PHYSICS OF GRAVITATIONAL WAVE EMISSION AND DETECTION: INTRODUCTION

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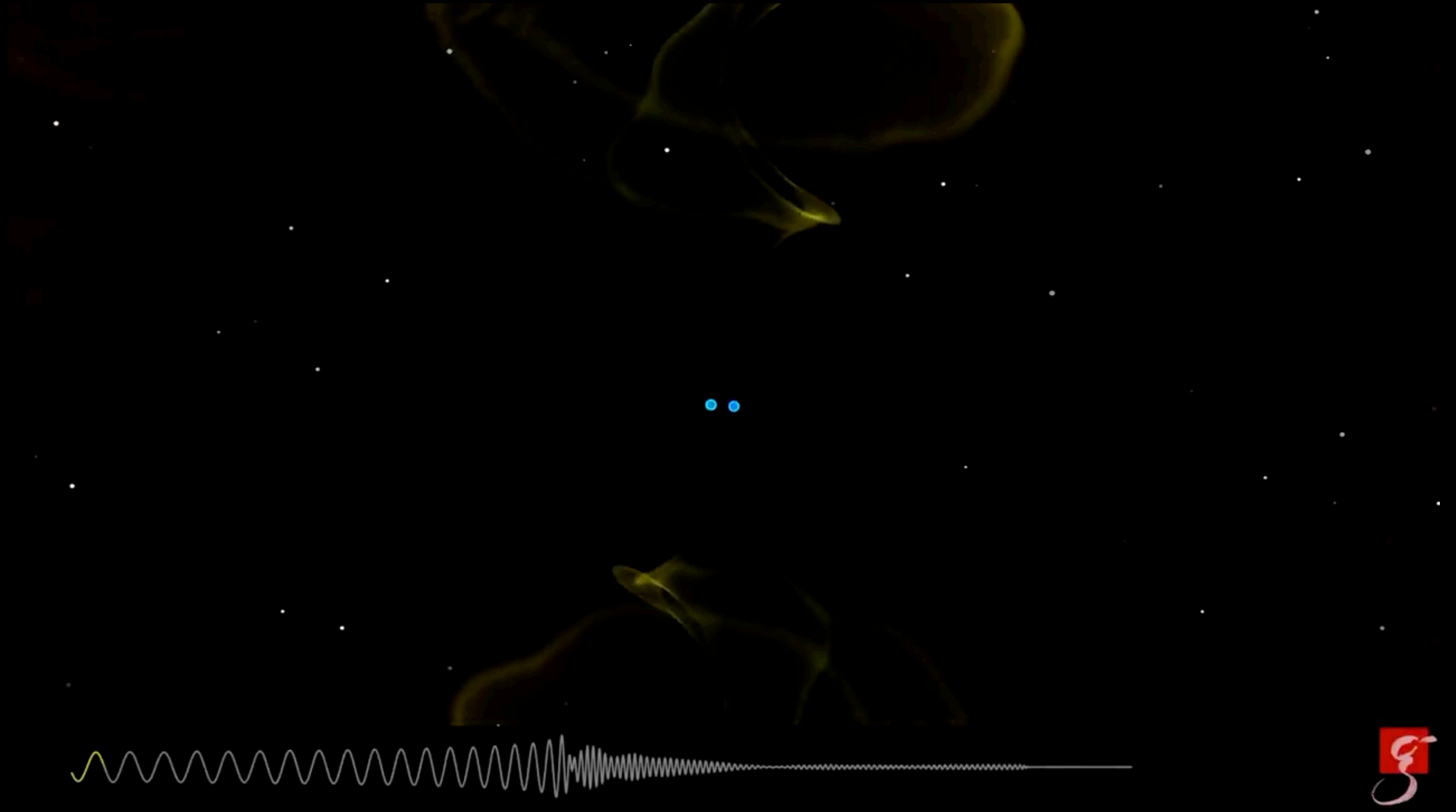
OUTLINE FOR TODAY

- Morning:
  - **Lecture 1 (this one): Overview of GW astronomy (slides)**
  - Lecture 2: GW parameter estimation & detection (whiteboard)
- Afternoon:
  - Lecture 3: Matched filtering with PyCBC (python tutorial)
  - Lecture 4: Parameter estimation with PyCBC (python tutorial)

GWS IN A NUTSHELL

- Gravitational wave (GW): a ripple in spacetime caused by accelerating masses
- Emitted by changing quadrupole moment
- Binaries emit GWs
- Lose energy as they do; eventually merge



T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno, AEI Potsdam

HISTORY*

- GWs predicted by Einstein in 1915
- First detected in 2015, exactly one century later
- What took so long?

1. GR is non-linear
2. GWs are weak

*Cervantes-Cota et al., “A Brief History of Gravitational Waves, arXiv:1609.09400 (2016)

EINSTEIN'S CHANGING VIEWS

- 22 Jun 1916, article: "*…so sieht man, daß A (die Ausstrahlung des Systems durch Gravitationswellen pro Zeiteneinheit) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.*" ["*…so you can see that A (the radiation of the system through gravitational waves per unit of time) must have a practically vanishing value in all conceivable cases.*"] -Nährungsweise Integration der Feldgleichungen, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 688

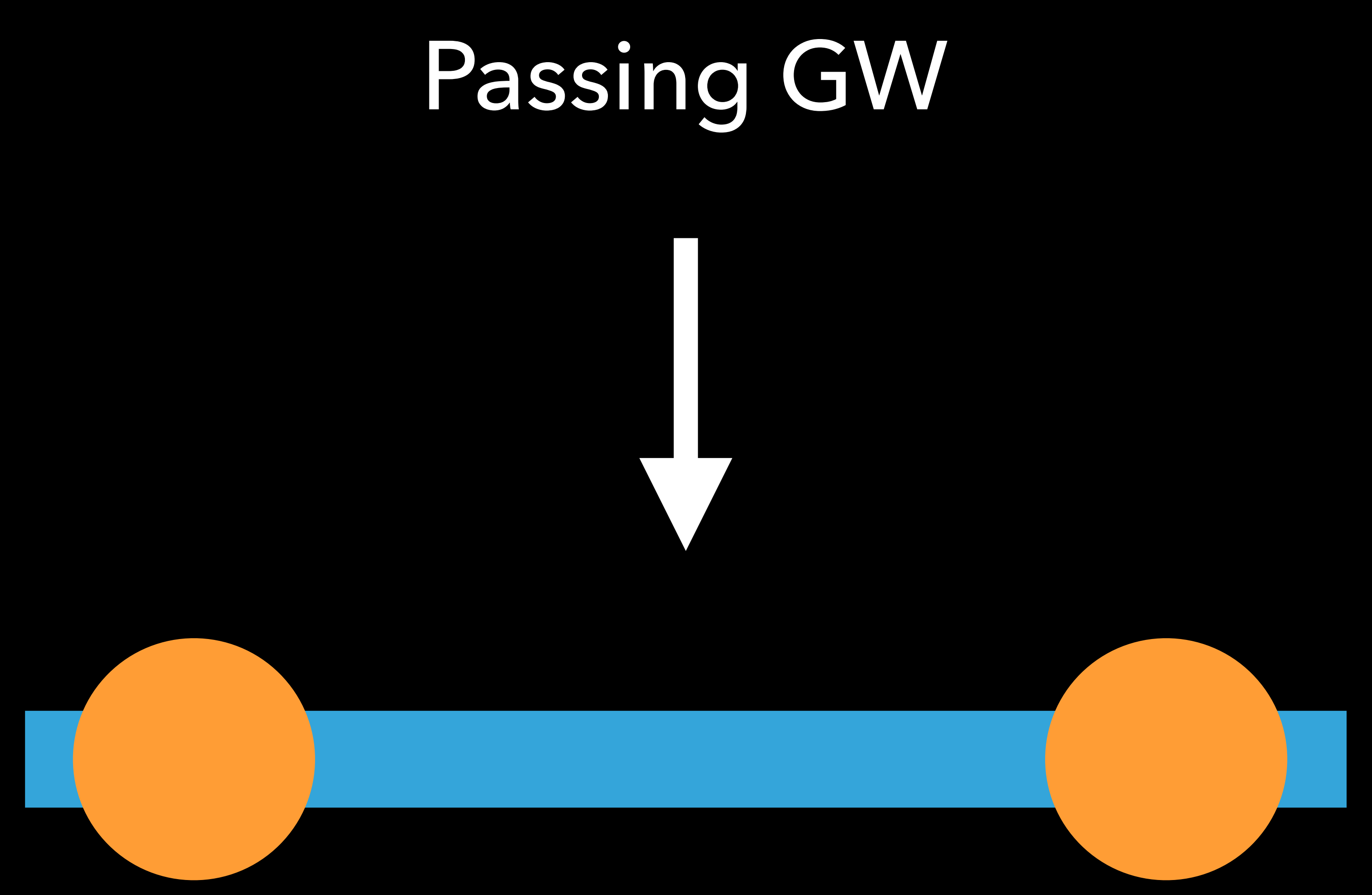
- 1936 undated letter to Max Born: "Together with a young collaborator [Nathan Rosen], I arrived at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation."

- 1936 Princeton lecture: "*If you ask me whether there are gravitational waves or not, I must answer that I do not know. But it is a highly interesting problem.*"

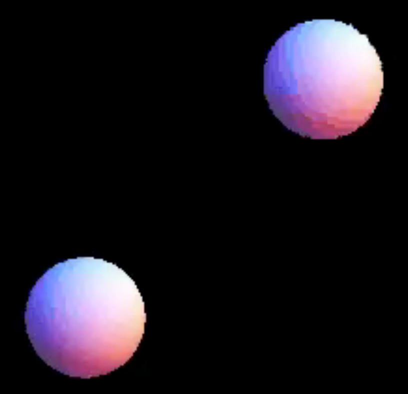
Quotes courtesy Alex Nielsen

STICKY BEAD ARGUMENT

- It was initially unclear whether or not gravitational waves carry energy
- Sticky bead argument: originally due to Feynman (1957 Chapel Hill meeting)



GWS ARE WEAK



- Consider two orbiting masses, m_1 and m_2, separated by distance a
- To leading order, power radiated in GWs is:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{32}{5}\frac{G^4}{c^5}\frac{(m_1 m_2)^2 M}{a^5}$$

- Power emitted in GWs by the Sun & Earth is ~200 Watts
  - about enough power to light an incandescent light bulb

- To get something measurable, need large masses & small separation

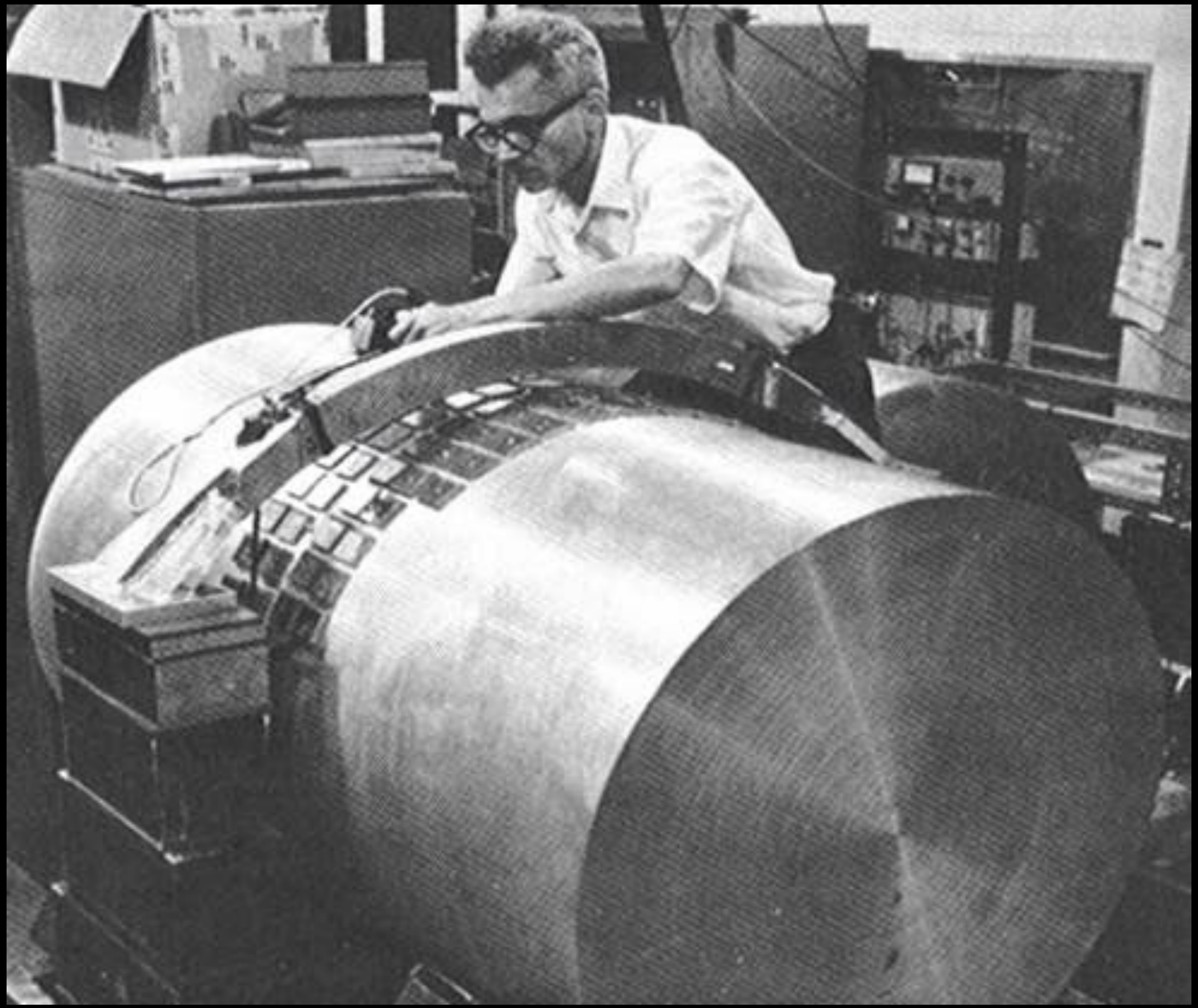
“I am not getting anything out of the meeting. I am learning nothing. Because there are no experiments this field is not an active one, so few of the best men are doing work in it. The result is that there are hosts of dopes here (126) and it is not good for my blood pressure… There is great deal of "activity in the field" these days, but this "activity" is mainly in showing that the previous "activity" of somebody else resulted in an error or in nothing useful or in nothing promising. It is like a lot of worms trying to get out of a bottle by crawling all over each other. It is not that the subject is hard; it is that the good men are occupied elsewhere. Remind me not to come to any more gravity conferences!”

- R. Feynman, letter to his wife, written while at the 1962 Warsaw meeting

From: R. Feynman, “What Do You Care What Other People Think?” P91, 1988

WEBER BARS

- First built by Joseph Weber, physicist at University of Maryland, in 60s and 70s
- Weber claimed detection of GWs from galactic center
- Problem! If his detection claims were true, amount of matter being converted to GWs in galactic center would be too large; Milky Way would have evaporated by now
- Others (e.g., Heinz Billing at MPI Garching) could not corroborate the results
- Even though claims were spurious, Weber was the first to take experimental detection of GWs seriously



Hawking's BH area theorem paper

"Weber has recently reported coinciding measurements of short bursts of gravitational radiation at a frequency of 1660 Hz. These occur at a rate of about one per day and the bursts appear to be coming from the center of the galaxy…. This would imply a mass loss from the center of the galaxy of about 20 000 $M_\odot$/yr. It is therefore possible that the mass of the galaxy might have been considerably higher in the past than it is now. This makes it important to estimate the efficiency with which rest-mass energy can be converted into gravitational radiation."

VOLUME 26, NUMBER 21 PHYSICAL REVIEW LETTERS 24 MAY 1971

§Permanent address: Institute for Atomic Physics, Bucharest, Rumania.

[1]See, e.g., G. A. Keyworth, G. C. Kyker, Jr., E. G. Bilpuch, and H. W. Newson, Nucl. Phys. 89, 590 (1966).

[2]M. Maruyama, K. Tsukada, K. Ozawa, F. Fujimoto, K. Komaki, M. Mannami, and T. Sakurai, Nucl. Phys. A145, 581 (1970).

[3]W. M. Gibson, M. Maruyama, D. W. Mingay, J. P. F. Sellschop, G. M. Temmer, and R. Van Bree, Bull. Amer. Phys. Soc. 16, 557 (1971).

[4]G. M. Temmer, M. Maruyama, D. W. Mingay, M. Petrașcu, and R. Van Bree, Bull. Amer. Phys. Soc. 16, 132 (1971).

[5]L. H. Goldman, Phys. Rev. 165, 1203 (1968).

[6]W. Darcey, J. Fenton, T. H. Kruse, and M. E. Williams, unpublished.

[7]R. Van Bree, unpublished computer program based in part on B. Teitelman and G. M. Temmer, Phys. Rev. 177, 1656 (1969), Appendix. This program does *not* allow for identical spins and parities, and the fit is therefore very tentative.

[8]J. R. Huizenga, private communication. This represents the best estimate, using a slight extrapolation from the *observed* neutron-capture $\frac{1}{2}^+$-level density at 7.6-MeV excitation.

[9]N. Williams, T. H. Kruse, M. E. Williams, J. A. Fenton, and G. L. Miller, to be published.

[10]H. Feshbach, A. K. Kerman, and R. H. Lemmer, Ann. Phys. (New York) 41, 230 (1967); R. A. Ferrell and W. M. MacDonald, Phys. Rev. Lett. 16, 187 (1966).

[11]*Intermediate Structure in Nuclear Reactions*, edited by H. P. Kennedy and R. Schrils (University of Kentucky Press, Lexington, Ky., 1968).

[12]J. D. Moses, thesis, Duke University, 1970 (unpublished).

[13]D. P. Lindstrom, H. W. Newson, E. G. Bilpuch, and G. E. Mitchell, to be published.

[14]J. C. Browne, H. W. Newson, E. G. Bilpuch, and G. E. Mitchell, Nucl. Phys. A153, 481 (1970).

[15]J. D. Moses, private communication.

[16]L. Meyer-Schützmeister, Z. Vager, R. E. Segel, and P. P. Singh, Nucl. Phys. A108, 180 (1968).

[17]J. A. Farrell, G. C. Kyker, Jr., E. G. Bilpuch, and H. W. Newson, Phys. Lett. 17, 286 (1965).

[18]J. E. Monahan and A. J. Elwyn, Phys. Rev. Lett. 20, 1119 (1968).

Gravitational Radiation from Colliding Black Holes

S. W. Hawking
Institute of Theoretical Astronomy, University of Cambridge, Cambridge, England
(Received 11 March 1971)

It is shown that there is an upper bound to the energy of the gravitational radiation emitted when one collapsed object captures another. In the case of two objects with equal masses m and zero intrinsic angular momenta, this upper bound is $(2-\sqrt{2})m$.

Weber[1-3] has recently reported coinciding measurements of short bursts of gravitational radiation at a frequency of 1660 Hz. These occur at a rate of about one per day and the bursts appear to be coming from the center of the galaxy. It seems likely[3,4] that the probability of a burst causing a coincidence between Weber's detectors is less than $\frac{1}{10}$. If one allows for this and assumes that the radiation is broadband, one finds that the energy flux in gravitational radiation must be at least 10^{10} erg/cm^2 day.[4] This would imply a mass loss from the center of the galaxy of about 20 000$M_\odot$/yr. It is therefore possible that the mass of the galaxy might have been considerably higher in the past than it is now.[5] This makes it important to estimate the efficiency with which rest-mass energy can be converted into gravitational radiation. Clearly nuclear reactions are insufficient since they release only about 1% of the rest mass. The efficiency might be higher in either the nonspherical gravitational collapse of a star or the collision and coalescence of two collapsed objects. Up to now no limits on the efficiency of the processes have been known. The object of this Letter is to show that there is a limit for the second process. For the case of two colliding collapsed objects, each of mass m and zero angular momentum, the amount of energy that can be carried away by gravitational or any other form of radiation is less than $(2-\sqrt{2})m$.

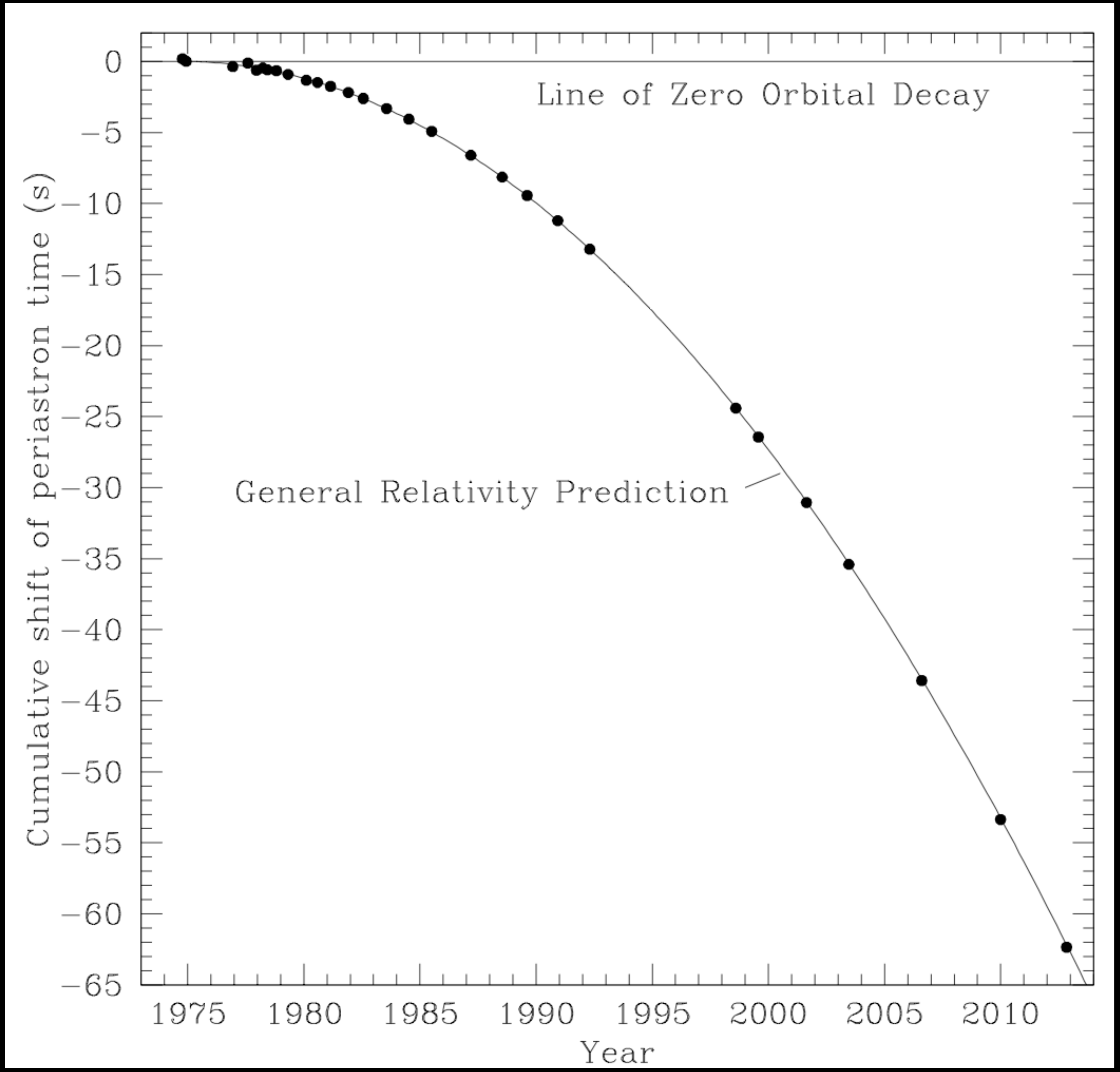
I assume the validity of the Carter-Israel conjucture[6,7] that the metric outside a collapsed object settles down to that of one of the Kerr family of solutions[8] with positive mass m and angular momentum a per unit mass less than or equal to m. (I am using units in which $G=c=1$.) Each of these solutions contains a nonsingular *event horizon*, two-dimensional sections of which are topographically spheres with area[9]

$$8\pi m[m+(m^2-a^2)^{1/2}]. \tag{1}$$

The event horizon is the boundary of the region of space-time from which particles or photons can escape to infinity. I shall consider only

HULSE-TAYLOR PULSAR (1974)

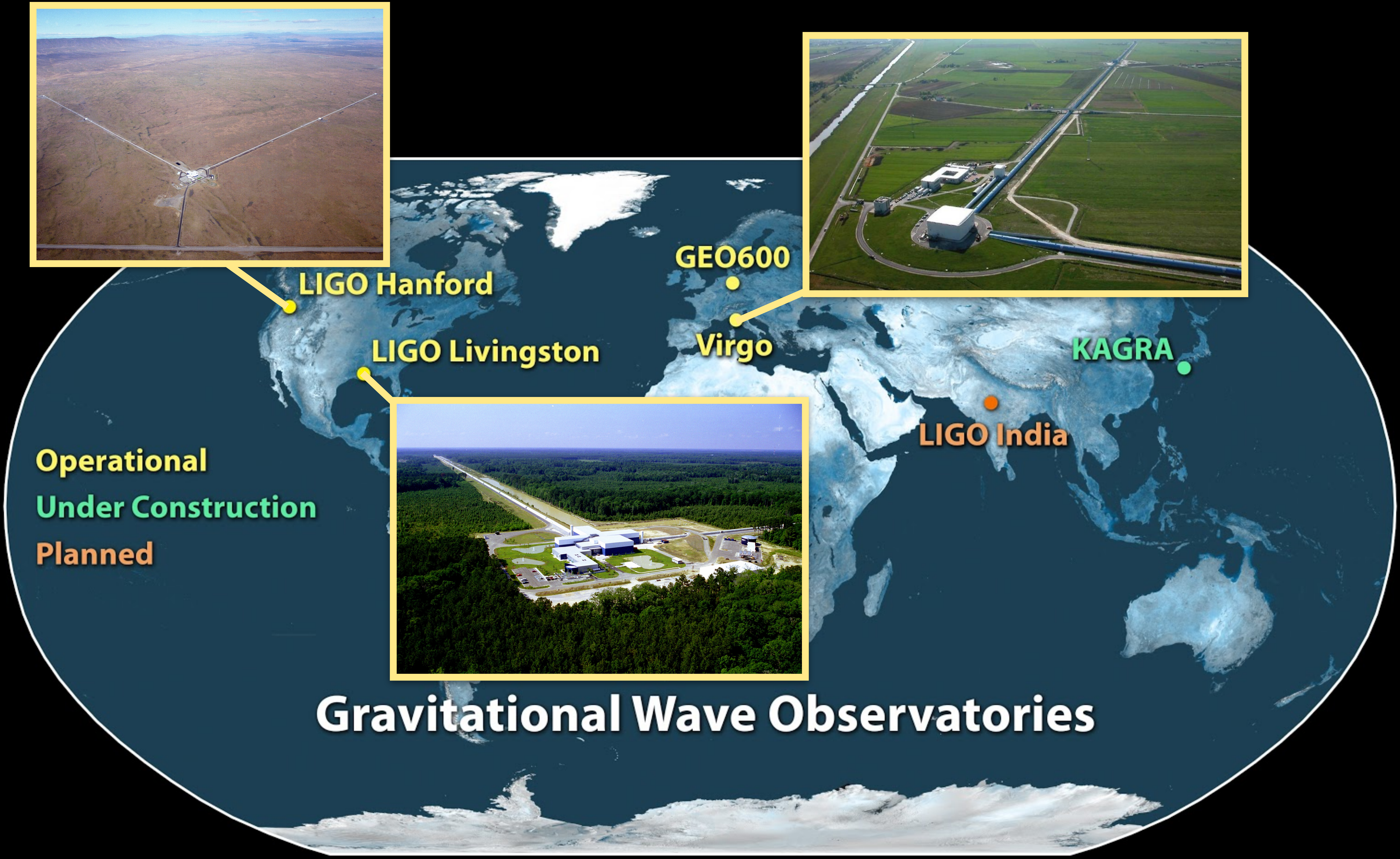
- PSR 1913+16 discovered by Russell Hulse and Joseph Taylor using Arecibo
- They realized the source was a binary pulsar; systematic variation in the pulses was due to periastron advance of the binary.
- Later found binary orbit was decaying
- Decay rate agreed exactly with energy loss due to GWs
- First indirect detection of GWs
- Hulse & Taylor awarded 1993 Nobel prize in Physics for the discovery



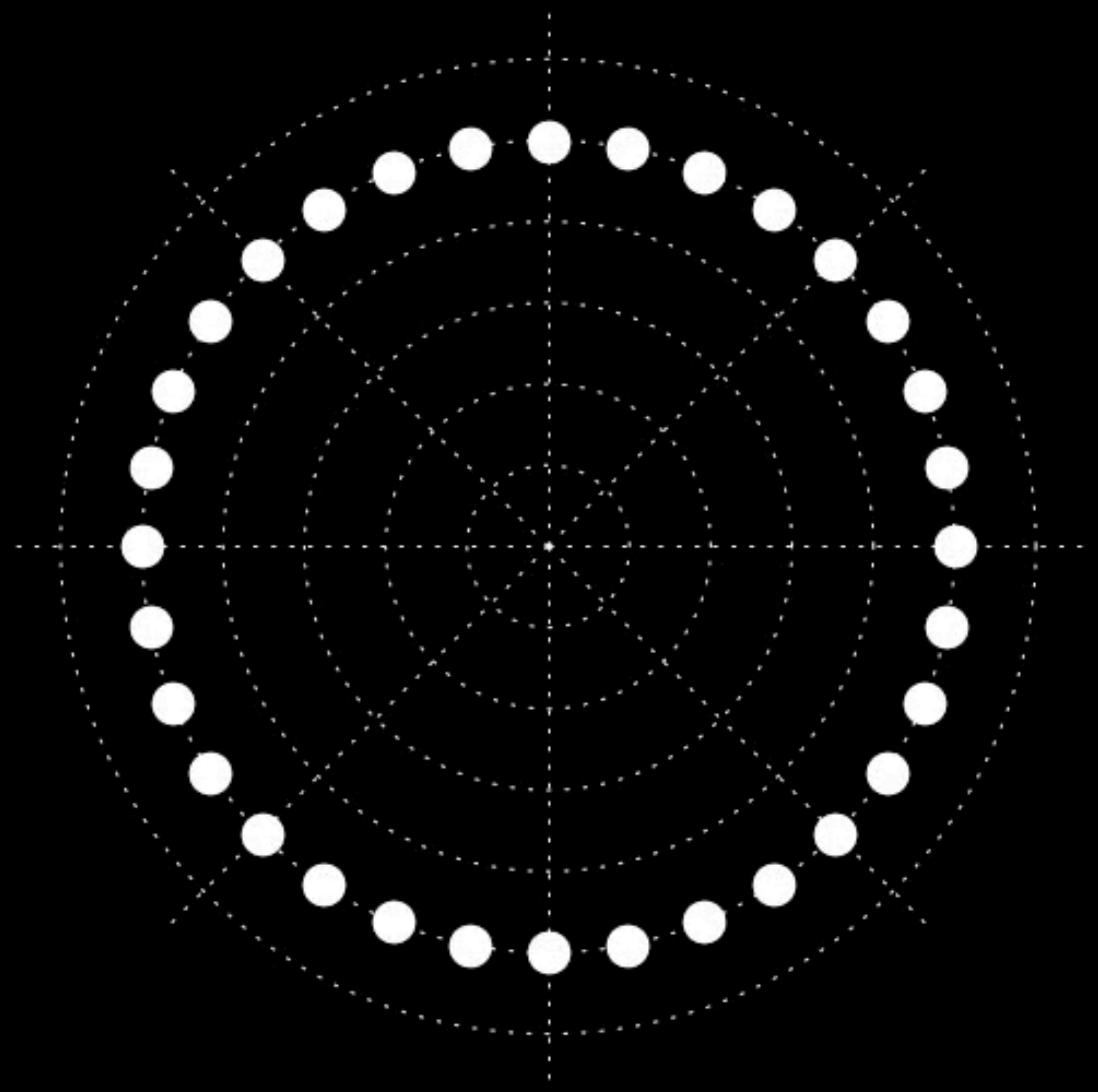
Weisberg & Huang, ApJ 829 55 (2016)

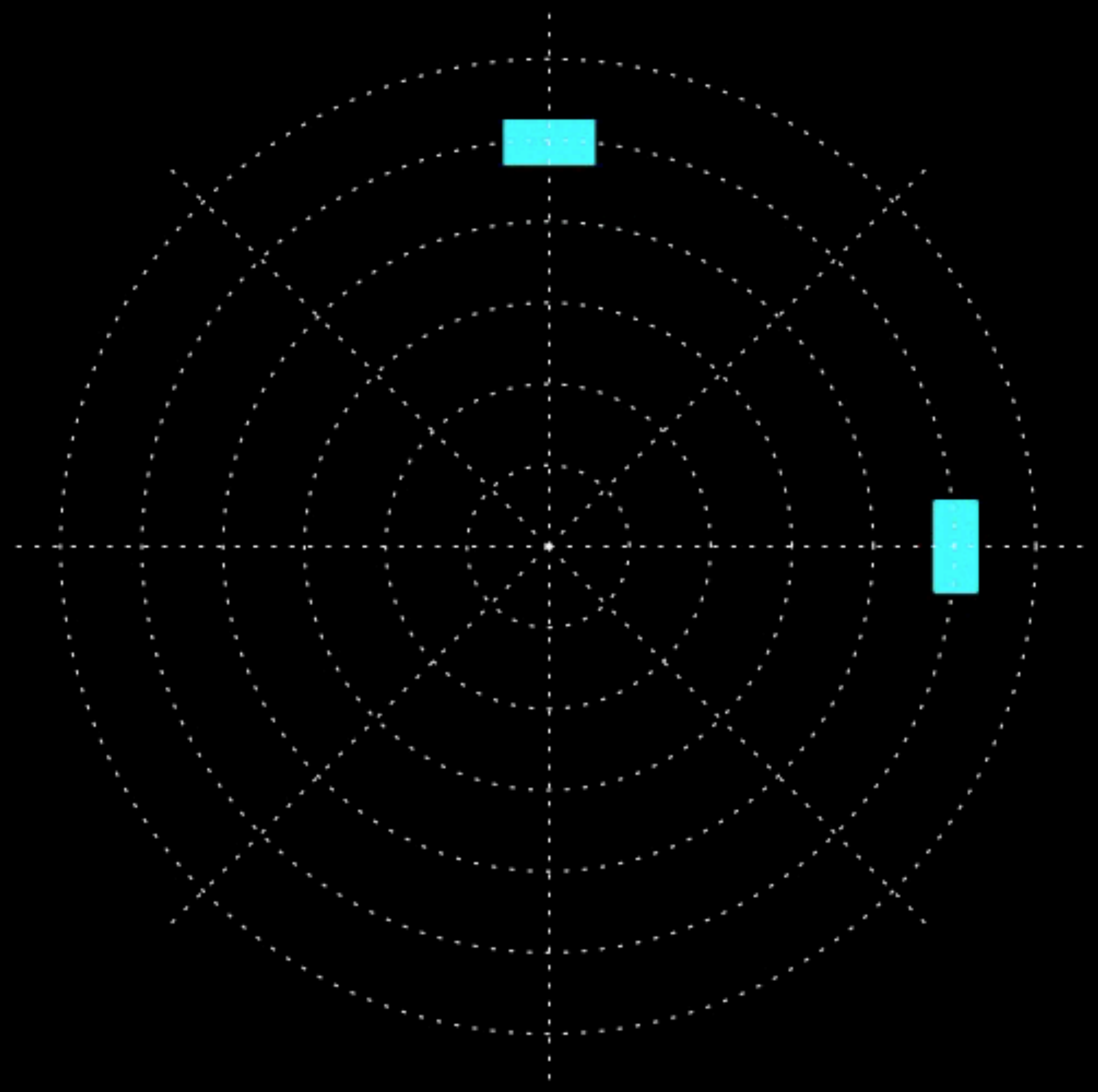
GW INTERFEROMETERS

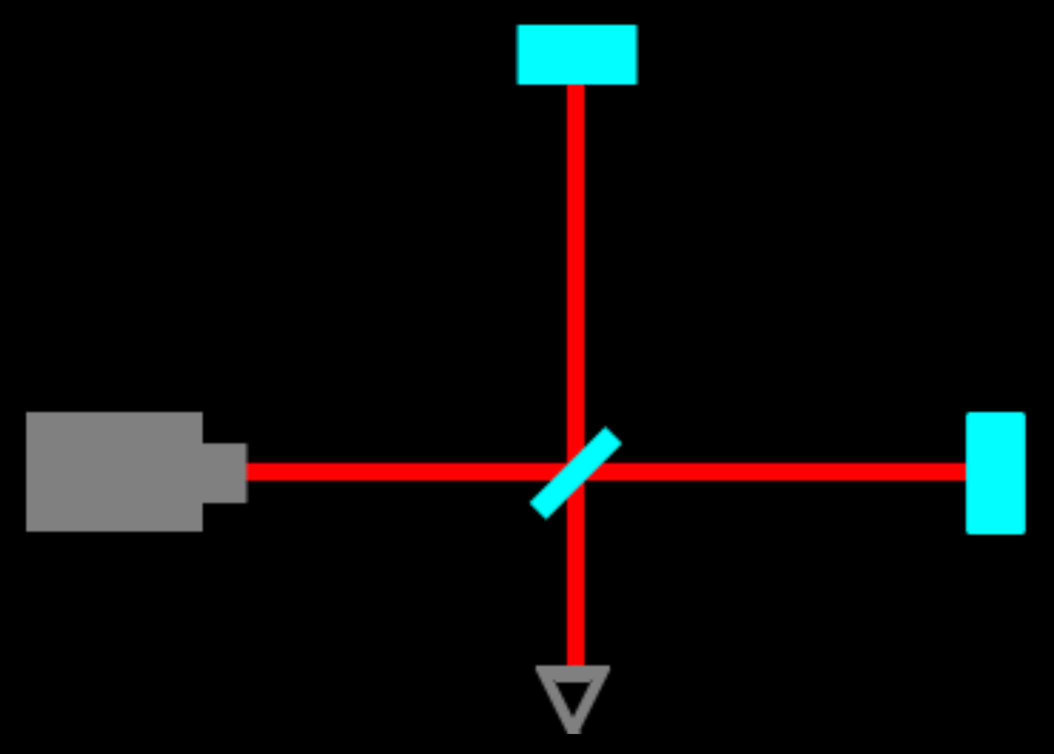
- Pioneering work by Weber and Hulse-Taylor pulsar discovery spurred development of better gravitational-wave detectors using interferometry
- 1980s: Planning & prototyping of kilometer-scale interferometers
- 1990s: LIGO & Virgo built
- 2000s: Initial LIGO & Virgo runs (no detections)
- 2010 – 2014: Advanced LIGO commissioned
- Sept. 2014: Advanced LIGO begins

