New horizons for (no-)horizon physics: from gauge to gravity and back

Stimulating Hawking Radiation of Gravitational waves: *from theory to observation*

Niayesh Afshordi

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

WATERLOO CENTRE FOR ASTROPHYSICS

UNIVERSITY OF WATERLOO

Strahlungs-Emission und -Absorption nach der Quantentheorie;

von A. Einstein.

(Eingegangen am 17. Juli 1916.)

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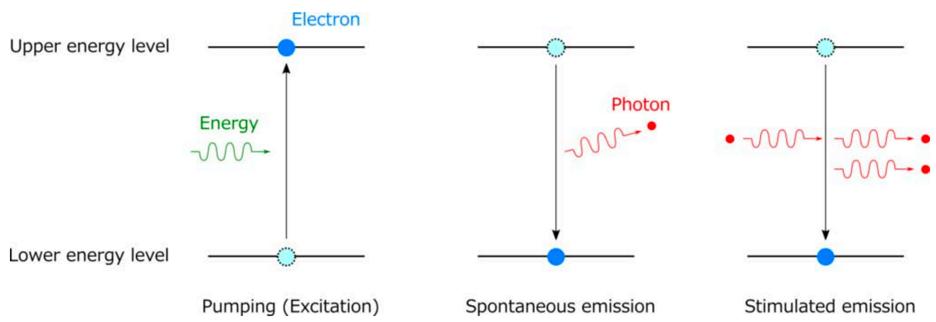

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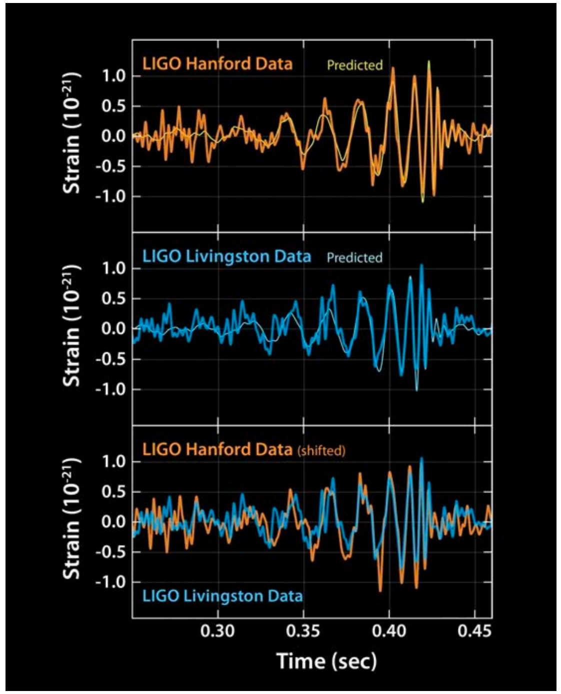

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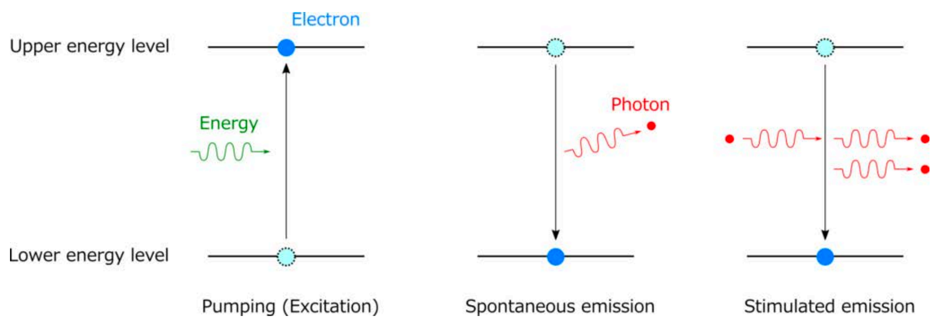

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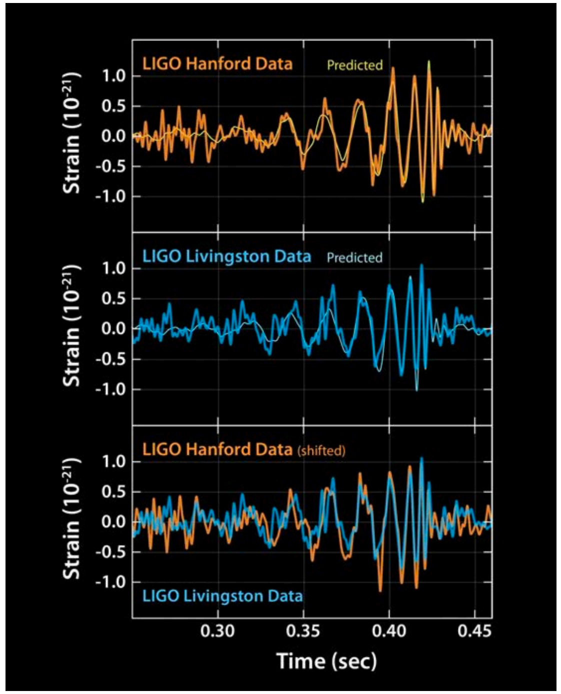

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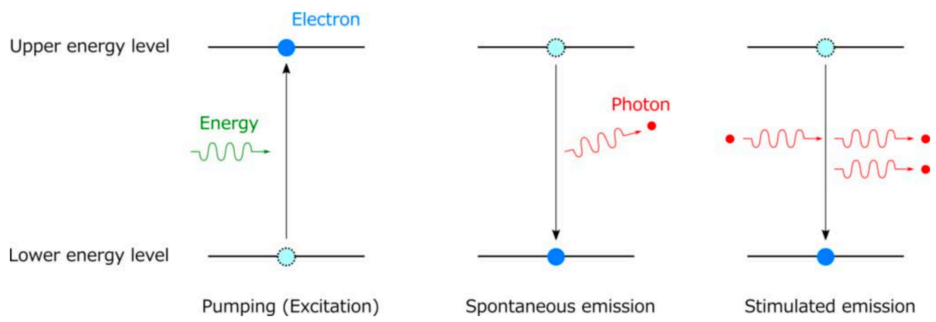

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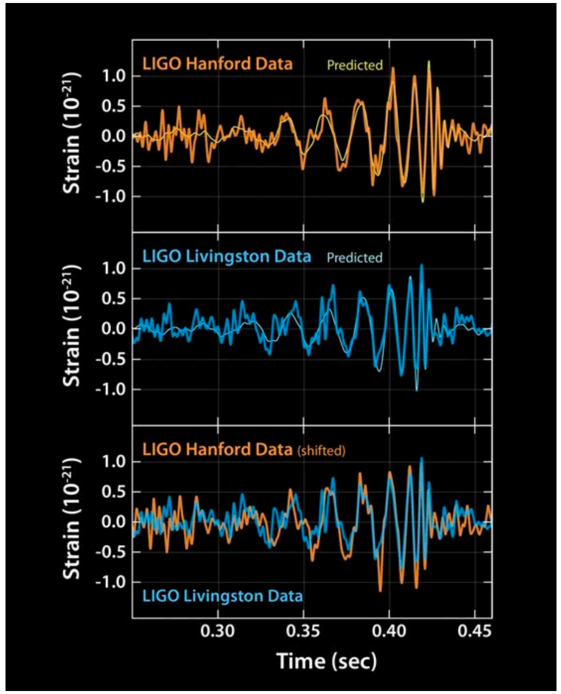

Outline

- Black Holes: *der Gravitation*
- Black Holes: *der Quantentheorie*
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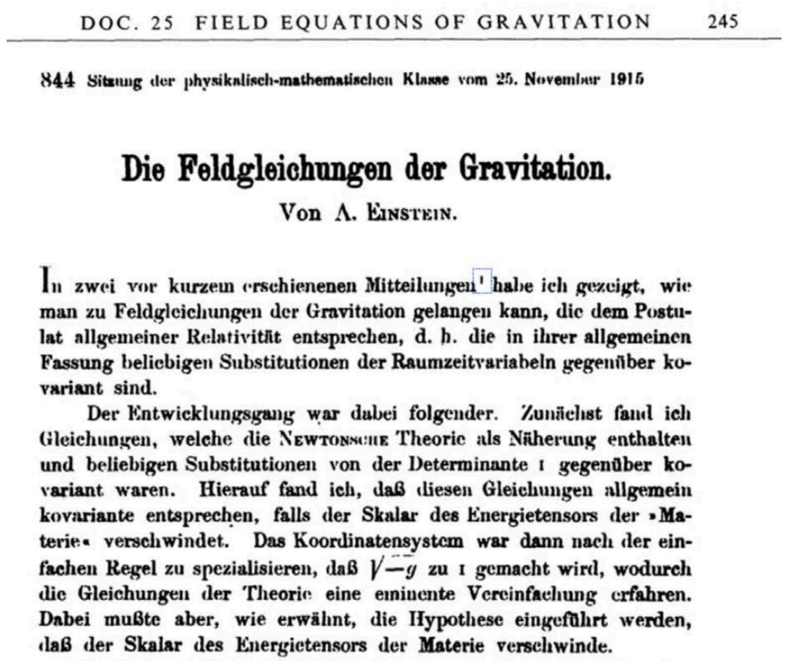

DOC. 25 FIELD EQUATIONS OF GRAVITATION 245

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

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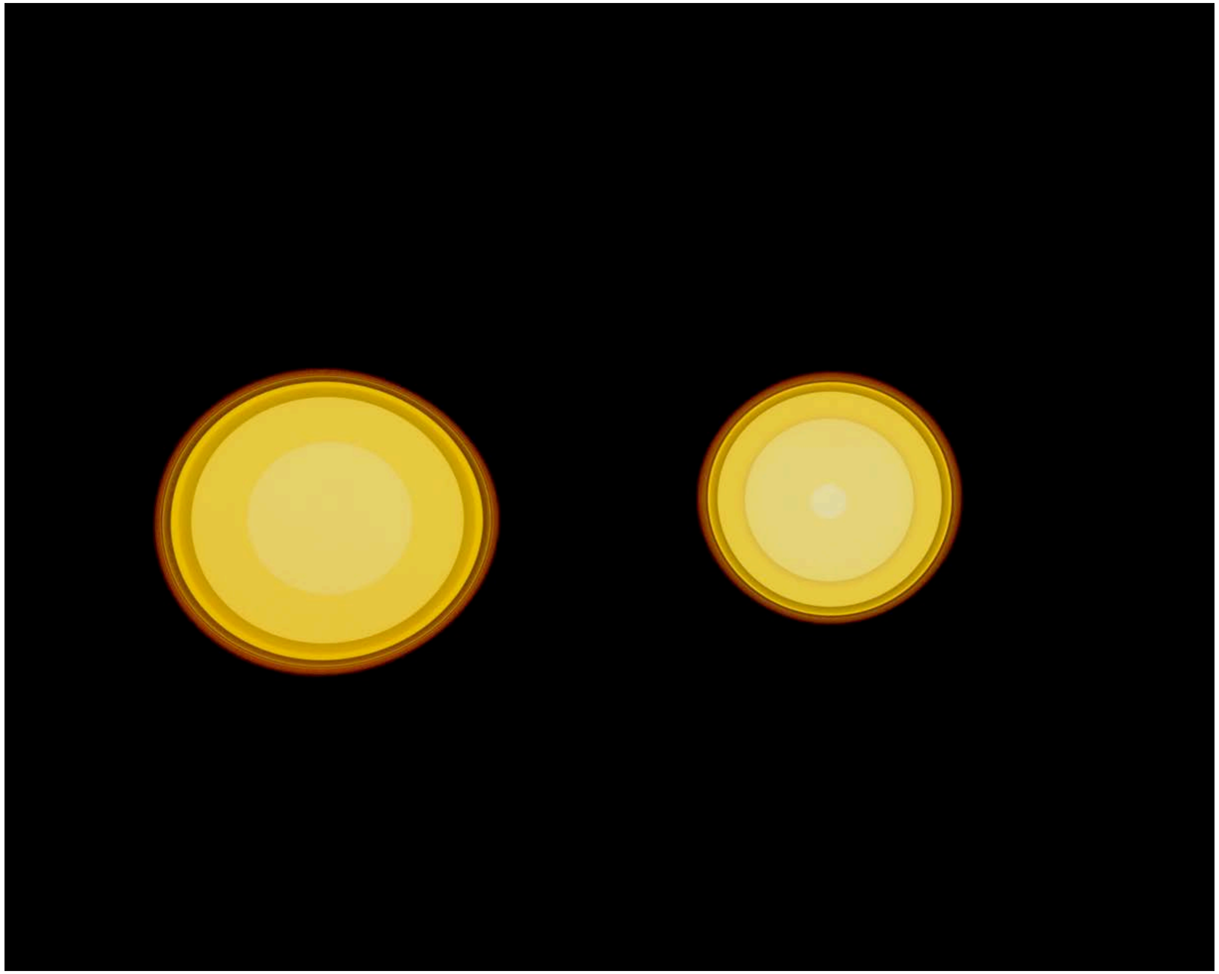
Einstein Gravity predicts formation of Black Holes



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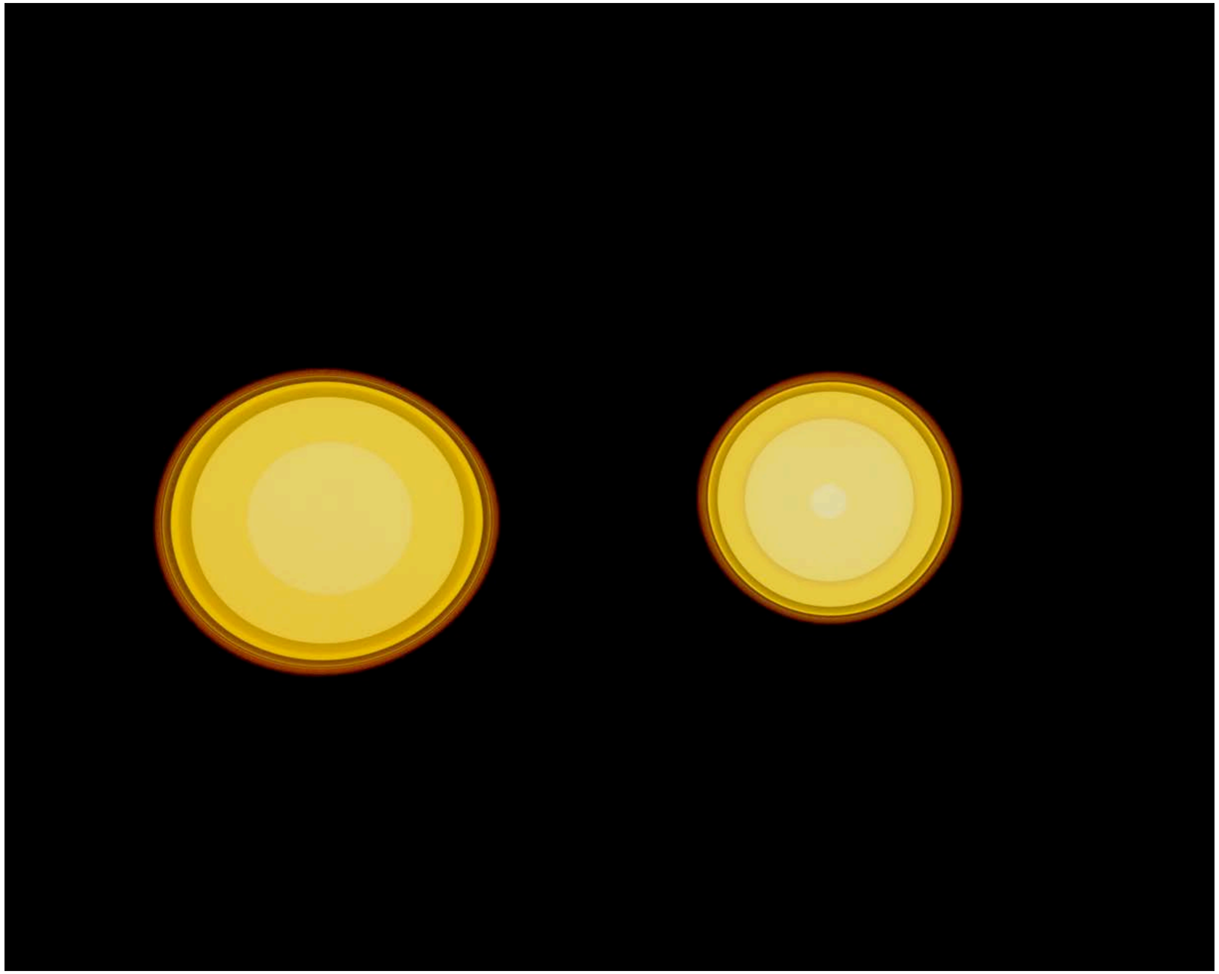

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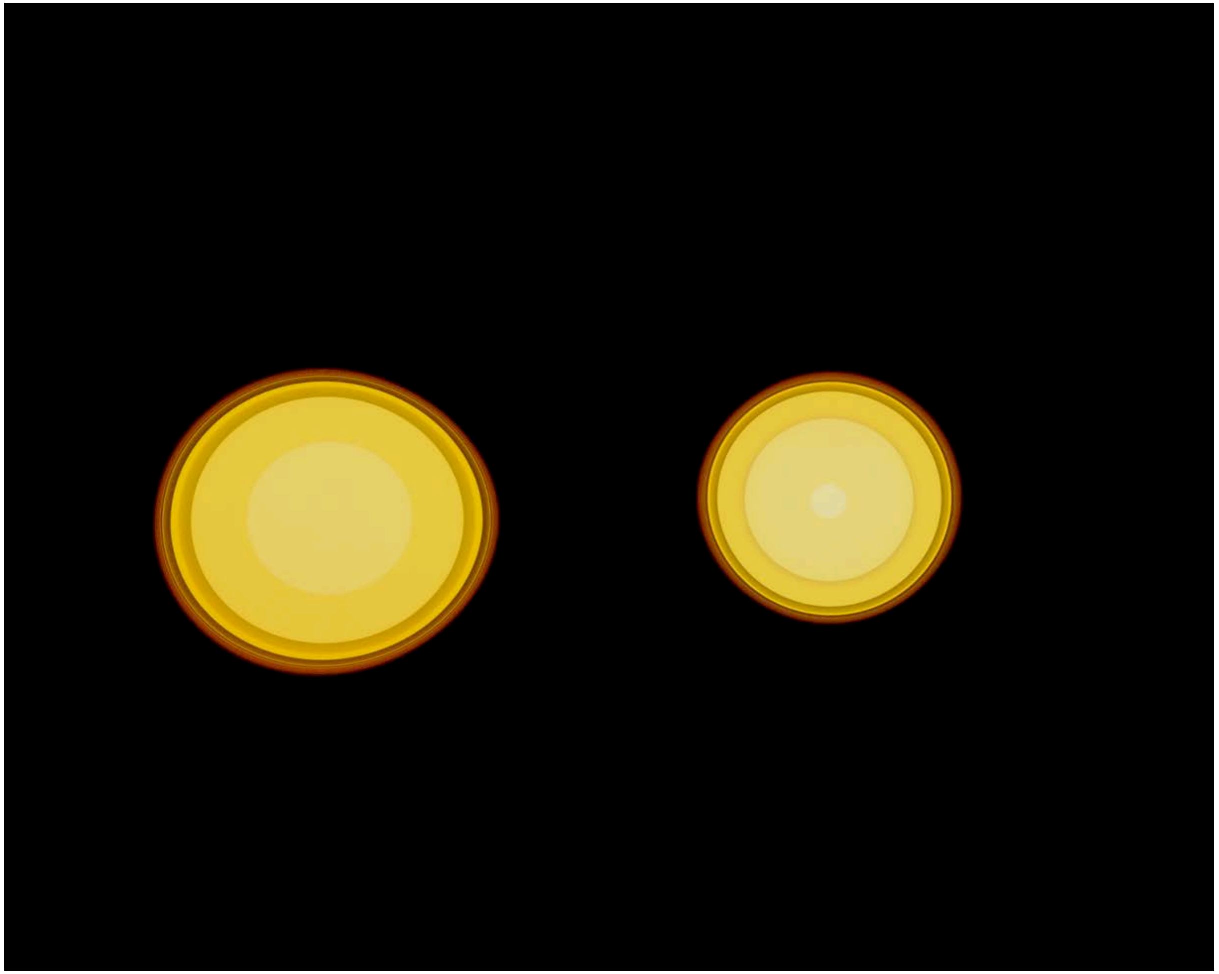

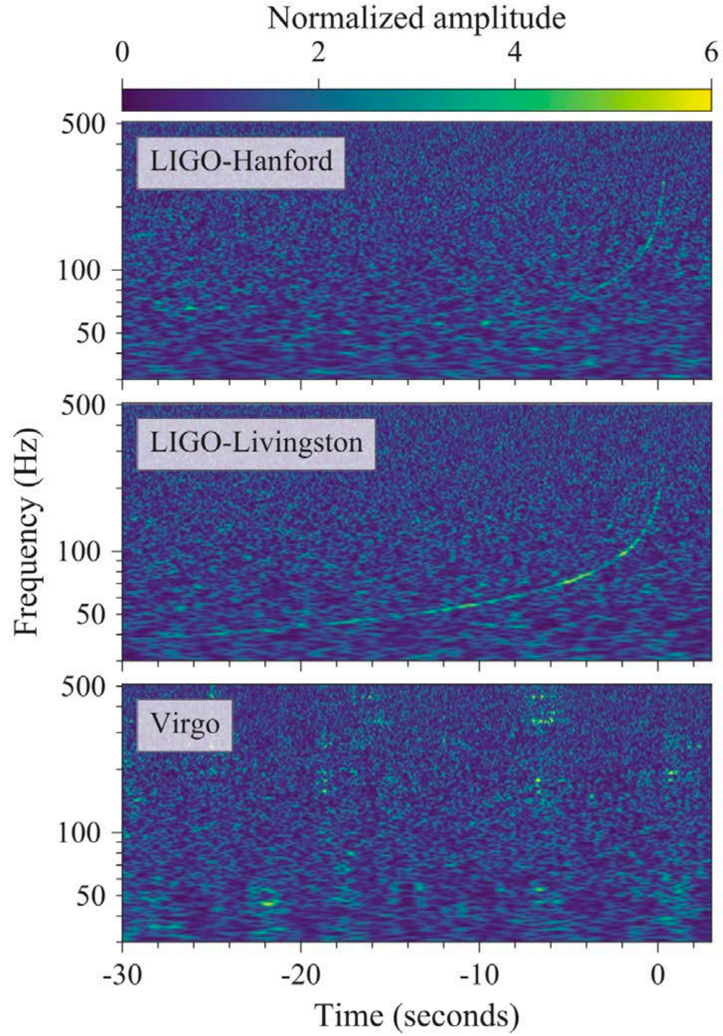

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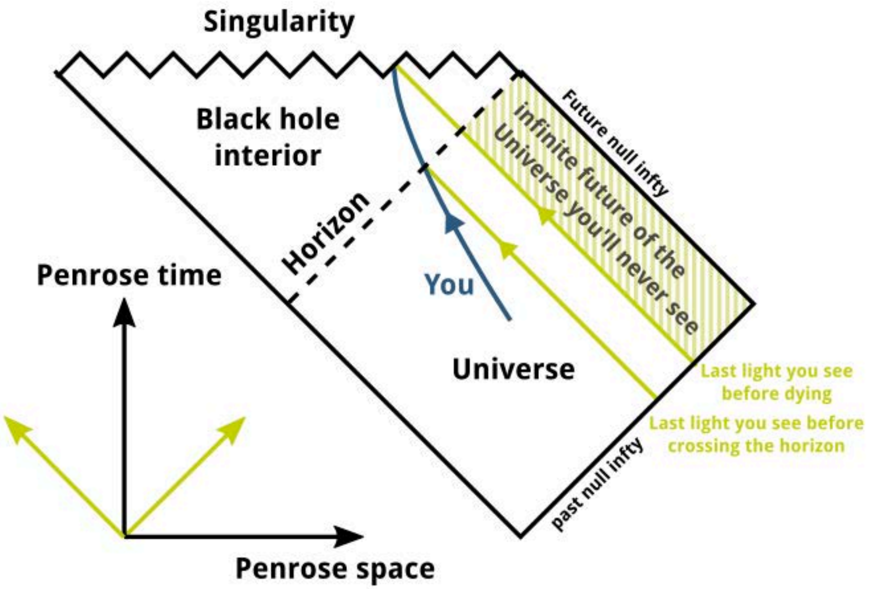
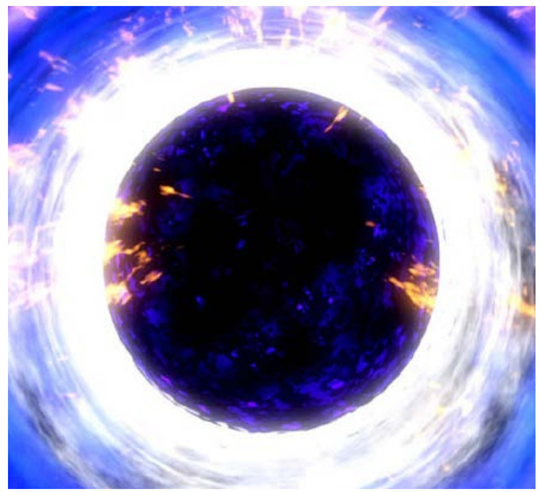
Event Horizons of Black Holes

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

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

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

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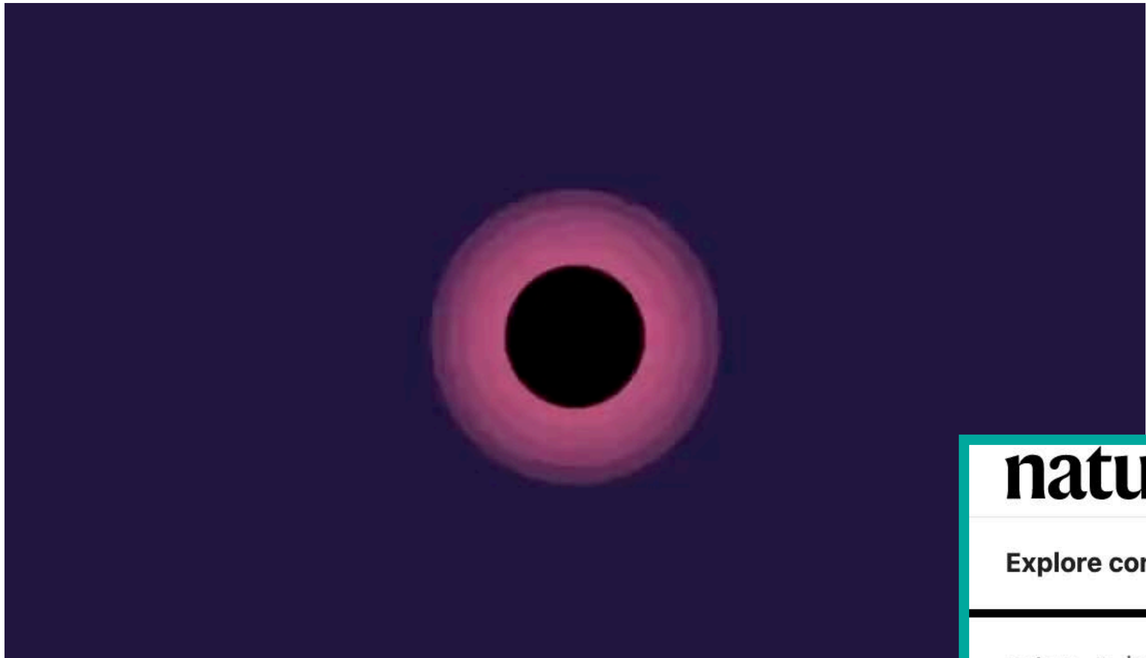
Which states does this entropy count?!

Black Holes Evaporate via Hawking Radiation



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Black hole explosions?

