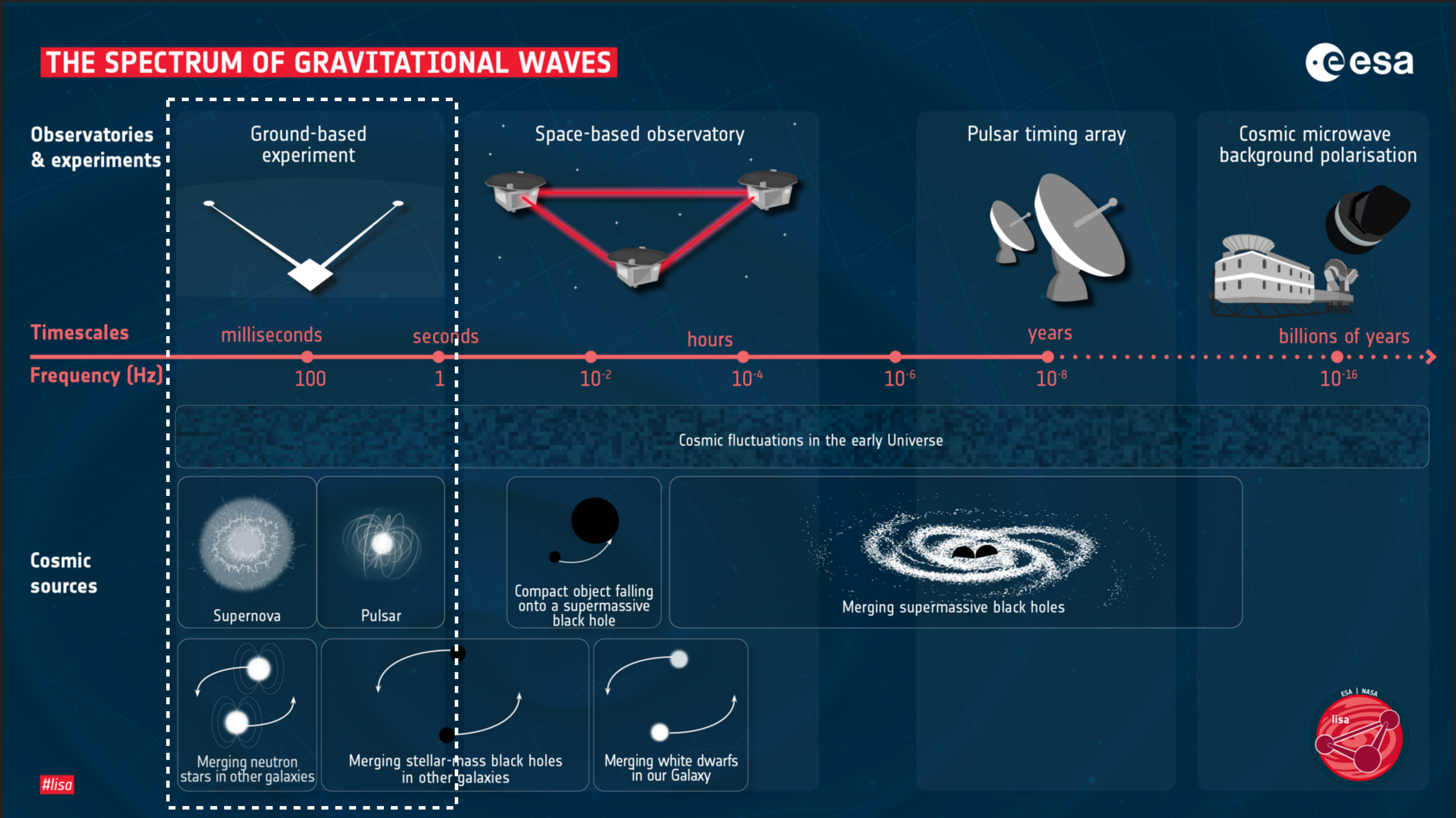
MARIA HANEY

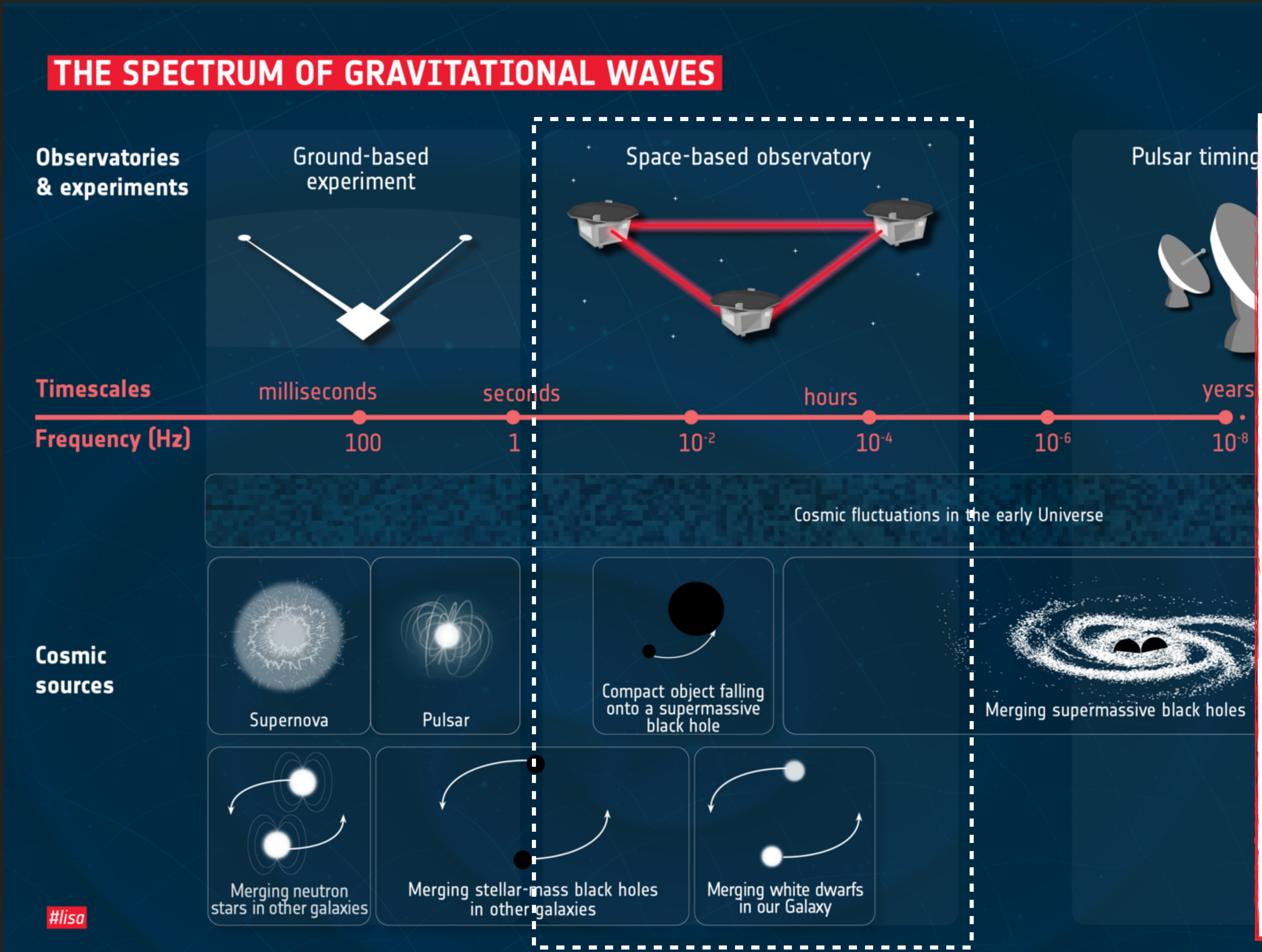
GRAVITATIONAL-WAVE ASTRONOMY: STATUS & PROSPECTS

EUROPEAN EINSTEIN TOOLKIT MEETING // JULY 11, 2024

GRAVITATIONAL-WAVE ASTRONOMY



GRAVITATIONAL-WAVE ASTRONOMY

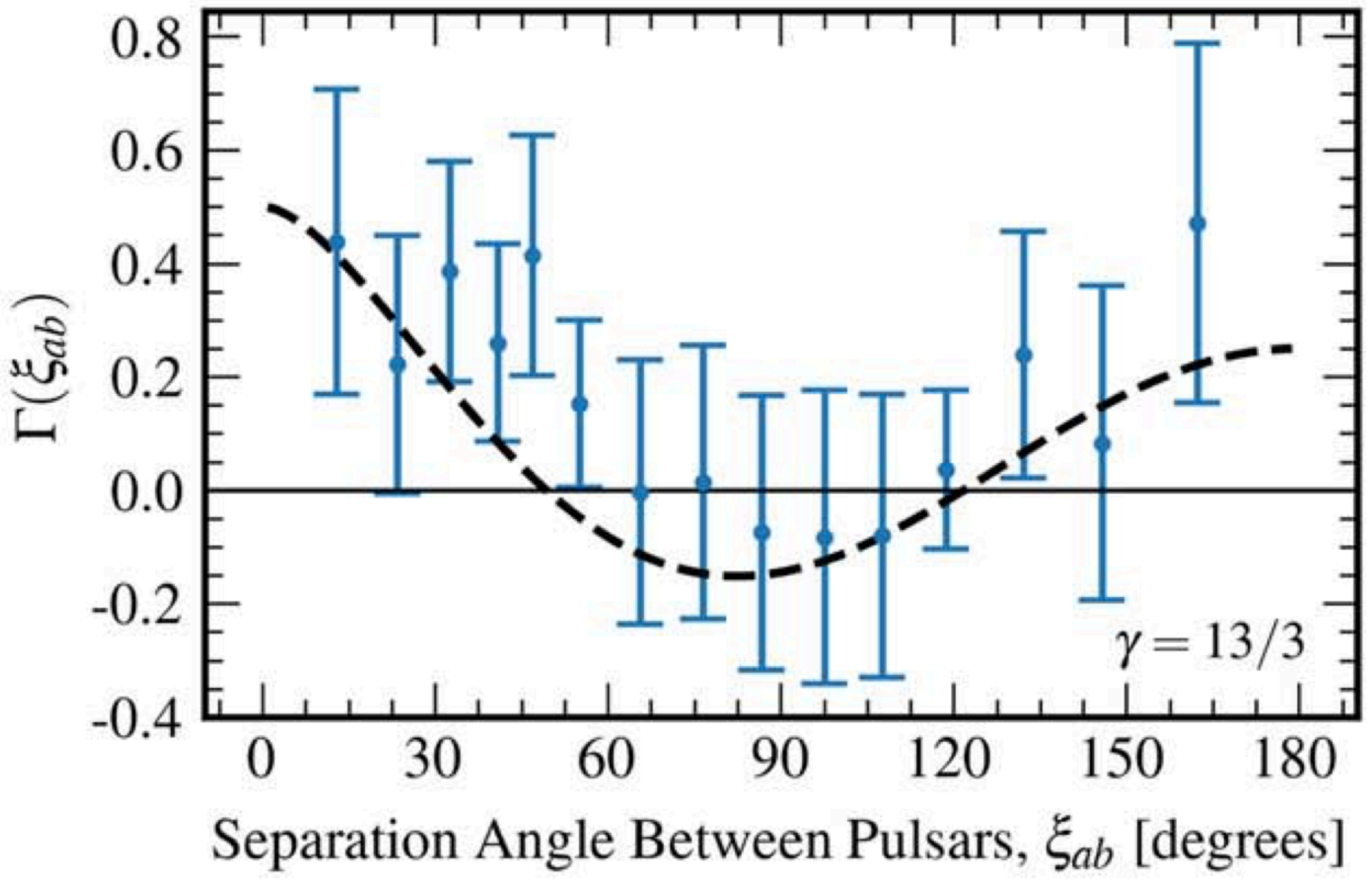


- Laser Interferometer Space Antenna (**LISA**)
- GW detection via inter-satellite ranging (relative phase shift between local and distant lasers)
- **ESA mission adoption** in January 2024, launch in mid 2030s
- LISA Data Processing Group has started pipeline design/ implementation

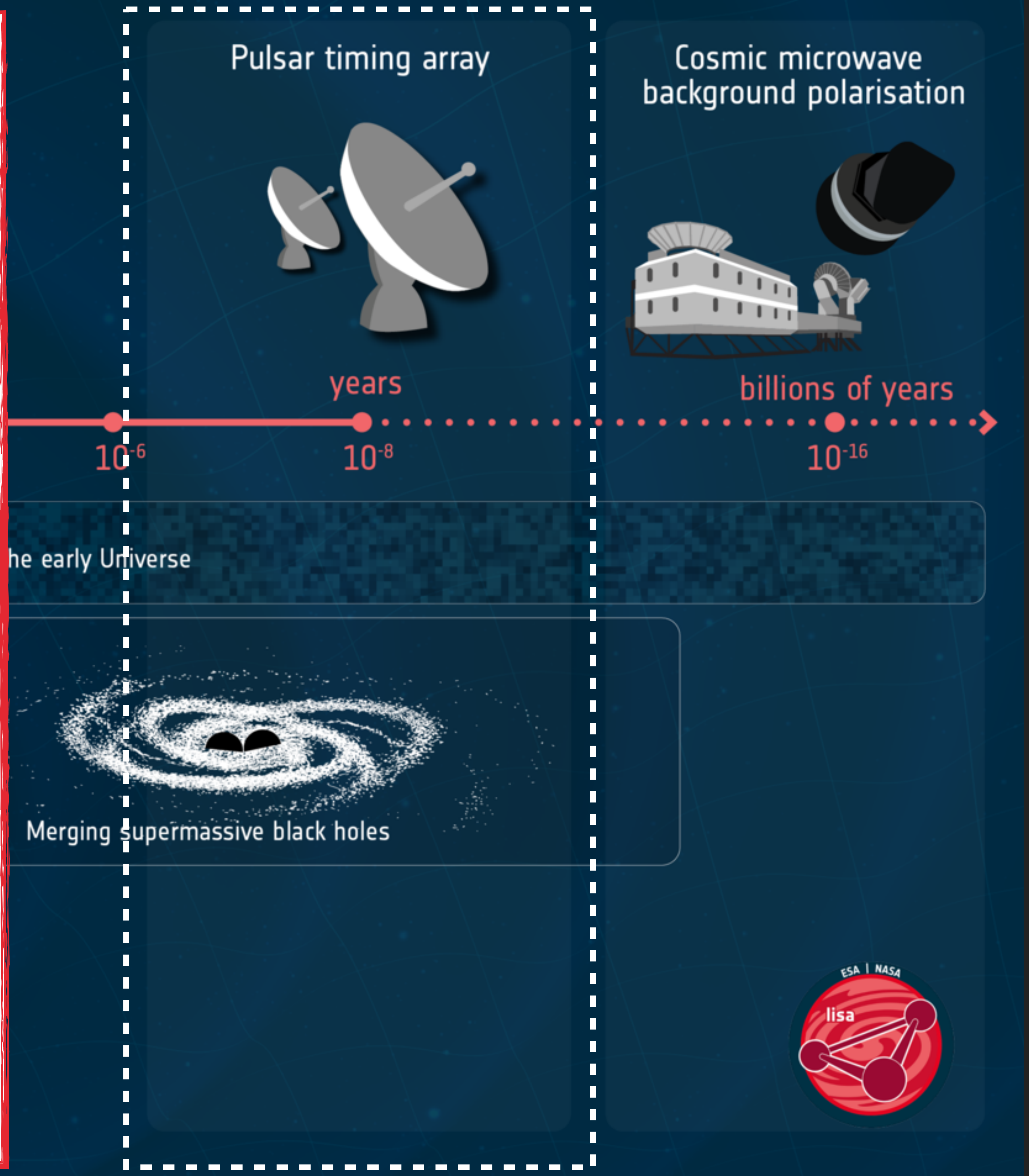
GRAVITATIONAL-WAVE ASTRONOMY

THE SPECTRUM OF GRAVITATIONAL WAVES

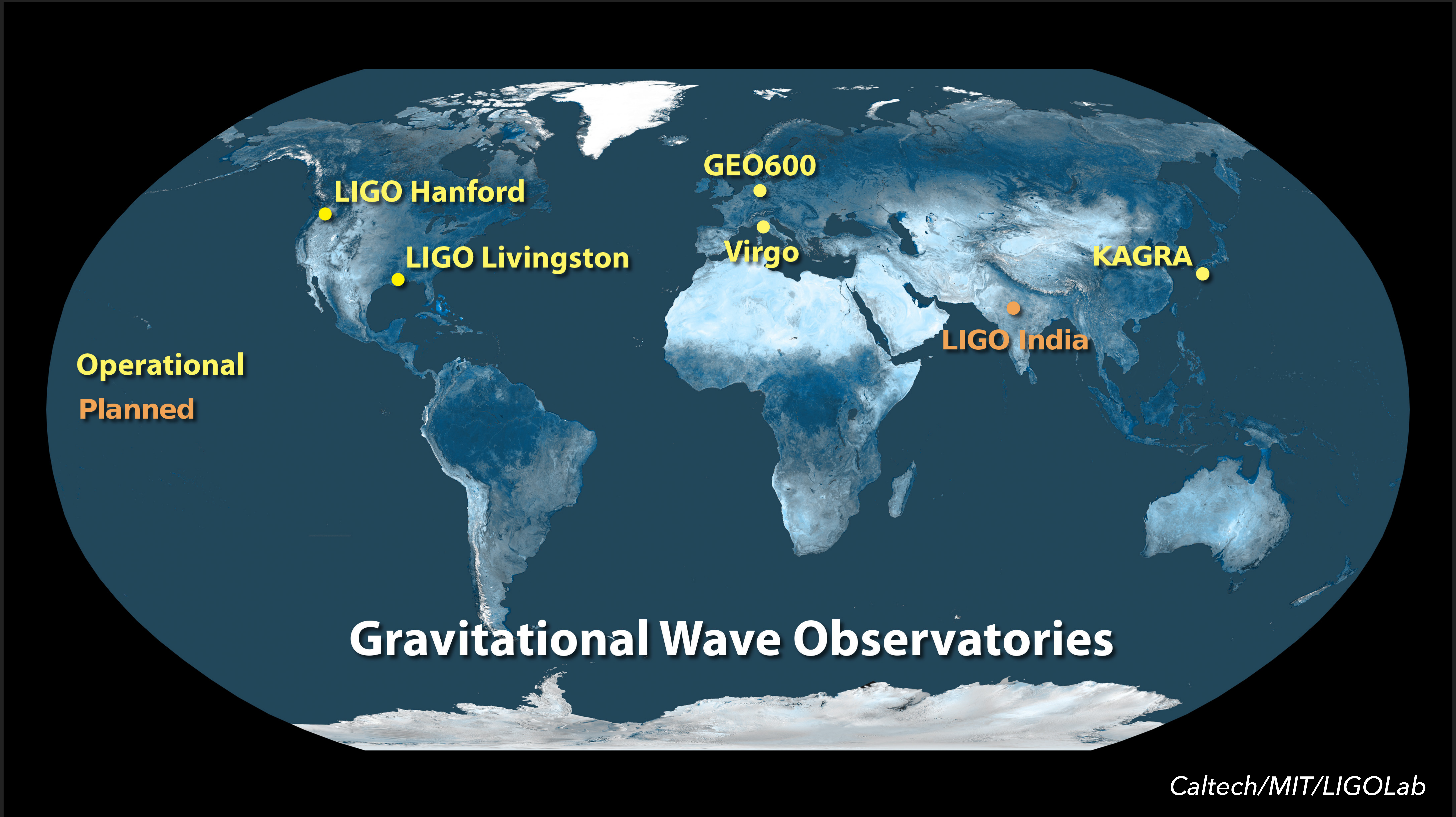
- GW background radiation & individual SMBH mergers → correlated signatures in pulsar timing residuals
- 2023: **evidence for an (astrophysical) GW background** → IPTA data follows Hellings-Downs curve



NanoGrav (2023)



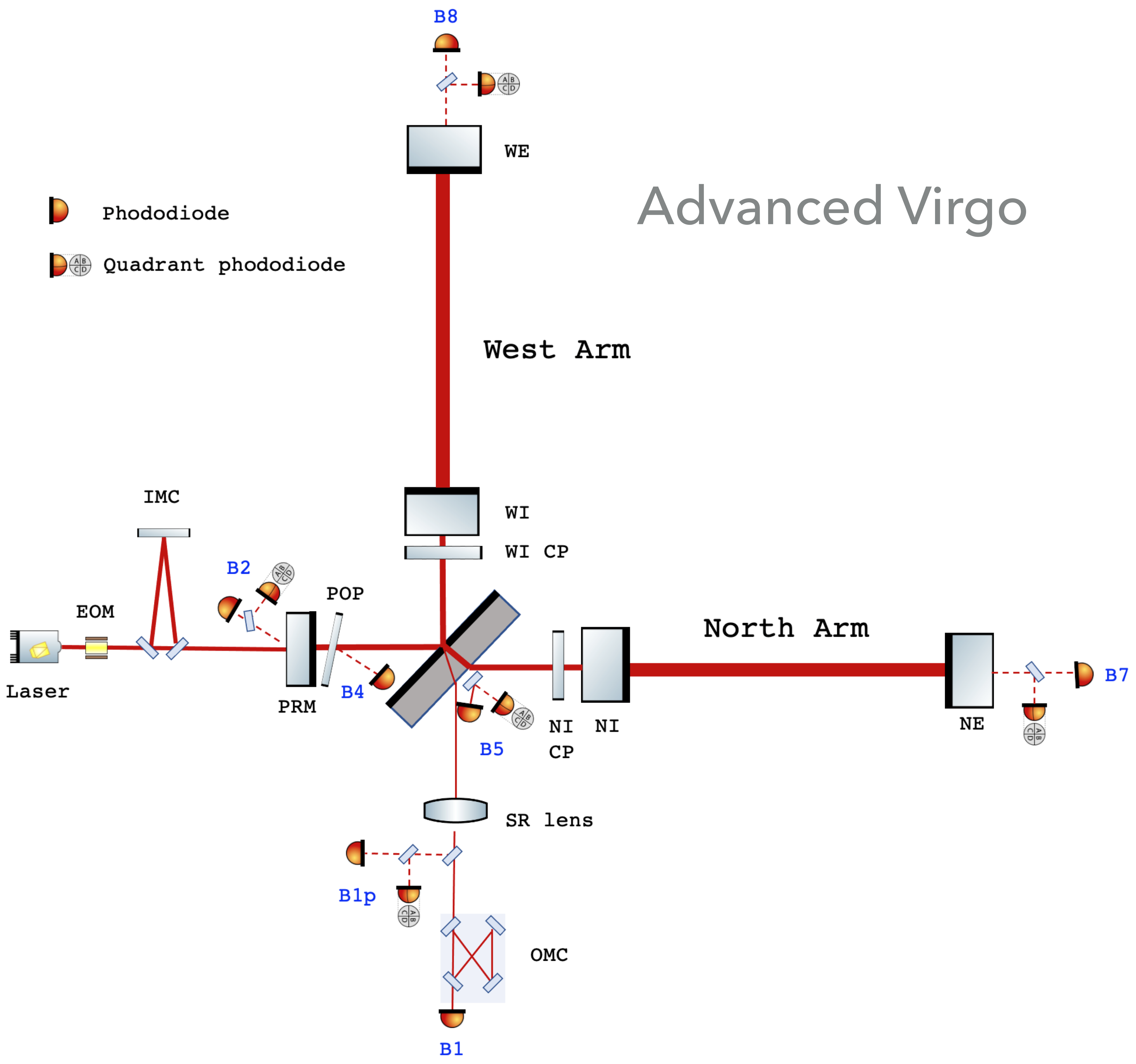
THE GROUND-BASED DETECTOR NETWORK



Caltech/MIT/LIGOLab

CURRENT DESIGN OF GROUND-BASED INTERFEROMETERS

- LIGO, Virgo, KAGRA: laser interferometers with **slightly different design** (optics, cryogenic/not, underground/not, …)
- GWs → distance changes of ~10^{-20} m/$\mathrm{Hz}^{-1/2}$ over baseline of ~several km
- input laser: infrared (1064nm), power ~tens of W
- mirrors: ~tens of kg high-purity fused silica substrates; highly reflective coatings
- resonant Fabry-Perot cavities (enhance response of interferometers)
- (frequency-dependent) "squeezing" for quantum noise reduction

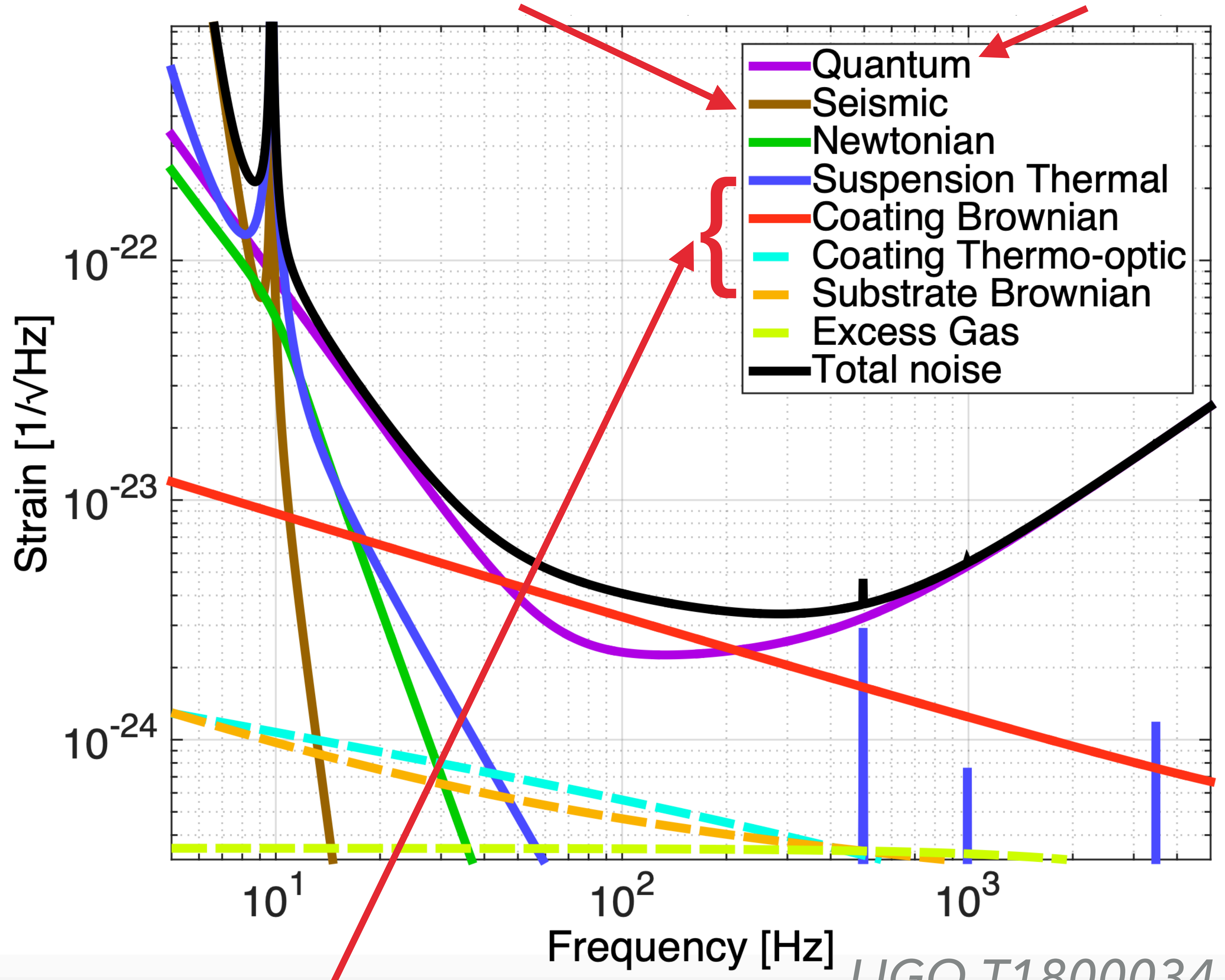


Advanced Virgo

Nardecchia (2022)

CURRENT DESIGN OF GROUND-BASED INTERFEROMETERS

- LIGO, Virgo, KAGRA: laser interferometers with **slightly different design** (optics, cryogenic/not, underground/not, …)
- GWs → distance changes of $\sim 10^{-20}$ m/Hz$^{-1/2}$ over baseline of ~several km
- input laser: infrared (1064nm), power ~tens of W
- mirrors: ~tens of kg high-purity fused silica substrates; highly reflective coatings
- resonant Fabry-Perot cavities (enhance response of interferometers)
- (frequency-dependent) "squeezing" for quantum noise reduction



