



*Recent Development of Quantum Gravity  
and Applications to Cosmology and Black Hole Physics*

*Hangzhou, China*

*May 31 to June 5, 2026*

# Quantum Gravity in the Wild

*Testing Horizon-Scale Physics with Gravitational Waves and Cosmology*

***Niayesh Afshordi***



# Outline

- ❑ *Intro:* the crisis in physics
- ❑ Quantum Big Bang
- ❑ Quantum Black Holes
- ❑ Quantum Dark Energy
- ❑ *Outro:* how the light gets in



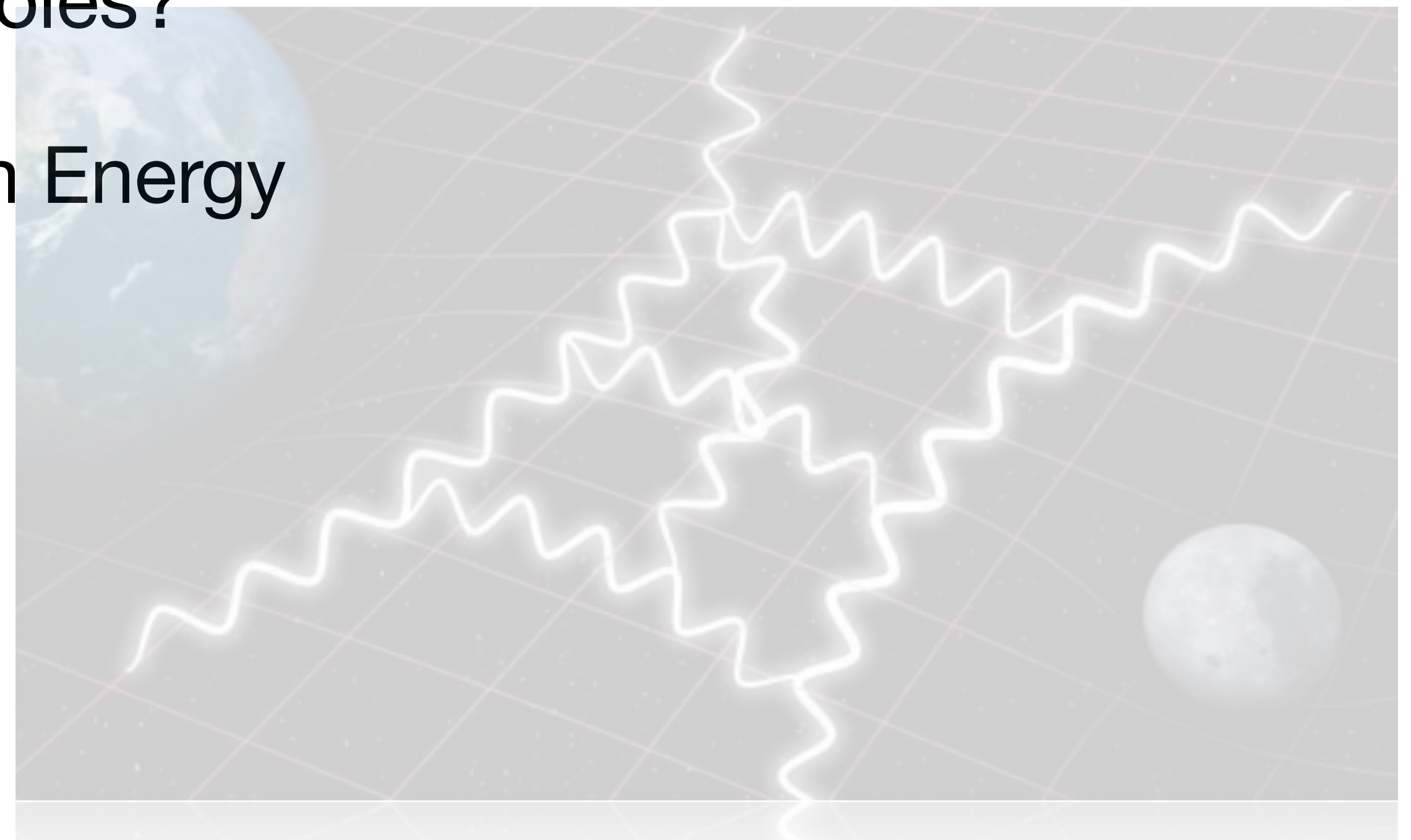
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# Chasms amongst our best theories and observations

- Quantum Mechanics + Relativity  $\rightarrow \infty$
- Singularities @hearts of Big Bang and Black Holes
- Information lost in evaporation of black holes?
- Dark Energy  $< 10^{-60} \times$  Quantum Vacuum Energy
- Is Standard Model “Technically Natural”?



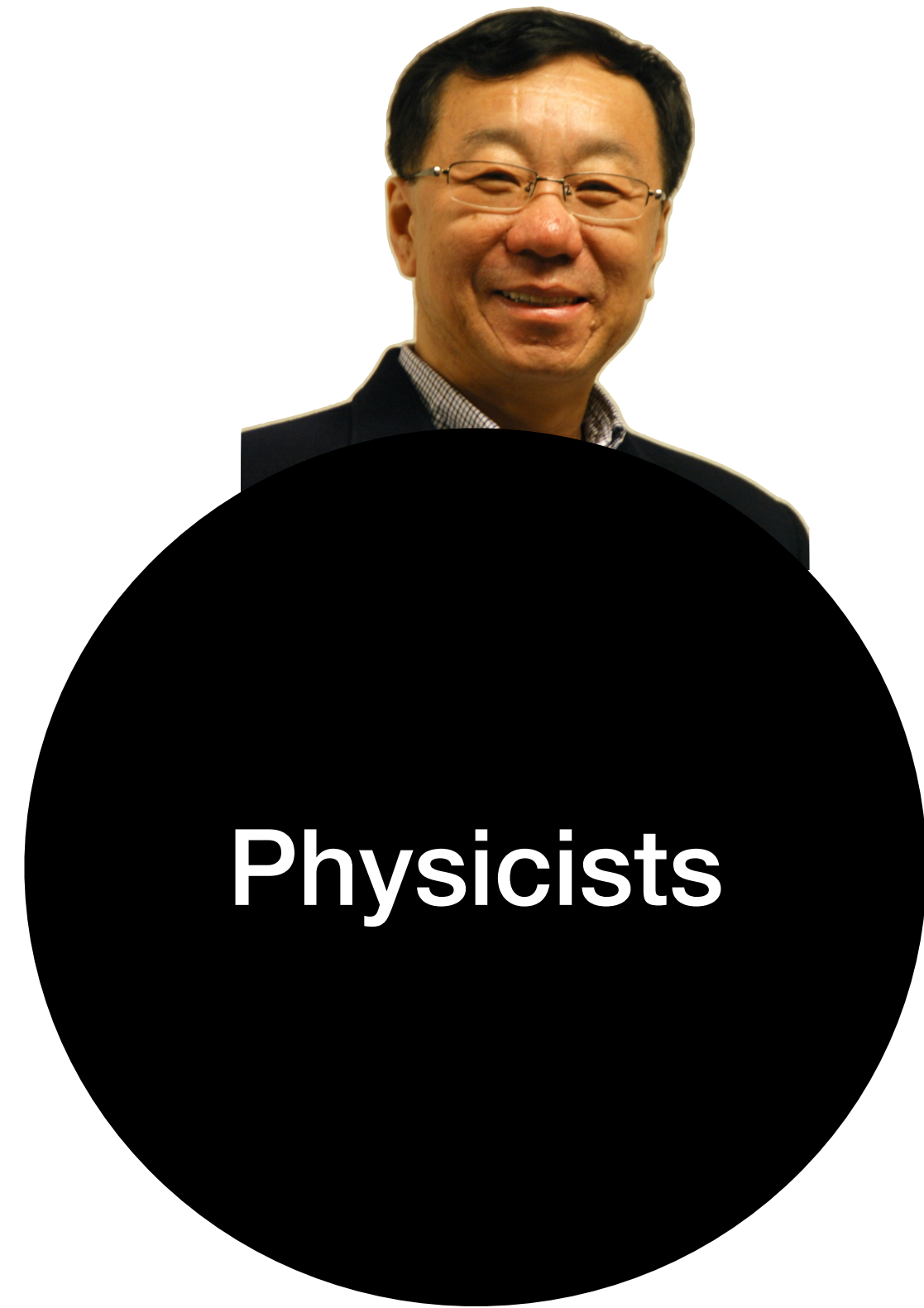


# Crisis of Falsifiability

- Landscape of  $10^{500}$  vacua in string theory
- ***No signature*** of Supersymmetry, Anti-deSitter space, or extra dimensions
- No concrete testable prediction from ***any quantum gravity proposal***
- ***Inflation***, leading theory of Big Bang, can fit ***any*** data
- Is ***Theoretical Physics*** turning into ***Religious Dogma?***

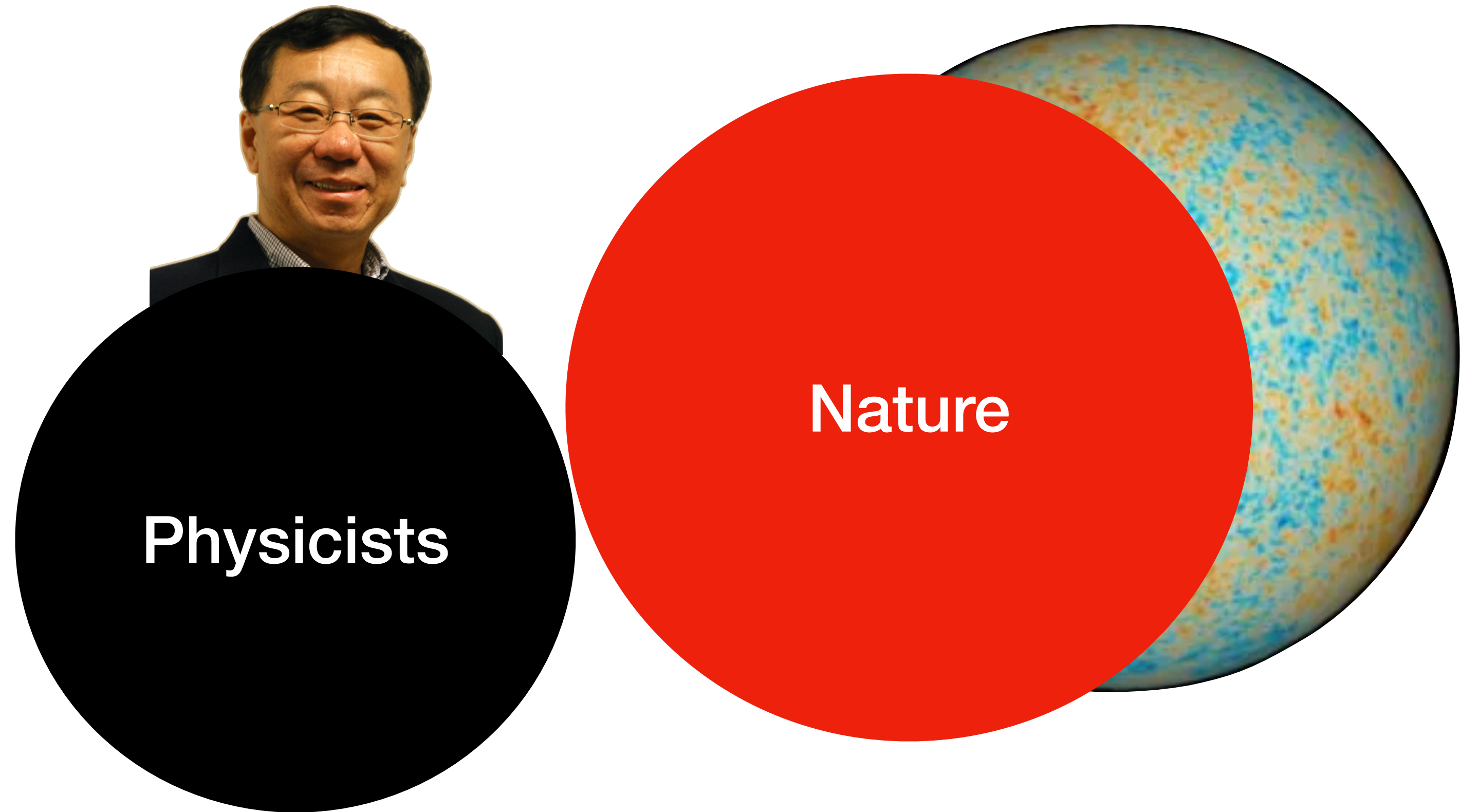


# The Crisis in Physics!



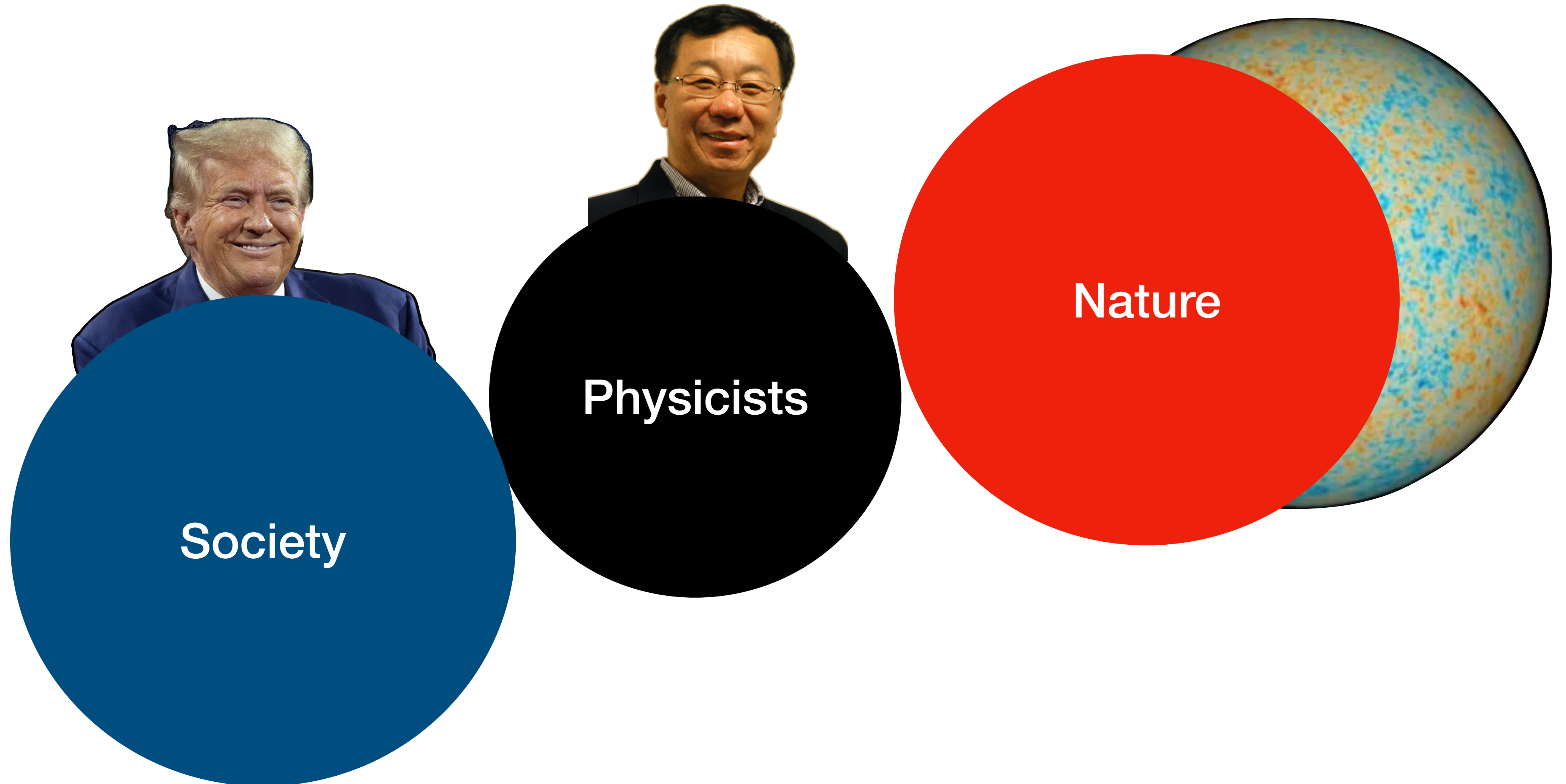


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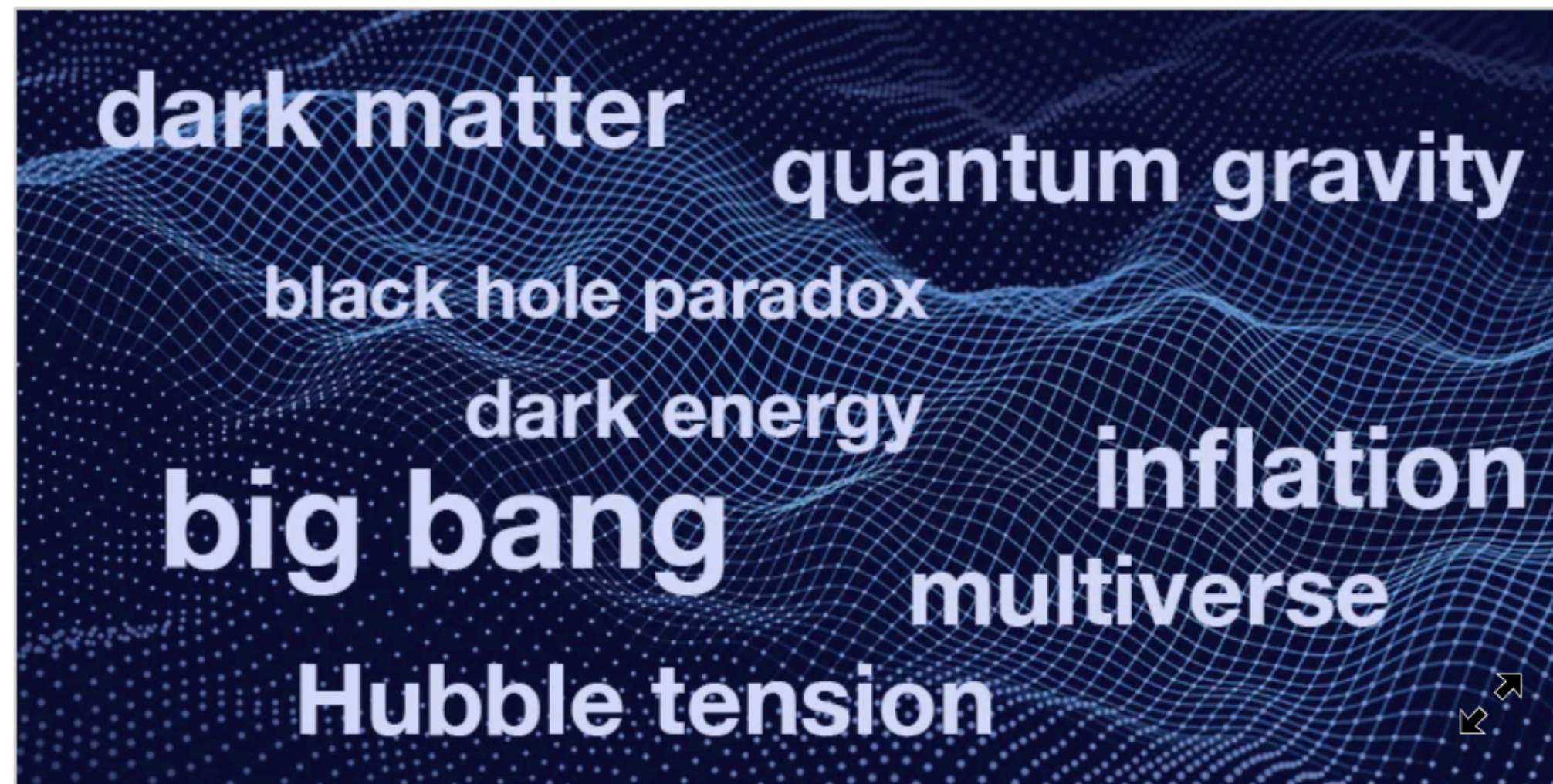


## SPECIAL FEATURE

# Take the Big Mysteries in Physics Survey

July 28, 2025 • *Physics* 18, 140

Did time start at the big bang? What happens if you fall into a black hole? What explains the mysterious dark matter? Weigh in on the toughest questions facing physicists today.



Ricardo/stock.adobe.com; adapted by APS



SPECIAL FEATURE

# Far from Settled: Respondents at Odds over Greatest Physics Mysteries

May 12, 2026 • *Physics* 19, 34

One of the largest physics surveys ever conducted finds respondents divided on most topics. Surprisingly, some “textbook” answers only racked up a minority of votes.

## Largest-ever survey of physicists puts Standard Model of cosmology under scrutiny



# Big Mysteries Survey Dashboard

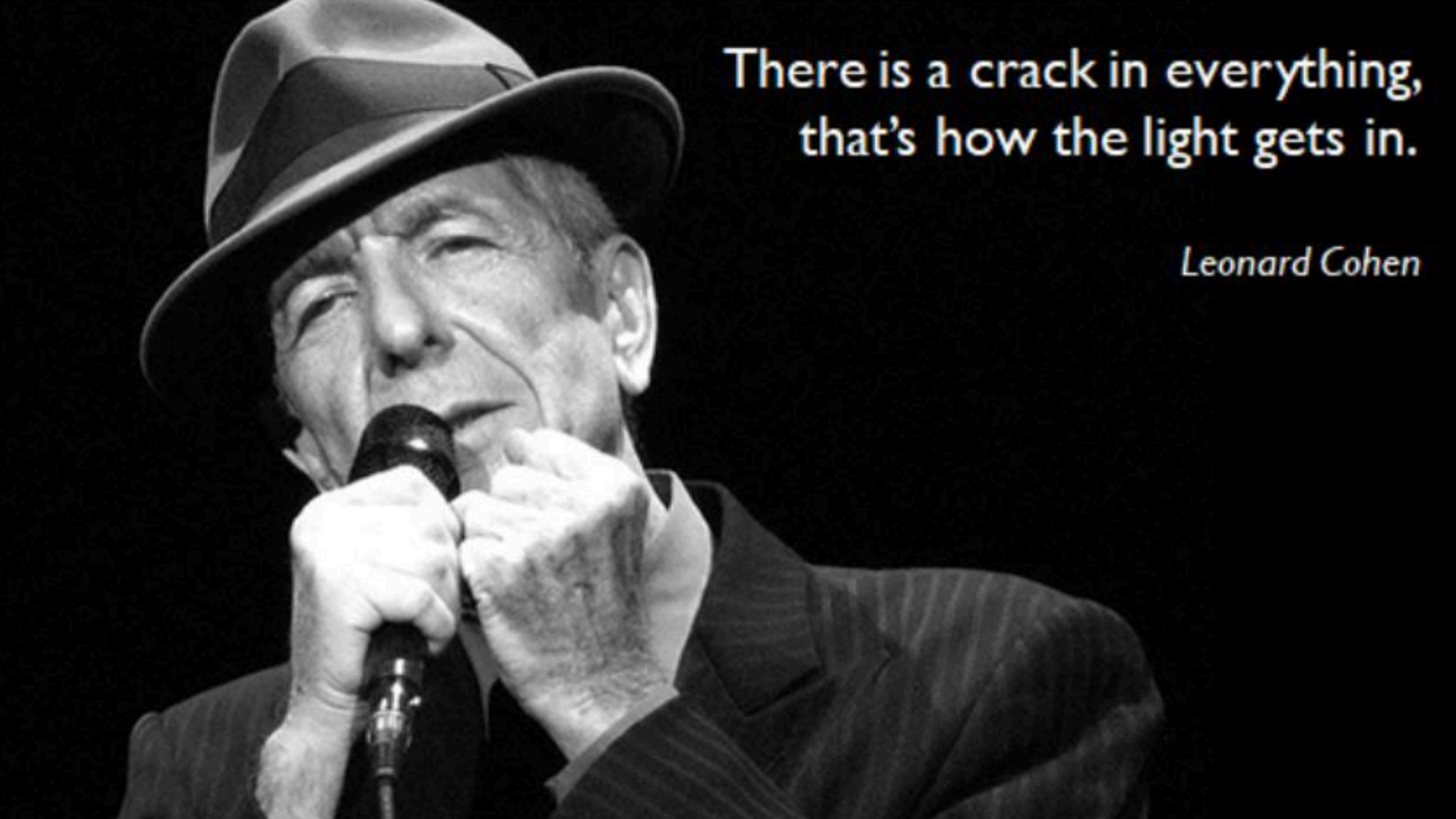
Explore how the distribution of answers to one survey question shifts when conditioning on a specific answer to another question. The chart overlays the unconditional distribution in sand and the conditional distribution in teal.

[nafshordi.github.io/aps-dashboard/](https://nafshordi.github.io/aps-dashboard/)



| BKGD ANSWERS -> Q10                                      | String Theory/M-Theory (replacing point particles with extended objects in higher dimensions) | Gravity is not quantum | Loop Quantum Gravity (quantizing areas and volumes in spacetime) | Asymptotic Safety (spacetime becomes a fractal on small scales) | Causal Sets (Discrete spacetime atoms, only connected by causal relations) | Hořava-Lifshitz Gravity (breaking speed of light limit at high energies) | Causal Dynamical Triangulation (gluing triangulate space in lay of time) |
|----------------------------------------------------------|-----------------------------------------------------------------------------------------------|------------------------|------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| A researcher in a field not listed above<br>n=291        | 24.1<br>%<br>n=70                                                                             | 37.1<br>%<br>n=108     | 18.2<br>%<br>n=53                                                | 11.0<br>%<br>n=32                                               | 6.5<br>%<br>n=19                                                           | 2.4<br>%<br>n=7                                                          | 0.7<br>%<br>n=2                                                          |
| A science enthusiast<br>n=251                            | 31.5<br>%<br>n=79                                                                             | 31.5<br>%<br>n=79      | 20.7<br>%<br>n=52                                                | 7.6<br>%<br>n=19                                                | 4.8<br>%<br>n=12                                                           | 2.0<br>%<br>n=5                                                          | 2.0<br>%<br>n=5                                                          |
| A researcher studying quantum physics<br>n=163           | 31.9<br>%<br>n=52                                                                             | 22.1<br>%<br>n=36      | 25.2<br>%<br>n=41                                                | 9.8<br>%<br>n=16                                                | 5.5<br>%<br>n=9                                                            | 0.6<br>%<br>n=1                                                          | 4.9<br>%<br>n=8                                                          |
| A researcher studying astrophysics or cosmology<br>n=113 | 38.1<br>%<br>n=43                                                                             | 27.4<br>%<br>n=31      | 21.2<br>%<br>n=24                                                | 6.2<br>%<br>n=7                                                 | 3.5<br>%<br>n=4                                                            | 3.5<br>%<br>n=4                                                          | 0.0<br>%<br>n=0                                                          |
| A researcher studying gravity<br>n=93                    | 49.5<br>%<br>n=46                                                                             | 10.8<br>%<br>n=10      | 26.9<br>%<br>n=25                                                | 7.5<br>%<br>n=7                                                 | 2.2<br>%<br>n=2                                                            | 2.2<br>%<br>n=2                                                          | 1.1<br>%<br>n=1                                                          |

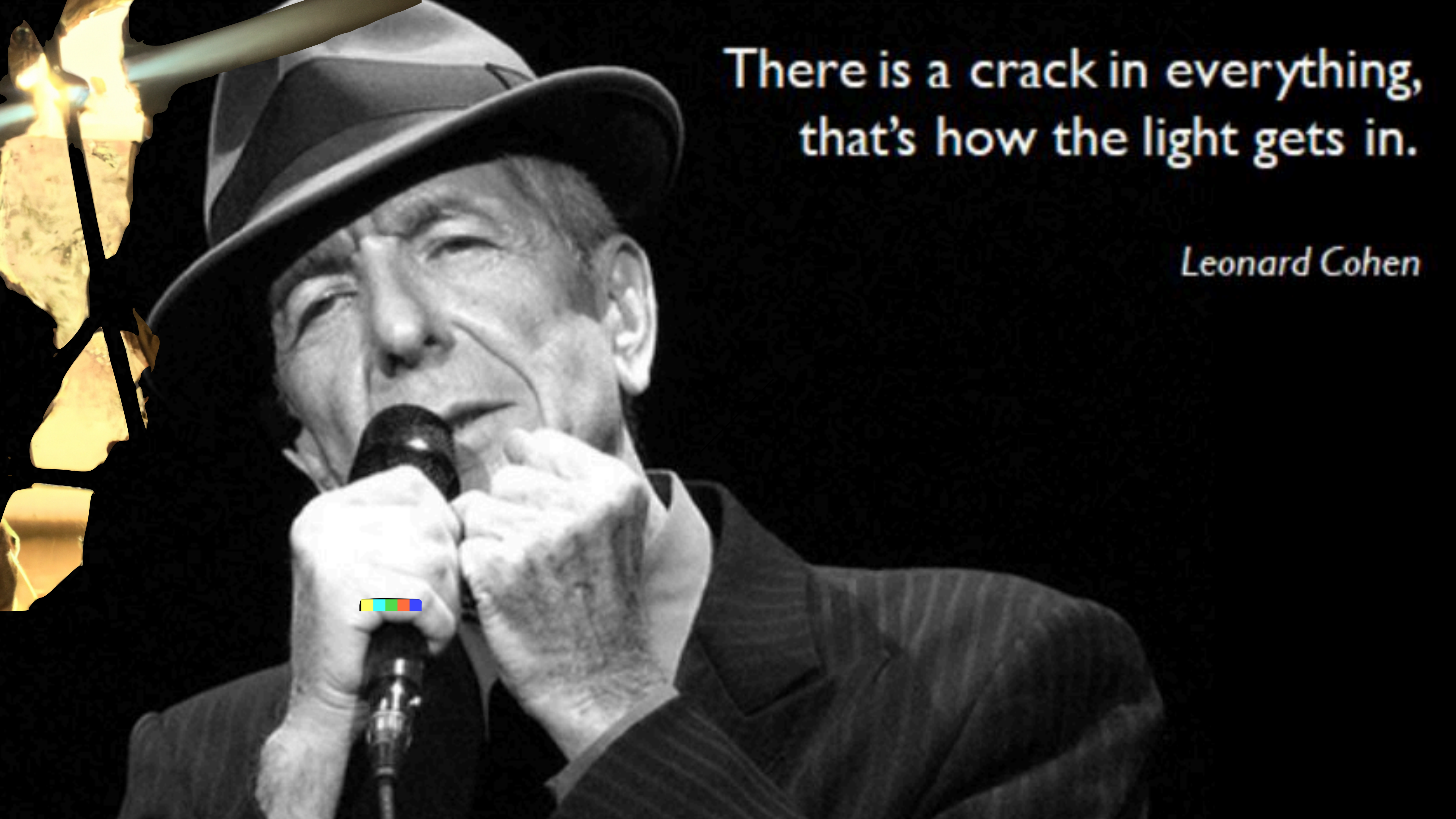


A black and white photograph of Leonard Cohen. He is wearing a dark fedora and a dark pinstriped suit jacket over a dark shirt. He is holding a vintage-style microphone with both hands, close to his mouth, and appears to be singing or speaking. The background is dark and out of focus.

There is a crack in everything,  
that's how the light gets in.

*Leonard Cohen*





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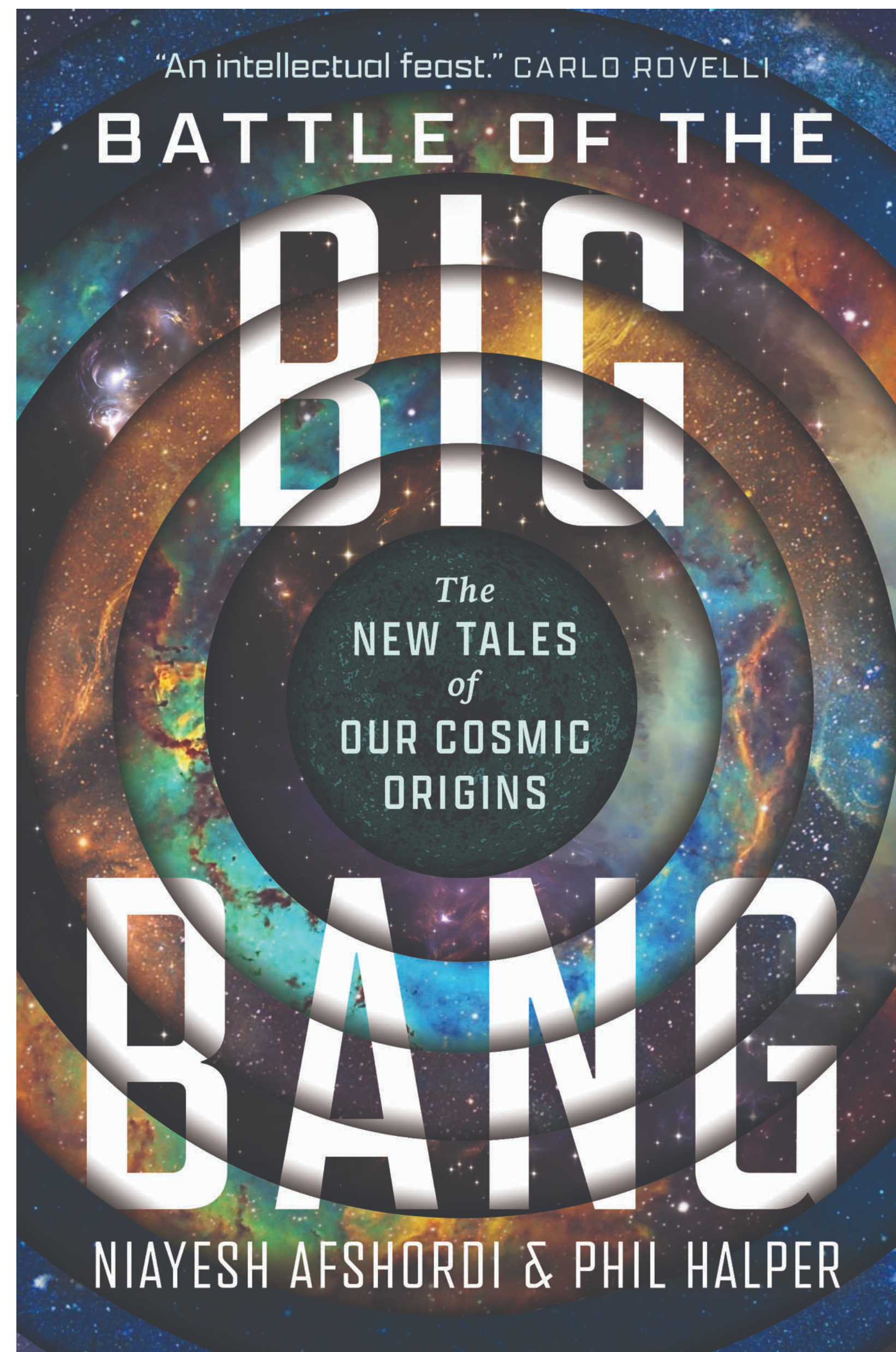
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Now on sale at all good book sellers



# Five Best: Cosmic Origins and Endings

Selected by the author of ‘The Echoing Universe: How Radio Astronomy Helps Us See the Invisible Cosmos.’

By Emma Chapman

May 19, 2026 2:13 pm ET

Aa 15 | Listen (2 m

## Five Best: Cosmic Origins and Endings

Selected in The Wall Street Journal by Emma Chapman



Included in WSJ’s Five Best  
Battle of the Big Bang

A lively picture of the contemporary frontiers of science  
where certainty does not belong

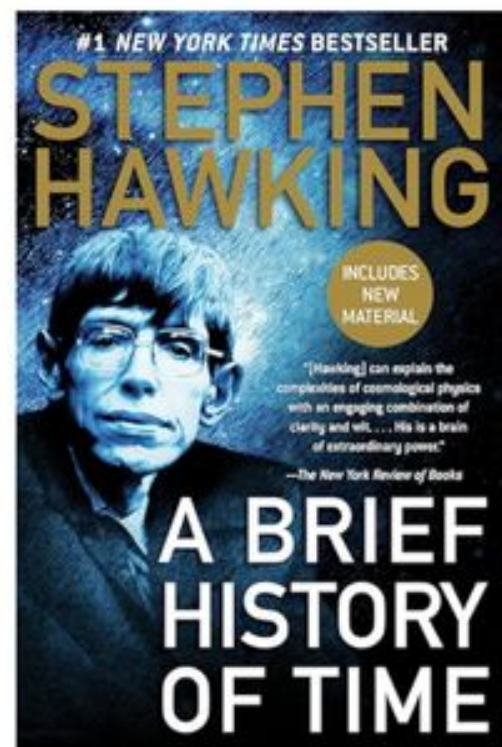


# Amazon Best Sellers

Our most popular products based on sales. Updated frequently.

## Best Sellers in Cosmology

#1



A Brief History of Time

> Stephen Hawking

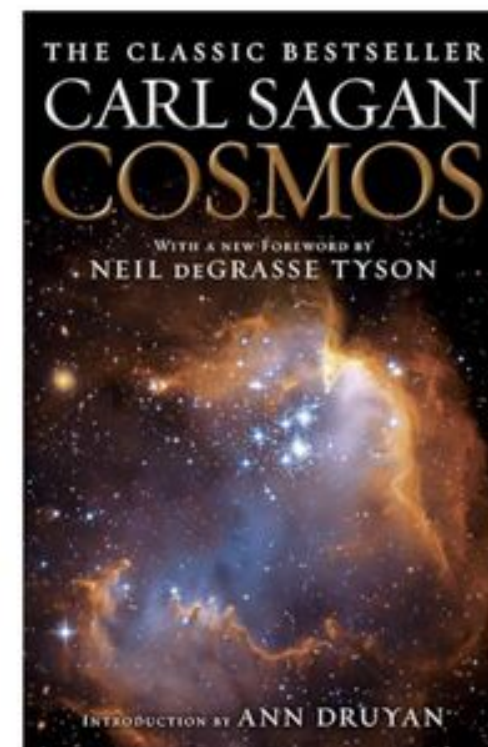
★★★★☆ 11,286

Kindle Edition

\$8.99

2 formats available

#2



Cosmos

> Carl Sagan

★★★★☆ 5,230

Paperback

\$11.14

3 formats available

#3



Battle of the Big Bang: The New Tales of Our...

Niayesh Afshordi

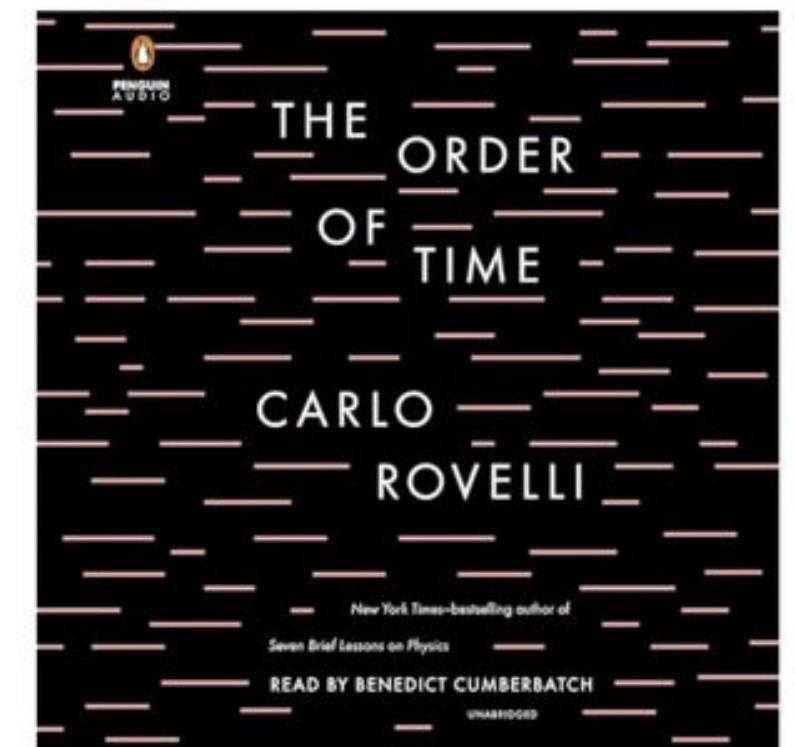
★★★★☆ 36

Hardcover

\$32.50

2 formats available

#4



The Order of Time

Carlo Rovelli

★★★★☆ 5,627

Audible Audiobook

\$12.60

5 formats available



# Quadratic Gravity is Renormalizable

PHYSICAL REVIEW D

VOLUME 16, NUMBER 4

15 AUGUST 1977

## Renormalization of higher-derivative quantum gravity\*

K. S. Stelle

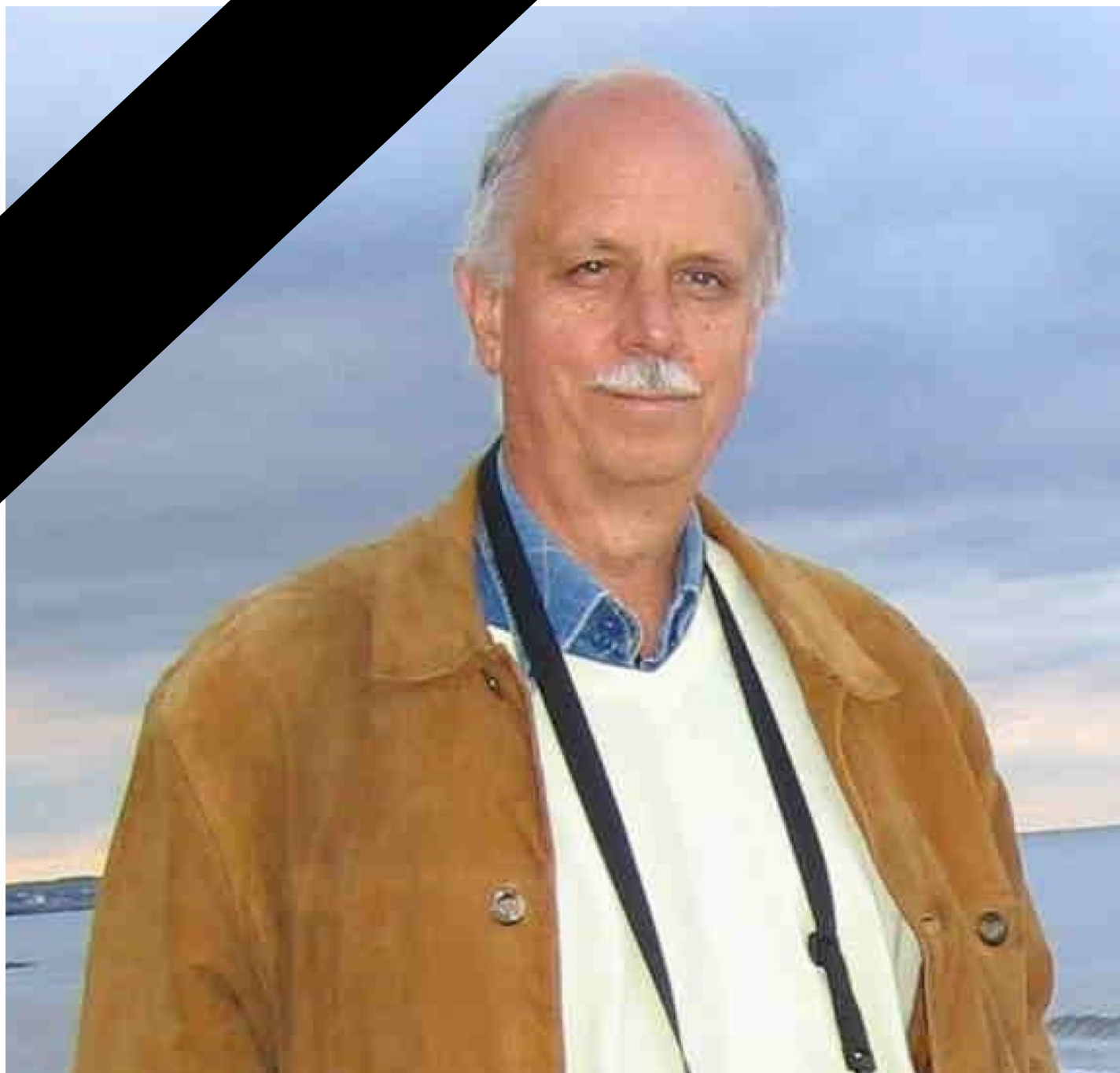
*Department of Physics, Brandeis University, Waltham, Massachusetts 02154*

(Received 15 November 1976)

Gravitational actions which include terms quadratic in the curvature tensor are renormalizable. The necessary Slavnov identities are derived from Becchi-Rouet-Stora (BRS) transformations of the gravitational and Faddeev-Popov ghost fields. In general, non-gauge-invariant divergences do arise, but they may be absorbed by nonlinear renormalizations of the gravitational and ghost fields (and of the BRS transformations). Fortunately, these artifactual divergences may be eliminated by letting the coefficient of the harmonic gauge-fixing term tend to infinity, thus considerably simplifying the renormalization procedure. Coupling to other renormalizable fields may then be handled in a straightforward manner.

$$I_{\text{sym}} = - \int d^4x \sqrt{-g} (\alpha R_{\mu\nu} R^{\mu\nu} - \beta R^2 + \kappa^{-2} \gamma R) ,$$





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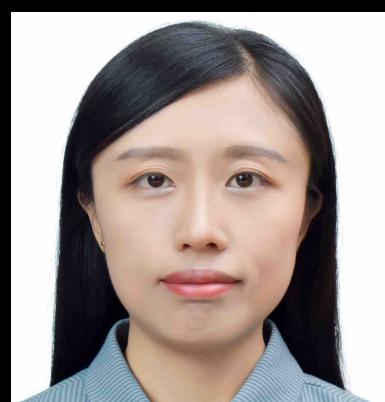


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*Holdom & Ren 2016*

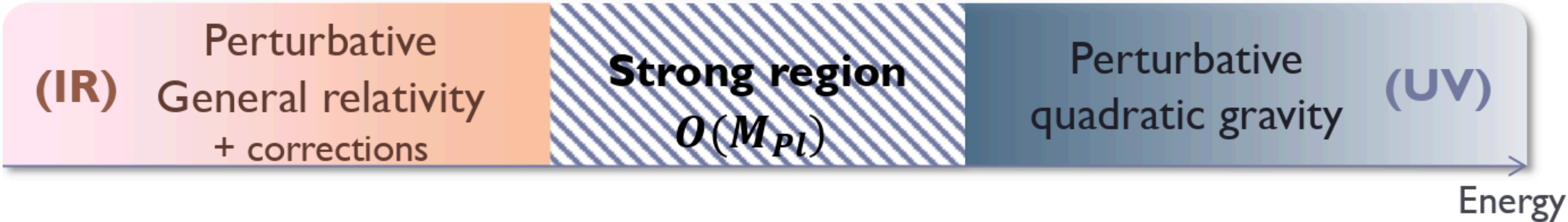




# Quadratic Gravity as Quantum Chromodynamics?

$$S_{\text{QG}} = \int d^4x \sqrt{-g} \left( \frac{1}{2} M^2 R - \frac{1}{2 f_2^2} C_{\mu\nu\alpha\beta} C^{\mu\nu\alpha\beta} + \frac{1}{3 f_0^2} R^2 \right)$$

| QCD                                                           | Quadratic Gravity                                                                                 |
|---------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| AF at UV, $g_s^2$ gets strong at $\Lambda_{QCD}$              | AF at UV, $f_0^2, f_2^2$ get strong at $\Lambda_{QG}$                                             |
| Perturbative transverse gluon removed from physical spectrum  | Perturbative ghost pole removed from physical spectrum                                            |
| Color singlet states described by Chiral Lagrangian in the IR | $M = 0$ , massless graviton described by General relativity in the IR, $M_{Pl} \sim \Lambda_{QG}$ |
| (Current quark mass gives pion mass)                          | New scale $M$ controls graviton mass gap                                                          |



(Different from QCD, the same field appears in both UV and IR)