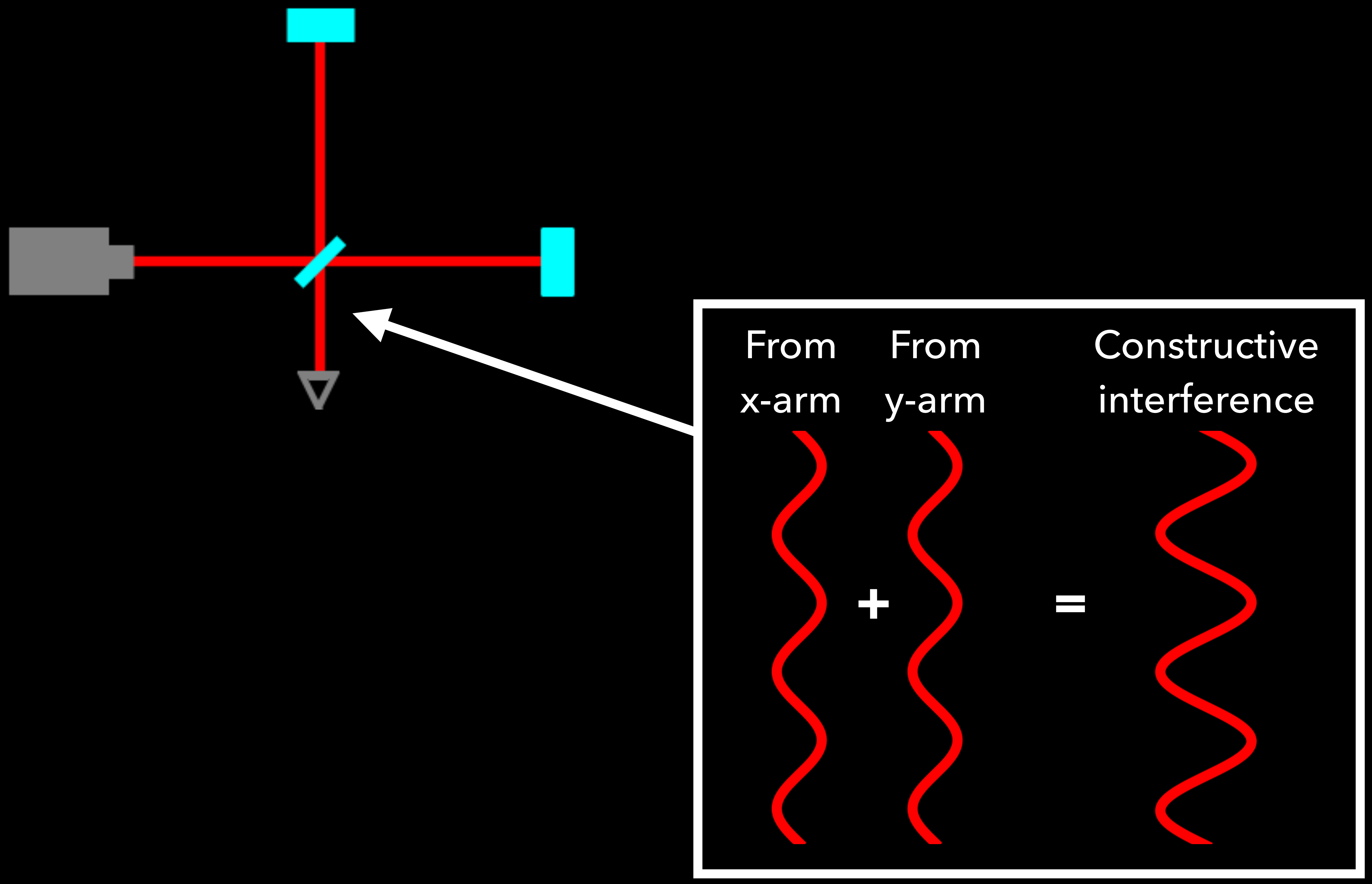


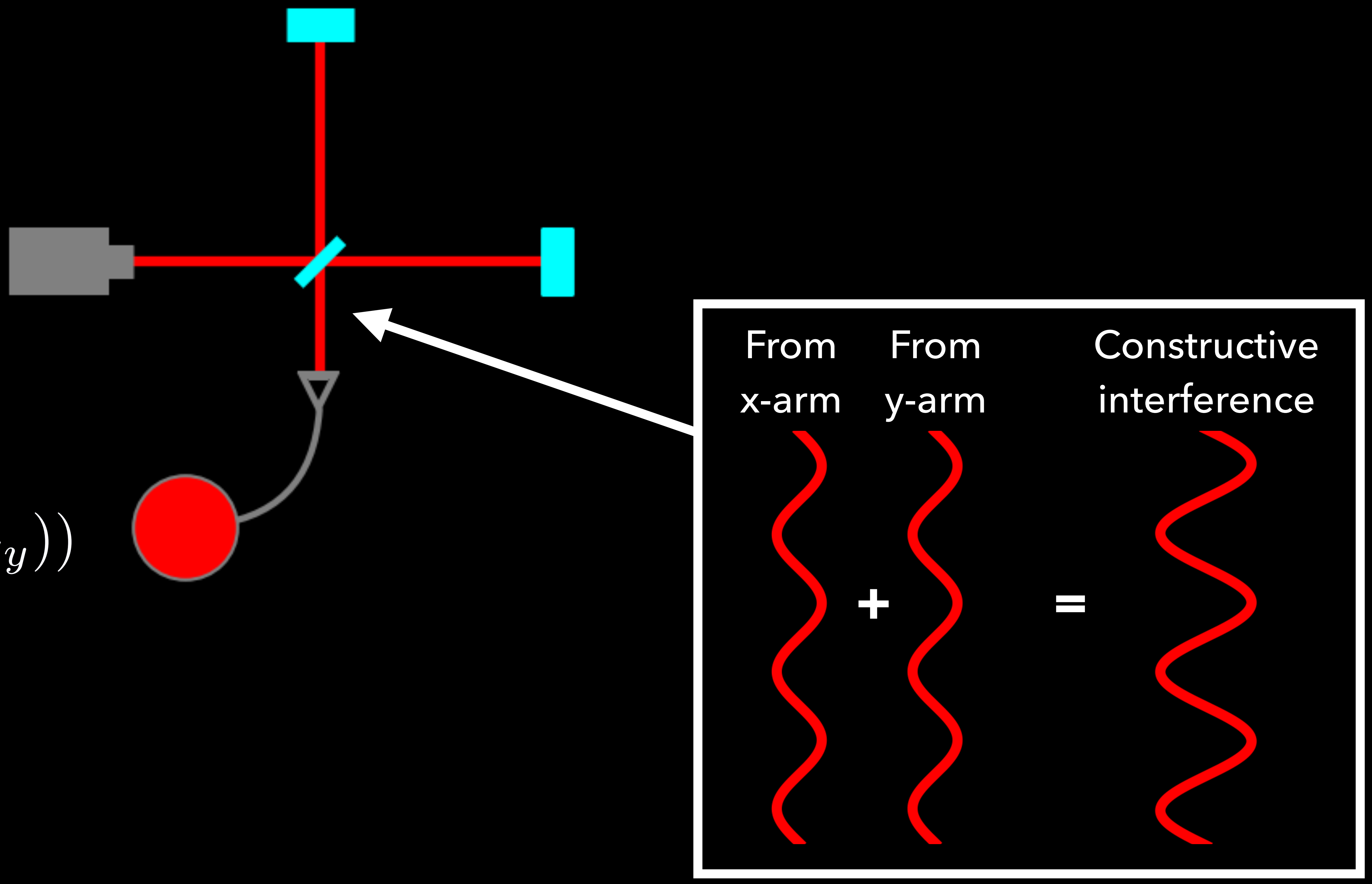
Caltech/MIT/LIGO Lab



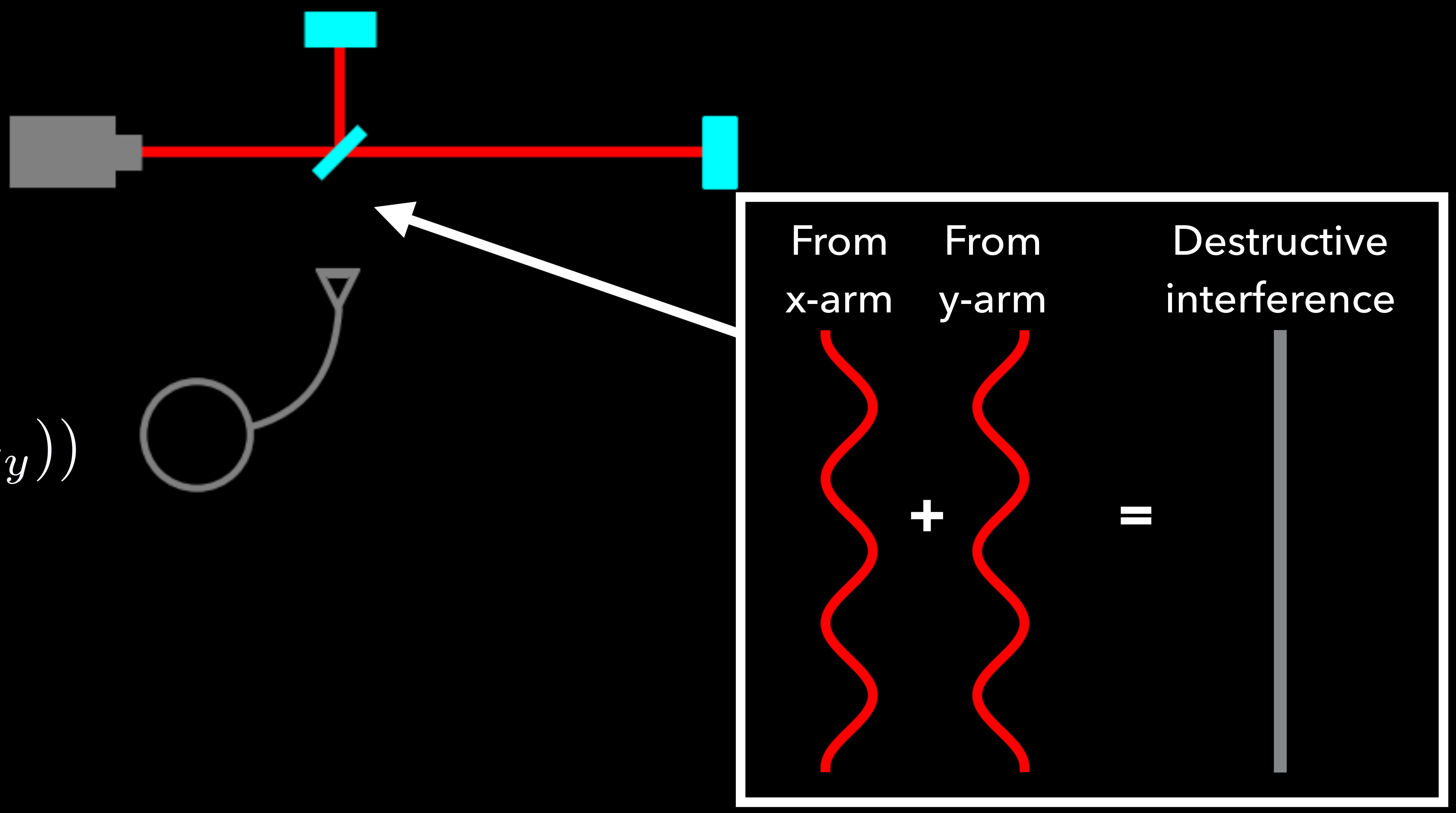





From
x-arm
From
y-arm
Constructive
interference
+
=



$$E_{\mathrm{out}} \sim \cos\left(2\pi f\left(L_x - L_y\right)\right)$$



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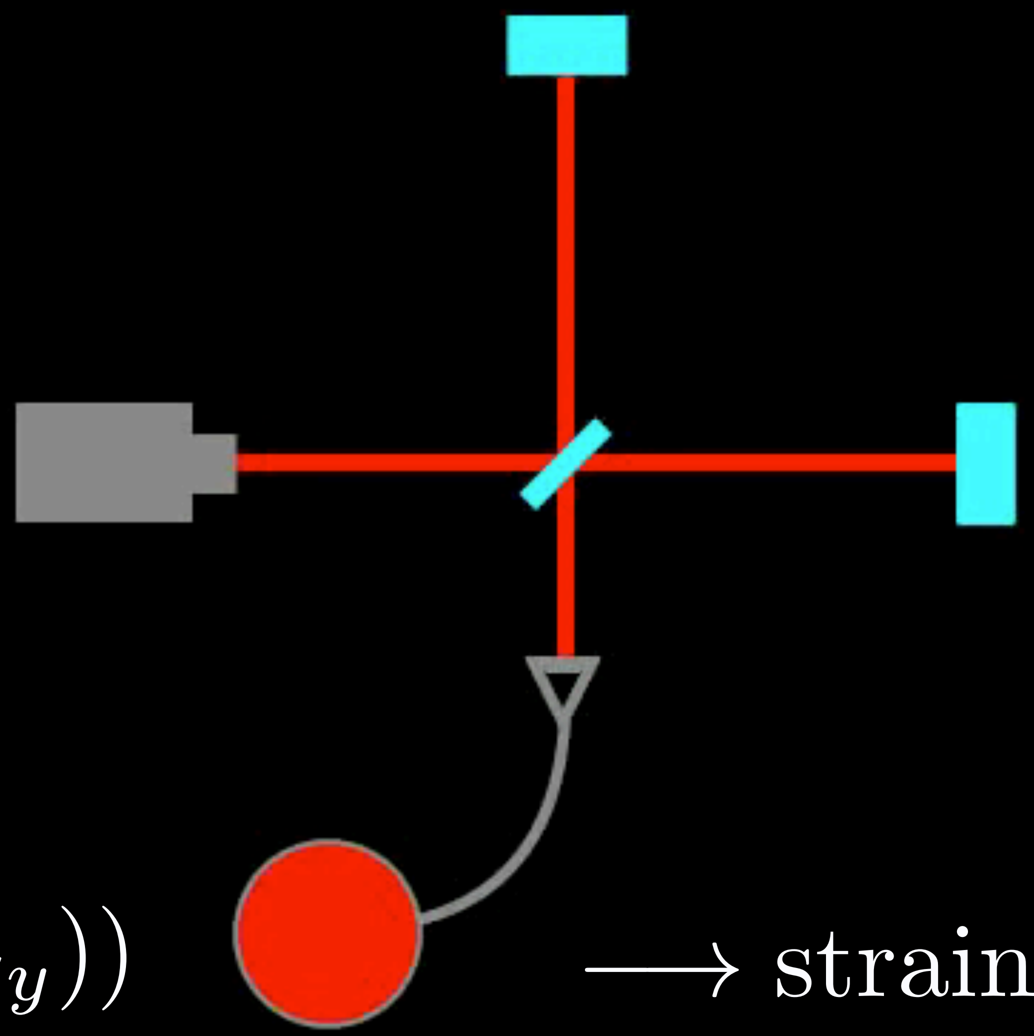
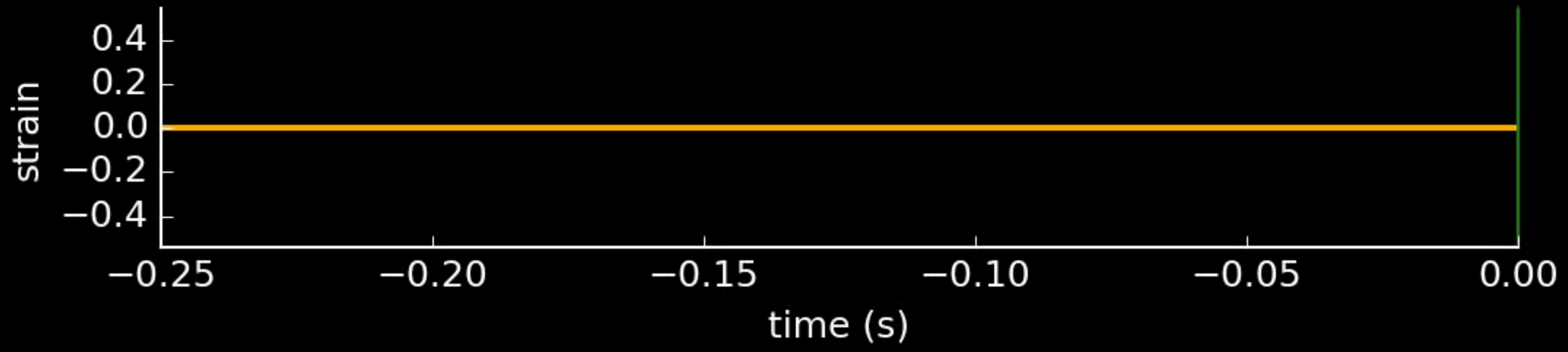
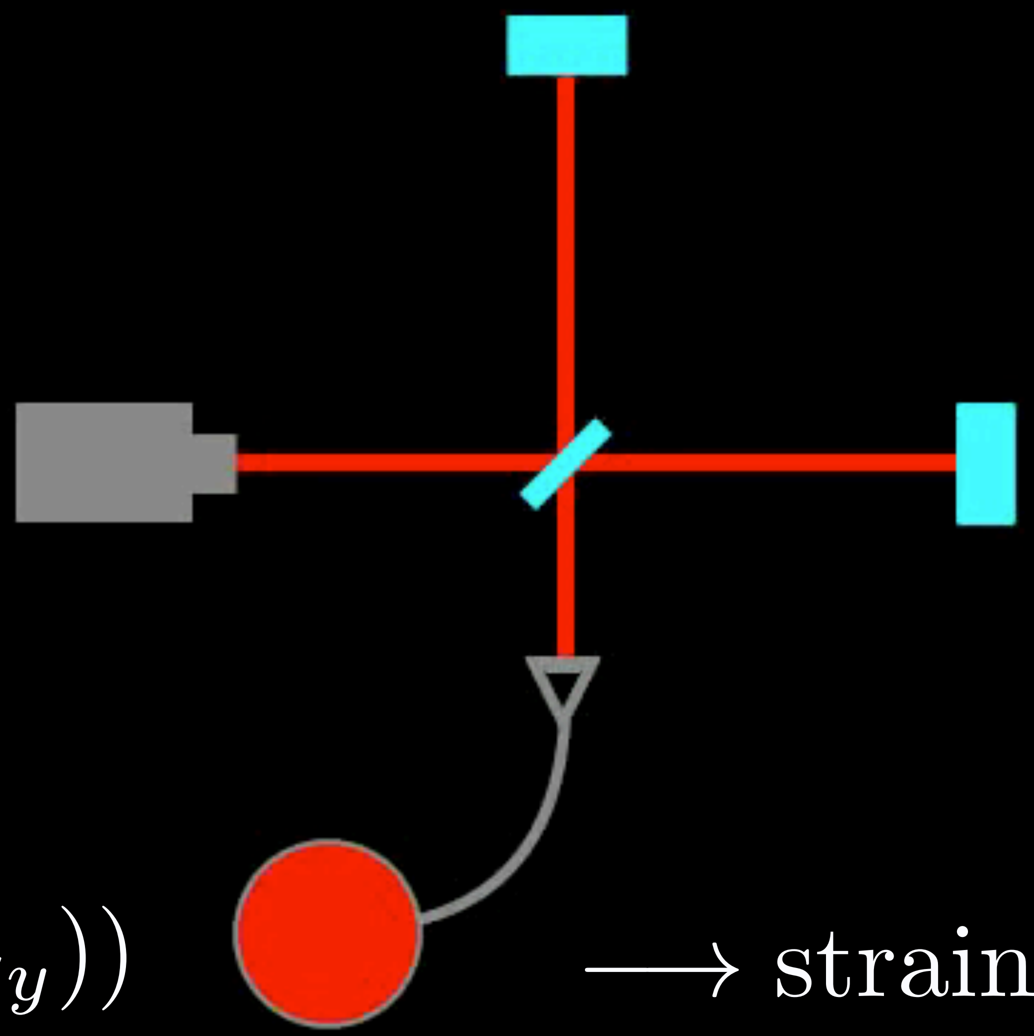


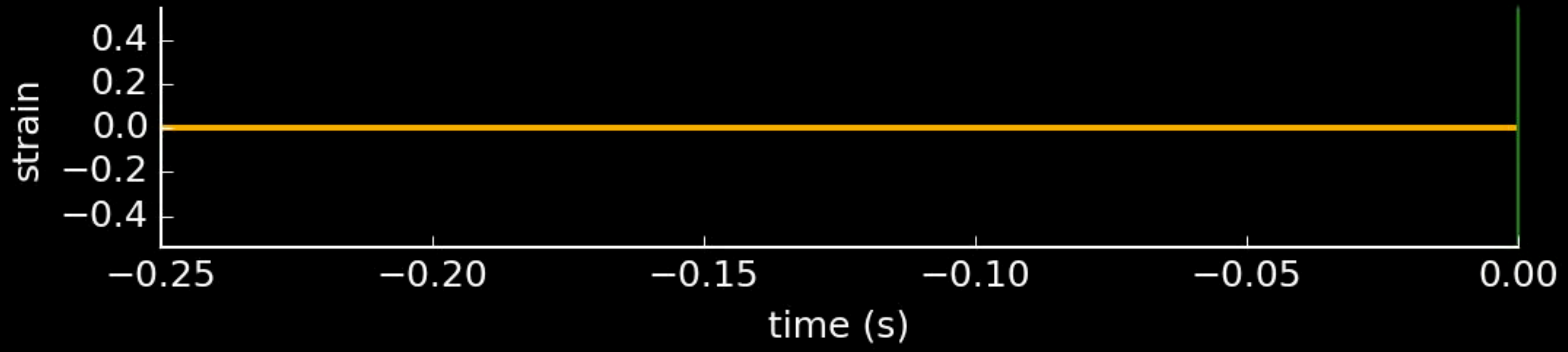
$$E_{\mathrm{out}} \sim \cos\left(2\pi f\left(L_x - L_y\right)\right) \longrightarrow \mathrm{strain} \equiv \frac{\Delta L}{L}$$



Q: Isn't the GW stretching spacetime, not moving the mirrors? How is any effect measured at all?



$$E_{\text{out}} \sim \cos\left(2\pi f\,(L_x - L_y)\right) \longrightarrow \text{strain} \equiv \frac{\Delta L}{L}$$



REALISTIC STRAINS

- Strain is proportional 1 / distance to source
- A BBH with $m_1 \sim m_2 \sim 30M_\odot$ that is 500Mpc* away will create a strain of:

$$\frac{\Delta L}{L} \sim 10^{-21}$$

- With L = $\mathcal{O}$(1km), need to measure mirror displacements of ~10^{-18} m
- About 0.1% the diameter of a proton

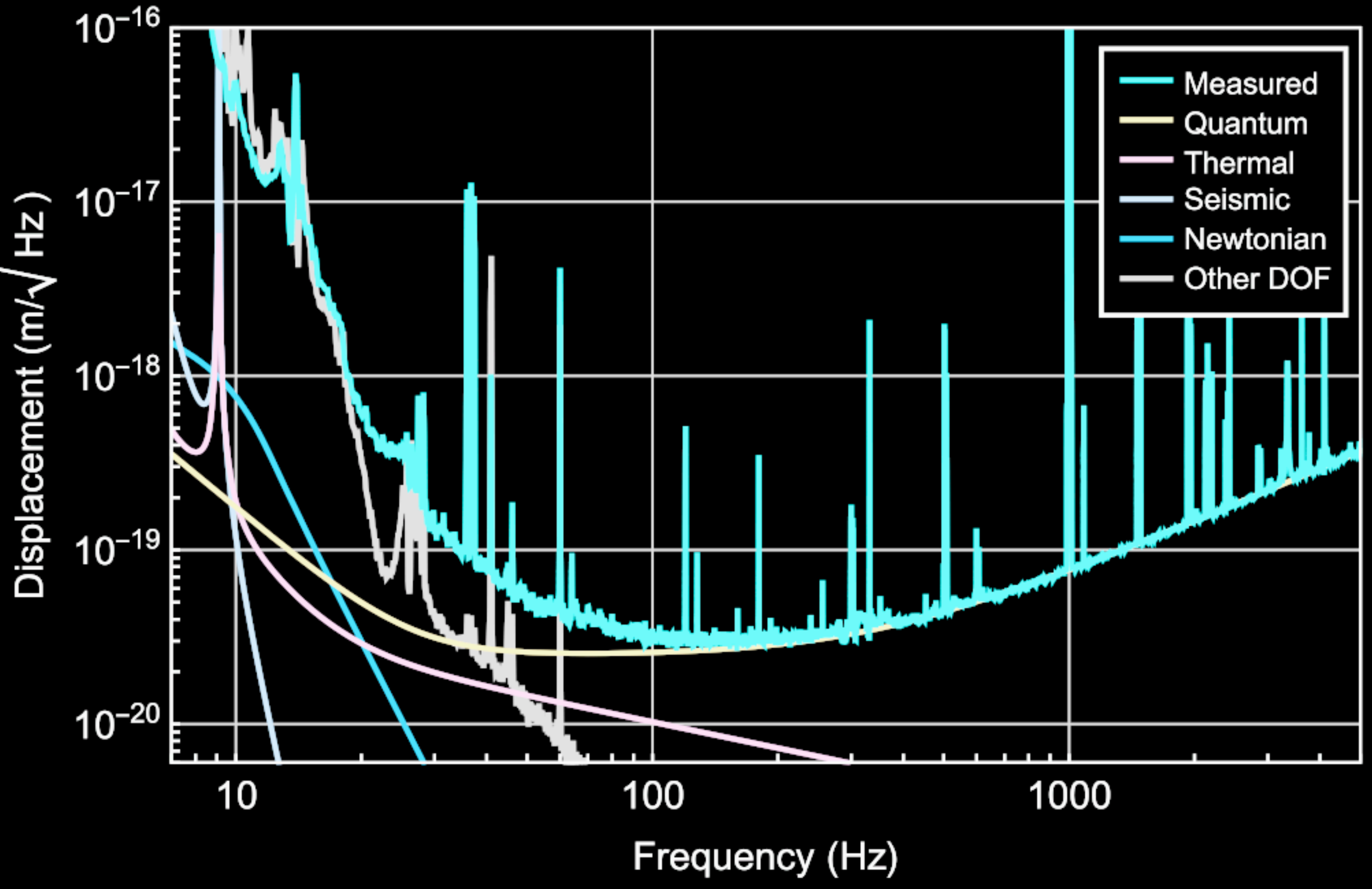
*1Mpc ~ 3 million light years

THE LIGO & VIRGO INTERFEROMETERS

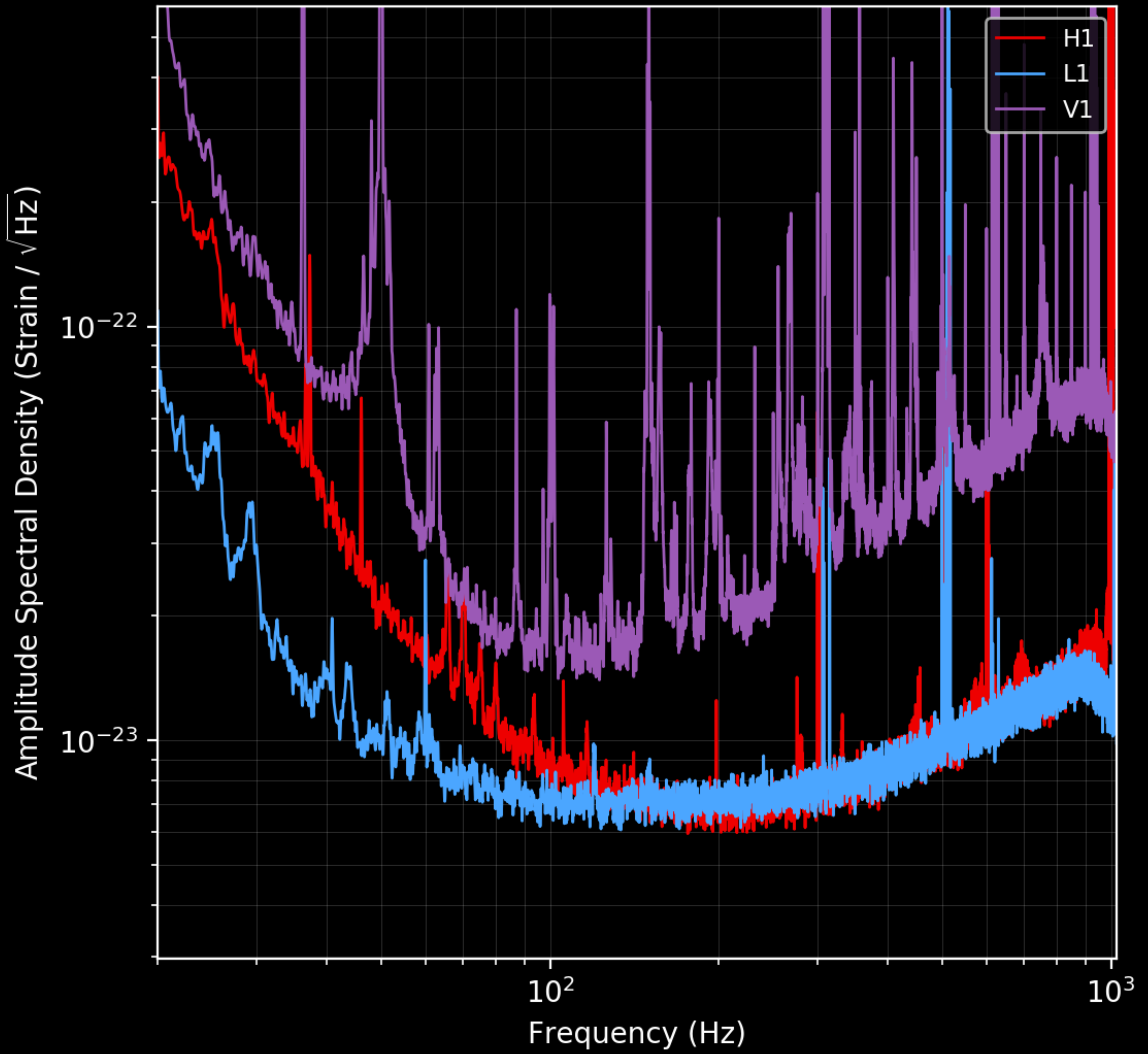
LSC, CQG 32, 074001 (2015)

D.V. Martynov et al., PRD 93, 112004 (2016)

O1 Noise budget (Hanford)



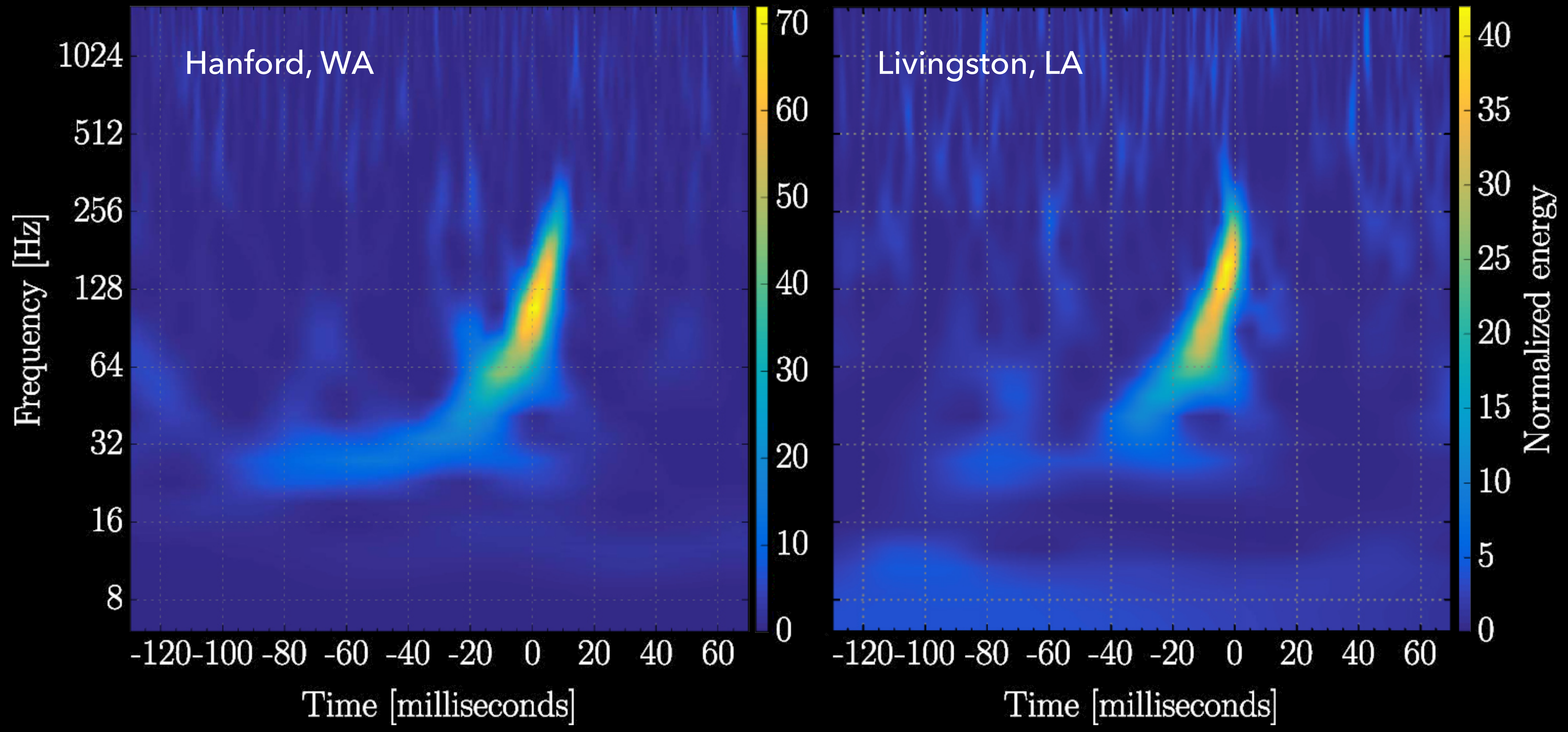
Strain sensitivities (O2)



LSC+Virgo, PRL 116, 131103 (2016)

THE FIRST EVENT: GW150914

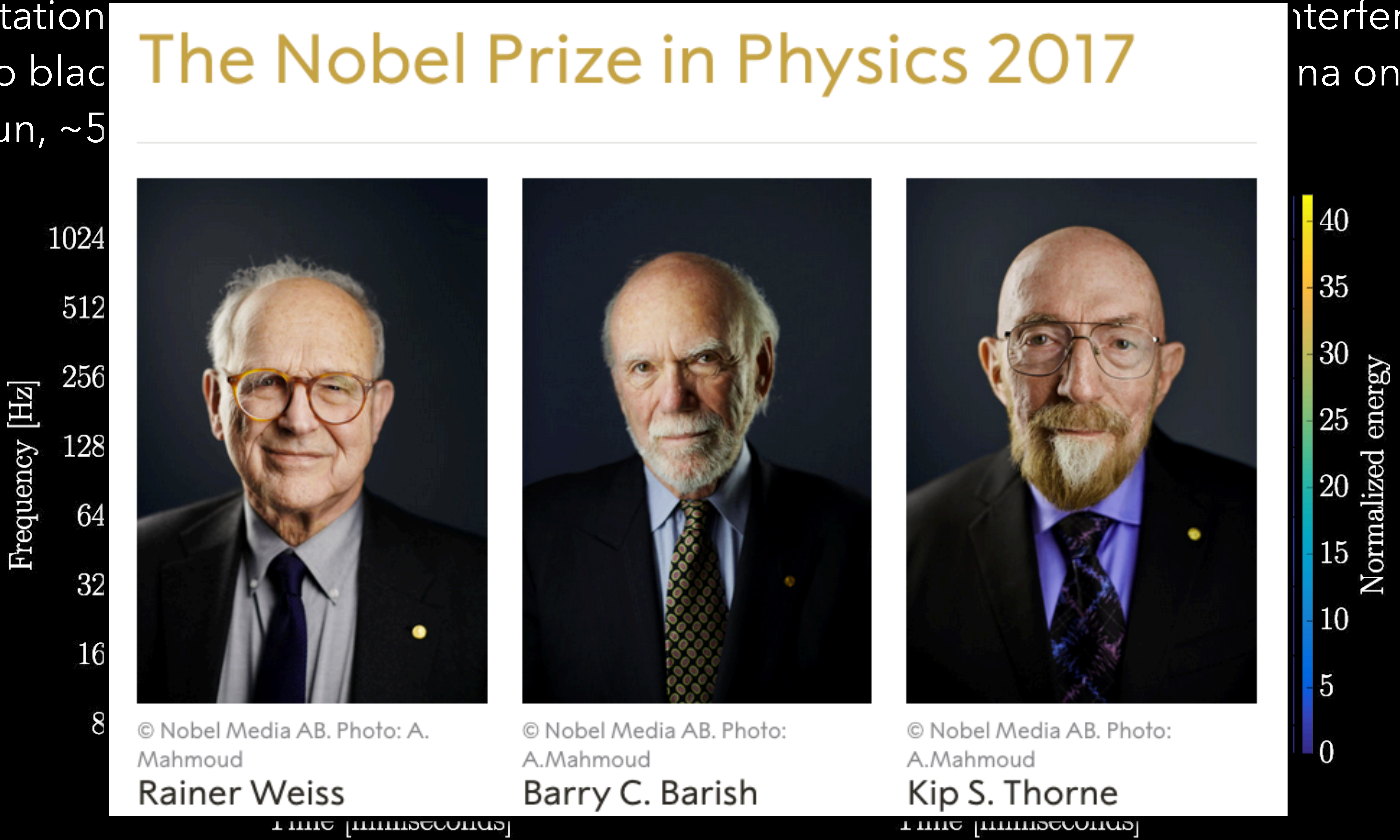
- Gravitational wave emitted by the merger of two black holes, each ~30x the mass of the sun, ~500 Mpc away.
- Detected by the LIGO interferometers in Washington and Louisiana on Sept. 14, 2015 at 09:50:45 UTC



LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, CQG 33, 134001 (2016)

THE FIRST EVENT: GW150914

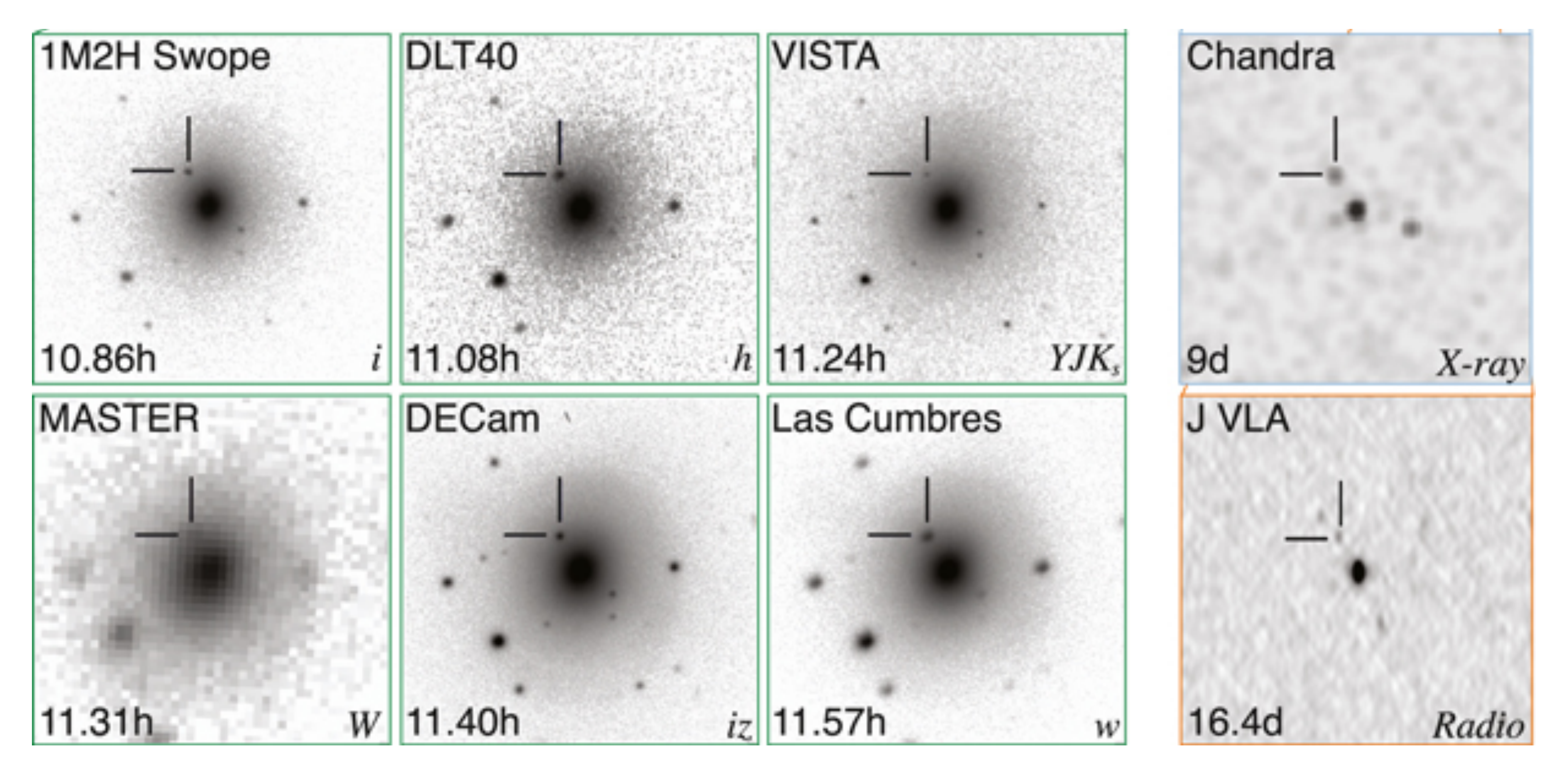
- Gravitation … nterferometers in of two blac … na on Sept. 14, the sun, ~5



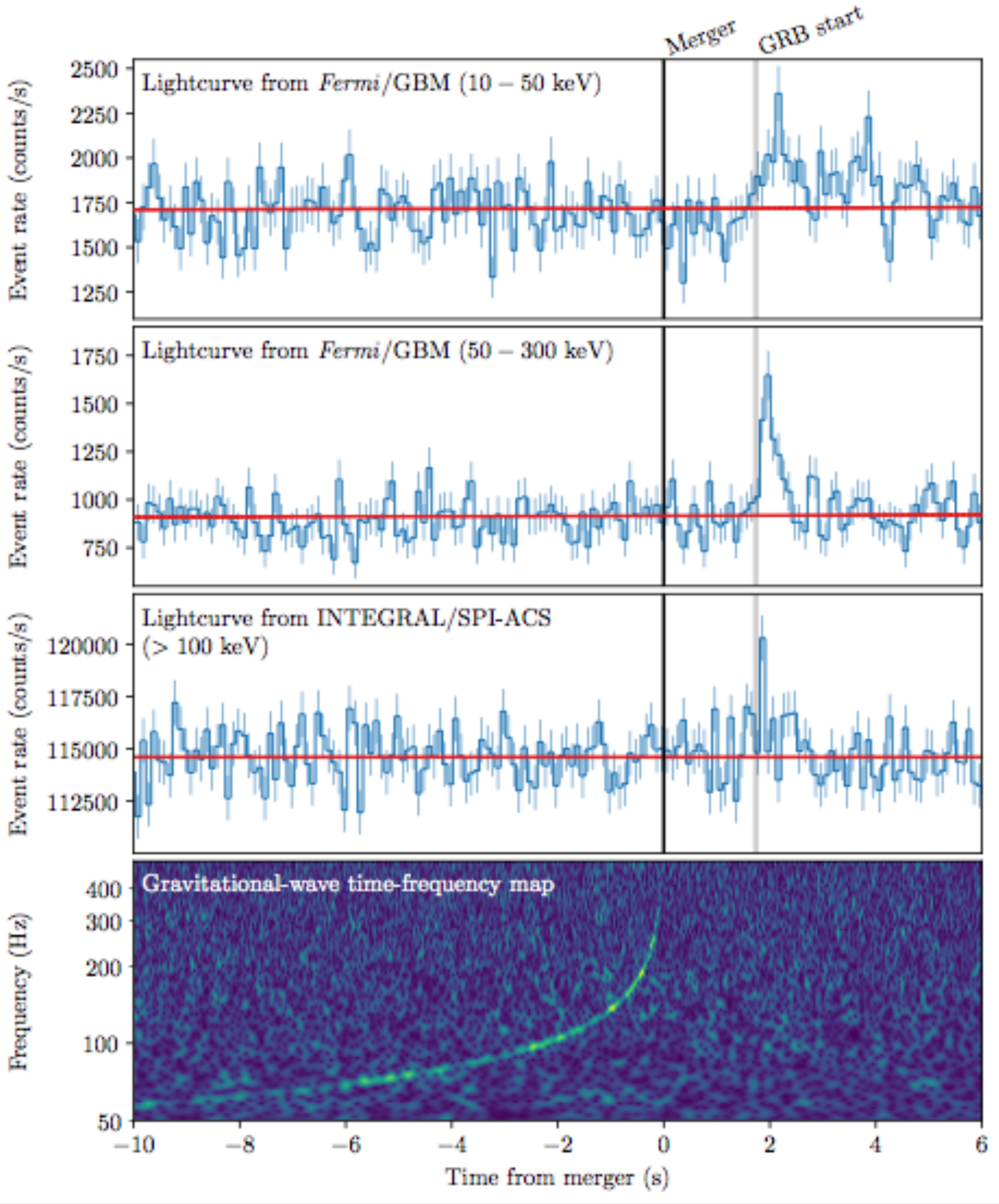
LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, CQG 33, 134001 (2016)

SECOND MILESTONE: GW170817

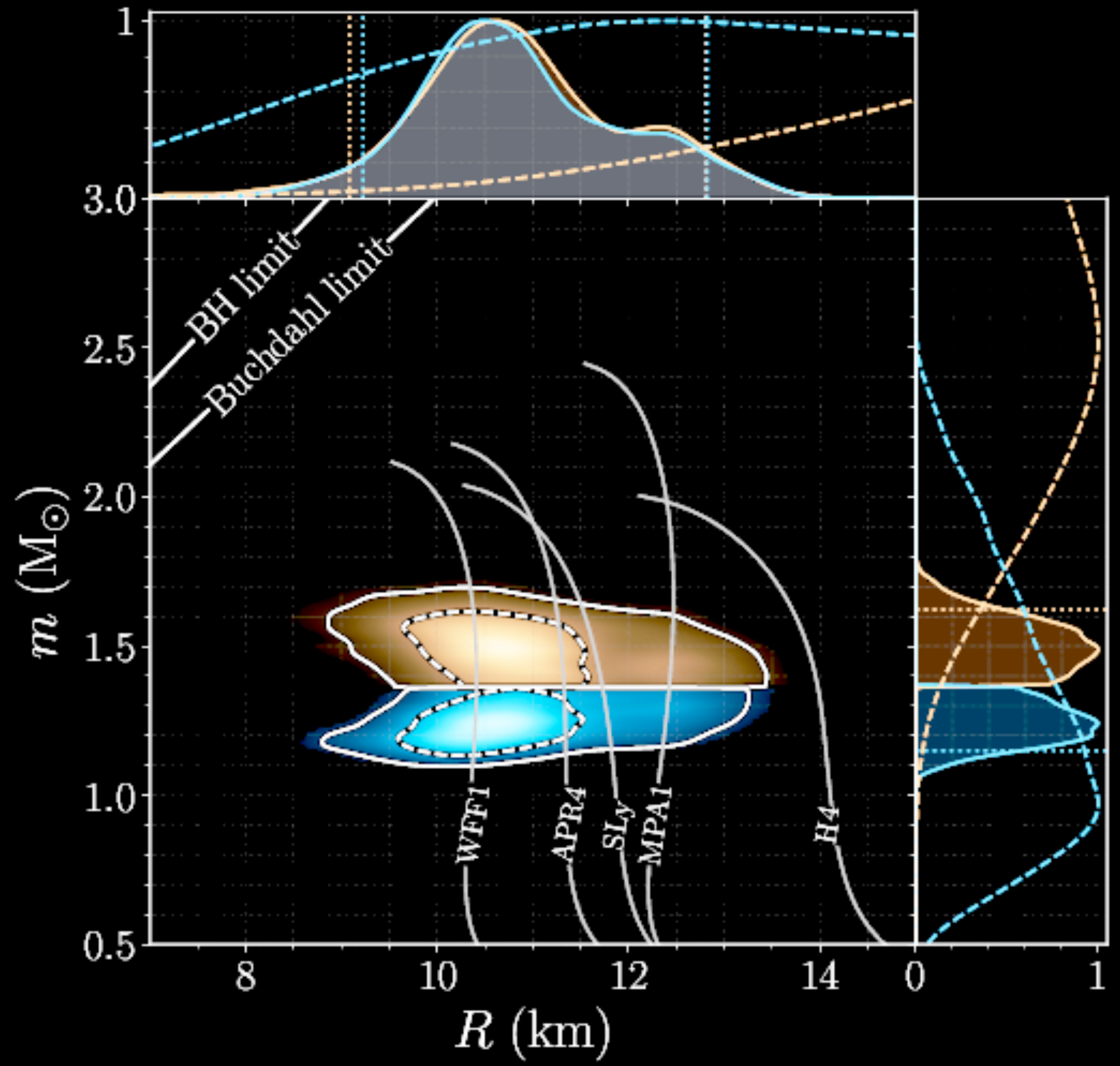
- First detection of a gravitational wave from merger of **two neutron stars** on Aug. 17, 2017.
- **An electromagnetic counterpart was also detected**, marking the first joint GW-EM detection.



A lot of people, ApJL 848 No.2, L12 (2017)



LSC+Virgo, Fermi GBM, & INTEGRAL, ApJL 848, L13 (2017)

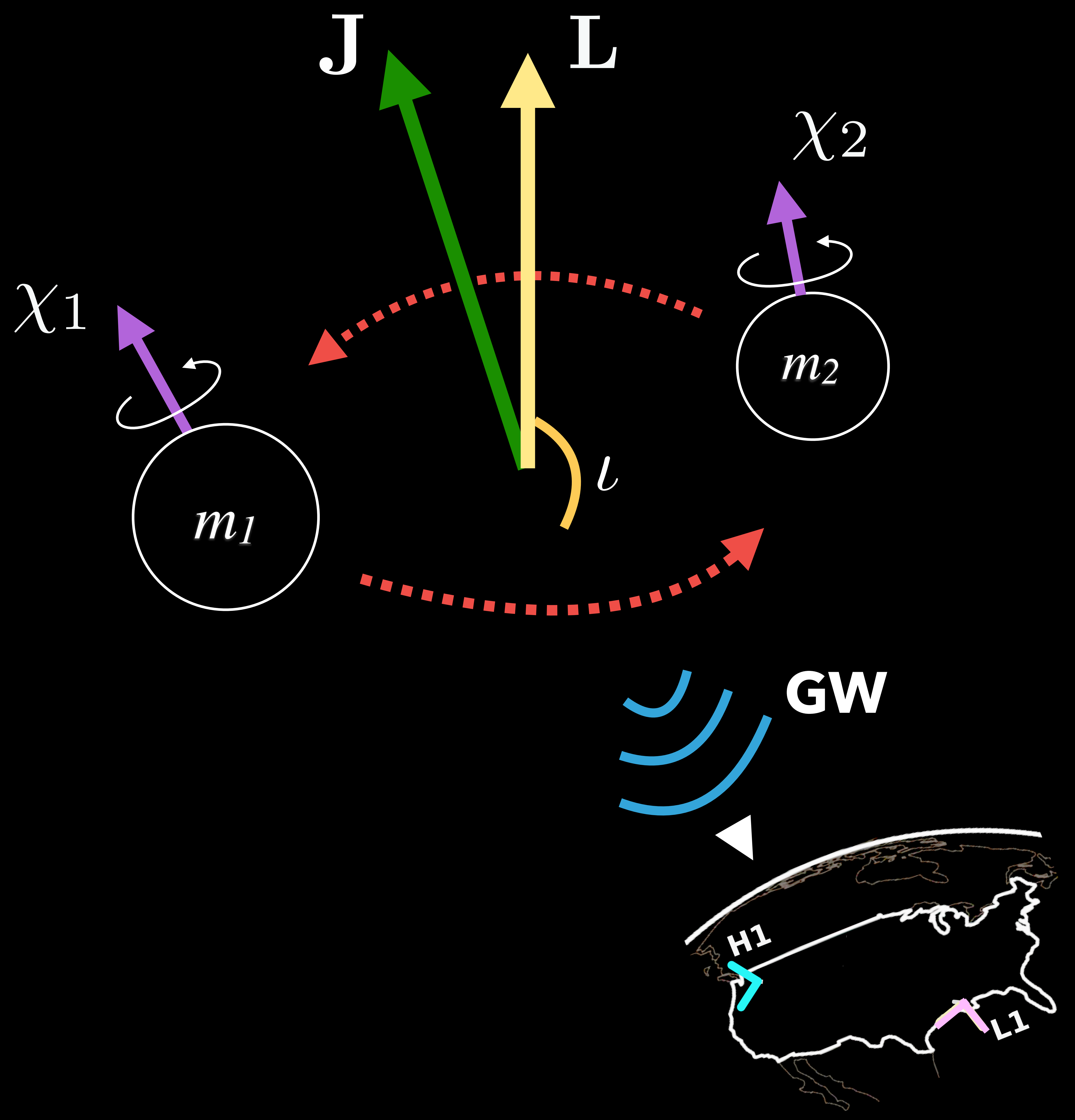


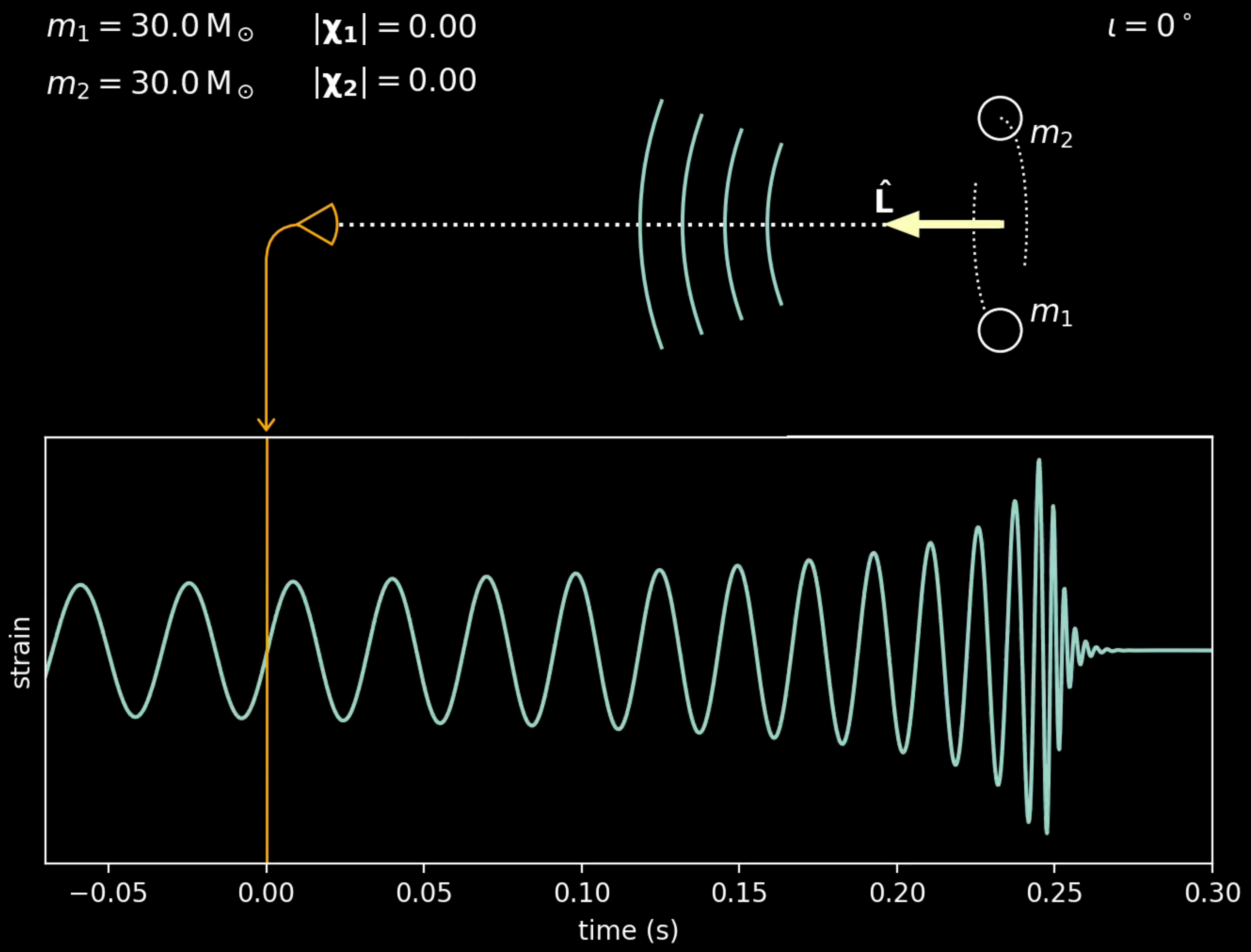
LSC+Virgo, PRL 121, 161101 (2018)

HOW DO WE DO SCIENCE WITH GWS?

BINARY BLACK HOLES

- Possible BBH parameters (#):
  - component masses m_1, m_2 (2)
  - dimensionless spins of components χ_1, χ_2 (6)
  - location & orientation (6)



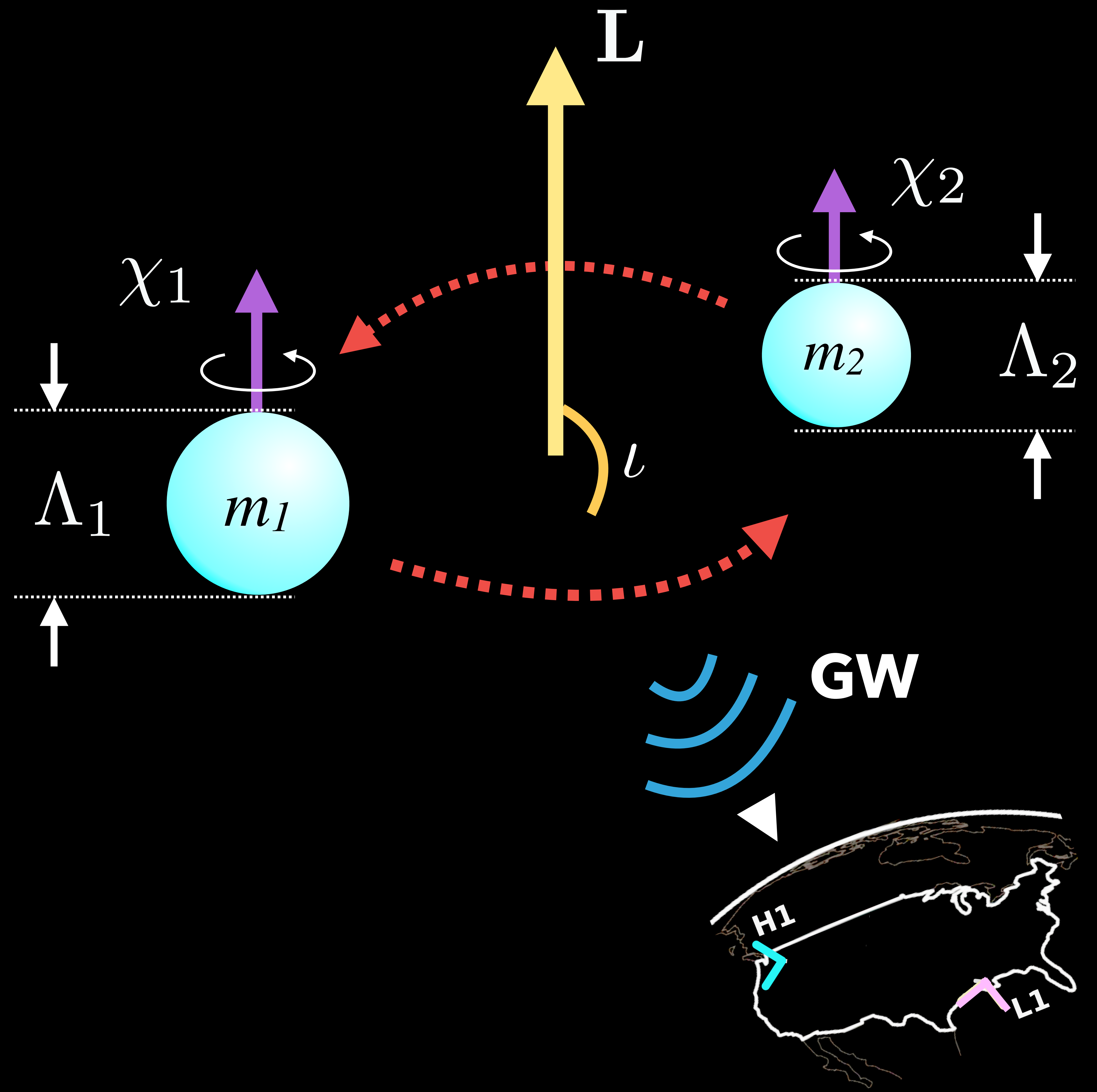

$m_1 = 30.0\,\mathrm{M}_\odot$
$m_2 = 30.0\,\mathrm{M}_\odot$
$|\boldsymbol{\chi}_1| = 0.00$
$|\boldsymbol{\chi}_2| = 0.00$
$\iota = 0^\circ$
m_2
m_1
$\hat{\mathbf{L}}$
strain
−0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
time (s)

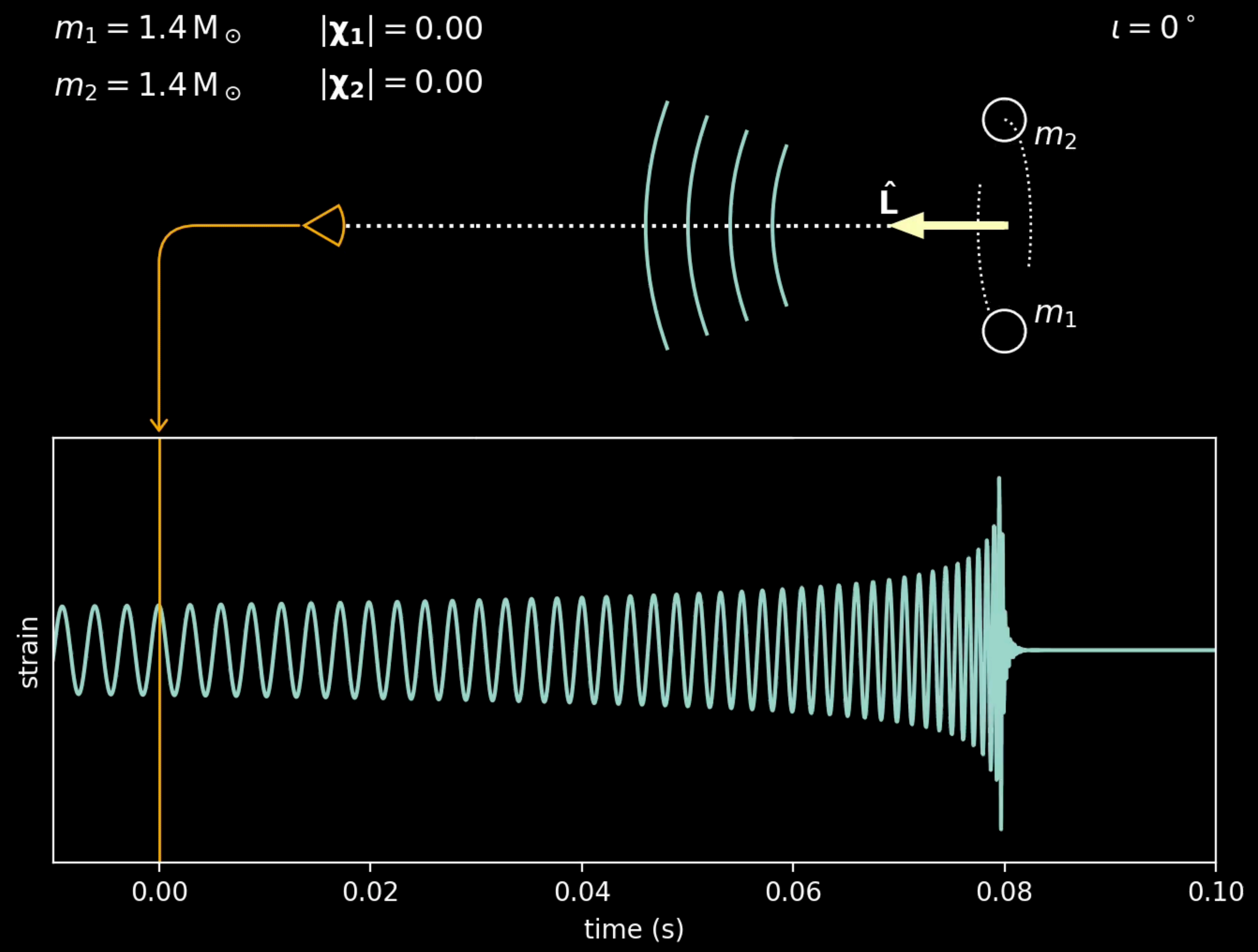
BINARY NEUTRON STARS

- Tidal forces cause neutron stars to deform

$$\Lambda_i \equiv \frac{2}{3} k_2 \left(\frac{R_i c^2}{G m_i} \right)^5$$

- Tidal deformability depends on the equation of state of the matter in the core
- Stars' deformability is encoded in gravitational wave




$m_1 = 1.4\,\mathrm{M}_\odot$
$m_2 = 1.4\,\mathrm{M}_\odot$
$|\chi_1| = 0.00$
$|\chi_2| = 0.00$
$\iota = 0^\circ$
m_2
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strain
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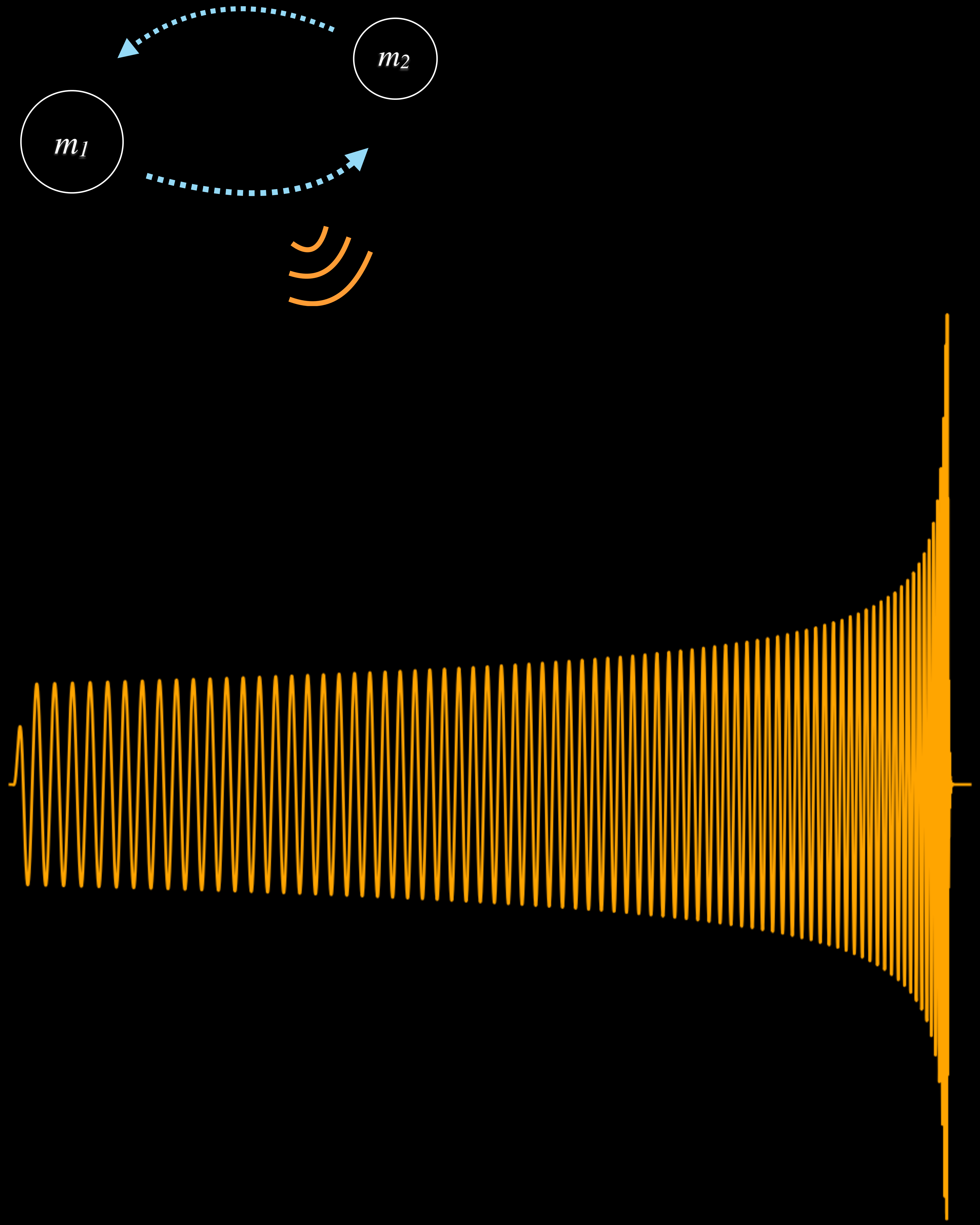
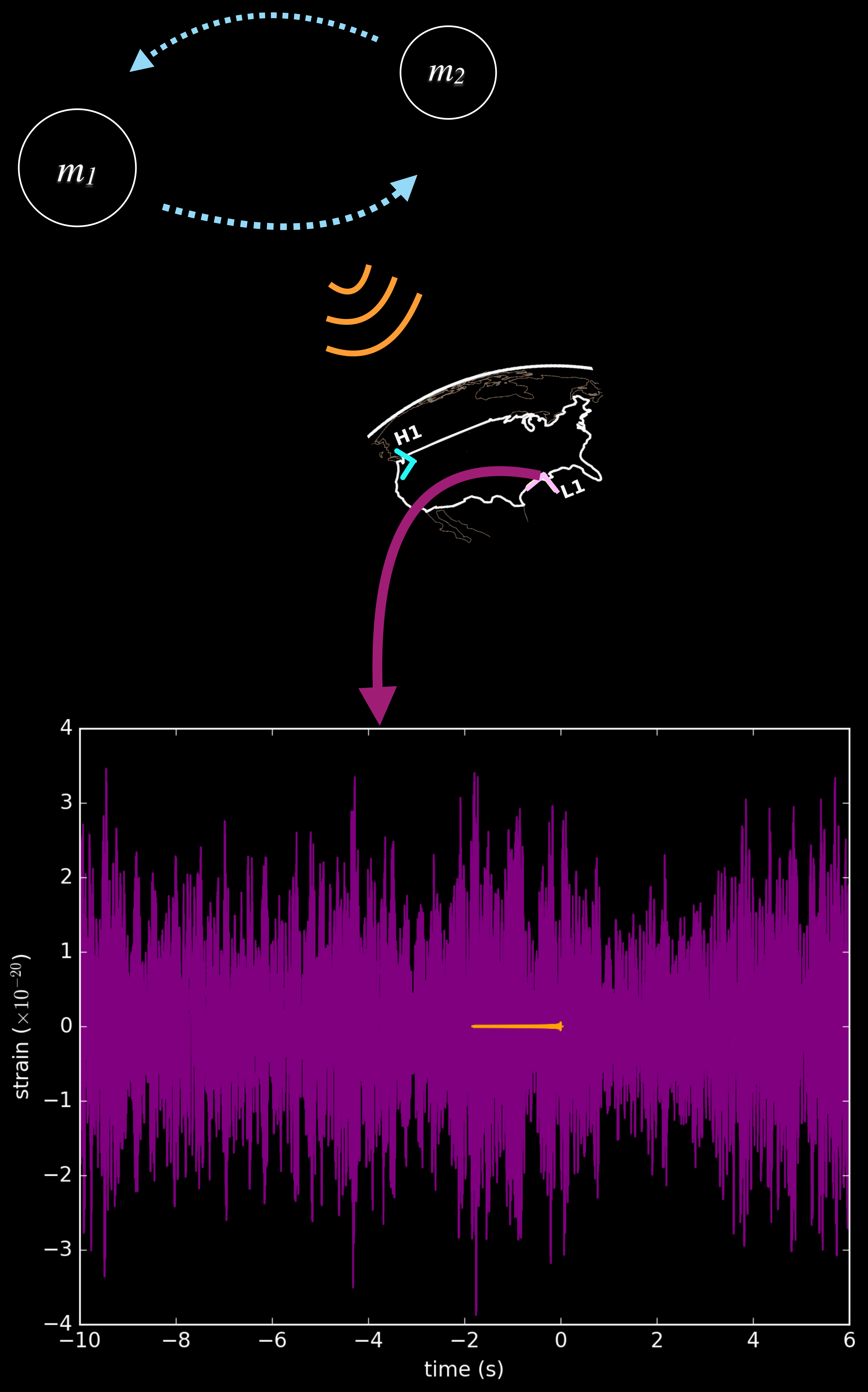
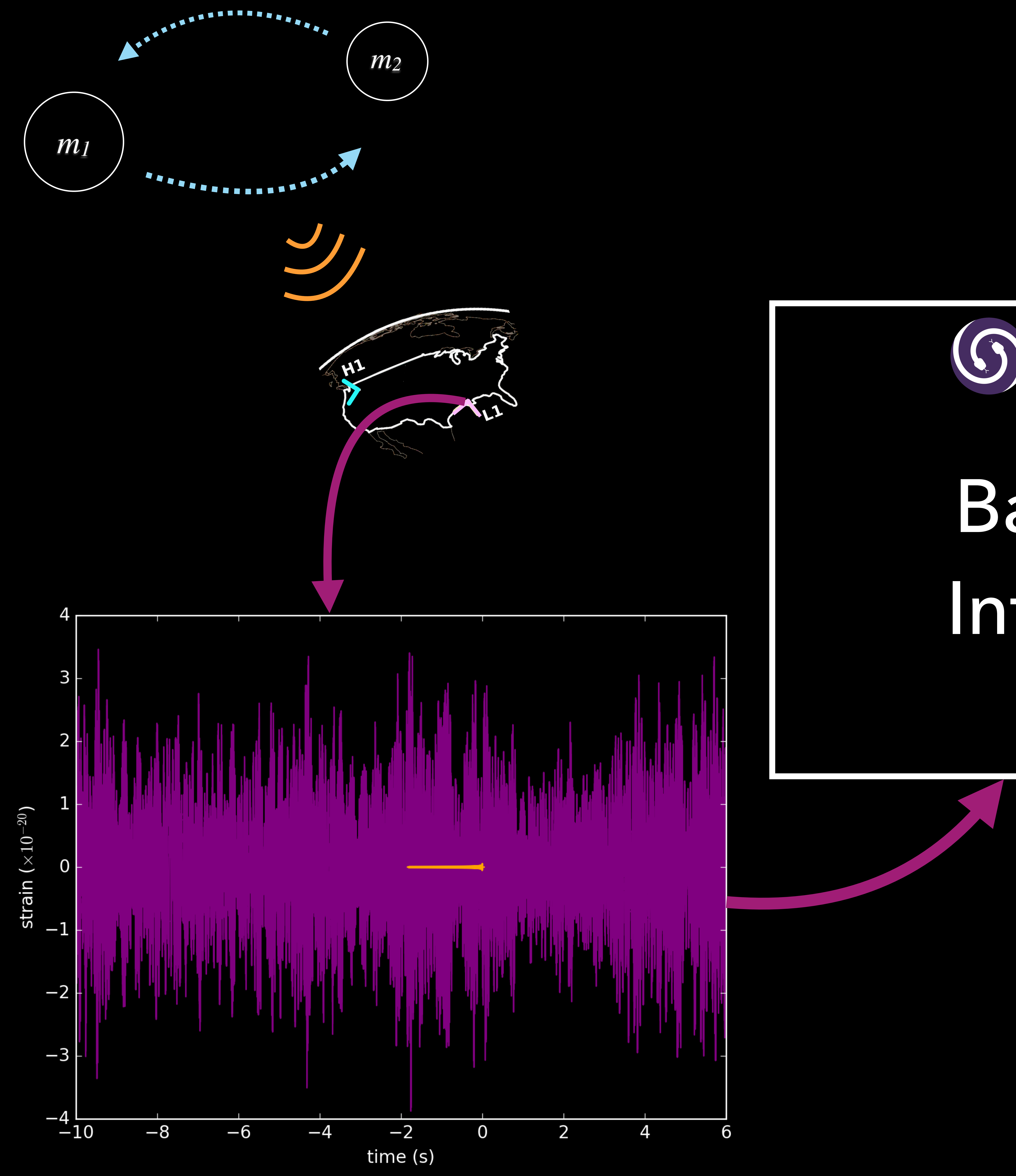
0.04
0.06
0.08
0.10
time (s)