LIGO-T1800034

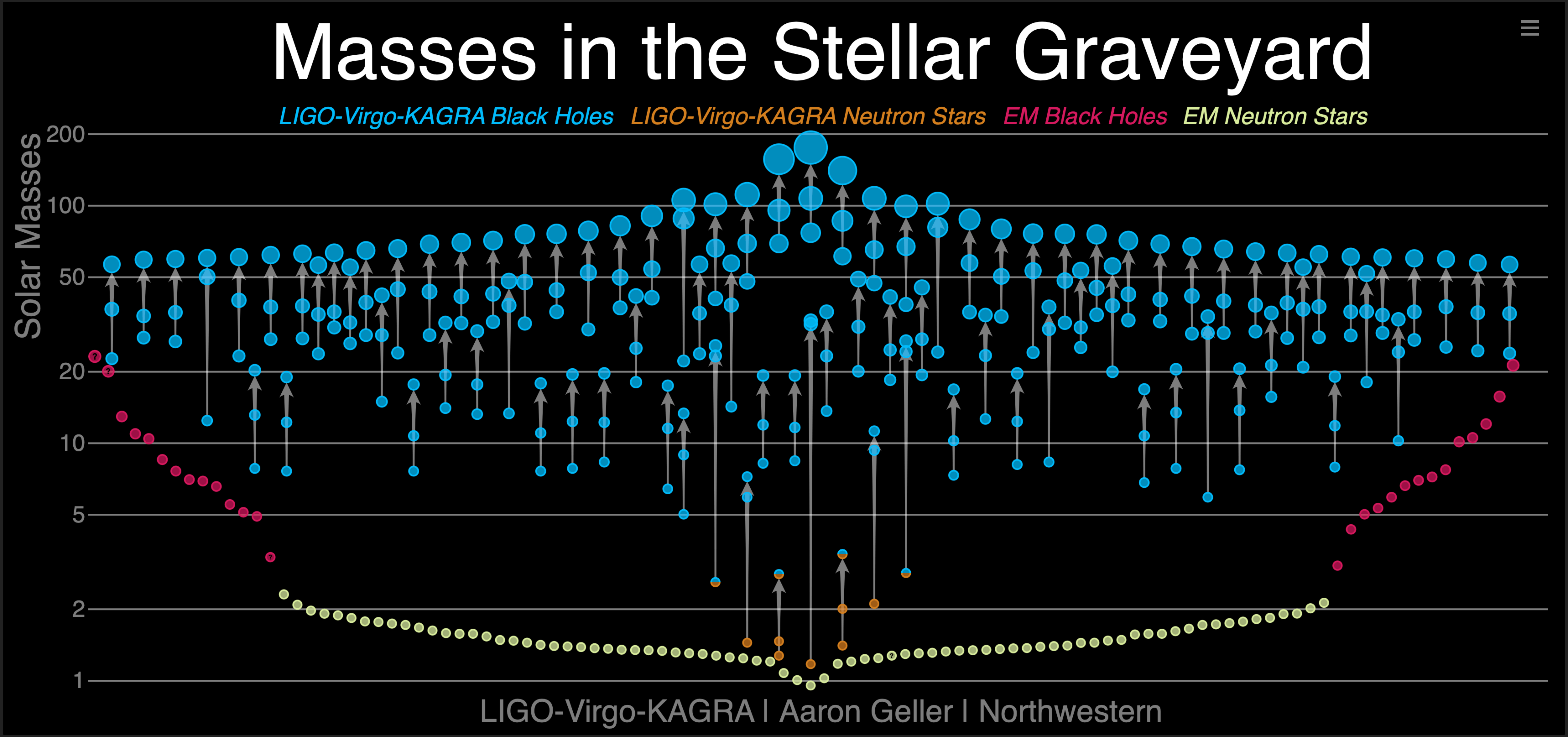
complex suspension chains of pendulums

frequency-dependent squeezing

pendulum, larger beam size, cryogenic, …

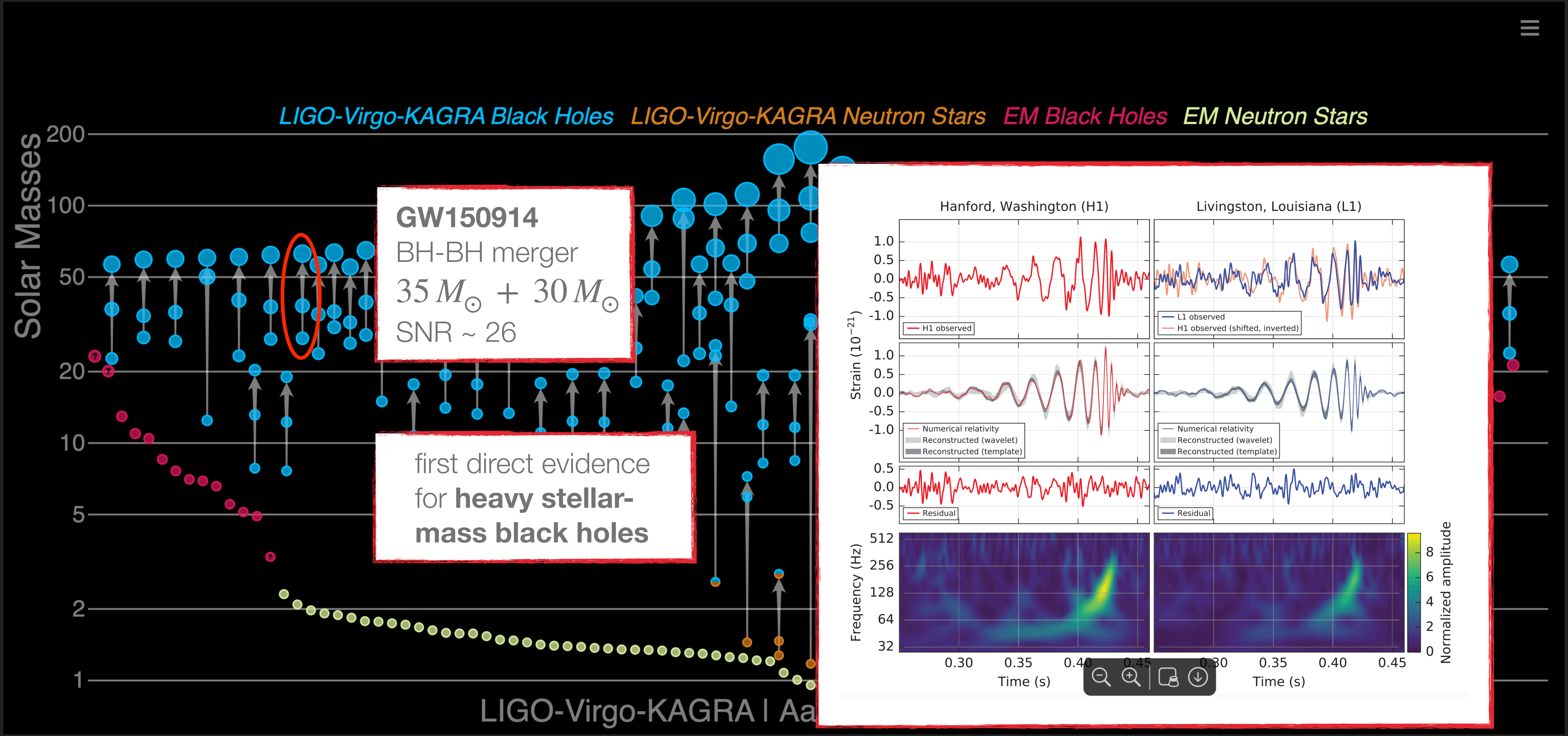
LIGO–VIRGO–KAGRA: THE FIRST THREE OBSERVING RUNS

HIGHLIGHTS FROM THE FIRST THREE OBSERVING RUNS



https://ligo.northwestern.edu/media/mass-plot/index.html

GW150914: THE FIRST DIRECT DETECTION OF GRAVITATIONAL WAVES



GW150914

BH-BH merger

$35\,M_\odot + 30\,M_\odot$

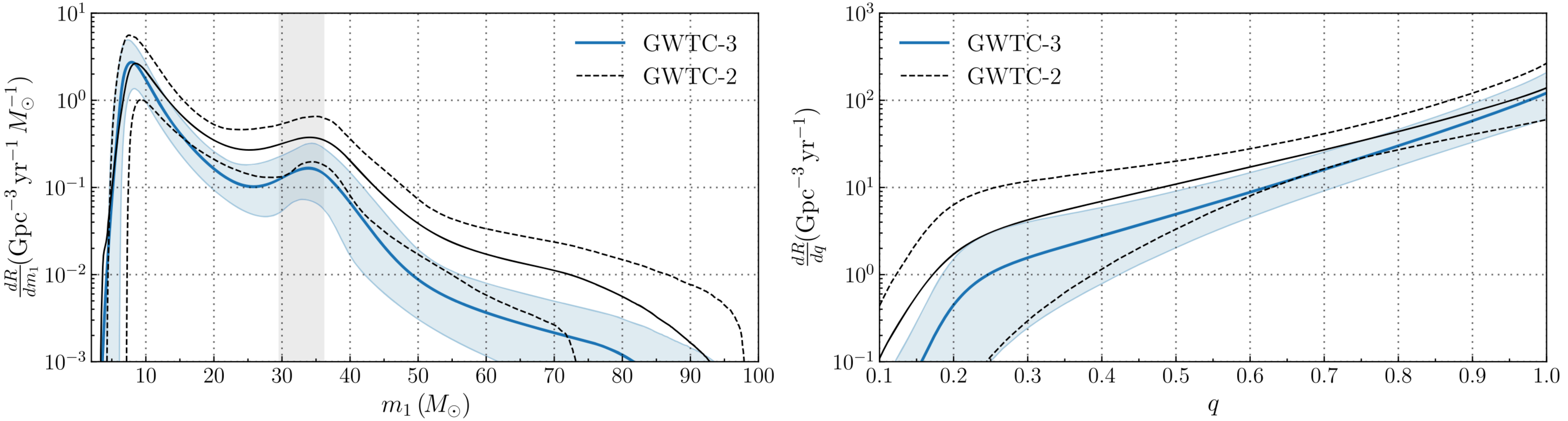
SNR ~ 26

first direct evidence for **heavy stellar-mass black holes**

https://ligo.northwestern.edu/media/mass-plot/index.html

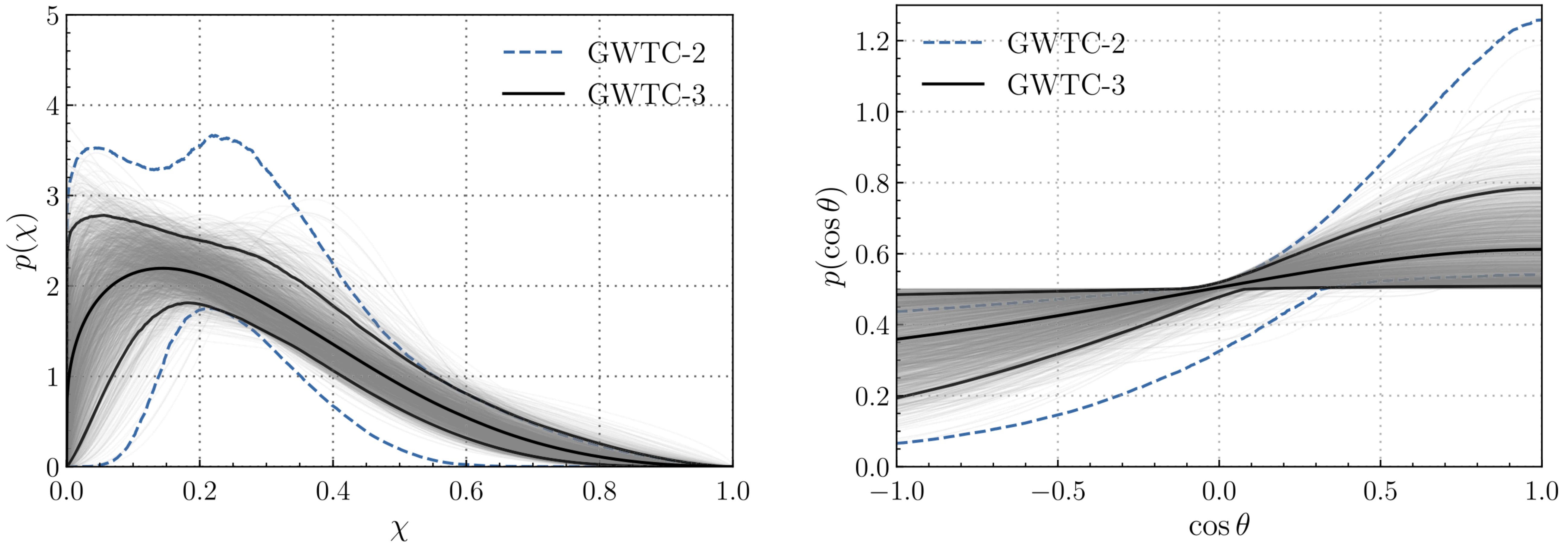
Abbott+ (LVC), PRL 2016

STELLAR-MASS BLACK HOLES: RATES & POPULATION



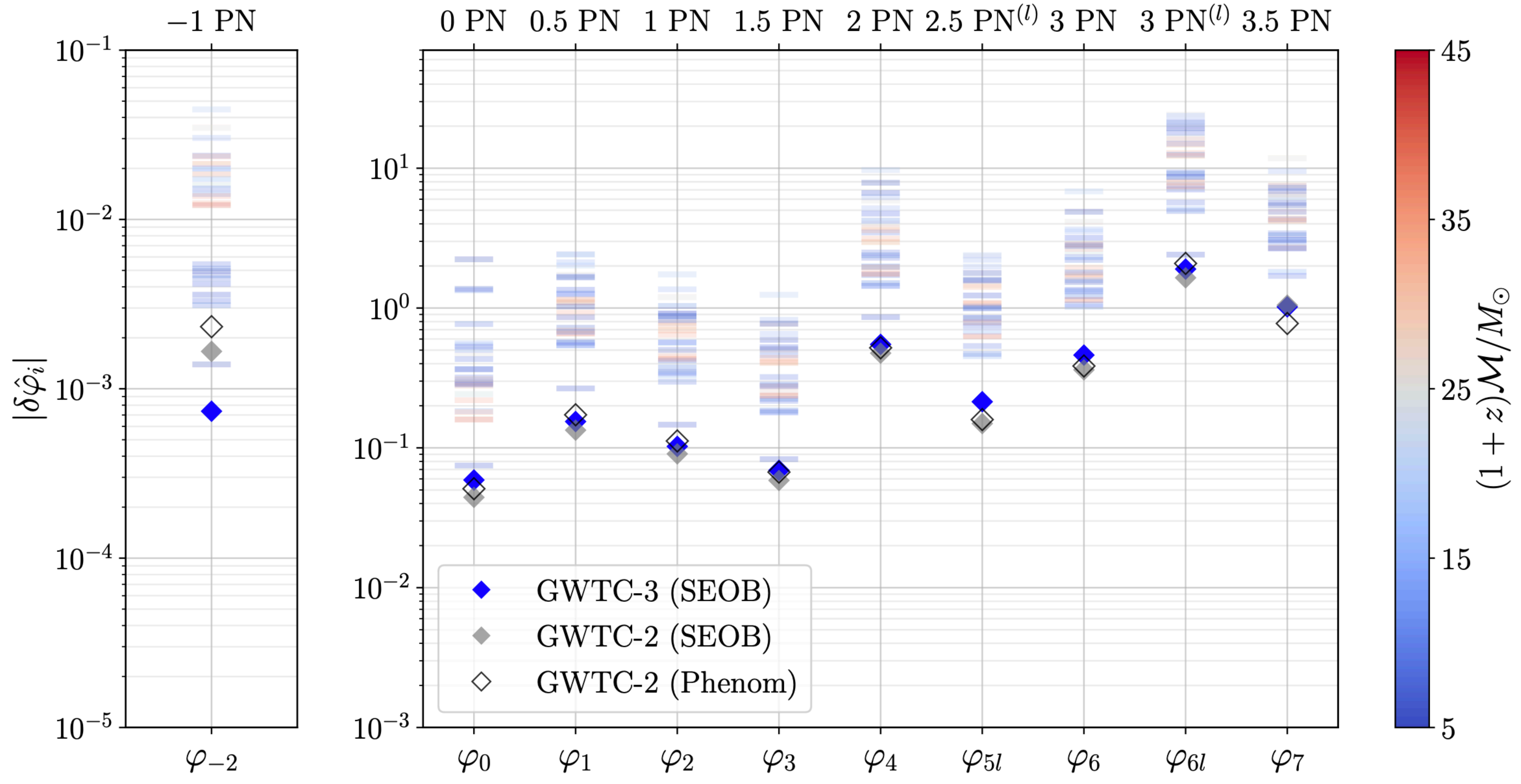
Abbott+ (LVK), PRX 2023

- **non-uniform** BH mass distribution (overdensities at 10 $M_\odot$ and 35 $M_\odot$)
- merger rate increases with redshift
- observed BH **spins are small** (evidence of anti aligned spins amongst population)

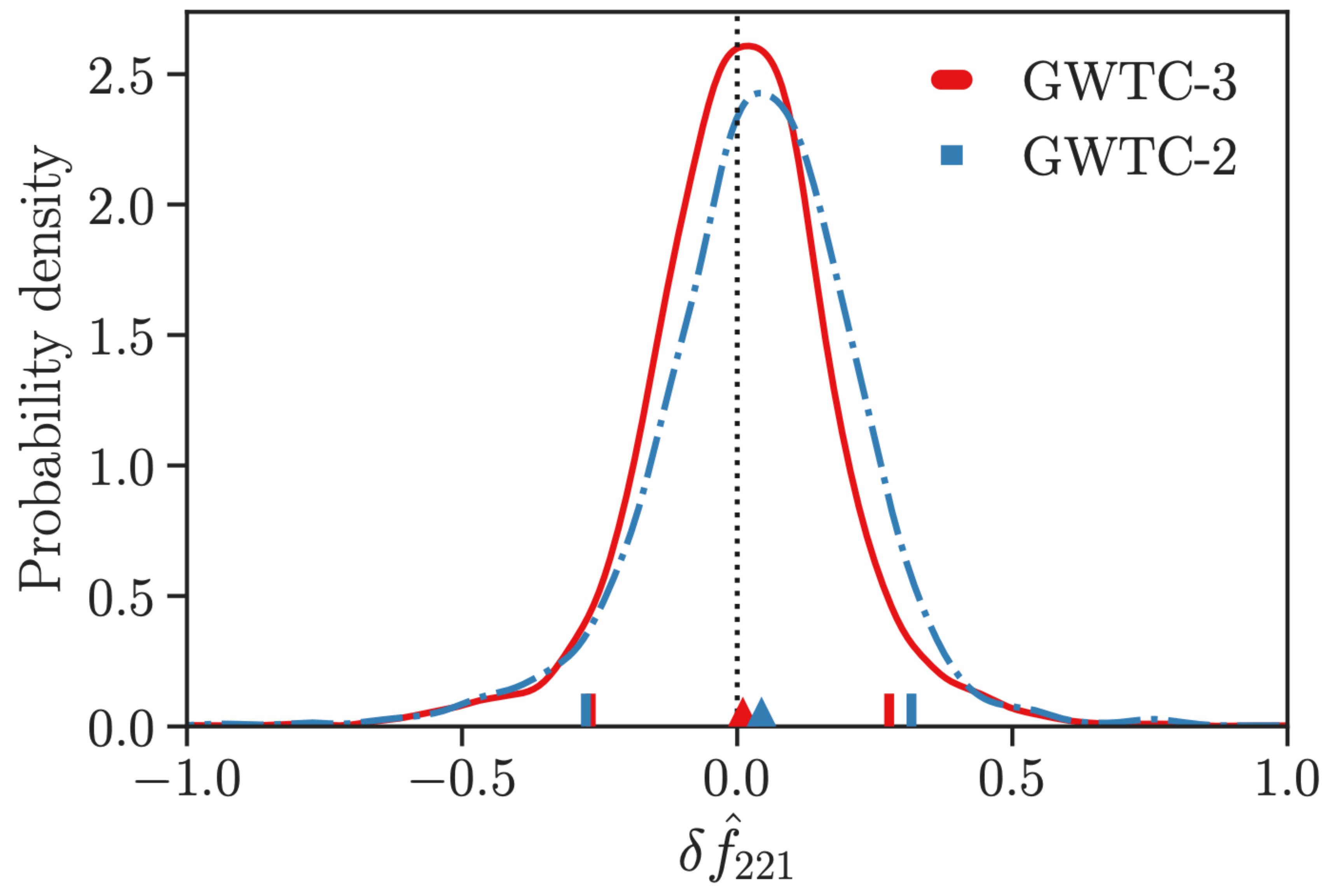


FUNDAMENTAL PHYSICS IMPLICATIONS OF LIGO-VIRGO BLACK HOLES

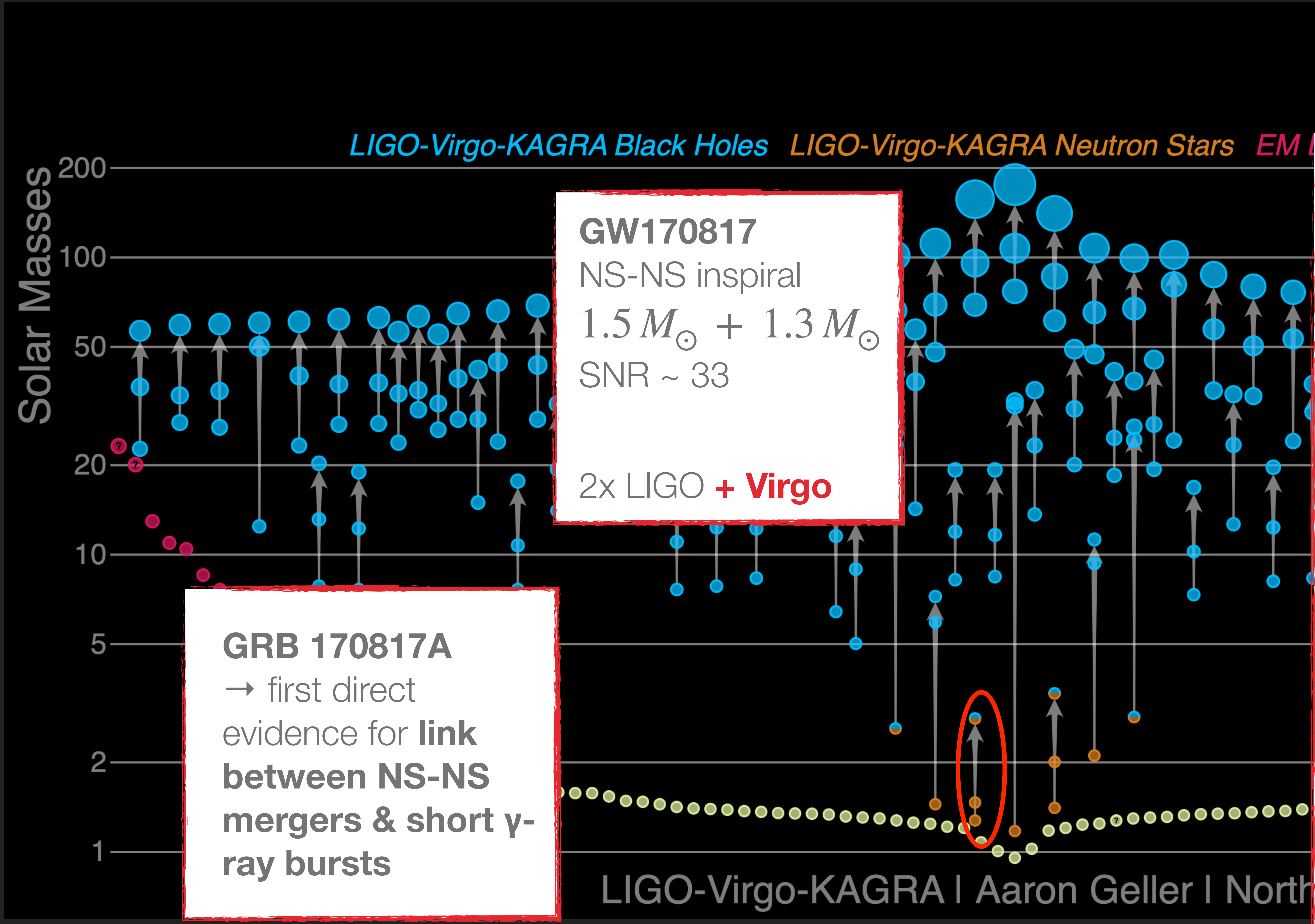
- since GW150914: testing gravity in the **strong-field regime**
- **generic non-GR modifications** in the binary motion / GW phase (l.), modified dispersion, polarization content, **testing BH no-hair theorem** with remnant properties (r.), …
- so far: **no evidence** in support of physics beyond General Relativity



Abbott+ (LVK), PRD 2022



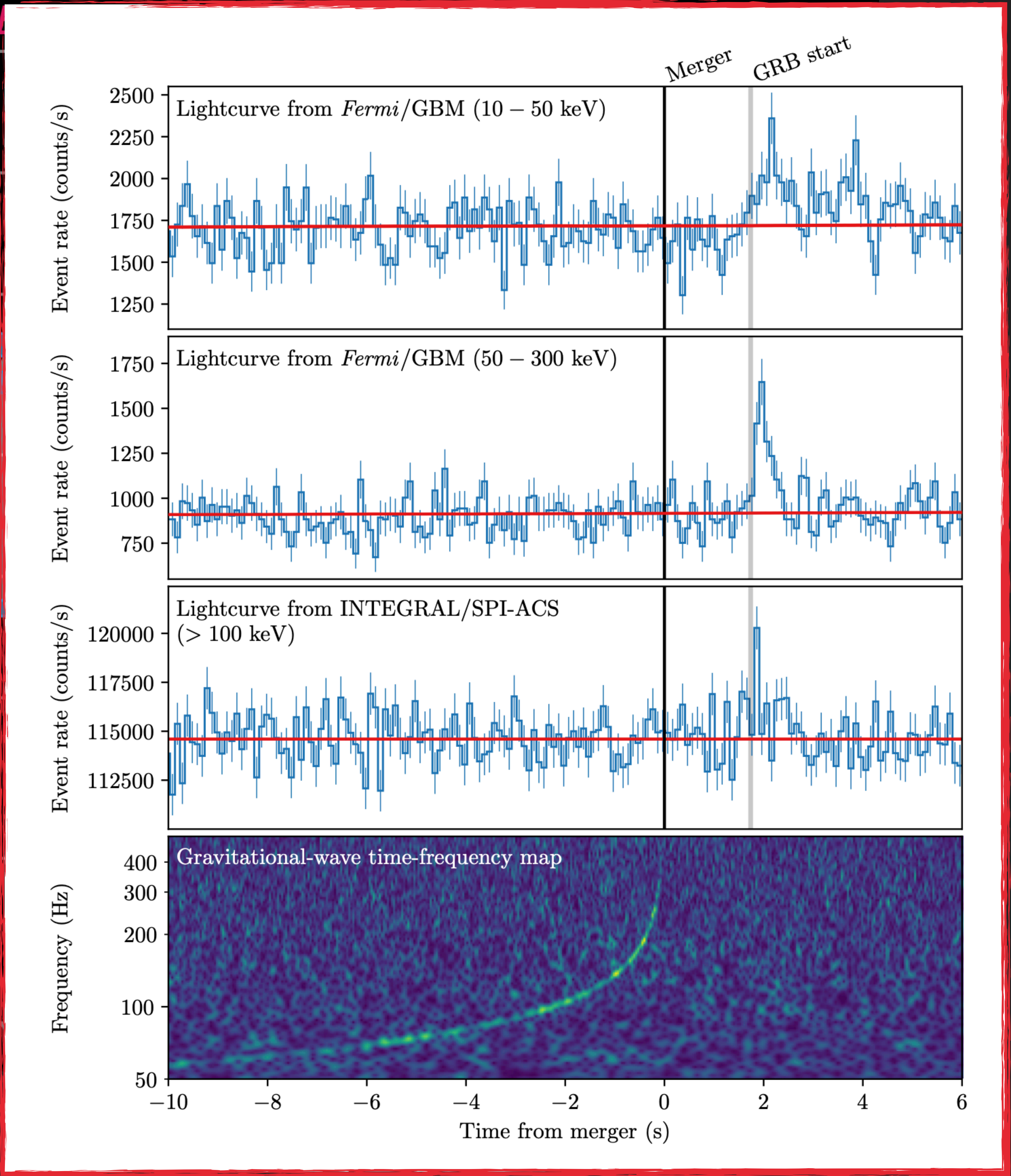
GW170817: MULTI-MESSENGER ASTRONOMY WITH GWS



GW170817
NS-NS inspiral
$1.5\,M_\odot + 1.3\,M_\odot$
SNR ~ 33

2x LIGO **+ Virgo**

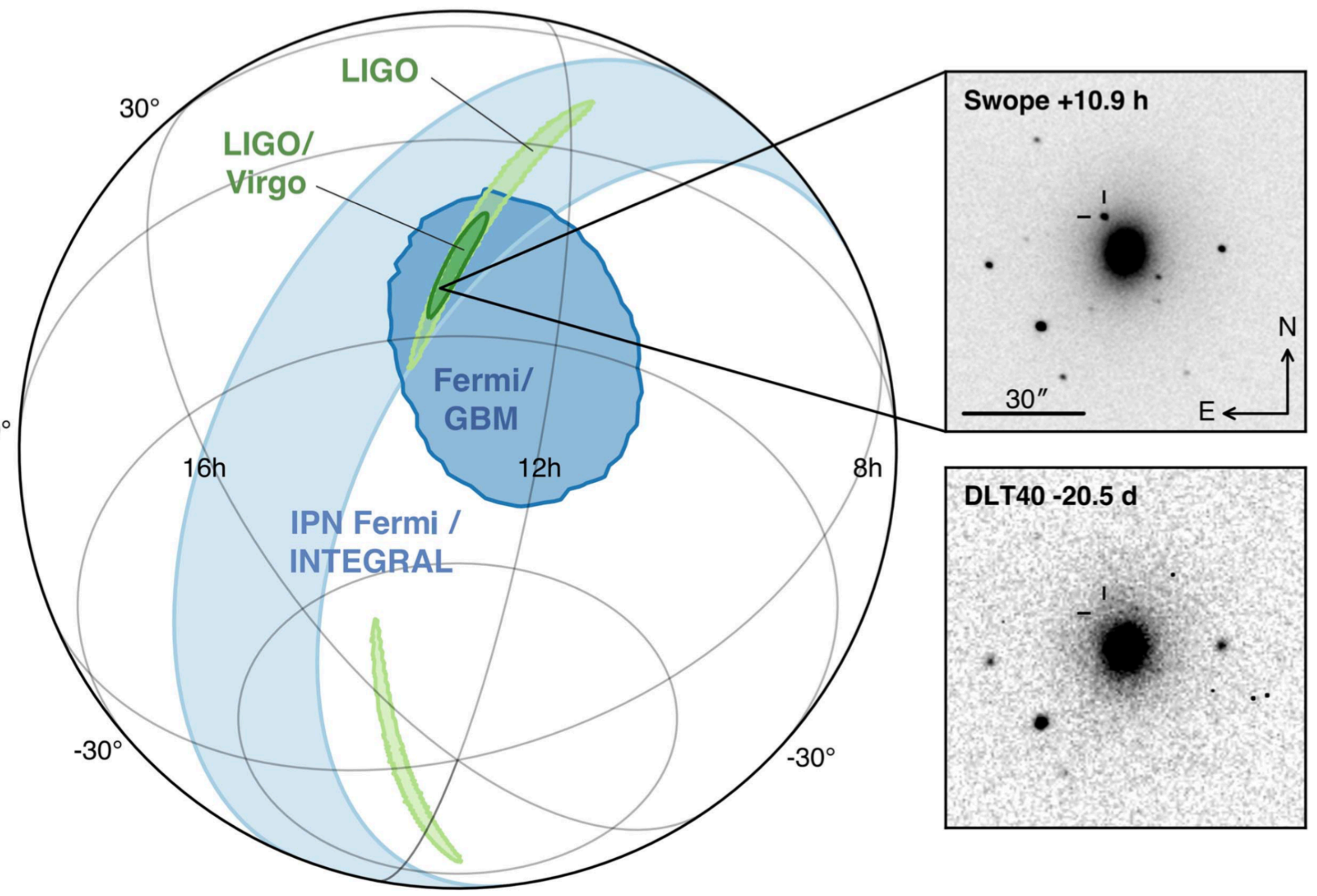
GRB 170817A
→ first direct evidence for **link between NS-NS mergers & short γ-ray bursts**



Abbott+ (LVC , Fermi/GBM, INTEGRAL), ApJL 2017

ELECTROMAGNETIC FOLLOW-UP: HOST GALAXY & KILONOVA

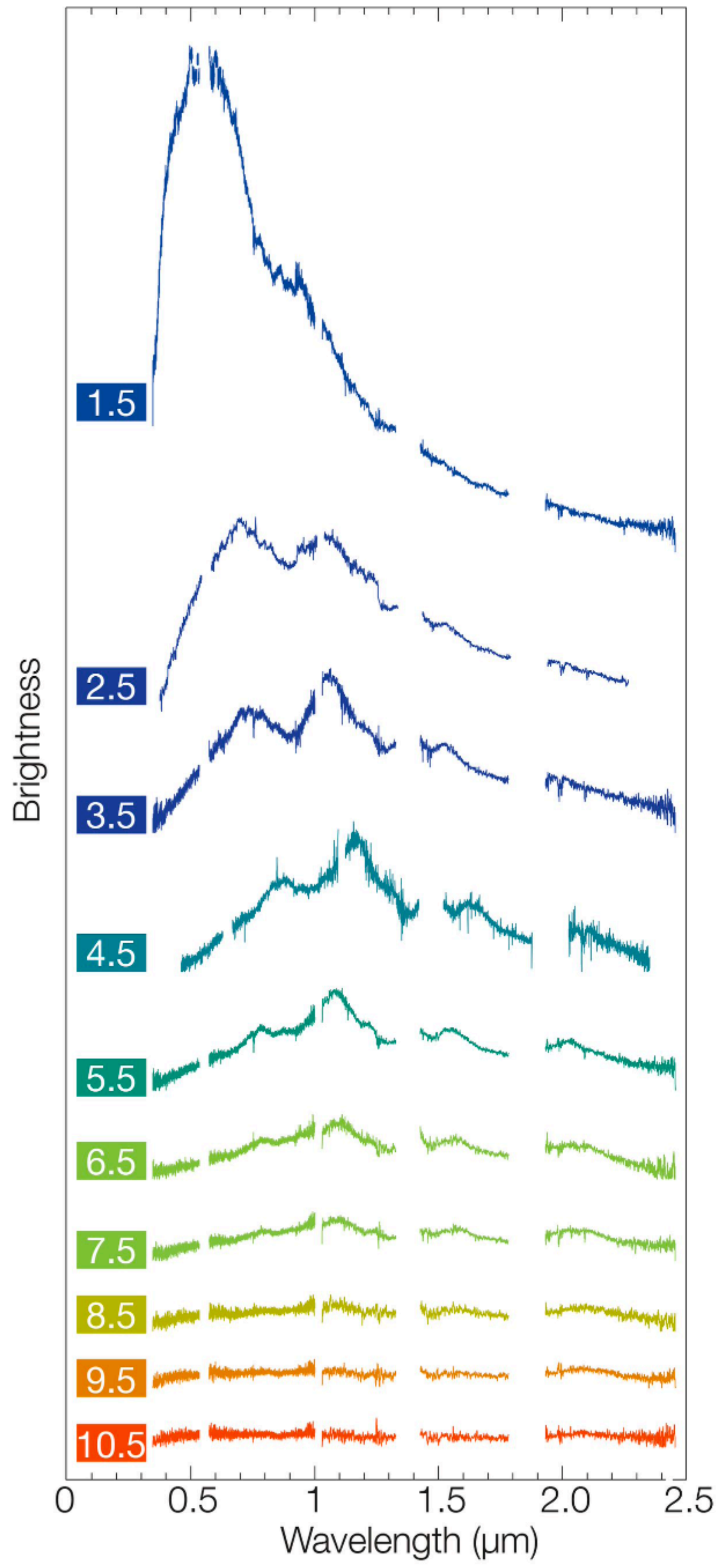
Abbott+ (LVC + EM), ApJL 2017



- associated **optical transient** (SSS17a/AT 2017gfo) discovered on August 18, 2017
- located ~10″ from the center of the **galaxy NGC 4993**, at a distance of 40 Mpc (consistent with the luminosity distance of the GW signal)
- identification of GW170817's host galaxy!

- spectral temporal evolution **consistent with a kilonova** (optical/NIR emission powered by radioactive decay of heavy nuclei, synthesized in the merger ejecta through r-processes)
- NS-NS mergers produce gold and other heavy elements

ESO/Pian+ / Smartt+ & ePESSTO (2017)



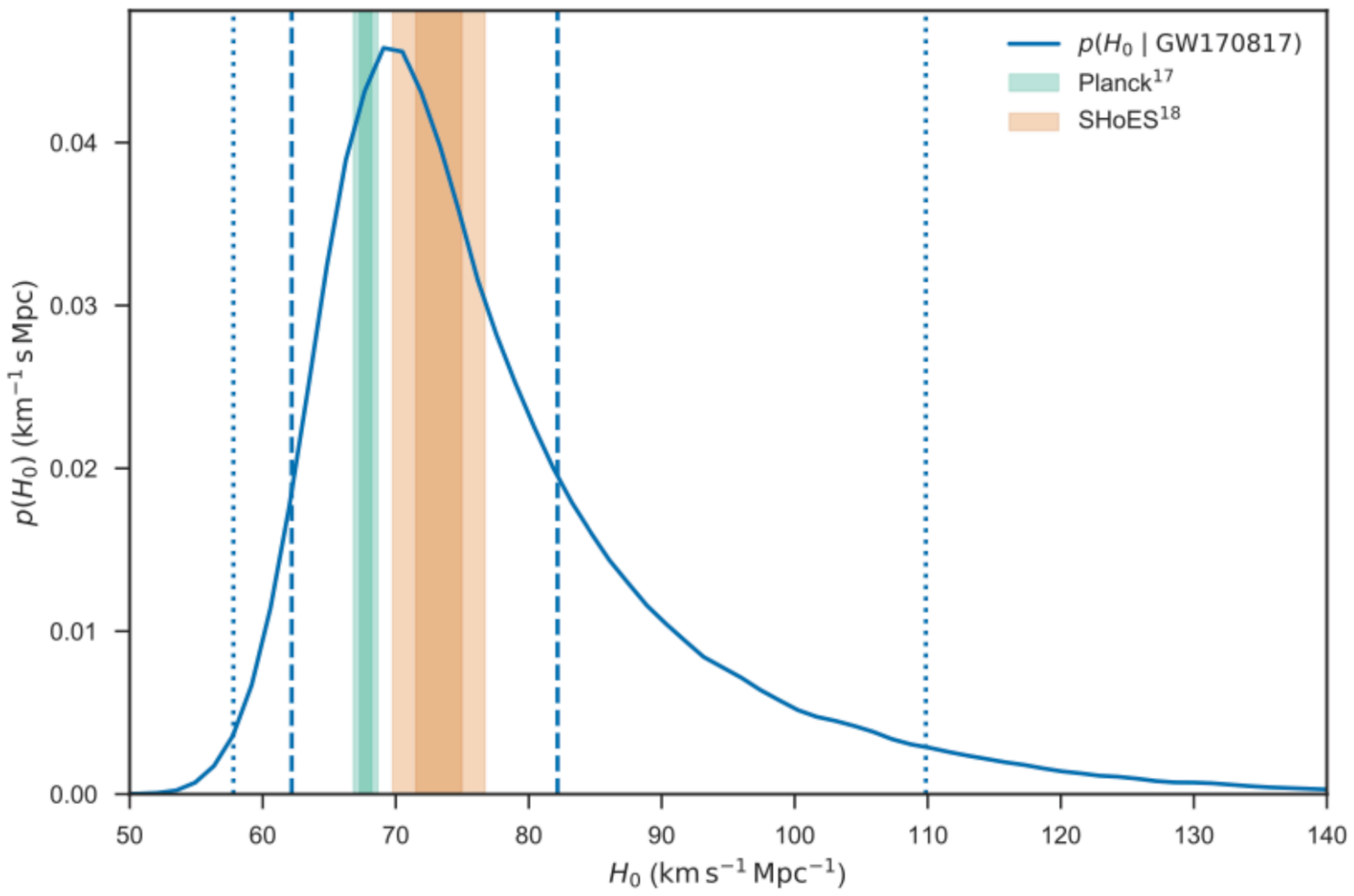
SCIENCE IMPLICATIONS OF GW170817

- GW170817: **“standard siren” for cosmology**
- EM-measured distance to host galaxy + GW luminosity distance:

$$d_{\rm L} \simeq \frac{c}{H_0} z \quad \Longrightarrow \quad \boxed{H_0 \; = \; 70.0^{+12.0}_{-8.0}\, {\rm km\, s^{-1}\, Mpc^{-1}}}$$

- future multimessenger observations: break Hubble tension?
- GW170817 + GRB 170817a + identification of host galaxy → **speed of gravity = speed of light**

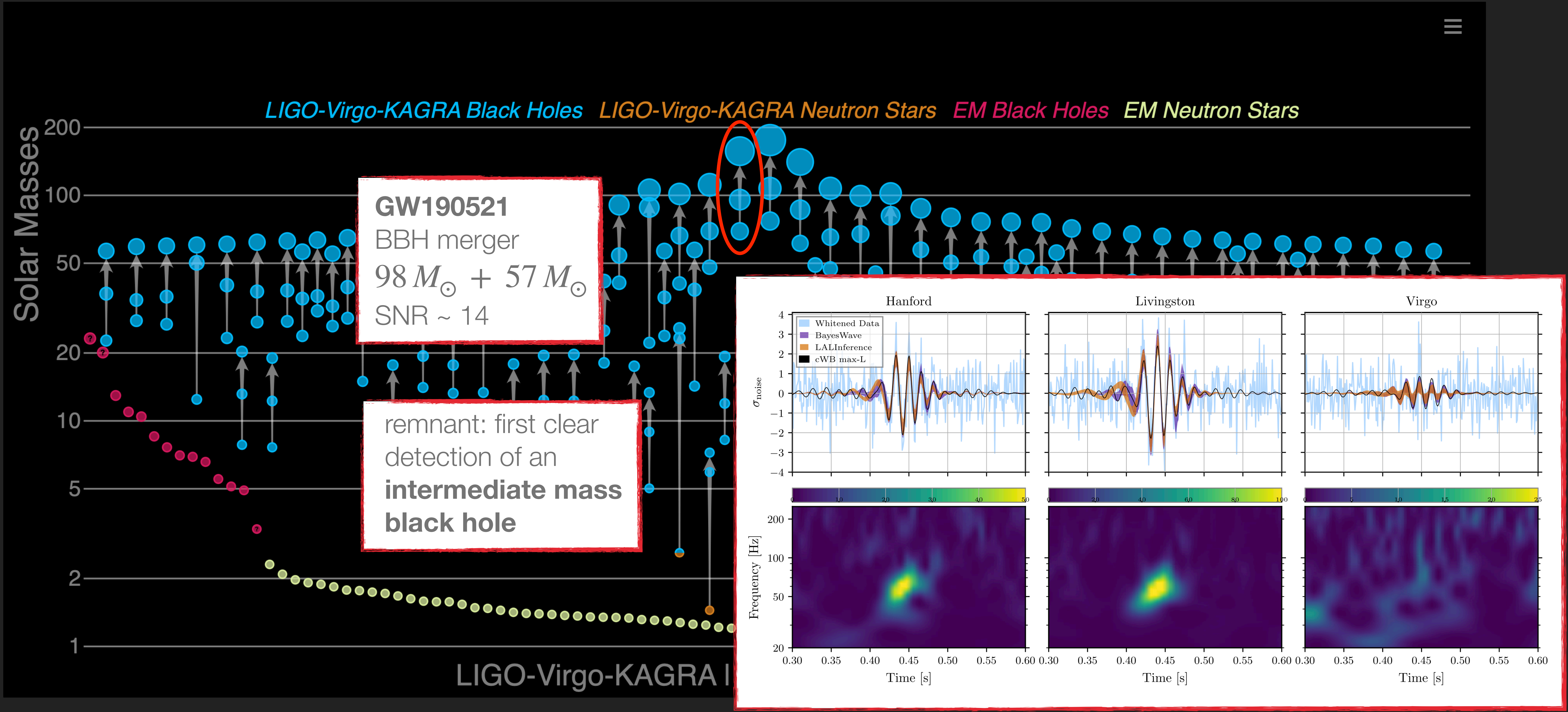
$$-3 \times 10^{-15} \leq \Delta\nu/\nu_{\rm EM} \leq +7 \times 10^{-16}$$



Abbott+ (LVC + EM), Nature 2017

- **GW190425**: second NS-NS merger
- total mass significantly larger (different formation channel?)
- more distant; no EM counterparts detected

