Gravity Seminar, University of Southampton, 2 Dec 2021

Niayesh Afshordi

UNIVERSITY OF WATERLOO

WATERLOO CENTRE FOR ASTROPHYSICS

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Strahlungs-Emission und -Absorption nach der Quantentheorie;

von A. Einstein.

(Eingegangen am 17. Juli 1916.)

Als Planck vor 16 Jahren die Quantentheorie ins Leben
[1] rief, und seine Strahlungsformel aufstellte, schlug er folgenden Weg ein. Er berechnete die mittlere Energie $\overline{E}$ des Resonators in Funktion der Temperatur nach von ihm neu aufgestellten, quantentheoretischen Grundsätzen und bestimmte dann hieraus die Strahlungsdichte ϱ in Funktion der Frequenz ν und der Temperatur, indem er auf elektromagnetischem Wege die Beziehung zwischen Strahlungsdichte und Resonatorenergie $\overline{E}$ auf-
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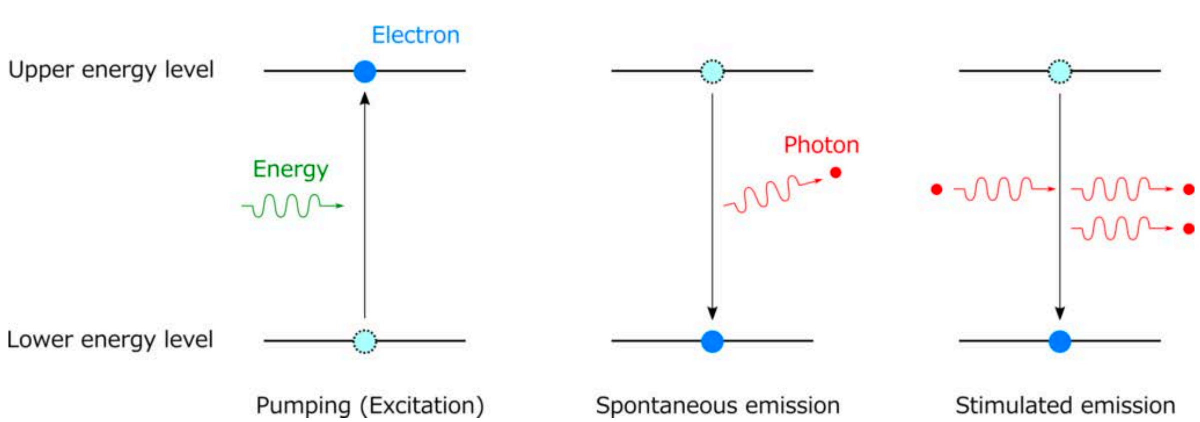
$$\overline{E} = \frac{c^3 \varrho}{8\pi\nu^2}. \qquad 1)$$



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$$A_m^n N_m + B_m^n N_m \varrho = B_n^m N_n \varrho. \qquad 3)$$

Andererseits liefert die Gleichung 2):

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

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

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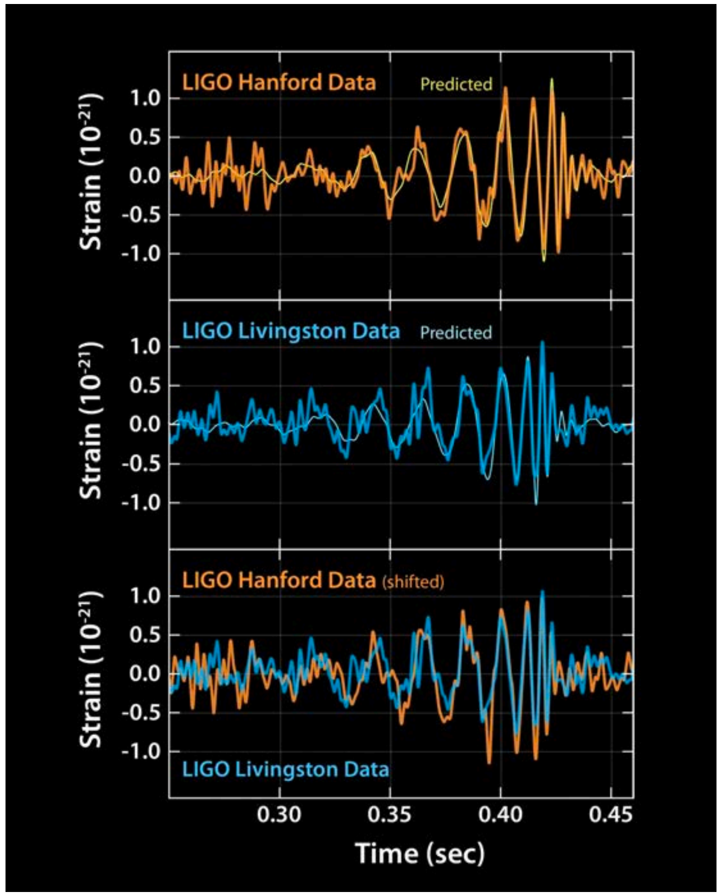
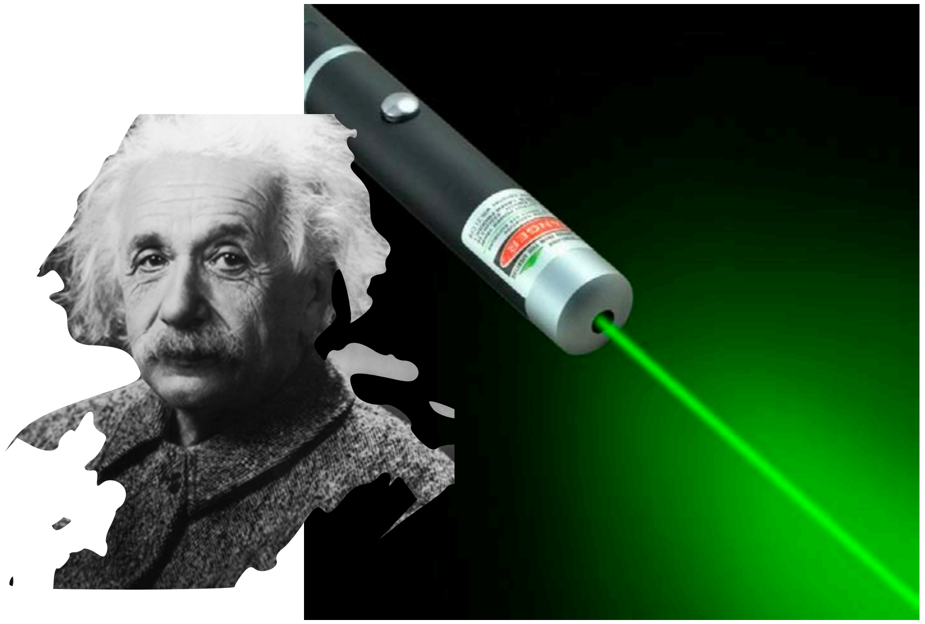
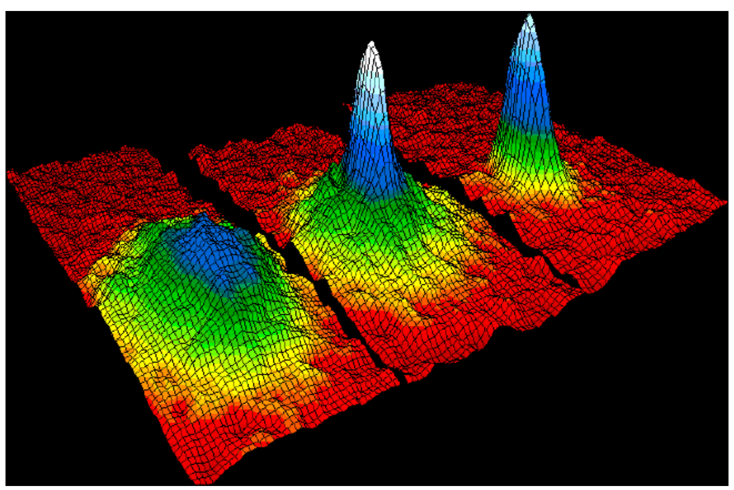
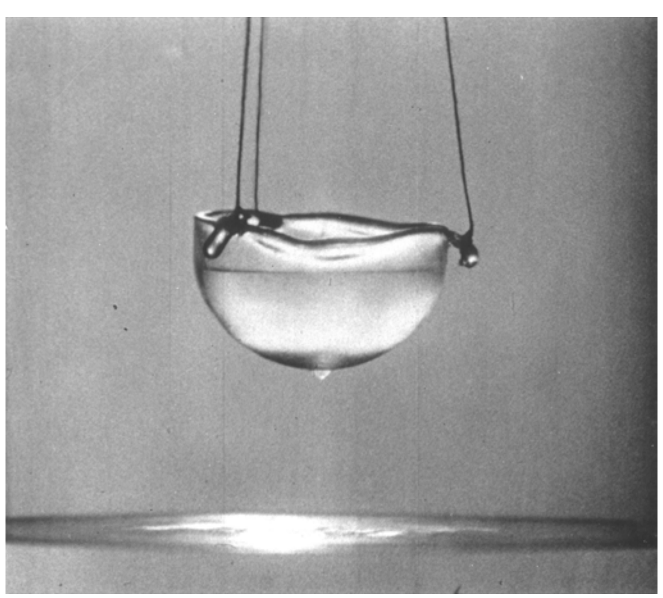
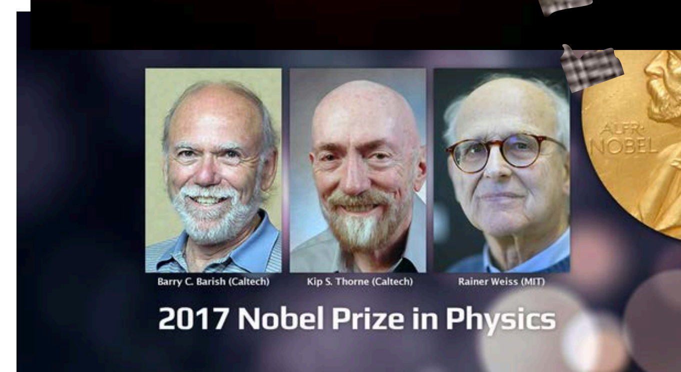
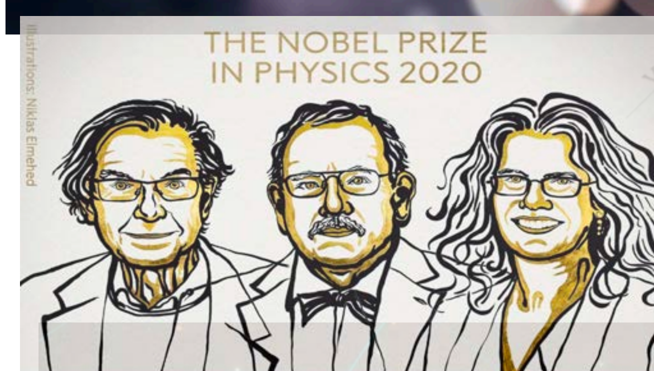


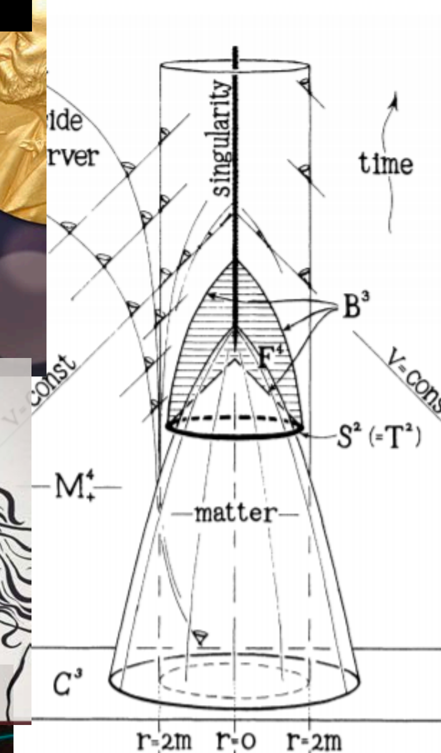


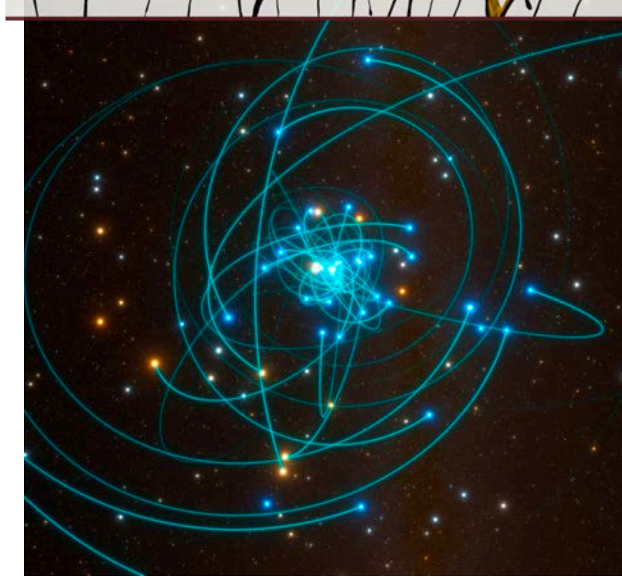





Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
2017 Nobel Prize in Physics


THE NOBEL PRIZE
IN PHYSICS 2020
Illustrations: Niklas Elmehed


singularity
time
matter
V=const
r=2m
r=0
r=2m



Outline

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

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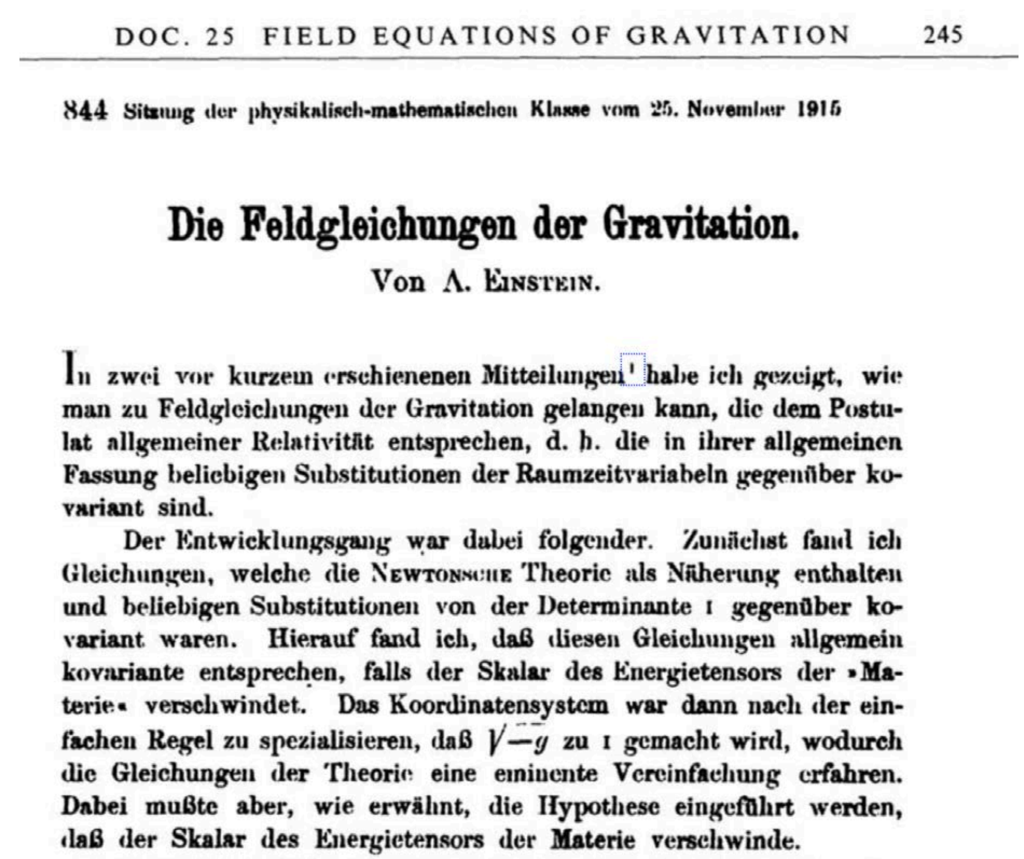
DOC. 25 FIELD EQUATIONS OF GRAVITATION 245

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

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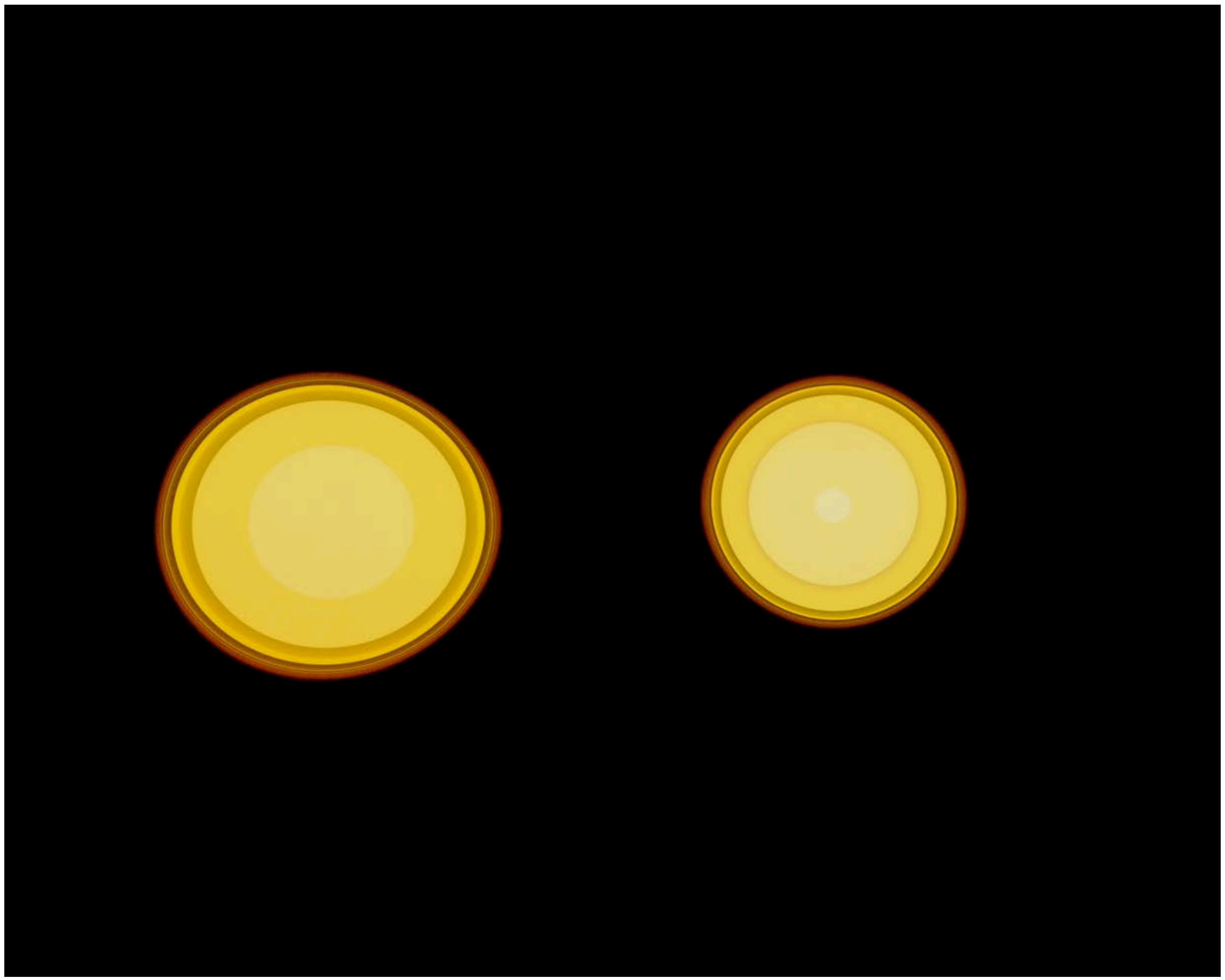
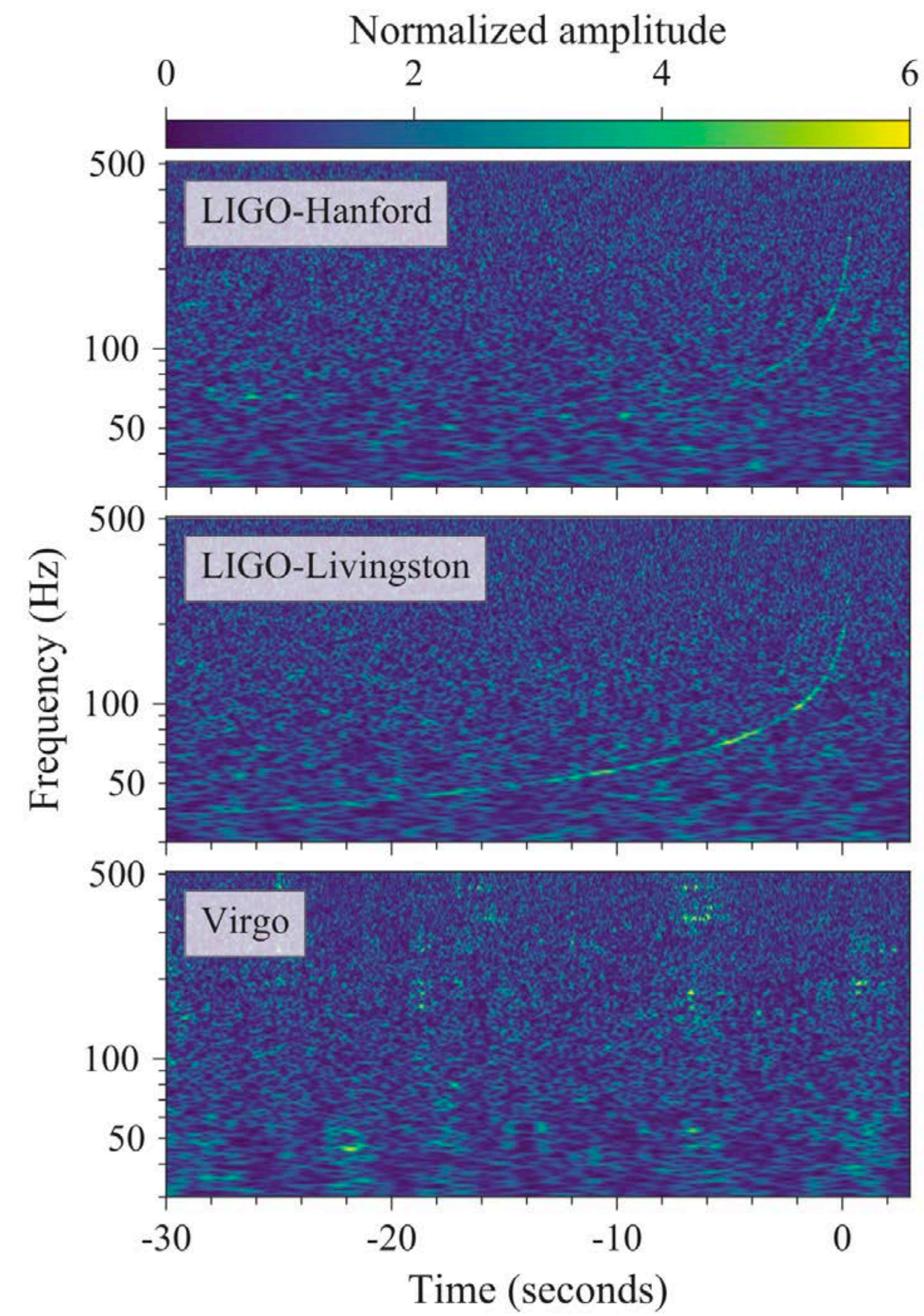
Einstein Gravity predicts formation of Black Holes



