Joint Colloquium, ITP/CEICO
Prague, Aug. 21, 2026

Quantum Gravity in the Wild

Black Hole Echoes, the Big Bang, and a Cosmic Glitch

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline

☐ *Intro:* the crisis in physics

☐ Quantum Big Bang

☐ Quantum Black Holes

☐ Quantum Dark Energy

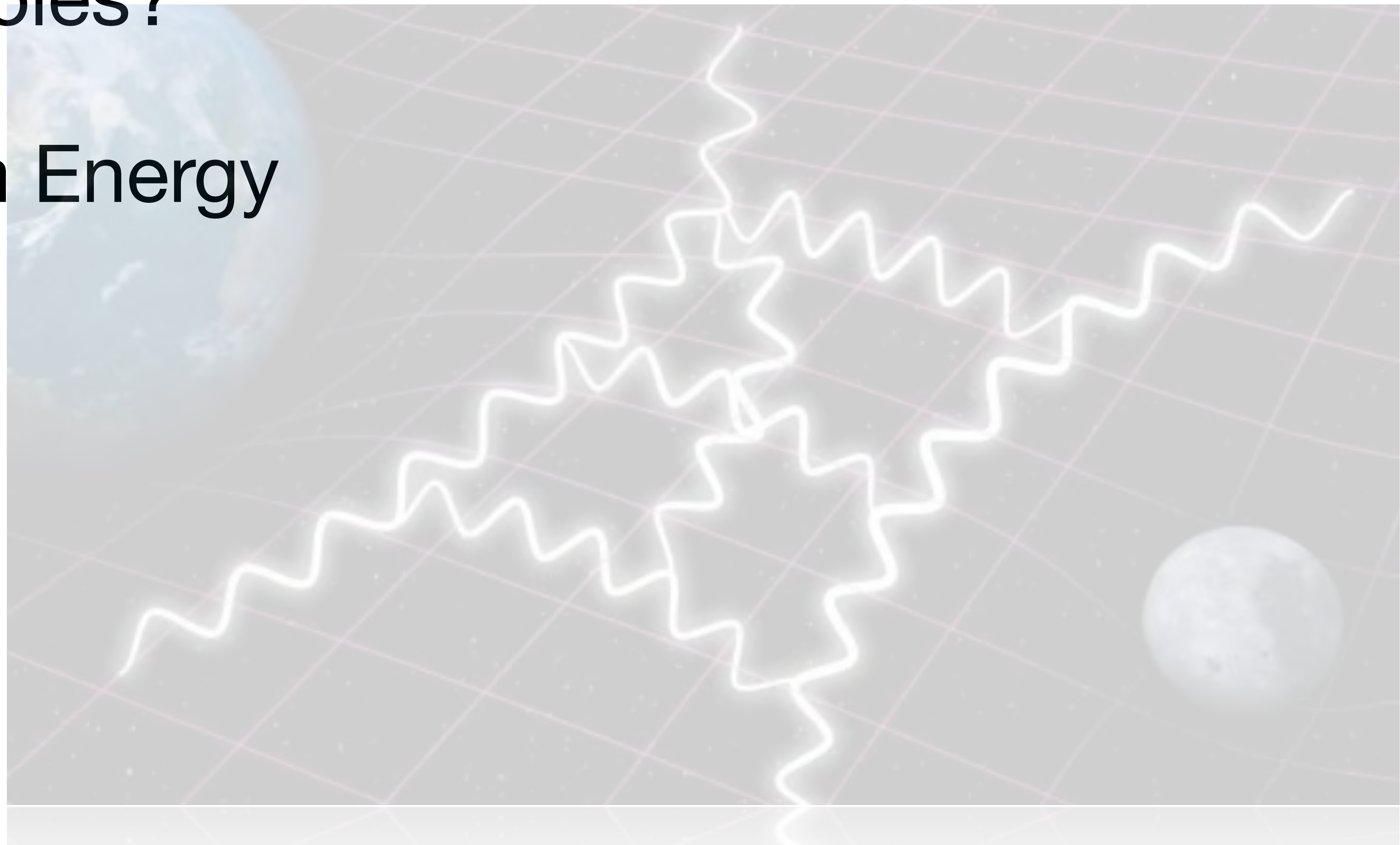
☐ *Outro:* how the light gets in

Outline

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

Chasms amongst our best theories and observations

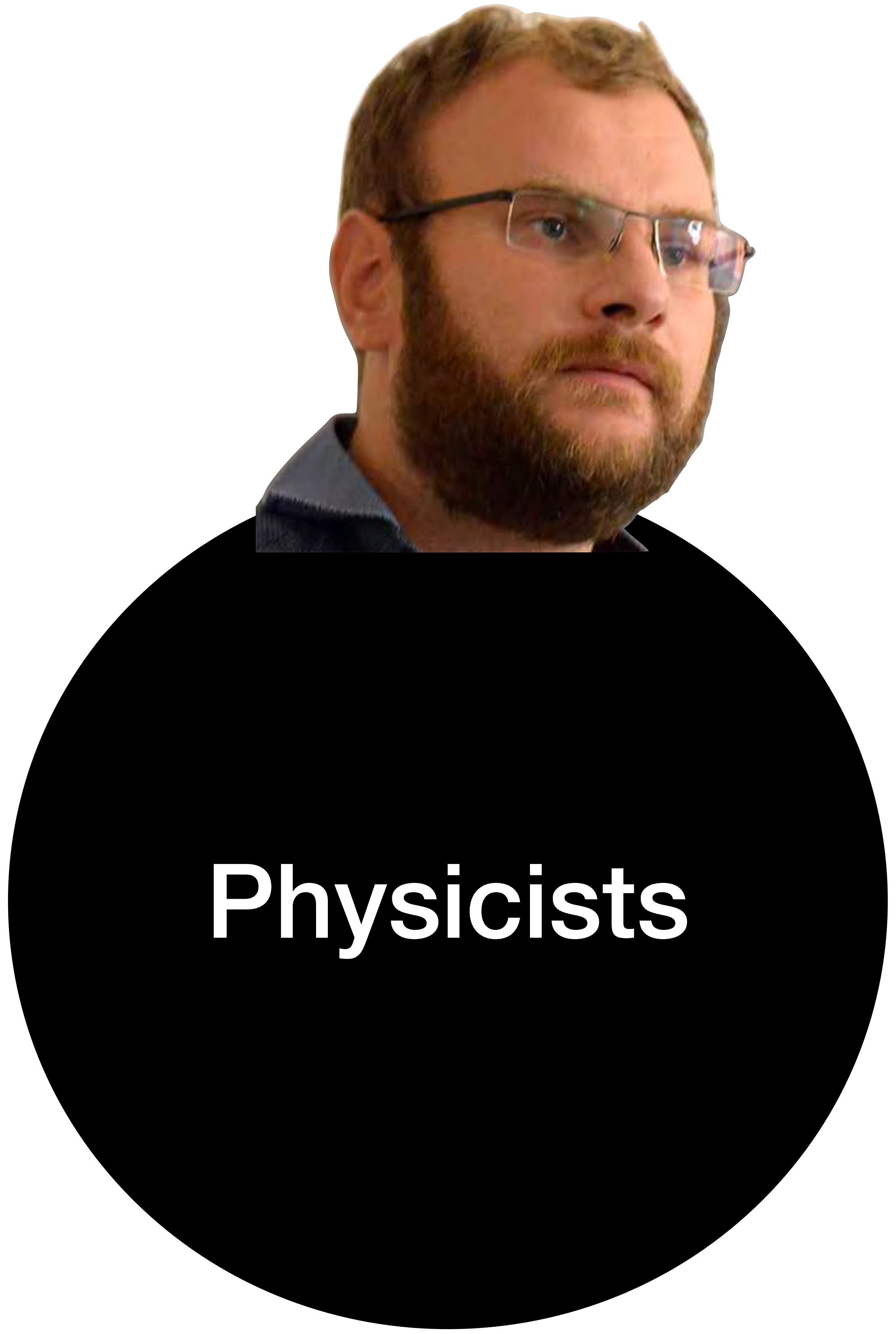
- Quantum Mechanics + Relativity $\rightarrow \infty$
- Singularities @hearts of Big Bang and Black Holes
- Information lost in evaporation of black holes?
- Dark Energy $< 10^{-60} \times$ Quantum Vacuum Energy
- Is Standard Model “Technically Natural”?



Crisis of Falsifiability

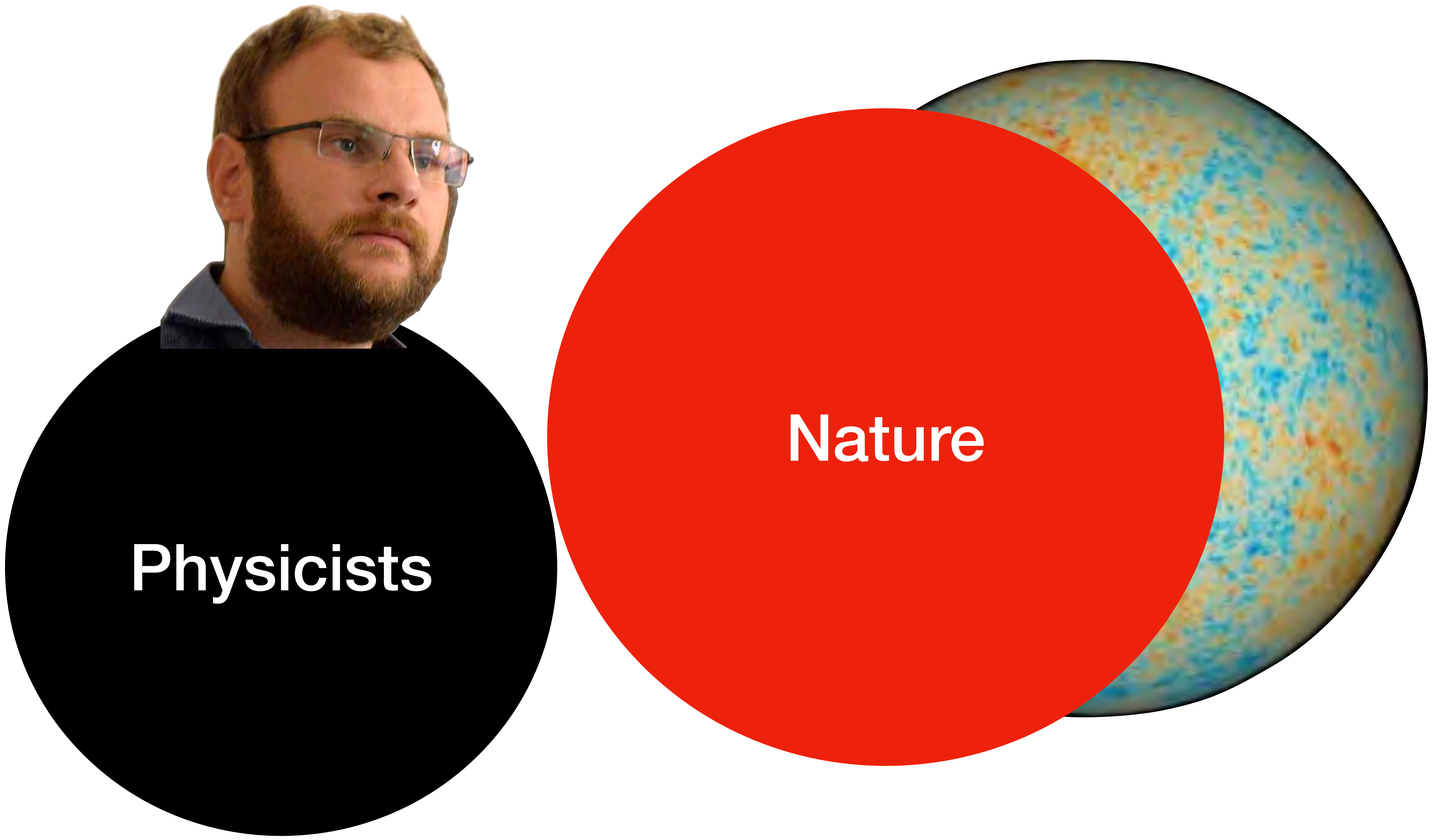
- Landscape of 10^{500} vacua in string theory
- ***No signature*** of Supersymmetry, Anti-deSitter space, or extra dimensions
- No concrete testable prediction from ***any quantum gravity proposal***
- ***Inflation***, leading theory of Big Bang, can fit ***any*** data
- Is ***Theoretical Physics***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

The Crisis in Physics!

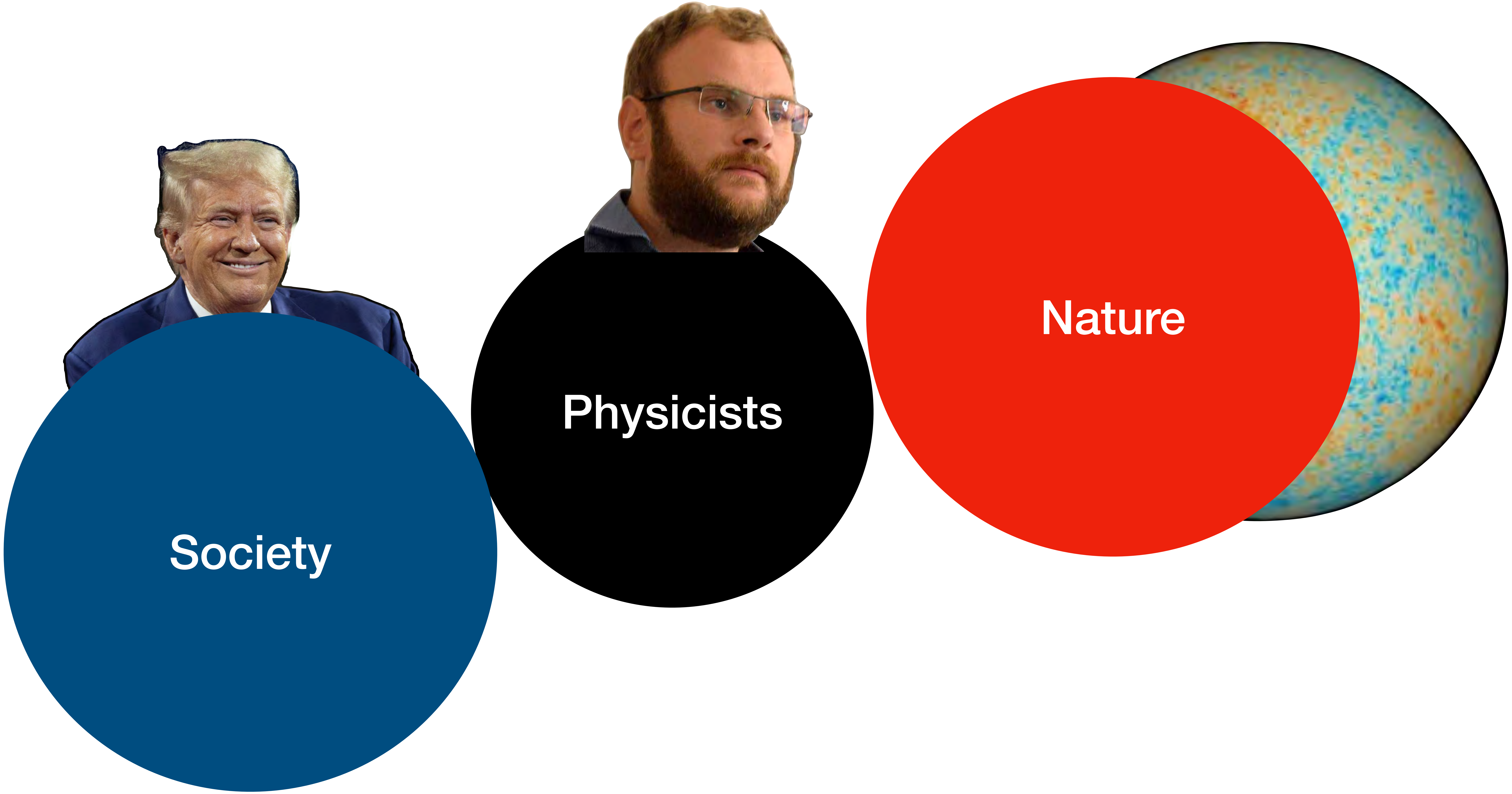


Physicists

The Crisis in Physics!



The Crisis in Physics!



Physicists

Nature

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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.

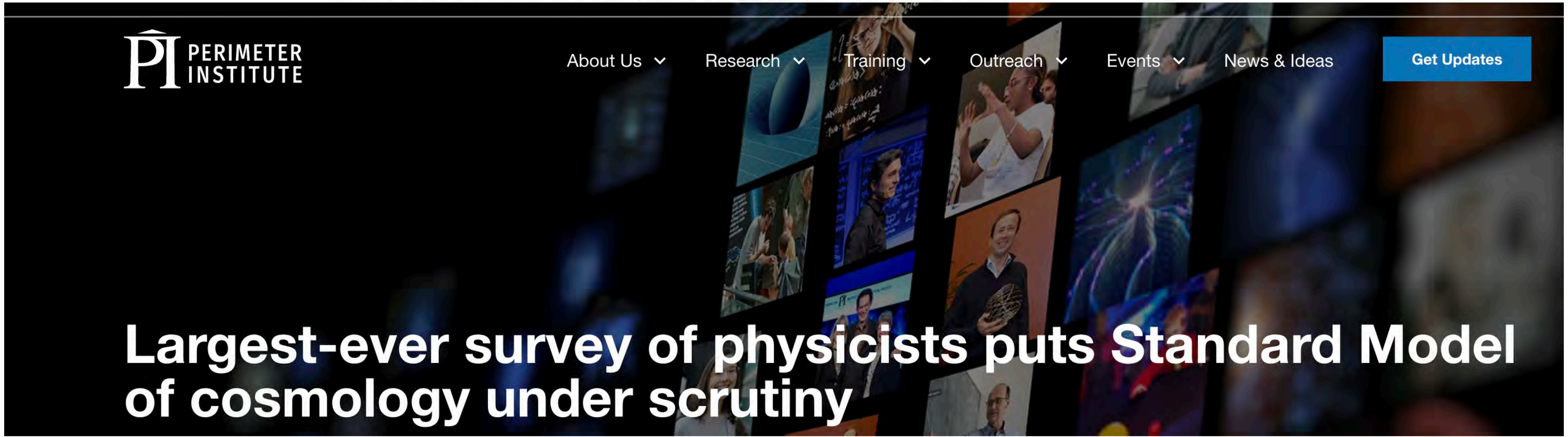
Ricardo/stock.adobe.com; adapted by APS

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

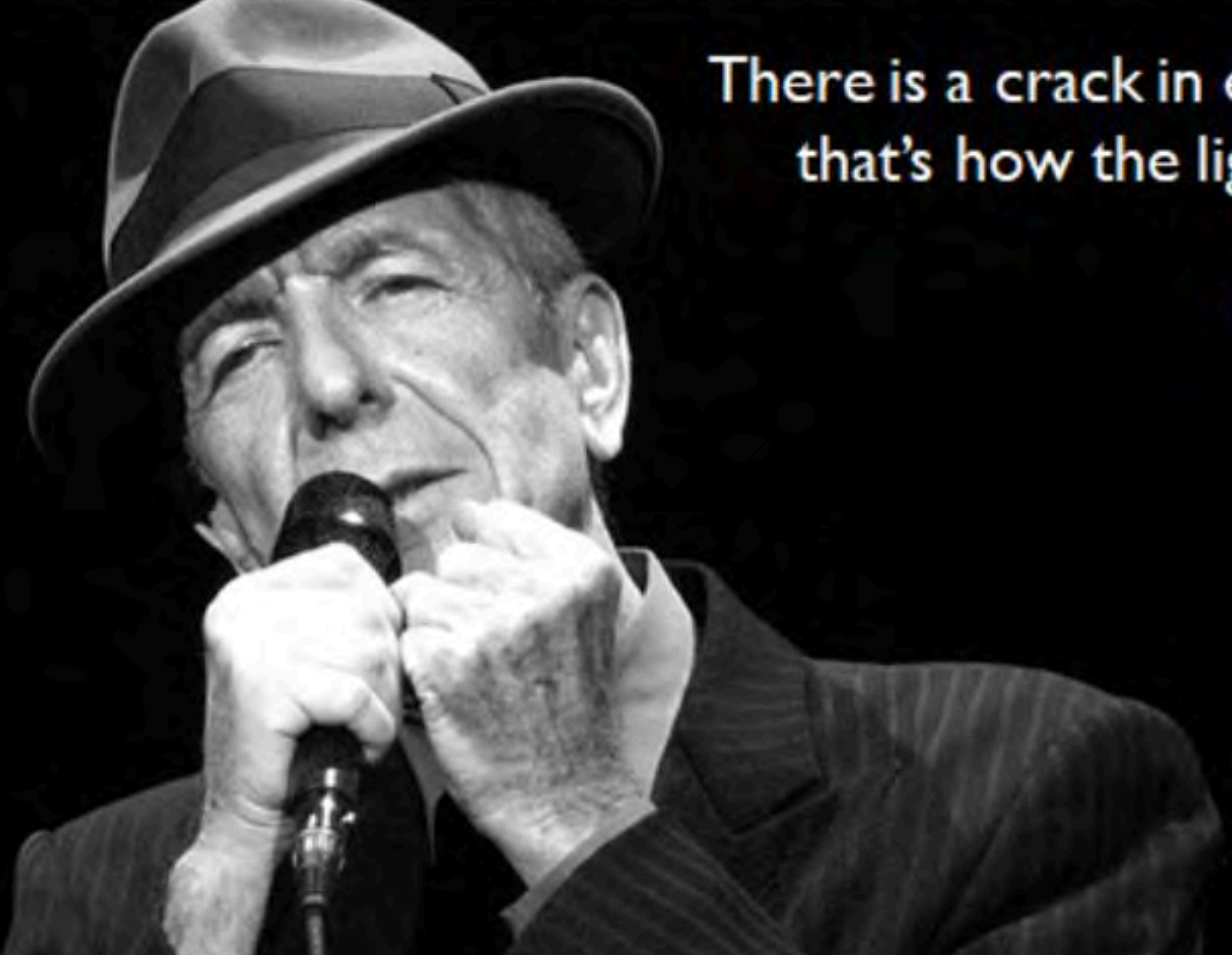
INTERACTIVE CONDITIONAL SURVEY EXPLORER

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/

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 Triangulati (gluing triangulate space in lay of time)
A researcher in a field not listed above n=291	**24.1** % n=70	**37.1** % n=108	**18.2** % n=53	**11.0** % n=32	**6.5** % n=19	**2.4** % n=7	**0.7** % n=2
A science enthusiast n=251	**31.5** % n=79	**31.5** % n=79	**20.7** % n=52	**7.6** % n=19	**4.8** % n=12	**2.0** % n=5	**2.0** % n=5
A researcher studying quantum physics n=163	**31.9** % n=52	**22.1** % n=36	**25.2** % n=41	**9.8** % n=16	**5.5** % n=9	**0.6** % n=1	**4.9** % n=8
A researcher studying astrophysics or cosmology n=113	**38.1** % n=43	**27.4** % n=31	**21.2** % n=24	**6.2** % n=7	**3.5** % n=4	**3.5** % n=4	**0.0** % n=0
A researcher studying gravity n=93	**49.5** % n=46	**10.8** % n=10	**26.9** % n=25	**7.5** % n=7	**2.2** % n=2	**2.2** % n=2	**1.1** % n=1



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

Leonard Cohen

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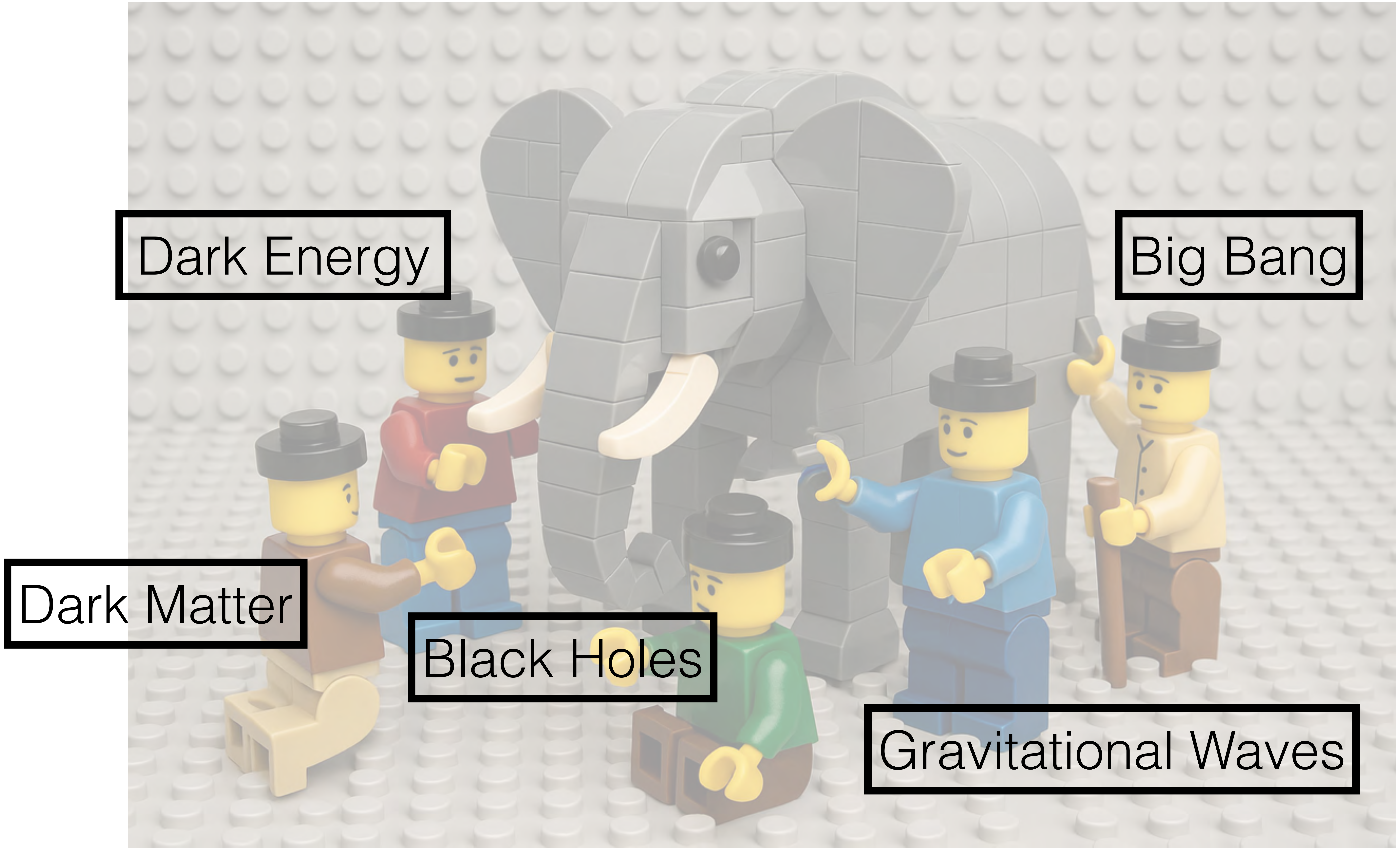


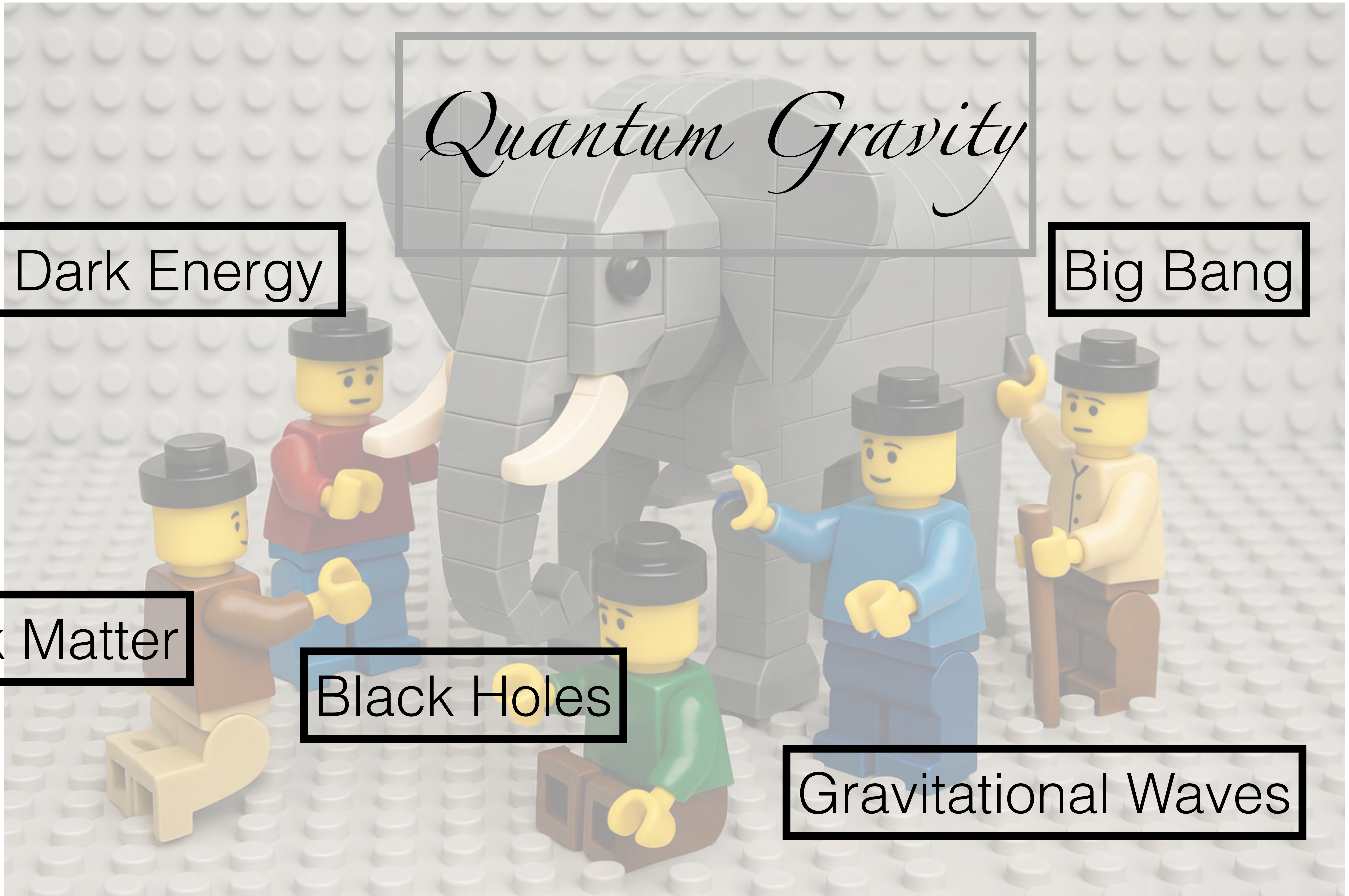
Dark Energy

Big Bang

Dark Matter

Black Holes

Gravitational Waves



Quantum Gravity

Dark Energy

Big Bang

Dark Matter

Black Holes

Gravitational Waves

Outline

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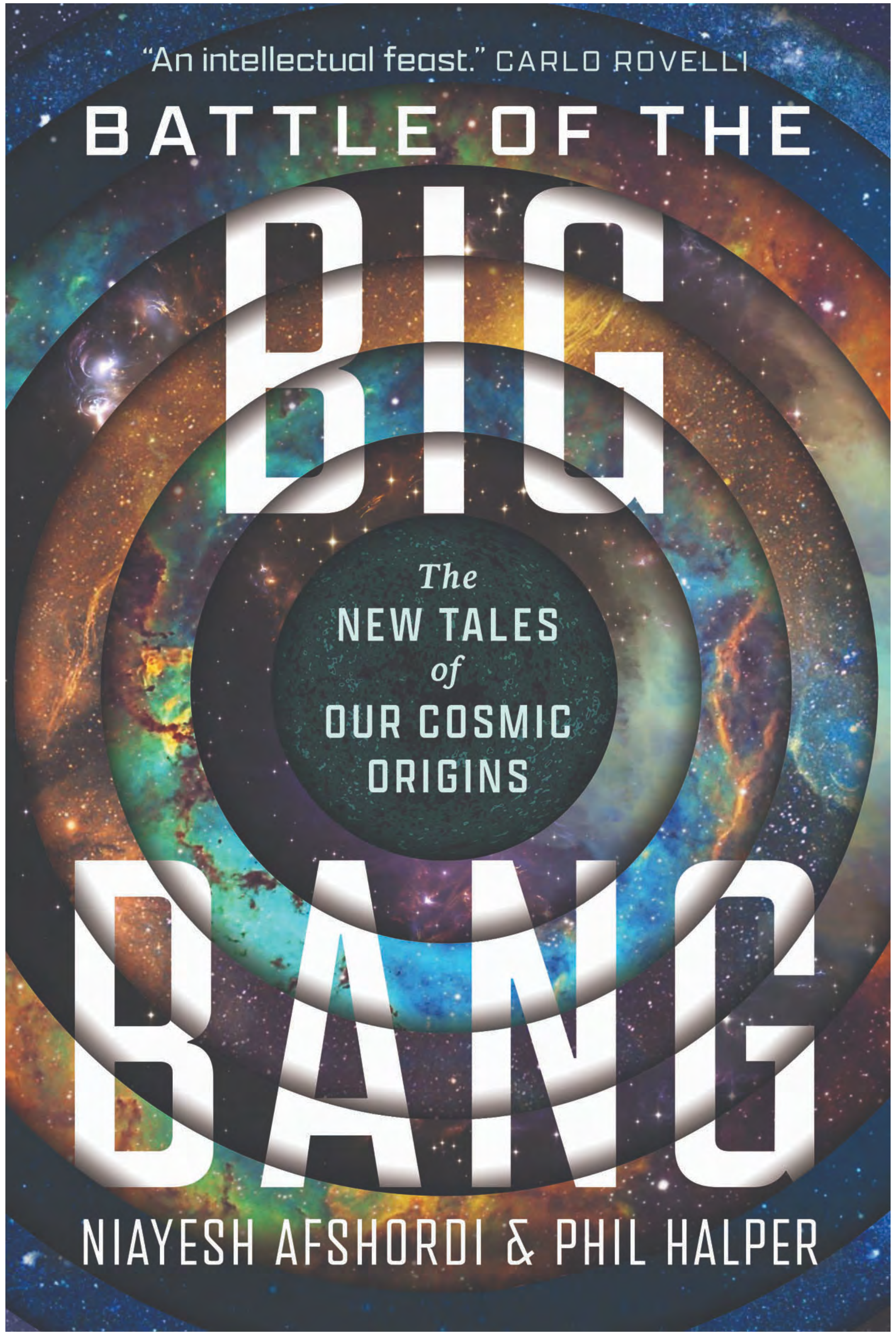

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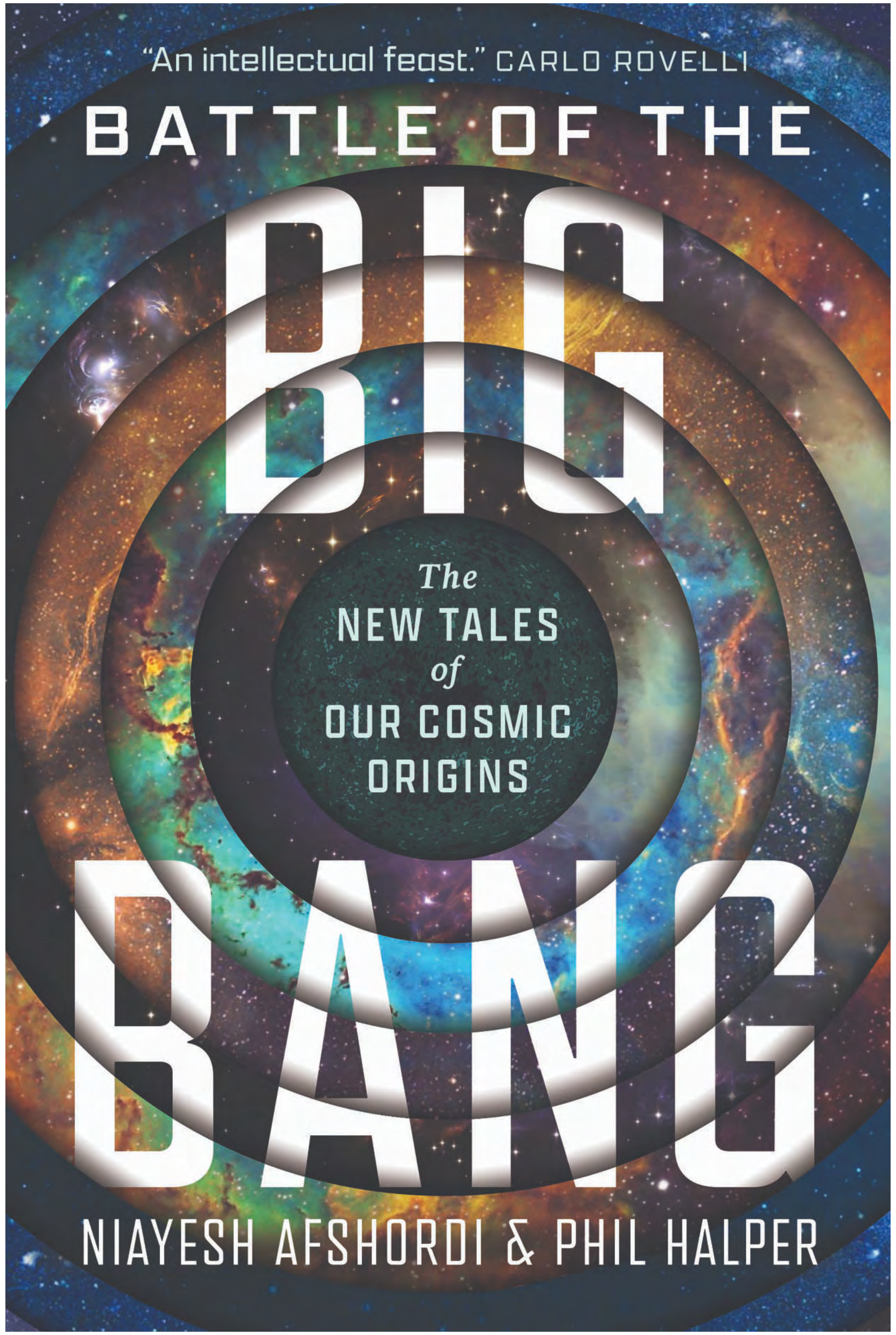

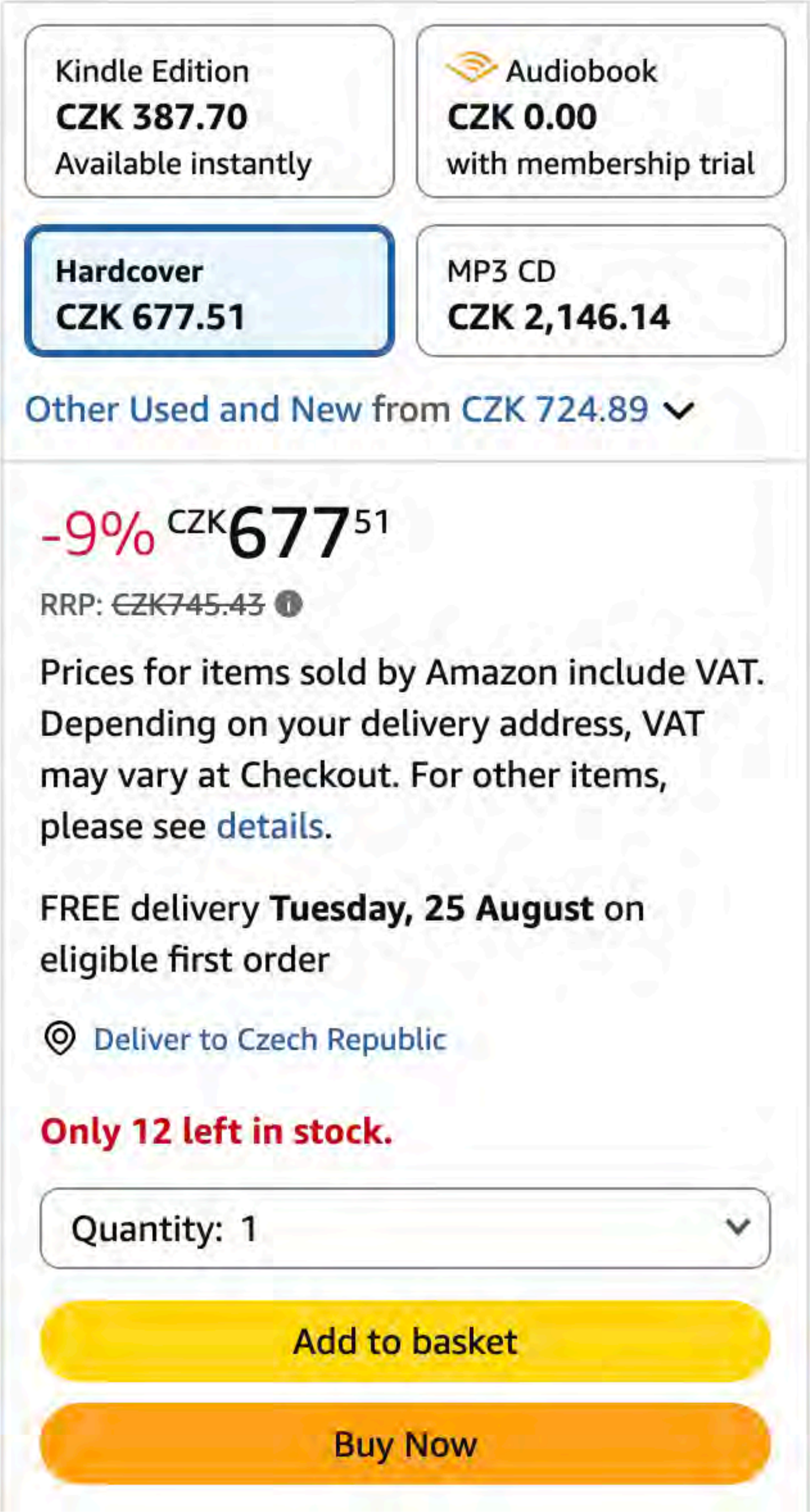

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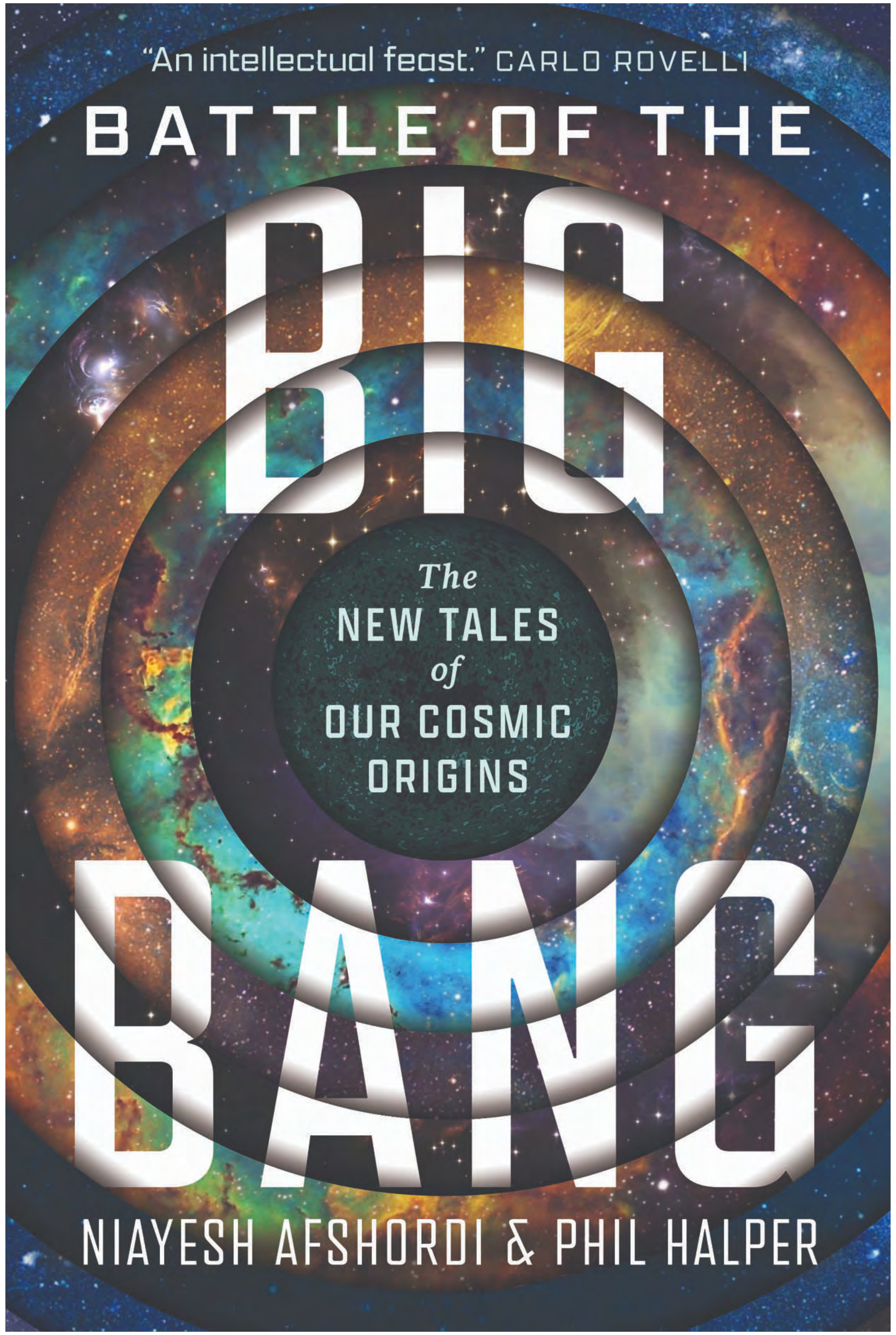

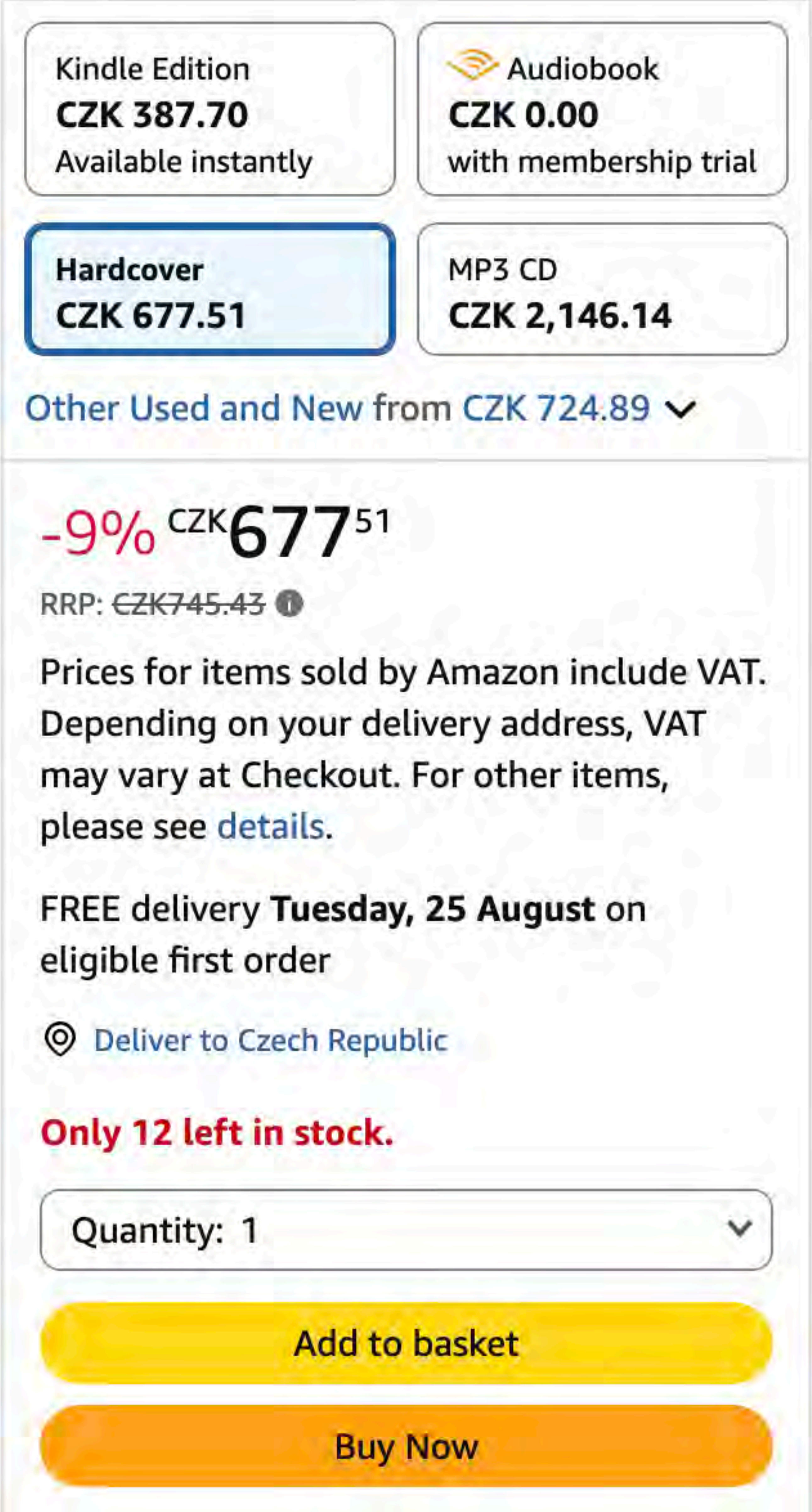
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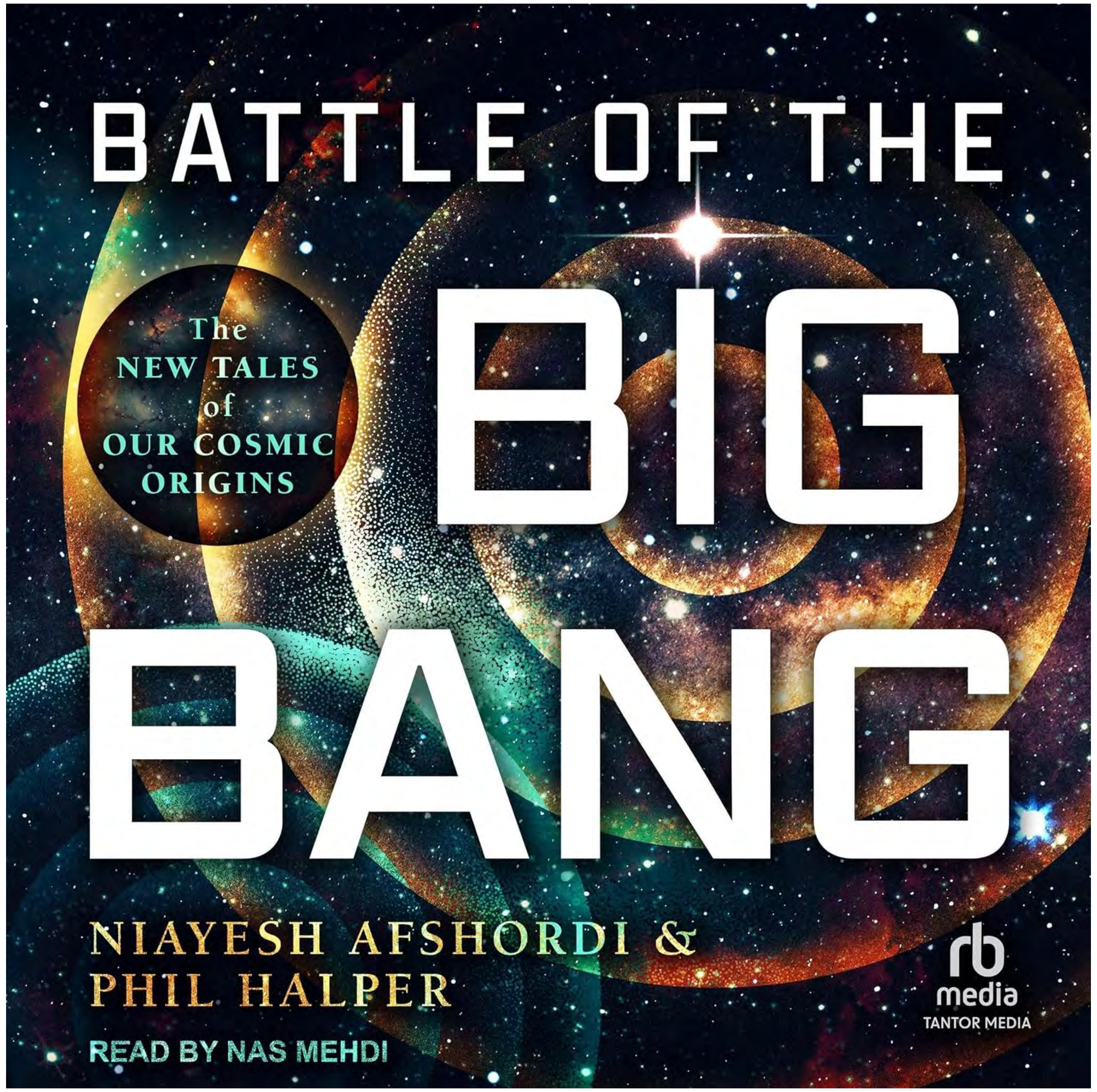

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By **Emma Chapman**

May 19, 2026 2:13 pm ET

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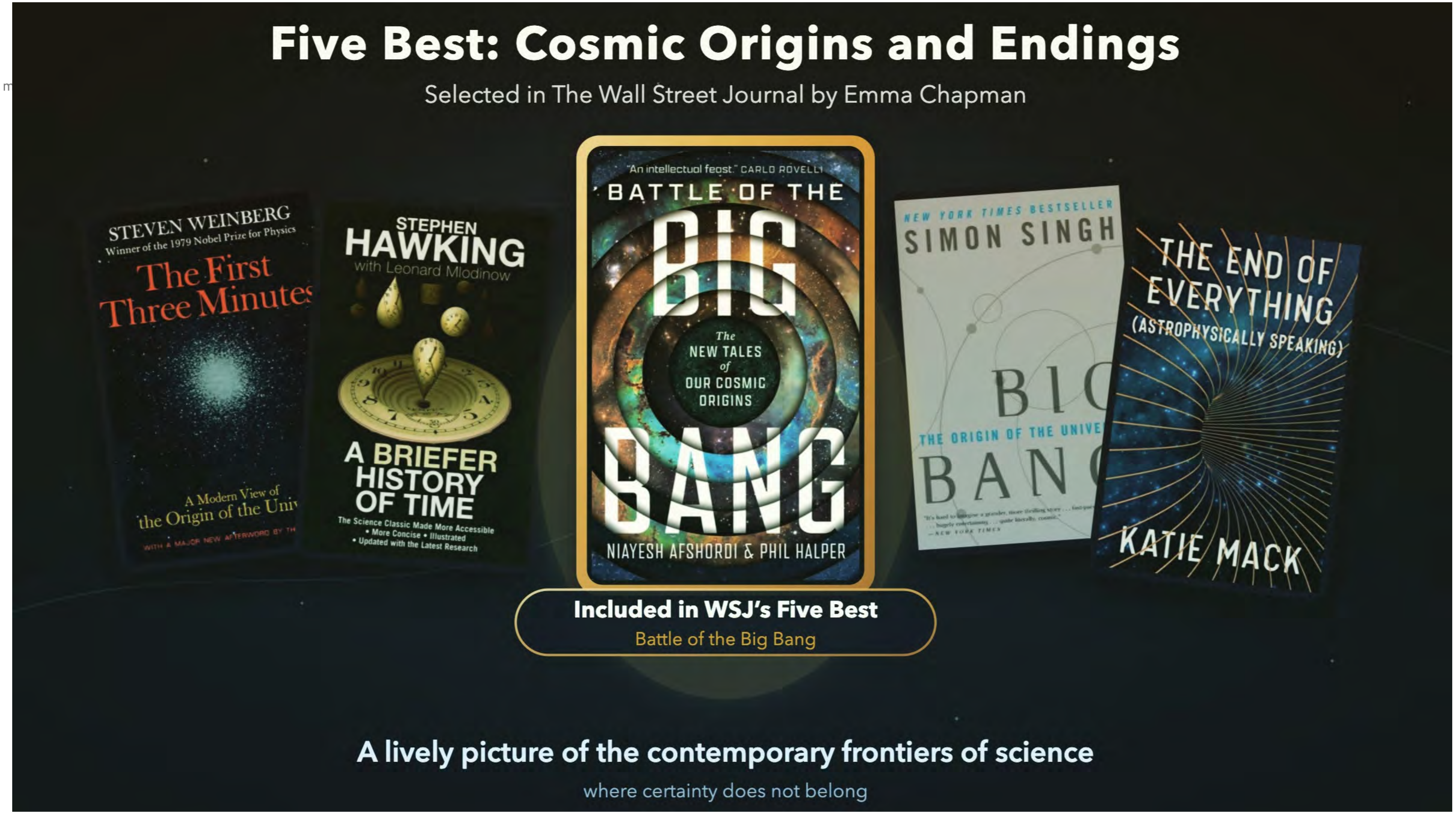

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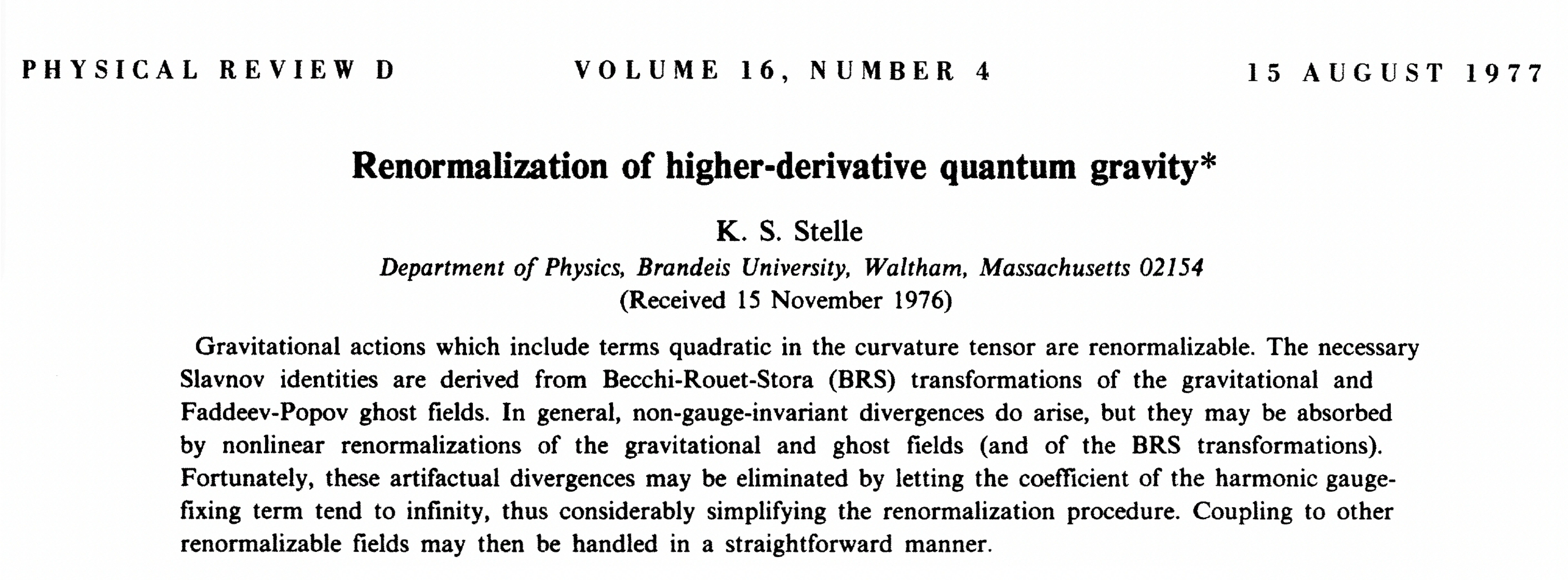
Quadratic Gravity is Renormalizable