GW190521: AN OBJECT IN THE UPPER MASS GAP



GW190521
BBH merger
$98\,M_\odot + 57\,M_\odot$
SNR ~ 14

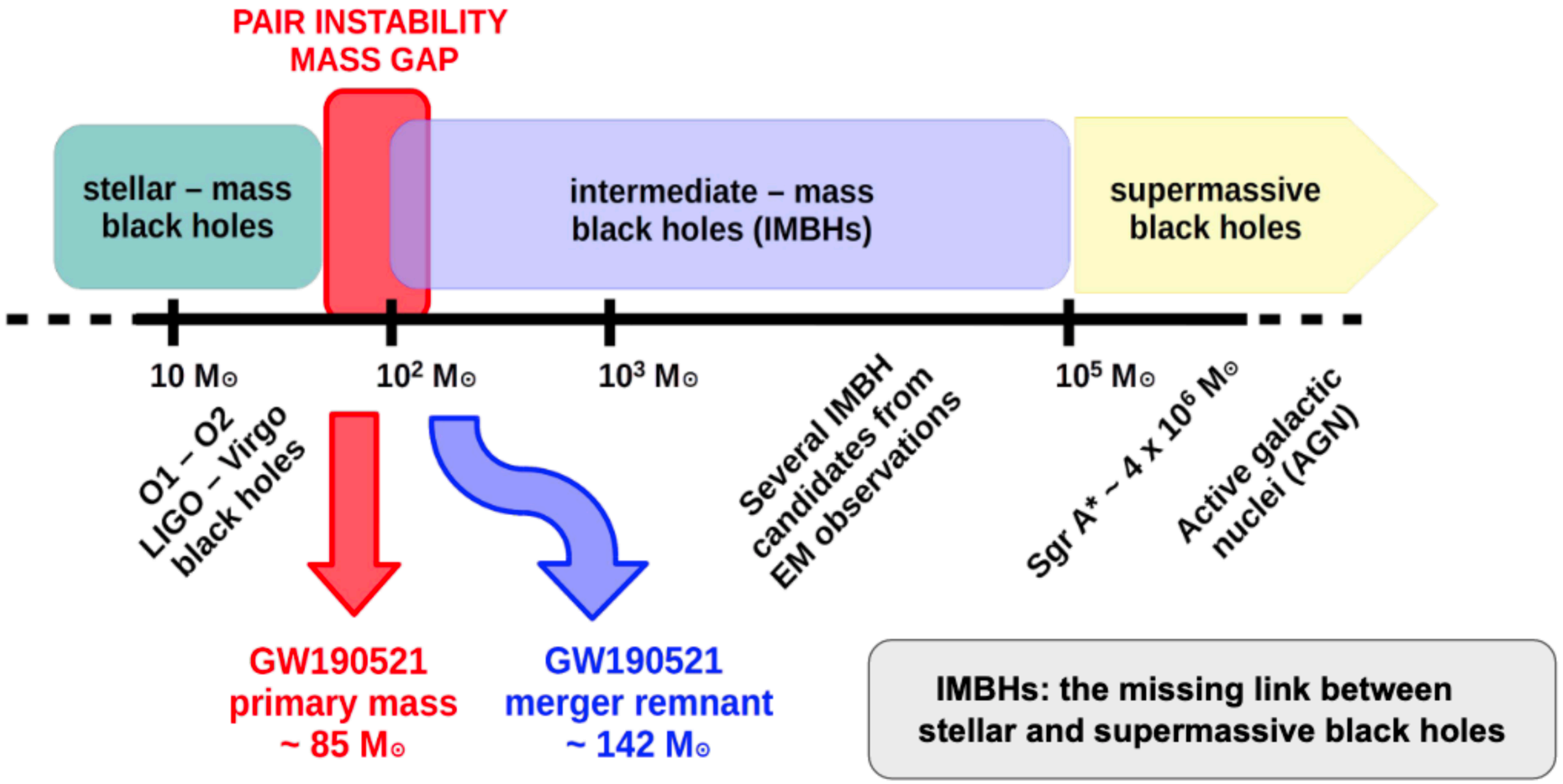
remnant: first clear detection of an **intermediate mass black hole**

https://ligo.northwestern.edu/media/mass-plot/index.html

Abbott+ (LVC), PRL 2020

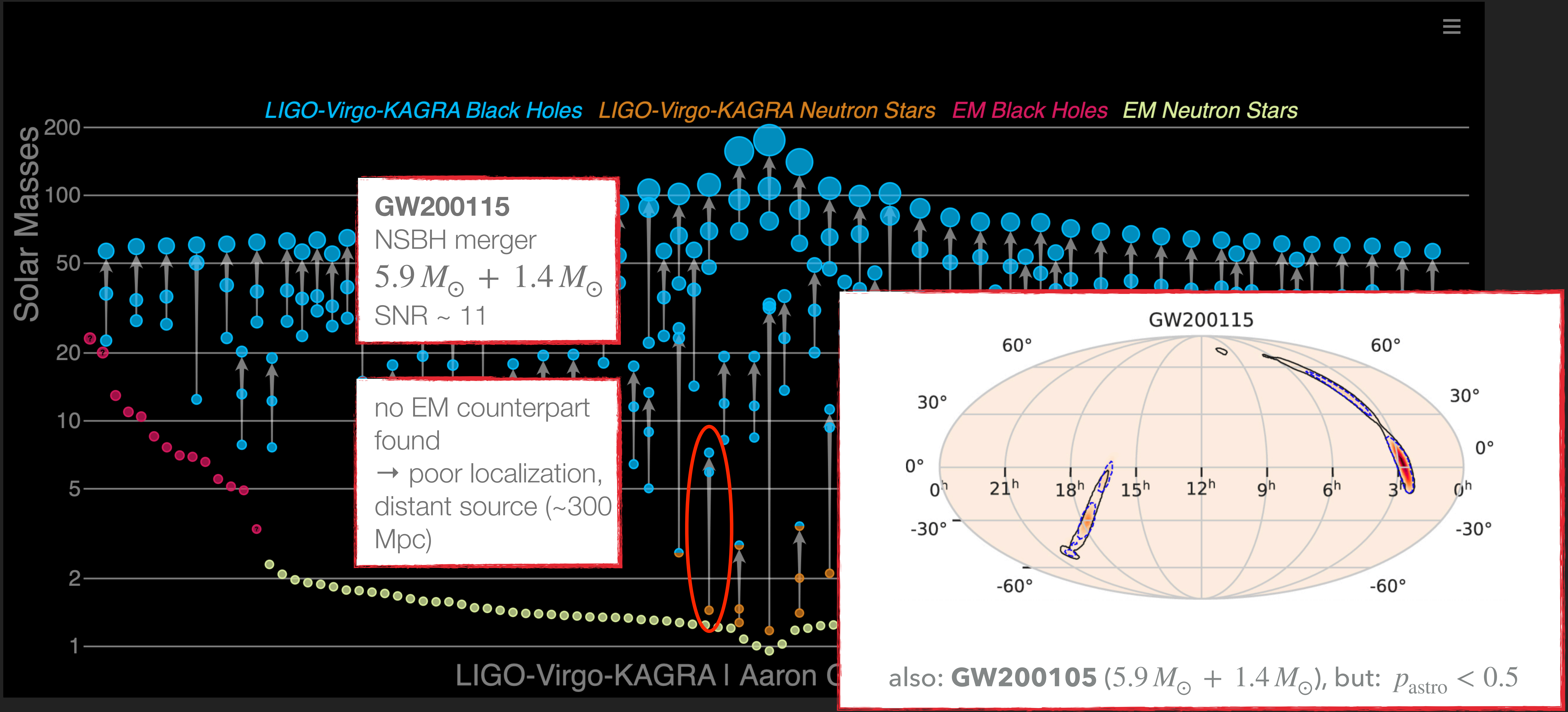
SCIENCE IMPLICATIONS OF GW190521

- **primary in upper mass gap**: challenge for stellar evolution models
- isolated binary evolution disfavoured → **hierarchical merger?** (primary is remnant of previous BH-BH merger, e.g., in AGN disk)
- ZTF detection of candidate optical counterpart in AGN J124942.3+344929



- conventional wisdom: GW190521 = coalescence of spin-precessing heavy black holes
- but: **almost no inspiral cycles** detected (signal dominated by merger-ringdown)
- **alternative interpretations**: highly eccentric BH merger? *(Romero-Shaw+, Gayatri+)* head-on collision? *(Calderon-Bustillo+)* merger of boson stars? *(Calderon-Bustillo+)*
- need more sensitivity at low frequencies to characterise GW190521-like mergers **(Einstein Telescope!)**

GW200115: A NEUTRON STAR – BLACK HOLE MERGER



GW200115
NSBH merger
$5.9\,M_\odot + 1.4\,M_\odot$
SNR ~ 11

no EM counterpart found
→ poor localization, distant source (~300 Mpc)

also: **GW200105** ($5.9\,M_\odot + 1.4\,M_\odot$), but: $p_{\mathrm{astro}} < 0.5$

https://ligo.northwestern.edu/media/mass-plot/index.html

Abbott+ (LVK), ApJL 2021

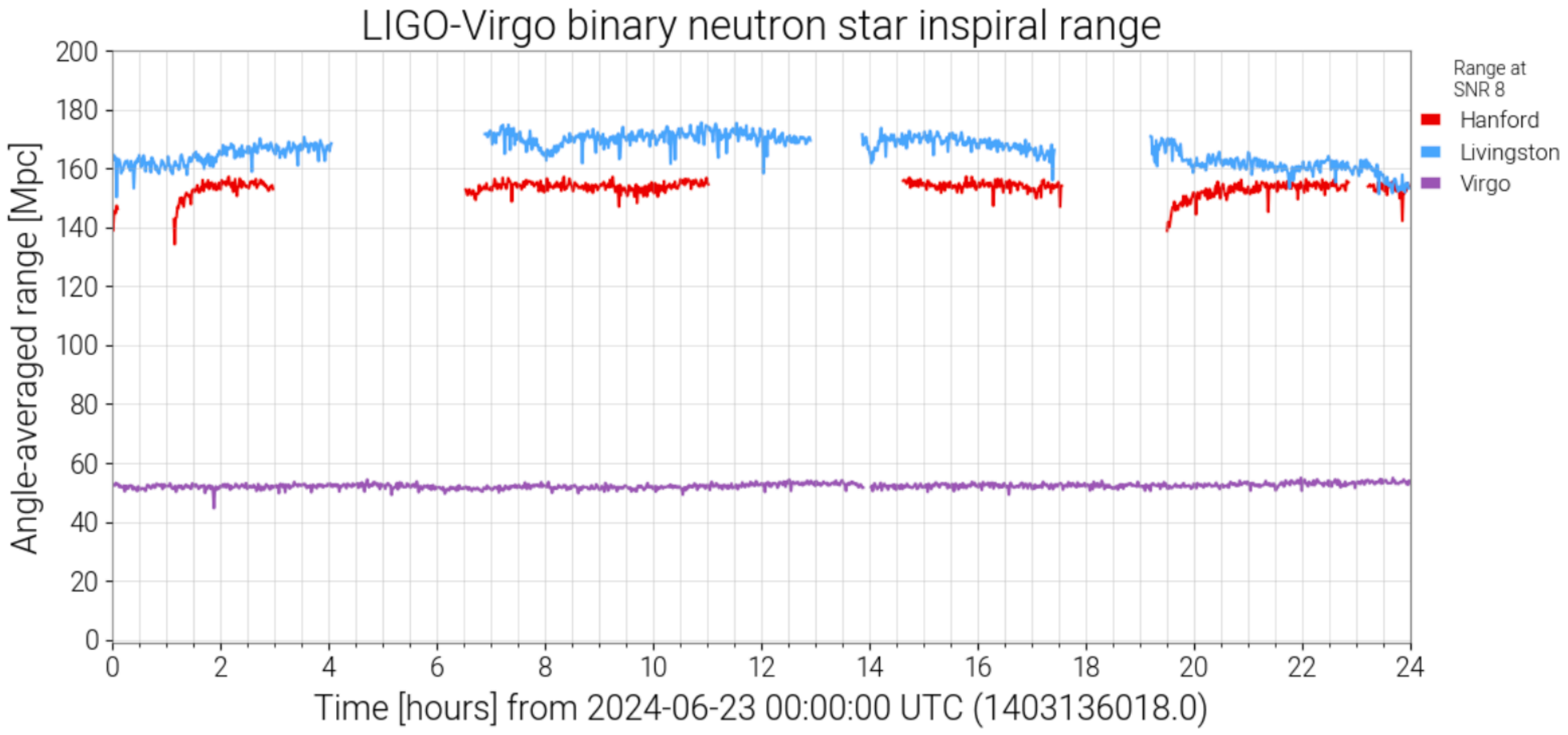
THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

Mastodon: @cplberry

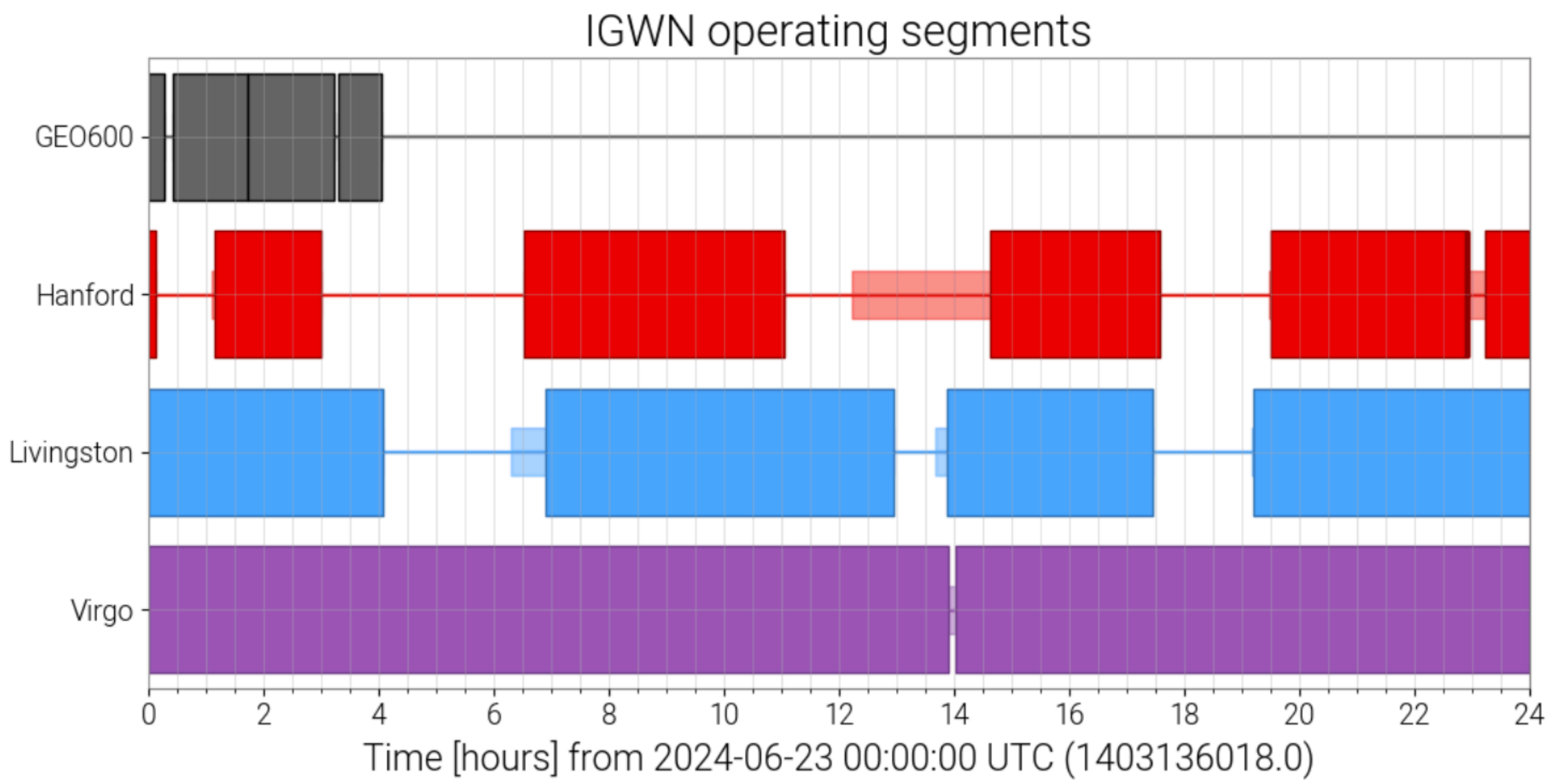
Gravitational-wave Candidate Event Database (GraceDB)

THE CURRENT OBSERVING RUN OF LIGO–VIRGO–KAGRA (O4)

- **4th observing run** (O4) started in May, 2023
- duration: nominally **20 months** (O4a: 9, commissioning: 2, O4b: 9)
- extension **to June, 2025**



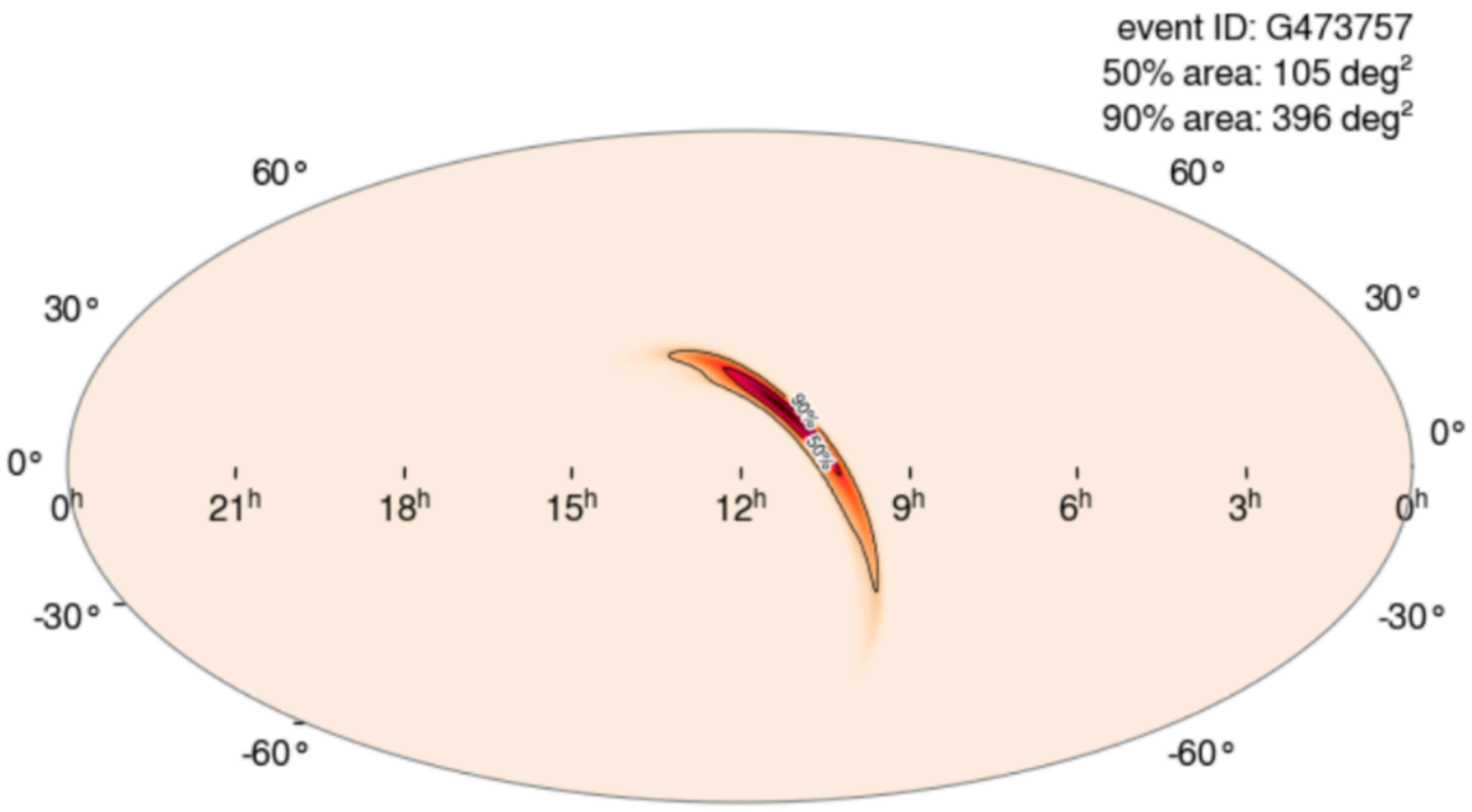
https://gwosc.org/detector_status/



- **Virgo**: persistent problems with broadband noise; only joined O4b & with limited sensitivity
- **KAGRA**: will join O4b in December 2024 (10 Mpc)

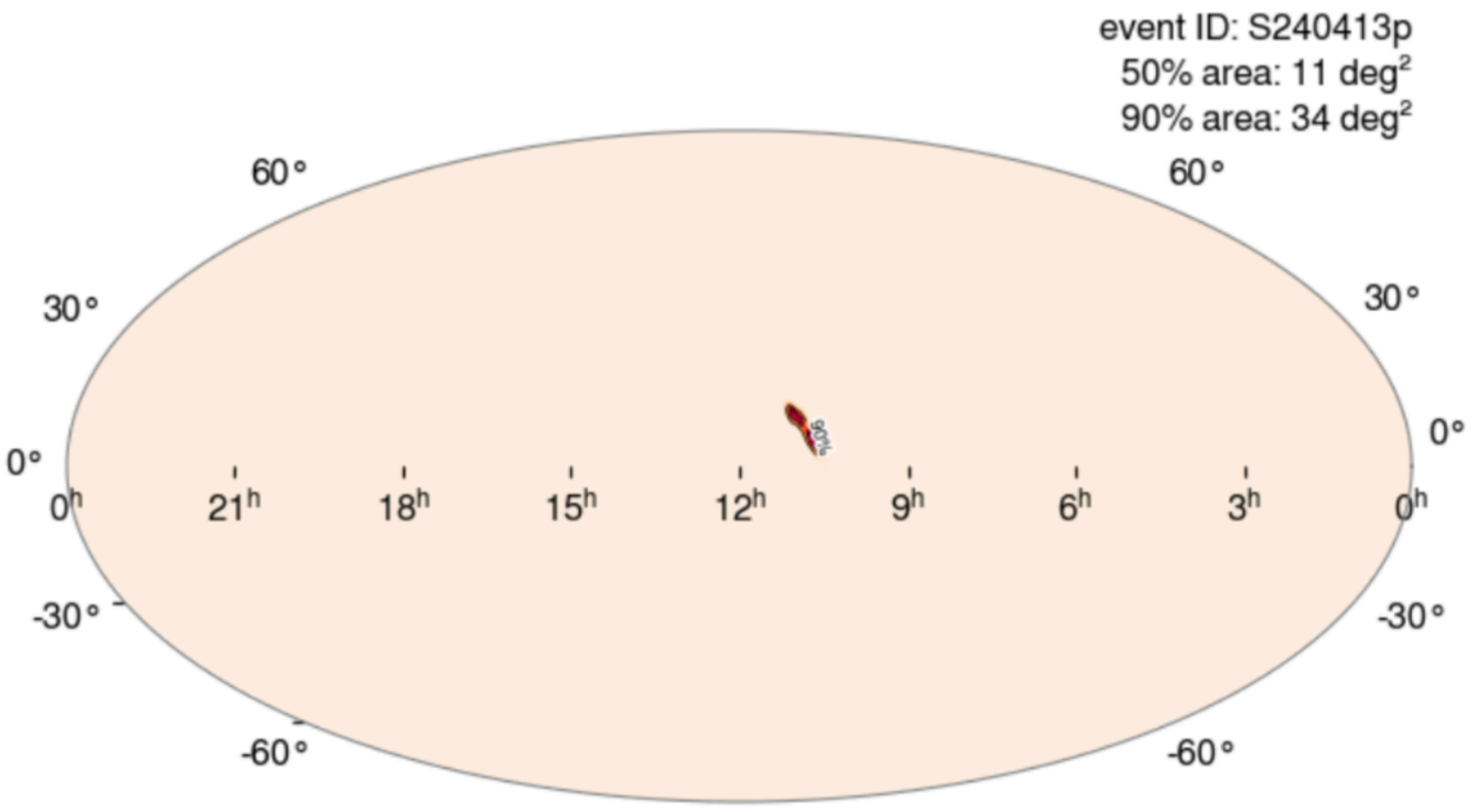
THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

O4a



2x LIGO

O4b



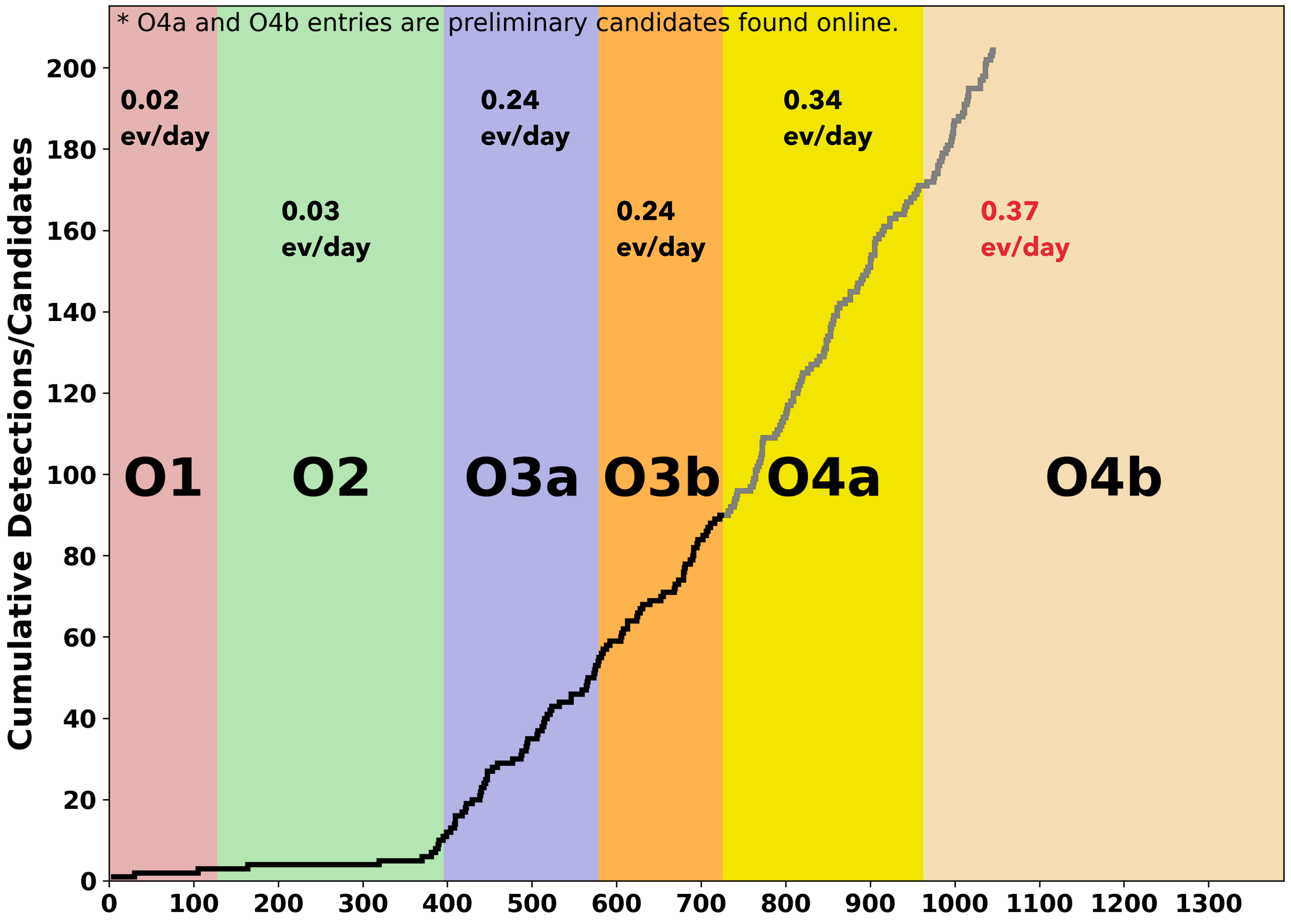
2x LIGO + Virgo

THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

- O4b sensitivities ("BNS range"):
  - LIGO: Hanford ~150 Mpc, Livingston ~170 Mpc)
  - Virgo: ~55 Mpc
- O4b duty cycles:
  - LIGO: 60-70%
  - Virgo: ≥ 80%
- O4 significant detection candidates (so far): **117** (133 Total - 16 Retracted)

36 207

O1+O2+O3 = 90, O4a* = 81, O4b* = ~~34~~, Total = ~~205~~

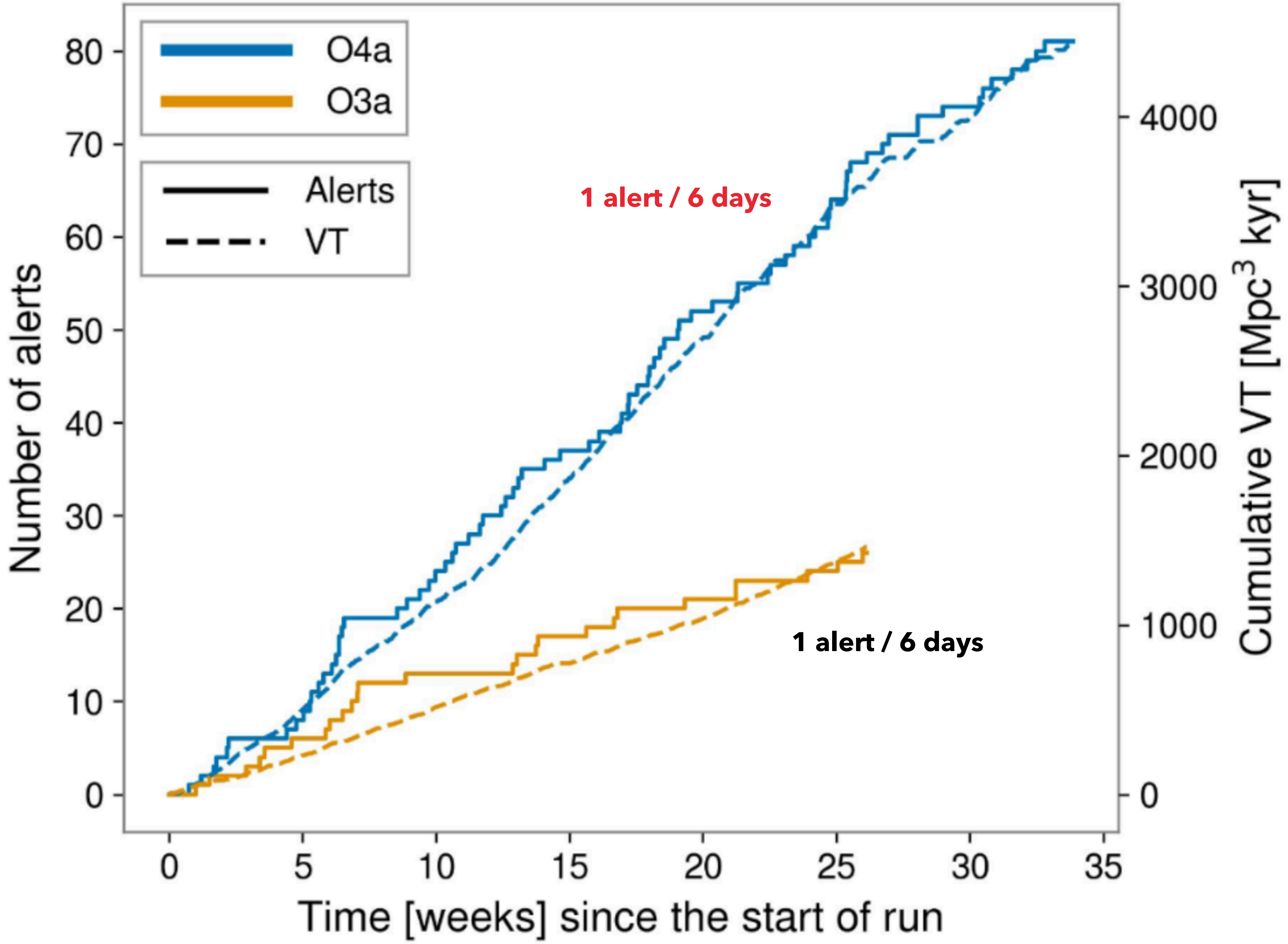


LIGO-G2302098(b517cf72), updated on 30 June, 2024

Credit: LIGO-Virgo-KAGRA Collaboration

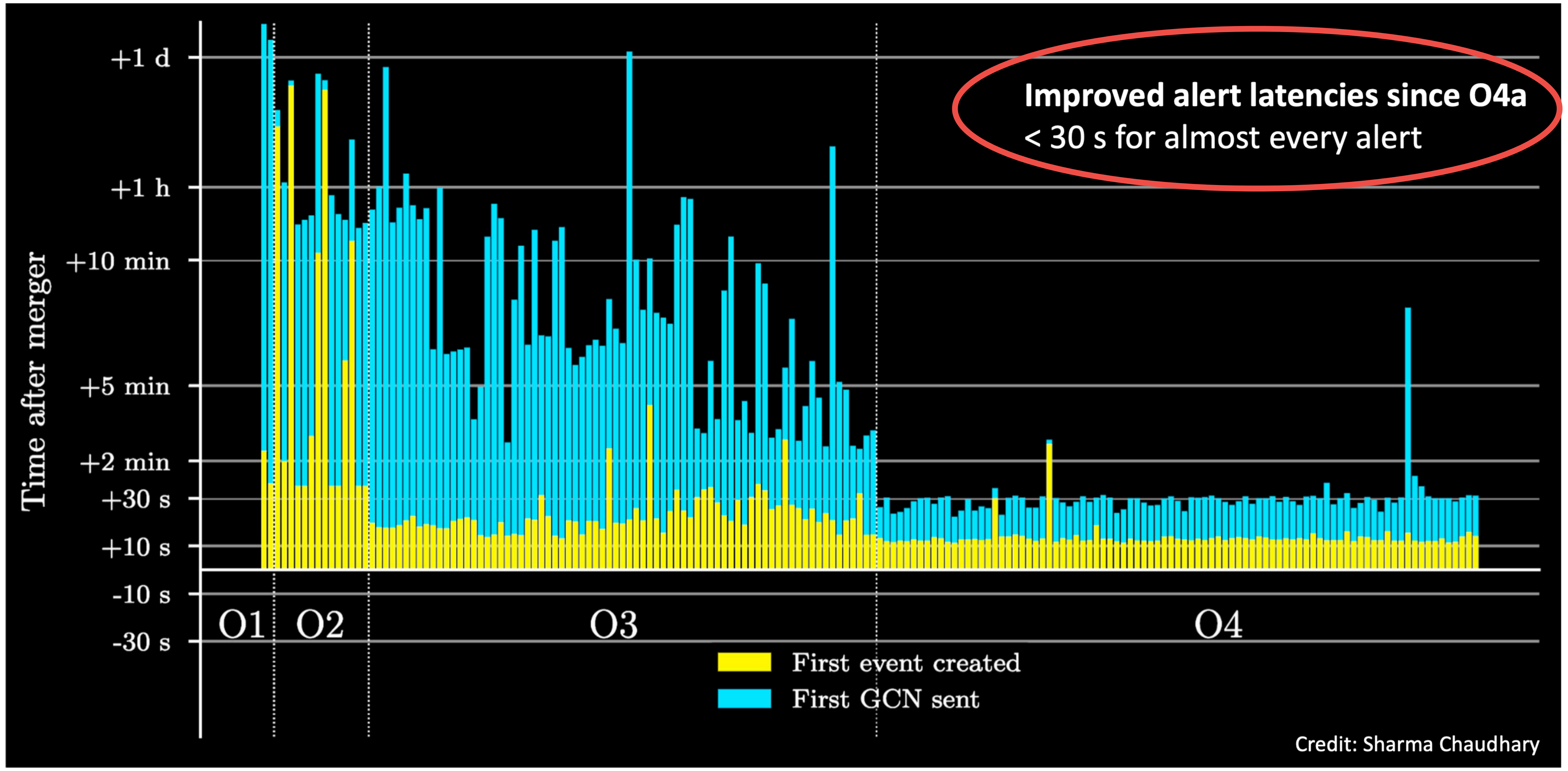
THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

- **O4a:** LIGO-Hanford + LIGO-Livingston
  - significant detection candidates: 80 BH-BH, 1 NS-BH
  - ~1600 low-significance candidates (SNR < 8)
- **O4b:** LIGO-Hanford + LIGO-Livingston + Virgo
  - significant detection candidates: 33 BH-BH, 1 NS-BH
  - ~550 low-significance candidates



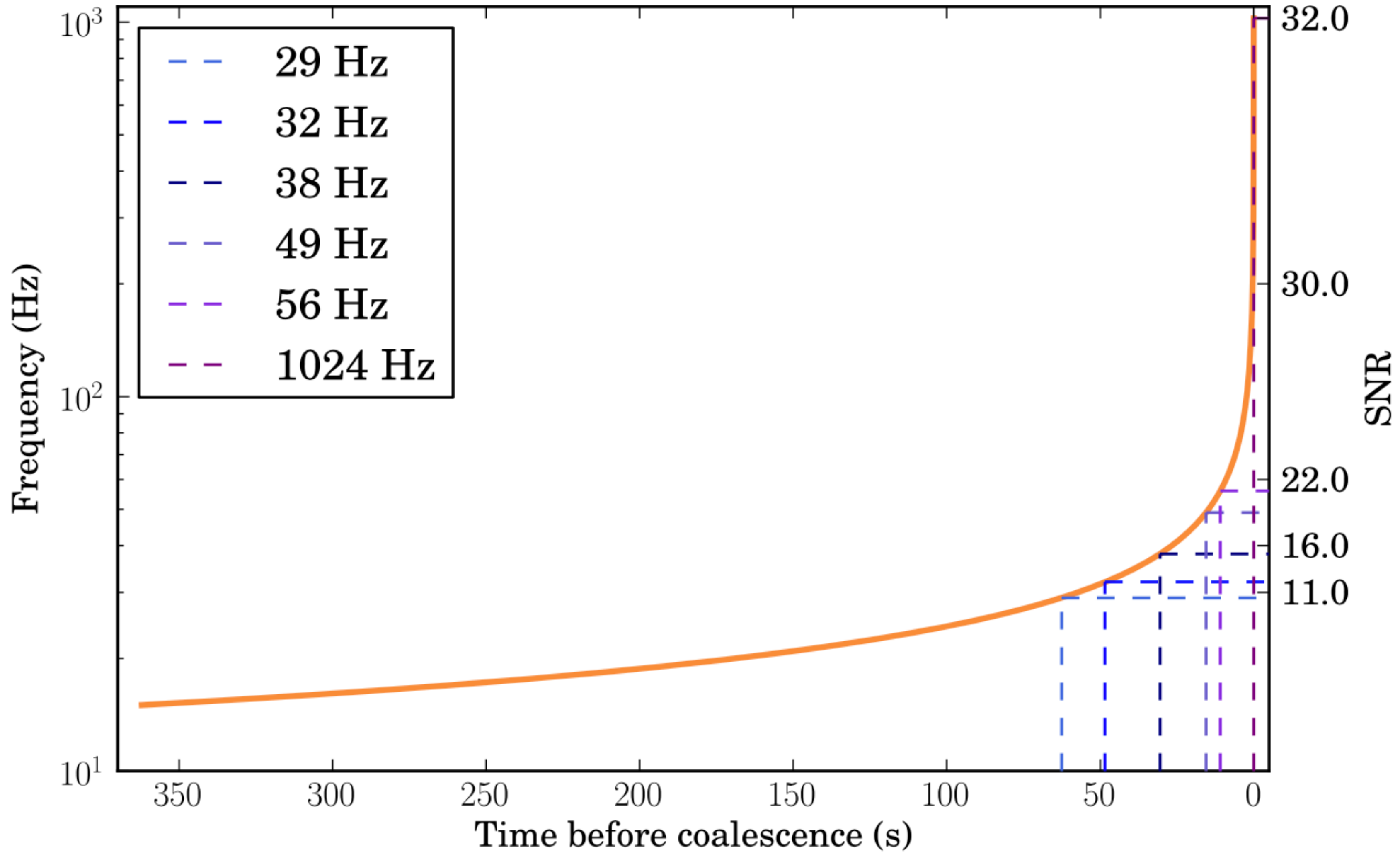
THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

- **O4** (online) detection pipelines: early-warning alerts!
  - accumulated SNR ~11 when NS-NS signal enters detector band (30Hz) → a minute before merger!