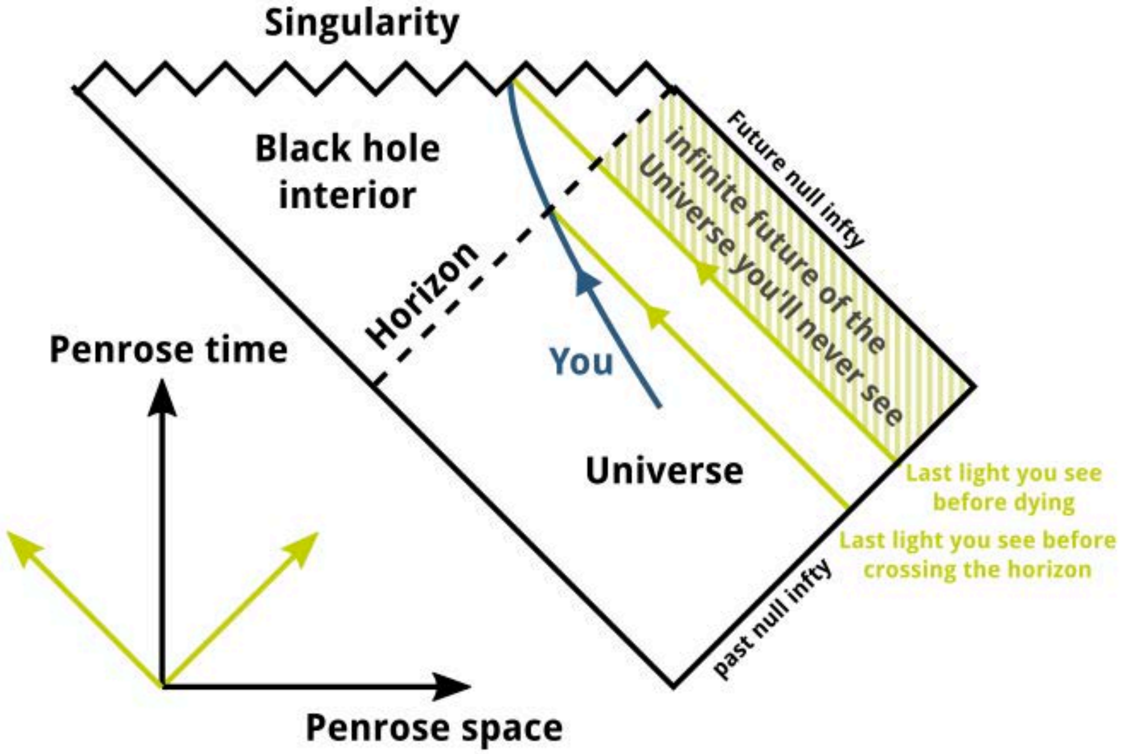


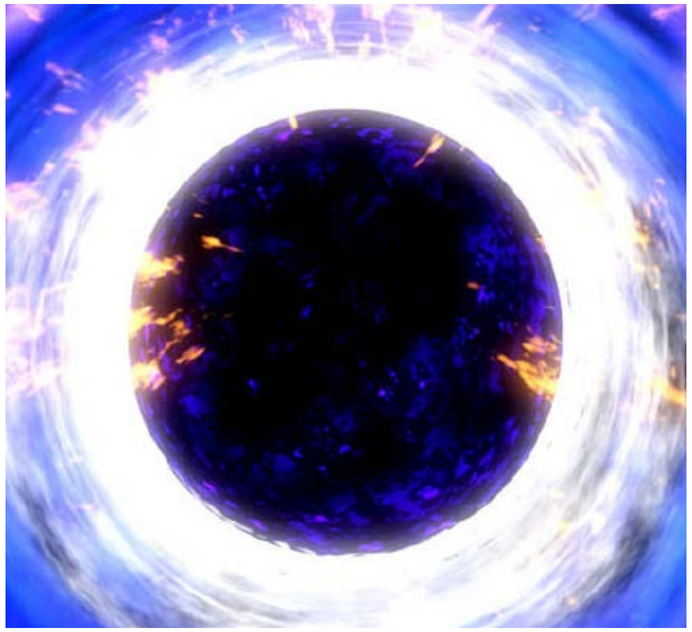
https://svs.gsfc.nasa.gov/11530

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

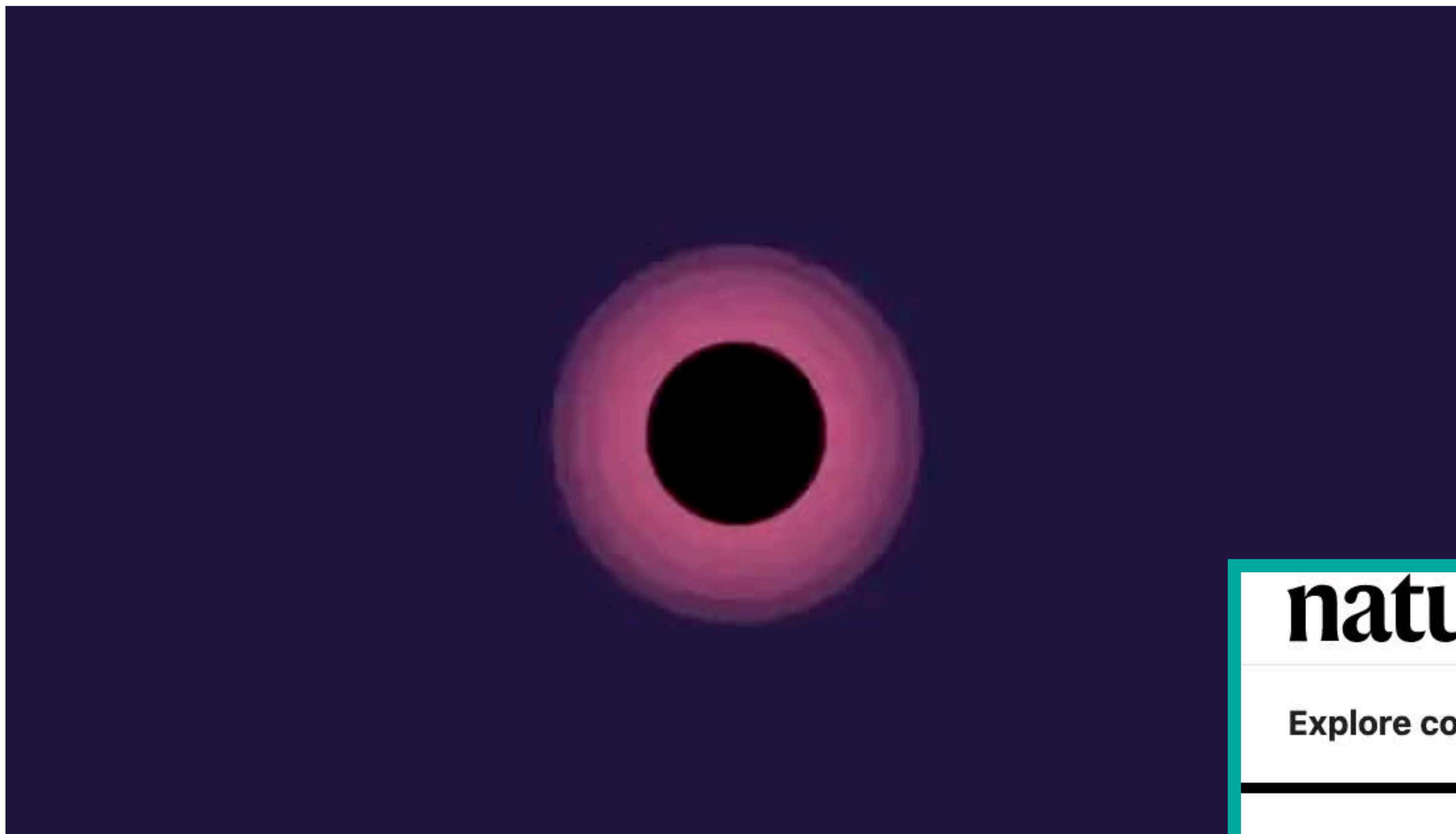
- Black Holes have temperature: $T = \frac{a}{2\pi}$
- Black Holes have entropy: $S = \frac{\text{Horizon Area}}{4G}$
- 1st & 2nd laws of thermodynamics:

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

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

Which states does this entropy count?!

Black Holes Evaporate via Hawking Radiation



nature

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nature > letters > article

Published: 01 March 1974

Black hole explosions?

S. W. HAWKING

Nature **248**, 30–31 (1974) | Cite this article

78k Accesses | **3079** Citations | **718** Altmetric | Metrics

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364 DOC. 34 EMISSION & ABSORPTION OF RADIATION

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

Strahlungs-Emission und -Absorption nach der Quantentheorie;

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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.)

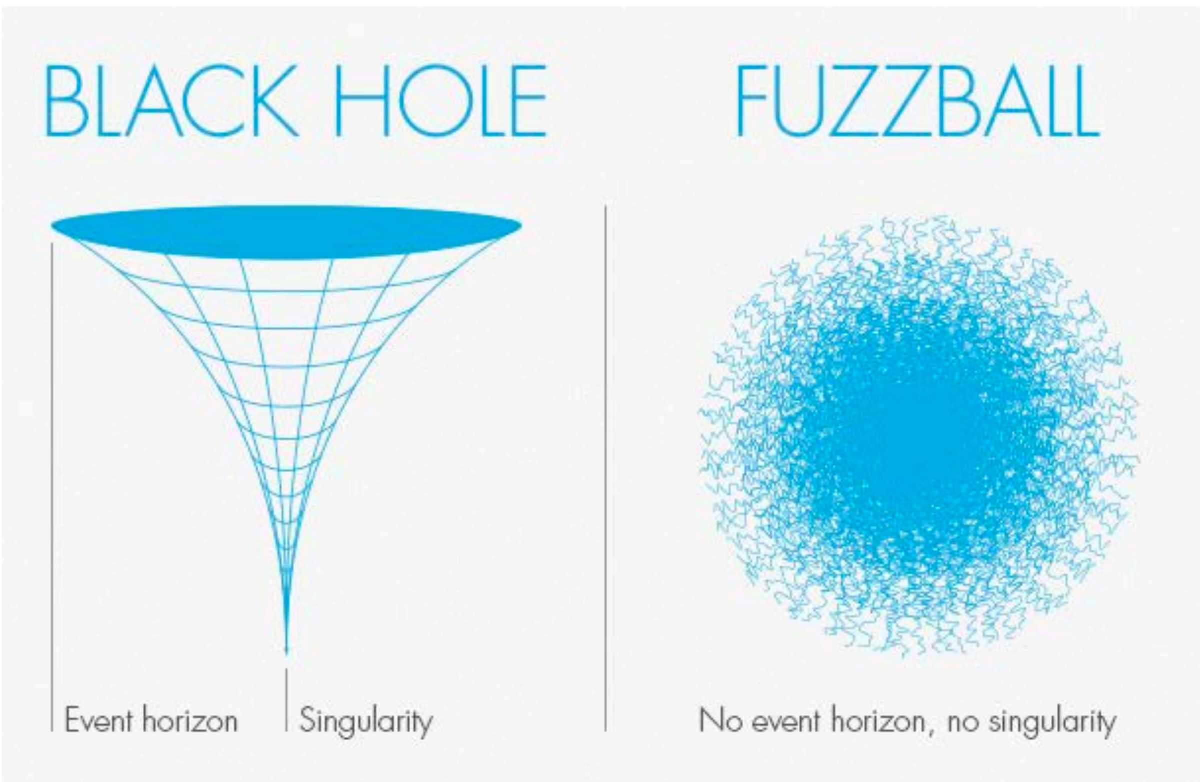
Firewall Paradox

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

Fuzzballs in String Theory



Physics Reports 467 (2008) 117–171

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Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

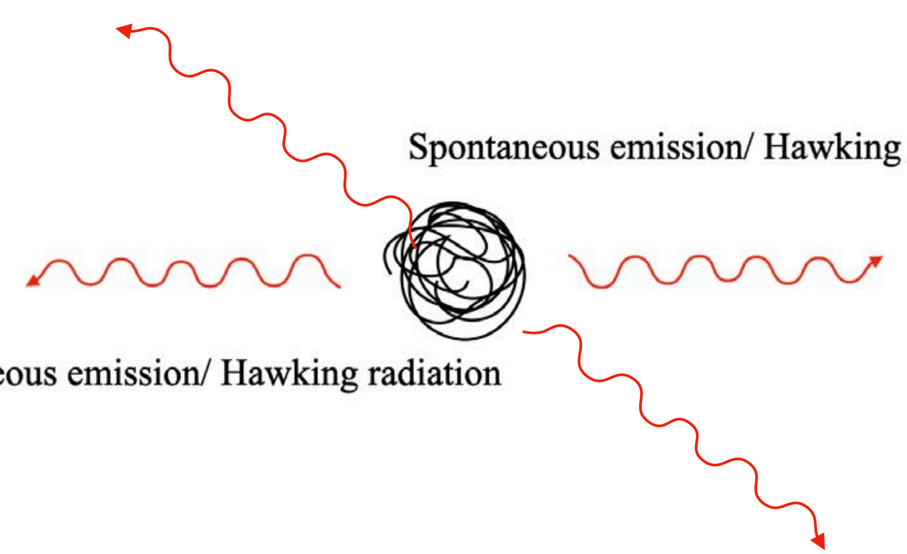
The fuzzball proposal for black holes

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

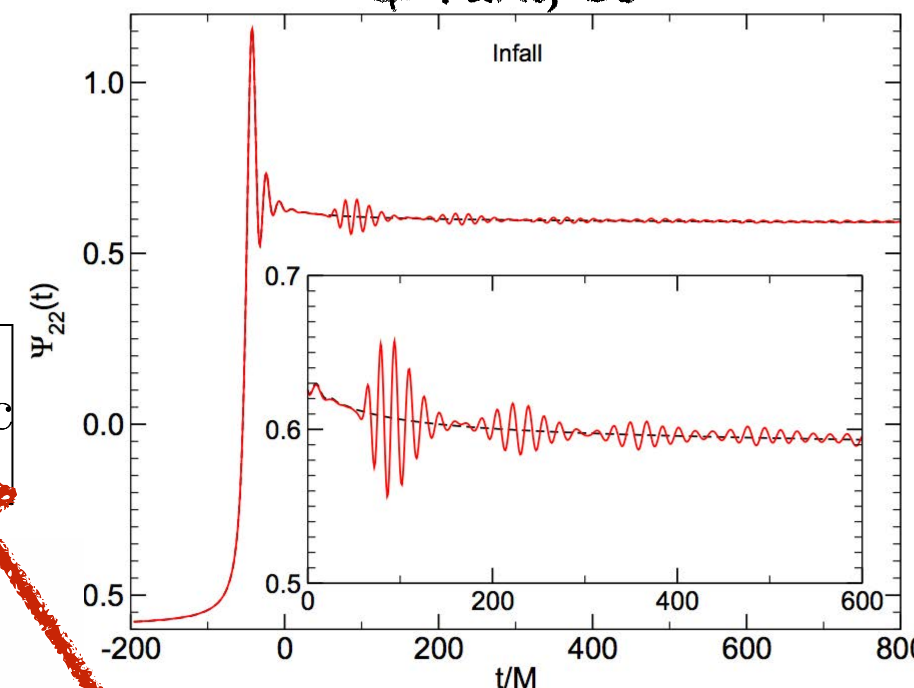
Received 3 March 2008
Published 17 June 2008
Online at stacks.iop.org/CQG/25/135005

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, Hopper, Macedo, Palenzuela, & Pani, 16



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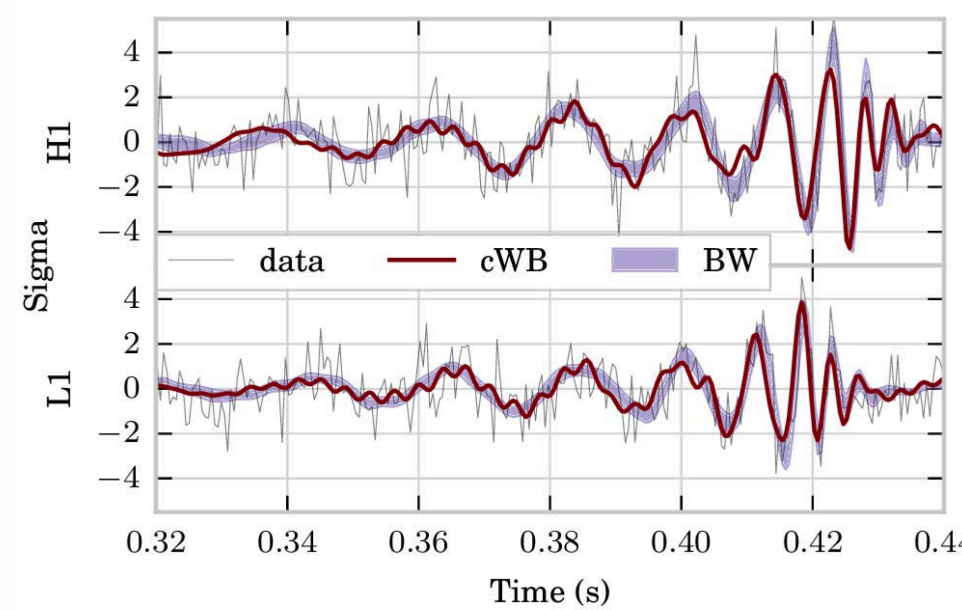
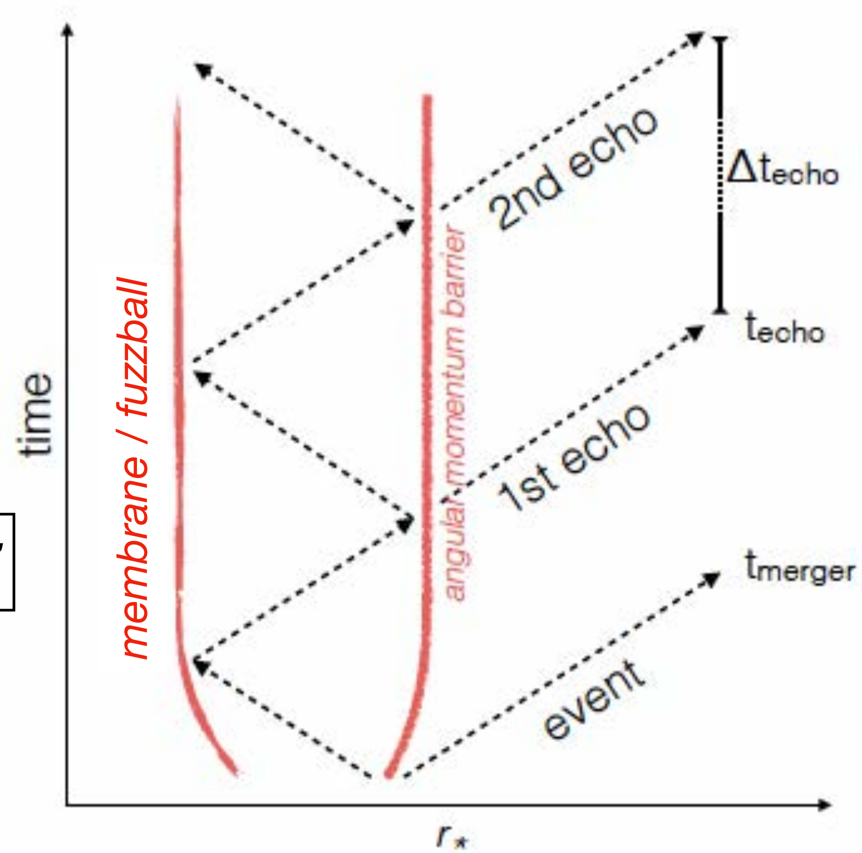