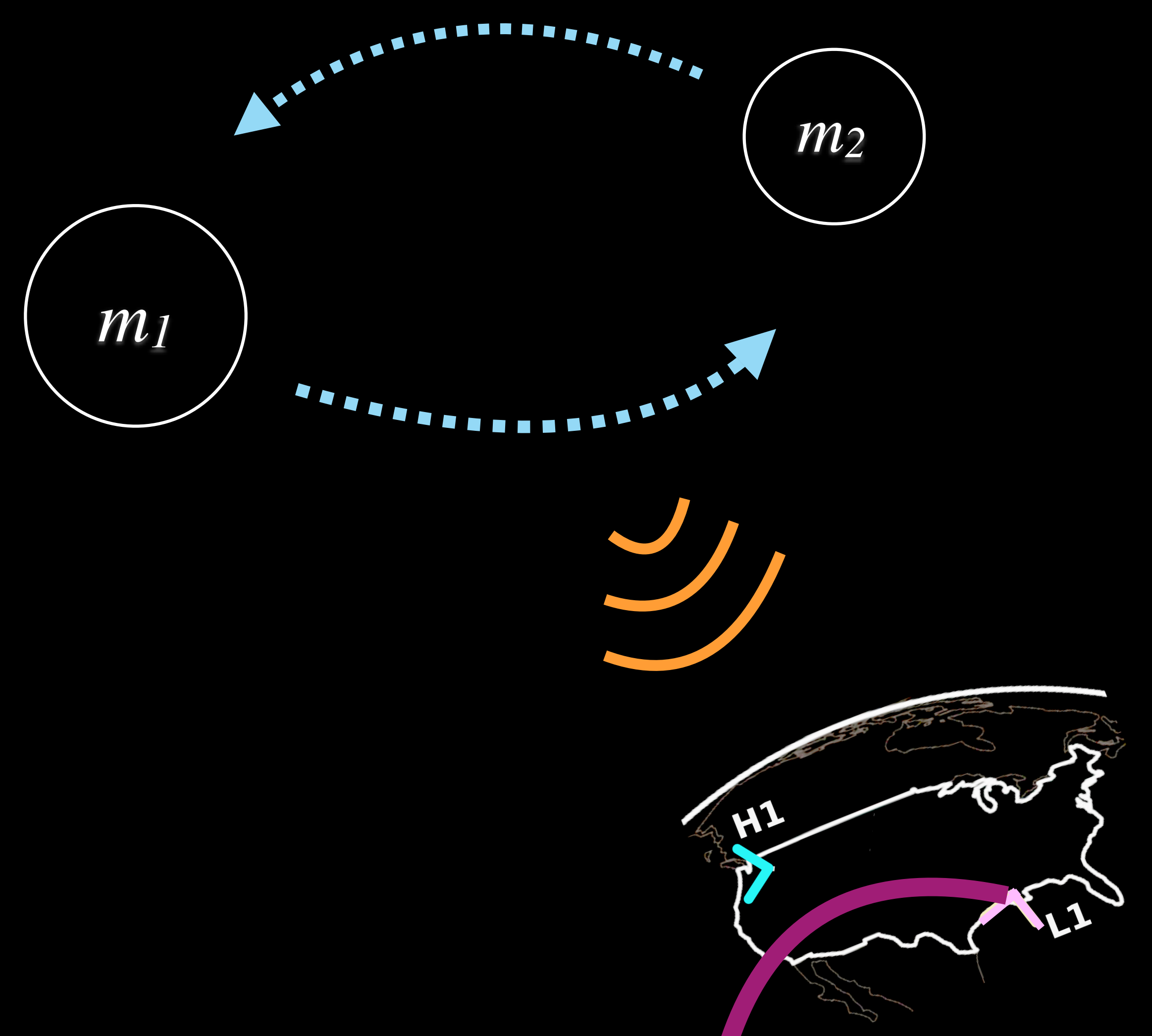

m1
m2

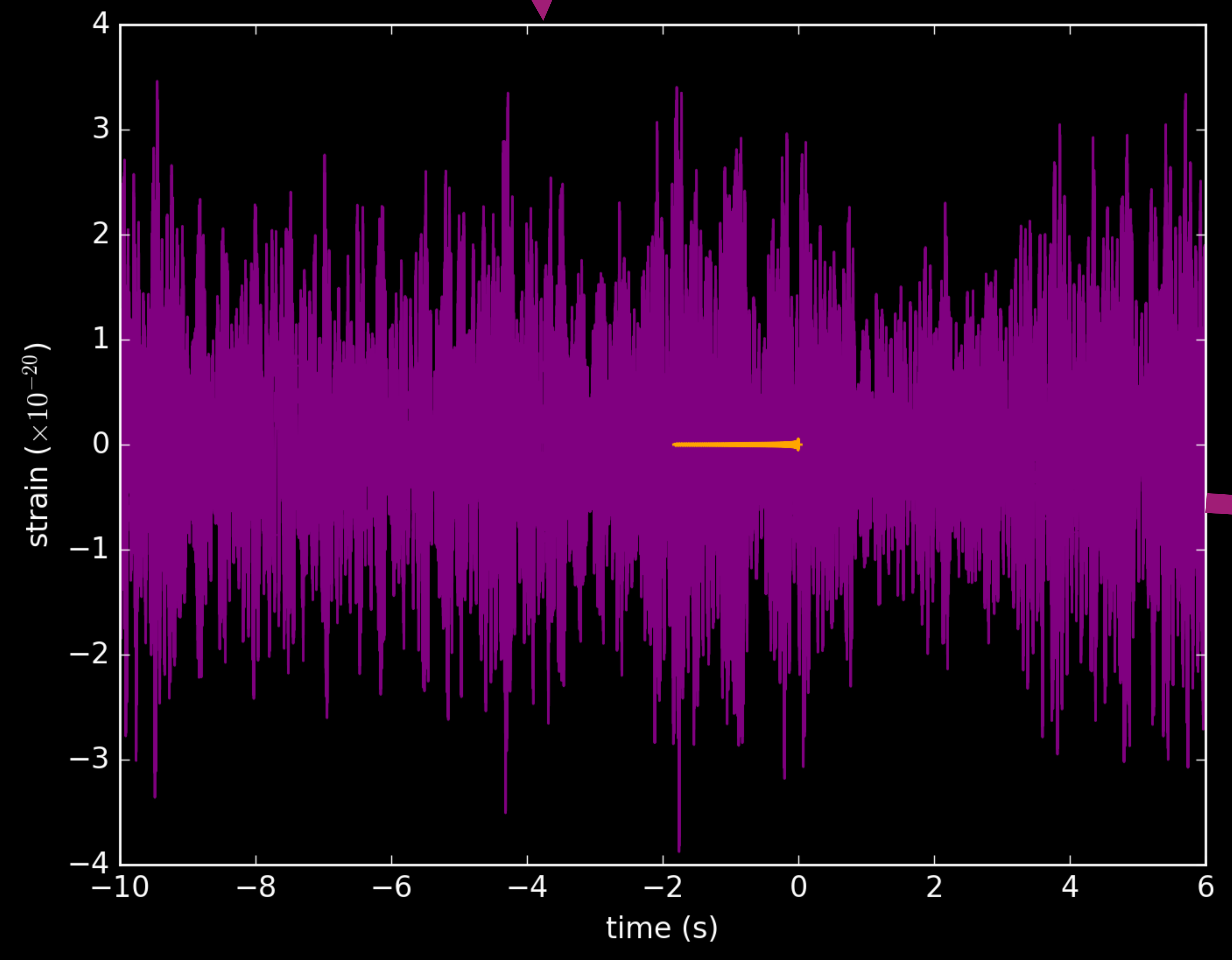

m_1
m_2
H1
L1
strain ($\times 10^{-20}$)
time (s)
4
3
2
1
0
−1
−2
−3
−4
−10
−8
−6
−4
−2
0
2
4
6



PyCBC

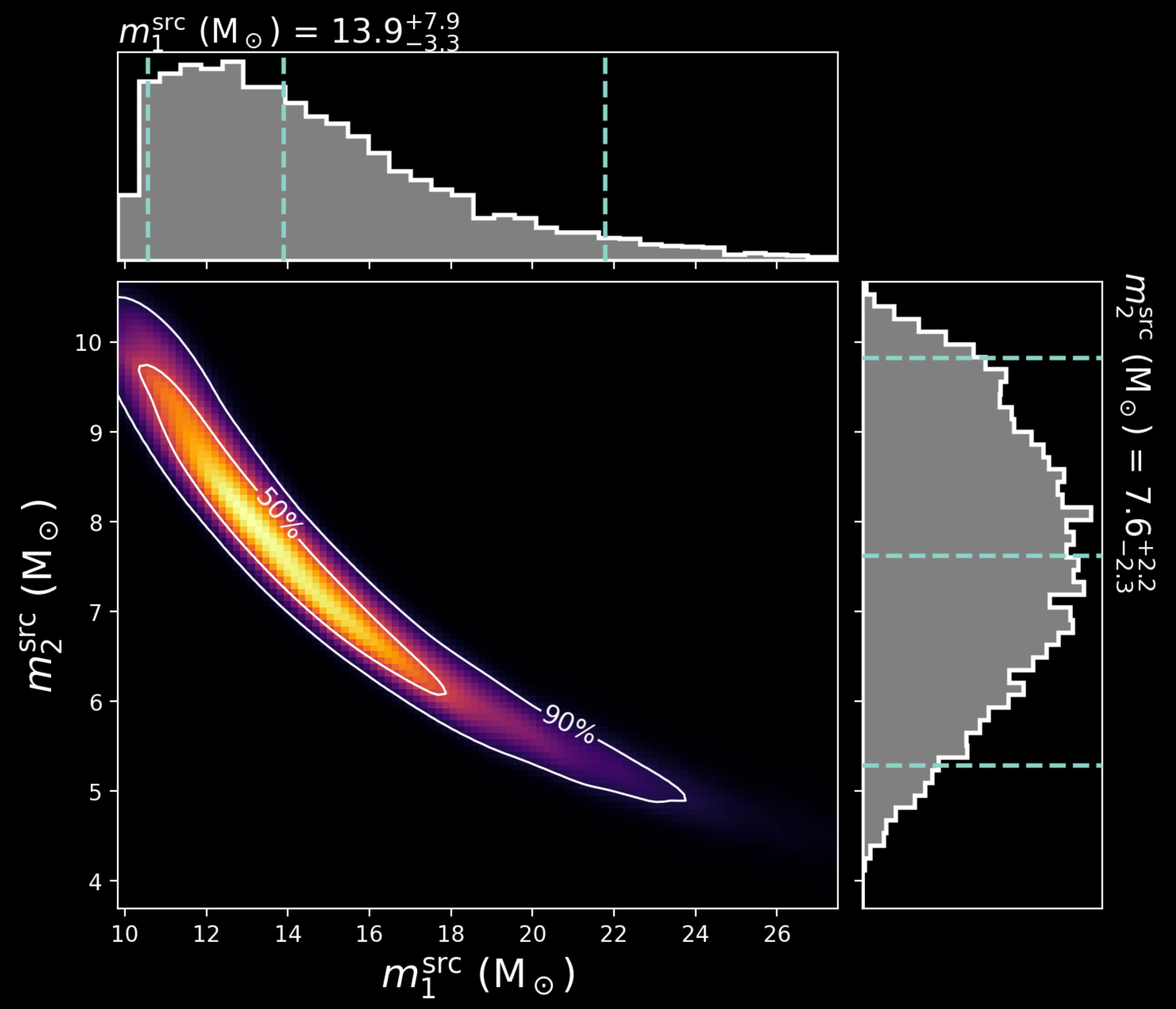
Bayesian Inference

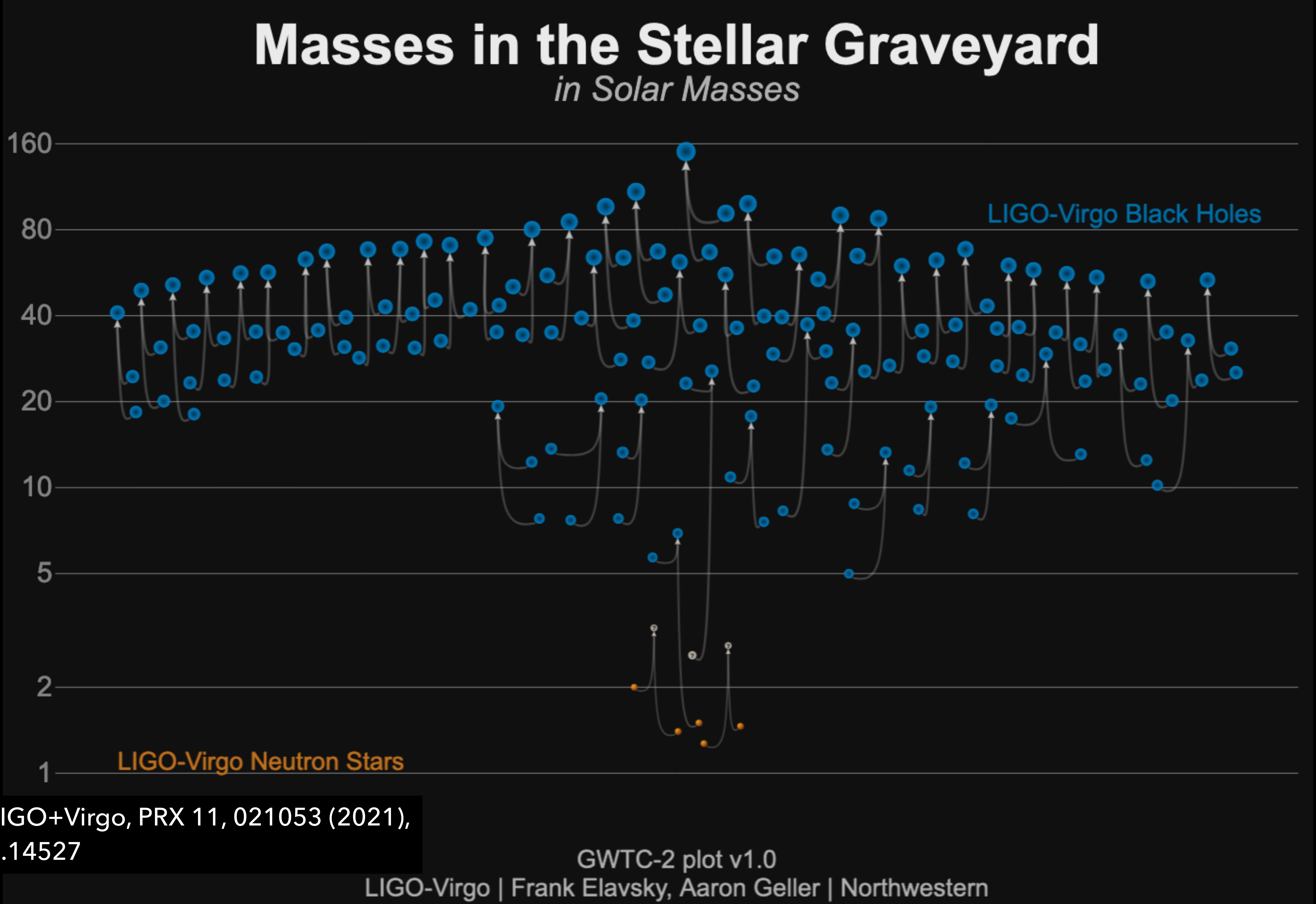




PyCBC

Bayesian Inference





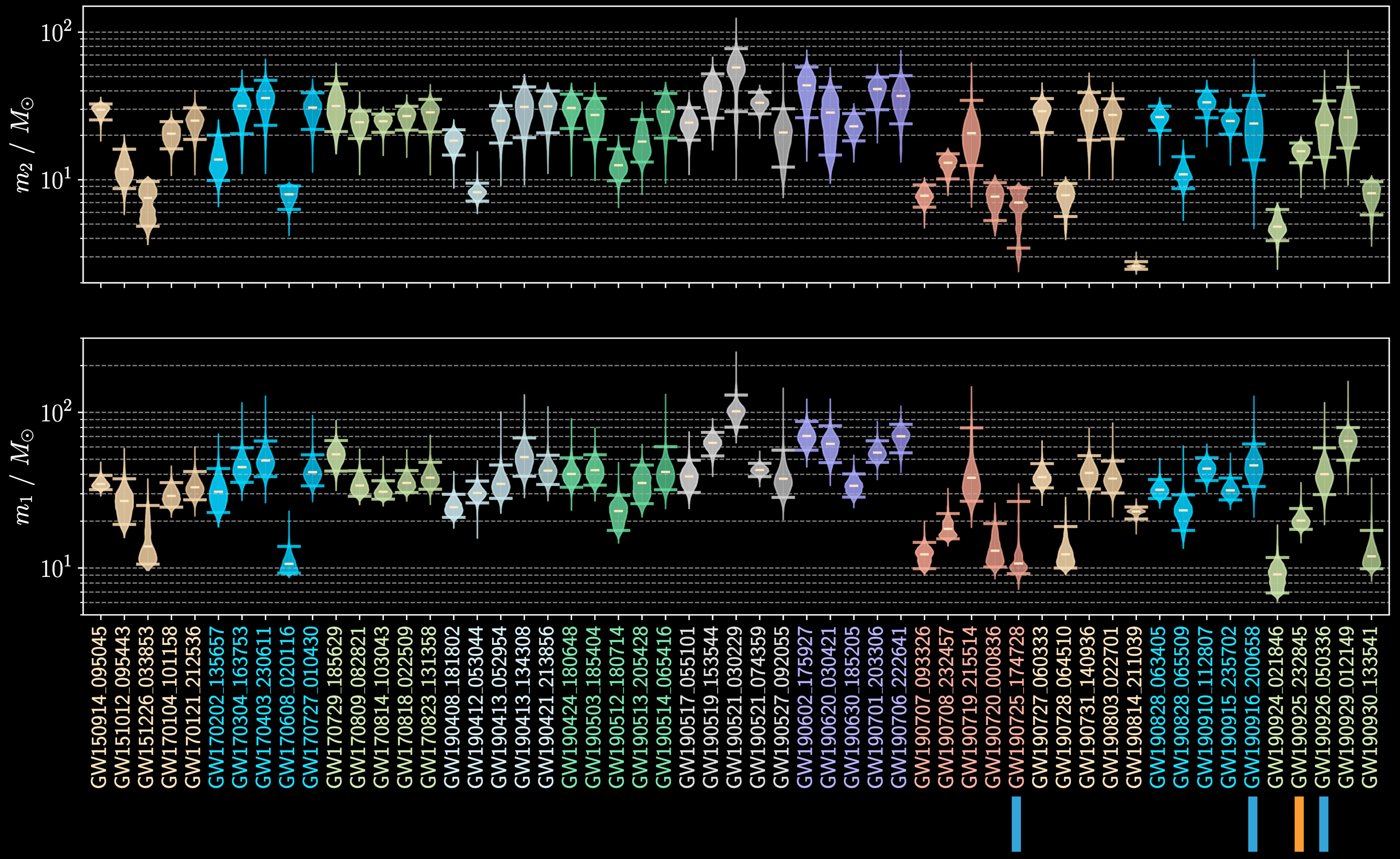
GWTC-2: LIGO+Virgo, PRX 11, 021053 (2021), arXiv:2010.14527

3-OGC: Catalog of gravitational waves from compact-binary mergers

Alexander H. Nitz,[1,2] Collin D. Capano,[1,2] Sumit Kumar,[1,2] Yi-Fan Wang (王一帆),[1,2] Shilpa Kastha,[1,2] Marlin Schäfer,[1,2] Rahul Dhurkunde,[1,2] and Miriam Cabero[3]

[1] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[3] *Department of Physics and Astronomy, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada,*

- 3-OGC: catalog produced by AEI using open data
- arXiv:2105.09151
- 57 detections (2 BNS, 55 BBH)
- 4 not previously found



RATE ESTIMATES

BBH - Observed **BBH - Reweighted**

Nitz, Capano, et al., arXiv:2105.09151

RATE ESTIMATES

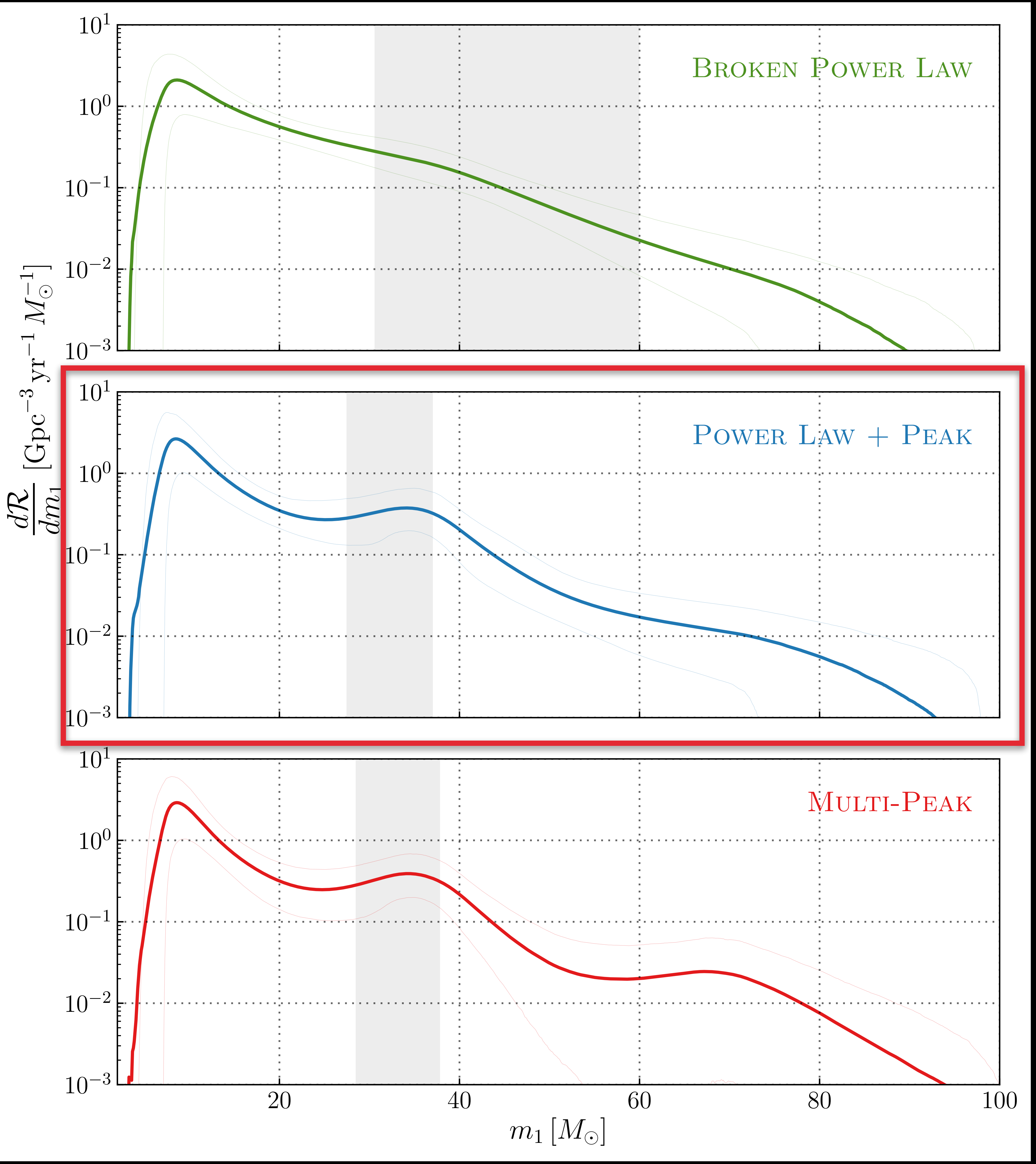
- From current LIGO-Virgo catalog (GWTC-2)*:

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

$$\mathcal{R}_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

* LIGO+Virgo, PRX 11, 021053 (2021), arXiv:2010.14527

Distribution of larger mass in BBH



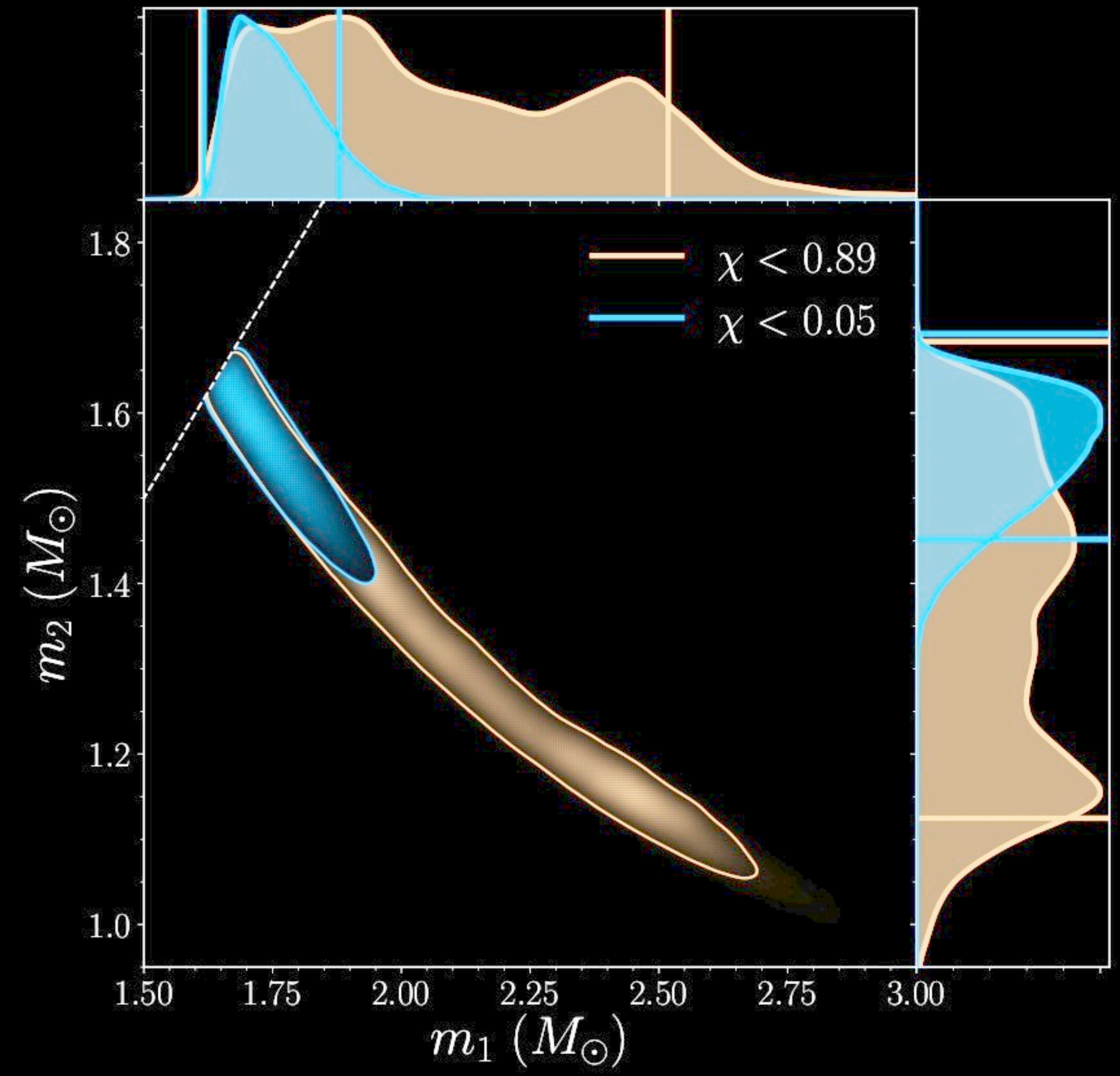
LIGO+Virgo, arXiv:2010.14533

(OTHER) INTERESTING EVENTS

GW190425

LSC+Virgo, arXiv:2001.01761 (2019)

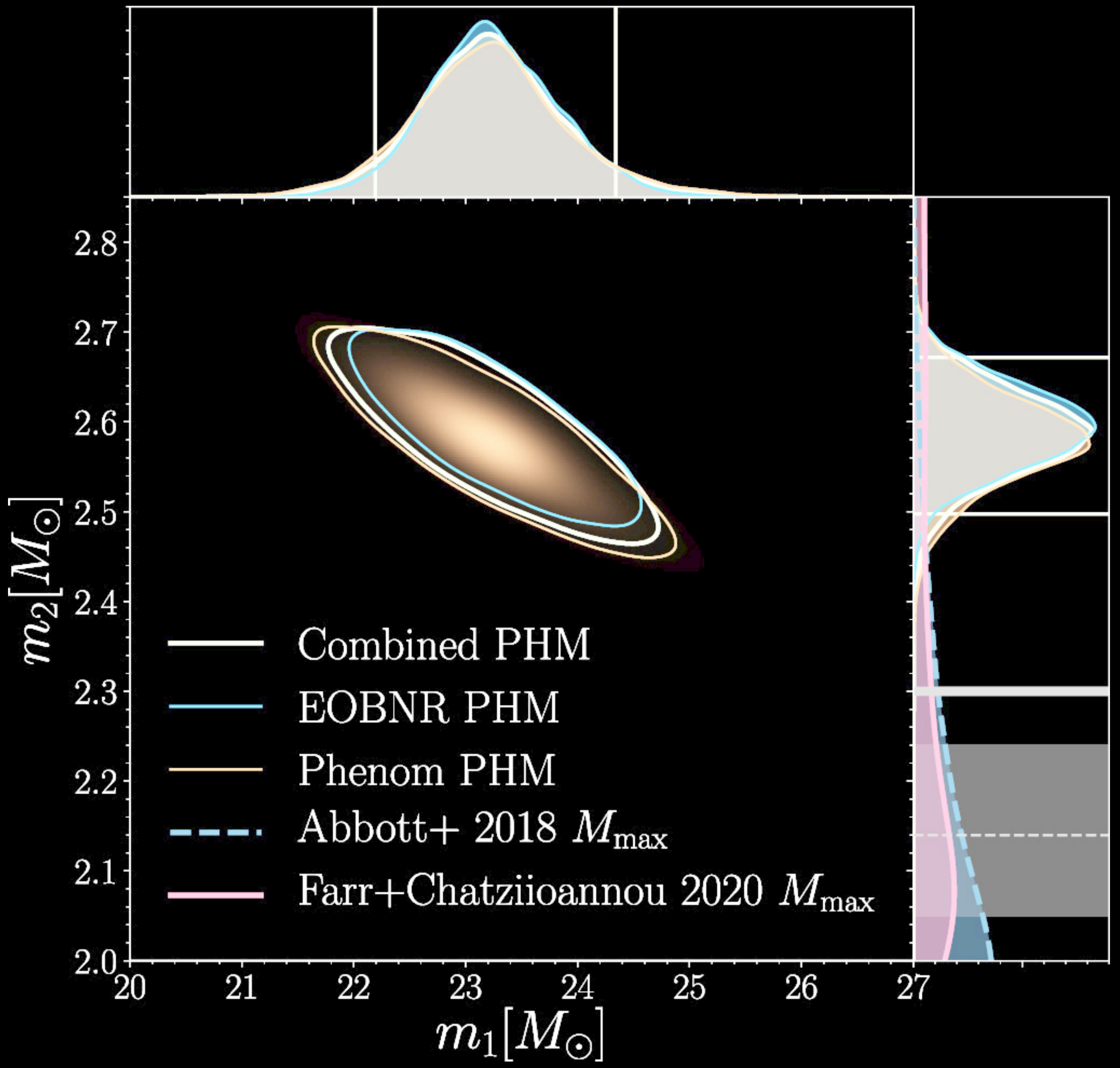
- LSC and Virgo detected another gravitational wave from a binary neutron star on 25 April 2019, GW190425
- Source ~3x farther away than GW170817
- Hanford was down at the time
- **Poor sky recovery, no EM**
- **Surprisingly large component masses**



	Low-spin prior ($\chi < 0.05$)	High-spin prior ($\chi < 0.89$)
Primary mass m_1	$1.62 - 1.88\ M_\odot$	$1.61 - 2.52\ M_\odot$
Secondary mass m_2	$1.45 - 1.69\ M_\odot$	$1.12 - 1.68\ M_\odot$

GW190814

- Merger of a 2.6 M⊙ object into a 23 M⊙ BH
- Not certain if smaller object is a NS or BH – more massive then most EOS would predict for NS, but also in BH "mass gap"

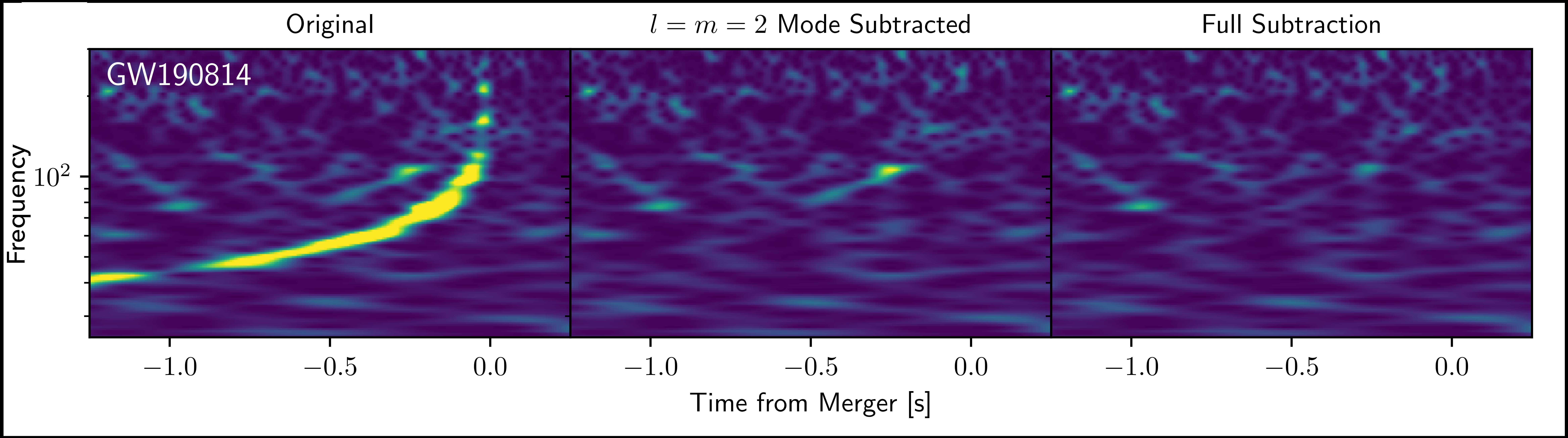


LSC+Virgo, ApJL 896 2 (2020)

