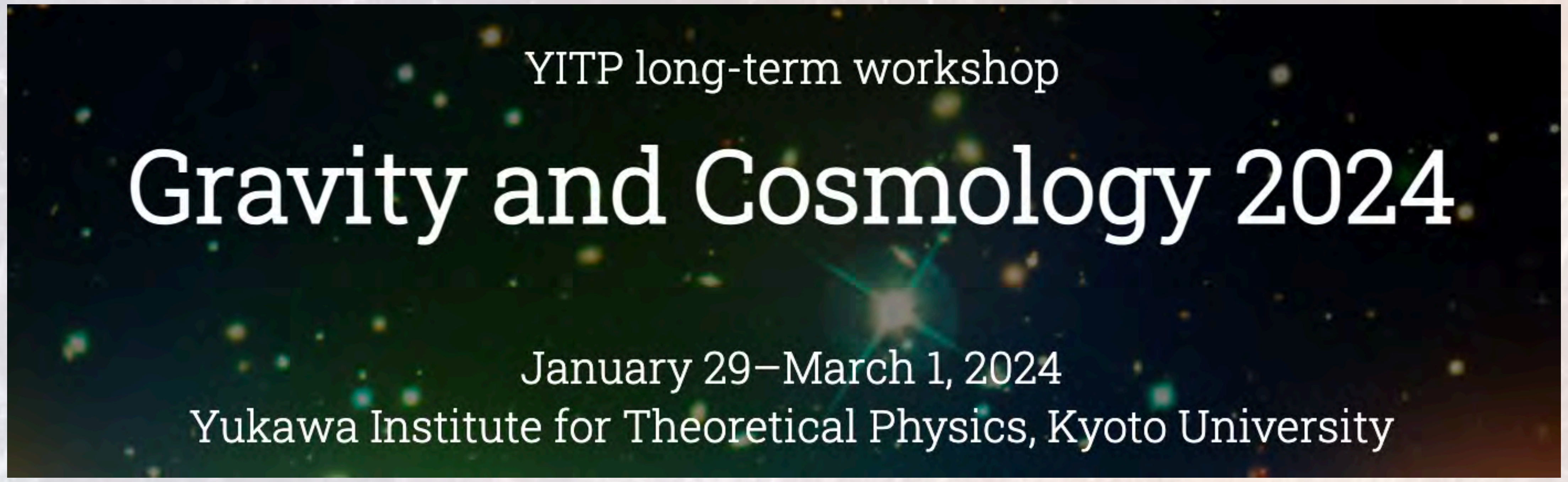


Precision Quantum Cosmology

Past, Present, and Future

Niayesh Afshordi

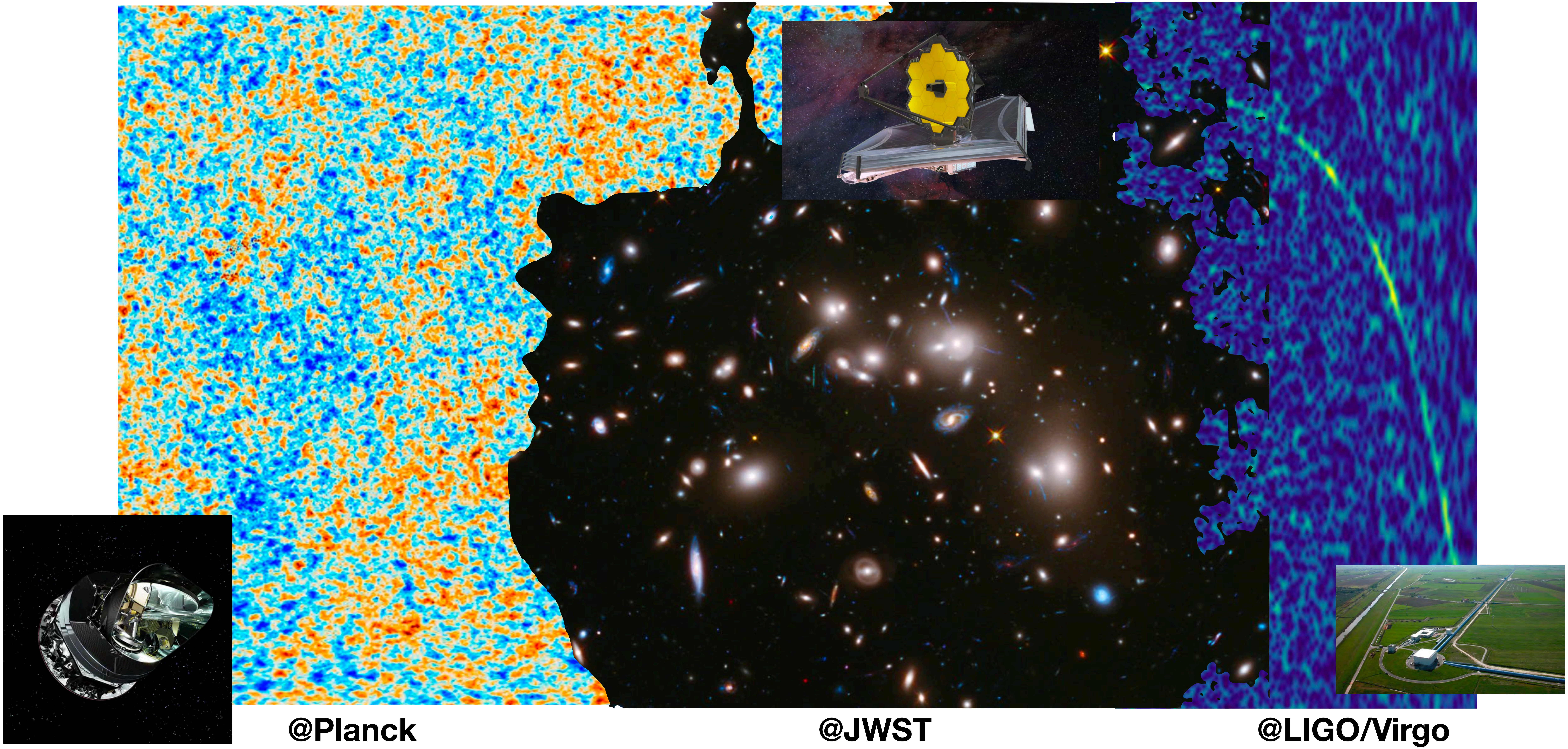
UNIVERSITY OF WATERLOO

WATERLOO CENTRE FOR ASTROPHYSICS

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

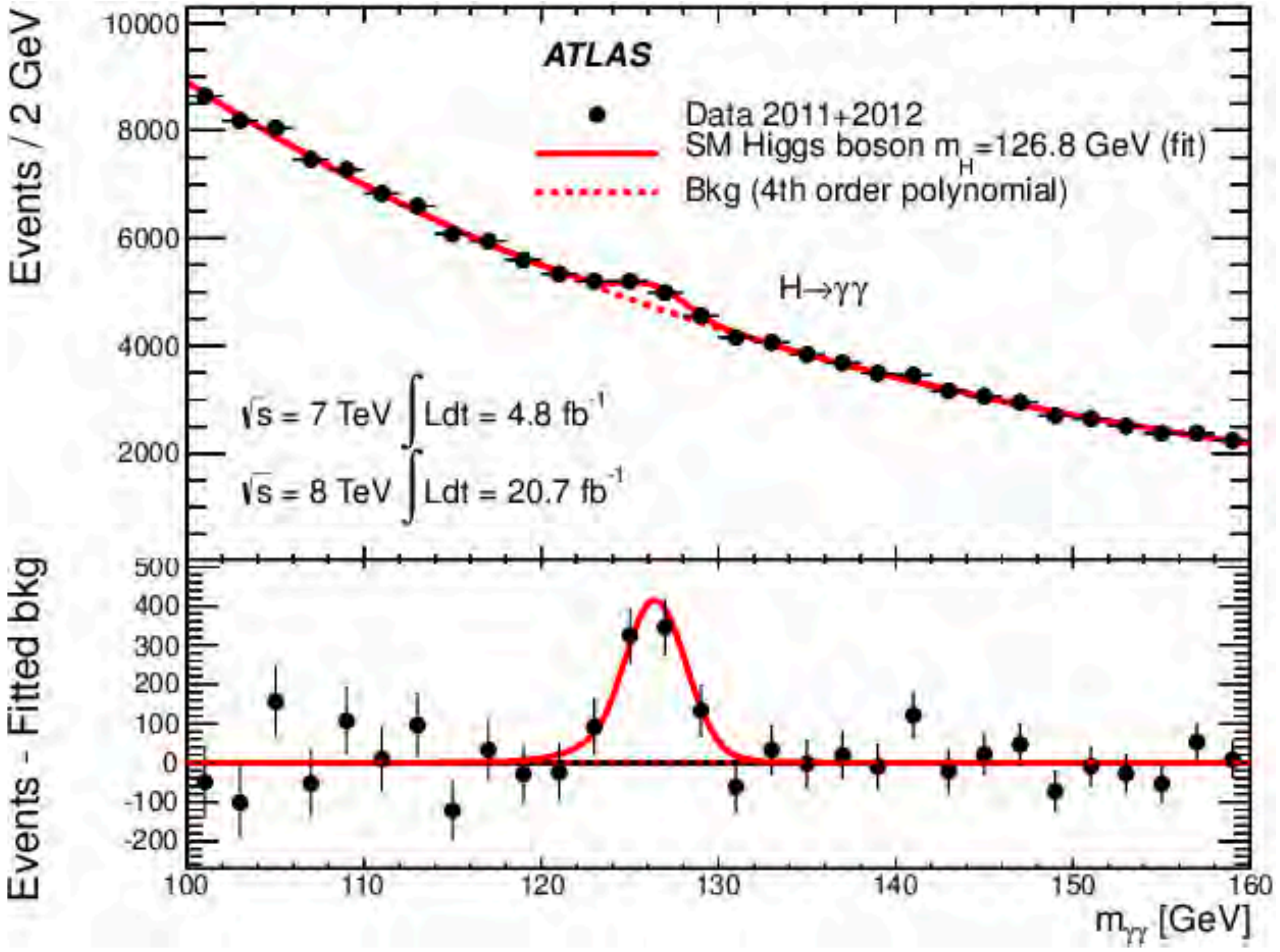

PAST

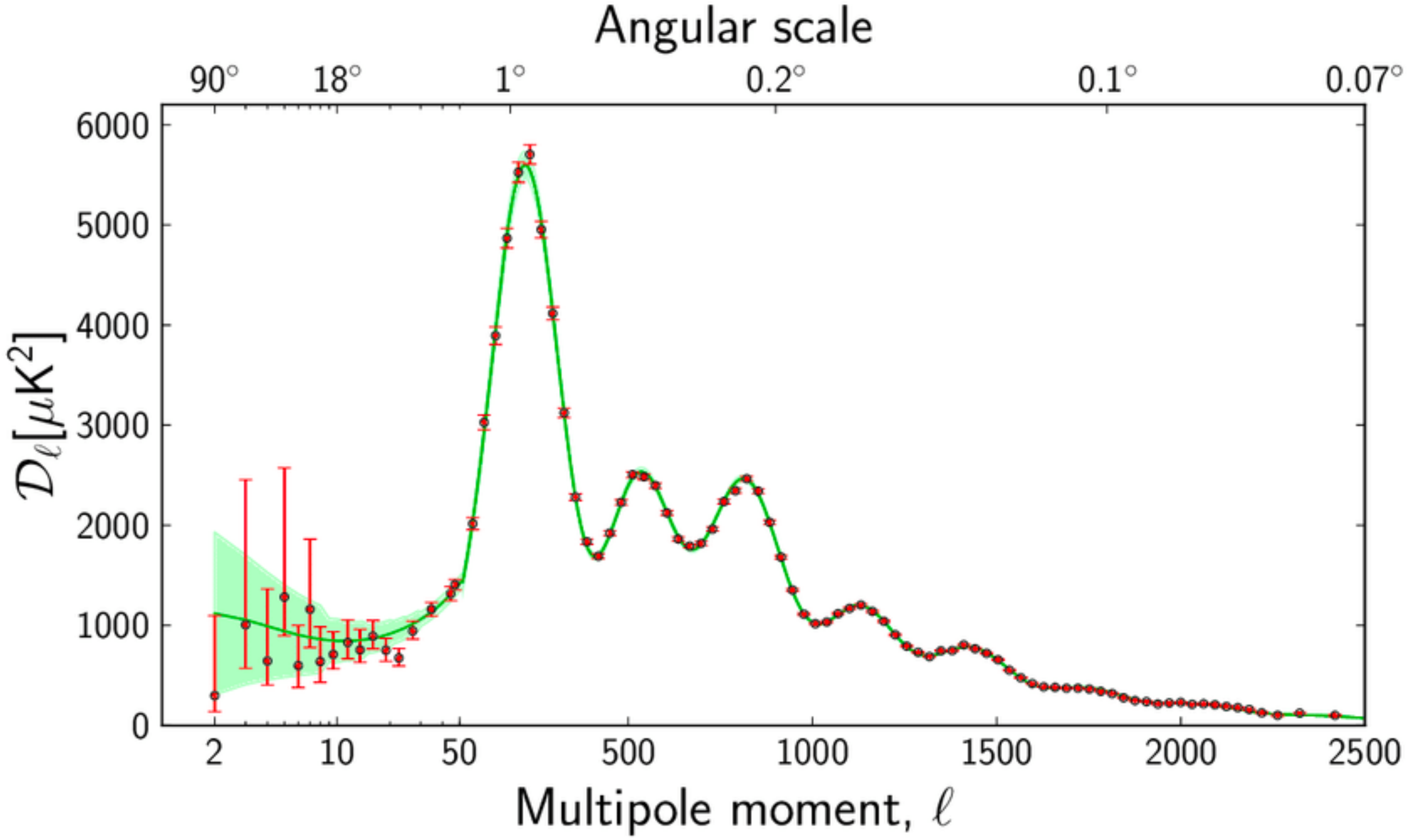
Our cosmic pictures, more beautiful than ever

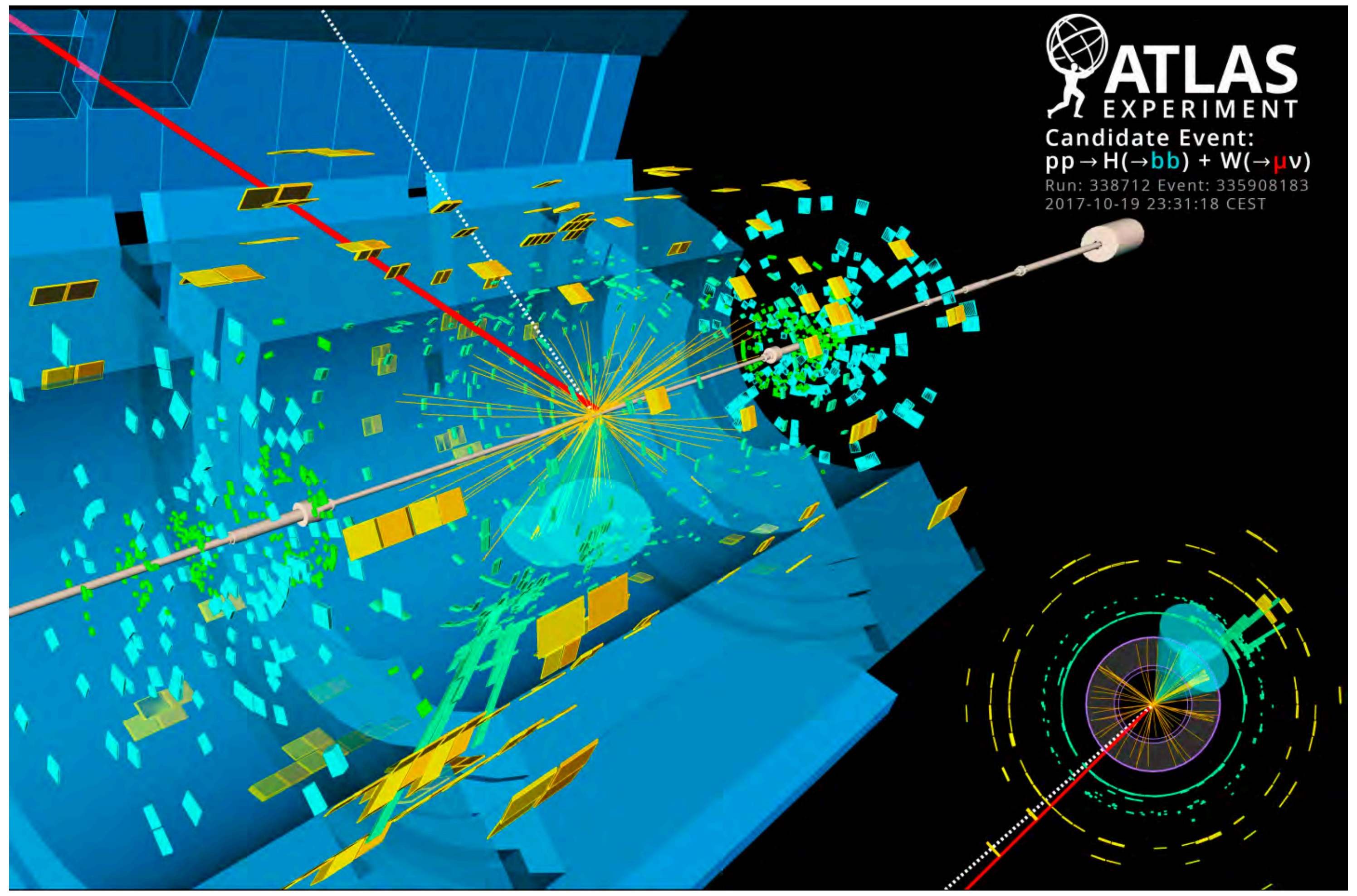


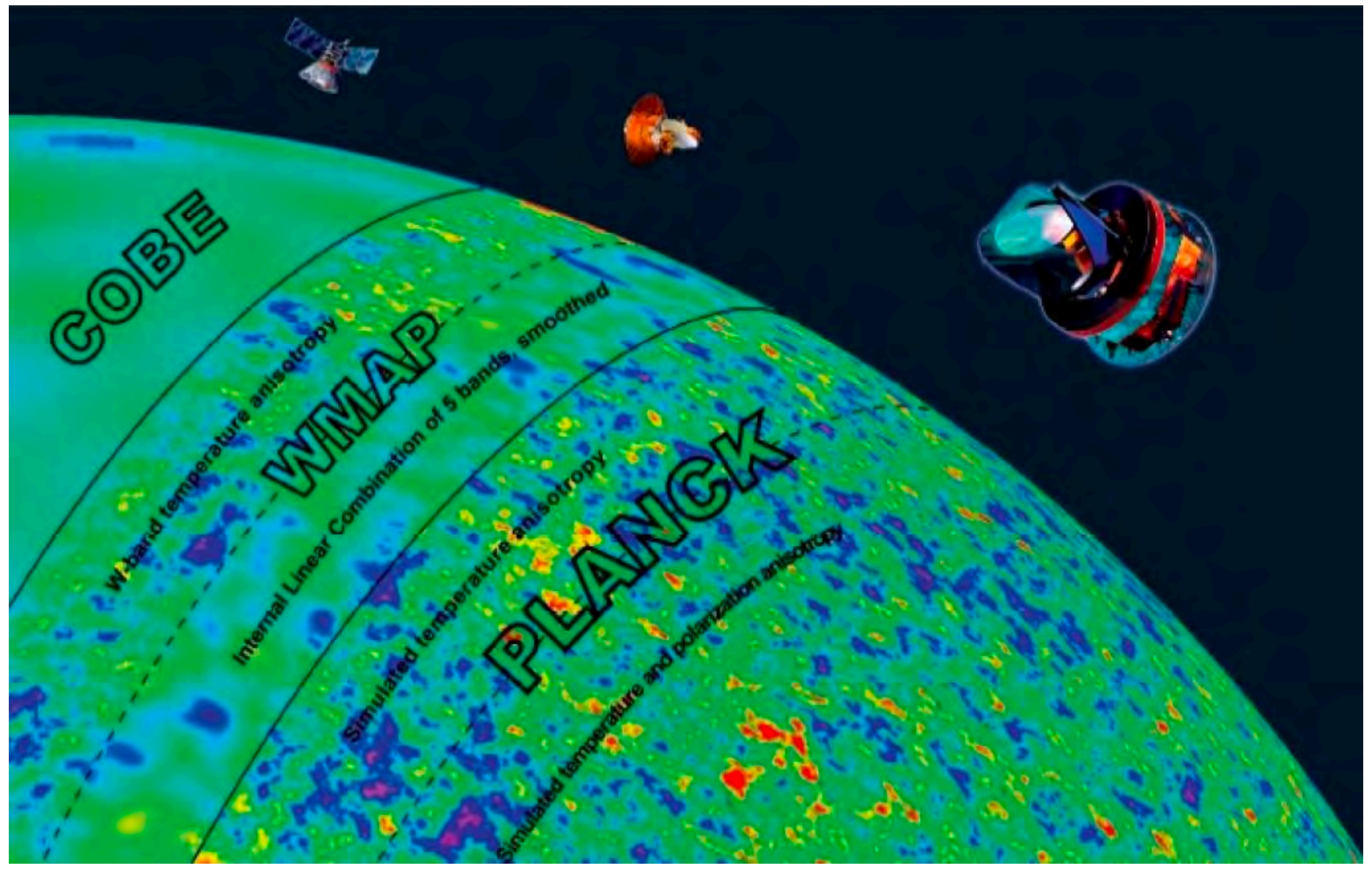
@Planck @JWST @LIGO/Virgo

and most complete, from smallest to largest scales



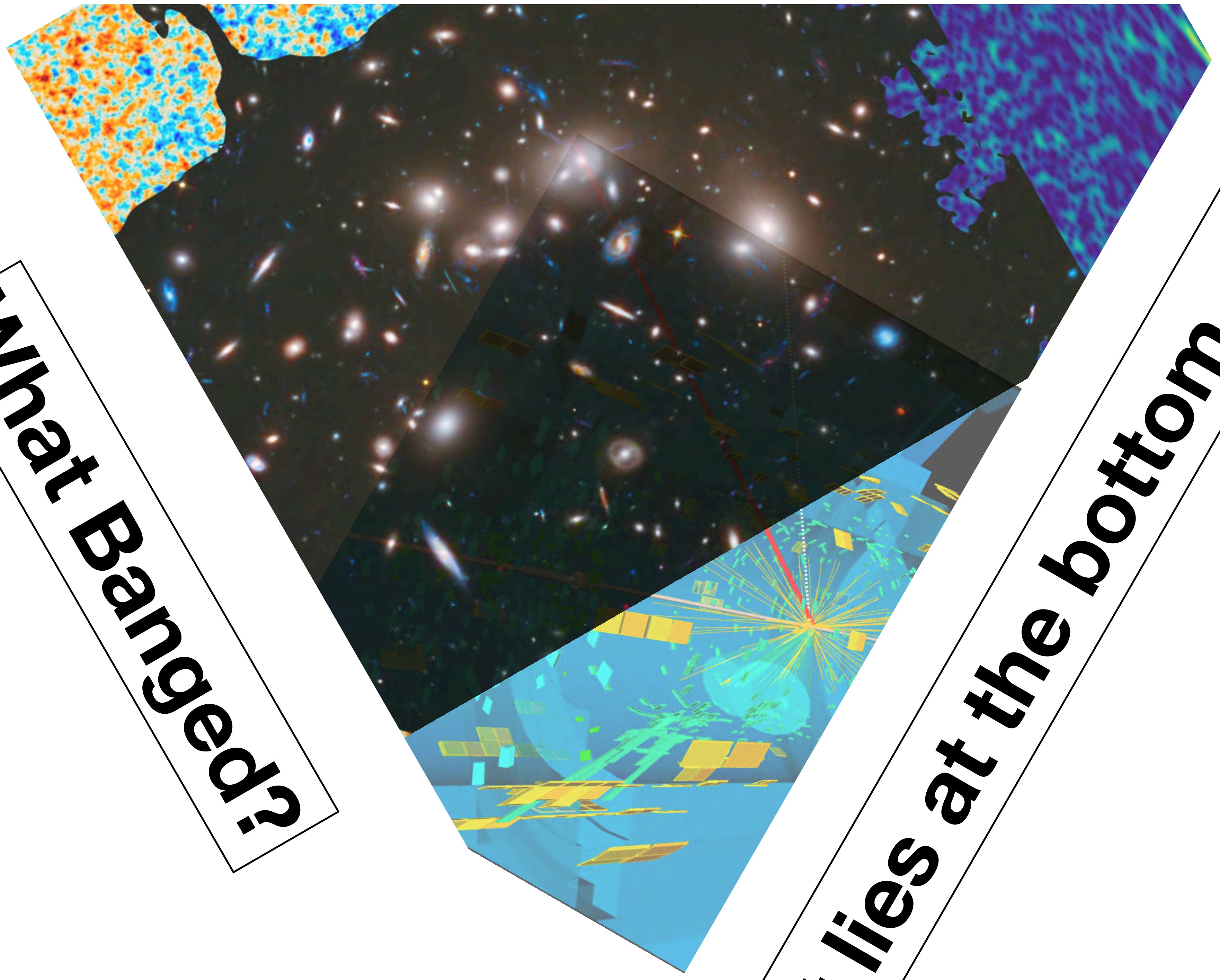






Yet, the Big Picture is surrounded by mysteries

Nature of Quantum Vacuum?

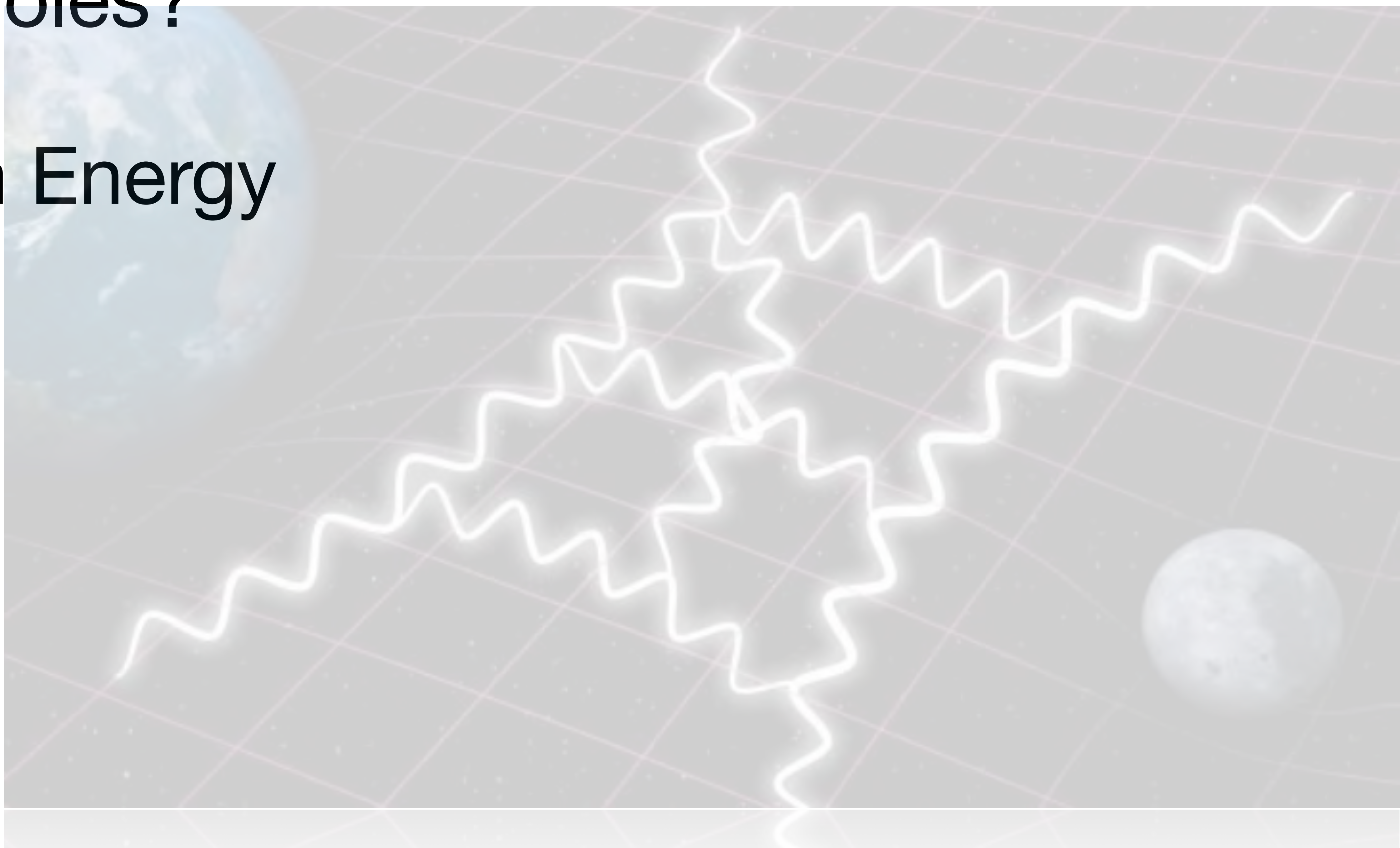


What Banged?

What lies at the bottom of Black Holes?

Chasms amongst our best theories and observations

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



Quantum Gravity Zoo

Too much of a good thing?

