Black Hole Whispers

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Remembering C.V. Vishveshwara

ICTS, Bangalore, February 24, 2017

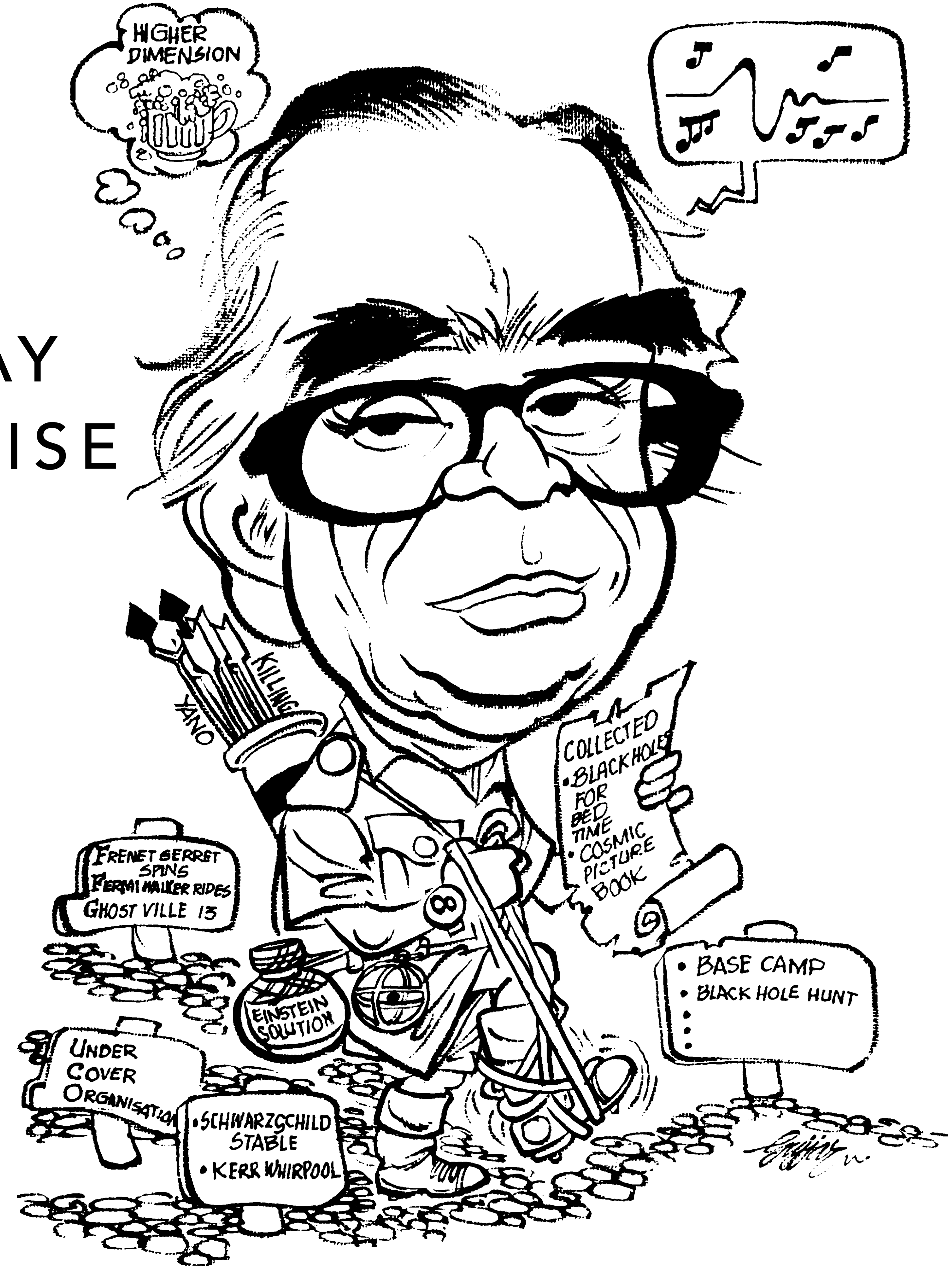
FIRST ENCOUNTERS

- Bangalore Science Forum (Est. 1969) conducts science festival each year during the month of July
- Vishu delivered an evening lecture at the Forum during the 1977 science festival
- It was the most fascinating physics I had heard until then
- full of humour with a very serious disposition, we didn't know if we were supposed to laugh!

A MISSED OPPORTUNITY

Drona and Ekalavya

60TH BIRTHDAY AND THE PROMISE



Gurudakshina

B.S. Sathyaprakash <B.Sathyaprakash@astro.cf.ac.uk> 11/02/2016
to CV

Dear Vishu,

I had promised nearly 20 years ago that one day I will come and tell you we have detected those dying tones of black holes one day. Well, now have done it! Here is the link the discovery paper and a paper in which we have looked at QNM. Congratulations!

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.116.061102
https://dcc.ligo.org/public/0122/P1500213/027/paper.pdf

Best,
Sathya

Vishveshwara <saruvishu@gmail.com> 15/02/2016
to B.S.

Dear Sathya,
Thank you immensely. But your promise was that you would 'come and tell you that we have seen the quasi-normal modes'. So, you have to come down to Bengaluru and keep your word. Don't forget to bring a few bottles of Cardiff champagne so we can celebrate the black hole ring down and the beginning of Indigo.
Seriously, Sathya, I went back and looked at your article. I am moved by what you say in the beginning as much as I was when the book reached my hand.
Warmest best wishes to you and hope to see you soon.
Yours,
Vishu
PS: I got the PRL discovery paper. Was there supposed to be another on QNMs?

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new tests of general relativity, especially in the dynamic strong-field regime.

Experiments to detect gravitational waves began with light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [8–10], and in the 1990s higher-order post-Newtonian calculations [11] preceded extensive analytical studies of relativistic two-body dynamics [12,13]. These advances, together with numerical relativity breakthroughs in the past decade [14–16], have enabled modeling of binary black hole mergers and accurate predictions of their gravitational waveforms. While numerous black hole light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

[8] C. V. Vishveshwara, Nature (London) **227**, 936 (1970).
[9] W. H. Press, Astrophys. J. **170**, L105 (1971).
[10] S. Chandrasekhar and S. L. Detweiler, Proc. R. Soc. A **344**, 441 (1975).

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QUASIMODO OF BLACK HOLES

- Vishu was the first to hear the sound of a black hole
- the “black hole man of India” showed the world how to listen to whispers of a black hole or of the spacetime warpage

