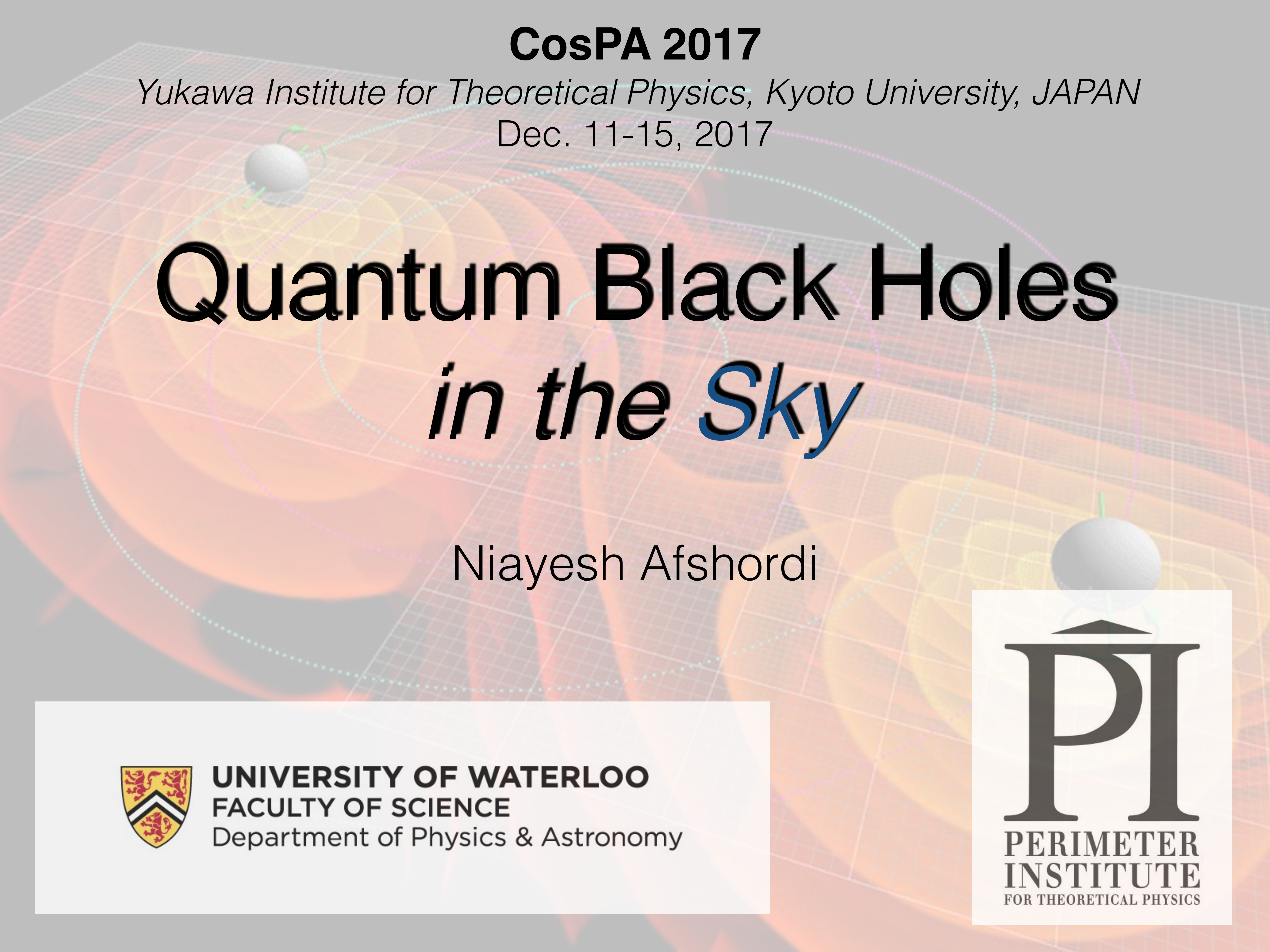
CosPA 2017

Yukawa Institute for Theoretical Physics, Kyoto University, JAPAN

Dec. 11-15, 2017



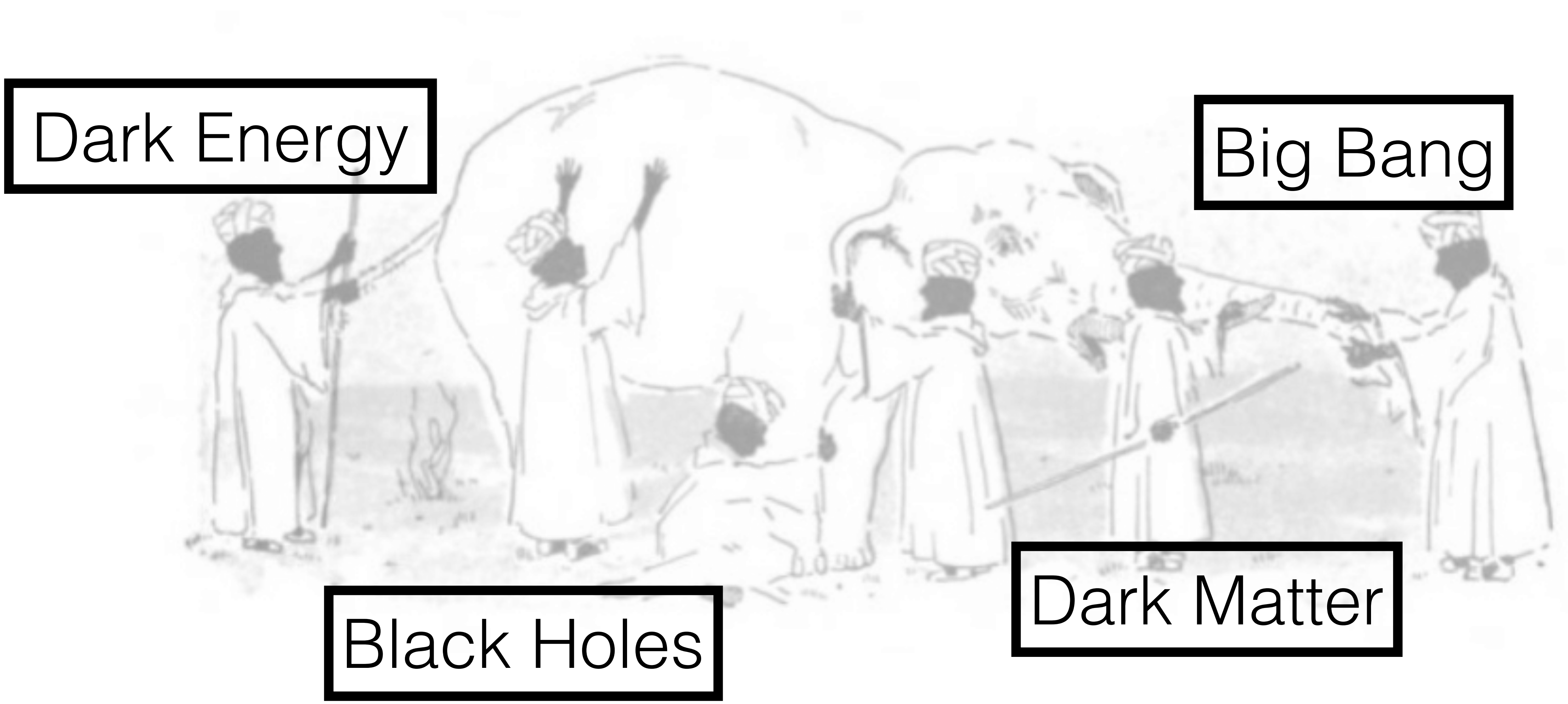
Quantum Black Holes *in the Sky*

Niayesh Afshordi

UNIVERSITY OF WATERLOO
FACULTY OF SCIENCE
Department of Physics & Astronomy

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Prelude: *Unravelling the Darkness*



Dark Energy

Big Bang

Black Holes

Dark Matter

Prelude: *Unravelling the Darkness*

Dark Energy

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Quantum Gravity

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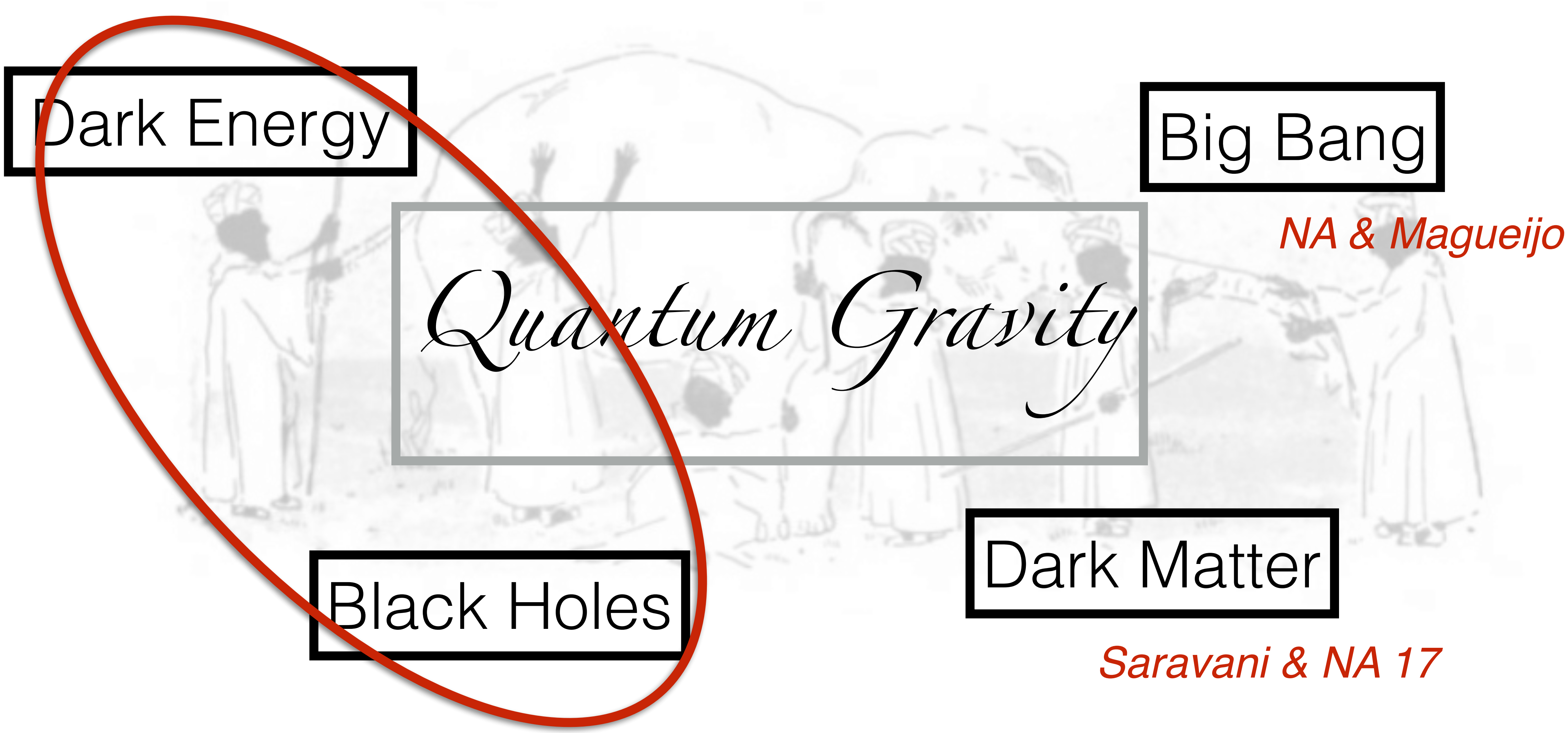
Prelude: *Unravelling the Darkness*



Dark Energy

Big Bang

NA & Magueijo 16

Quantum Gravity

Dark Matter

Black Holes

Saravani & NA 17

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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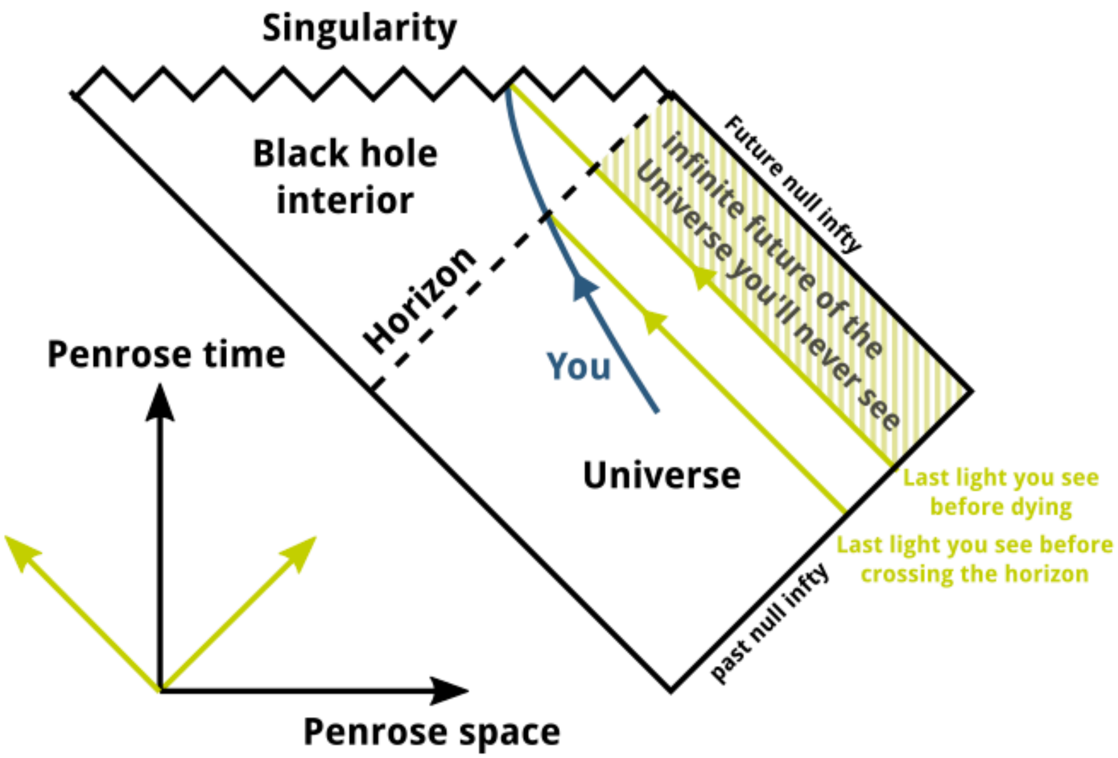
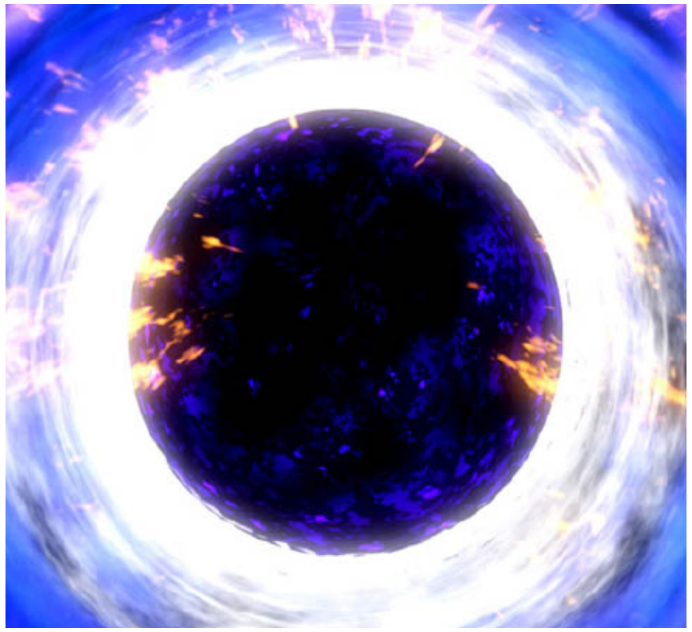
Event Horizons in Relativity