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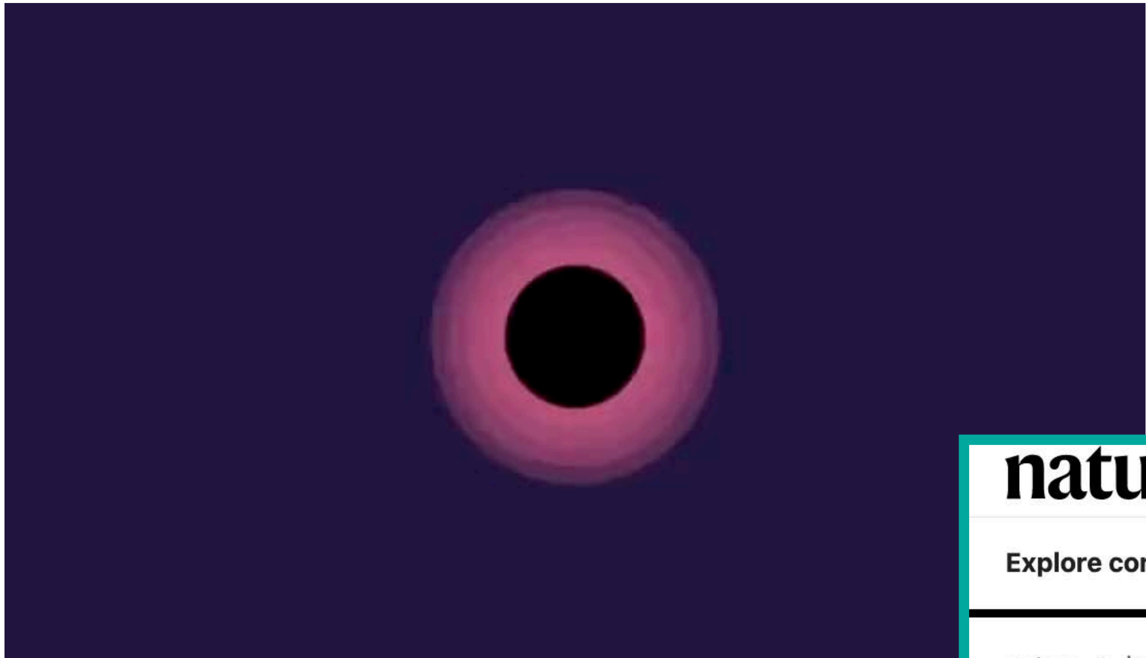

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364 DOC. 34 EMISSION & ABSORPTION OF RADIATION

318 A. Einstein, [Nr. 13/14.

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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:** $exp(-S_E)x\ exp(entropy) \sim 1$ → 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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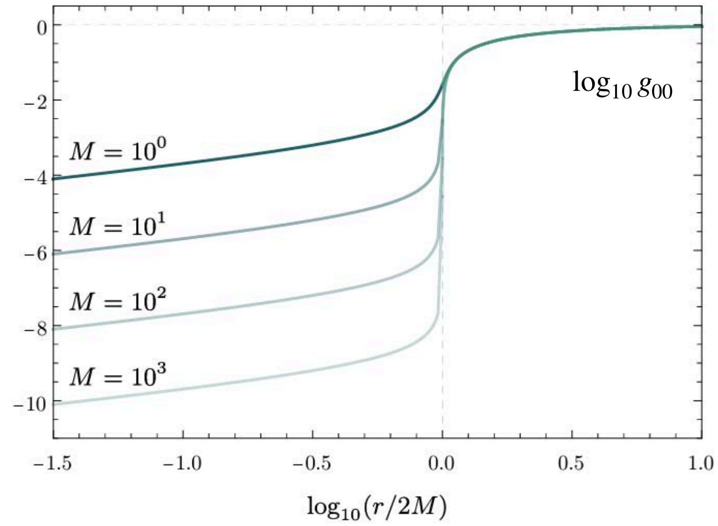
Firewalls in Asymptotic Safety

- Assume that RG-dependence of coupling constants on local temperature; k~T
- Non-trivial UV fixed point
- ***No horizon***
- Scale-invariant core near UV fixed point; $g_{00} \sim r^{\sqrt{3}-1}$

$$S = \int \mathrm{d}^4x \sqrt{-g} \frac{1}{16\pi G(k)} (R - 2\Lambda(k)),$$



arXiv > gr-qc > arXiv:2203.02559

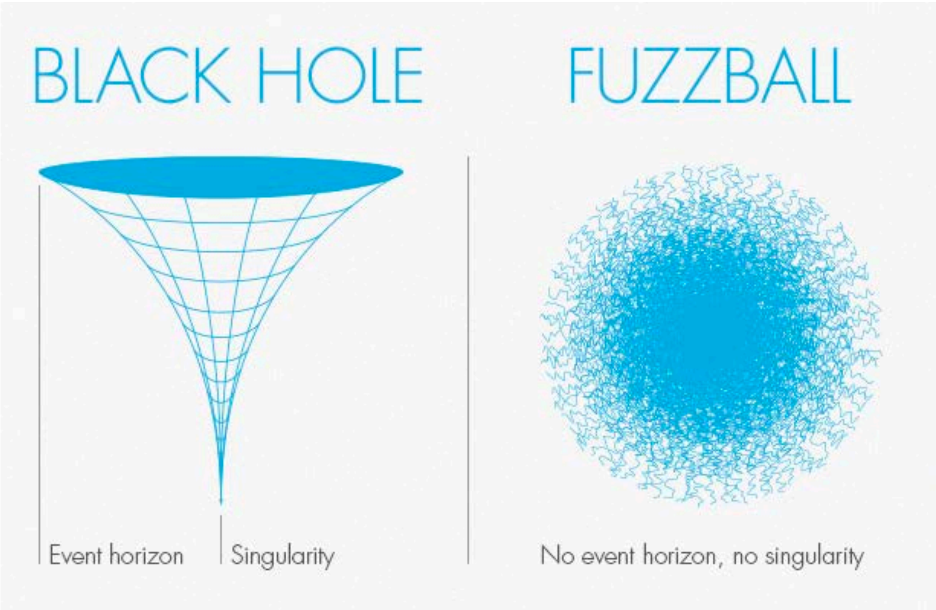
General Relativity and Quantum Cosmology

[Submitted on 4 Mar 2022]

Scale-Invariance at the Core of Quantum Black Holes

Johanna N. Borissova, Aaron Held, Niayesh Afshordi

Fuzzballs in String Theory



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The fuzzball proposal for black holes

Kostas Skenderis *, Marika Taylor

Institute for Theoretical Physics, University of Amsterdam, Valckenierstraat 65, 1018XE Amsterdam, The Netherlands

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **25** (2008) 135005 (45pp) doi:10.1088/0264-9381/25/13/135005

Radiation from the non-extremal fuzzball

Borun D Chowdhury and Samir D Mathur

Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: borundev@mps.ohio-state.edu and mathur@mps.ohio-state.edu

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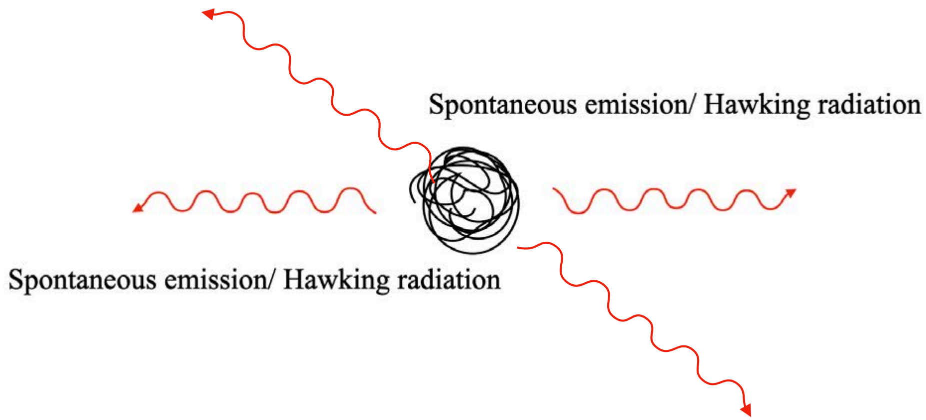
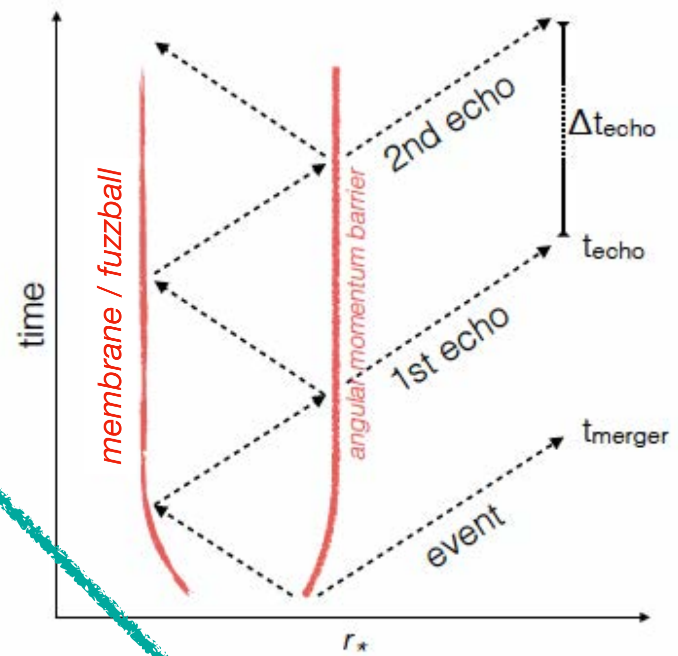


Echoes from the Abyss?

- Delayed echoes from Planckian structure near horizon

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



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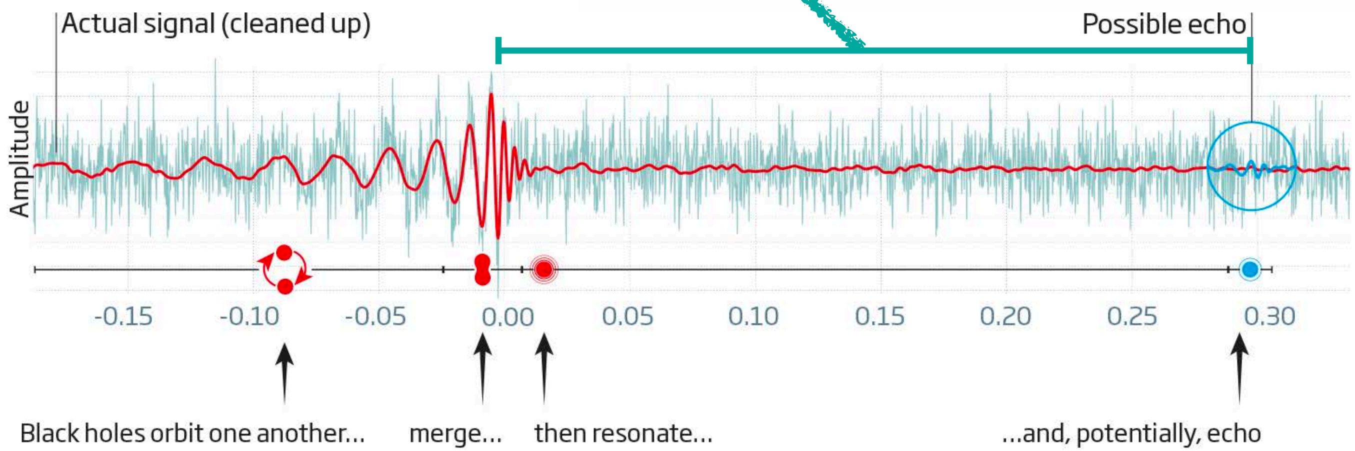
-*Cardoso, Franzin & Pani 2016*
-*Cardoso, Hopper, Macedo, Palenzuela & Pani 2016*
-*Abedi, Dykaar & NA 2017*



Universal Reflectivity of Quantum Horizons

- 3*(+2)* **independent** derivations for Boltzmann reflectivity:

  (1) *Fluctuation-Dissipation Theorem*

  (2) Stimulated Hawking Radiation

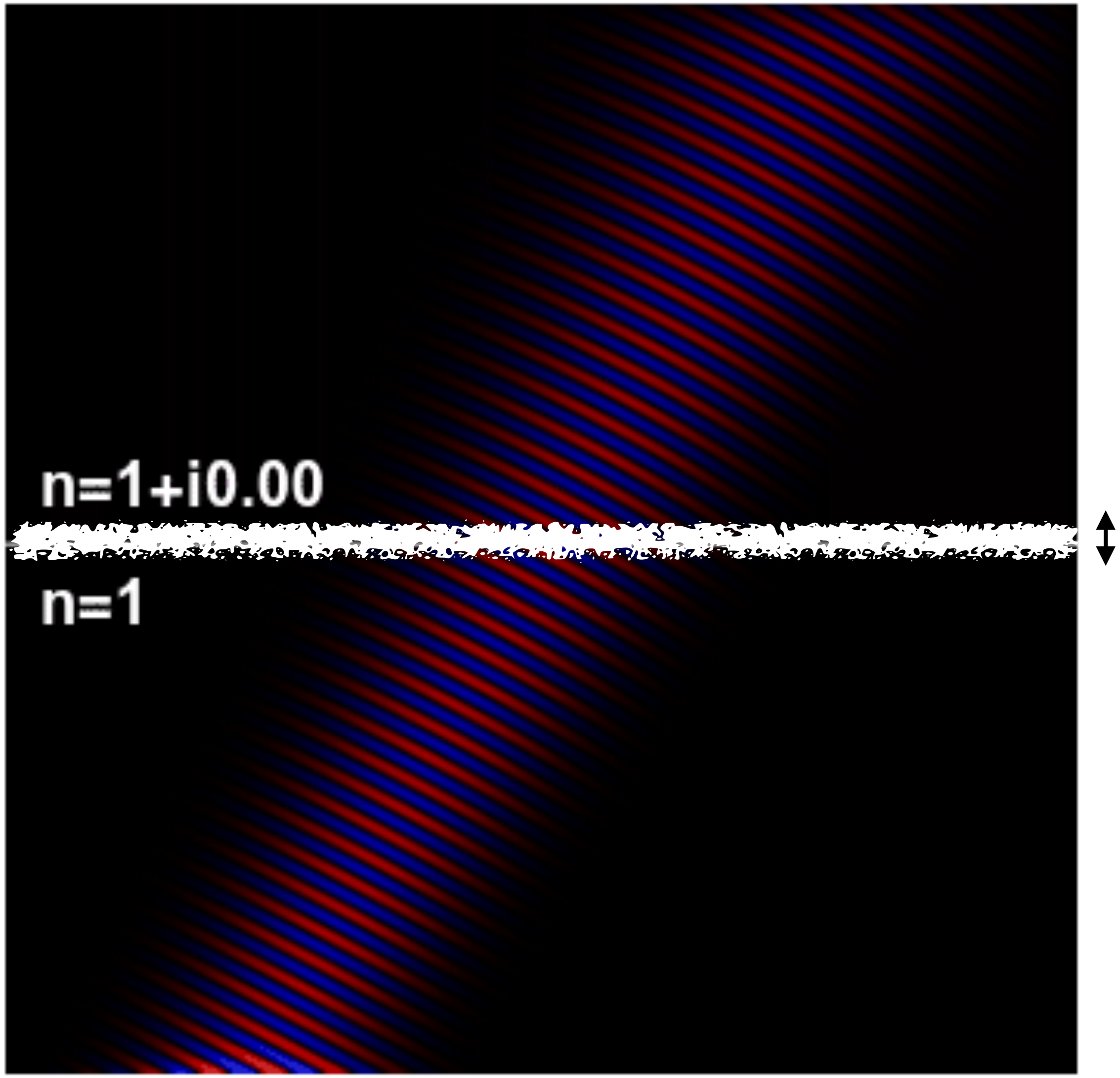
  (3) CP-symmetry

- **Echoes are stimulated Hawking Radiation; max@ horizon frequency**

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

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

Abrupt Dissipation → ~~WKB~~ → Reflection



$\beta = 1/T_{\mathrm{H}}$

https://twitter.com/j_bertolotti/status/1465294009325260802

$$\omega^2 + i\frac{\omega^3}{\Lambda} + \ldots = k^2 \Rightarrow$$

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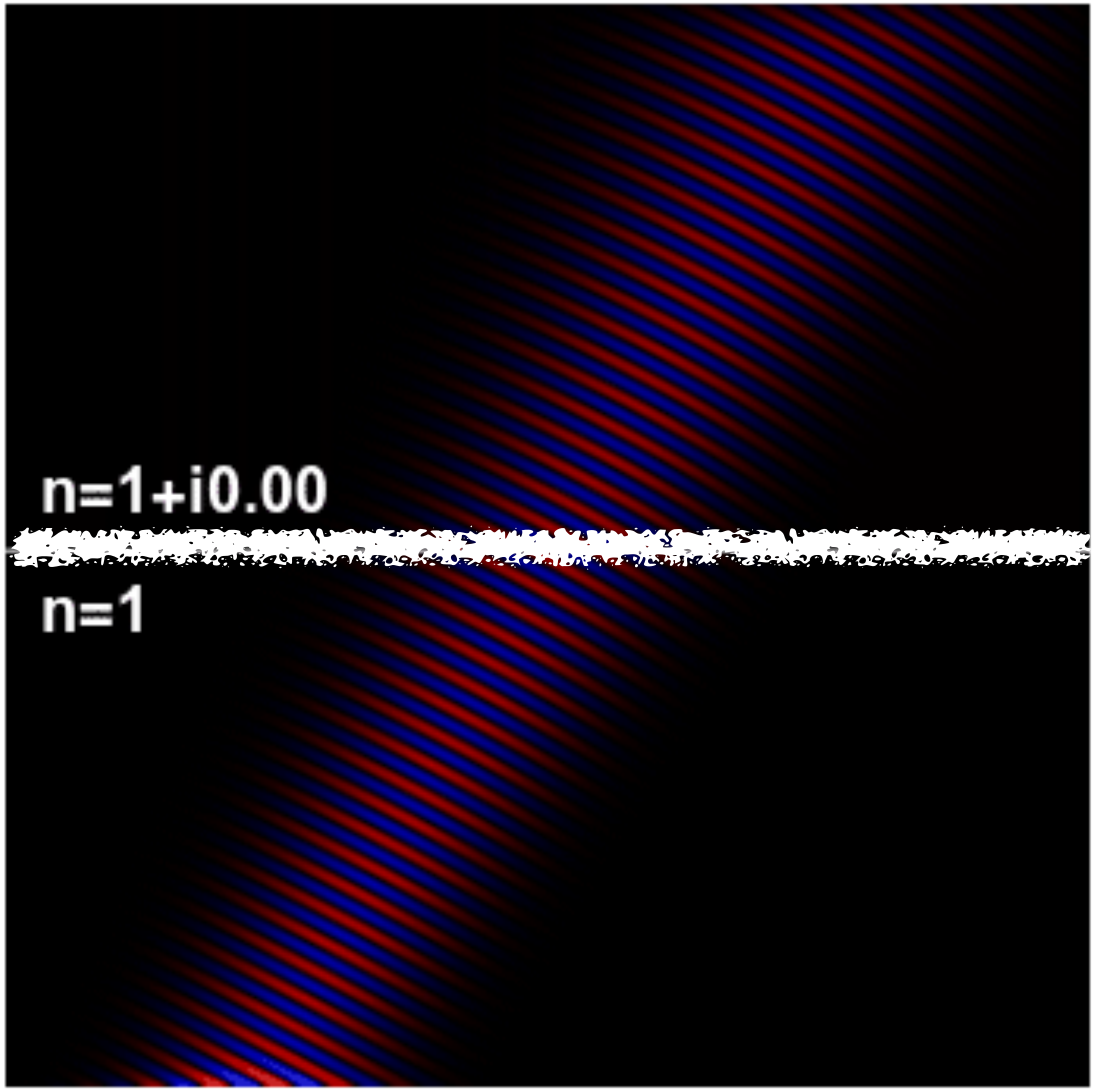

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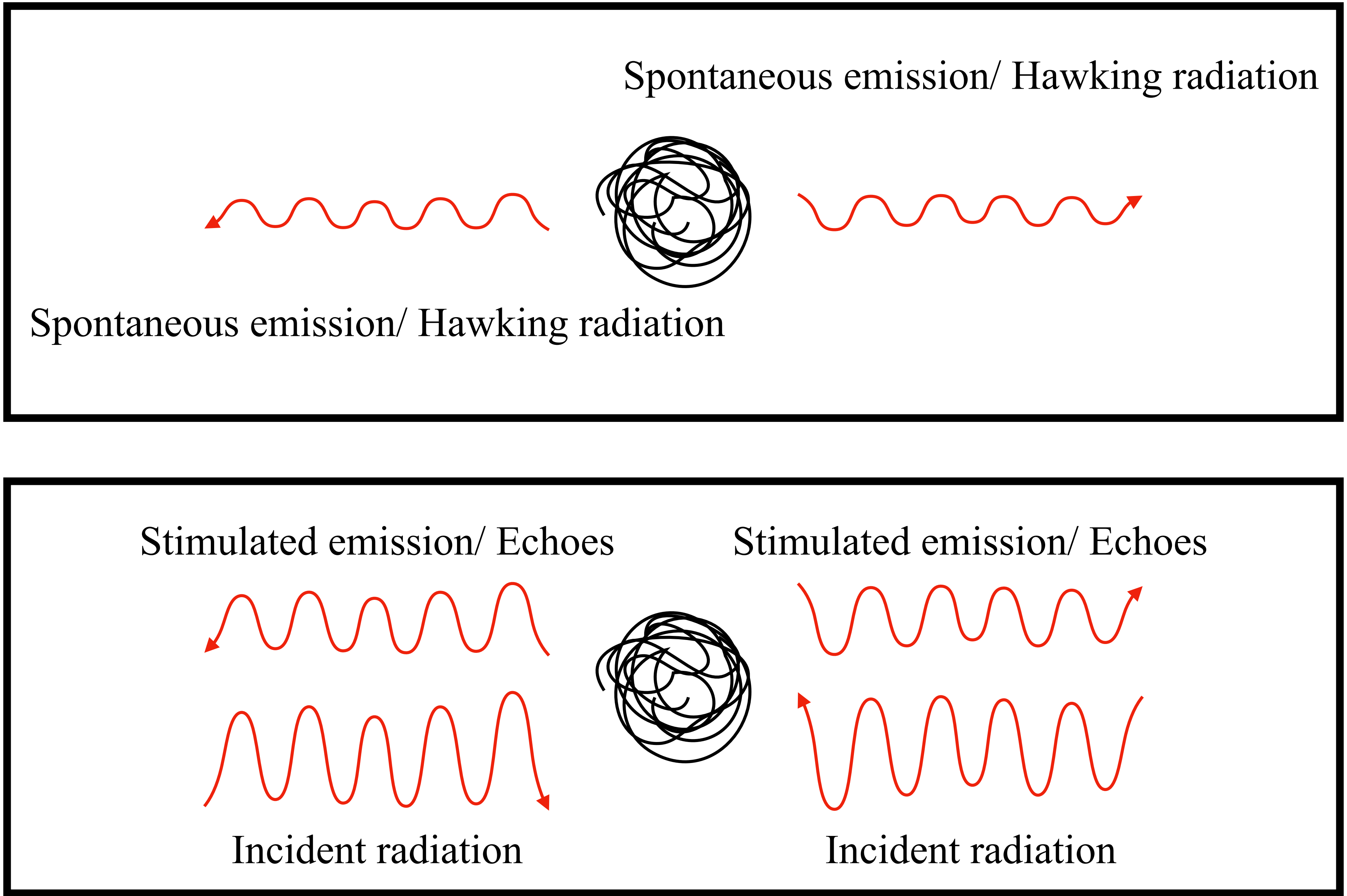

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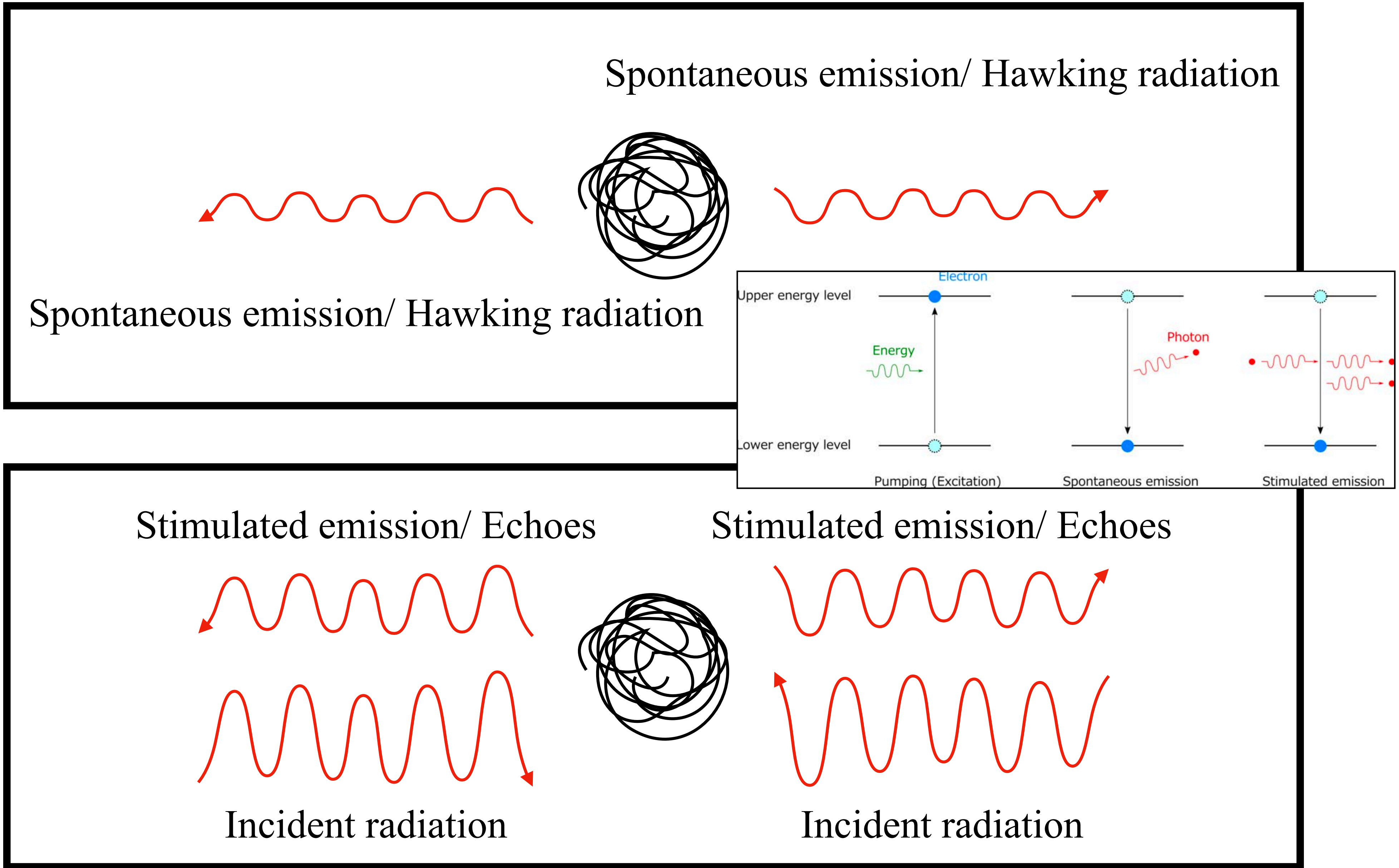

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CP-symmetry (RP^3 geon)

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.

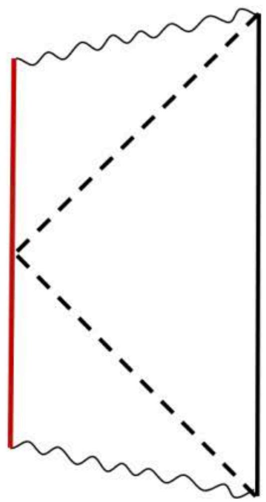


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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

CP-symmetry (RP^3 geon)

Z_2 identification → Boltzmann reflection

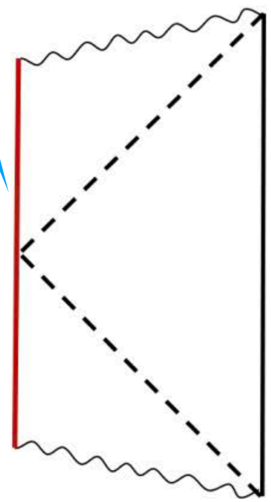


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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

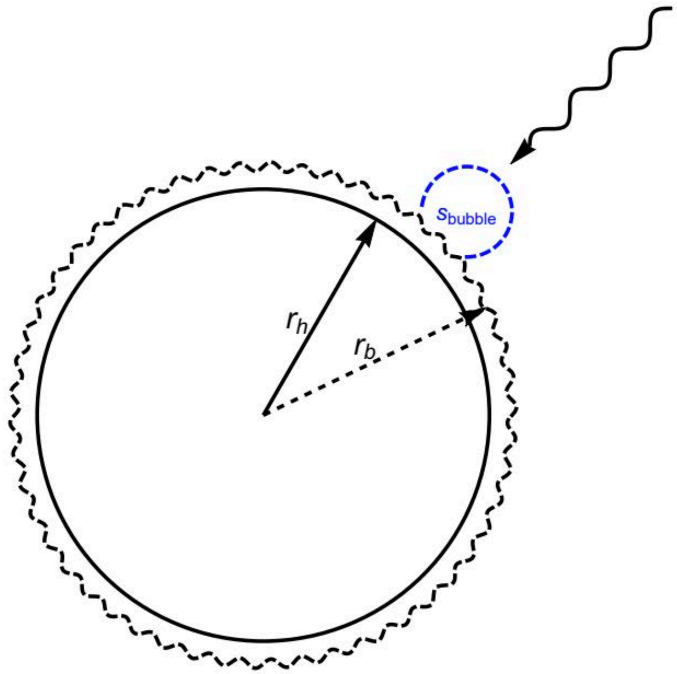
Abstract

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.

