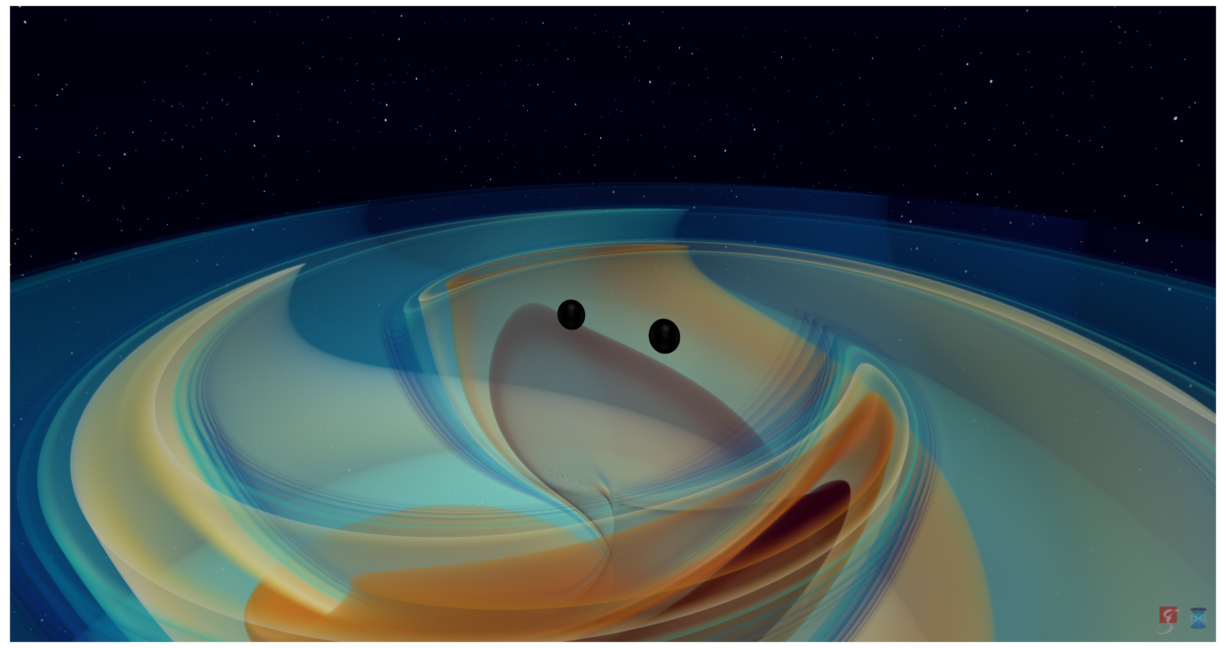  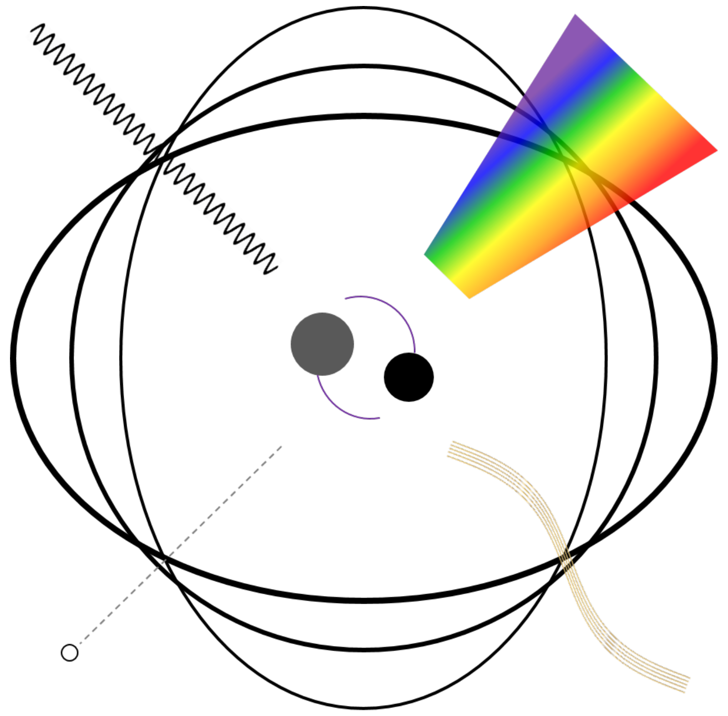 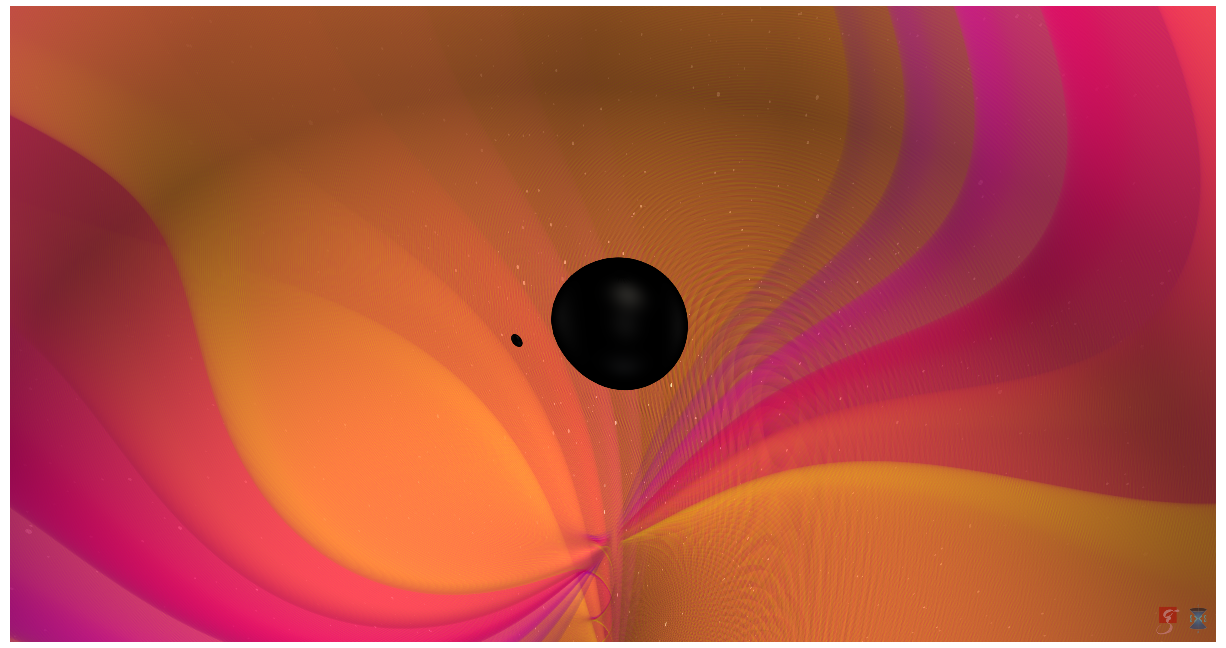

Gravitational Waves as Probes of Astrophysics, Fundamental Physics & Gravity

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Department of Physics, University of Maryland

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UNIVERSITY OF MARYLAND 1856

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

The ICASU Inaugural Conference, UIUC

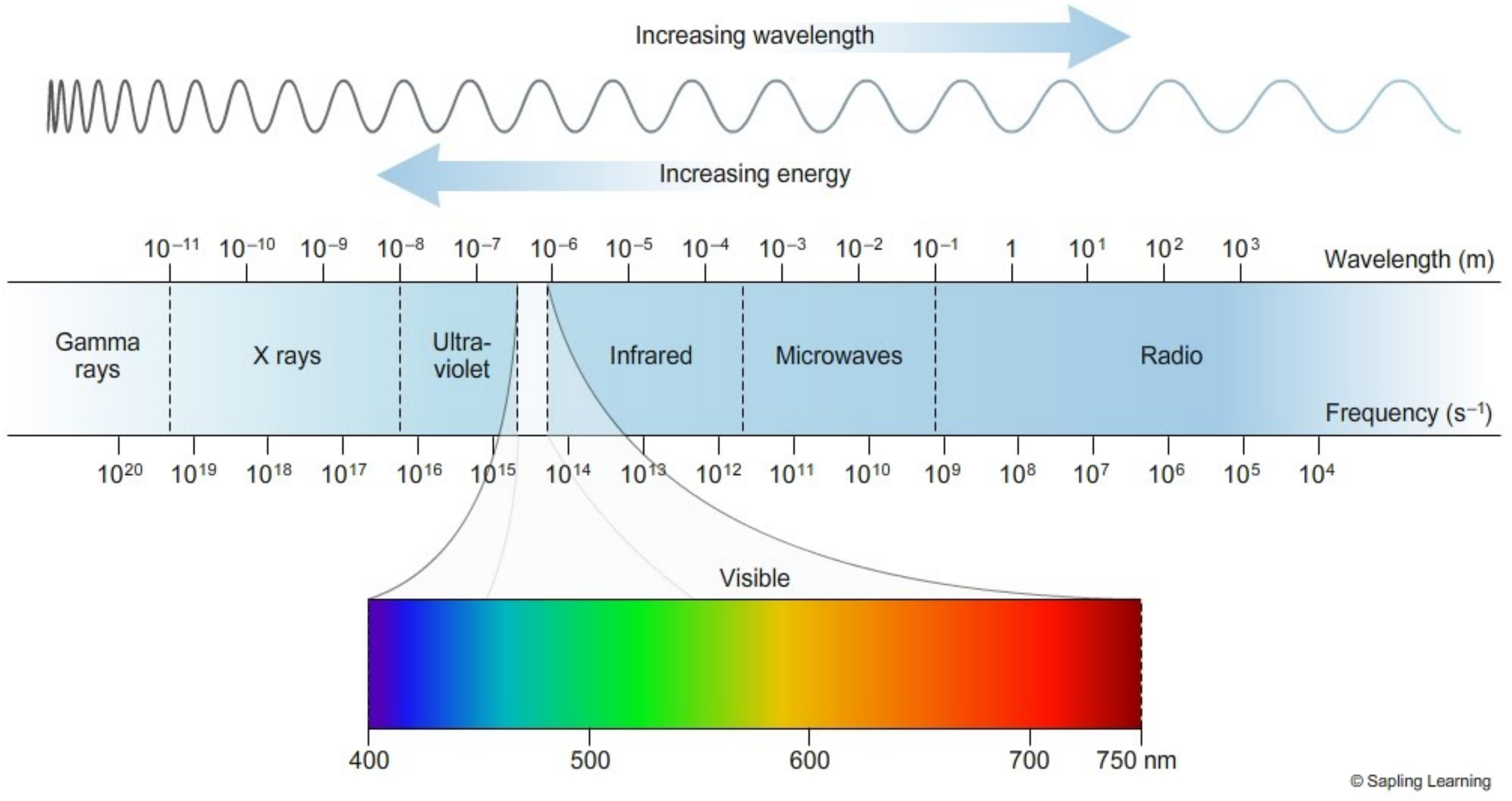
May 20, 2022

Electromagnetic Astronomy

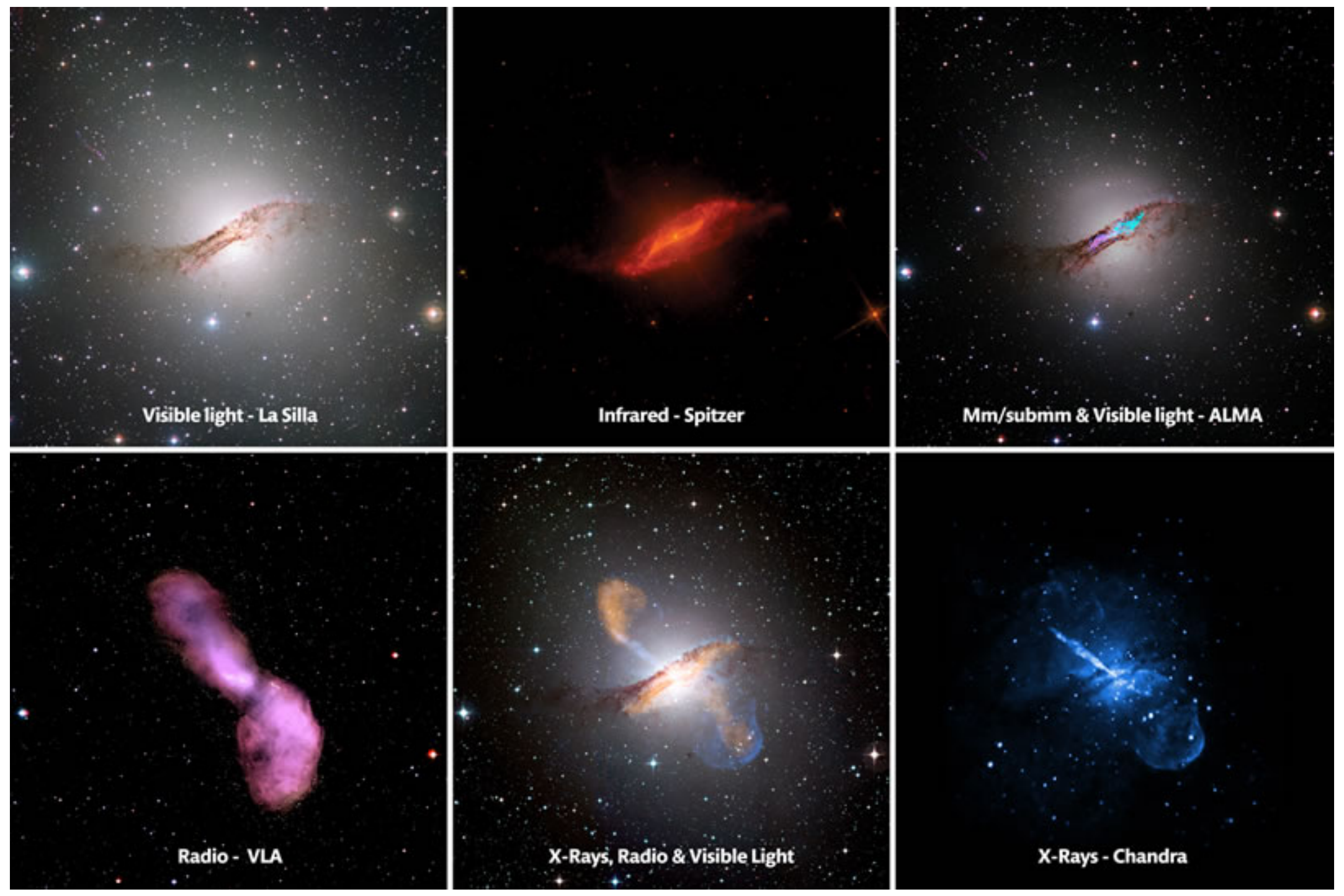
- Four centuries ago, **Galileo first pointed a telescope skyward**.

- Since then, we have **witnessed remarkable discoveries** and have **reached deeper understanding** of our Universe.

- **Electromagnetic** spectrum:



- **EM radiation** produced by **incoherent superposition** of radiation from **individual electrons, atoms or molecules.**



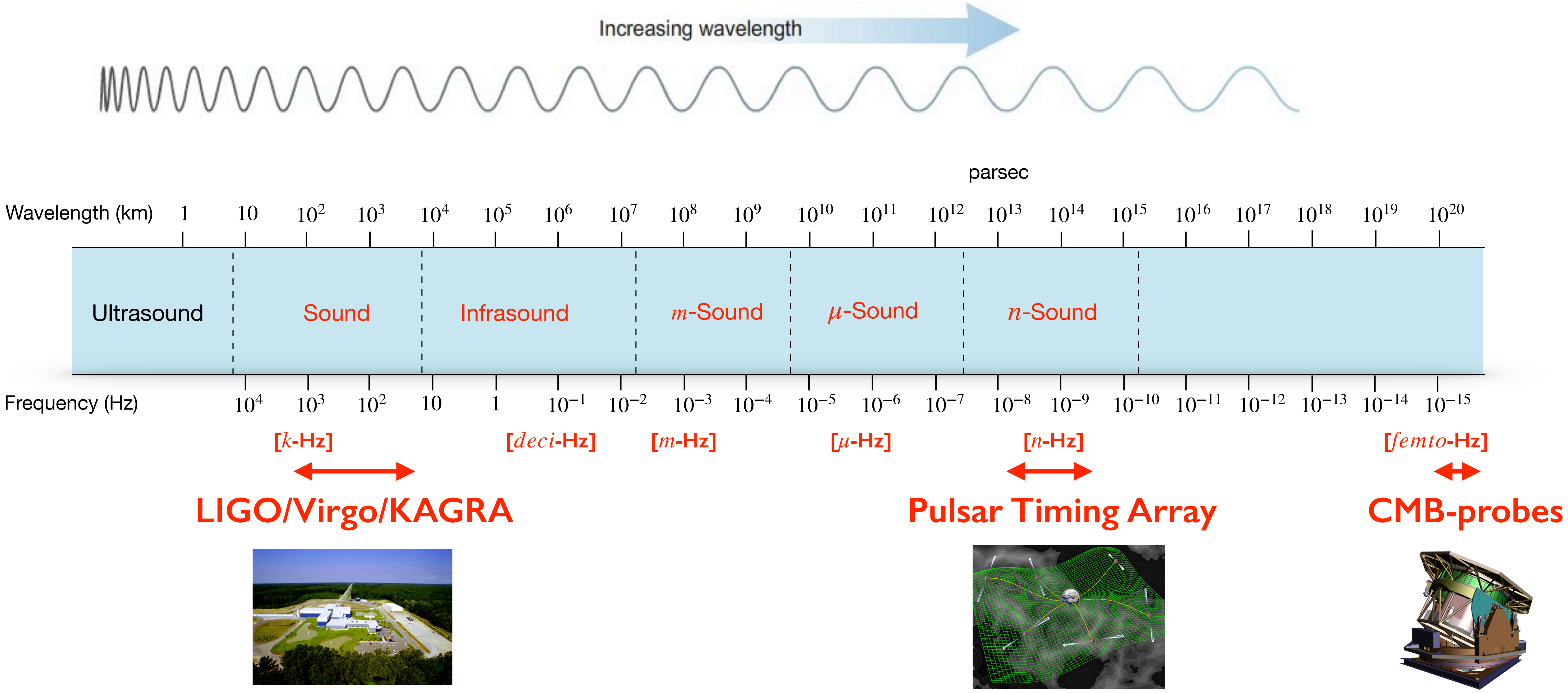
Centaurus A galaxy in different light bands

- **Each bandwidth** has allowed us to discover **new astrophysical objects or phenomena**.

Gravitational-Wave Astronomy

- **Gravitational waves** are produced by **coherent, bulk acceleration** of **huge** amount of **mass**, either in the form of matter or the mass-energy of warped space-time.

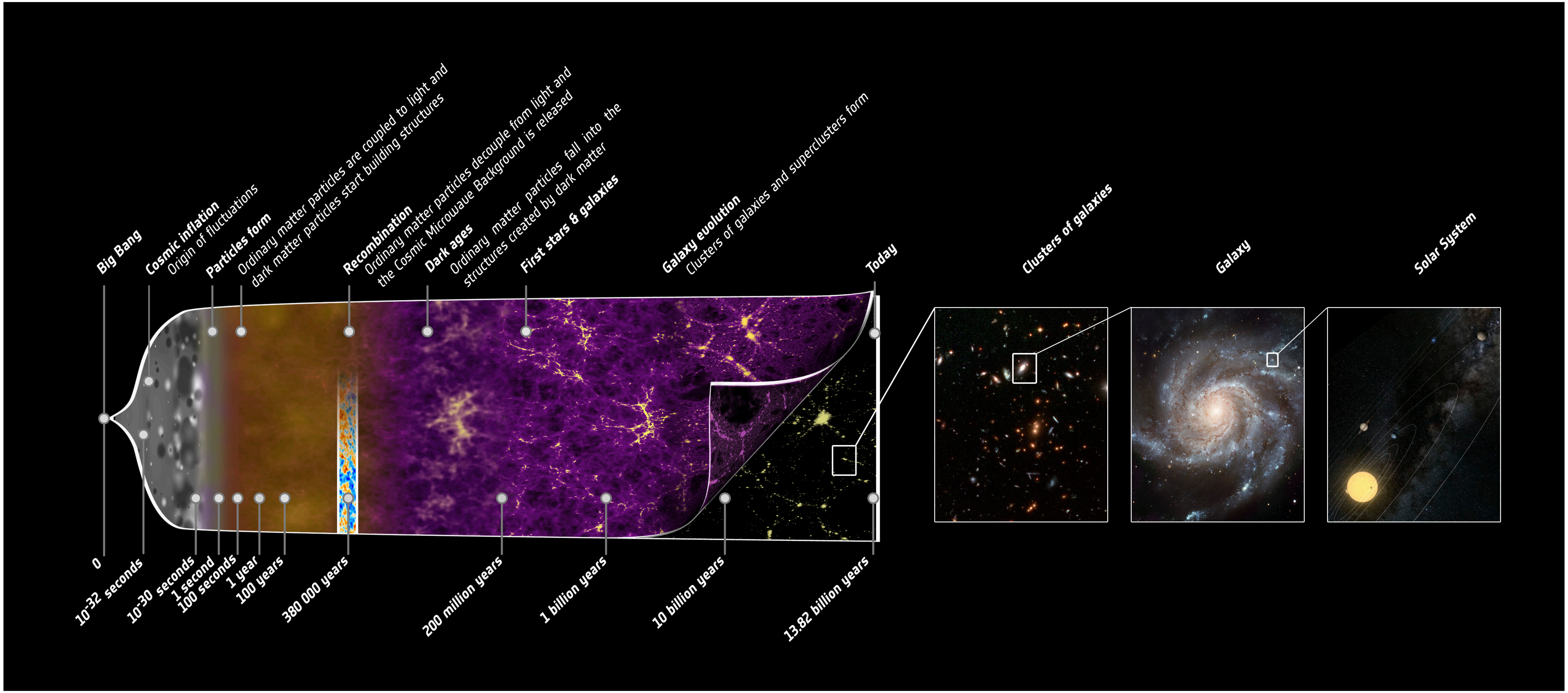
- **Gravitational-wave** spectrum



- **Different wavelengths** probe **black holes** of **different sizes** (from stellar to billion solar masses), at **different times of** their **life**, interacting with **different astrophysical environments.**

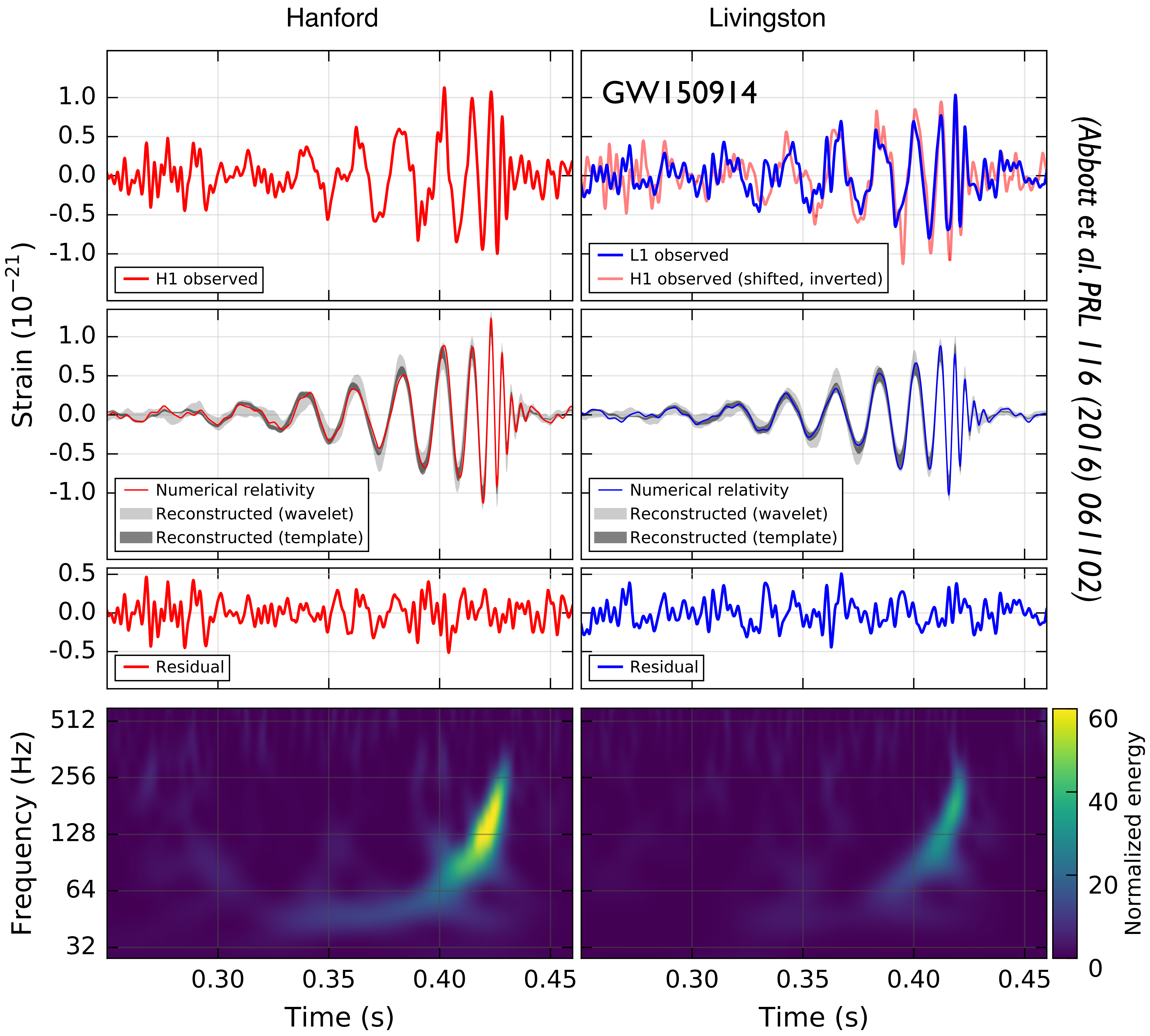
- **Different wavelengths** probe **different cataclysmic phenomena** dominated by gravity, and **swift changes** in gravitational field **during cosmic expansion.**

Probing Astrophysical Objects and Gravity at Different Scales with GWs



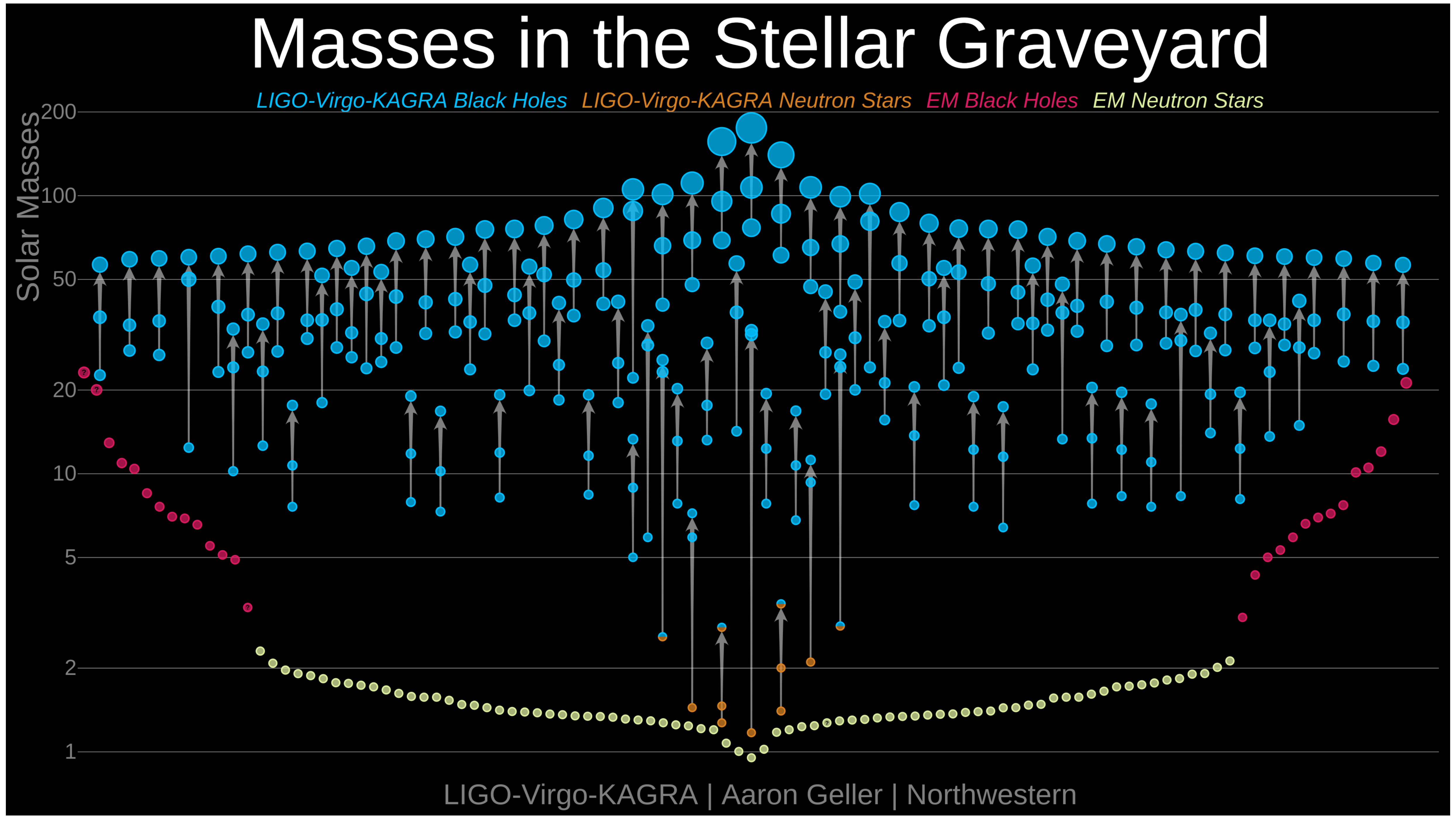
Gravitational Waves Ushered in New Era of Astrophysics

- **Discovery** of **GW** from **a binary black-hole merger** by LIGO and Virgo Collaborations



(Abbott et al. PRL 116 (2016) 061102)

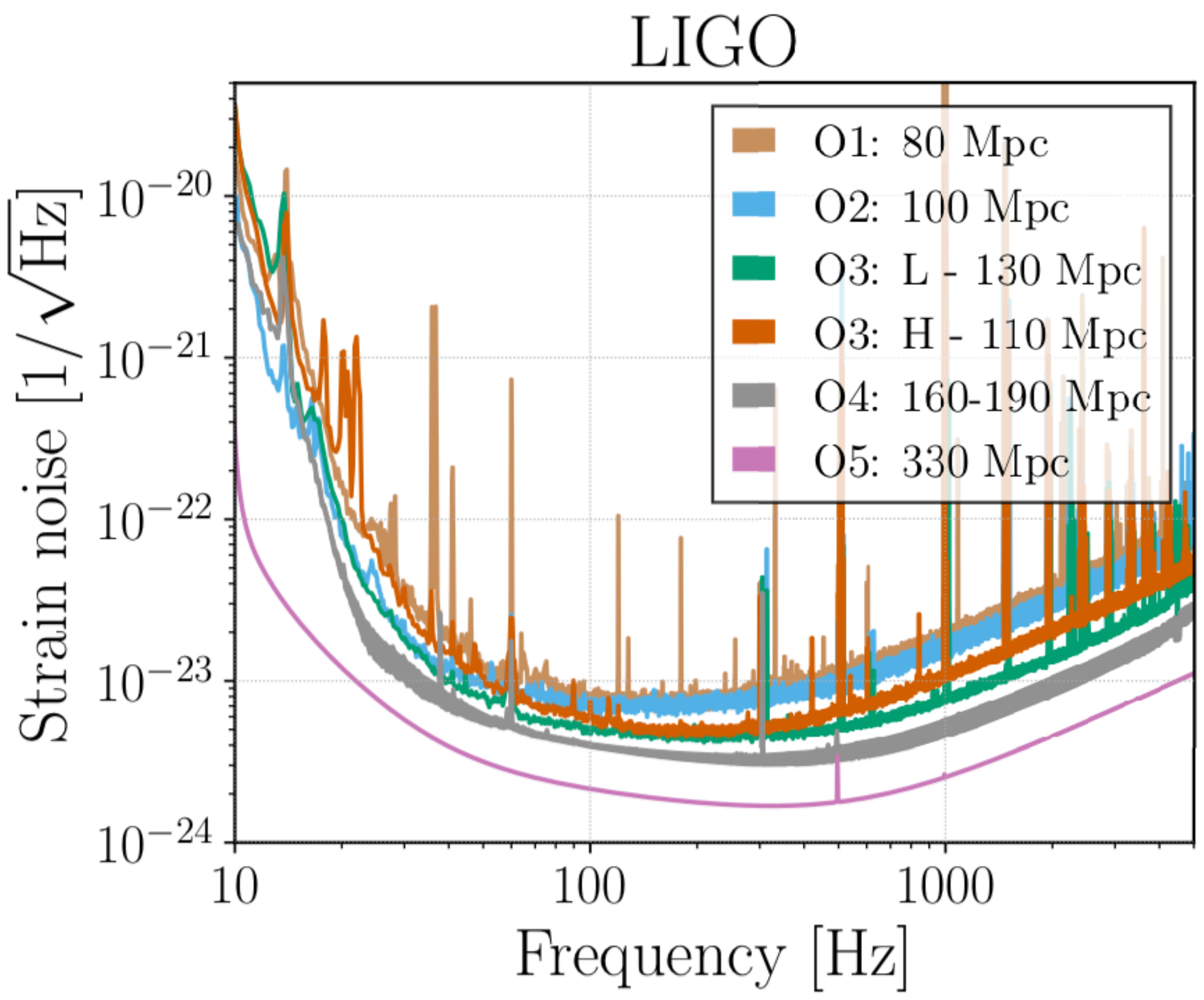
- **Since GW150914** was observed, **89 more** GW events were discovered; the majority are **binary black holes (BBH)**, but also **2 binary neutron stars (BNS) and mixed NSBHs**.