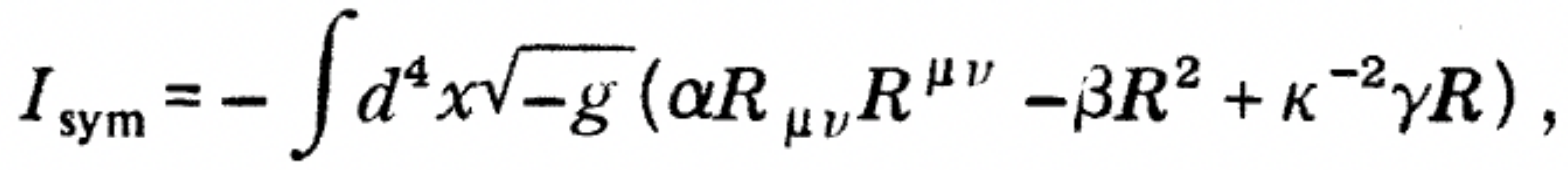
PHYSICAL REVIEW D VOLUME 16, NUMBER 4 15 AUGUST 1977

Renormalization of higher-derivative quantum gravity*

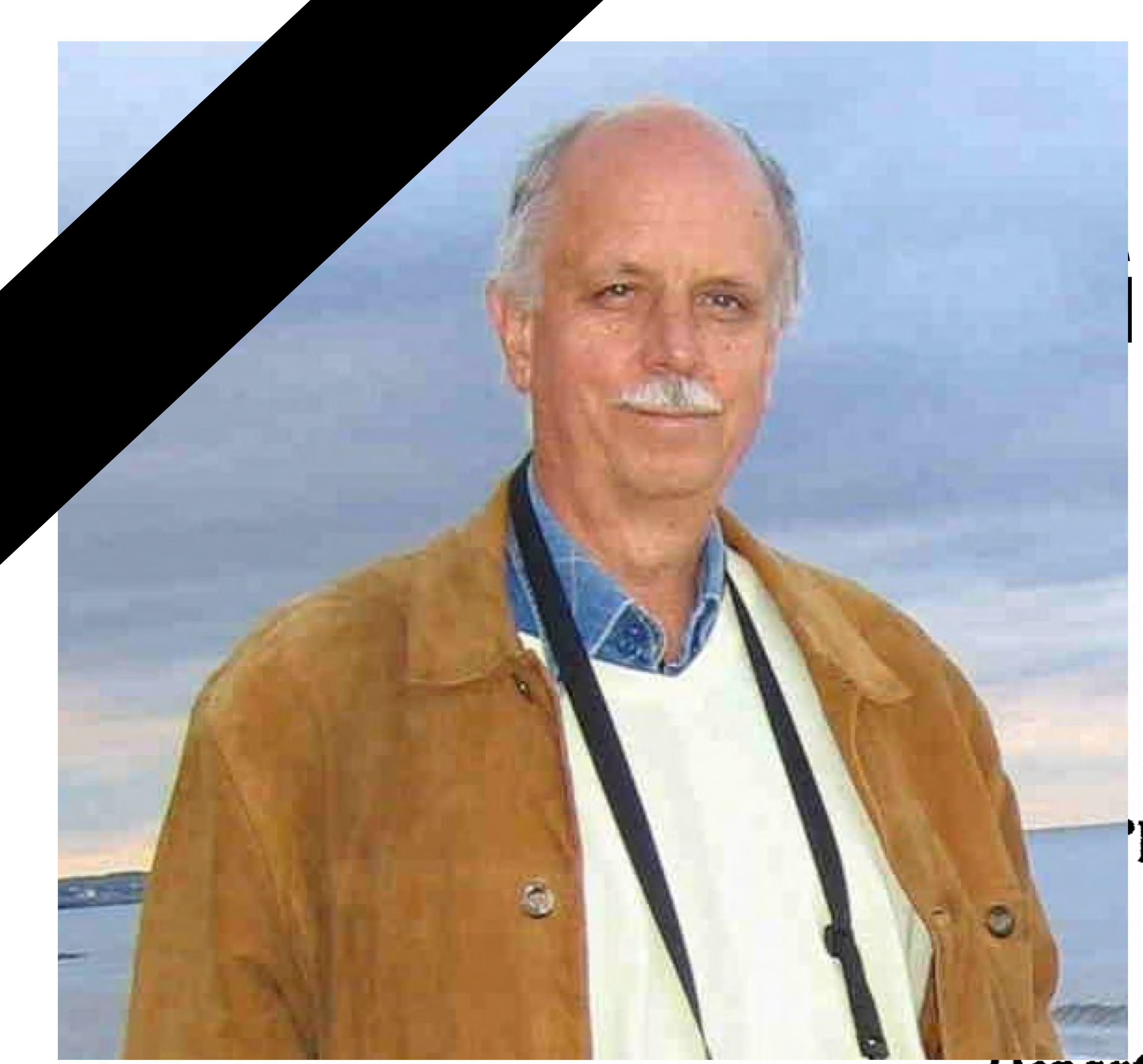
K. S. Stelle
Department of Physics, Brandeis University, Waltham, Massachusetts 02154

(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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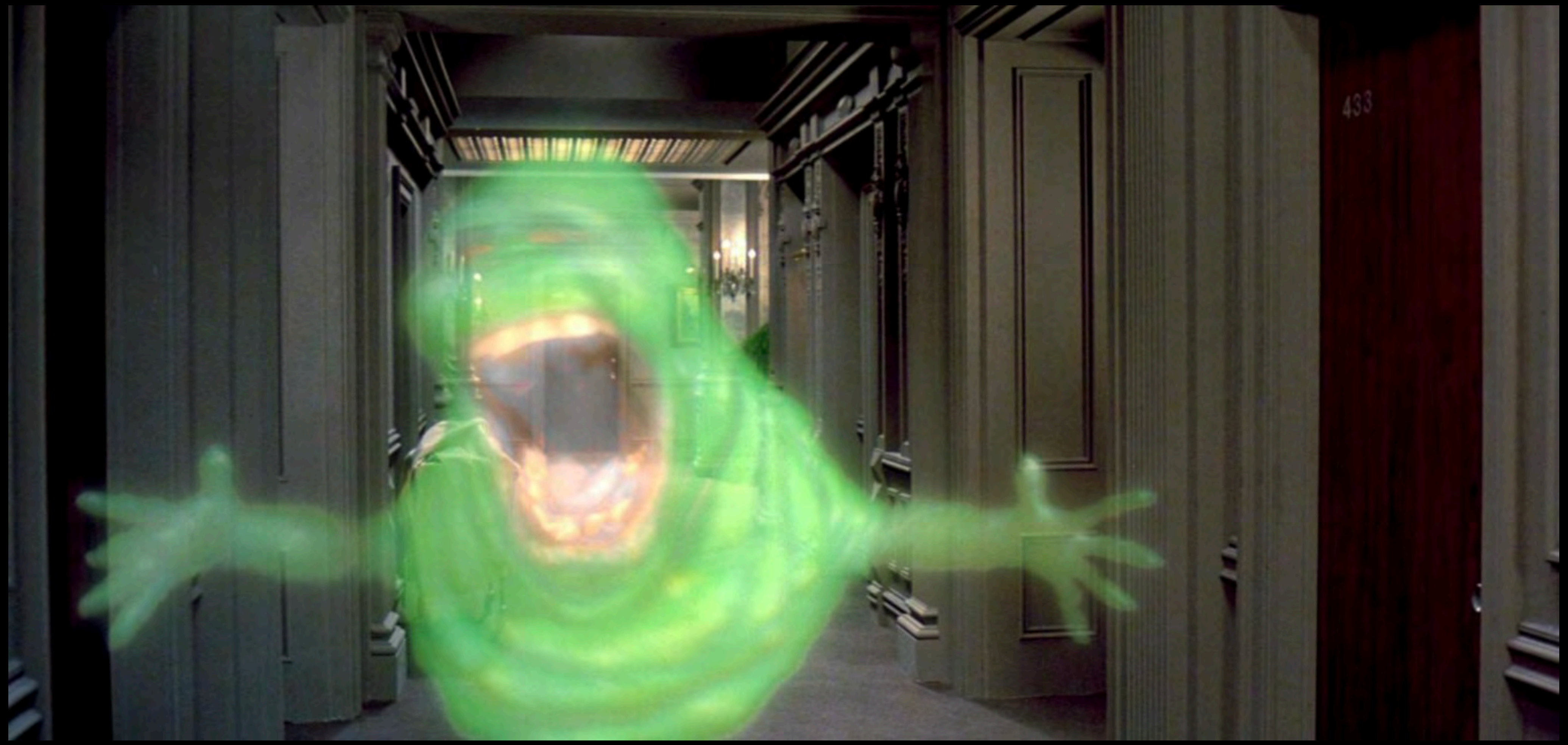
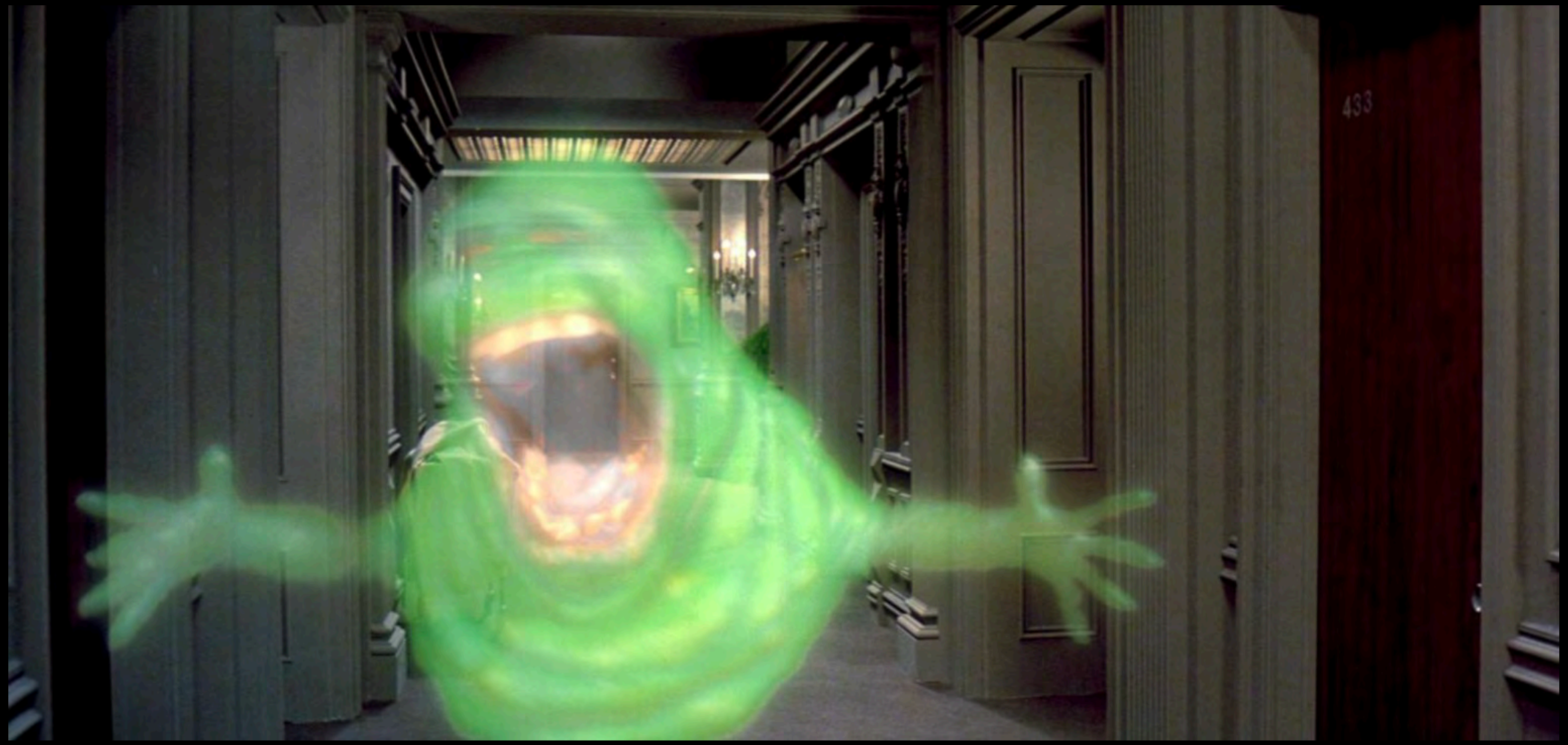
- Free ghosts cause wild instabilities and/or violate unitarity



- Free ghosts cause wild instabilities and/or violate unitarity

- UV-Confined ghosts cannot last long, and will not lead to IR instabilities🤞



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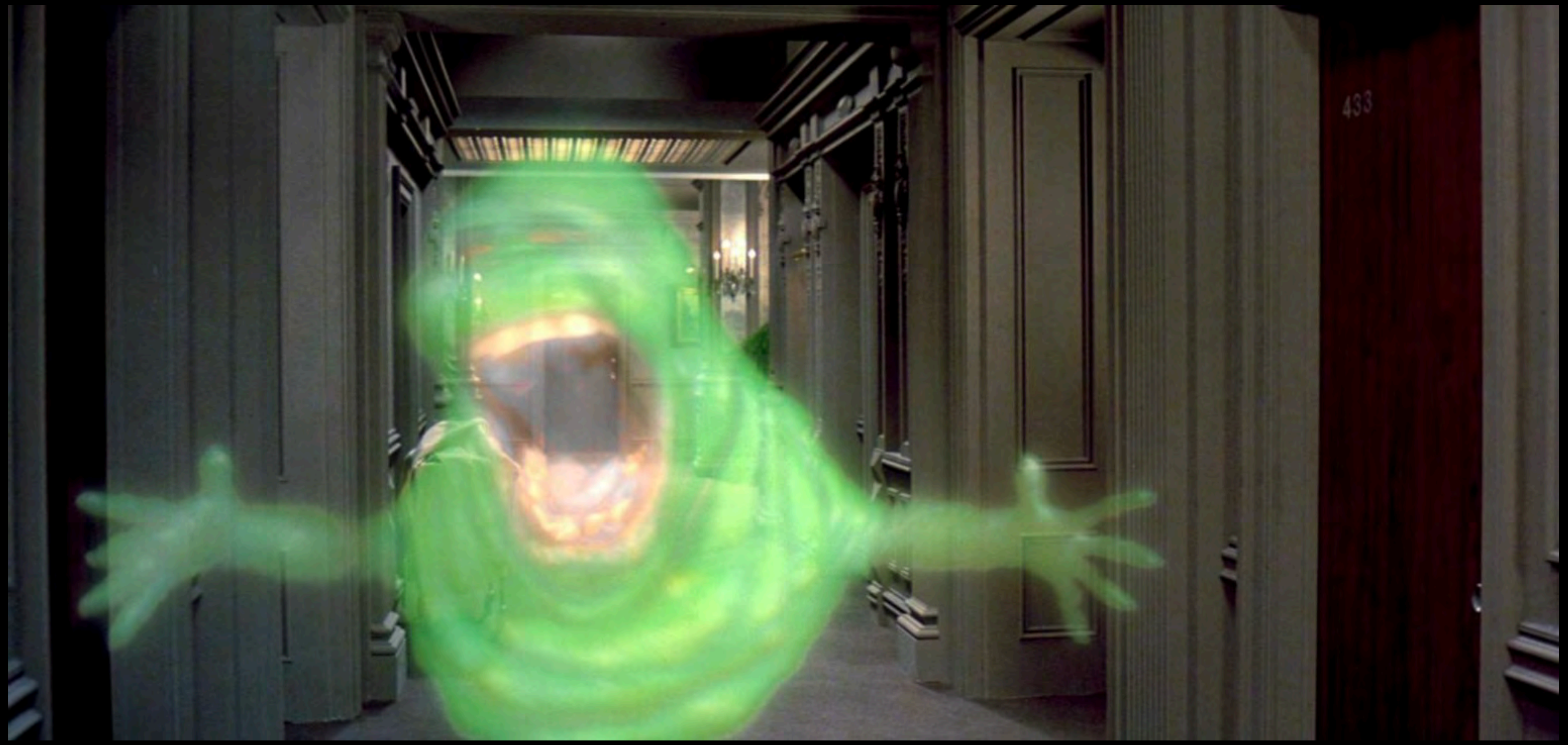
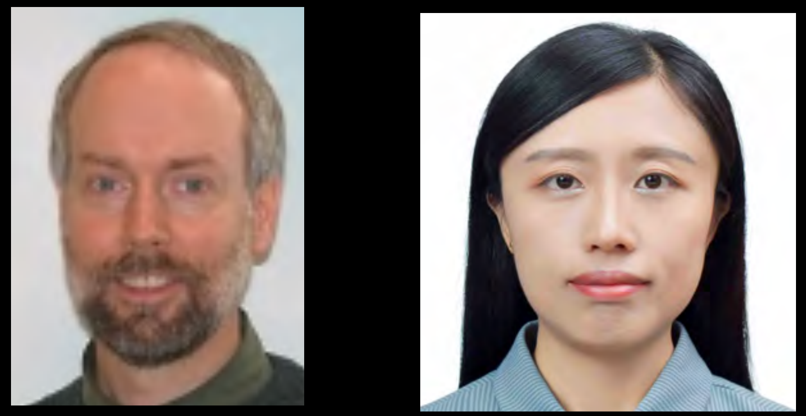


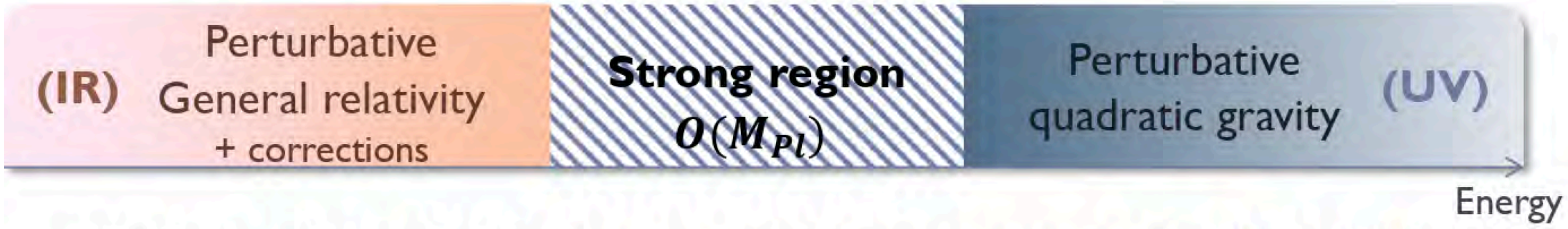


Holdom & Ren 2016

Quadratic Gravity as Quantum Chromodynamics?

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

QCD	Quadratic Gravity
AF at UV, g_s^2 gets strong at Λ_{QCD}	AF at UV, f_0^2, f_2^2 get strong at $\Lambda_{\rm QG}$
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


(IR) Perturbative General relativity + corrections

Strong region $O(M_{Pl})$

Perturbative quadratic gravity (UV)

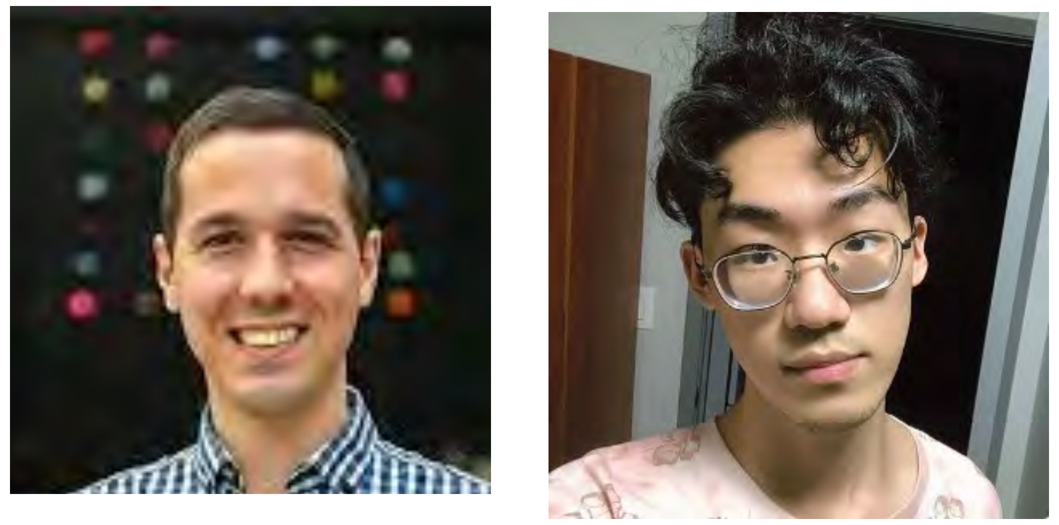
Energy

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

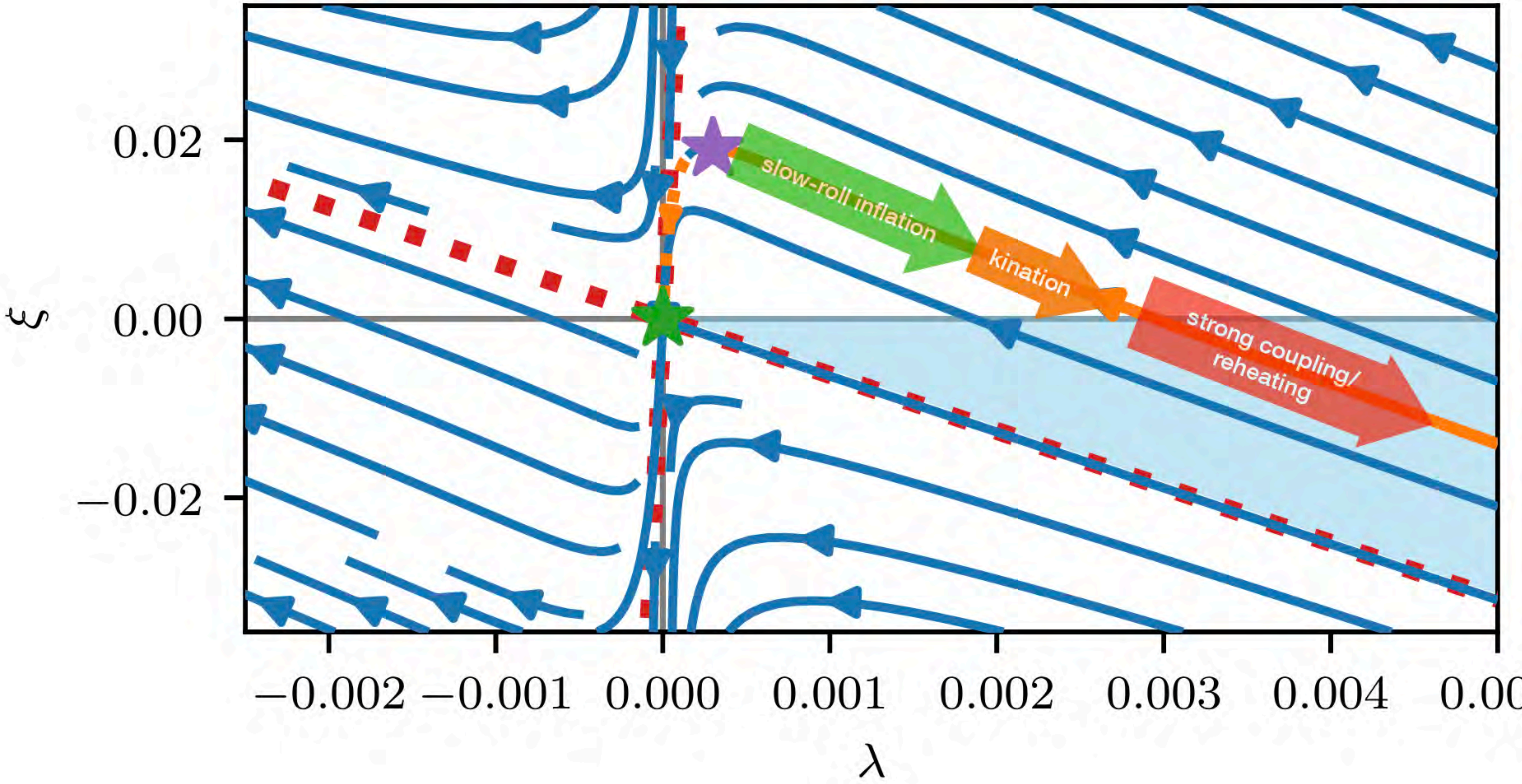
Courtesy of Jing Ren

Cosmology of Quadratic Gravity under RG Flow

Quintin, Liu & NA 2025



$$S = \int \mathrm{d}^4x\, \sqrt{-g} \left(\cancel{\frac{R}{16\pi G_{\mathrm{N}}}} - \frac{R^2}{\xi} - \frac{C^2_{\mu\nu\rho\sigma}}{2\lambda} \right)$$



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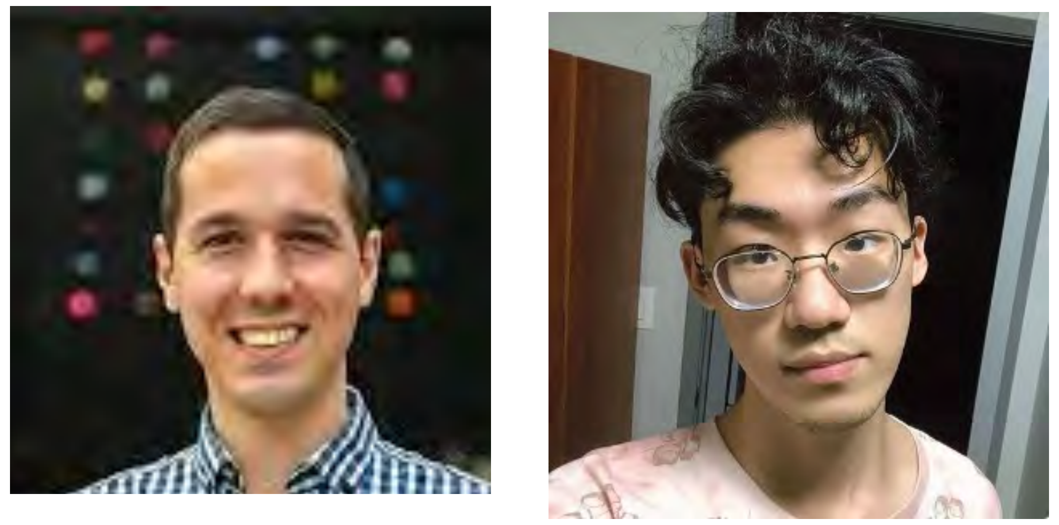
$$\beta_\lambda = \frac{\mathrm{d}\lambda}{\mathrm{d}\ln\mu} = -\frac{1}{(4\pi)^2}\,\frac{\left[\left(1617 + 90\mathcal{N}\right)\lambda - 20\xi\right]\lambda}{90}\,,$$

$$\mathcal{N} = \frac{1}{60}\mathcal{N}_{\mathrm{scalar}} + \frac{1}{5}\mathcal{N}_{\mathrm{vector}} + \frac{1}{20}\mathcal{N}_{\mathrm{fermion}}\,,$$

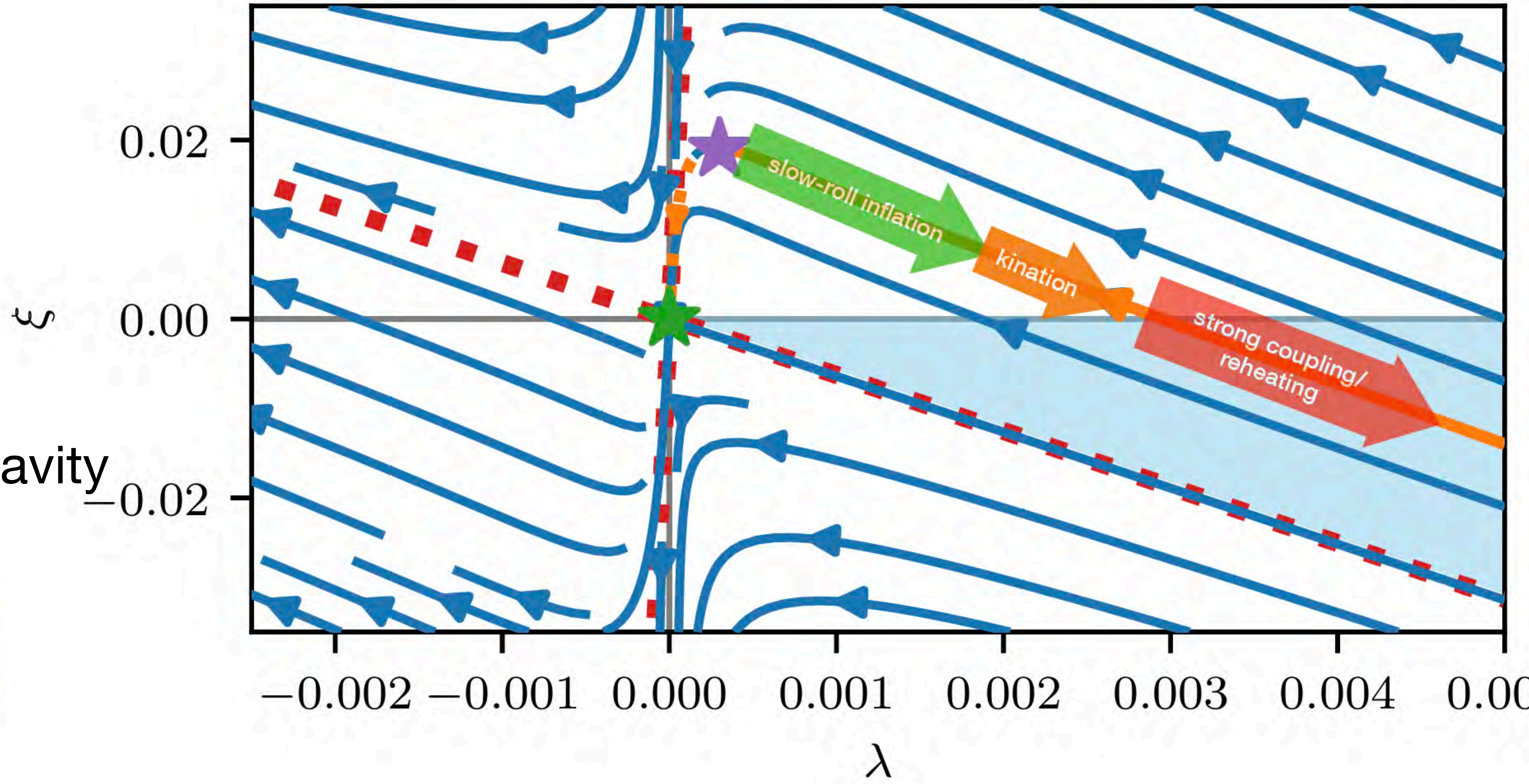
Cosmology of Quadratic Gravity under RG Flow

Quintin, Liu & NA 2025



- Consider RG flow of purely quadratic gravity

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



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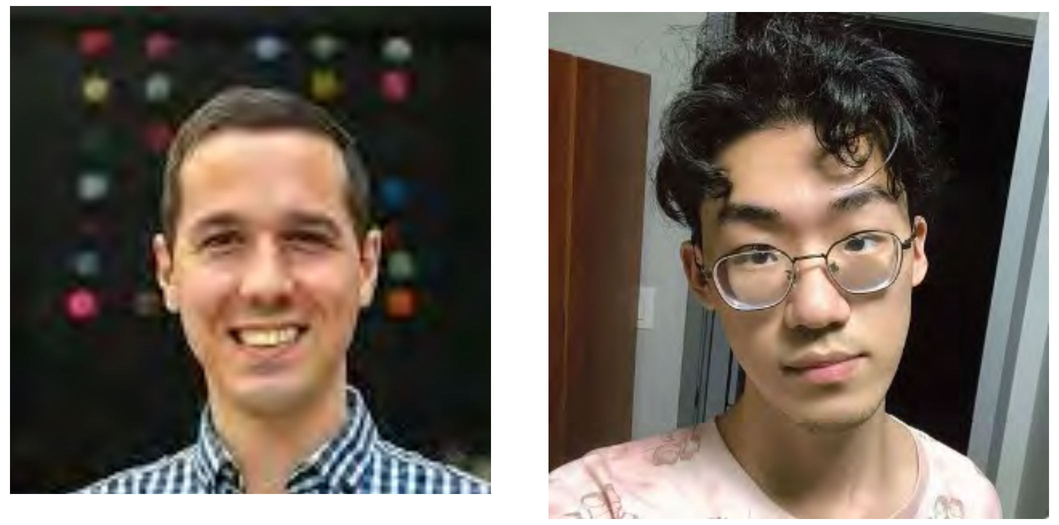

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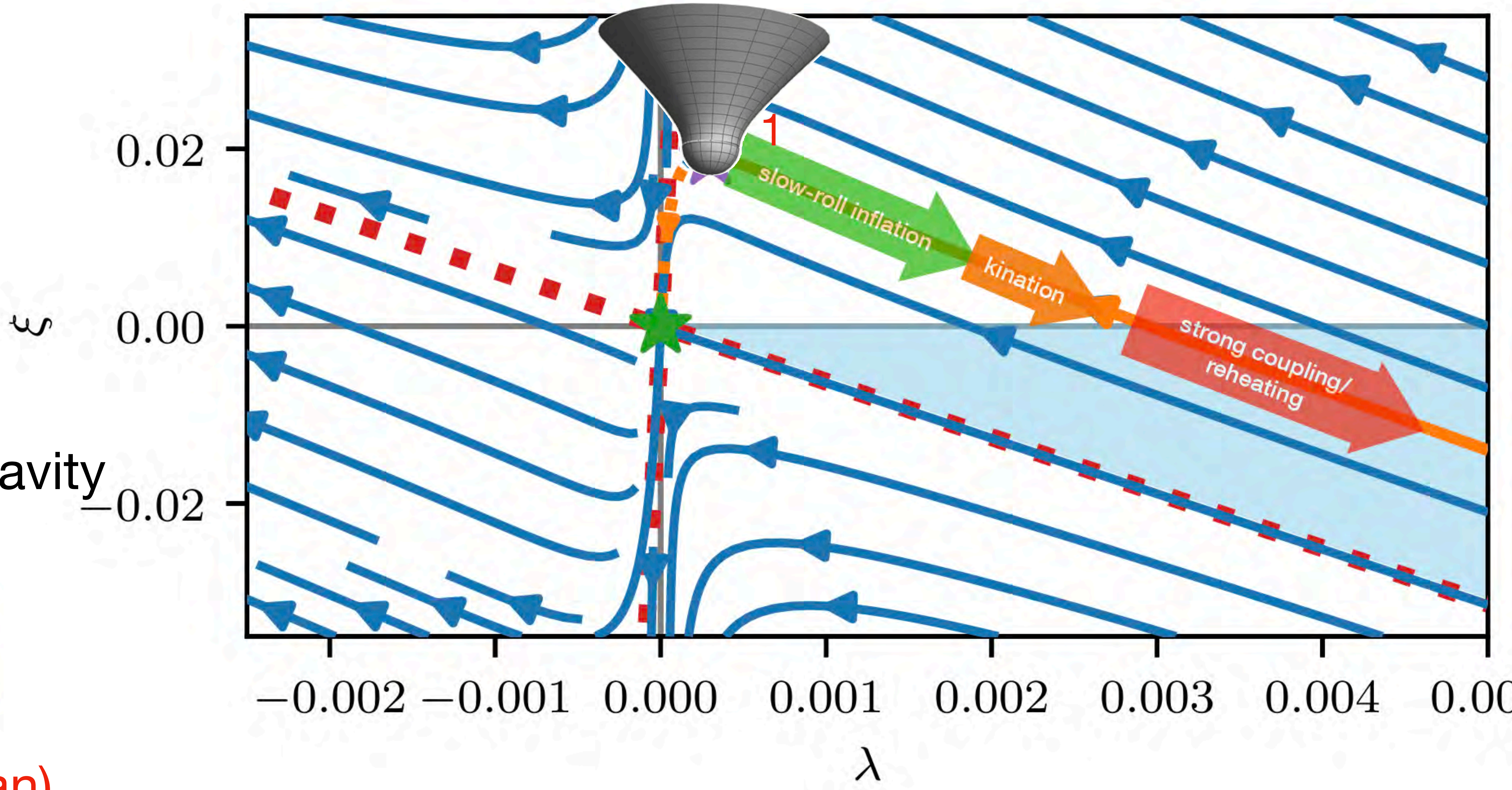

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Quintin, Liu & NA 2025

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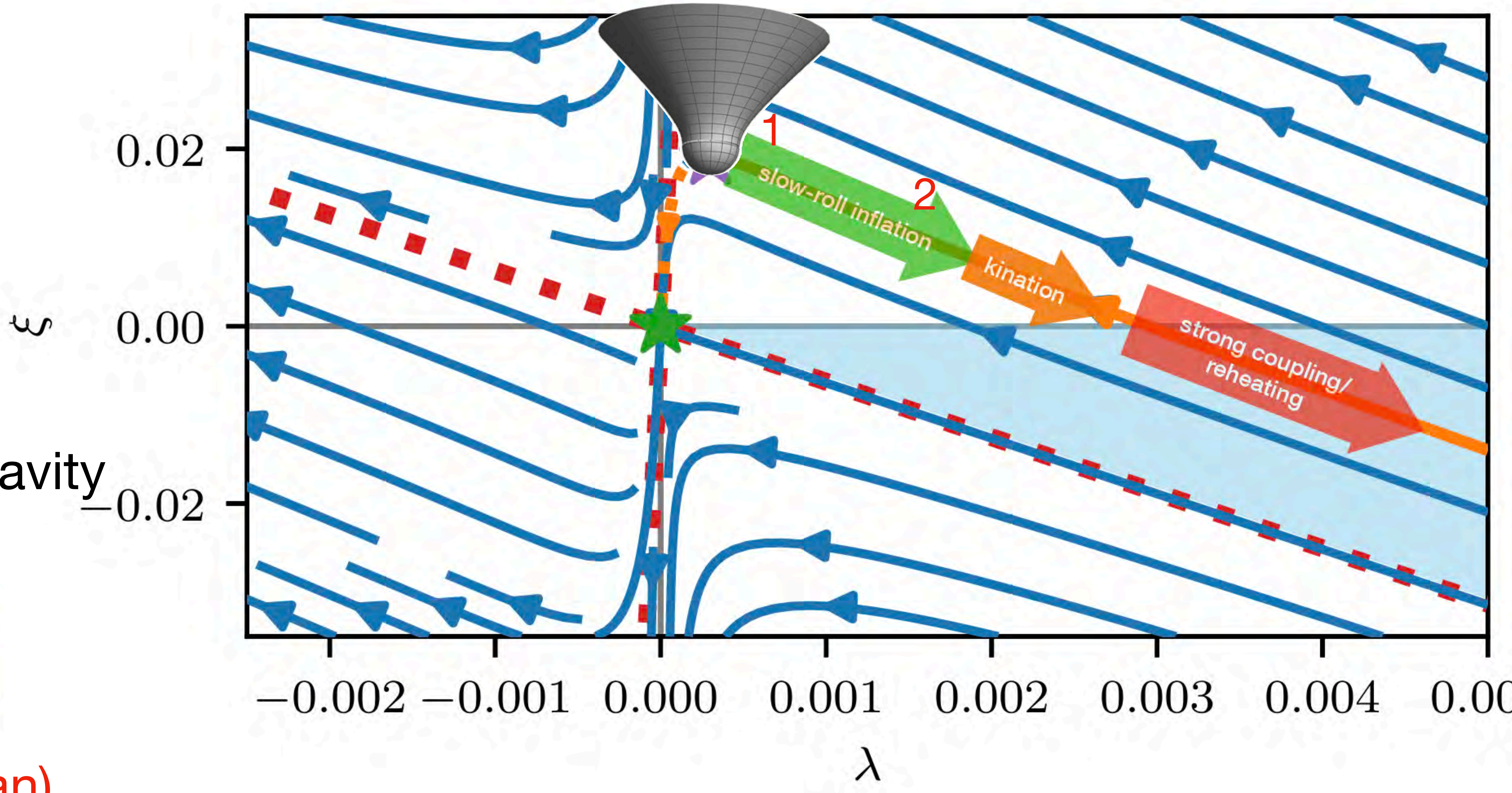
2. Slow-roll inflation w/ QG



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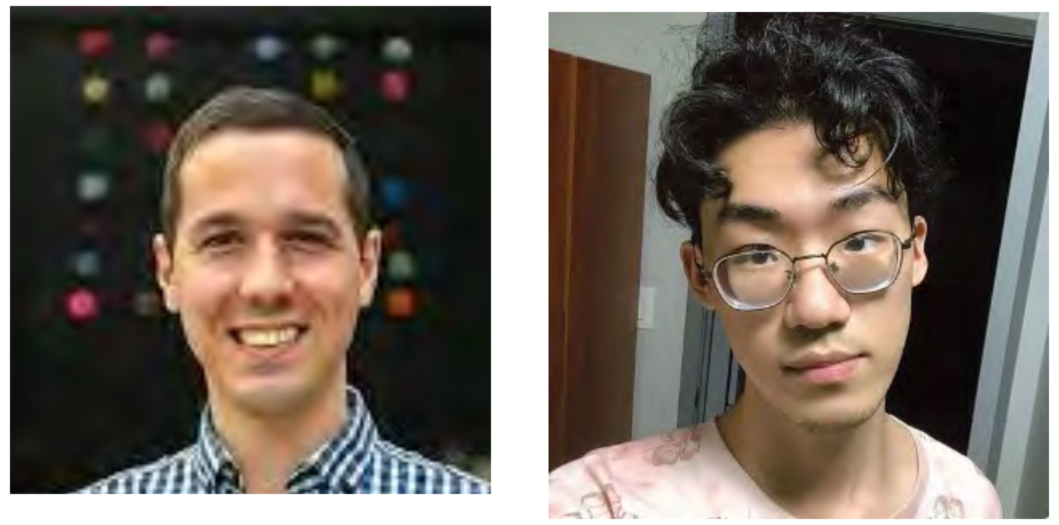

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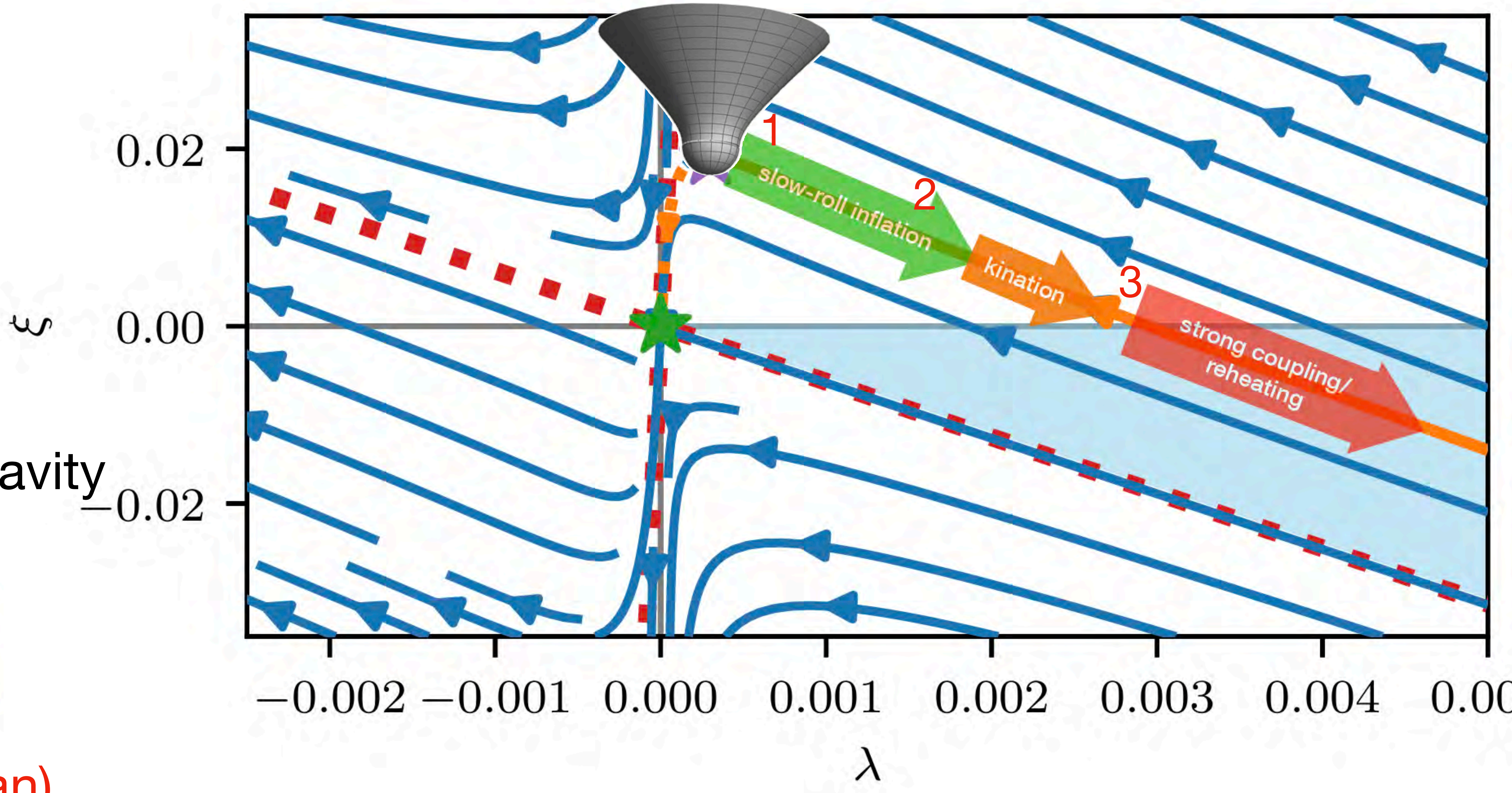
1. Hartle-Hawking (Euclidean → Lorentzian)
2. Slow-roll inflation w/ QG
3. Strong coupling/reheating



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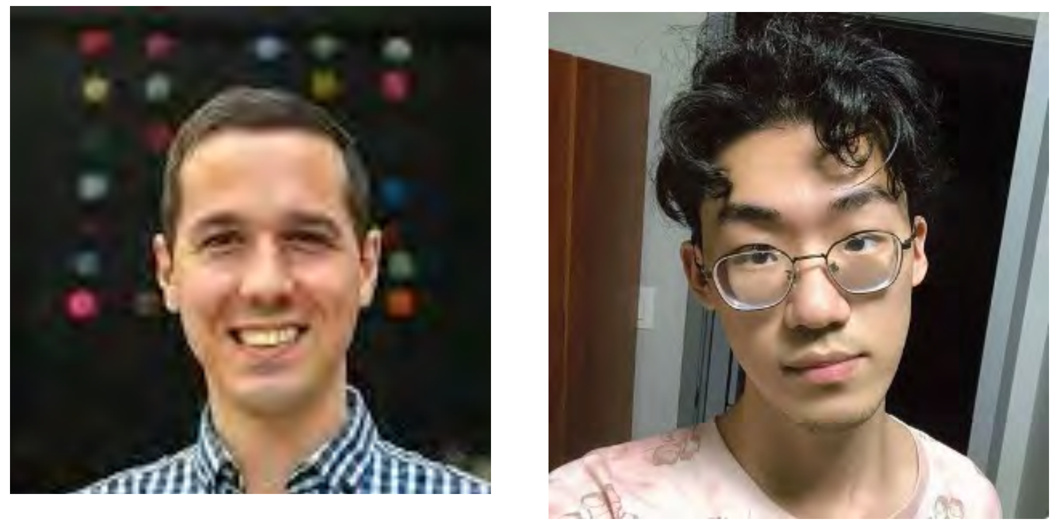

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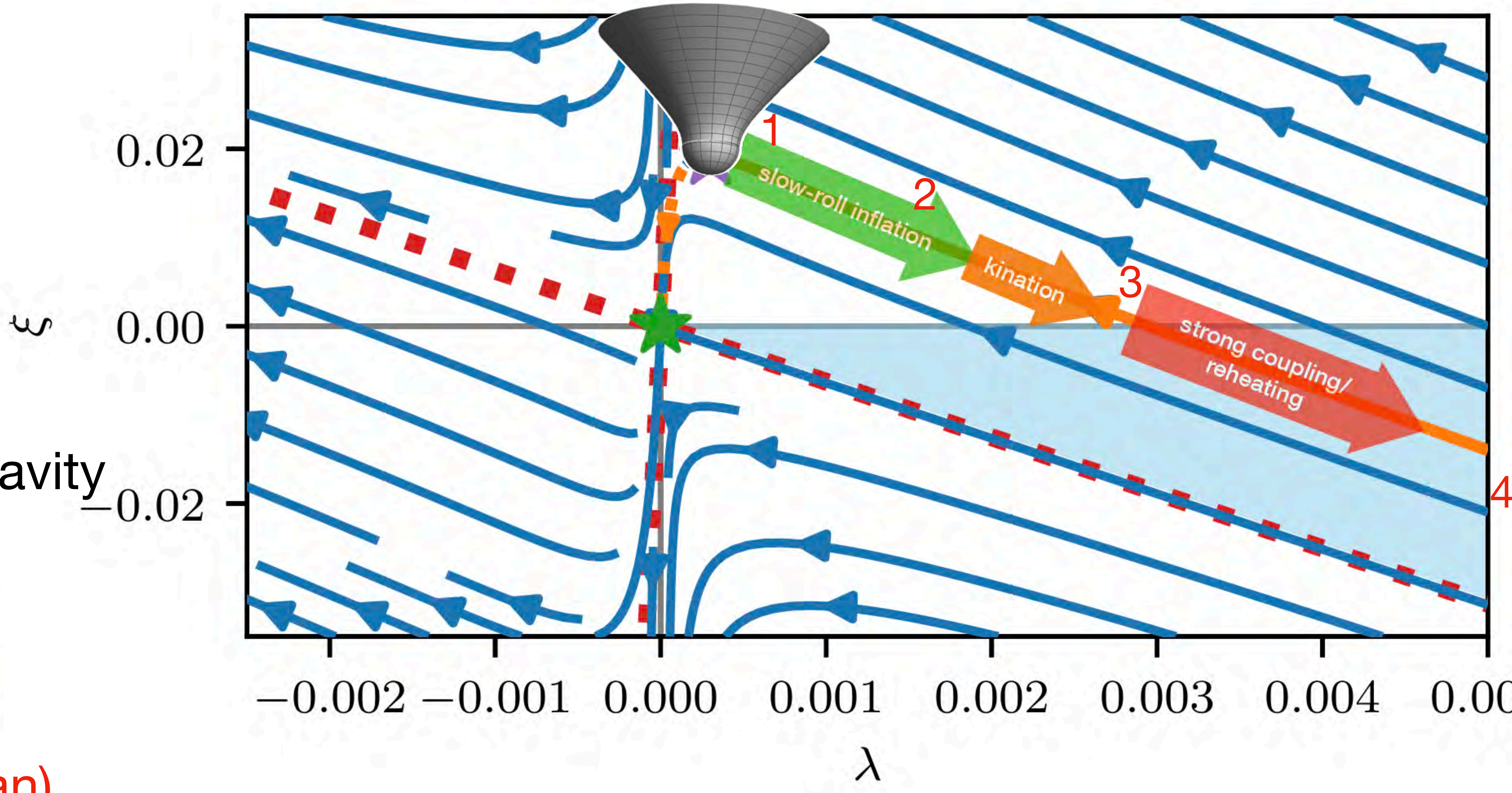
1. Hartle-Hawking (Euclidean → Lorentzian)
2. Slow-roll inflation w/ QG
3. Strong coupling/reheating
4. Hot Big Bang w/ GR



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

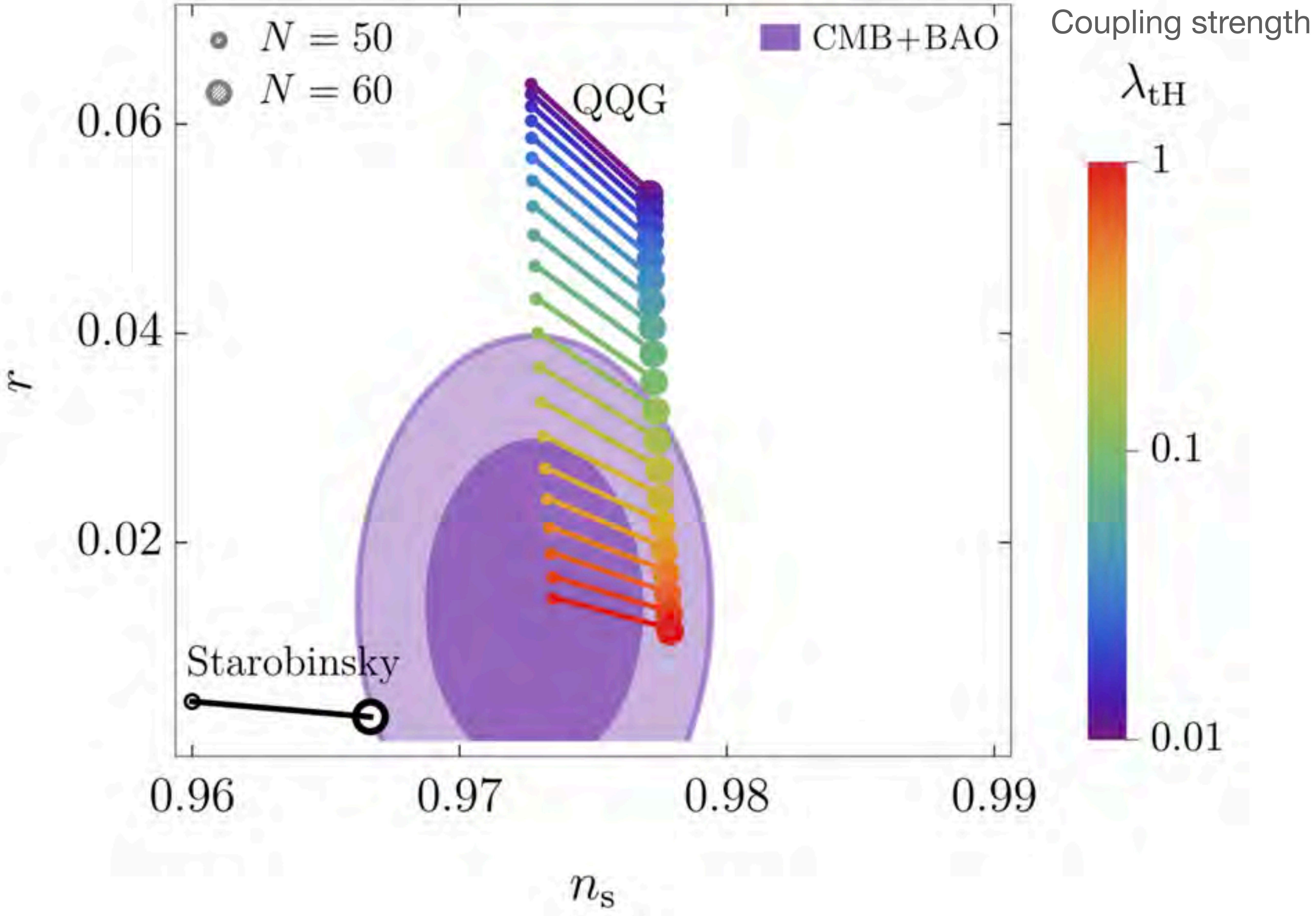
$$\beta_\lambda = \frac{\mathrm{d}\lambda}{\mathrm{d}\ln\mu} = -\frac{1}{(4\pi)^2}\frac{\left[(1617 + 90\mathcal{N})\lambda - 20\xi\right]\lambda}{90},$$

$$\mathcal{N} = \frac{1}{60}\mathcal{N}_{\mathrm{scalar}} + \frac{1}{5}\mathcal{N}_{\mathrm{vector}} + \frac{1}{20}\mathcal{N}_{\mathrm{fermion}}\,,$$

CMB+BAO constraints

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

$$n_{\mathrm{s}} \sim 1 - \frac{4}{3N}, \qquad r \sim \frac{8}{3}\left(\frac{2}{\lambda_{\mathrm{tH}}^2 N^4}\right)^{1/3}.$$



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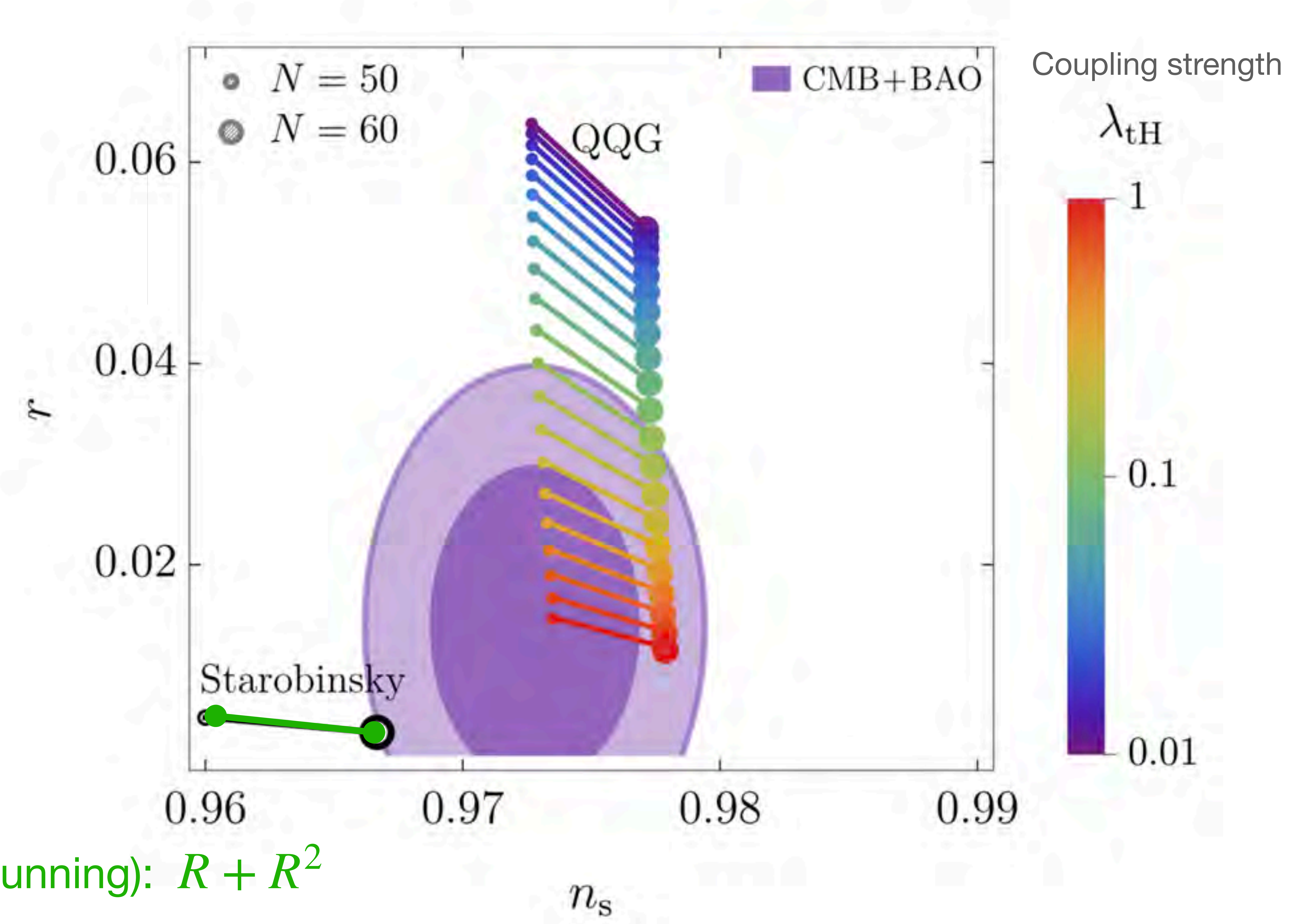

