Title: Not quite black holes at LIGO

Speakers: Bob Holdom

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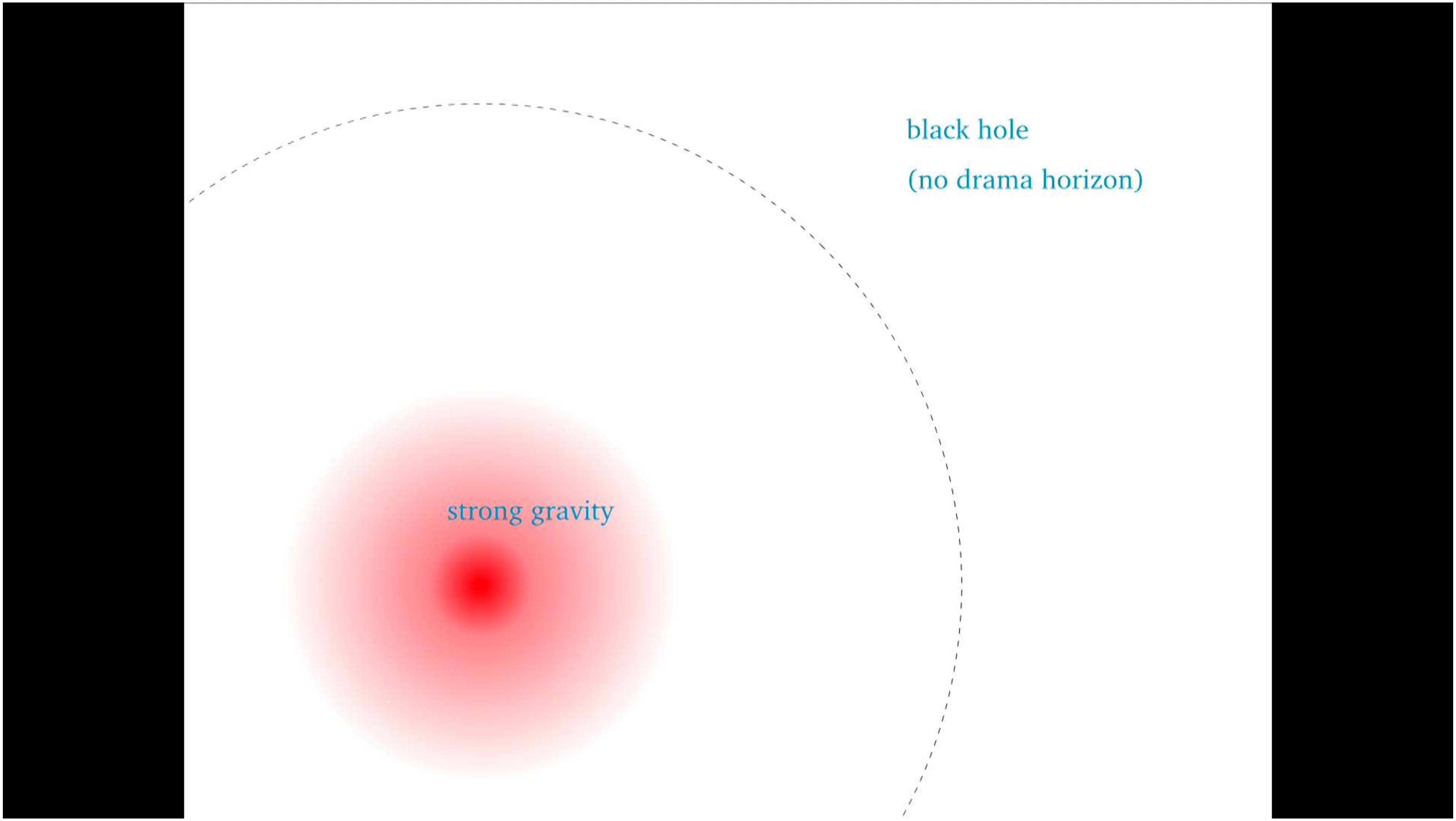
Abstract: The Einstein action has made us very accustomed to black holes and their â€œno dramaâ€• event horizons. But the Einstein action will eventually be subsumed into a UV complete theory of gravity, and in such a theory there can be a new class of solutions that are not quite black holes. Within a Planck length of the would-be horizon, strong gravity and high curvatures quickly turn on. These solutions are analogous to the hadrons and/or the quark matter states of QCD. They are very close to being completely black, but not quite. An ideal probe to test for not quite black holes are the low frequency gravitational waves that are excited in and around them when they are newly formed, as in the merger events observed by LIGO. There are some key features of waves that escape the interior of not quite black holes, and from this we describe our own search and search results using LIGO data.

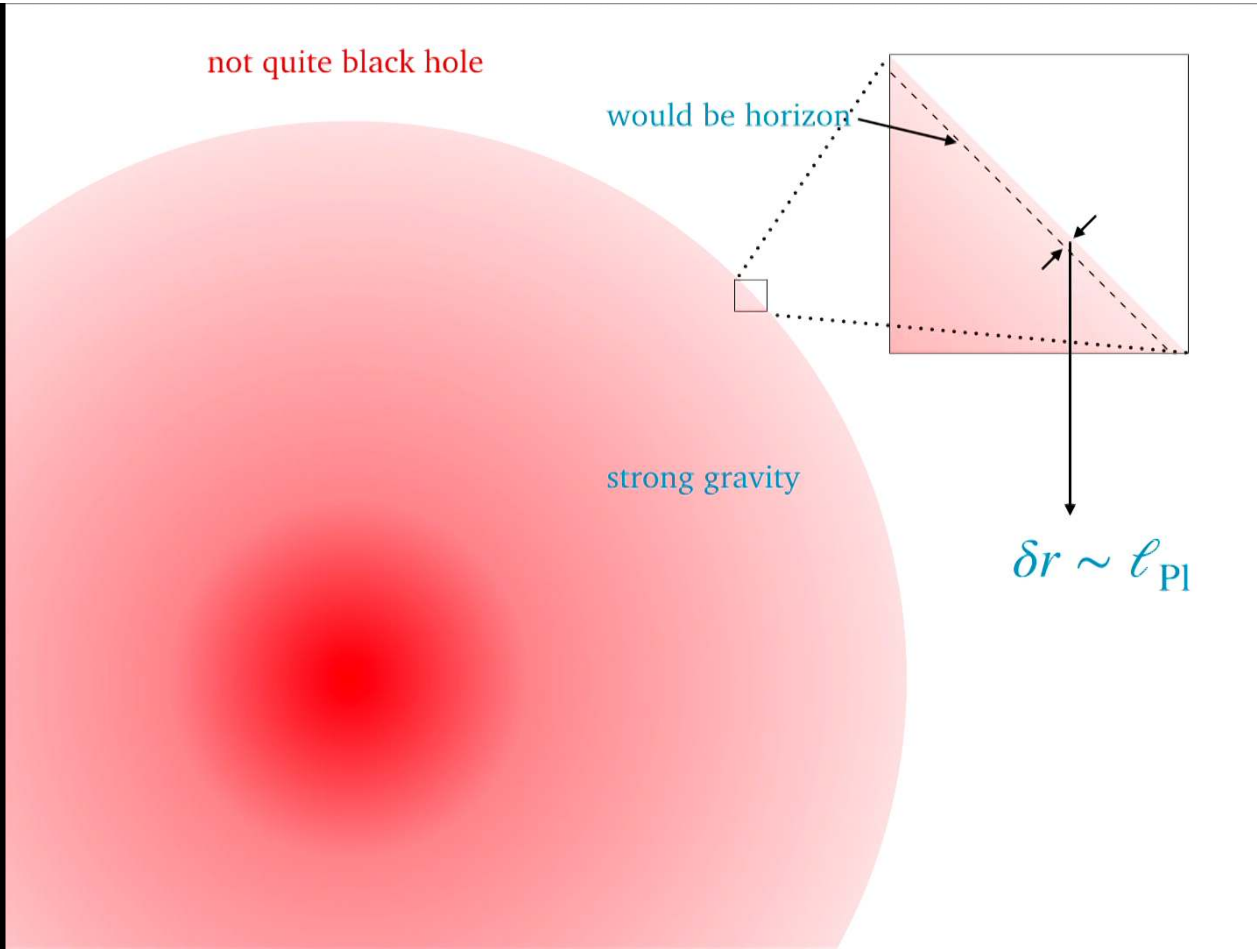
Not quite black holes at LIGO

Bob Holdom

COSMOLOGICAL FRONTIERS IN FUNDAMENTAL PHYSICS 2019

Perimeter Institute, Sept 5

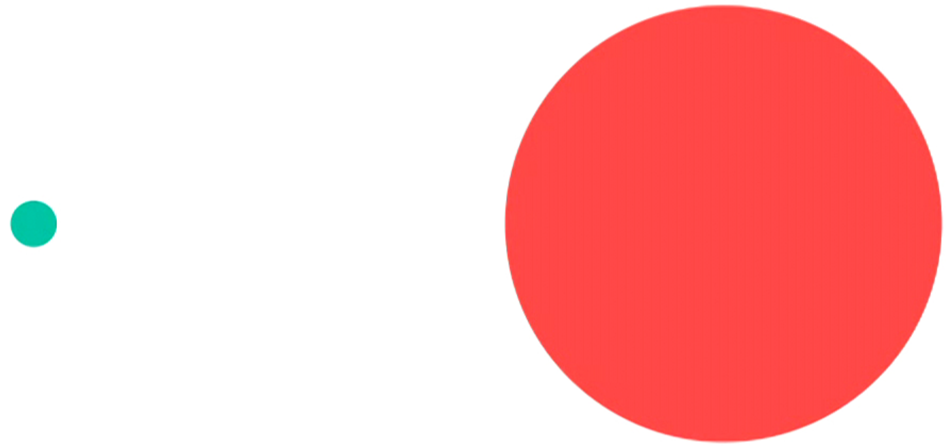

black hole
(no drama horizon)
strong gravity


not quite black hole
would be horizon
strong gravity
$\delta r \sim \ell_{\rm Pl}$

why “not quite black holes”?