- 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:

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

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

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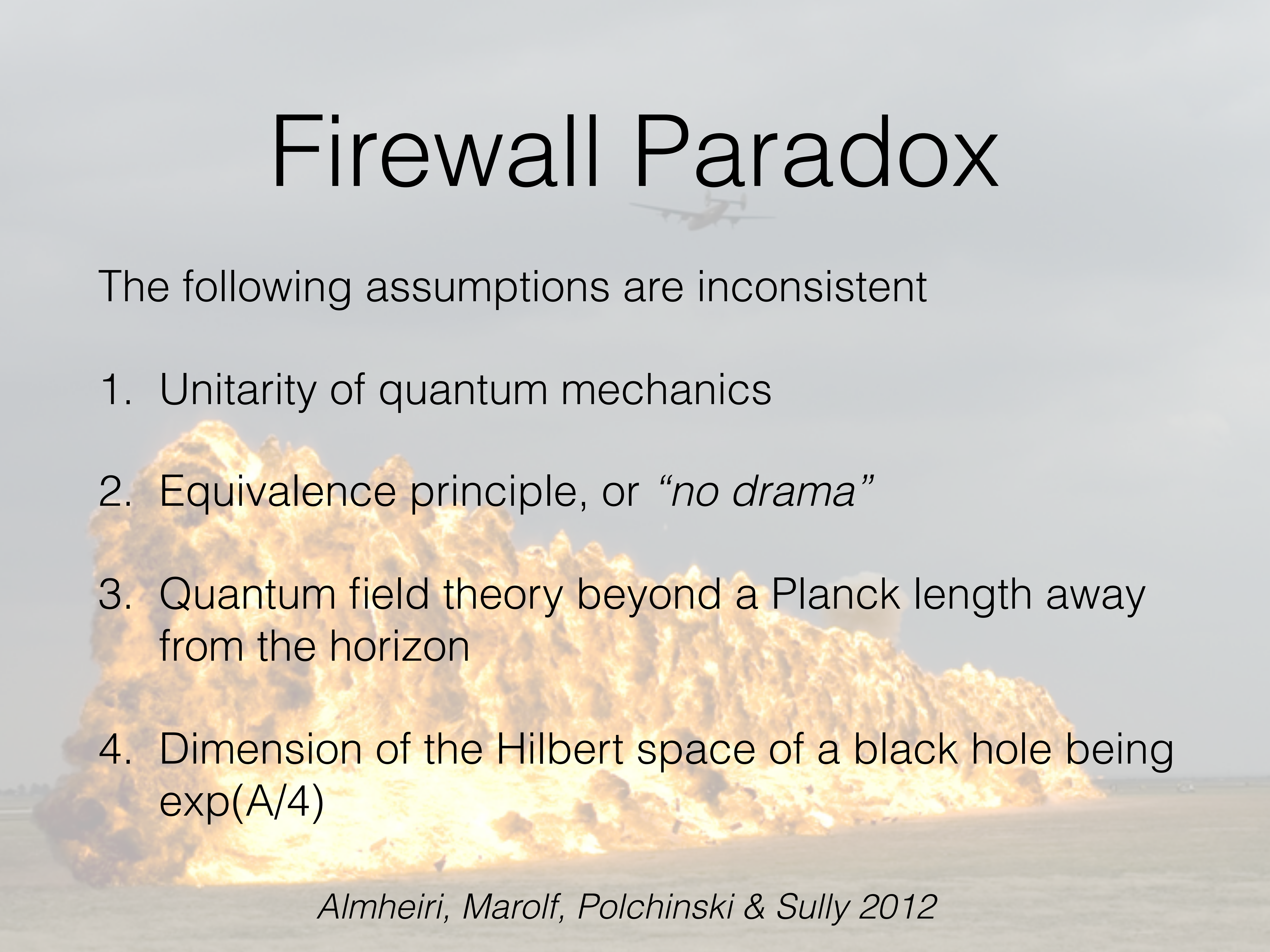
Which states does this entropy count?!

What is wrong with horizons?

- **Information paradox:** unitary black hole evaporation, not consistent with <u>local physics</u>+<u>smooth horizon</u> *(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)*



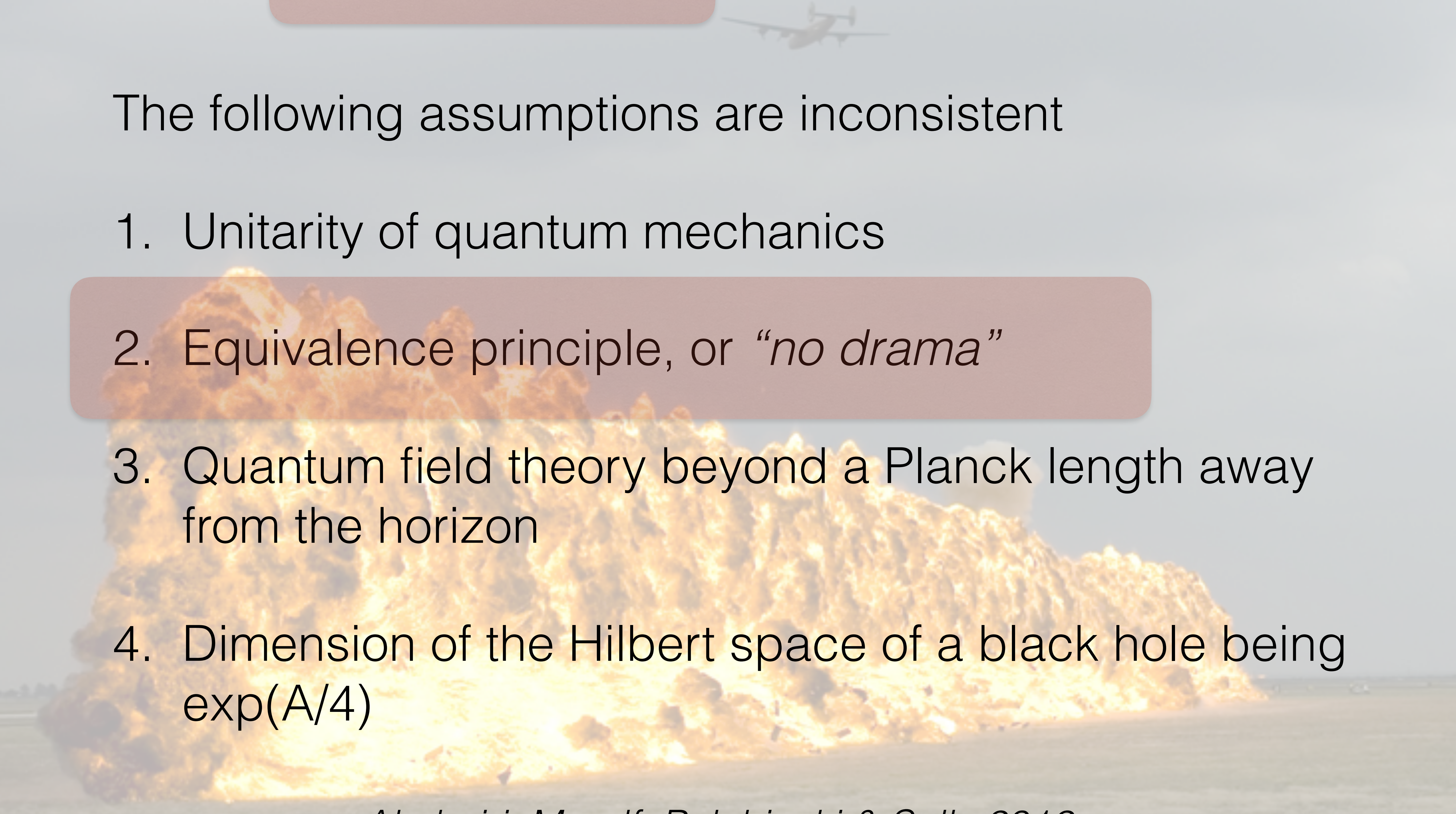
Firewall Paradox

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

Firewall Paradox



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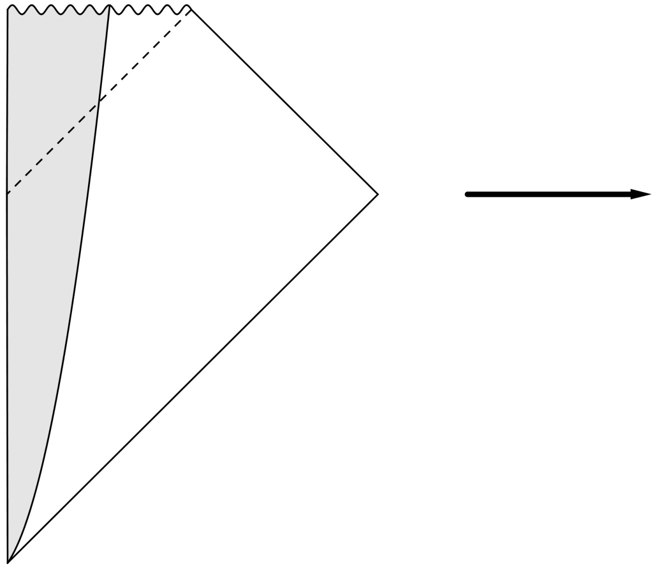
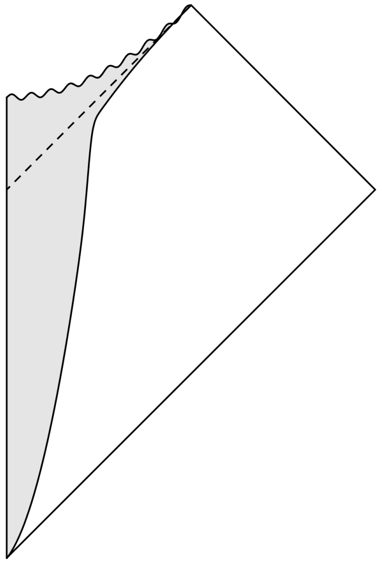
What else could it be?

- **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, …



Collapsing Schwarzschild Black Hole



Collapsing Aether Black Hole

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)*

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

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
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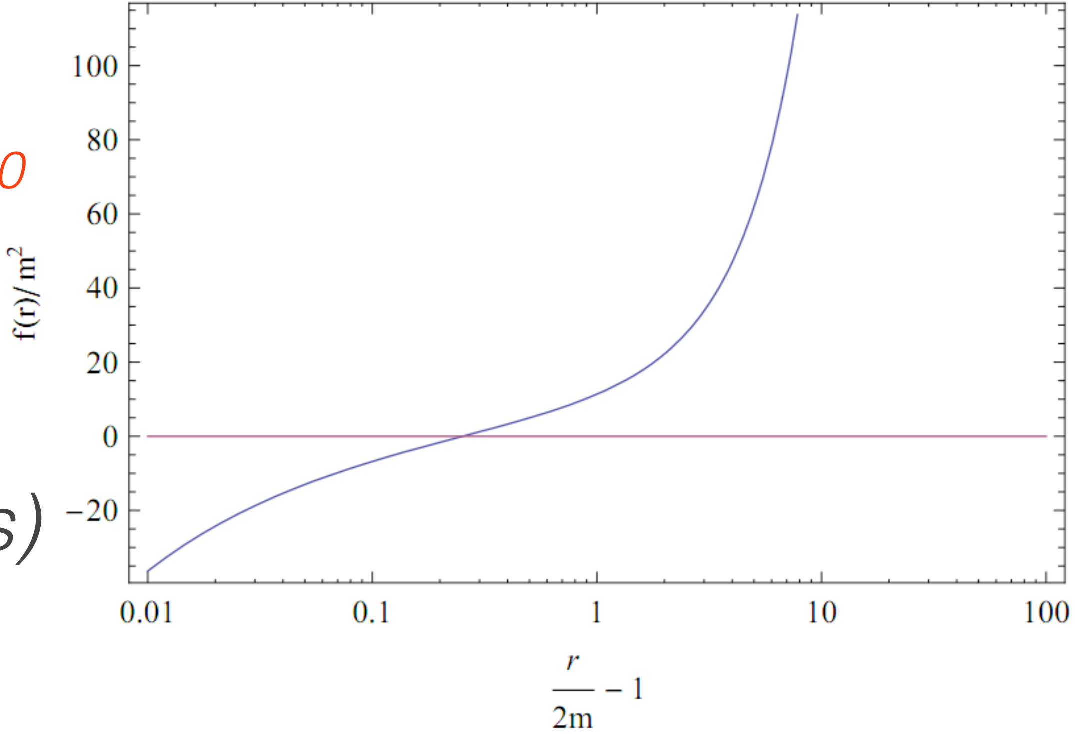


... and dark energy!

- Assume:

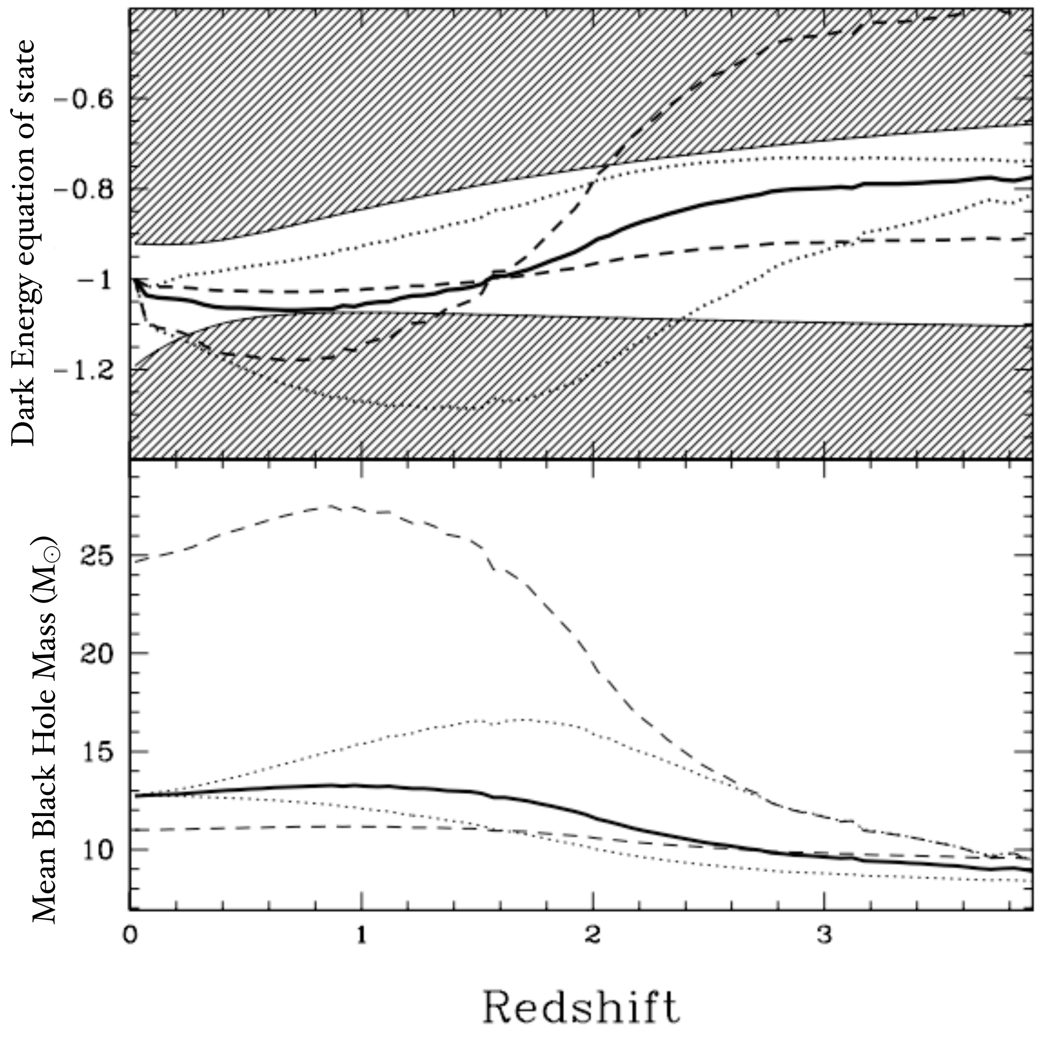
$$\boxed{1+z_{\max}\sim\frac{\text{Planck temperature}}{\text{Hawking temperature}}}$$