Starobinsky (no running): $R + R^2$

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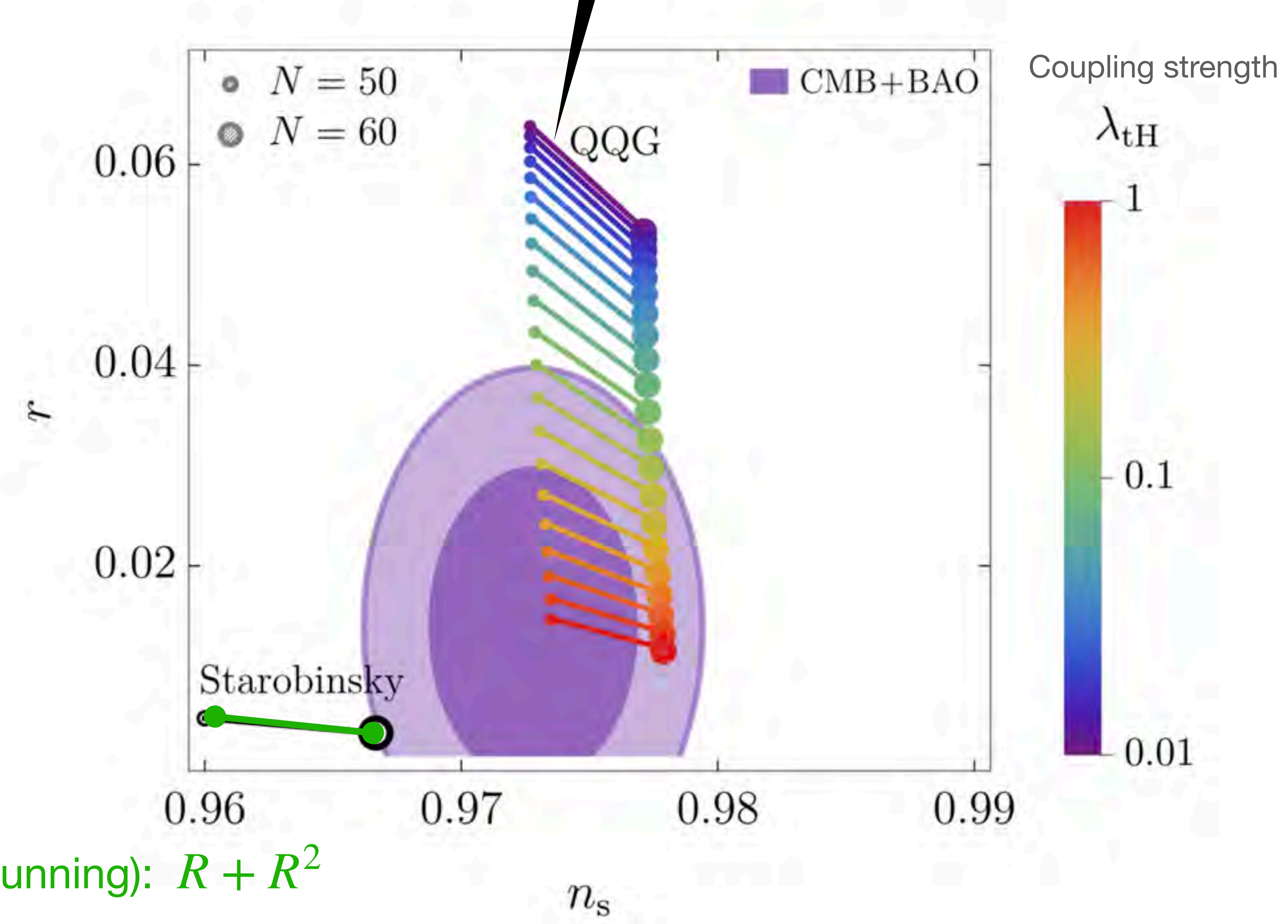
Quantum Quadratic Gravity



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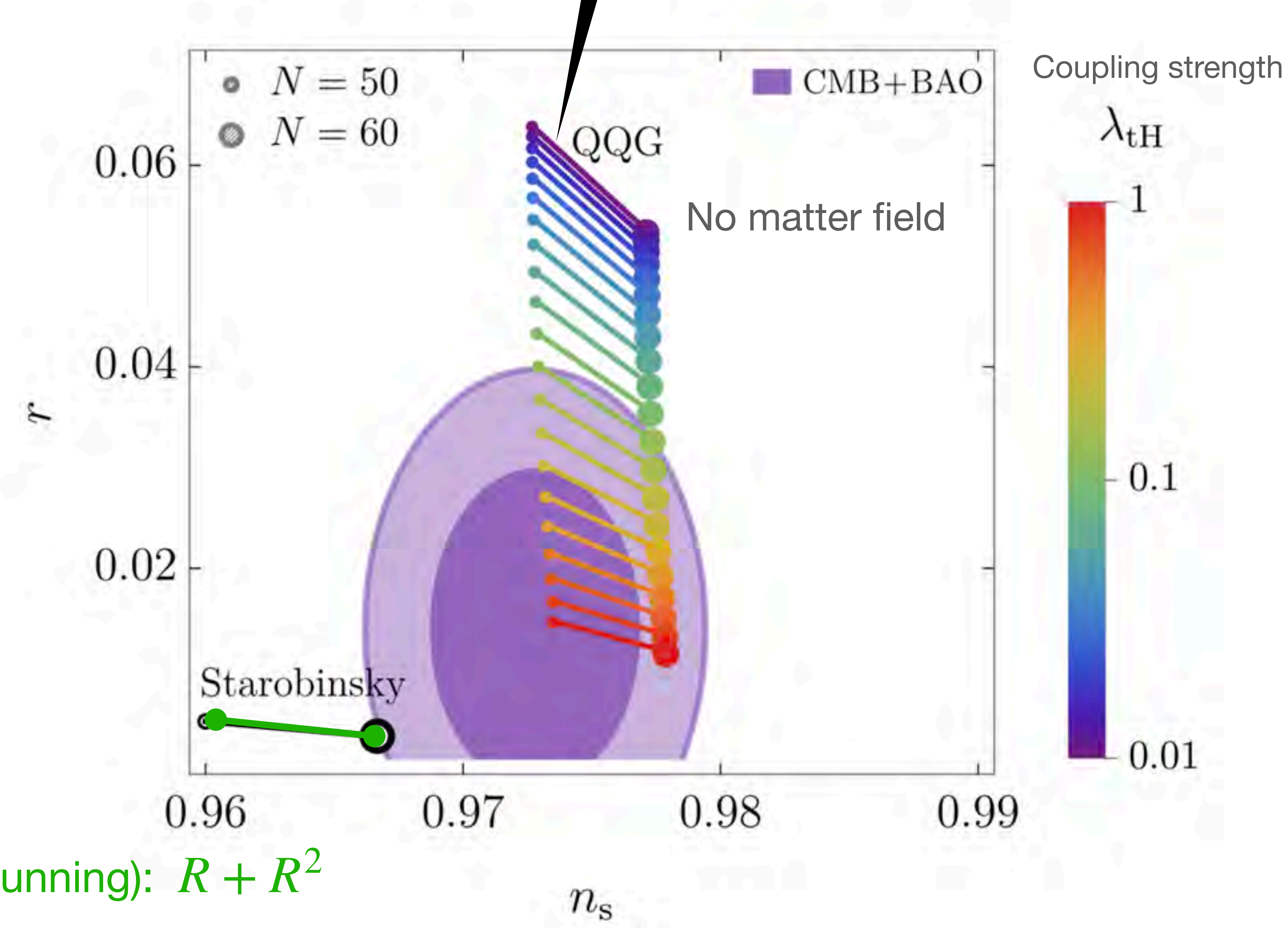

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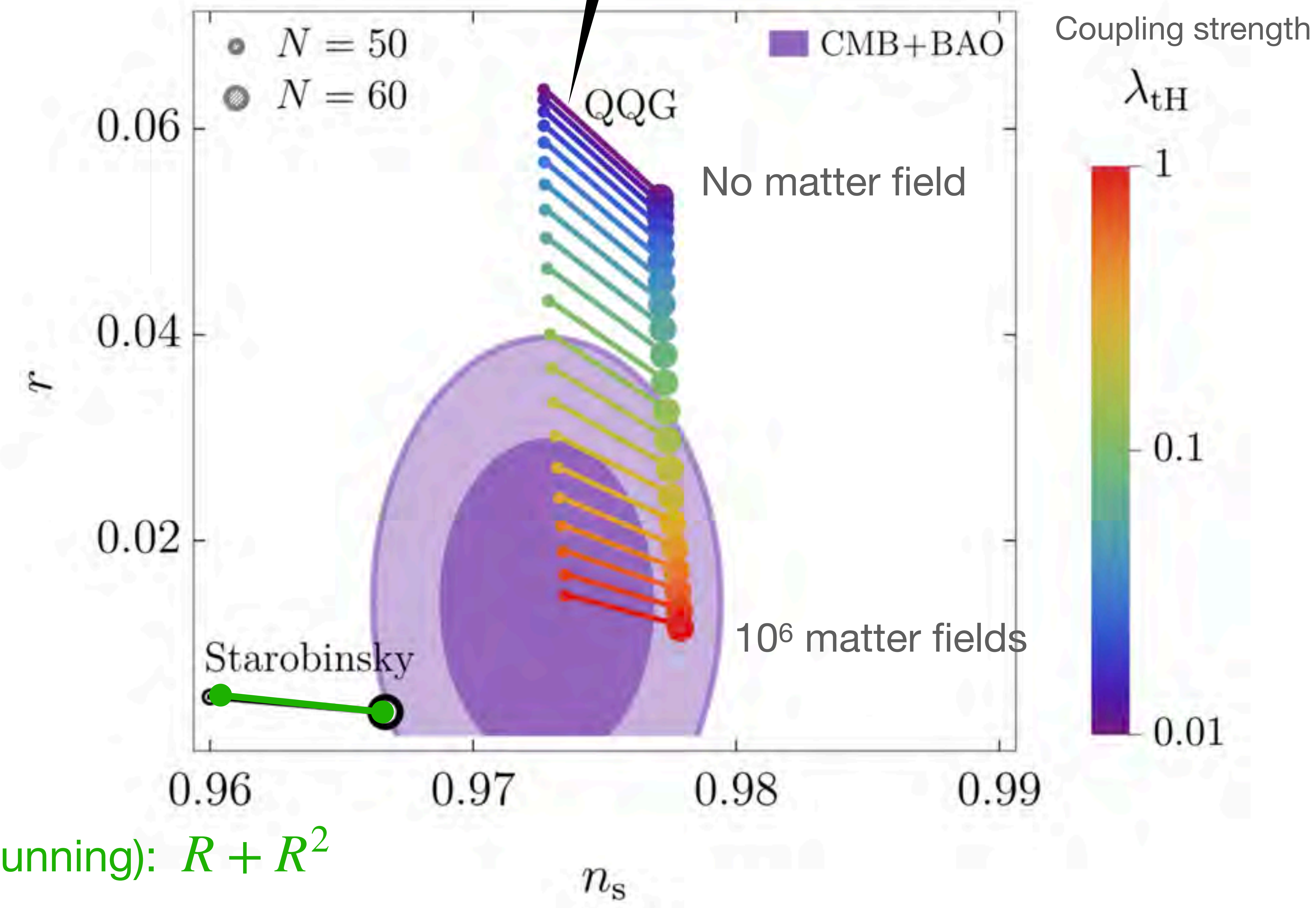

Quantum Quadratic Gravity

No matter field

10^6 matter fields

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

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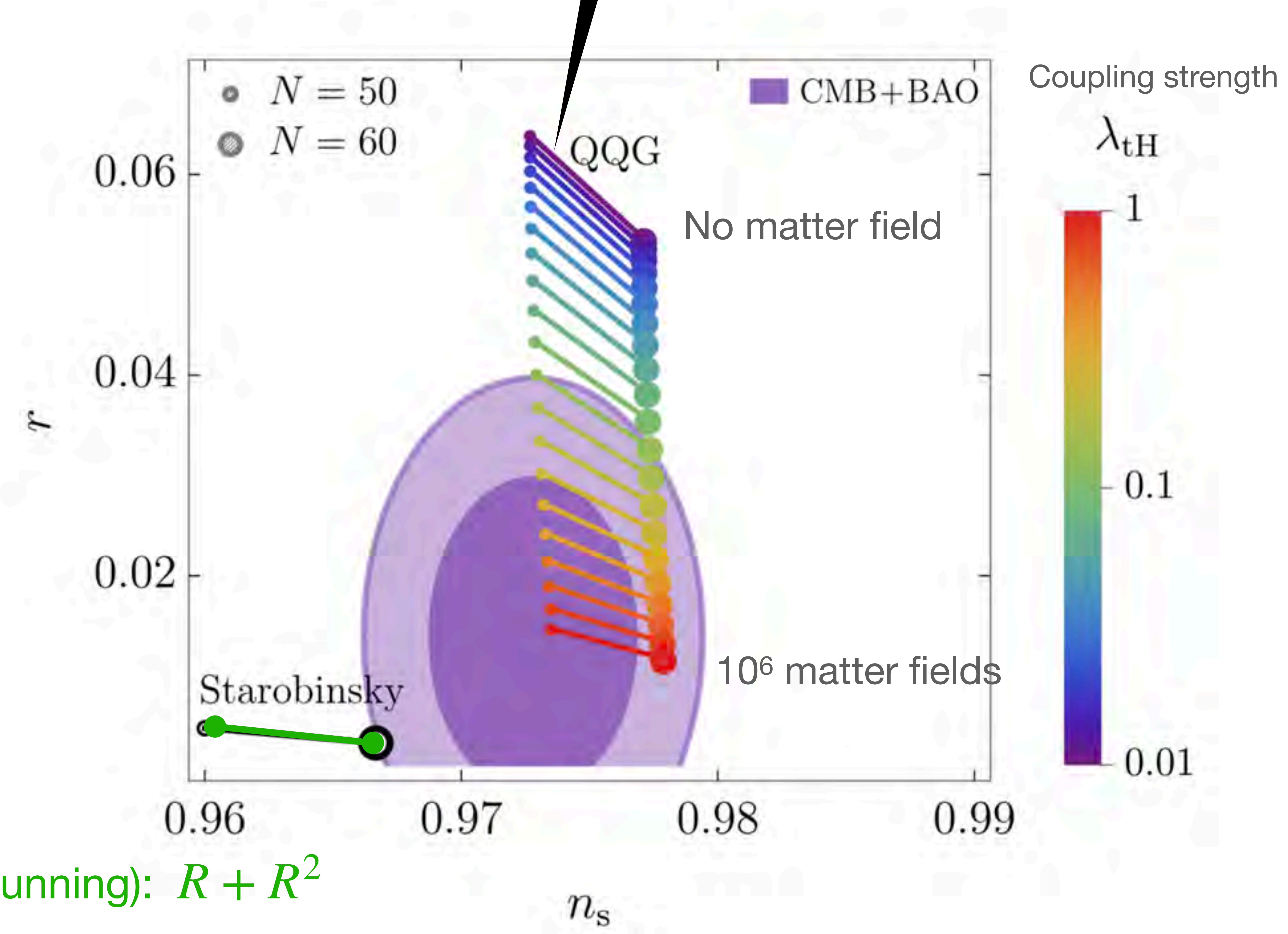
$$\boxed{r \gtrsim 0.01}$$

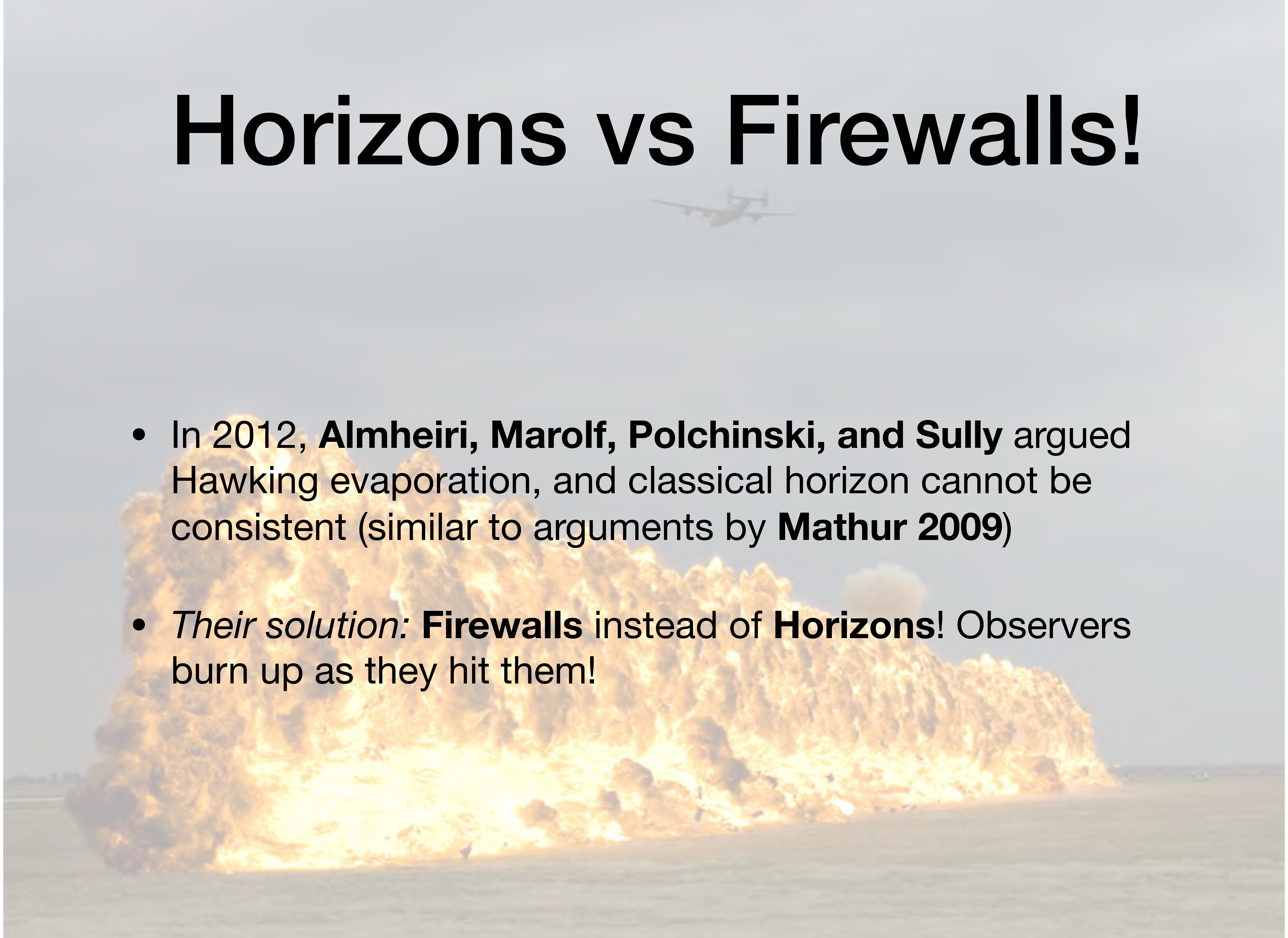
Quantum Quadratic Gravity



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

Outline

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

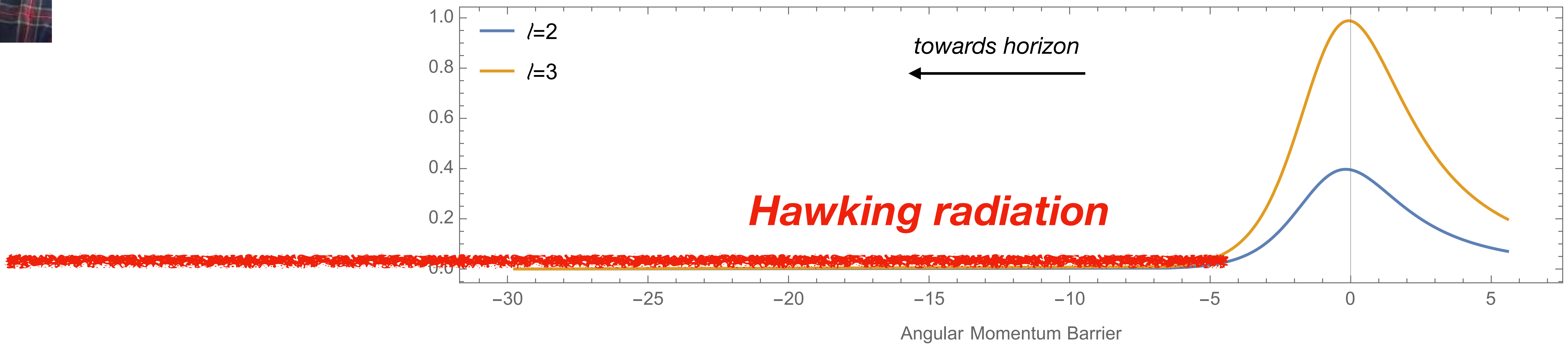


Horizons vs Firewalls!

- 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: $t_{\mathrm{echo}} \to \infty$!



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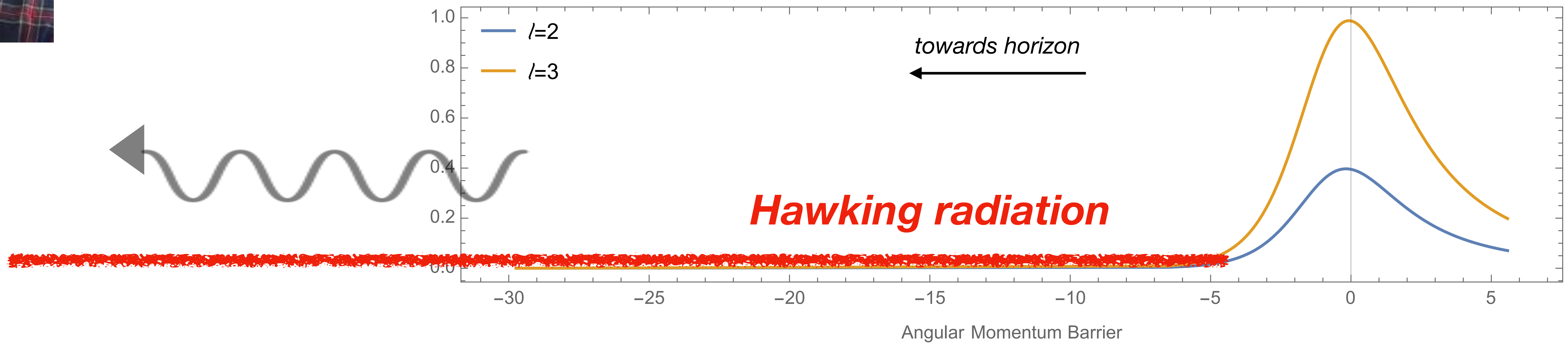

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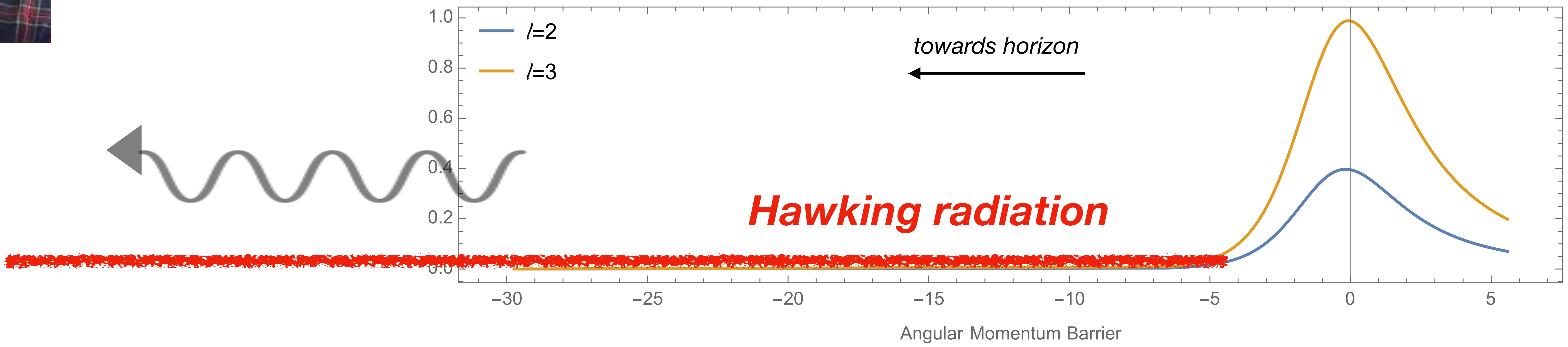
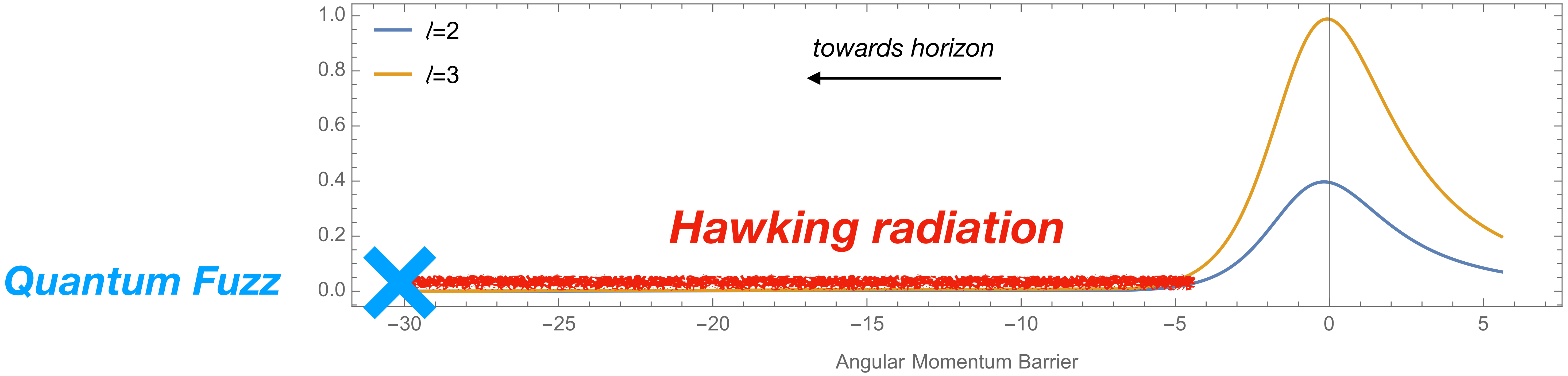


- Finite Entropy & Echoes: $t_{\rm echo} = \dfrac{\ln\left[{\rm Entropy}/\ell(\ell+1)\right]}{2\pi \times {\rm Hawking\ Temperature}}$



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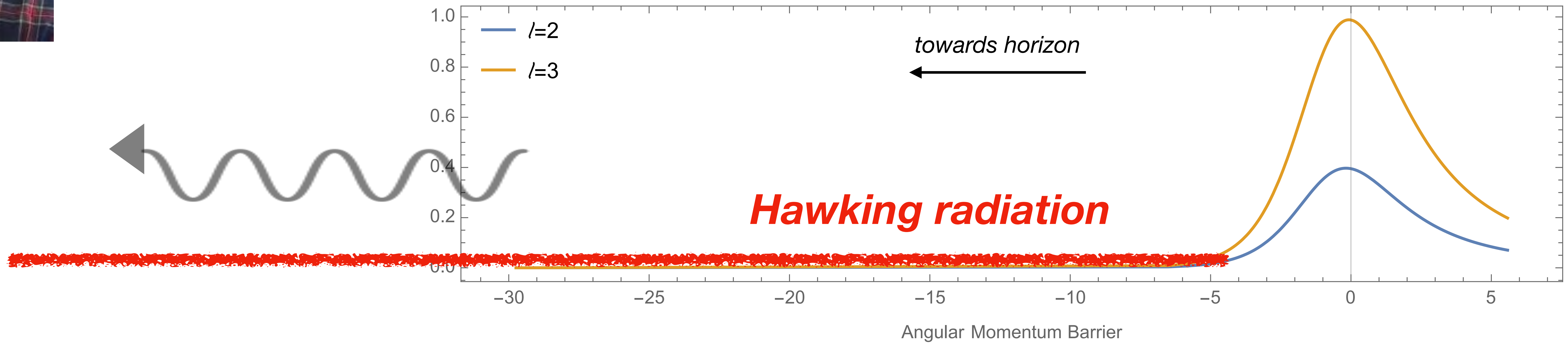

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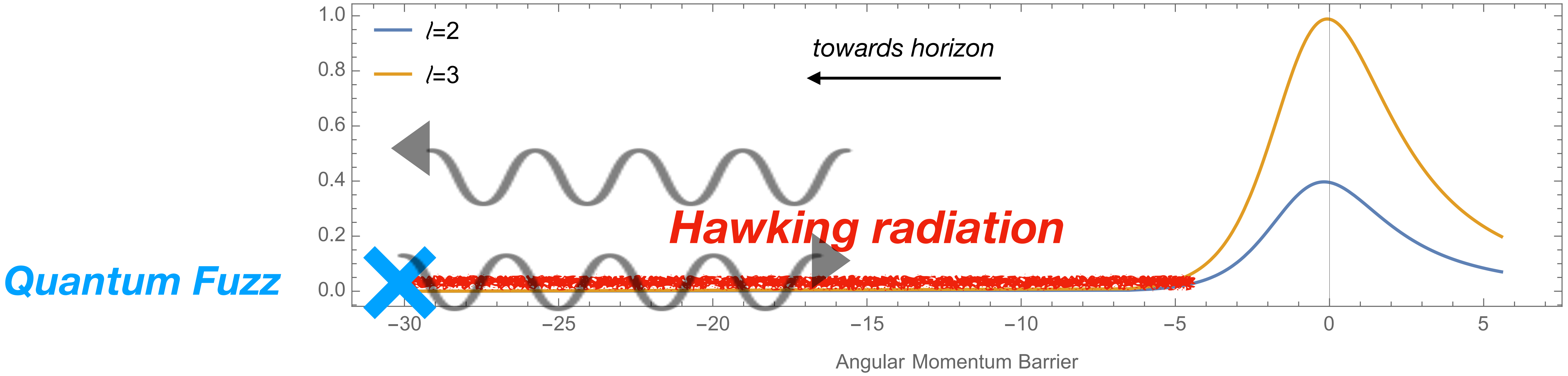
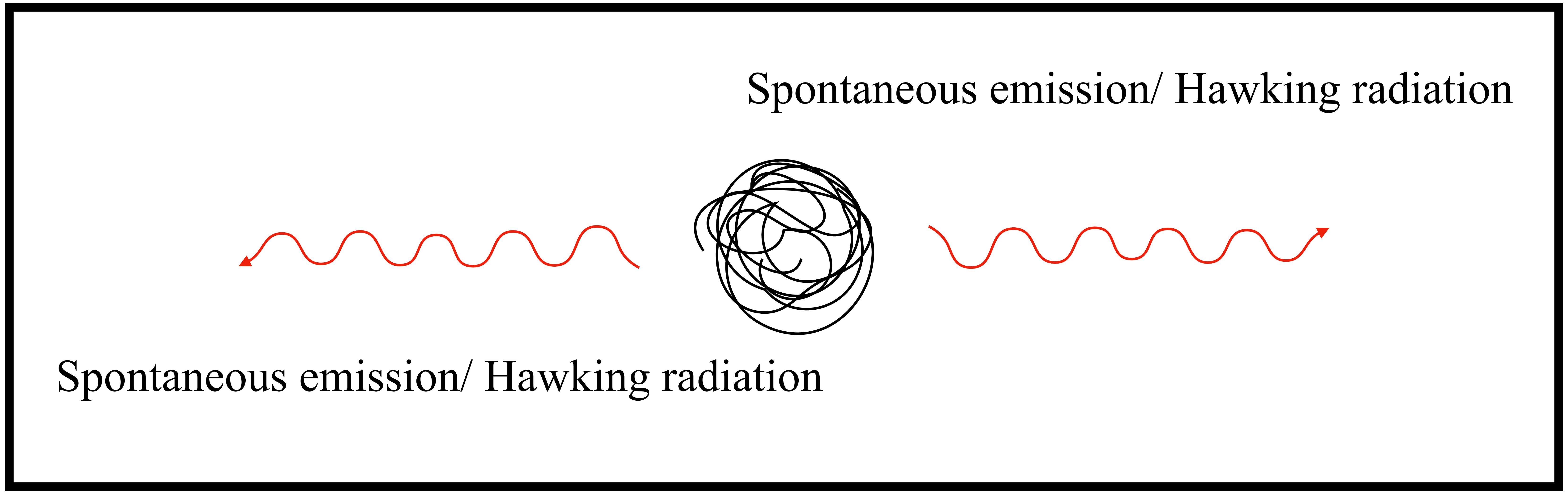
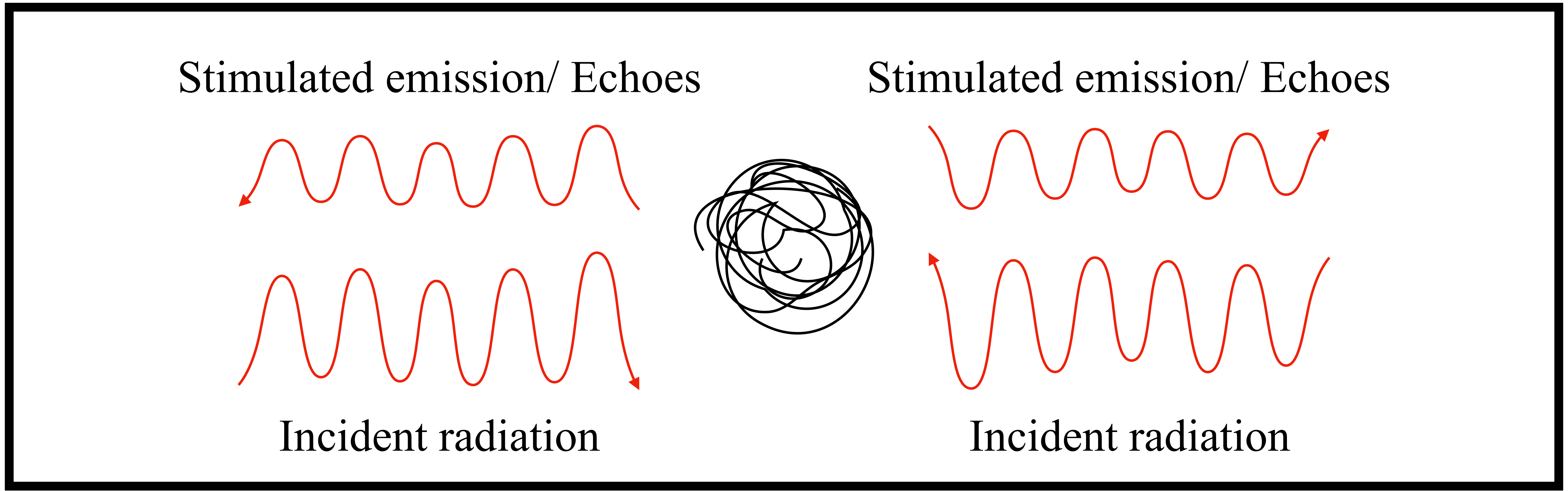




Spontaneous emission/ Hawking radiation

Spontaneous emission/ Hawking radiation



Stimulated emission/ Echoes

Stimulated emission/ Echoes

Incident radiation

Incident radiation

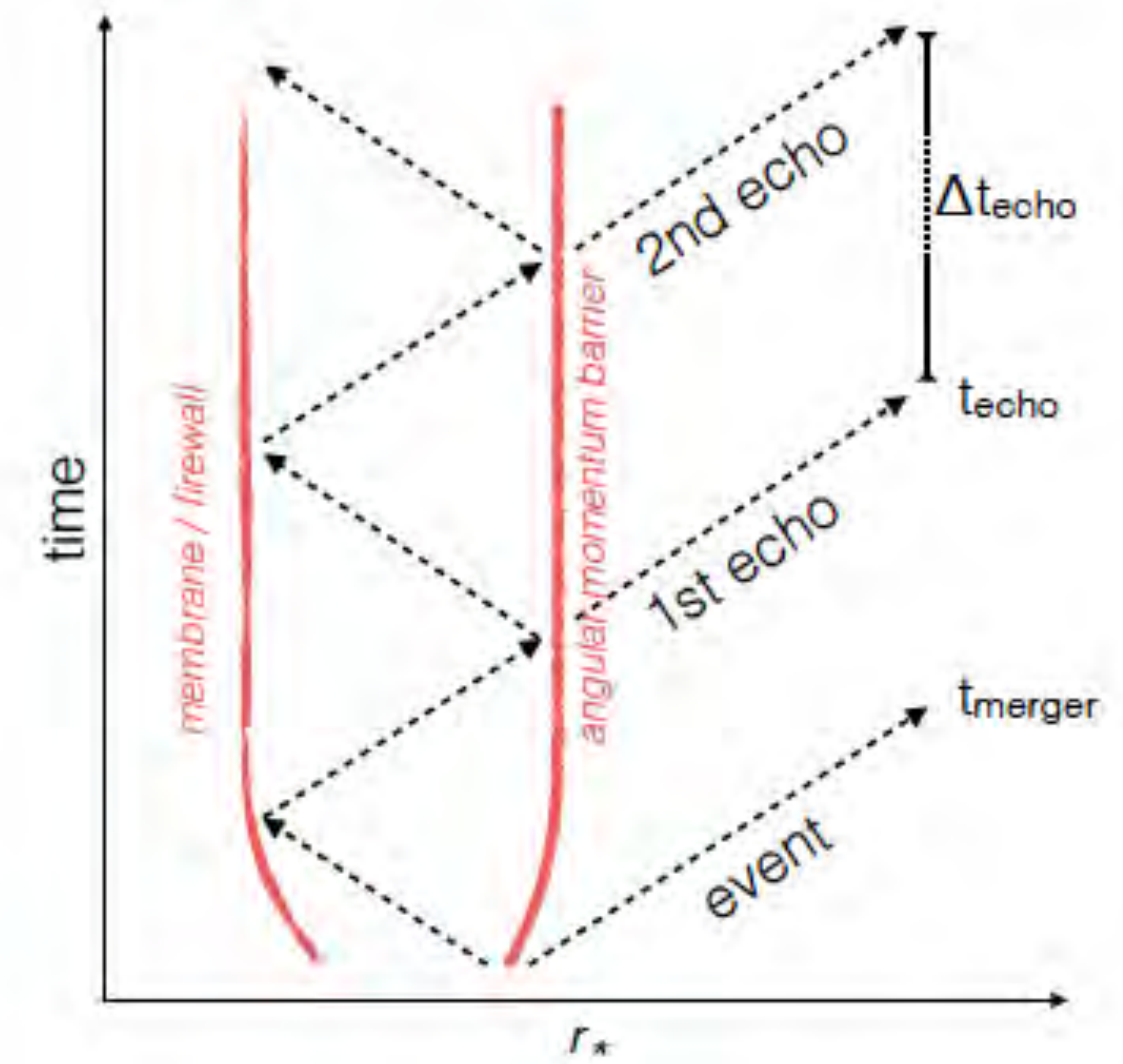
$$\boxed{R = \exp\left(-\frac{\hbar\omega}{kT_H}\right)}$$

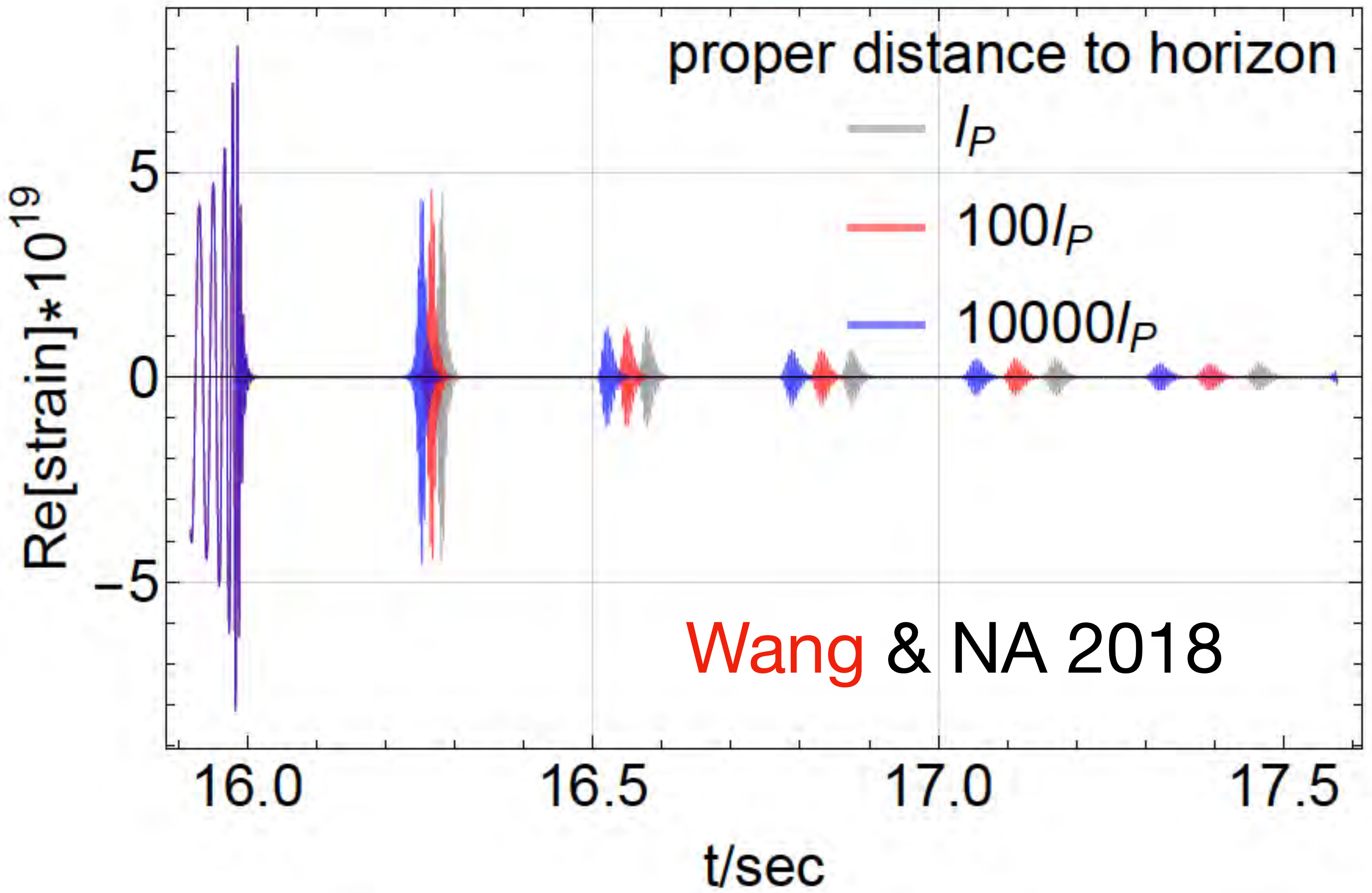
From Planck to LIGO!

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

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

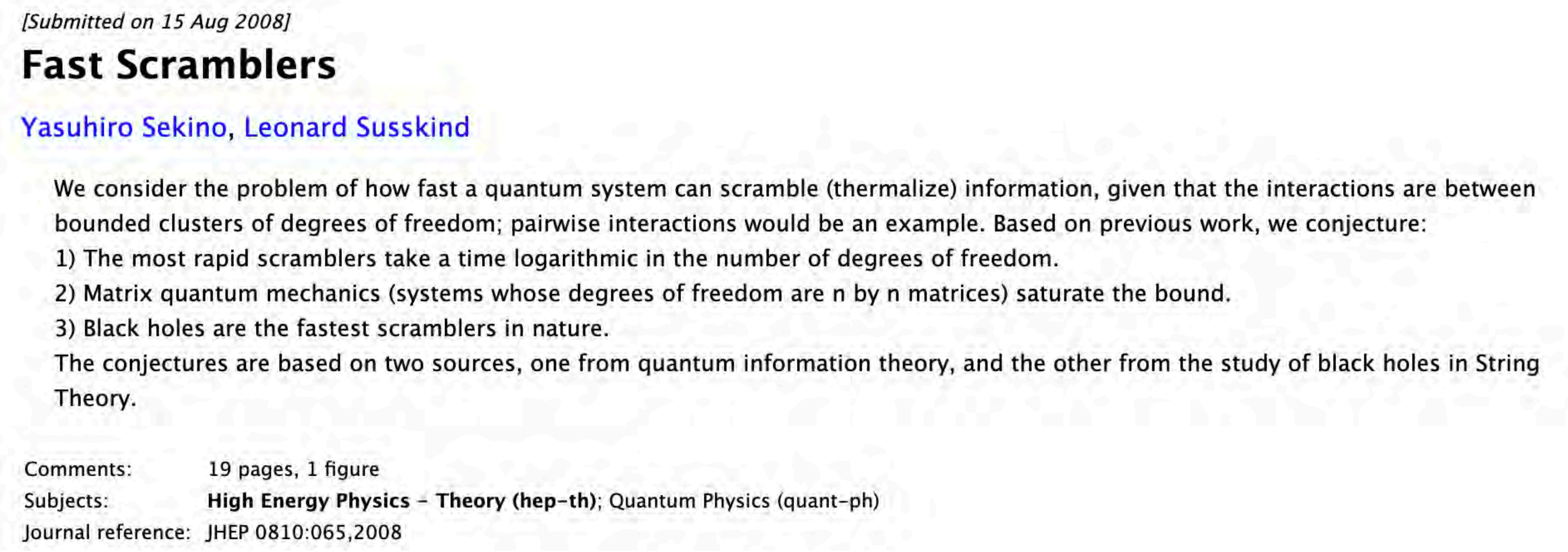
- *Stimulated Hawking Radiation (Oshita, Wang & NA 2020)*





Wang & NA 2018

Black Holes as Fast Scramblers of Quantum Information



[Submitted on 15 Aug 2008]

Fast Scramblers

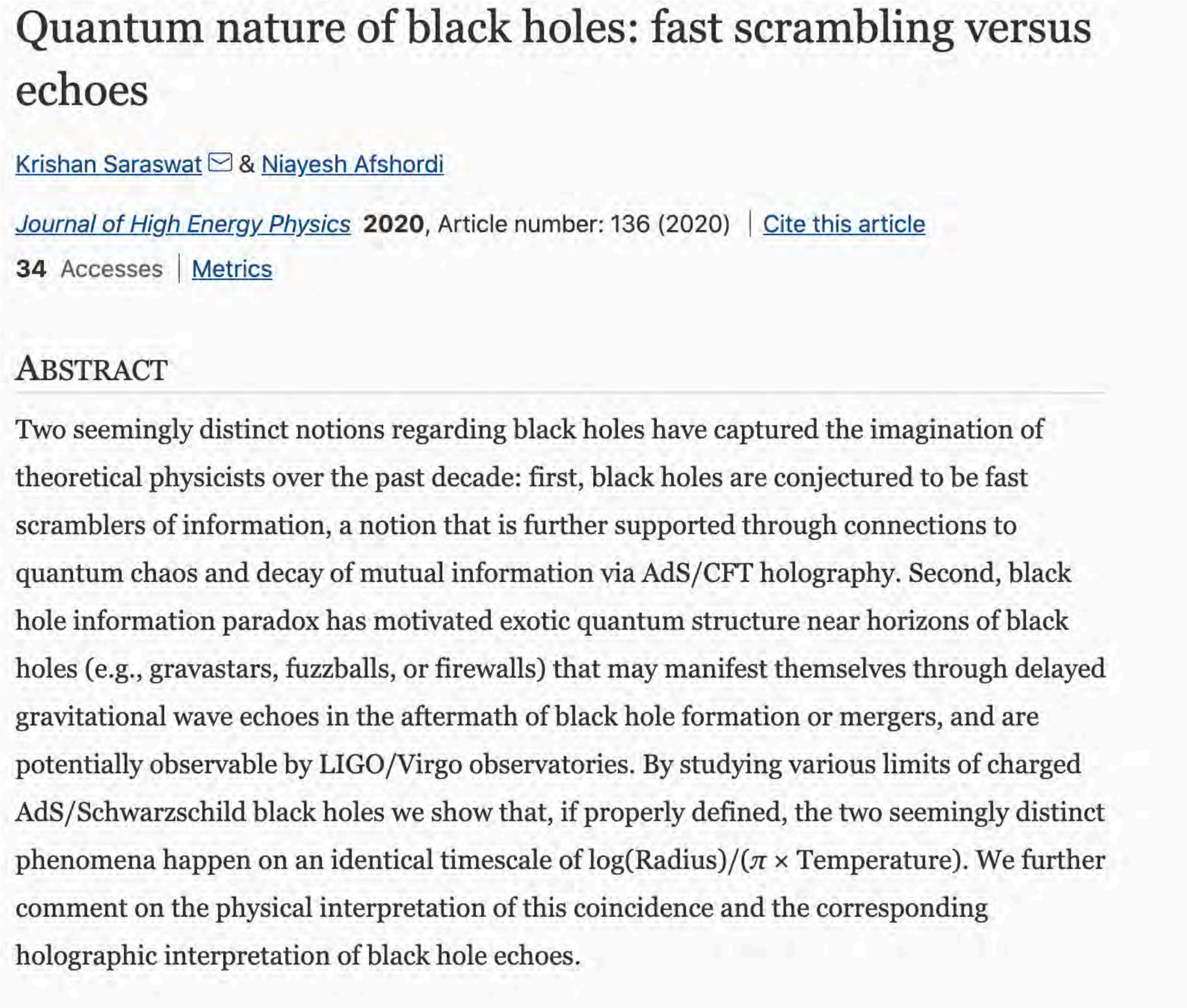
Yasuhiro Sekino, Leonard Susskind

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(Radius)/(π × Temperature). We further comment on the physical interpretation of this coincidence and the corresponding holographic interpretation of black hole echoes.

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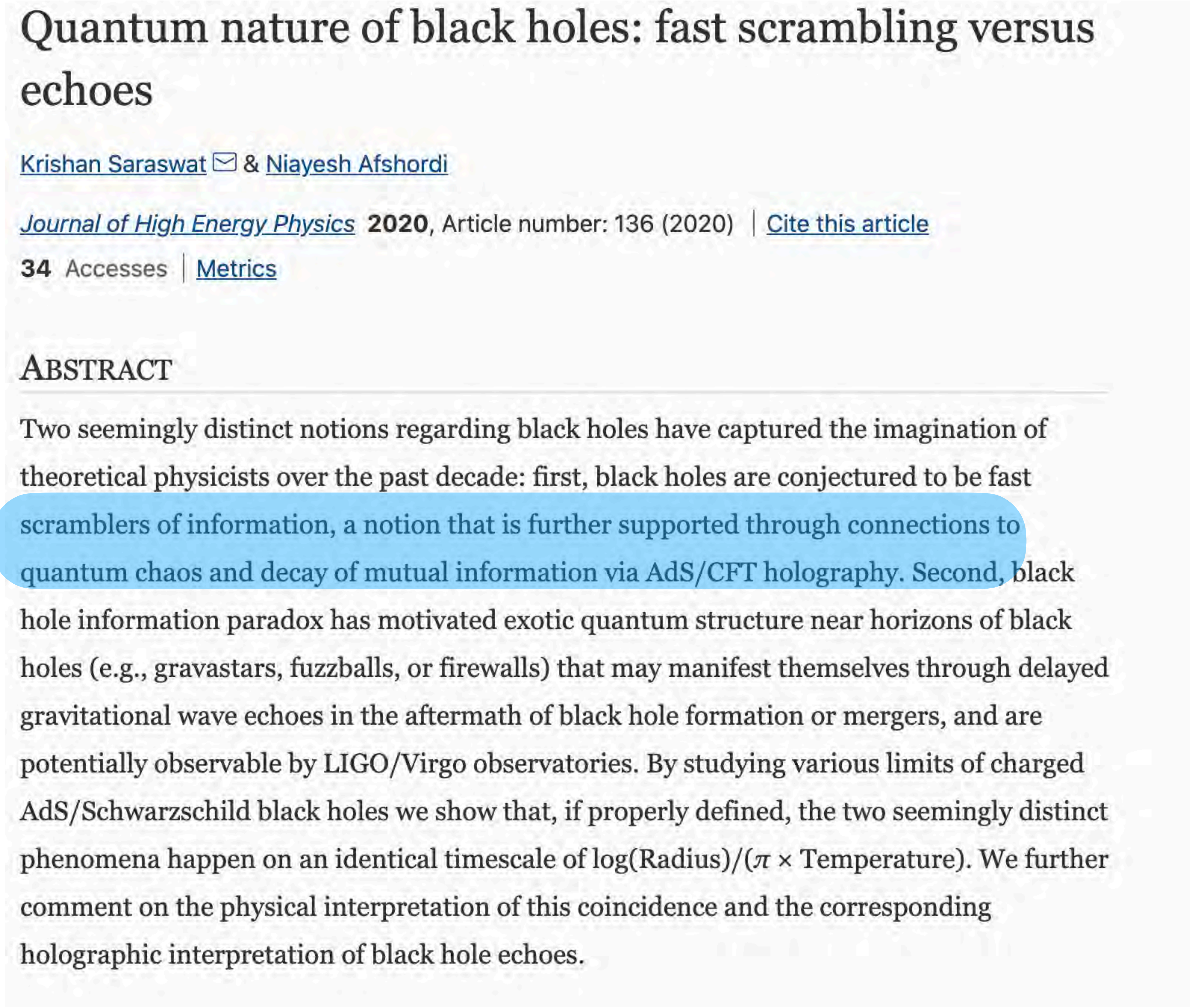

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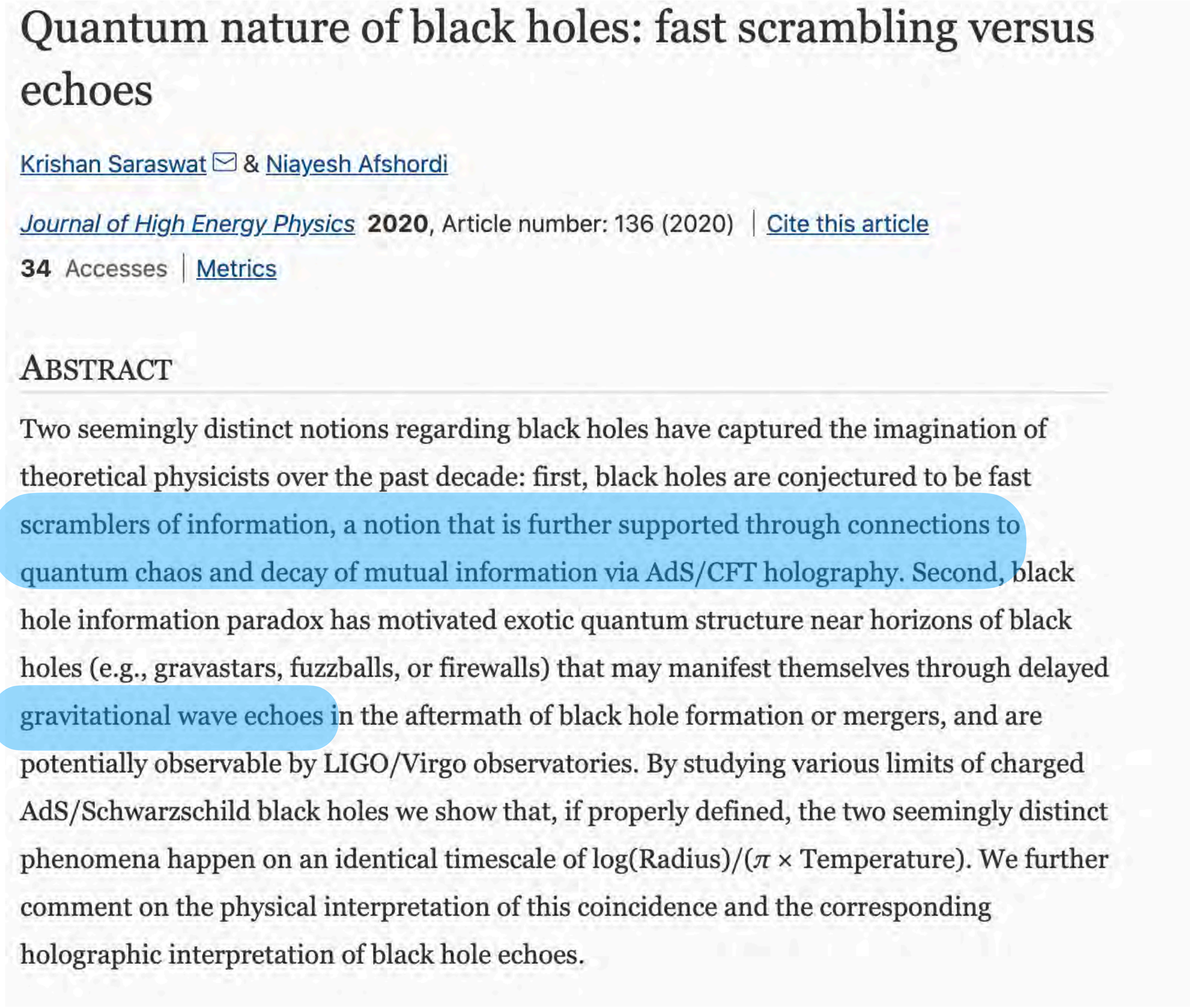

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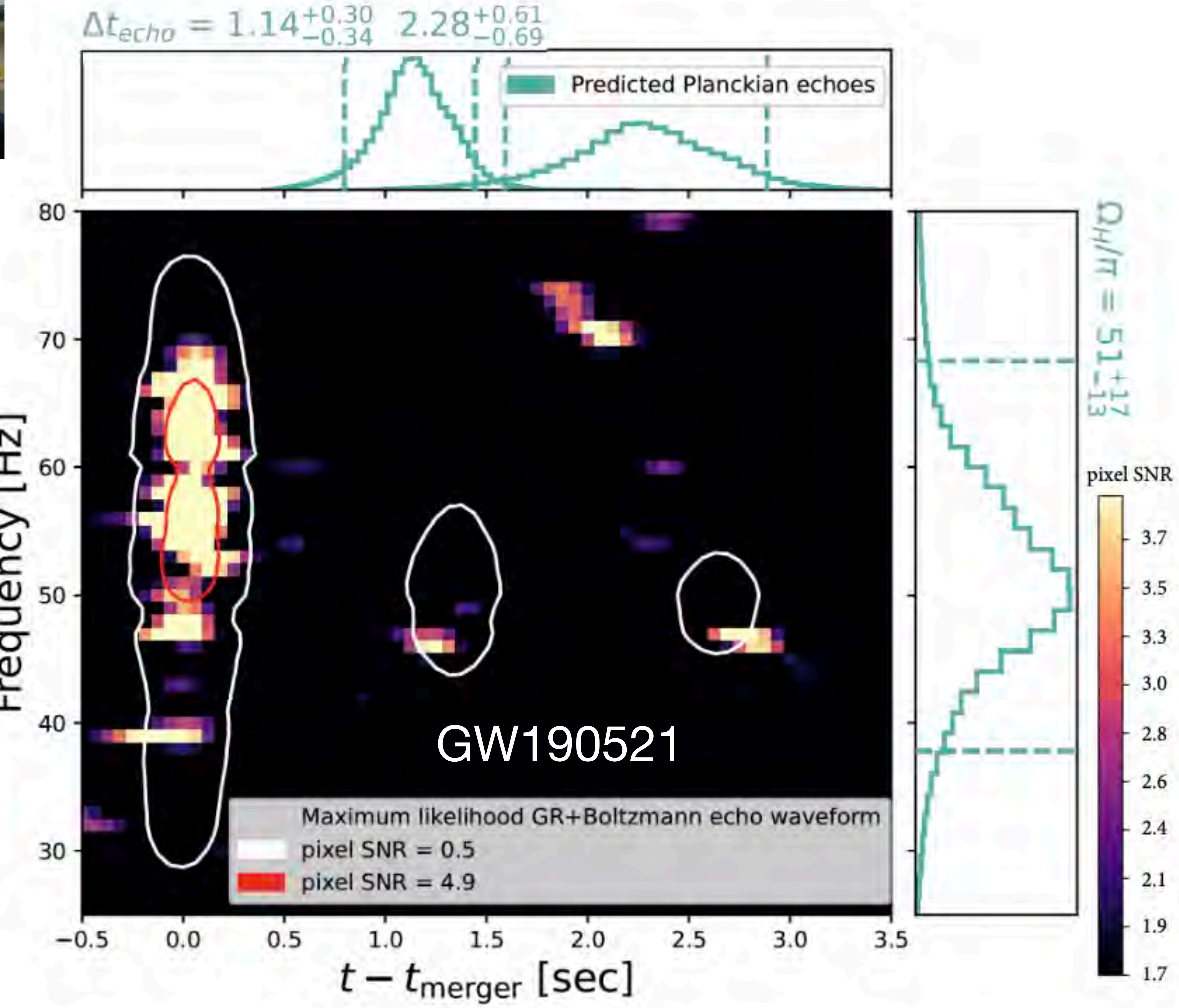
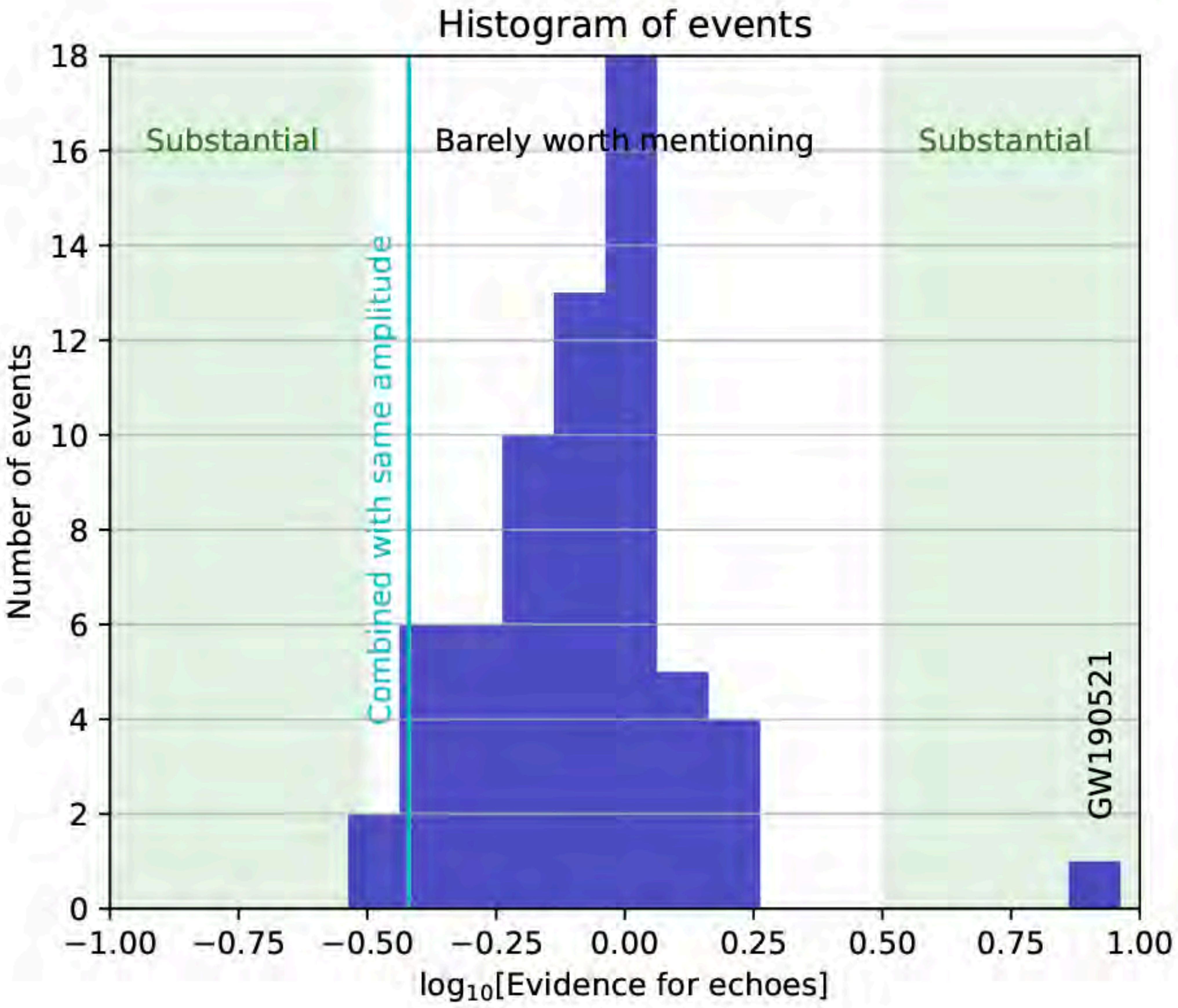
Are there echoes in LIGO data?