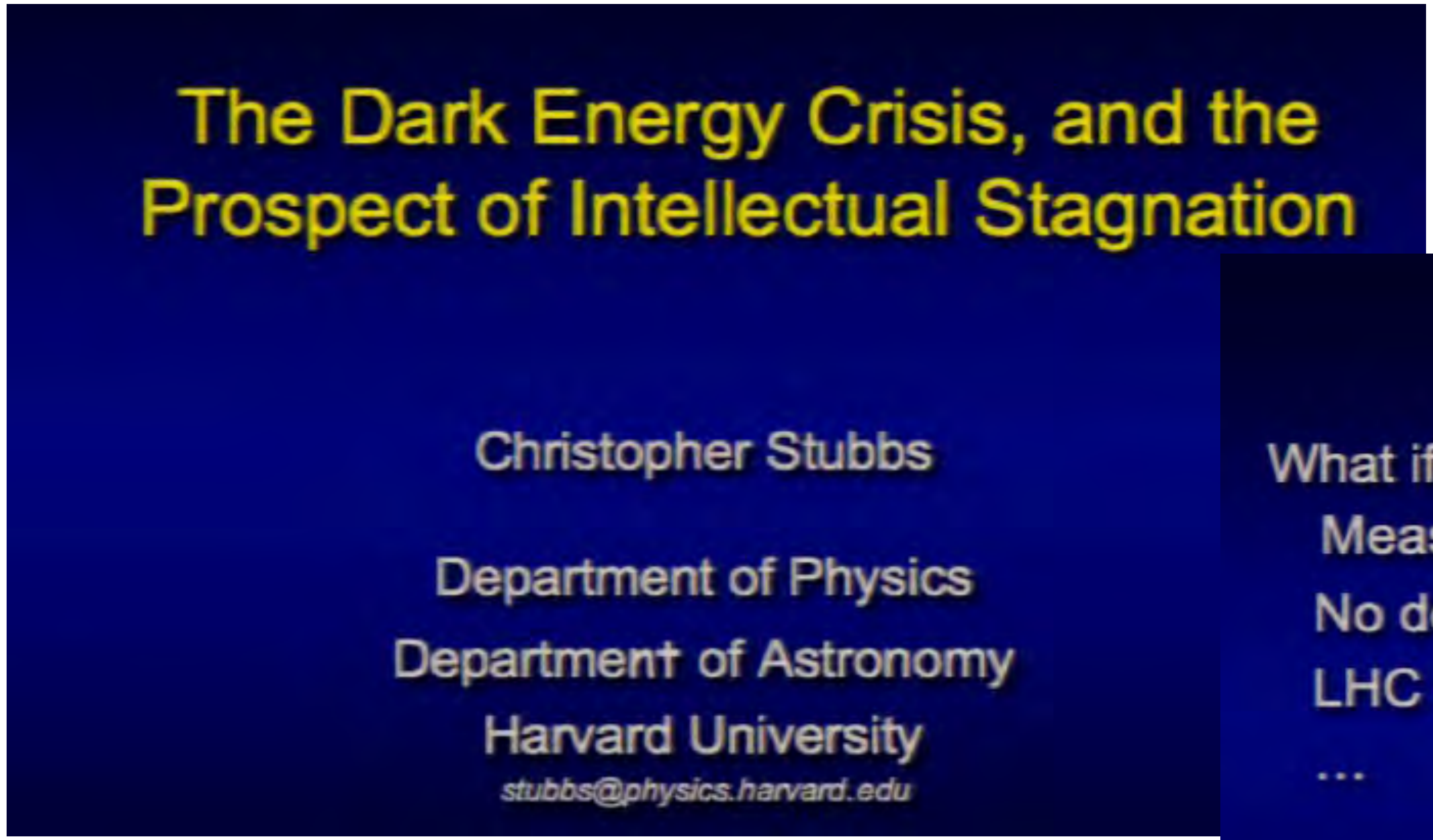
- String Theory and Holography
- Loop Quantum Gravity and Spin Foams
- Asymptotic Safety
- Causal Dynamical Triangulation
- Causal Sets
- Horava-Lifshitz gravity
- …

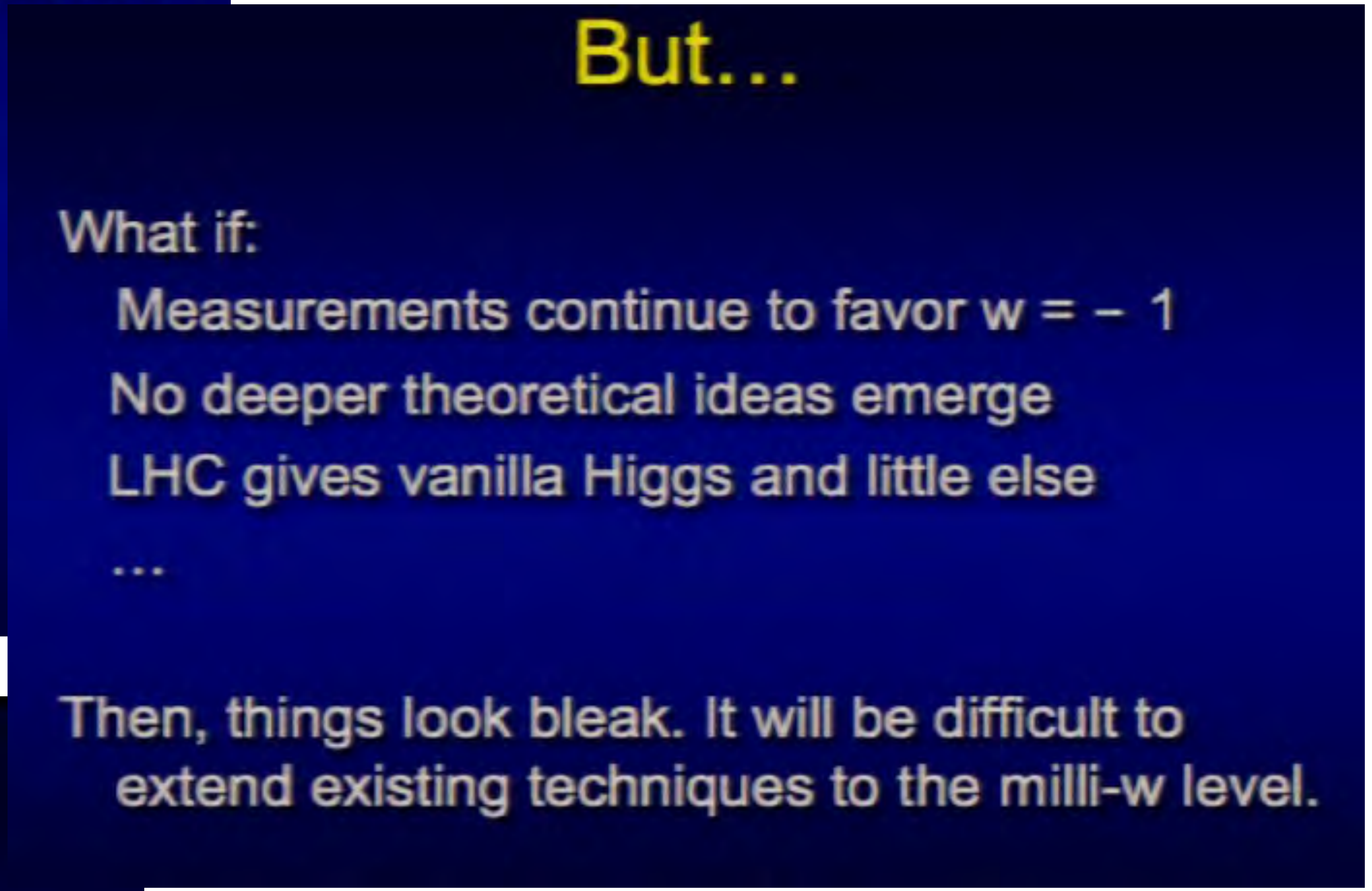
Olena Shmahalo/Quanta Magazine

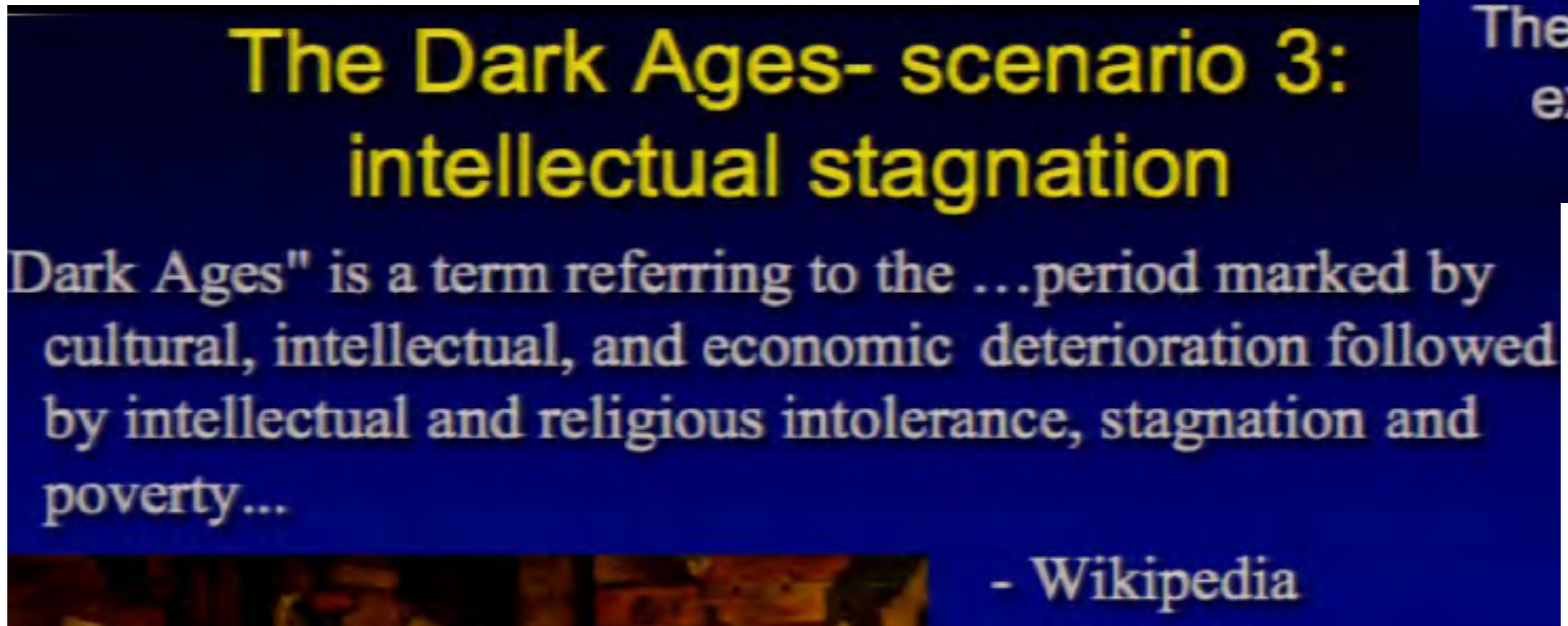
Crisis of Falsifiability

- 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?***

Intellectual Stagnation?



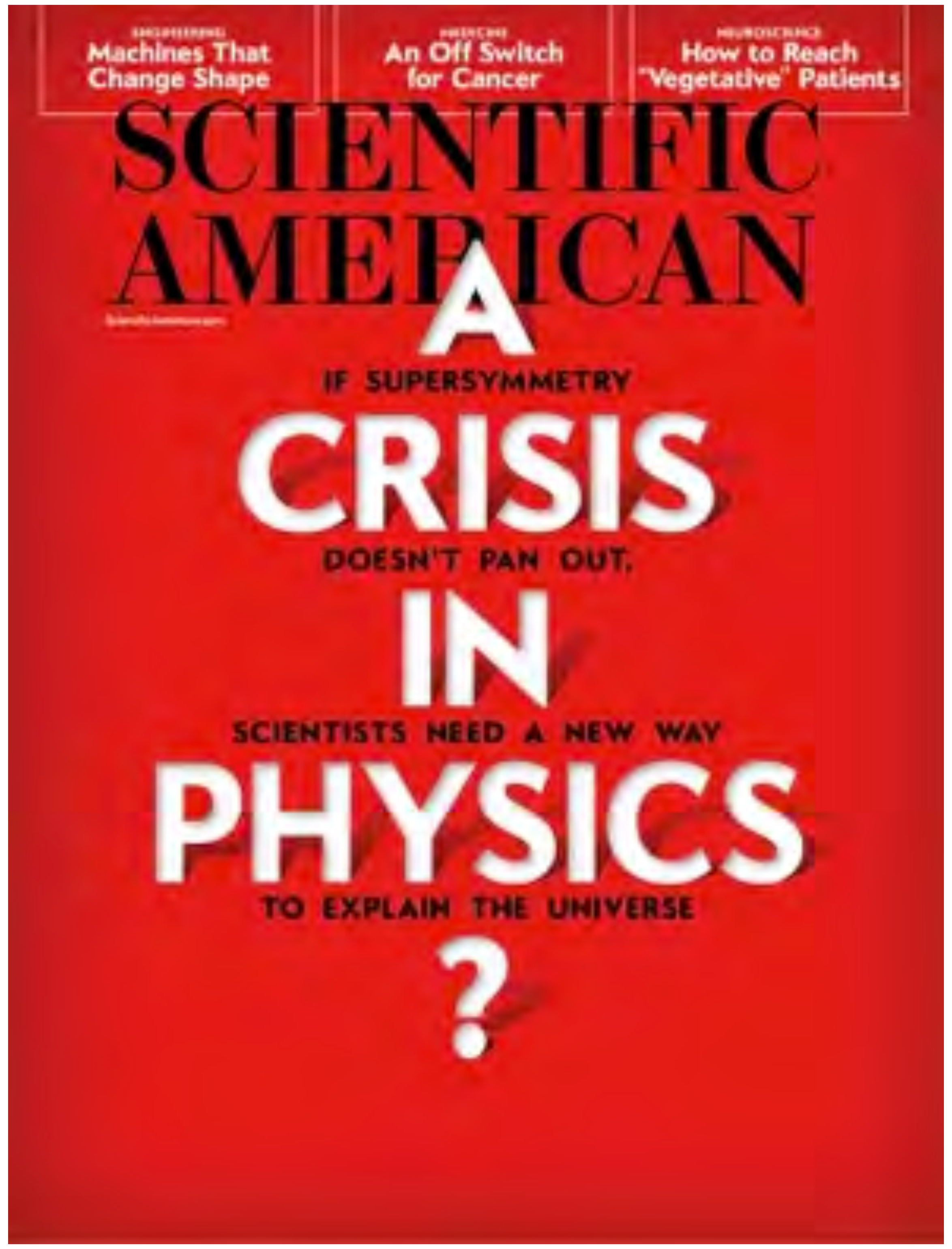


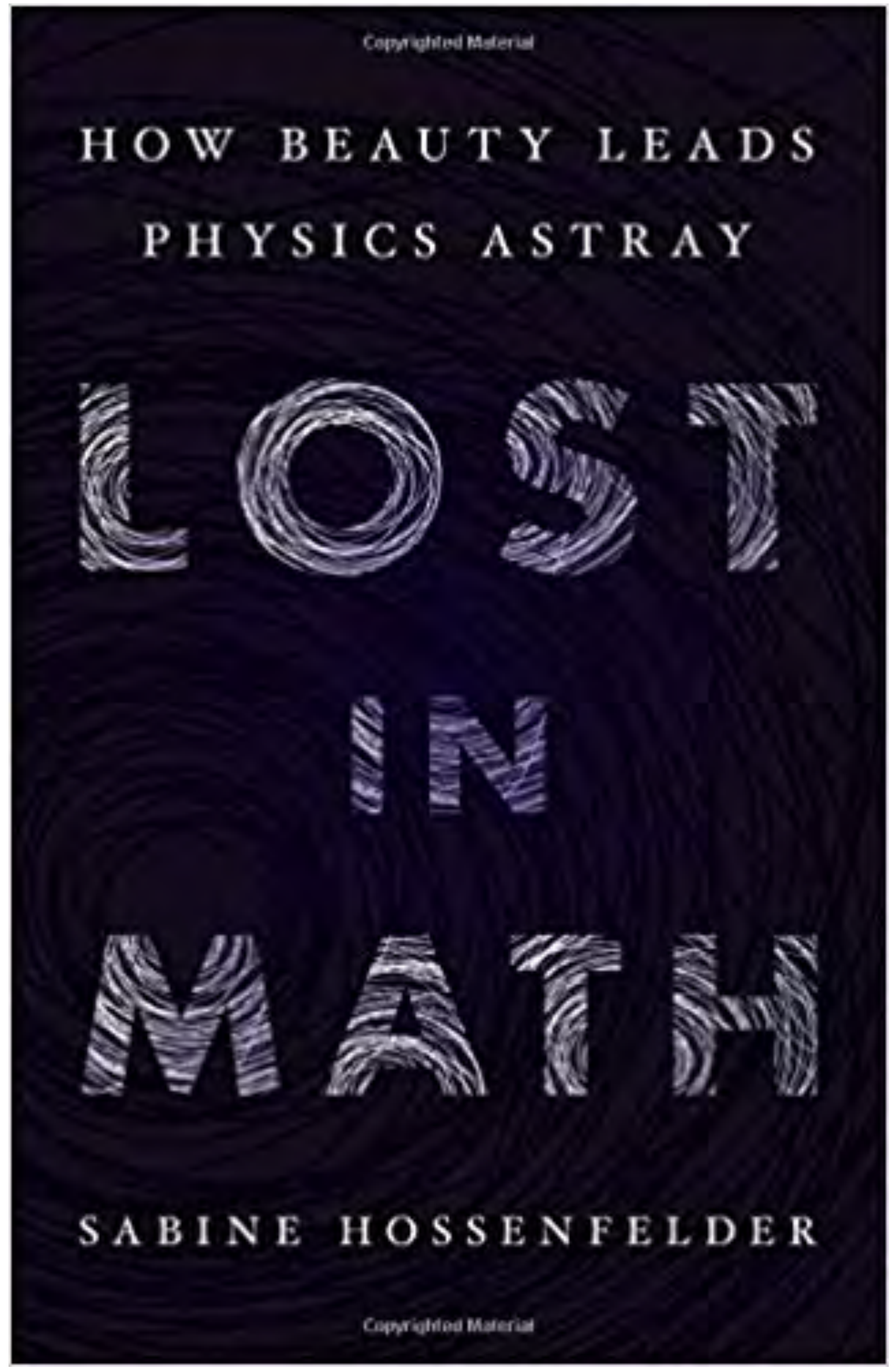


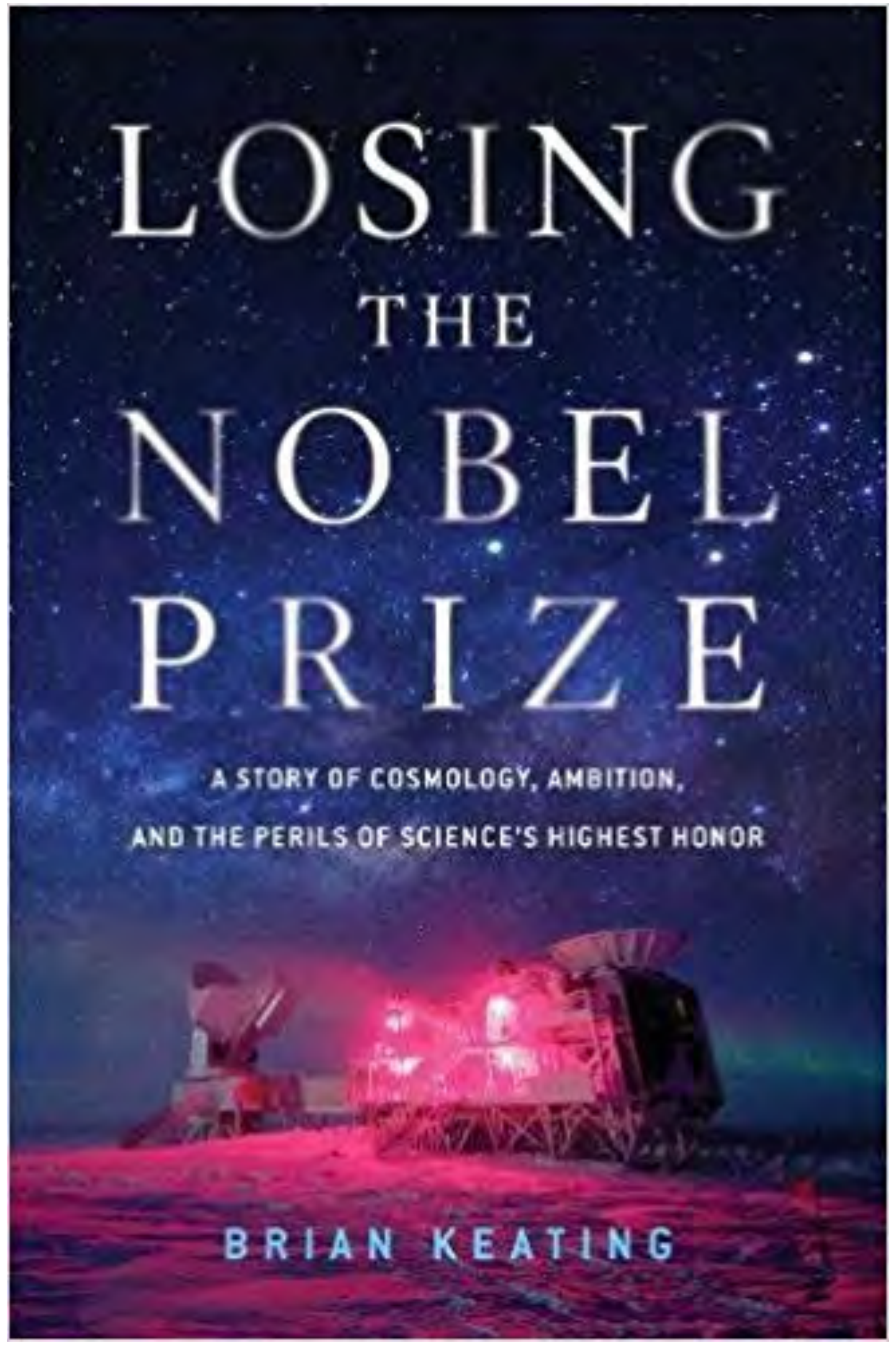
http://pirsa.org/11040058/

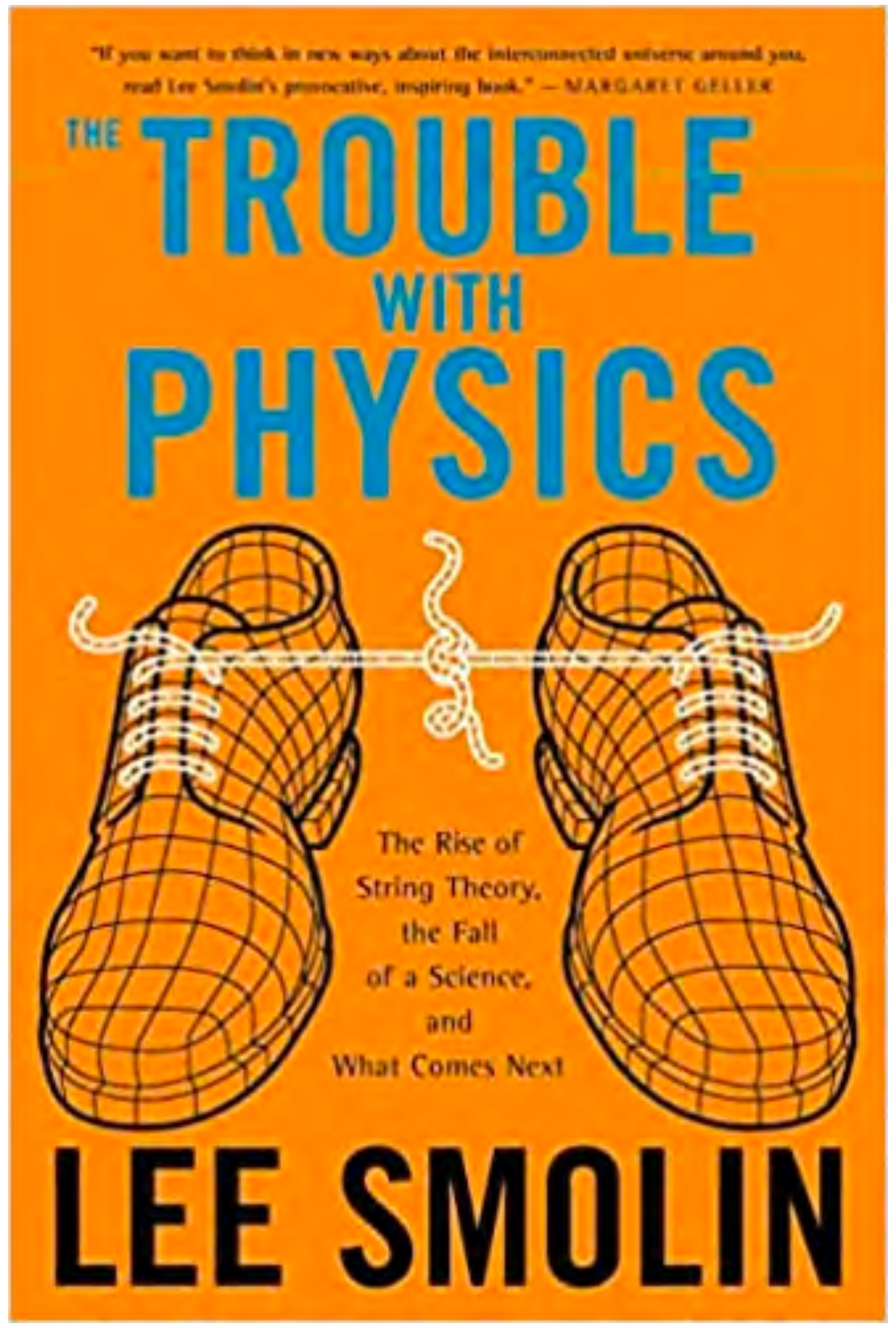
April 20, 2011

Crisis and Desperation?





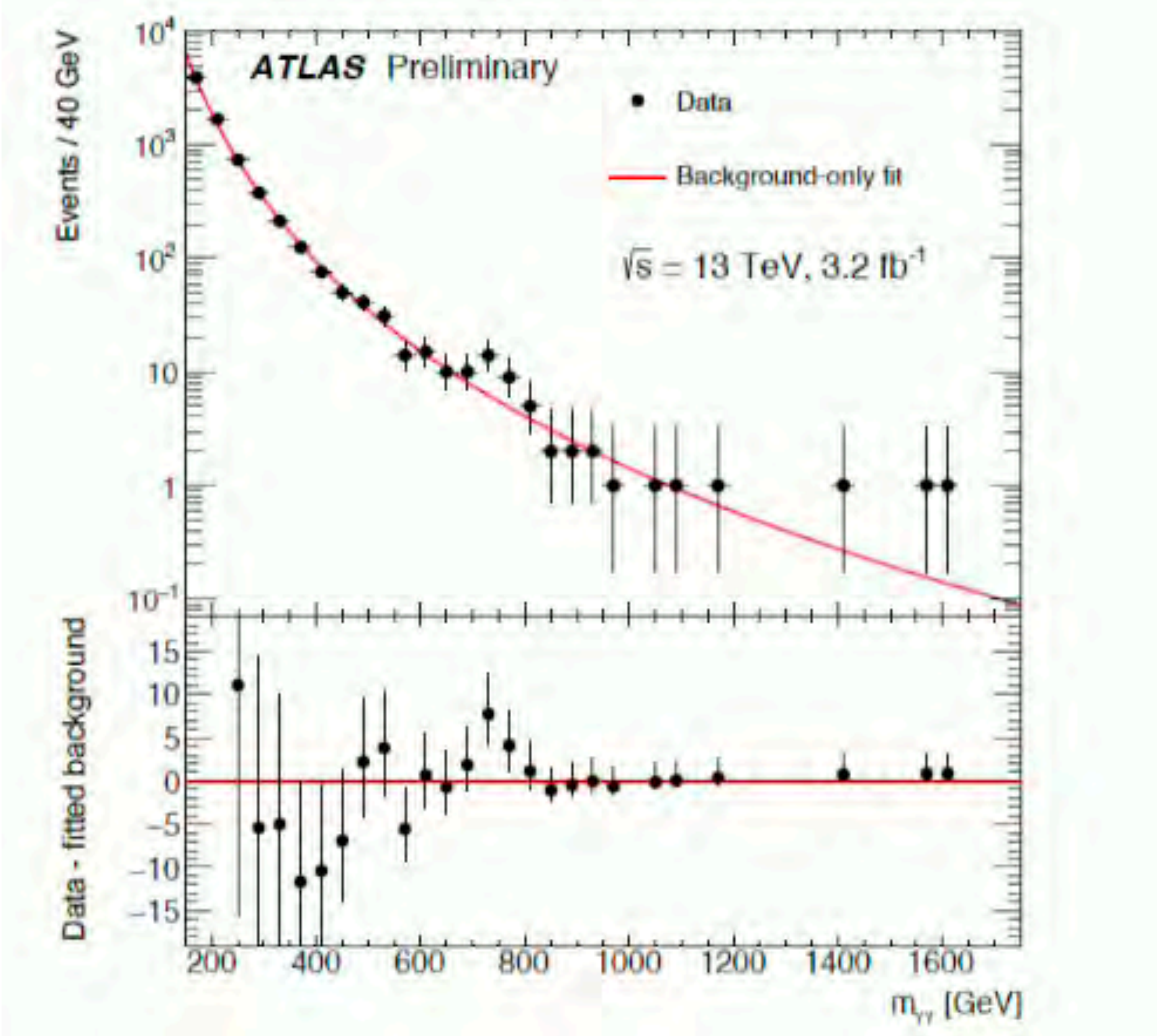


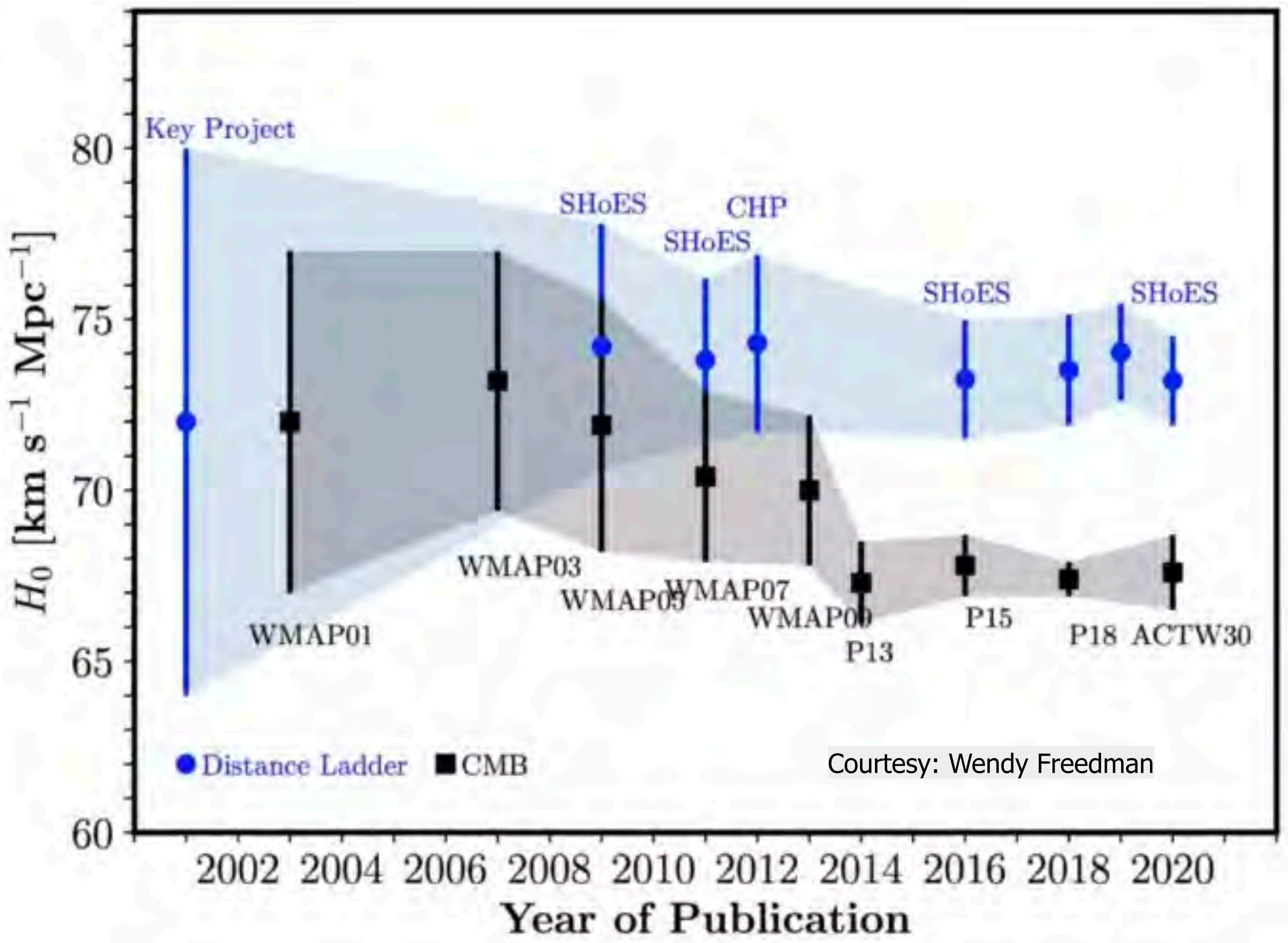


50 years in theoretical wasteland!