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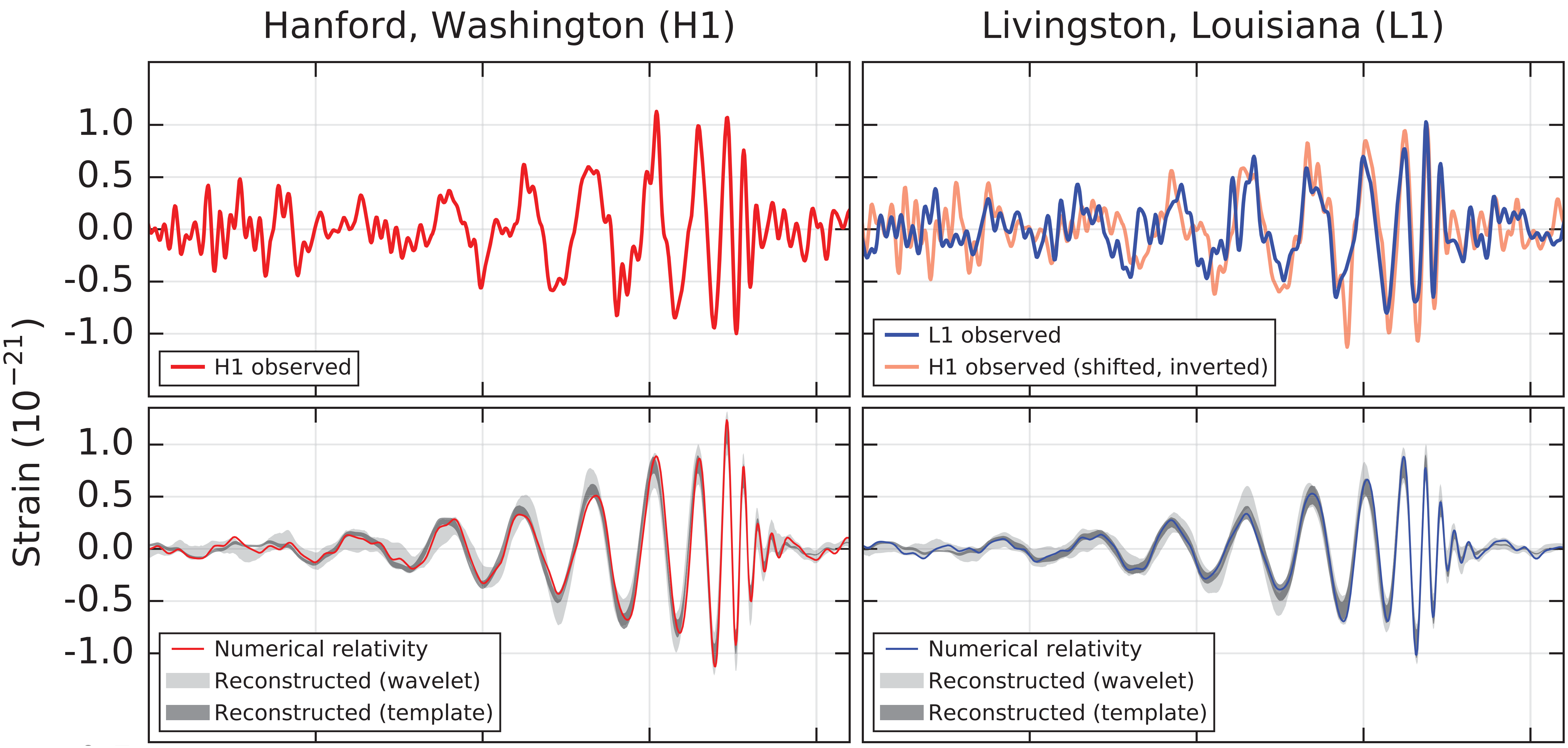
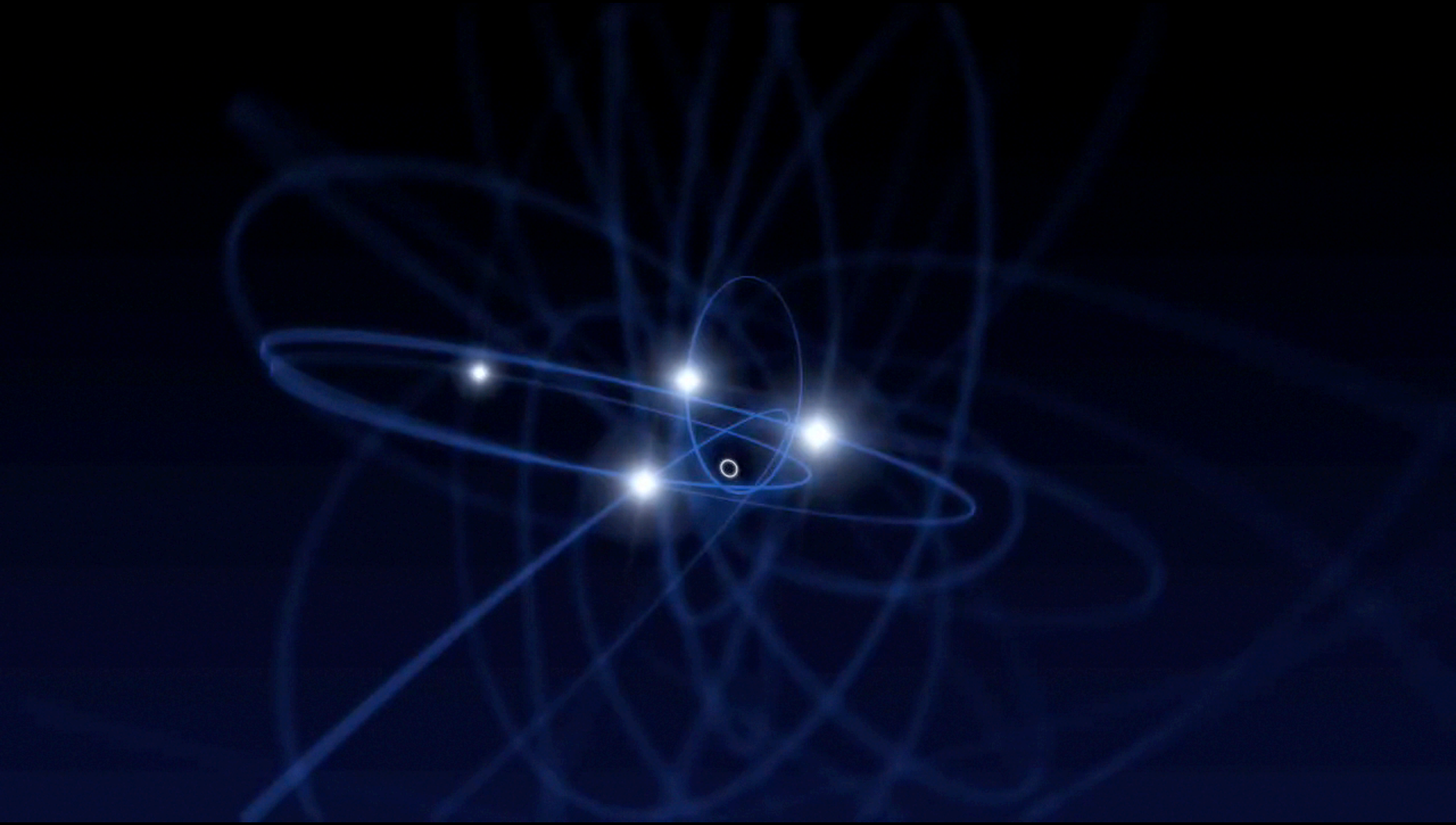
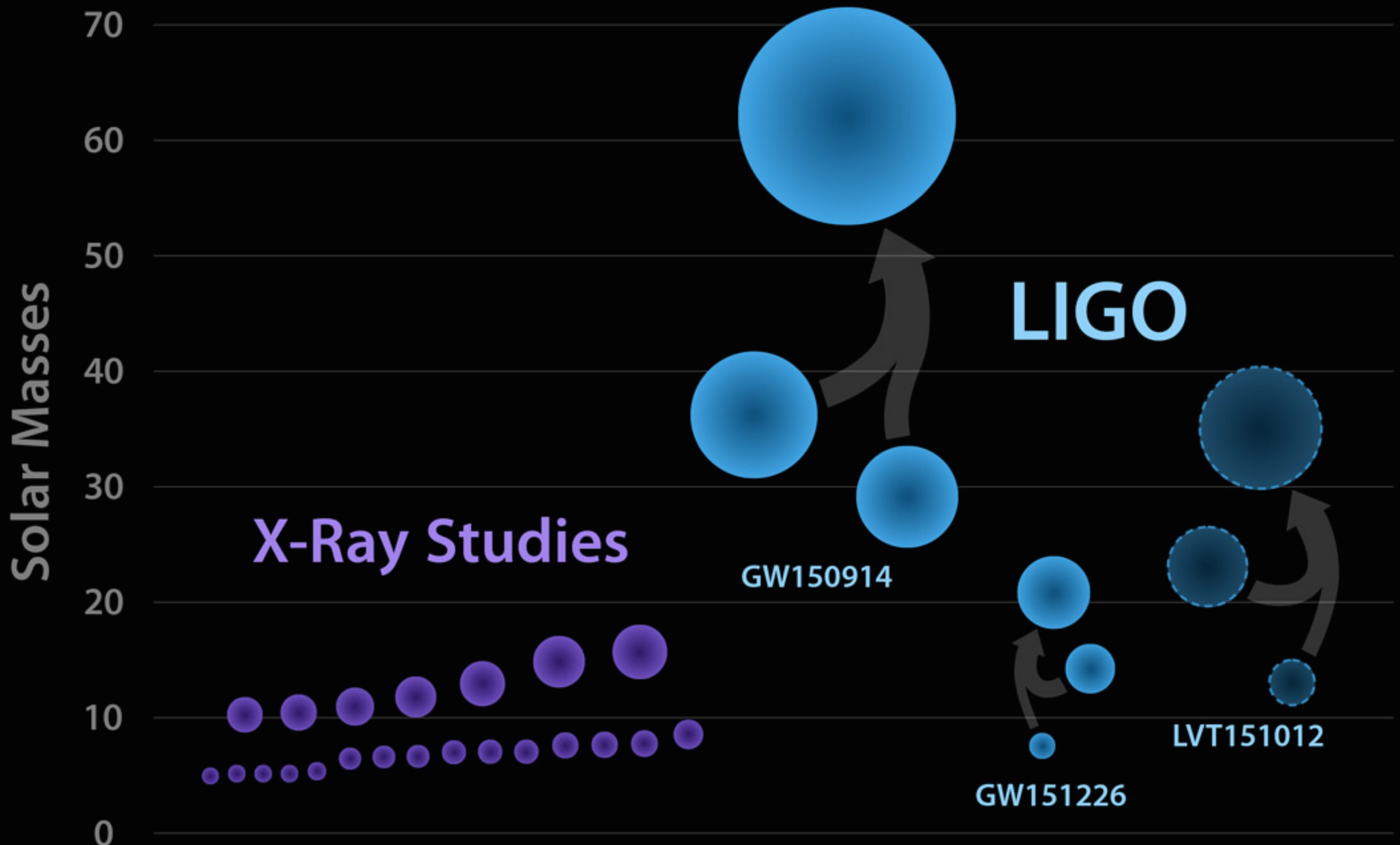


BLACK HOLES ARE UBIQUITOUS

BLACK HOLE AT THE GALACTIC CENTRE



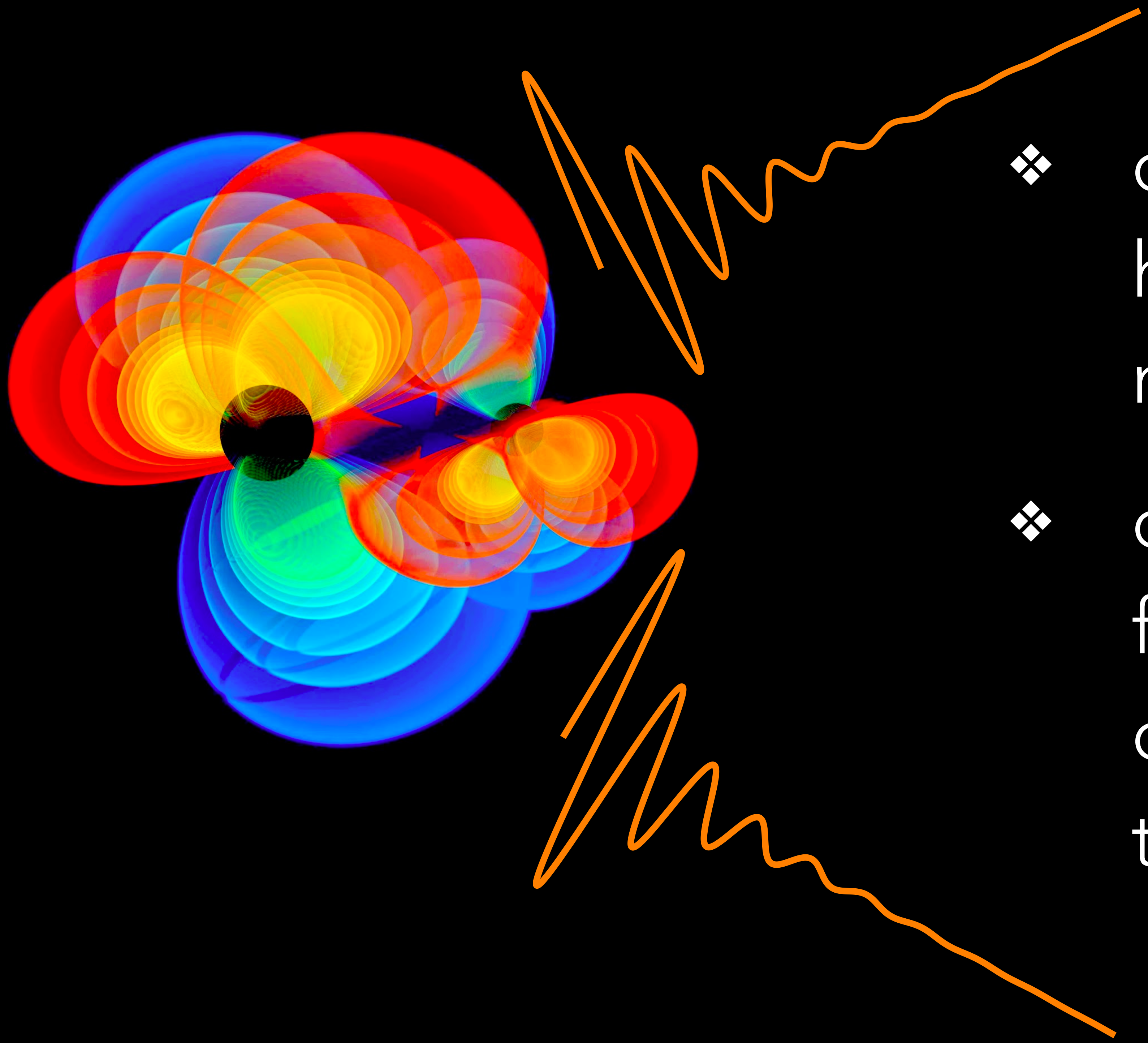
LIGO BLACK HOLES



ligo.caltech.org

LISTENING TO BLACK HOLES

TESTING BH NO-HAIR THEOREM



- deformed black holes emit quasi-normal modes
- complex frequencies depend only on the mass and spin

