Testing Gravity 2017

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Echoes from the Abyss

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PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

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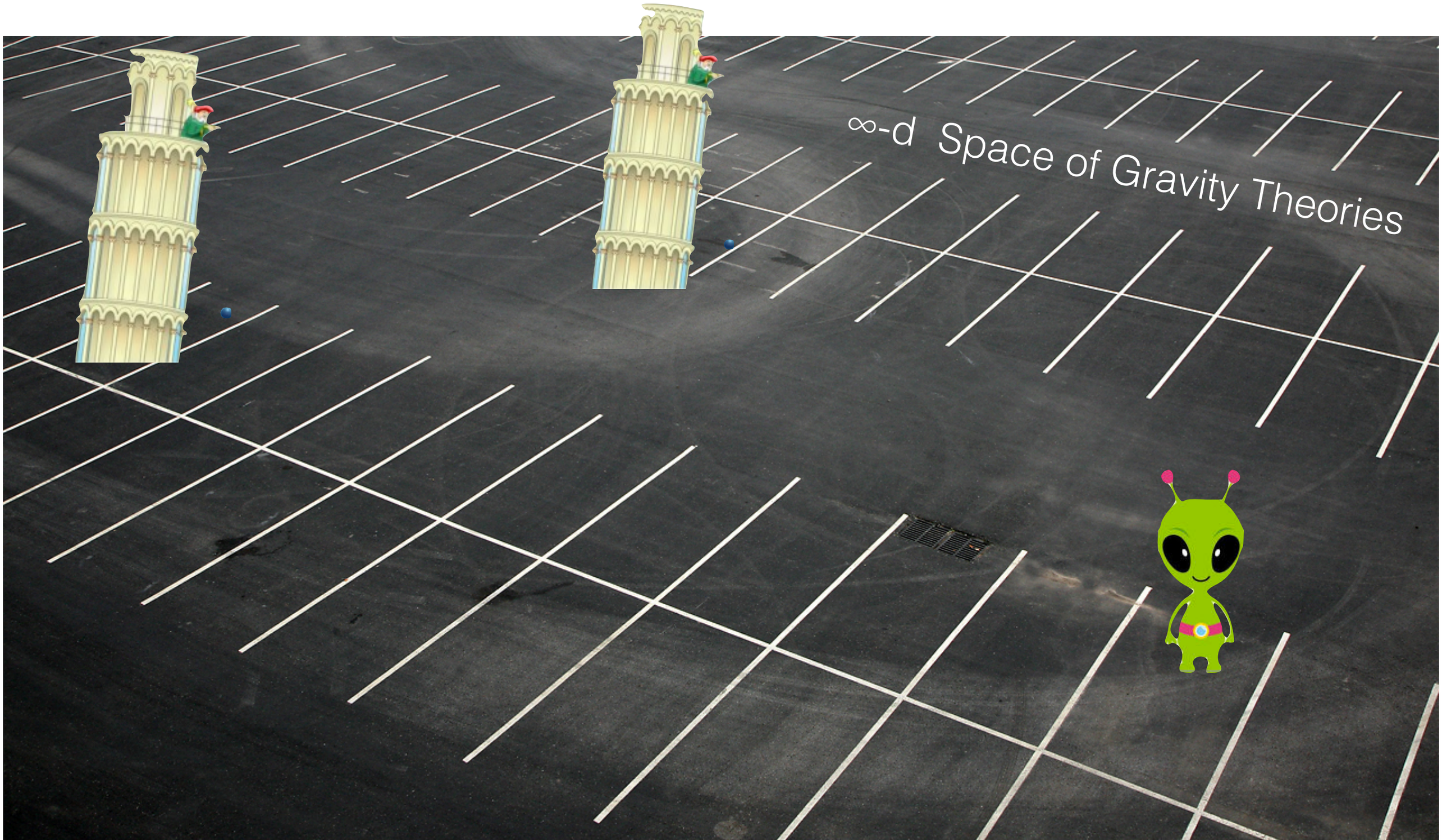

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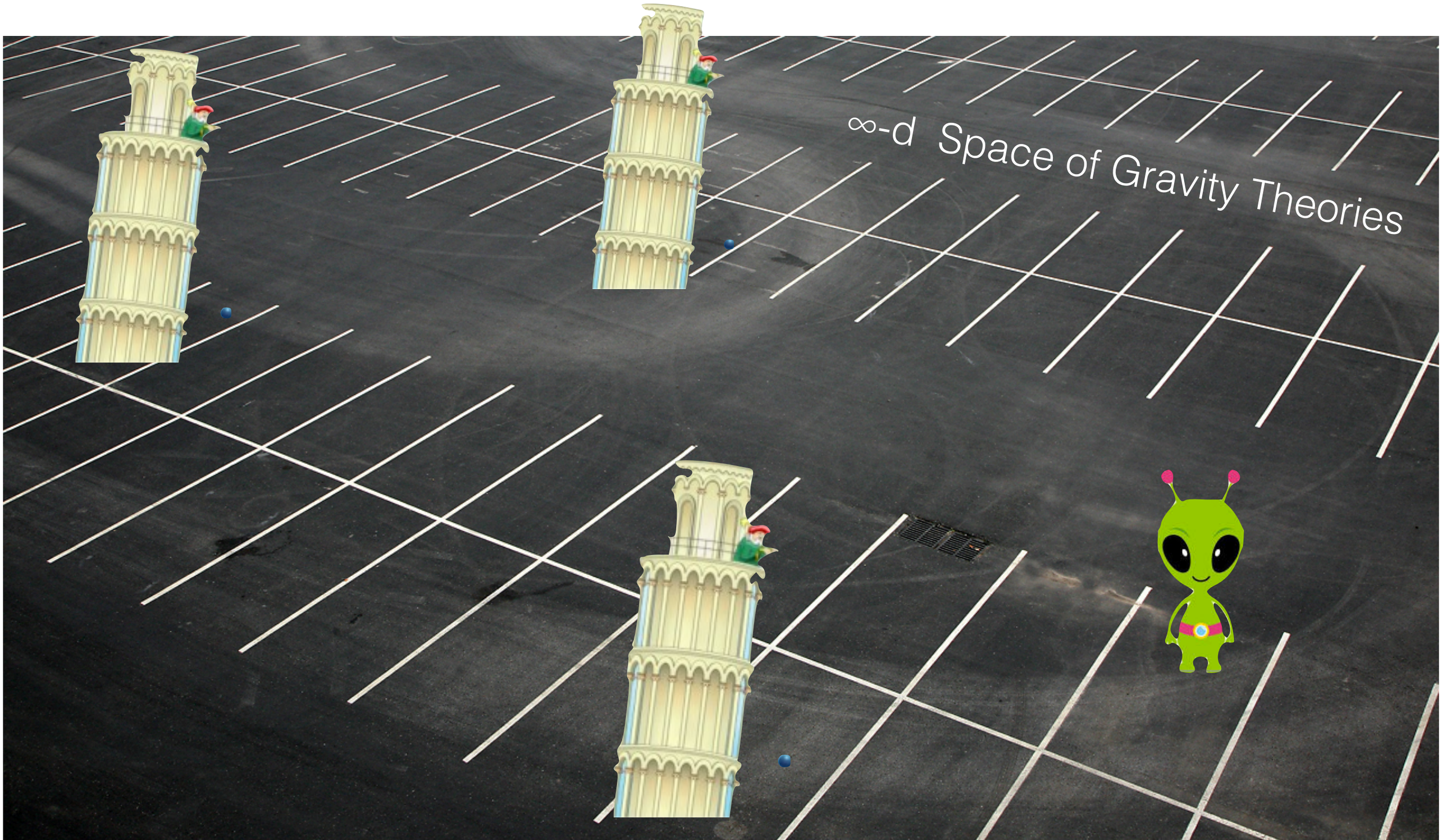