GW190814: HIGHER HARMONICS

- Higher harmonic of the GW detected with signal-to-noise ratio ~7

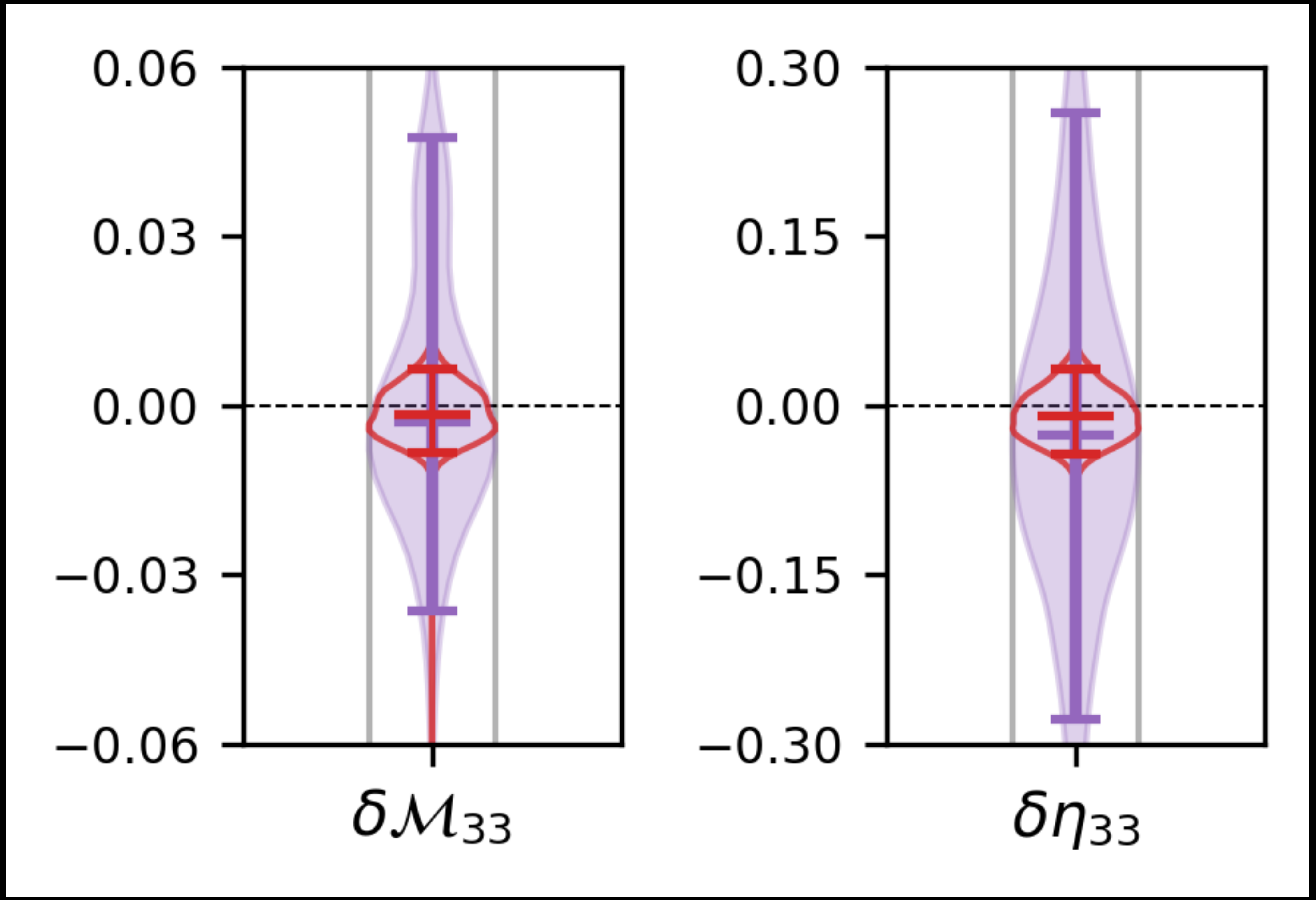
$$h_{(+,\times)}(t) = (\Re, \Im) \sum_{\ell m} {}_{-2}Y_{\ell m}(\iota, \phi) A_{\ell m}(\mathbf{\Theta}) \exp\left[-i\left(\Psi_{\ell m}(\mathbf{\Theta}) + m\phi_0\right)\right]$$

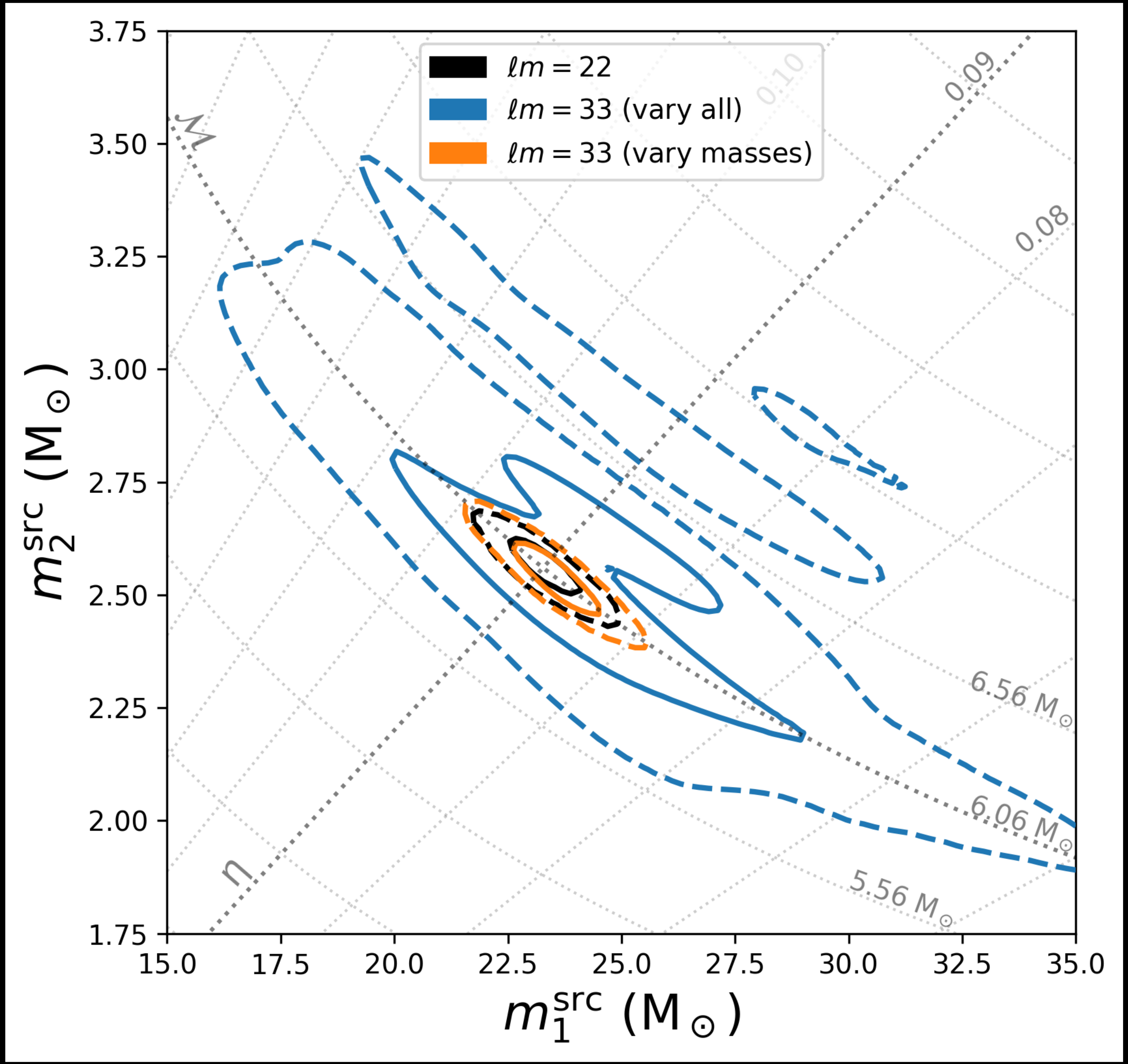


Capano & Nitz, PRD 102, 124070 (2020)

GW190814: HIGHER HARMONICS

- Test GR by independently measure masses from each harmonic
- Constrain deviation of "chirp mass" to O(1%)

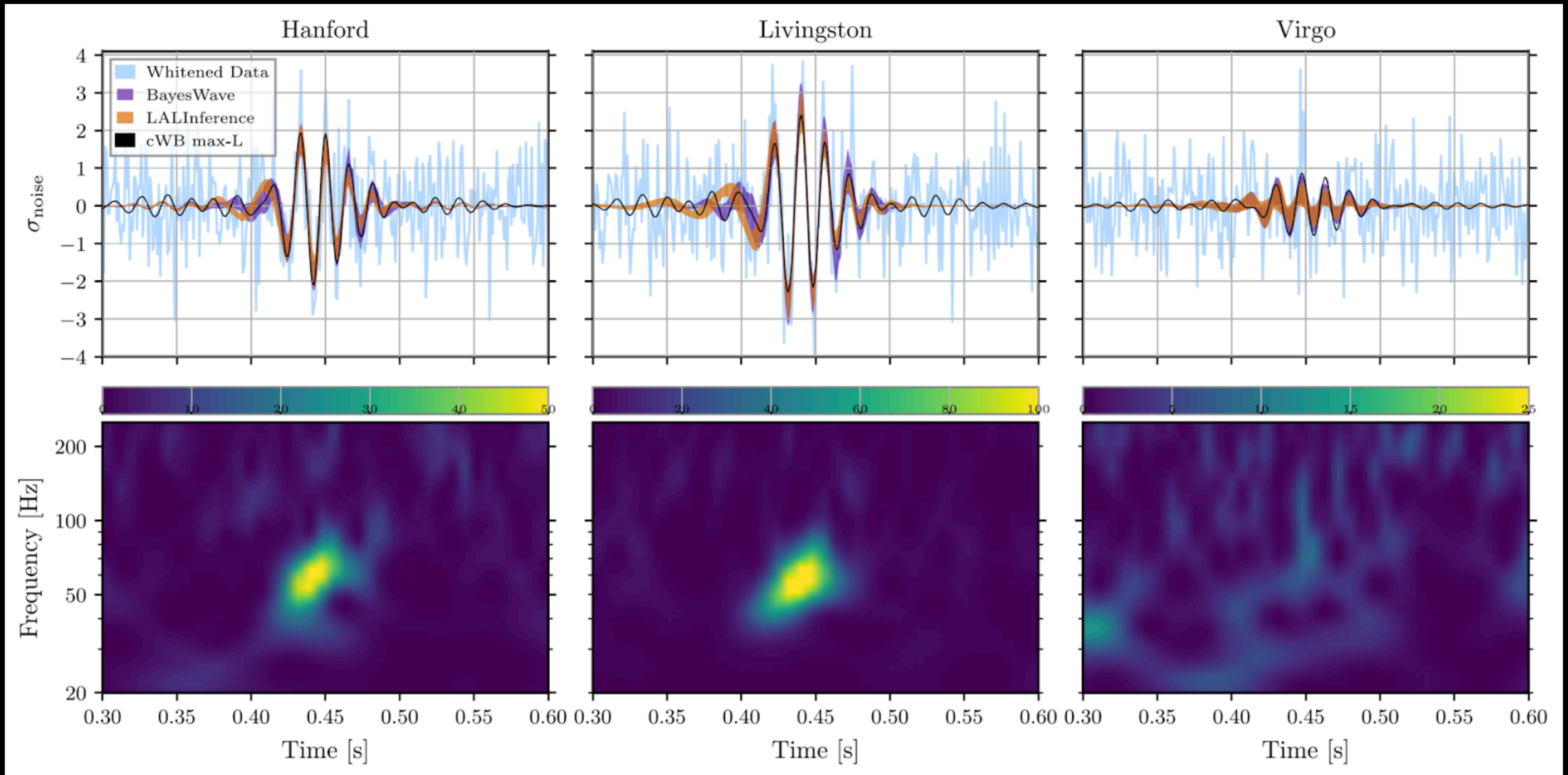


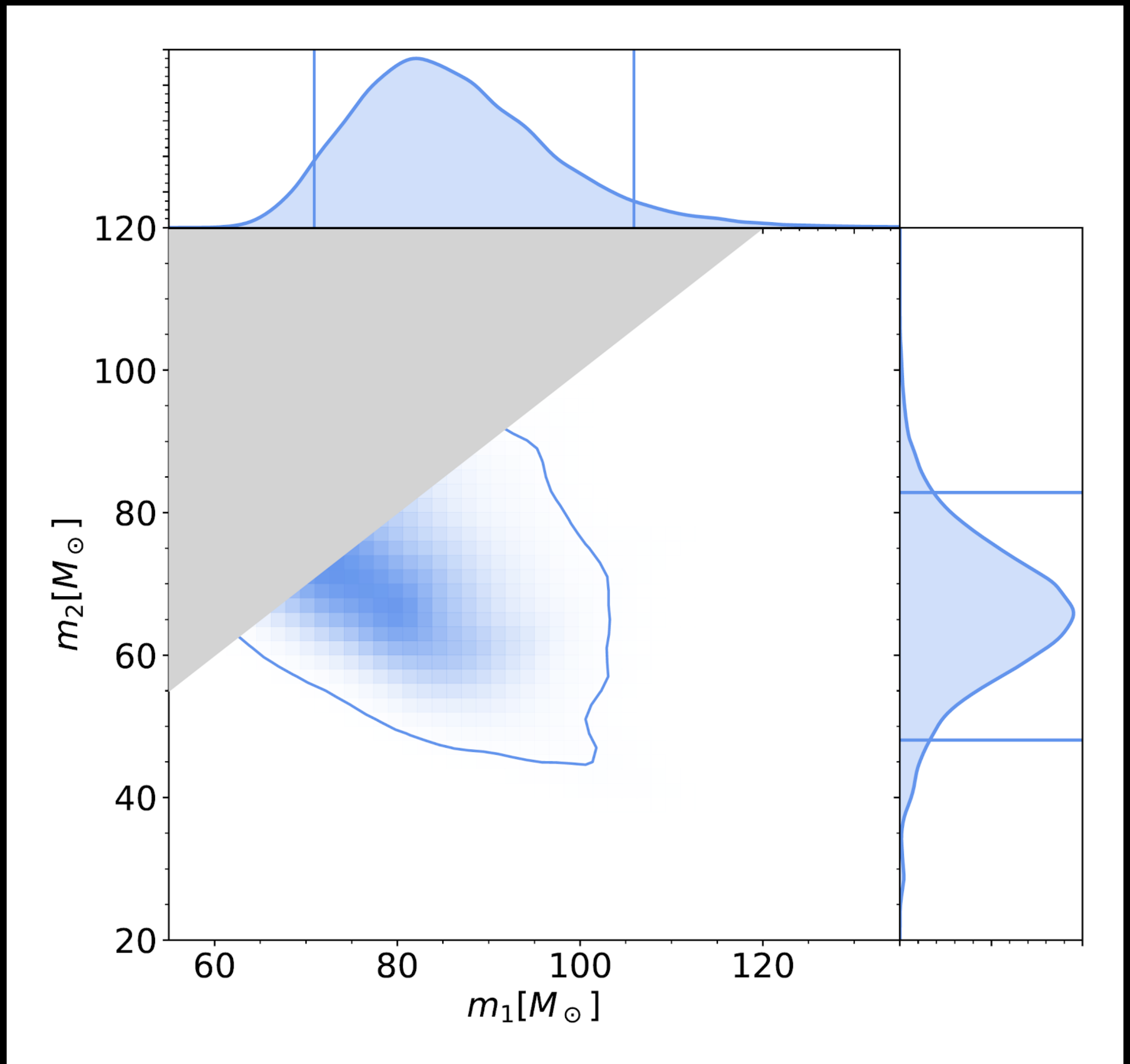


Capano & Nitz, PRD 102, 124070 (2020)

GW190521

- Most massive binary detected to date
- LVC estimates: m1 ~ 85$M_\odot$, m2 ~ 66$M_\odot$
- Black holes from direct stellar collapse not expected between ~50-120$M_\odot$ due to Pair-instability Supernovae (PISN)

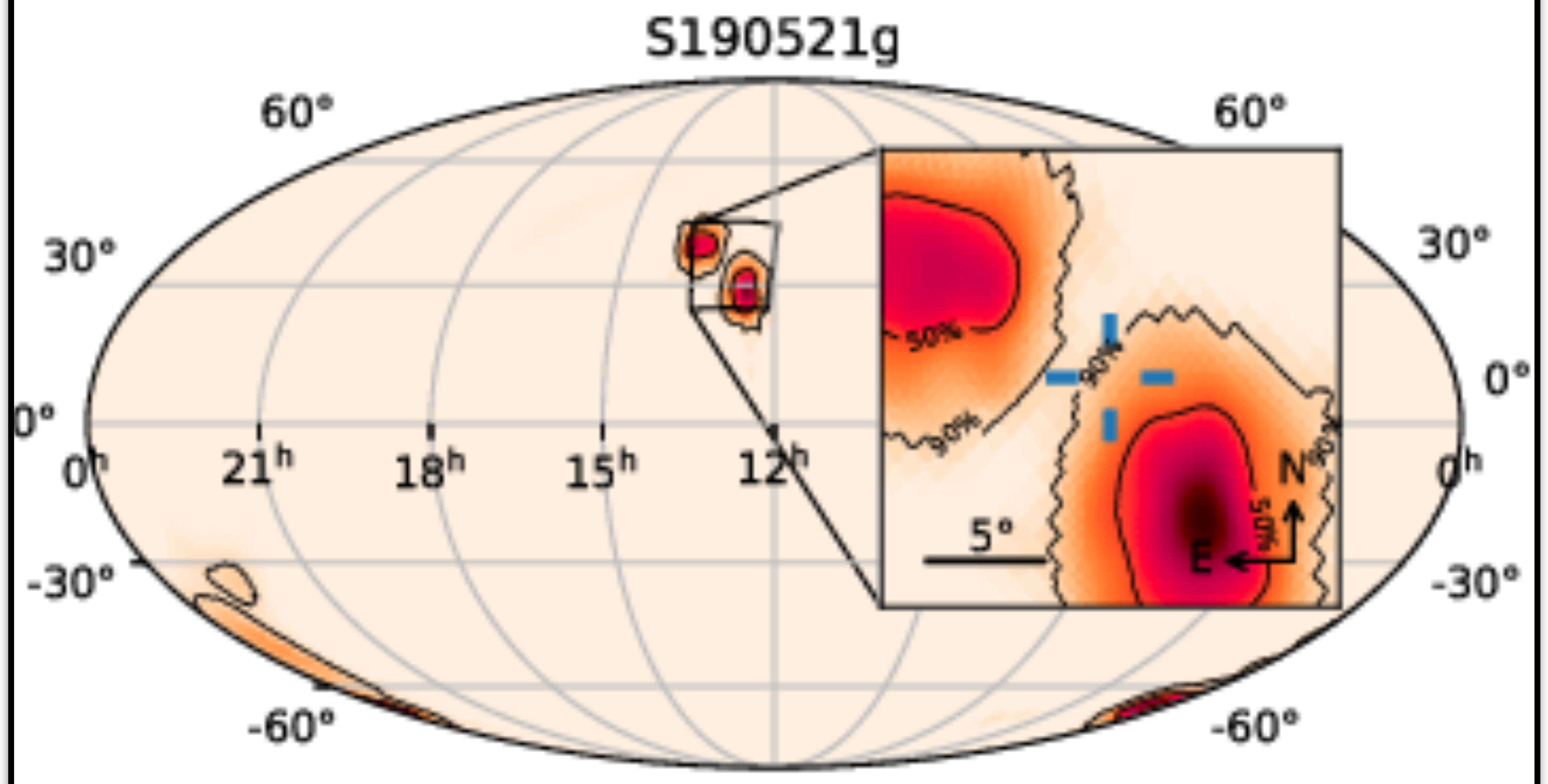




LVC, PRL 125, 101102 (2020)

GW190521: EM COUNTERPART?

- Possible EM counterpart detected by ZTF ~1 month later
- AGN J124942.3+344929 (ZTF19abanrhr)
- If the EM counterpart was caused by GW190521, suggests merger occurred within AGN disk.
- Unfortunately, evidence for common source is weak [ln B ~ -4 – 2.3]



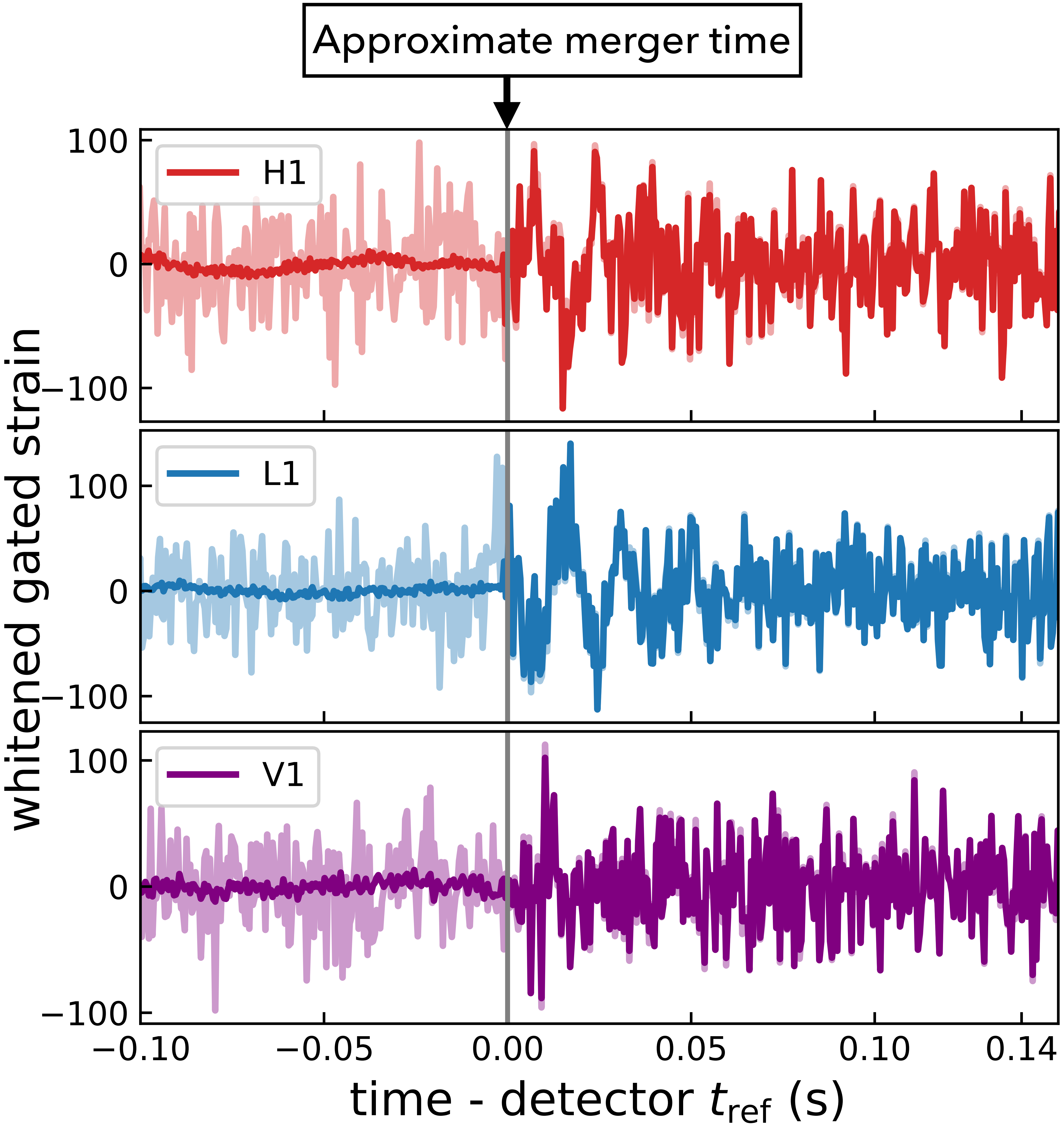
Graham, et al., PRL 124, 251102 (2020)

GW190521: INTERMEDIATE MASS RATIO INSPIRAL?

Nitz & Capano, ApJL 907 1 L9 (2021), arXiv:2010.12558

GW190521

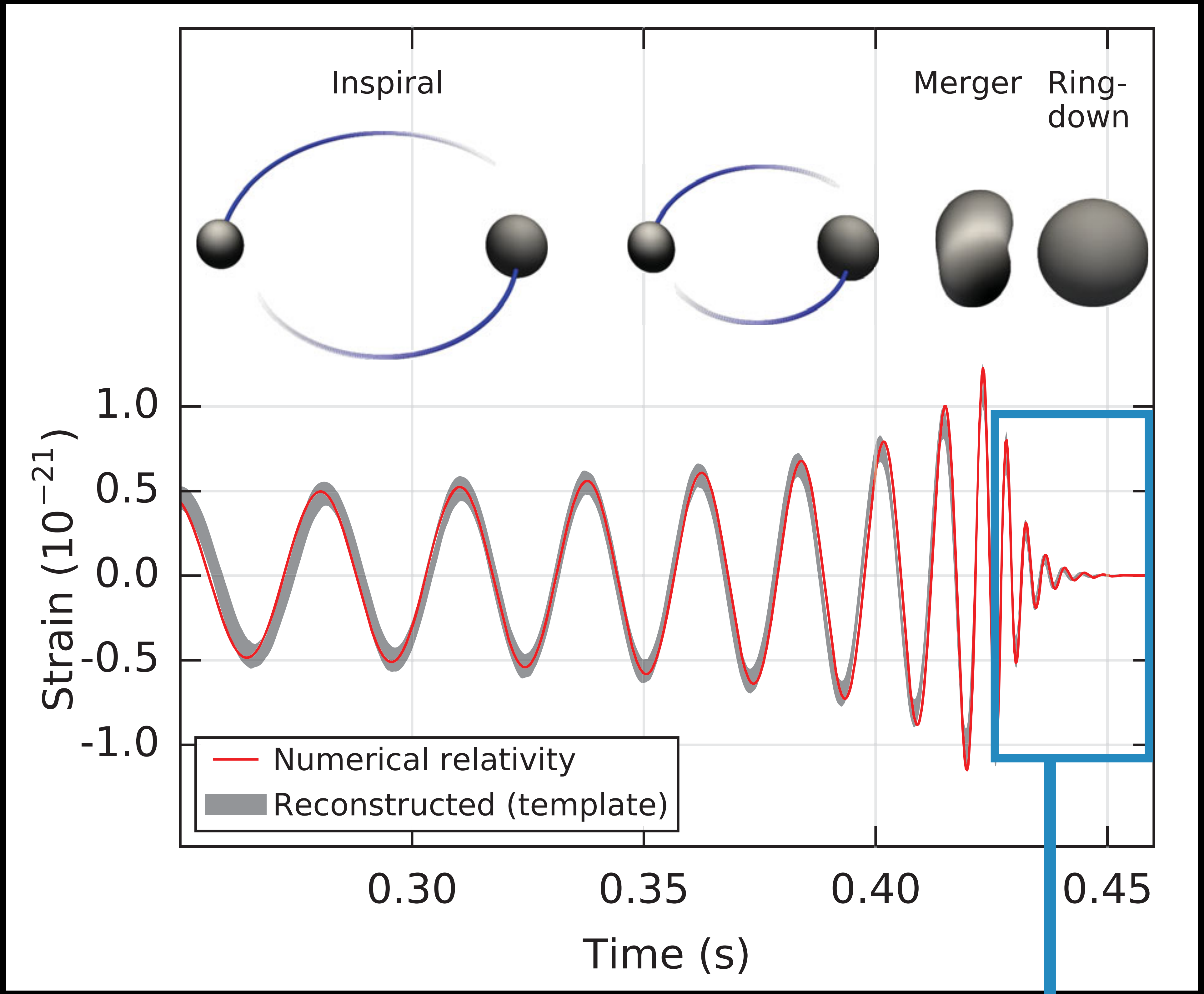
- Why so much confusion about the progenitor masses?
- “Worst case scenario” for waveform models
- Likely large spin on larger mass, partially in the plane of the binary
- Maybe eccentricity?
- Majority of the observable signal comes from after the merger
- Black hole spectroscopy!



Capano et al., arXiv:2105.05238 (2021)

BLACK HOLE SPECTROSCOPY

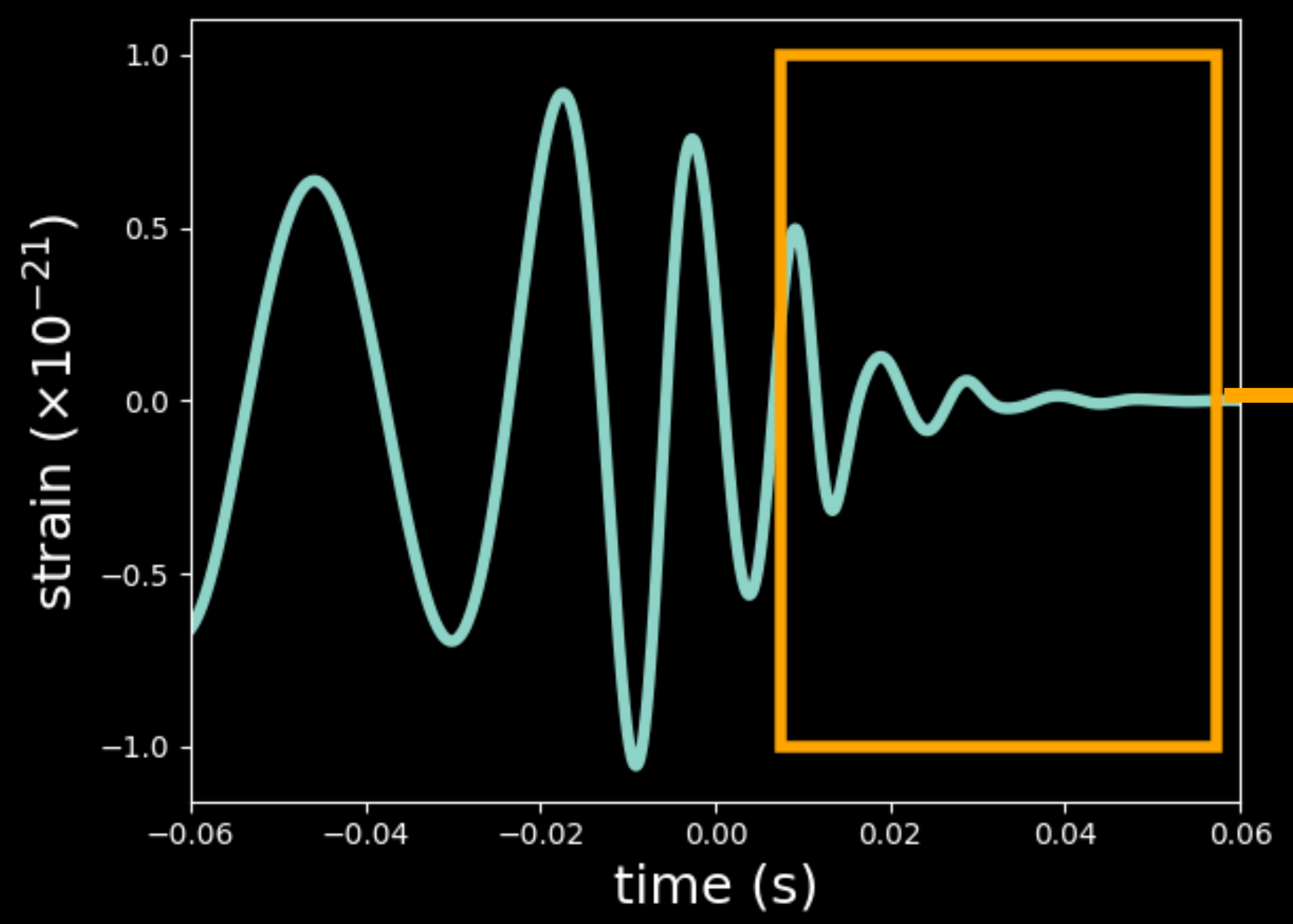
- A perturbed black hole is formed immediately after BBH merger
- Perturbation is radiated away in GWs
- Ringdown is a superposition of quasi-normal modes (QNM)
- No-hair theorem: mass and spin fully characterize all stationary astrophysical black holes
- No-hair theorem → final mass and spin determine frequencies and damping times of all modes



LSC+Virgo, PRL 116, 061102 (2016)

$$h_{\mathrm{RD}}(t) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{\infty} {}_{-2}S_{\ell mn} A_{\ell mn} e^{-t/\tau_{\ell mn}} \cos\left(2\pi f_{\ell mn} t + \phi_{\ell mn}\right)$$

$$h_{\mathrm{RD}}(t) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{\infty} {}_{-2}S_{\ell mn} A_{\ell mn} e^{-t/\tau_{\ell mn}} \cos\left(2\pi f_{\ell mn} t + \phi_{\ell mn}\right)$$



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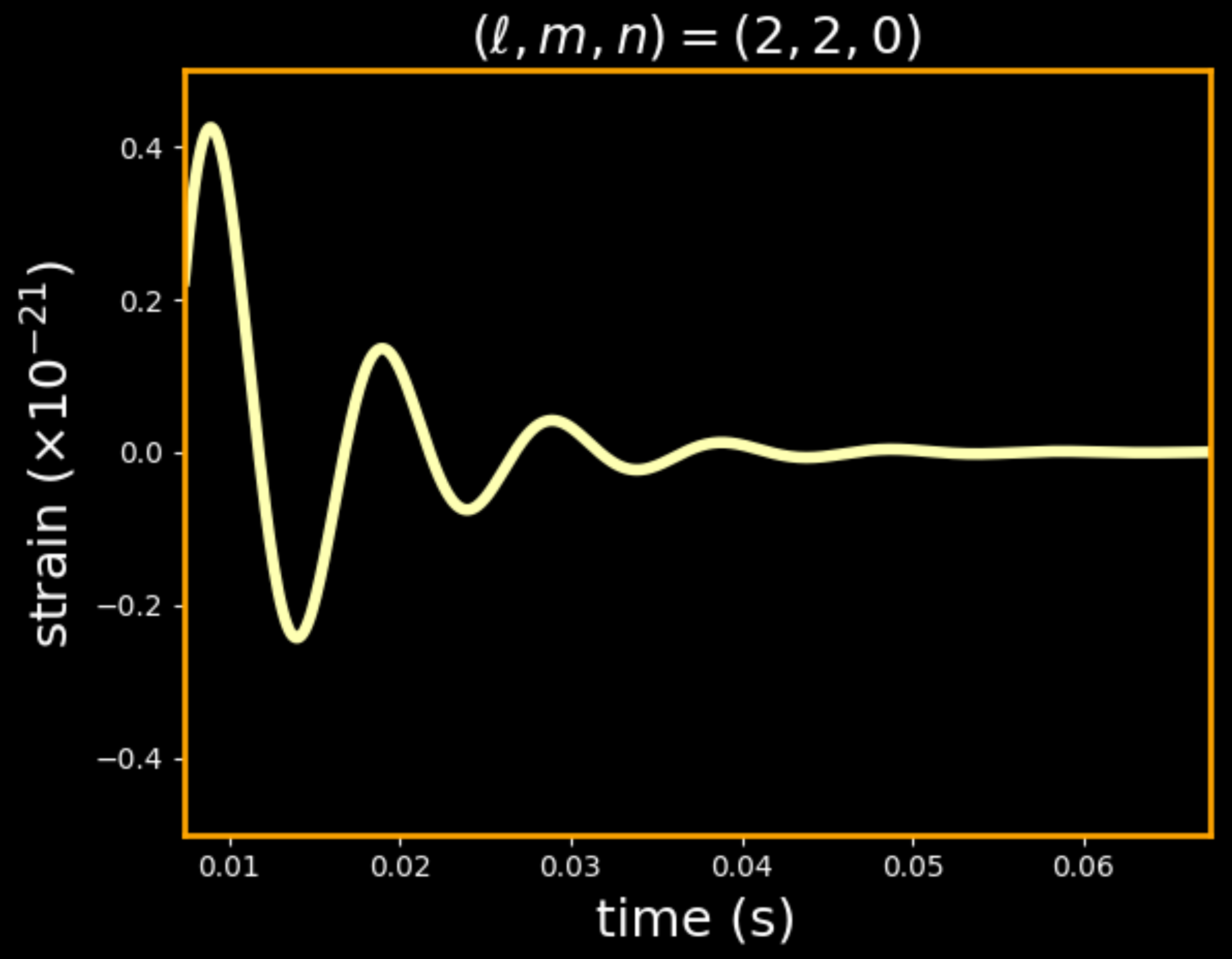

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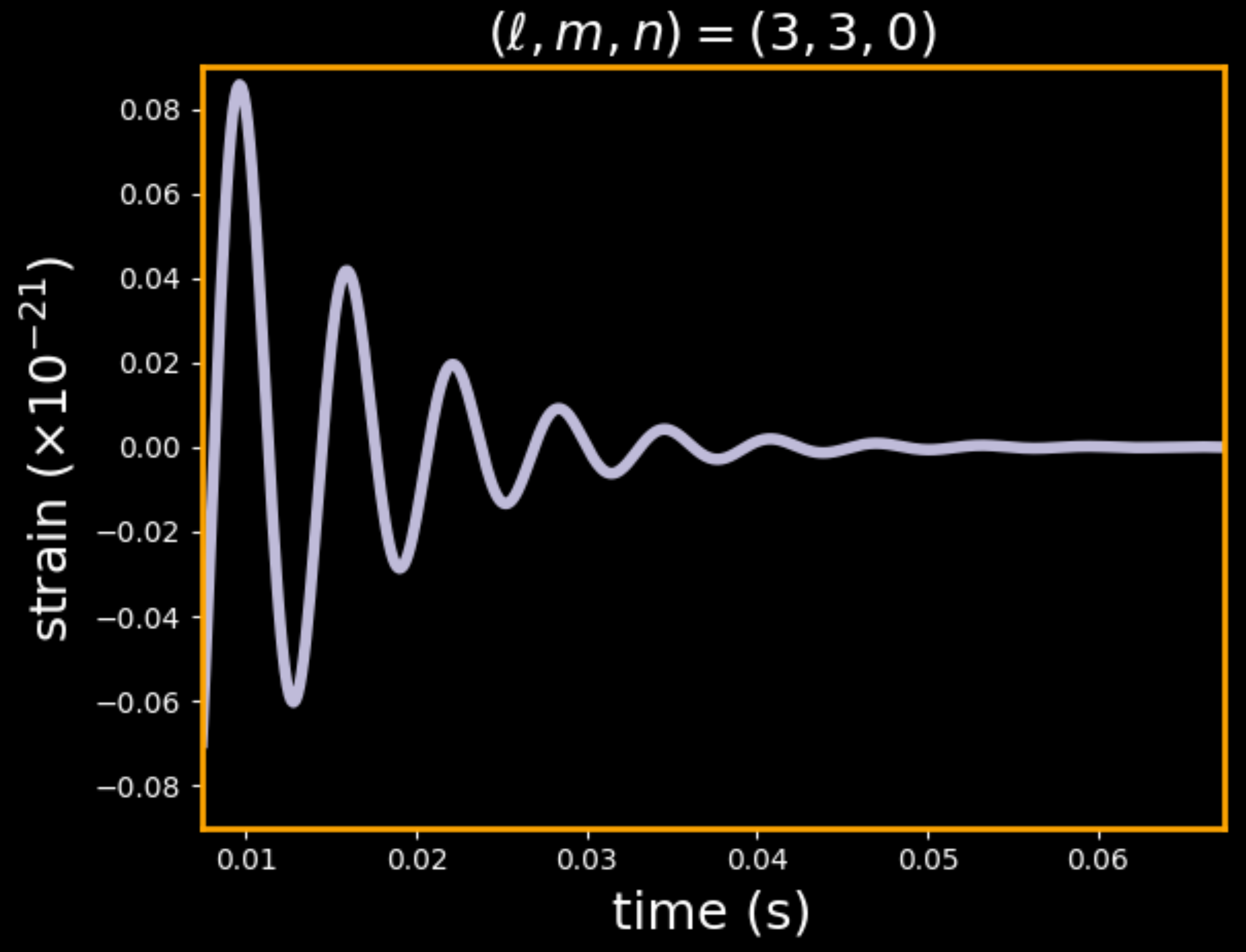

+ ...