QUASI-NORMAL MODES

- They are damped sinusoids with characteristic frequencies and decay times which depend on only the mass and spin of the black hole (below assume j=0)
- There are infinitely large number of modes. For the dominant mode:
- $h(t) = A\, e^{-t/\tau} \cos(\omega t + \varphi)$
- $f(M, j) = \omega/(2\pi) = 1200$ Hz $(10\ M_\odot/M)$ (2 kHz for j=0.9)
- $\tau(M, j) = 0.55$ ms $(M/10\ M_\odot)$
- $Q = \tau\omega/2 \sim 2$ (for j=0.9, Q=5)

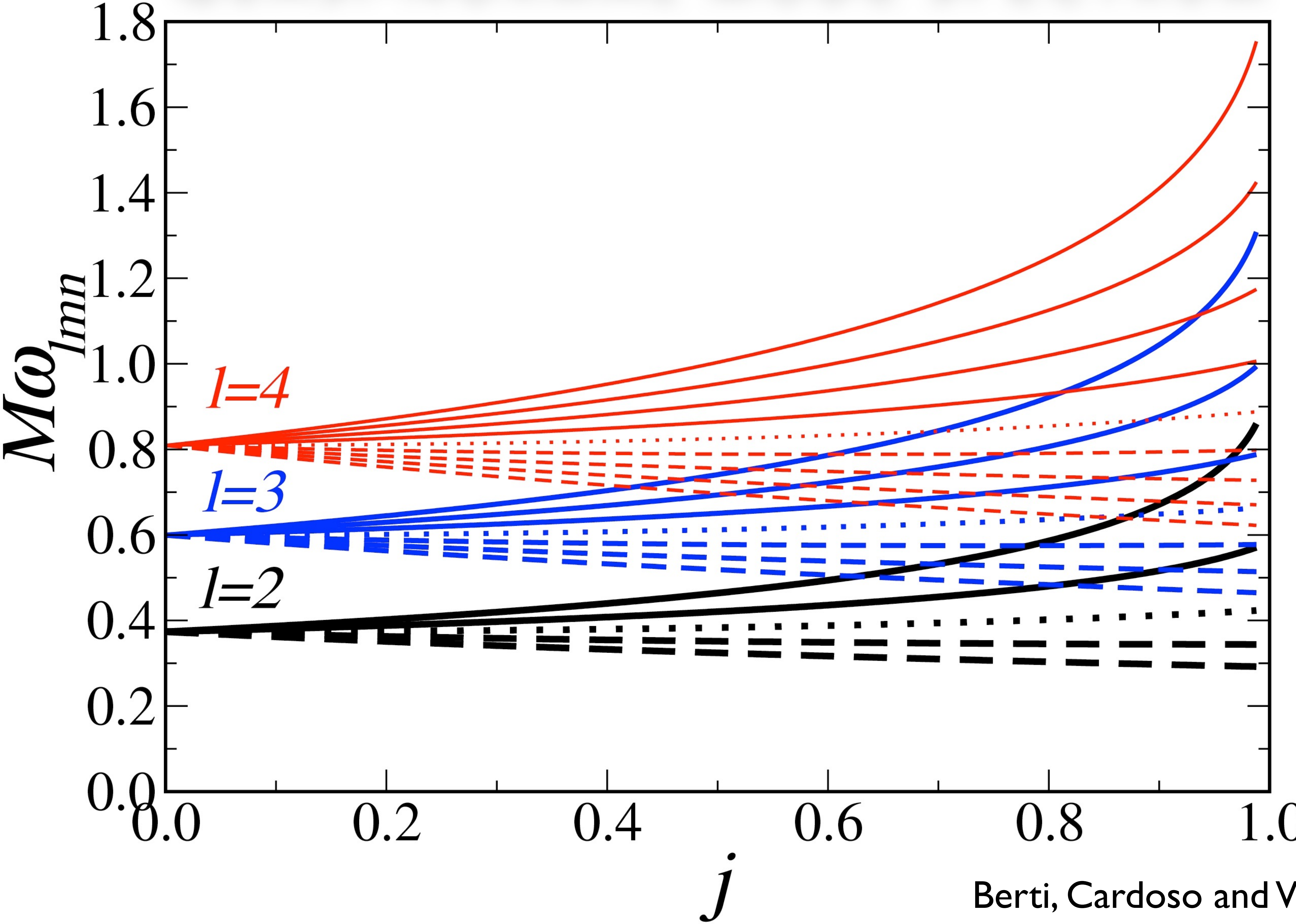
WHY ARE QNM IMPORTANT?

- QNM are the true test of whether the final remnant is a black hole
  - If not a black hole oscillation frequencies would depend on parameters other than remnant's mass and spin
- Abrupt turn off of the signal not quite enough
  - to claim the remnant is a black hole requires, to some degree, that the signal respects the no-hair theorem

TESTING THE NO-HAIR THEOREM

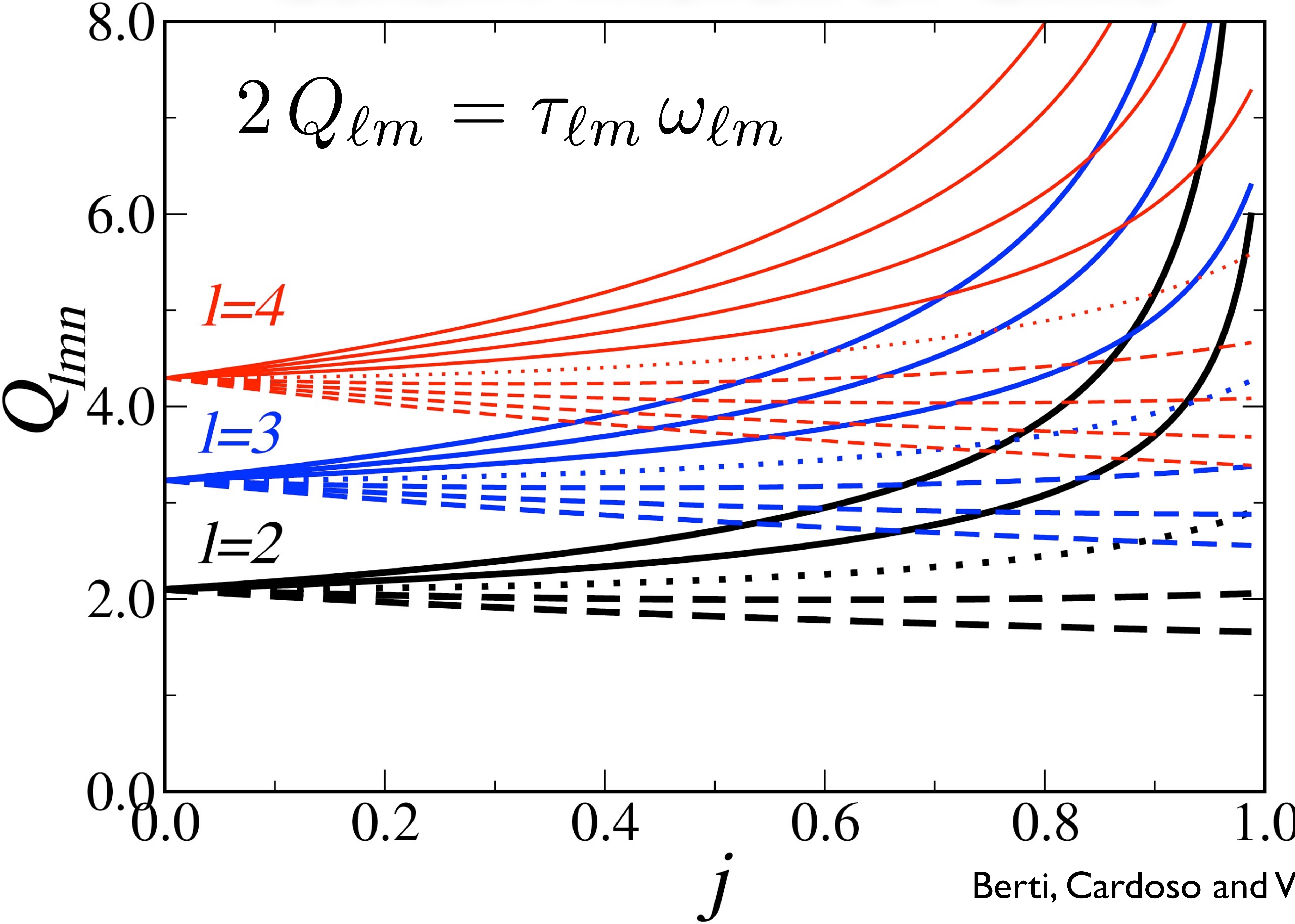
- There are infinitely many quasi-normal modes enumerated by integers (l,m,n):
  - $m = -l, \ldots, l$ and overtones $n=0,1,2,3,\ldots$
  - In general relativity frequencies f_{lmn} and decay times τ_{lmn} all depend only on the mass M and spin j of the black hole
- Measurement of a single mode could give the mass and spin of the black hole
- Measuring two or modes would constrain General Relativity or provide smoking gun evidence of black holes
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail
- Absence of quasi-normal modes after merger would reveal failure of GR