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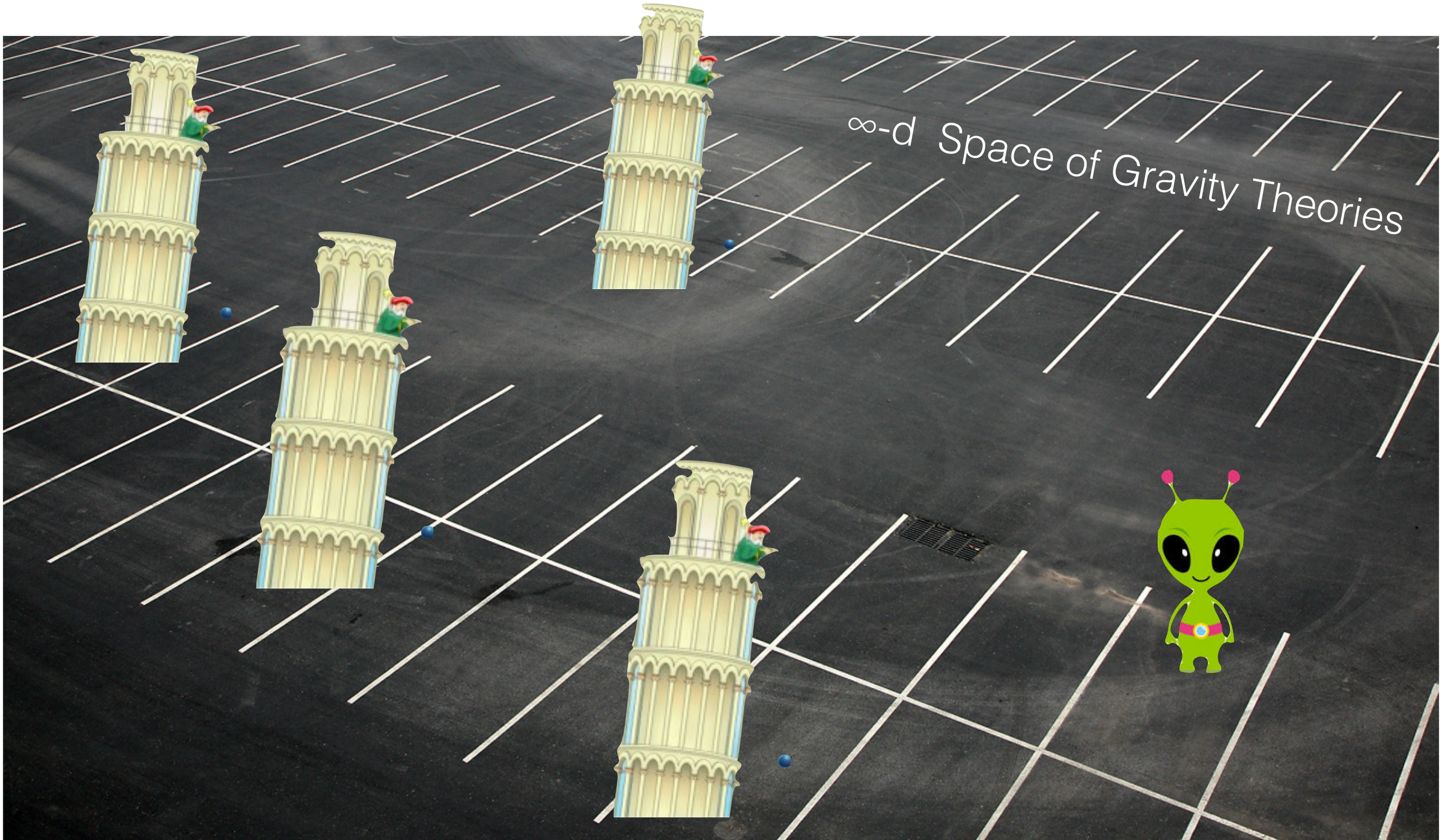

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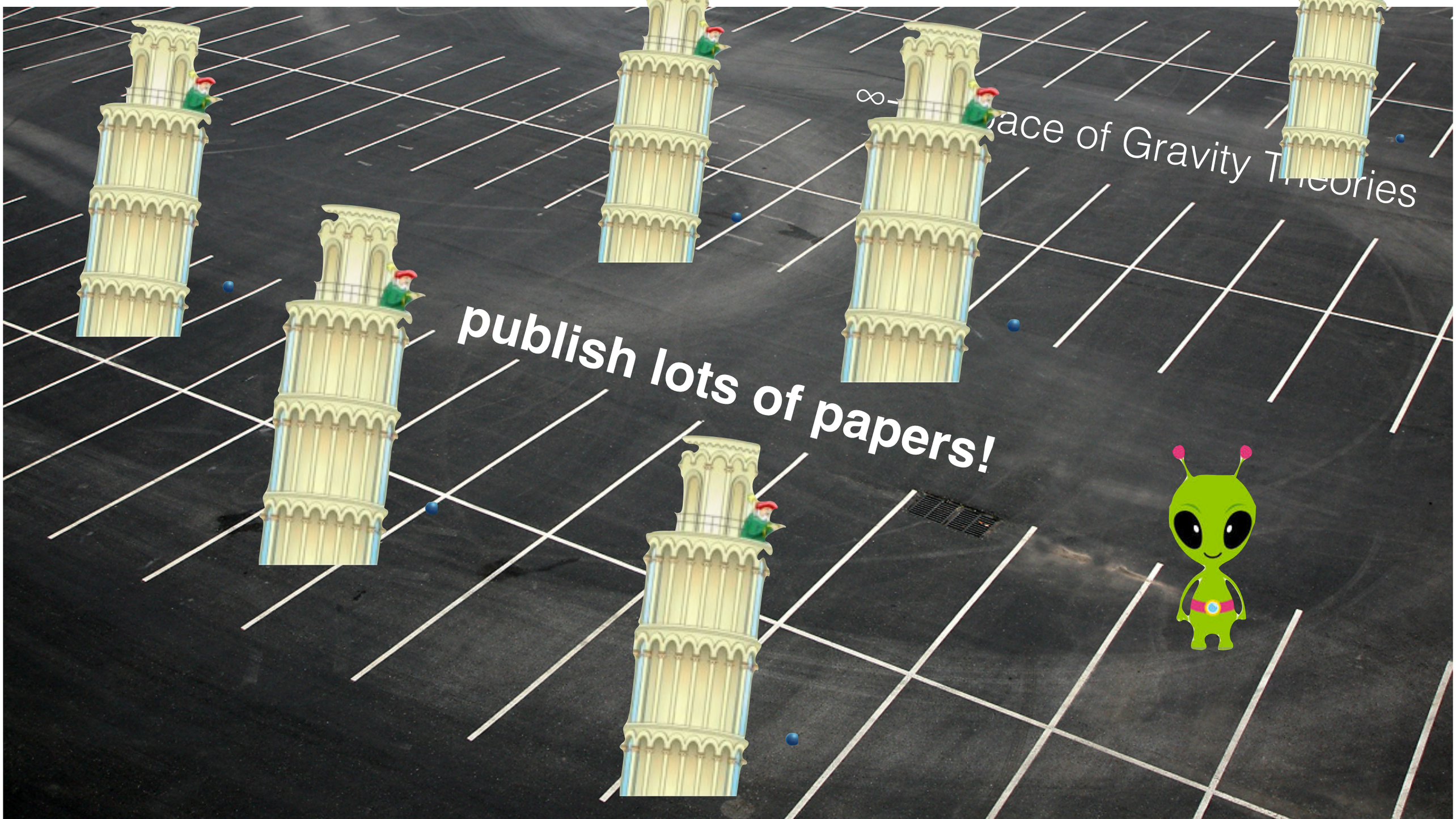


Testing Gravity 2017!

Where is the alien?!

- **Planck scale:** Quantum Gravity is important
- **Black hole horizons:** Information Paradox
- **Dark Energy:** Cosmological constant problem

What is wrong with *Black Hole* horizons?

- **Information paradox:** unitary black hole evaporation, not consistent with local physics+smooth horizon *(Hawking … firewall paradox 2013)*

- **Quantum Tunnelling:** $exp(-S_E) \times exp(entropy) \sim 1$
  → collapsing stars tunnel to a generic Quantum Gravity state at *O(1)* probability *(Mathur 2008)*

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

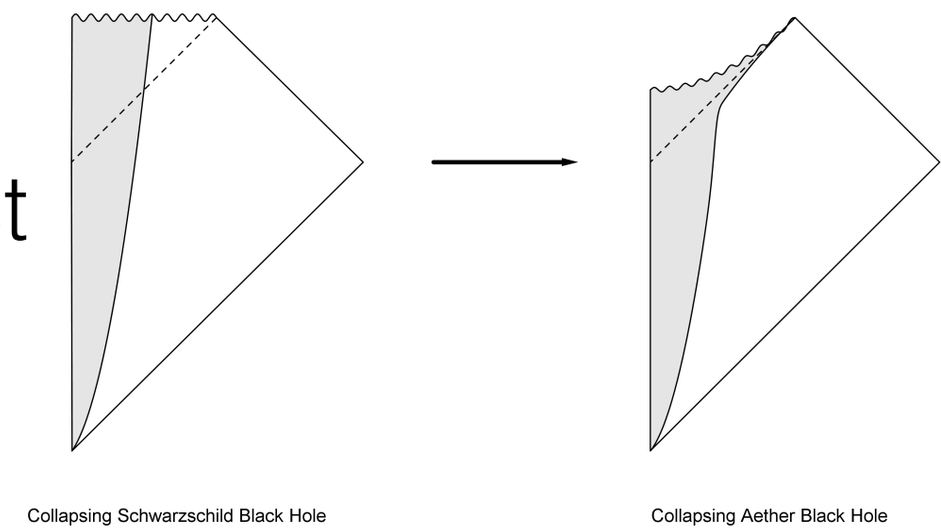
(sensible)