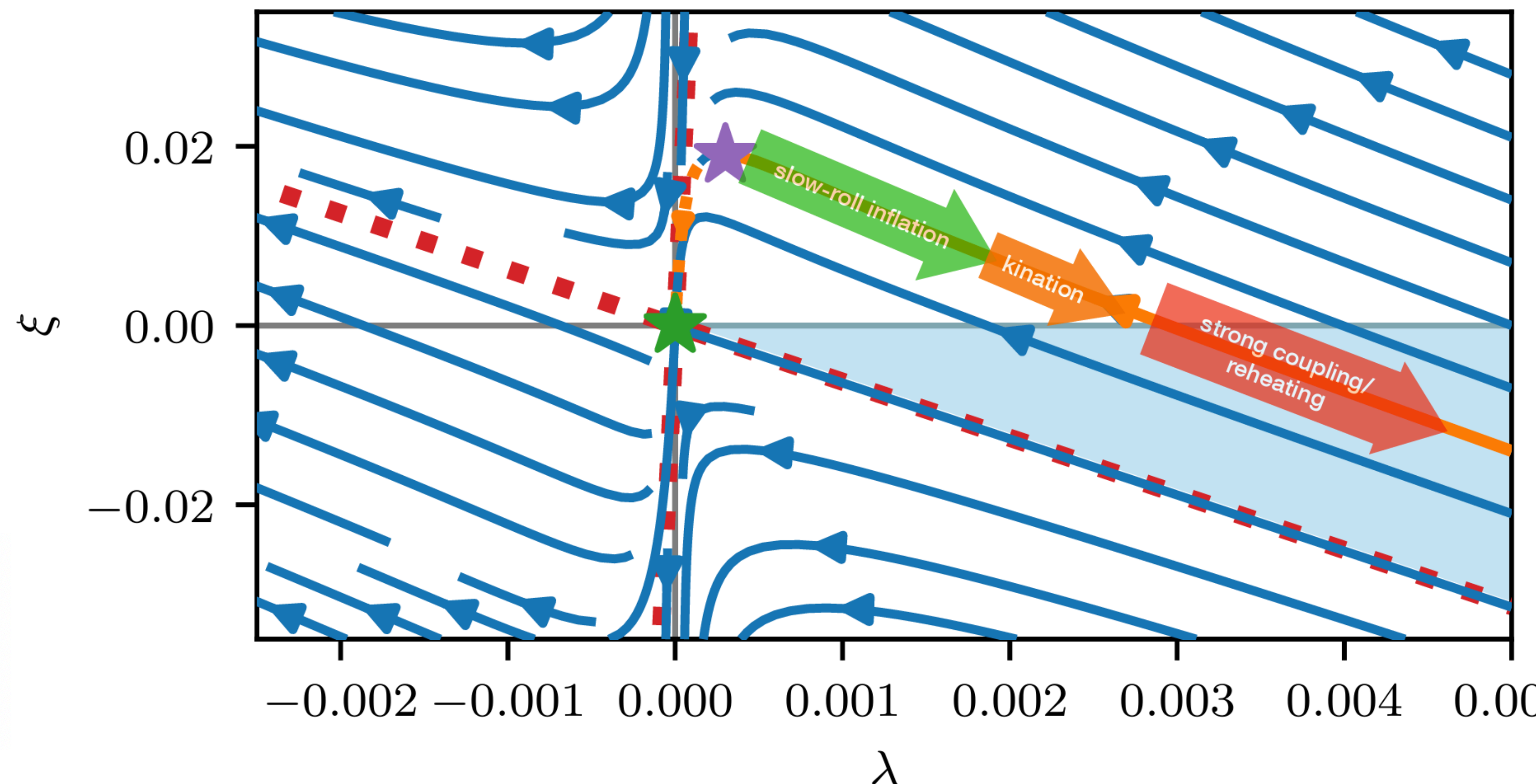


# Cosmology of Quadratic Gravity under RG Flow

Quintin, Liu & NA 2025



$$S = \int d^4x \sqrt{-g} \left( \cancel{\frac{R}{16\pi G_N}} - \frac{R^2}{\xi} - \frac{C_{\mu\nu\rho\sigma}^2}{2\lambda} \right)$$



$$\beta_{\xi} = \frac{d\xi}{d\ln\mu} = -\frac{1}{(4\pi)^2} \frac{\xi^2 - 36\lambda\xi - 2520\lambda^2}{36},$$

$$\beta_{\lambda} = \frac{d\lambda}{d\ln\mu} = -\frac{1}{(4\pi)^2} \frac{[(1617 + 90\mathcal{N})\lambda - 20\xi]\lambda}{90},$$

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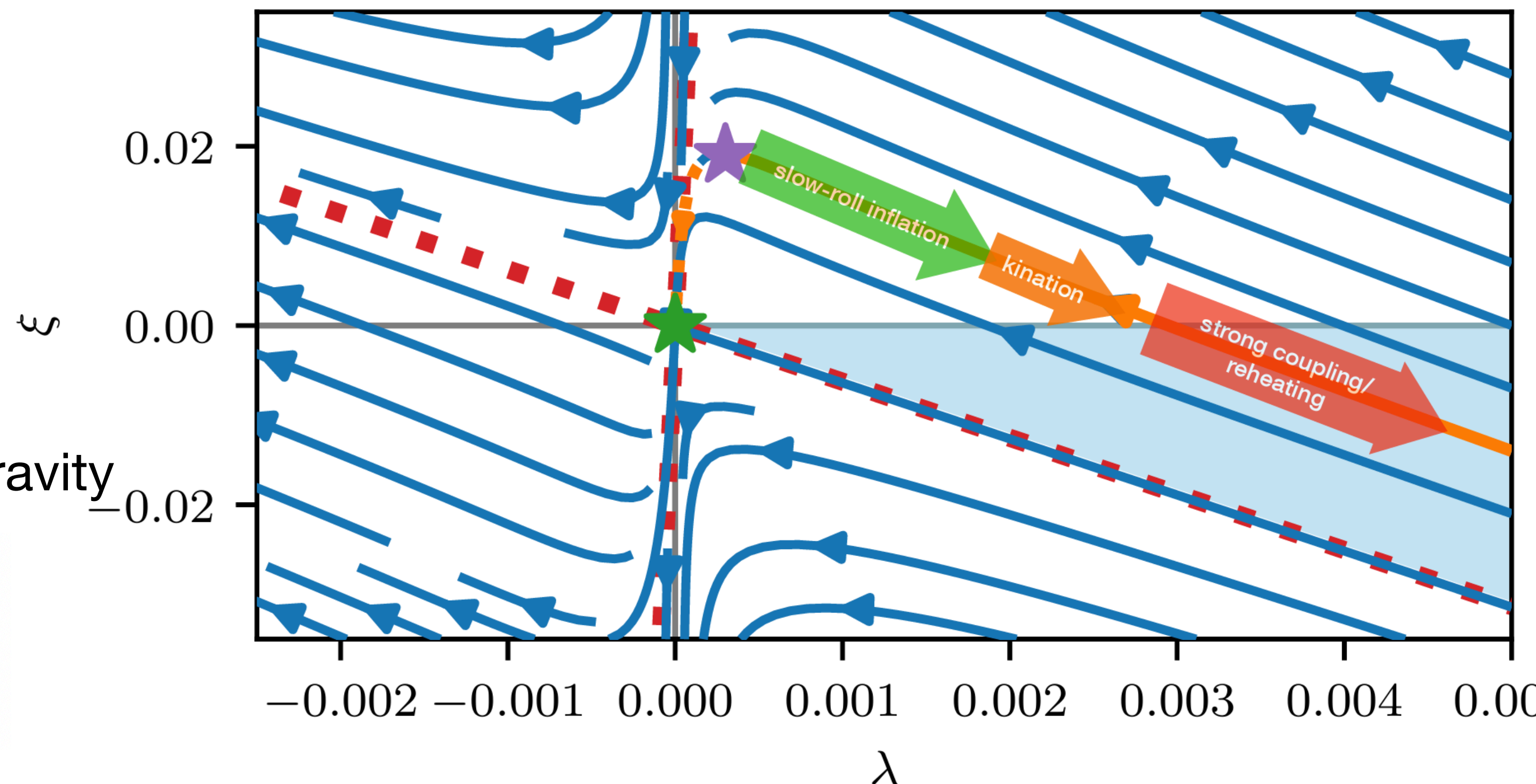
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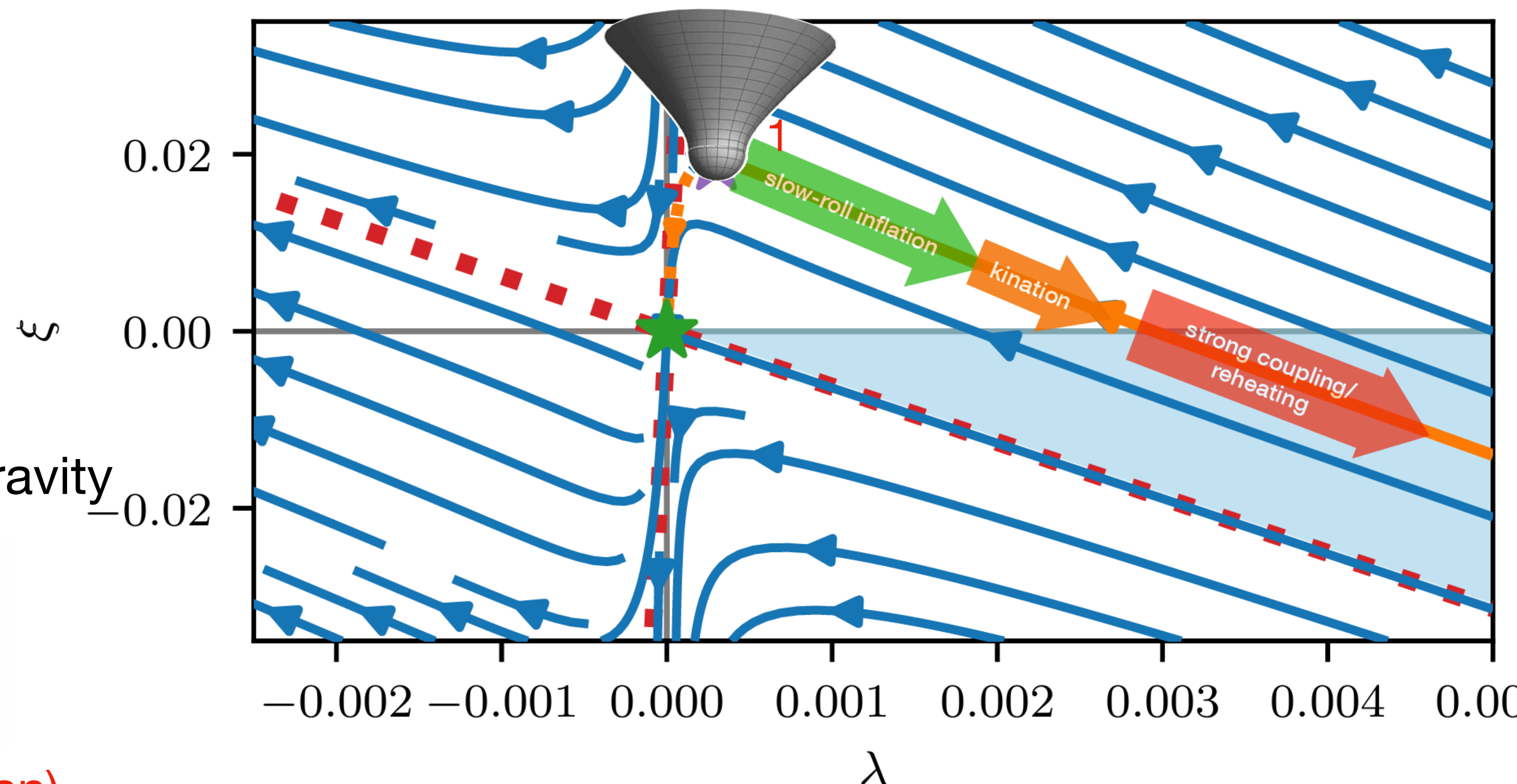
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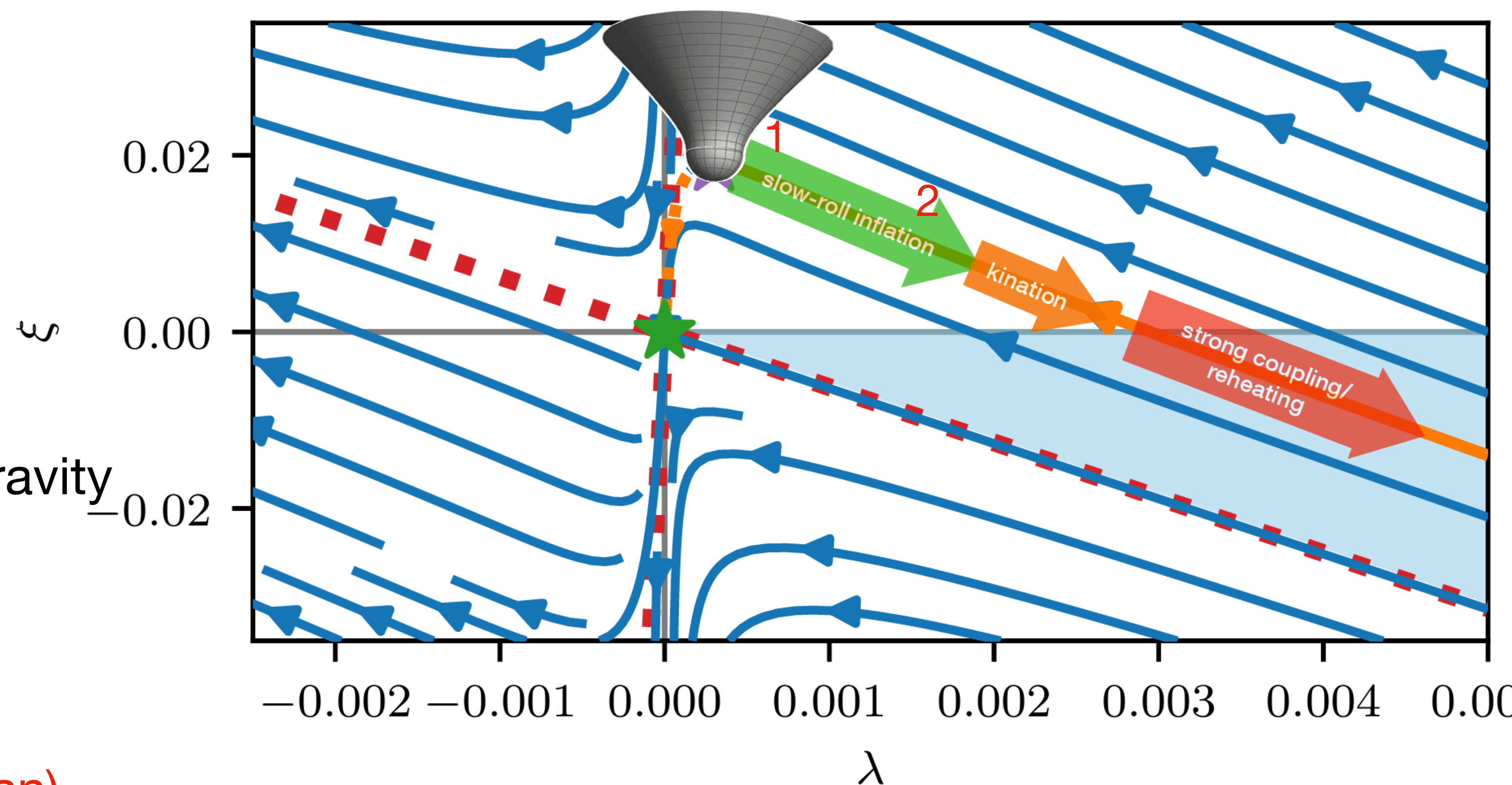


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2. Slow-roll inflation w/ QG



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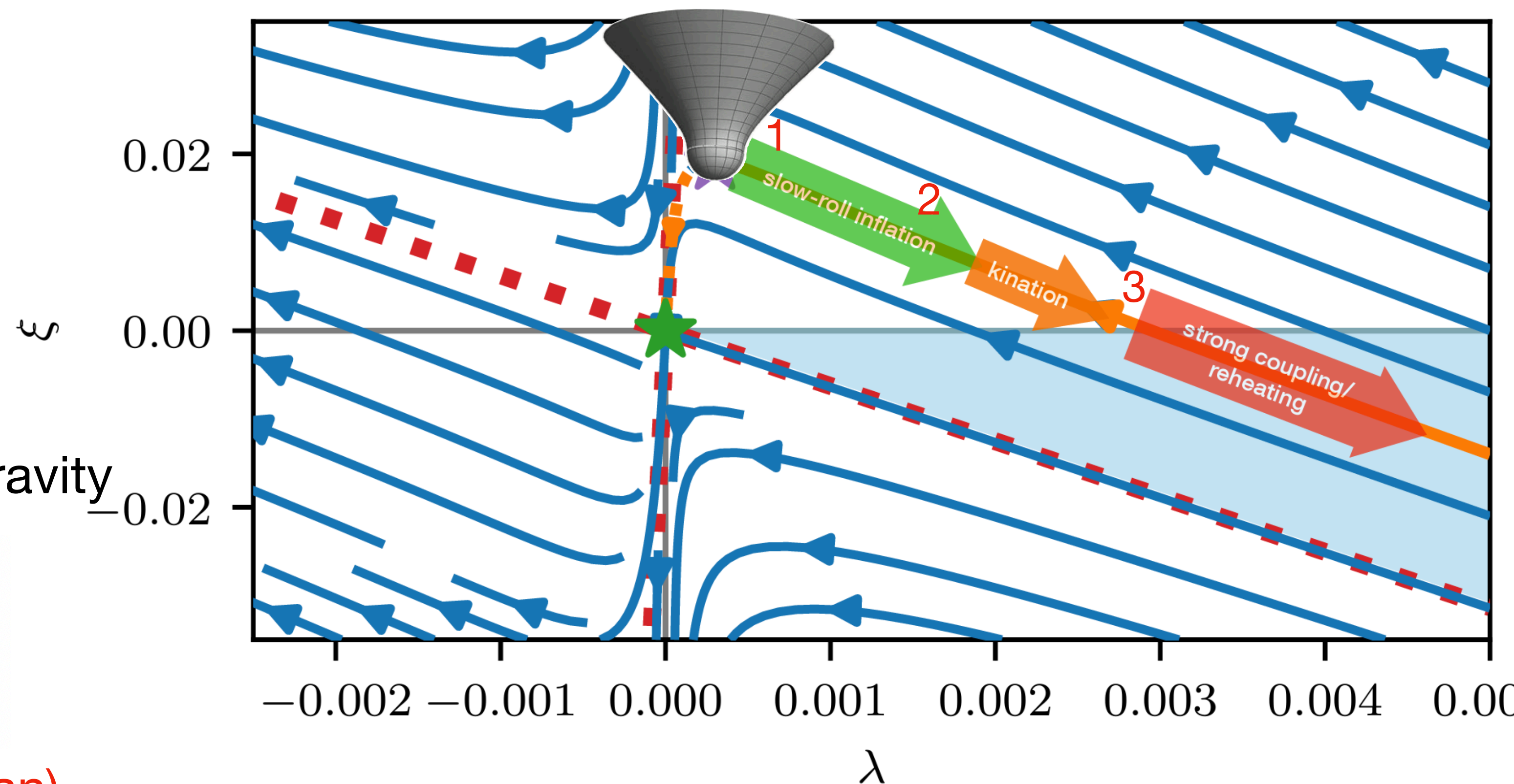
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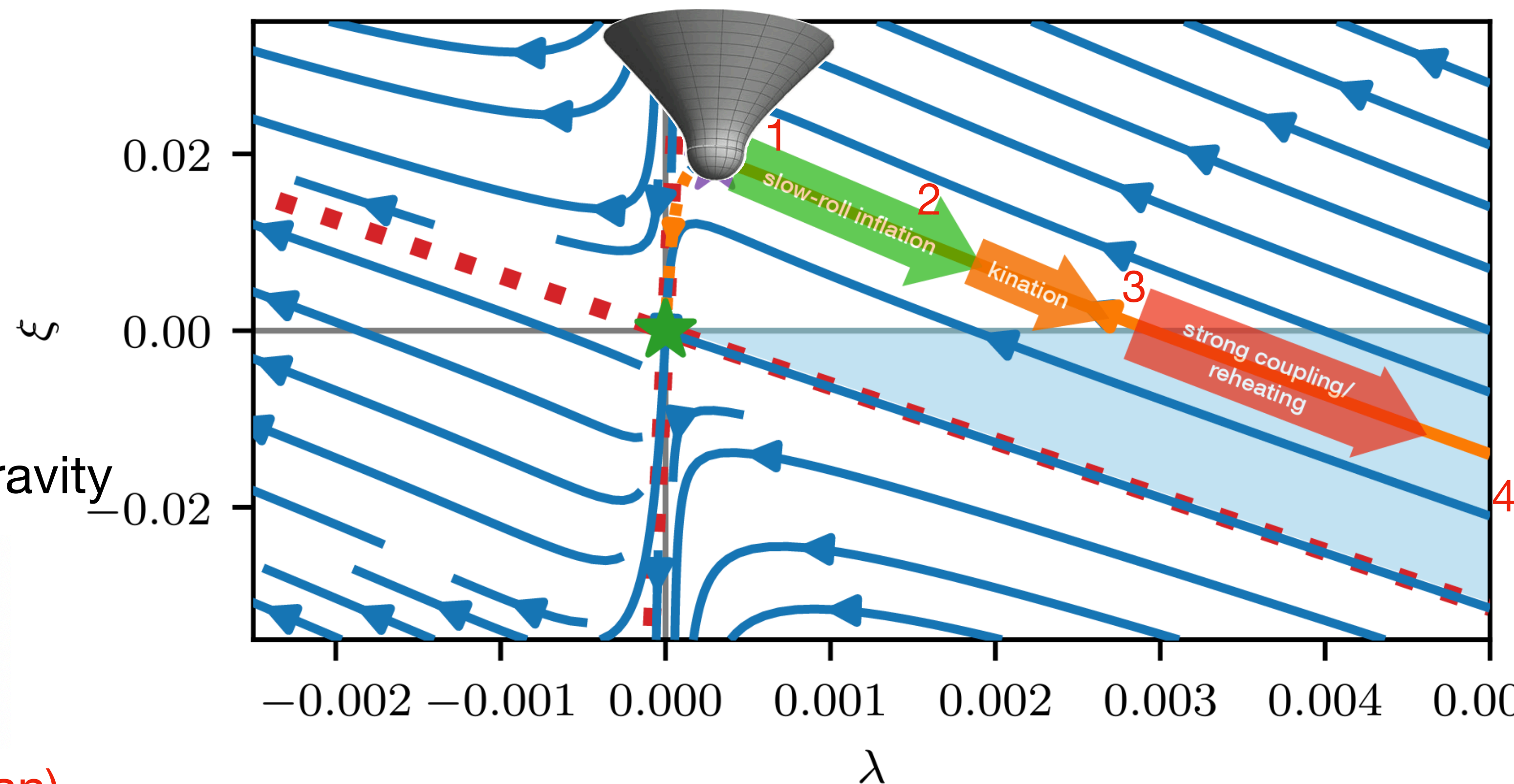
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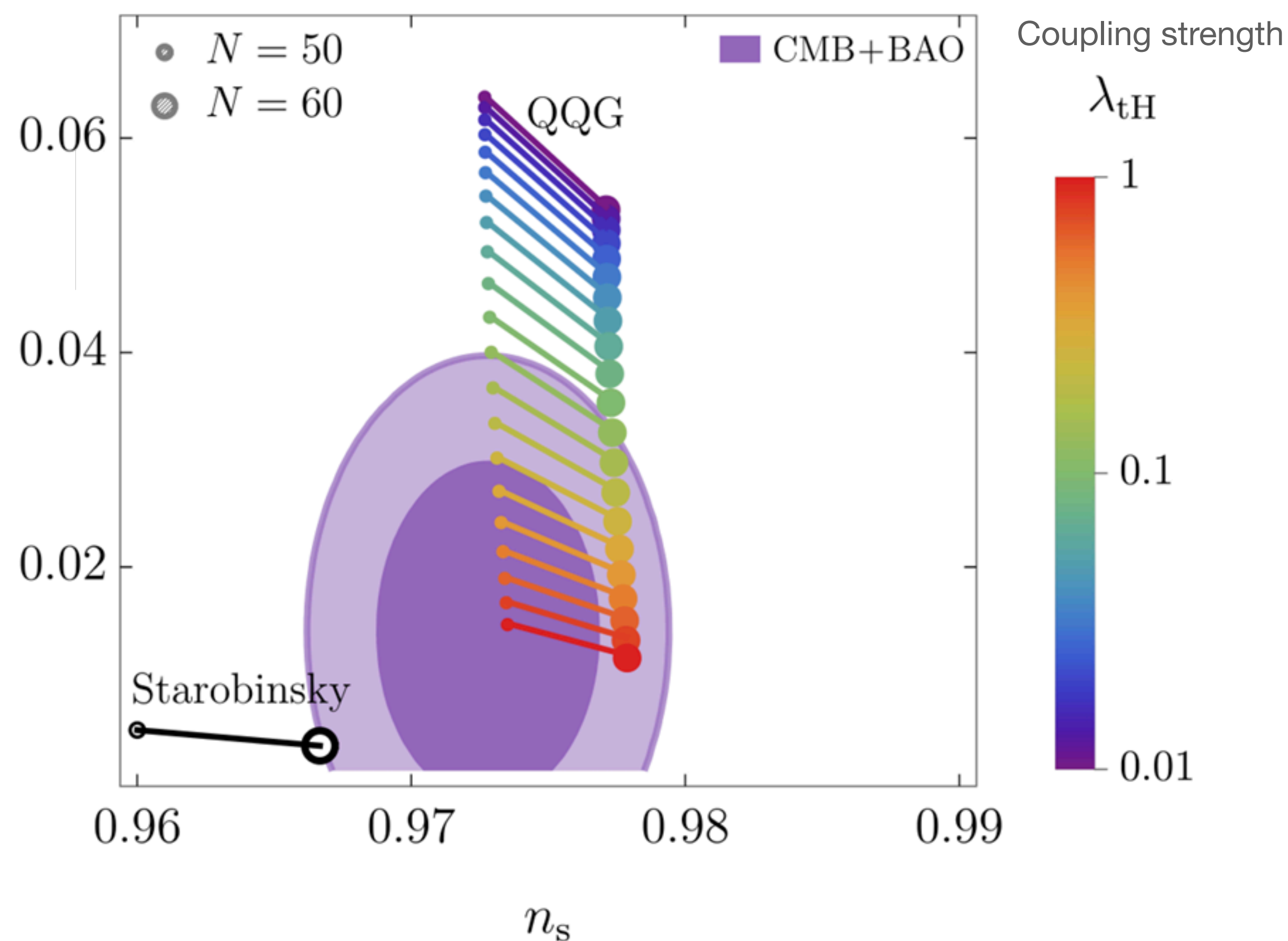
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# CMB+BAO constraints

$$\xi(\mu) \simeq \frac{35\lambda_0^2 \ln(\mu/\mu_0)}{8\pi^2[1 + \lambda_{\text{tH}} \ln(\mu/\mu_0)]},$$

$$n_s \sim 1 - \frac{4}{3N}, \quad r \sim \frac{8}{3} \left( \frac{2}{\lambda_{\text{tH}}^2 N^4} \right)^{1/3}.$$

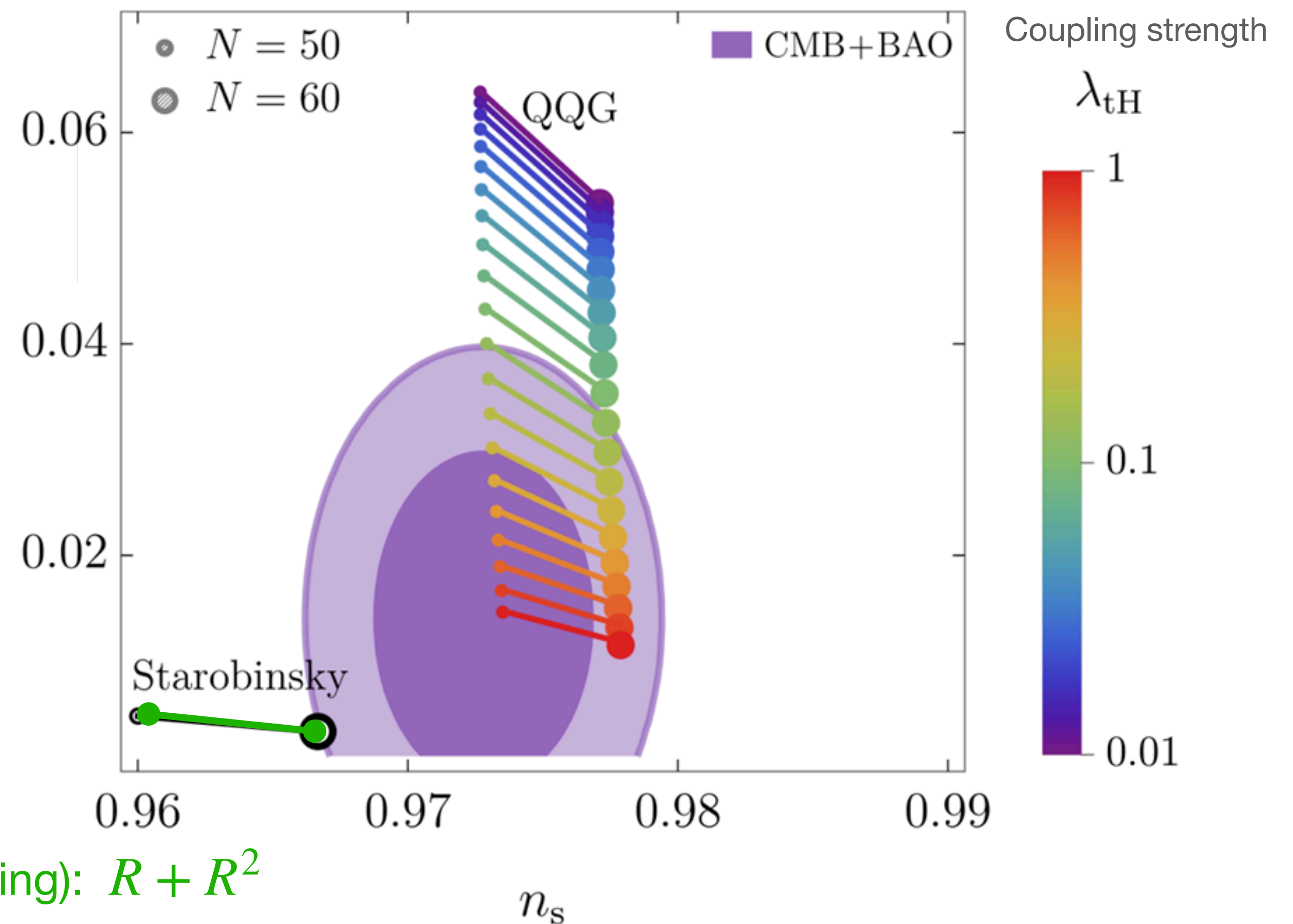




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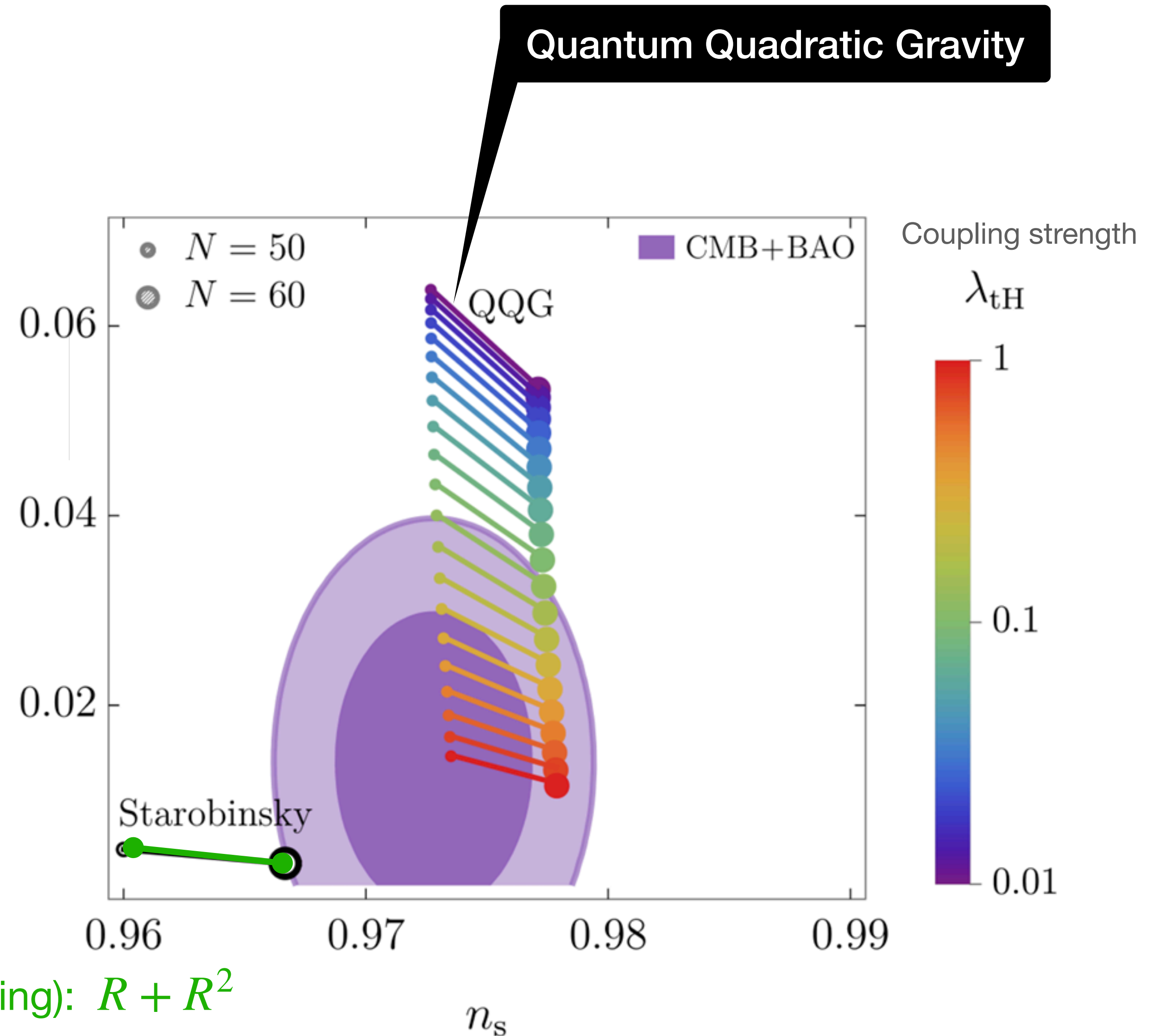




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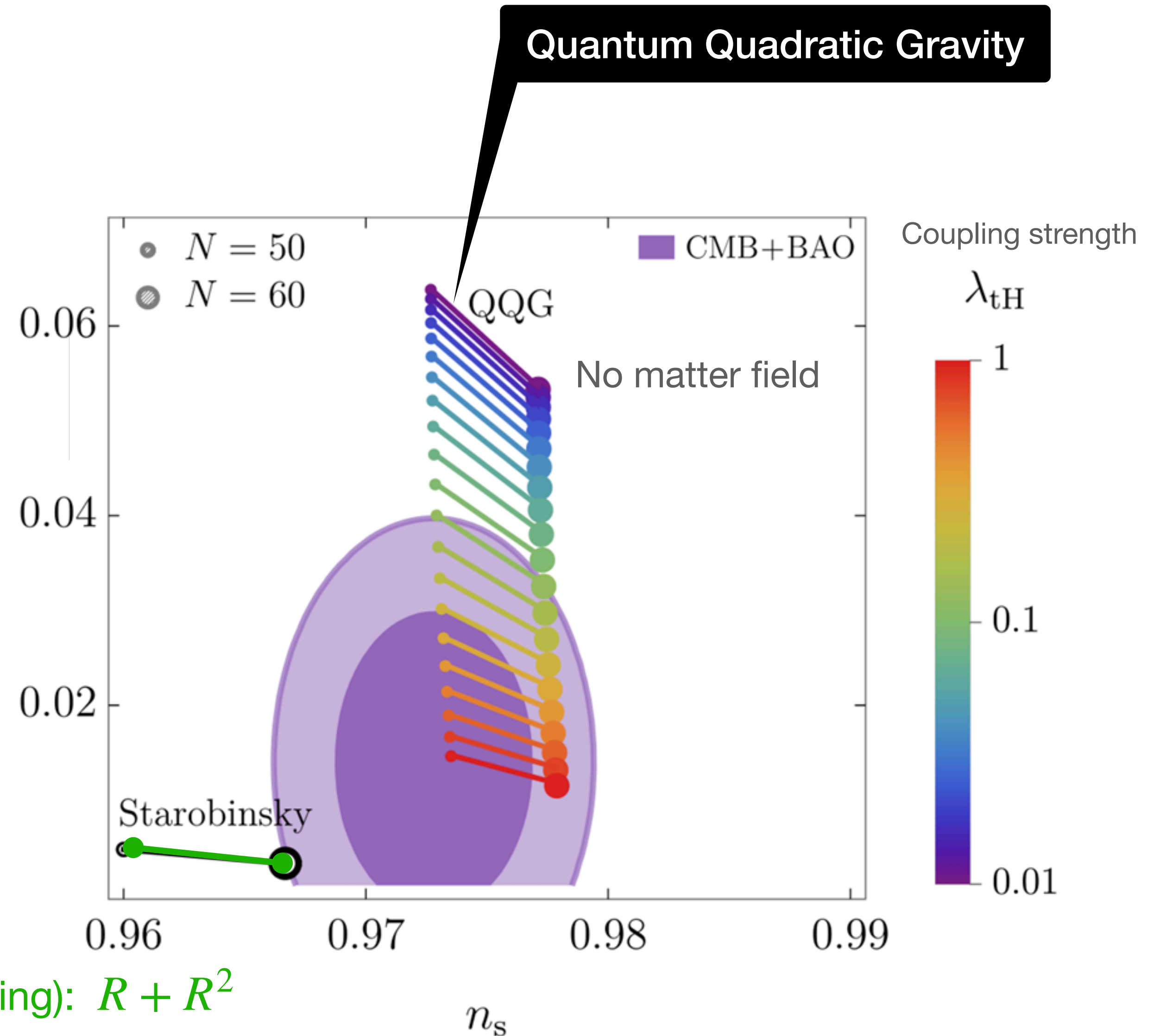
Starobinsky (no running):  $R + R^2$



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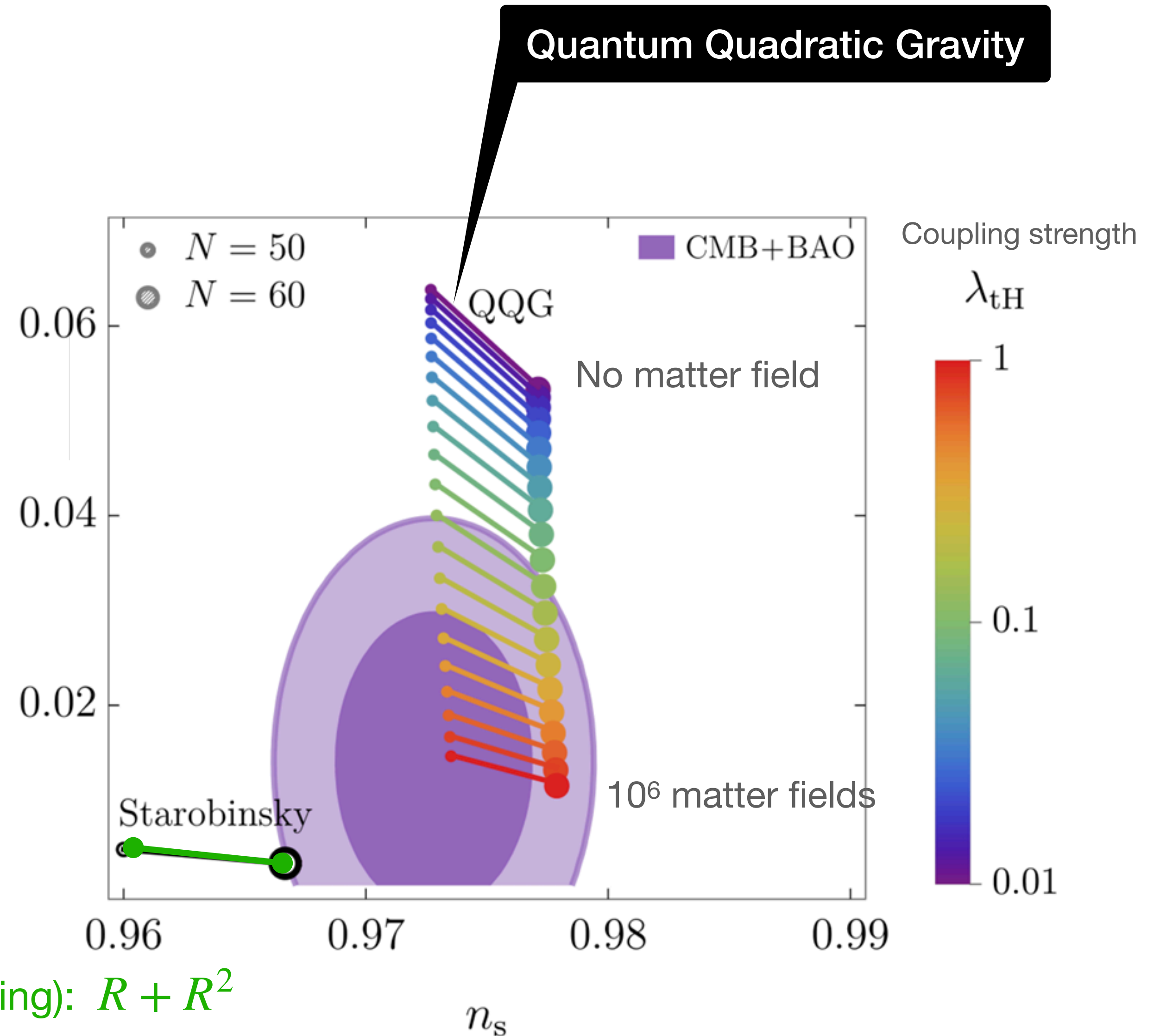




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# Horizons vs Firewalls!

- 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!

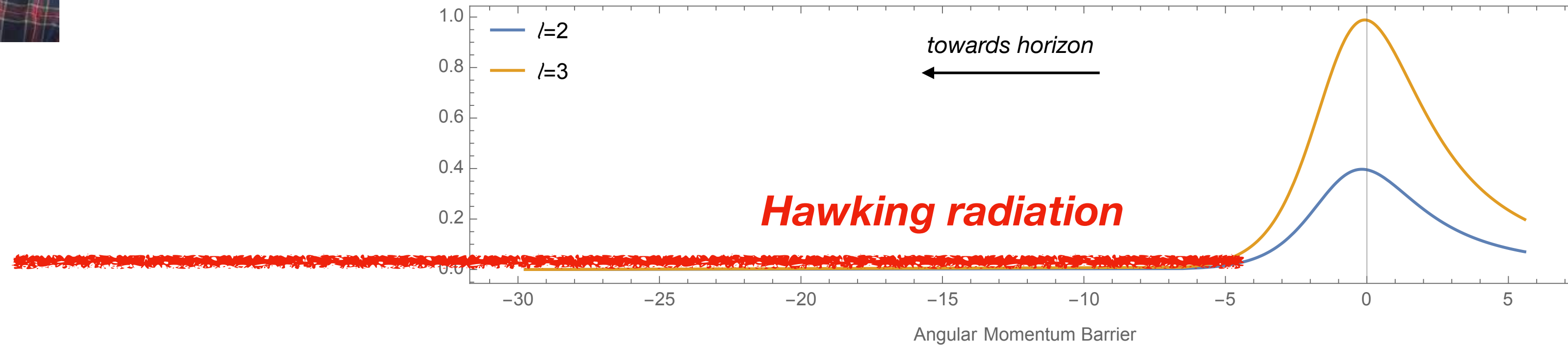


# Finite Entropy of Hawking radiation

➡ **Echoes** (*Oshita & NA 2023*)



- Infinite Entropy & No Echoes:  $t_{\text{echo}} \rightarrow \infty$ !



