SCIENCE CASE FOR FUTURE GRAVITATIONAL WAVE DETECTORS

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CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

OVERVIEW

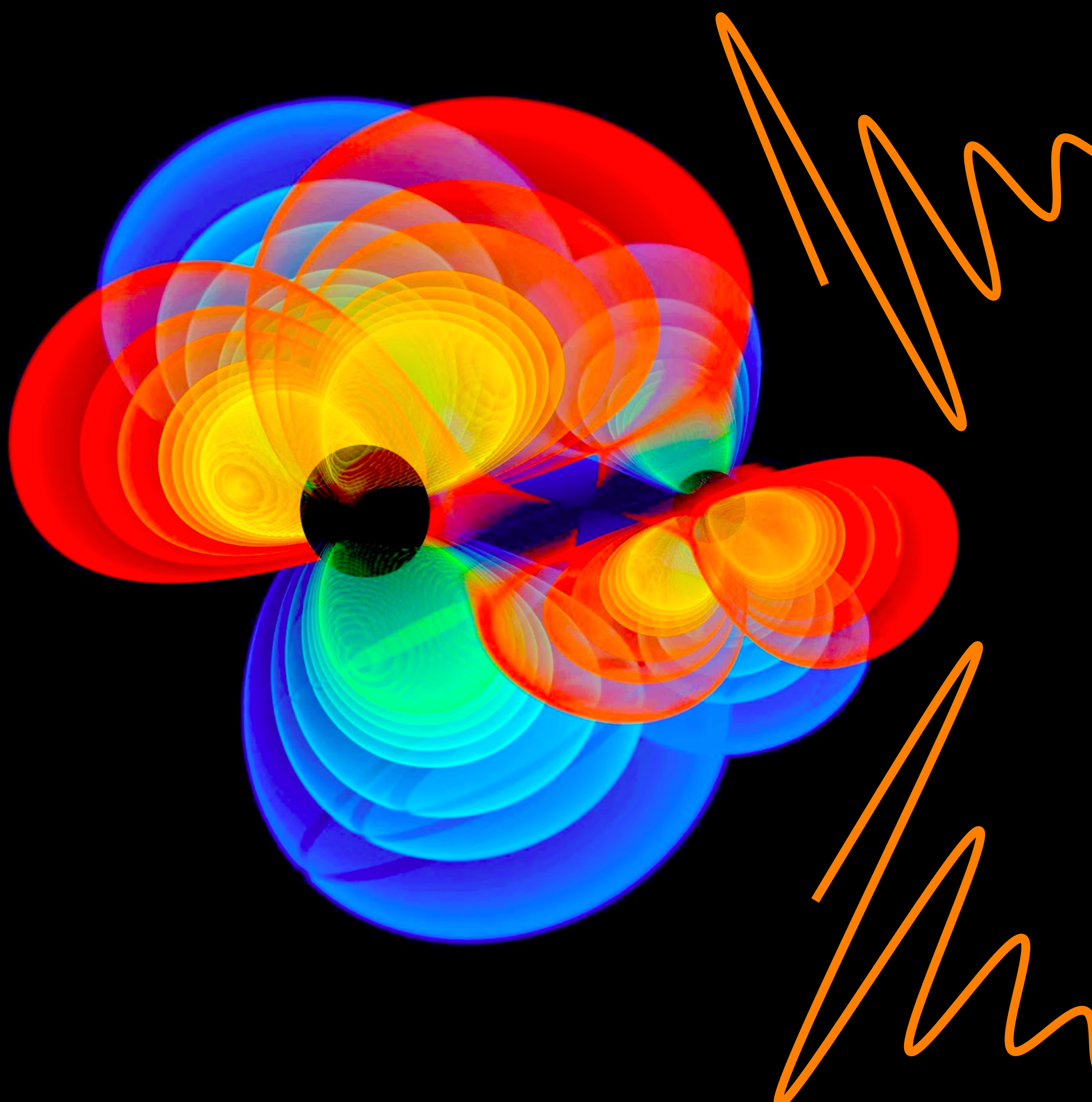
- First discovery:
  - what didn't we observe?
- 2G, 2G+ detector network
  - What can we expect advanced detectors to have accomplished by ~2025?
- 3G science beyond 2025+
  - what will be the most compelling problems in 2025?

GW150914: UNFINISHED STORY

- Long adiabatic inspiral
- Higher-order multipoles beyond quadrupole radiation
- Extremal black hole spins
- Spin-induced precession and frame dragging
- EM counterpart
- Late time quasi-normal modes

(LATE TIME) QUASI-NORMAL MODES

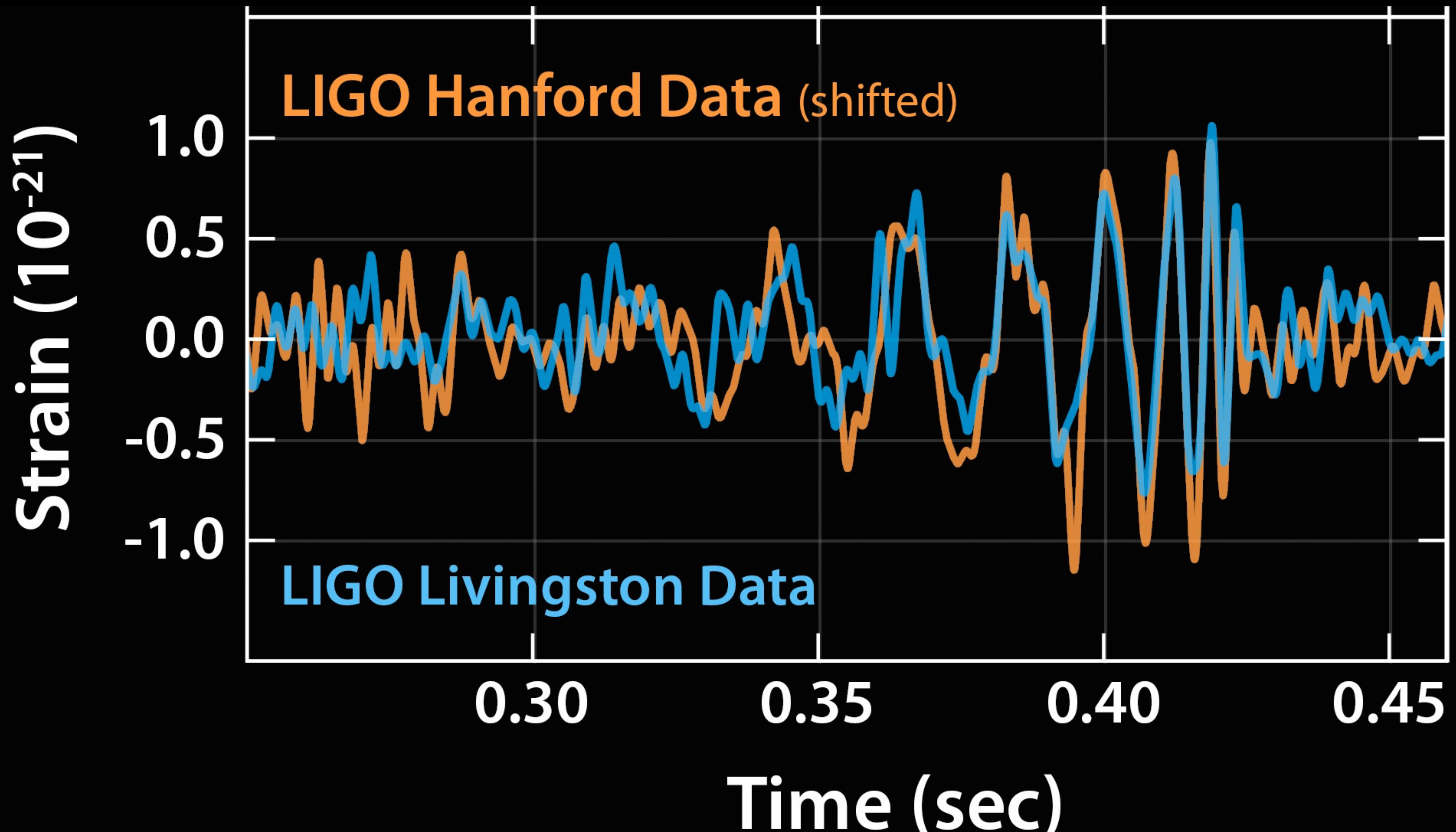
TESTING NO-HAIR THEOREM



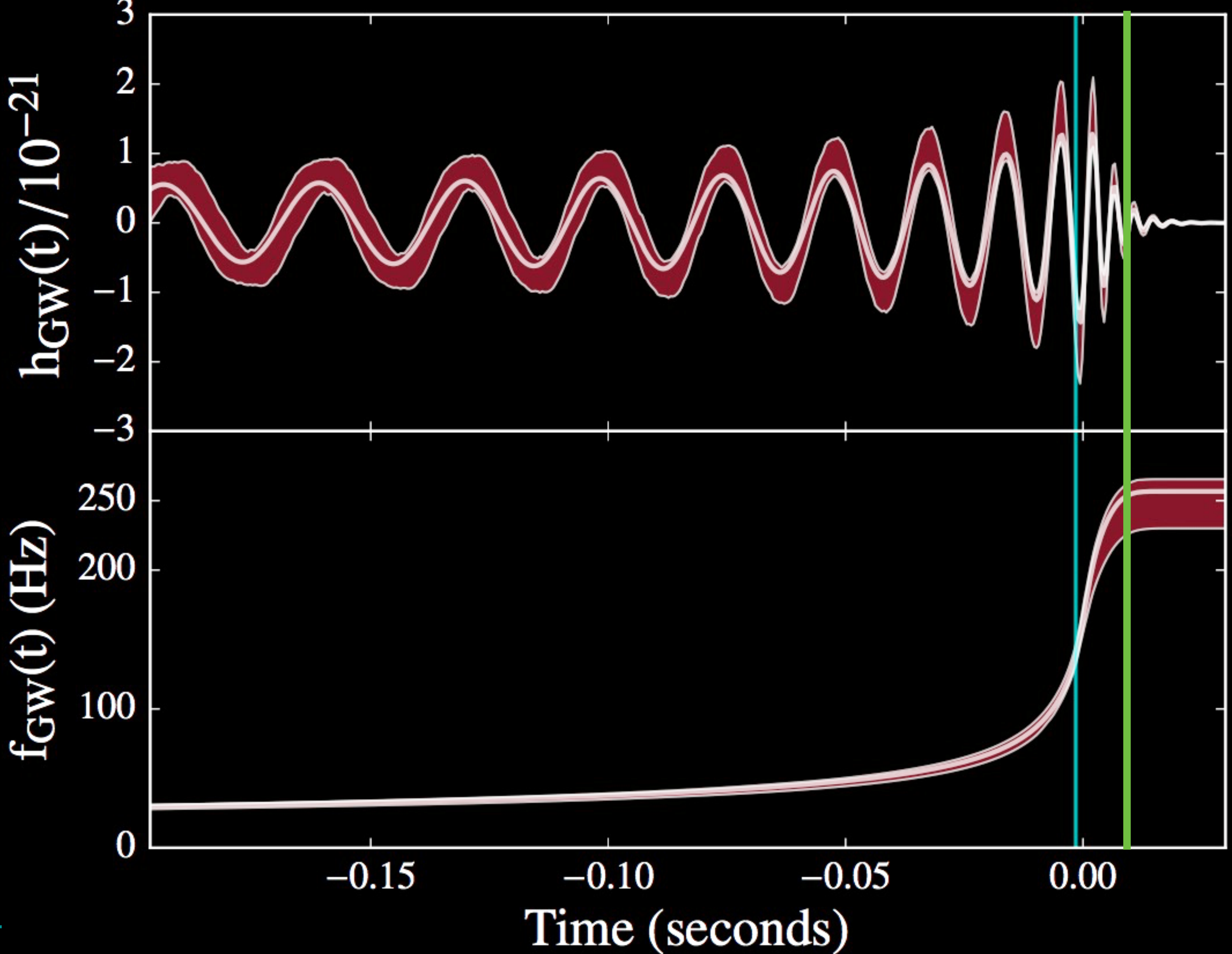
- Deformed black holes emit quasi-normal modes
  - complex frequencies depend only on the mass and spin
- Measuring two or modes would provide a smoking gun evidence of black holes
  - If modes depend on other parameters, consistency between different mode frequencies would fail