- then we get

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

- *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



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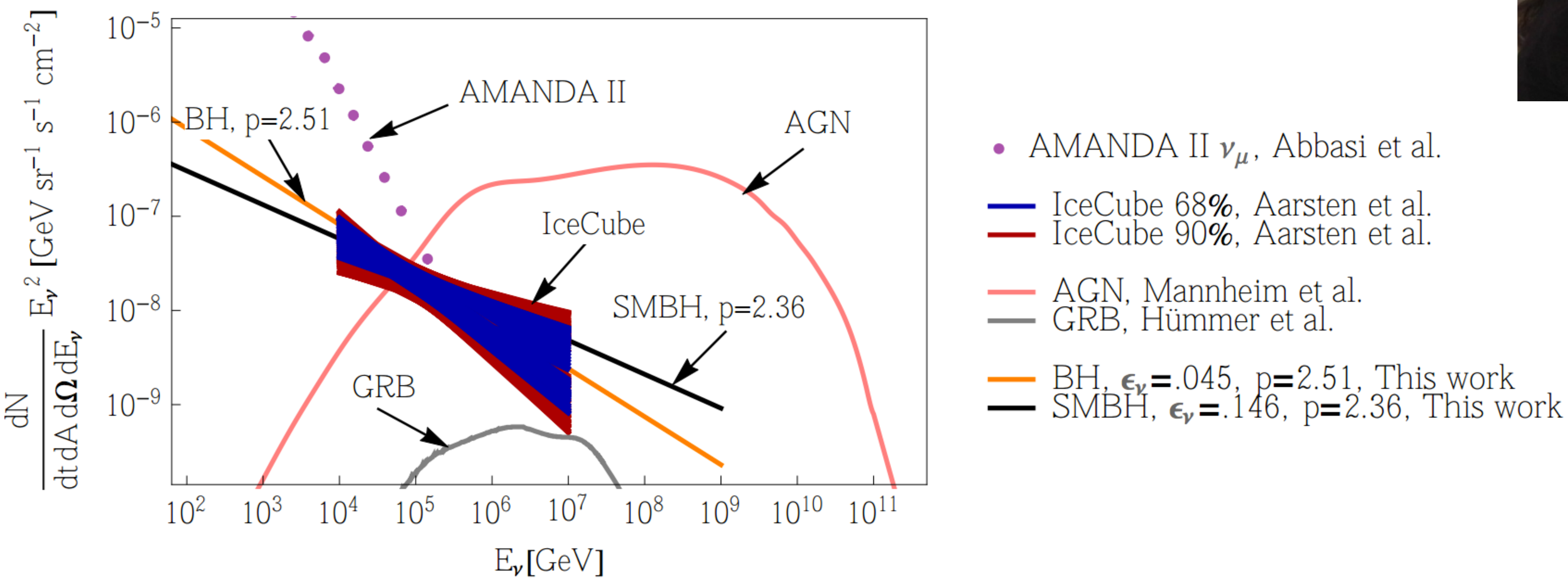
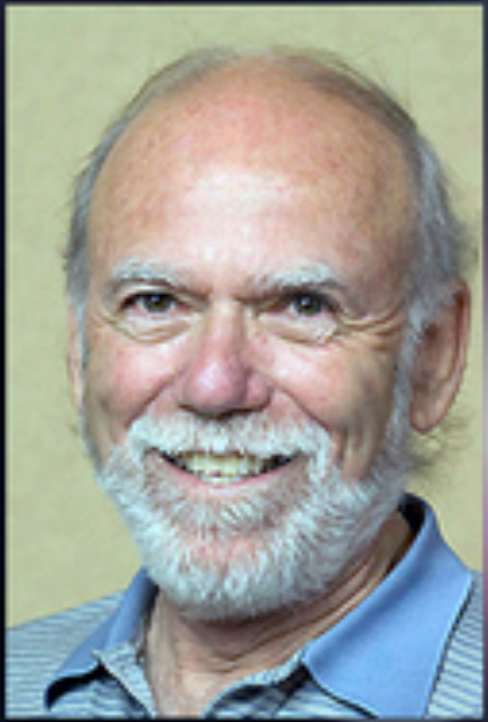
Fuzzball Phenomenology

- Radio or Infrared signals? (Broderick, et al.)
- Pulsar timing near Sgr A*? (Broderick & Pen)
- Ultra high energy neutrinos? (Yazdi & NA 16)





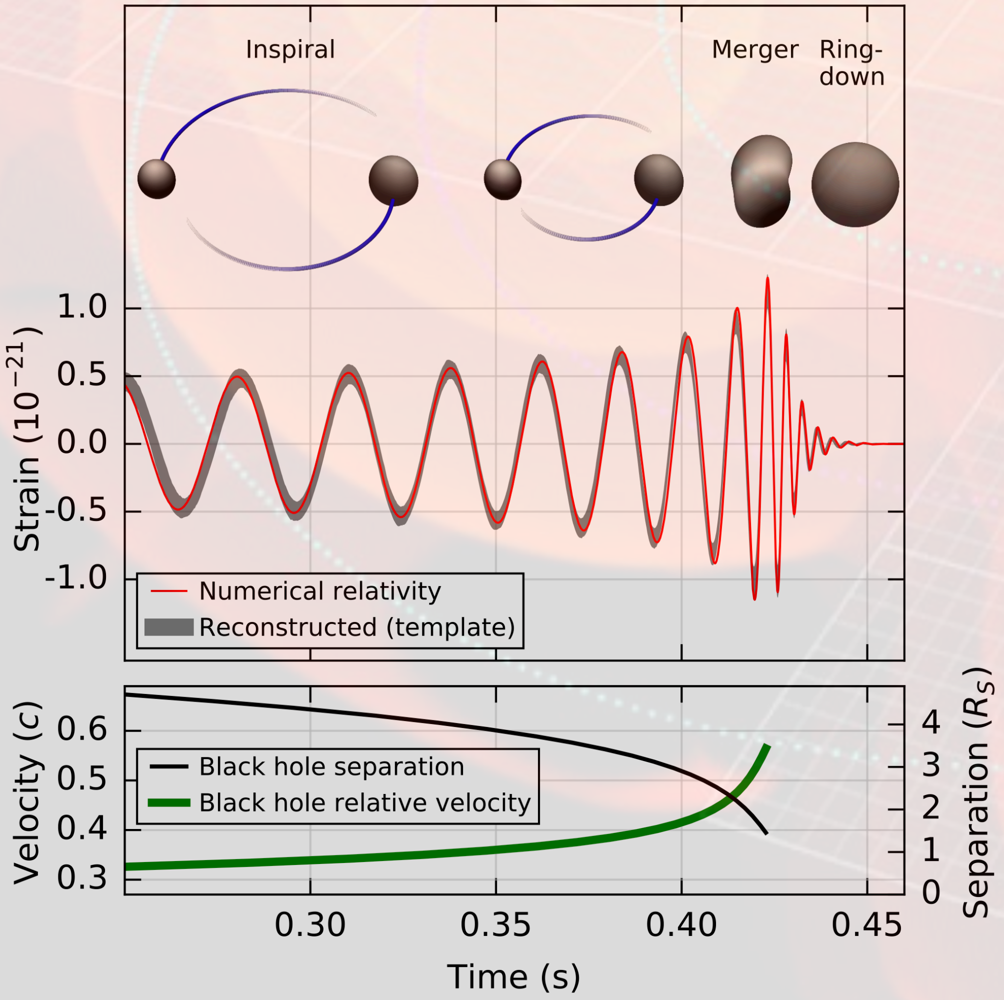
Barry C. Barish (Caltech)

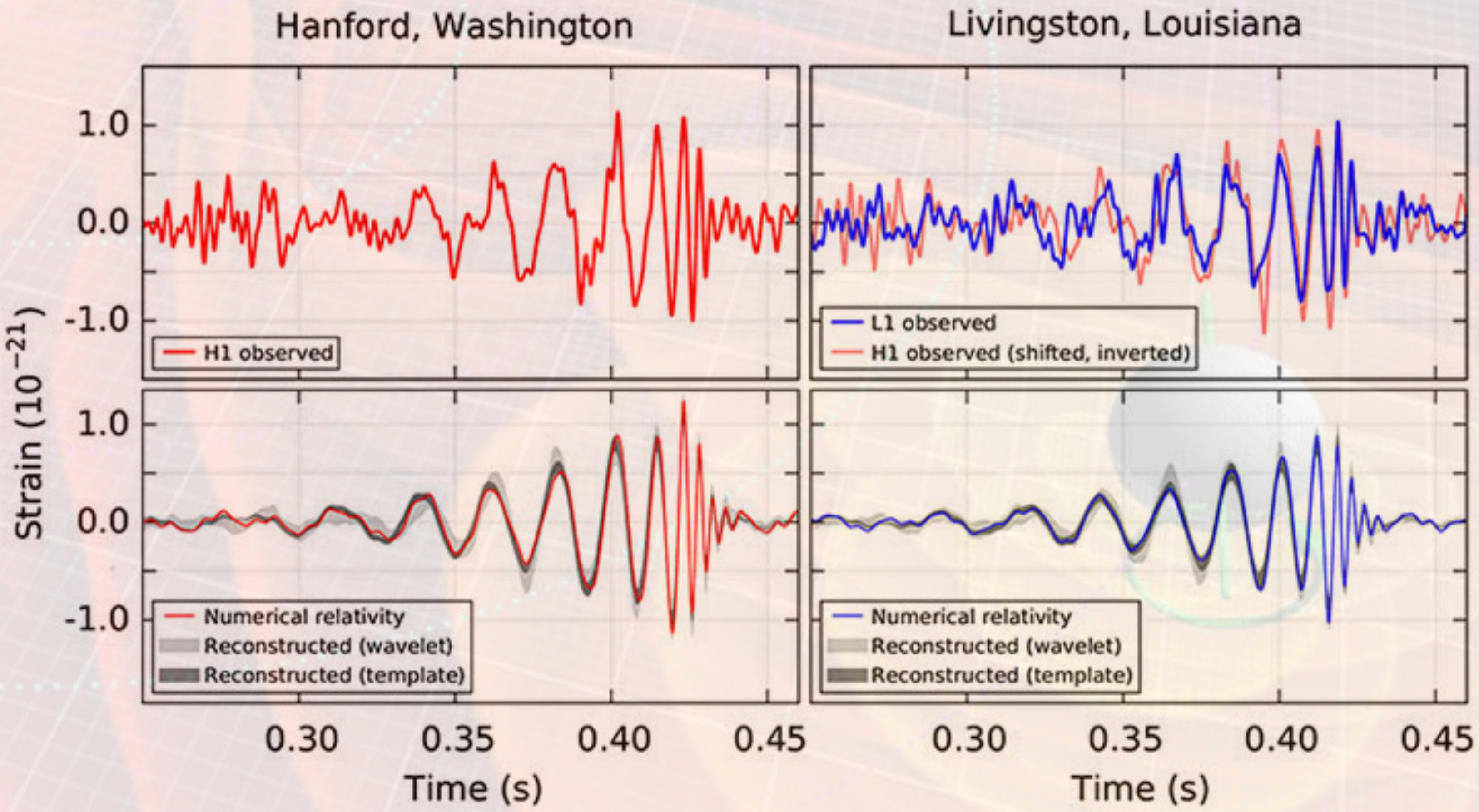
Kip S. Thorne (Caltech)

Rainer Weiss (MIT)

2017 Nobel Prize in Physics

The Future is NOW!





LIGO collaboration, 2016

What should we see?

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

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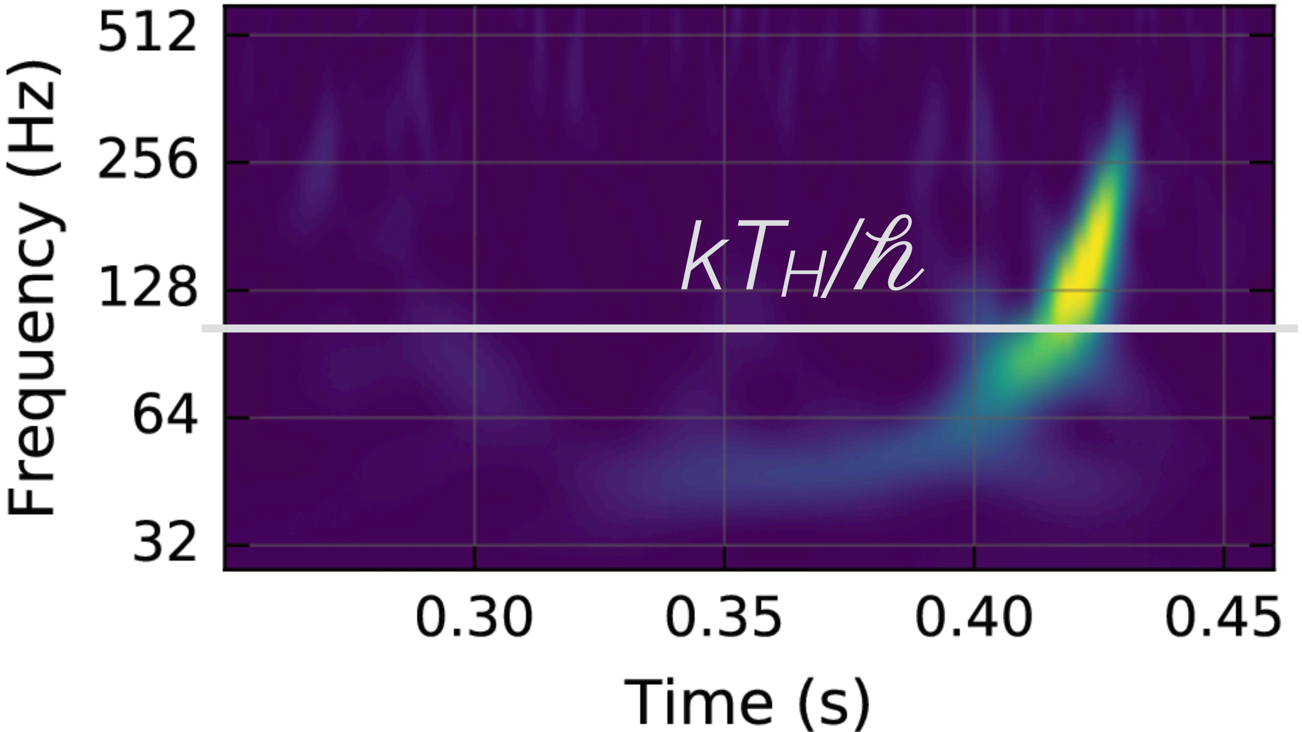
- Particles with $E \gtrsim kT_H$ can excite fuzzball microstates, and so *may be* absorbed
- Particles with $E \lesssim kT_H$ will be reflected
- Ringdown of black holes $\hbar\omega \sim kT_H$



