Title: Quantum Black Holes in the Sky: from Quantum Gravity to Astrophysics and Cosmology

Date: Feb 27, 2018 11:00 AM

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Abstract: In classical General Relativity (GR), an observer falling into an astrophysical black hole (BH) is not expected to experience anything dramatic as she crosses the event horizon. However, tentative resolutions to problems in quantum gravity, such as the cosmological constant problem or the black hole information paradox, invoke significant departures from classicality in the vicinity of the horizon. I outline theoretical and phenomenological arguments for these departures. I will then discuss the tentative observational evidence for Planck-scale structure near BH horizons, seen as "echoes" in LIGO gravitational wave observations, which has now been found by three independent groups. Finally, I present preliminary analysis which strongly suggest formation of a highly spinning black hole within 0.5 second of GW170817 binary neutron star merger, based on prominent echoes in the LIGO strain data.

Cosmology and Gravitation Seminar
Feb. 27, 2018

Quantum Black Holes in the Sky

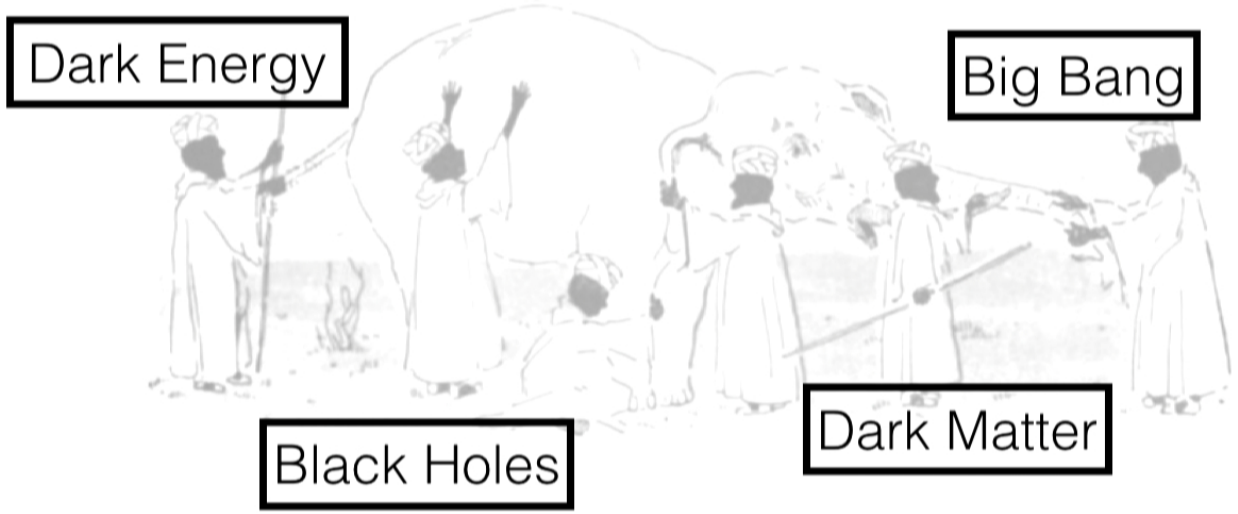
from Quantum Gravity to Astrophysics and Cosmology

Niayesh Afshordi

UNIVERSITY OF WATERLOO
FACULTY OF SCIENCE
Department of Physics & Astronomy

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Prelude: *Unravelling the Darkness*



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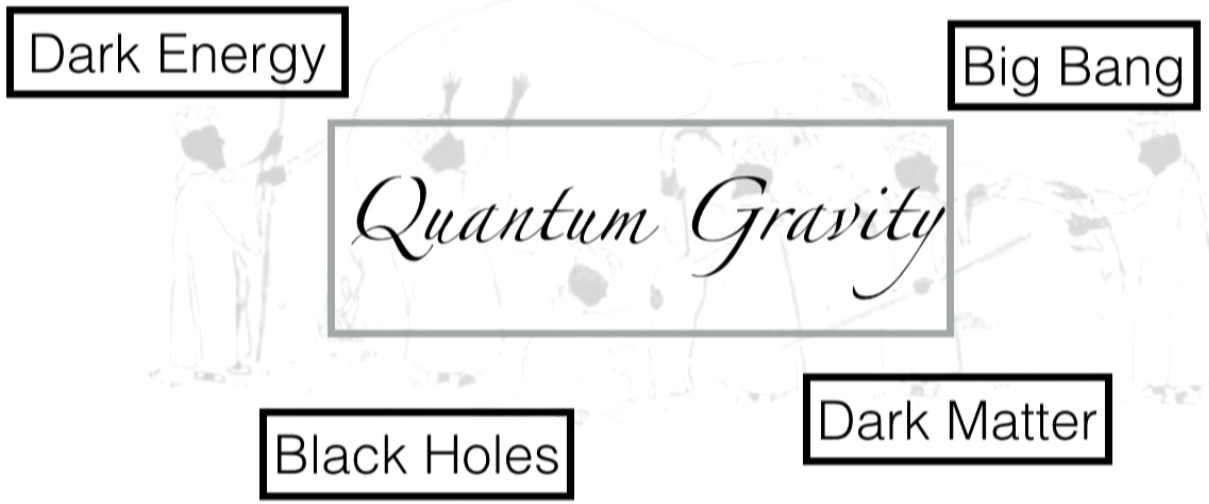
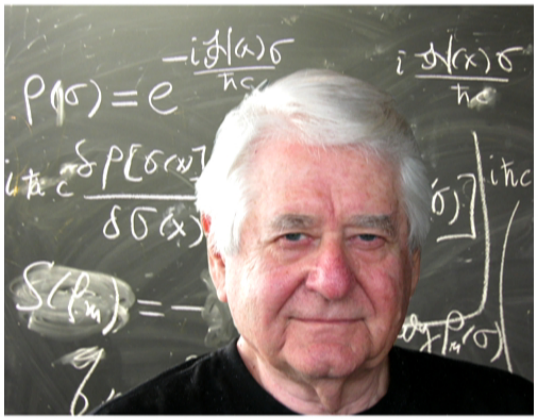


Now, John objects that we haven't seen dark matter yet.



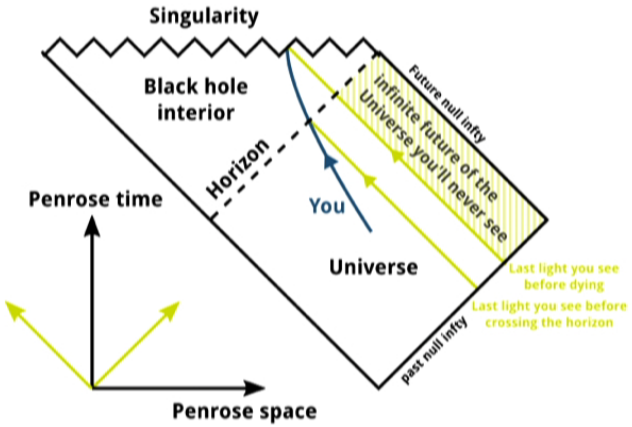
Prelude: *Unravelling the Darkness*

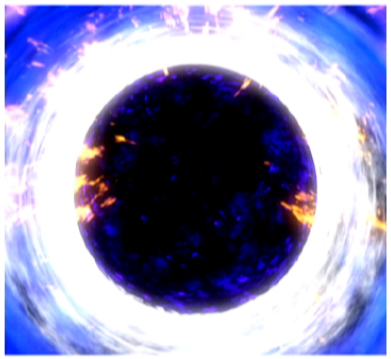
Outline

- What is wrong with horizons?
- What else could it be?
- What to look for?
- What we see: Echoes from the Abyss

Event Horizons in Relativity

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





Black Hole Thermodynamics

- Black Holes have temperature: $T = \frac{a}{2\pi}$
- 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?!