Anomaly-Industrial Complex

- Undeniable draw of young scientists to chase latest exciting experimental anomalies →maximize citations?
- Does this help or hinder the progress of science?





In his farewell address, President Dwight D. Eisenhower famously warned U.S. citizens about the "military–industrial complex".


PRESENT

Black Holes

Big Bang

Vacuum Energy

Lorentz Violation

Black Holes

Big Bang

Vacuum Energy

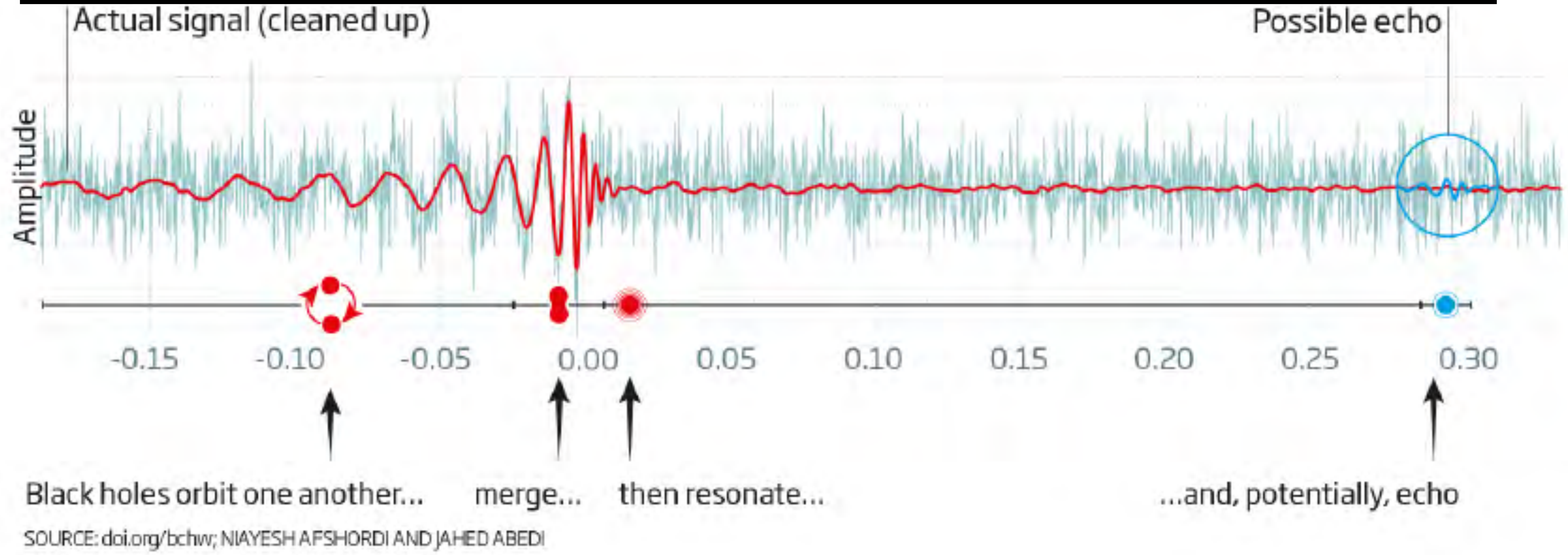
Lorentz Violation

Horizons vs Firewalls!

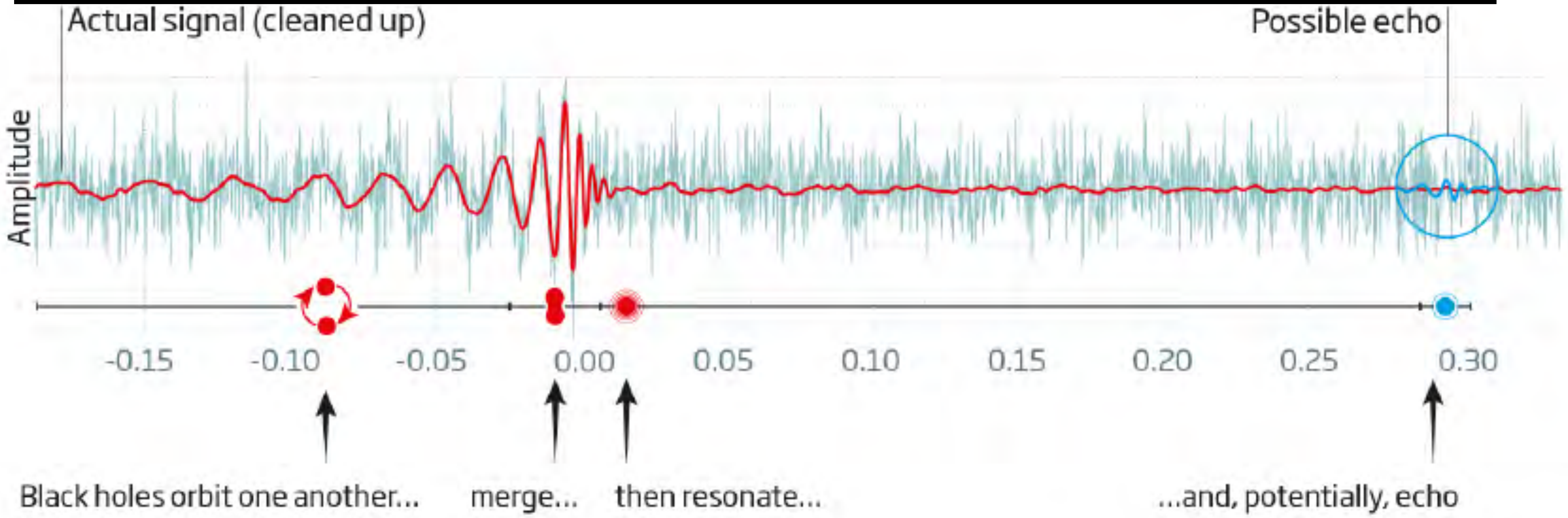
- In 2012, **Almheiri, Marolf, Polchinski, and Sully** argued Hawking evaporation, and classical horizon cannot be consistent (similar to arguments by **Mathur 2009**)

- *Their solution:* **Firewalls** instead of **Horizons**! Observers burn up as they hit them!

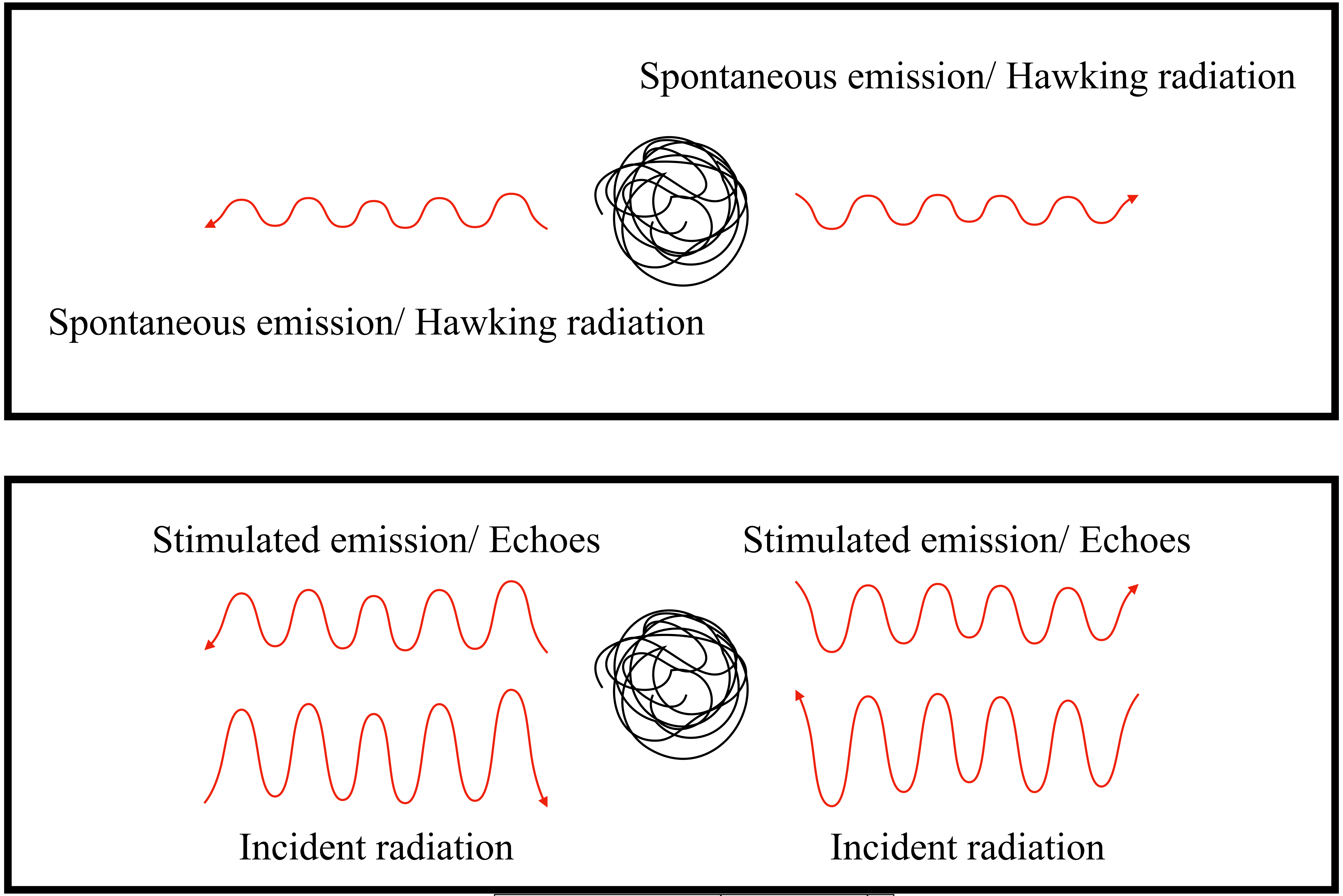
Gravitational Waves from firewalls?



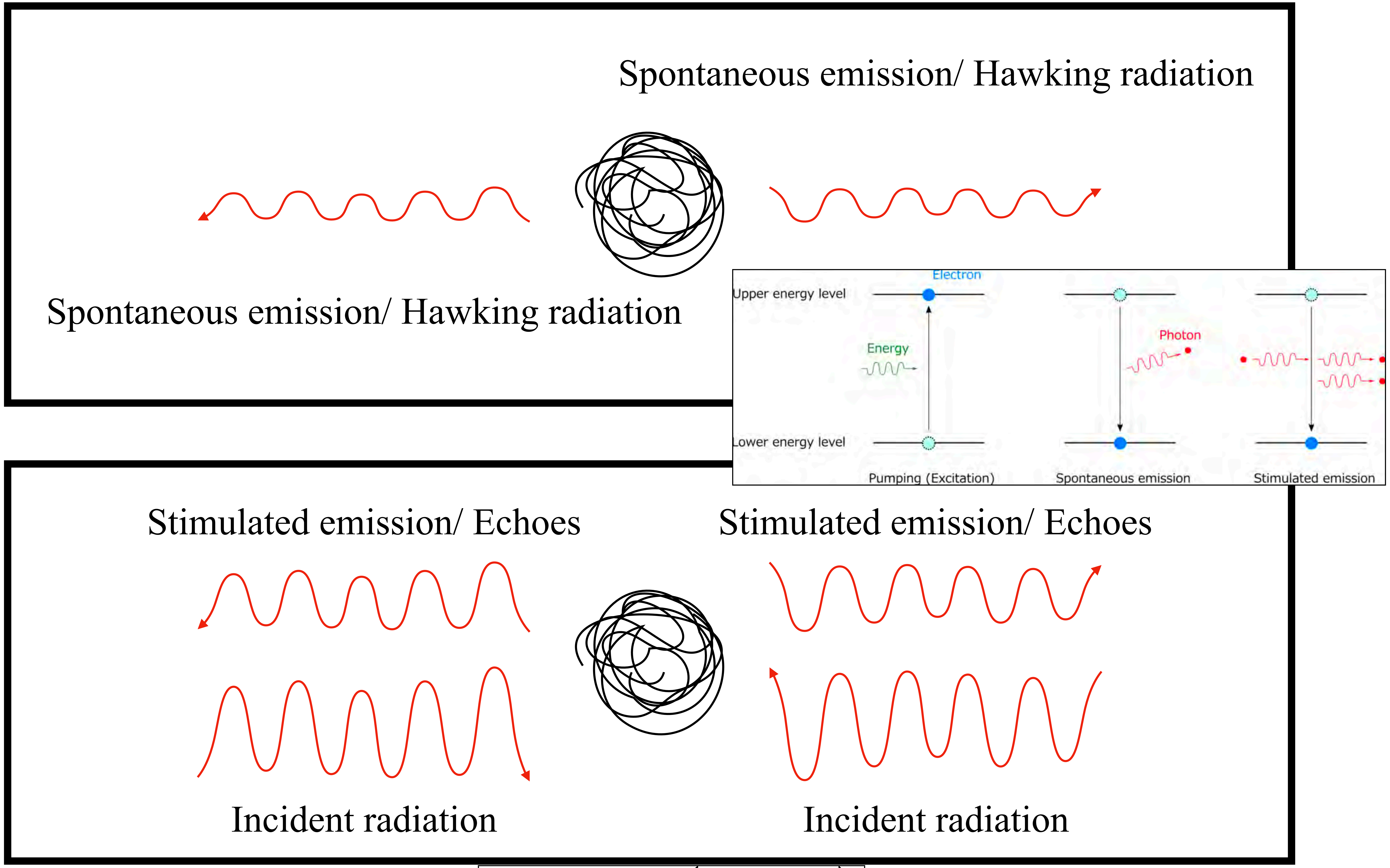
Gravitational Waves from firewalls?



SOURCE: doi.org/bchw; NIAYESH AFSHORDI AND JAHED ABEDI



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



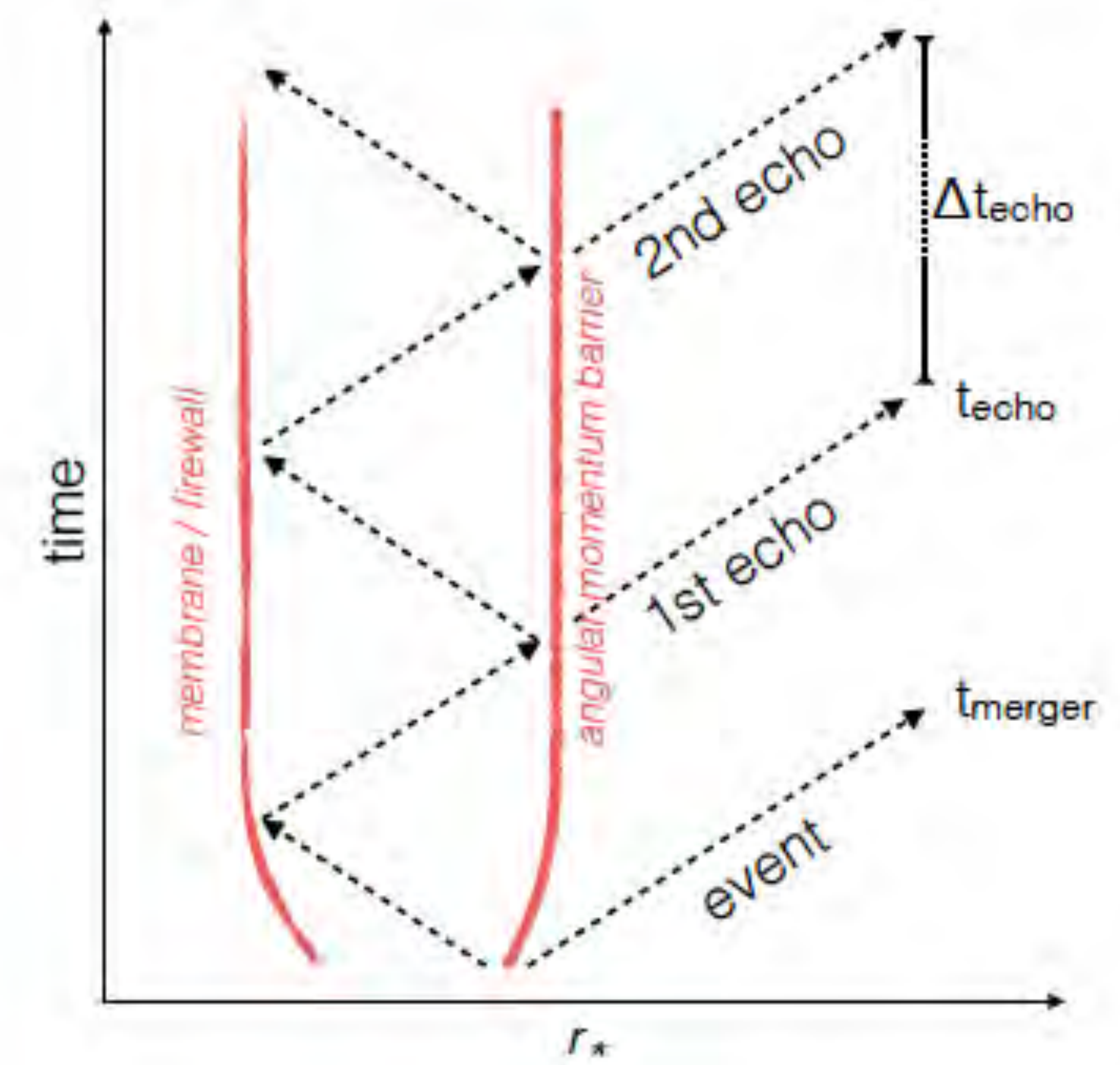
$$R = \exp\left(-\frac{\hbar\omega}{kT_H}\right)$$

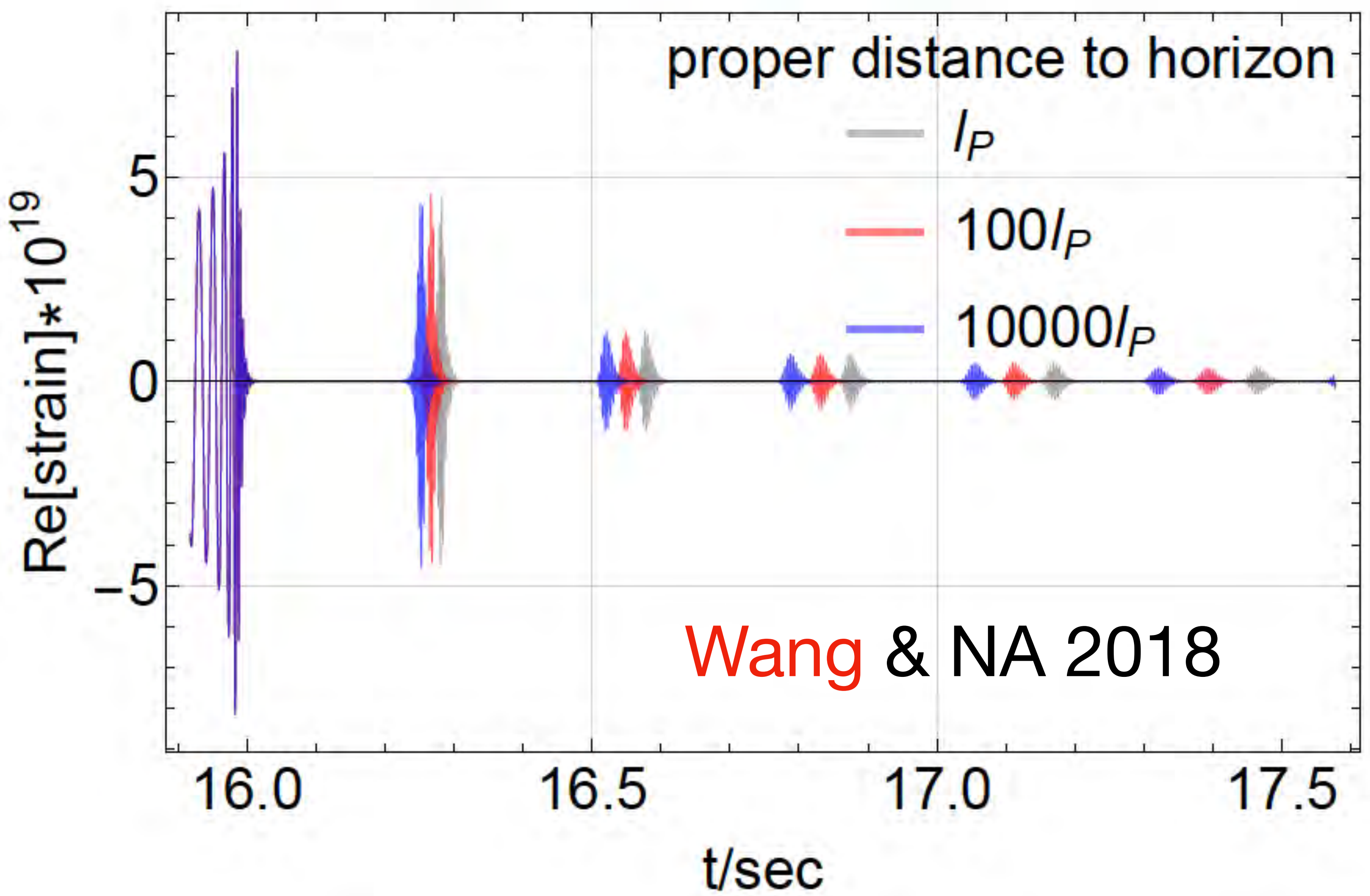
From Planck to LIGO!

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

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

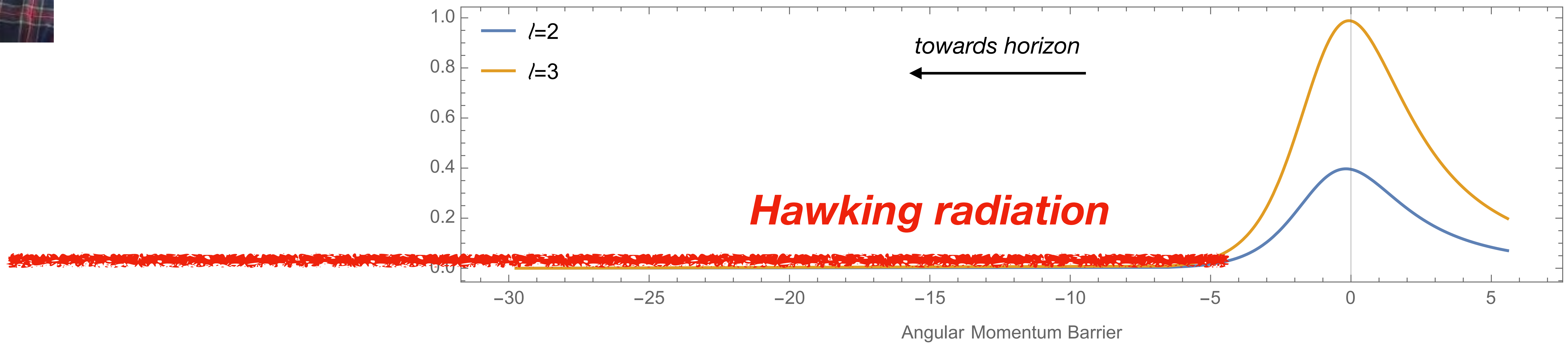
- *Stimulated Hawking Radiation (Oshita, Wang & NA 2020)*





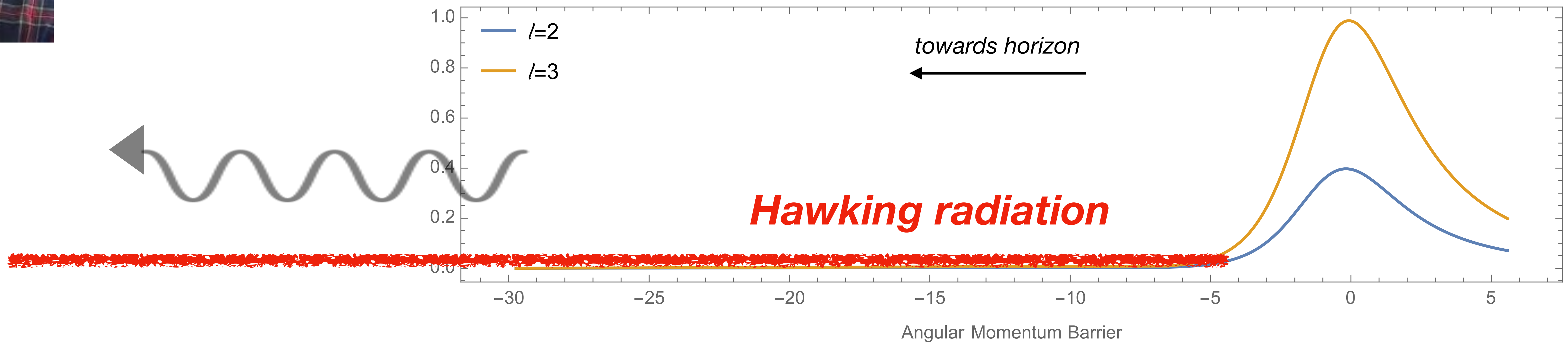
Finite Entropy of Hawking radiation ➡ Echoes *(Oshita & NA 2023)*

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



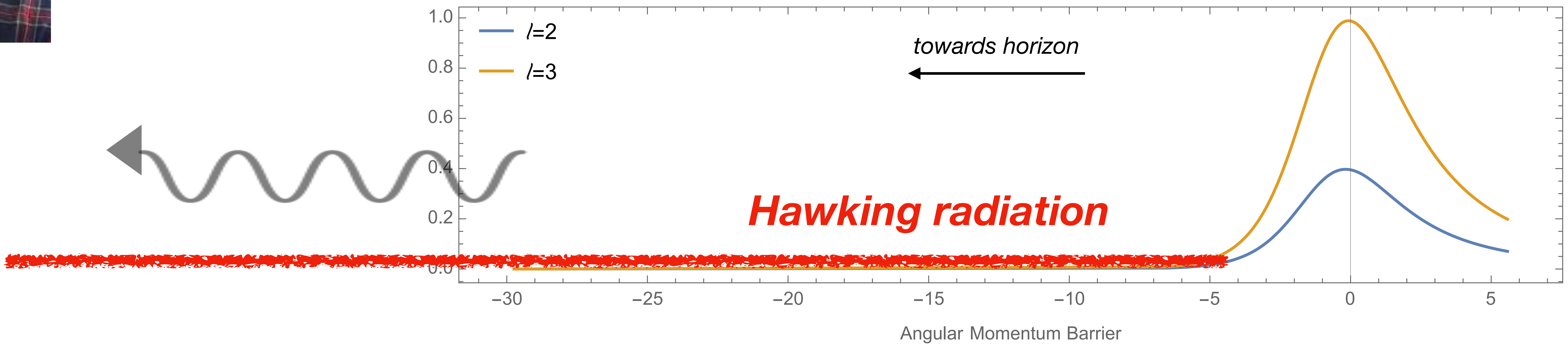
Finite Entropy of Hawking radiation ➡ Echoes *(Oshita & NA 2023)*

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

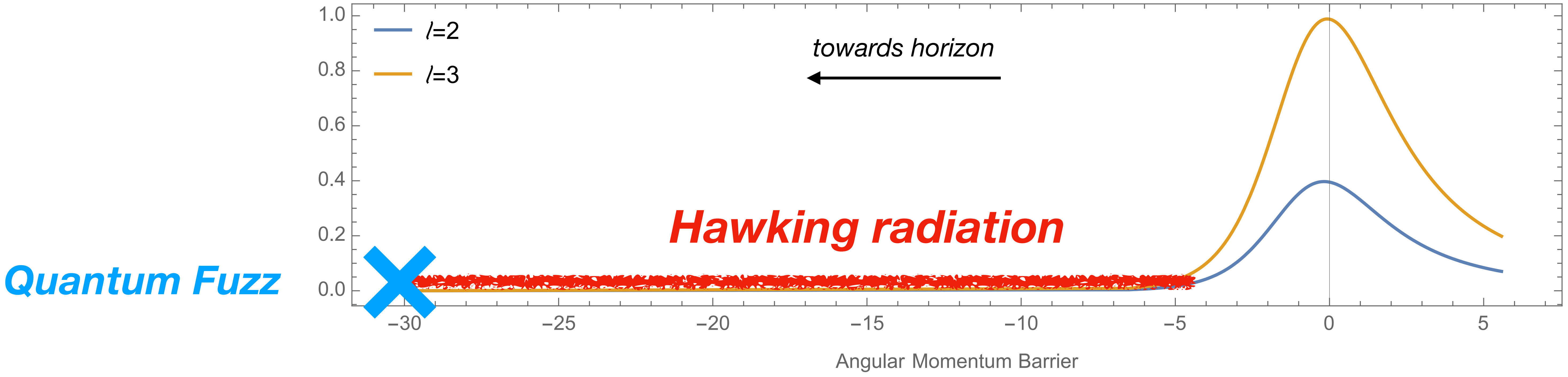


Finite Entropy of Hawking radiation ➡ Echoes *(Oshita & NA 2023)*

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

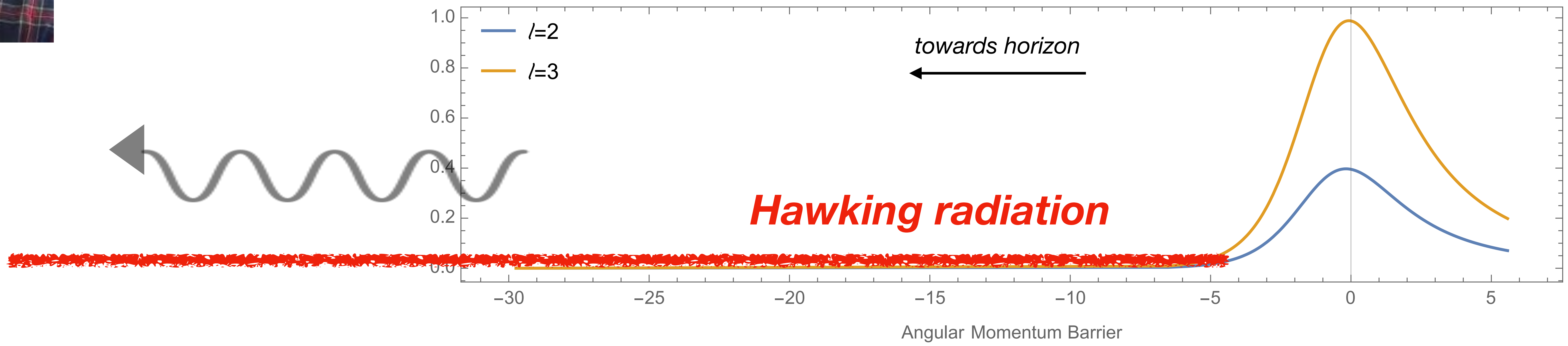


- Finite Entropy & Echoes: $t_{\rm echo} = \dfrac{\ln\left[\text{Entropy}/\ell(\ell+1)\right]}{2\pi \times \text{Hawking Temperature}}$

