Copernicus Webinar Series, 4 May 2021

Black Holes *Unscripted*

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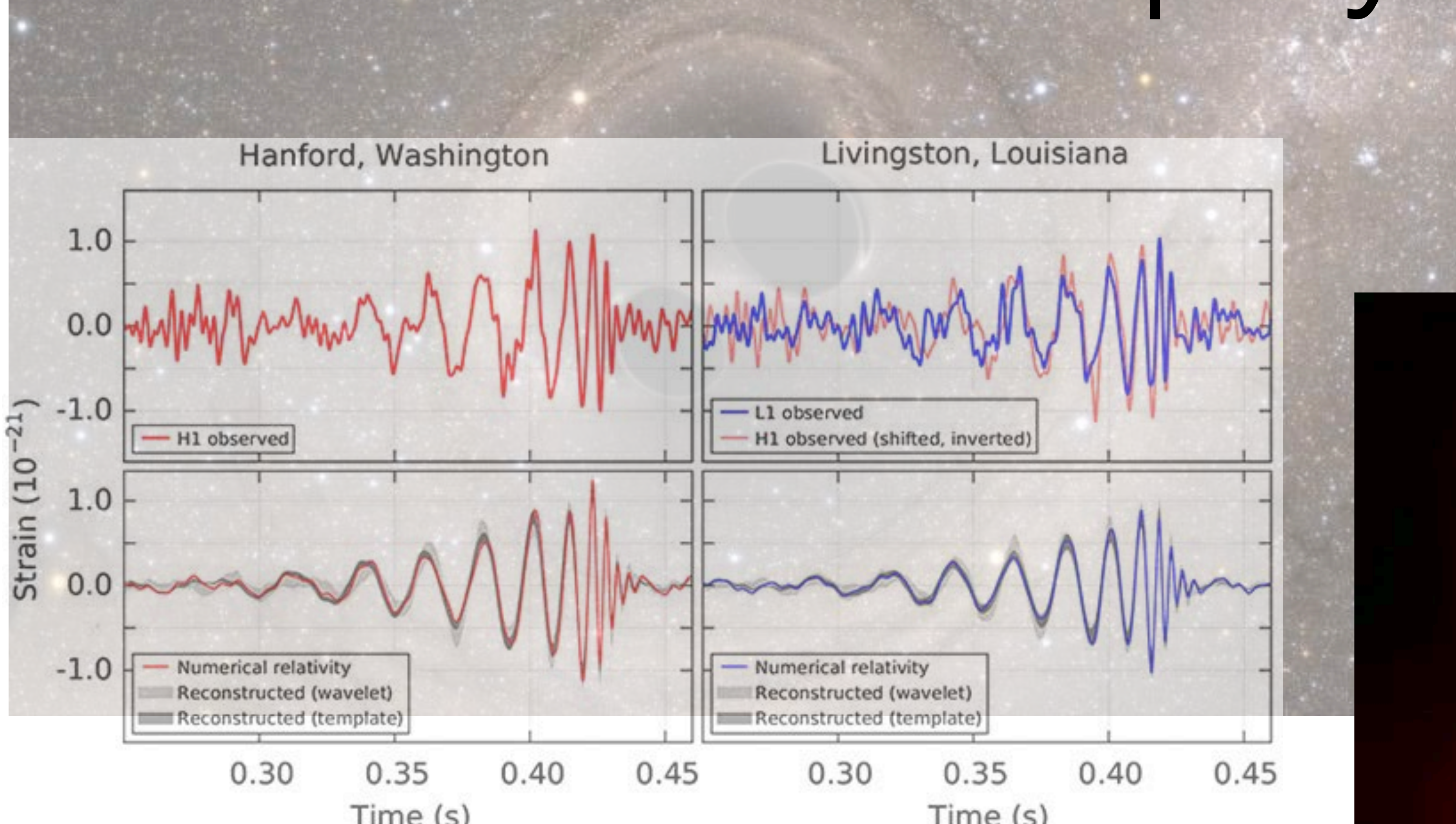
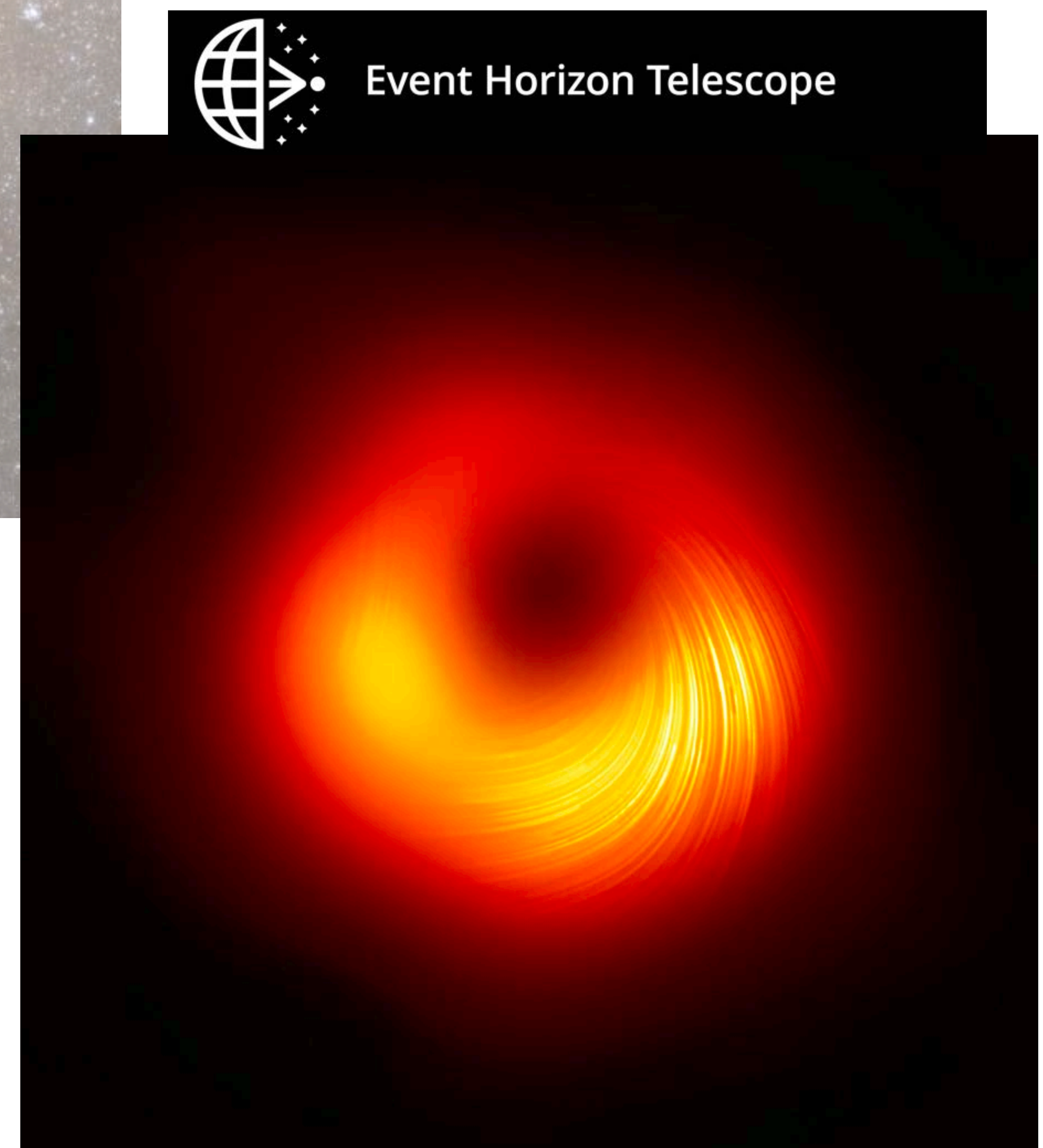
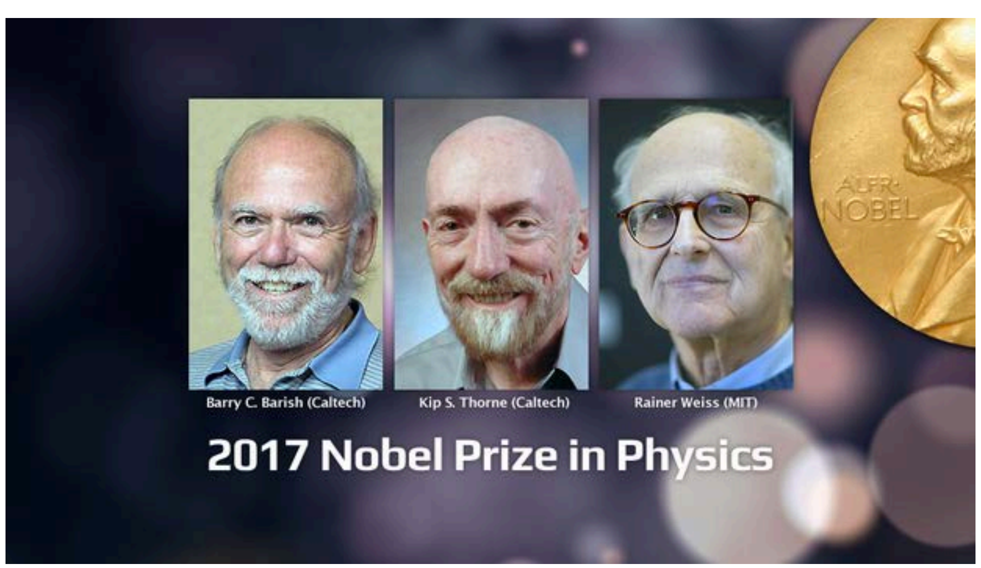
Golden Age of Black Hole Astrophysics







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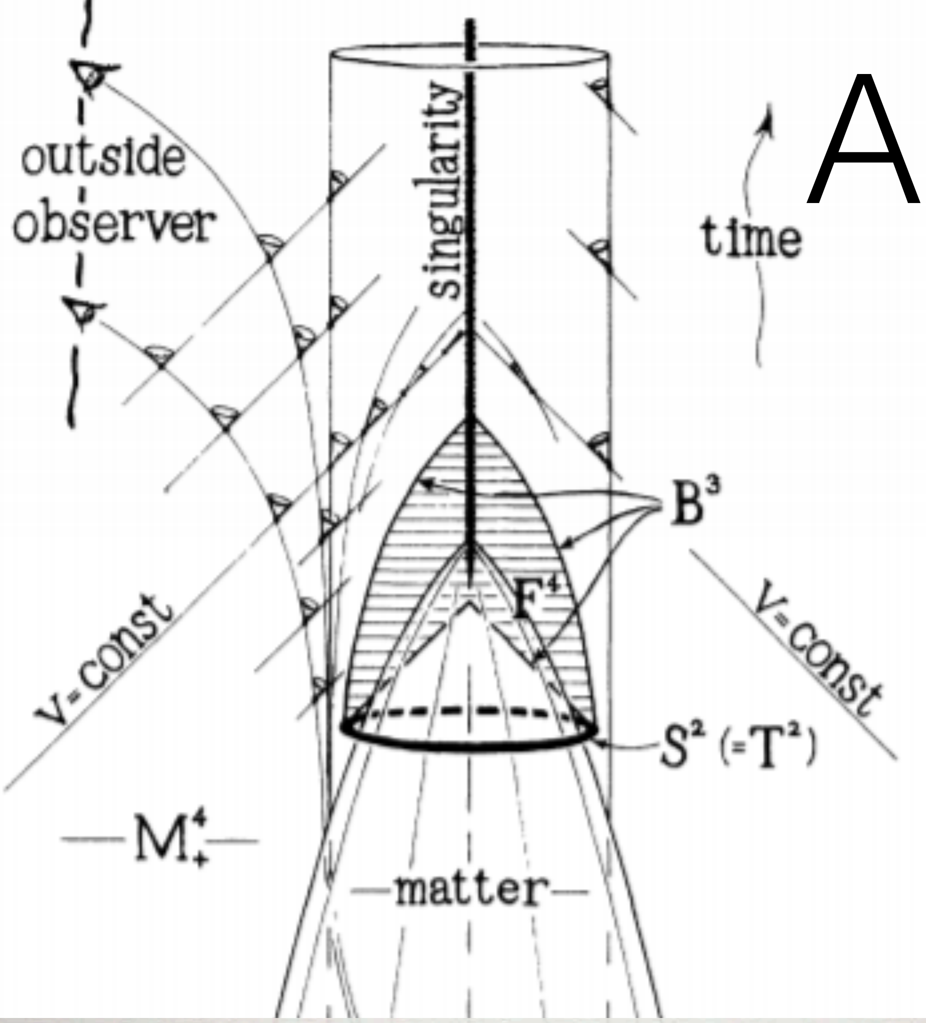

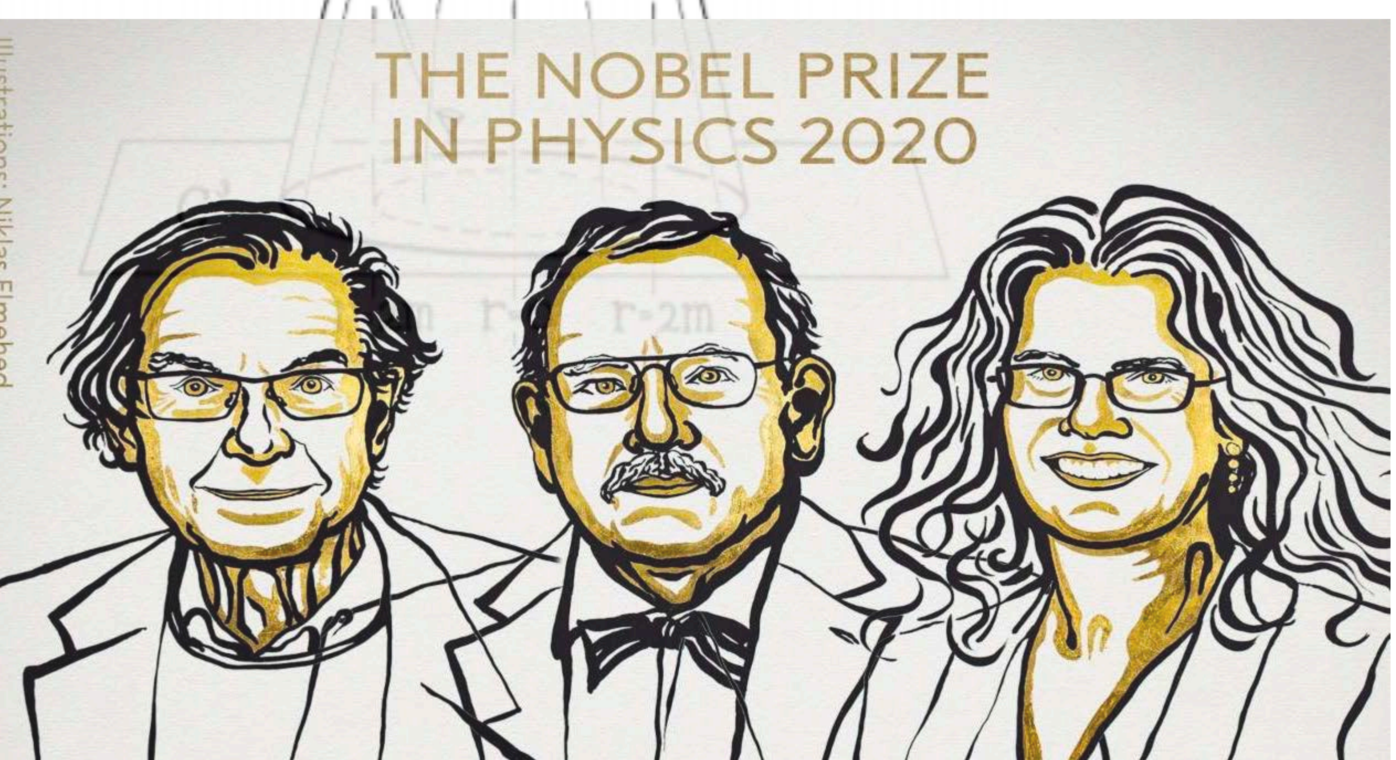

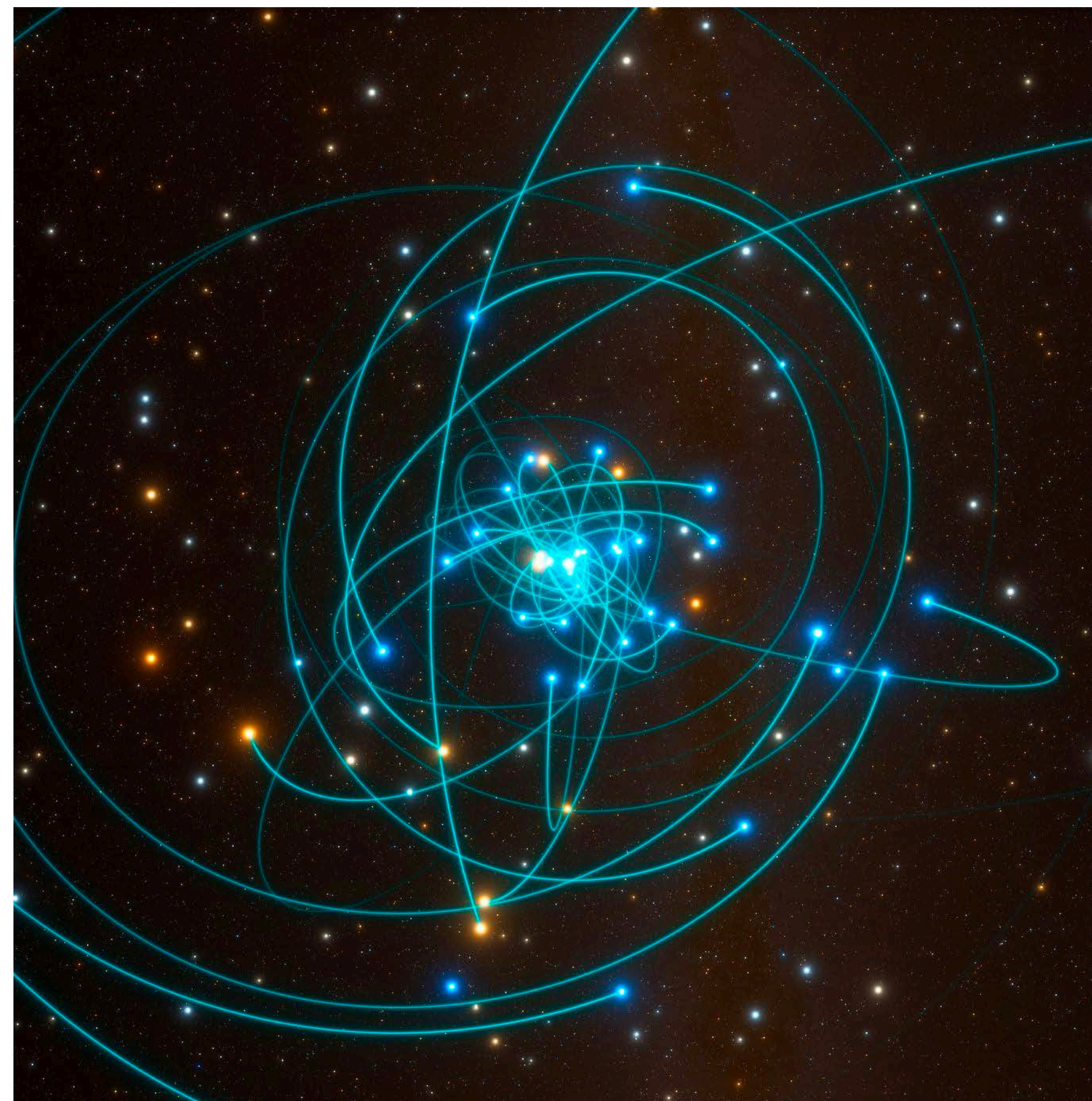

Outline

- Black Holes, the Script
- Black Holes, Unscripted!
- Quantum Black Holes: From Fairy tale to Physics
- Conclusions

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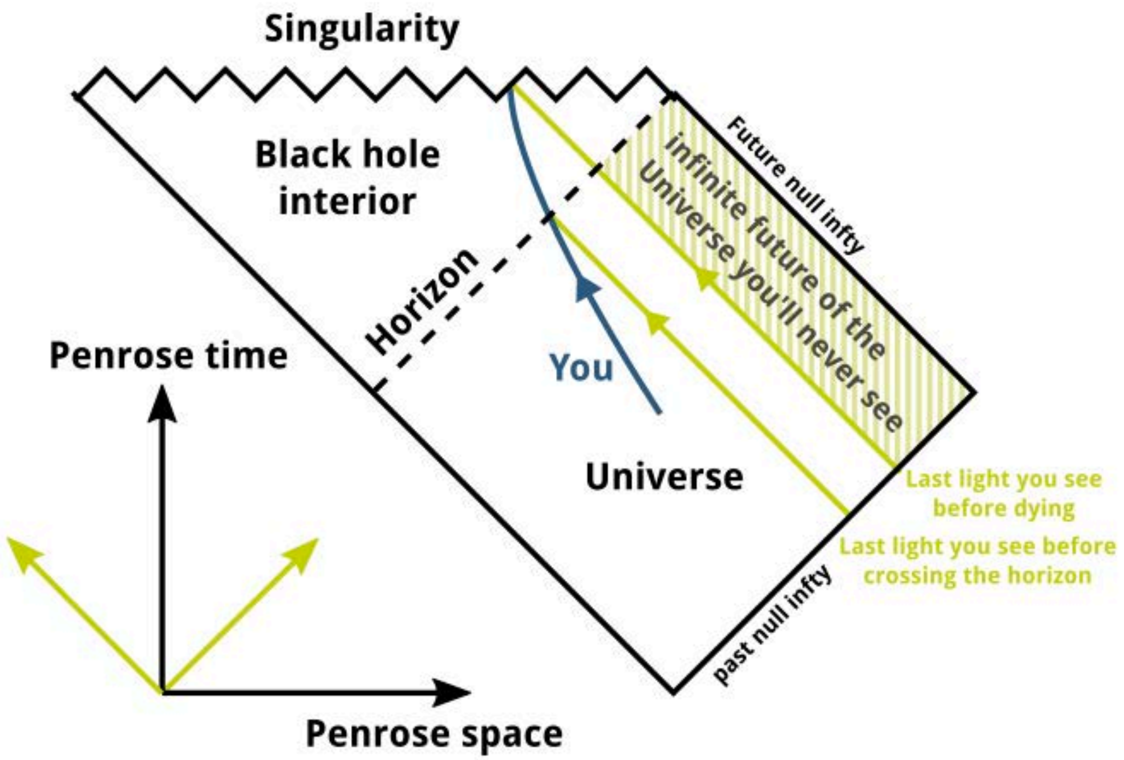
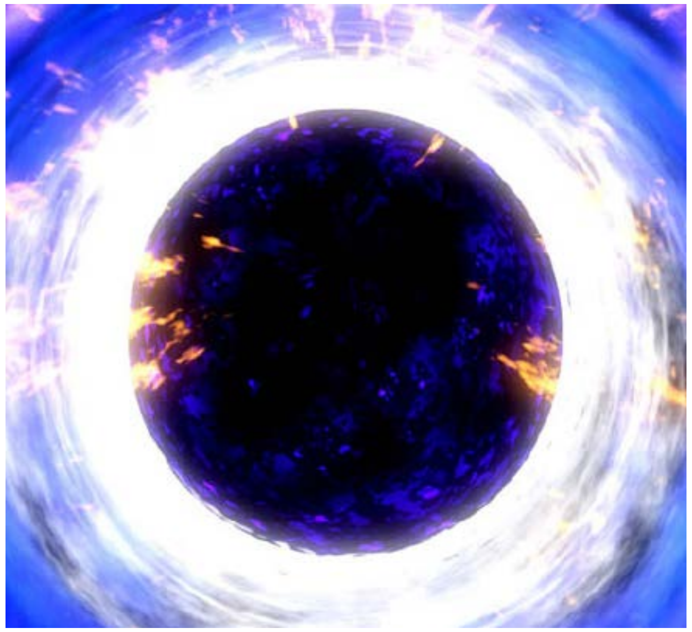
Event Horizons in Relativity

- Global structure of some spacetimes lead to event horizons
- In classical GR, local observers experience “no drama” at horizon





Black Hole Thermodynamics

- Black Holes have temperature: $T = \dfrac{a}{2\pi}$
- Black Holes have entropy: $S = \dfrac{\text{Horizon Area}}{4G}$
- 1st & 2nd laws of thermodynamics:

$$dE = TdS + \Omega dJ + \Phi dQ \qquad\qquad \frac{dS}{dt} \geq 0$$

Bardeen, Carter, Hawking (1973), Bekenstein (1973), Hawking (1975), Unruh (1976)

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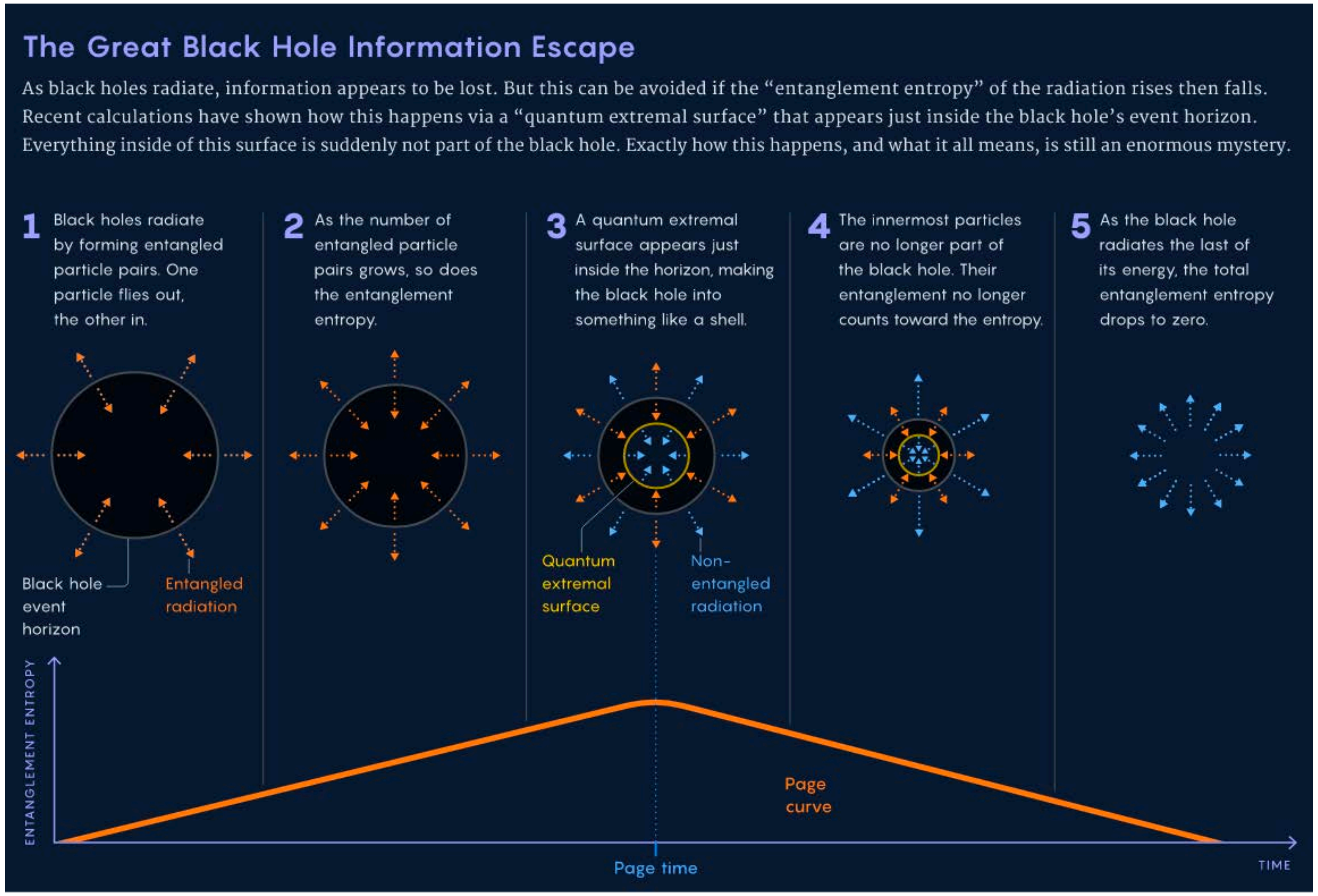
Which states does this entropy count?!

