Intermediate mass black holes in the IGWN

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AAPCOS-2023, SINP

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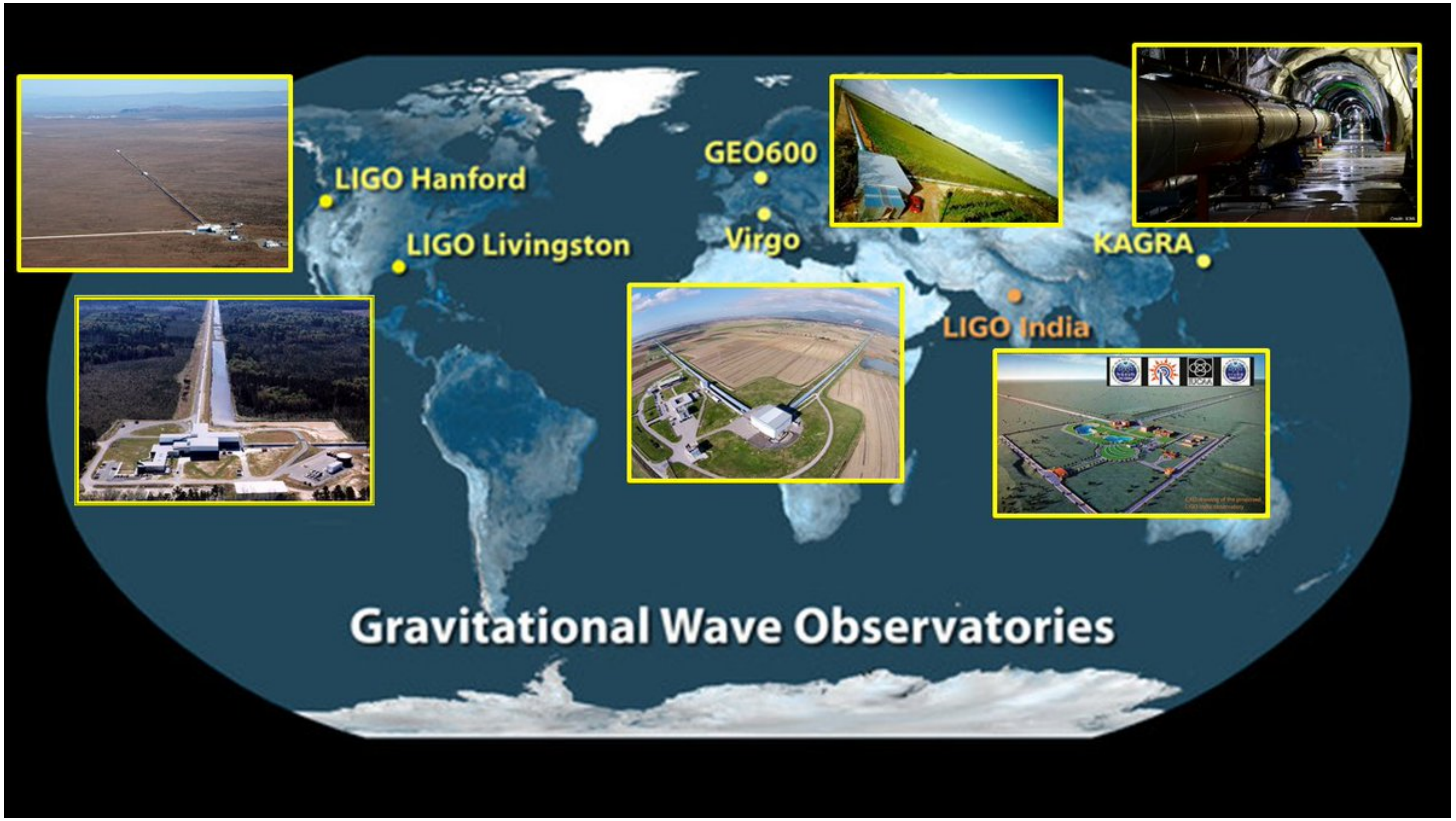
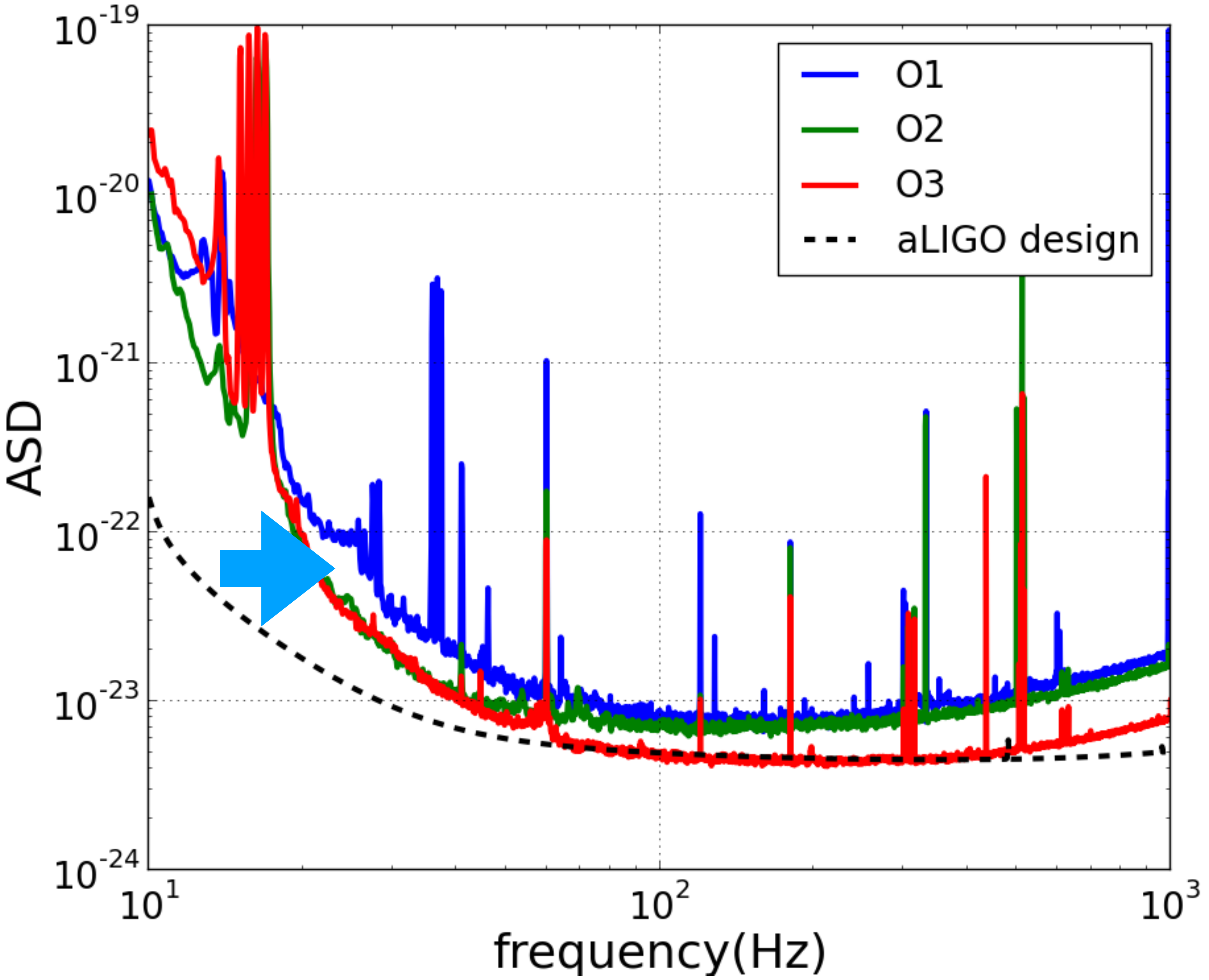




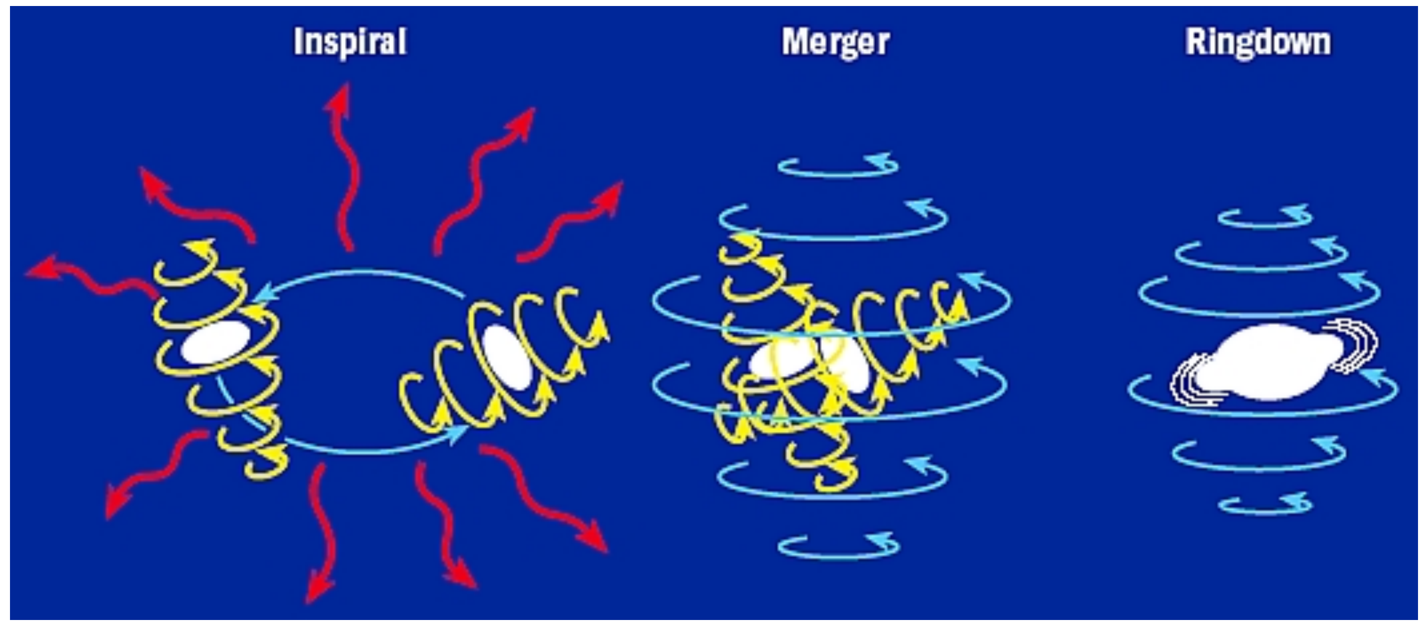
Observational runs of LIGO-Virgo detectors (IGWN)

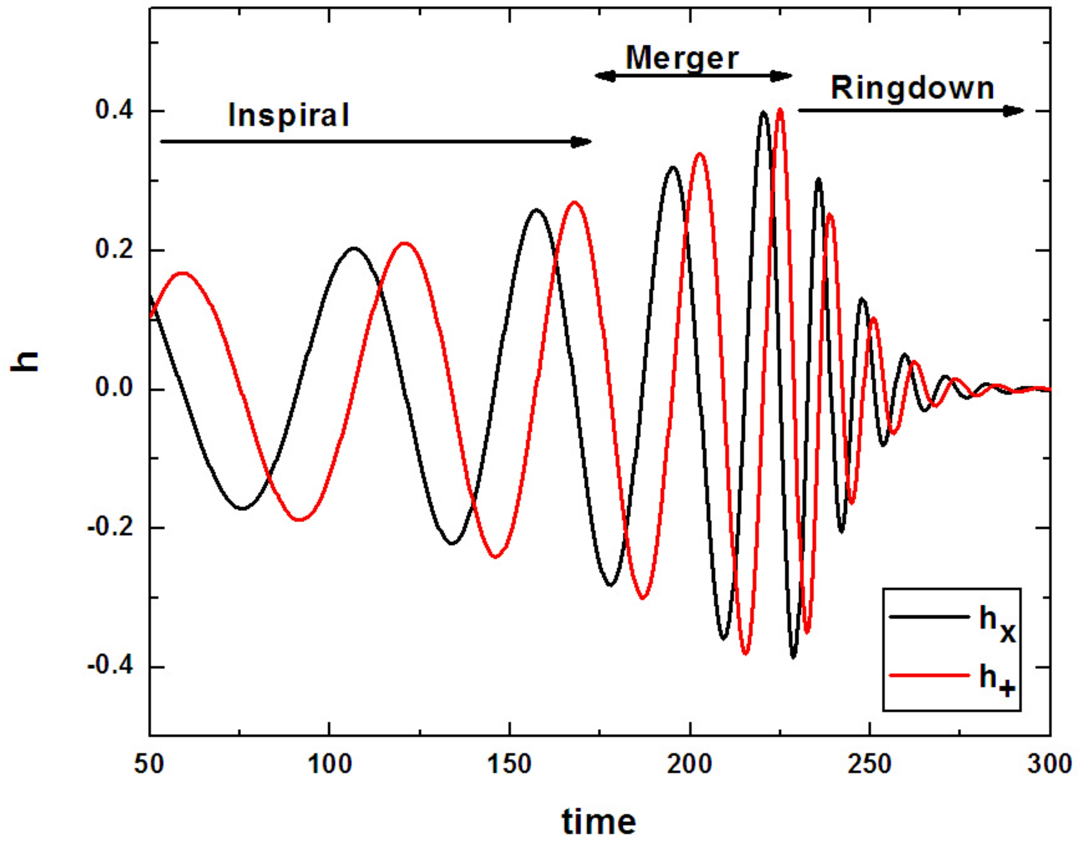
O1: First observational run (Sept 2015 — January 2016) — Two Advanced LIGOs

O2: Second observational run (November 2016 — August 2017) — Advanced LIGO + Virgo

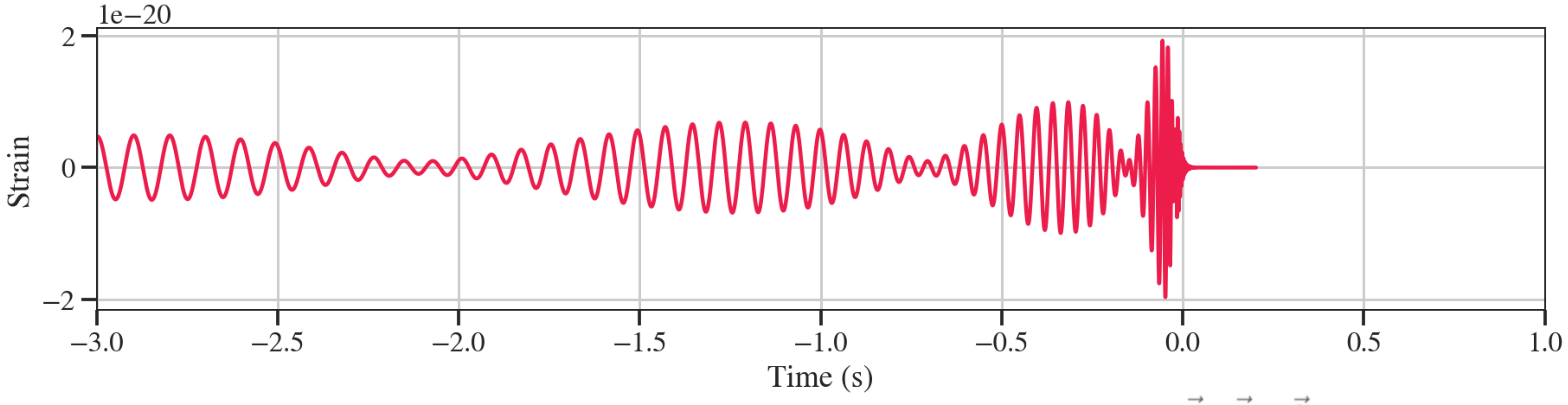
O3: Third observational run (April 2019 — March 2020) — Advanced LIGO +Virgo

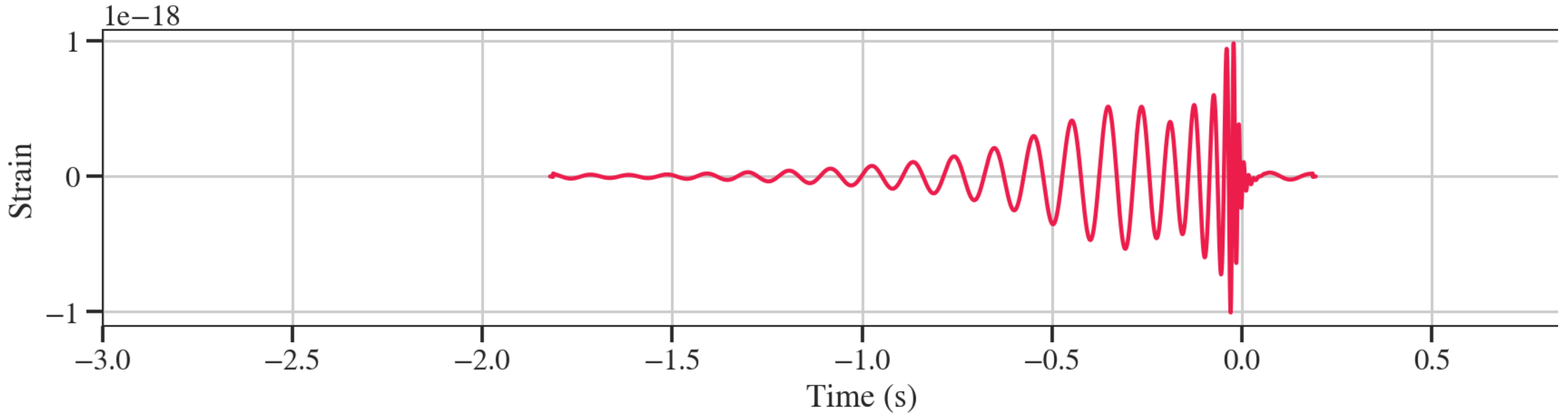
Stellar mass coalescing compact binaries in IGWN

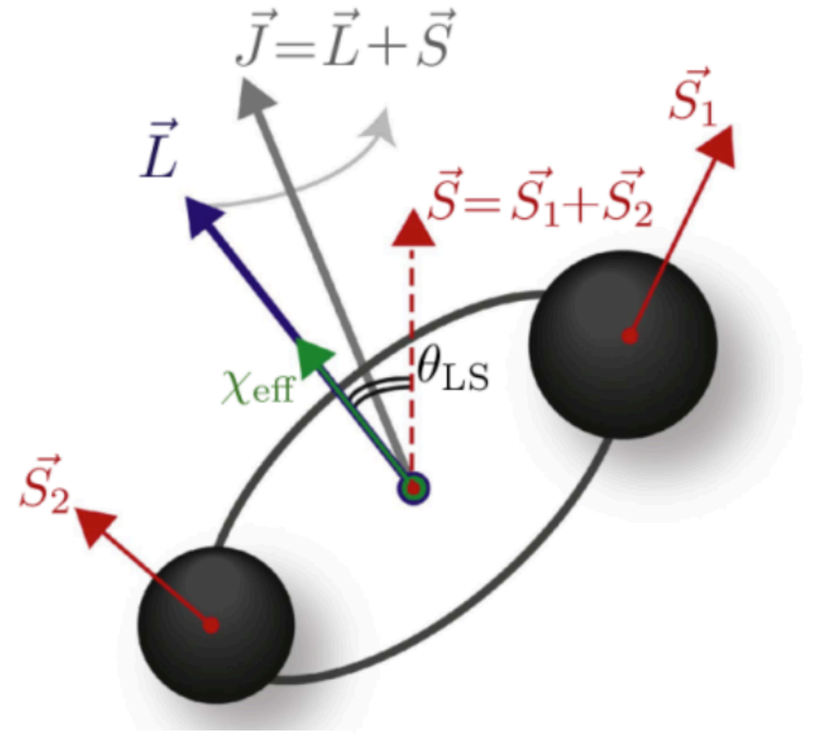


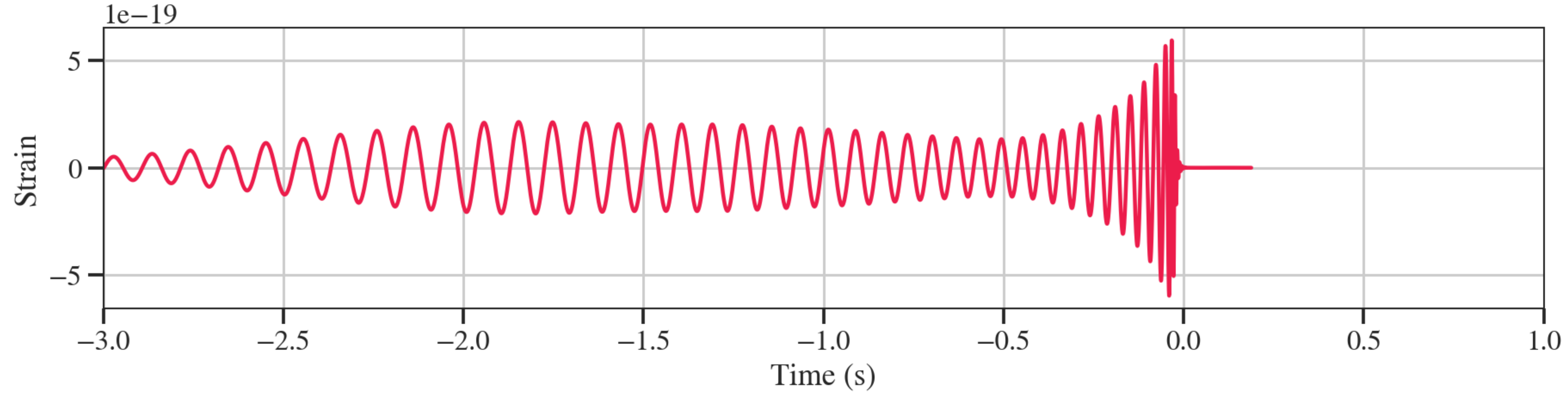


GW signal from compact binary signal: 15 dimensional signal manifold Distance(1), Masses(2), Spins(6), Binary orientation(2), Source location(2), Initial time and phase (2)