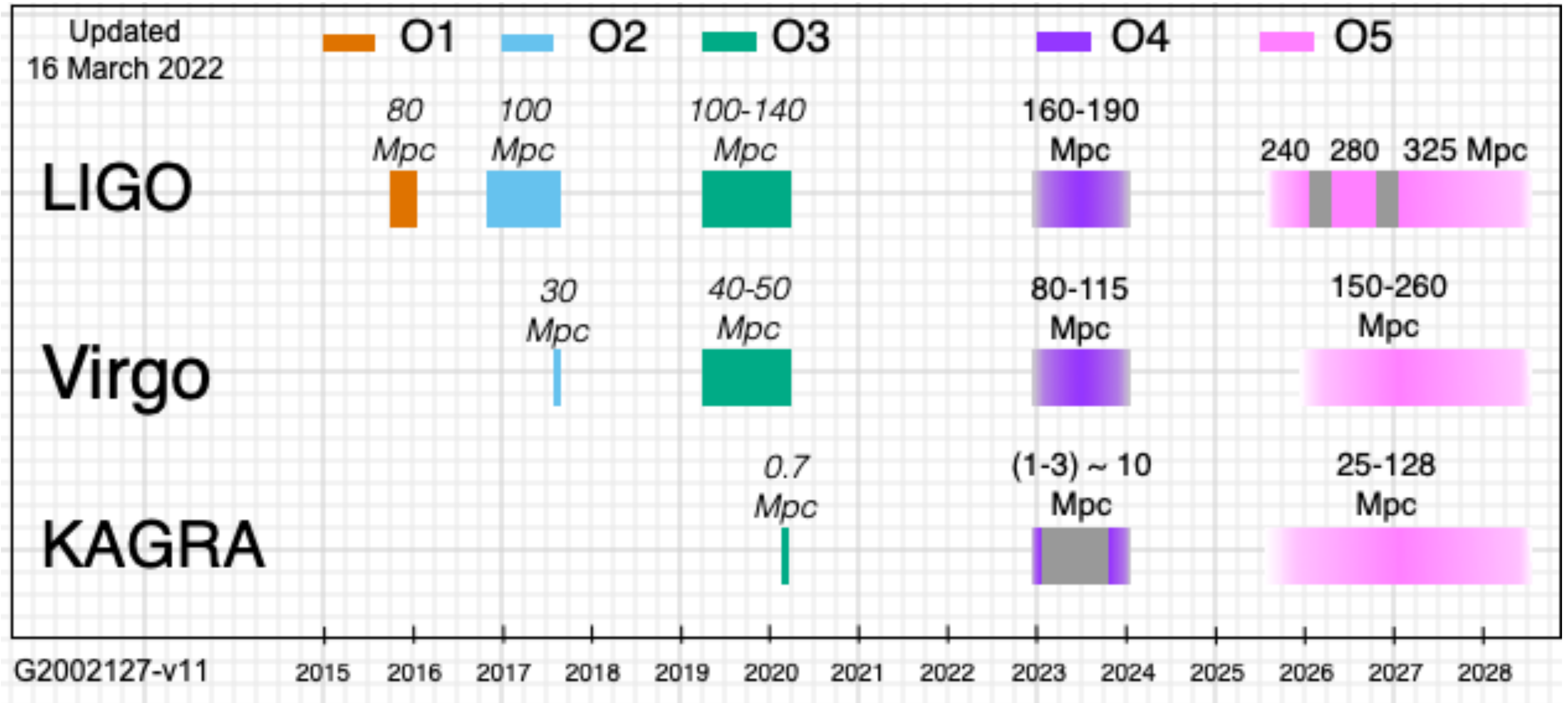
- **GW events** found also with **independent searches.**

(Nitz et al. 19-21; Venumadhav et al. 20; Zackay et al. 20, Nitz et al. 21, Olsen et al. 22)

Gravitational-Wave Landscape until ~2030



(update of Aasi et al. Living Rev. Rel. 21, 2020)



- From **several tens to hundreds** of binary detections per year.
- Inference of **astrophysical properties** of BBHs, NSBHs and BNSs **in local Universe.**

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}

(Aasi et al. Living Rev. Rel. 21, 2020)

Outline

- **Observing** gravitational waves and **inferring astrophysical/physical information** hinges on our **ability** to make **precise predictions** of **two-body dynamics** and **gravitational radiation.**

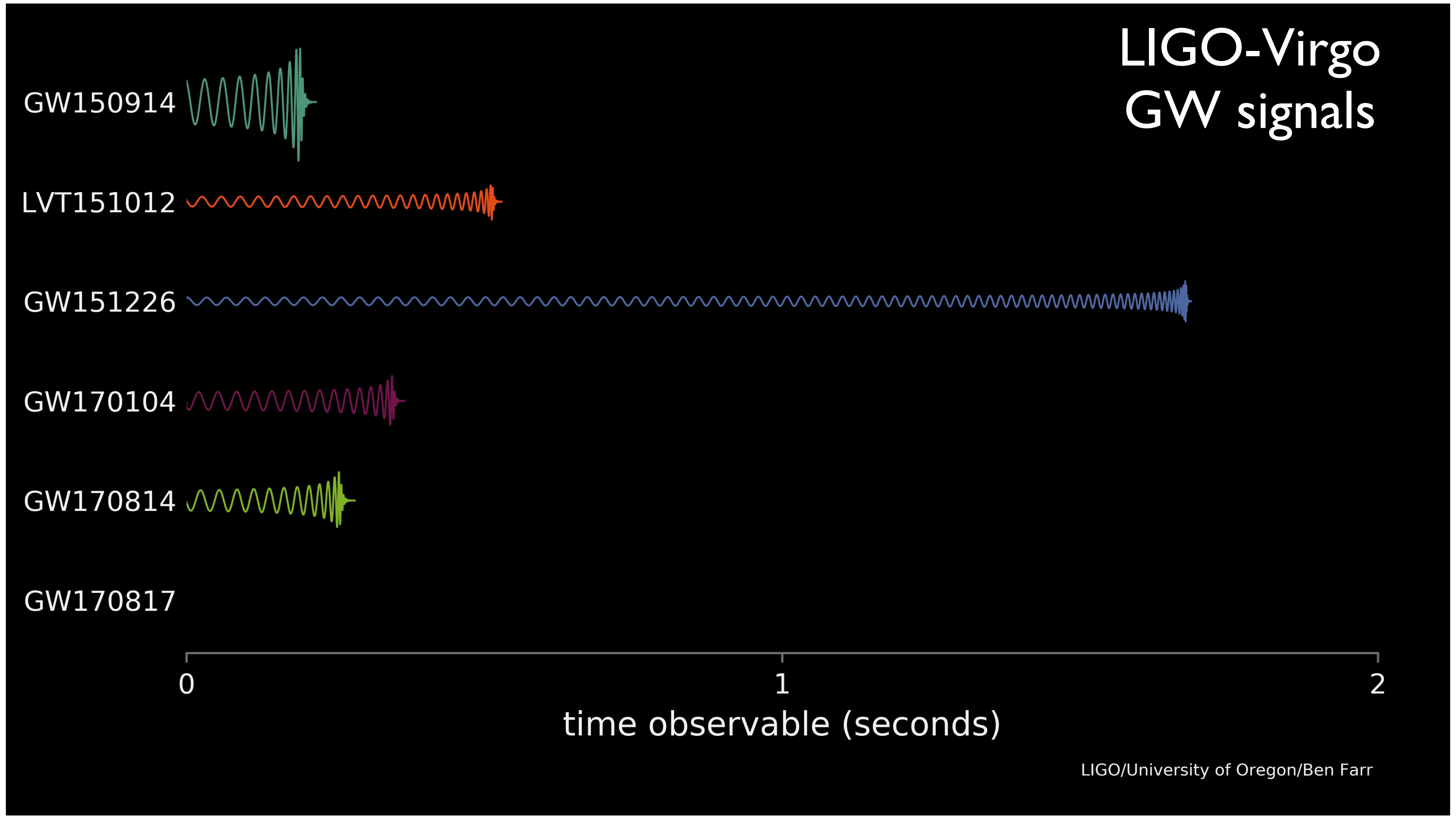
- How do we build the hundred-thousand **accurate** and **efficient waveform models** employed in **LIGO/Virgo searches** and **inference studies**?

- **Highlights on science** (astrophysical-source properties, neutron-star equation-of-state, tests of General Relativity) **from the latest observing run** of LIGO and Virgo.

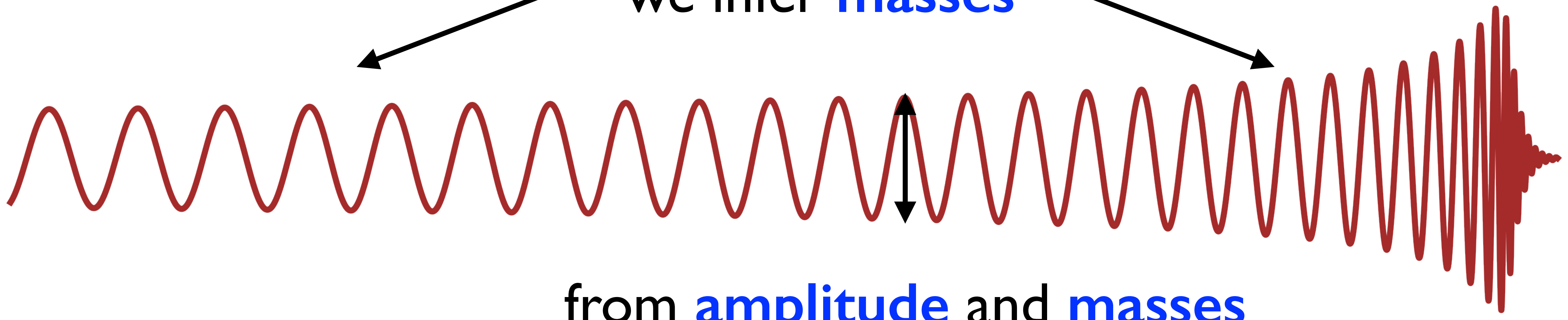
- What have we **learned from the "exceptional" GW events** of the latest observing run? Is a **clear picture of the population properties** of compact-object binaries **emerging**?

- In view of **future, ever more sensitive** runs and detectors, **challenges and opportunities** to take **full advantage** of **discovery potential**.

Gravitational Waves are Fingerprints of Sources

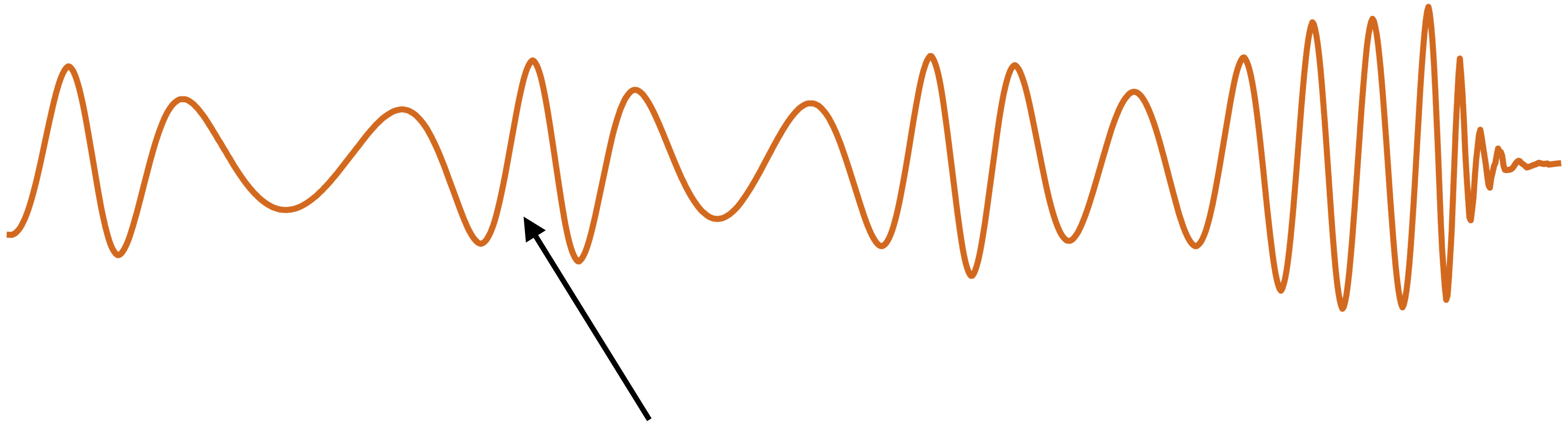


from **frequency evolution** we infer **masses**



from **amplitude** and **masses** we infer **distance**

from **time of arrival**, **amplitude and phase** at detectors we infer **sky location**



from **modulations** of **amplitude and phase** we infer **spins and eccentricity**

By **comparing to waveforms with deviations from GR**, we can **probe gravity**

- At fixed binary's mass, the **lower** the GW **frequency**, the **larger** the **binary's separation**, and the **earlier** the **inspiral stage**

$$\omega = \sqrt{\frac{GM}{r^3}} \qquad f_{\rm GW} = \frac{\omega}{\pi}$$

orbital frequency

orbital separation

- Binary black holes **merge** at $f_{\rm GW} \sim \frac{4400\ {\rm Hz}}{M/M_{\rm Sun}}$

Solving Two-Body Problem in General Relativity

- **GR** is **non-linear theory**. $$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

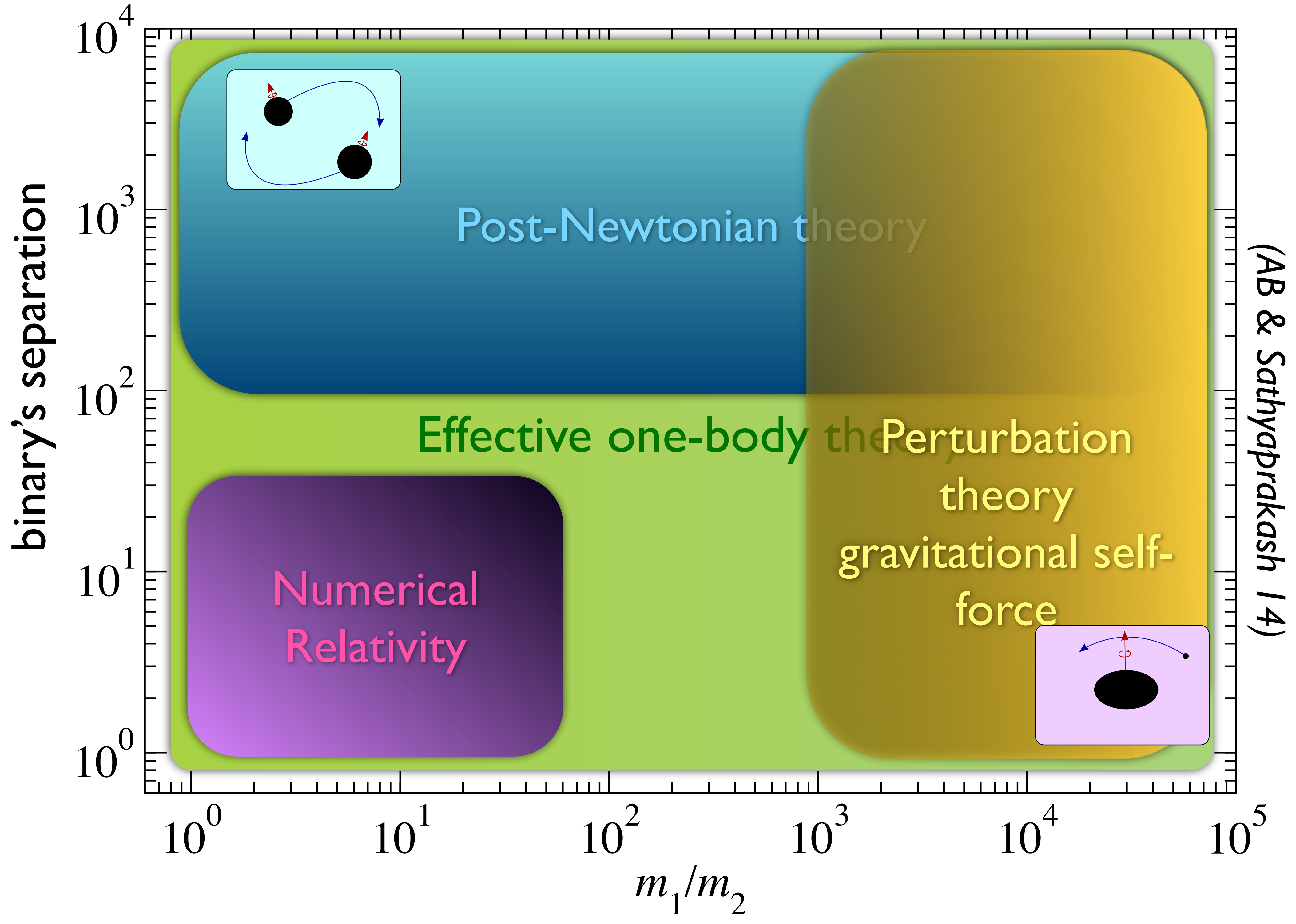
- Einstein's field equations can be solved:

-**approximately,** but **analytically** (**fast** way)

-**accurately**, but **numerically** on supercomputers (**slow** way)

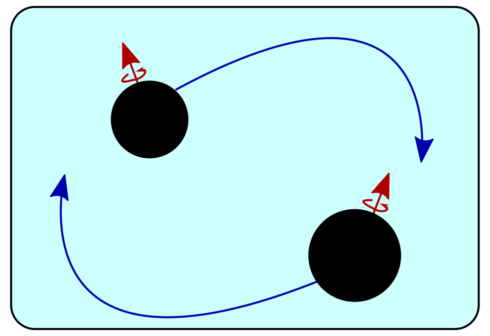
- **Synergy** between **analytical** and **numerical relativity** is **crucial** to **provide GW detectors with templates** to use for **searches** and **inference analyses**.

bound orbits: $v^2/c^2 \sim GM/rc^2$



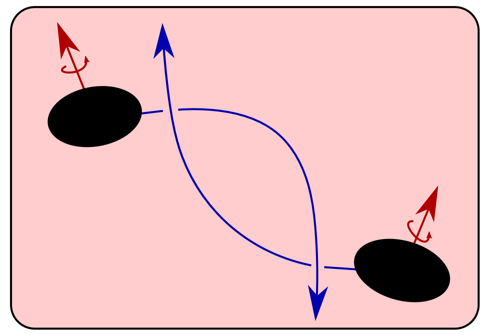
- **Post-Newtonian** (PN) (large separation, and slow motion, **bound motion**, i.e., **early inspiral**)

expansion in $v^2/c^2 \sim GM/rc^2$



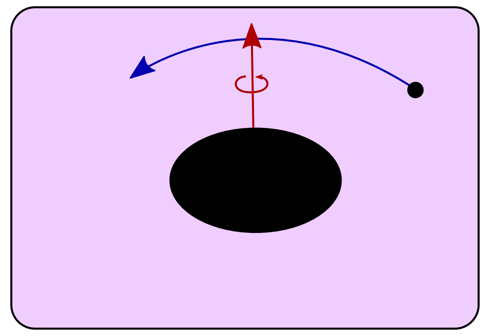
- **Post-Minkowskian** (PM) (large separation, **unbound motion**, i.e., **scattering**)

expansion in G



- **Small mass-ratio** (gravitational self-force, GSF, i.e., **early to late inspiral**)

expansion in m_2/m_1



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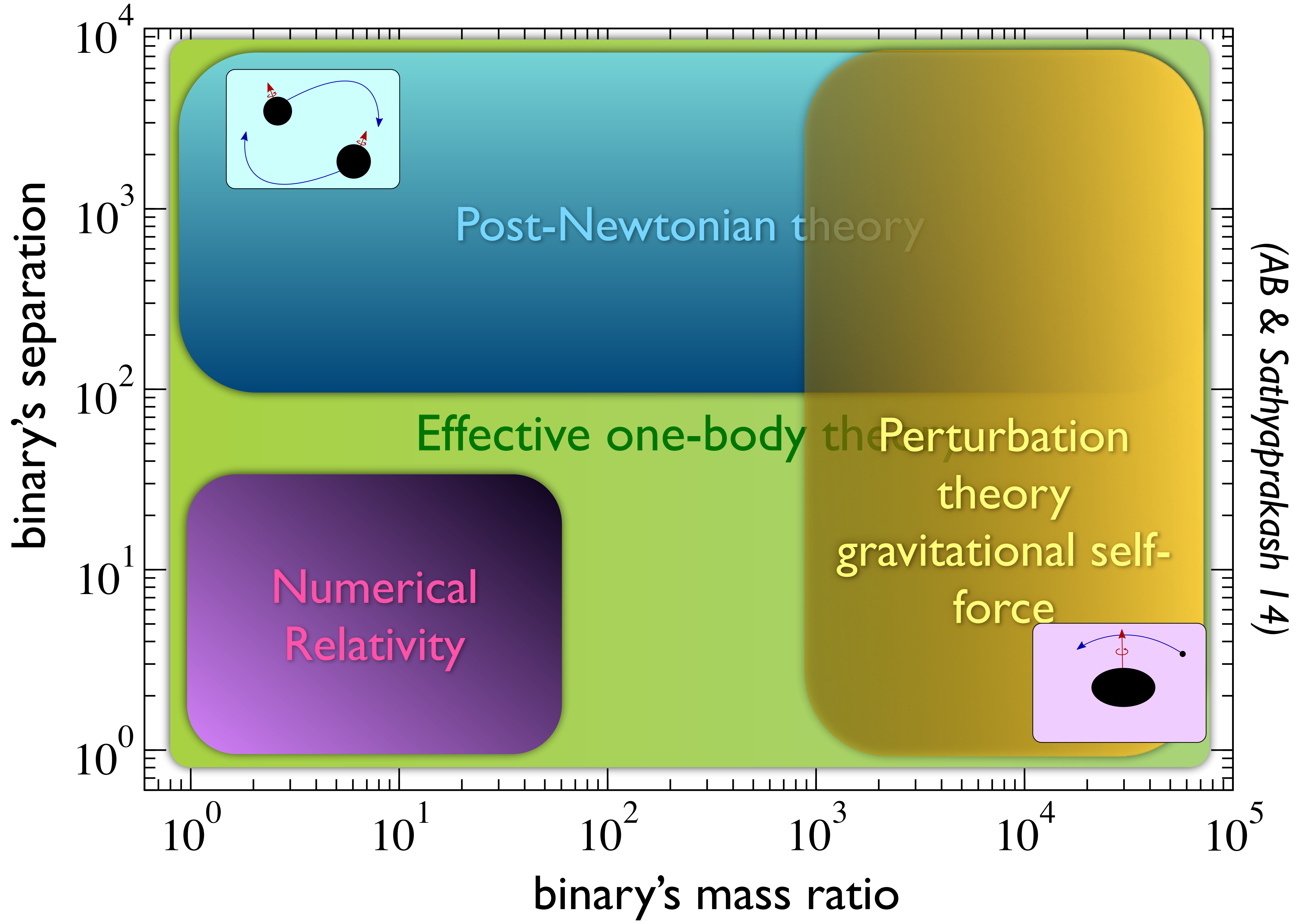
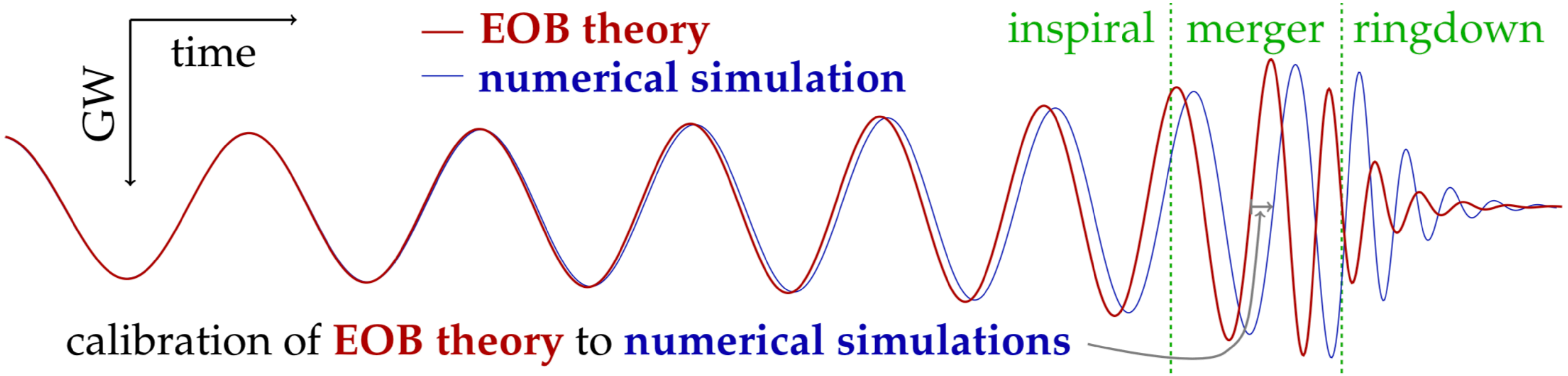
bound orbits: $v^2/c^2 \sim GM/rc^2$



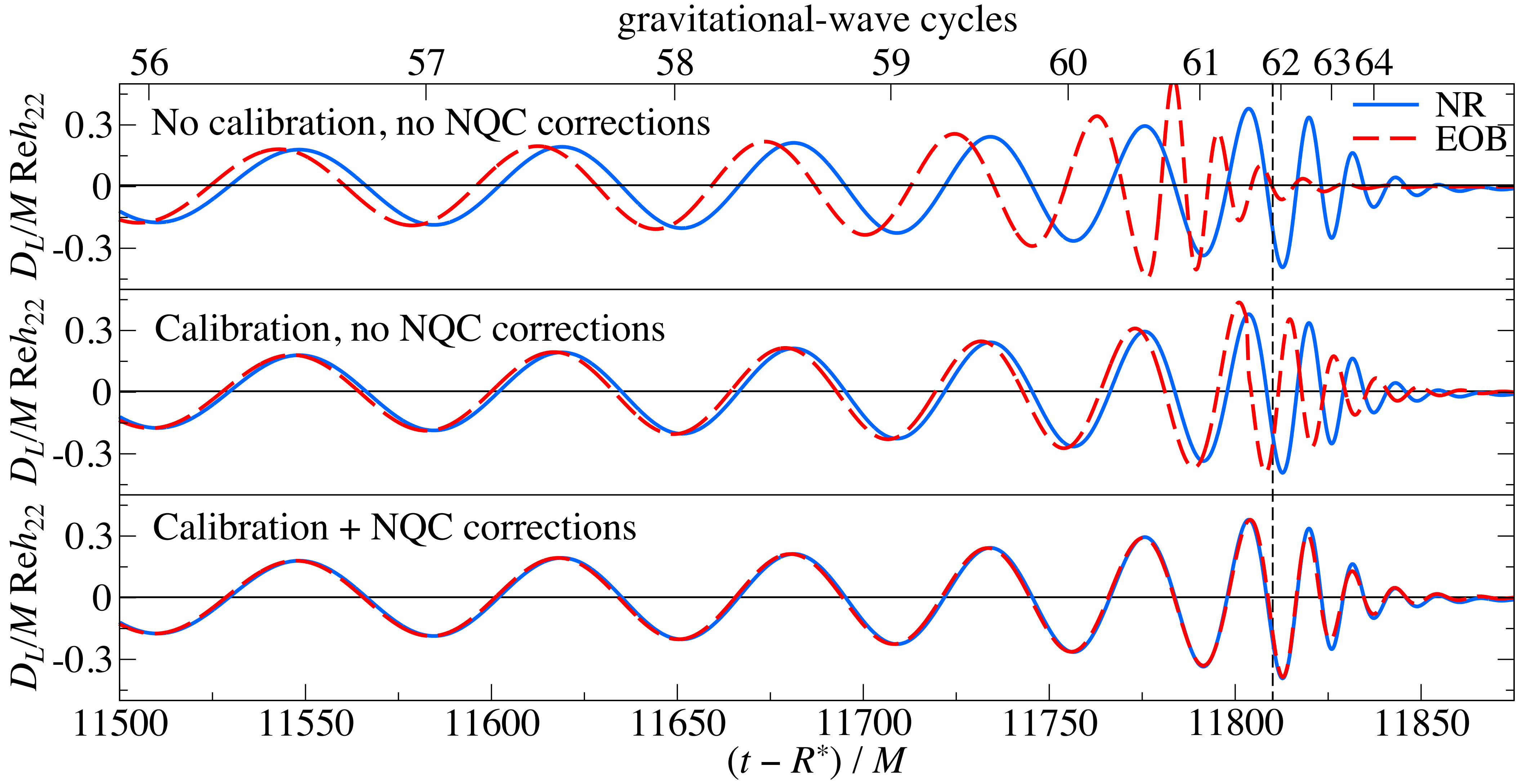
- **Effective-one-body** (EOB) **theory** (combines results from all methods, i.e., for **entire coalescence**)

- **Phenomenological frequency-domain** waveforms (Phenom) hybridizing EOB and NR waveforms, and fitting.



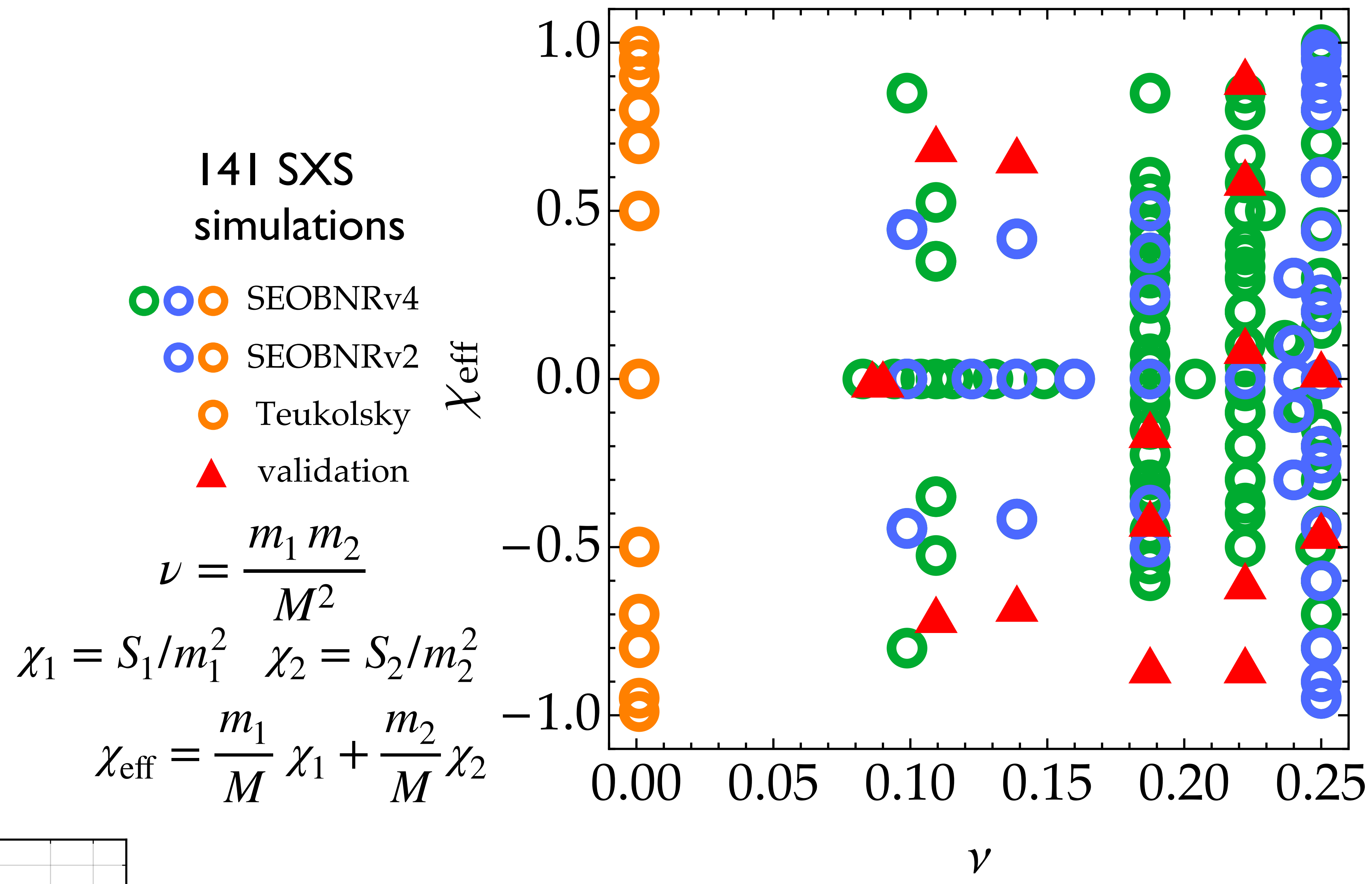
Completing EOB Waveforms with NR Information & Template Bank

- We calibrate models to **inspiral-merger-ringdown NR** waveforms.