Story of Black Hole Evaporation

- Assume semi-classical evaporation
- Invent rules to match the story!
- Testable predictions?
- What do we learn about Quantum Gravity?



Pennington, Almheiri, et al., Marolf & Maxfield, …
(Image courtesy of Quanta magazine)

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What is wrong with the story?

- **Information paradox:** unitary black hole evaporation, not consistent with local physics+smooth horizon *(Hawking … AMPS 2013)*

- **Quantum Tunnelling:** *exp(-S_E)x exp(entropy) ~ 1* ➞ collapsing stars tunnel to a generic Quantum Gravity state at *O(1)* probability *(Mathur 2008)*

- **Dark Energy:** equilibrium with stellar BH's ➞ scale of dark energy+no horizon
(Presocd-Weinstein, NA, Balogh 2009, Hergott & NA, in prep.)

Firewall Paradox

The following assumptions are inconsistent

1. Unitarity of quantum mechanics

2. Equivalence principle, or *“no drama”*

3. Quantum field theory beyond a Planck length away from the horizon

4. Dimension of the Hilbert space of a black hole being exp(A/4)

Almheiri, Marolf, Polchinski & Sully 2012 (AMPS), Mathur 2008

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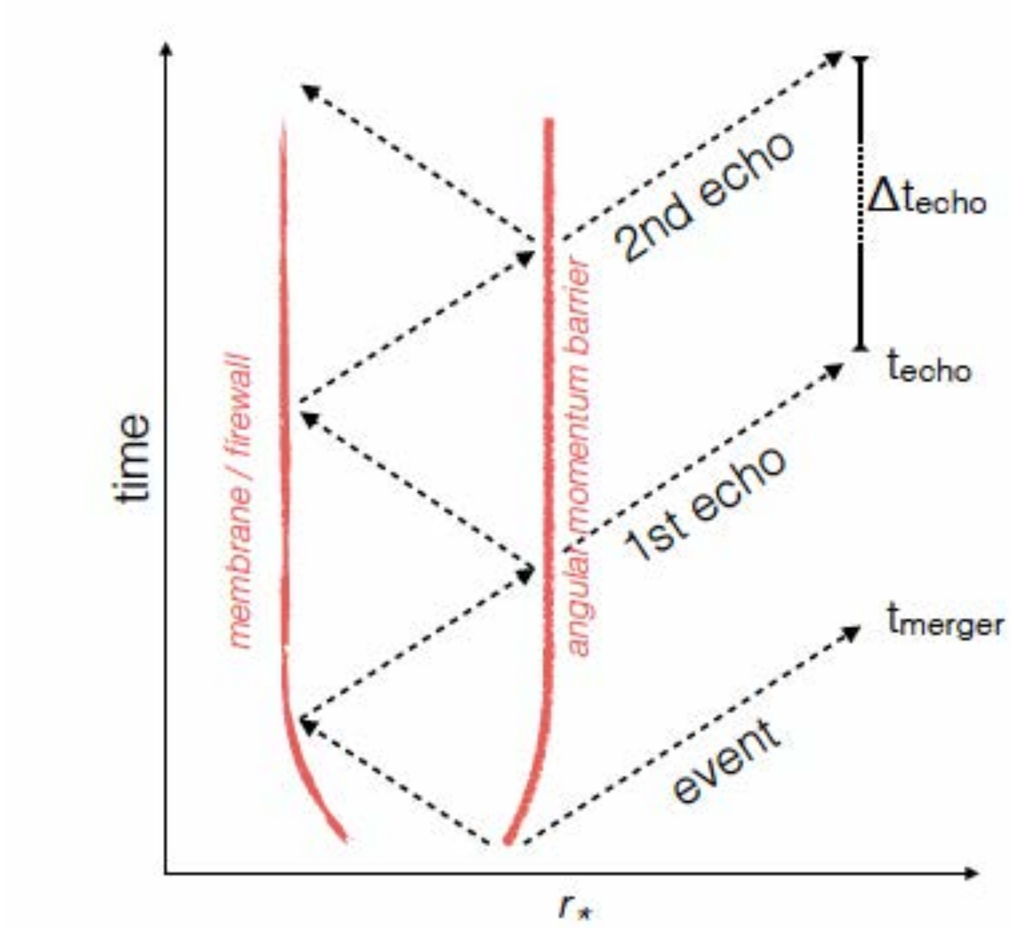
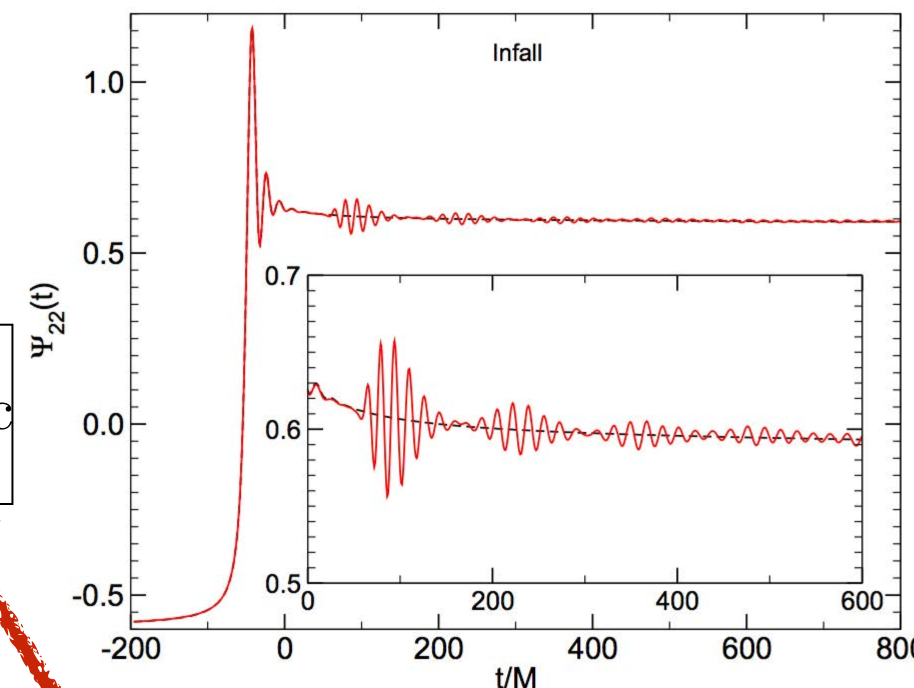
Echoes from the Abyss!

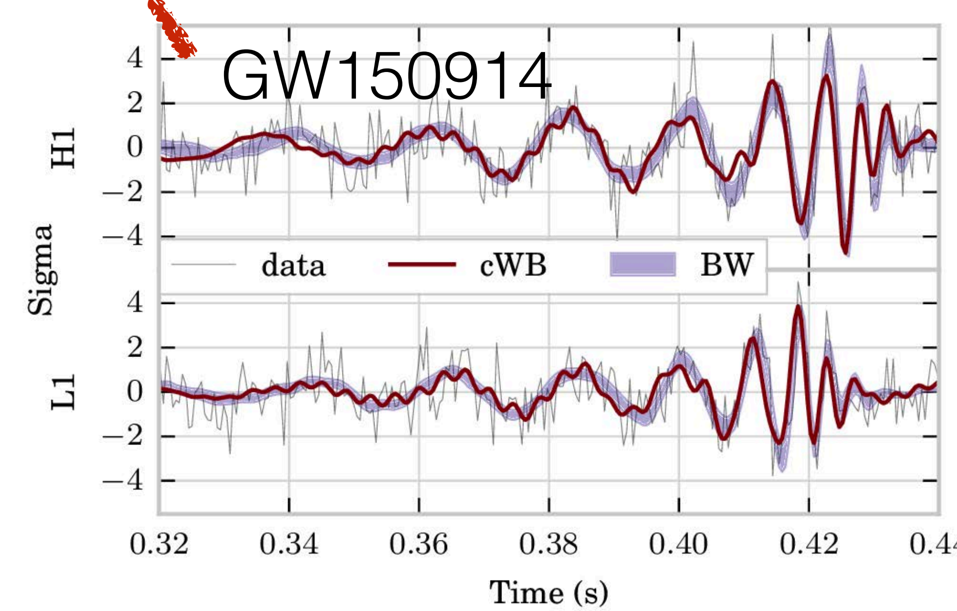
- Delayed echoes from Planckian structure near horizon

$$\Delta t_{\rm echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a_*^2}}\right)\times \ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right) \simeq 0.3 \text{ sec}$$



Cardoso, et al. 16





Universal Reflectivity of Quantum Horizons

- Three independent arguments for Boltzmann reflectivity:

  (1) *Fluctuation-Dissipation Theorem*

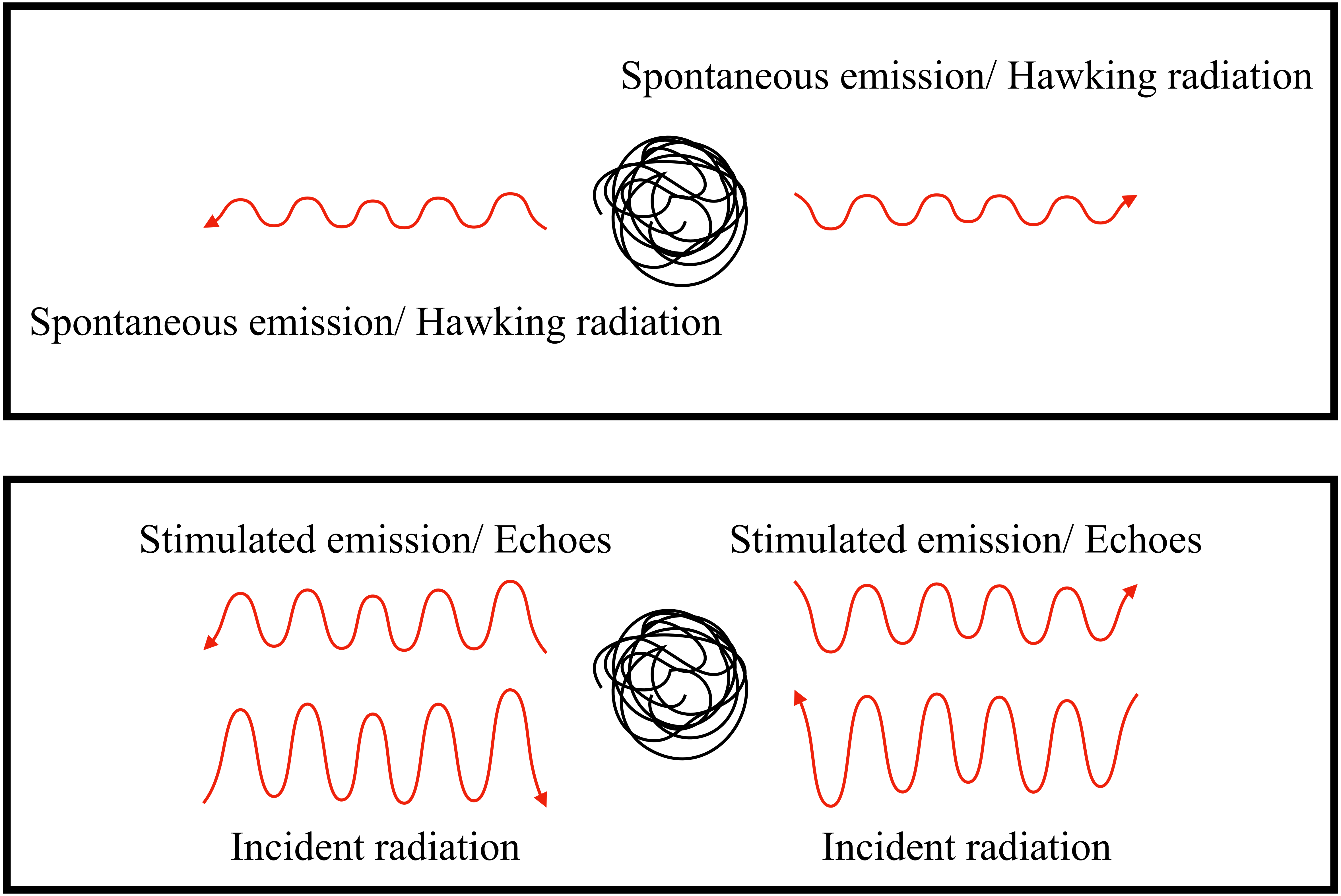
  (2) Thermodynamic Detailed Balance

  (3) CP-symmetry

- **Echoes are stimulated Hawking Radiation**

$$R = \exp\left(-\frac{\hbar\omega}{kT_H}\right)$$

Oshita, Wang & NA 2020
Wang, Oshita, & NA 2020



Spontaneous emission/ Hawking radiation
Spontaneous emission/ Hawking radiation
Stimulated emission/ Echoes
Stimulated emission/ Echoes
Incident radiation
Incident radiation

CP-symmetry (RP^3 geon)

Black hole microstates vs the additivity conjectures

Patrick Hayden[1] and Geoff Penington,[2]

[1] *Stanford Institute for Theoretical Physics, Stanford University, Stanford CA 94305 USA*
[2] *Center for Theoretical Physics,, University of California, Berkeley, CA 94720 USA*

December 16, 2020

Abstract

We argue that one of the following statements must be true: (a) extensive violations of quantum information theory's additivity conjectures exist or (b) there exists a set of 'disentangled' black hole microstates that can account for the entire Bekenstein-Hawking entropy, up to at most a subleading $O(1)$ correction. Possibility (a) would be a significant result in quantum communication theory, demonstrating that entanglement can enhance the ability to transmit information much more than has currently been established. Option (b) would provide new insight into the microphysics of black holes. In particular, the disentangled microstates would have to have nontrivial structure at or outside the black hole horizon, assuming the validity of the quantum extremal surface prescription for calculating entanglement entropy in AdS/CFT.

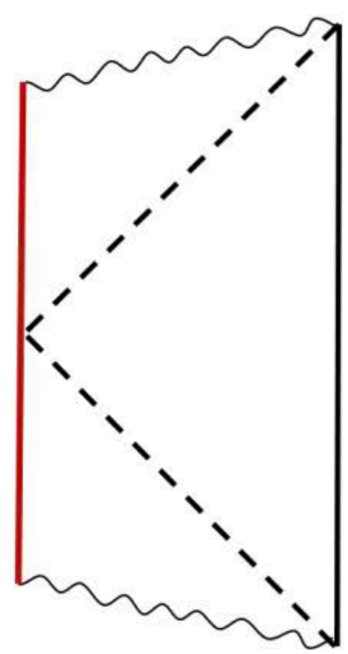
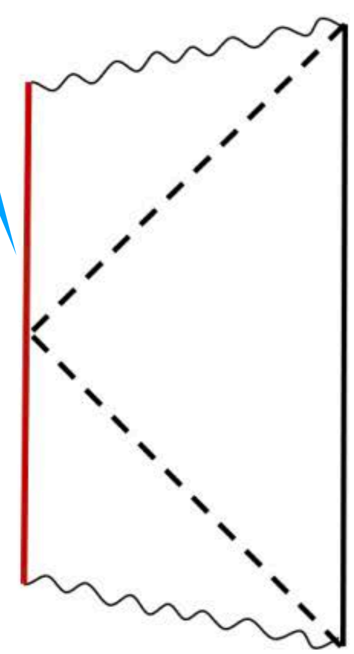


Figure 3: Penrose diagram for a $\mathbb{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

CP-symmetry (RP^3 geon)

Z_2 identification → Boltzmann reflection



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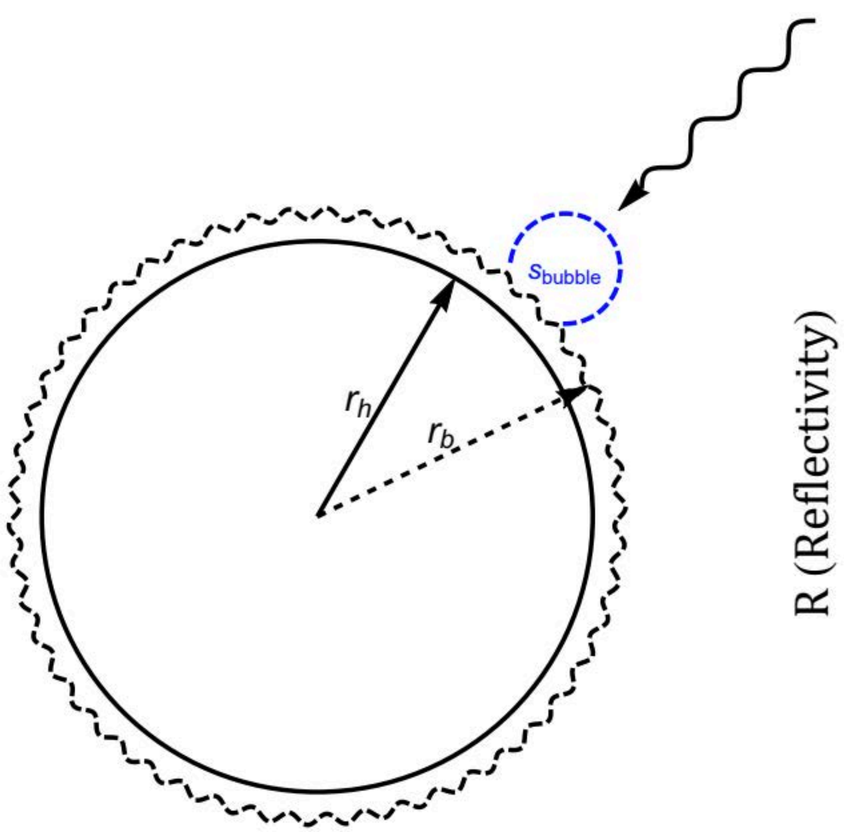
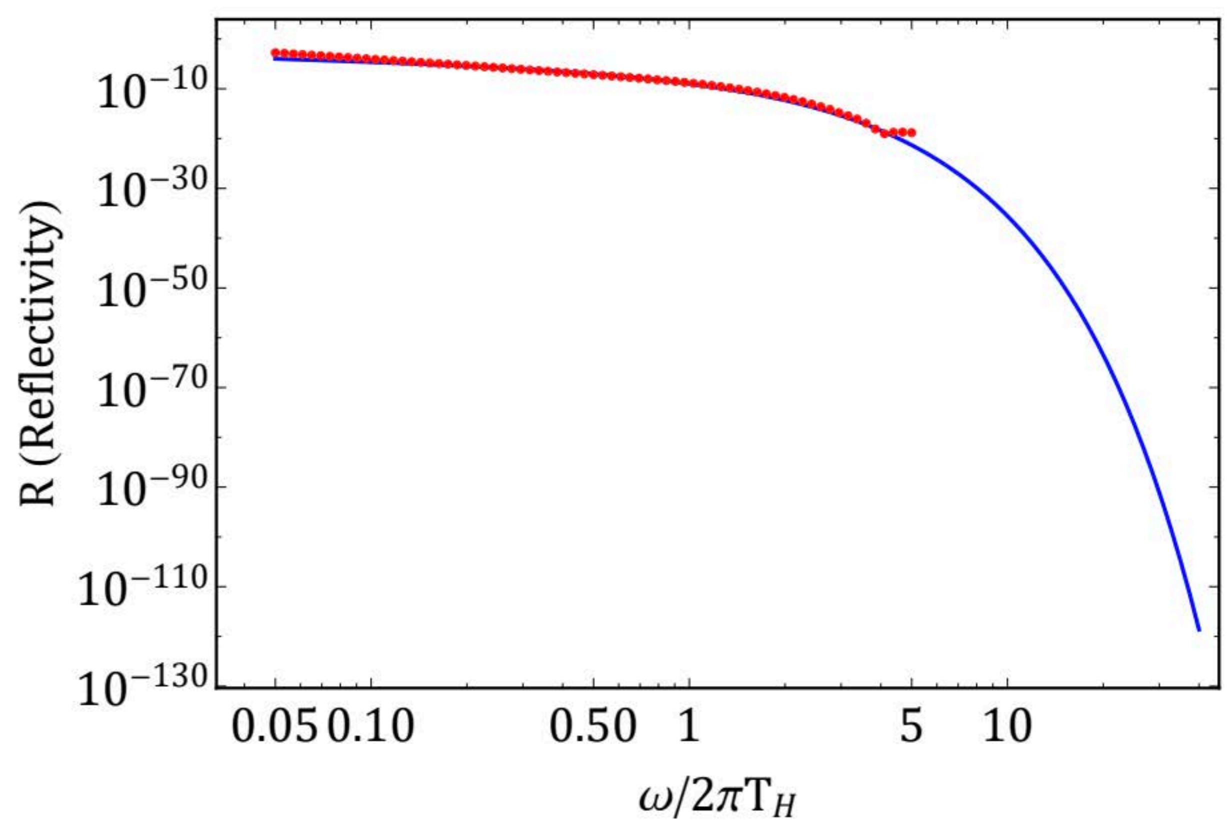
Electromagnetic Albedo of Quantum Black Holes *(w/ Wan Zhen Chua)*

- Reflection off virtual electron-positron pairs near horizon → Boltzmann Albedo for photons
- No quantum gravity needed!





Black Holes as Fast Scramblers of Quantum Information

[Submitted on 15 Aug 2008]

Fast Scramblers

Yasuhiro Sekino, Leonard Susskind

We consider the problem of how fast a quantum system can scramble (thermalize) information, given that the interactions are between bounded clusters of degrees of freedom; pairwise interactions would be an example. Based on previous work, we conjecture:
1) The most rapid scramblers take a time logarithmic in the number of degrees of freedom.
2) Matrix quantum mechanics (systems whose degrees of freedom are n by n matrices) saturate the bound.
3) Black holes are the fastest scramblers in nature.
The conjectures are based on two sources, one from quantum information theory, and the other from the study of black holes in String Theory.

Comments: 19 pages, 1 figure
Subjects: **High Energy Physics - Theory (hep-th)**; Quantum Physics (quant-ph)
Journal reference: JHEP 0810:065,2008

$$\tau = \frac{t_*}{\beta} = C \log N$$

Scrambling Time=Echo Time!

Quantum nature of black holes: fast scrambling versus echoes

Krishan Saraswat & Niayesh Afshordi

Journal of High Energy Physics **2020**, Article number: 136 (2020) | Cite this article

ABSTRACT

Two seemingly distinct notions regarding black holes have captured the imagination of theoretical physicists over the past decade: first, black holes are conjectured to be fast scramblers of information, a notion that is further supported through connections to quantum chaos and decay of mutual information via AdS/CFT holography. Second, black hole information paradox has motivated exotic quantum structure near horizons of black holes (e.g., gravastars, fuzzballs, or firewalls) that may manifest themselves through delayed gravitational wave echoes in the aftermath of black hole formation or mergers, and are potentially observable by LIGO/Virgo observatories. By studying various limits of charged AdS/Schwarzschild black holes we show that, if properly defined, the two seemingly distinct phenomena happen on an identical timescale of log(Radius)/($\pi \times$ Temperature). We further comment on the physical interpretation of this coincidence and the corresponding holographic interpretation of black hole echoes.