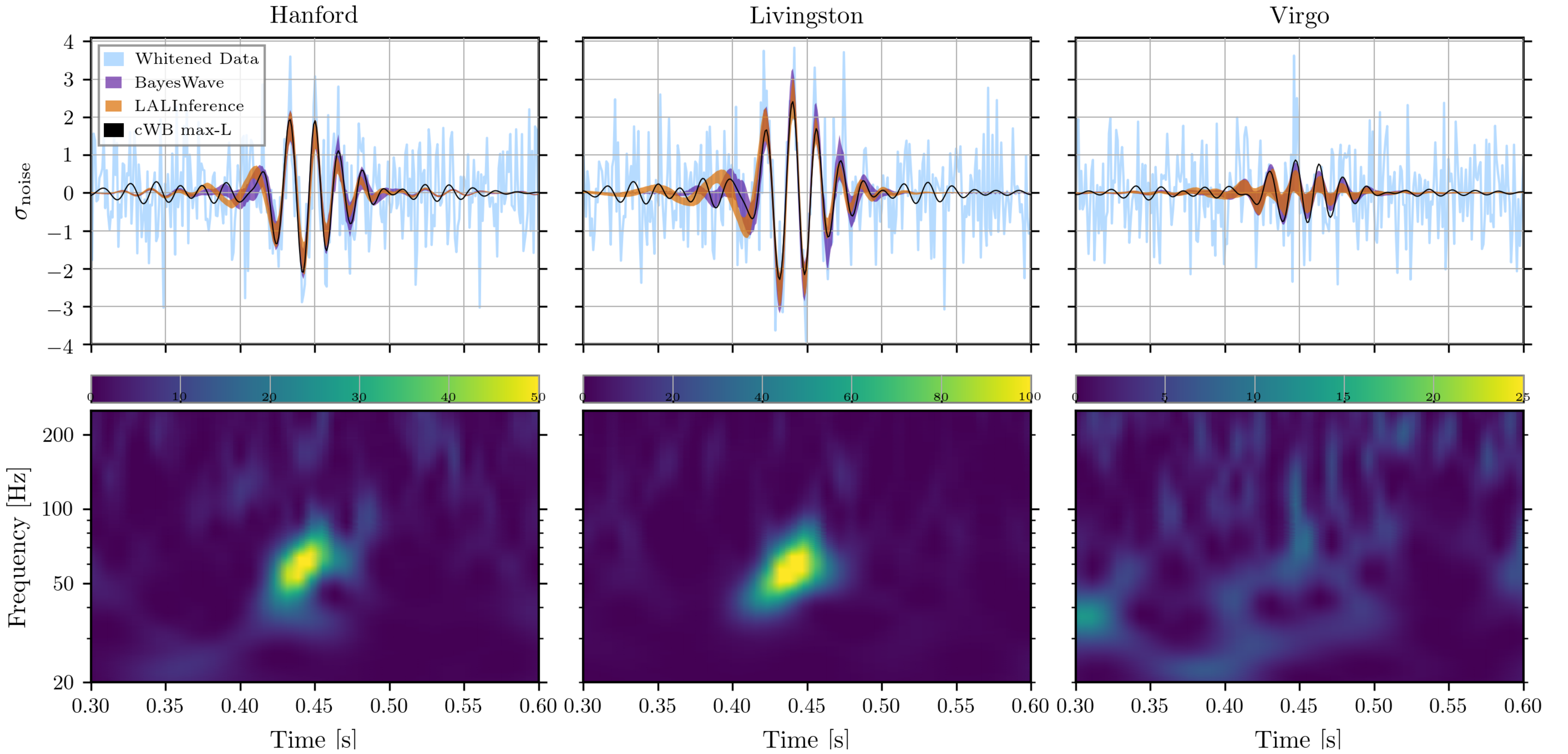




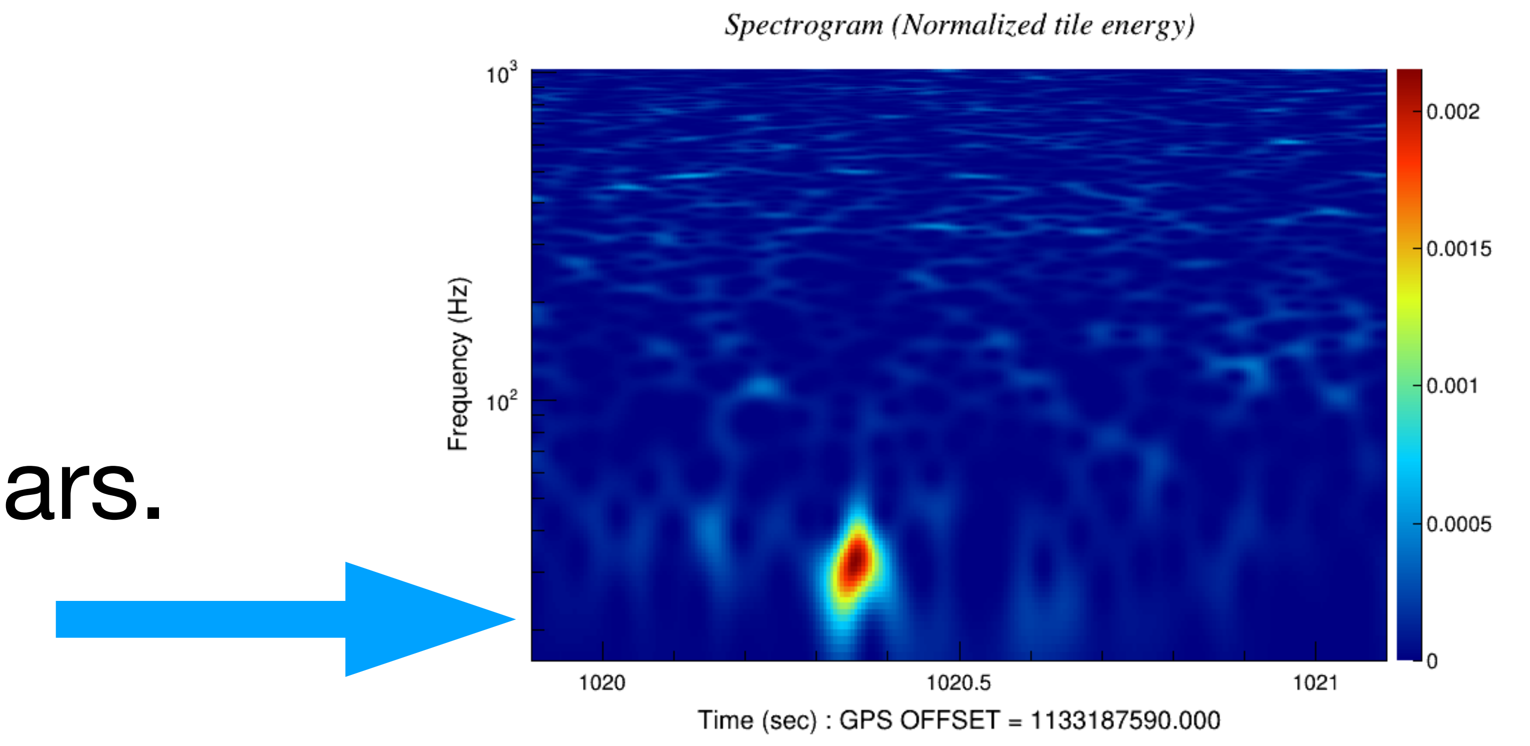
Spins mis-aligned with the orbital angular momentum gives modulation in the signal driven by spin-orbit precession

Discovery of GW190521

Coincident transient between two LIGO detectors on May 21, 2019



- Short transient signal with **0.1sec duration in** the frequency band of 30-80Hz with peak frequency at 60Hz.
- Network SNR of **14.7.** Corresponding False alarm rate of 1 in 5000 years.
- GW detectors exhibit frequent noisy glitches at ~50Hz !!



LVC, PRL 125, 101102(2020)

GW190521: First confident IMBH event

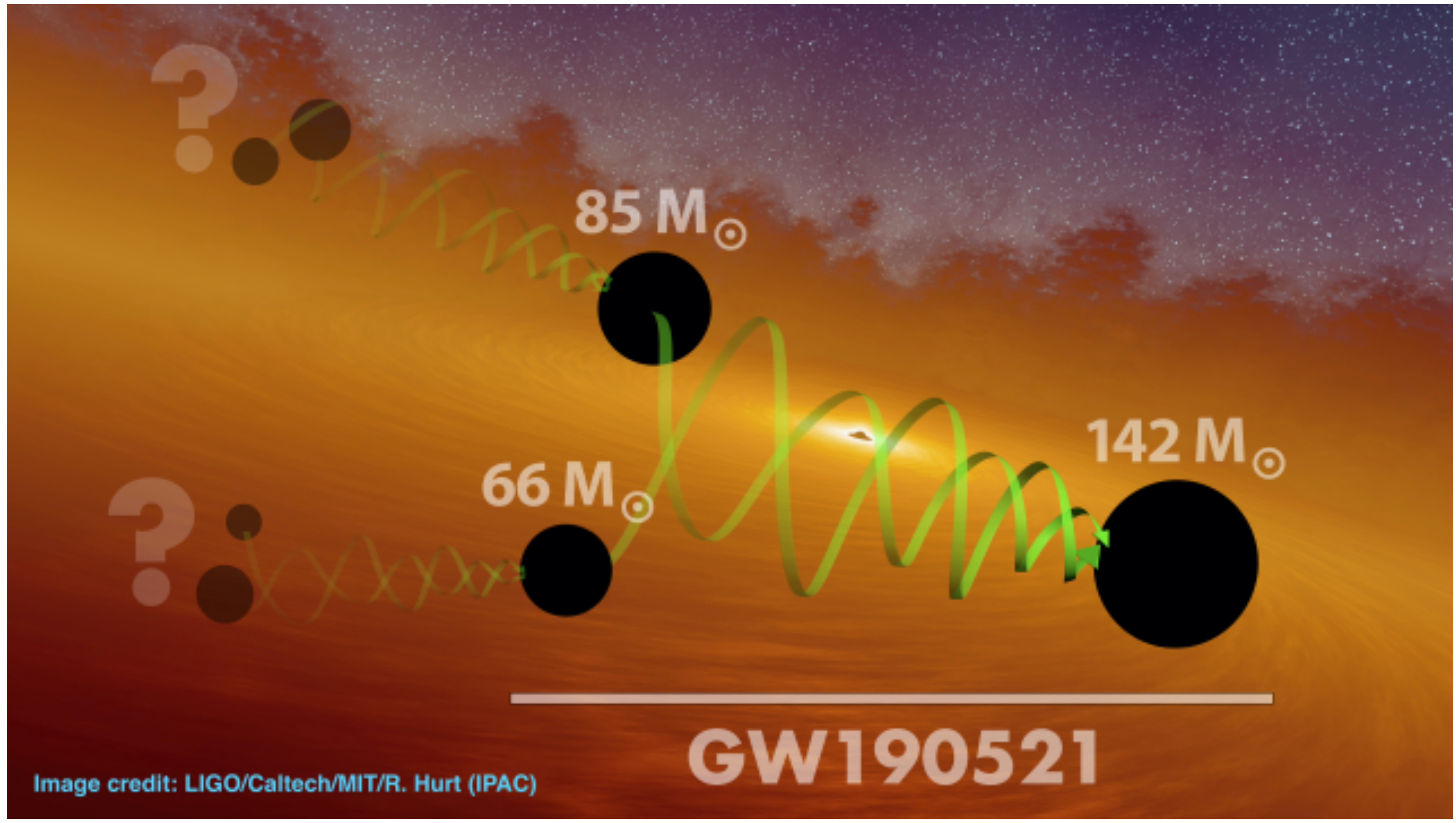
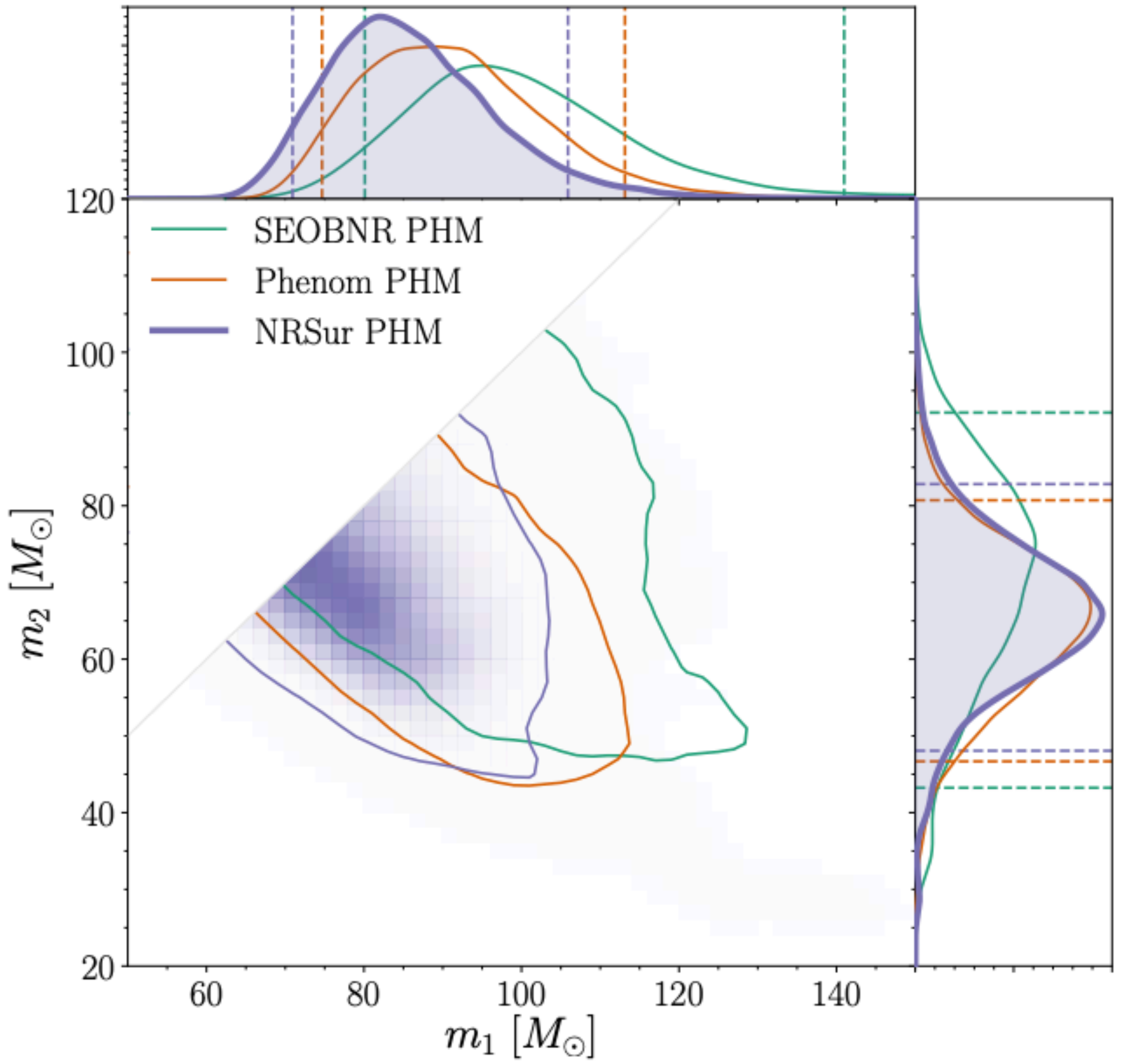
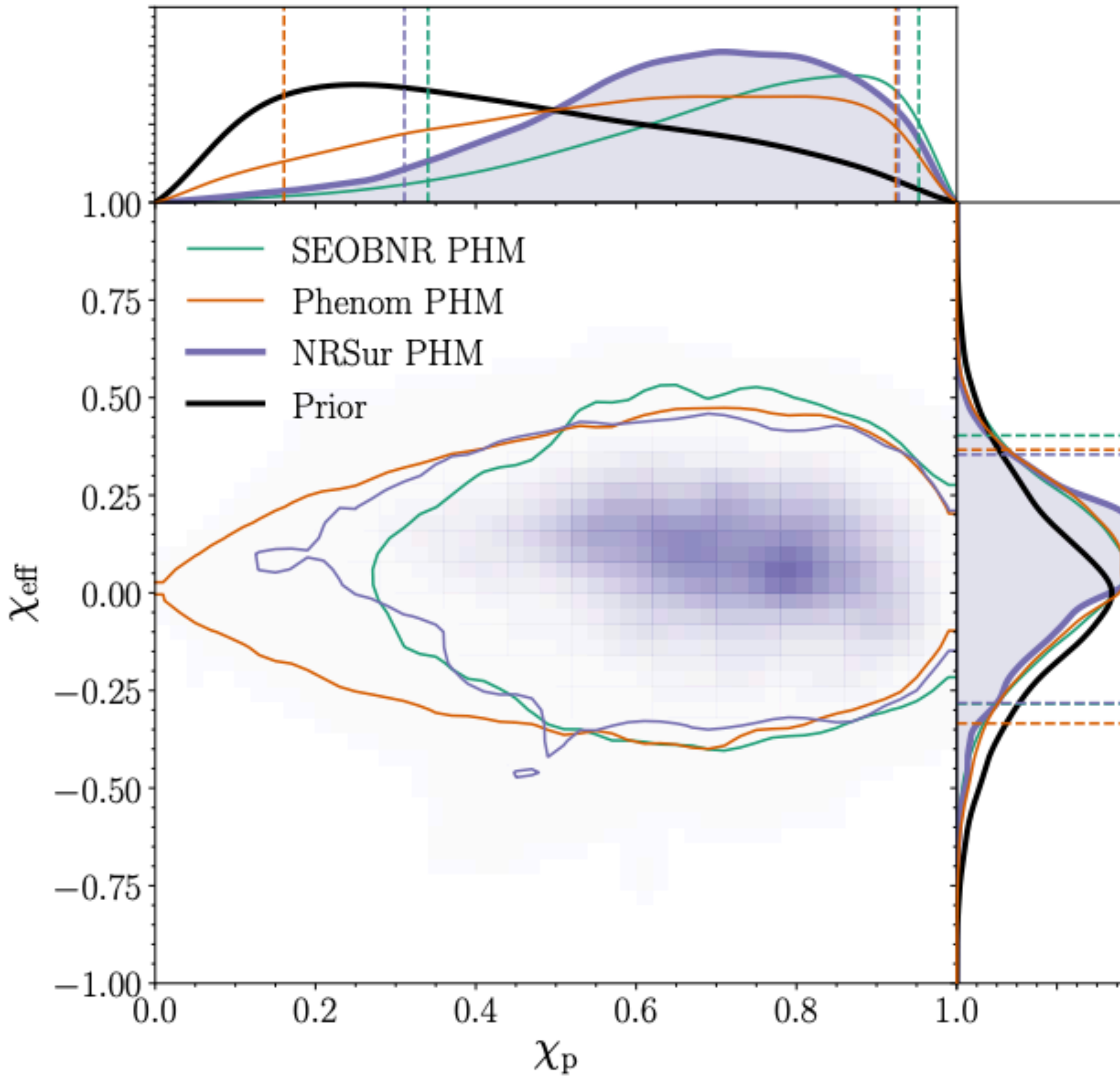


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

- Most massive binary BH system observed with remnant mass as an IMBH **(142 Msun)**.
- Component masses **(85-66 Msun)**
- Distance: **5Gpc**.
- Power radiated in GW is equivalent to **~8Msun.**
- First direct evidence of existence of IMBH with mass < 1000 Msun.
- Short signal with mostly merger and post-merger.
- Showed evidence with mild precession.