Dreyer+ 2004, Berti+ 2006, Berti+ 2007, Kamaretsos+ 2012, Gossan+2012

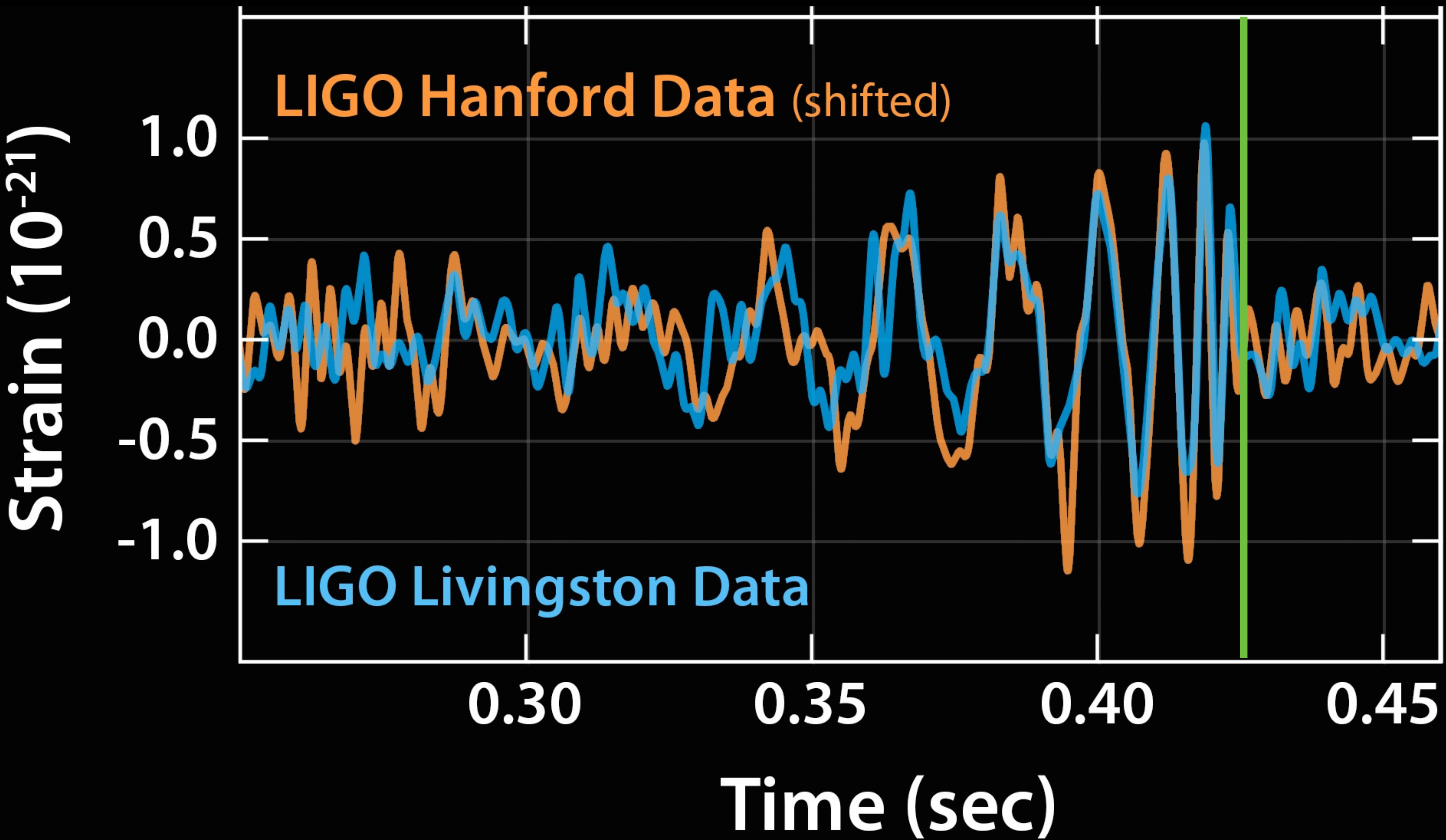
WHAT DID WE OBSERVE?



WHEN DO QNM BEGIN?



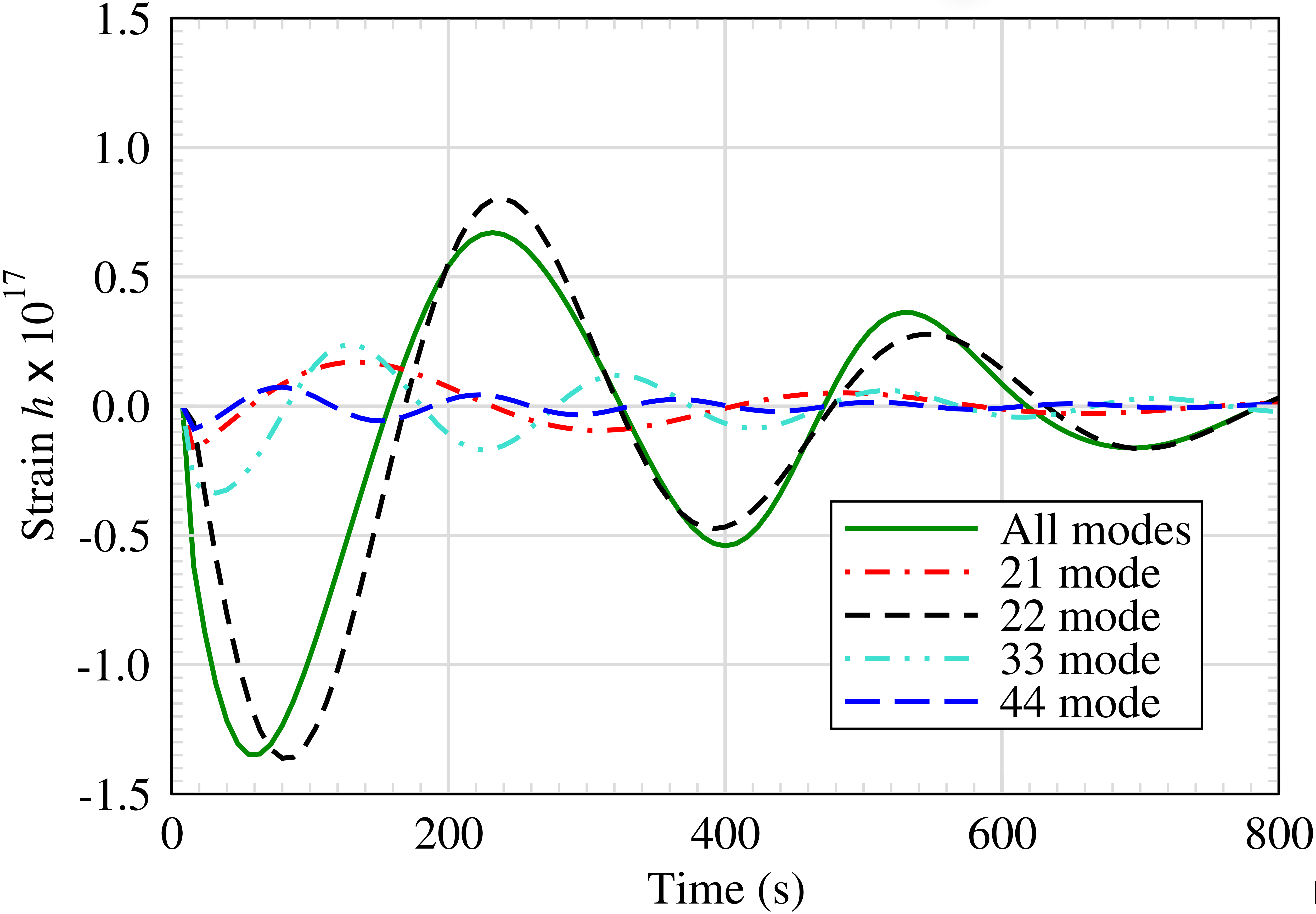
SO, DO WE SEE QNM?



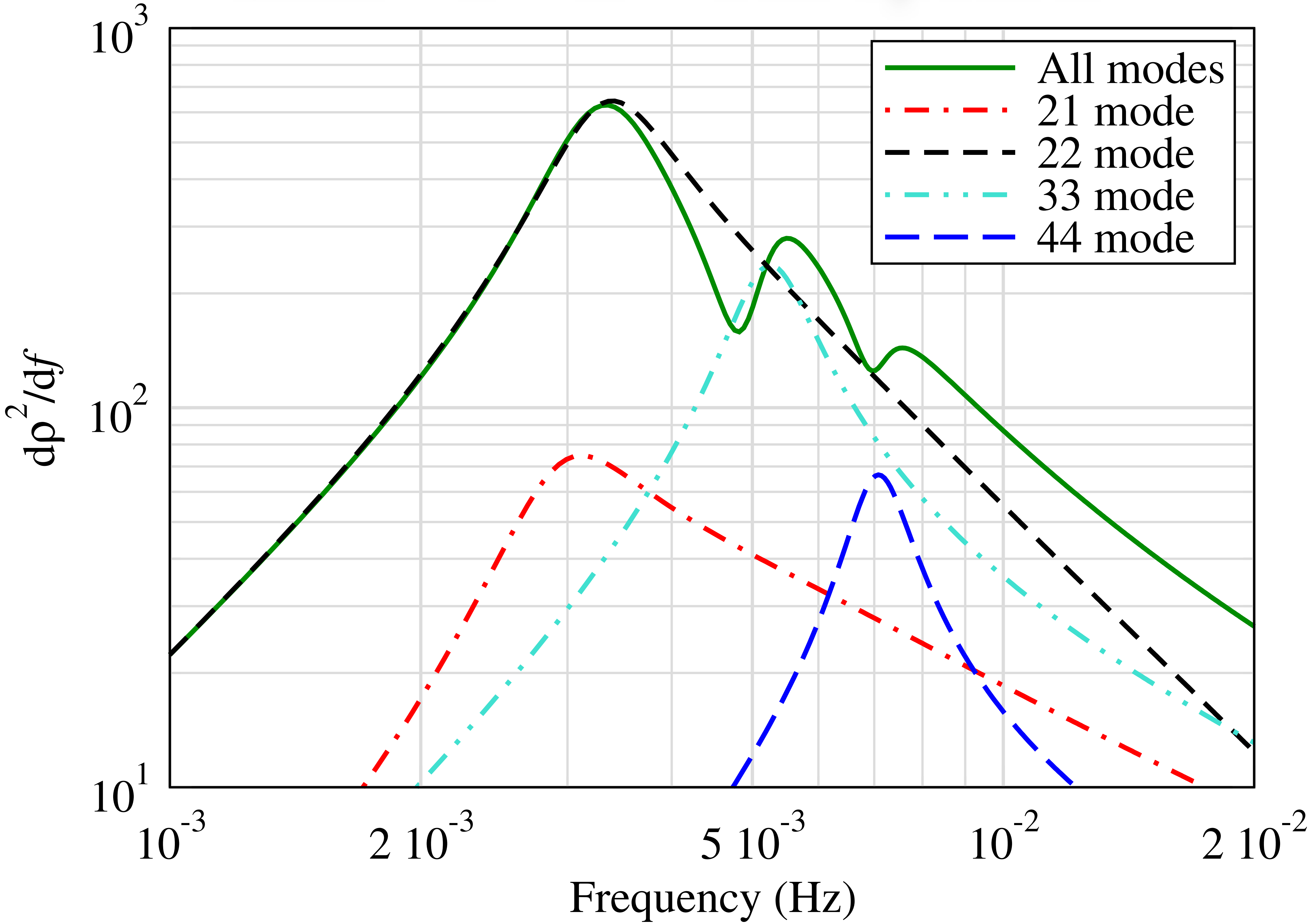
WHY ARE QNM IMPORTANT?

