Theoretical High Energy Physics Seminar
McGill University
Apr. 6, 2018

Quantum Black Holes in the Sky

from Quantum Gravity to Astrophysics and Cosmology

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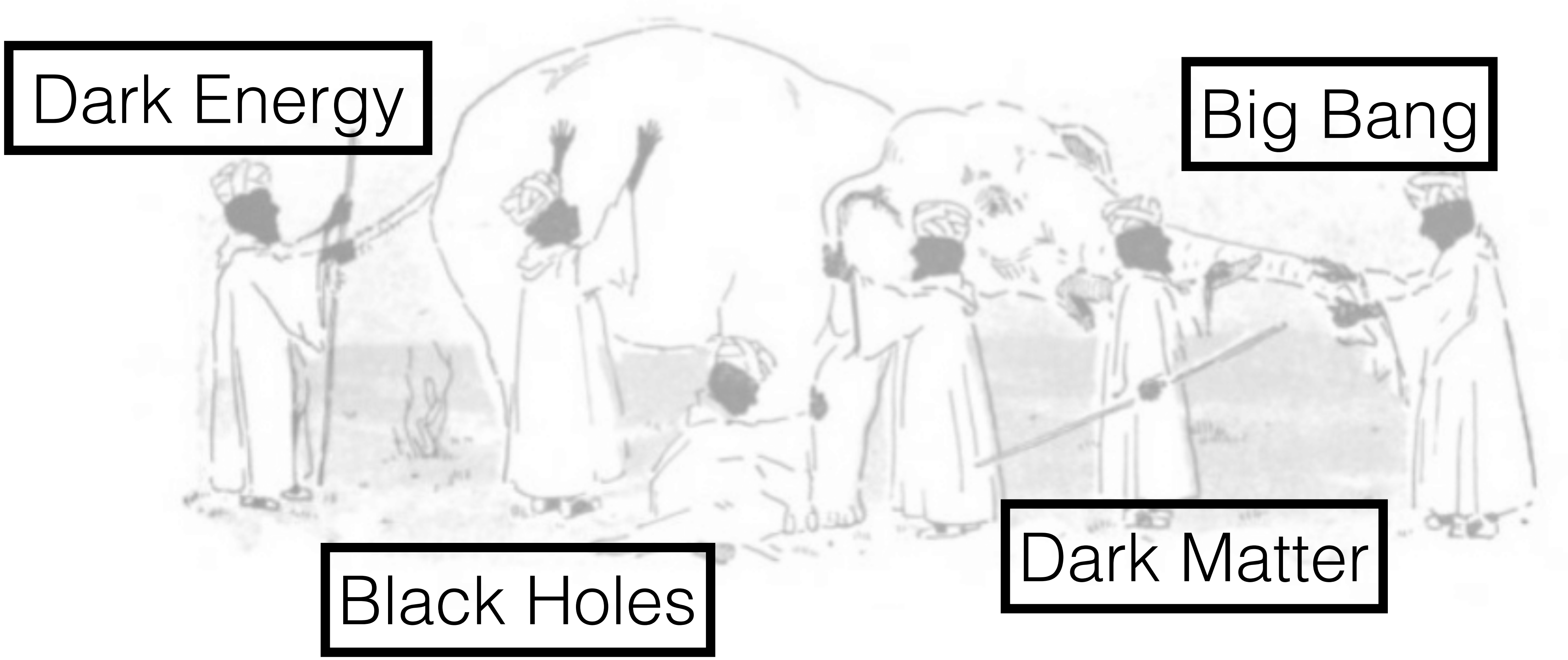
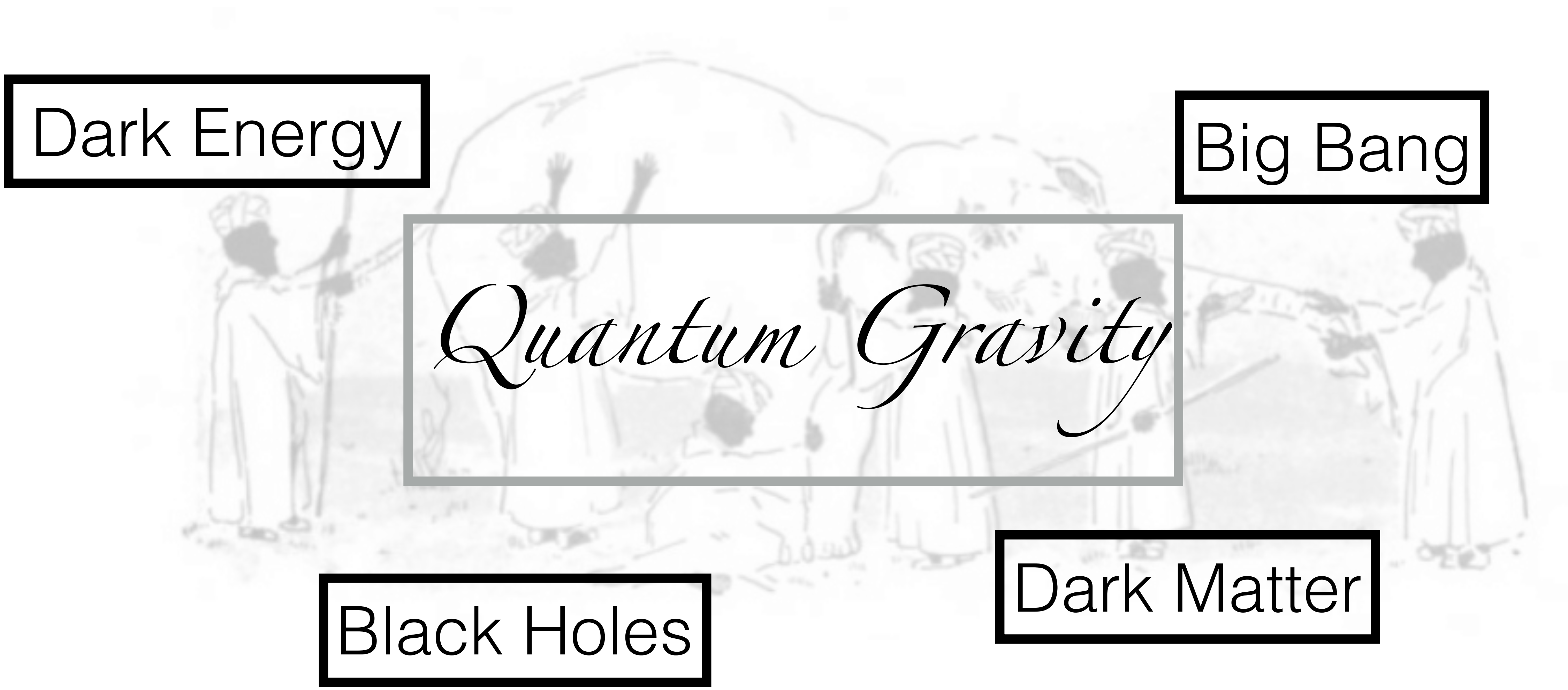
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Prelude: *Unravelling the Darkness*



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

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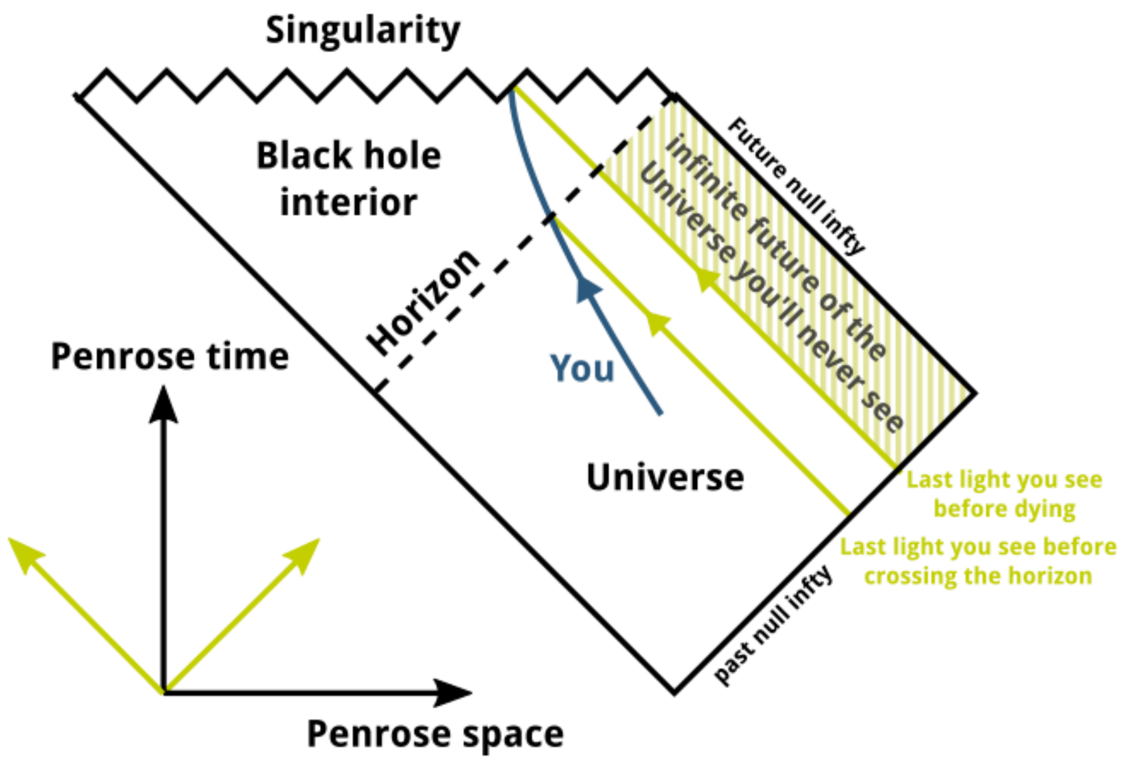
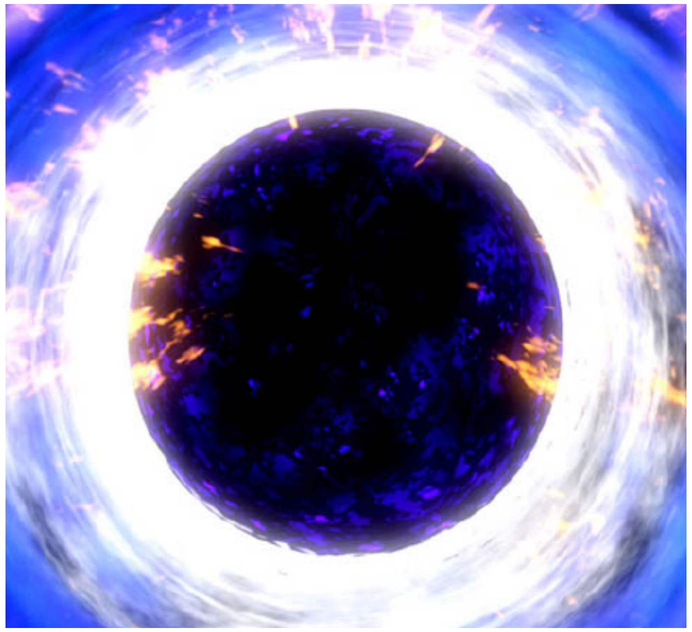
Event Horizons in Relativity

- Global structure of some spacetimes lead to event horizons

- In classical GR, local observers experience “no drama” at horizon





Black Hole Thermodynamics

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

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

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

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Which states does this entropy count?!

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) ~ 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)*

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)

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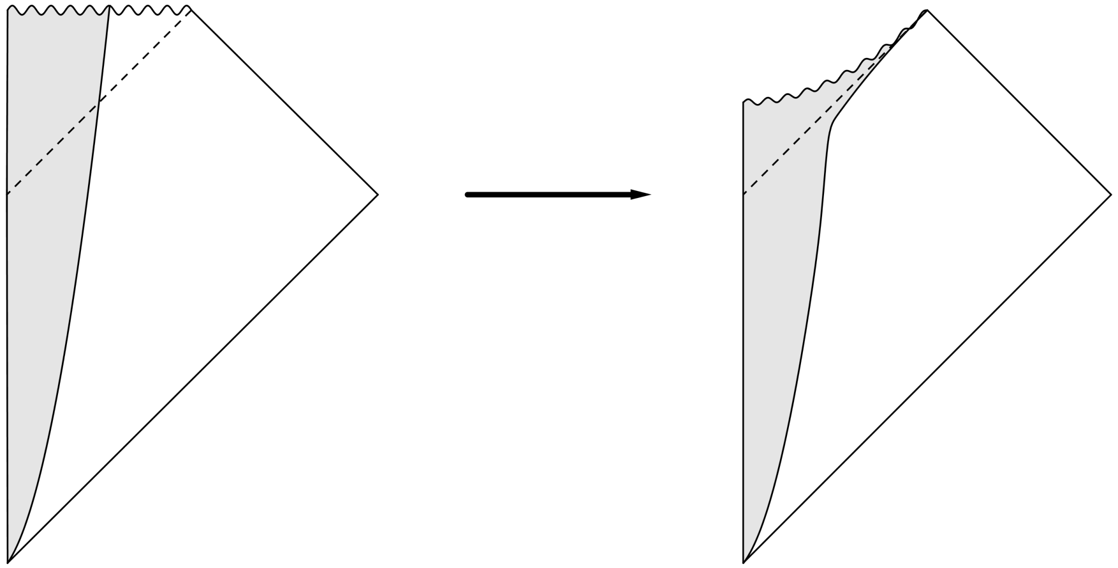
What else could it be?

- **Fuzzballs** (*a la* Mathur)**:** classical horizon-less spacetimes, account for BH entropy

- **Aether Holes** *(NA, Prescod-Weinstein, Balogh, Mann, Saravani)***:** membrane with Z_2 symmetry, account of BH entropy, *explain dark energy*

- Gravastar, 2-2 hole, Planck star, …



Collapsing Schwarzschild Black Hole

Collapsing Aether Black Hole

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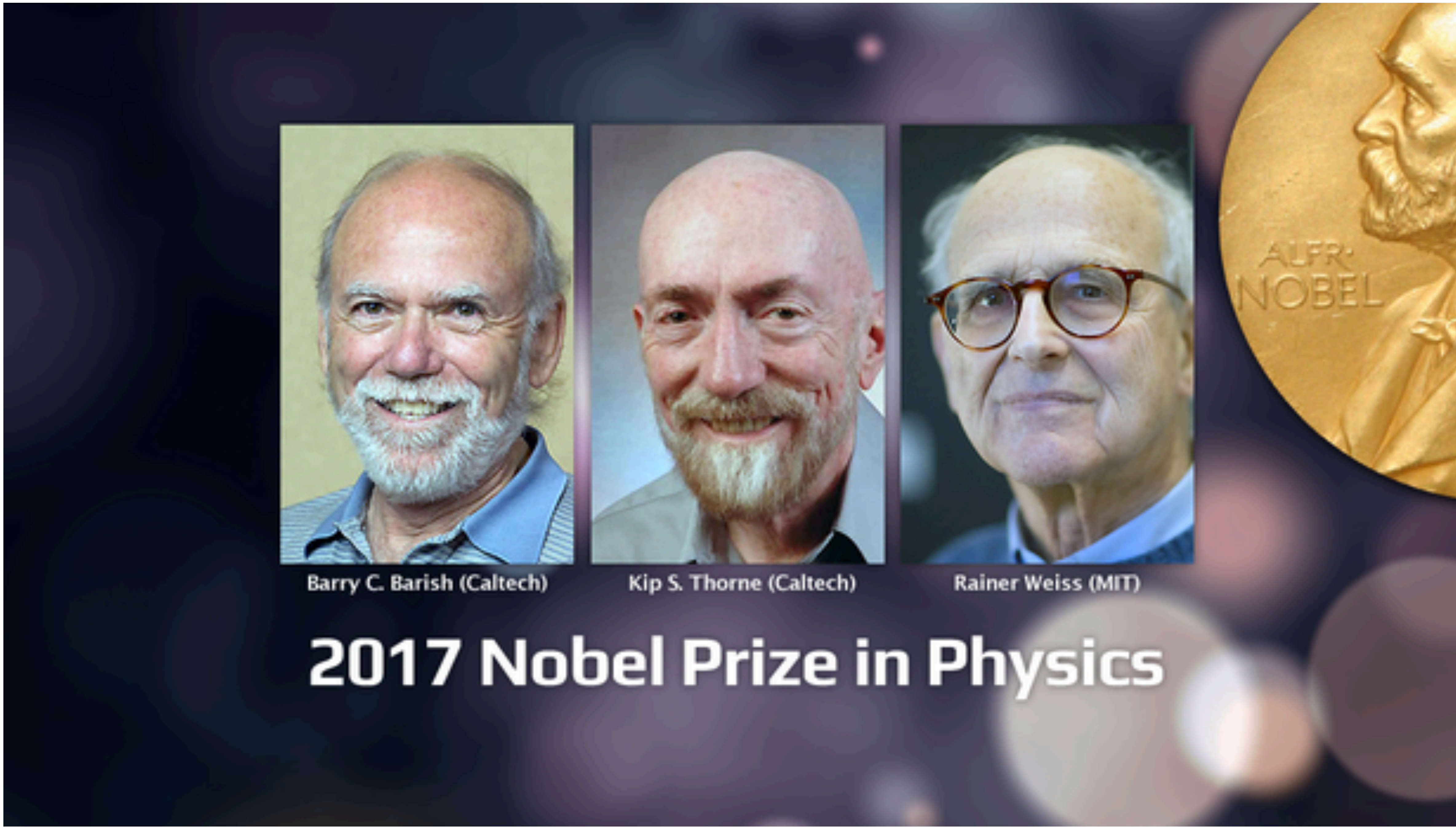
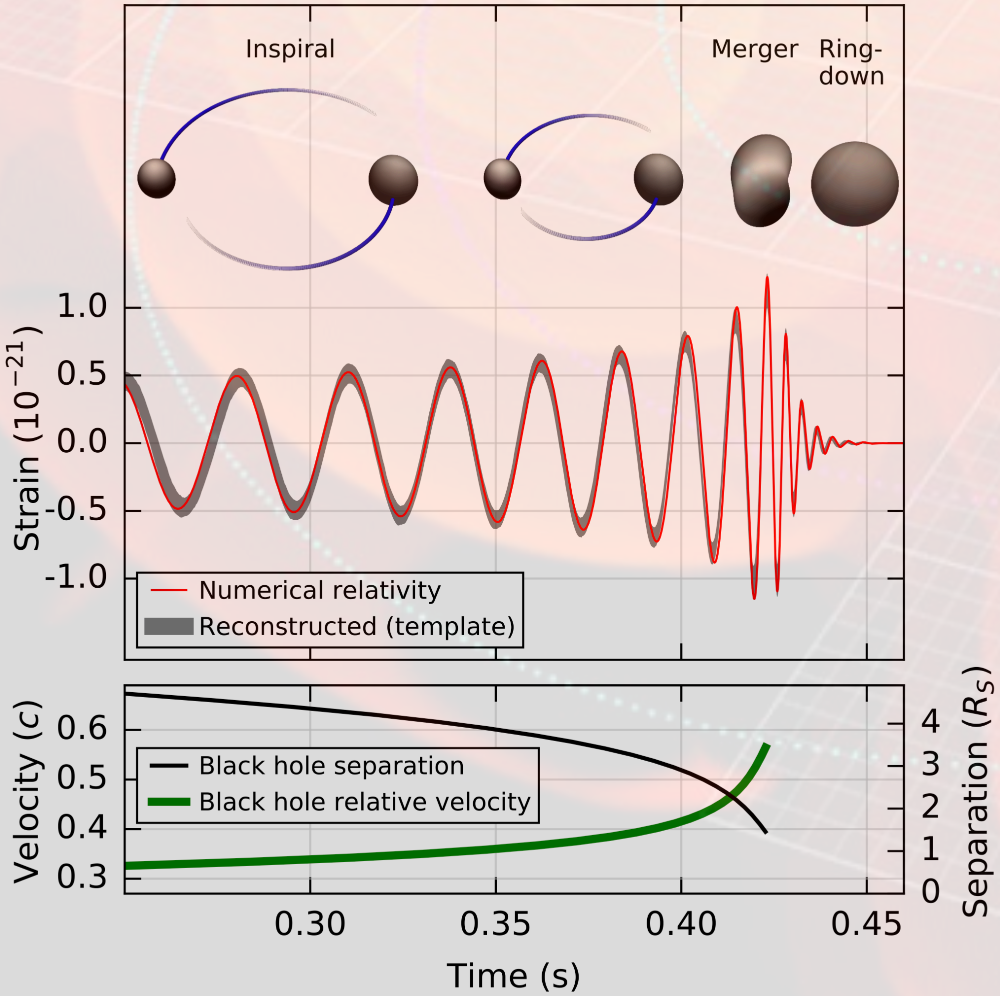
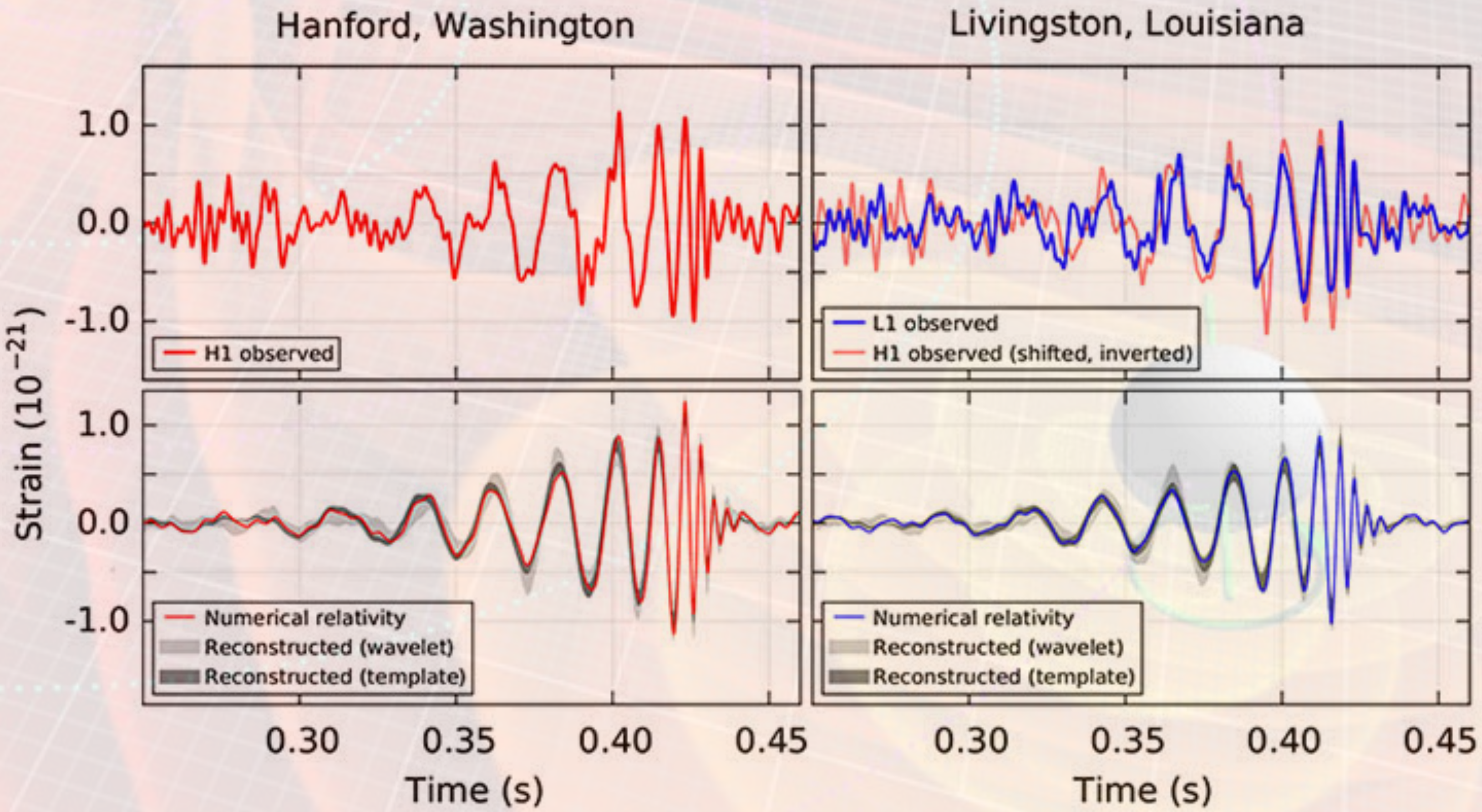

Barry C. Barish (Caltech)
Kip S. Thorne (Caltech)
Rainer Weiss (MIT)
2017 Nobel Prize in Physics
ALFR. NOBEL

The Future is NOW!