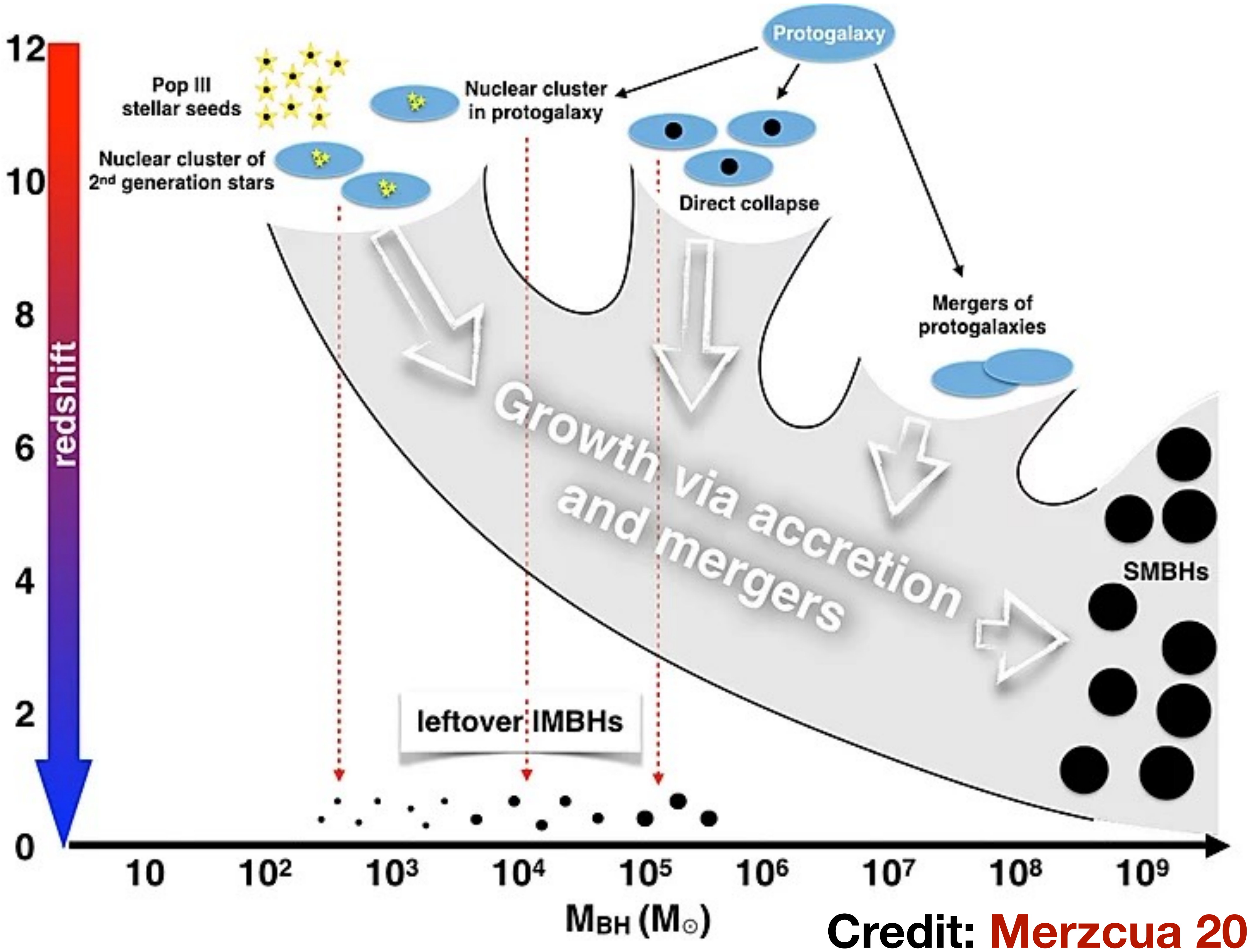




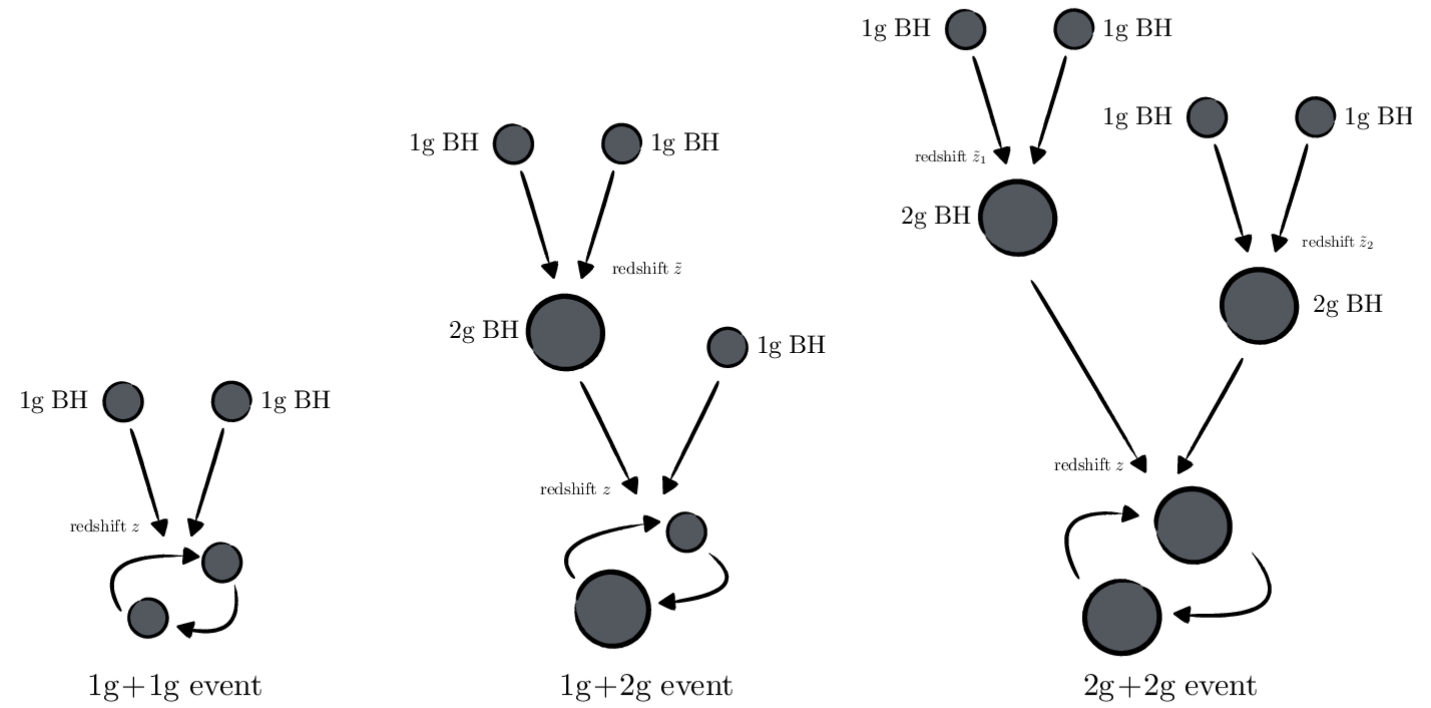
LVC, PRL 2020 LVC, ApJ Letts 2020

Intermediate mass black holes

- Intermediate mass range (100-100,000 Msun).
- Formation possibilities: [Merzcua 2017]
  - Direct collapse of Pop III stars
  - Collapse in metal-free protogalaxy
  - Mergers of stellar mass black holes in the dense environments in a runaway collision process
    - globular clusters
    - galactic centres
  - Multiple collisions of stars in young clusters
- **Different channels leave signatures in properties of the merger.**

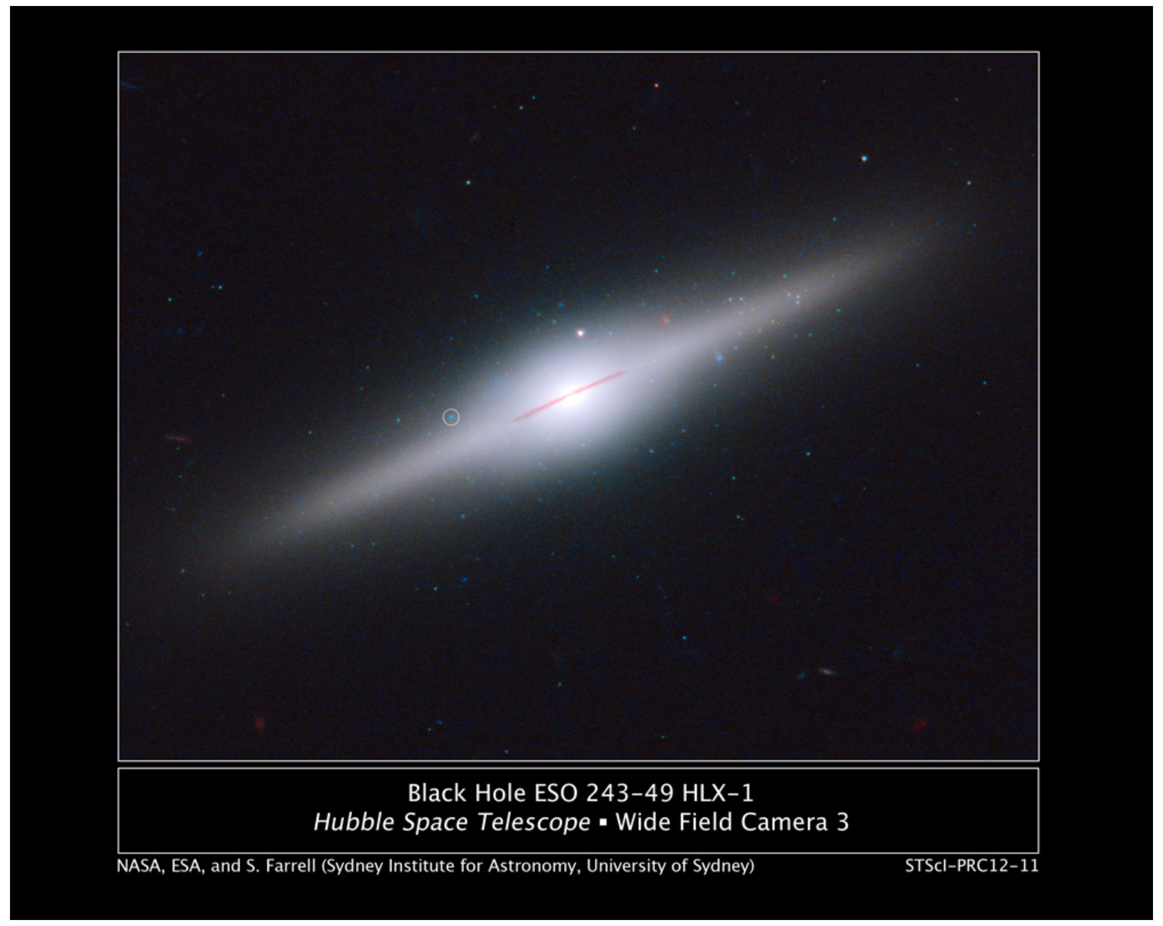


Credit: Merzcua 2017



IMBH in electromagnetic band

- **Several IMBH candidates with indirect/deduced evidence on their masses**
  - Mass estimation due to the kinematics in dense cluster or galaxies [Kizilten, Baumgardt, Loeb, Book, Seth+] e.g. NGC 104
  - The mass extrapolation using the scaling relation between mass and velocity dispersion to the dense clusters [Bosch, Van den Ven, Gebhardt, Noyola +] e.g. M15, G1 in M31, Omega Centauri.
  - Presence of ULX that are brighter than the accreting X-ray sources with stellar mass BHs [Kaaret, Feng, Roberts, Farell, Webb, Godet+] e.g. M74
  - Recent evidence of IMBH in the Andromeda galaxy— 100,000 Msun hidden in B023-G078 [Pachetti et al, ApJ 2022]
- **HLX1: Most promising IMBH candidate**
  - Power radiated $10^{42} ergs/sec$ (million times that of our Sun)
  - Estimated mass ~ 100,000 Msun



Black Hole ESO 243-49 HLX-1
Hubble Space Telescope • Wide Field Camera 3
NASA, ESA, and S. Farrell (Sydney Institute for Astronomy, University of Sydney) STScI-PRC12-11

Peculiarity of GW190521

- **Upper stellar mass gap ~ 50-120 Msun?** [Woolsey, Mappeli, Farmer, Belczynski , Spera, Costa +]

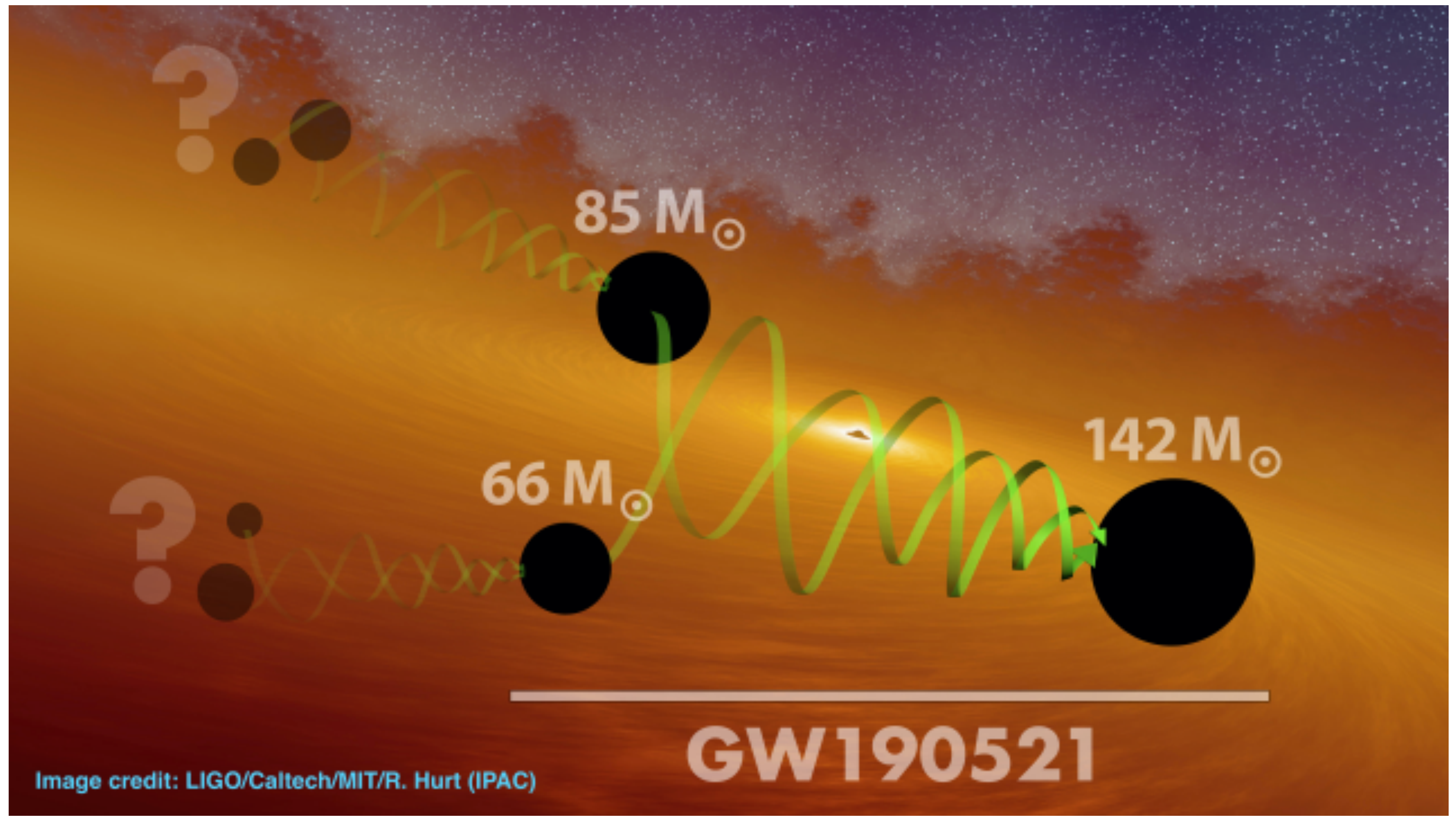


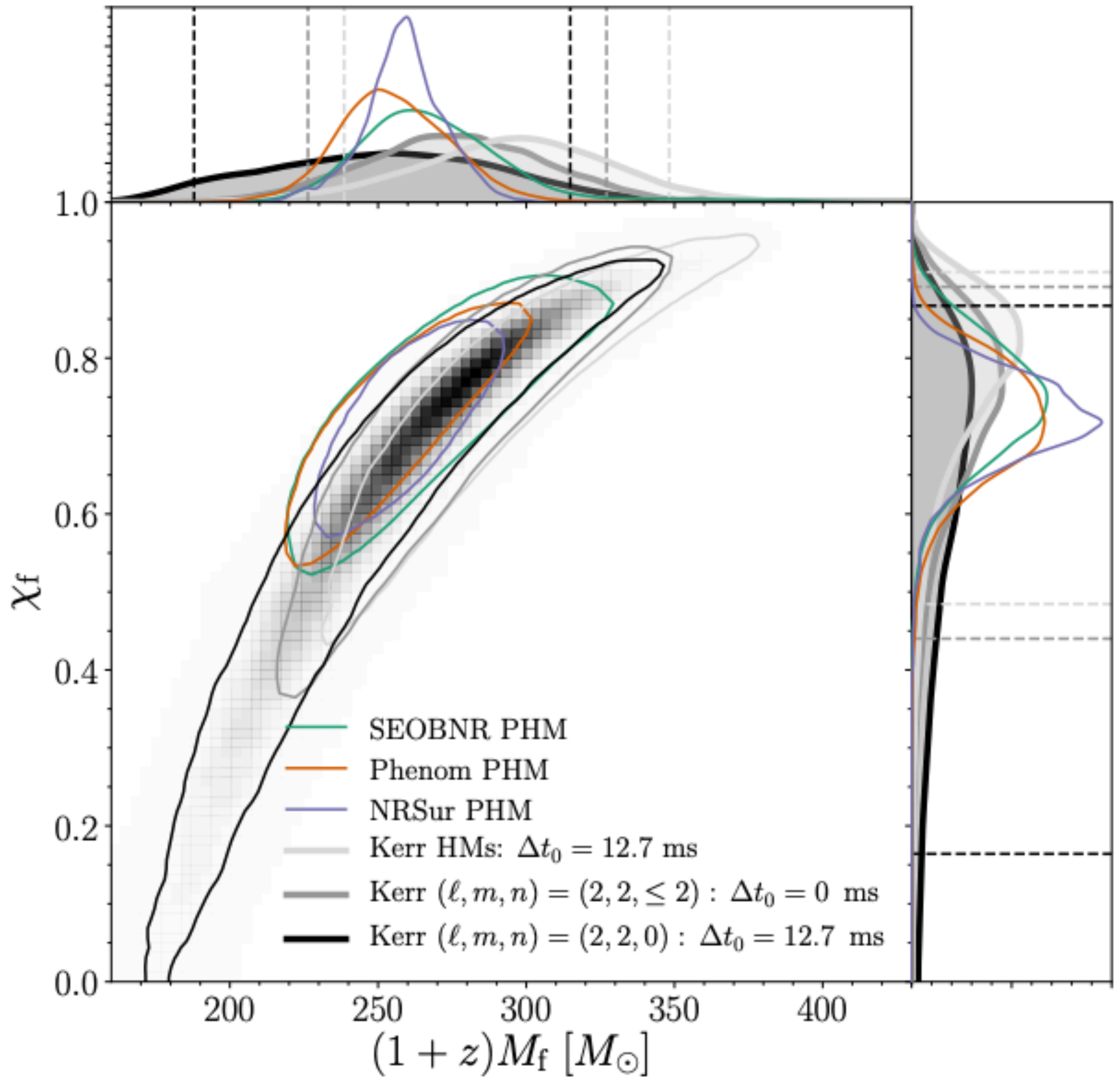
Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

  - Stellar models prediction: Mass of the He core decides the fate.
    - He core mass: 32-64 Msun —— BH below < 50 Msun
    - He core mass: 64-135 Msun, SN explosion leaves no remnant
    - He core mass > 135 Msun —— BH > 120 Msun
  - Uncertainty in the gap due to nuclear reaction rate, metallicity, convection etc

- Component masses of GW190521: **(85-66 Msun)**
  Significant overlap with the mass gap.
  - Are they first generation BHs or remnant of earlier merger event? Need **more IMBH detections**. Need **better detection algorithms**!
  - Indication of high mass BH population through merger/hierarchical merger channel?