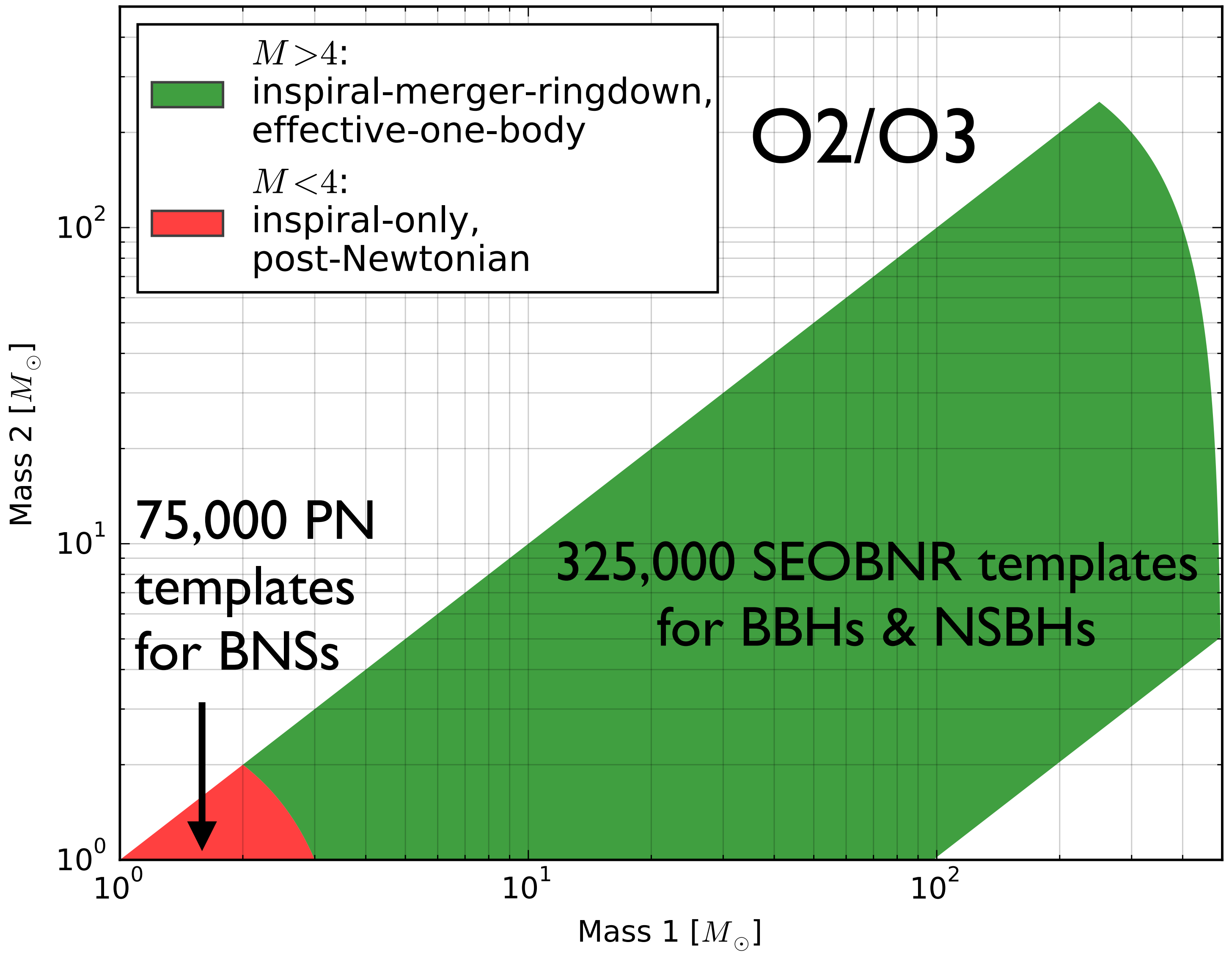
(credit: Taracchini)

Calibration of SEOBNR for O2-O3 searches and inference studies



(Bohé et al. 17)

- **Matched filtering** employed in LIGO/Virgo searches.



(Dal Canton & Harry 17)

(Pan, AB et al. 13, Taracchini, AB et al. 14, Pürrer 15, Bohé, Shao, Taracchini, AB & SXS 17, Babak et al. 16; Cotesta et al. 18, 20, Ossokine et al. 20, Khalil, AB et al. 20; ***SEOBNR****)*

(Schmidt et al. 12; Hannam et al. 13; Khan et al. 15; Husa et al. 15; Khan et al. 18-19; García-Quíros et al. 20, Pratten et al. 20; ***IMRPhenom****)*

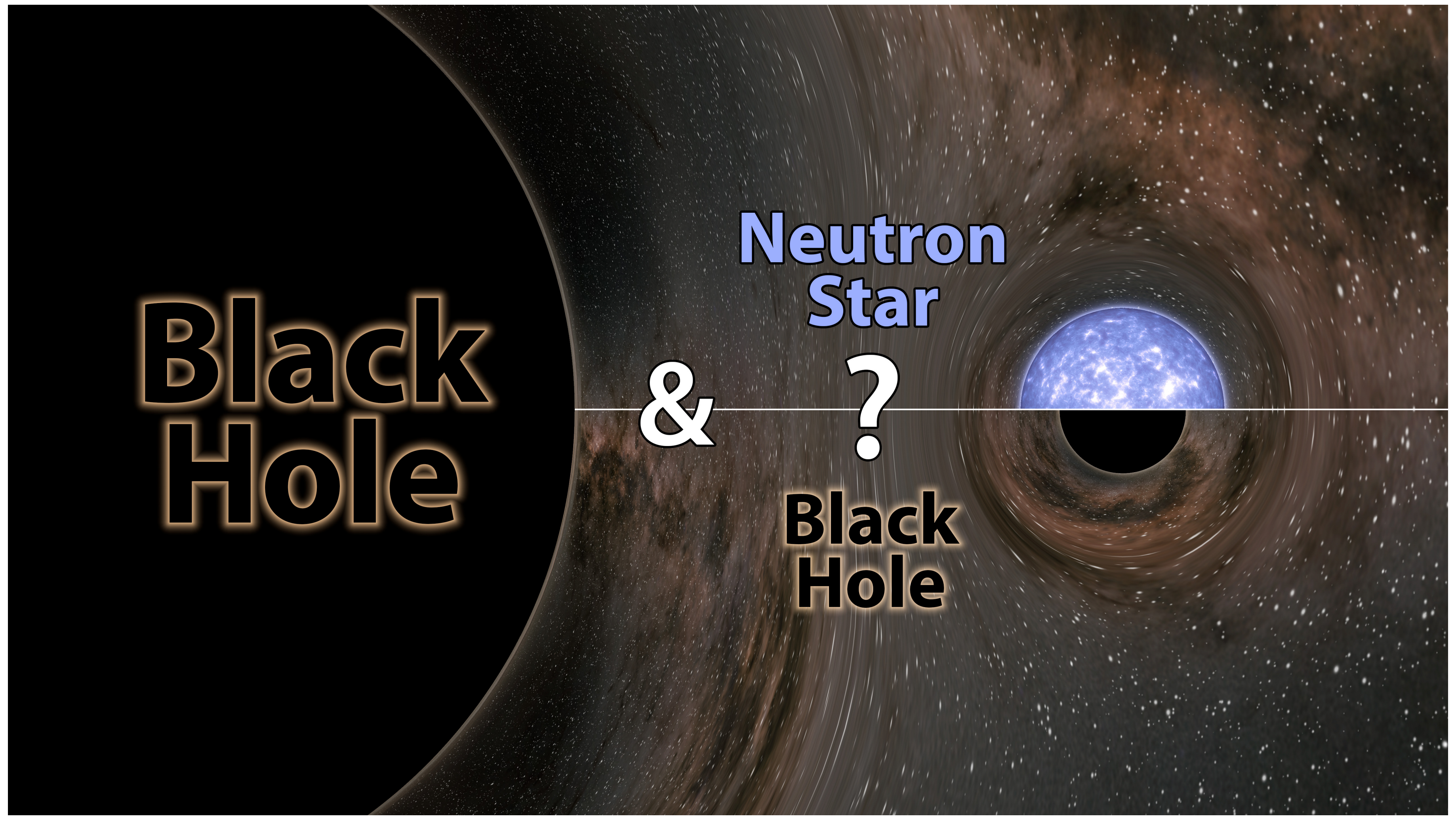
(Damour & Nagar 14, Nagar et al. 18, 19, 20, Rettegno et al. 20, Riemenschneider et al. 21, Gamba et al. 21; ***TEOBResumS****)*

(Field et al. 11, 14; Blackman et al. 15; Canizares et al. 15, Varma et al. 19; ***NRSur****)*

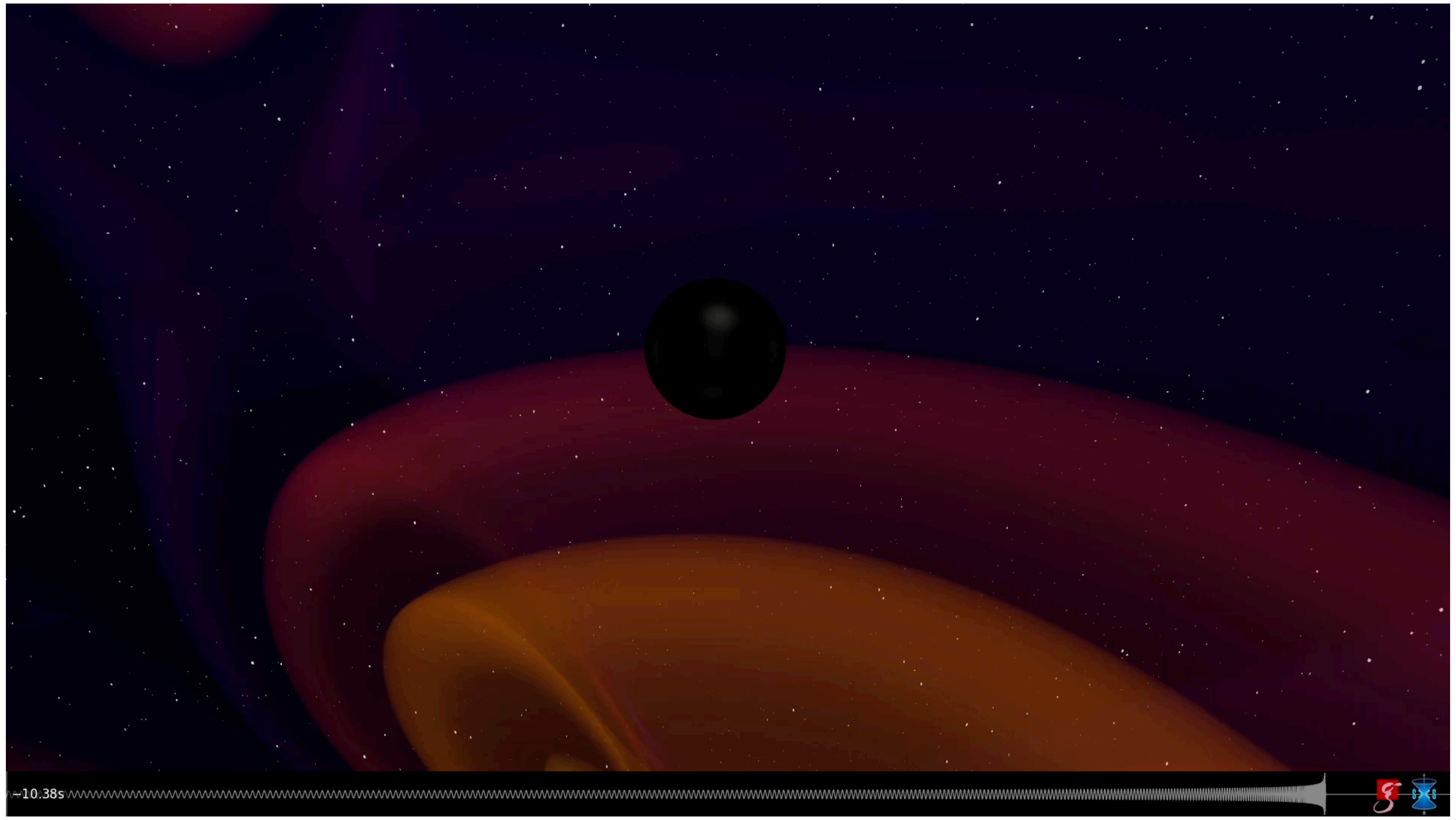
GW190814: a Binary with a Puzzling Companion

- Either the **largest neutron star** or the **smallest black hole.**

$$m_1 = 23.2^{+1.1}_{-1.0}\,M_\odot \qquad m_2 = 2.59^{+0.08}_{-0.09}\,M_\odot$$



- The **more substructure and complexity** the binary has (e.g., masses or spins of BHs are different) **the richer is the spectrum of radiation** emitted.



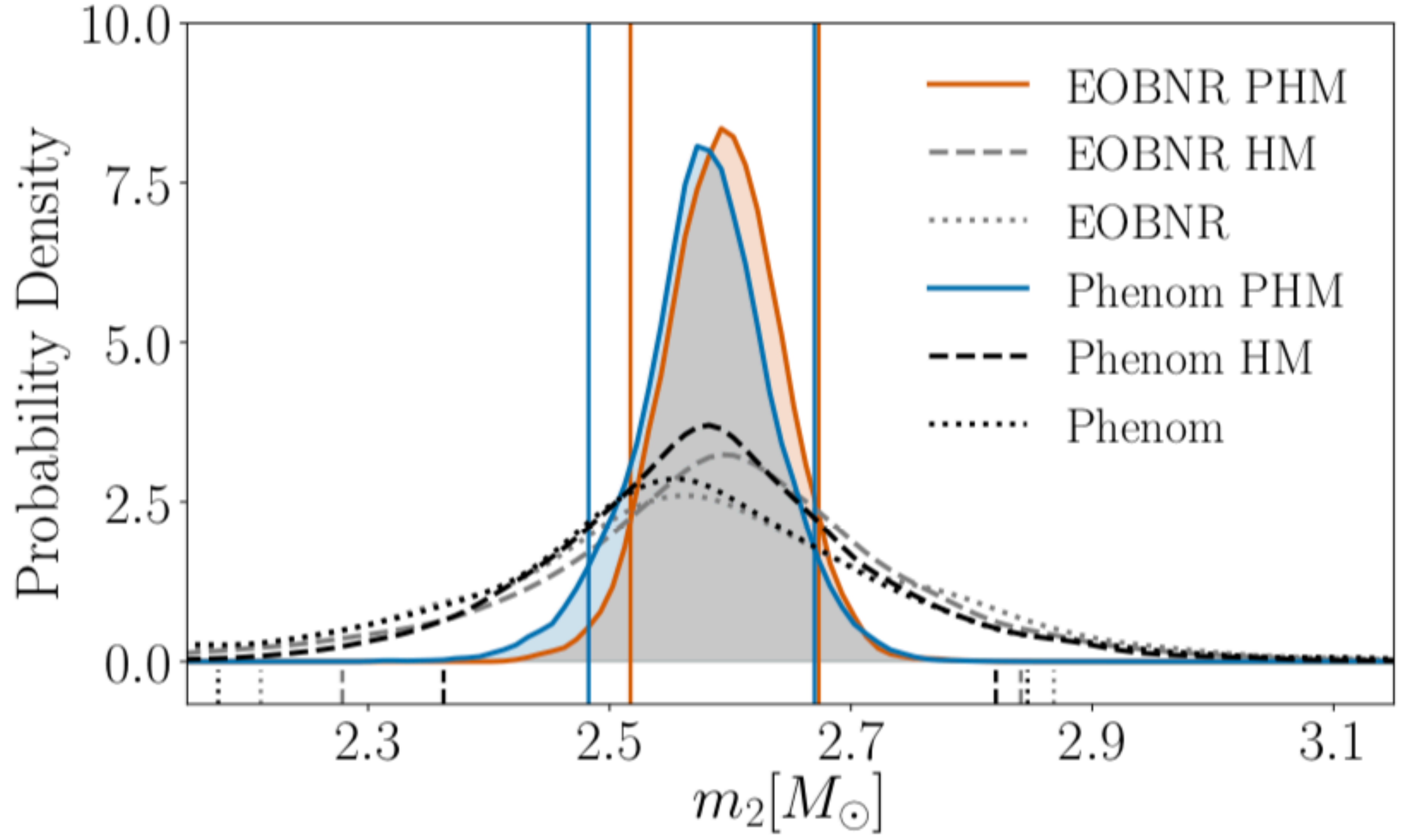
(credit: Fischer, Pfeiffer, Ossokine & AB; SXS Collaboration)

GW190814: a Binary with a Puzzling Companion (contd.)

- Either the **largest neutron star** or the **smallest black hole.**

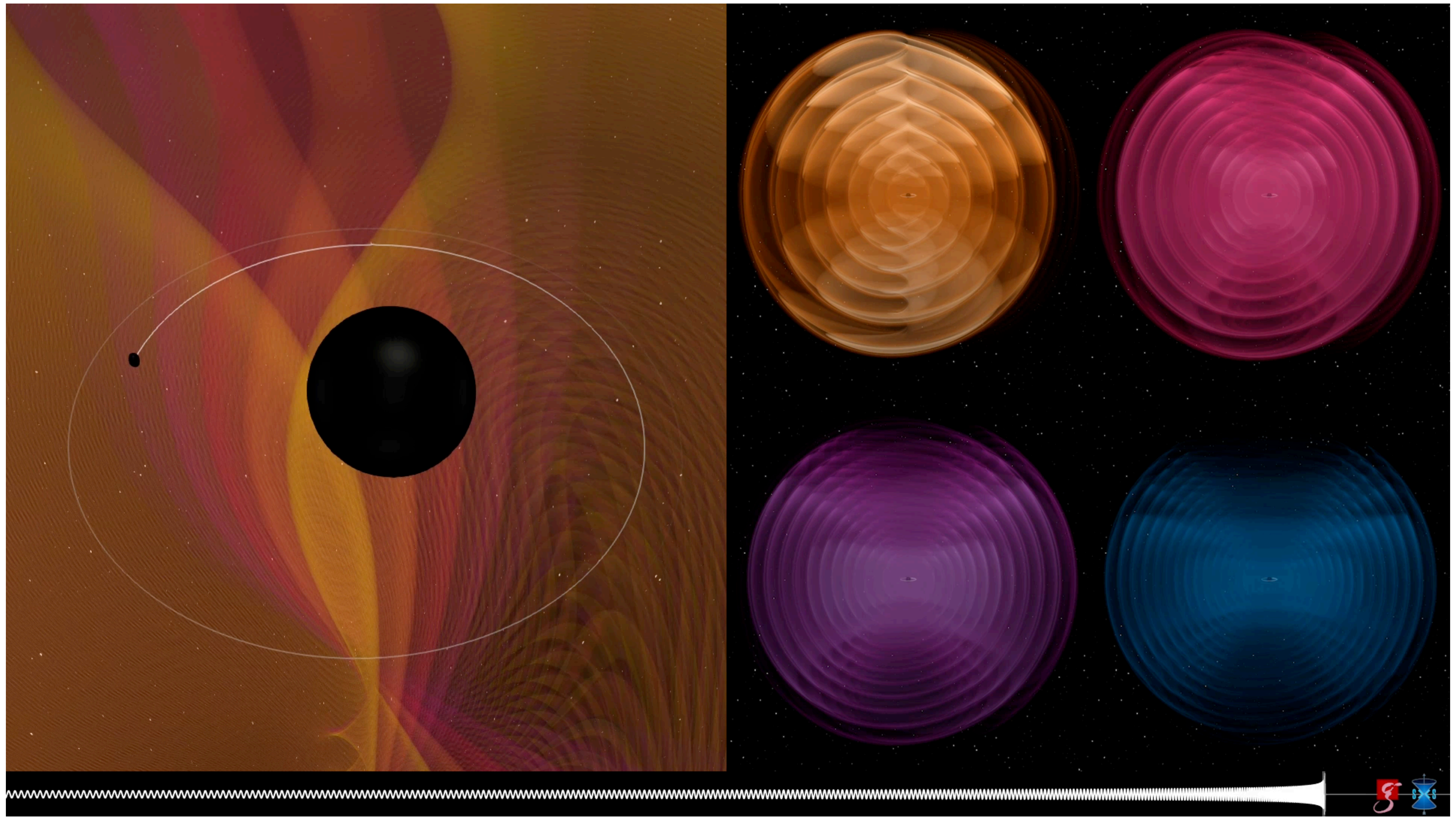
$$m_1 = 23.2^{+1.1}_{-1.0}\,M_\odot \qquad m_2 = 2.59^{+0.08}_{-0.09}\,M_\odot$$

(Abbott et al. ApJ Lett 896(2020) L44)



- Using waveform models with **higher-modes and spin-precession constrains more tightly** the **secondary mass.**

- The **more substructure and complexity** the binary has (e.g., masses or spins of BHs are different) **the richer is the spectrum of radiation** emitted.



(credit: Fischer, Pfeiffer, Ossokine & AB; SXS Collaboration)

GW190521: a Signal Produced by the Largest BHs so far

(Abbott et al. PRL 125 (2020) 10, ApJ Lett 900 (2020) L13)

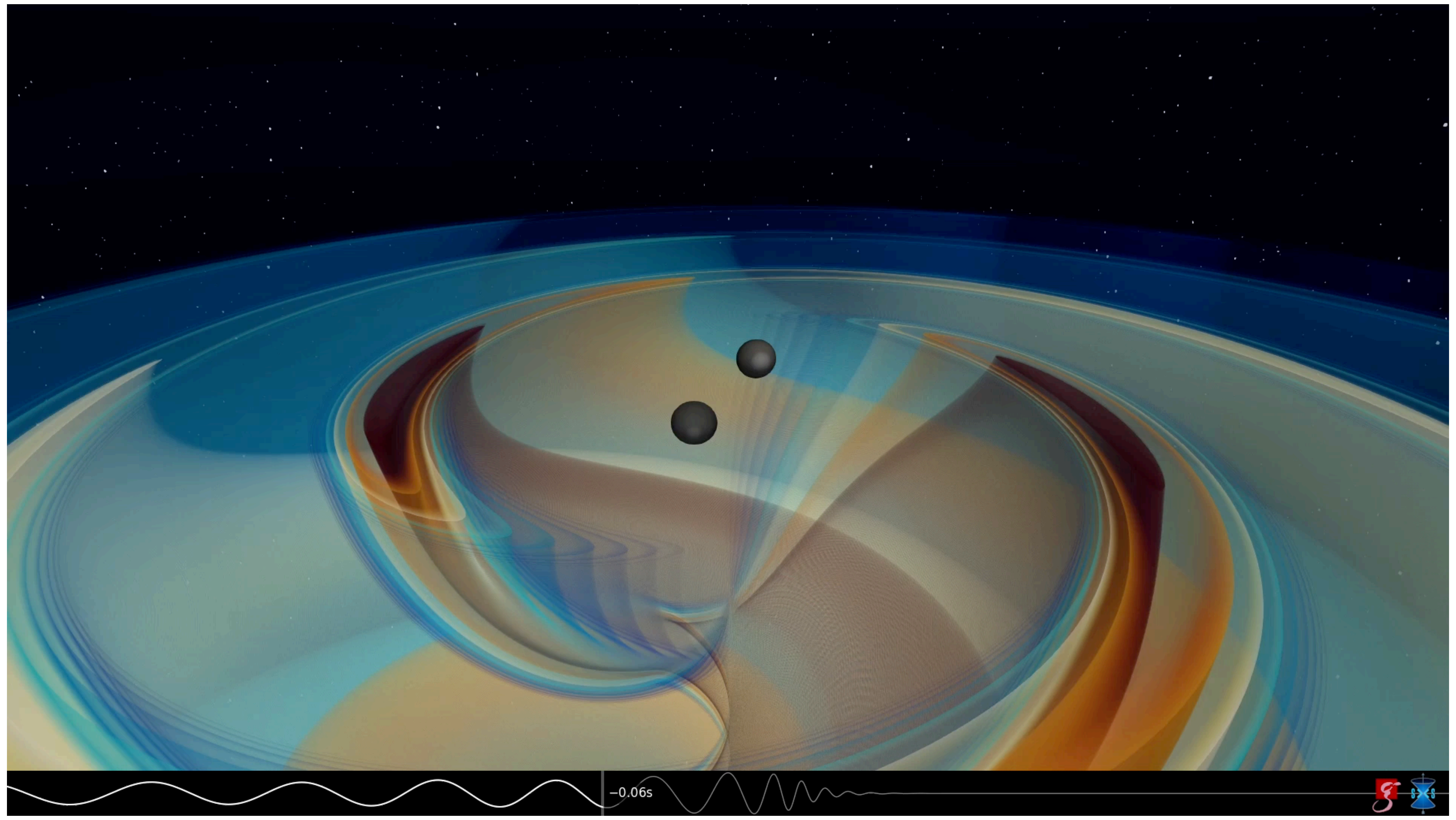
- Likely, BHs **too massive** to have been formed **from a collapsed star, because of Pair-Instability SN (high mass gap).**

$$m_1 = 91.4^{+29.3}_{-17.5}\,M_\odot \qquad m_2 = 66.8^{+20.7}_{-20.7}\,M_\odot$$

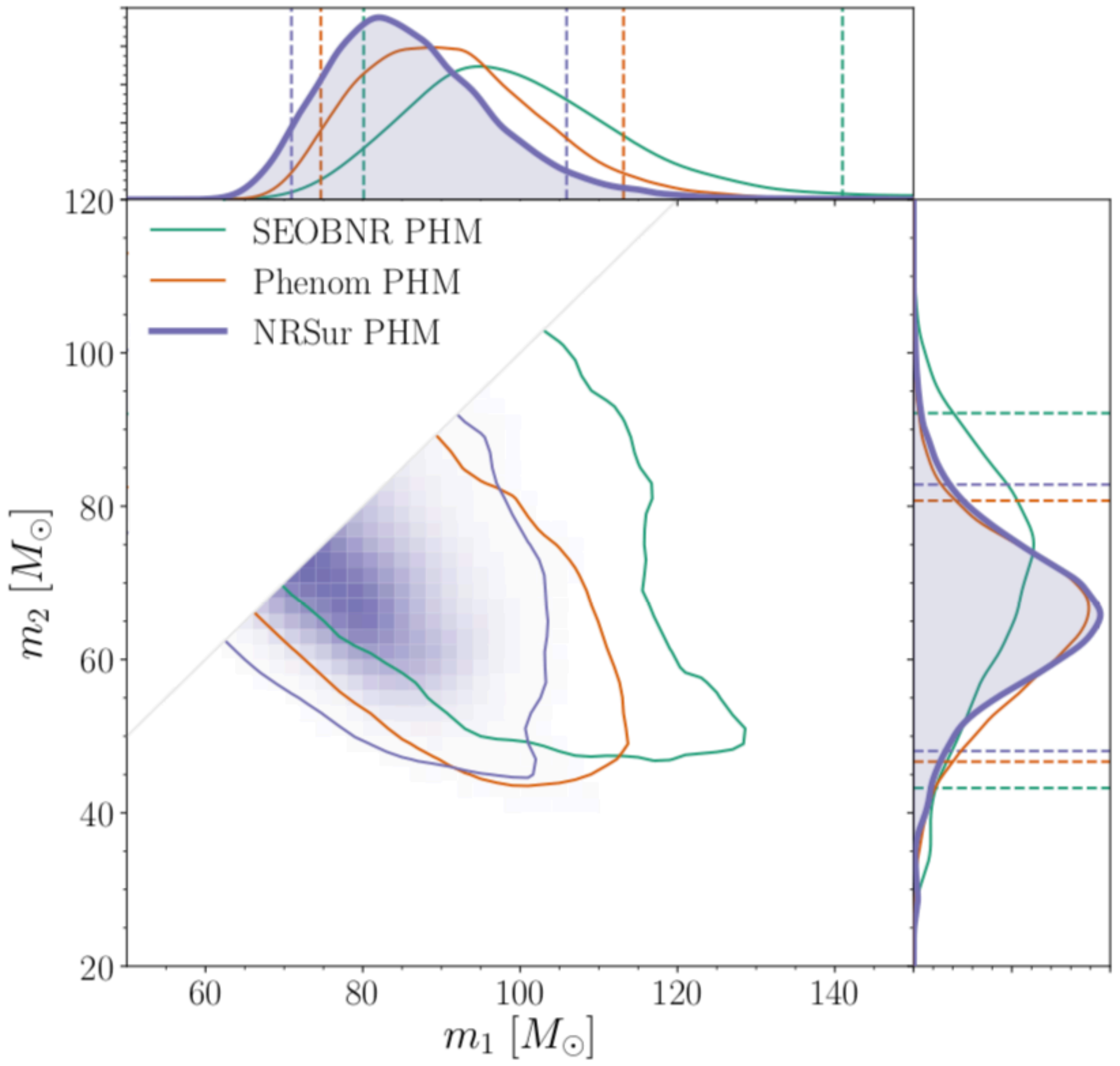
$$q = m_1/m_2 \qquad \chi_1 = S_1/m_1^2 \qquad \chi_2 = S_2/m_2^2$$

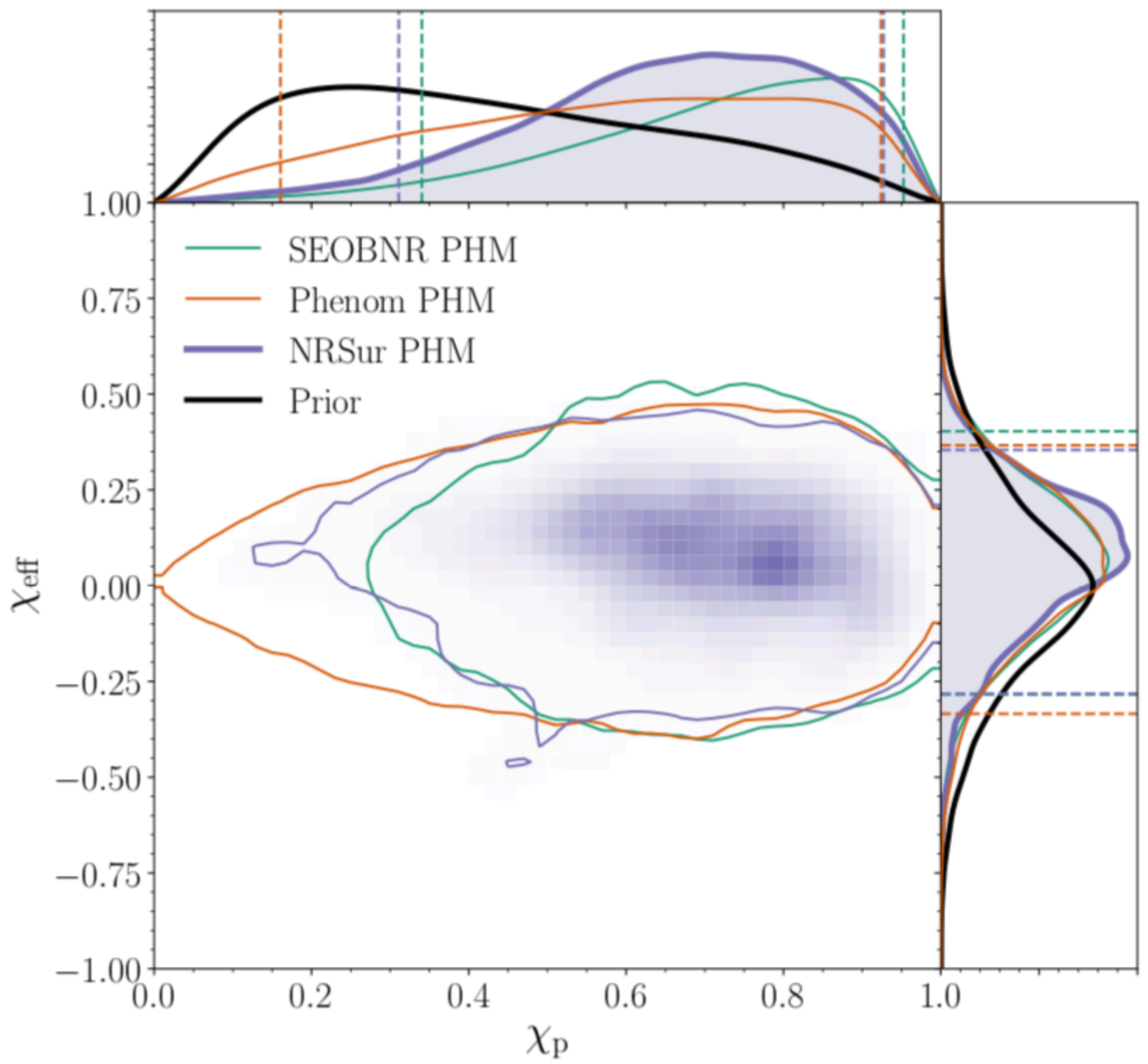
$$\chi_{\rm eff} = \left(\frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2\right)\cdot \hat{\mathbf{L}}$$

χ_p measures the spin components on the orbital plane



(credit: Fischer, Pfeiffer & AB; SXS Collaboration)