- Abedi, Longo & NA 2023

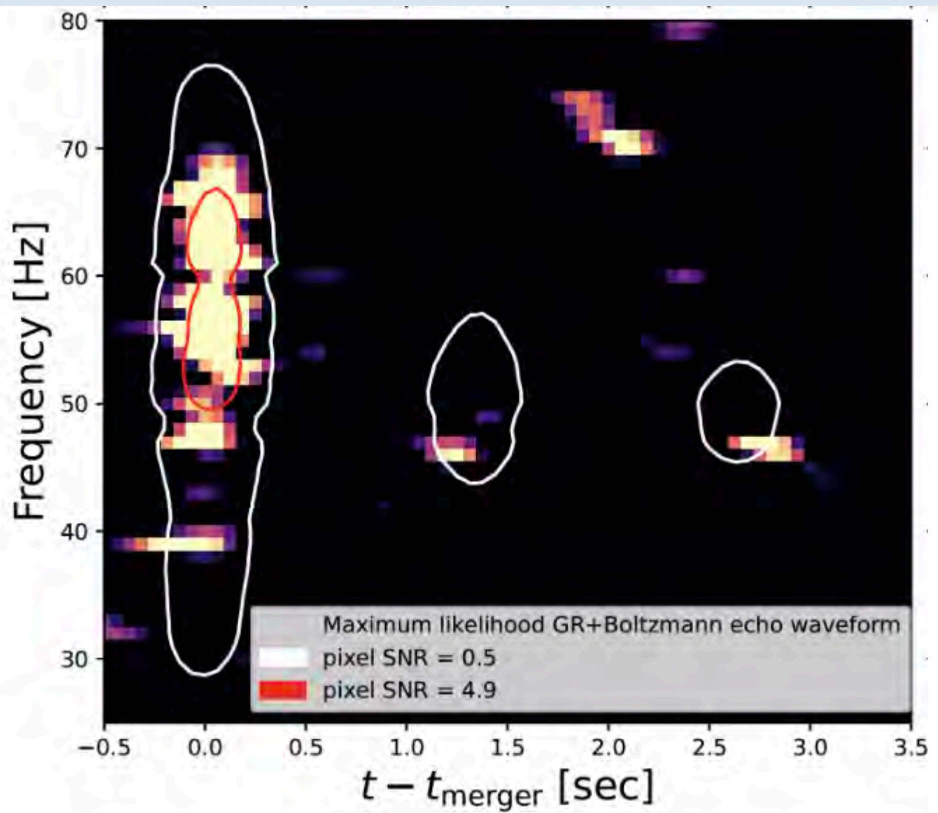
Abedi 2025





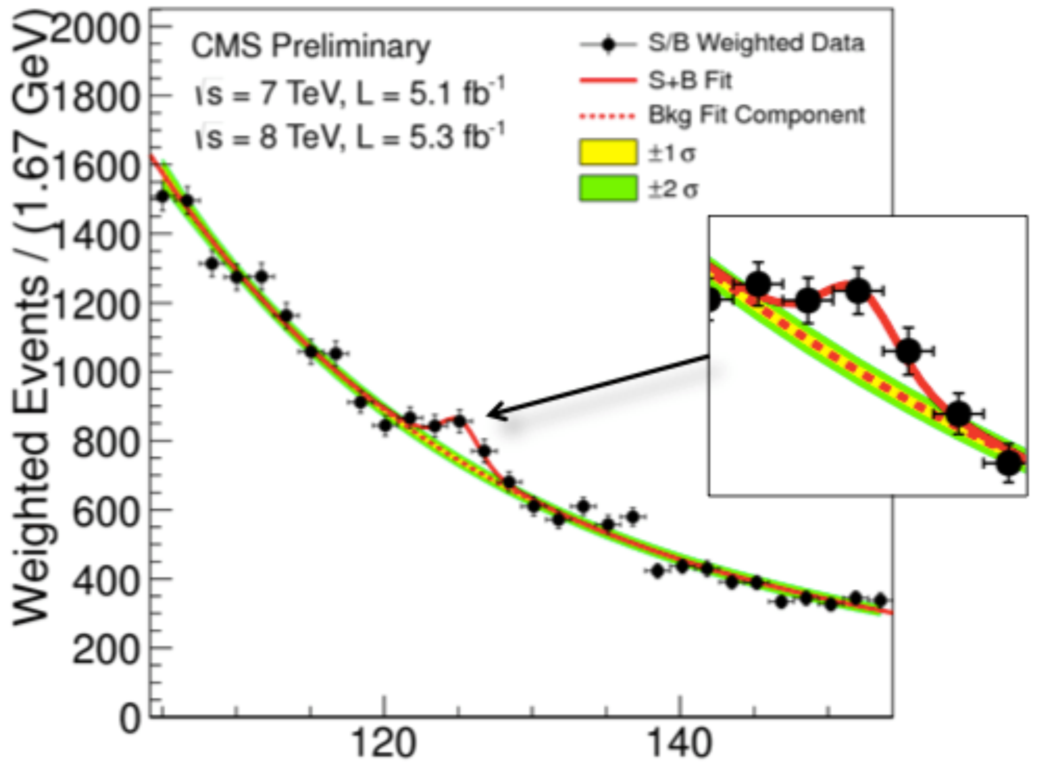
Echoes to *LIGO*

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



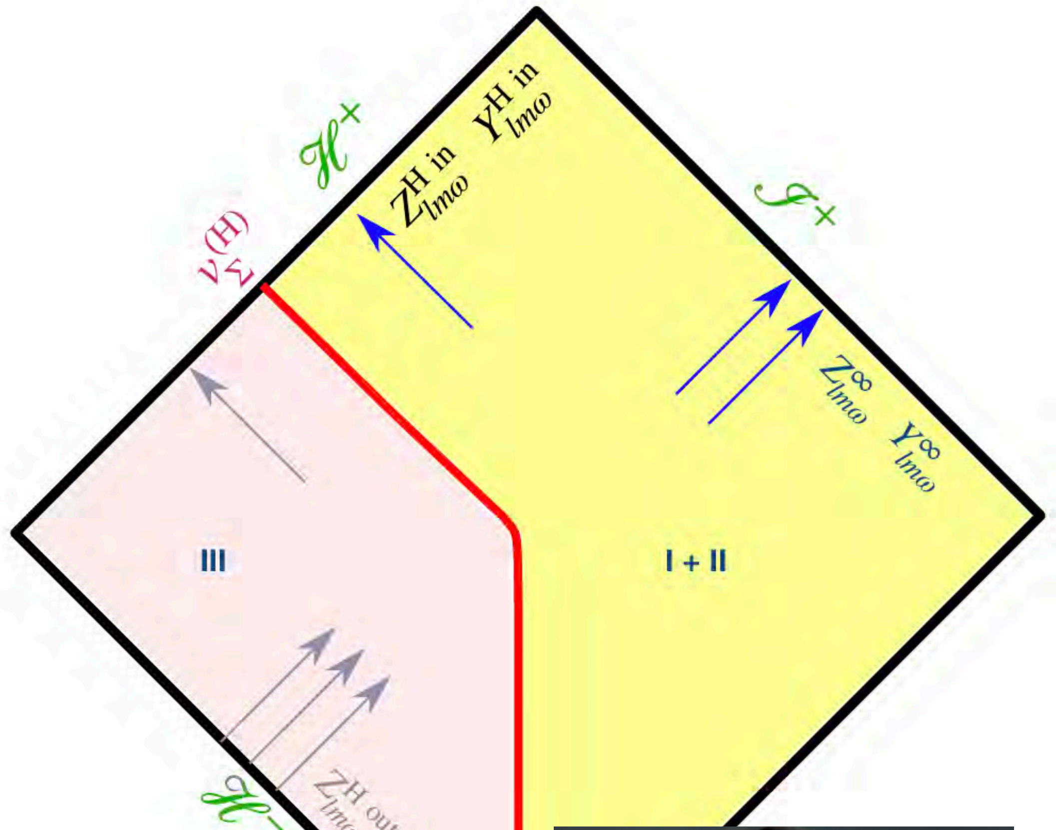
Higgs to *LHC*

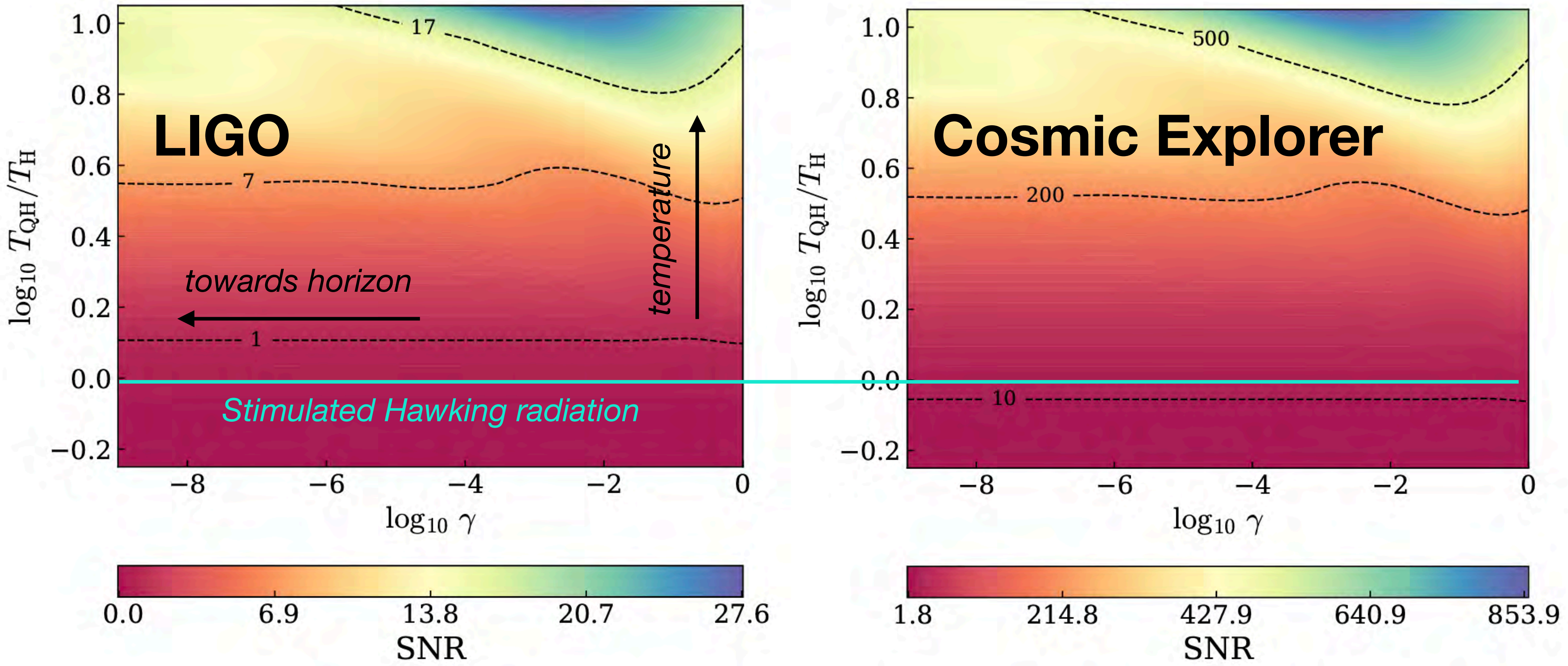
- Unitarity
- (Perturbative) Effective Field Theory
- Gauge Symmetries of Standard Model



Future is bright!

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





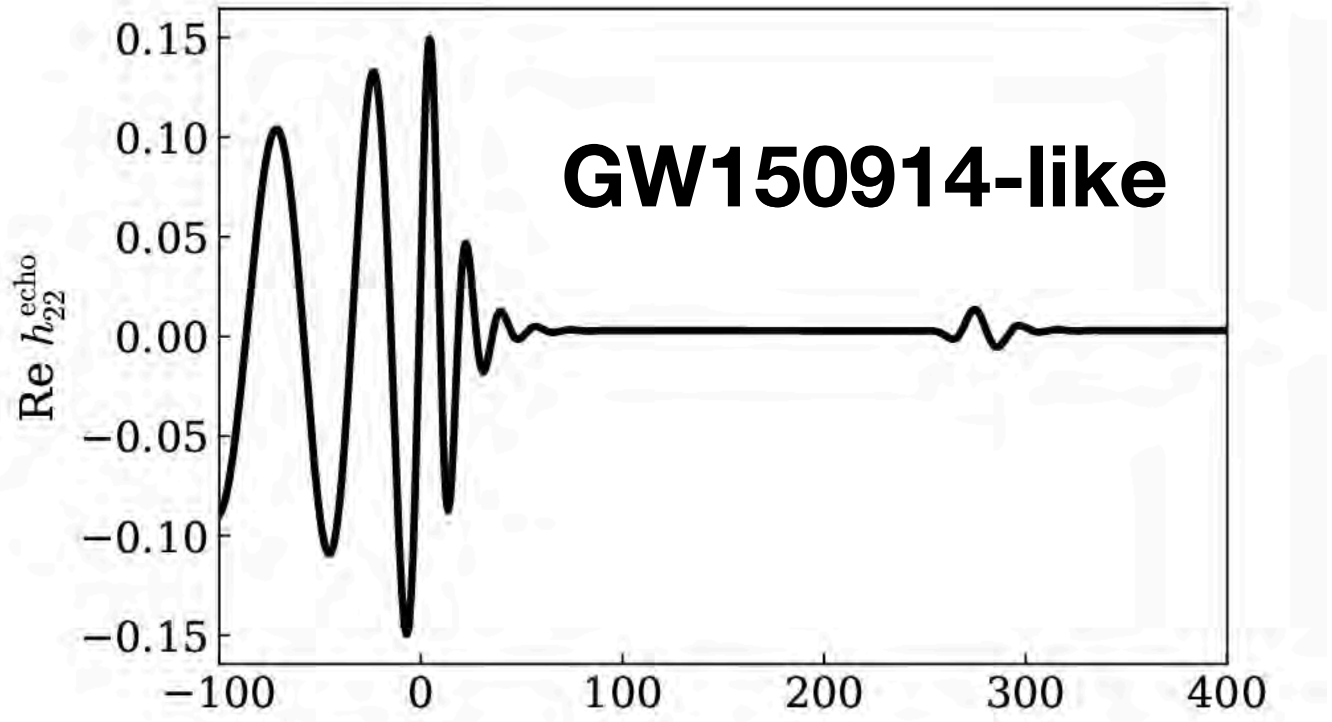


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set $v_\Sigma^{(\mathrm{H})} = -13, \Delta v = 2/\kappa = 8, \gamma = 10^{-15}$, and $T_{\mathrm{QH}} = T_H$.

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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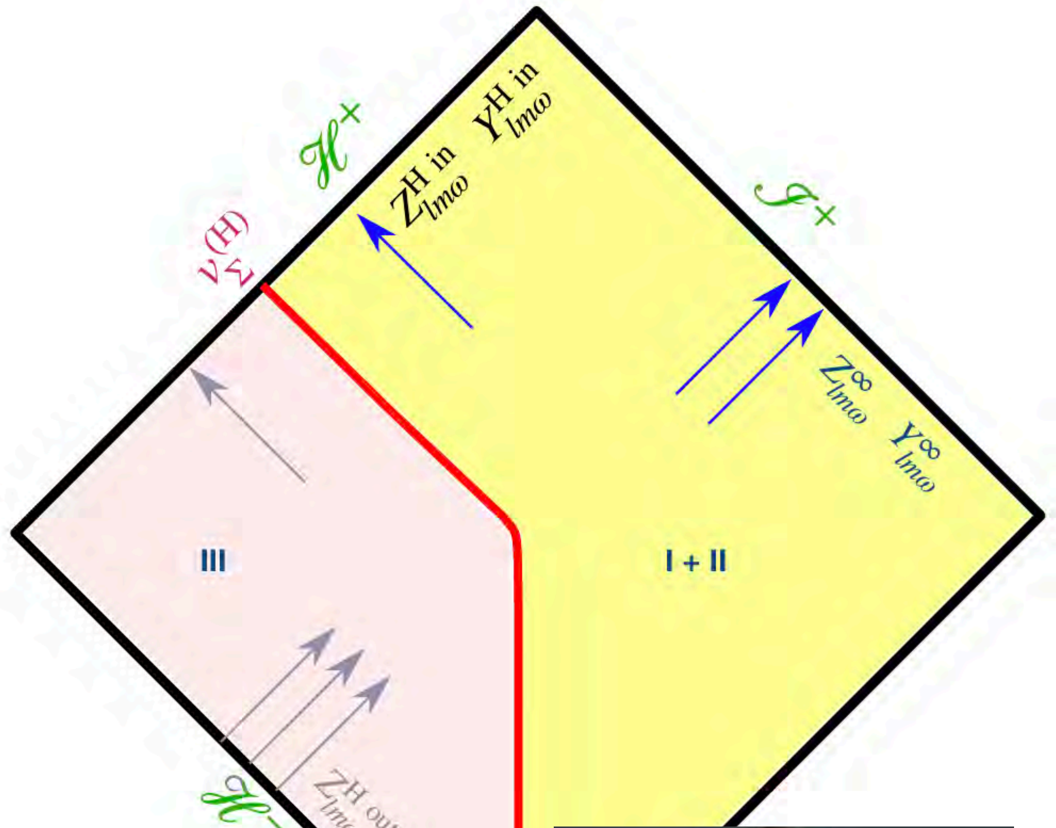

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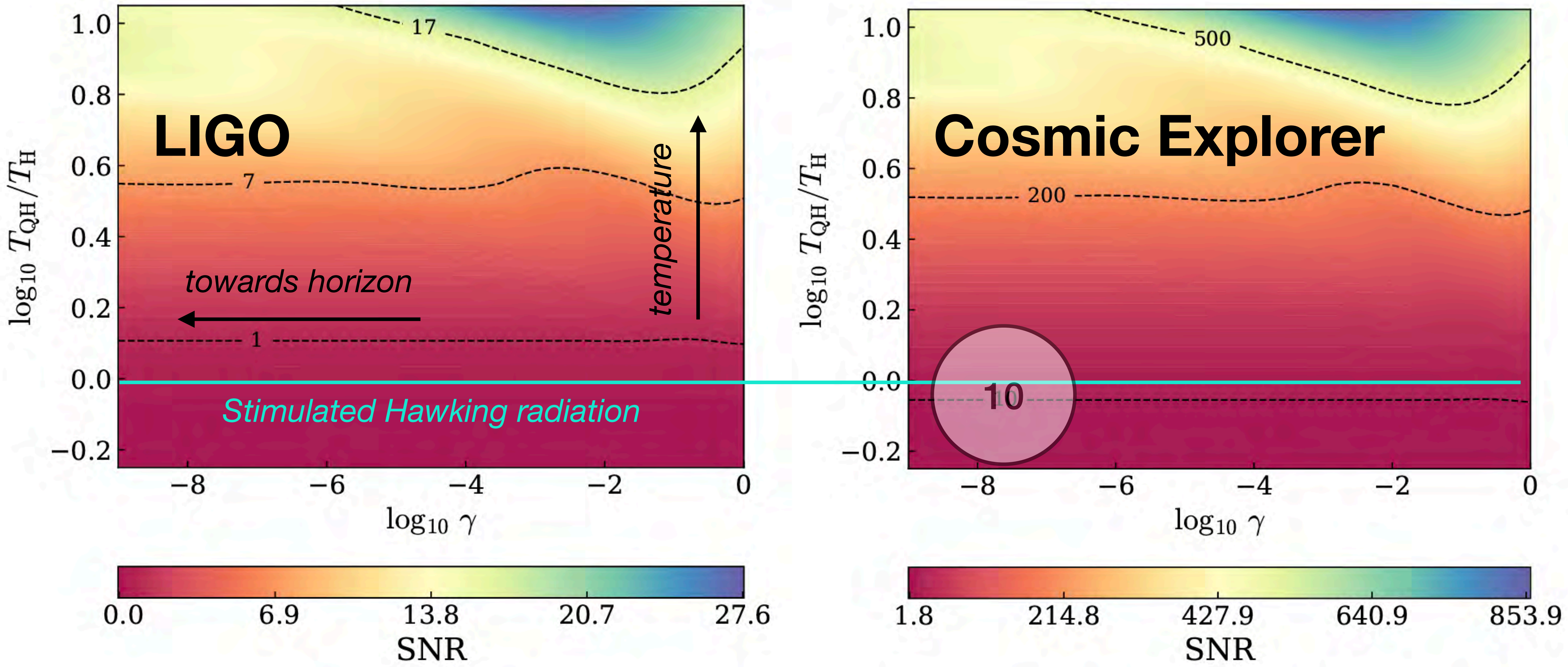

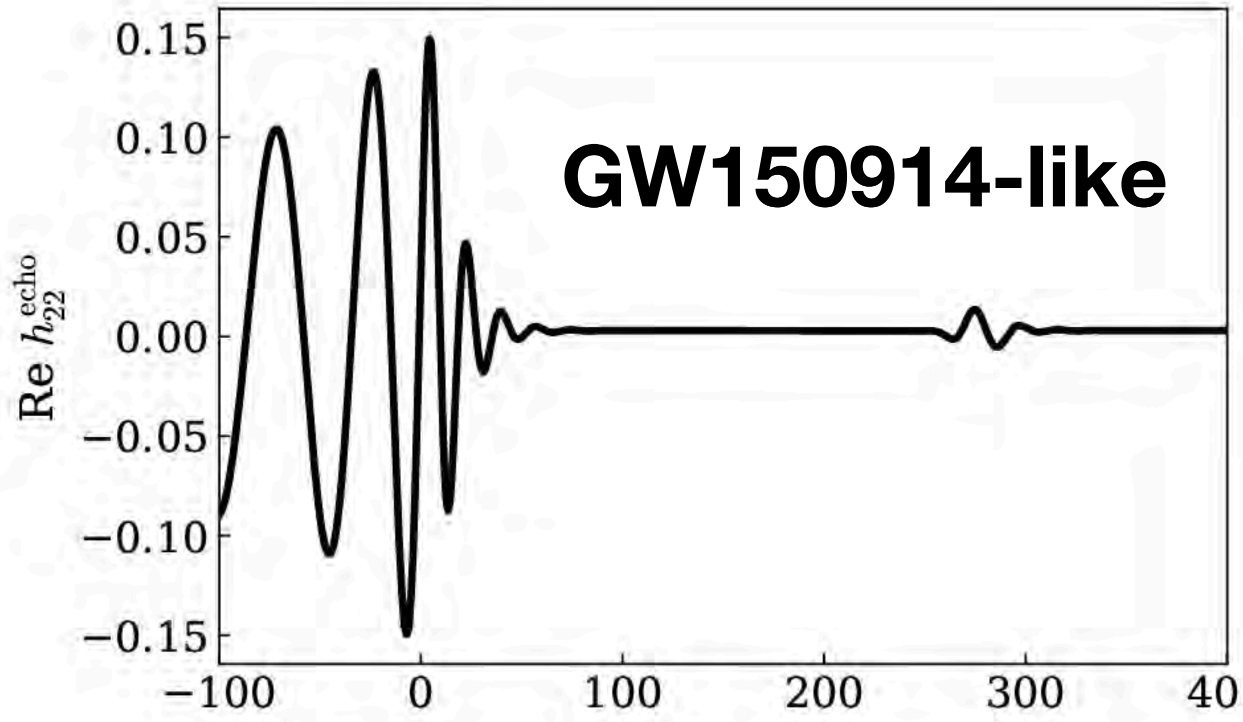

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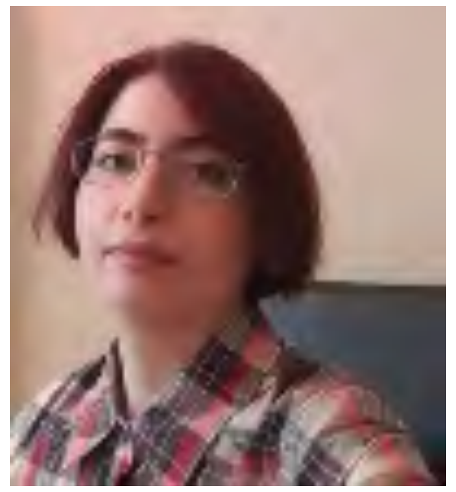
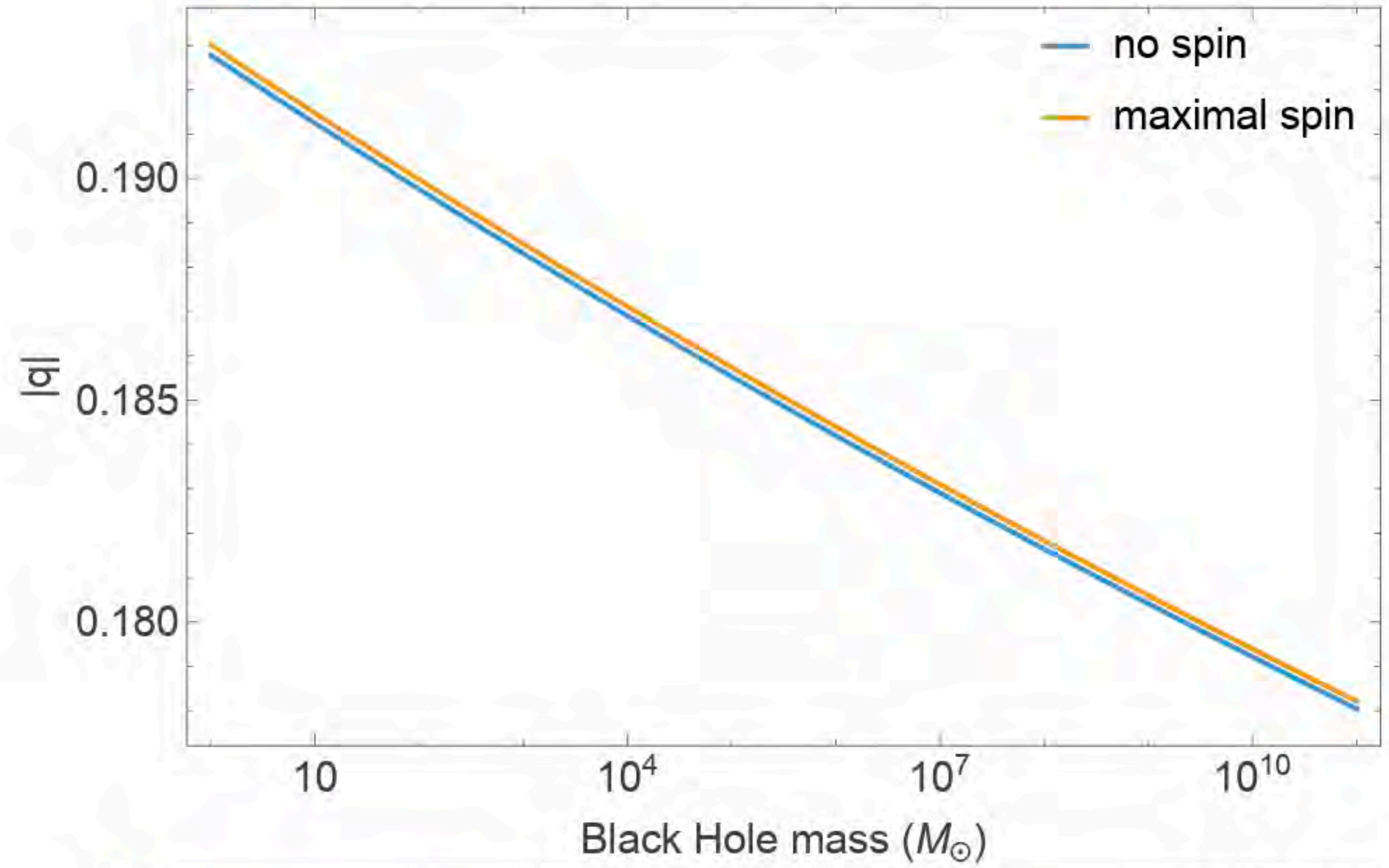


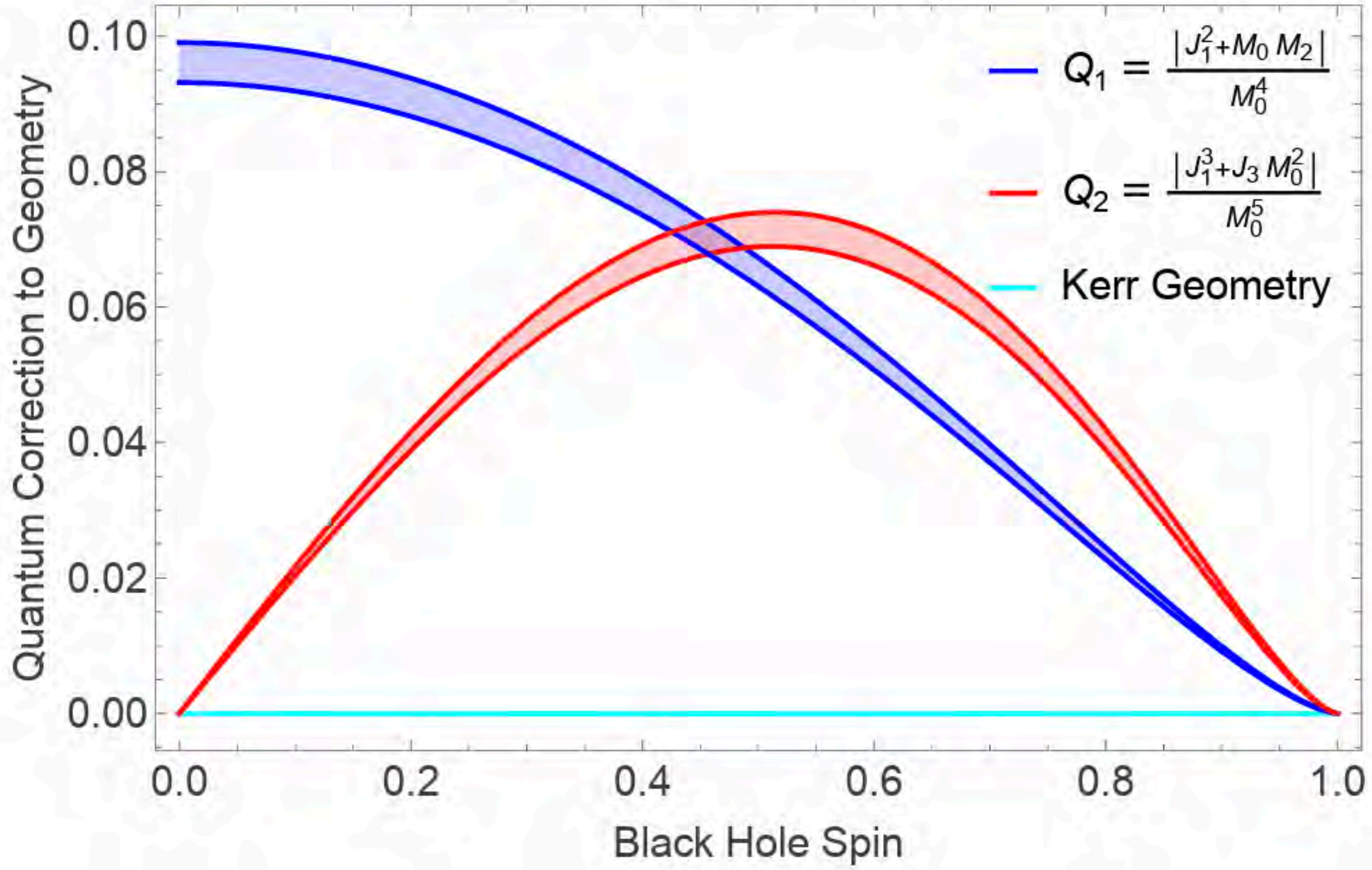
Quantum Violations of No-Hair Theorem

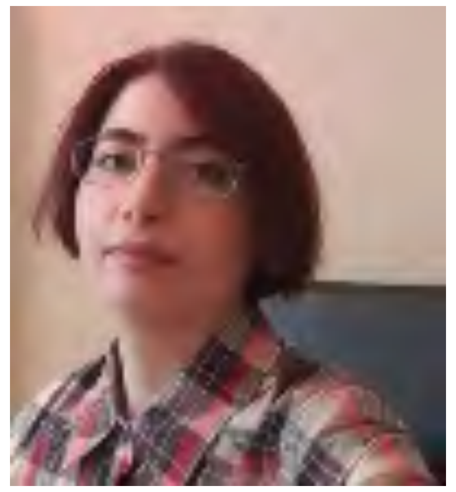
Faraji & NA 2025



- 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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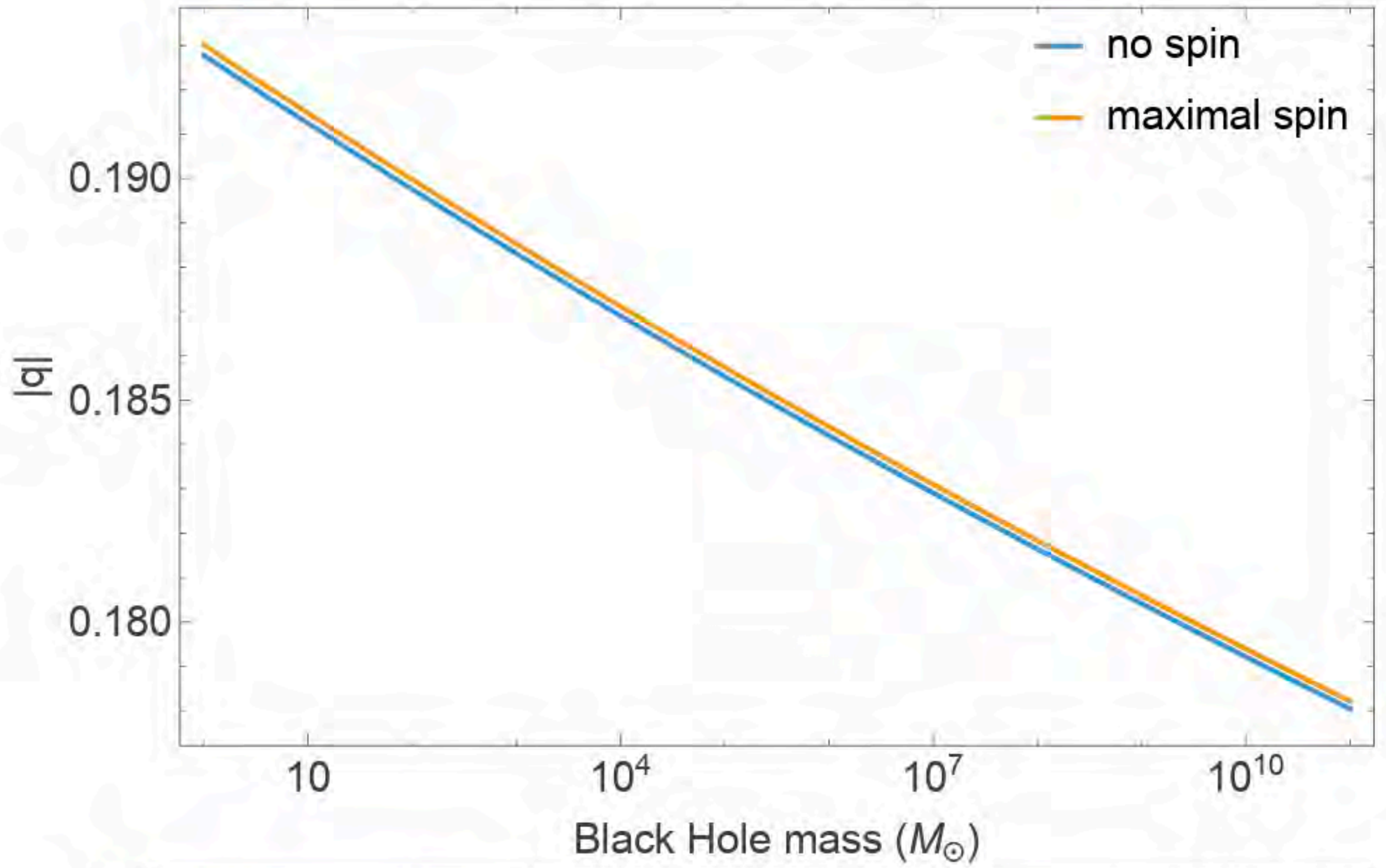

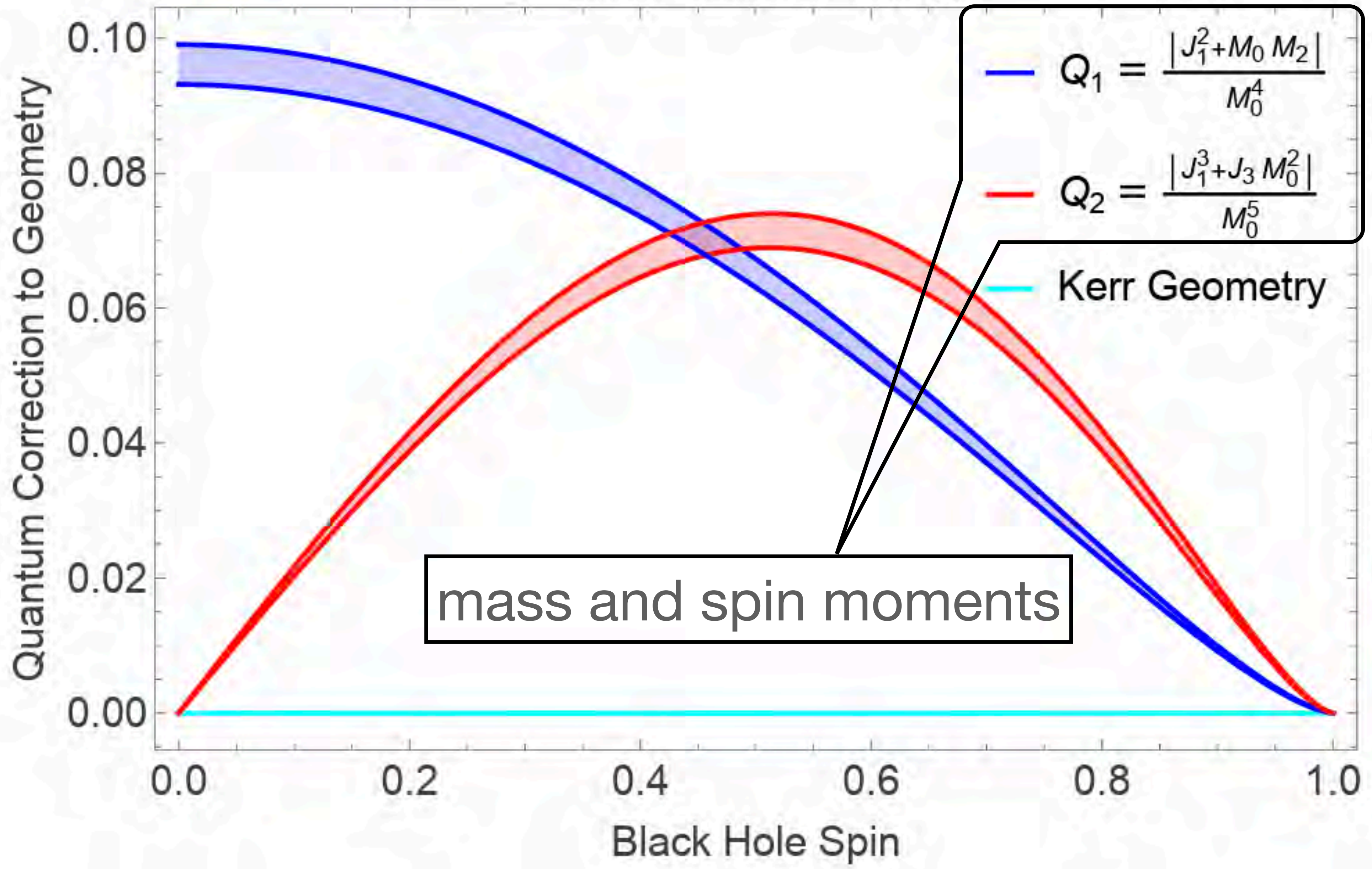

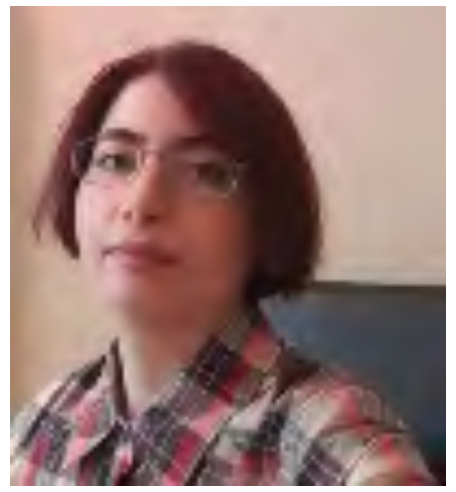

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Faraji & NA 2025

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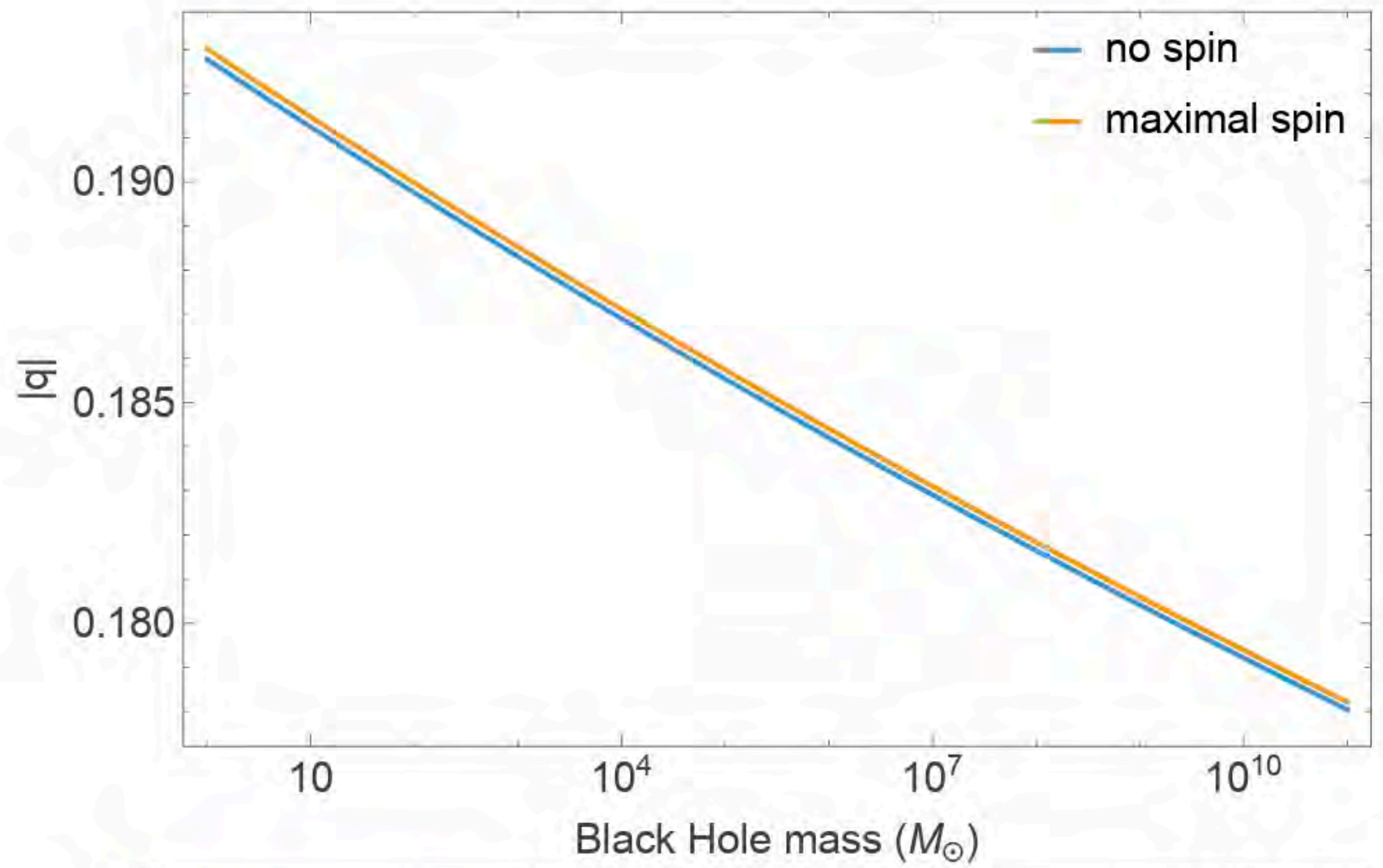
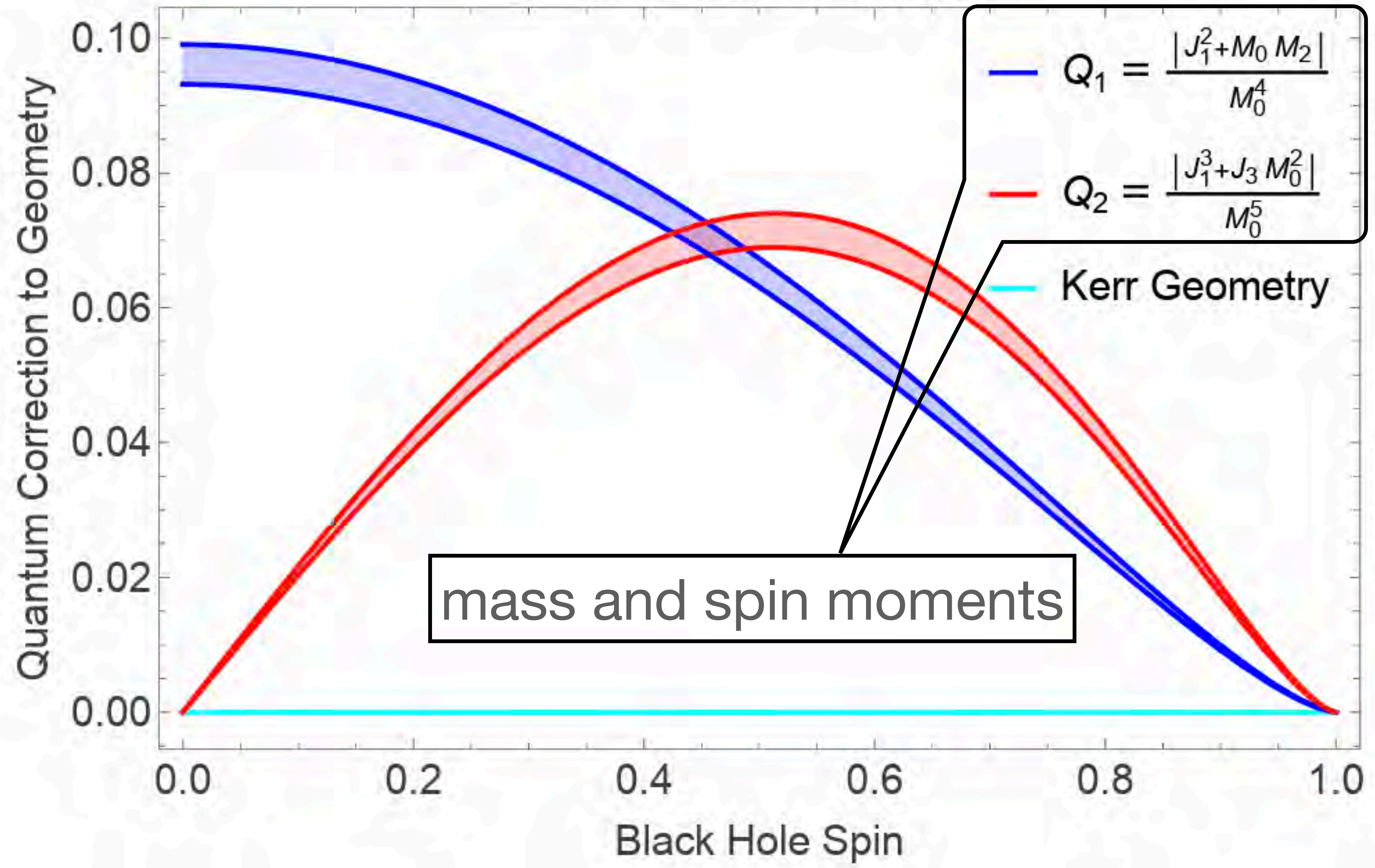
$$\boxed{q(S) \approx \sqrt{\frac{4W\left(\frac{\ln S}{4\pi\sqrt{e}}\right)}{\ln S}}.}$$

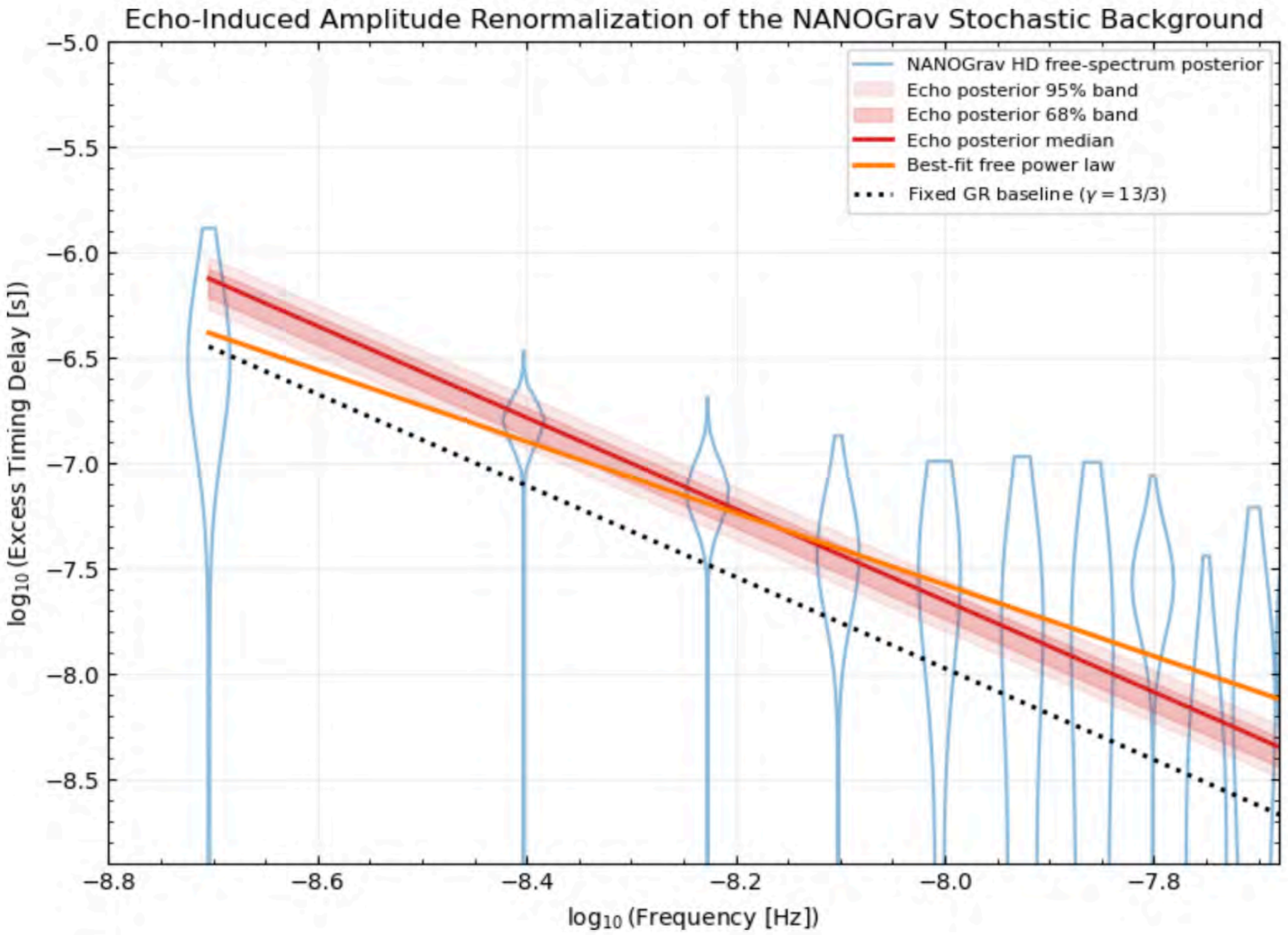
Finite entropy of Hawking radiation in q-metric

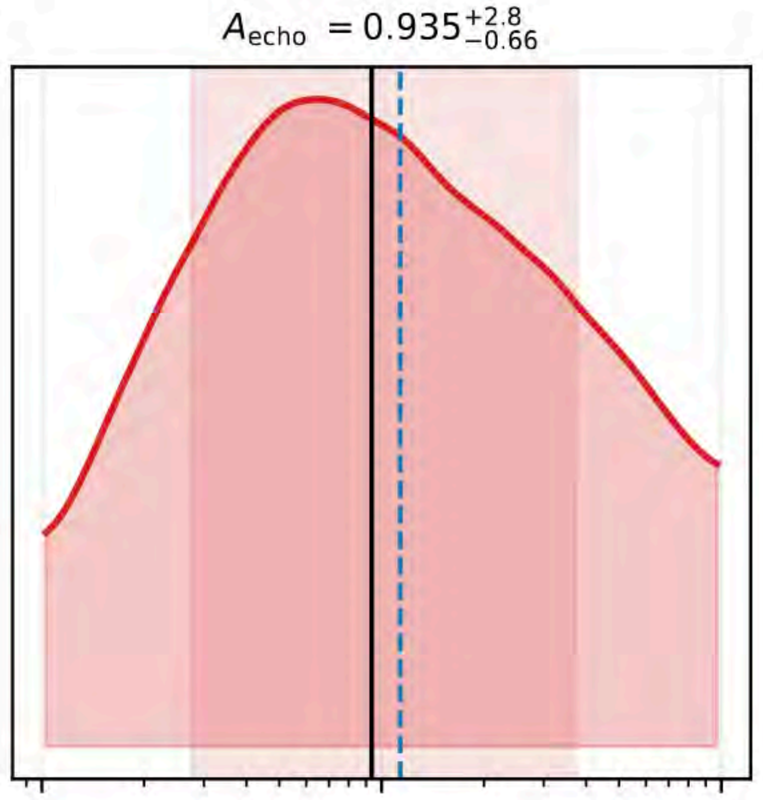




Echoes in Pulsar Timing Arrays?

Subhi & NA, in prep.