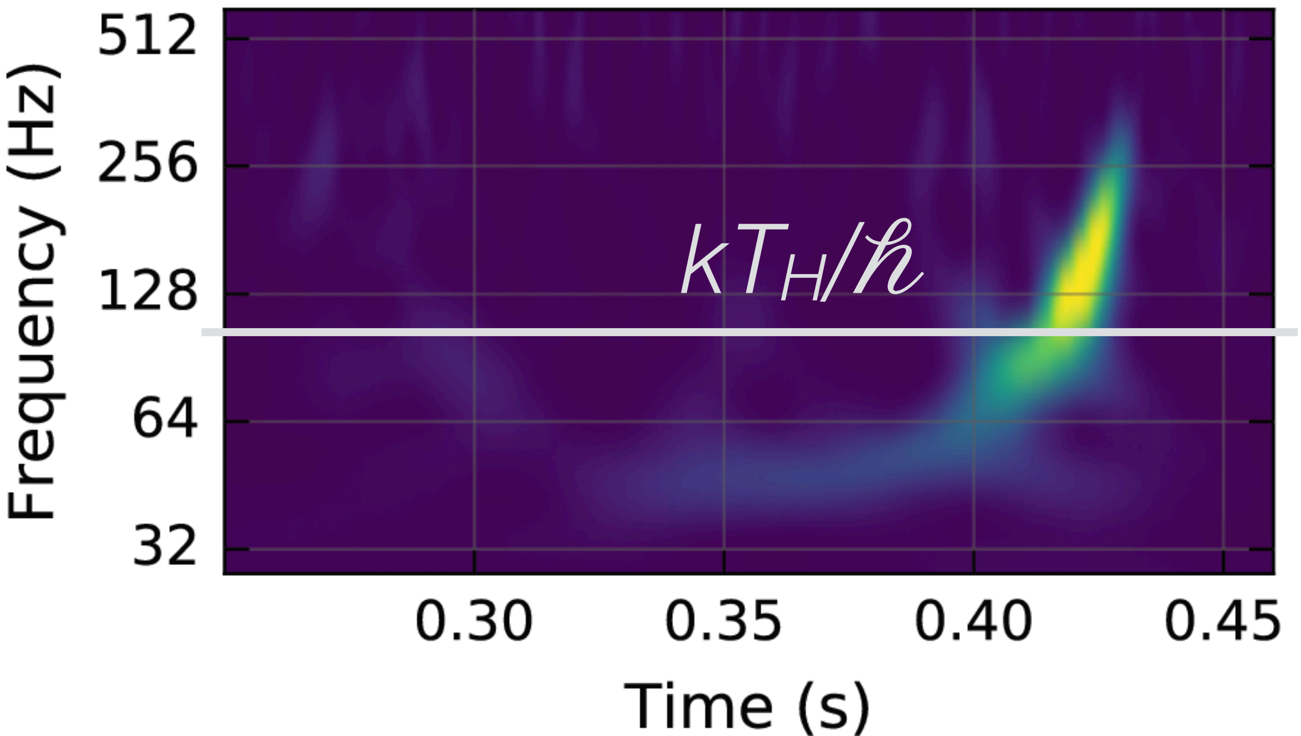
LIGO collaboration, 2016

What should we see?

- Particles with $E \gtrsim kT_H$ can black hole microstates, and so *may be* absorbed

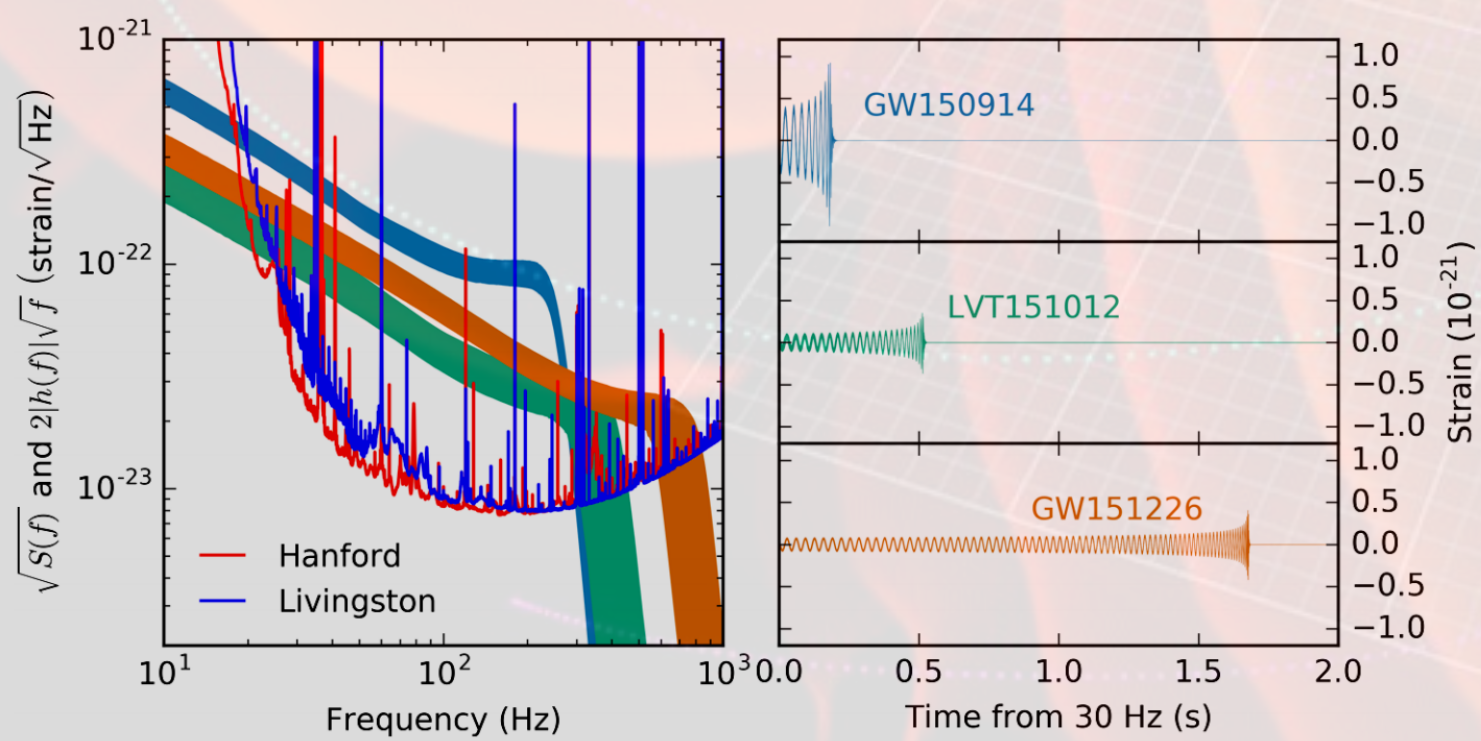
- Particles with $E \lesssim kT_H$ will be reflected

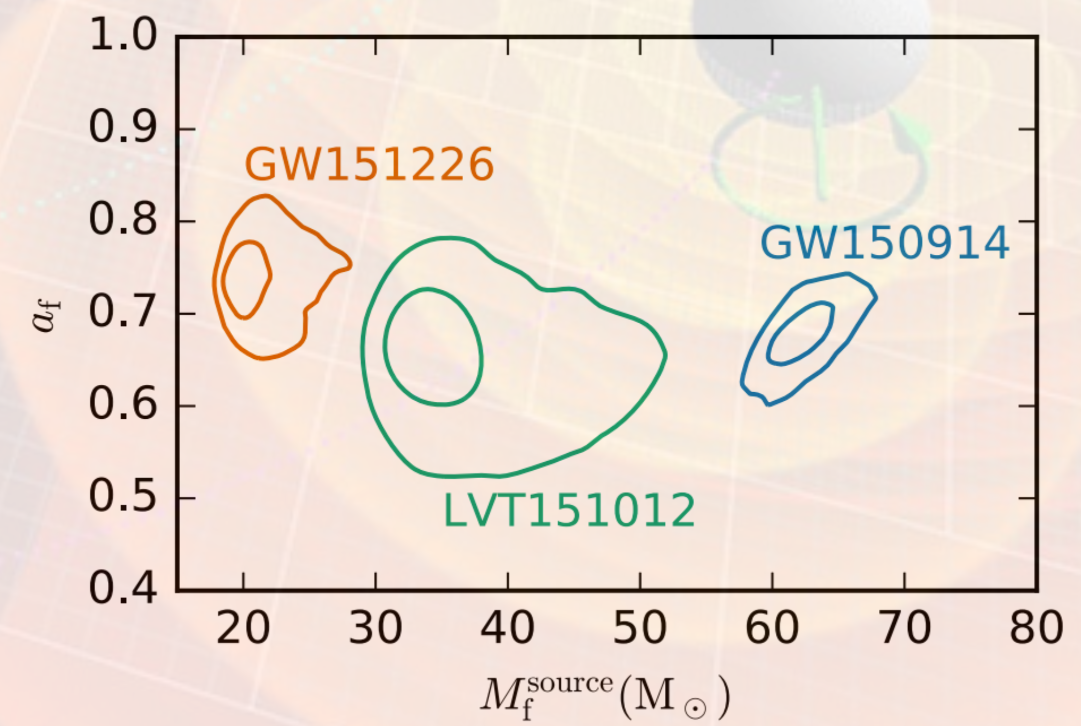
- Ringdown of black holes $\hbar\omega \sim kT_H$

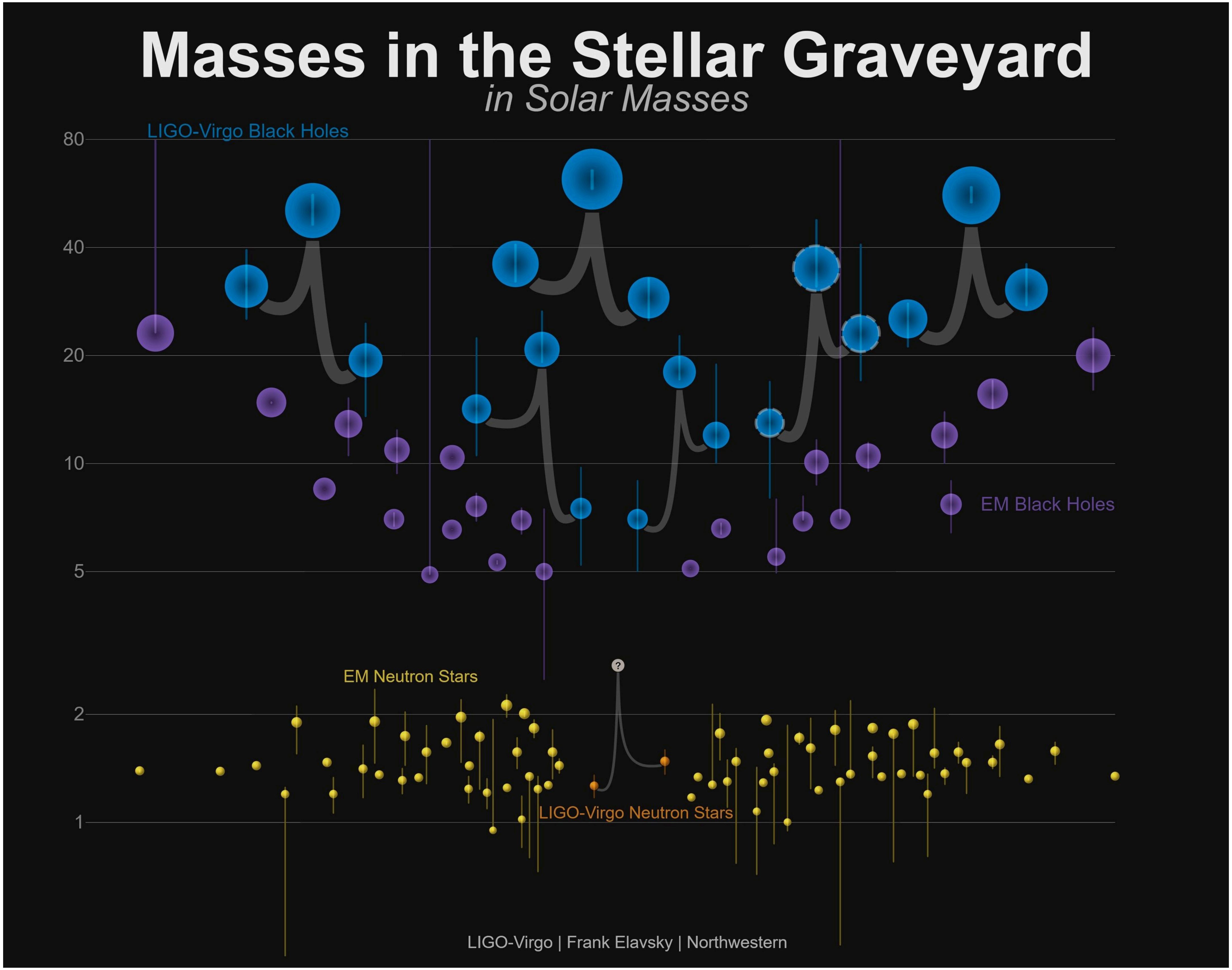


Advanced LIGO
GW150914

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 $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	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 $\Delta\Omega/\mathrm{deg}^2$	230	850	1600





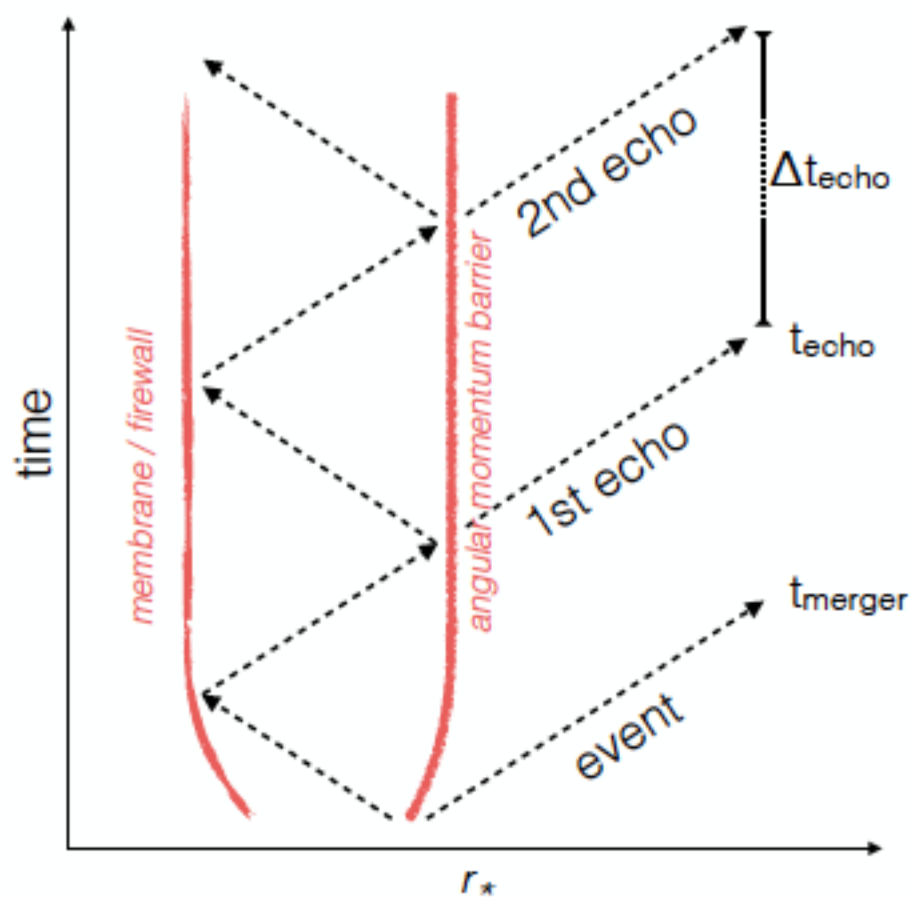


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
?
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

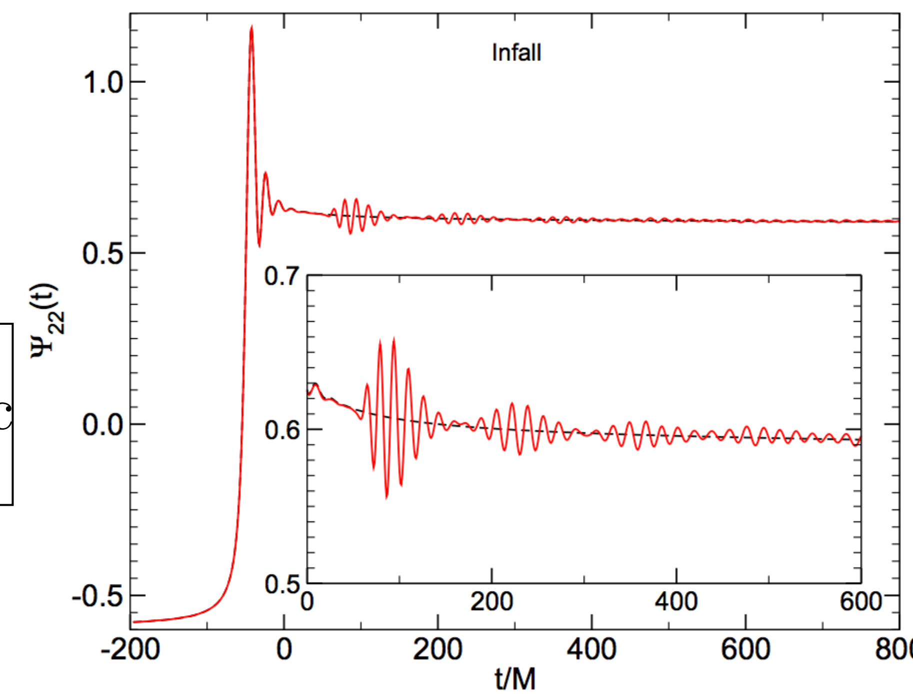
Echoes from the Abyss!