What is wrong with horizons?

- **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:** Aether in equilibrium with stellar BH's
  → scale of dark energy *(Presocd-Weinstein, NA, Balogh 2009)*

Keith now objects!

Keith says he's not convinced
but we can discuss it over lunch!

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

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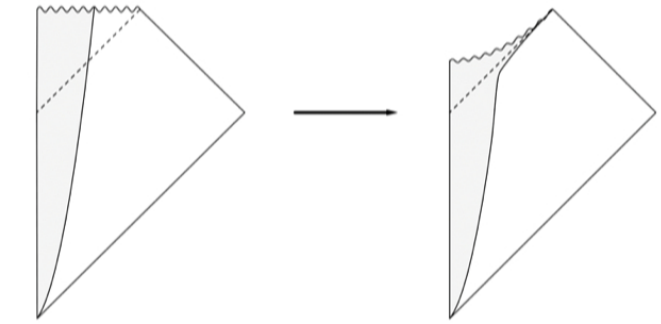
What else could it be?

- **Fuzzballs** (*a la* Mathur)**:** classical horizon-less spacetimes, account for BH entropy
- **Aether Holes** *(NA, Prescod-Weinstein, Balogh, Mann, Saravani)***:** membrane with mirror symmetry, account of BH entropy, couple to dark energy
- Gravastar, 2-2 hole, Planck star, …



Aether Holes: *Entropy*

- Assume space-time ends near horizon
- *Israel Junction* condition+ mirror symmetry:
  - ➡ membrane has vanishing surface density
  - ➡ integrated (surface) pressure: = BH Temperature/4
  - ➡ Entropy per unit area = 1/4 *…voila!!*

Saravani, NA, Mann 2012

Aether Holes: *metric*

- We can solve for the black hole spacetime with an *incompressible aether*

$$ds^2 = \left(1 - \frac{2m}{r}\right)\left[1 + 4\pi p_0 f(r)\right]^2 dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

- p_0 is the aether pressure at infinity
- *f(r):* analytic function of *r* diverging at $r \approx 2m$ & $r \to \infty$
- ➥ *UV-IR coupling thru aether pressure, p_0*
- ➥ *Finite redshift at r=2m*
- ➥ *No Horizon (similar to Fuzzball models)*

$$f(r) = \frac{1}{2}\left(1 - \frac{2m}{r}\right)^{-1/2}\left(-30m^2 + 5mr + r^2\right) + \frac{15}{2}m^2 \ln\left[\frac{r}{m} - 1 + \frac{r}{m}\left(1 - \frac{2m}{r}\right)^{1/2}\right],$$

Aether Holes: *metric*

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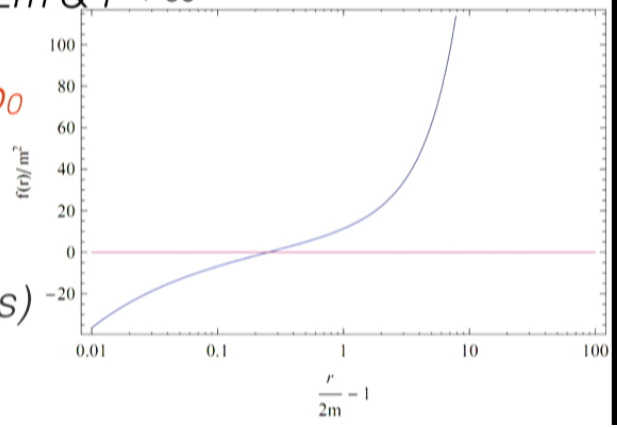


… and dark energy!

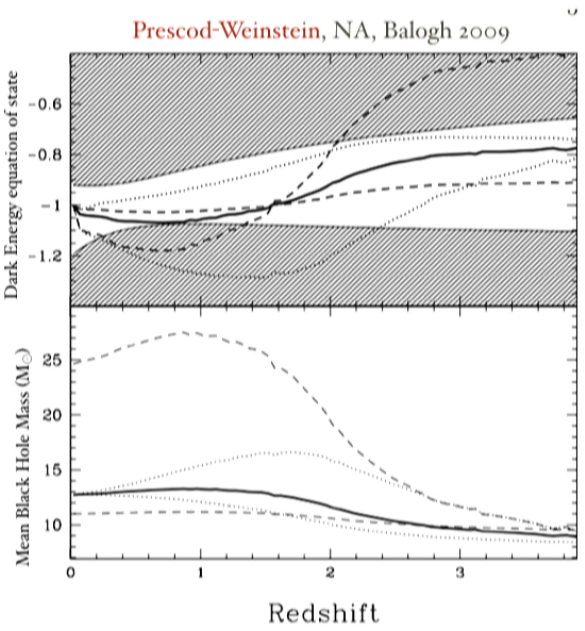
- Assume:

$$1 + z_{\max} \sim \frac{\text{Planck temperature}}{\text{Hawking temperature}}$$

- then we get

$$p_0 = -\frac{1}{256\pi^2 m^3} \simeq \left(\frac{m}{74\ M_\odot}\right)^{-3} p_{\rm DE,obs}!!$$

- *Pressure* has the same sign and magnitude as *Dark Energy* for stellar mass black holes!
- ➥Conjecture: Formation of stellar black holes causes cosmic acceleration
- ➥Conjecture: Evolution of Astrophysical black holes leads to dynamical Dark Energy



Confession 😕😖😱

- Some of my brightest students and I have tried to come up with a consistent dark energy model with many black holes … and have failed!
- Maybe one doesn't exist 😞
- Or, maybe it's because we haven't yet asked **you** 🤩