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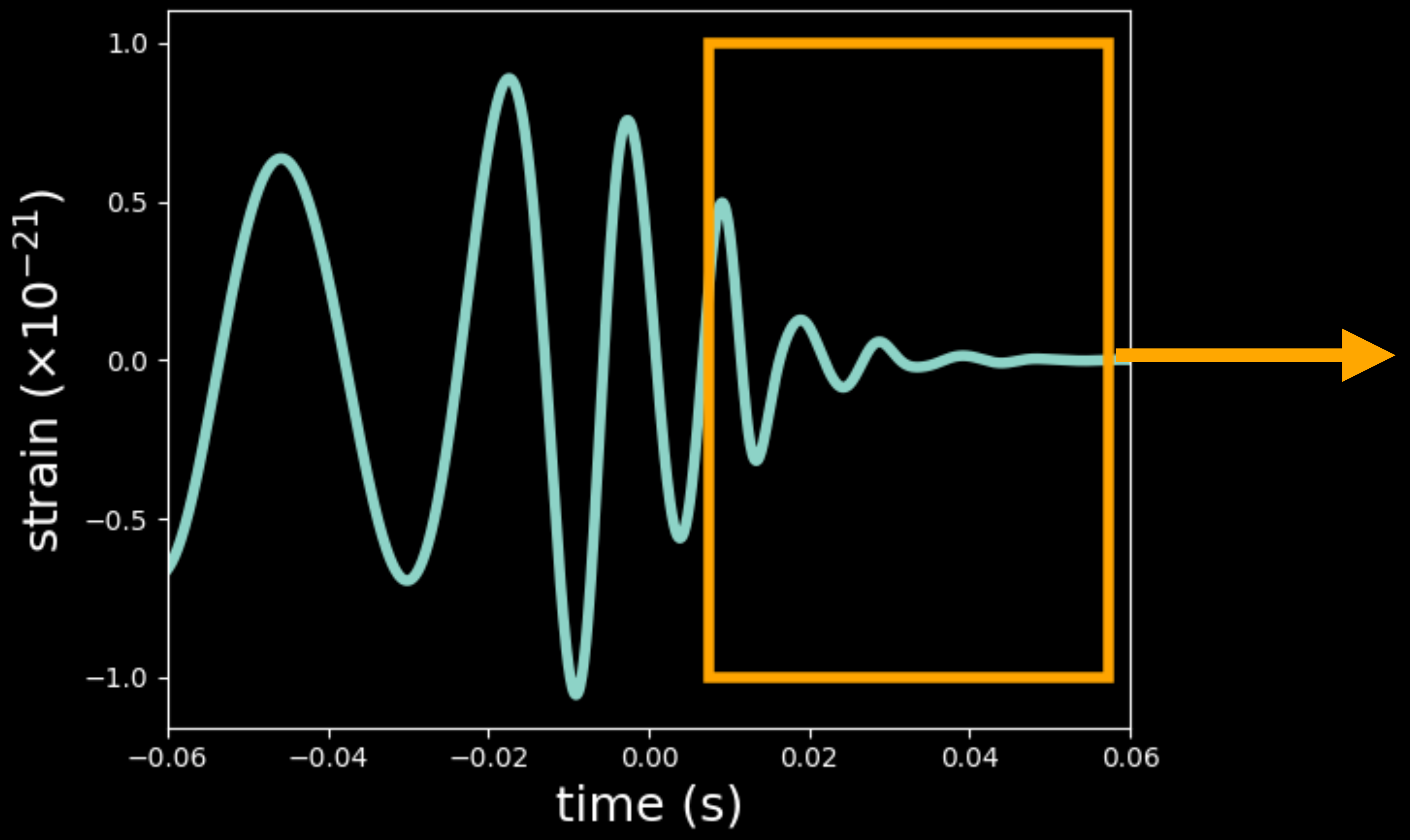

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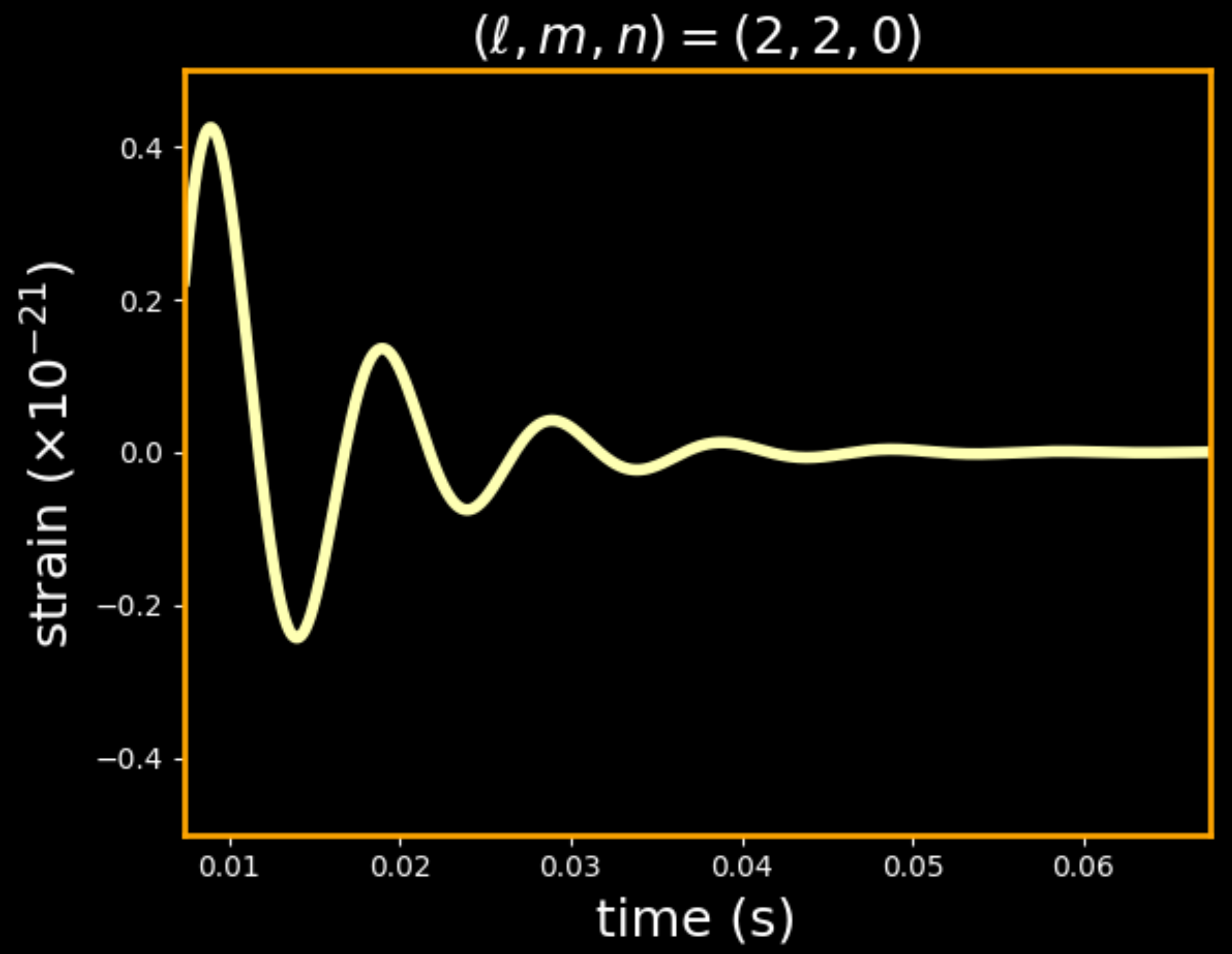

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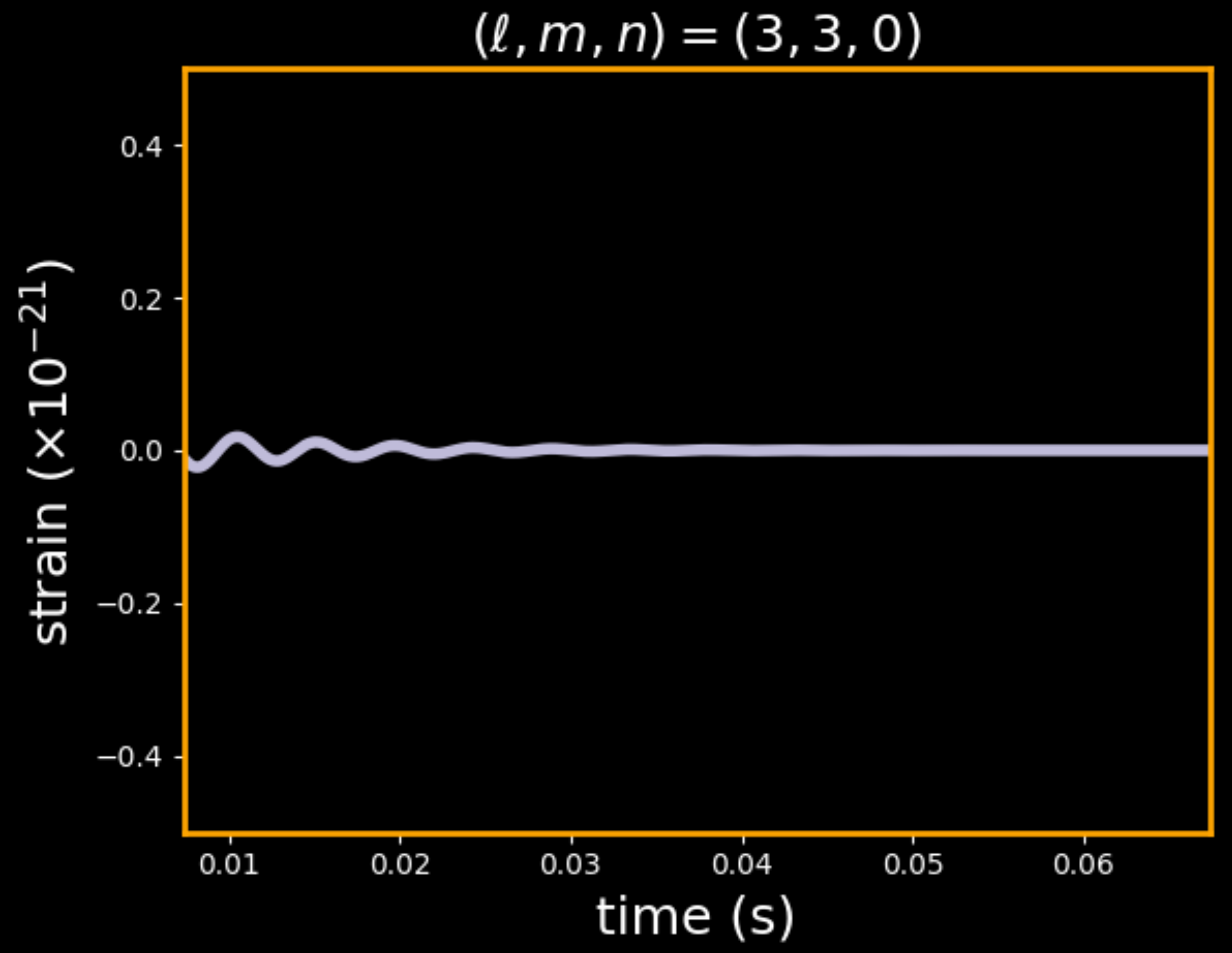
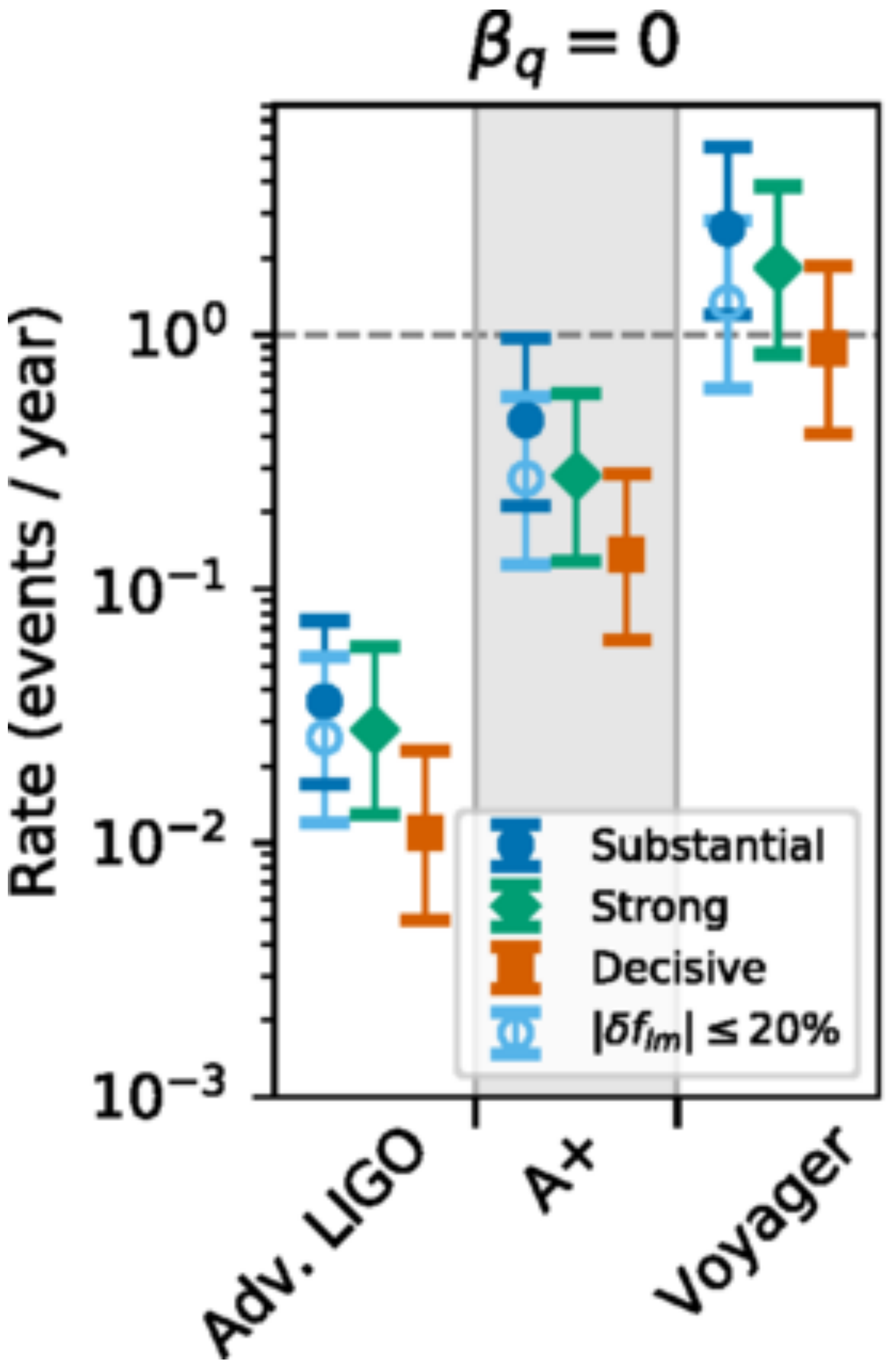


+ ...

BH SPECTROSCOPY CHALLENGES

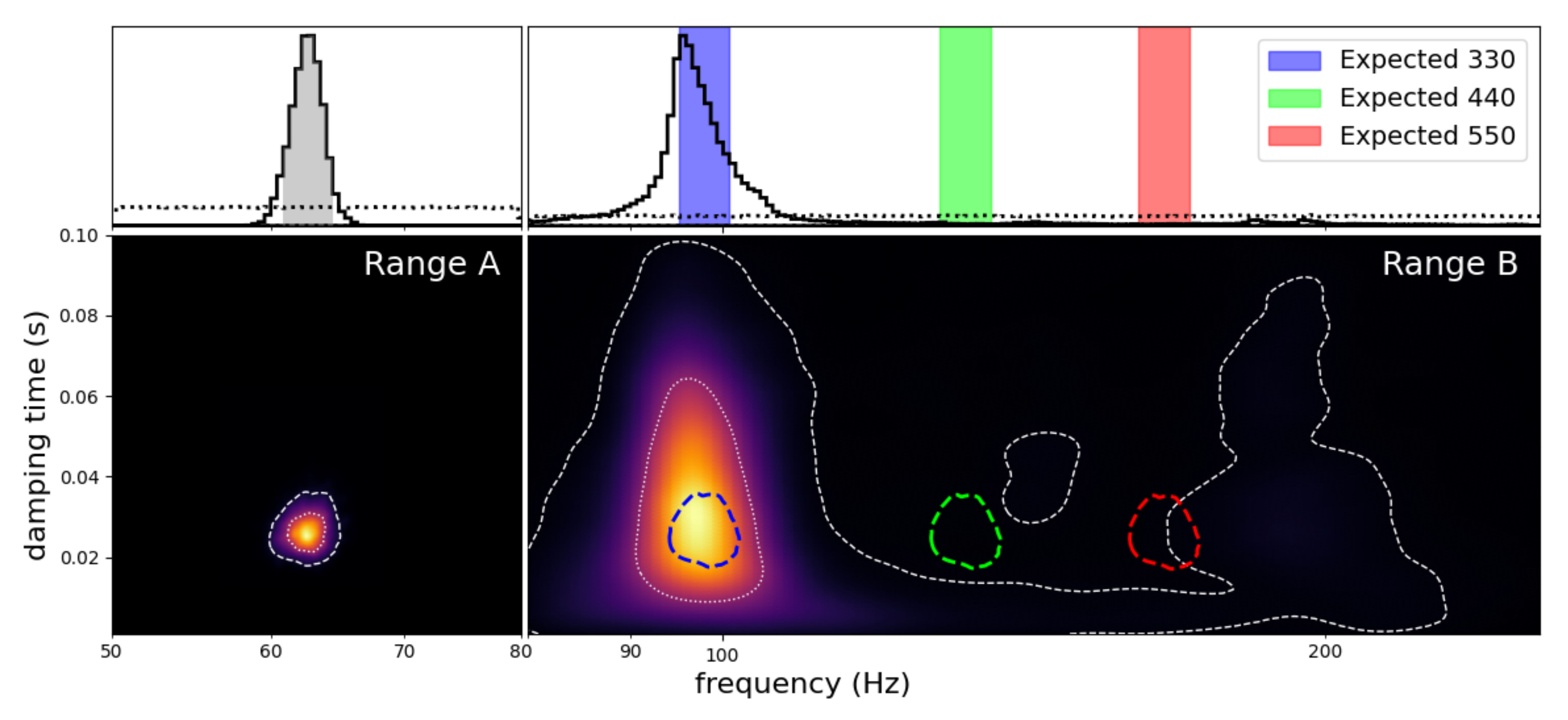
- BH spectroscopy requires observation of at least two modes in the ringdown
- Ringdown SNR of dominant mode is weak, sub-dominant modes weaker
- Need binary with large total mass & asymmetric mass ratio to measure
- We thought we'd have to wait for LIGO Voyager or LISA (10-15 years from now) to be able to obtain any constraints
- Then GW190521 came along…



Cabero, …, Capano, et al., PRD 101, 064044 (2020)

GW190521: BH SPECTROSCOPY

- Agnostic analysis: Search for dominant QNM in frequency range [50, 80) Hz
- Search for a second QNM in [80, 256) Hz, don't assume any relation between modes



Capano et al., arXiv:2105.05238 (2021)

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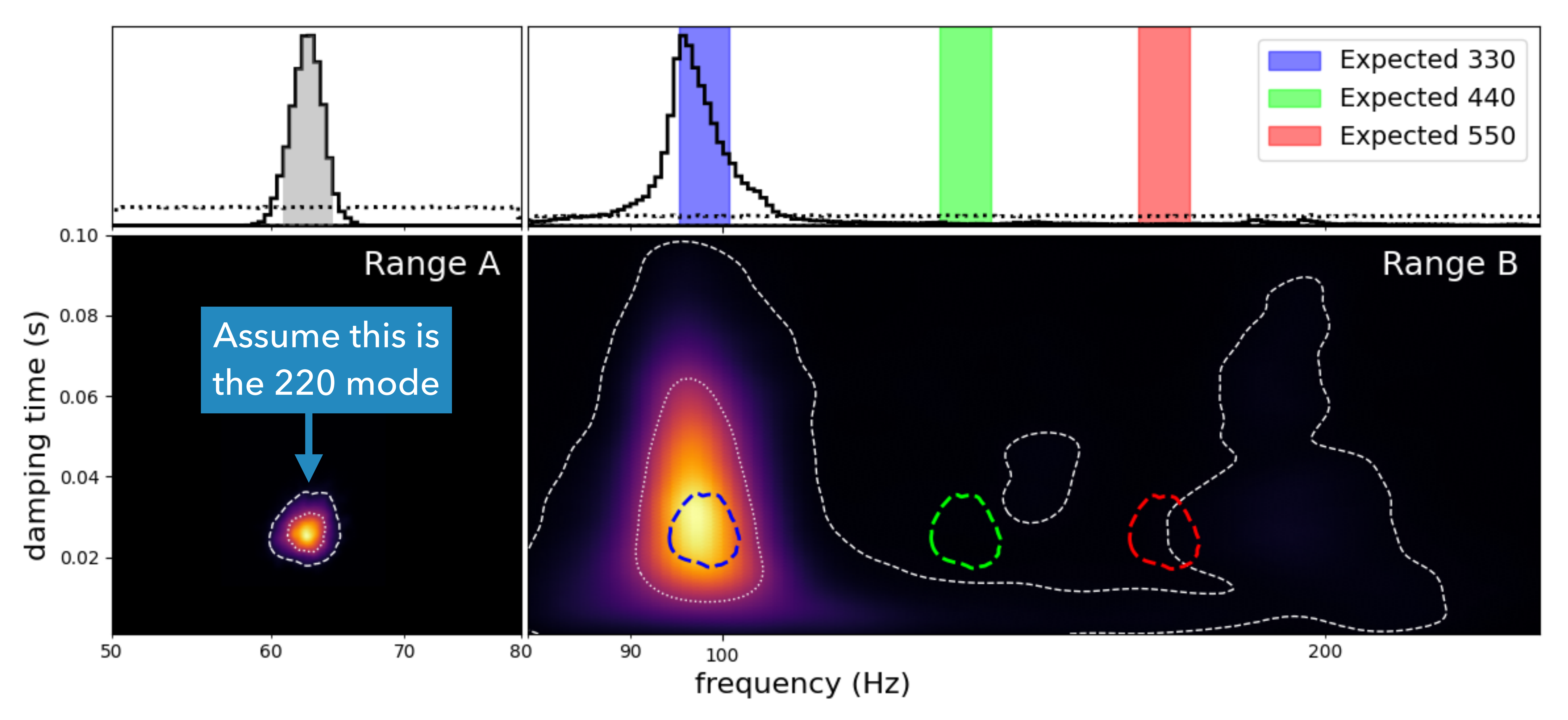

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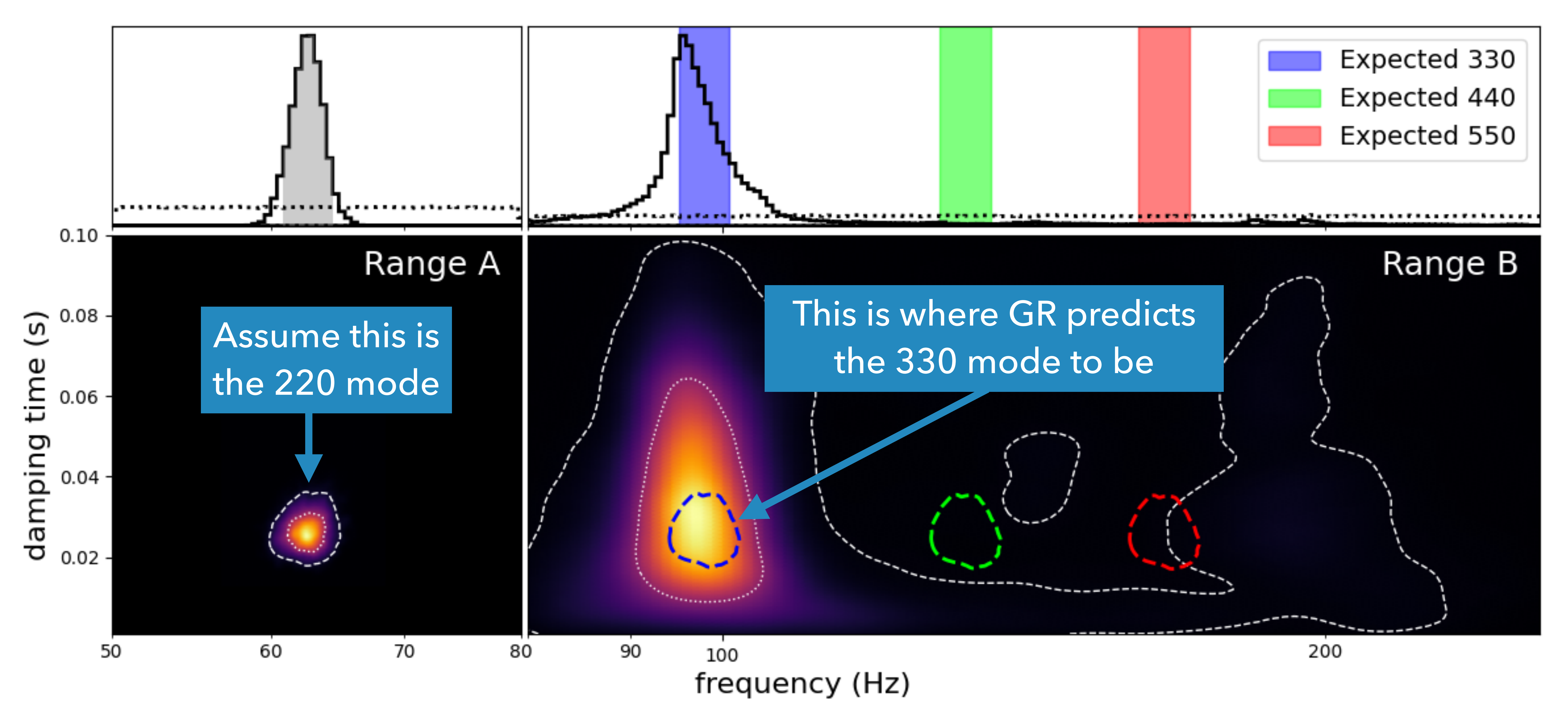
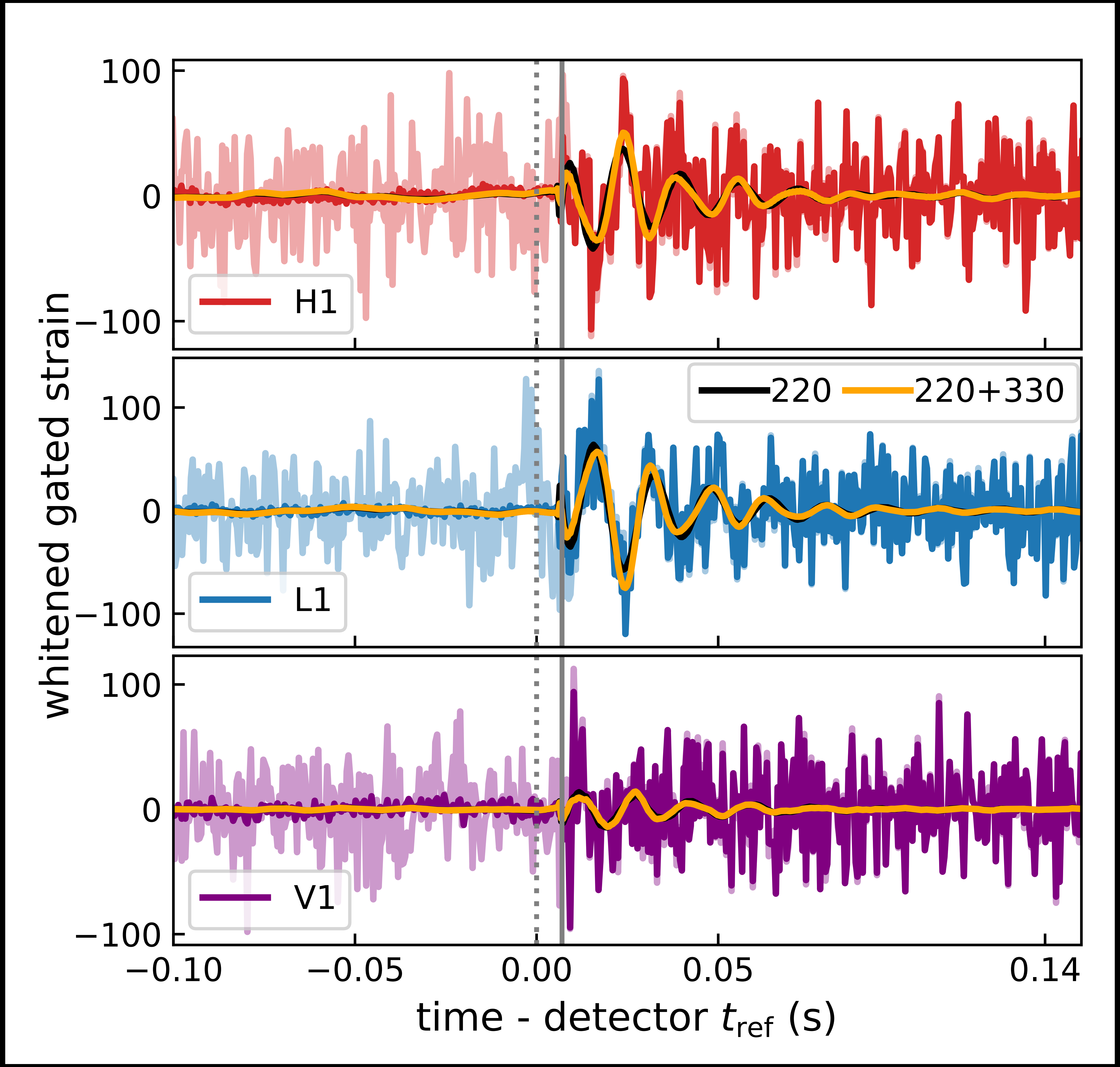


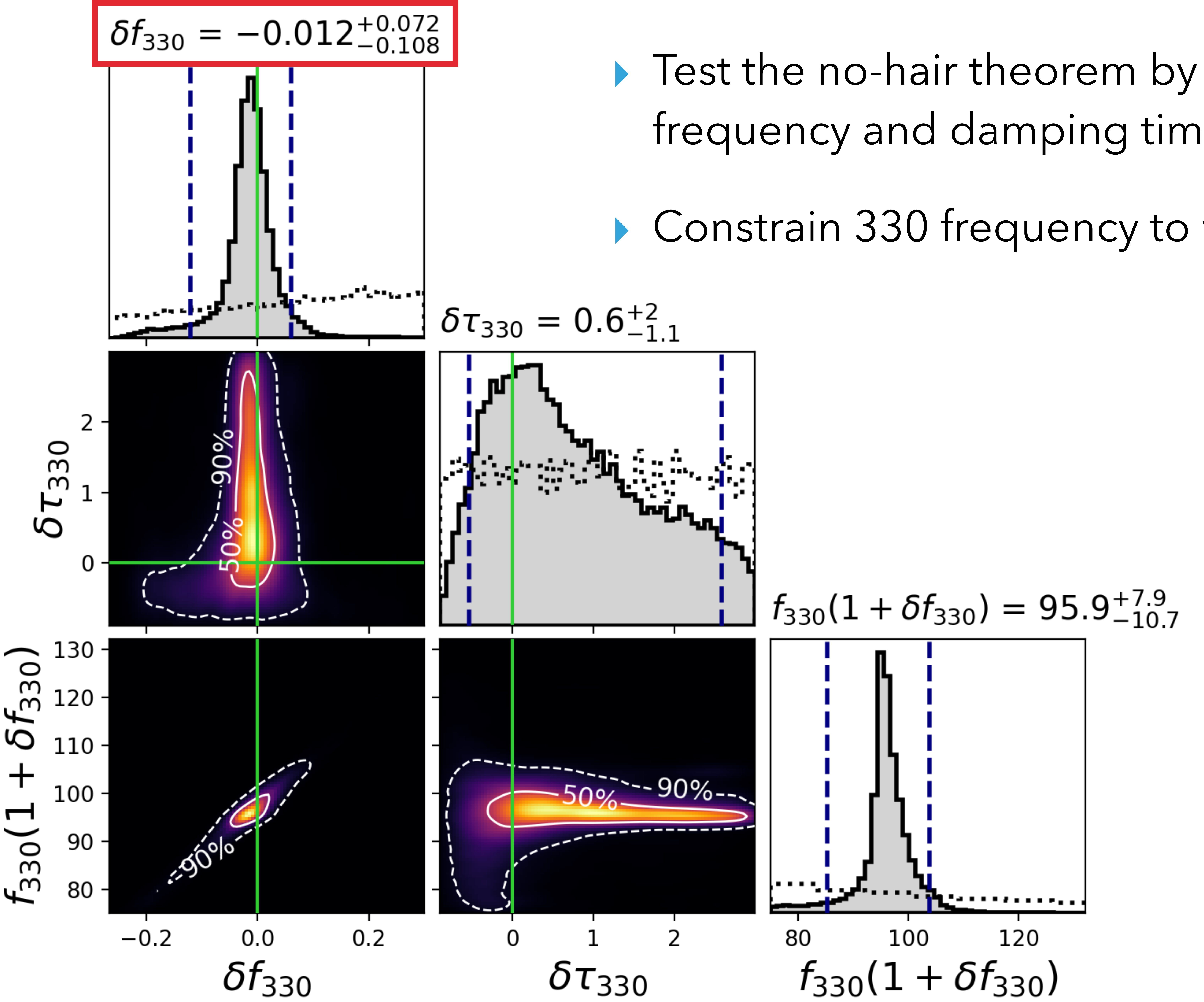
Capano et al., arXiv:2105.05238 (2021)