Observational implication of IMBH events

- **Implication on stellar evolution**
    - Constraints on the stellar evolution models
    - Understand the upper BH mass gap better.
    - Understand the BH population distribution
- **Testing GR with IMBH systems**
    - Signals with merger and post-merger content in IGWN frequency window
    - Probe the BH ring-down modes and hence QNM structure of the perturbed BH [Vishweshwara Nature 1970]



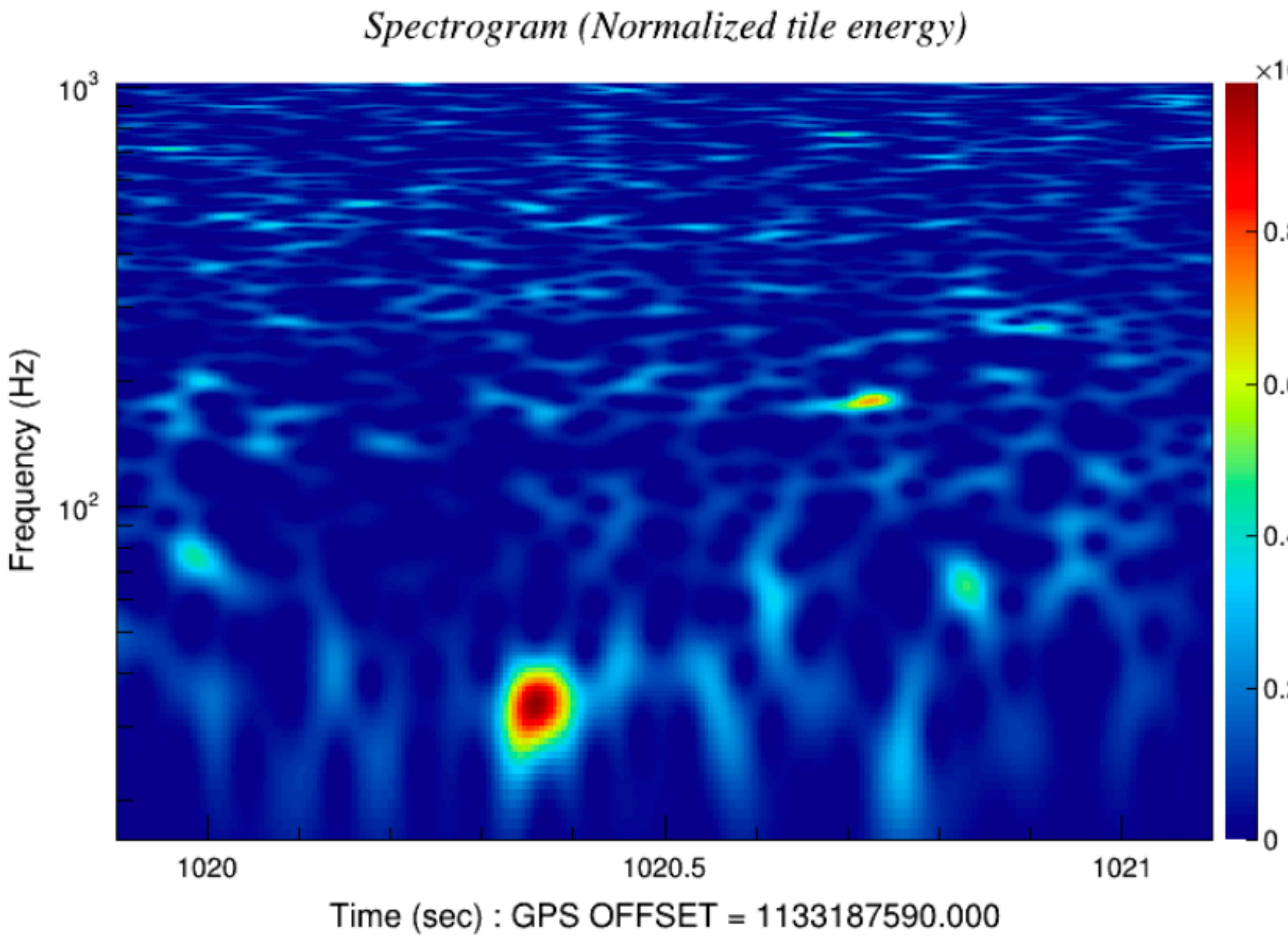
LVC, ApJ Letts 2020

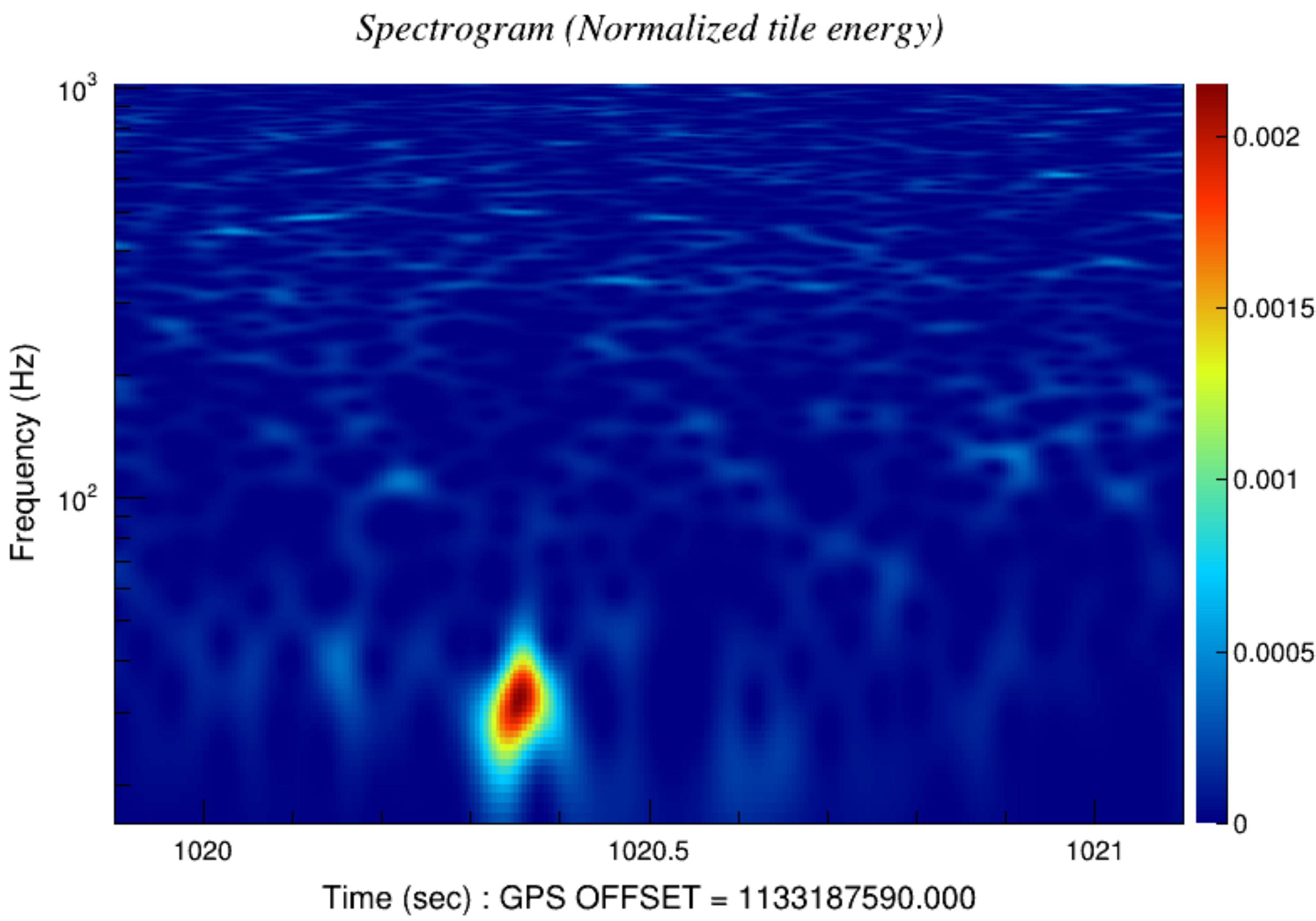
Detection algorithms of IMBH binaries

Challenges involved in the IMBH binary detection/ parameter estimation

- Short signal with mostly merger and post-merger phase. No information of the chirp mass.
- Short duration noisy transients appear like an IMBH signal i.e. short duration blips, tomtes glitches
- Need to take special care **not to mis-classify** the noisy transient as an astrophysical event.
  - O3 IMBH paper — S200114f [LVK, O3 IMBH A&A 2022]
- Need to devise special noise vetos so that we do not miss the actual IMBH binary merger — **Detection challenges**
- Opens up alternative interpretations on the component masses [Nitz, capano 2021, Gayathri et al 2021]— **Parameter estimation challenges**

IMBH binary

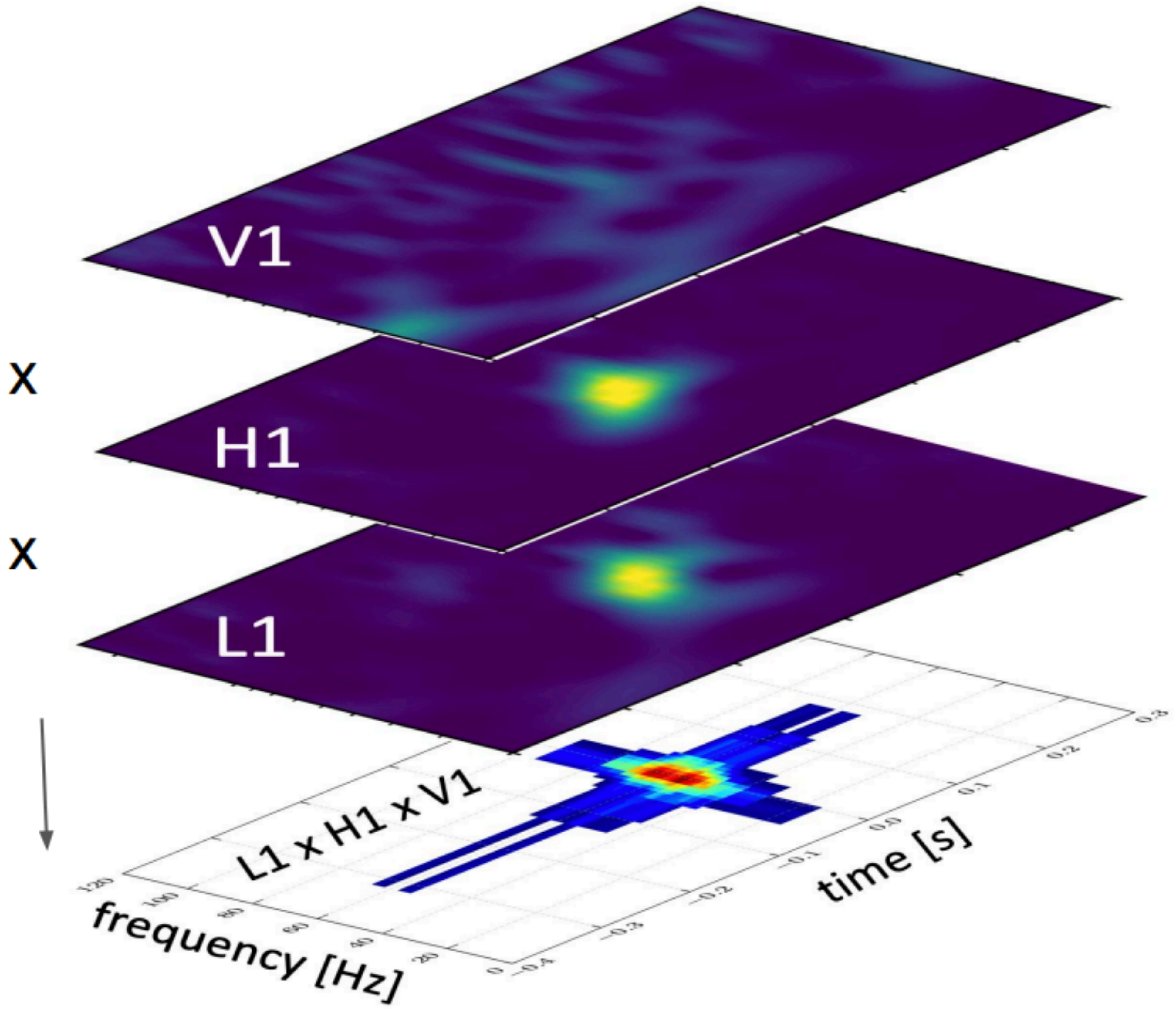




Noisy transient

cWB: Wavelet based model agnostic search = Quite natural for massive black holes

- Coherent Wave-Burst (cWB): Project the data on the wavelet domain characterised by (time,freq,scale).
- Combine the time-frequency energy from detectors (incorporating possible delays) and obtain energetic pixels for each scale.
- Clustering scheme combines the TF pixels from different scales which constructs clusters.
- Maximum likelihood ratio statistic is used for each cluster to obtain multi-detector statistic.
- A large variety of time-frequency morphology based vetos are applied.[LVC O1-O2 IMBH PRD 2019]



[Klimenko etal PRD 2016]

Model based GW transient searches = Matched filtering

Fetching weak signal in the noisy data
d(t)=h(t)+n(t)

Matched filtering is a phase matching technique
Coherent addition of Signal and Incoherent addition of Noise

- Model based Gravitational wave search = A needle in a haystack problem [Dhurandhar, Sathyaprakash, Owen+]

- A large variety of GW signal for a binary system as predicted using Einstein's gravity) are used as templates

- If the output (likelihood statistic) is loud enough, the trigger is selected and scrutinised.

$$\rho(t;\vec{\zeta}) = \sqrt{\langle d|\hat{h}_s\rangle^2 + \langle d|\hat{h}_c\rangle^2},$$

- Simple model **with quasi-circular aligned spin dominant mode waveforms**

Credit: Anirban

Lessons learnt from GW190521 detection story…

- **GW190521 was detected**
  - With ~ 5000 years of associated False Alarm Rate with cWB **(O1-O2 cWB setting won!)**
  - With ~ 1 per year FAR with matched filtering PyCBC search!! **Needed to improve**
- **Why matched-filter based PyCBC investigation was less significant?**
  - Do we want to fold-in more physics in waveforms like precession, Higher Order modes? **No. GW190521 was nearly equal mass system.**
  - PyCBC bank (BNS-BBH-IMBHB) was increasing the false alarms — **Look elsewhere effect!**

- [Chandra et al, PRD 2021]

Optimised PyCBC-IMBH bank

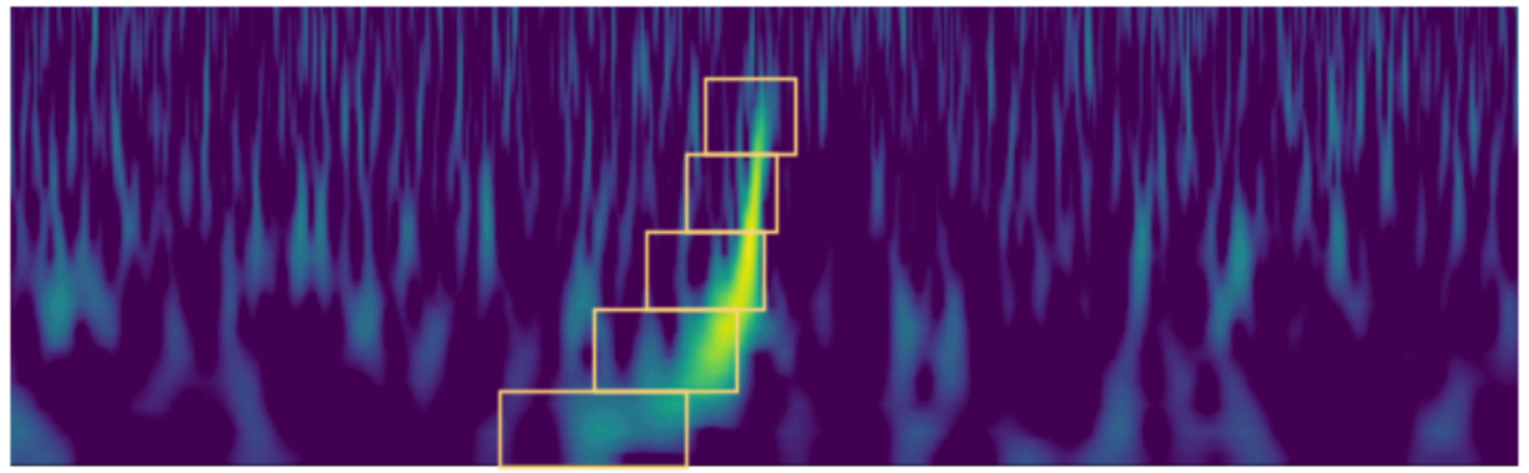
- [Chandra et al, PRD 2021]

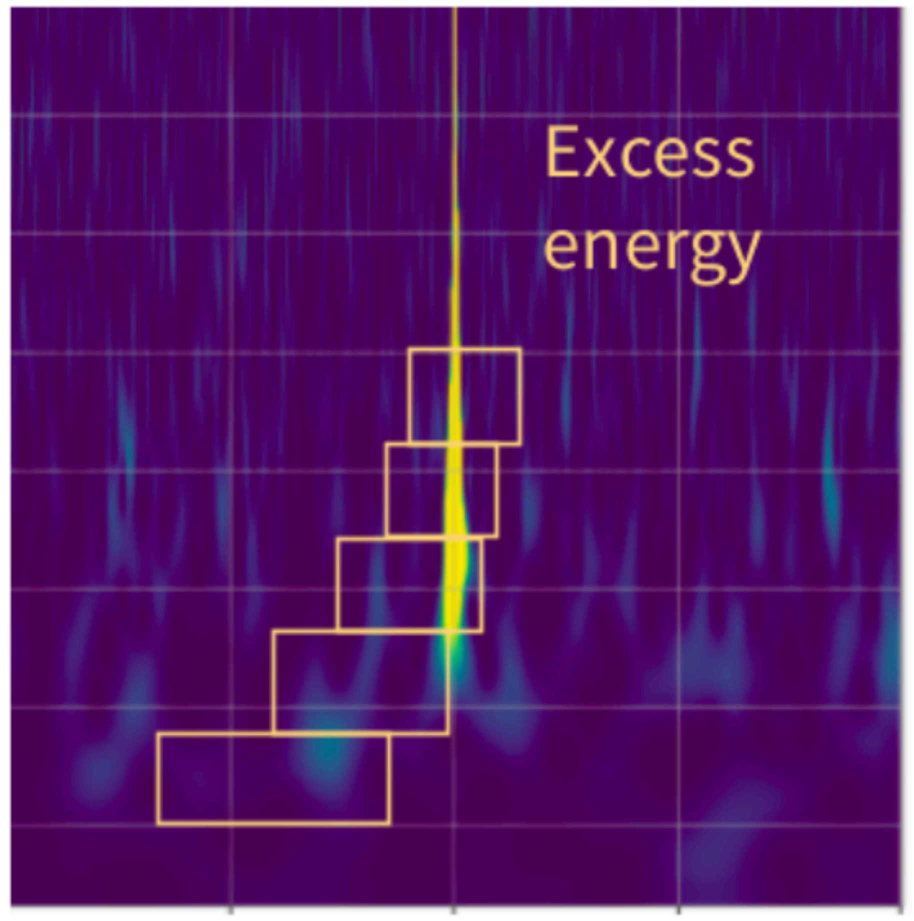
- **Optimised PyCBC IMBH bank** — denser bank focussed in the IMBH space
- Optimally tuned noise vetos by extensive simulation
  - Chi-square veto: Compare the consistency between the spectral content between data and template
  - Sine-Gaussian veto: Probe if the data content has spectral leakage similar to the noisy glitch.