- QNM are the true test of whether the final remnant is a black hole
  - If not a black hole QNM 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

QNM Time-Domain Signal



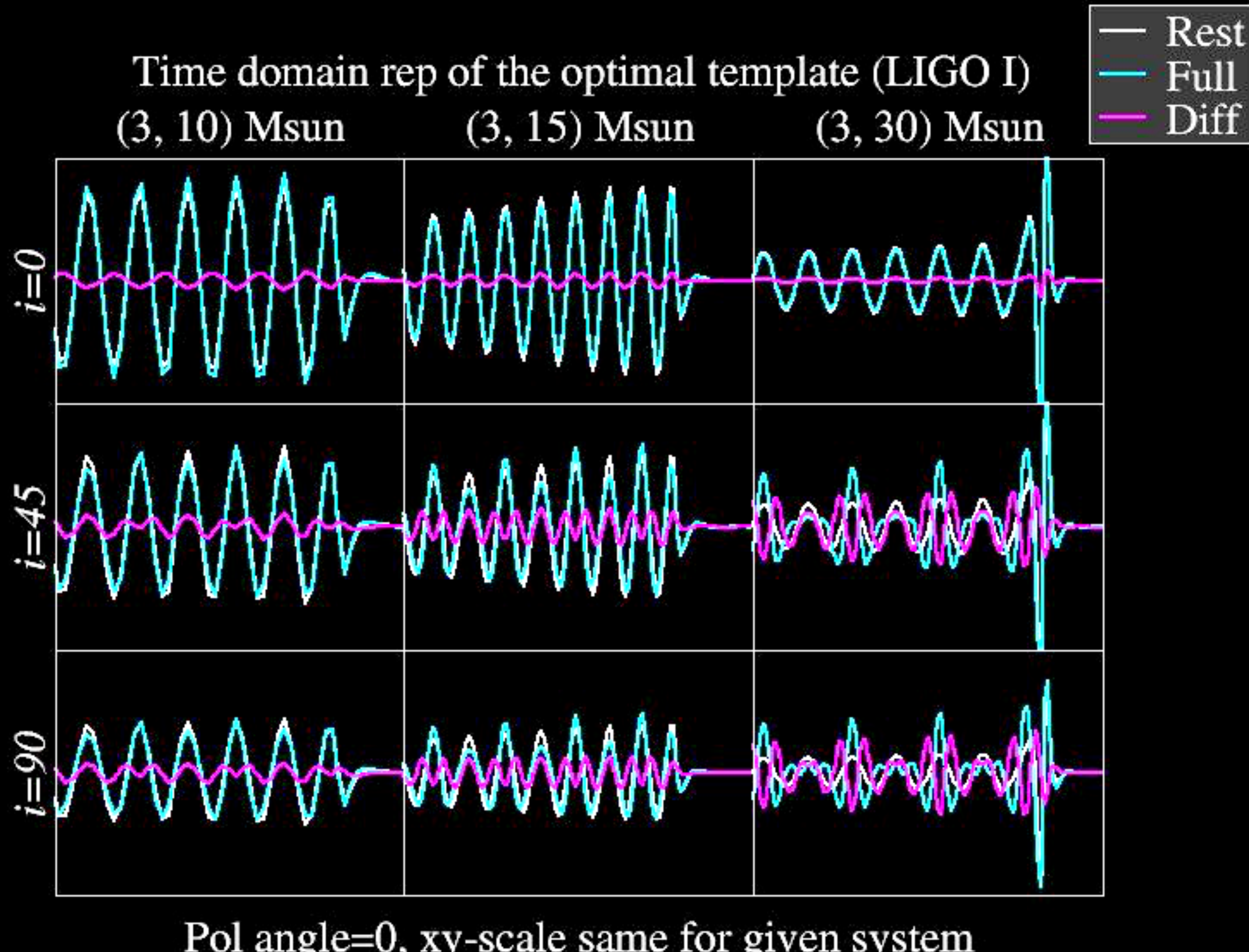
Quasi-normal mode Spectrum



HIGHER ORDER MODES

$$h_+ - ih_\times = \sum {}_{-2}Y_{\ell m} h_{\ell m}$$

BINARY BLACK HOLE SPECTROSCOPY



WHY HIGHER MODES?

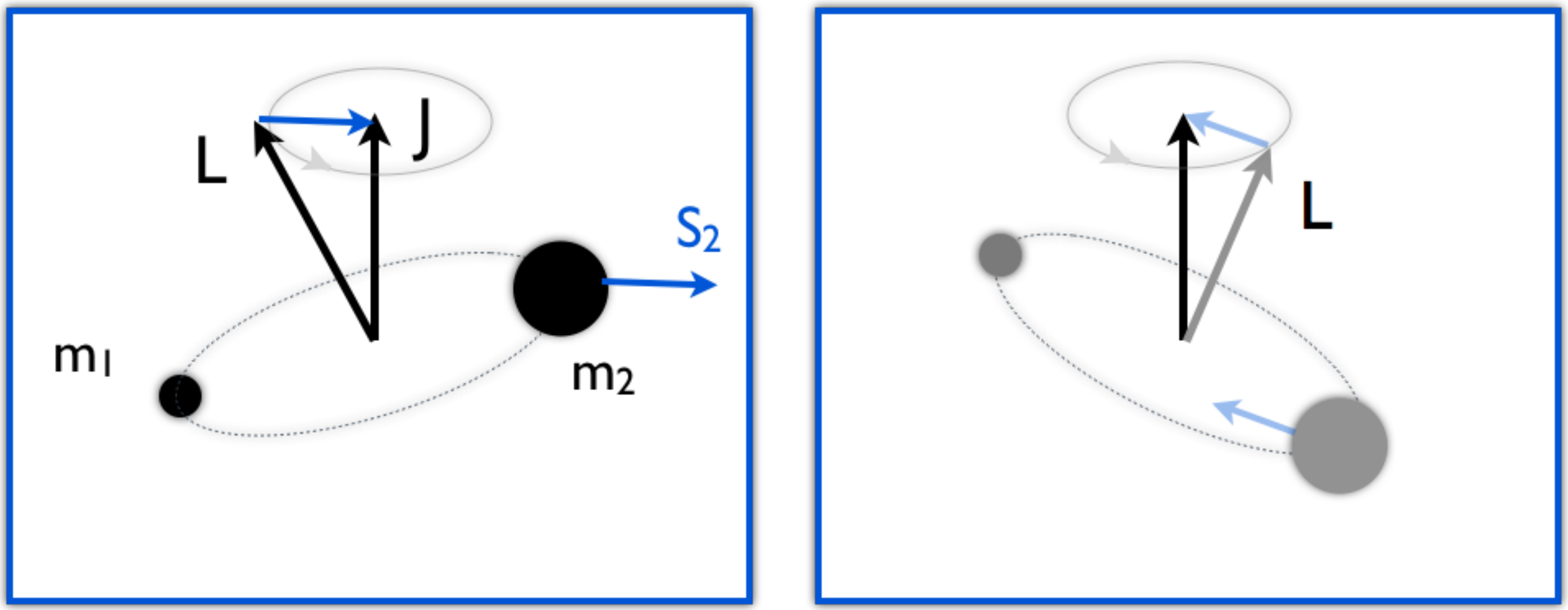
- Higher modes potentially contain more physics and more information about the dynamics
- They break certain parameter degeneracies
- They help in better localisation of the source

EXTREMAL BLACK HOLE SPINS

- Some astronomical candidates seem to suggest black hole spins could be the maximum spin allowed by the Kerr solution
- Remnant spin is no where near that extremum
- It would be interesting to observe black hole binaries with large spins