Black Hole alternatives

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

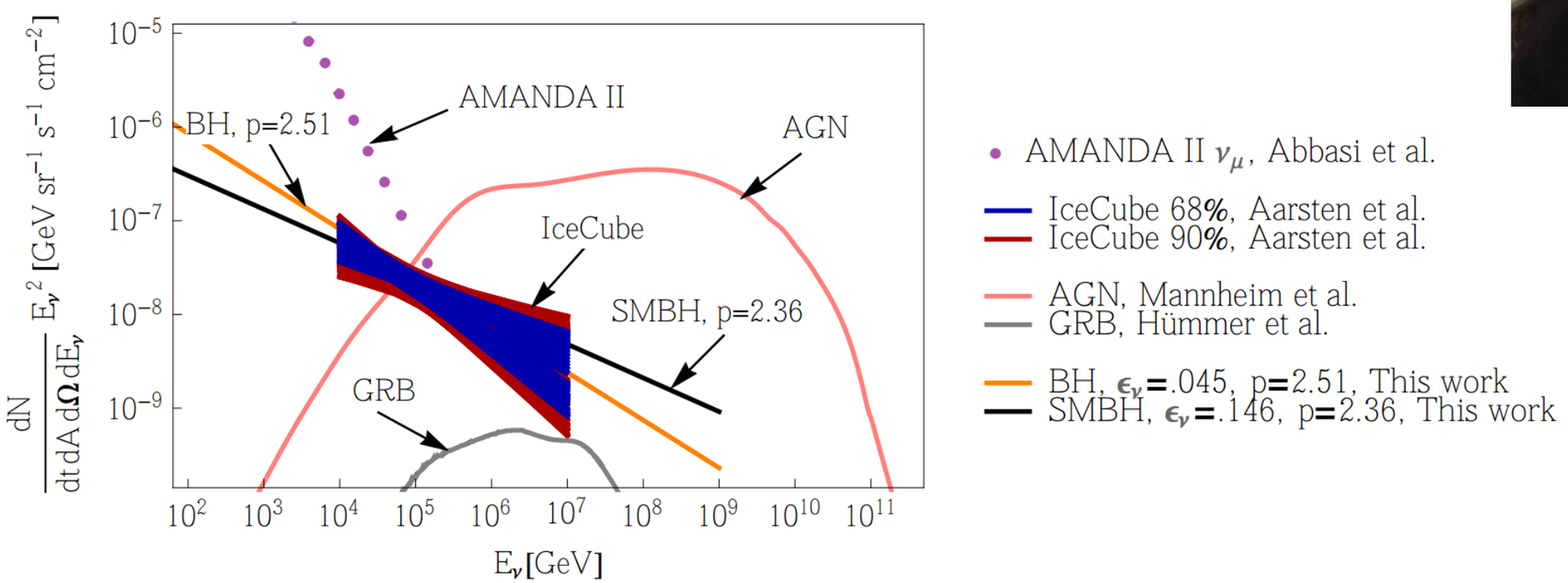
- **Aether Holes** *(NA, Prescod-Weinstein, Balogh, Mann, Saravani)***:** membrane with Z_2 b.c., account of BH entropy, couple to dark energy

- **Not quite a BH** *(Holdom & Ren)***:** exact sol's in conformal gravity



“Firewall” Phenomenology

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



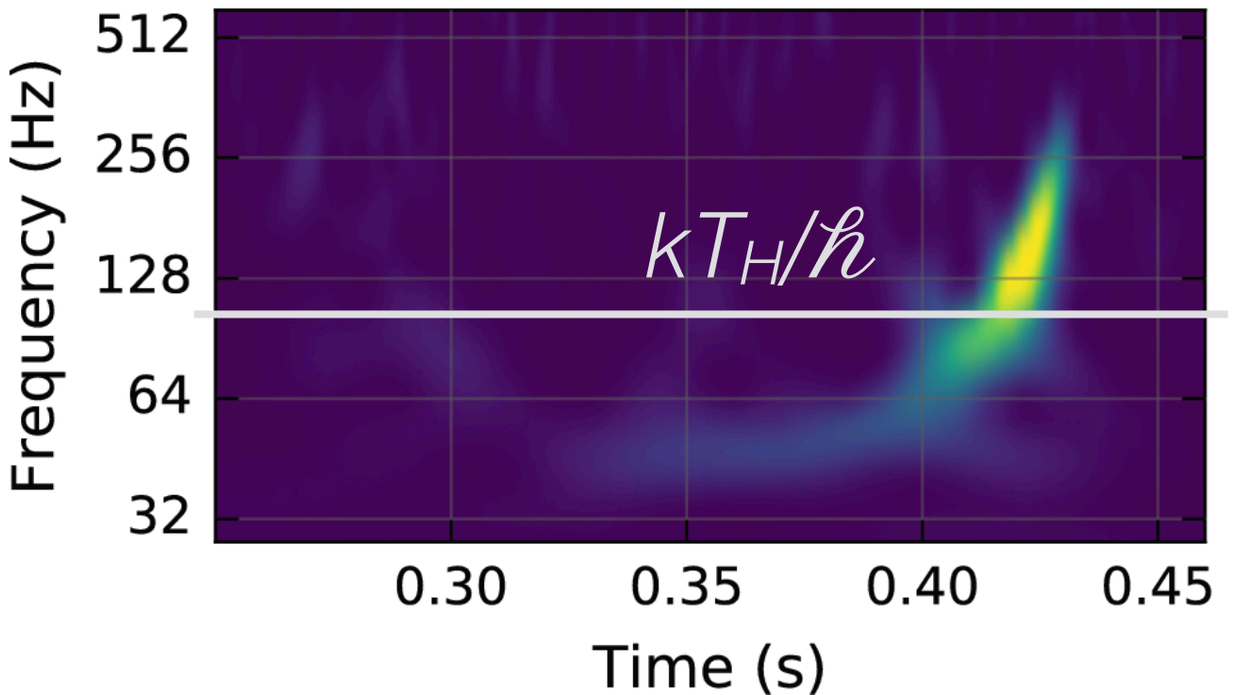
- AMANDA II ν_μ, Abbasi et al.
- IceCube 68%, Aarsten et al.
- IceCube 90%, Aarsten et al.
- AGN, Mannheim et al.
- GRB, Hümmer et al.
- BH, ϵ_ν=.045, p=2.51, This work
- SMBH, ϵ_ν=.146, p=2.36, This work

What should we see?

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

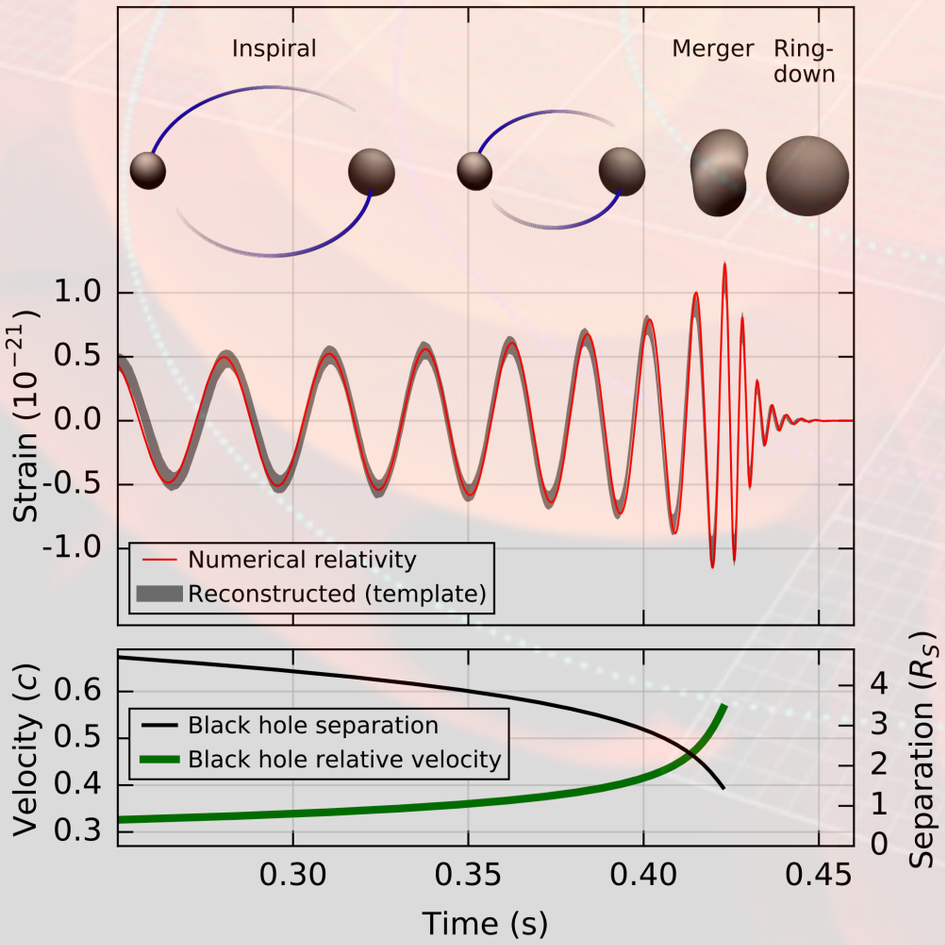
- Particles with $E \lesssim kT_H$ will be reflected