- does a UV complete theory of gravity permit some other endpoint of gravitational collapse?
- one needs only to turn to an action quadratic in curvature to find “not quite black hole” solutions
  - quadratic gravity is an old candidate for a UV complete theory, since its quantum version is renormalizable and asymptotically free
- we call these “2-2-holes”, and recently we found 2-2-hole solutions that are sourced by an ordinary relativistic gas
- these objects have a well defined and easy to calculate entropy that is somewhat larger than the entropy of a same size black hole
  - in this way they may be preferred as the endpoint of gravitational collapse

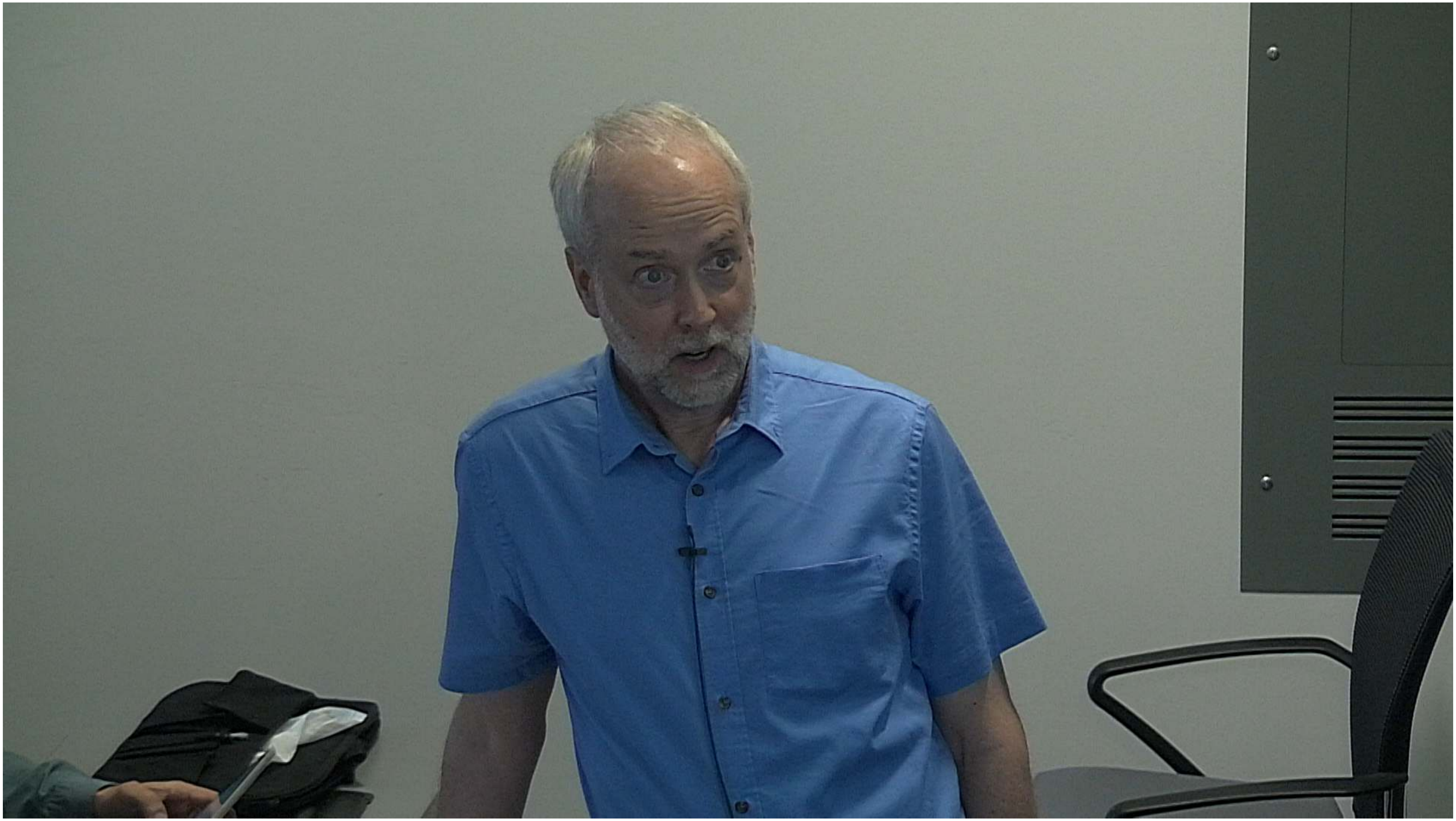
- 2-2-holes come in two types:



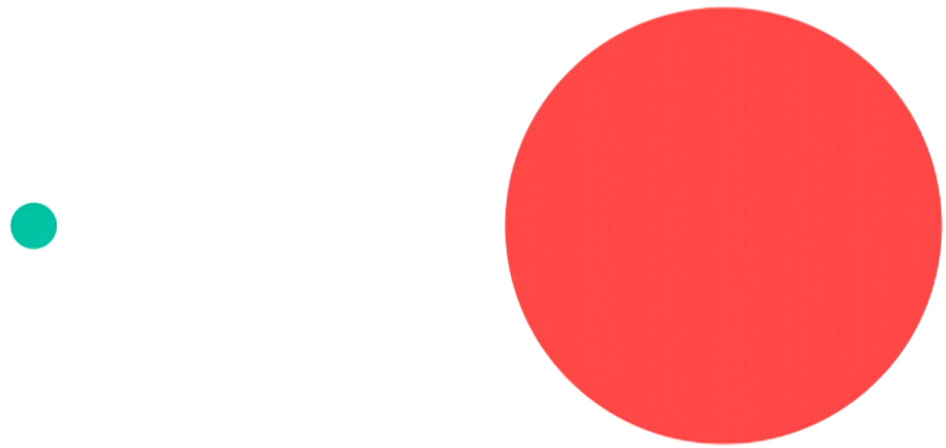
smallest ones with Planck size

large ones with no upper limit on size

- inner structure of the two types is quite different
- different size large ones are related by a scaling relation



- not unlike QCD:



hadrons with fixed size

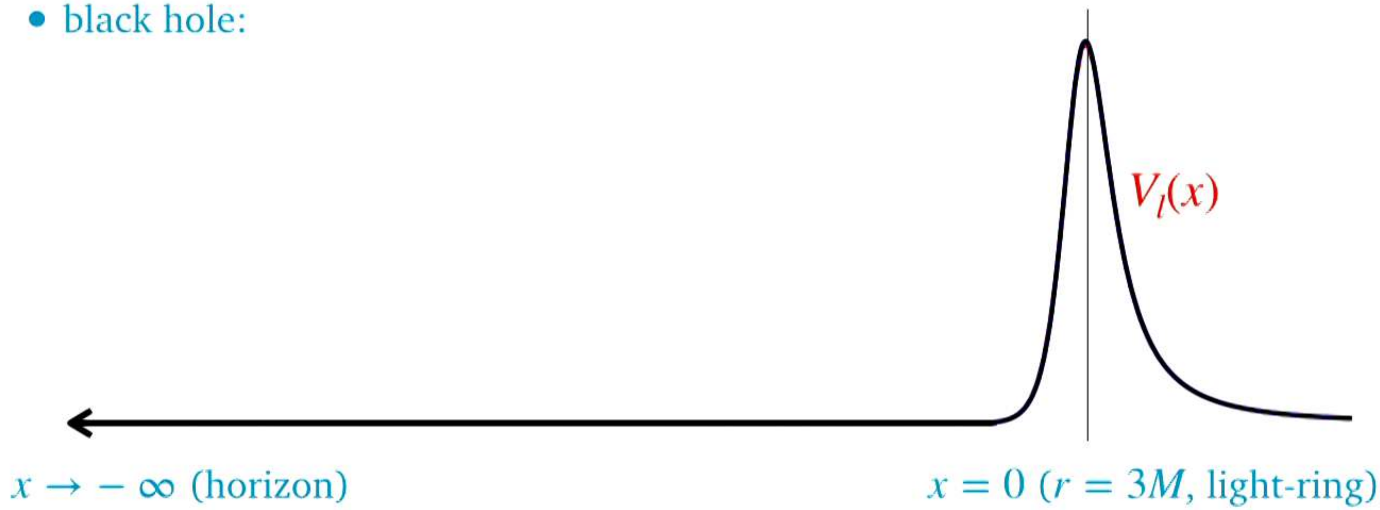
variable size quark matter states that extend up to neutron star size