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

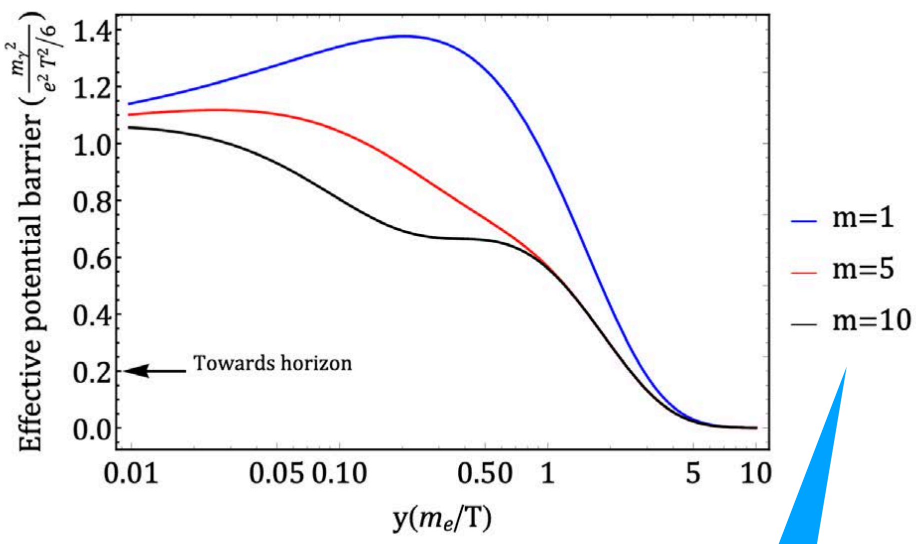
Electromagnetic Albedo of Quantum Black Holes *(Chua & NA 2021)*

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



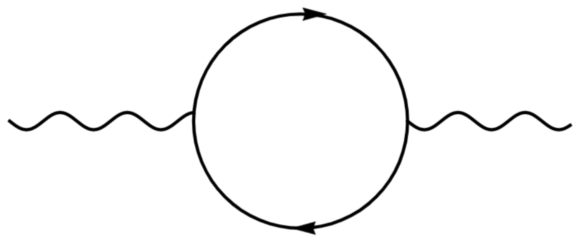
Two independent derivations

- Photon mass acquired through Hawking Plasma



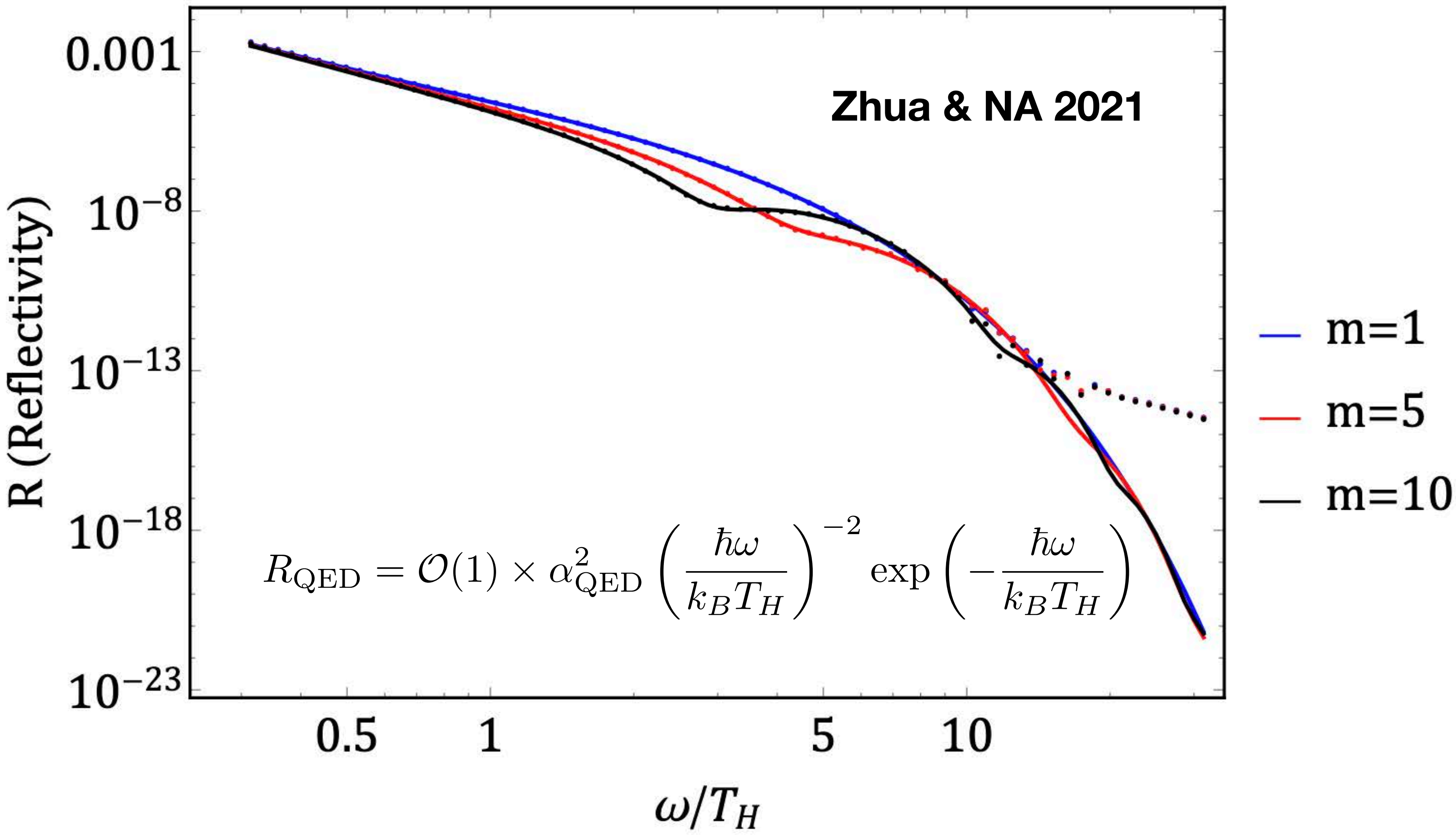
different interpolations

- Projecting photon 1-loop propagator from Minkowski to Rindler



$$\Delta^M_{\mu\nu}(p) = \frac{\eta_{\mu\nu} + (\xi - 1)\frac{p_\mu p_\nu}{p^2}}{(p^2 + i\epsilon)(1 - \pi^M(p^2))} \, ,$$

$$\pi^M(p^2) = \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln\left(1 + \frac{p^2 x(1-x)}{m_e^2}\right)$$



- This is consistent with simple Boltzmann reflectivity for gravitational fine-structure constant: $\alpha_{\rm G} \sim \frac{\hat{E}_{\rm infalling} T}{M_p^2}$, which becomes O(1) within a Planck length of the horizon

$$\boxed{R_{\rm QG} = \mathcal{O}(1) \times \exp\left(-\frac{\hbar\omega}{k_B T_H}\right)}$$

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)/(π × 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

August 29, 2018

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

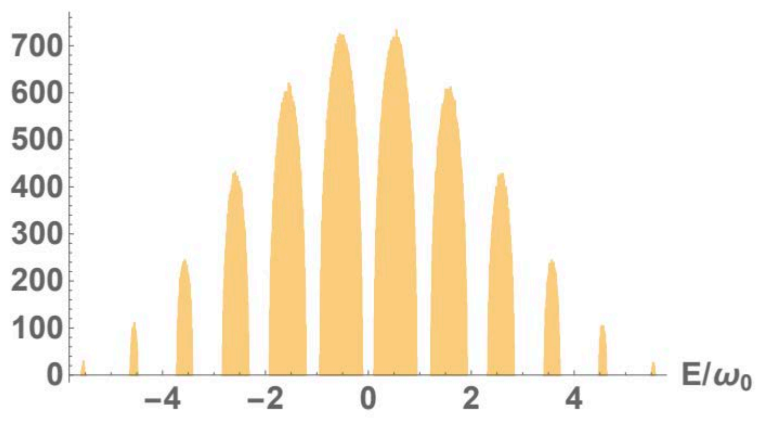
Black Holes and Random Matrices

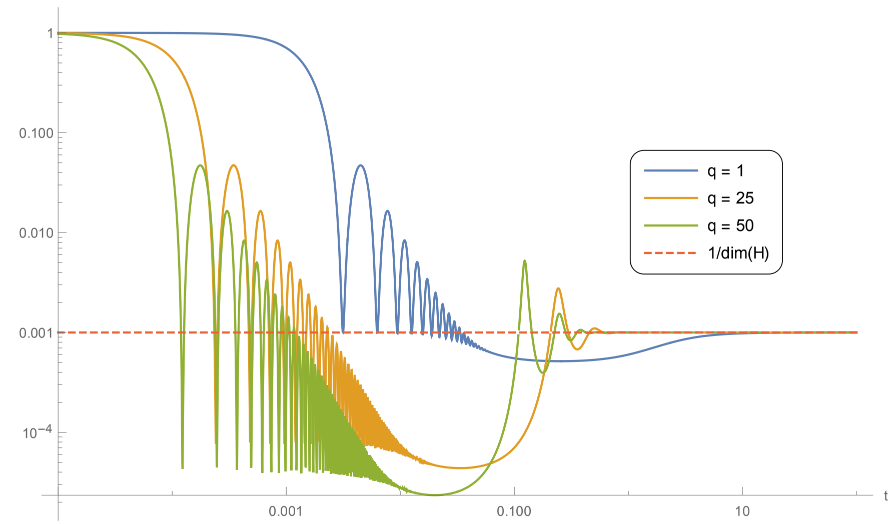
Jordan S. Cotler[a], Guy Gur-Ari[a], Masanori Hanada[abc], Joseph Polchinski[de], Phil Saad[a], Stephen H. Shenker[a], Douglas Stanford[f], Alexandre Streicher[ad], and Masaki Tezuka[g]

Spacing Statistics of Energy Spectra: Random Matrices, Black Hole Thermalization, and Echoes

Krishan Saraswat[a,b,c] and Niayesh Afshordi[a,b,c]

- From Spectral form-factor of *generalized* random matrices, or approximate *symmetries/degeneracies* *(Saraswat & NA 2022)*





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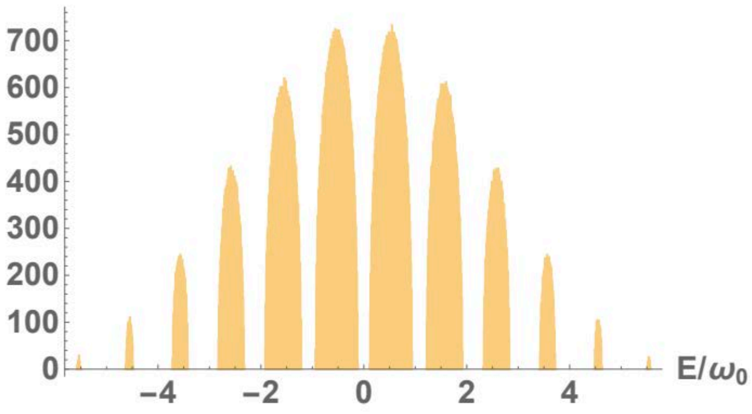
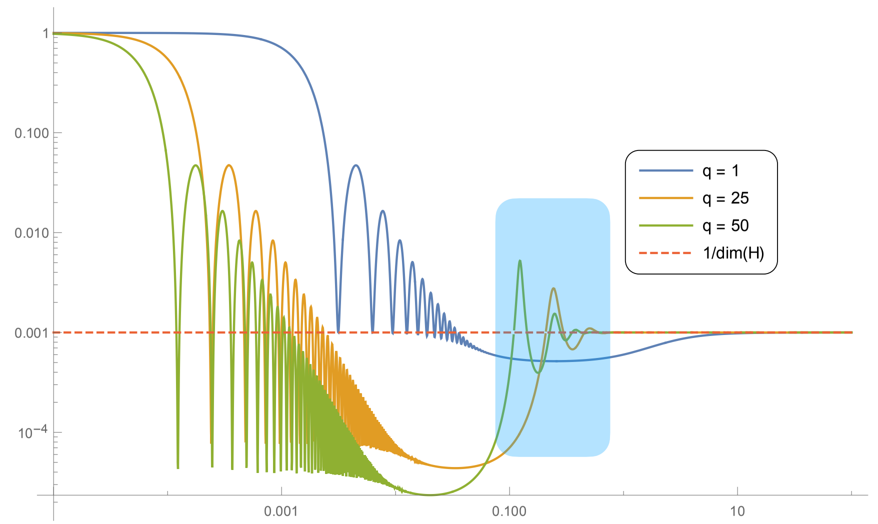
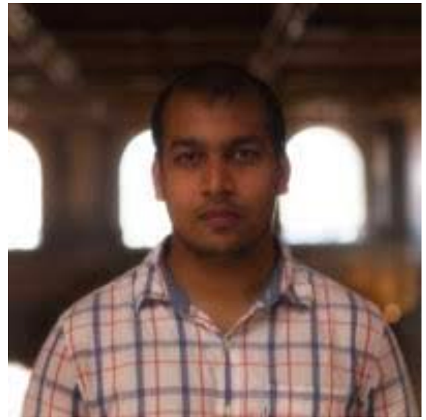


Averaged Spectral Form Factor for Gamma Distribution NNS (β = 0, dim(H) = 1000)



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[†]

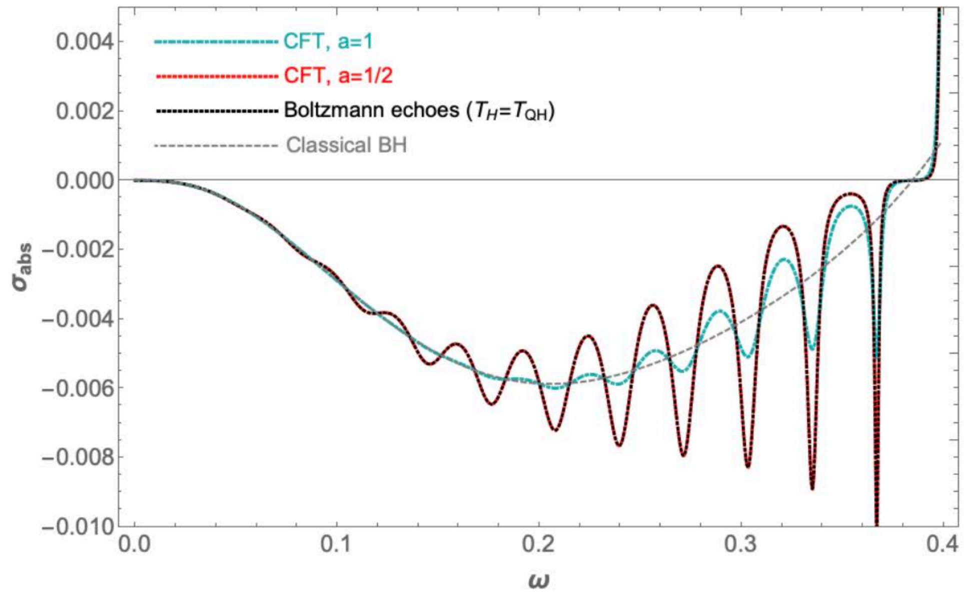
[◇] *Physics Department, McGill University, Montreal, CA*

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

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

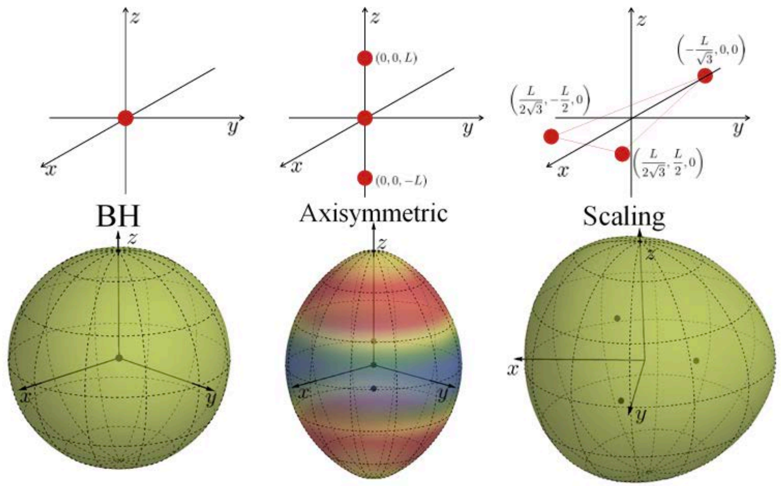
$$c_L = c_R = 12J$$

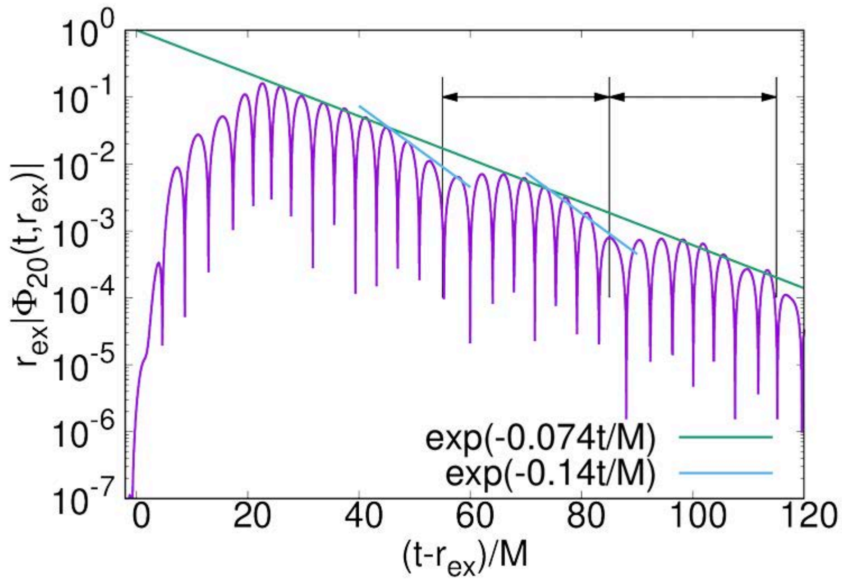
$$S_{micro} = \frac{\pi^2}{3}(c_L T_L + c_R T_R) = 2\pi(M^2 + \sqrt{M^4 - J^2}) = \frac{\text{Area}}{4}$$



Dey & NA 2020

Echoes from Fuzzballs?





Featured in Physics

Black-hole microstate spectroscopy: Ringdown, quasinormal modes, and echoes

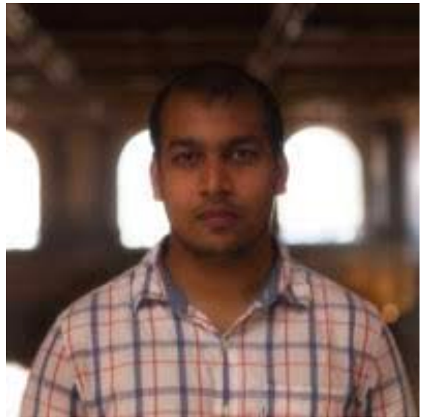
Taishi Ikeda, Massimo Bianchi, Dario Consoli, Alfredo Grillo, Josè Francisco Morales, Paolo Pani, and Guilherme Raposo

Phys. Rev. D **104**, 066021 – Published 16 September 2021

Physics See synopsis: A Way to Experimentally Test String Theory's "Fuzzball" Prediction

Echoes in Kerr/CFT

(w/ Ramit Dey)



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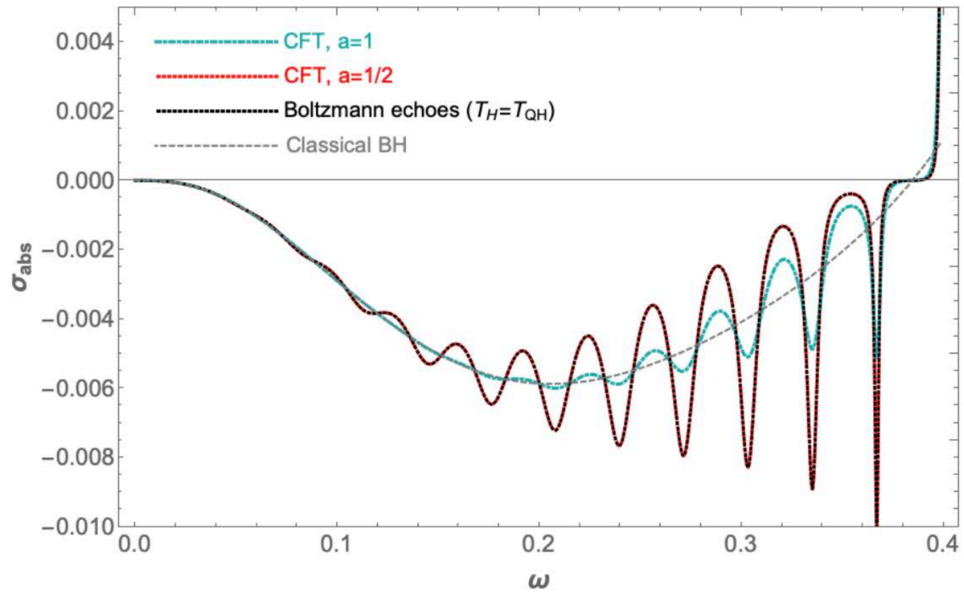
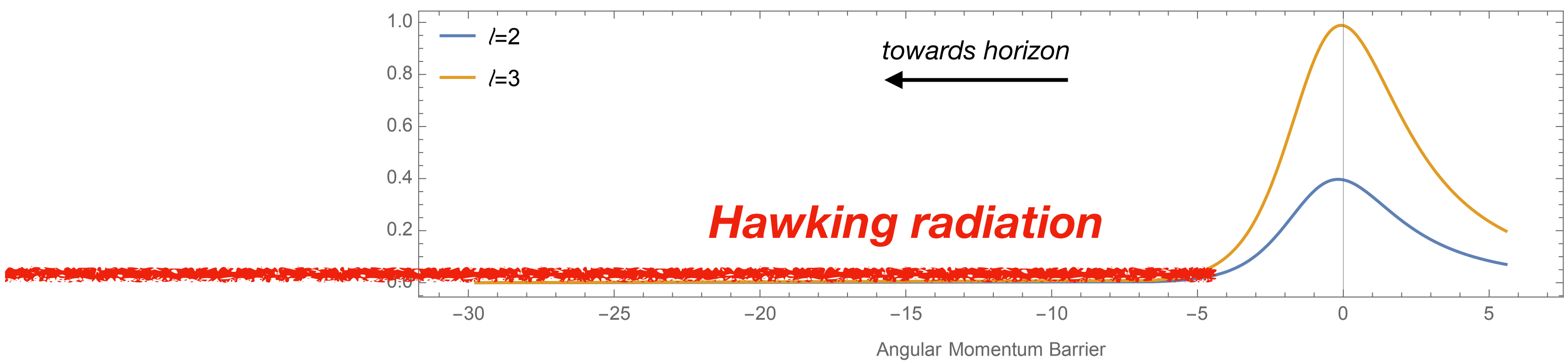


Dey & NA 2020

Finite Entropy of Hawking radiation ➡ Echoes *(Oshita & NA, in prep.)*

- Infinite Entropy & No Echoes: $t_{\rm echo} \to \infty$!



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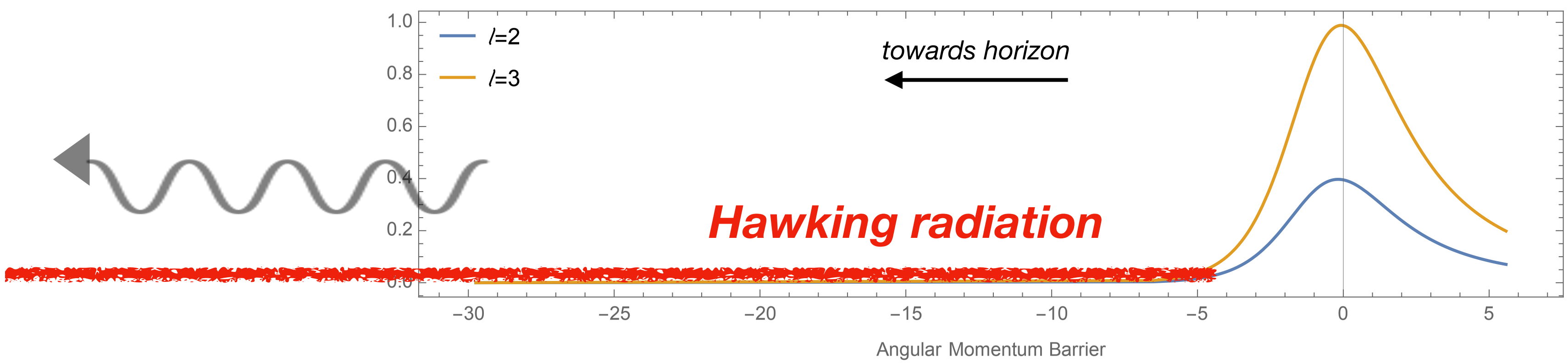

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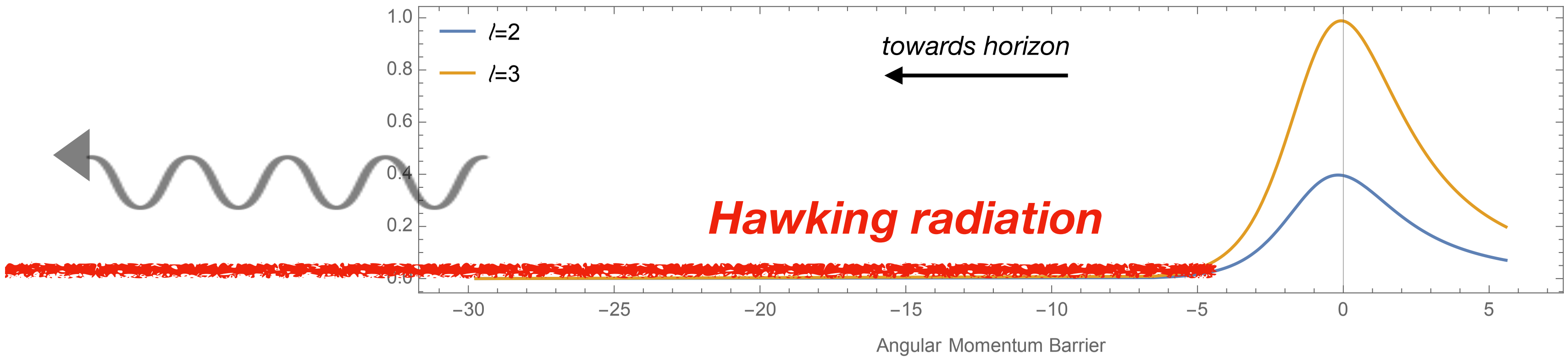
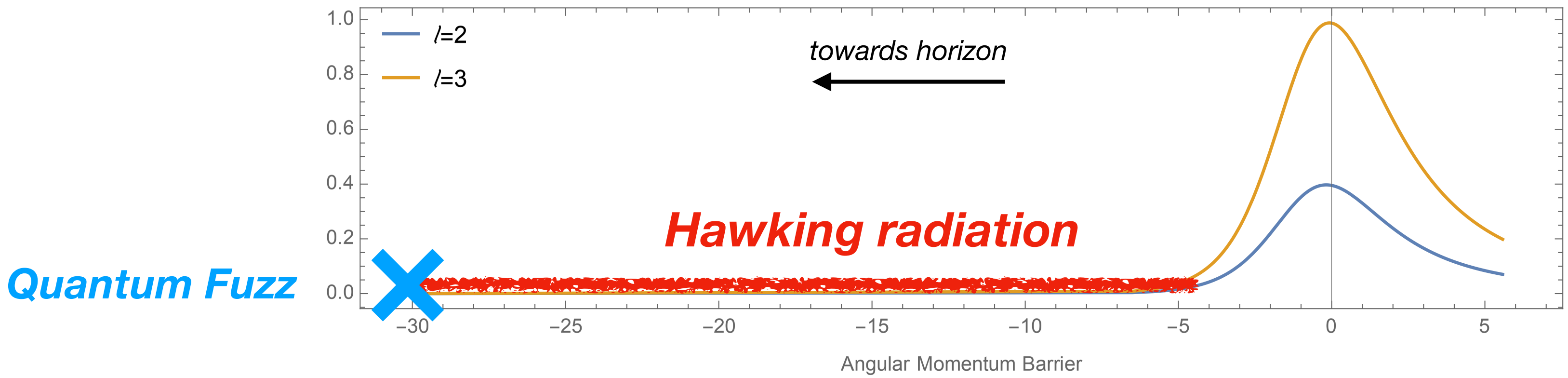


- Finite Entropy & Echoes: $t_{\rm echo} = \dfrac{\ln\left[\text{Entropy}/\ell(\ell+1)\right]}{2\pi \times \text{Hawking Temperature}}$



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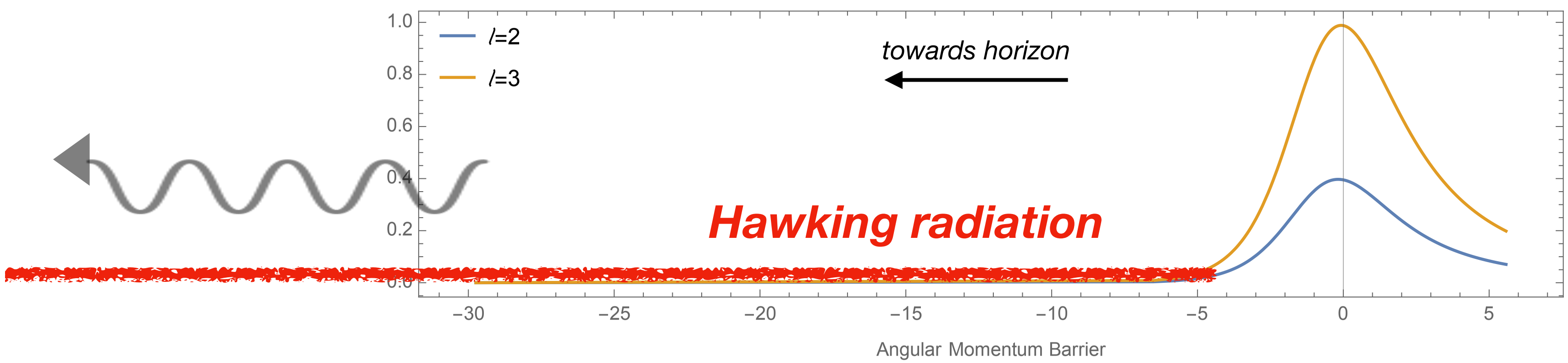

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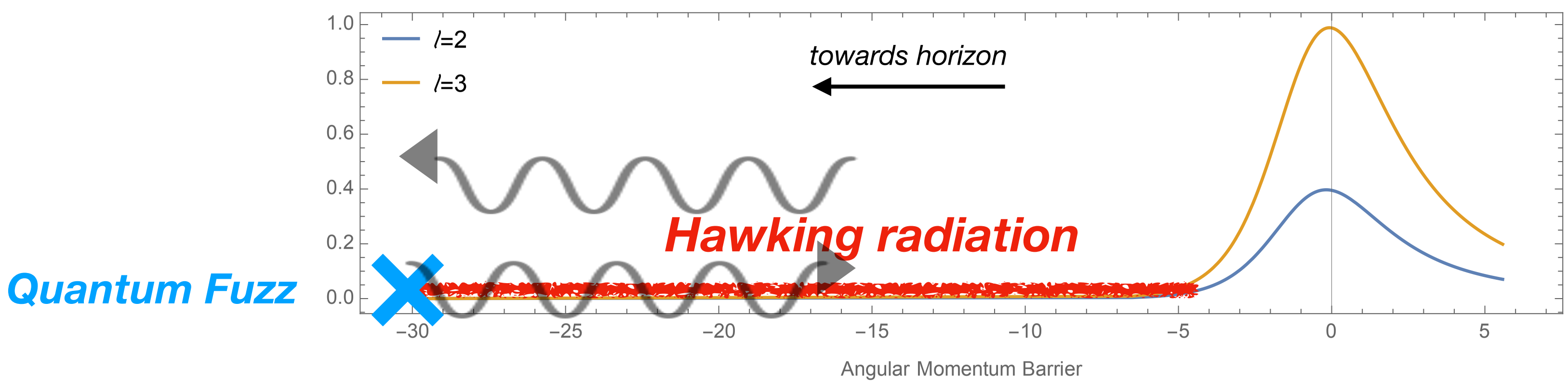
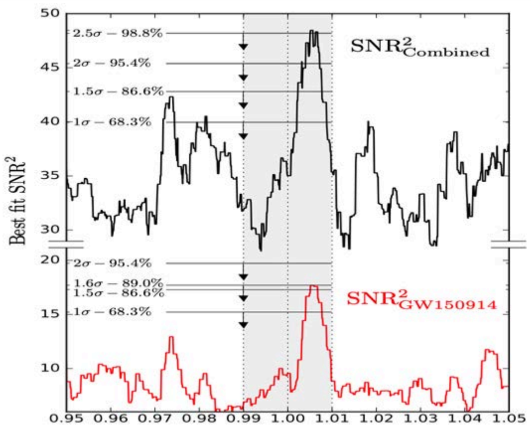