Parameter	
$M_T(1+z)$	$(100\,\mathrm{M}_\odot,\ 600\,\mathrm{M}_\odot)$
$q = m_1/m_2$	$(1,\ 10)$
m_i	$(40\,\mathrm{M}_\odot,\ 540\,\mathrm{M}_\odot)$
$\chi_{\mathrm{i,z}}$	$(-0.998,\ 0.998)$
f_{low}	15 Hz
Minimum Match	0.99
Minimum Template Duration	70 ms
Waveform Model	`SEOBNRv4_ROM`
Number of templates	630

TABLE I. Summary of the Template Bank used for the search.

GW190521

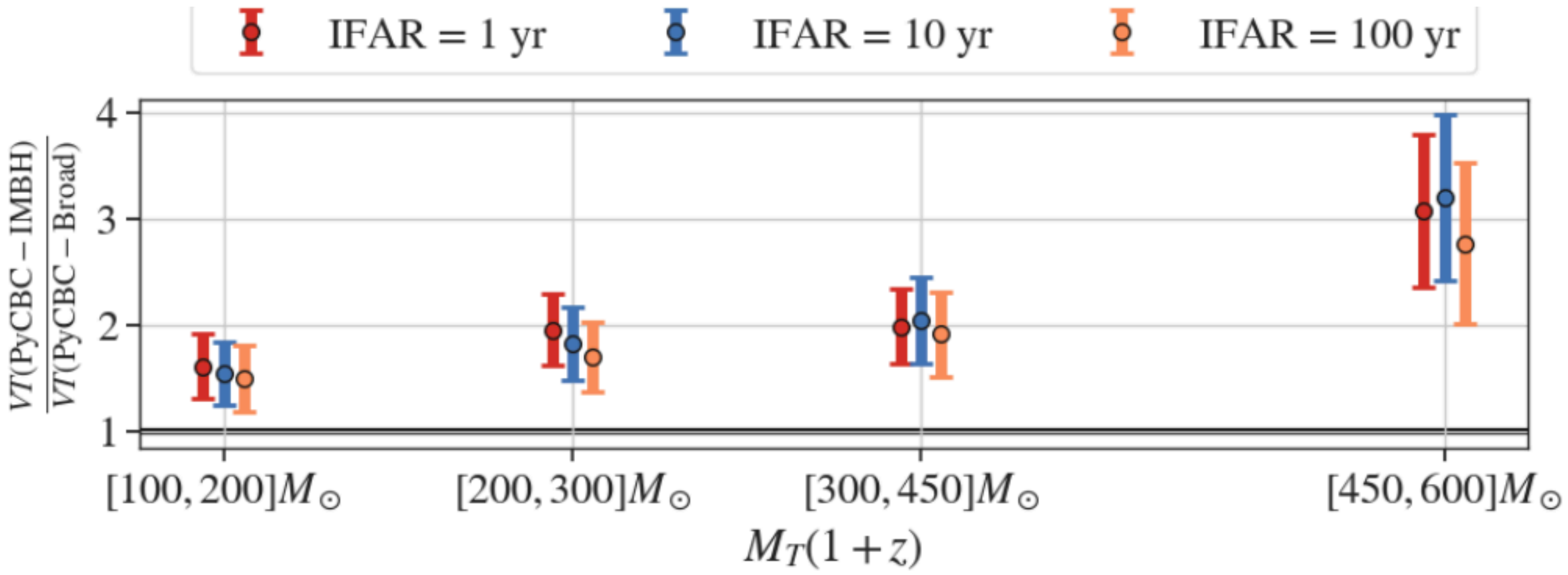




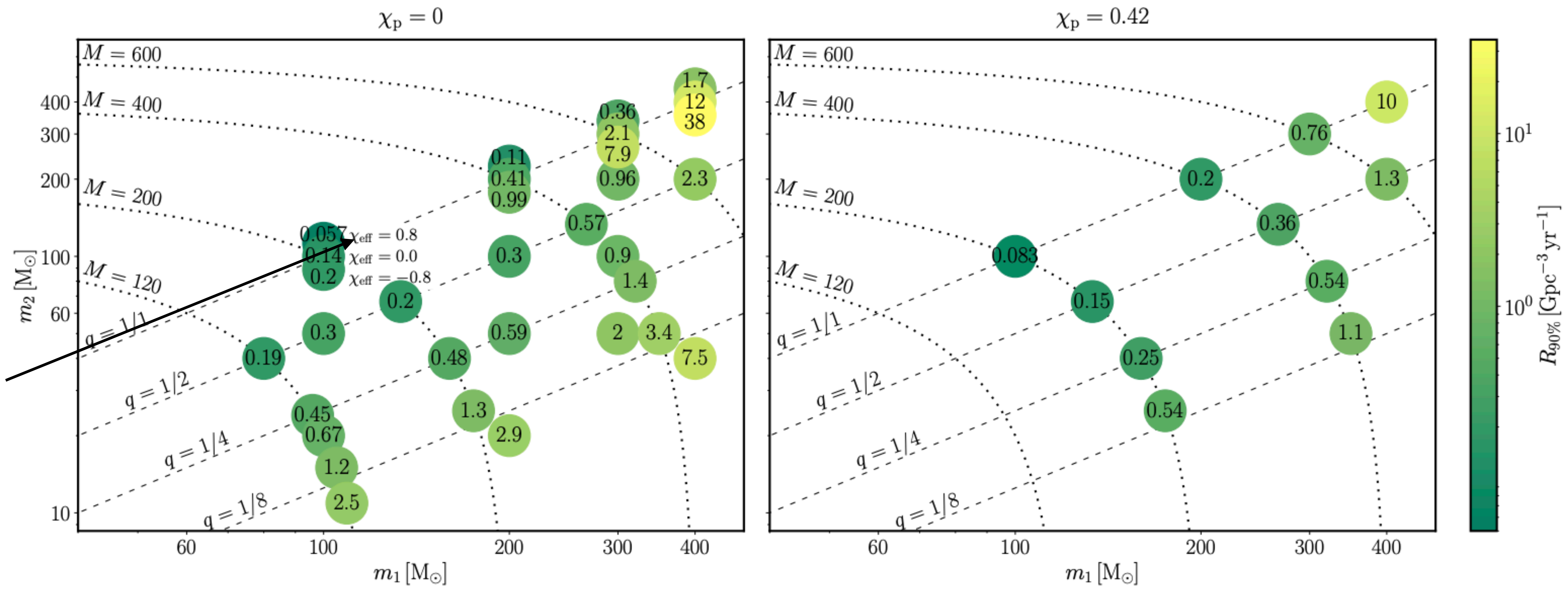
Credit: Chandra

Sensitivity of O3 optimised PyCBC-IMBH bank

- Revised significance of GW190521: Associated false alarm rate of **1 per 730 years.**
- Optimized PyCBC bank showed improvement by a factor up to 4 in volume sensitivity.
- Used in All-sky O3 IMBH search [LVK, O3 IMBH A&A 2022]
- No new significant IMBH binary was detected except GW190521.
- **Optimised PyCBC search performs comparable to cWB in most of the IMBH mass bins — 2 sensitive and independent algorithms**
- **O3 IMBH search — The upper limit on the merger rate density for 100-100 Msun is 0.056 per Gpc^3per year. ~ One merger event per Globular Cluster in its lifetime. [LVK, O3 IMBH A&A 2022]**

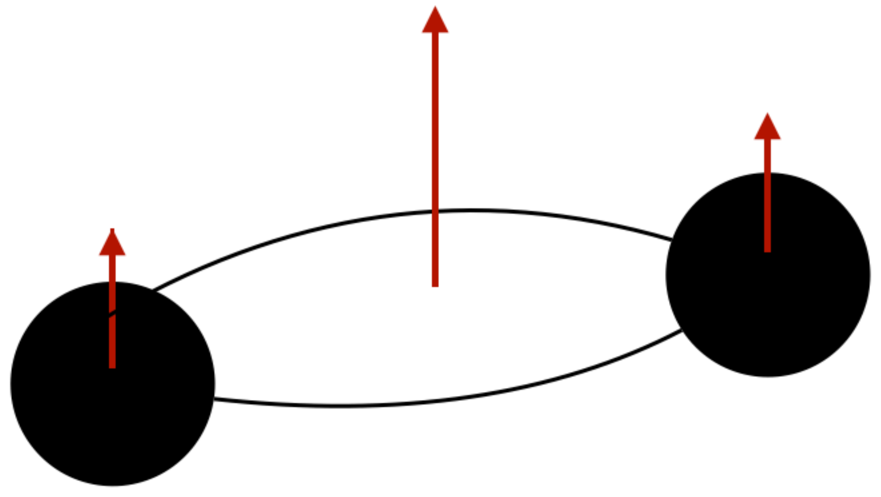


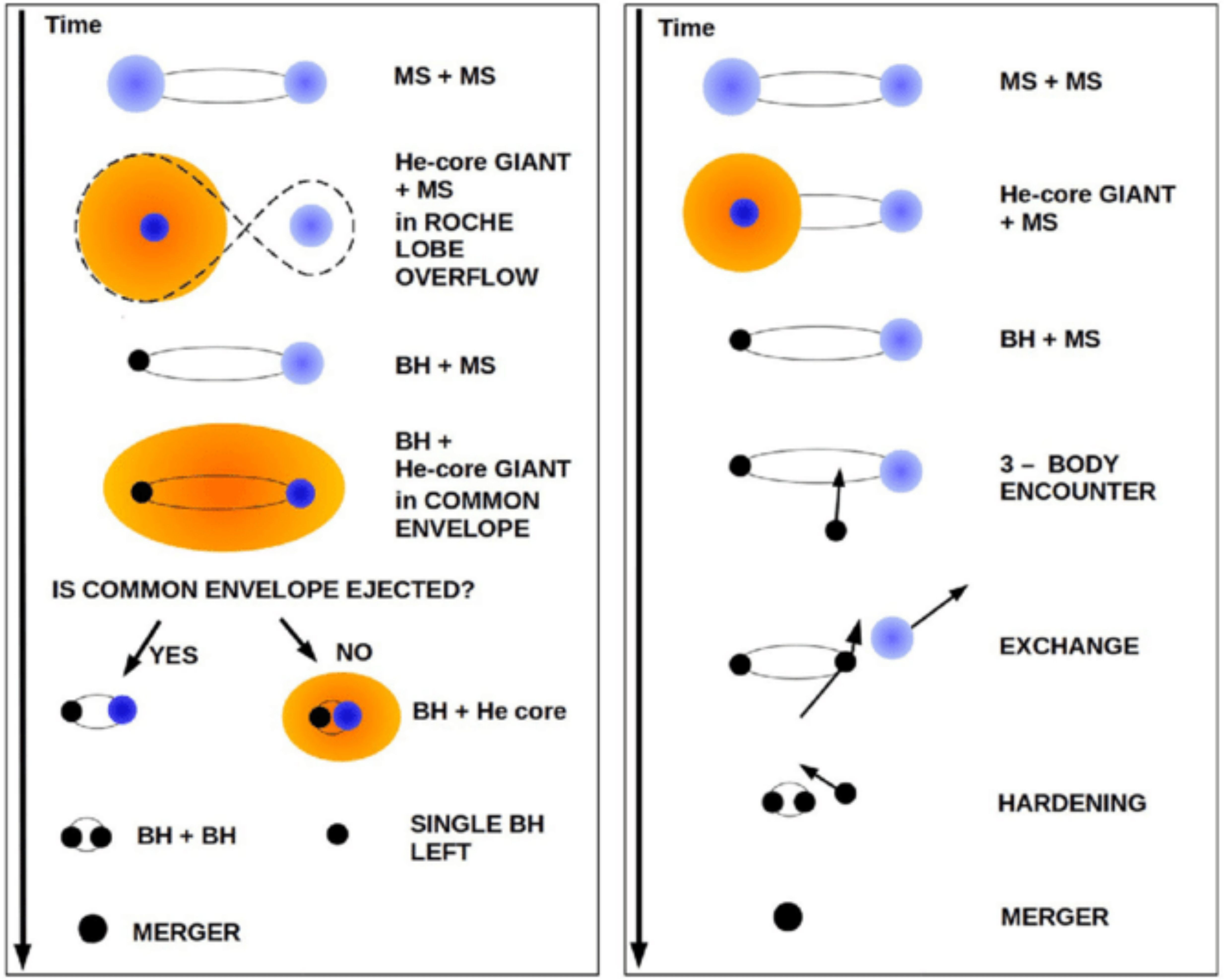
- [Chandra et al, PRD 2021]



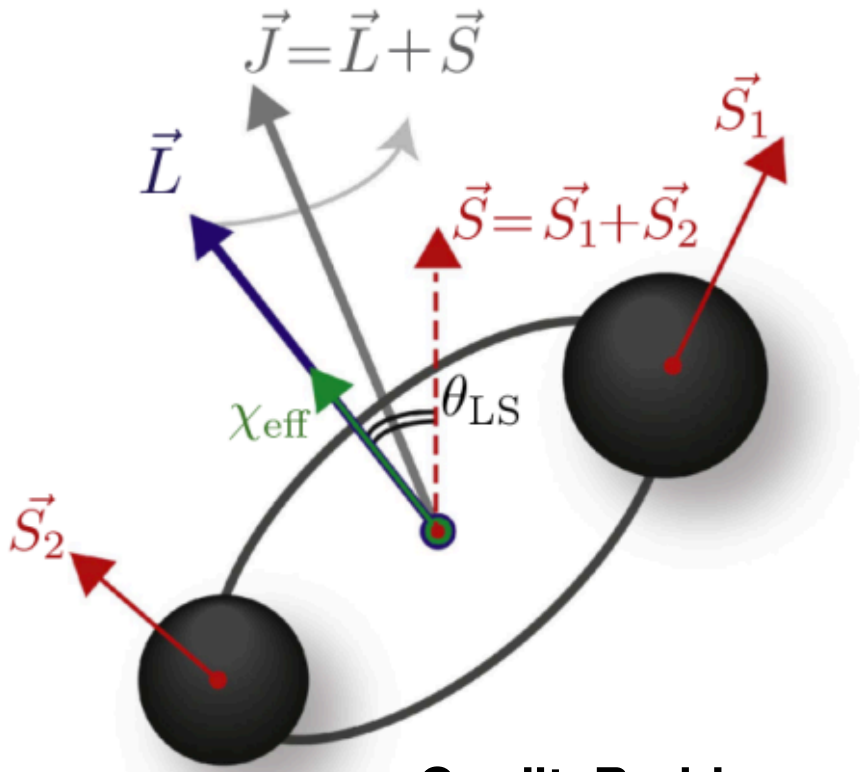
Broad class of black-hole binary formation

Isolated black-hole binaries — Expect to shed the asymmetry. Spins aligned with the orbital angular momentum.





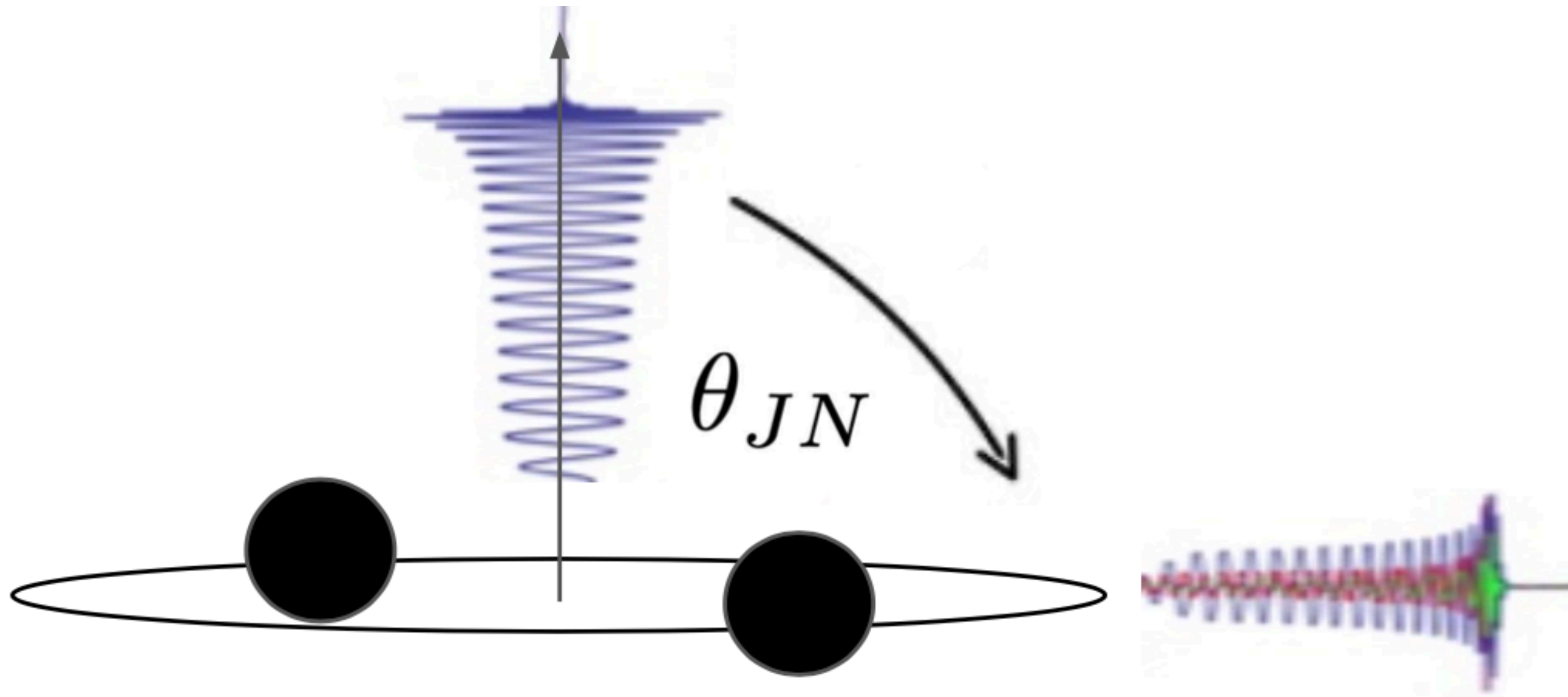
Binaries formed in the crowded environment — Individual spins are randomly oriented with respect to the orbital angular momentum.