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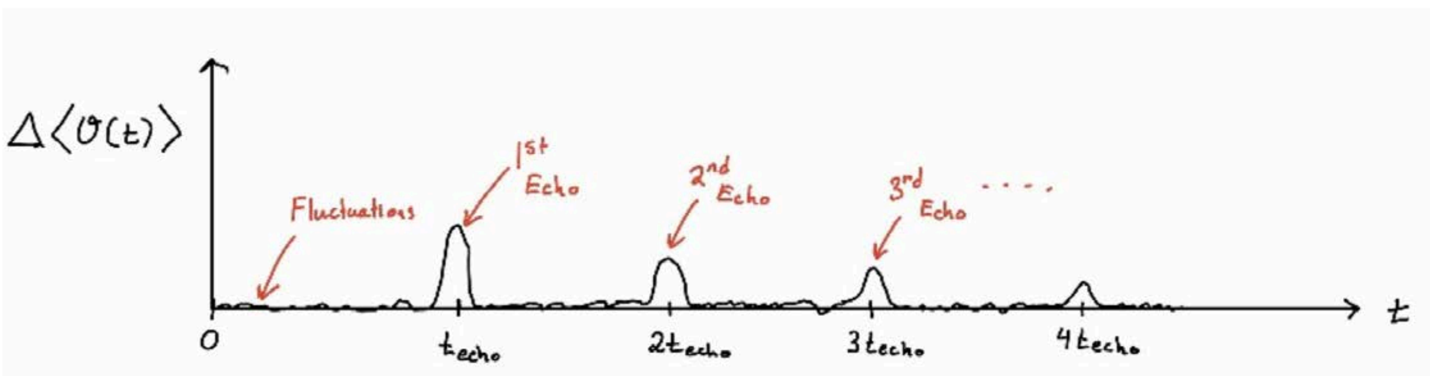
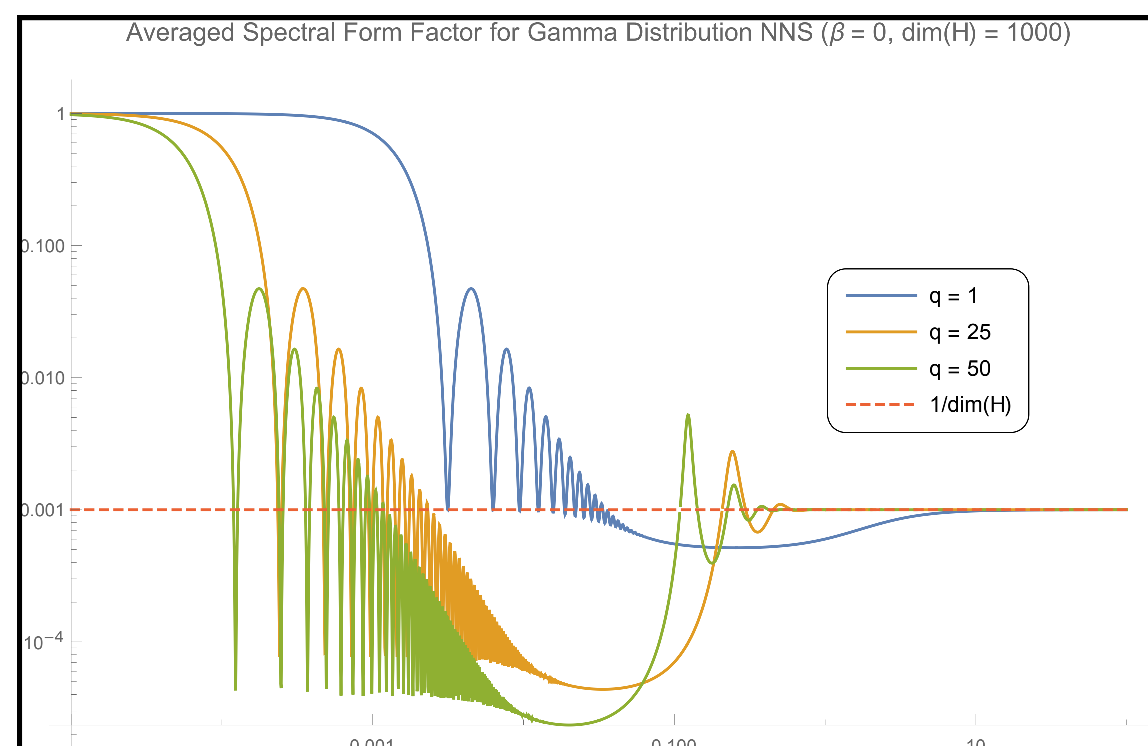
Towards a Holographic Understanding of Echoes

- From Boundary Out-of-time-order correlators (Saraswat & NA 2020)



- From Spectral form-factor of random matrices (Saraswat & NA, in prep)



August 29, 2018

SU-ITP-16/19
YITP-16-124

Black Holes and Random Matrices

Jordan S. Cotler[a], Guy Gur-Ari[a], Masanori Hanada[abc], Joseph Polchinski[de],
Phil Saad[a], Stephen H. Shenker[a], Douglas Stanford[f],
Alexandre Streicher[ad], and Masaki Tezuka[g]

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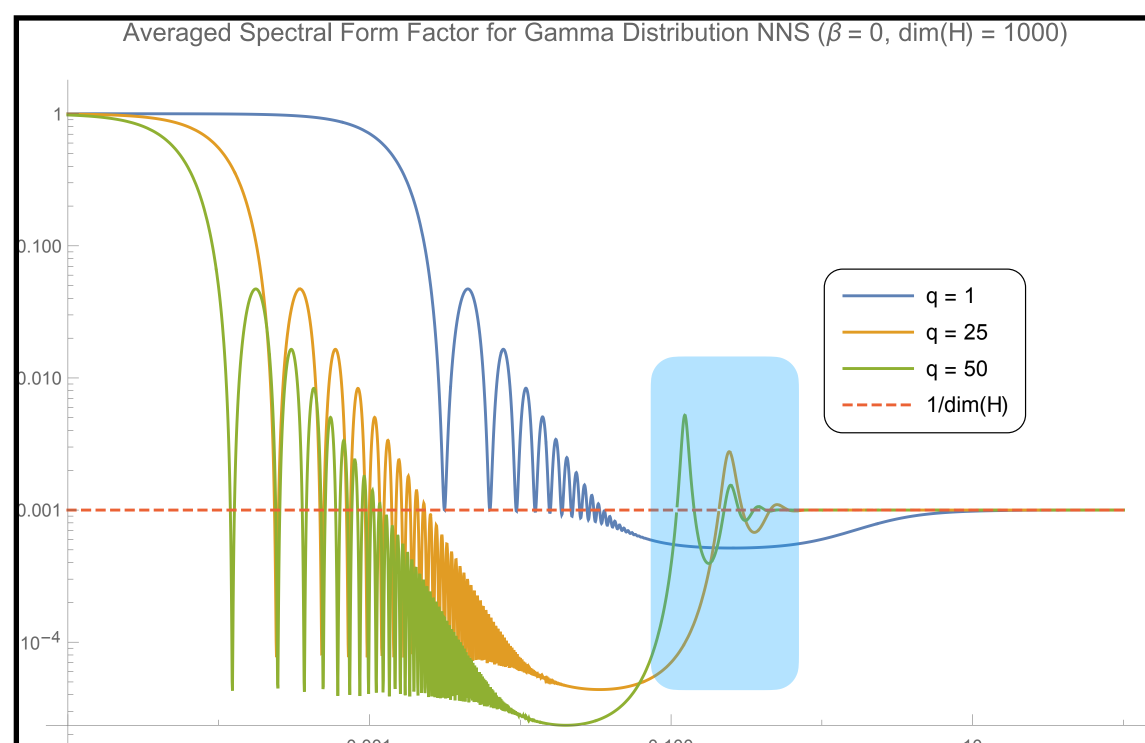
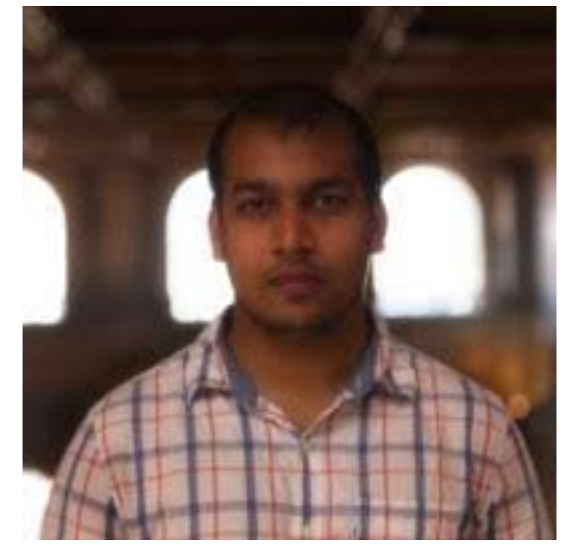


Echoes in Kerr/CFT

(w/ Ramit Dey)



- modular identification of 1+1 CFT also leads to Boltzmann echoes, *a la* "Hidden Conformal Symmetry of the Kerr Black Hole"

[hep-th] 7 Apr 2010

Hidden Conformal Symmetry of the Kerr Black Hole

Alejandra Castro◇, Alexander Maloney◇ and Andrew Strominger†

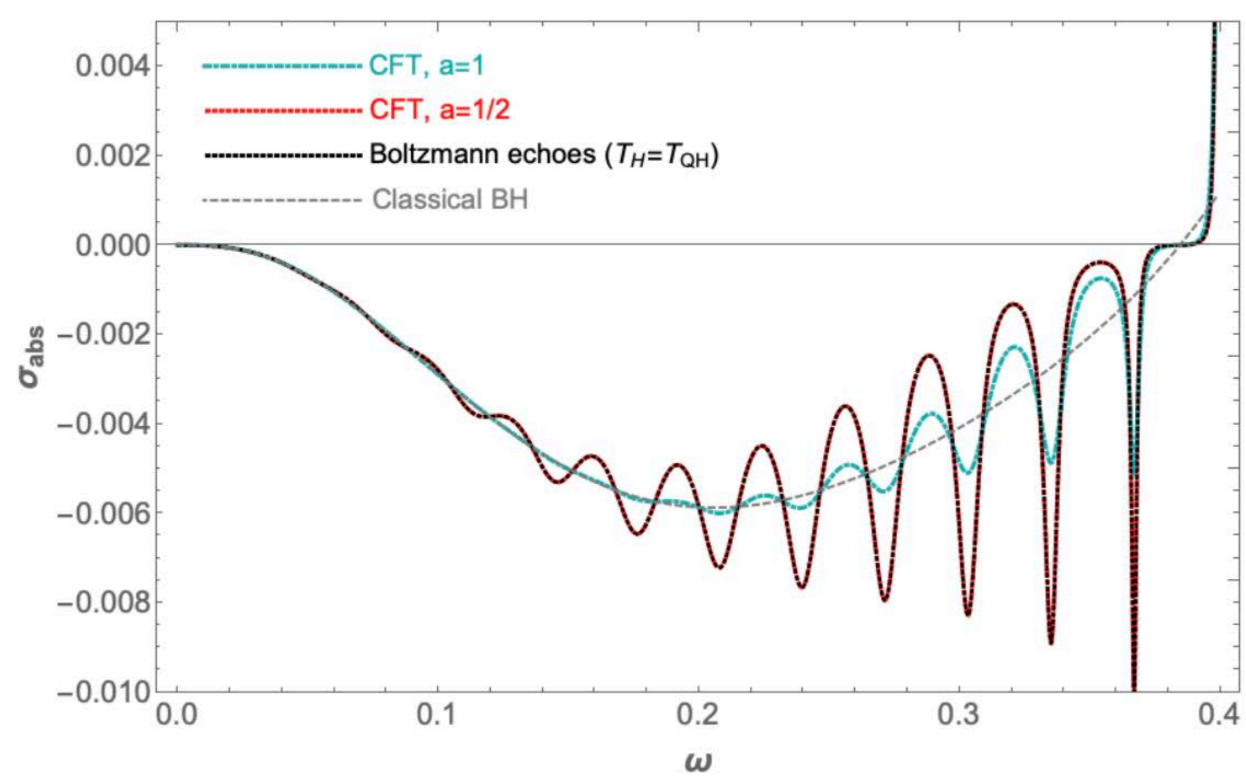
◇*Physics Department, McGill University, Montreal, CA*

†*Center for the Fundamental Laws of Nature, Harvard University, Cambridge, MA, USA*

$$T_L = M^2/2\pi J \text{ and } T_R = \sqrt{M^4 - J^2}/2\pi J$$

$$c_L = c_R = 12J$$

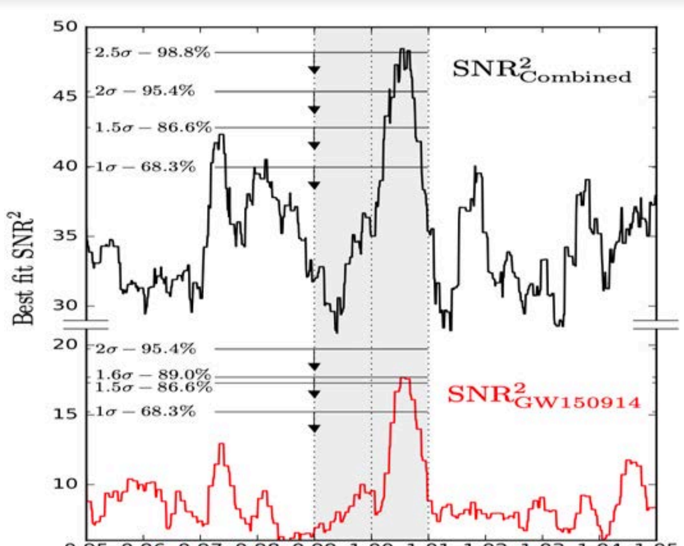
$$S_{micro} = \frac{\pi^2}{3}(c_L T_L + c_R T_R) = 2\pi(M^2 + \sqrt{M^4 - J^2}) = \frac{\text{Area}}{4}$$

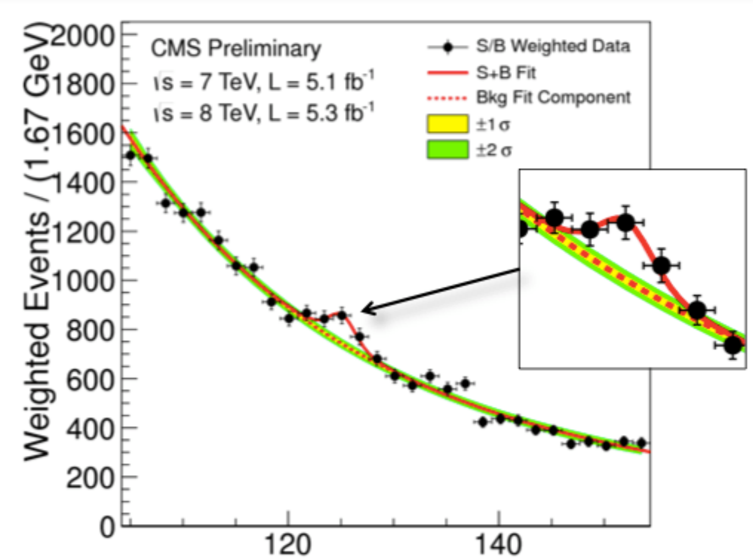


Dey & NA 2020

- Unitarity
- (Perturbative) Effective Field Theory
- Holographic Entropy ↔ Diffeomorphism sym.

- Unitarity
- (Perturbative) Effective Field Theory
- Gauge Symmetries of Standard Model





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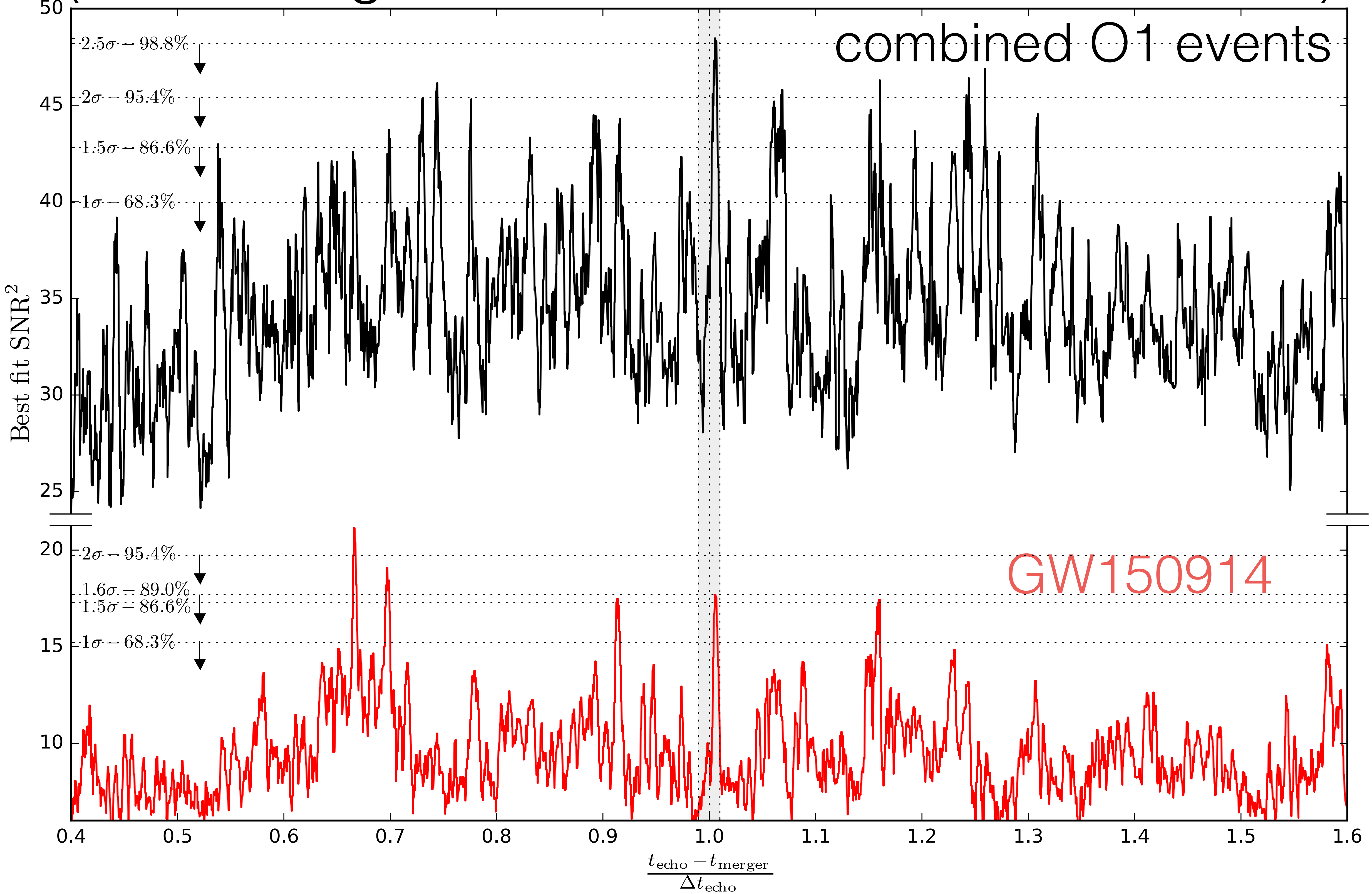
Abedi, Dykaar & NA 2017

Echoes: *seen @ p-value of 1%*

(accounting for all the "look-elsewhere" effects)



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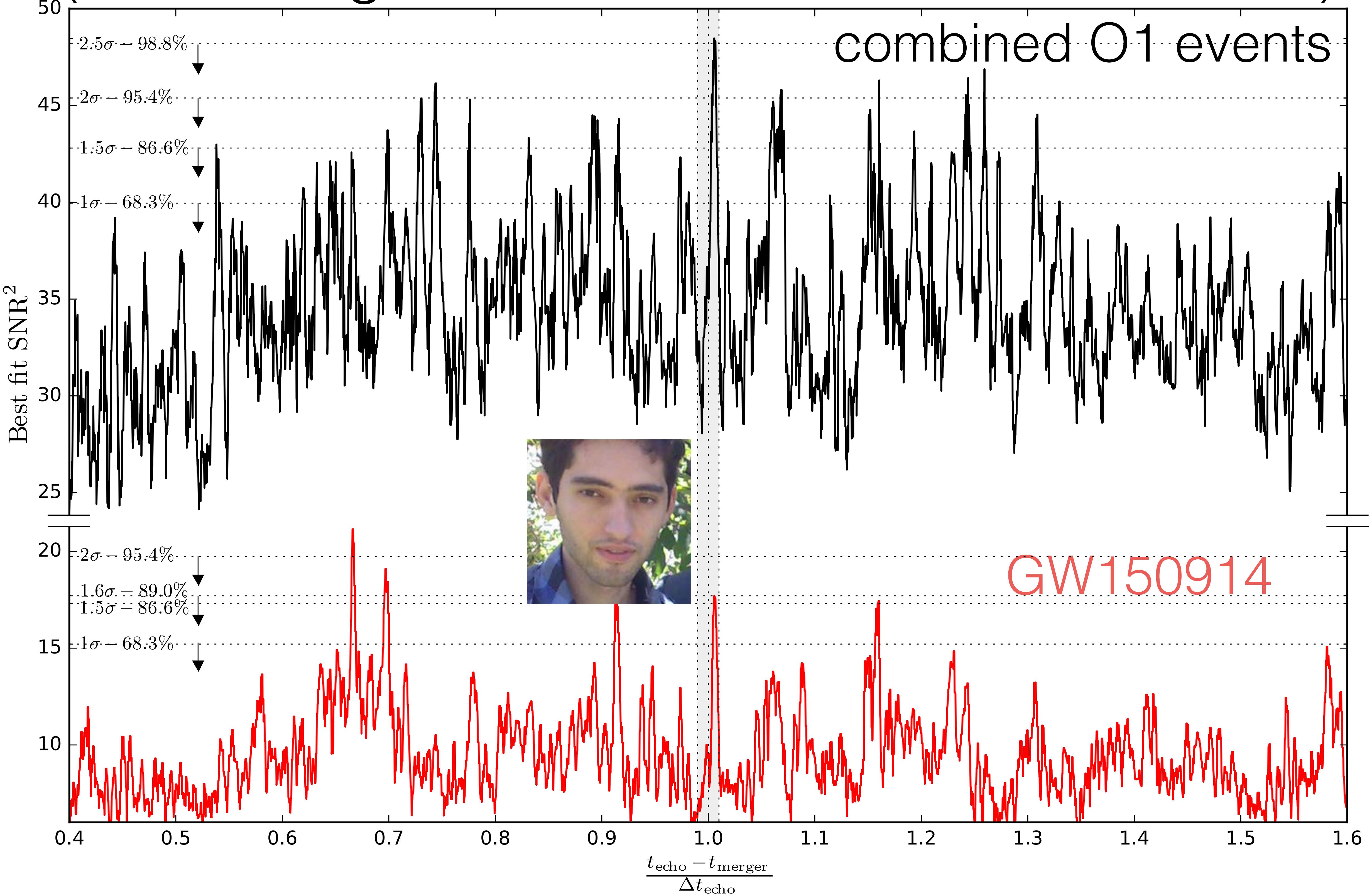

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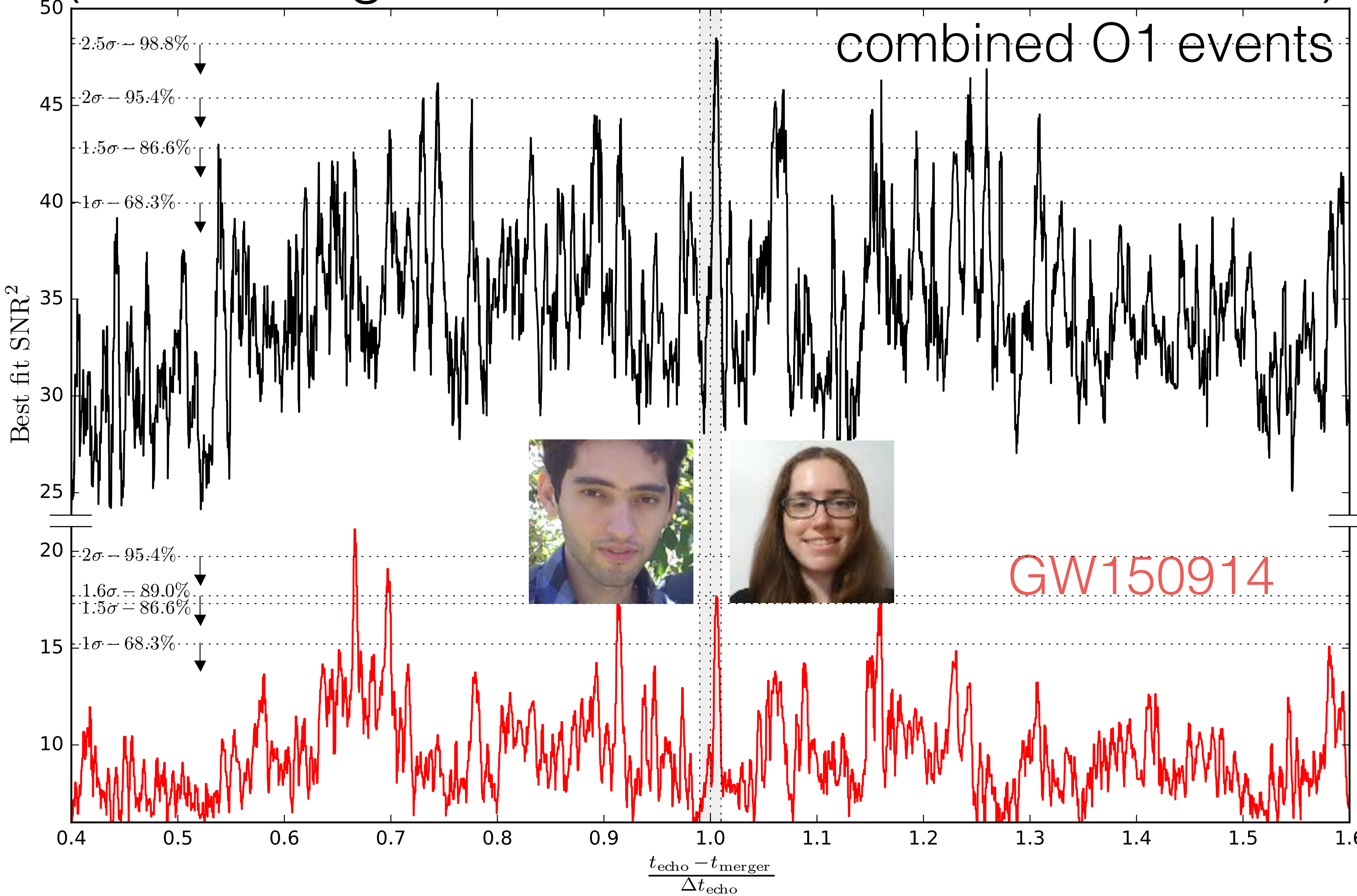


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A wider look at the gravitational-wave transients from GWTC-1 using an unmodeled reconstruction method

arXiv:1905.09260

F. Salemi,[1] E. Milotti,[2] G. A. Prodi,[3,4] G. Vedovato,[5]
C. Lazzaro,[6] S. Tiwari,[7] S. Vinciguerra,[1]
M. Drago,[6,8] and S. Klimenko[9]

[1] *Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[2] *Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste, Via Valerio, 2, I-34127 Trieste, Italy*
[3] *Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[4] *INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
[5] *INFN, Sezione di Padova, I-35131 Padova, Italy*
[6] *Gran Sasso Science Institute, Via F. Crispi 7, I-67100, L'Aquila, Italy*
[7] *Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[8] *INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[9] *University of Florida, Gainesville, FL 32611, USA*

(Dated: June 4, 2019)

In this paper, we investigate the morphology of the events from the GWTC-1 catalog of compact binary coalescences as reconstructed by a method based on coherent excess power: we use an open-source version of the coherent WaveBurst (cWB) analysis pipeline, which does not make use of waveform models. The coherent response of the LIGO-Virgo network of detectors is estimated by using loose bounds on the duration and bandwidth of the signal. This pipeline version reproduces the same results that are reported for cWB in recent publications by the LIGO and Virgo collaborations. In particular, the sky localization and waveform reconstruction are in a good agreement with those produced by methods which exploit the detailed theoretical knowledge of the expected waveform for compact binary coalescences. However, in some cases cWB also detects features in excess in well-localized regions of the time-frequency plane. Here we focus on such deviations and present the methods devised to assess their significance. Out of the eleven events reported in the GWTC-1, in two cases – GW151012 and GW151226 – cWB detects an excess of coherent energy after the merger ($\Delta t \simeq 0.2$ s and $\simeq 0.1$ s, respectively) with p-values that call for further investigations (0.004 and 0.03, respectively), though they are not sufficient to exclude noise fluctuations. We discuss the morphological properties and plausible interpretations of these features. We believe that the methodology described in the paper shall be useful in future searches for compact binary coalescences.

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M. Drago,[6,8] and S. Klimenko[9]

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[2]*Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste, Via Valerio, 2, I-34127 Trieste, Italy*
[3]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
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[6]*Gran Sasso Science Institute, Via F. Crispi 7, I-67100, L'Aquila, Italy*
[7]*Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[8]*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[9]*University of Florida, Gainesville, FL 32611, USA*
(Dated: June 4, 2019)

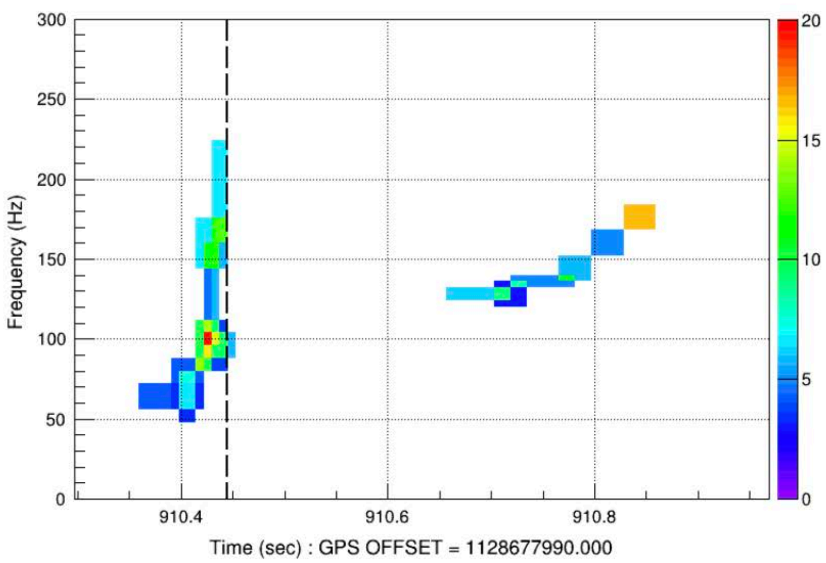
In this paper, we investigate the morphology of the events from the GWTC-1 catalog of compact binary coalescences as reconstructed by a method based on coherent excess power: we use an open-source version of the coherent WaveBurst (cWB) analysis pipeline, which does not make use of waveform models. The coherent response of the LIGO-Virgo network of detectors is estimated by using loose bounds on the duration and bandwidth of the signal. This pipeline version reproduces the same results that are reported for cWB in recent publications by the LIGO and Virgo collaborations. In particular, the sky localization and waveform reconstruction are in a good agreement with those produced by methods which exploit the detailed theoretical knowledge of the expected waveform for compact binary coalescences. However, in some cases cWB also detects features in excess in well-localized regions of the time-frequency plane. Here we focus on such deviations and present the methods devised to assess their significance. Out of the eleven events reported in the GWTC-1, in two cases – GW151012 and GW151226 – cWB detects an excess of coherent energy after the merger ($\Delta t \simeq 0.2$ s and $\simeq 0.1$ s, respectively) with p-values that call for further investigations (0.004 and 0.03, respectively), though they are not sufficient to exclude noise fluctuations. We discuss the morphological properties and plausible interpretations of these features. We believe that the methodology described in the paper shall be useful in future searches for compact binary coalescences.