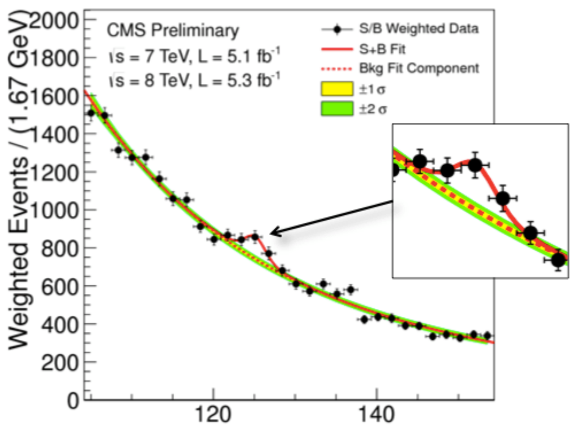
Echoes to *LIGO*

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



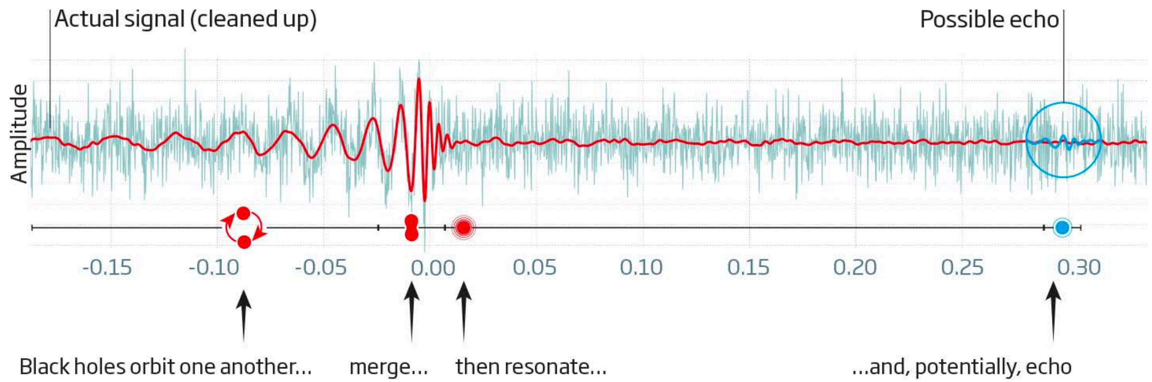
Higgs to *LHC*

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



Outline

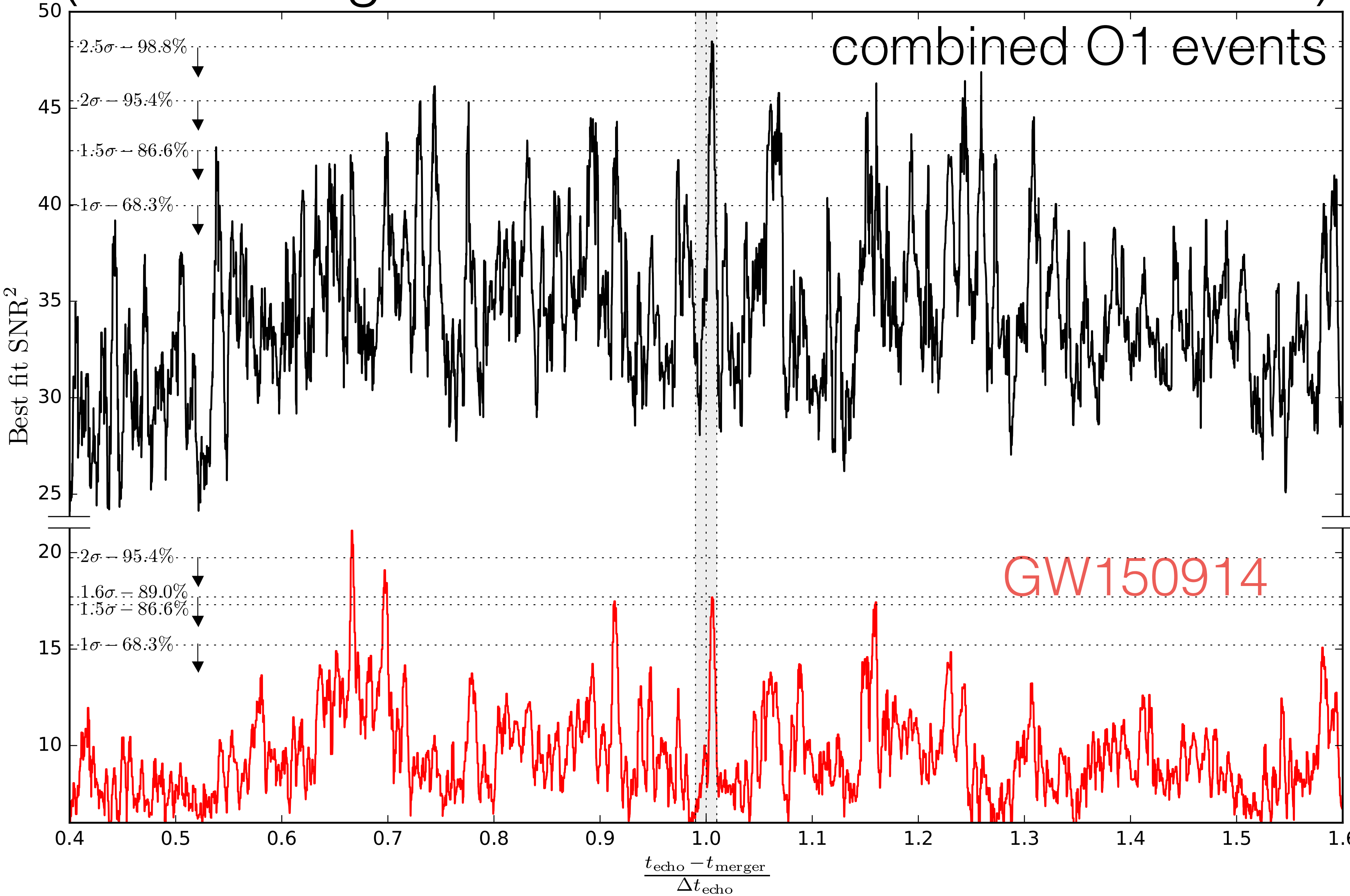
- Black Holes: *der Gravitation*
- Black Holes: *der Quantentheorie*
- Black Holes: *Fantasie bis Physik*
- Einstein vs Einstein



Abedi, Dykaar & NA 2017

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

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



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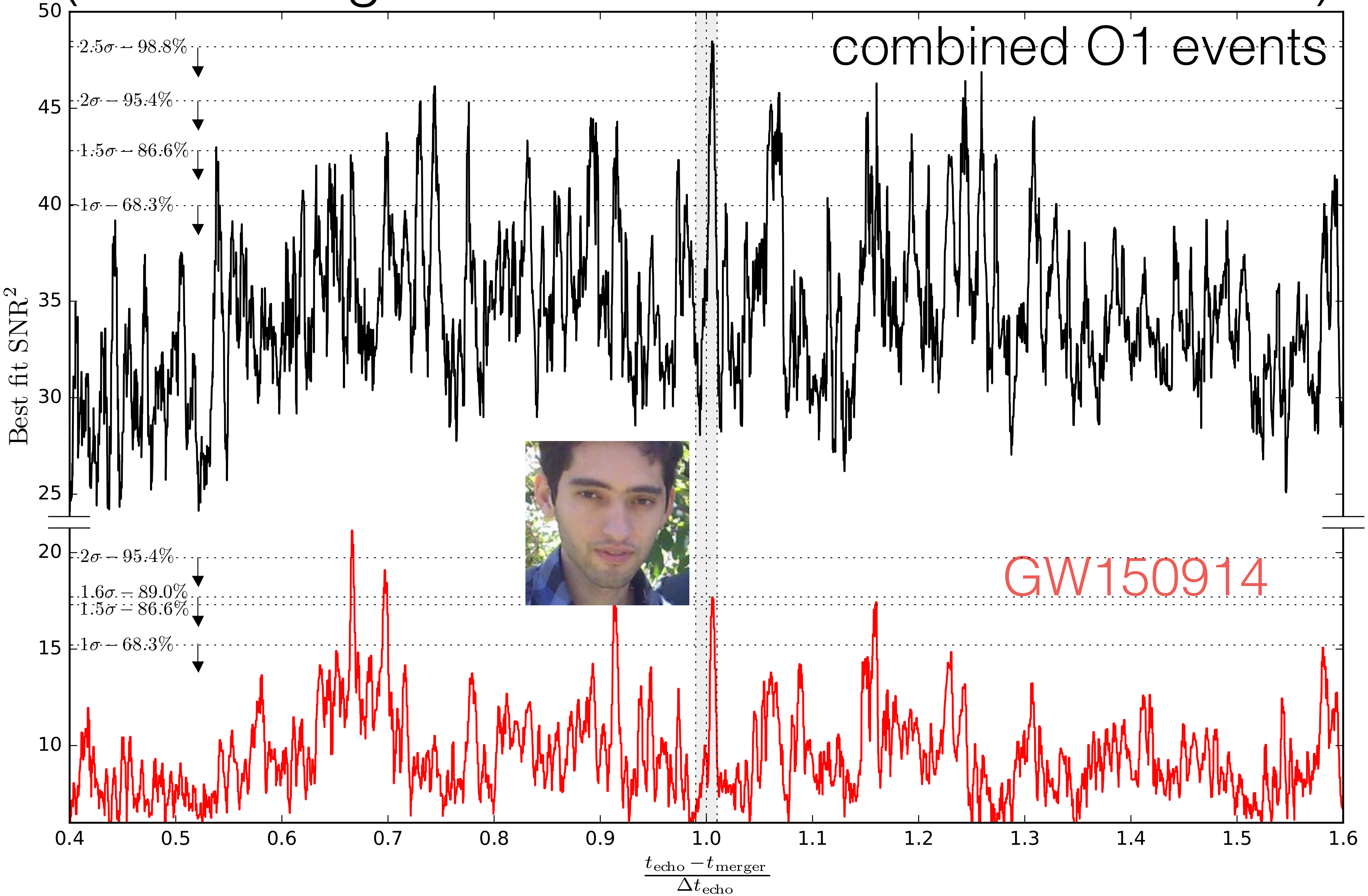

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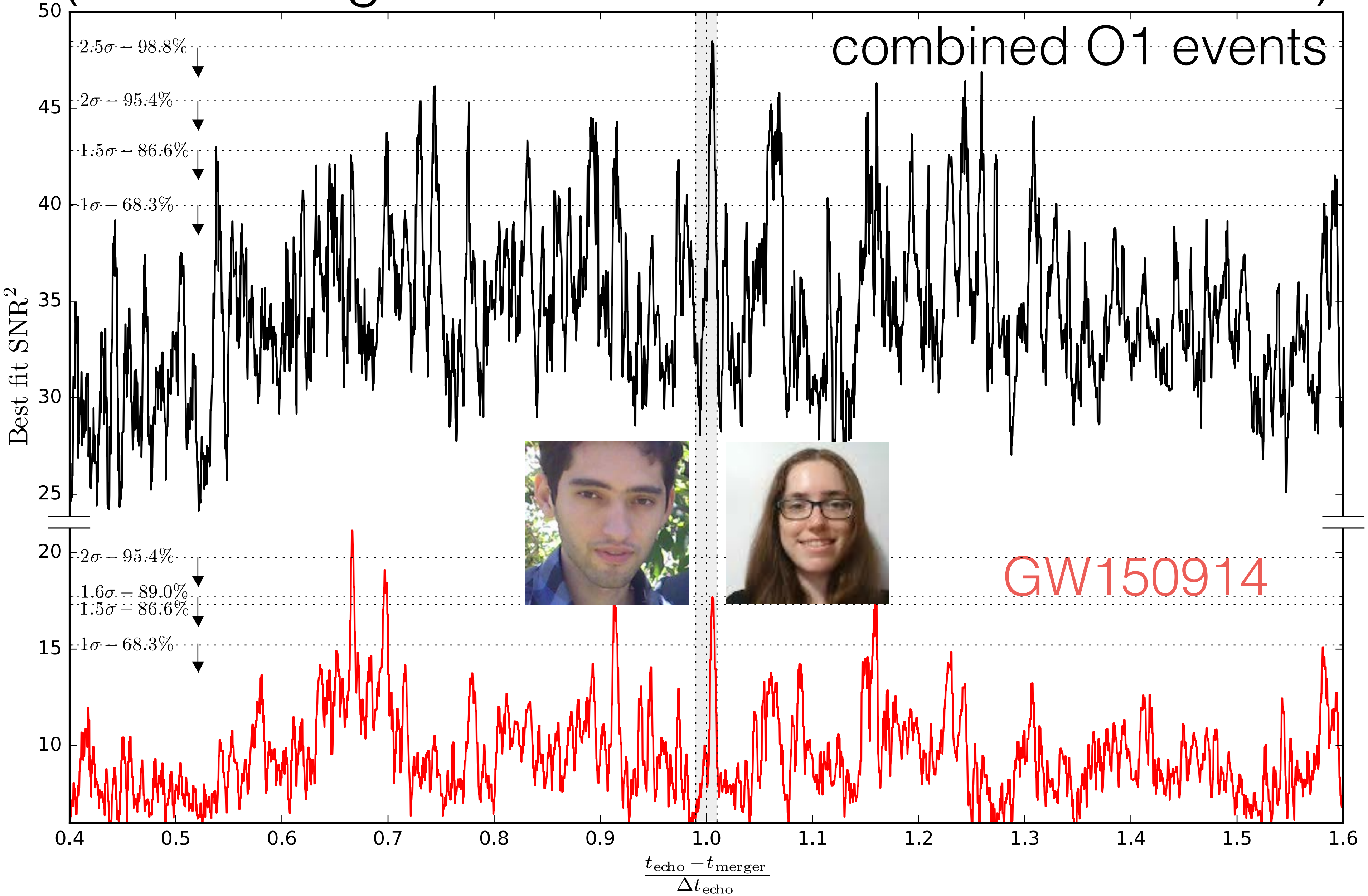


#nobelprize
THE NOBEL PRIZE

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

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]

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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*
[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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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)

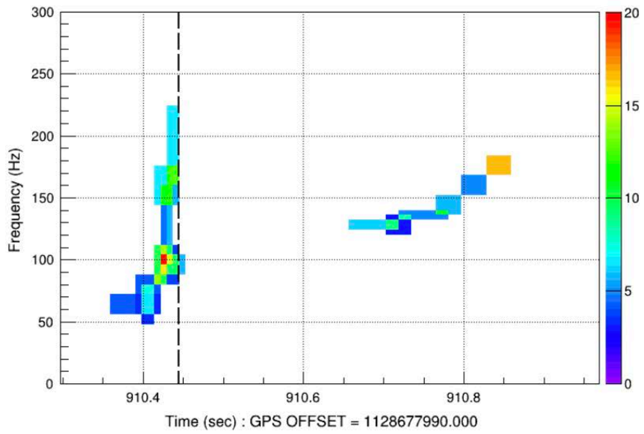
In this paper, we investigate the morphology of the events from the GWTC-1 catalog of compact binary coalescences as reconstructed by a method based on coherent excess power: we use an open-source version of the coherent WaveBurst (cWB) analysis pipeline, which does not make use of waveform models. The 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.

Predictions in Abedi, Dykaar, NA 2017

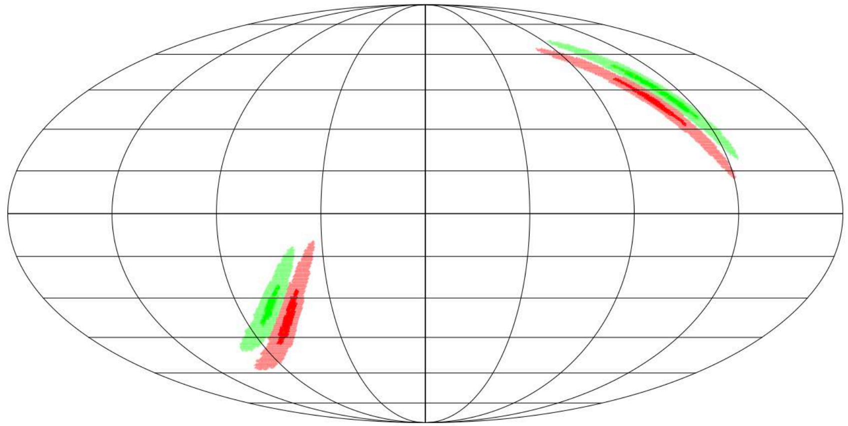
$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

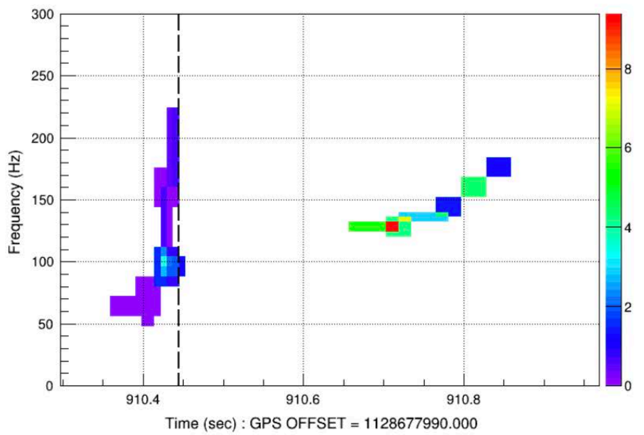
arXiv:1612.00266

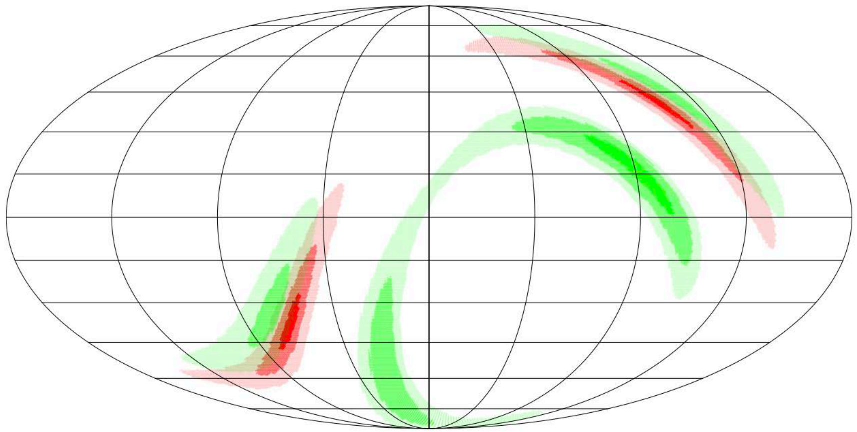
coherent Wave Burst (cWB)
GW151012



(a)

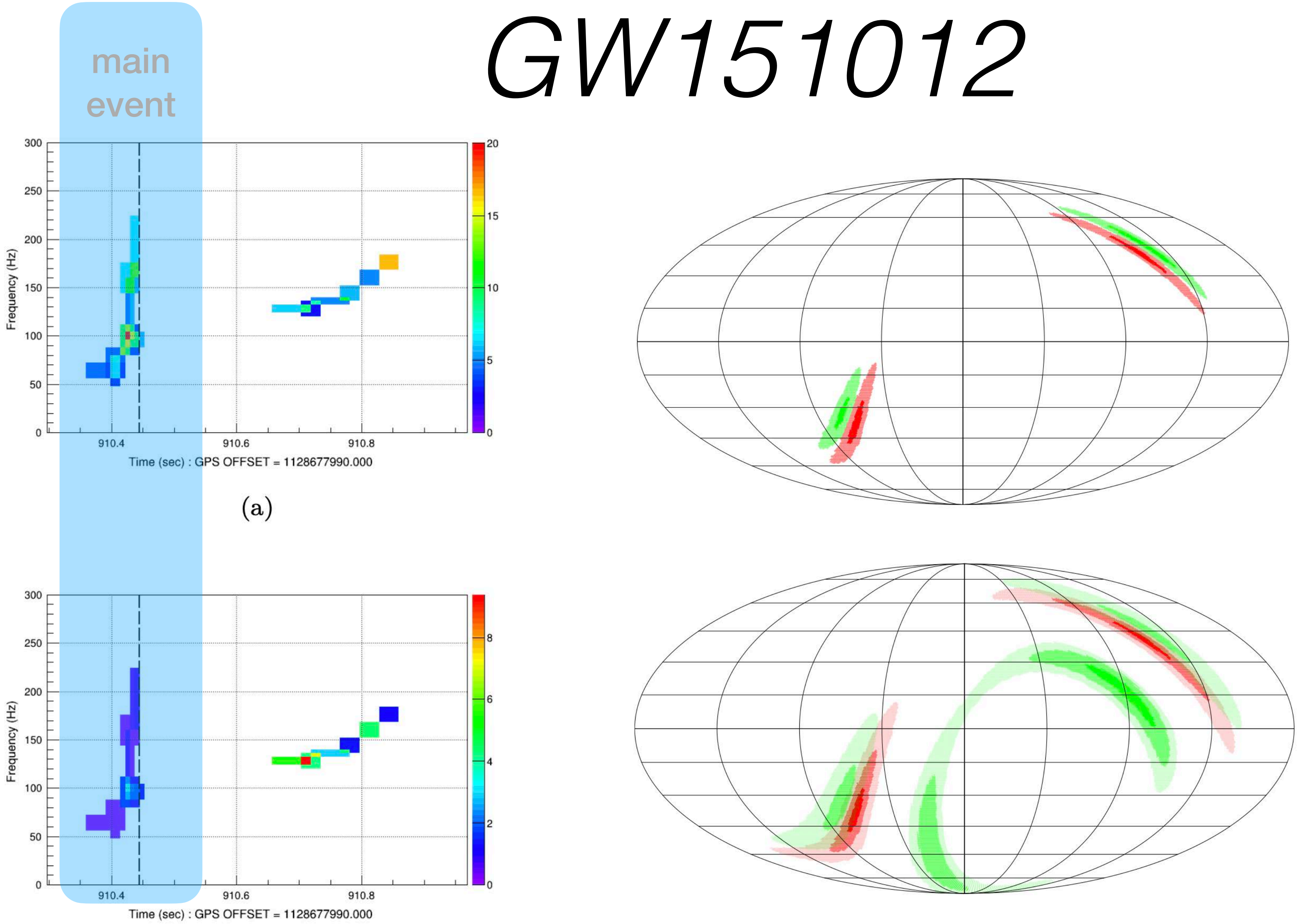






Salemi, et al. 2019

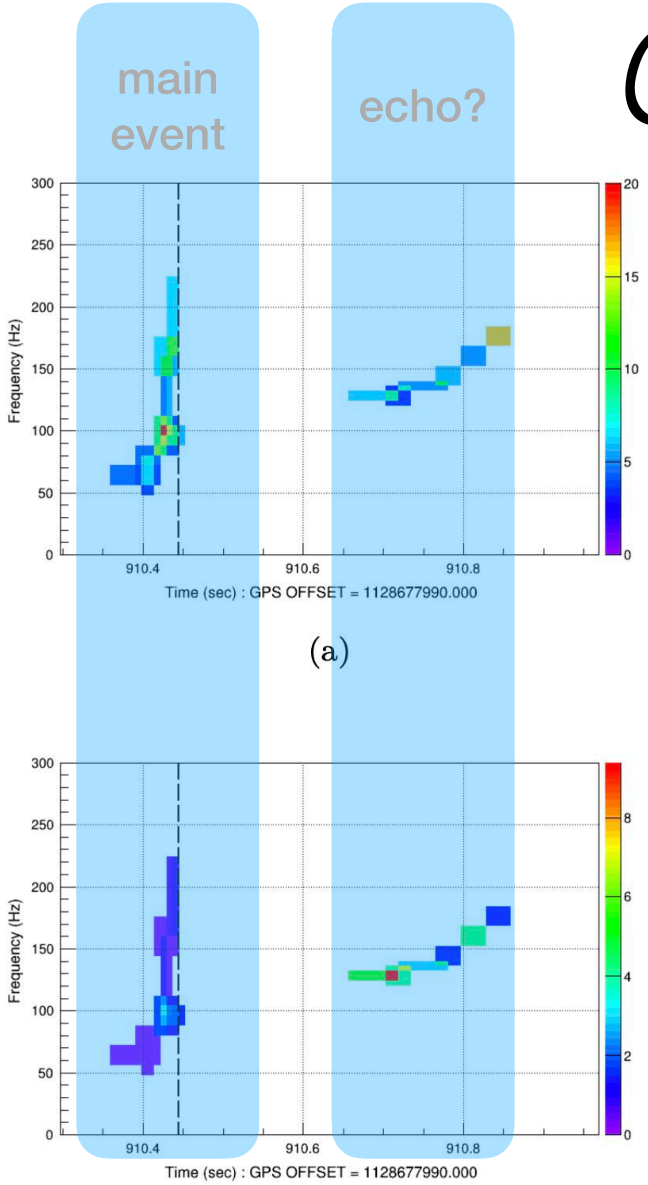
coherent Wave Burst (cWB) *GW151012*



Salemi, et al. 2019

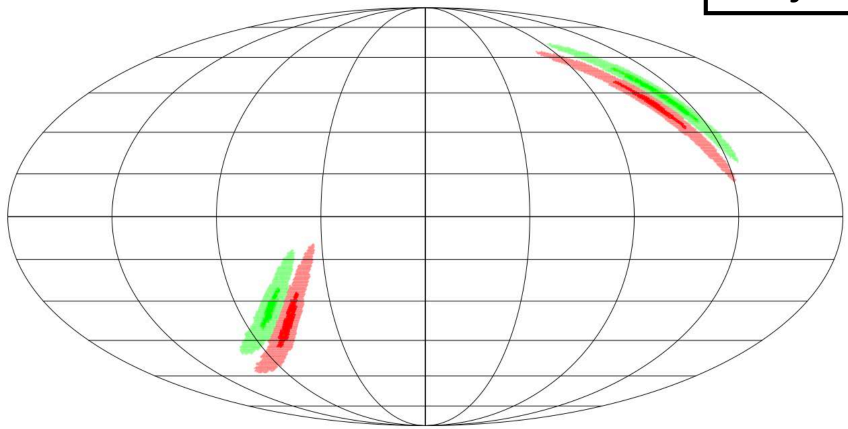
coherent Wave Burst (cWB)

GW151012

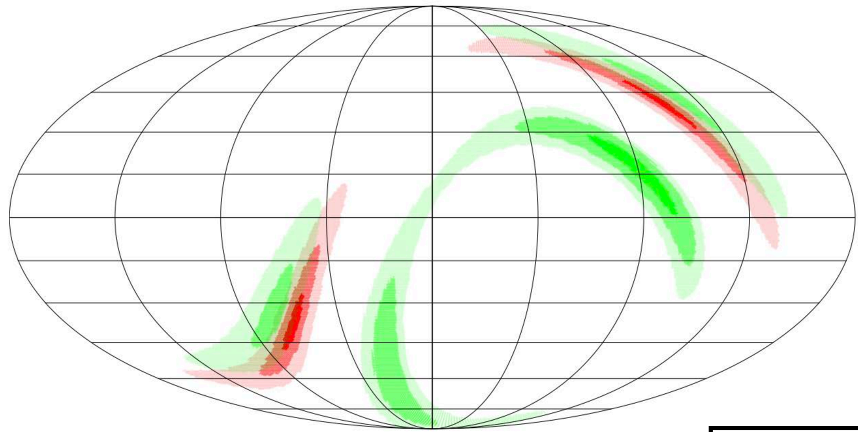


Salemi, et al. 2019

sky co-localization
Bayes factor = 5.4



Abedi, Longo & NA 2022



sky co-localization
Bayes factor = 1.6

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].