- macroscopically large objects involving strong interactions are not so weird

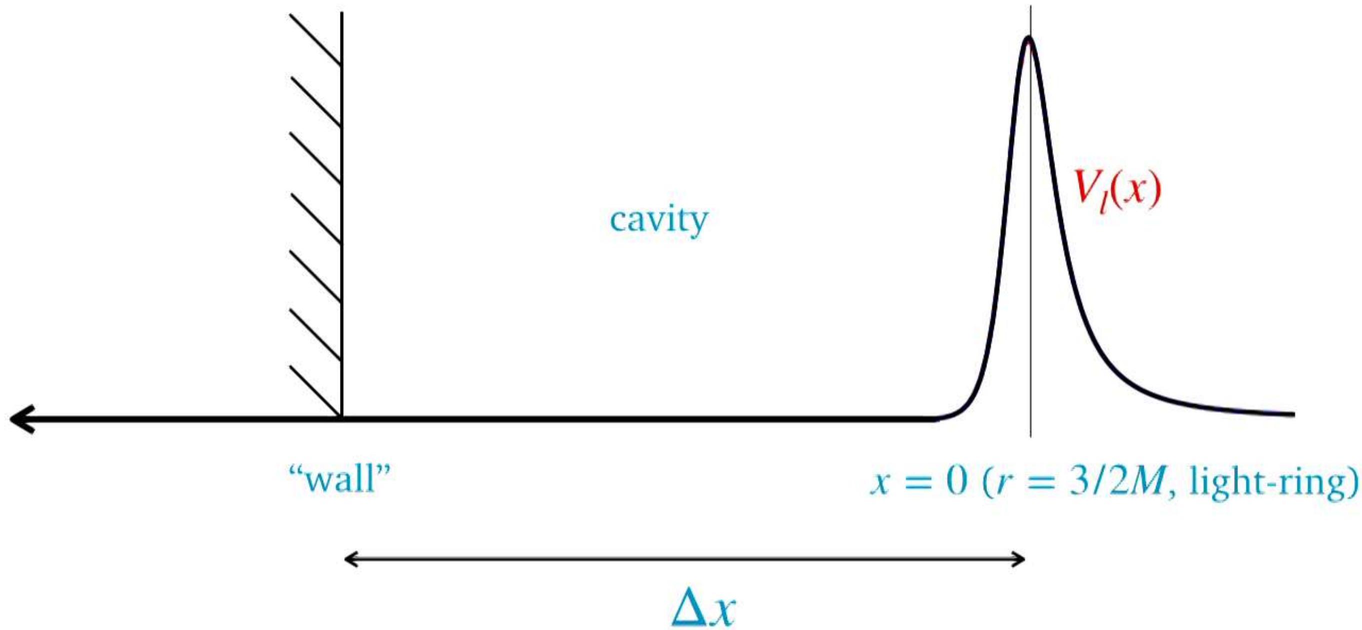
- scalar wave equation in Schd background using tortoise coordinate x

$$(\partial_x^2 + \omega^2 - V_l(x))\Psi_l = 0$$

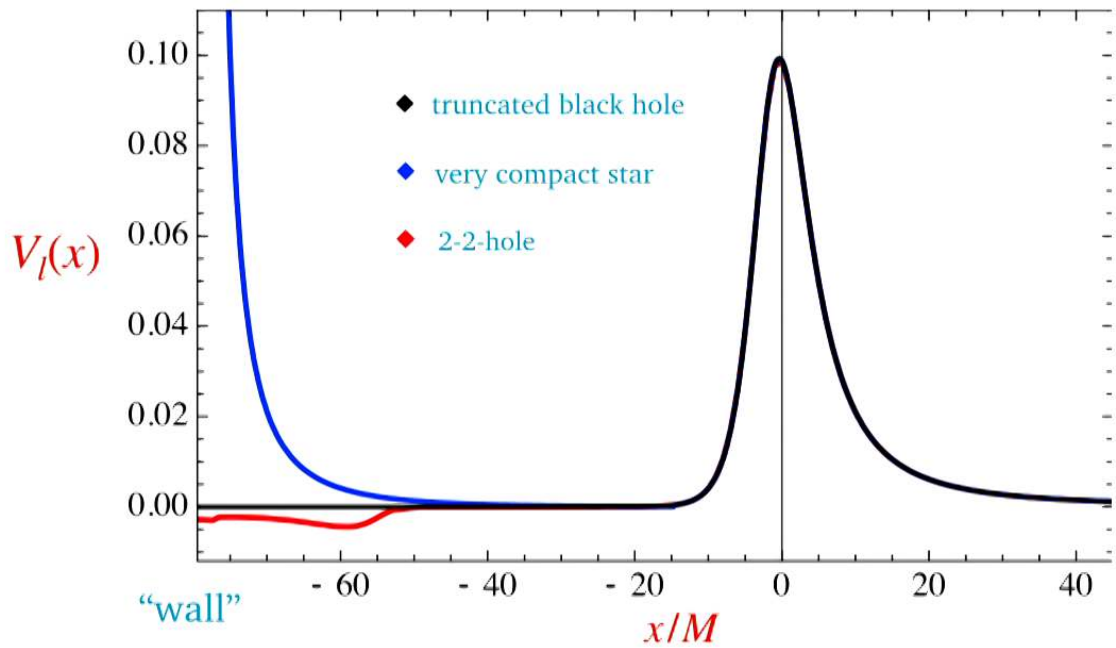
- black hole:



- for not quite black holes, waves have a finite travel time to the origin
- implies a boundary at a finite tortoise coordinate



- round trip travel time in cavity is $\Delta t = 2\Delta x$



- truncated black hole (wall just outside the horizon) is not bad approximation to a 2-2-hole
- but a 2-2-hole, like a star, has an origin ($r = 0$), not a wall
- "wall" in this talk will mean either a wall or an origin

the cavity structure

- the effective radial description of low frequency waves is that of a 1D cavity with one end that slightly leaks
- thus a pulse that moves back and forth in the cavity will produce a periodic pulse (an echo) observed on the outside (Cardoso and Pani)

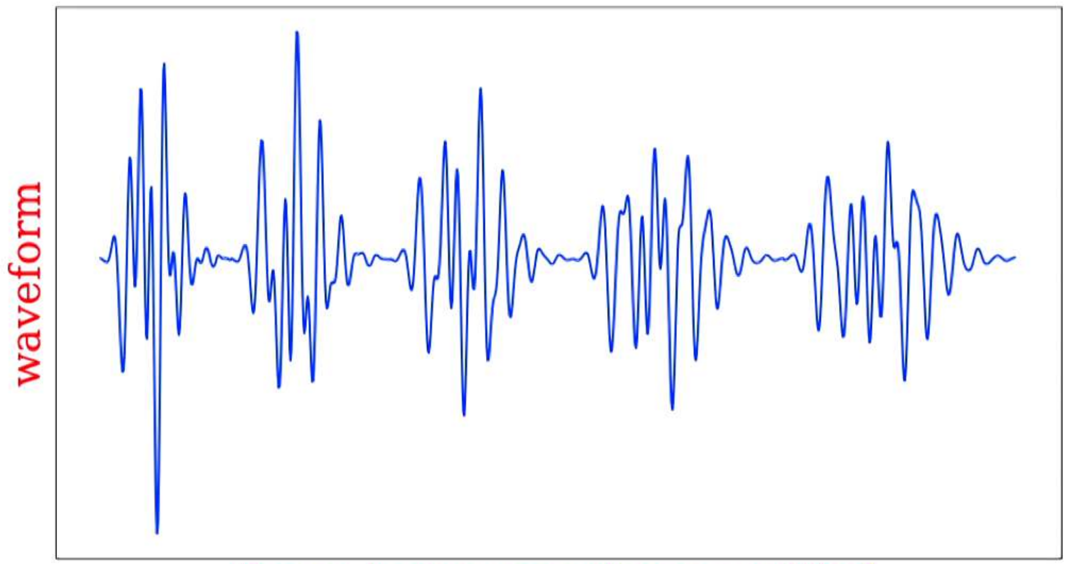
- but what if the perturbed state of a newly formed “BH” is more complicated, resulting not in a simple pulse moving back and forth?
  - there might not be a simple echo structure

- a 1D cavity has a more general feature: an evenly spaced resonance spectrum

$$\Delta f = \frac{1}{2\Delta x} = \frac{1}{\Delta t}$$

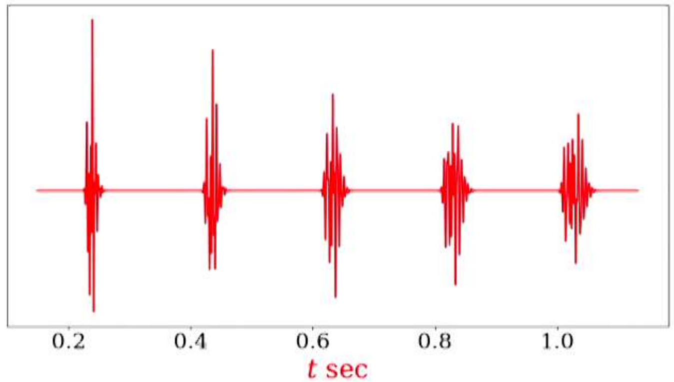
- LIGO should be thinking of a resonance search!

- even one pulse moving back and forth gives a nontrivial waveform
- first 5 echoes, with inactive time between echoes removed



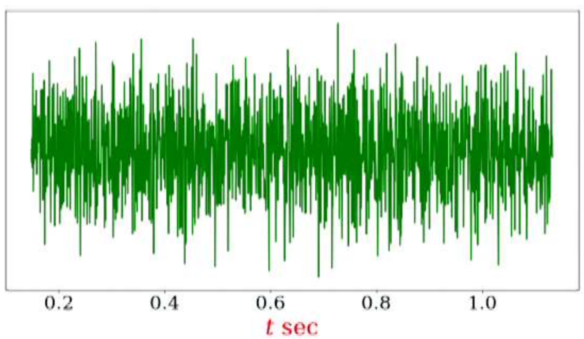
- rather more difficult to model than the merger waveform