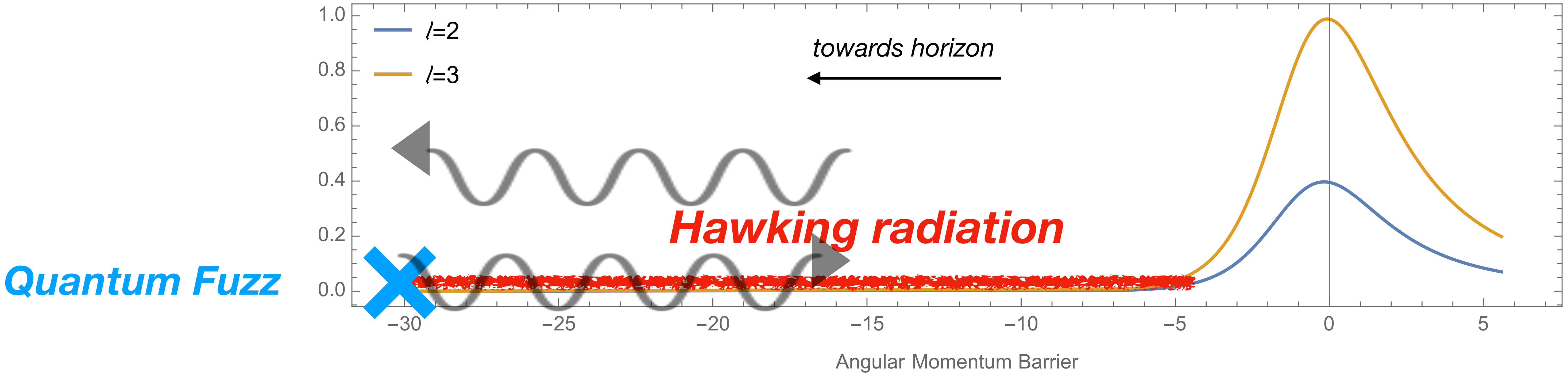


Finite Entropy of Hawking radiation ➡ Echoes *(Oshita & NA 2023)*

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

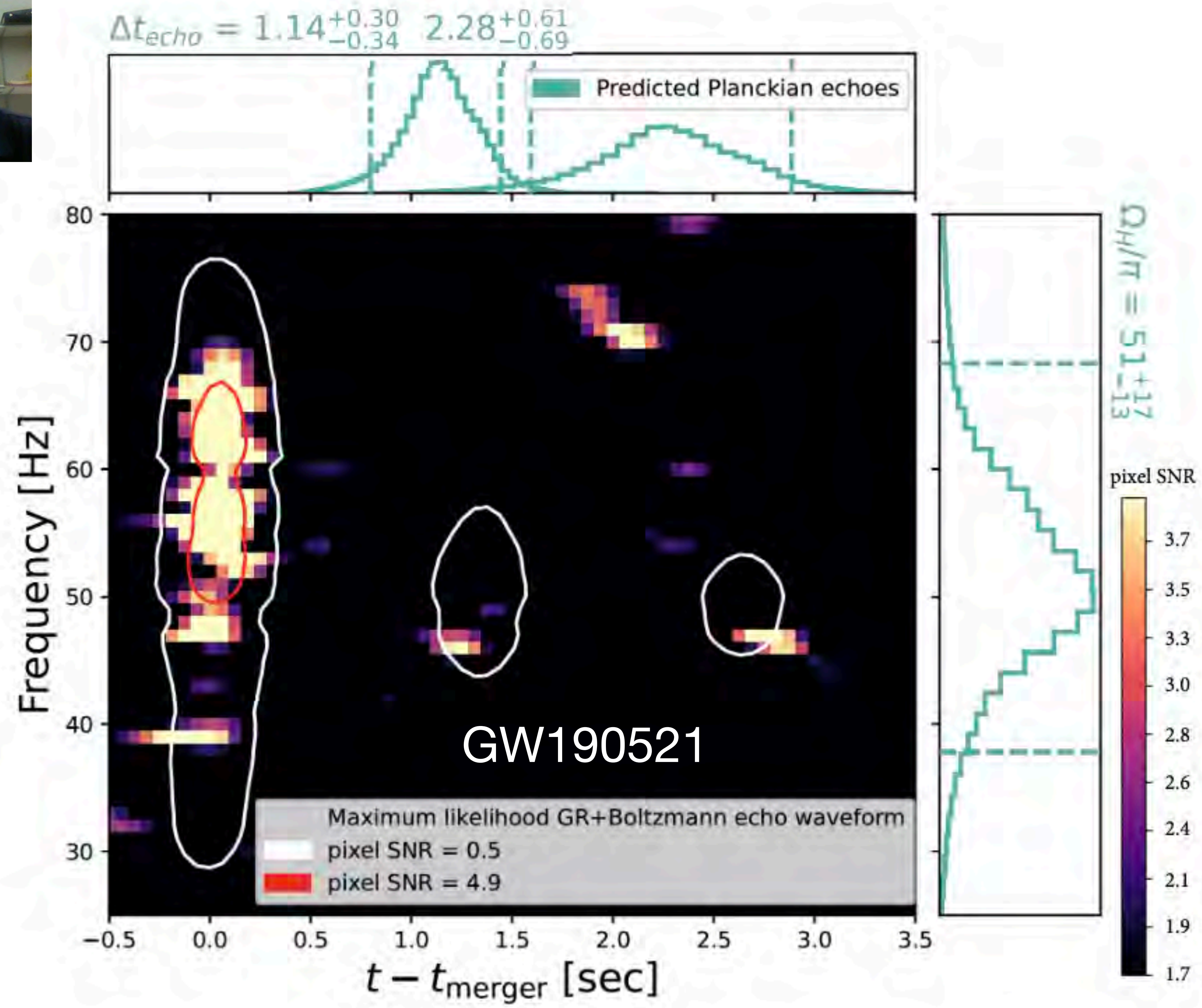


- Finite Entropy & Echoes: $t_{\text{echo}} = \dfrac{\ln\left[\text{Entropy}/\ell(\ell+1)\right]}{2\pi \times \text{Hawking Temperature}}$

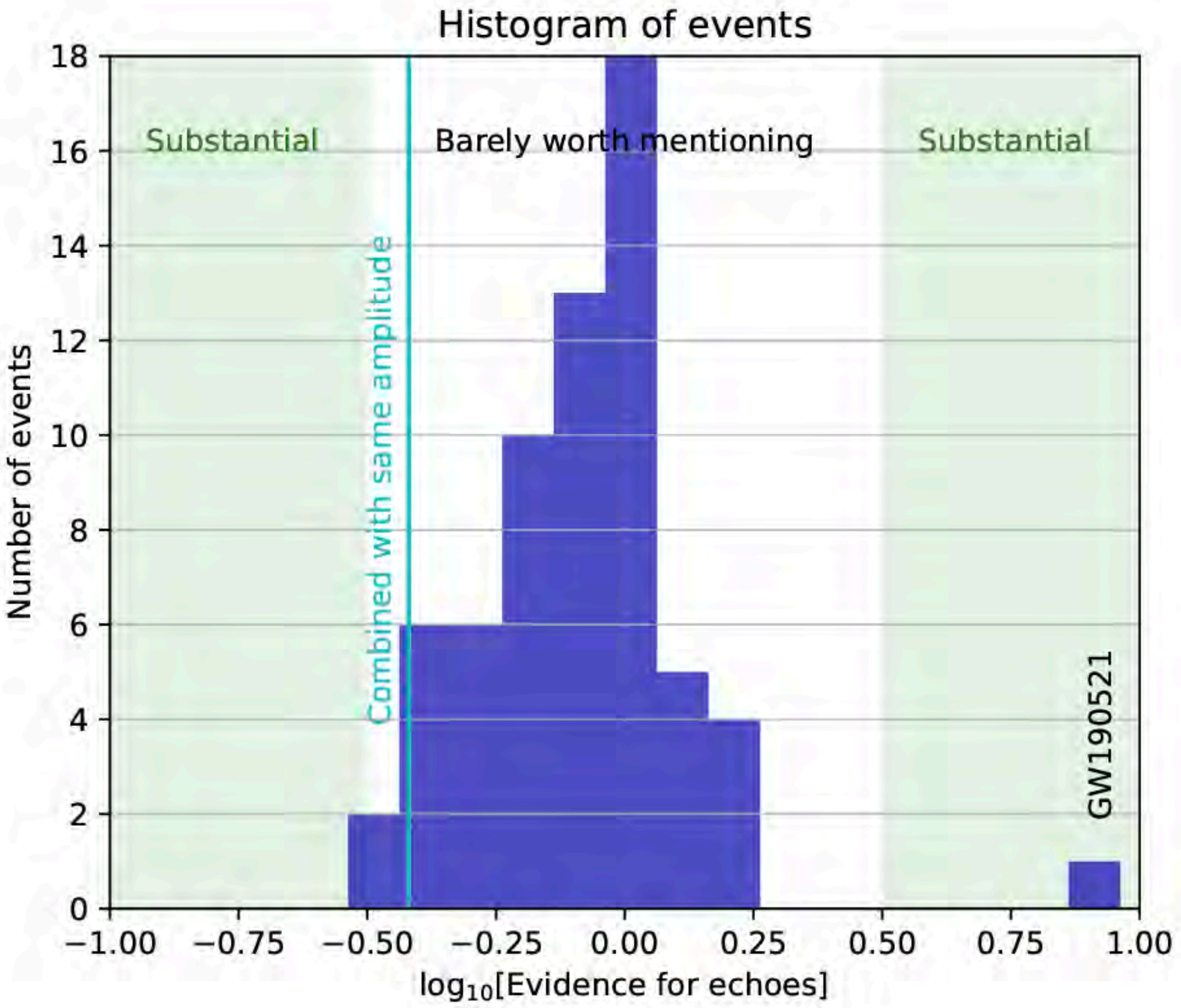


Are there echoes in LIGO data?

- Abedi, Longo & NA 2023



Abedi 2023



Can we image Quantum Black Holes?

the case of q-metric

$$ds^2 = -\left(1-\frac{2m}{r}\right)^{1+q} dt^2 + \left(1-\frac{2m}{r}\right)^{-1-q} \left(\frac{r^2-2mr+m^2\sin^2\theta}{r^2-2mr}\right)^{-q(2+q)} dr^2$$
$$+\left(1-\frac{2m}{r}\right)^{-q} r^2(d\theta^2+\sin^2\theta d\phi^2).$$

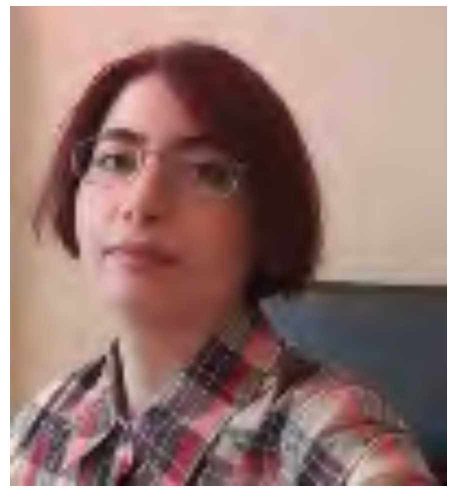
- Generalized to spinning spacetime by Toktarbay & Quevedo 2014
- Modified the mass and spin multipoles of the Kerr spacetime

$$M_0 = m + q\sigma,$$
$$M_2 = -m^3 - 3m^2 q\sigma - m\left(q^2-1\right)\sigma^2 - \frac{1}{3}q\left(q^2-7\right)\sigma^3,$$
$$J_1 = a(m+2q\sigma),$$
$$J_3 = -a\left[3m^3+12m^2q\sigma+3m\left(3q^2-1\right)\sigma^2+2q\left(q^2-4\right)\sigma^3\right]/3,$$

$$\sigma = \sqrt{m^2-a^2}$$

Imaging Quantum Black Holes?

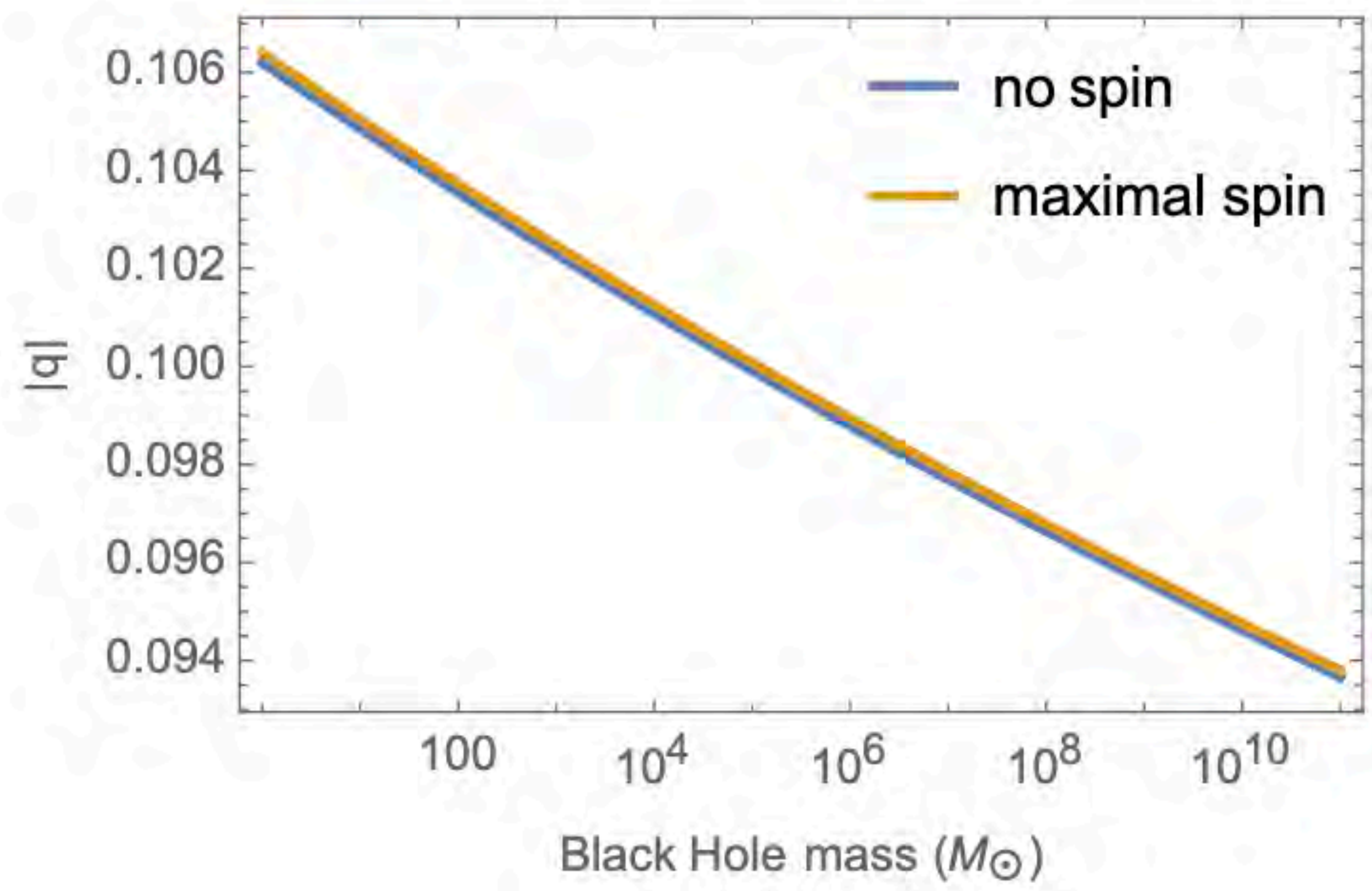
Faraji, NA, et al. (in prep.)

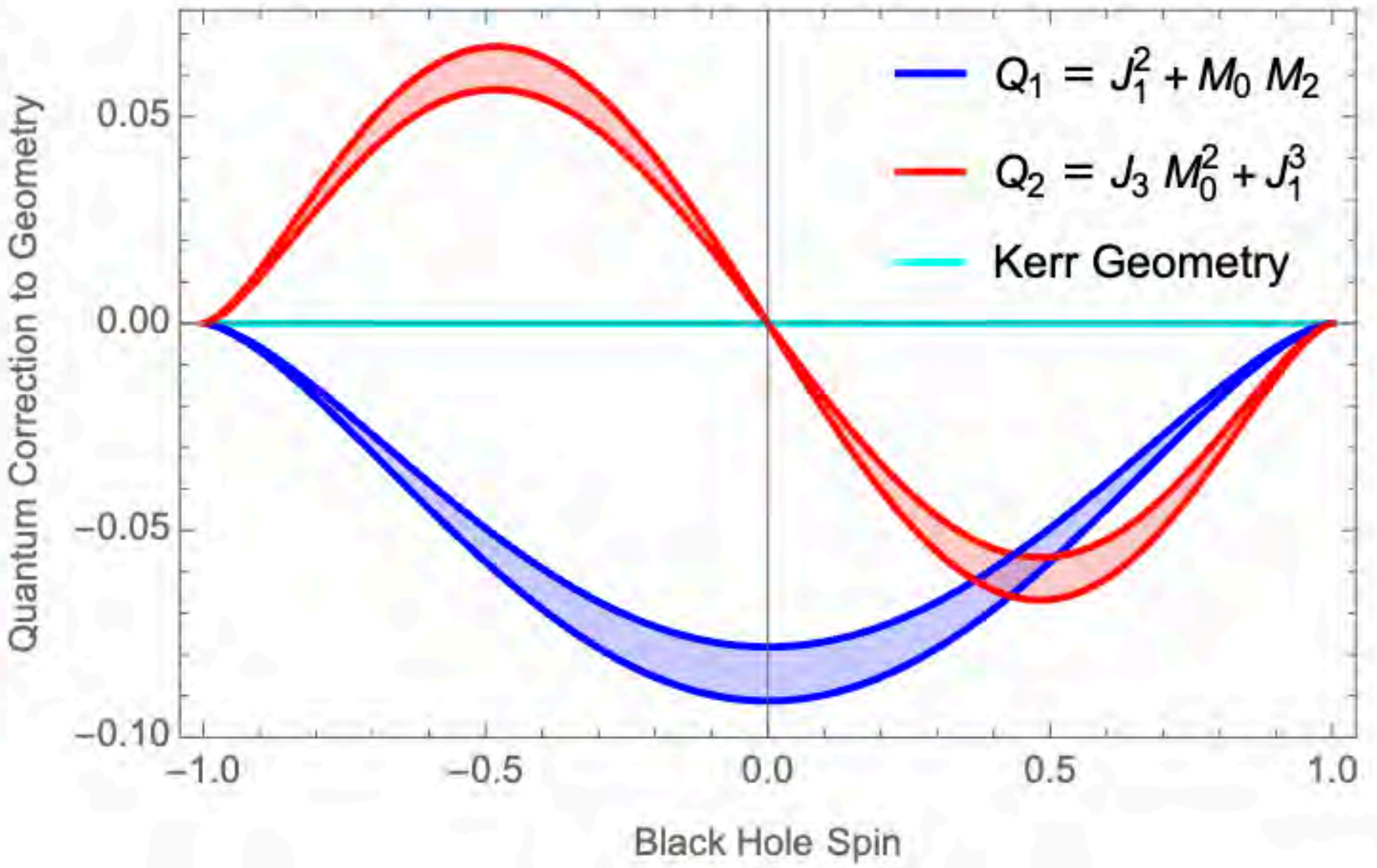


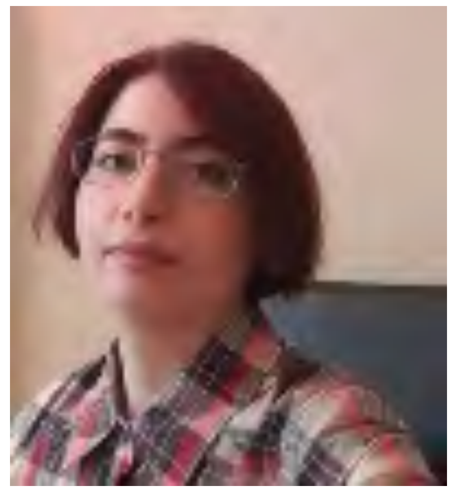
- Quantum effects violate the no-hair theorem
  ➡ mass and spin multipoles differ from Kerr

- Example: q-metric

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







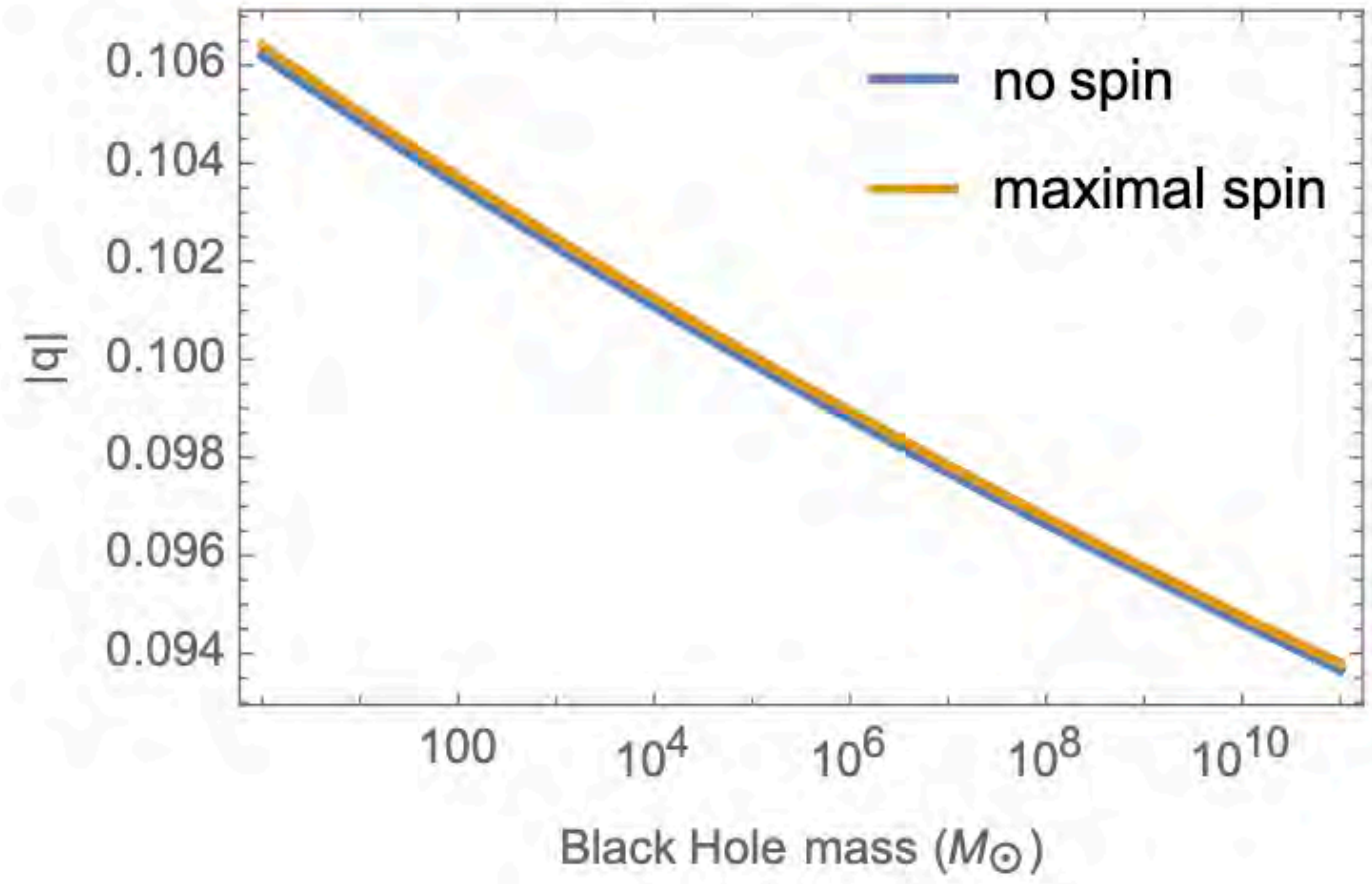
Imaging Quantum Black Holes?

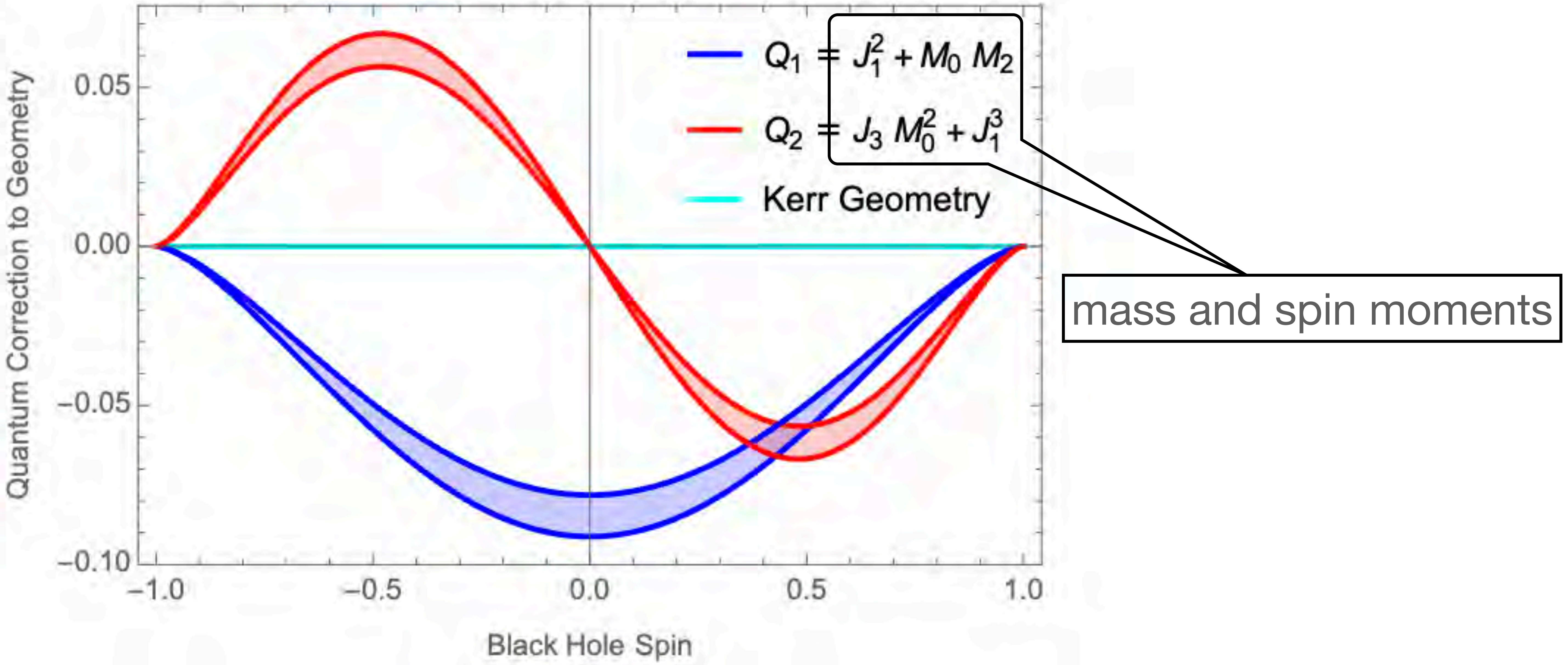
Faraji, NA, et al. (in prep.)