Not quite black holes at LIGO

Bob Holdom*

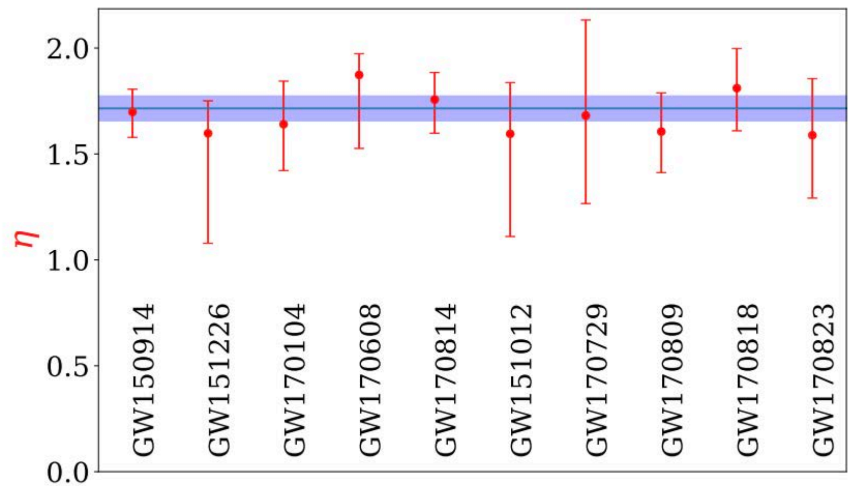
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

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

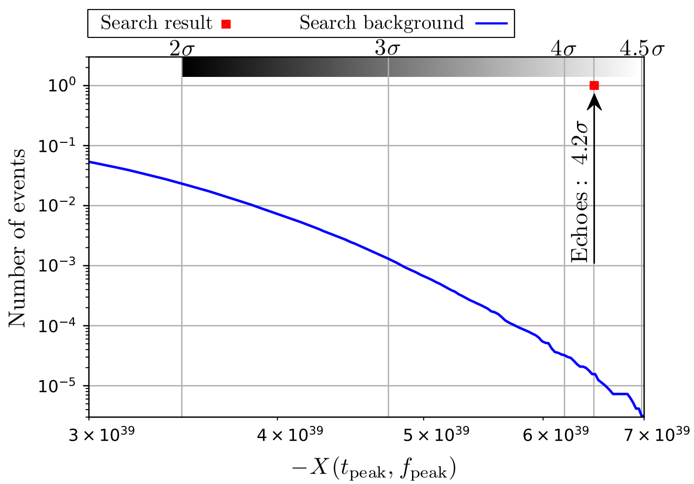


- p-values

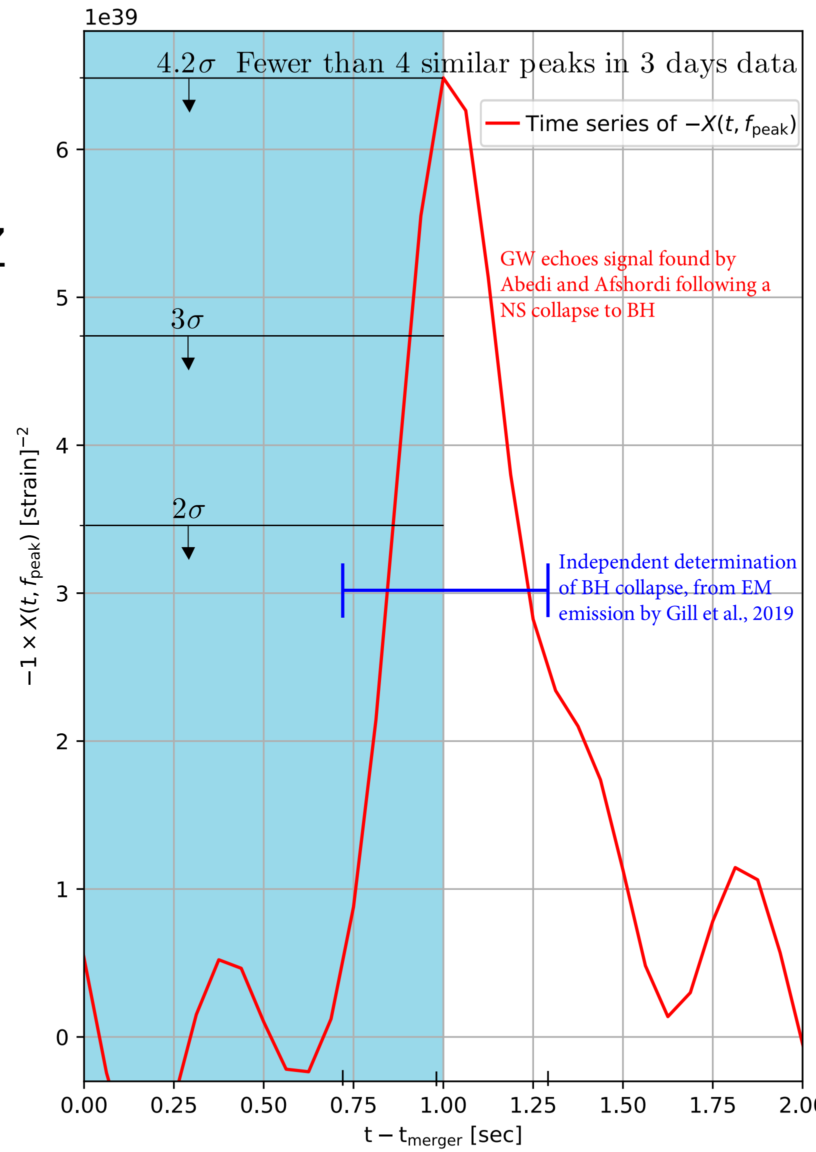
GW150914	0.008	GW151226	0.014
GW170104	0.33	GW170814	0.098
GW170608	0.038	GW170809	0.081
GW151012	0.0016	GW170823	0.026
GW170818	0.0094	GW170729	0.0010 & 0.0006

Binary Neutron Star merger

- Echoes within 1 sec after GW170817 merger @ f= 72 Hz
- p-value =1.6x10^{-5}, **4.2σ tentative detection,** *high-spin BH remnant*



Abedi & NA 2019



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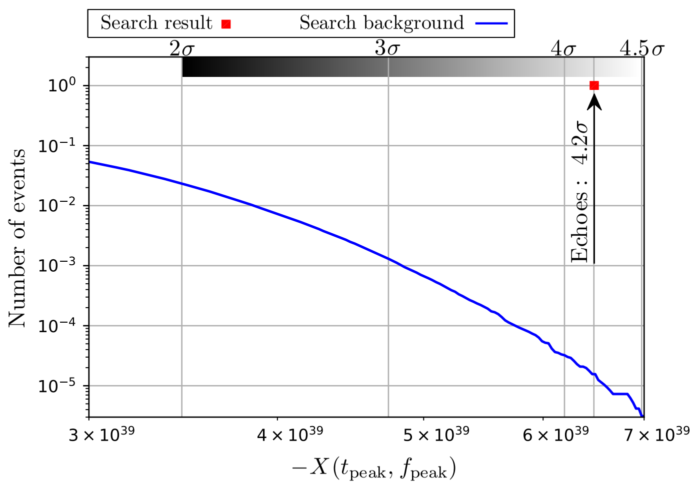
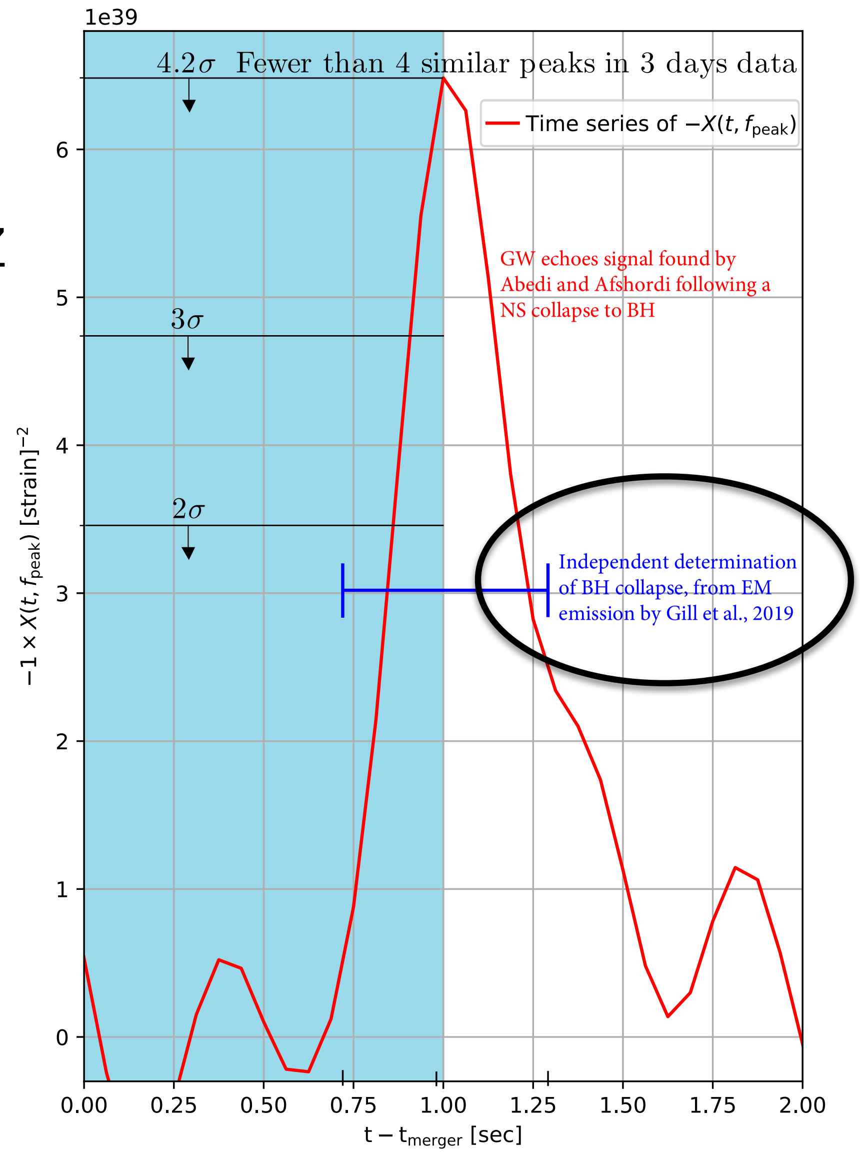


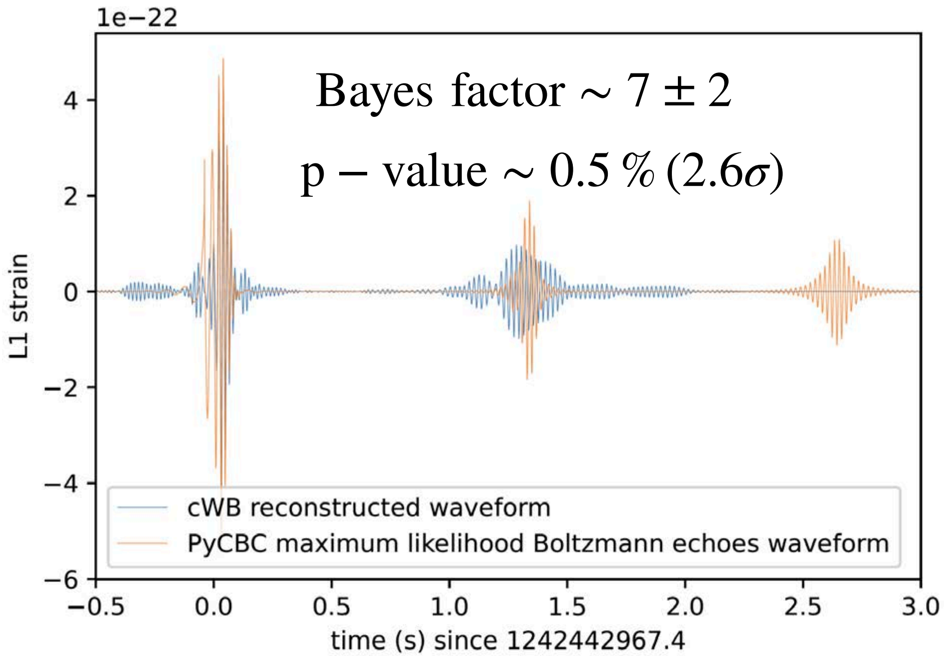
Abedi & NA 2019

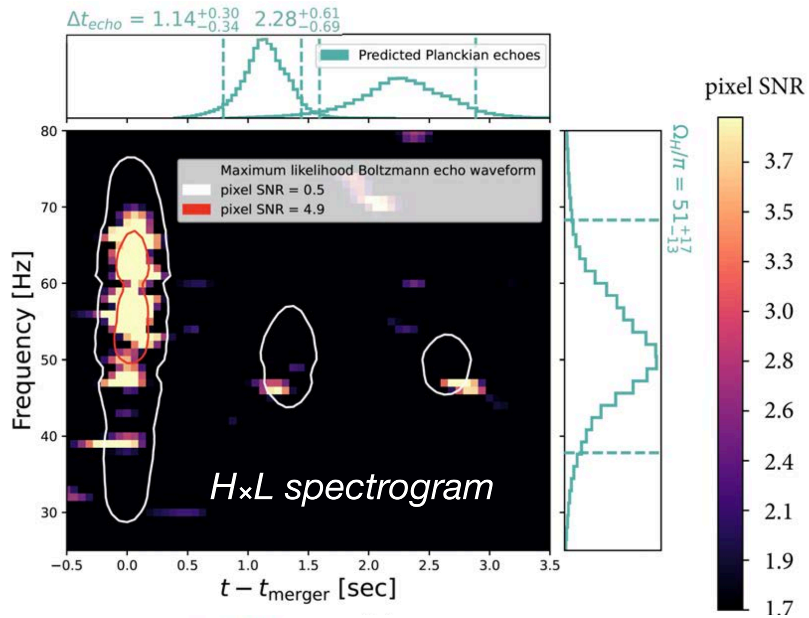


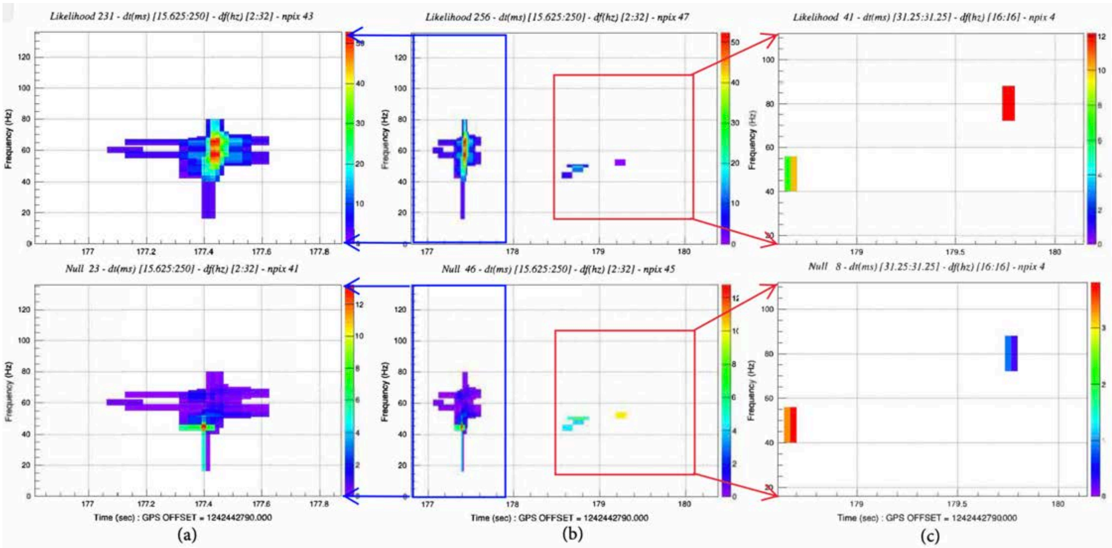
GW190521: First Measurement of Stimulated Hawking Radiation from Black Holes

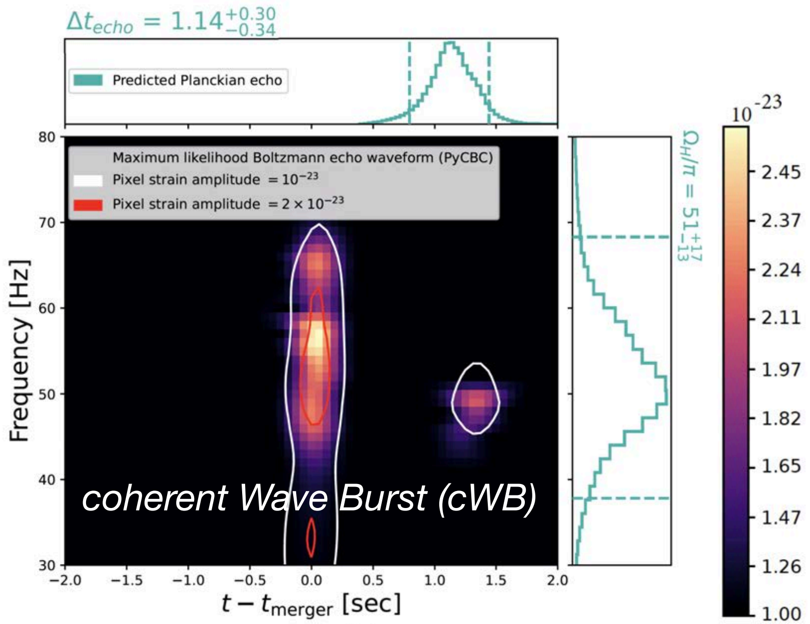
Jahed Abedi,[1,2,3,*] Luís Felipe Longo Micchi,[4,†] and Niayesh Afshordi[5,6,7,‡]

arXiv:2201.00047 (also Conklin & NA arXiv:2201.00027)









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		

arXiv.org > gr-qc > arXiv:2112.06861

General Relativity and Quantum Cosmology

[Submitted on 13 Dec 2021]

Tests of General Relativity with GWTC-3

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration:

TABLE XIV. Results of the echoes analysis (Sec. VIII B). List of p-values for signal to noise Bayes Factor $\mathcal{B}^{\rm S}_{\rm N}$ for the events that are analysed. In the absence of any echoes signal these should be uniformly distributed between [0, 1]. Fig. 15 shows the corresponding PP plot with 90% credible intervals superimposed on it. There is no evidence for the presence of echoes.

Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27

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$t_{echo} < 0.5$ sec

arXiv.org > gr-qc > arXiv:2112.06861

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missing GW190521

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 Holdom 2020**	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, O2	5.5%,3.9%
6	**Salemi, et al. 2019**	coherent WaveBurst	151012,151226	0.4%,3%
7	**Abedi & NA 2019**	spectral comb	170817 (BNS)	0.0016%
8	**Gill, Nathanail, Rezolla 2019**	Astro Modelling	BNS EM	$t_{coll}=t_{echo}$
9	**Abedi, Longo, NA 2022**	Boltzmann, cWB	190521	0.5%

Failed Searches

	Authors	Method	Data	possible caveat
1	**Westerweck, et al. 2018**	ADA template	O1	"Infinite" prior
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3	**Uchikata, et al. 2019**	ADA, hi-pass	O1,O2	no low-frequencies
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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)
7	**Abbott, et al. 2020**	ADA+Bayes	O1-O3	"Infinite" prior
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Abedi, NA, Oshita & Wang 2020 (Review++)

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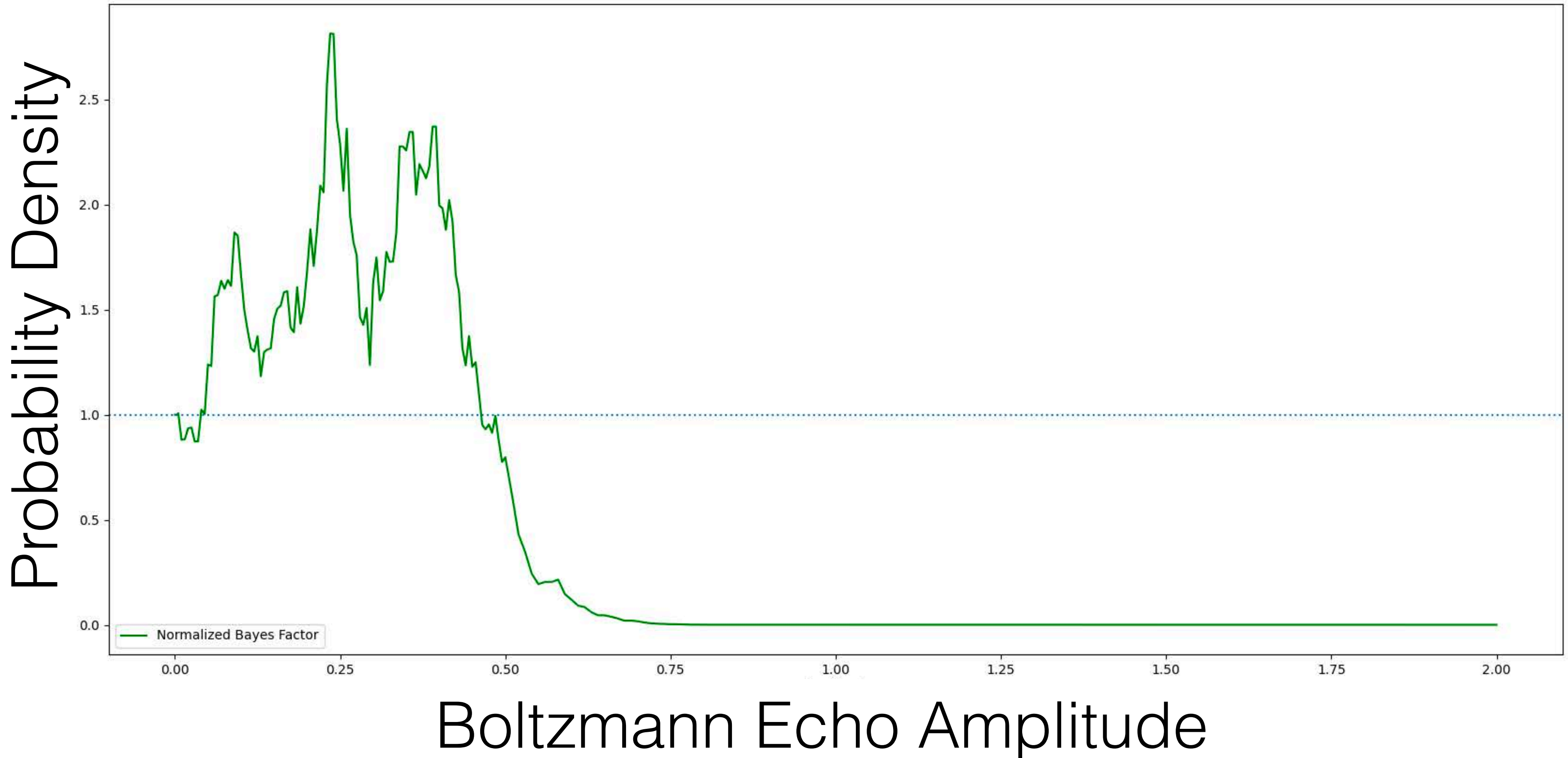
Preliminary: Joint constraint from 66 LIGO events *(by Abedi)*

- Boltzmann Echo Amplitude < 0.5



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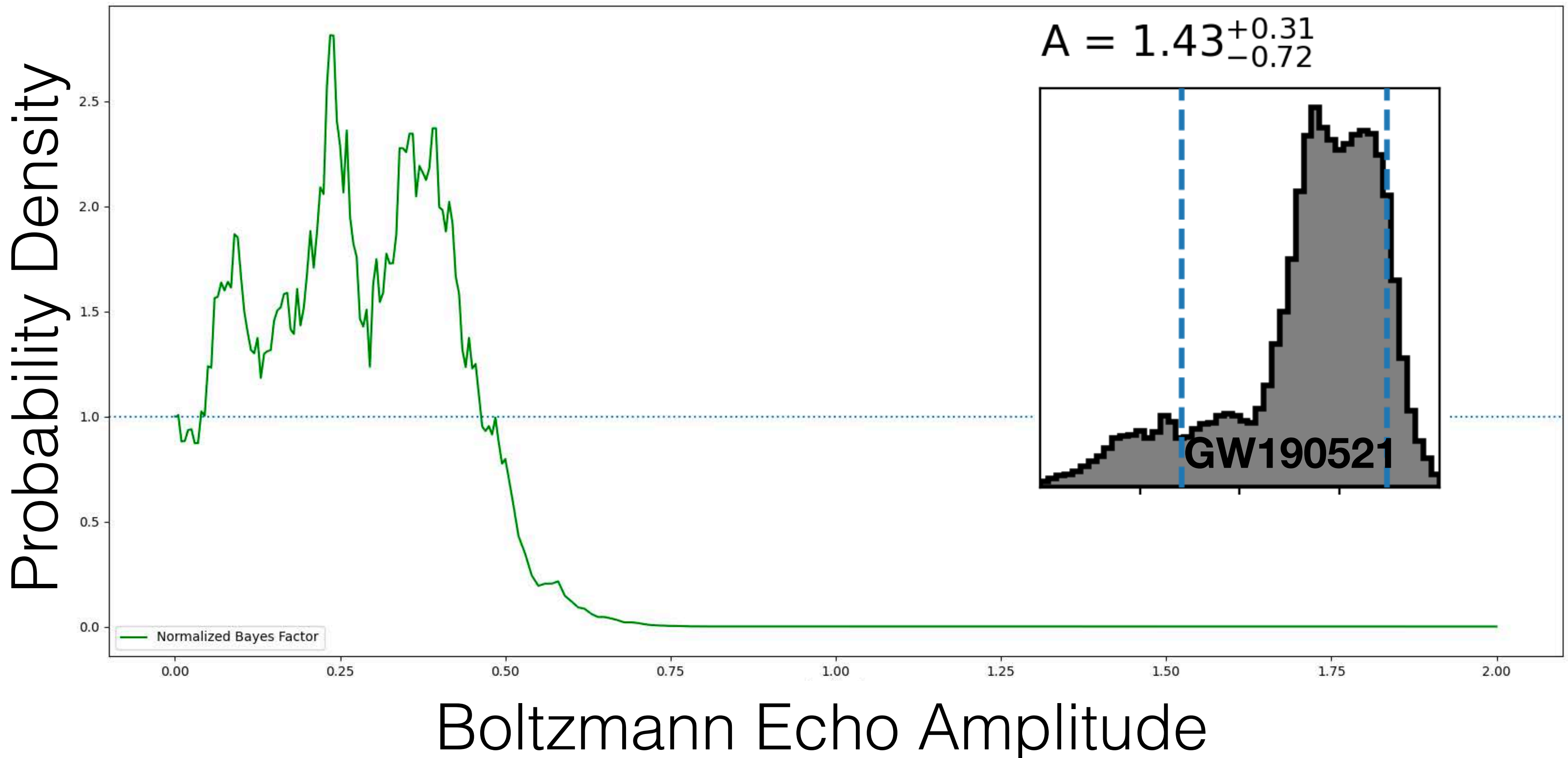
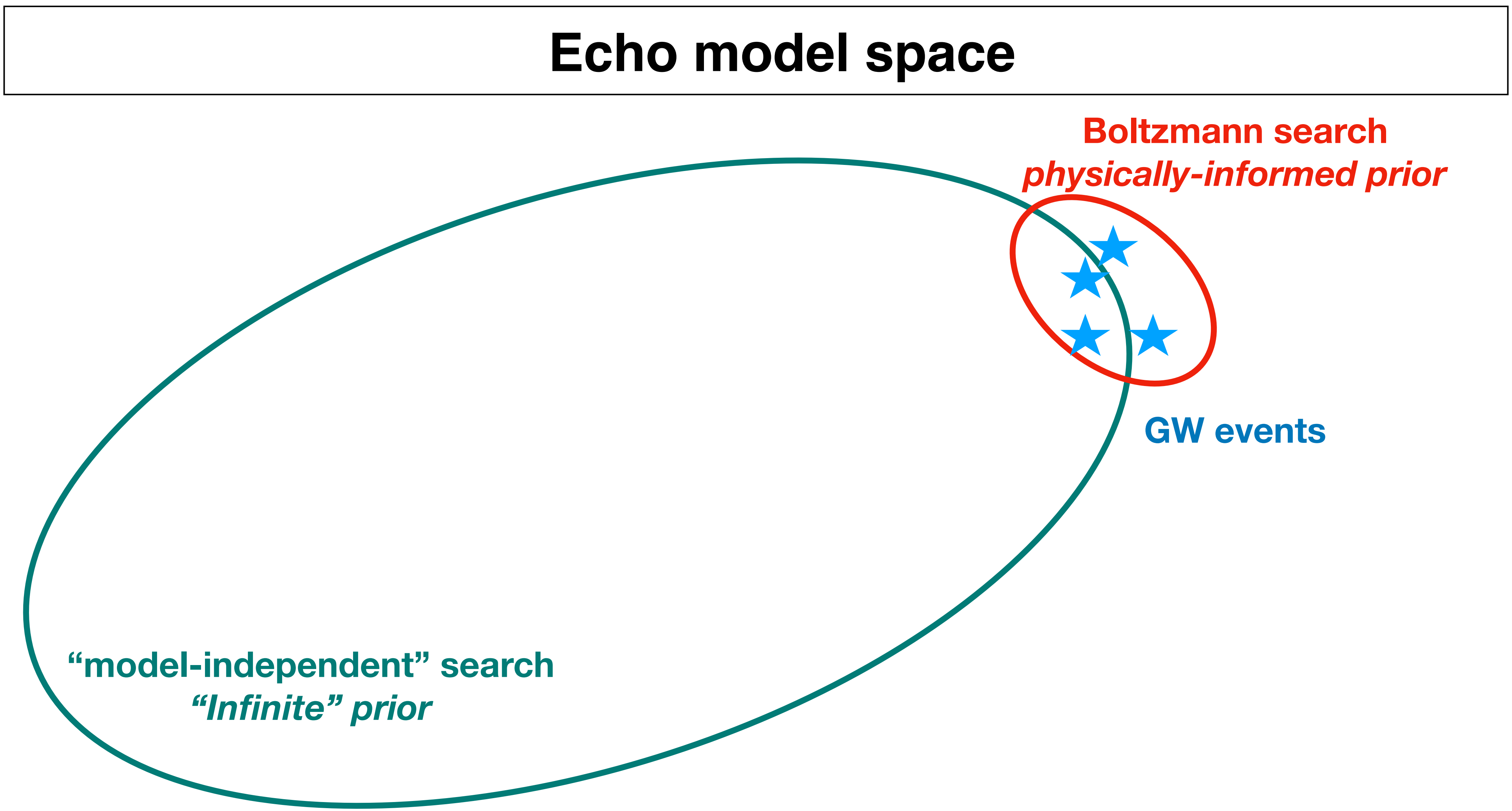


But why do different methods disagree?



