

Scrambled Spacetime

Qubits, black holes, and the speed of causality

Niayesh Afshordi

University of Waterloo · Perimeter Institute

Qiskit Fall Fest 2026 · B1 271 · Thursday 5 November

Warm-up poll: what is QM telling us?

?

Which interpretation is most likely correct?

- [ ] Copenhagen
- [ ] Many Worlds
- [ ] QBism
- [ ] Pilot wave (de Broglie–Bohm)
- [ ] Objective collapse
- [ ] Consistent histories
- [ ] Other / no opinion

We asked 85 black-hole physicists the same question

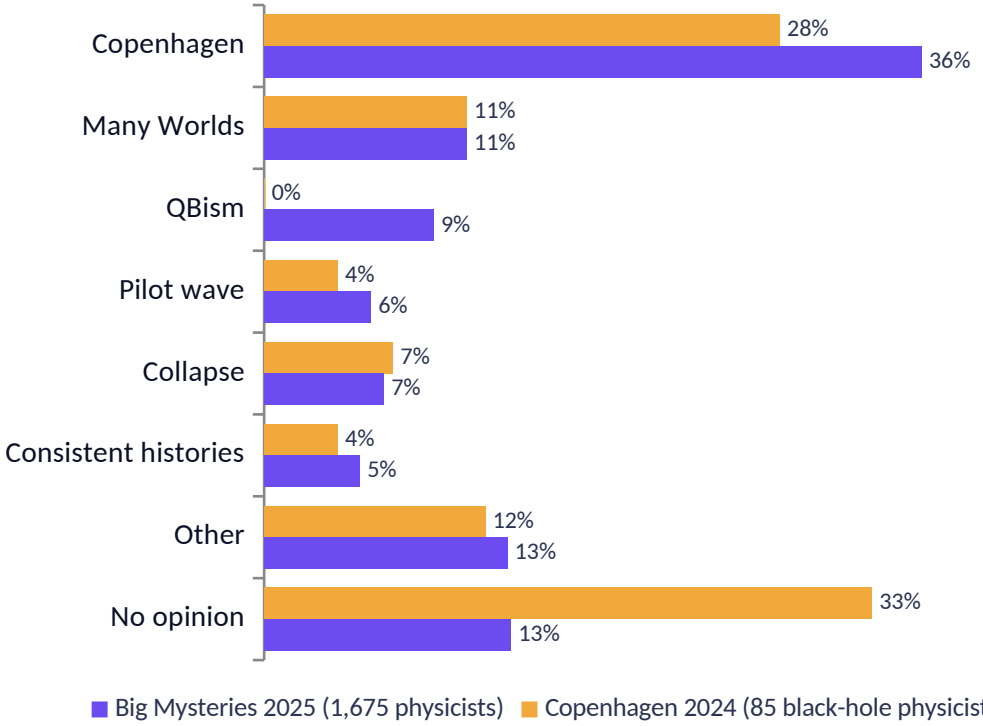
Copenhagen, 2024 workshop “Black Holes Inside and Out”

Lesson: experts disagree on the foundations. Polls don’t decide physics; observations do.

Chen, Halper & Afshordi, “Copenhagen Survey on Black Holes and Fundamental Physics”, arXiv:2503.15776

What physicists actually say

?



36%

pick Copenhagen in the big survey; 28% among black-hole experts

1 in 3

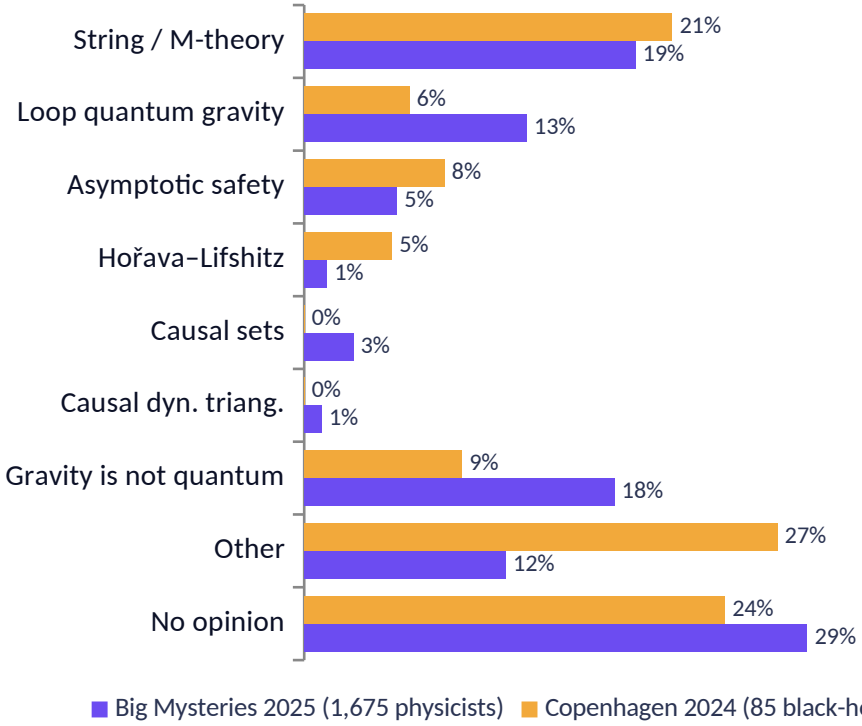
black-hole experts have no opinion at all

No interpretation has a majority. The question is open.

Chen, Halper & NA, arXiv:2503.15776 · NA, Halper, Rini & Schirber, arXiv:2605.11058 · nafshordi.com/aps-dashboard

…and about quantum gravity

?