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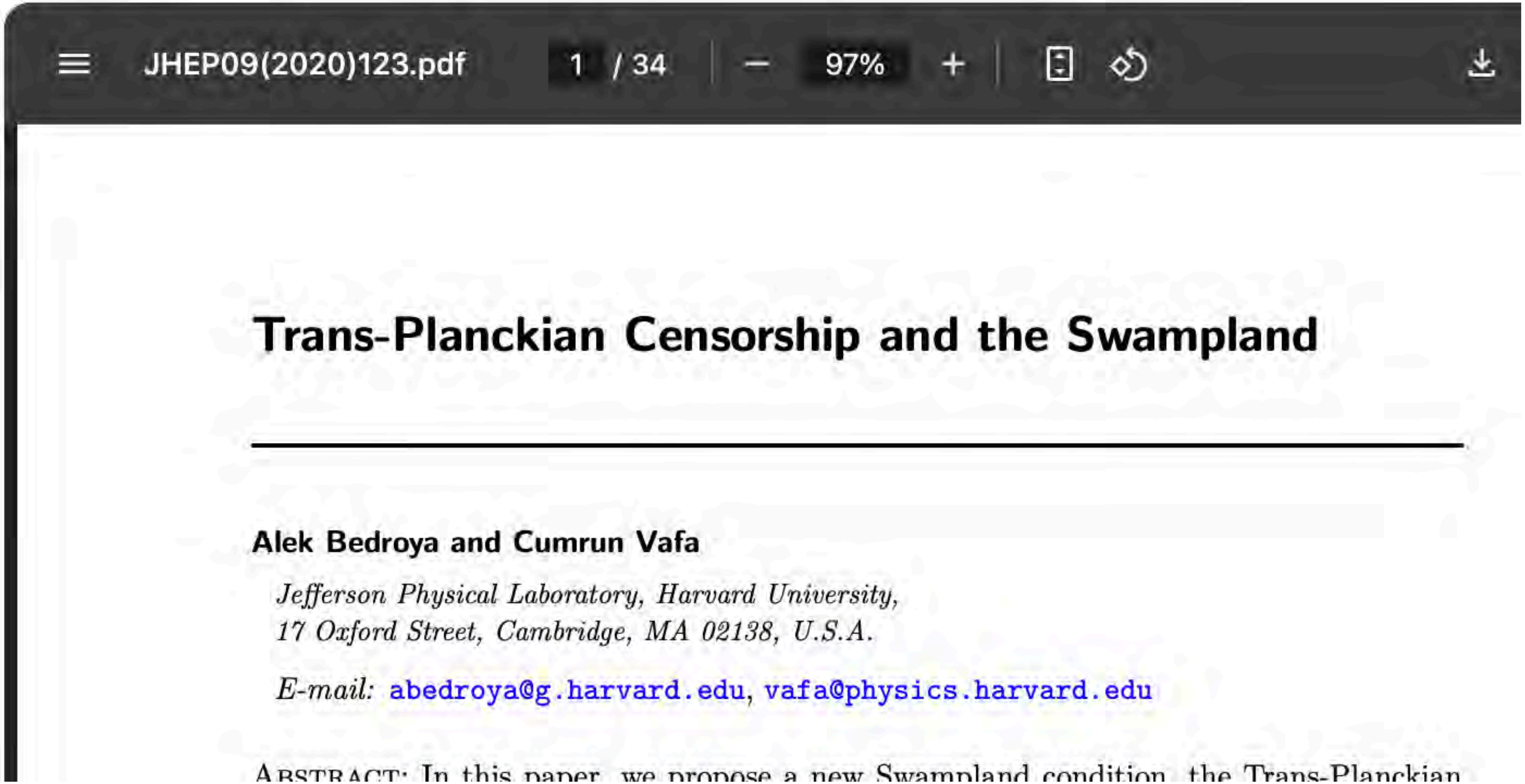
- ☐ **Quantum Dark Energy**
- ☐ *Outro:* how the light gets in

Scrambling time for de Sitter Horizon



Trans-Planckian Censorship and the Swampland

Alek Bedroya and Cumrun Vafa

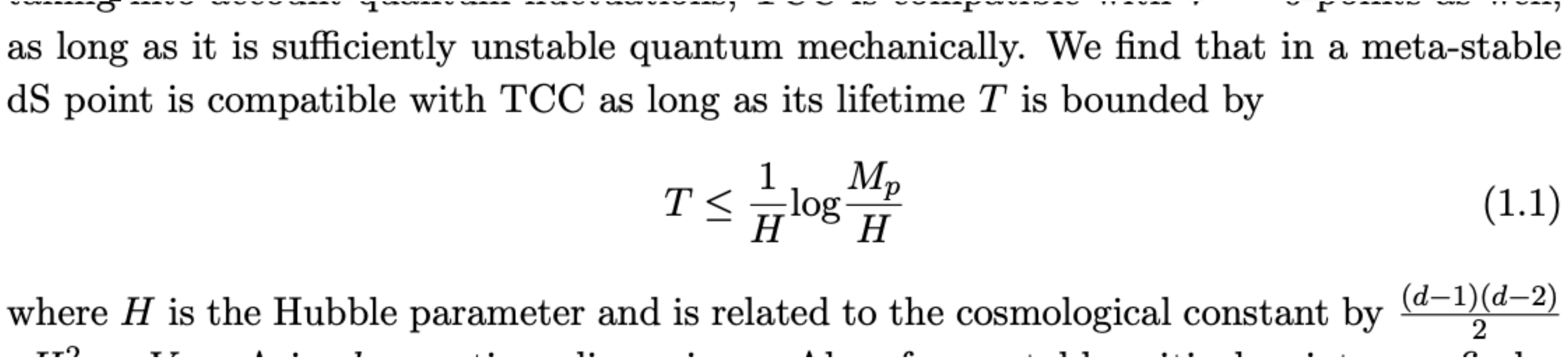
Jefferson Physical Laboratory, Harvard University,
17 Oxford Street, Cambridge, MA 02138, U.S.A.

E-mail: abedroya@g.harvard.edu, vafa@physics.harvard.edu

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

Scrambling time for de Sitter Horizon

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

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

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

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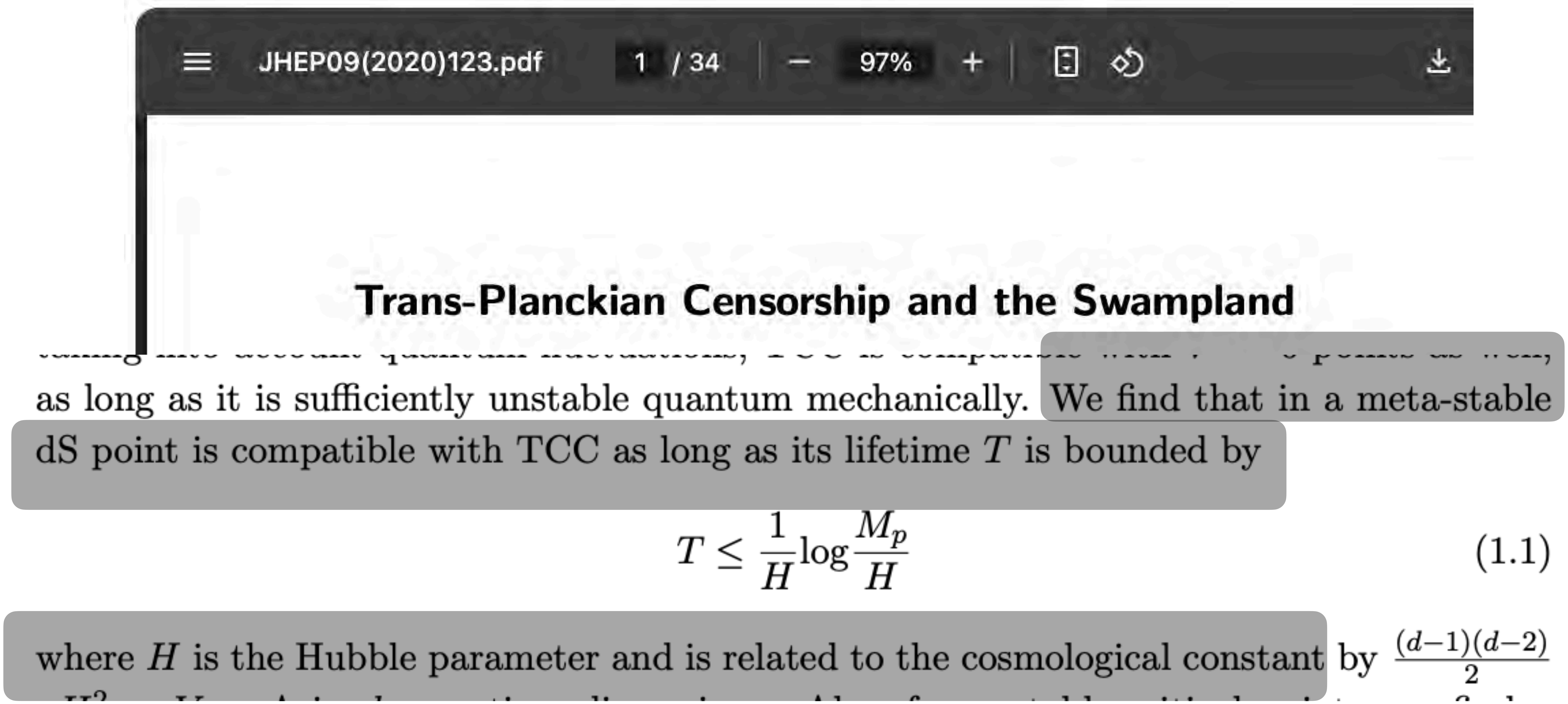

Trans-Planckian Censorship and the Swampland

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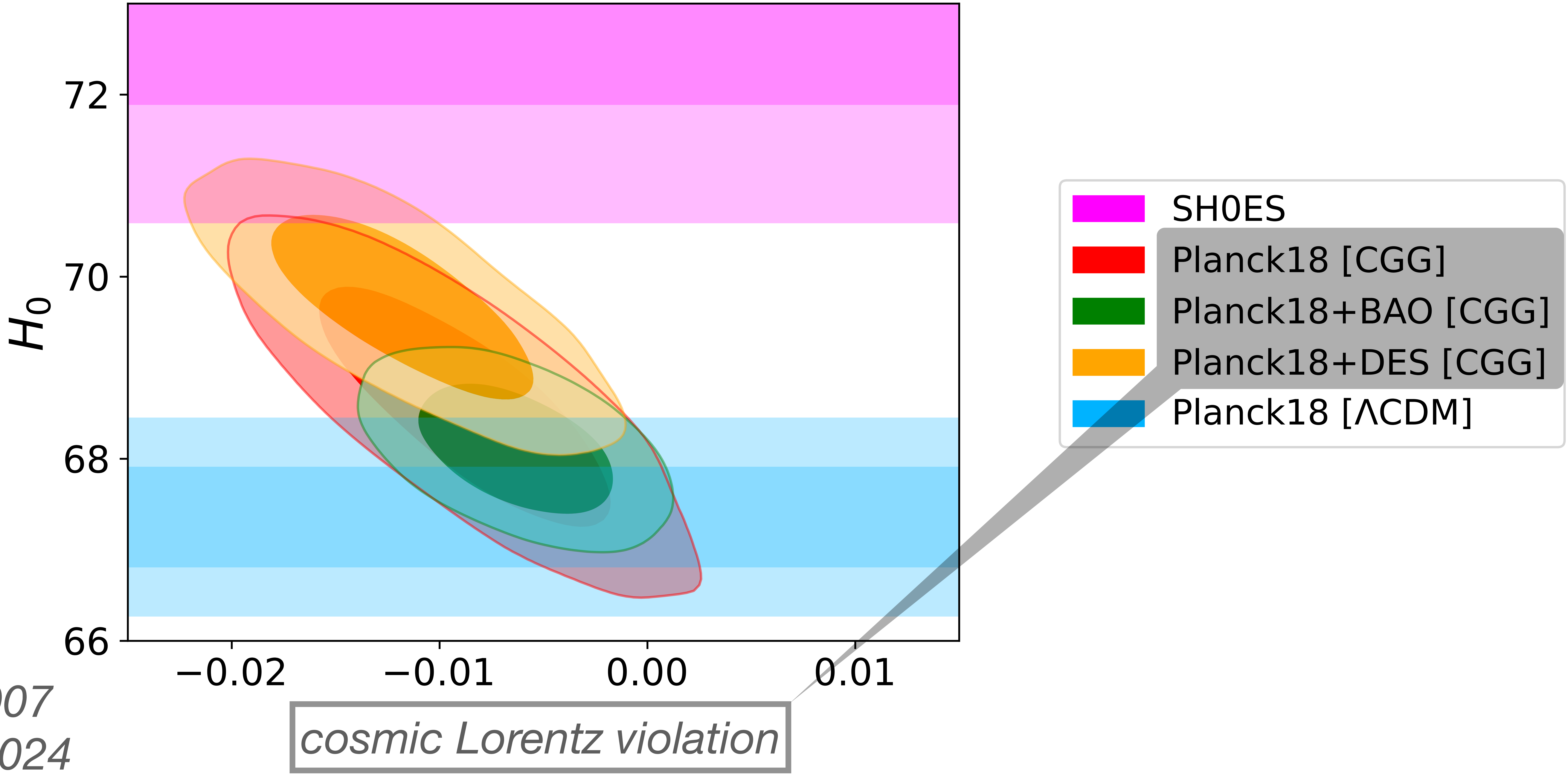
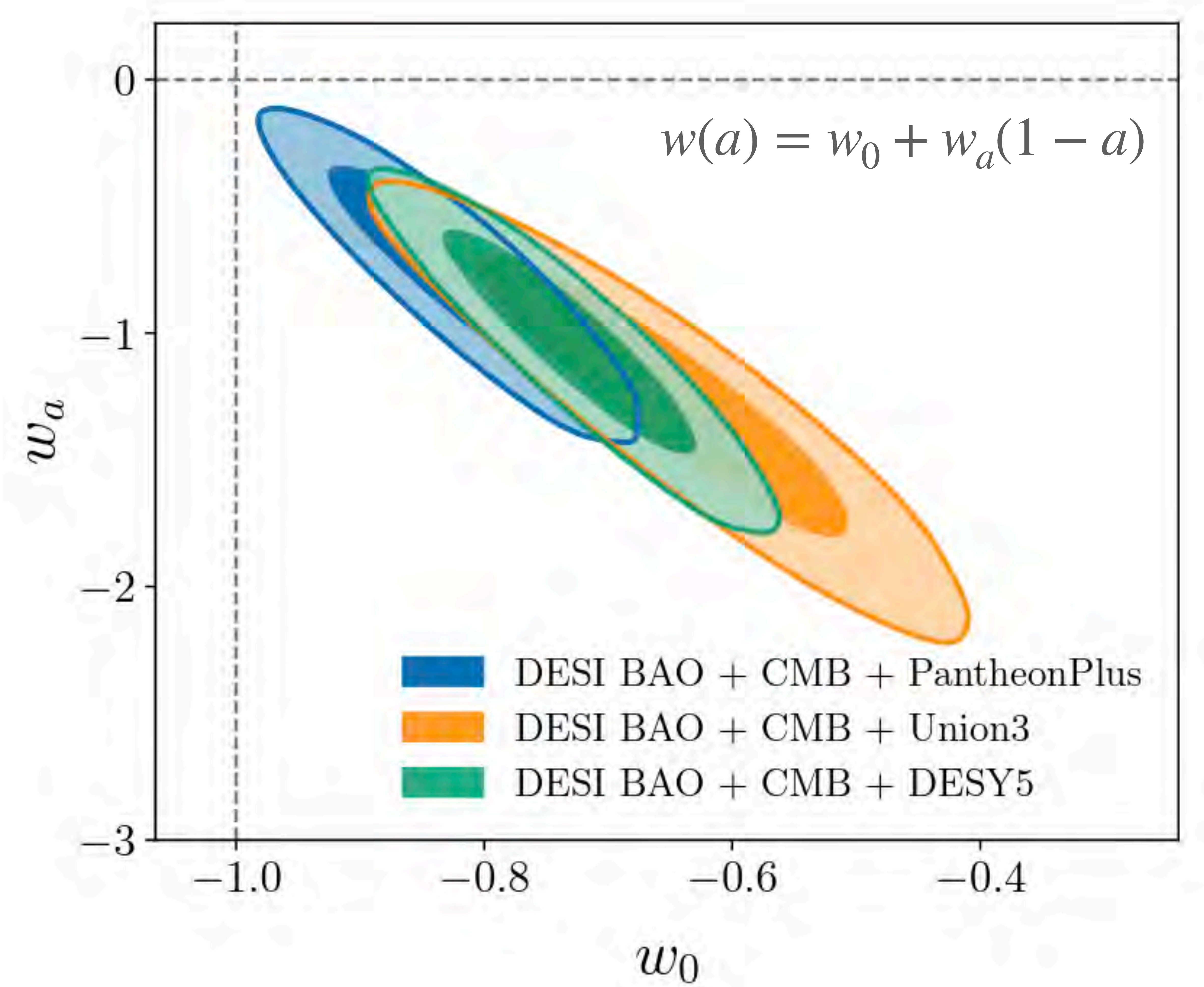
A Cosmic Glitch in Gravity (CGG)

- Do cosmology and Newtonian gravity use the same G's? What if $G_N \neq G_{\rm cosmo}$?

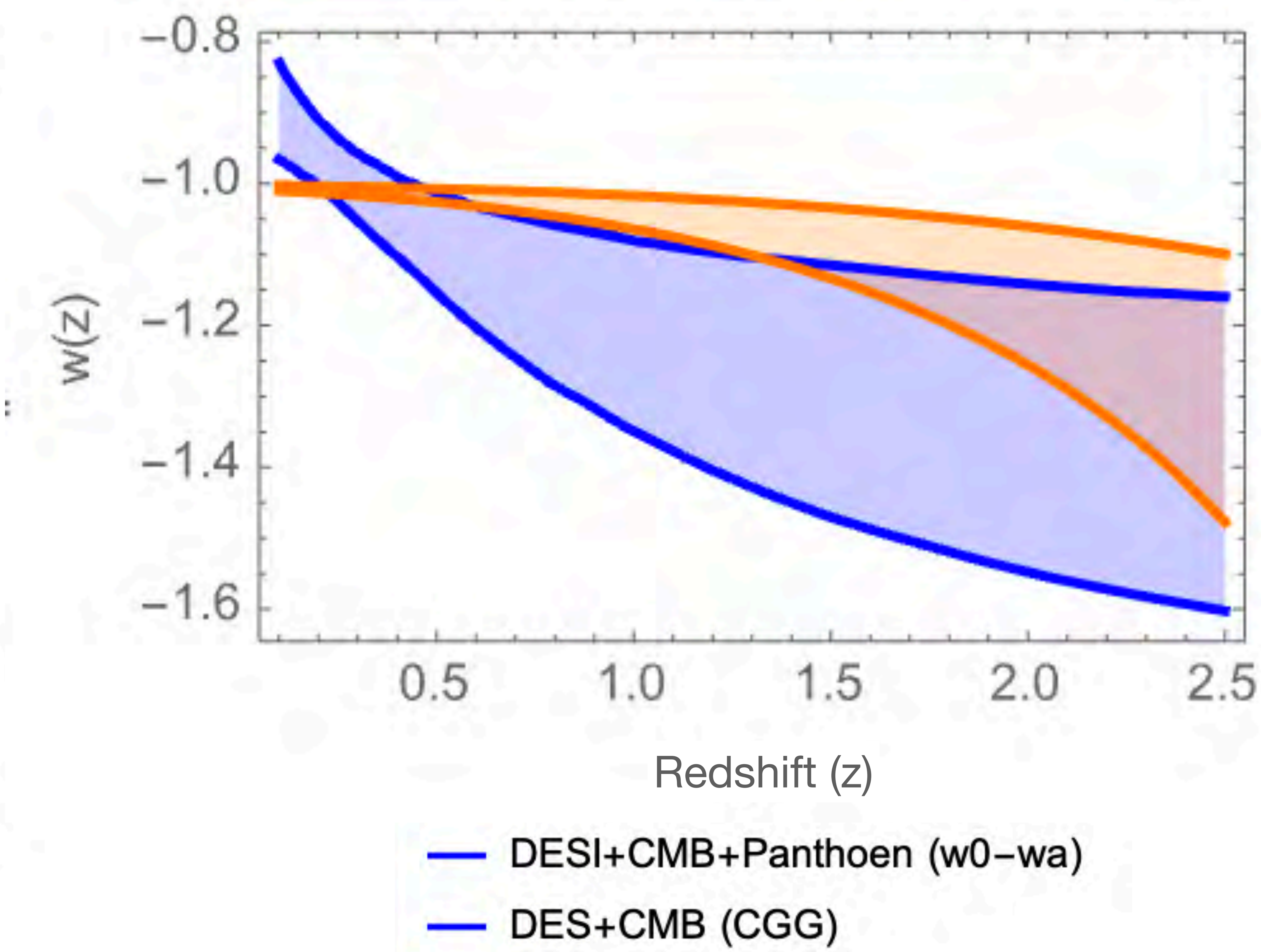


Robbers, NA & Doran, 2007
Wen, Hergt, NA & Scott, 2024

DESI tension?

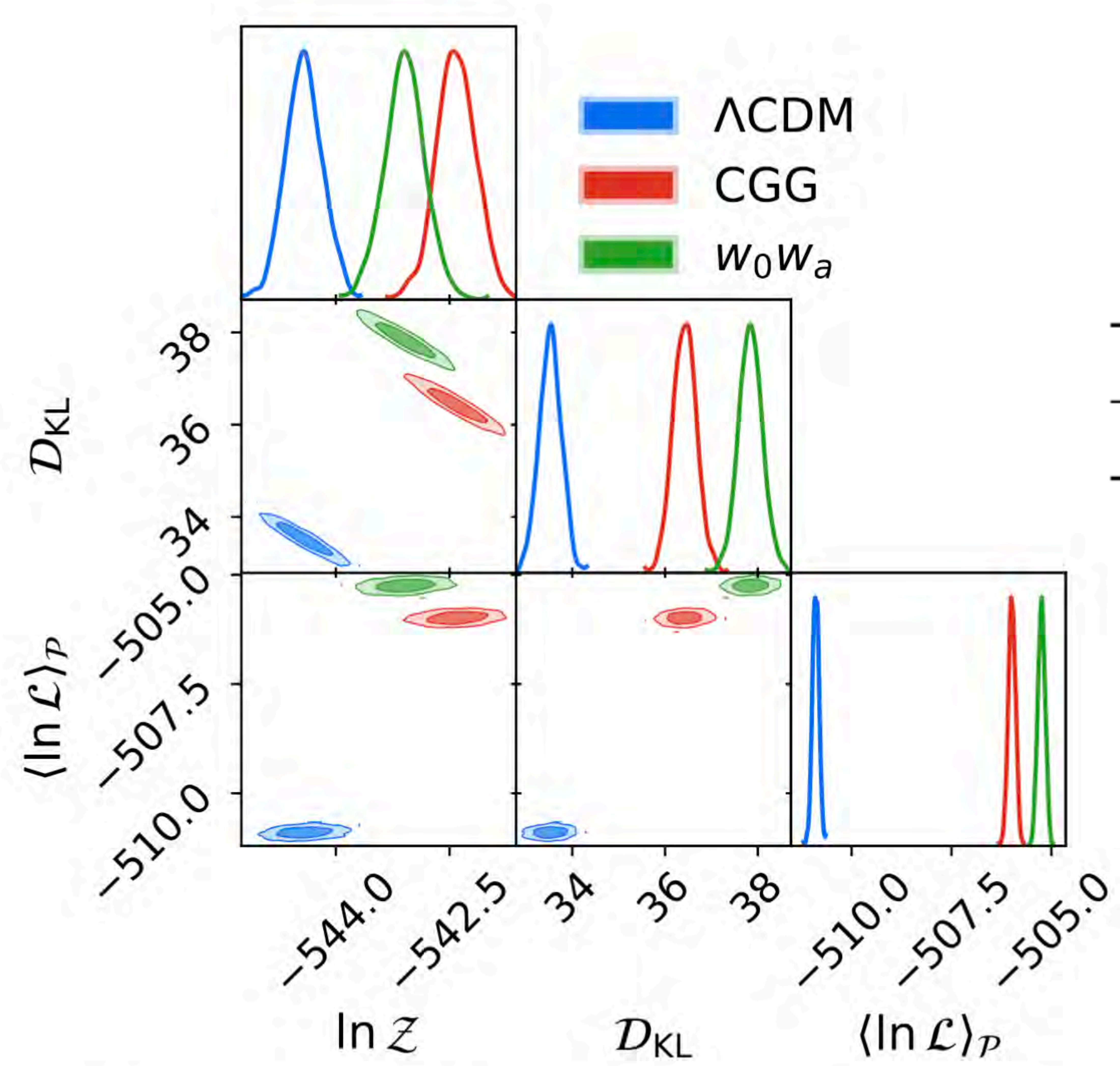


DESI collaboration 2024



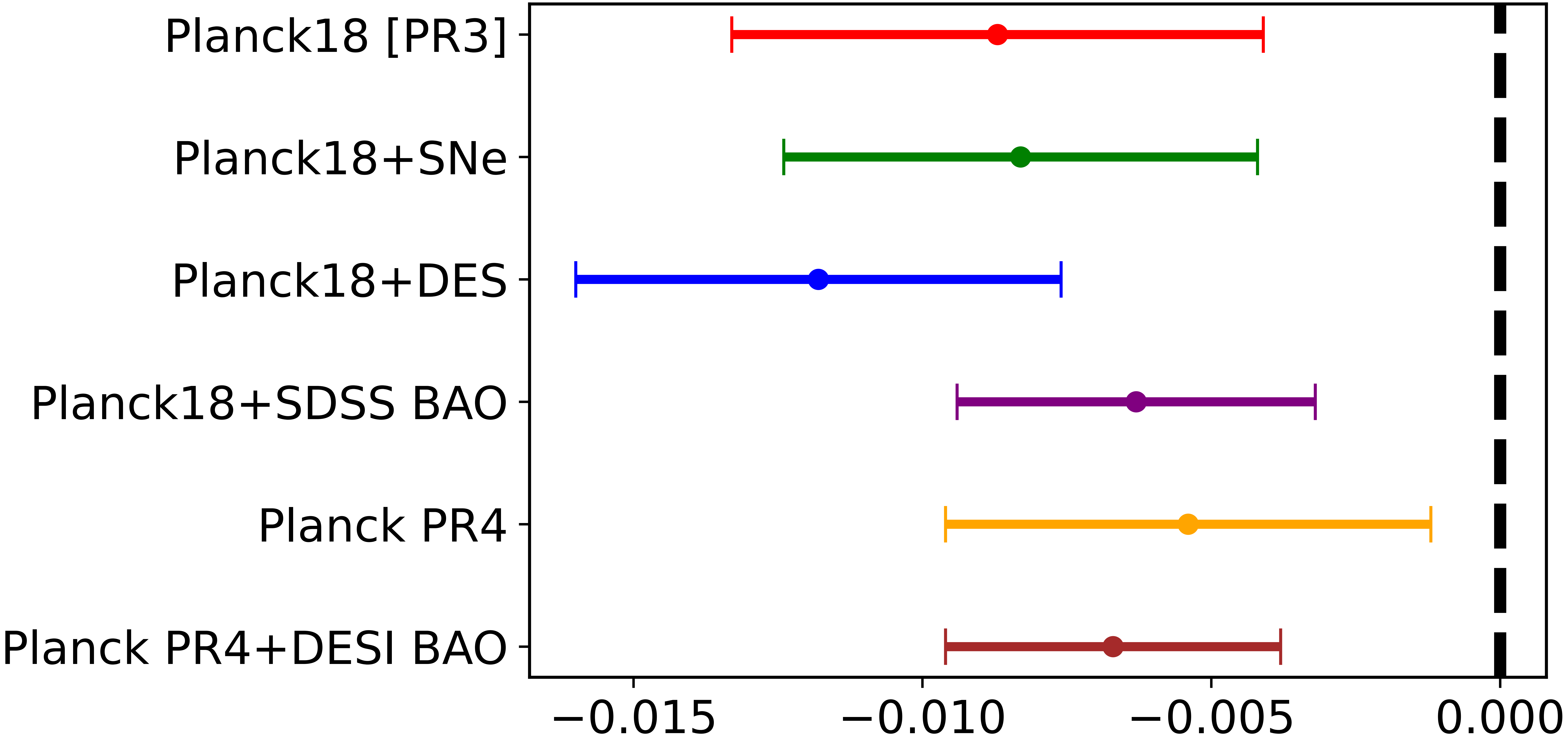
(90% confidence intervals)

CGG is preferred to w0wa



$\ln \mathcal{Z}_{\Lambda\mathrm{CDM}}$	$\Delta \ln \mathcal{Z}_{\mathrm{CGG}}$	$\Delta \ln \mathcal{Z}_{w_0 w_a}$	$\ln B_{\mathrm{CGG}/w_0 w_a}$
-544.4 ± 0.2	$+2.0 \pm 0.4$	$+1.3 \pm 0.4$	$+0.7 \pm 0.4$

Is gravity weaker on superhorizon scales?



cosmic Lorentz violation

Wen, Hergt, NA & Scott, 2024

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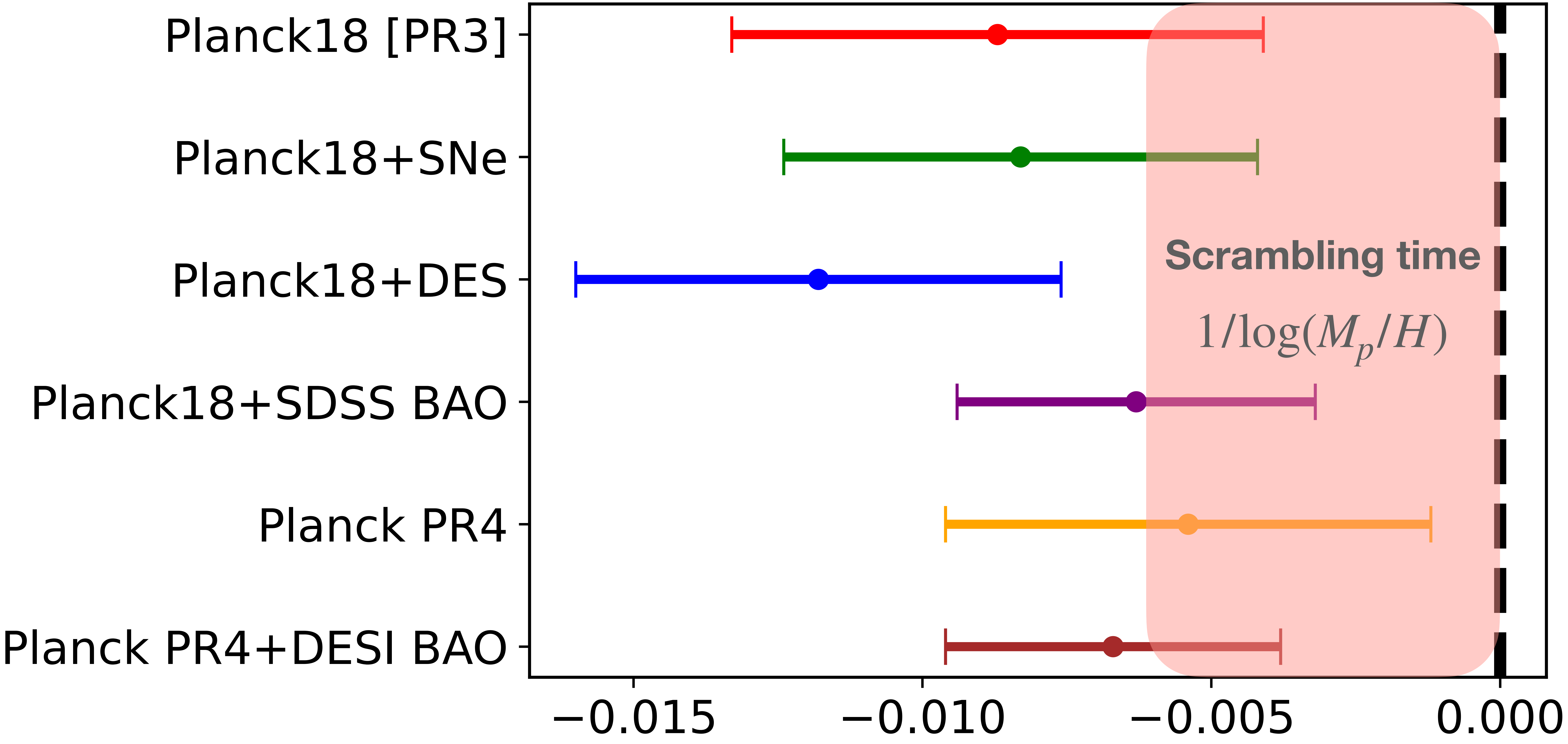
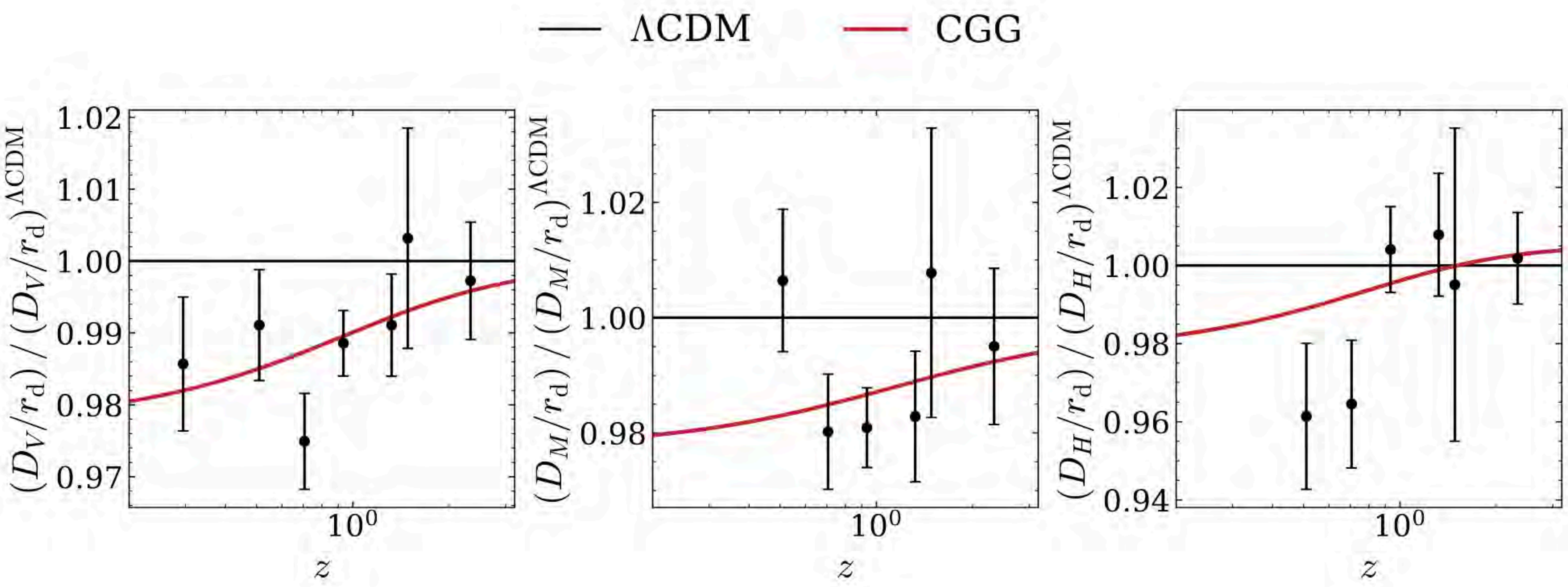
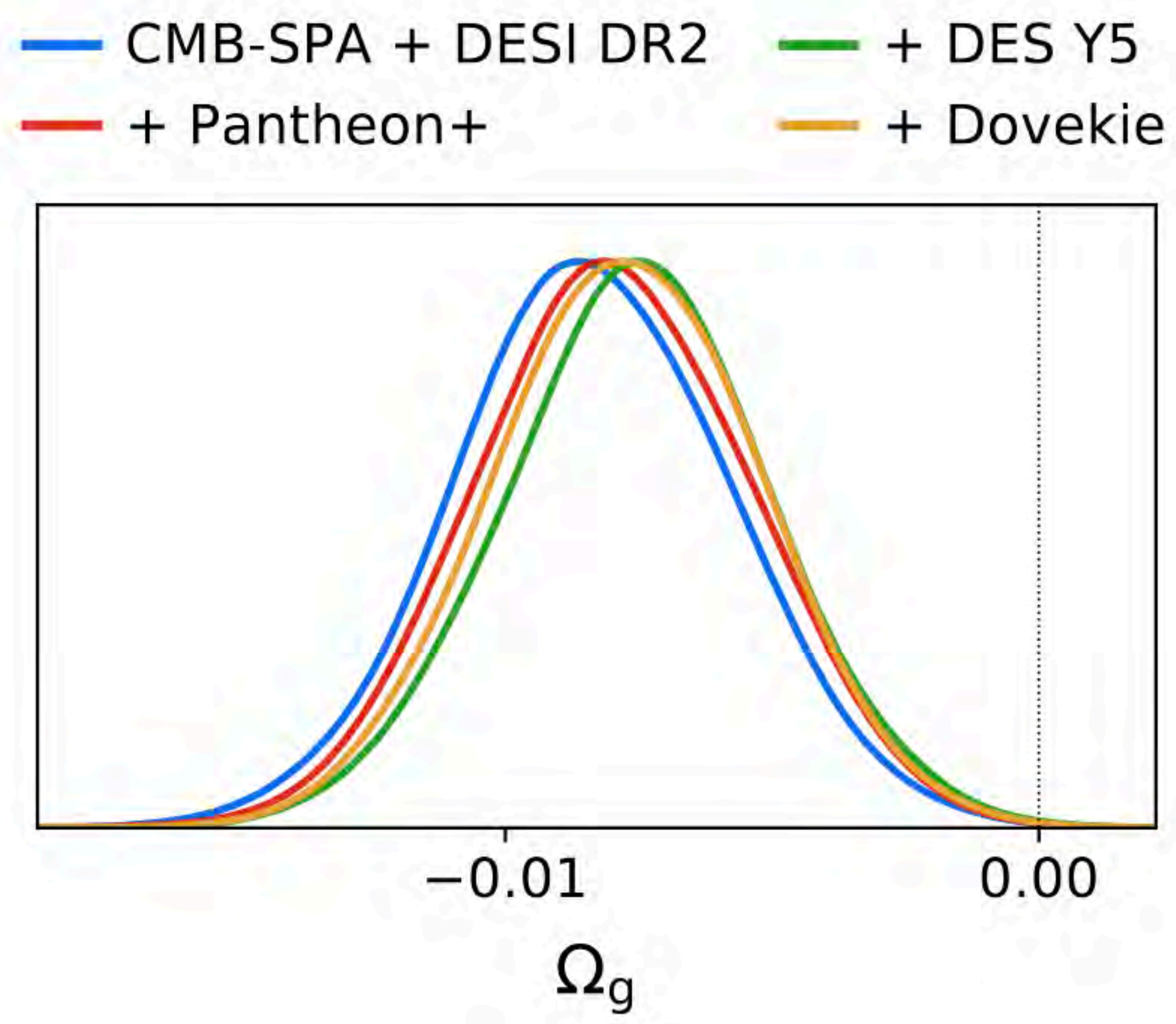


cosmic Lorentz violation

Wen, Hergt, NA & Scott, 2024

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





Evidence for Horava quantum gravity at 3σ!

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

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

$$\Omega_\mathrm{g} = -0.0084 \pm 0.0026,$$

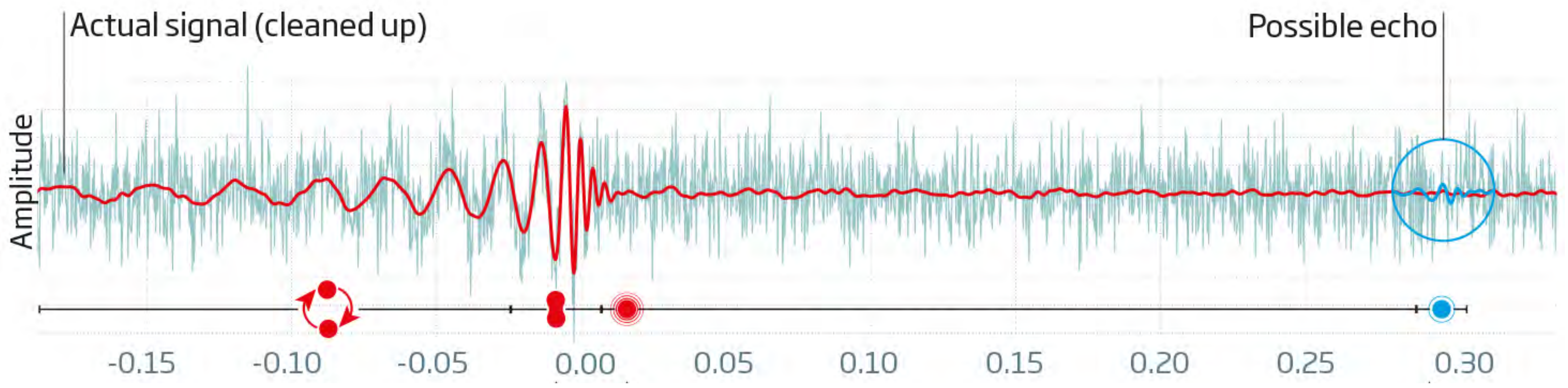
$$\frac{G_\mathrm{cosmo}}{G_\mathrm{N}} = \frac{1}{1-\Omega_\mathrm{g}} = 0.9917 \pm 0.0026,$$

Wen, Hergt, NA & Scott, in prep

Does the same logarithm appear for two horizons?

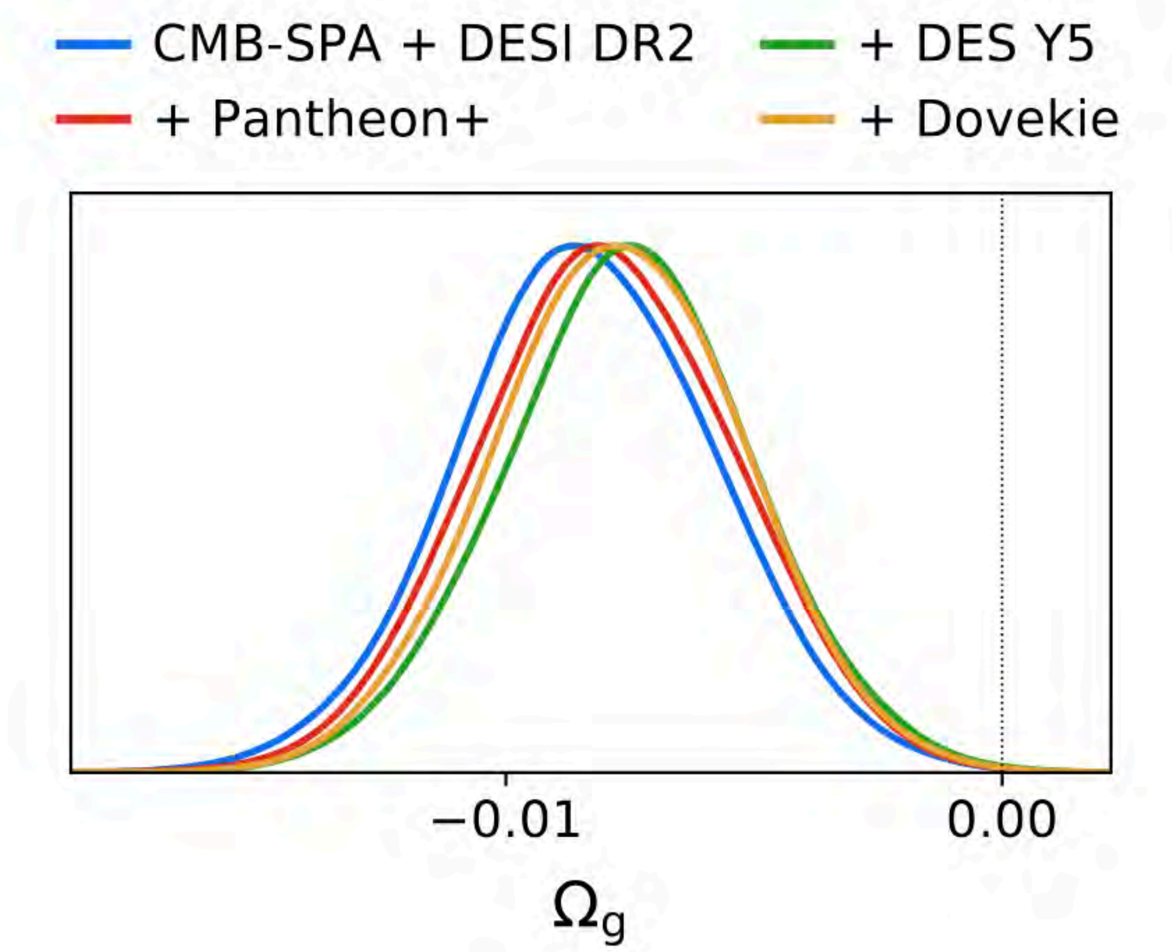
Black Hole Echoes

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



Cosmological scrambling time

$$t_{\mathrm{scr,dS}} = \frac{\ln\left[\text{de Sitter Entropy}\right]}{\text{Hubble Rate}} \sim \frac{1}{0.004 \times \text{Hubble Rate}}$$



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

Outline

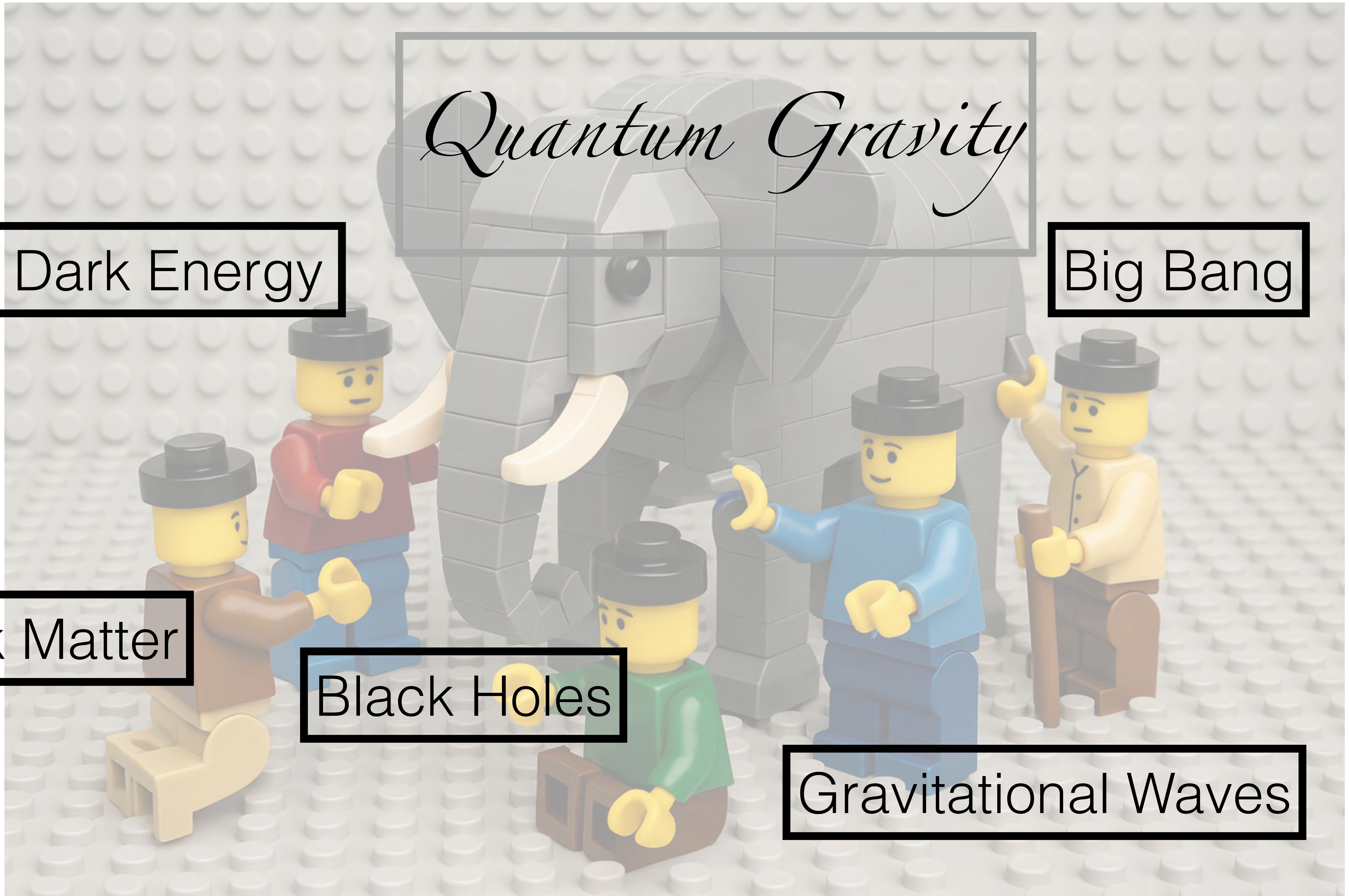
☑ *Intro:* the crisis in physics

☑ Quantum Big Bang

☑ Quantum Black Holes

☑ Quantum Dark Energy

☐ ***Outro:* how the light gets in**



Quantum Gravity

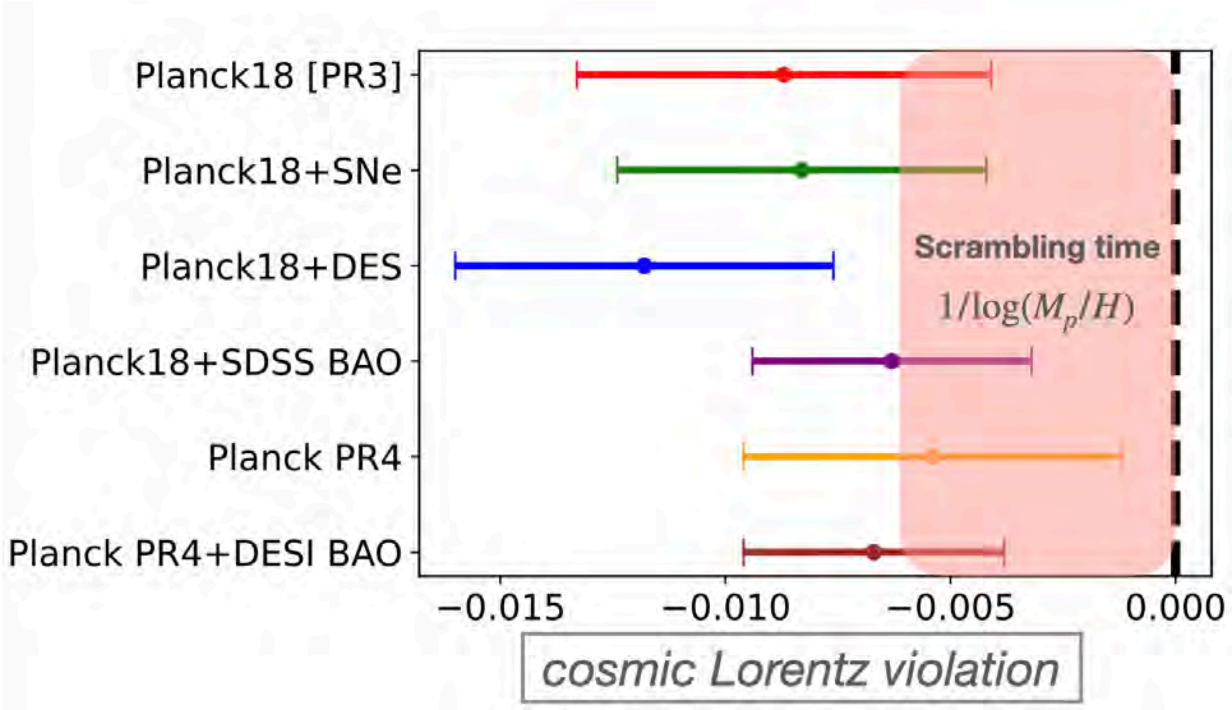
Dark Energy

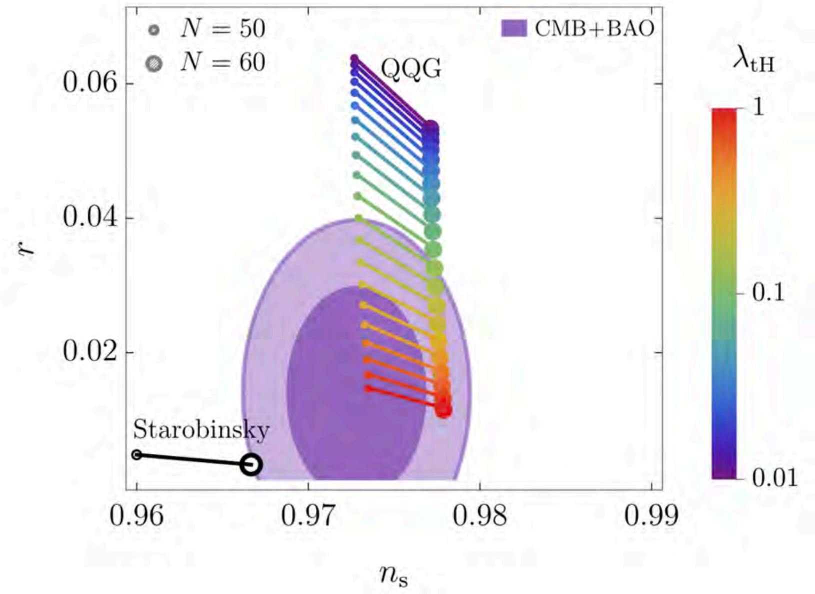
Big Bang

Dark Matter

Black Holes

Gravitational Waves





Quantum Gravity

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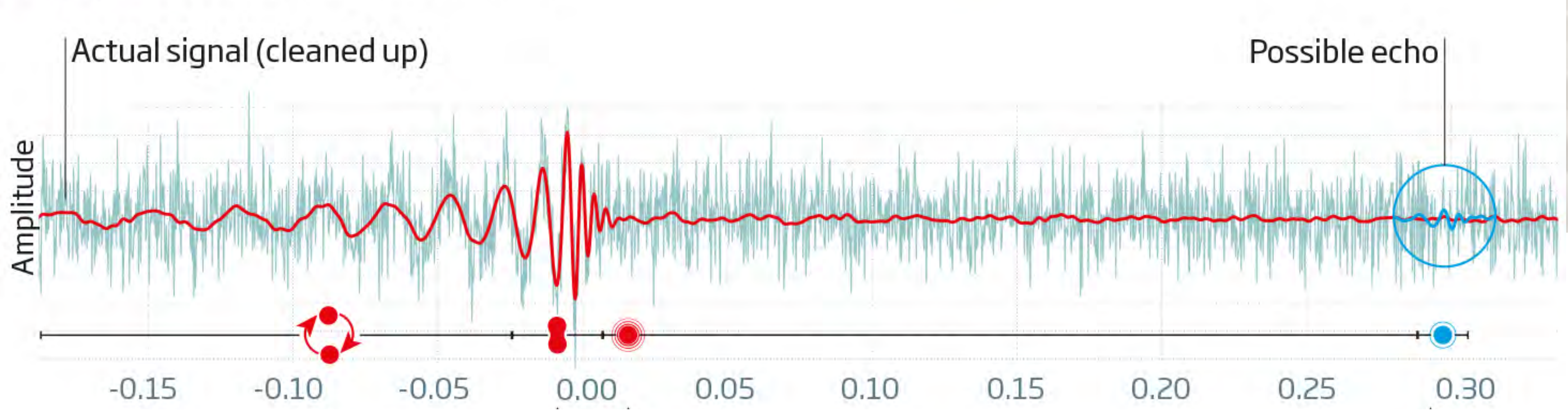


> There is a crack in everything,
> that's how the light gets in.
>
> *Leonard Cohen*

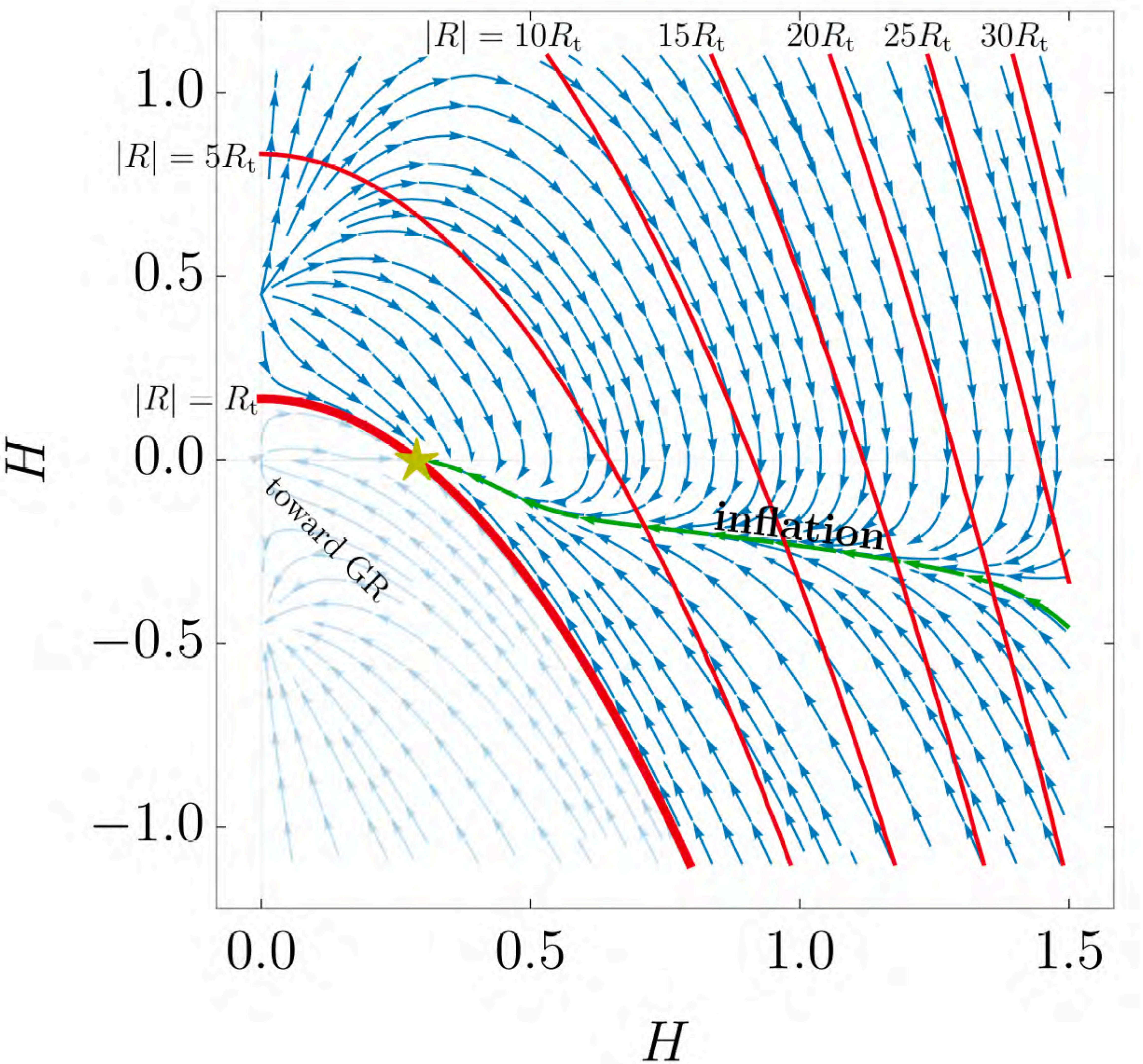
Quantum Gravity in the Wild

- **Empirical Frontier**
  - Black holes: Echoes, Multipoles
  - Big Bang: tensor, tilt, running, non-gaussianity
  - Dark Energy: scrambling time → 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