- Late echoes from Planckian structure near horizon

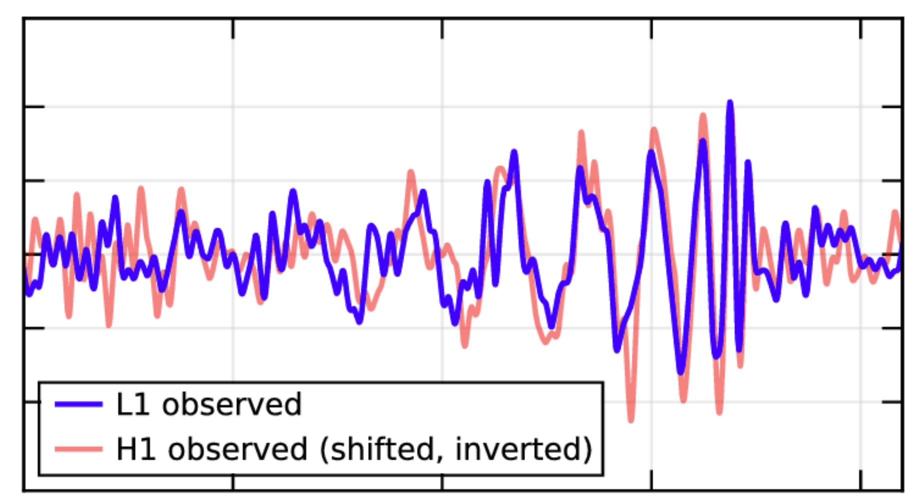
$$\Delta t_{\rm echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a_*^2}}\right) \times \ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right) \simeq 0.3 \text{ sec}$$



Cardoso, et al. 16



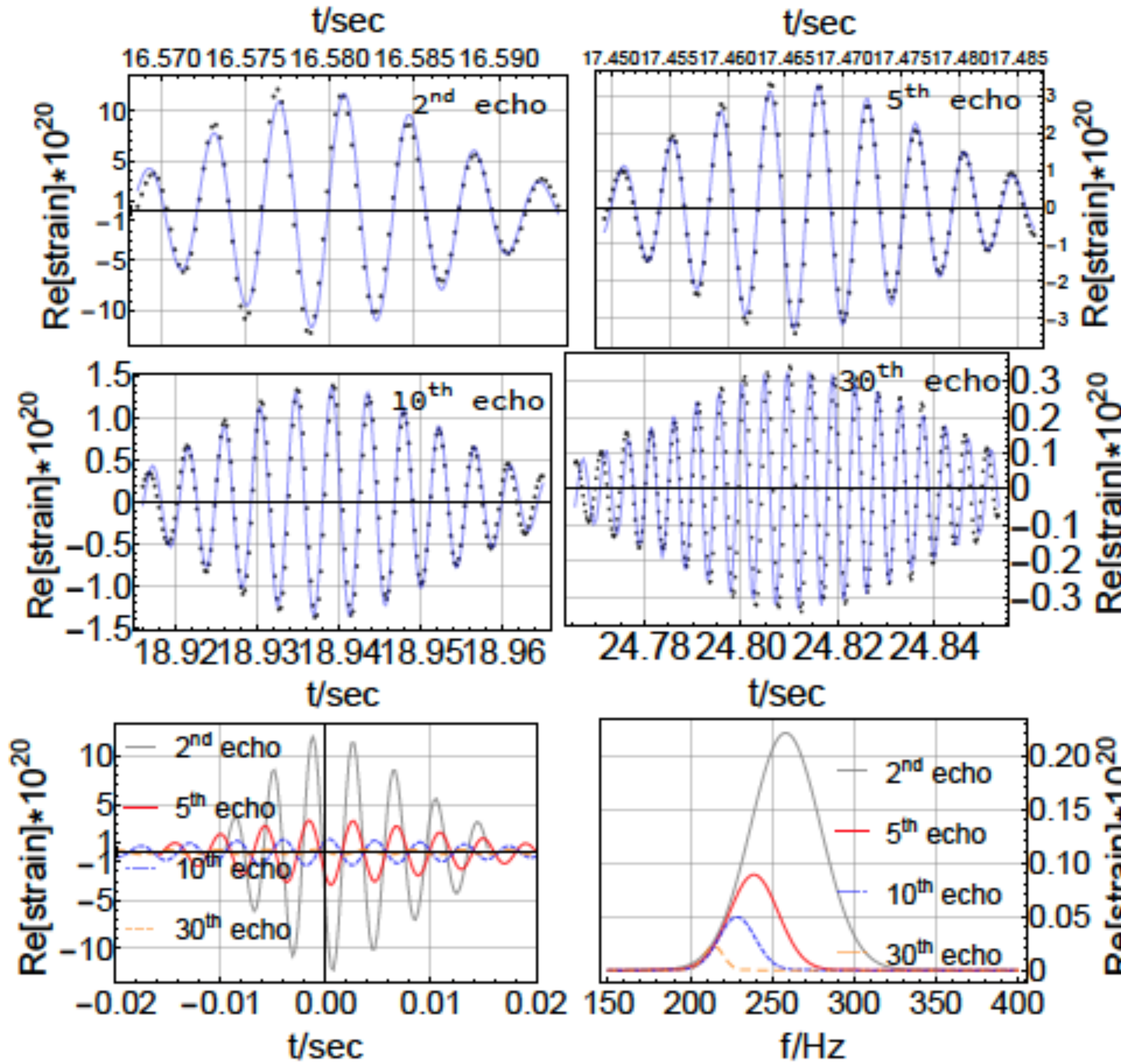
Livingston, Louisiana (L1)

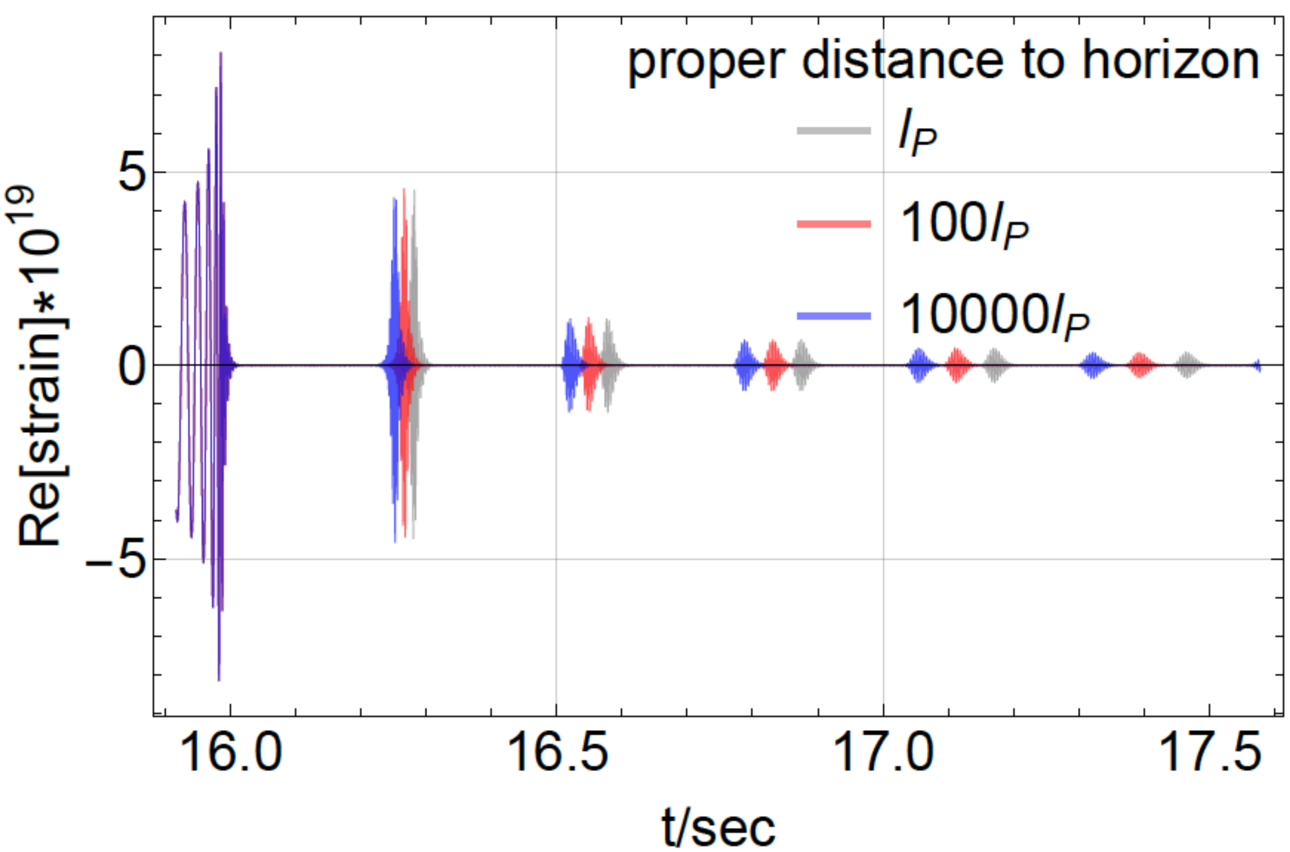


Black Hole Echology: The Observer's Manual

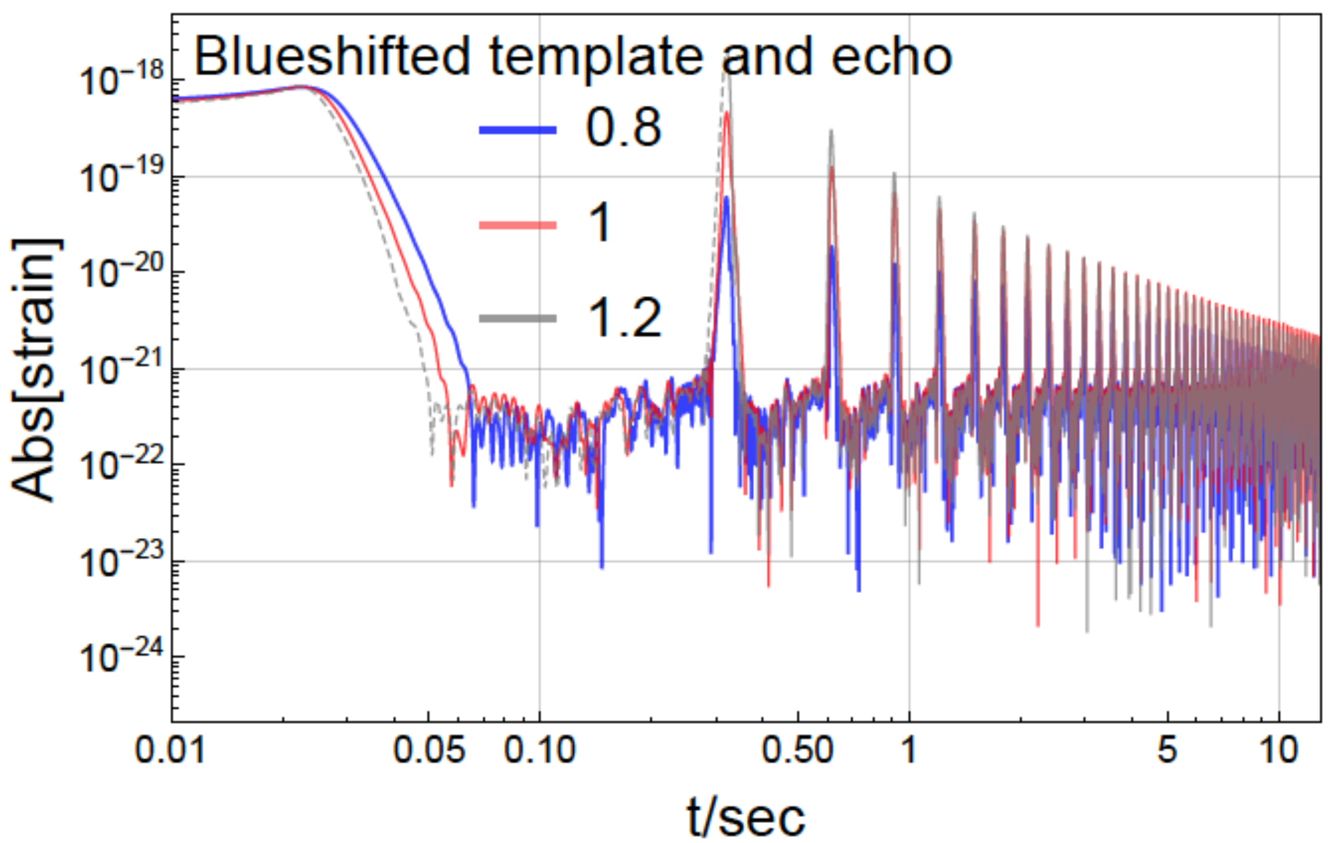
Qingwen Wang* and Niayesh Afshordi†
Perimeter Institute for Theoretical Physics
31 Caroline Street N, Waterloo,
ON, N2L 2Y5, Canada and
Department of Physics and Astronomy, University of Waterloo,
200 University Avenue West, Waterloo, ON, N2L 3G1, Canada

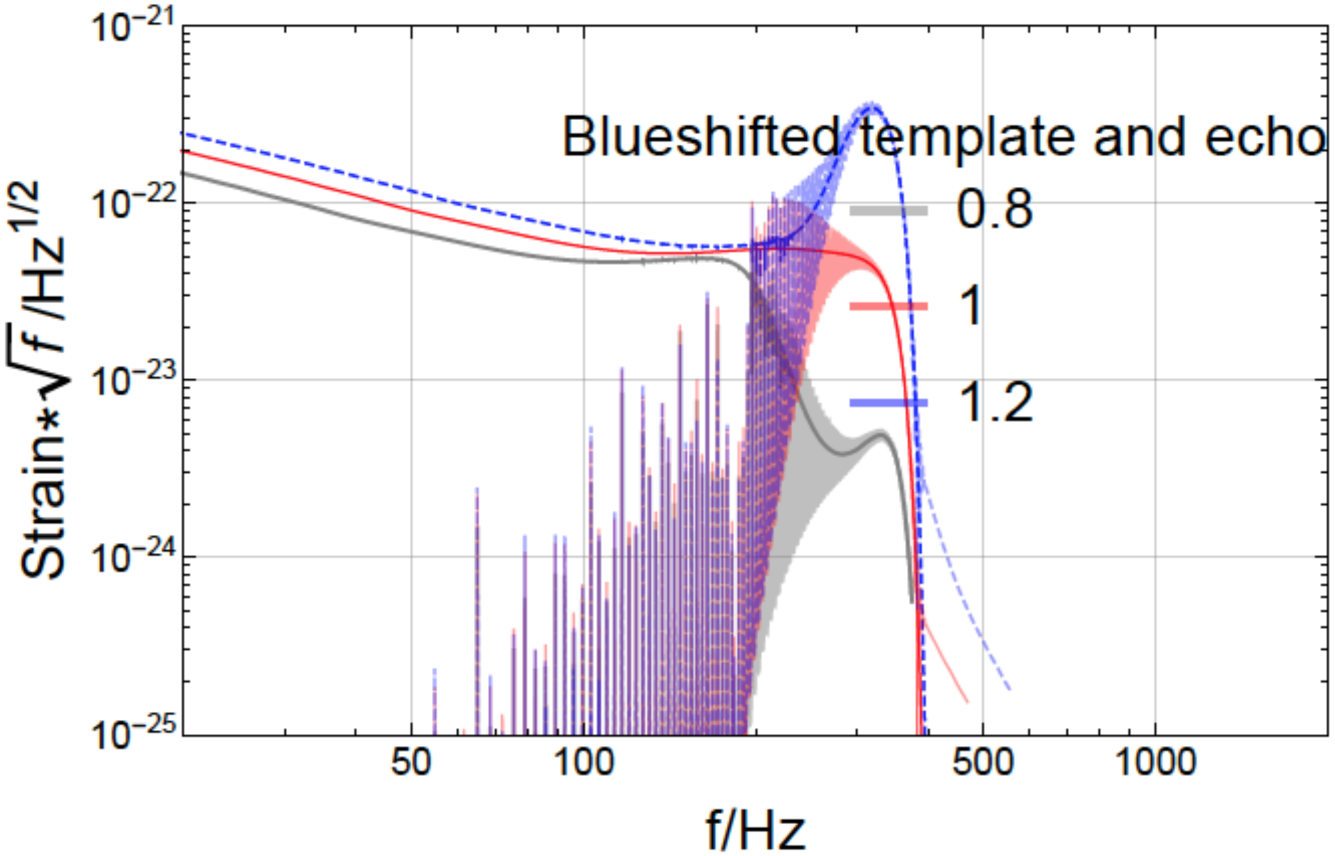
(Dated: February 21, 2018)