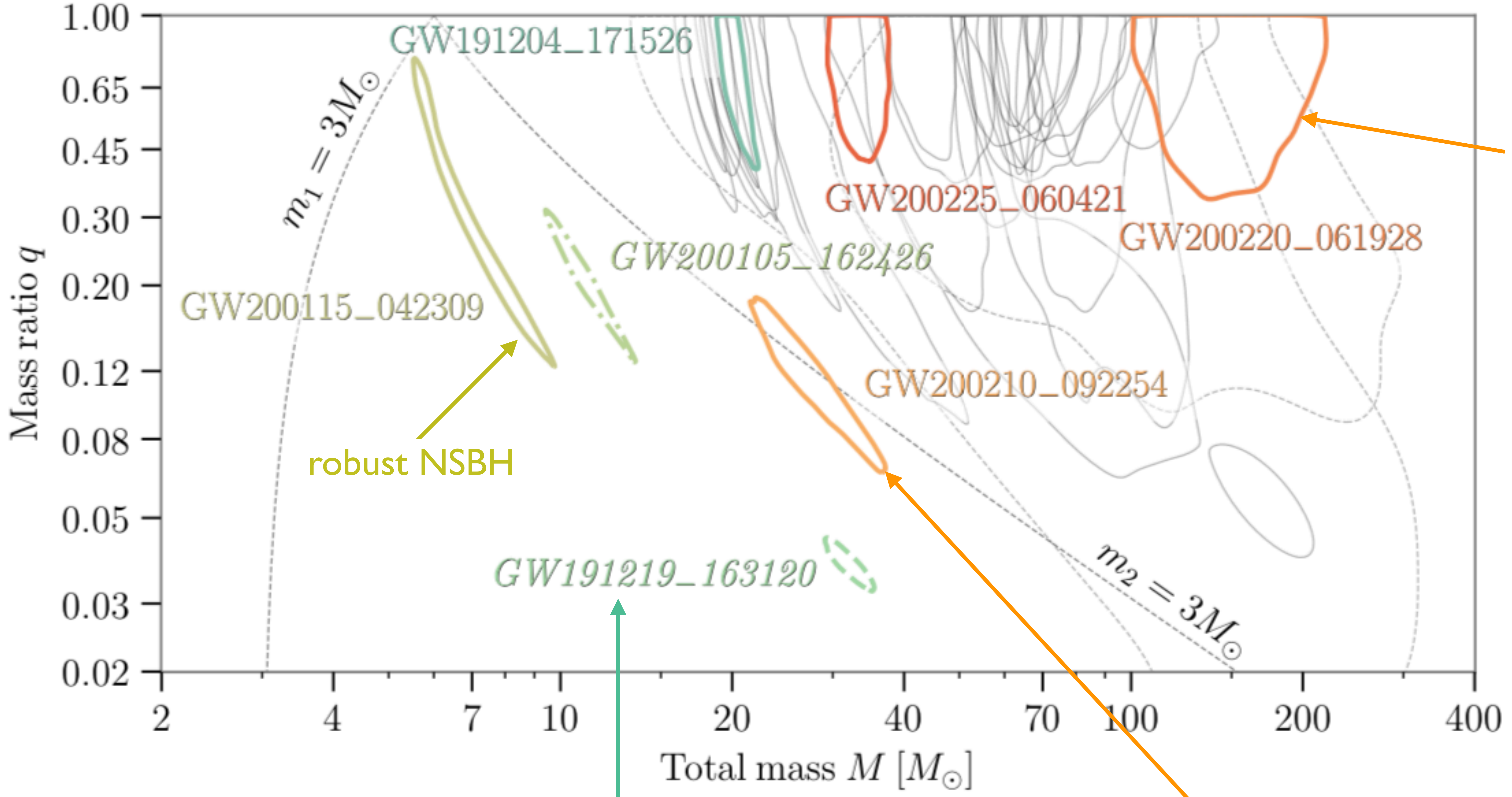




- **Systematics** due to waveform modeling **are not negligible when spin precession** and **higher modes are relevant,** but they are still **subdominant with respect to statistical uncertainty.**

Gravitational-Wave Transient Catalog 3: Source Properties

(Abbott et al. arXiv:2111.03606)



Highest total mass in O3b, furthest away (6 Gpc)

robust NSBH

maybe a NSBH; most asymmetric binary, so far

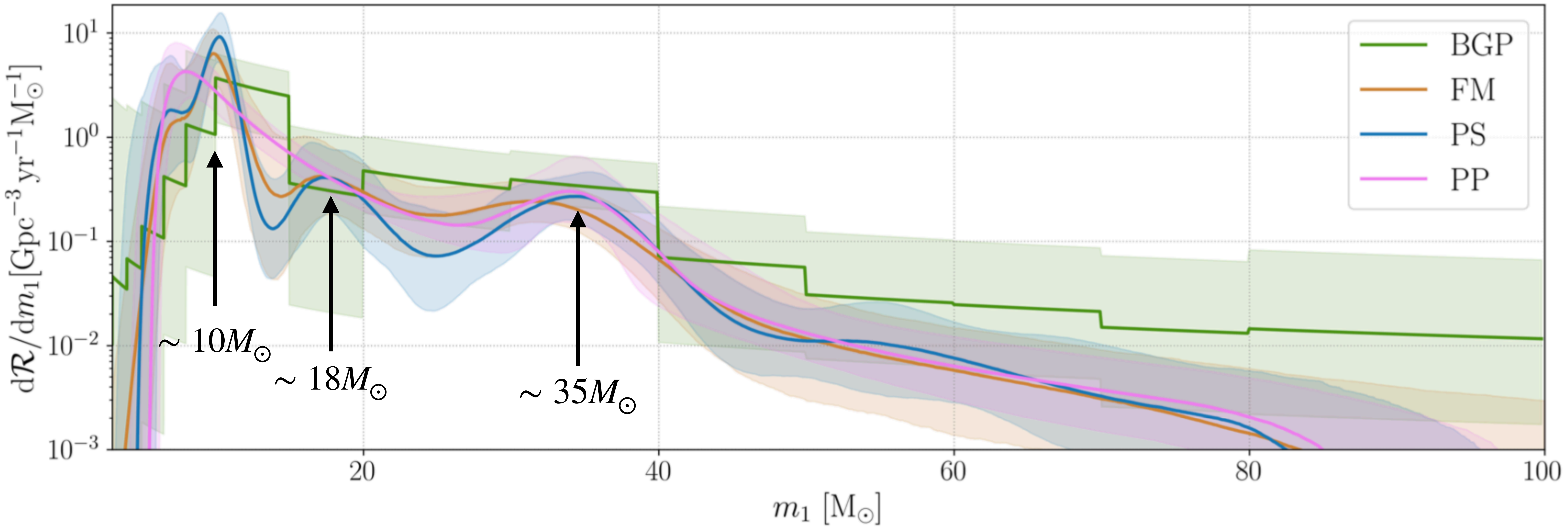
with a puzzling companion

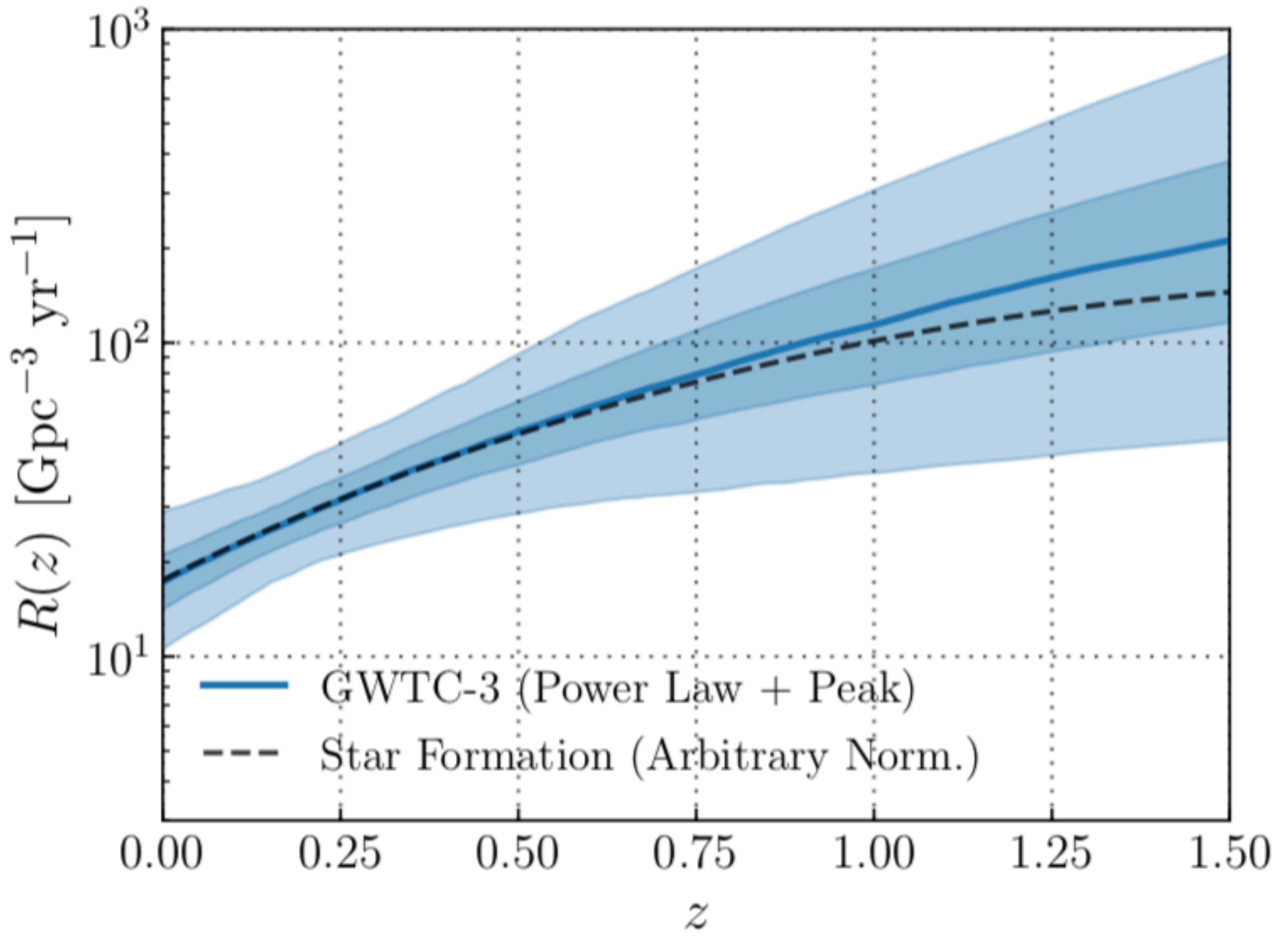
Gravitational-Wave Transient Catalog 3: Primary-Mass Properties

Using hierarchical Bayesian approach

- BBH primary-mass spectrum is **not well-described as simple power-law $p(m_1) \propto m_1^{-\alpha}$, with abrupt cut-off**.
- **Strong statistical preference** for other mass-distribution models with **non-trivial features. No evidence** of a strongly **suppressed merger rate above $\sim 60 M_\odot$**.
- **Dearth of BBHs** with masses between $\sim 2.6\, M_\odot$ **and** $\sim 6\, M_\odot$.
- **Merger rate increases with redshift**, consistent with evolution tracing star formation.

astrophysical merger-rate density

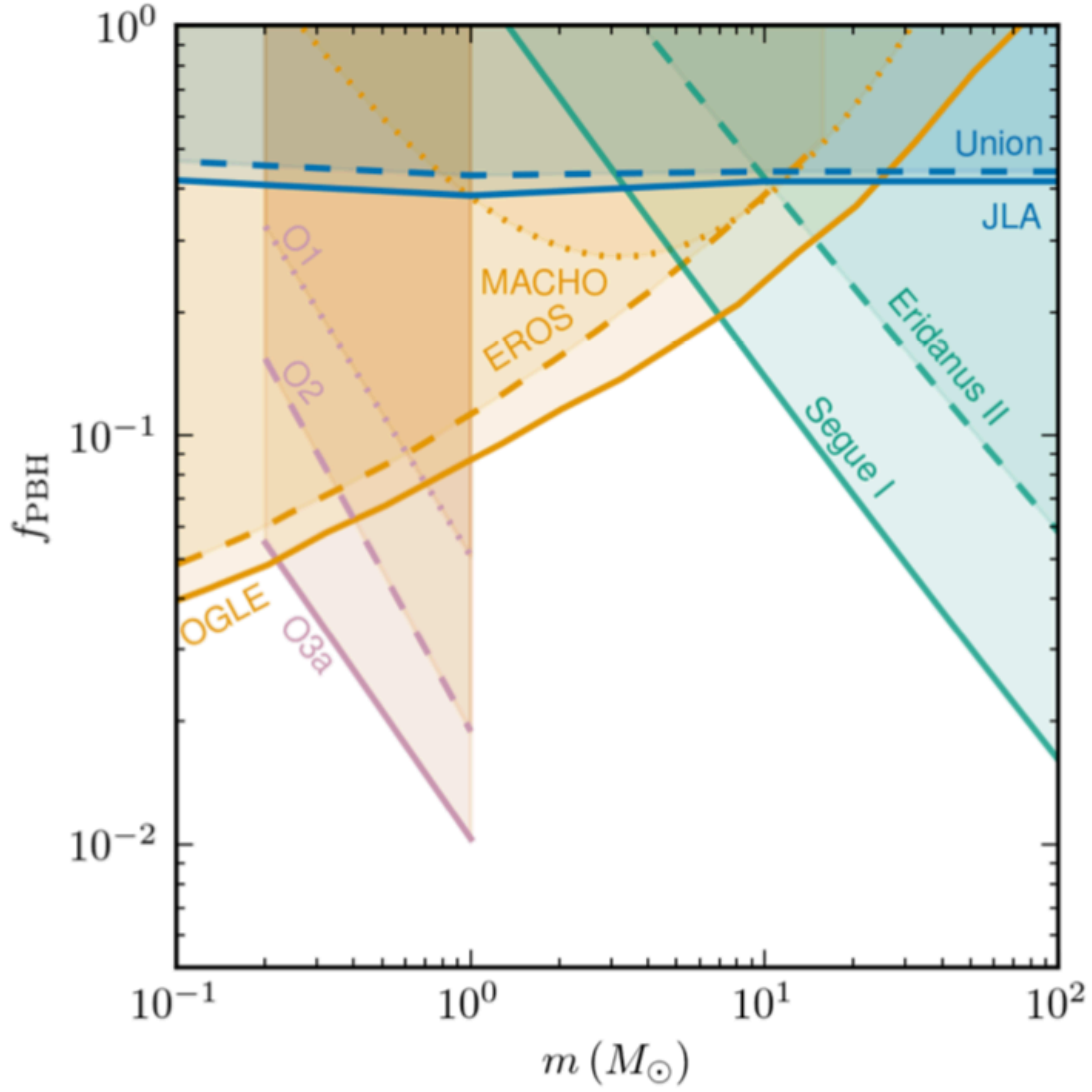




(Abbott et al. arXiv:2111.03634)

Constraints on Sub-Solar Ultra-Compact Binaries

- Search with binary **component masses** in the range $0.2 - 1\, M_\odot$ and **no spin**. Bank of about one-million templates.
- We do **not expect BHs/NSs** to **form** in this mass range **through conventional stellar evolution**. BHs could **form in primordial Universe** through large density fluctuations.

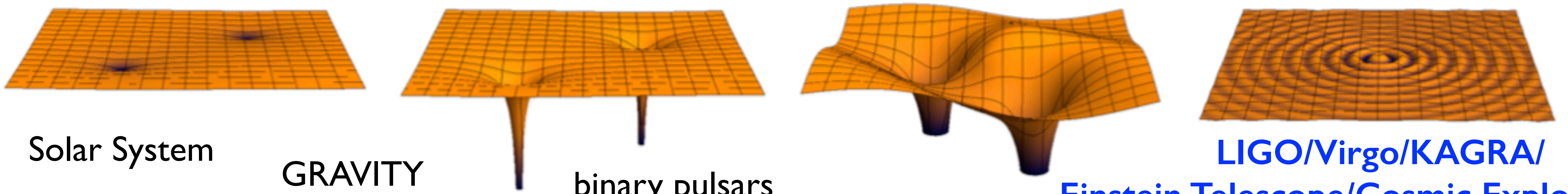


(Abbott et al. 2109.12197)

Tests of General Relativity

strong and highly dynamical regime

(Wex 2014)



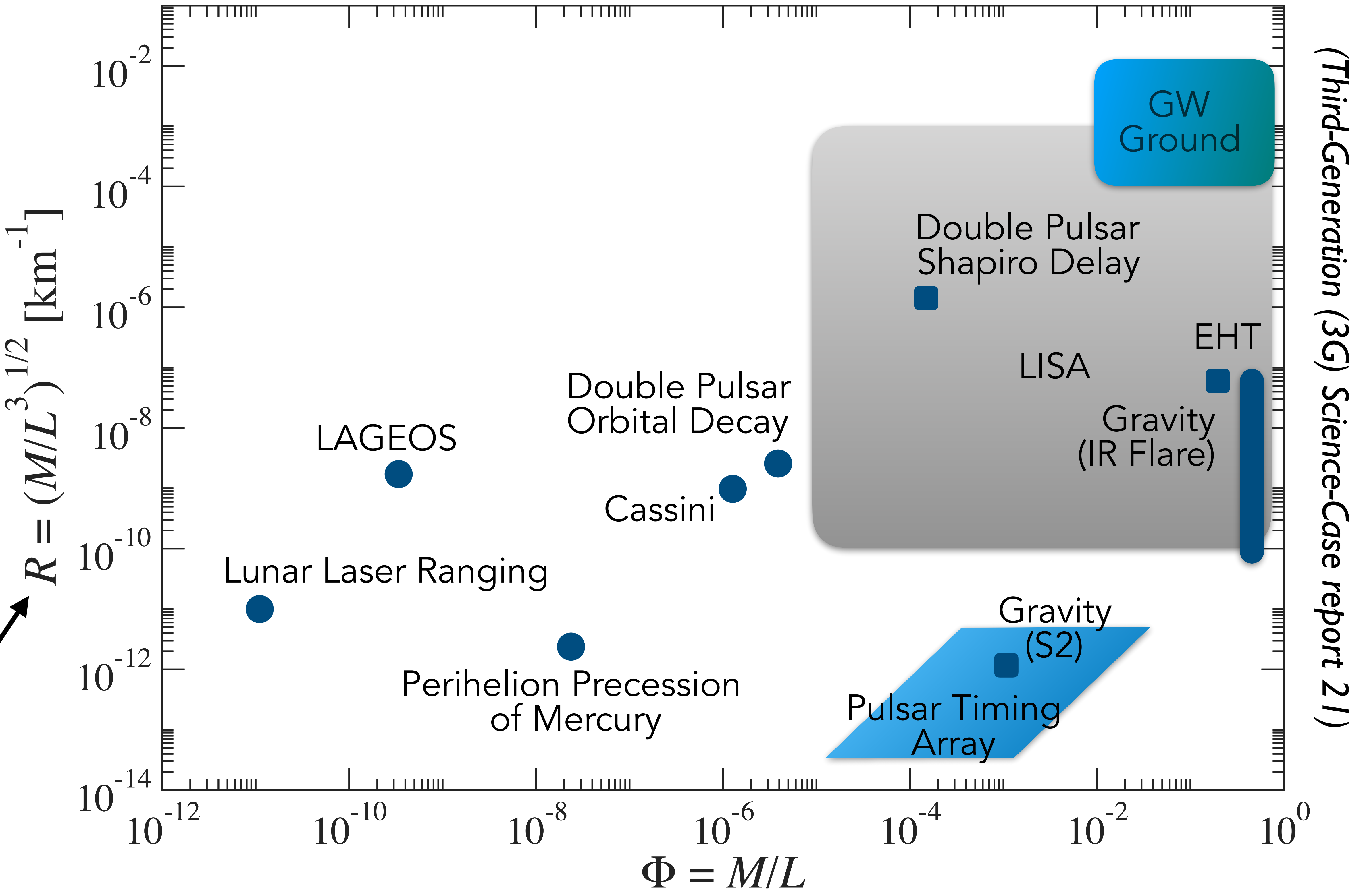
Solar System

GRAVITY

Event Horizon Telescope

binary pulsars

LIGO/Virgo/KAGRA/
Einstein Telescope/Cosmic Explorer/LISA



curvature

Parameterized Test of GW Generation: Phasing

- BBHs/BNS/NSBH **rapidly varying orbital periods** allow us to **probe gravitational phase** (phasing) of GW signals.

- Inspiral(-Plunge):

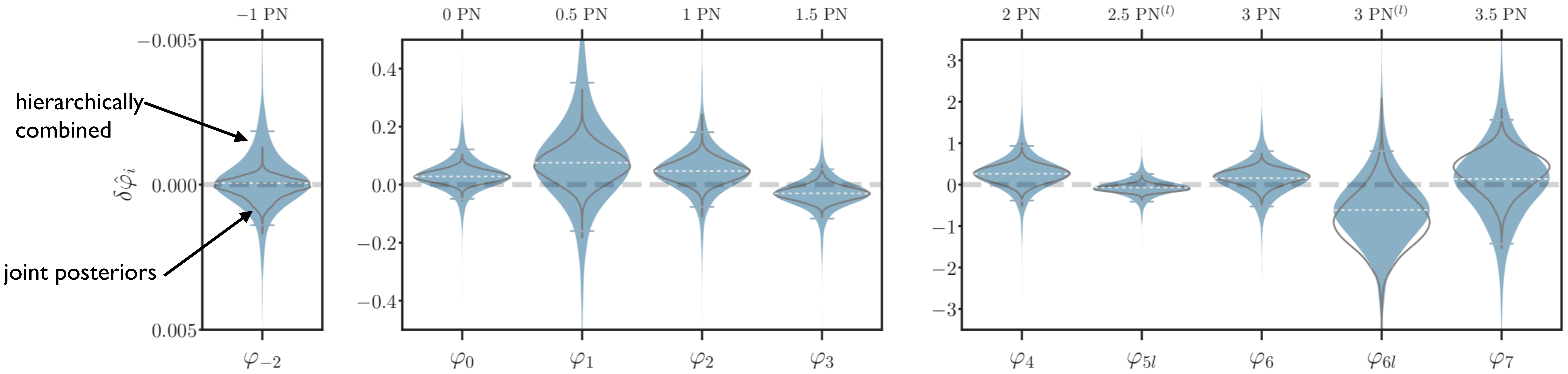
(Blanchet & Sathyaprakash 1995, Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

$$h_{\rm GW}(f) = \mathcal{A}_{\rm GW}(f)\, e^{i\varphi_{\rm GW}(f)} \qquad \varphi_{\rm GW}(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + v^{-5}\left[\sum_{n=-2}^{7} \varphi_n^{\rm (GR)}(1+\delta\hat{\varphi}_n)v^n + \sum_{n=5}^{6} \varphi_{n\,\ell}^{\rm (GR)}(1+\delta\hat{\varphi}_{n\,\ell})v^n \log v\right]$$

$$v = (\pi M f)^{1/3}$$

- **PN parameters** describe physical effects: **spin-orbit** and **spin-spin** couplings, **tidal** and **absorption** effects, **tails** of radiation due to backscattering with warped geometry.

inspiral-plunge



GR is at $\delta\hat{\varphi}_i = 0$

(Abbott et al. arXiv:2112.06861, Mehta, AB, Cotesta, Ghosh & Steinhoff 22)

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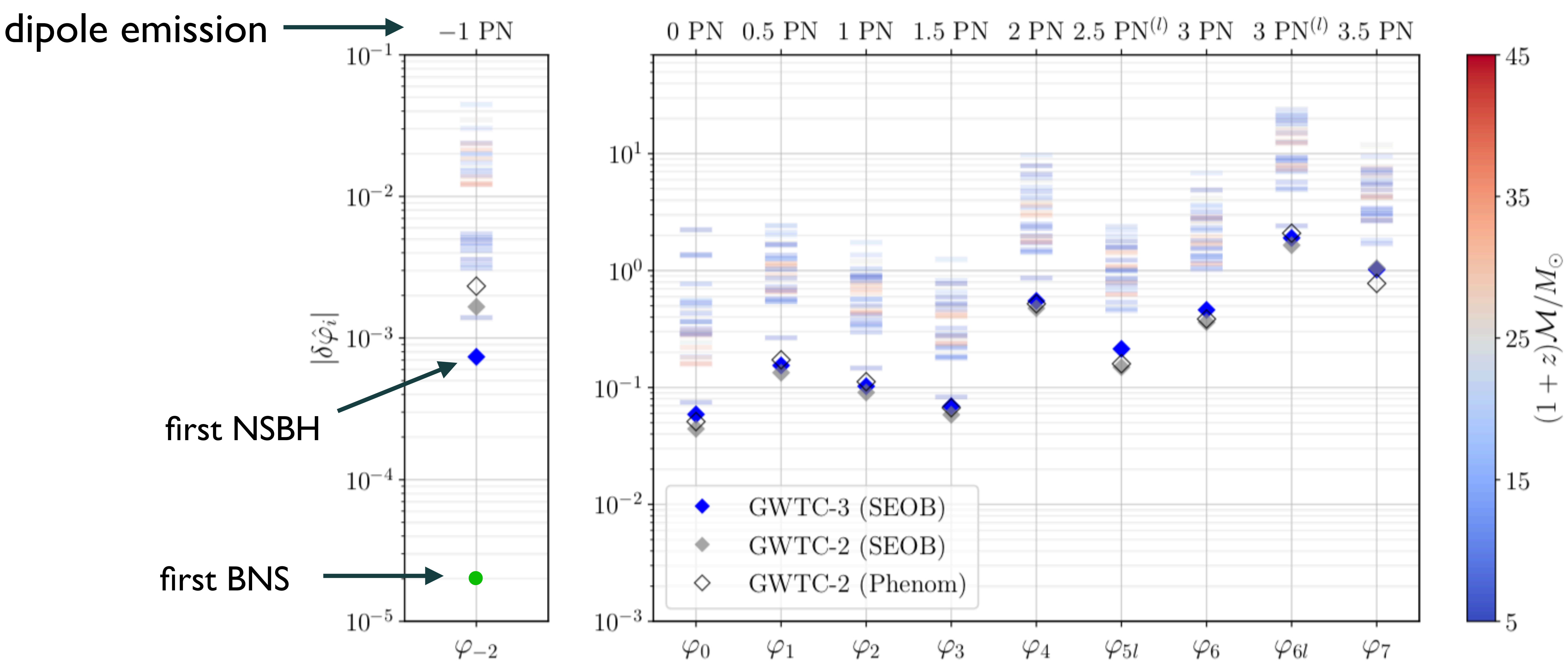
inspiral(-plunge)



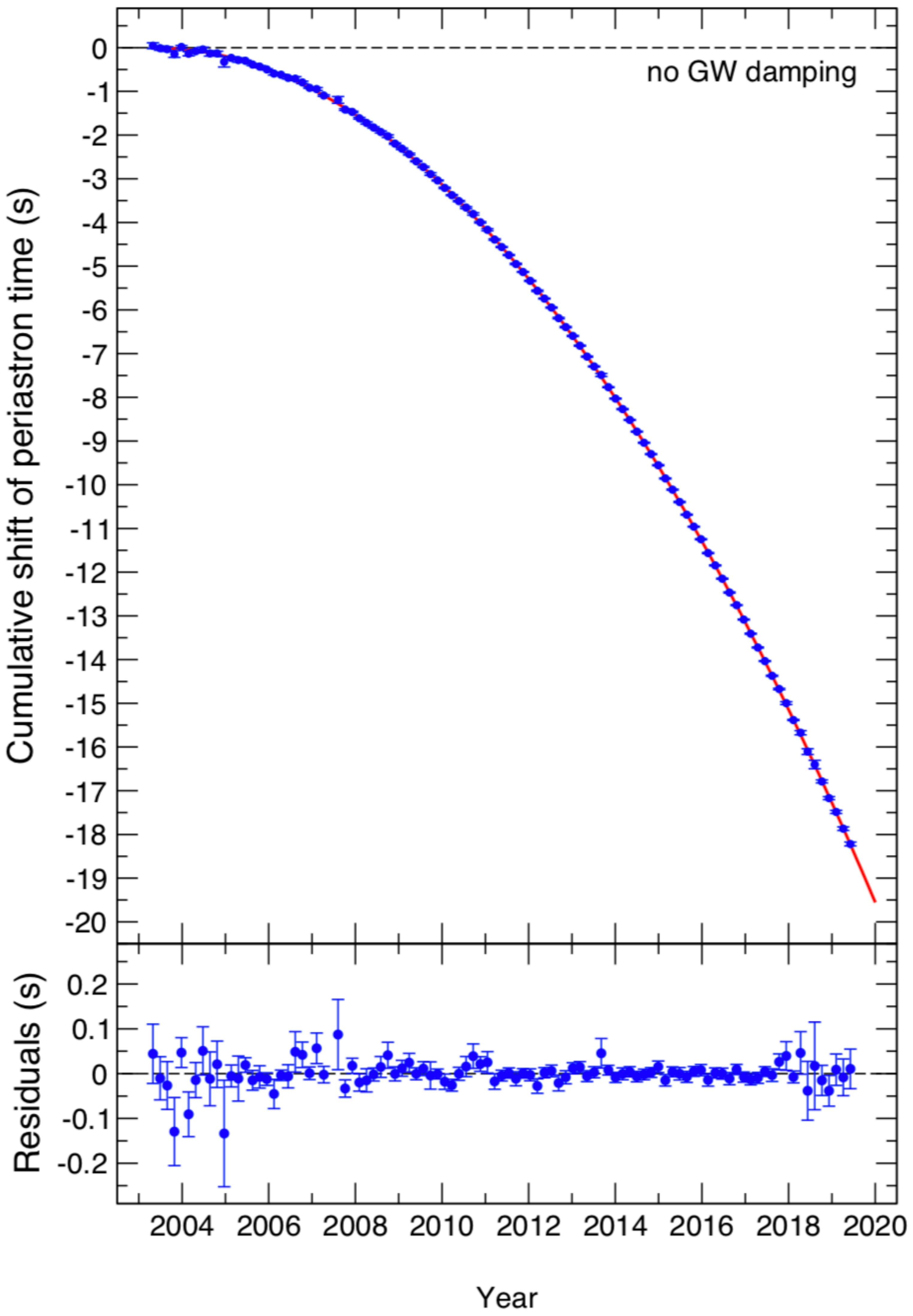
(Abbott et al. arXiv:2112.06861, Agathos et al. 14, Mehta, AB, Cotesta, Ghosh & Steinhoff 22)

- Tests of **non-perturbative phenomena** (e.g., dynamical scalarization) **require full waveform models** in modified theories of gravity.

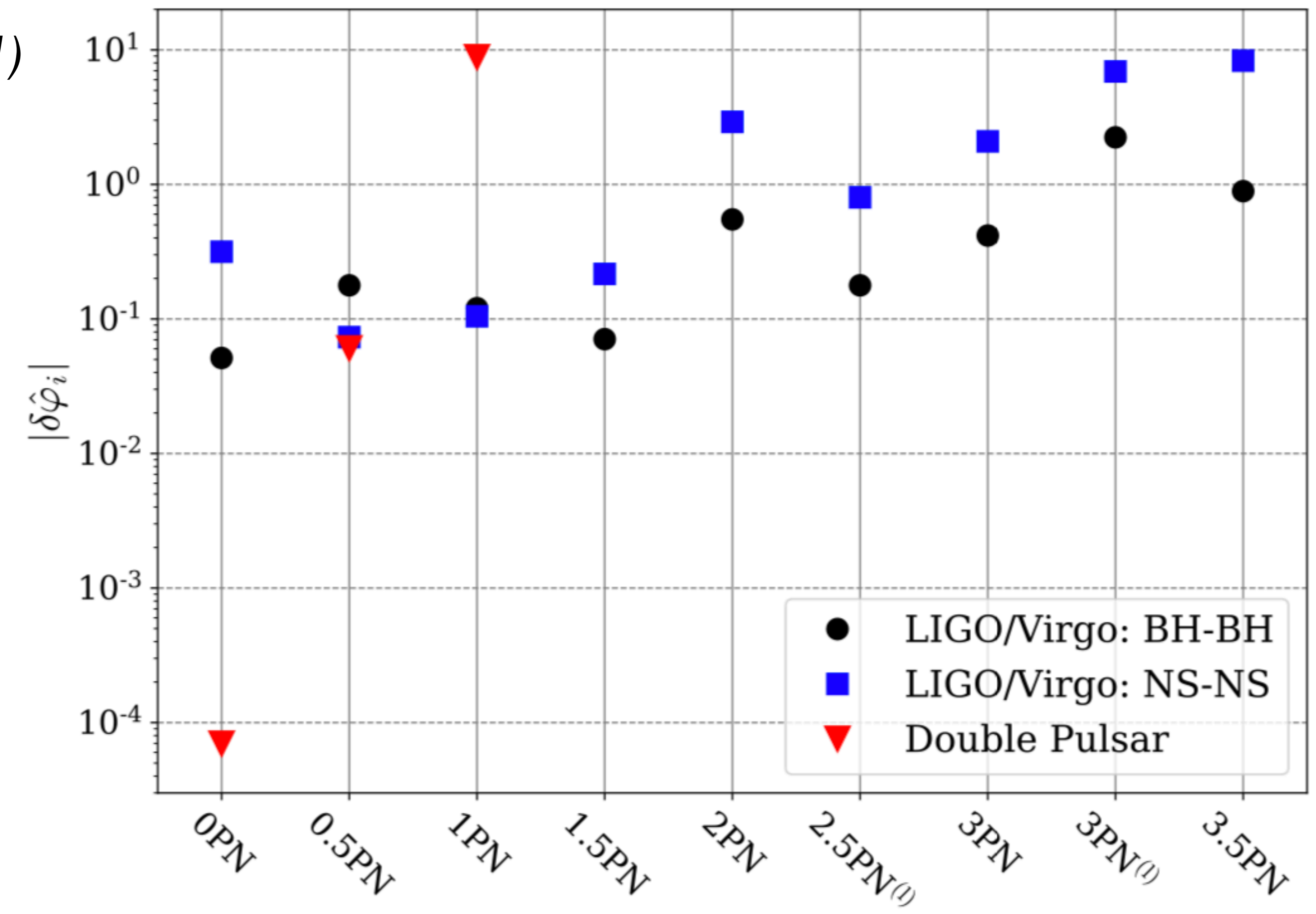
(Damour & Esposito-Farese 1992, Barausse et al. 13, Shibata, … AB 14, Palenzuela et al. 14, Witek et al. 19, Herderio et al. 21, Silva et al. 21, Elley et al. 22)

Comparing LIGO-Virgo Bounds on PN Parameters with Double Pulsar

PSR J0737-3039 A/B (Double Pulsar)



(Kramer et al. 21)



- Since 2003, about **60,000 orbital cycles were tracked** with high precision in a phase-coherent timing solution.
- Double-Pulsar observation constrains leading, **quadrupole radiation much more tightly** (i.e., low PN-orders).
- Due to **much smaller velocity** $v/c \sim 2 \times 10^{-3}$, Double-Pulsar observation becomes very quickly **less constraining** for high PN orders.
- Future GW detectors in space and on the ground will **improve considerably such bounds**. *(e.g., Perkins et al. 21)*

Tests of GR with GW Observations: Remnant Properties

- In GR, **remnant object** resulting from coalescence of two astrophysical BHs **is a perturbed Kerr BH**.