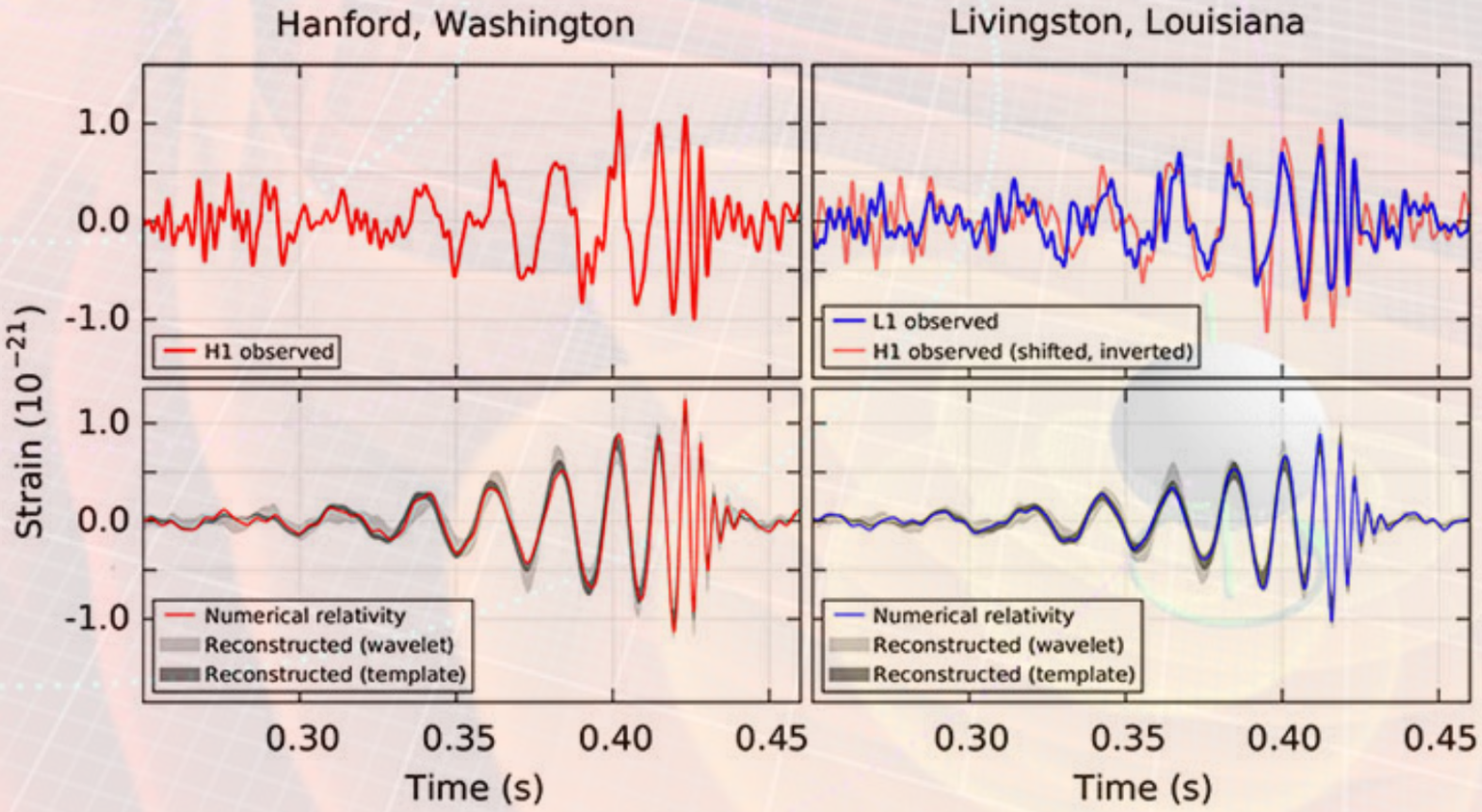
- Ringdown of black holes $\hbar\omega \sim kT_H$



Advanced LIGO
GW150914

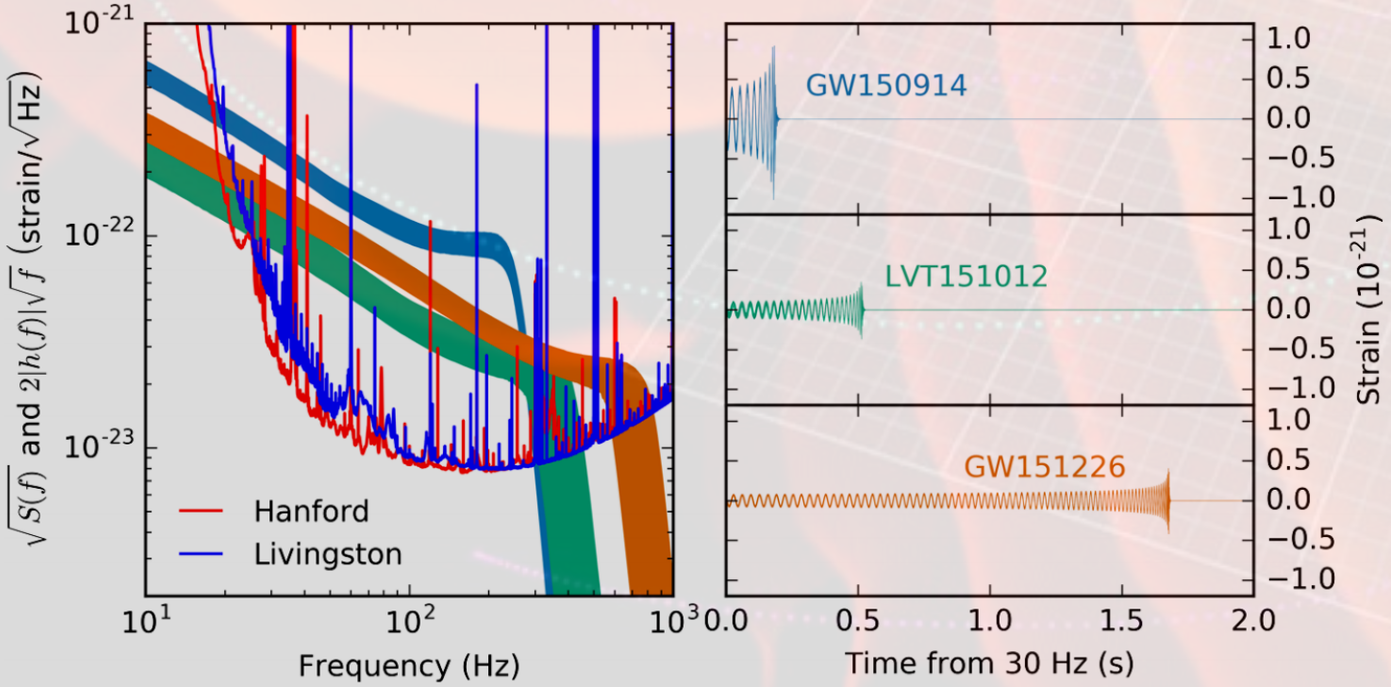
The Future is NOW!