- Quantum effects violate the no-hair theorem
  ➡ mass and spin multipoles differ from Kerr

- Example: q-metric

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





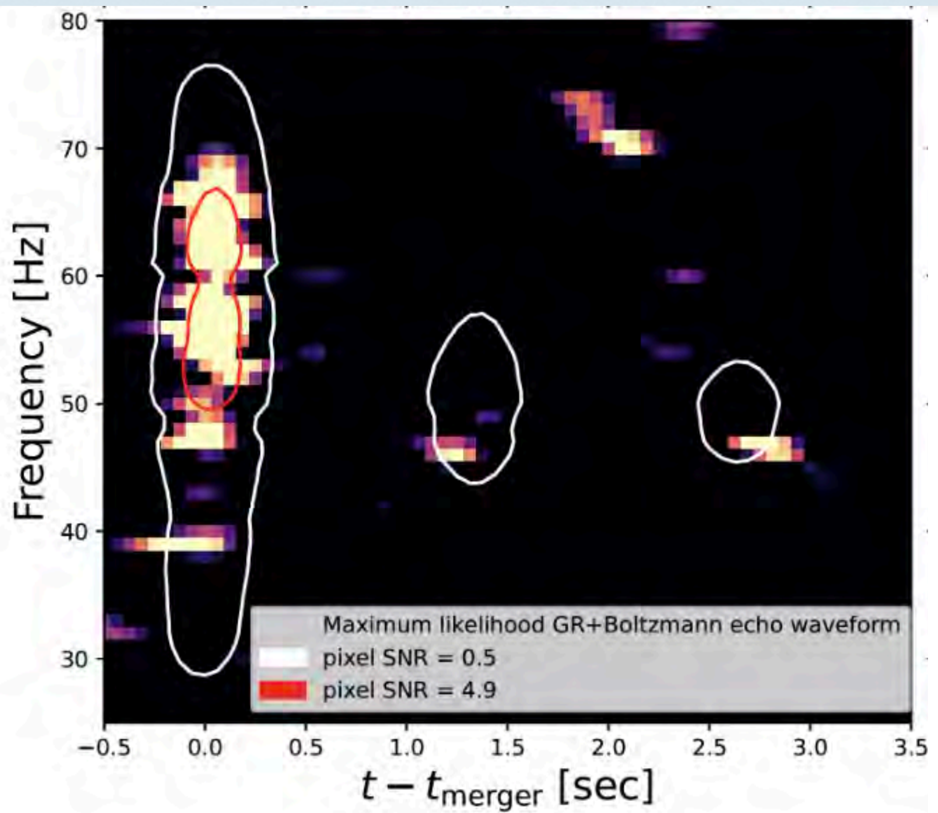
Echoes to *LIGO*	**Higgs to *LHC***

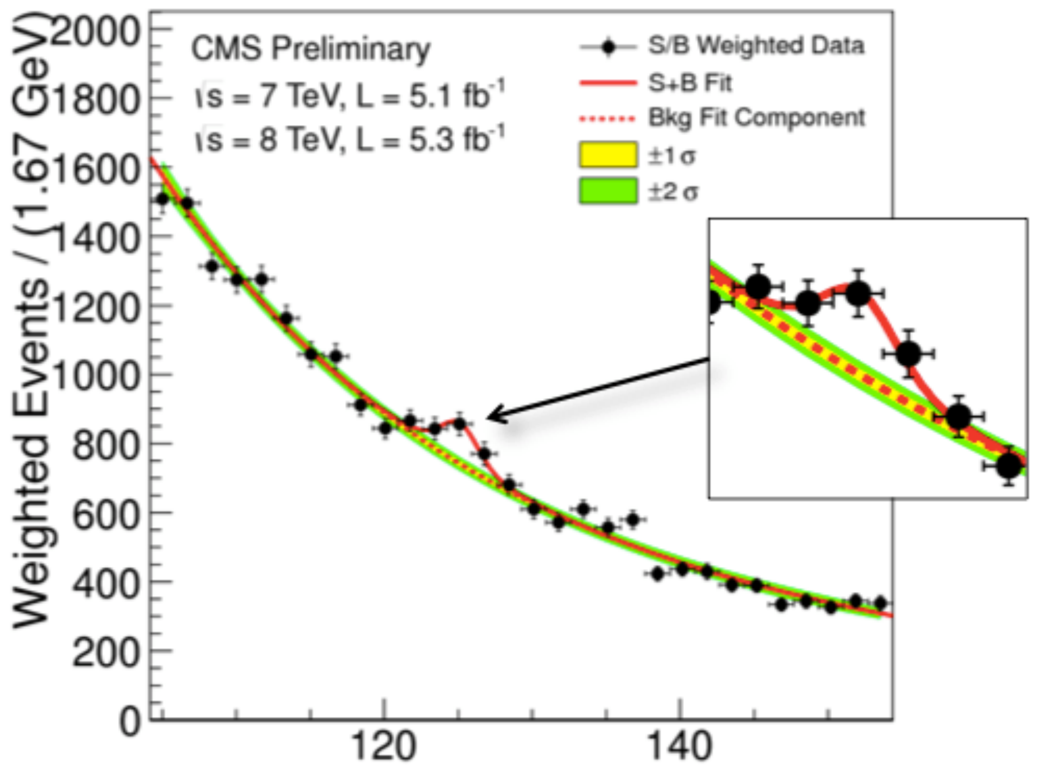
Echoes to *LIGO*

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

Higgs to *LHC*

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





Black Holes

Big Bang

Vacuum Energy

Lorentz Violation

Wave function of the Big Bang connects

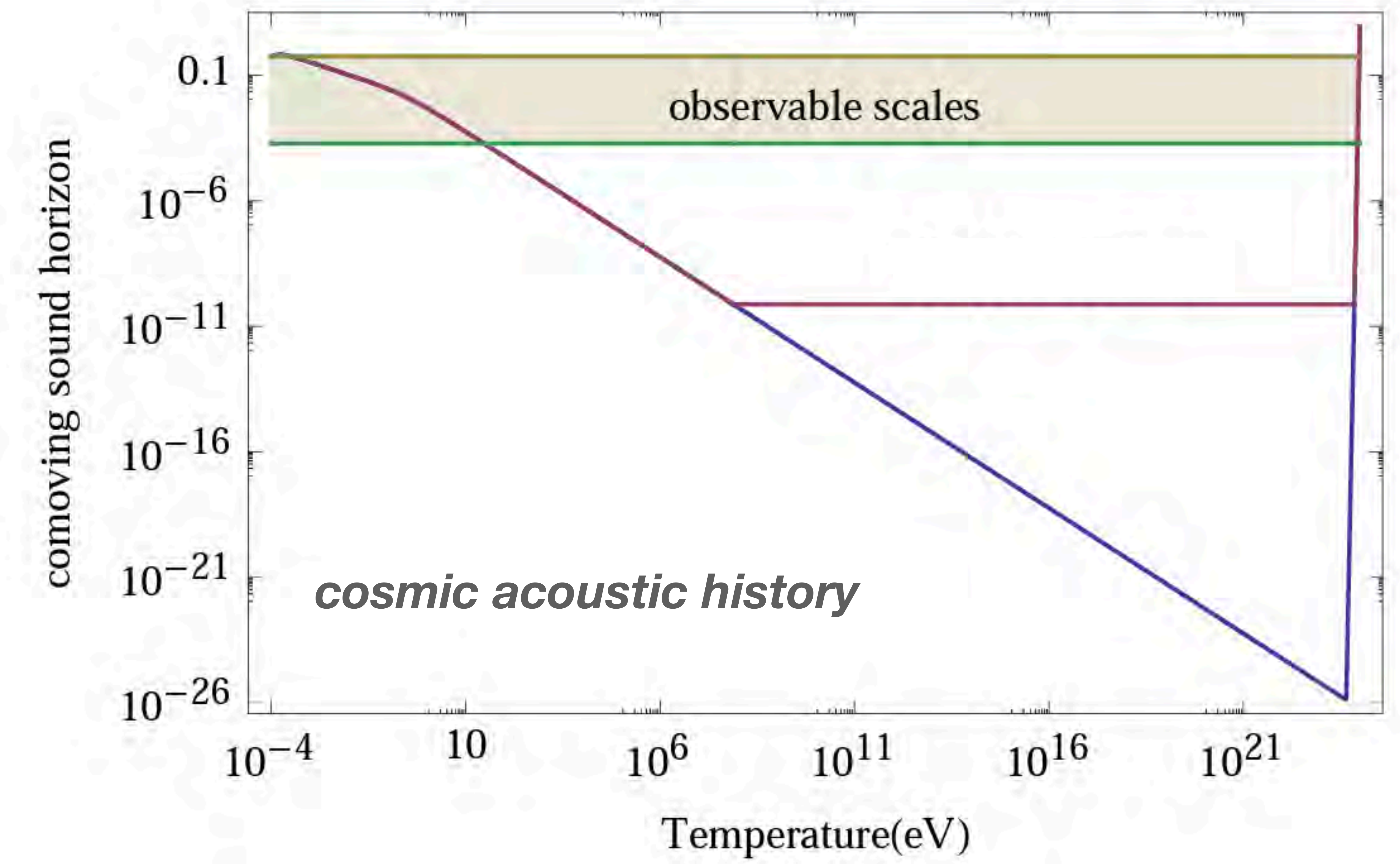
- Shape and amplitude of the primordial power spectrum (2-point function)
- Shape and amplitude of the primordial bispectrum (3-point function)
- Dark Energy/cosmological constant

Wave function of the Big Bang connects

- Shape and amplitude of the primordial power spectrum (2-point function)
- Shape and amplitude of the primordial bispectrum (3-point function)
- Dark Energy/cosmological constant

This may sound trivial, but has very non-trivial consequences!

A speedy sound at the Big Bang?



Magueijo & Pogosian 2003
Magueijo 2008
Agarwal & NA 2014

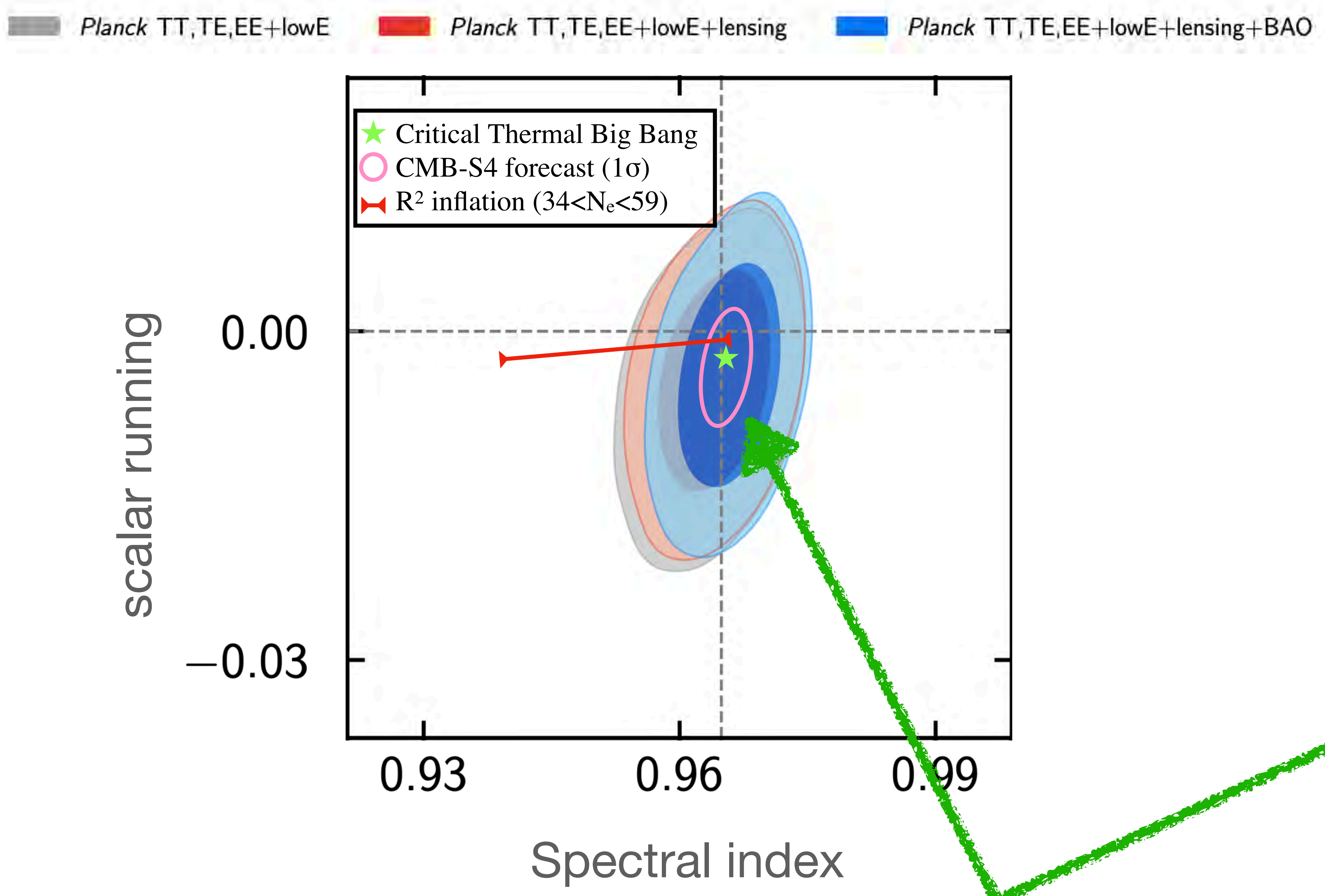
- A fully thermal Big Bang History (no reheating)
- Scale-invariant tensor modes (transition to Horava gravity)

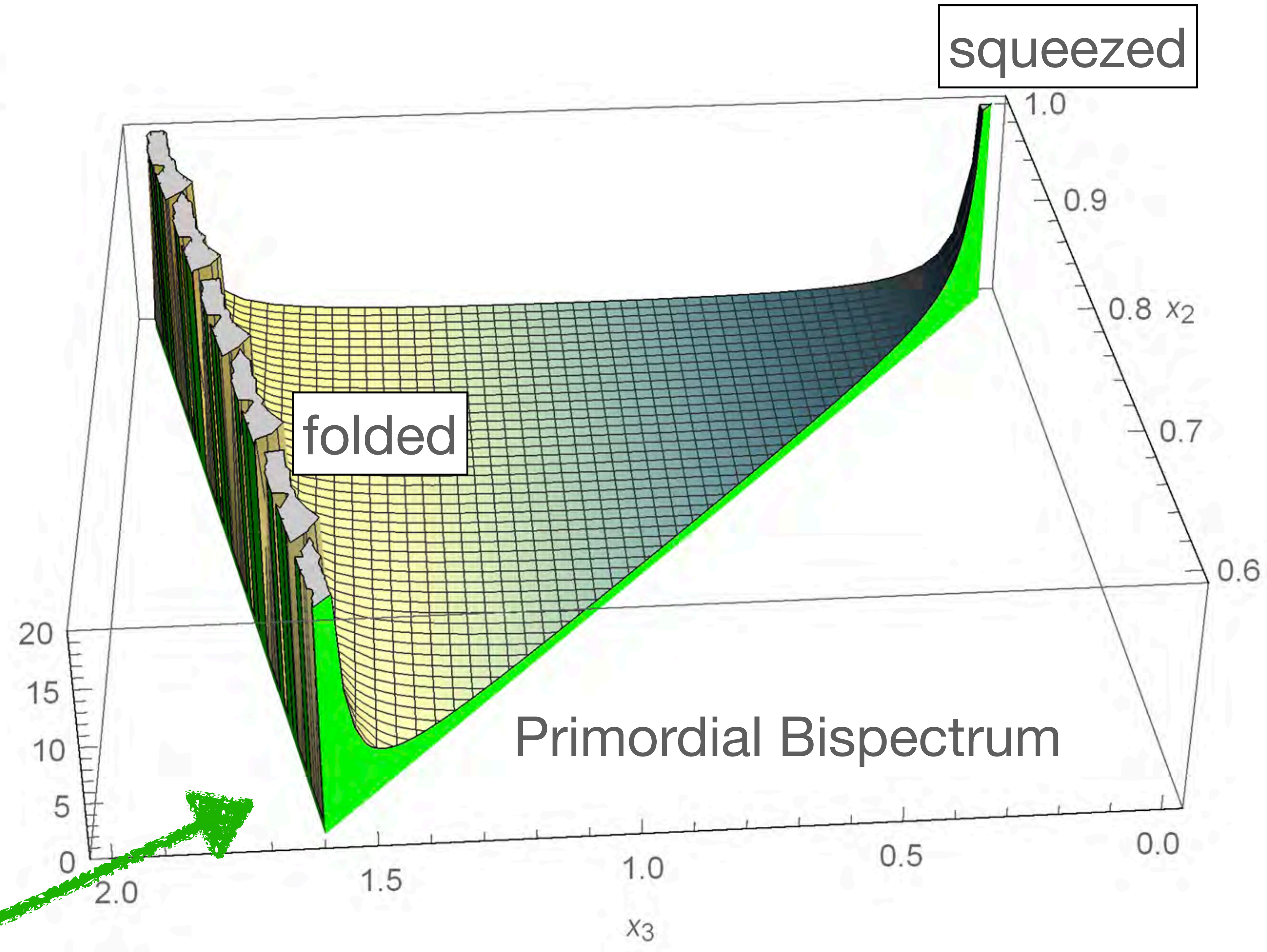
$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_\zeta} \gtrsim 1 \times 10^{-3} \left(\frac{g_*}{100}\right)^{1/3},$$

Agarwal & NA 2014

Bi-Thermal Big Bang

Most predictive model of the Early Universe! ~~Inflation~~





Does Quantum Gravity break the speed of light limit?

NA, Chung & Geshnizjani 2006; NA & Magueijo 2016
Mylova, Moschou, NA, & Magueijo 2022

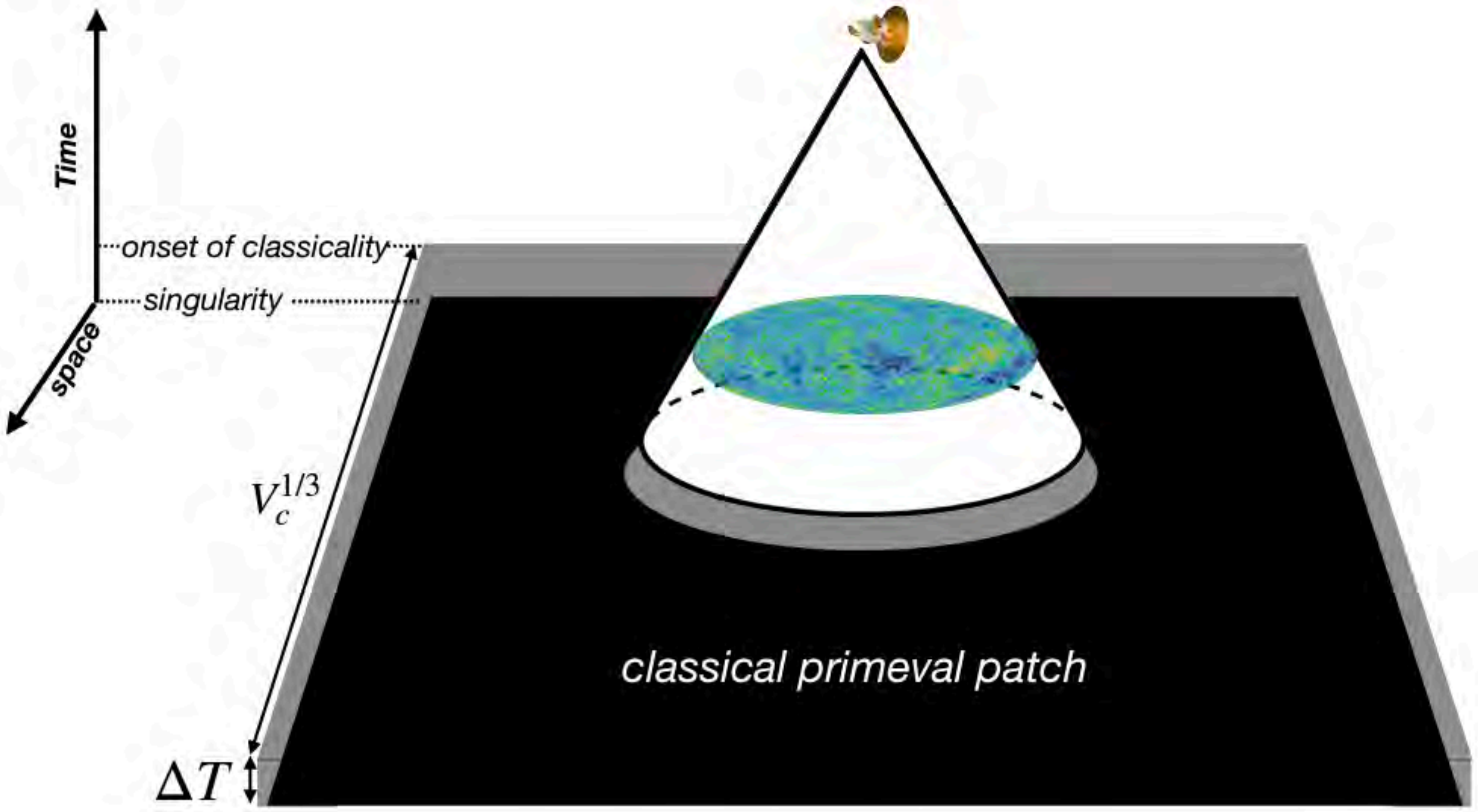
$$S = M^4 \int d^4x \sqrt{-g} \left[\frac{1}{\phi^2} \sqrt{1 + \frac{(\partial\phi)^2}{M^4}} - \frac{3}{4} (\ln \phi)^2 \right]$$

$$M \simeq 2.9 \times 10^{-4}$$

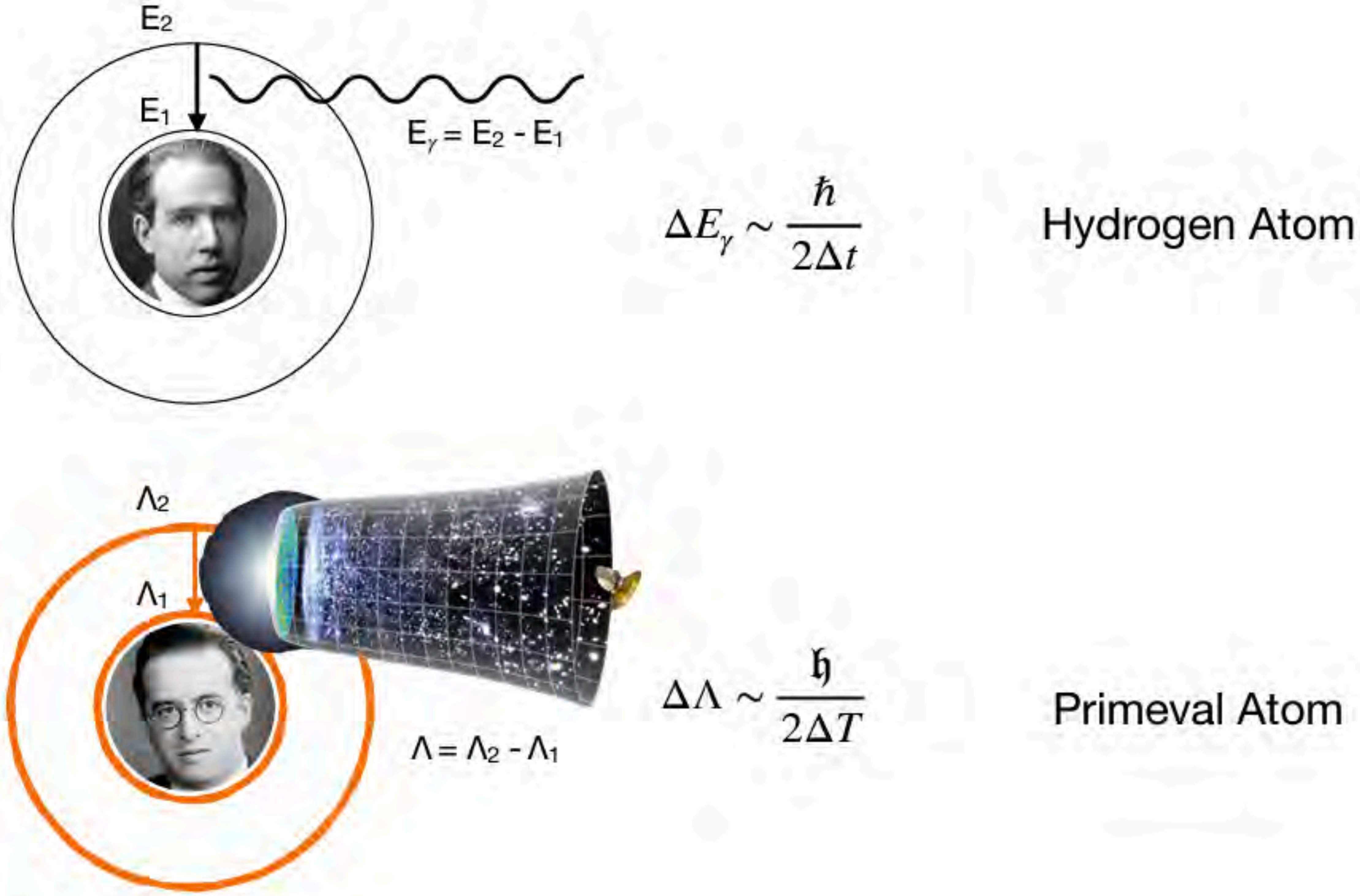

Black Holes
Big Bang
Vacuum Energy
Lorentz Violation
PRESENT

Cosmological constant from the classicality of the "Primeval Atom"

- Heisenberg Uncertainty Relation between cosmological constant, and the classical primeval patch 4-volume

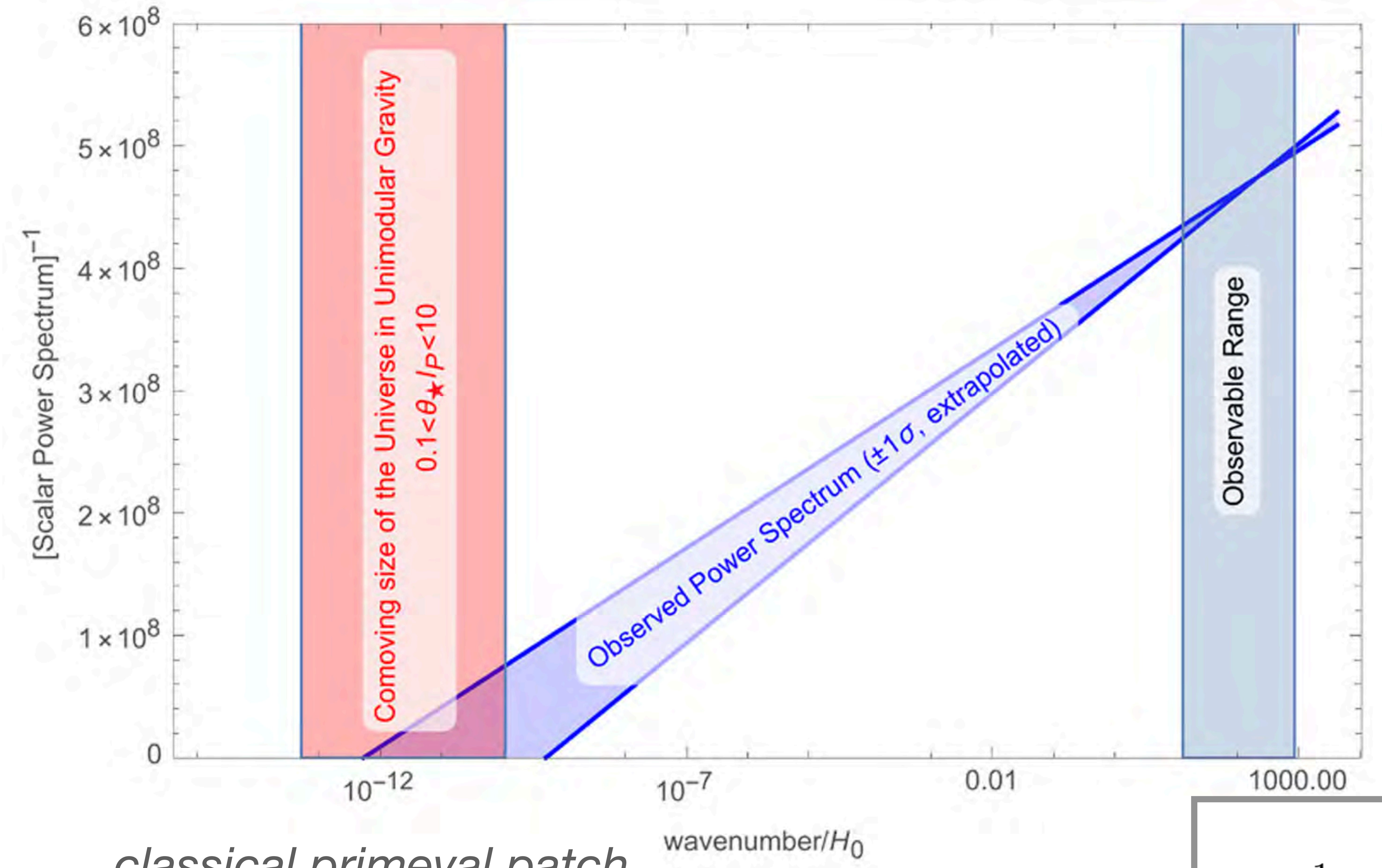


$$\int a^3(t)dt = T > T_\star = \frac{l_P^2}{6V_c\Lambda_0\epsilon} > \frac{l_P^2}{6V_c\Lambda_0}.$$



NA & Magueijo 2022

Quantum Cosmology ties dark energy (Λ) and early universe (n_s)



classical primeval patch

NA & Magueijo 2022

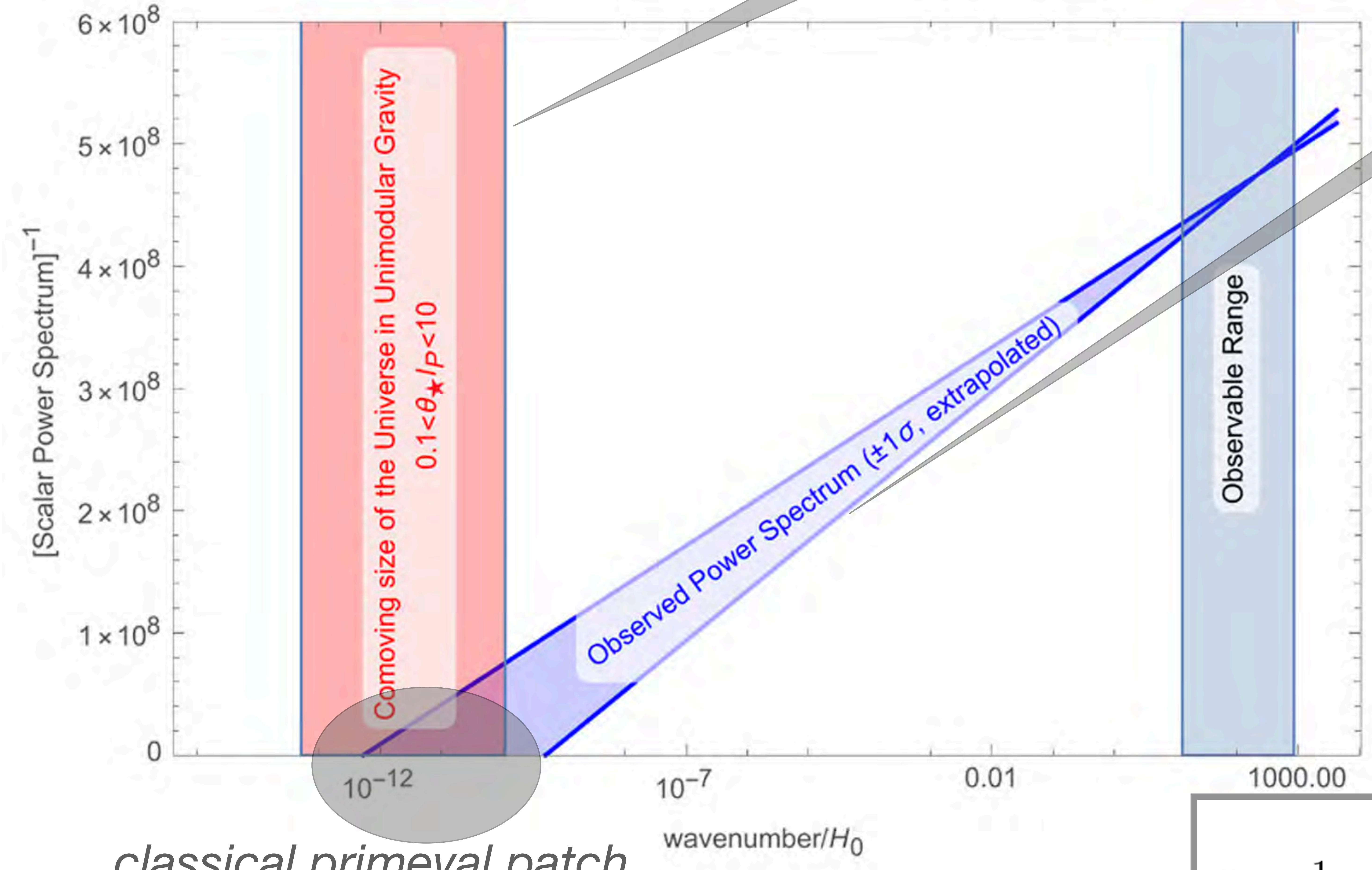
(Holographic cosmology, renormalization group)

$$P_s(k) = \frac{A_s}{1-(n_s-1)\ln(k/k_0)},$$

Prediction of Planckian primeval atom

$$n_s = 1 - \frac{1}{32.17 + \ln(\theta_\star l_P)} \simeq 0.9689 + 1.6\times 10^{-4}\ln(\theta_\star l_P)$$

Quantum Cosmology ties dark energy (Λ) and early universe (n_s)



classical primeval patch

NA & Magueijo 2022

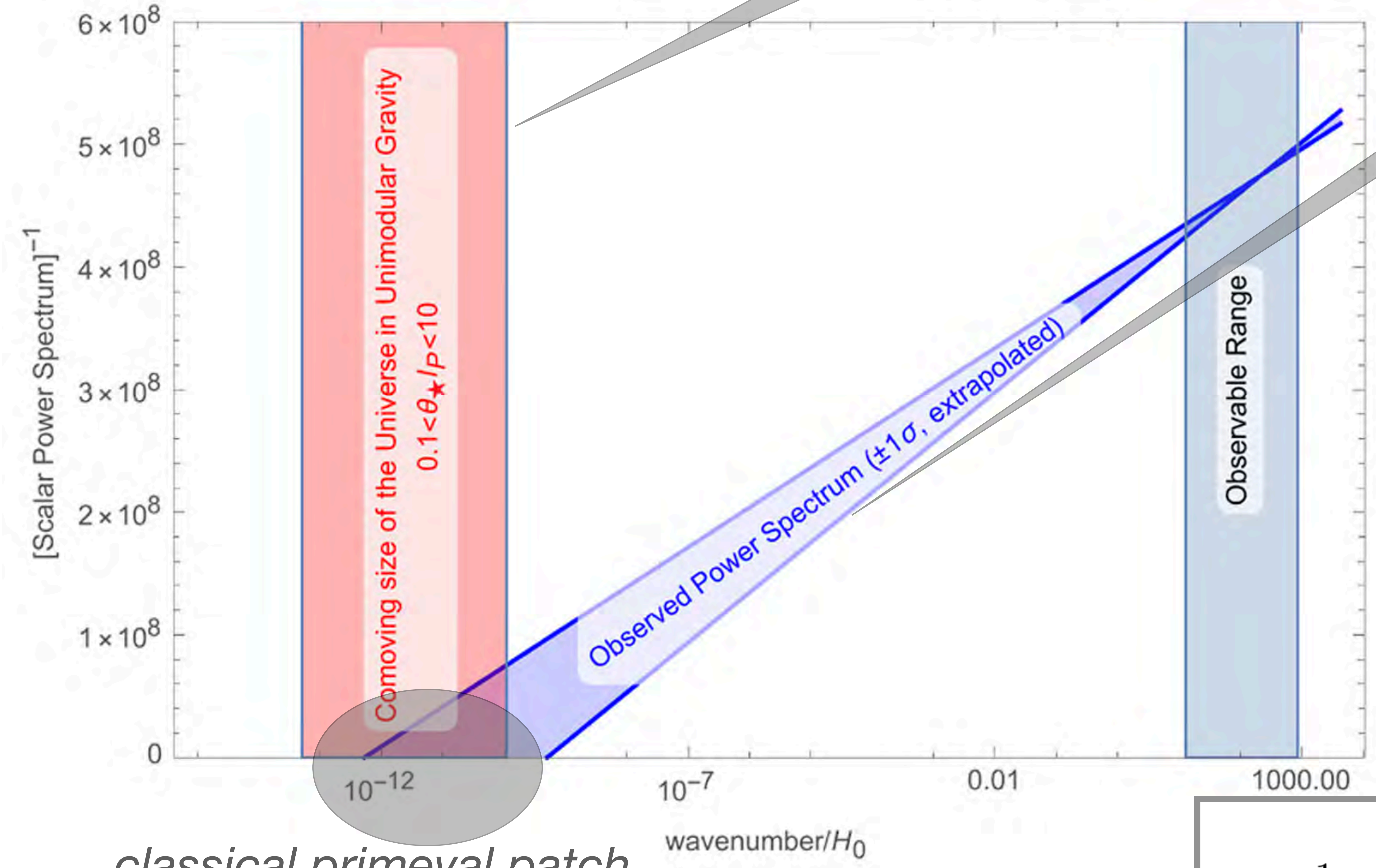
(Holographic cosmology, renormalization group)

$$P_s(k) = \frac{A_s}{1-(n_s-1)\ln(k/k_0)},$$

Prediction of Planckian primeval atom

$$n_s = 1 - \frac{1}{32.17+\ln(\theta_\star l_P)} \simeq 0.9689 + 1.6\times10^{-4}\ln(\theta_\star l_P)$$

Quantum Cosmology ties dark energy (Λ) and early universe (n_s)



classical primeval patch

NA & Magueijo 2022

(Holographic cosmology, renormalization group)

$$P_s(k) = \frac{A_s}{1-(n_s-1)\ln(k/k_0)},$$

Prediction of Planckian primeval atom

$$n_s = 1 - \frac{1}{32.17+\ln(\theta_\star l_P)} \simeq 0.9689 + 1.6\times10^{-4}\ln(\theta_\star l_P)$$

$n_s = 0.9649 \pm 0.0042$ *(Planck 2018)*

Black Holes

Big Bang

Vacuum Energy

Lorentz Violation

Does Quantum Gravity violate relativistic causality?