SPIN-INDUCED PRECESSION

SPIN-ORBIT COUPLING

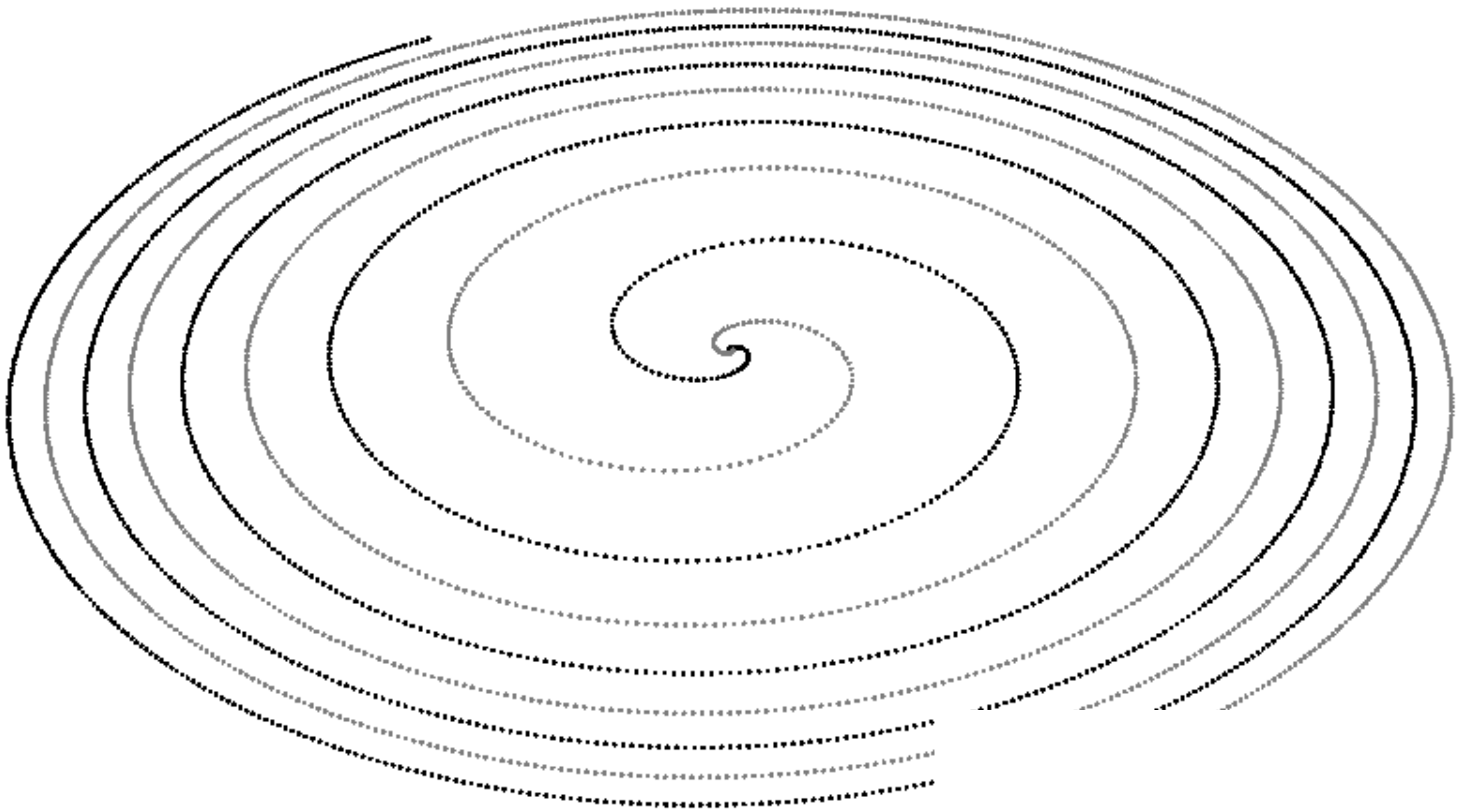


General relativity

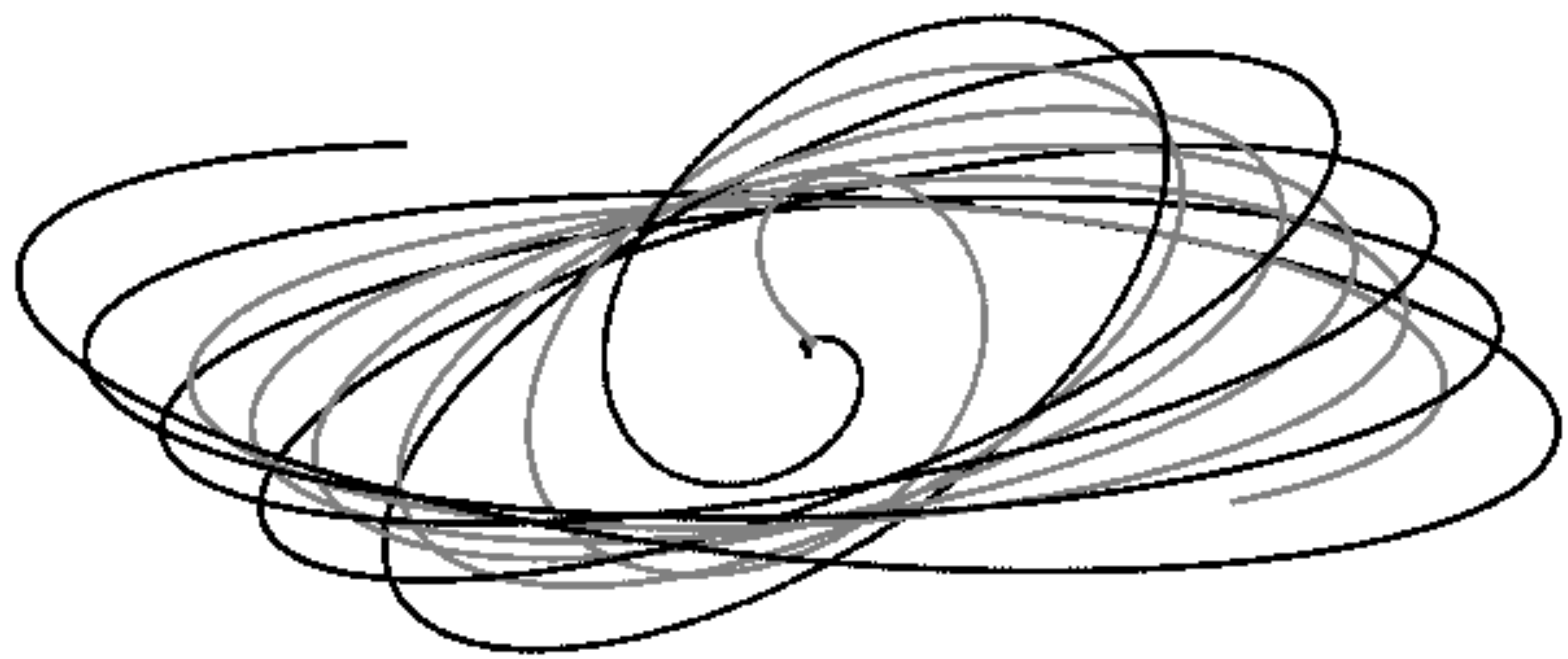
(L, S_1, S_2) precess around J

Credit:Mark Hannam

ORBITAL PRECESSION



Equal-mass, non-spinning BBH consistent with GW150914



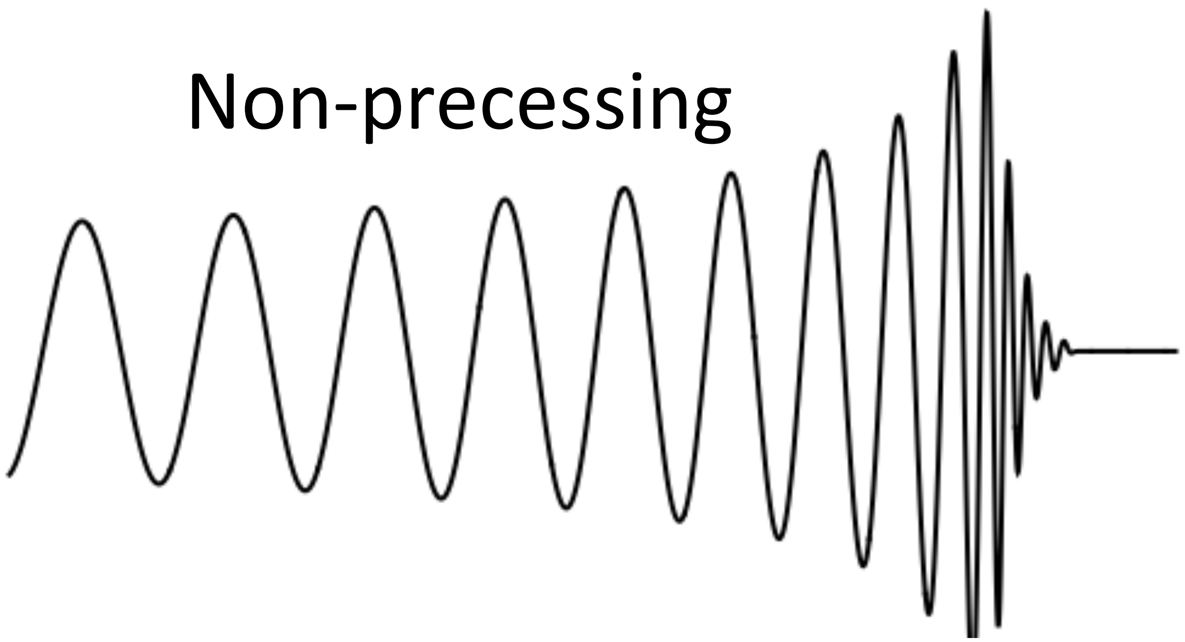
Unequal-mass, precessing BBH consistent with GW150914