Abedi, Dykaar & NA 2017



Universal Reflectivity of Quantum Horizons

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

  (1) *Fluctuation-Dissipation Theorem*

  (2) Stimulated Hawking Radiation

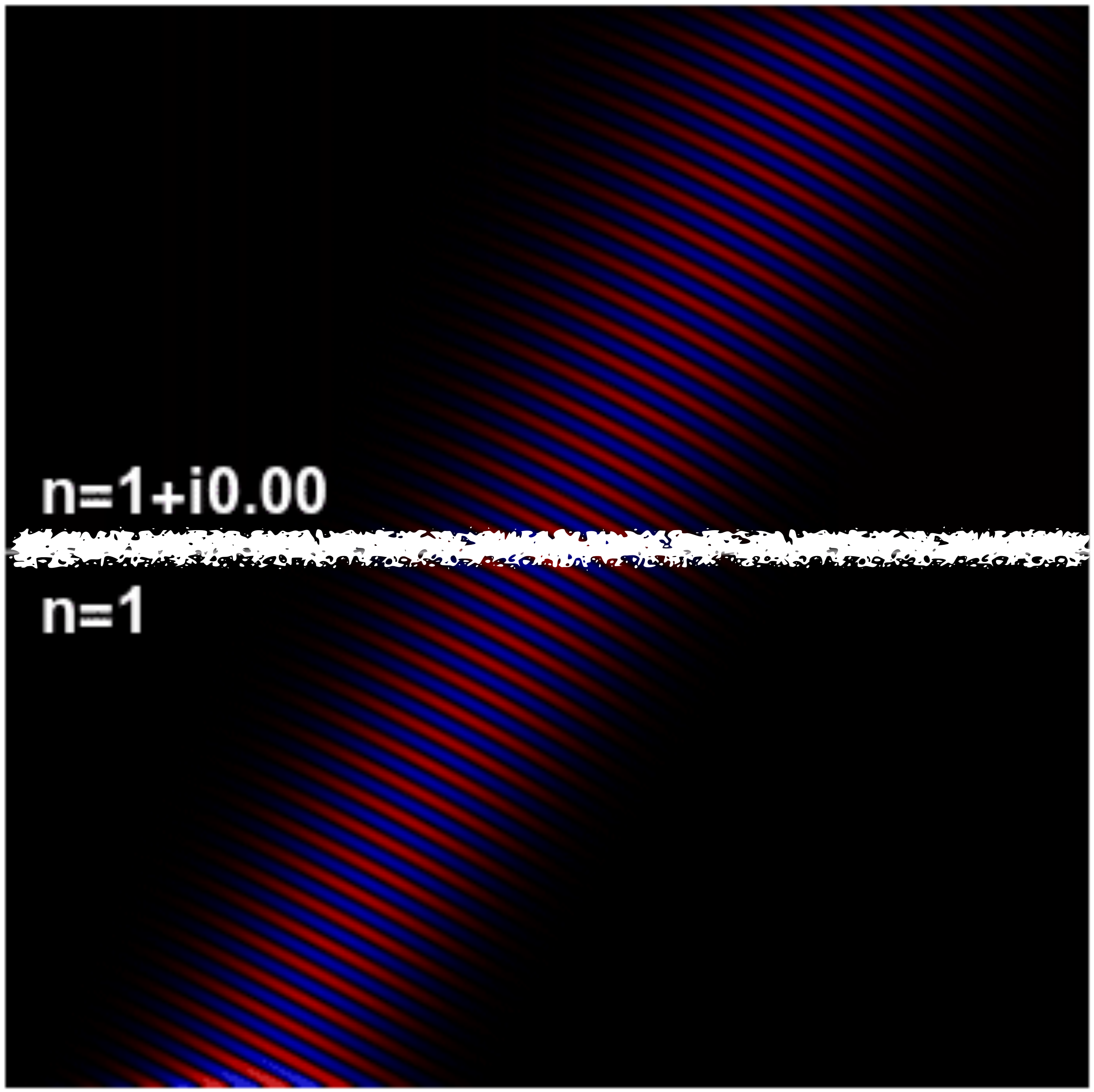
  (3) CP-symmetry

- **Echoes are stimulated Hawking Radiation**

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

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

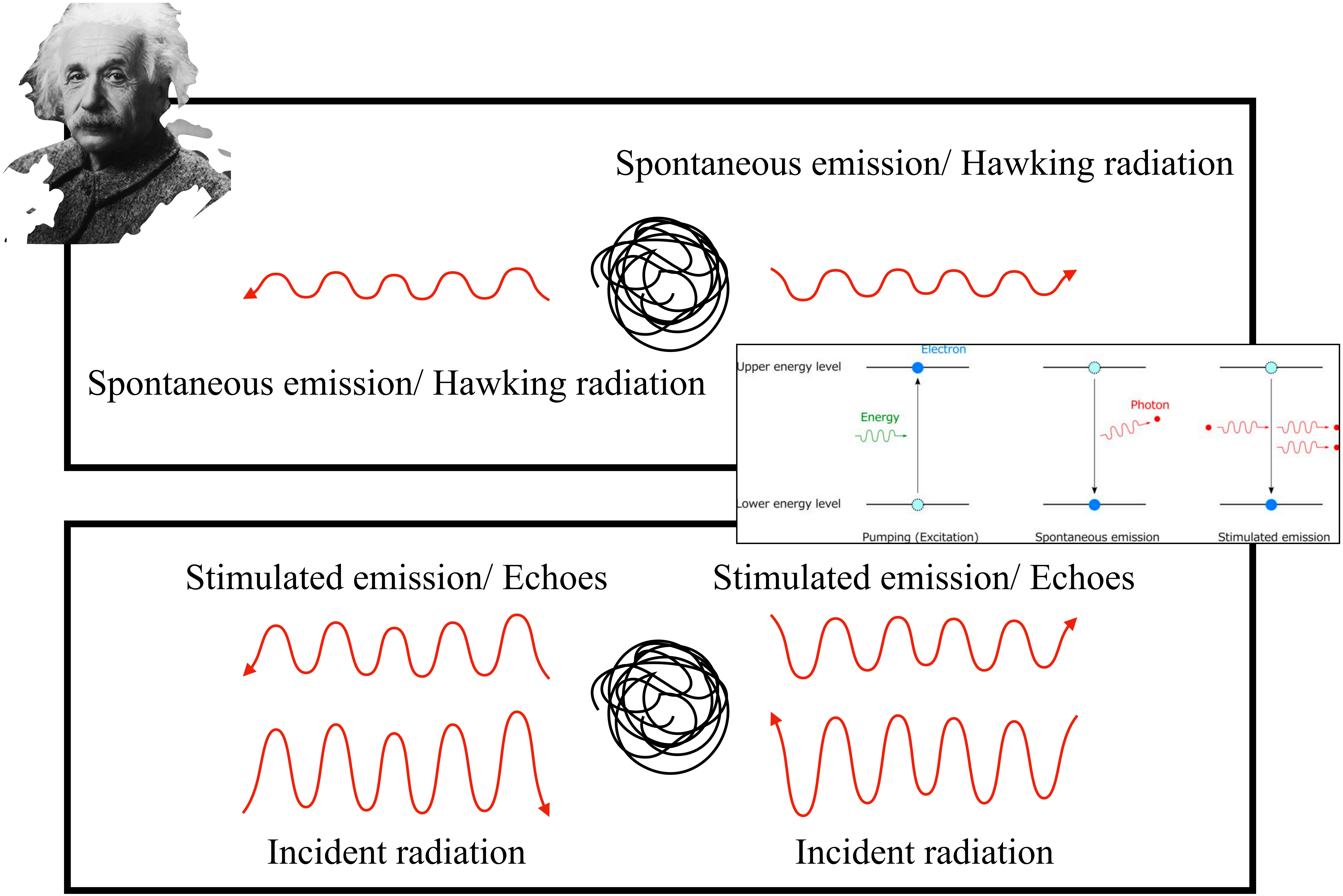
Abrupt Dissipation → ~~WKB~~ → Reflection



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

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

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



Spontaneous emission/ Hawking radiation
Spontaneous emission/ Hawking radiation
Electron
Upper energy level
Energy
Photon
Lower energy level
Pumping (Excitation)
Spontaneous emission
Stimulated emission
Stimulated emission/ Echoes
Stimulated emission/ Echoes
Incident radiation
Incident radiation

CP-symmetry (RP^3 geon)

Z_2 identification → Boltzmann reflection

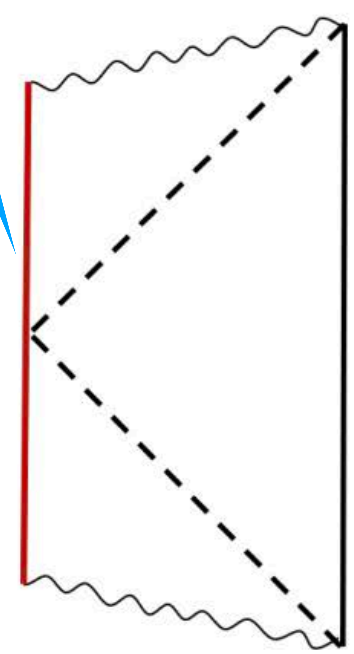


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(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*

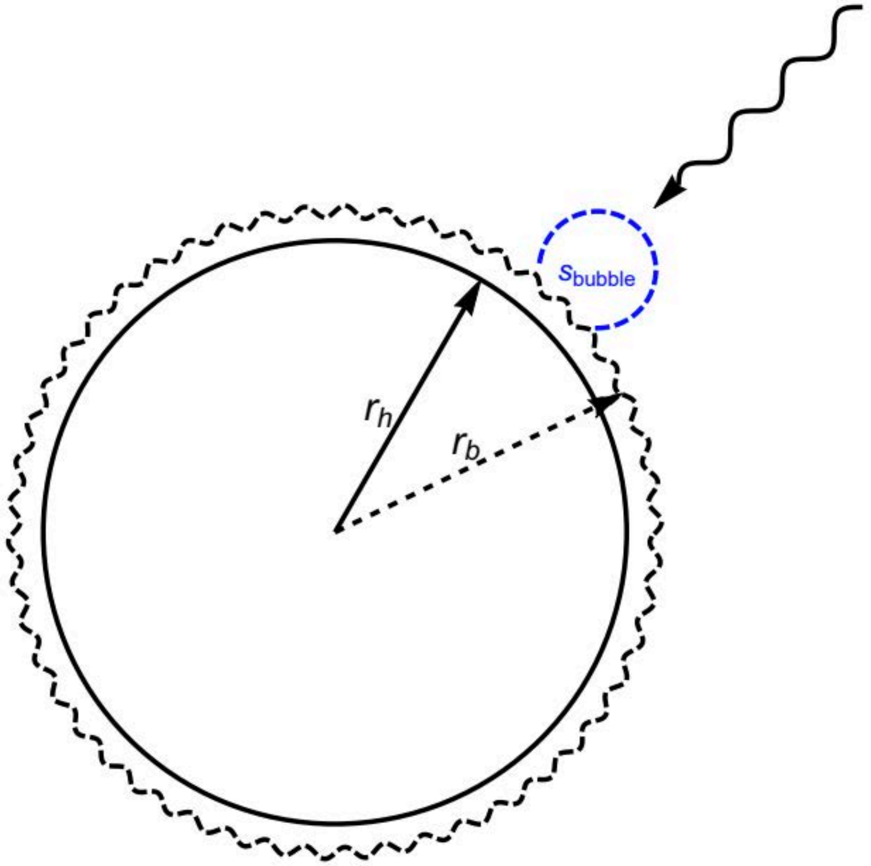
December 16, 2020

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.

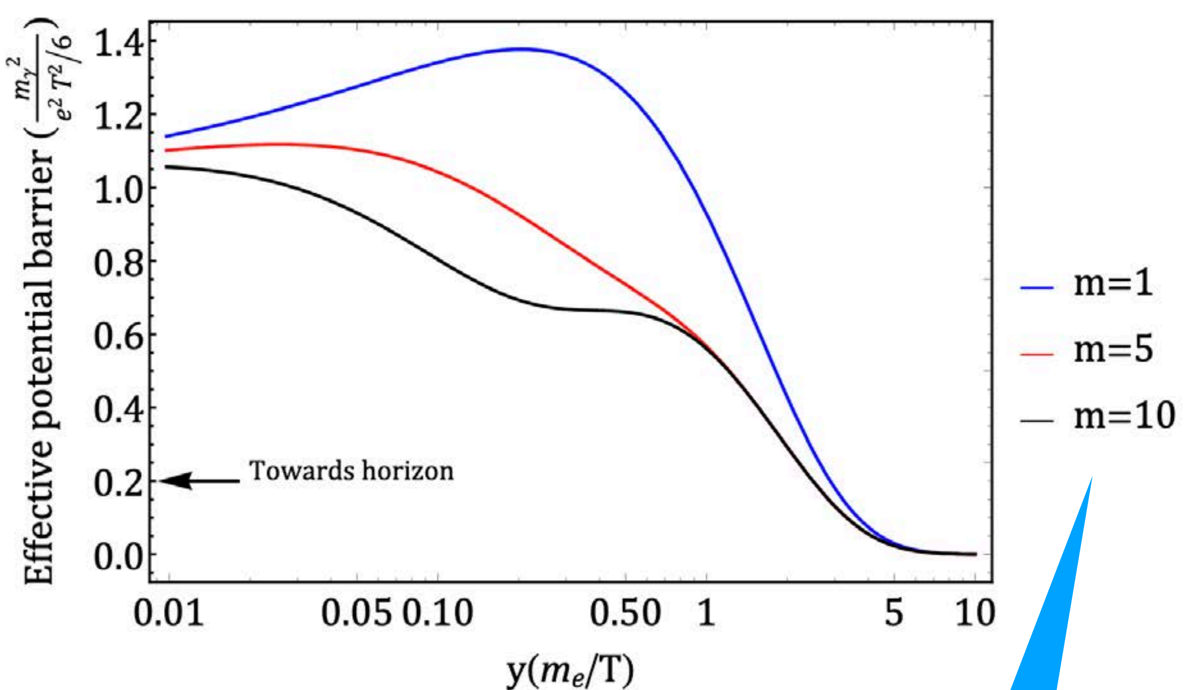
Electromagnetic Albedo of Quantum Black Holes *(Chua & NA 2021)*

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



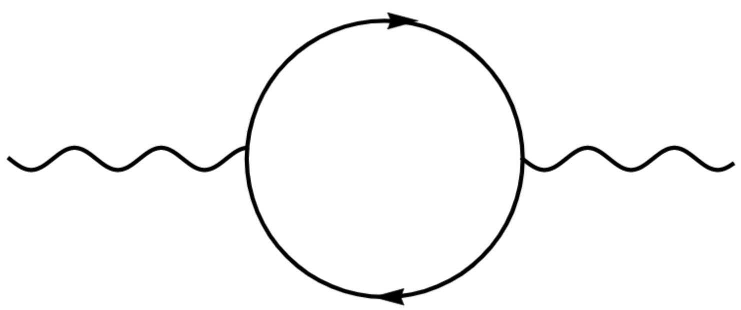
Two independent derivations

- Photon mass acquired through Hawking Plasma



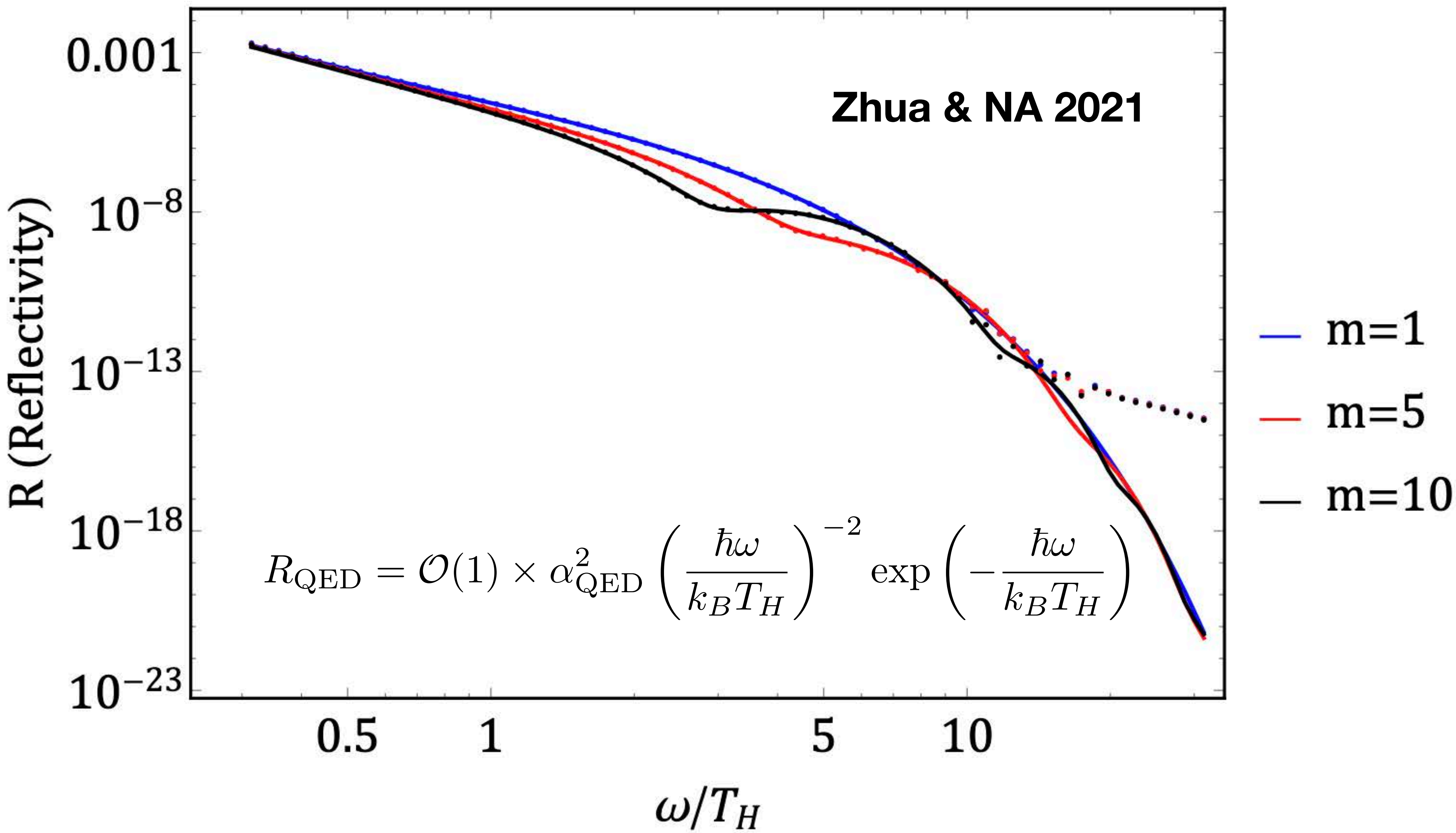
different interpolations

- 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

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

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.

Towards a Holographic Understanding of Echoes

August 29, 2018

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

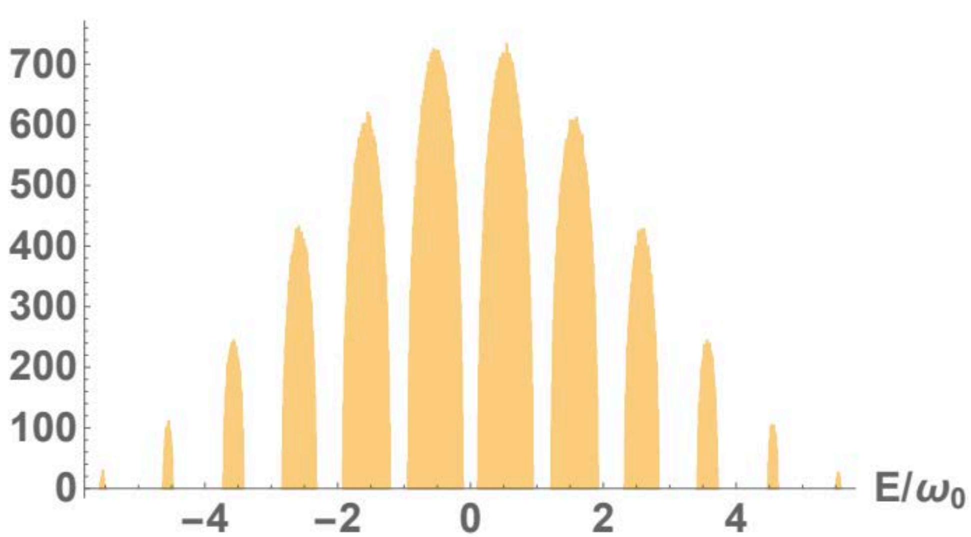
Black Holes and Random Matrices

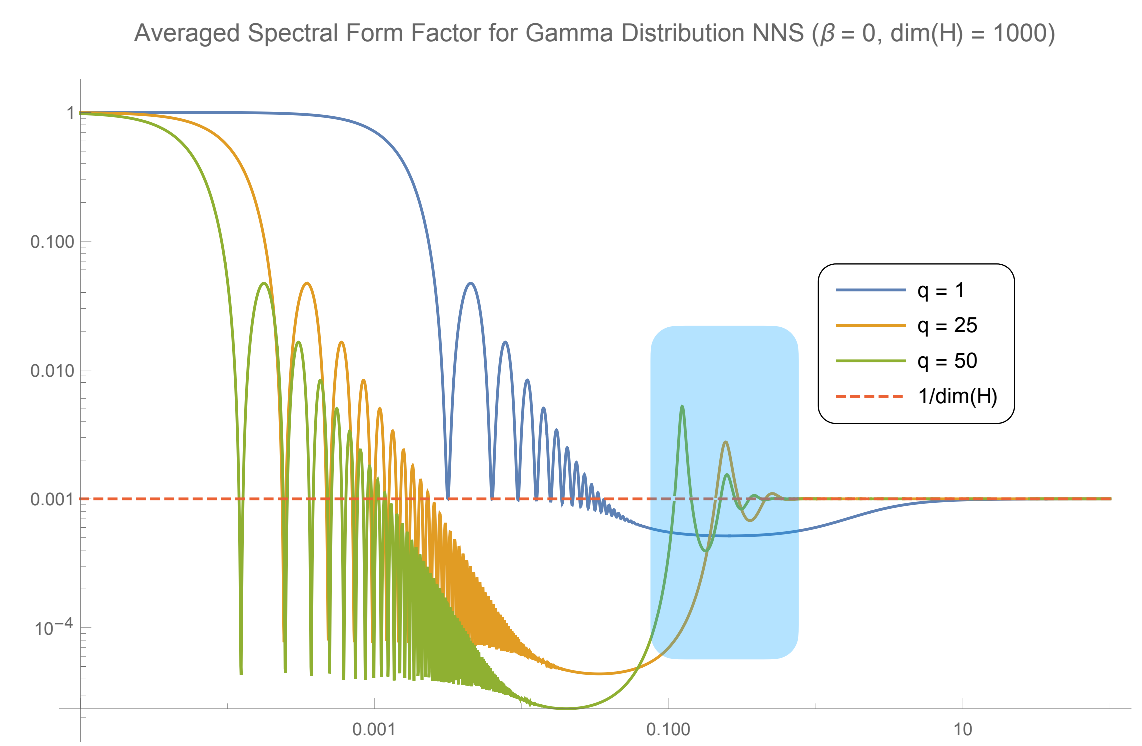
Jordan S. Cotler[a], Guy Gur-Ari[a], Masanori Hanada[abc], Joseph Polchinski[de], Phil Saad[a], Stephen H. Shenker[a], Douglas Stanford[f], Alexandre Streicher[ad], and Masaki Tezuka[g]

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

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

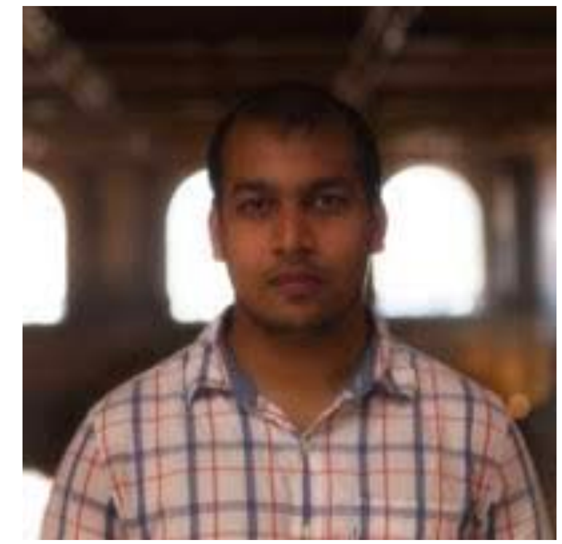
- From Spectral form-factor of *generalized* random matrices, or approximate *symmetries/degeneracies* *(Saraswat & NA 2021)*





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[†]