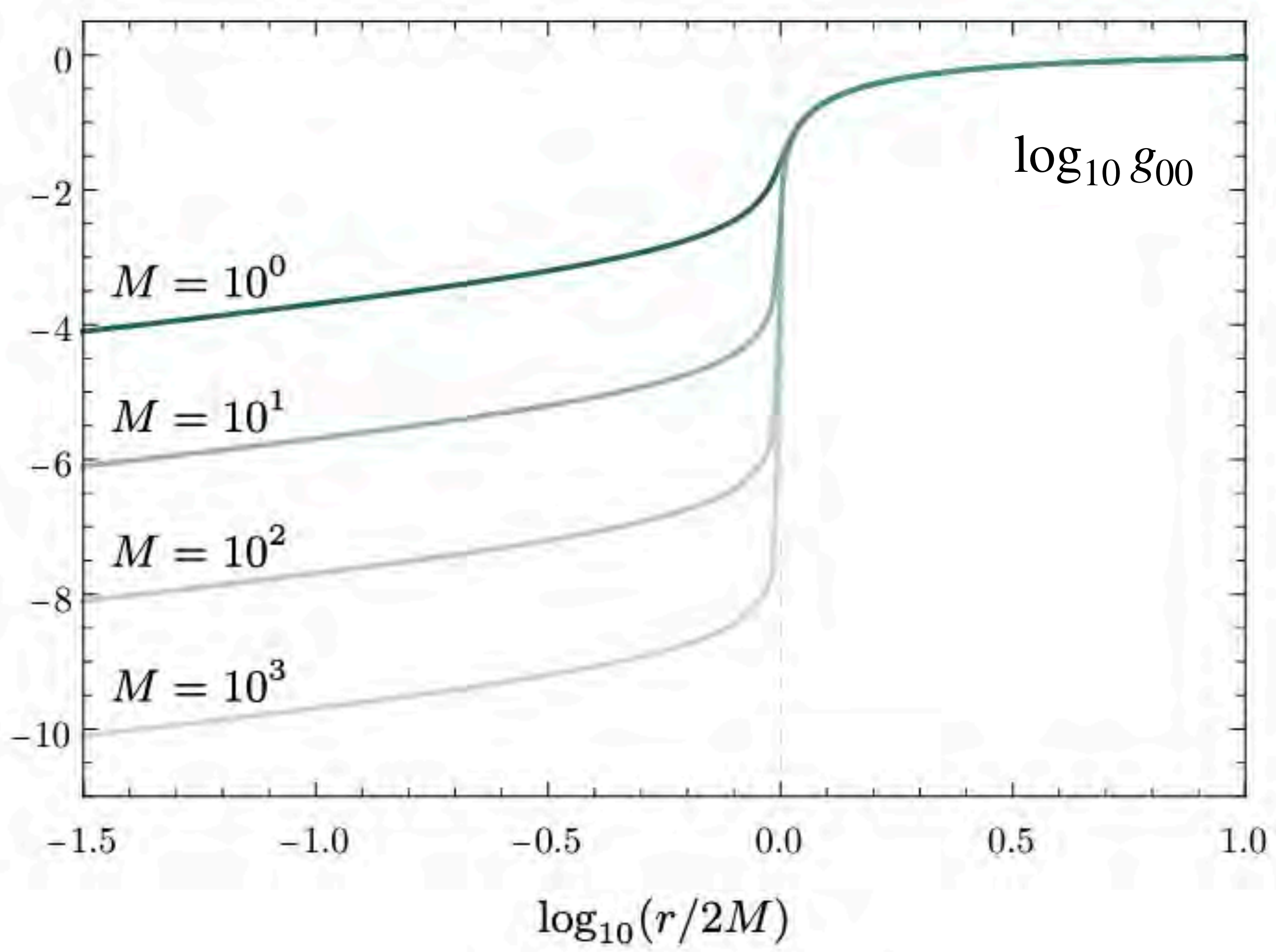
w/ generic RG scale identification

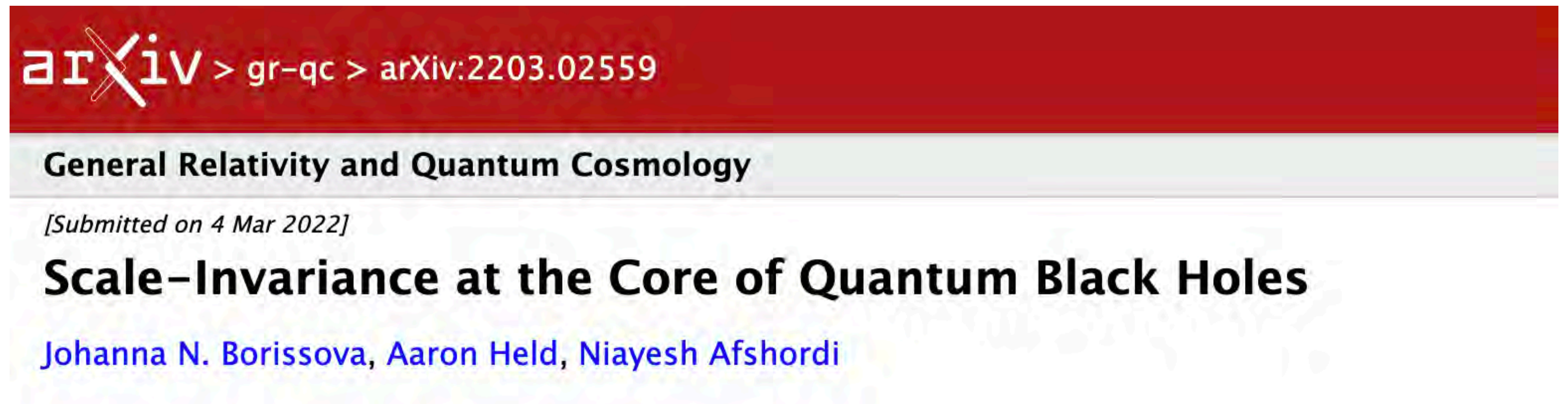


Warmup: Quantum Black Holes in Asymptotic Safety

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

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





arXiv > gr-qc > arXiv:2203.02559

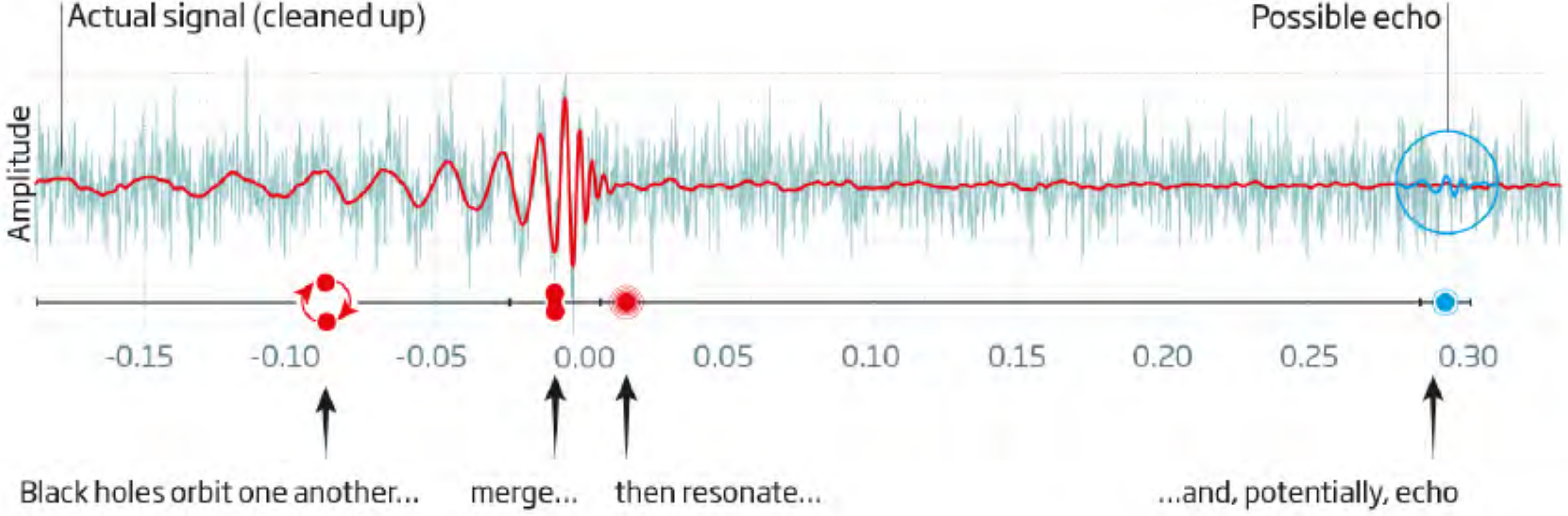
General Relativity and Quantum Cosmology

[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/bchw; NIAYESH AFSHORDI AND JAHED ABEDI

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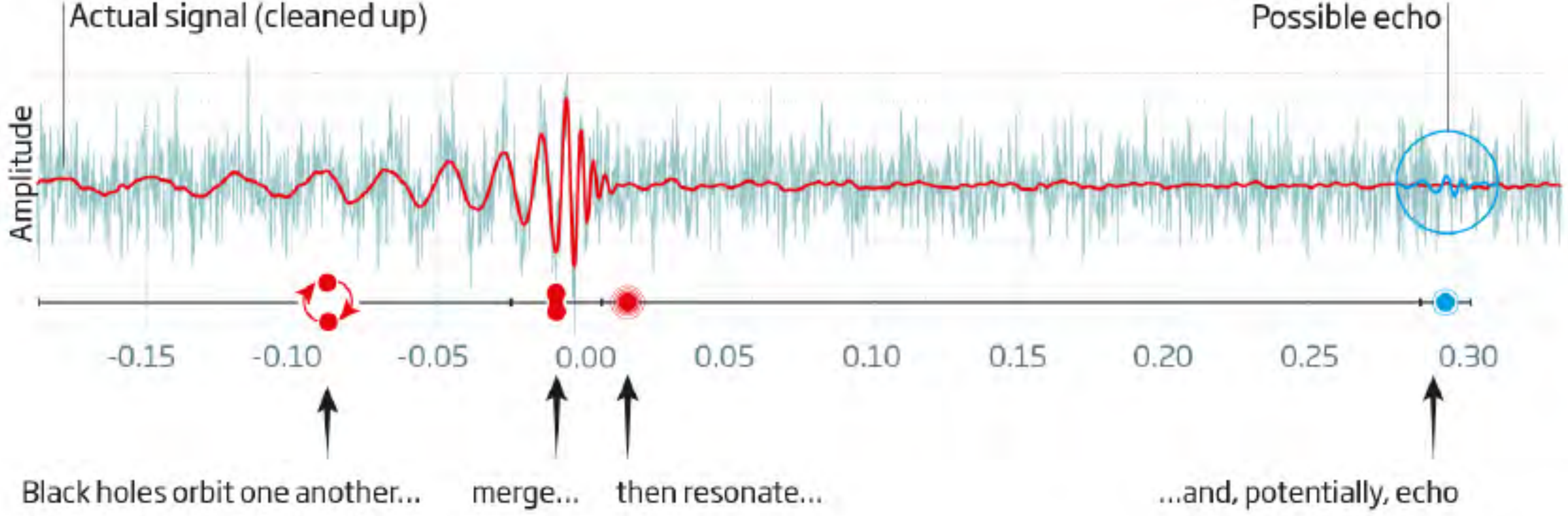

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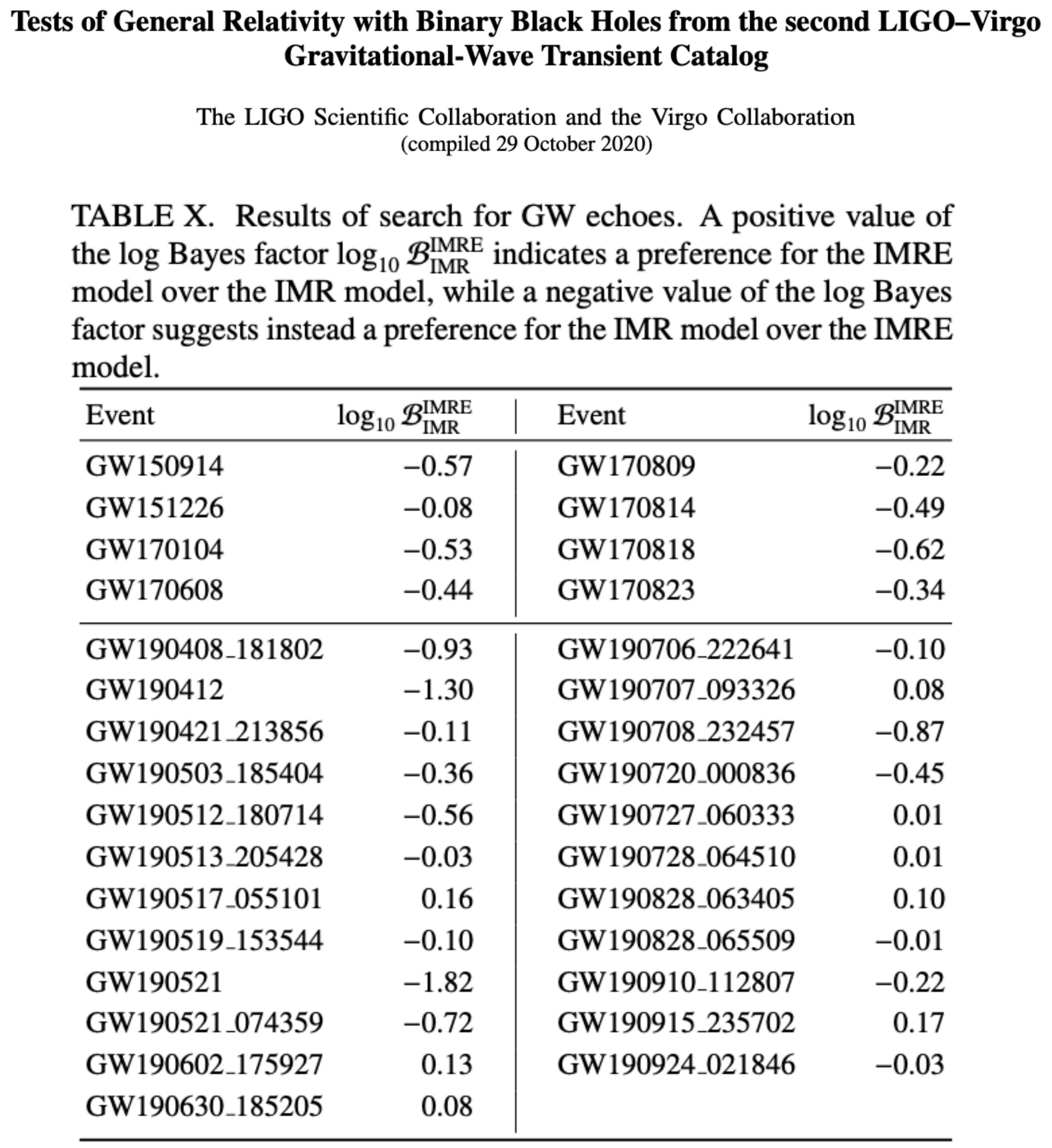
But not everyone finds echoes!
different methods/events

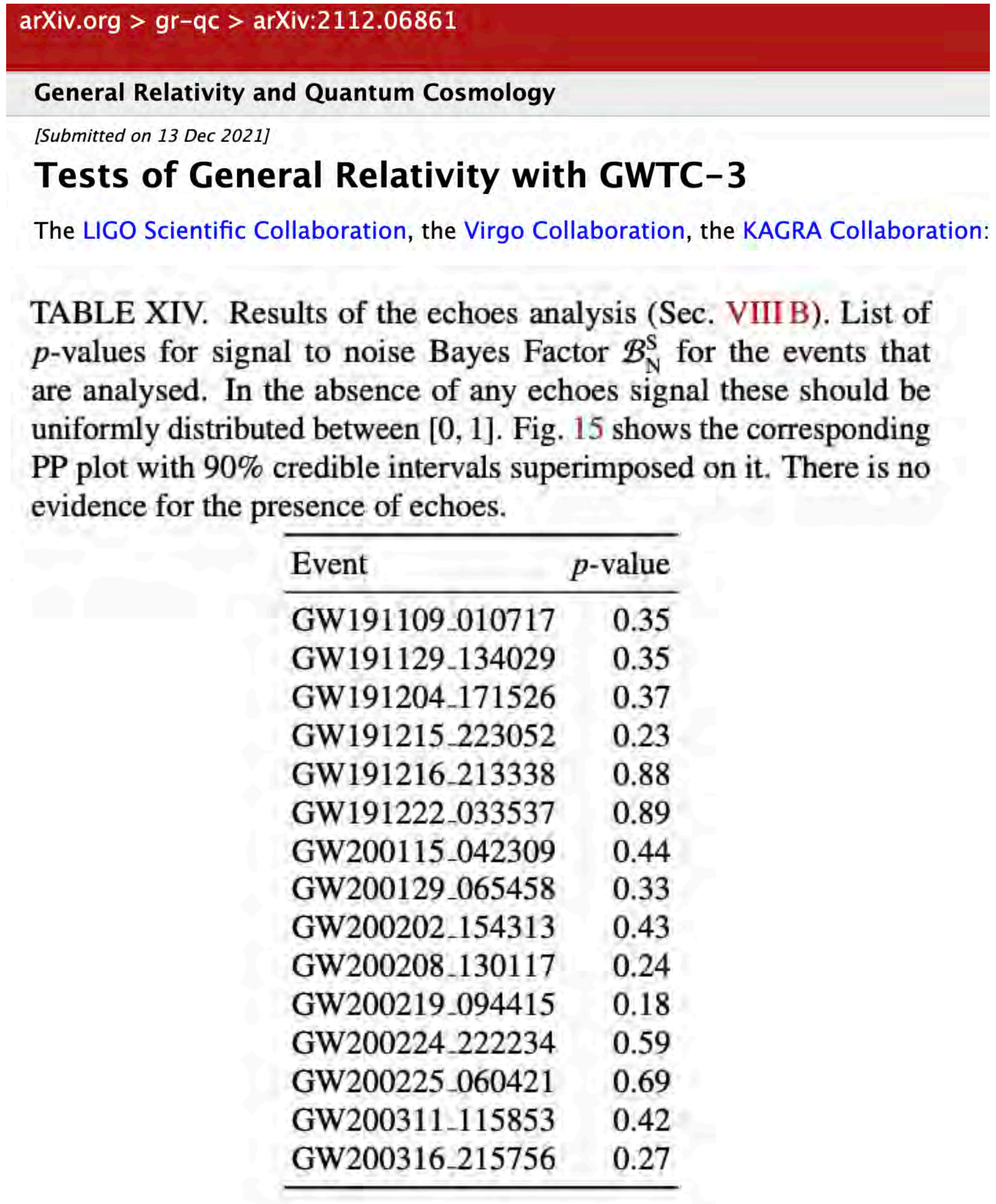


Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog

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 $\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$ 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	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$	Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$
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		



arXiv.org > gr-qc > arXiv:2112.06861

General Relativity and Quantum Cosmology

[Submitted on 13 Dec 2021]

Tests of General Relativity with GWTC-3

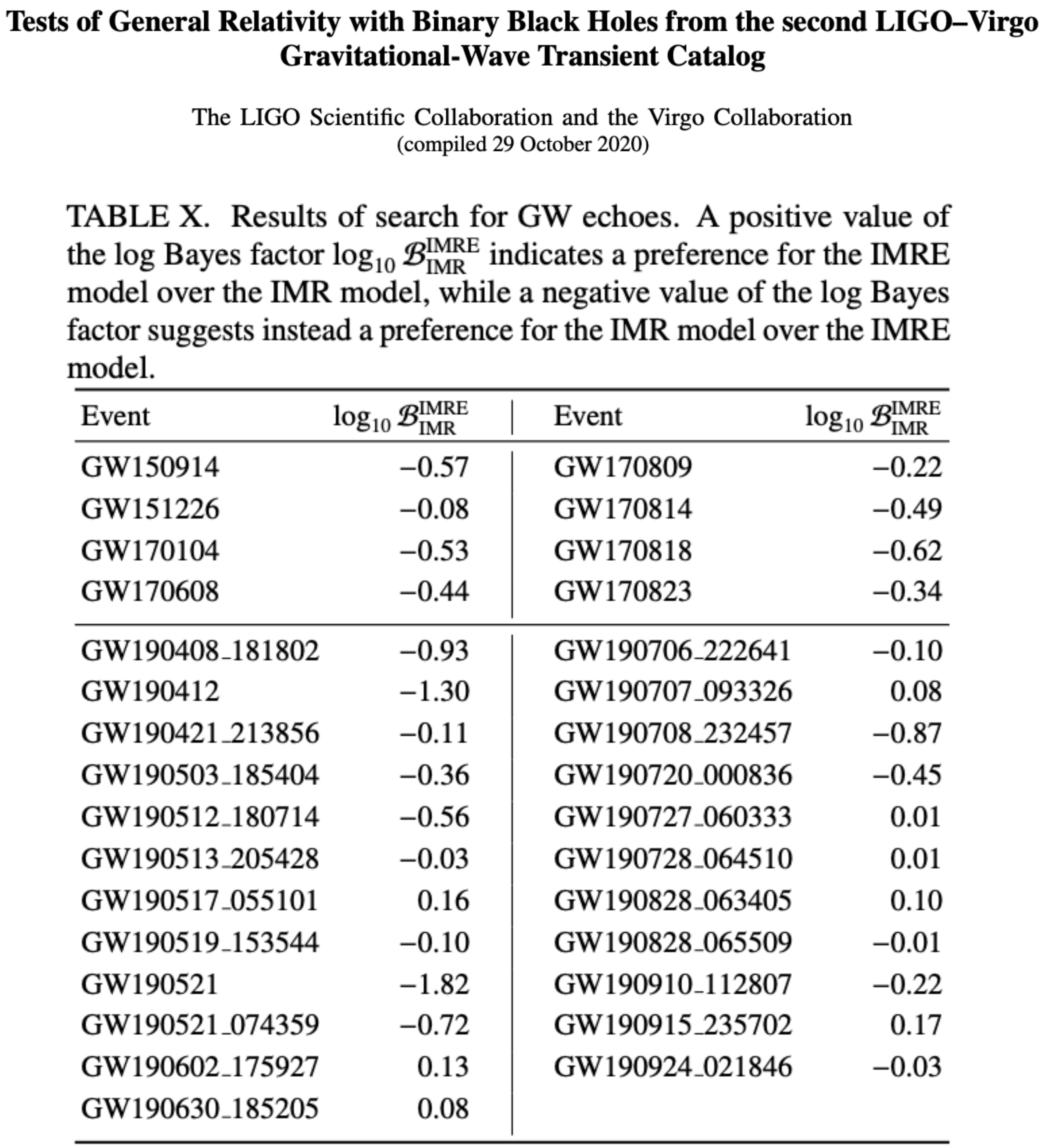
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration:

TABLE XIV. Results of the echoes analysis (Sec. VIII B). List of p-values for signal to noise Bayes Factor $\mathcal{B}^{\mathrm{S}}_{\mathrm{N}}$ 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

But not everyone finds echoes!

different methods/events



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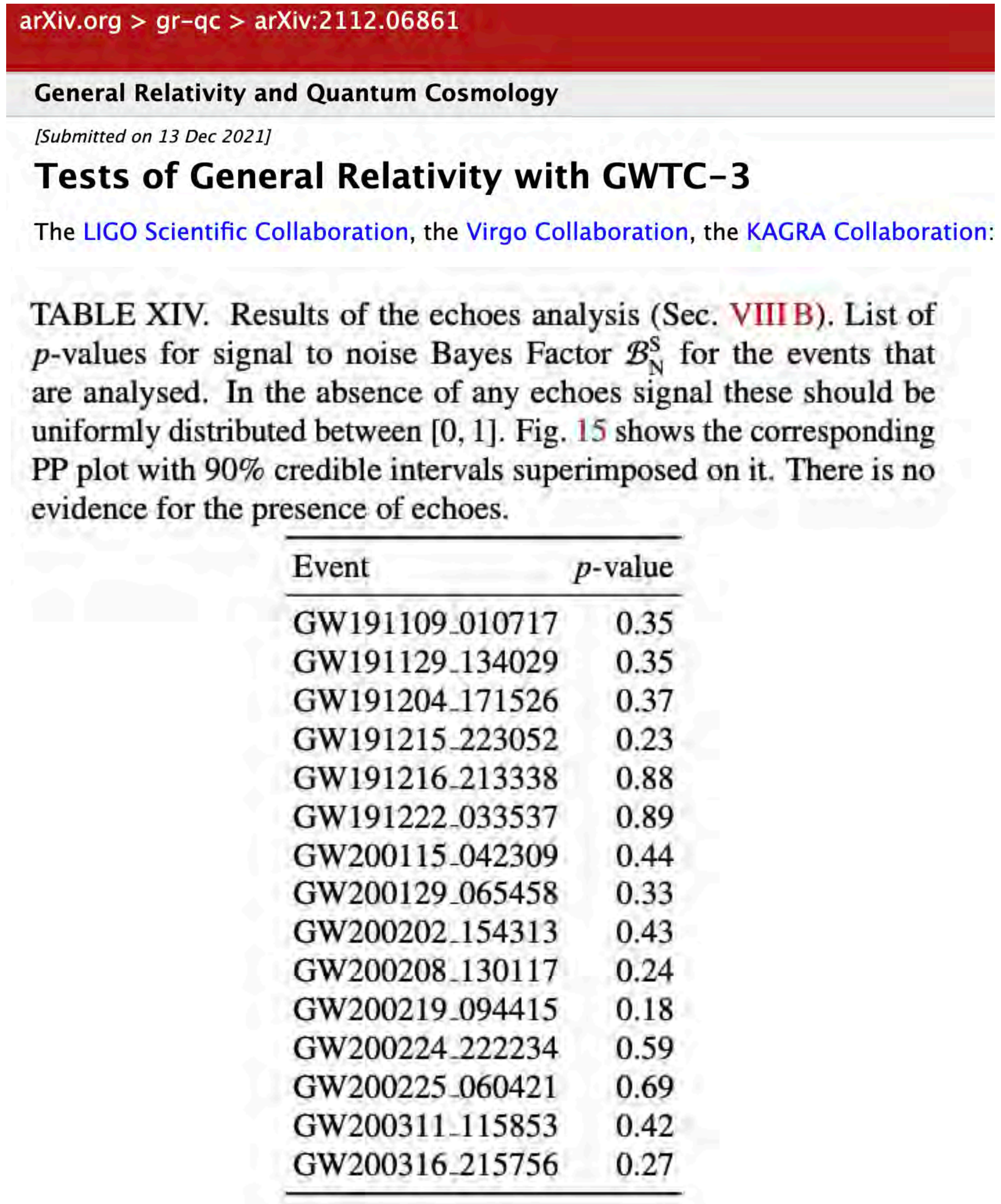
$t_{\rm echo} < 0.5$ sec



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missing GW190521

Different methods,
Different events!

Positive Evidence (p-value ≦ 5%)

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

Failed Searches

	Authors	Method	Data	possible caveat
1	**Westerweck, et al. 2018**	ADA template	O1	"Infinite" prior
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3	**Uchikata, et al. 2019**	ADA, hi-pass	O1,O2	no low-frequencies
4	**Salemi, et al. 2019**	coherent WaveBurst	O1,O2 **	mass-ratio dependence, only 1st echo
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Different methods, Different events!

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

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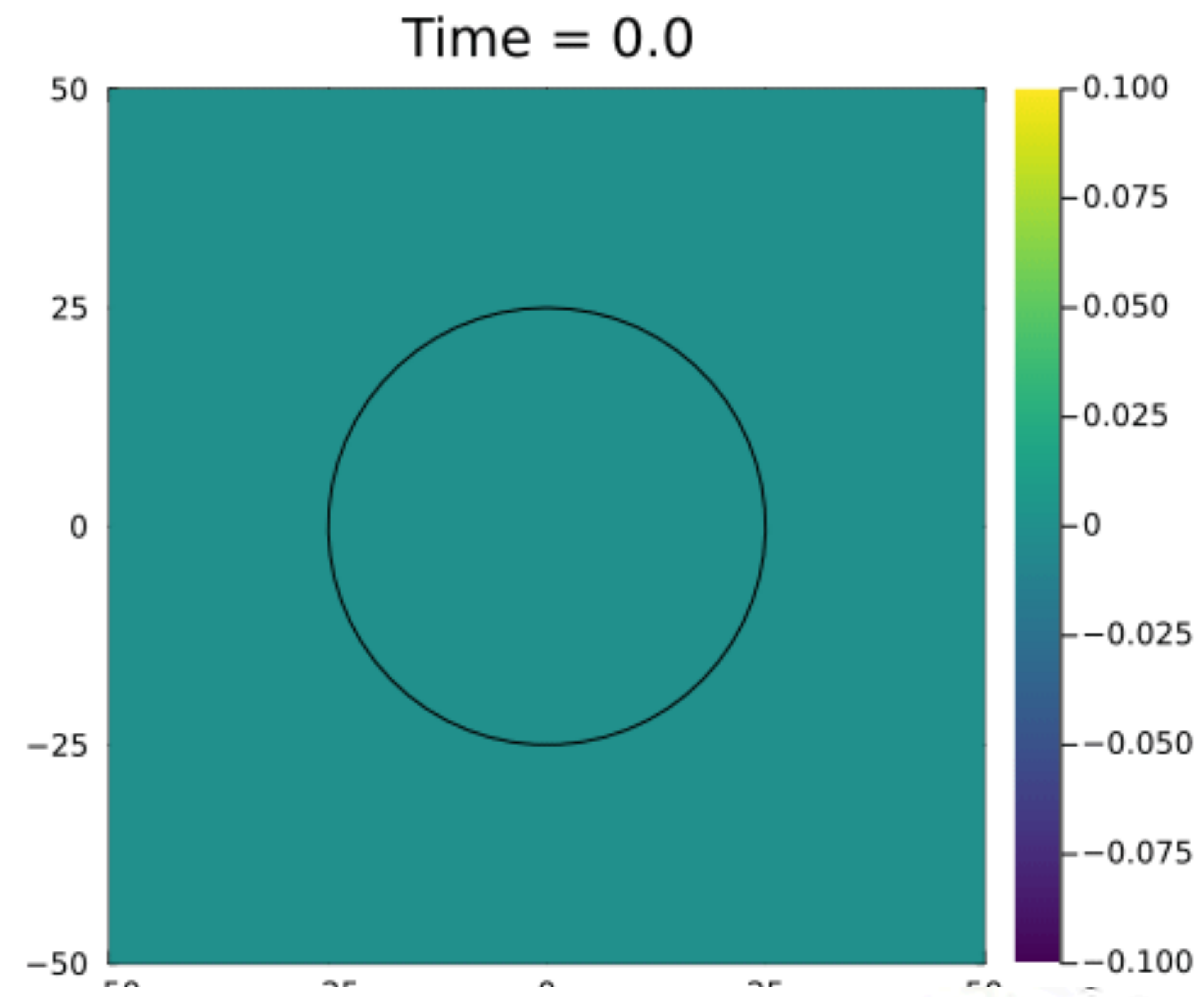
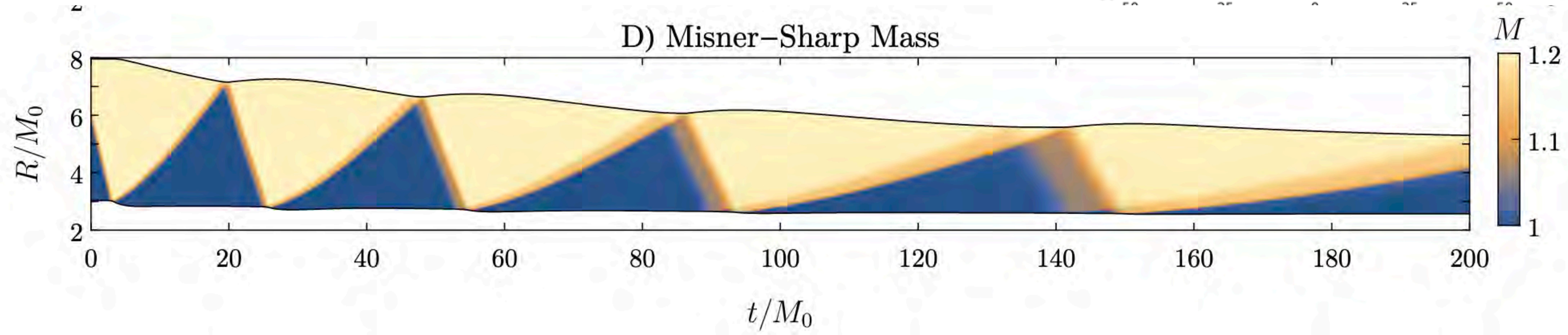
Black Hole Echoes in Numerical Relativity

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

Dailey, NA & Schnetter 2023, 2024





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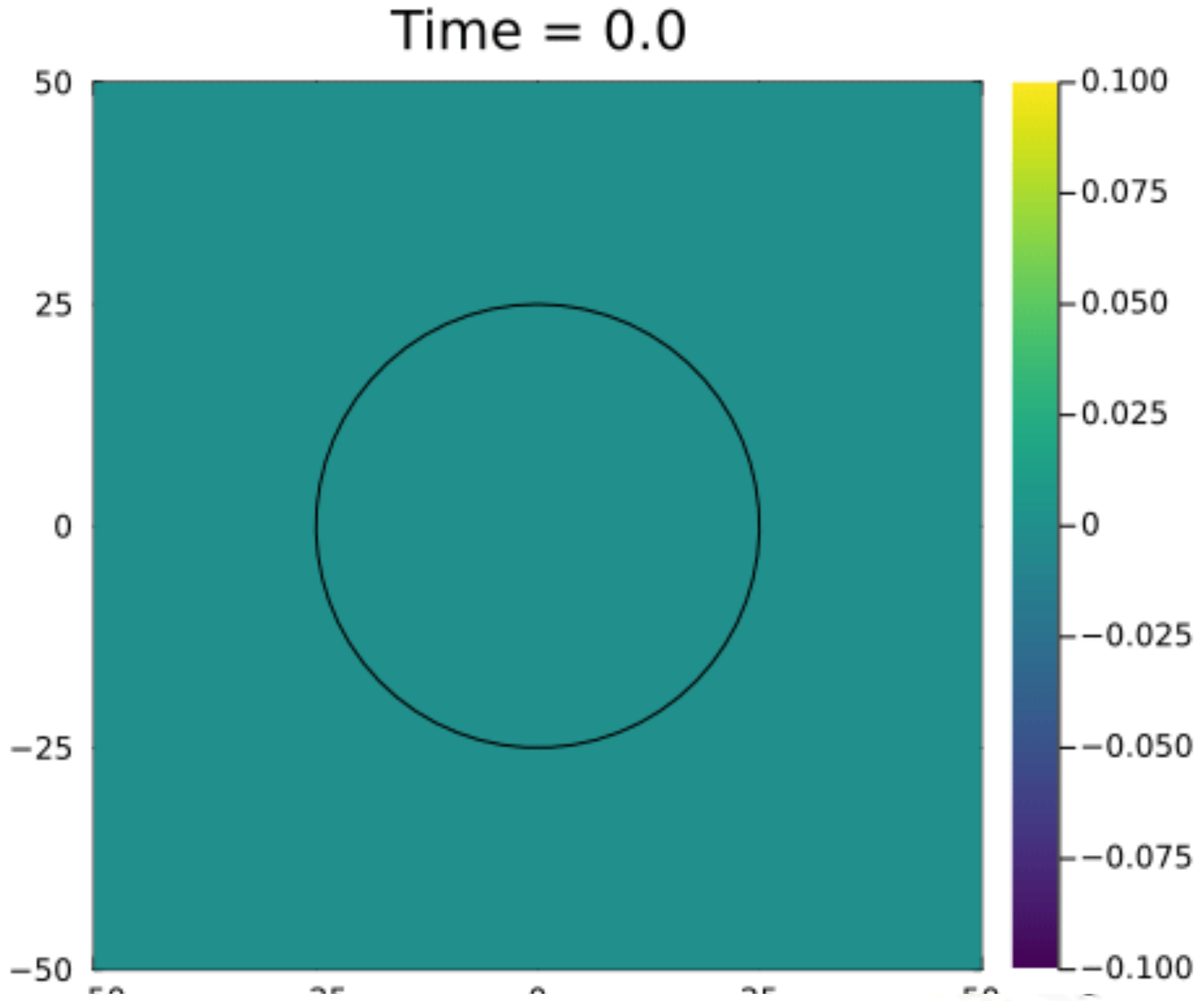
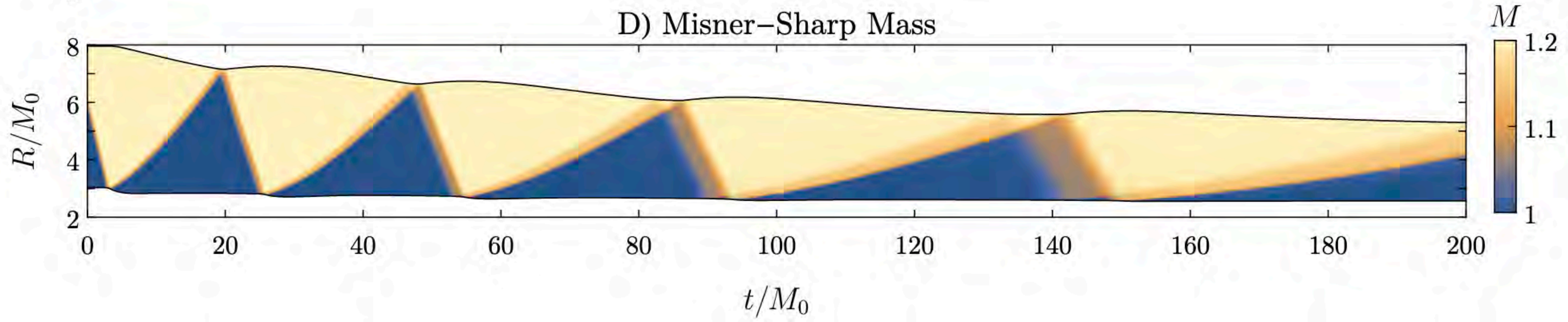
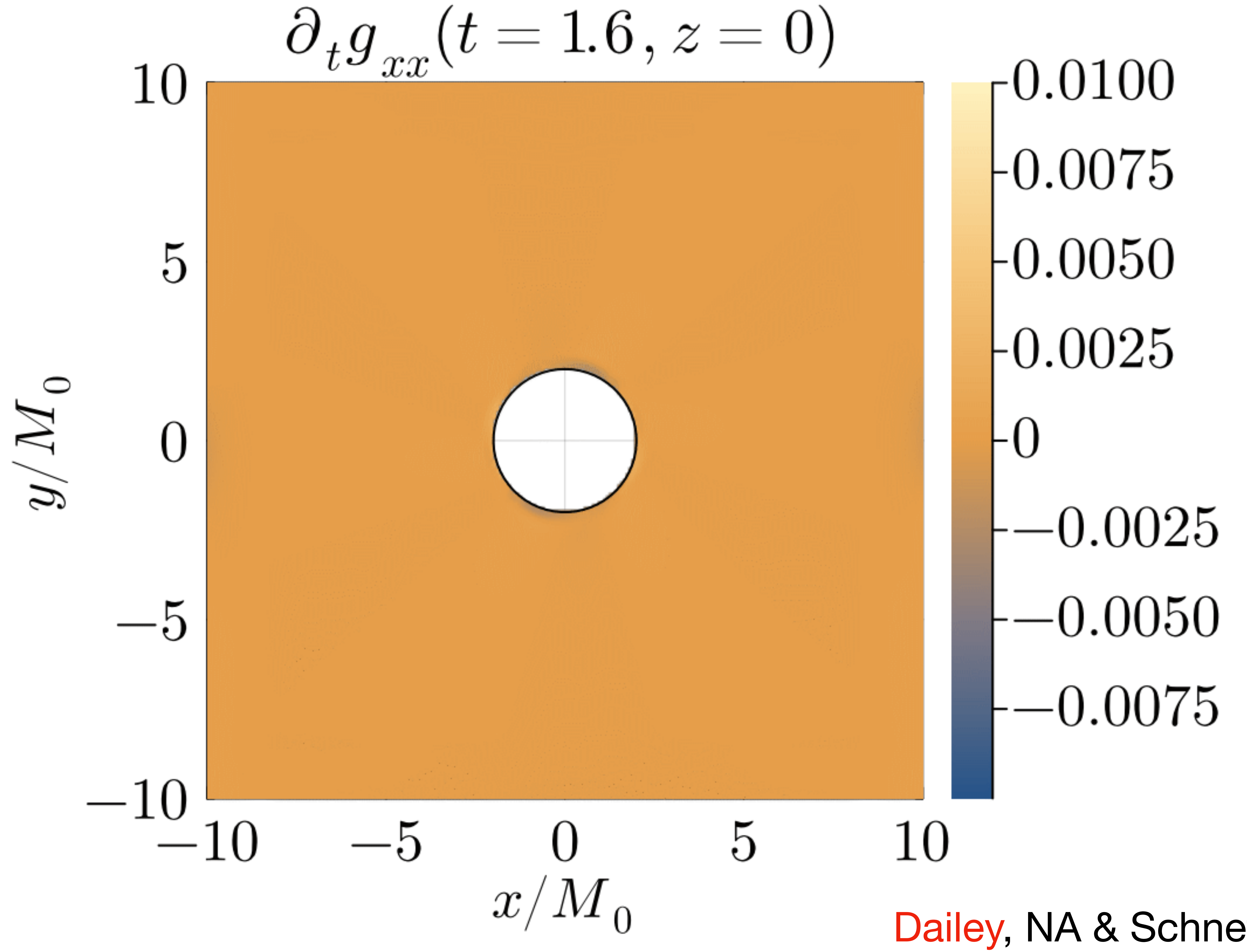
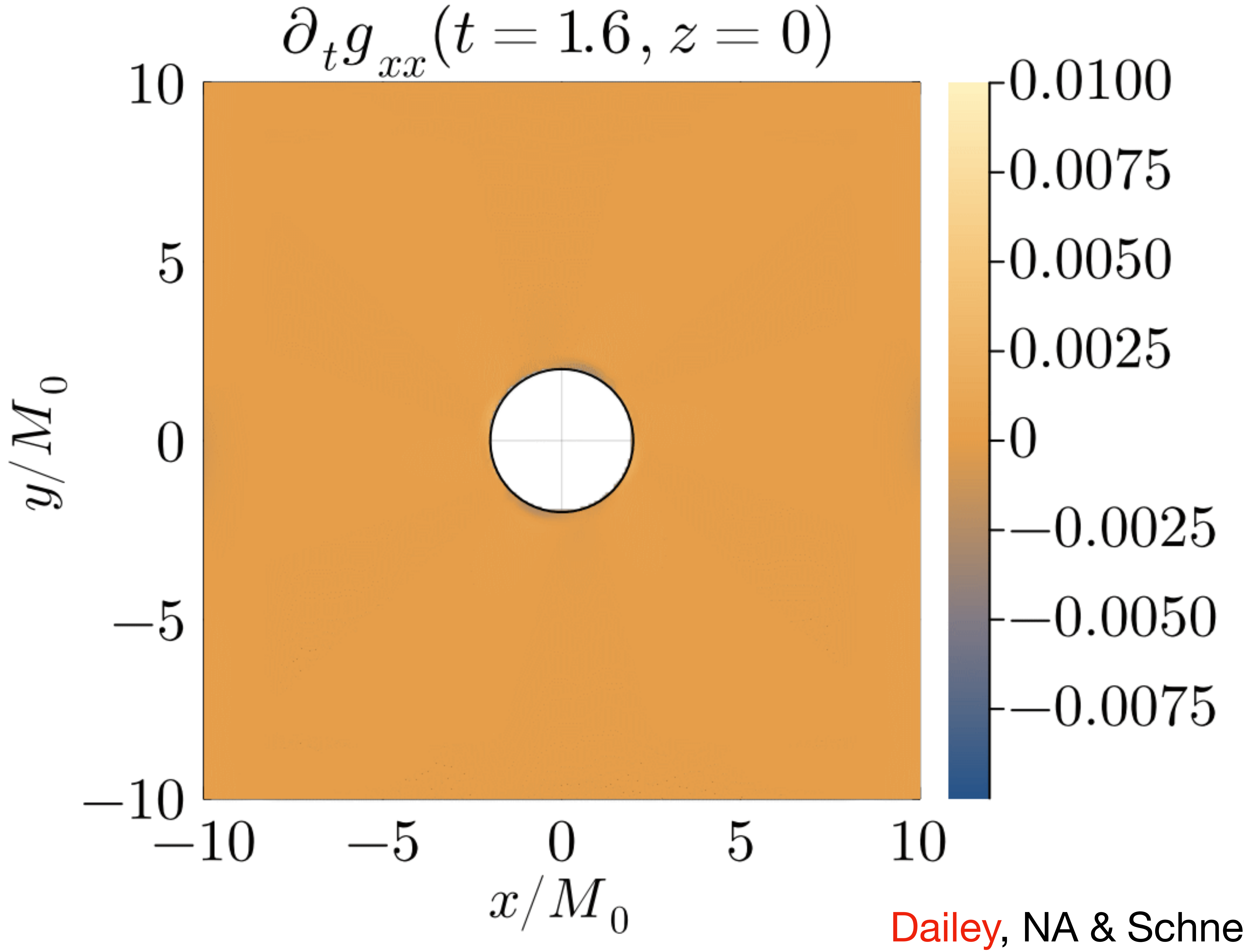






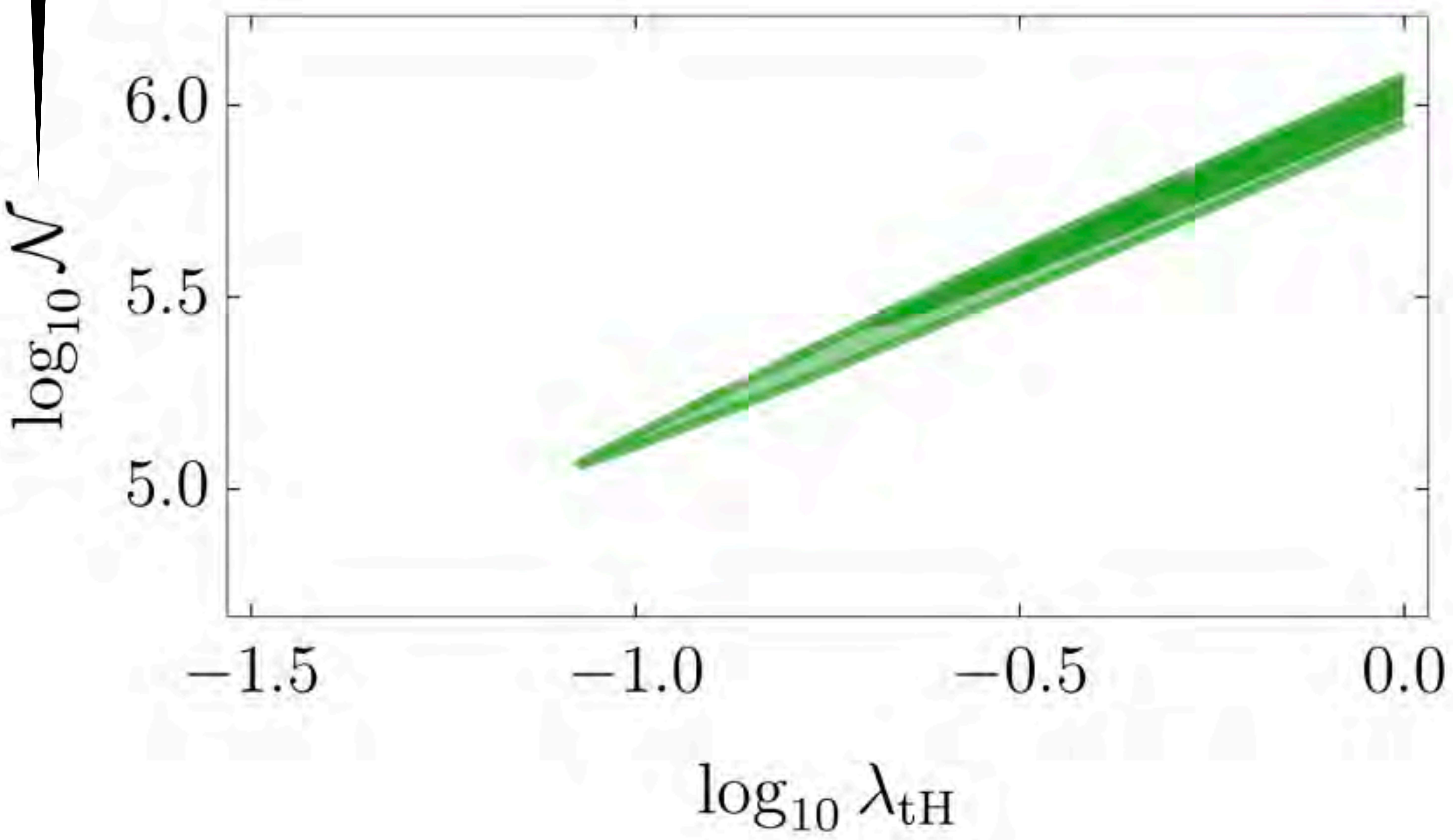
Dailey, NA & Schnetter 2024



Dailey, NA & Schnetter 2024

~Number of fields:

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

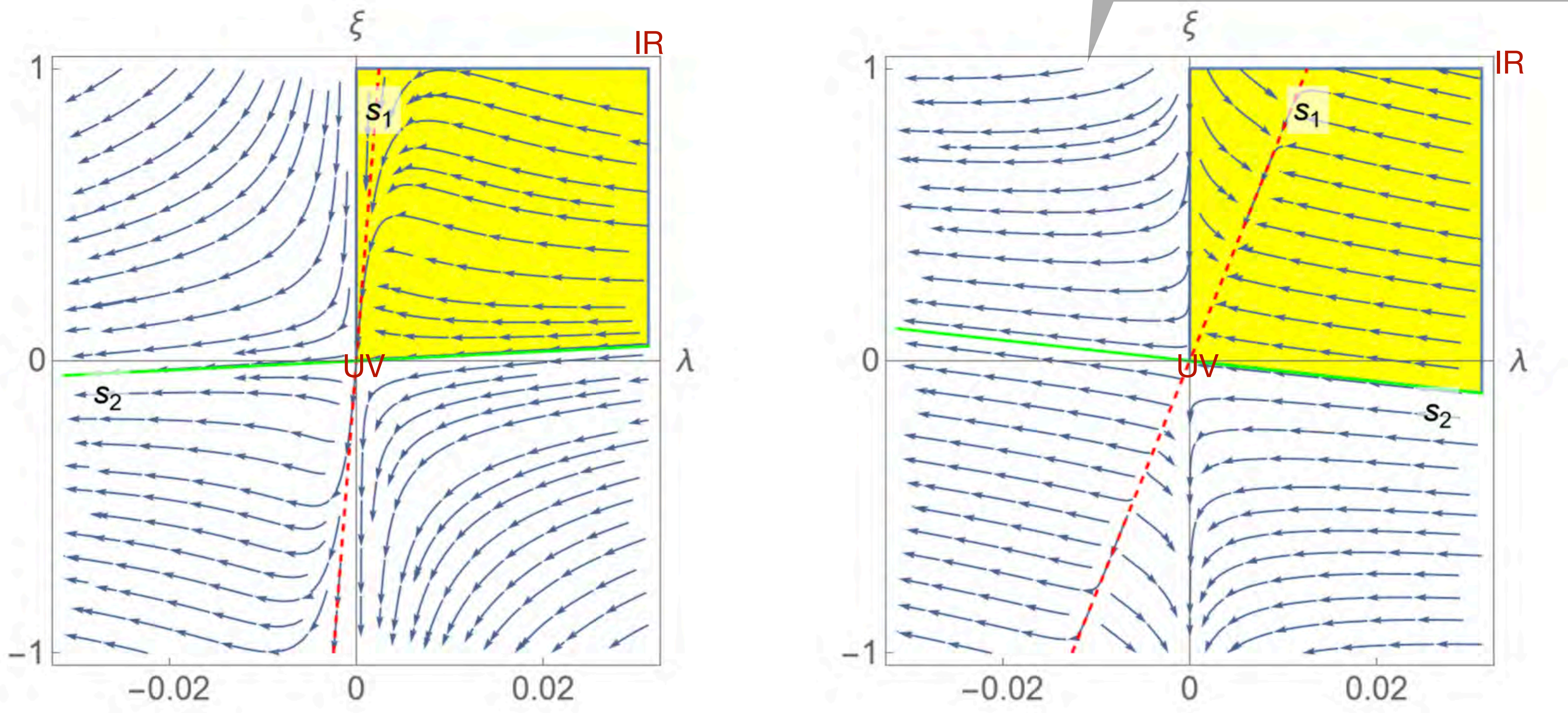


Coupling strength

RG runnings (old & new)

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

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.



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

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

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

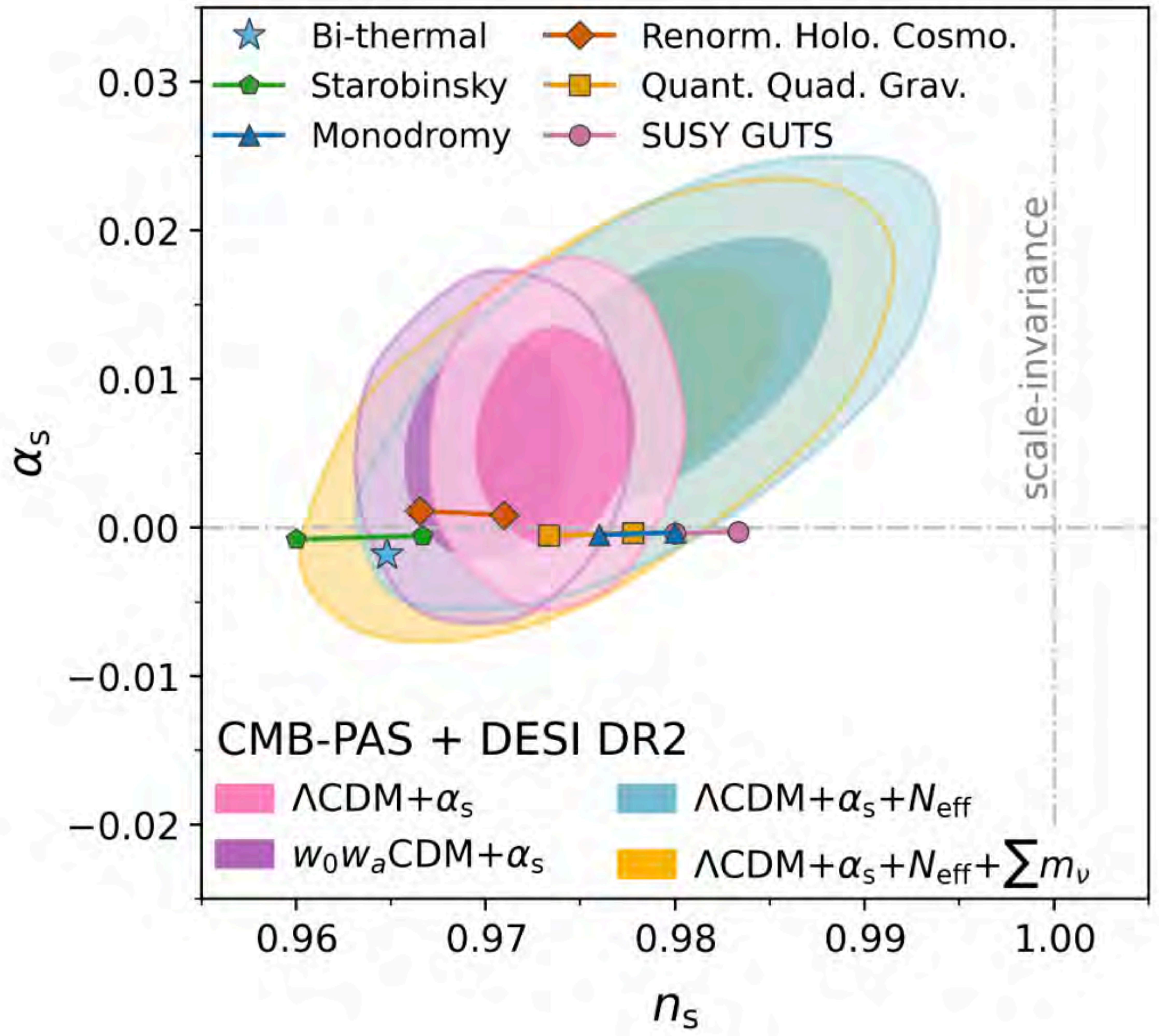
$$\beta_\lambda = -\frac{1}{(4\pi)^2}\frac{(1617\lambda - 20\xi)\lambda}{90} ,$$

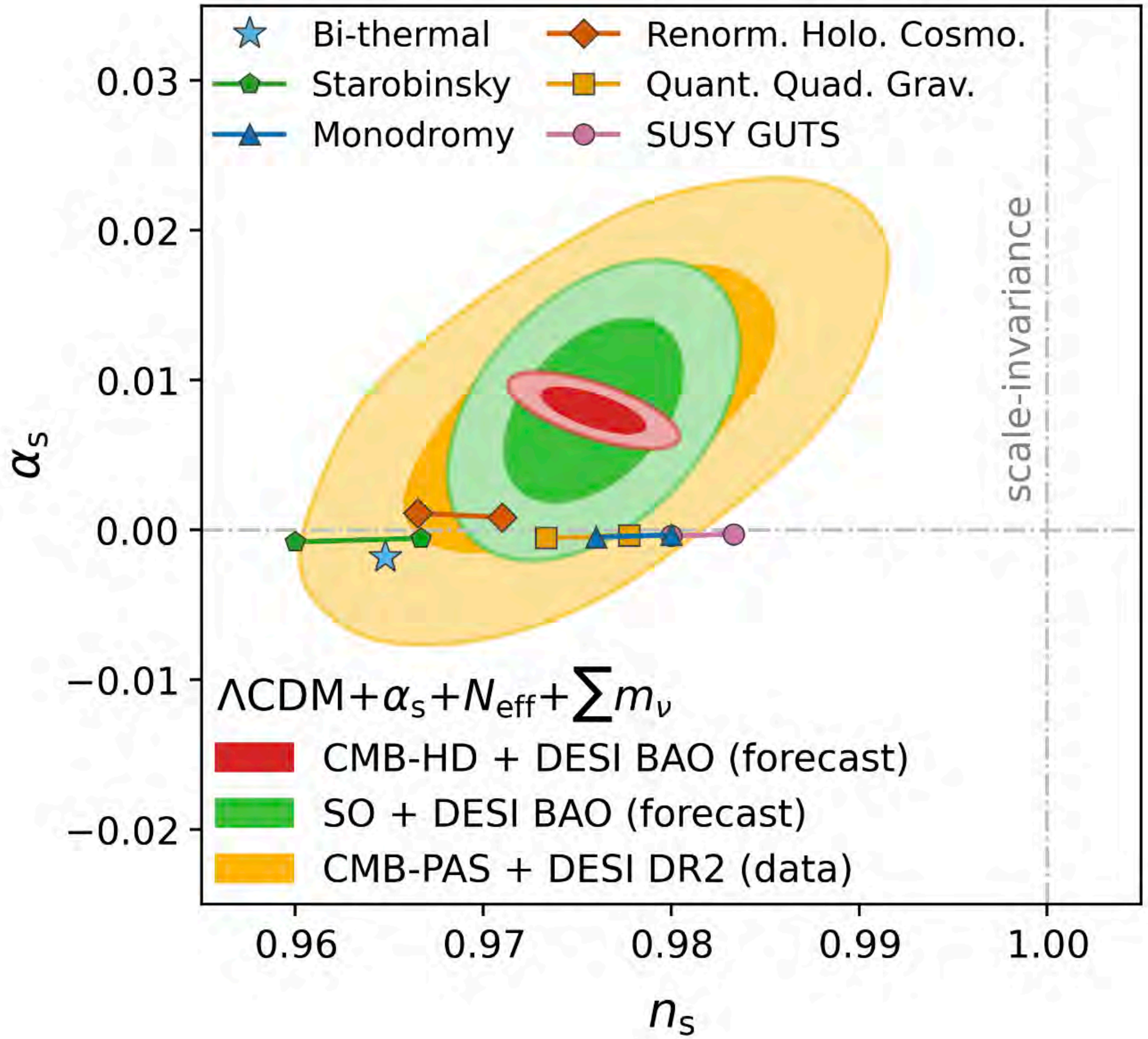
$$\beta_\xi = -\frac{1}{(4\pi)^2}\frac{\xi^2 - 36\lambda\xi - 2520\lambda^2}{36} .$$

Percacci & Vacca 25

Future is Bright!