Credit:Mark Hannam

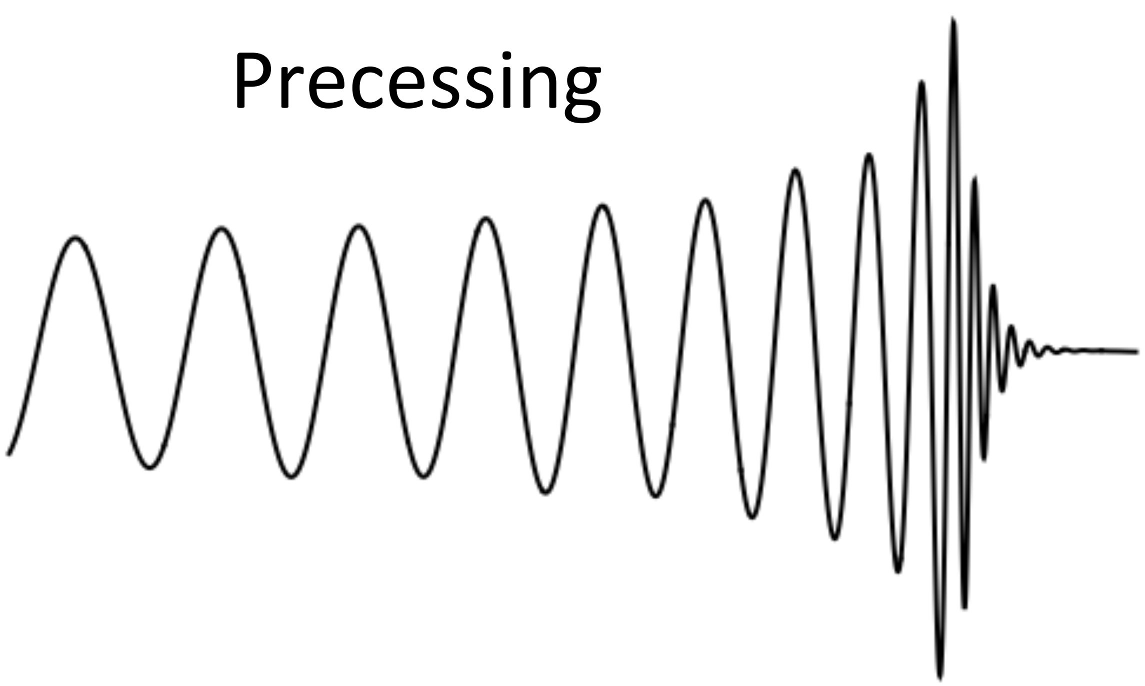
SIGNATURE OF PRECESSION

“Face-on” to the source

Non-precessing

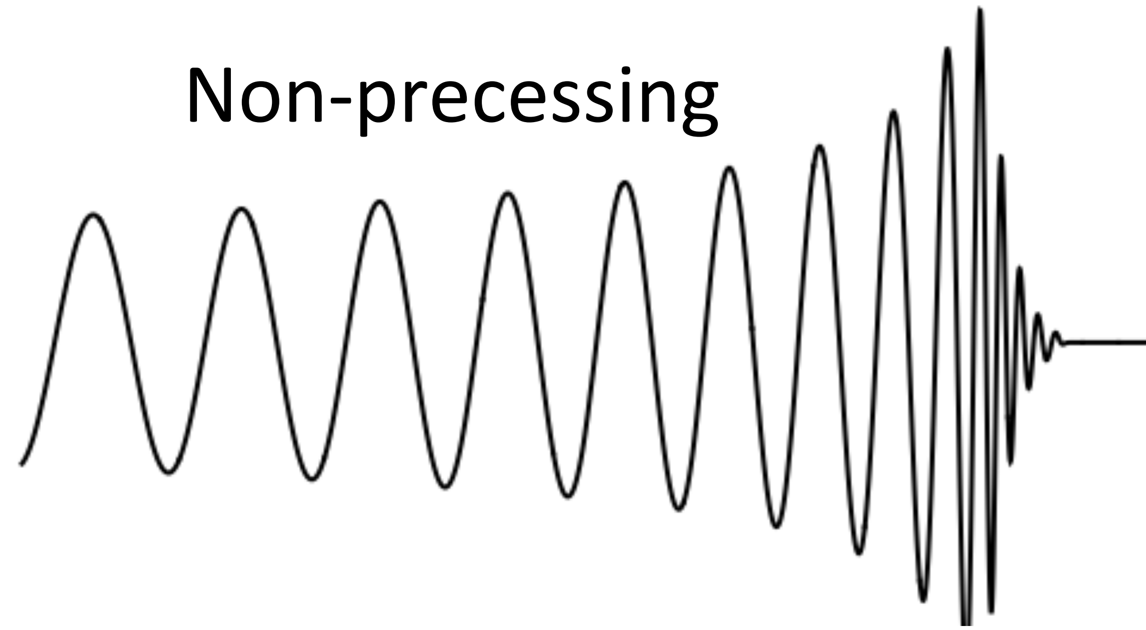


Precessing

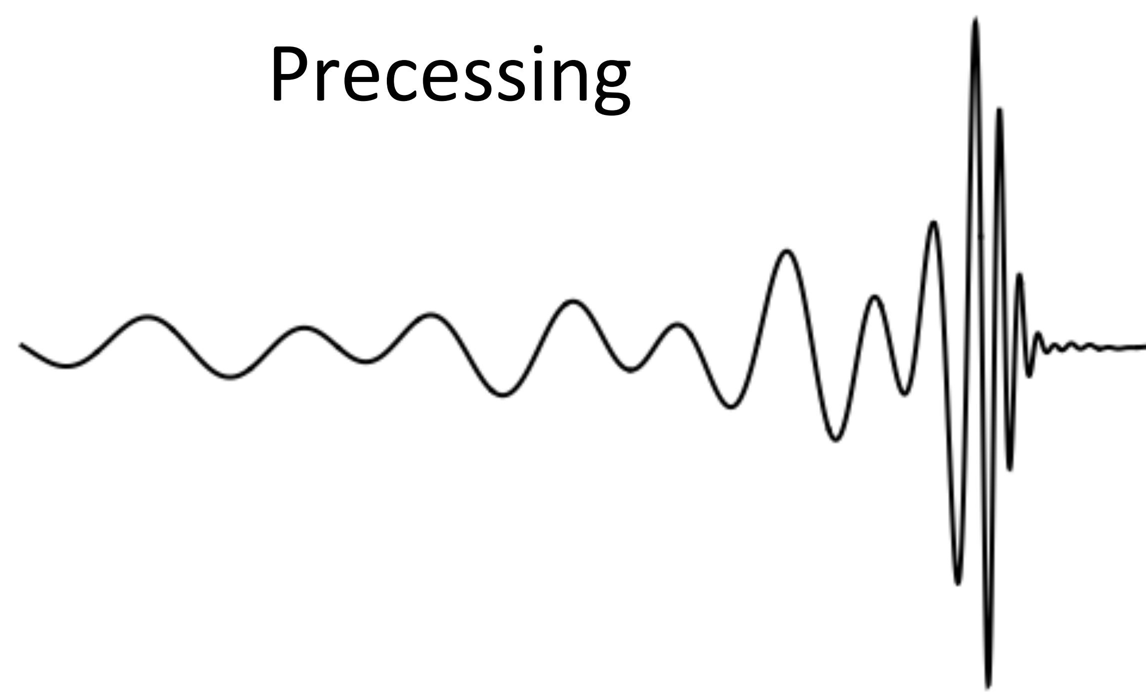


“Edge-on” to the source

Non-precessing



Precessing



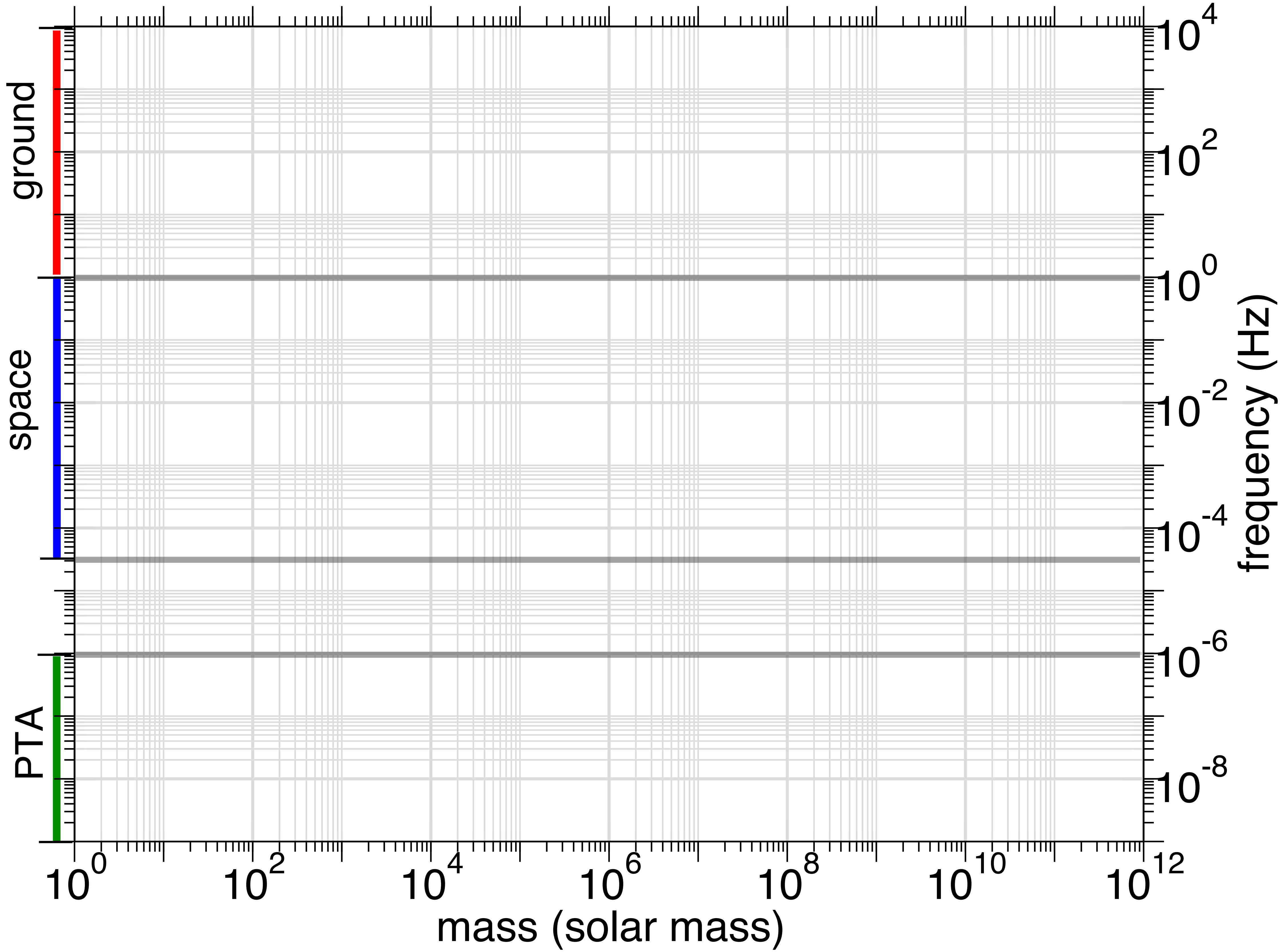
Credit:Mark Hannam

EM COUNTERPARTS

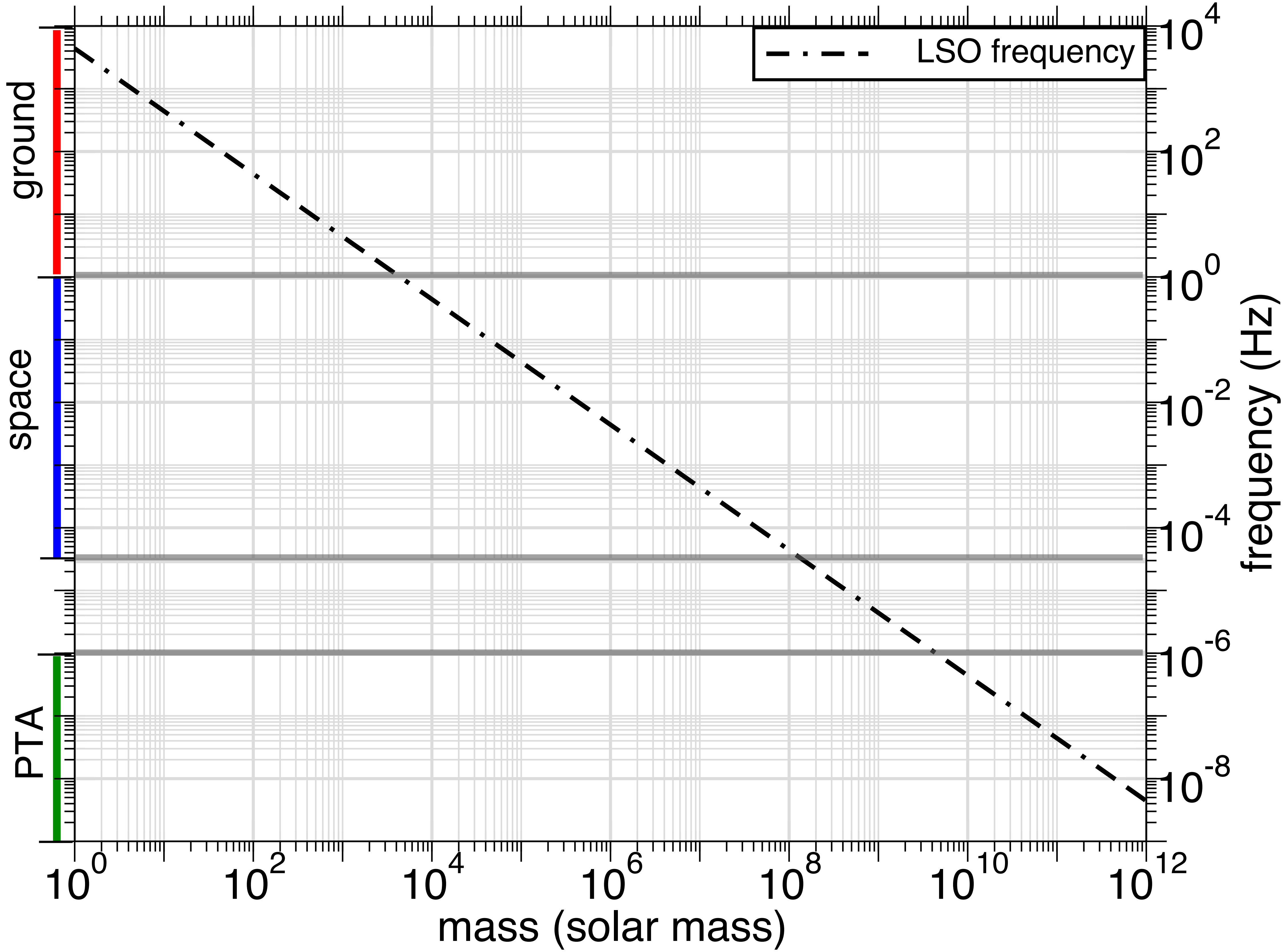
- Black hole binary mergers are not expected to result in any EM afterglow unless …
  - intriguing (if opportunistic) triggers in Fermi sub-threshold data
  - unconfirmed by Integral
- Observing EM afterglows could be a huge paradigm shift in understanding formation and evolution of BBH