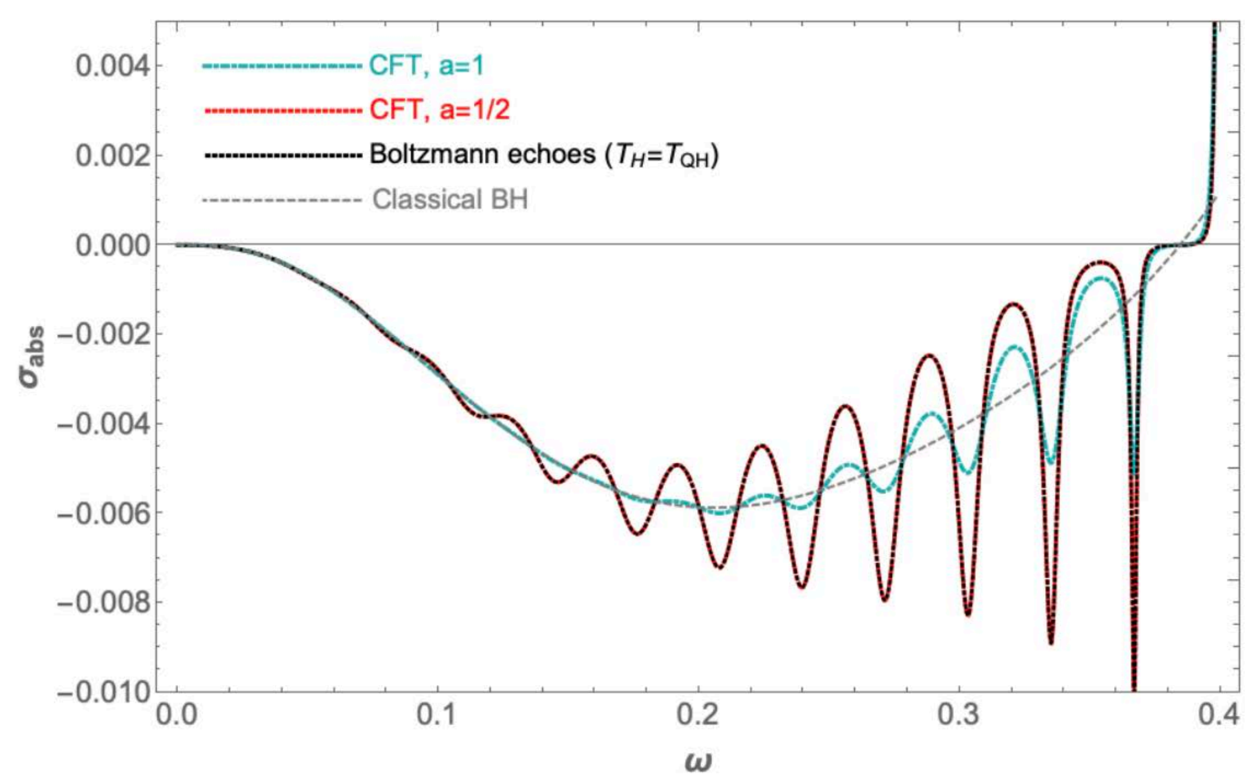
[◇]*Physics Department, McGill University, Montreal, CA*

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

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

$$c_L = c_R = 12J$$

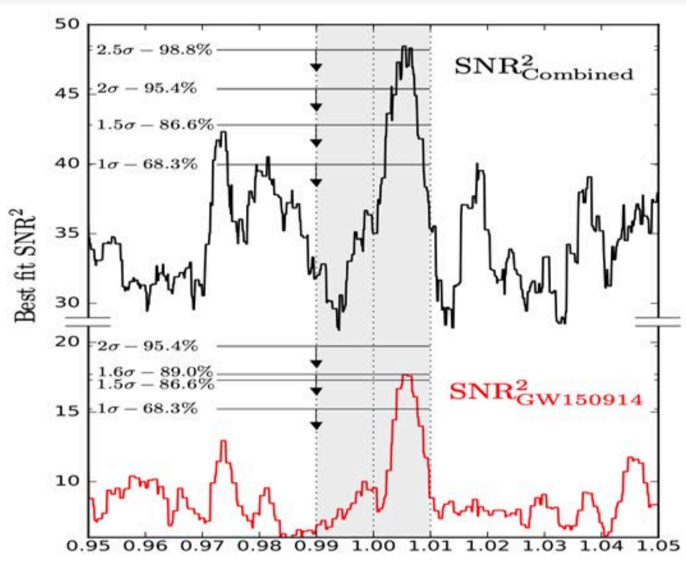
$$S_{micro} = \frac{\pi^2}{3}(c_L T_L + c_R T_R) = 2\pi(M^2 + \sqrt{M^4 - J^2}) = \frac{\text{Area}}{4}$$

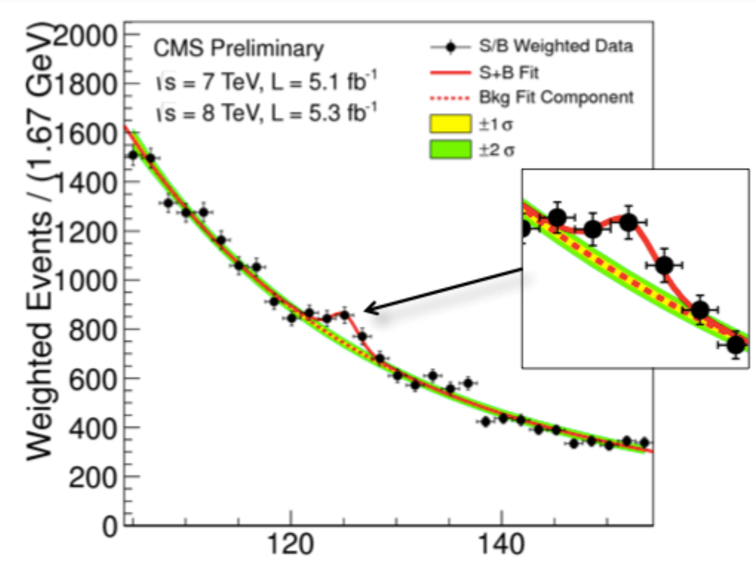


Dey & NA 2020

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

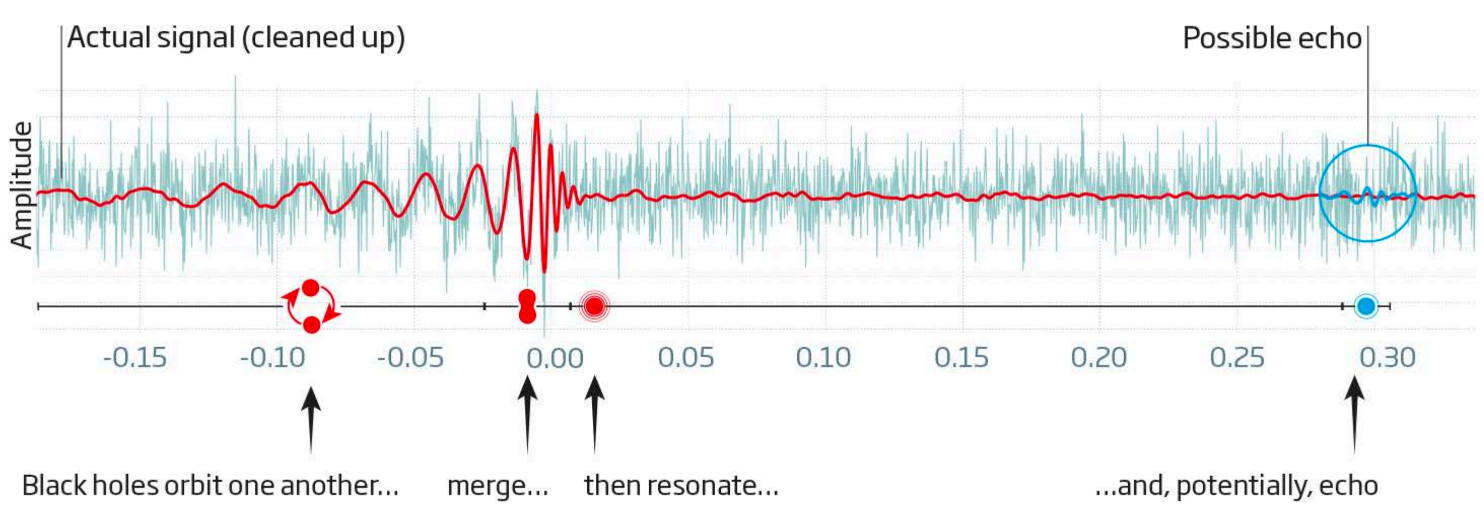
- Unitarity
- (Perturbative) Effective Field Theory
- Gauge Symmetries of Standard Model





Outline

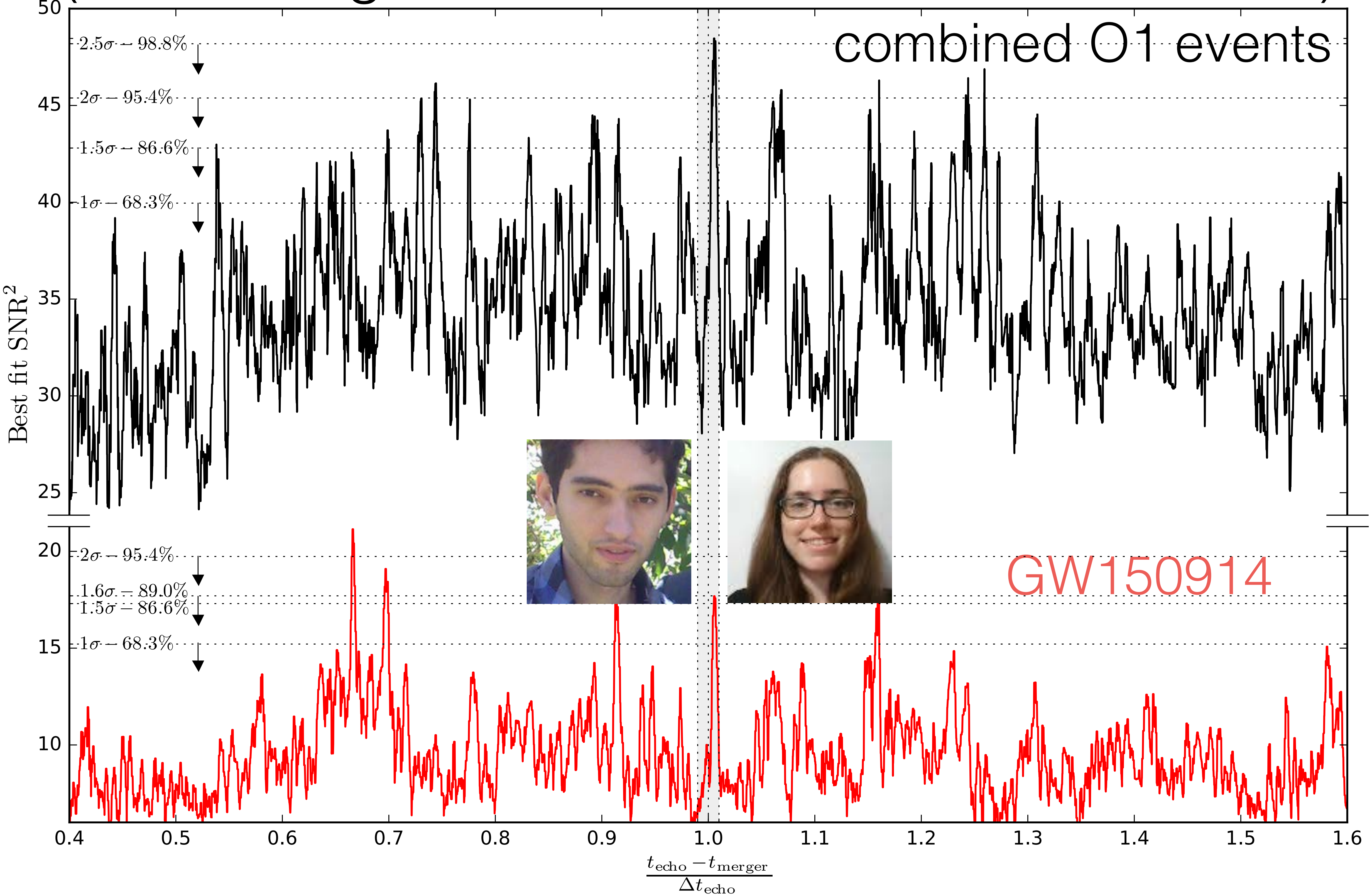
- Black Holes: *der Gravitation*
- Black Holes: *der Quantentheorie*
- Black Holes: *Fantasie bis Physik*
- Einstein vs Einstein



Abedi, Dykaar & NA 2017

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

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

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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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[9] *University of Florida, Gainesville, FL 32611, USA*
(Dated: June 4, 2019)

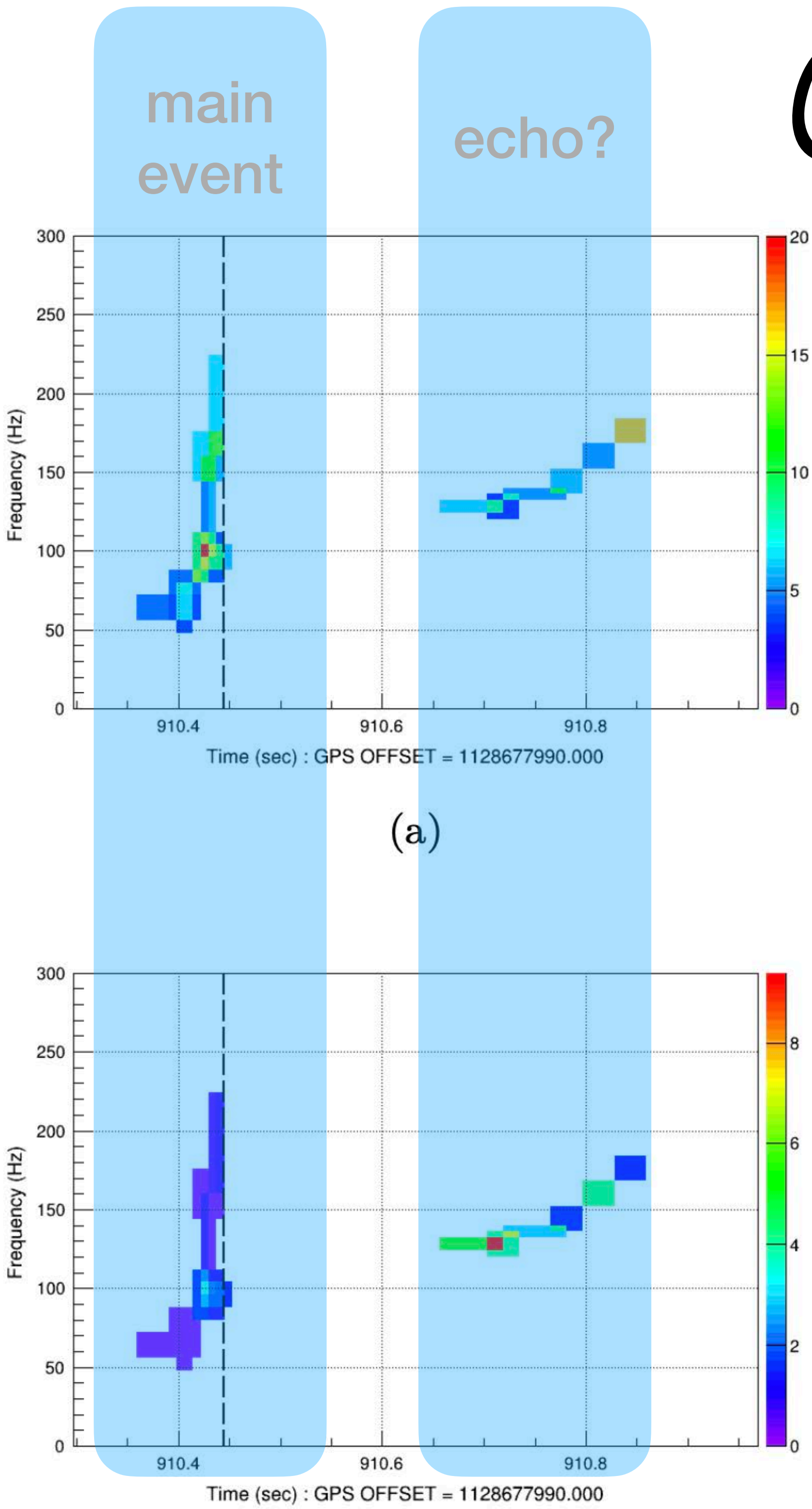
In this paper, we investigate the morphology of the events from the GWTC-1 catalog of compact binary coalescences as reconstructed by a method based on coherent excess power: we use an open-source version of the coherent WaveBurst (cWB) analysis pipeline, which does not make use of waveform models. The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

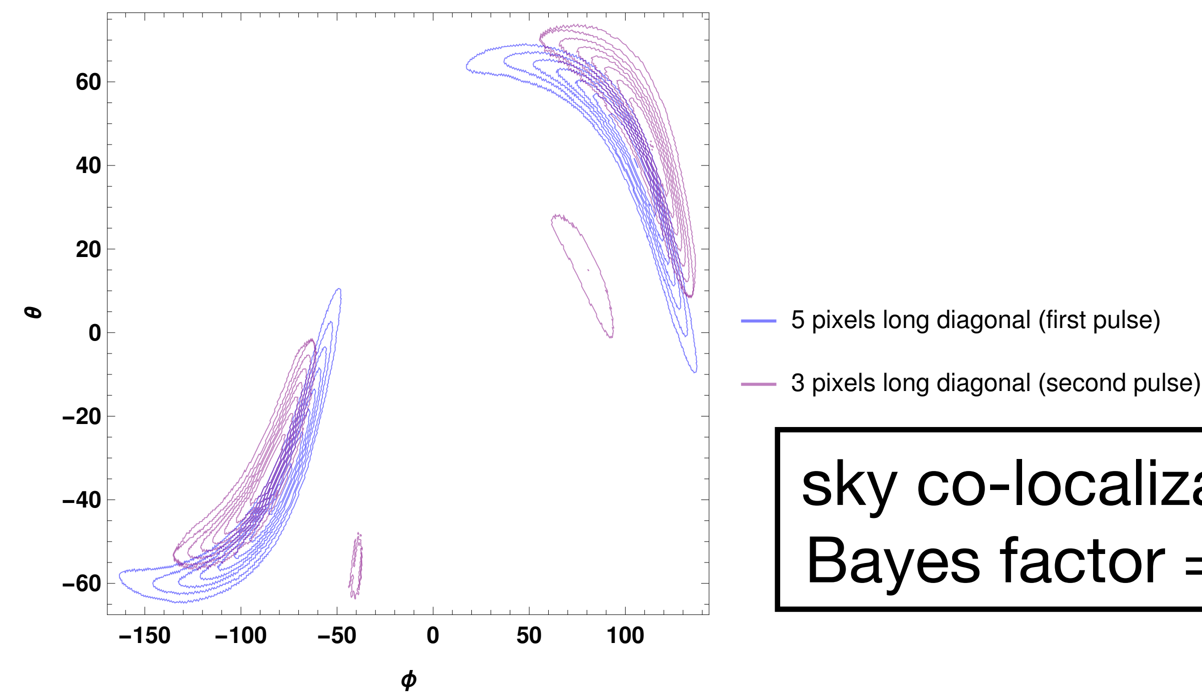
$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

arXiv:1612.00266

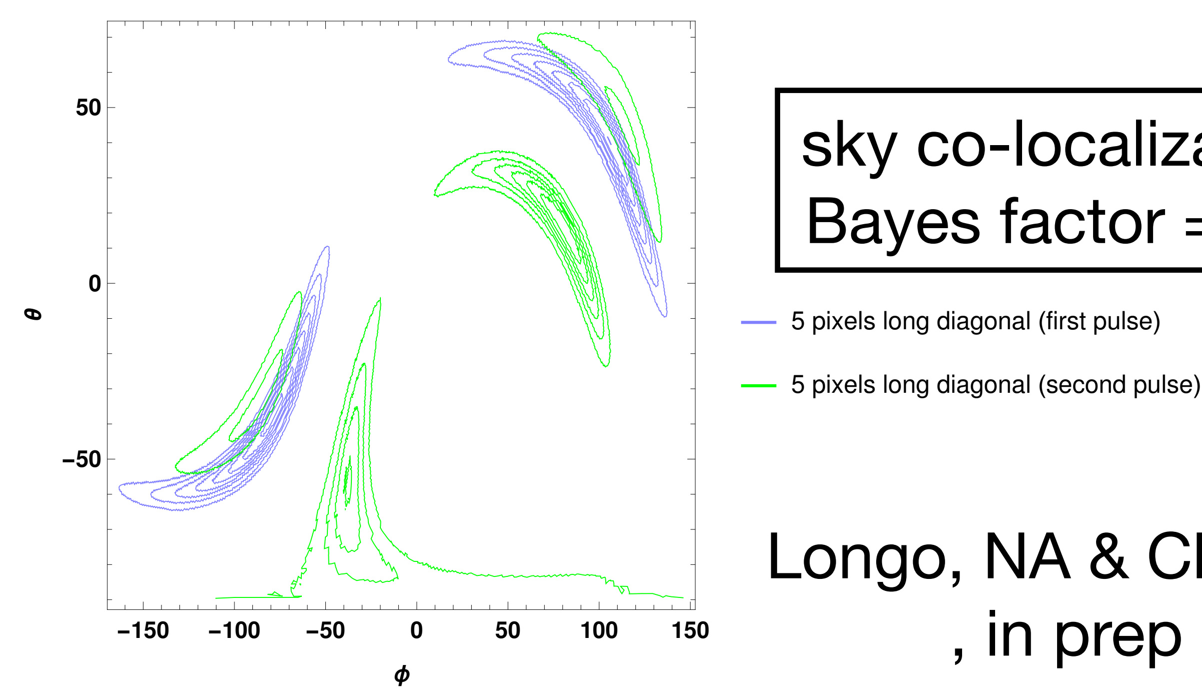
coherent Wave Burst (cWB)
GW151012



Salemi, et al. 2019



sky co-localization
Bayes factor = 5.4



sky co-localization
Bayes factor = 1.6

Longo, NA & Chirenti, in prep

Not quite black holes at LIGO

Bob Holdom*

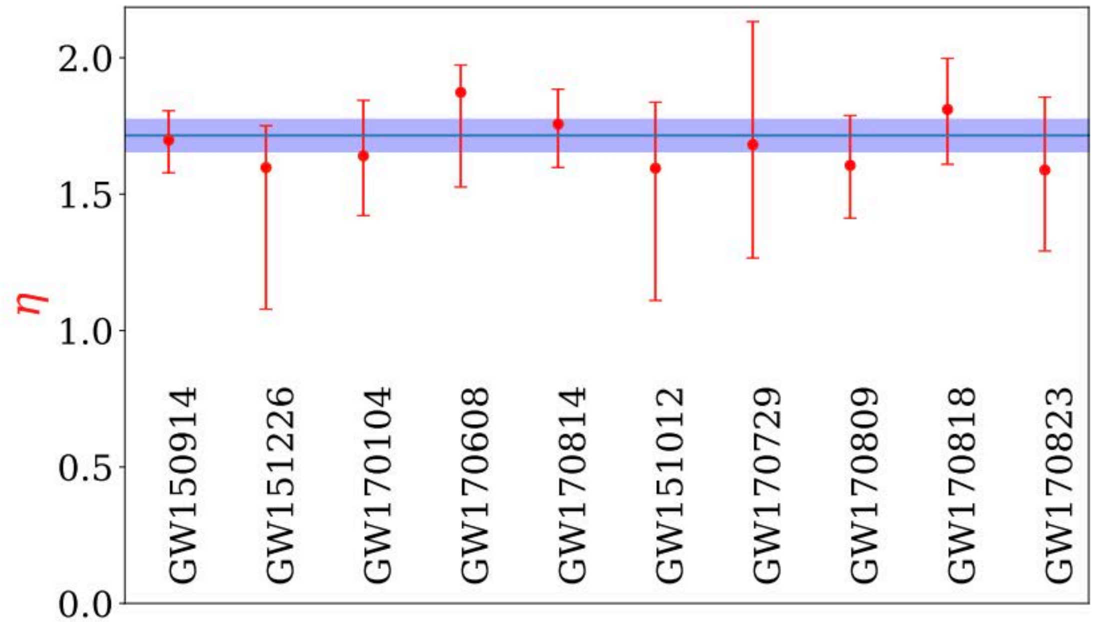
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Phys. Rev. D 101, 064063 (2020)