✓ **Quantum Gravity:** $\mathrm{Energy} \propto \mathrm{momemntum}^3$ makes it renormalizable (Horava 2009)

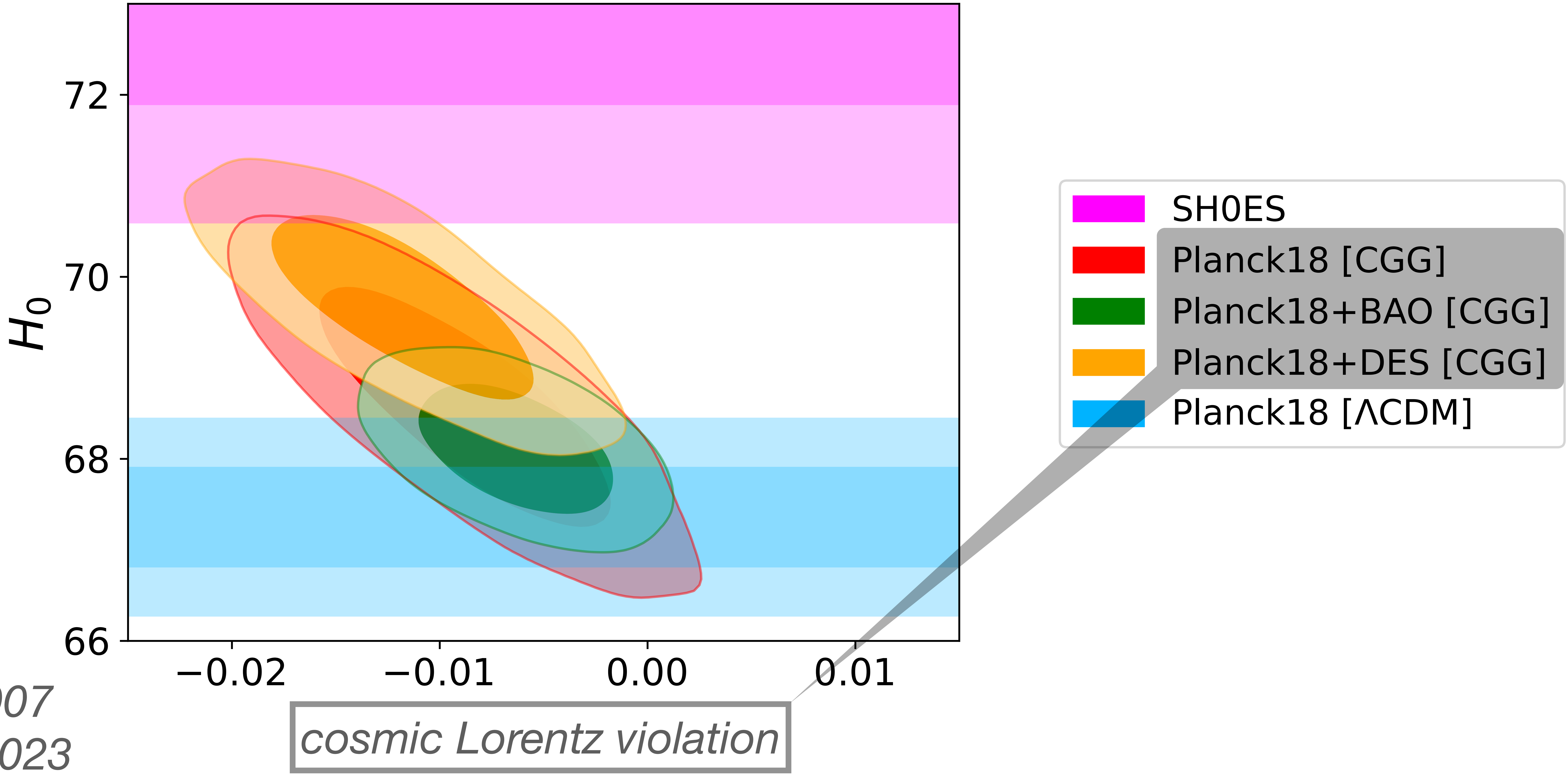
✓ **Black Holes:** information loss, echoes

✓ **Big Bang:** Cosmological horizon problem, super-horizon fluctuations

? **Lorentz:** accidental/emergent symmetry at low energies

Quantum Gravity and Hubble Tension:
A Cosmic Glitch in Gravity

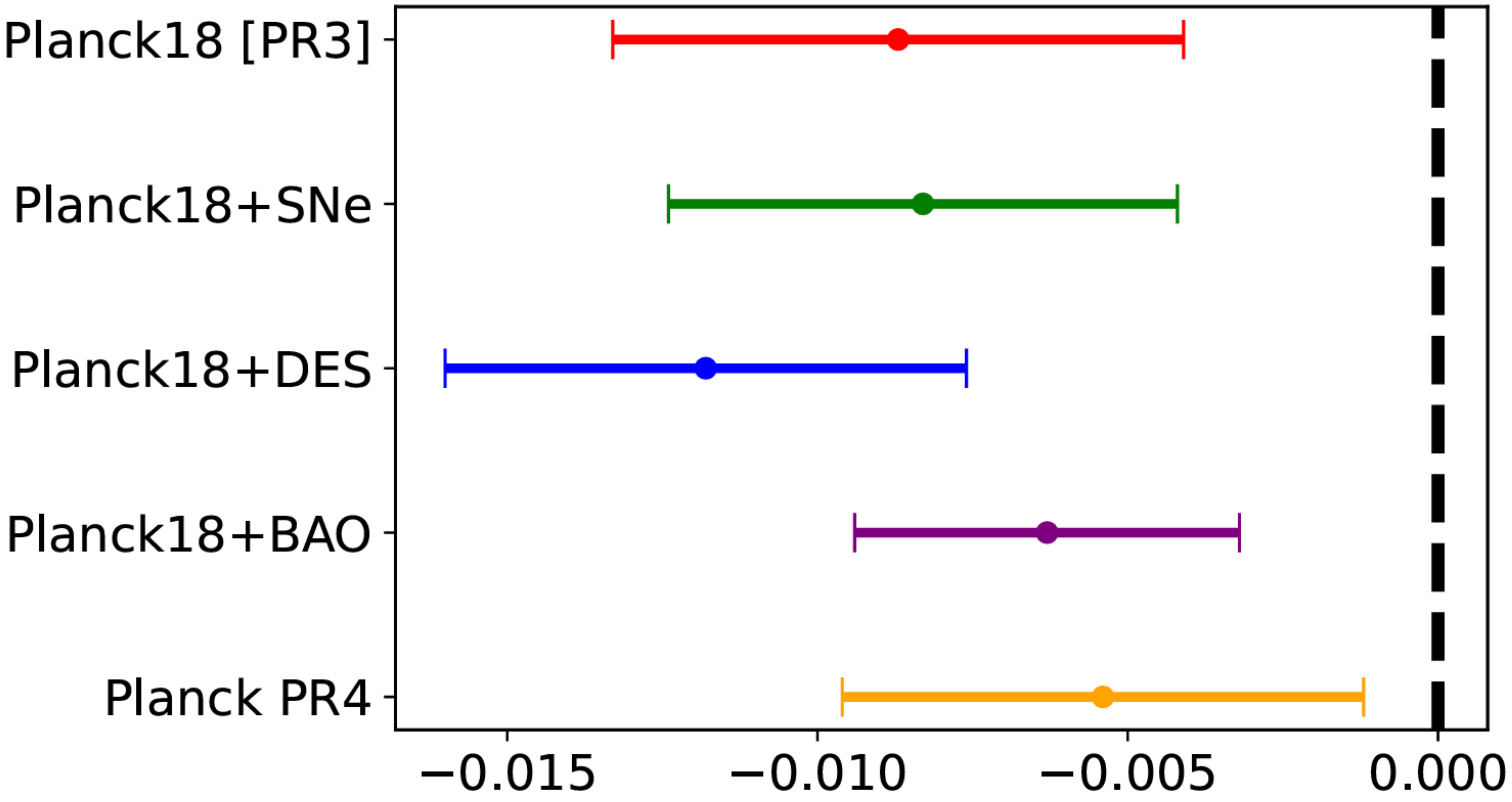
- Can Hubble tension be a signature of Lorentz violation in the theory of gravity?



Robbers, NA & Doran, 2007
Wen, Hergt, NA & Scott, 2023

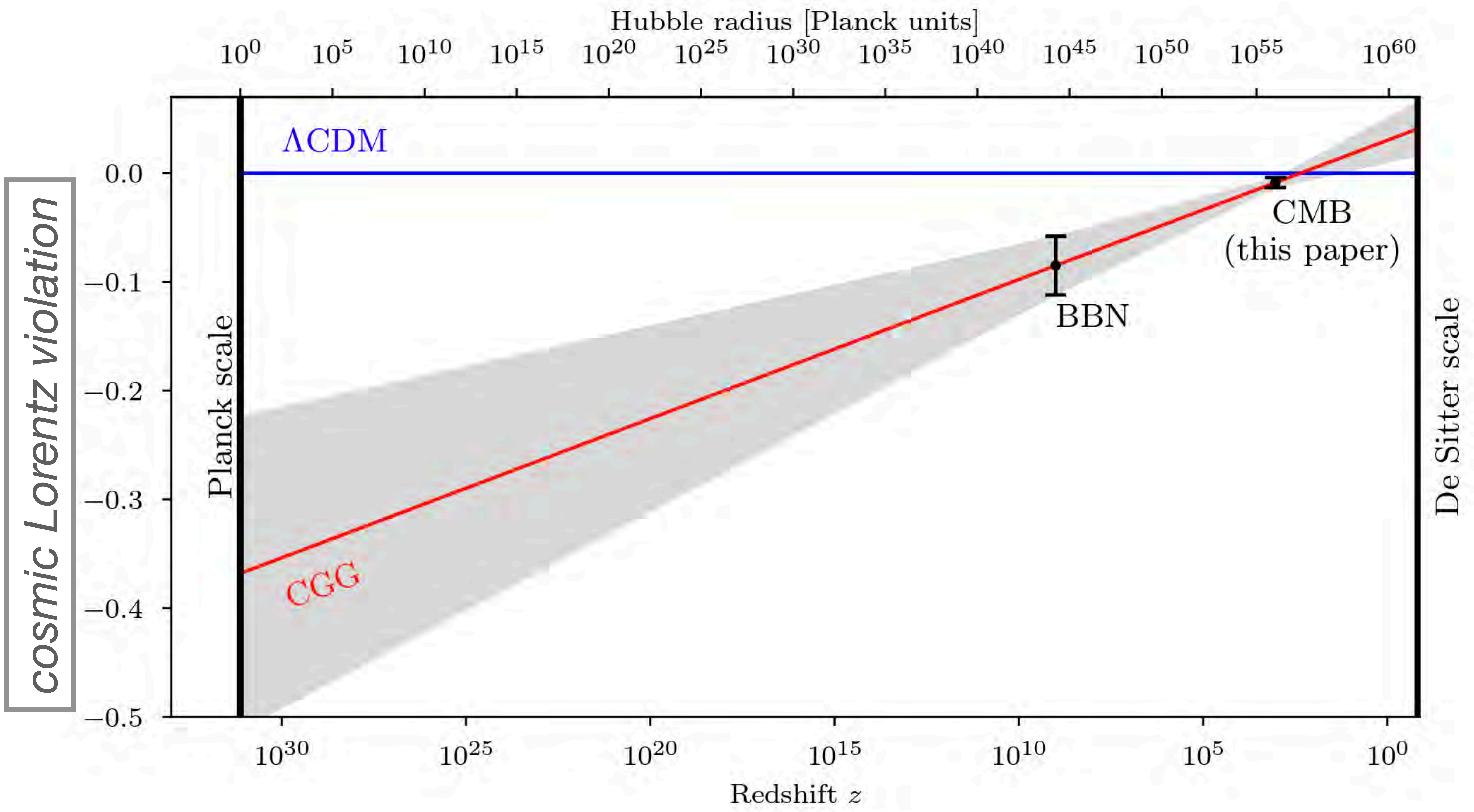
Is gravity weaker on superhorizon scales?

(Horava's little λ)



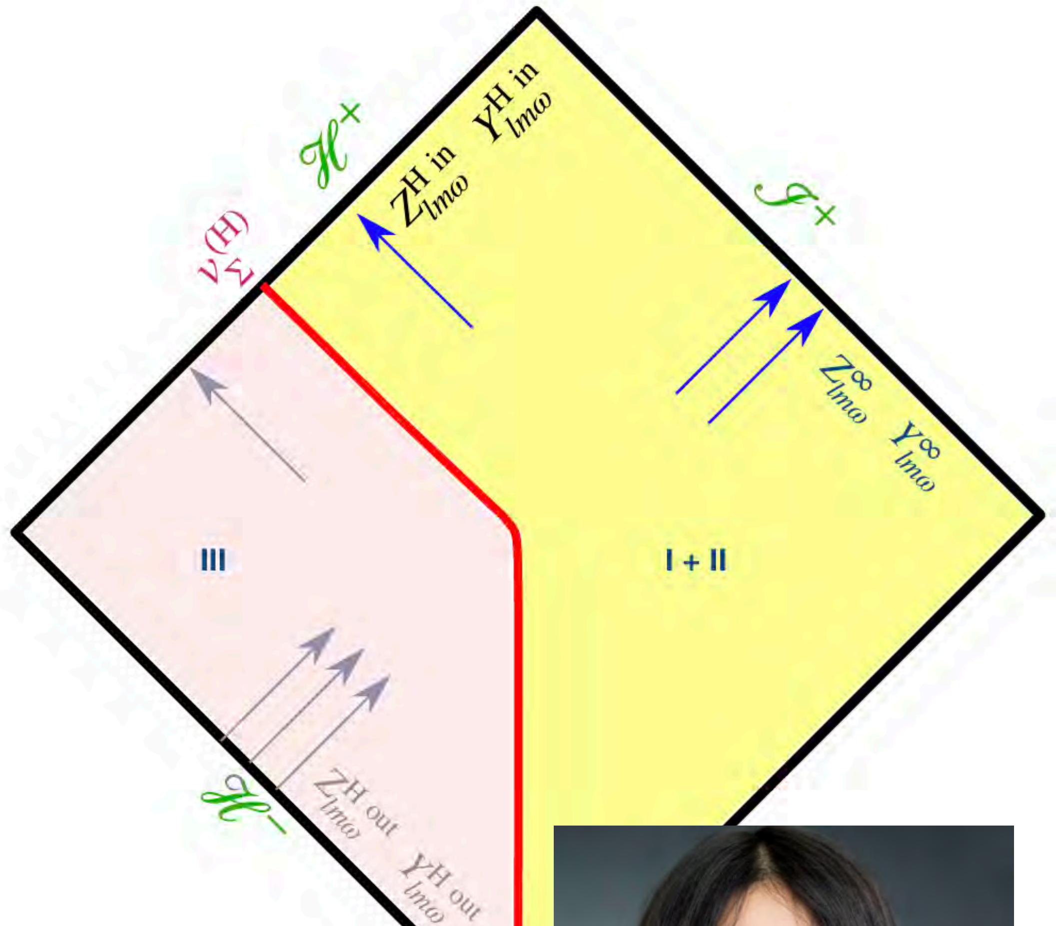
cosmic Lorentz violation

Running of Lorentz violation w/ scale?

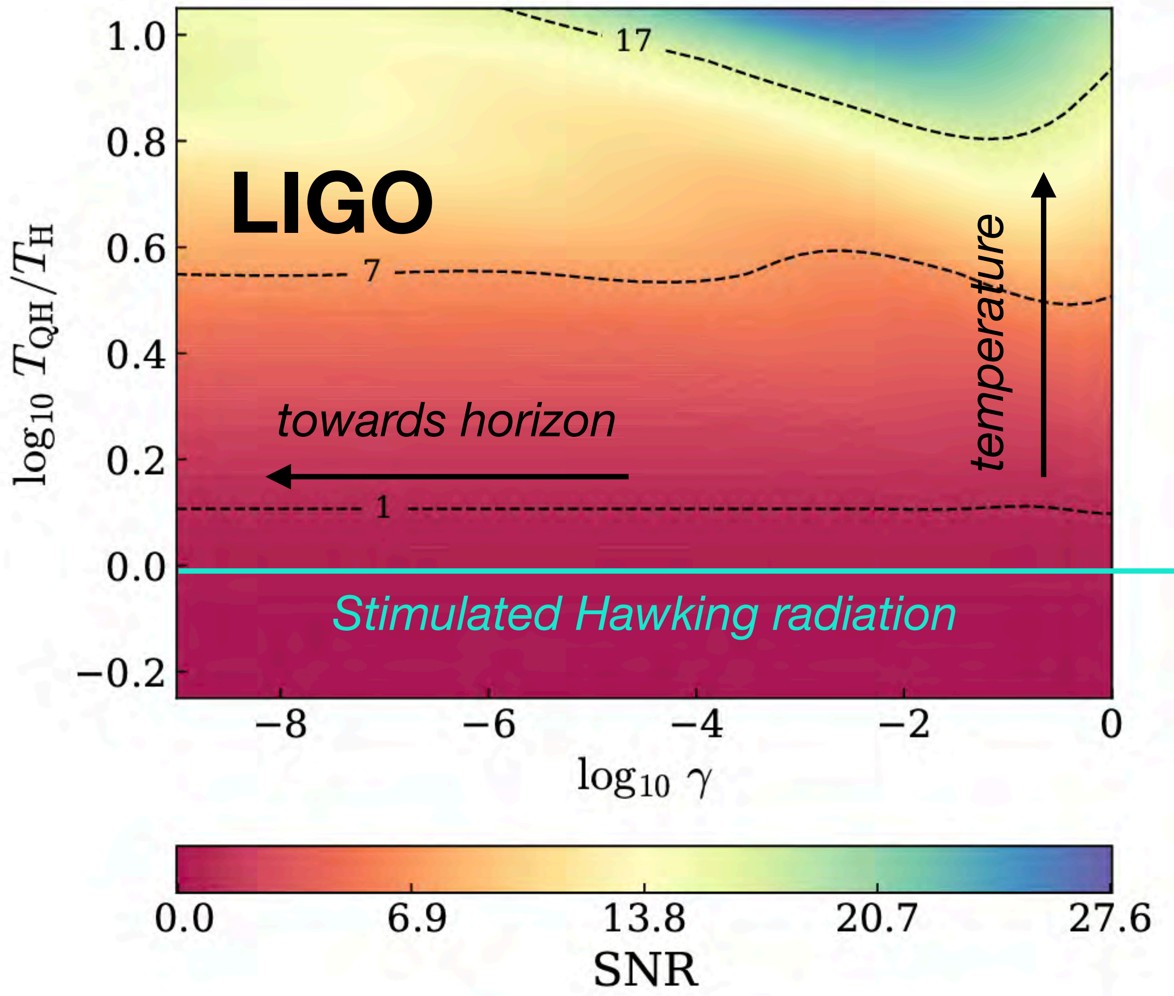


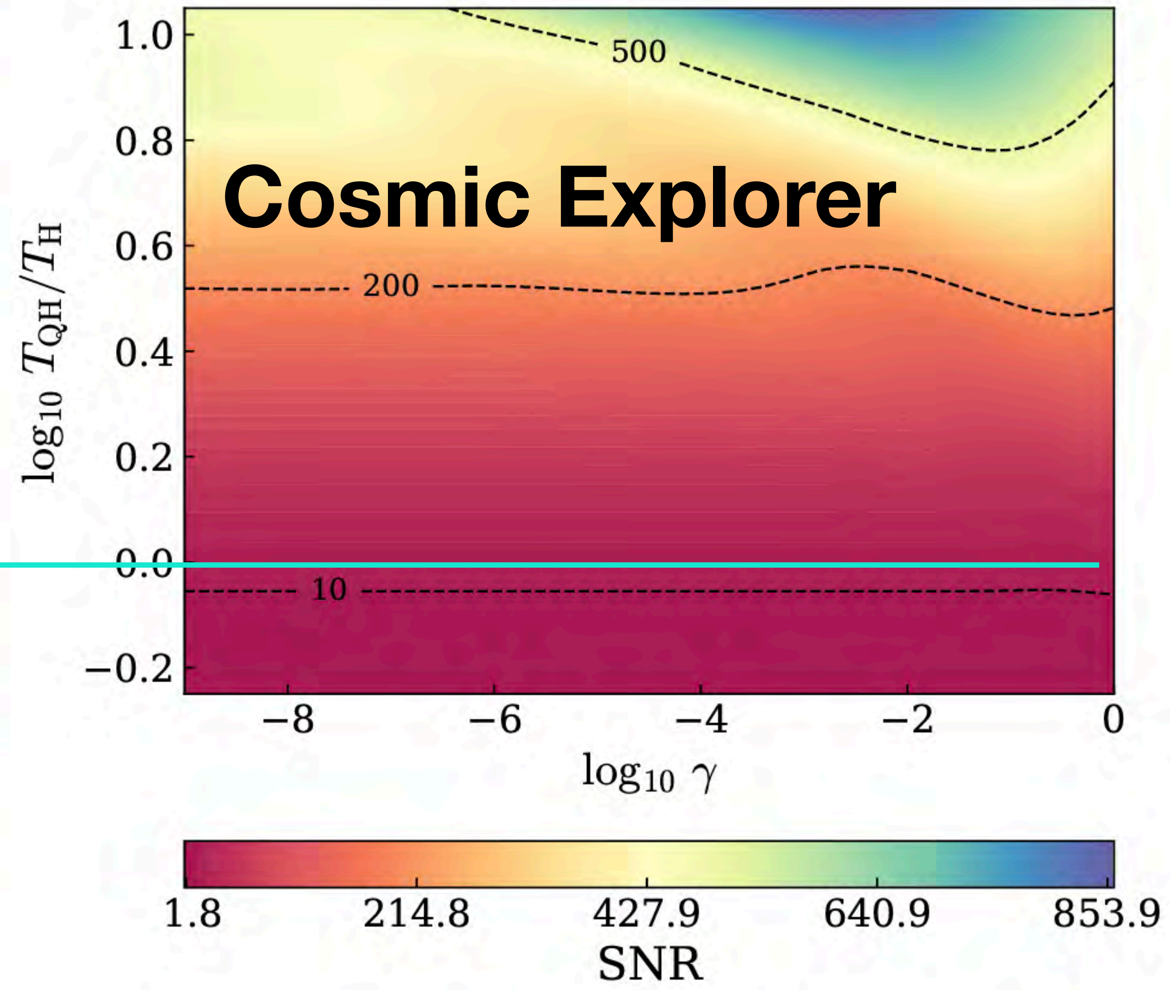

FUTURE

Future is bright!



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





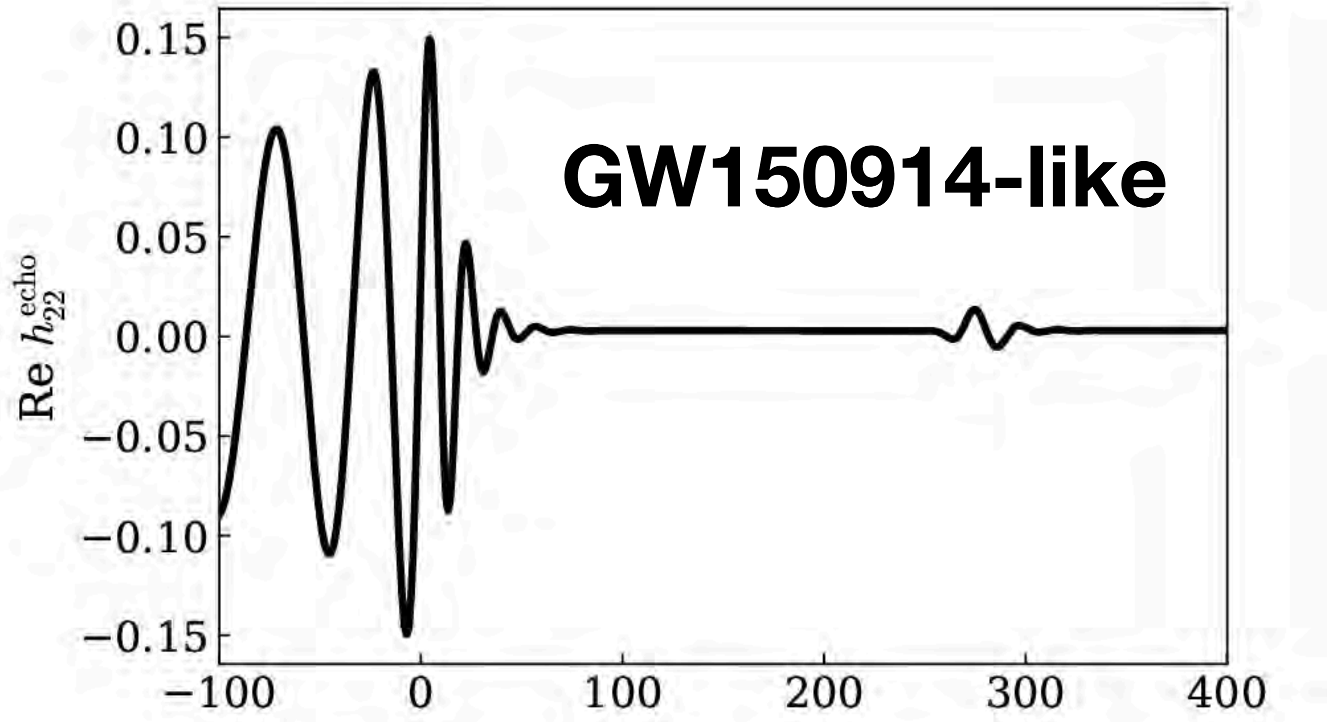


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set $v_\Sigma^{(H)} = -13, \Delta v = 2/\kappa = 8, \gamma = 10^{-15}$, and $T_{\rm QH} = T_H$.

arXiv > gr-qc > arXiv:2203.03174

Search...