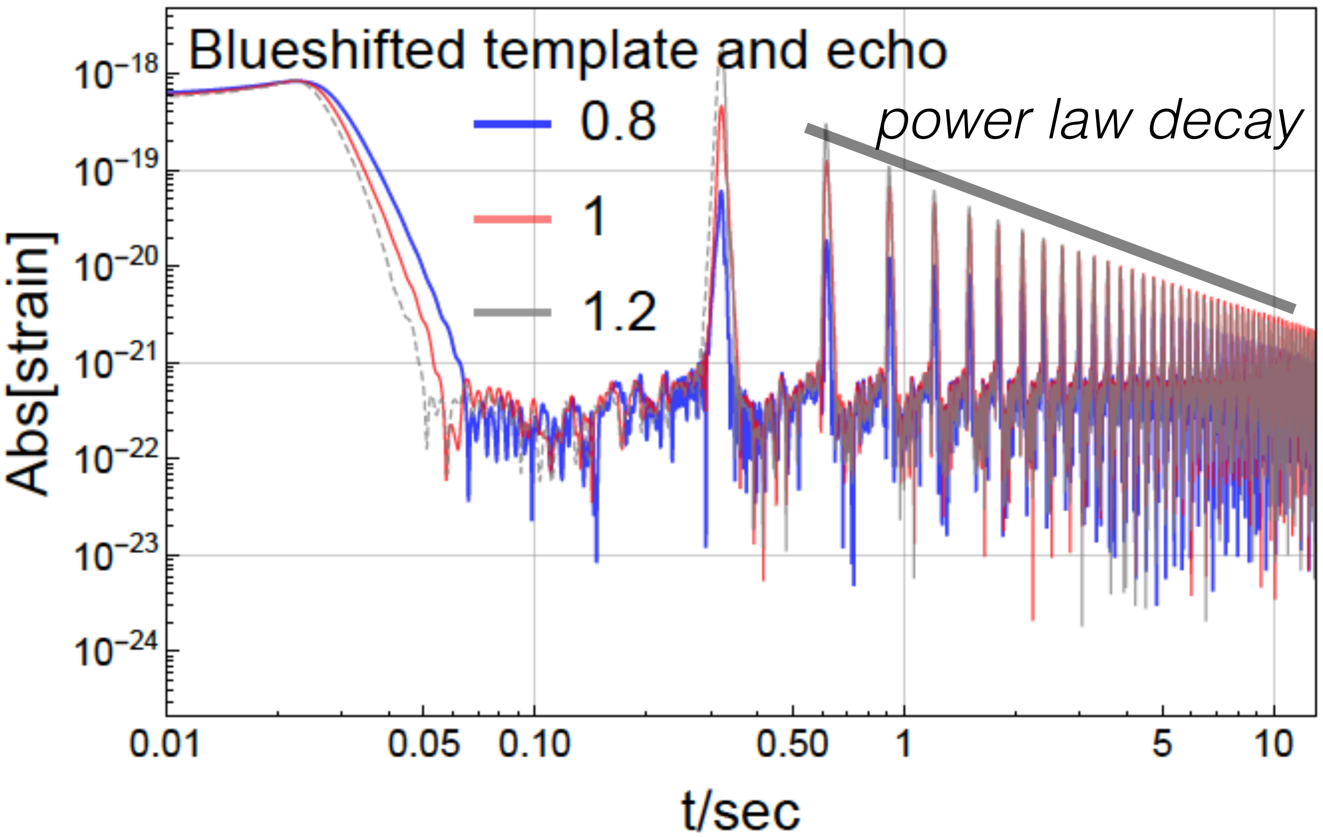


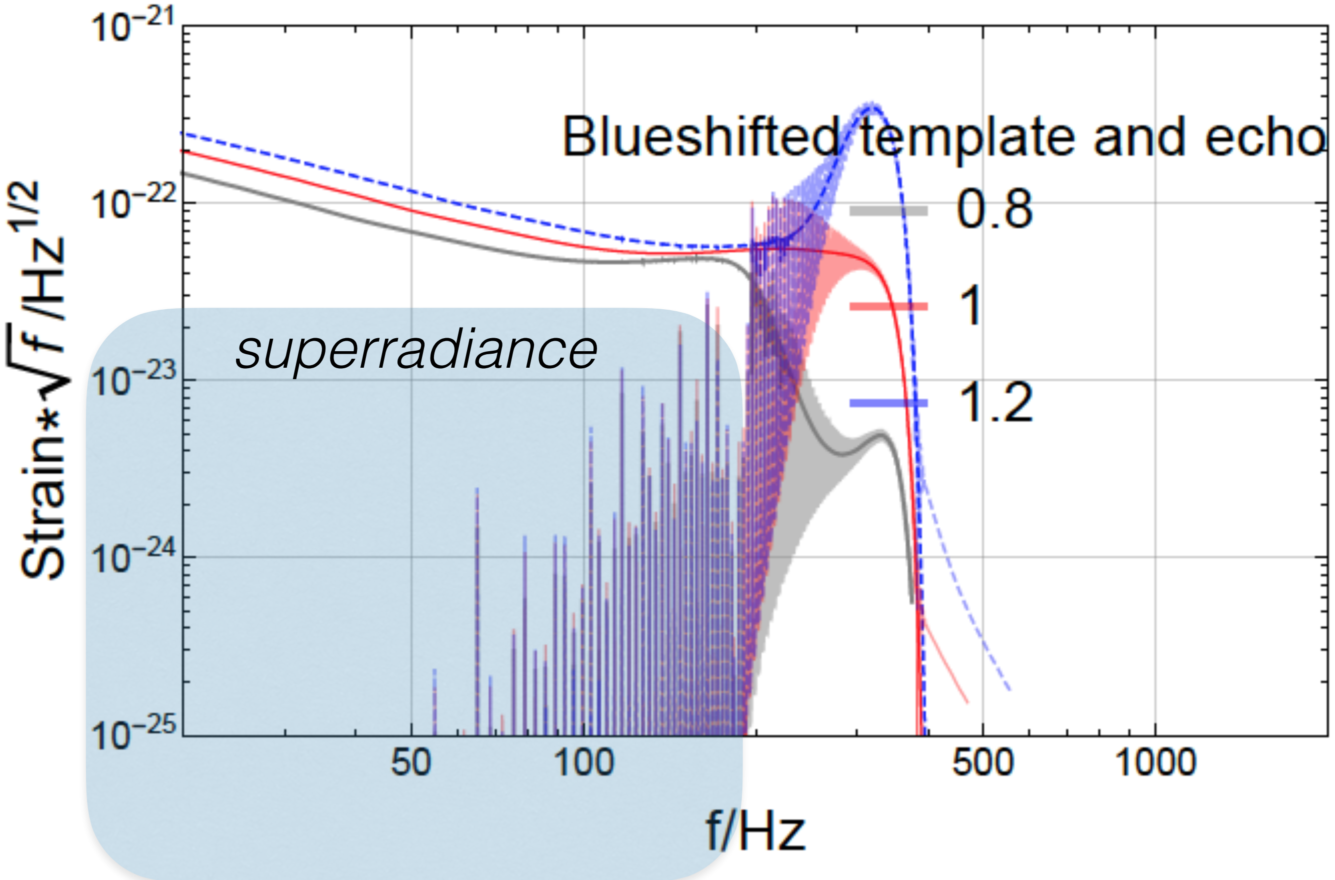
Echology 101





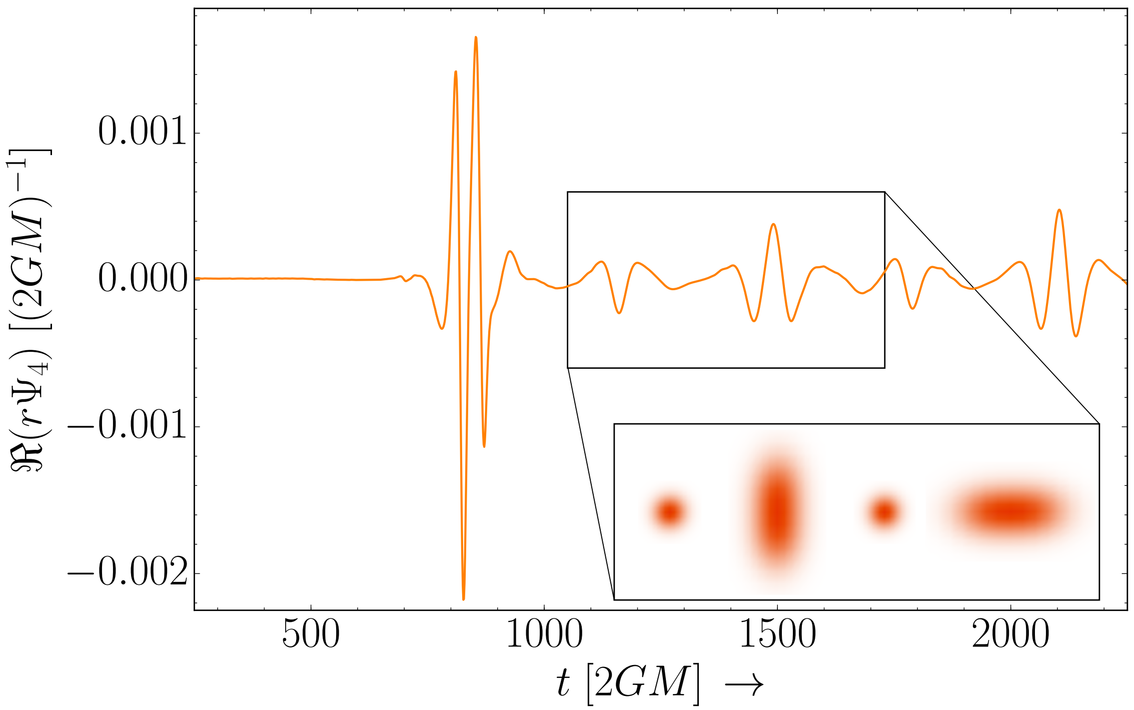
Echology 101





Simulating Echoes?

- Compact 3d field configurations (typically) unstable to forming BH's
- Quantum 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

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

Model

Data

detector noise

How to find the echoes?

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

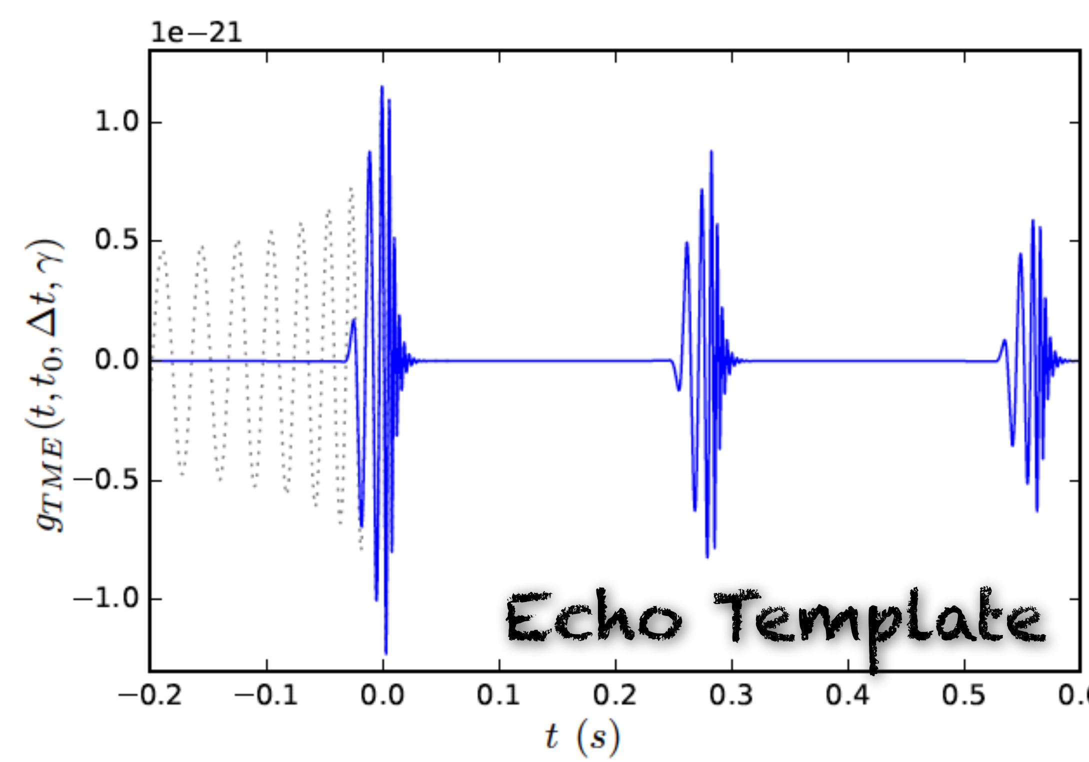
$$\Delta t_{\text{echo},I}(\text{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \text{GW150914} \\ 0.1013 \pm 0.01152 & I = \text{GW151226} \\ 0.1778 \pm 0.02789 & I = \text{LVT151012} \end{cases}$$

- Toy model for echo template

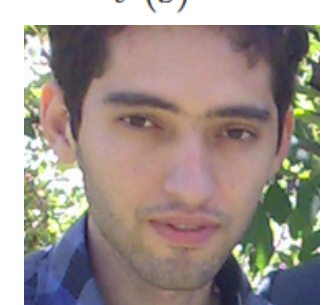
$$M_{TE,I}(t) \equiv A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}_{T,I}(t + t_{\text{merger}} - t_{\text{echo}} - n\Delta t_{\text{echo}}, t_0)$$

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

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



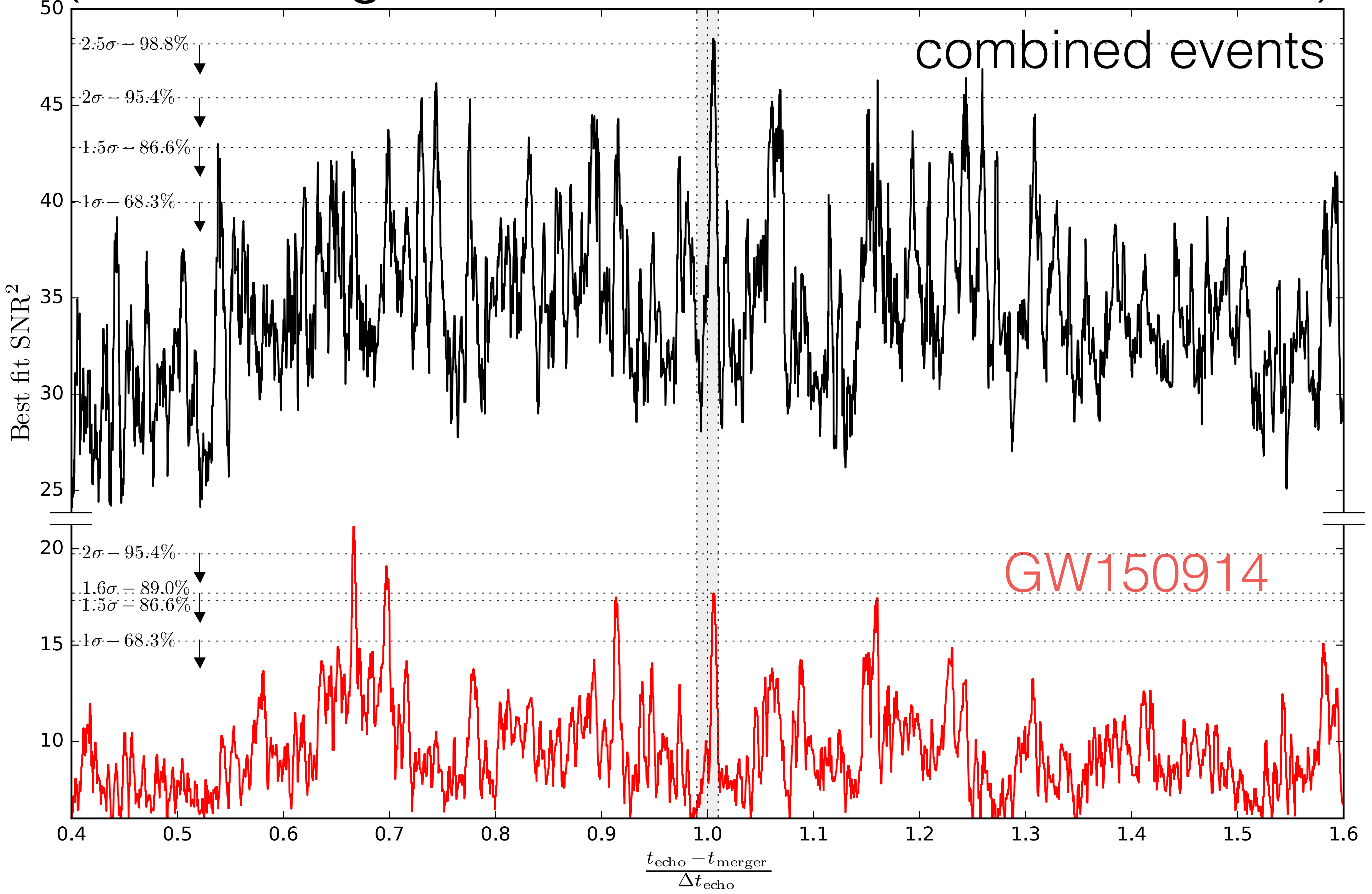
Abedi, *Dykaar* & *NA 2017*



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/

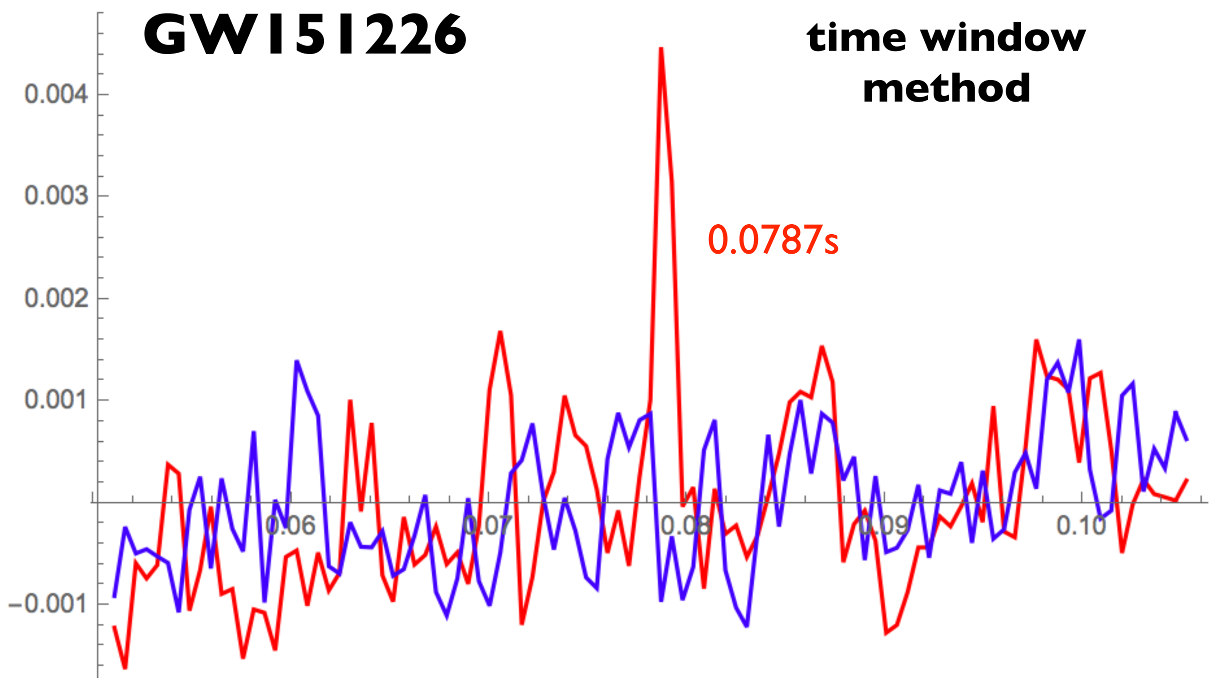
Low significance of evidence for black hole echoes in gravitational wave data

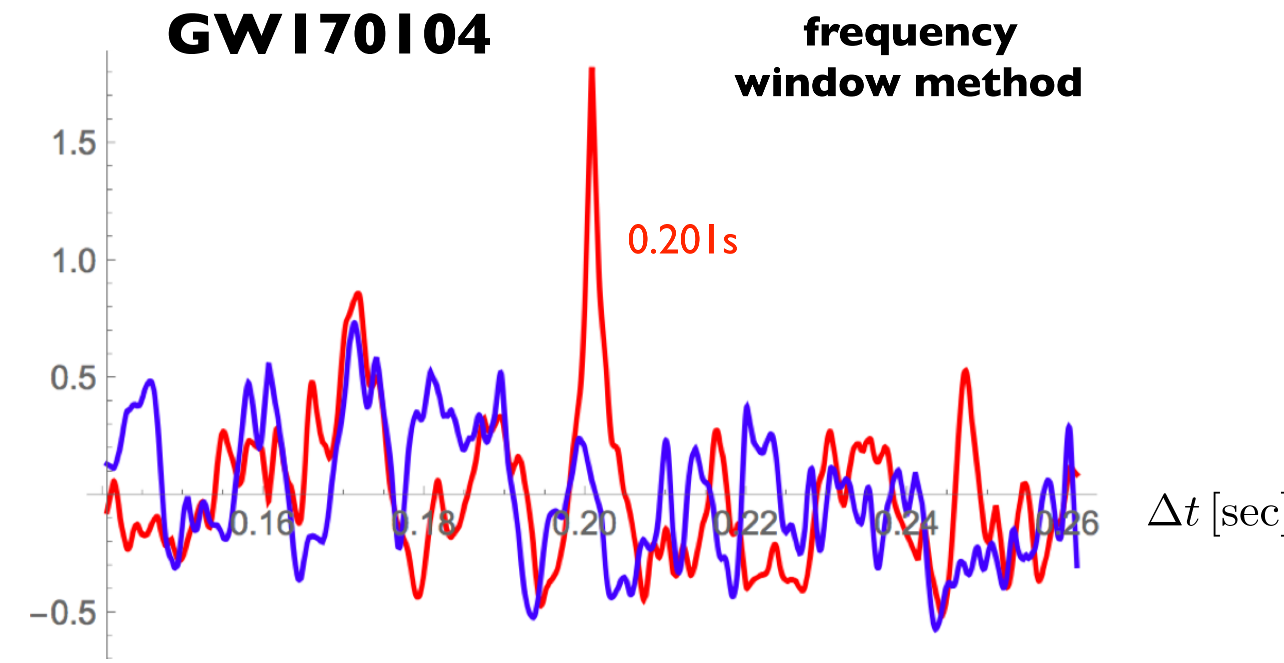
Julian Westerweck,[1,2,*] Alex B. Nielsen,[1,2,†] Ofek Fischer-Birnholtz,[1,2,3,‡] Miriam Cabero,[1,2] Collin Capano,[1,2] Thomas Dent,[1,2] Badri Krishnan,[1,2] Grant Meadors,[1,4,5] and Alexander H. Nitz[1,2]

[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 $\Delta t/M \sim 550\text{-}850$

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

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

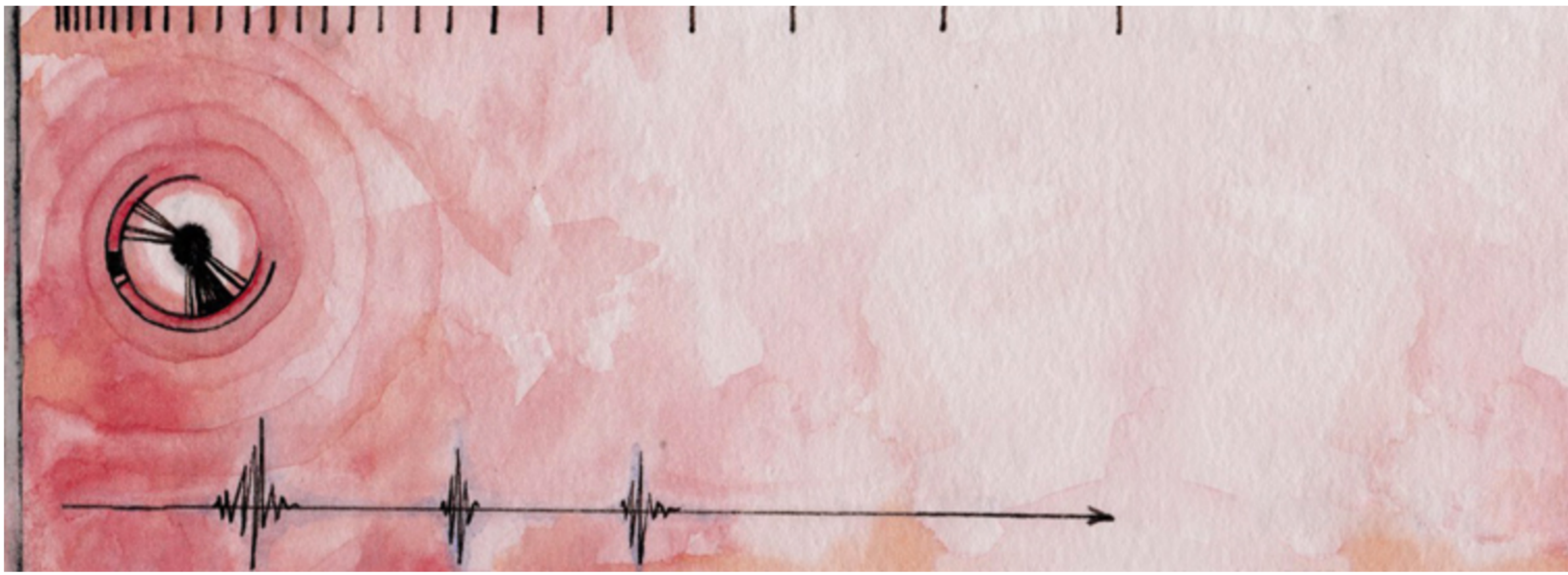
Randy Conklin, Bob Holdom, Jing Ren

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

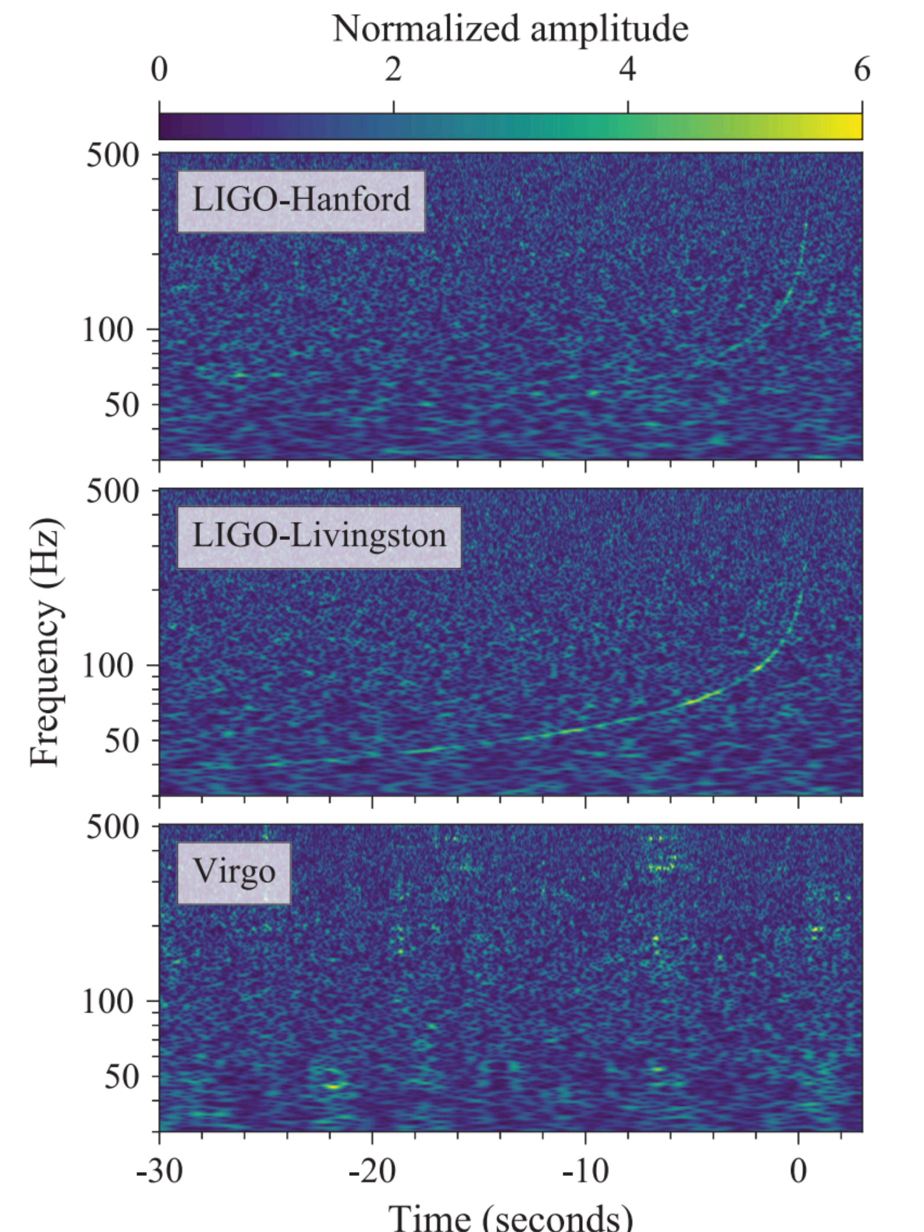
http://pirsa.org/C17055



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)