- Echo Time delay

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

- consistent across events



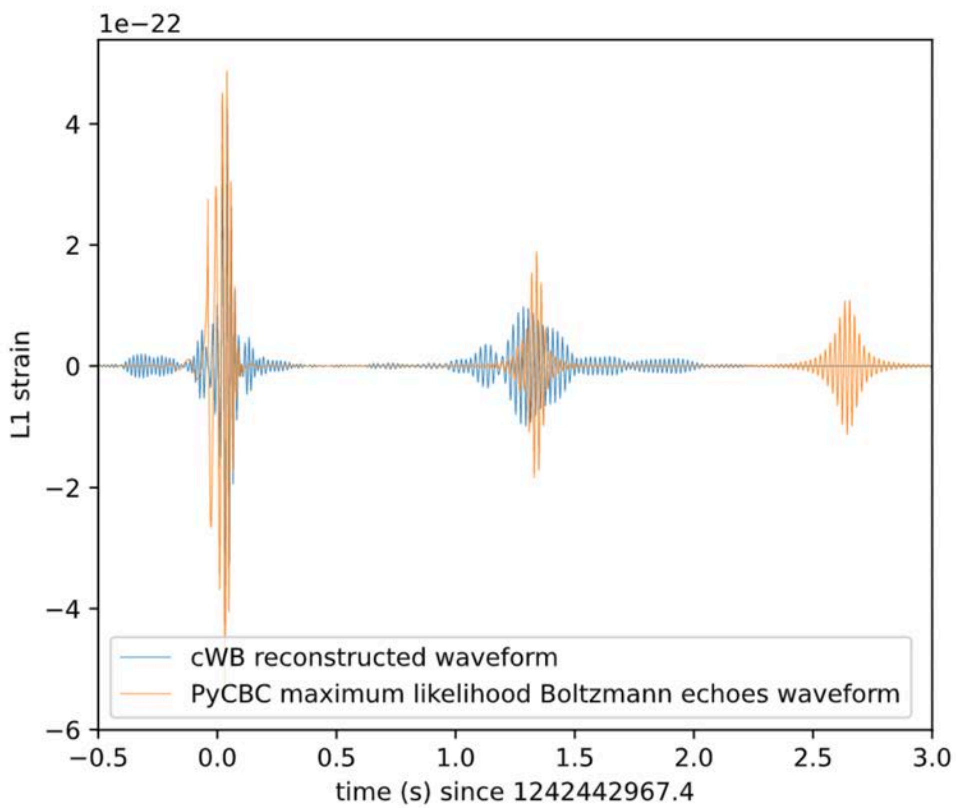
- p-values

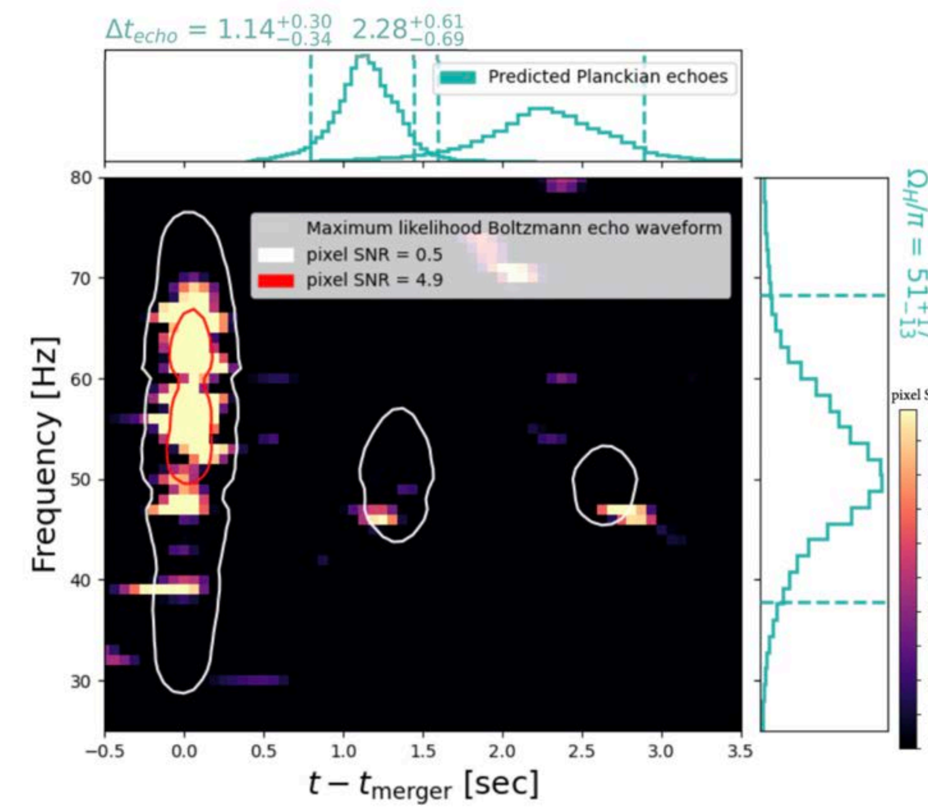
GW150914	0.008	GW151226	0.014
GW170104	0.33	GW170814	0.098
GW170608	0.038	GW170809	0.081
GW151012	0.0016	GW170823	0.026
GW170818	0.0094	GW170729	0.0010 & 0.0006

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,‡]

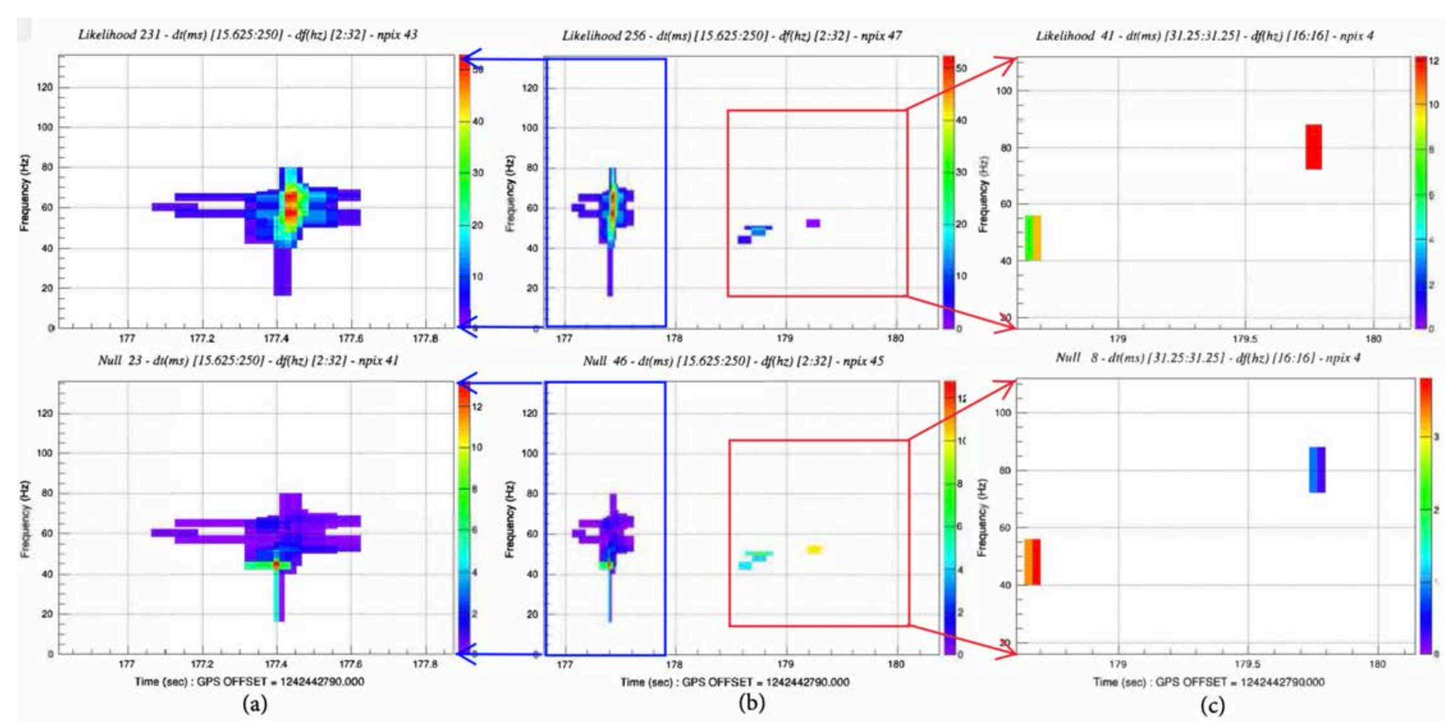
arXiv:2112.XXXXX





Bayes factor $\sim 7 \pm 2$

p − value $\sim 0.6\,\%\,(2.5\sigma)$



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		

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,†]

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2 Leibniz Universität Hannover, D-30167 Hannover, Germany
3 Department of Physics and Astronomy, University of Waterloo, Waterloo, ON N2L 3G1, Canada
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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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Received: 16 January 2020 / Revised: 3 March 2020 / Accepted: 4 March 2020 / Published: 10 March 2020

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

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PIRSA:C20018 - Echoes in Southern Ontario

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!

Abedi, NA, Oshita & Wang 2020 (Review)

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

Conclusions

- We are still fighting Einstein's demons in his "Great War"
- One battleground is the quantum nature of black holes
- Stimulated Hawking radiation → Logarithmically delayed echoes, probing quantum black hole microstructure
- Tantalizing though controversial hints for echoes in LIGO: *which events? which templates?*
- Possible first measurement of stimulated Hawking radiation

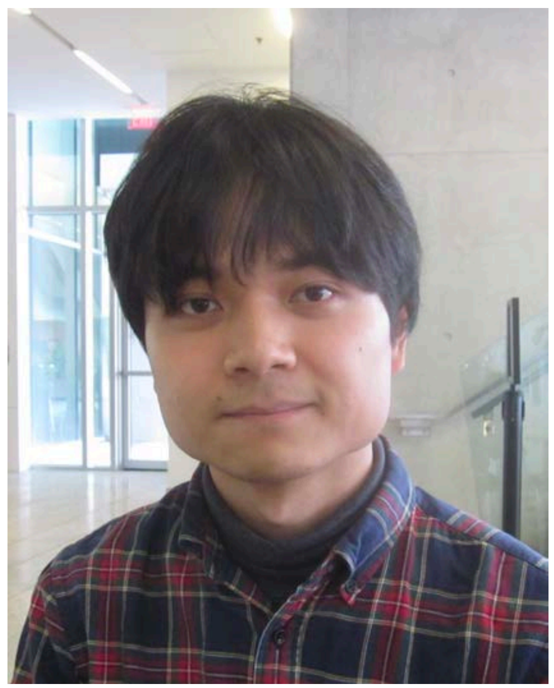
Thank You

“The greatest war is the war within you”

Vasael Al Shia

Bonus Slides!

Into the future: Quantum Black Hole Seismology



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

Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

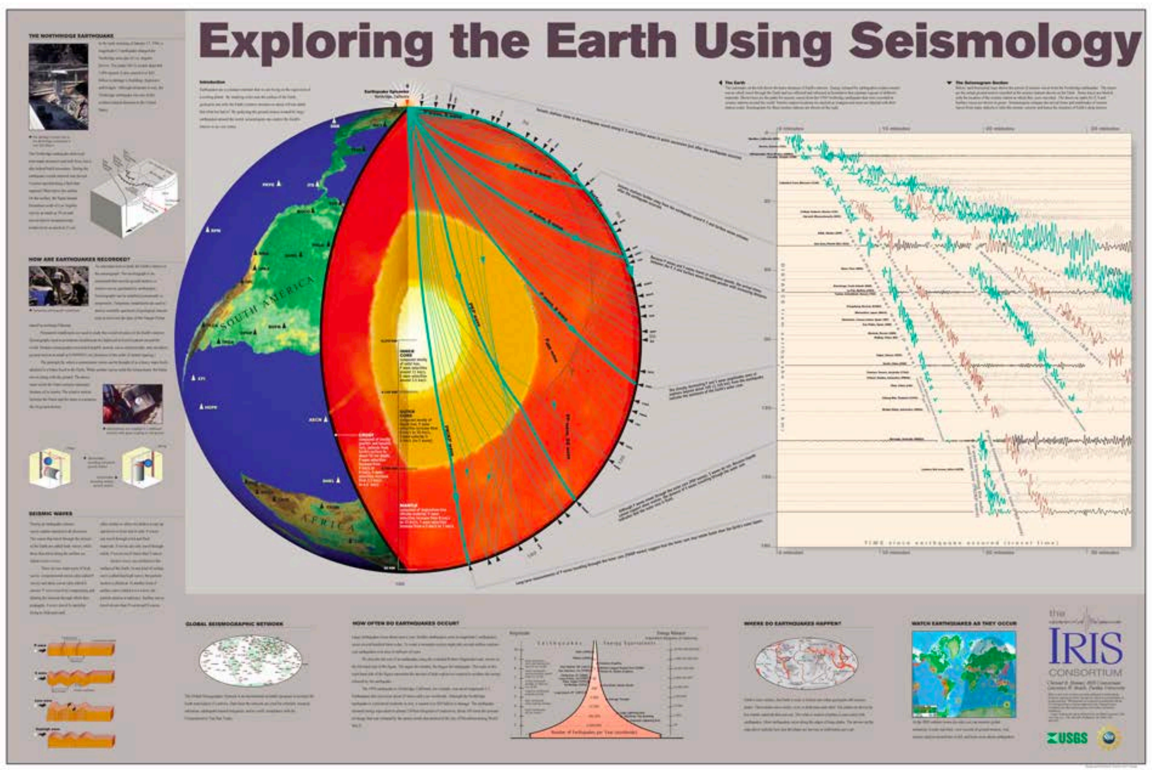
arXiv:2001.11642, PRD

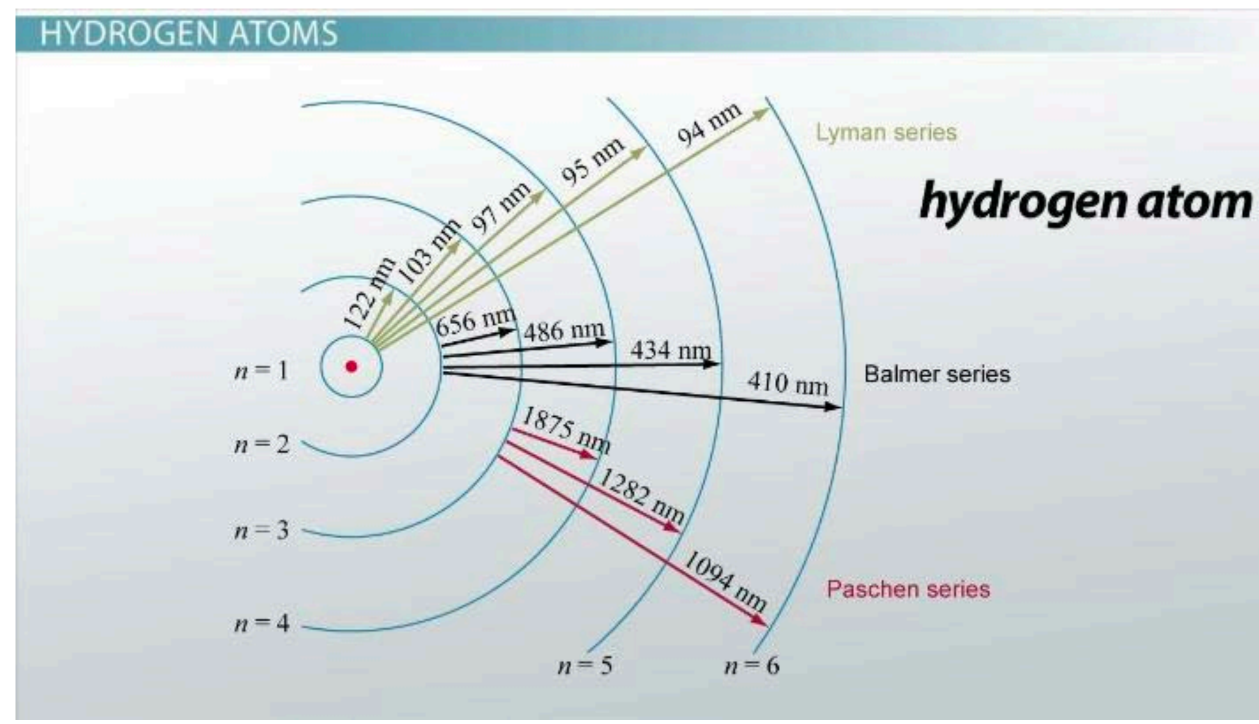
Quantum Black Hole Seismology II: Applications to Astrophysical Black Holes

Naritaka Oshita, Daichi Tsuna, Niayesh Afshordi

arXiv:2004.06276, PRD

Seismology vs Spectroscopy



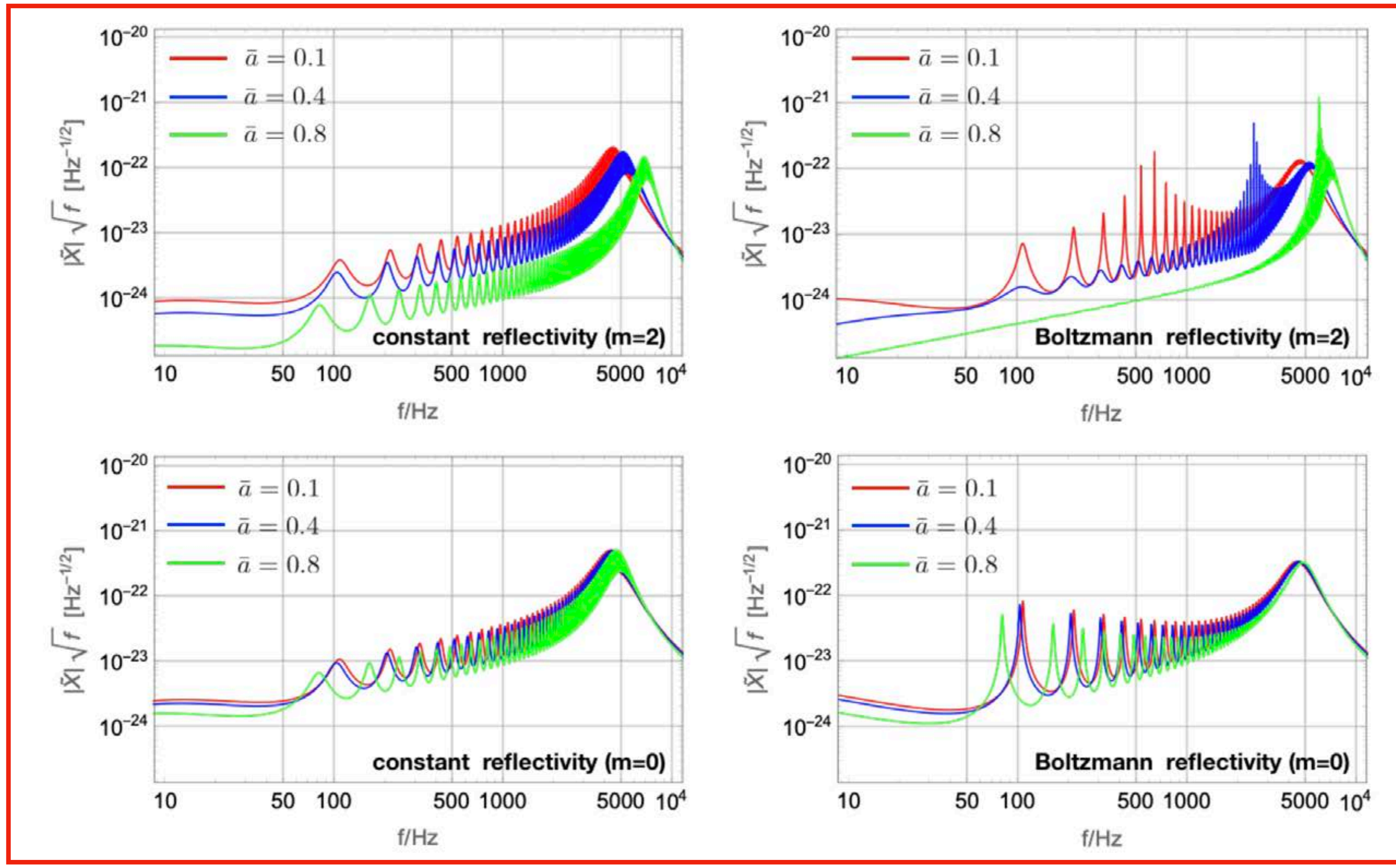


What's inside the Black Hole (replaces event horizon ~2M)