QUASI-NORMAL MODE SPECTRUM



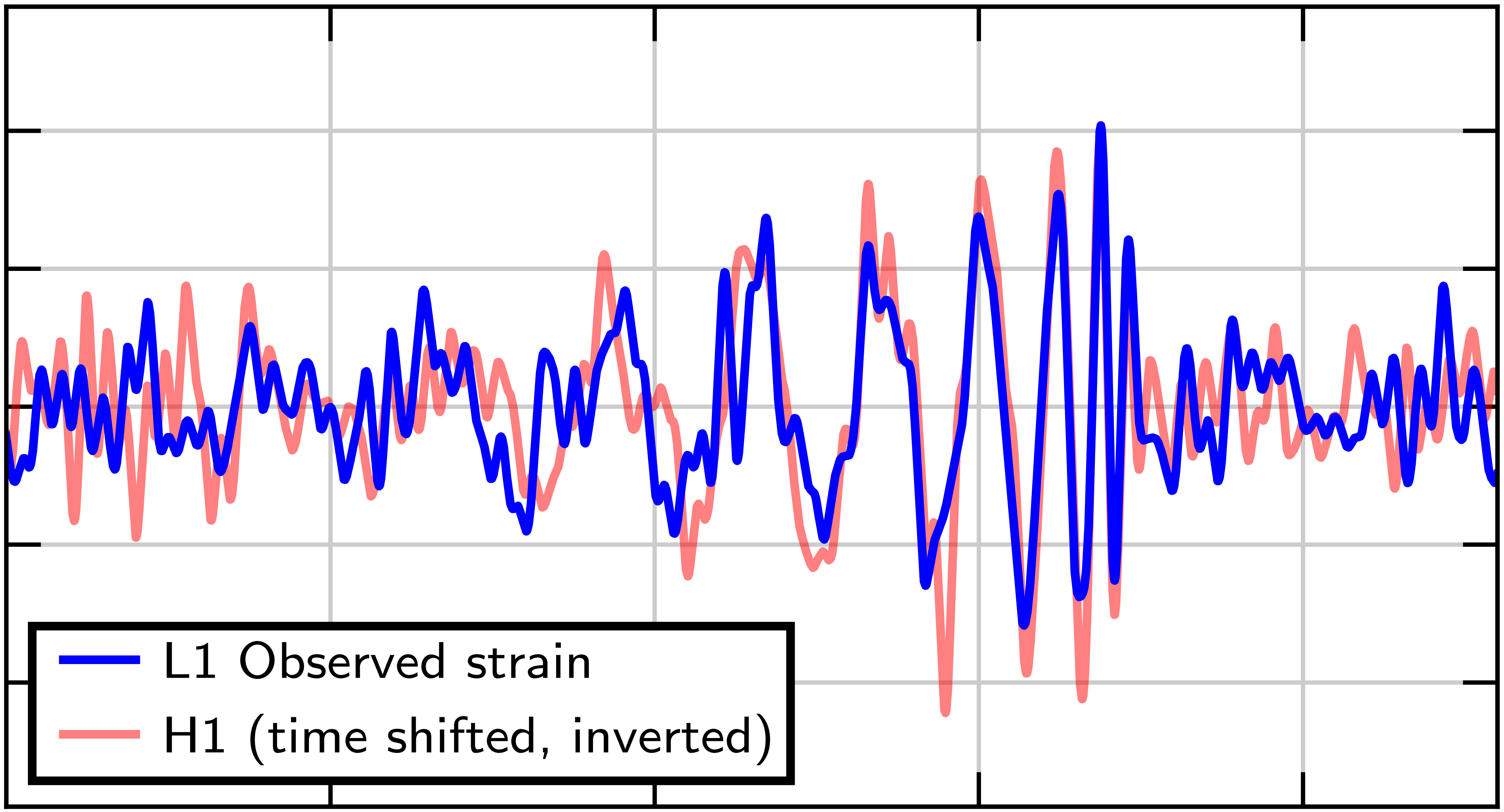
Berti, Cardoso and Will

QUALITY FACTOR OF QNMS



Berti, Cardoso and Will

WHAT DID WE OBSERVE?



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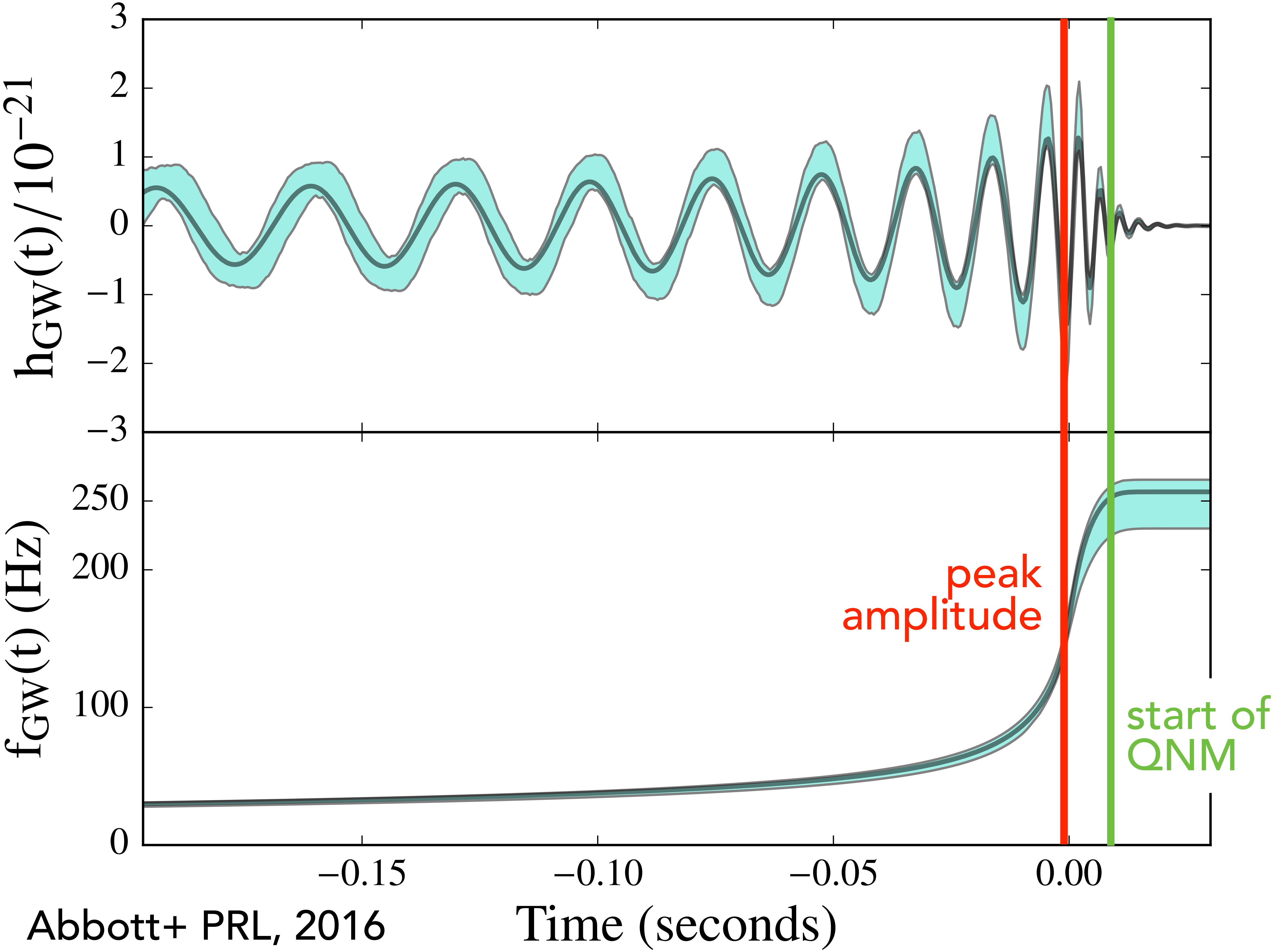
WHEN DO QNM BEGIN?



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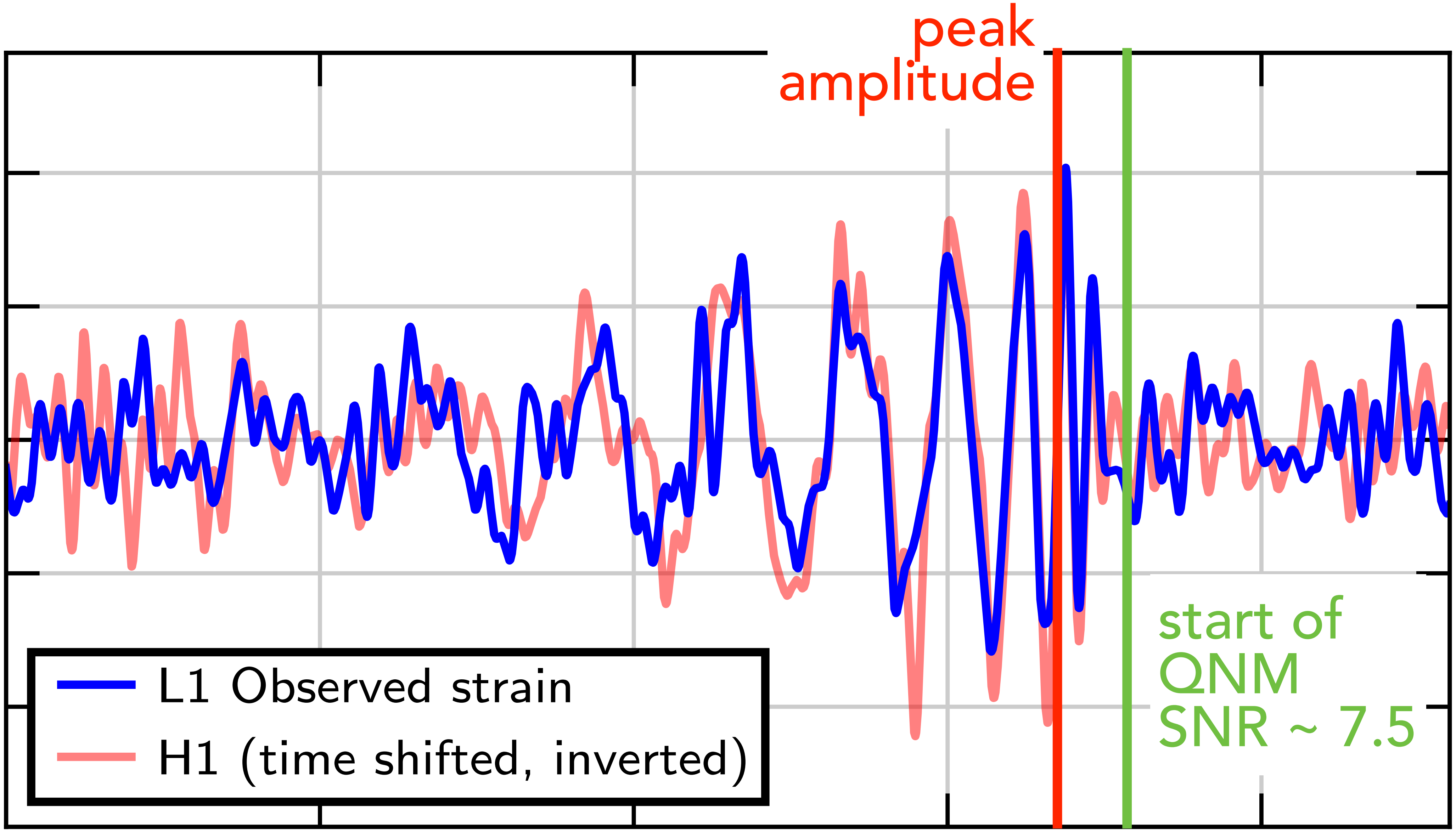
SO, DO WE SEE QNM?