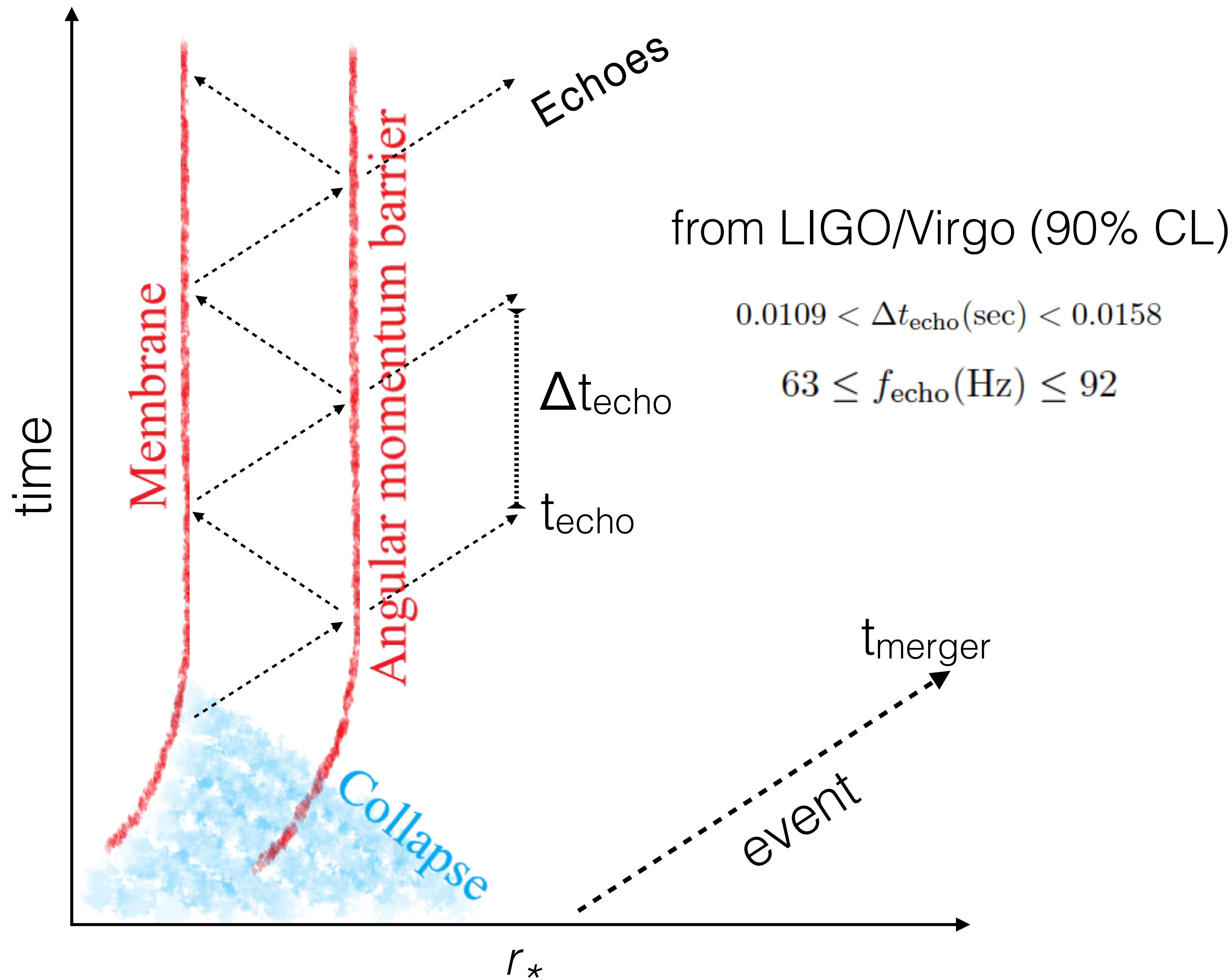
Echoes from the Abyss: A highly spinning black hole remnant for the binary neutron star merger GW170817

Jahed Abedi, Niayesh Afshordi

(Submitted on 28 Mar 2018)

The first direct observation of a binary neutron star (BNS) merger was a watershed moment in multi-messenger astronomy. However, gravitational waves from GW170817 have only been observed prior to the BNS merger, but electromagnetic observations all follow the merger event. While post-merger gravitational wave signal in general relativity is too faint (given current detector sensitivities), here we present the first tentative detection of post-merger gravitational wave "echoes" from a highly spinning "black hole" remnant. The echoes may be expected in different models of quantum black holes that replace event horizons by exotic Planck-scale structure and tentative evidence for them has been found in binary black hole merger events. The fact that the echo frequency is suppressed by $\log M$ (in Planck units) puts it squarely in the LIGO sensitivity window, allowing us to build an optimal model-agnostic search strategy via cross-correlating the two detectors in frequency/time. We find a tentative detection of echoes at $f_{\rm echo} \simeq 72$ Hz, around 1.0 sec after the BNS merger, consistent with a 2.6-2.7 $M_\odot$ "black hole" remnant with dimensionless spin $0.84-0.87$. Accounting for all the "look-elsewhere" effects, we find a significance of 4.2σ, or a false alarm probability of 1.6×10^{-5}, i.e. a similar cross-correlation within the expected frequency/time window after the merger cannot be found more than 4 times in 3 days. If confirmed, this finding will have significant consequences for both physics of quantum black holes and astrophysics of binary neutron star mergers.

Comments: Dedicated to the memories of Stephen Hawking and Joe Polchinski, two of the champions of the black hole information paradox
Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; High Energy Astrophysical Phenomena (astro-ph.HE); High Energy Physics - Theory (hep-th)
Cite as: **arXiv:1803.10454 [gr-qc]**



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

A model-agnostic search for unresolved echoes

- Optimal search strategy for *a periodically repeating delta-function*:

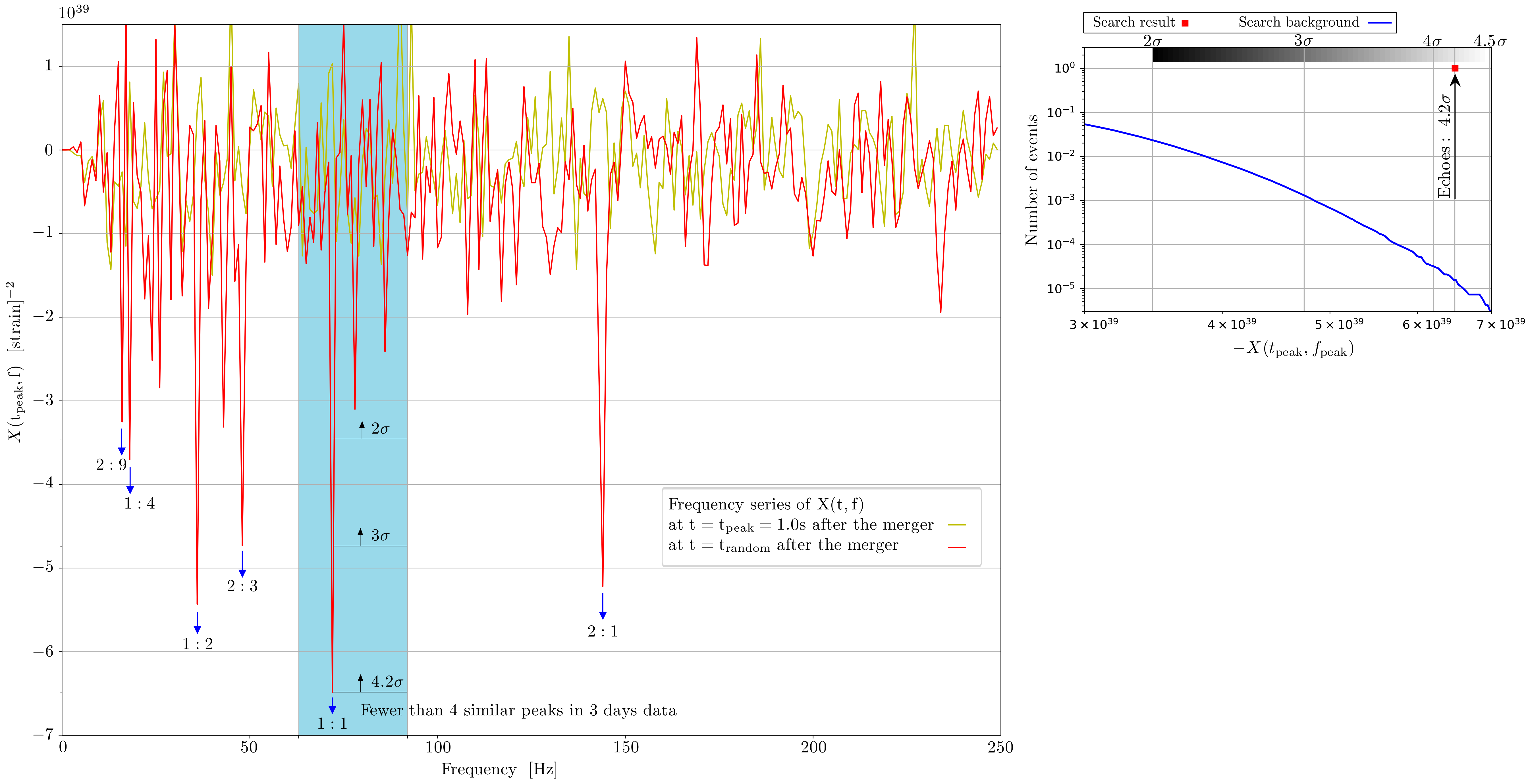
  ★ Wiener filter (time shifted) Hanford and Livingston data

$$H(t,f) = \mathrm{Spectrogram}\left[\mathrm{IFFT}\left(\frac{\mathrm{FFT(h_H(t-\delta t))}}{\mathrm{ASD_L^2}}\right)\right] \quad L(t,f) = \mathrm{Spectrogram}\left[\mathrm{IFFT}\left(\frac{\mathrm{FFT(h_L(t))}}{\mathrm{ASD_L^2}}\right)\right]$$

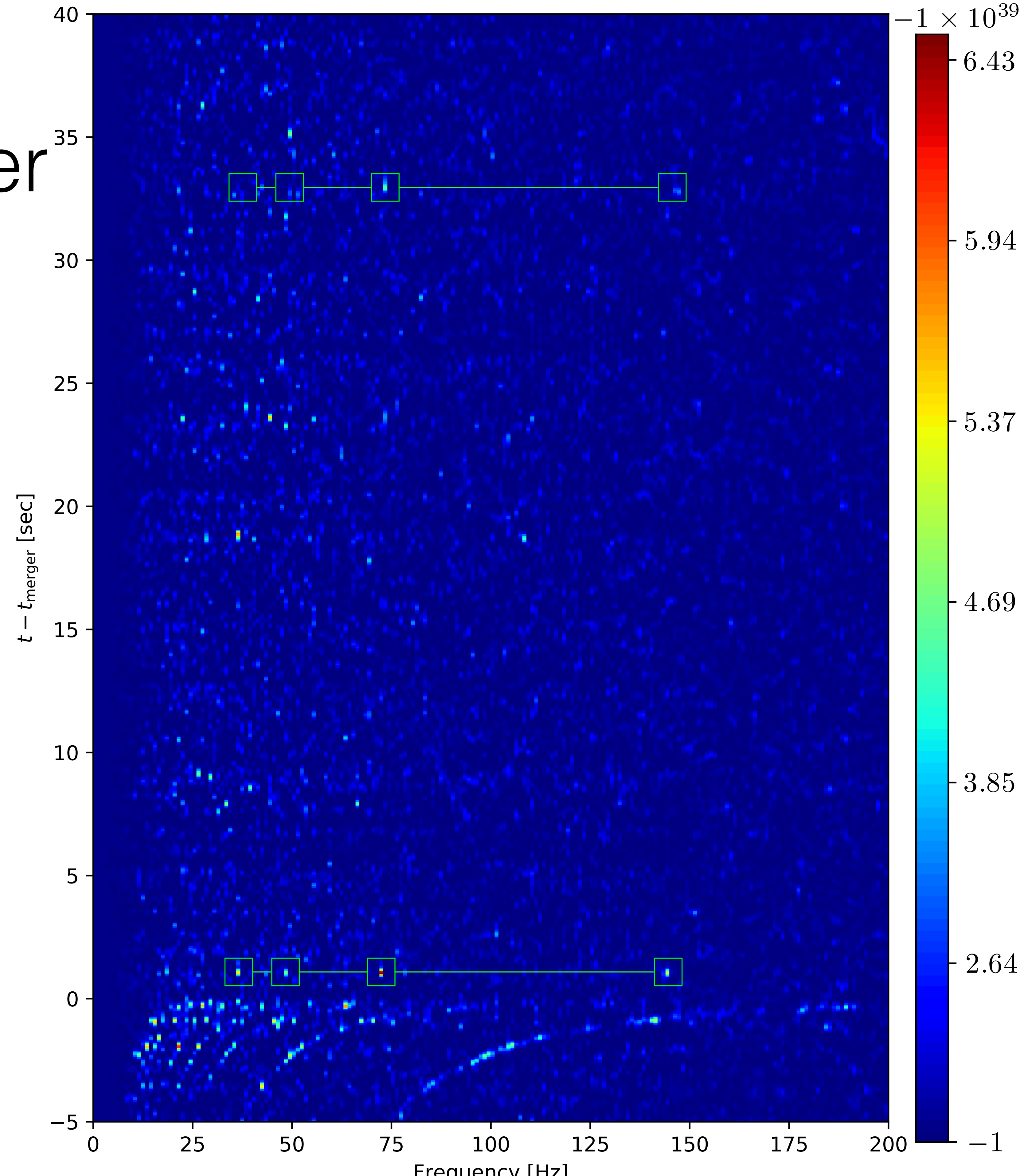
  ★ Cross-correlate the two signals and look for peaks

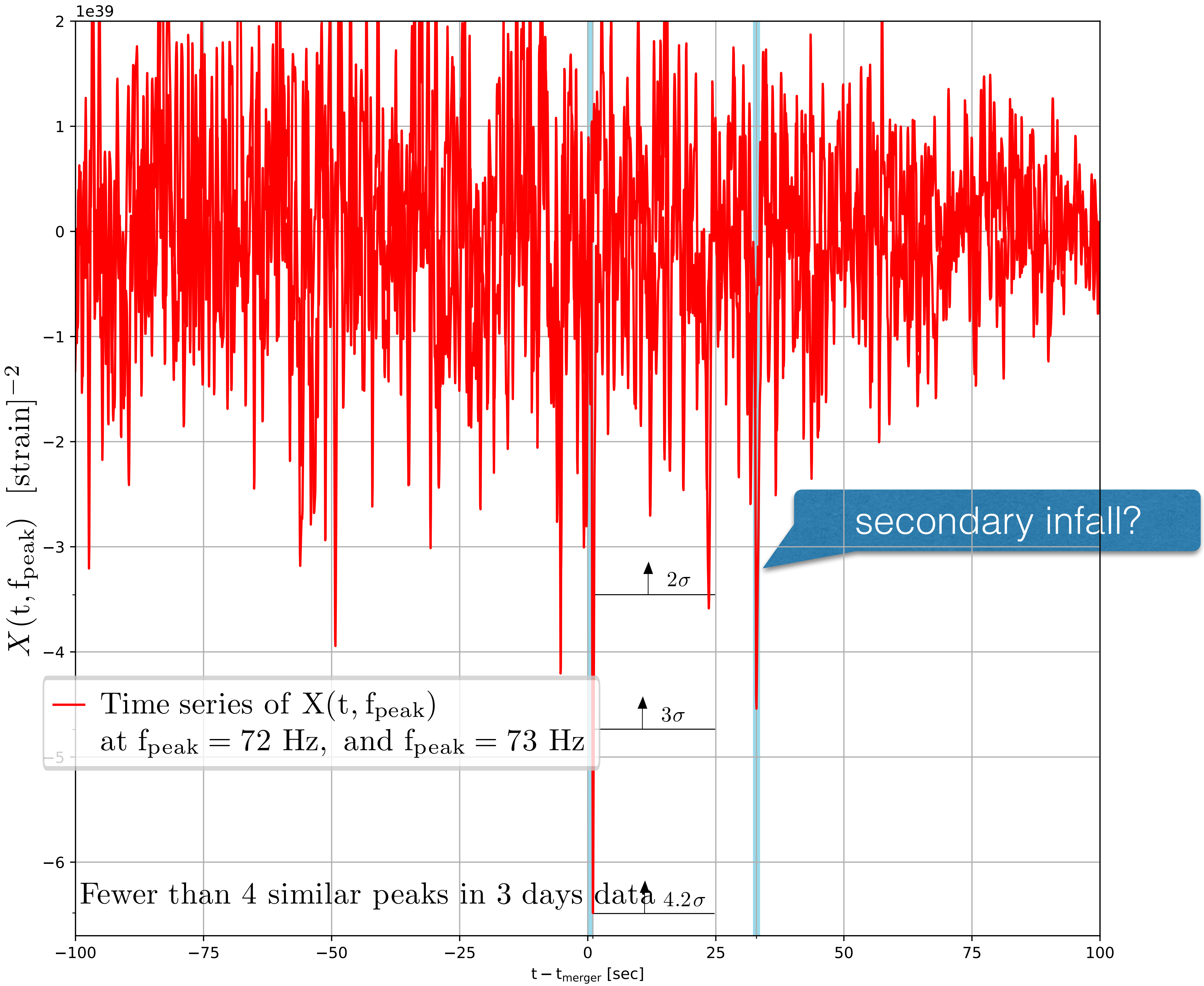
$$X(t,f) = \sum_{n=1}^{10} Real(H(t,nf) \times L(t,nf)^*)$$

Echoes 0.5 sec after GW170817

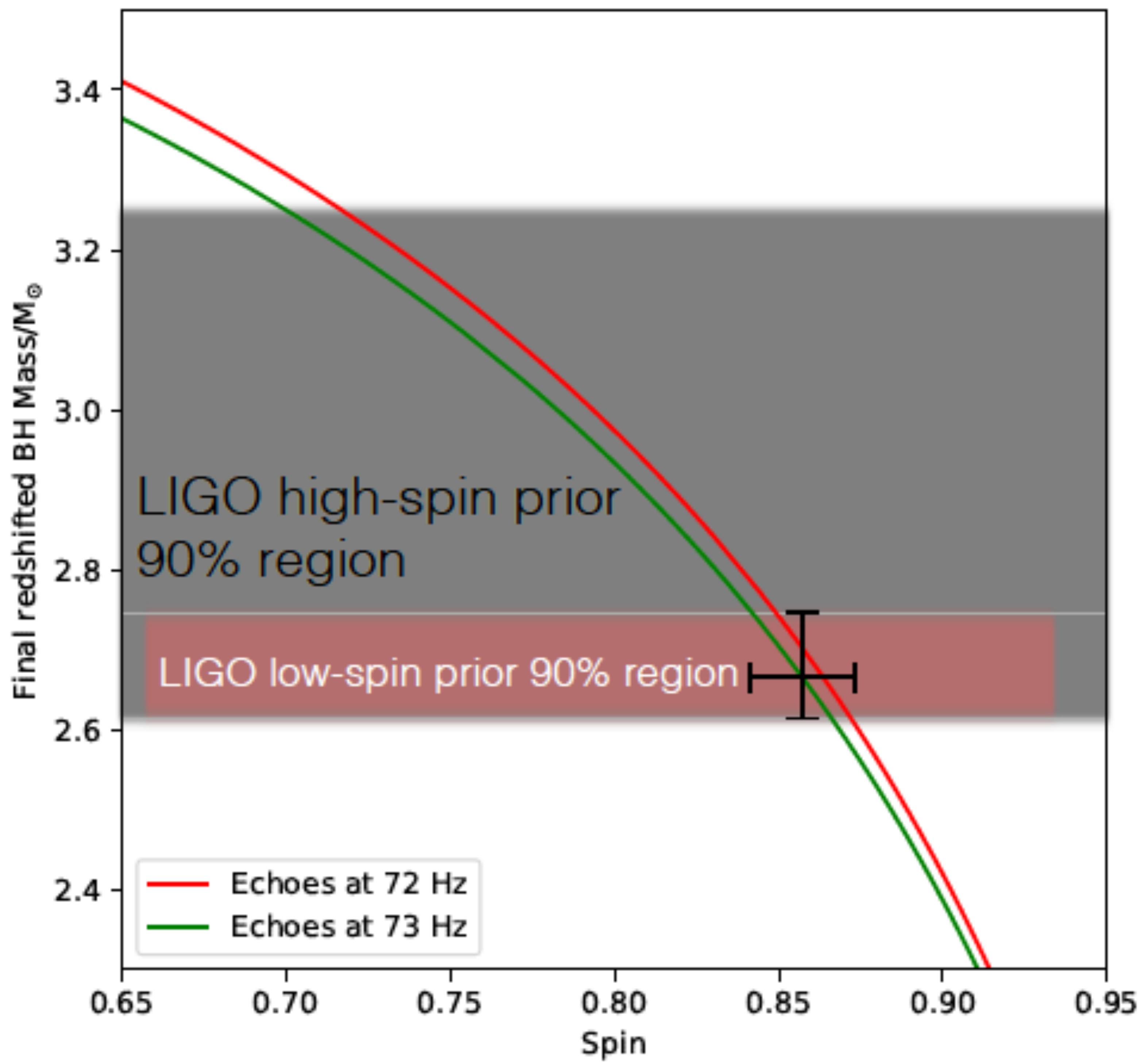


GW170817
:before vs after




1e39
$X(t, f_{peak})$ [strain]$^{-2}$
$t - t_{merger}$ [sec]
secondary infall?
2σ
3σ
4.2σ
Time series of $X(t, f_{peak})$
at $f_{peak} = 72$ Hz, and $f_{peak} = 73$ Hz
Fewer than 4 similar peaks in 3 days data

A Kerr BH at a=0.84-0.87?