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

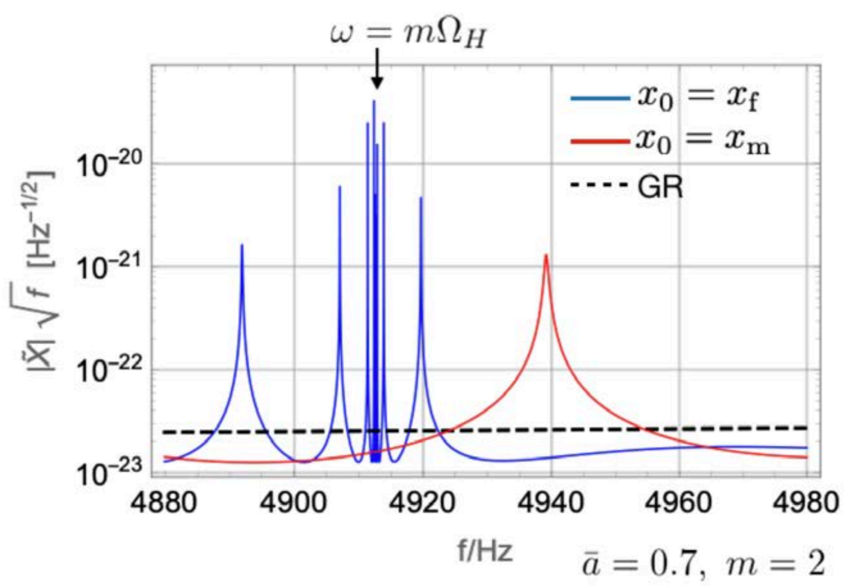


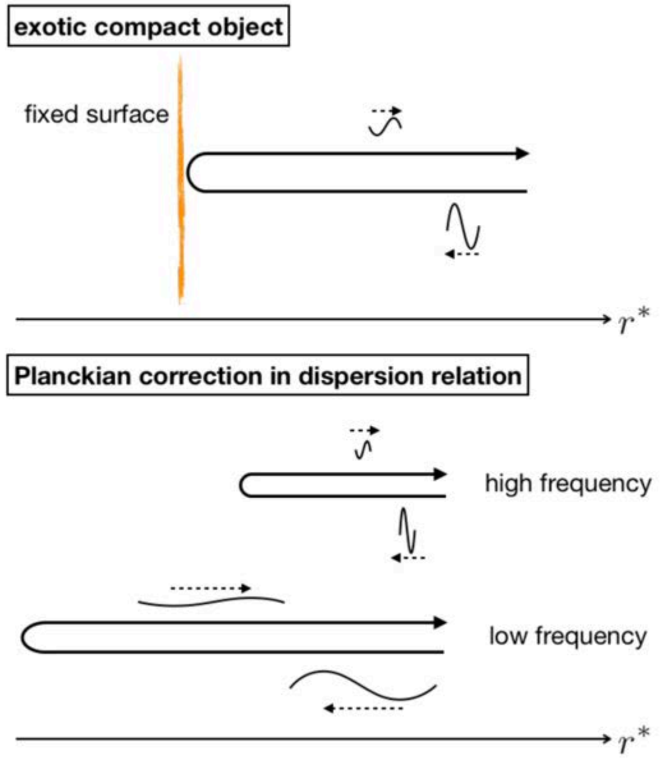
Oshita, Tsuna, & NA 2020

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

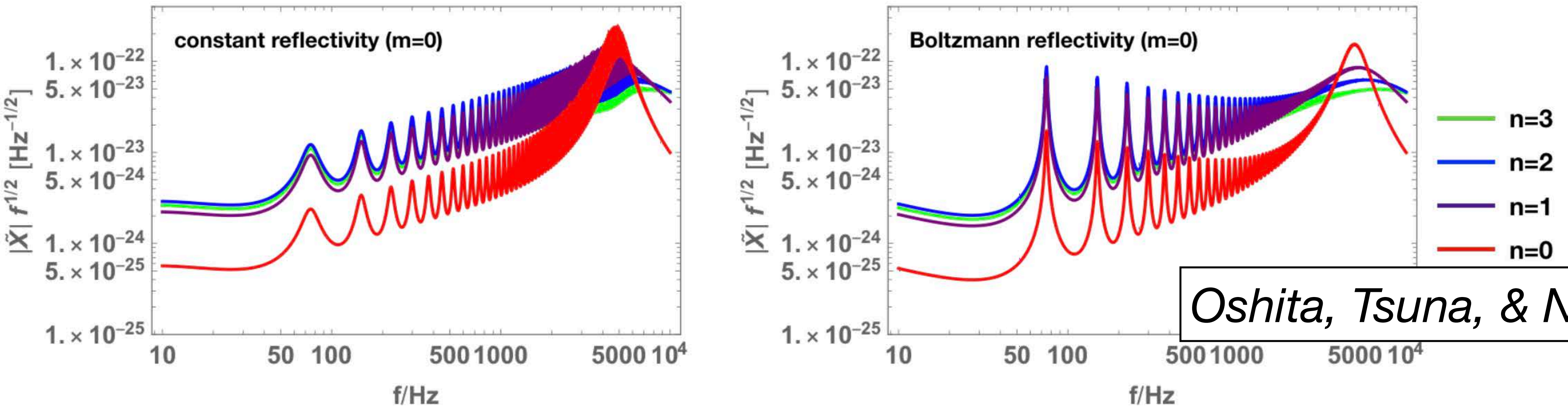
What Black Hole Seismology teaches us 2/3

- Exotic Compact Object vs Modified Dispersion Relation





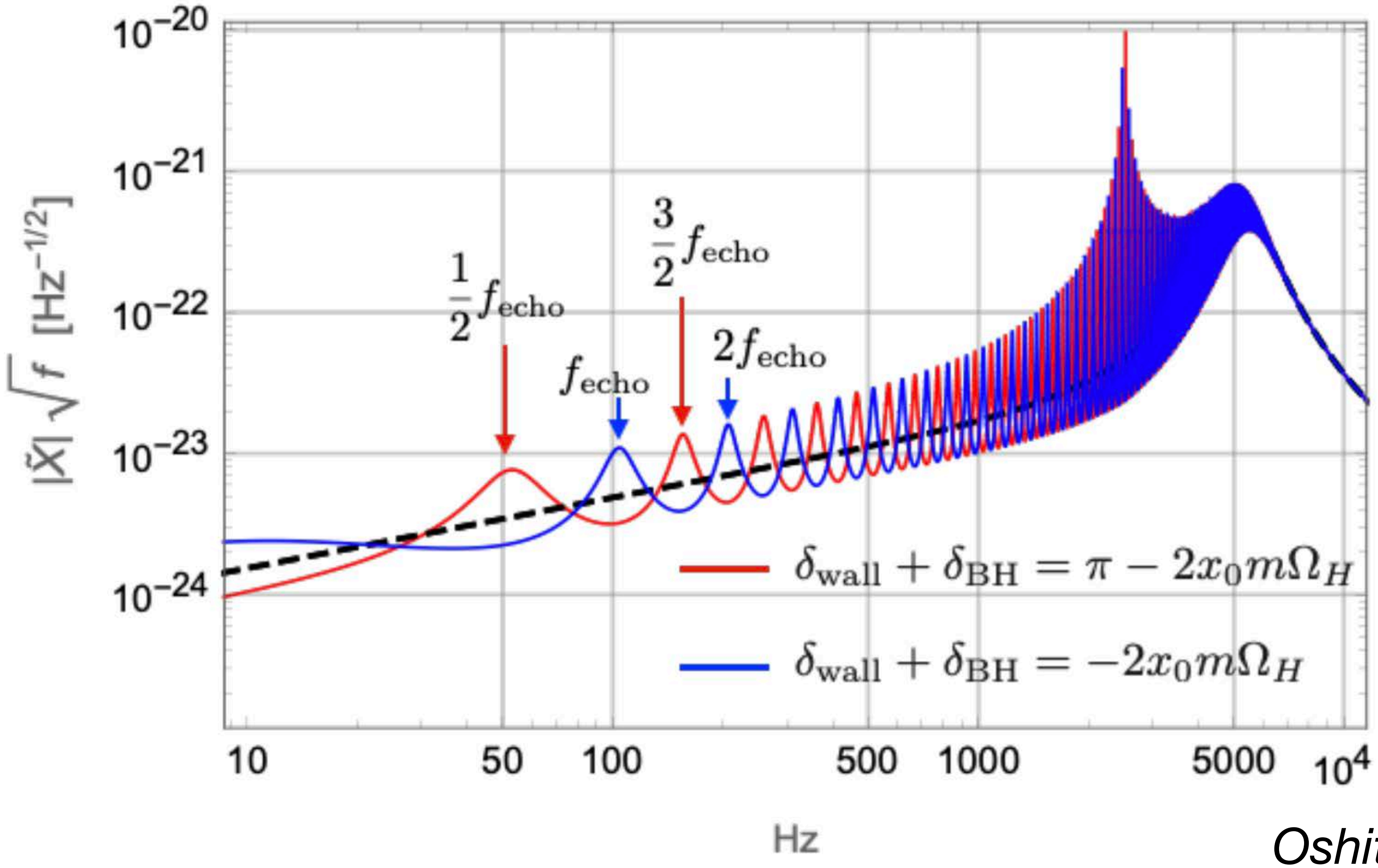
- Which overtones are excited



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

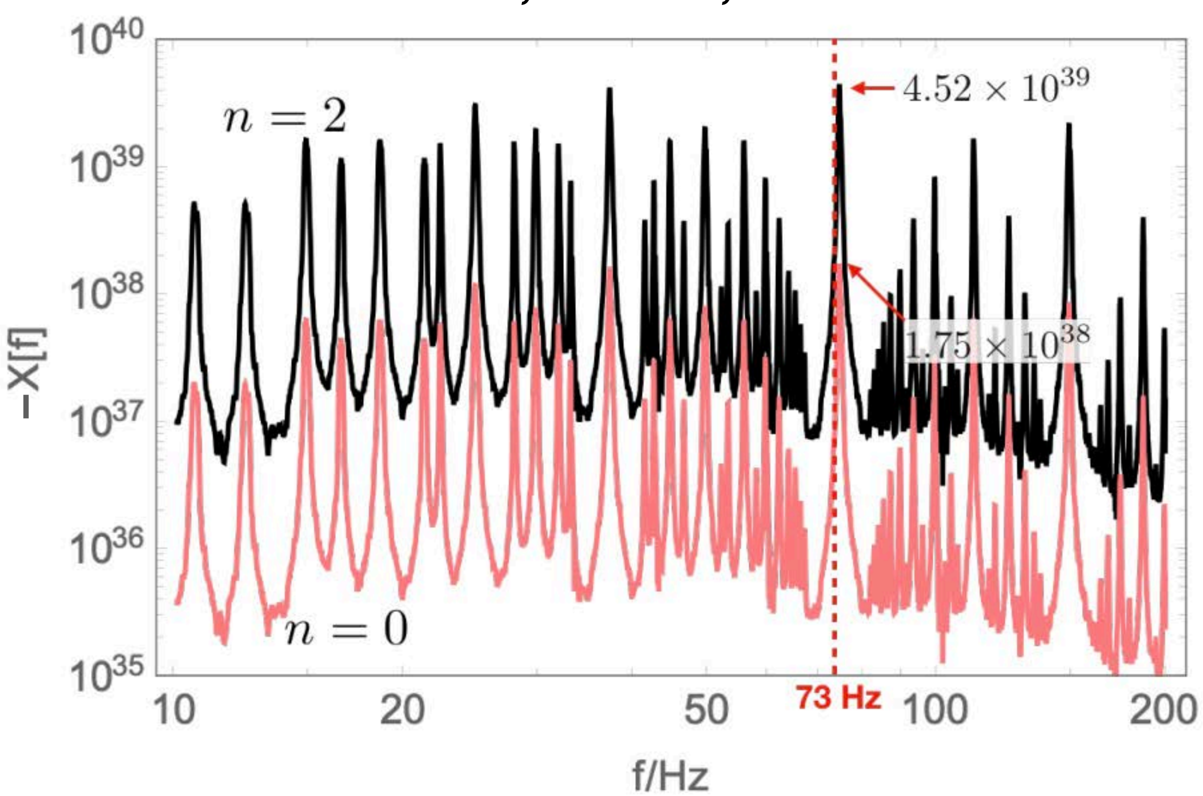
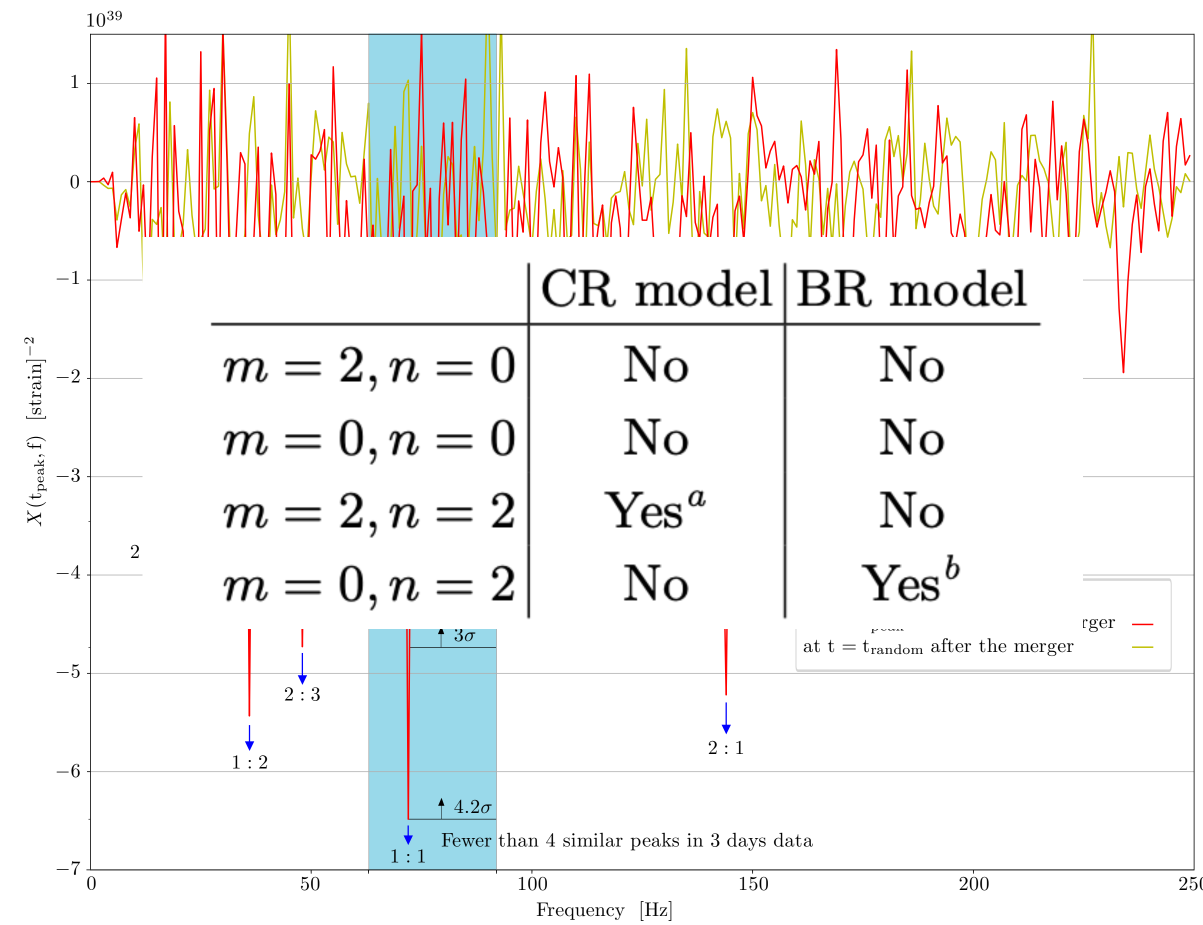
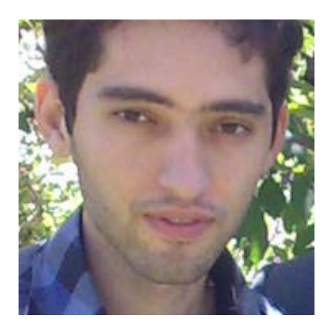


FIG. 6: Plots of $X(f)$ obtained in the BR model for the overtone QNM with $n = 2$ (black) and the least damping QNM (pink). For both cases, we set $\ell = 2$, $m = 0$, $\bar{a} = 0.85$, $\epsilon_{\rm rd} = 0.7\%$, $\theta = 33°$, $D_L = 40$ Mpc, $T_{\rm H}/T_{\rm QH} = 0.1$, and $\gamma = 1$.



	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]

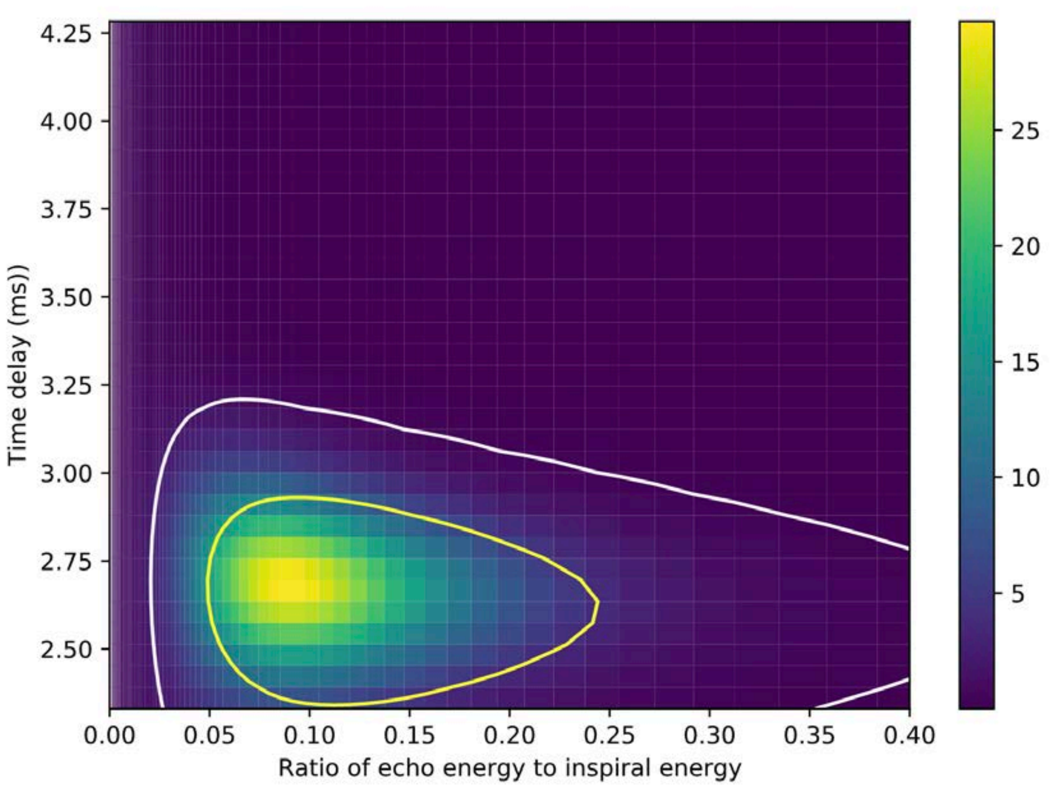


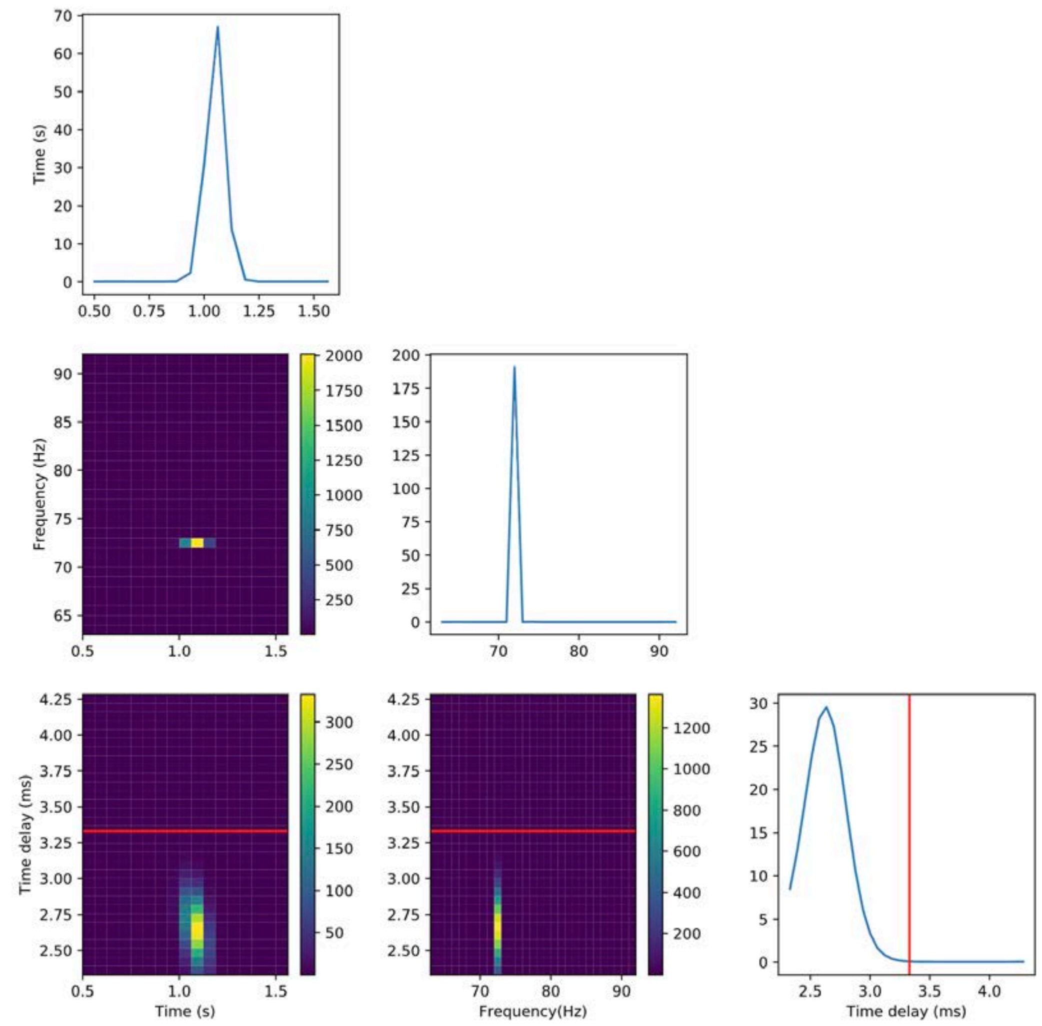
Abedi & NA, 2019

Bayesian approach to BH seismology

(Petra Duff & NA, in prep)

