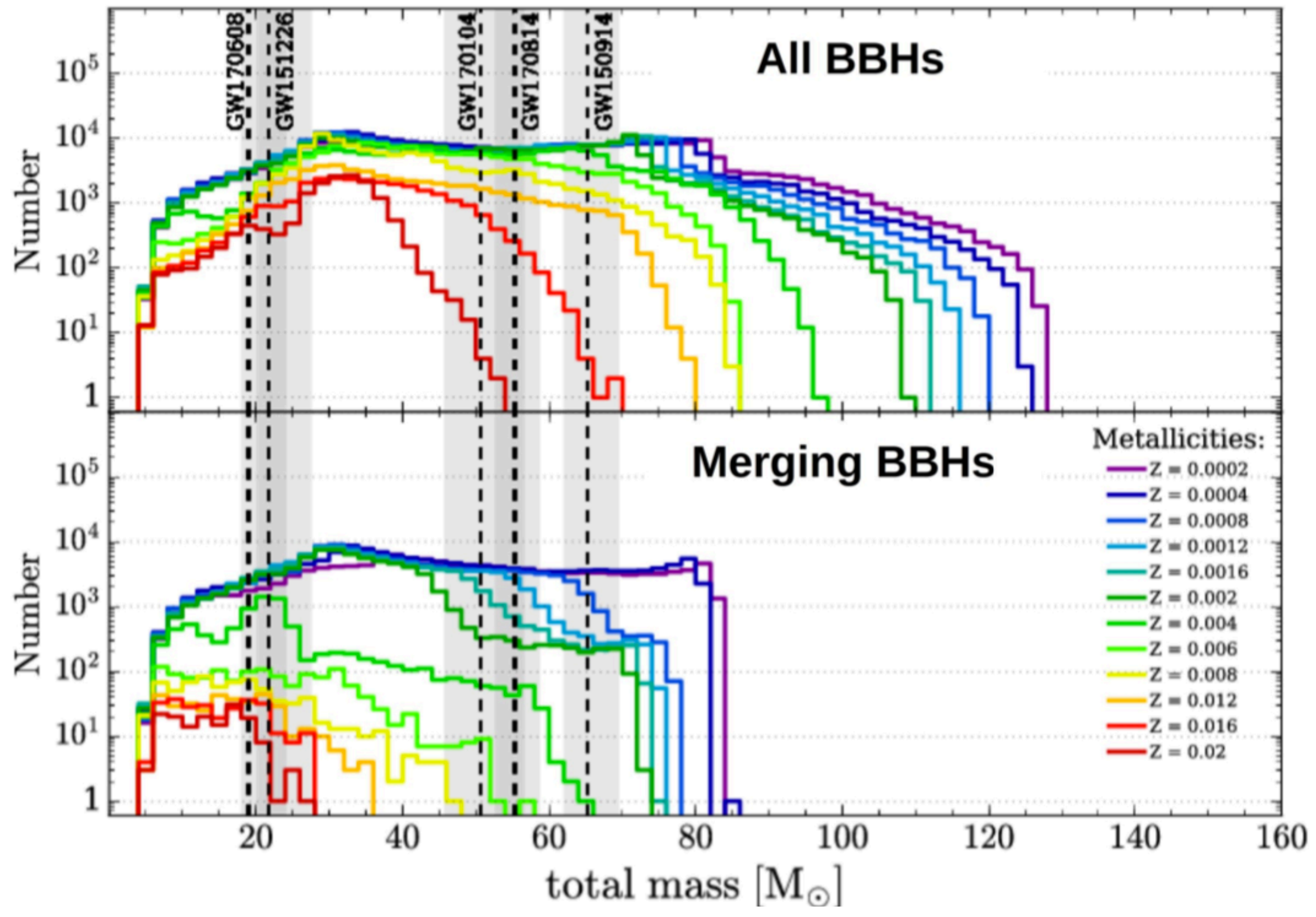
stellar winds and direct collapse



Pair instability + core collapse supernova + stellar wind mass loss

Spera & Mapelli 2017, using PARSEC models from Chen et al. 2015





Giacobbo & Mapelli 2018; Spera et al. 2019

The isolated evolution scenario of BBH:

dependency of the BHH mass, number of BBH and BBH mergers on the metallicity