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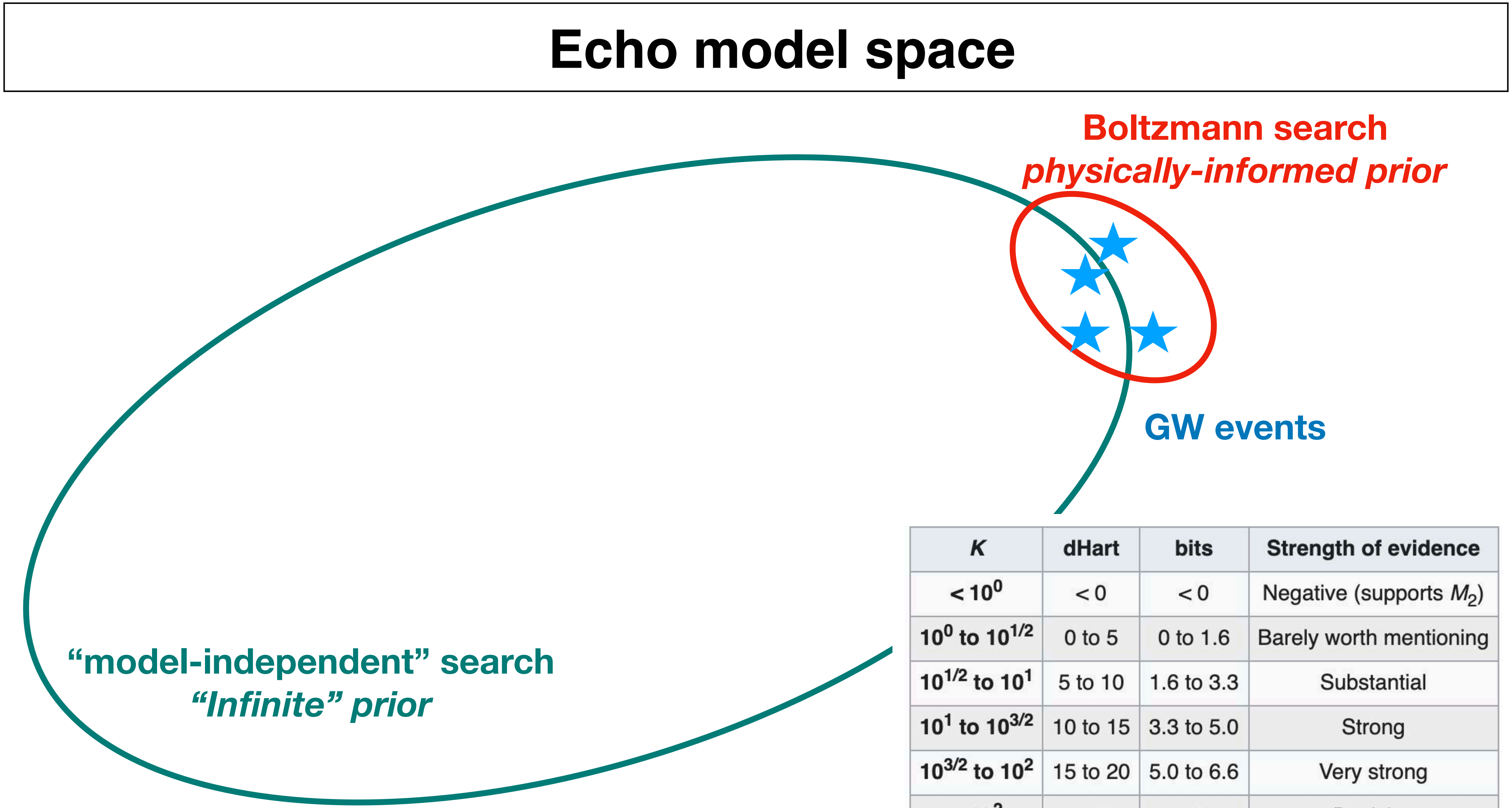
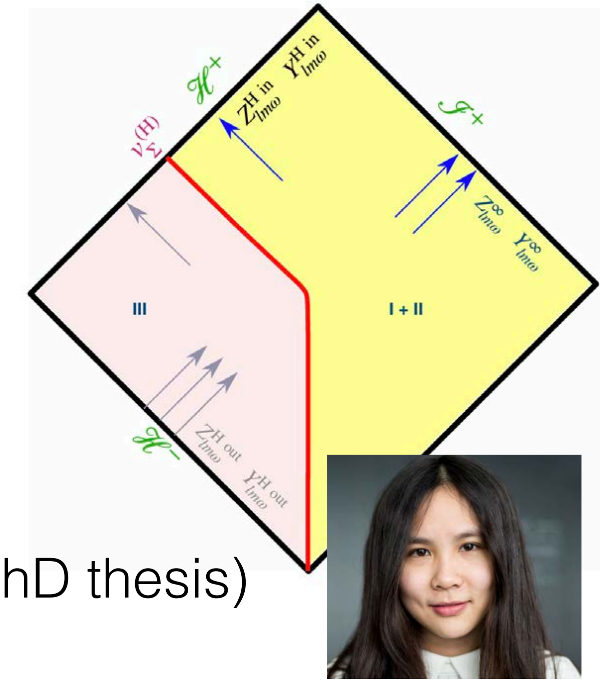


K	dHart	bits	Strength of evidence
$< 10^0$	< 0	< 0	Negative (supports M_2)
10^0 to $10^{1/2}$	0 to 5	0 to 1.6	Barely worth mentioning
$10^{1/2}$ to 10^1	5 to 10	1.6 to 3.3	Substantial
10^1 to $10^{3/2}$	10 to 15	3.3 to 5.0	Strong
$10^{3/2}$ to 10^2	15 to 20	5.0 to 6.6	Very strong
$> 10^2$	> 20	> 6.6	Decisive

Future is bright!



- Echoes in "numerical relativity"?
- Hybrid PPN+Teukolsky with matching (Qingwen Wang's PhD thesis)

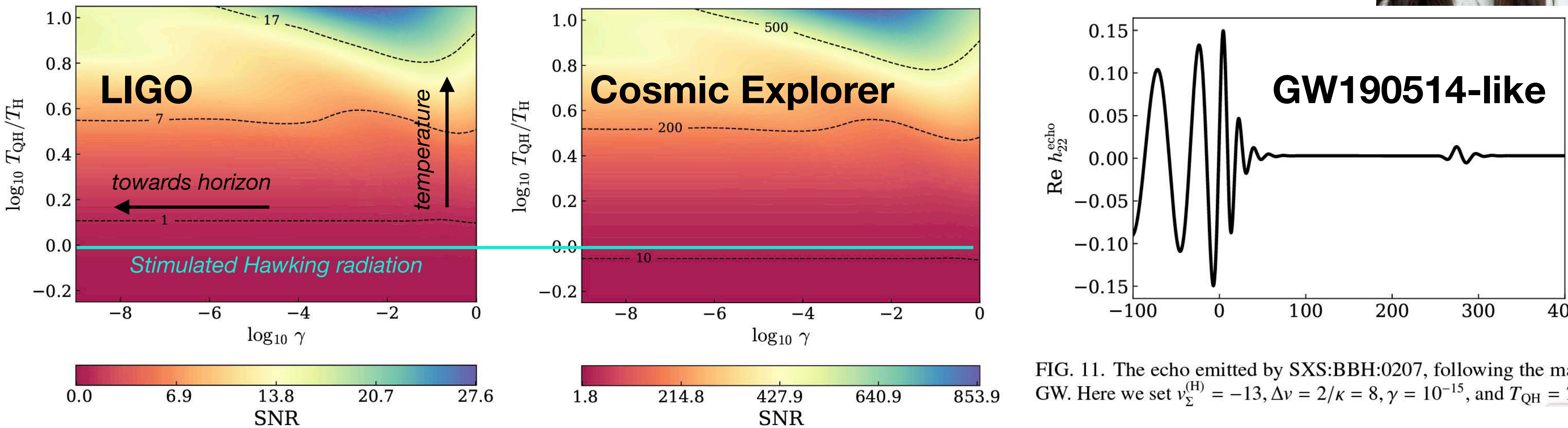


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set $\nu_\Sigma^{(H)} = -13, \Delta v = 2/\kappa = 8, \gamma = 10^{-15}$, and $T_{QH} = T_H$.

arXiv > gr-qc > arXiv:2203.03174

General Relativity and Quantum Cosmology

[Submitted on 7 Mar 2022]

Gravitational-wave echoes from numerical-relativity waveforms via space-time construction near merging compact objects

Sizheng Ma, Qingwen Wang, Nils Deppe, Nils L. Fischer, François Hébert, Lawrence E. Kidder, Jordan Moxon, William Throwe, Mark A. Scheel, Yanbei Chen

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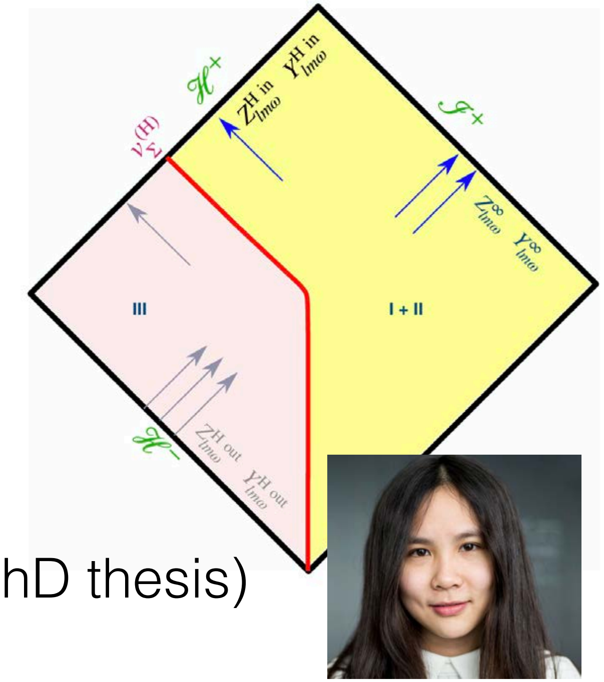

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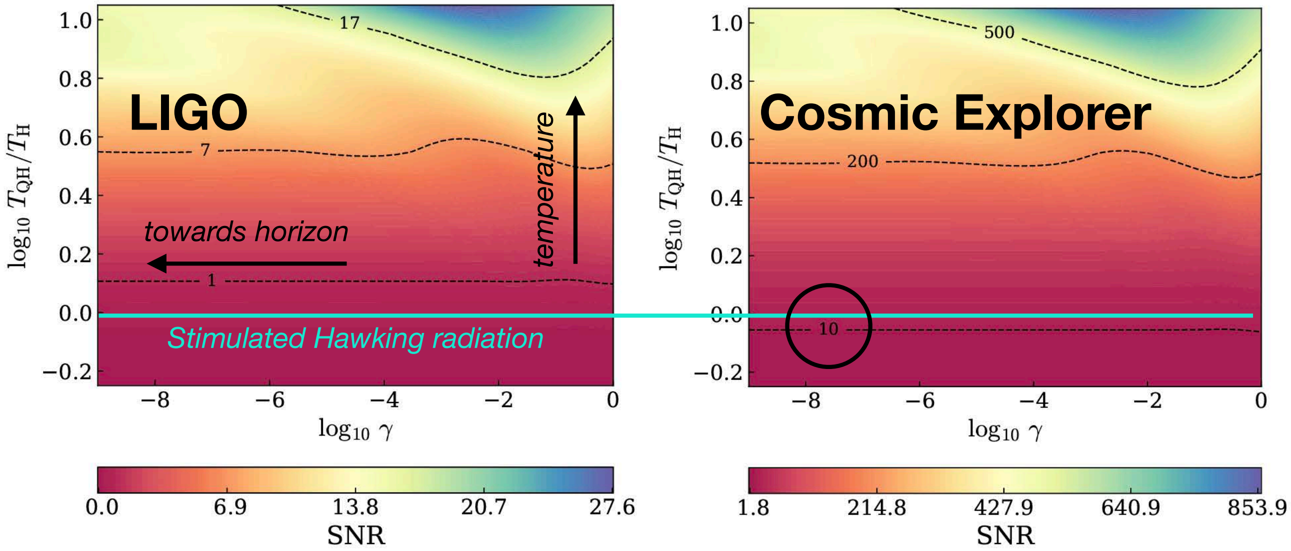

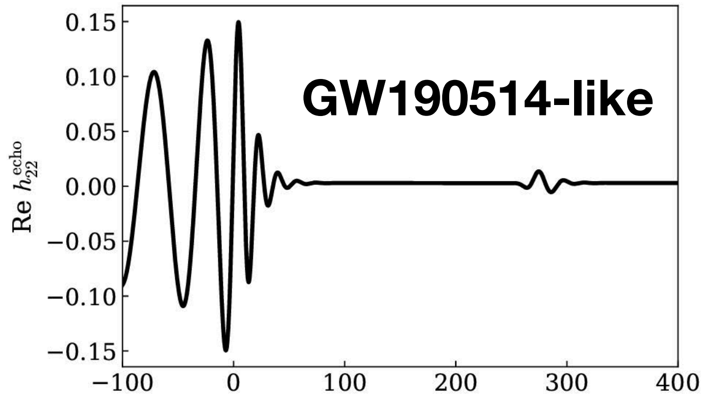

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arXiv > gr-qc > arXiv:2203.03174

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- One battleground is the quantum nature of black holes
- No Echoes = No Quantum Mechanics!
- Stimulated Hawking radiation → Logarithmically delayed echoes @horizon frequency, probing quantum black hole microstructure

Conclusions

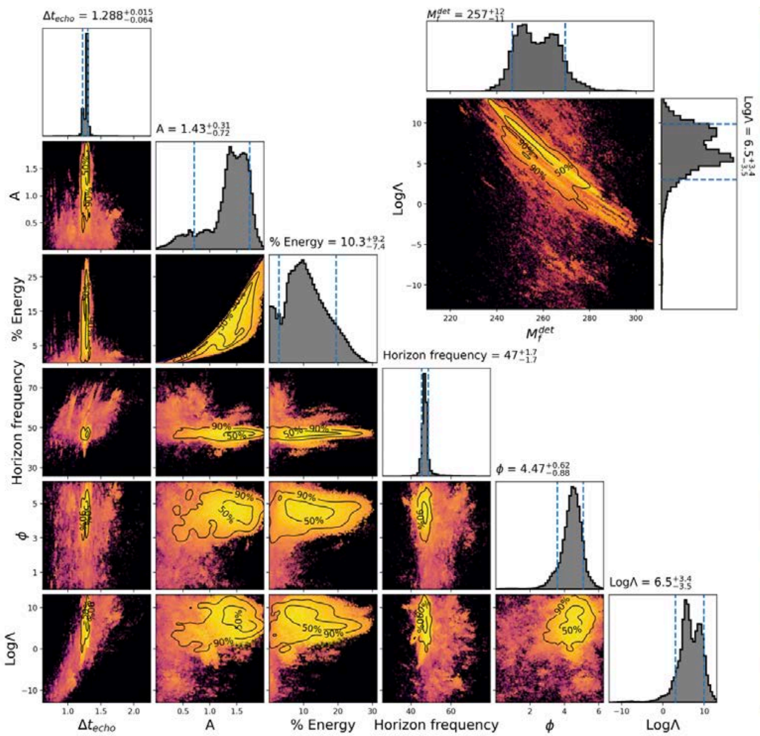
- We are still fighting Einstein’s demons in his “Great War”
- One battleground is the quantum nature of black holes
- No Echoes = No Quantum Mechanics!
- Stimulated Hawking radiation → Logarithmically delayed echoes @horizon frequency, probing quantum black hole microstructure
- Tantalizing though controversial hints for echoes in LIGO: *which events? which templates? which search method?*

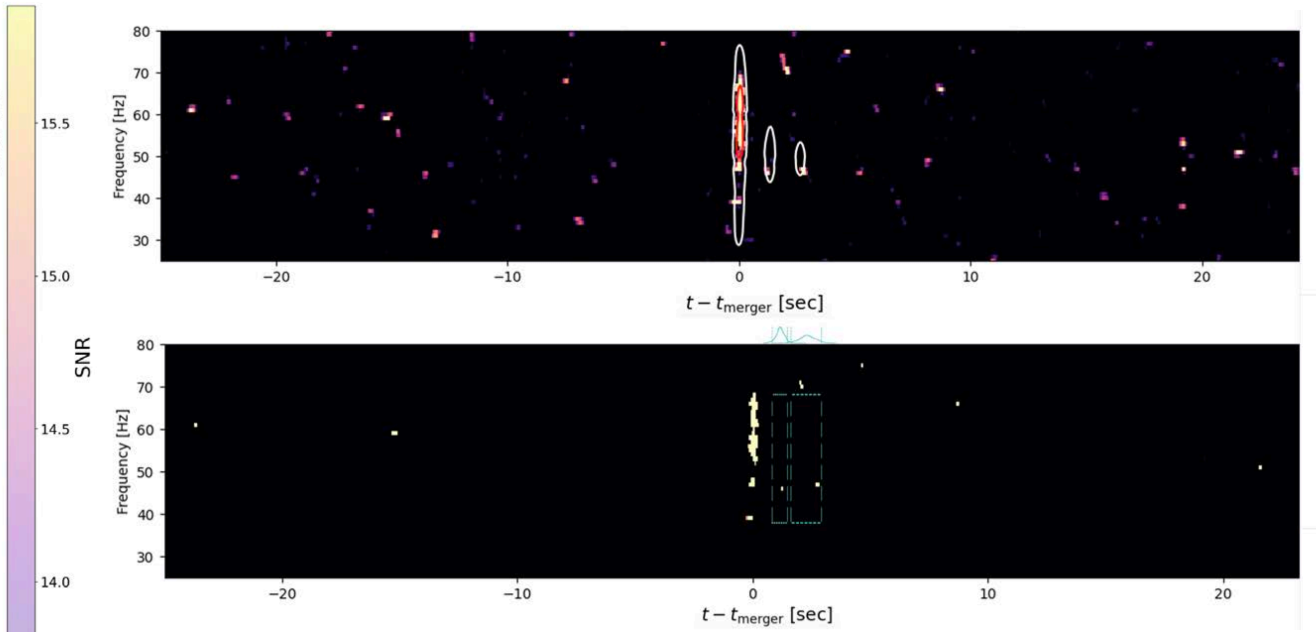
Conclusions

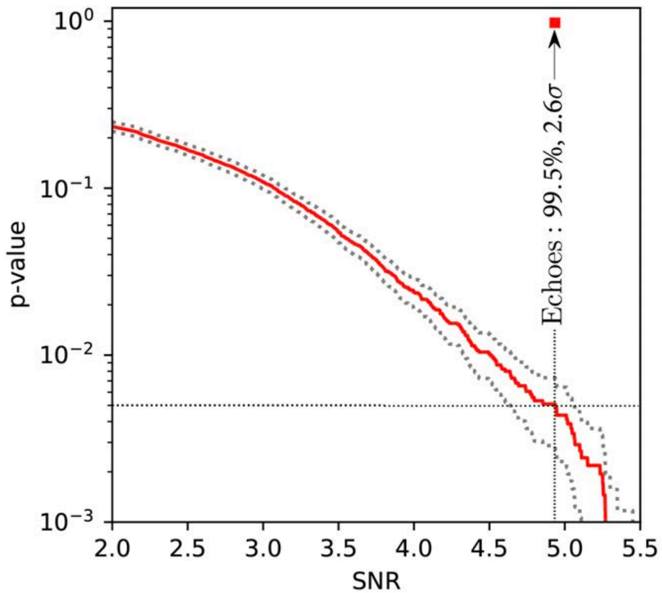
- We are still fighting Einstein's demons in his "Great War"
- One battleground is the quantum nature of black holes
- No Echoes = No Quantum Mechanics!
- Stimulated Hawking radiation → Logarithmically delayed echoes @horizon frequency, probing quantum black hole microstructure
- Tantalizing though controversial hints for echoes in LIGO: *which events? which templates? which search method?*
- Possible first measurement of stimulated Hawking radiation

Bonus Slides!

Stimulated Hawking in GW190521







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

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,†]

[1] Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
[2] Leibniz Universität Hannover, D-30167 Hannover, Germany
[3] Department of Physics and Astronomy, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[4] Waterloo Centre for Astrophysics, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[5] Perimeter Institute For Theoretical Physics, 31 Caroline St N, Waterloo, ON N2L 2Y5, Canada
[*] Author to whom correspondence should be addressed.
[†] 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

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Quantum Black Holes in the Sky?

Organizer(s): Niayesh Afshordi Vitor Cardoso Samir Mathur

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Into the future:
Quantum Black Hole Seismology

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

Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

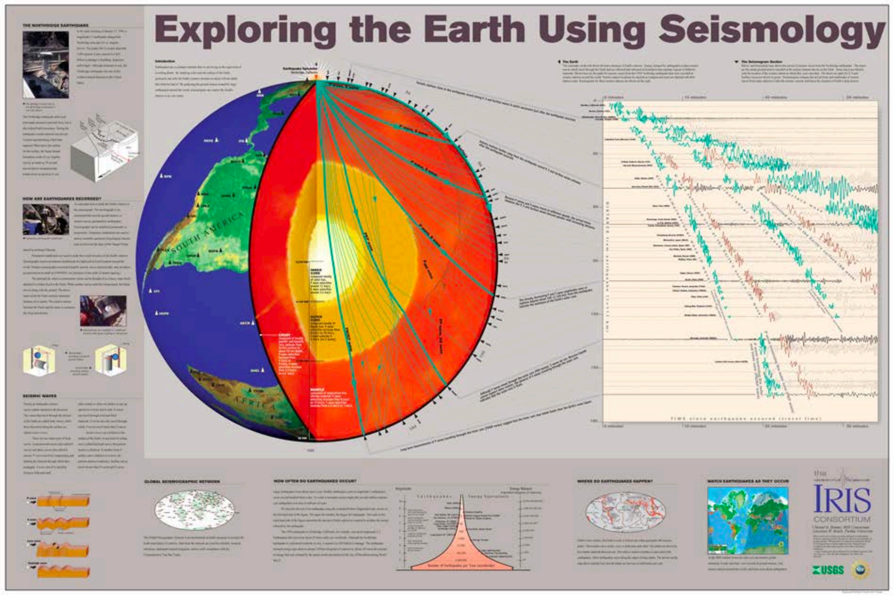
arXiv:2001.11642, PRD

Quantum Black Hole Seismology II: Applications to Astrophysical Black Holes

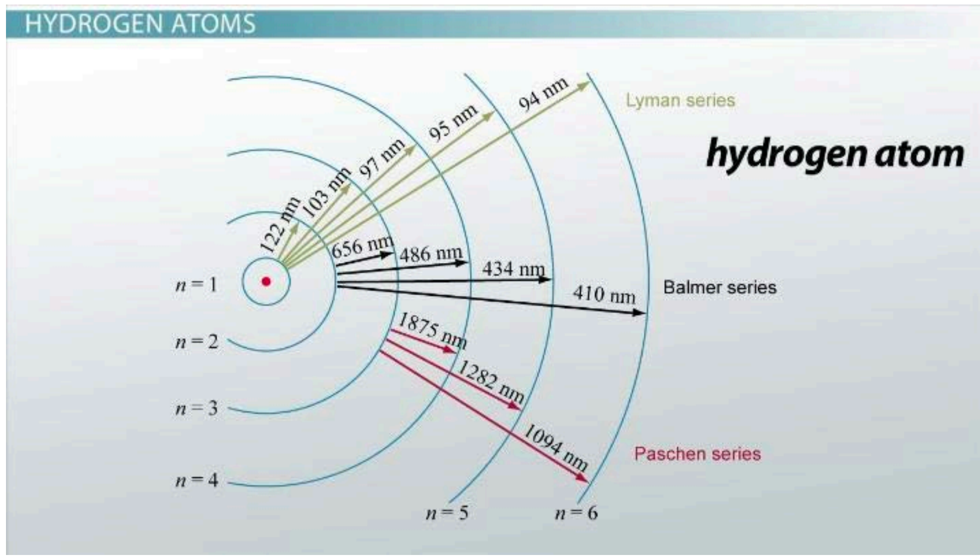
Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

arXiv:2004.06276, PRD

Seismology vs Spectroscopy



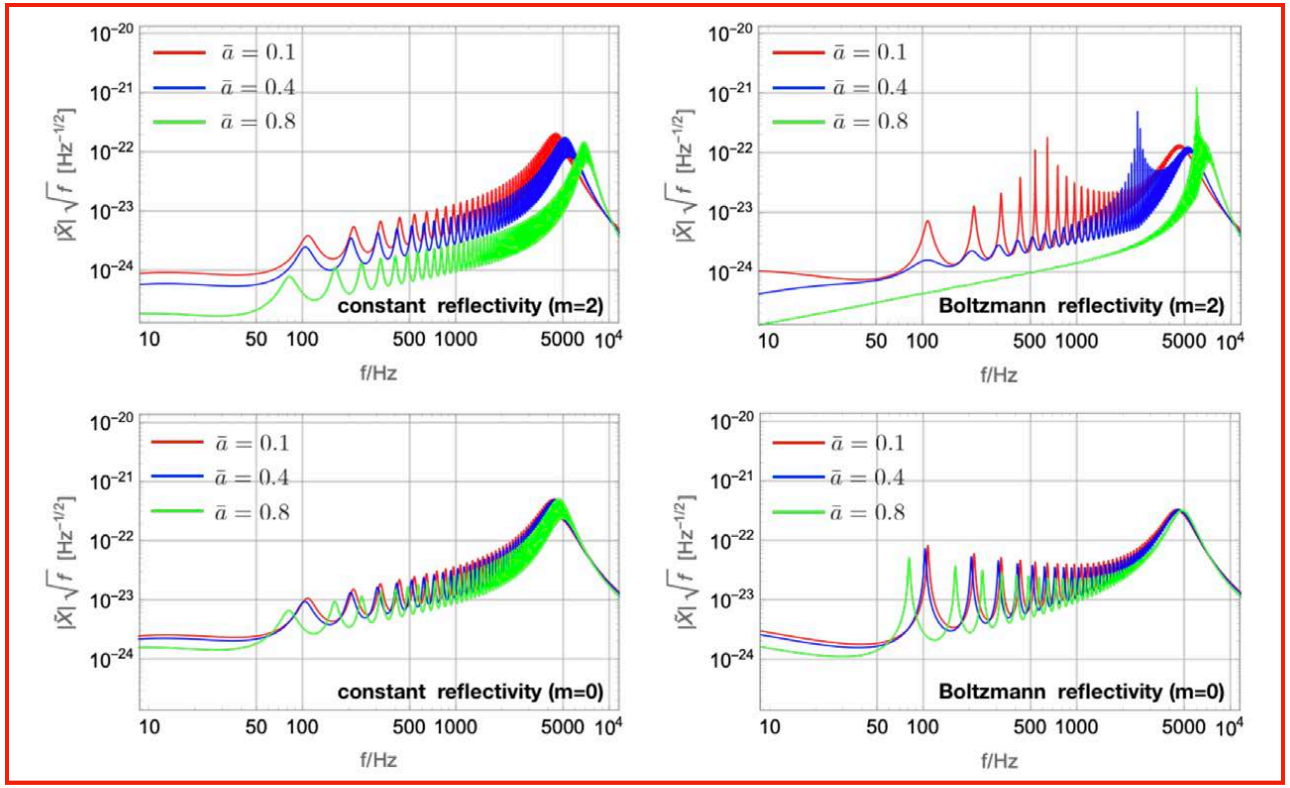
What's inside the Black Hole
(replaces event horizon ~2M)



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

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

What Black Hole Seismology teaches us 1/3

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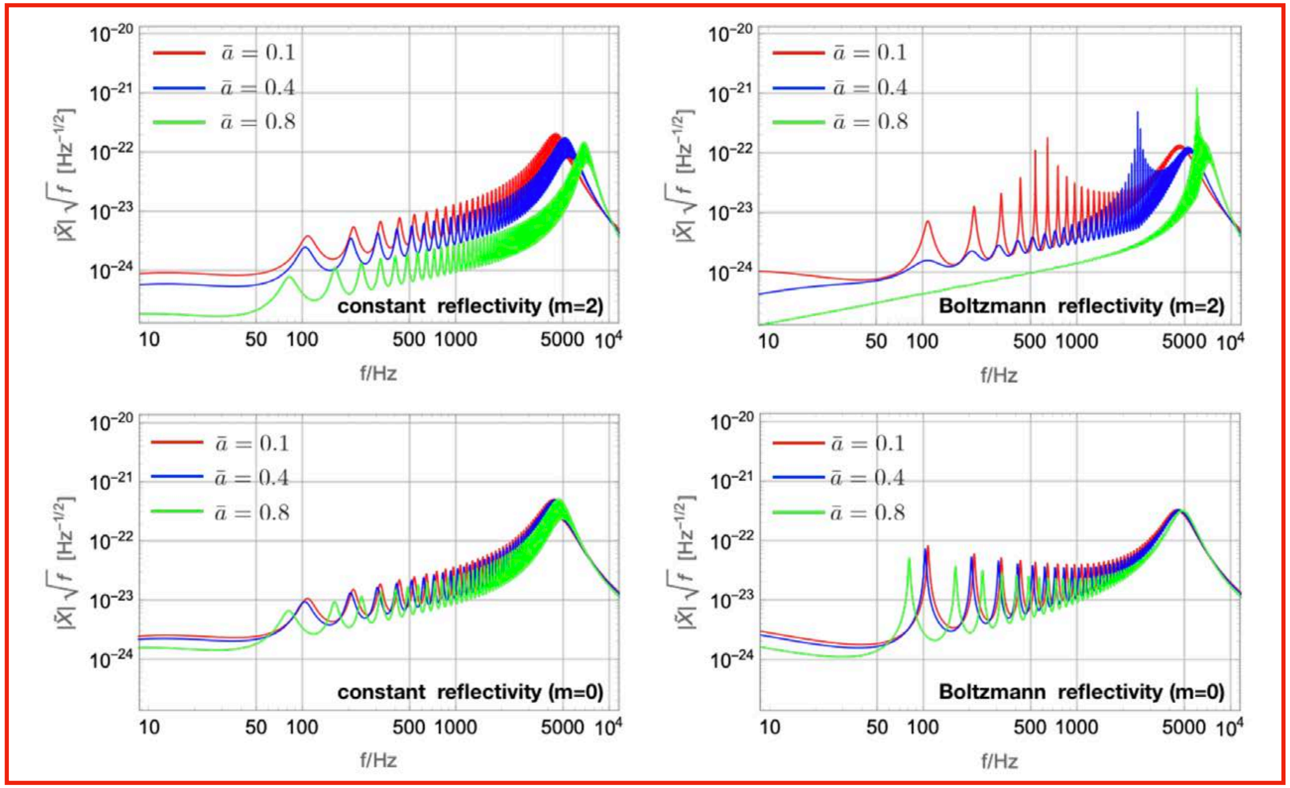