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

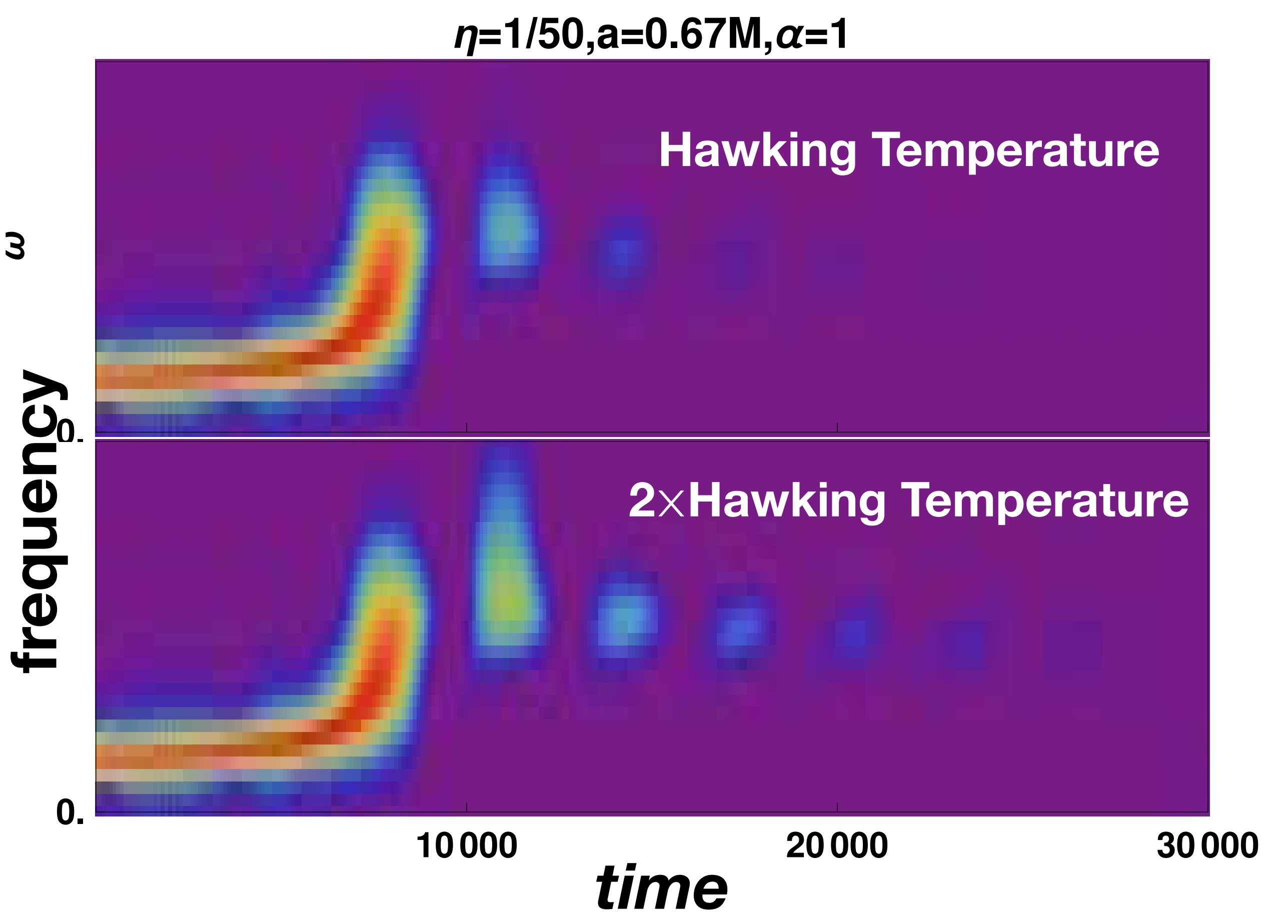


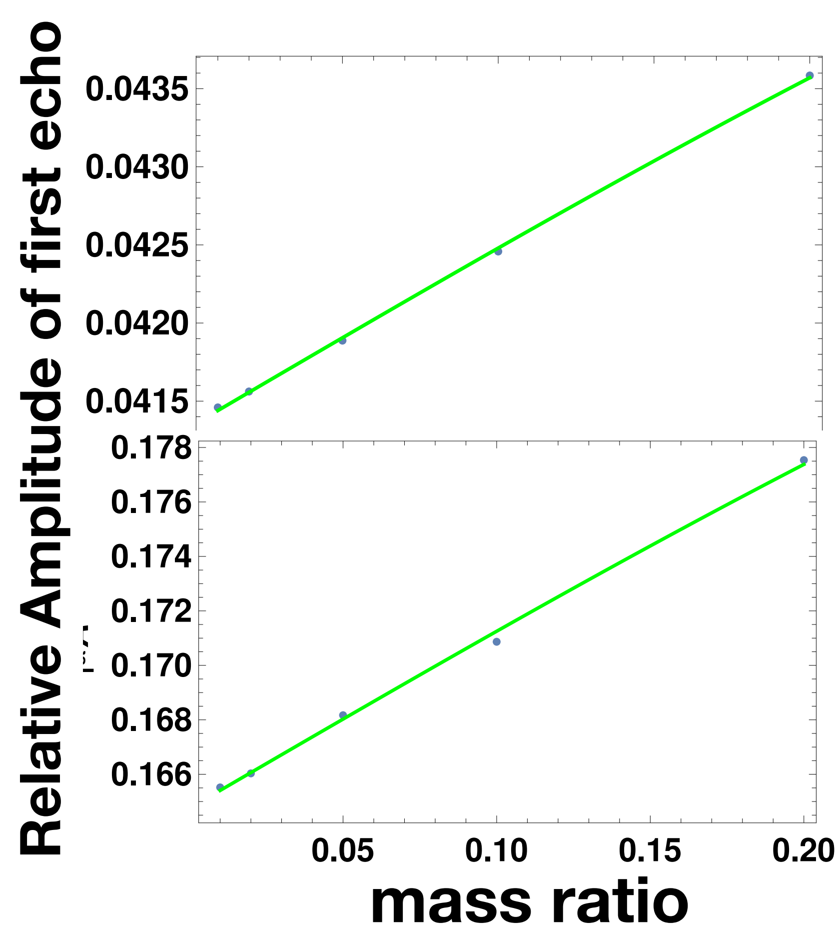


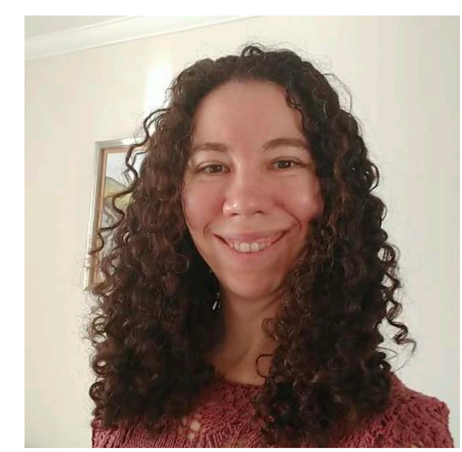
Echo-Diversity: How initial conditions impact seismology

- *Upcoming work with Luis Longo and Cecilia Chirenti*

- Solving for GW radiation of an ***inspiralling point*** mass into a Quantum Black Hole



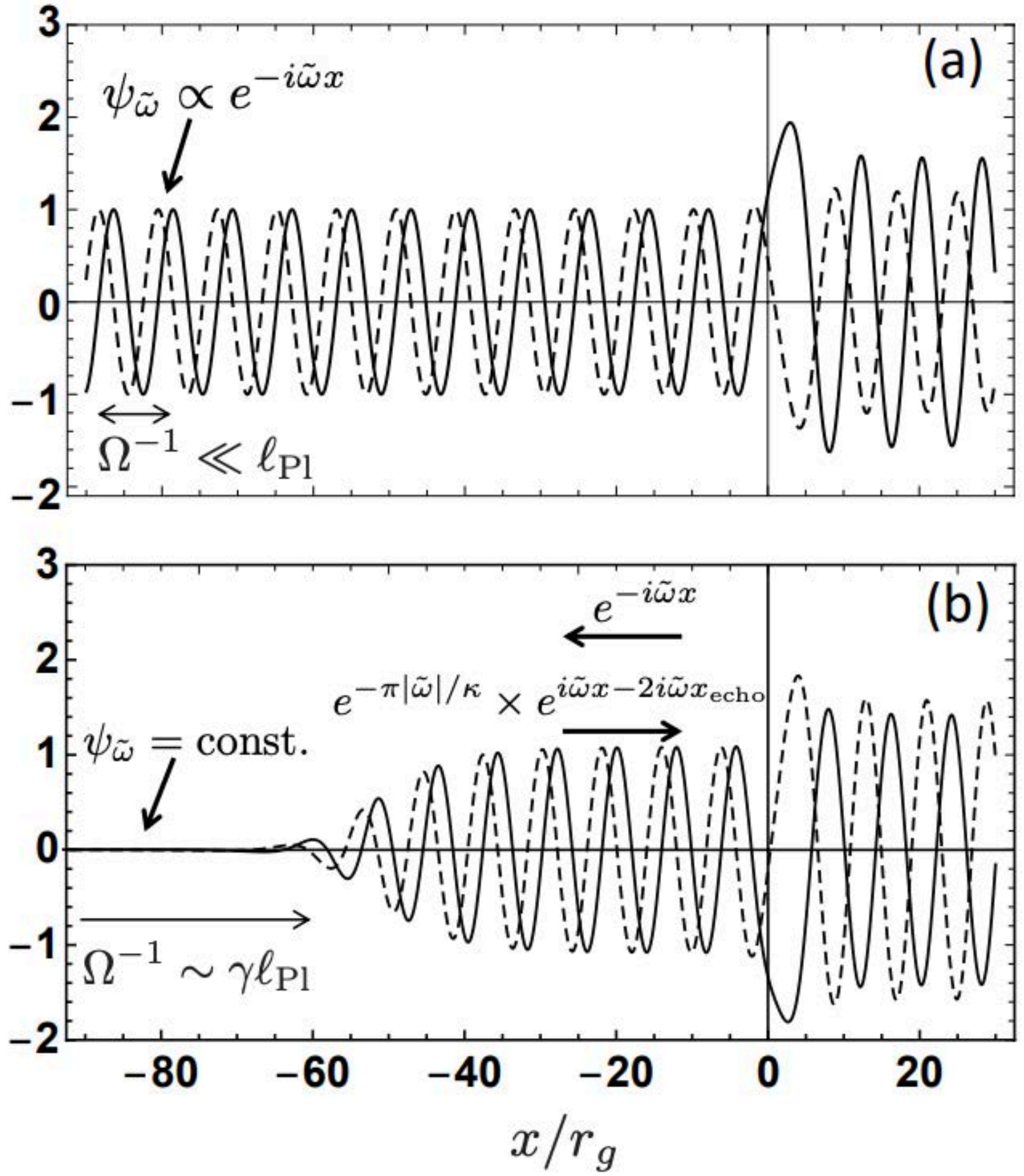




Fluctuation-Dissipation Theorem —> Boltzmann echoes

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

dissipation



independent of γ

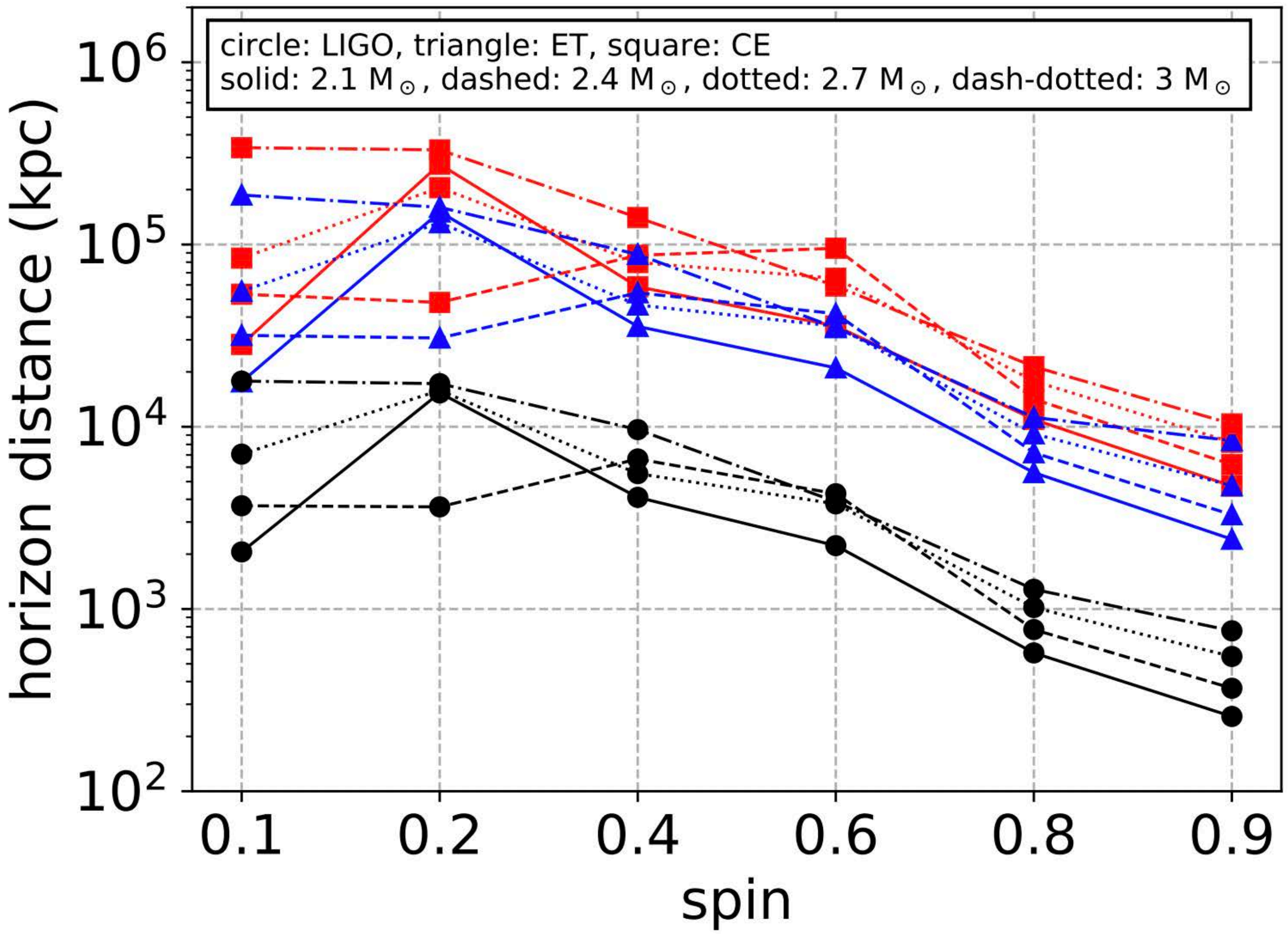
$$R=\exp\left(-\frac{\hbar\omega}{kT_H}\right)$$

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

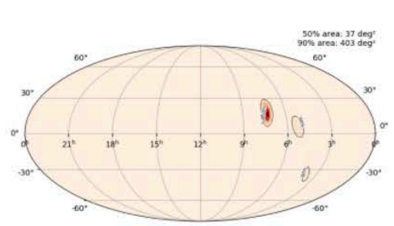
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S200114f	Production	EM_READY ADVOK EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1.226e-09	1 per 25.838 years	1263002916.225766	1263002916.239300	1263002916.252885	2020-01-14 02:11:12 UTC	Data

Preferred Event Info

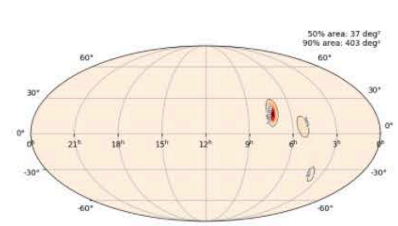
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
Burst	CWB	IMBH	H1,L1,V1	1263002916.2393	2020-01-14 02:12:26 UTC

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

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]

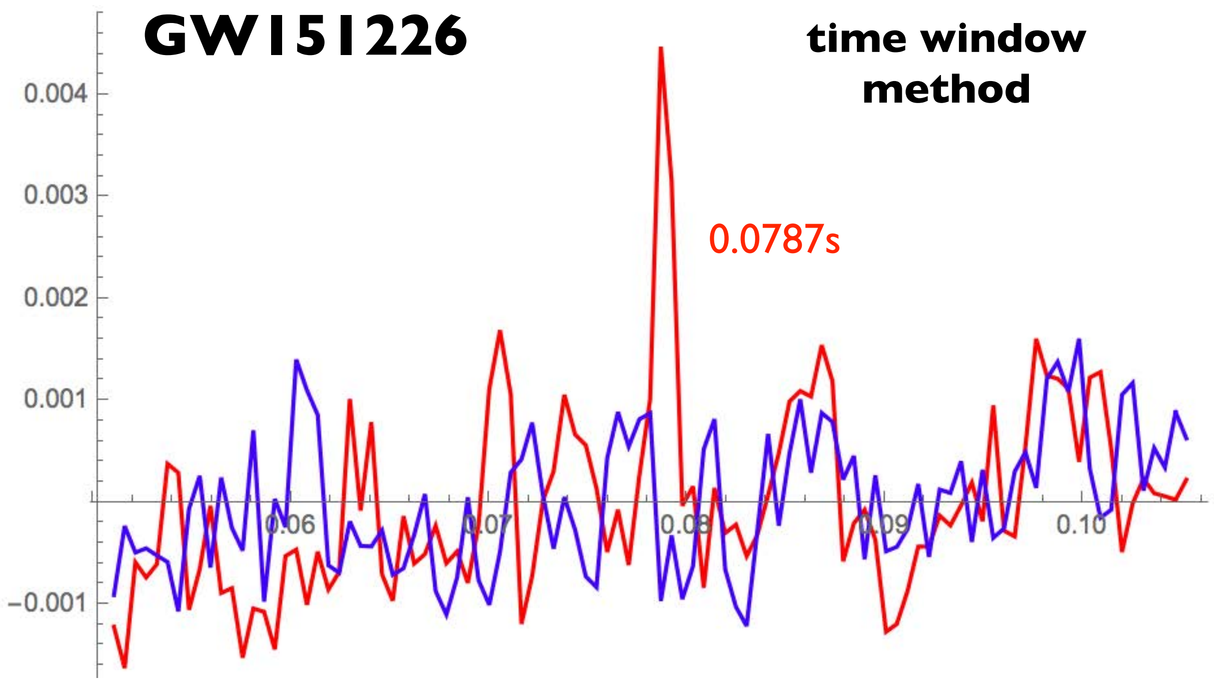
[1] *Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[3] *Rochester Institute of Technology, Rochester, NY 14623, USA*
[4] *Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*
[5] *OzGrav, School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

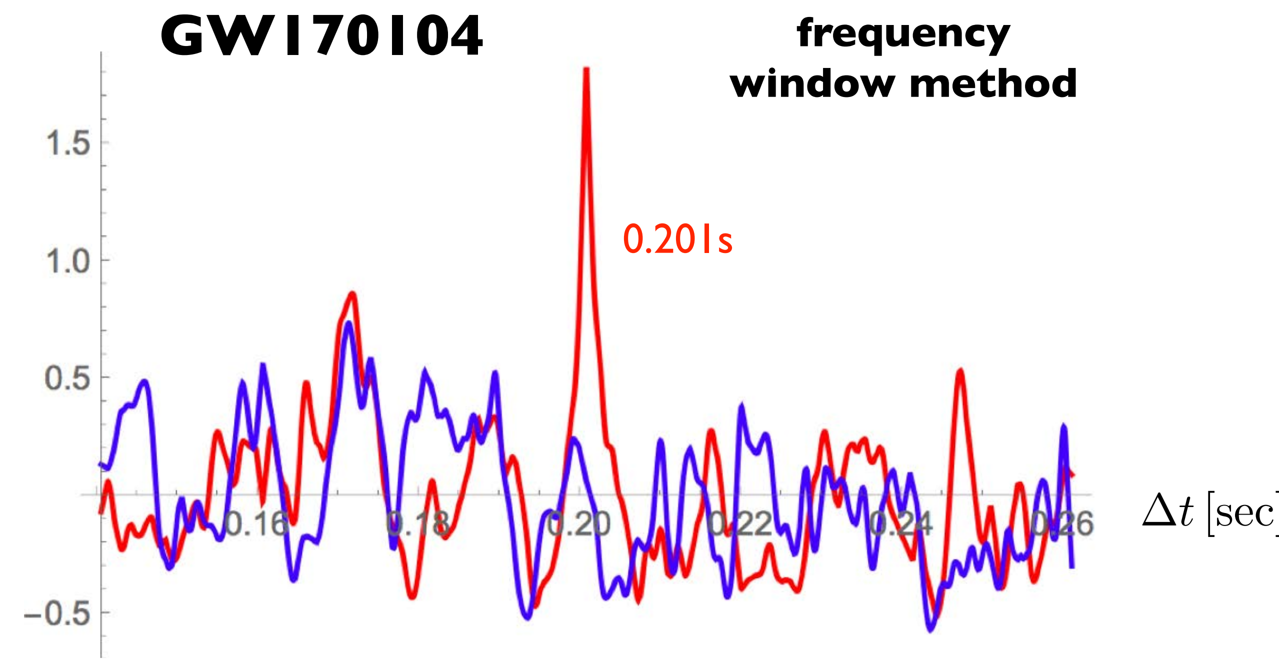
arXiv:1712.09966

Randy Conklin, Bob Holdom & Jing Ren 2018

Another independent search for echoes

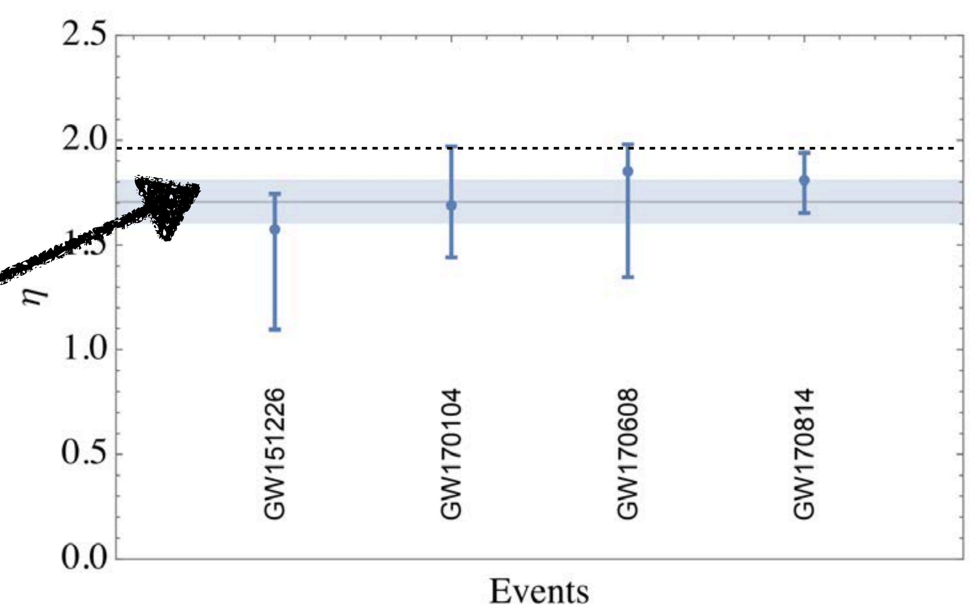
- ***Search strategies***: using window functions to find the ***preferred time delay*** of echoes from the correlation of two LIGO detectors (red and blue curves are for data after and before merger)



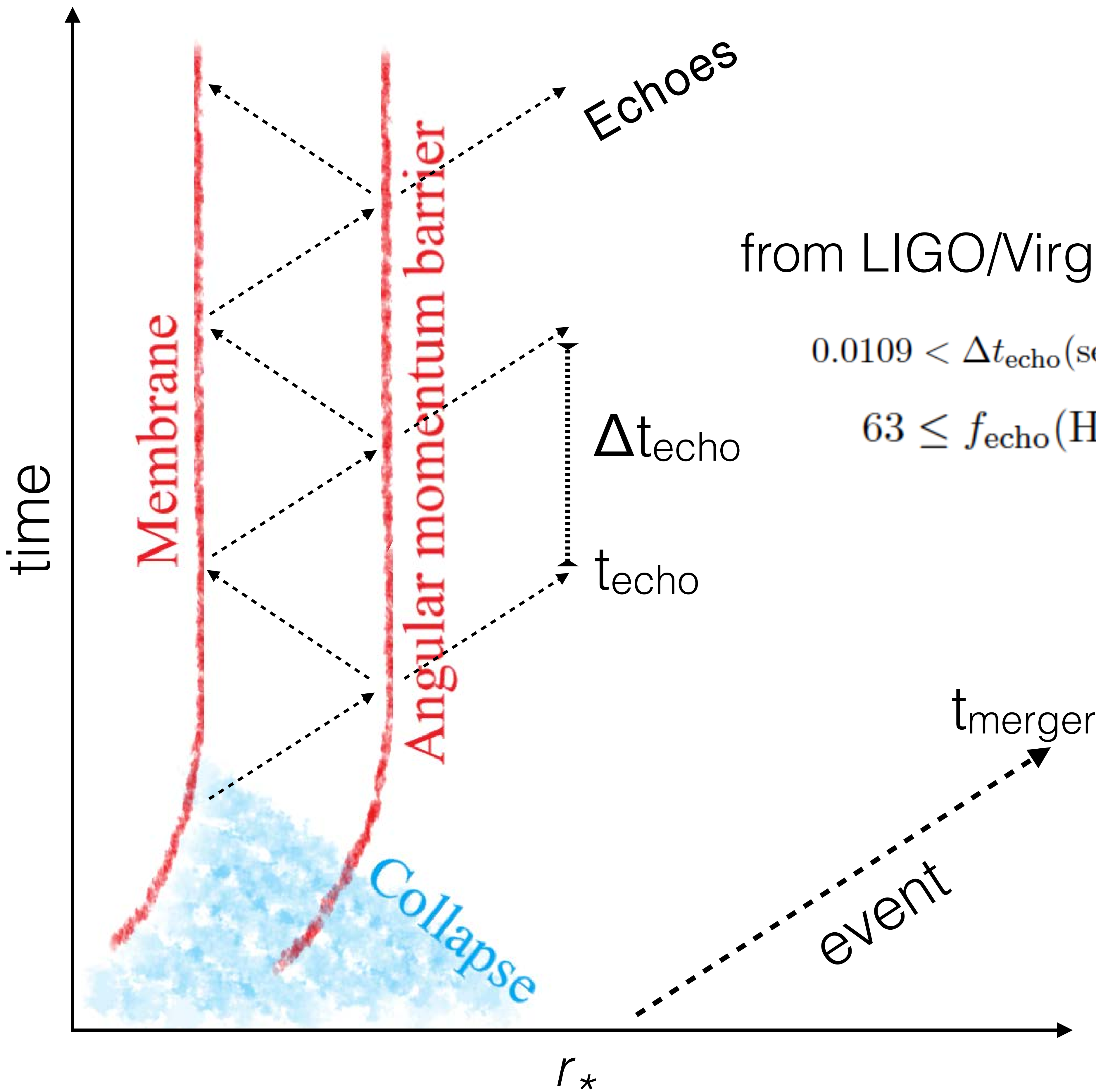


- Tentative signal peaks for *GW151226, GW170104, GW170608, GW170814, GW170817*
- **p-values ~ 0.2%-0.8%**
- consistent w/ GUT or "Inflation" scales