EXPLORING BLACK HOLES USING GRAVITATIONAL WAVES

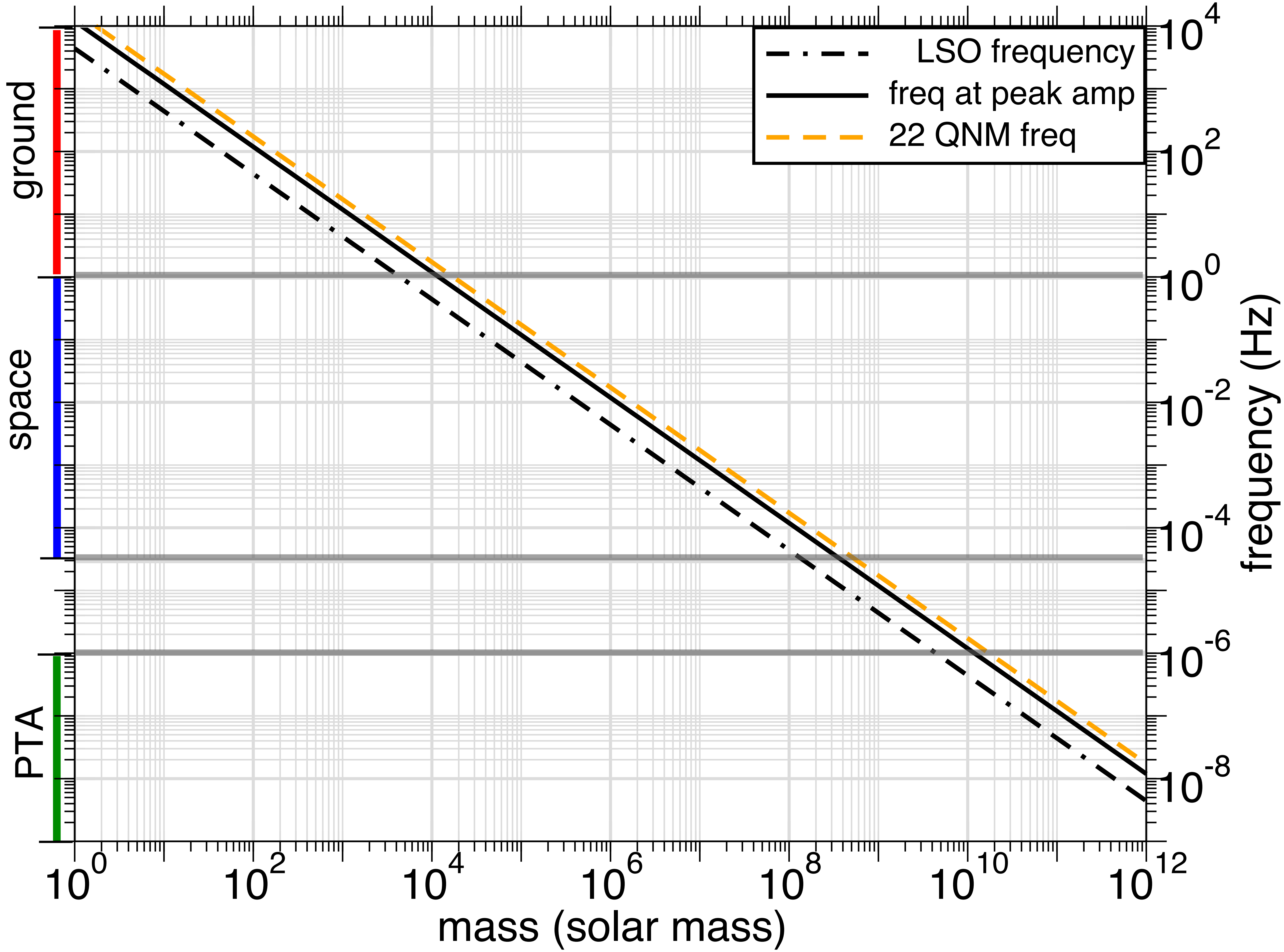
FREQUENCY SPAN OF VARIOUS DETECTORS



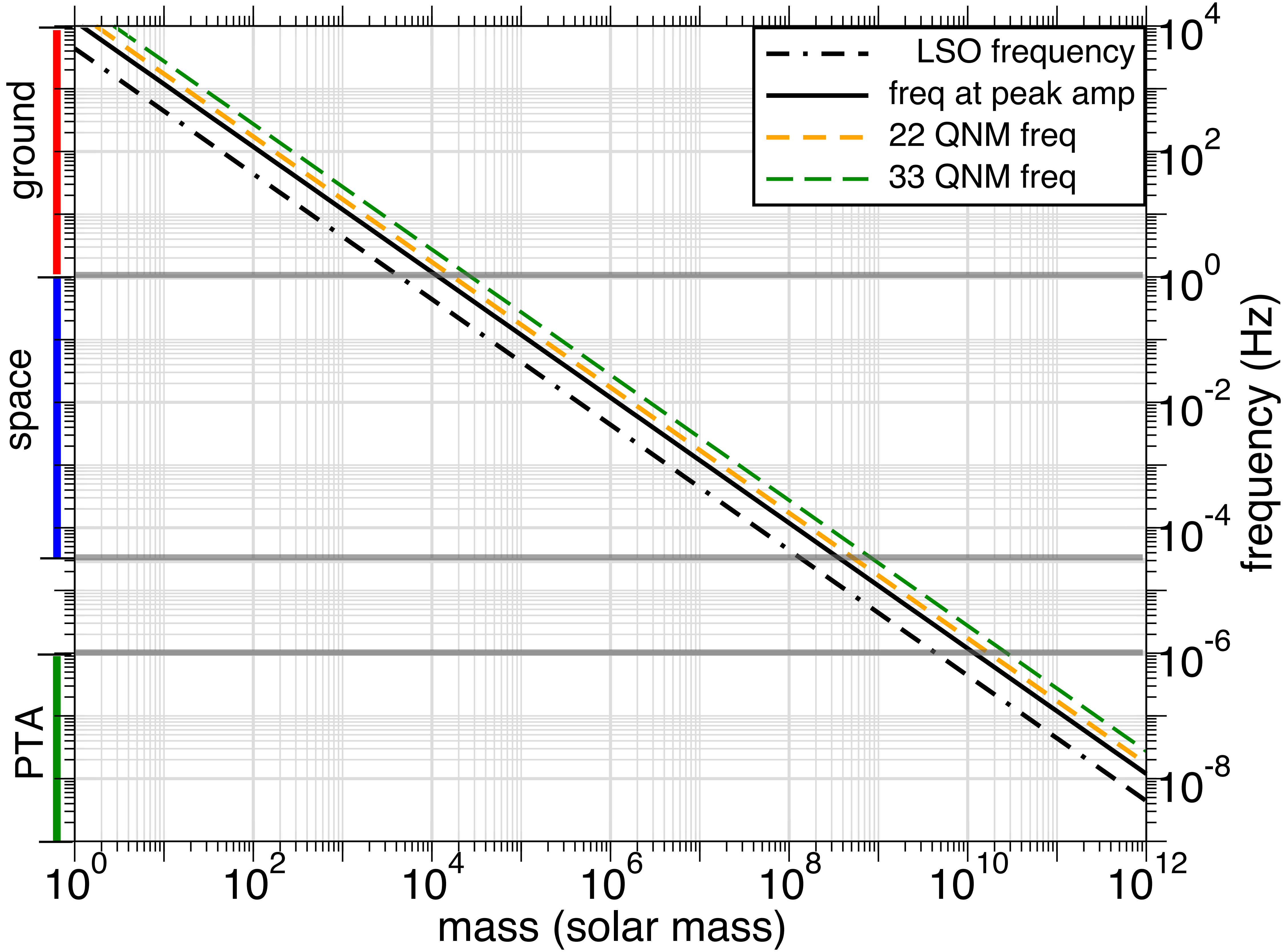
LAST STABLE ORBIT FREQUENCY: SCHWARZSCHILD BLACK HOLE



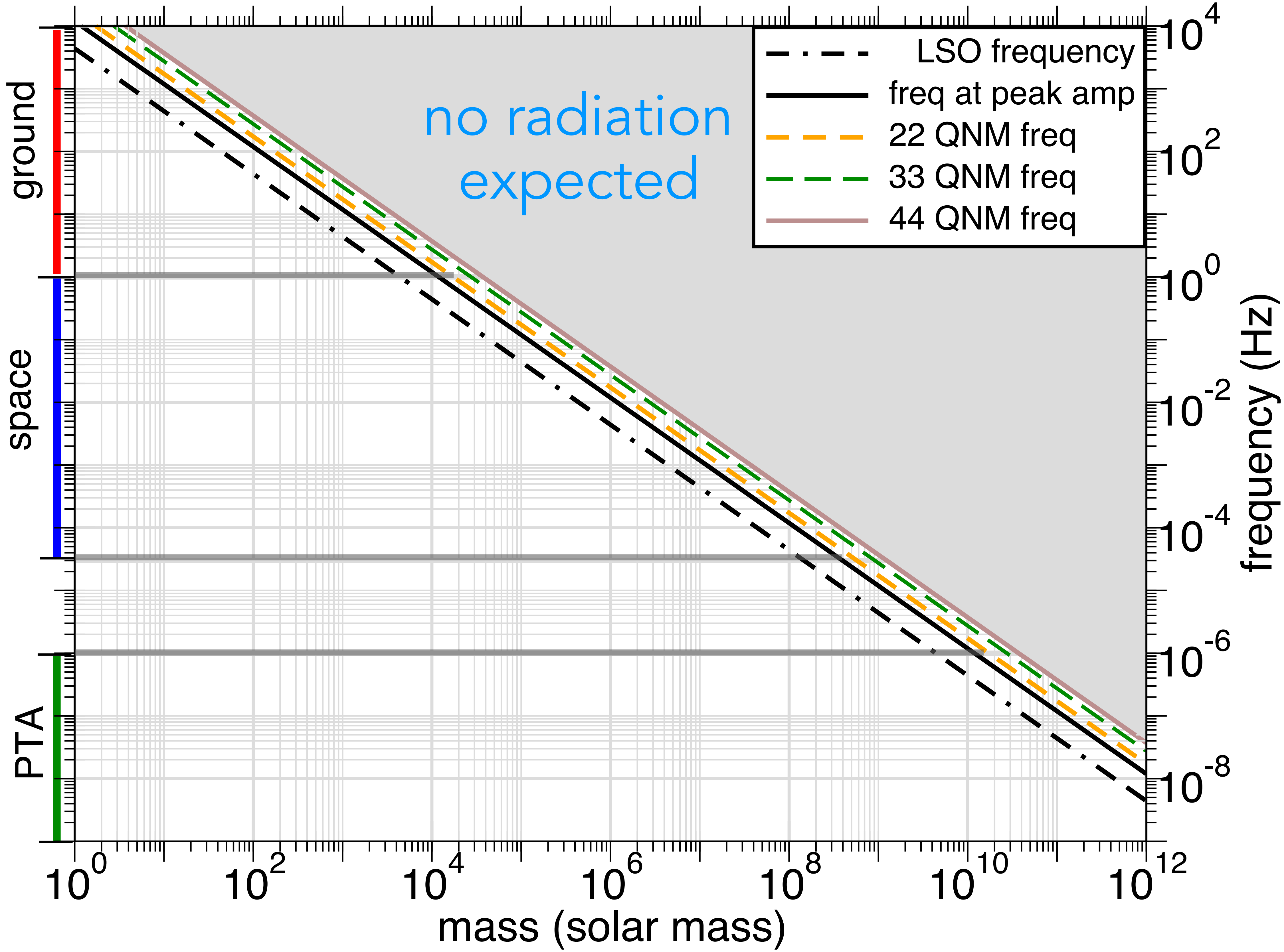
DOMINANT QUASI-NORMAL MODE FREQUENCY



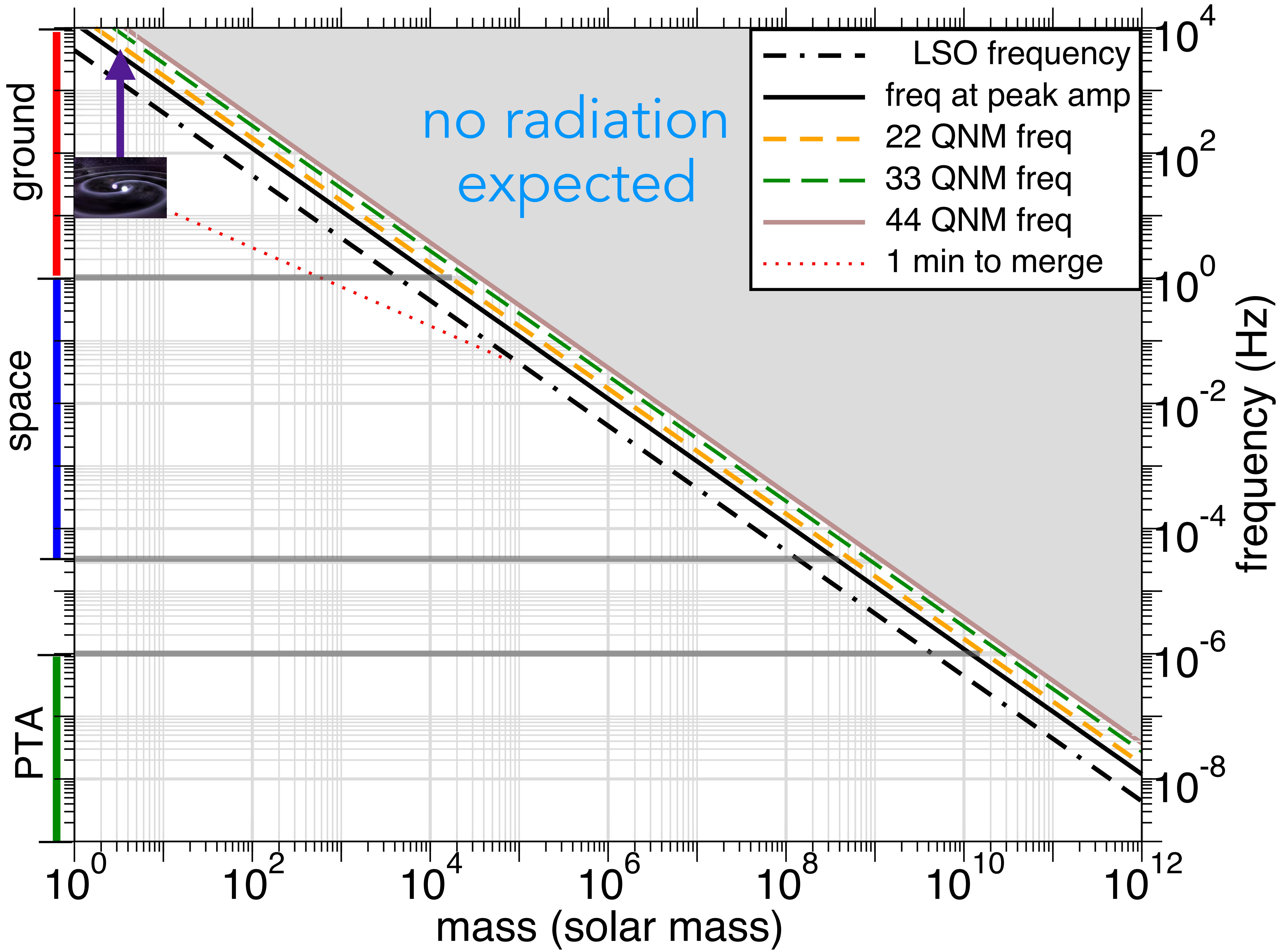
HIGHER ORDER QUASI-NORMAL MODES: SUB-DOMINANT



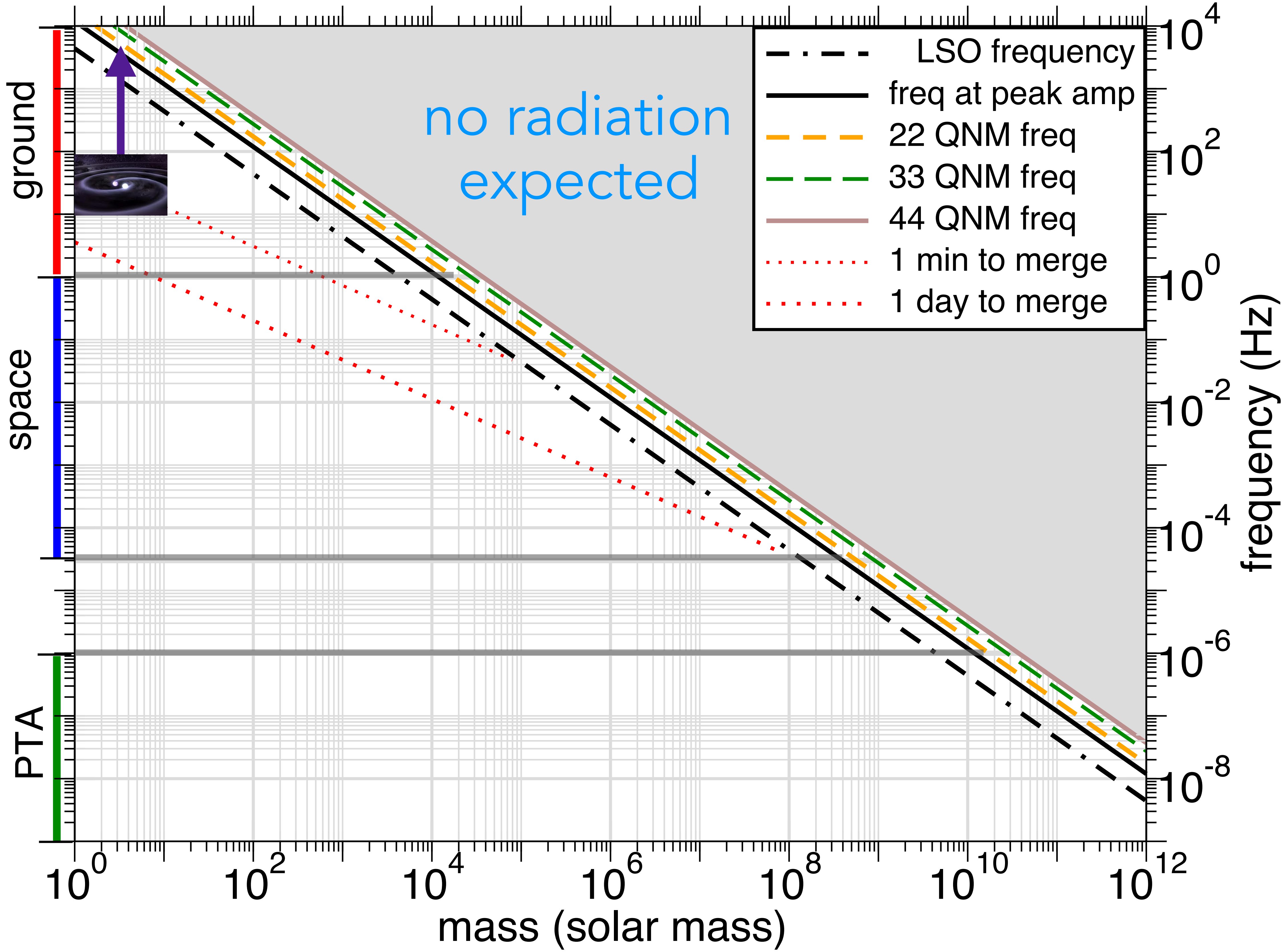
NO RADIATION FROM INSIDE A BLACK HOLE



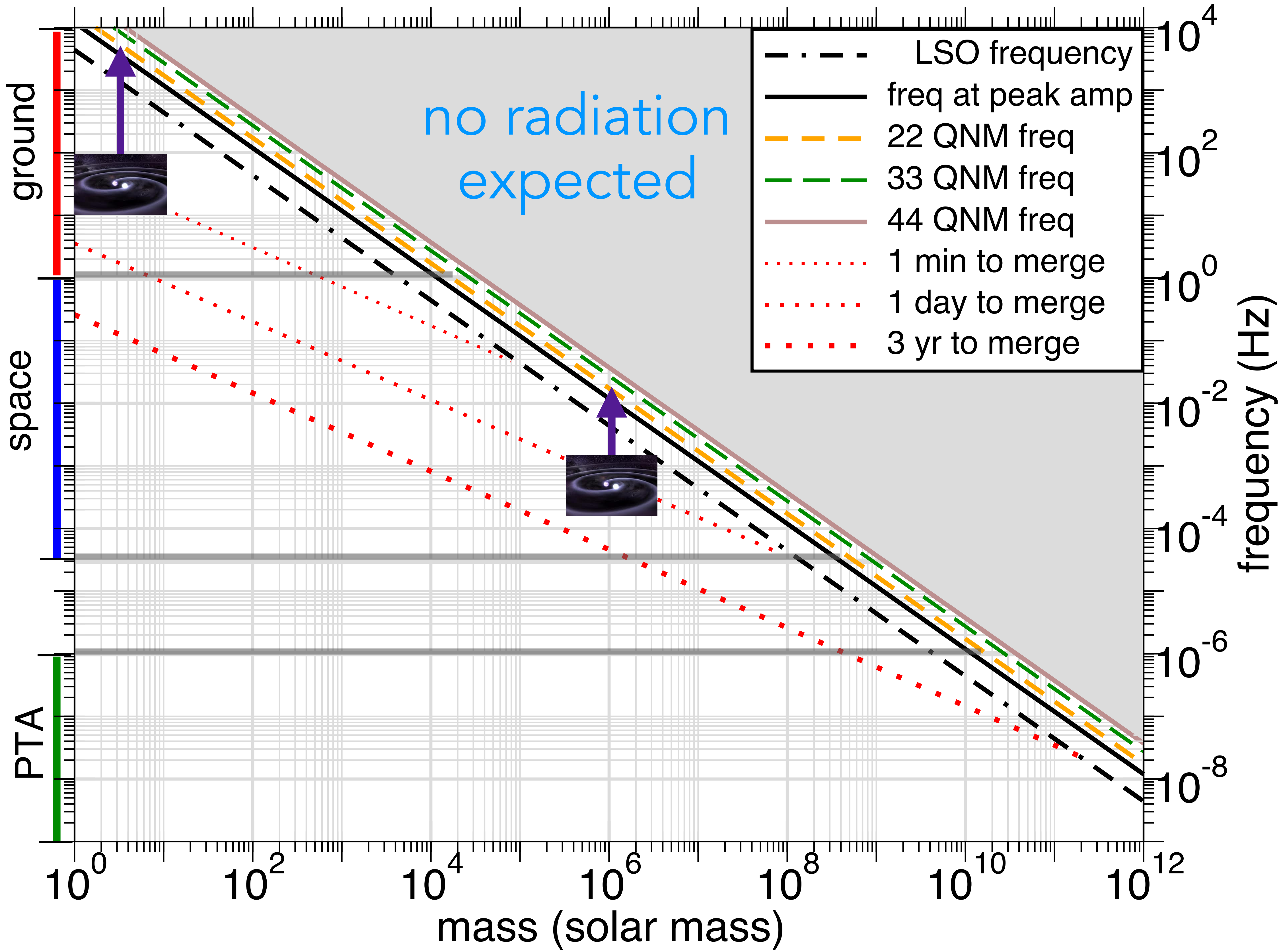
BINARIES OBSERVED BY LIGO/VIRGO MERGE WITHIN A FEW MINS OR ...



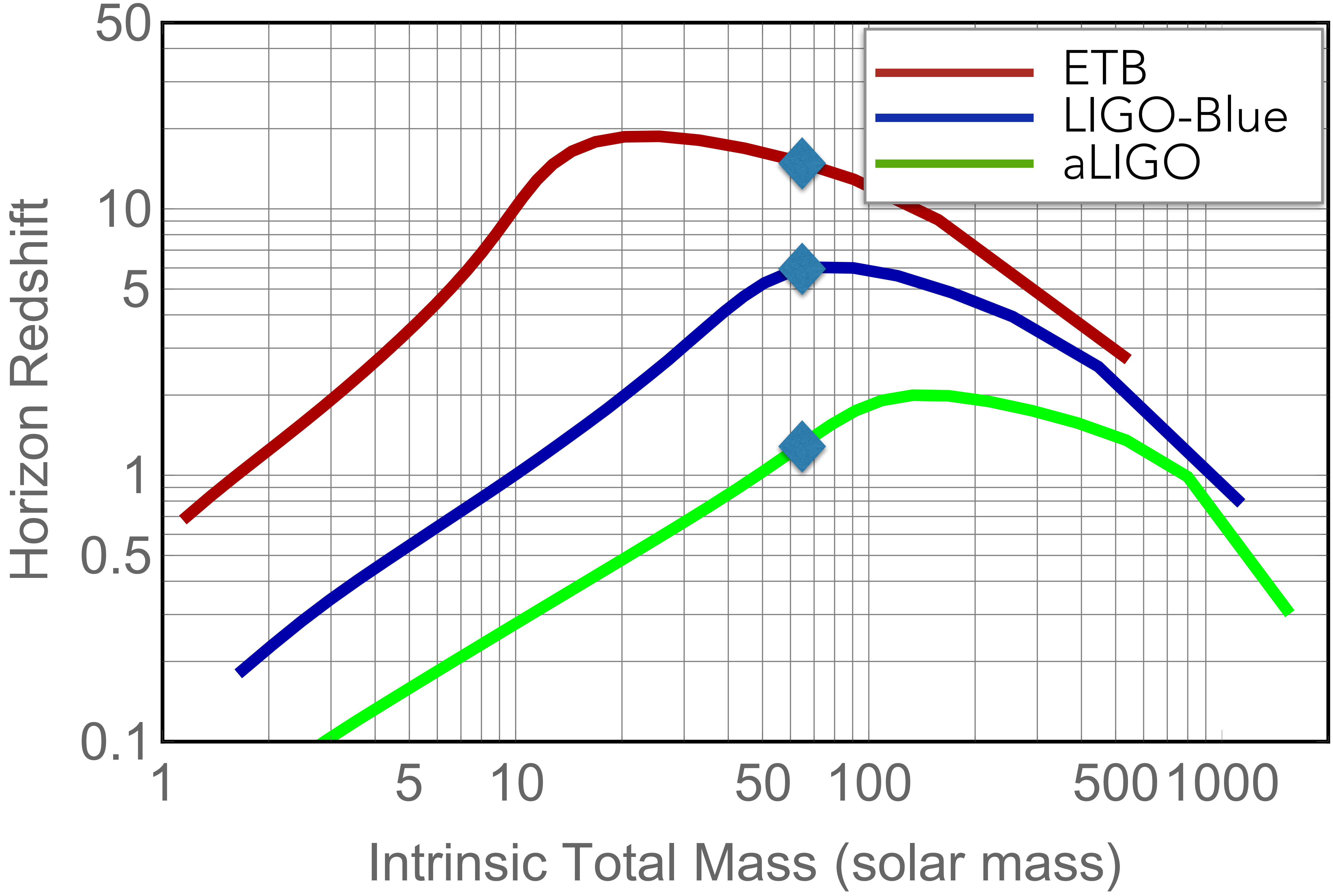
... WITHIN A FEW DAYS