~1 in 5

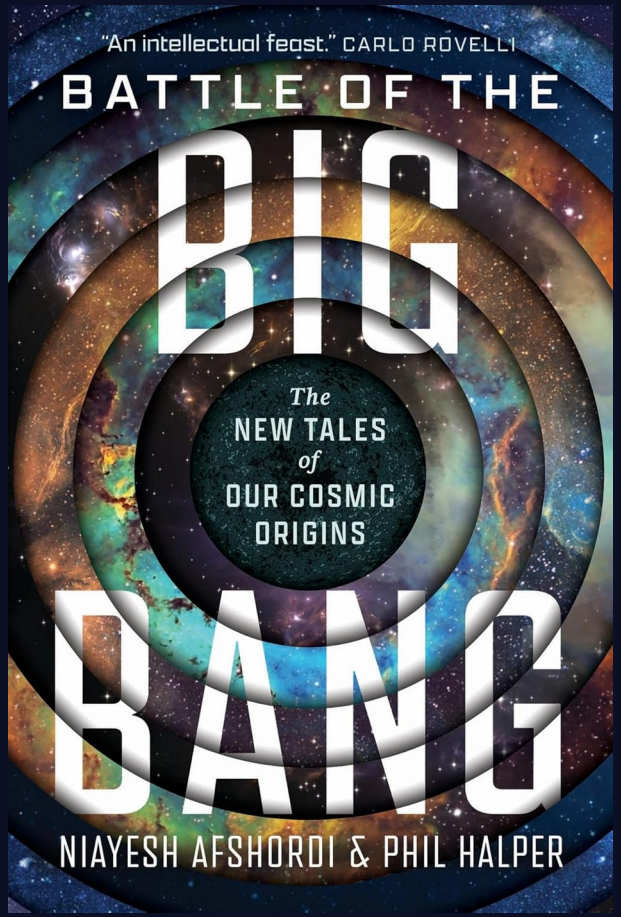
back string theory, in both surveys

18%

say gravity is not quantum at all

No theory wins by vote. Only observations can decide, and that is what this talk is about.

Chen, Halper & NA, arXiv:2503.15776 · NA, Halper, Rini & Schirber, arXiv:2605.11058 · nafshordi.com/aps-dashboard



Both surveys grew out of this book

Battle of the Big Bang: The New Tales of Our Cosmic Origins

Niayesh Afshordi & Phil Halper · University of Chicago Press, 2025

- What really happened before the Big Bang? Inflation, bounces, cyclic models, the no-boundary proposal, and the people behind them
- Why the "consensus" story is shakier than it looks (the surveys started as a chapter)
- Written for anyone who can follow this talk

"An intellectual feast." — Carlo Rovelli

Two speed limits on information

≤

CAUSALITY

Where can it go?

$$v \leq c$$

Light cones · no-signalling

SCRAMBLING

How fast does it hide?

$$t^* \approx (\beta / 2\pi) \ln S$$

Local → global correlations

Horizons push both limits to the edge; quantum circuits let us test the mechanisms.

Plan

1	**Causality**	light cones in circuits, no-signalling, Sorkin's impossible measurements, an infinitely fast field
2	**Scrambling**	OTOCs, the chaos bound, and why wiring sets the clock
3	**Black holes**	the fastest scramblers, and their echoes in LIGO data
4	**The cosmic horizon**	the same logarithm, and a 0.8% glitch in gravity?
5	**Your turn**	lab vs sky, and hackathon seeds for tomorrow

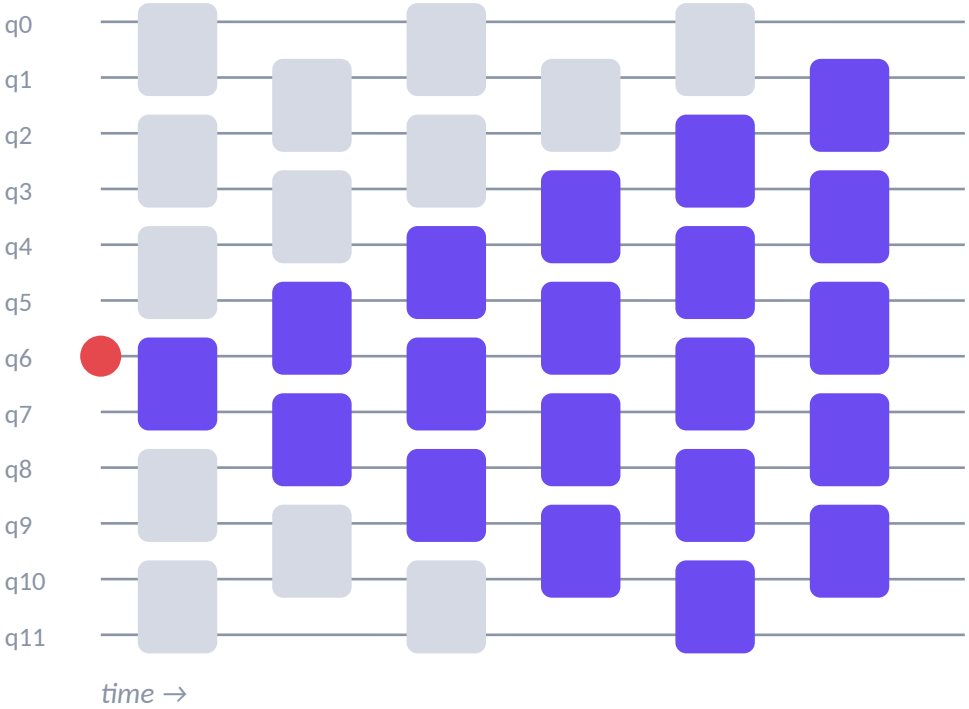
1

Causality

Where is information allowed to go?