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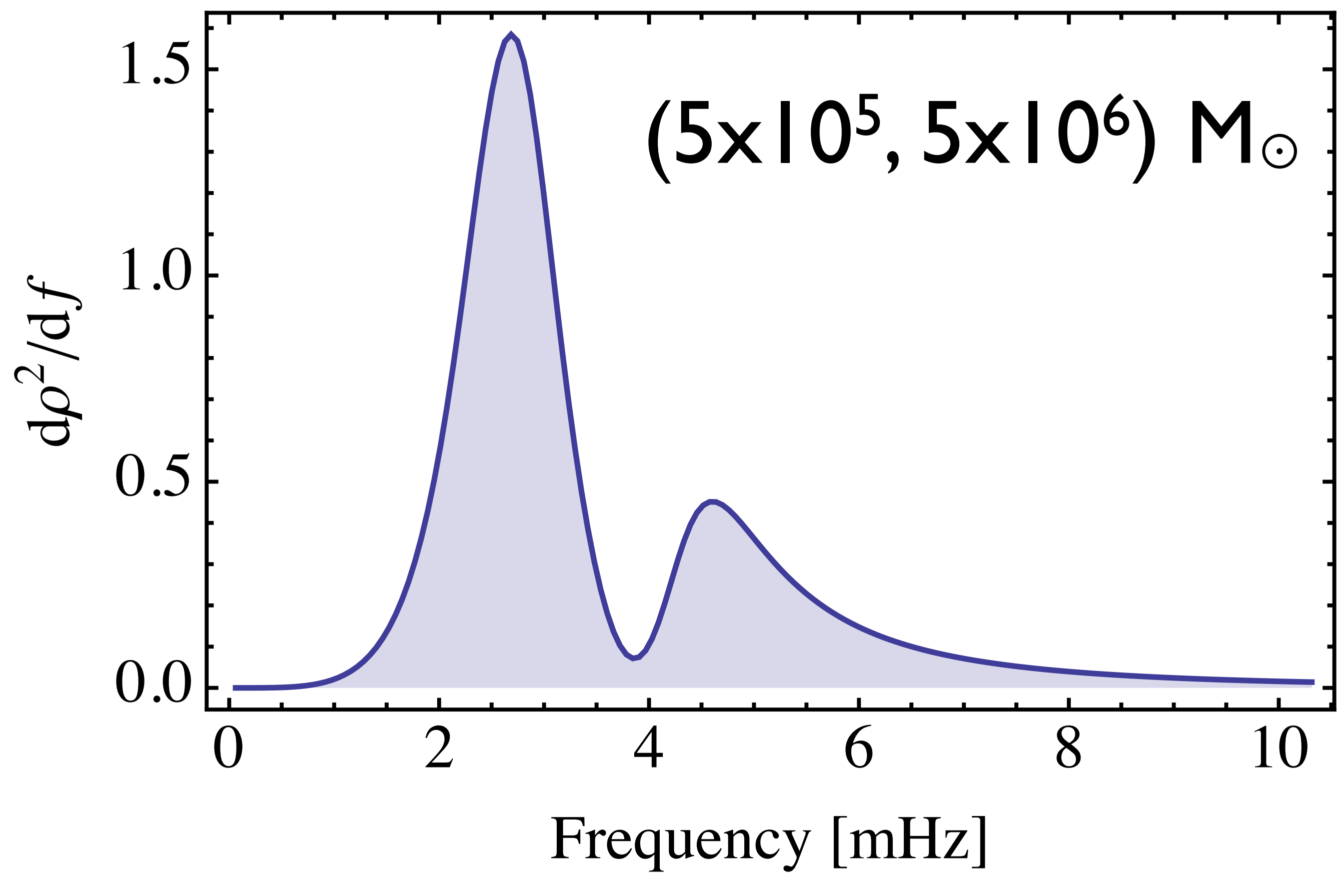
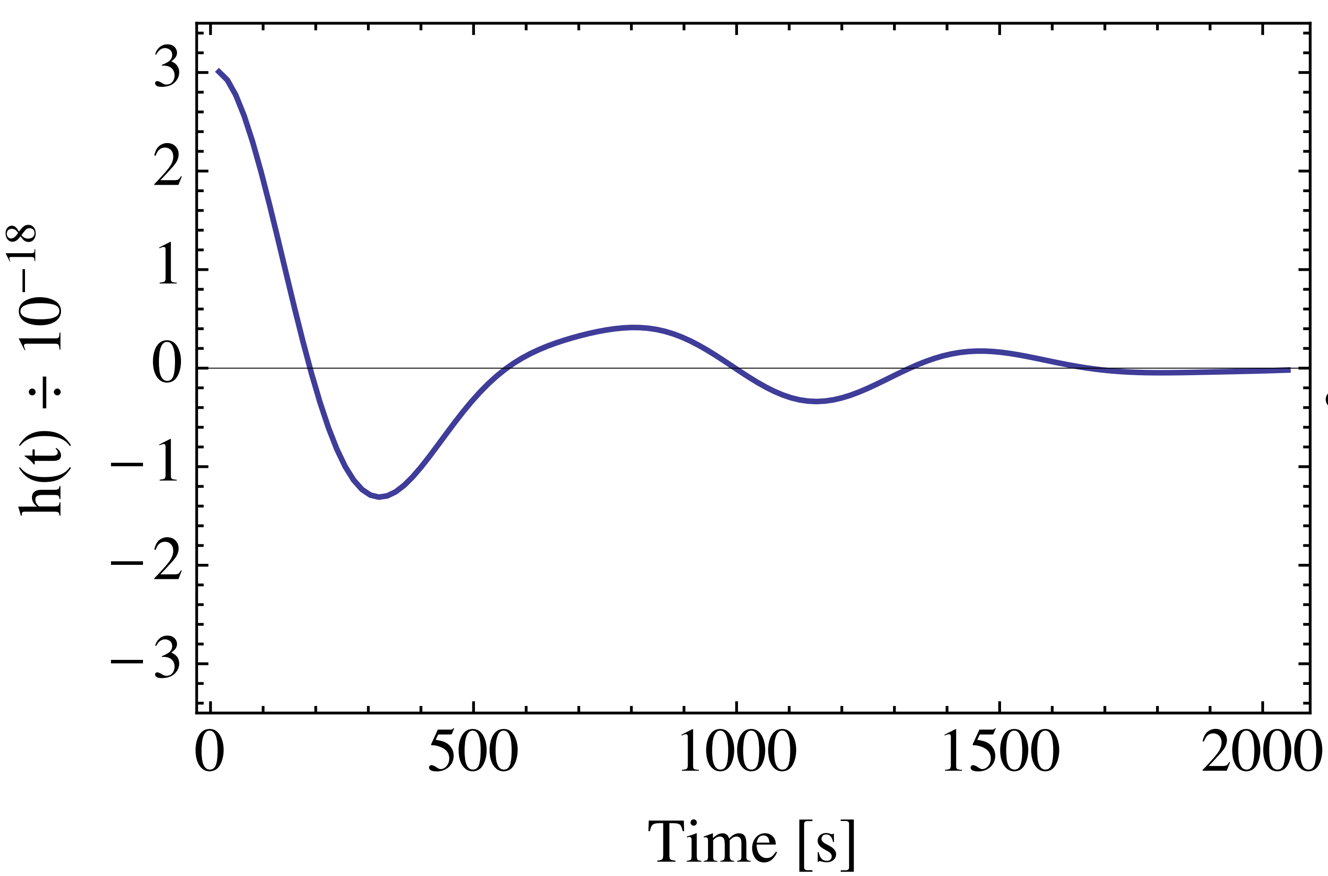
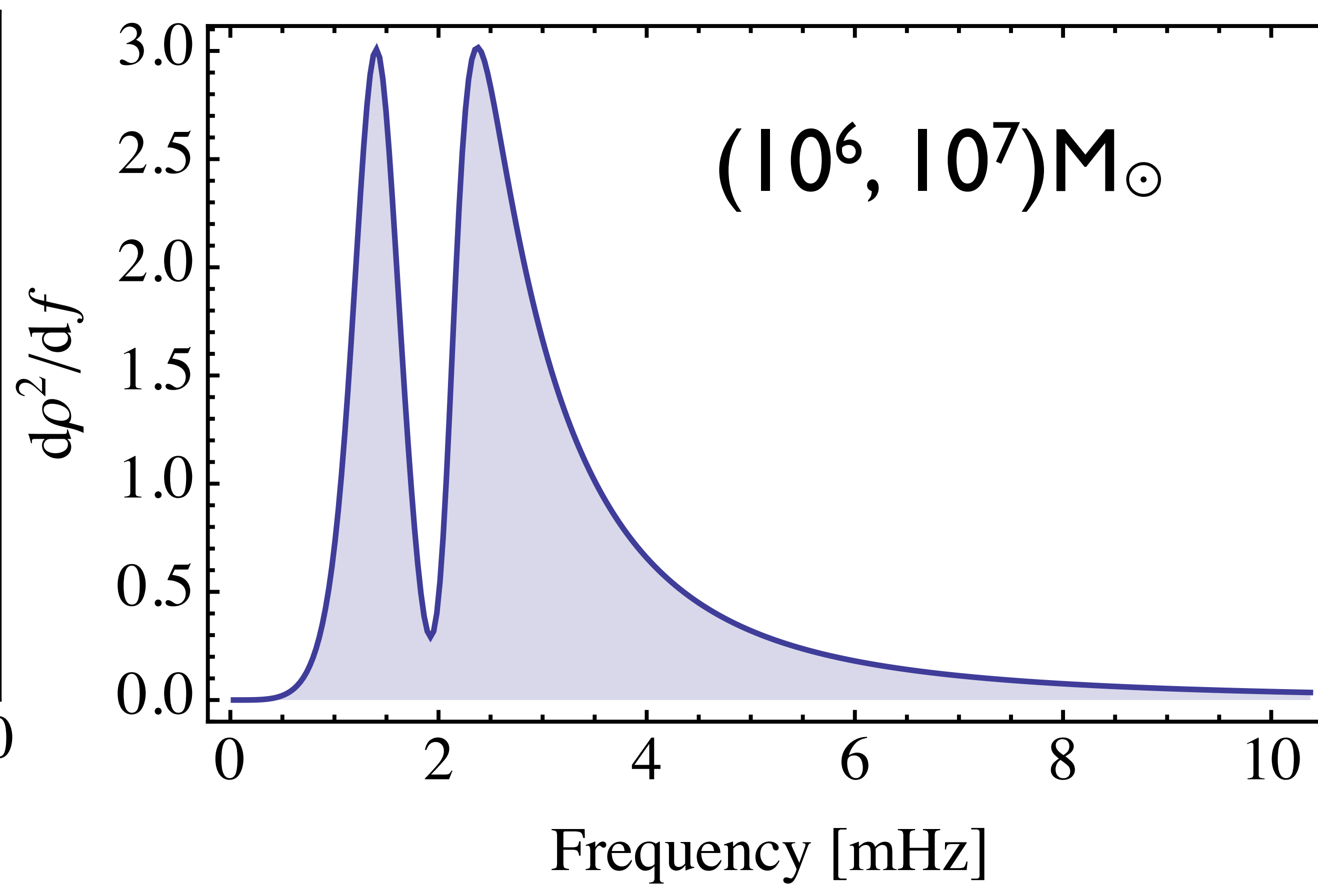
FROM RINGDOWN BACK TO INSPIRAL