Advanced LIGO
GW150914

Outline

- What is wrong with horizons?
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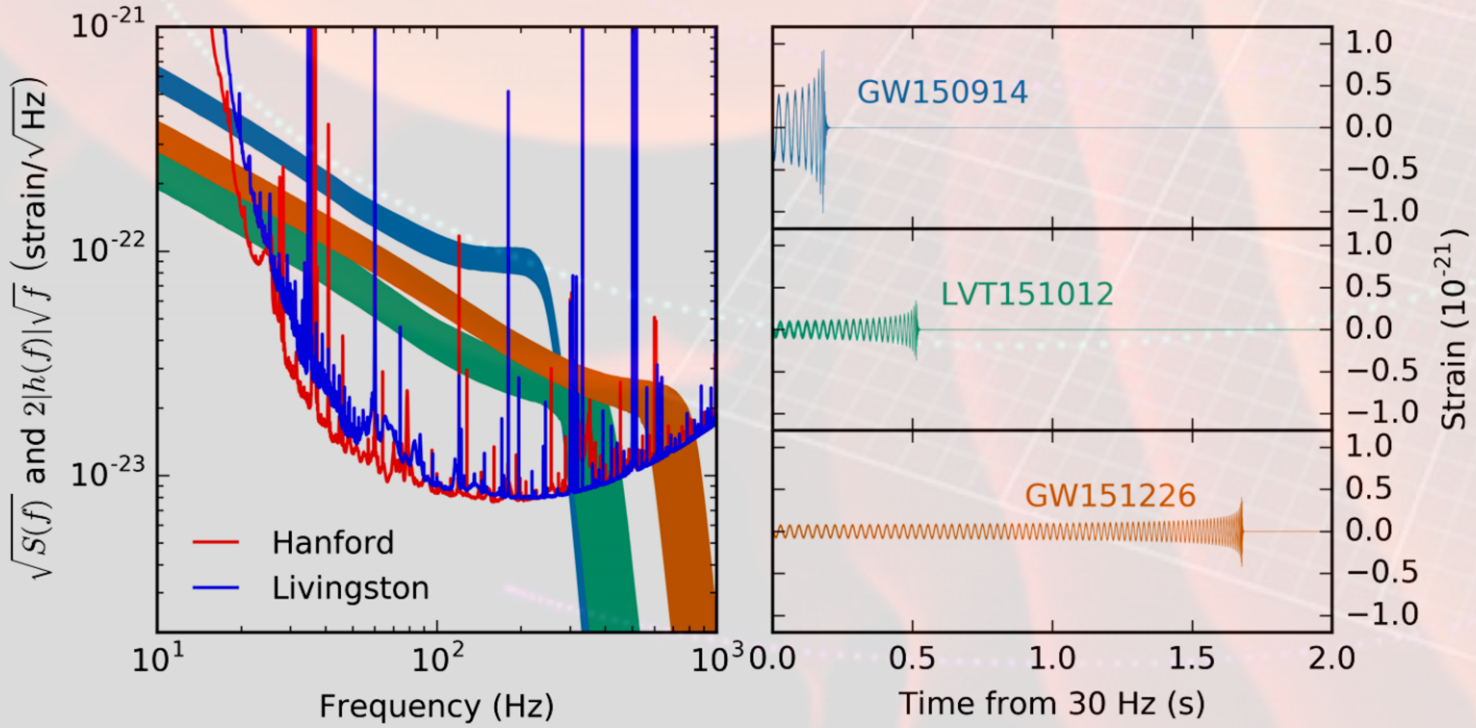
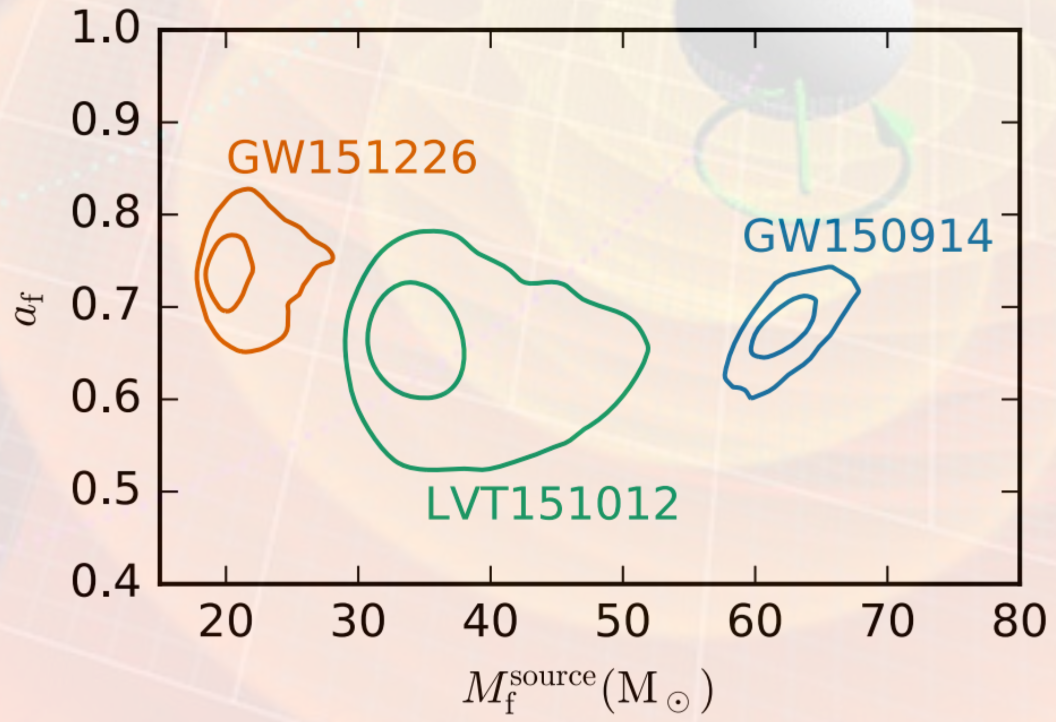
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	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



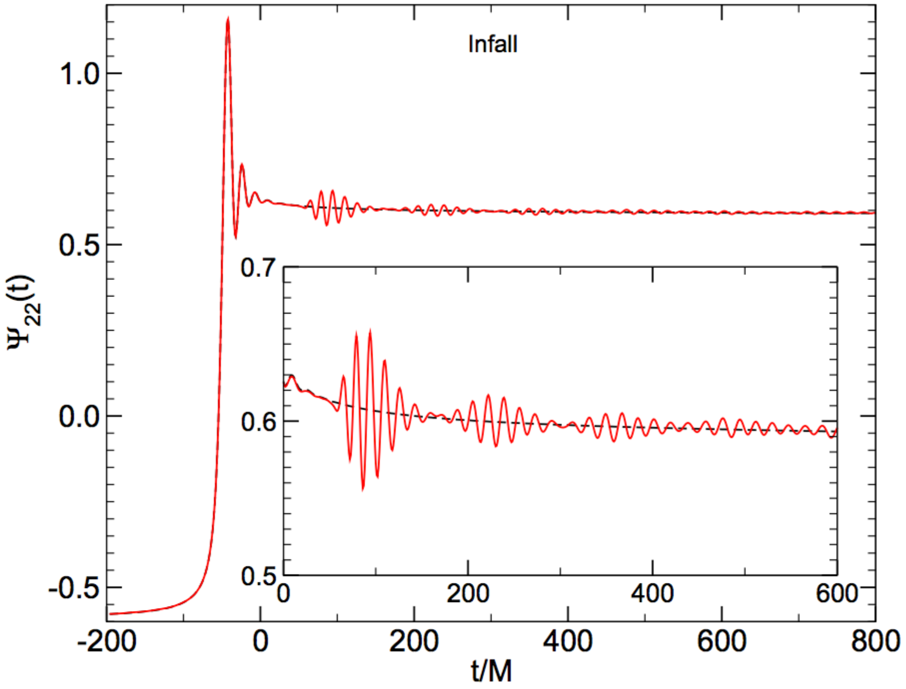


Echoes from the Abyss!

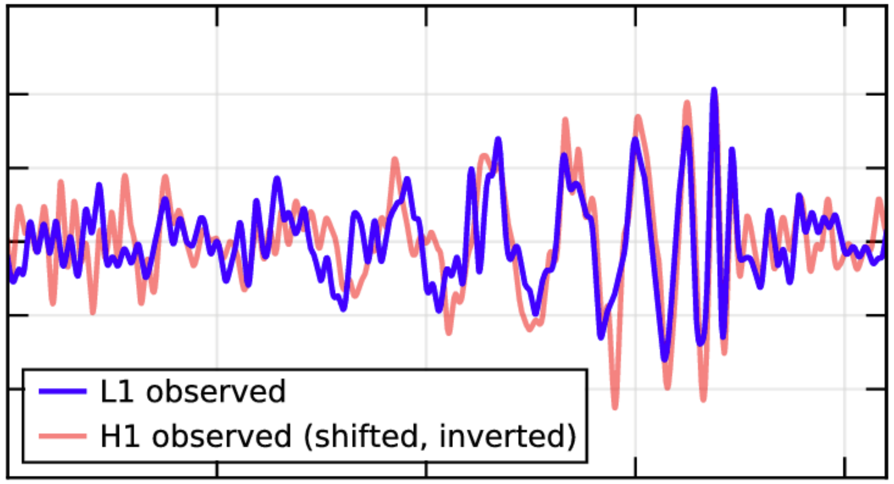
- Late echoes from Planckian structure near horizon

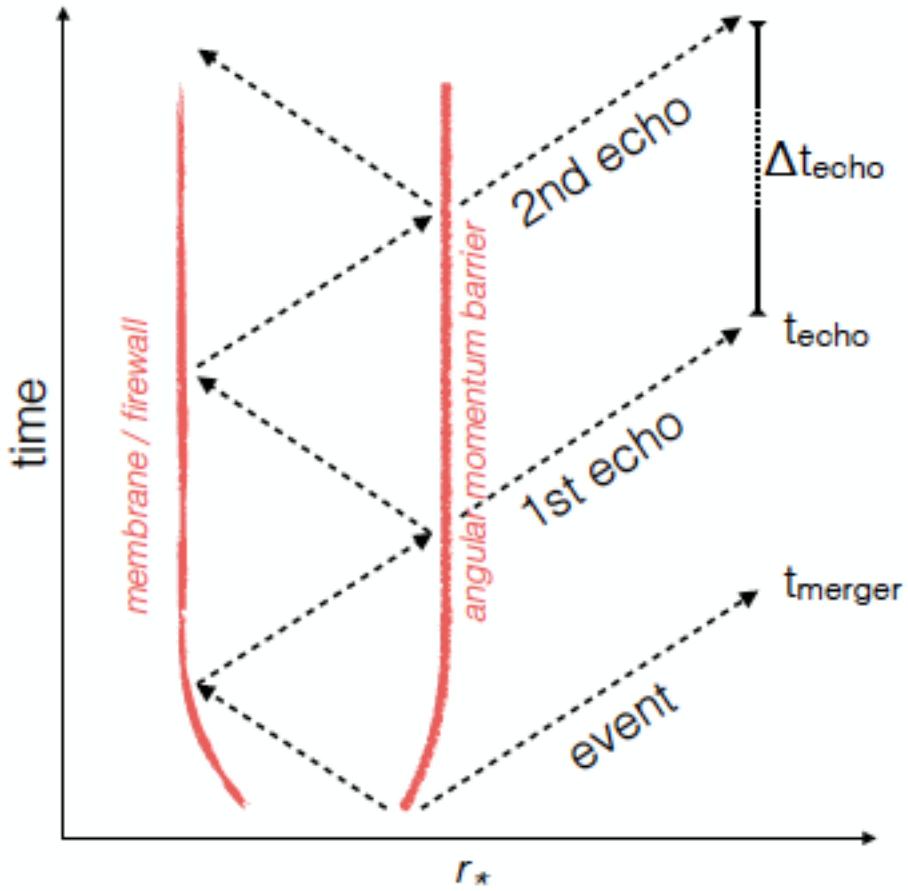
$$\boxed{\Delta t \simeq 8 M_{BH} \log\left(\frac{M_{BH}}{M_P}\right) \simeq 0.25\ \mathrm{sec}}$$

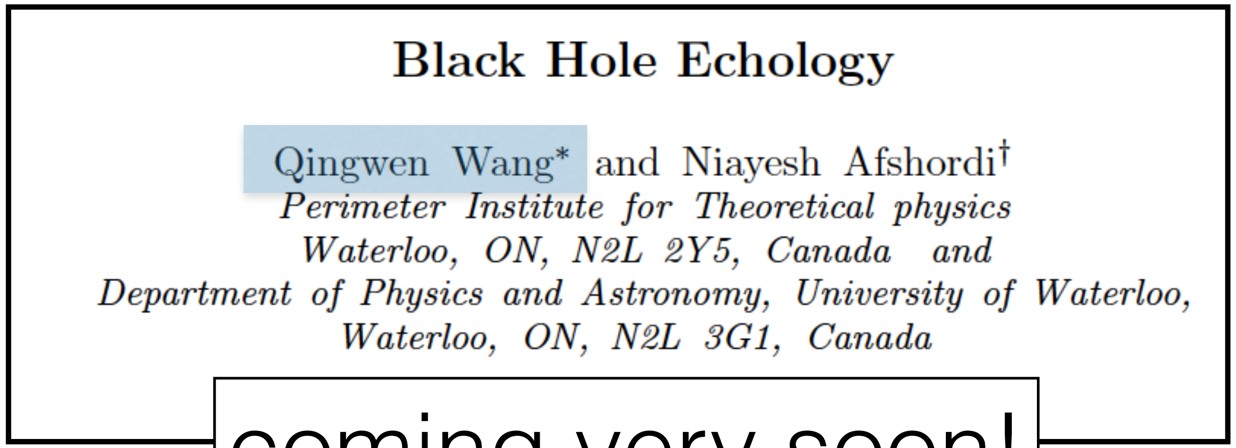
Cardoso, et al. 16



Livingston, Louisiana (L1)