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



Oshita & NA 2019



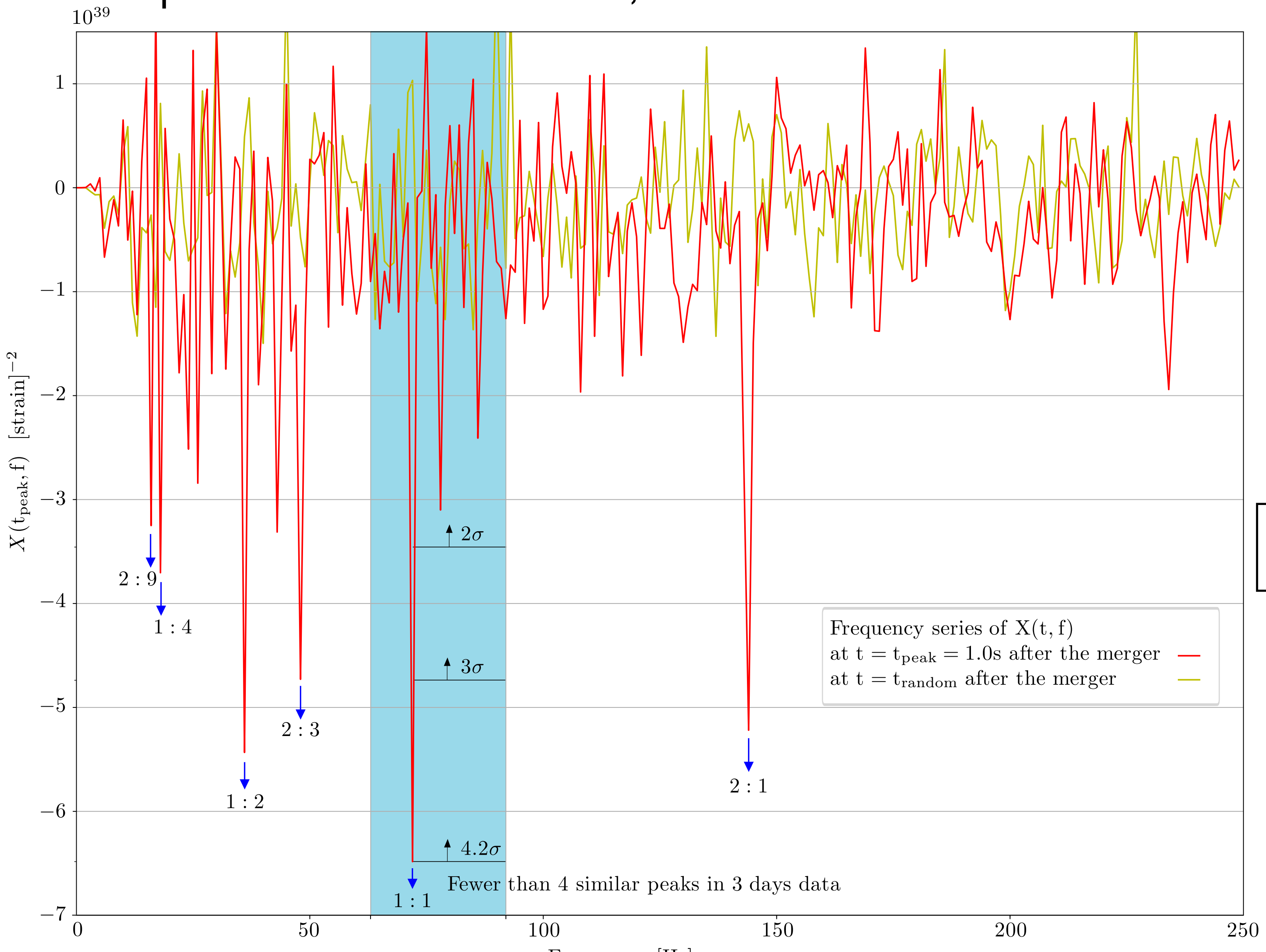
from LIGO/Virgo (90% CL)

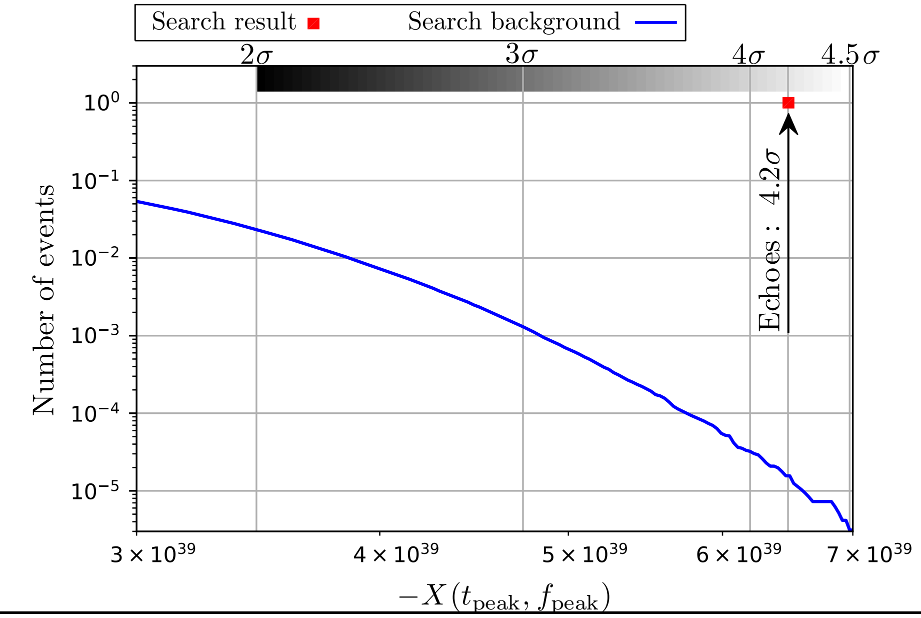
$$0.0109 < \Delta t_{\rm echo}(\rm sec) < 0.0158$$

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

Binary Neutron Star merger

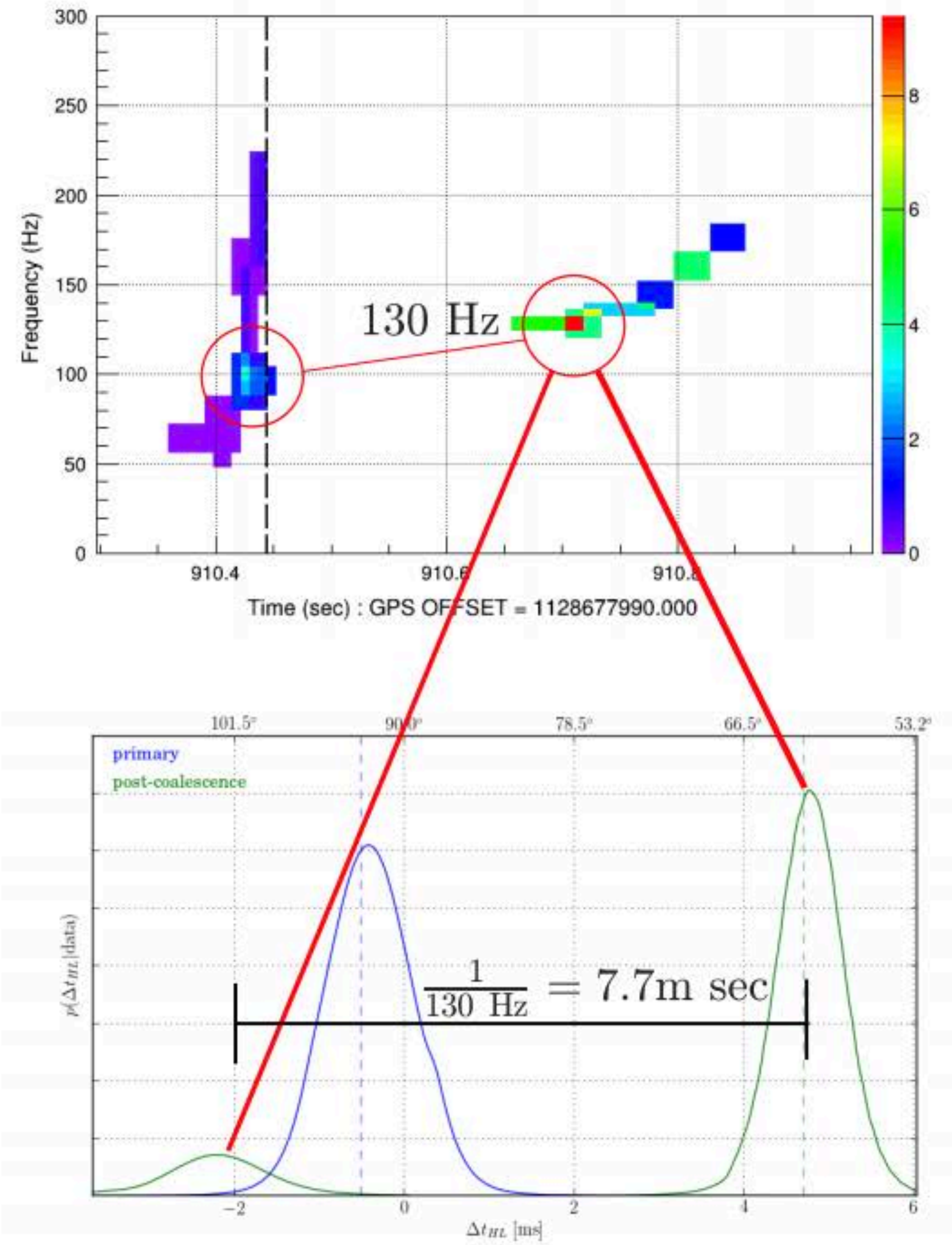
- Echoes within 1 sec after GW170817 merger @ f= 72 Hz
- p-value =1.6×10^{-5}, **4.2σ tentative detection,** *high-spin BH remnant*

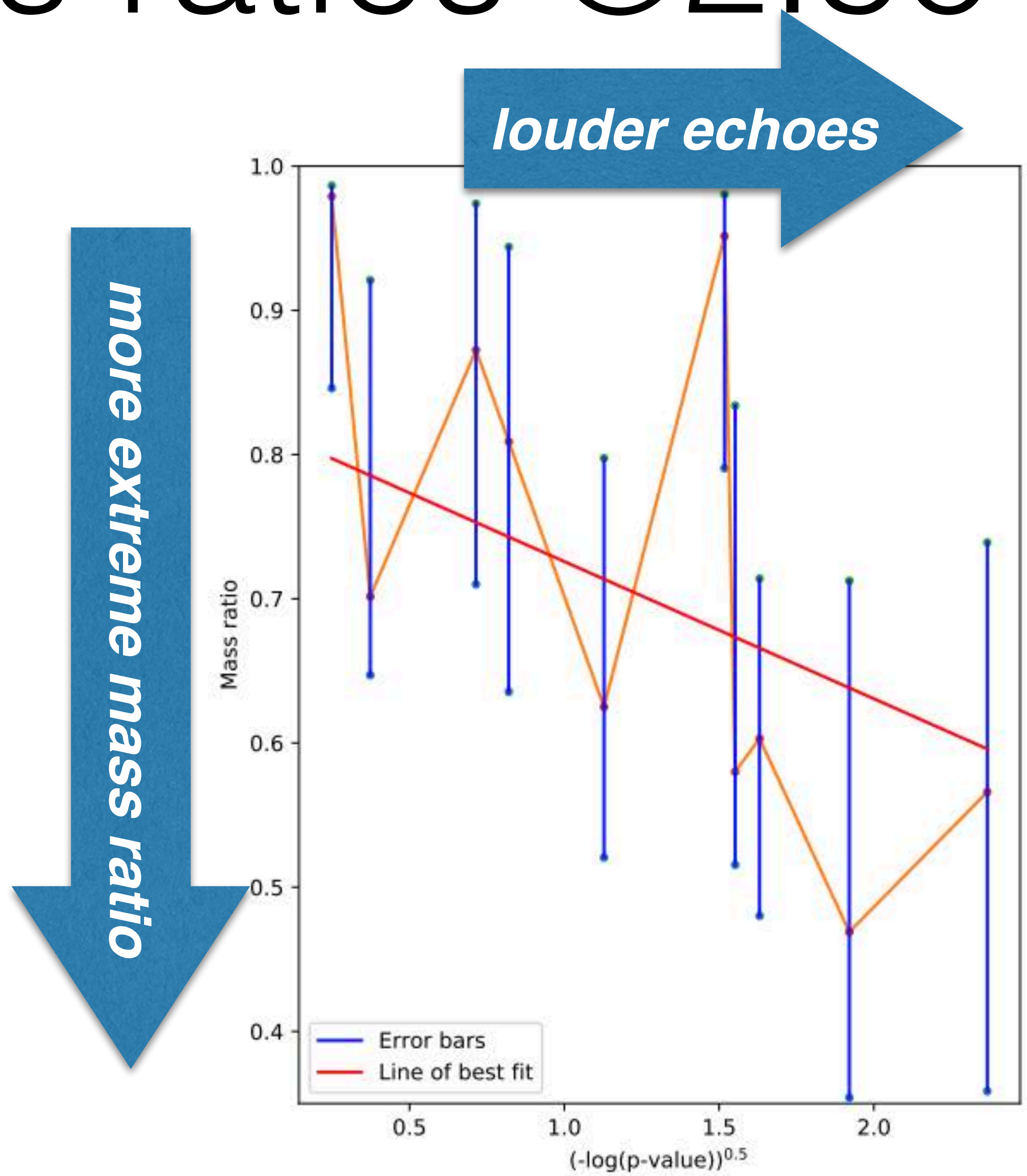




Abedi & NA, arXiv:1803.10454

Echoes are louder for more extreme mass ratios @2.5σ

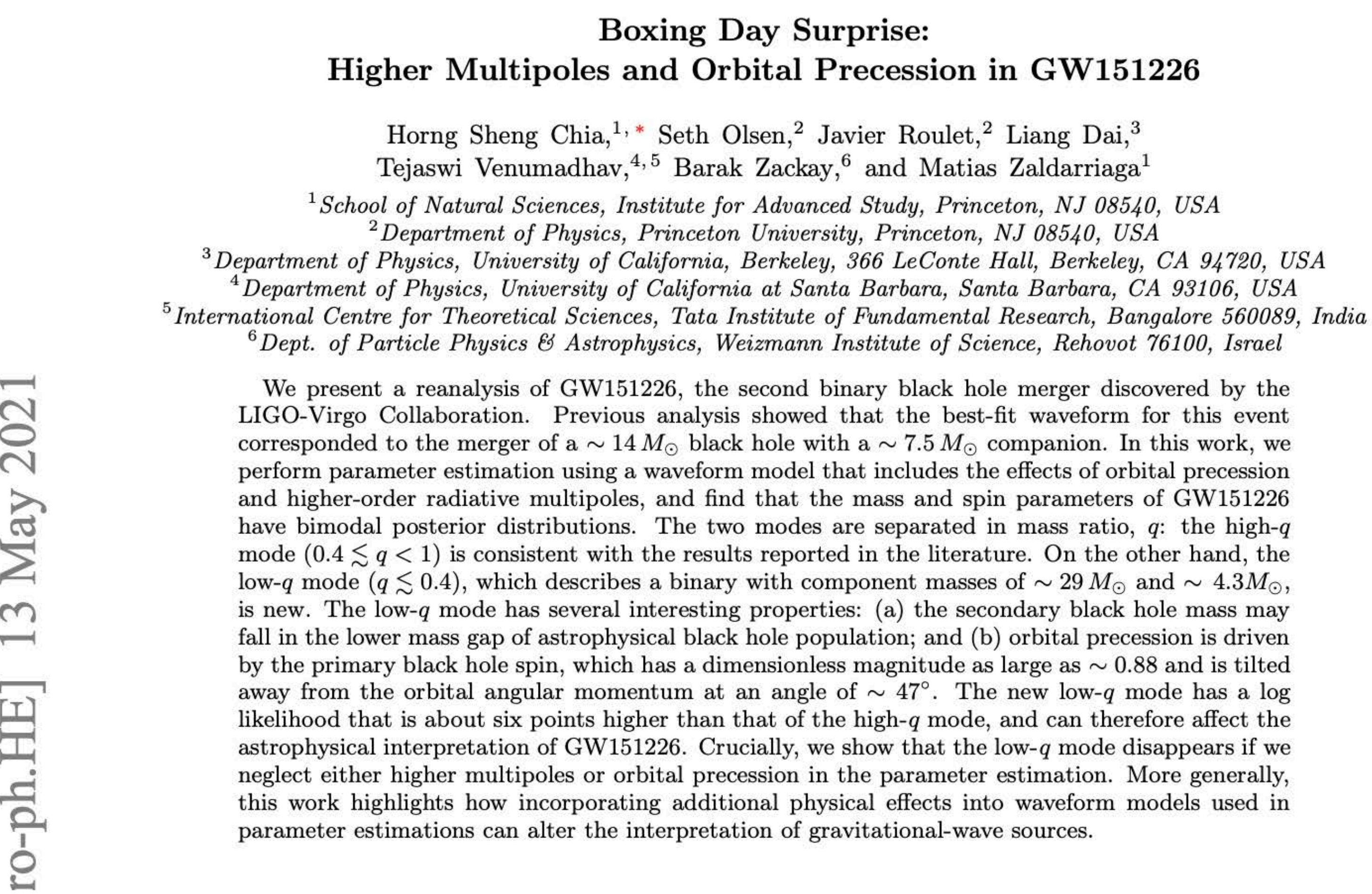




[15] F. Salemi, E. Milotti, G. A. Prodi, G. Vedovato, C. Lazzaro, S. Tiwari, S. Vinciguerra, M. Drago, and S. Klimenko, Phys. Rev. **D100**, 042003 (2019), arXiv:1905.09260 [gr-qc].

p-values from Salemi, et al. 2019

Echoes visible for more extreme mass ratio mergers?



ro-ph.HE] 13 May 2021

Boxing Day Surprise:
Higher Multipoles and Orbital Precession in GW151226

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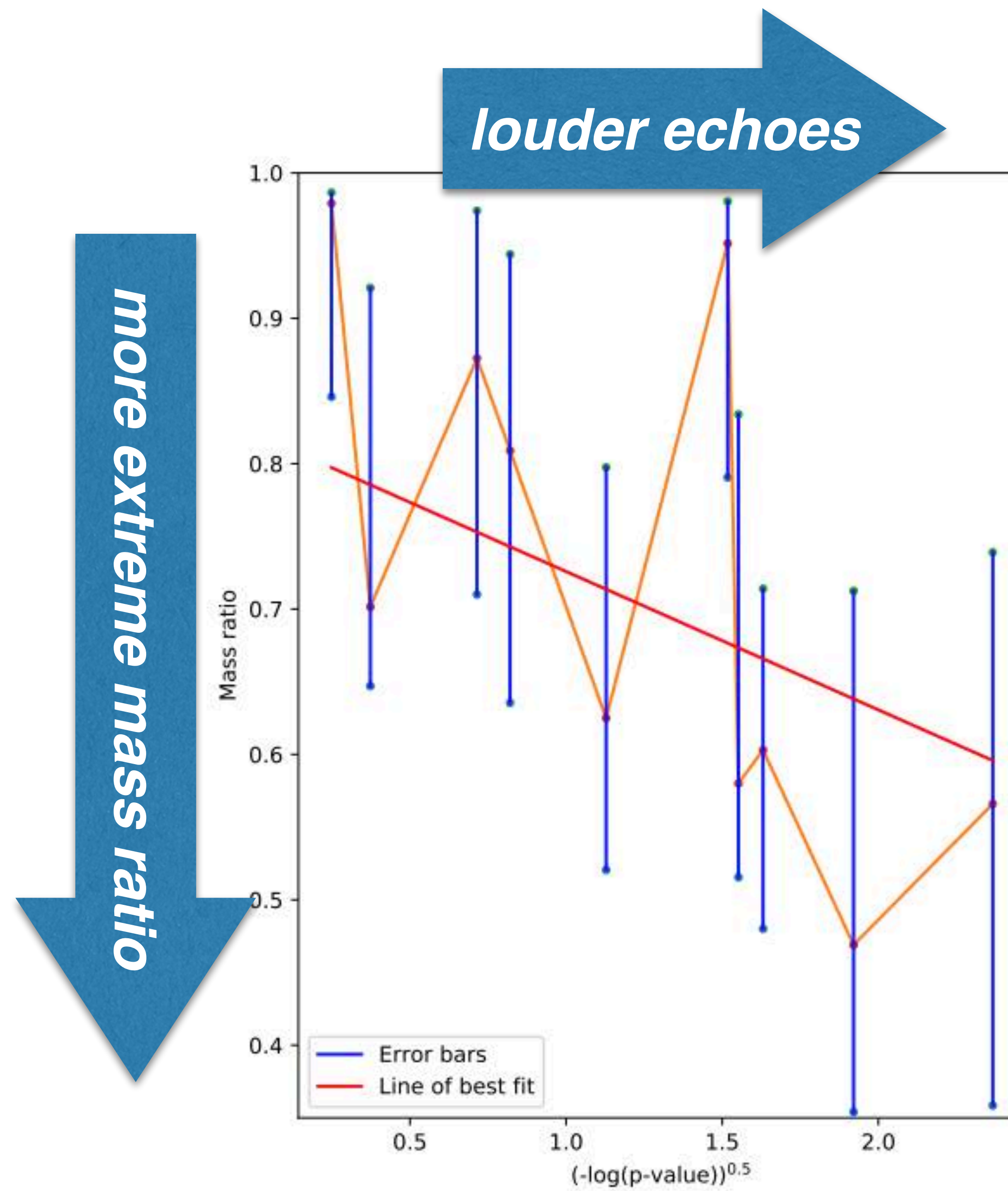
We present a reanalysis of GW151226, the second binary black hole merger discovered by the LIGO-Virgo Collaboration. Previous analysis showed that the best-fit waveform for this event corresponded to the merger of a $\sim 14\,M_\odot$ black hole with a $\sim 7.5\,M_\odot$ companion. In this work, we 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**	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)

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

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