QUASI-NORMAL MODES IN LISA

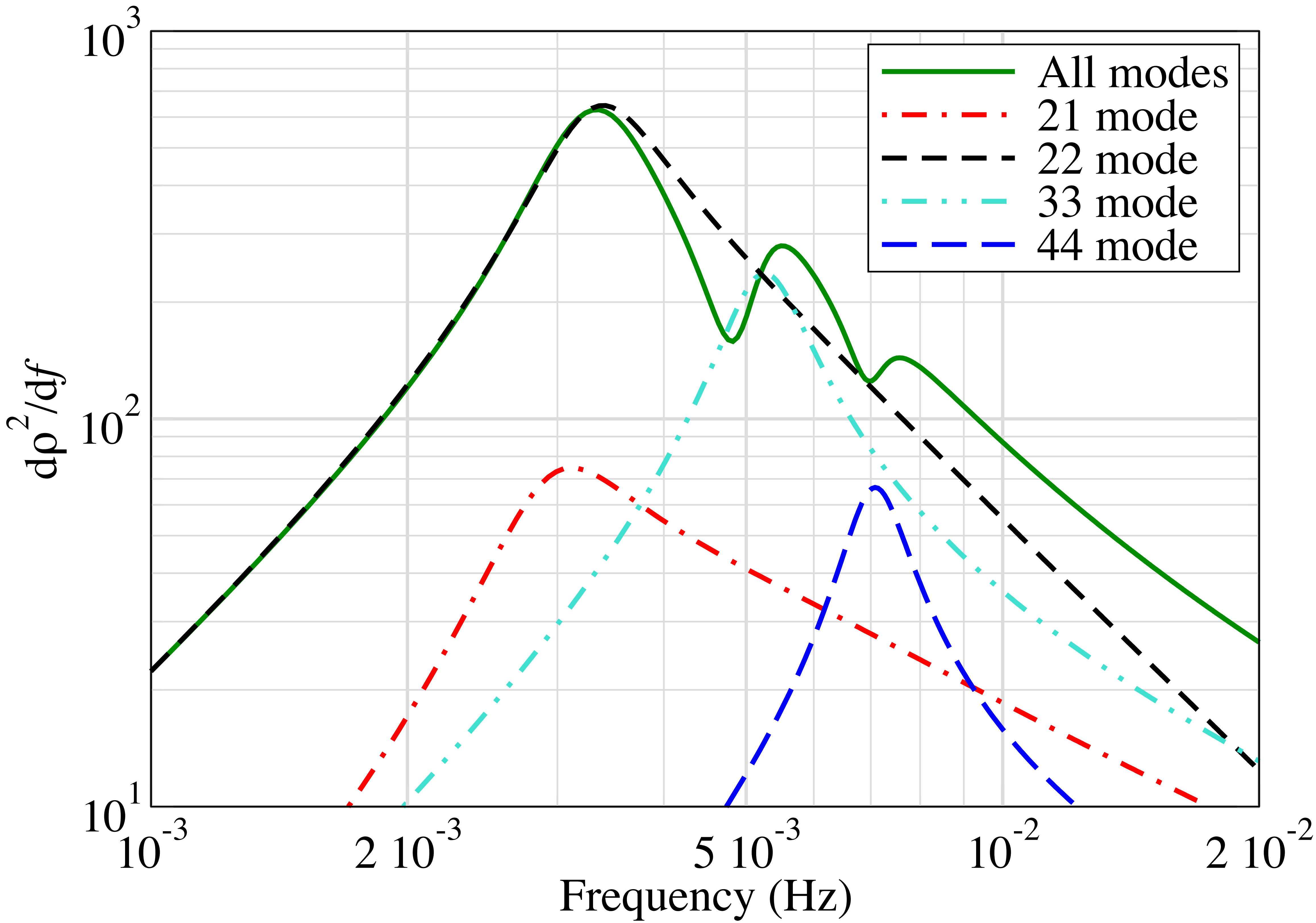
Depending on the mass of the black hole and mass ratio of the progenitor one or more modes could be visible