Credit: Rodrigues

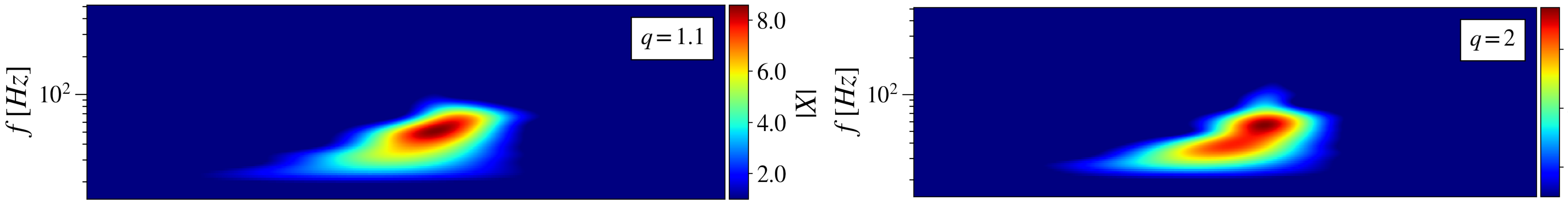
Credit: Michela

IMBH formed in the crowded dynamical environment : Signatures

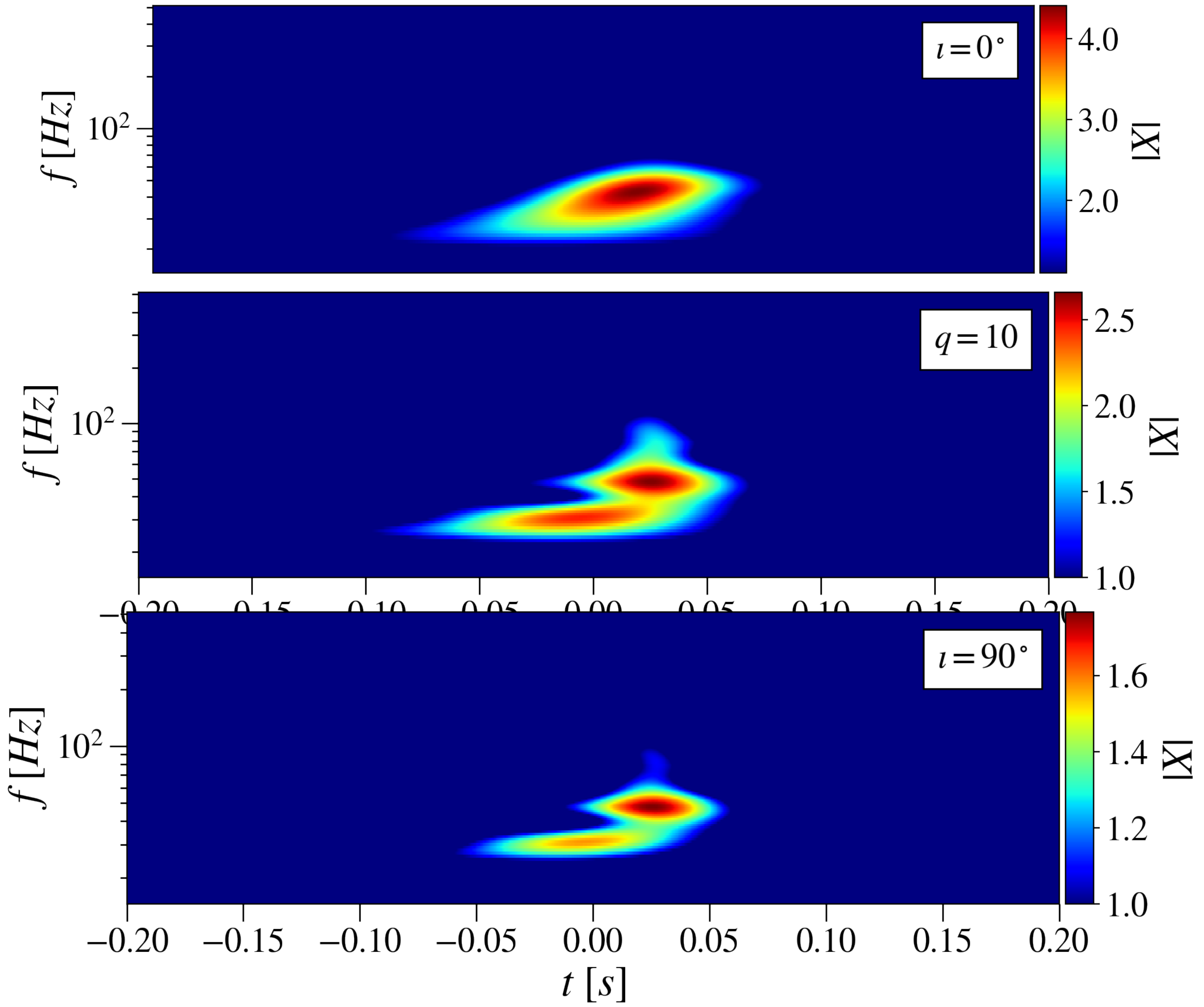


- In crowded environment like galactic centres, globular cluster, no time for system to shed away the symmetry
  - **Asymmetric masses (mass ratio q>1):**
    — Higher order modes, higher than (2,2) in the signal. Weak but complex.
    — Increases the complexity of the signal with higher inclination

Effect of high q



Effect of high inclination



IMBH formed in the crowded dynamical environment : Signatures

- In crowded environment like galactic centres, globular cluster, no time for system to shed the symmetry
  - **Asymmetric masses (mass ratio q>1):**
    - Higher order modes, higher than (2,2) in the signal. Increased complexity of the signal with higher mass ratio and high inclination
    - **Waveforms are available : Two pronged approach**
      - **Matched filter based** IMBH search with higher modes: PyCBC-HM [Chandra et al PRD 2022]
      - **Convolutional neural network based** IMBH search with higher modes: THAMES [Sharma, Chandra, AP arXiv:2208.02545]
        - THAMES leverages on the ability of the machine learning algorithms to capture the time frequency based features **to classify between the noisy glitches and the IMBH-HM signals**

Salient features of PyCBC-HM

Chandra et al PRD 2022

- Targeted to **nearly edge-on quasi-circular IMBH binary** systems (systems with high higher order mode impa

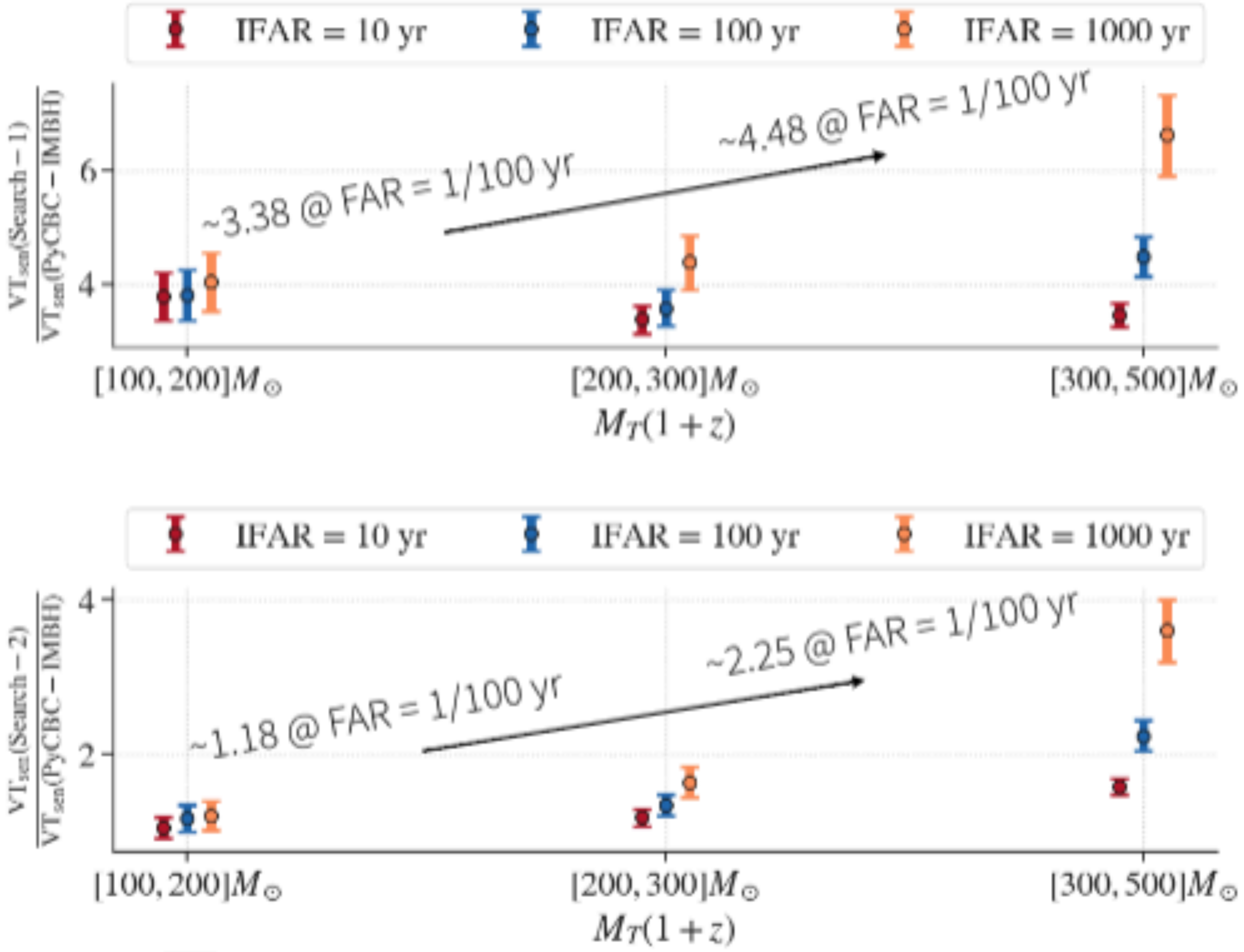
- Improved detection statistic

$$\frac{(d|\hat{h}_+)^2 + (d|\hat{h}_\times)^2 - 2(d|\hat{h}_+)(d|\hat{h}_\times)(\hat{h}_+|\hat{h}_\times)}{1 - (\hat{h}_+|\hat{h}_\times)^2}$$

- Appropriate minor tuning of vetos

$$\text{Target Space:} \begin{cases} M_T(1+z) \in [100, 500]\ M_\odot \\ 1 \leq q \leq 10 \\ |\chi_{\text{eff}}| \leq 0.99 \\ 75^\circ \leq \iota \leq 105^\circ \\ 0 \leq \phi \leq 360 \end{cases}$$

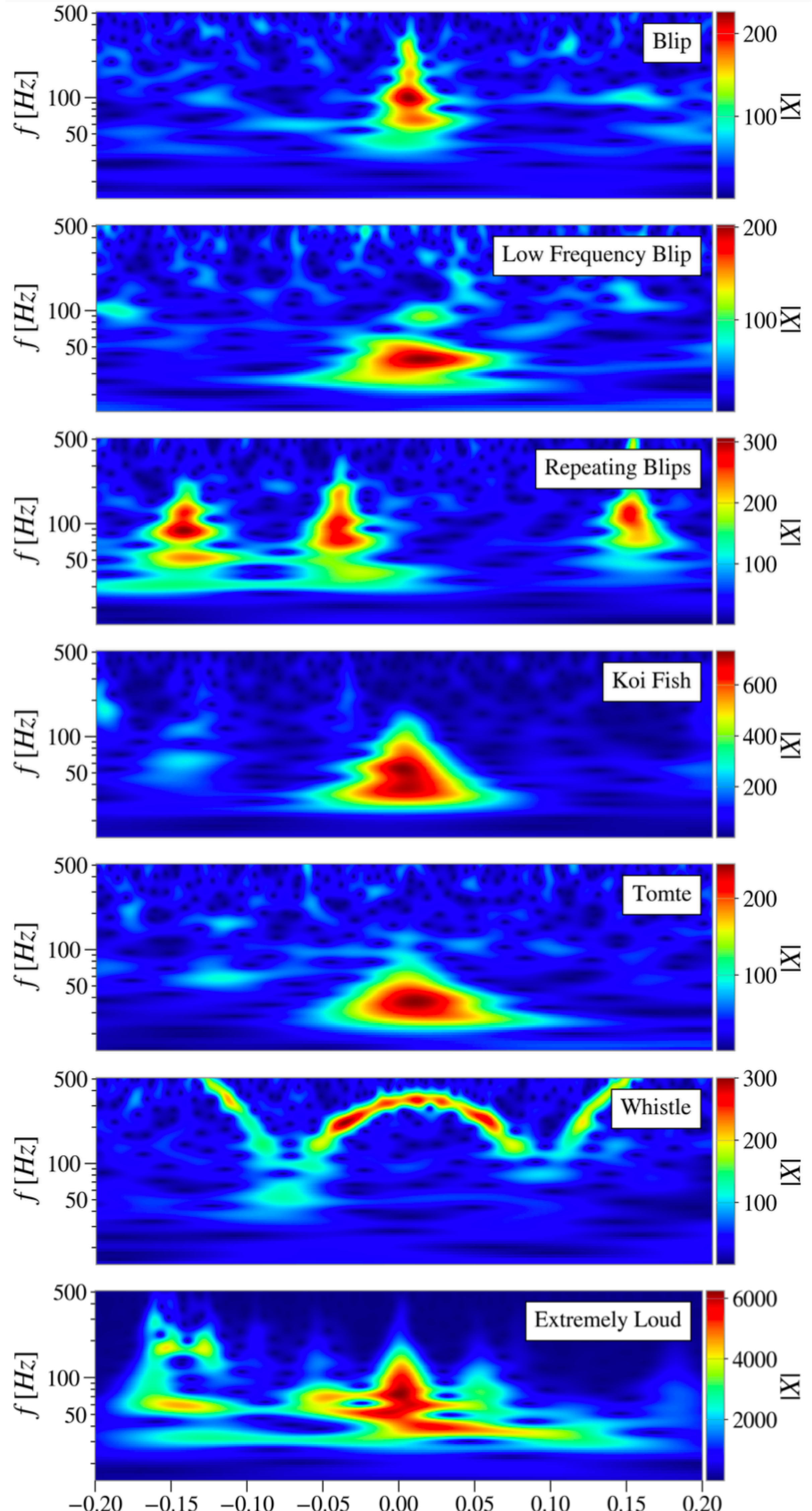
$$\text{OtherDetails} = \begin{cases} \text{Approximant} = \texttt{SEOBNRv4HM\_ROM} \\ f_{\text{low}} = 15Hz \\ \text{Minimal Match} = 0.97 \end{cases}$$



Salient features of THAMES

- [Sharma, Chandra ,AP arXiv:2208.02545]

- **THAMES: T**ransfer learning for **H**igher order modes from **A**symmetric **M**assive **E**dge-on **S**ystems
- Based on Convolutional Neural Network with Transfer Learning
- **Time-frequency morphology used for training**
  - Signals: IMBH with nearly edge-on systems
  - Noisy transients: A large variety of noisy glitches affecting massive BH binary searches
- Two detector network with **newly designed statistic.**
- **Newly designed noise vetos** based on the glitch morphology in time-frequency map
- **Performs comparable to the PyCBC-HM bank [Chandra et al PRD 2022] for GW190521 like systems**



IMBH formed in the crowded dynamical environment : Signatures

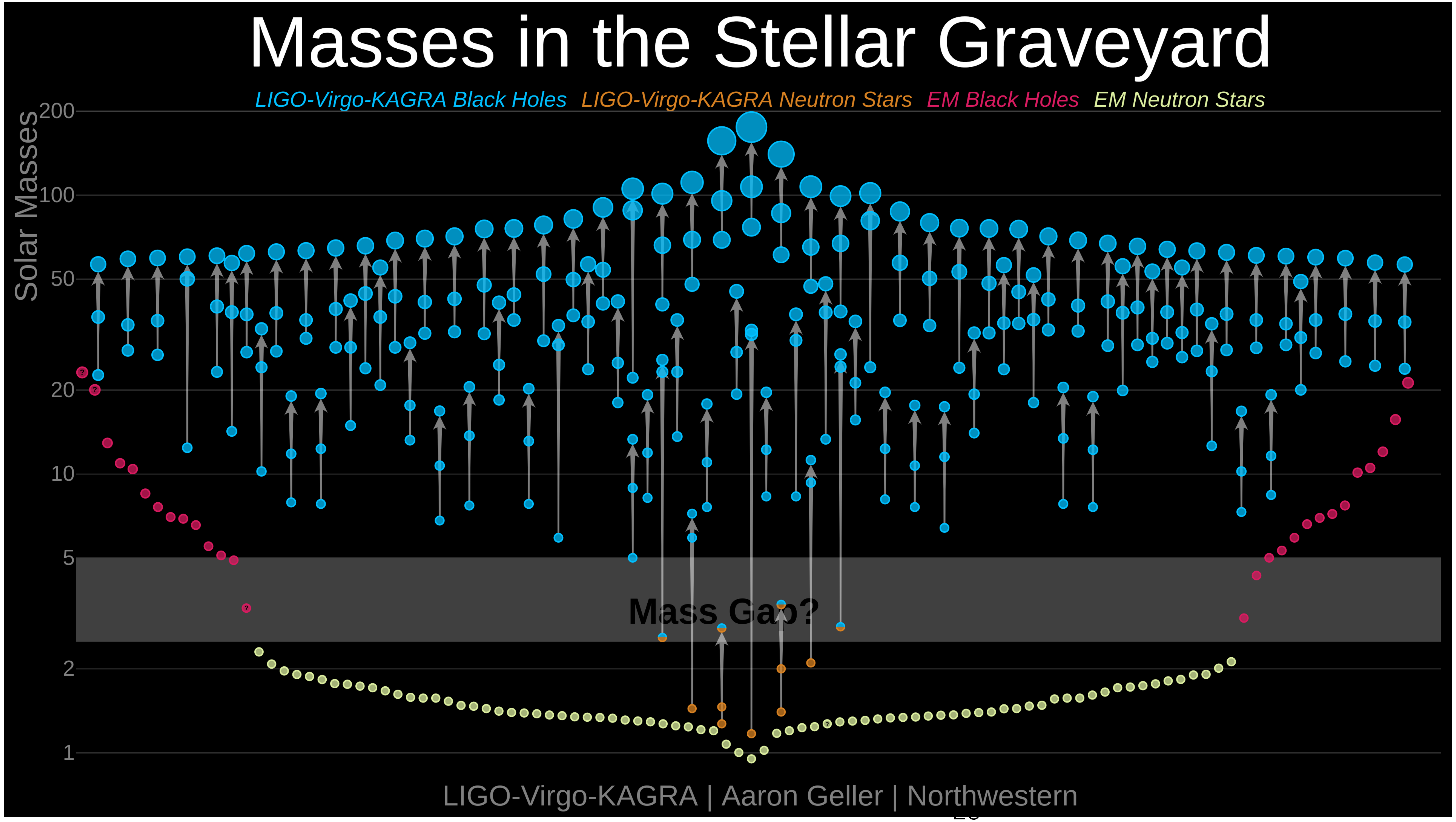
- In crowded environment like galactic centres, globular cluster, no time for system to shed the symmetry
  - **Asymmetric masses** — Higher order modes, higher than (2,2) modes in the signal
    - **Waveforms are available :** Two pronged approach taken
      - **Matched filter based** IMBH search with HM: **PyCBC-HM** — [Chandra et al PRD 2022]
      - **Convolutional neural network based** IMBH search with higher modes: **THAMES** — [Sharma, Chandra, AP arXiv:2208.025
  - **Spin-precession** — Spin-orbit coupling introduces signal modulation which increases complexity
  - **Non-circular binaries —** Eccentricity brings new features
- While all the three effects are expected to be together! REAL WORLD IS ALWAYS COMPLEX
  - Currently **no reliable waveform is available with HM, high mass ratios, precession and eccentricity**

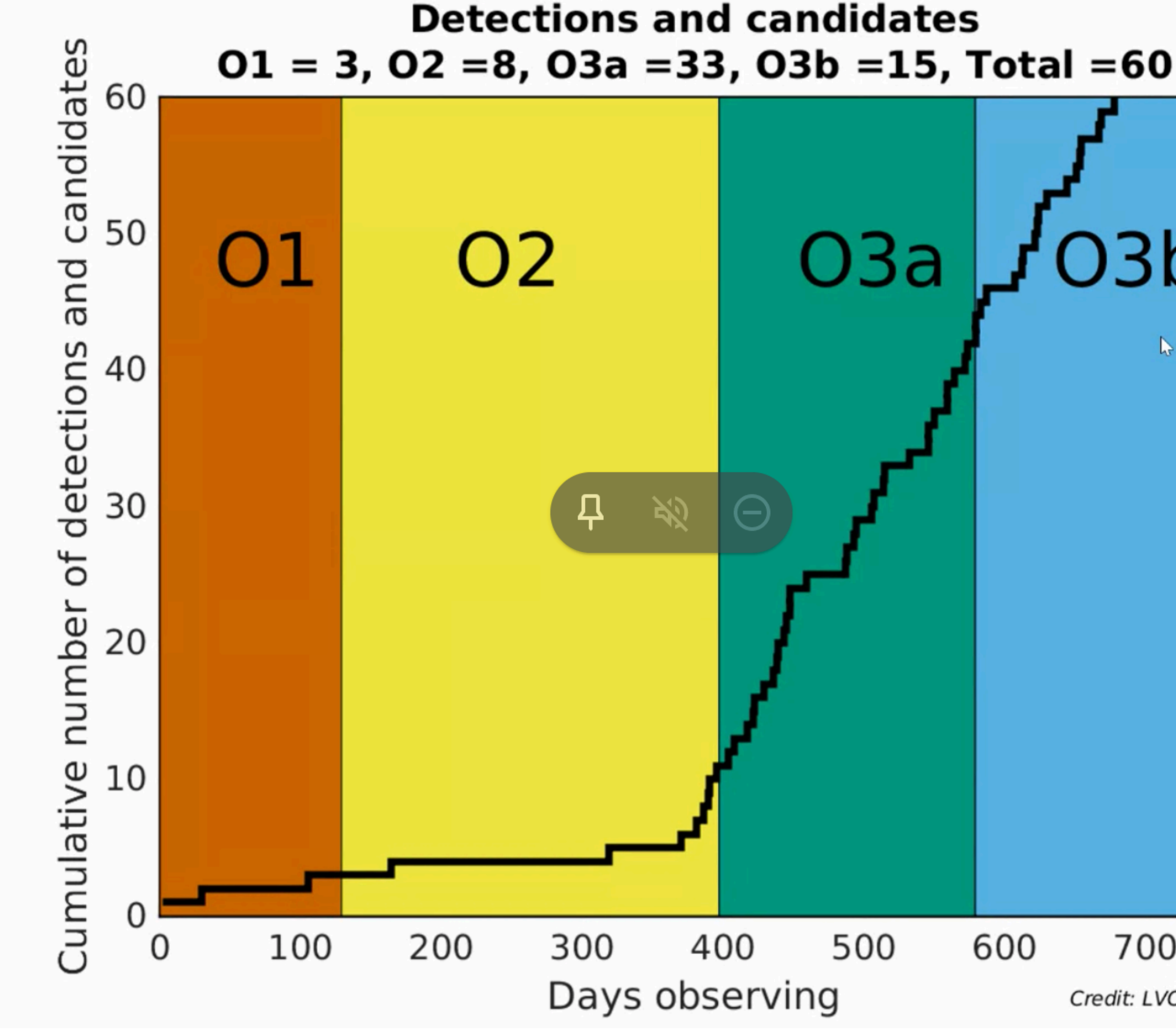
Alternative interpretation of GW190521

- GW190521 is a short duration signal with close to NO inspiral content. Probing chirp mass OR component masses is a challenging endeavour. Alternative interpretation of the signal due to degeneracy!
- GW190521 is a **asymmetric system** [Nitz+Capano, ApJ Lett. 2021]
  - Masses 171-16 Msun — both the components outside the mass-gap.
  - High mass ratio, claim to have detected higher mode
  - Sensitive to waveform choice: IMRPhenomXPHM Vs waveform with no HM support of higher q support
- GW190521 is **an eccentric system** [Gayathri et al Nat. Astronommy 2021]
  - Both masses in the upper mass-gap
  - Equal mass system, eccentricity ~ 0.7, Precession ~0.7 (Like LVC result)
  - Using NR simulations