- irregular echoes are easy to lose in noise

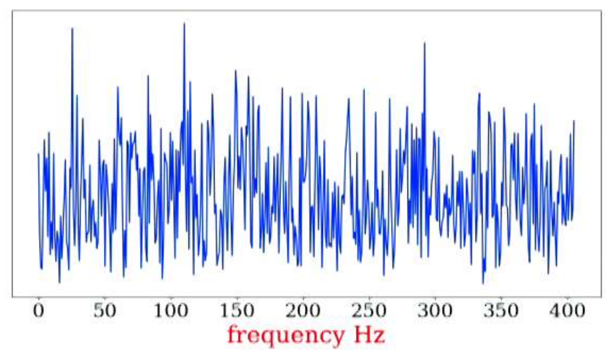


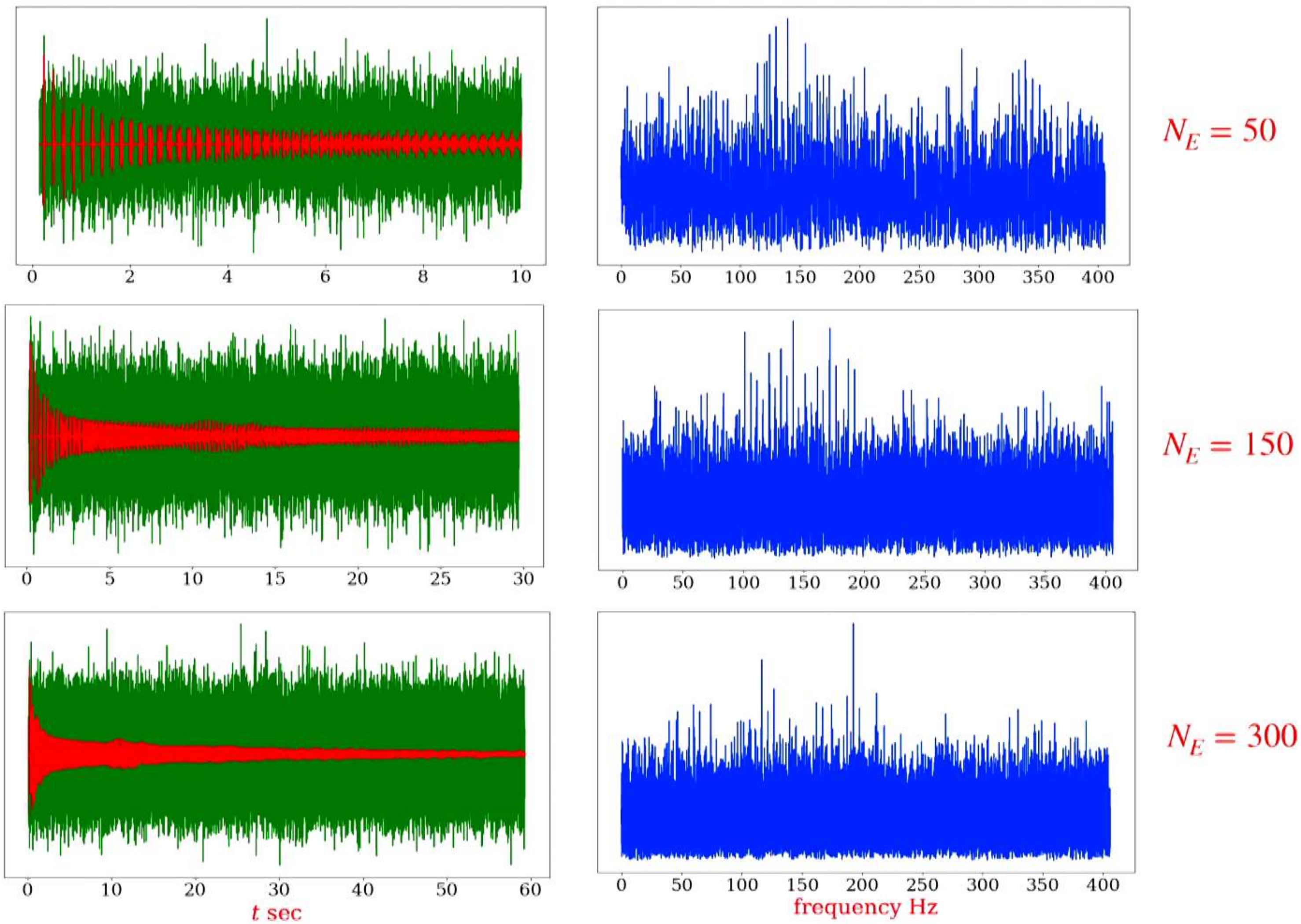
$N_E = 5$

signal + noise



|Fourier transform| of signal + noise




0
2
4
6
8
10
0
50
100
150
200
250
300
350
400
$N_E = 50$
0
5
10
15
20
25
30
$N_E = 150$
0
10
20
30
40
50
60
t sec
frequency Hz
$N_E = 300$

- we are considering gravitational waves on a truncated Kerr background and we focus on the $\ell = m = 2$ mode
- this is a complex amplitude describing two polarizations

$$h_{22}(t, \Omega) = h_{+}(t, \Omega) - i h_{\times}(t, \Omega) = \psi(t) Y_{22}(\Omega)$$

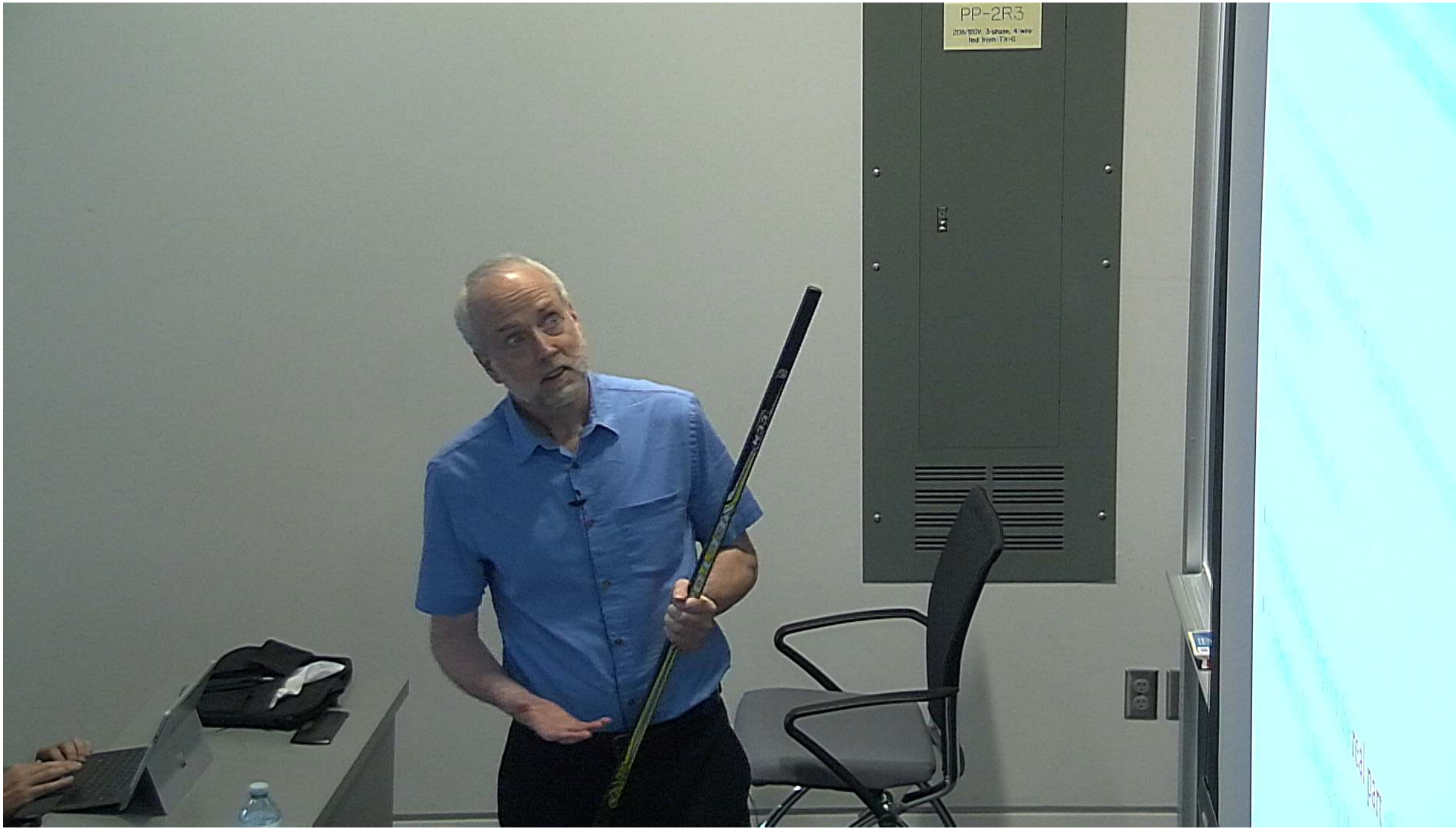
- let the "Fourier transform" of the complex $\psi(t)$ be ψ_{ω}
- ψ_{ω} is not conjugate symmetric about $\omega = 0$
- ψ_{ω} can be obtained from a solution to the Sasaki-Nakamura (SN) equation, $\psi(\omega, x) \rightarrow \psi_{\omega} e^{i\omega x}$ for $x \rightarrow \infty$

- thus we get ψ_{ω} first and then $\psi(t)$, from which we see the irregular waveform and the dependence on initial conditions
- we will return to this later...