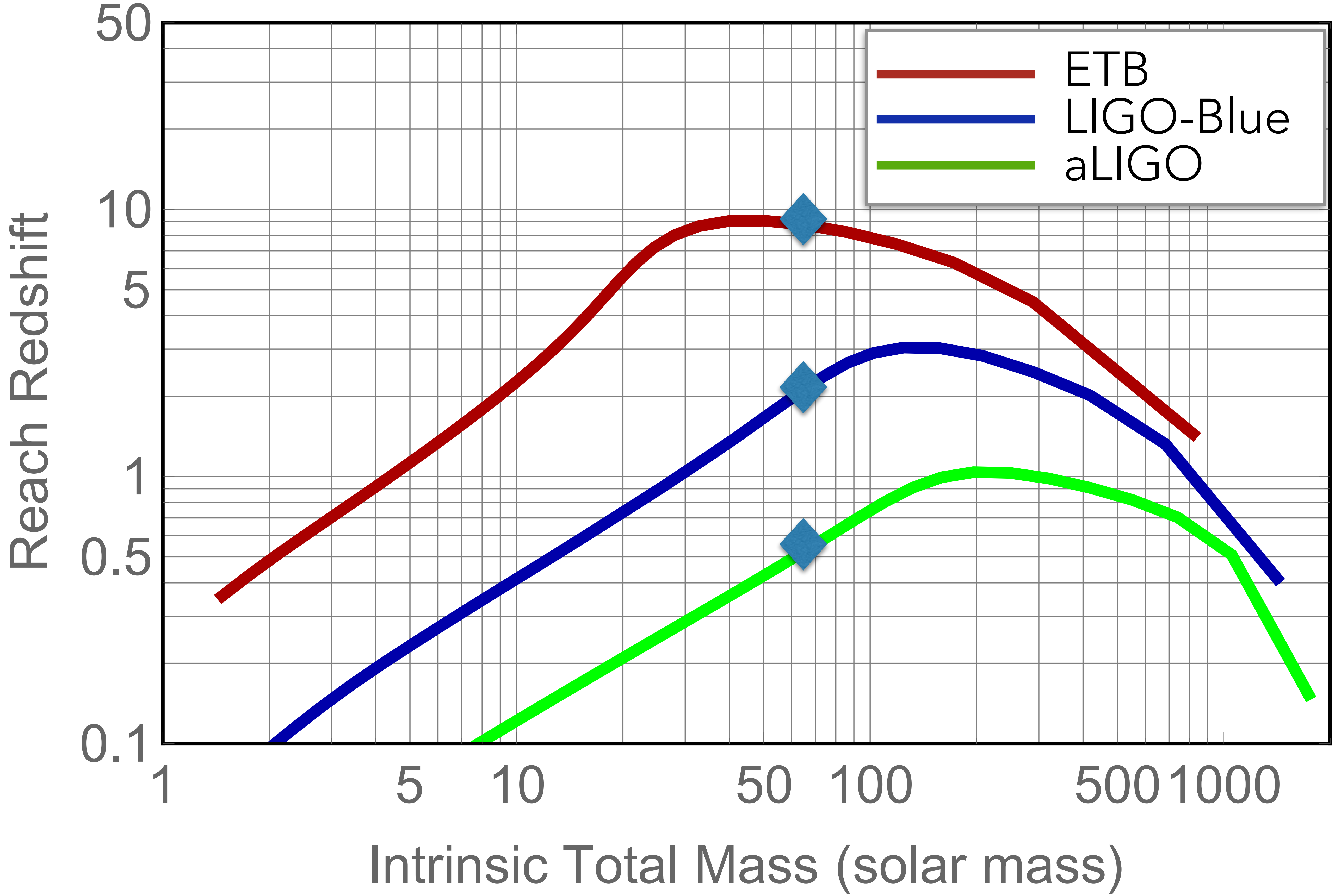
MASSIVE BLACK HOLE BINARIES WILL BE VISIBLE ~ YEARS BEFORE THEY MERGE



MAXIMUM DISTANCE AT WHICH GW150914 WILL BE OBSERVABLE



AVERAGE DISTANCE AT WHICH GW150914 IS OBSERVABLE



GW ASTRONOMY BY 2025

GW ASTRONOMY BY 2025

- Astrophysics by 2025
- we would have measured the rate, confirmed the existence of BBH/NSBH, confirmed GRB progenitors, but probably not much else
    - astrophysical modelling would require a large sample of events: different spins, mass ratios
- it is unlikely that aLIGO or aLIGO+ detectors would detect supernovae or magnetars
- NS ellipticities could be really low < 10^{-8}: might need to go beyond aLIGO+