Every circuit has a light cone

C

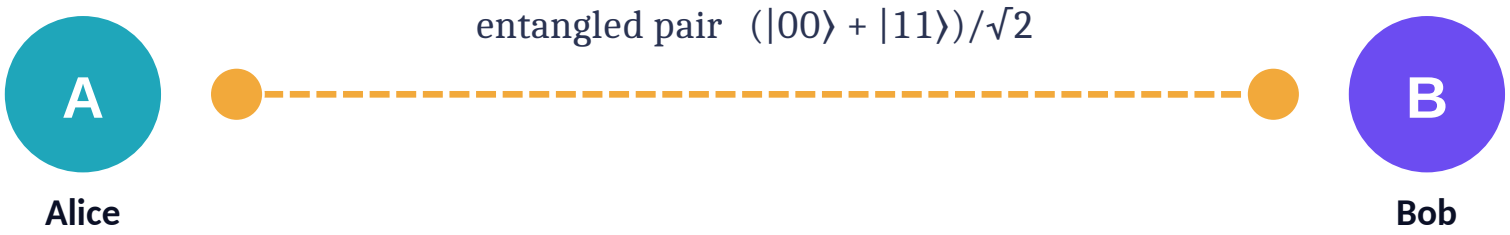


- Local 2-qubit gates ⟹ influence spreads ≤ 1 qubit per layer
- The “speed of light” is emergent: it comes from who talks to whom
- Lieb–Robinson (1972): same for any local Hamiltonian, with v_LR set by couplings

Lieb & Robinson, Commun. Math. Phys. 28, 251 (1972)

Entanglement cannot send a message

C



ALICE DOES ANYTHING

- **R** rotate it
- **M** measure it
- **×** throw it away

WHAT BOB'S QUBIT LOOKS LIKE

before

$$\begin{pmatrix} ½ & 0 \\ 0 & ½ \end{pmatrix}$$

=

after

$$\begin{pmatrix} ½ & 0 \\ 0 & ½ \end{pmatrix}$$

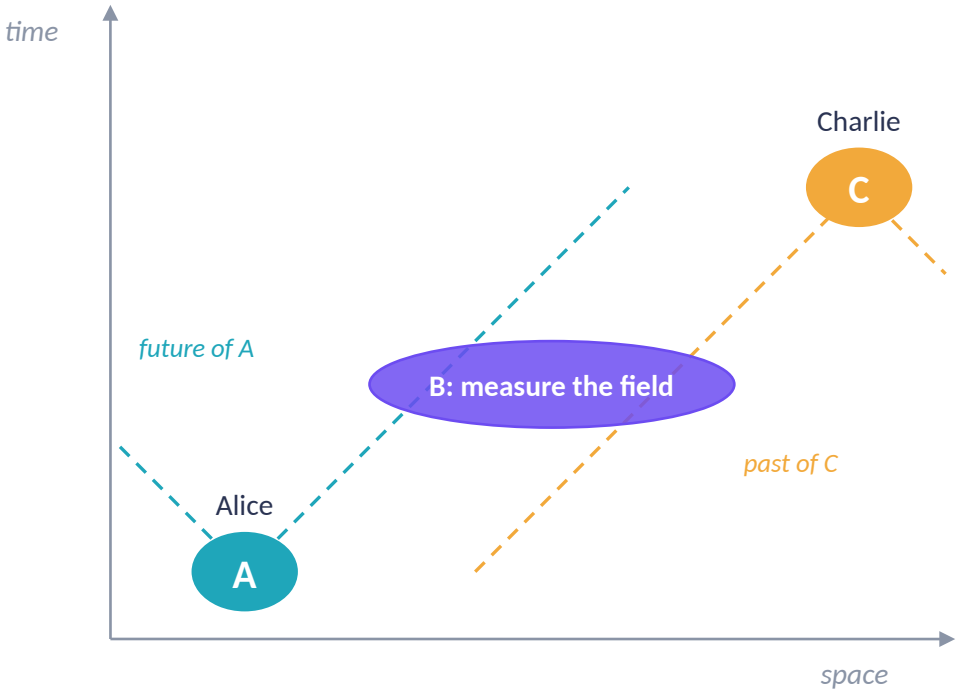
$\rho = I/2$

50/50, no phase

The correlations are real, but seeing them needs a classical phone call. Bell nonlocality is not superluminal signalling.

…but idealized measurements can signal

C



- A and C are spacelike: Alice should not reach Charlie
- Apply the textbook projection rule to a nonlocal field observable in B ⟹ Alice's choice changes Charlie's statistics
- Lesson: causality restricts which operators are measurable in QFT

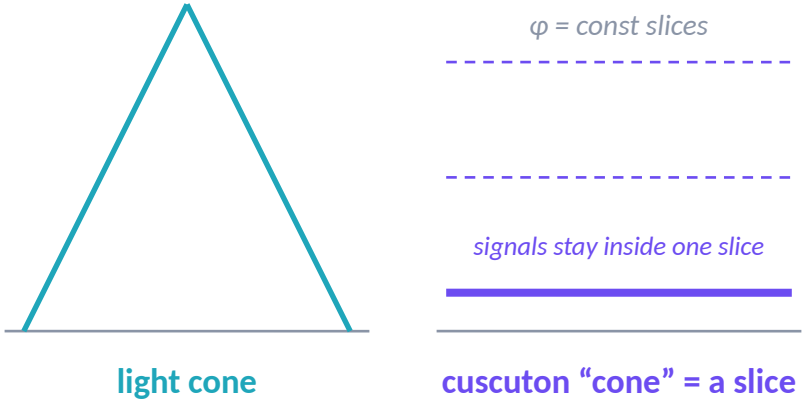
R. D. Sorkin, "Impossible measurements on quantum fields" (1993), gr-qc/9302018 · In memory of Rafael Sorkin (1945–2026)