Predictions in Abedi, Dykaar, NA 2017

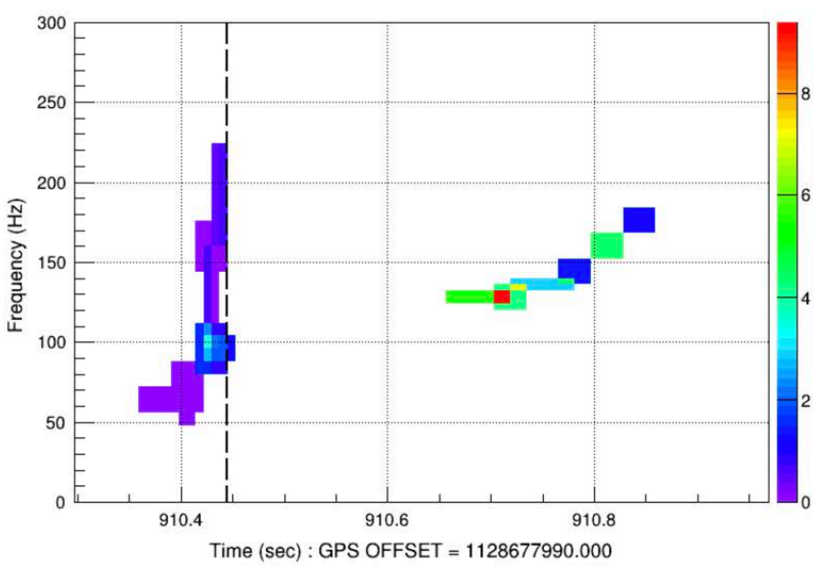
$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

arXiv:1612.00266

coherent Wave Burst (cWB)
GW151012

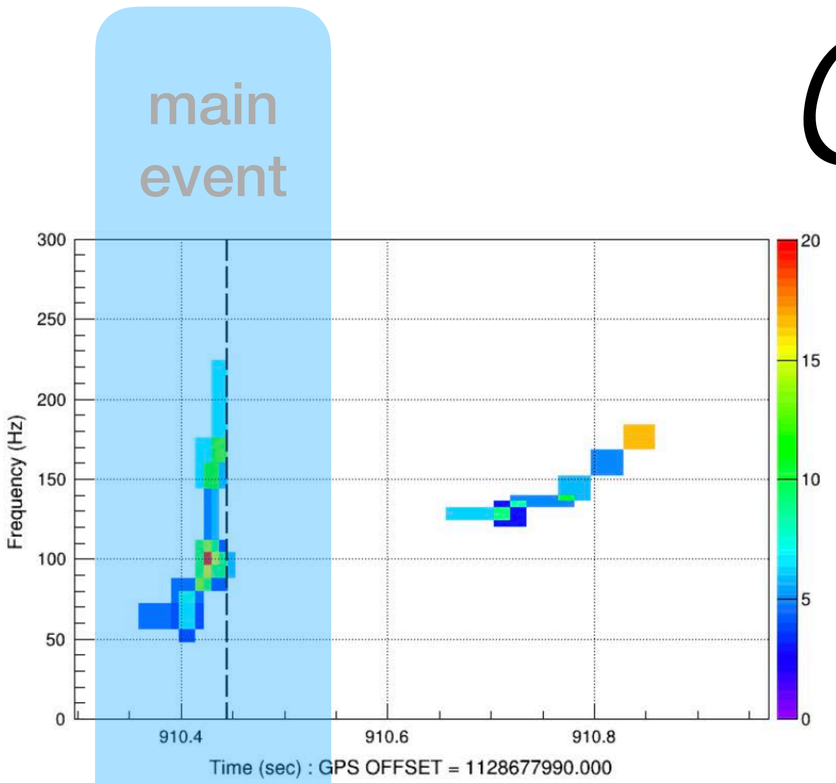


(a)

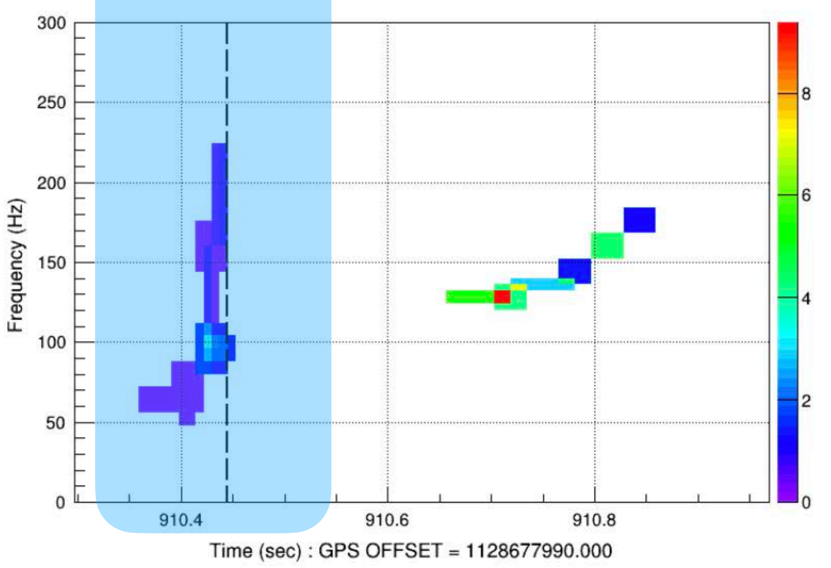


Salemi, et al. 2019

coherent Wave Burst (cWB) *GW151012*



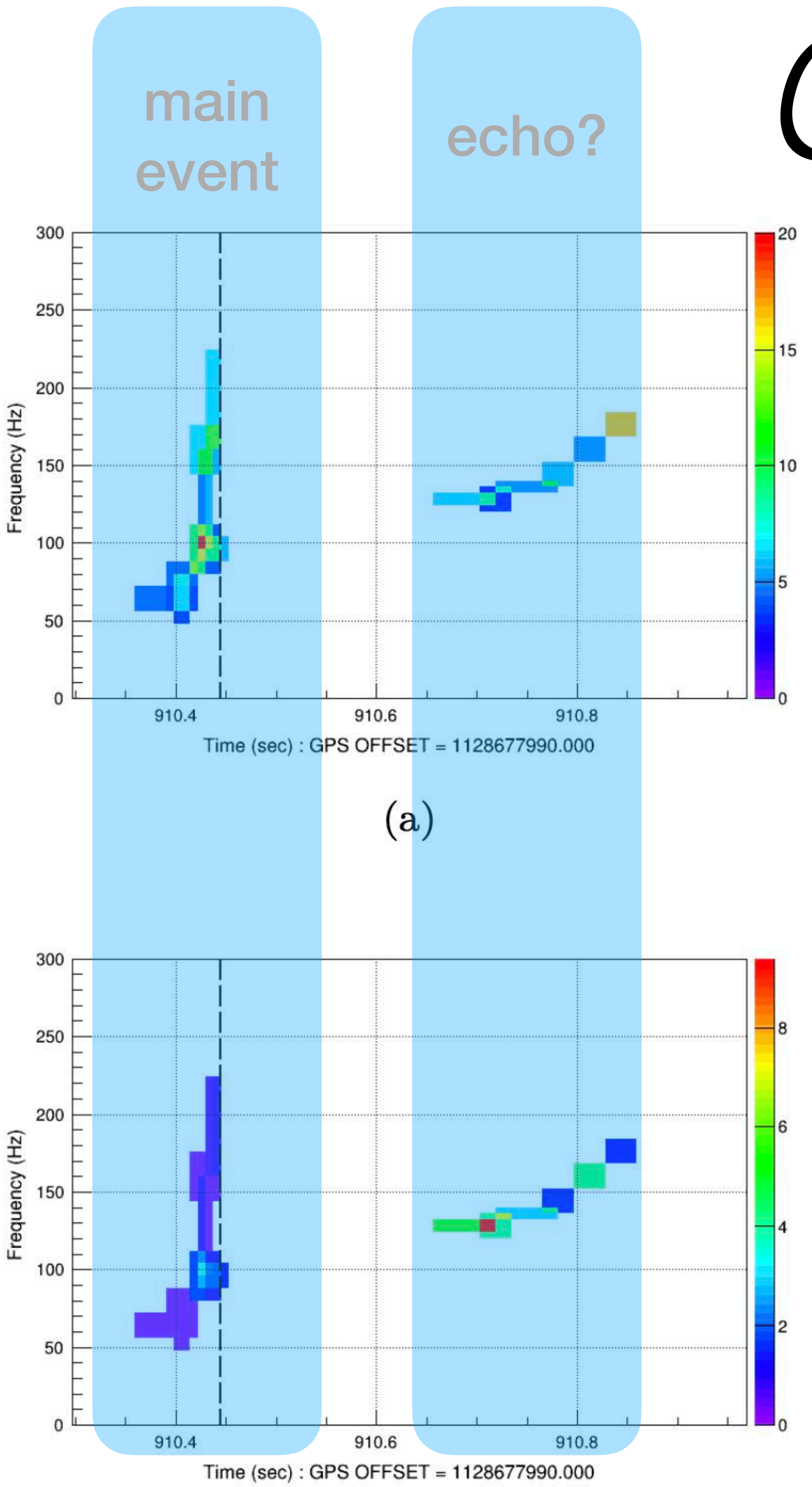
(a)



Salemi, et al. 2019

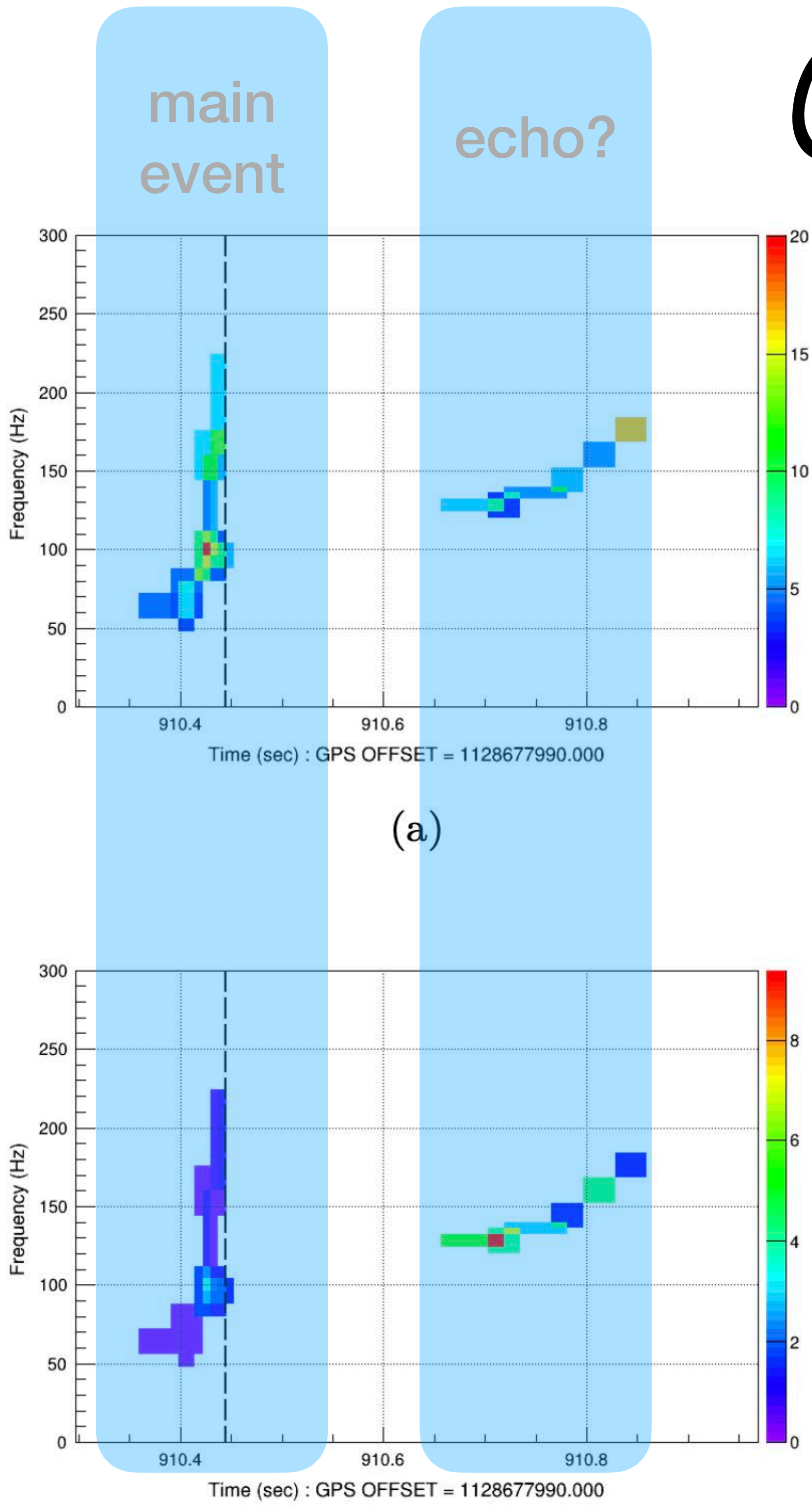
coherent Wave Burst (cWB)

GW151012

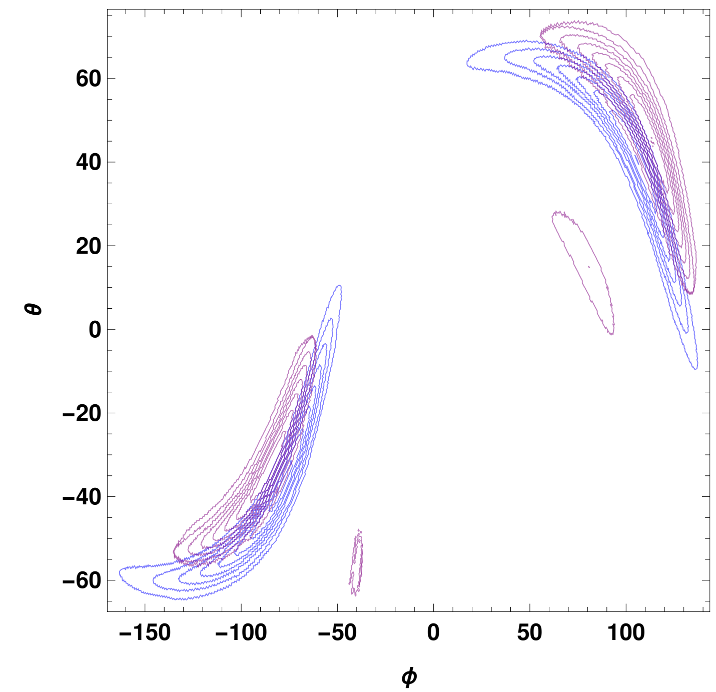


Salemi, et al. 2019

coherent Wave Burst (cWB) *GW151012*



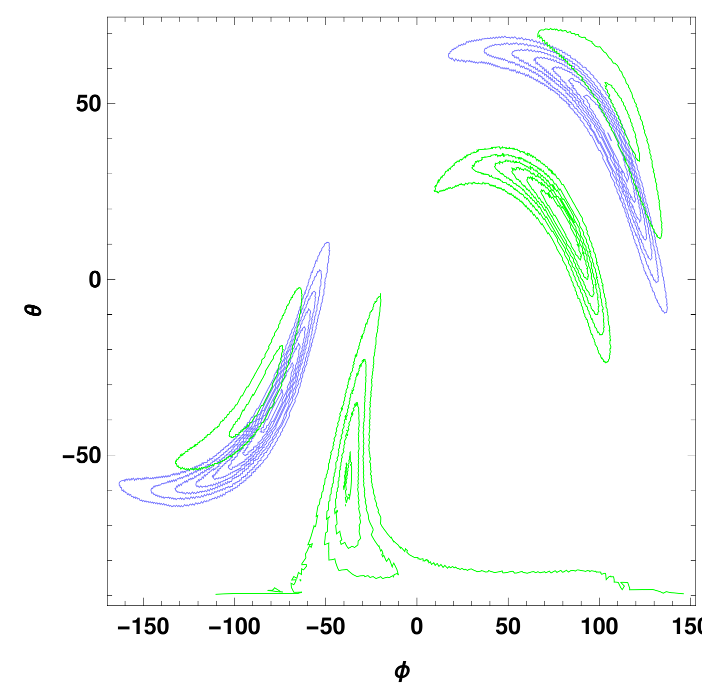
Salemi, et al. 2019



5 pixels long diagonal (first pulse)

3 pixels long diagonal (second pulse)

sky co-localization
Bayes factor = 5.4



sky co-localization
Bayes factor = 1.6

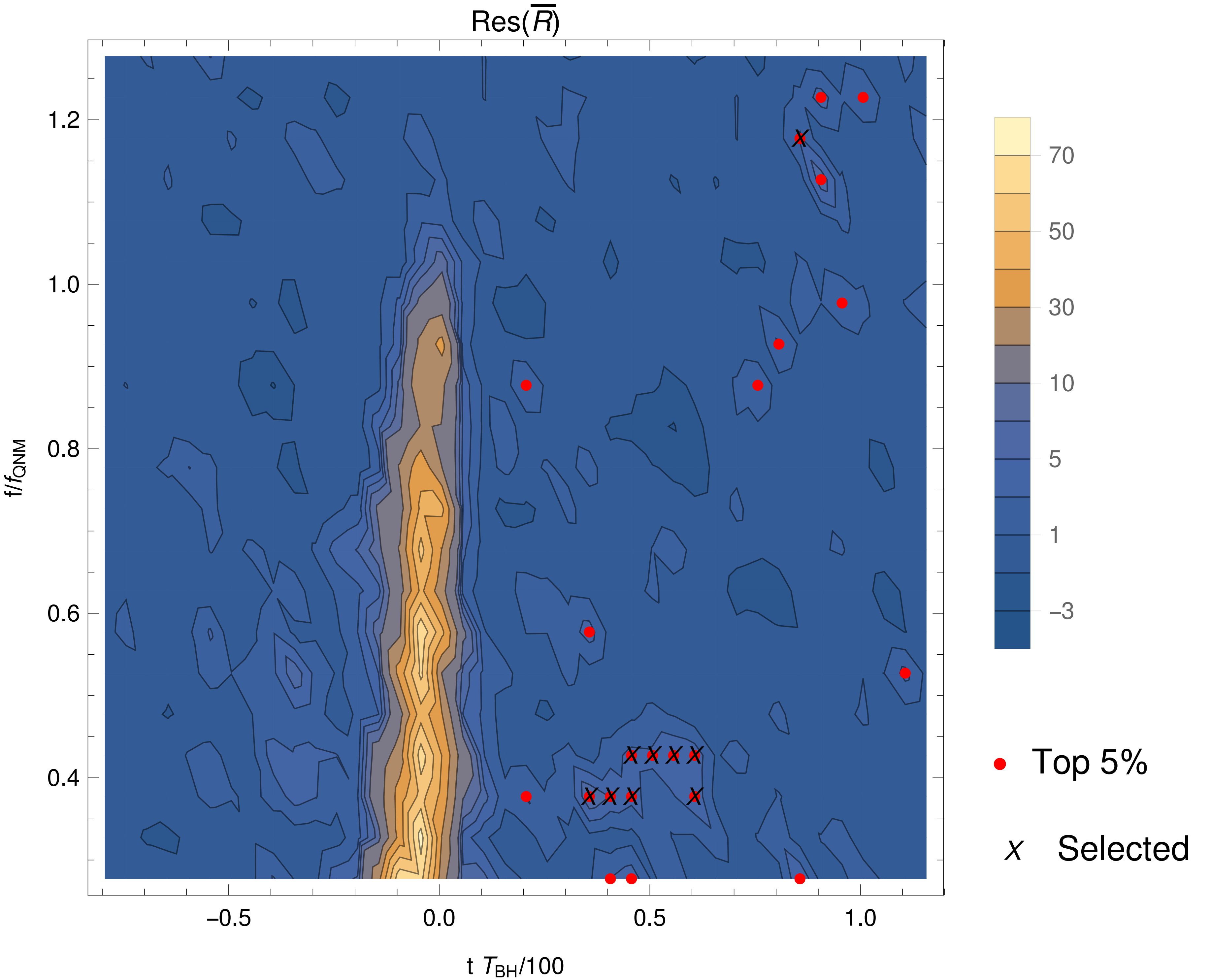
5 pixels long diagonal (first pulse)

5 pixels long diagonal (second pulse)

Longo, NA & Chirenti, in prep

coherent Wave Burst (cWB)

stacking 39 LIGO/Virgo events



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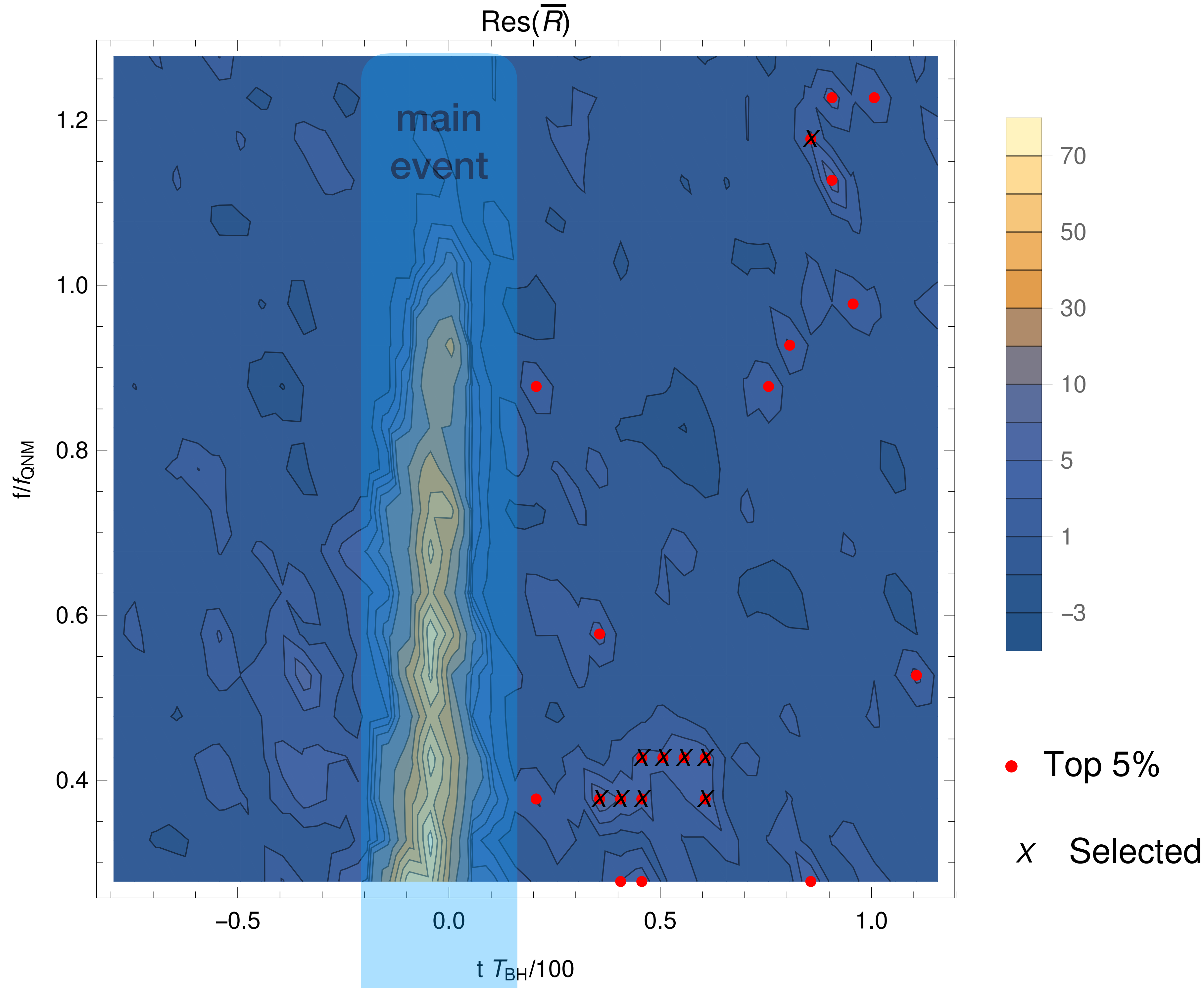

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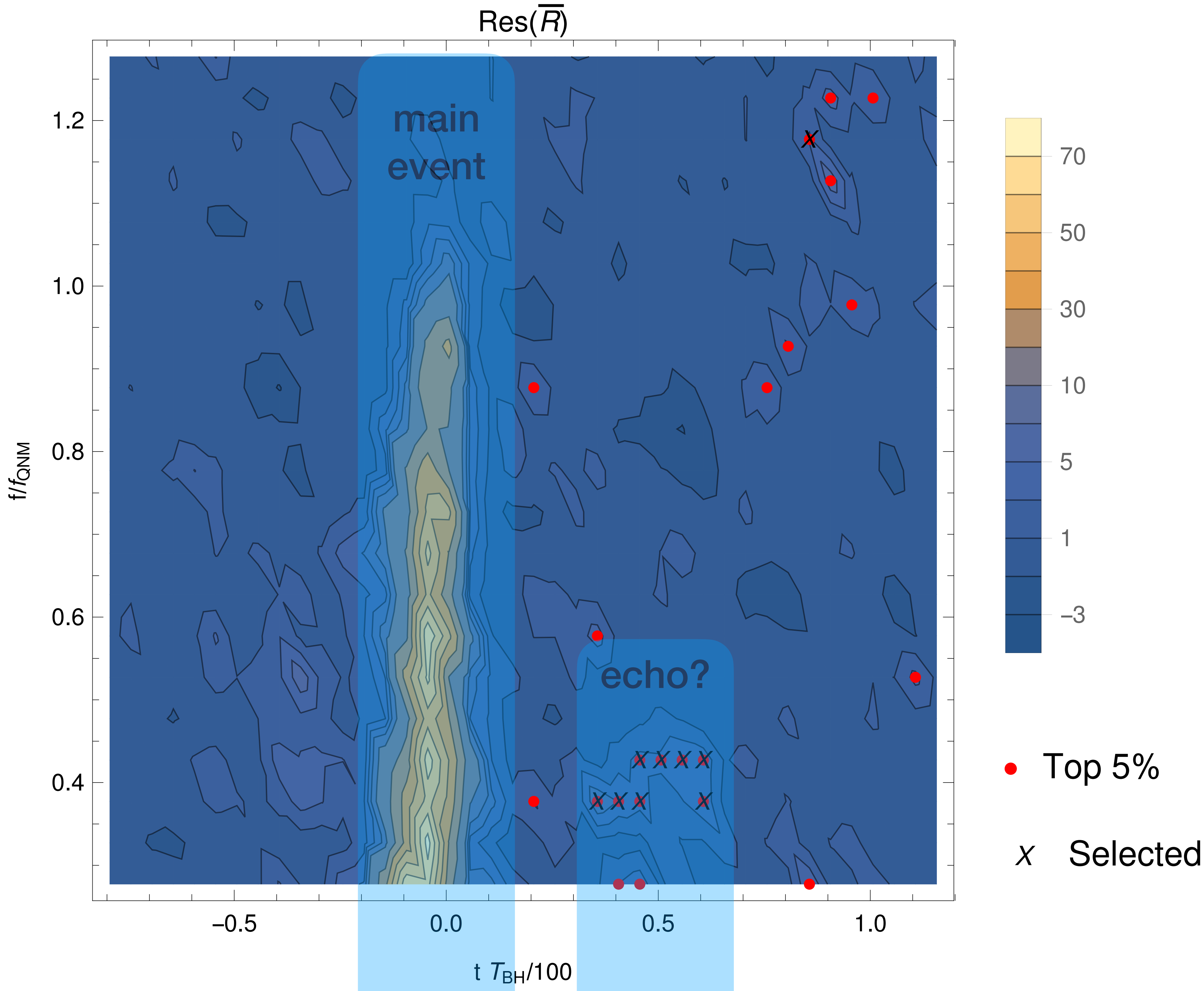