GW ASTRONOMY BY 2025

- Cosmology and Cosmography
  - Advanced LIGO and Virgo and aLIGO+ would observe black holes when the universe was about 3-8 billion years old
- ET/Cosmic Explorer will take a census of black holes when the Universe was a mere 650 million years old

GW ASTRONOMY BY 2025

- Fundamental physics by 2025
- equation of state of neutron stars would require 20-30 events (or few within 50 Mpc) - possible in the aLIGO or aLIGO+ era
    - ET/Cosmic Explorer could constrain the NS radius to within 500 m
- dark energy equation of state - would require thousands of BNS or even 10^5 sources, will only be possible with 3G
- testing gravity would require 100's or even 1000's of events, again in the 3G era

3G STRATEGY

- it is best to focus on a few very strong messages
  - too many goals will fail to send a strong and clear message about what we want from 3G detectors
- identify what gravitational wave detectors can do best and put that in our chief science goals
  - organise current science goals under 3 or 4 main headings
- identify 3 most important problems that can only be addressed and understood by 3G detectors

PARAMETER ESTIMATION - ANGULAR RESOLUTION: (1.38+1.42) BNS, ARBITRARY LOCATION AND ORIENTATION

$$\theta = \pi/6, \varphi = \pi/5, \psi = \pi/8, \iota = \pi/10, D = 3\,\mathrm{Gpc}$$

	SNR	SKY $\Delta\Omega$ DEG^2	SNR	SKY $\Delta\Omega$ DEG^2	SNR	SKY $\Delta\Omega$ DEG^2
HLVIJ	9.4	16	71	4.6	24	19
HLVIJ + CE	13.3	11	102	2.0	34	15
HLVIJ + ET	33	8.7	247	2.2	84	11
HLVIJ + CE + ET	**34**	**5.4**	**259**	**0.97**	**87**	**5.2**

3G SCIENCE CASE

- *extremes of physics*
- *black holes through cosmic history*
- *explosive phenomena*

UNDERSTANDING EXTREMES OF PHYSICS

WHAT IS THE MOST COMPACT OBJECT IN NATURE?

WHAT IS THE EQUATION OF STATE OF NEUTRON STAR CORES?

BLACK HOLES THROUGH COSMIC HISTORY

WHAT IS THE NATURE OF BLACK HOLES?

HOW DID BLACK HOLES FORM AND GROW TO BE SUPERMASSIVE?

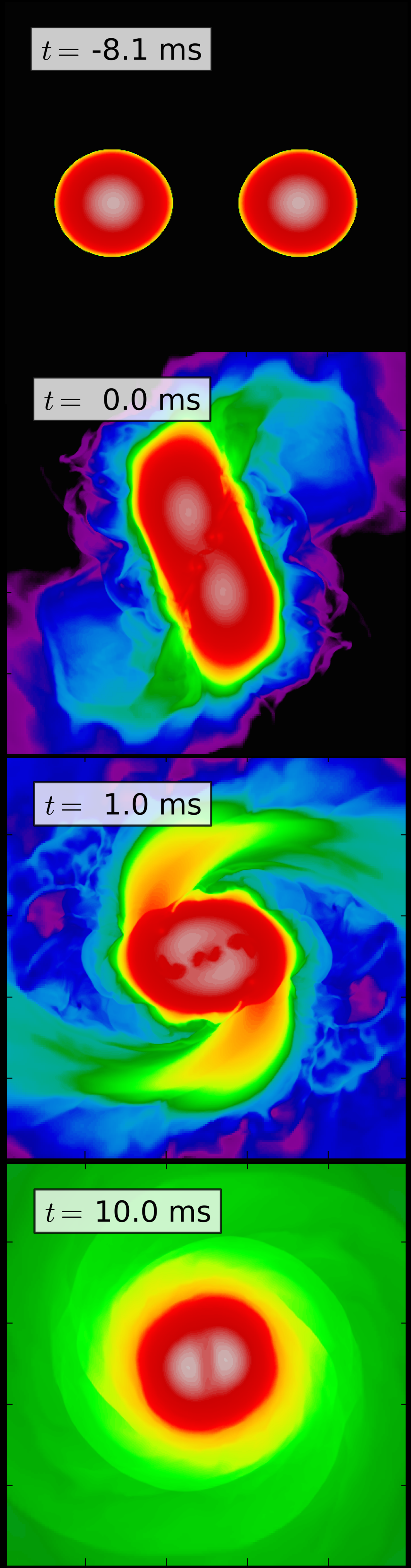
PROBING THE TRANSIENT UNIVERSE

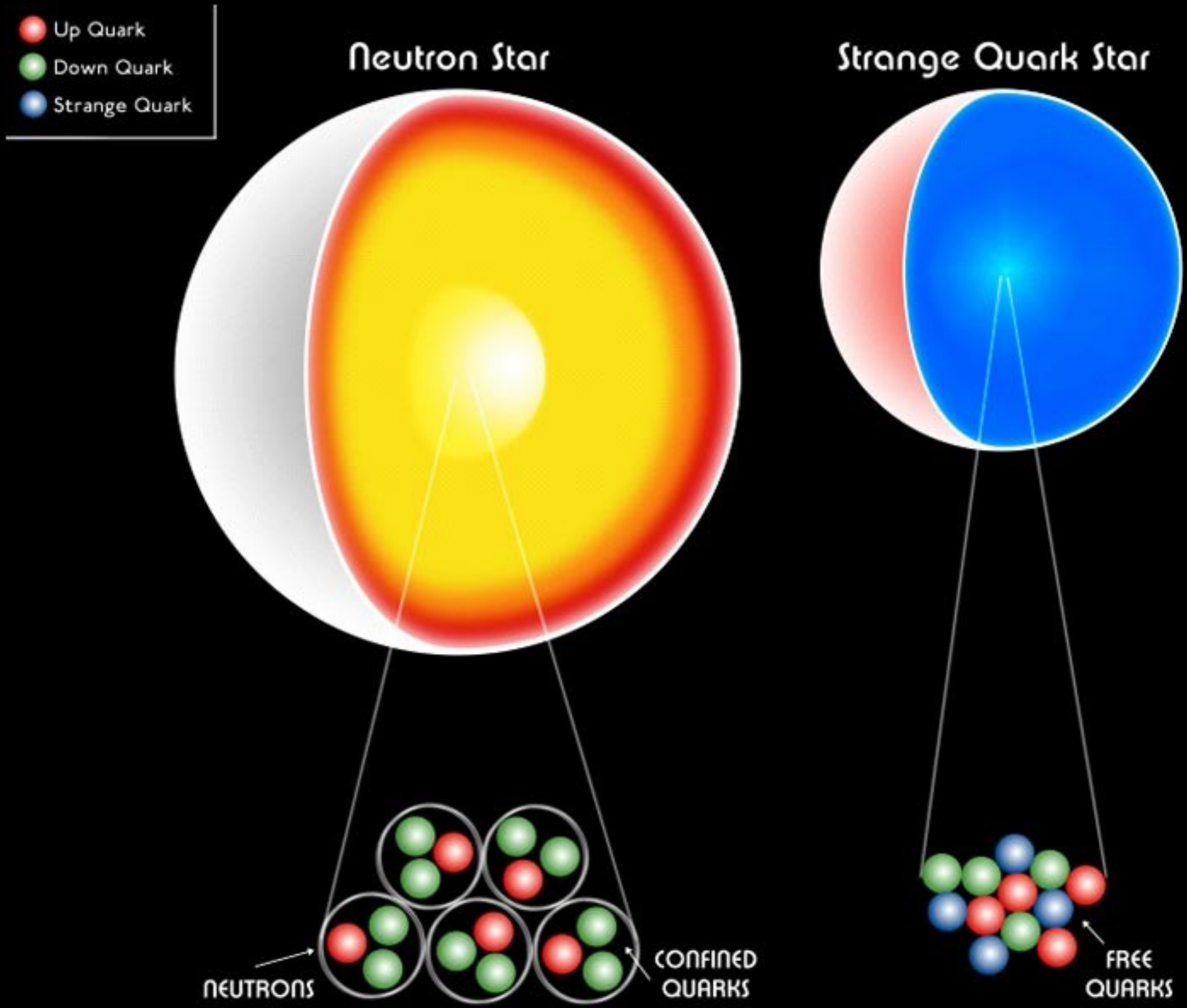
WHAT ARE PROGENITORS OF GAMMA RAY BURSTS AND WHY IS THERE SUCH A VARIETY OF THEM?

WHAT CAUSES CORE BOUNCE IN SUPERNOVAE?

EXAMPLE OF EXOTIC SCIENCE

Measuring Neutron Star Equation of State

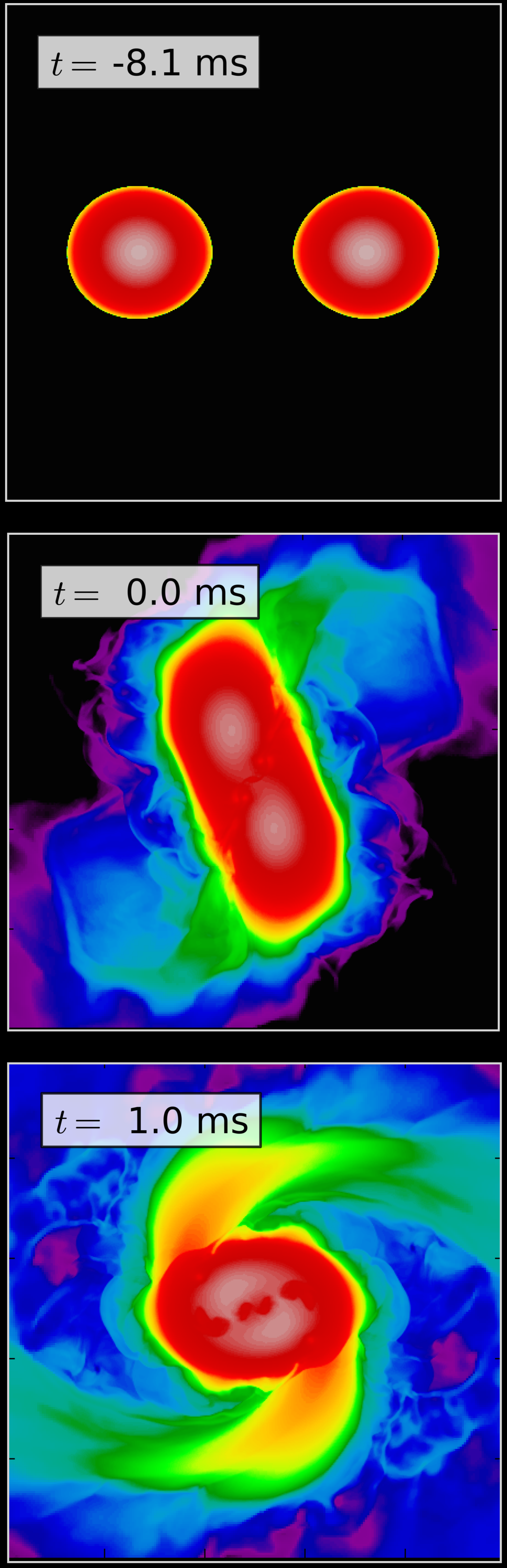




Densities ~ 4 x10^{17} kg/m^3

NEUTRON STAR BINARY SPECTROSCOPY: BASIC IDEA

- Inspiral signal is followed by a merger waveform: merger signal depends on the neutron star equation of state
- For most equations of state, heavier neutron stars are smaller and so larger post-merger oscillations
- But here is the tension:
  - cosmological expansion causes the frequency to redshift
  - so the **observed mass** of the binary is larger
  - but larger masses should have greater frequencies
- This tension between cosmology and microphysics helps resolve the mass-redshift degeneracy



3G SCIENCE CASE

- *extremes of physics*
  - structure and dynamics of neutron stars
  - physics of extreme gravity and quantum geometry
- *black holes through cosmic history*
  - formation, evolution and growth of black holes and their properties
- *explosive phenomena*
  - gamma ray bursts, gravitational collapse and supernovae

Expected Signal-to-Noise Ratios: ET and eLISA

Some systems observed by eLISA might also be observable by ET

Caution: Only inspiral part is considered when computing the SNR