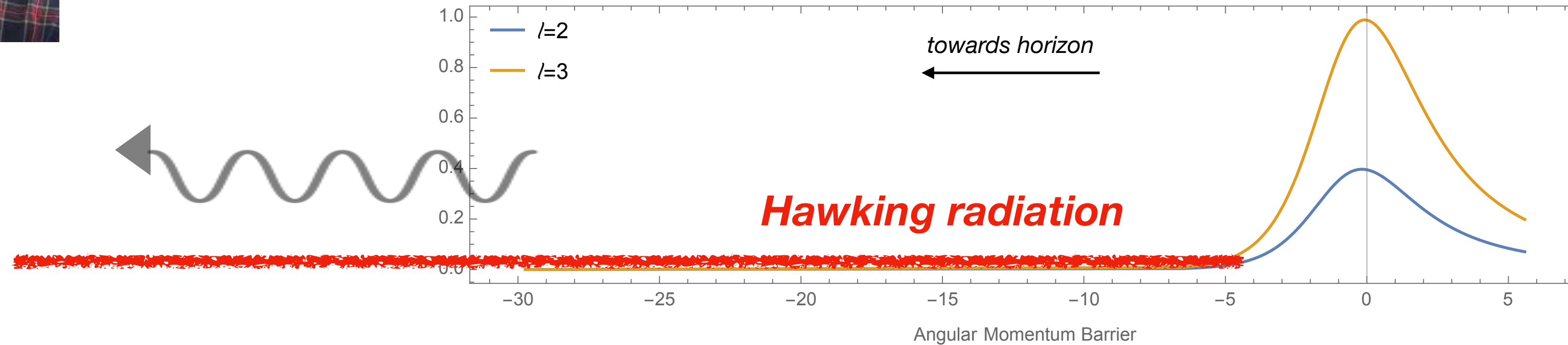


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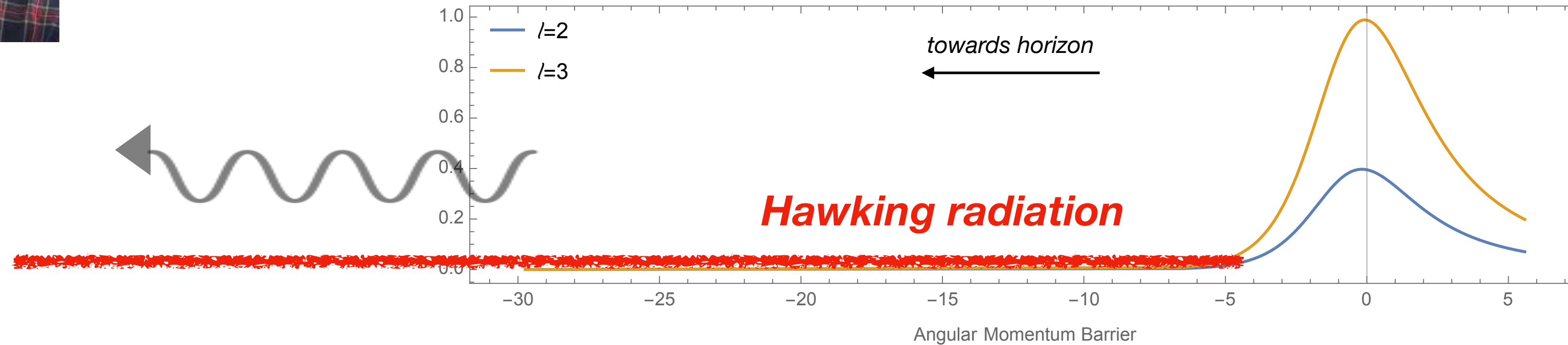


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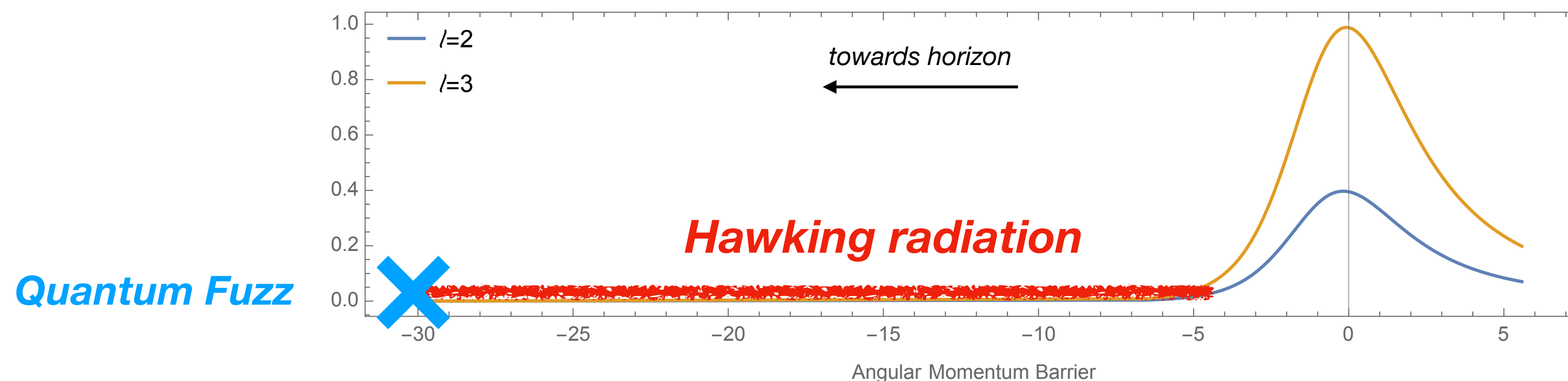
## ➡ Echoes *(Oshita & NA 2023)*



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



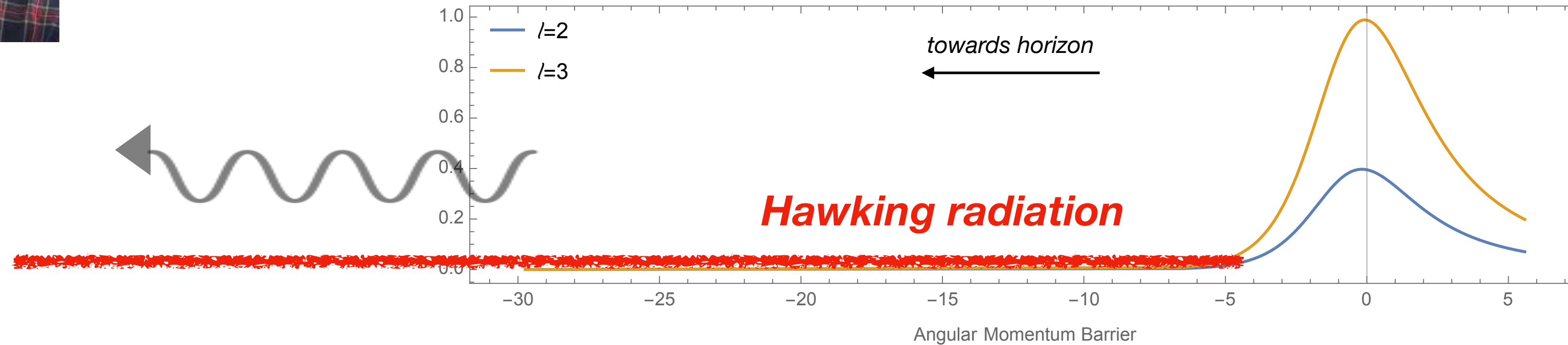


# Finite Entropy of Hawking radiation

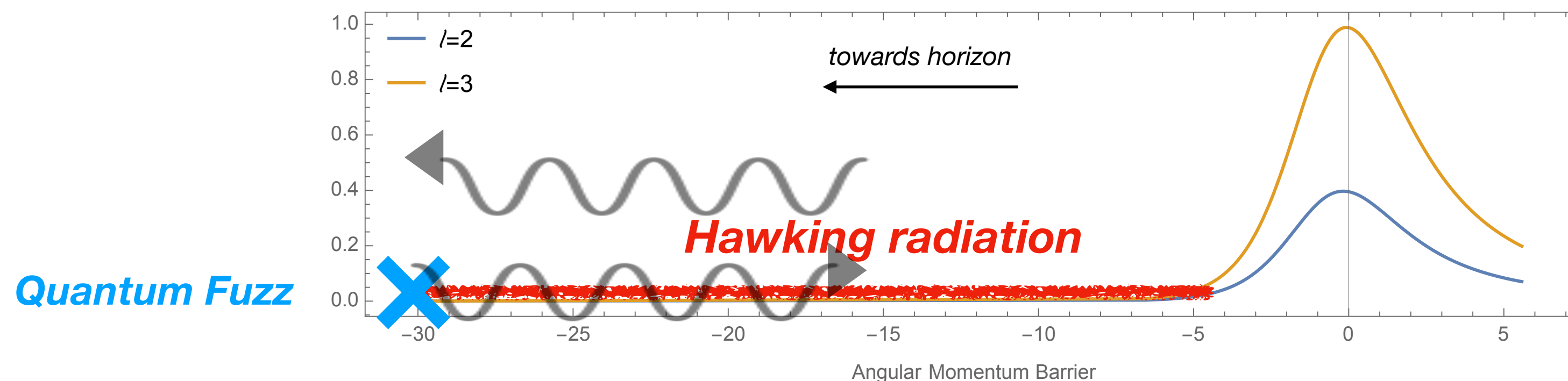
## ➡ Echoes *(Oshita & NA 2023)*



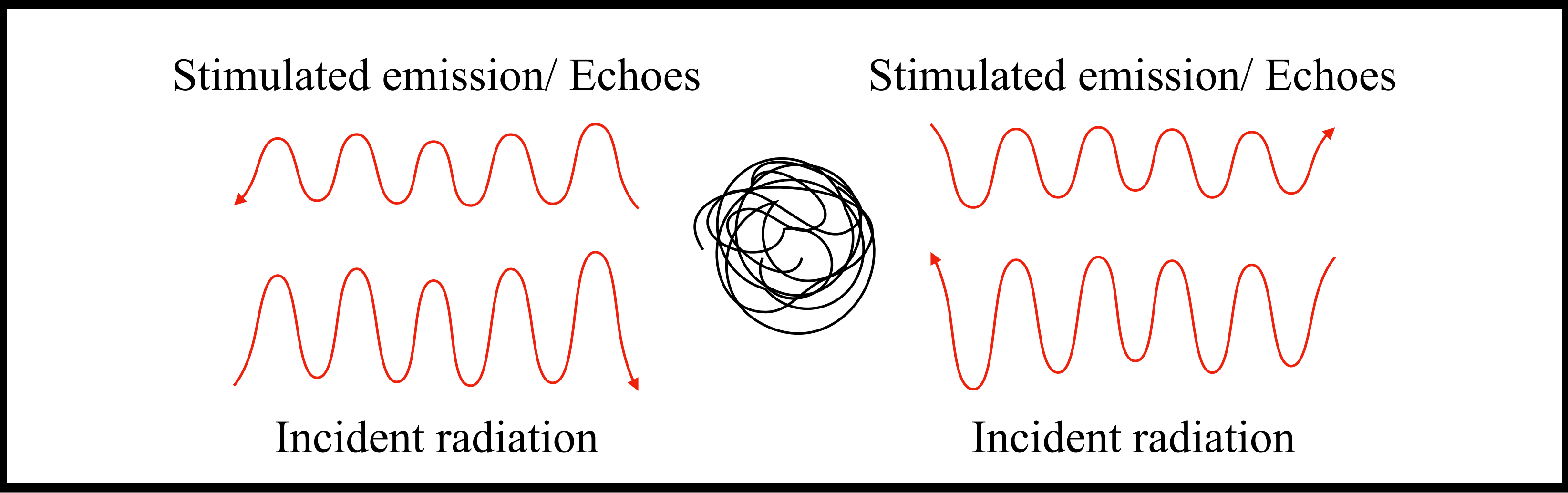
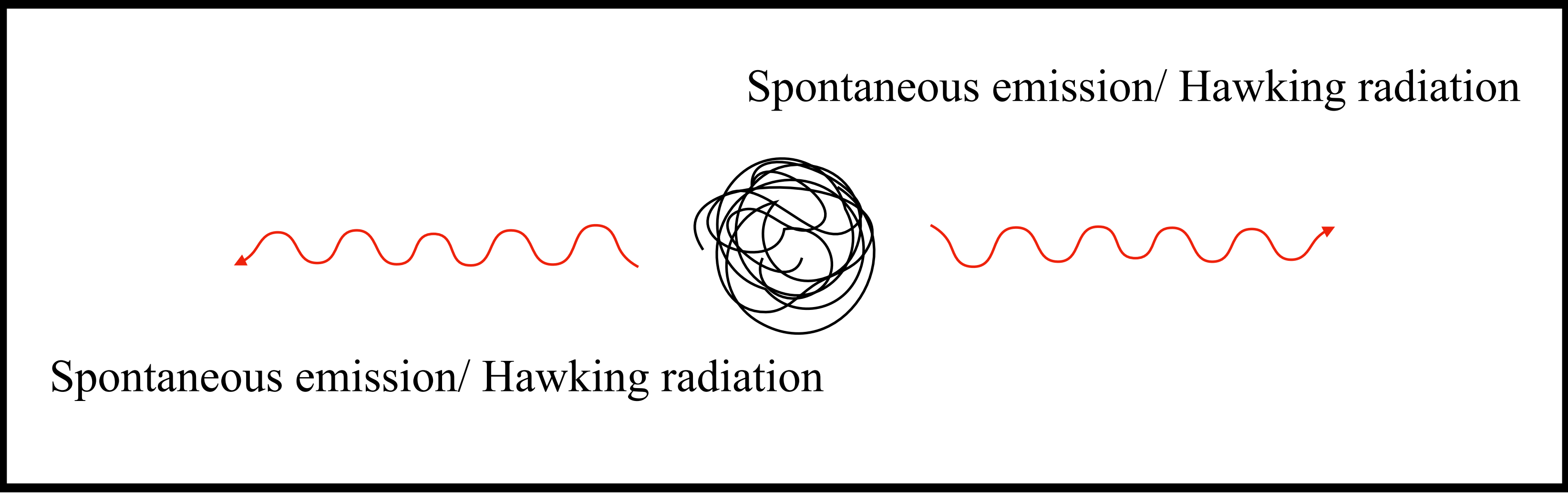
- Infinite Entropy & No Echoes:  $t_{\text{echo}} \rightarrow \infty$ !



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







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

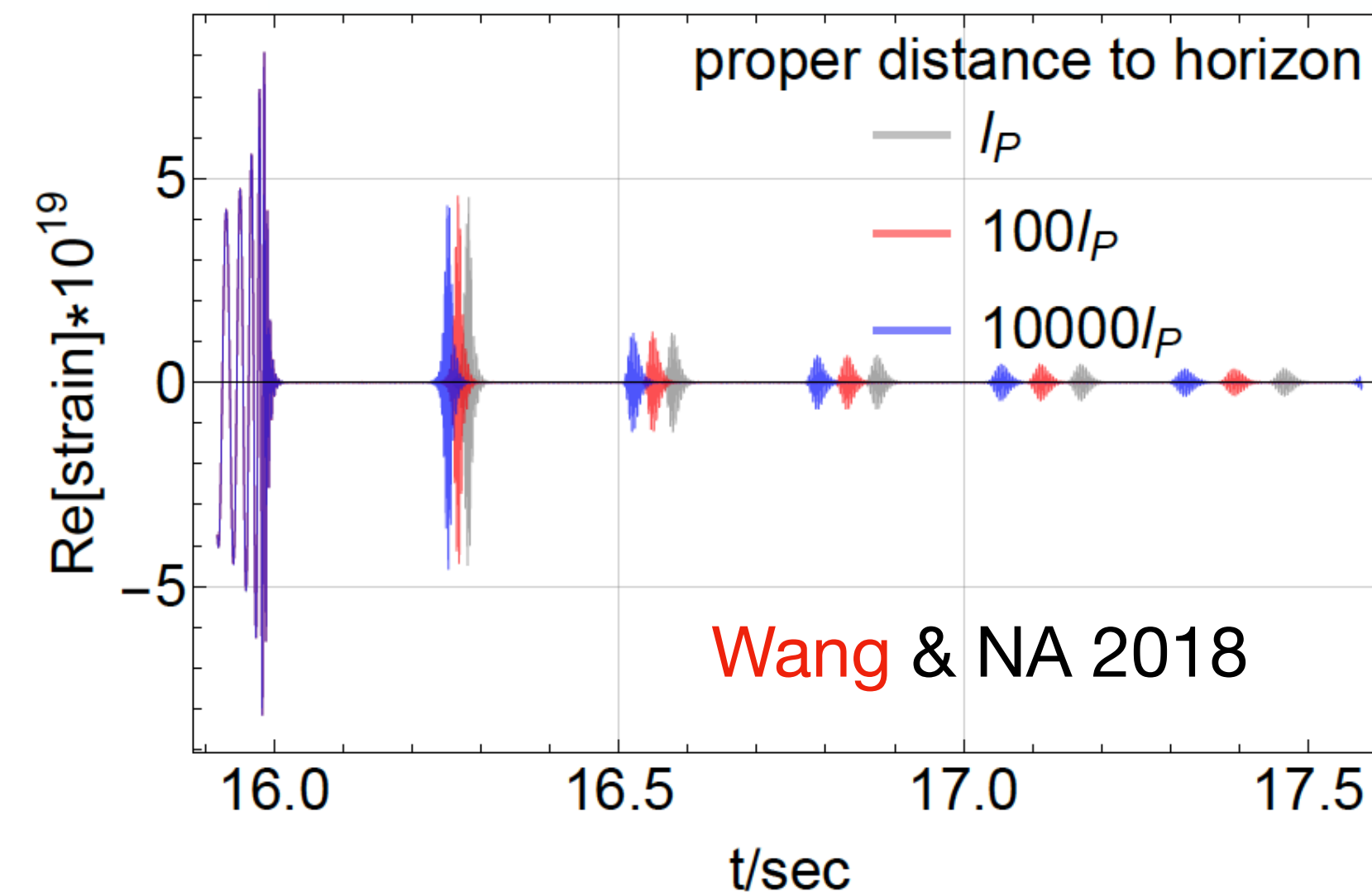
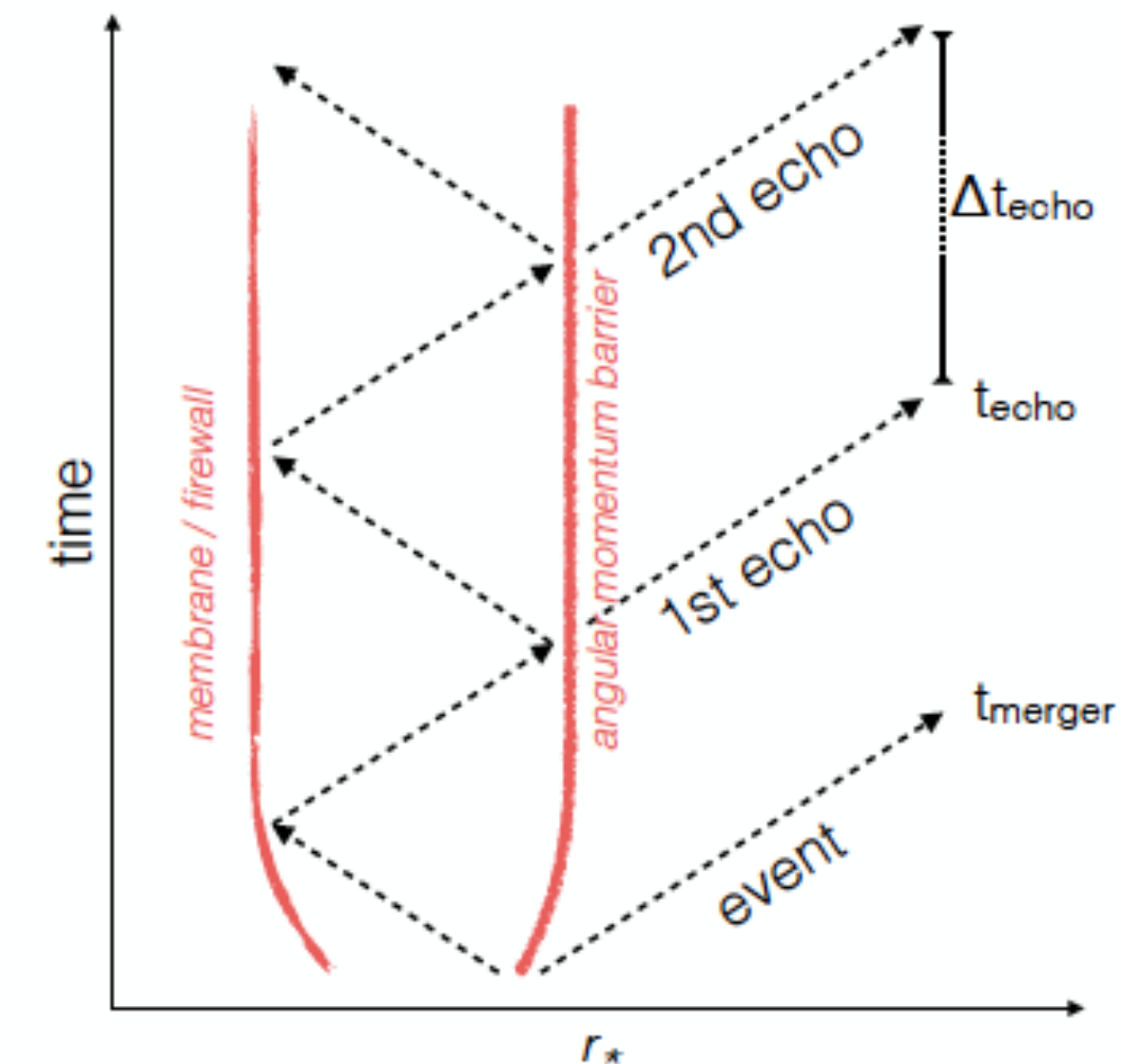


# From Planck to LIGO!

- Quantum effects within a Planck length of horizon
- “Echoes” in LIGO observations  
(Cardoso, Franzin & Pani 16)

$$\Delta t_{\text{echo}} \simeq \frac{4GM_{\text{BH}}}{c^3} \left( 1 + \frac{1}{\sqrt{1-a^2}} \right) \times \ln \left( \frac{GM_{\text{BH}}}{c^2 \ell_{\text{QG}}} \right)$$

- *Stimulated Hawking Radiation*  
(Oshita, Wang & NA 2020)





# 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

$$\tau = \frac{t_*}{\beta} = C \log N$$



# *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  $\log(\text{Radius})/(\pi \times \text{Temperature})$ . We further comment on the physical interpretation of this coincidence and the corresponding holographic interpretation of black hole echoes.





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### ABSTRACT

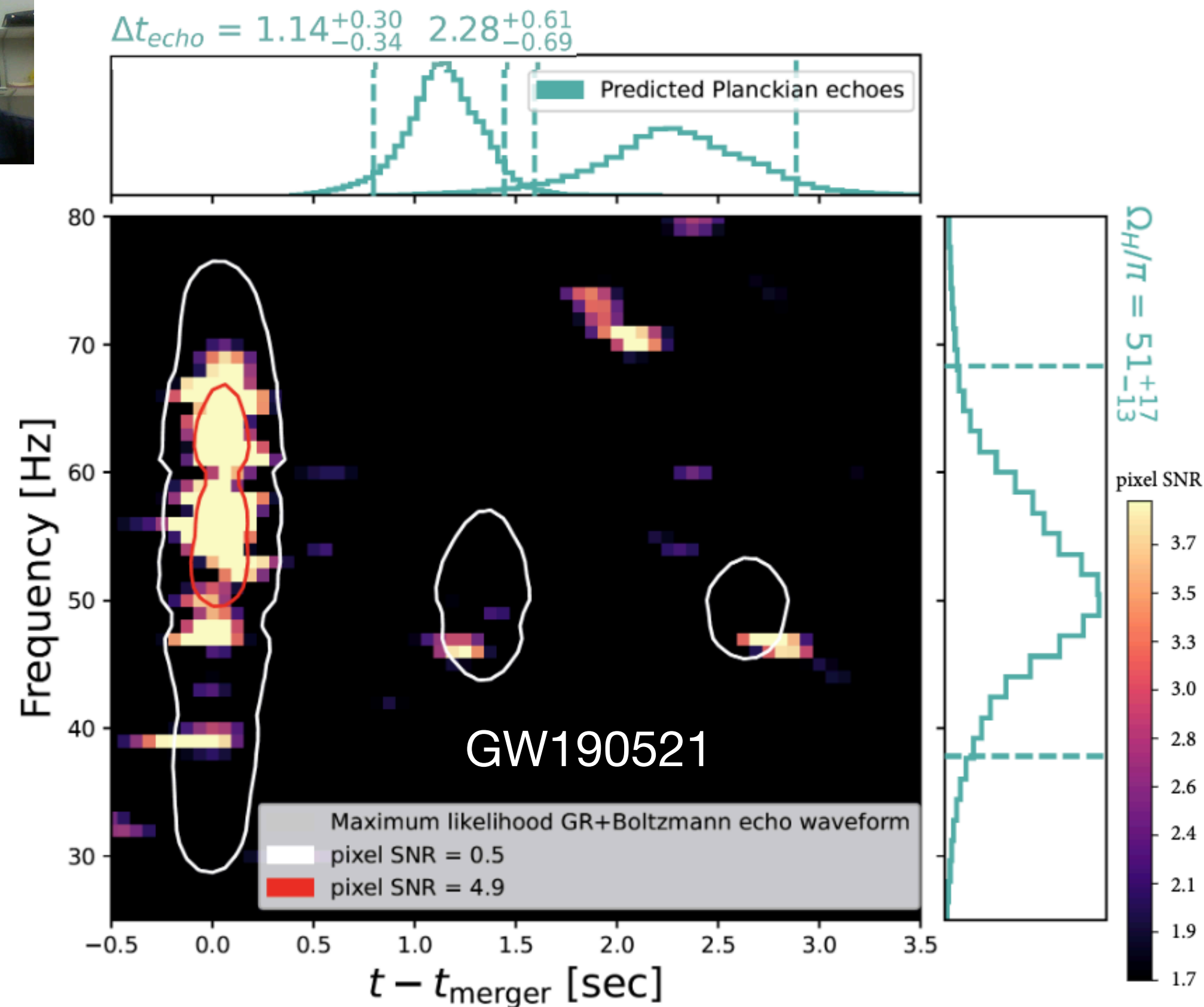
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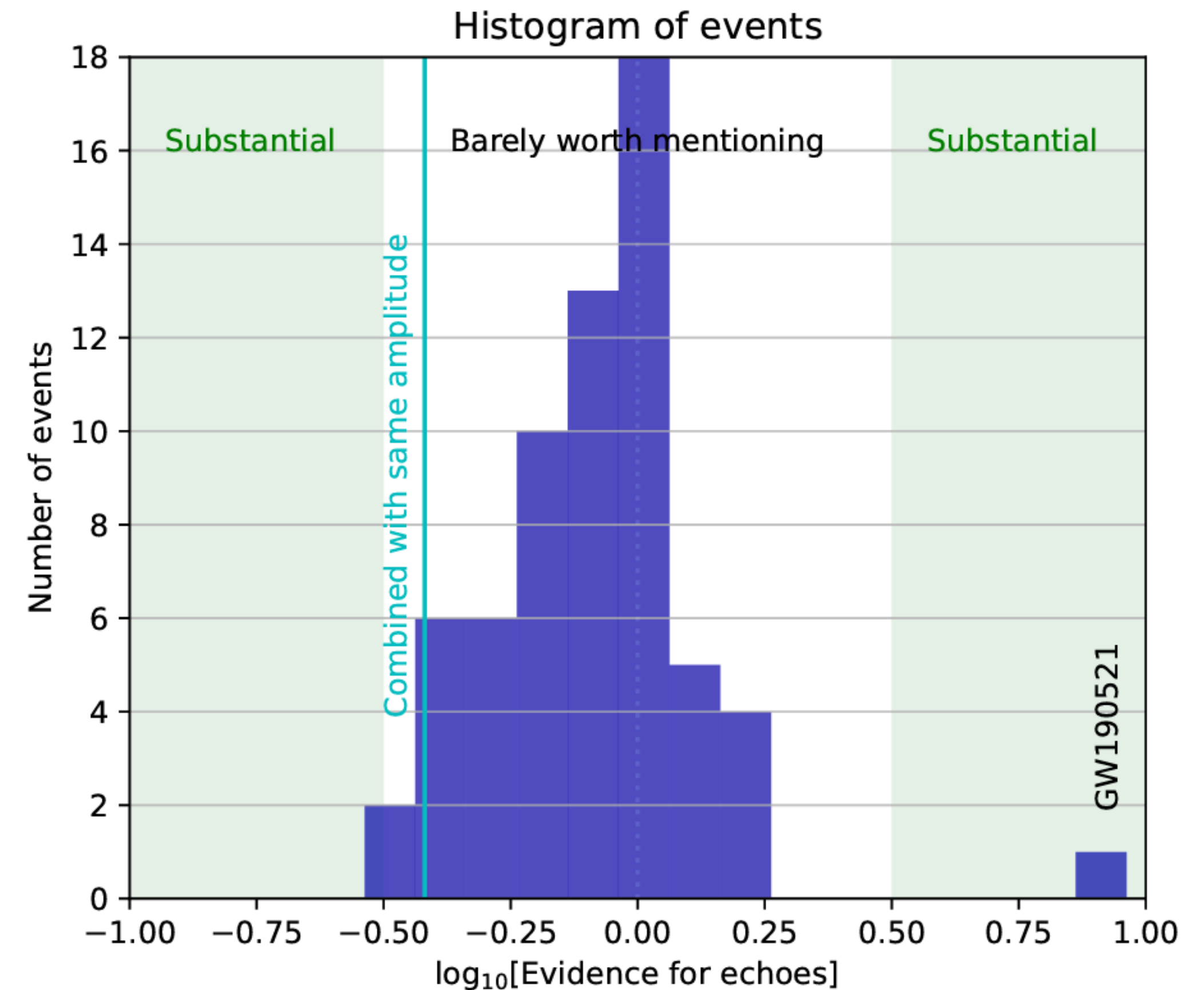


# Are there echoes in LIGO data?

- Abedi, Longo & NA 2023



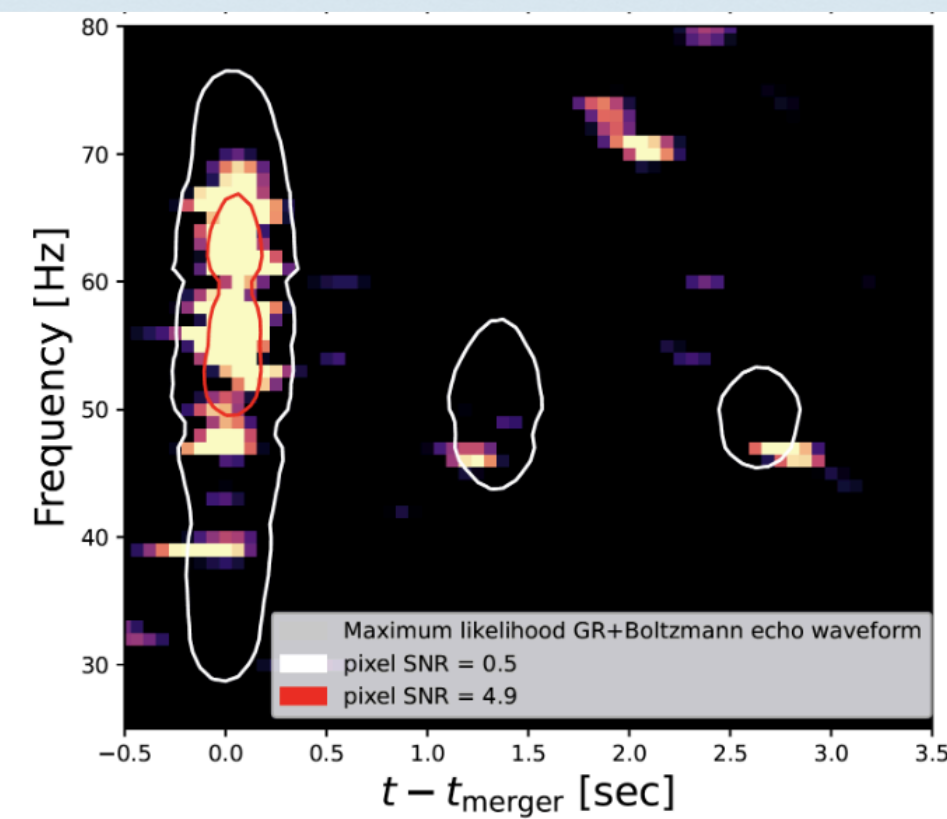
Abedi 2025





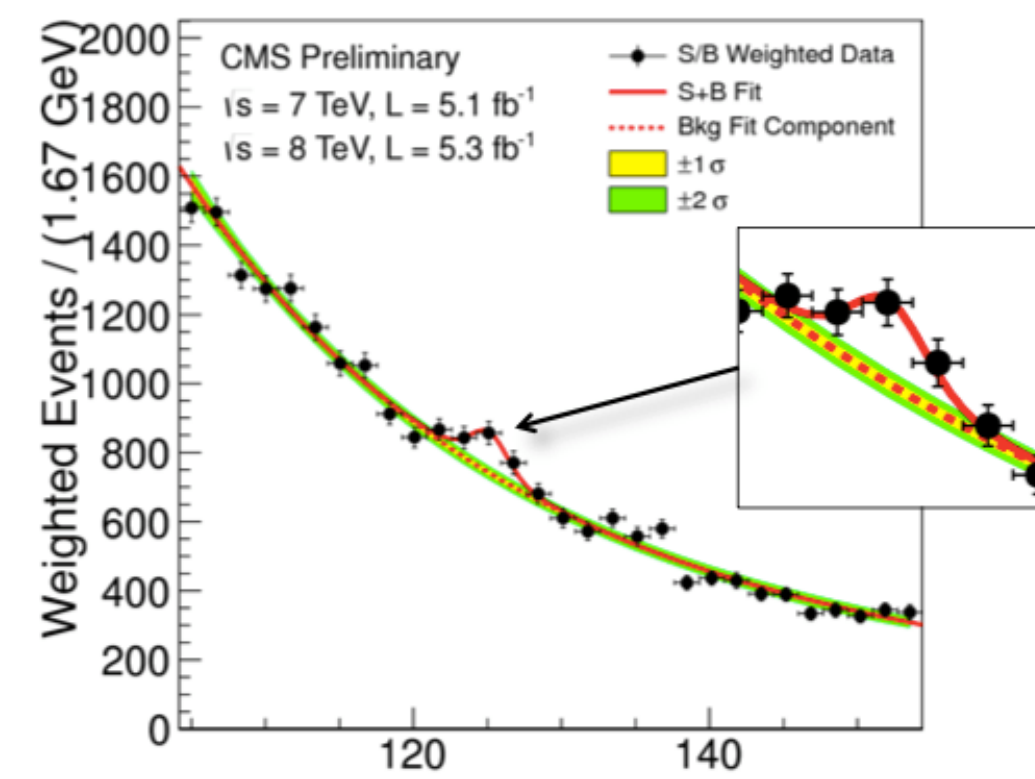
# Echoes to *LIGO*

- Unitarity
- (Perturbative) Effective Field Theory
- Holographic Entropy ↔  
Diffeomorphism sym.



# Higgs to *LHC*

- Unitarity
- (Perturbative) Effective Field Theory
- Gauge Symmetries of Standard Model





# Future is bright!

- Echoes in “numerical relativity”?
- Hybrid PPN+Teukolsky with matching (Qingwen Wang’s PhD thesis)

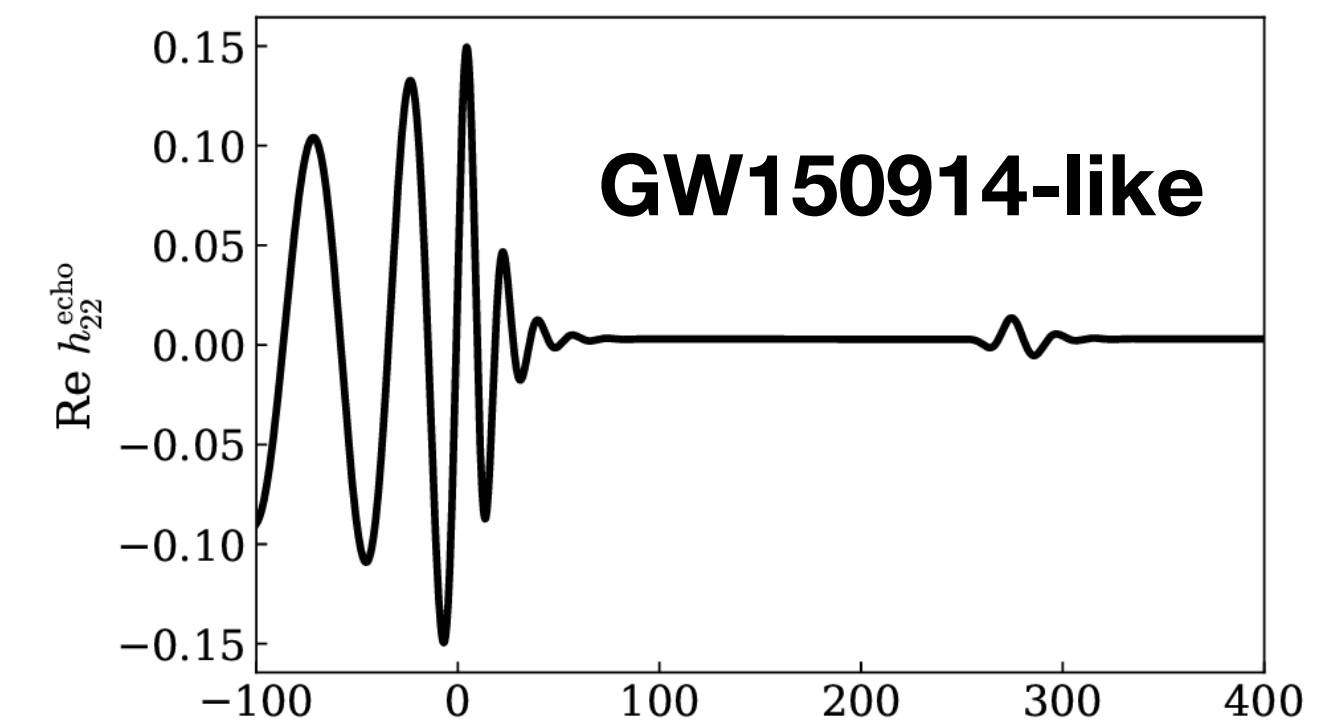
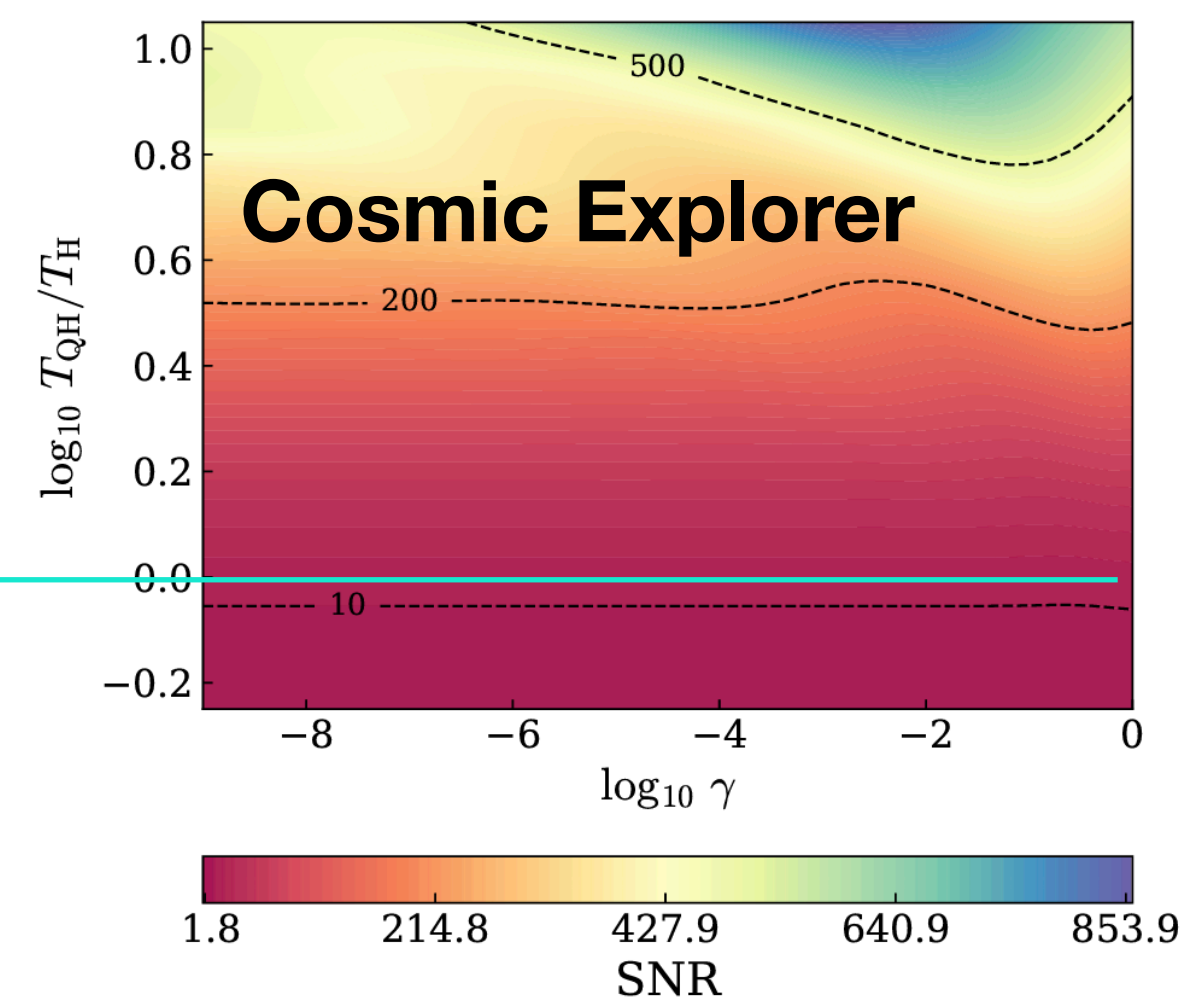
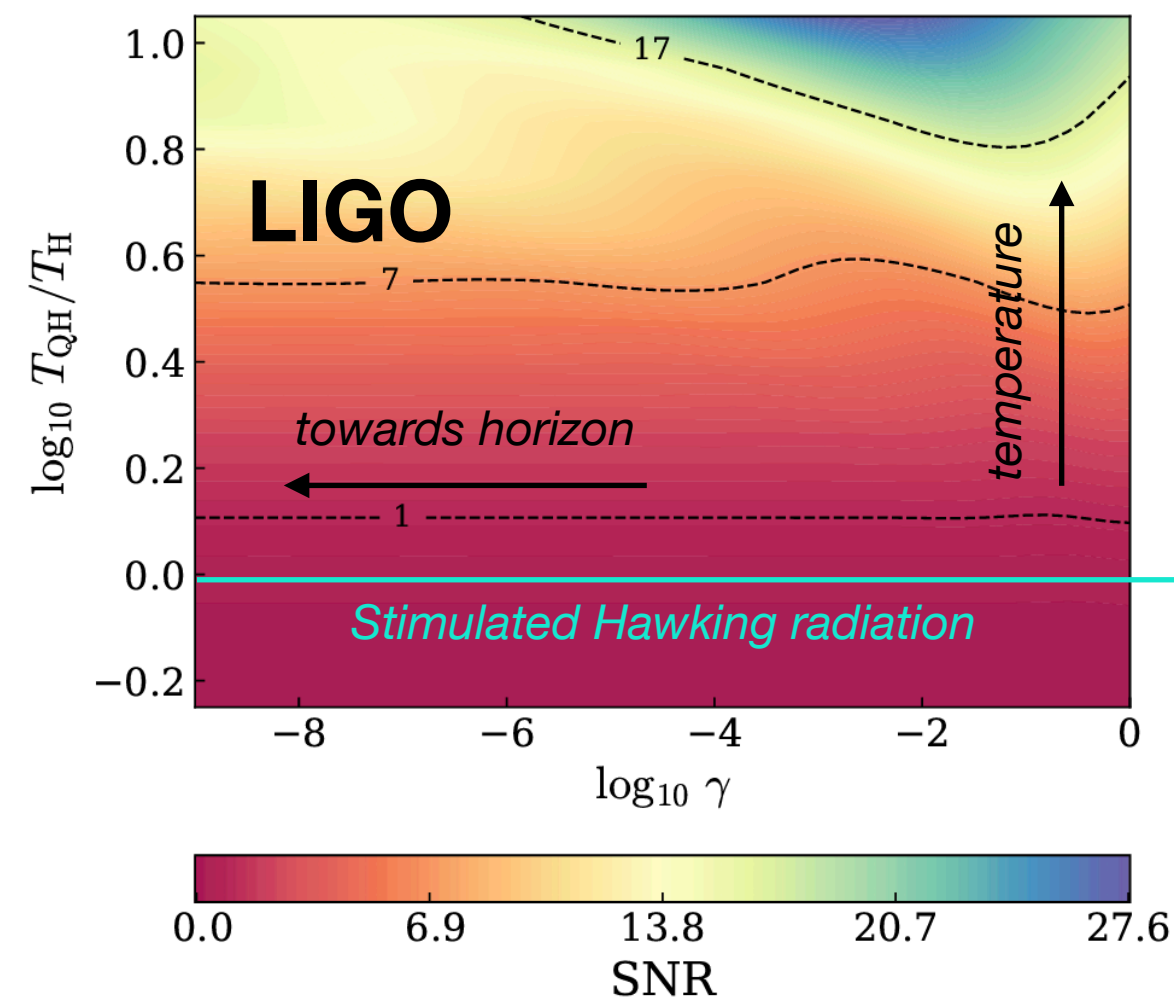
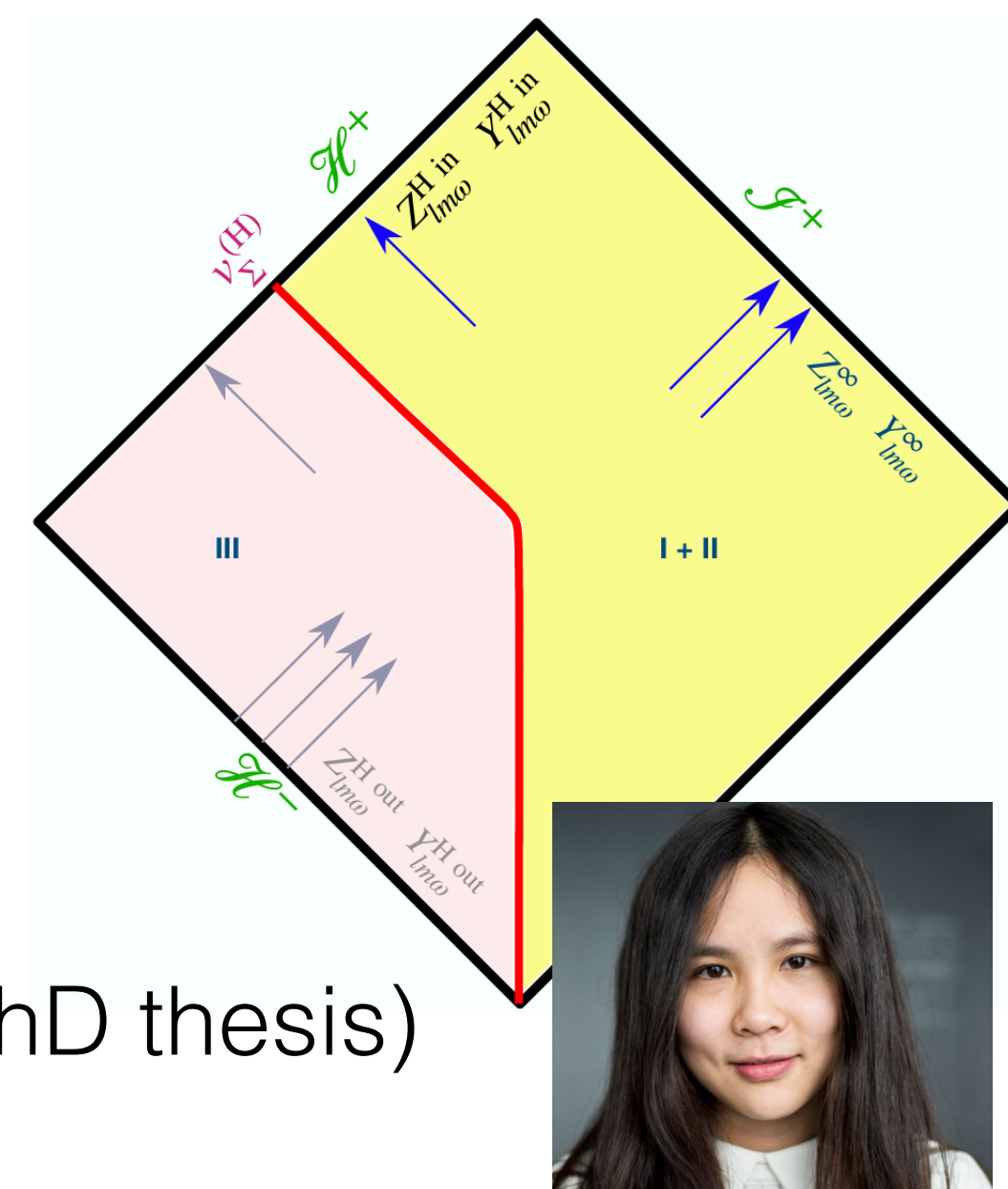


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set  $v_{\Sigma}^{(H)} = -13$ ,  $\Delta v = 2/\kappa = 8$ ,  $\gamma = 10^{-15}$ , and  $T_{QH} = T_H$ .

arXiv > gr-qc > arXiv:2203.03174

General Relativity and Quantum Cosmology

[Submitted on 7 Mar 2022]

**Gravitational-wave echoes from numerical-relativity waveforms via space-time construction near merging compact objects**

Sizheng Ma, Qingwen Wang, Nils Deppe, Nils L. Fischer, François Hébert, Lawrence E. Kidder, Jordan Moxon, William Throwe, Mark A. Scheel, Yanbei Chen