- The remnant **BH relaxes** to its stationary Kerr state **by emitting quasi-normal modes (QNMs).**

(Vishveshwara 70, Press 71, Chandrasekhar et al. 75)

- The QNM's **frequencies and decay times** only depend on **BH's mass and spin** (no-hair conjecture).

(Israel 69, Carter 71; Hawking 71, Bardeen 73)

- The **no-hair conjecture can be disproved** if more than one QNM is observed

(Dreyer et al. 2004, Berti et al. 2006, Gossan et al. 2012, Meidam et al. 2014, Giesler et al. 19)

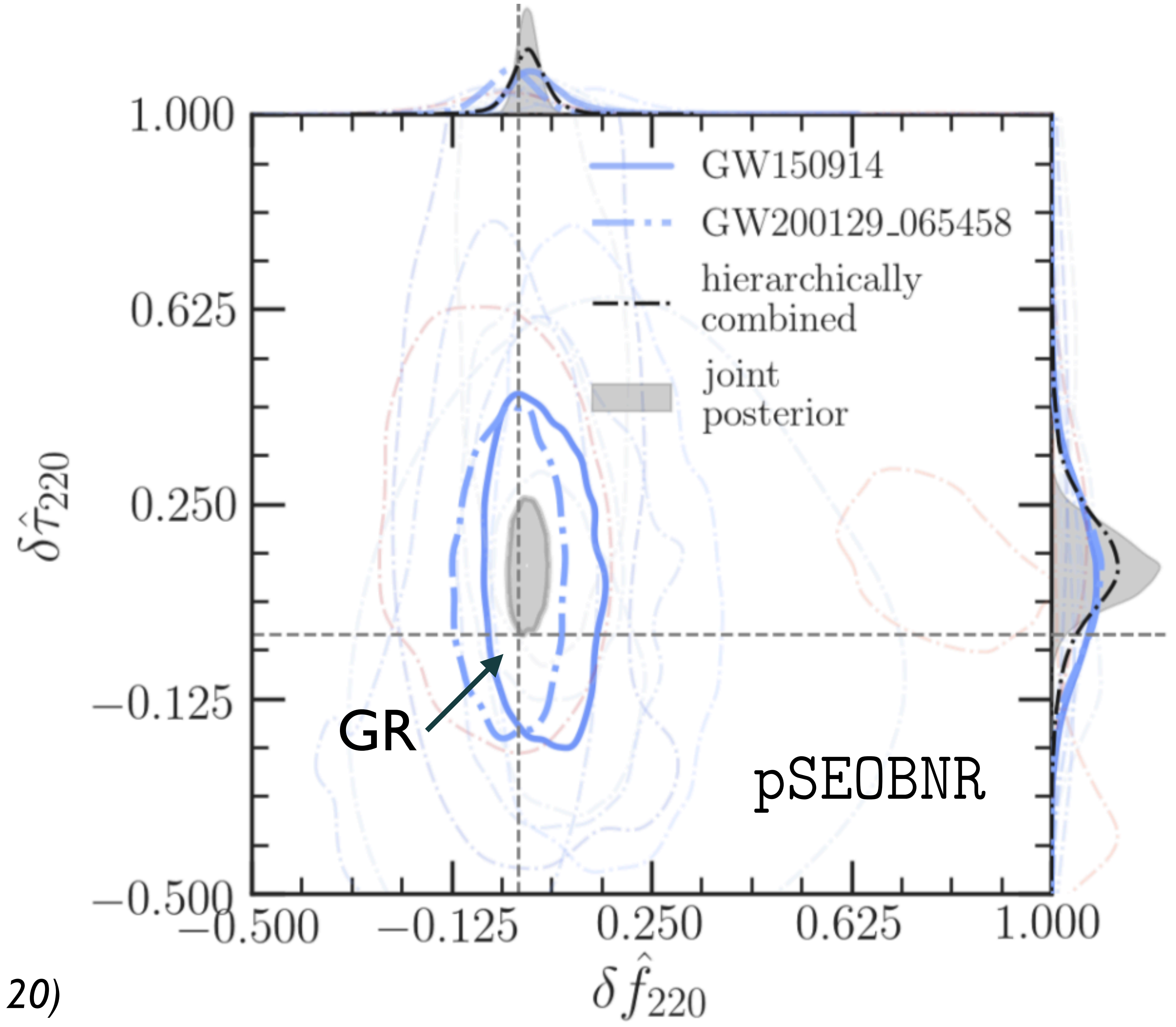
- **Inspiral-merger-ringdown** waveform model **with parameterized QNM**'s frequency and decay time (pSEOBNR):

(Abbott et al. PRL 116 (2016) 221101, PRD 103 (2021) 12, 122002, Brito, AB & Raymond 18, Ghosh, Brito & AB 21)

$$f_{\ell m0} = f_{\ell m0}^{\rm GR}(1 + \delta\hat{f}_{\ell m0}) \qquad \delta\hat{f}_{220} = 0.02^{+0.07}_{-0.07}$$

$$\tau_{\ell m0} = \tau_{\ell m0}^{\rm GR}(1 + \delta\hat{\tau}_{\ell m0}) \qquad \delta\hat{\tau}_{220} = 0.13^{+0.21}_{-0.22}$$

(Abbott et al. arXiv:2112.06861)



- **QNM decay time** (effective viscosity of dark object) **strongly hints to a BH.**

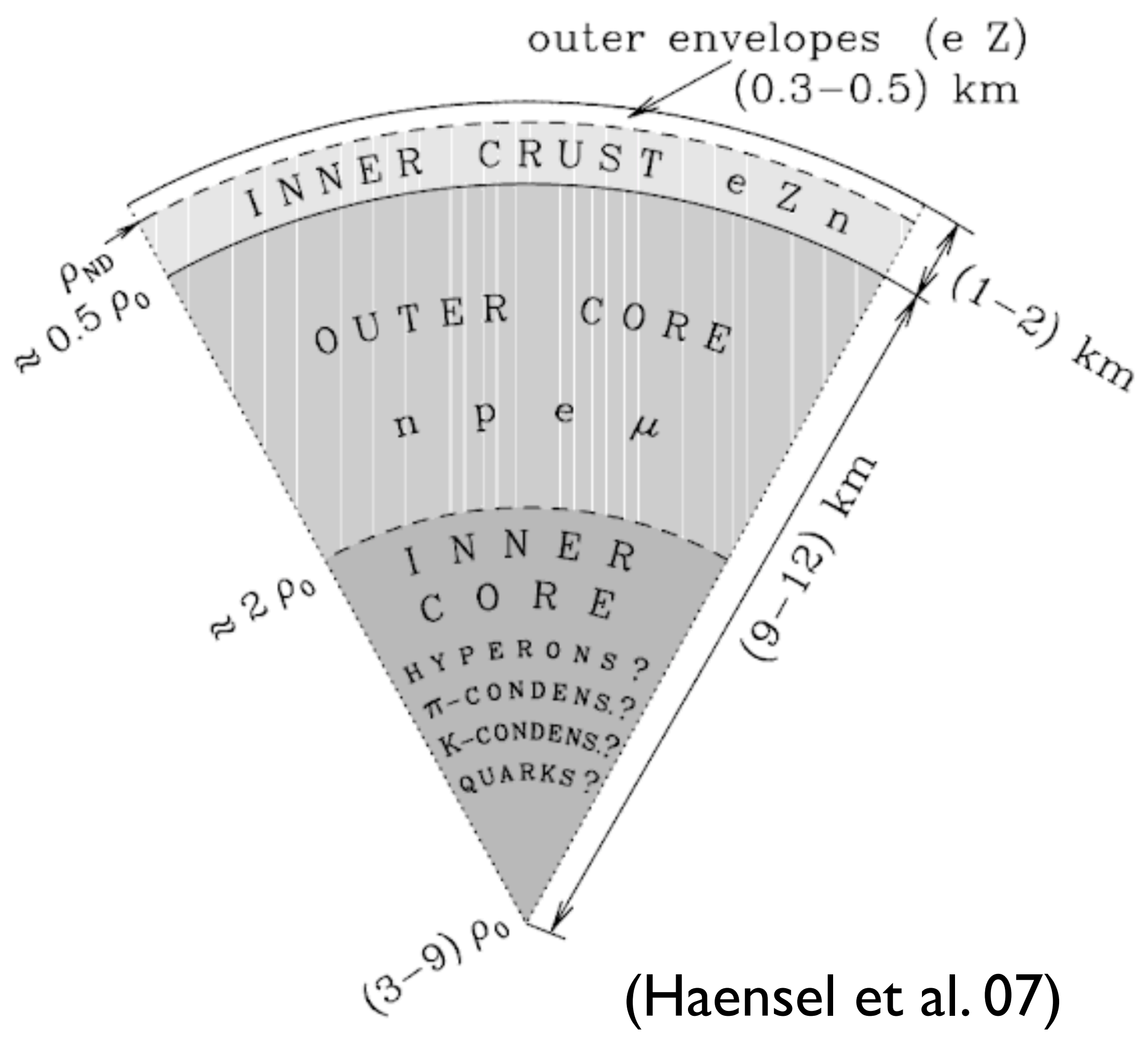
(Yunes & Pretorius 16)

- **These measurements are** already **informing us on the nature** of the **dark object** (compactness, light-ring, horizon, etc). *(Cardoso et al. 18-20, Völkel et al. 20, Maggio et al. 20)*

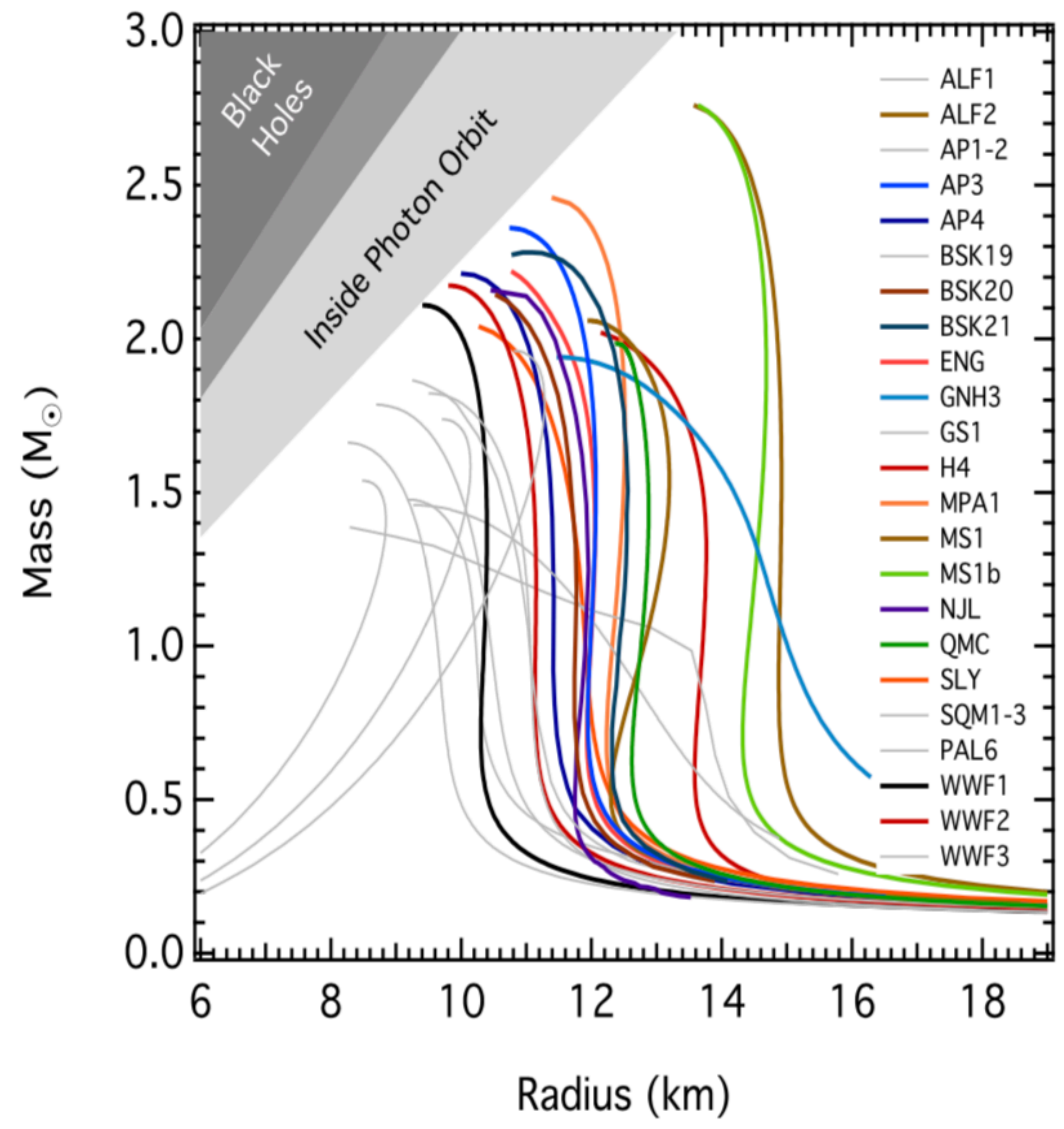
Probing Extreme-Matter with Gravitational Waves

- **Neutron-star (NS)** properties:

- mass: $1 - 3\, M_{\rm Sun}$
- radius: $9 - 15$ km
- inner core density > $2 \times (2.8 \times 10^{14})$ g/cm^3 (nuclear density: 2.8×10^{14})
- magnetic field: ~$10^{15} \times$ @Earth
- surface temperature: ~$10^{3} \times$ @Earth
- pressure: ~$10^{27} \times$ @Earth



(Haensel et al. 07)



(Özel & Freire 2016)

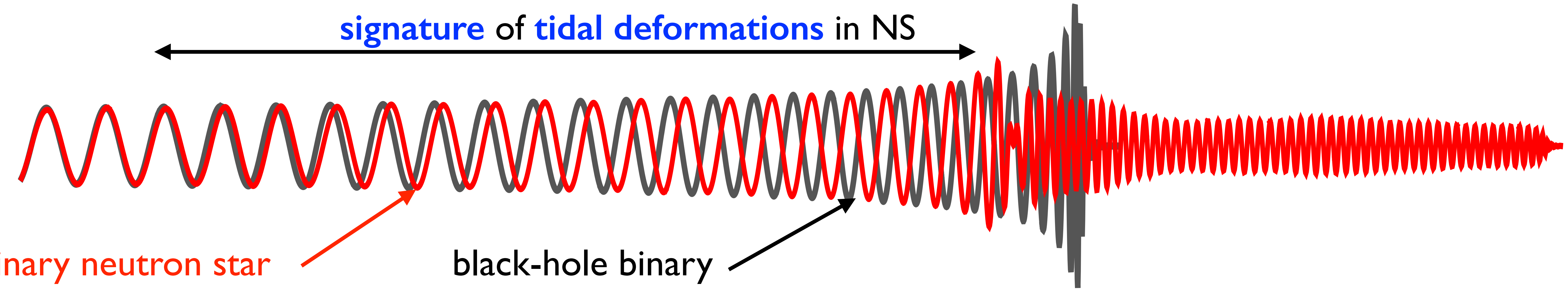
- What is the **internal structure** and **composition** of **neutron stars**?

- **NS equation of state** (EOS) affects gravitational **waveform** during **late inspiral, merger** and **post-merger**.

- New parameter in BNS: **tidal deformability** λ.

$$Q_{ij} = -\,\lambda\, \mathcal{E}_{ij}$$

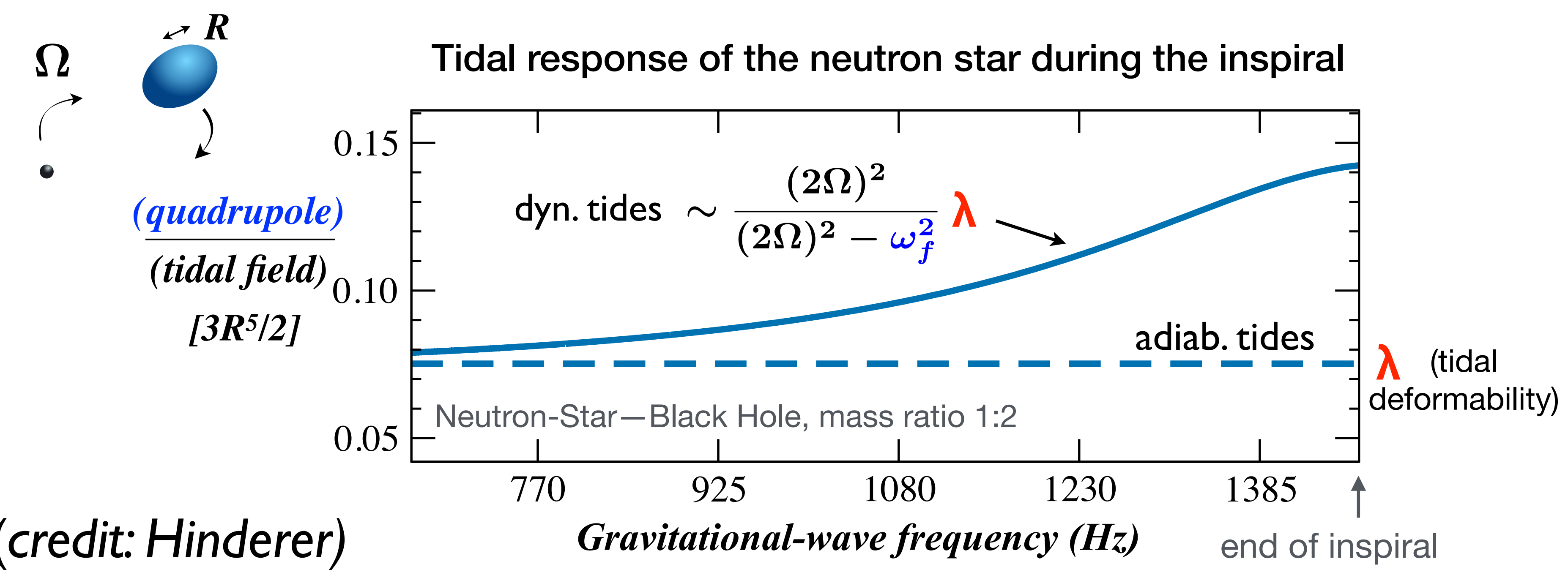
quadrupole moment — depends on EOS — external tidal field



Waveforms for Binary Neutron Stars

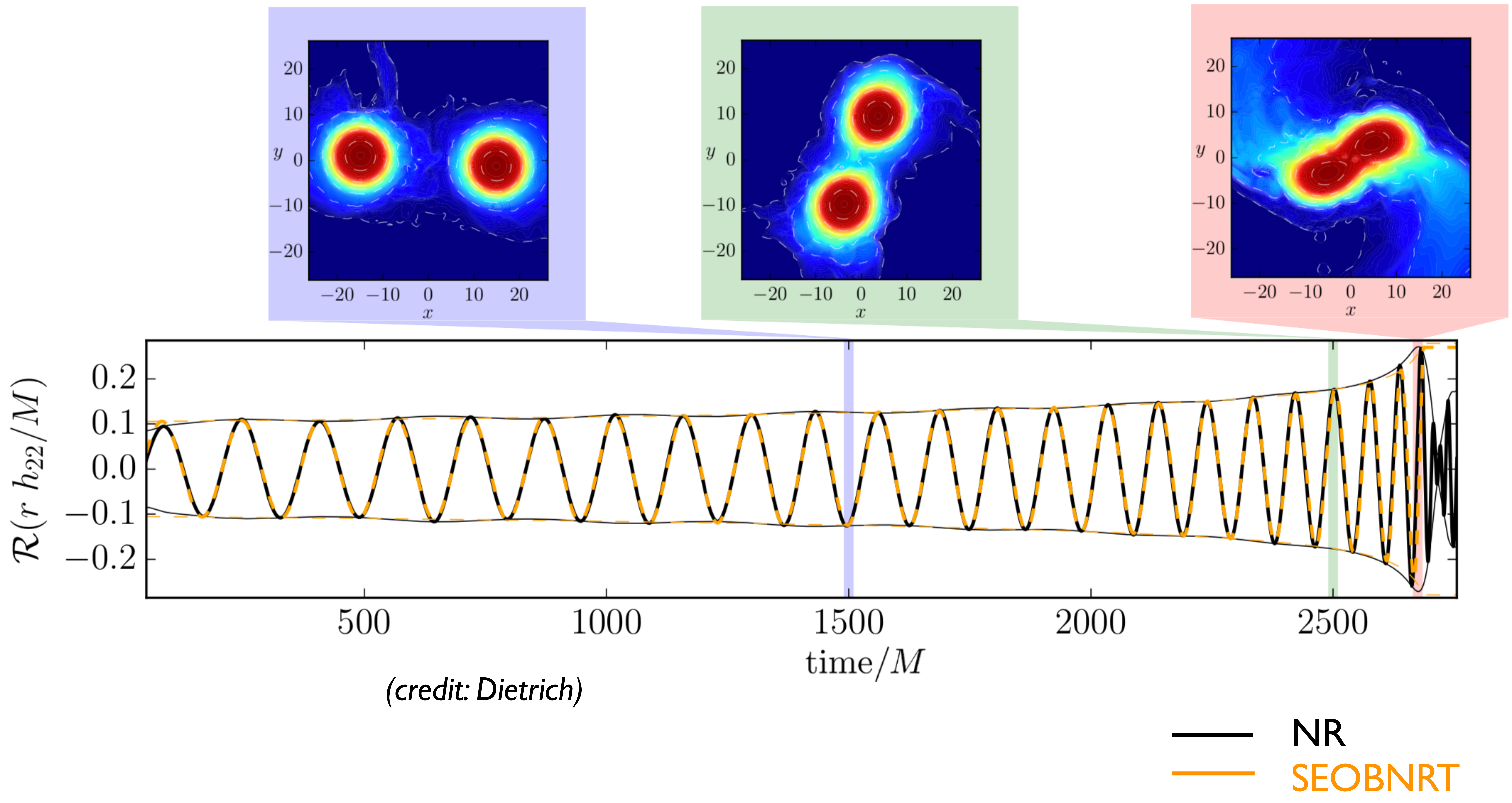
- Synergy between **analytical** and **numerical work** is **crucial.**

- **Dynamical tides**



(credit: Hinderer)

(Hinderer, …AB … et al. 16, Steinhoff, … AB … et al. 16, Steinhoff et al. 21)



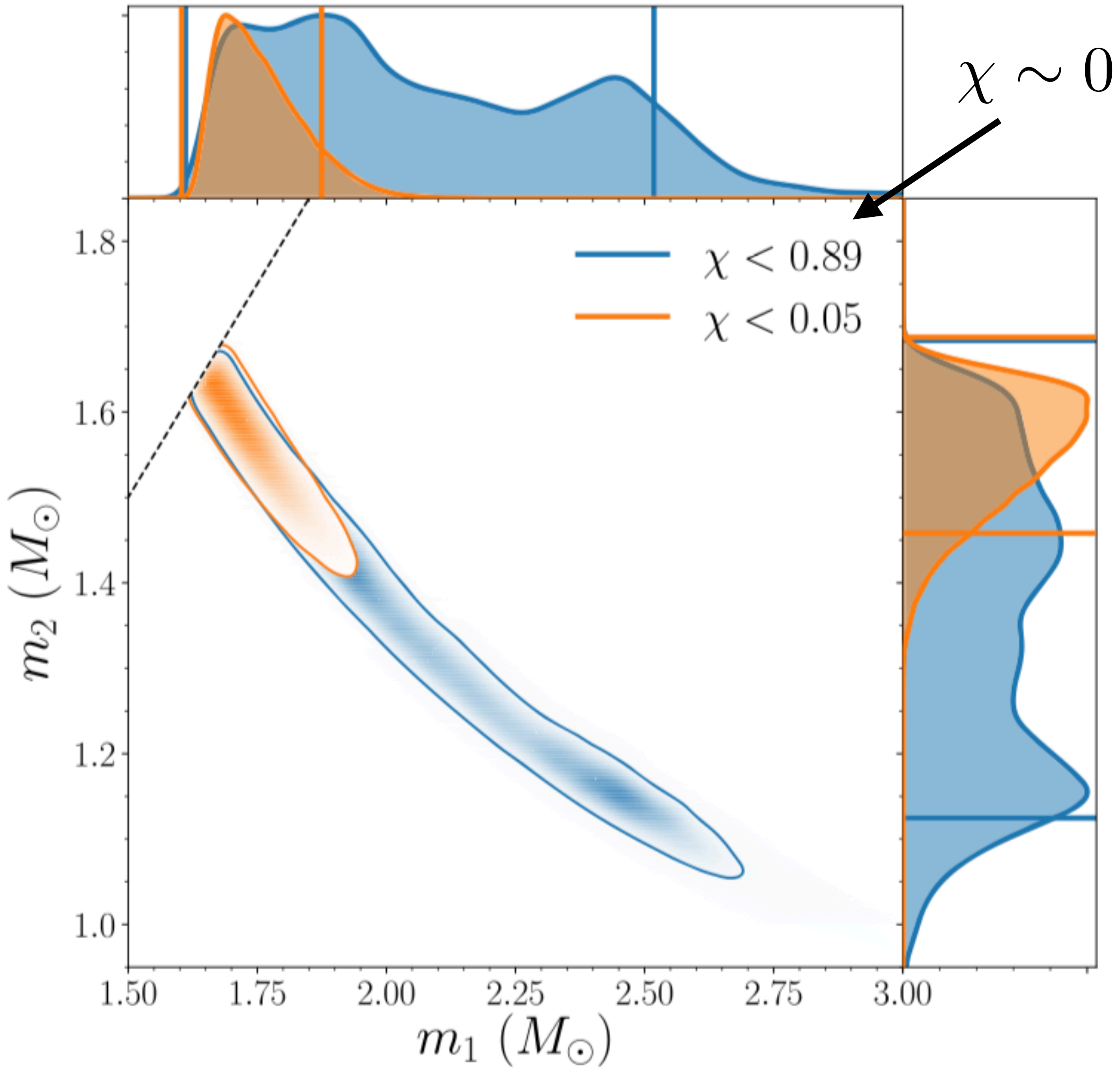
(credit: Dietrich)

(see also Damour 1983, Flanagan & Hinderer 08, Binnington & Poisson 09, Vines et al. 11, Damour & Nagar 09, 12, Bernuzzi et al. 15, Dietrich et al. 17-19, Nagar et al. 18, Gamba et al. 20)

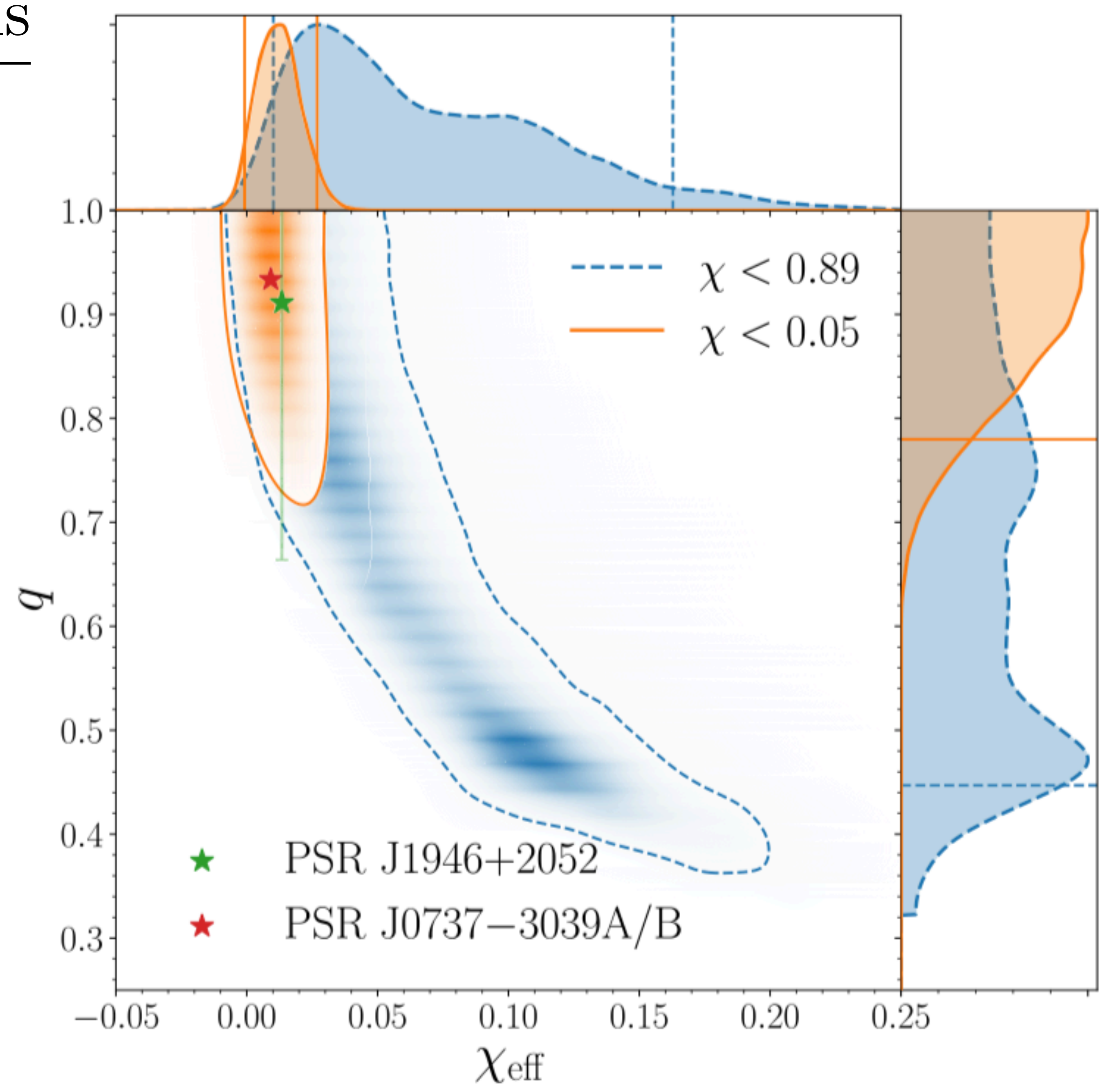
- **BNS waveforms** were used to infer properties **of GW170817 & GW190425**.

GW190425: a Binary Neutron Star with Surprisingly High Mass

(Abbott et al. ApJ Lett 892 (2020))



$\chi \sim 0.4 \frac{1\mathrm{ms}}{T}$



$$q = m_1/m_2$$

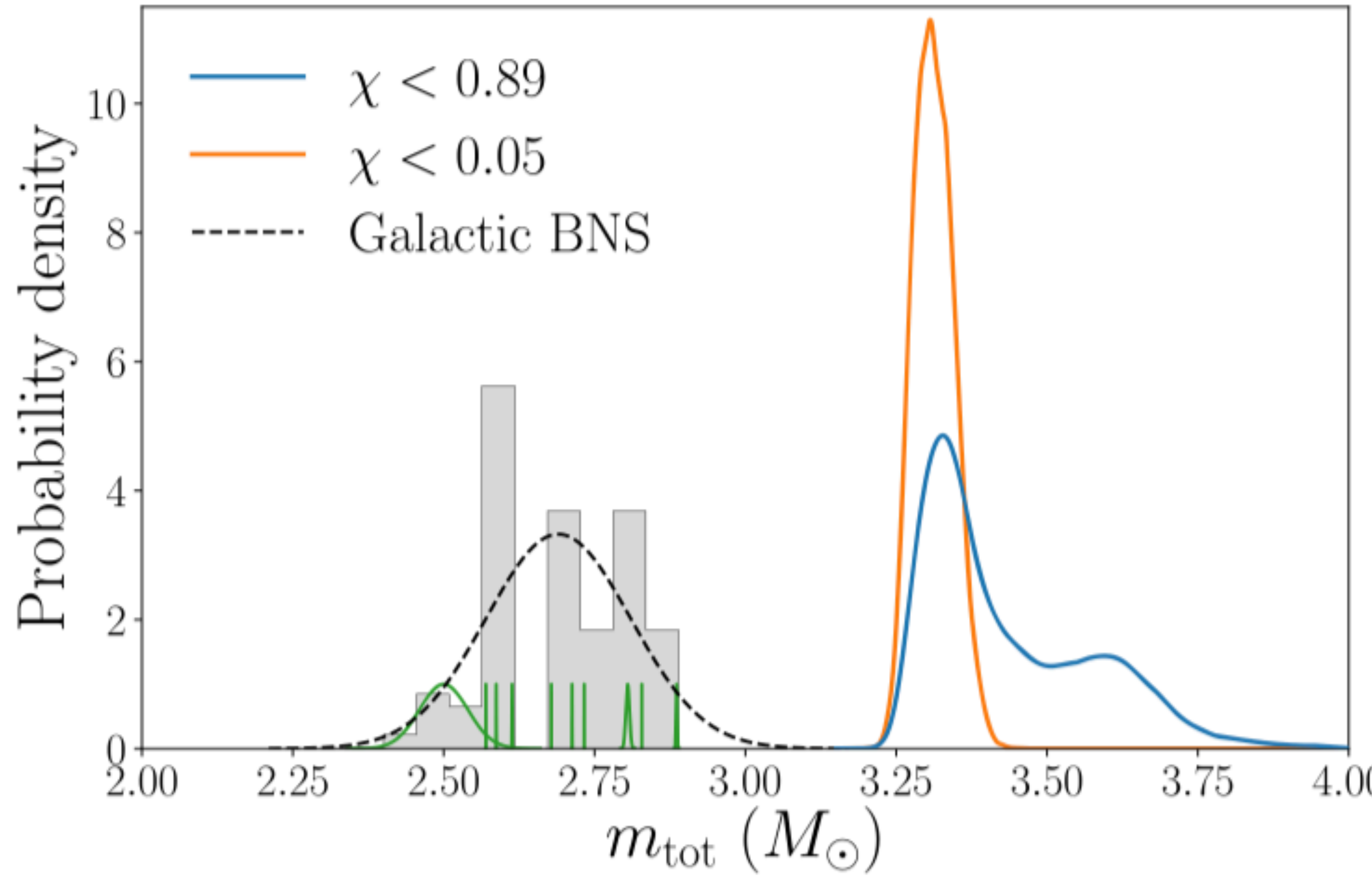
$$\chi_1 = S_1/m_1^2$$

$$\chi_2 = S_2/m_2^2$$

$$\chi_{\mathrm{eff}} = \left(\frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2\right)\cdot\hat{\mathbf{L}}$$

- **GW190425's masses** are **consistent with mass measurements of NSs** in binaries.