Improved alert latencies since O4a
< 30 s for almost every alert

Credit: Sharma Chaudhary

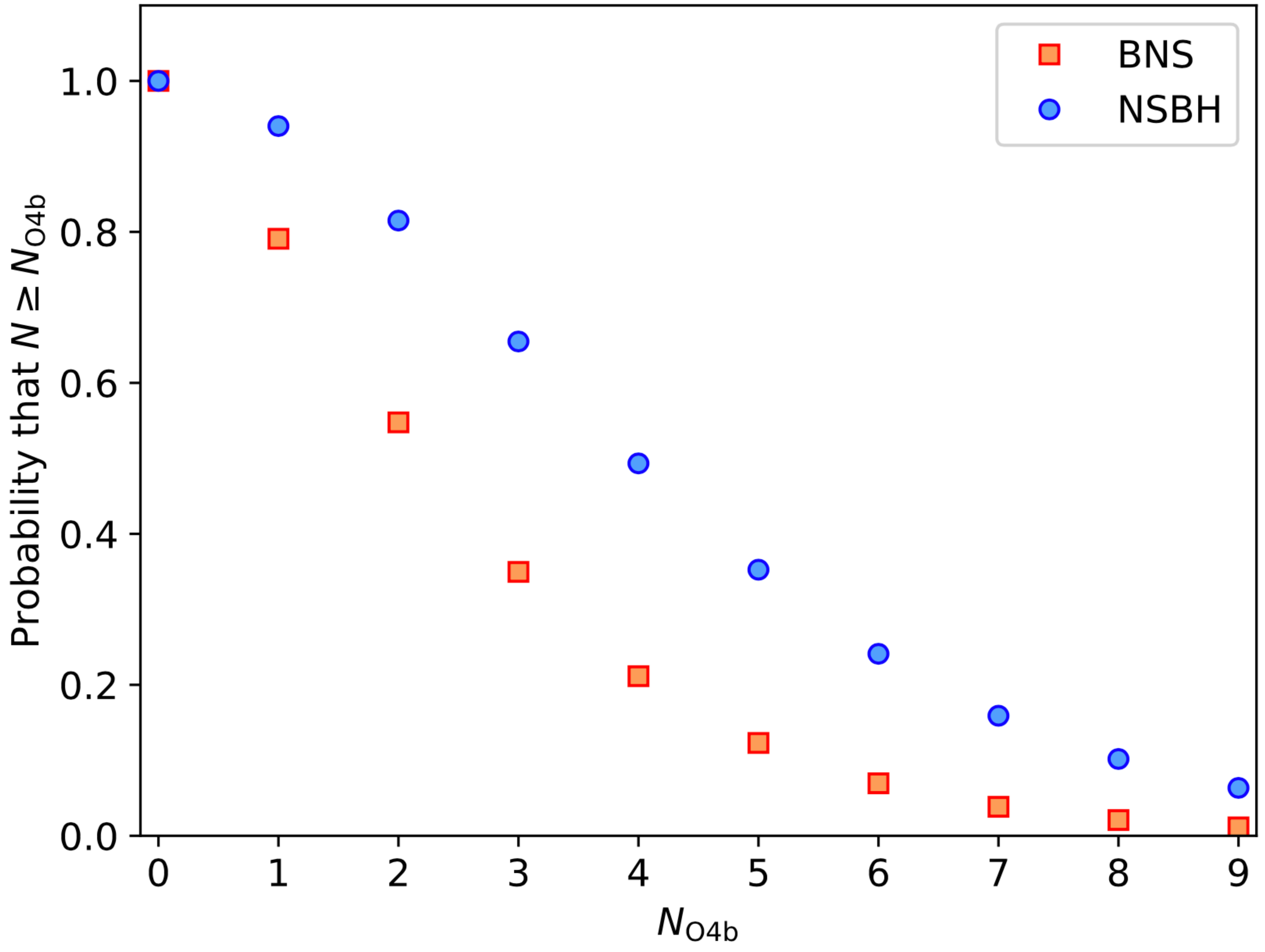


The time evolution of the gravitational-wave frequency and the cumulative SNR for a GW170817-like BNS system.

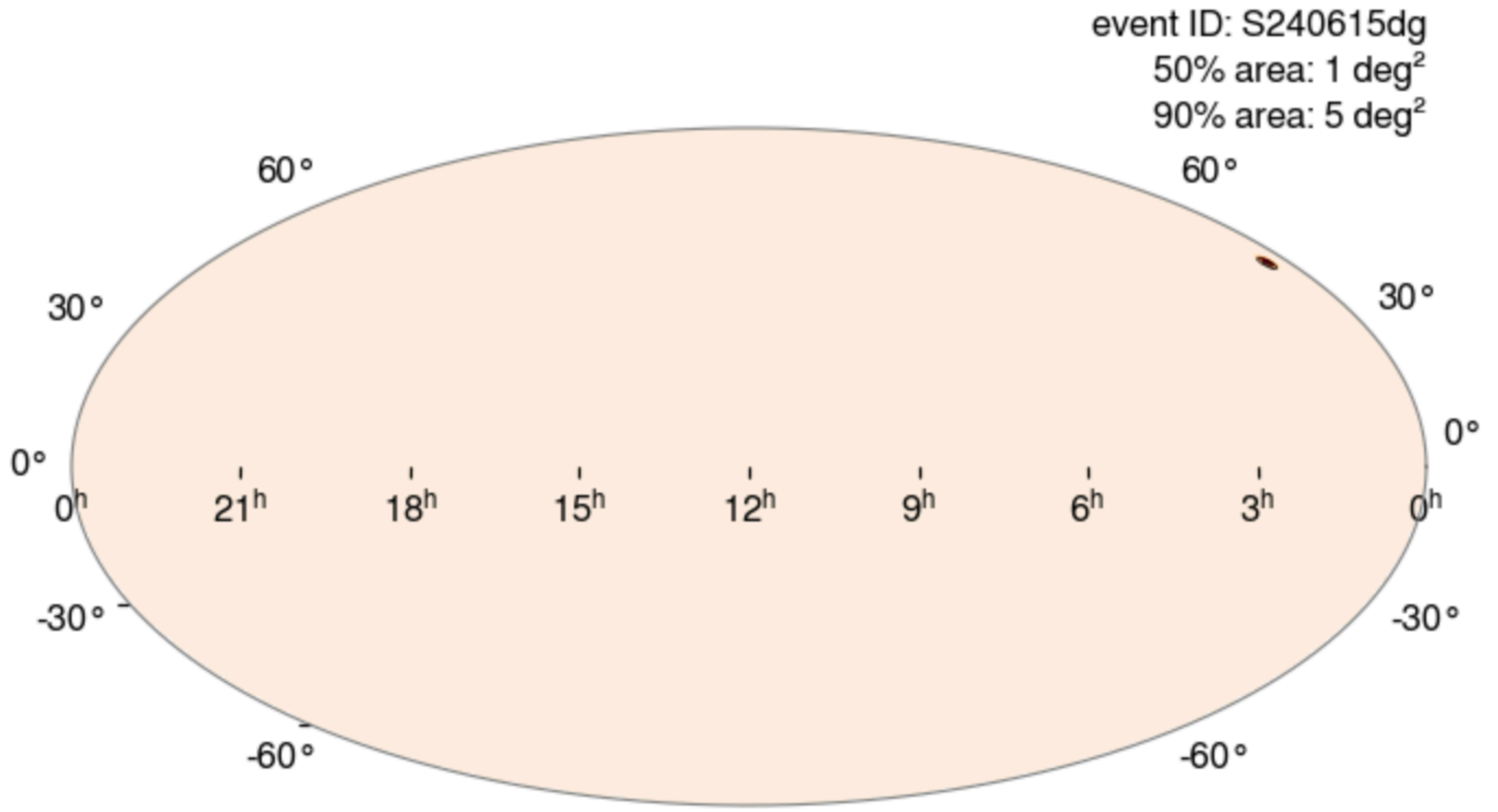
https://emfollow.docs.ligo.org

THE CURRENT OBSERVING RUN OF LIGO-VIRGO-KAGRA (O4)

- **mostly BH-BH** candidates (no EM counterparts)
- **no NS-NS** so far (expect at least 1 during O4b)



https://emfollow.docs.ligo.org

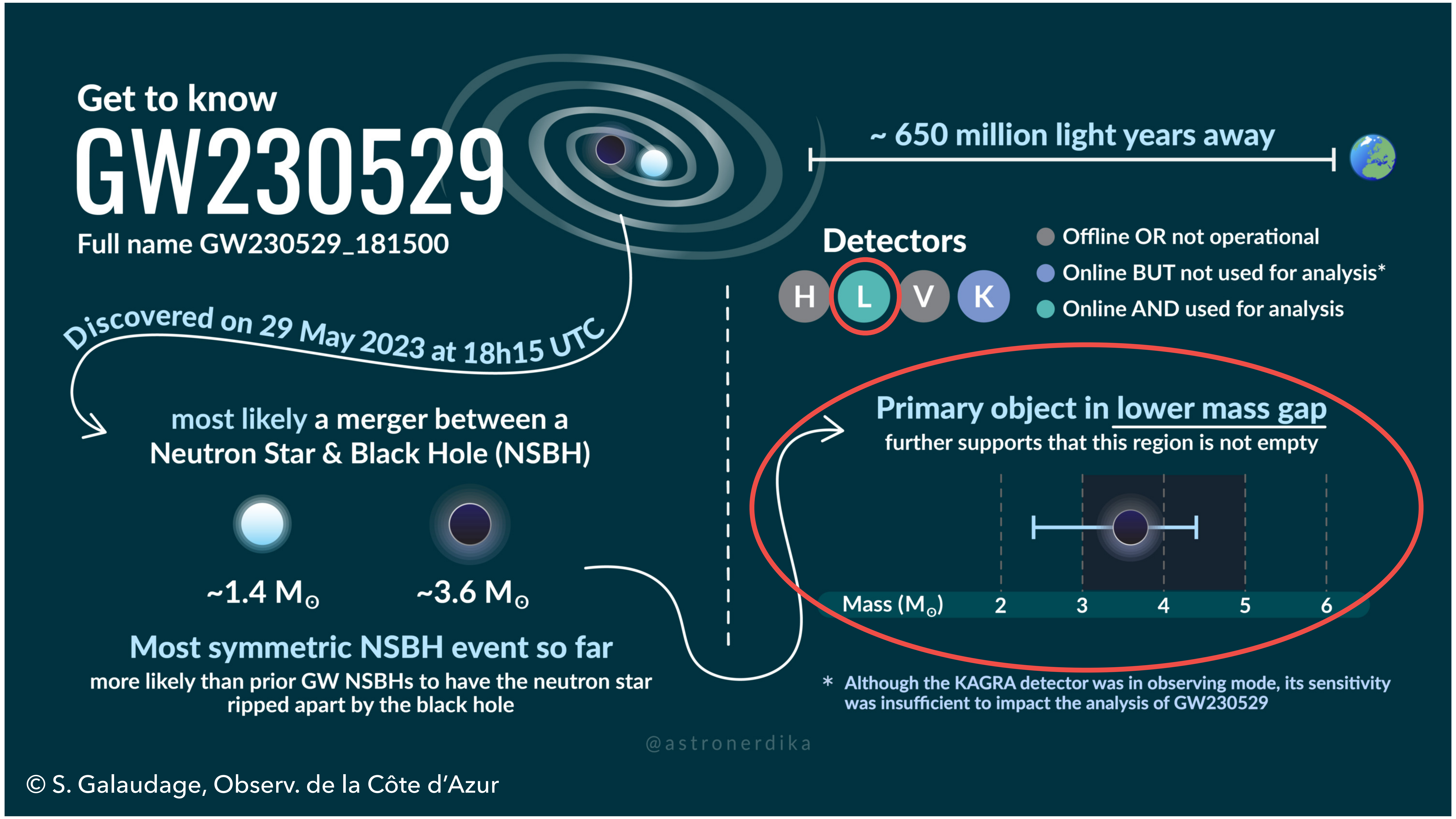


2x LIGO + Virgo

(O4b) BH-BH candidate: https://gracedb.ligo.org

- offline analyses of O4a data have started
- watch out for future GW transient catalogs!

PRELIMINARY O4A SCIENCE: AN OBJECT IN THE LOWER MASS-GAP



most likely a merger between a Neutron Star & Black Hole (NSBH)

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

Primary object in lower mass gap

further supports that this region is not empty

* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

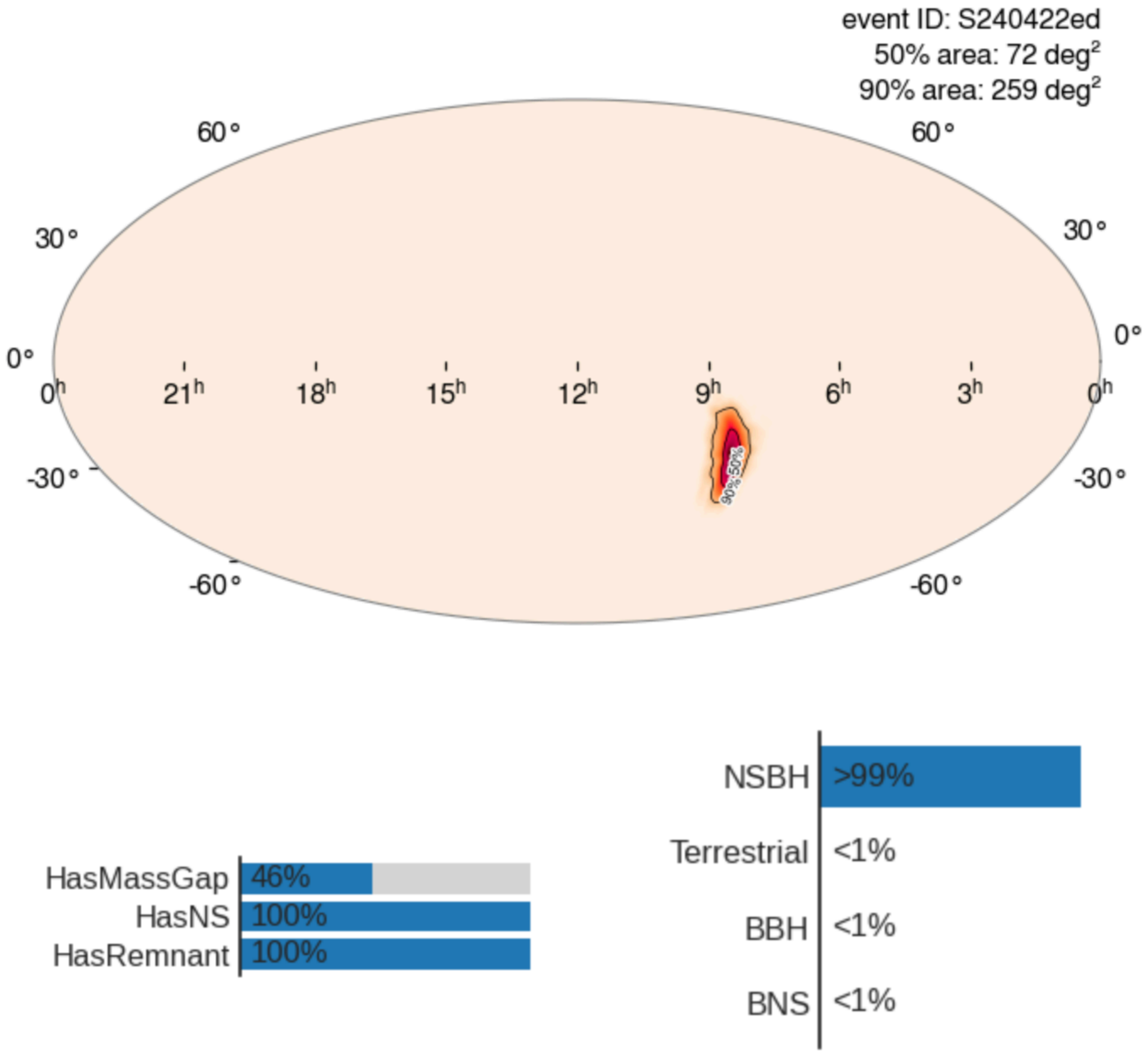
© S. Galaudage, Observ. de la Côte d'Azur

- GW230529 paper: arXiv:2404.04248 (to appear in ApJL)

- formation of lower mass-gap objects?
- **incomplete understanding of core collapse in massive stars!** (e.g., delayed explosion timescales?, stochasticity of remnant masses?
- or: progenitor of mass-gap object was **hierarchical merger between two neutron stars**?

PRELIMINARY O4B SCIENCE: AN NS–BH DETECTION CANDIDATE

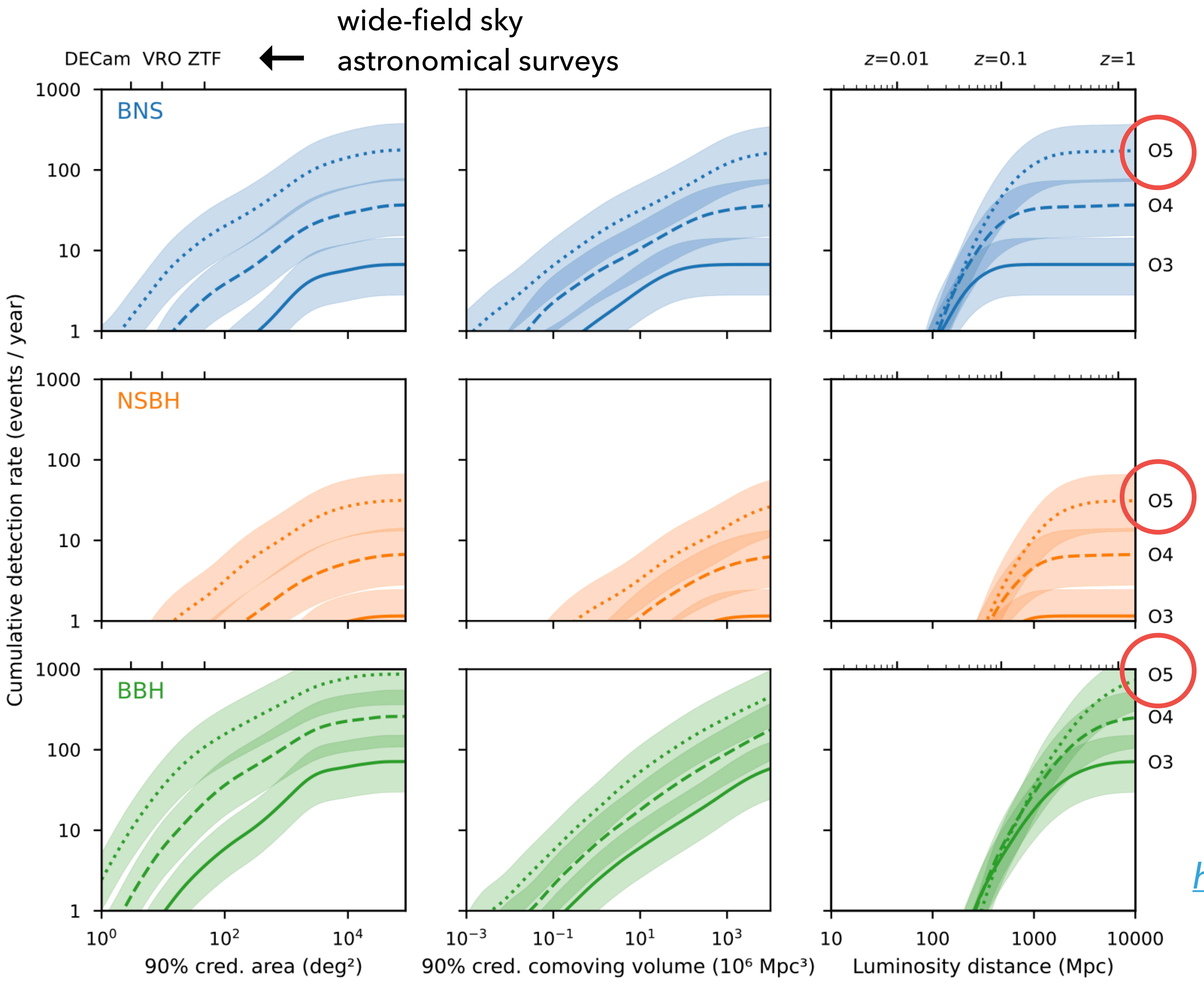
- **S240422ed:** https://gracedb.ligo.org/superevents/S240422ed/view/
- **when?** 2024-04-22 21:35:13 UTC
- **which instruments?** LIGO (Hanford & Livingston), Virgo
- **how significant?** false-alarm rate: 1 per 10^5 years (preliminary)
- > 80 EM follow-up observations (from radio to γ-rays, neutrinos searches, …)
  → **no counterpart found**



FUTURE PROSPECTS FOR THE CURRENT GENERATION OF DETECTORS

LIGO India: approved, under construction … operational from 2030?

FUTURE PROSPECTS FOR THE CURRENT GENERATION OF DETECTORS

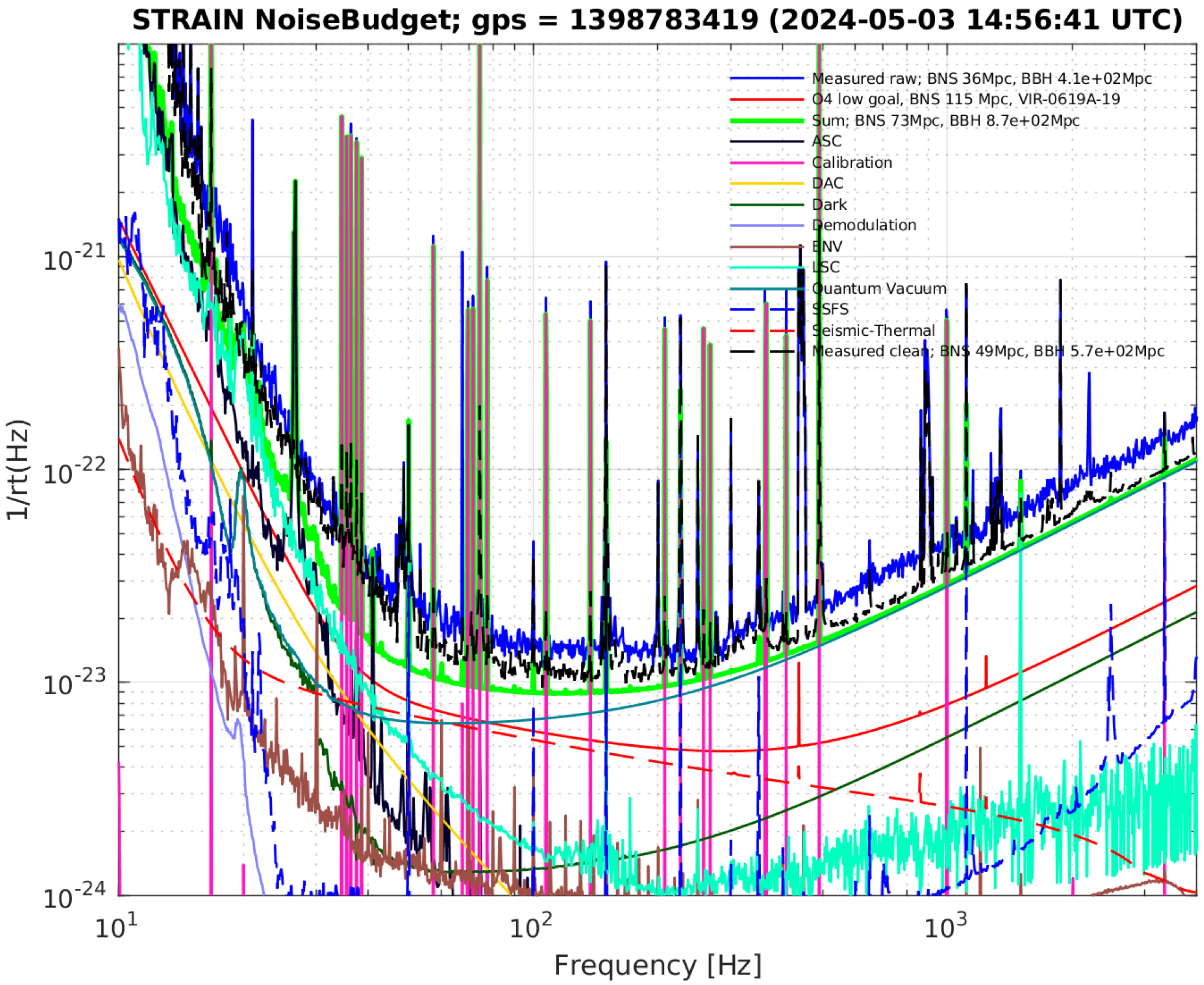


https://emfollow.docs.ligo.org

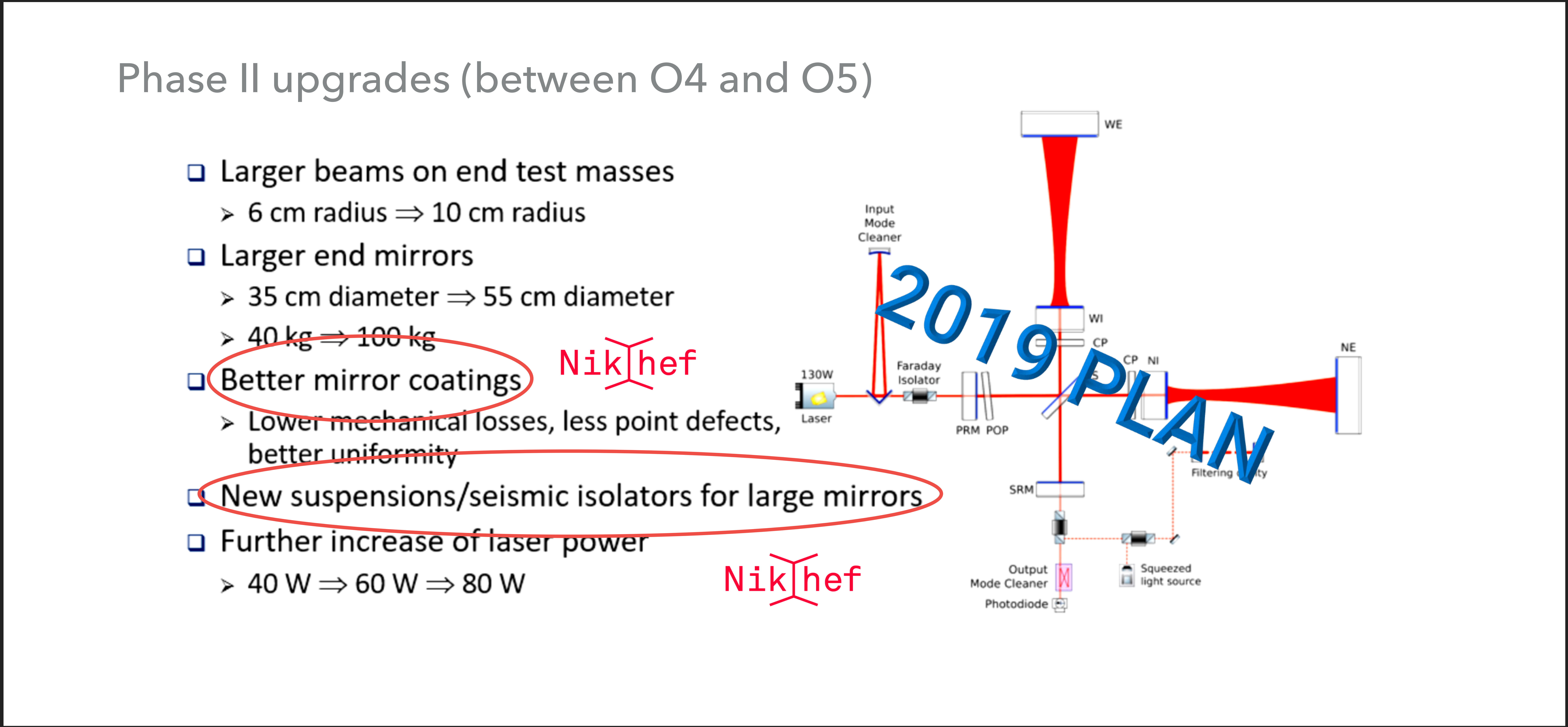
VIRGO: STATUS & FUTURE UPGRADES

VIRGO DURING O4: NOISE BUDGET AND «MYSTERY NOISE»

- previously expected Virgo sensitivity for O4: 80-115 Mpc
- **currently missing ~30 Mpc**
- at low frequencies: unknown f^{-4} noise (possibly control noise)
- from 4-200 Hz: broadband **mystery noise** ($f^{-2/3}$); ???
- noise hunting still ongoing



VIRGO ON THE PATH TOWARDS O5



Phase II upgrades (between O4 and O5)

- ❑ Larger beams on end test masses
  - ➢ 6 cm radius ⇒ 10 cm radius
- ❑ Larger end mirrors
  - ➢ 35 cm diameter ⇒ 55 cm diameter
  - ➢ 40 kg ⇒ 100 kg
- ❑ Better mirror coatings
  - ➢ Lower mechanical losses, less point defects, better uniformity
- ❑ New suspensions/seismic isolators for large mirrors
- ❑ Further increase of laser power
  - ➢ 40 W ⇒ 60 W ⇒ 80 W

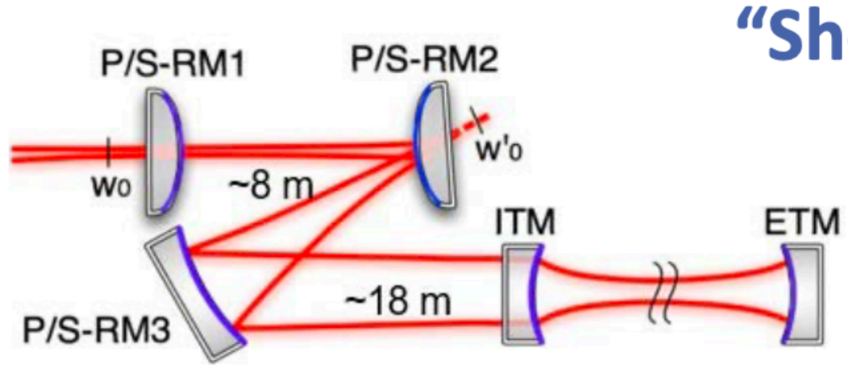
Nikhef

Nikhef

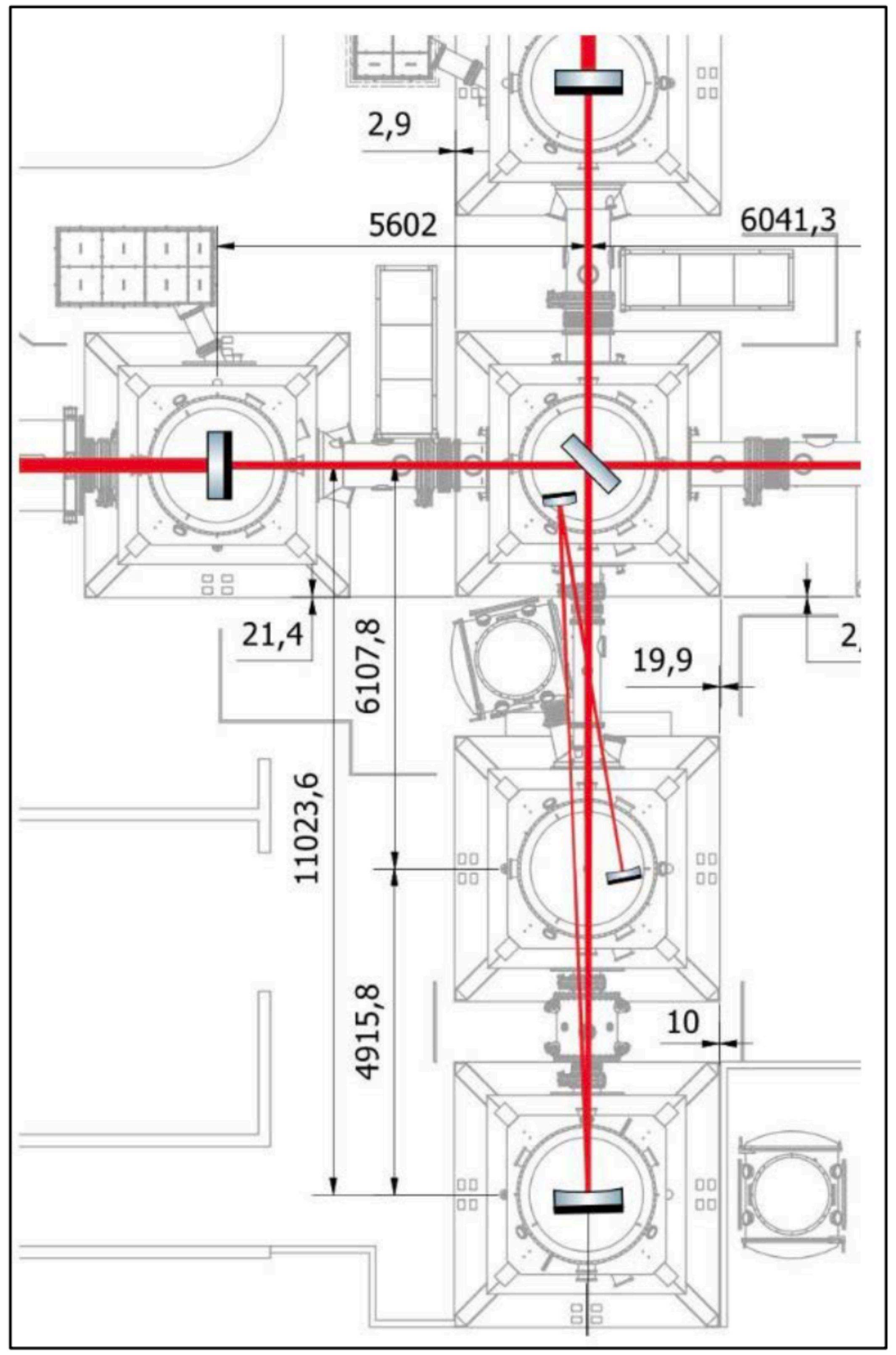
2019 PLAN

VIRGO TOWARDS O5: STABLE RECYCLING CAVITIES

- power recycling: boosts power of laser light stored inside arm cavities
- signal recycling: tunes the detector response to the GW frequency band
- major difference between LIGO & Virgo: Virgo has **marginally stable recycling cavities** (= simpler design)
- Virgo more sensitive to defects in test masses (thermal, optical)
- **for O5: install (short) stable recycling cavities** in existing infrastructure
- impact building infrastructure and vacuum system



"Short" stable



Virgo post-O4 proposal

THE EINSTEIN TELESCOPE: A 3THIRD-GENERATION DETECTOR IN EUROPE

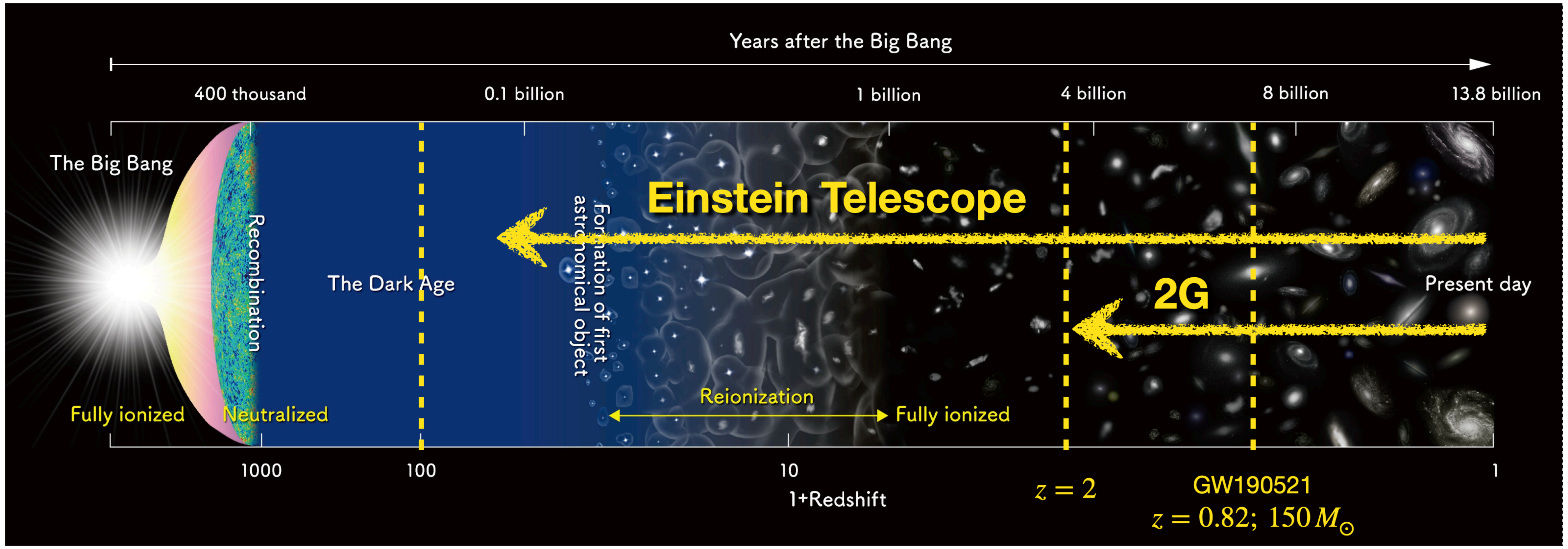
Two cryogenic detectors in each corner (HF and LF)

10x more sensitive than 2G detectors. Sensitive from 3Hz.