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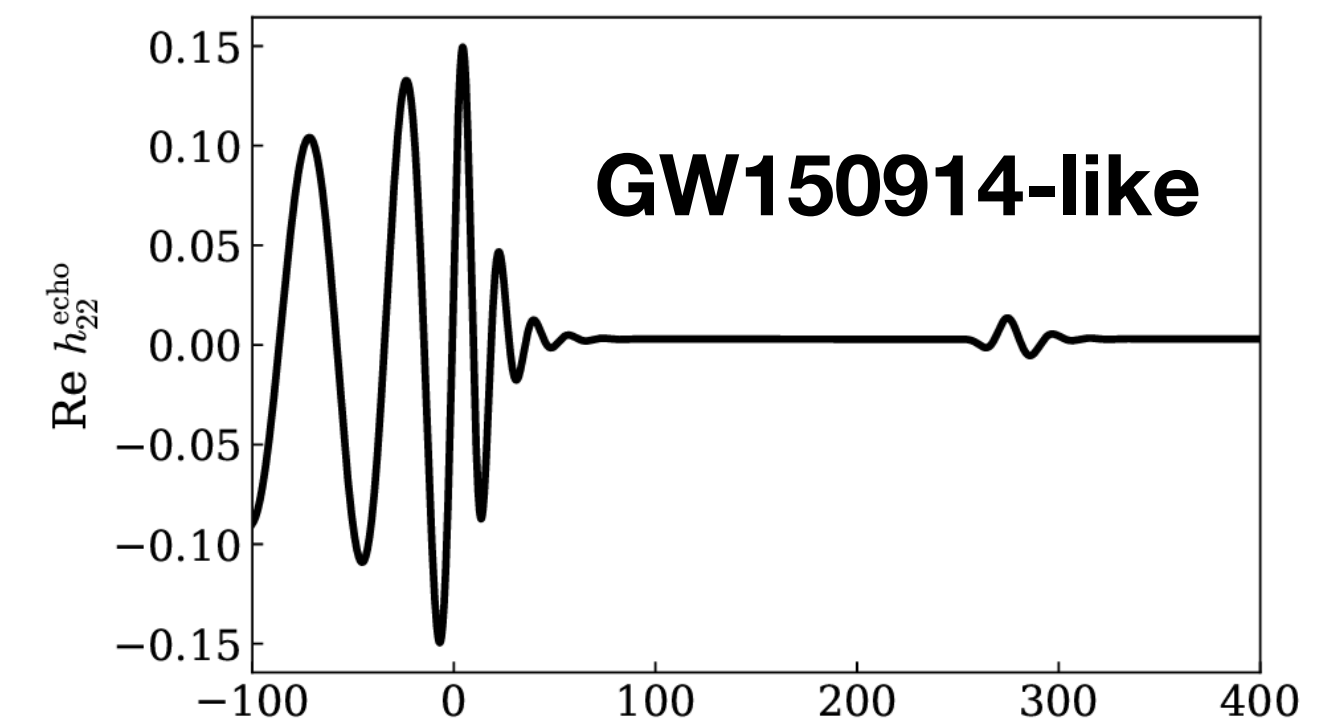
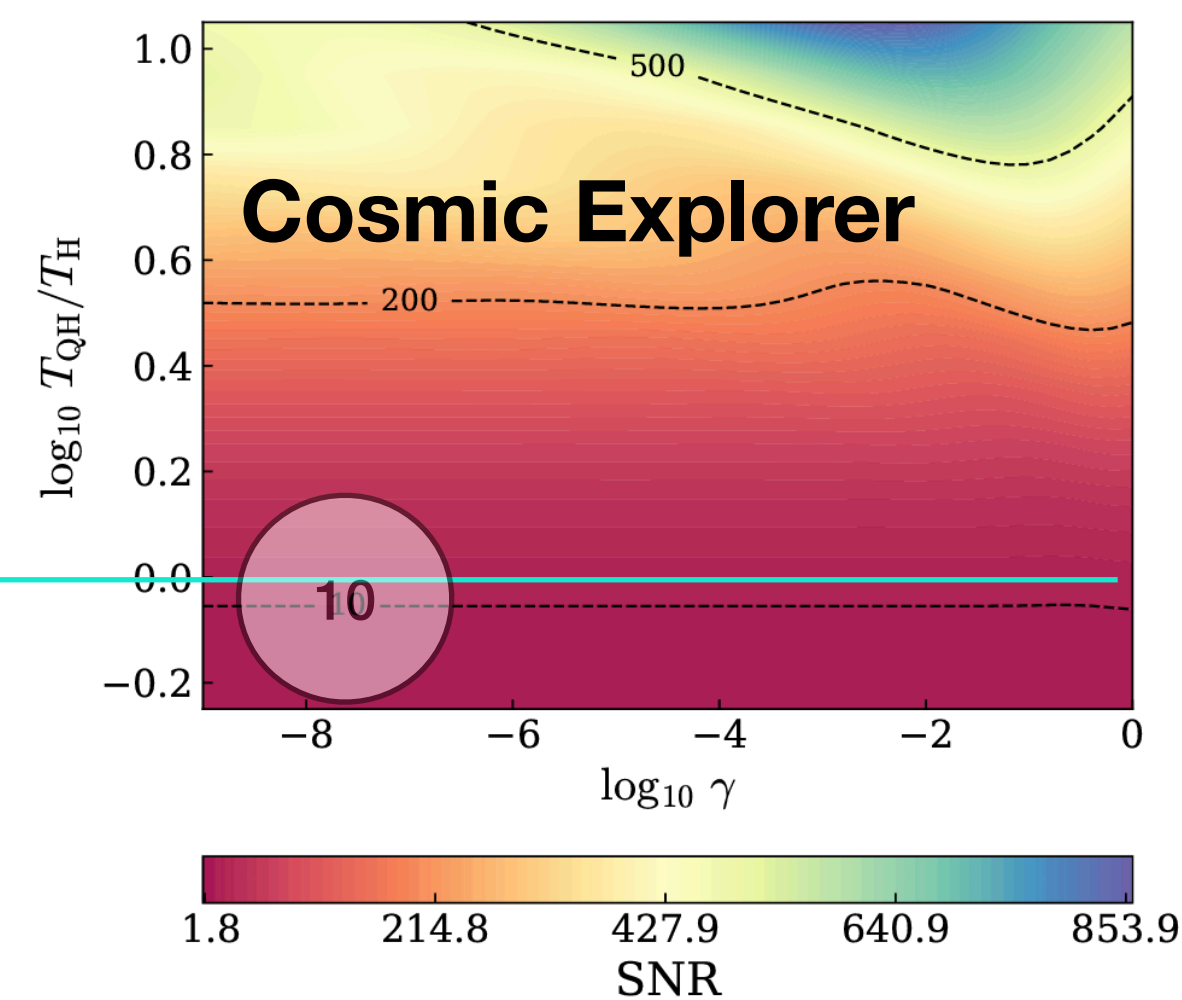
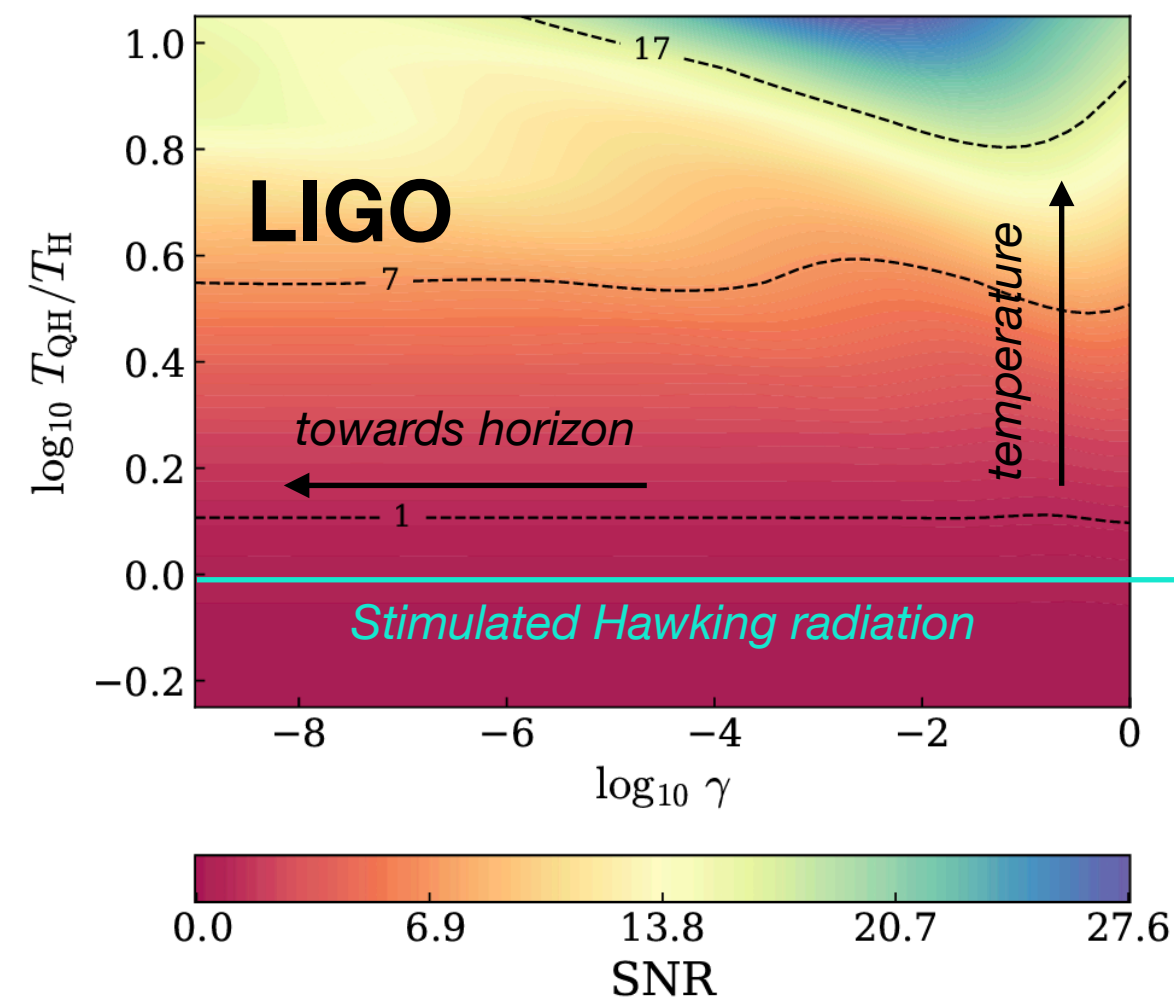
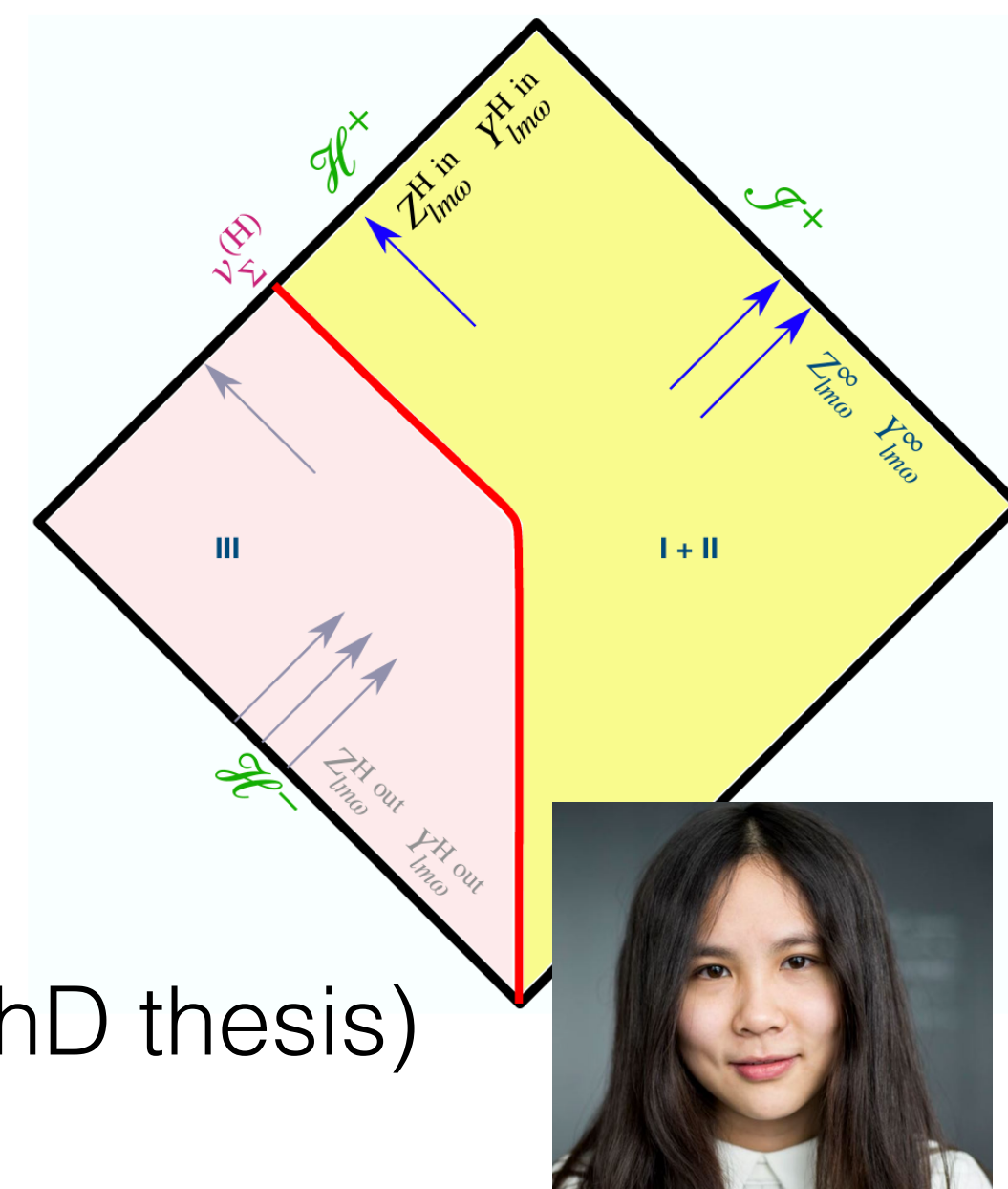


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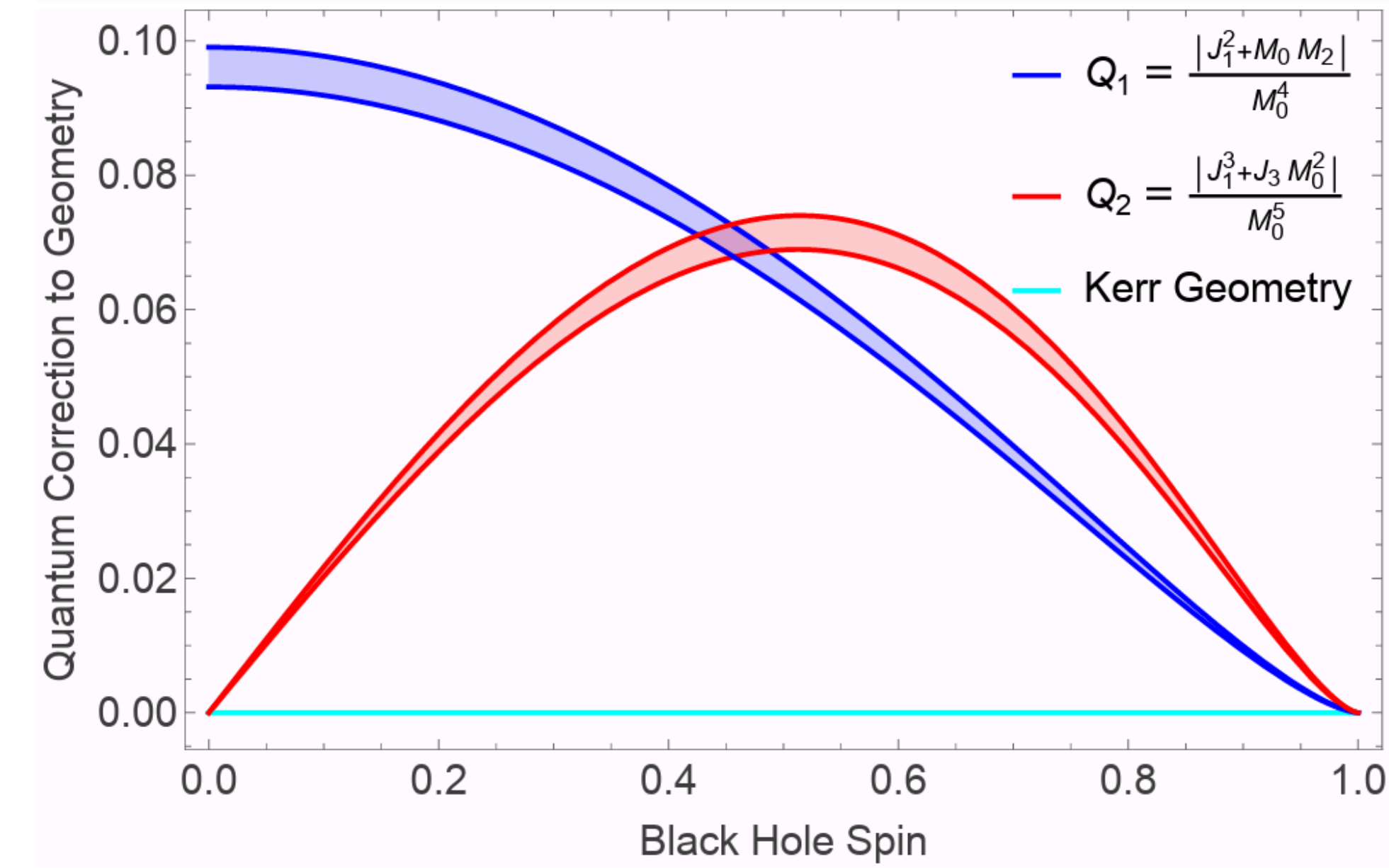
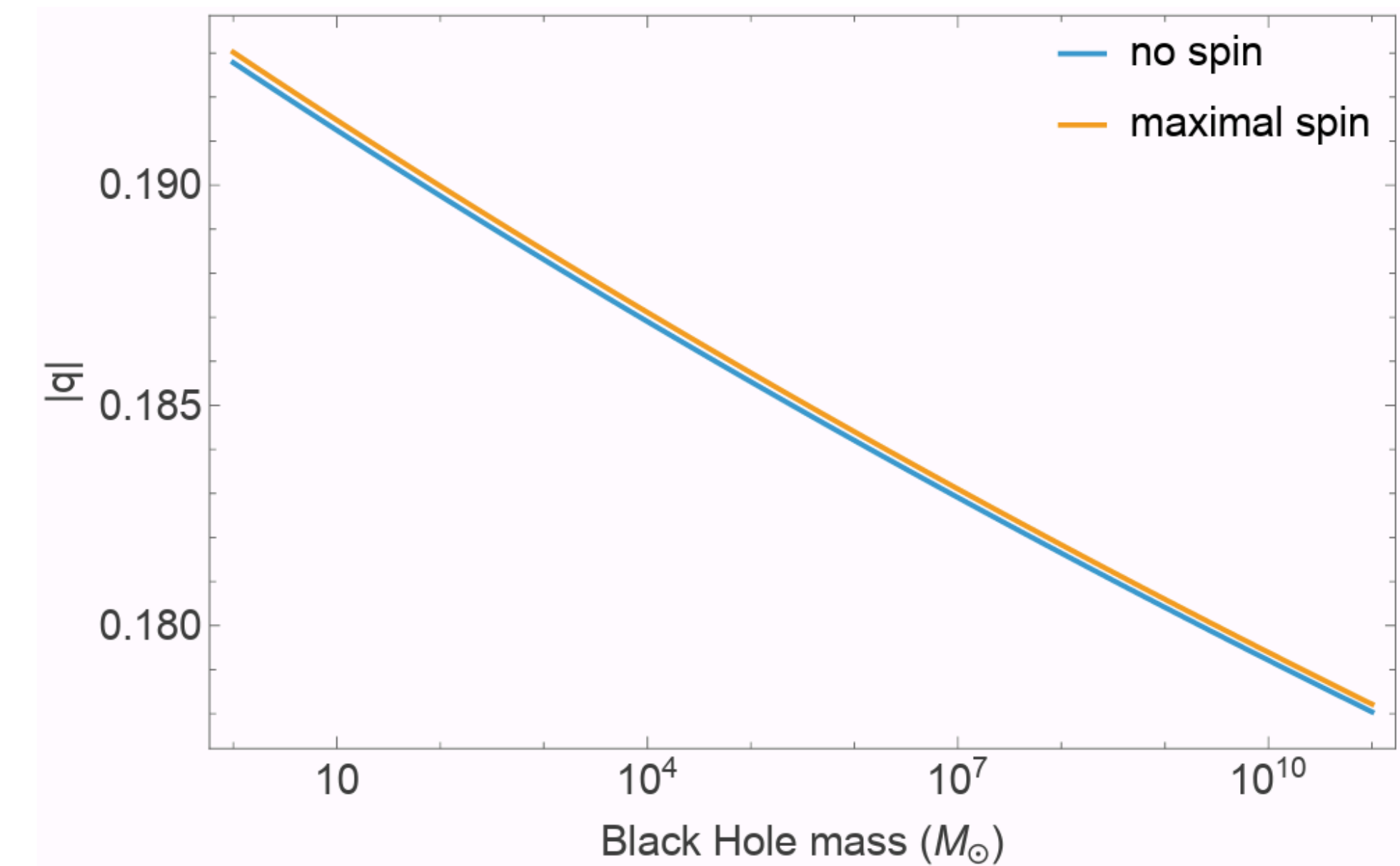


# Quantum Violations of No-Hair Theorem

Faraji & NA 2025

- Quantum effects violate the no-hair theorem  
 ➔ mass and spin multipoles differ from Kerr
- Example: q-metric

$$t_{\text{echo}} \lesssim \frac{\ln S}{2\pi T_H} \Rightarrow q^2 \gtrsim \frac{2}{\ln S}.$$





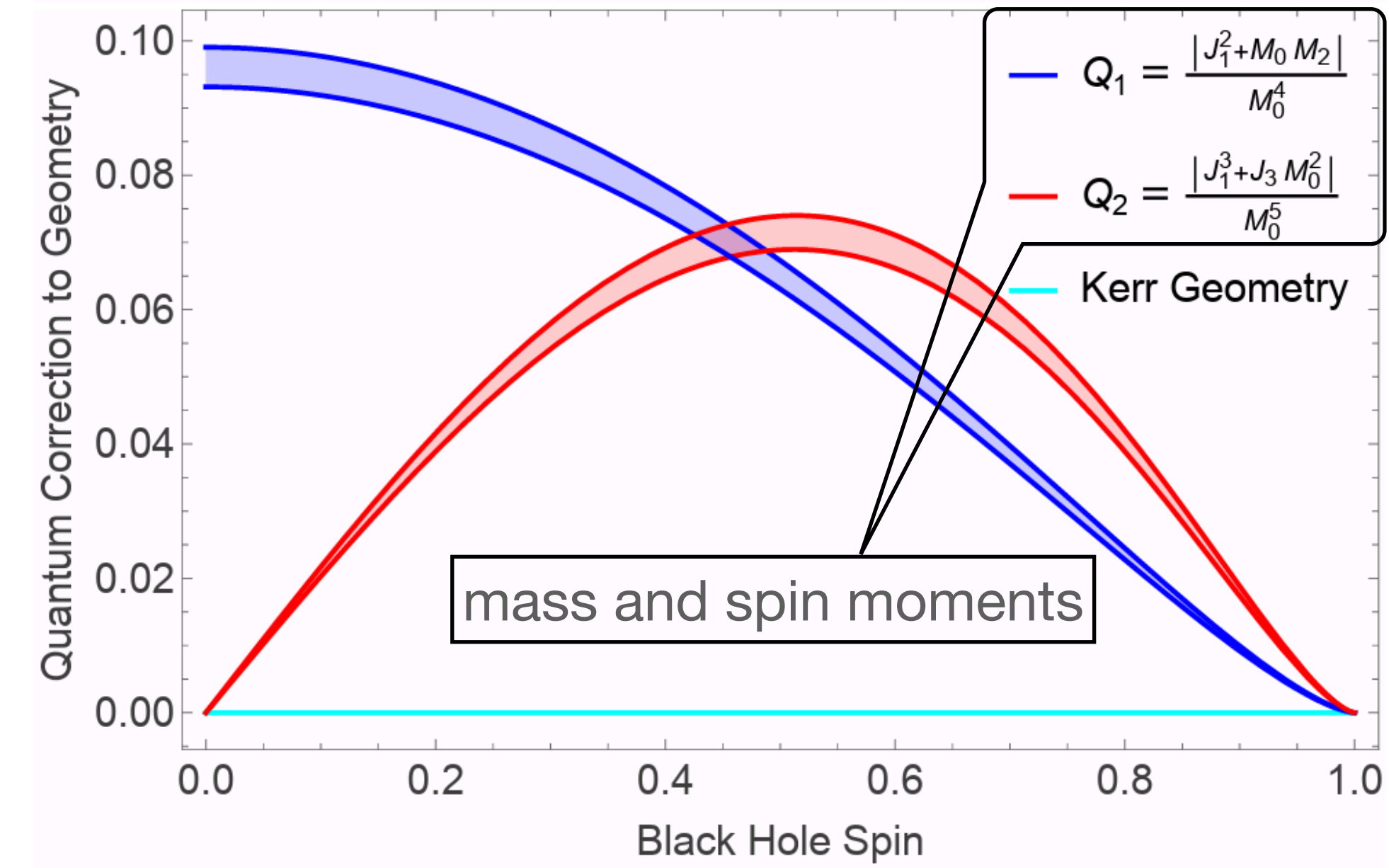
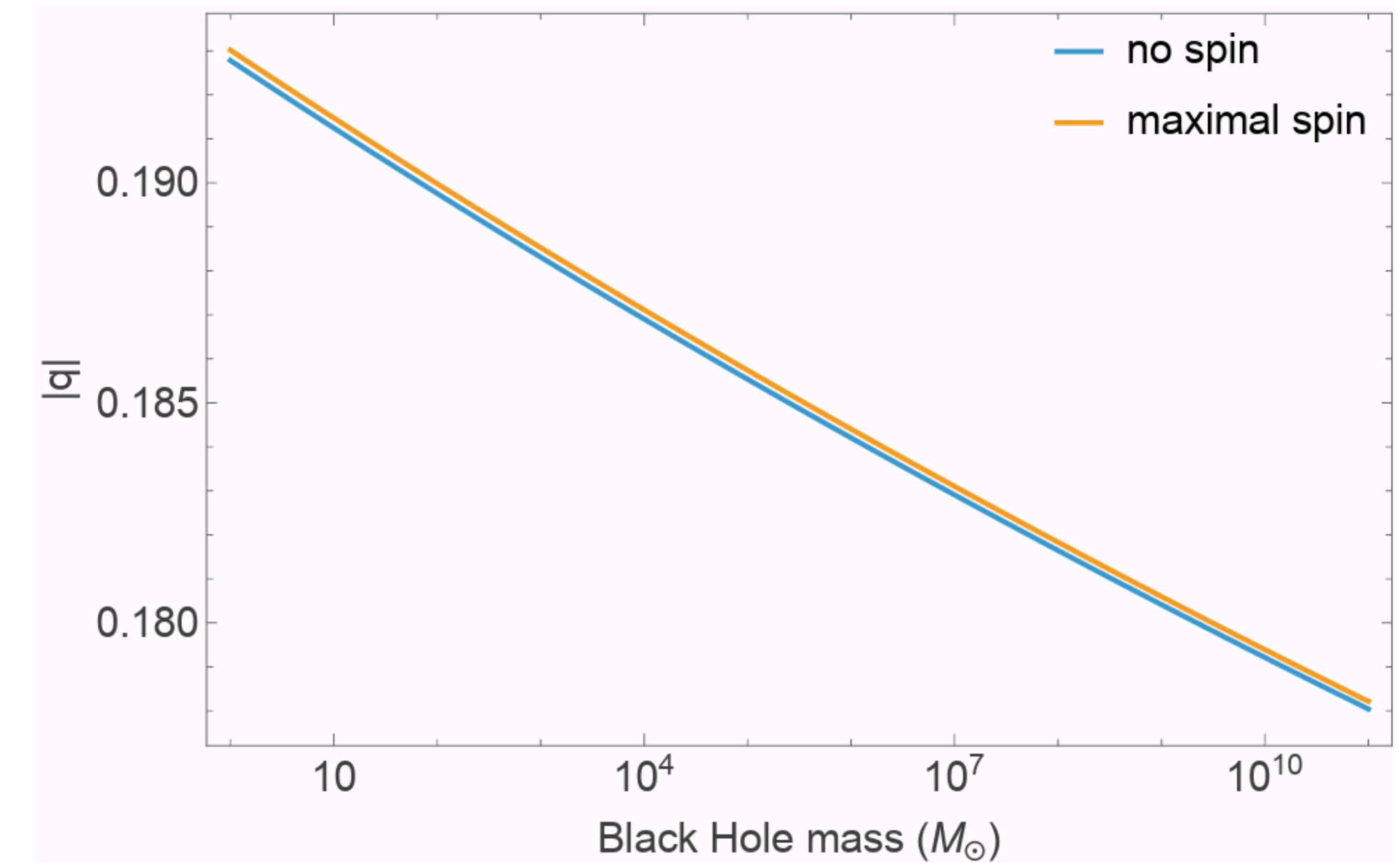
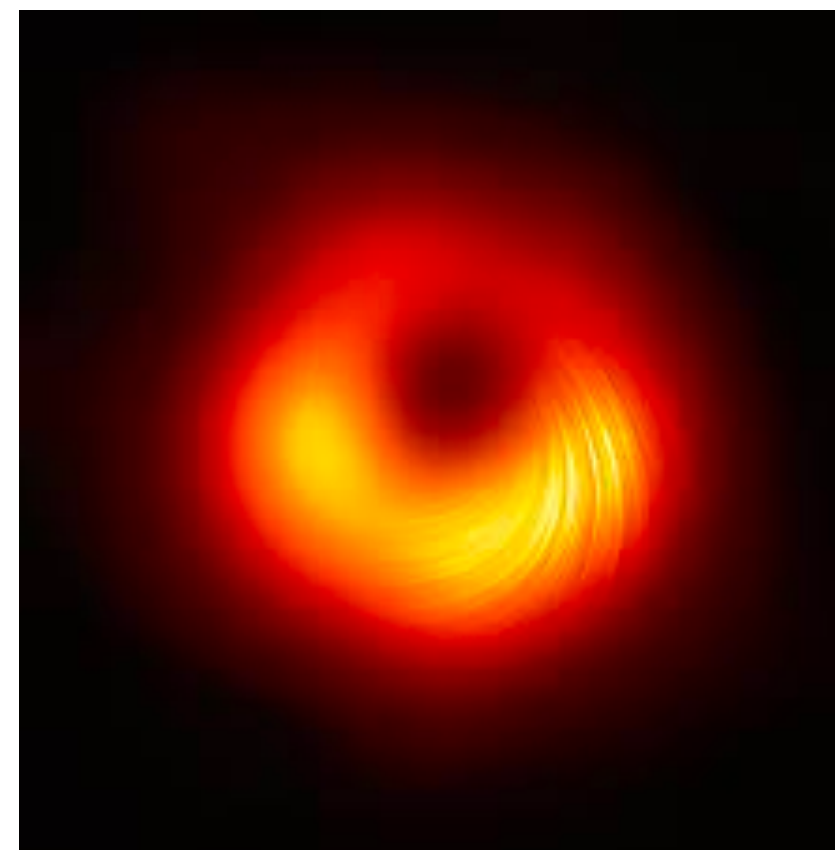


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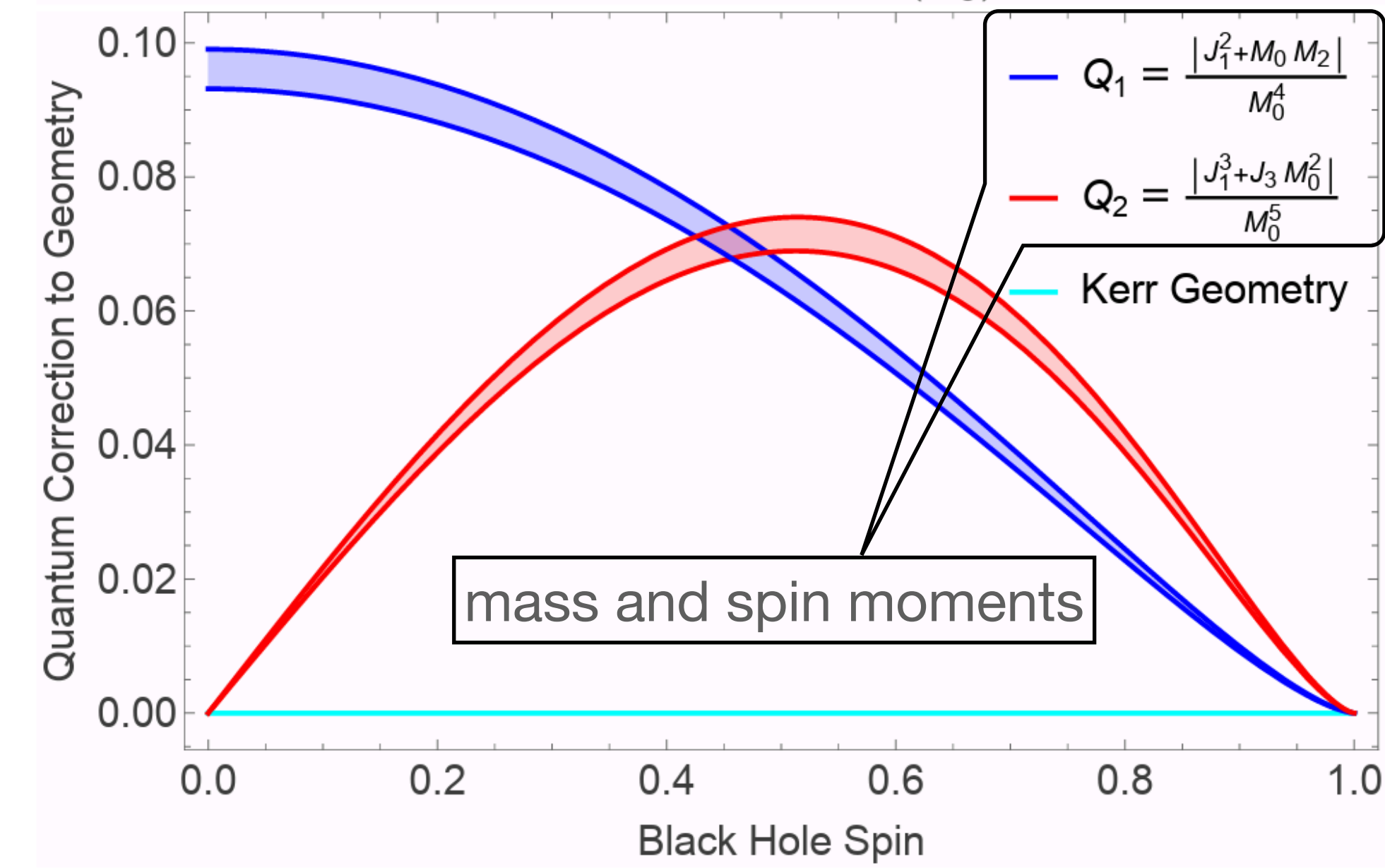
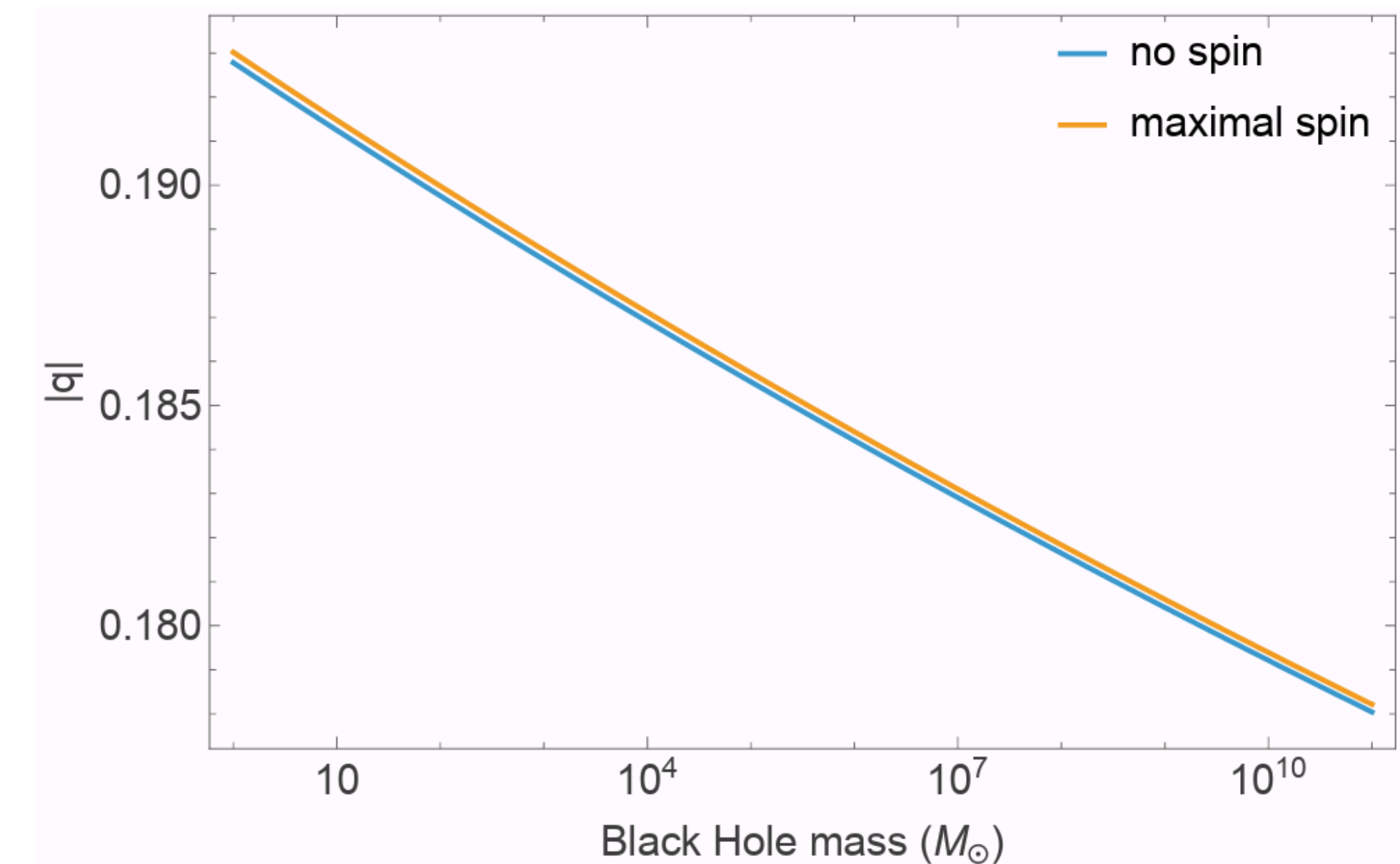
# Quantum Violations of No-Hair Theorem

Faraji & NA 2025

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- Example: q-metric

$$q(S) \approx \sqrt{\frac{4W \left( \frac{\ln S}{4\pi \sqrt{e}} \right)}{\ln S}}.$$

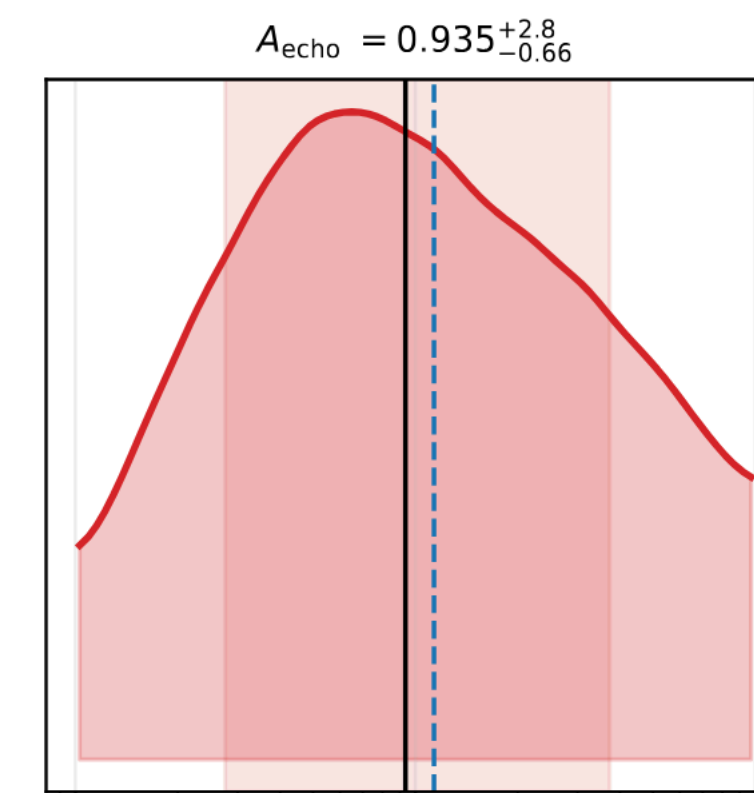
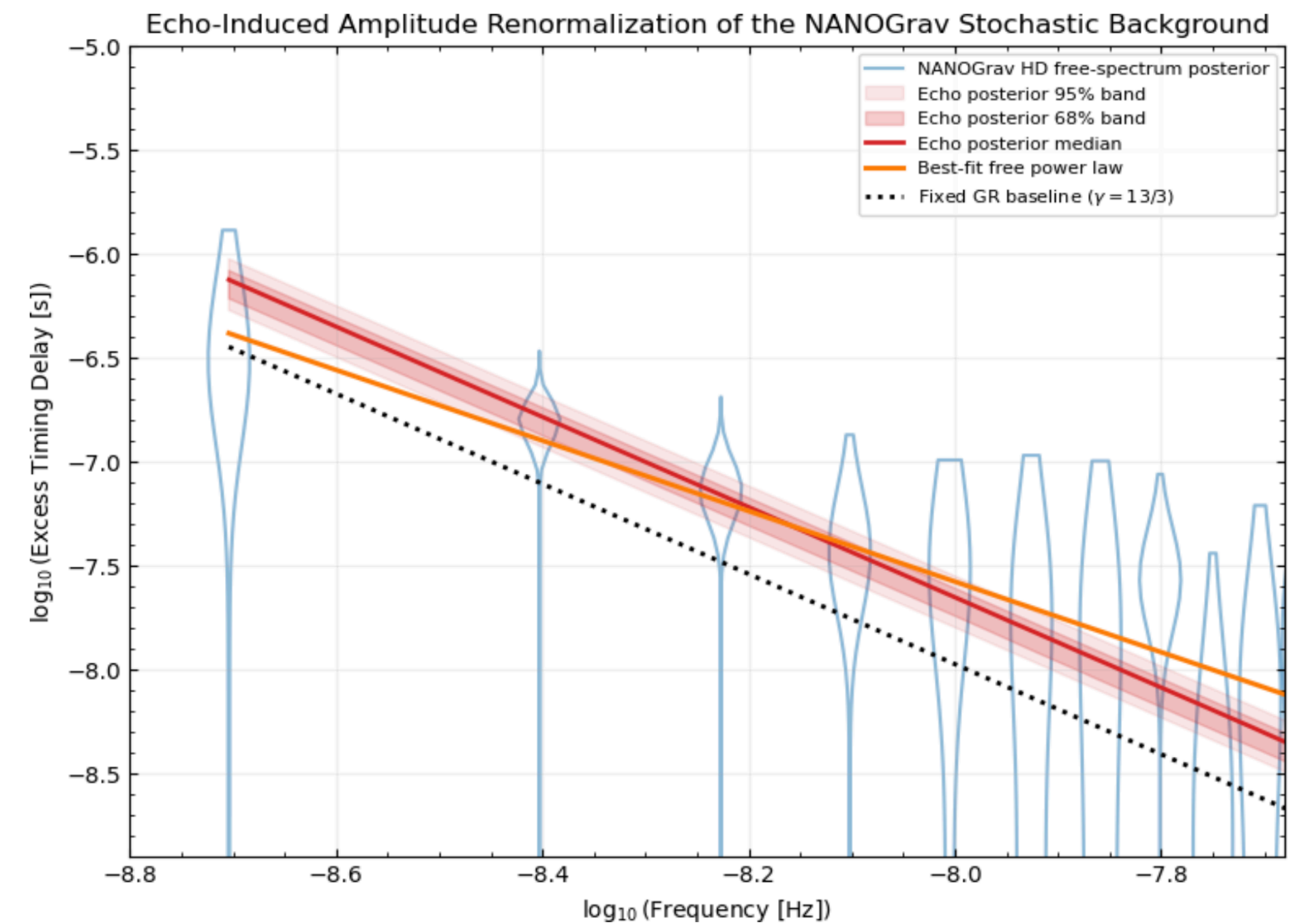
Finite entropy of Hawking radiation  
in q-metric





# Echoes in Pulsar Timing Arrays?

Subhi & NA, in prep.





# Outline

- ☒ *Intro:* the crisis in physics
- ☒ Quantum Big Bang
- ☒ Quantum Black Holes
- ☐ **Quantum Dark Energy**
- ☐ *Outro:* how the light gets in



# Scrambling time for de Sitter Horizon



JHEP09(2020)123.pdf

1 / 34



97%



## Trans-Planckian Censorship and the Swampland

---

**Alek Bedroya and Cumrun Vafa**

*Jefferson Physical Laboratory, Harvard University,  
17 Oxford Street, Cambridge, MA 02138, U.S.A.*

*E-mail:* [abedroya@harvard.edu](mailto:abedroya@harvard.edu), [vafa@physics.harvard.edu](mailto:vafa@physics.harvard.edu)

ABSTRACT: In this paper we propose a new Swampland condition: the Trans-Planckian



# Scrambling time for de Sitter Horizon



JHEP09(2020)123.pdf

1 / 34



97%



## Trans-Planckian Censorship and the Swampland

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

$$T \leq \frac{1}{H} \log \frac{M_p}{H} \quad (1.1)$$

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



# Scrambling time for de Sitter Horizon



JHEP09(2020)123.pdf

1 / 34



97%



## Trans-Planckian Censorship and the Swampland

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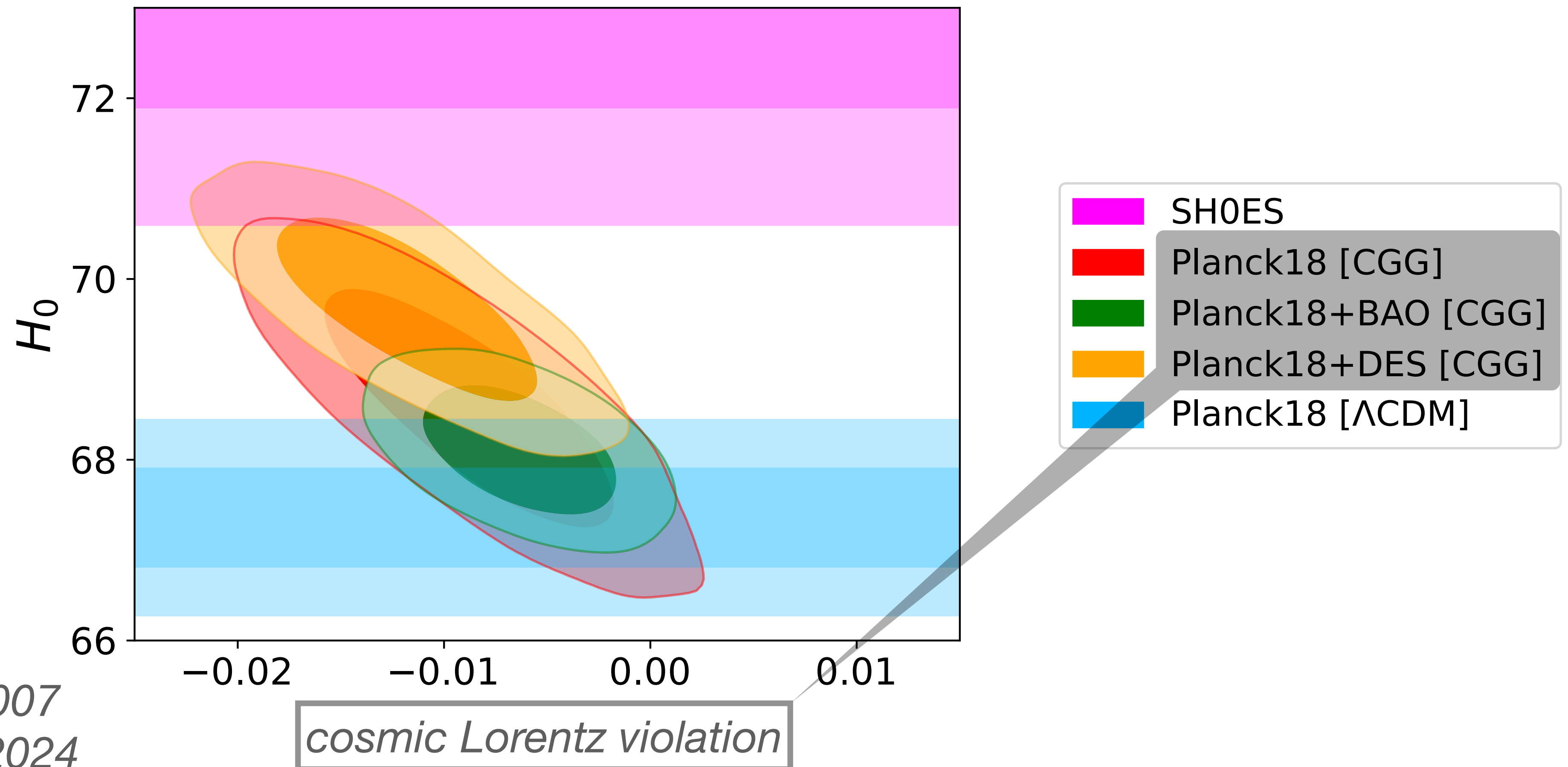


# Quantum Cosmological Horizons

- Can Hubble tension be a signature of Lorentz violation in the theory of gravity?