Not quite black holes at LIGO

Bob Holdom*

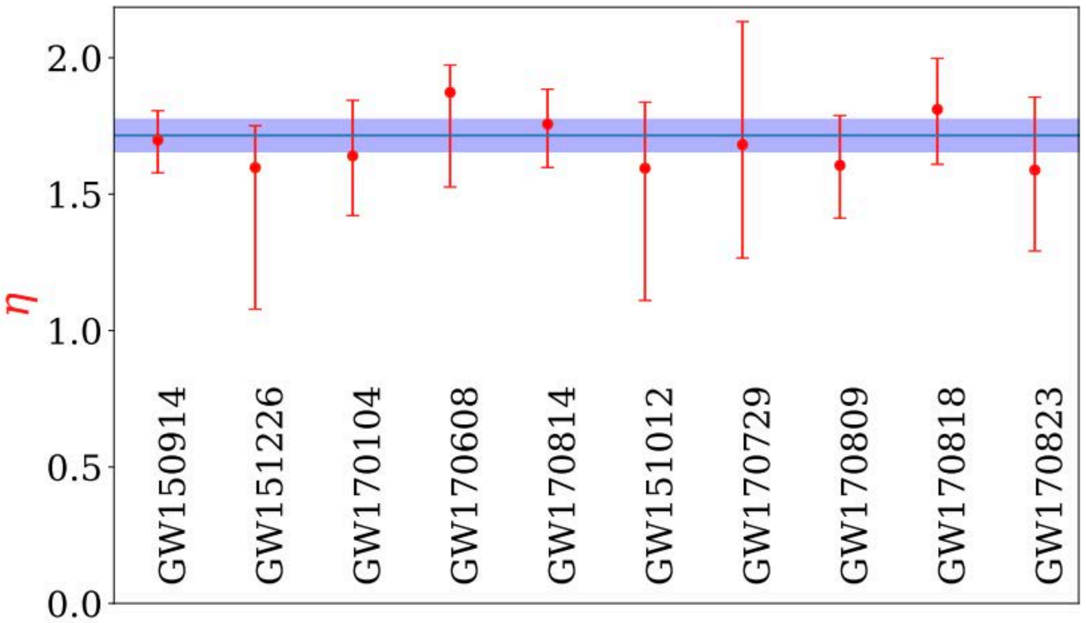
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Phys. Rev. D 101, 064063 (2020)

- Echo Time delay

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

- consistent across events



- p-values

GW150914	0.008	GW151226	0.014
GW170104	0.33	GW170814	0.098
GW170608	0.038	GW170809	0.081
GW151012	0.0016	GW170823	0.026
GW170818	0.0094	GW170729	0.0010 & 0.0006

But not everyone finds echoes!

Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog

The LIGO Scientific Collaboration and the Virgo Collaboration
(compiled 29 October 2020)

TABLE X. Results of search for GW echoes. A positive value of the log Bayes factor $\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$ indicates a preference for the IMRE model over the IMR model, while a negative value of the log Bayes factor suggests instead a preference for the IMR model over the IMRE model.

Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$	Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		

https://www.mdpi.com/2218-1997/6/3/43

Open Access Review

Quantum Black Holes in the Sky

by Jahed Abedi [1,2,†], Niayesh Afshordi [3,4,5,*,†], Naritaka Oshita [5,†] and Qingwen Wang [3,4,5,†]

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† All authors have contributed equally to this work. The order of authors is alphabetical.

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(This article belongs to the Special Issue Probing New Physics with Black Holes)

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Echoes in Southern Ontario

Organizer(s): Niayesh Afshordi

Collection URL: http://pirsa.org/C20018

PIRSA:C17055 - Quantum Black Holes in the Sky? Subscribe to podcast

Quantum Black Holes in the Sky?

Organizer(s): Niayesh Afshordi Vitor Cardoso Samir Mathur

Collection URL: http://pirsa.org/C17055

Different methods, Different events!

Positive Evidence (p-value ≦ 5%)

	Authors	Method	Data	p-value
1	Abedi, Dykaar, NA 2017 (ADA)	ADA template	O1	1.1%
2	Conklin, Holdom, & Ren 2018	spectral comb	O1+O2	0.2%-0.8% (now 10^{-10}!)
3	Westerweck, et al. 2018	ADA template	O1	2.0%
4	Nielsen, et al. 2019	ADA+Bayes	151012,151226	2%*
5	Uchikata, et al. 2019	ADA template	O1	5.5%
6	Uchikata, et al. 2019	ADA template	O2	3.9%
7	Salemi, et al. 2019	coherent WaveBurst	151012,151226	0.4%,3%
8	Abedi & NA 2019	spectral comb	BNS	0.0016%
9	Gill, Nathanail, Rezolla 2019	Astro Modelling	BNS EM	$t_{coll}=t_{echo}$

Failed Searches

	Authors	Method	Data	possible caveat
1	Westerweck, et al. 2018	ADA template	O1	“Infinite” prior
2	Nielsen, et al. 2019	ADA+Bayes	150914	mass-ratio dependence
3	Uchikata, et al. 2019	ADA, hi-pass	O1, O2	no low-frequencies
4	Salemi, et al. 2019	coherent WaveBurst	O1, O2 **	mass-ratio dependence, only 1st echo
5	Lo, et al. 2019	ADA+Bayes	O1	“Infinite” prior
6	Tsang, et al. 2019	BayesWave	O1+O2	needs very loud echoes (9 free parameters)

… and many more since Jan. 2020

Different methods, Different events!

Abedi, NA, Oshita & Wang 2020 (Review)

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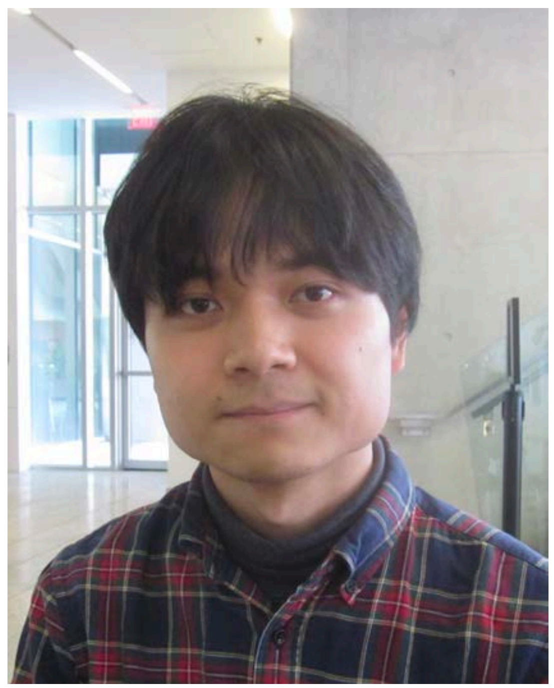
… and many more since Jan. 2020

Into the future: Quantum Black Hole Seismology



Quantum Black Hole Seismology I: Echoes, Ergospheres, and Spectra

Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

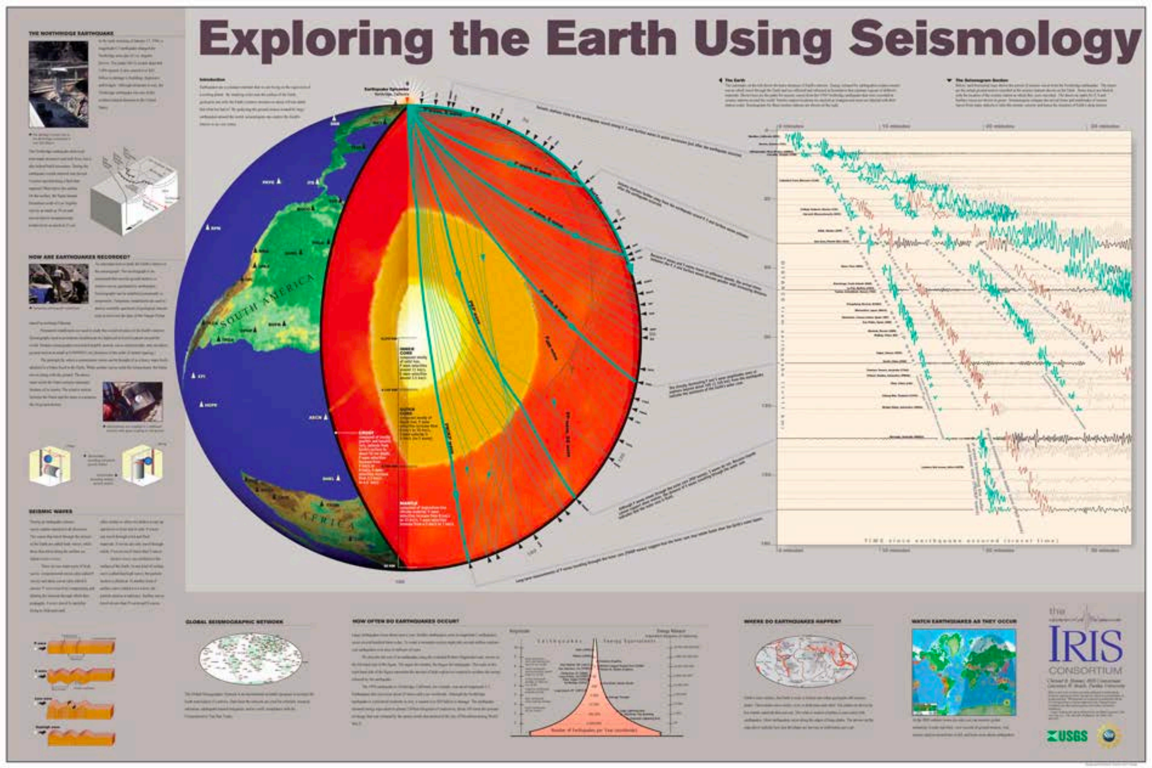
arXiv:2001.11642, PRD

Quantum Black Hole Seismology II: Applications to Astrophysical Black Holes

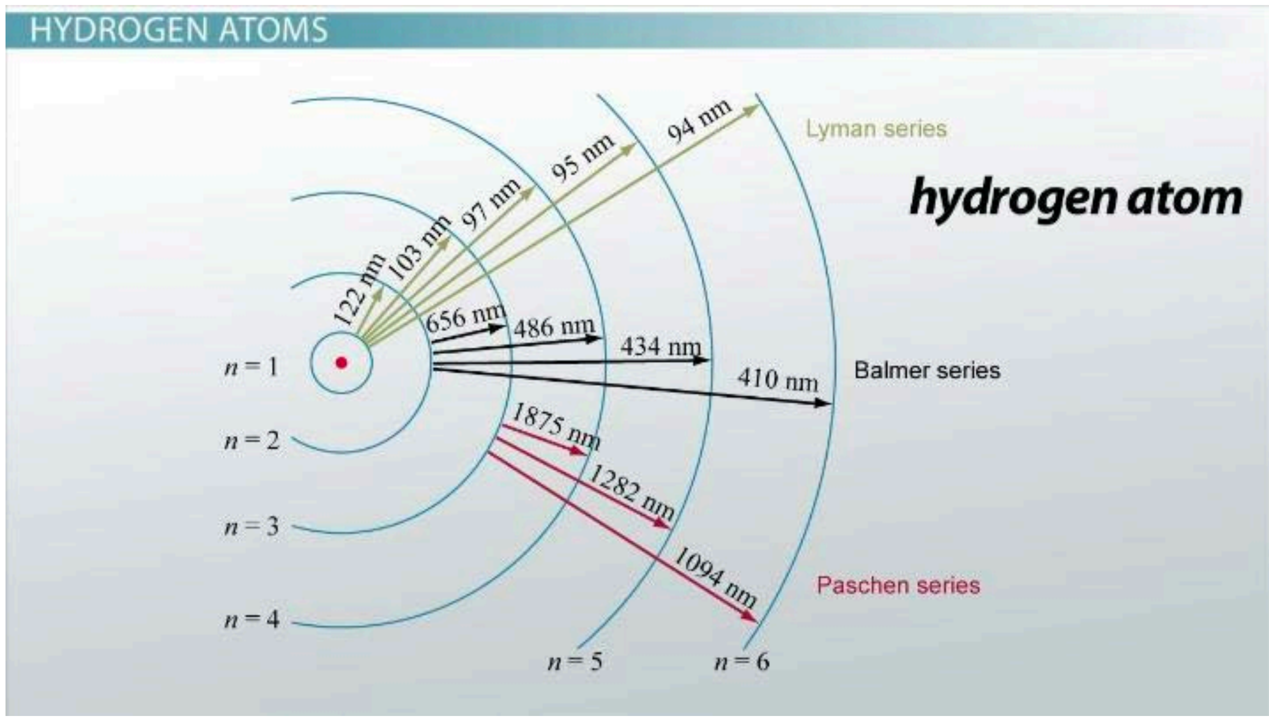
Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

arXiv:2004.06276, PRD

Seismology vs Spectroscopy



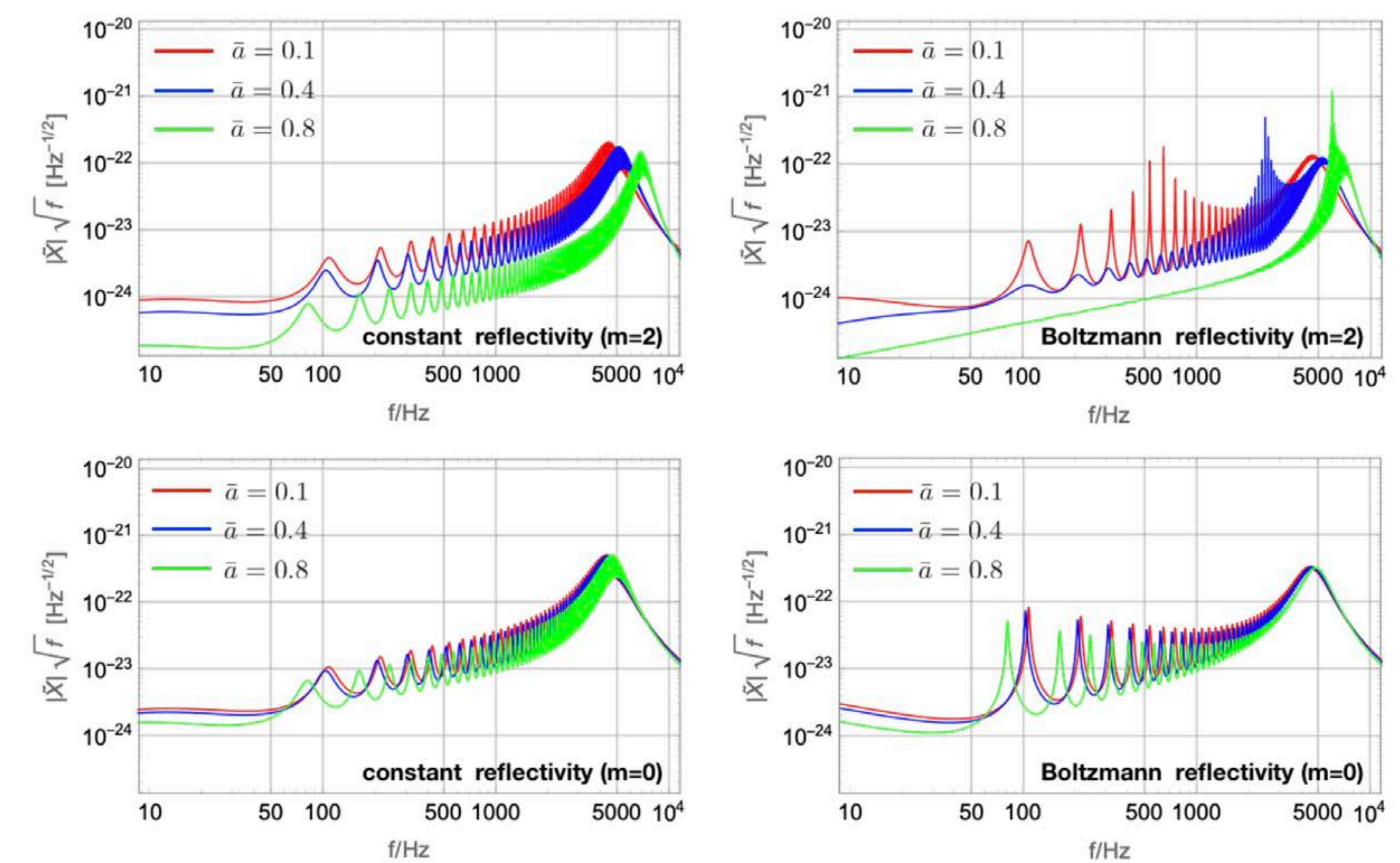
What's inside the Black Hole
(replaces event horizon ~2M)



What's outside the Black Hole
(near the photon ring ~3M)

What Black Hole Seismology teaches us 1/3

- Reflectivity law of the quantum horizons
- Which harmonics are excited
- Quantum Horizon Temperature



Oshita, Tsuna, & NA 2020

$$\mathcal{R} = \begin{cases} R_c e^{i\delta_{\rm wall}} & \text{constant reflectivity model,} \\ \exp\left(-\dfrac{|\tilde{\omega}|}{2T_{\rm QH}} + i\delta_{\rm wall}\right) & \text{Boltzmann reflectivity model,} \end{cases}$$

What Black Hole Seismology teaches us 1/3

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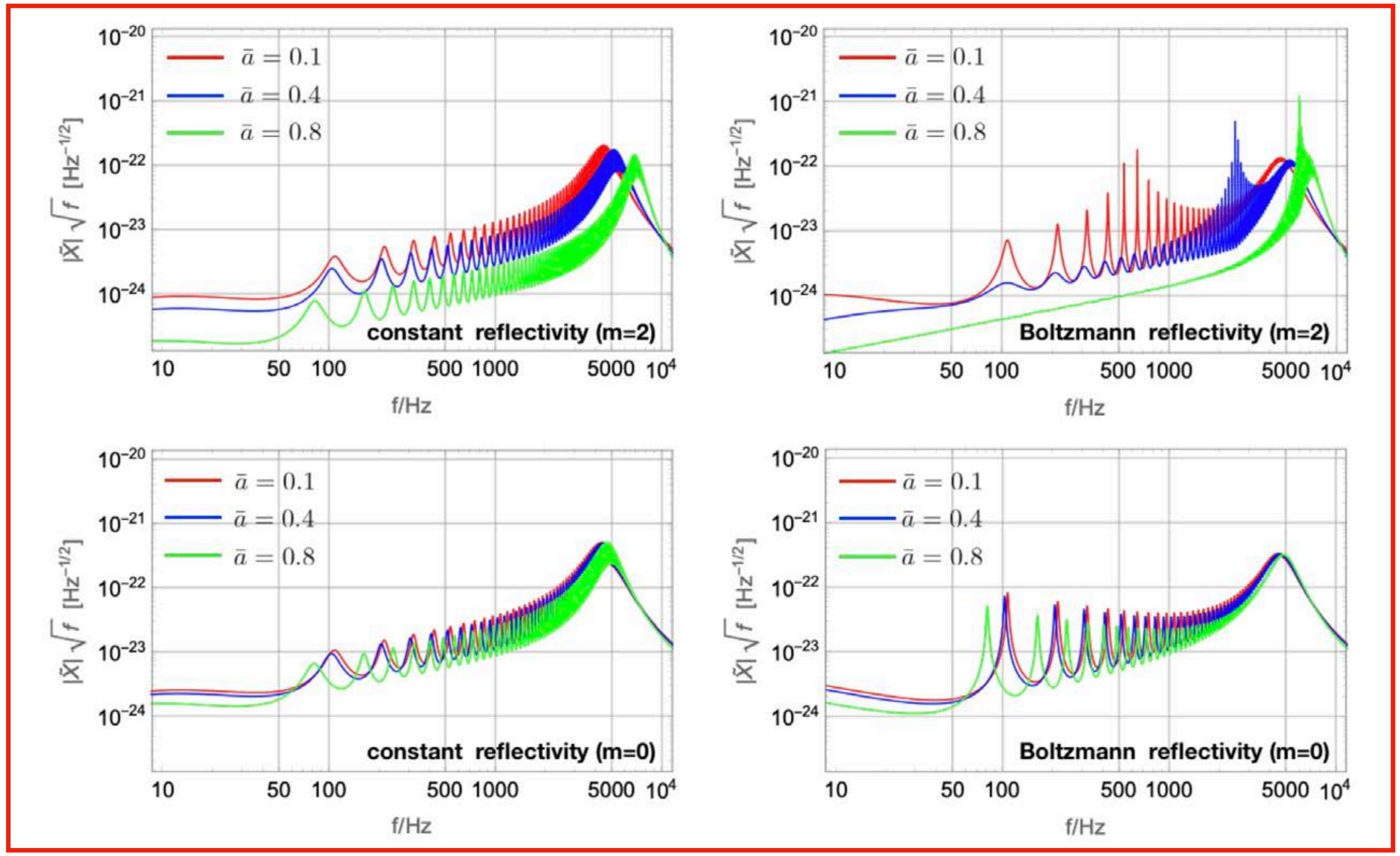

Oshita, Tsuna, & NA 2020

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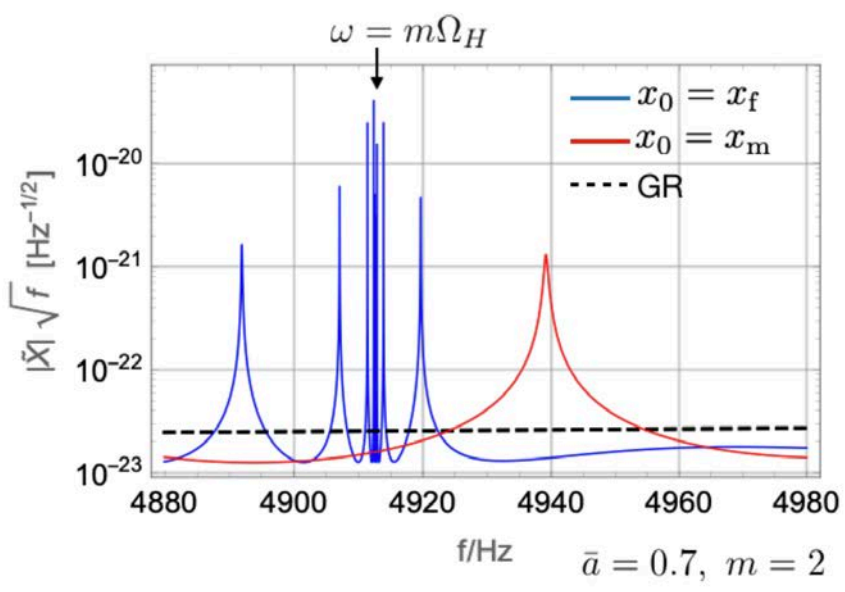
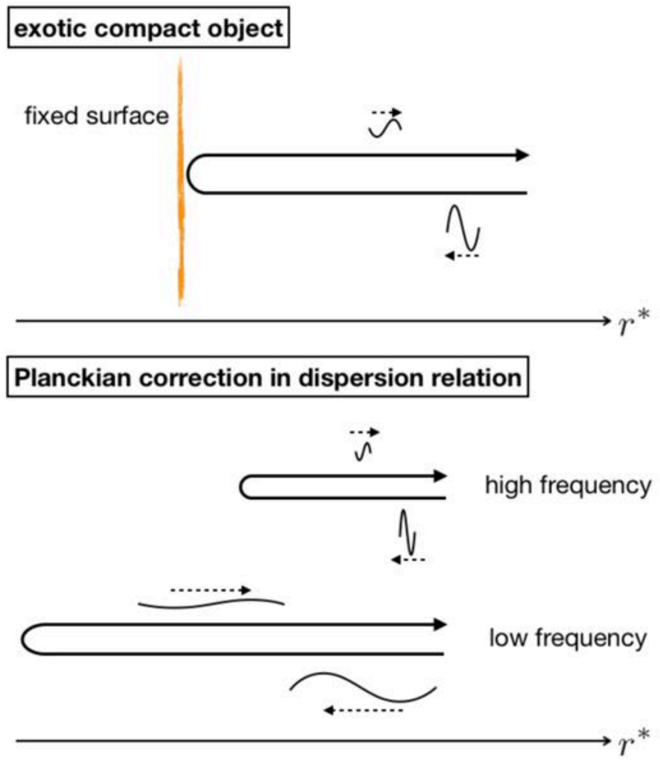
What Black Hole Seismology teaches us 2/3