GW190521: BH SPECTROSCOPY

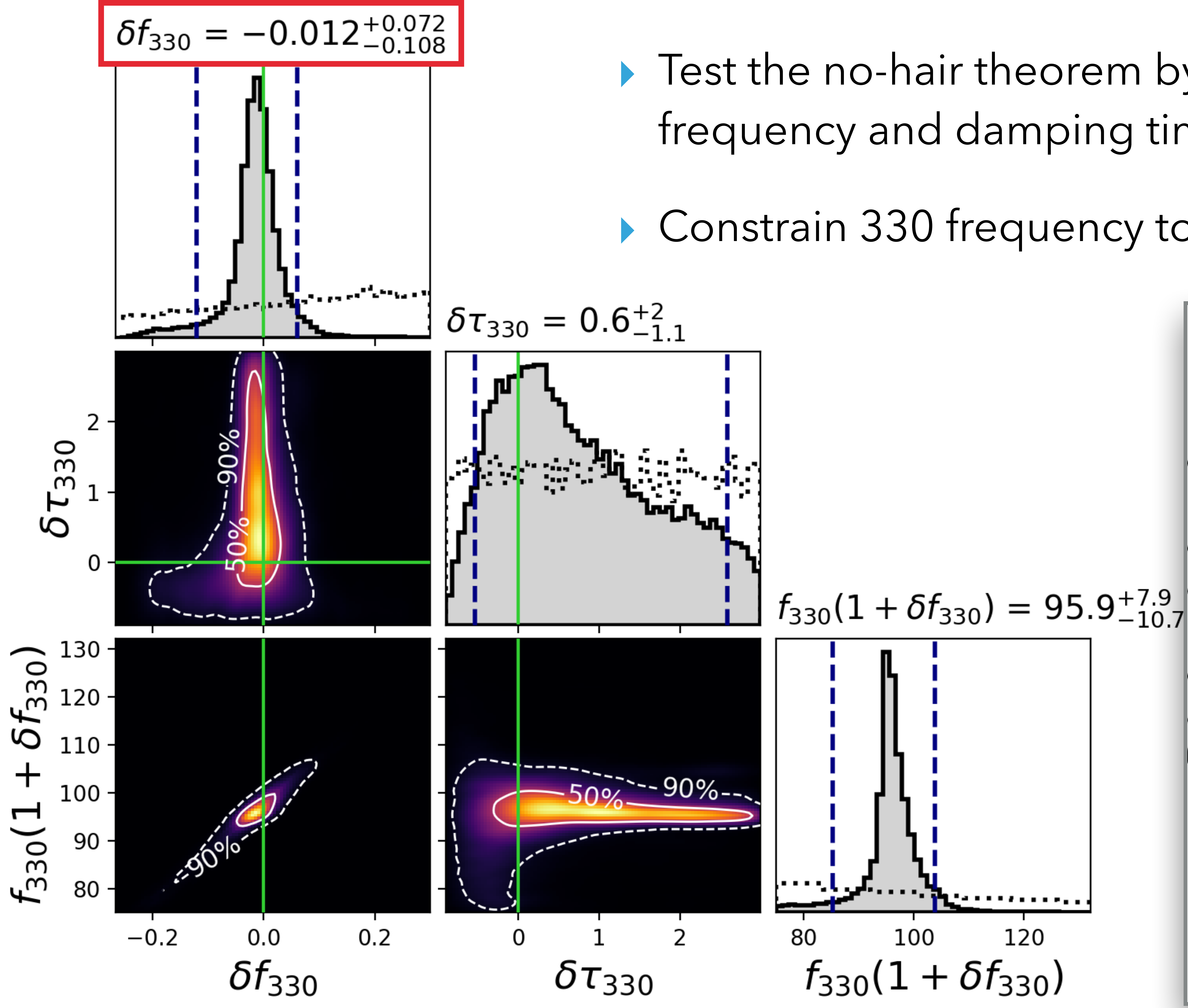
- We're confident the second mode is in the signal and not a noise artifact
- Get a Bayes factor of ~40 in favor of model with 220+330 vs 220 mode only



Capano et al., arXiv:2105.05238 (2021)



- Test the no-hair theorem by allowing the 330 frequency and damping time to deviate from GR
- Constrain 330 frequency to within ~10% of GR



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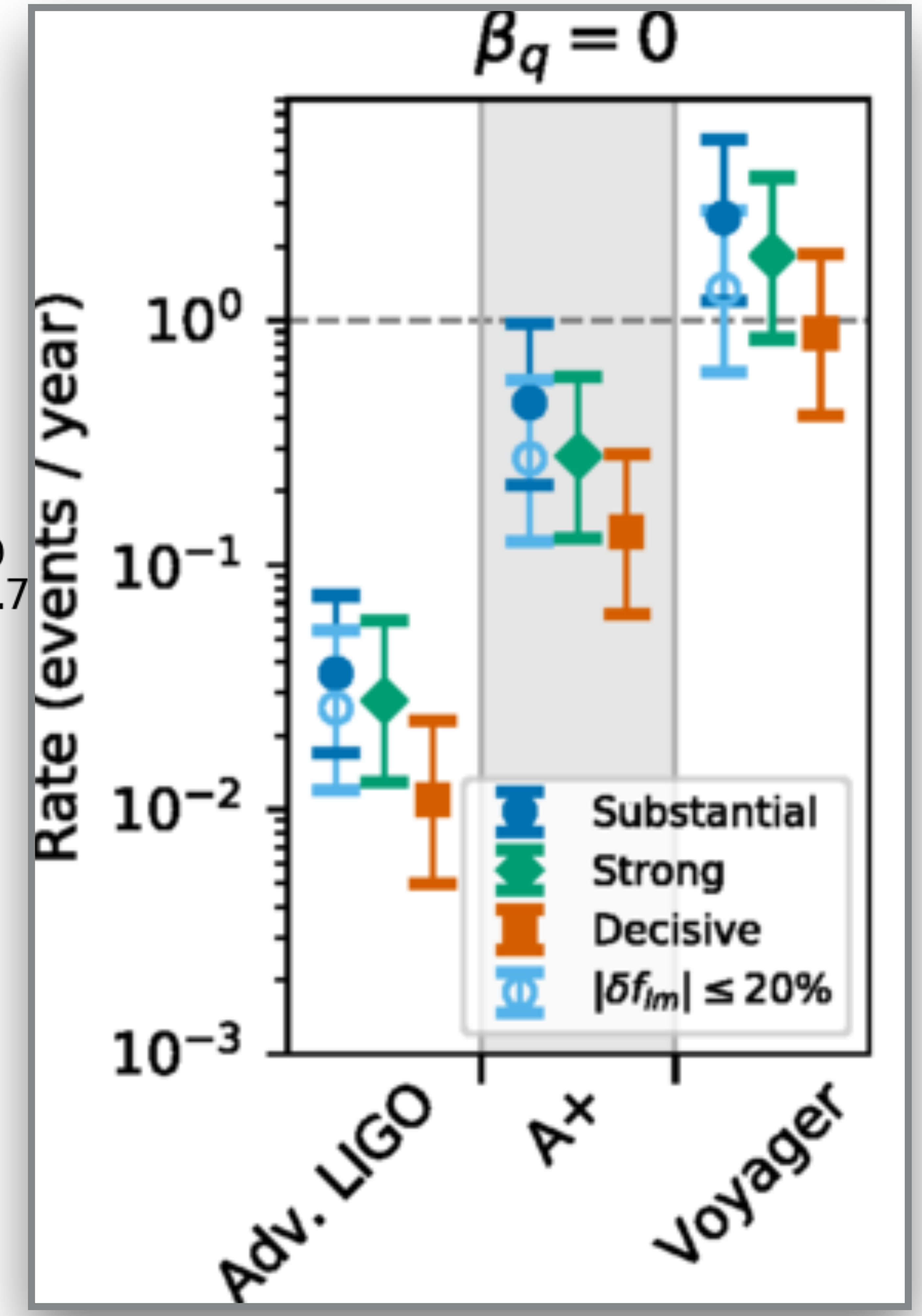
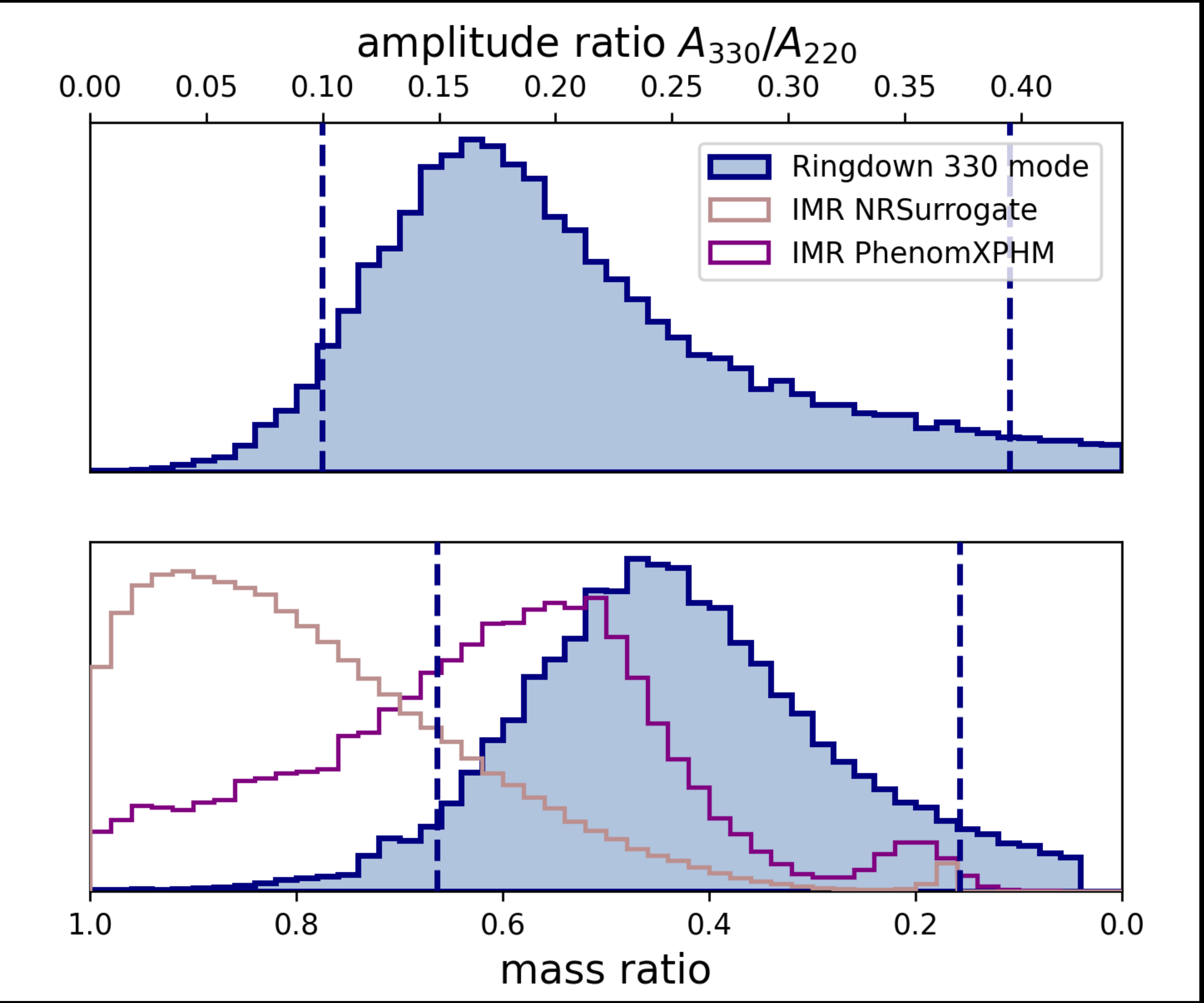


GW190521: STILL A MYSTERY

- Final object is a Kerr BH; what were the progenitors?
- Can infer the mass ratio of the binary from the amplitude of the 330 mode
- Get something in between the equal mass and high mass ratio results from IMR models
- Need better waveform models
- More events



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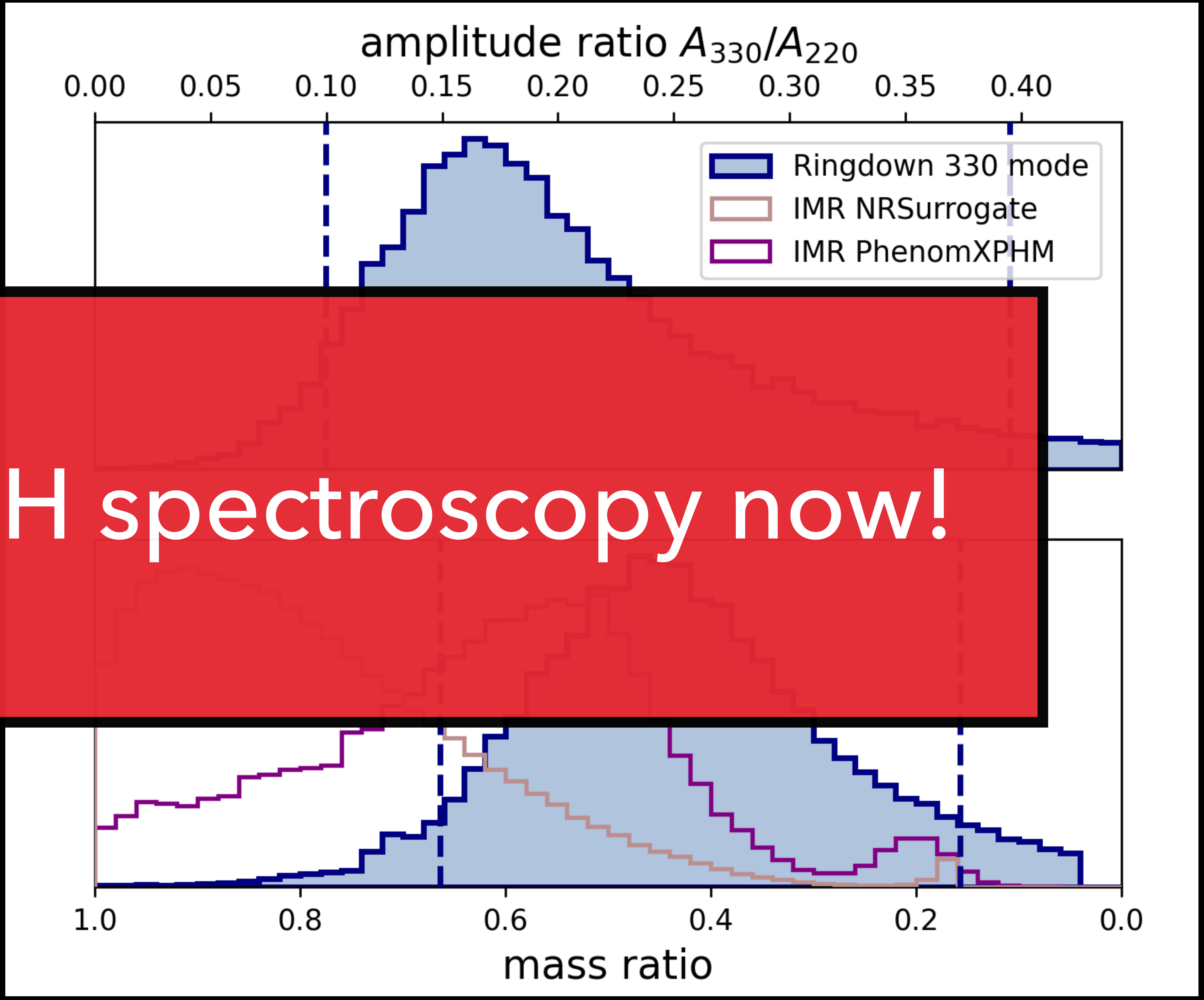
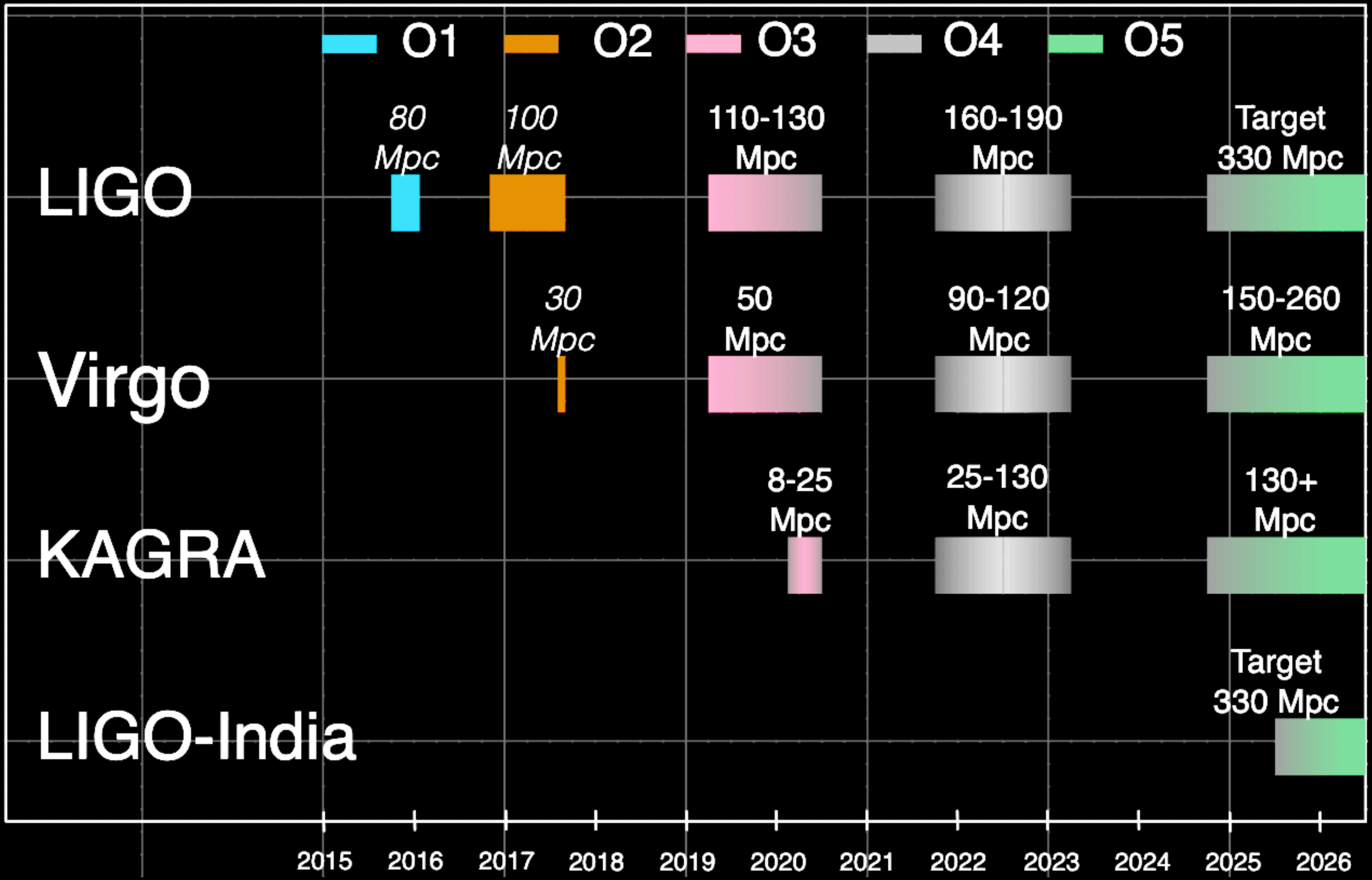


Capano et al., arXiv:2105.05238 (2021)

We're doing BH spectroscopy now!

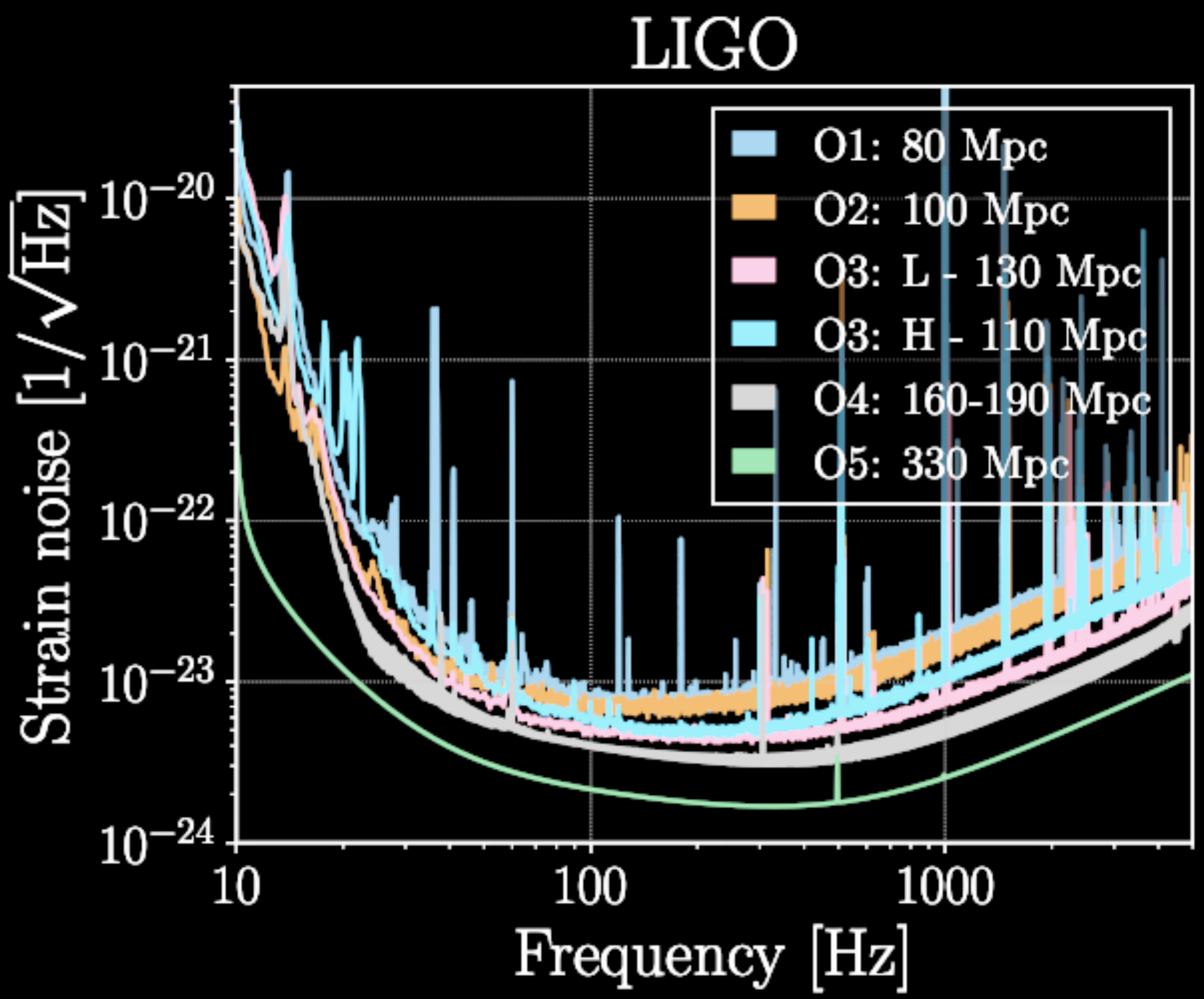
FUTURE PROSPECTS

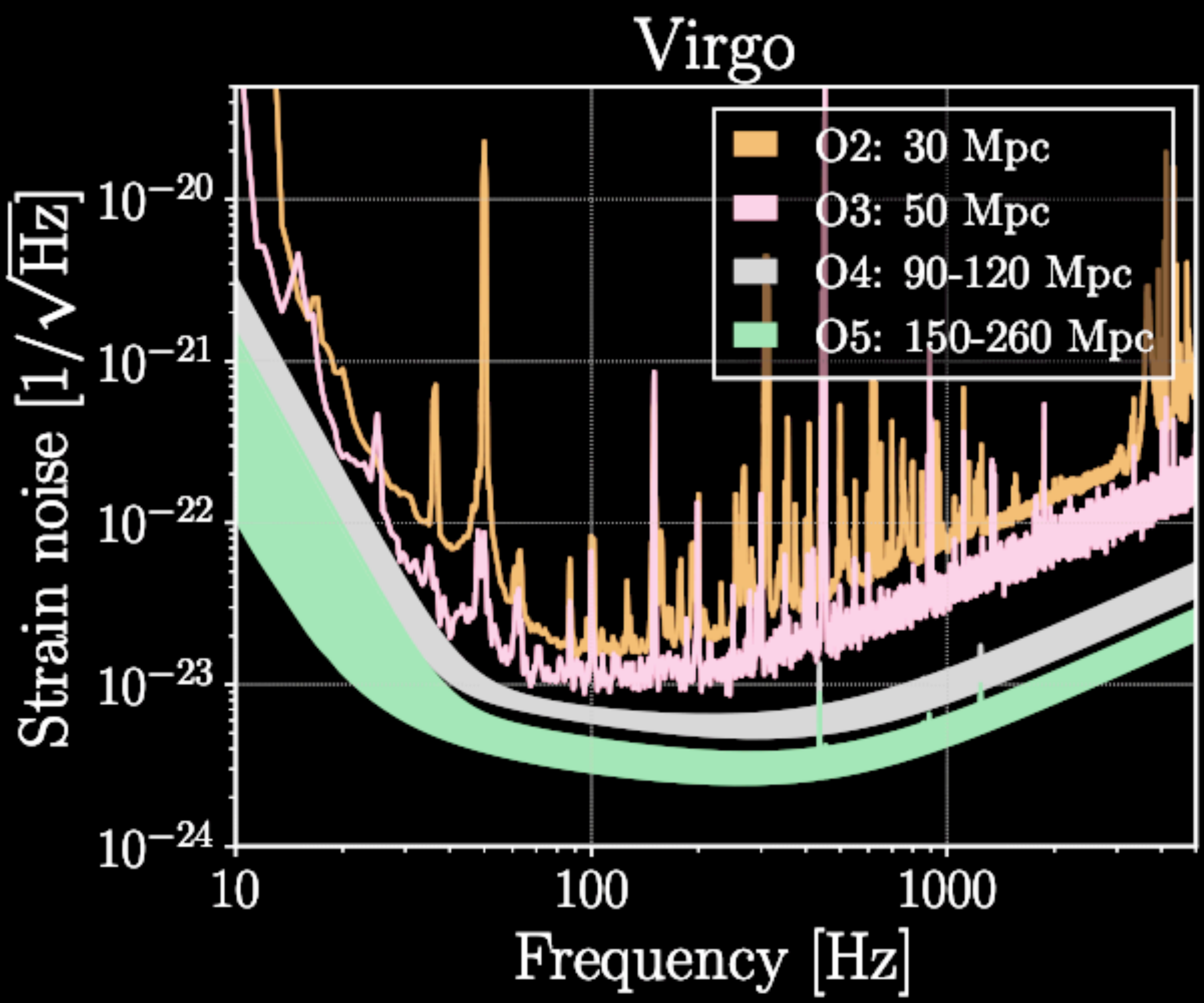
Gravitational-wave detectors are continually getting more sensitive



Reitze et al., arXiv:1903.04615

Reitze et al., arXiv:1903.04615

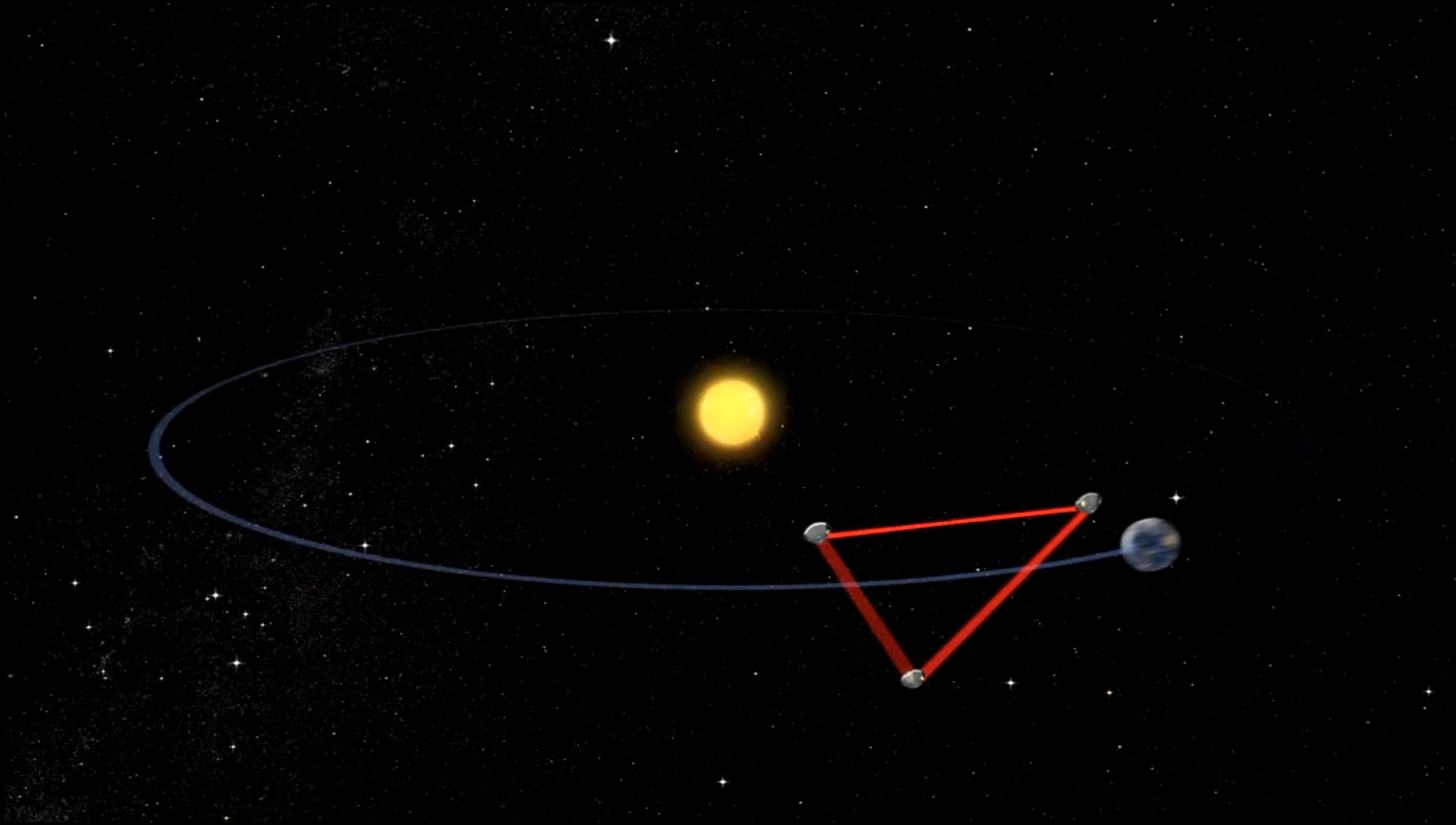




- ~2030: **LIGO Voyager** (not shown): ~2x more sensitive than O5

LISA

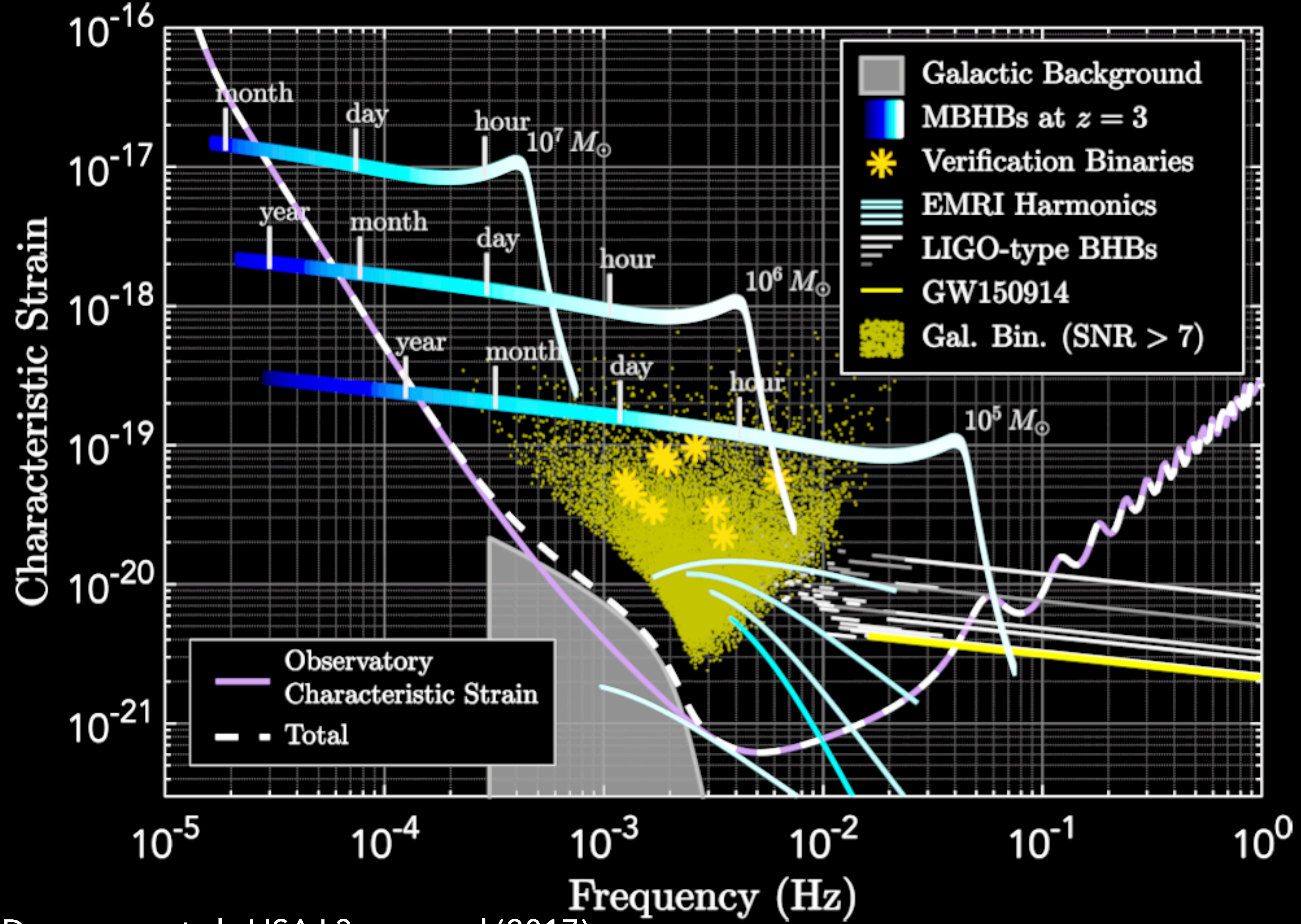
- Space-based interferometer
- Planned to launch in 2034
- ~5 year mission
- 2.5 million km long arms



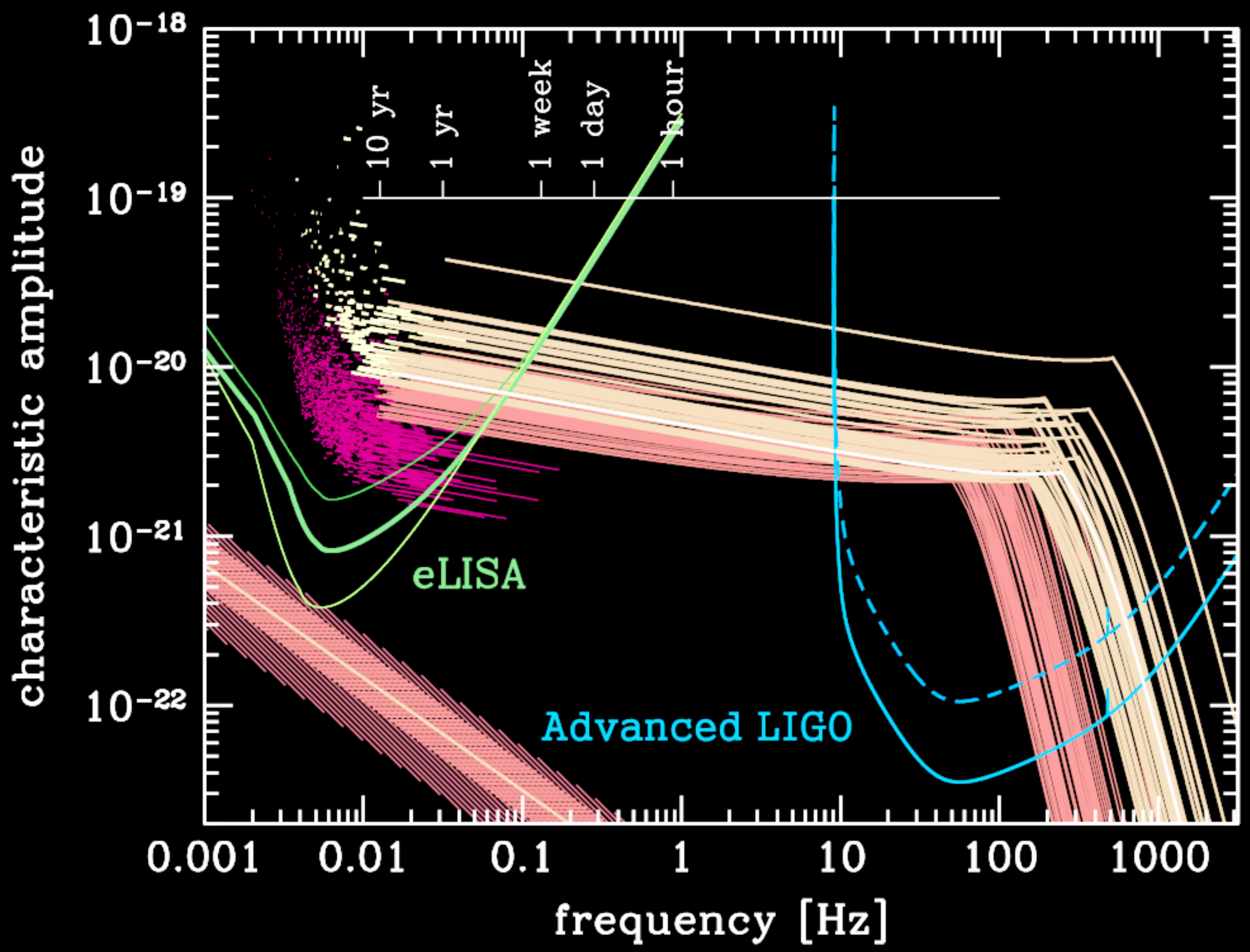
Albert Einstein Institute/Milde Marketing/exozet effects, https://youtu.be/x-k112InxfY