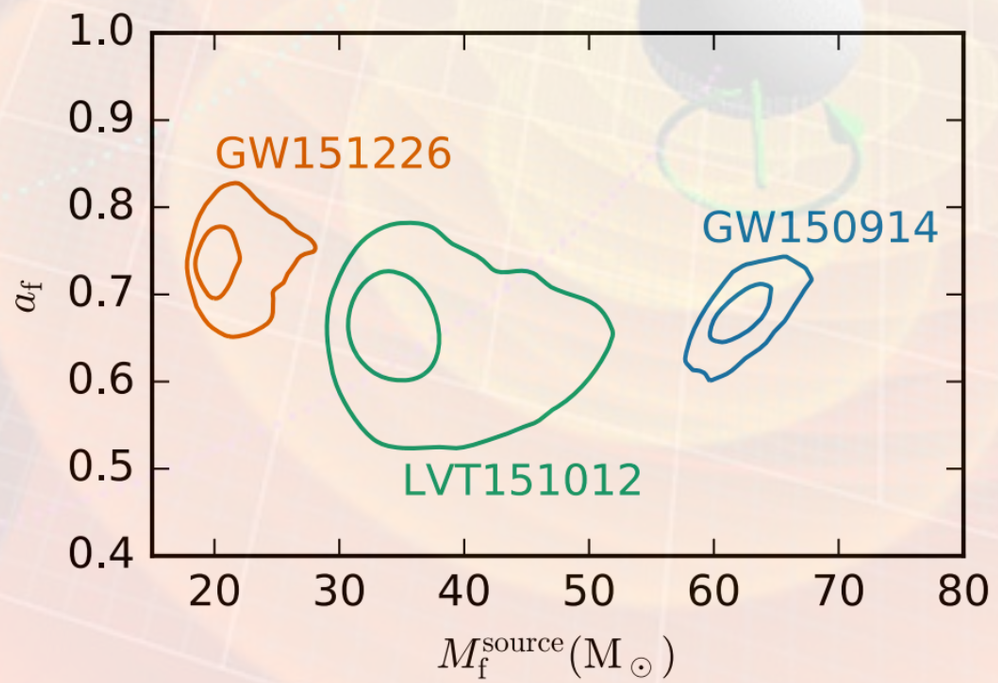




LIGO collaboration, 2016

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 $D_{\rm L}$/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

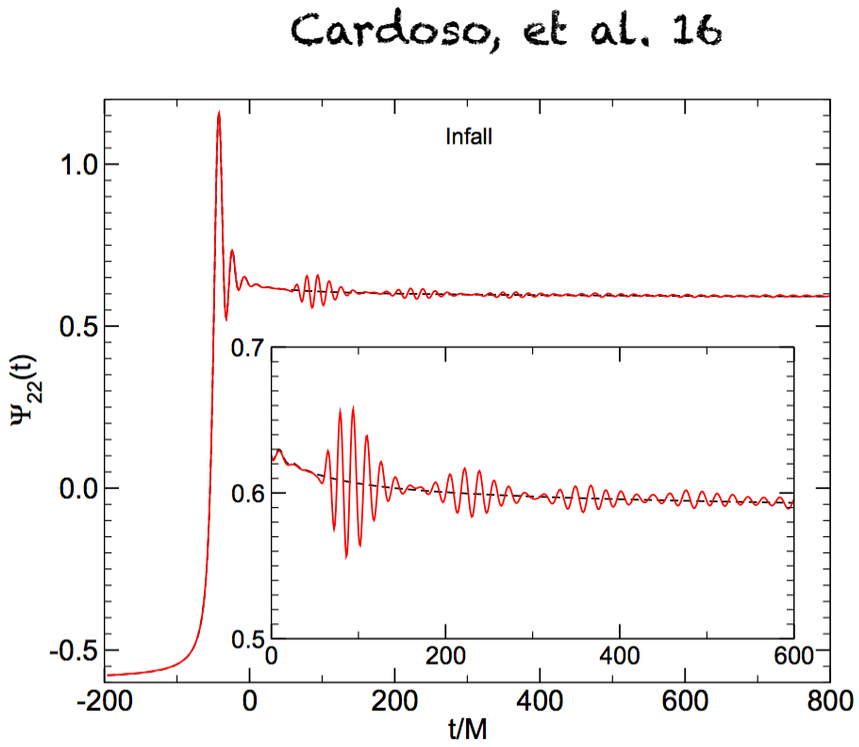


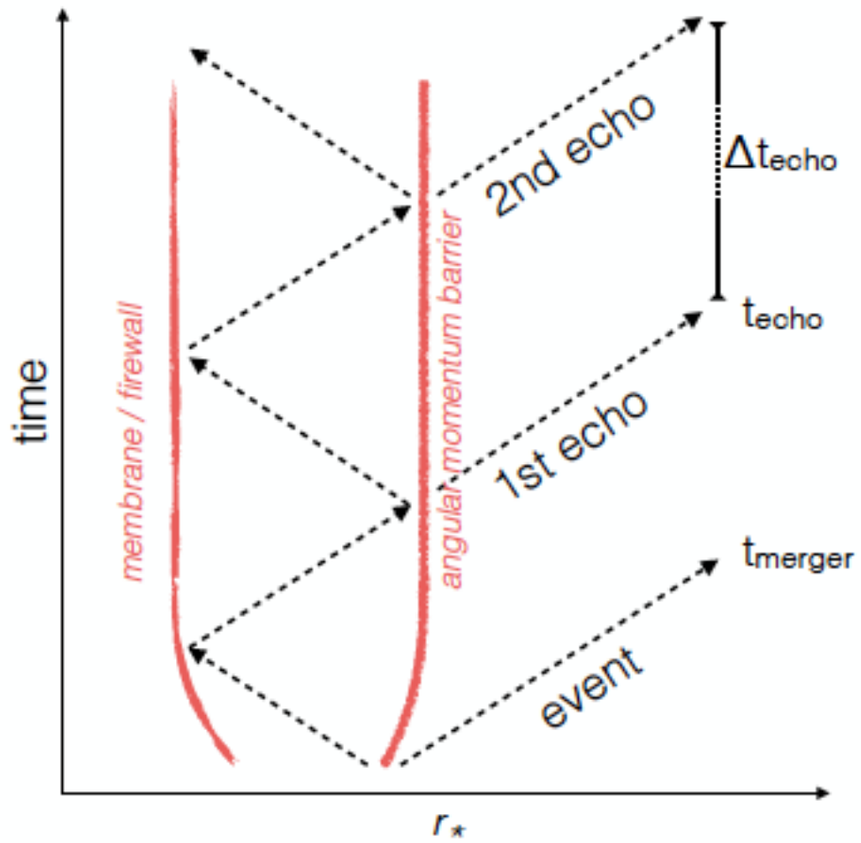


Echoes from the Abyss!

- Late echoes from Planckian structure near horizon

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





How to find the echoes?

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

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

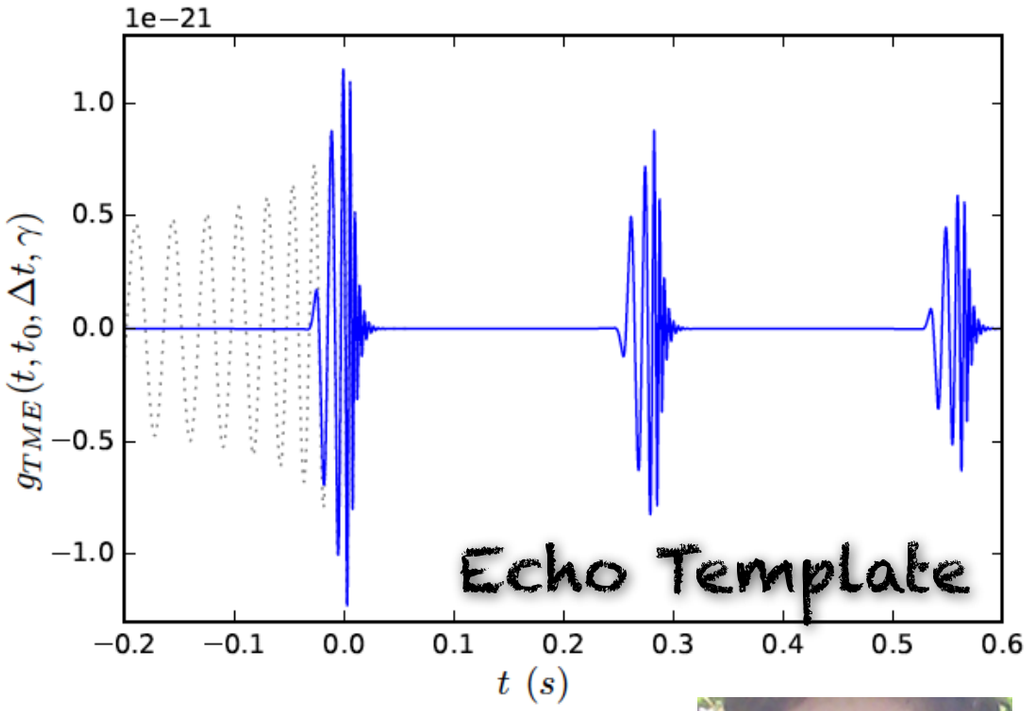
- Toy model for echo template

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

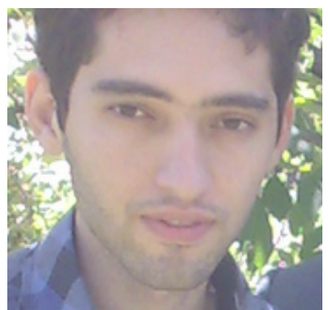
$$A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}_{T,I}(t + t_{\mathrm{merger}} - t_{\mathrm{echo}} - n\Delta t_{\mathrm{echo}}, t_0)$$