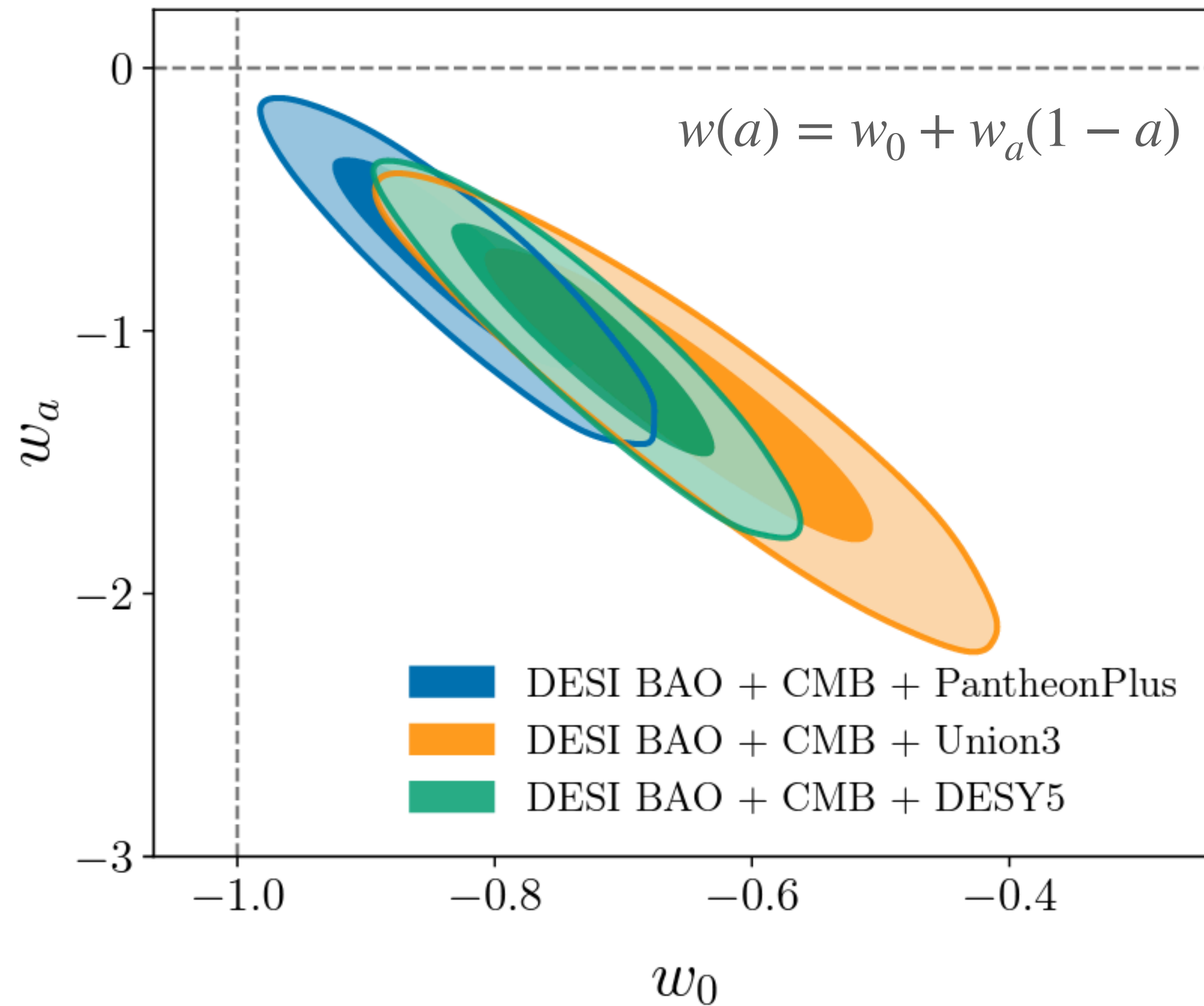


*Robbers, NA & Doran, 2007*  
*Wen, Hergt, NA & Scott, 2024*

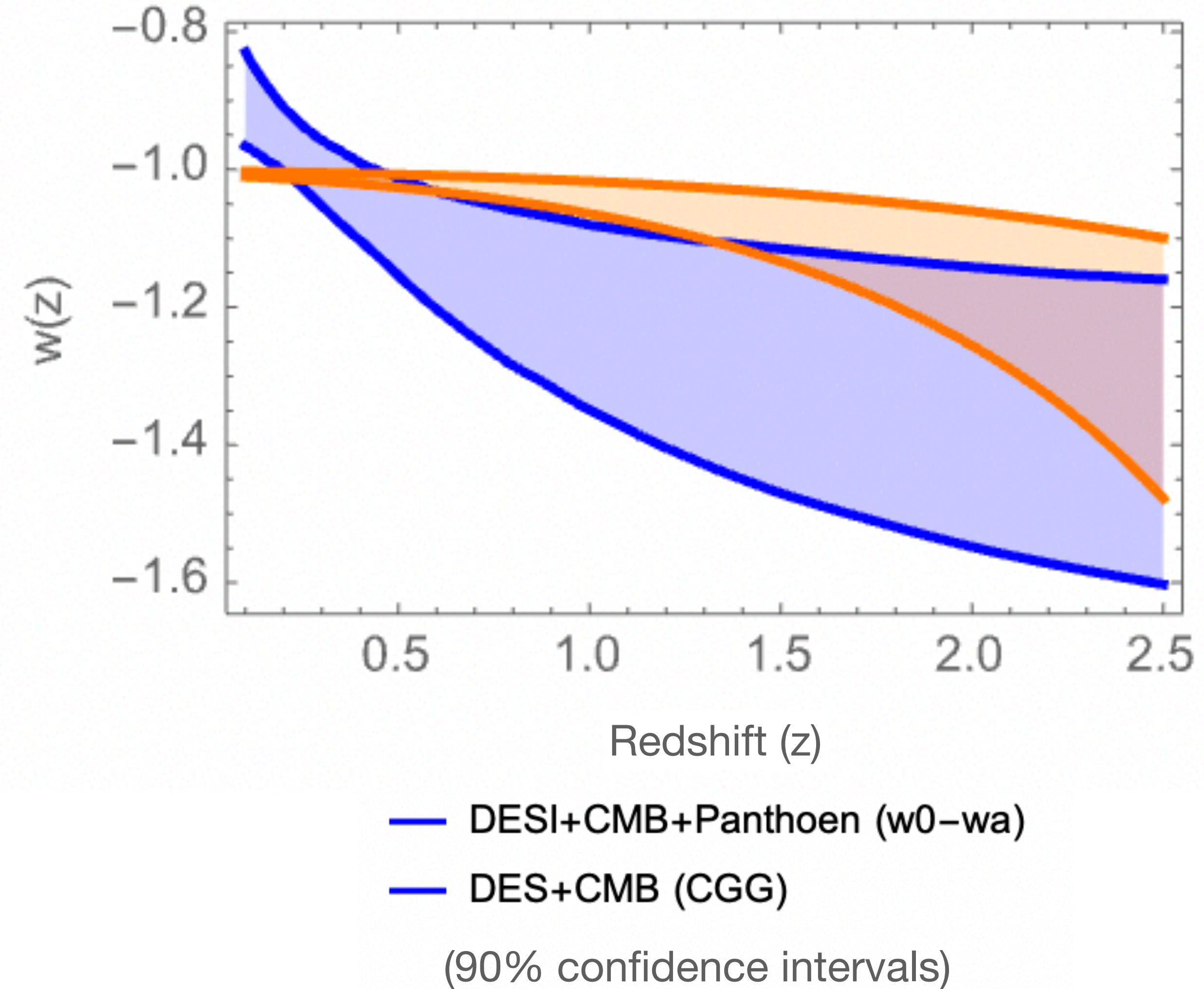




# DESI tension?

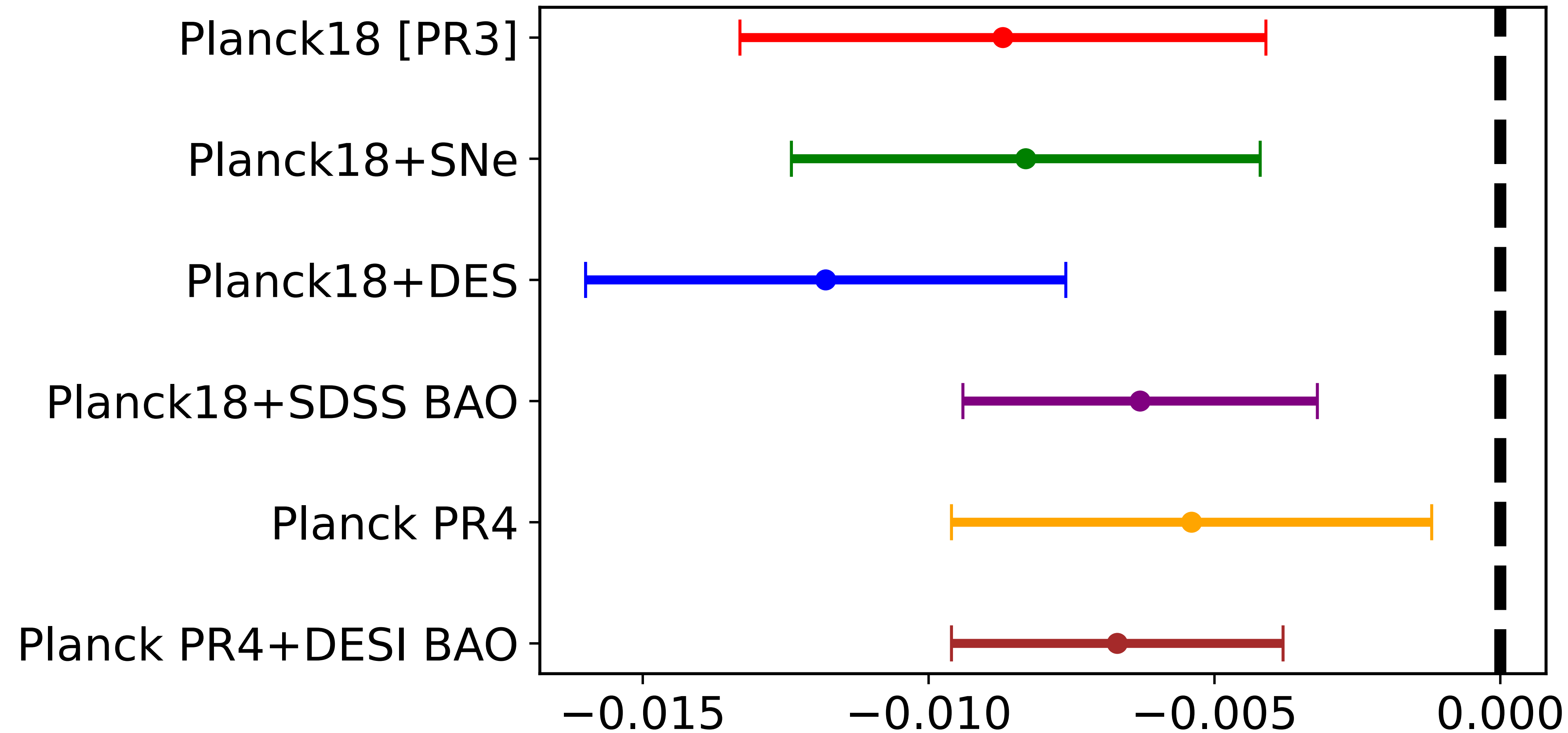


DESI collaboration 2024





# *Is gravity weaker on superhorizon scales?*



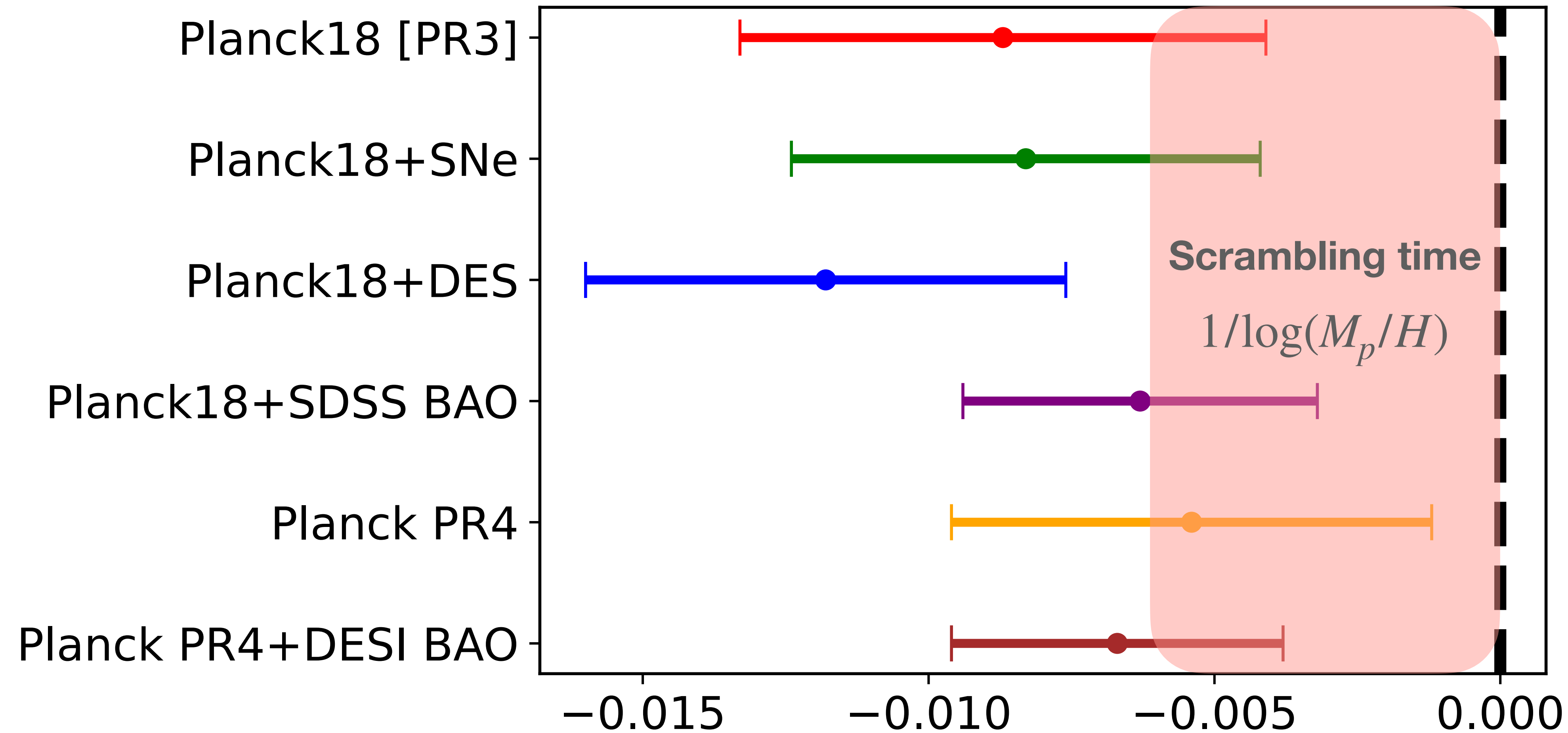
*cosmic Lorentz violation*

*Wen, Hergt, NA & Scott, 2024*





# *Is gravity weaker on superhorizon scales?*



*cosmic Lorentz violation*

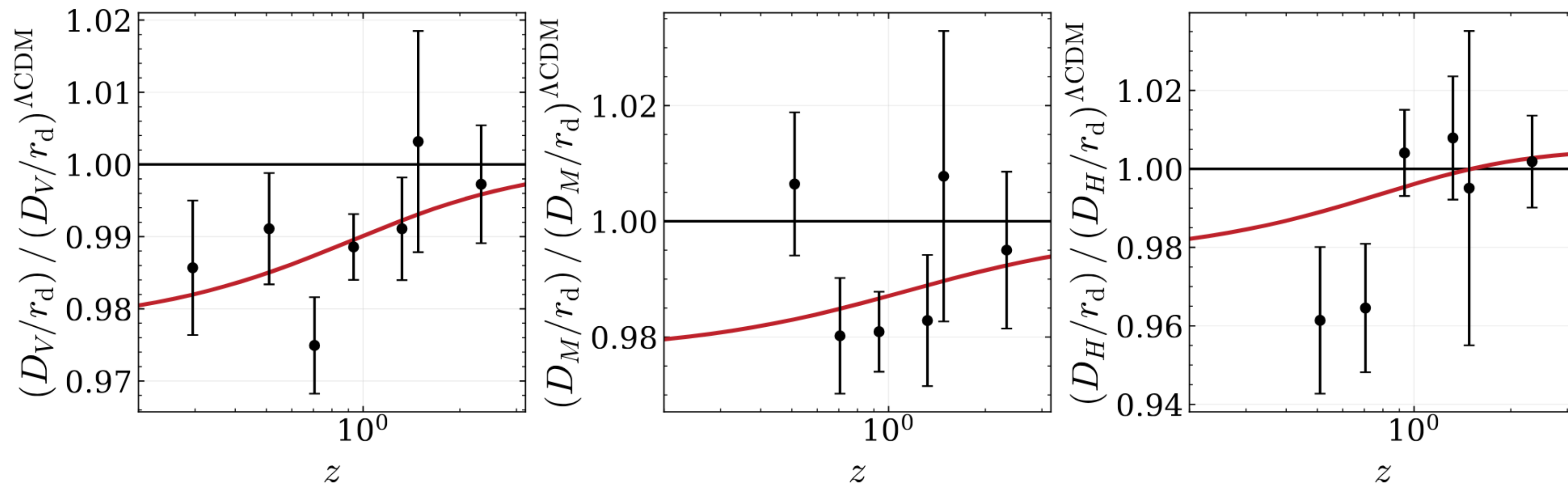
Wen, Hergt, NA & Scott, 2024



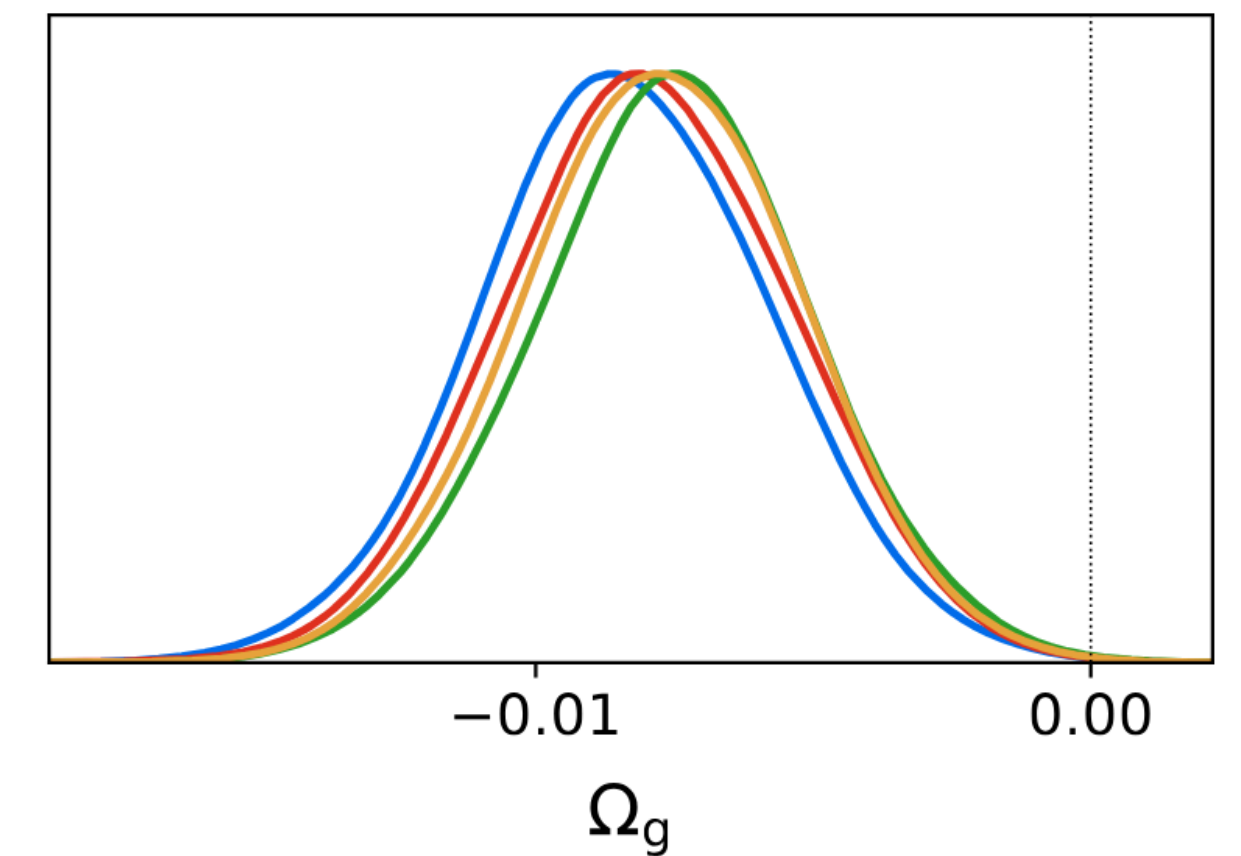


# Is DESI Seeing Dynamical Dark Energy, or a *Cosmic Glitch in Gravity*?

—  $\Lambda$ CDM    — CGG



— CMB-SPA + DESI DR2    — + DES Y5  
— + Pantheon+    — + Dovekie



Evidence for Horava quantum gravity at  $3\sigma$ !

$$\lambda - 1 = 0.0056 \pm 0.0017.$$

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

$$\Omega_g = -0.0084 \pm 0.0026,$$

$$\frac{G_{\text{cosmo}}}{G_N} = \frac{1}{1 - \Omega_g} = 0.9917 \pm 0.0026,$$

Wen, Hergt, NA & Scott, in prep

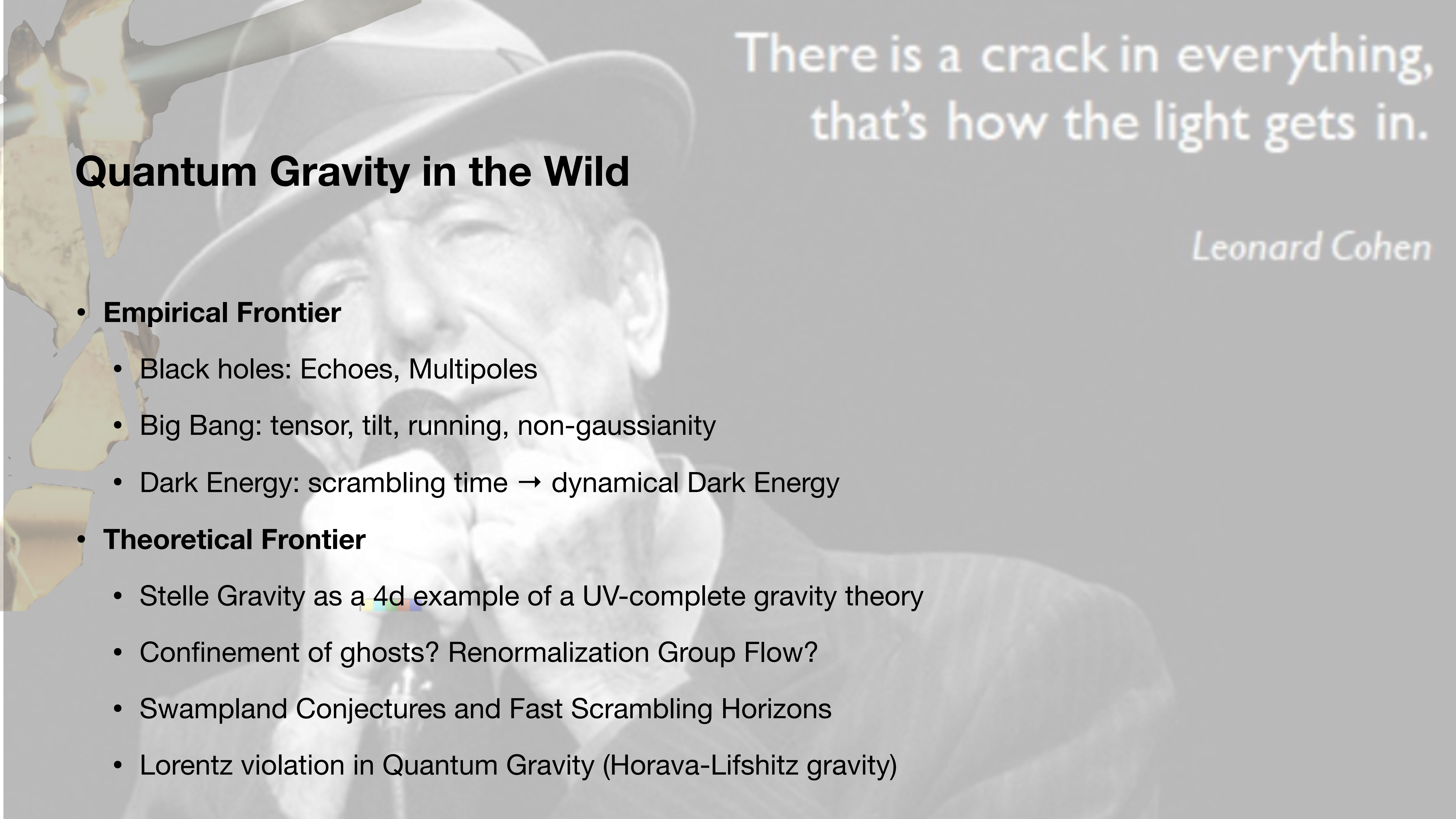




# Outline

- ☒ *Intro:* the crisis in physics
- ☒ Quantum Big Bang
- ☒ Quantum Black Holes
- ☒ Quantum Dark Energy
- ☐ ***Outro:* how the light gets in**



A faded, grayscale background image of Leonard Cohen wearing a fedora and holding a microphone. On the left side, there are several torn, yellowish paper-like shapes.

There is a crack in everything,  
that's how the light gets in.

*Leonard Cohen*

## Quantum Gravity in the Wild

- **Empirical Frontier**

- Black holes: Echoes, Multipoles
- Big Bang: tensor, tilt, running, non-gaussianity
- Dark Energy: scrambling time  $\rightarrow$  dynamical Dark Energy

- **Theoretical Frontier**

- Stelle Gravity as a 4d example of a UV-complete gravity theory
- Confinement of ghosts? Renormalization Group Flow?
- Swampland Conjectures and Fast Scrambling Horizons
- Lorentz violation in Quantum Gravity (Horava-Lifshitz gravity)

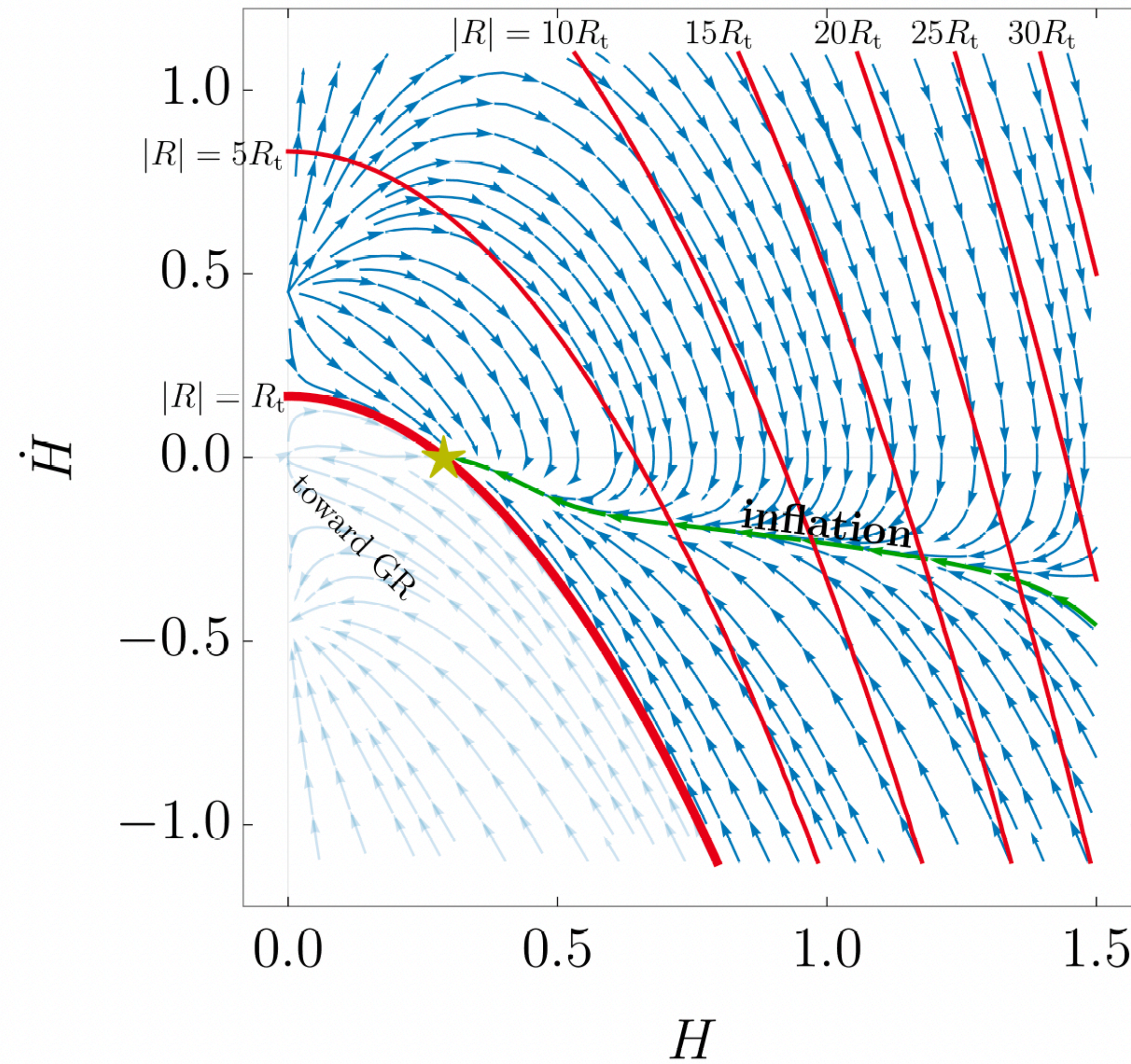


# **Bonus slides**



# Cross tachynonic divide @ end of slow-roll inflation

w/ generic RG scale identification

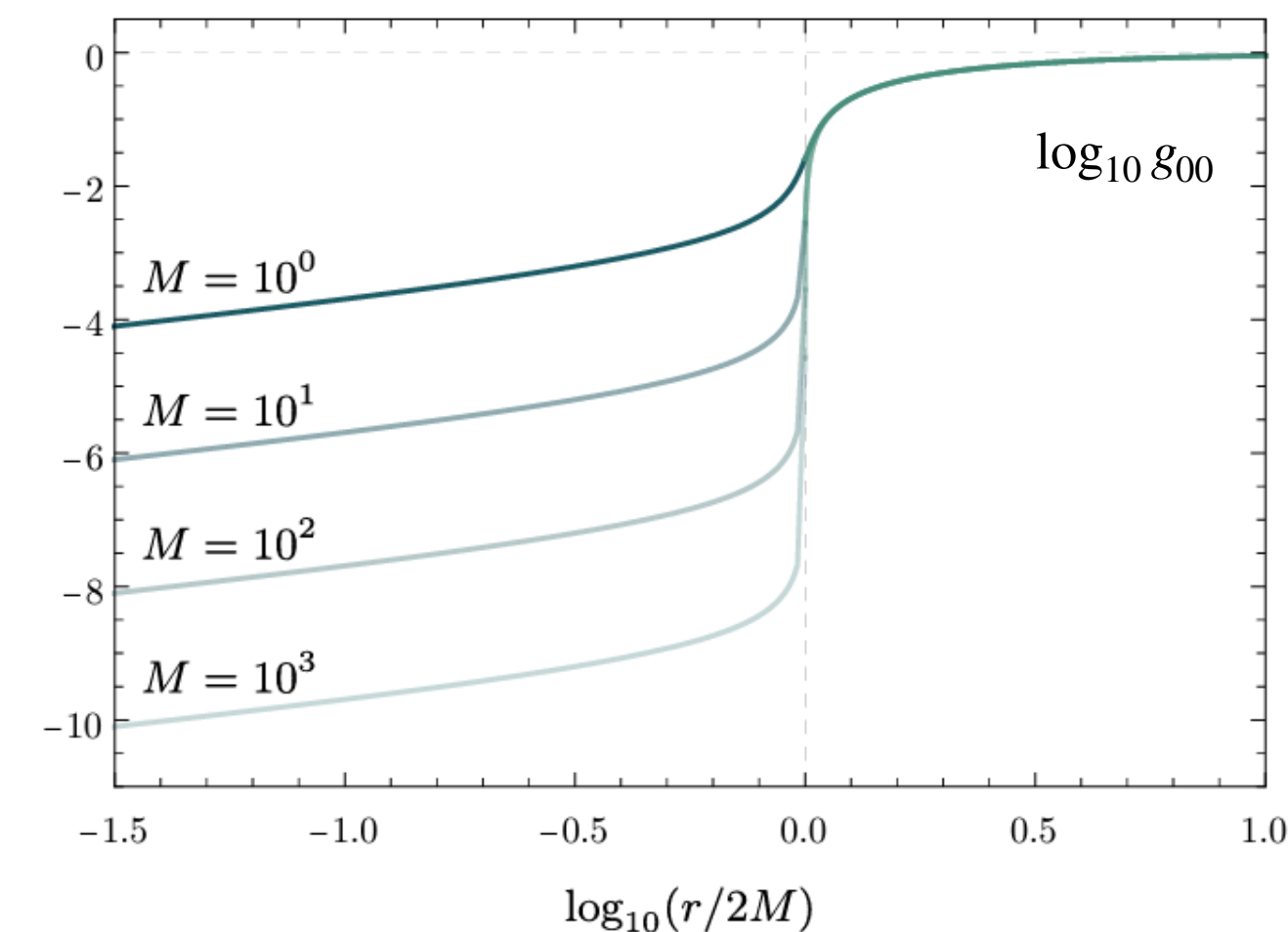




# Warmup: Quantum Black Holes in Asymptotic Safety

- Assume that RG-dependence of coupling constants on local temperature;  $k \sim T$
- Non-trivial UV fixed point
- **No horizon**
- Scale-invariant core near UV fixed point;  $g_{00} \sim r^{\sqrt{3}-1}$

$$S = \int d^4x \sqrt{-g} \frac{1}{16\pi G(k)} (R - 2\Lambda(k)),$$



arXiv > gr-qc > arXiv:2203.02559

General Relativity and Quantum Cosmology

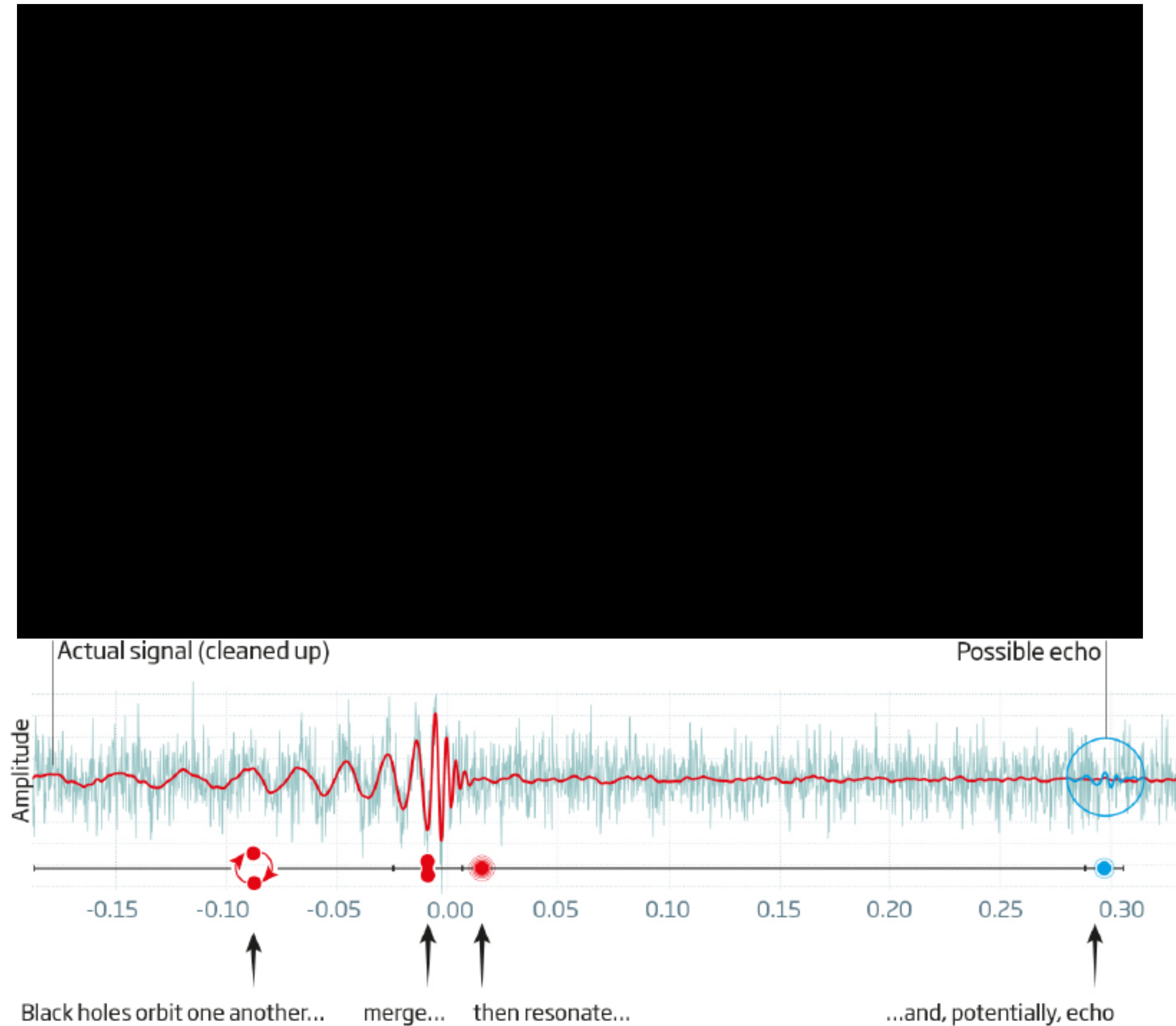
[Submitted on 4 Mar 2022]

**Scale-Invariance at the Core of Quantum Black Holes**

Johanna N. Borissova, Aaron Held, Niayesh Afshordi



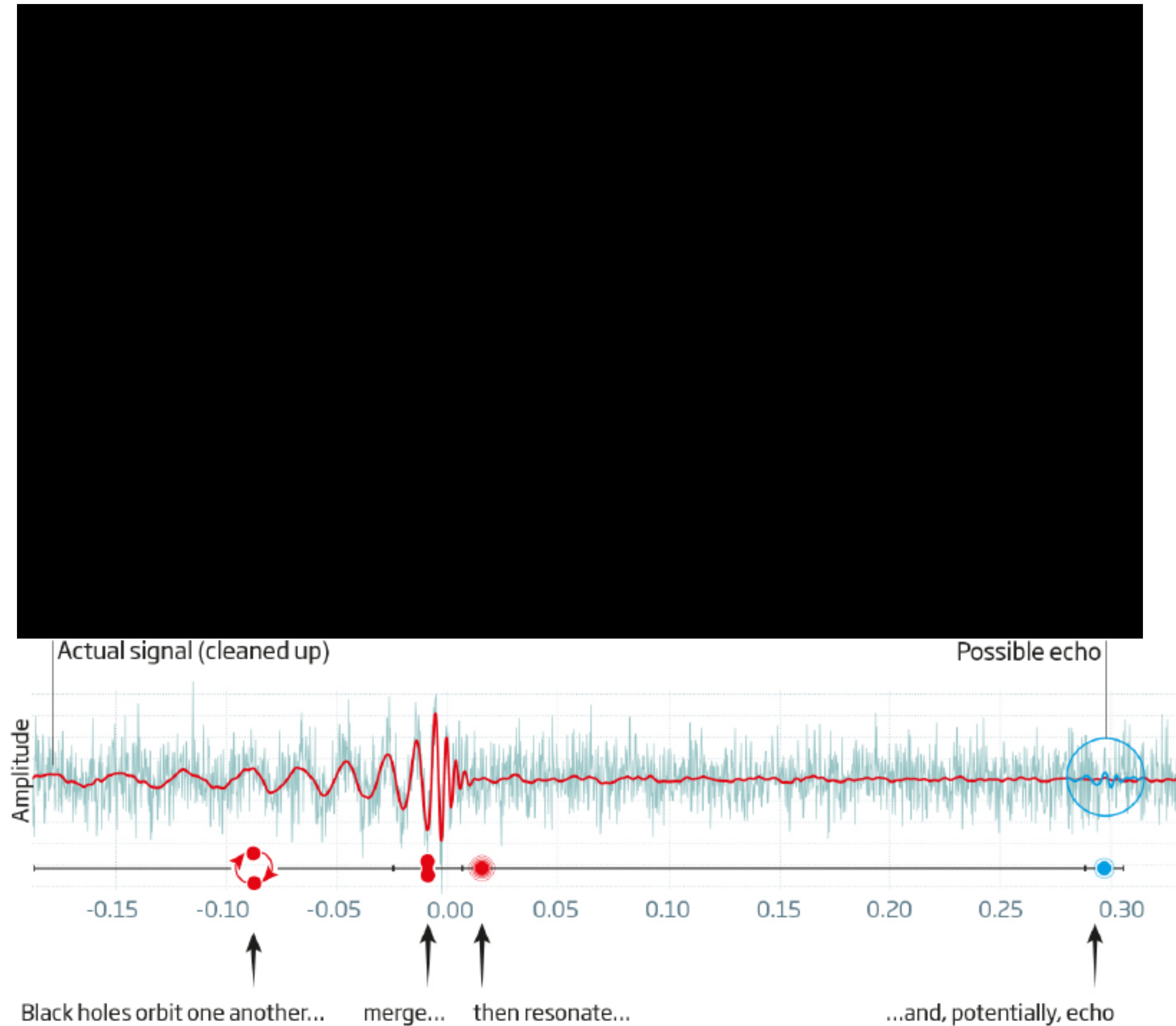
# Gravitational Waves from firewalls?



SOURCE: [doi.org/bchwr](https://doi.org/bchwr); NIAYESH AFSHORDI AND JAHED ABEDI



# Gravitational Waves from firewalls?



SOURCE: [doi.org/bchwr](https://doi.org/bchwr); NIAYESH AFSHORDI AND JAHED ABEDI



# 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  $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$  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           | $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$ | Event           | $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$ |
|-----------------|----------------------------------------------------|-----------------|----------------------------------------------------|
| 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                                               |                 |                                                    |

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  $\mathcal{B}_{\text{N}}^{\text{S}}$  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       |



# 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  $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$  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           | $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$ | Event           | $\log_{10} \mathcal{B}_{\text{IMR}}^{\text{IMRE}}$ |
|-----------------|----------------------------------------------------|-----------------|----------------------------------------------------|
| 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                                               |                 |                                                    |

**$t_{\text{echo}} < 0.5 \text{ sec}$**

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  $\mathcal{B}_{\text{N}}^{\text{S}}$  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**



# Different methods, Different events!

Positive Evidence (p-value  $\leq 5\%$ )

|   | Authors                                          | Method             | Data          | p-value                           |
|---|--------------------------------------------------|--------------------|---------------|-----------------------------------|
| 1 | <b>Abedi, Dykaar, NA 2017 (ADA)</b>              | ADA template       | O1            | 1.1%                              |
| 2 | <b>Conklin, Holdom, Ren 2018<br/>Holdom 2020</b> | spectral comb      | O1,O2         | 0.2%-0.8%<br>(now $10^{-10}!$ )   |
| 3 | <b>Westerweck, et al. 2018</b>                   | ADA template       | O1            | 2.0%                              |
| 4 | <b>Nielsen, et al. 2019</b>                      | ADA+Bayes          | 151012,151226 | 2%*                               |
| 5 | <b>Uchikata, et al. 2019</b>                     | ADA template       | O1, O2        | 5.5%,3.9%                         |
| 6 | <b>Salemi, et al. 2019</b>                       | coherent WaveBurst | 151012,151226 | 0.4%,3%                           |
| 7 | <b>Abedi &amp; NA 2019</b>                       | spectral comb      | 170817 (BNS)  | 0.0016%                           |
| 8 | <b>Gill, Nathanail, Rezolla 2019</b>             | Astro Modelling    | BNS EM        | $t_{\text{coll}}=t_{\text{echo}}$ |
| 9 | <b>Abedi, Longo, NA 2022</b>                     | Boltzmann, cWB     | 190521        | 0.5%                              |

Failed Searches

|   | Authors                        | Method                 | Data            | possible caveat                            |
|---|--------------------------------|------------------------|-----------------|--------------------------------------------|
| 1 | <b>Westerweck, et al. 2018</b> | ADA template           | O1              | "Infinite" prior                           |
| 2 | <b>Nielsen, et al. 2019</b>    | ADA+Bayes              | 150914          | mass-ratio dependence                      |
| 3 | <b>Uchikata, et al. 2019</b>   | ADA, hi-pass           | O1,O2           | no low-frequencies                         |
| 4 | <b>Salemi, et al. 2019</b>     | coherent WaveBurst     | O1,O2 **        | mass-ratio dependence, only 1st echo       |
| 5 | <b>Lo, et al. 2019</b>         | ADA+Bayes              | O1              | "Infinite" prior                           |
| 6 | <b>Tsang, et al. 2019</b>      | BayesWave              | O1,O2           | needs very loud echoes (9 free parameters) |
| 7 | <b>Abbott, et al. 2020</b>     | ADA+Bayes              | O1-O3           | "Infinite" prior                           |
| 8 | <b>Abbott, et al. 2021</b>     | BayesWave              | O2,O3 (-190521) | "                                          |
| 9 | <b>Ren &amp; Wu 2021</b>       | Bayesian spectral comb | 150921, 151012  | no phase information                       |



# Different methods, Different events!

Abedi, NA, Oshita & Wang 2020 (Review++)

Positive Evidence (p-value  $\leq 5\%$ )

Failed Searches

|   | Authors                                  | Method             | Data          | p-value                           |   | Authors                 | Method                 | Data            | possible caveat                            |
|---|------------------------------------------|--------------------|---------------|-----------------------------------|---|-------------------------|------------------------|-----------------|--------------------------------------------|
| 1 | Abedi, Dykaar, NA 2017 (ADA)             | ADA template       | O1            | 1.1%                              | 1 | Westerweck, et al. 2018 | ADA template           | O1              | "Infinite" prior                           |
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| 7 | Abedi & NA 2019                          | spectral comb      | 170817 (BNS)  | 0.0016%                           | 7 | Abbott, et al. 2020     | ADA+Bayes              | O1-O3           | "Infinite" prior                           |
| 8 | Gill, Nathanail, Rezolla 2019            | Astro Modelling    | BNS EM        | $t_{\text{coll}}=t_{\text{echo}}$ | 8 | Abbott, et al. 2021     | BayesWave              | O2,O3 (-190521) | "                                          |
| 9 | Abedi, Longo, NA 2022                    | Boltzmann, cWB     | 190521        | 0.5%                              | 9 | Ren & Wu 2021           | Bayesian spectral comb | 150921, 151012  | no phase information                       |

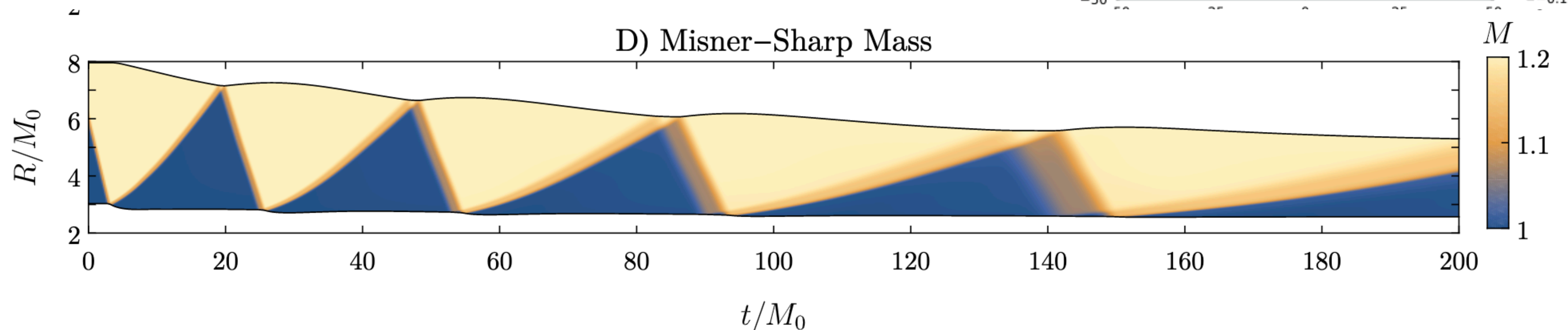
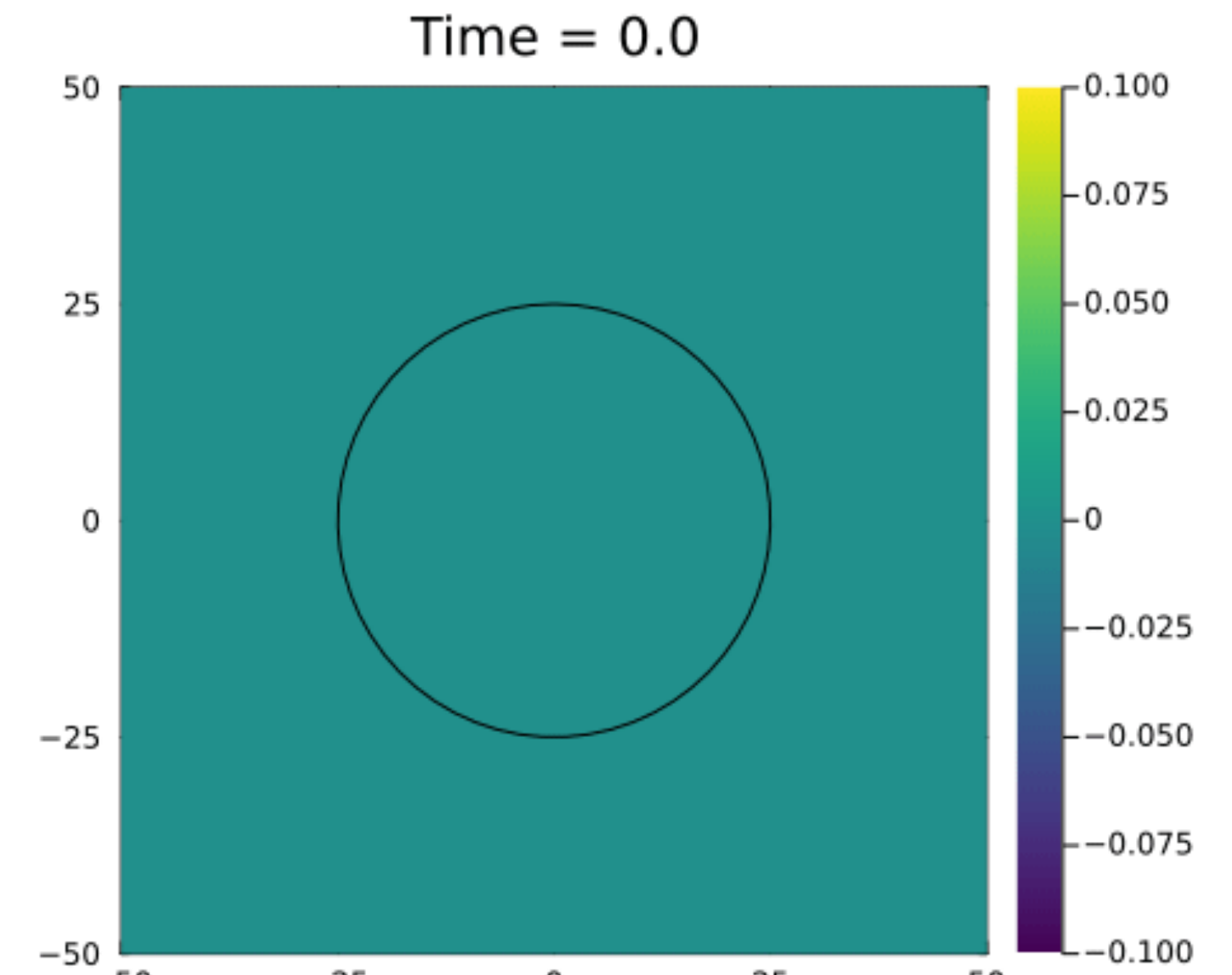