Superluminal, yet causal: the cuscuton

C

$$S = \int d^4x \sqrt{-g}\left[\mu^2 \sqrt{|\partial_\mu \varphi \, \partial^\mu \varphi|} - V(\varphi)\right]$$

- Infinite speed of sound on cosmological backgrounds
- No closed causal loops: φ = const slices give a global time order
- No communication: quanta energy → ∞
- Low-energy limit of Hořava–Lifshitz Quantum gravity



Afshordi, Chung & Geshnizjani, PRD 75, 083513 (2007) · Afshordi, PRD 80, 081502 (2009)

Causality is an ordering, not a speed

C

1

Light cone

Relativity, and local quantum circuits

$v \leq c$

2

Global time slice

Cuscuton, Hořava gravity

$v = \infty$, still no loops

3

Pure order

Causal sets: Order + Number = Geometry

$x \prec y$

Open question: is causality fundamental, or does it emerge (like the circuit light cone)?

Bombelli, Lee, Meyer & Sorkin, PRL 59, 521 (1987)

2

Scrambling

Reversible is not the same as recoverable

Scrambling: hidden in plain sight

S

- Unitary ⟹ nothing is lost in principle
- But local information spreads into many-body correlations
- No small subsystem can read it out any more
- Scrambling time t*: when a local poke has touched everything

OUT-OF-TIME-ORDER CORRELATOR

$$C(t) = \langle\, |[W(t), V]|^2 \,\rangle \propto \exp(\lambda t)$$

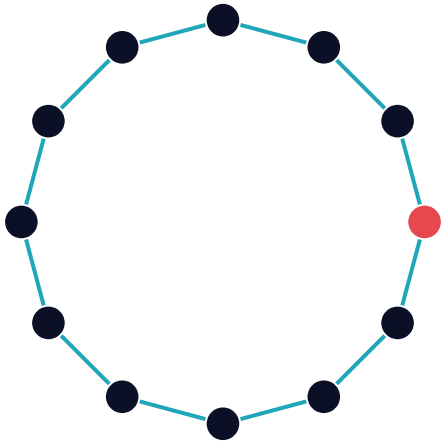
CHAOS BOUND

$$\lambda \le 2\pi\, k_B\, T \,/\, \hbar$$

Black holes saturate it

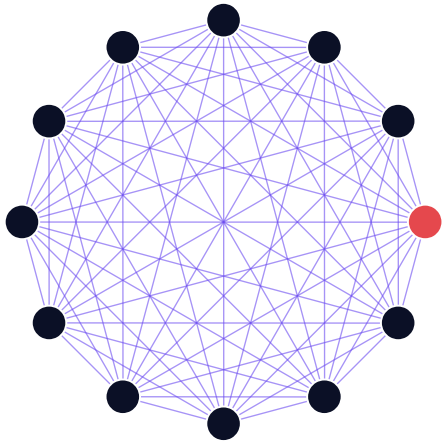
Maldacena, Shenker & Stanford, JHEP 08 (2016) 106

Geometry sets the clock: local vs all-to-all



Local (ring, lattice)

$t^* \sim N / v$



All-to-all (black hole?)