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

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



Abedi, Dykaar, & NA 2016, 2017



Data Analysis Primer

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

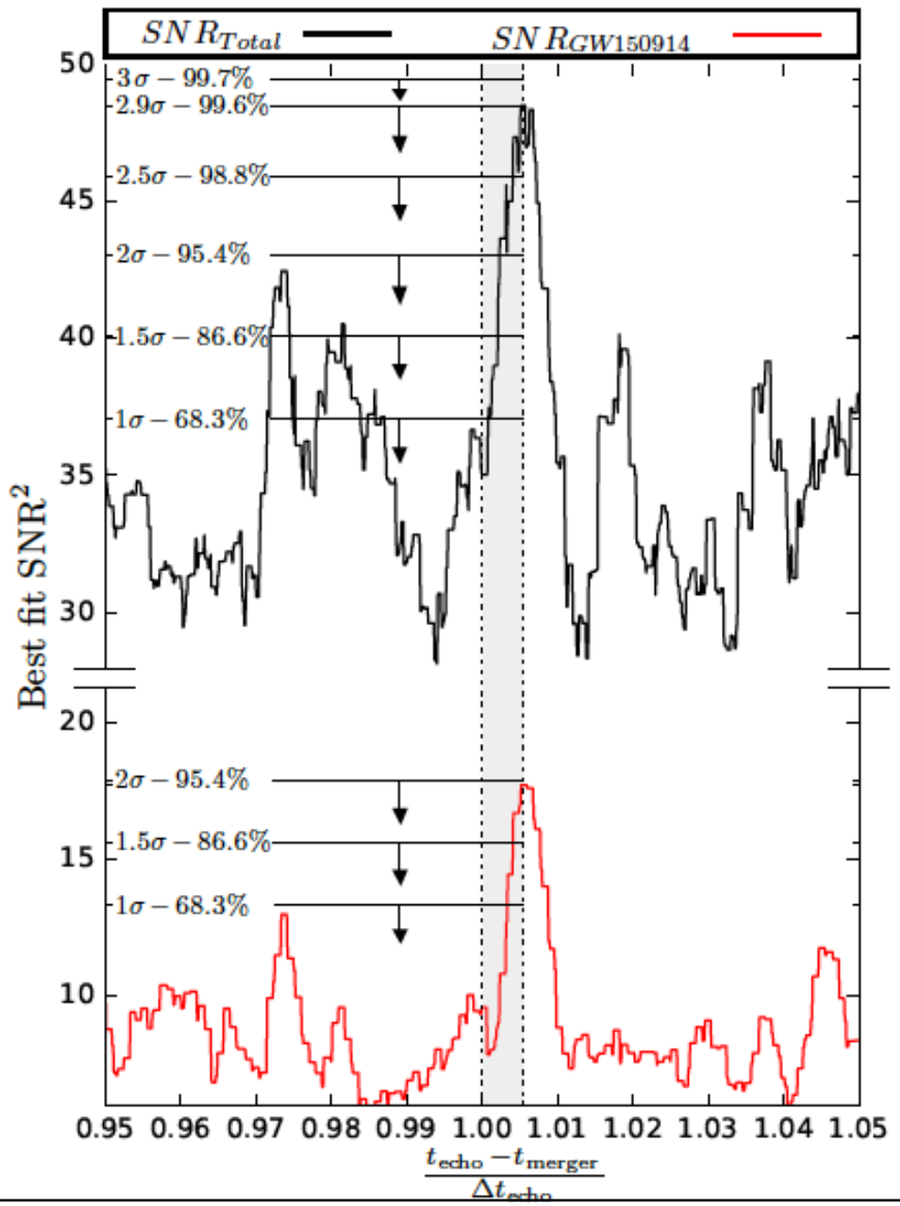
$$\mathrm{SNR}^2 = \frac{\left[\sum_\omega \frac{M_\omega D_\omega^*}{\sigma_\omega^2}\right]^2}{\sum_\omega \frac{|M_\omega|^2}{\sigma_\omega^2}}$$