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





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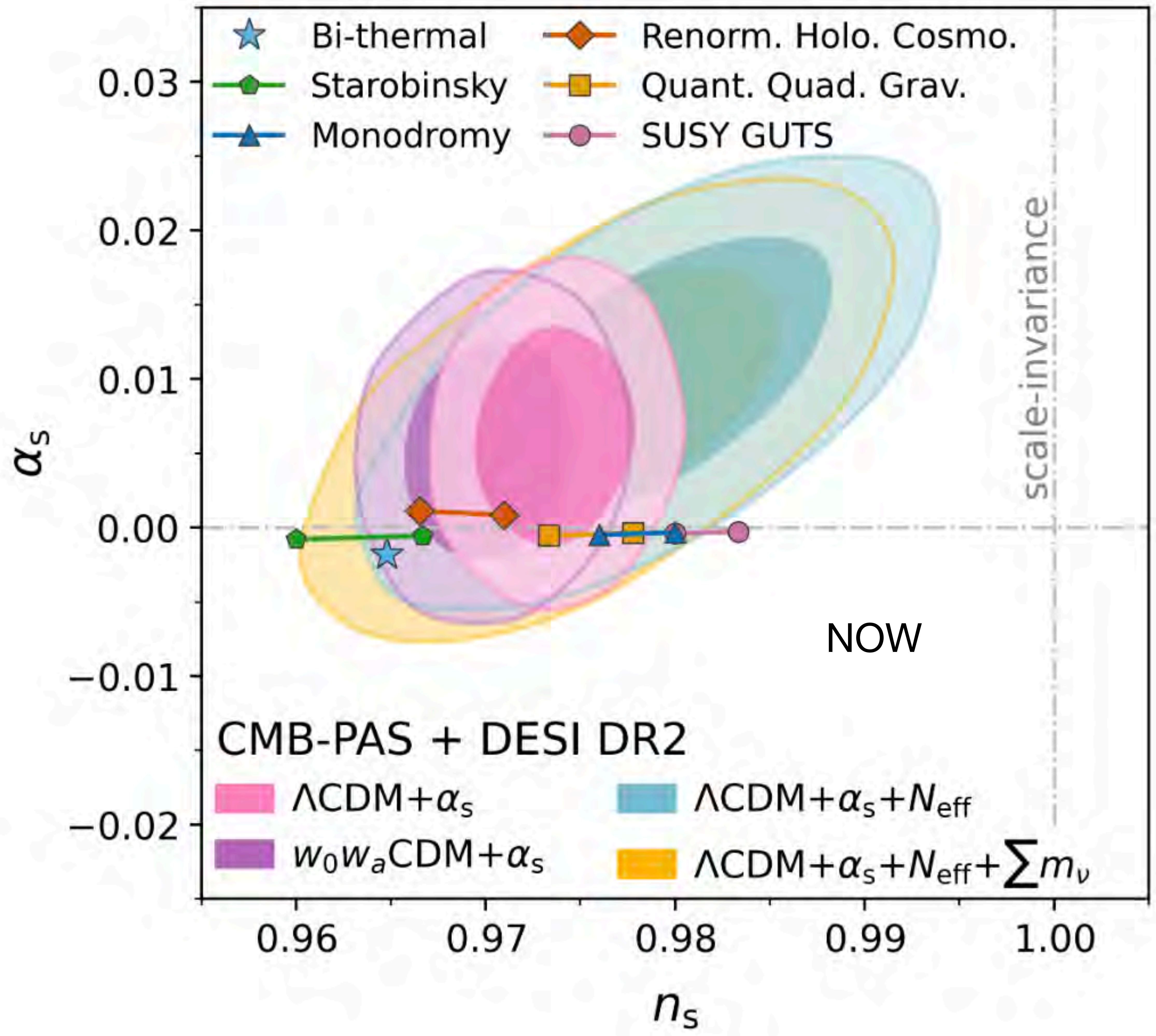
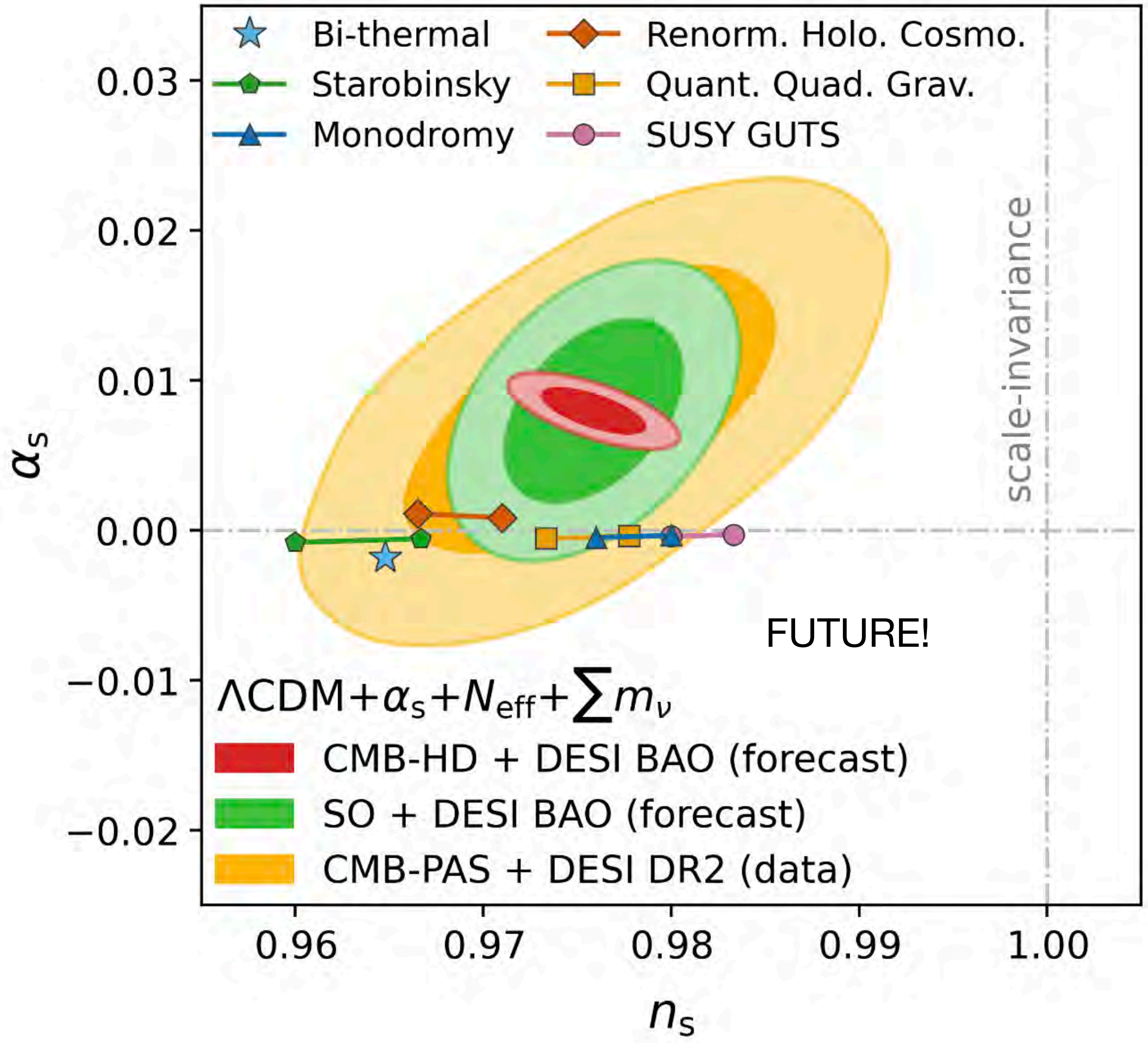




Future is Bright!

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

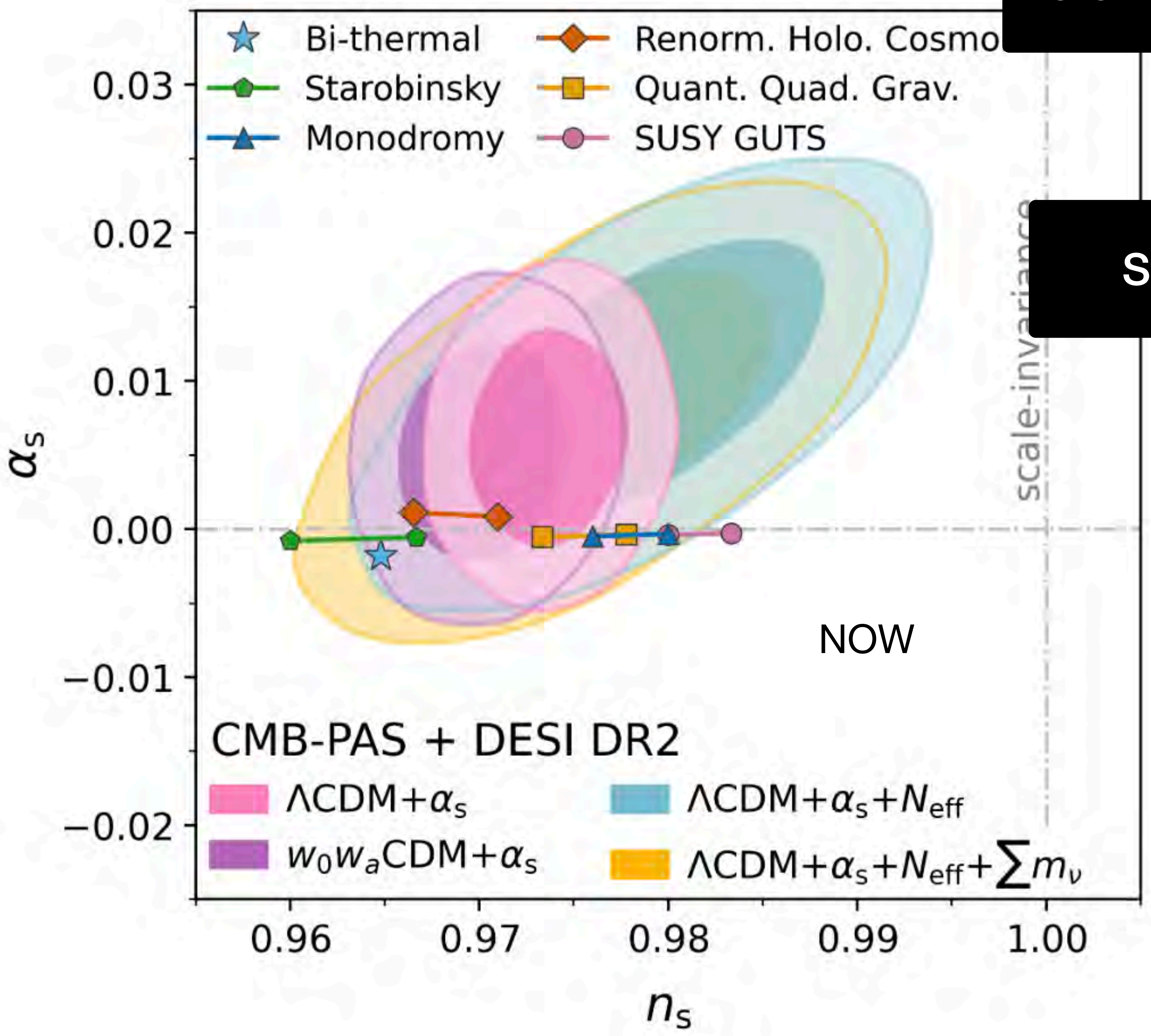


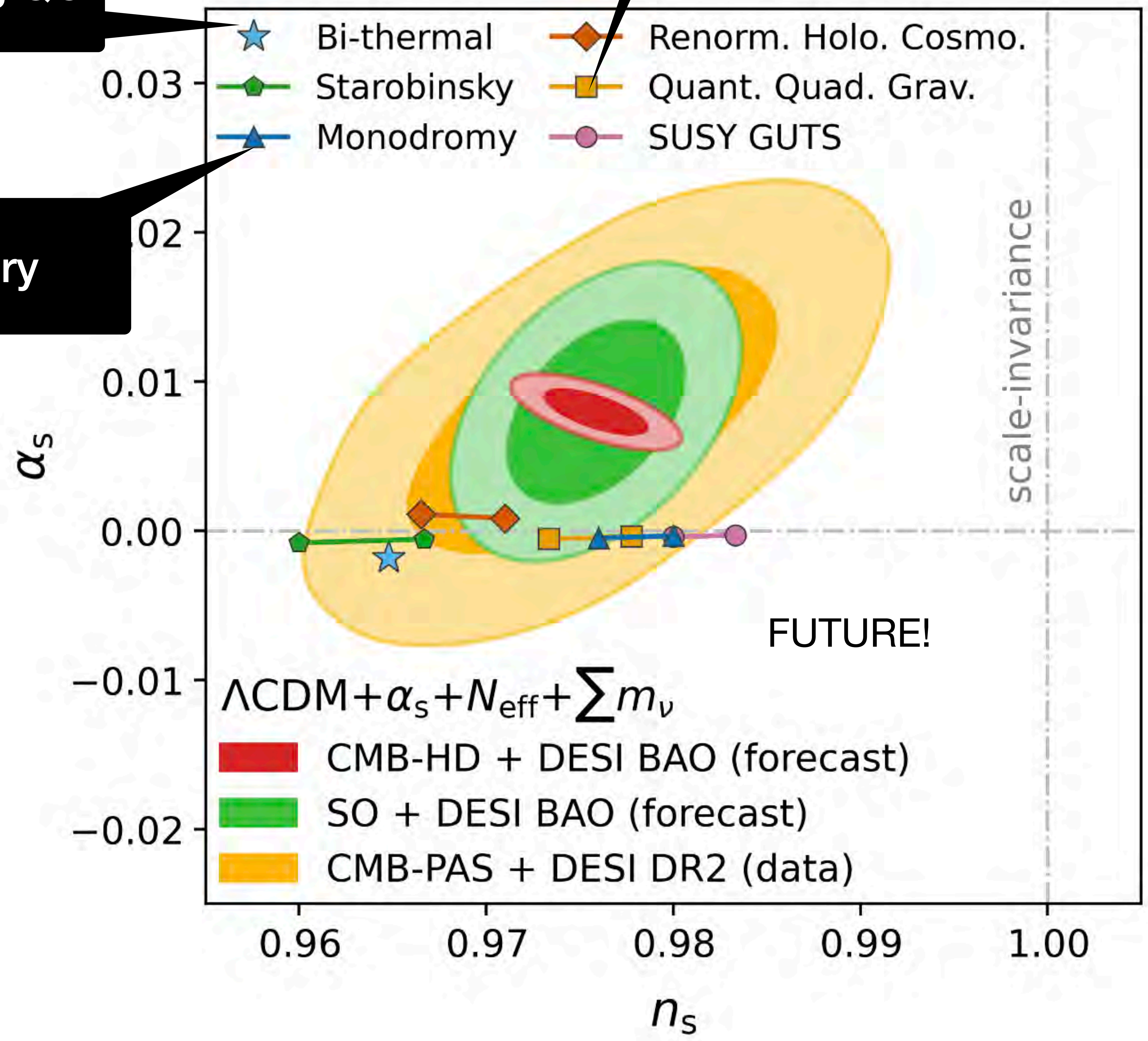


Quadratic QG

Lorentz-violating QG

String Theory





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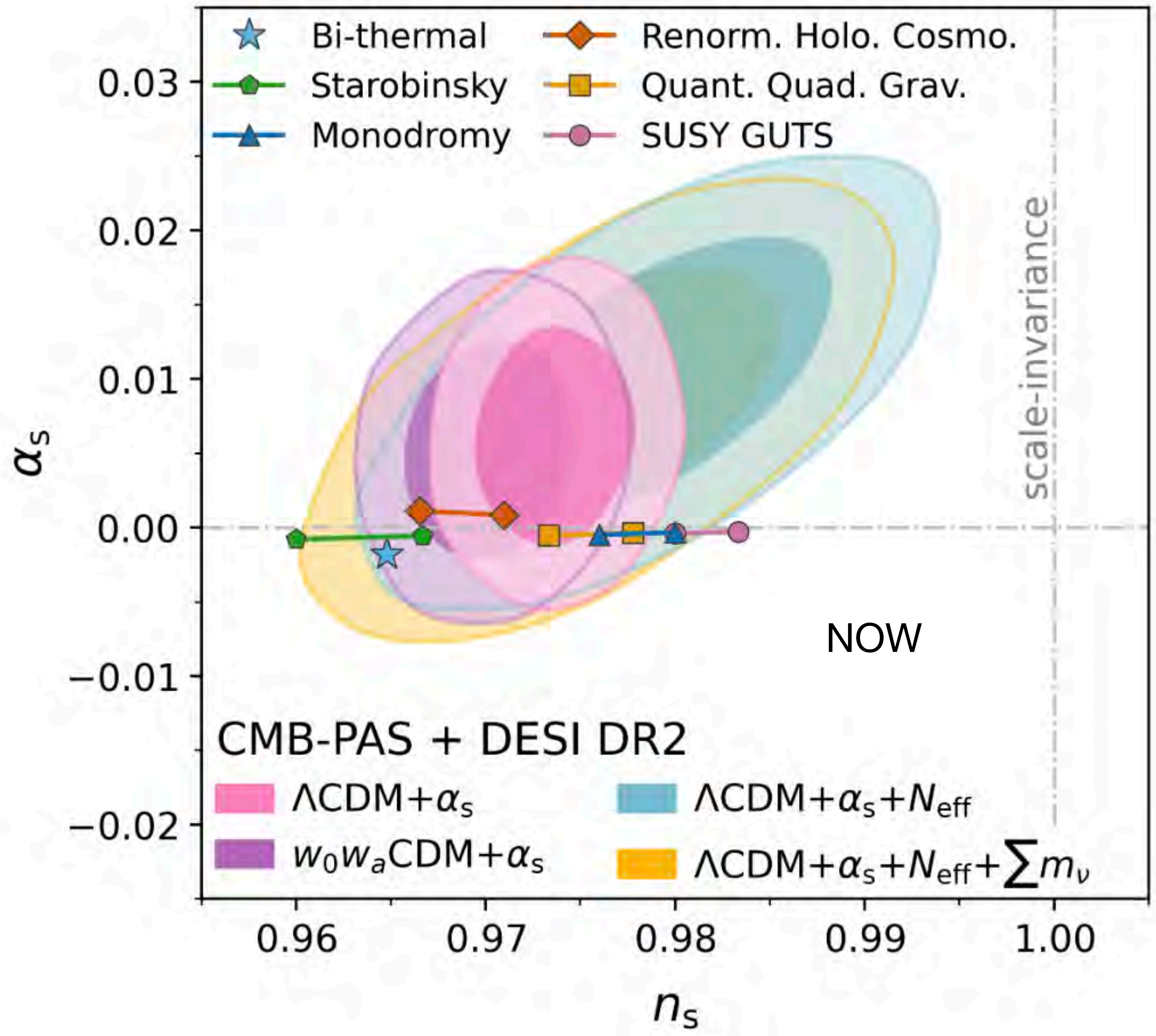
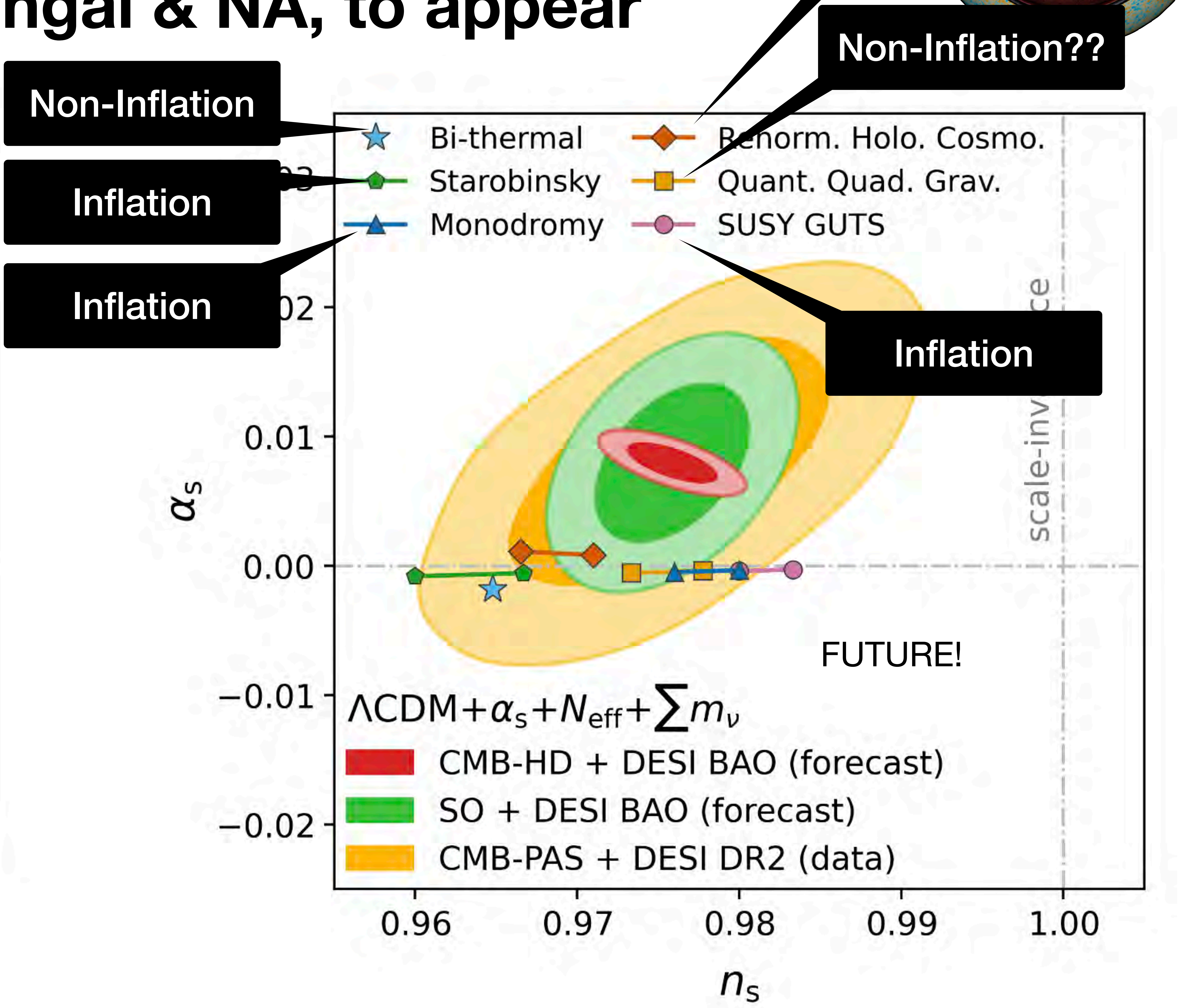




Non-Inflation

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:

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

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

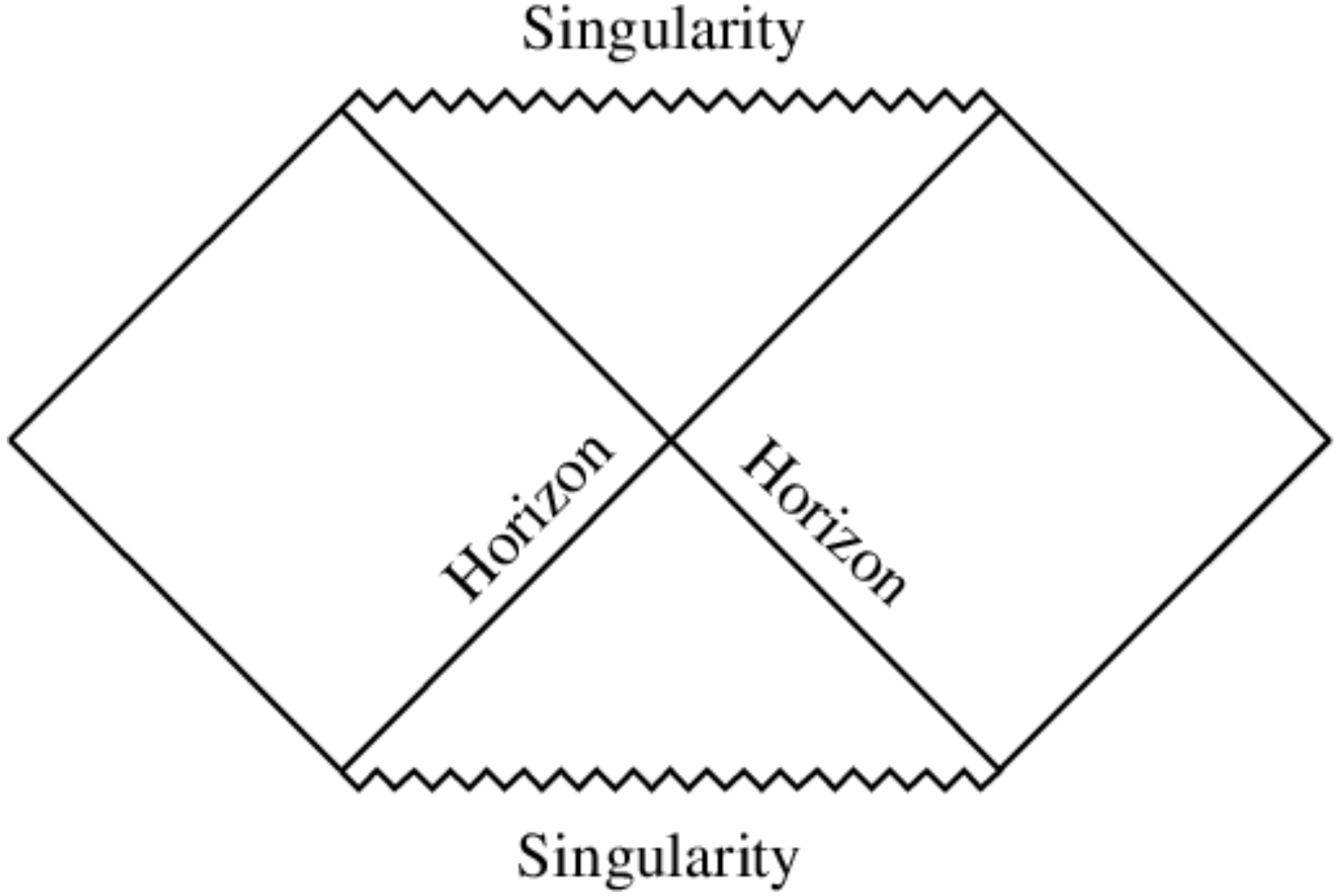
$$\alpha = \alpha_\mp \equiv \frac{1}{2}\left(1 \mp i\sqrt{15}\right) , \qquad b = b_\mp \equiv \frac{3}{8}\left(1 \mp i\sqrt{15}\right)$$

arXiv:2411.19311 [PRD]

Complex Powerballs:

Conformal Cores of Quantum Black Holes in Quadratic Gravity

Niayesh Afshordi,[1,2,3] Ruolin Liu,[1,2,3] and Jerome Quintin[4,3,2]



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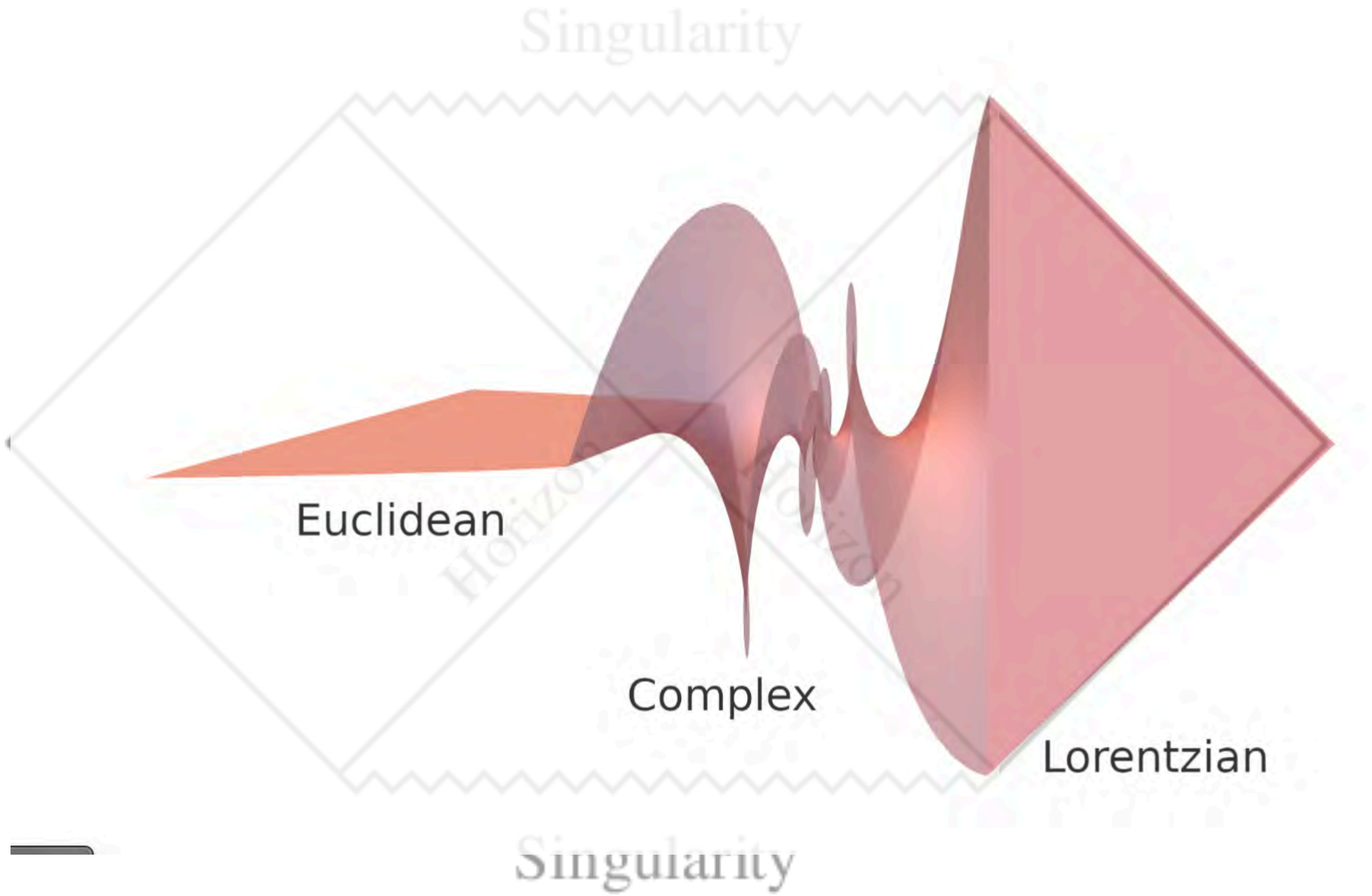
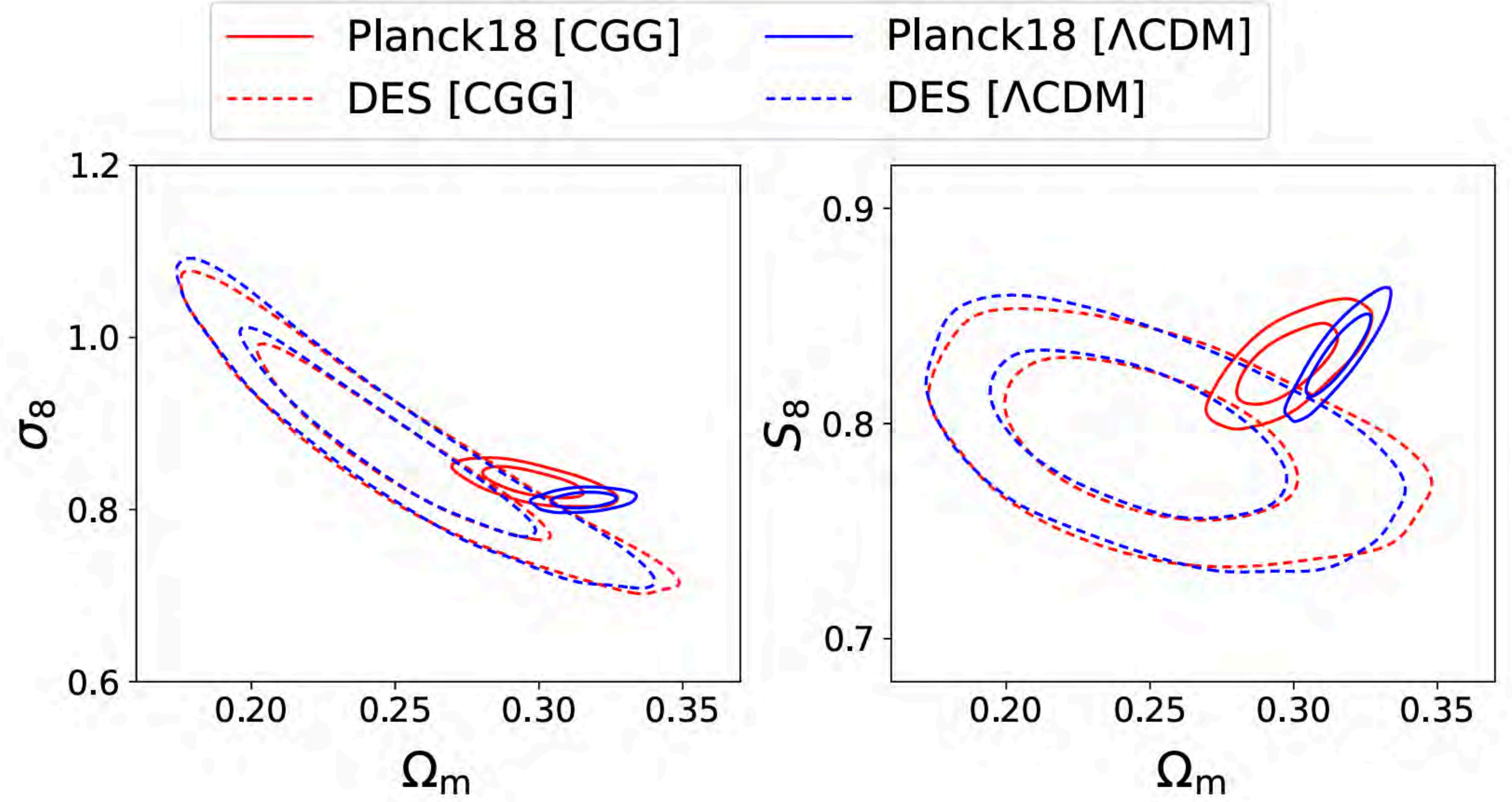
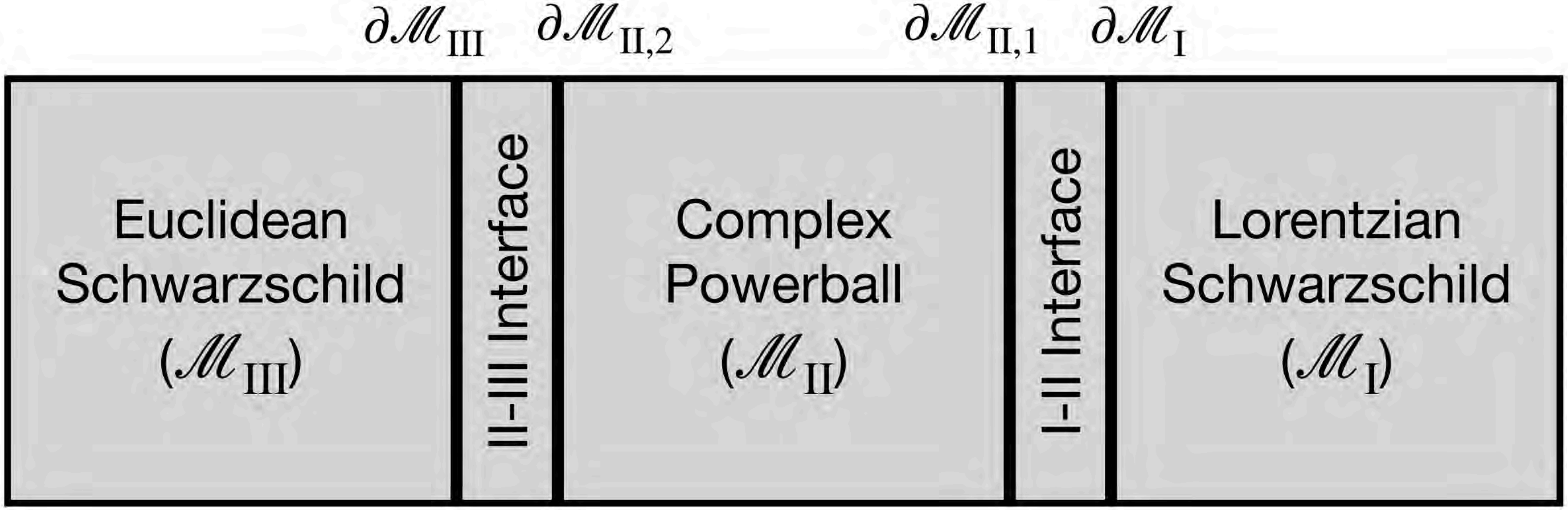


S_8 tension


Planck18 [CGG]
DES [CGG]
Planck18 [ΛCDM]
DES [ΛCDM]
σ_8
1.2
1.0
0.8
0.6
0.20
0.25
0.30
0.35
Ω_m
S_8
0.9
0.8
0.7
0.20
0.25
0.30
0.35
Ω_m

Matching GR to QG across strong-coupling membrane



$\partial\mathscr{M}_{\mathrm{III}}$ $\partial\mathscr{M}_{\mathrm{II},2}$ $\partial\mathscr{M}_{\mathrm{II},1}$ $\partial\mathscr{M}_{\mathrm{I}}$

Euclidean Schwarzschild ($\mathscr{M}_{\mathrm{III}}$)

II-III Interface

Complex Powerball ($\mathscr{M}_{\mathrm{II}}$)

I-II Interface

Lorentzian Schwarzschild ($\mathscr{M}_{\mathrm{I}}$)

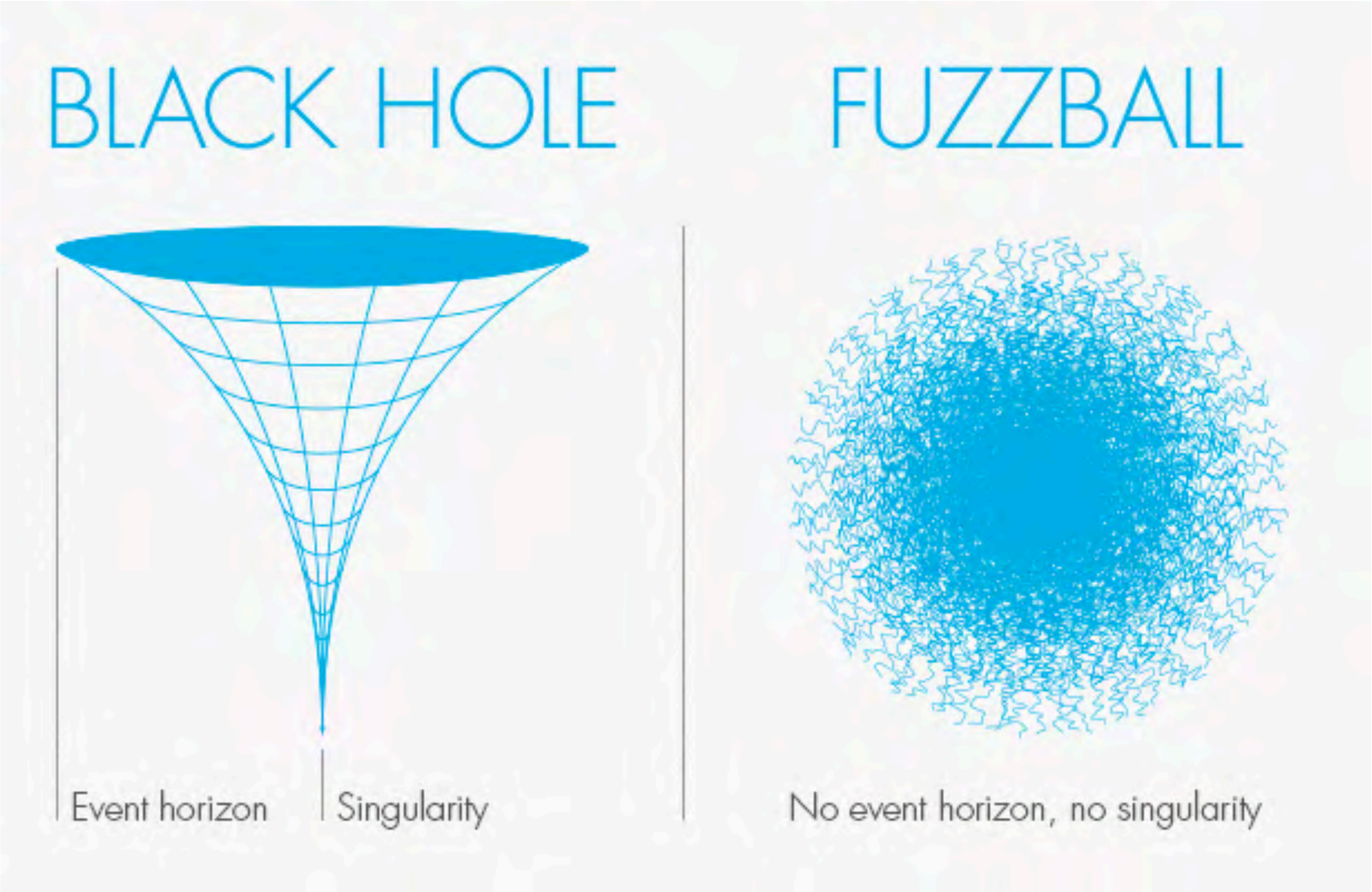
Euclidean GR

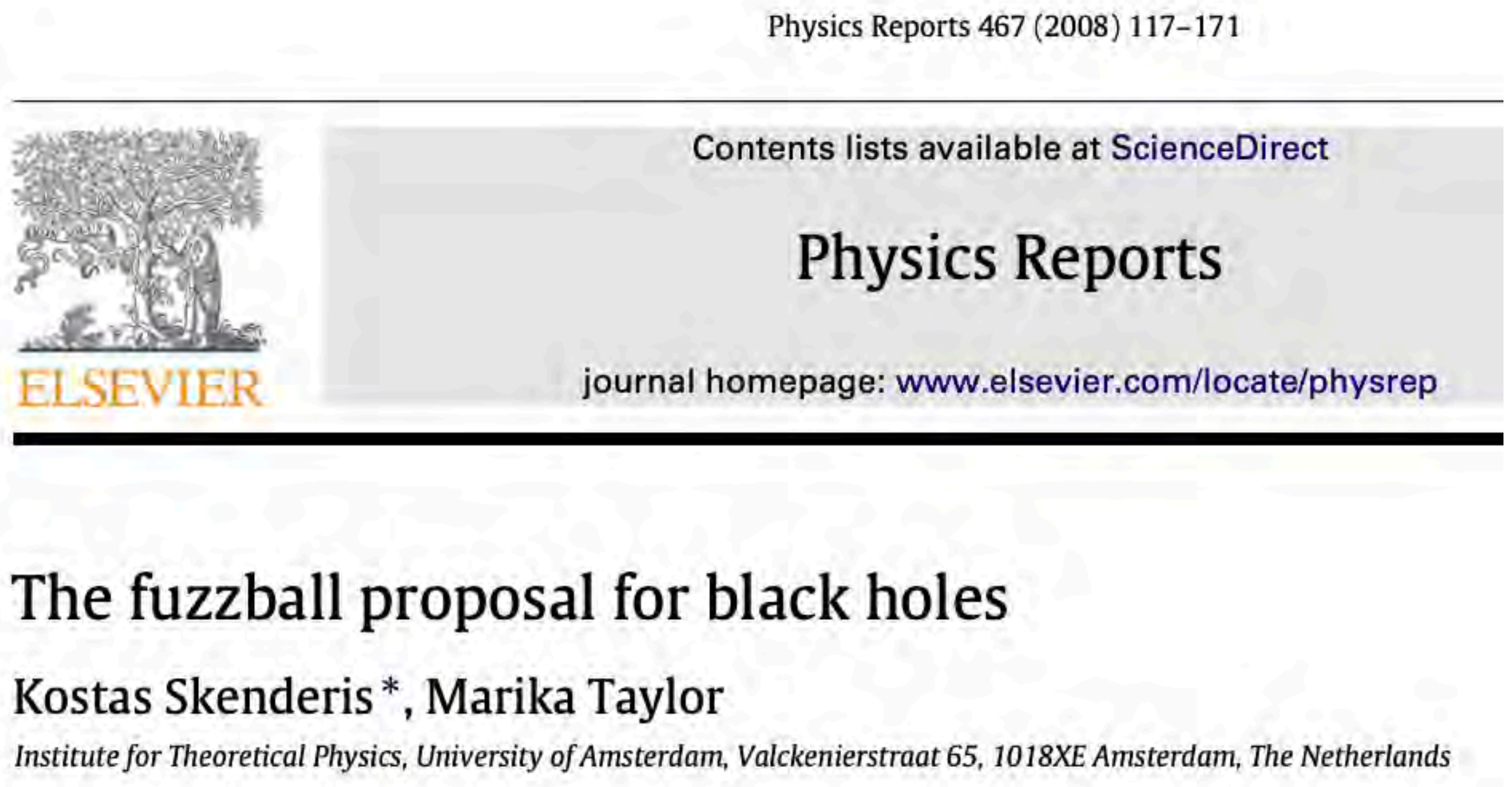
Complex QG

Lorentzian GR

- 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

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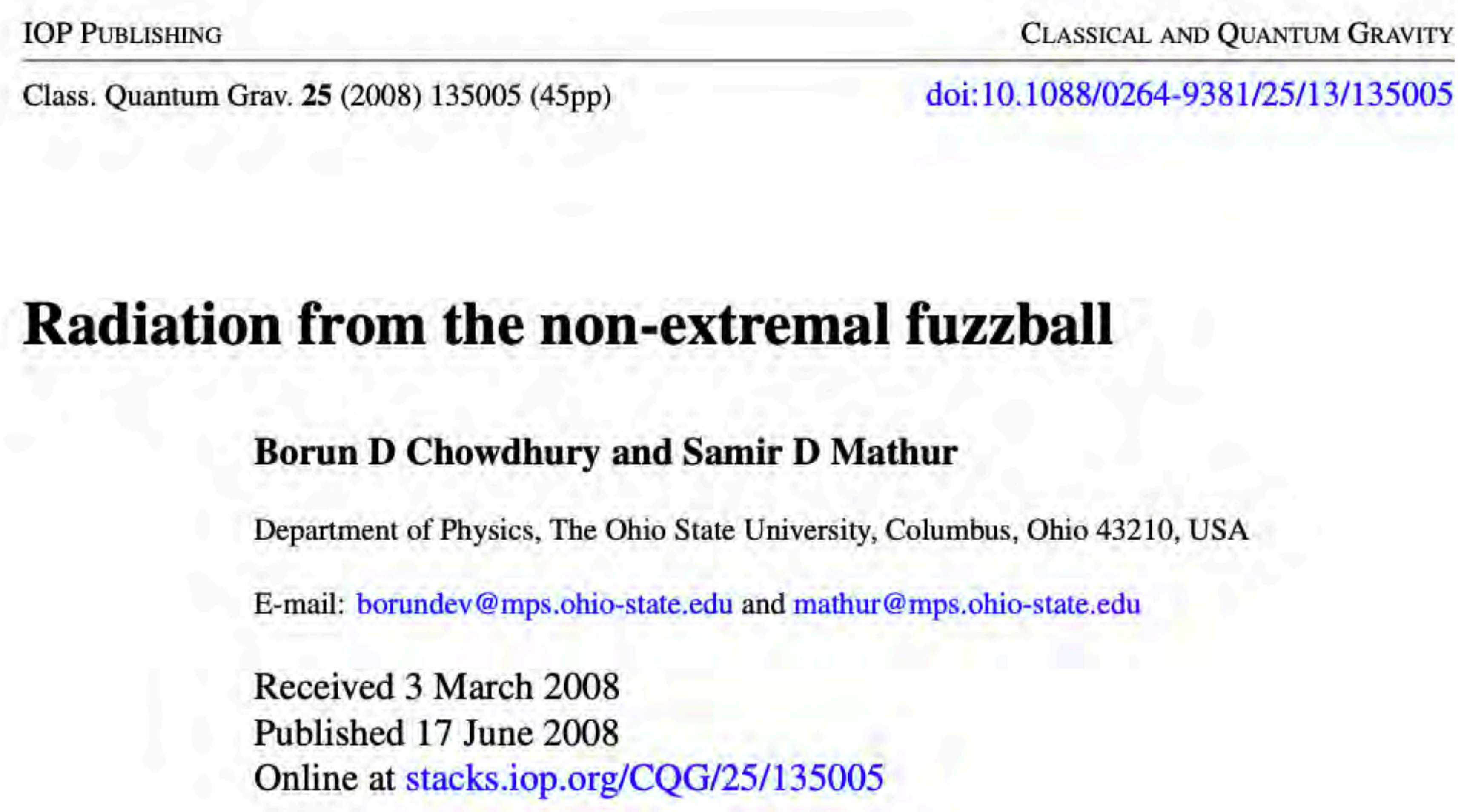
Kostas Skenderis *, Marika Taylor

Institute for Theoretical Physics, University of Amsterdam, Valckenierstraat 65, 1018XE Amsterdam, The Netherlands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Class. Quantum Grav. **25** (2008) 135005 (45pp) doi: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

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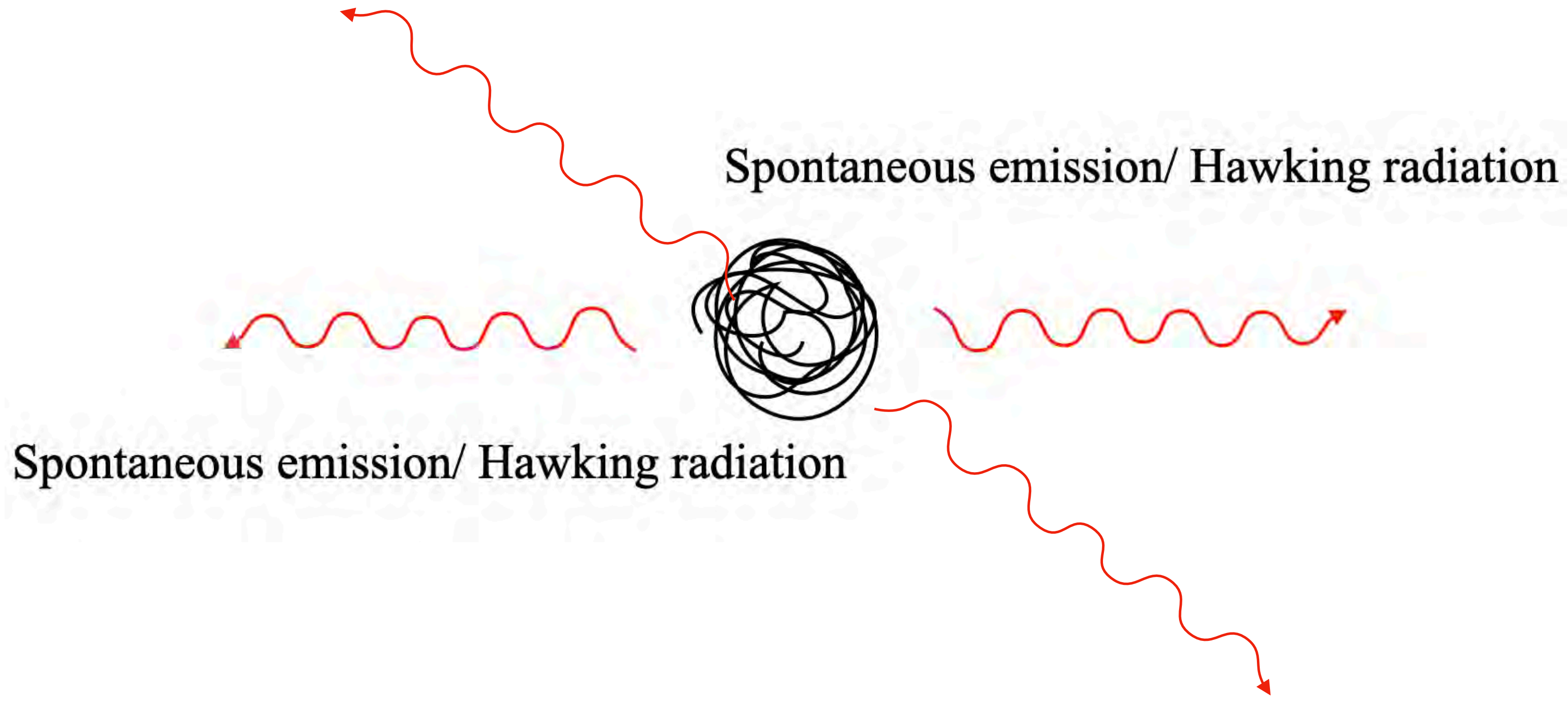
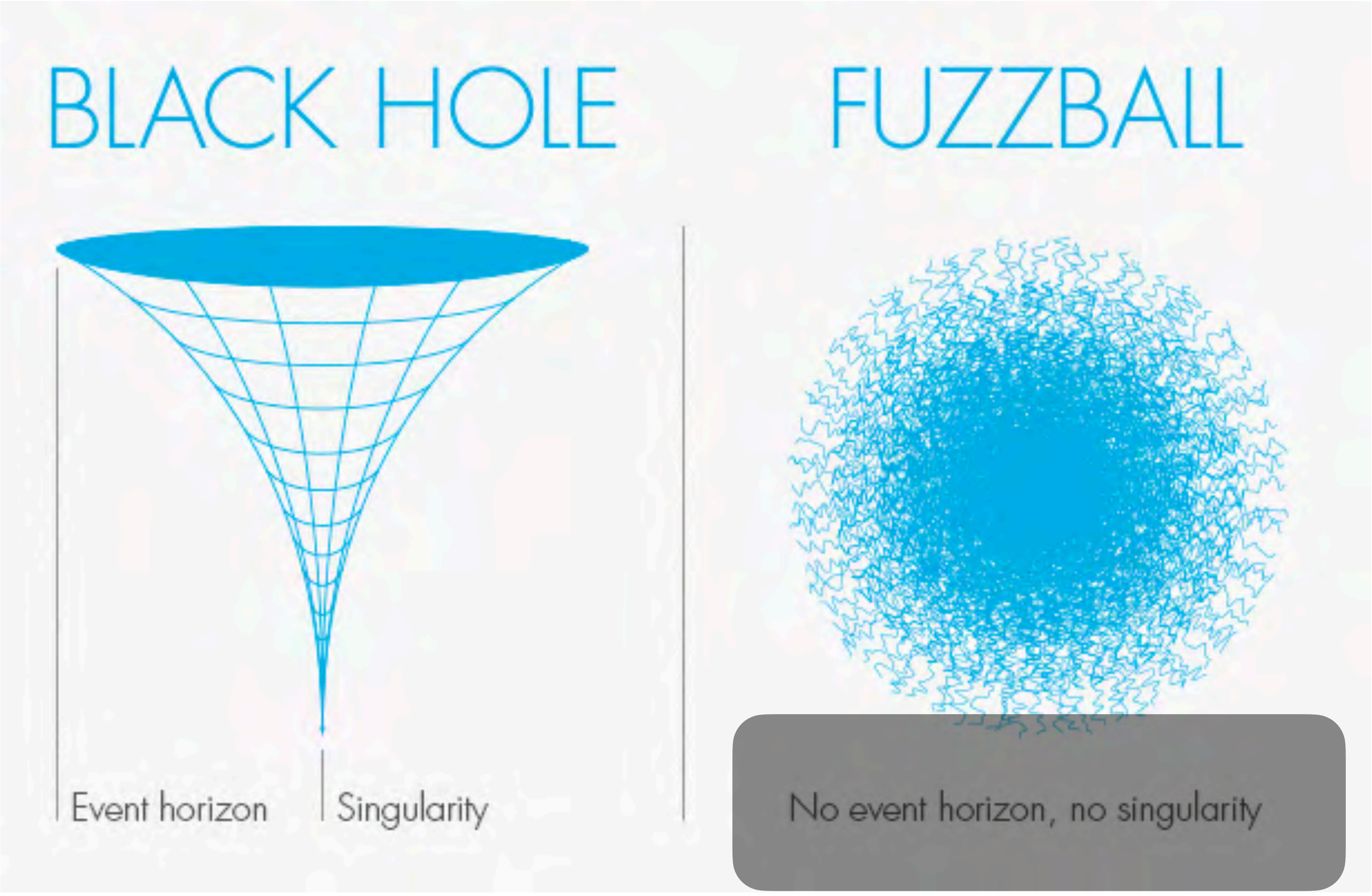
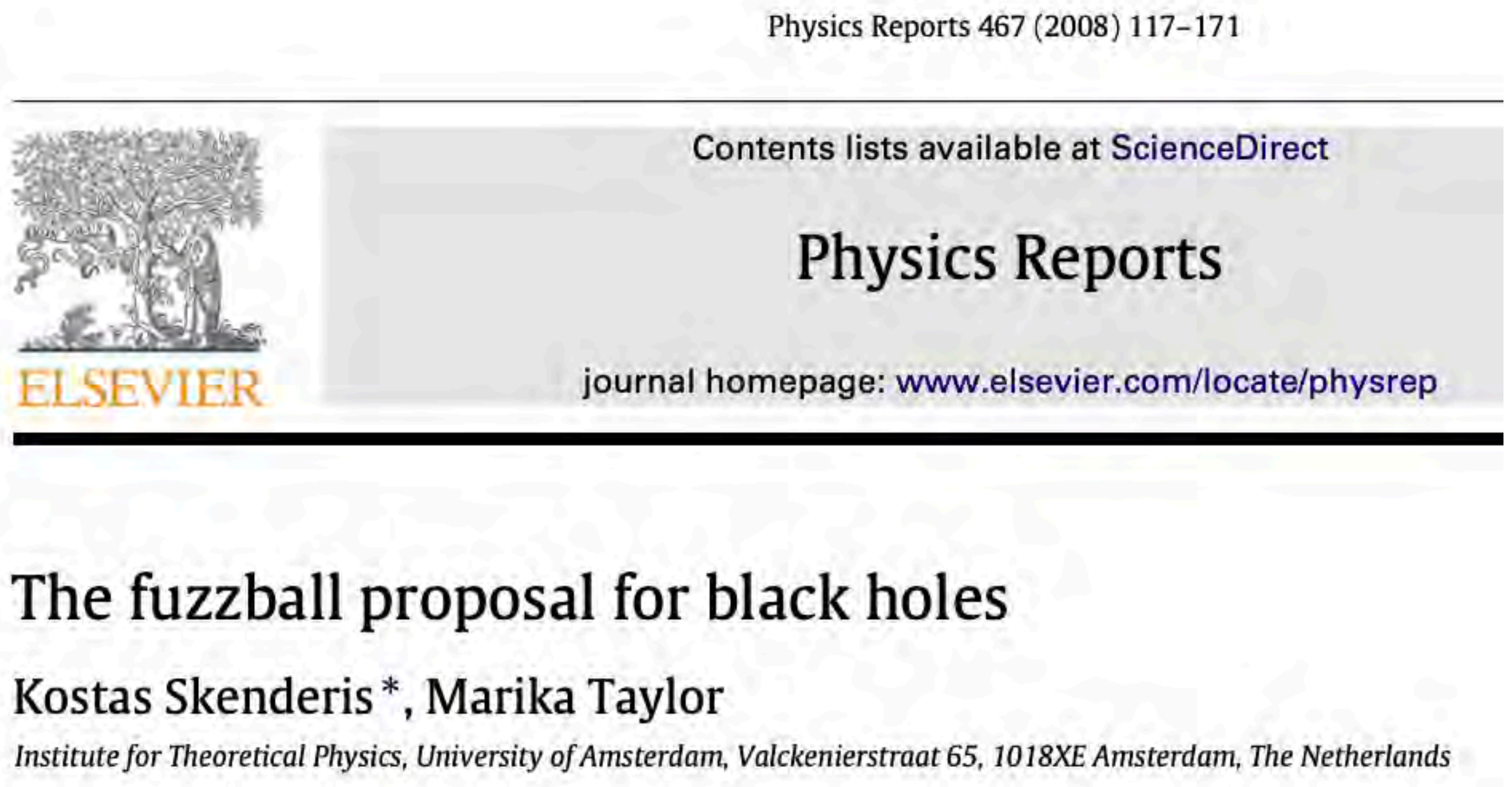
Received 3 March 2008
Published 17 June 2008
Online at stacks.iop.org/CQG/25/135005