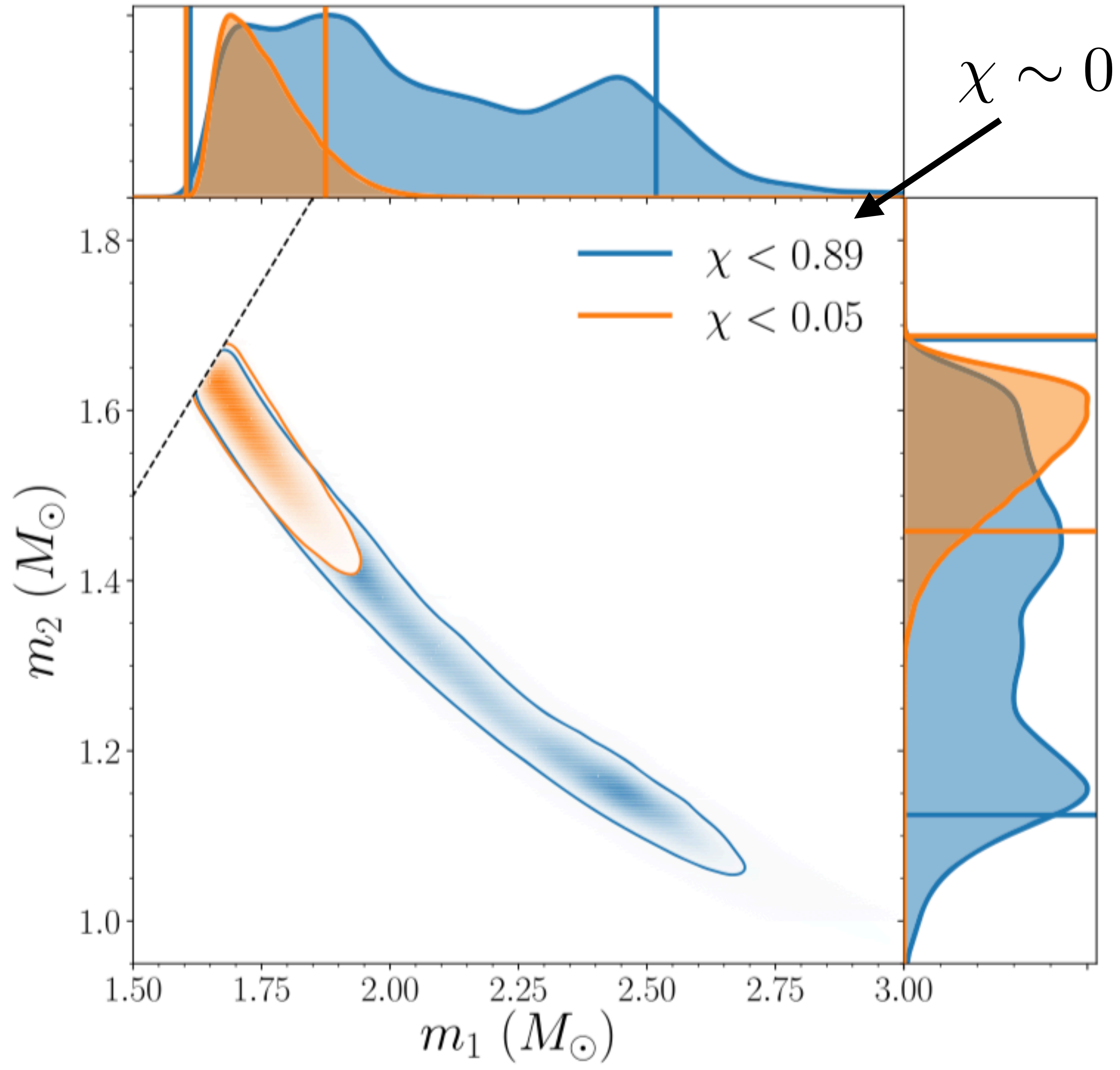
- **GW190425's total mass** $3.4^{+0.3}_{-0.1} M_\odot$ is larger than BNSs in our galaxy: **new population of BNS?**

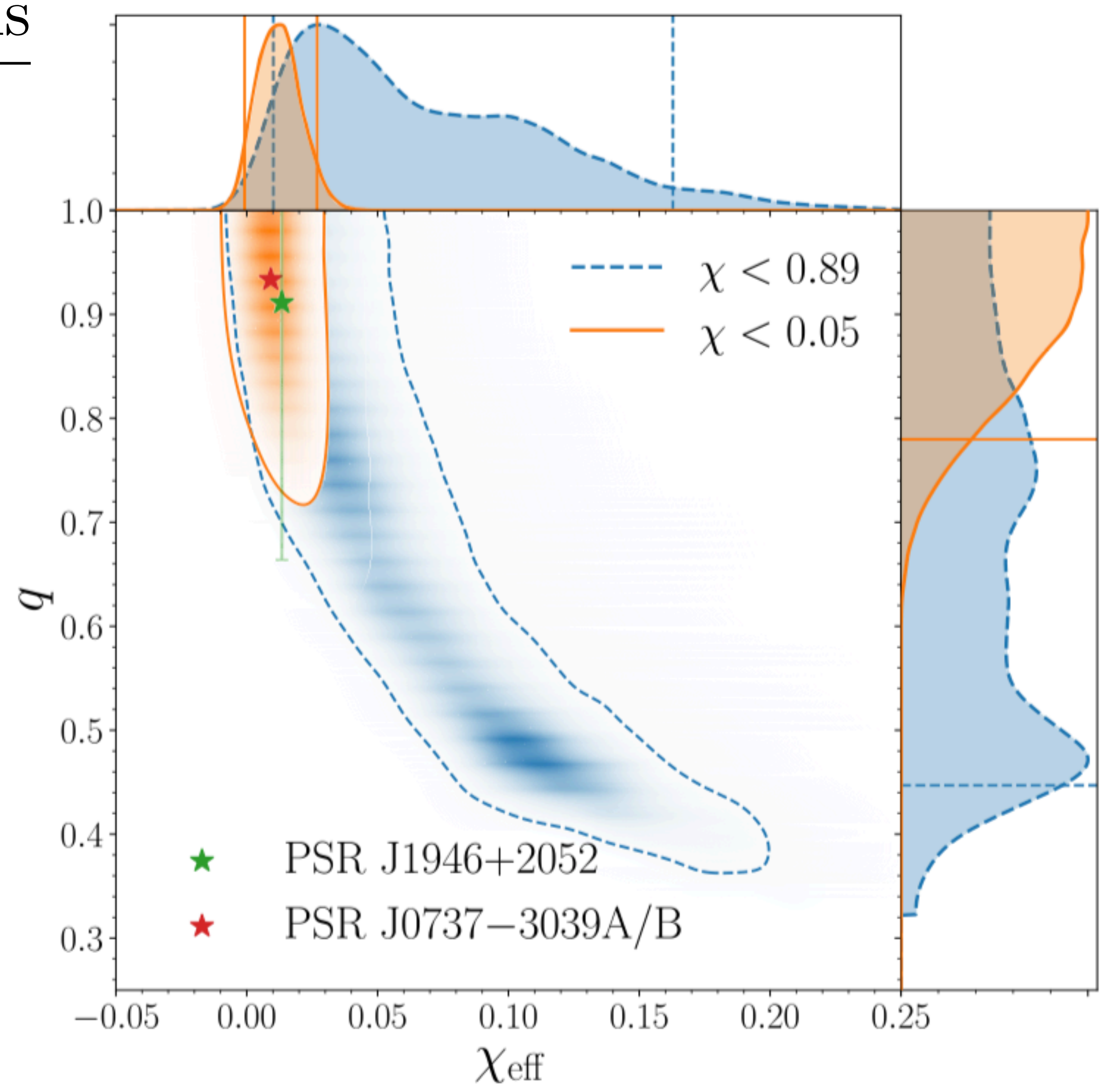


GW190425: it does not provide tighter constraints on NS EOS

(Abbott et al. ApJ Lett 892 (2020))

$$\chi \sim 0.4 \, \frac{1\text{ms}}{T}$$



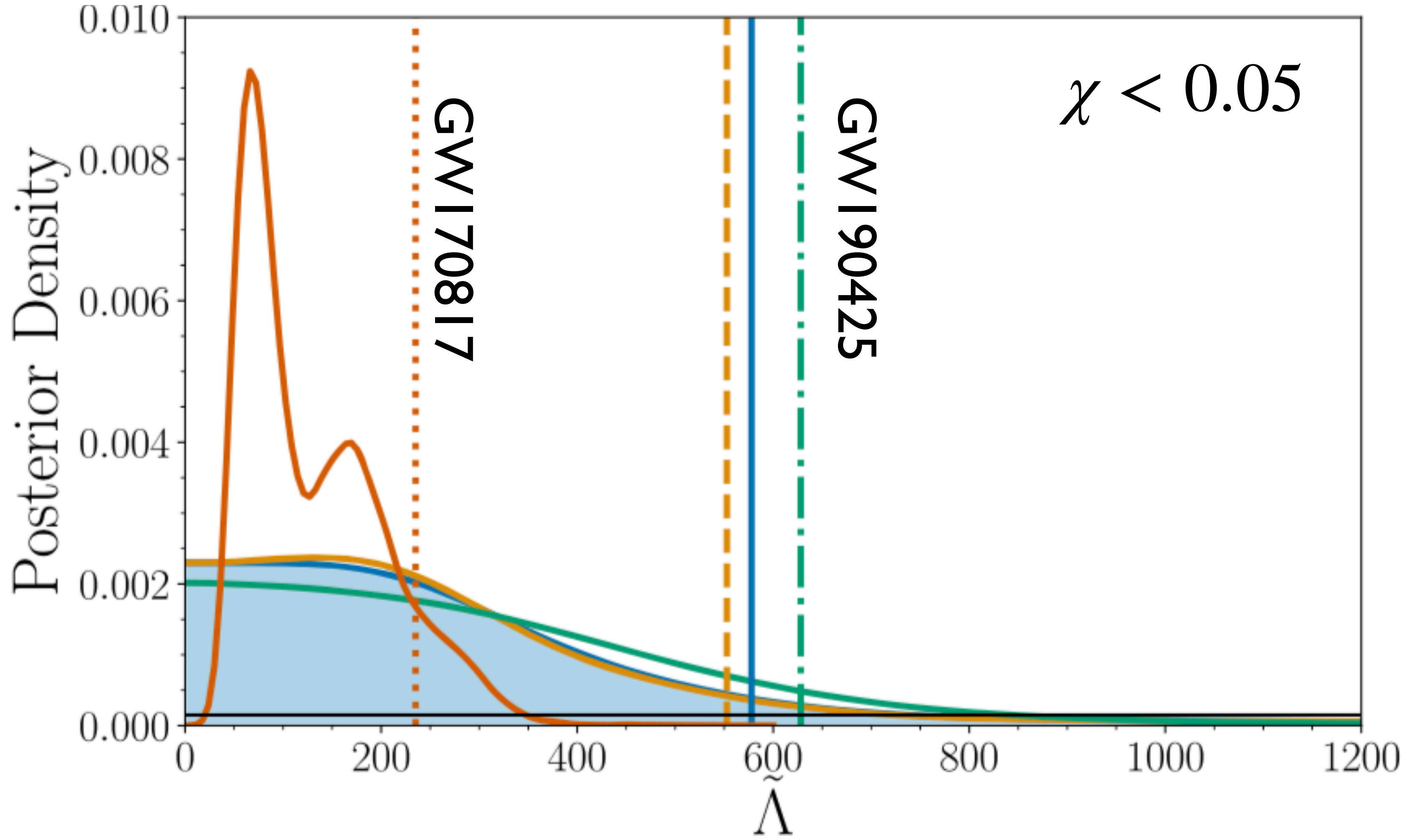


$$q = m_1/m_2$$

$$\chi_1 = S_1/m_1^2$$

$$\chi_2 = S_2/m_2^2$$

$$\chi_{\rm eff} = \left(\frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2\right)\cdot\hat{\mathbf{L}}$$

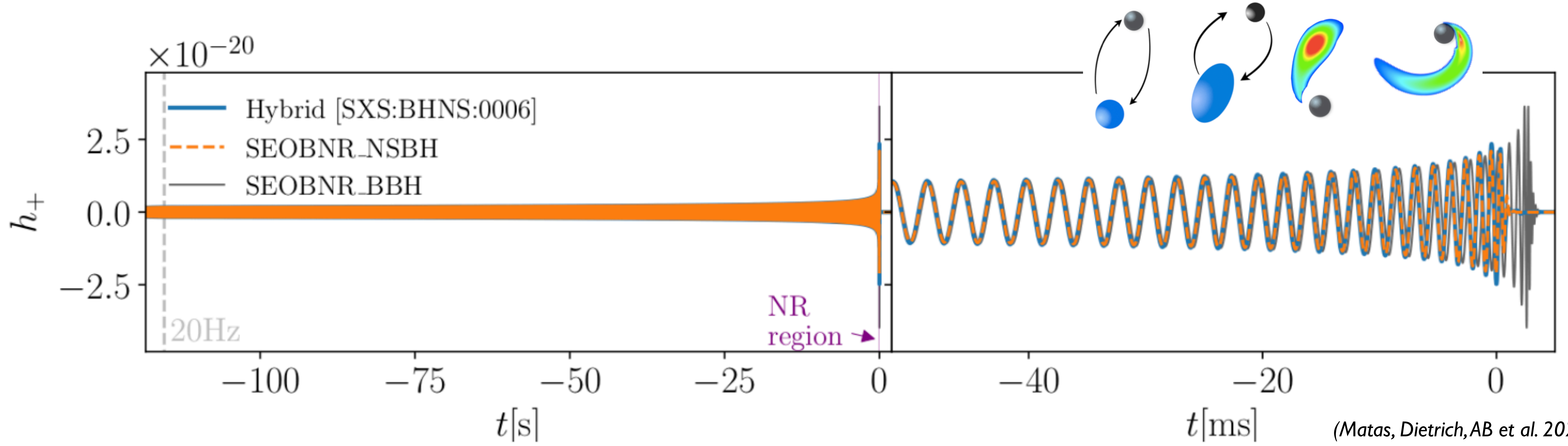


- **GW190425's masses** are **consistent with mass measurements of NSs** in binaries.

- **GW190425's SNR is lower (~ 13)** than GW170817's SNR (~ 34): **looser constraint** on tidal deformability.

Waveforms for Neutron-Star—Black-Hole Binaries

- Synergy between **analytical** and **numerical work** is **crucial.**



(Matas, Dietrich, AB et al. 2020)

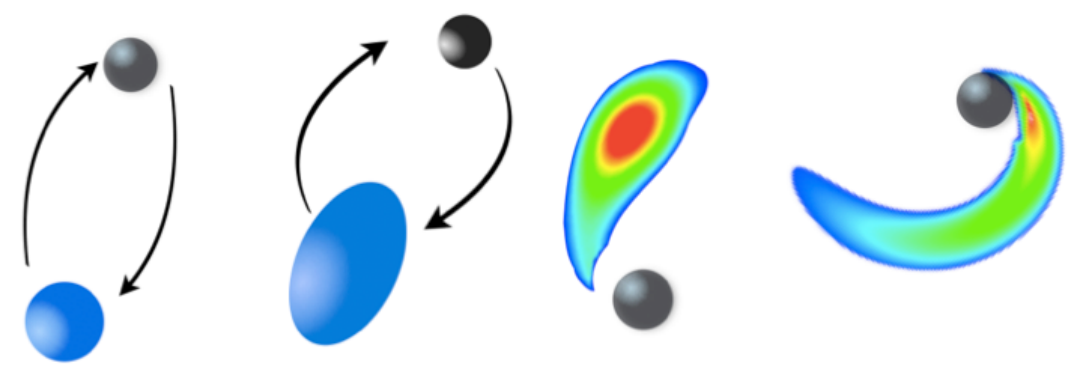
(see also Thompson et al. 2020)

(see also Lackey et al. 14, Pannarale et al. 15, 16, Pürrer et al. 17, Chakravarti et al. 17)

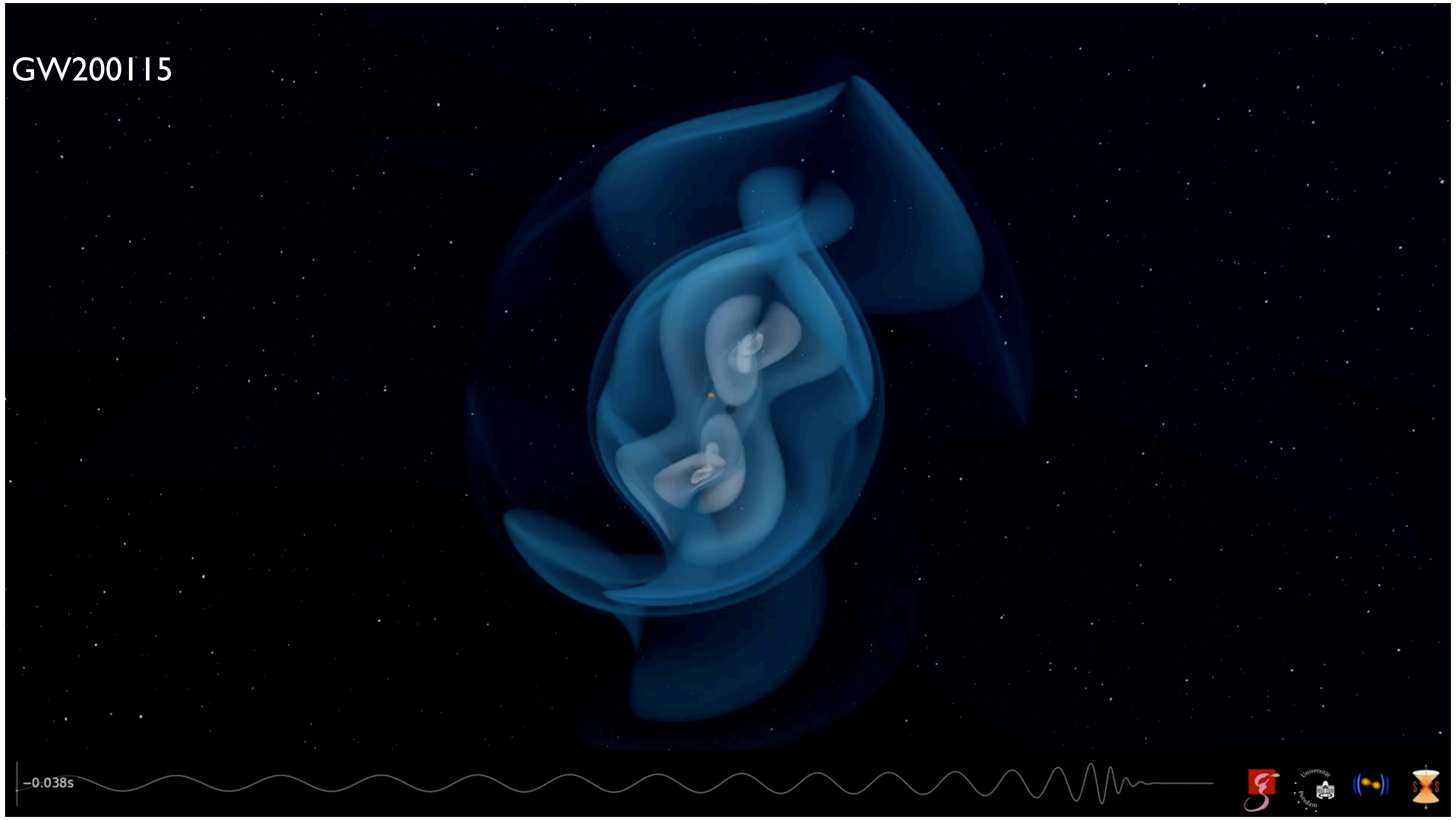
- So far, **NSBH waveforms** were used **to infer properties** of **GW190814 and NSBHs discovered during O3.**

GW200115: a BH swallowing the NS whole

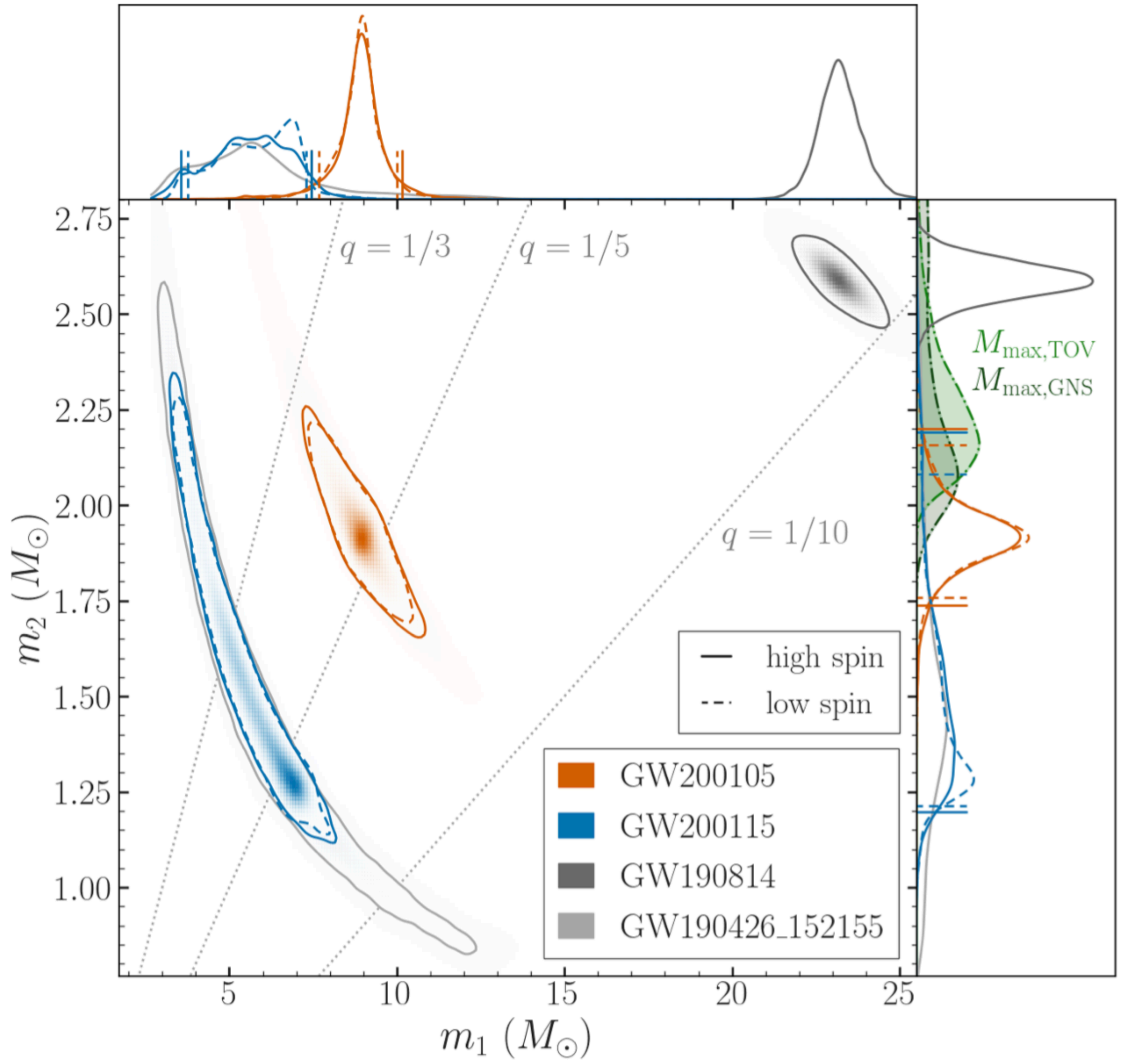
- First **robust detection** of a mixed binary.



(Abbott et al. ApJ 915 (2021))

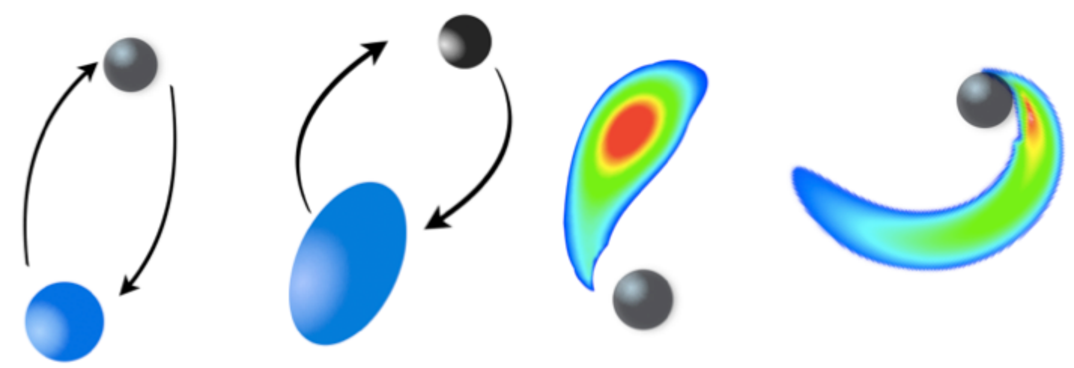


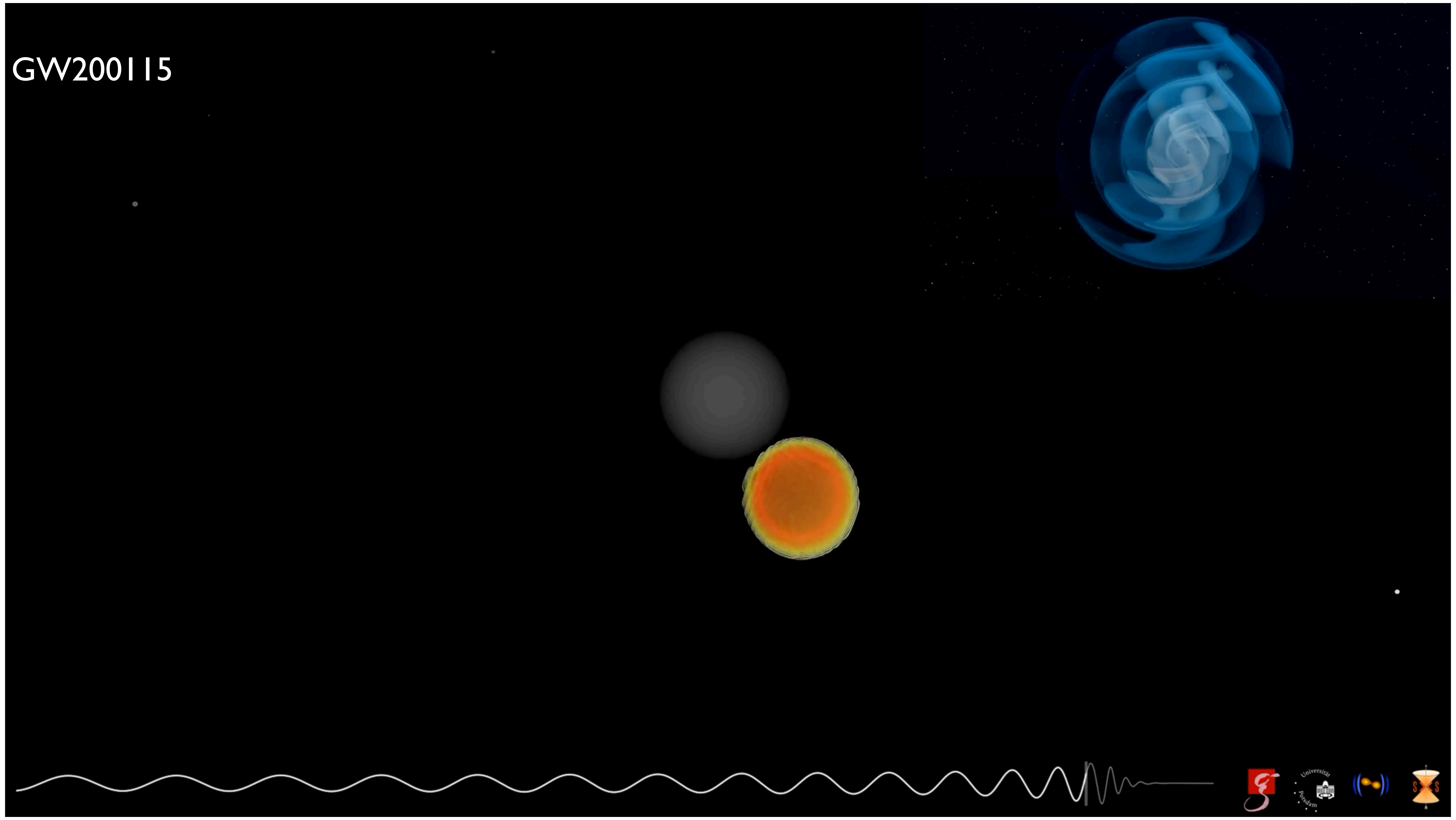
(credit: Chaurasia, Dietrich, Fischer, Ossokine & Pfeiffer)



GW200115: a BH swallowing the NS whole

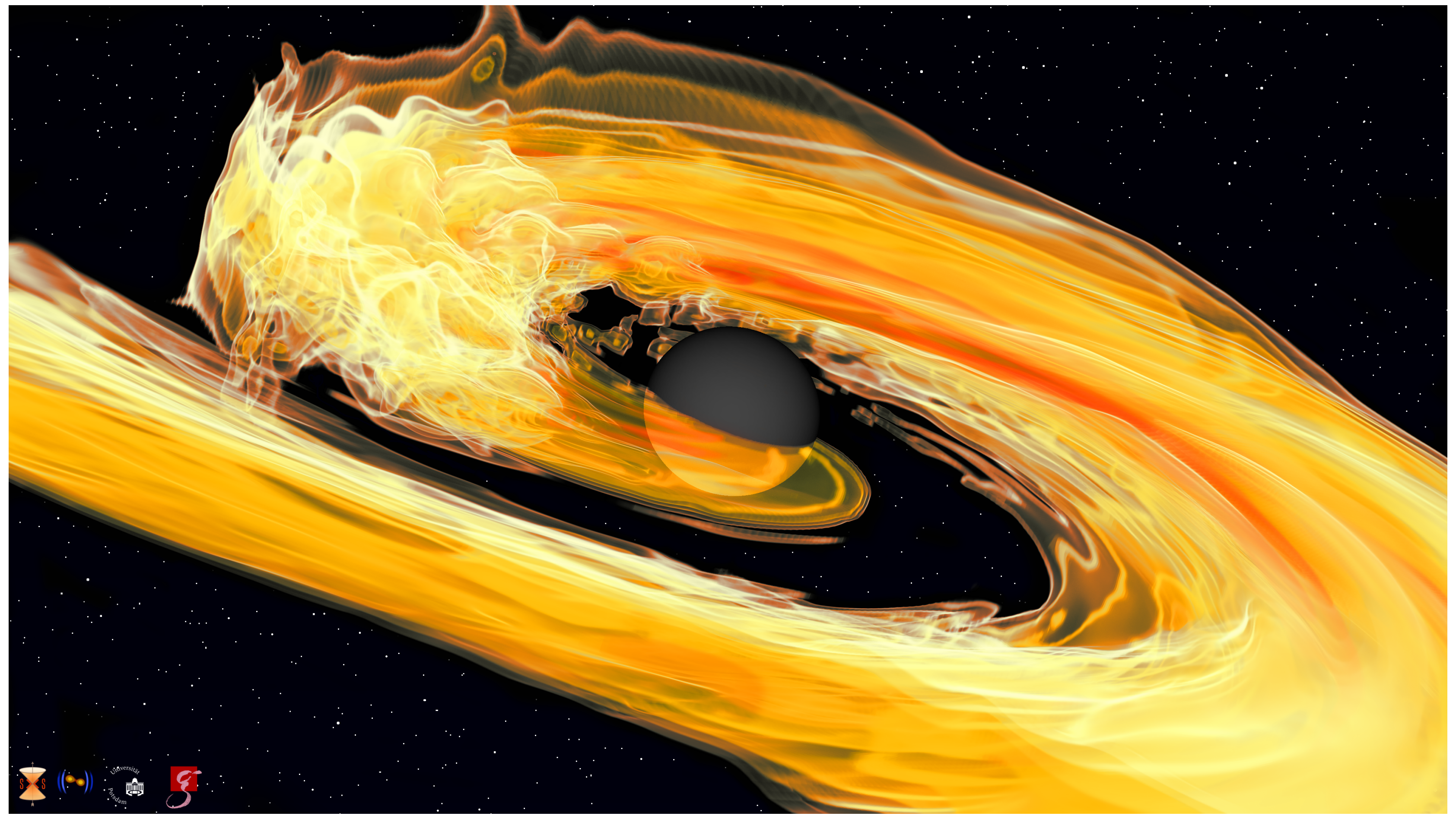
- First **robust detection** of a mixed binary.





(credit: Chaurasia, Dietrich, Fischer, Ossokine & Pfeiffer)

- In the future, we might observe **NSBHs with** accretion disk and **EM counterpart**.



(credit: Chaurasia, Dietrich, Fischer, Ossokine & Pfeiffer)

Cosmography with Gravitational Waves

- Compact-object **binaries are standard candles** (sirens).
- **Standard candles** are **sources whose distance** from Earth can be **inferred from** their **luminosity**.