Model

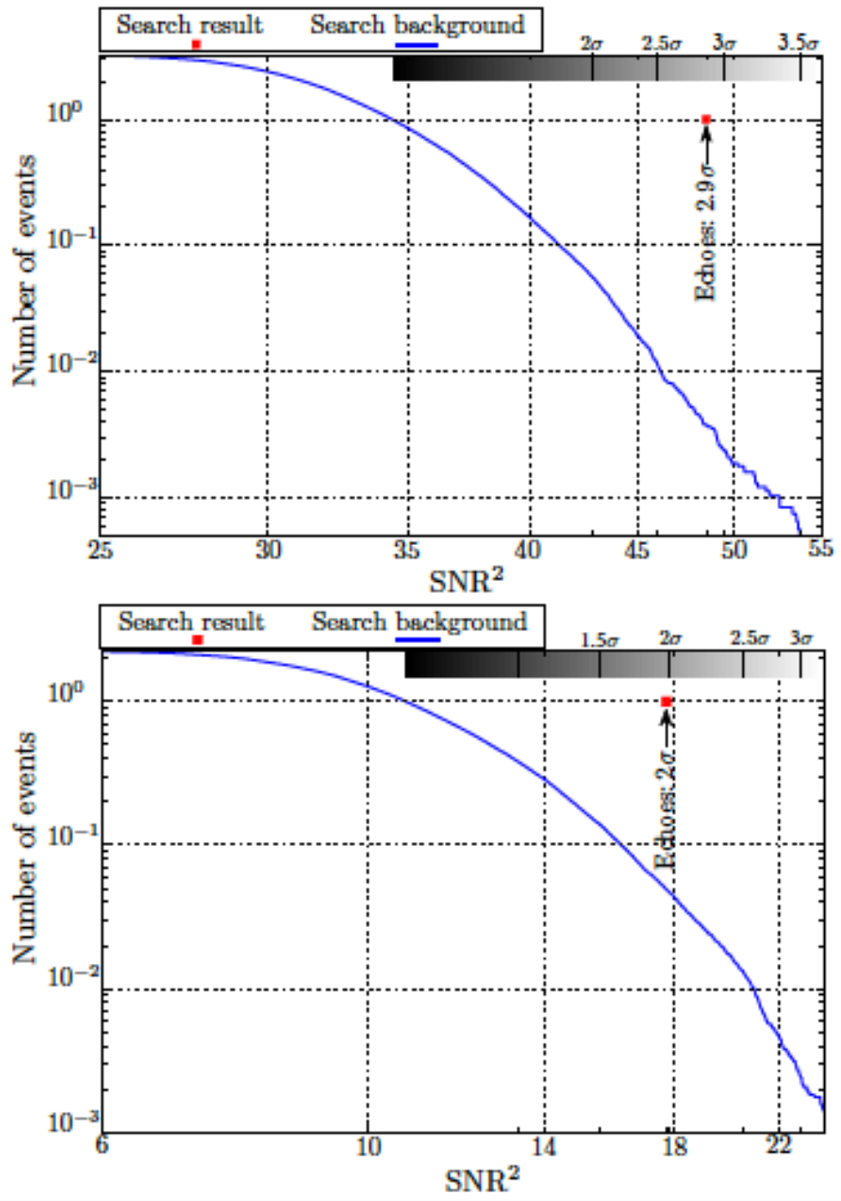
Data

Error

… and *voilla!*



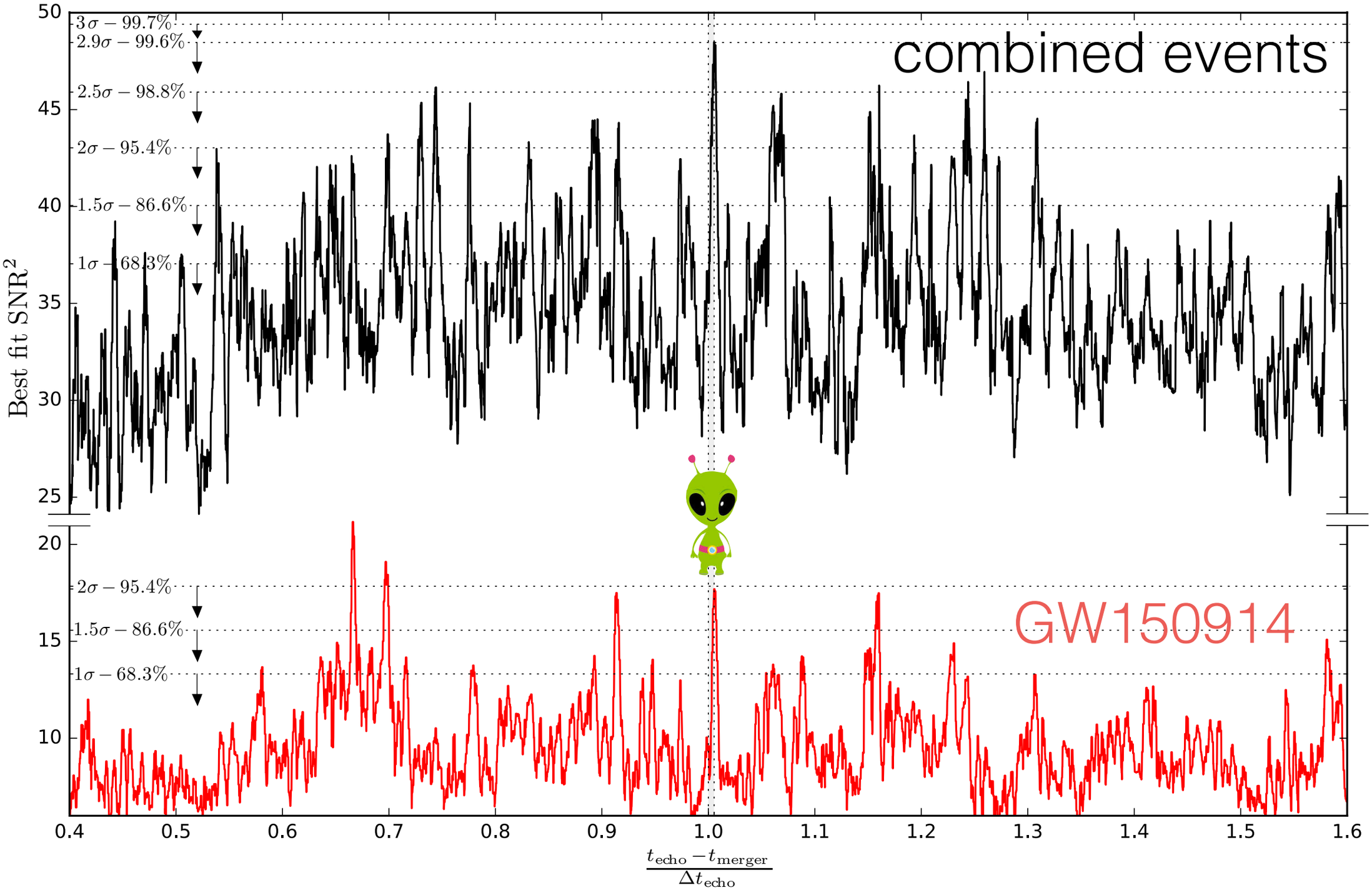
Best fit SNR^2: echoes are predicted to be at x=1



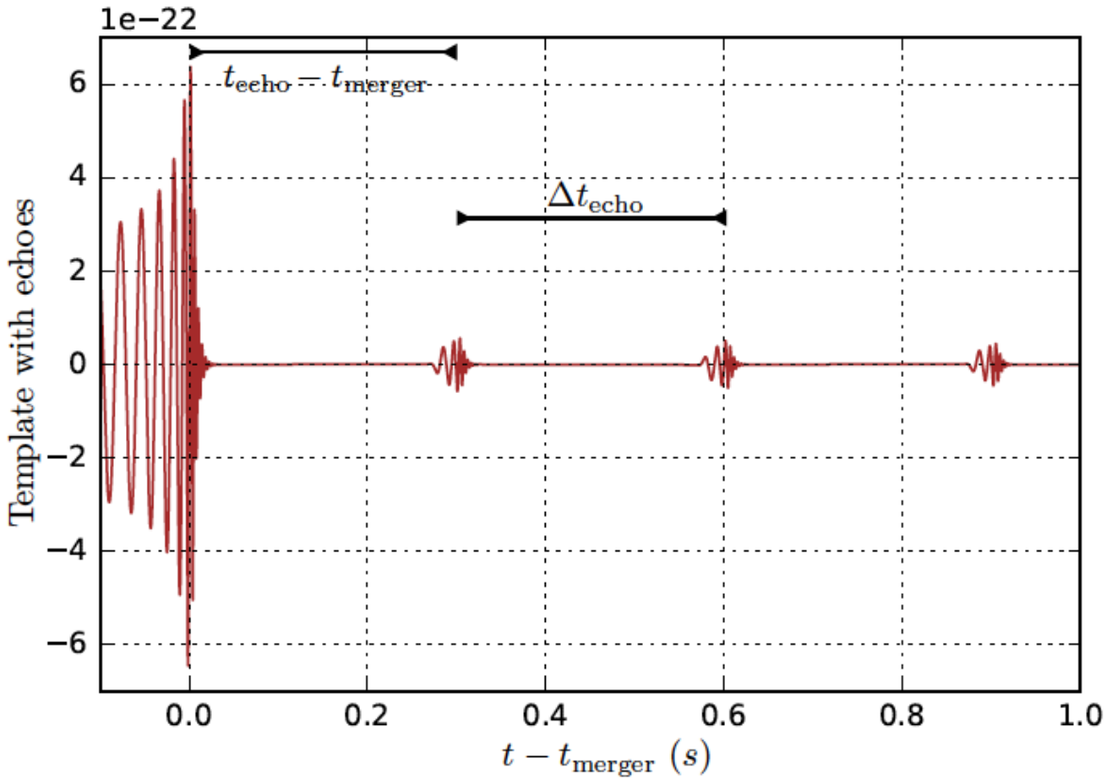
False detection probability for the echoes

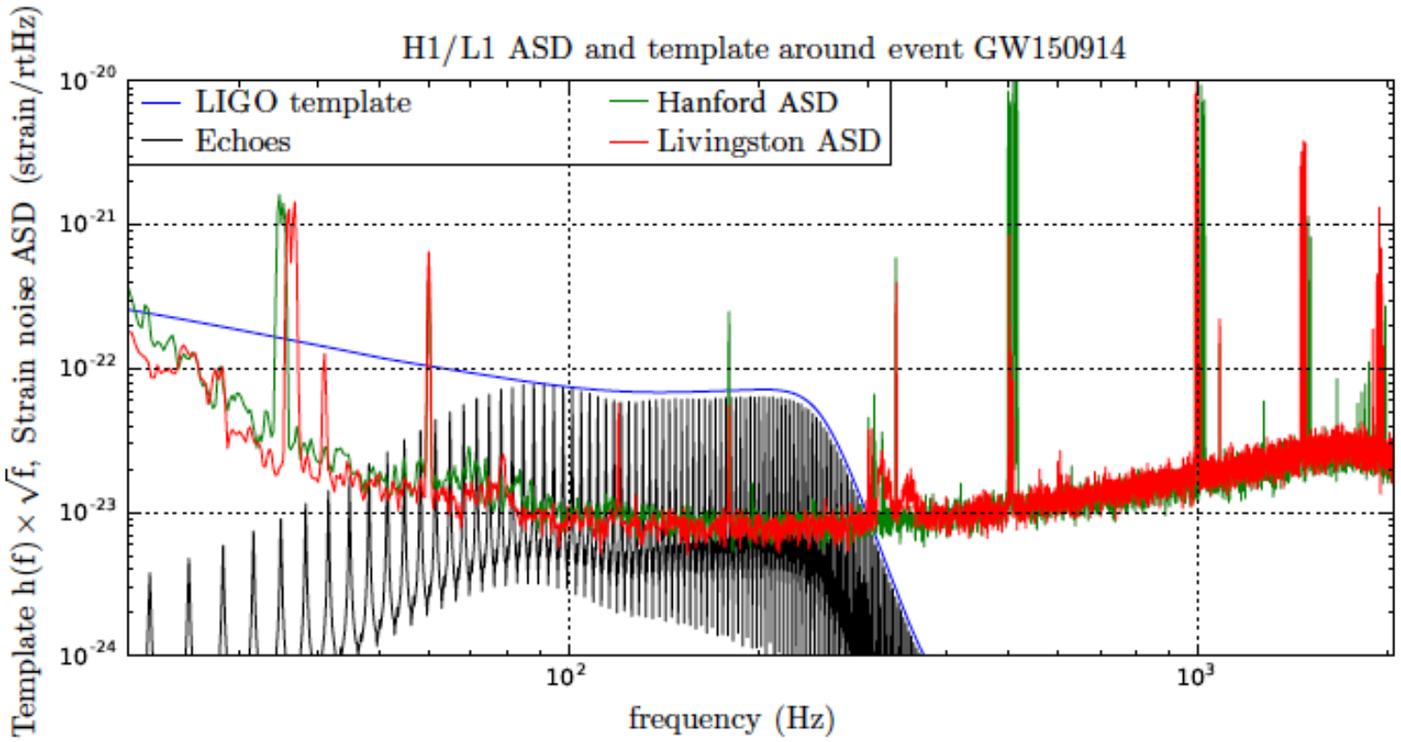
Echo landscape: *confidence > 99%*

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



best fit echoes





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

(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

Conclusions

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

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

- Confirm *Aether Holes, Fuzzballs or …* (but which one?)