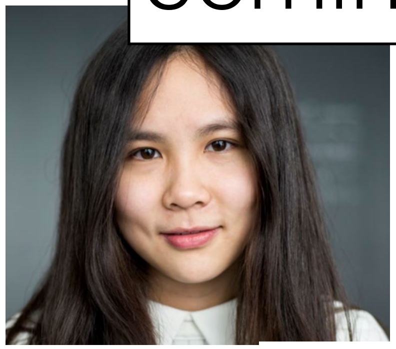


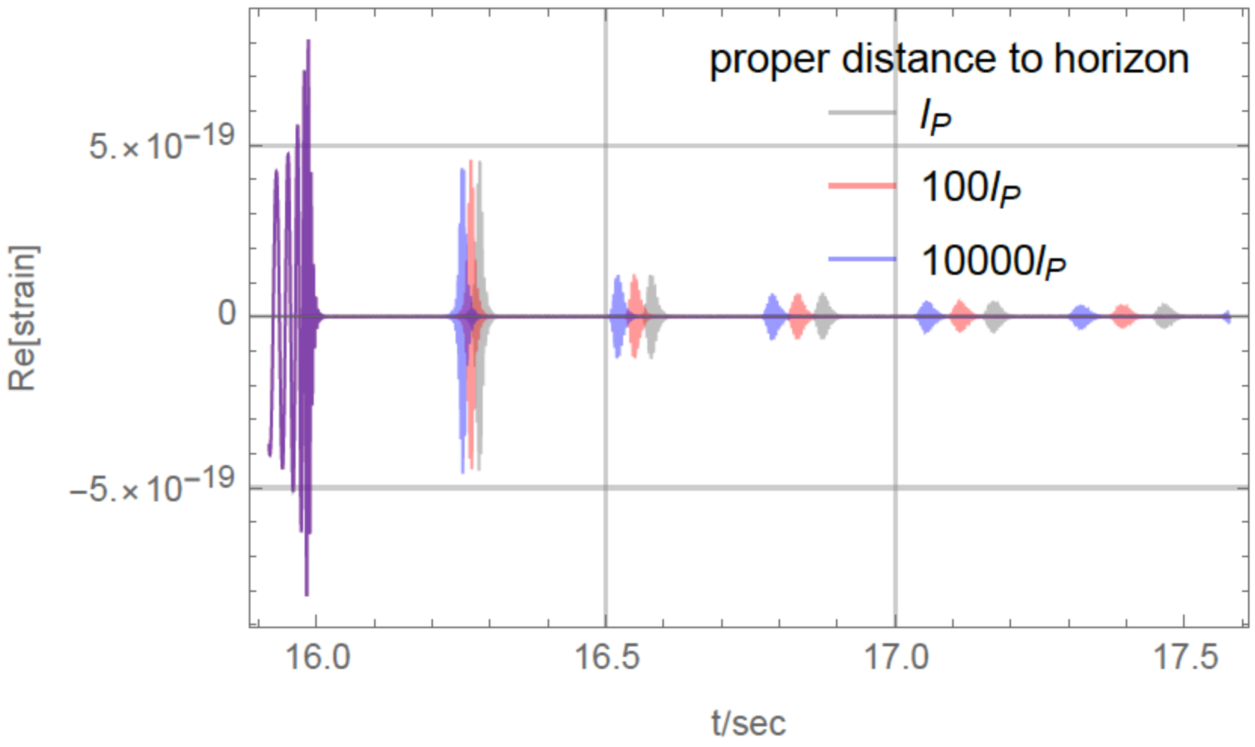


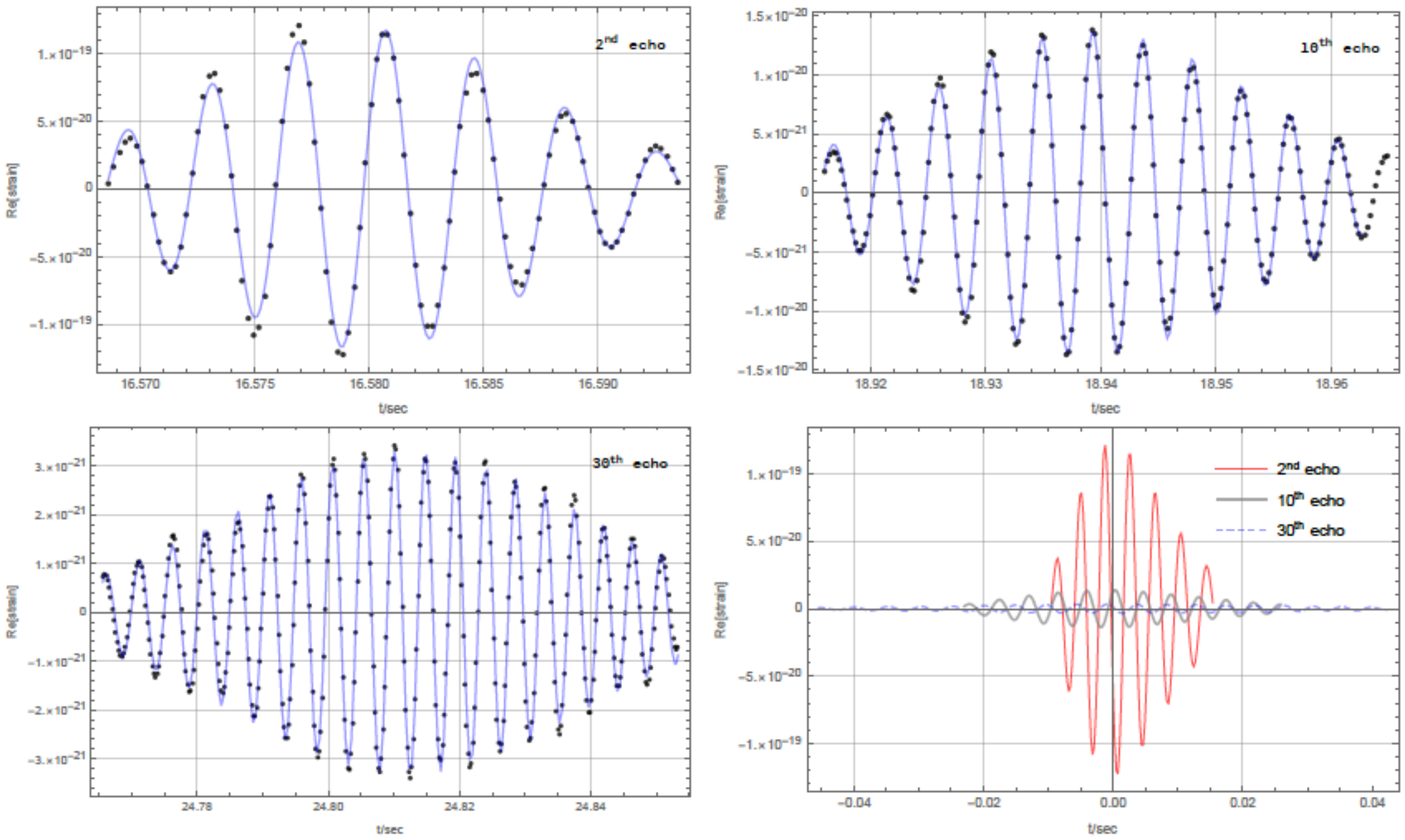
Black Hole Echology

Qingwen Wang* and Niayesh Afshordi†
Perimeter Institute for Theoretical physics
Waterloo, ON, N2L 2Y5, Canada and
Department of Physics and Astronomy, University of Waterloo,
Waterloo, ON, N2L 3G1, Canada

coming very soon!







Data Analysis Primer

- 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

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

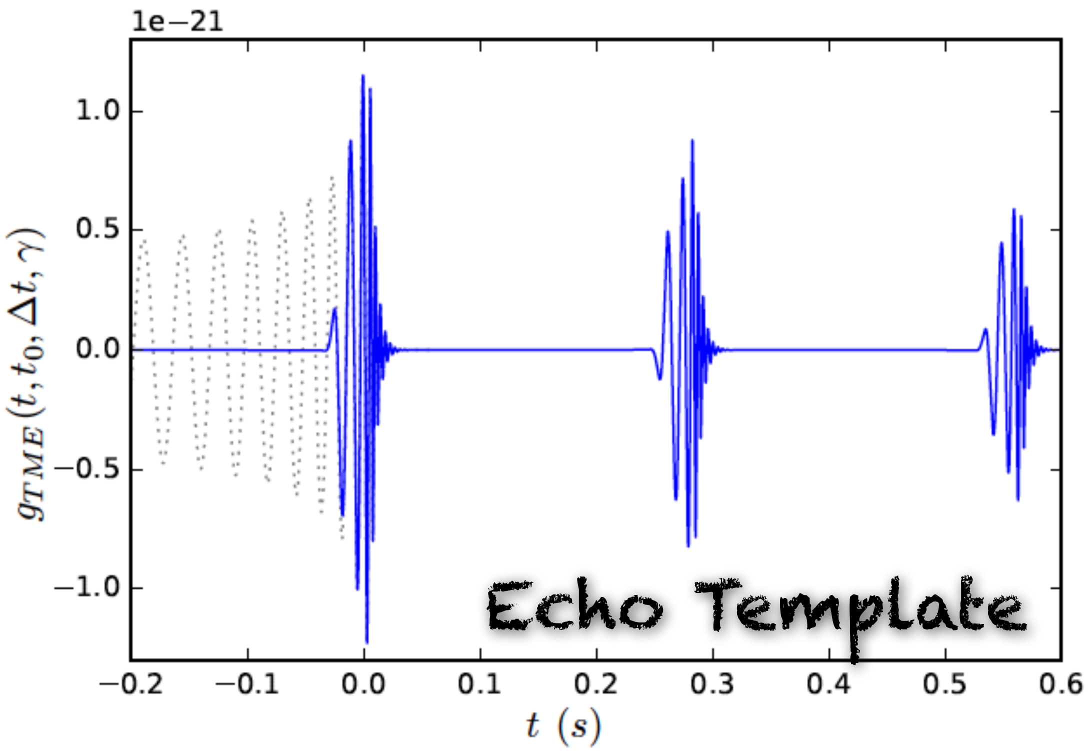
- Toy model for echo template

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

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

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

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



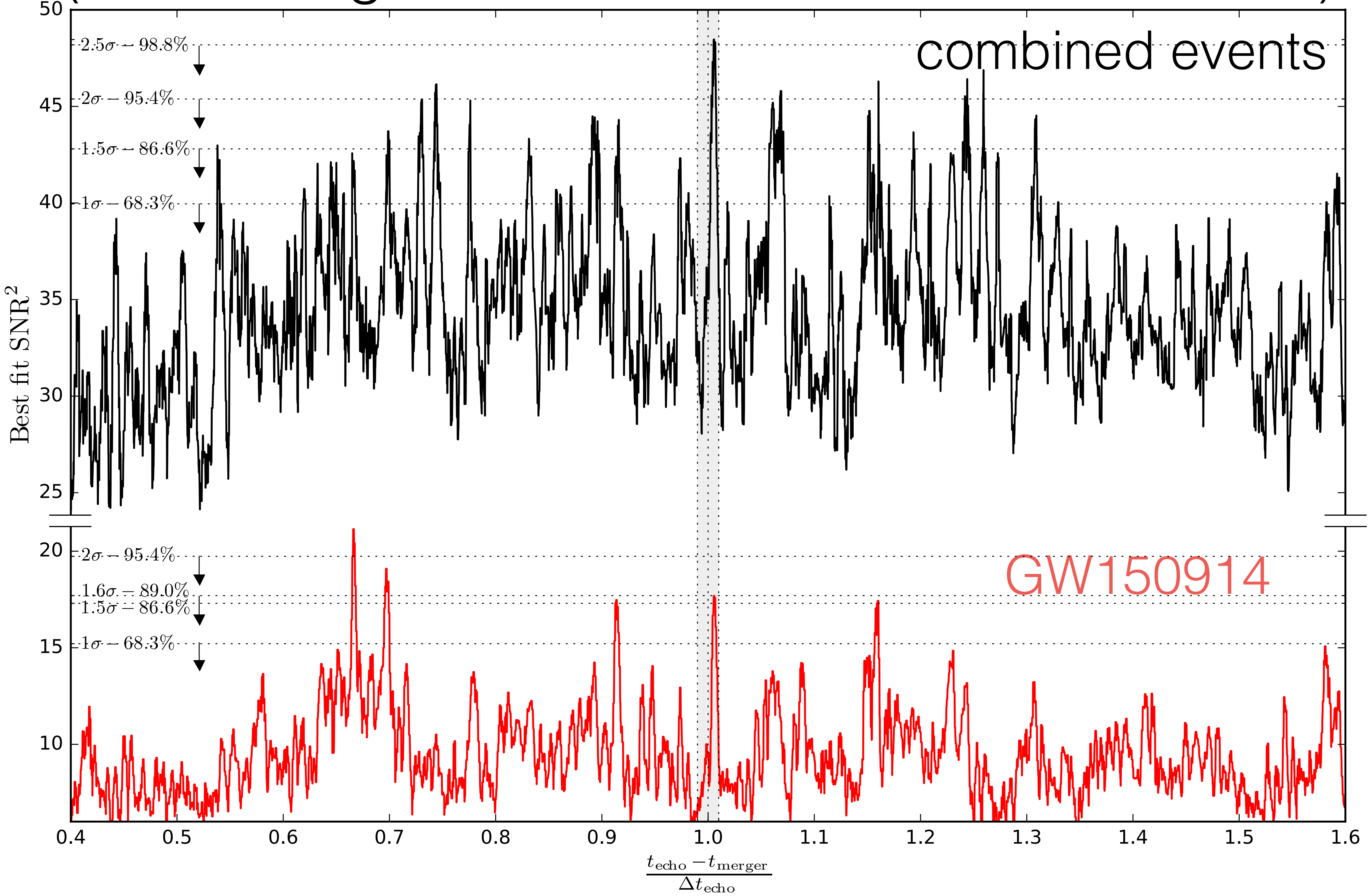
Echo Template

Abedi, *Dykaar & NA 2017*

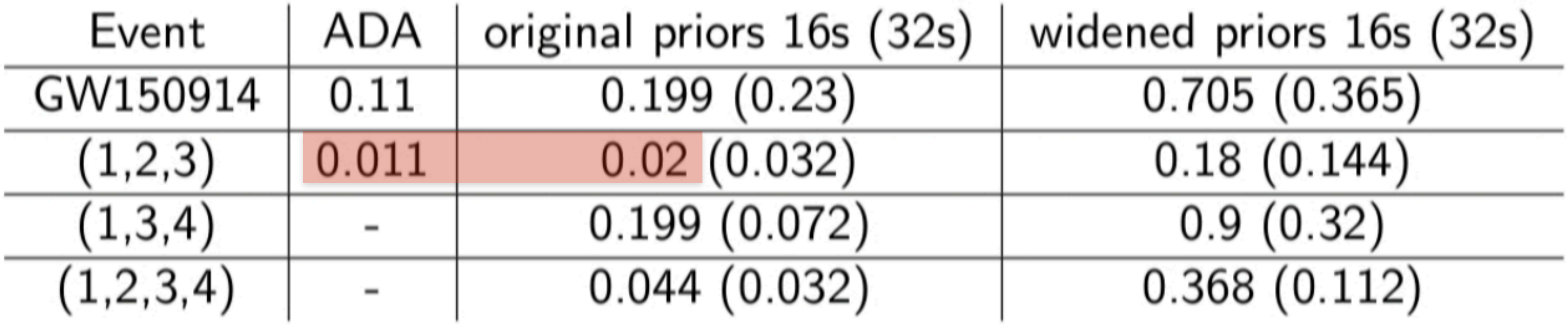
Abedi, Dykaar & NA 2017

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

(accounting for all the “look-elsewhere” effects)