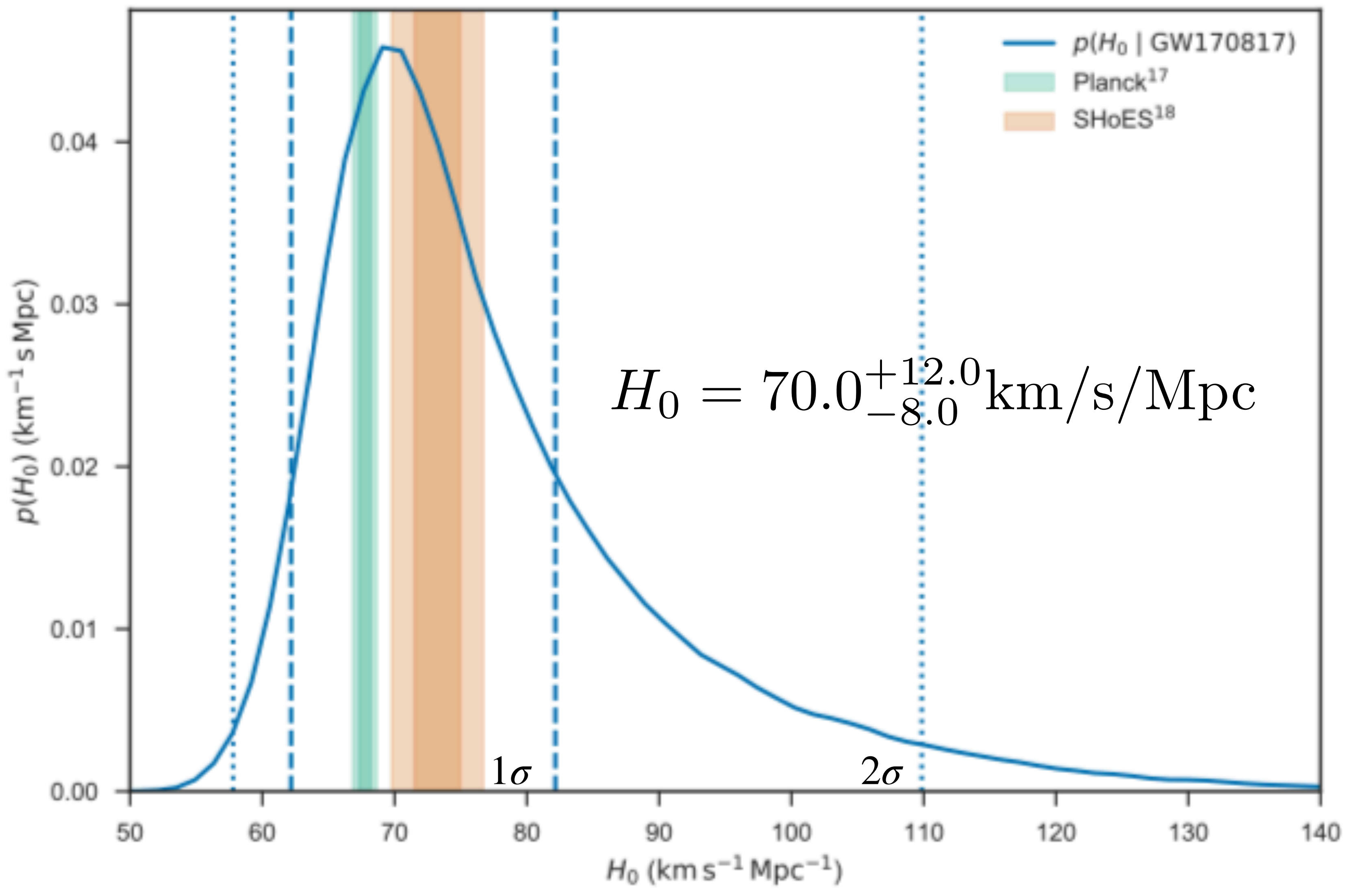
Hubble flow velocity

source's distance

$$v_H = H_0 d$$

Hubble constant

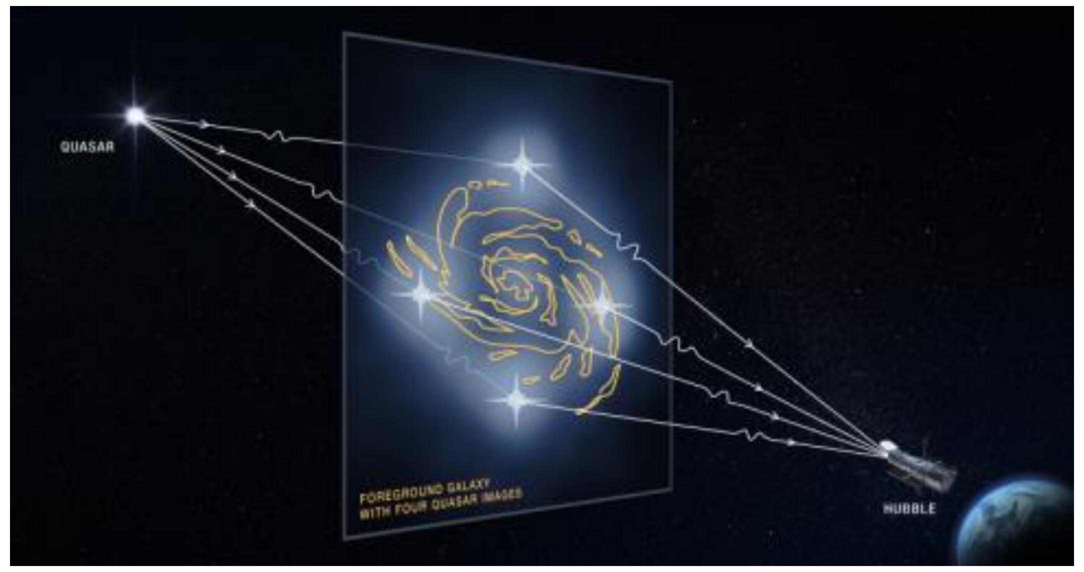
- Exploit identification of **host galaxy NGC4993** (optical counterpart) to obtain Hubble flow velocity.

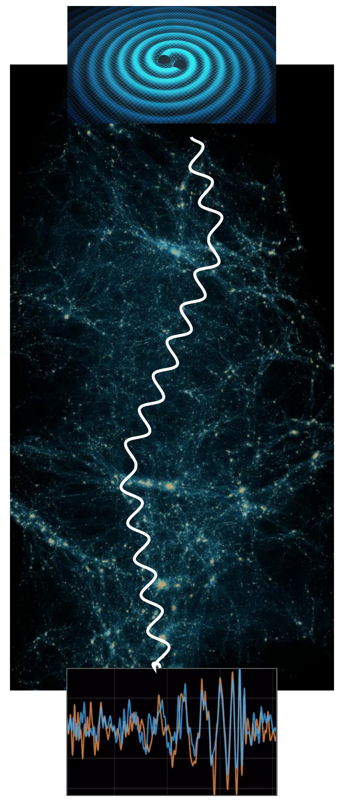


(Abbott et al. Nature (2017) 24471)

- Measurement of H_0 **improved by $17 - 42\ \%$** when considering 47 BBHs detected in O3. *(Abbott et al. arXiv:2111.03604)*

- **Gravitational lensing**



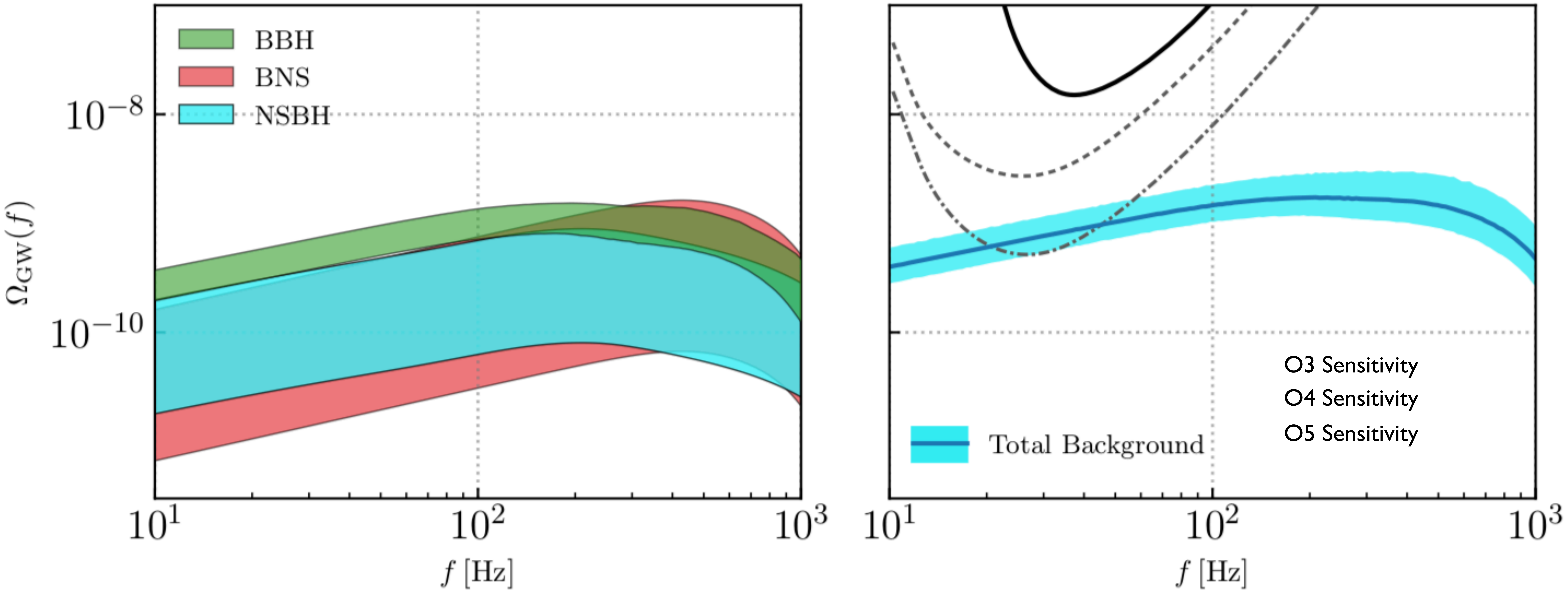


(credit: Zumalacarregui)

- Like EM waves, **GWs** can be **lensed by intervening objects** (stars, black holes, galaxies, cluster of galaxies).
- **Lensing magnification** produces overall **amplification of GWs.**
- **Multiple images** would appear as **"repeated" GW events.**
- **No lensing effects** observed, so far. *(Abbott et al. ApJ 923 (2021) 1, 14)*

Forecast of Astrophysical Backgrounds from Compact-Object Binaries

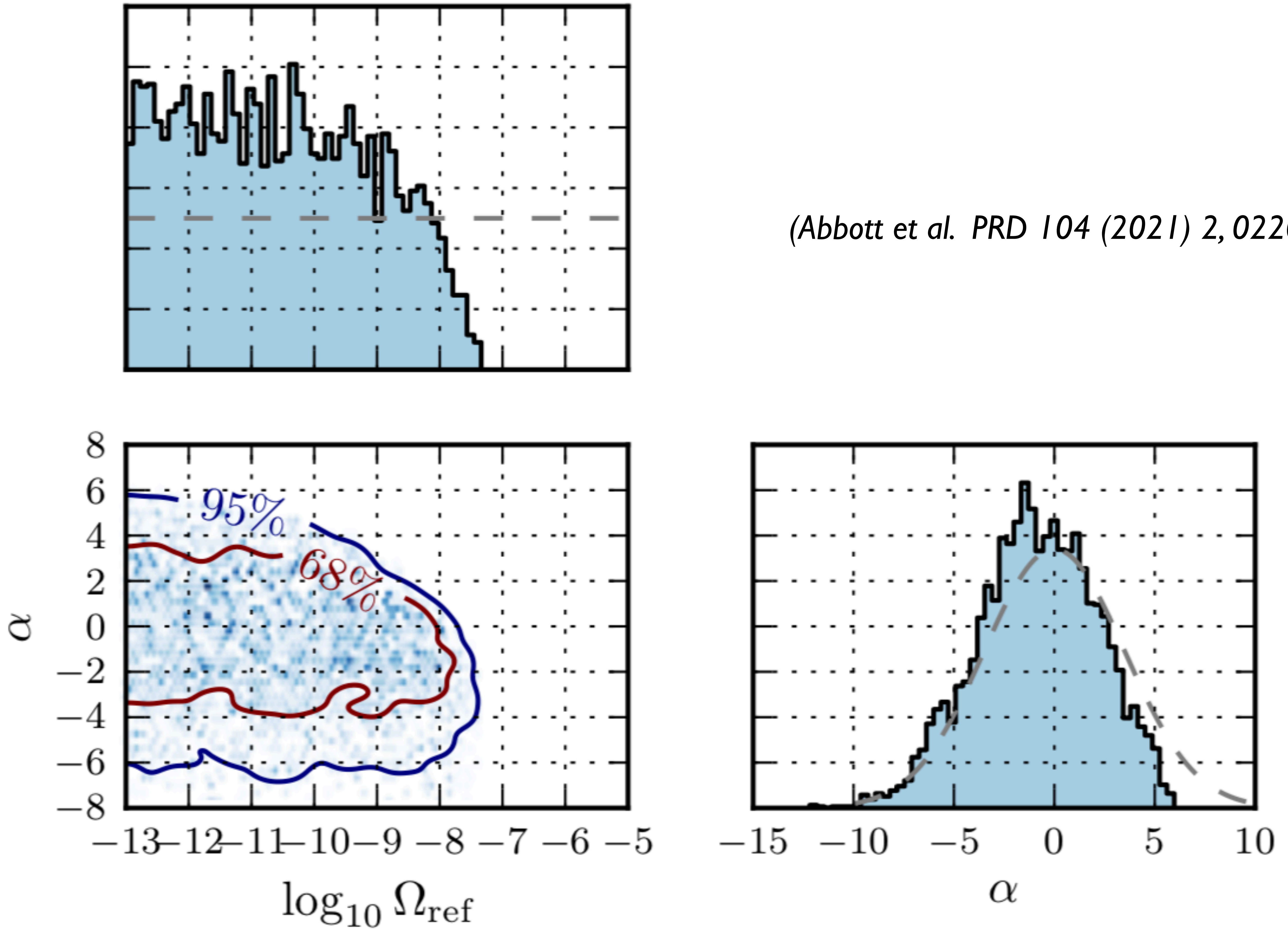
(Abbott et al. arXiv:2111.03634)



Upper Limit on Stochastic Gravitational-Wave Background

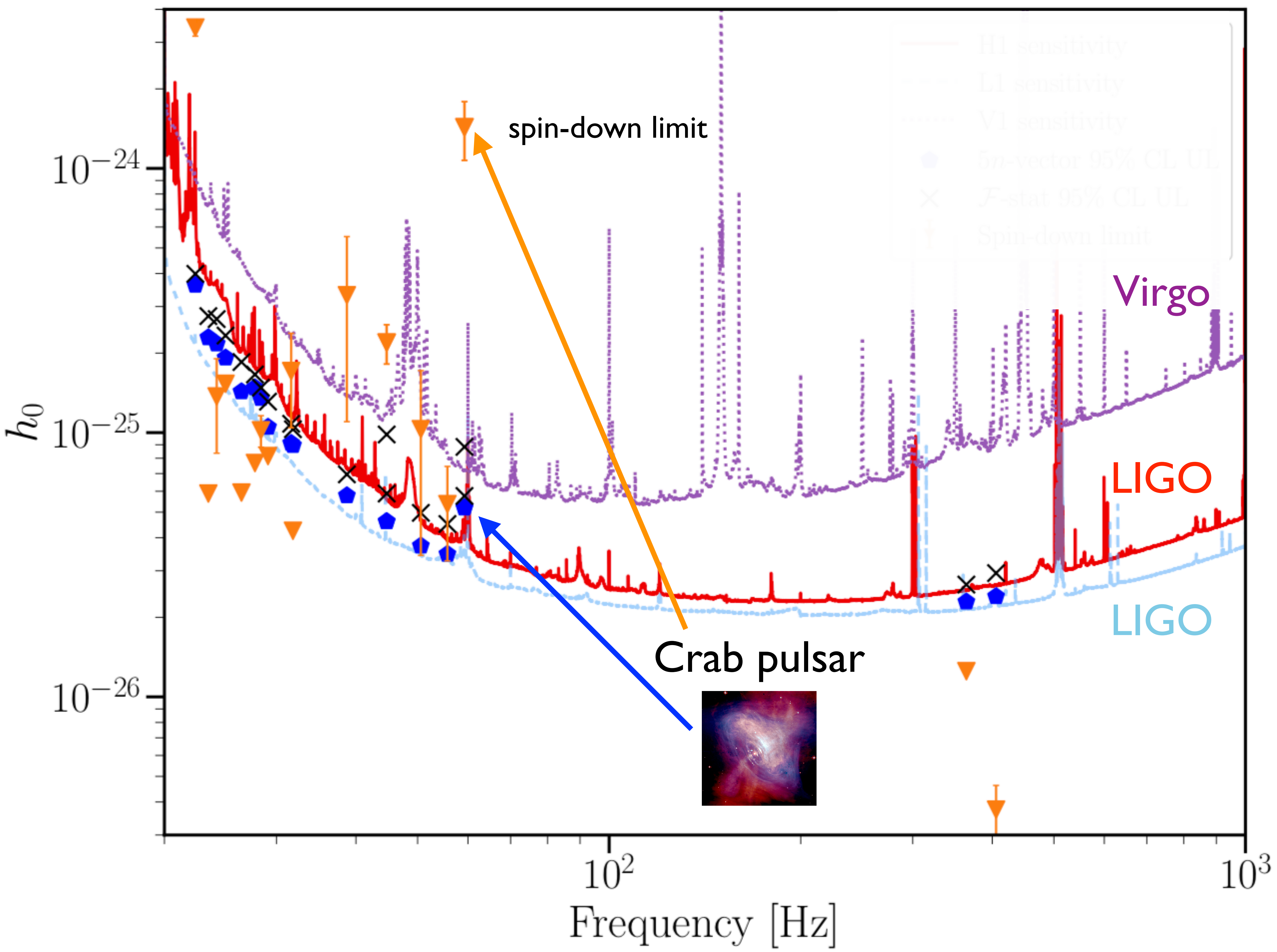
- Dimensionless **energy density** $\Omega_{GW} \leq 5.8 \times 10^{-9}$ at the $95\,\%$ credible level for flat (frequency-independent) GW background.

$$\Omega_{GW}(f) = \Omega_{ref} \left(\frac{f}{f_{ref}} \right)^{\alpha}$$



(Abbott et al. PRD 104 (2021) 2, 022004)

Upper Limits on Known Pulsars



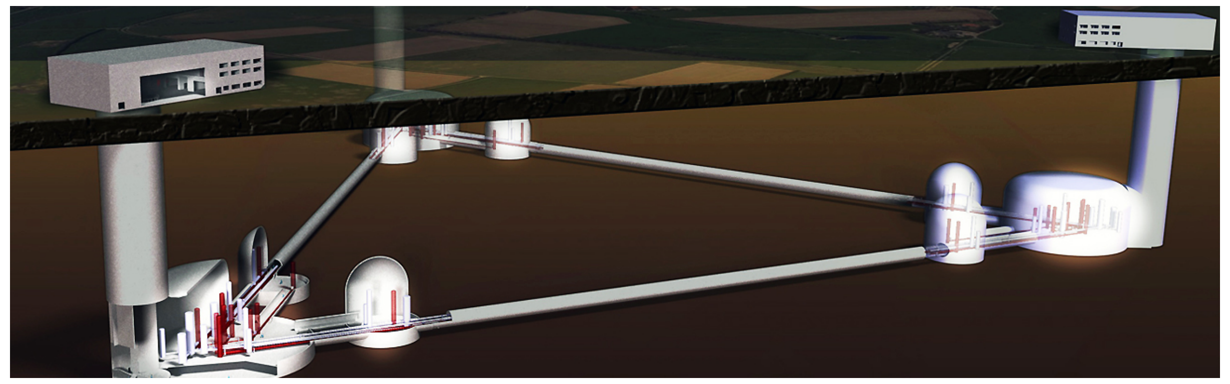
(Abbott et al. arXiv:2112.10990)

- Best **constraint on ellipticity** of known pulsars is 10^{-8}, corresponding to **NS "mountains" of 100 microns**!

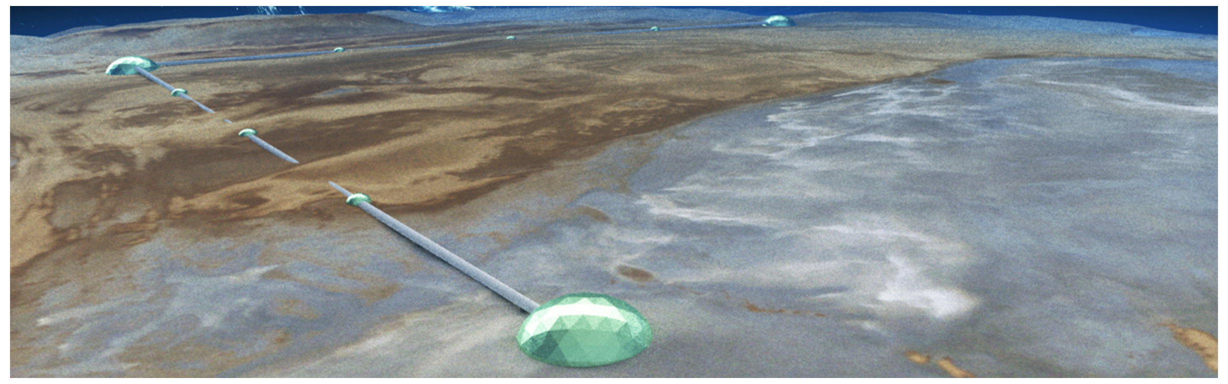
(Abbott et al. ApJL 902 (2020) 1, L21)

Gravitational-Wave Landscape in late 2030 on the Ground

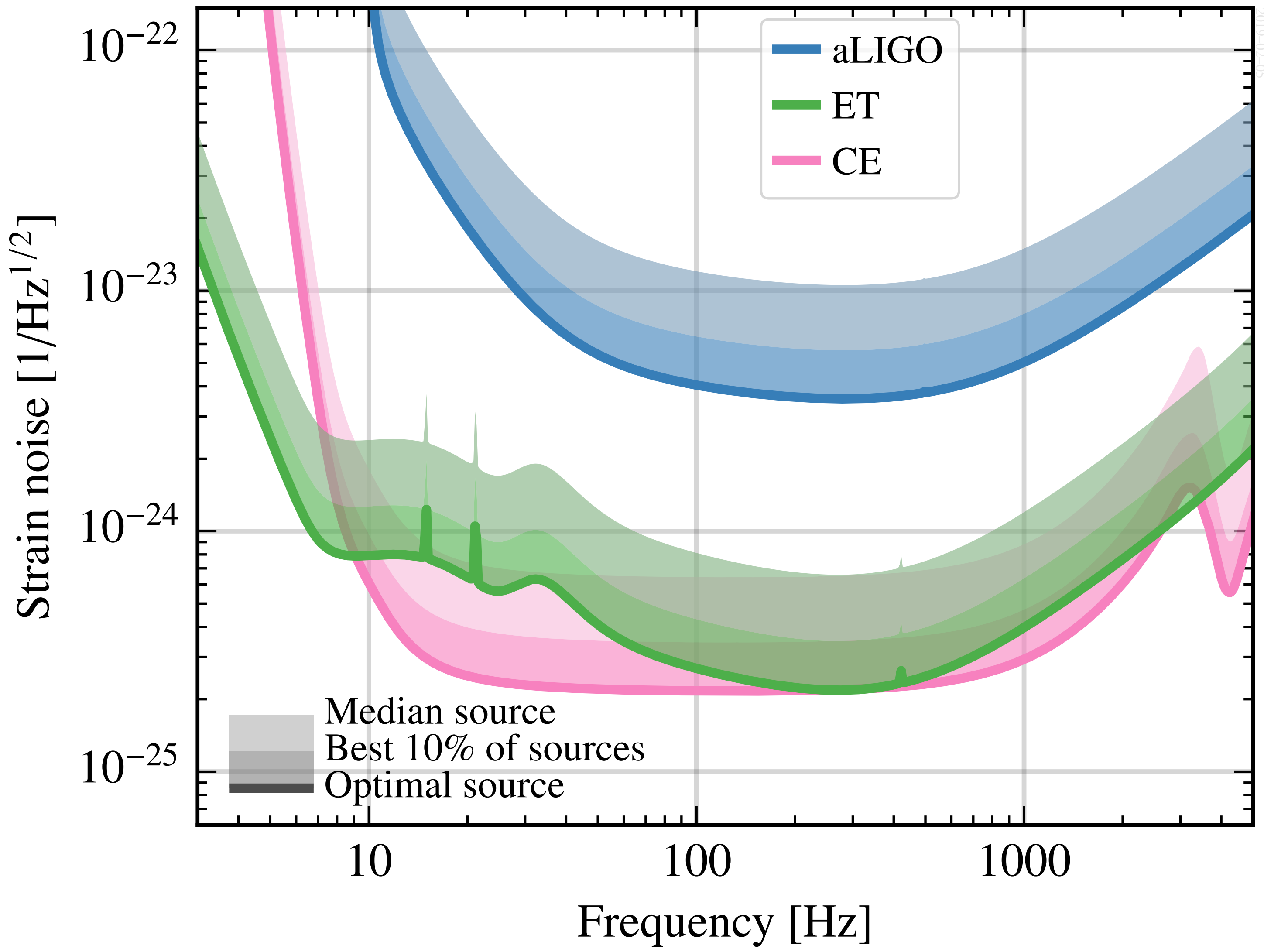
Einstein Telescope

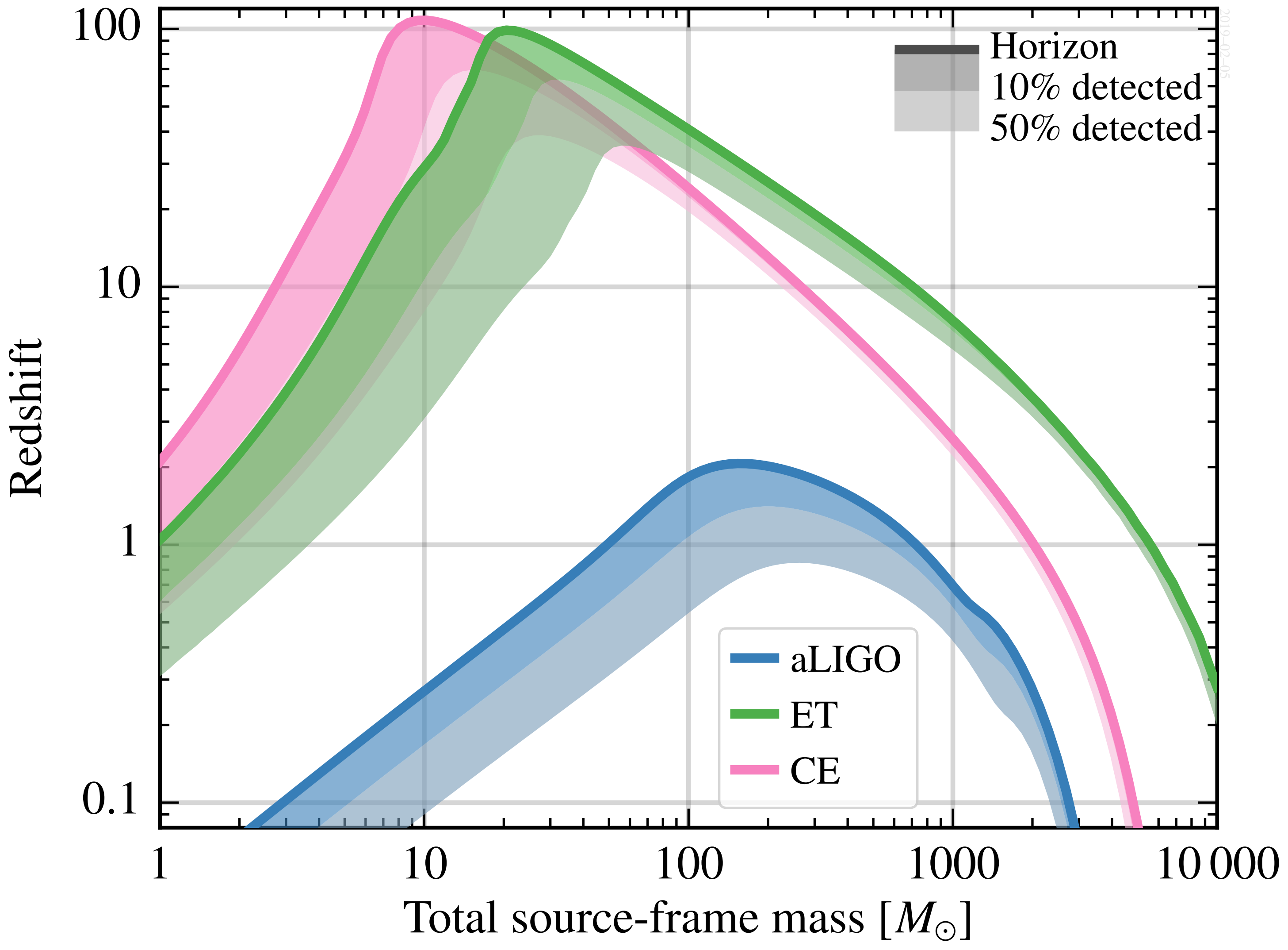


Cosmic Explorer



(3G Science-Case Report 21)

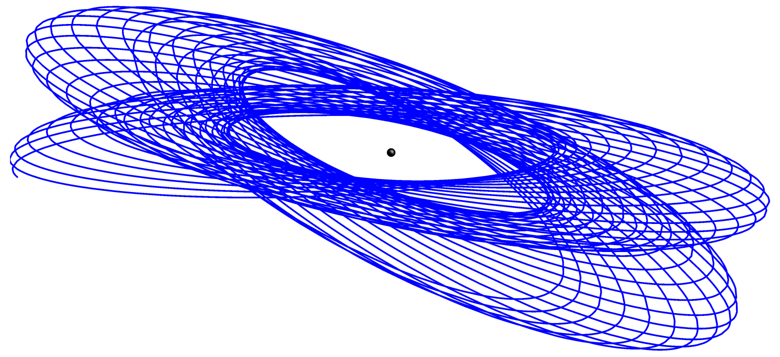




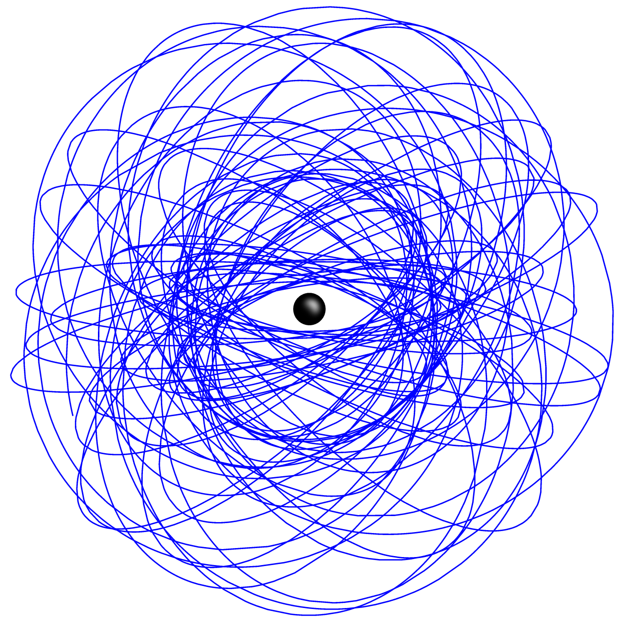
- **Stellar-mass binaries:**
  - Observe each year ~ 30 **BBH signals**, which last for up to 10 minutes, with **SNRs** > 1000 (and $20{,}000$ BBHs with SNRs > 100).
  - Observe each year ~ 10 **BNS signals**, which last several hours, with **SNRs** > 500 (and 780 BNSs with SNRs > 100).