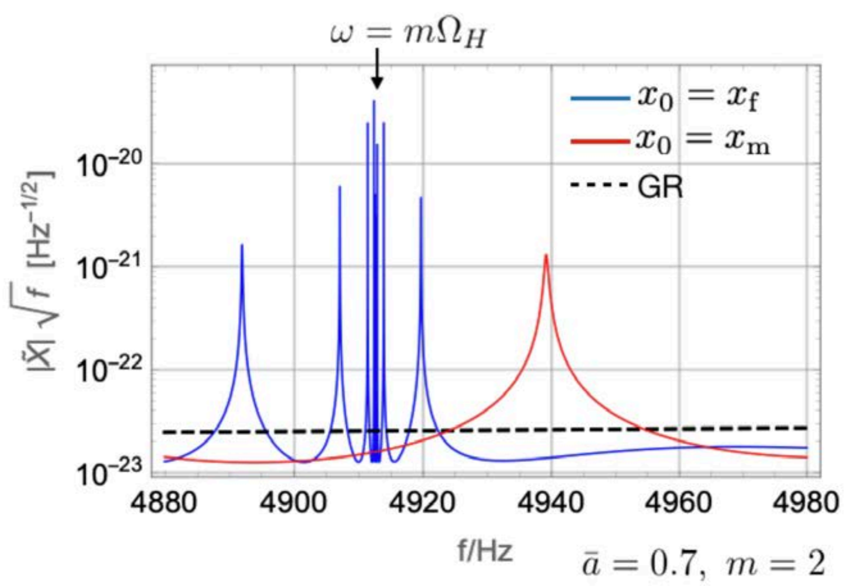


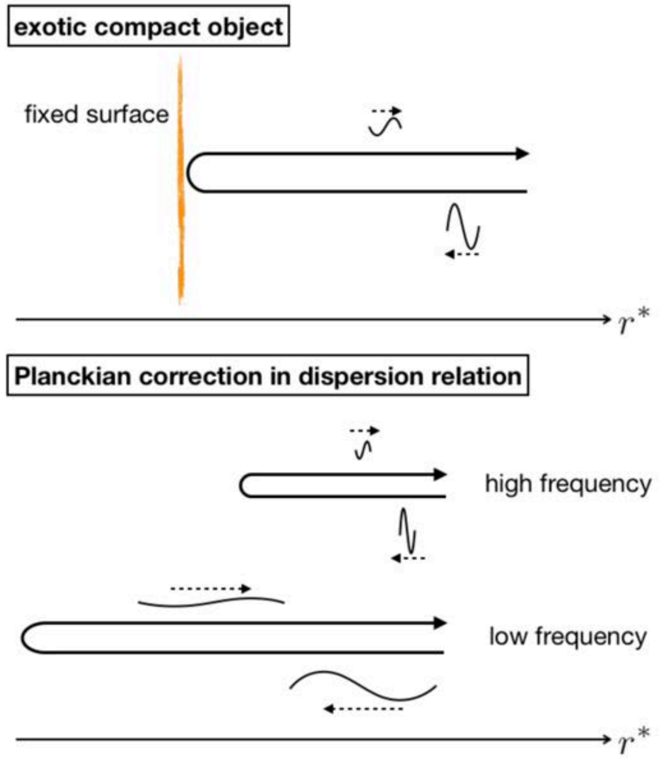


Oshita, Tsuna, & NA 2020

What Black Hole Seismology teaches us 2/3

- Exotic Compact Object vs Modified Dispersion Relation





Oshita, Tsuna, & NA 2020

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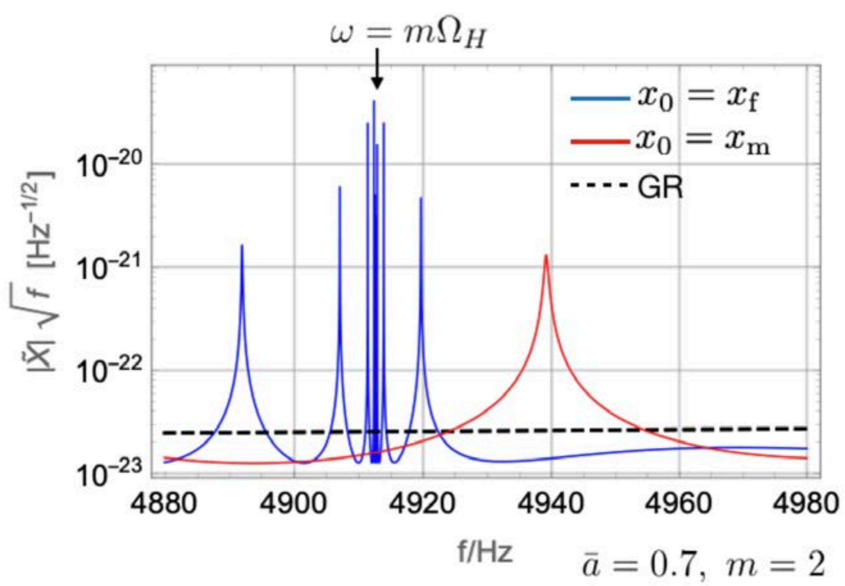
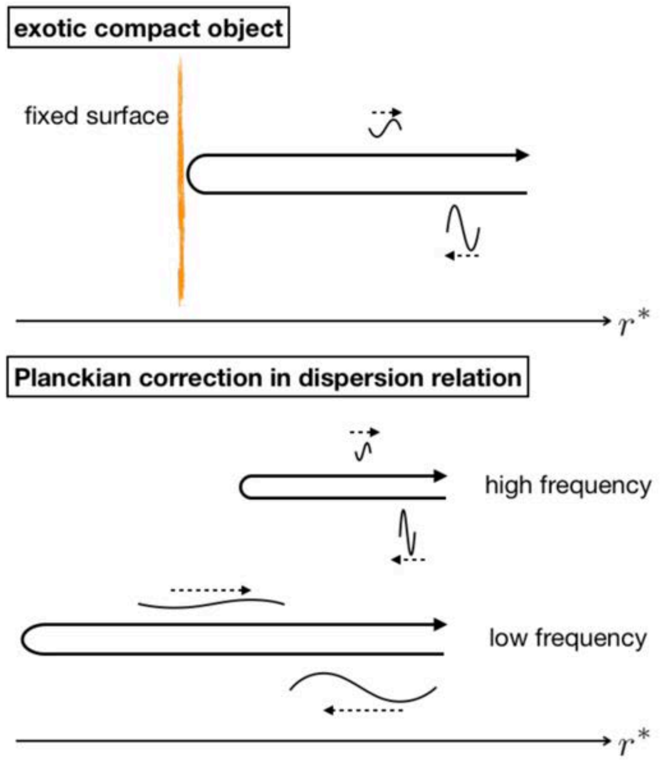
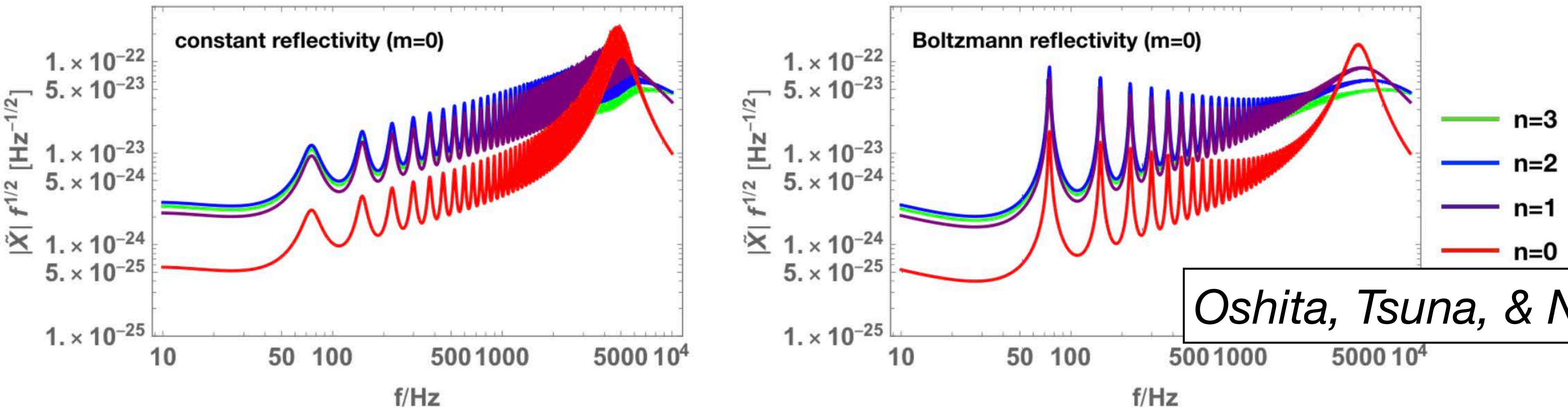




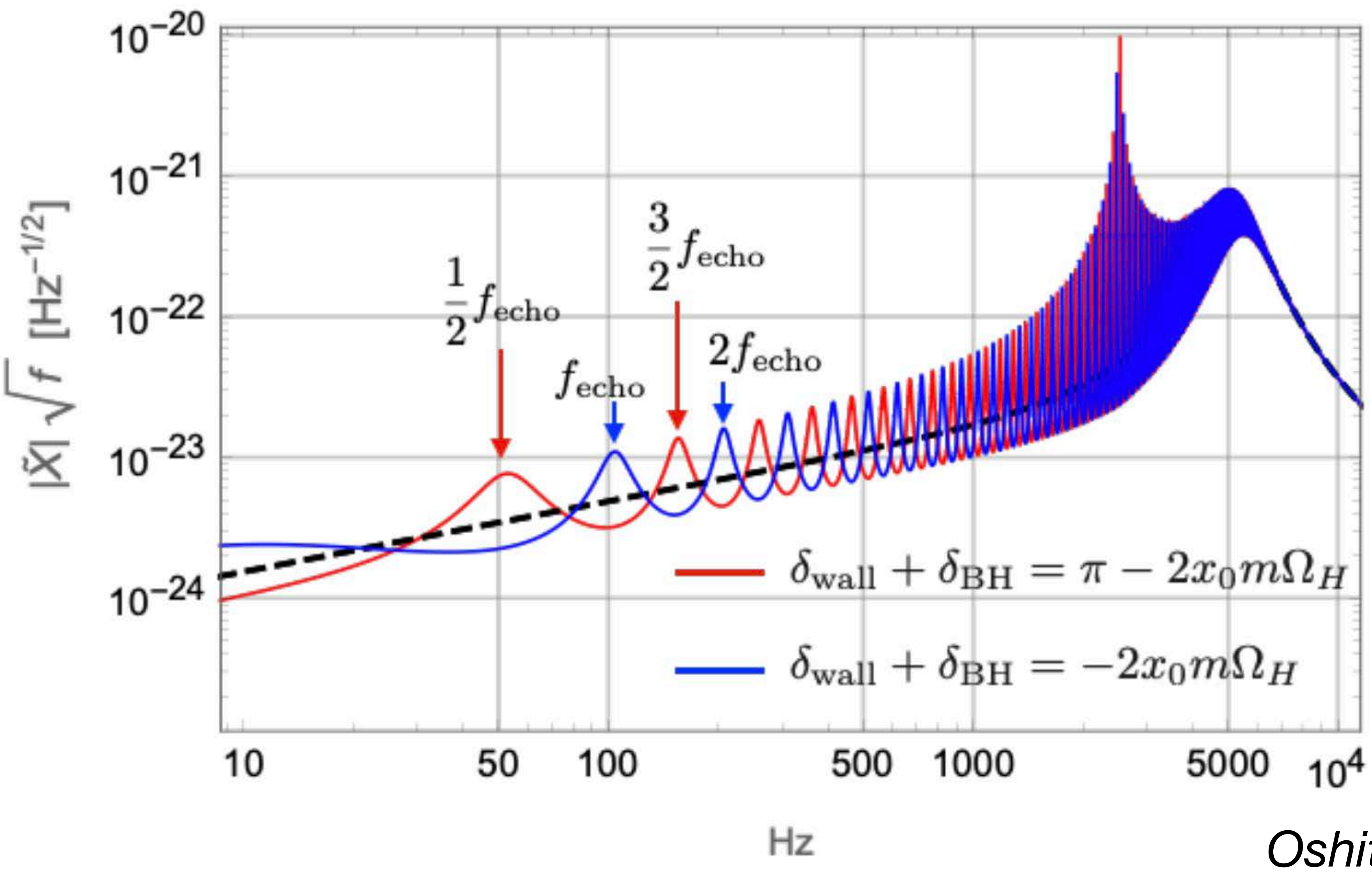
- Which overtones are excited



Oshita, Tsuna, & NA 2020

What Black Hole Seismology teaches us 3/3

- Phase of Reflection



Oshita, Tsuna, & NA 2020

Seismology for the GW170817 remnant: Theory vs Data

Oshita, Tsuna, & NA 2020

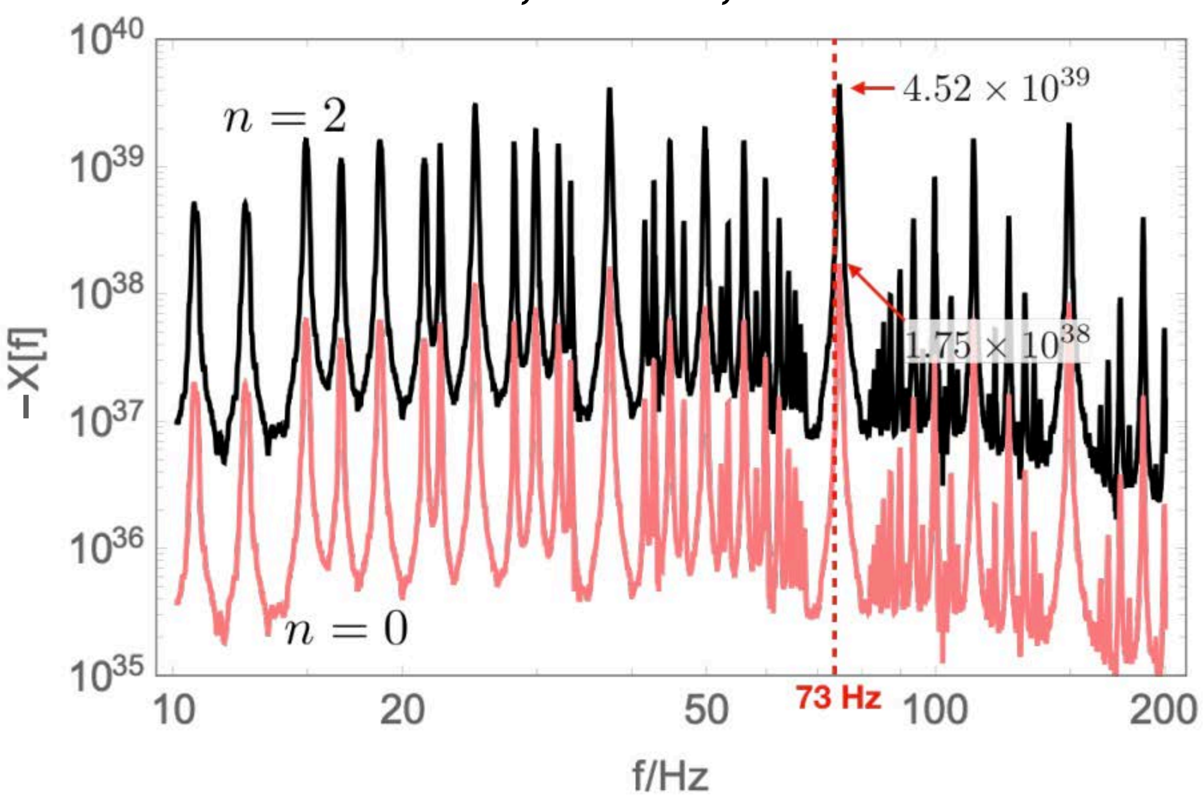
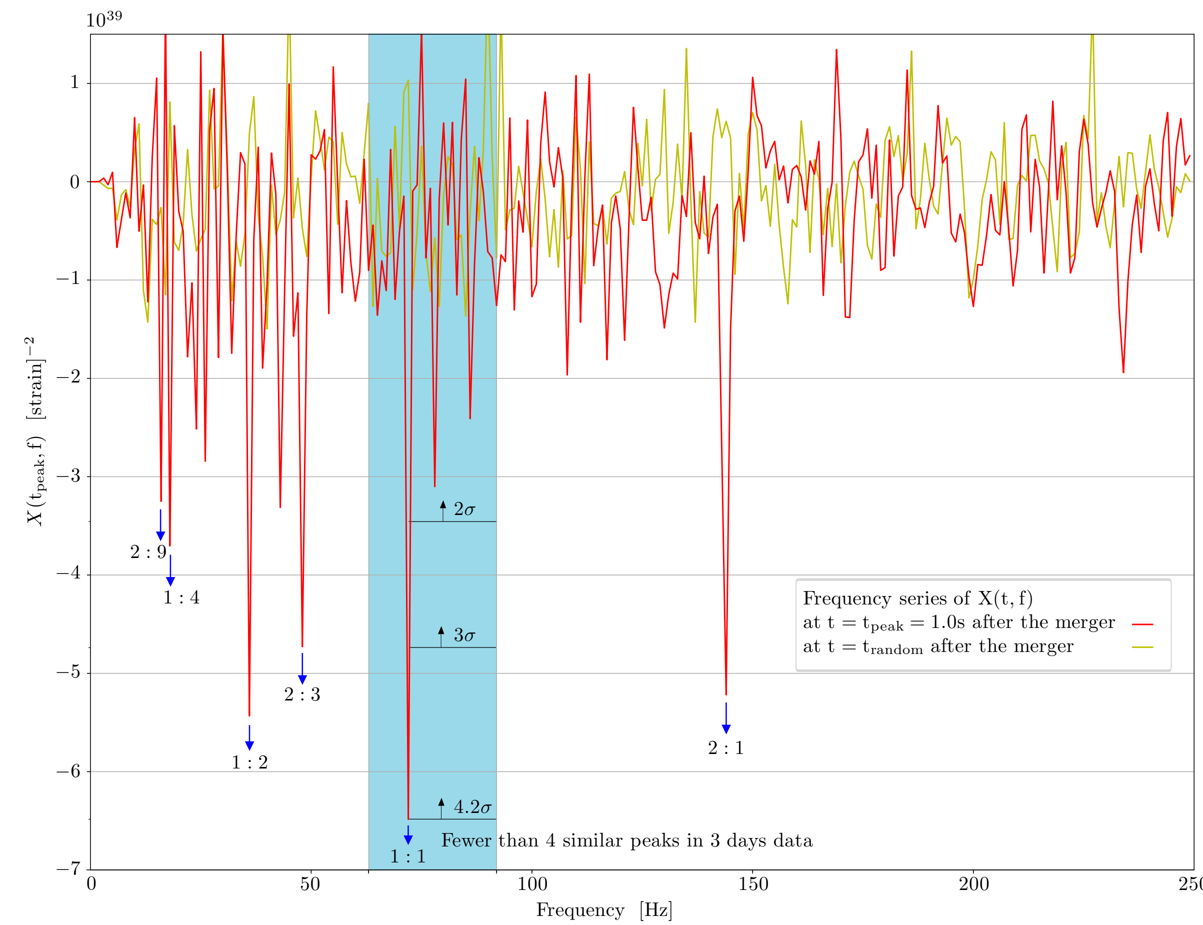
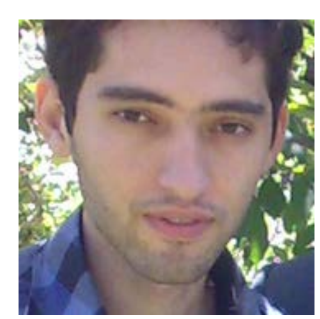


FIG. 6: Plots of $X(f)$ obtained in the BR model for the overtone QNM with $n = 2$ (black) and the least damping QNM (pink). For both cases, we set $\ell = 2$, $m = 0$, $\bar{a} = 0.85$, $\epsilon_{\rm rd} = 0.7\%$, $\theta = 33°$, $D_L = 40$ Mpc, $T_{\rm H}/T_{\rm QH} = 0.1$, and $\gamma = 1$.





Abedi & NA, 2019

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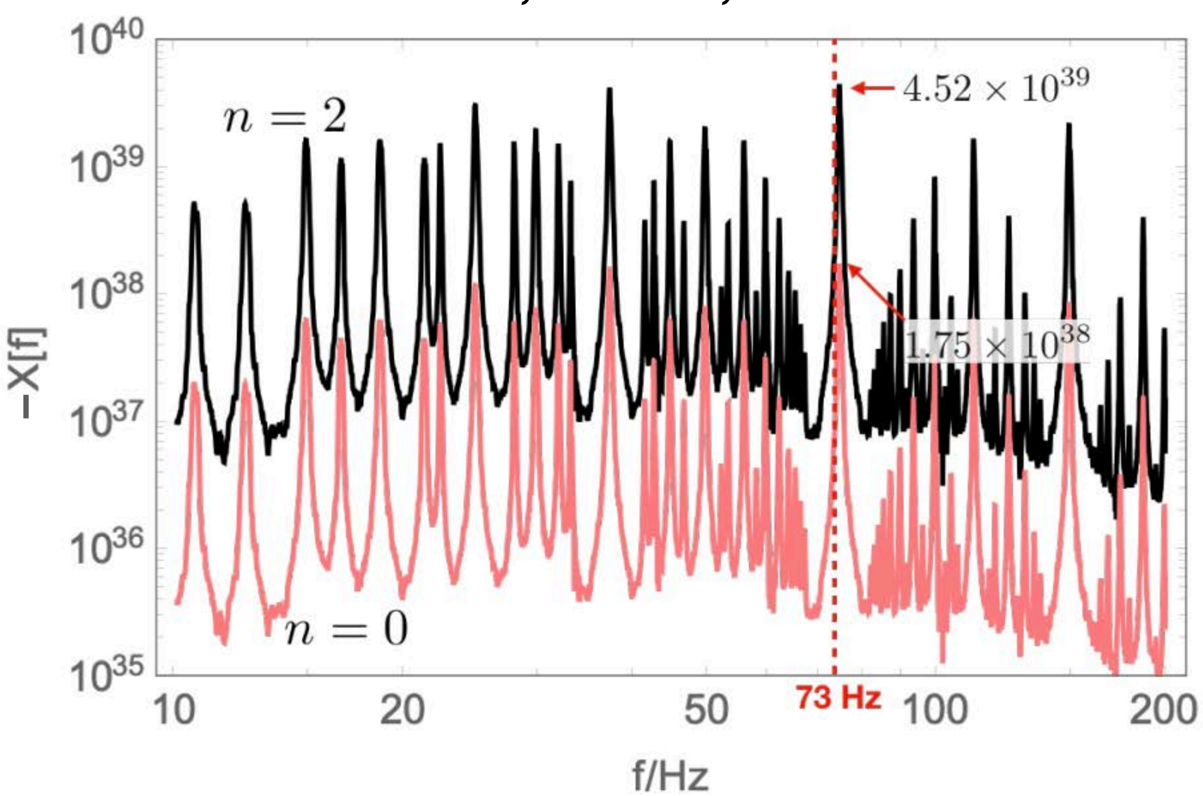
Oshita, Tsuna, & NA 2020



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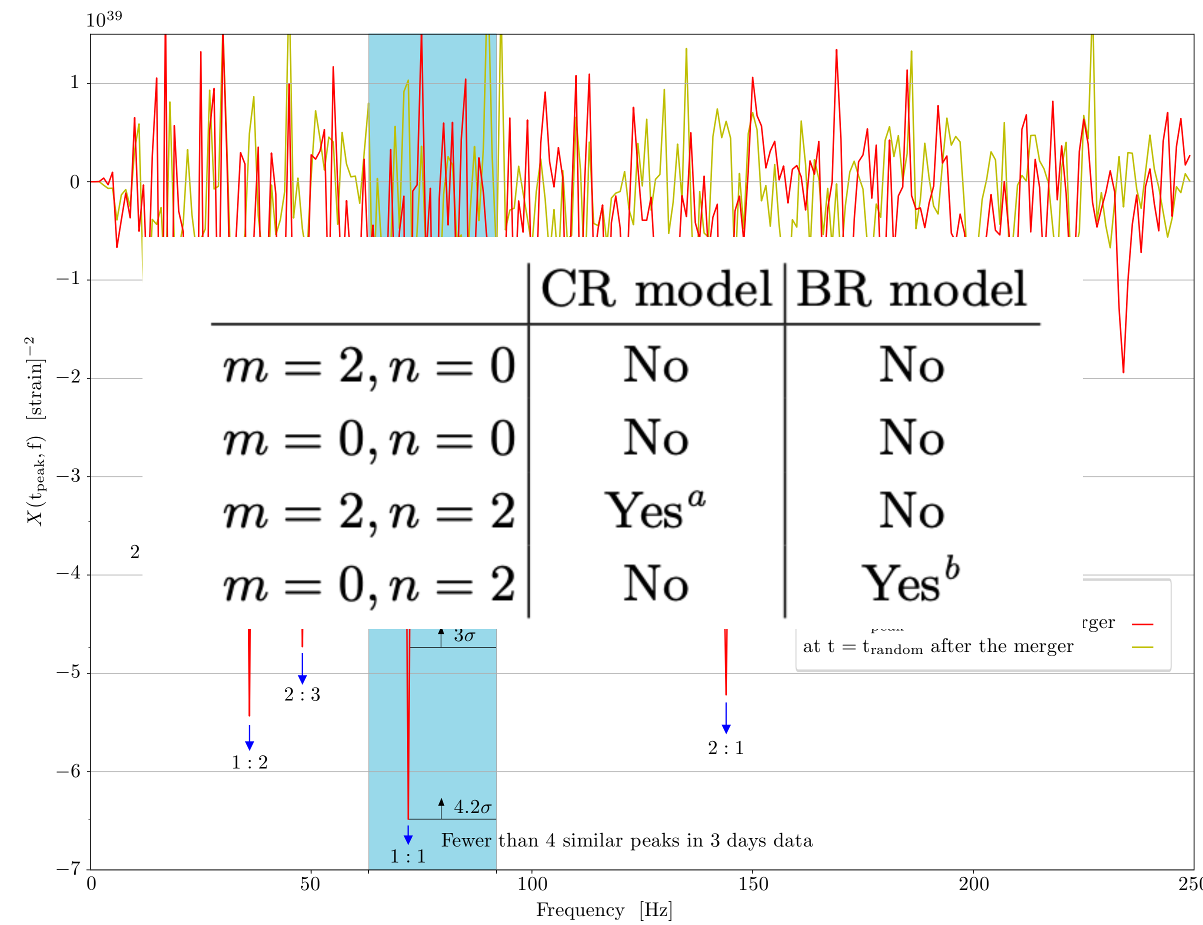
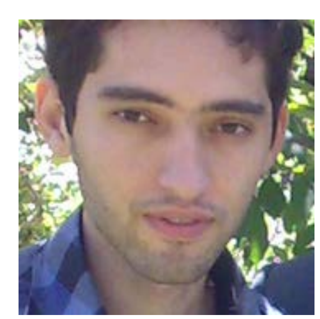


	CR model	BR model
$m = 2, n = 0$	No	No
$m = 0, n = 0$	No	No
$m = 2, n = 2$	Yes[a]	No
$m = 0, n = 2$	No	Yes[b]