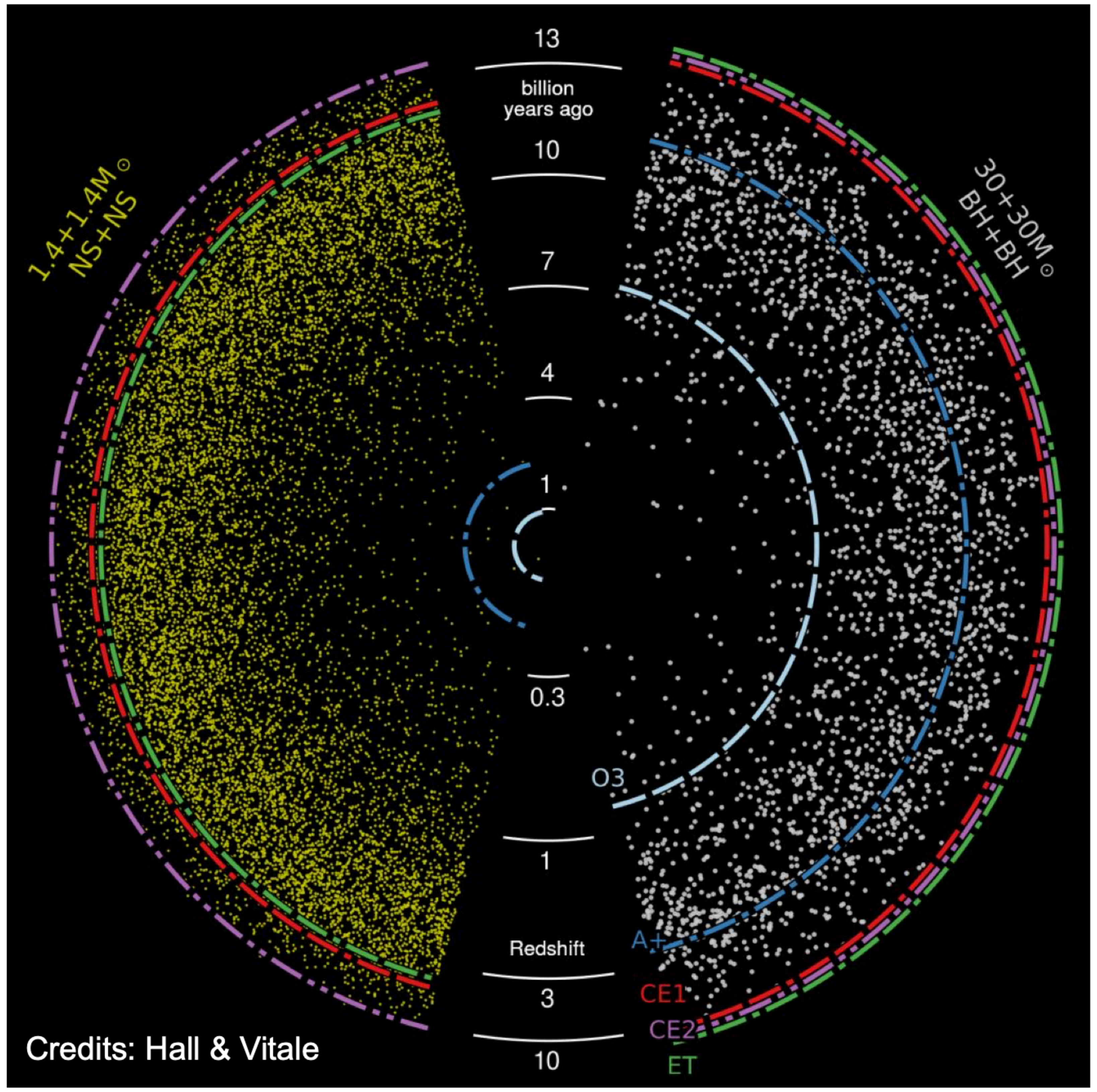
Laser beams and super-polished optics in ultra-high vacuum systems

Equilateral triangle design, more than 200m underground (for seismic isolation)

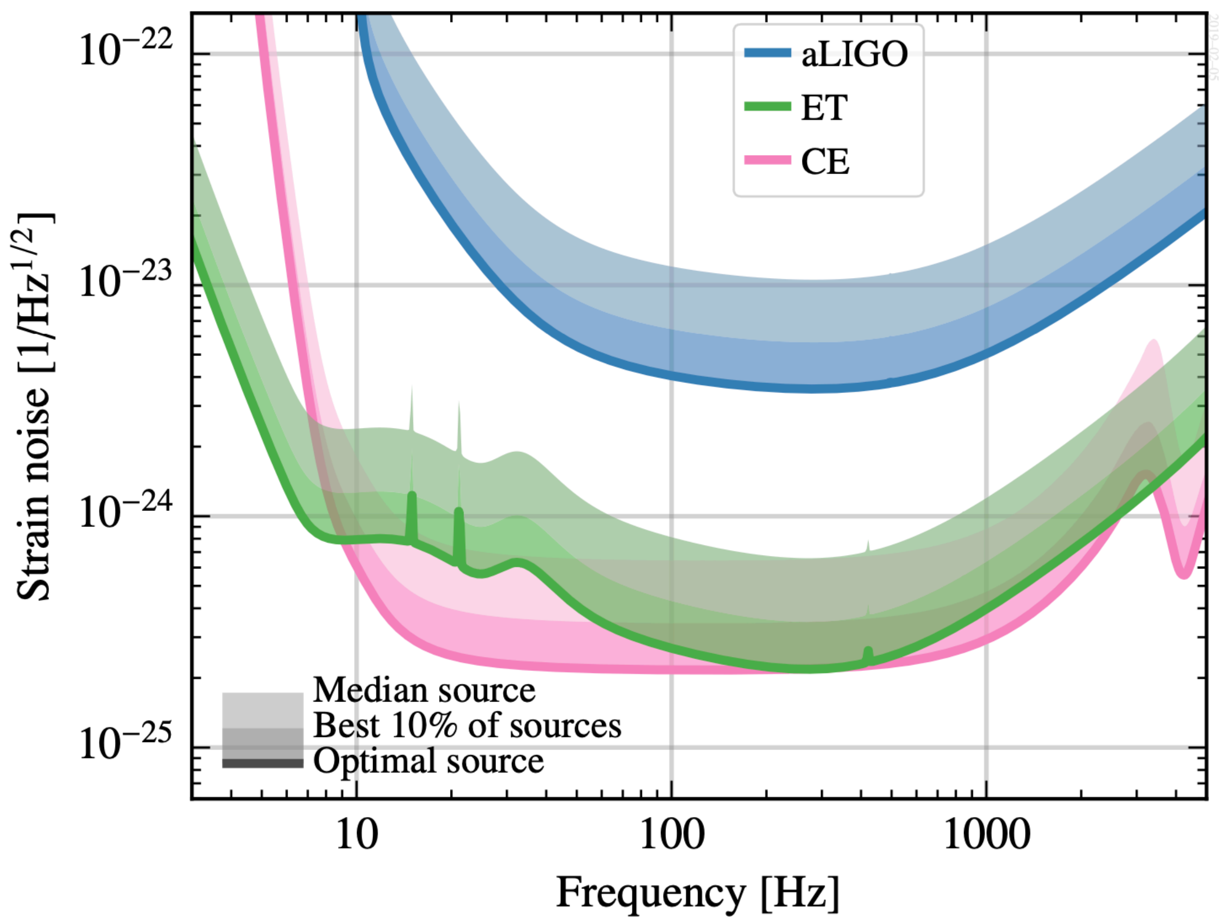
WHY BUILD THE EINSTEIN TELESCOPE?

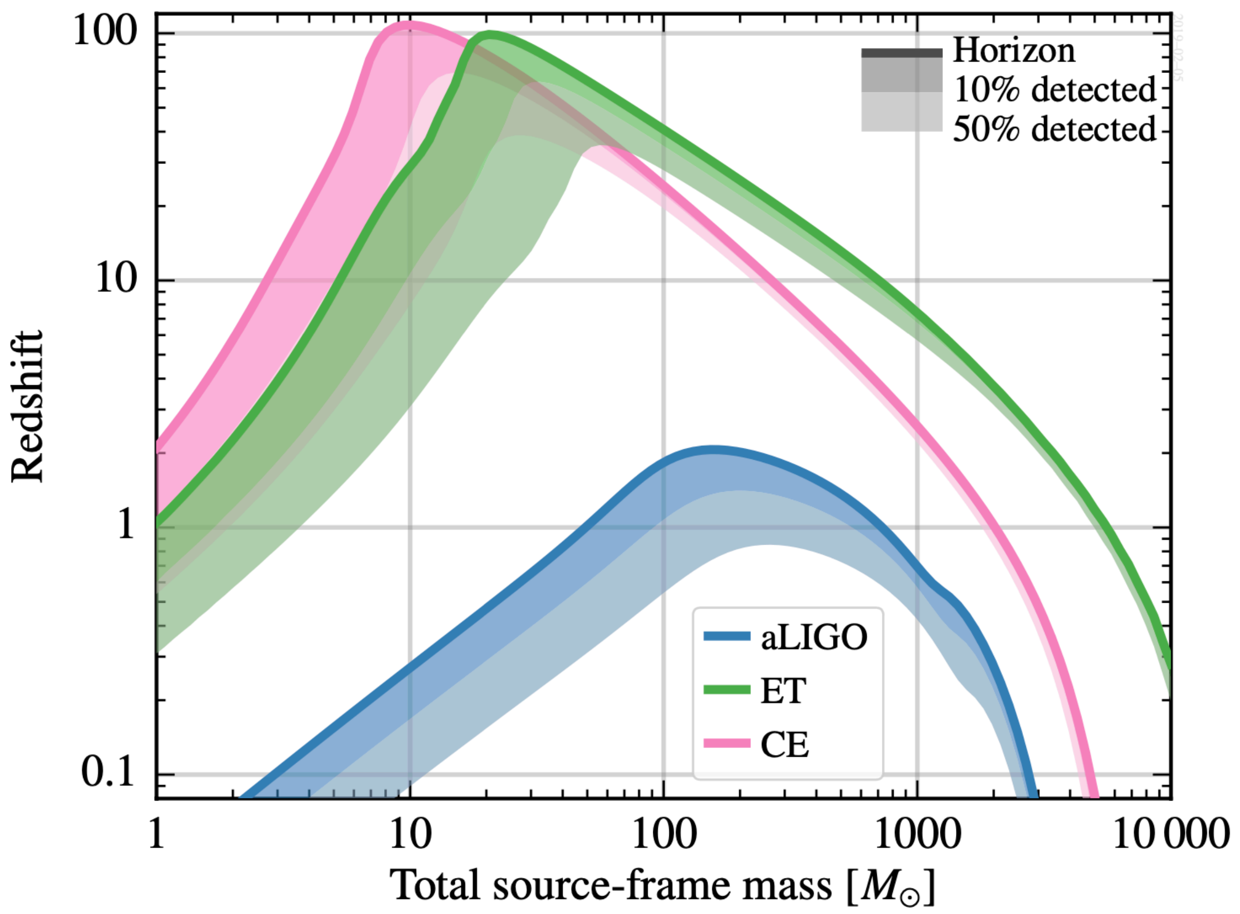


Credit: ALMA Collaboration



Credits: Hall & Vitale

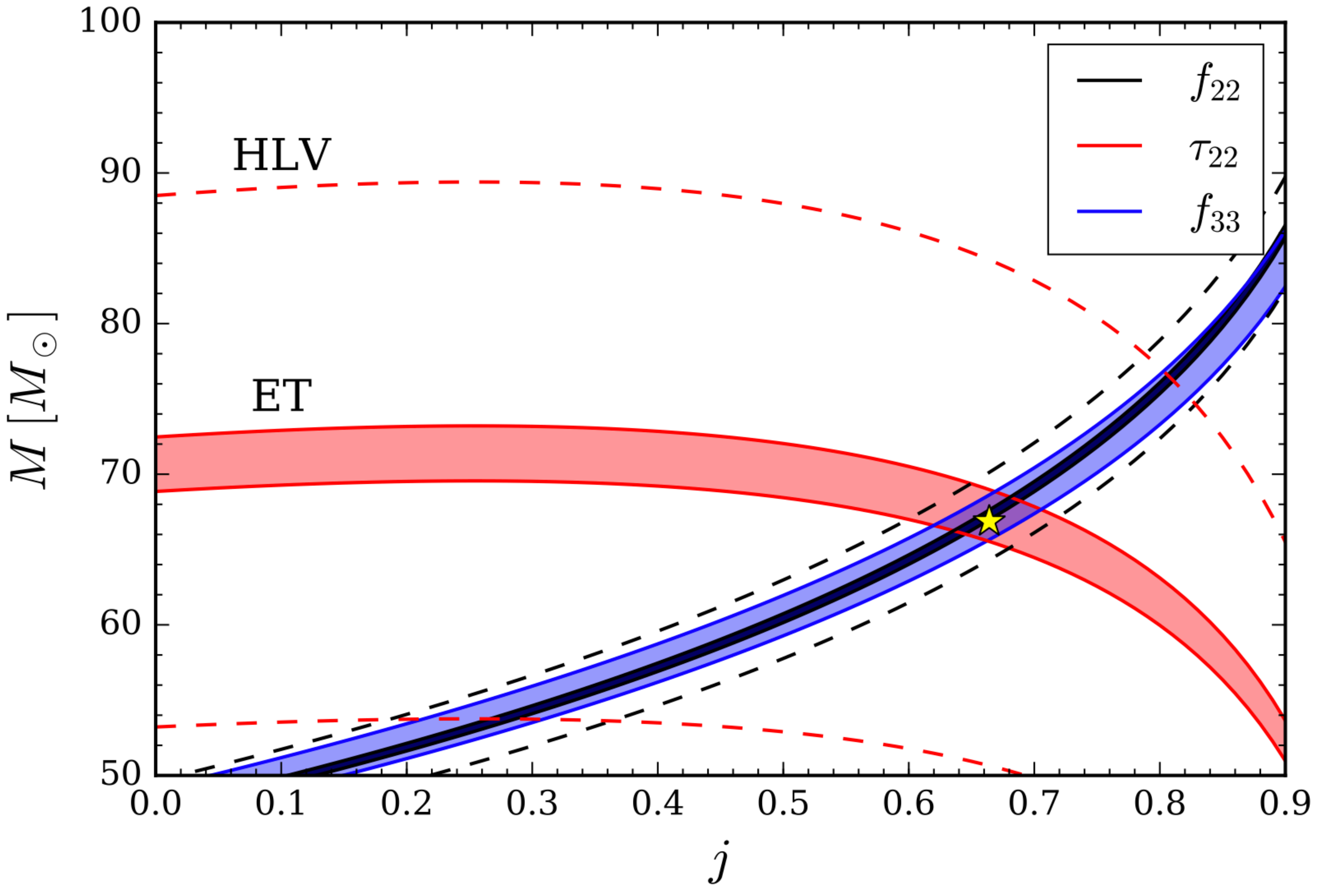




10^5 BH-BH alerts per year,
10^5 NS-NS alerts per year

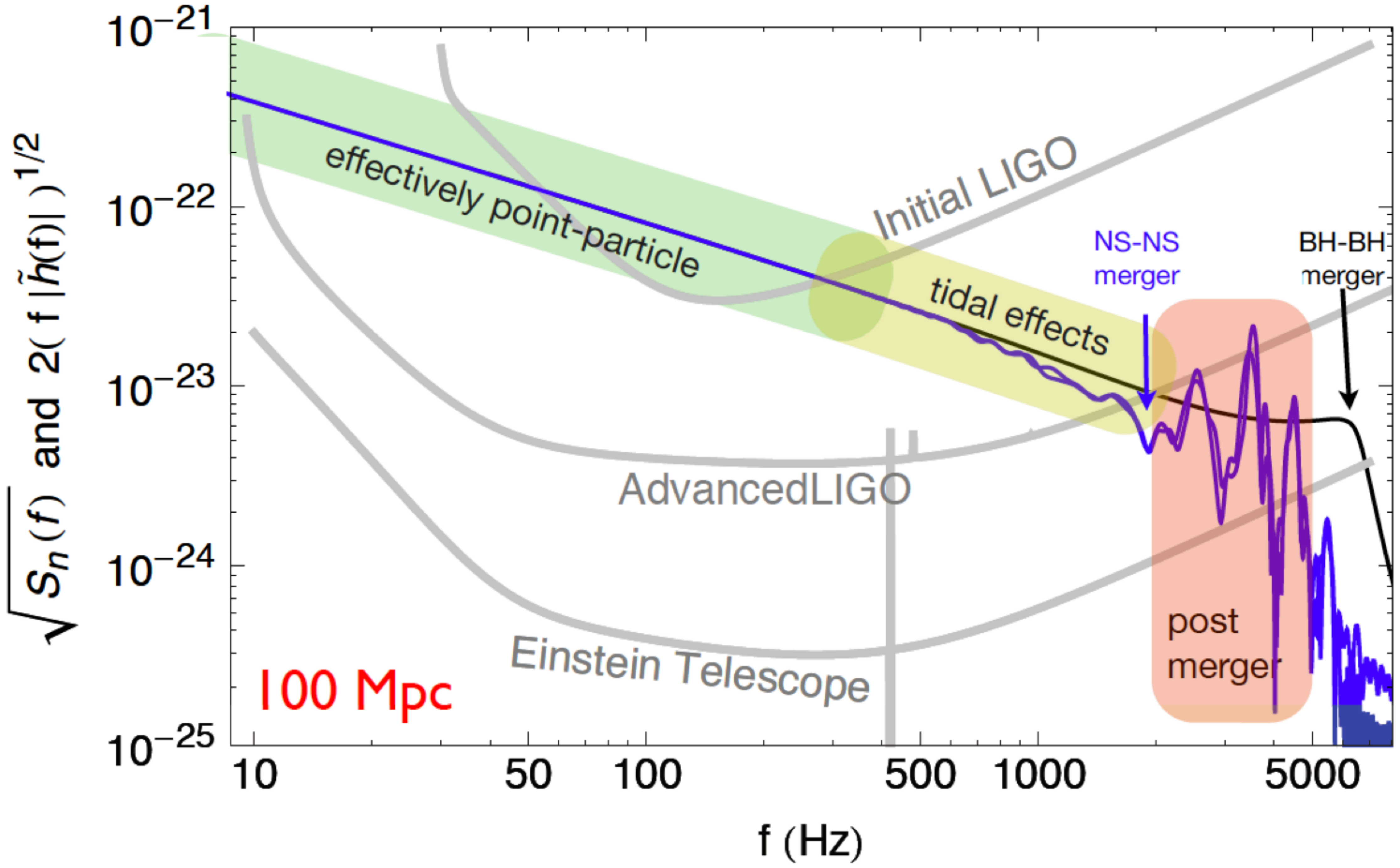
O(100) detections per year with sky localisation < 100 deg^2

A BRIEF GLIMPSE OF EINSTEIN TELESCOPE SCIENCE



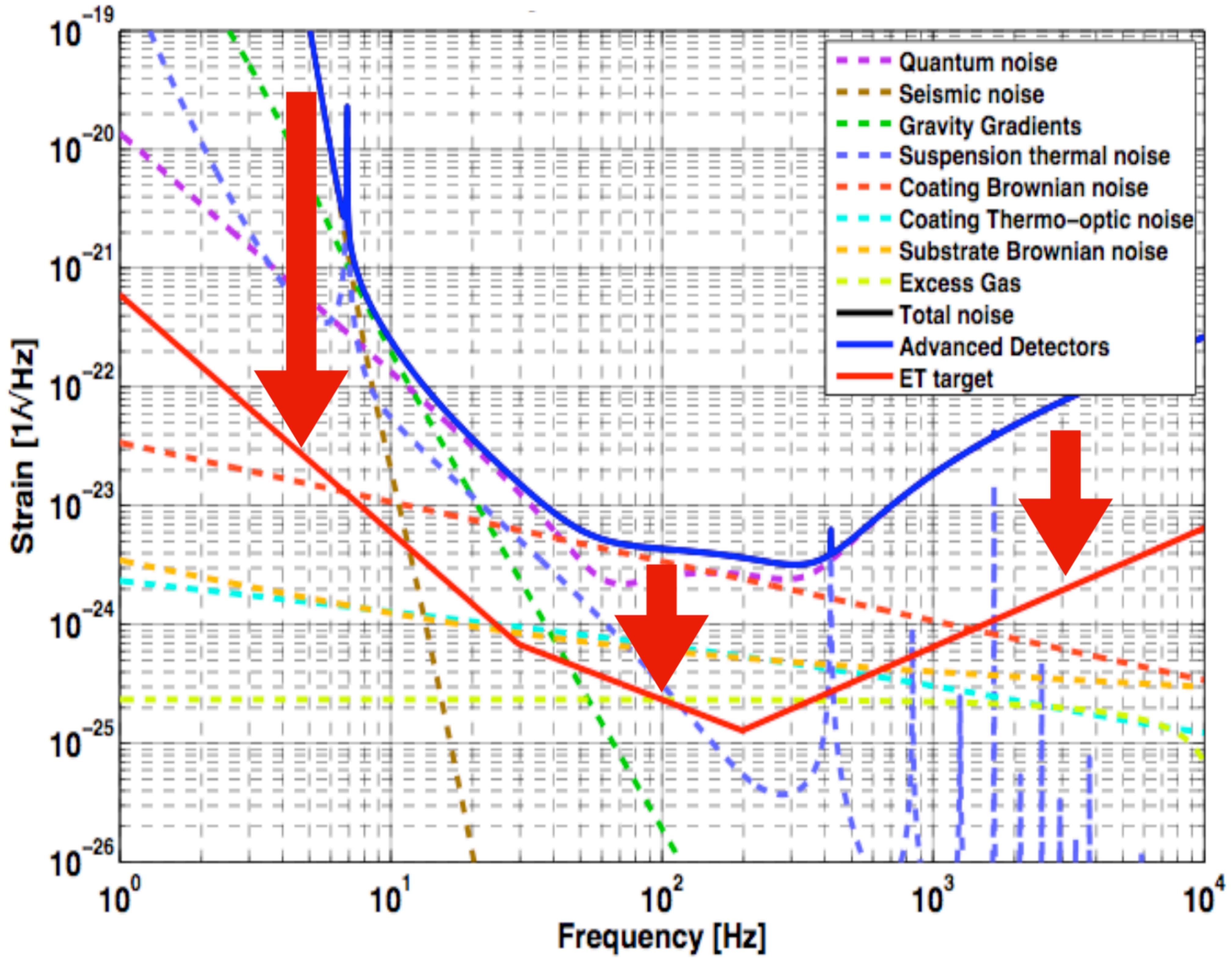
- Testing the BH ‘no-hair theorem’: consistency of quasi-normal mode frequencies & damping

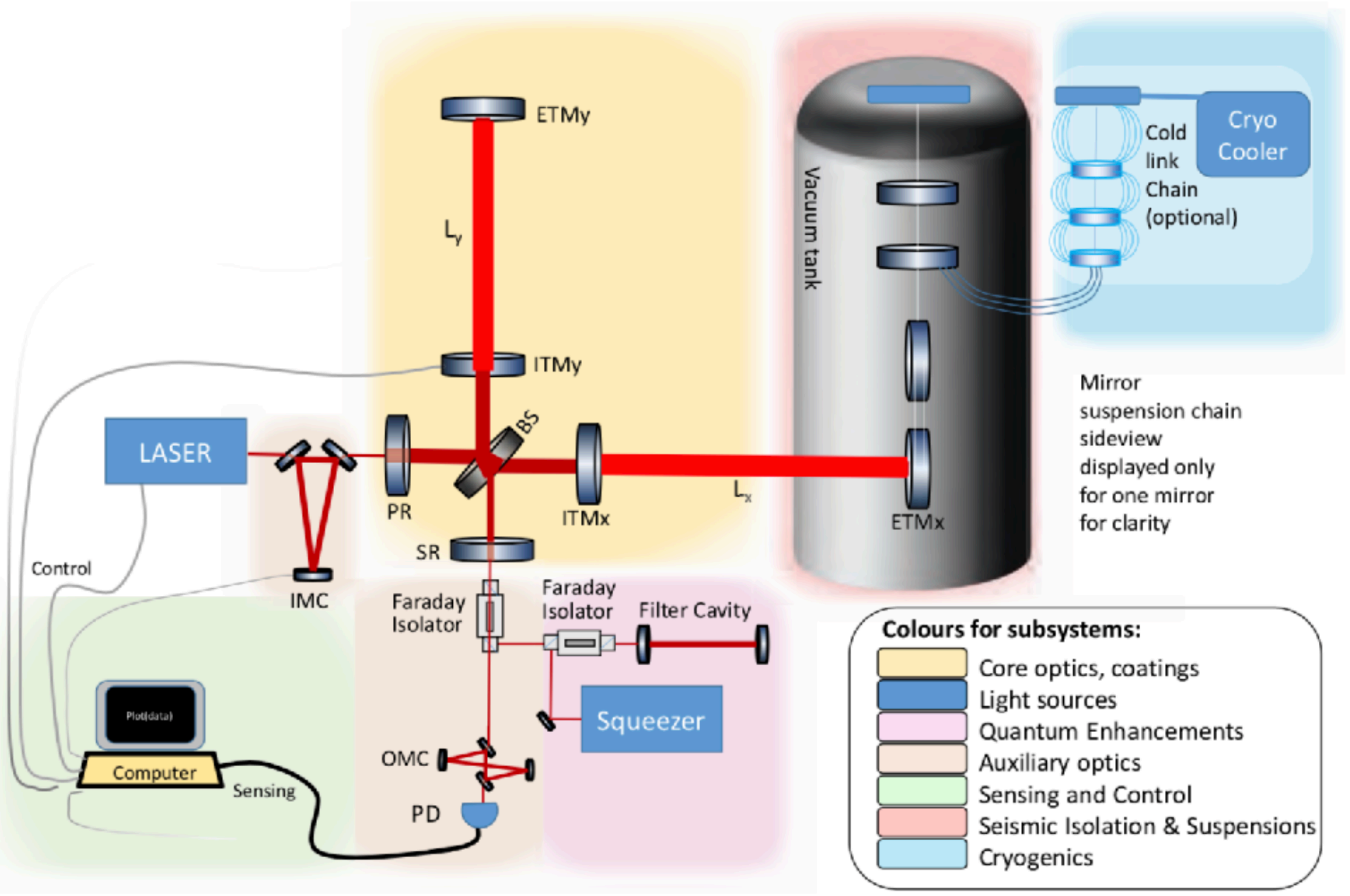
- Post-merger signals of binary neutron stars



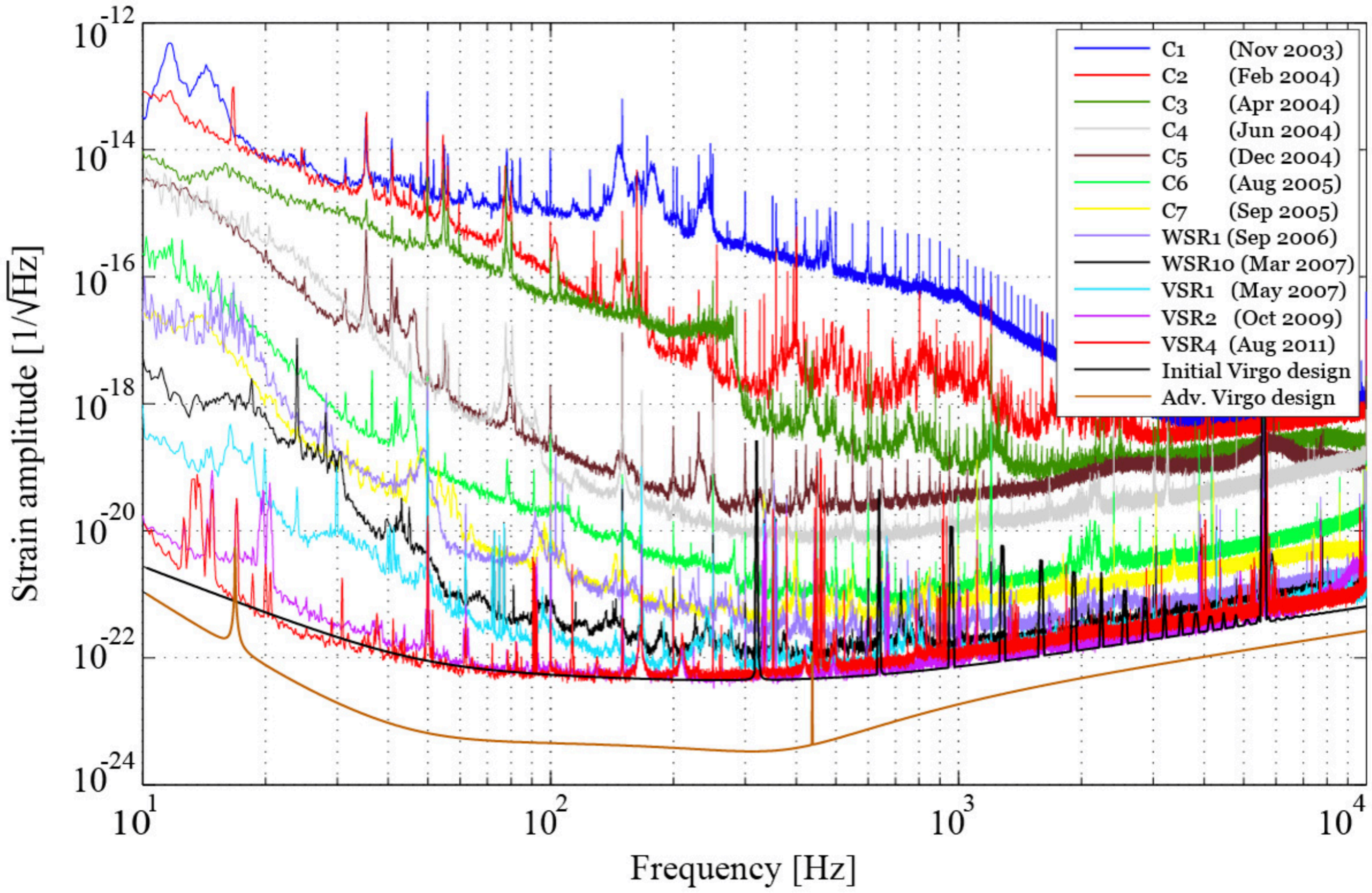
Maggiore et al. 2020: arXiv:1912.02622

SENSITIVITY IMPROVEMENT IS A SUBSTANTIAL CHALLENGE



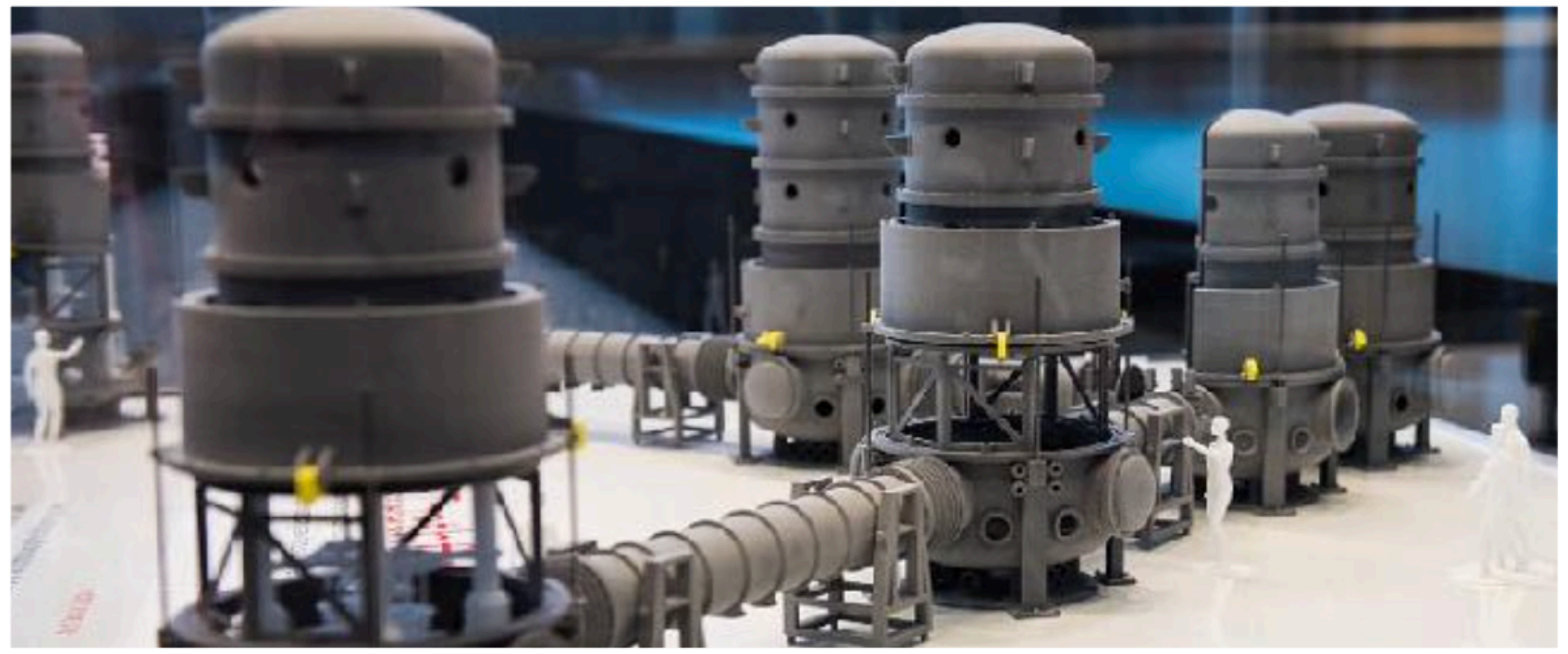


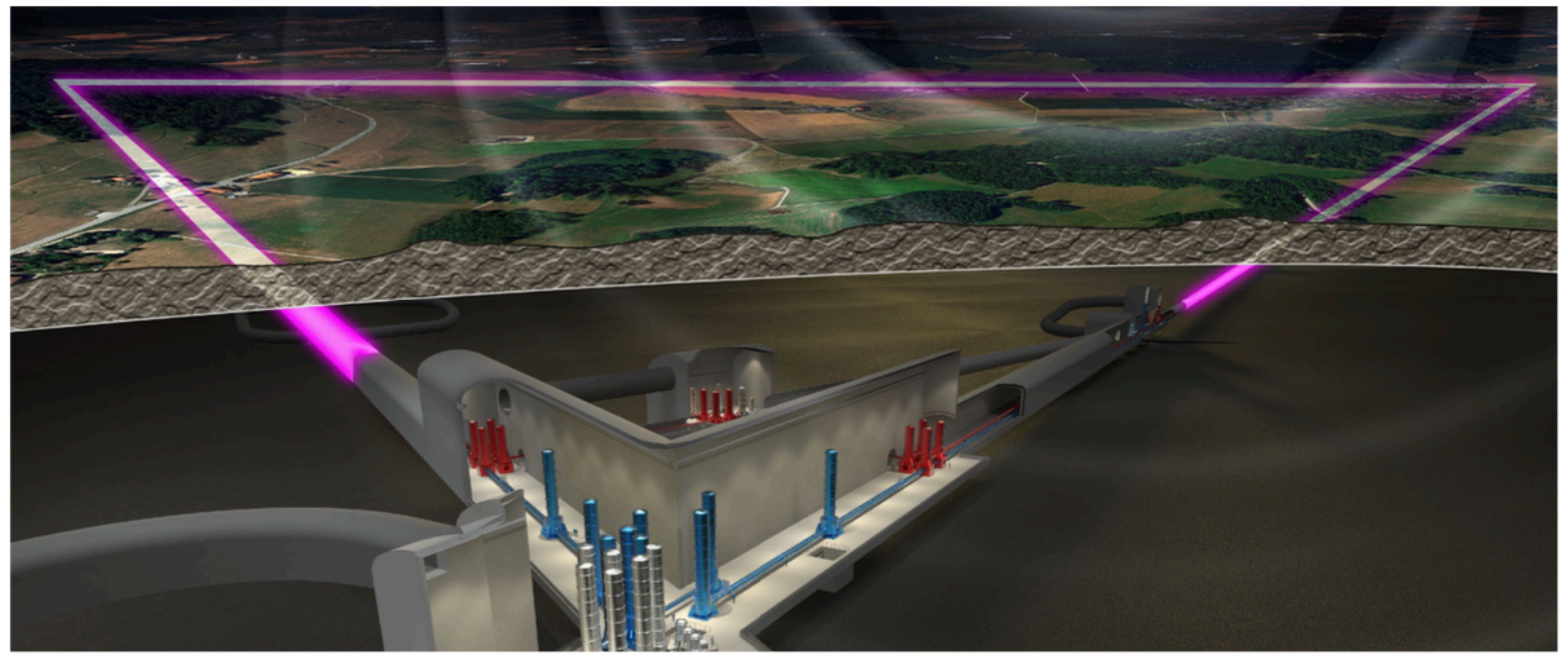
NEEDS ENTIRELY NEW INSTRUMENT DESIGNS!