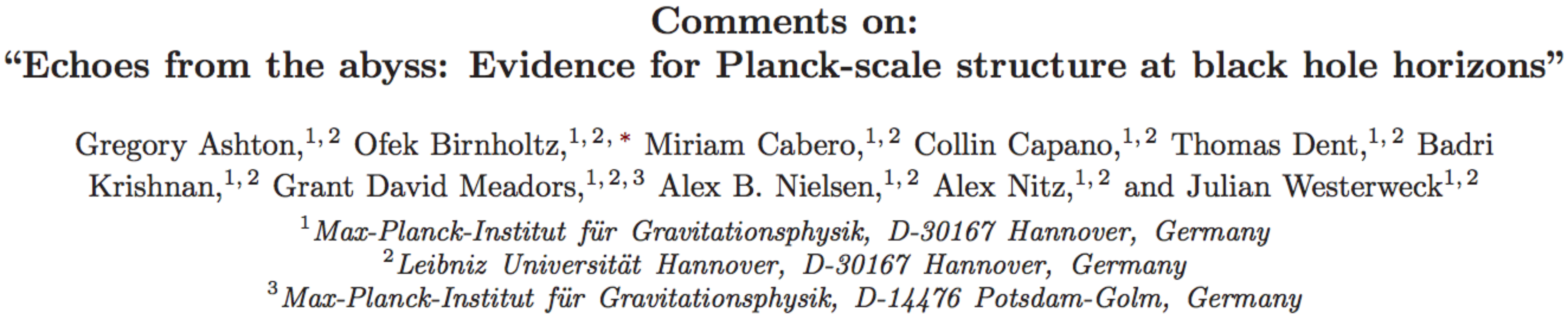


Independent Confirmation by AEI group



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/

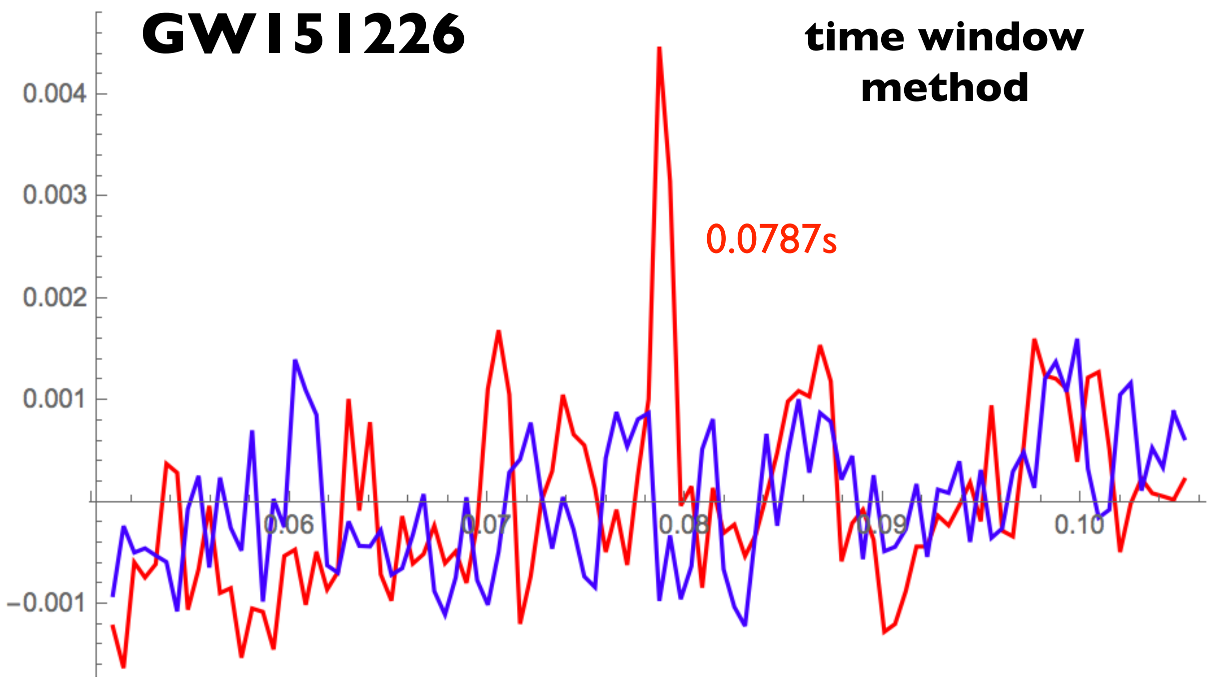


Comments on:
"Echoes from the abyss: Evidence for Planck-scale structure at black hole horizons"

Gregory Ashton,[1,2] Ofek Birnholtz,[1,2,*] Miriam Cabero,[1,2] Collin Capano,[1,2] Thomas Dent,[1,2] Badri Krishnan,[1,2] Grant David Meadors,[1,2,3] Alex B. Nielsen,[1,2] Alex Nitz,[1,2] and Julian Westerweck[1,2]
[1] *Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[3] *Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*

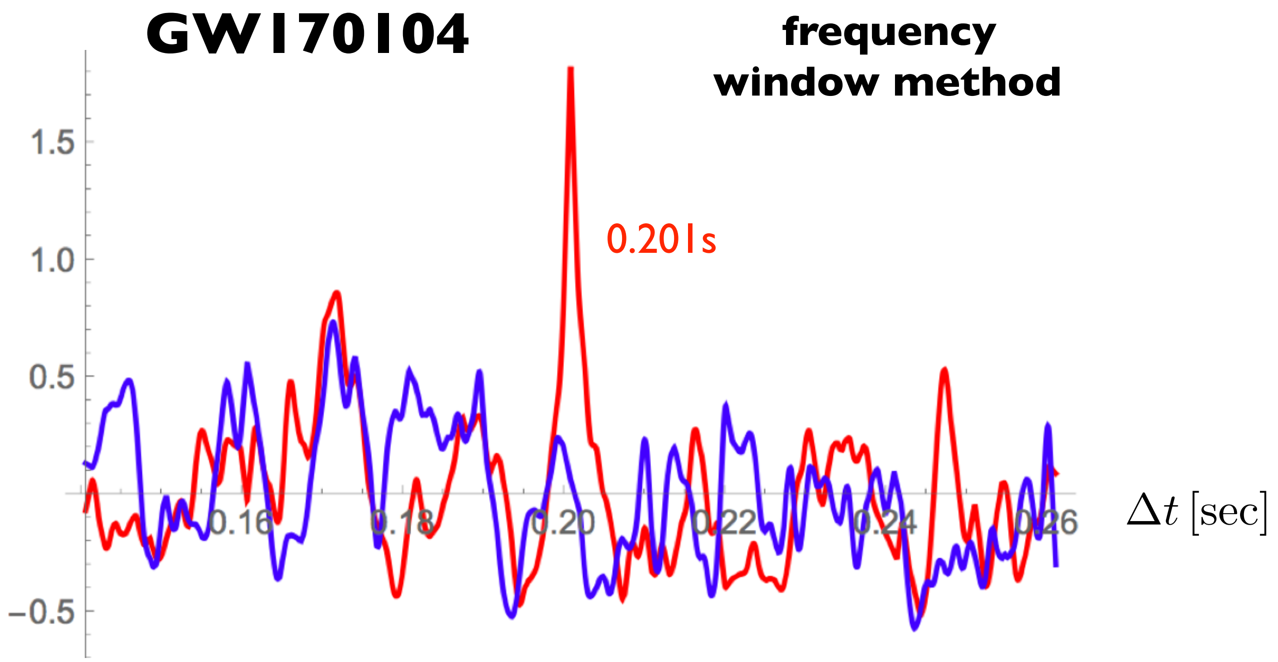
Another independent search for echoes

- ***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)



GW151226

time window method



GW170104

frequency window method

- ***Results***: finding tentative signal peaks for *GW151226, GW170104, GW170608, GW170814* 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/)

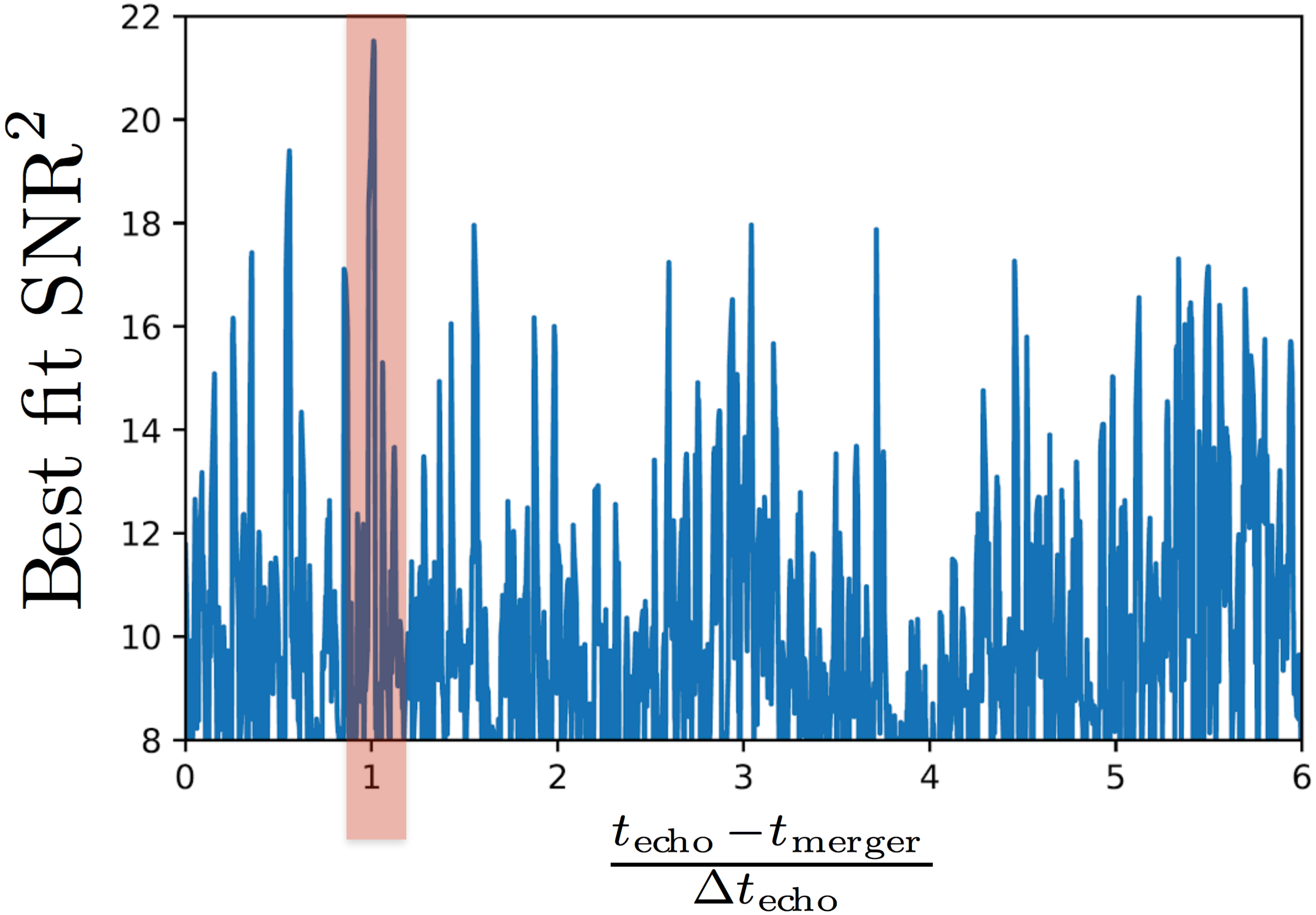
- More to come in the paper *arXiv: 1712.xxxxx*: the initial estimation of the ***p-values are around 1% or below.***

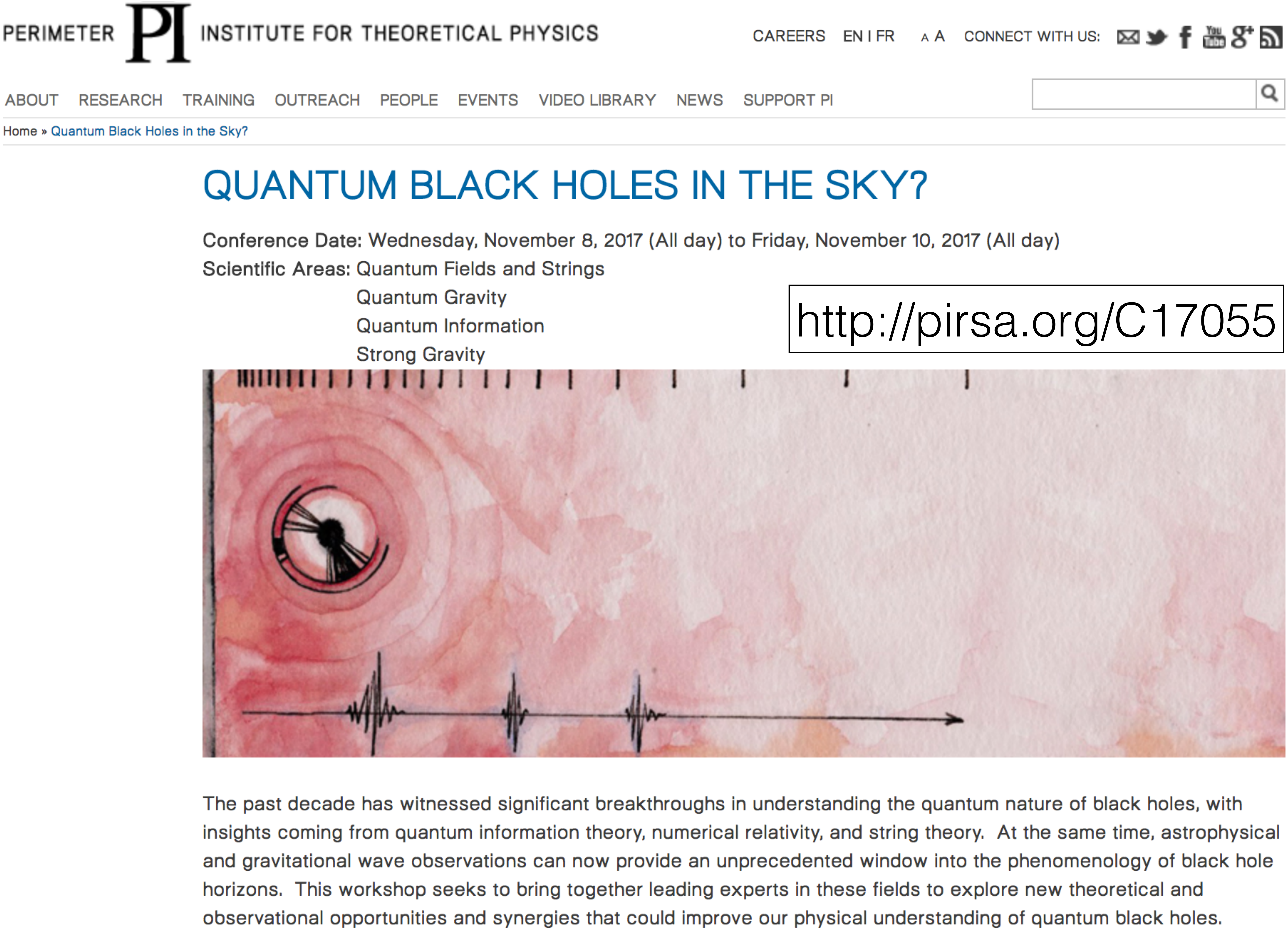
Randy Conklin, Bob Holdom, Jing Ren

Preliminary model-agnostic search

- Where are the two detectors most correlated?
- p-value = 0.2% (3.1σ) for 8 echoes in GW150914
- some look-elsewhere effects

Jahed Abedi





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.

Conclusions

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- Strong motivations for alternatives to BH horizons: *Information paradox, Tunnelling, Dark Energy*

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- Tentative evidence (2-3σ) for echoes from Planck-scale structures near BH horizons: *False detection probability < 1%*

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- Tentative evidence (2-3σ) for echoes from Planck-scale structures near BH horizons: *False detection probability < 1%*
- Confirm *Aether Holes, Fuzzballs, Firewalls* (but which one?)