Future prospects

Compact binaries from IGWN



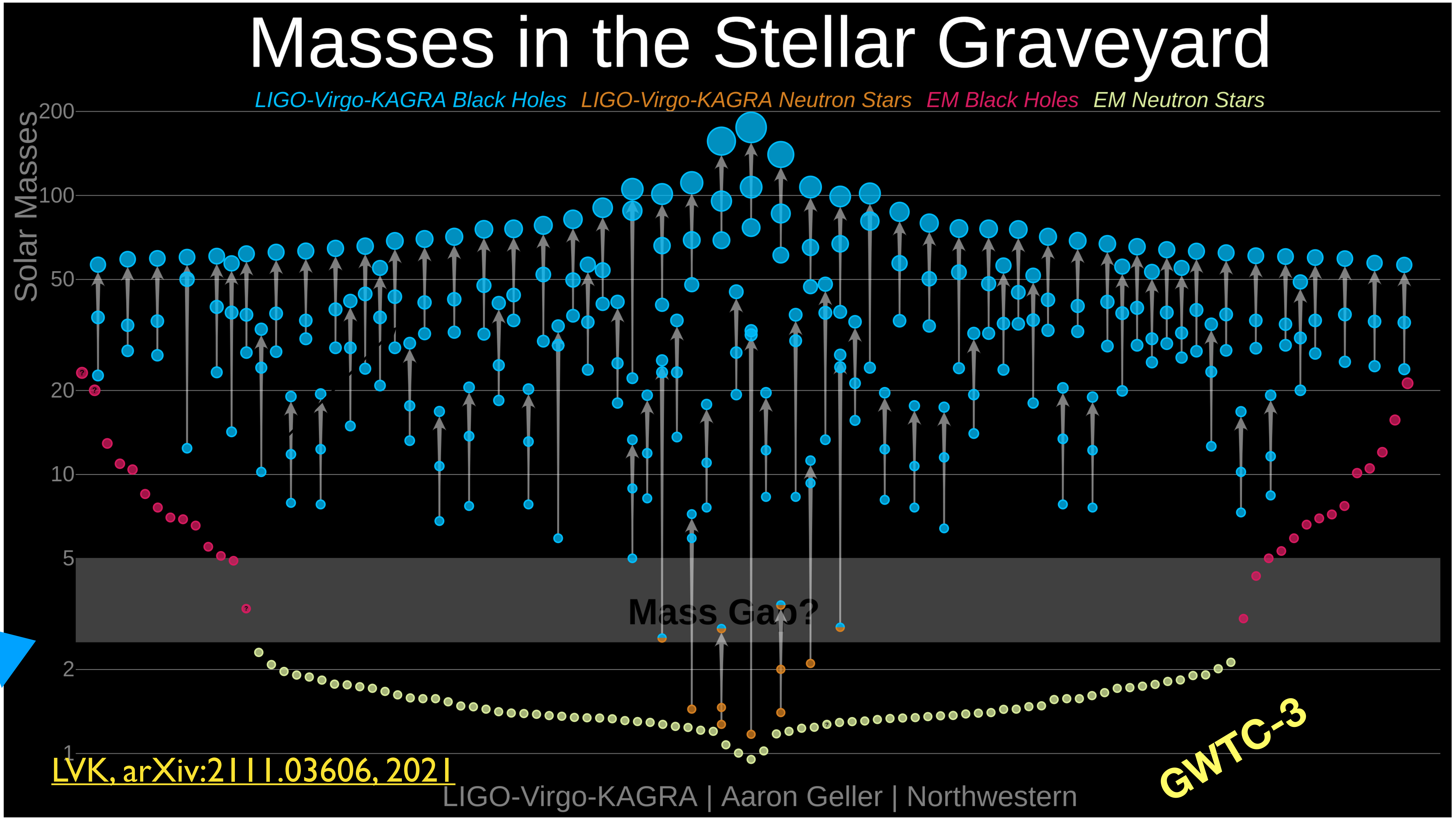


76 compact binary merger Events are with associated false alarm rate < 1per year which includes

2 BNS mergers
2 NSBH mergers
1 IMBH binary merger (GW190521)

Masses of the compact binary mergers

- Majority compact binary mergers are binary black hole mergers and **nearly equal mass.**
- A large fraction of the BH masses inferred in GW window extend **well above the BH masses observed in the X-ray binaries**.
- X-ray observations are drawn from binaries with near solar metallicity. Higher is the metallicity, more is the mass loss due to winds and hence less massive remnants — **Possible observational bias**
- Studying the component masses of BHs gives direct input on the **formation and progenitors**.
- Compact objects **lower mass gap** (3-5 Msun) predicted from the X-ray observations. Does this exist?
- Compact objects in the lower mass-gap makes the nature of the object inconclusive.

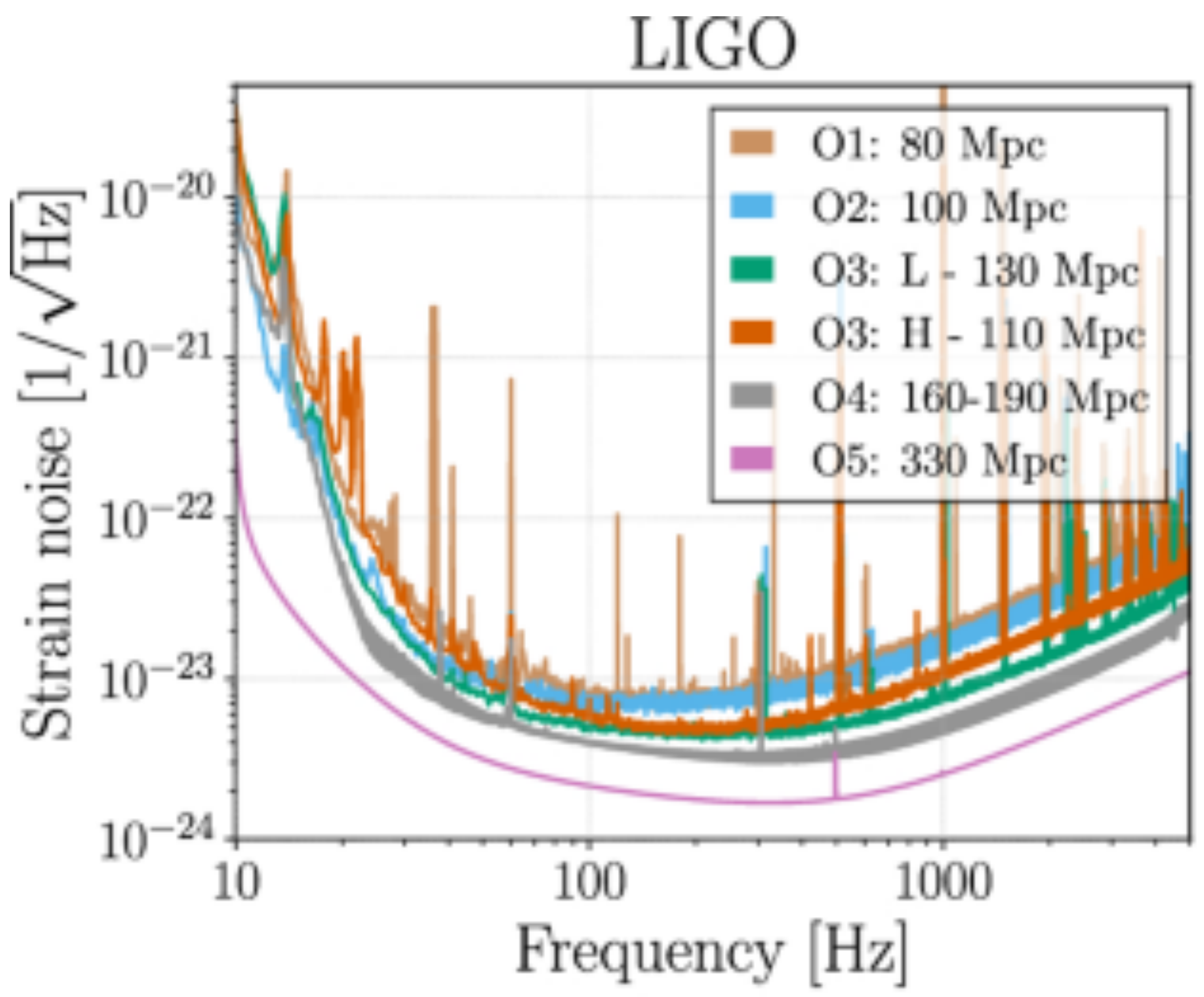


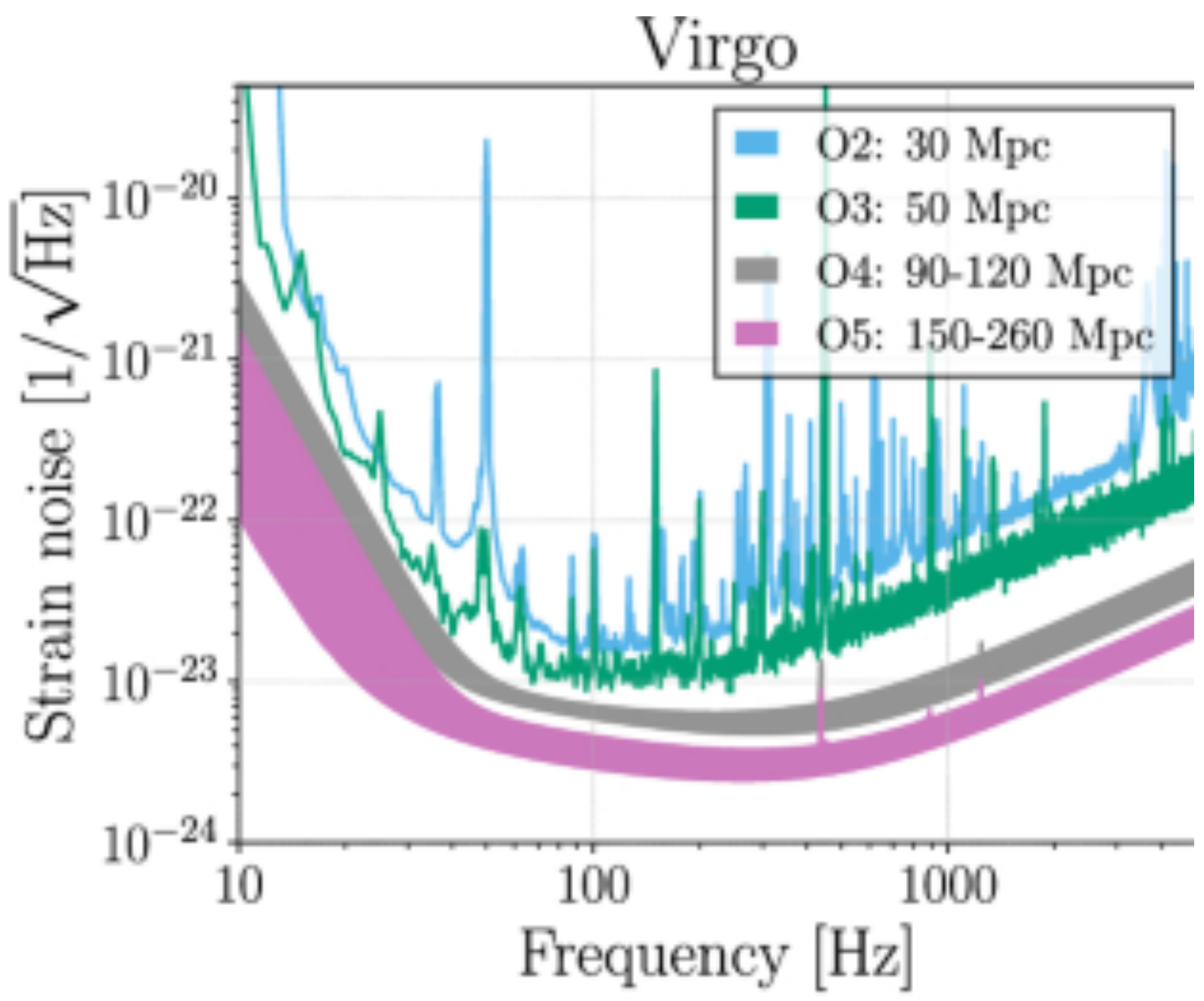
LVK, arXiv:2111.03606, 2021

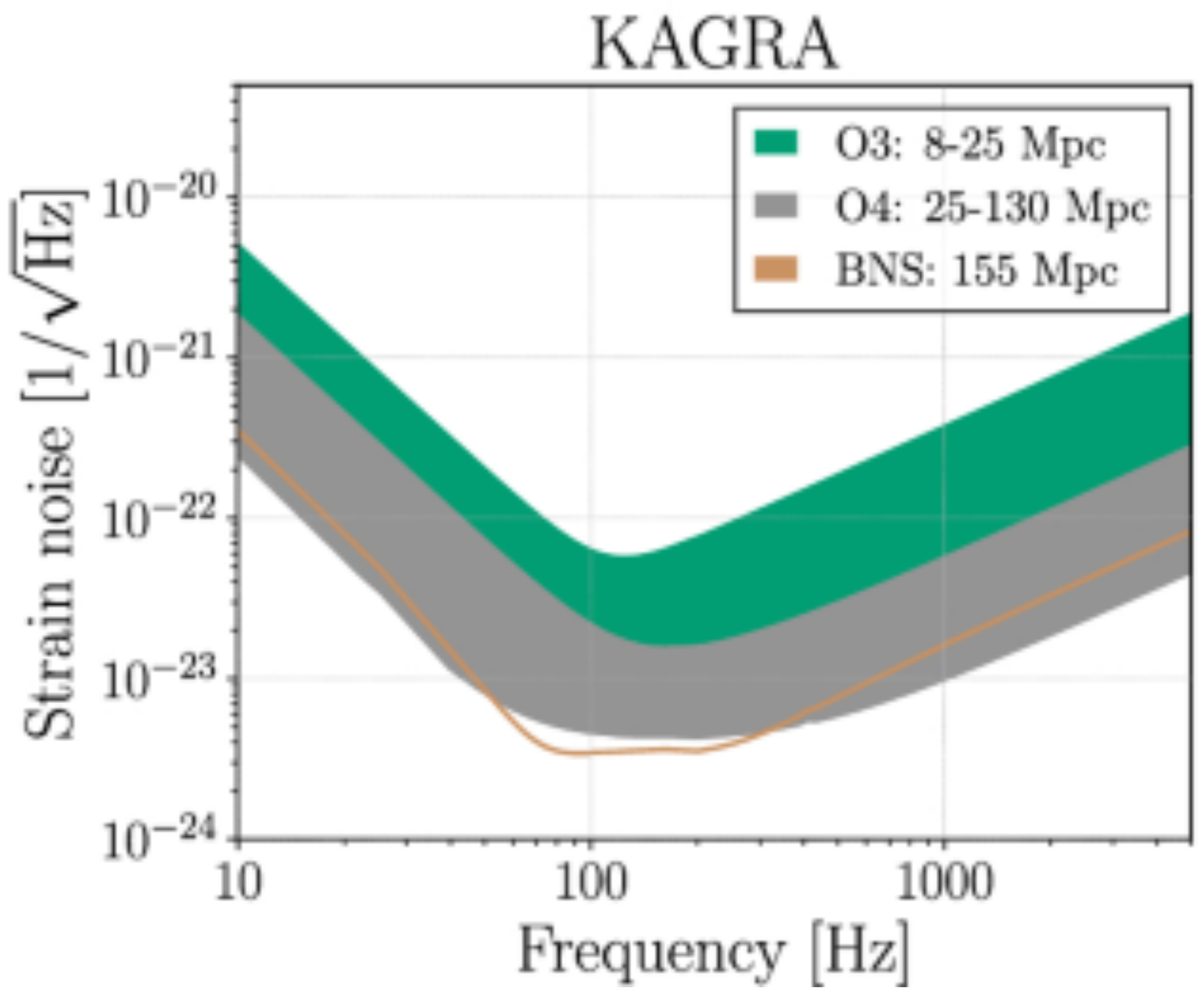
LVK, GWTC3

Observing prospects from future runs

- Next run (O4) is scheduled to start in few months
- O5 run will be in Aplus configuration with LIGO-India
- Improved distance reach for binary NS
  - 1.5 times (upto 180 Mpc with AdL) in O4
  - 3 times (upto 300 Mpc with AdL) in O5
- Improved distance reach for NSBH
  - 1.5 times (upto 300 Mpc with AdL) in O4
  - 3 times (upto 600 Mpc with AdL) in O5
- Improved distance reach for binary BHs
  - 1.5 times (upto 1.5 Gpc with AdL) in O4
  - 2.5 times (upto 2.5 Gpc with AdL) in O5







LVK, Liv Rev in Relativity (2020)