Help | Advar

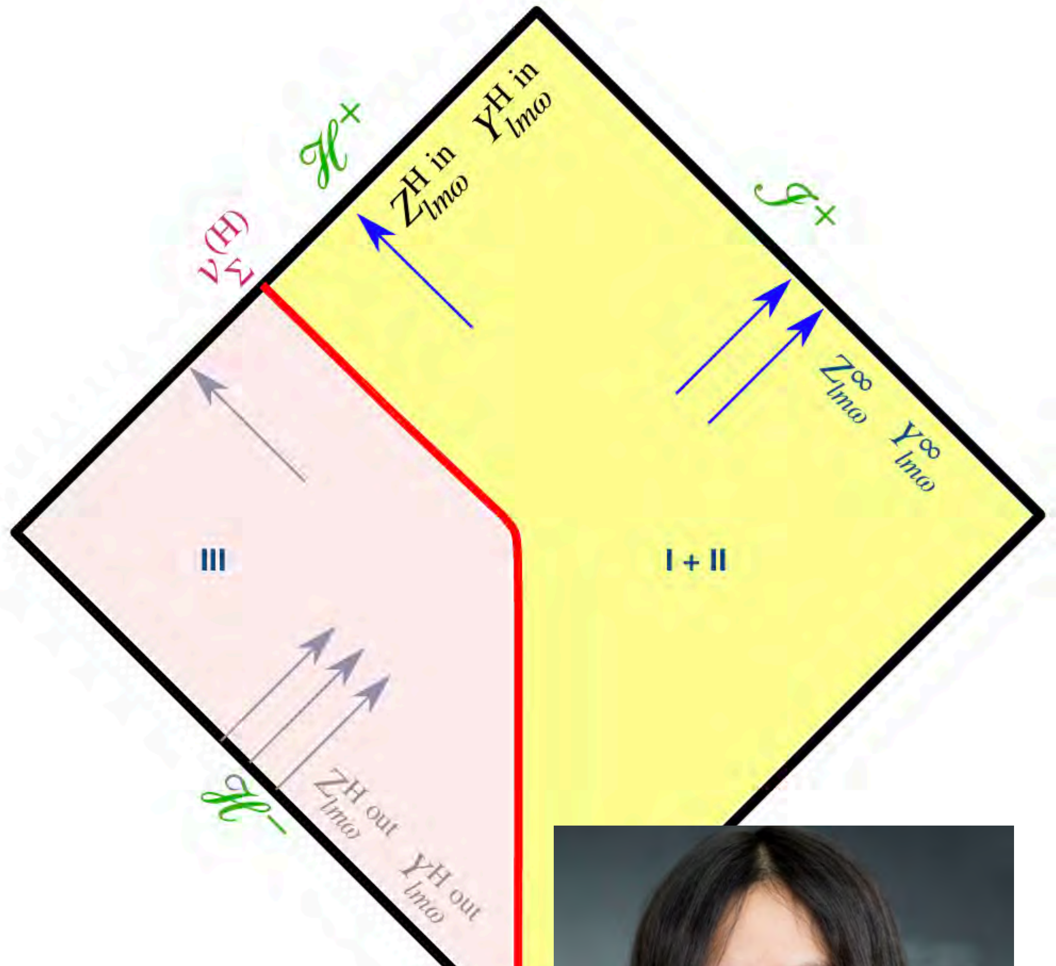
General Relativity and Quantum Cosmology

[Submitted on 7 Mar 2022]

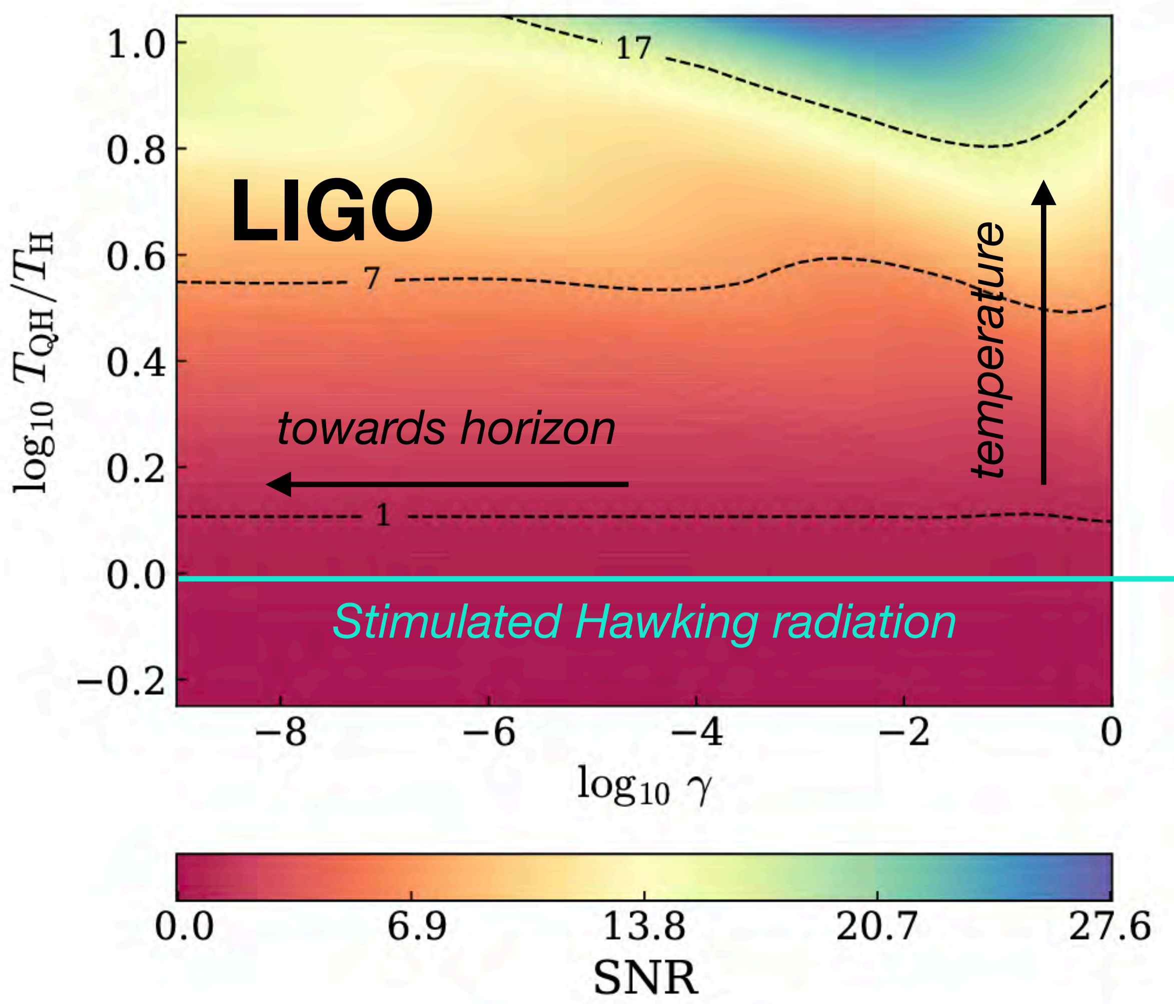
Gravitational-wave echoes from numerical-relativity waveforms via space-time construction near merging compact objects

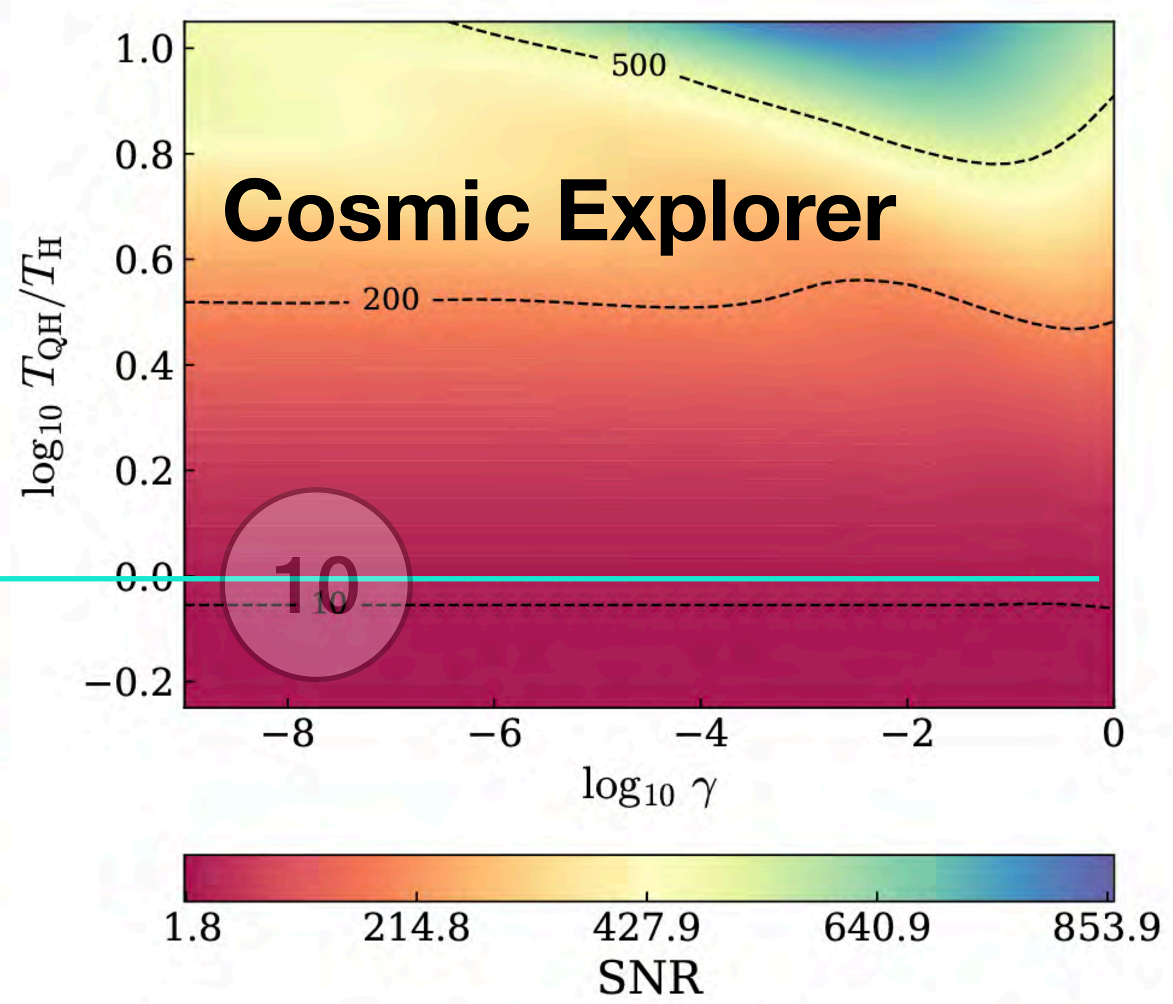
Sizheng Ma, Qingwen Wang, Nils Deppe, Nils L. Fischer, François Hébert, Lawrence E. Kidder, Jordan Moxon, William Throwe, Mark A. Scheel, Yanbei Chen

Future is bright!



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





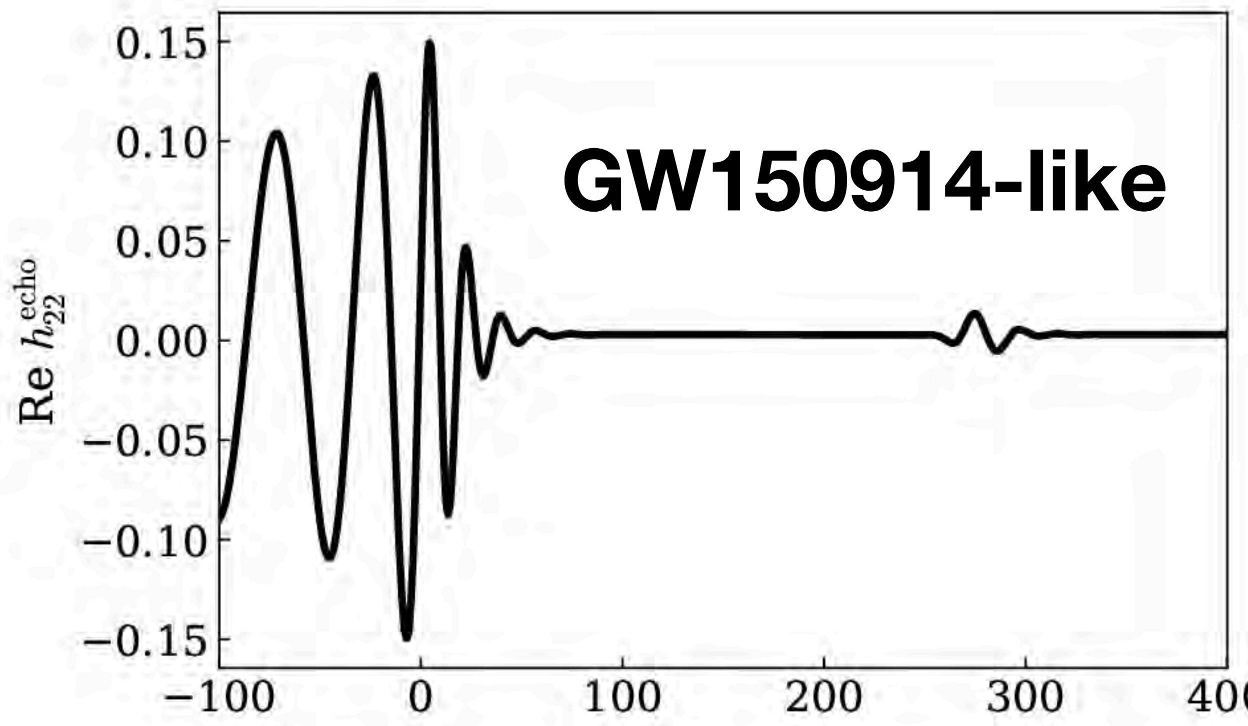


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set $v_\Sigma^{(H)} = -13, \Delta v = 2/\kappa = 8, \gamma = 10^{-15}$, and $T_{QH} = T_H$.

arXiv > gr-qc > arXiv:2203.03174

Search...
Help | Advan

General Relativity and Quantum Cosmology

[Submitted on 7 Mar 2022]

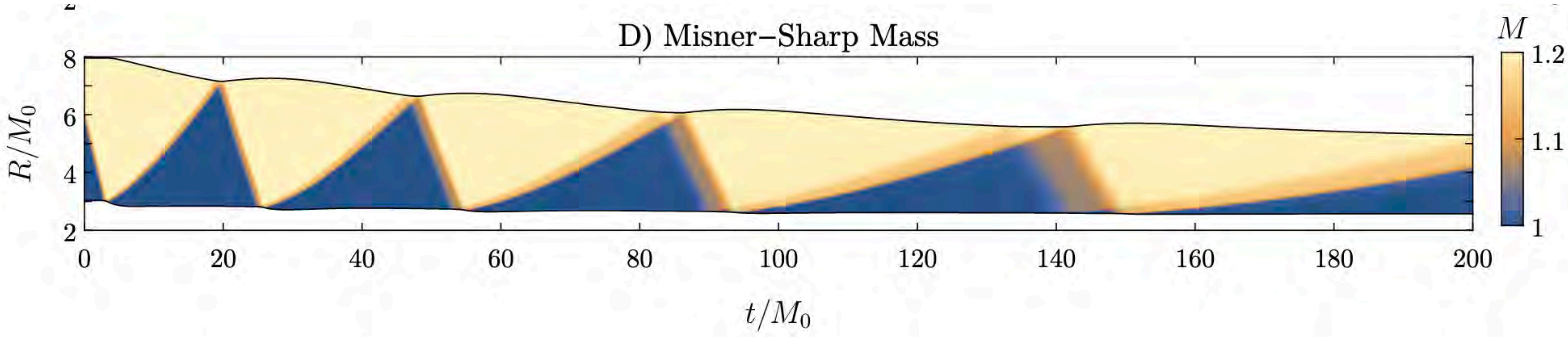
Gravitational-wave echoes from numerical-relativity waveforms via space-time construction near merging compact objects

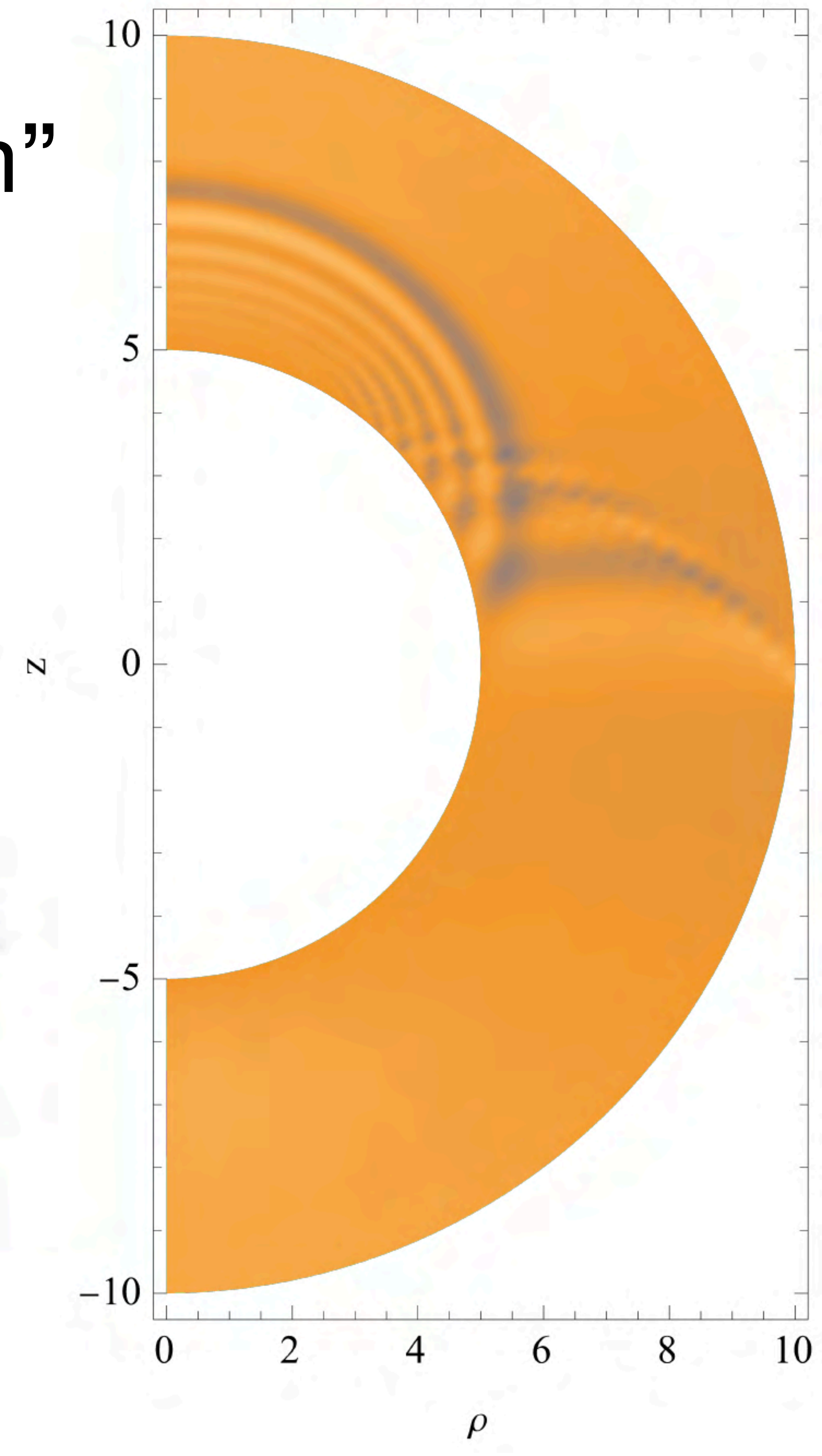
Sizheng Ma, Qingwen Wang, Nils Deppe, Nils L. Fischer, François Hébert, Lawrence E. Kidder, Jordan Moxon, William Throwe, Mark A. Scheel, Yanbei Chen

Black Hole Echoes in Numerical Relativity

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

Dailey, NA & Schnetter 2023 (+ in prep.)





Can we detect the cosmic preferred frame in the solar system?

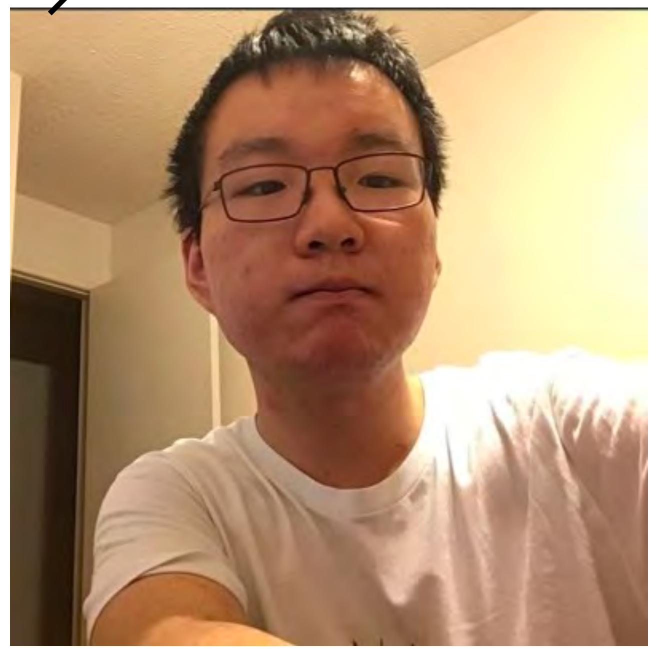
arXiv > gr-qc > arXiv:2311.17873

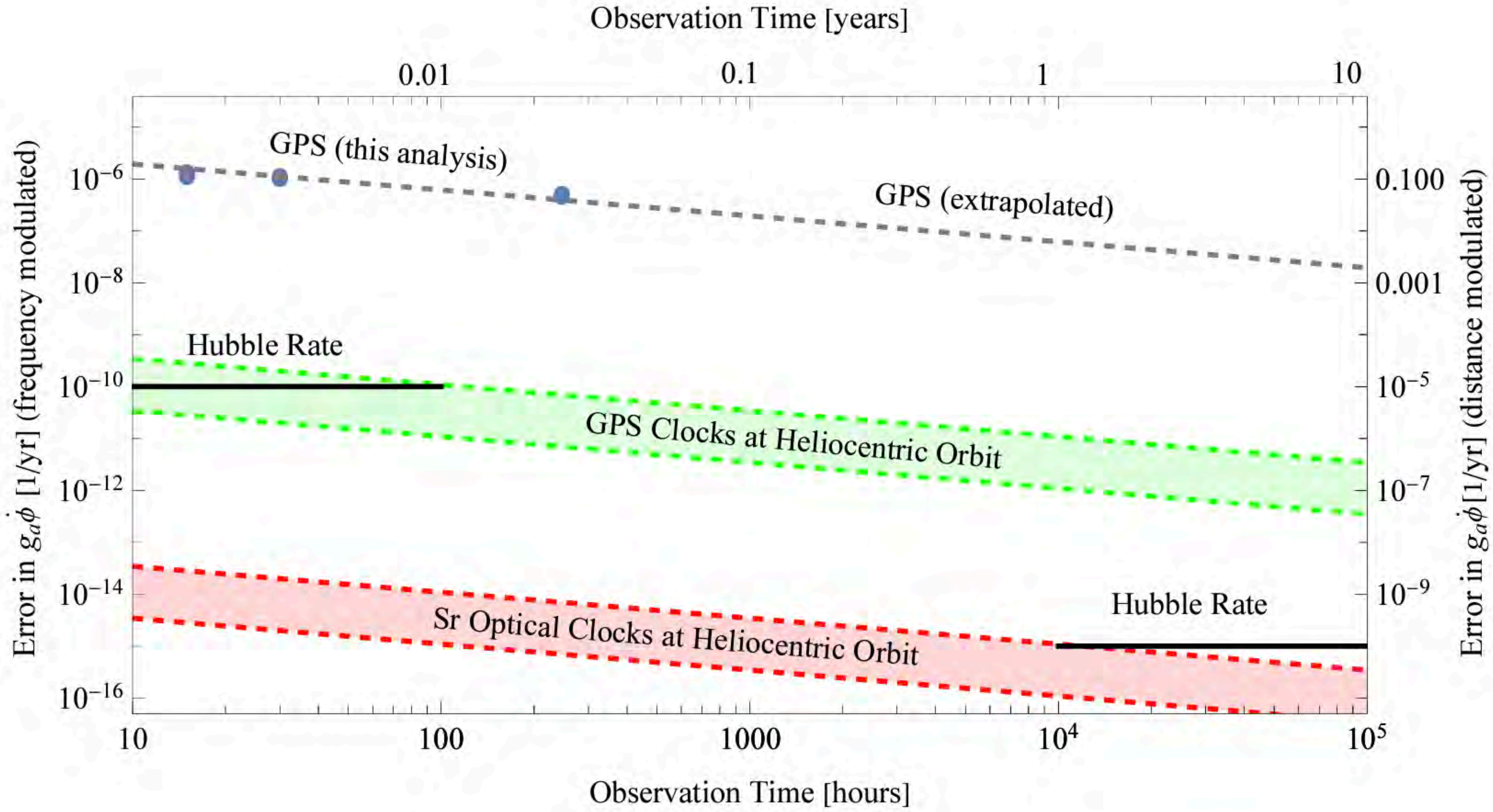
General Relativity and Quantum Cosmology

[Submitted on 29 Nov 2023]

Detecting cosmological scalar fields using orbital networks of quantum sensors

Yu Li, Ruolin Liu, Conner Dailey, Niayesh Afshordi



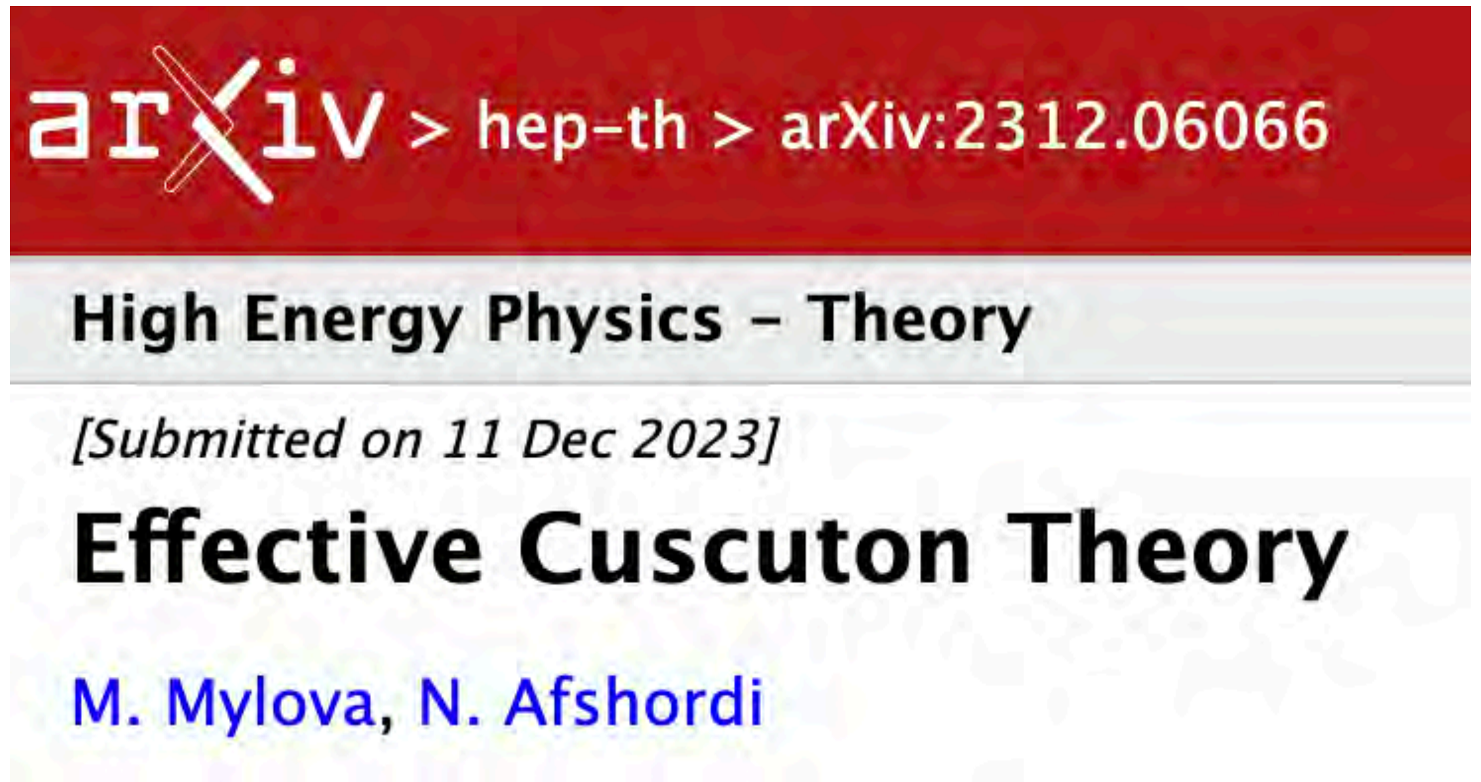


An aether revival?

- **Horava-Lifshitz gravity:** $\text{Energy} \propto \text{momentum}^3$ makes quantum gravity renormalizable (but *violates Lorentz symmetry*)
- **Dark Matter**
- **Dark Energy**
- **Big Bang Reference Frame**
- **Bell's inequality:** realist quantum mechanics

An aether revival?