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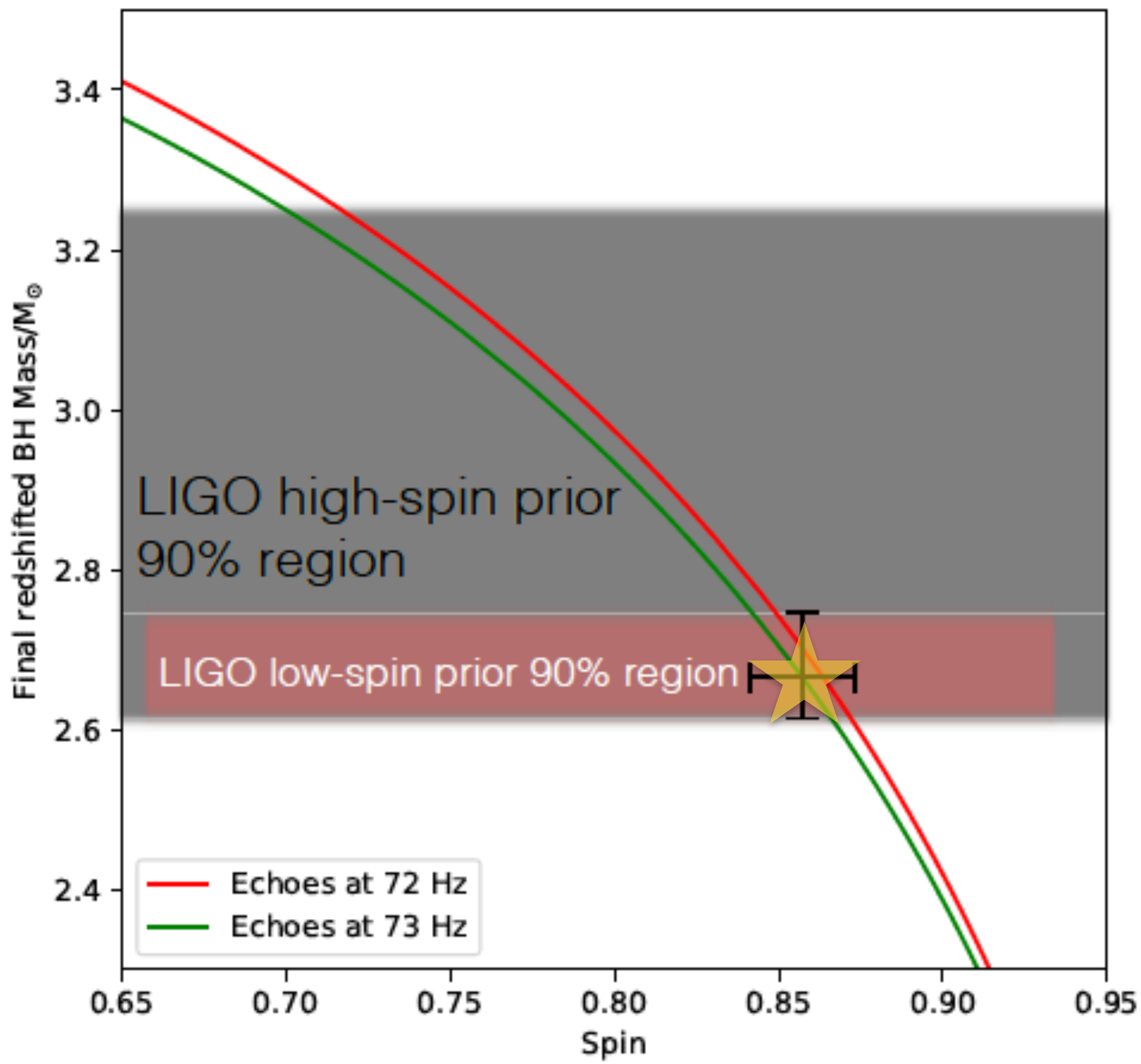
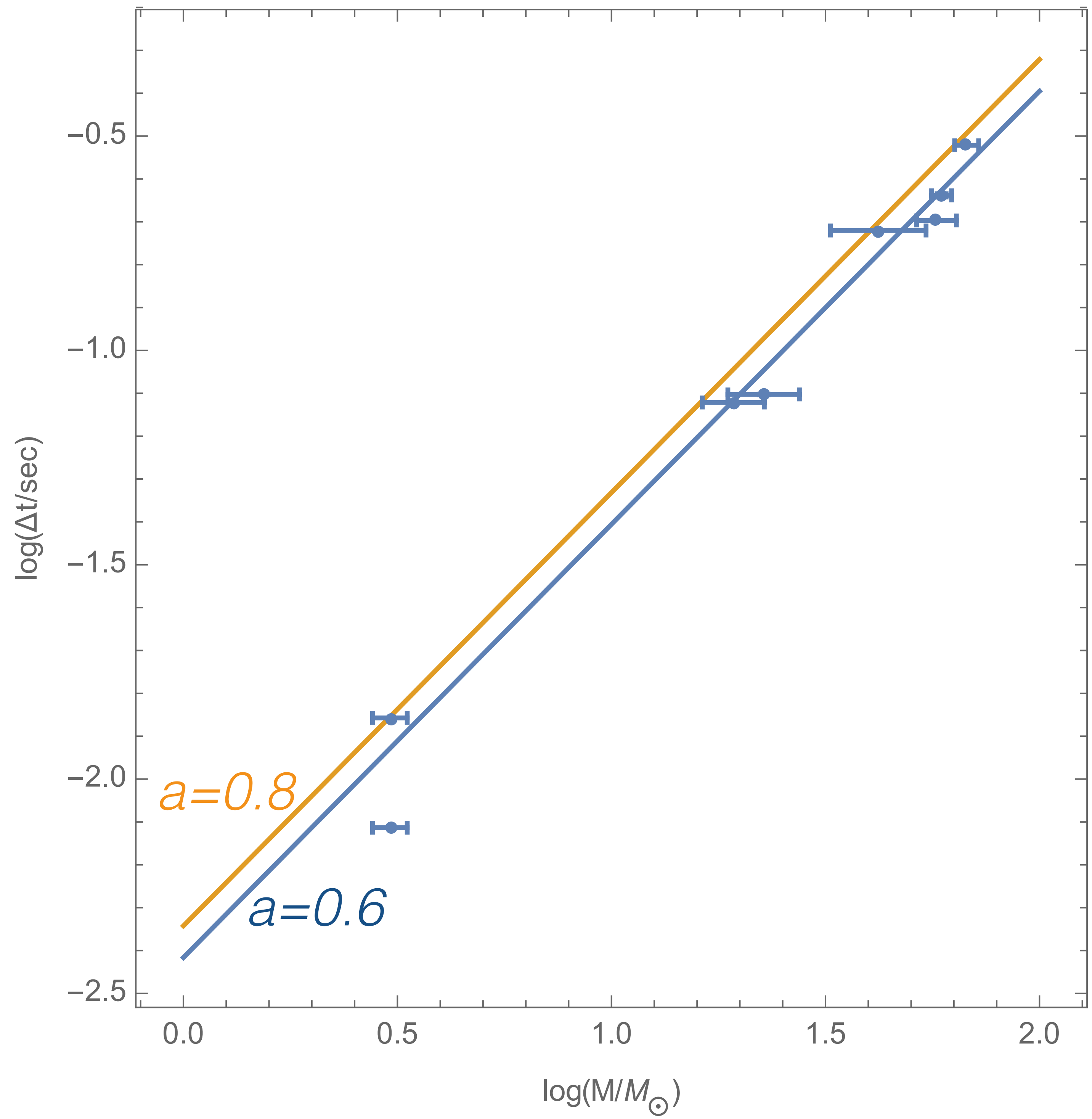


Anyone who has looked for echoes has found them!™*



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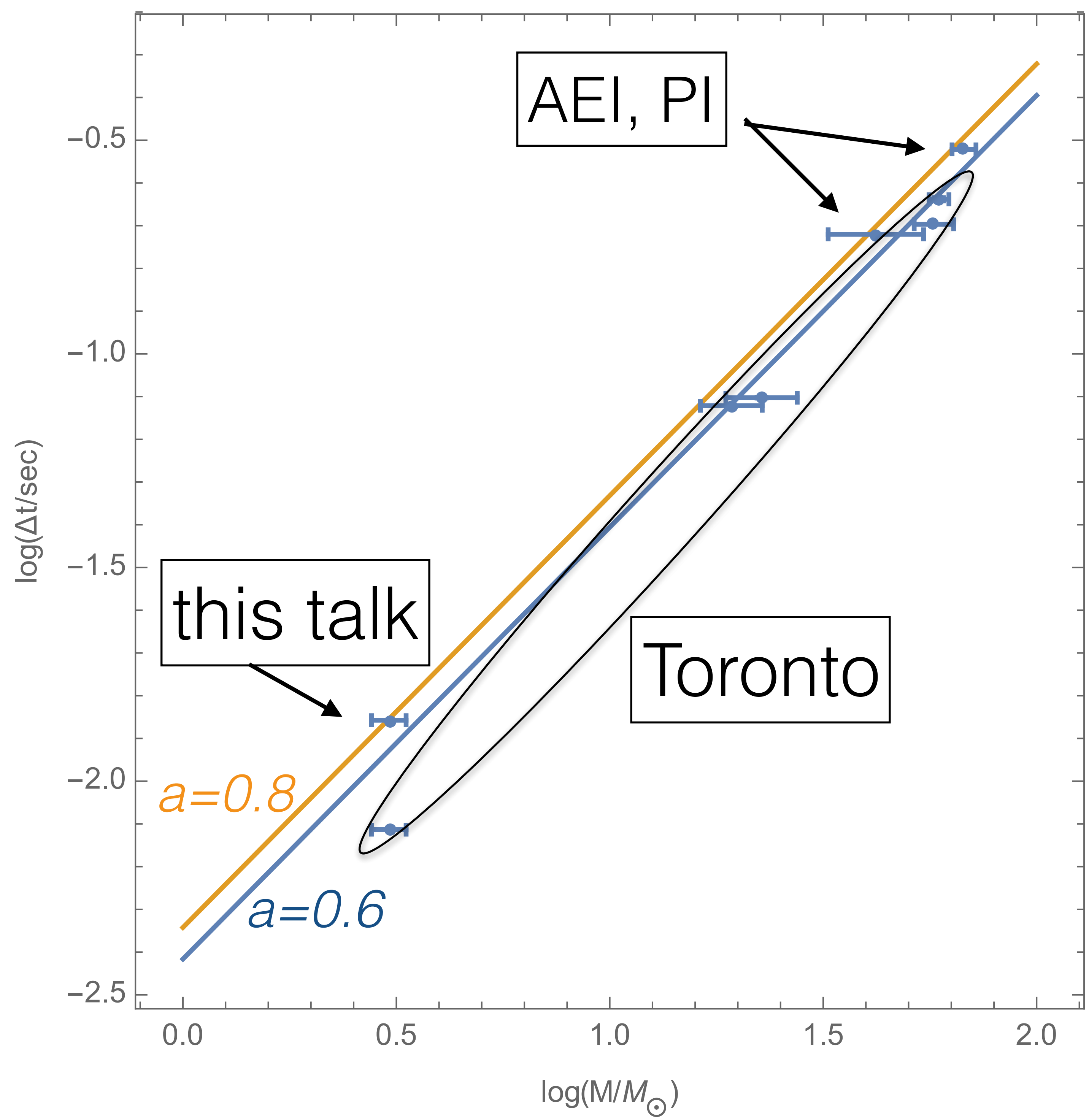

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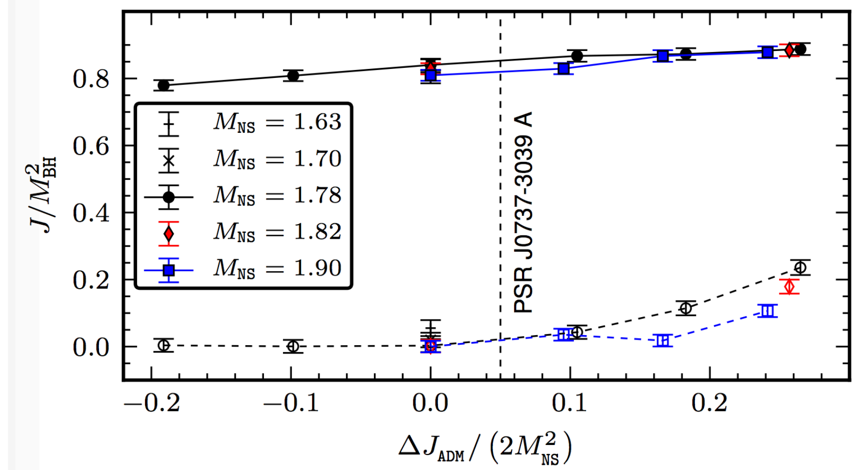
    - ➡ *Black Hole with spin 0.84-0.87*

Kastaun, et al. 2013



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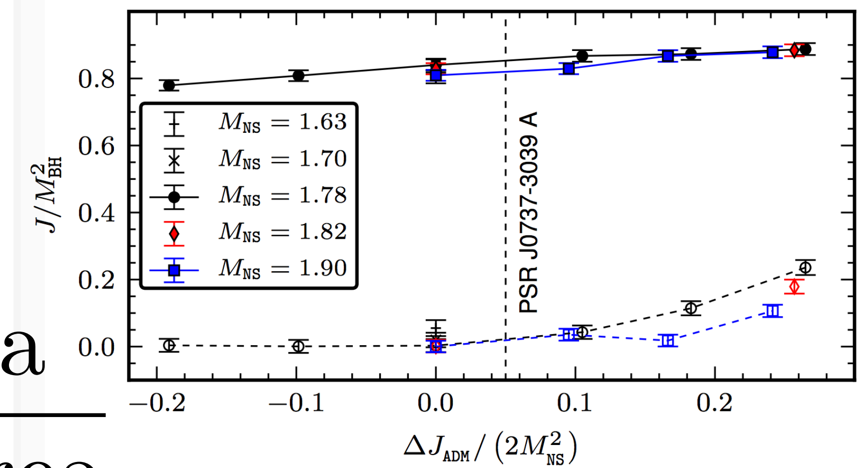

- Black Hole Entropy = $\dfrac{\text{Horizon Area}}{4 \times \text{Planck Area}}$
  - ➡ *Planck-scale horizon structure*

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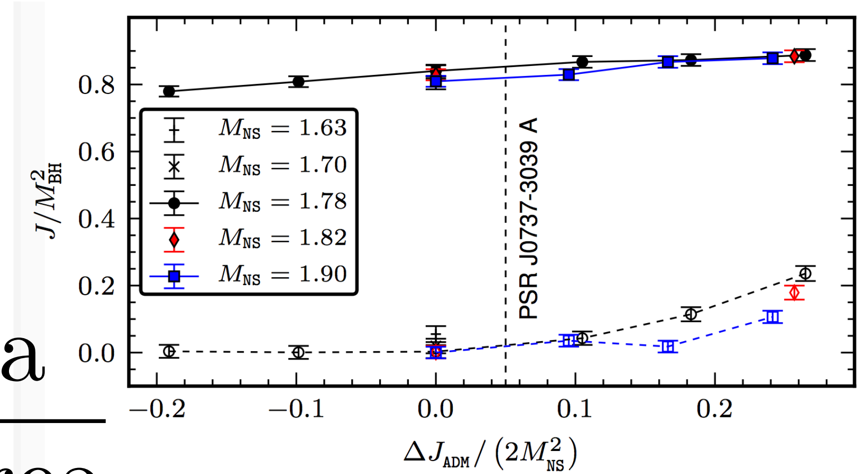

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- *Confirm most conservative possible outcome for GW170817 (if you believe in Quantum Mechanics)* 😉

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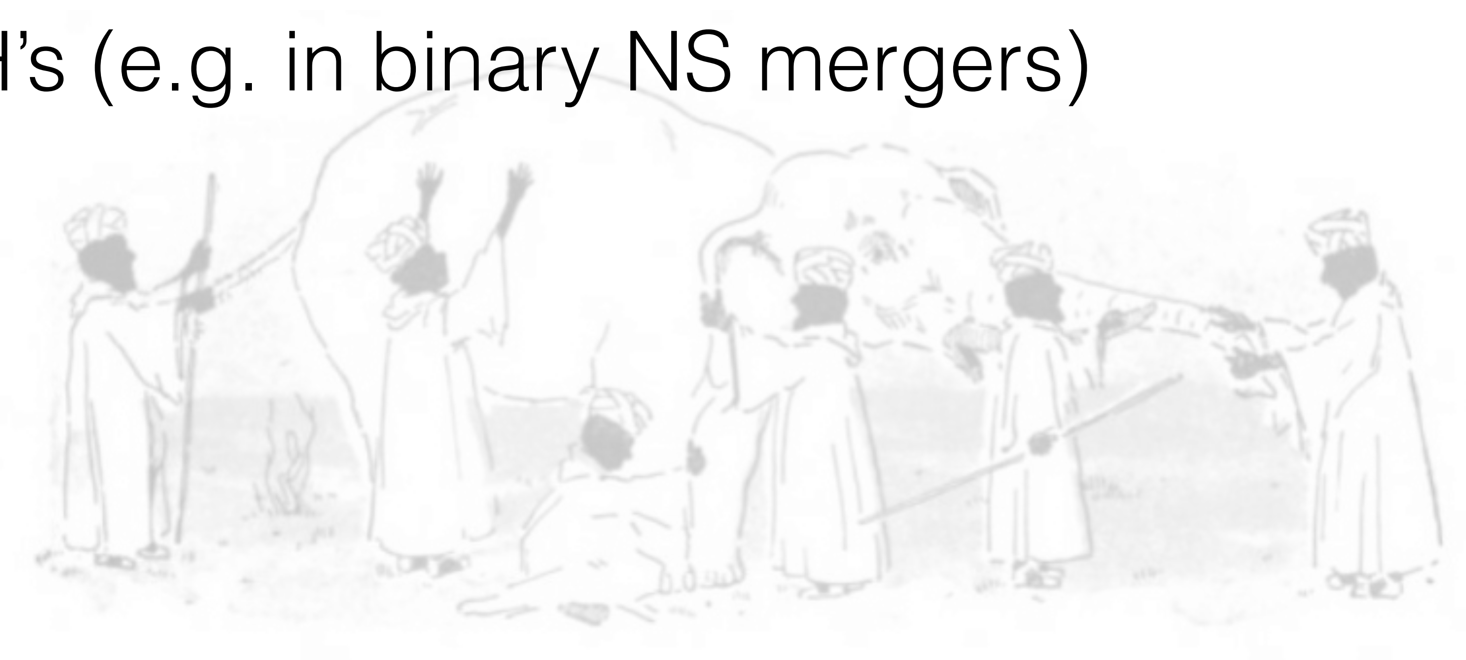

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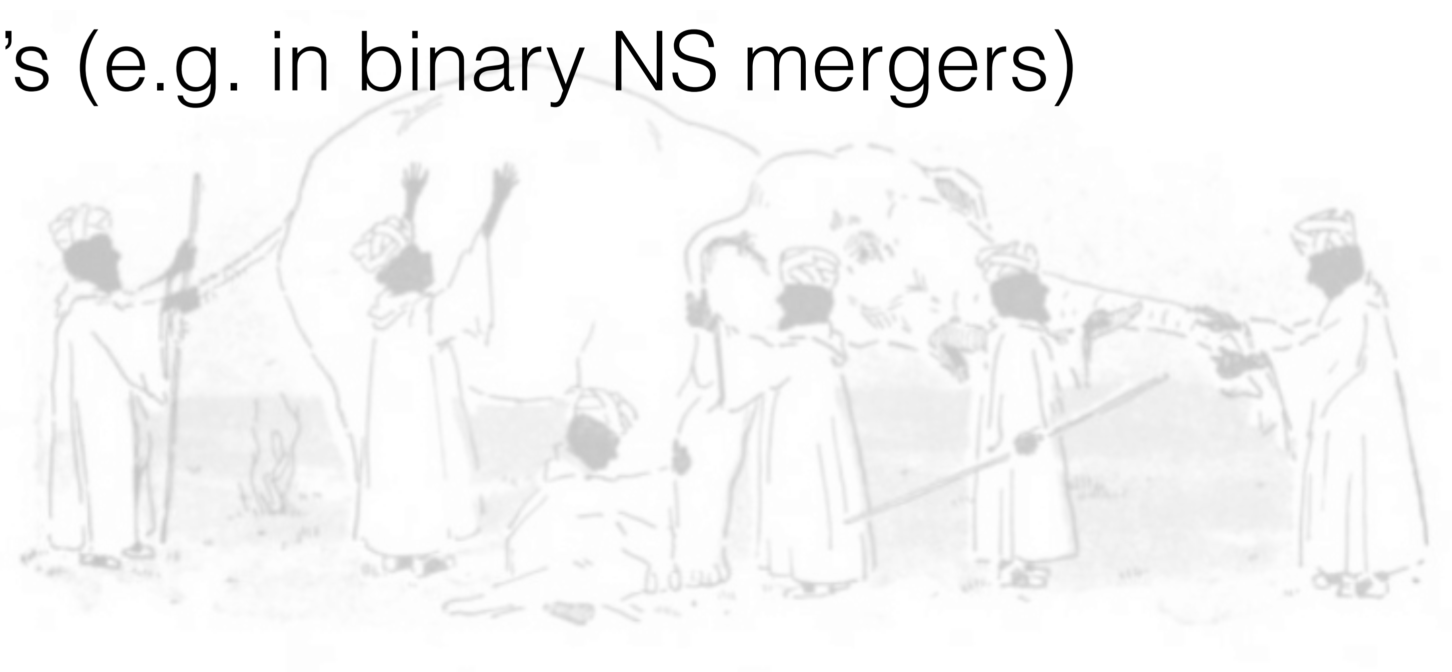

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Stay Tuned!