Conclusions

- Strong motivations for alternatives to BH horizons: *Information paradox, Tunnelling, Dark Energy*
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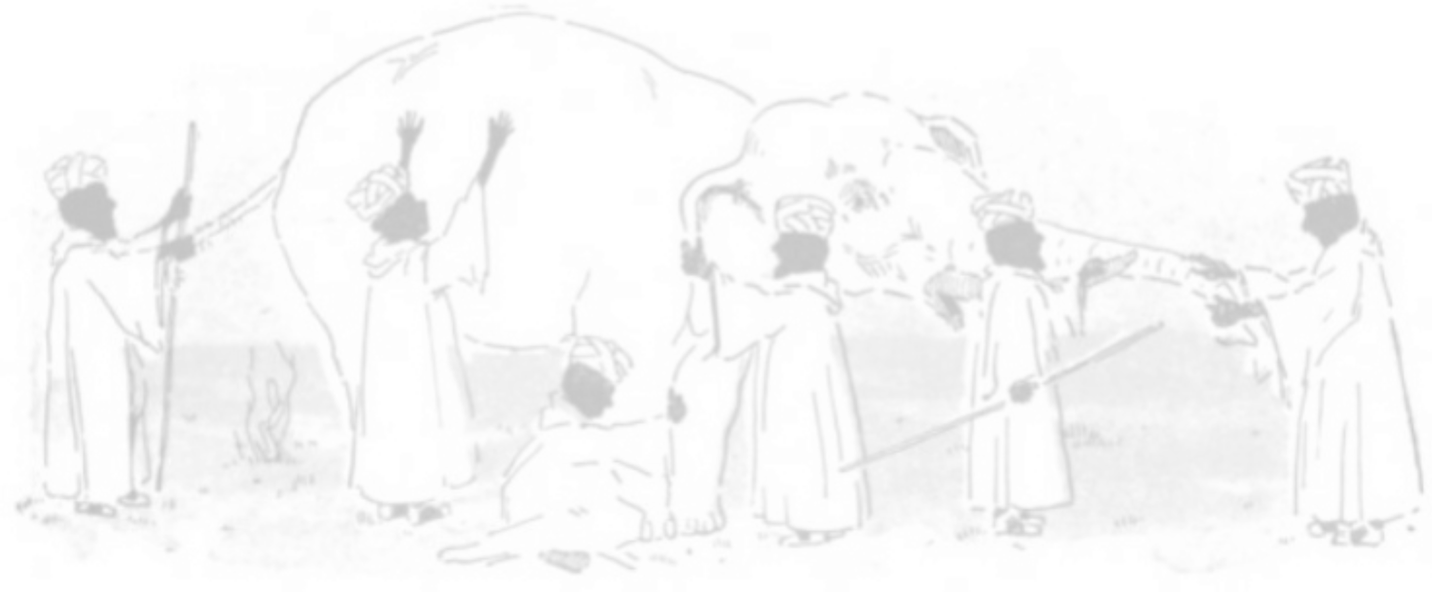

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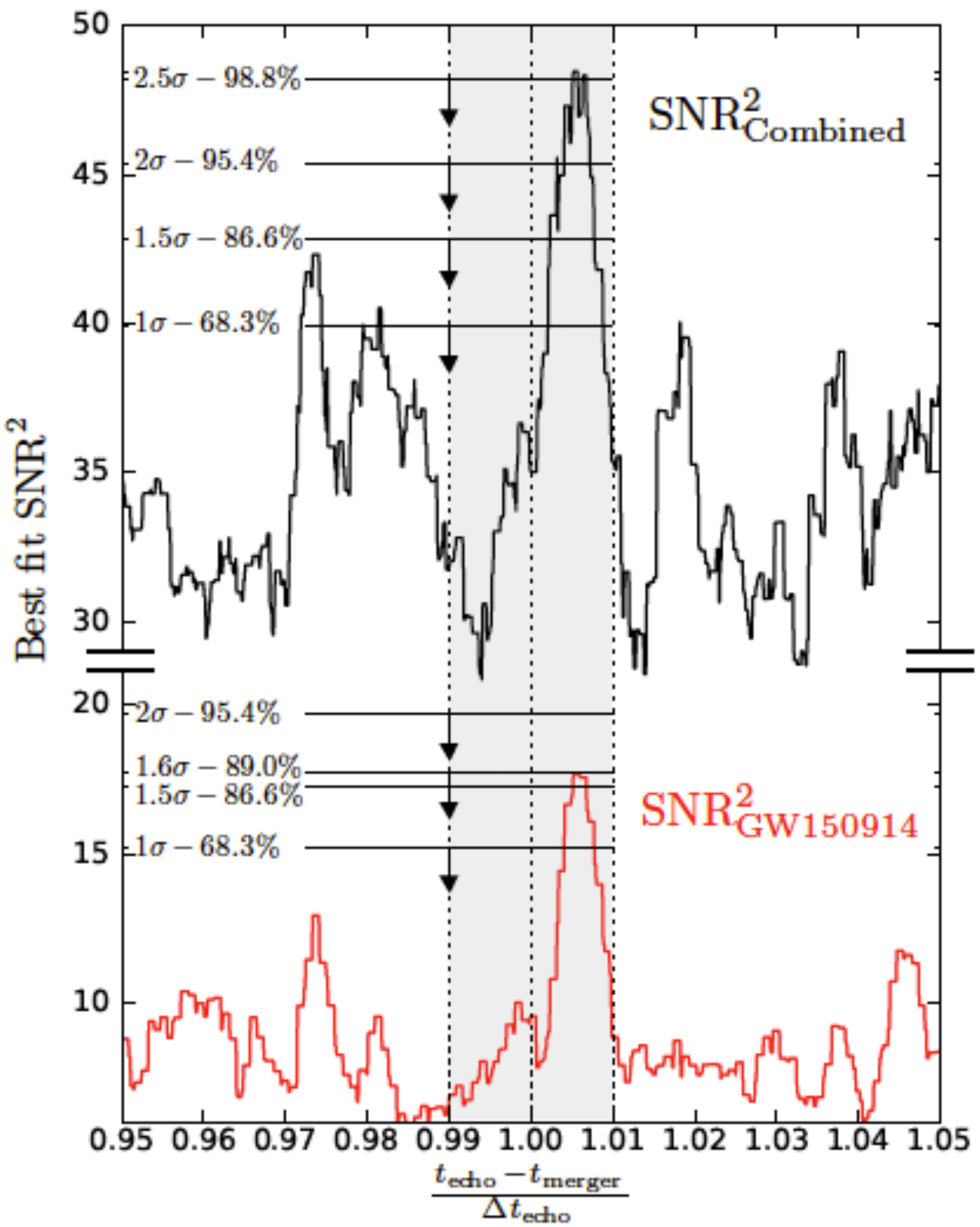
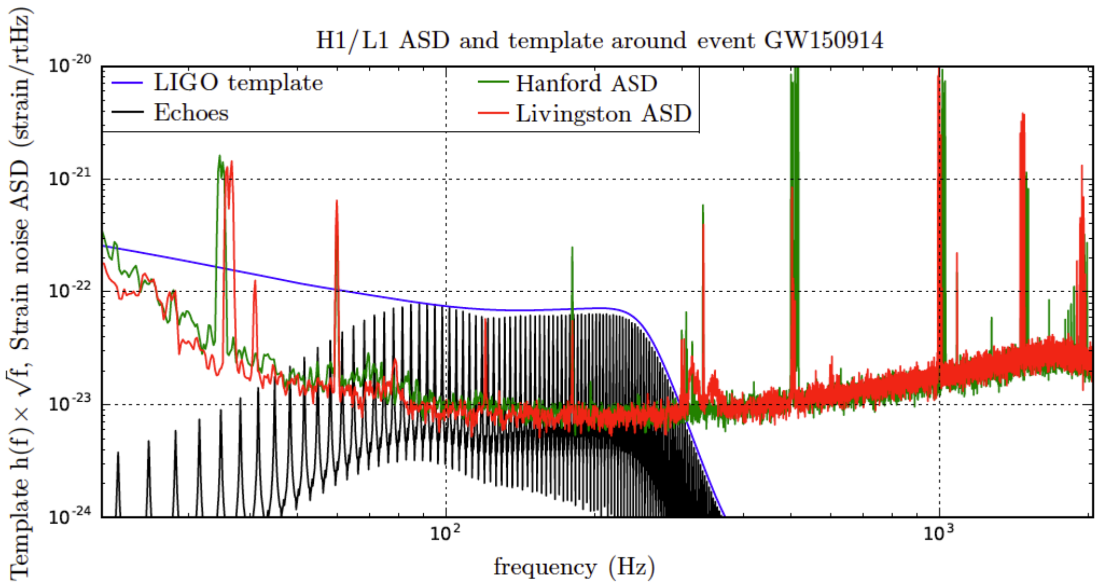
Stay Tuned!

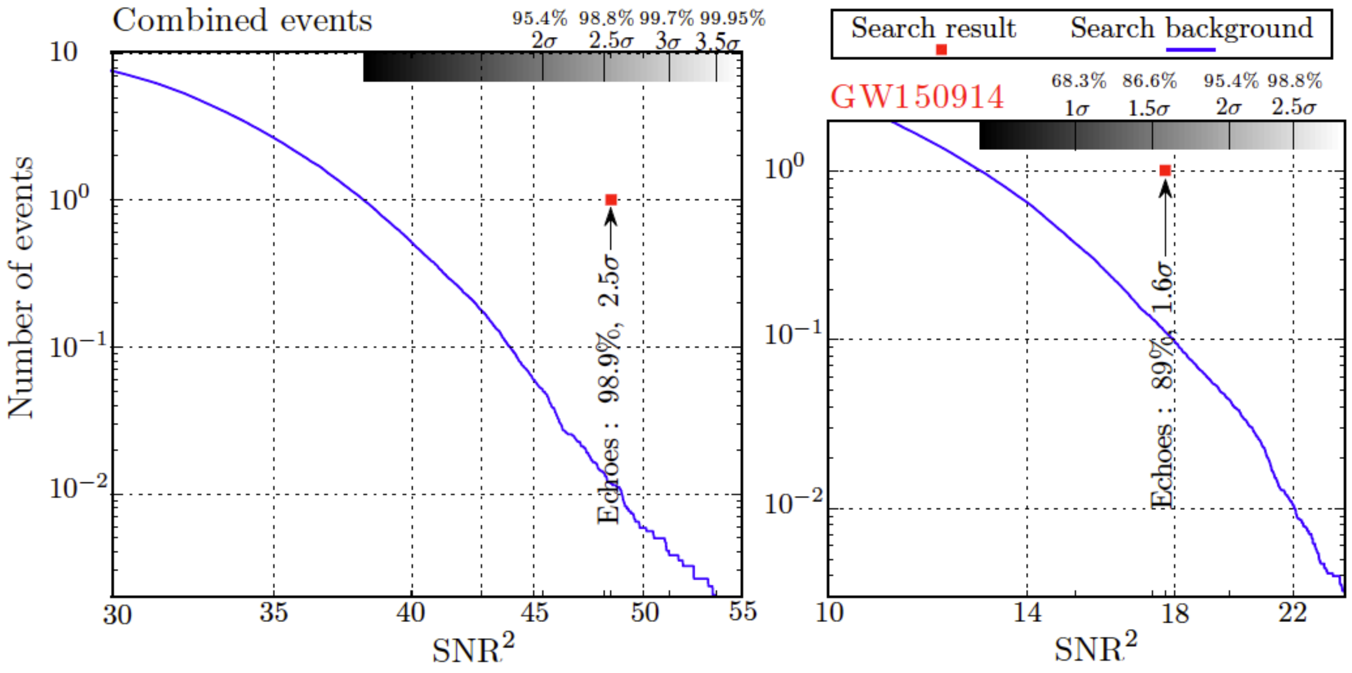
Setting space on fire (Jan. 2017, CQG+)

Bonus Slides

… and *voila!*







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

False detection probability for the echoes

Further tests

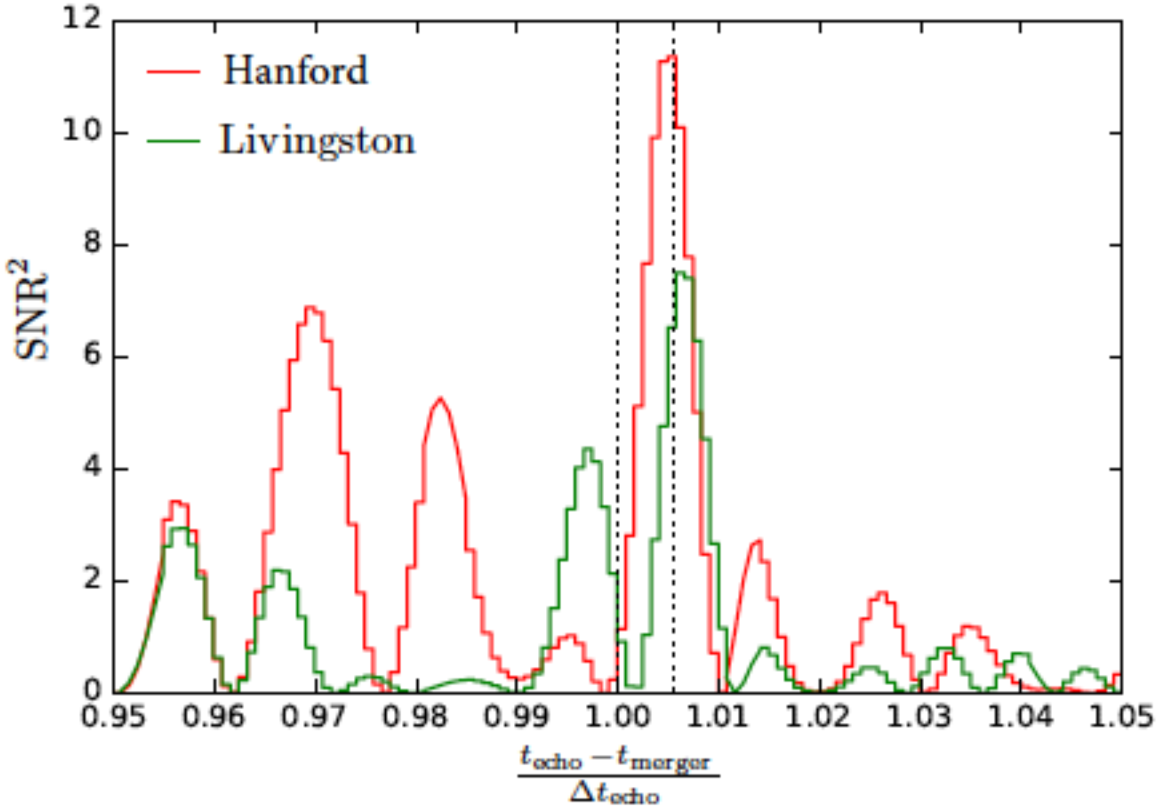


FIG. 2: SNR^2 near the expected time of merger echoes (Eq. 1) for GW150914 in Hanford (red) and Livingston (green) detectors. Interestingly, their SNR ratio $2.74/3.37 = 0.81$ is comparable to the SNR ratio for the main event $13.3/18.6 = 0.72$. Note that, unlike Fig. (1), here we have fixed the echo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