Oshita, Tsuna, & NA 2020

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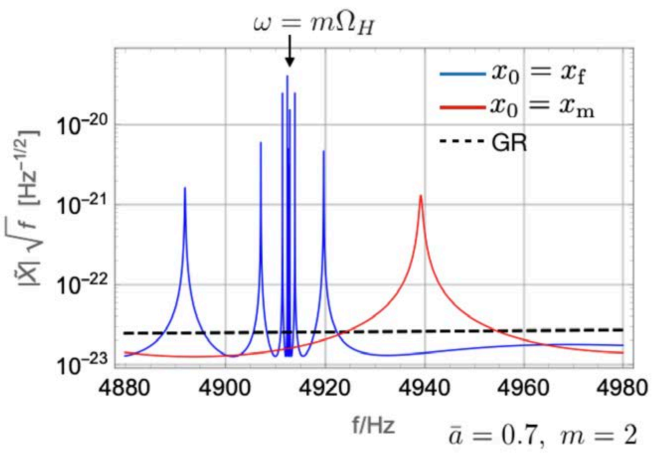
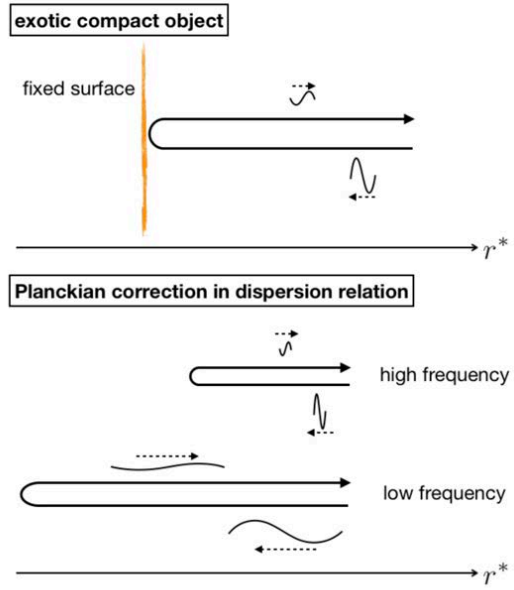
What Black Hole Seismology teaches us 2/3

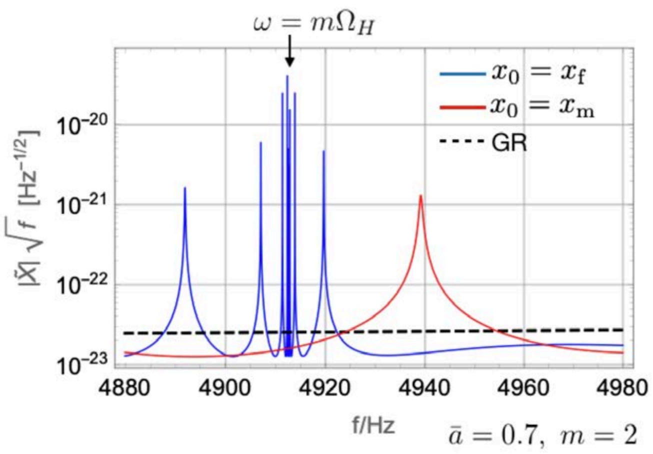


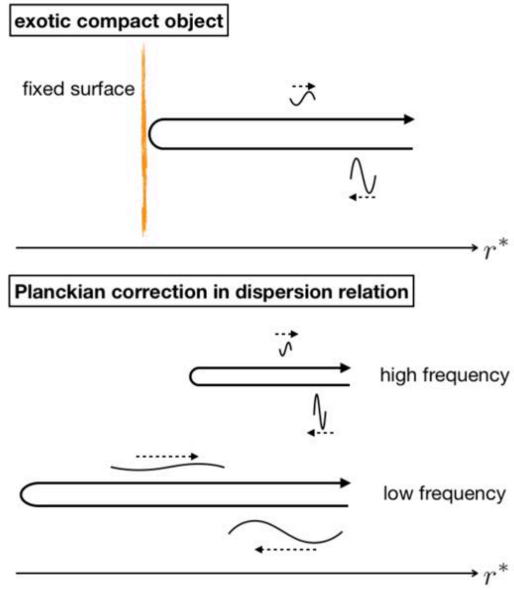


Oshita, Tsuna, & NA 2020

What Black Hole Seismology teaches us 2/3

- Exotic Compact Object vs Modified Dispersion Relation





Oshita, Tsuna, & NA 2020

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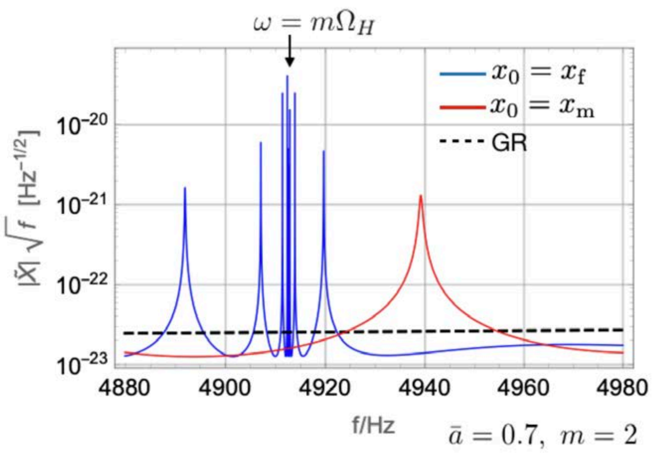
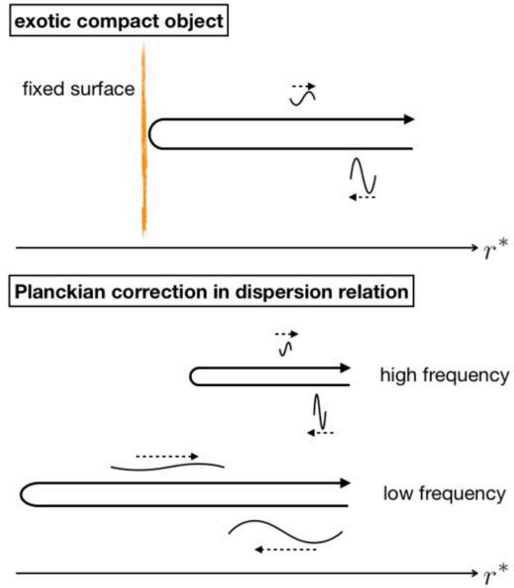
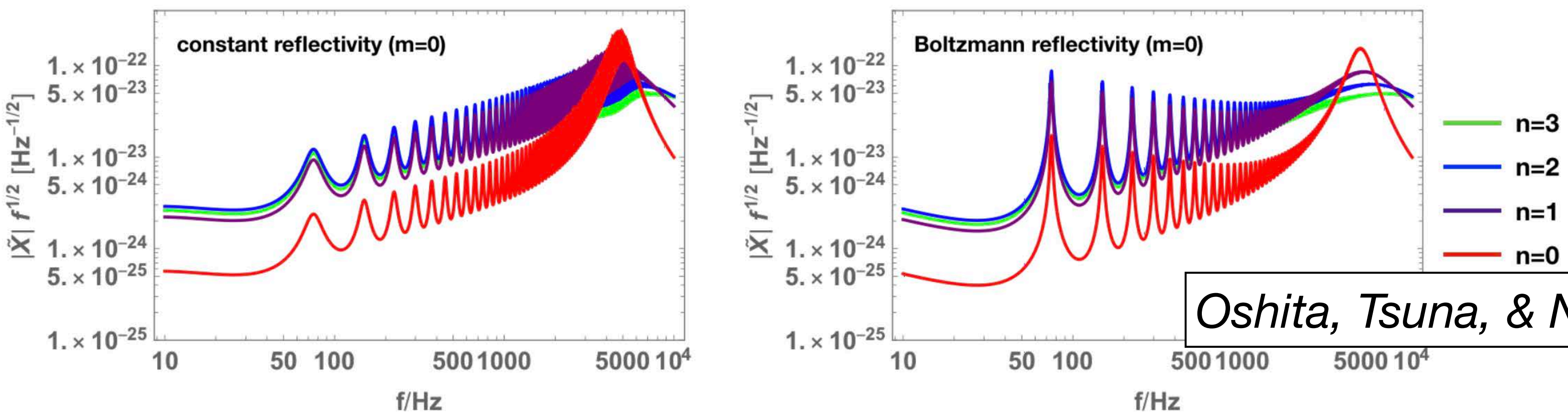




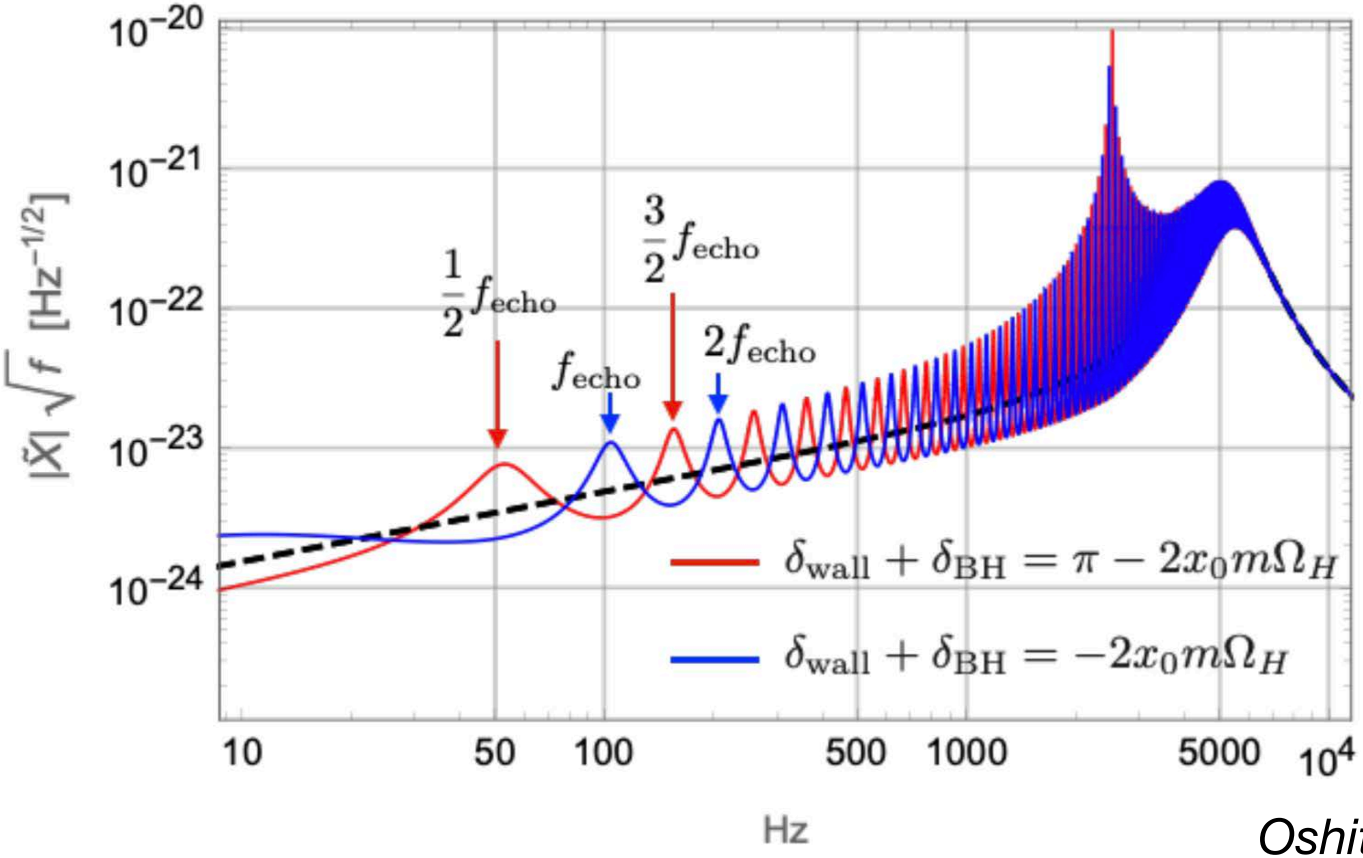
- Which overtones are excited



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

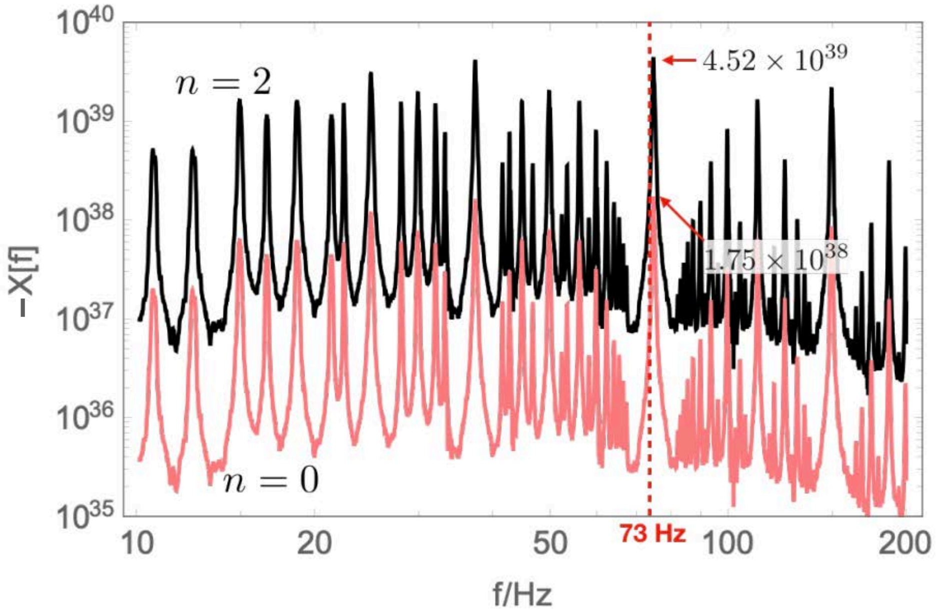
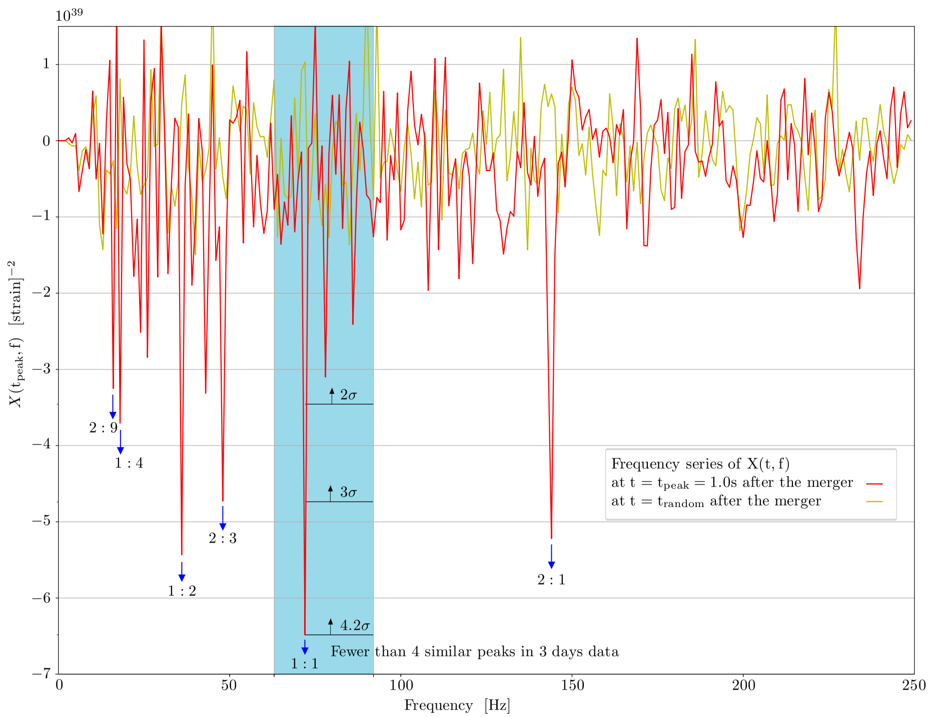


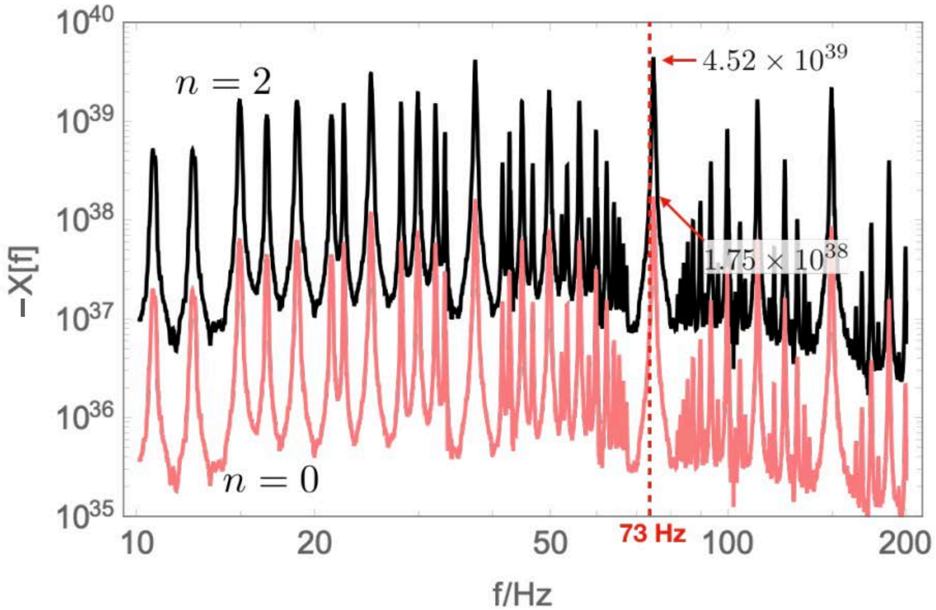
FIG. 6: Plots of $X(f)$ obtained in the BR model for the overtone QNM with $n = 2$ (black) and the least damping QNM (pink). For both cases, we set $\ell = 2$, $m = 0$, $\bar{a} = 0.85$, $\epsilon_{rd} = 0.7\%$, $\theta = 33°$, $D_L = 40$ Mpc, $T_H/T_{QH} = 0.1$, and $\gamma = 1$.



Abedi & NA, 2019

Seismology for the GW170817 remnant: Theory vs Data

Oshita, Tsuna, & NA 2020



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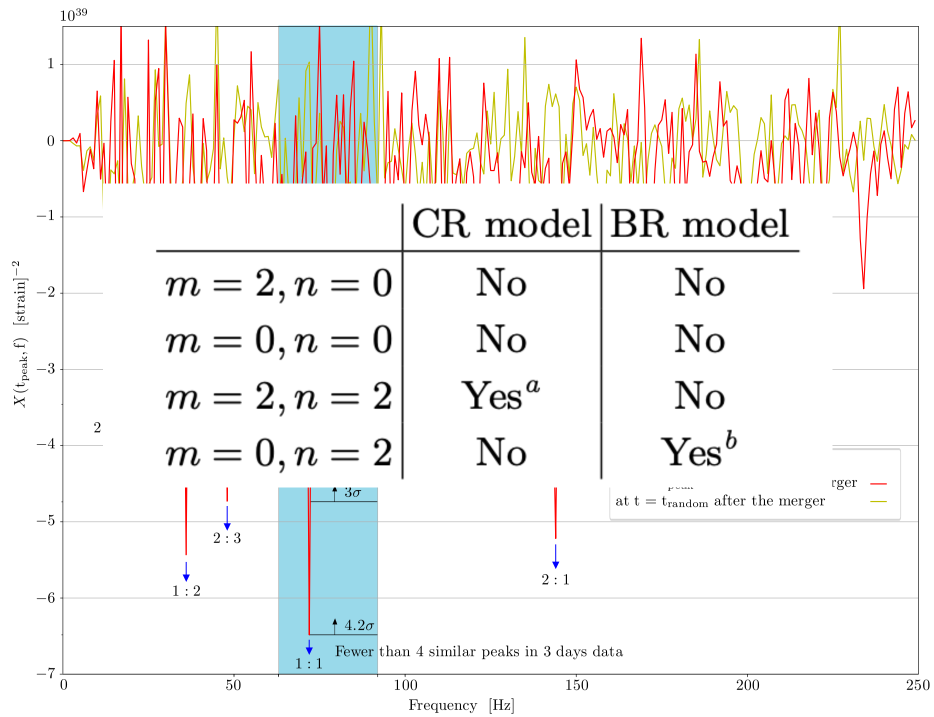


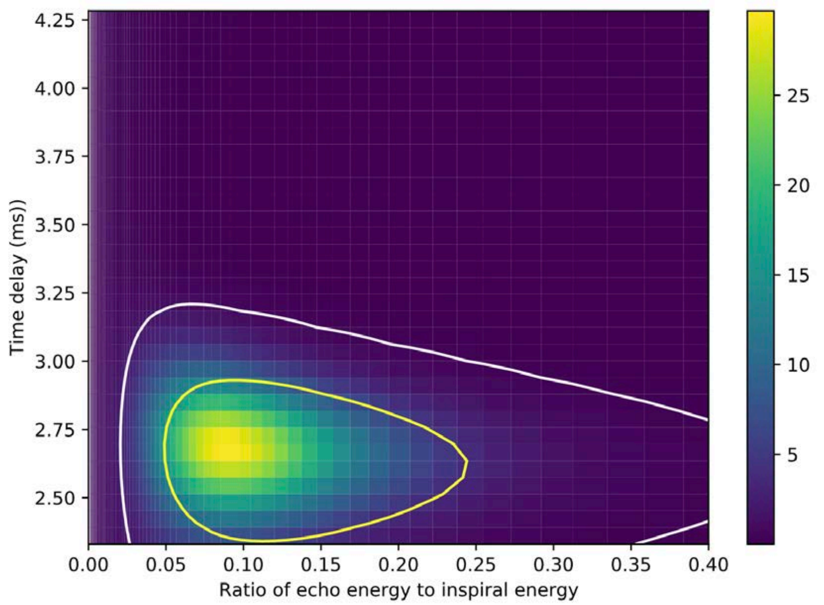
	CR model	BR model
$m = 2, n = 0$	No	No
$m = 0, n = 0$	No	No
$m = 2, n = 2$	Yes[a]	No
$m = 0, n = 2$	No	Yes[b]

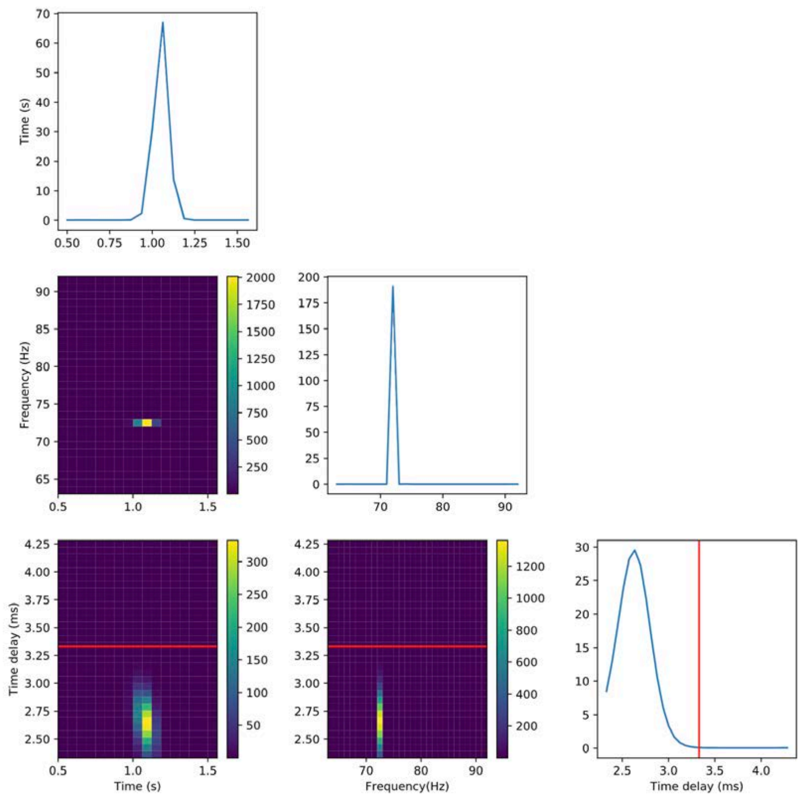
Abedi & NA, 2019

Bayesian approach to BH seismology

(Petra Duff & NA, in prep)

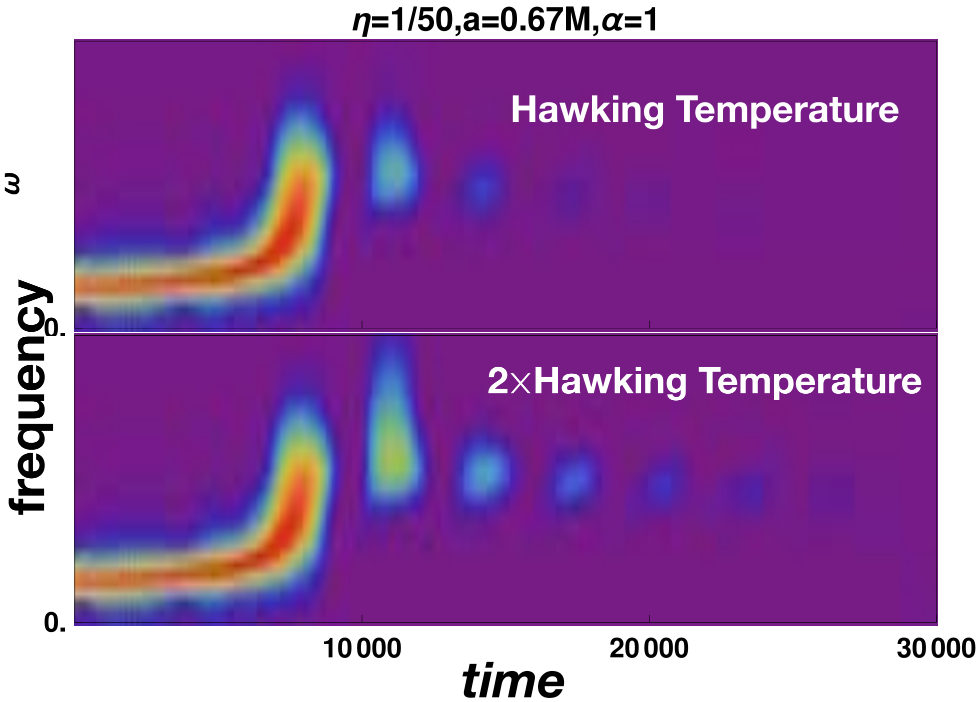
- Echoes after GW170817, Bayes factor of **~10**
- Geometric time-delay ≠ Observed time delay

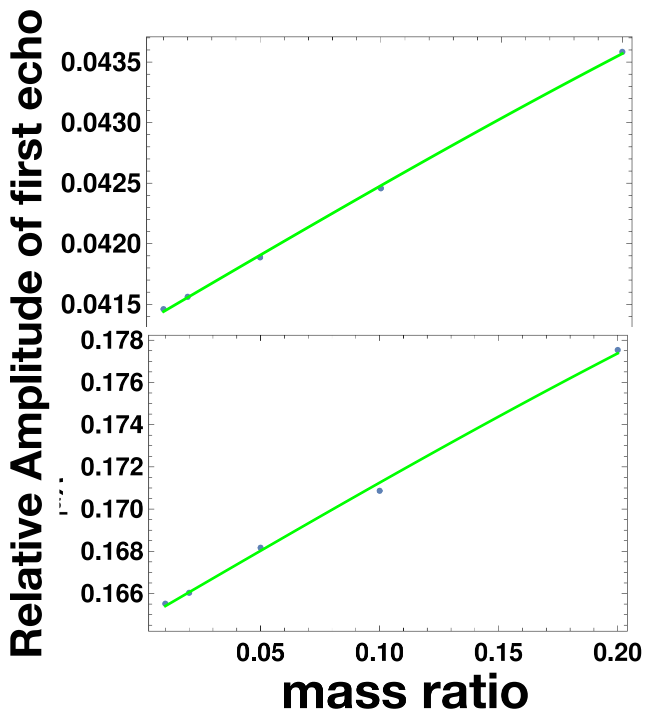




Echo-Diversity: How initial conditions impact seismology

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

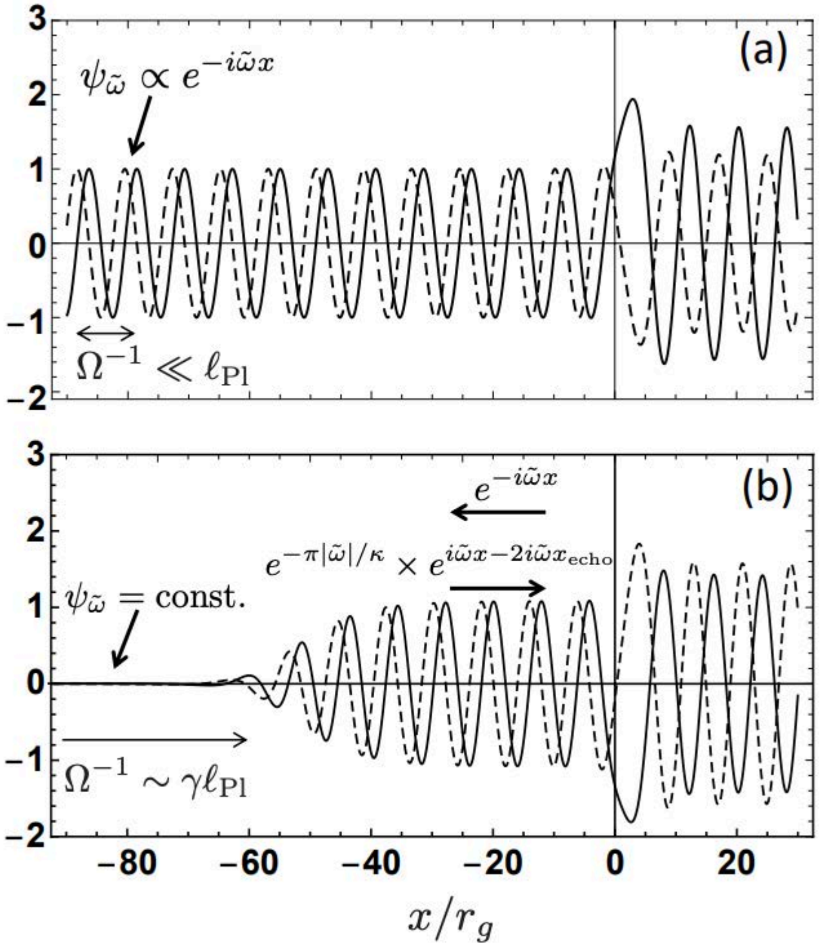




Fluctuation-Dissipation Theorem —> Boltzmann echoes

$$\left[-i\frac{\gamma\Omega(x)}{E_{\rm Pl}}\frac{d^2}{dx^2}+\frac{d^2}{dx^2}+\tilde{\omega}^2-V(x)\right]\psi_{\tilde{\omega}}(x)=\xi_{\tilde{\omega}}(x),$$

dissipation



independent of γ

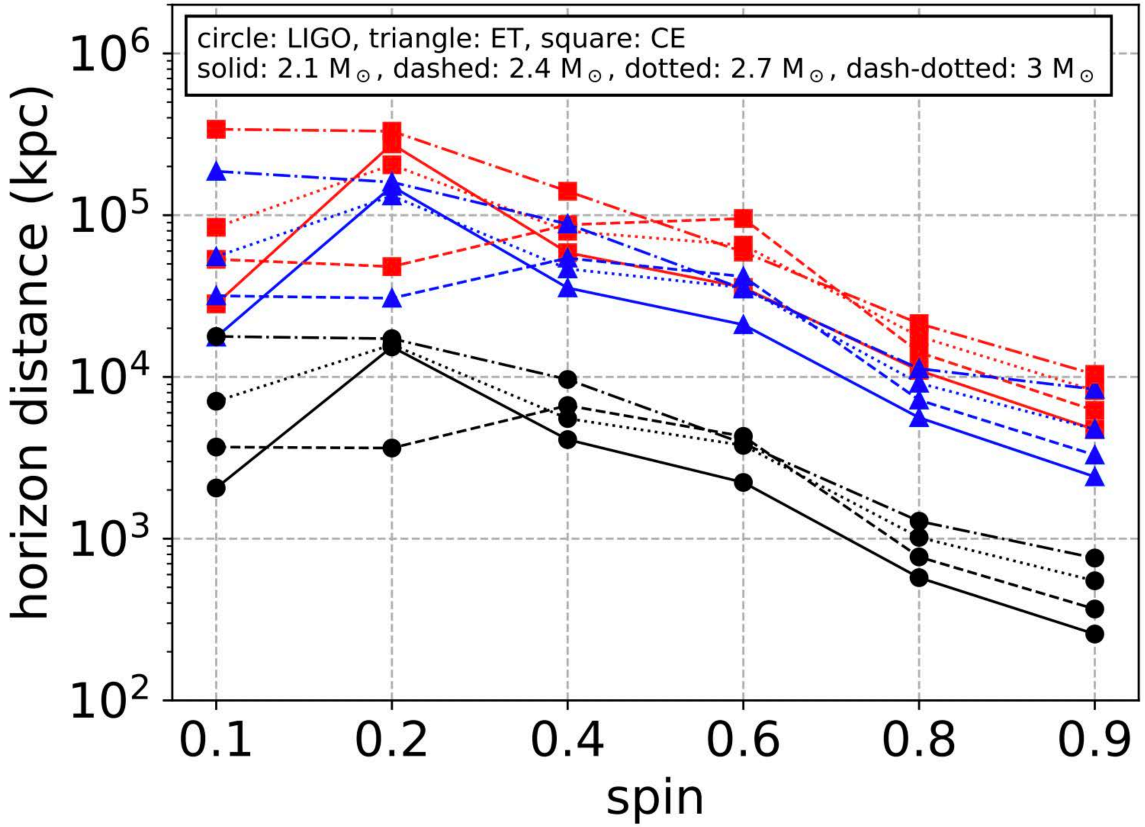
$$R = \exp\left(-\frac{\hbar\omega}{kT_H}\right)$$