$t^* \sim \log N$

Sekino & Susskind, JHEP 10 (2008) 065: black holes are the fastest scramblers

3

Black holes

Nature’s fastest scramblers, and what LIGO might hear

A black hole is a quantum hard drive

BH

10^{77}

entropy (k_B) of a Sun-mass black hole: $S = A / 4\ell_P^2$

60 nK

its Hawking temperature

~3 ms

scrambling time $t^* = (4GM/c^3) \ln S$, Sun mass

~0.2 s

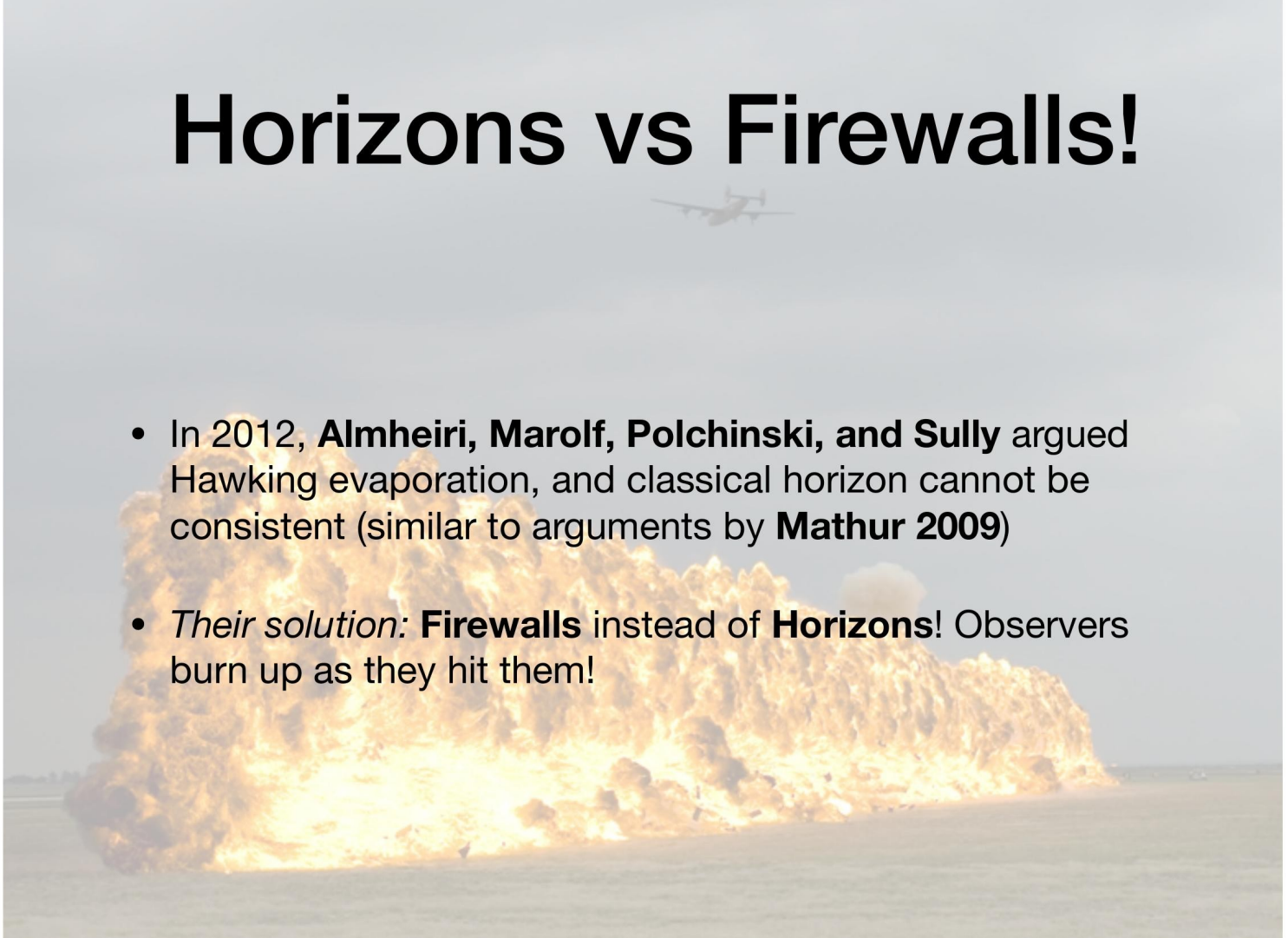
the same for a 60 $M_\odot$ LIGO black hole

HAYDEN–PRESKILL MIRROR

- Throw a diary into an old black hole
- After ~t^* it is readable from a few extra qubits of Hawking radiation
- A teleportation protocol, and a great Qiskit exercise

Hayden & Preskill, JHEP 09 (2007) 120

Horizons vs Firewalls!



- In 2012, **Almheiri, Marolf, Polchinski, and Sully** argued Hawking evaporation, and classical horizon cannot be consistent (similar to arguments by **Mathur 2009**)
- *Their solution:* **Firewalls** instead of **Horizons**! Observers burn up as they hit them!

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.

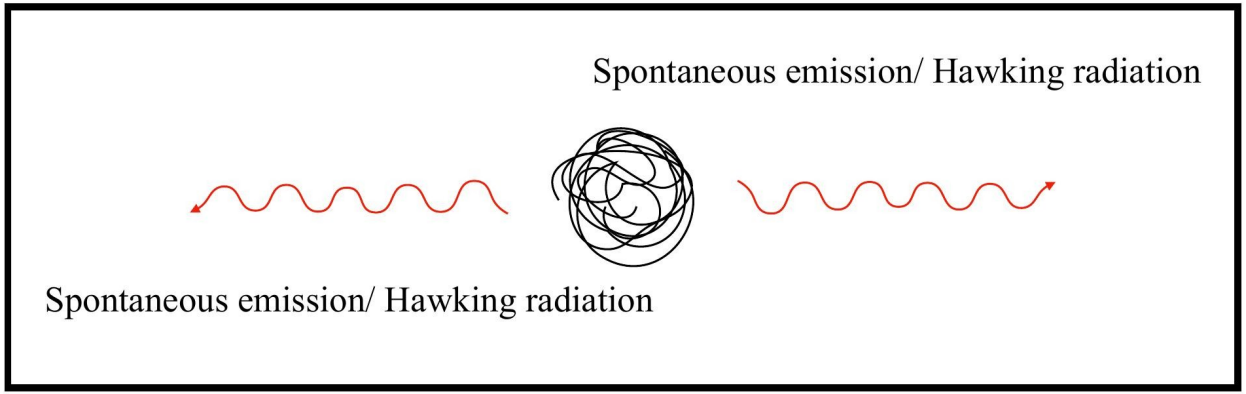
Comments: 19 pages, 1 figure
Subjects: **High Energy Physics - Theory (hep-th)**; Quantum Physics (quant-ph)
Journal reference: JHEP 0810:065,2008