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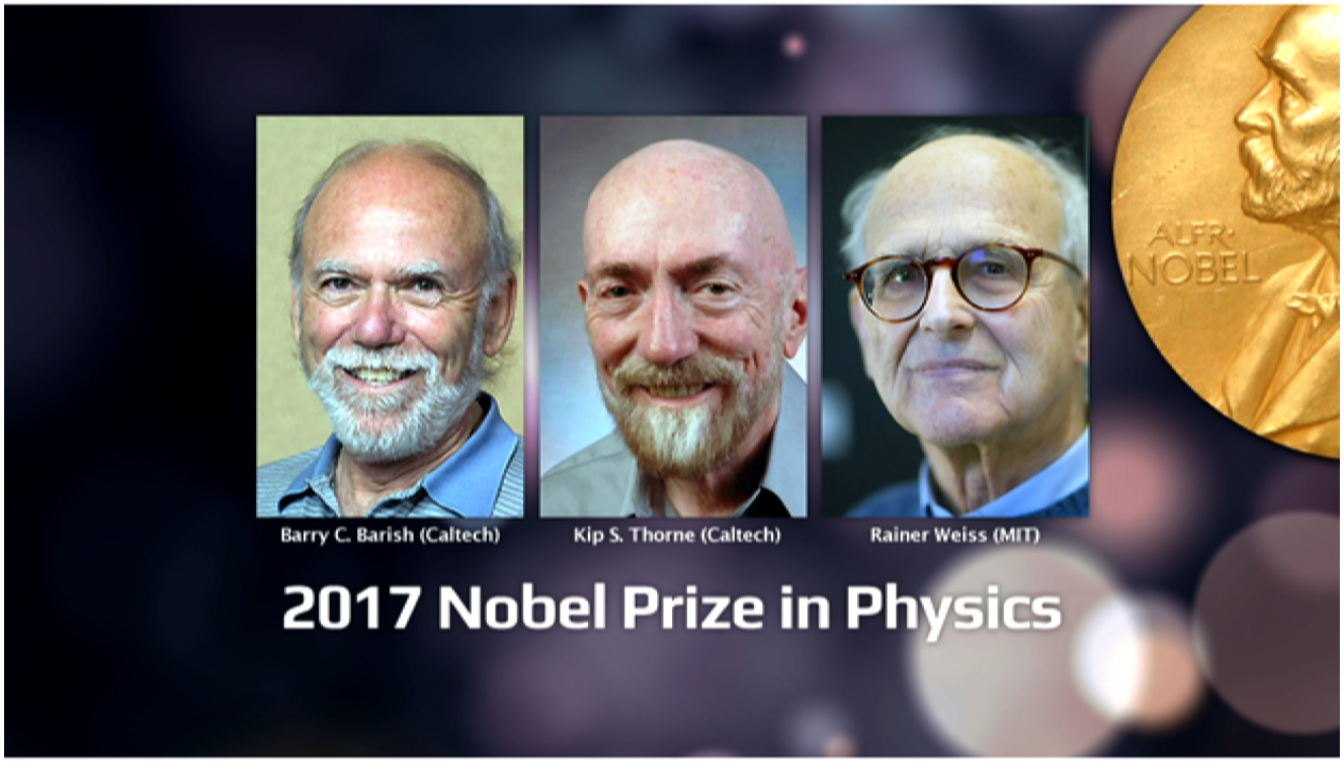
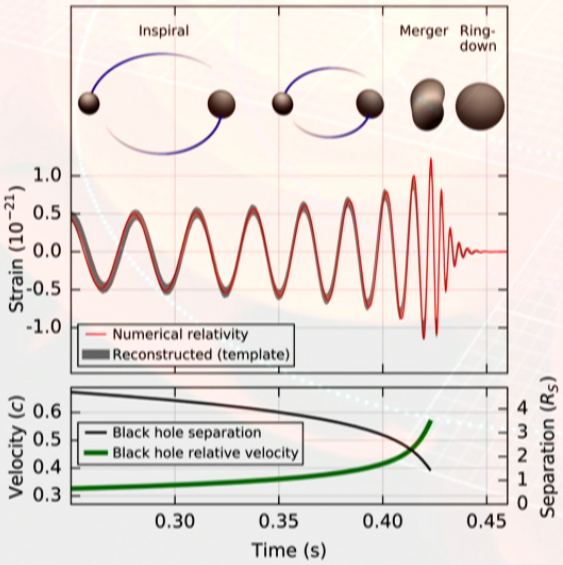
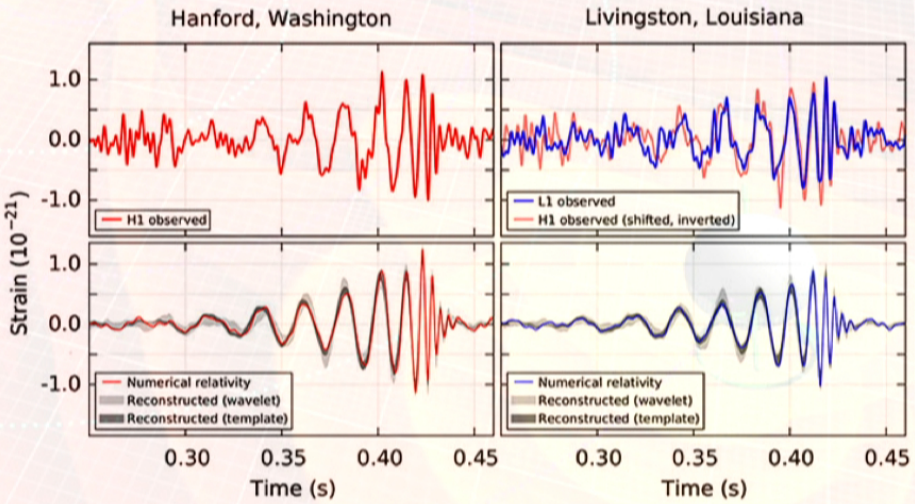

Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
ALFR
NOBEL
2017 Nobel Prize in Physics

The Future is NOW!

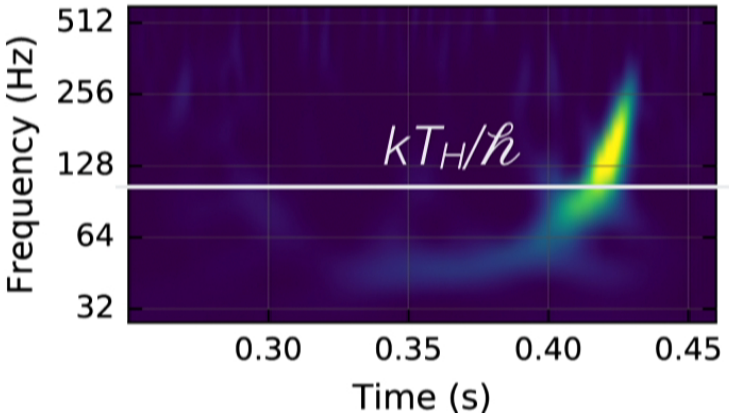




LIGO collaboration, 2016

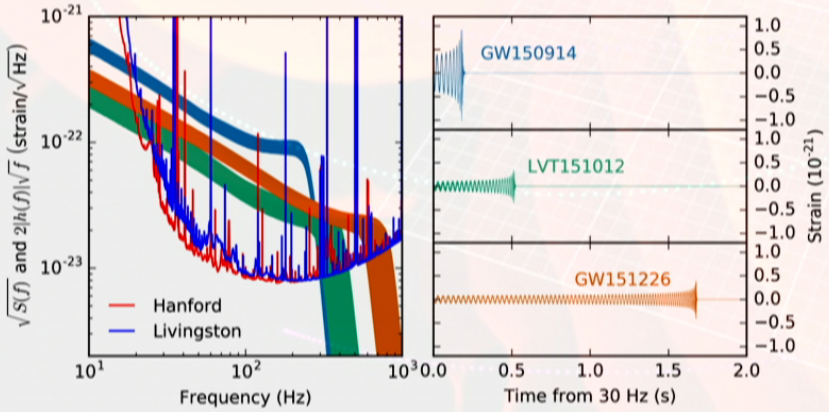
What should we see?

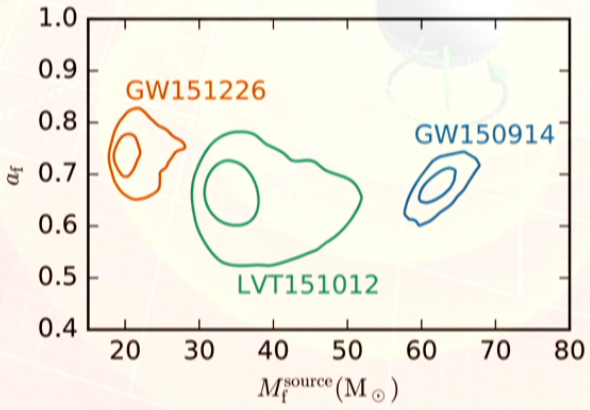
- Particles with $E \gtrsim kT_H$ can excite fuzzball microstates, and so *may be* absorbed
- Particles with $E \lesssim kT_H$ will be reflected
- Ringdown of black holes $\hbar\omega \sim kT_H$