Spontaneous emission/ Hawking radiation

Spontaneous emission/ Hawking radiation

Fuzzballs in String Theory

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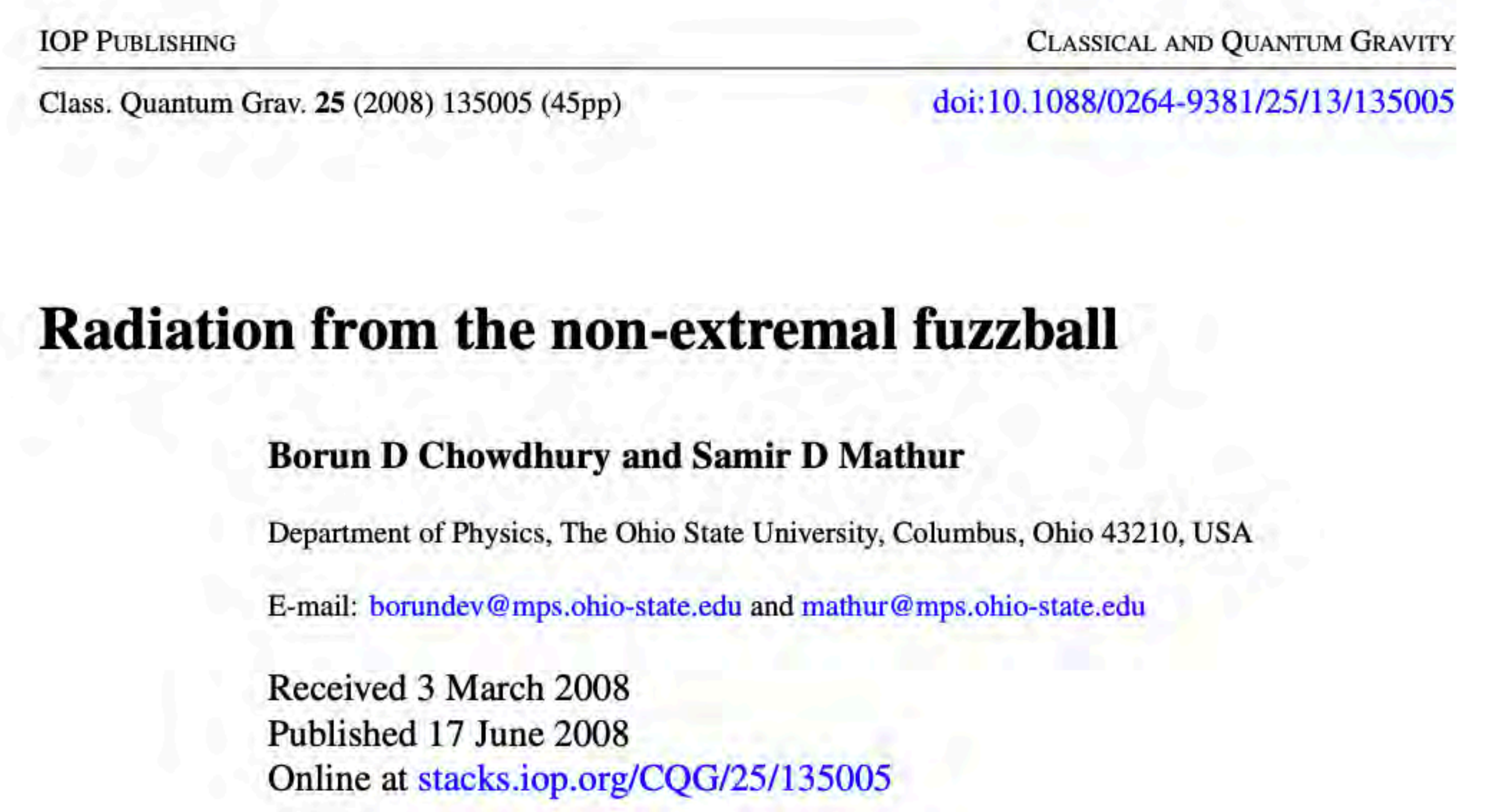
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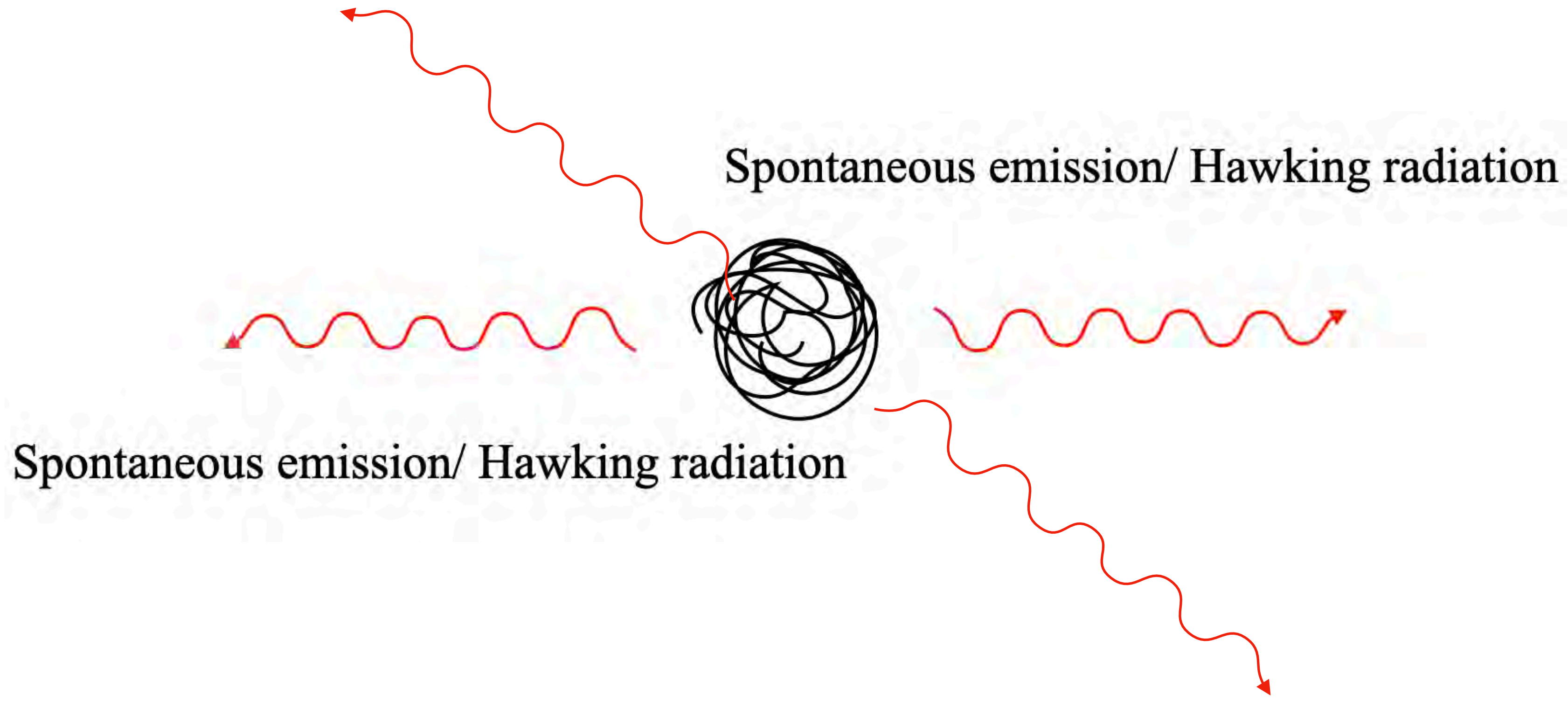


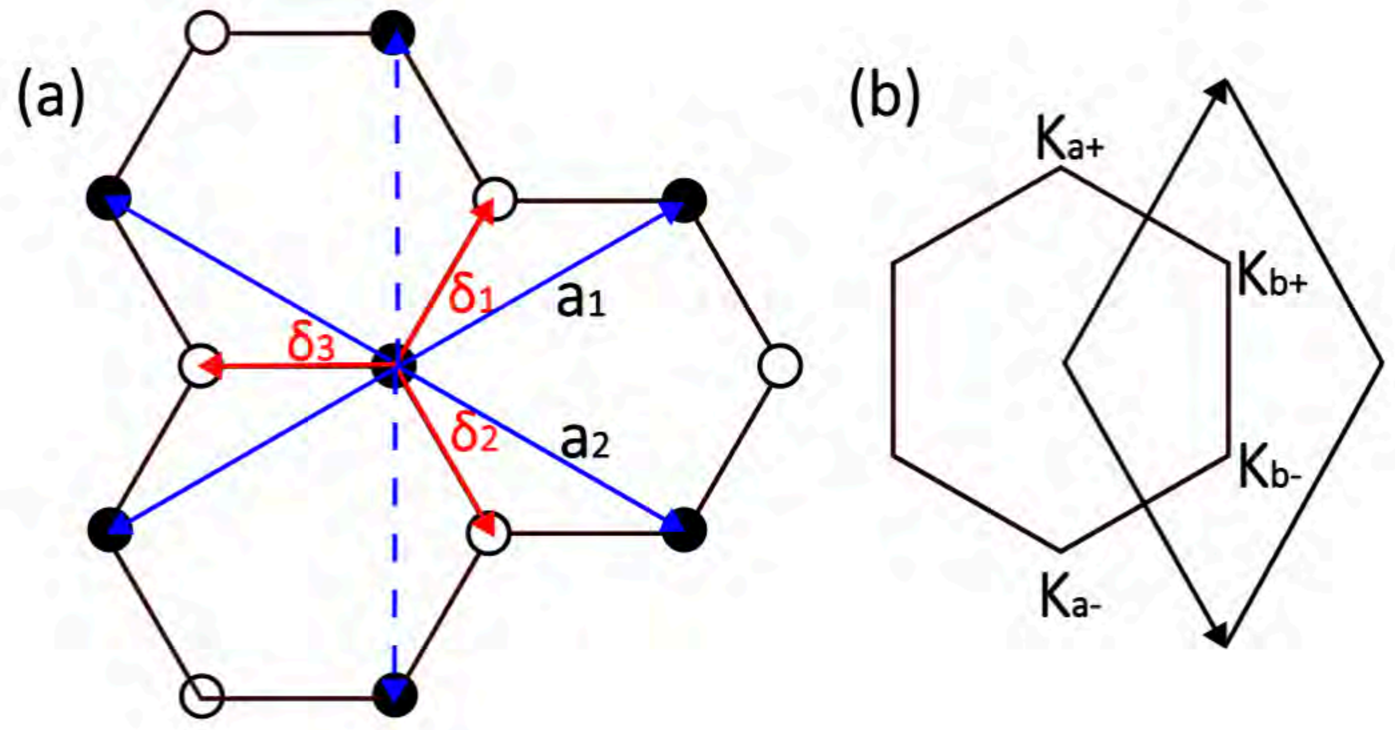
arXiv:2412.08517 [JHEP]

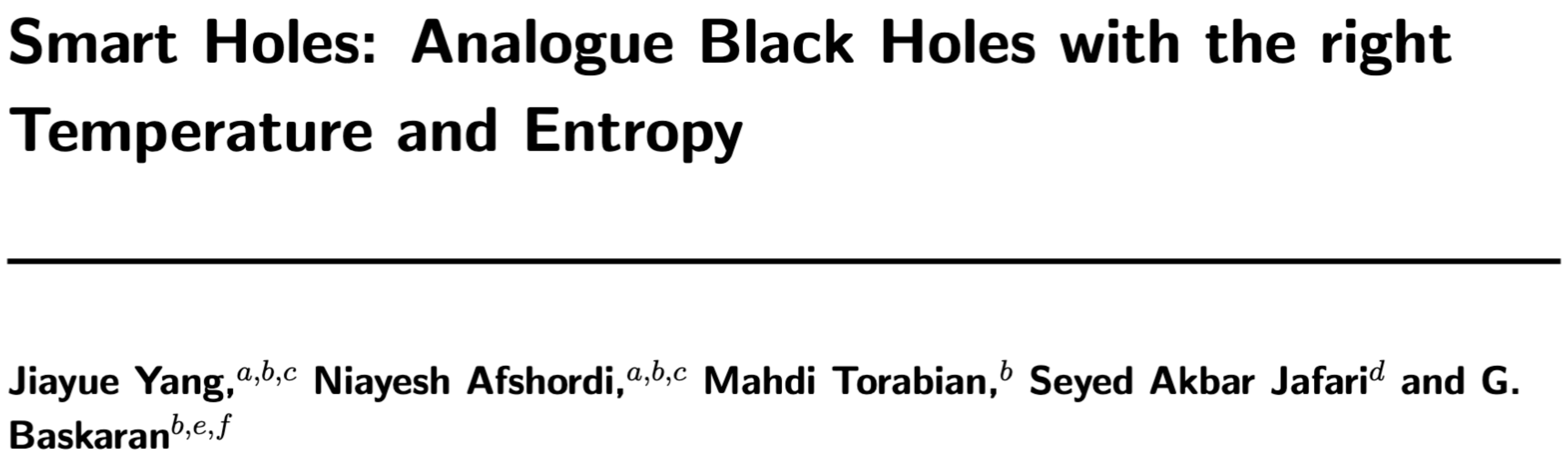
Smart Holes™

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?

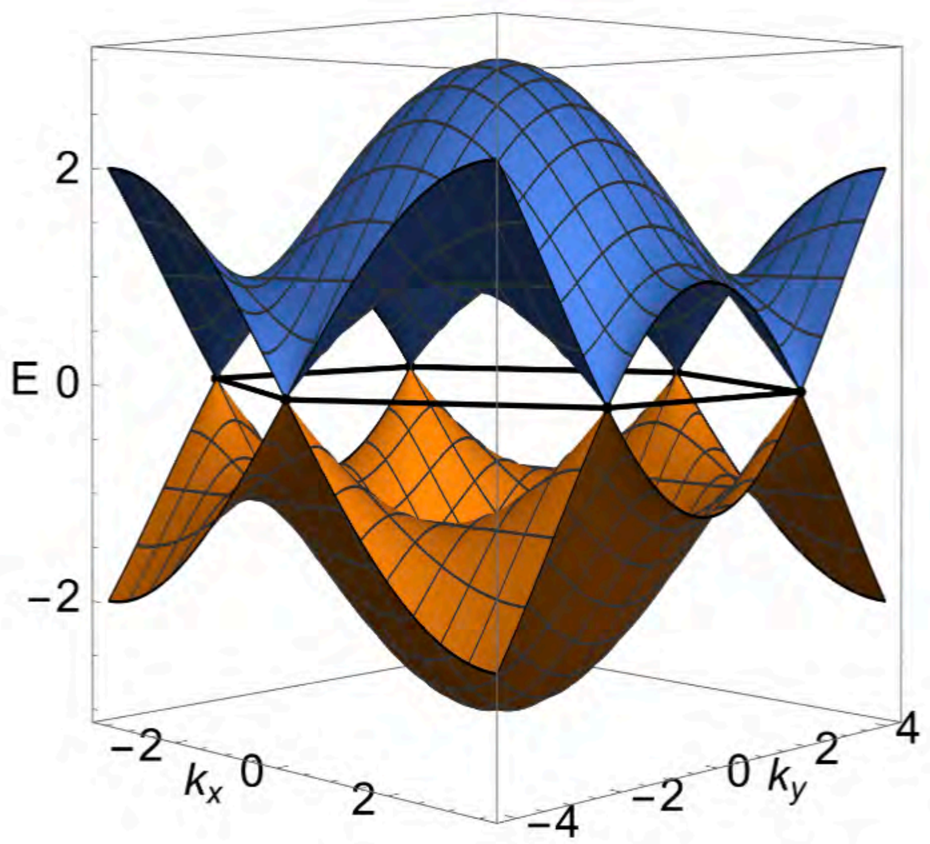




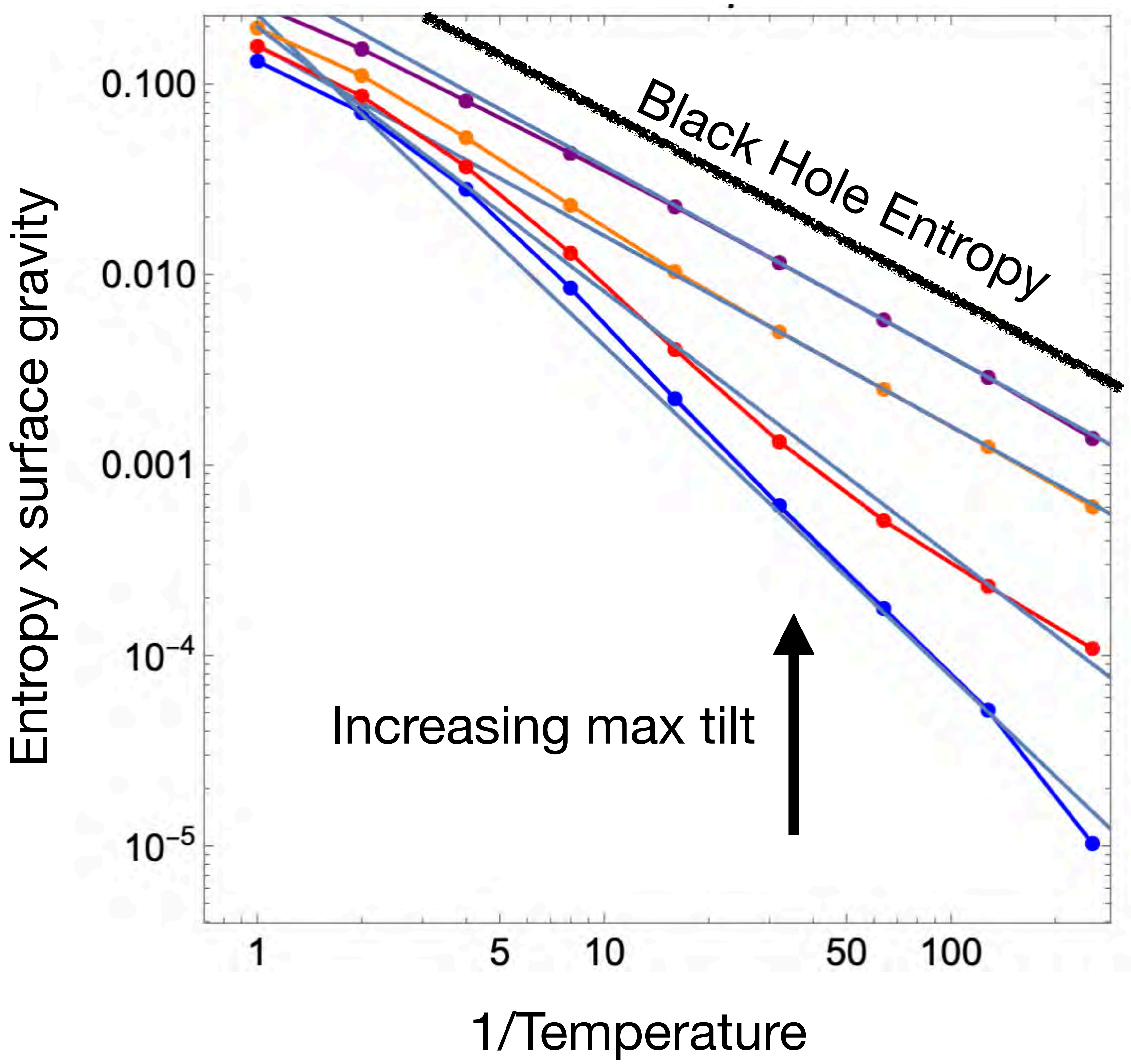
Smart Holes: Analogue Black Holes with the right Temperature and Entropy

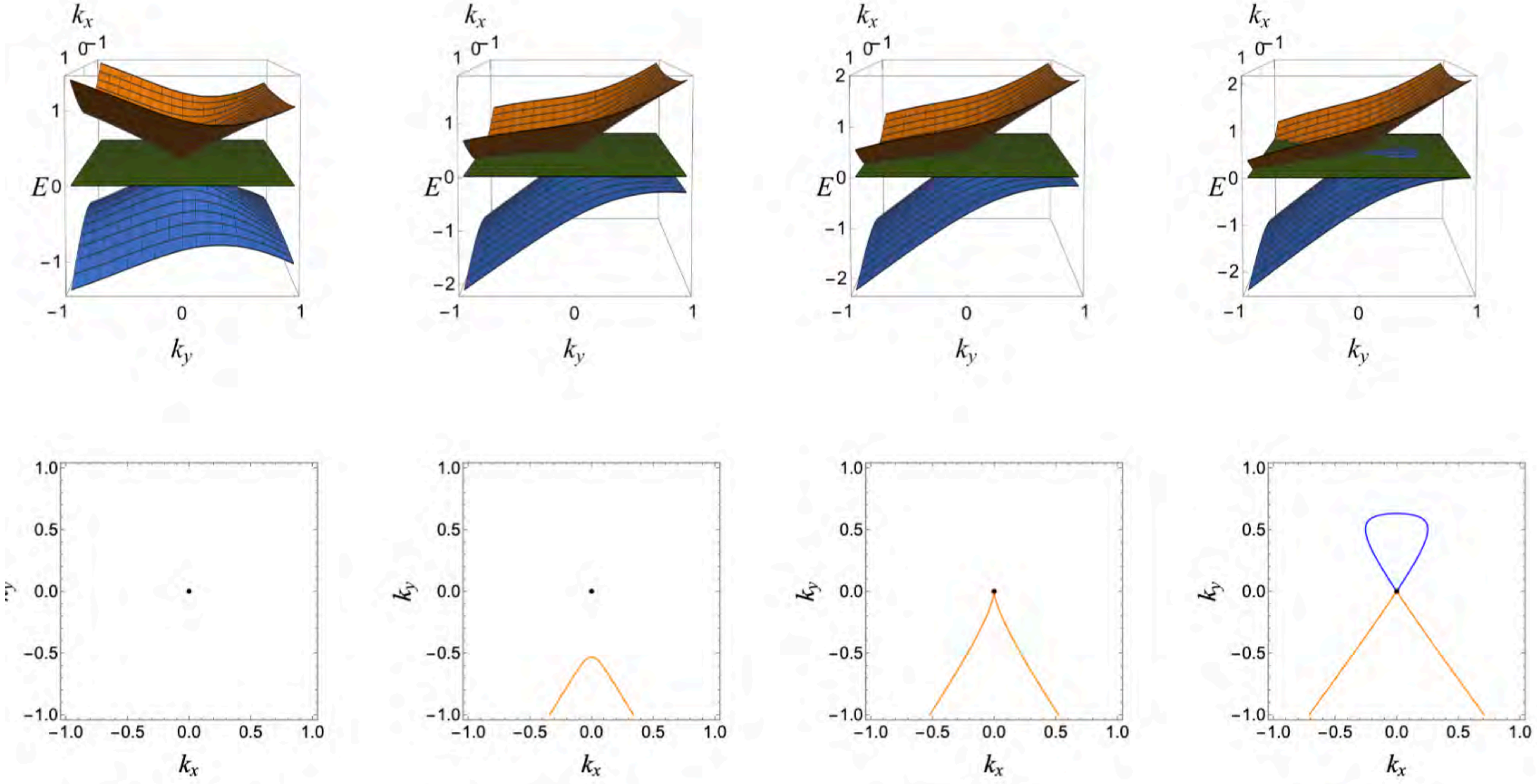
---

Jiayue Yang,[a,b,c] Niayesh Afshordi,[a,b,c] Mahdi Torabian,[b] Seyed Akbar Jafari[d] and G. Baskaran[b,e,f]



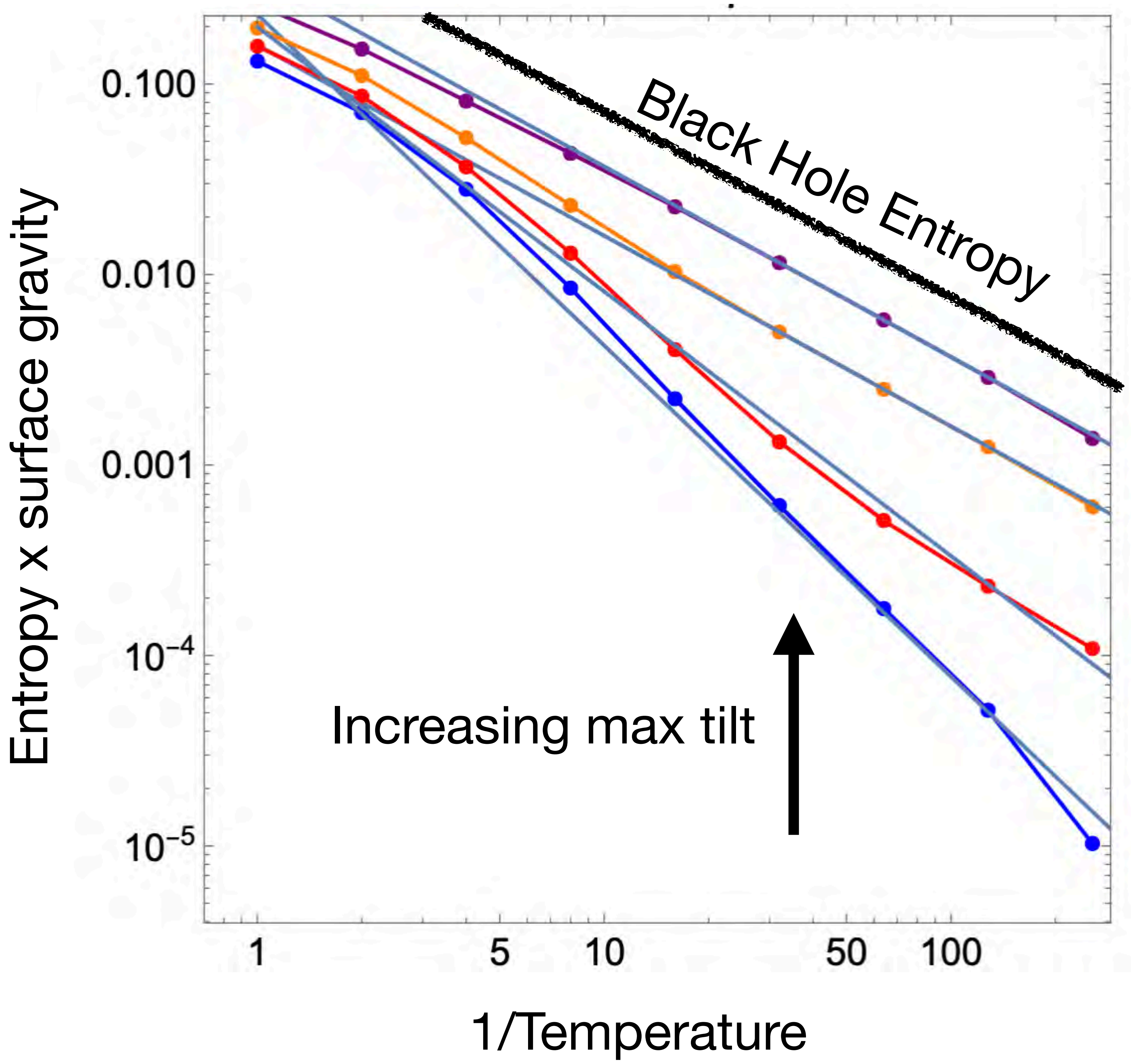
Tilting the Dirac cone in honeycomb lattice

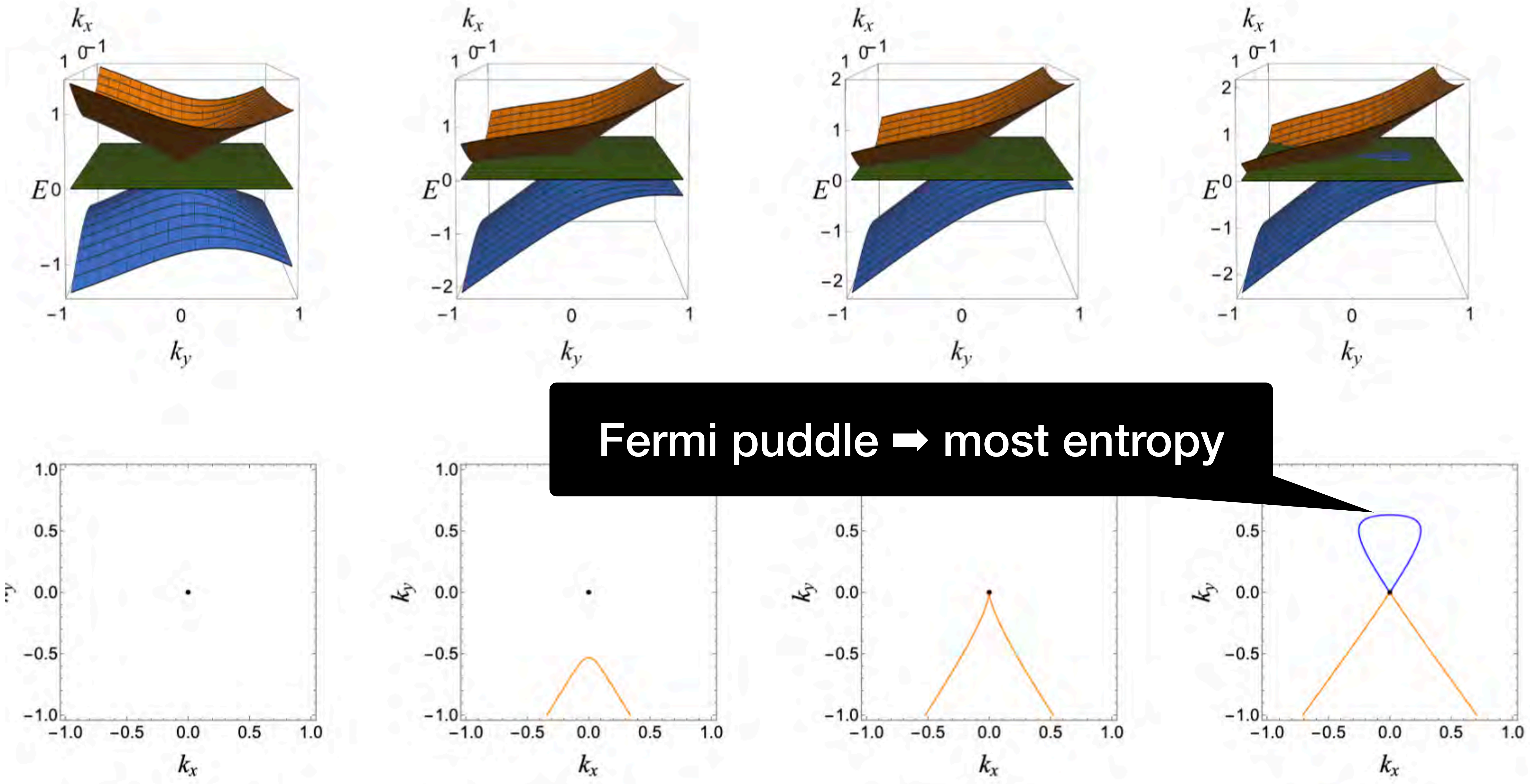




(a) Tilt $\zeta = 0$ (b) Tilt $\zeta = 6/7$ (c) Tilt $\zeta = 1$ (d) Tilt $\zeta = 6/5$

Tilting the Dirac cone in honeycomb lattice

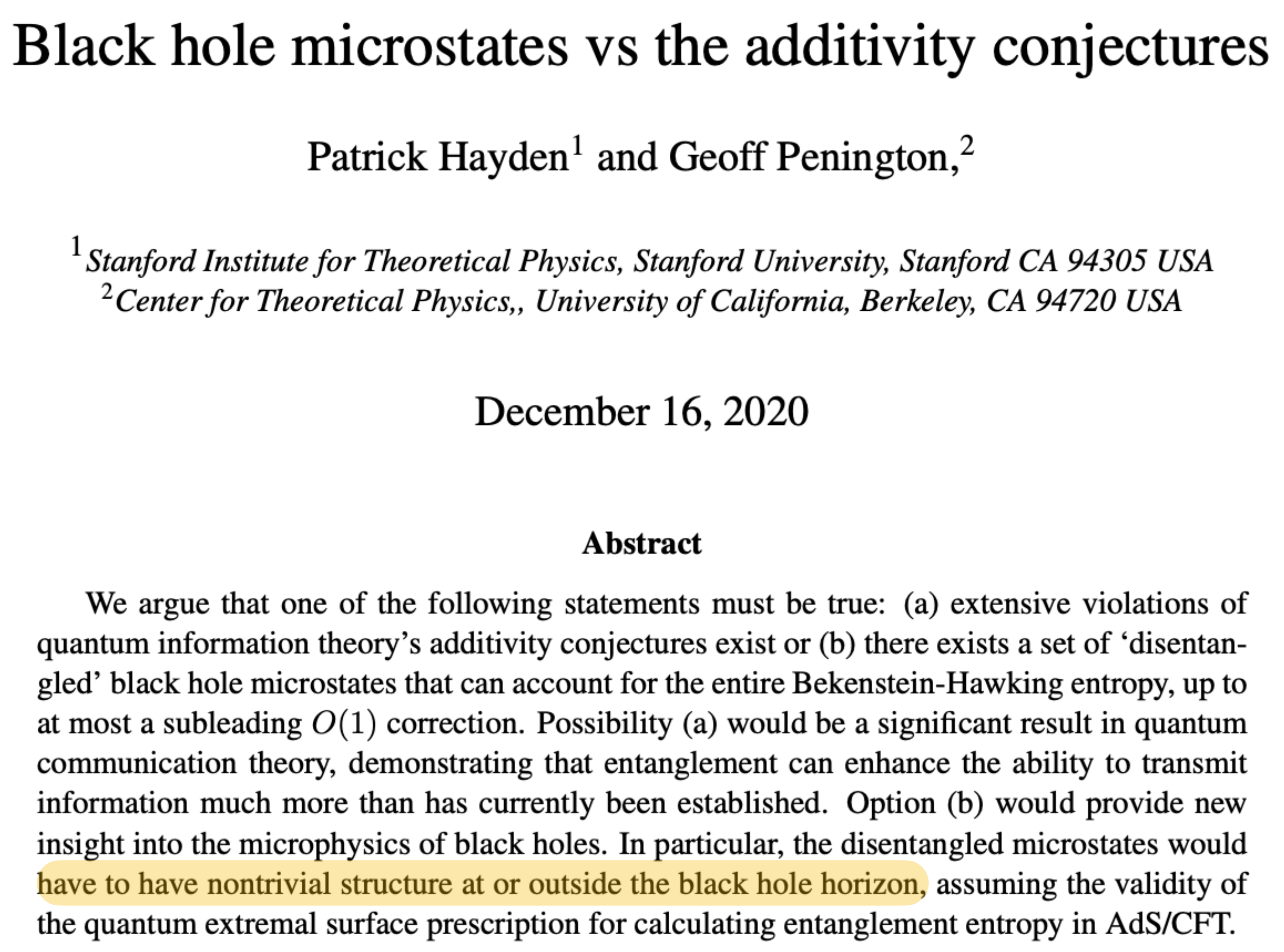




Fermi puddle ➡ most entropy

(a) Tilt $\zeta = 0$ (b) Tilt $\zeta = 6/7$ (c) Tilt $\zeta = 1$ (d) Tilt $\zeta = 6/5$

CP-symmetry (RP3 geon)



Black hole microstates vs the additivity conjectures

Patrick Hayden[1] and Geoff Penington,[2]

[1] *Stanford Institute for Theoretical Physics, Stanford University, Stanford CA 94305 USA*
[2] *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.

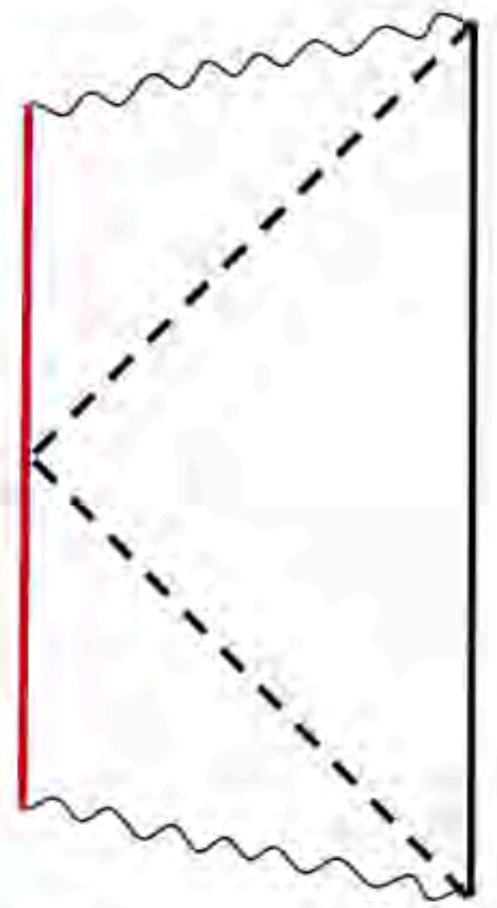


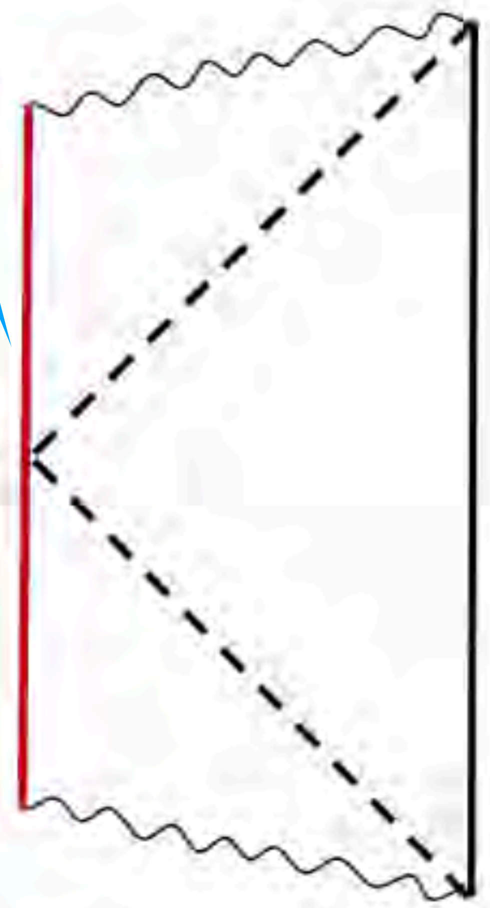
Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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

CP-symmetry (RP³ geon)

Z_2 identification → Boltzmann reflection



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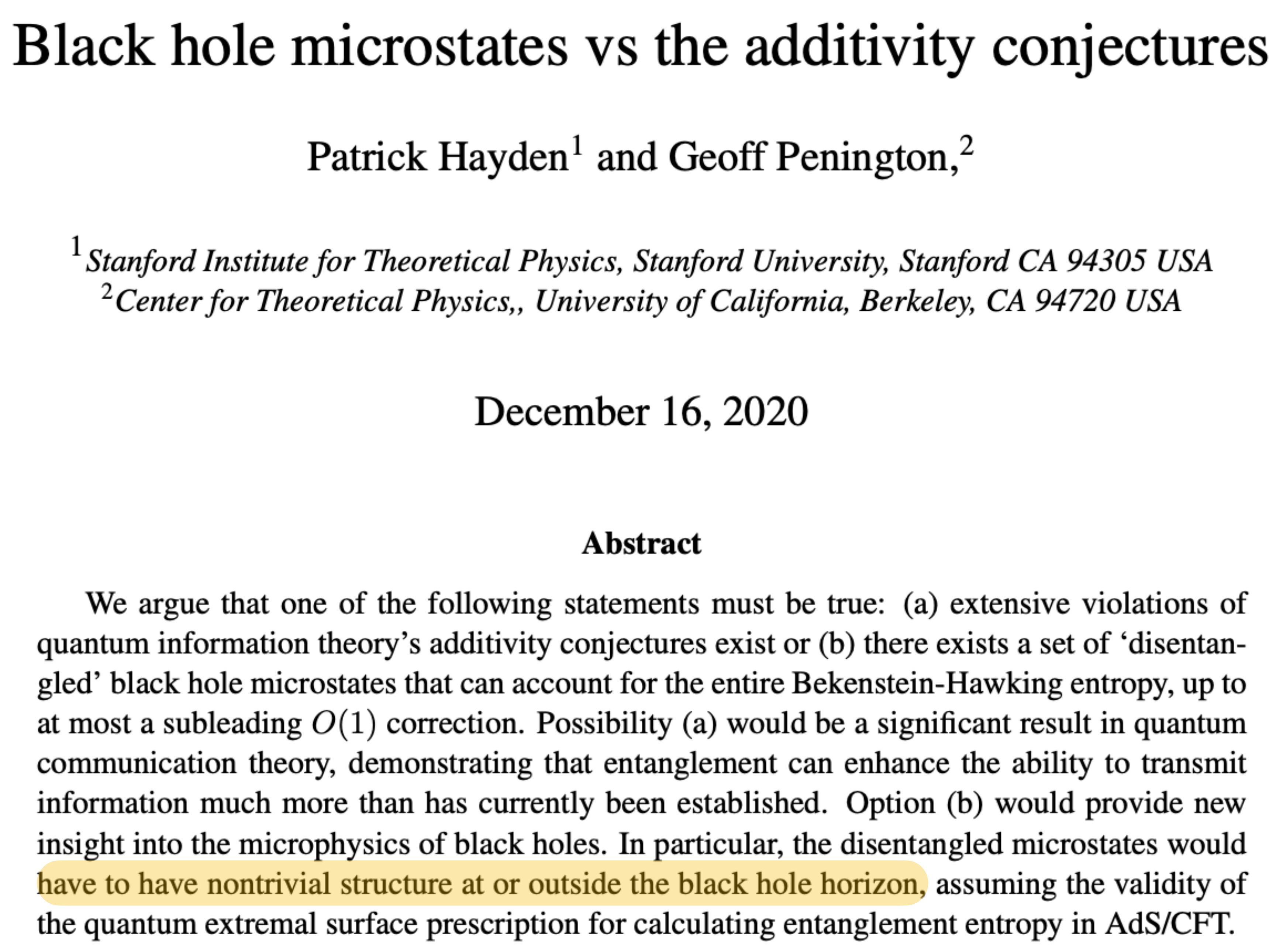

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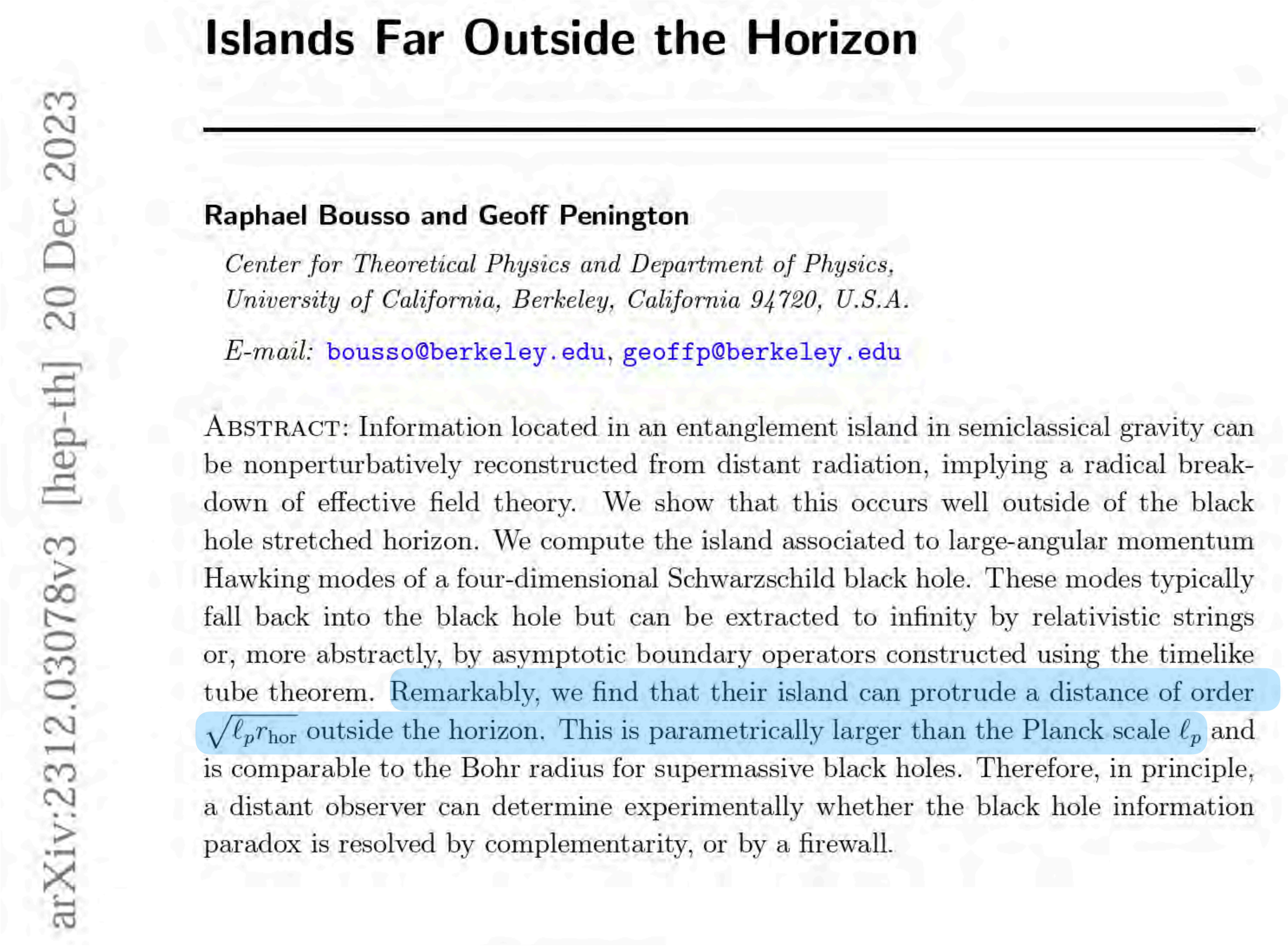


Islands Far Outside the Horizon

Raphael Bousso and Geoff Penington

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

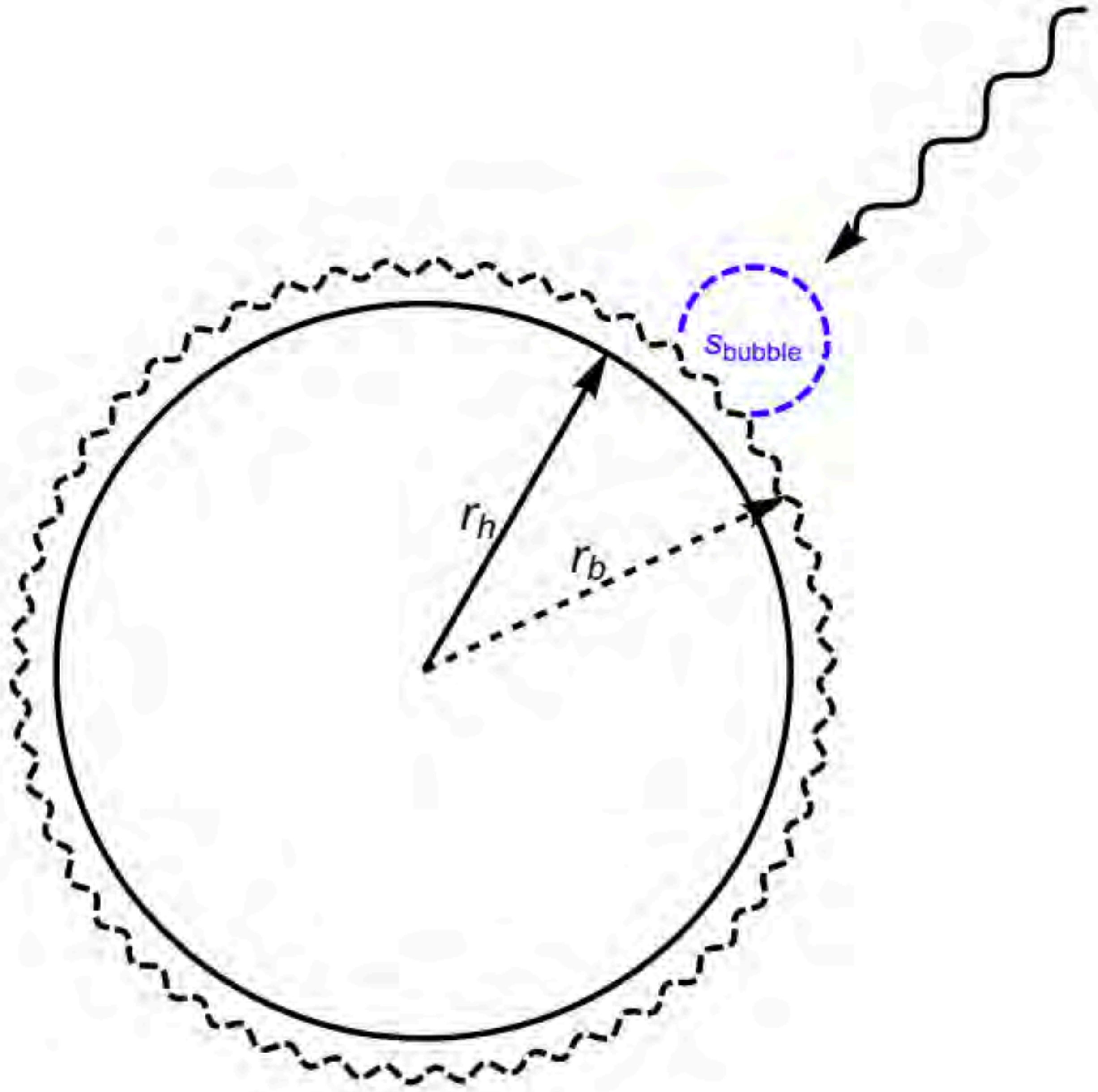
E-mail: bousso@berkeley.edu, geoffp@berkeley.edu

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 $\sqrt{\ell_p r_{\rm hor}}$ outside the horizon. This is parametrically larger than the Planck scale ℓ_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)*

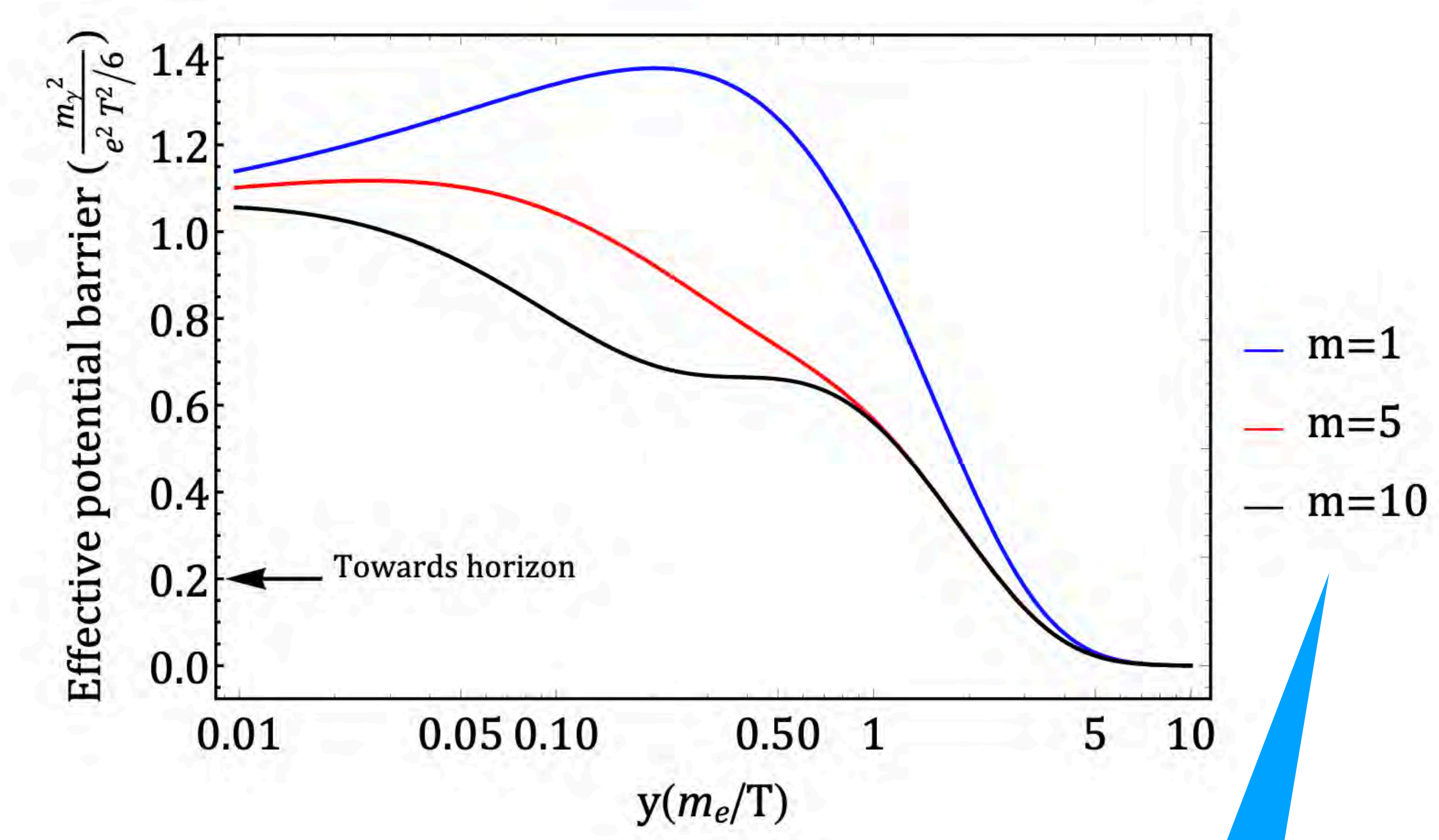
- Reflection off virtual electron-positron pairs near horizon → Boltzmann Albedo for photons

- No quantum gravity needed!



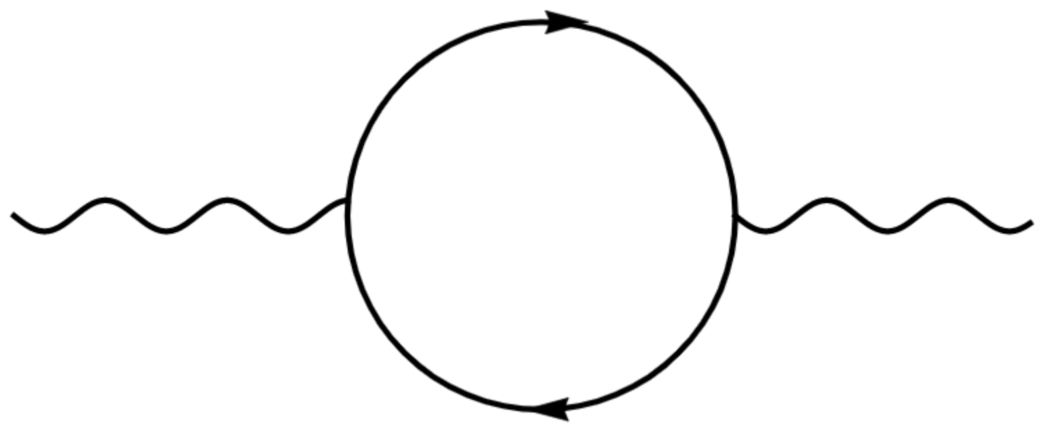
Two independent derivations

- Photon mass acquired through Hawking Plasma



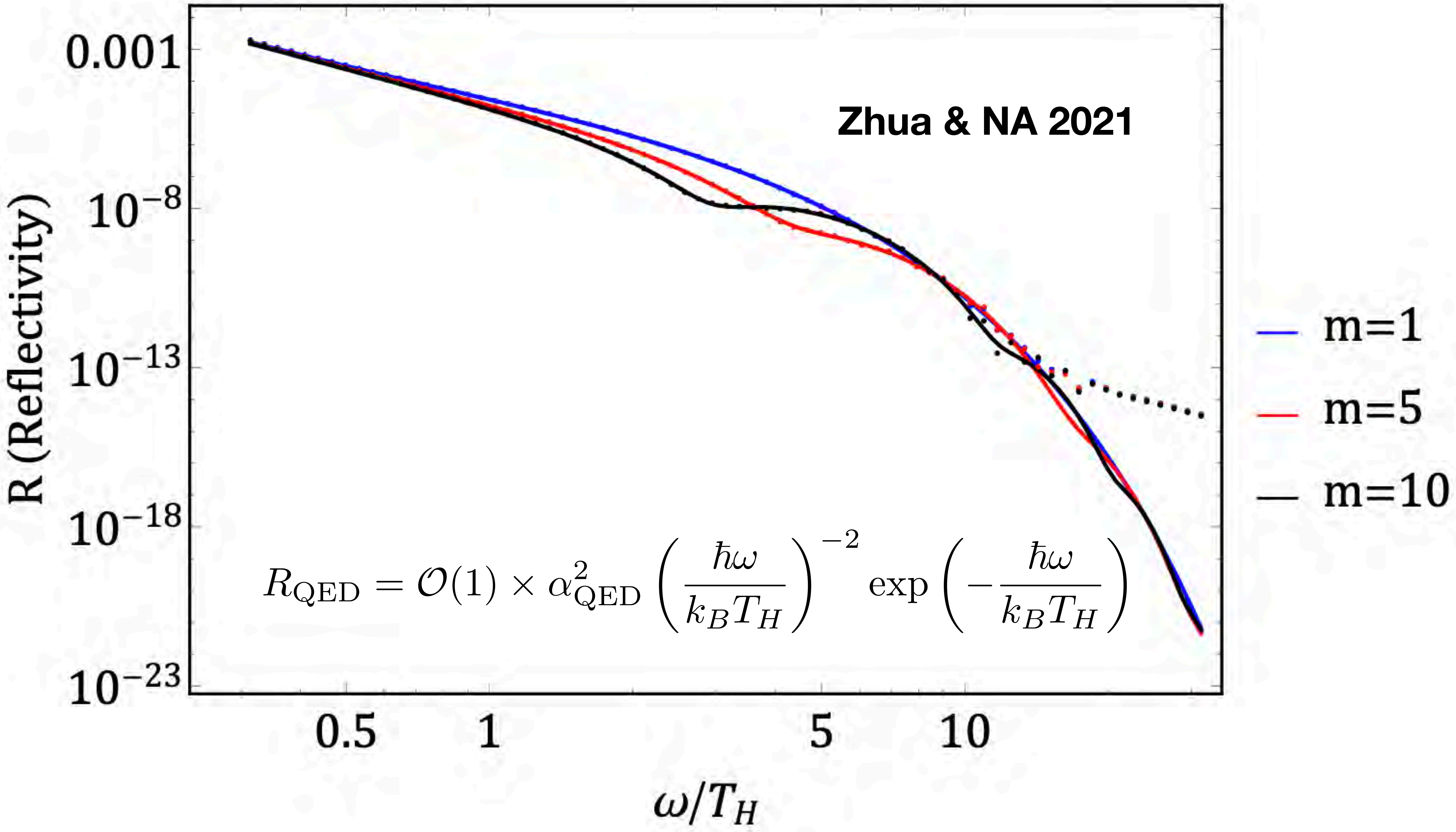
different interpolations

- Projecting photon 1-loop propagator from Minkowski to Rindler



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

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



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

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