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

Detectability of Failed SNe for maximum stable horizon temperature

Oshita, Tsuna, & NA 2020



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

GraceDB — Gravitational-Wave Candidate Event Database

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Superevent Info

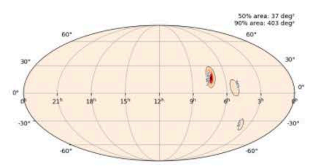
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S200114f	Production	EM_READY ADVOK EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1.226e-09	1 per 25.838 years	1263002916.225766	1263002916.239300	1263002916.252885	2020-01-14 02:11:12 UTC	Data

Preferred Event Info

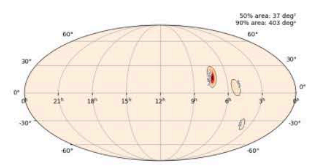
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
Burst	CWB	IMBH	H1,L1,V1	1263002916.2393	2020-01-14 02:12:26 UTC

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

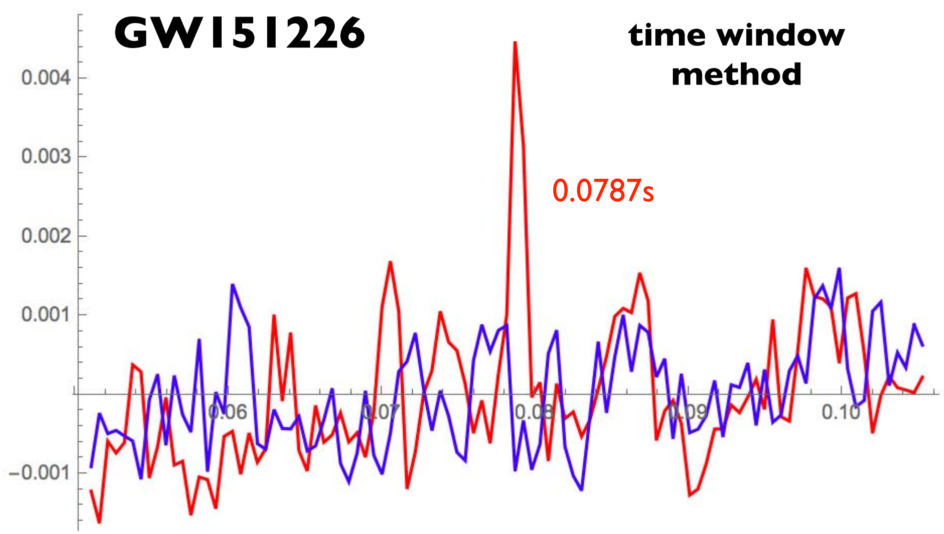


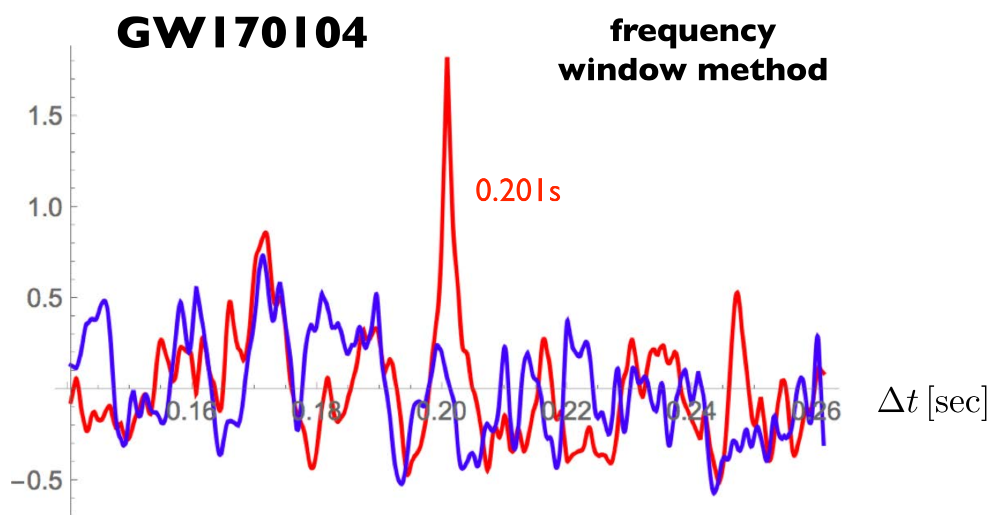
Mollweide projection of cWB.fits.gz cWB.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 14, 2020 02:18:50 UTC

Randy Conklin, Bob Holdom & Jing Ren 2018

Another independent search for echoes

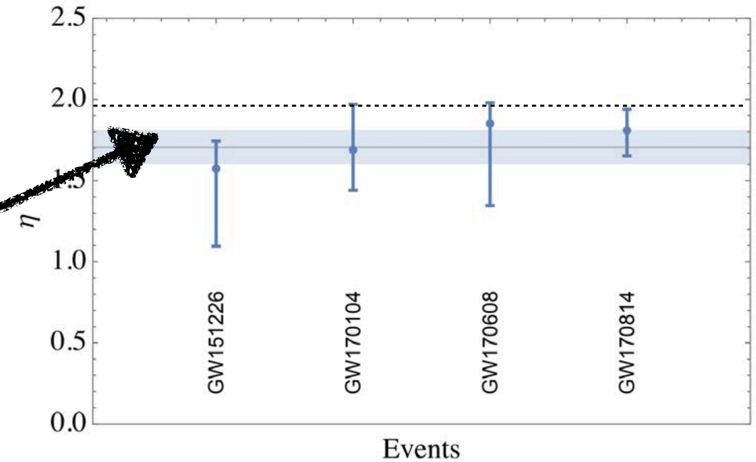
- ***Search strategies***: using window functions to find the ***preferred time delay*** of echoes from the correlation of two LIGO detectors (red and blue curves are for data after and before merger)



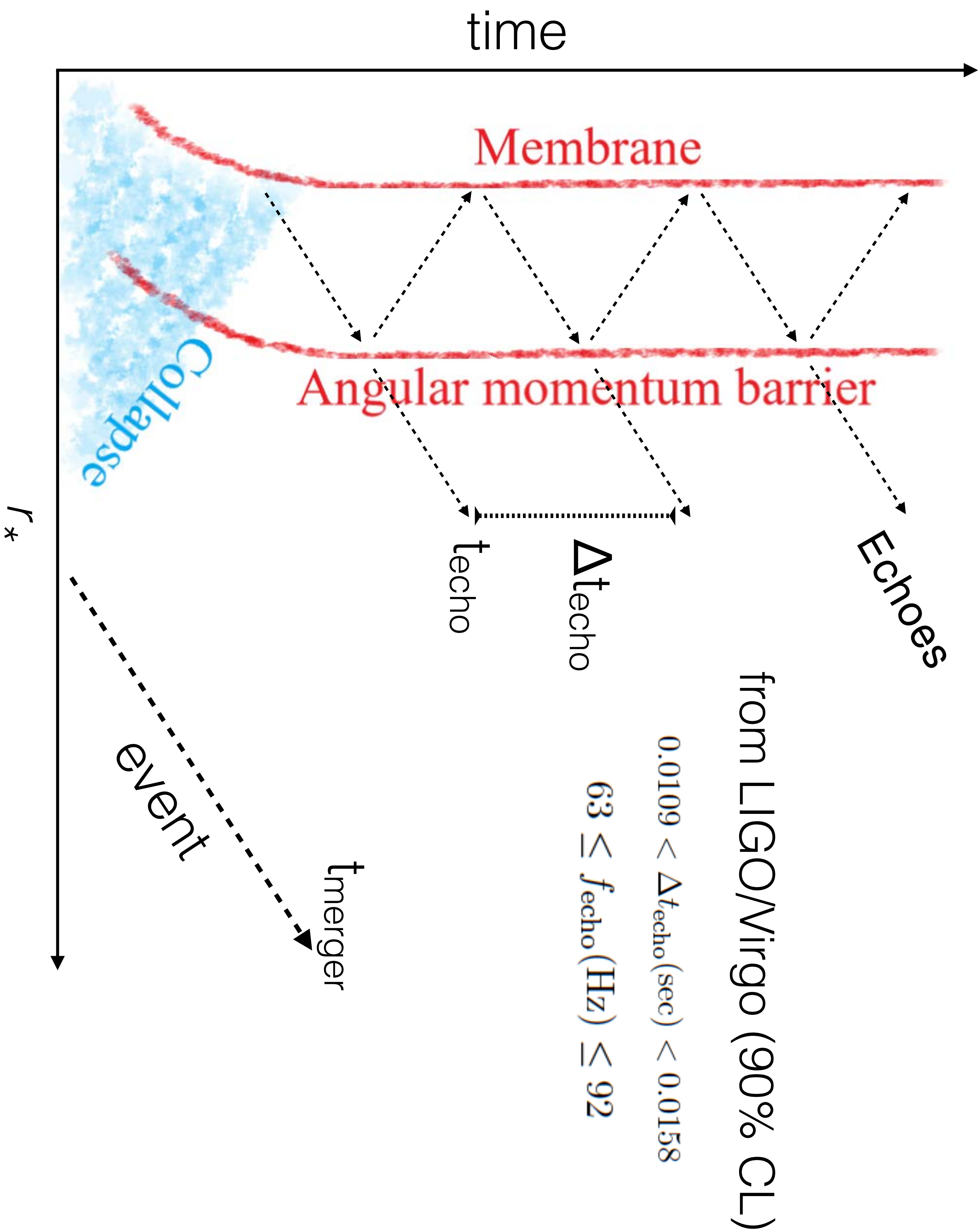


- Tentative signal peaks for *GW151226, GW170104, GW170608, GW170814, GW170817*
- **p-values ~ 0.2%-0.8%**
- consistent w/ GUT or "Inflation" scales

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



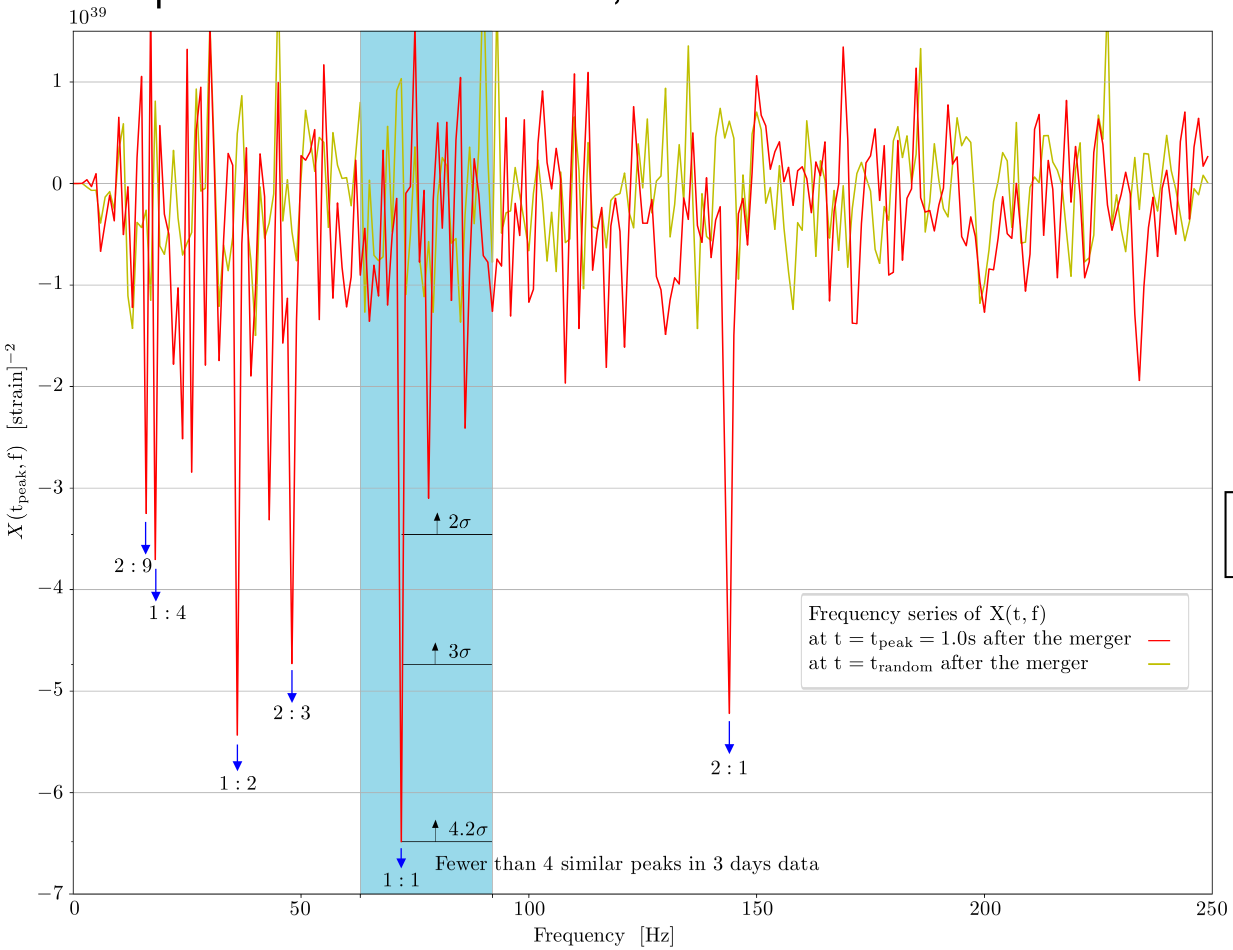
Oshita & NA 2019

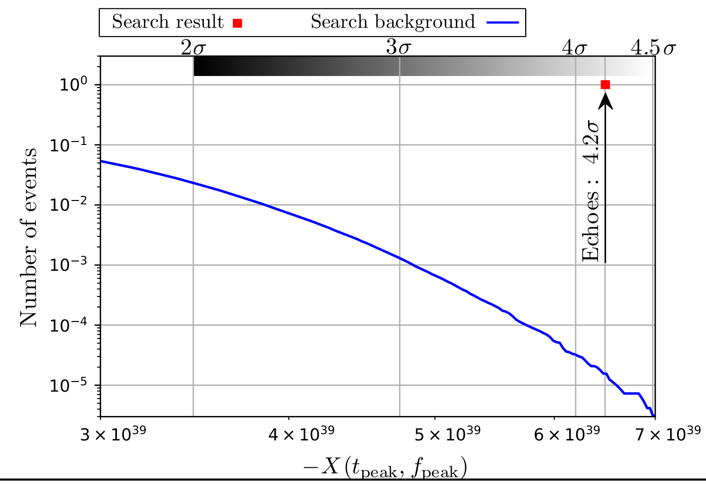


time
Membrane
Angular momentum barrier
Collapse
r_*
t_{echo}
Δt_{echo}
Echoes
event
t_{merger}
from LIGO/Virgo (90% CL)
$0.0109 < \Delta t_{echo}(\mathrm{sec}) < 0.0158$
$63 \leq f_{echo}(\mathrm{Hz}) \leq 92$

Binary Neutron Star merger

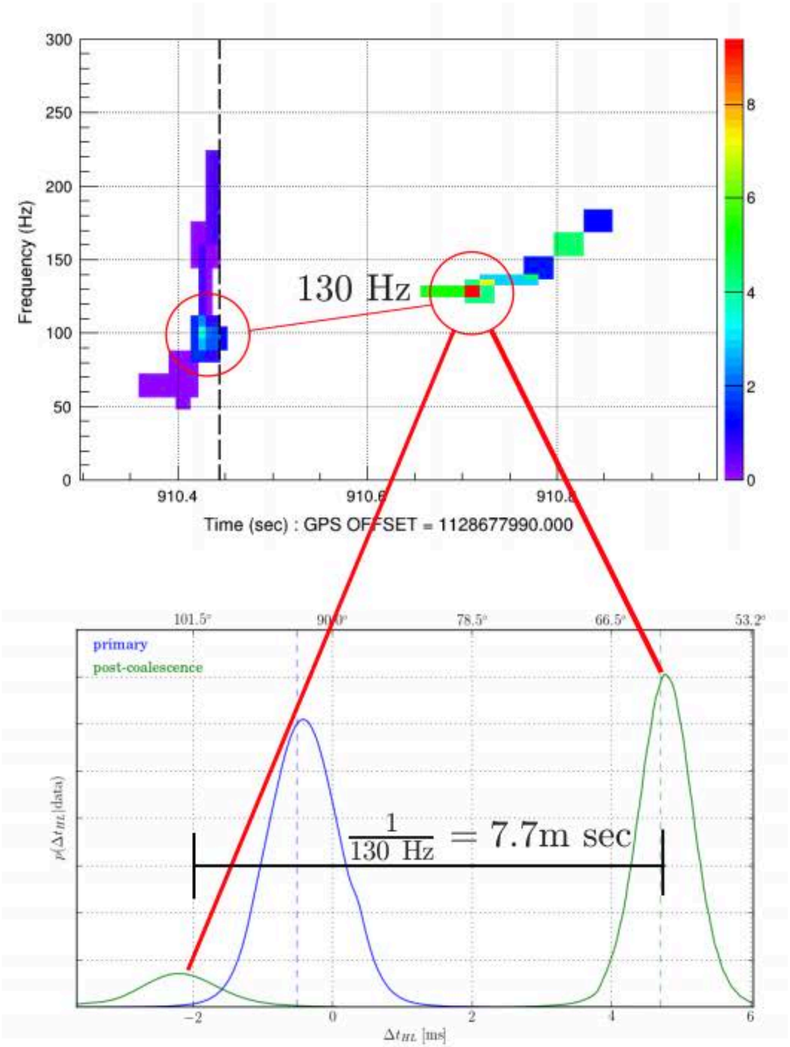
- Echoes within 1 sec after GW170817 merger @ f= 72 Hz
- p-value =1.6x10^{-5}, **4.2σ tentative detection,** *high-spin BH remnant*



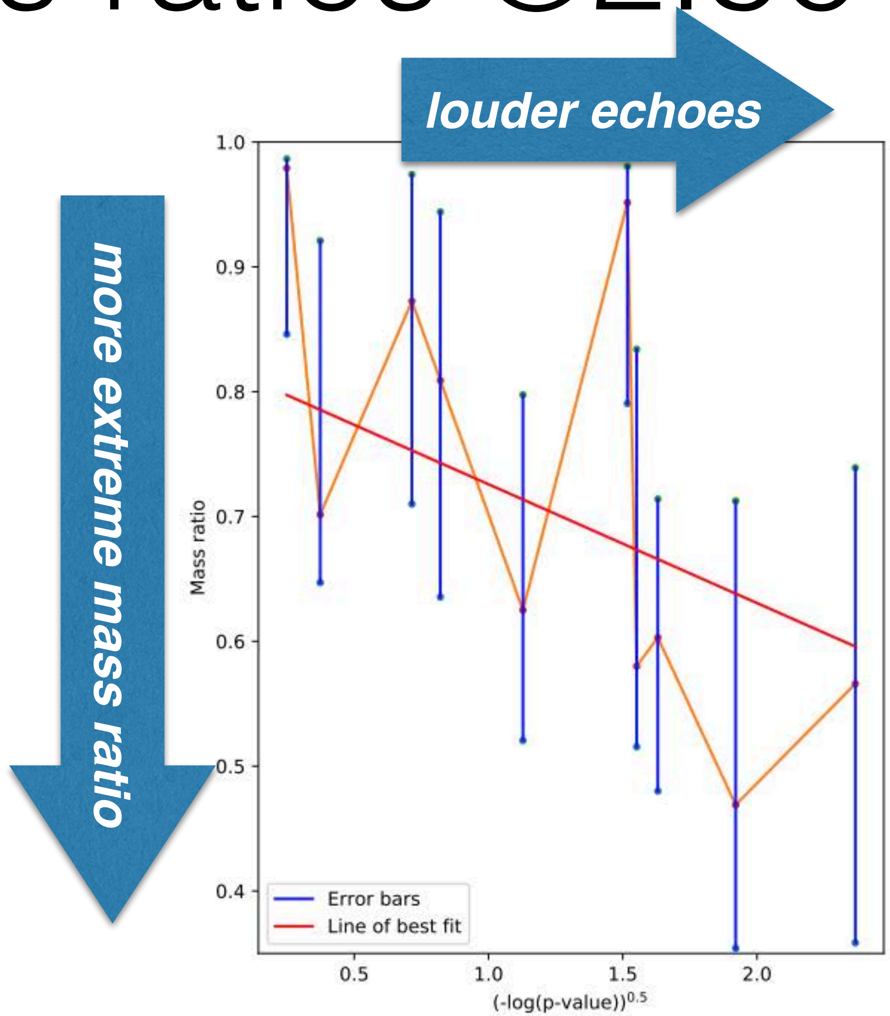


Abedi & NA, arXiv:1803.10454

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

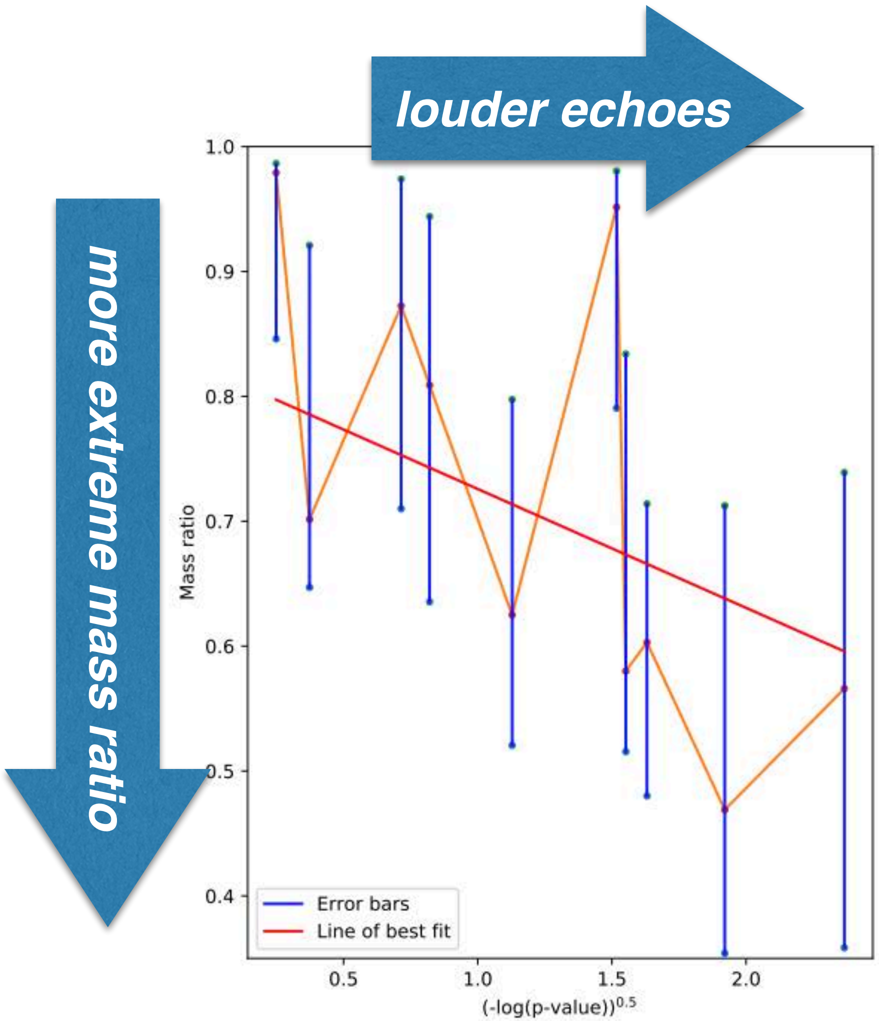
Echoes visible for more extreme mass ratio mergers?

Boxing Day Surprise:
Higher Multipoles and Orbital Precession in GW151226

Horng Sheng Chia,[1,*] Seth Olsen,[2] Javier Roulet,[2] Liang Dai,[3]
Tejaswi Venumadhav,[4,5] Barak Zackay,[6] and Matias Zaldarriaga[1]

[1] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*
[2] *Department of Physics, Princeton University, Princeton, NJ 08540, USA*
[3] *Department of Physics, University of California, Berkeley, 366 LeConte Hall, Berkeley, CA 94720, USA*
[4] *Department of Physics, University of California at Santa Barbara, Santa Barbara, CA 93106, USA*
[5] *International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560089, India*
[6] *Dept. of Particle Physics & Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

We present a reanalysis of GW151226, the second binary black hole merger discovered by the LIGO-Virgo Collaboration. Previous analysis showed that the best-fit waveform for this event corresponded to the merger of a $\sim 14\,M_\odot$ black hole with a $\sim 7.5\,M_\odot$ companion. In this work, we perform parameter estimation using a waveform model that includes the effects of orbital precession and higher-order radiative multipoles, and find that the mass and spin parameters of GW151226 have bimodal posterior distributions. The two modes are separated in mass ratio, q: the high-q mode $(0.4 \lesssim q < 1)$ is consistent with the results reported in the literature. On the other hand, the low-q mode $(q \lesssim 0.4)$, which describes a binary with component masses of $\sim 29\,M_\odot$ and $\sim 4.3 M_\odot$, is new. The low-q mode has several interesting properties: (a) the secondary black hole mass may fall in the lower mass gap of astrophysical black hole population; and (b) orbital precession is driven by the primary black hole spin, which has a dimensionless magnitude as large as ~ 0.88 and is tilted away from the orbital angular momentum at an angle of $\sim 47°$. The new low-q mode has a log likelihood that is about six points higher than that of the high-q mode, and can therefore affect the astrophysical interpretation of GW151226. Crucially, we show that the low-q mode disappears if we neglect either higher multipoles or orbital precession in the parameter estimation. More generally, this work highlights how incorporating additional physical effects into waveform models used in parameter estimations can alter the interpretation of gravitational-wave sources.



NA & Abedi 2020

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 Holdom 2020**	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, O2	5.5%,3.9%
6	**Salemi, et al. 2019**	coherent WaveBurst	151012,151226	0.4%,3%
7	**Abedi & NA 2019**	spectral comb	170817 (BNS)	0.0016%
8	**Gill, Nathanail, Rezolla 2019**	Astro Modelling	BNS EM	$t_{coll}=t_{echo}$
9	**Abedi, Longo, NA 2022**	Boltzmann, cWB	190521	0.5%

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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)
7	**Abbott, et al. 2020**	ADA+Bayes	O1-O3	“Infinite” prior
8	**Abbott, et al. 2021**	BayesWave	O2,O3 (-190521)	“
9	**Ren & Wu 2021**	Bayesian spectral comb	150921, 151012	no phase information