- What's next?
  A. *Independent confirmation*
  B. *More events*
  C. *More physical echo templates*

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

Bonus slides!

Further tests

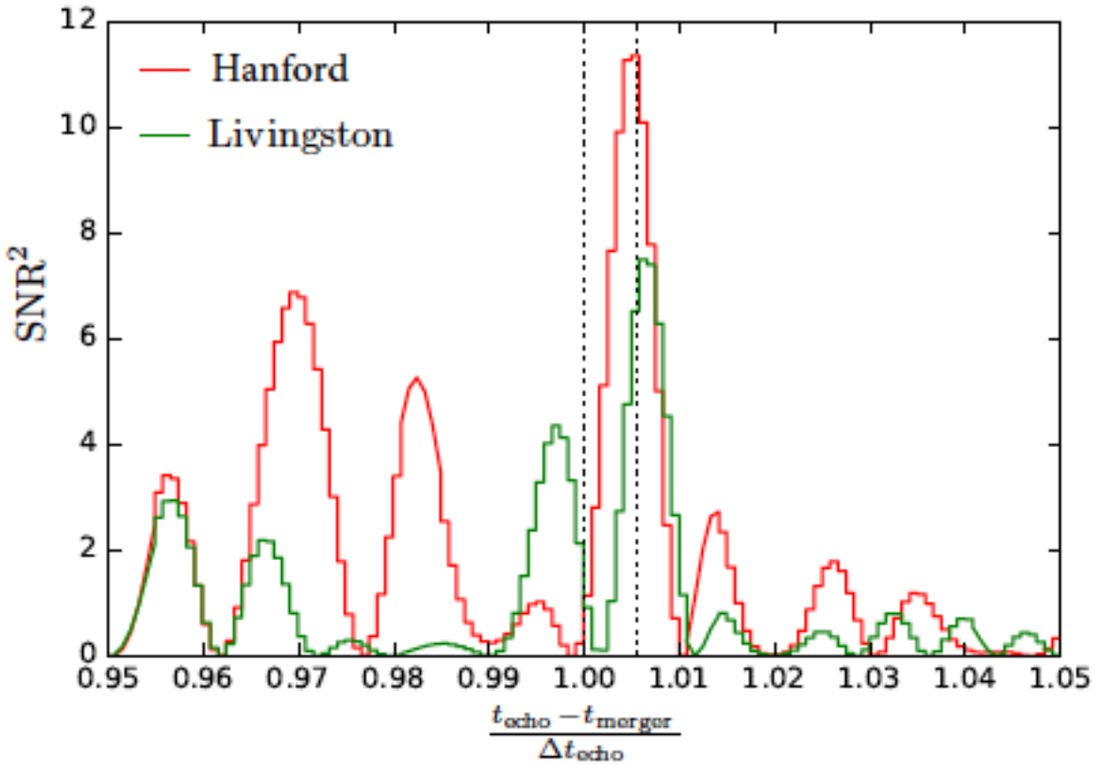


FIG. 2: SNR^2 near the expected time of merger echoes (Eq. 1) for GW150914 in Hanford (red) and Livingston (green) detectors. Interestingly, their SNR ratio $2.74/3.37 = 0.81$ is comparable to the SNR ratio for the main event $13.3/18.6 = 0.72$. Note that, unlike Fig. (1), here we have fixed the echo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

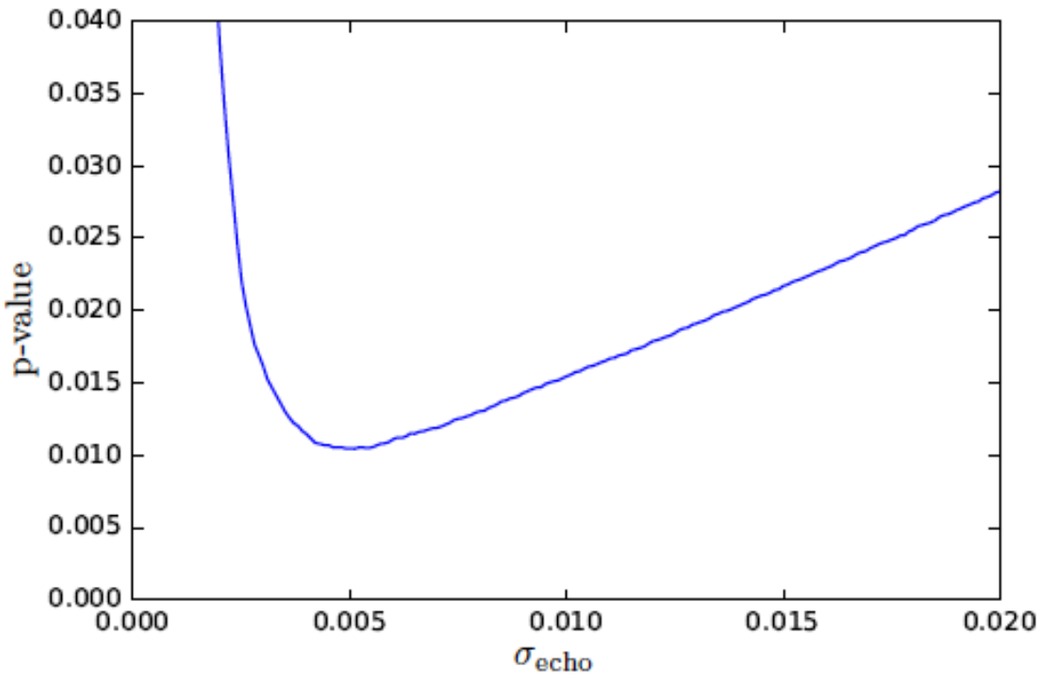


FIG. 5: An alternative false detection probability (p-value) as a function of uncertainty in $t_{\rm echo}$ defined in Eq. (3).

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

Aether Holes: *Entropy*

- Assume space-time ends at stretched horizon
- Israel Junction condition+Z_2 symmetry:

➡ membrane has <u>vanishing surface density</u>

➡ integrated (surface) pressure: = Unruh Temperature/4

➡ Entropy per unit area = 1/4 *(Bekenstein-Hawking)!*

Saravani, NA, Mann 2012

Aether Holes: *metric*

- We can solve for the black hole spacetime with 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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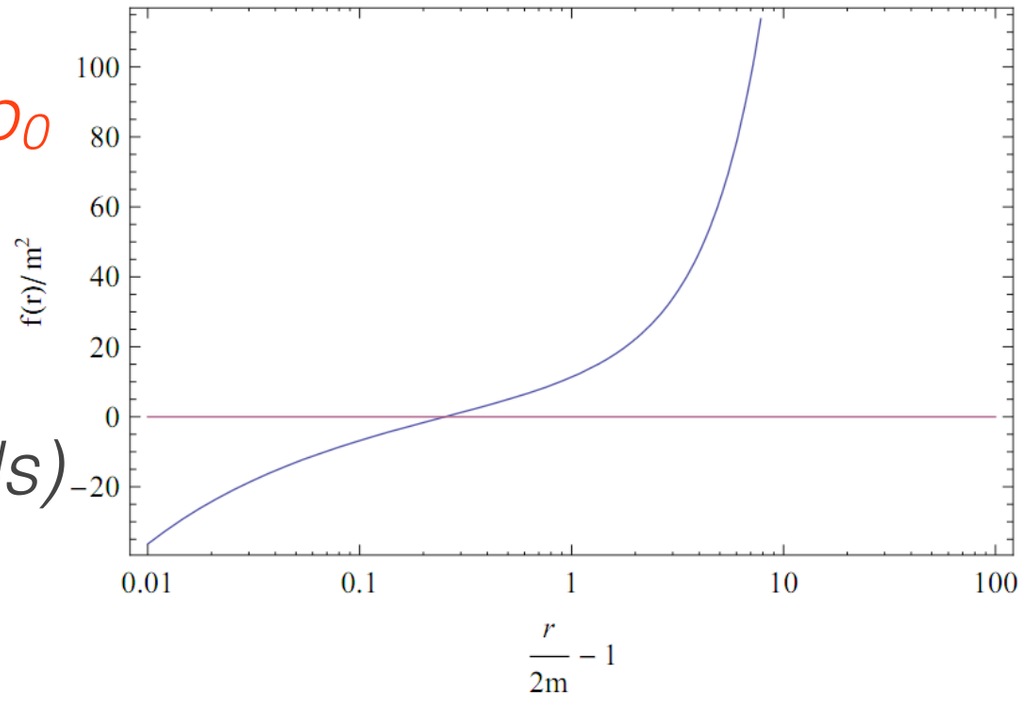

… and dark energy!

- Assume:

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

- then we get

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

- *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

Prescod-Weinstein, NA, Balogh 2009