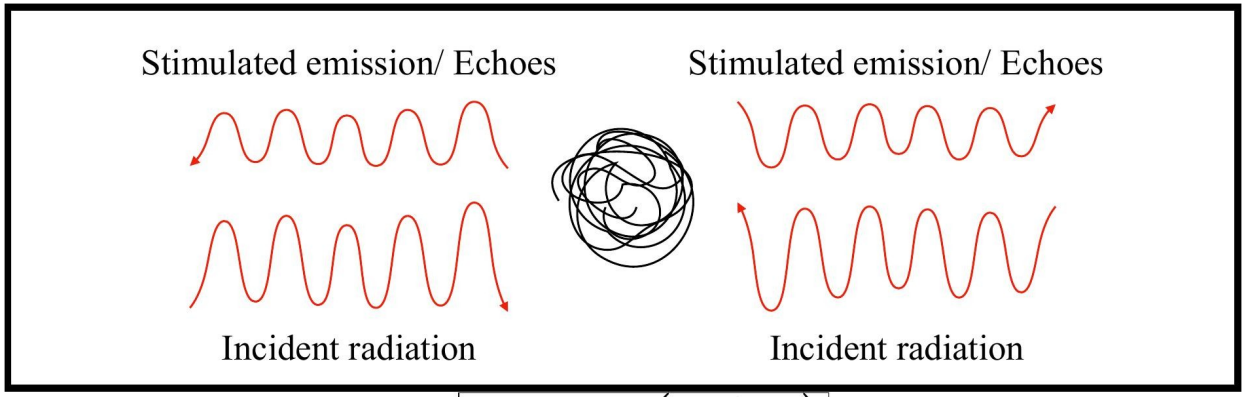
Inverse Temperature

Entropy

$$t_{\text{scramb.}} = \frac{\beta}{2\pi} \log S$$

Scrambling time: *How fast can local information spread across a quantum system?*



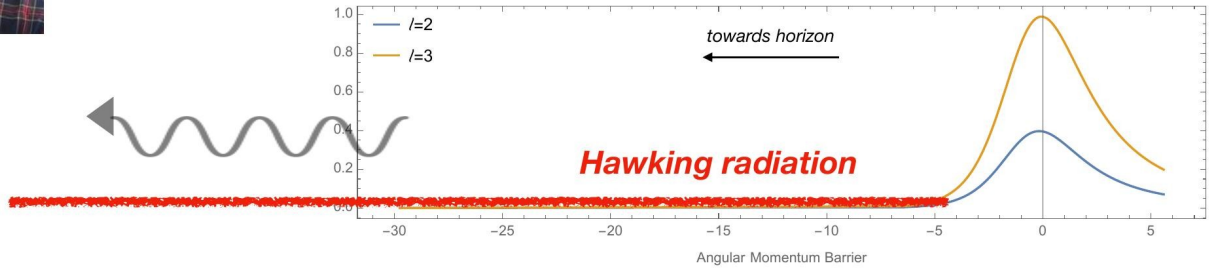


$$R = \exp\left(-\frac{\hbar\omega}{kT_H}\right)$$

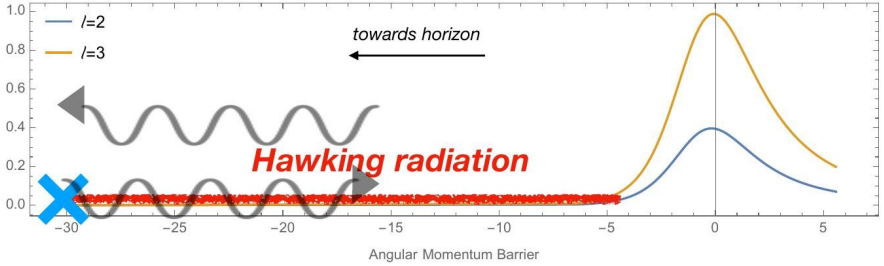
Finite Entropy of Hawking radiation
➡ Echoes *(Oshita & NA 2023)*



- Infinite Entropy & No Echoes: $t_{\rm echo} \to \infty$!



- Finite Entropy & Echoes: $t_{\rm echo} = \dfrac{\ln\left[\text{Entropy}/\ell(\ell+1)\right]}{2\pi \times \text{Hawking Temperature}}$



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

34 Accesses | Metrics

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.

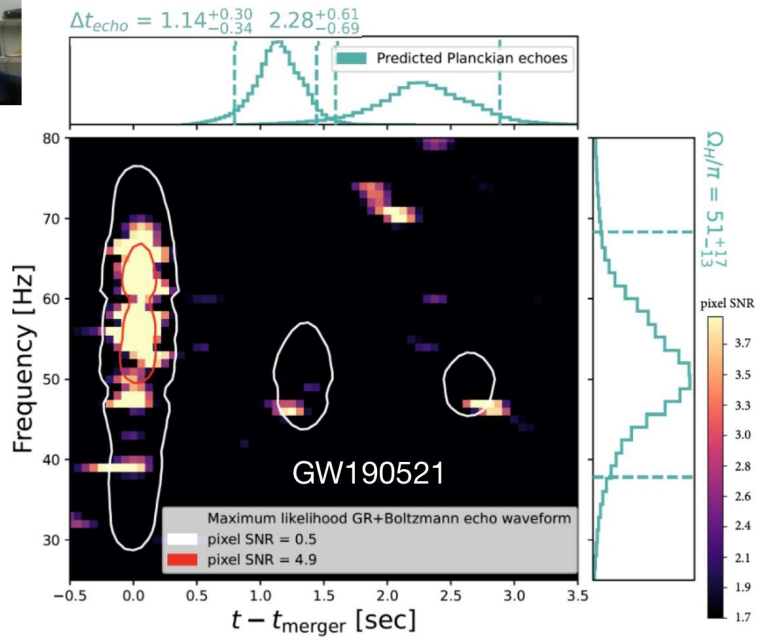


$$t_{\text{scramb.}} = t_{\text{echo}} = \frac{\beta}{2\pi} \log S$$

Are there echoes in LIGO data?