Open questions

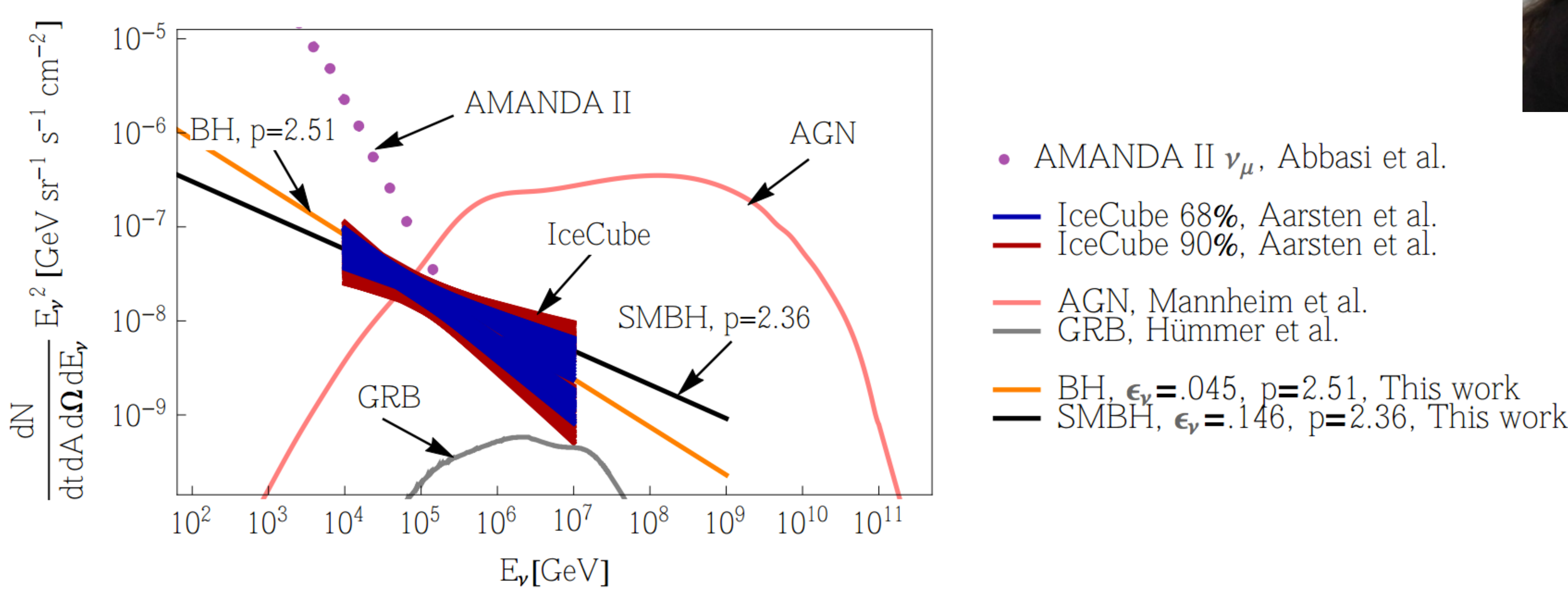
- Dark Energy w/multiple BH’s? Tests?
- Physical covariant boundary conditions?
- *Resonance* of *inspiral* and *echo* frequencies?
- Optimal Model-Agnostic search?

Bonus Slides

Setting space on fire (Jan. 2017, CQG+)

Fuzzball Phenomenology

- Radio or Infrared signals? (Broderick, et al.)
- Pulsar timing near Sgr A*? (Broderick & Pen)
- Ultra high energy neutrinos? (Yazdi & NA 15)



Aether Holes: *Entropy*

- Assume space-time ends near horizon
- *Israel Junction* condition+ mirror symmetry:
  - ➡ membrane has <u>vanishing surface density</u>
  - ➡ 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)*

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

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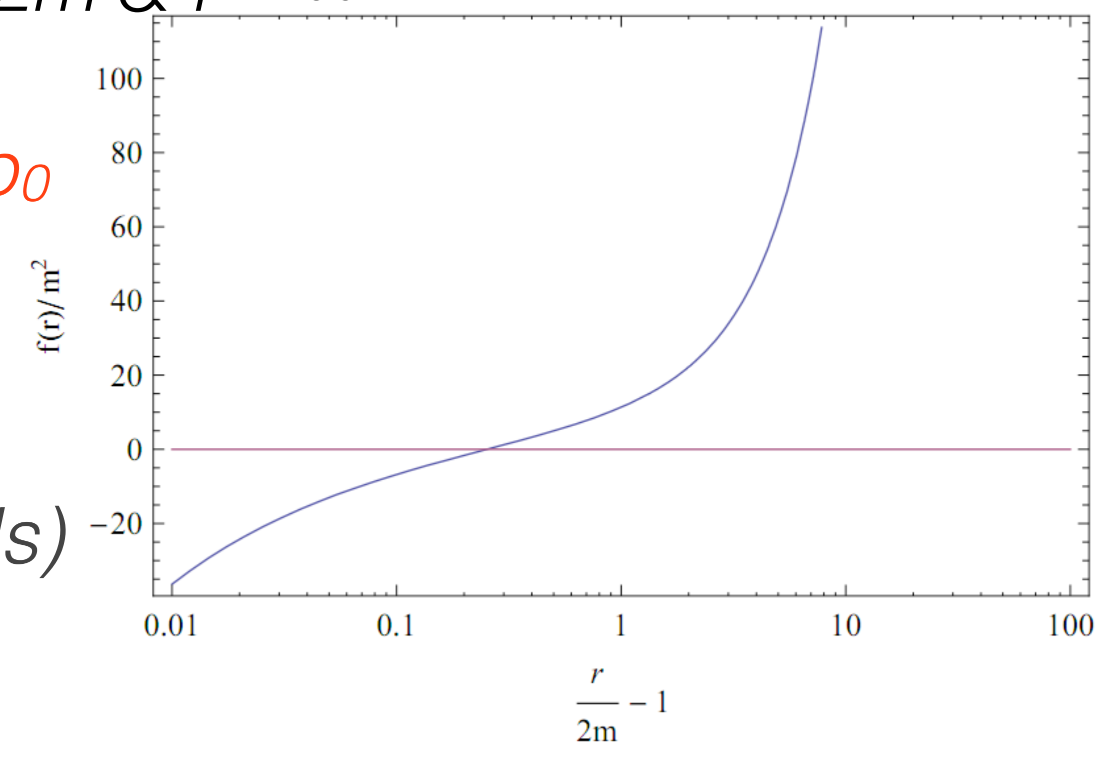


... and dark energy!

- Assume:

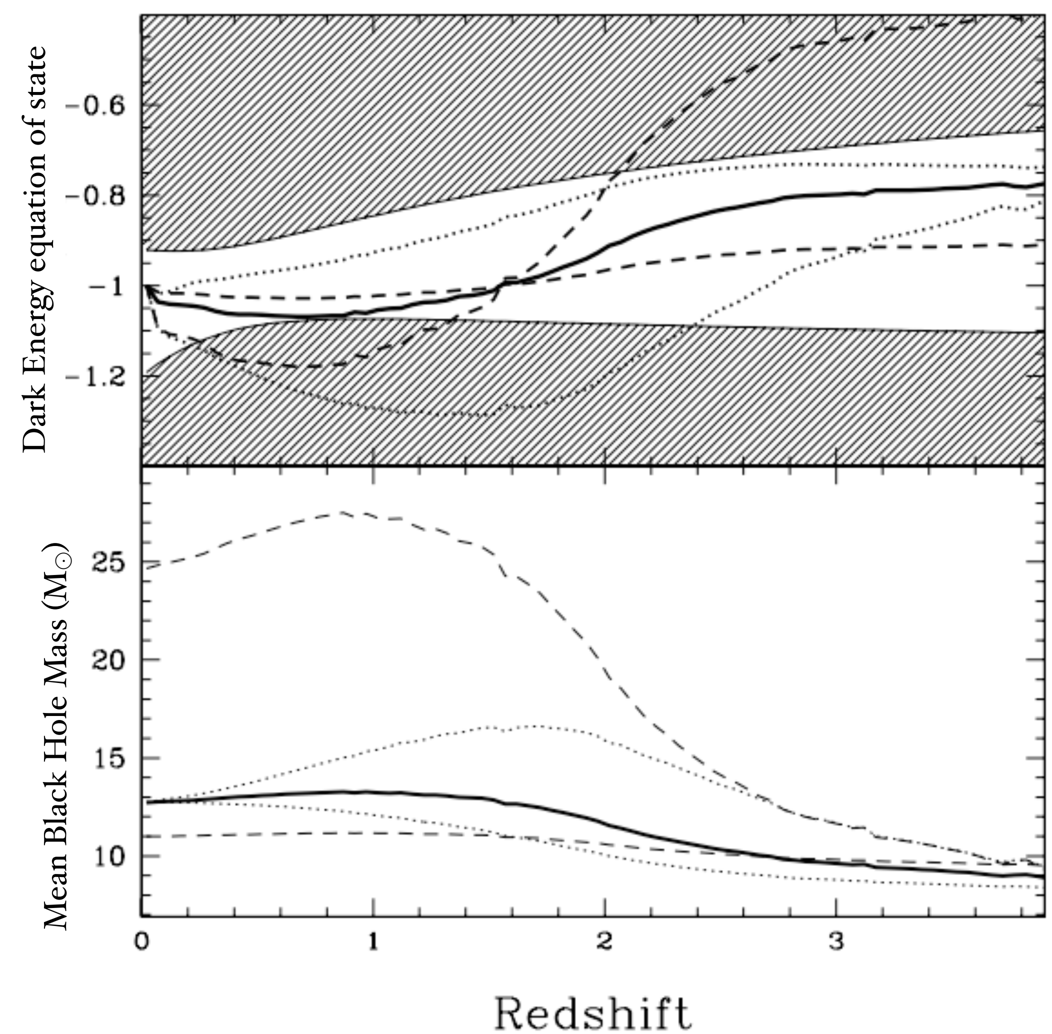
$$1 + z_{\max} \sim \frac{\text{Planck temperature}}{\text{Hawking temperature}}$$

- then we get

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

- *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

Prescod-Weinstein, NA, Balogh 2009



Confession 😕😖😱

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- 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!

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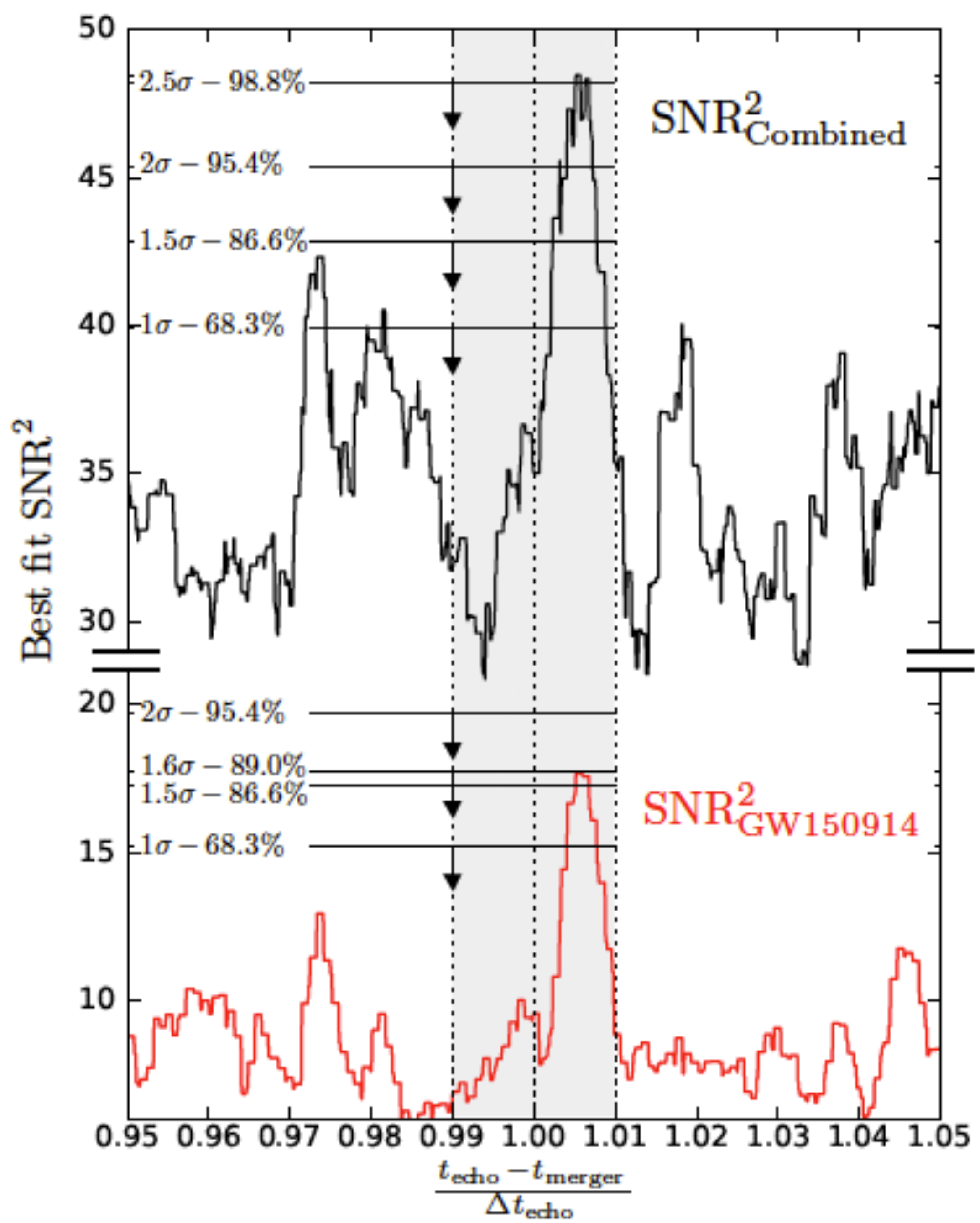
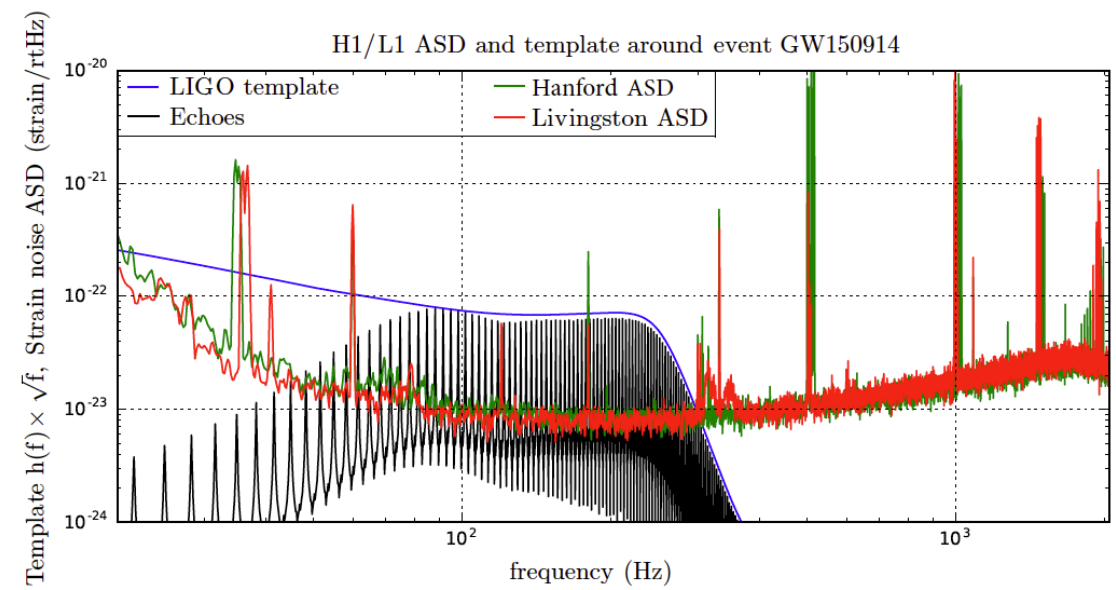
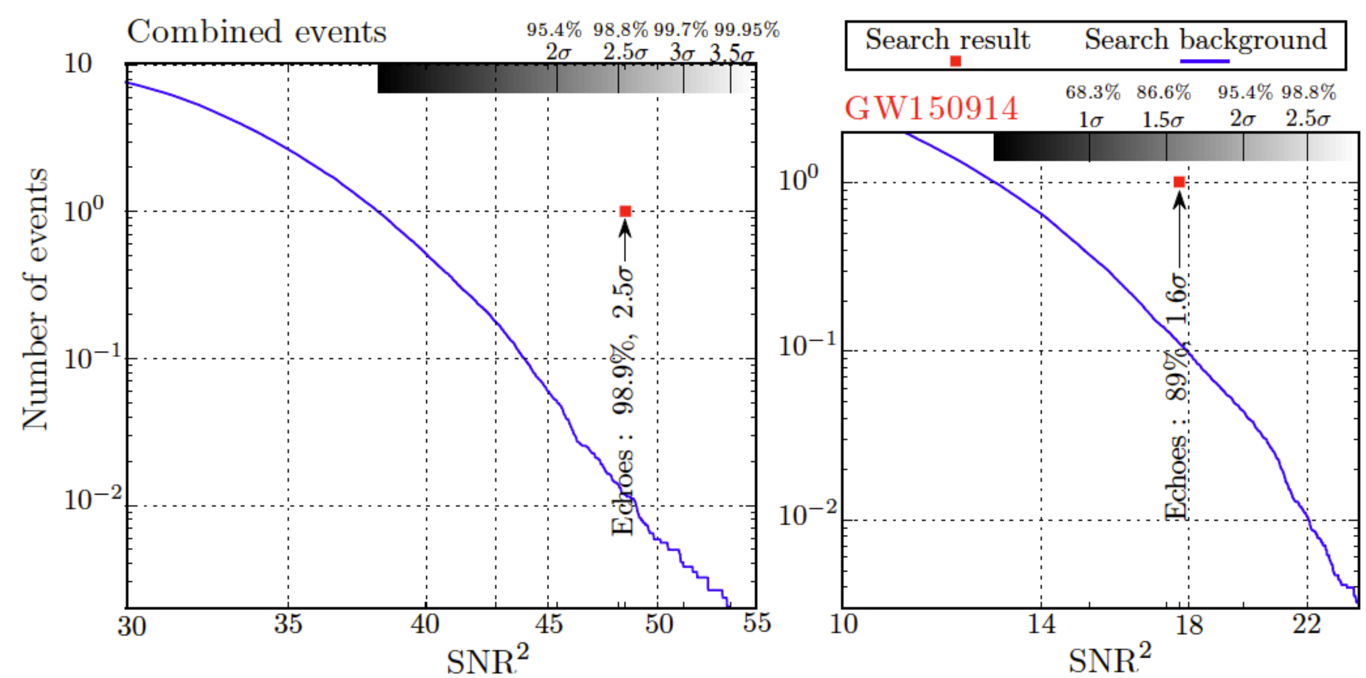
- Or, maybe it's because we haven't yet asked **you** 🤩