Advanced LIGO
GW150914

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/{\rm deg}^2$	230	850	1600

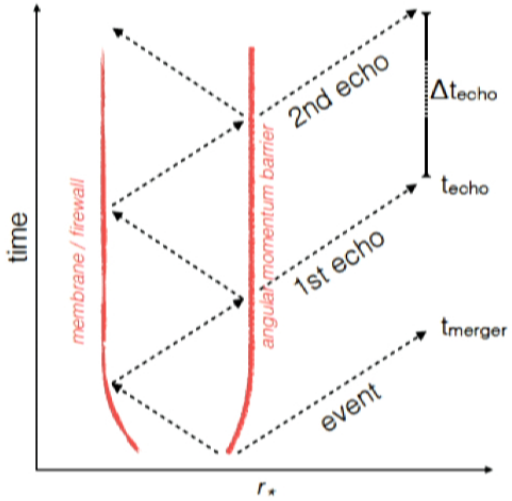




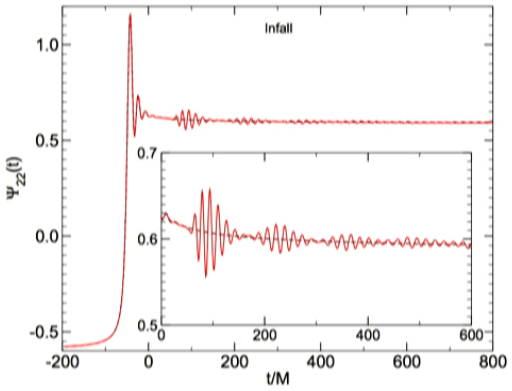
Echoes from the Abyss!

- Late echoes from Planckian structure near horizon

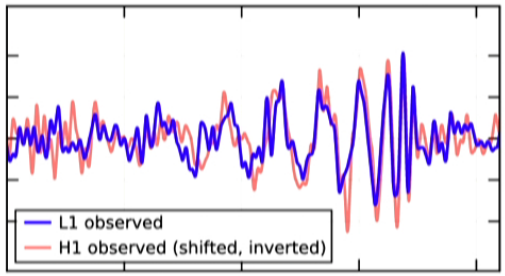
$$\Delta t_{\rm echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a_*^2}}\right)\times \ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right) \simeq 0.3 \text{ sec}$$



Cardoso, et al. 16



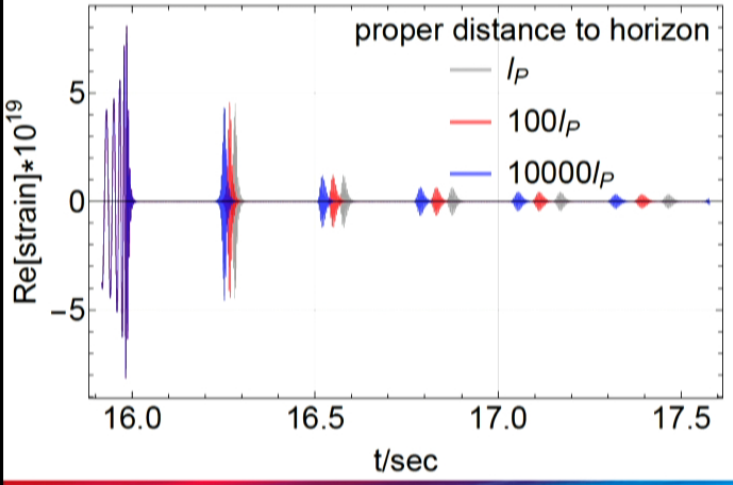
Livingston, Louisiana (L1)

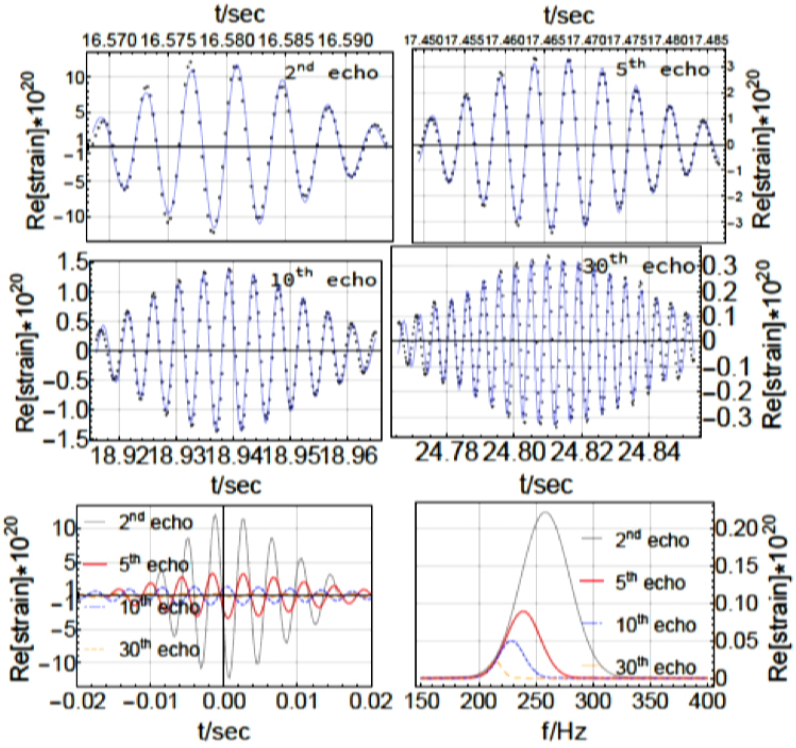


Black Hole Echology: The Observer's Manual

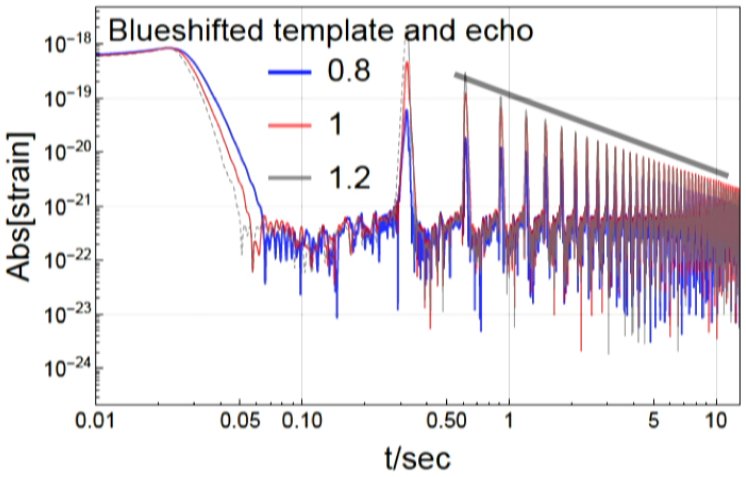
Qingwen Wang* and Niayesh Afshordi†
Perimeter Institute for Theoretical Physics
31 Caroline Street N, Waterloo,
ON, N2L 2Y5, Canada and
Department of Physics and Astronomy, University of Waterloo,
200 University Avenue West, Waterloo, ON, N2L 3G1, Canada

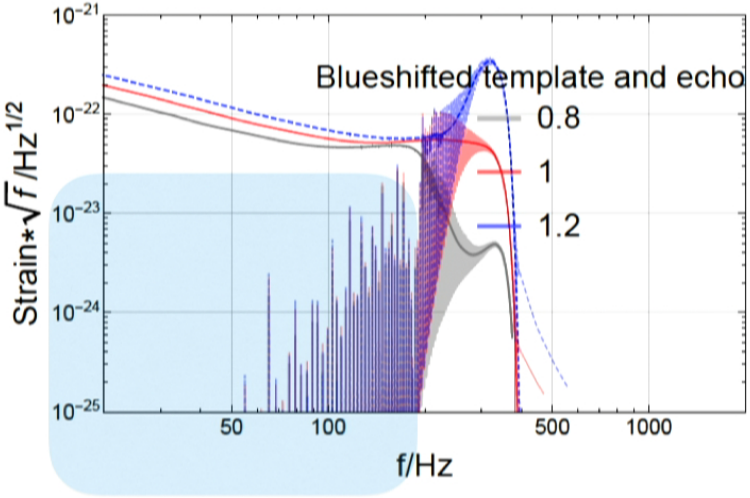
coming very soon!