# Black Hole Echoes in Numerical Relativity

We are starting to simulate general relativistic spacetimes with “quantum” physical boundaries

Dailey, NA & Schnetter 2023, 2024



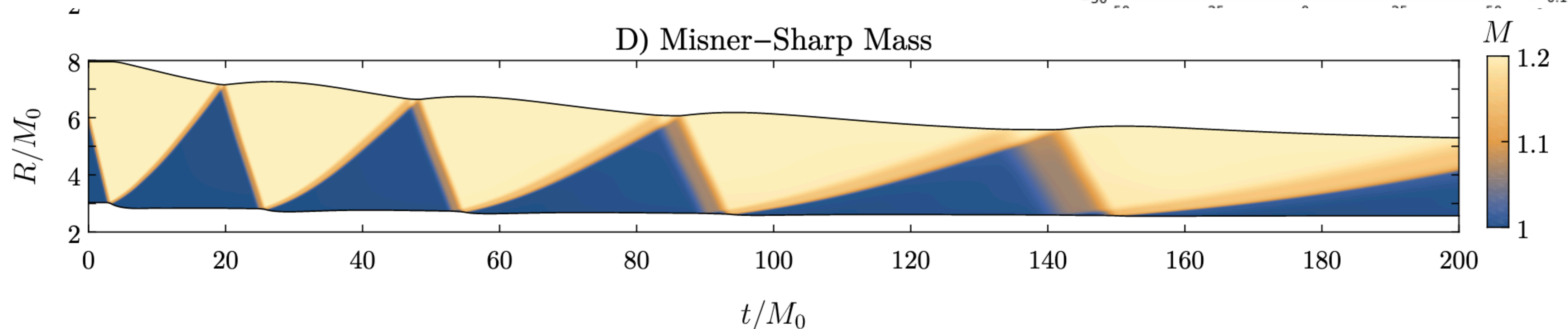
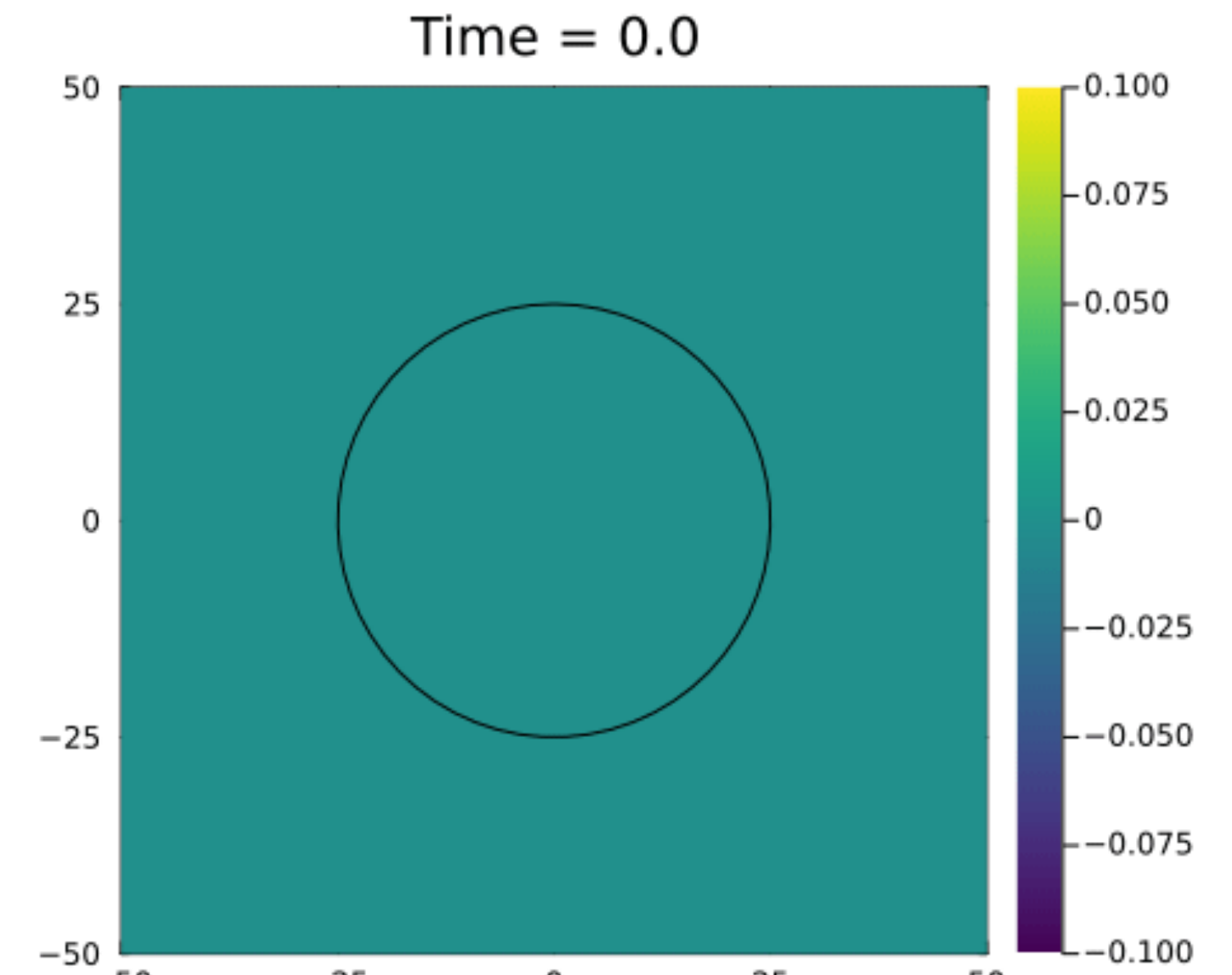




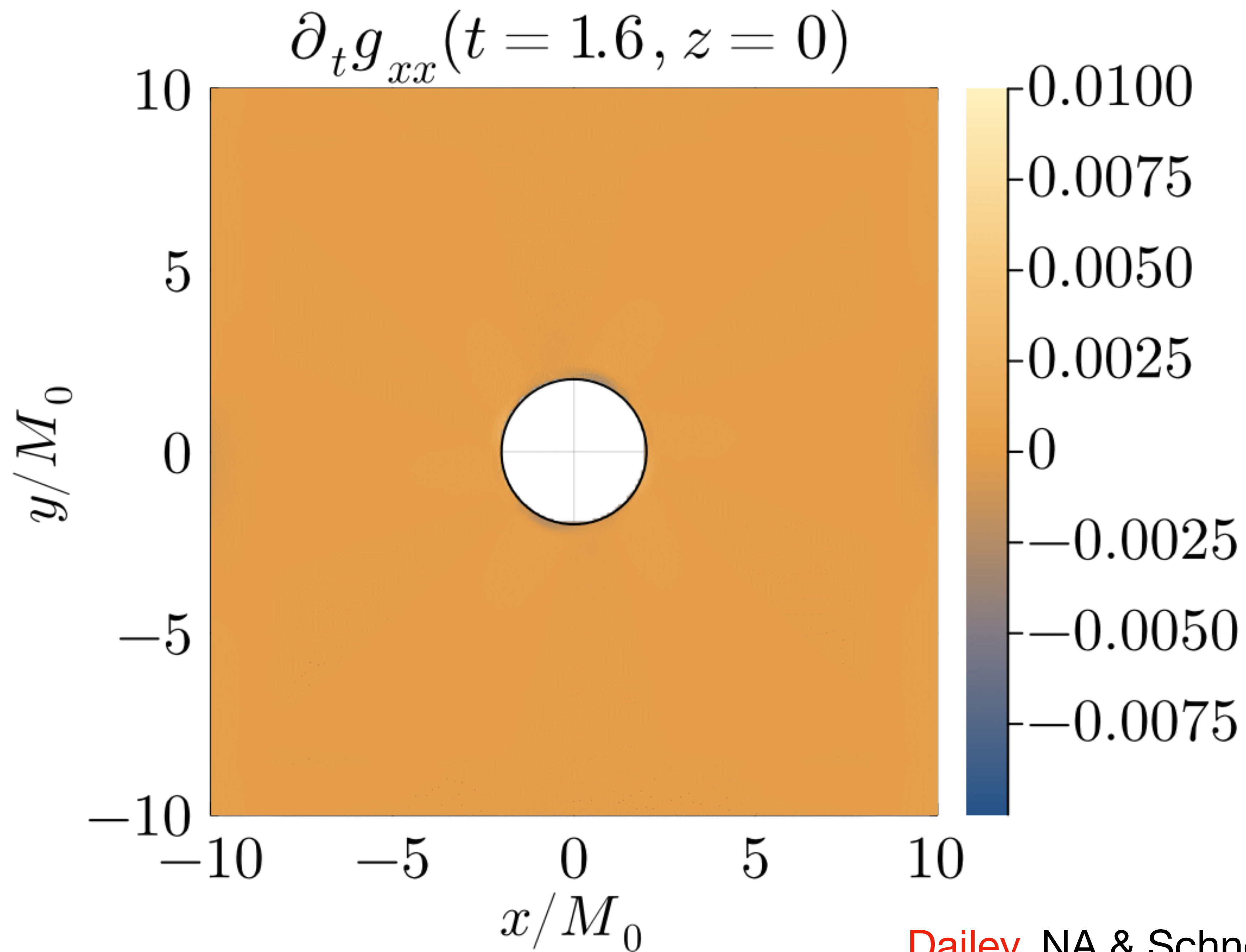
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We are starting to simulate general relativistic spacetimes with “quantum” physical boundaries

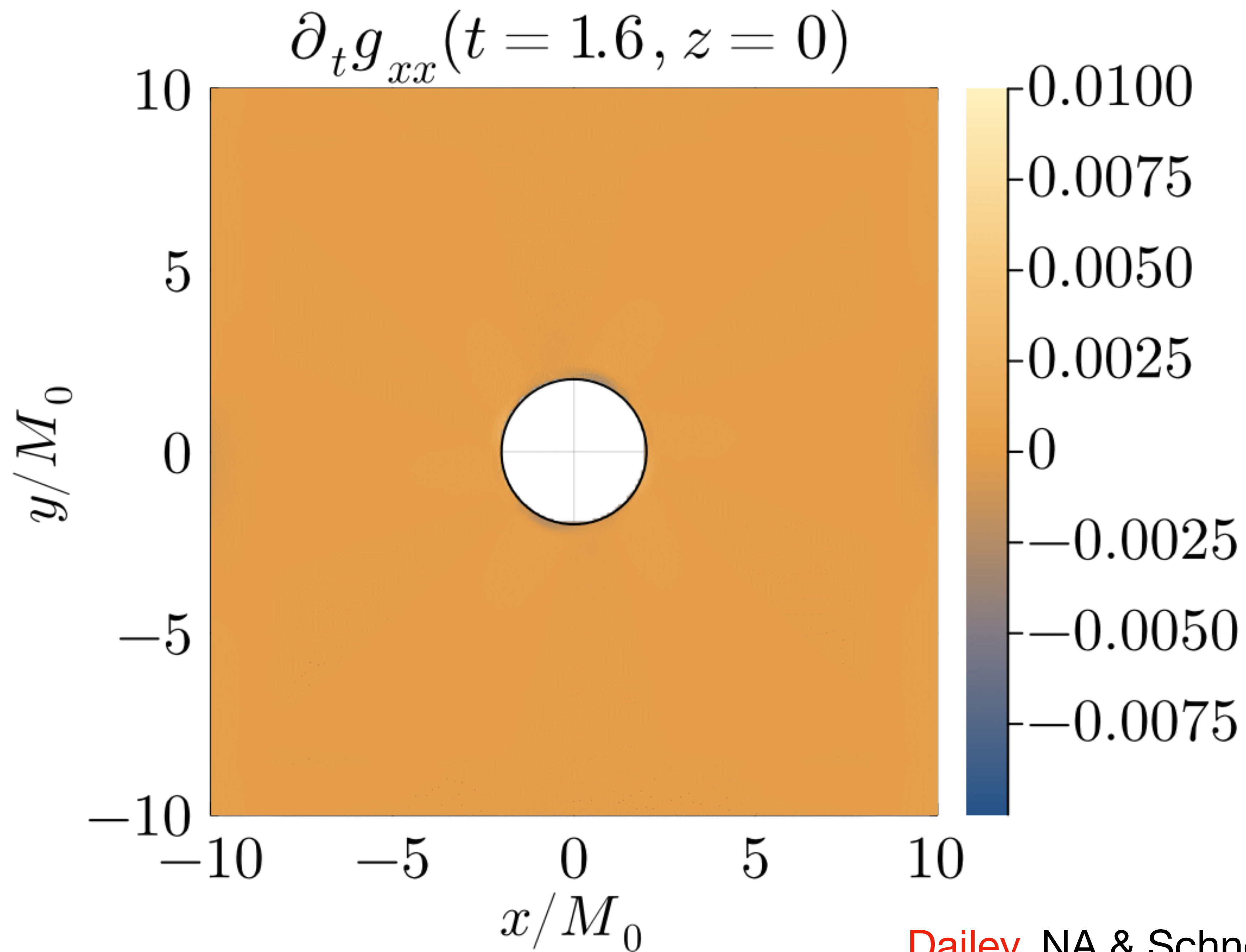
Dailey, NA & Schnetter 2023, 2024







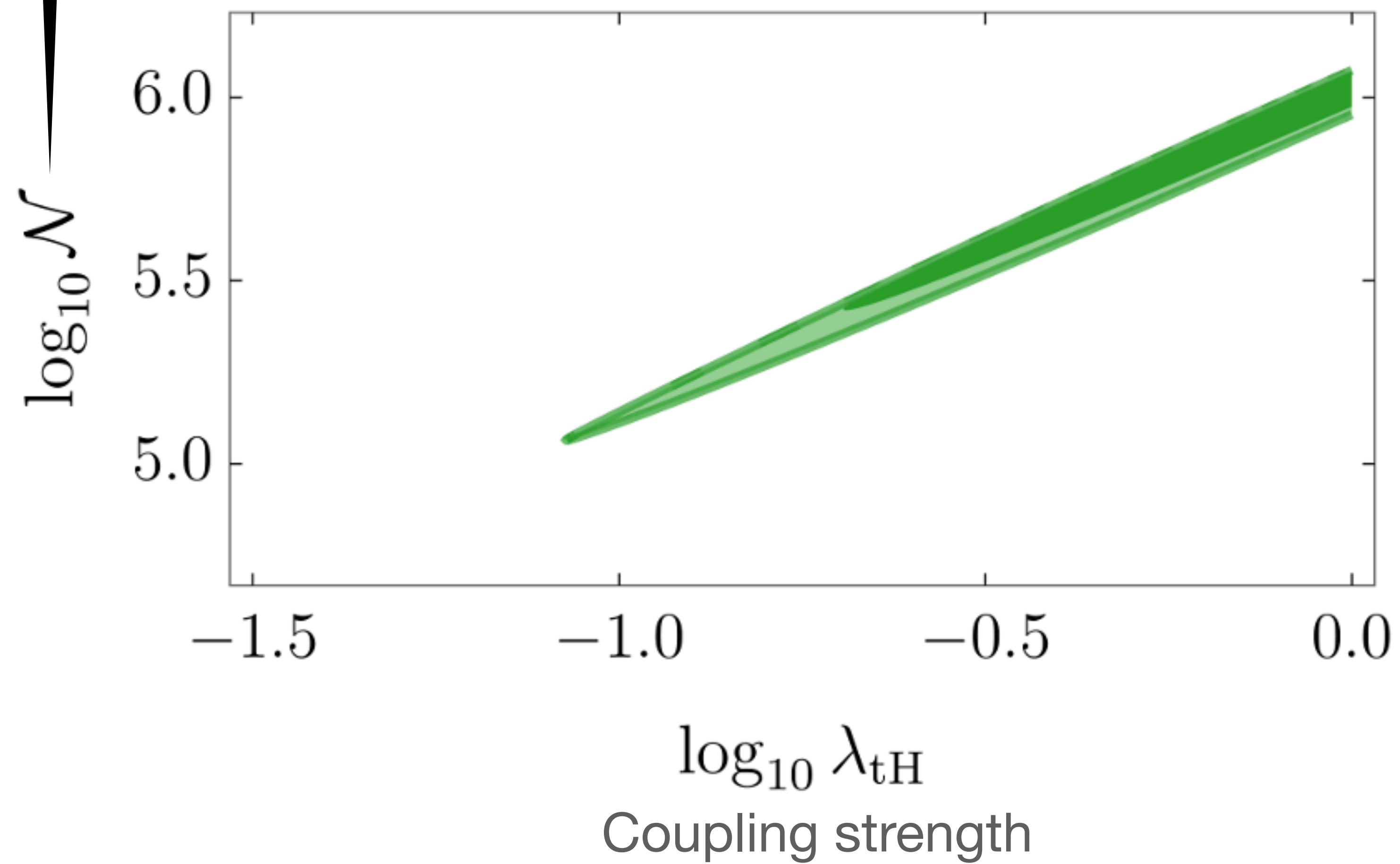






~Number of fields:

$$\frac{N_V}{5} + \frac{N_F}{20} + \frac{N_S}{60}$$

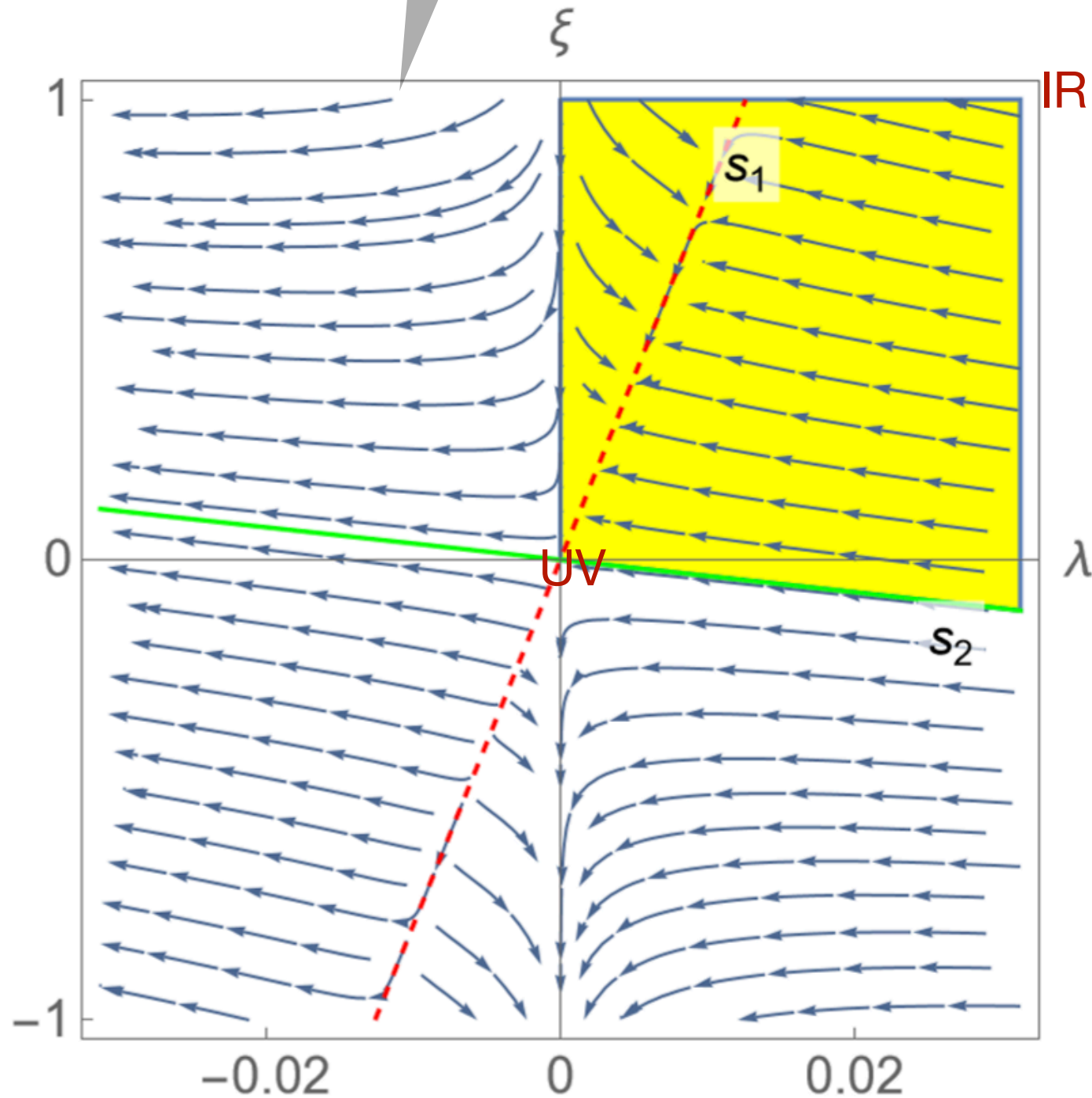
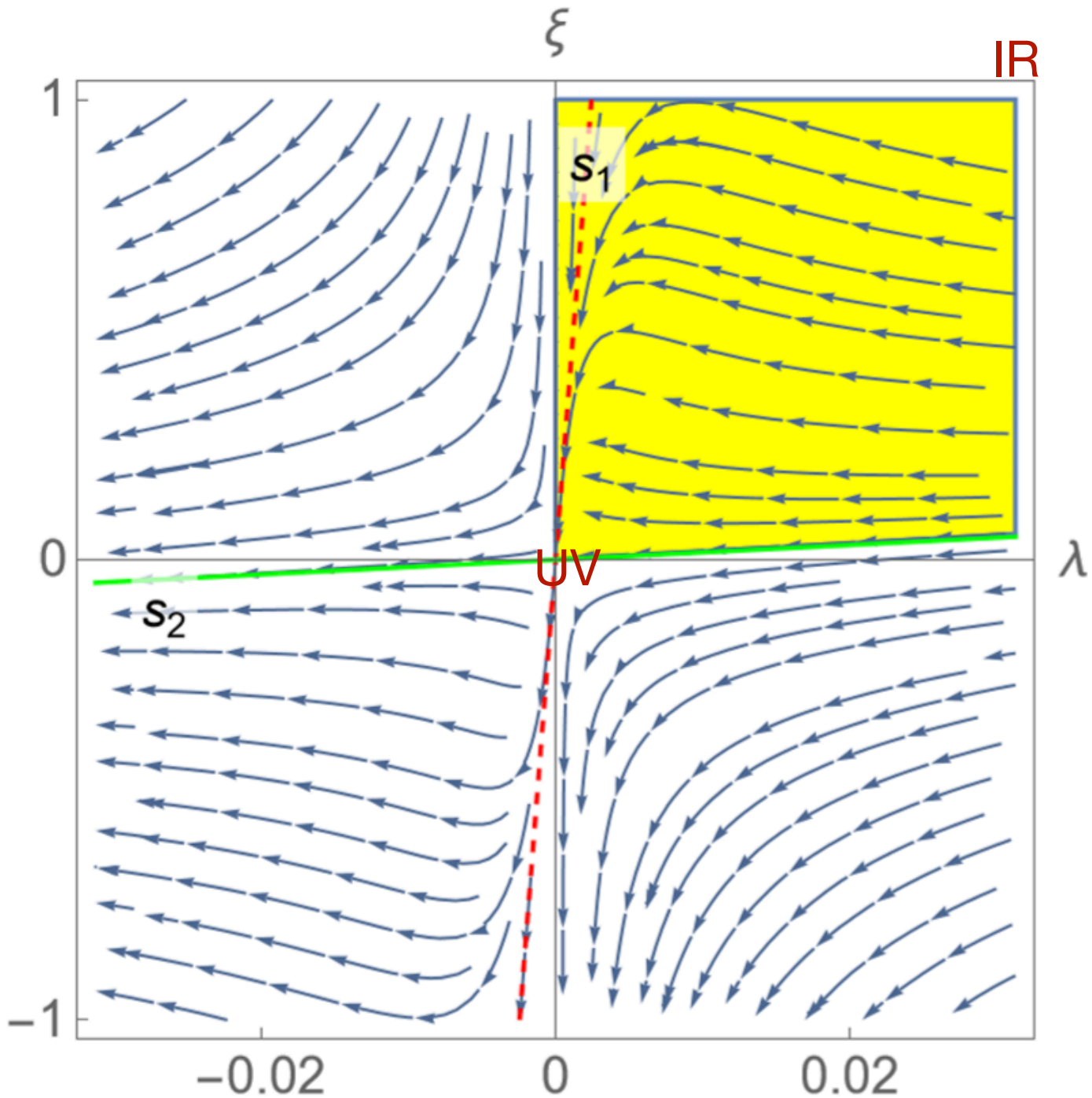




# RG runnings (old & new)

$$S = \int d^4x \sqrt{|g|} \left[ \frac{M_{\text{Pl}}^2}{2} (R - 2\Lambda) - \frac{1}{2\lambda} C^2 - \frac{1}{\xi} R^2 \right] ,$$

D. Buccio, J. F. Donoghue, G. Menezes and R. Percacci, Physical Running of Couplings in Quadratic Gravity, Phys. Rev. Lett. **133** 021604 (2024) no.2.



$$\beta_\lambda = -\frac{1}{(4\pi)^2} \frac{133}{10} \lambda^2 ,$$

$$\beta_\xi = -\frac{1}{(4\pi)^2} \frac{5(72\lambda^2 - 36\lambda\xi + \xi^2)}{36} ,$$

Left: old “mu” flow. Right: new “physical” flow.

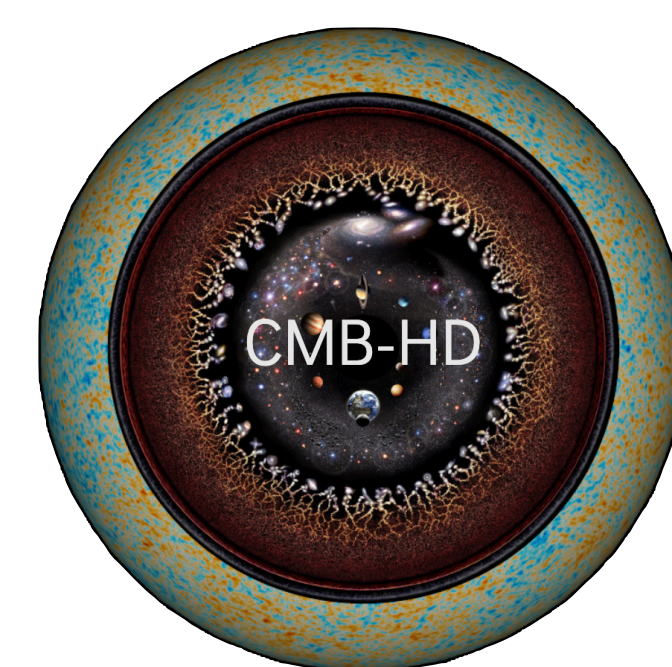
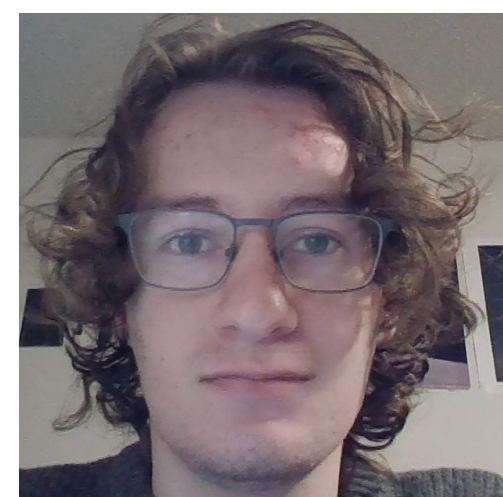
Percacci & Vacca 25

$$\beta_\lambda = -\frac{1}{(4\pi)^2} \frac{(1617\lambda - 20\xi)\lambda}{90} ,$$

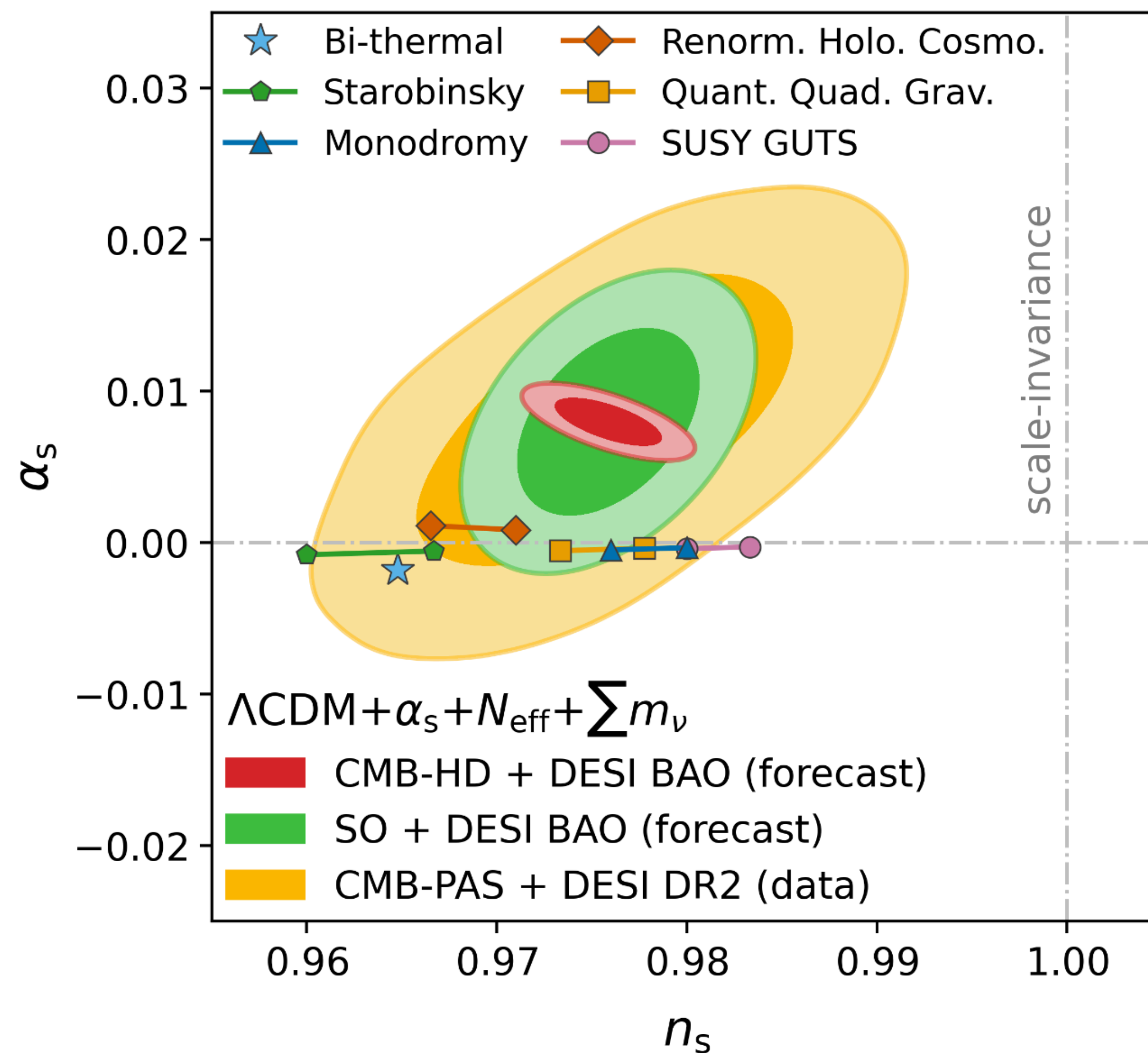
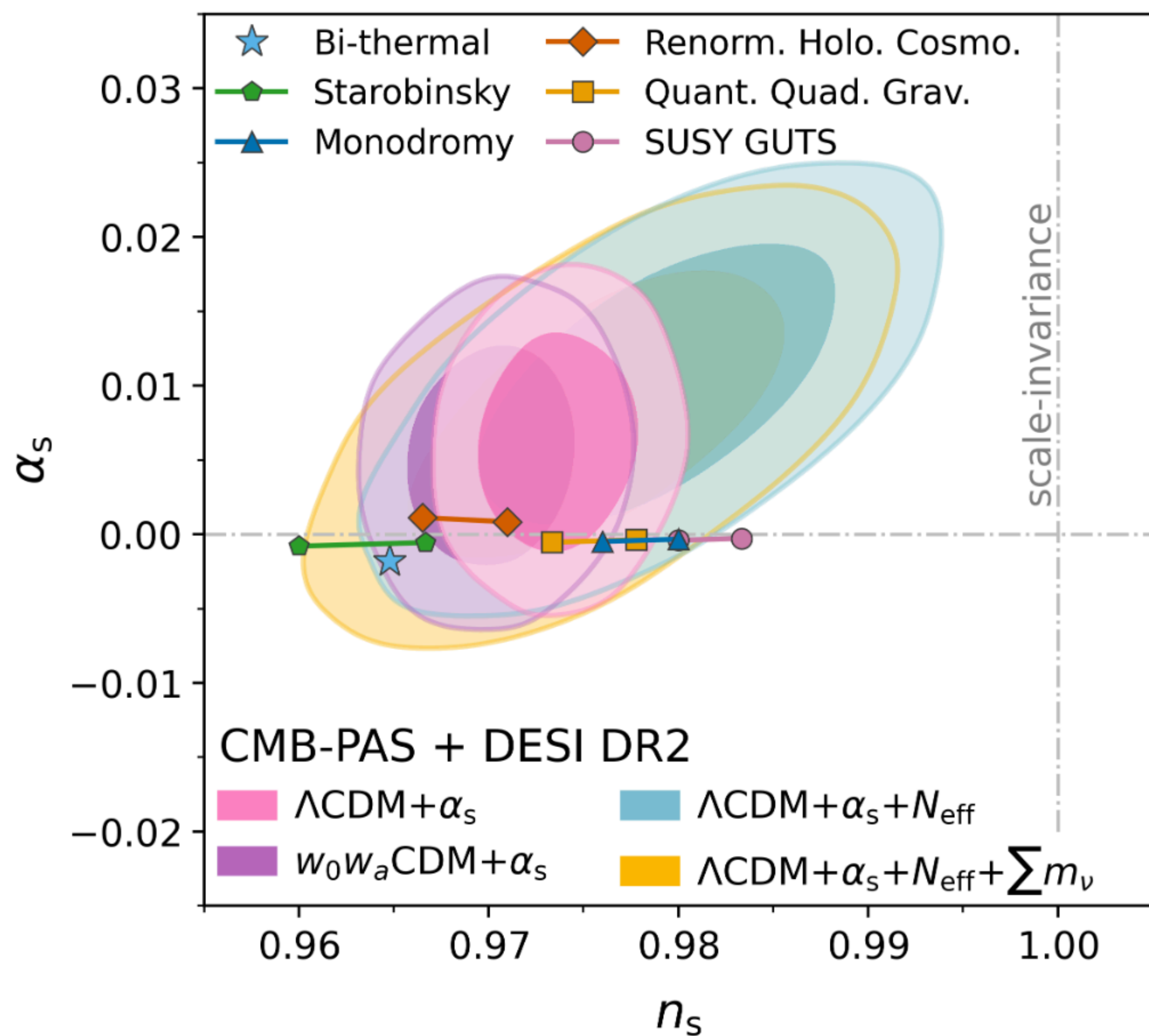
$$\beta_\xi = -\frac{1}{(4\pi)^2} \frac{\xi^2 - 36\lambda\xi - 2520\lambda^2}{36} .$$



# Future is Bright!



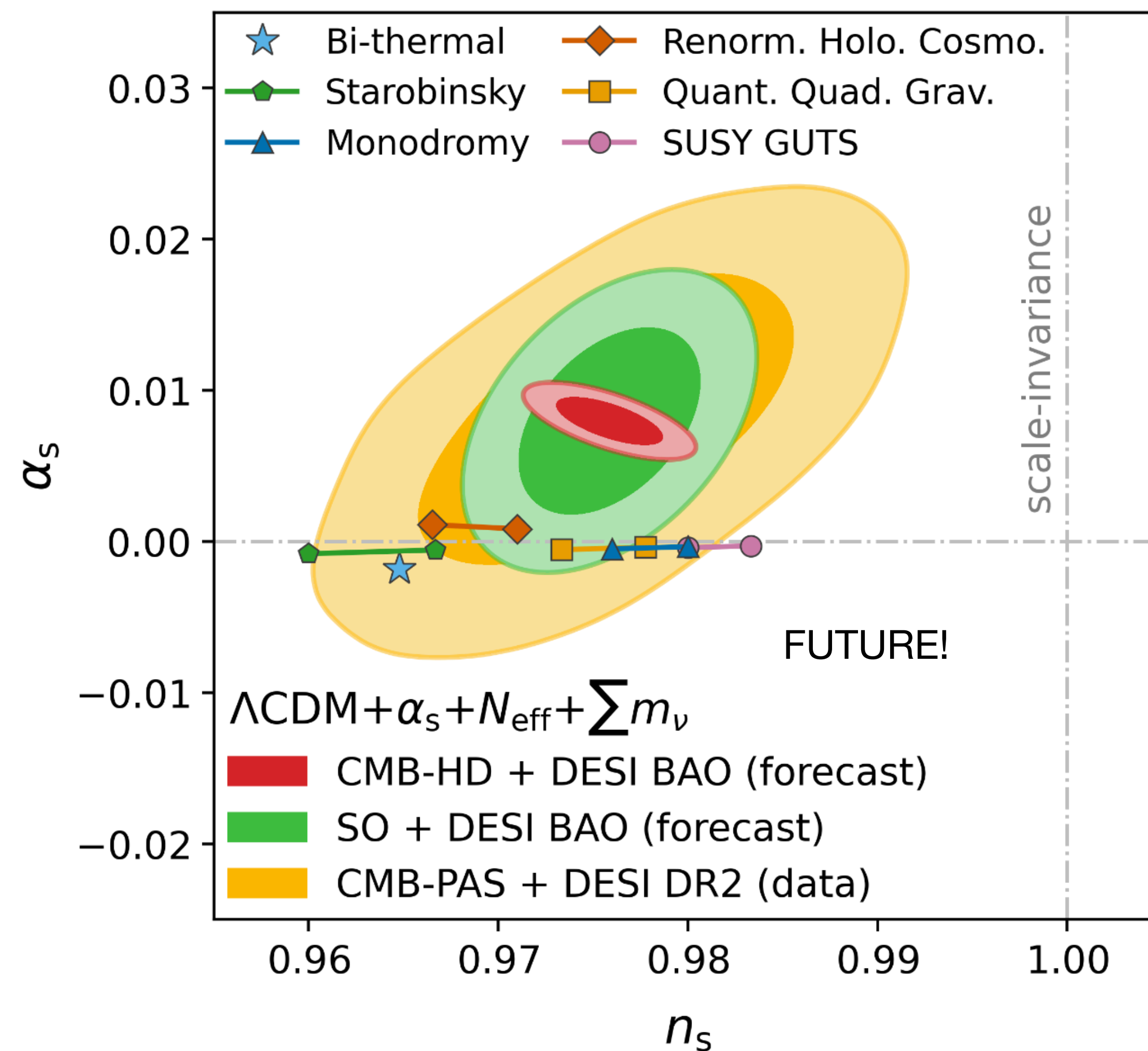
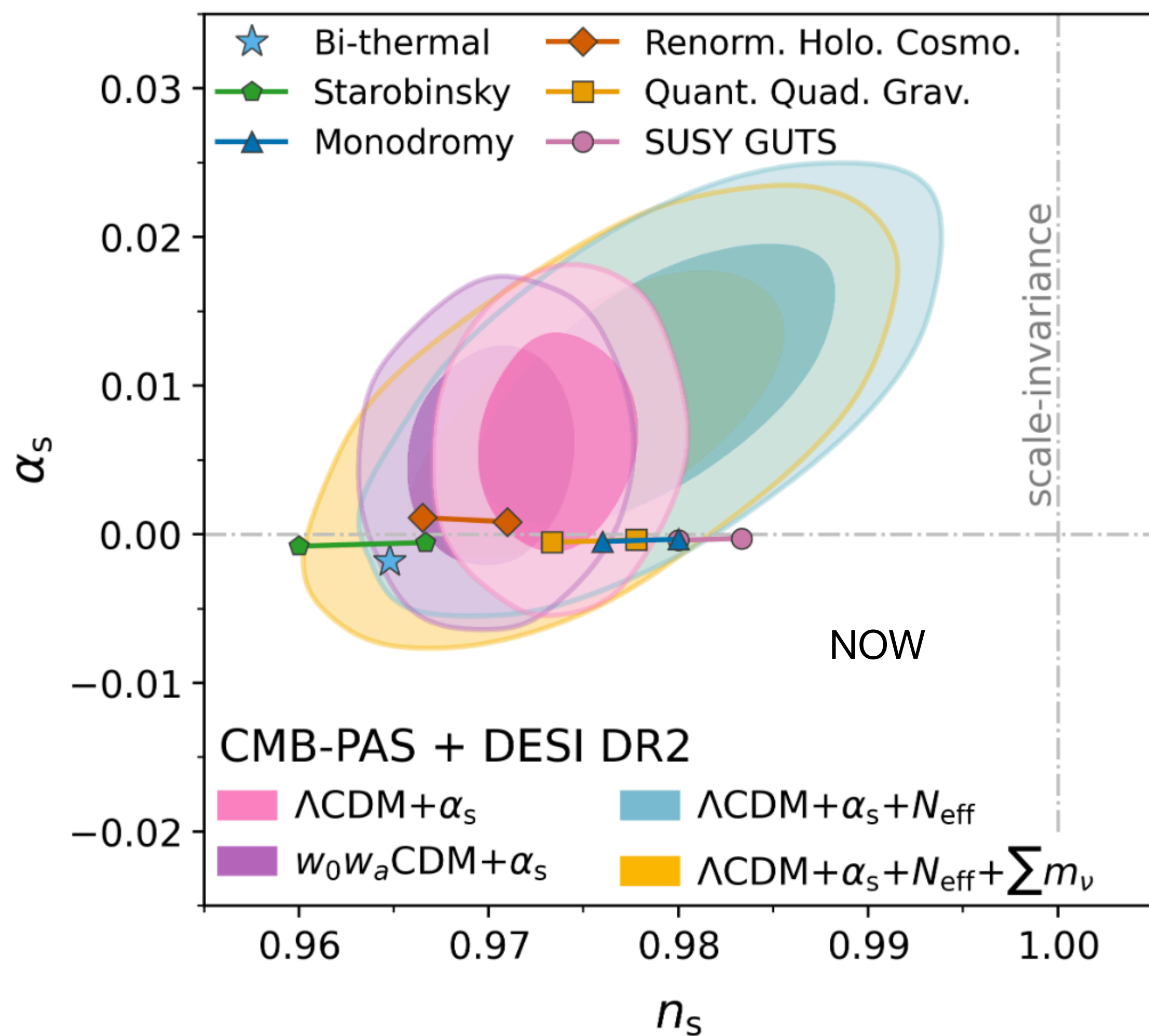
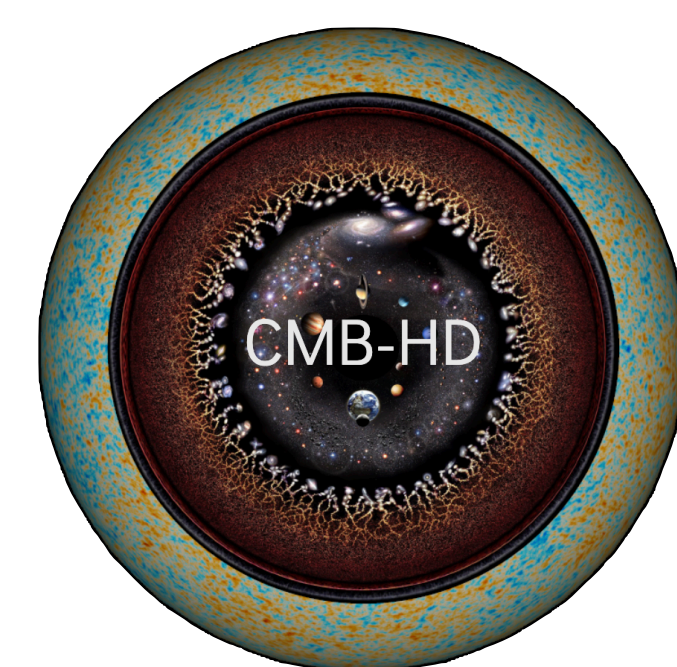
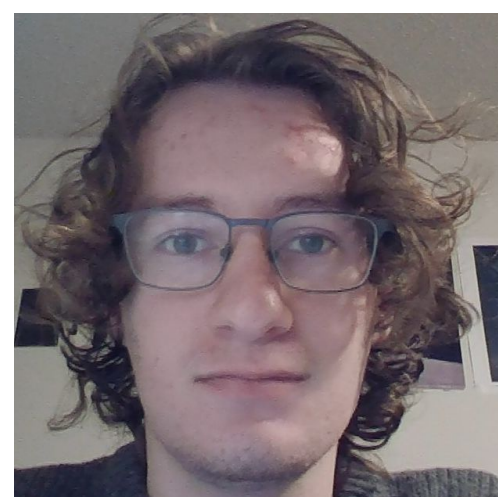
Cheslog, Finson, MacInnis, Sehgal & NA, to appear





# Future is Bright!

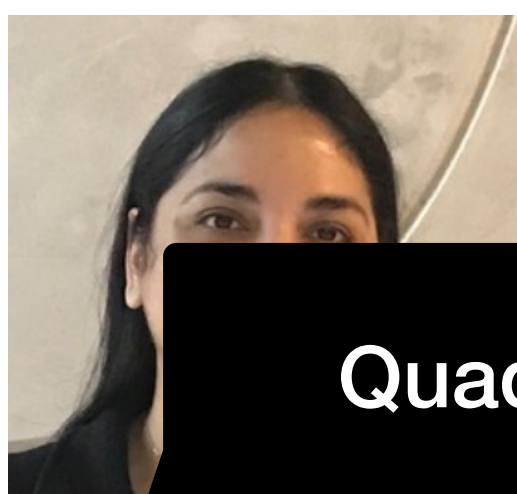
Cheslog, Finson, MacInnis, Sehgal & NA, to appear