LISA

- Will be sensitive to BH binaries with masses $10^3 - 10^9$
- Will also be possible to do joint detections between LISA & ground-based detectors



Danzmann et al., LISA L3 proposal (2017)

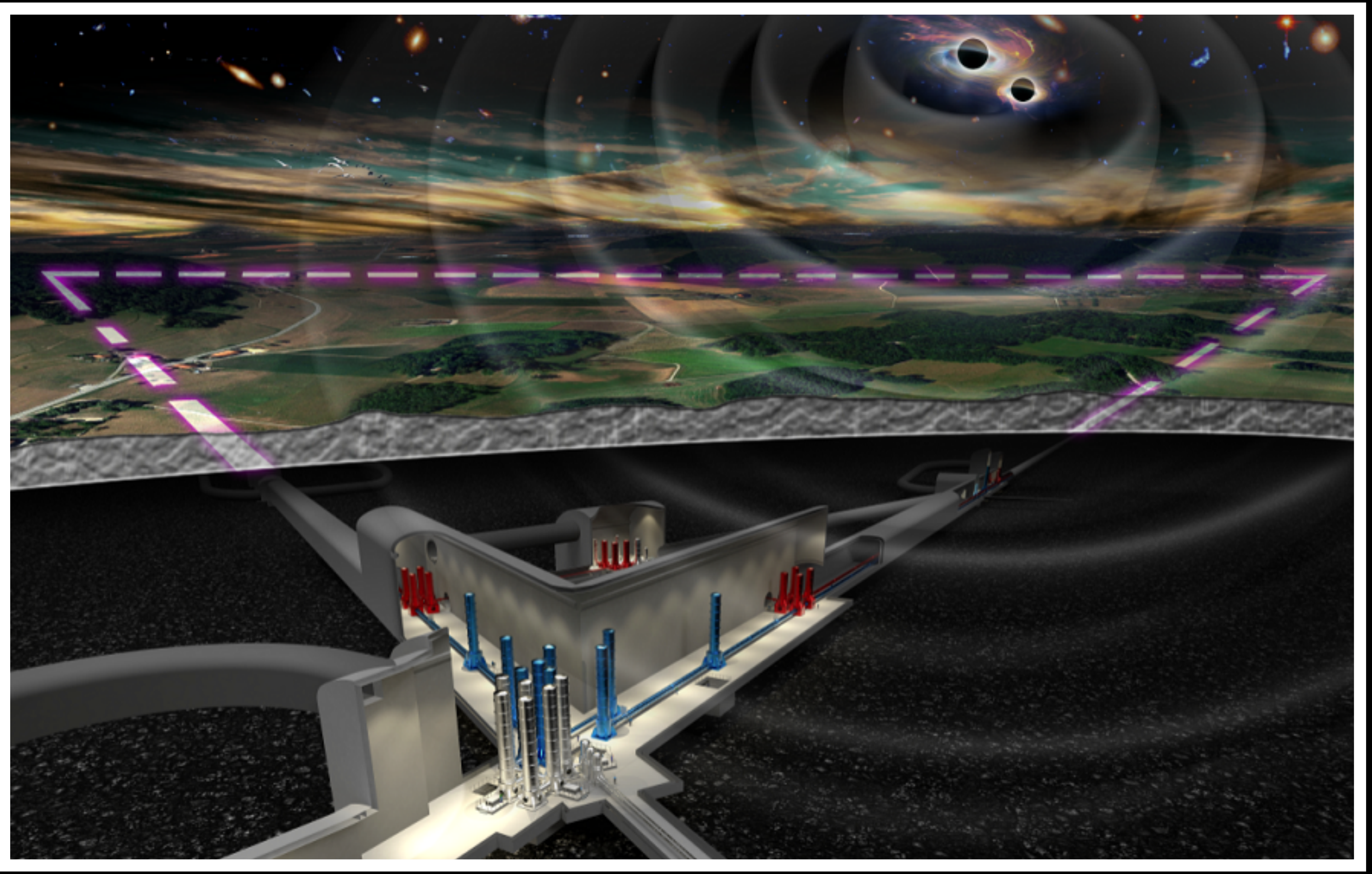


A. Sesana, PRL 116, 231102 (2016)

3G DETECTORS: LATE 2030s — 2040s

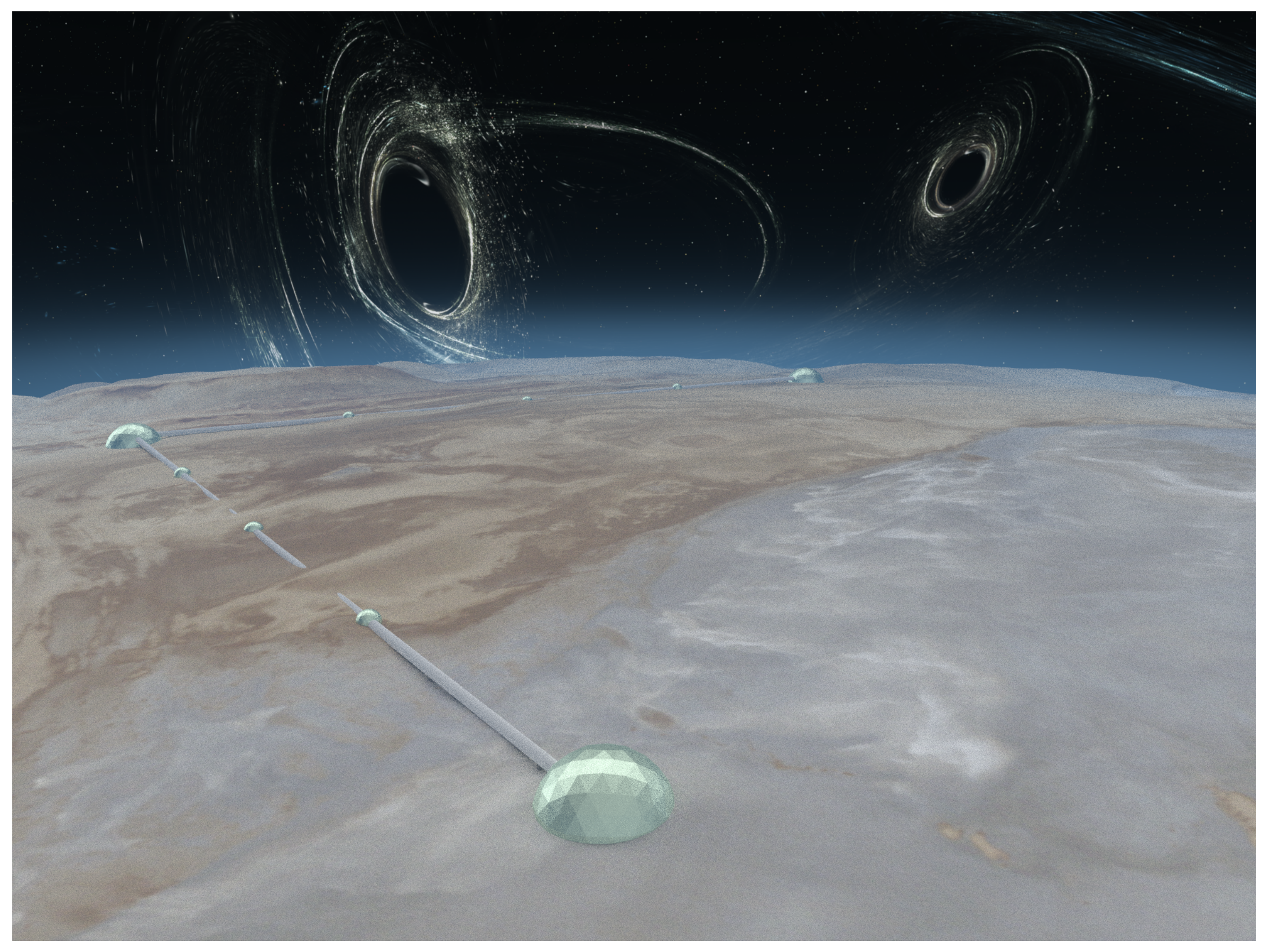
Europe: Einstein Telescope (ET)

10km underground arms in triangle formation

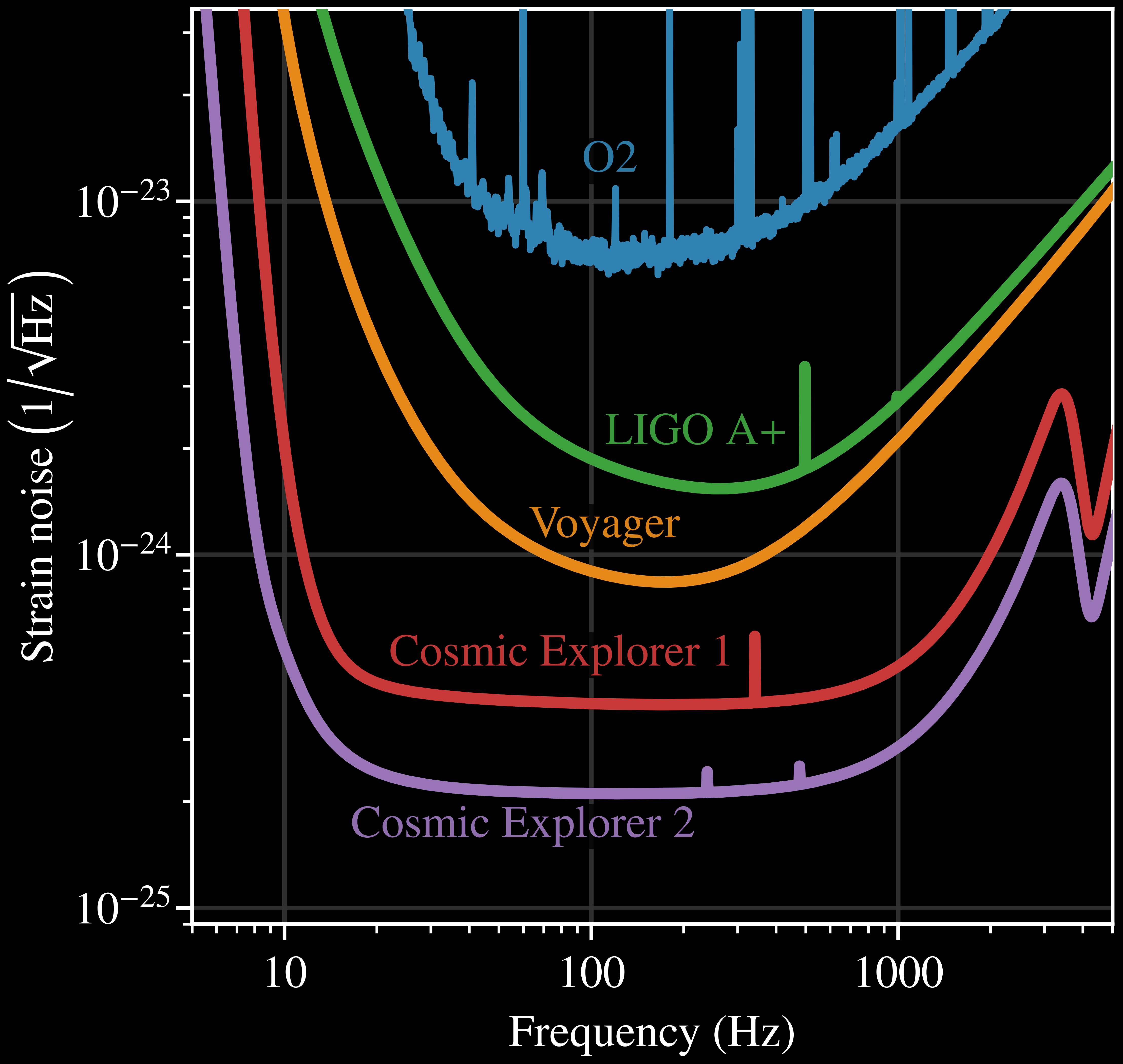


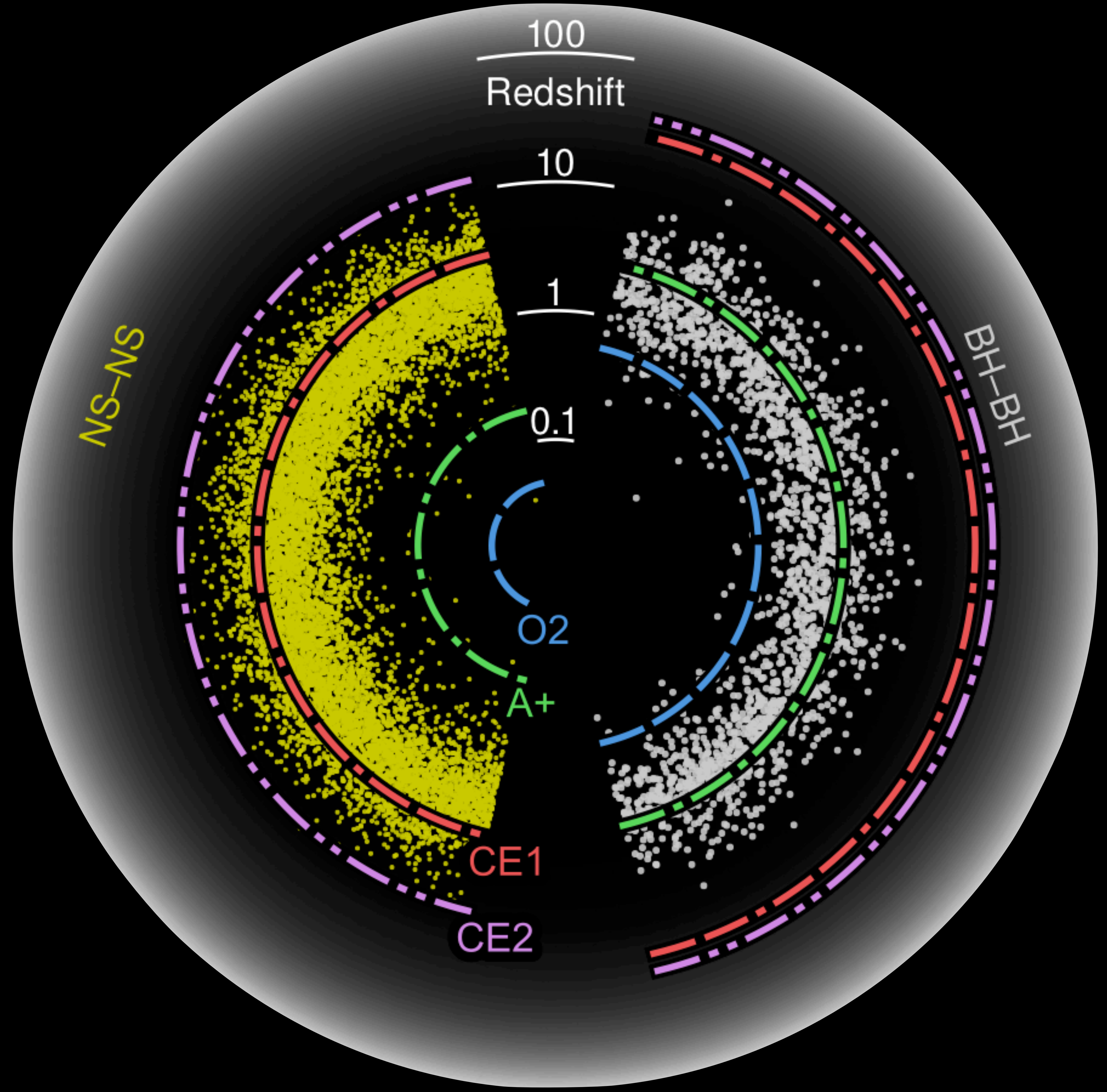
US: Cosmic Explorer (CE)

40km arms (L shaped)



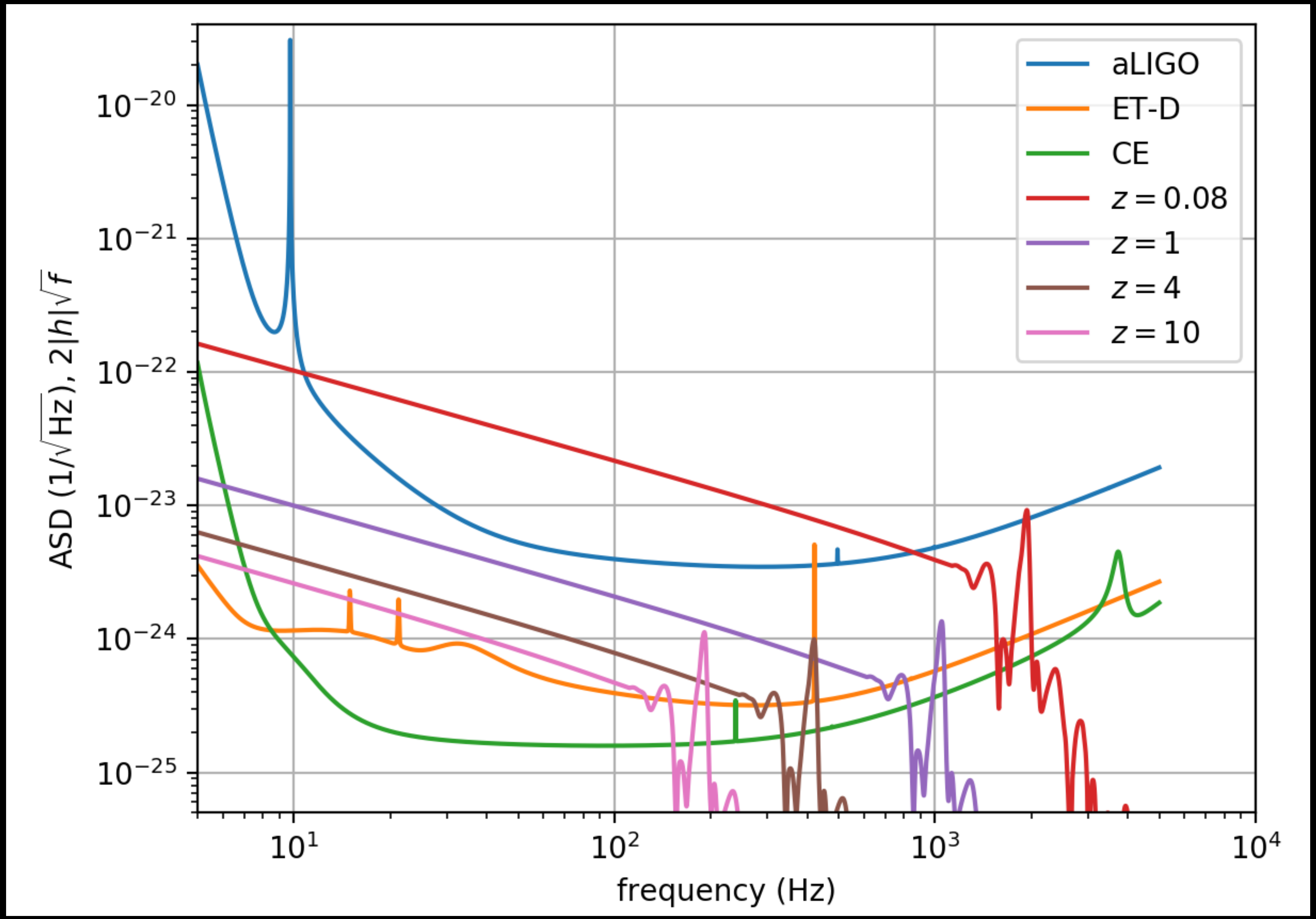
FUTURE SENSITIVITY



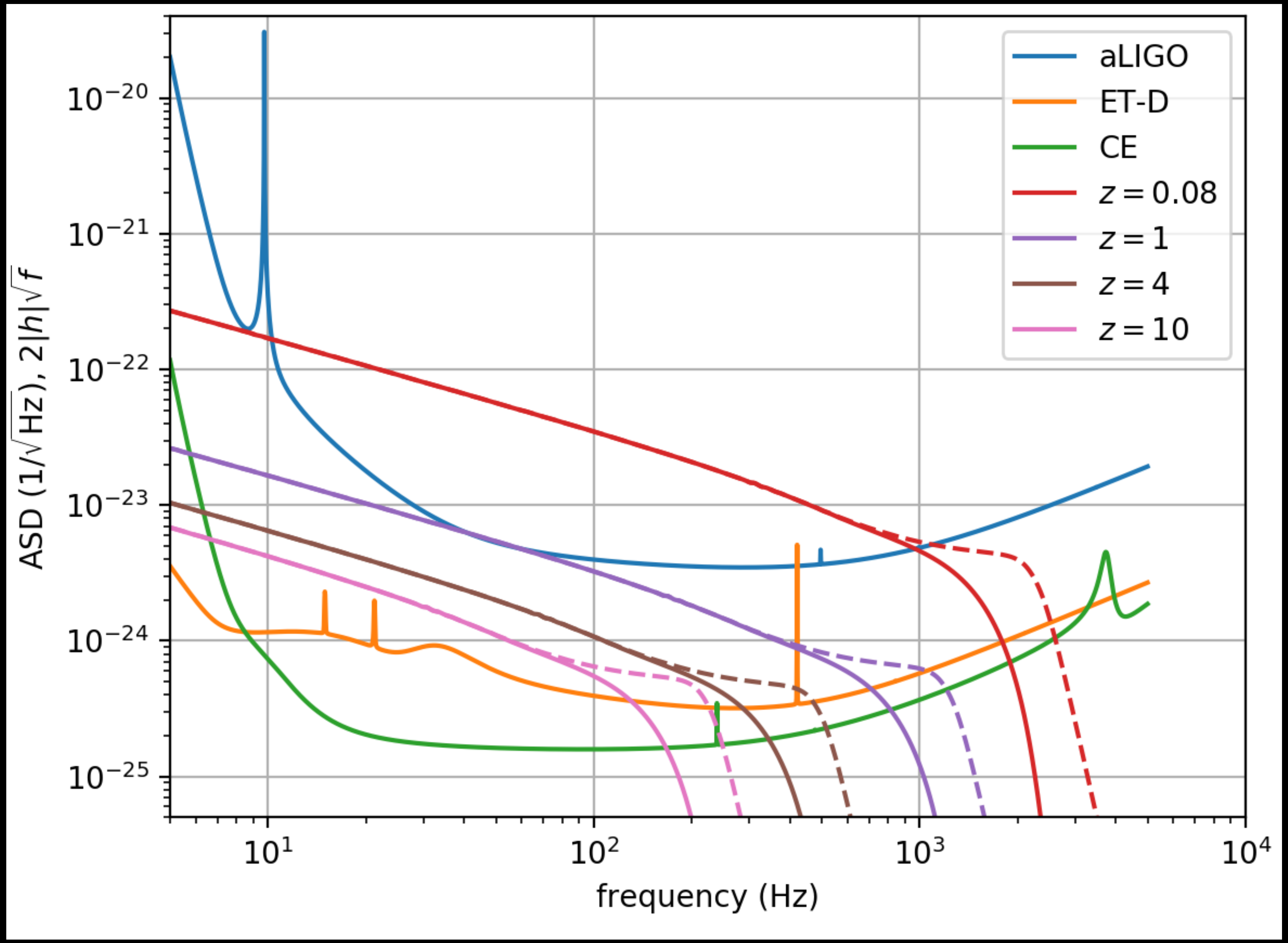


Reitze et al., arXiv:1903.04615

Binary neutron star
(with simulated post-merger signal*)



Tidally disrupted NSBH



- Will be possible to measure post-merger signal, even at cosmological distances [1]

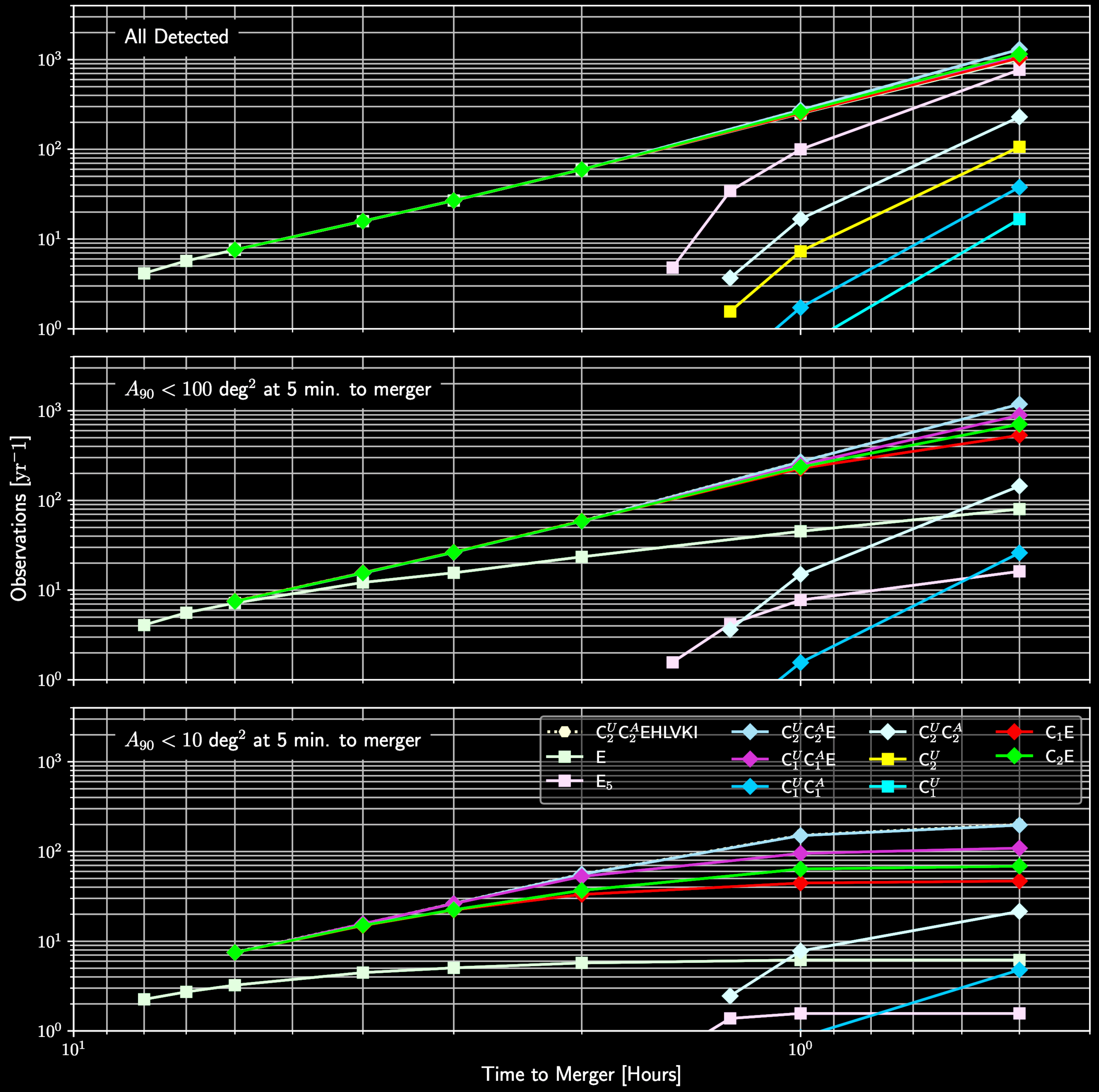
[1] Haster et al., PRL 125, 261101 (2020)

*BNS post-merger from Fig. 7 of: J.A. Clark et al., CQG 33 085003 (2016)

PRE-MERGER ALERTS

- With 3G detectors we will be able to localize BNS before merger
- Localization capabilities depends on the network that is built
- Best case: ET + a CE in US + a CE in Australia
  - ~200 BNS / year localized to <10 deg² 5 min. before merger
  - ~7/year < 1 deg²

Nitz and Dal Canton, in prep.

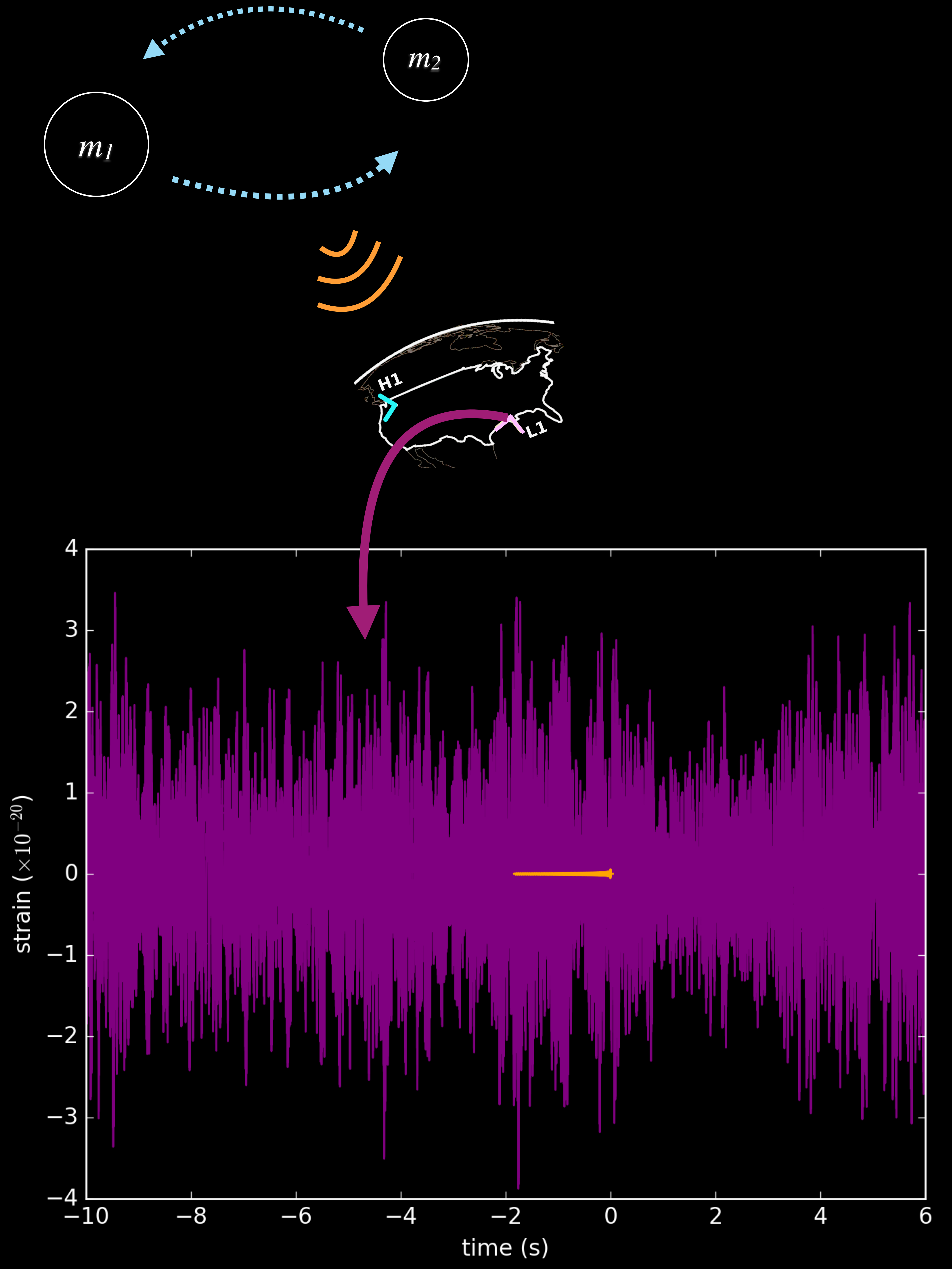


RECAP

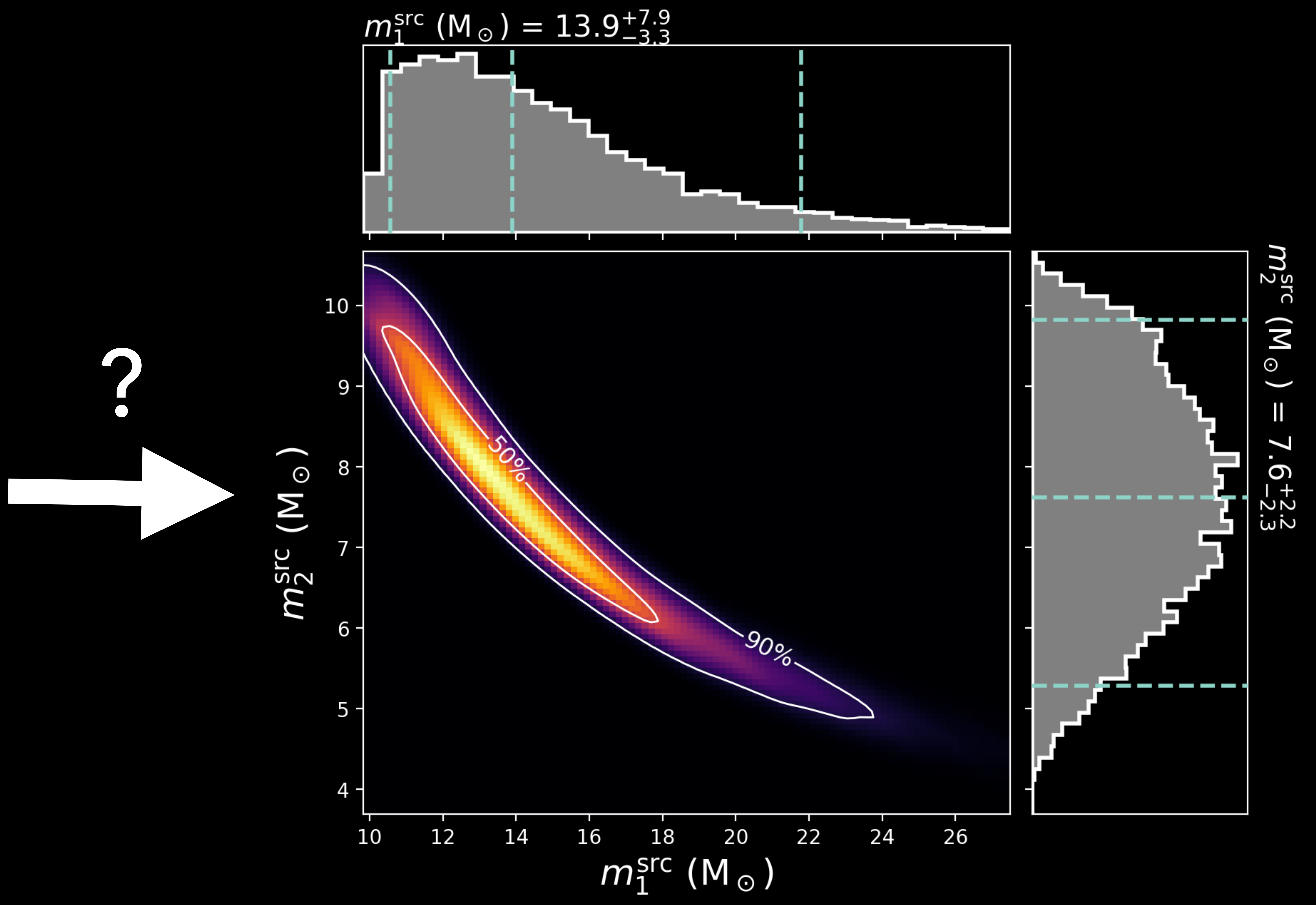
- It has taken a century of developments to detect GWs.
- Now that we are detecting them, we’re able to do astrophysics and test fundamental physics.
- Future observatories will make it possible to do ever higher precision measurements.

OUTLINE FOR TODAY

- Morning:
  - Lecture 1 (this one): Overview and current results (slides)
  - **Lecture 2: GW parameter estimation & detection (whiteboard)**
- Afternoon:
  - Lecture 3: Matched filtering with PyCBC (python tutorial)
  - Lecture 4: Parameter estimation with PyCBC (python tutorial)



m1
m2
H1
L1
strain (×10^-20)
time (s)



?
m_1^{src} (M$_\odot$) = $13.9^{+7.9}_{-3.3}$
m_2^{src} (M$_\odot$) = $7.6^{+2.2}_{-2.3}$
50%
90%
m_1^{src} (M$_\odot$)
m_2^{src} (M$_\odot$)

EXTRAS

GWS AT COSMOLOGICAL DISTANCES

$$|\tilde{h}| \sim \frac{M_{\rm det}^{5/6} f_{\rm det}^{-7/6}}{d_L}$$

$$M_{\rm det} = (1+z) M_{\rm src}$$

$$f_{\rm det} = \frac{f_{\rm src}}{1+z}$$

$$\boxed{\rightarrow |\tilde{h}| \sim \frac{(1+z)^2}{d_L} M_{\rm src}^{5/6} f_{\rm src}^{-7/6}}$$

For z ≳ 1.6, GW amplitude at fixed frequency *grows* with increasing redshift