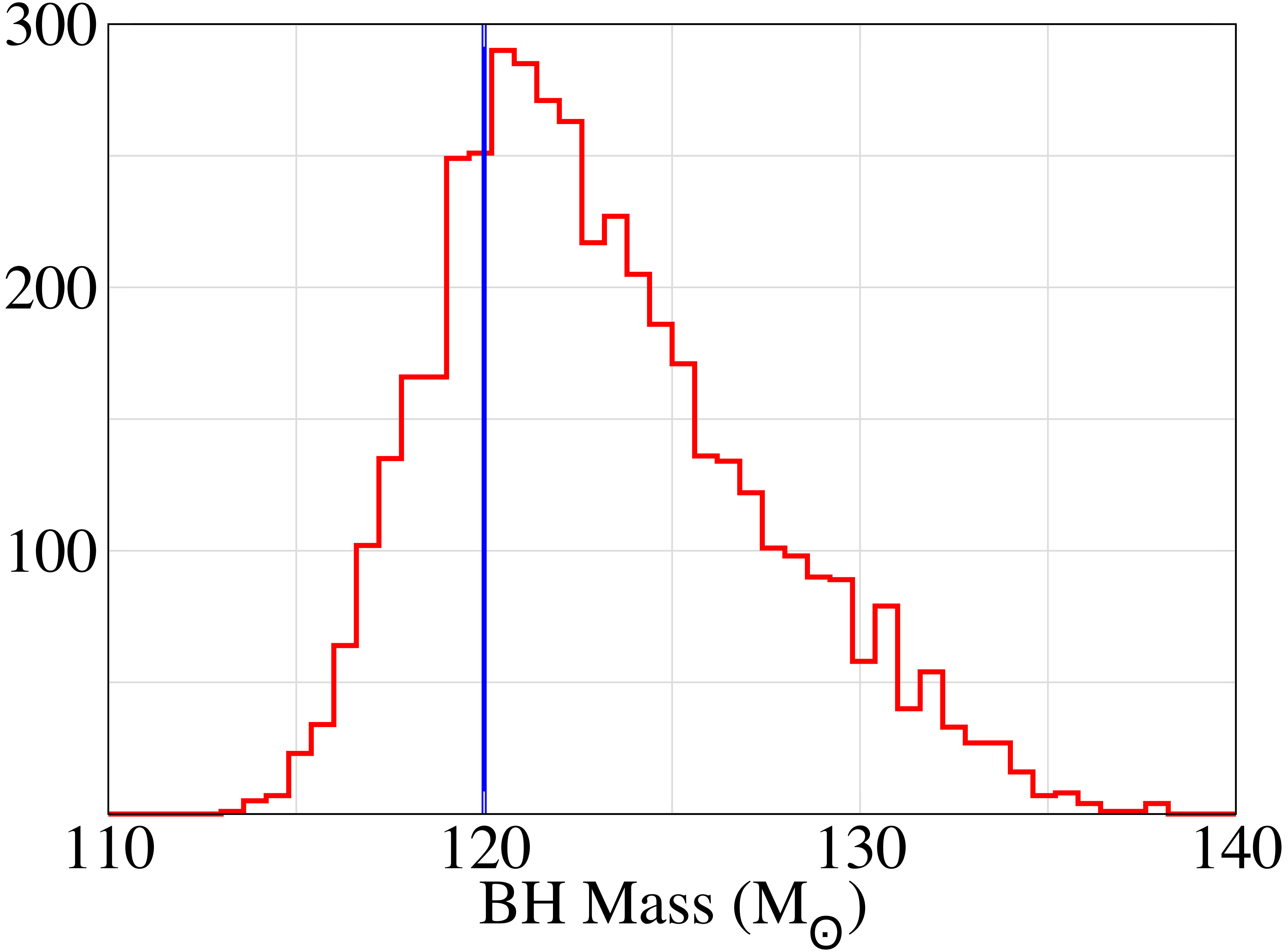


BLACK HOLE RAINBOWS

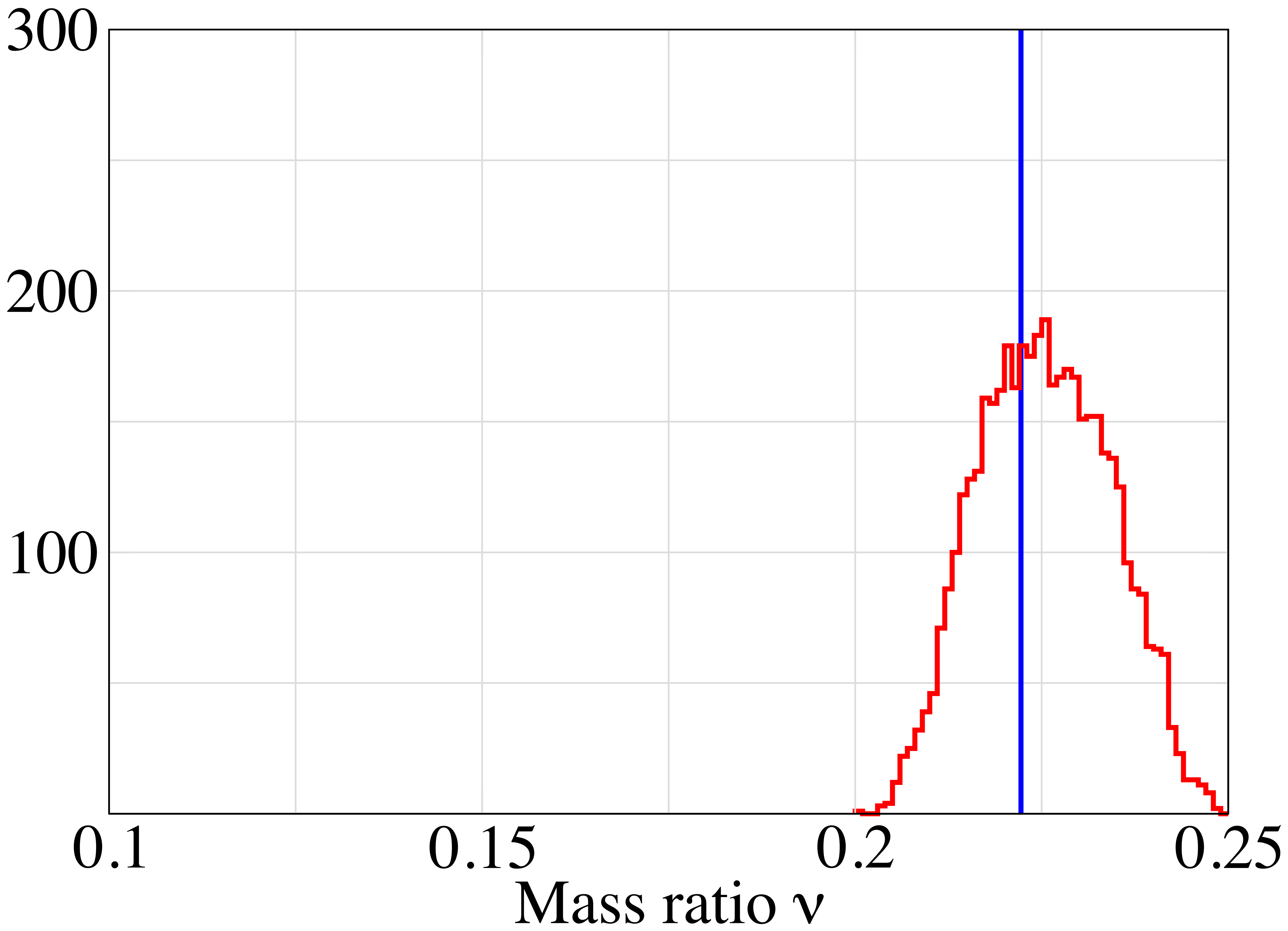


PROGENITOR BINARY PARAMETERS FROM RINGDOWNS

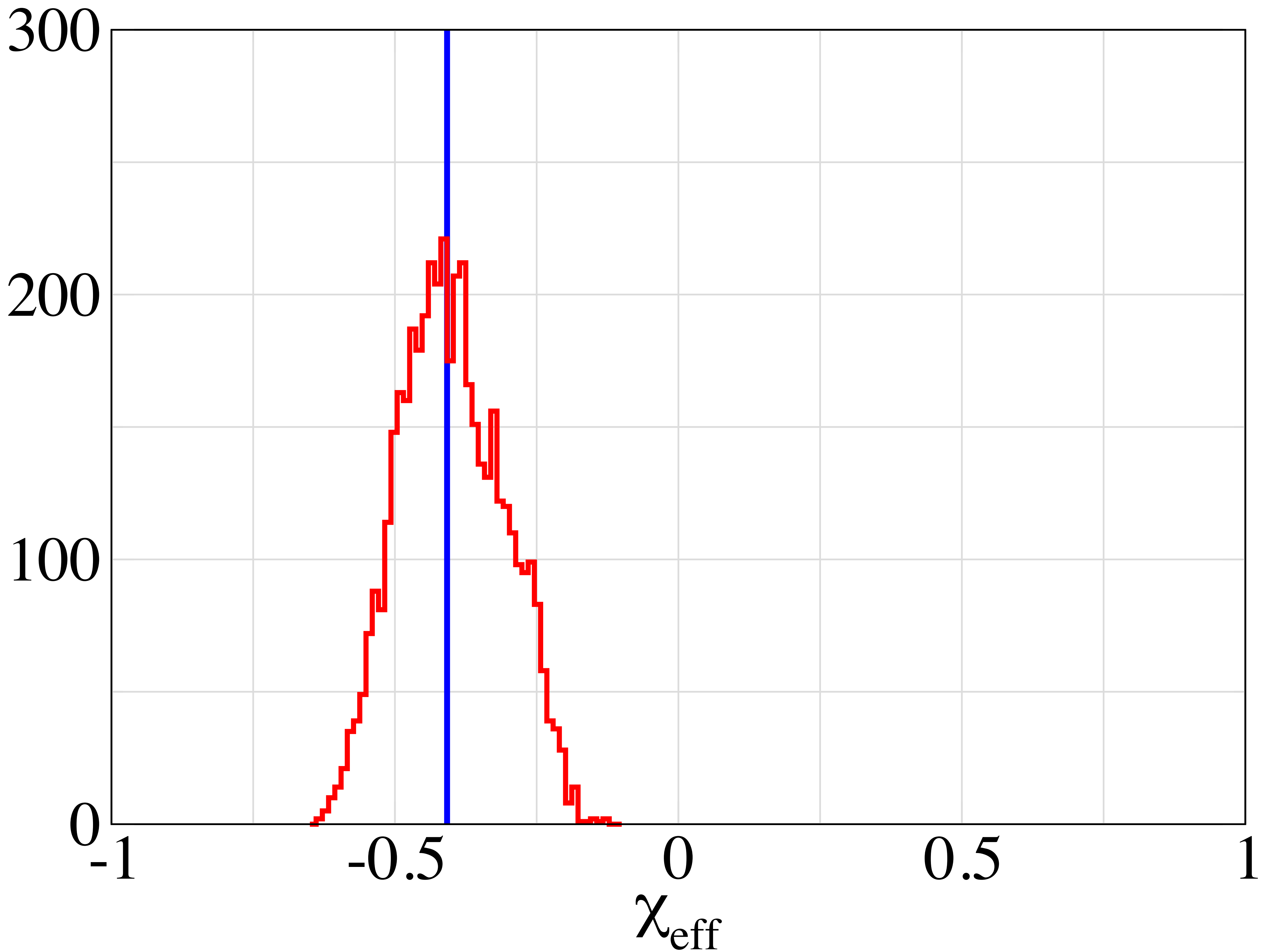
POSTERIOR DENSITY OF BINARY BLACK HOLE MASS



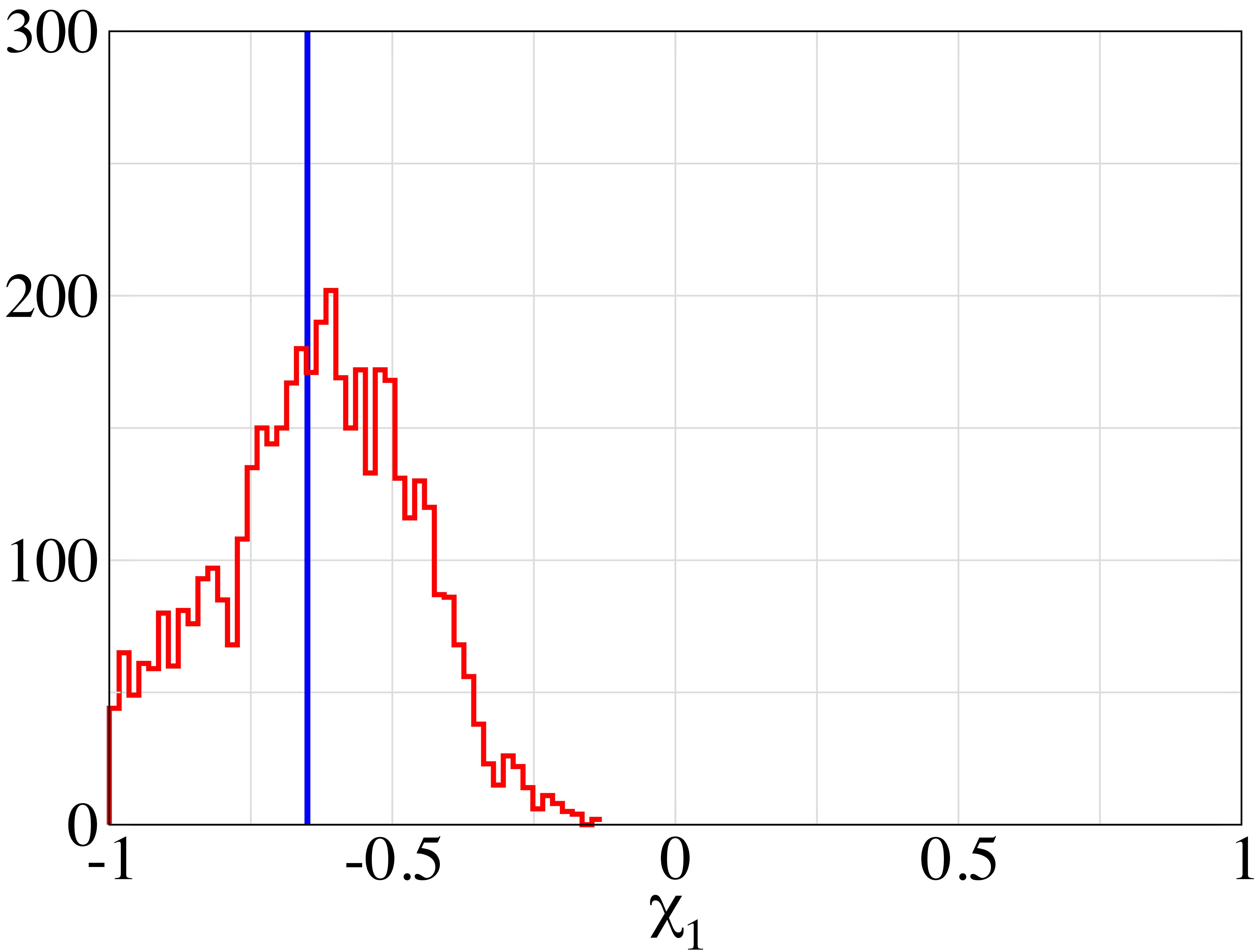
POSTERIOR PDF OF BINARY MASS RATIO



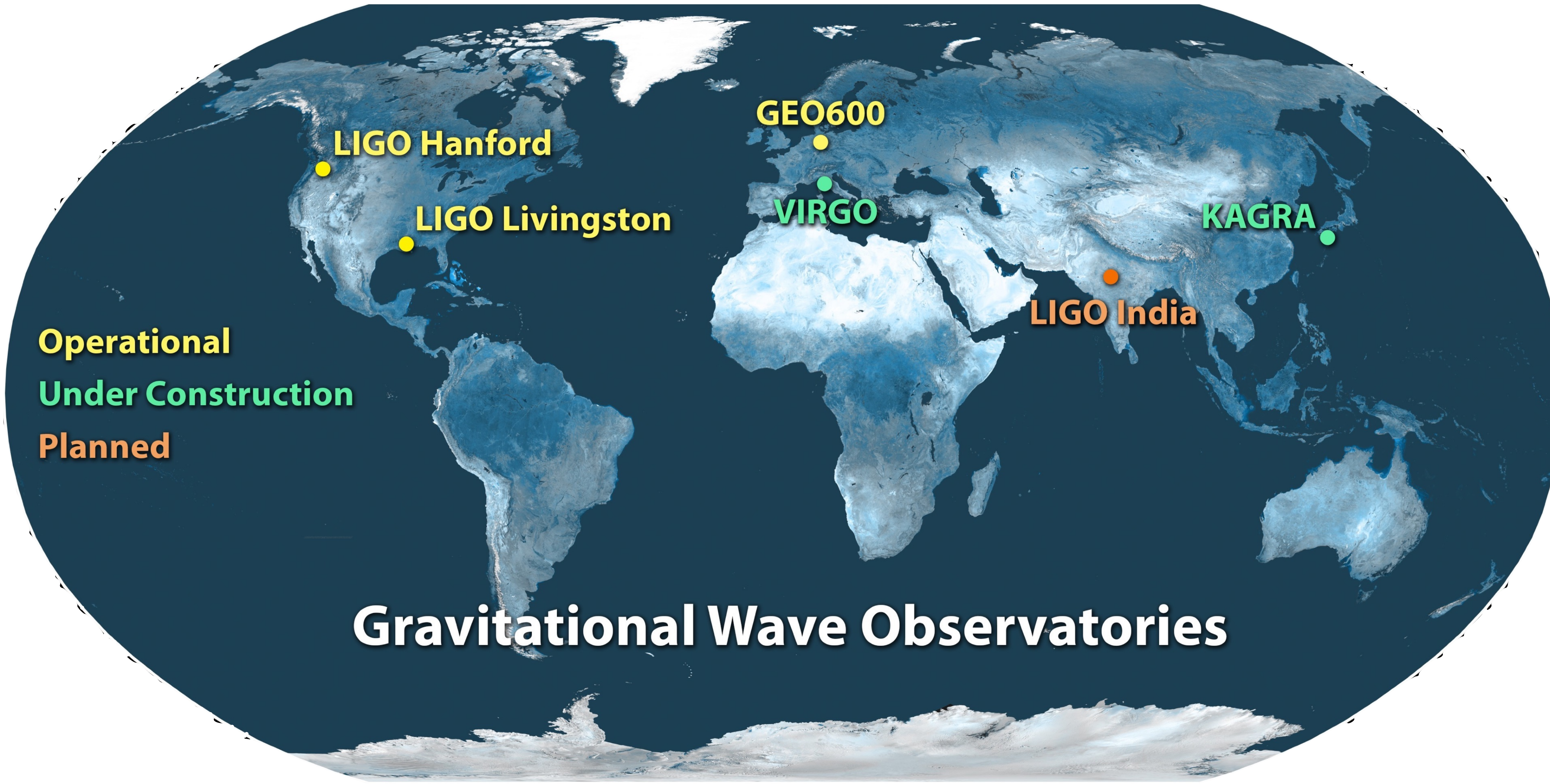
POSTERIOR PDF OF EFFECTIVE SPIN



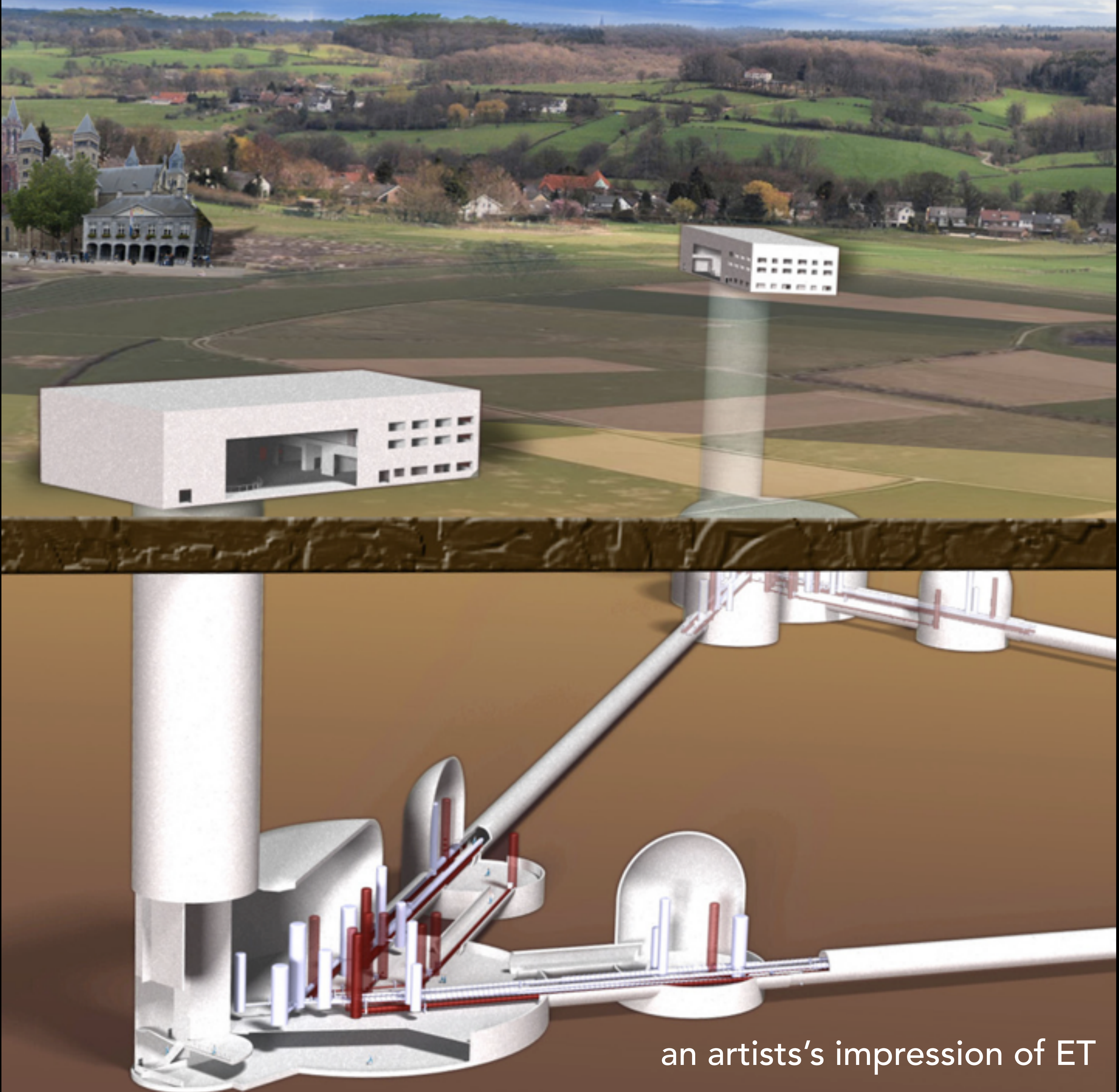
POSTERIOR PDF OF COMPONENT SPIN



A GLOBAL NETWORK OF GRAVITATIONAL WAVE DETECTORS



BEYOND ADVANCED DETECTORS



an artists's impression of ET

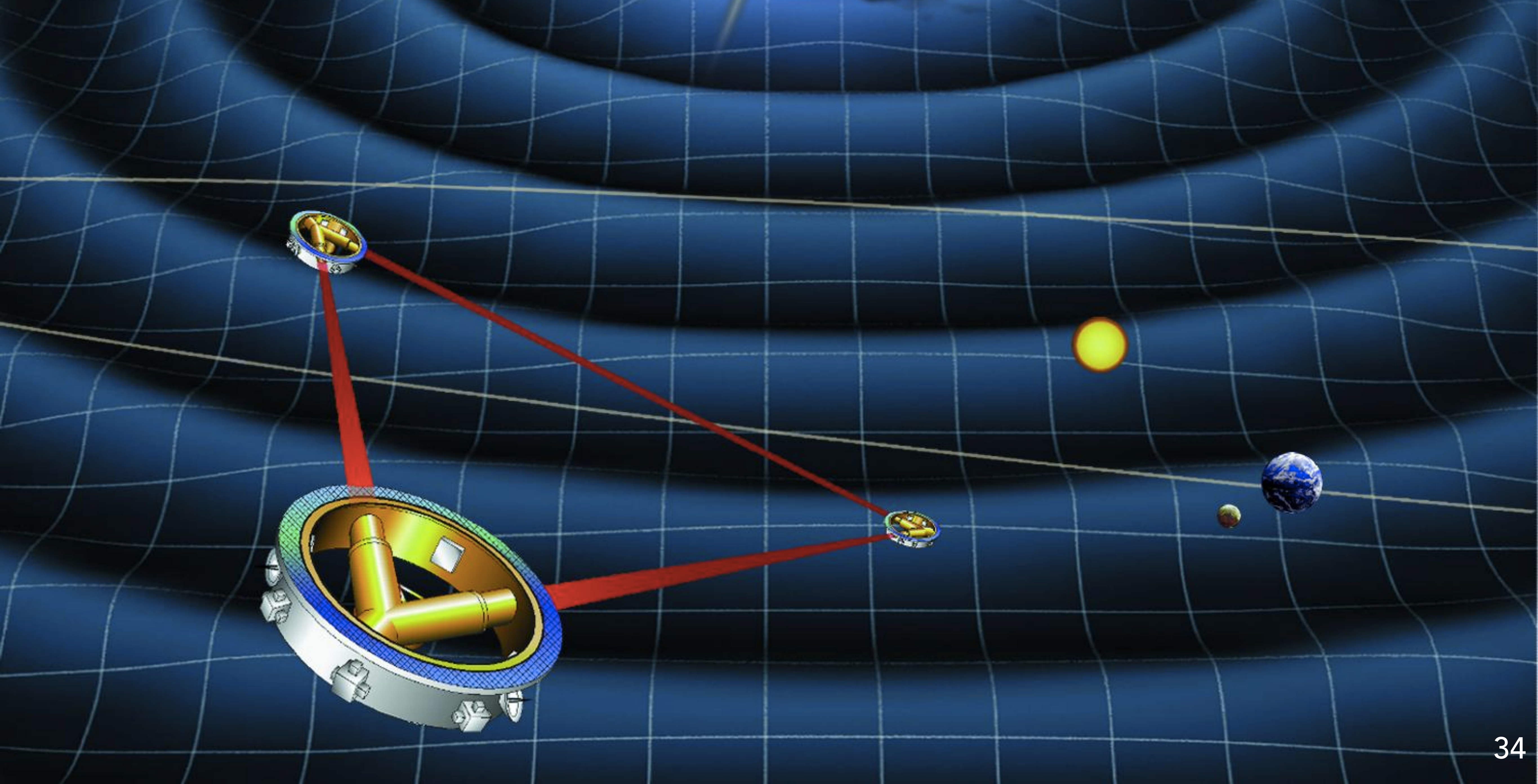
VOYAGER:
x 3 improvement in aLIGO strain sensitivity

EINSTEIN TELESCOPE:
Triangular, 10 km arm length, underground, cryogenic detectors

COSMIC EXPLORER:
40 km arm length, cryogenic, overground interferometer

LASER INTERFEROMETER SPACE ANTENNA (LISA)

- L-class ESA mission selected for launch in 2034



PATH TO TESTING THE NO-HAIR THEOREM

Detector	GW150914 SNR	QNM SNR
O1	25	7
Advanced LIGO	80	20
LIGO-India ALIGO+ (2024)	250	80
ET (2030)	800	200
Cosmic Explorer (2034)	2400	800
LISA (2034)	10,000	2,400

BLACK HOLE KEYBOARD

- A musical keyboard based on quasi-normal modes
  - developed by Daniel George and Chad Hanna at Penn State
  - each key corresponds to black hole of a specific mass and spin
- On going effort to compose music with this new keyboard