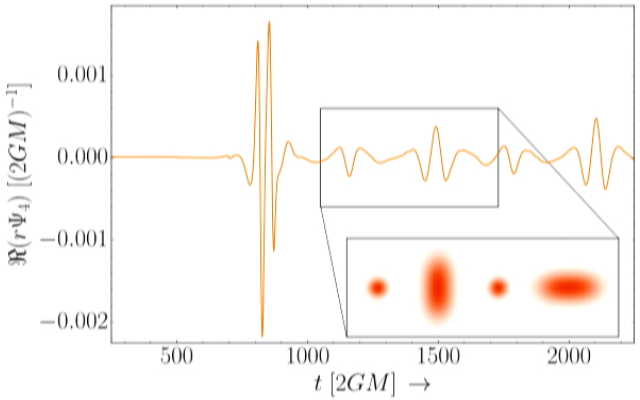
Echology 101





Simulating Echoes?

- Compact 3d field configurations (typically) unstable to forming BH's
- Q-tunnelling prevents this in fuzzballs
- 2d membrane dynamics, with covariant boundary condition, on extrinsic curvature?



Head-on collision of oscillatons
(Helfer, Lim, Garcia & Amin 2018)

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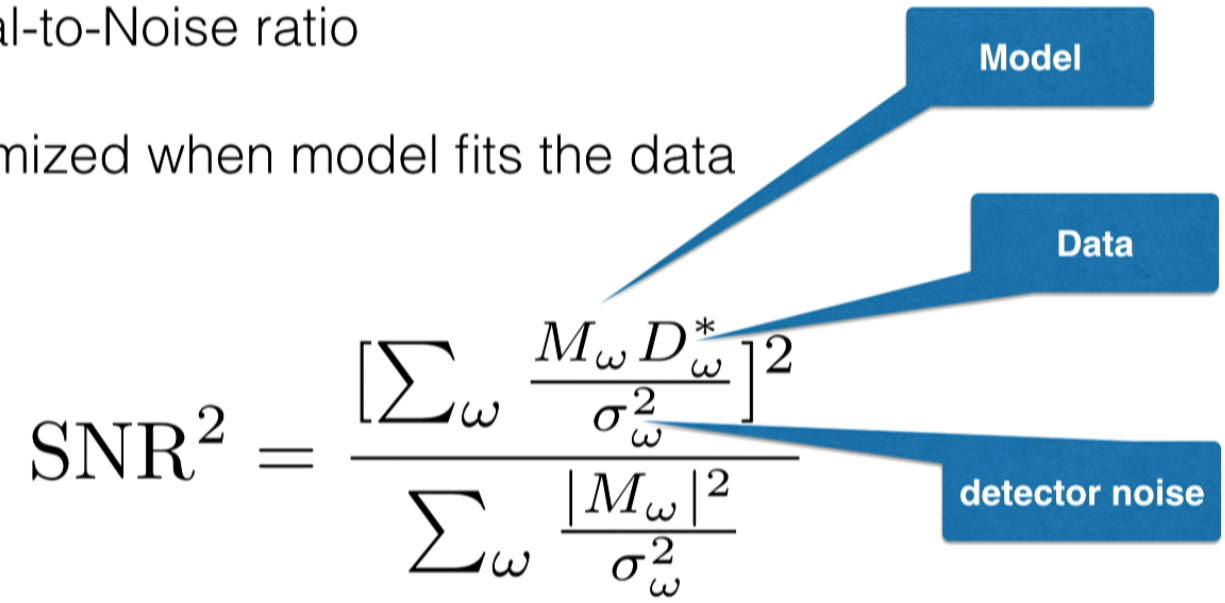
Data Analysis 101

- Signal-to-Noise ratio
- Maximized when model fits the data best



$$\mathrm{SNR}^2 = \frac{\left[\sum_\omega \frac{M_\omega D^*_\omega}{\sigma^2_\omega}\right]^2}{\sum_\omega \frac{|M_\omega|^2}{\sigma^2_\omega}}$$

How to find the echoes?

- BH mass+spin predict the time-delay for Planck-scale echoes

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

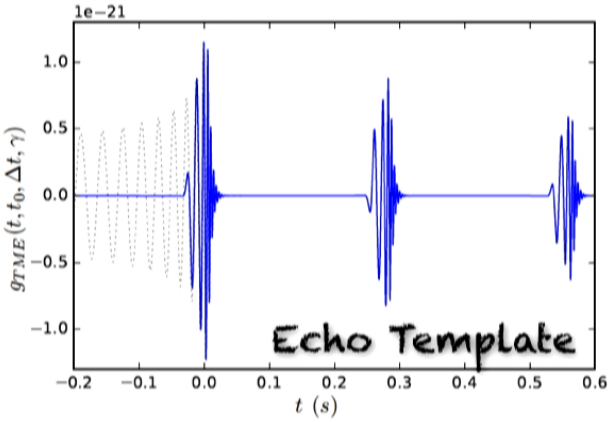
- Toy model for echo template

$$M_{TE,I}(t) \equiv$$

$$A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}_{T,I}(t + t_{\mathrm{merger}} - t_{\mathrm{echo}} - n\Delta t_{\mathrm{echo}}, t_0)$$

$$\mathcal{M}_{T,I}(t, t_0) \equiv \Theta_I(t, t_0)\mathcal{M}_I(t).$$

$$\Theta_I(t, t_0) \equiv \frac{1}{2}\left\{1 + \tanh\left[\frac{1}{2}\omega_I(t)(t - t_{\mathrm{merger}} - t_0)\right]\right\}$$