... and *voila!*







Best fit SNR^2: echoes are predicted to be at $x=1\pm0.01$

False detection probability for the echoes

Further tests

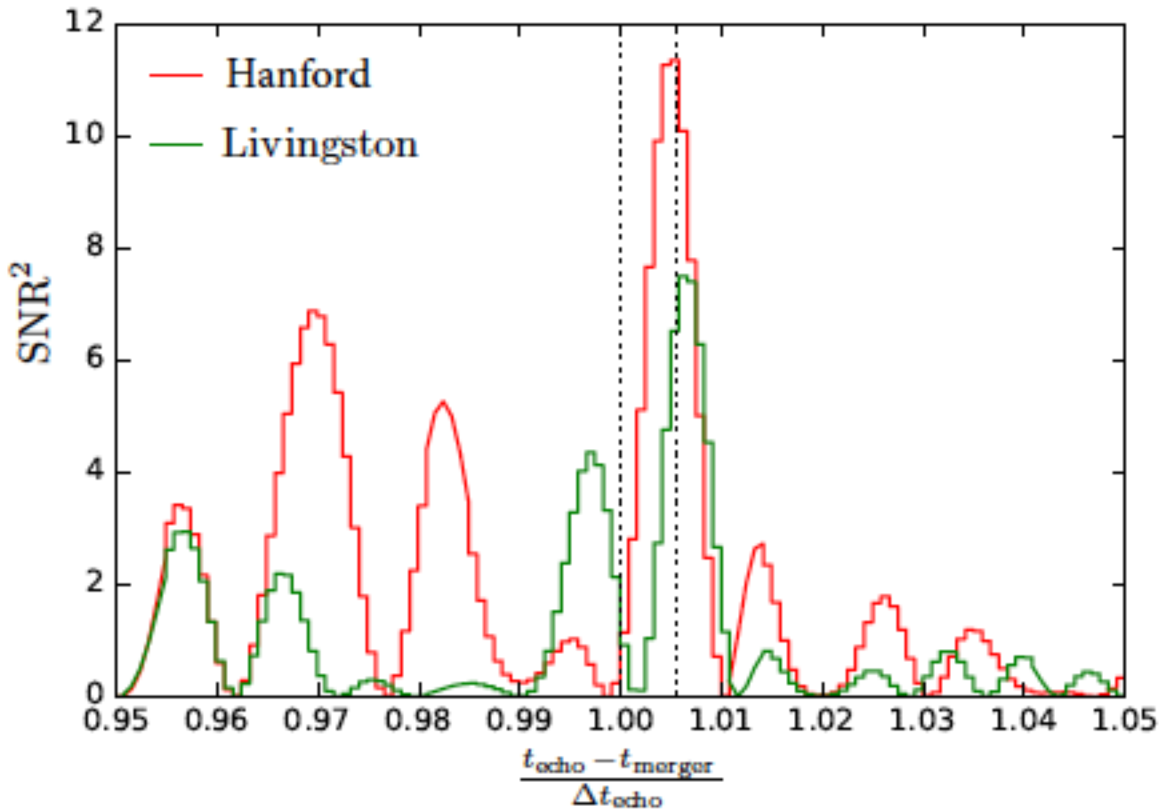


FIG. 2: SNR^2 near the expected time of merger echoes (Eq. 1) for GW150914 in Hanford (red) and Livingston (green) detectors. Interestingly, their SNR ratio $2.74/3.37 = 0.81$ is comparable to the SNR ratio for the main event $13.3/18.6 = 0.72$. Note that, unlike Fig. (1), here we have fixed the echo parameters to their best fit values for combined detectors.

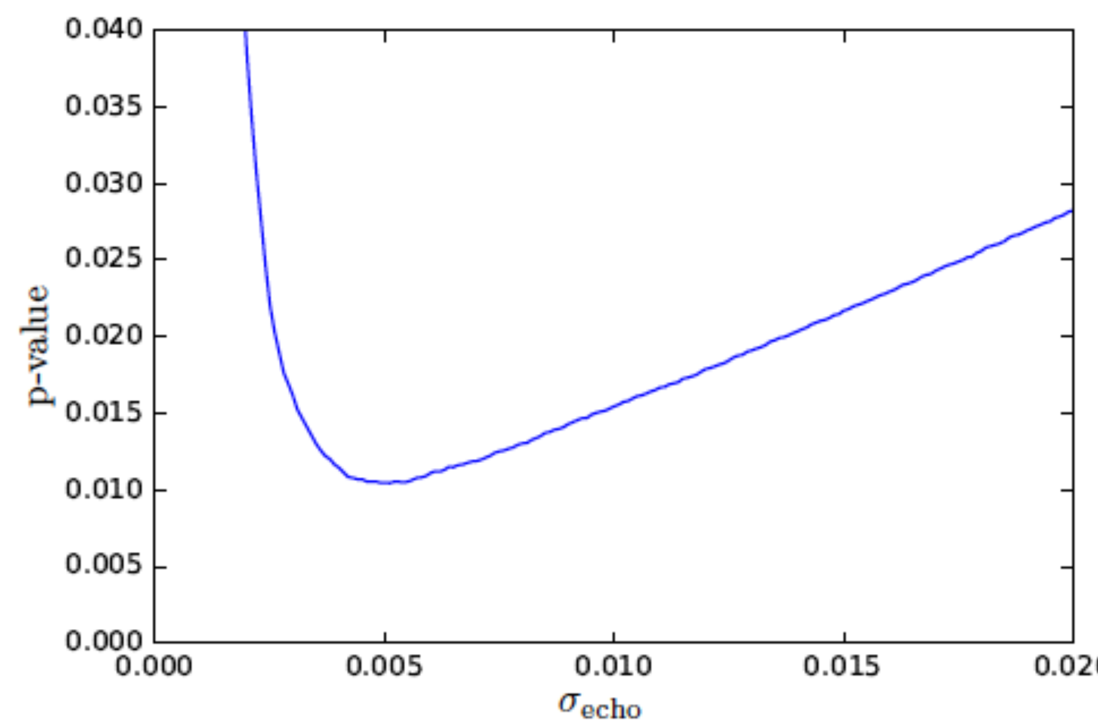
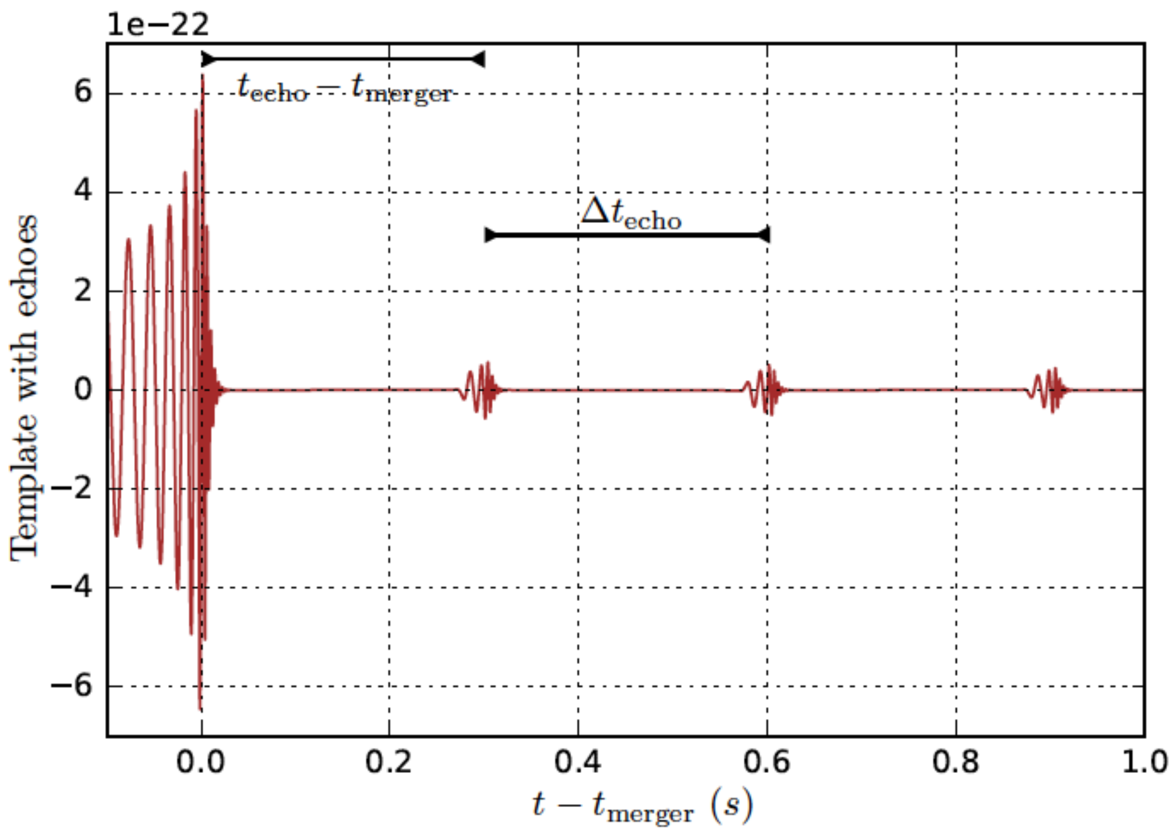
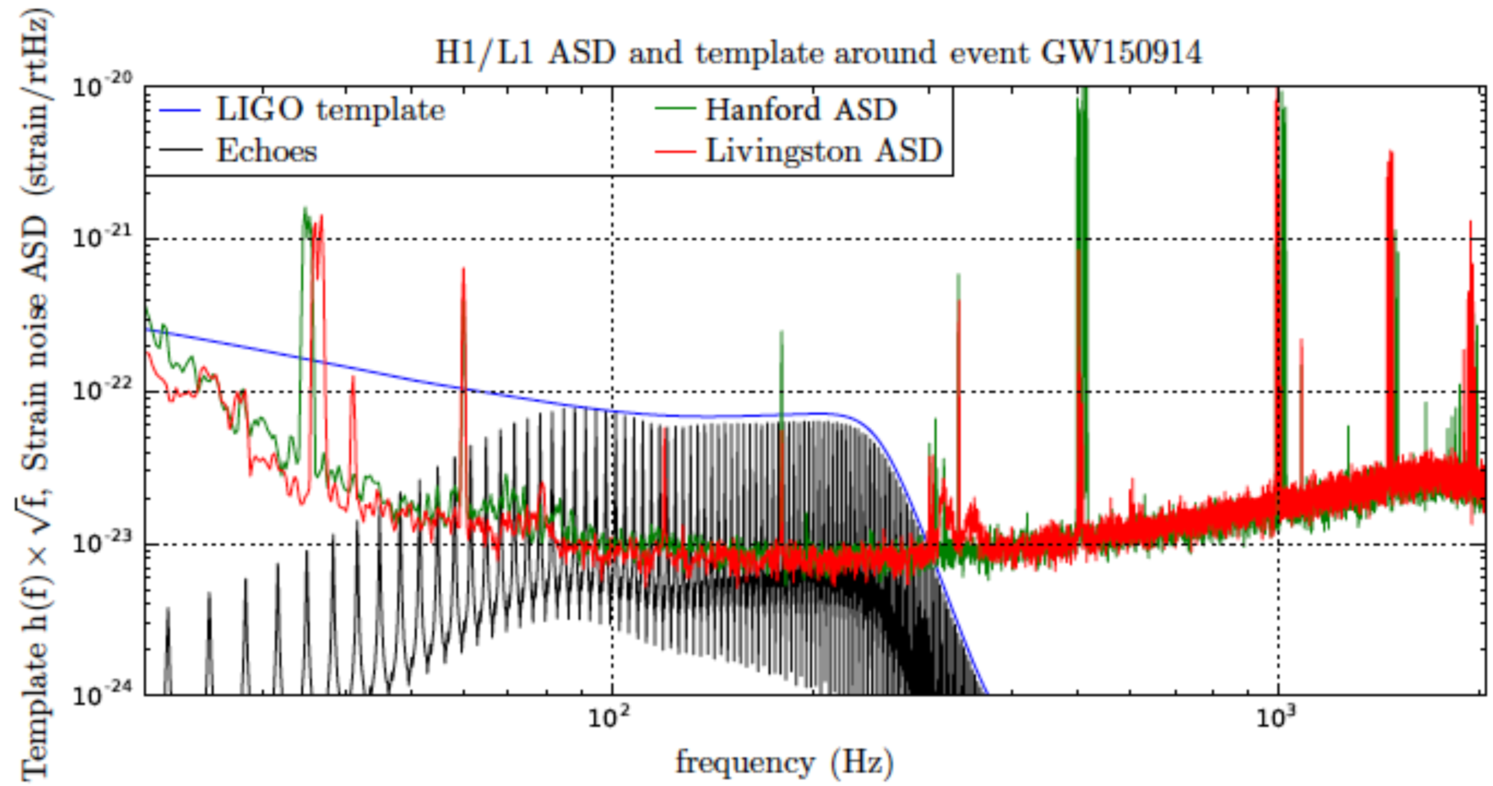


FIG. 5: An alternative false detection probability (p-value) as a function of uncertainty in t_{echo} defined in Eq. (3).

$$L(x, \sigma_{echo}) \equiv \int \exp\left[\frac{\mathrm{SNR}^2_{total}(x')}{2}\right] \times \frac{\exp\left[-\frac{(x-x')^2}{2\sigma^2_{echo}}\right]}{\sqrt{2\pi\sigma^2_{echo}}} dx'. \quad (3)$$

best fit echoes



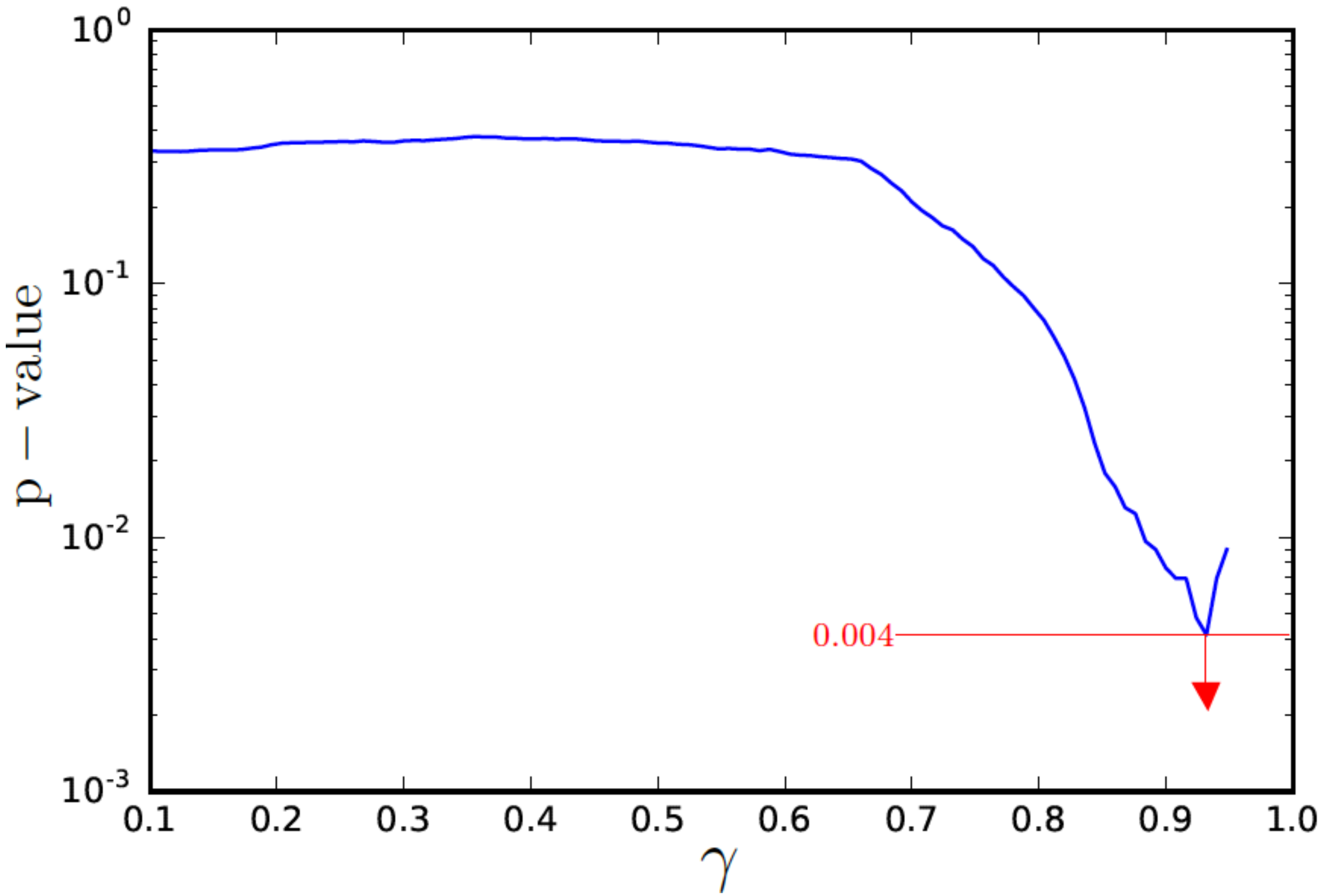


$$\boxed{\frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 1 \pm \mathcal{O}(1\%),}$$

(non-linear effects)

	Range	GW150914	Combined
$(t_{echo} - t_{merger})/\Delta t_{echo}$	(0.95,1.05)	1.0054	1.0054
γ	(0.1,0.9)	0.89	0.9
$t_0/\overline{\Delta t}_{echo}$	(-0.1,0)	-0.084	-0.1
Amplitude		0.0992	0.124
SNR_{max}		4.21	6.96
p-value		4.6×10^{-2}	3.7×10^{-3}
significance		2.0σ	2.9σ

Echoes are long-lived!



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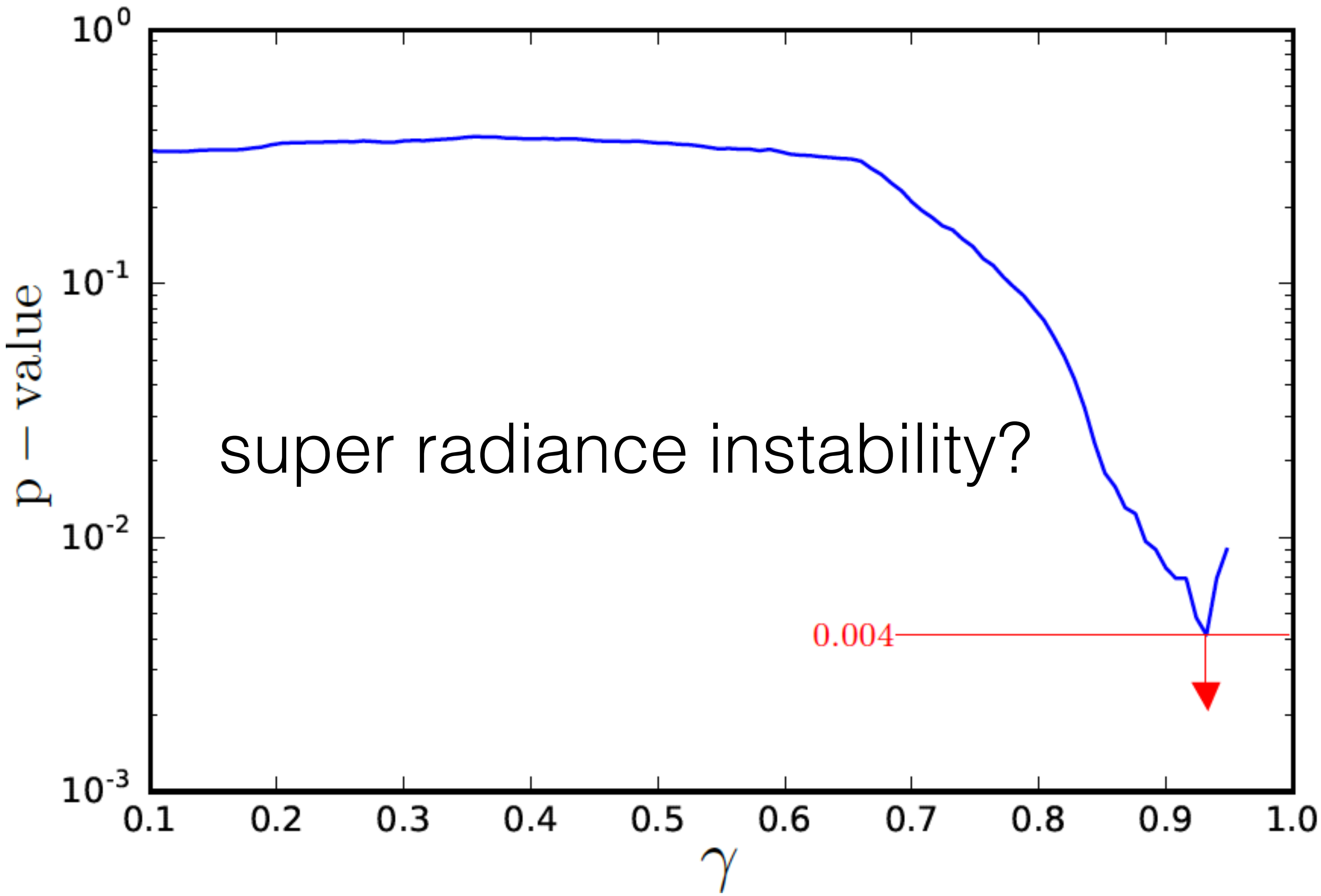

Echo sanity checks II