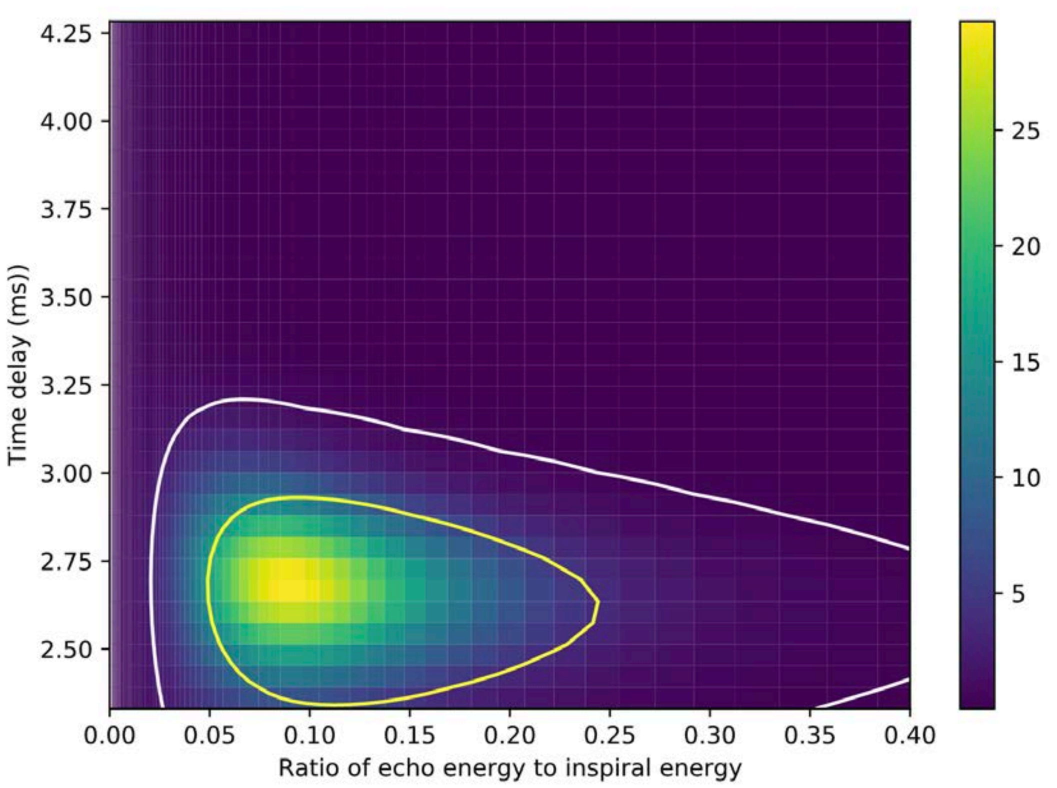


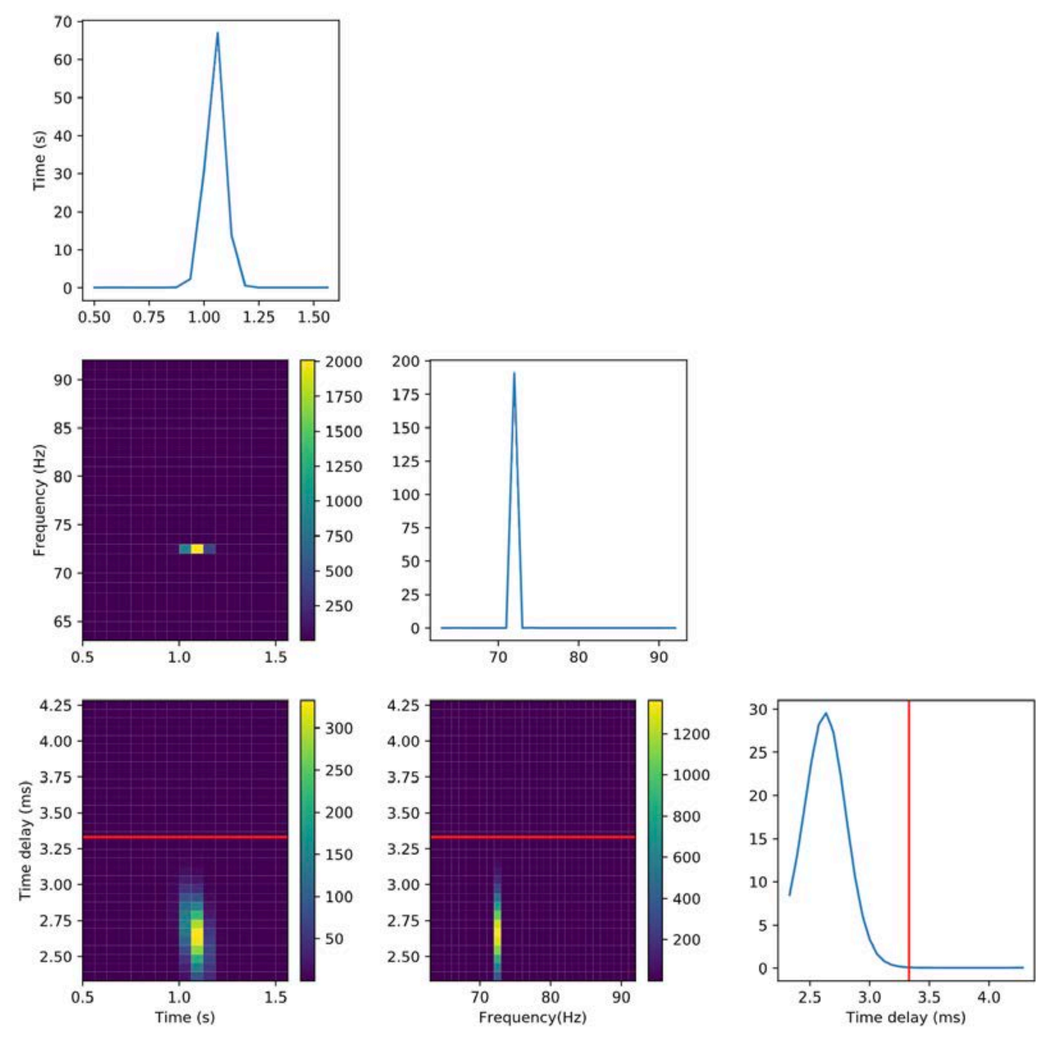
Abedi & NA, 2019

Bayesian approach to BH seismology

(Petra Duff & NA, in prep)

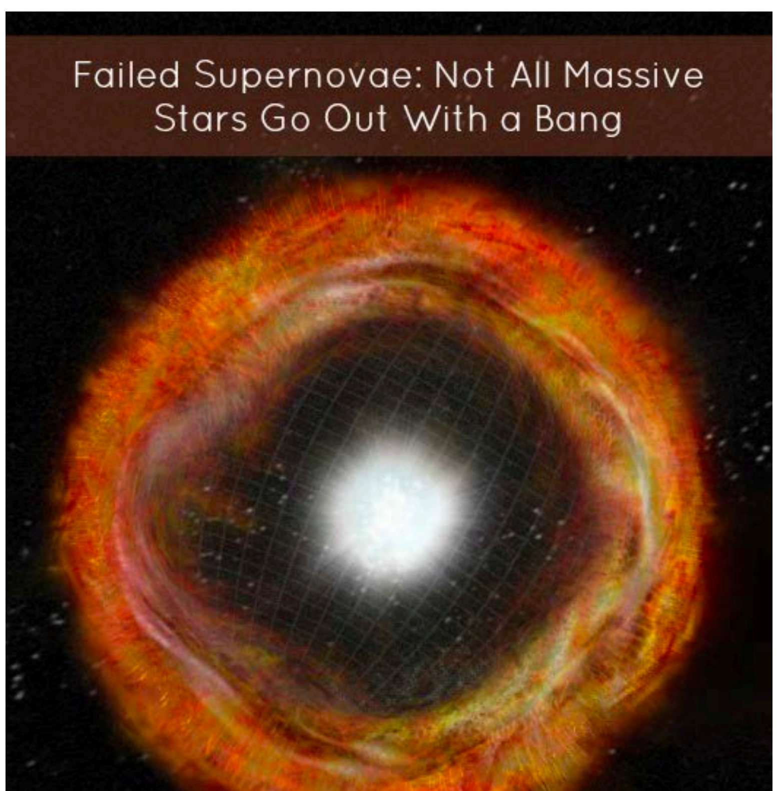
- Echoes after GW170817, Bayes factor of **~10**
- Geometric time-delay ≠ Observed time delay



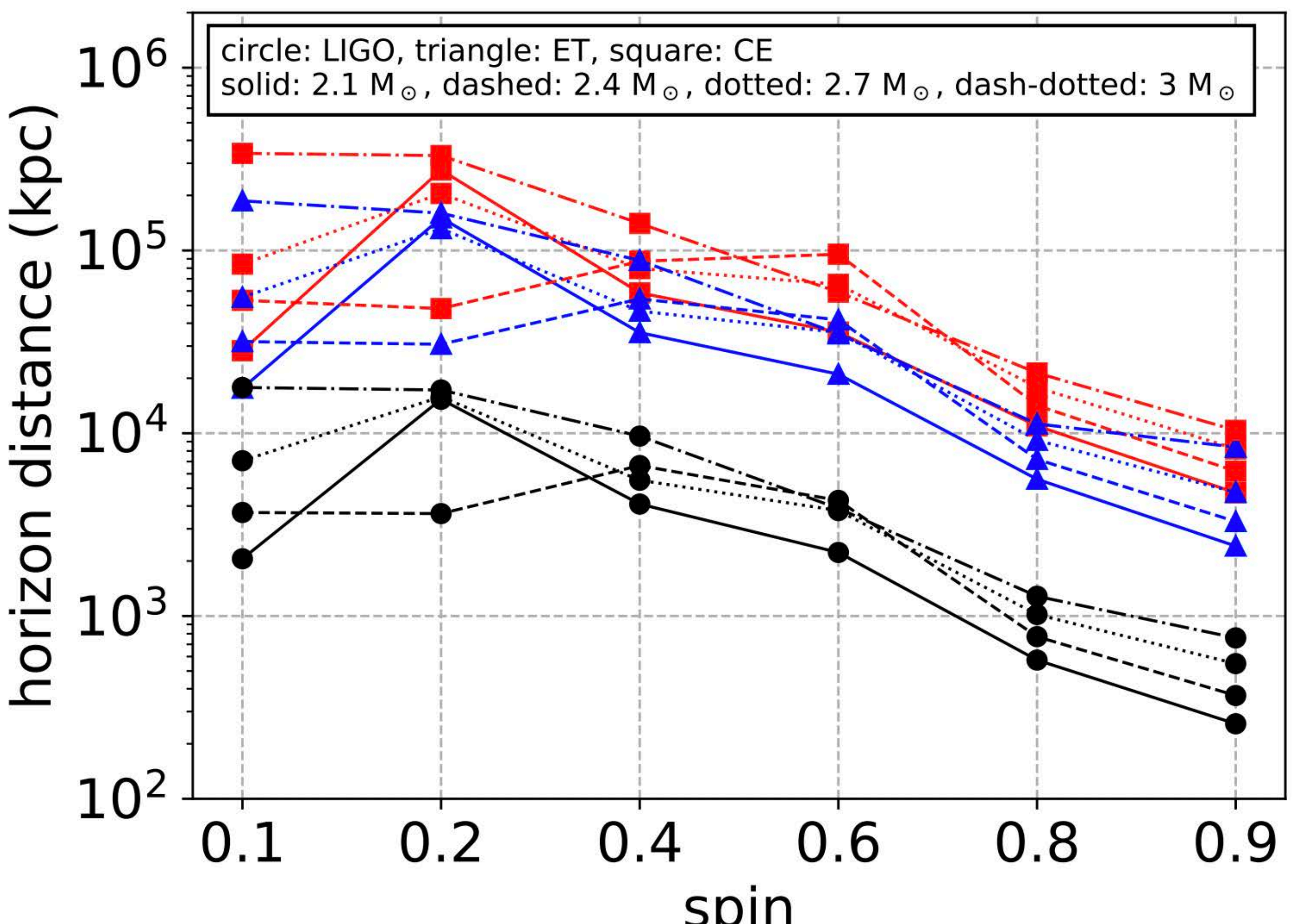


Failed Supernova Echoes?

- GR Ringdown frequency for few$\times M_\odot$ BH is beyond LIGO sensitivity
- But echo harmonics have much lower frequencies
- We may only see their echoes



Oshita, Tsuna, & NA 2020



Detectability of Failed SNe for maximum stable horizon temperature

Conclusions

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- Logarithmically delayed echoes are physical probes of quantum black hole microstructure
- Tantalizing though controversial hints for echoes in LIGO
- Black Hole Seismology: a systematic way to probe quantum structure of black holes

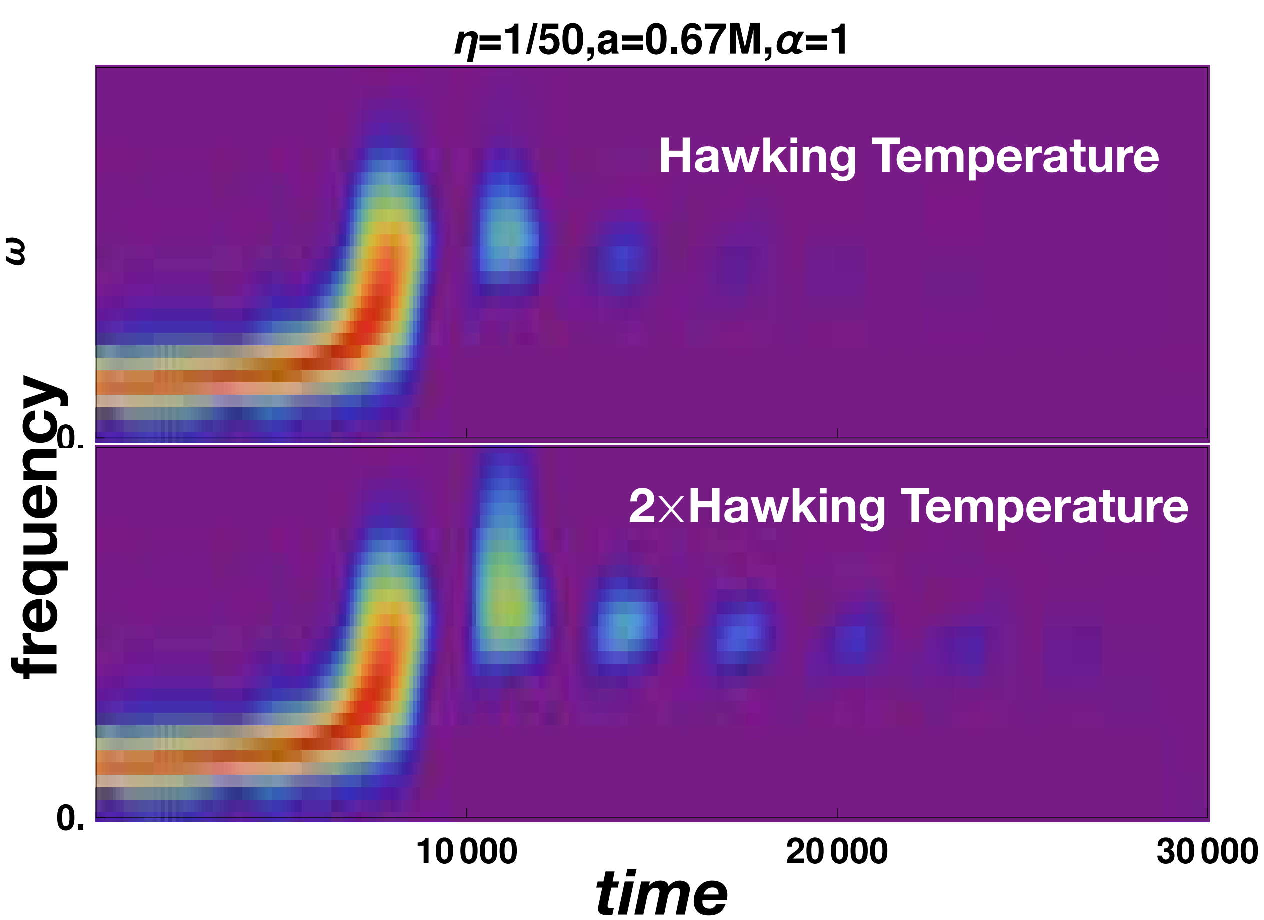
Conclusions

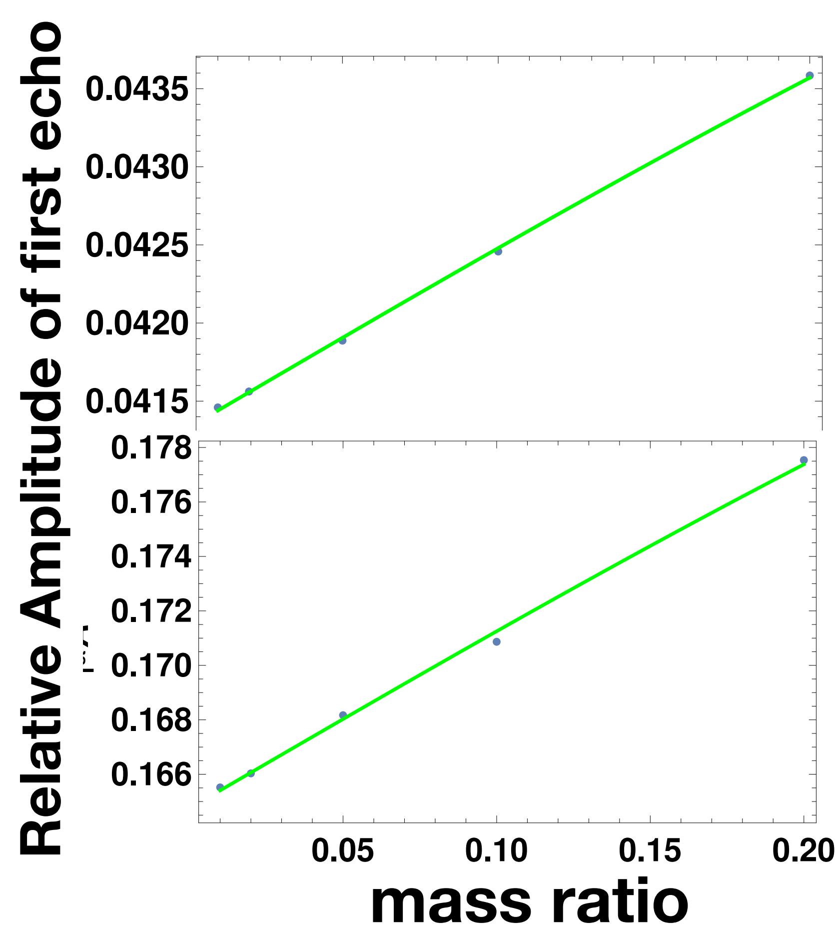
- Much of the fair tales about (what lies within) black holes has no empirical evidence
- Logarithmically delayed echoes are physical probes of quantum black hole microstructure
- Tantalizing though controversial hints for echoes in LIGO
- Black Hole Seismology: a systematic way to probe quantum structure of black holes
- Don’t ask what echoes can do for you, ask what you can do for echoes!

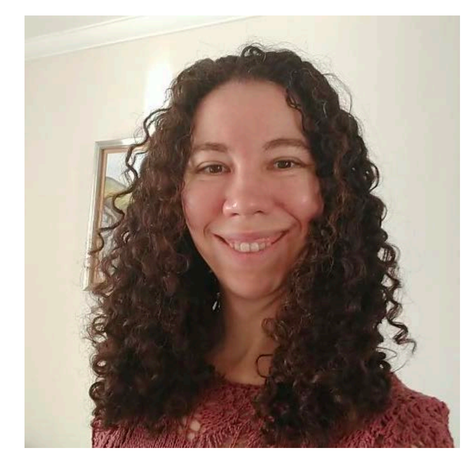
Bonus Slides!

Echo-Diversity: How initial conditions impact seismology

- *Upcoming work with Luis Longo and Cecilia Chirenti*
- Solving for GW radiation of an ***inspiralling point*** mass into a Quantum Black Hole







Has LIGO already seen one on Jan. 14, 2020?!

GraceDB — Gravitational-Wave Candidate Event Database

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Superevent Info

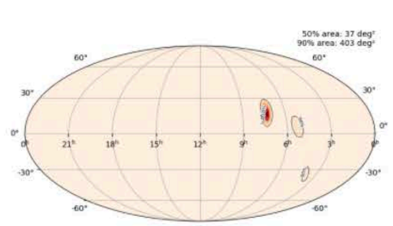
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S200114f	Production	EM_READY ADVOK EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1.226e-09	1 per 25.838 years	1263002916.225766	1263002916.239300	1263002916.252885	2020-01-14 02:11:12 UTC	Data

Preferred Event Info

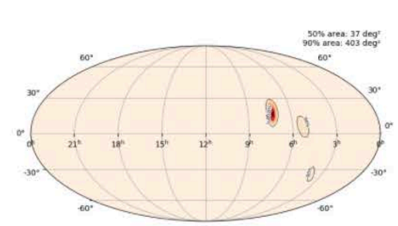
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
Burst	CWB	IMBH	H1,L1,V1	1263002916.2393	2020-01-14 02:12:26 UTC

Superevent Log Messages

Sky Localization



Mollweide projection of cWB.fits.gz cWB.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 14, 2020 02:13:42 UTC



Mollweide projection of cWB.fits.gz cWB.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 14, 2020 02:18:50 UTC

Independent confirmation by AEI group *(in spite of their title 😕)*

Event	[21]	original 16s (32s)
GW150914	0.11	0.199 (0.238)
LVT151012	-	0.056 (0.063)
GW151226	-	0.414 (0.476)
GW170104	-	0.725
(1,2)	-	0.004
(1,3)	-	0.159
(1,2,3)	0.011	0.020 (0.032)
(1,3,4)	-	0.199 (0.072)
(1,2,3,4)	-	0.044 (0.032)

- 3σ "detection" w/ 1st & 2nd events
- None in the 3rd & 4th

A. *(un)lucky coincidence?*

B. *Echoes are more complex?*

Low significance of evidence for black hole echoes in gravitational wave data

Julian Westerweck,[1,2,*] Alex B. Nielsen,[1,2,†] Ofek Fischer-Birnholtz,[1,2,3,‡] Miriam Cabero,[1,2] Collin Capano,[1,2] Thomas Dent,[1,2] Badri Krishnan,[1,2] Grant Meadors,[1,4,5] and Alexander H. Nitz[1,2]

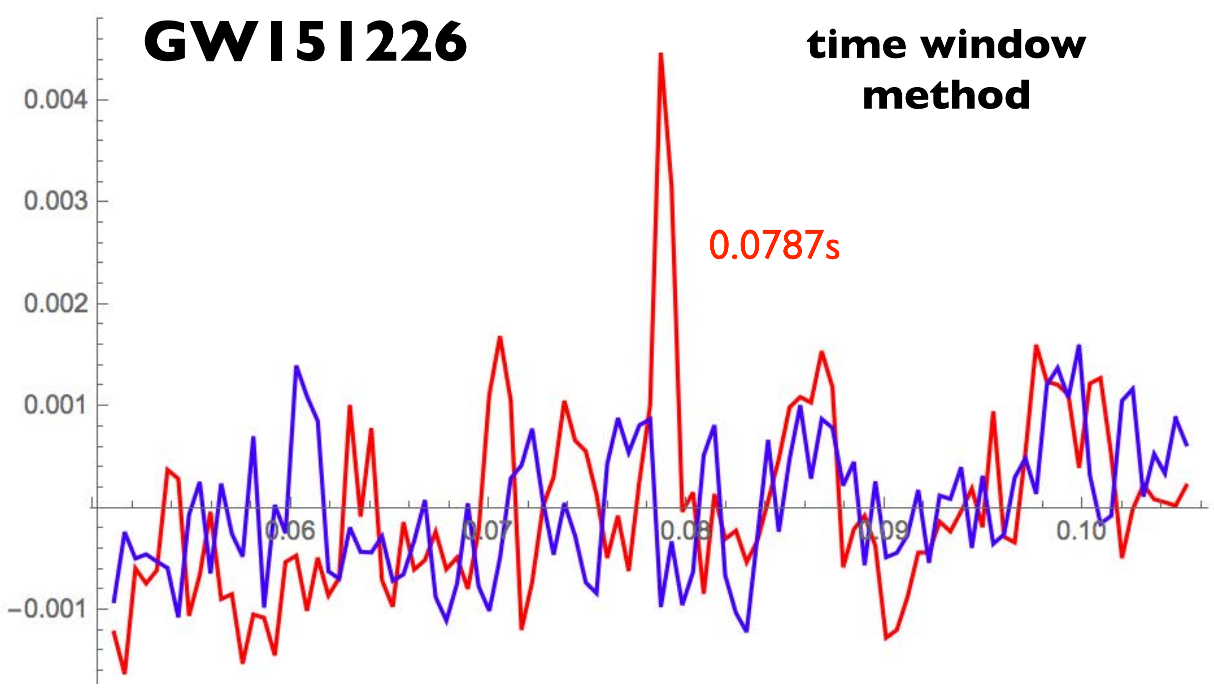
[1] *Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[3] *Rochester Institute of Technology, Rochester, NY 14623, USA*
[4] *Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*
[5] *OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*

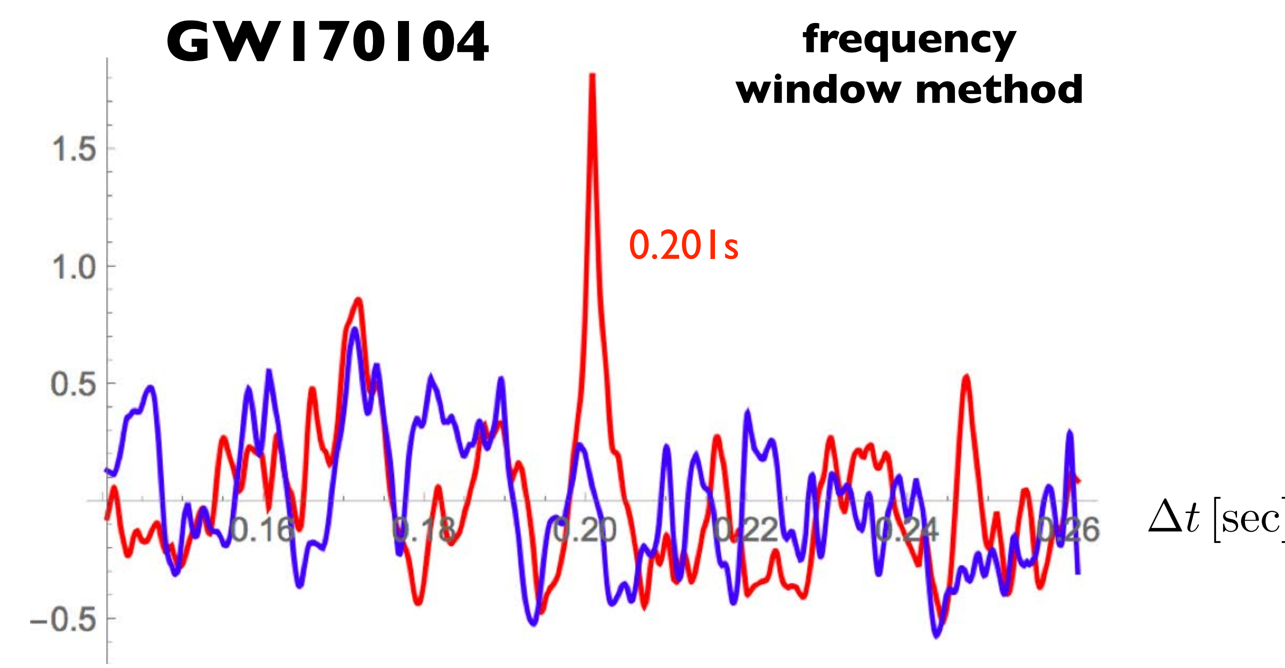
arXiv:1712.09966

Randy Conklin, Bob Holdom & Jing Ren 2018

Another independent search for echoes

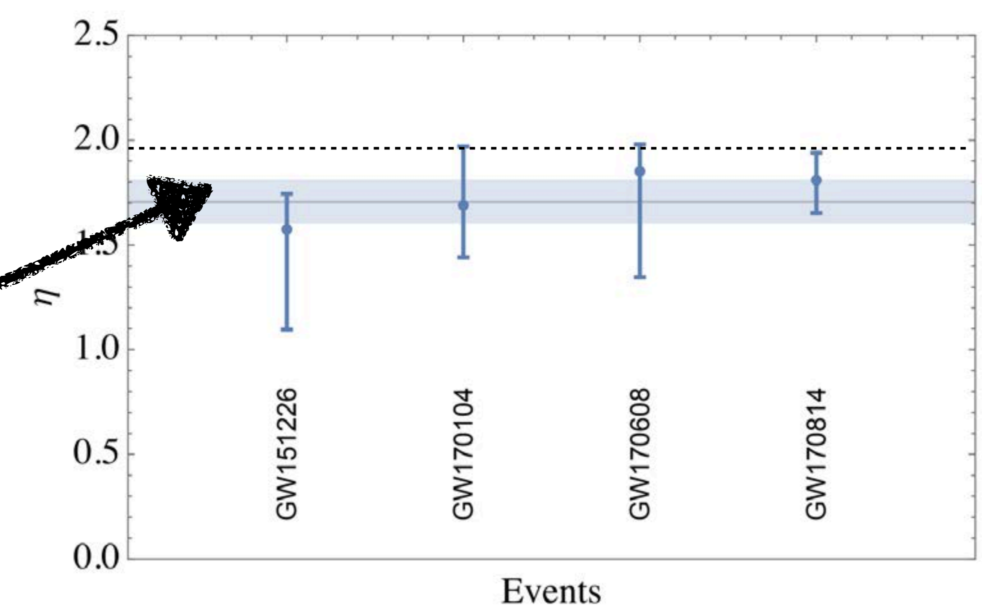
- ***Search strategies***: using window functions to find the ***preferred time delay*** of echoes from the correlation of two LIGO detectors (red and blue curves are for data after and before merger)