- a LIGO detector projects the complex waveform into a set of real numbers, the "strain data"
- we take the real part of the signal waveform $\psi(t)$ to model this projection (different projections give qualitatively similar results)

- to search for a resonance pattern:
  - choose the time duration $T = N_E \Delta t$ of the data to analyze
  - take the FFT
  - take the absolute value

- carrying out these steps on the real part of $\psi(t)$ gives a "reconstructed" $|\psi_\omega|$
- it depends on N_E, as well as M, χ (the spin) and Δt


PP-2R3

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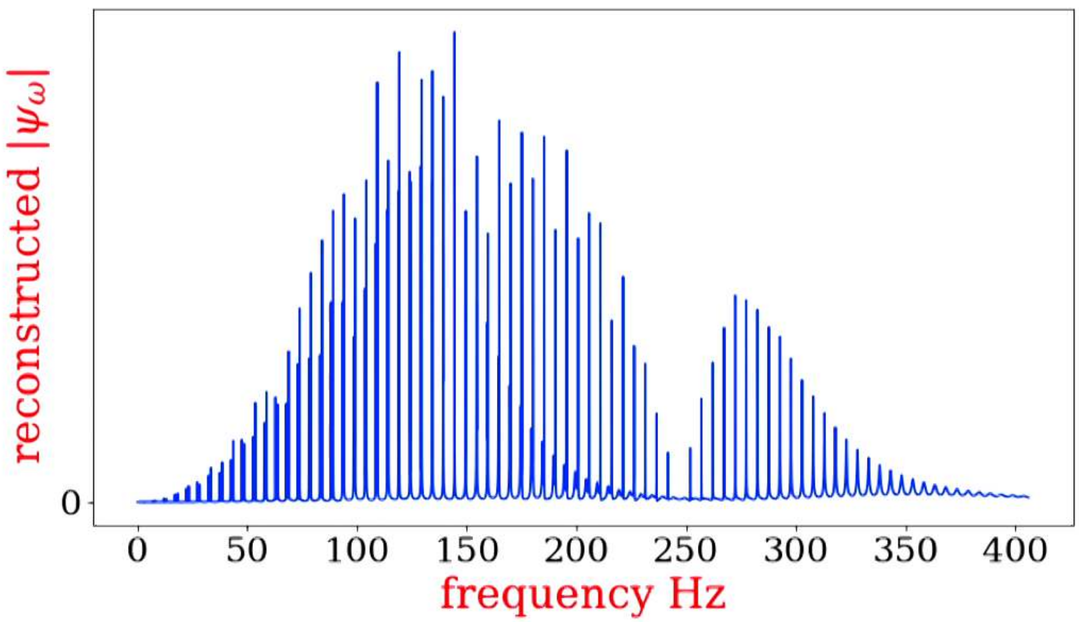
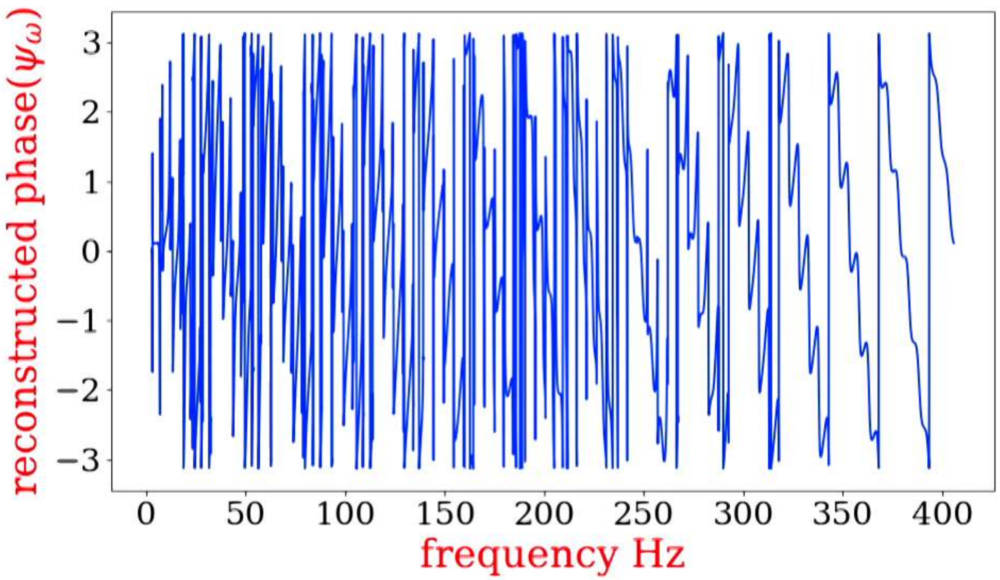
- an example for $N_E = 180, \chi = 2/3, M = 50M_\odot, \Delta t/M = 800$
- two component structure due to the real projection
- lower frequency structure comes from the negative frequency part of ψ_ω

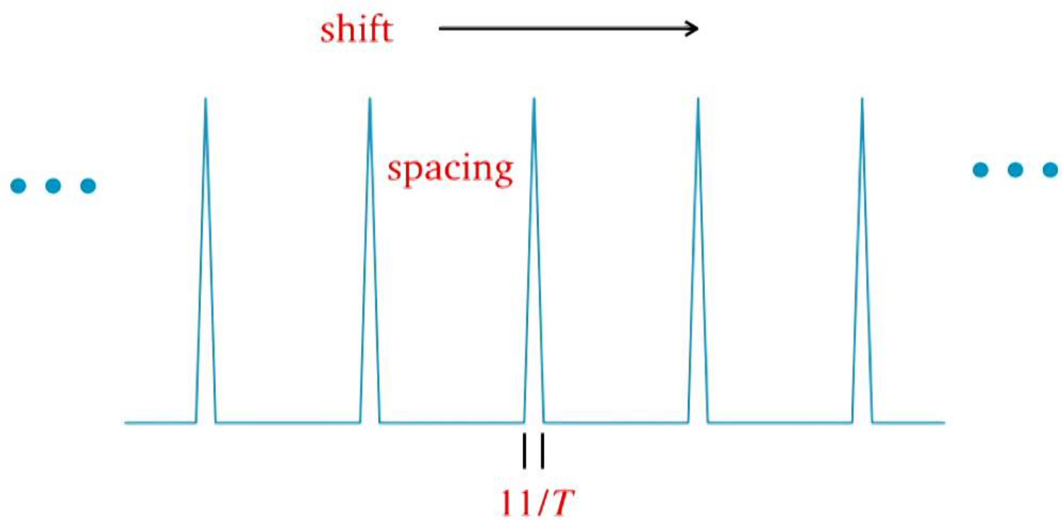


- all other echo searches try to model the full waveform
- in our notation the full information is in the reconstructed versions of $|\psi_\omega|$ and the phase(ψ_ω); here is the latter:



- if templates don't get this right then matched filter searches may fail

- |FFT(data of duration T after merger)| is a function of f and onto this we apply a bandpass $f_{\rm min} < f < f_{\rm max}$
- multiply by a uniform comb structure characterized by a spacing between teeth and an overall shift
- take these amplitudes from the two detectors and search for a correlated enhancement for some spacing and shift



- within errors, the spin of the final BH can be grouped into one of three categories

spin (χ)	2/3	0.72	0.81
	GW150914 (.5)	GW151226 (.8)	GW170729 (.5)
	GW170104 (1)	GW170814 (1)	
	GW170608 (1)	GW170809 (1)	
	GW151012 (.5)	GW170823 (.5)	
	GW170818 (.5)		
R_{wall}	– 0.995	– 0.994	– 0.992
$E_{\omega<0}/\lvert E\rvert_{\text{tot}}$	0.06	0.06	0.13

- last row parameterizes the initial pulse
- whitening of data was done with 300 segments, with duration of each segment (in seconds) given in the table

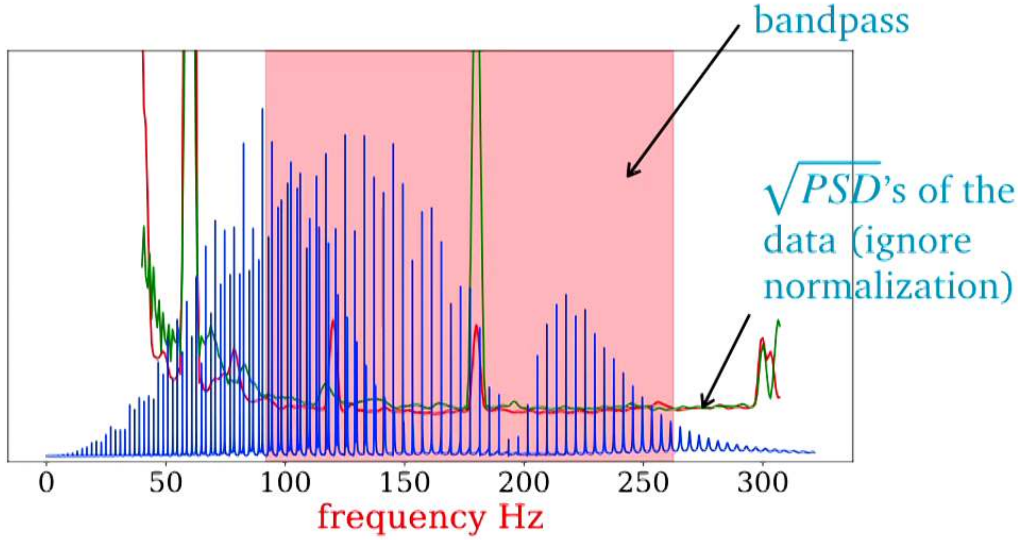
same analysis for each event

- express comb spacing Δf as an integer $n = \Delta f/(1/T) = T/\Delta t$
- plot the correlation as a function of n and look for a peak
- can vary Δt and T while holding the peak at some $n = N_E$

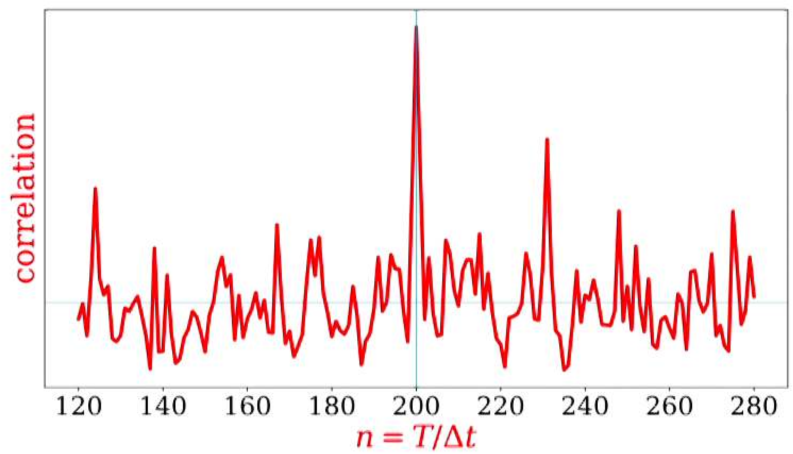
- optimize the signal (the peak height):
  - vary N_E (some multiple of 10)
  - vary the frequency bandpass $f_{\rm min} < f < f_{\rm max}$

- compare this bandpass and the reconstructed $|\psi_\omega|$ from $M, \chi, \Delta t, N_E$
  - are they consistent with each other?