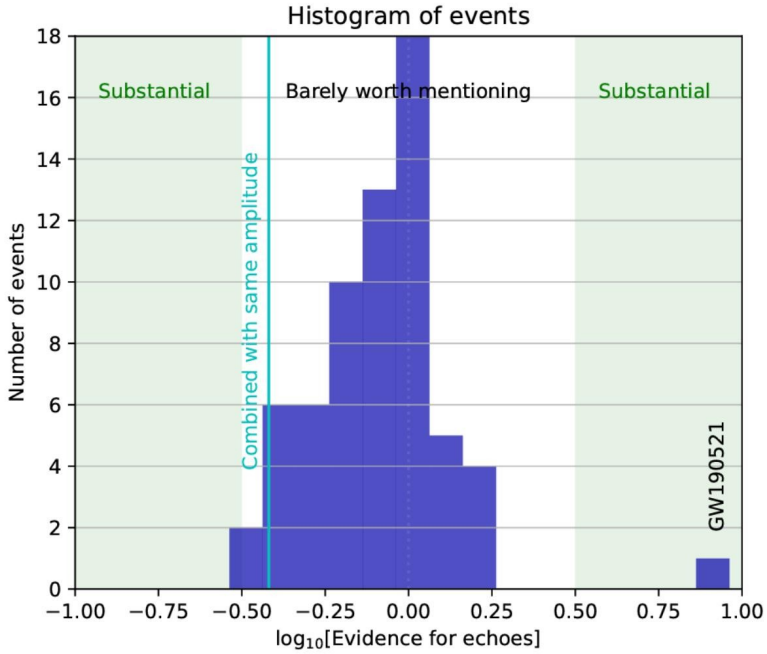
- Abedi, Longo Micchi & NA 2023





Abedi 2025





But not everyone finds echoes!
different methods/events

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		

t_{echo} < 0.5 sec

arXiv.org > gr-qc > arXiv:2112.06861

General Relativity and Quantum Cosmology

[Submitted on 13 Dec 2021]

Tests of General Relativity with GWTC-3

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration:

TABLE XIV. Results of the echoes analysis (Sec. VIII B). List of p-values for signal to noise Bayes Factor $\mathcal{B}^{S}_{N}$ for the events that are analysed. In the absence of any echoes signal these should be uniformly distributed between [0, 1]. Fig. 15 shows the corresponding PP plot with 90% credible intervals superimposed on it. There is no evidence for the presence of echoes.

Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27

missing GW190521

4

The cosmic horizon

The same logarithm, on the scale of the universe

The Loophole: *Logarithms*

- Naively, quantum gravity is suppressed by powers of $\ell_{\rm P}/L$: $\sim 10^{-40}$ at black holes, $\sim 10^{-60}$ at the cosmic horizon
- But horizon physics and RG running come in logs: $\log(M_{\rm BH}/M_{\rm P}) \approx 90$, $\log(M_{\rm P}/H_0) \approx 140$
- Big Bang: couplings run with log(curvature) $\Rightarrow 1 - n_s \approx \dfrac{4}{3N} \approx 2.5\,\%$
- Black holes: echo delay $\sim M_{\rm BH} \log(M_{\rm BH}/M_{\rm P}) \approx$ 0.1–1 s for LIGO
- Cosmic glitch: $1/\log(M_{\rm P}/H_0) \approx 0.7\,\%$ change in G on cosmic scales

Scrambling time for de Sitter Horizon

Trans-Planckian Censorship and the Swampland

Alek Bedroya and Cumrun Vafa

as long as it is sufficiently unstable quantum mechanically. We find that in a meta-stable dS point is compatible with TCC as long as its lifetime T is bounded by

$$T \leq \frac{1}{H} \log \frac{M_p}{H} \tag{1.1}$$

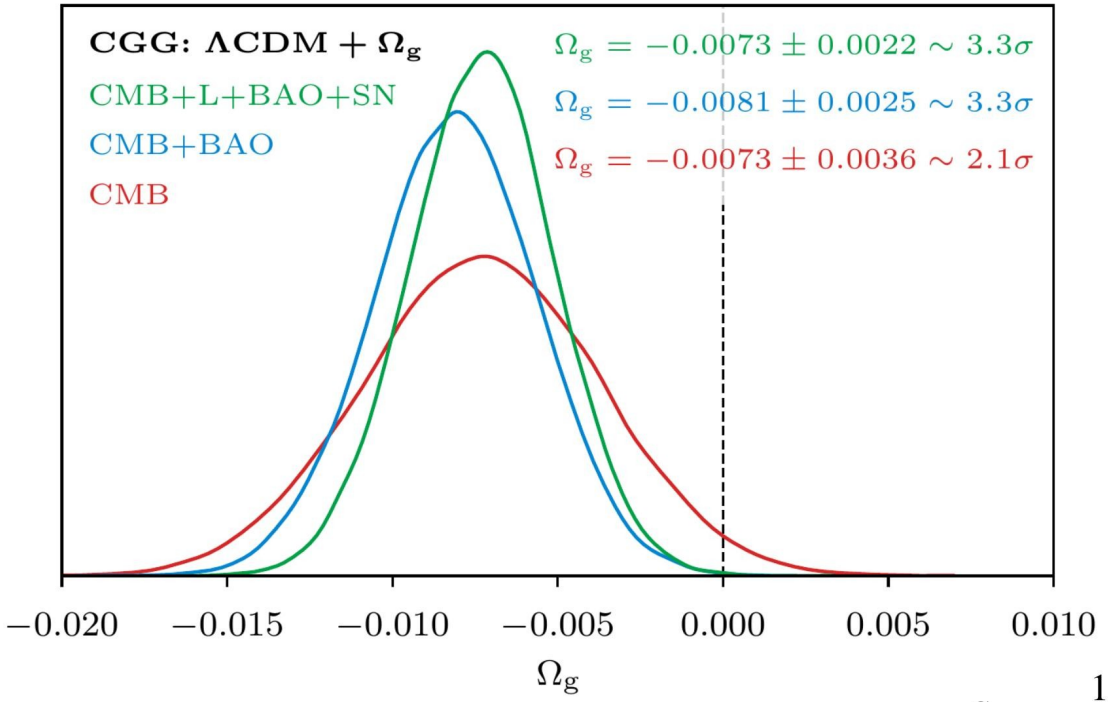
where H is the Hubble parameter and is related to the cosmological constant by $\frac{(d-1)(d-2)}{2}$