- Updating detector technology piece by piece will not be enough!
- **Initial Virgo**: took **8 years** from first operations to (almost) design sensitivity!

SYNERGIES IN EUROPEAN INSTRUMENT DEVELOPMENT?





- Lessons learned from **Virgo**
- **ETpathfinder** (under construction in Maastricht):
  - 10m-scale prototype interferometer in Maastricht (NL), operations at different cryogenic temperatures (123K and 18K)
  - with regional industry partners
  - testbed for future GW technologies even beyond 3rd generation! (see: GEO600)
- **Einstein Telescope (ET)**:
  - currently at design and site selection stage
  - research and technology development
- Collaborations with technical teams at **CERN**? (e.g., ET vacuum pipe technical design for noise level $<10^{-25}$ Hz$^{-1/2}$)

ETpathfinder

Spring 2023

POSSIBLE EINSTEIN TELESCOPE SITES

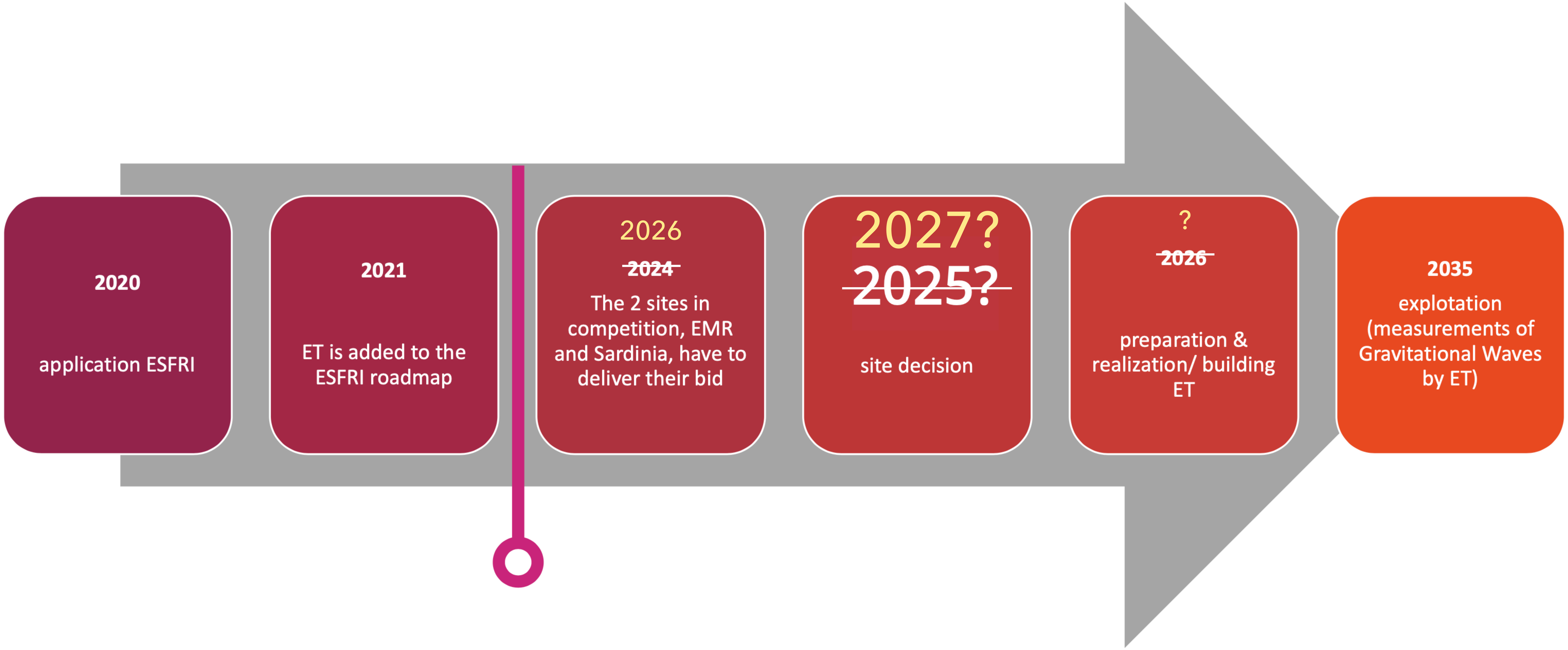
- Currently two ET candidate sites:
  - **Sardinia**: near Sos Enattos mine
  - **Euregio Meuse-Rhin (EMR)**: close to NL-B-D border
- Third option in **Saxony (Germany)**: under discussion (funding for site studies?)

EMR: GEOLOGY STUDIES

[Wim Walk, presentation at ET Symposium 2023]

EINSTEIN TELESCOPE TIMELINE

- Project will be carried out within framework of *European Strategy Forum for Research Infrastructures (ESFRI)*



2020
application ESFRI

2021
ET is added to the ESFRI roadmap

2026
~~2024~~
The 2 sites in competition, EMR and Sardinia, have to deliver their bid

2027?
~~2025?~~
site decision

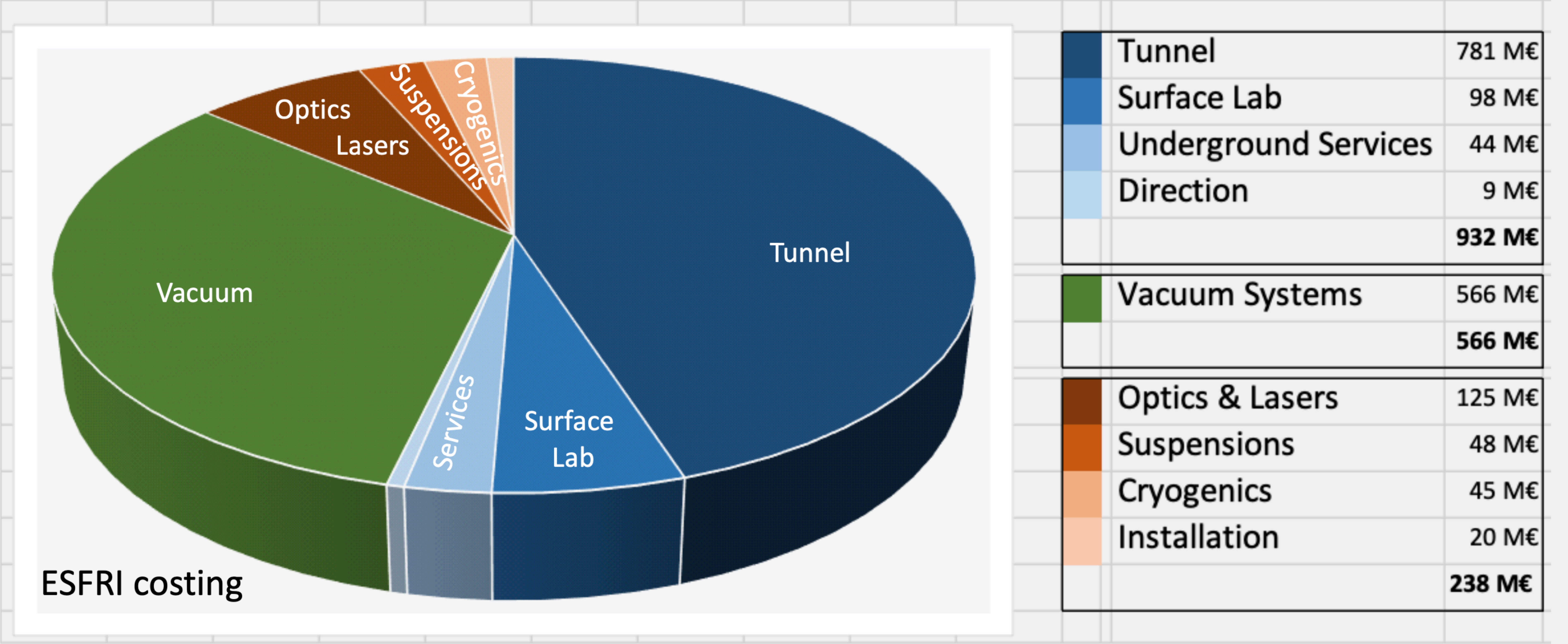
?
~~2026~~
preparation & realization/ building ET

2035
explotation (measurements of Gravitational Waves by ET)

- Schedule from ESFRI proposal. (Needs updating, based on detailed work plan / engineering studies.)

HOW MUCH WILL IT COST?

- Cost of underground infrastructure (for >50 years of operation):



🟦	Tunnel	781 M€
🟦	Surface Lab	98 M€
🟦	Underground Services	44 M€
🟦	Direction	9 M€
		932 M€
🟩	Vacuum Systems	566 M€
		566 M€
🟫	Optics & Lasers	125 M€
🟧	Suspensions	48 M€
🟧	Cryogenics	45 M€
🟧	Installation	20 M€
		238 M€

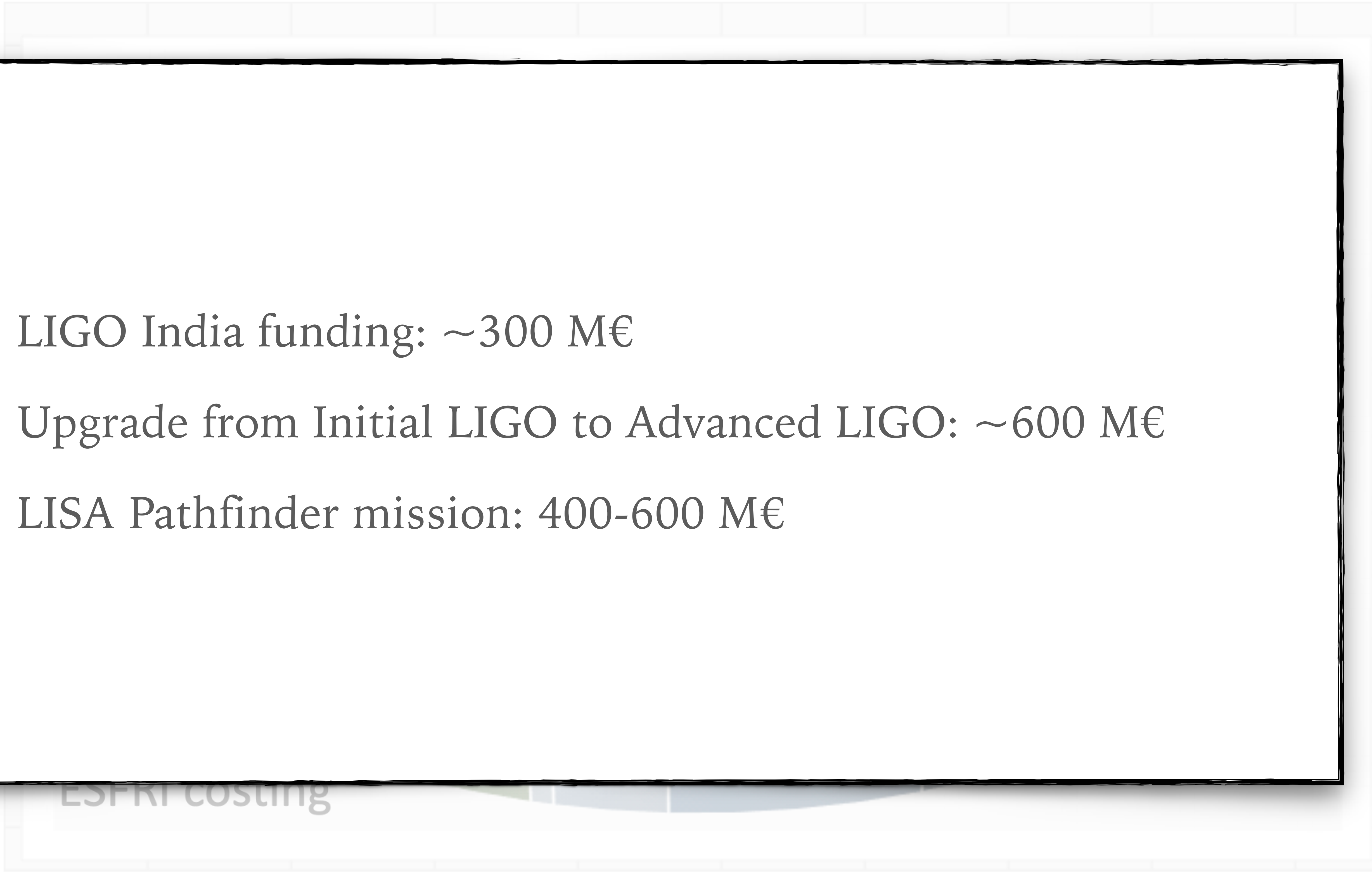
Plus design & development cost: ~200 M€

Total cost (excluding personnel!): **~1’900 M€**

- Based on conceptual designs only. (Costing following technical designs?)

HOW MUCH WILL IT COST?

- Cost of underground infrastructure (for >50 years of operation):



Tunnel	781 M€
Surface Lab	98 M€
Underground Services	44 M€
Direction	9 M€
	932 M€
Vacuum Systems	566 M€
	566 M€
Optics & Lasers	125 M€
Suspensions	48 M€
Cryogenics	45 M€
Installation	20 M€
	238 M€

LIGO India funding: ~300 M€

Upgrade from Initial LIGO to Advanced LIGO: ~600 M€

LISA Pathfinder mission: 400-600 M€

Plus design & development cost: ~200 M€

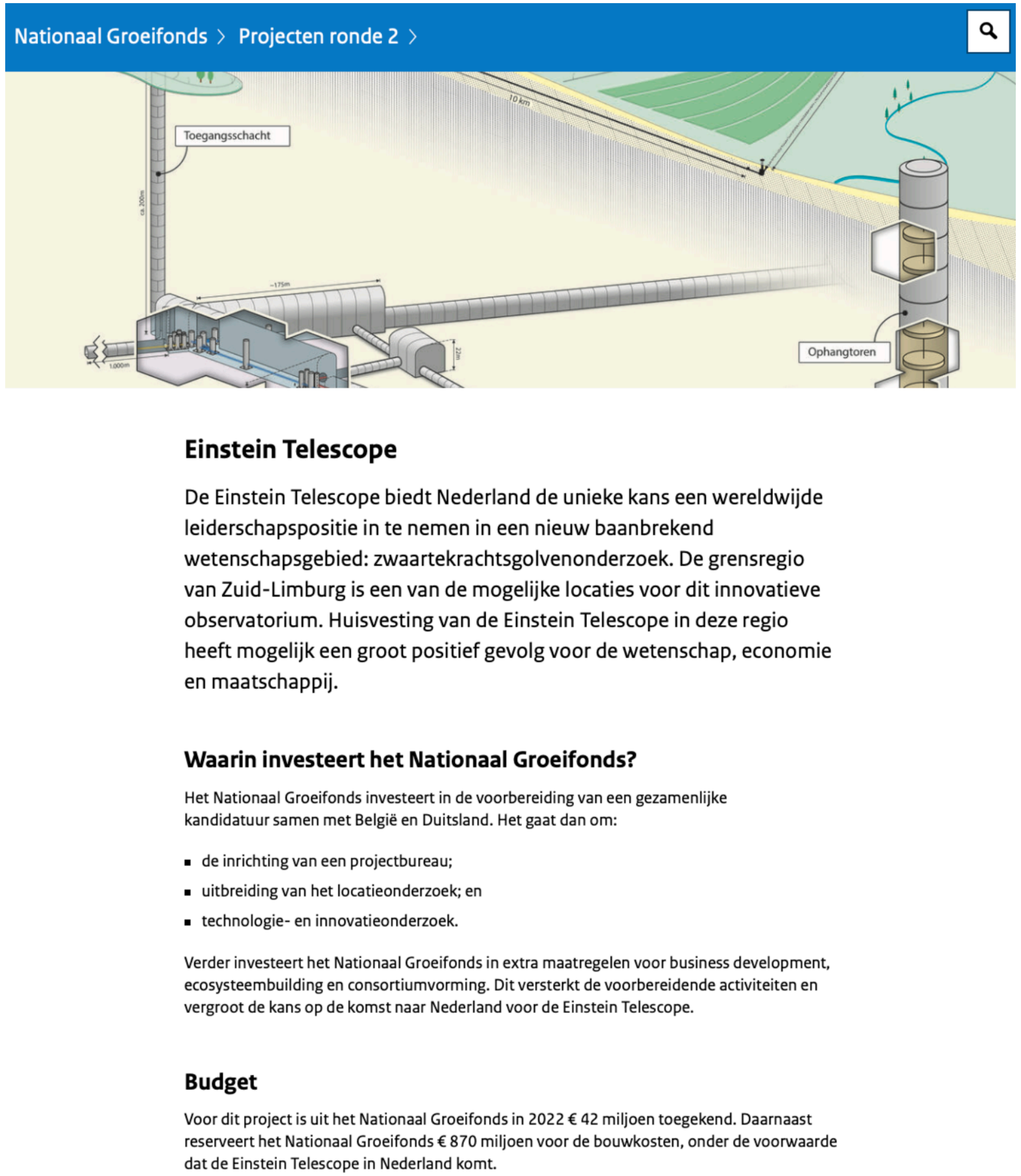
Total cost (excluding personnel!): **~1’900 M€**

- Based on conceptual designs only. (Costing following technical designs?)

DUTCH FUNDING FOR THE EINSTEIN TELESCOPE

- July 2022: Einstein Telescope awarded 42 M€ from Dutch National Growth fund
  - Connections to Dutch industry for research/innovation (19 M€)
  - Preparation towards underground infrastructure; project organisation/management (23 M€)
- Additional 870 M€ reserved for ET construction
  - Conditional! (Only if NL-B-D border region selected as location for ET)
- Separate ETpathfinder funding

- Similar commitments from Italian government



Einstein Telescope

De Einstein Telescope biedt Nederland de unieke kans een wereldwijde leiderschapspositie in te nemen in een nieuw baanbrekend wetenschapsgebied: zwaartekrachtsgolvenonderzoek. De grensregio van Zuid-Limburg is een van de mogelijke locaties voor dit innovatieve observatorium. Huisvesting van de Einstein Telescope in deze regio heeft mogelijk een groot positief gevolg voor de wetenschap, economie en maatschappij.

Waarin investeert het Nationaal Groeifonds?

Het Nationaal Groeifonds investeert in de voorbereiding van een gezamenlijke kandidatuur samen met België en Duitsland. Het gaat dan om:

- de inrichting van een projectbureau;
- uitbreiding van het locatieonderzoek; en
- technologie- en innovatieonderzoek.

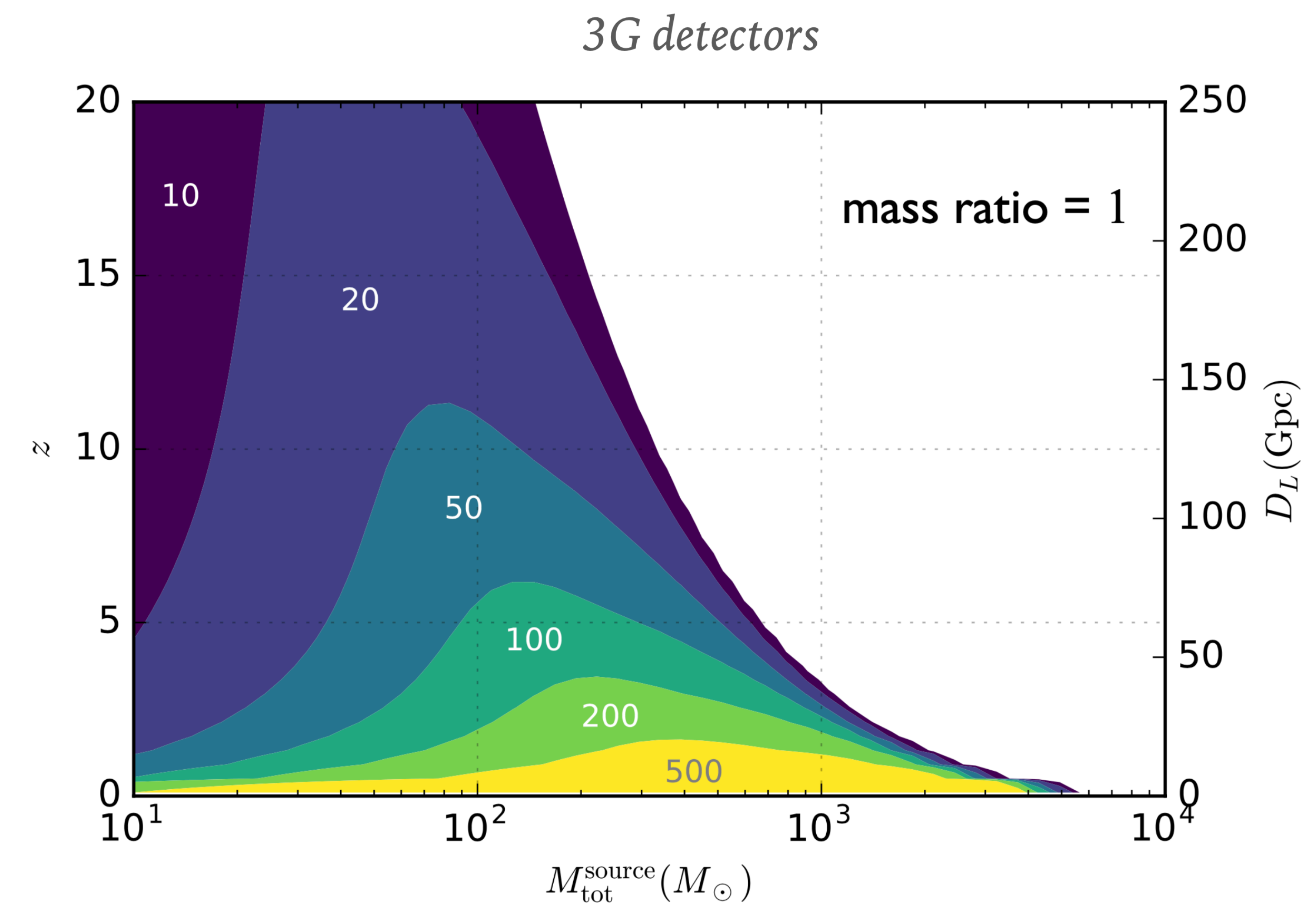
Verder investeert het Nationaal Groeifonds in extra maatregelen voor business development, ecosysteembuilding en consortiumvorming. Dit versterkt de voorbereidende activiteiten en vergroot de kans op de komst naar Nederland voor de Einstein Telescope.

Budget

Voor dit project is uit het Nationaal Groeifonds in 2022 € 42 miljoen toegekend. Daarnaast reserveert het Nationaal Groeifonds € 870 miljoen voor de bouwkosten, onder de voorwaarde dat de Einstein Telescope in Nederland komt.

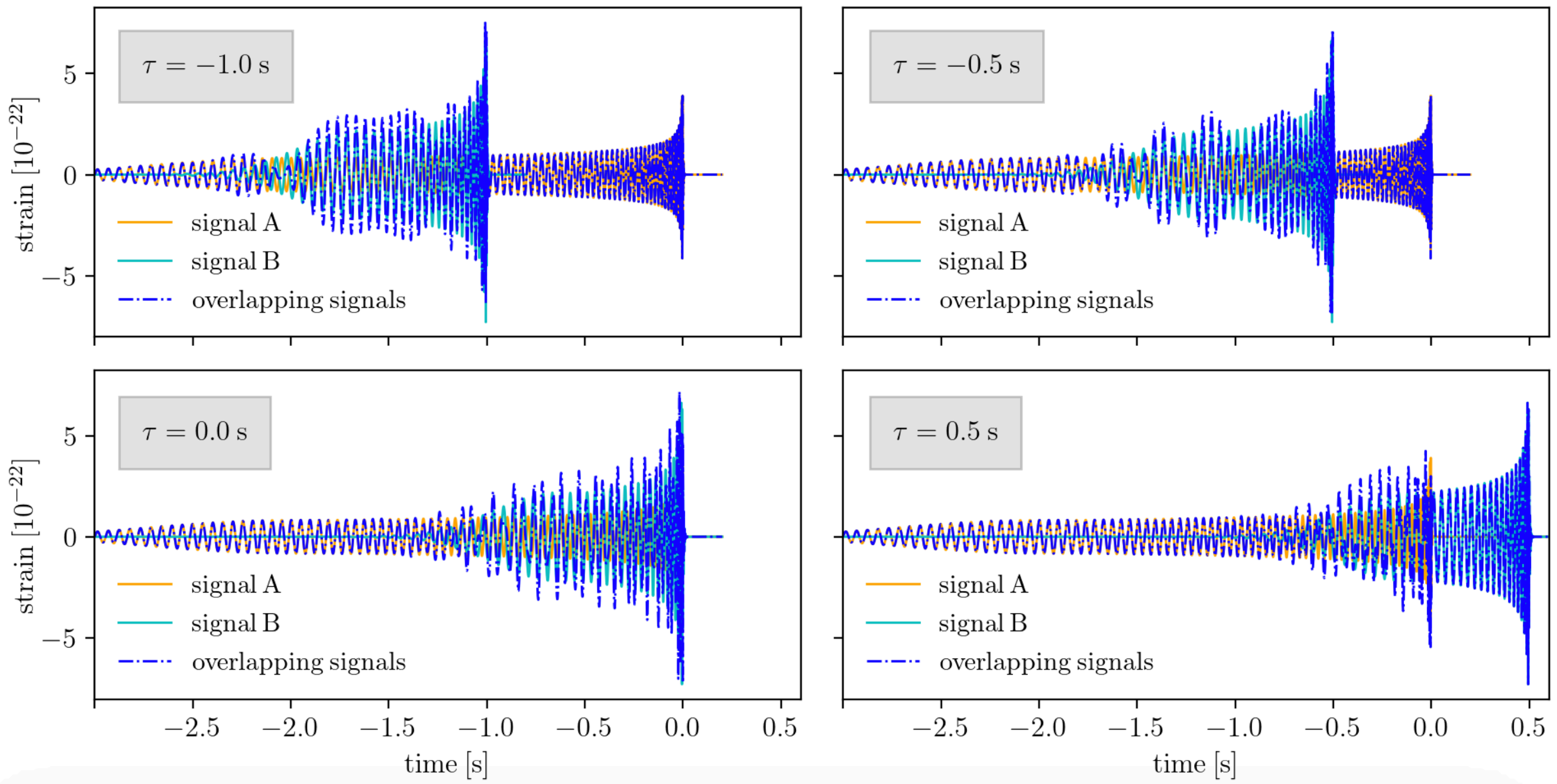
DATA ANALYSIS CHALLENGES IN THE EINSTEIN TELESCOPE ERA

- **long signals:**
  - for LIGO-Virgo: GW170817 only in-band for minutes, but data analysis took months!
  - same signal observed with ET: in-band for hours
- **loud signals:**
  - accuracy requirements AND computing requirements increase with signal-to-noise ratio
- **large number of signals:**
  - computational challenge
  - **overlapping signals** (e.g., NS-NS with at least one BH-BH) → need to be disentangled for precision science!
  - how to characterise **noise properties** if signals are always present in data? → triangular detector shape permits “null stream” (sum of detector outputs signal-free)



Kalogera+ (2021)

Pizzati+ (2022)

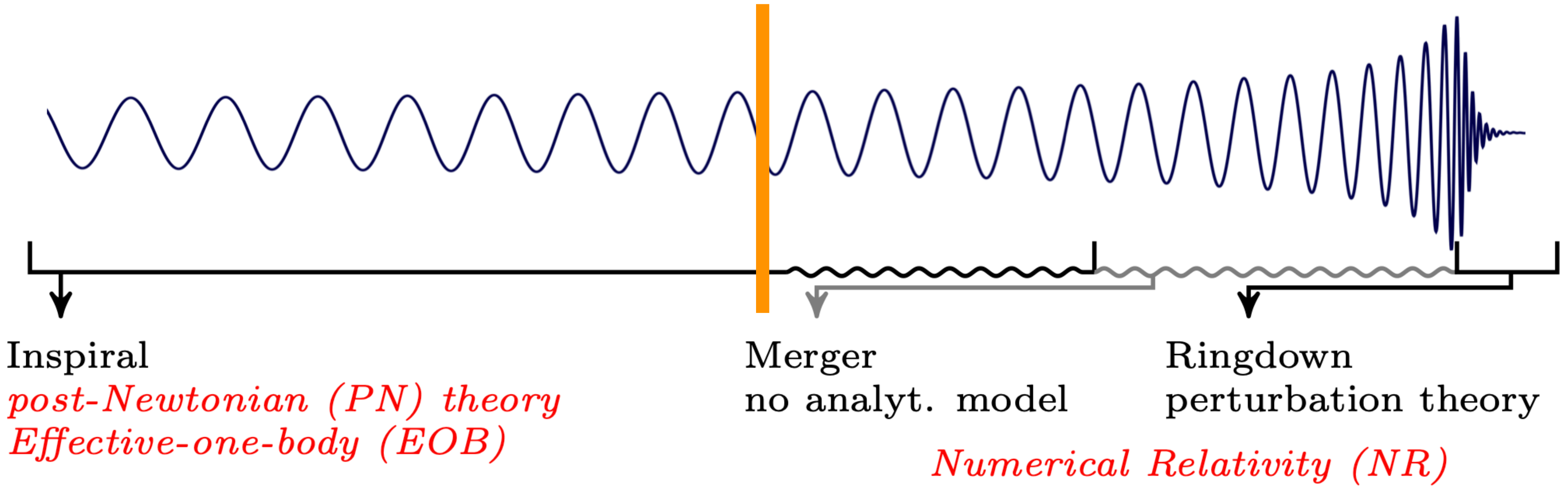


THANK YOU!