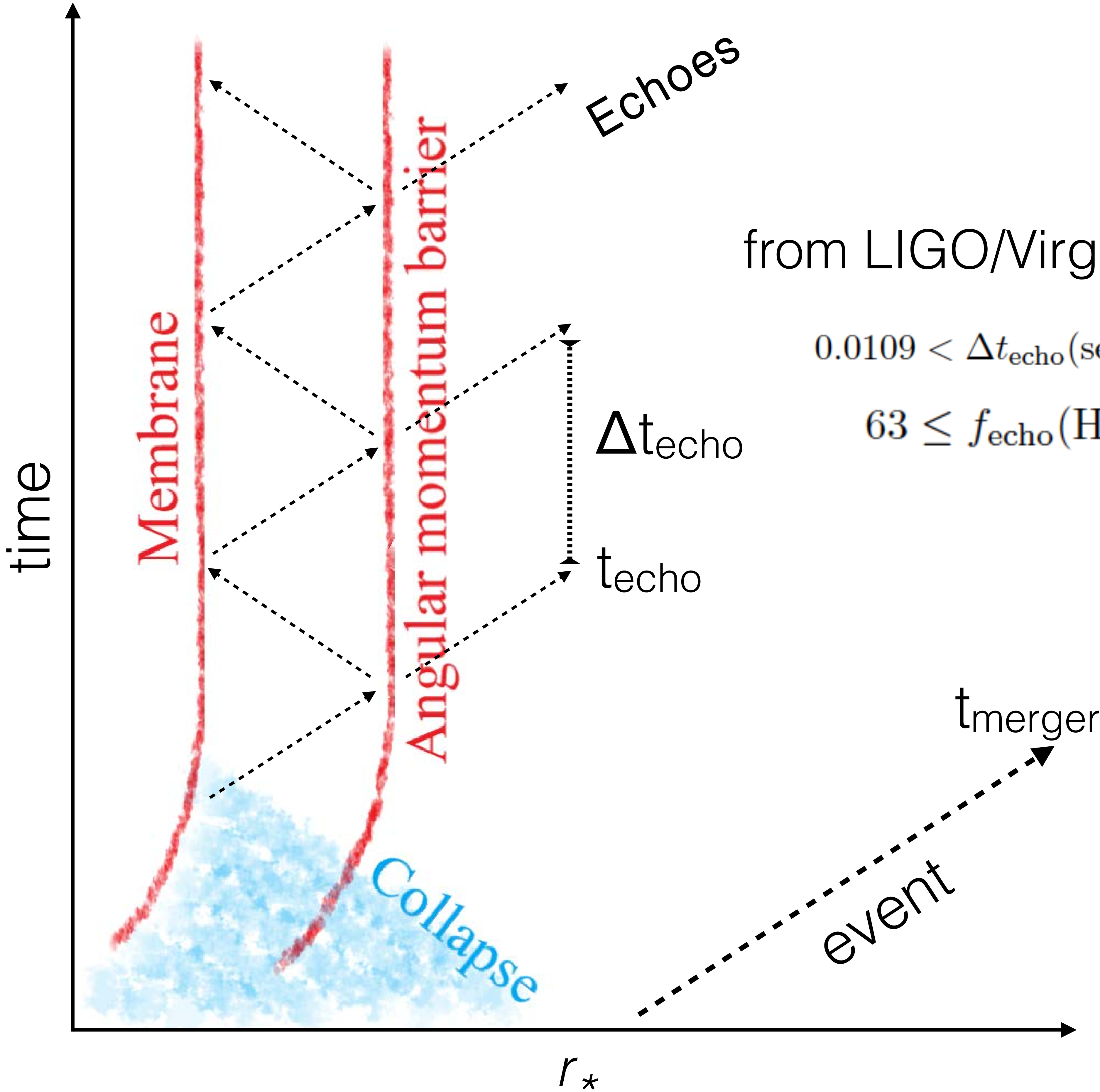


- Tentative signal peaks for *GW151226, GW170104, GW170608, GW170814, GW170817*
- **p-values ~ 0.2%-0.8%**
- consistent w/ GUT or "Inflation" scales

$$K_{\rm max} \sim E_{\rm Pl}/C \sim 10^{-6\pm2} E_{\rm Pl} = 10^{13\pm2}\ \text{GeV}$$



Oshita & NA 2019



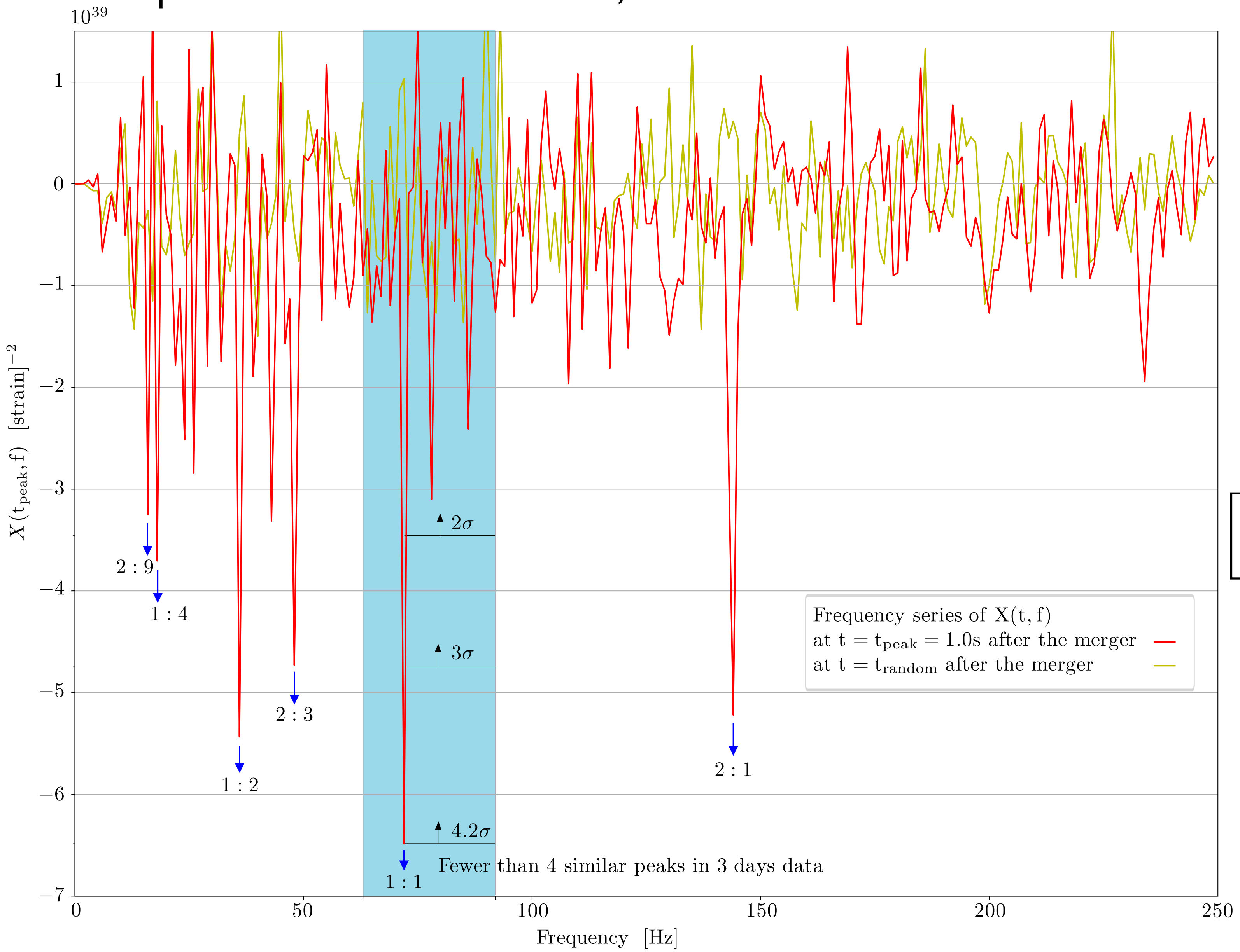
from LIGO/Virgo (90% CL)

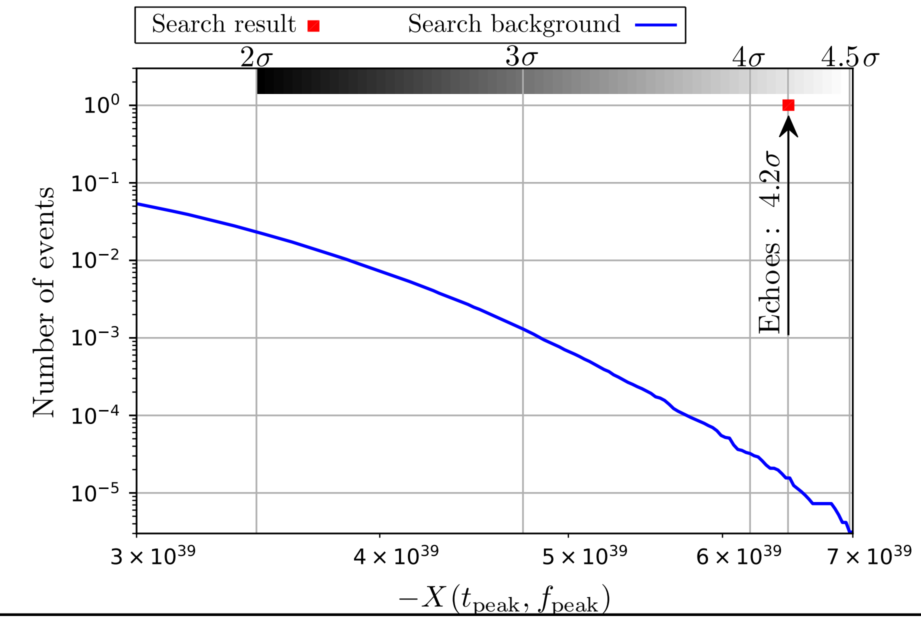
$$0.0109 < \Delta t_{\rm echo}(\rm sec) < 0.0158$$

$$63 \leq f_{\rm echo}(\rm Hz) \leq 92$$

Binary Neutron Star merger

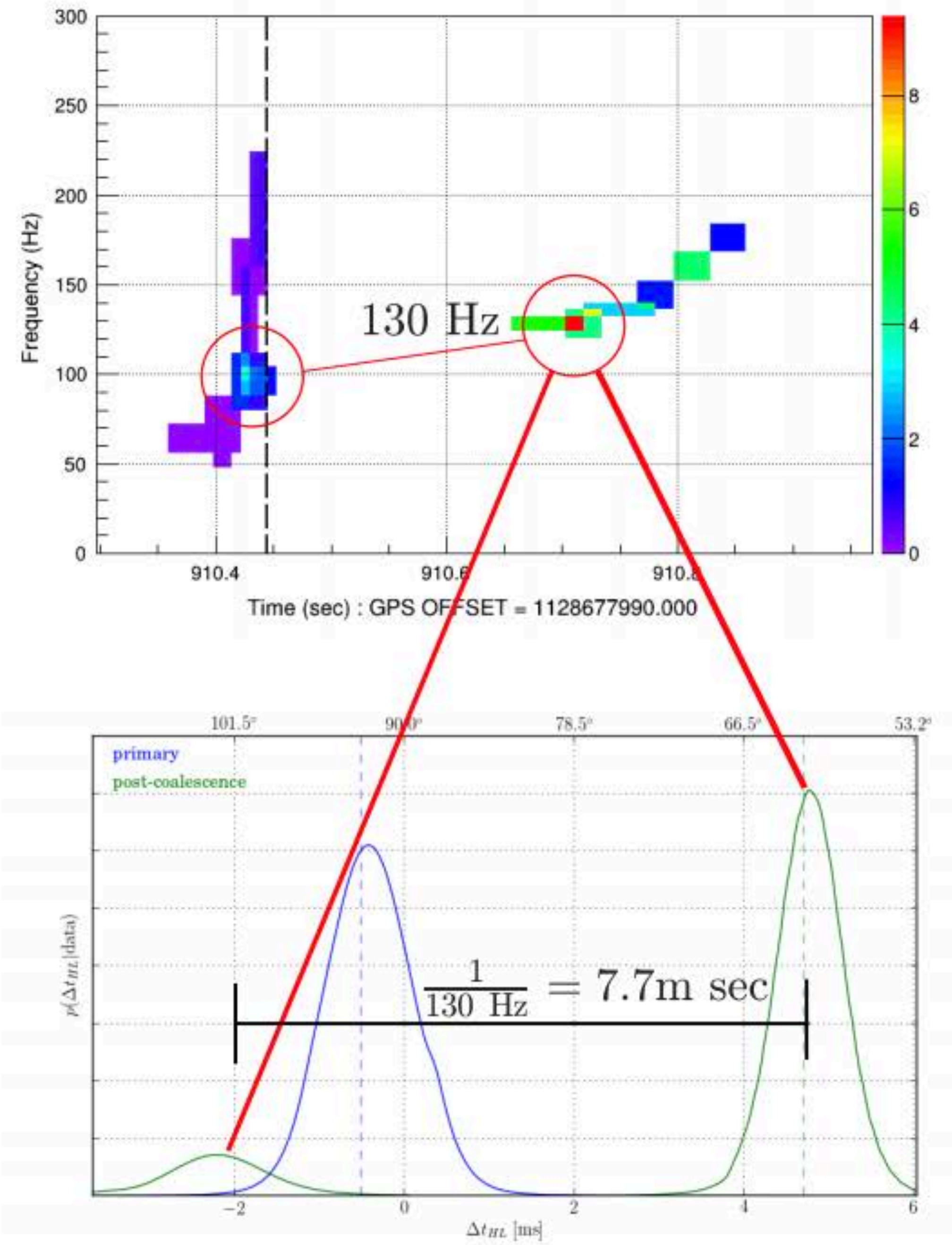
- Echoes within 1 sec after GW170817 merger @ f= 72 Hz
- p-value =1.6×10^{-5}, **4.2σ tentative detection,** *high-spin BH remnant*

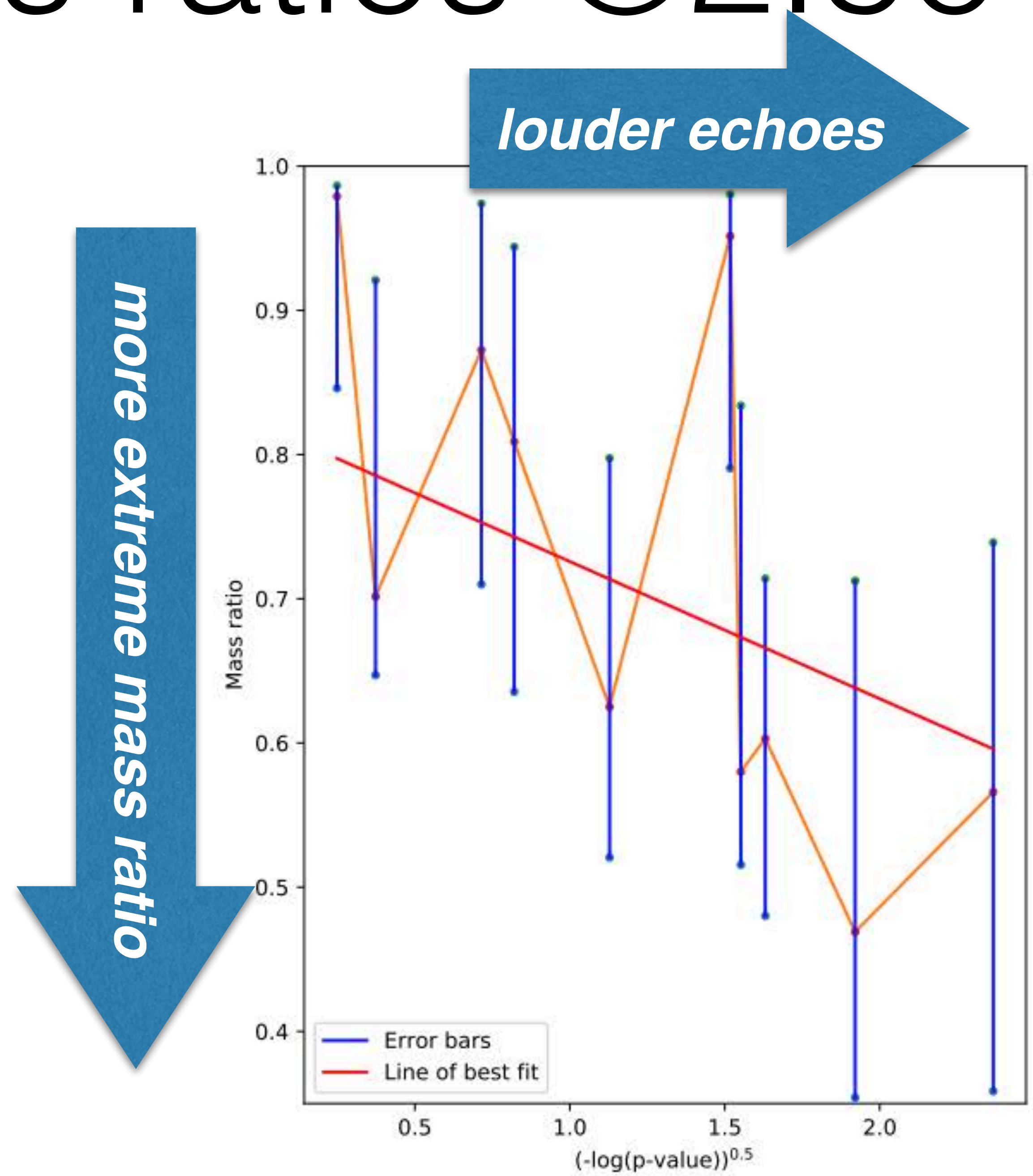




Abedi & NA, arXiv:1803.10454

Echoes are louder for more extreme mass ratios @2.5σ





[15] F. Salemi, E. Milotti, G. A. Prodi, G. Vedovato, C. Lazzaro, S. Tiwari, S. Vinciguerra, M. Drago, and S. Klimenko, Phys. Rev. D100, 042003 (2019), arXiv:1905.09260 [gr-qc].

p-values from Salemi, et al. 2019

Positive Evidence (p-value ≦ 5%)

	Authors	Method	Data	p-value
1	**Abedi, Dykaar, NA 2017 (ADA)**	ADA template	O1	1.1%
2	**Conklin, Holdom, & Ren 2018**	spectral comb	O1+O2	0.2%-0.8% (now 10^{-10}!)
3	**Westerweck, et al. 2018**	ADA template	O1	2.0%
4	**Nielsen, et al. 2019**	ADA+Bayes	151012,151226	2%*
5	**Uchikata, et al. 2019**	ADA template	O1	5.5%
6	**Uchikata, et al. 2019**	ADA template	O2	3.9%
7	**Salemi, et al. 2019**	coherent WaveBurst	151012,151226	0.4%,3%
8	**Abedi & NA 2019**	spectral comb	BNS	0.0016%
9	**Gill, Nathanail, Rezolla 2019**	Astro Modelling	BNS EM	$t_{coll}=t_{echo}$

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Failed Searches

	Authors	Method	Data	possible caveat
1	**Westerweck, et al. 2018**	ADA template	O1	“Infinite” prior
2	**Nielsen, et al. 2019**	ADA+Bayes	150914	mass-ratio dependence
3	**Uchikata, et al. 2019**	ADA, hi-pass	O1, O2	no low-frequencies
4	**Salemi, et al. 2019**	coherent WaveBurst	O1, O2 **	mass-ratio dependence, only 1st echo
5	**Lo, et al. 2019**	ADA+Bayes	O1	“Infinite” prior
6	**Tsang, et al. 2019**	BayesWave	O1+O2	needs very loud echoes (9 free parameters)

Independent Evidence for Echoes in O2

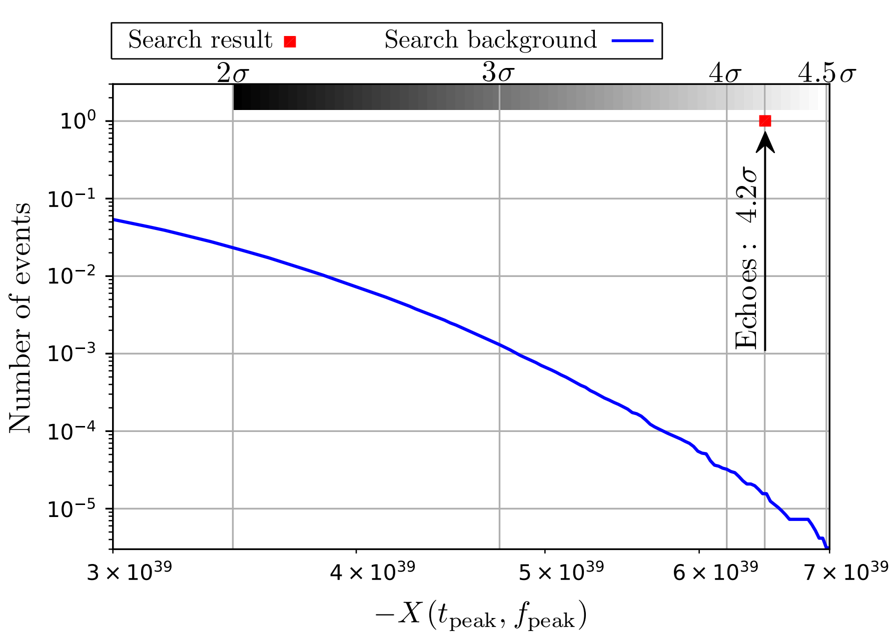
Event	Uchikata et al. [11]
GW170104	0.071
GW170608	0.079
GW170729	0.567
GW170814	0.024
GW170818	0.929
GW170823	0.055
Total	0.039

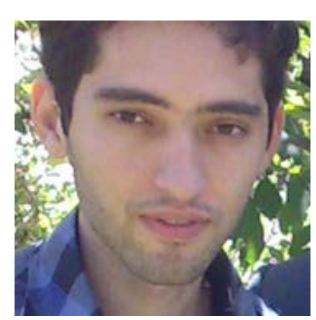
TABLE III: P-values for O2 events [11]. The results show O2 events have same small p-values as O1.

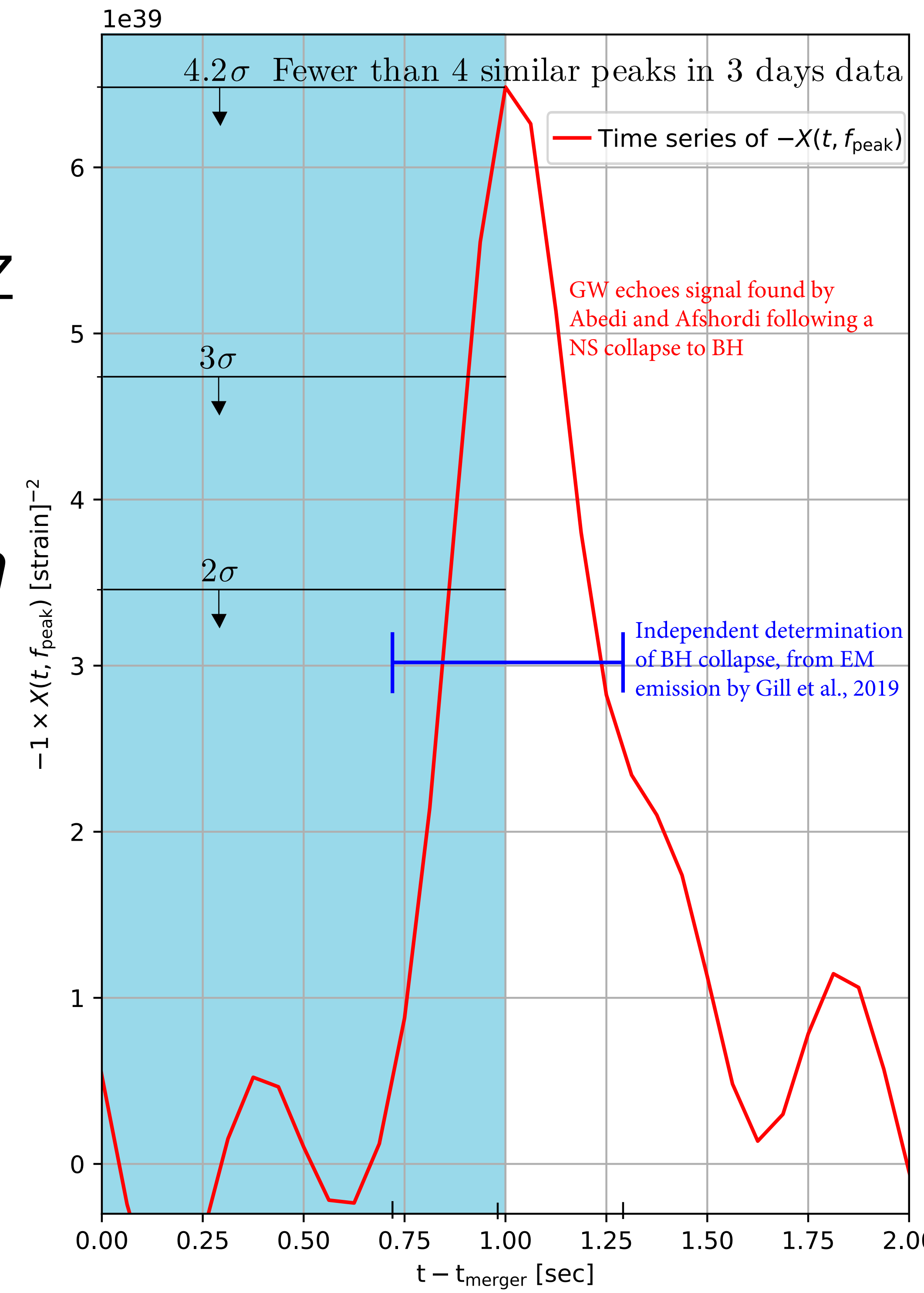
[11] N. Uchikata, H. Nakano, T. Narikawa, N. Sago, H. Tagoshi, and T. Tanaka, Phys. Rev. **D100**, 062006 (2019), arXiv:1906.00838 [gr-qc].

Binary Neutron Star merger

- Echoes within 1 sec after GW170817 merger @ f= 72 Hz
- p-value =1.6×10^{-5}, **4.2σ tentative detection,** *high-spin BH remnant*







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