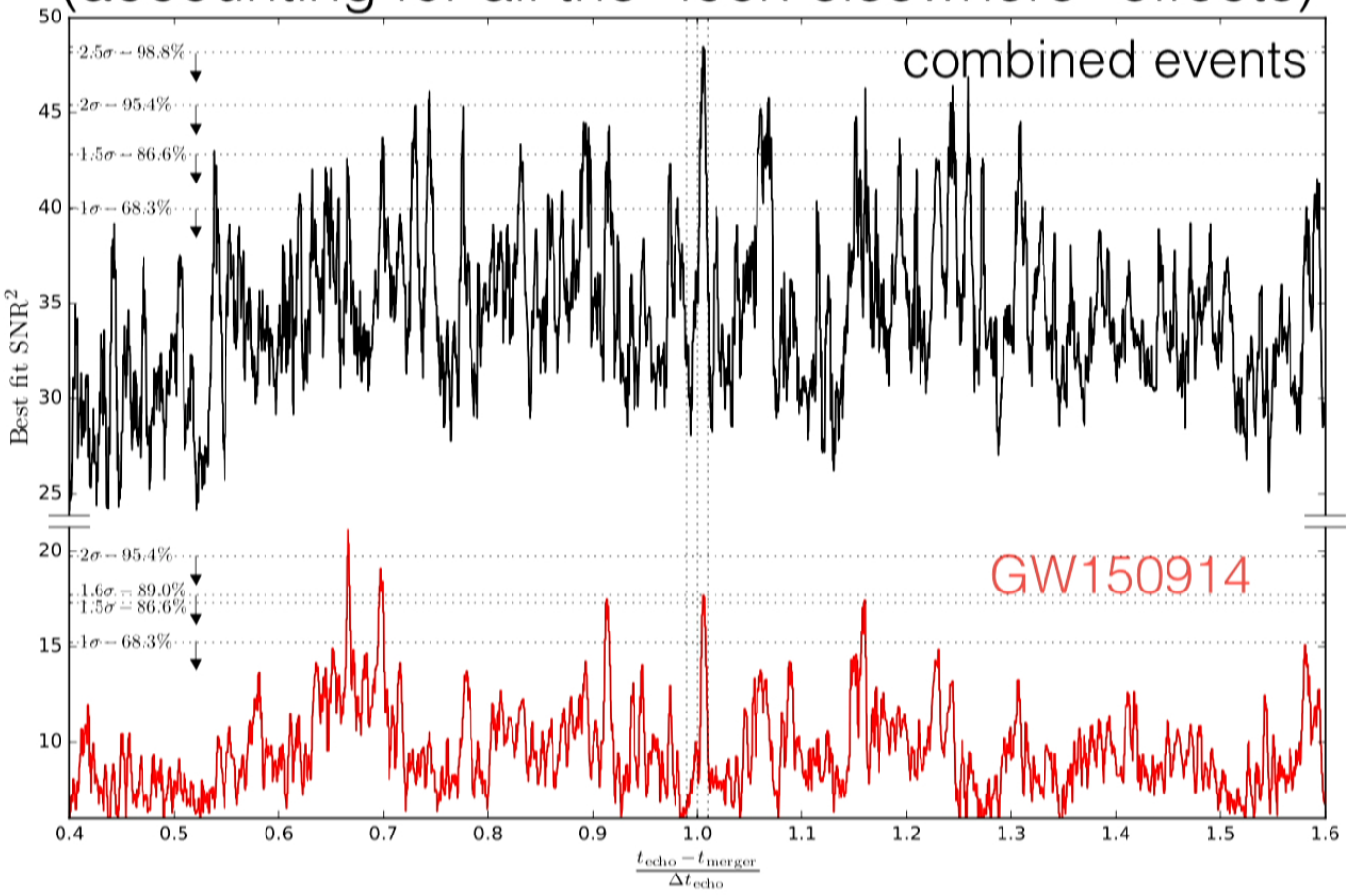


Abedi, Dykaar & NA 2017

Abedi, Dykaar & NA 2017

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

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



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

Event	ADA	original priors 16s (32s)	widened priors 16s (32s)
GW150914	0.11	0.199 (0.23)	0.705 (0.365)
(1,2,3)	0.011	0.02 (0.032)	0.18 (0.144)
(1,3,4)	-	0.199 (0.072)	0.9 (0.32)
(1,2,3,4)	-	0.044 (0.032)	0.368 (0.112)

see talk by *Julian Westerweck* (AEI) at http://pirsa.org/17110073/

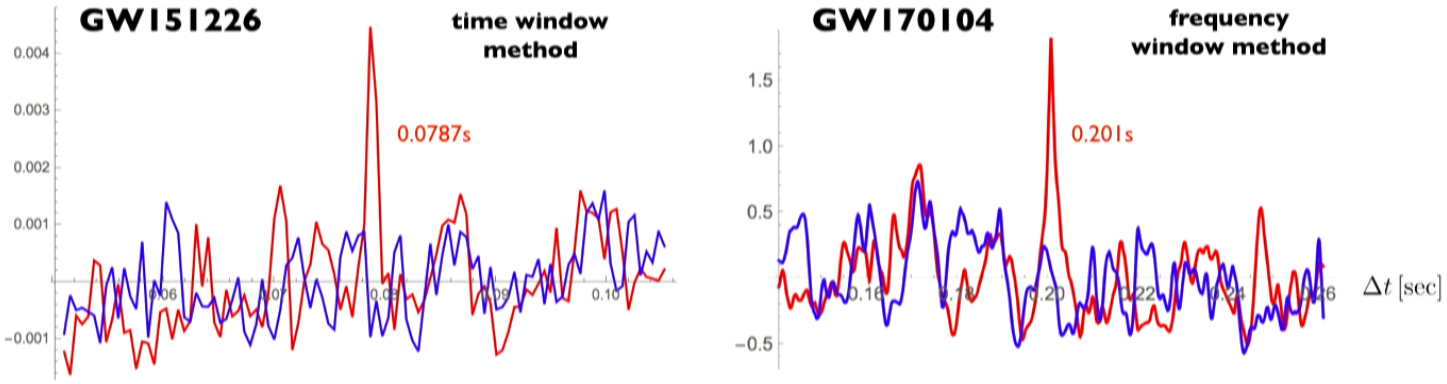
Low significance of evidence for black hole echoes in gravitational wave data

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*

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)



- ***Results***: finding tentative signal peaks for *GW151226, GW170104, GW170608, GW170814, GW170817* among the five confirmed BBH events, the best fit time delay $\Delta t/M \sim$ 550-850

  (See Jing Ren's talk at http://pirsa.org/17110087/)

- *arXiv: 1712.06517*: ***p-values ~ 0.2%-0.8%***

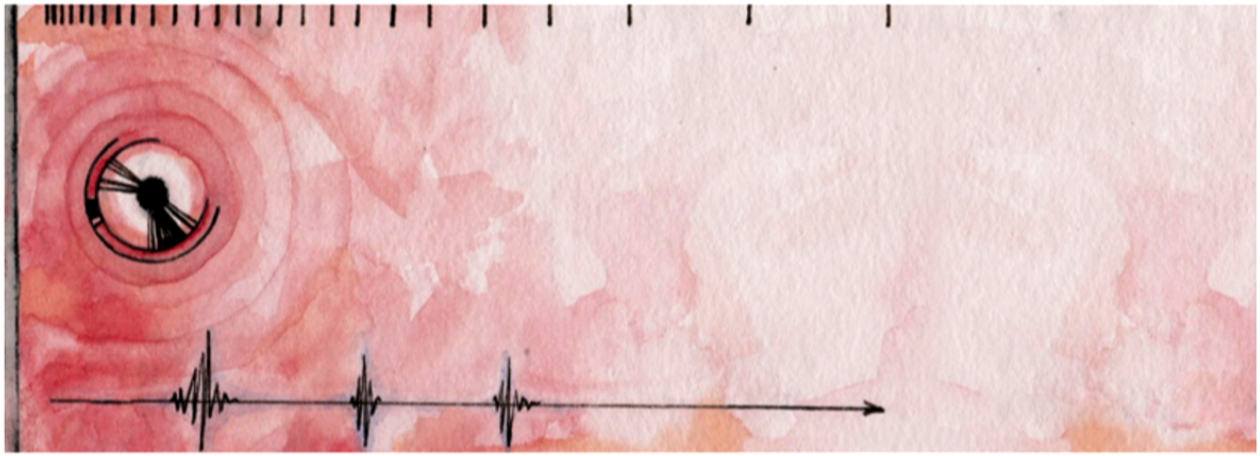
Randy Conklin, Bob Holdom, Jing Ren

QUANTUM BLACK HOLES IN THE SKY?