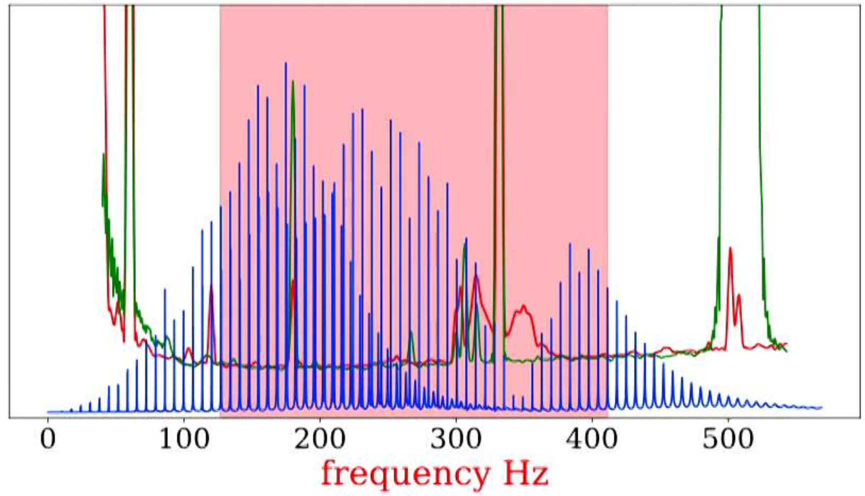
GW150914



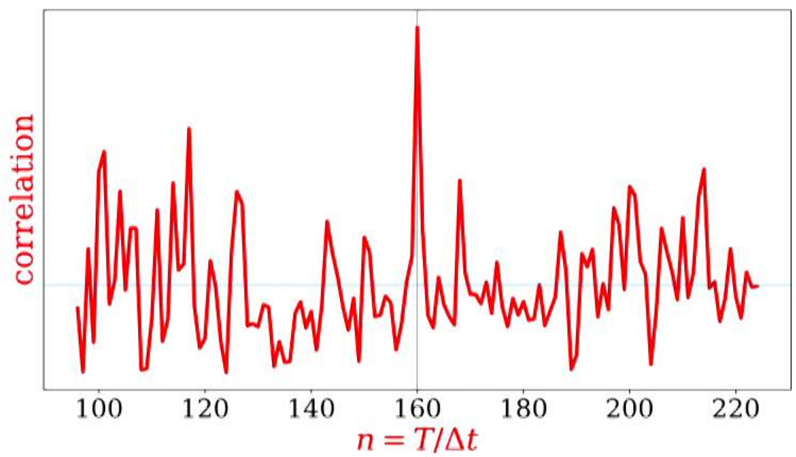
N_E	200
Δt	0.251s
$\frac{\Delta t}{M}$	806



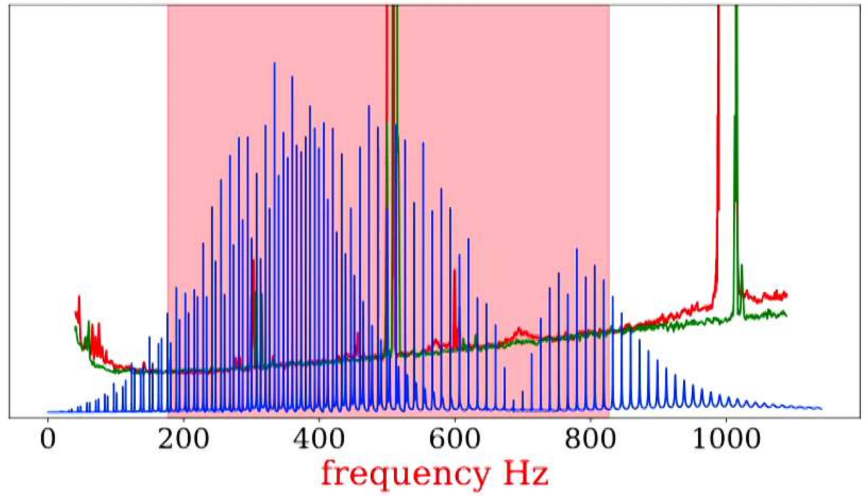
GW151012



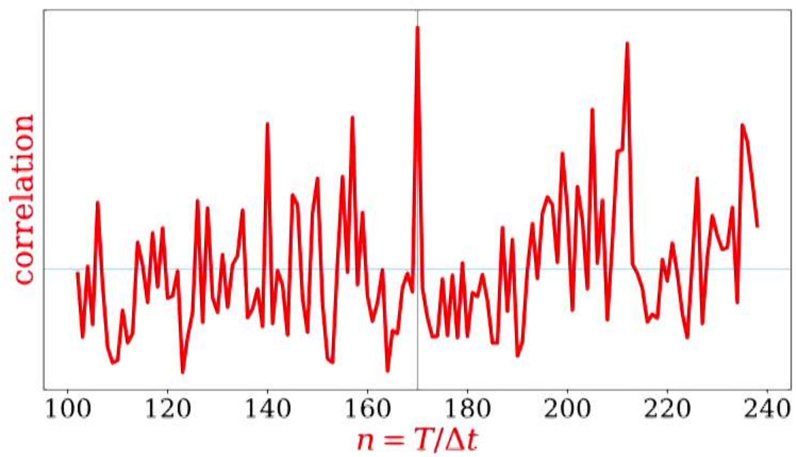
N_E	160
Δt	0.145s
$\frac{\Delta t}{M}$	826



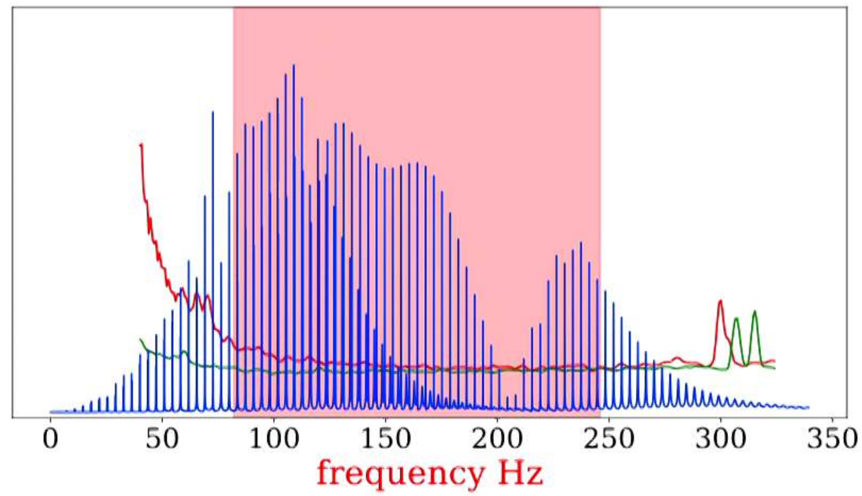
GW170608



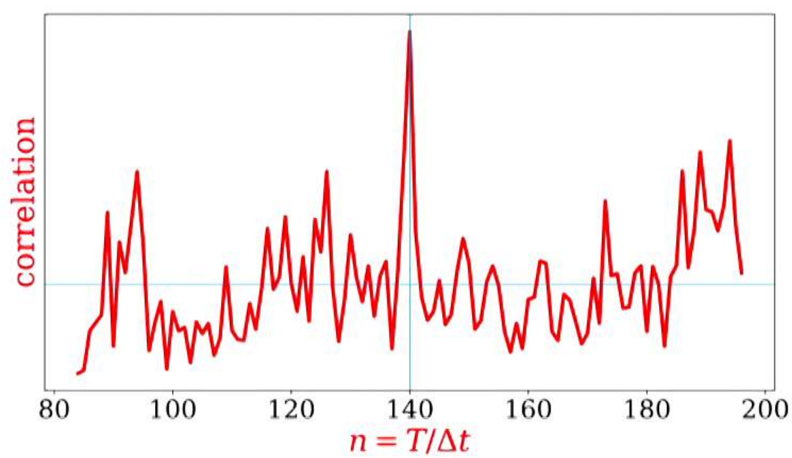
N_E	200
Δt	0.0756s
$\frac{\Delta t}{M}$	862