# Future is Bright!

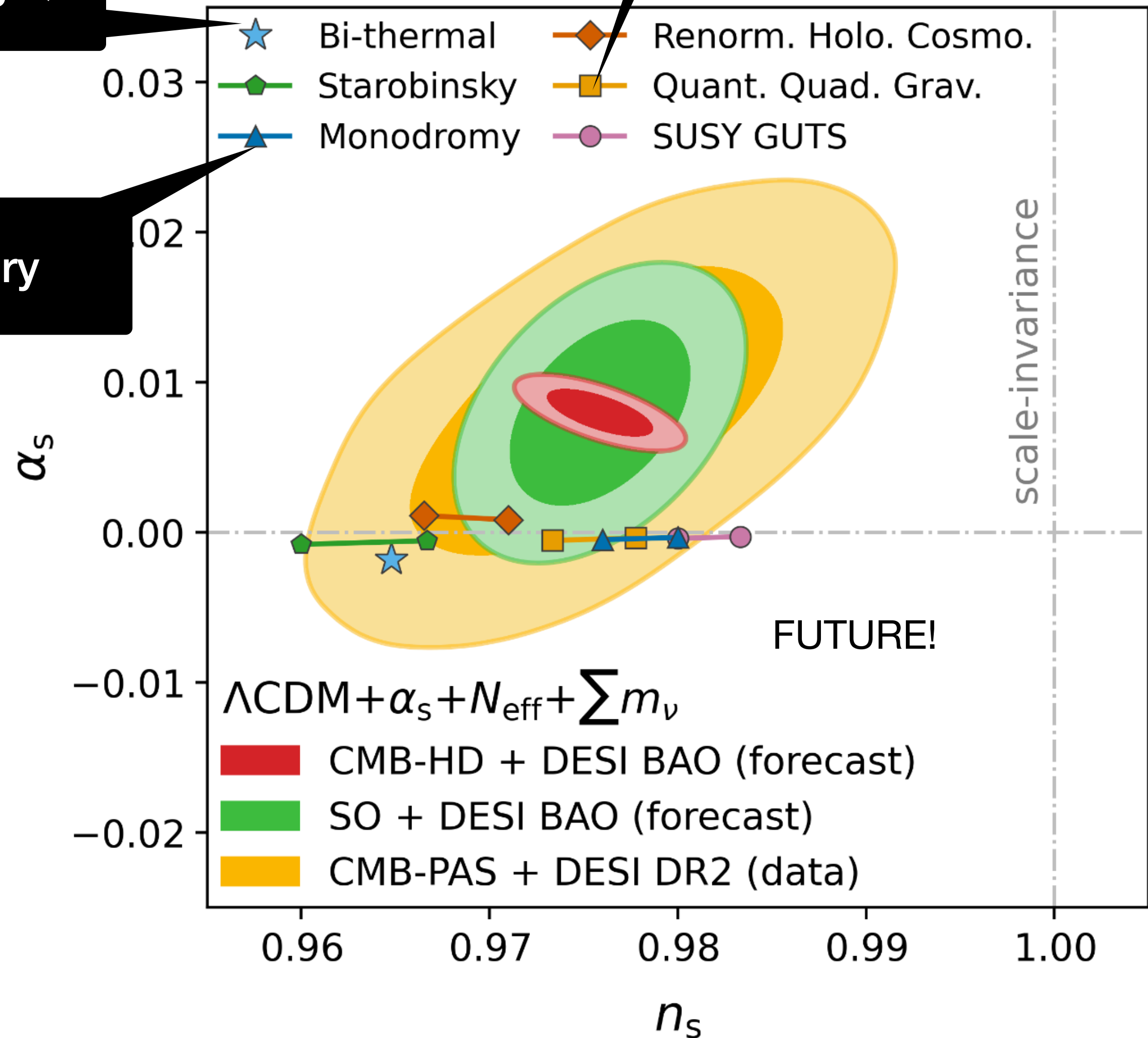
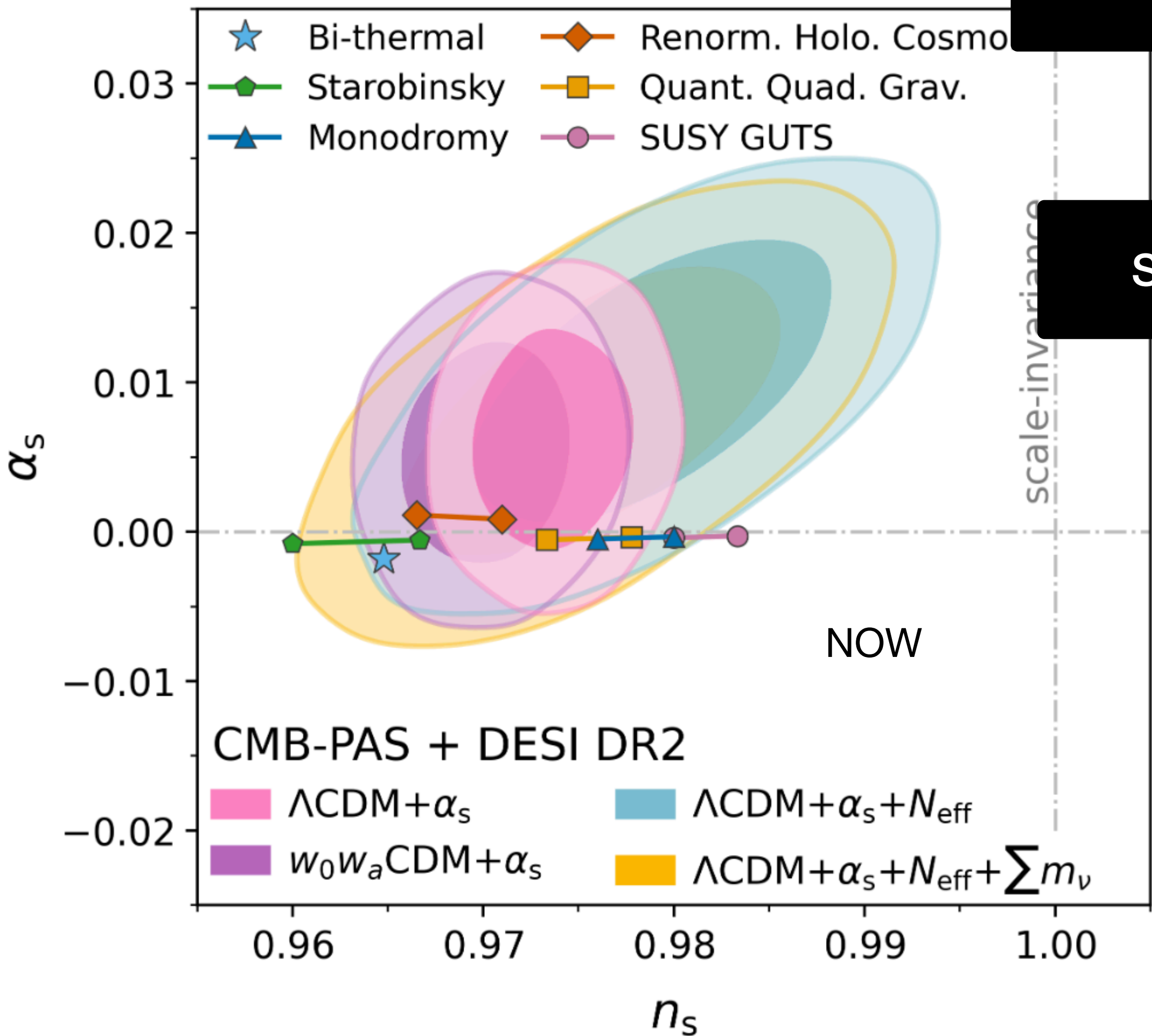
Cheslog, Finson, MacInnis, Sehgal & NA, to appear



Quadratic QG

Lorentz-violating QG

String Theory





# Future is Bright!

Cheslog, Finson, MacInnis, Sehgal & NA, to appear



Non-Inflation

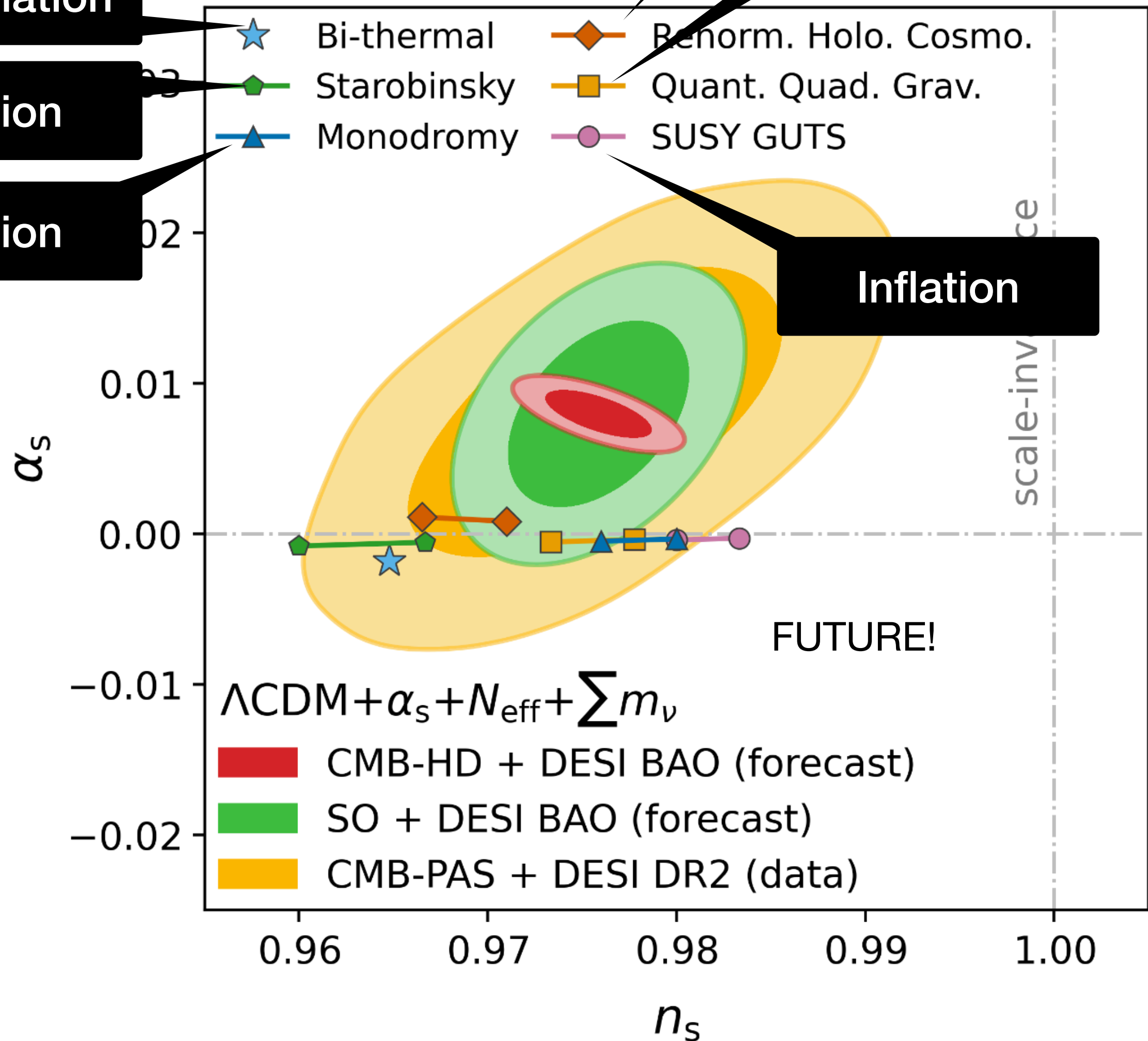
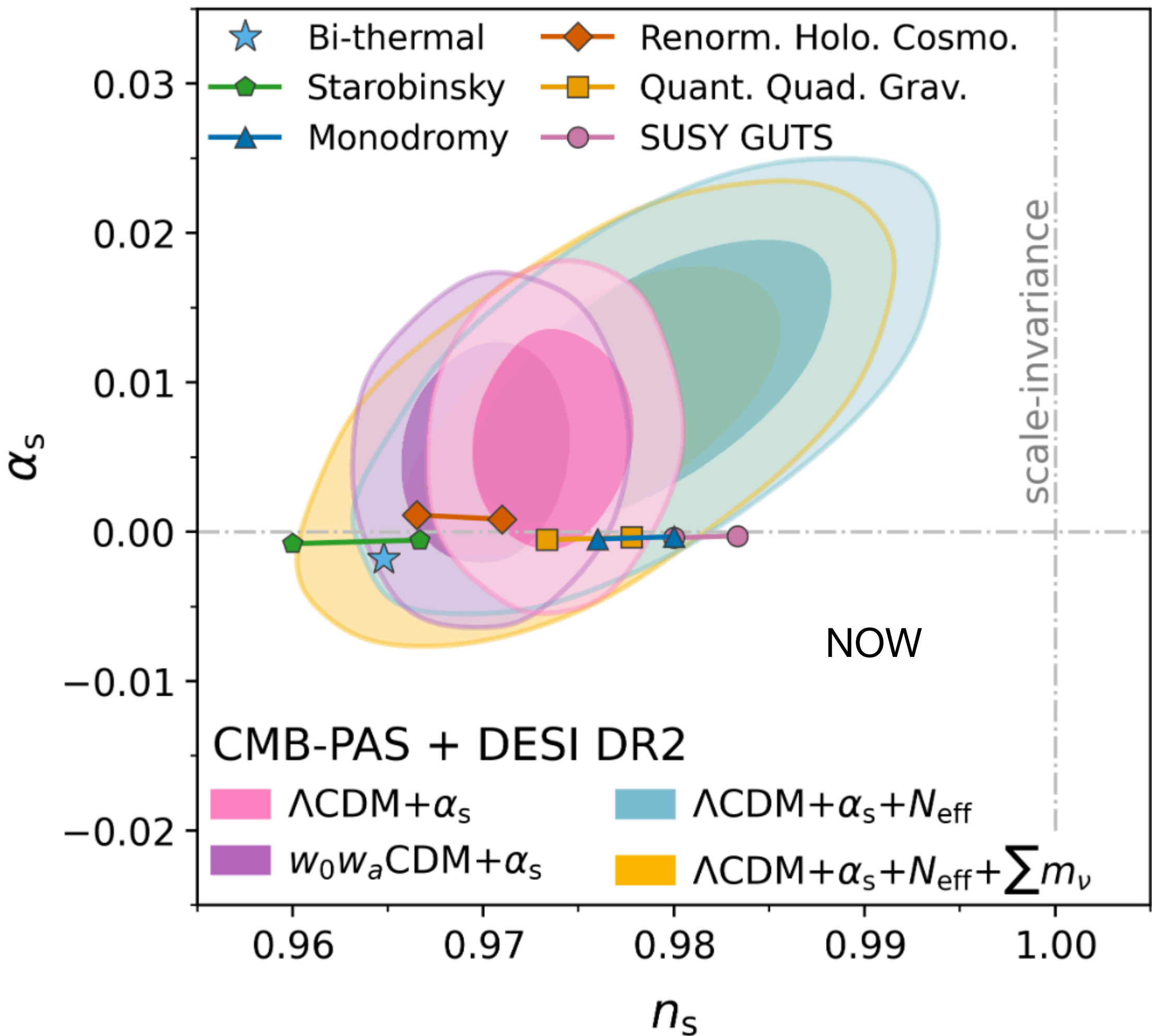
Non-Inflation??

Non-Inflation

Inflation

Inflation

Inflation





# Complex powerballs?

- Maybe the best description of spacetime inside black holes is a complex saddle point
- Quadratic (or Stelle) gravity: the only 4d diff-invariant renormalizable theory of gravity:

$$S_{\text{pure-grav}} = \int d^4x \sqrt{-g} \left( \frac{\omega}{3\sigma} R^2 - \frac{1}{2\sigma} C_{\mu\nu\rho\sigma}^2 \right)$$

- 2-2 holes: horizonless solutions (Holdom & Ren 2016, 2018)
- 🔥 Novel exact scale-invariant (but complex) solutions:  $ds^2 = -r^\alpha dt^2 + bdr^2 + r^2 d\Omega^2$

$$\alpha = \alpha_{\mp} \equiv \frac{1}{2} \left( 1 \mp i\sqrt{15} \right), \quad b = b_{\mp} \equiv \frac{3}{8} \left( 1 \mp i\sqrt{15} \right)$$

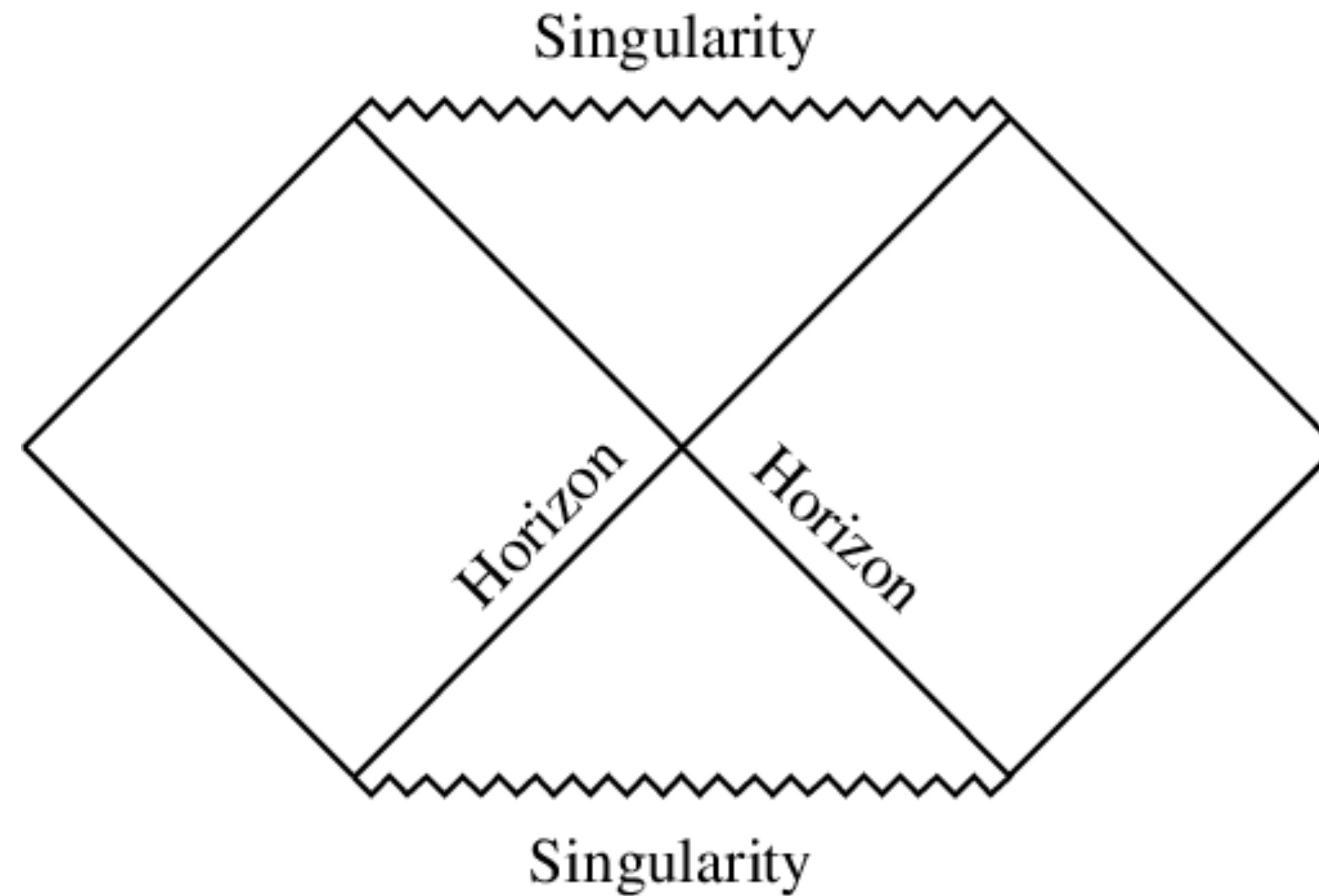


# Complex Powerballs:

## *Conformal Cores of Quantum Black Holes in Quadratic Gravity*



Niayesh Afshordi,<sup>1,2,3</sup> Ruolin Liu,<sup>1,2,3</sup> and Jerome Quintin<sup>4,3,2</sup>

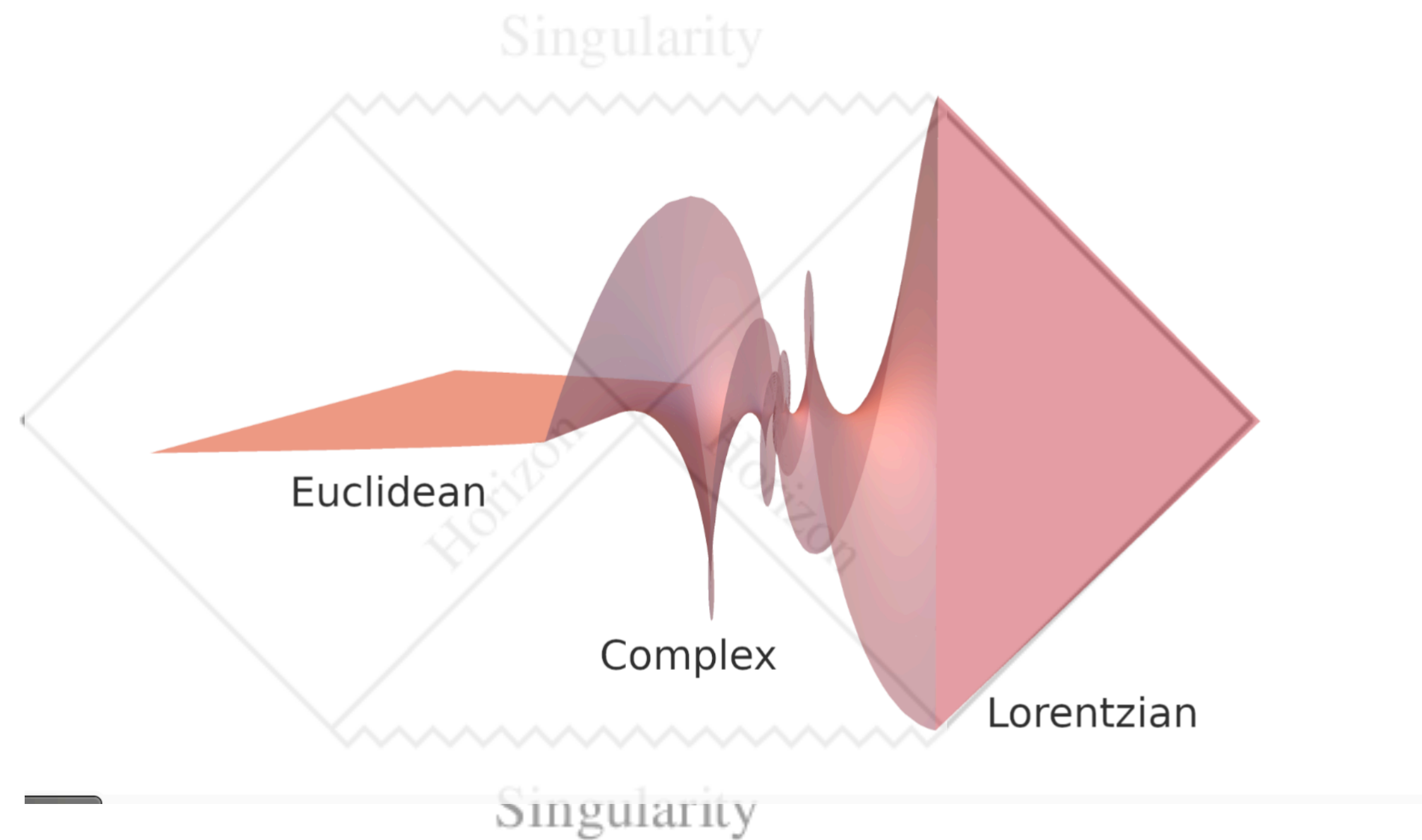




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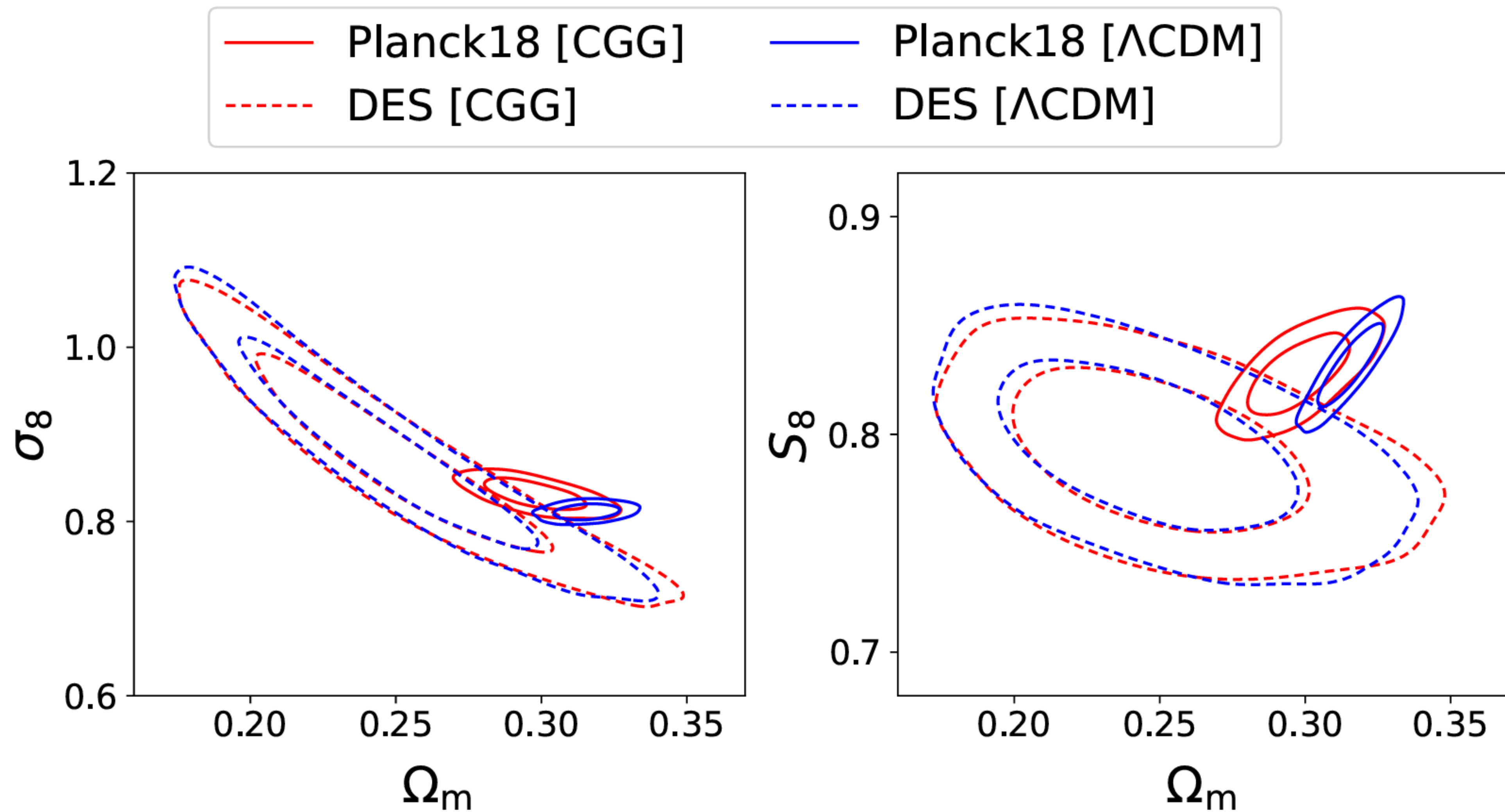


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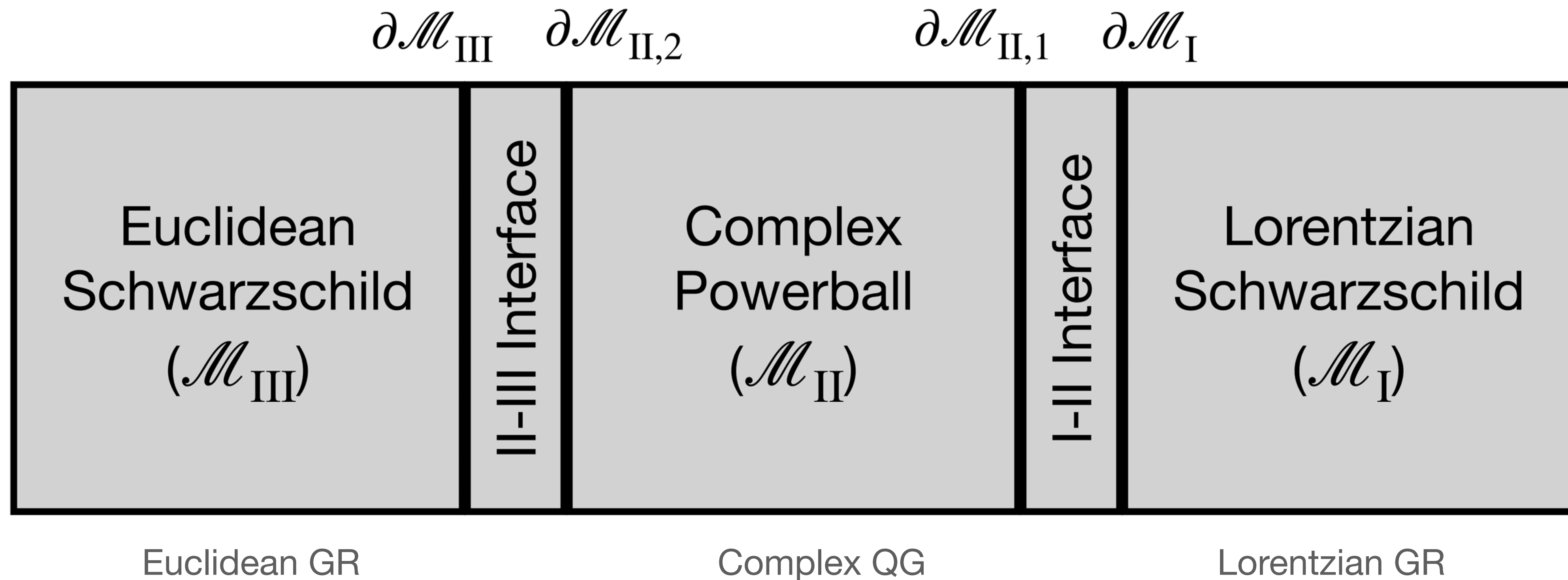


# $S_8$ tension





# Matching GR to QG across strong-coupling membrane

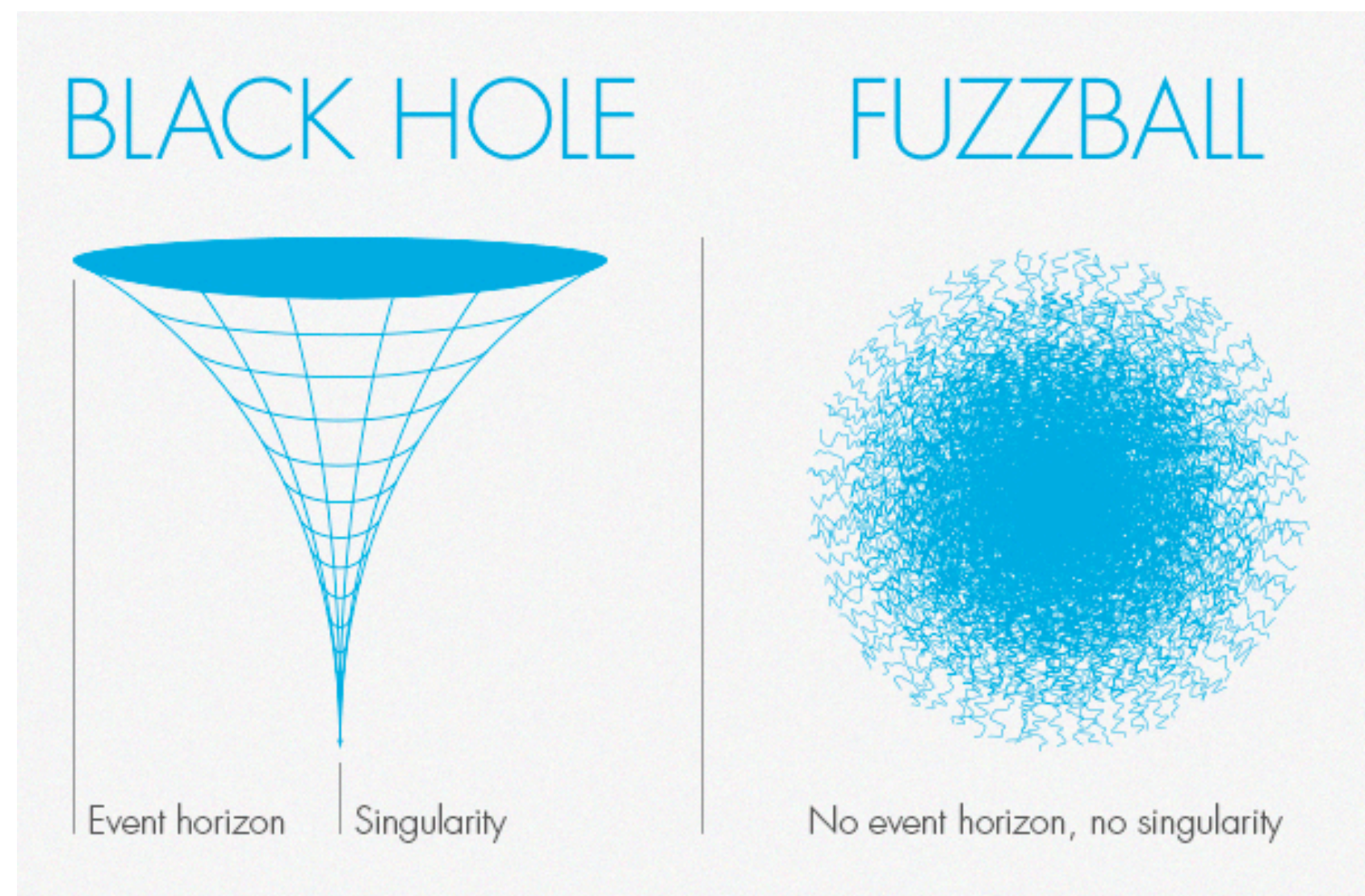


- For strong coupling @Planck scale, membrane hovers a Planck proper length outside the would-be horizon



# Fuzzballs in String Theory

Physics Reports 467 (2008) 117–171



Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)

## The fuzzball proposal for black holes

Kostas Skenderis\*, Marika Taylor

*Institute for Theoretical Physics, University of Amsterdam, Valckenierstraat 65, 1018XE Amsterdam, The Netherlands*

IOP PUBLISHING

CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **25** (2008) 135005 (45pp)

[doi:10.1088/0264-9381/25/13/135005](https://doi.org/10.1088/0264-9381/25/13/135005)

## Radiation from the non-extremal fuzzball

Borun D Chowdhury and Samir D Mathur

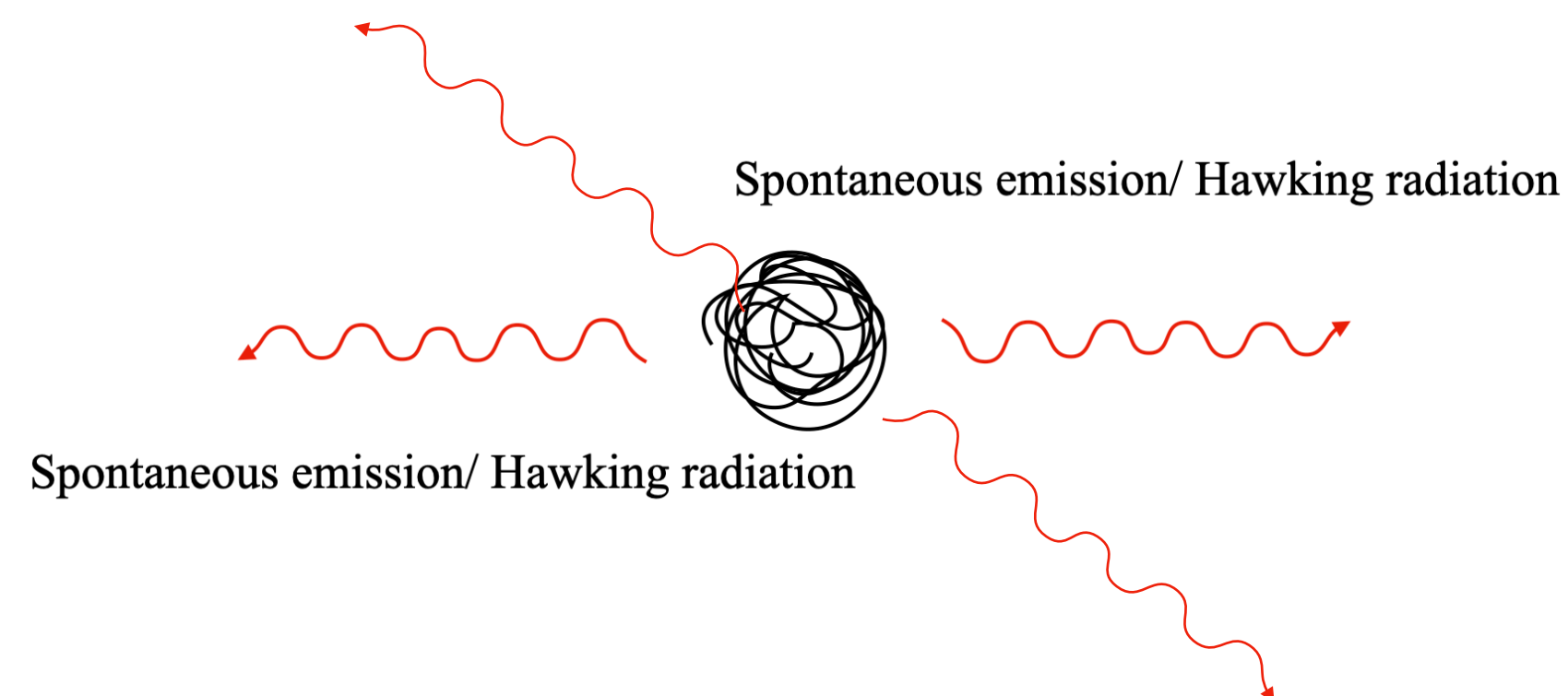
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: [borundev@mps.ohio-state.edu](mailto:borundev@mps.ohio-state.edu) and [mathur@mps.ohio-state.edu](mailto:mathur@mps.ohio-state.edu)

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Published 17 June 2008

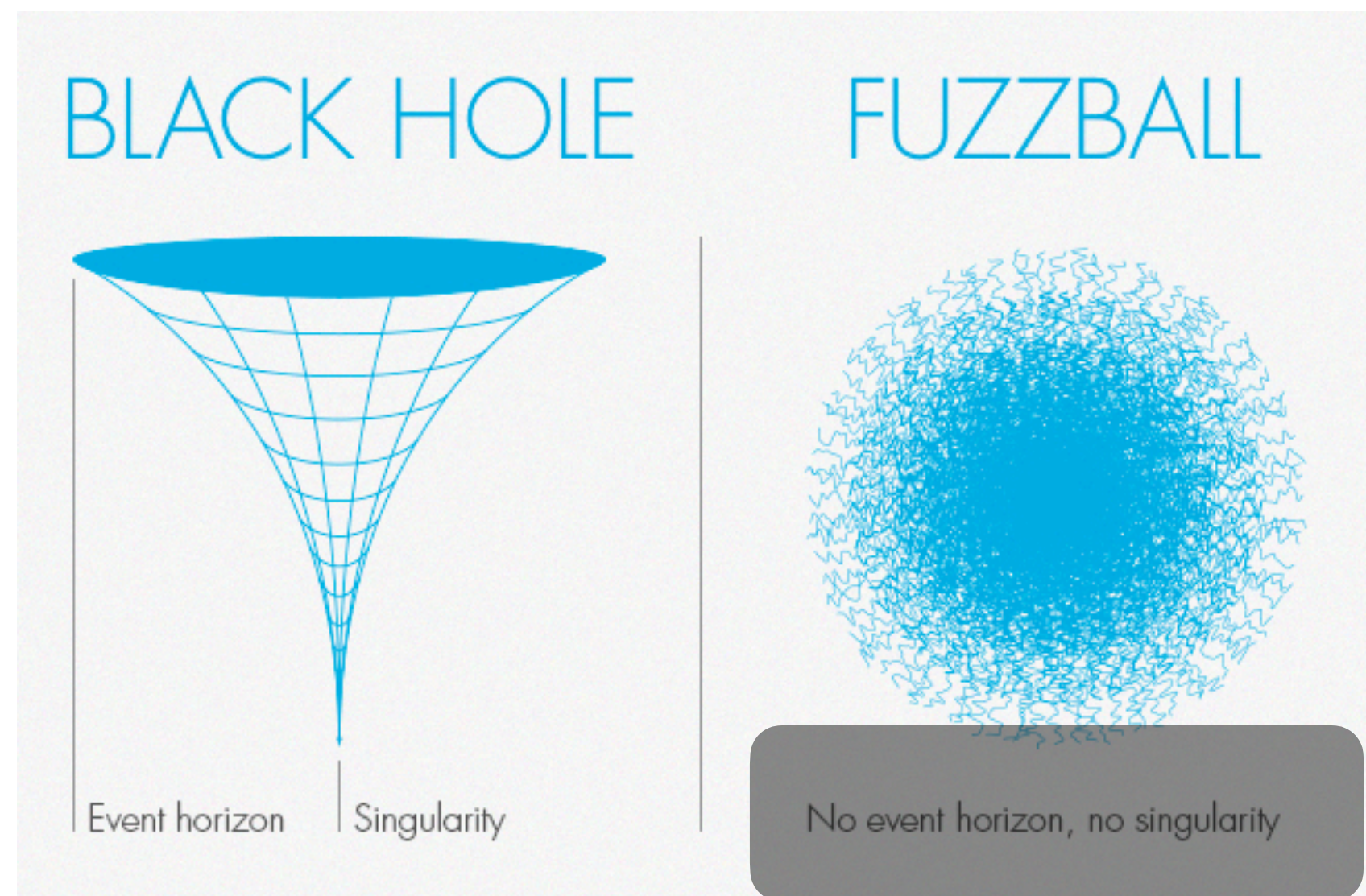
Online at [stacks.iop.org/CQG/25/135005](http://stacks.iop.org/CQG/25/135005)





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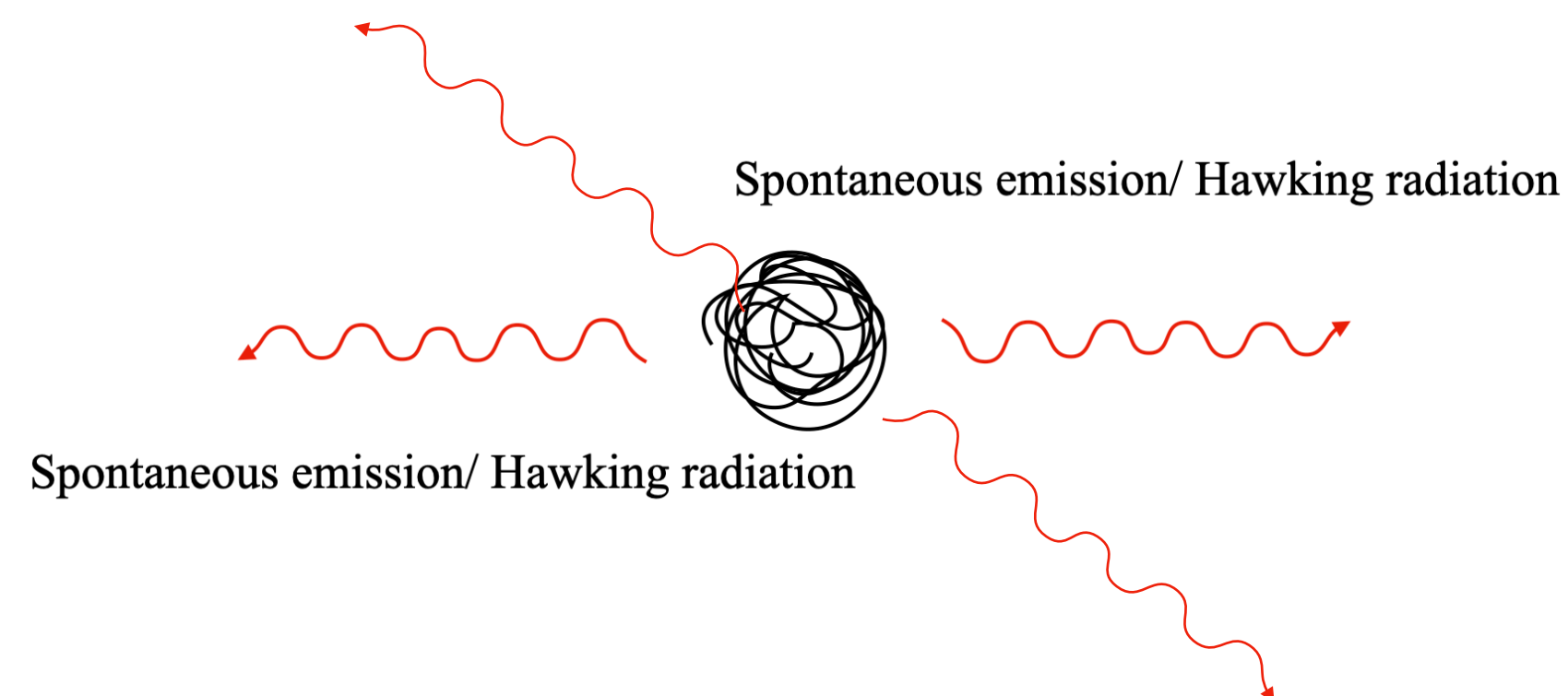
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

E-mail: [borundev@mps.ohio-state.edu](mailto:borundev@mps.ohio-state.edu) and [mathur@mps.ohio-state.edu](mailto:mathur@mps.ohio-state.edu)

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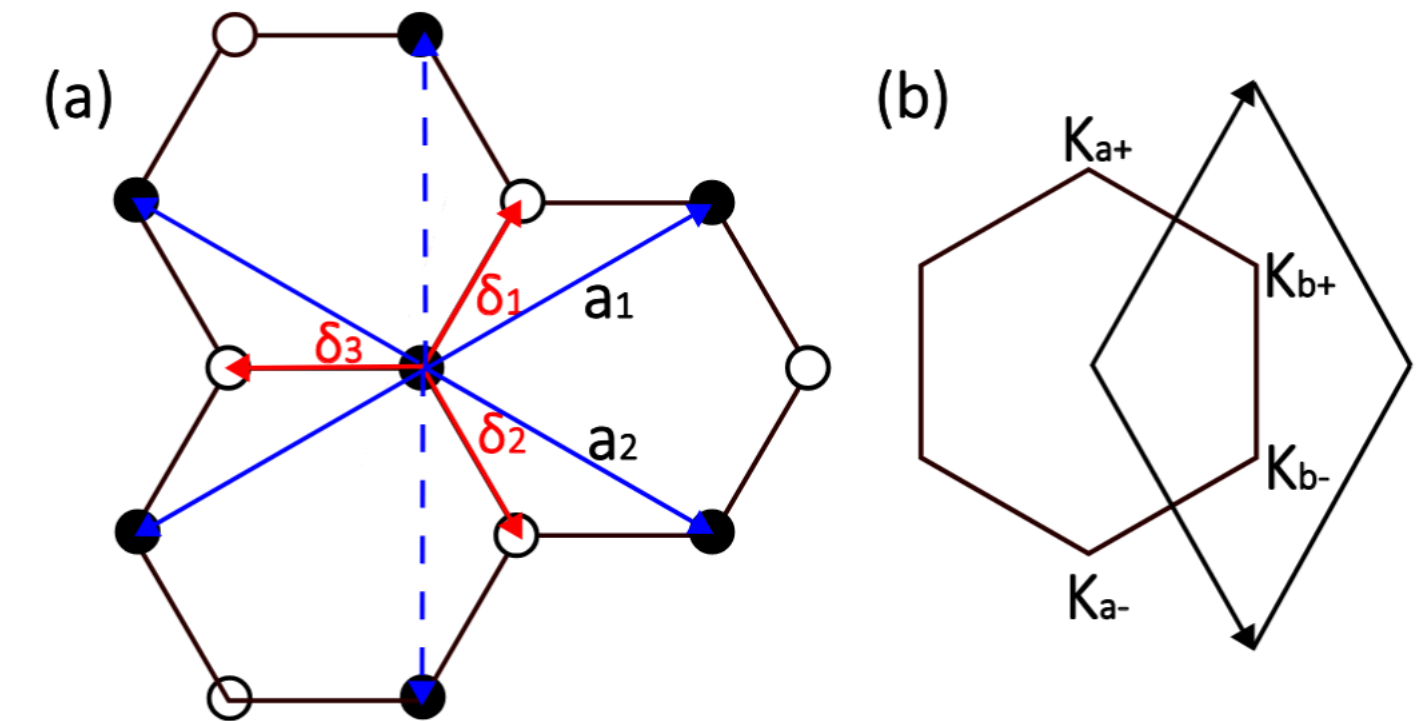




# Smart Holes<sup>TM</sup>

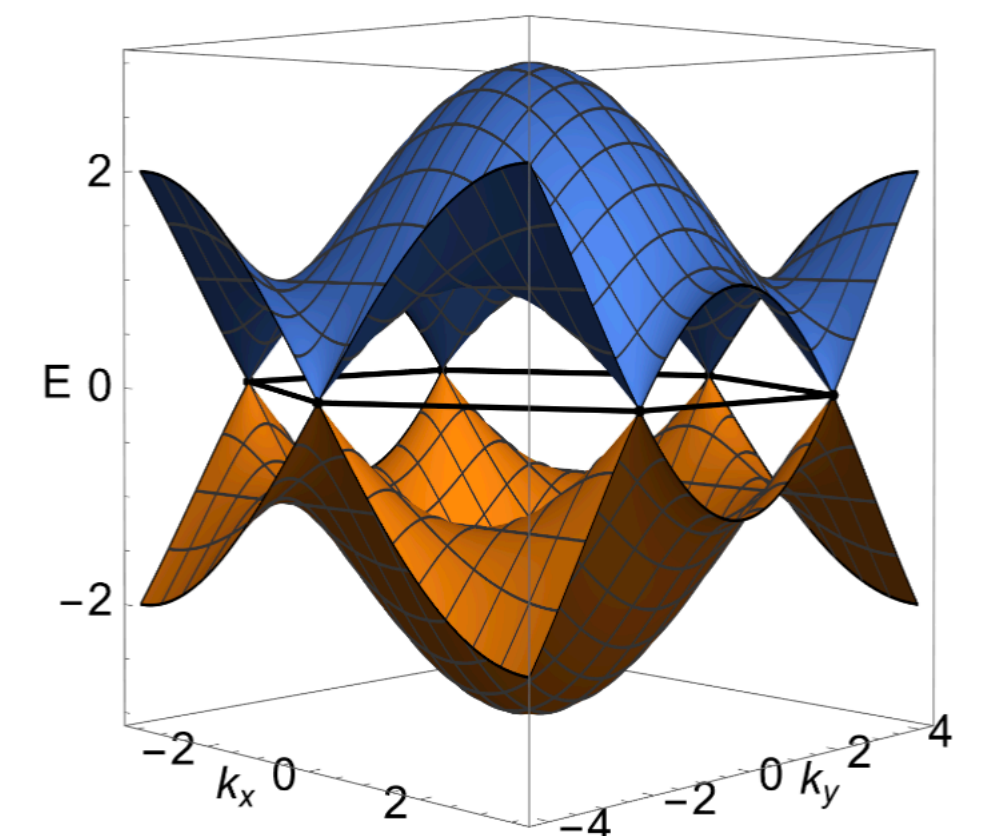
## Towards quantum simulations of black holes

- We can construct **condensed matter systems** that have the same **entropy** *and* **temperature** as **black holes**
- Can they show echoes?