BACK-UP SLIDES

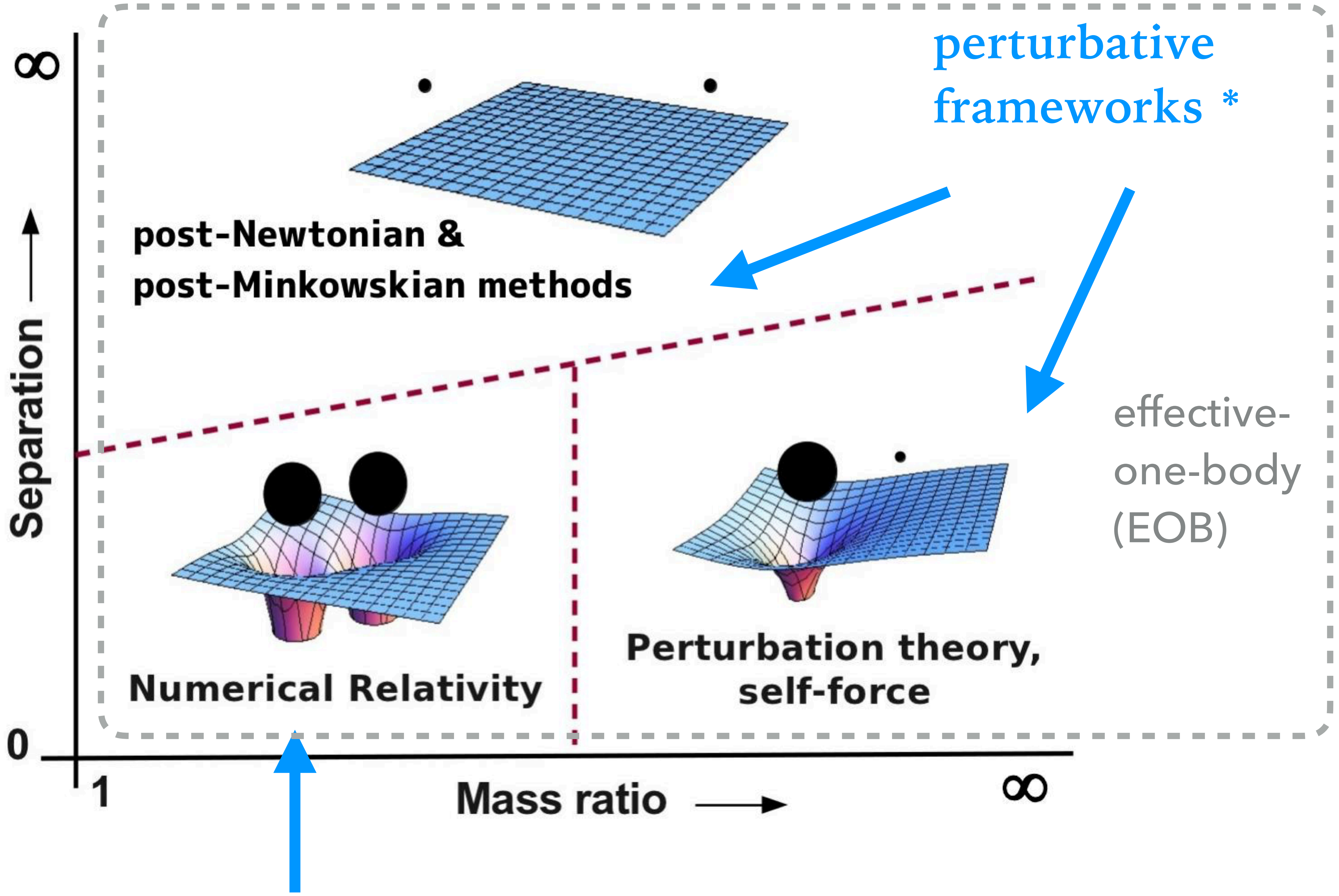
MODELING THE COMPLETE COALESCENCE

- **IMR waveforms:** “inspiral, merger & ringdown”
- **inspiral:** analytic solutions to the relativistic two-body problem
- **post-inspiral:** numerical simulations of coalescing black holes in full GR
- combination: **semi-analytic waveform models** as functions of both time and frequency
- effective-one-body (**EOB**) models, phenomenological (**Phenom**) models, **surrogate** models



weak field, slow motion

strong field, $v \to c$



perturbative frameworks *

effective-one-body (EOB)

exact framework *

(*) to solve Einstein’s field equations in GR

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

EFFECTIVE-ONE-BODY (EOB) MODELS

- 2-body problem mapped onto (Hamiltonian) **test particle motion in the effective exterior metric of a massive spinning central black hole**

  → deformation of components of black-hole spacetime metric, dependent on mass ratio ν

  $$\mathrm{d}s^2 = -A(r)\mathrm{d}t^2 + B(r)\mathrm{d}t^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2)\,, \quad A(r) = 1 - \frac{2Gm}{c^2r} + a_3(\nu)(\frac{Gm}{c^2r})^3 + \ldots$$

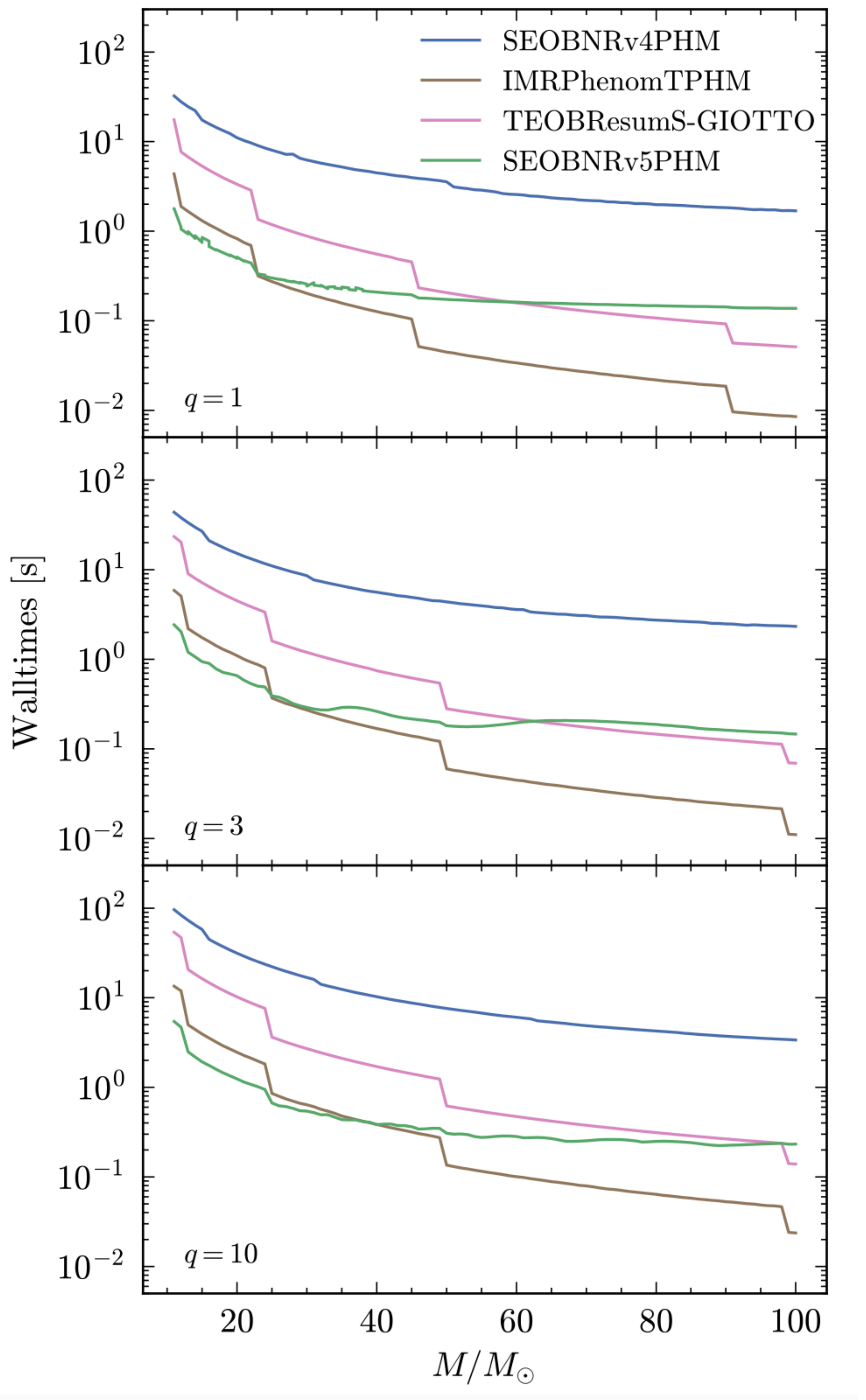
- solving Hamiltonian eqs. of motion: $\frac{\mathrm{d}r}{\mathrm{d}t} = \sqrt{\frac{A}{B}}\frac{\partial \mathscr{H}_{\mathrm{EOB}}}{\partial p_{r^*}}\,, \quad \frac{\mathrm{d}p_{r^*}}{\mathrm{d}t} = -\sqrt{\frac{A}{B}}\frac{\partial \mathscr{H}_{\mathrm{EOB}}}{\partial r}\,, \quad \frac{\mathrm{d}\varphi}{\mathrm{d}t} = \frac{\partial \mathscr{H}_{\mathrm{EOB}}}{\partial p_\varphi}\,, \quad \frac{\mathrm{d}p_\varphi}{\mathrm{d}t} = \mathscr{F}_\varphi^{\mathrm{GW}}$

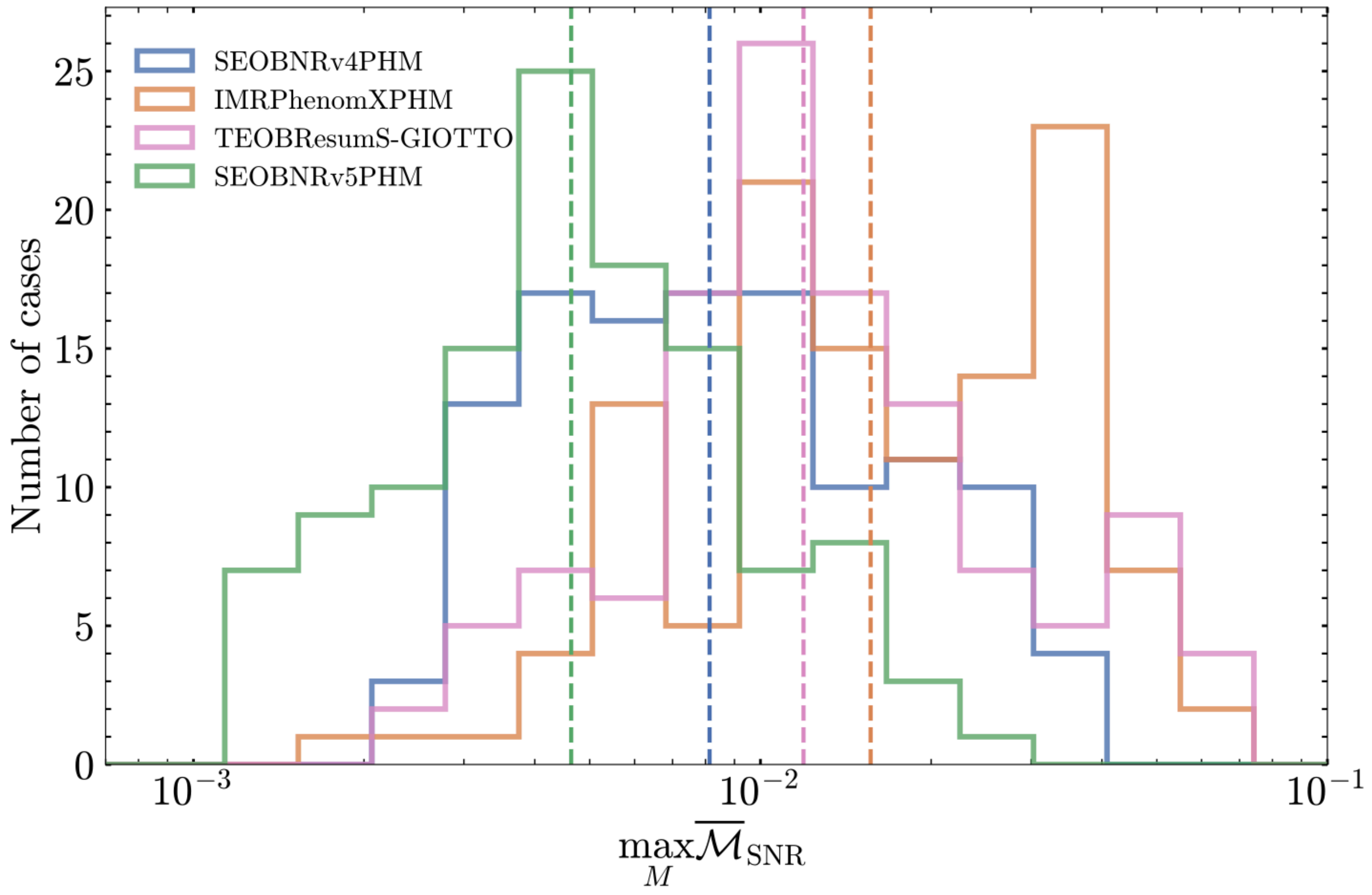
  with simple effective Hamiltonian $\mathscr{H}_{\mathrm{eff}} = \sqrt{p_{r^*}^2 + A(r)(1 + \frac{p_\varphi^2}{r^2} + z_3\frac{p_{r^*}^4}{r^2})}$

- mapping back to 2-body system in center-of-mass frame: $\mathscr{H}_{\mathrm{EOB}} = m\sqrt{1 + 2\nu(\mathscr{H}_{\mathrm{eff}} - 1)}$
- models **completed by post-Newtonian (PN) and NR information**: PN expansion and resummation of EOB radial potential $A(r)$ and multipoles / GW flux $\mathscr{F}_\varphi$; function fits (a_i, z_3) to NR improve merger
- time-domain waveforms: solutions of eqs. of motion **computationally expensive**
- **speed-up:** e.g., suitable prescription for spin-precession dynamics, approximate analytic Fourier transforms, reduced-order modeling

STATE-OF-THE-ART OF EOB MODELS

- two state-of-the-art waveform families: **SEOBNRv5*** (…, *Pompili+ (2023), Ramos-Buades+ (2023)*) and **TEOBResumS** (*Nagar+ (2018), Nagar+ (2019), Nagar+ (2020), Akcay+ (2020), …, Nagar+ (2023)*)
- differences: Hamiltonian descriptions, PN resummation choices, inclusion of spins, NR data sets (see, e.g., *Rettegno+ (2020)*)
- both waveform families: incorporate precession through solutions of PN-accurate spin evolution eqs., include higher-order multipoles of radiation

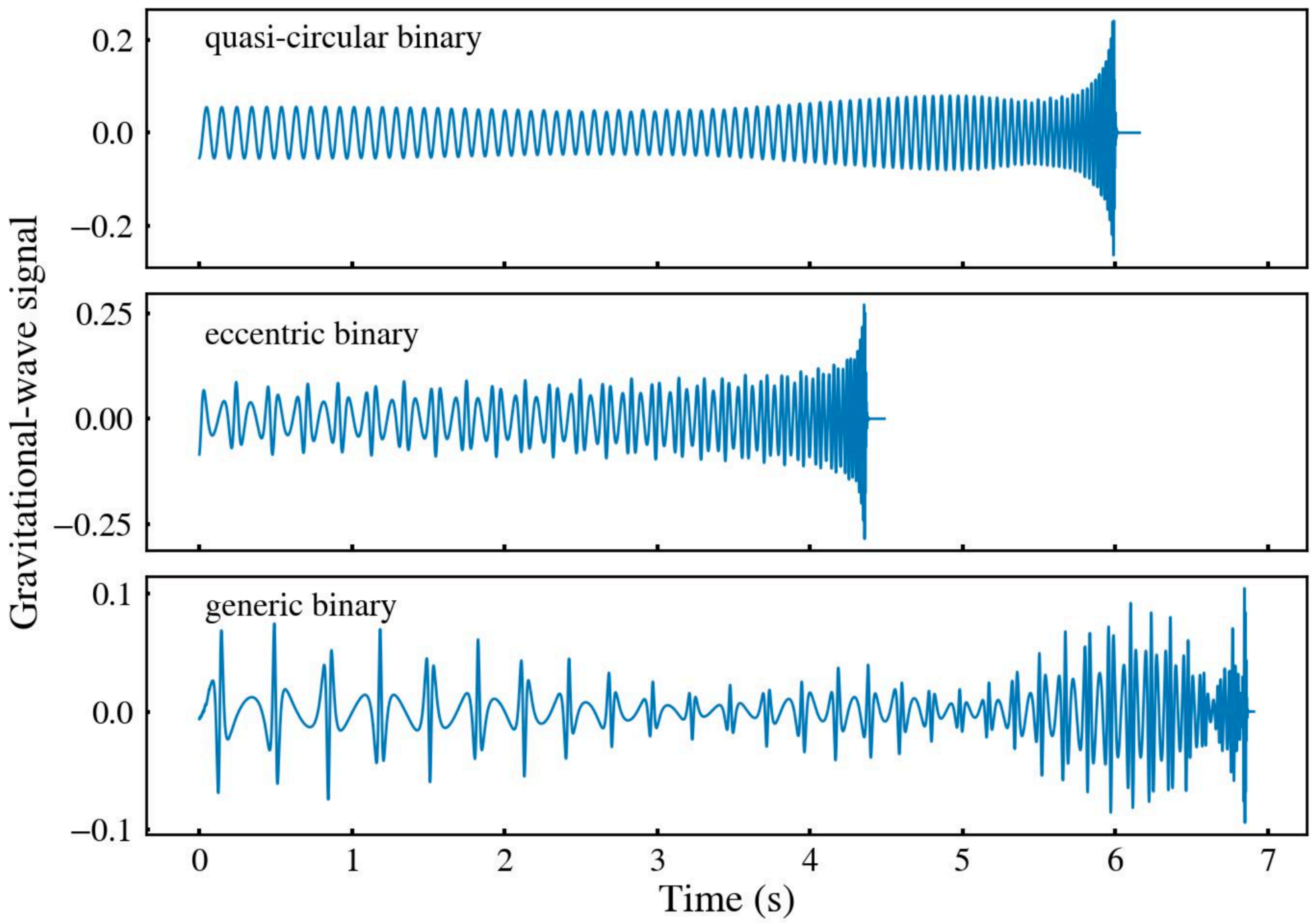




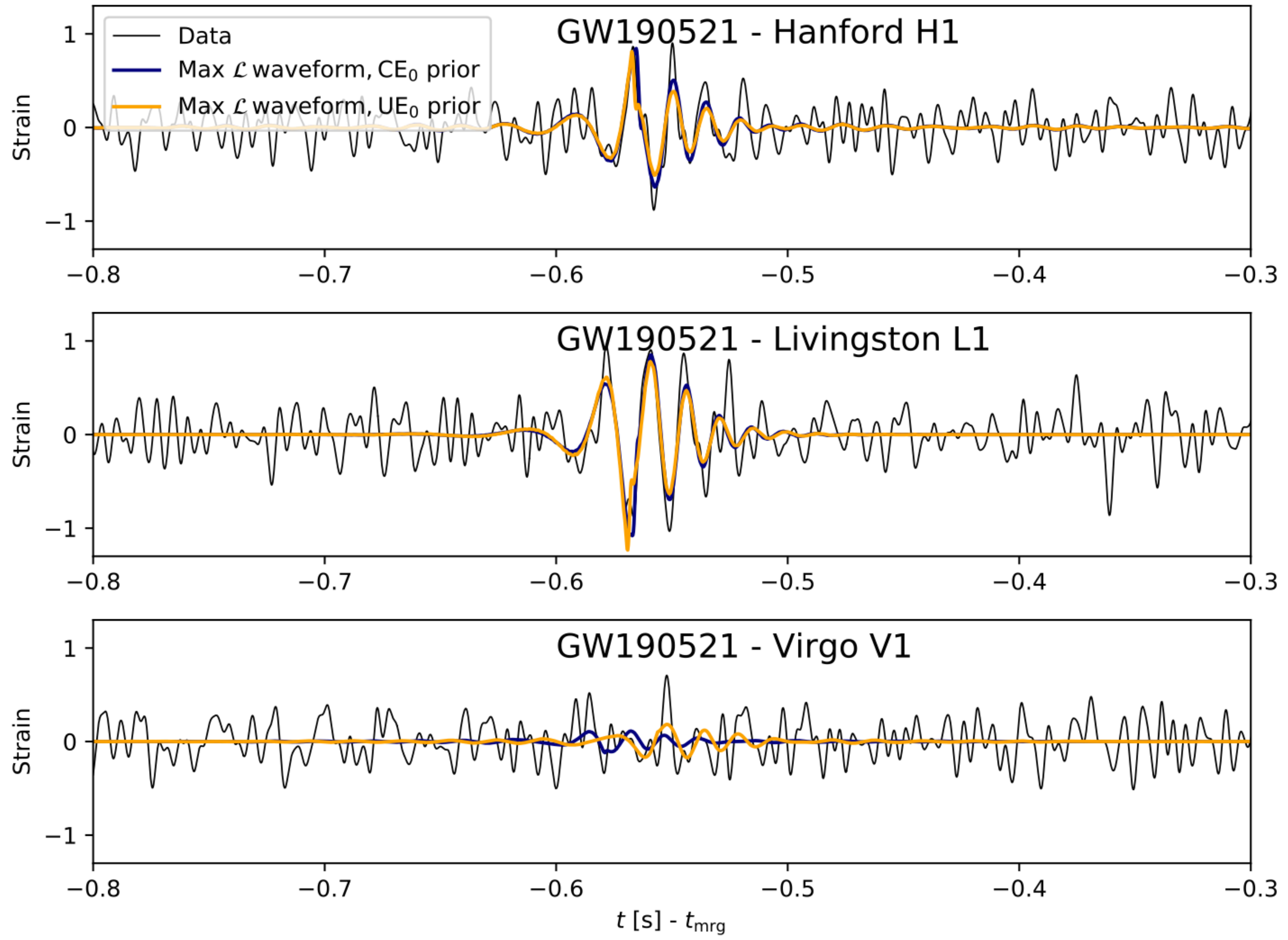
Ramos-Buades+ (2023)

EOB MODELS: STATUS AND CHALLENGES

- **BBH on generic orbits:** significant progress in modeling aligned-spin BBH on generic orbits **(highly eccentric, dynamical capture, hyperbolic scattering)**
  - for both EOB frameworks (e.g., most recently: *Chiaramello+ (2020)*, *Nagar+ (2020-2024)*, *Ramos-Buades+ (2021)*)
- parameter-space coverage for **BNS systems**: two EOB frameworks provide accurate analytic BNS waveforms
  - SEOBNRv4T and TEOBResumS → more complete description of tidal effects compared to IMRPhenom models
- parameter-space coverage for **NSBH systems**: SEOBNR waveforms in frequency-domain (*Matas+ (2020)*), TEOBResumS (*Gonzalez+ (2022)*) in time-domain
  - differences in included tidal effects; different approaches to analytically model the tidal disruption-plunge of the NS, different NR calibration



Ramos-Buades+ (2023)



Gamba+ (2022)

PHENOMENOLOGICAL (IMRPHENOM) WAVEFORM MODELS

- **phenomenological** inspiral-merger-ringdown models (**PN ansatz at low frequencies, NR fits in strong-field regime** during late inspiral and merger, NR predictions for remnant)
  → **waveform modeling in frequency domain** through *Stationary Phase Approximation* (analytic approximate of Fourier transform of $h(t)$)

- phenomenological Ansatz for the GW phase:

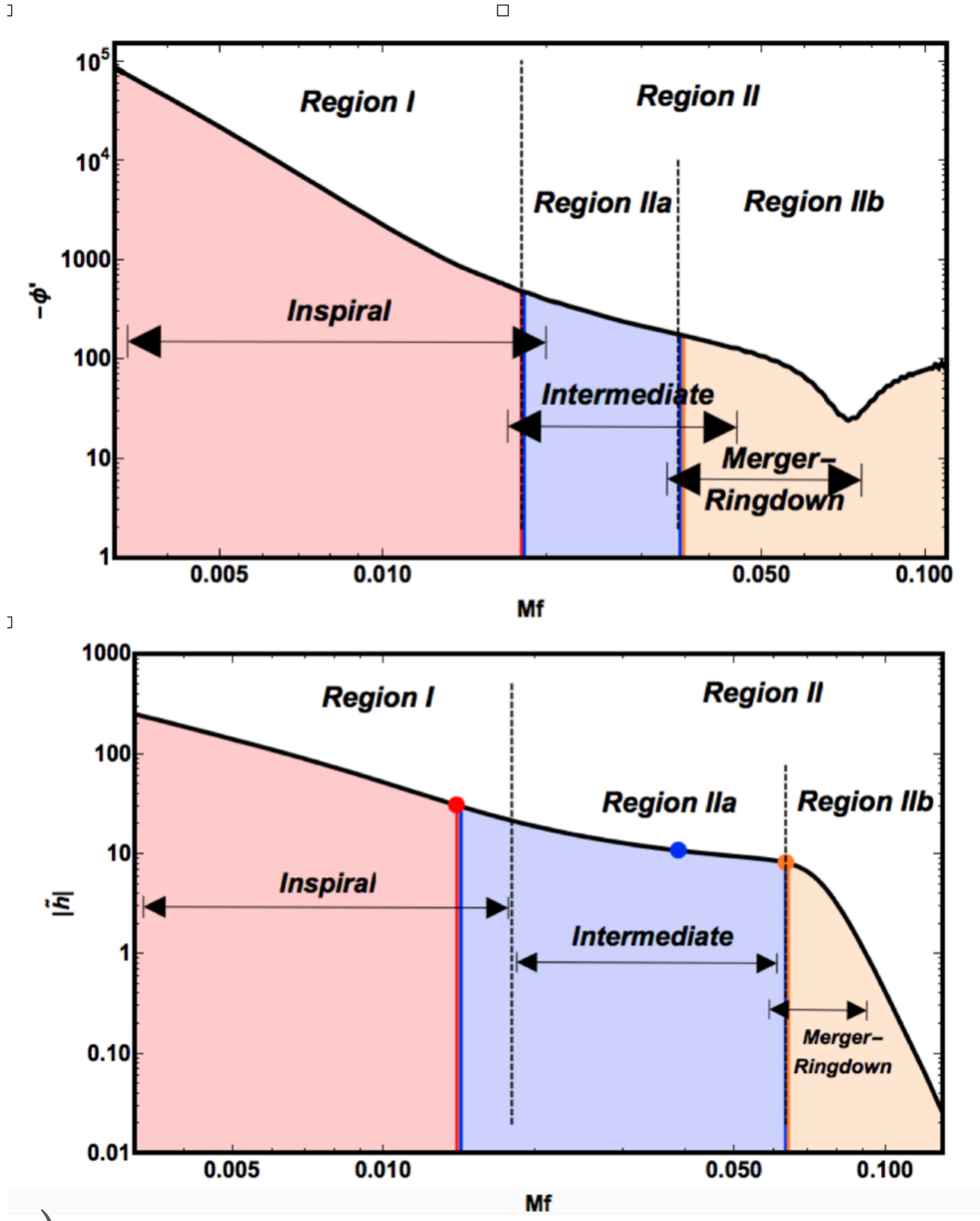
$\varphi(\Xi)$: PN coefficients
(in terms of η, spins)

early inspiral
$$\phi_{PN}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\,\eta}\left(\pi f M\right)^{-5/3}\sum_{i=0}^{7}\varphi(\Xi)\left(\pi f M\right)^{i/3}$$

beyond
$$\phi_{Ins} = \phi_{PN}(Mf;\,\Xi) + \frac{1}{\eta}\left(\sigma_0 + \sigma_1 f + \frac{3}{4}\sigma_2 f^{4/3} + \frac{3}{5}\sigma_3 f^{5/3} + \frac{1}{2}\sigma_4 f^2\right)$$

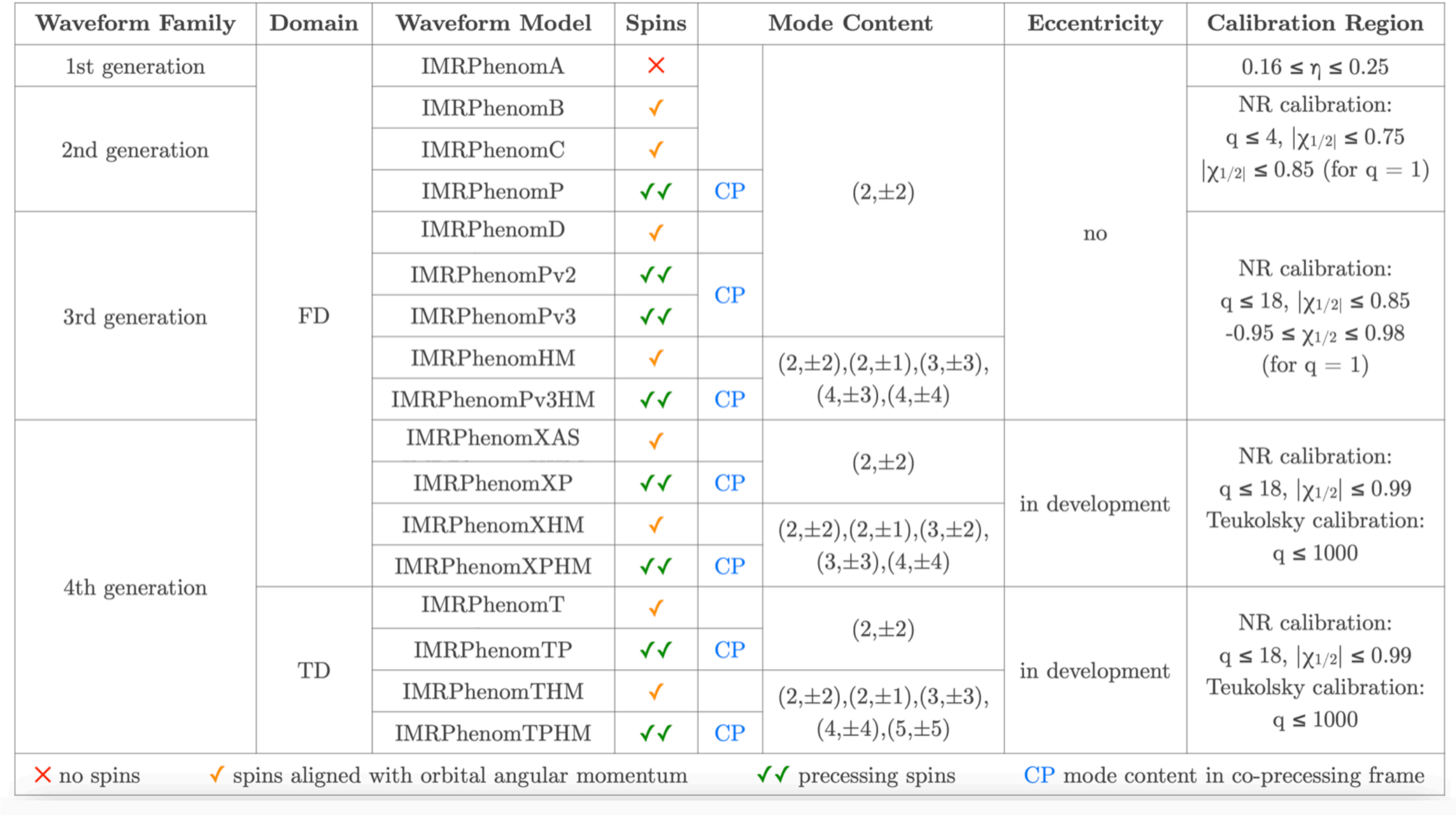
NR-calibrated pseudo-PN terms (coefficients σ_i in terms of η, spins)

M: total mass,
$\eta = m_1 m_2/M^2$: symmetric mass ratio



Khan+ (2016)

STATUS OF PHENOMENOLOGICAL MODELS



Waveform Family	Domain	Waveform Model	Spins	Mode Content		Eccentricity	Calibration Region
1st generation	FD	IMRPhenomA	✗		(2,±2)	no	$0.16 \le \eta \le 0.25$
2nd generation		IMRPhenomB	✓				NR calibration: $q \le 4$, $\lvert\chi_{1/2}\rvert \le 0.75$ $\lvert\chi_{1/2}\rvert \le 0.85$ (for $q = 1$)
		IMRPhenomC	✓				
		IMRPhenomP	✓✓	CP			
3rd generation		IMRPhenomD	✓				NR calibration: $q \le 18$, $\lvert\chi_{1/2}\rvert \le 0.85$ $-0.95 \le \chi_{1/2} \le 0.98$ (for $q = 1$)
		IMRPhenomPv2	✓✓	CP			
		IMRPhenomPv3	✓✓				
		IMRPhenomHM	✓		(2,±2),(2,±1),(3,±3), (4,±3),(4,±4)		
		IMRPhenomPv3HM	✓✓	CP			
4th generation		IMRPhenomXAS	✓		(2,±2)	in development	NR calibration: $q \le 18$, $\lvert\chi_{1/2}\rvert \le 0.99$ Teukolsky calibration: $q \le 1000$
		IMRPhenomXP	✓✓	CP			
		IMRPhenomXHM	✓		(2,±2),(2,±1),(3,±2), (3,±3),(4,±4)		
		IMRPhenomXPHM	✓✓	CP			
	TD	IMRPhenomT	✓		(2,±2)	in development	NR calibration: $q \le 18$, $\lvert\chi_{1/2}\rvert \le 0.99$ Teukolsky calibration: $q \le 1000$
		IMRPhenomTP	✓✓	CP			
		IMRPhenomTHM	✓		(2,±2),(2,±1),(3,±3), (4,±4),(5,±5)		
		IMRPhenomTPHM	✓✓	CP			

✗ no spins ✓ spins aligned with orbital angular momentum ✓✓ precessing spins CP mode content in co-precessing frame

Ajith+ (2007, 2008), Santamaria+ (2010)

Husa+ (2016), Khan+ 2016, Schmidt+ (2012), Hannam+ (2014), London+ (2017), Khan+ (2019, 2020)

Pratten+ (2020, 2021), Garcia-Quiros+ (2020)

Estelles+ (2021, 2022)

CURRENT STATE-OF-THE-ART OF PHENOMENOLOGICAL MODELS

- **IMRPhenomX*:** current state-of-the-art of phenomenological waveform modeling in frequency domain
  → tuned to 652 NR simulations including test particle limit waveforms
  → dominant (2,2), and subdominant harmonics of the radiation (provided in co-precessing frame)
  → "twisting up" to inertial frame (spins with arbitrary orientations): two-spin or single-spin Post-Newtonian description for Euler angles describing the spin precession dynamics
  → significant improvement over previous generations of Phenom waveforms in accuracy & computational efficiency

- provides **work-horse waveform models for GW transient catalogs since O3b**

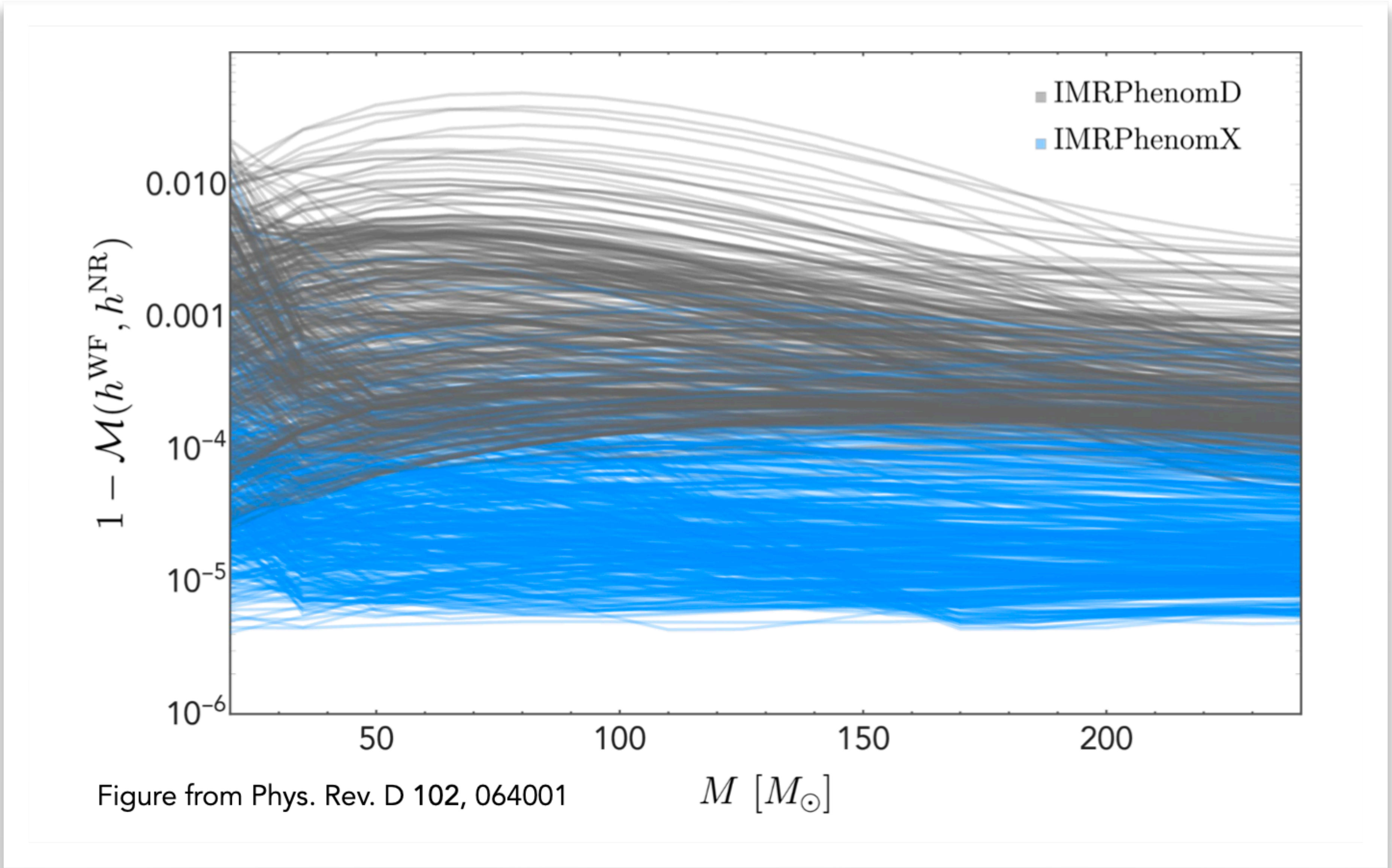
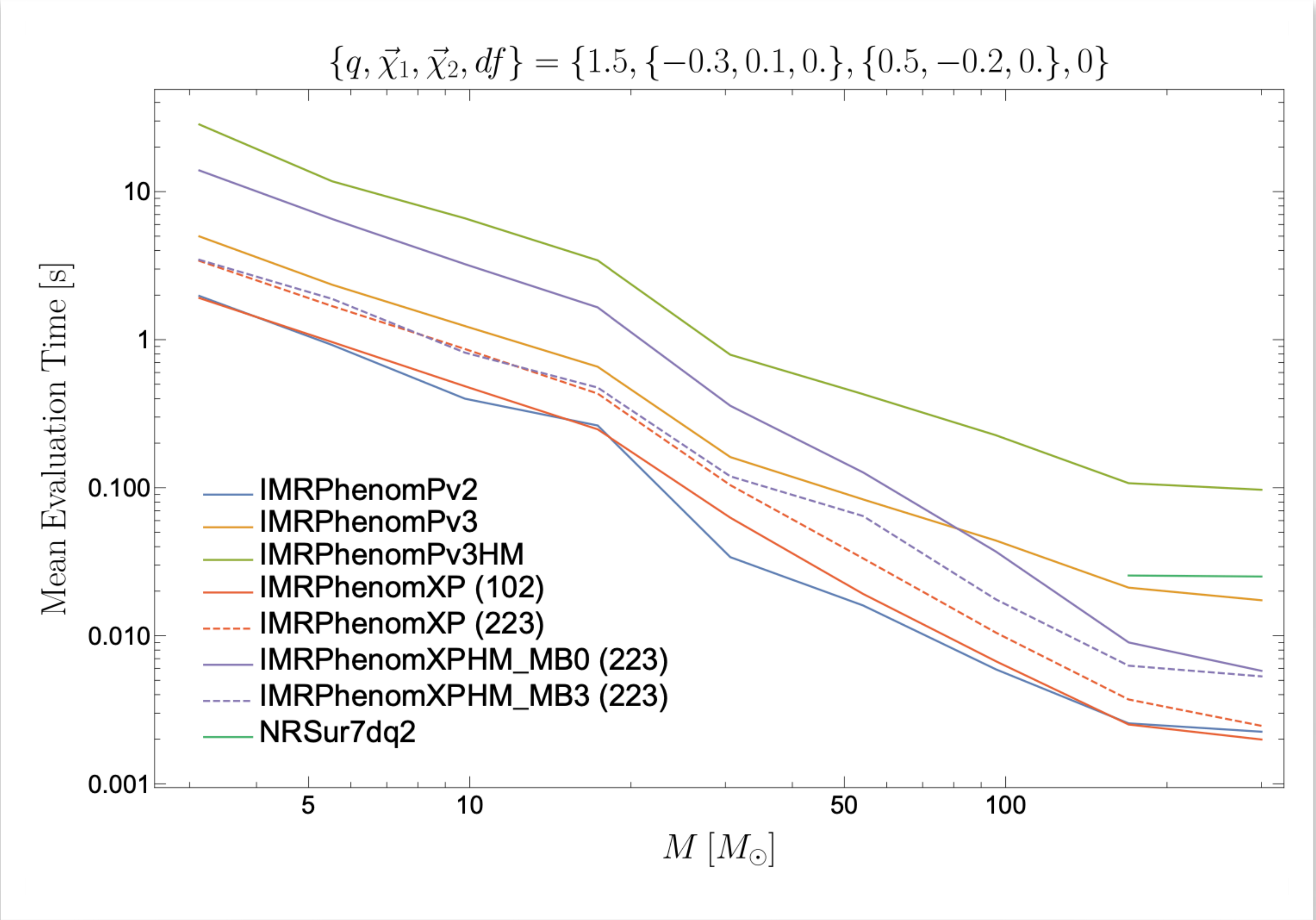