GW170818

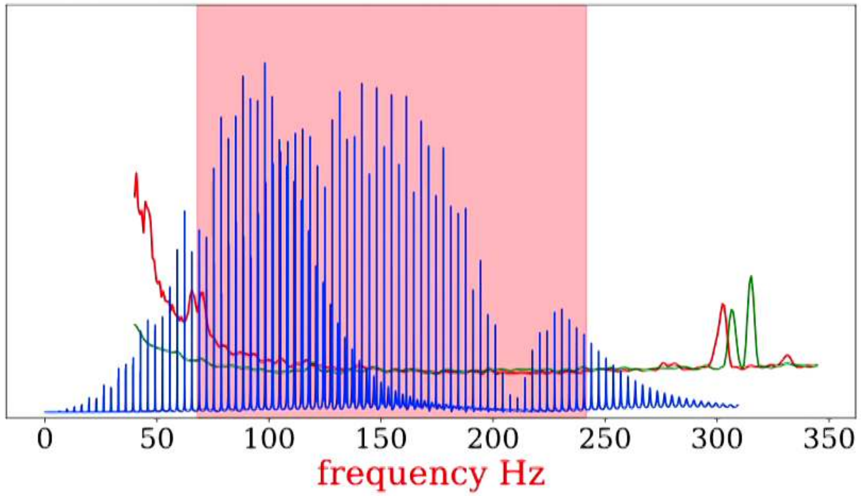


N_E	140
Δt	0.275s
$\frac{\Delta t}{M}$	933

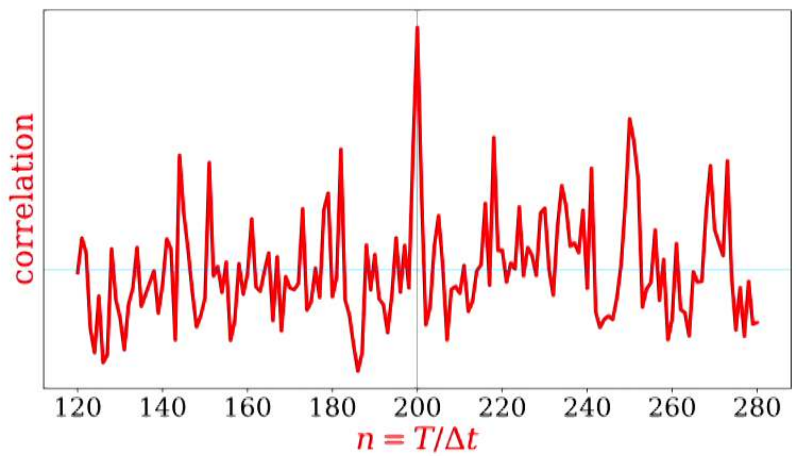


$\chi = 0.72$

GW170823



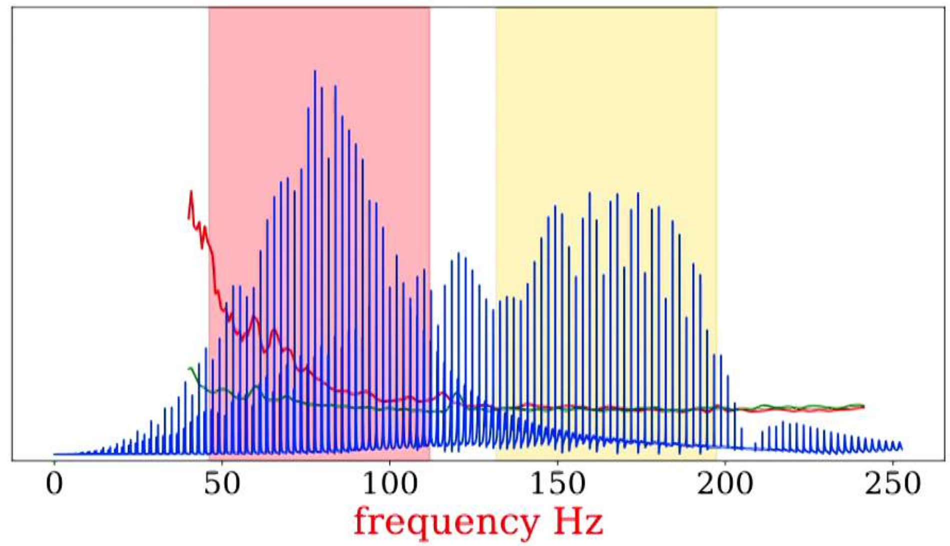
N_E	200
Δt	0.305s
$\frac{\Delta t}{M}$	942

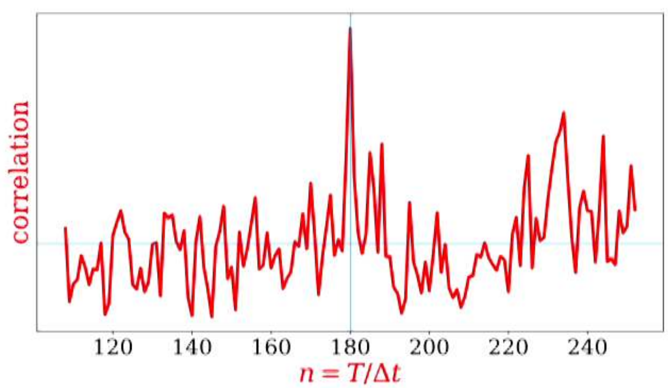


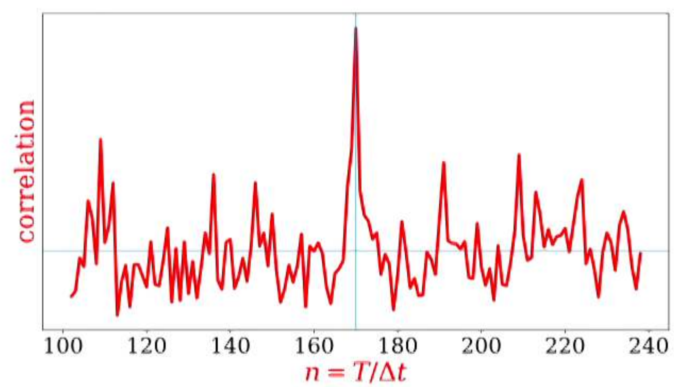
$\chi = 0.81$

GW170729

N_E	180/170
Δt	0.489s
$\frac{\Delta t}{M}$	1240







- Δt for a truncated Kerr BH has known dependence on mass M, spin χ and redshift z

$$\frac{\Delta t}{M} = 4\,\eta \log(\frac{M}{\ell_{\rm Pl}})\,(\frac{1+(1-\chi^2)^{-\frac{1}{2}}}{2})\,(1+z)$$

- a resonance signal determines Δt with negligible error
- LIGO measures M, χ and z of final BH with uncertainties
- thus determine an η for each event

- η determines δr, the distance from the would-be horizon to where the deviation from the BH metric occurs

$$\delta r \approx \left(\frac{\ell_{\rm Pl}}{M}\right)^{(\eta-1)} \ell_{\rm Pl} \approx \left(\frac{M}{\ell_{\rm Pl}}\right)^{(2-\eta)} \text{(proper Planck length)}$$

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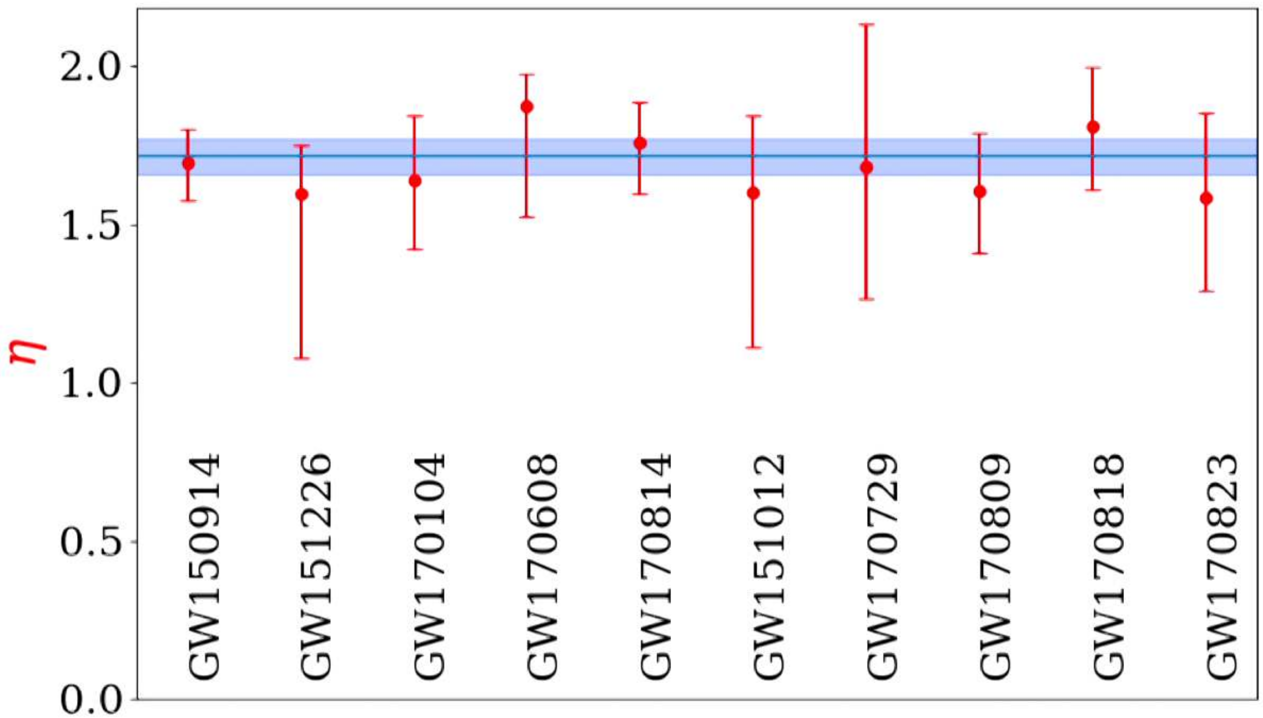
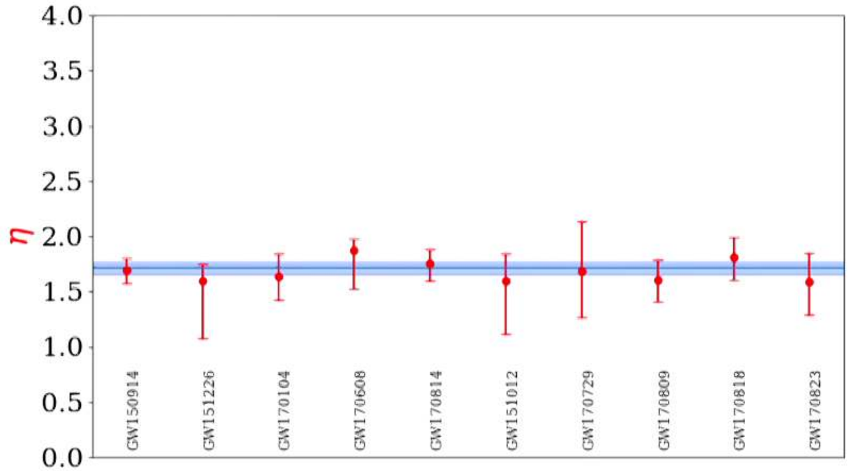
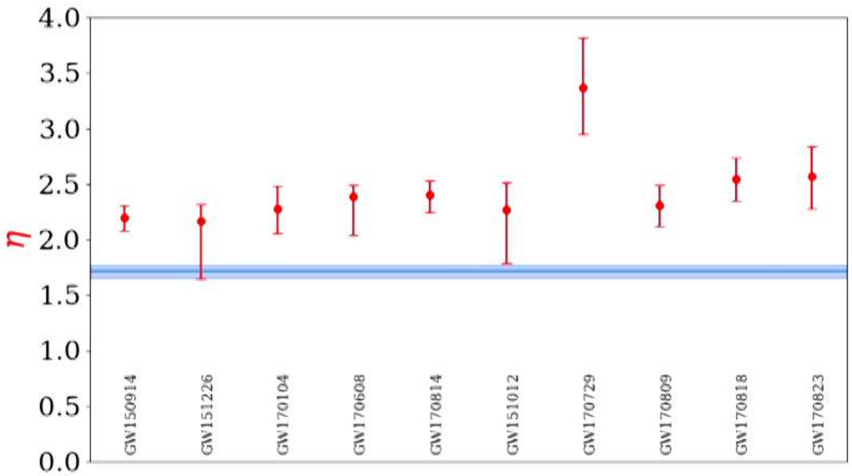