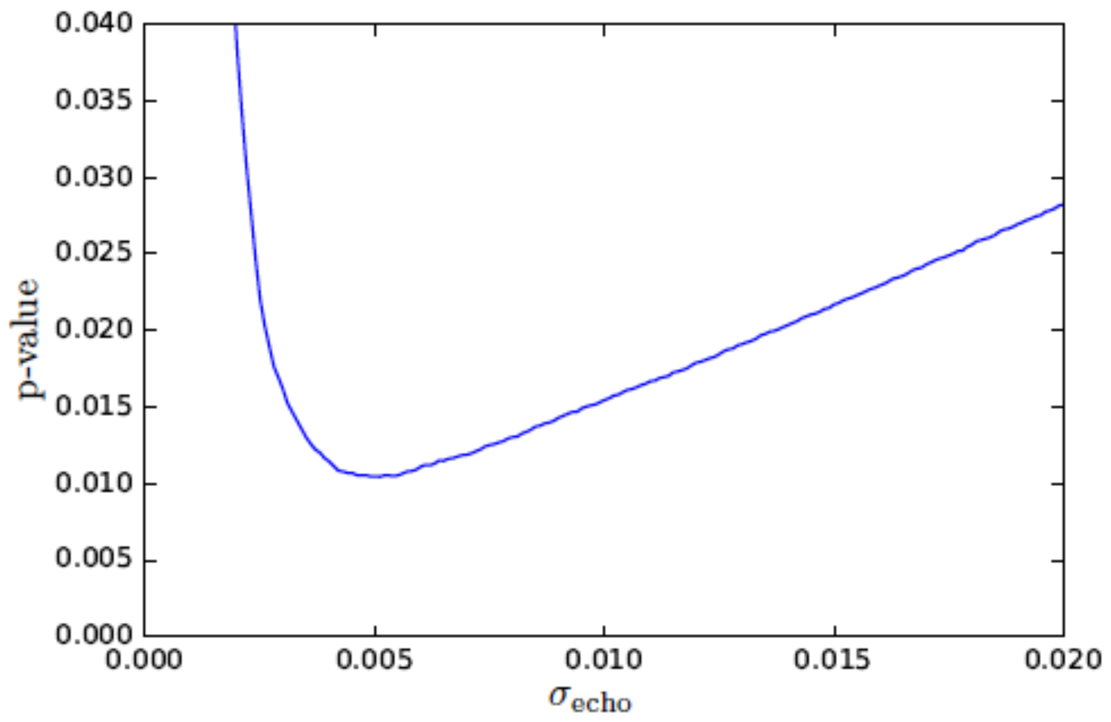
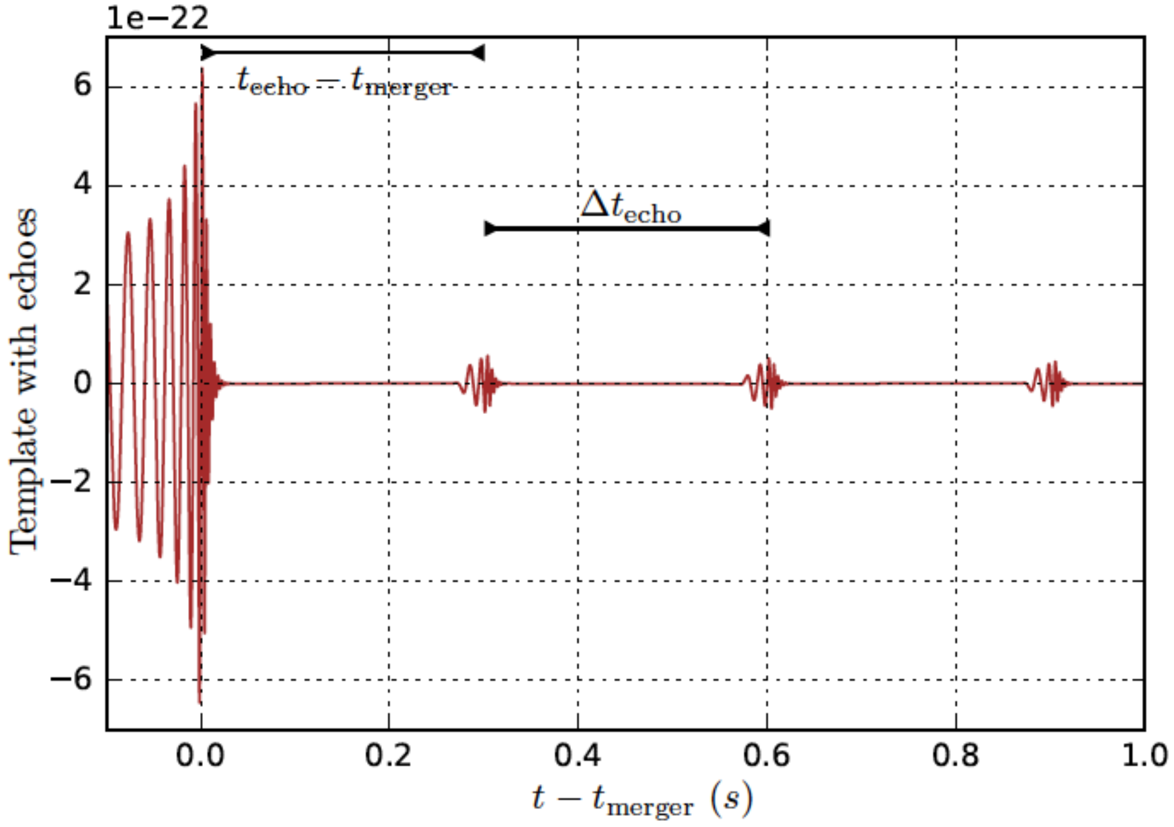
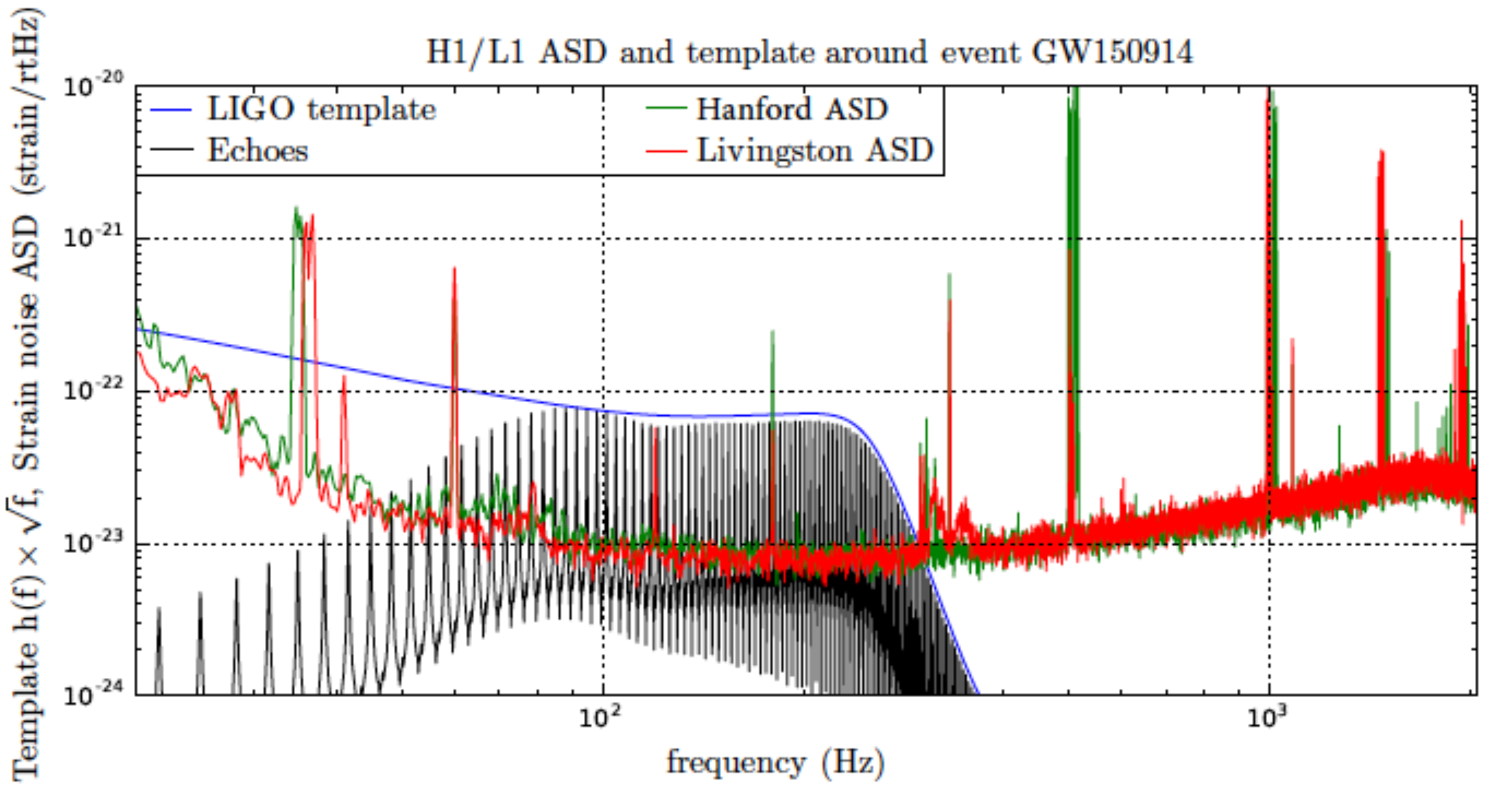


FIG. 5: An alternative false detection probability (p-value) as a function of uncertainty in $t_{\rm echo}$ defined in Eq. (3).

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

best fit echoes



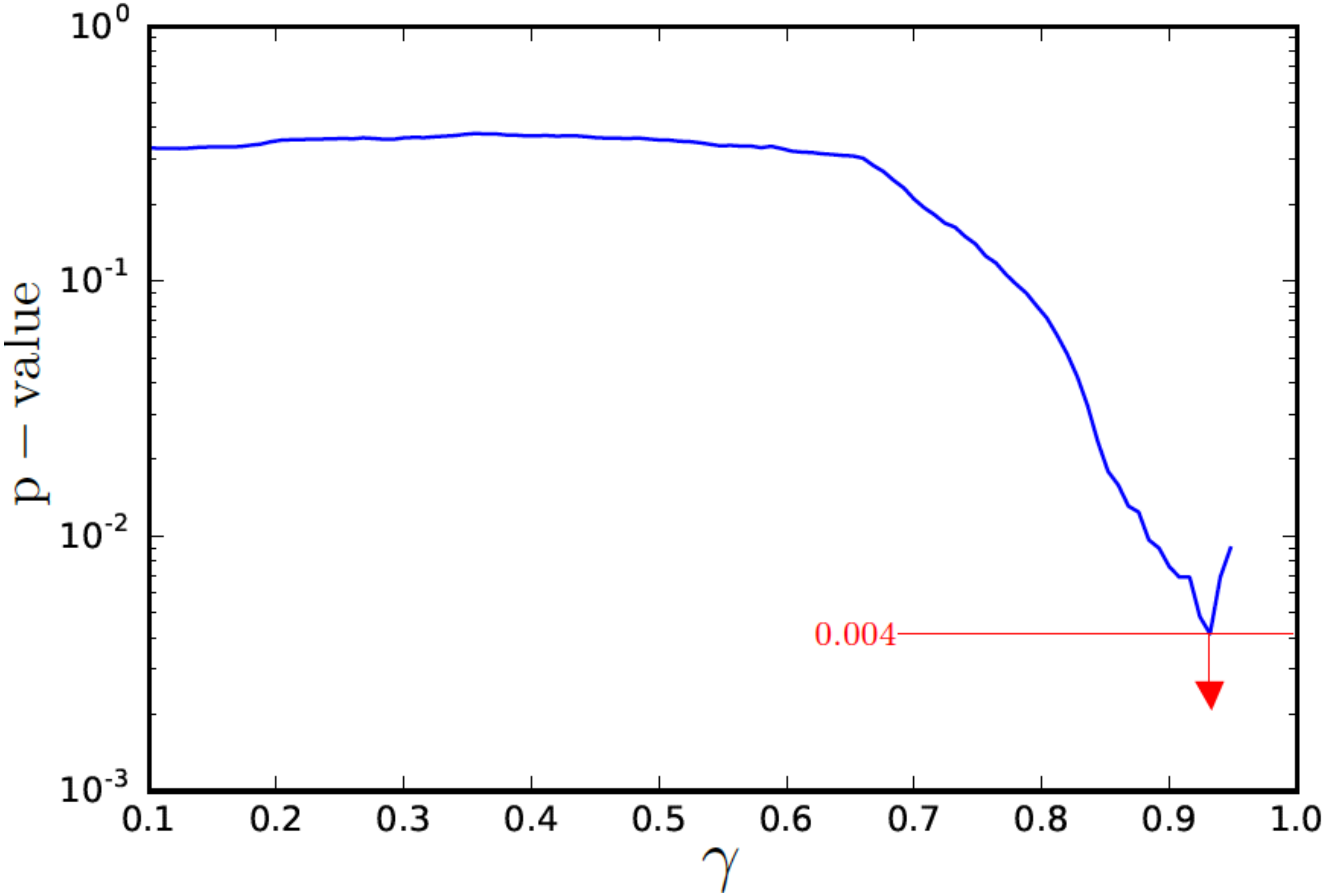


$$\boxed{\frac{t_{\rm echo} - t_{\rm merger}}{\Delta t_{\rm echo}} = 1 \pm \mathcal{O}(1\%),}$$

(non-linear effects)

	Range	GW150914	Combined
$(t_{\rm echo} - t_{\rm merger})/\Delta t_{\rm echo}$	(0.95,1.05)	1.0054	1.0054
γ	(0.1,0.9)	0.89	0.9
$t_0/\overline{\Delta t}_{\rm echo}$	(-0.1,0)	-0.084	-0.1
Amplitude		0.0992	0.124
$\rm SNR_{max}$		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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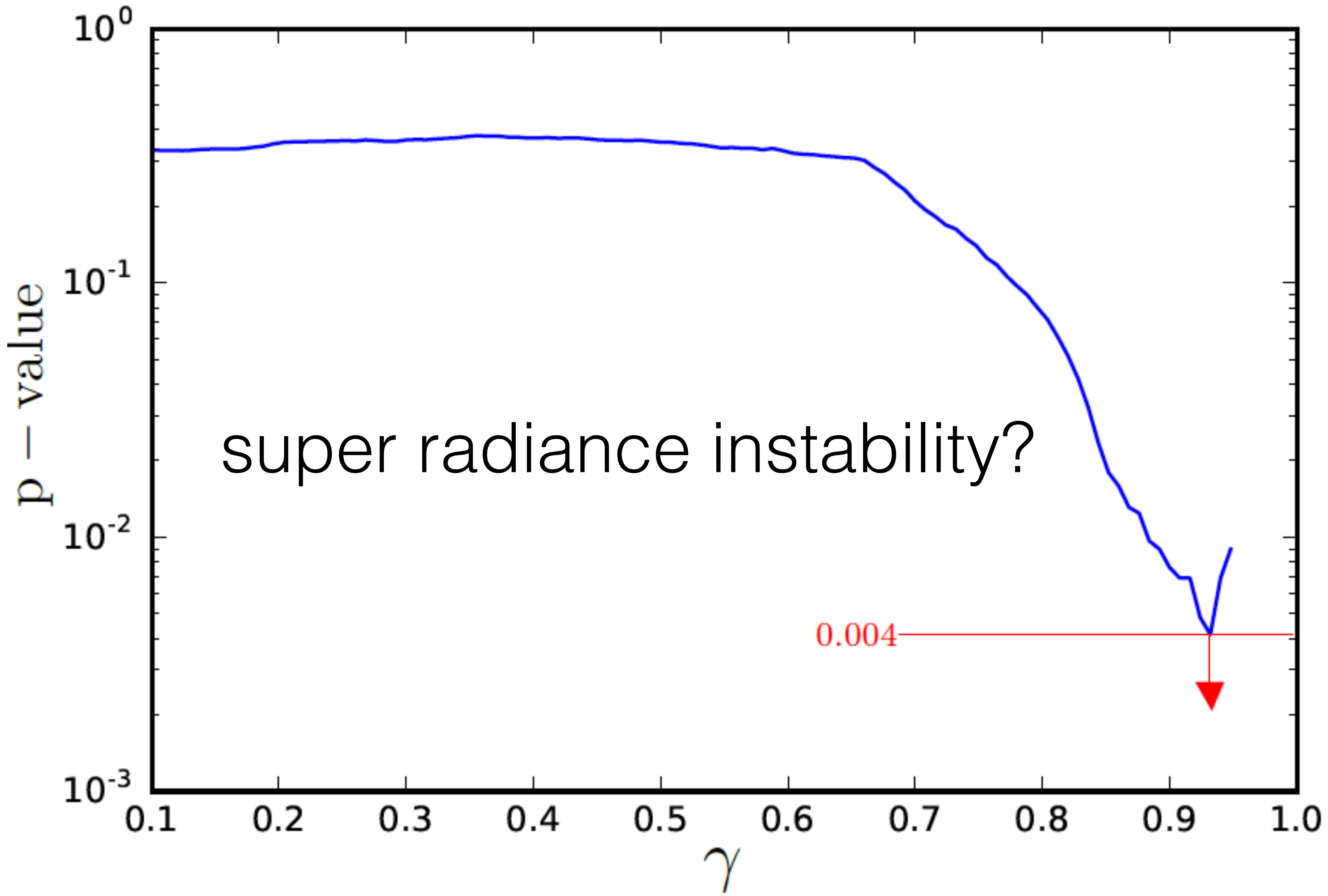

super radiance instability?

Echo sanity checks II