Figure from Phys. Rev. D 102, 064001



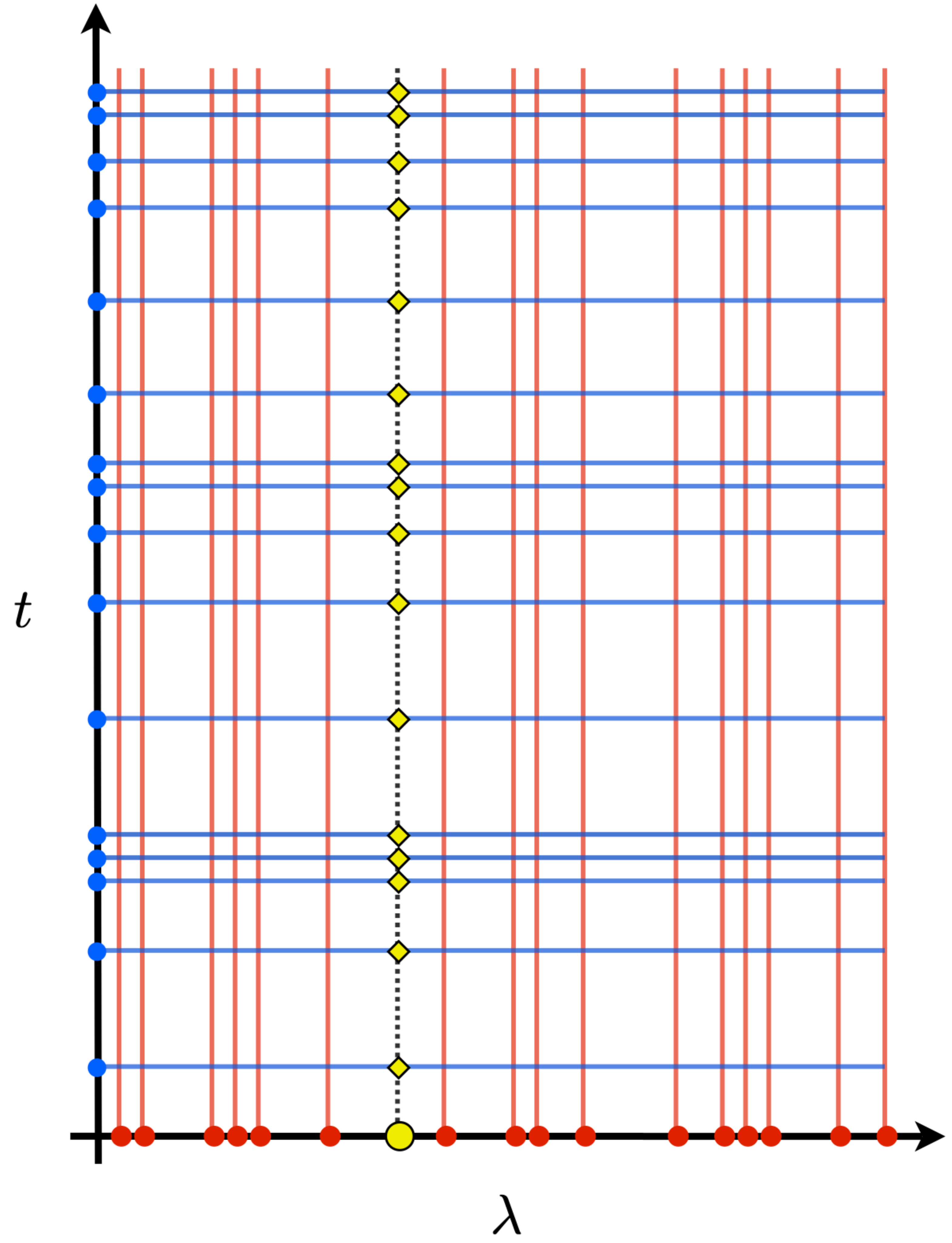
Pratten+ (2021)

IMRPHENOM: STATUS AND CHALLENGES

- extensions to **BNS systems**: NRTidal (*Tichy+ (2017), Dietrich+ (2019), Abac+ (2024)*) → tidal contributions in GW phase and amplitude of (2,2)-mode through phenomenological fits to NR (CoRe, SACRA) BNS simulations (inspiral-to-merger)
- extensions to **NSBH systems**: *Thompson+ (2020)* → NRTidalv2 ansatz + NSBH tidal disruption-plunge calibrated to NR
- in development:
  - **improved BBH precession in inspiral**: Euler angles through numerical evolution of orbital-averaged, PN-expanded spin-precession eqs. (→ default waveform model in **source parameter estimation during O4**)
  - **improved BBH precession in merger and ringdown**: calibration of precession angles against single-spin precessing NR simulations (Hamilton+ (2021), Thompson+ (2024))
  - **extensions to generic orbits**: incorporate analytic Fourier-domain eccentric inspiral waveforms into IMRPhenomX* ansatz
  - but: SPA necessitates small-eccentricity expansion

SURROGATE MODELS

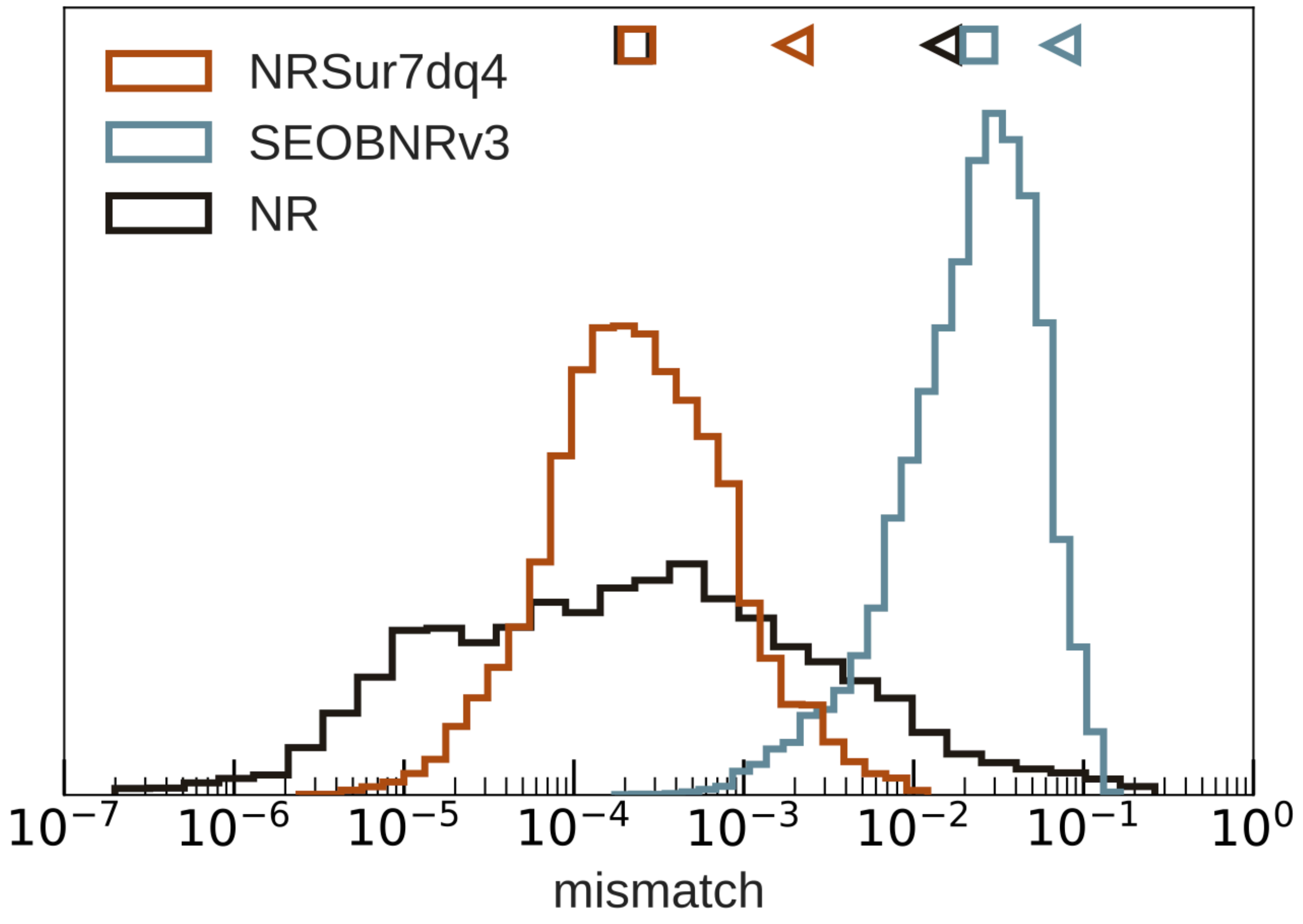
- **reduced-order modeling**, trained on fiducial waveform data sets (*Field+ (2014)*)
- surrogates for: **NR simulations**, PN/EOB-NR hybrids, remnant properties
- also: computationally efficient surrogates of semi-analytical models (e.g., SEOBNRv4PHM, *Gadre+ (2022)*)
  - construct **reduced basis** that spans parameter space $\vec{\lambda}$ of waveforms training set
  - **empirical interpolation** in time using basis waveforms
  - **fits for parameter-dependent waveform quantities** at each empirical time
  - **evaluation for arbitrary values** of $\vec{\lambda}$ at all times



Field+ (2014)

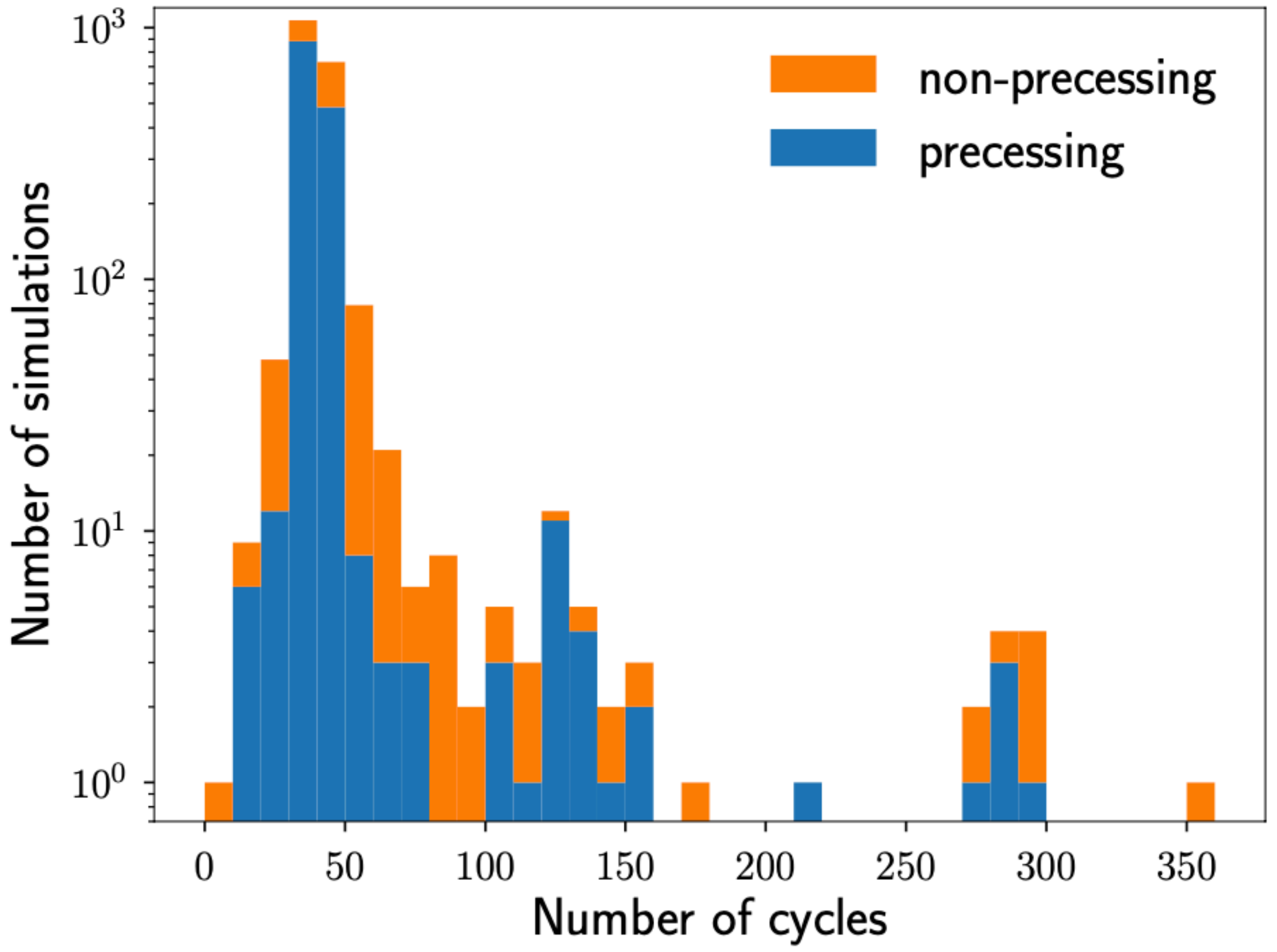
SURROGATE MODELS: STATUS AND CHALLENGES

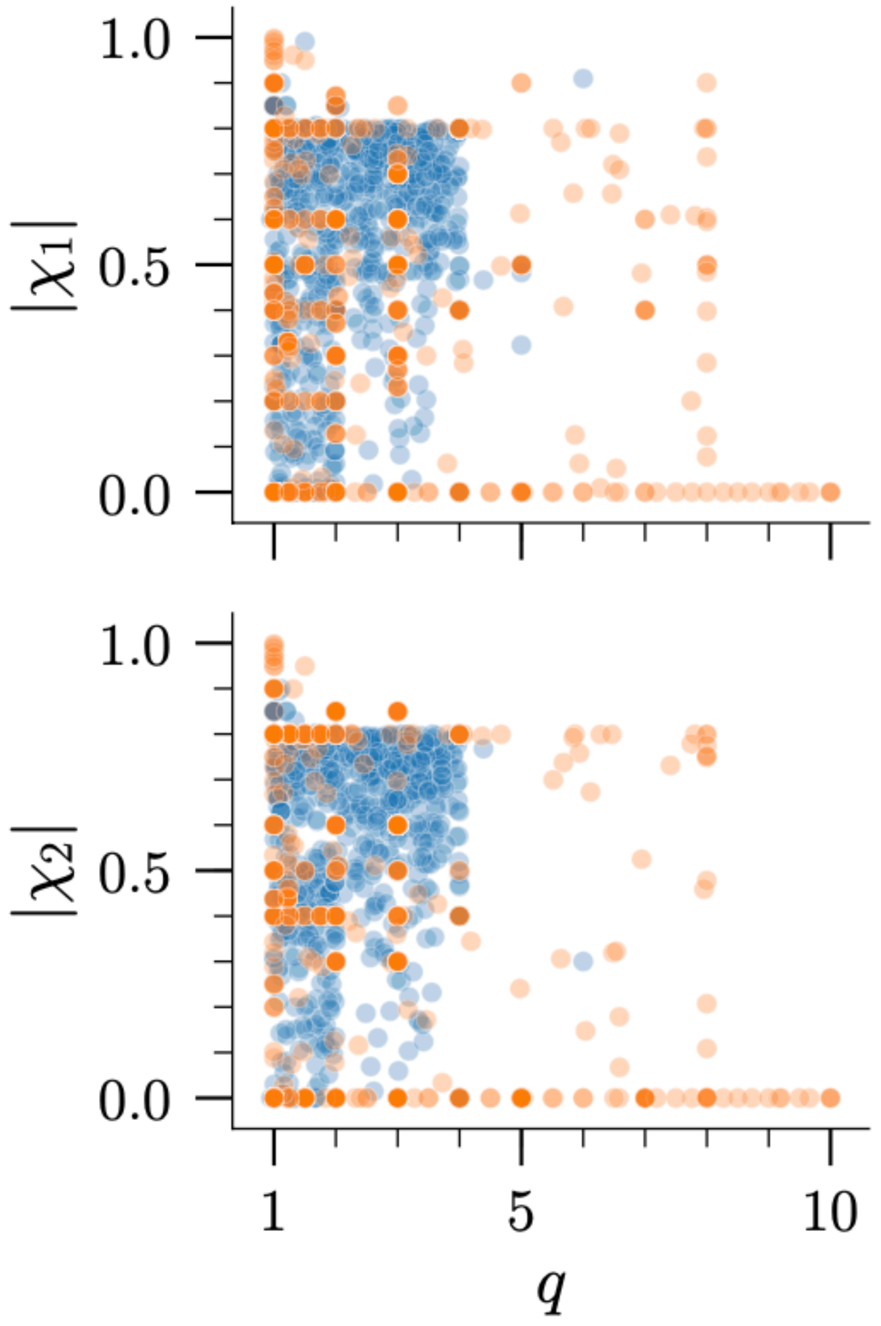
- current **state-of-the-art: NR surrogate of ~1500 precessing (SXS) simulations for** $q \leq 4\,,\, \chi_{1,2} \leq 0.8$ including all $l \leq 4$ spin-weighted spherical harmonics (NRSur7dq4, *Varma+ (2019)*)
- challenges:
  - inherit **limited parameter space coverage** of (precessing) NR simulations
  - inherit limited resolution
  - inherit **limited duration** (NRSur7dq4: 20 orbits before merger, $M \geq 66 M_\odot$ for $f_0 = 20\text{Hz}$)
- **hybridisation**: surrogates of non-precessing hybrids, e.g., NRHybSur3dq8 (*Varma+ (2019)*)
  - NR simulations stitched together with analytic PN+EOB inspiral waveforms ($M \geq 2.25 M_\odot\,,\; q \leq 8$)
  - NR hybrid surrogates for precessing waveforms in development



Varma+ (2019)

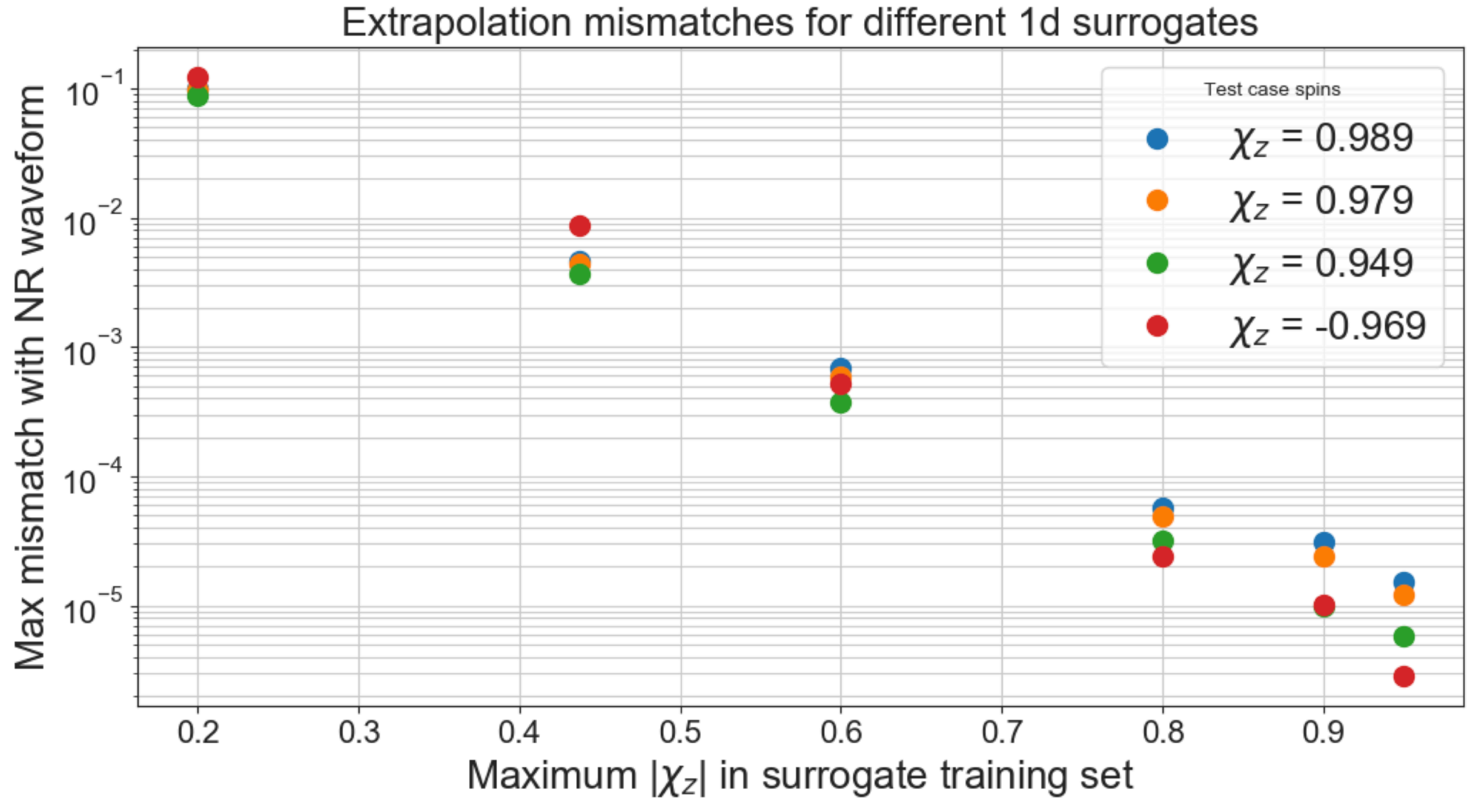
SXS Collab. (2019)



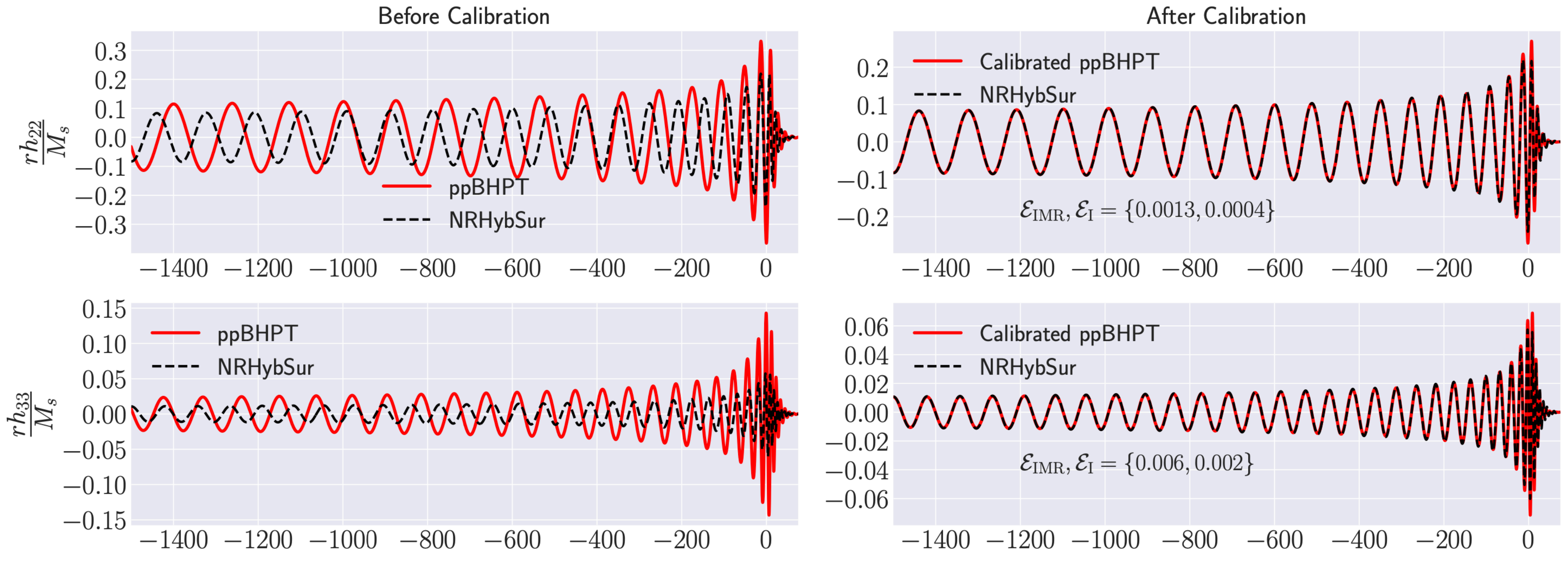


SURROGATE MODELS: STATUS AND CHALLENGES

- computational cost → NR simulations lacking for extremal spins ($\chi_i \sim 1$), high mass ratios, eccentric orbits
- extensions of NRSur to **nearly extremal spins**:
  - *Walker+ (2022)*: extrapolation of 1D (equal-mass, equal-spin) surrogate to nearly extremal spins
  - no longer viable for 3G detectors (SNR ~1000)
- extensions of NRSur to **high mass ratios**:
  - surrogates for (perturbation theory) EMRI waveforms with $2.5 \leq q \leq 10^4$, calibrated to NR
  - *Islam+ (2022)*: good agreement with NR-hybrid surrogates for comparable masses
- extensions of NRSur to **generic orbits**:
  - *Islam+ (2021)*: NR surrogate for GWs and remnant properties of eccentric, non-spinning binaries ($e \leq 0.2\,, \;\; q = 1$)
  - limited NR data set: ~50 simulations



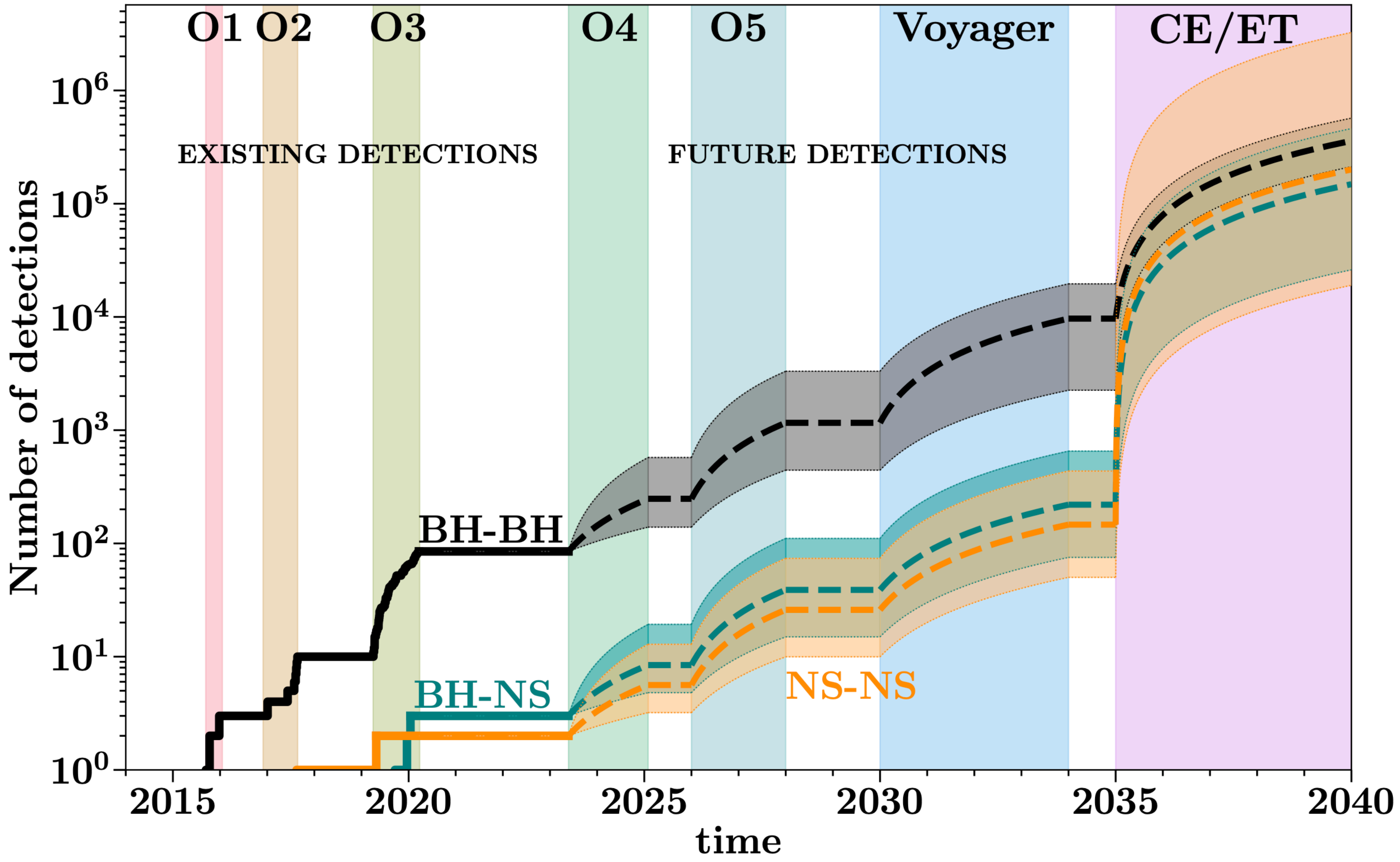
Walker+ (2022)



Islam+ (2022)

WAVEFORMS IN THE 3G ERA: THE CHALLENGE OF INCREASED SENSITIVITY

- 3G era: tens of thousands of BBH mergers! low frequency = long duration in band! many more wave cycles!
- expect “golden binary mergers” in 3G era: close and loud!
- need to revisit interface of waveform models with:
  - ***post-Newtonian theory*** (beyond current PN order? approximations to Fourier transform?)
  - ***numerical relativity*** (higher resolution? longer duration?)
  - ***gravitational self-force*** (high mass ratios?)

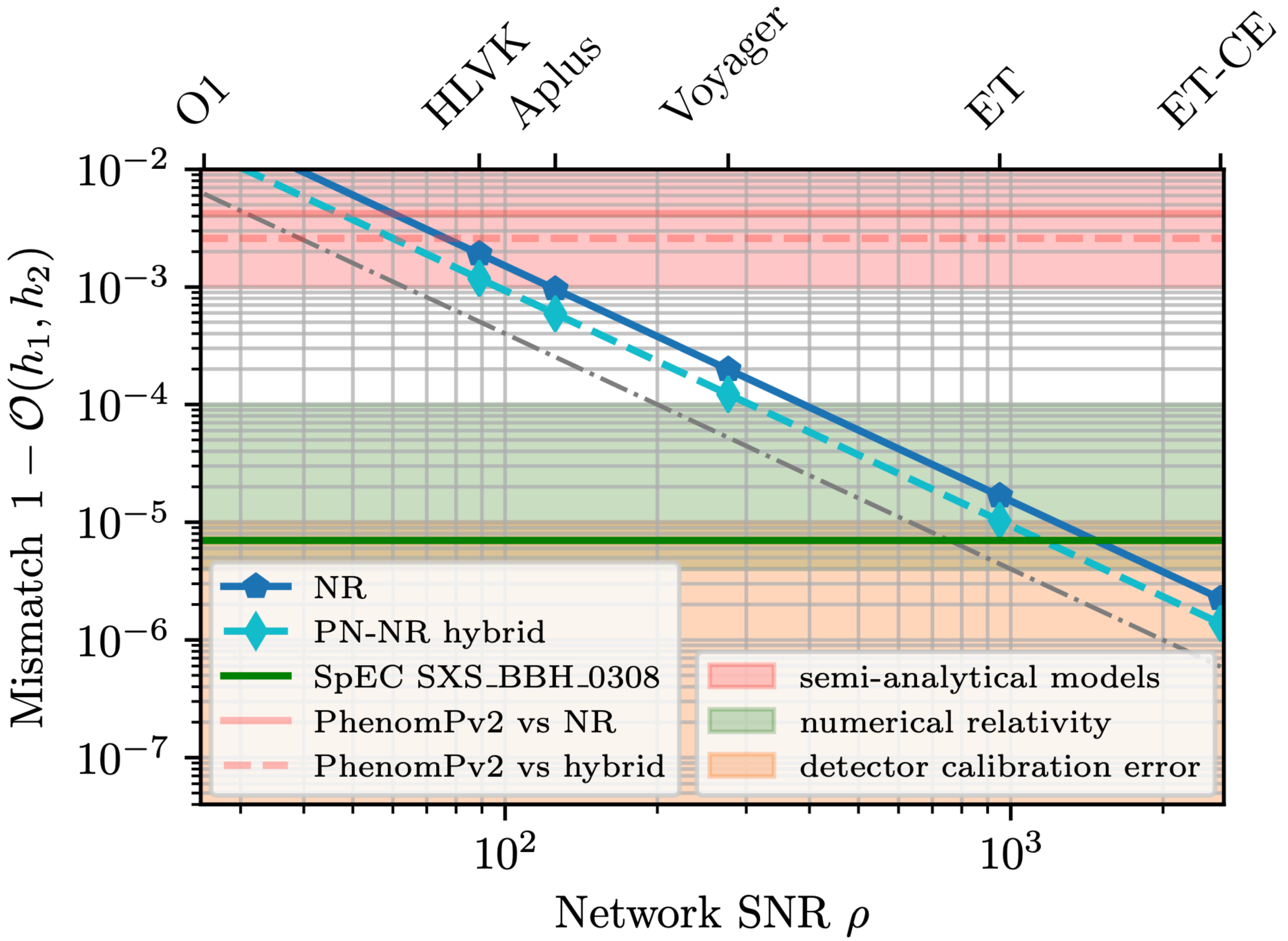


Broekgaarden 2023: arXiv:2303.17628

- computational efficiency in waveform generation & data analysis algorithms (e.g., using neural networks as surrogates for Bayesian posteriors → inference time reduced to minute per event!)

WAVEFORM MODEL REQUIREMENTS IN THE 3G ERA

- expect “golden binary mergers” in 3G era: close and loud!
- Waveform model requirements quantified by “distinguishability” $1 - \mathcal{O}(h_1, h_2) < D/(2\rho^2)$
- Blue lines: mismatch below which systematic and statistical errors indistinguishable (i.e., sufficient model accuracy, unbiased source parameter estimation possible)
- **Numerical relativity needs to improve by one order of magnitude in 3G era, semi-analytical models by three!**



Pürrer, Haster 2020: arXiv:1912.10055