- $\eta = 1.7$ means that $\delta r \approx 10^{-28} \ell_{\rm Pl} \approx 10^{12} \times$ (proper Planck length)

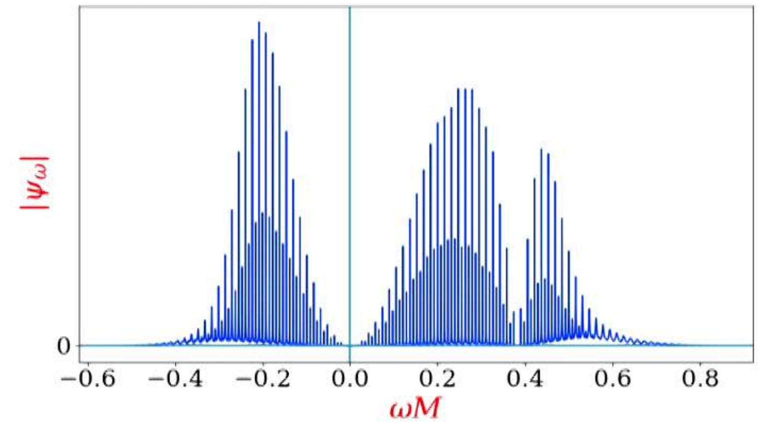


- same a previous plot

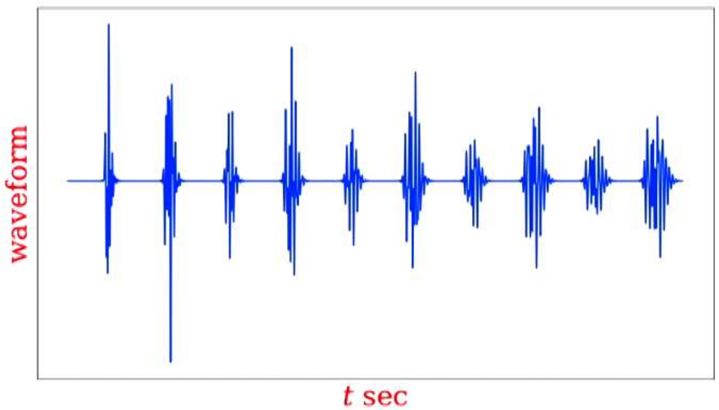


- remove the spin and red-shift factors from the formula for η
- then $\eta > 2$
- draws attention to GW170729

$$\psi_\omega = K(\omega)D(\omega)$$

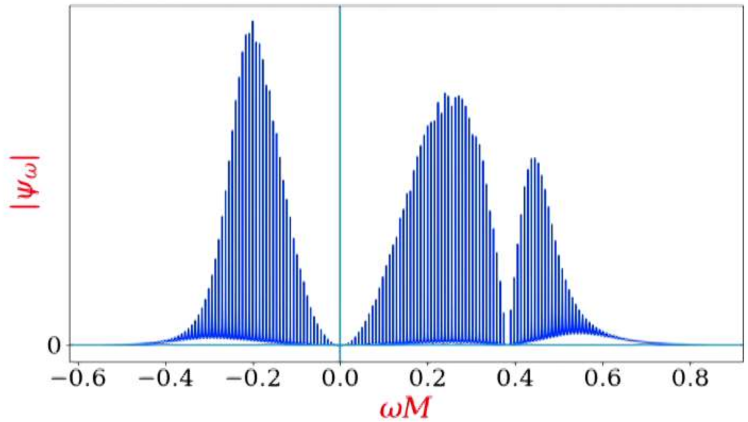


- ingoing pulse starting near potential barrier and smaller outgoing pulse starting near wall
- every second spike is suppressed

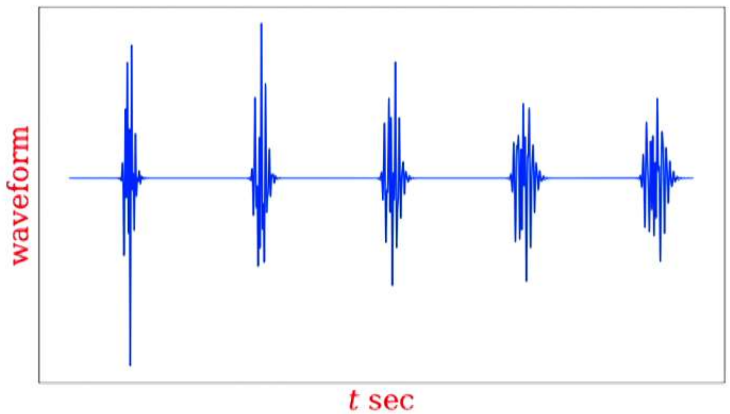


- interleaved echoes

$$\psi_\omega = K(\omega)D(\omega)$$

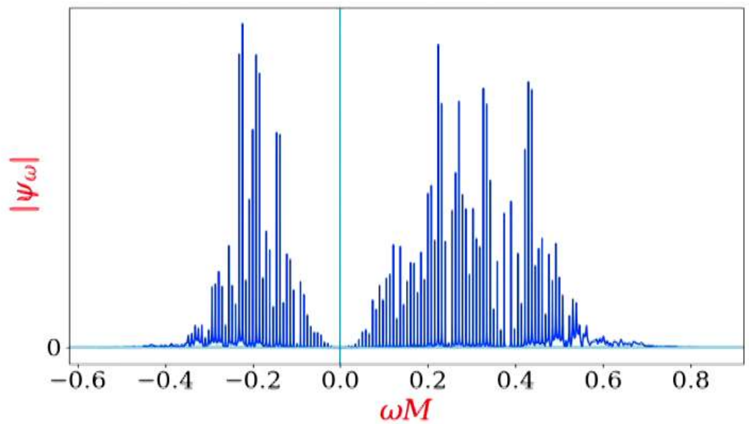


- single pulse
- notice the zero at ω_0 and some enhancement of negative frequencies

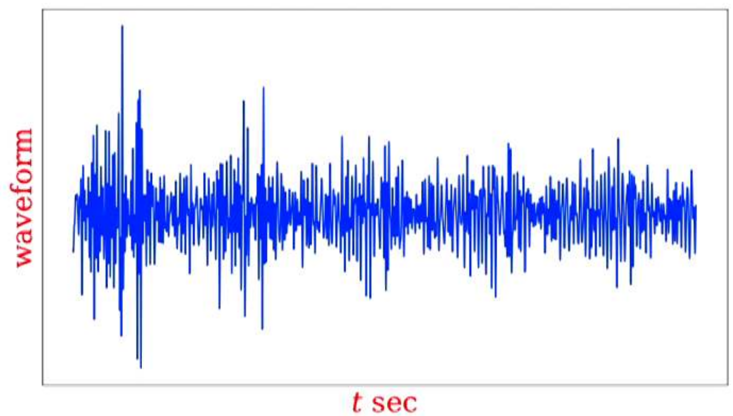


- origin of irregular echoes

$$\psi_\omega = K(\omega)D(\omega)$$



- 100 random pulses to simulate nontrivial perturbation throughout the cavity
- resonance structure is still present



- echo structure is gone

Conclusions

- LIGO is sensitive to not quite black holes
- this sensitivity to Planck scale physics is under appreciated

- signal waveform may be too variable and complicated for template analysis
- equally spaced resonance pattern is robust and relatively easy to search for
  - there is still a two component structure to explore

- evidence is already accumulating from all 10 events
  - consistency of bandpasses with predicted spectrum
  - consistency of $\Delta t/M$ values with spin and red-shift dependence
  - sometimes secondary signals at $\Delta t/2$ (interleaved echoes)