(Borhanian & Sathyaprakash 22)

- **Intermediate Mass-Ratio Inspirals (IMRIs),** with mass ratio 10^3



at GW frequency ~1Hz

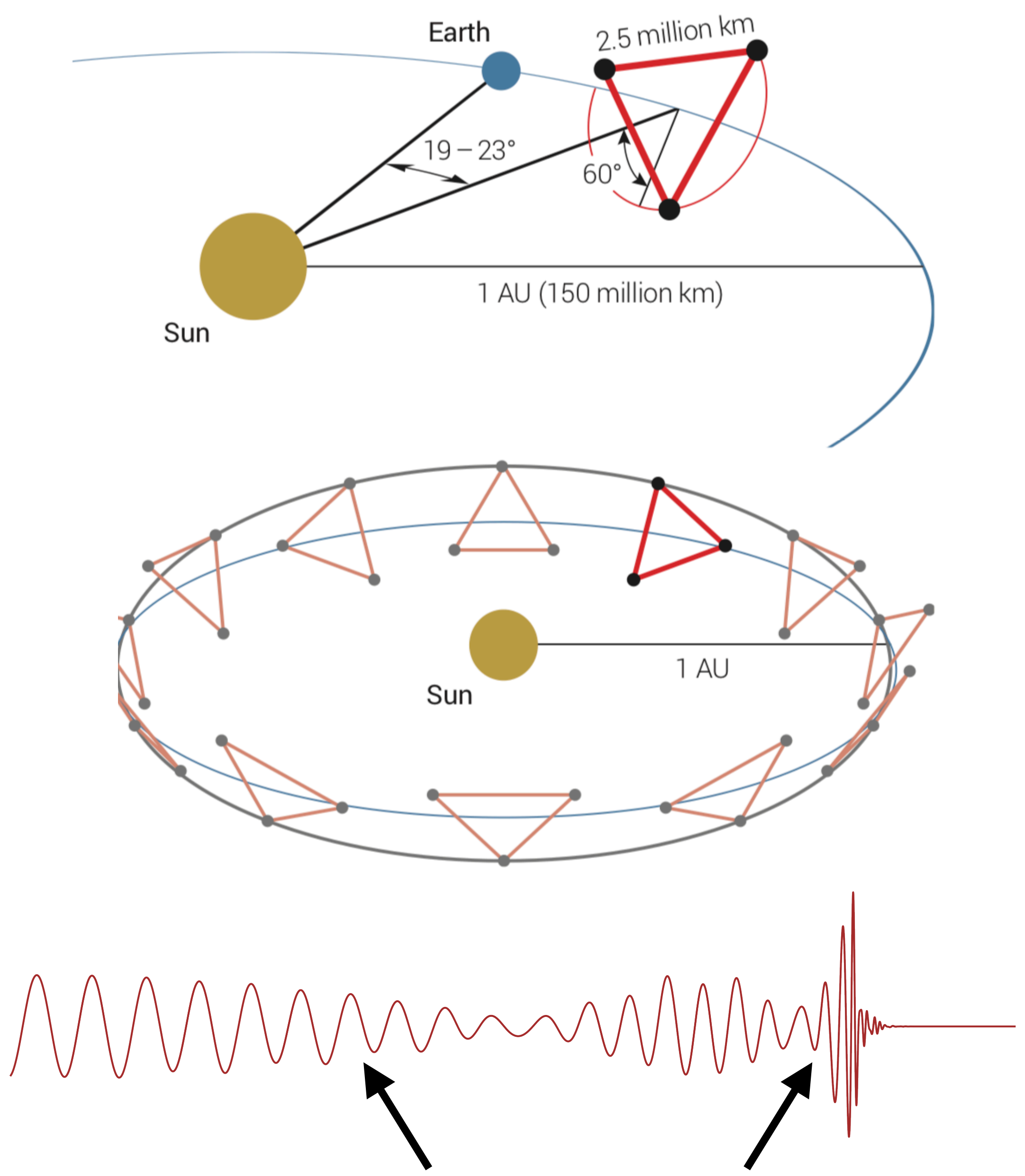


at GW frequency ~10 Hz

(credit: van de Meent)

Gravitational-Wave Landscape in late 2030 in Space

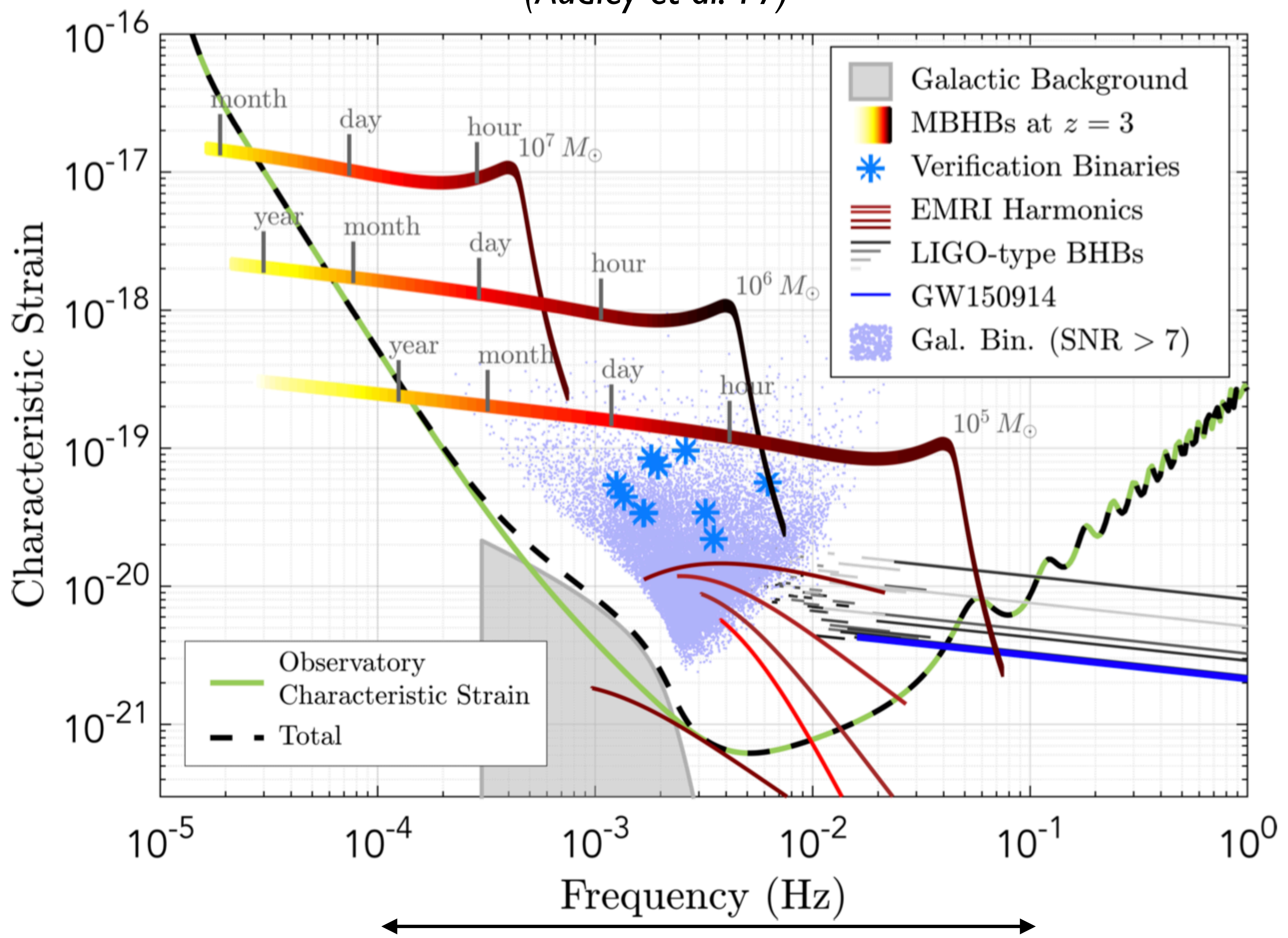
LISA



modulations provide sky location

ESA leading mission with NASA junior partner

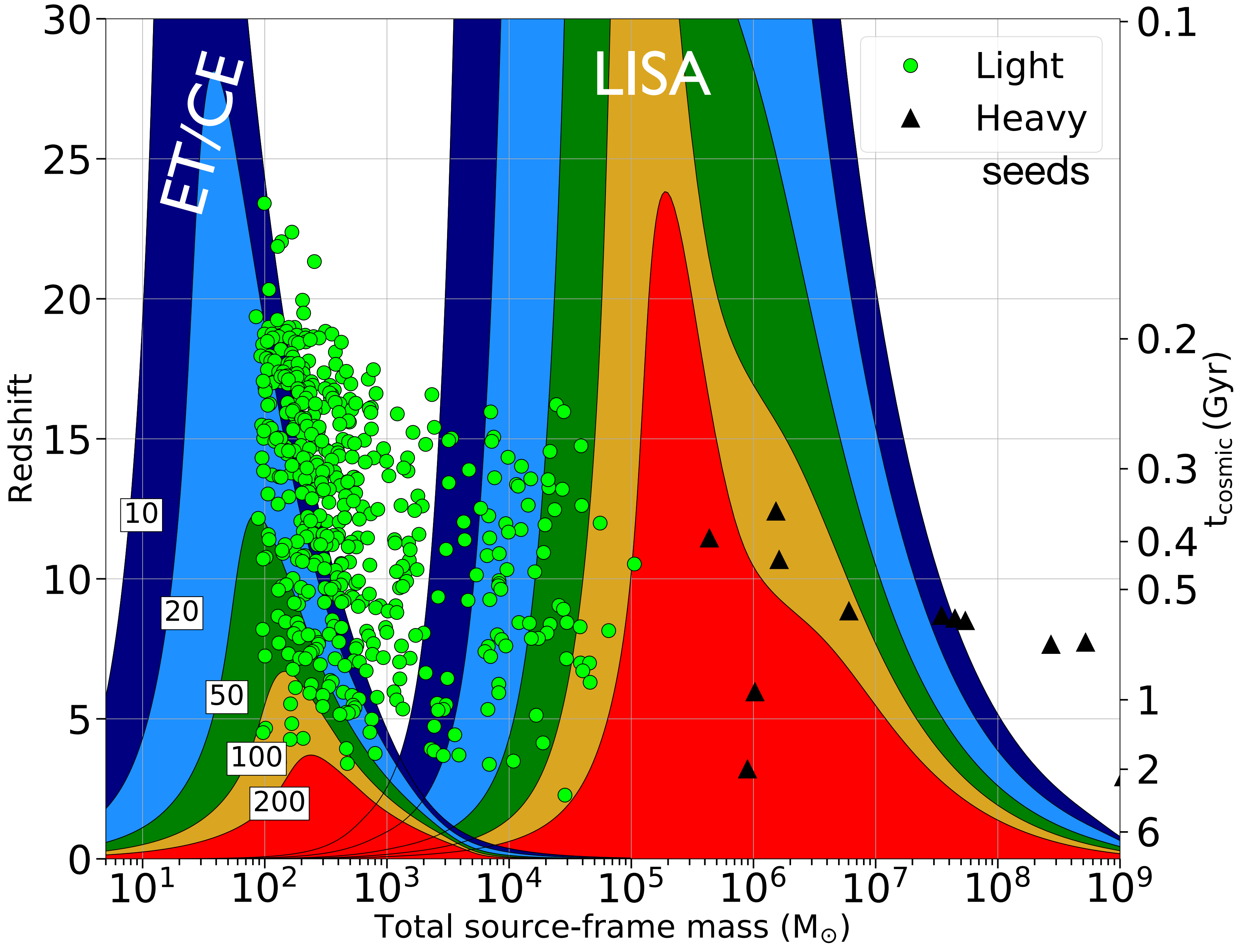
(Audley et al. 17)



opening **three decades** of GW spectrum

- **New** GW **sources**:
  - extreme mass-ratio inspirals (**EMRIs**)
  - massive BHs (**MBHs**)
  - WD binaries in our galaxy

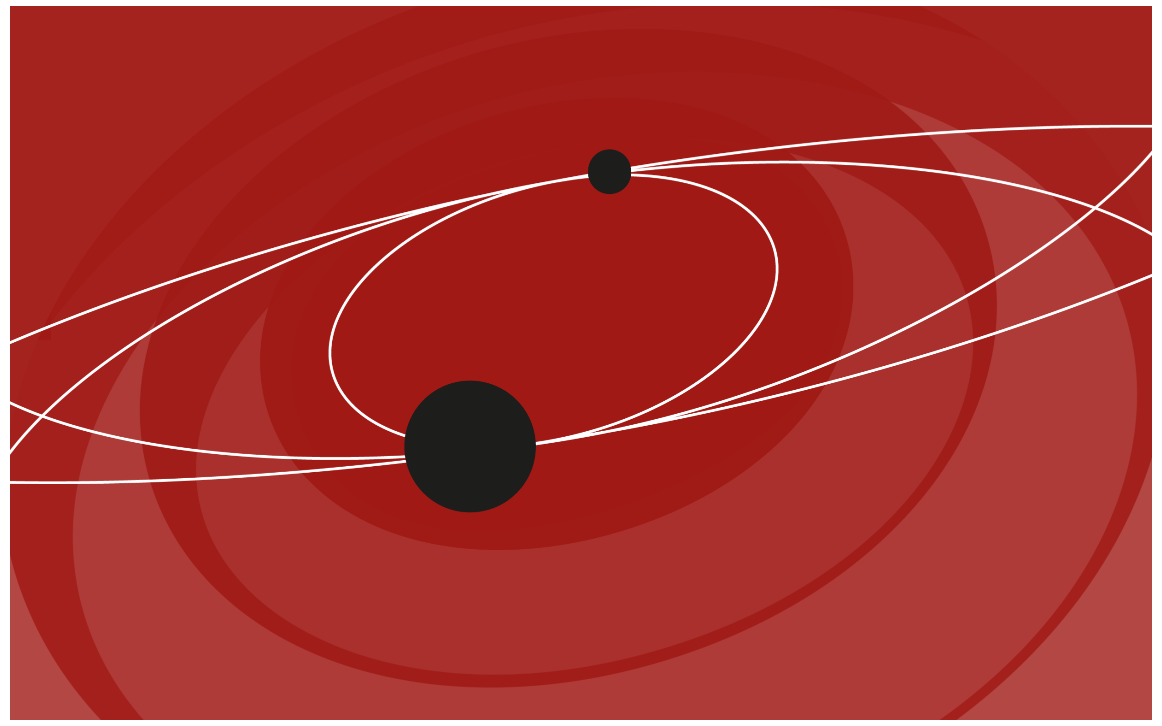
(3G Science-Case Report 21)



Scattering Amplitude: A New Way to Study 2-body Problem

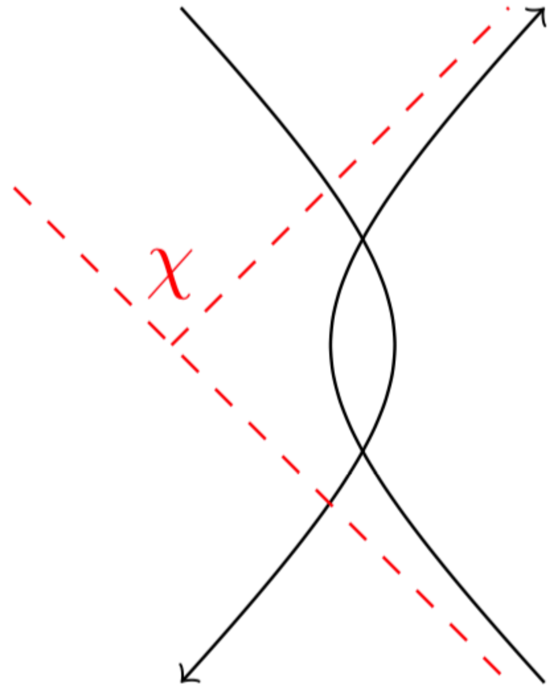
•Relativistic 2-body dynamics

(credit: Carvalho)

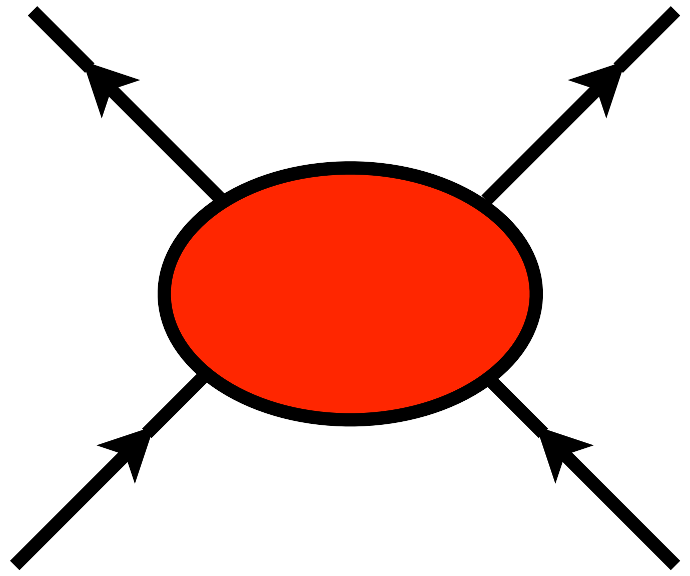


•Classical scattering: scattering angle χ

(credit: Steinhoff)



•Quantum scattering amplitude



e.g., in Born approximation: Fourier transform of potential is related to scattering amplitude

•2-body **Hamiltonian at 4PM (3 loops)** for nonspinning BHs on hyperbolic orbits. *(Cheung et al. 19, 20, Bern et al. 19, Blümlein et al. 20, Kälin et al. 20, Bern et al 21, Dalpa et al. 21)*

Small parameter is $GM/rc^2 << 1$, $v^2/c^2 \sim 1$, large separation, natural **for unbound motion/scattering**

$$H(\boldsymbol{p},\boldsymbol{r}) = \sqrt{\boldsymbol{p}^2 + m_1^2} + \sqrt{\boldsymbol{p}^2 + m_2^2} + V(\boldsymbol{p},\boldsymbol{r})$$

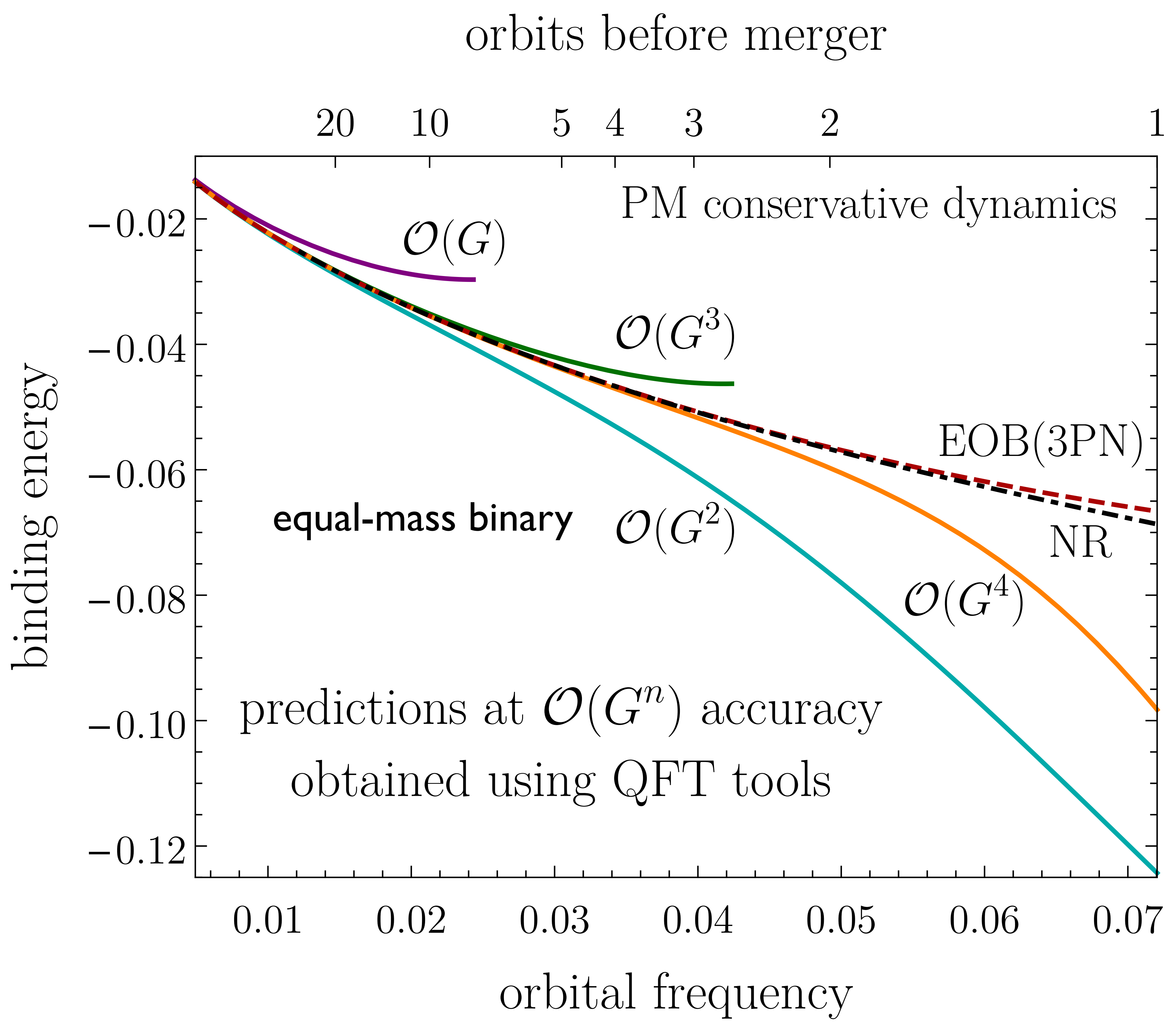
$$V(\boldsymbol{p},\boldsymbol{r}) = \sum_{i=1}^{\infty} c_i(\boldsymbol{p}^2)\left(\frac{G}{|\boldsymbol{r}|}\right)^i$$

$$V^{(1)}(\mathbf{p},\mathbf{q}) = \int \frac{\mathbf{d^3r}}{(2\pi)^3}\, \mathcal{M}^{\text{tree}}(\mathbf{p},\mathbf{q})\, \mathbf{e}^{-\mathbf{ir\cdot q}}$$

Newtonian potential ↑ ↑ scattering amplitude

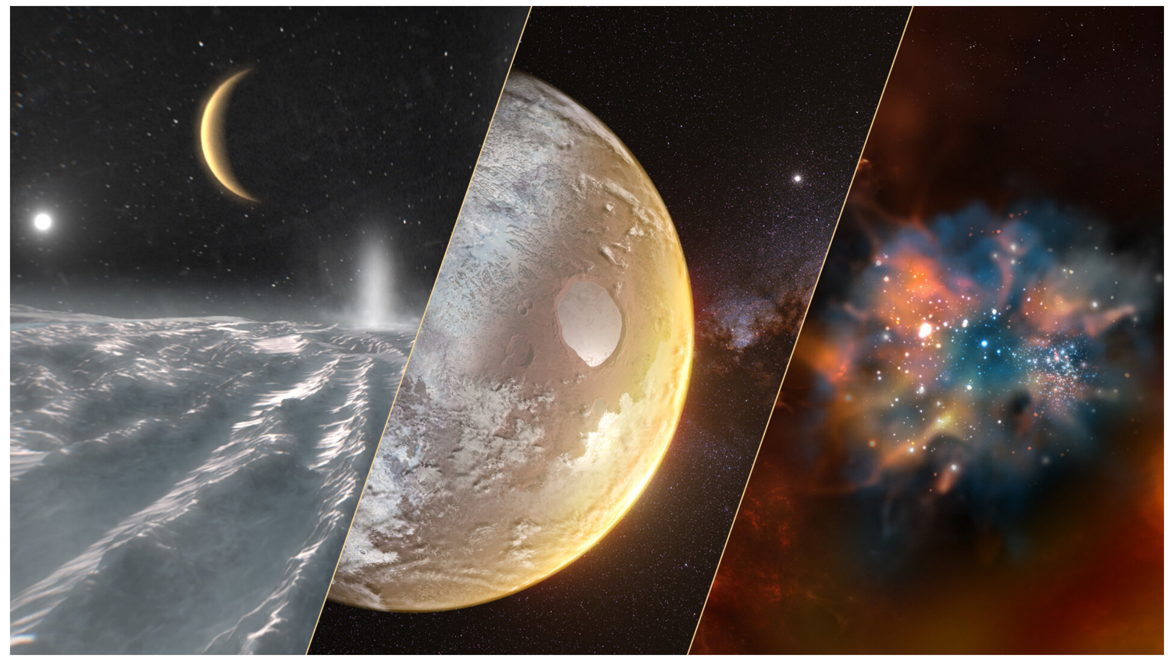
Assessing Accuracy of PM Calculations: Nonspinning Binary

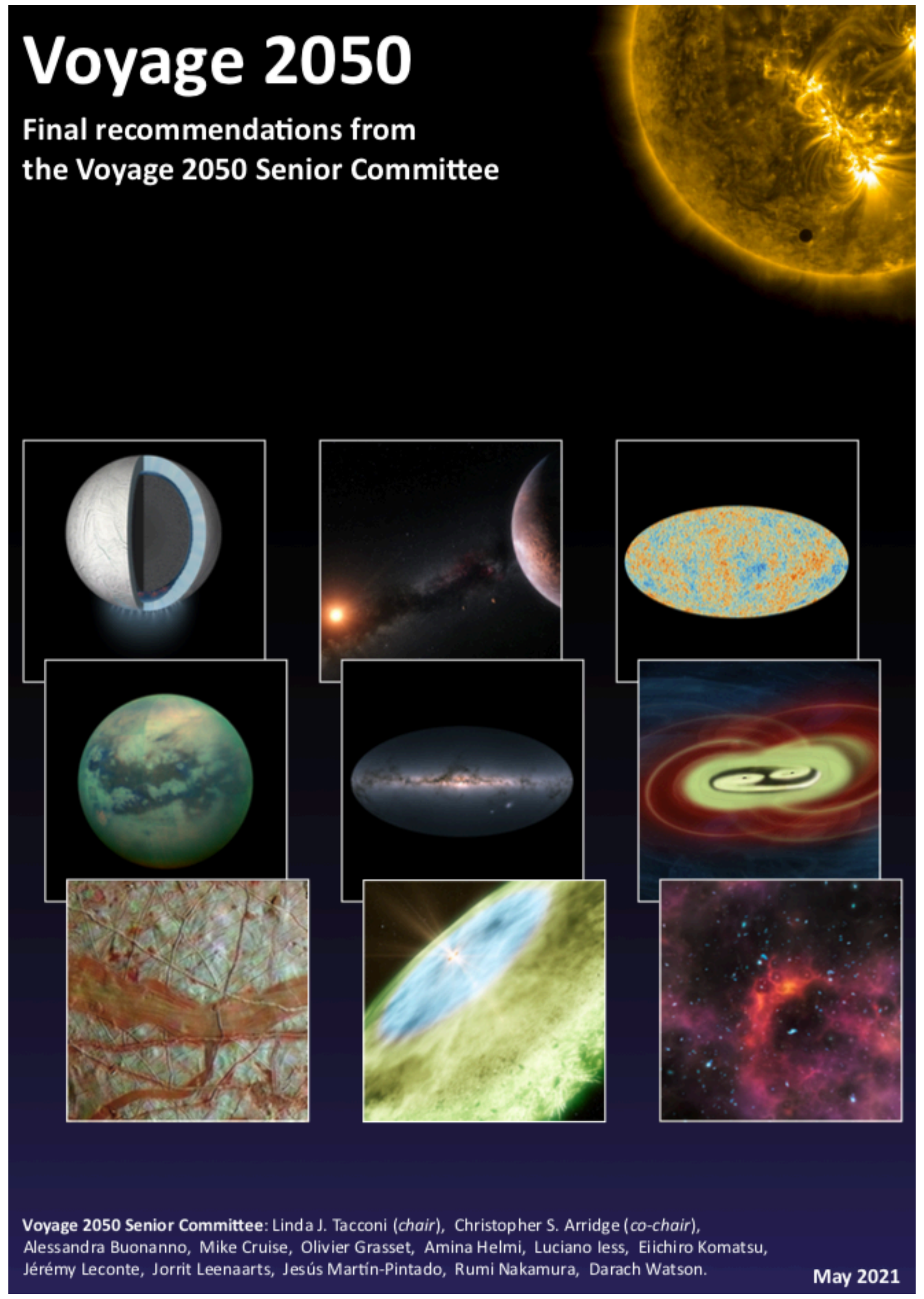
(Khalil, AB, Steinhoff & Vines 22, AB, Khalil, O'Connell, Roiban, Solon & Zeng 22)



- **Effective-field-theory and scattering-amplitudes** methods have **brought new and fresh perspectives (and tools)** to solve the relativistic two-body problem, unveiling **new paths to intertwine** the different perturbative approaches **(PN, PM and GSF)**.
- **Scalability** of perturbative approaches **remains still uncertain**. **Resummation** methods still **needed.**
- **Waveform accuracy** would need to be **improved by one or two orders of magnitude** depending on the parameter space.

(Possible) Gravitational-Wave Landscape in 2050 in Space





- In June 2021, the ESA's Director of Science and the Science Program Committee (SPC) **announced the next ESA Science Program Voyage 2050**, selecting **three themes:**

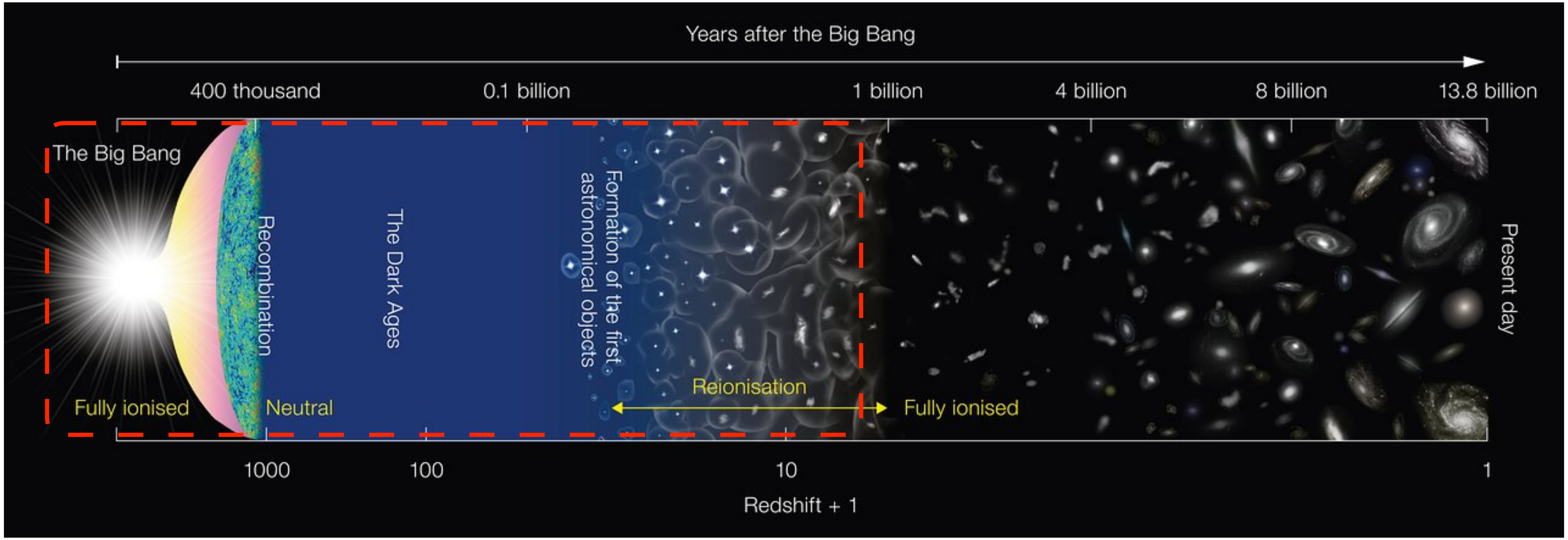
  - Moons of Giant Planets.

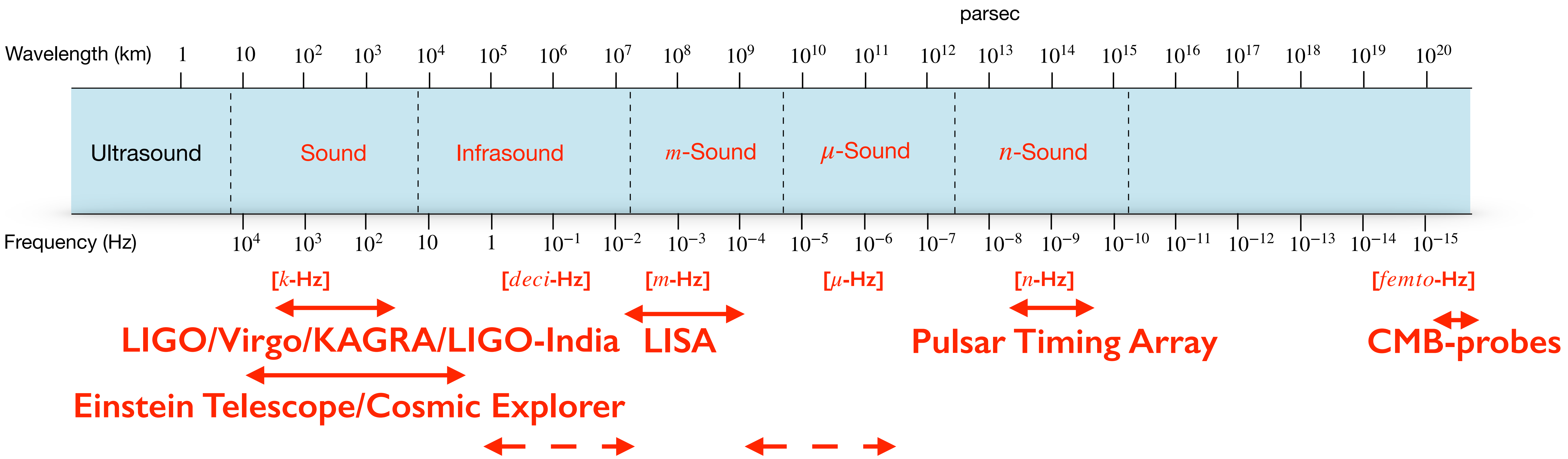
  - From Temperate Exoplanets to the Milky Way.

  - **New Physical Probes of the Early Universe.**

    "How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from Planck and the expected scientific return from LISA."

New Opportunities to Extend the GW Spectrum from Space





Summary & Outlook

- With O1 & O2 we observed the "tip of the iceberg" of the binary population, with the improved detectors' sensitivity, O3 has unveiled a richer picture and several "exceptional" sources. In O3 NSBHs were observed.

- Some outstanding questions: What is the nature of the secondary object in GW190814 and GW200210? What is the origin of the BBHs in the high-mass gap?

- A variety of null tests of GR (agnostic and specific) have been performed, which will be enriched by more comprehensive tests of modified theories of gravity when inspiral-merger-ringdown waveforms are available.

- Bright future: next few years (decades) will bring hundreds (thousands) more BBH and BNS/NSBH observations, with diverse properties at much higher SNRs, probing fundamental and subatomic physics, dark matter, and cosmological model of our Universe.

- To address open questions and take full advantage of discovery potential in next years (and decades), novel data-analysis methods and high-precision waveforms that cover the entire parameter space and include all physical effects (higher modes, matter, spin precession, eccentricity, deviations from GR, etc.) would be needed. Interdisciplinary effort!

The "Astrophysical and Cosmological Relativity" Division

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LIGO
VIRGO
KAGRA

Thank You!