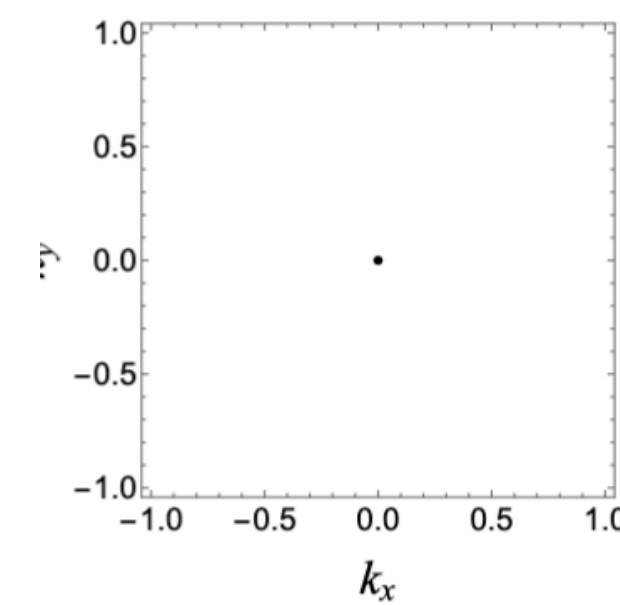
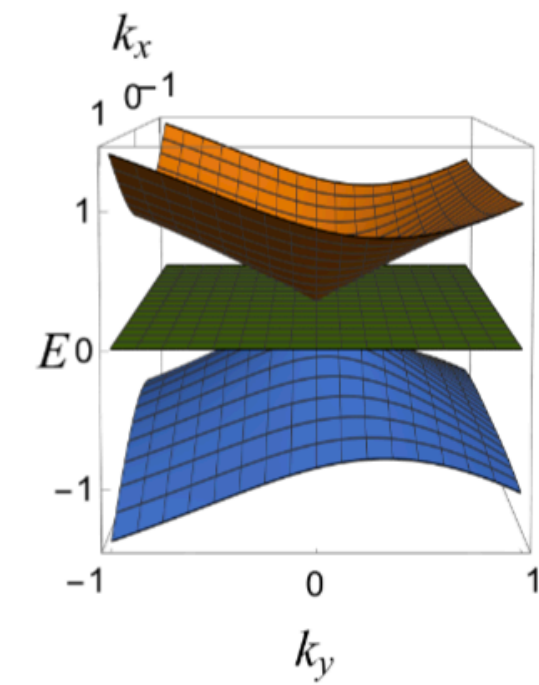
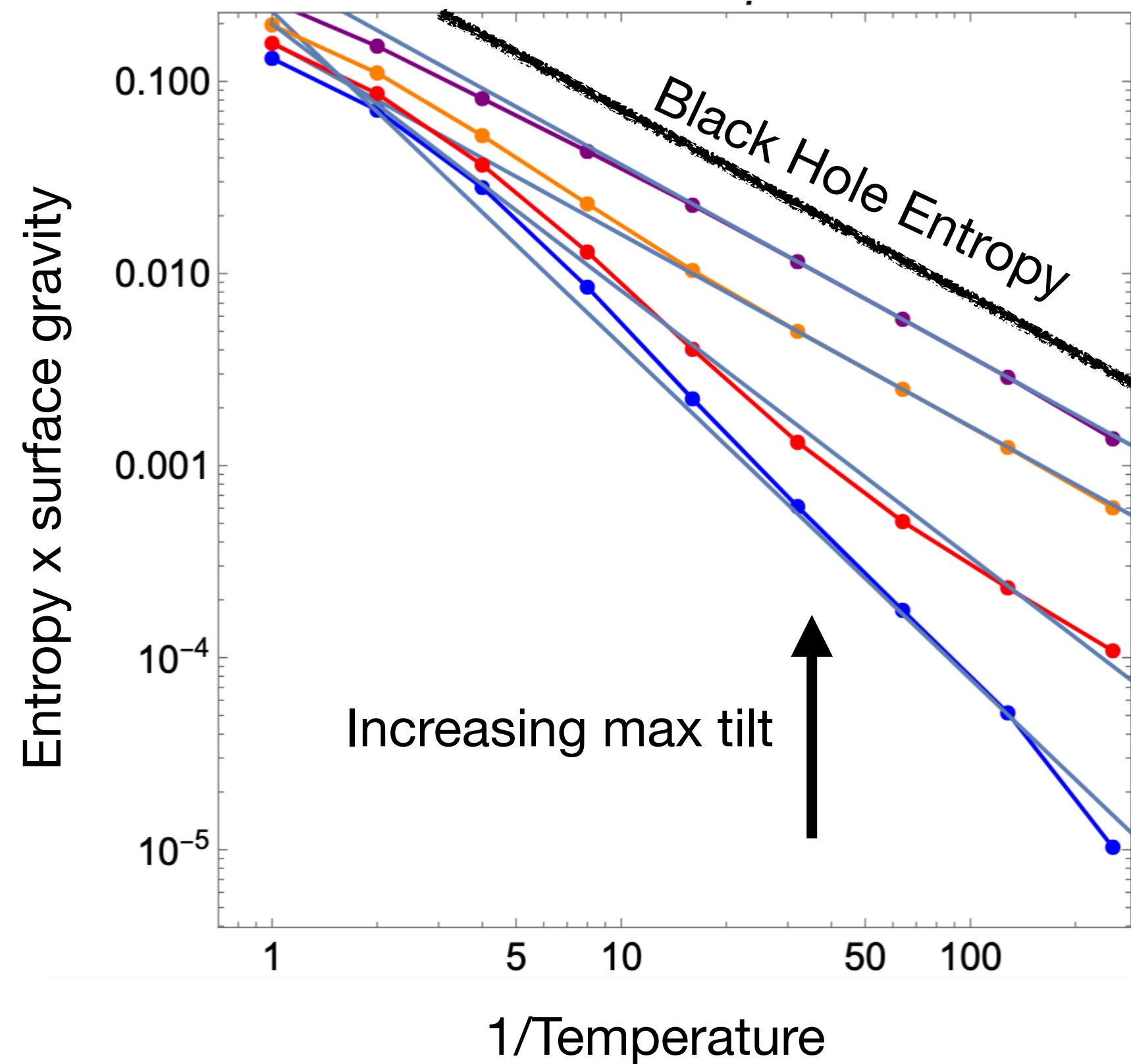
**Smart Holes: Analogue Black Holes with the right Temperature and Entropy**

Jiayue Yang,<sup>a,b,c</sup> Niayesh Afshordi,<sup>a,b,c</sup> Mahdi Torabian,<sup>b</sup> Seyed Akbar Jafari<sup>d</sup> and G. Baskaran<sup>b,e,f</sup>

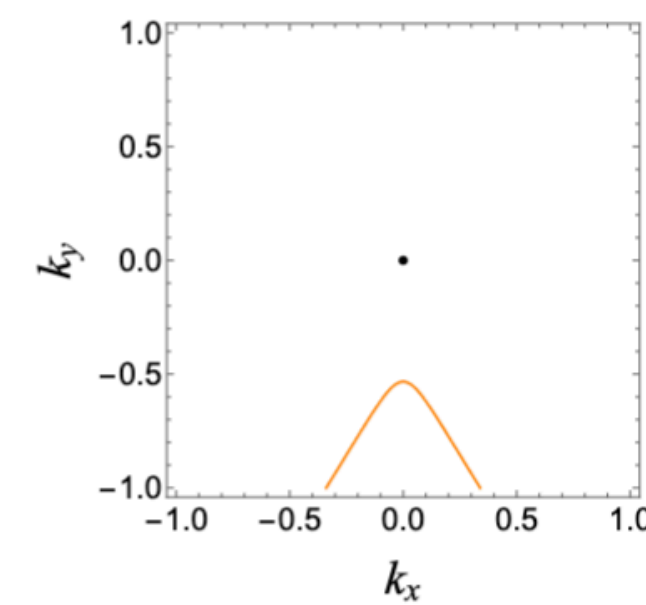
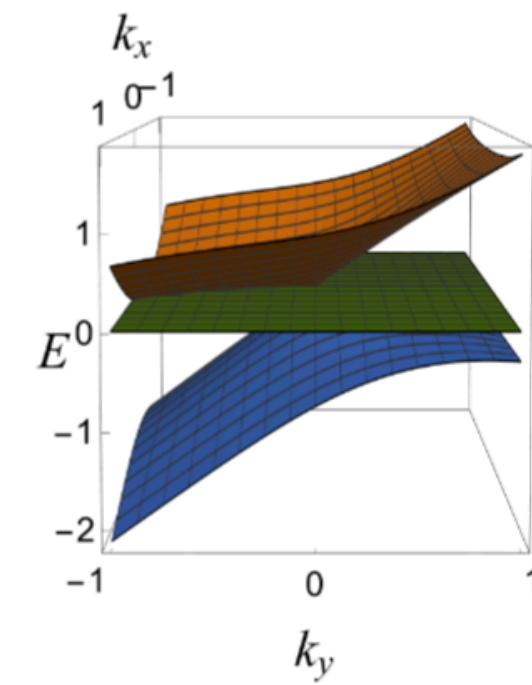




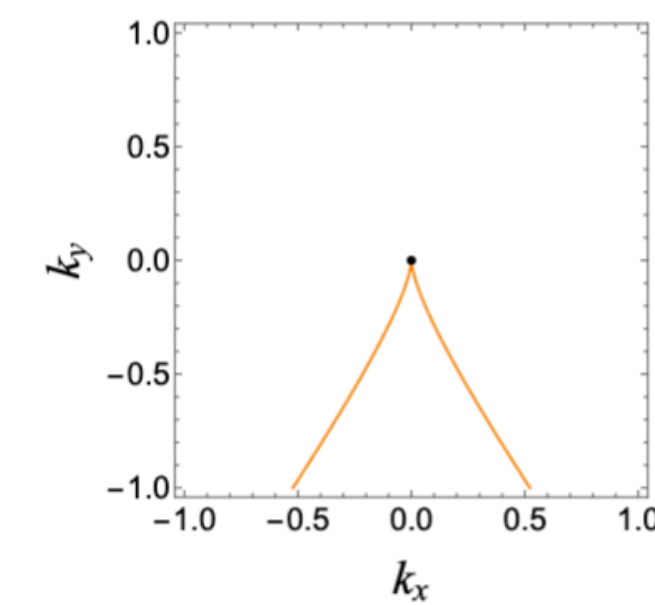
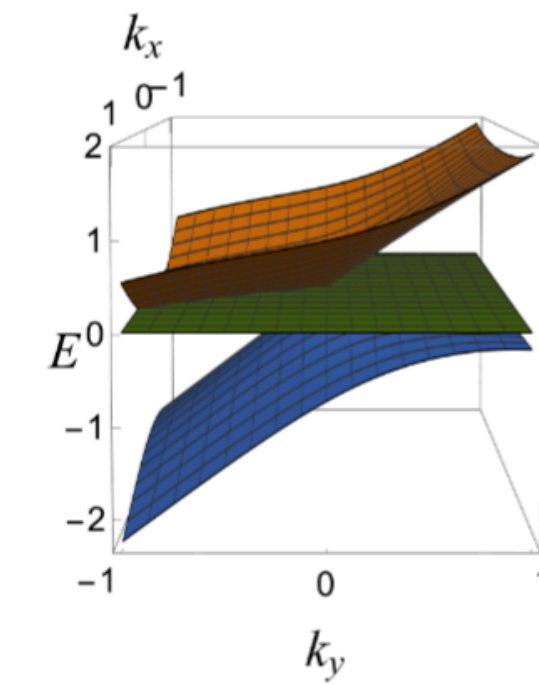
# Tilting the Dirac cone in honeycomb lattice



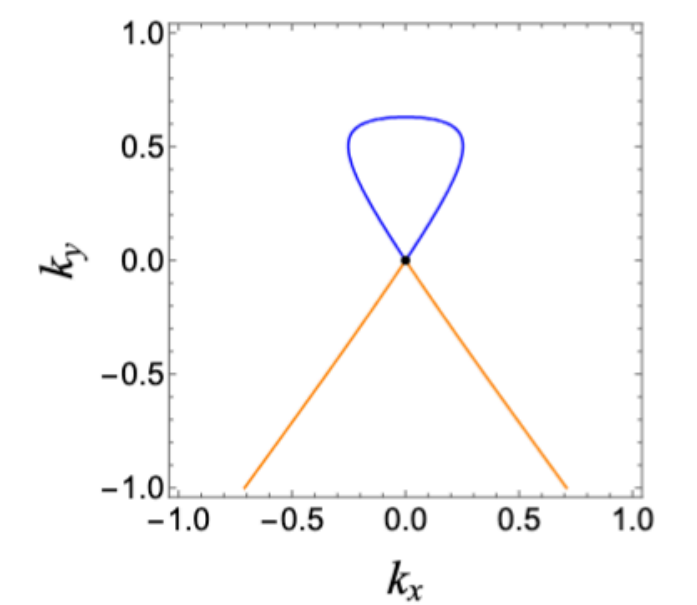
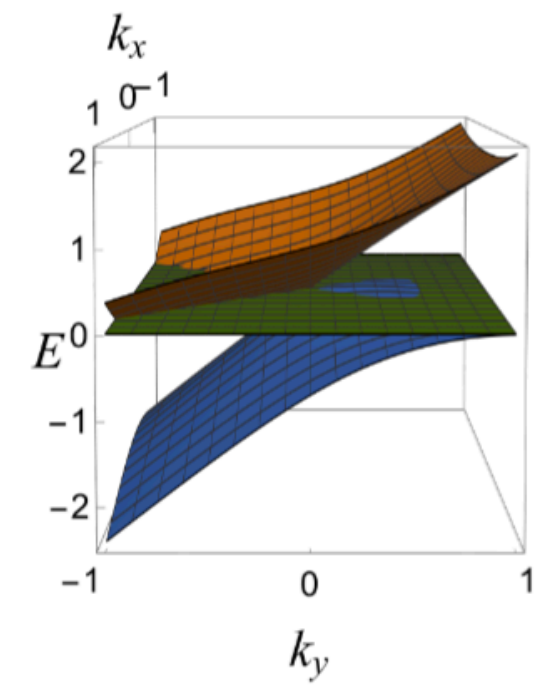
(a) Tilt  $\zeta = 0$



(b) Tilt  $\zeta = 6/7$



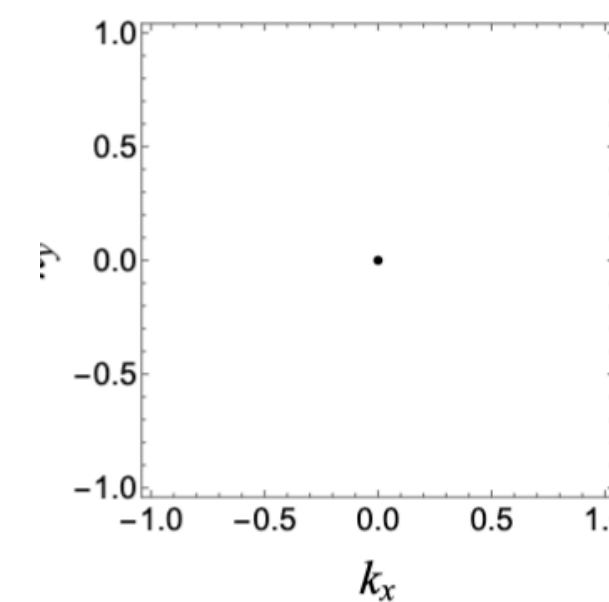
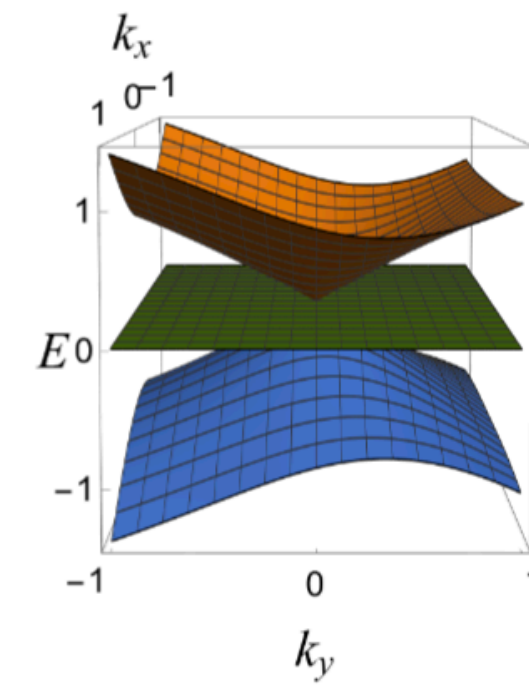
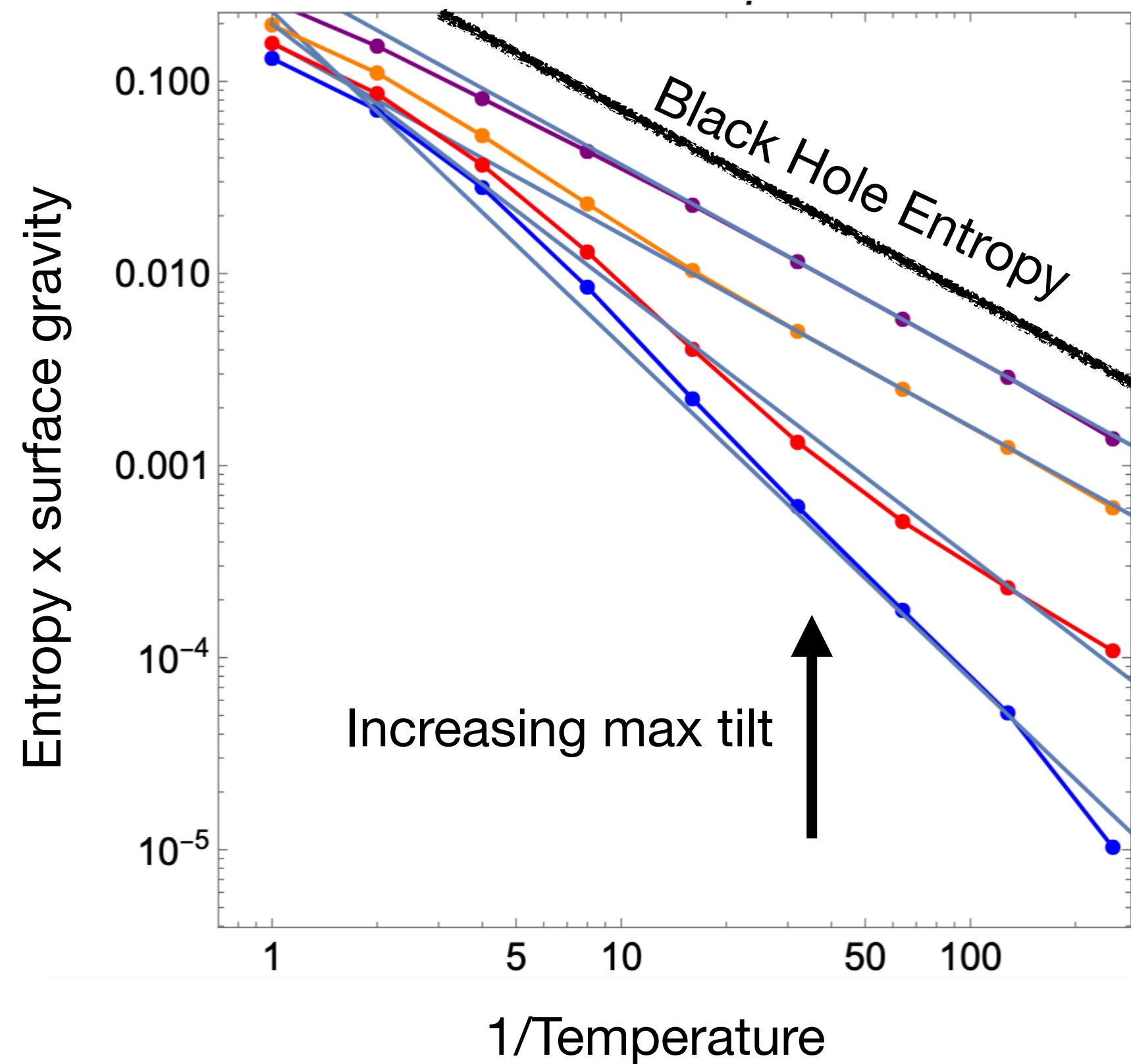
(c) Tilt  $\zeta = 1$



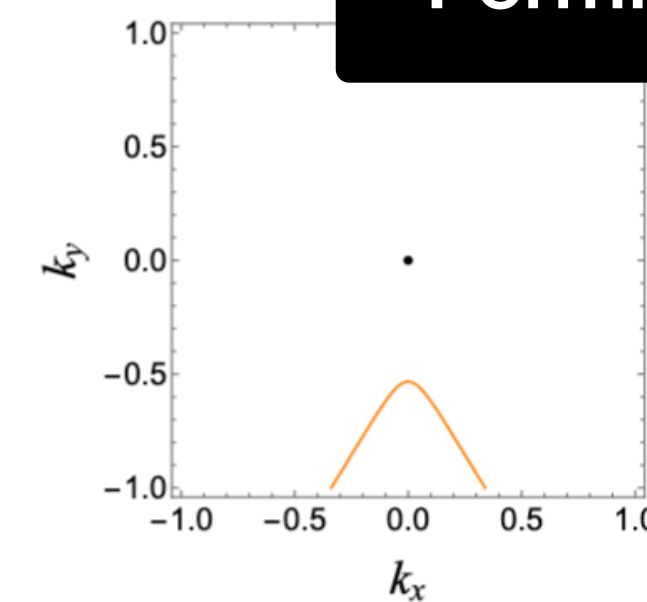
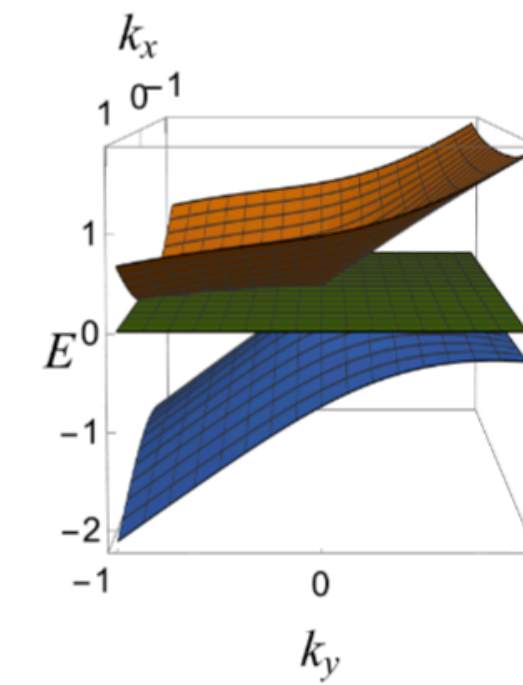
(d) Tilt  $\zeta = 6/5$



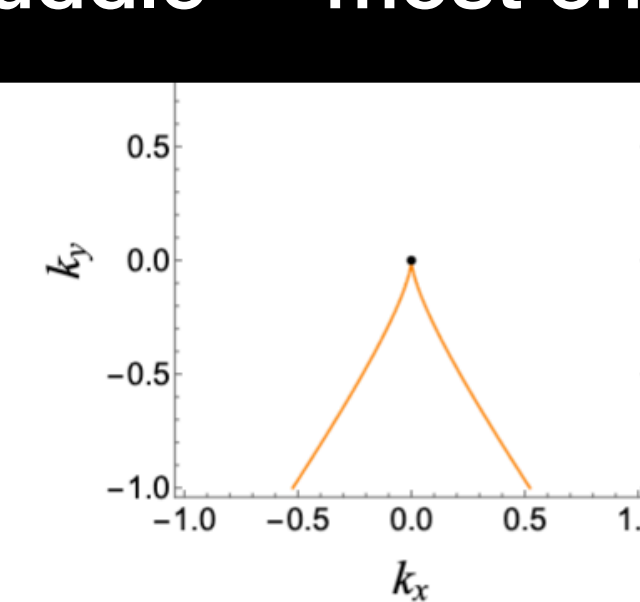
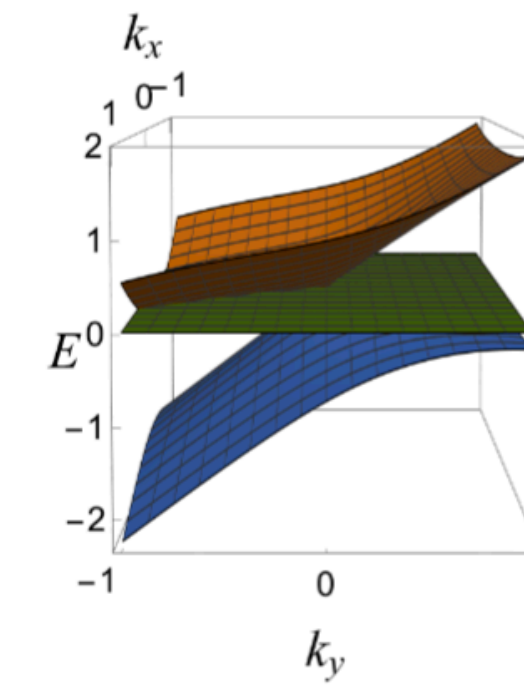
# Tilting the Dirac cone in honeycomb lattice



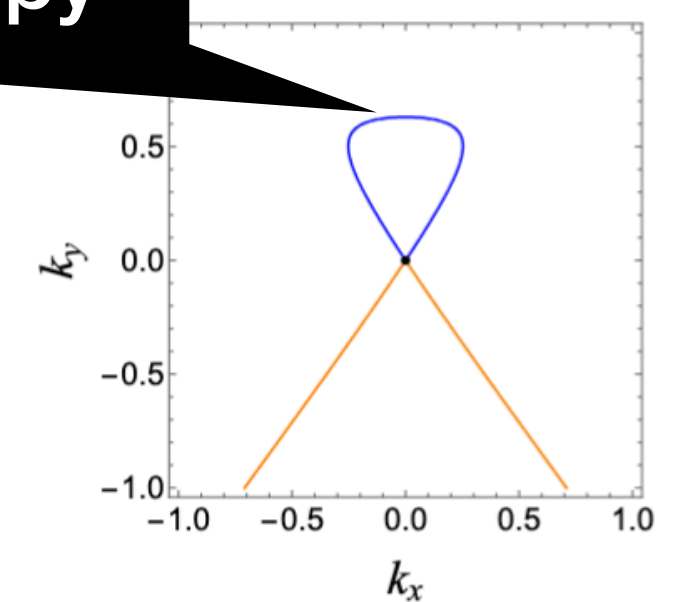
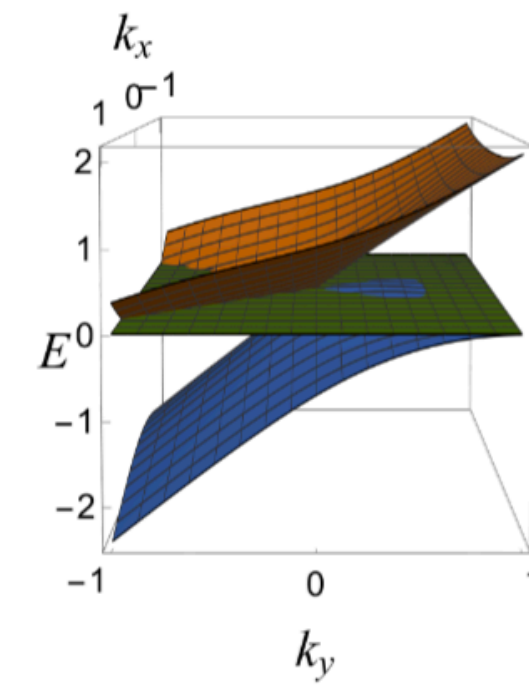
(a) Tilt  $\zeta = 0$



(b) Tilt  $\zeta = 6/7$



(c) Tilt  $\zeta = 1$



(d) Tilt  $\zeta = 6/5$

Fermi puddle  $\Rightarrow$  most entropy



# CP-symmetry ( $\mathbb{RP}^3$ geon)

Black hole microstates vs the additivity conjectures

Patrick Hayden<sup>1</sup> and Geoff Penington,<sup>2</sup>

<sup>1</sup>*Stanford Institute for Theoretical Physics, Stanford University, Stanford CA 94305 USA*

<sup>2</sup>*Center for Theoretical Physics,, University of California, Berkeley, CA 94720 USA*

December 16, 2020

## Abstract

We argue that one of the following statements must be true: (a) extensive violations of quantum information theory's additivity conjectures exist or (b) there exists a set of 'disentangled' black hole microstates that can account for the entire Bekenstein-Hawking entropy, up to at most a subleading  $O(1)$  correction. Possibility (a) would be a significant result in quantum communication theory, demonstrating that entanglement can enhance the ability to transmit information much more than has currently been established. Option (b) would provide new insight into the microphysics of black holes. In particular, the disentangled microstates would have to have nontrivial structure at or outside the black hole horizon, assuming the validity of the quantum extremal surface prescription for calculating entanglement entropy in AdS/CFT.

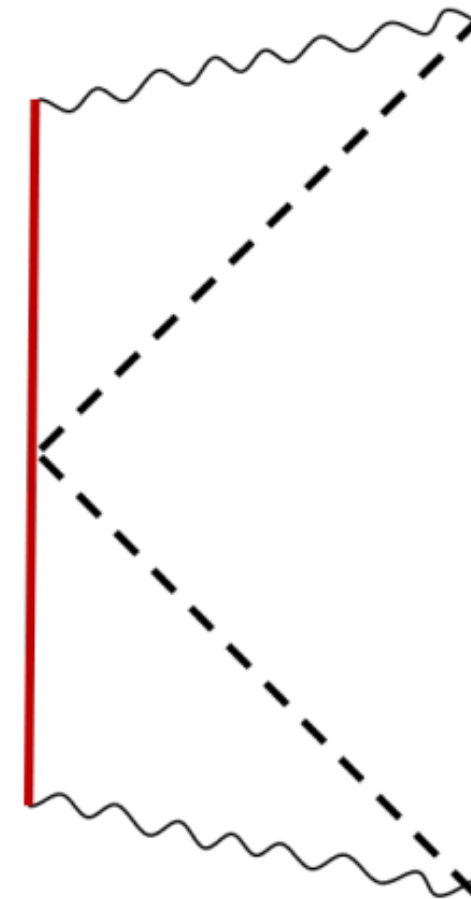


Figure 3: Penrose diagram for a  $\mathbb{Z}_2$  quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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



# CP-symmetry ( $\mathbb{RP}^3$ geon)

$\mathbb{Z}_2$  identification  $\rightarrow$   
Boltzmann reflection

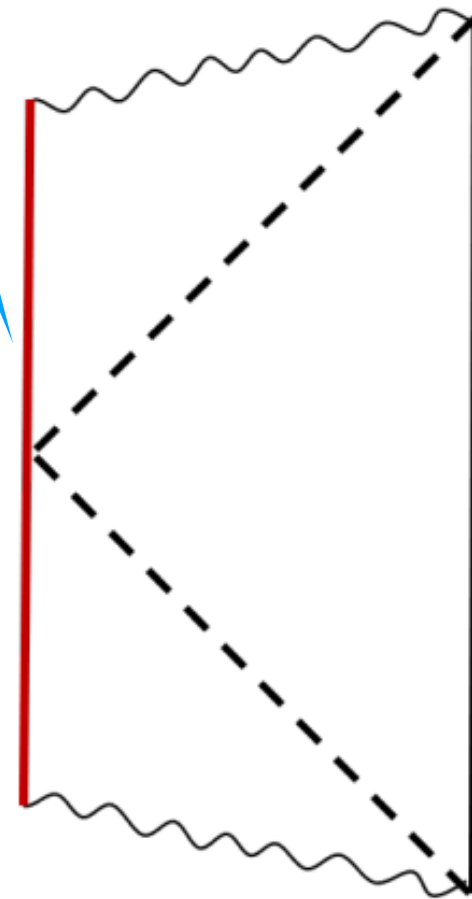


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$$R = \exp \left( -\frac{\hbar\omega}{kT_H} \right)$$



# Islands Far Outside the Horizon

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**Raphael Bousso and Geoff Penington**

*Center for Theoretical Physics and Department of Physics,  
University of California, Berkeley, California 94720, U.S.A.*

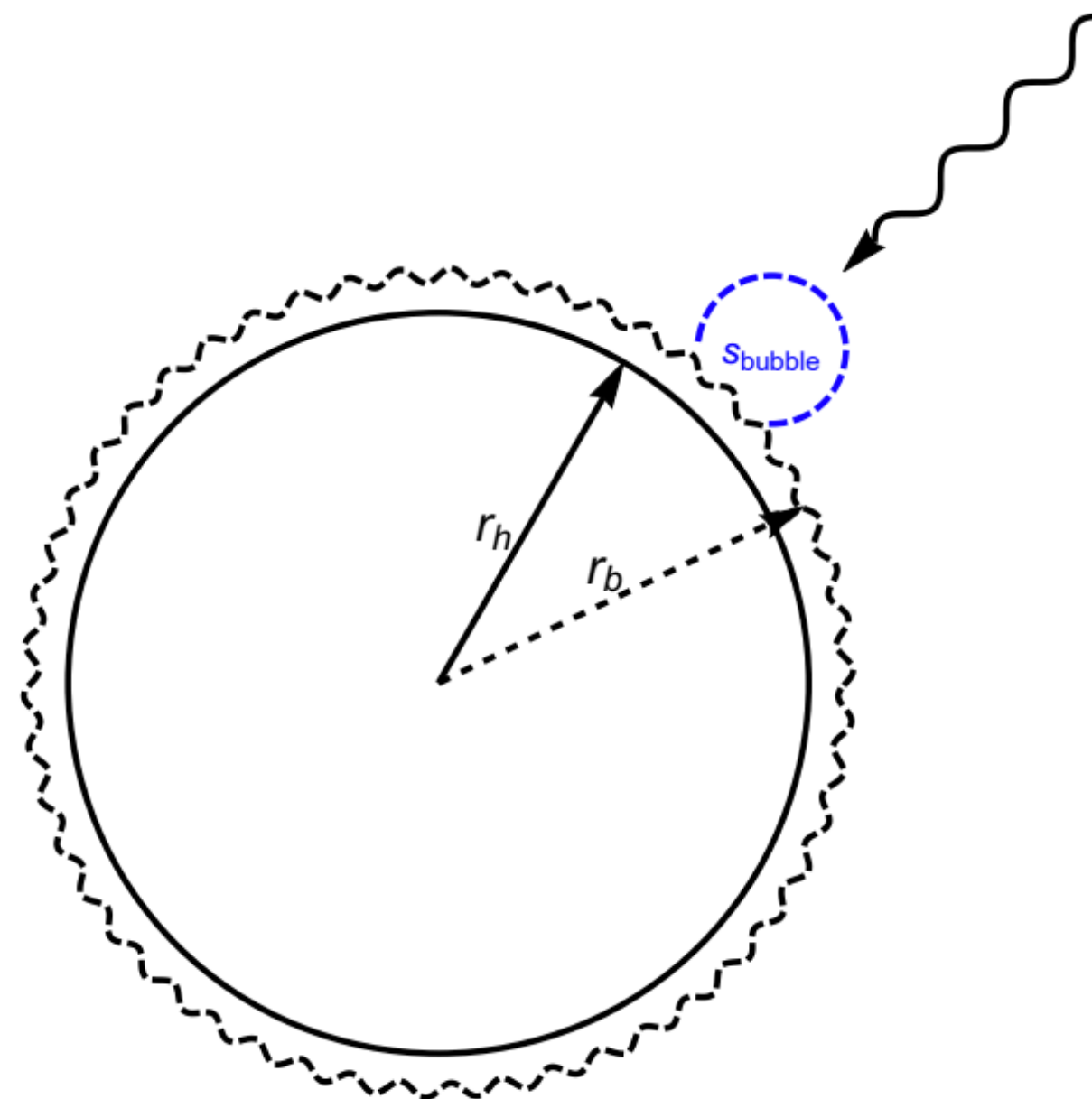
*E-mail:* [bousso@berkeley.edu](mailto:bousso@berkeley.edu), [geoffp@berkeley.edu](mailto:geoffp@berkeley.edu)

**ABSTRACT:** Information located in an entanglement island in semiclassical gravity can be nonperturbatively reconstructed from distant radiation, implying a radical breakdown of effective field theory. We show that this occurs well outside of the black hole stretched horizon. We compute the island associated to large-angular momentum Hawking modes of a four-dimensional Schwarzschild black hole. These modes typically fall back into the black hole but can be extracted to infinity by relativistic strings or, more abstractly, by asymptotic boundary operators constructed using the timelike tube theorem. Remarkably, we find that their island can protrude a distance of order  $\sqrt{\ell_p r_{\text{hor}}}$  outside the horizon. This is parametrically larger than the Planck scale  $\ell_p$  and is comparable to the Bohr radius for supermassive black holes. Therefore, in principle, a distant observer can determine experimentally whether the black hole information paradox is resolved by complementarity, or by a firewall.



# Electromagnetic Albedo of Quantum Black Holes *(Chua & NA 2021)*

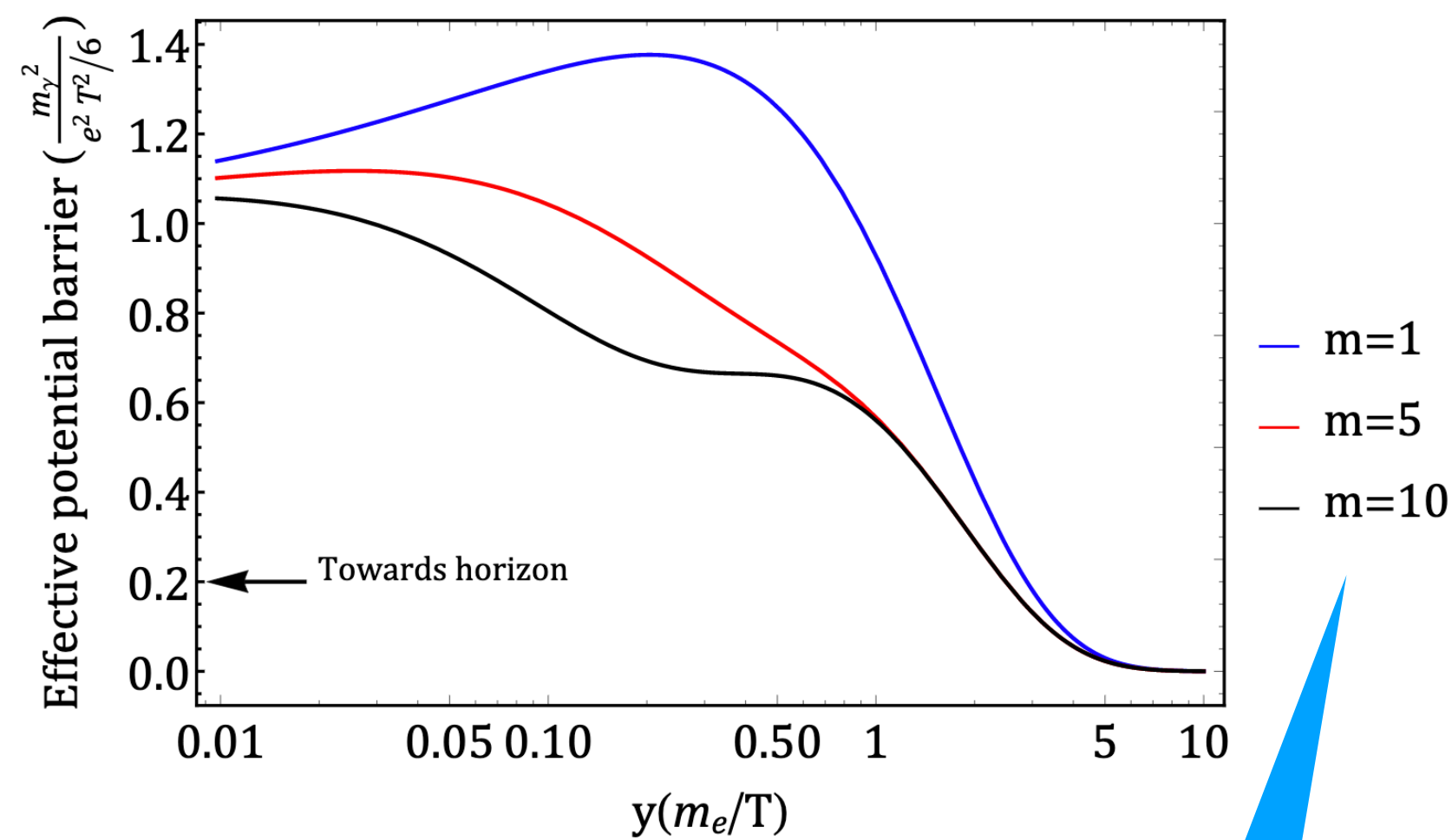
- Reflection off virtual electron-positron pairs near horizon  $\rightarrow$  Boltzmann Albedo for photons
- No quantum gravity needed!



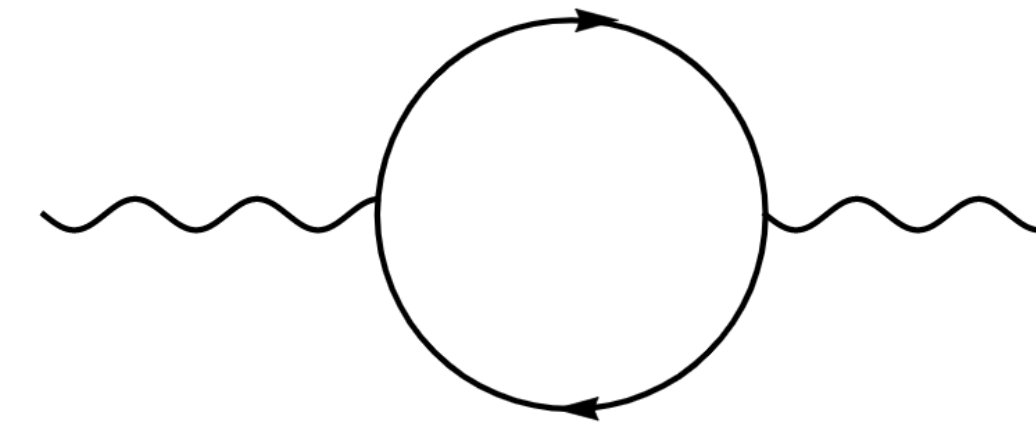


# Two independent derivations

- Photon mass acquired through Hawking Plasma
- Projecting photon 1-loop propagator from Minkowski to Rindler



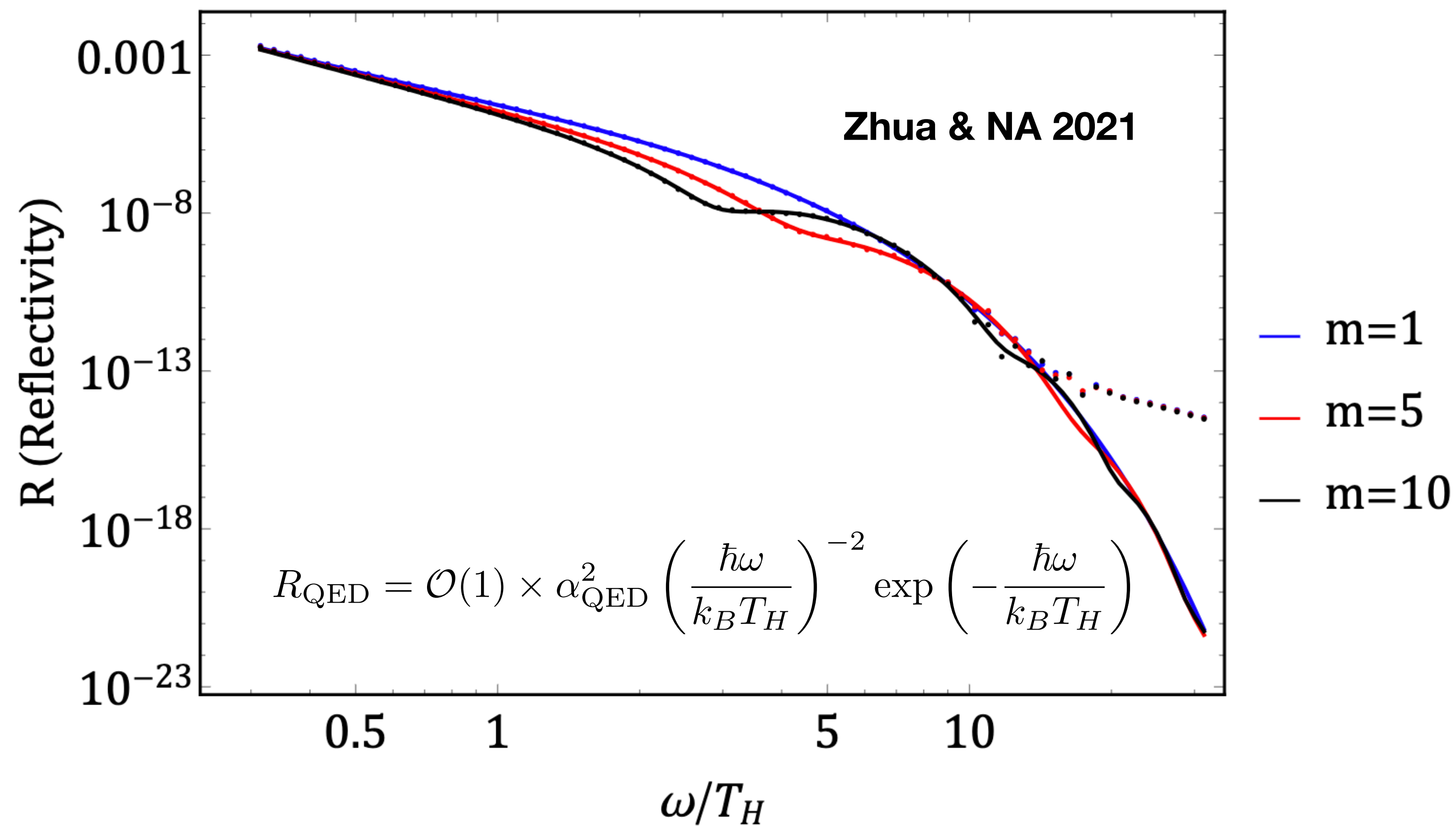
different interpolations



$$\Delta_{\mu\nu}^M(p) = \frac{\eta_{\mu\nu} + (\xi - 1) \frac{p_\mu p_\nu}{p^2}}{(p^2 + i\epsilon)(1 - \pi^M(p^2))} ,$$

$$\pi^M(p^2) = \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln \left( 1 + \frac{p^2 x(1-x)}{m_e^2} \right)$$





- This is consistent with simple Boltzmann reflectivity for gravitational fine-structure constant:  $\alpha_G \sim \frac{\hat{E}_{\text{infalling}} T}{M_p^2}$ , which becomes  $\mathcal{O}(1)$  within a Planck length of the horizon

$$R_{\text{QG}} = \mathcal{O}(1) \times \exp \left( -\frac{\hbar\omega}{k_B T_H} \right)$$