Thank you 🙏

Acknowledgement: SERB, DST India

Astrophysical merger rate density estimates

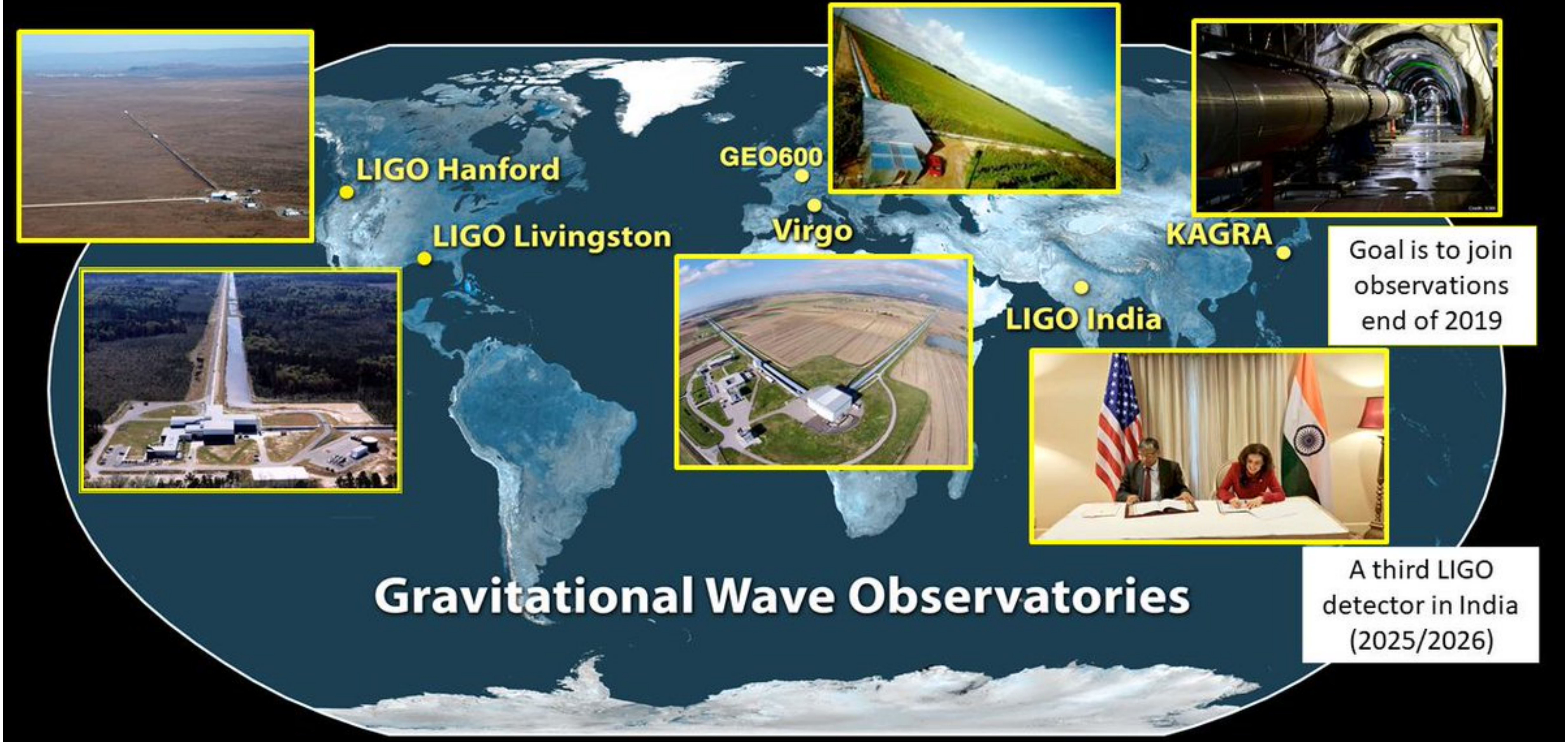
- Binary NS merger rate estimates (10-1700) $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- NS-BH merger rate density estimates (7.8-140) $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Binary BH merger rate density estimate (16 - 61) $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- IMBH binary merger rate density for 100-100 system is 0.056 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.
- Merger rate density of GW190521 like sources is 0.08 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

LVK — Population Study,
LVK-O3 IMBH

Take home message

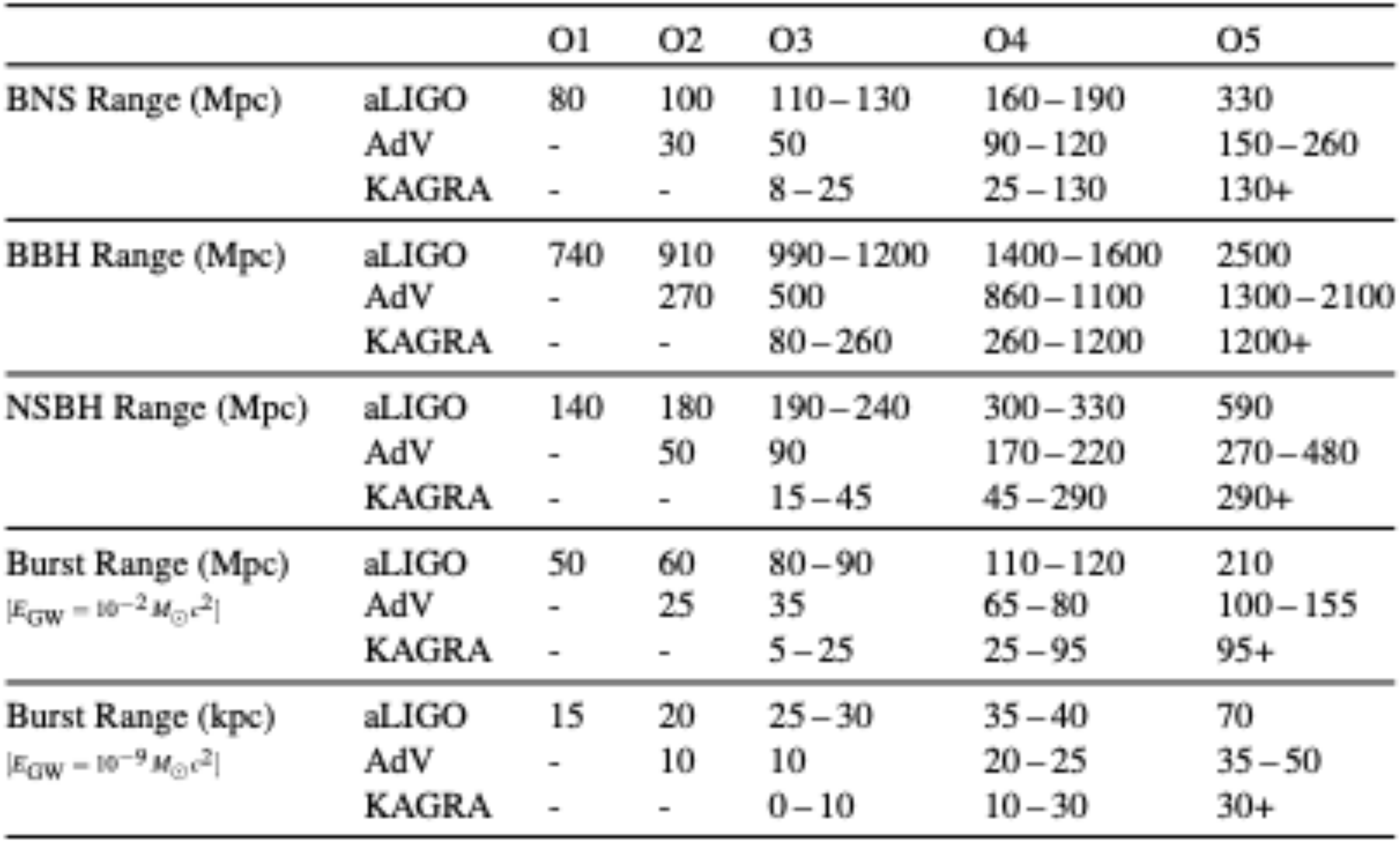
- BH population: Result of various formation channels **(multi-modality in the distribution)**
- BH Properties: Direct signature of formation channels
- Is low mass gap real or some observational selection bias?
- High mass gap — 50-120 Msun?
  - Predicted by stellar evolution of massive starts as a result of pair instability
  - Depends on various factors nuclear reaction rate, metallicity, rotation etc
- More number of observations will give better constraints on the rates, BBH channels and on population models
- Need more complete waveform models with all the complexities.
- Need algorithm to disentangle massive BBH signals from noisy glitches [See Sayantan's Poster]

Gravitational Wave Observatories



Goal is to join observations end of 2019

A third LIGO detector in India (2025/2026)



		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc) $[E_{GW} = 10^{-2} M_{\odot} c^2]$	aLIGO	50	60	80 – 90	110 – 120	210
	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc) $[E_{GW} = 10^{-9} M_{\odot} c^2]$	aLIGO	15	20	25 – 30	35 – 40	70
	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

Abbott+ arXiv 1304.0670

Future projections

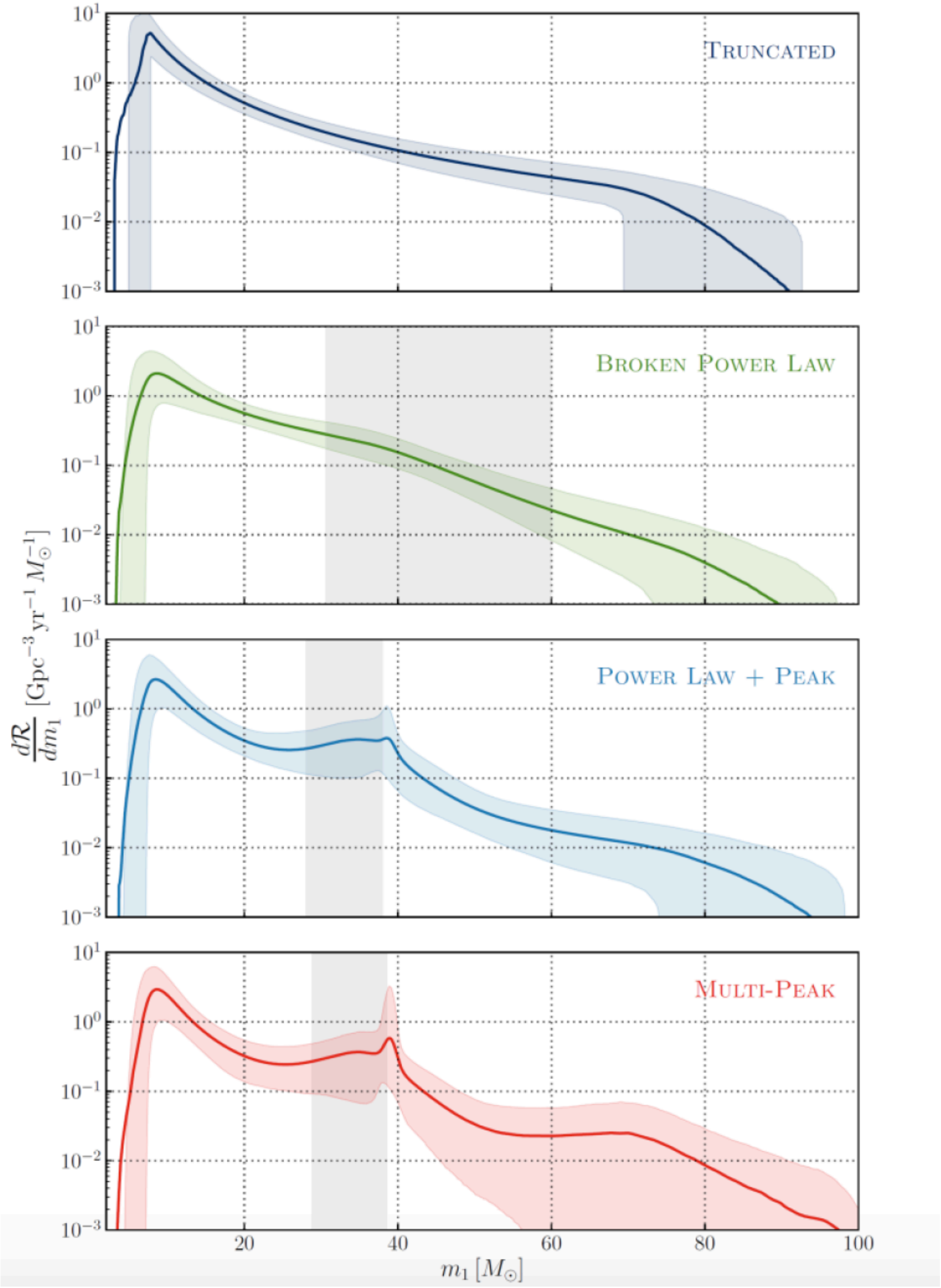
LIGO — O4: 1.5 X,   O5: > 2.5X

Events —O4 > 3X,   O5: > 15X

Astrophysical merger rate estimates

- Binary NS merger rate estimates $R_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Consistent with the lower black hole mass gap of 2.6 Msun- 6 Msun
- The detections show evidence of distribution not following a simple power law — Need to account for massive black holes
- Models with peak in the distribution by incorporating Gaussian profile in addition to the power law is preferred by the data.
- Binary BH merger rate estimates

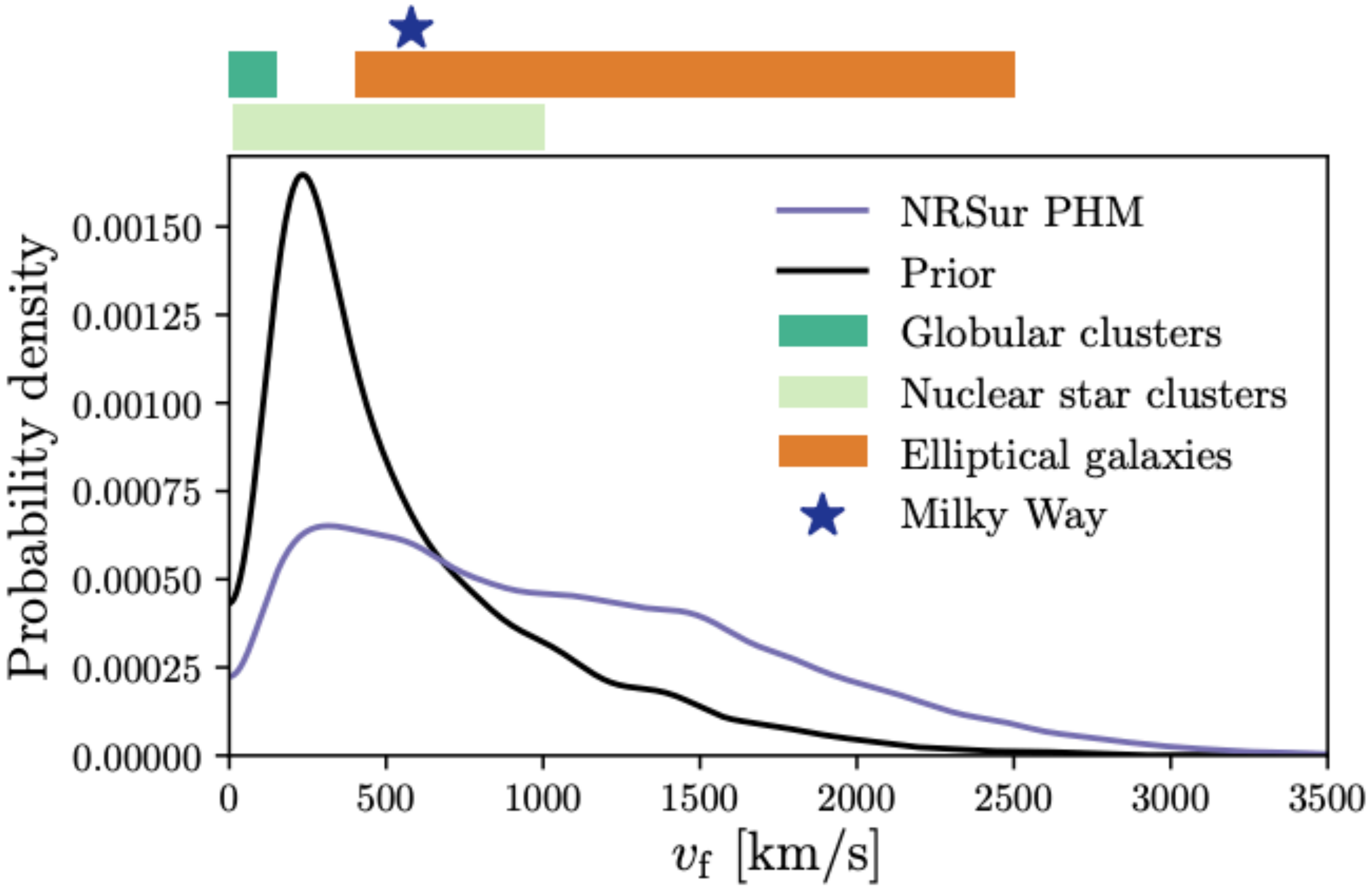
$$R_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

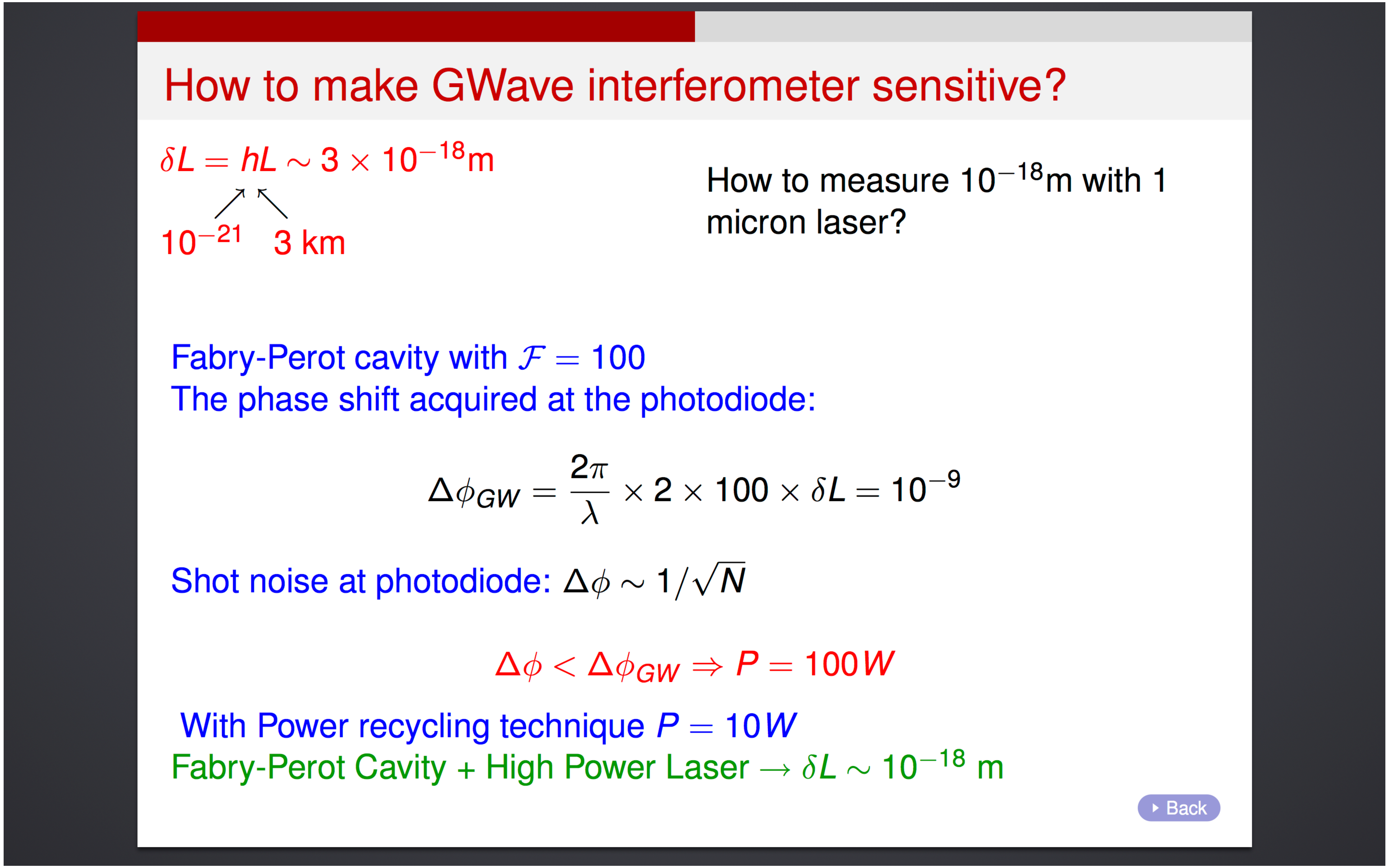


LVC, https://arxiv.org/abs/2010.14533

Study of the kick velocity from GW190521

- GW emission should impart kick to the remnant BH.
- For precessing systems, we expect high values of the kicks [Favata, Lousto+]
- Study of the posterior implies support for high values.
- Kick velocity is higher than the escape velocities of the GC.





How to make GWave interferometer sensitive?

$$\delta L = \underset{\substack{\nearrow \\ 10^{-21}}}{h}\underset{\substack{\nwarrow \\ 3\text{ km}}}{L} \sim 3 \times 10^{-18}\text{m}$$

How to measure 10^{-18}m with 1 micron laser?

Fabry-Perot cavity with $\mathcal{F} = 100$
The phase shift acquired at the photodiode:

$$\Delta\phi_{GW} = \frac{2\pi}{\lambda} \times 2 \times 100 \times \delta L = 10^{-9}$$

Shot noise at photodiode: $\Delta\phi \sim 1/\sqrt{N}$

$$\Delta\phi < \Delta\phi_{GW} \Rightarrow P = 100W$$

With Power recycling technique $P = 10W$
Fabry-Perot Cavity + High Power Laser $\rightarrow \delta L \sim 10^{-18}$ m

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