Dark Energy, or a Cosmic Glitch in Gravity?

Wen, Hergt, NA & Scott, arXiv:2609.40176

Gravity is 0.8% weaker on cosmic scales (3.3σ)



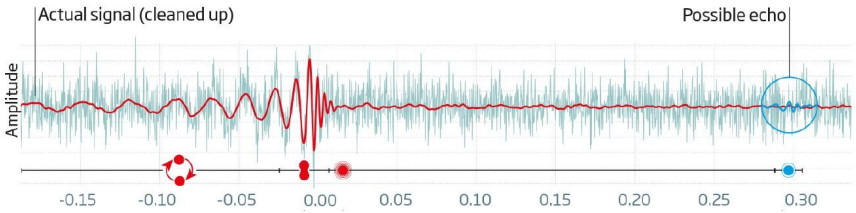
- Planck + ACT + SPT + DESI DR2:
  $G_c/G_N = 0.9920 \pm 0.0025$
  (3.3σ)
- + CMB lensing + SNe: still 3.3σ; CMB alone: 2.1σ
- Hořava reading:
  $\lambda - 1 = 0.0054 \pm 0.0017$

$$S_H = \frac{1}{16\pi G}\int N\,dt\,\sqrt{g}\,d^3\vec{x}\,\left(K^{ij}K_{ij} - \lambda K^2 + R - 2\Lambda\right) + \ldots,$$

Does the same logarithm appear for two horizons?

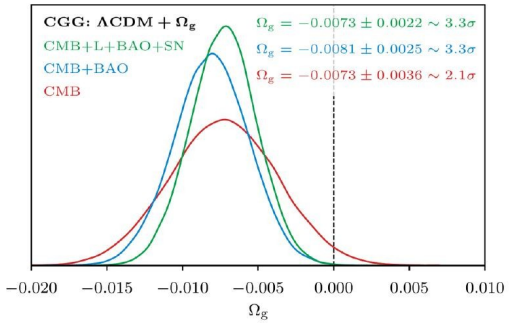
Black Hole Echoes

$$t_{\text{echo}} = \frac{\ln\left[\text{Black Hole Entropy}\right]}{2\pi \times \text{Hawking Temperature}}$$



Cosmological scrambling time

$$t_{\text{scr,dS}} \simeq \frac{\ln\left(M_{\text{P}}/H\right)}{\text{Hubble Rate}} \sim \frac{1}{0.007 \times \text{Hubble Rate}}$$



Is it possible that DESI is detecting the echoes of the cosmological horizon?

5

Your turn

Lab vs sky, and ideas for tomorrow’s demos

Scrambling in the lab

5

2019

Verified scrambling

7 trapped-ion qubits, Hayden –Preskill teleportation

Landsman et al., Nature 567, 61

2021

OTOCs at scale

53 superconducting qubits, operator spreading

Mi et al., Science 374, 1479

2022

“Wormhole on a chip”

Learned toy model; its gravity reading was debated

Jafferis et al., Nature 612, 51

Circuits test the mechanism. Only the sky tells us what real horizons do.

Notebook-sized ideas for tomorrow

5

1

Butterfly meter

Ring vs all-to-all random circuits: measure an OTOC vs depth and watch the scrambling time drop from ~N to ~log N

Bridge: black-hole scrambling

2

Black-hole mirror

3–7 qubit Hayden–Preskill decoder: throw in a qubit, recover it from a few “radiation” qubits

Bridge: information paradox

3

Can you signal?

Bell pairs + mid-circuit measurement + feed-forward: track which qubits can influence which

Bridge: relativistic causality

4

Make echoes

Wave packet hits a barrier whose inner wall reflects with R = exp(−ħω/kT). Time the echo train and fit T. Classical wave sim, or a leaky qubit chain

Bridge: quantum black holes

Take-homes

1

Causality is an ordering

Light cones can emerge, and even infinite speeds can be causal

2

Scrambling has a speed limit

$t^* \approx (\beta/2\pi) \ln S$; all-to-all wiring gets there in ~log N

3

Horizons may leave logarithmic fingerprints

Echo delays in LIGO data; a 0.8% glitch in cosmic gravity?

4

Your circuits are a lab for this

Test the mechanism on qubits; let the sky decide the physics

Thank you!

Questions, and come find me about projects

Reading

Battle of the Big Bang (Afshordi & Halper, U. Chicago Press, 2025)
Scrambling = echoes: Saraswat & Afshordi, JHEP 2020
Cosmic glitch: Wen, Hergt, Afshordi & Scott, arXiv:2609.40176