Conference Date: Wednesday, November 8, 2017 (All day) to Friday, November 10, 2017 (All day)

Scientific Areas: Quantum Fields and Strings
Quantum Gravity
Quantum Information
Strong Gravity

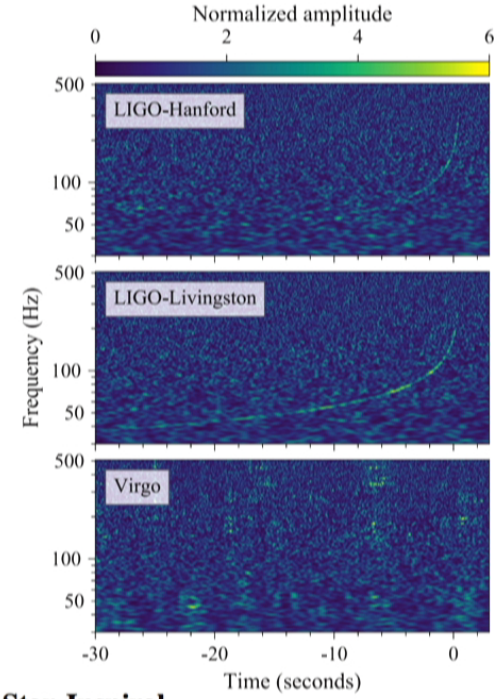
http://pirsa.org/C17055



The past decade has witnessed significant breakthroughs in understanding the quantum nature of black holes, with insights coming from quantum information theory, numerical relativity, and string theory. At the same time, astrophysical and gravitational wave observations can now provide an unprecedented window into the phenomenology of black hole horizons. This workshop seeks to bring together leading experts in these fields to explore new theoretical and observational opportunities and synergies that could improve our physical understanding of quantum black holes.

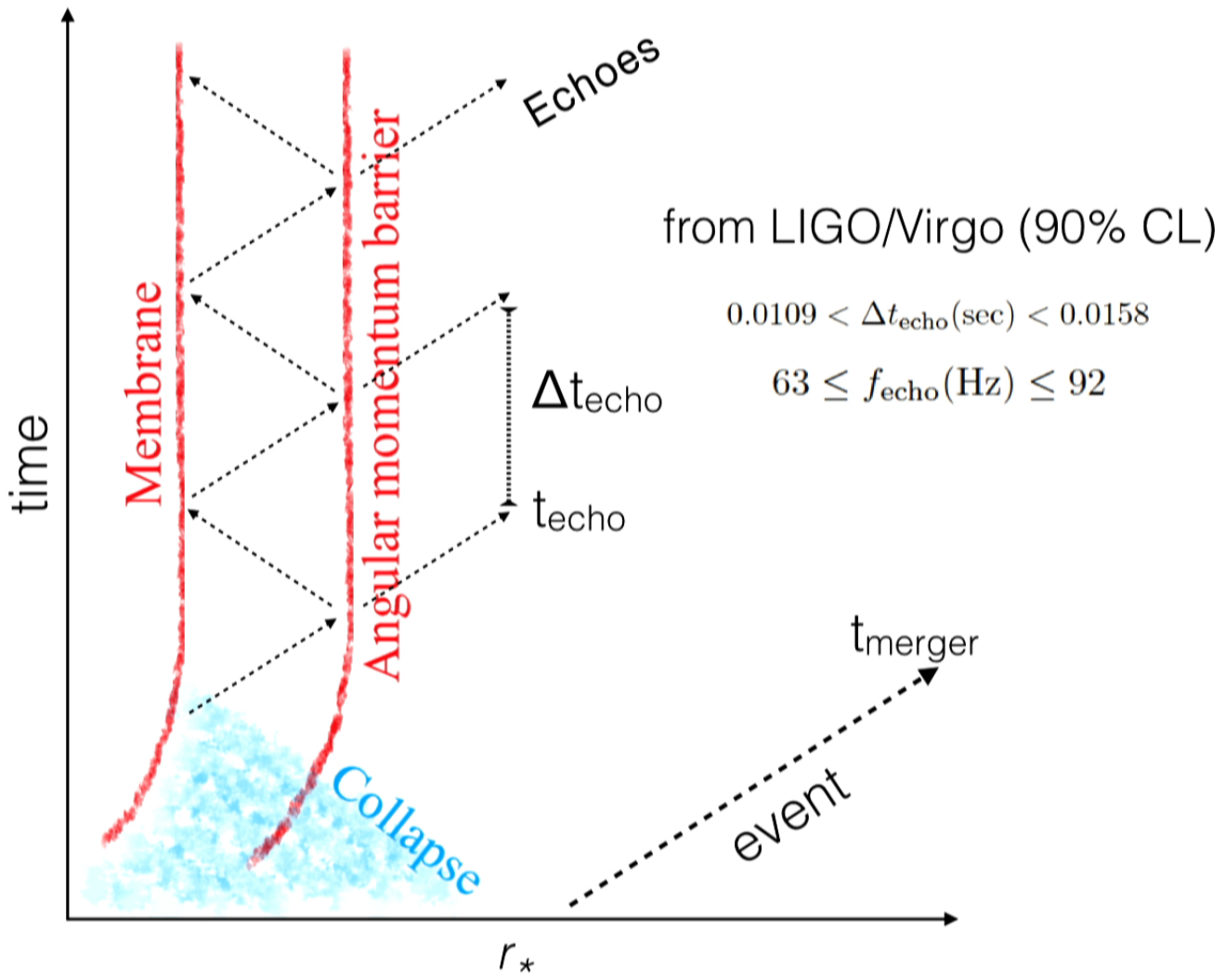
GW170817: Echoes from Binary Neutron Star mergers?!

- No post-merger signal seen (or expected) in LIGO/Virgo
- Echoes could provide unique window into formation/properties of remnant black hole
- Very different frequency range!



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)


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

A model-agnostic search for <u>unresolved</u> echoes

- Optimal search strategy for *<u>a periodically repeating delta-function</u>*:

  ★ Wiener filter (time shifted) Hanford and Livingston data

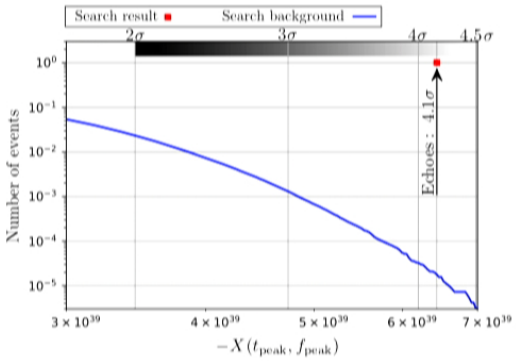
$$H(t,f) = \text{Spectrogram}\left[\text{IFFT}\left(\frac{\text{FFT}(\text{h}_\text{H}(\text{t}-\delta\text{t}))}{\text{ASD}_\text{L}^2}\right)\right] \quad L(t,f) = \text{Spectrogram}\left[\text{IFFT}\left(\frac{\text{FFT}(\text{h}_\text{L}(\text{t}))}{\text{ASD}_\text{L}^2}\right)\right]$$

  ★ Cross-correlate the two signals and look for peaks

$$X(t,f) = \sum_{n=1}^{10} Real(H(t,nf) \times L(t,nf)^*)$$

preliminary

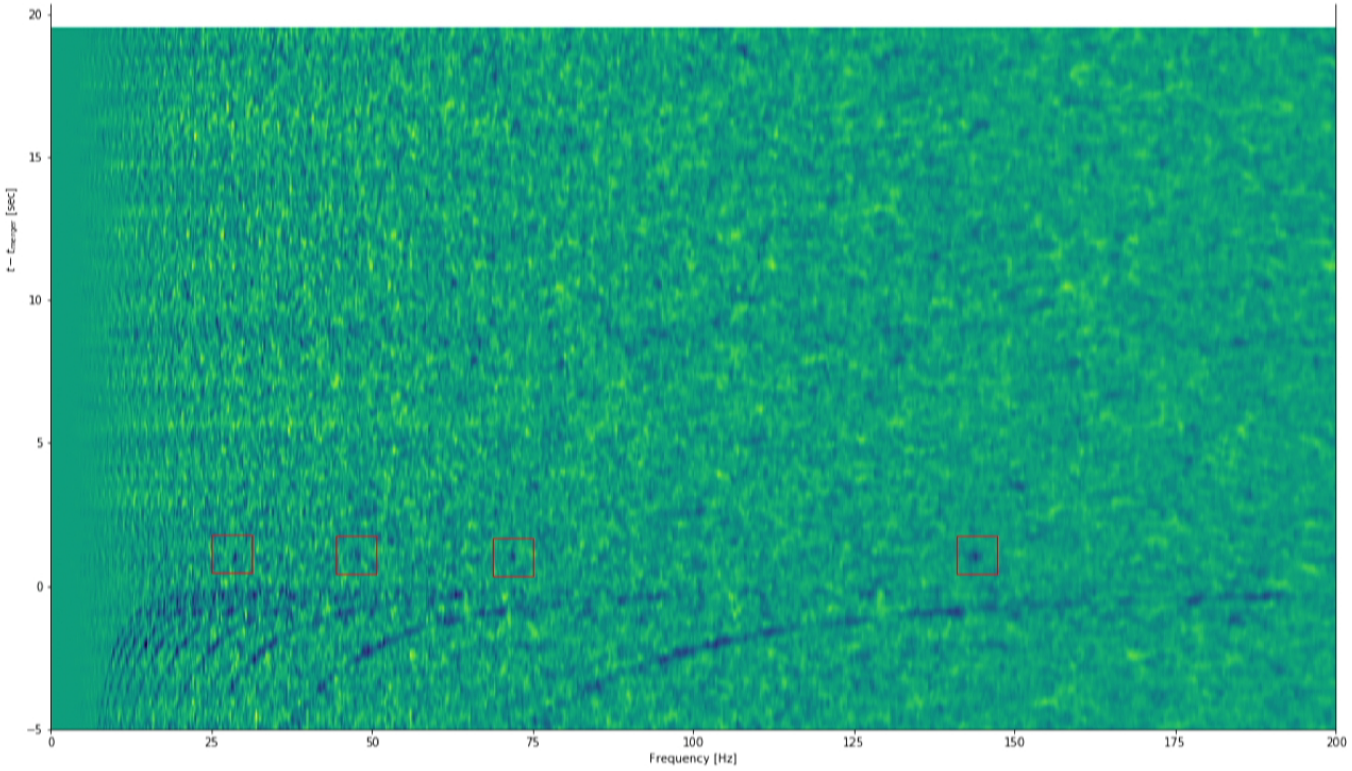
Echoes 0.5 sec after GW170817



w/ Jahed Abedi

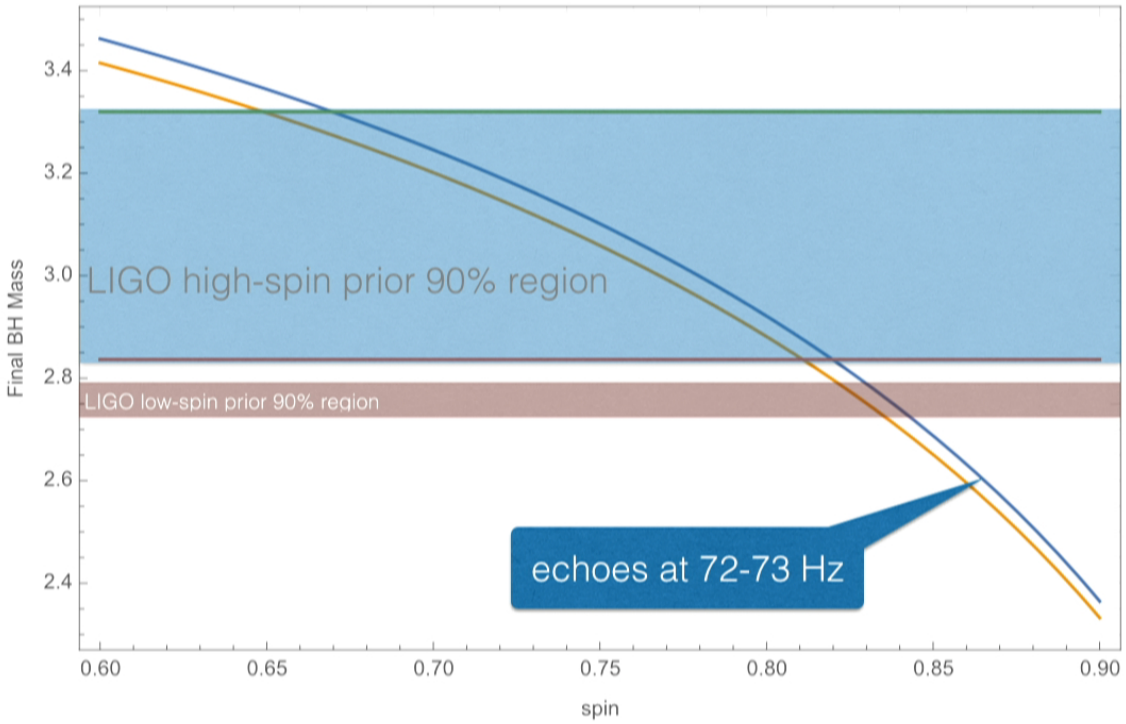
preliminary

GW170817:before vs after

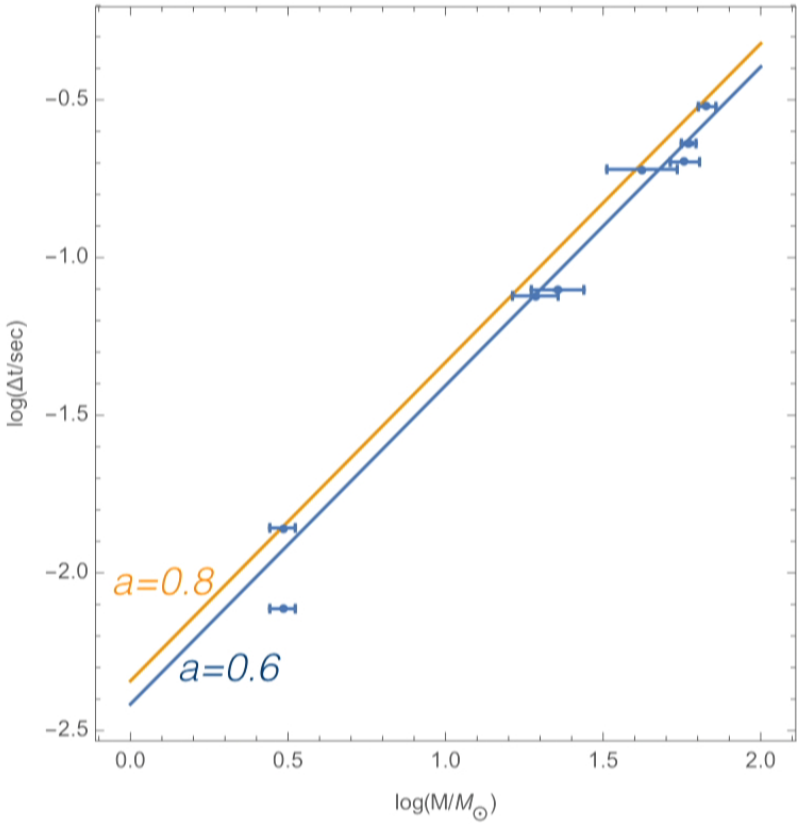


preliminary

A Kerr BH at a=0.83?



Anyone who has looked for echoes has found them!™*



* to my knowledge!