- **Horava-Lifshitz gravity:** $\text{Energy} \propto \text{momentum}^3$ makes quantum gravity renormalizable (but *violates Lorentz symmetry*)
- **Dark Matter**
- **Dark Energy**
- **Big Bang Reference Frame**
- **Bell's inequality:** realist quantum mechanics



arXiv > hep-th > arXiv:2312.06066

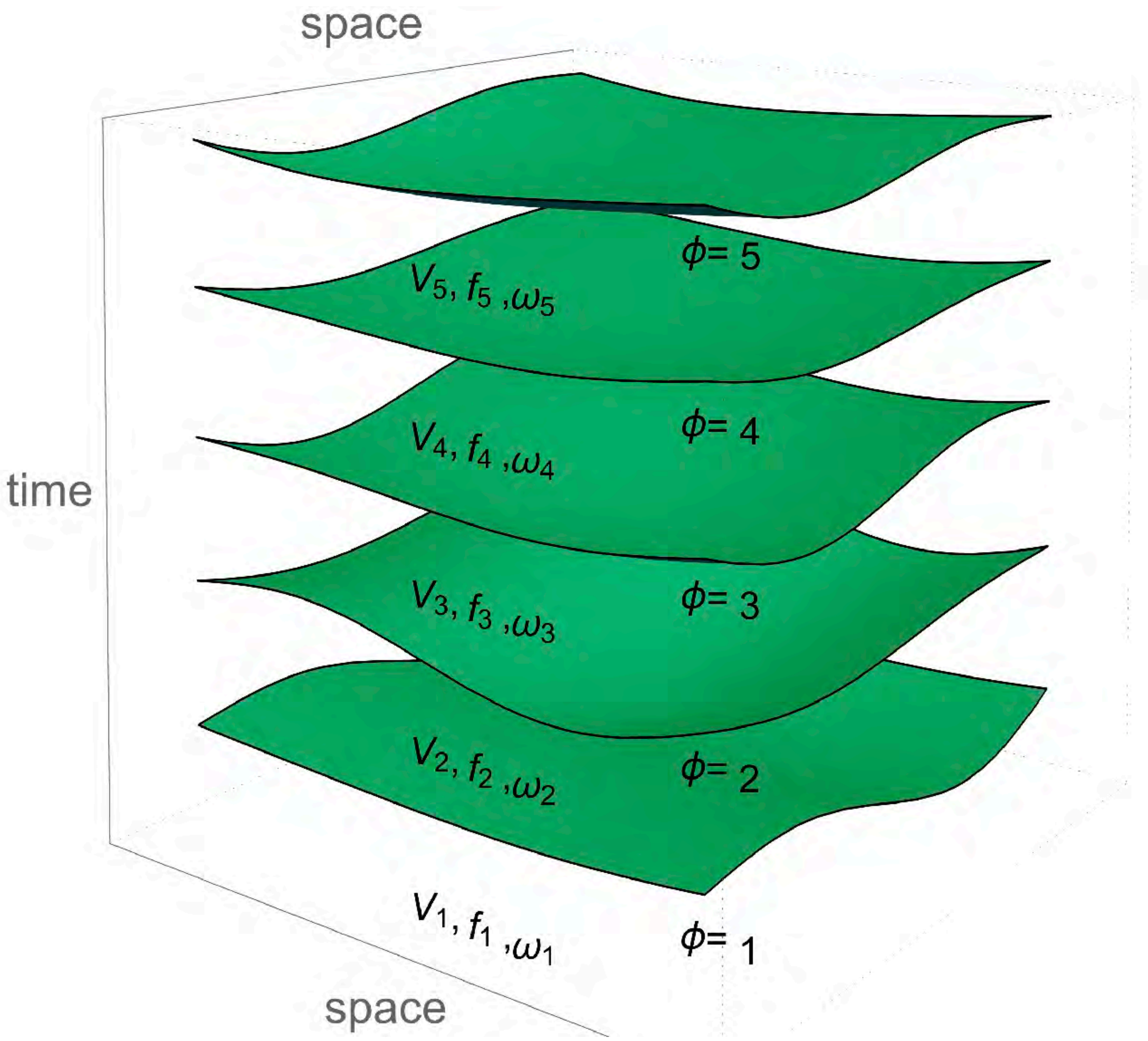
High Energy Physics – Theory

[Submitted on 11 Dec 2023]

Effective Cuscuton Theory

M. Mylova, N. Afshordi

A covariant non-dynamical aether
(see Maria's talk next week)



Can we find (further) evidence for

- Black Hole Echoes?
- Beyond-Kerr multipoles?
- Shape of the power spectrum from “primeval atom”?
- Tensor Modes?
- (Folded) Bispectrum of a thermal Big Bang?
- Cosmic Lorentz violation?

We shall observe the hell out of early and late cosmos!

esa
euclid

SPHEREx

LSST
Legacy Survey of Space and Time

DARK ENERGY SPECTROSCOPIC INSTRUMENT

LiteBIRD

lisa

COSMIC EXPLORER

Einstein Telescope

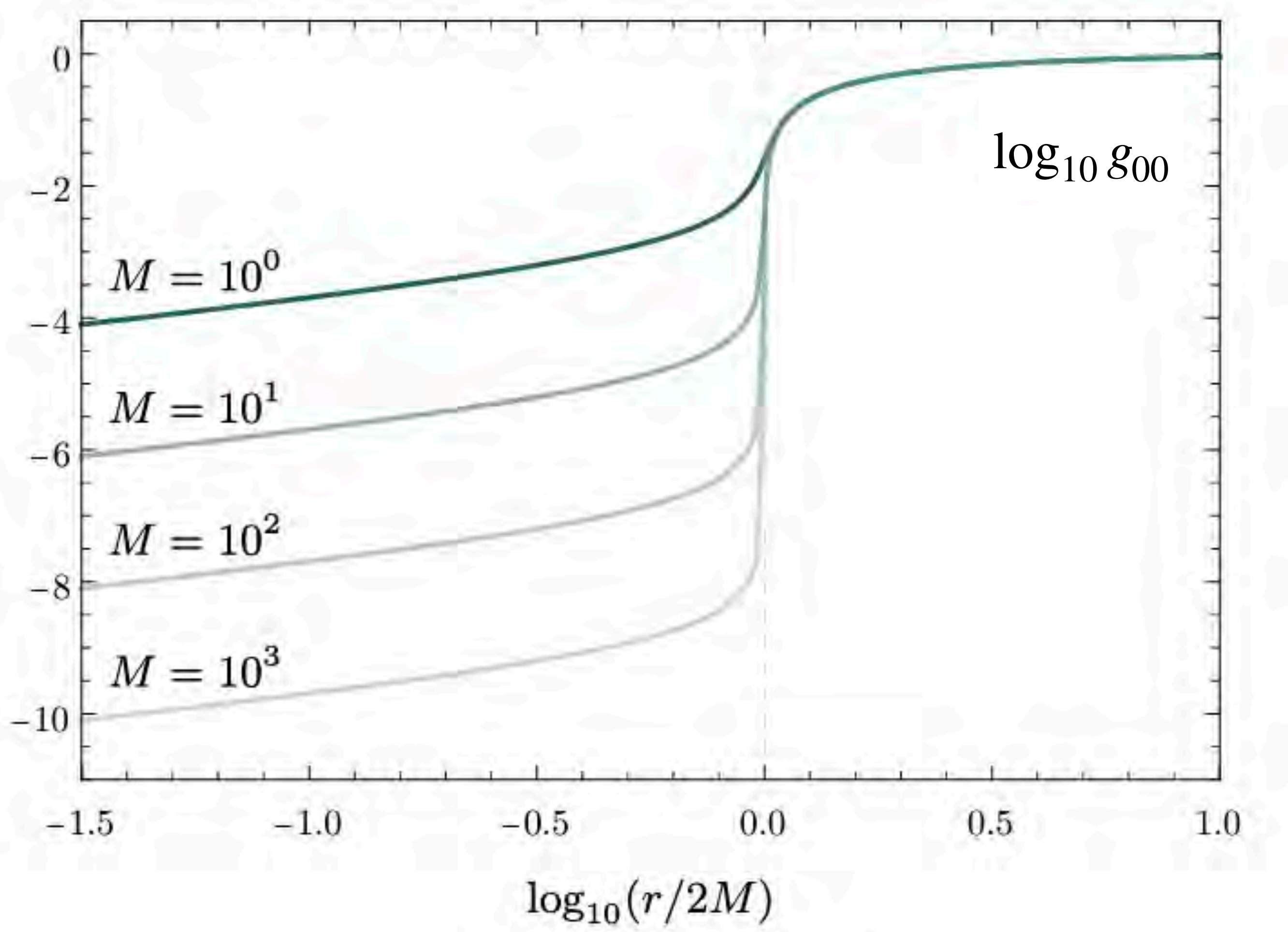
We shall know!

Bonus slides

Firewalls 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; $g_{00} \sim r^{\sqrt{3}-1}$

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




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

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.

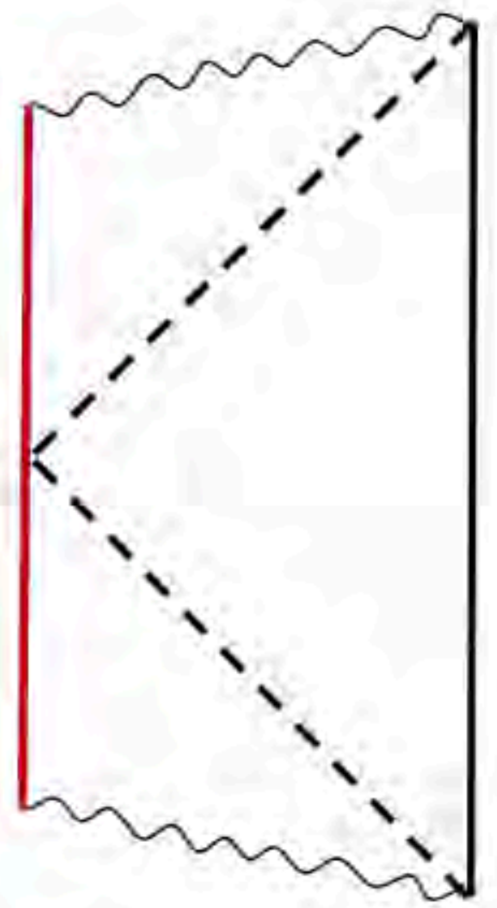


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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

CP-symmetry (RP^3 geon)

Z_2 identification → Boltzmann reflection

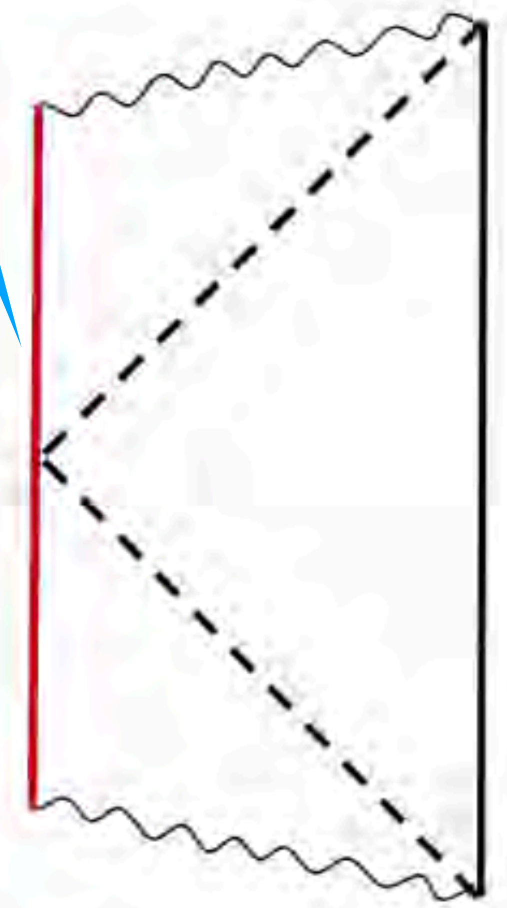


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(Hartman & Maldacena 2013)

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.

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

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

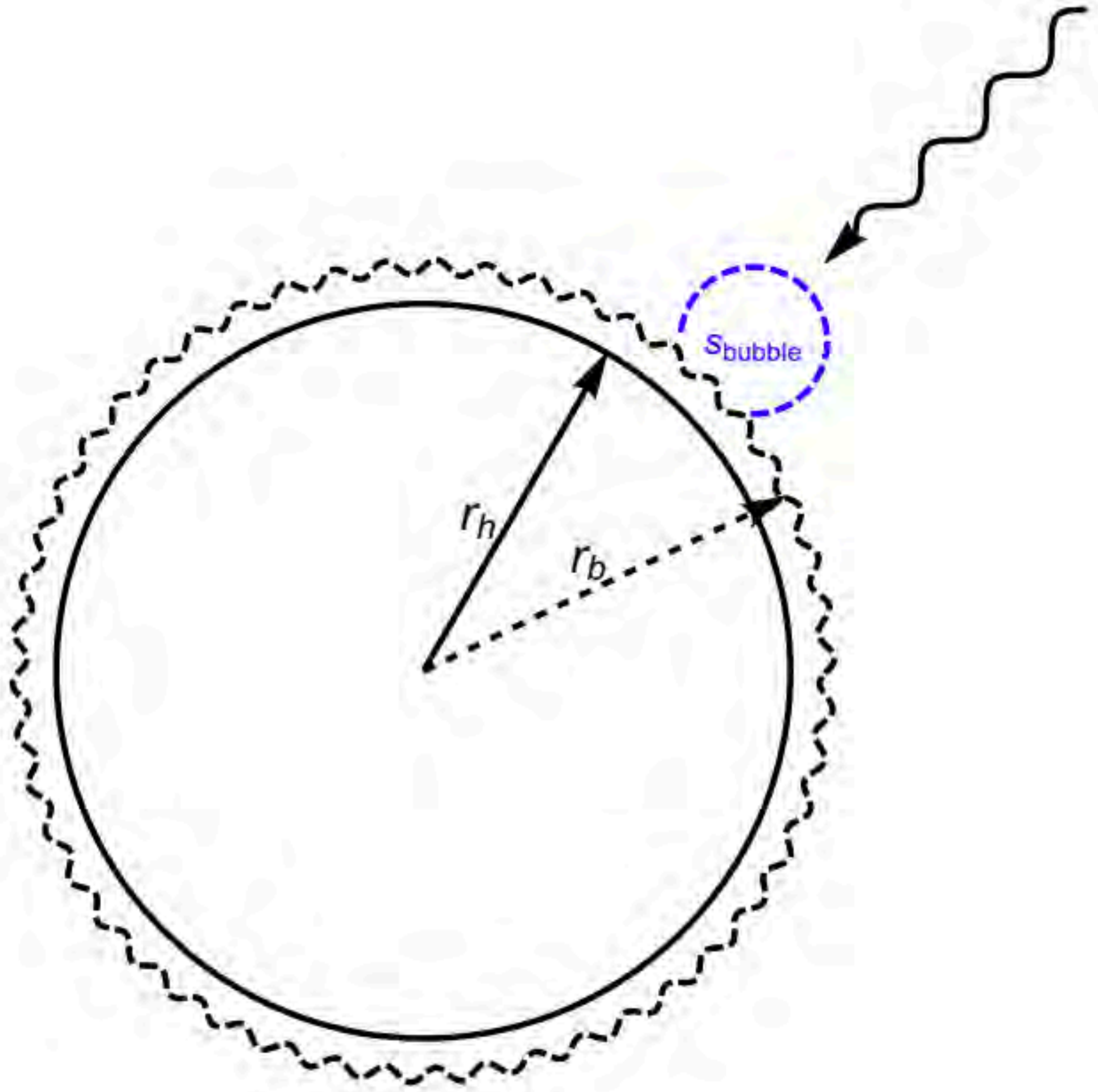
Abstract: Information located in an entanglement island in semiclassical gravity can be nonperturbatively reconstructed from distant radiation, implying a radical breakdown of effective field theory. We show that this occurs well outside of the black hole stretched horizon. We compute the island associated 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.

arXiv:2312.03078v3 [hep-th] 20 Dec 2023

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

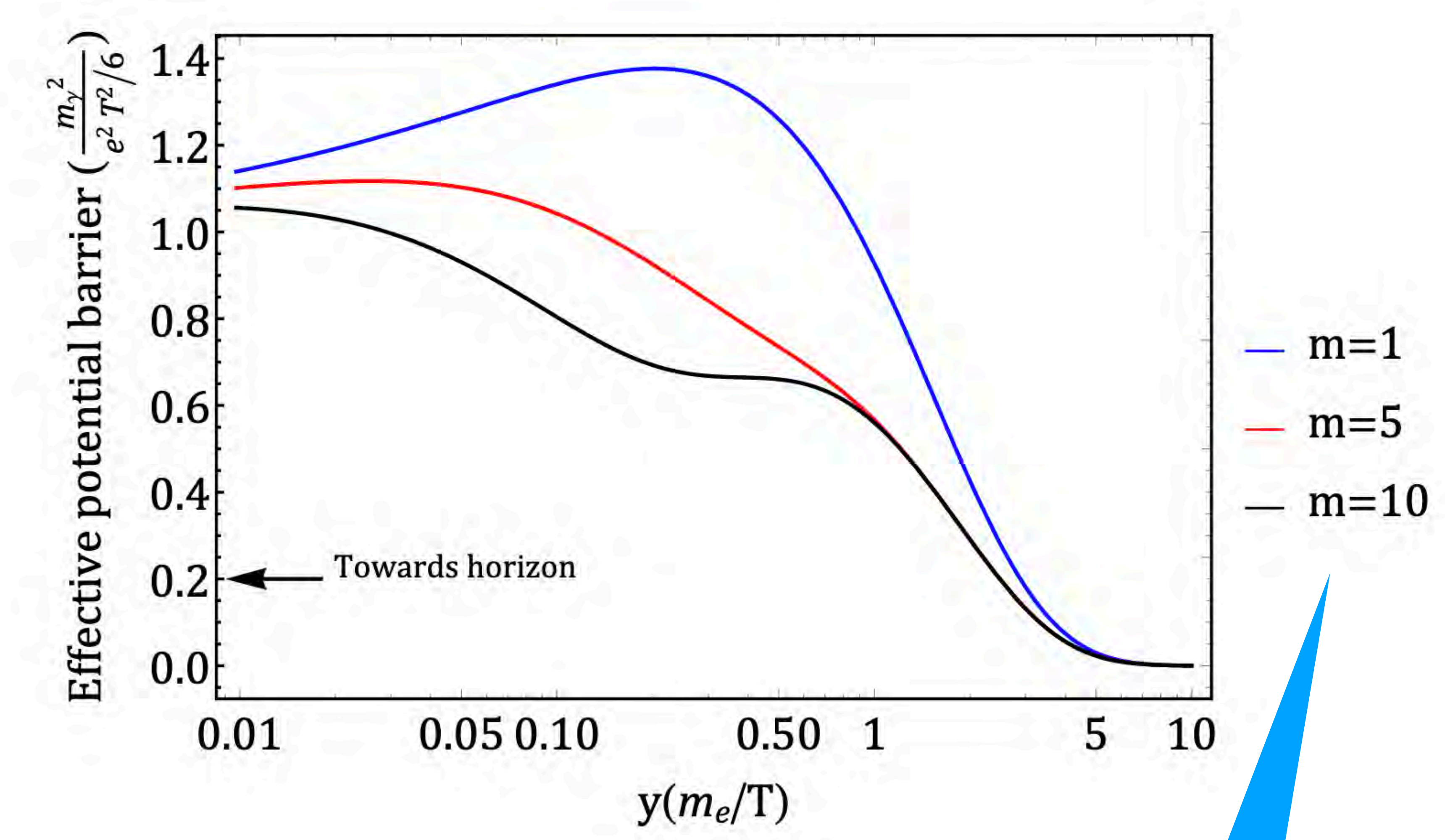
- Reflection off virtual electron-positron pairs near horizon → Boltzmann Albedo for photons

- No quantum gravity needed!



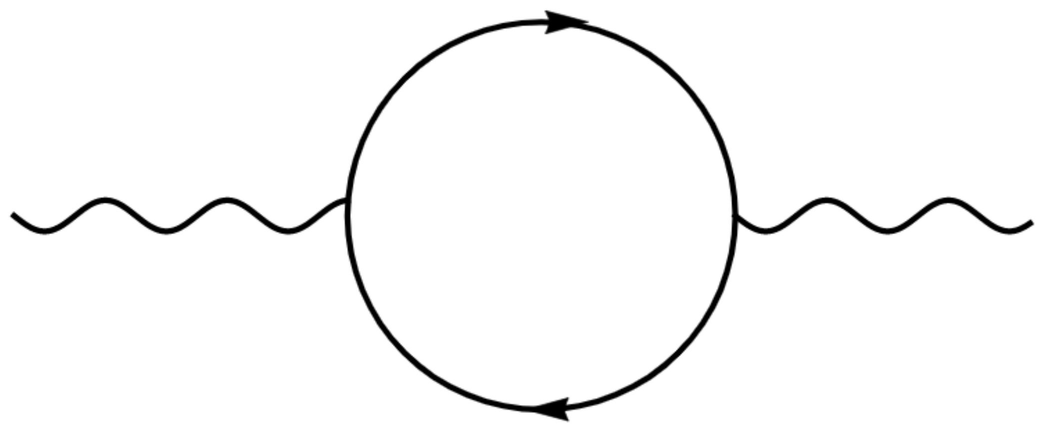
Two independent derivations

- Photon mass acquired through Hawking Plasma



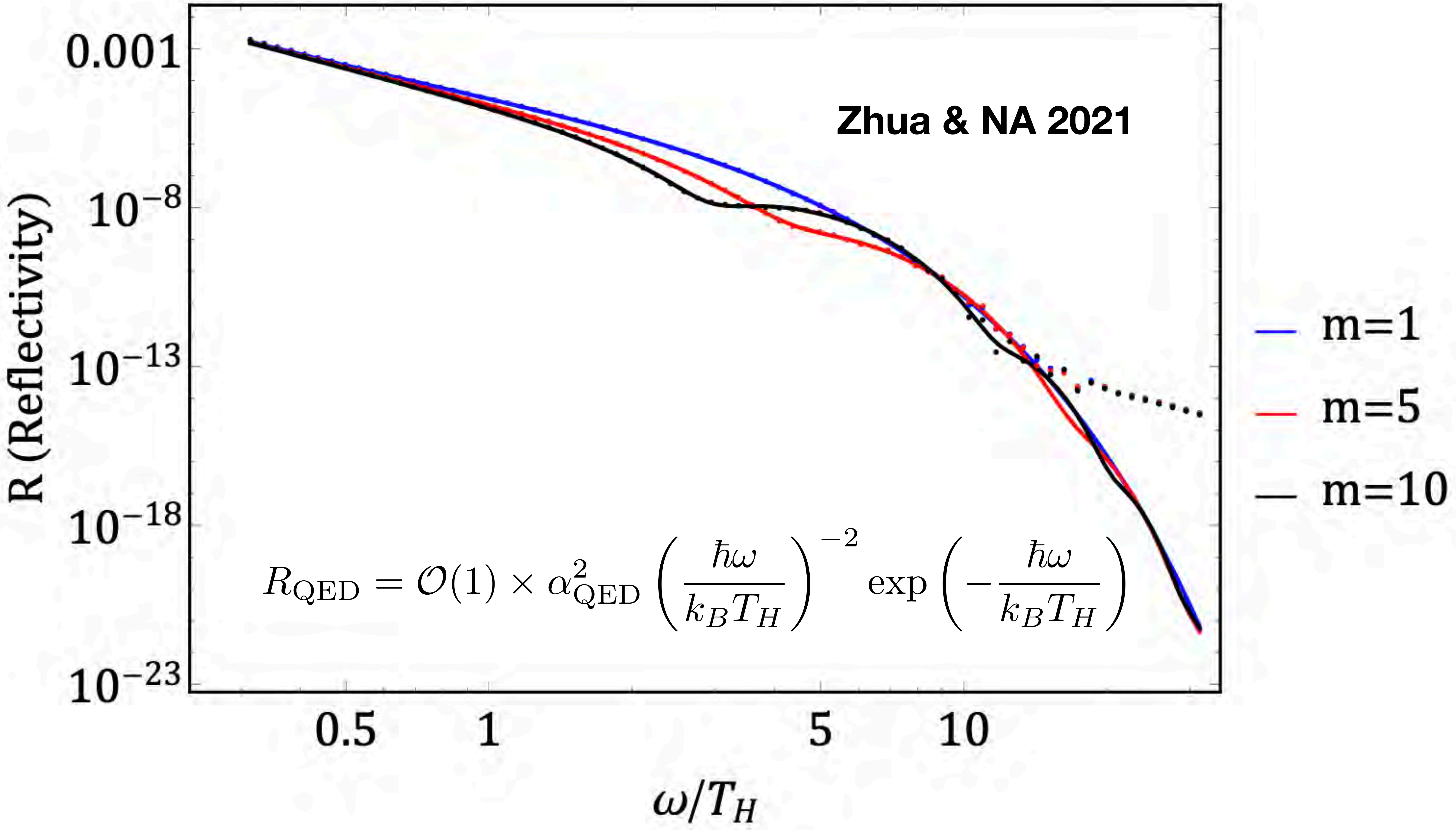
different interpolations

- Projecting photon 1-loop propagator from Minkowski to Rindler



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

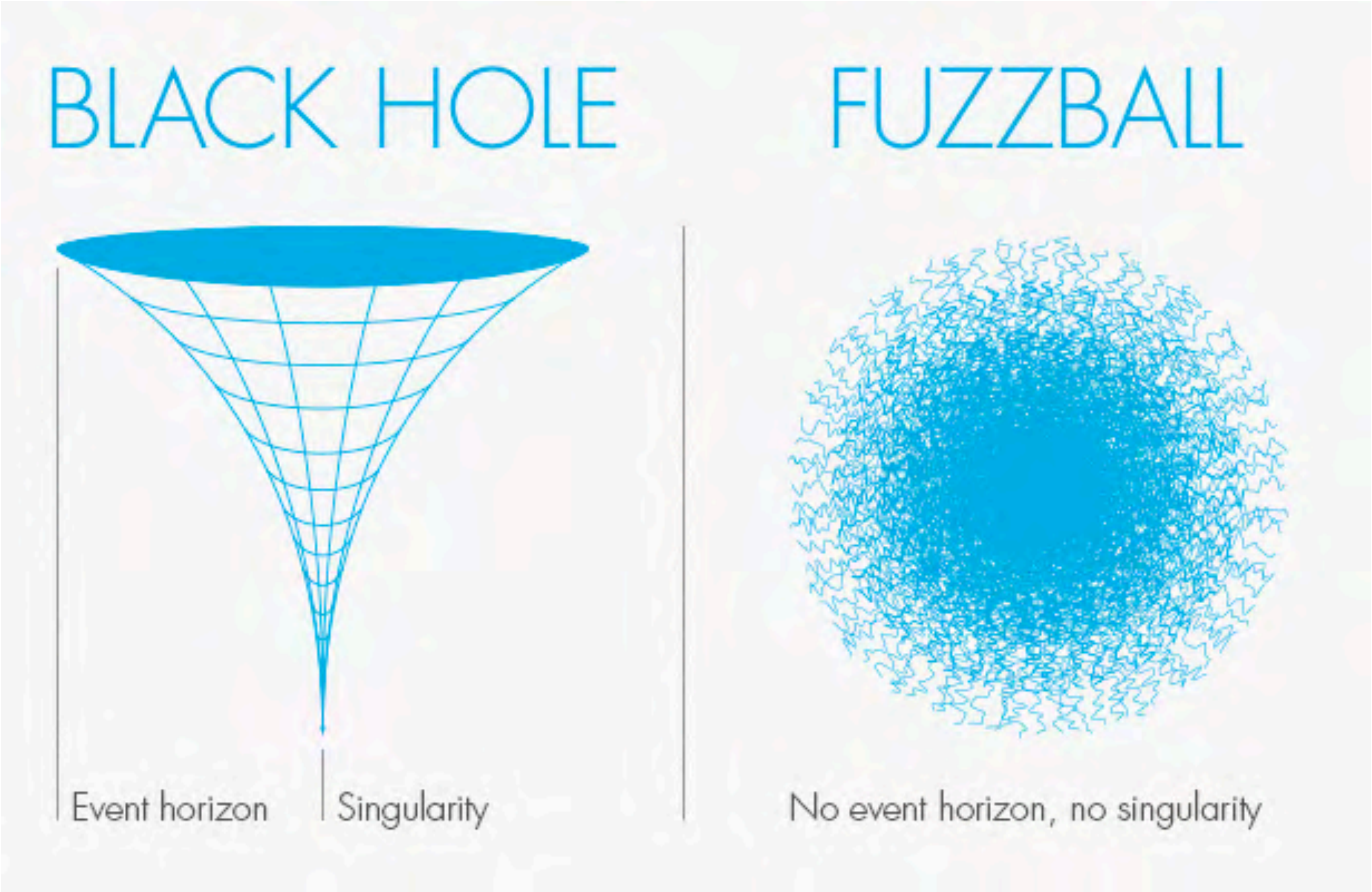
$$\pi^M(p^2) = \frac{e^2}{2\pi^2}\int_0^1 dx x(1-x)\ln\left(1 + \frac{p^2 x(1-x)}{m_e^2}\right)$$



- 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

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

Fuzzballs in String Theory



Physics Reports 467 (2008) 117–171

Contents lists available at ScienceDirect

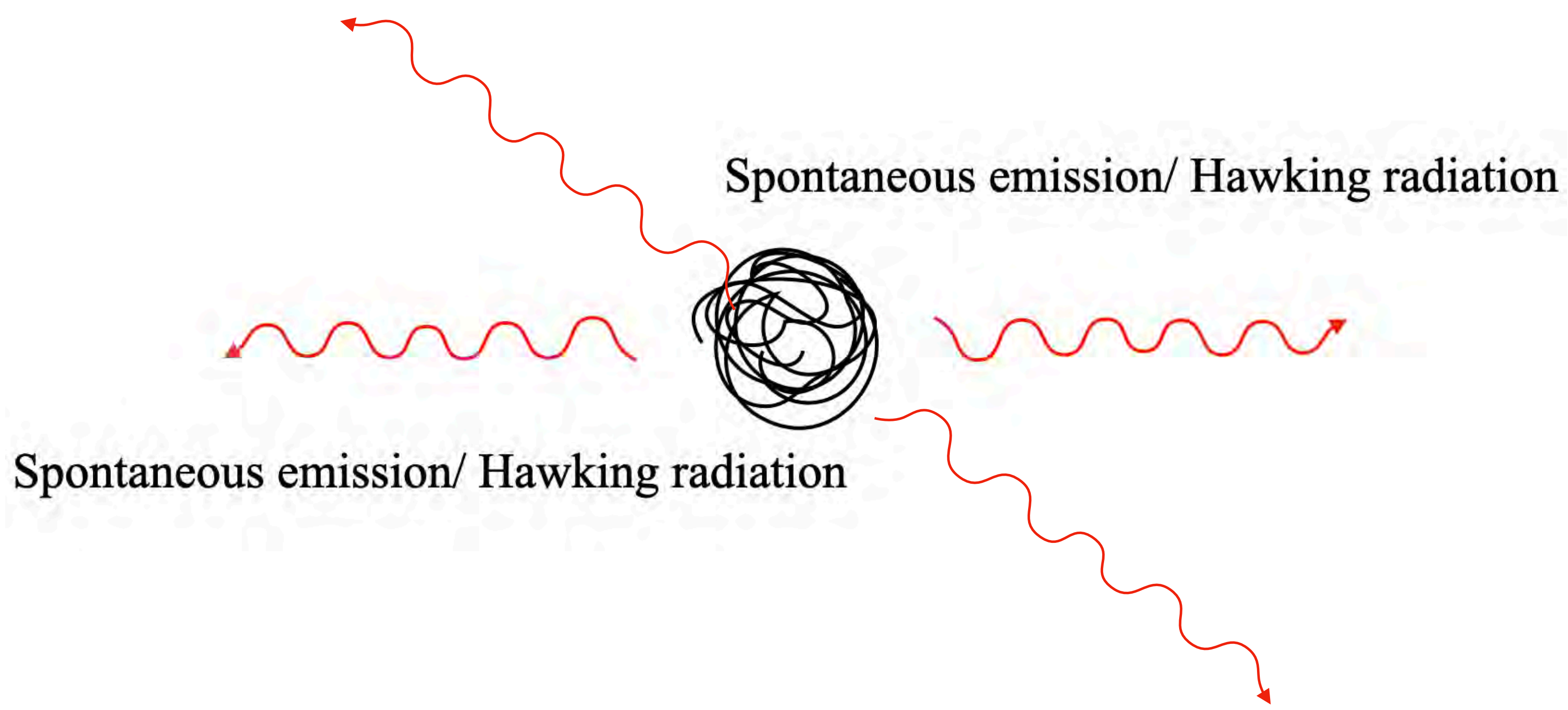
Physics Reports

journal homepage: 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

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 and mathur@mps.ohio-state.edu

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

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

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.

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

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)/($\pi \times$ Temperature). We further comment on the physical interpretation of this coincidence and the corresponding holographic interpretation of black hole echoes.

Scrambling Time=Echo Time!

Quantum nature of black holes: fast scrambling versus echoes

Krishan Saraswat & Niayesh Afshordi

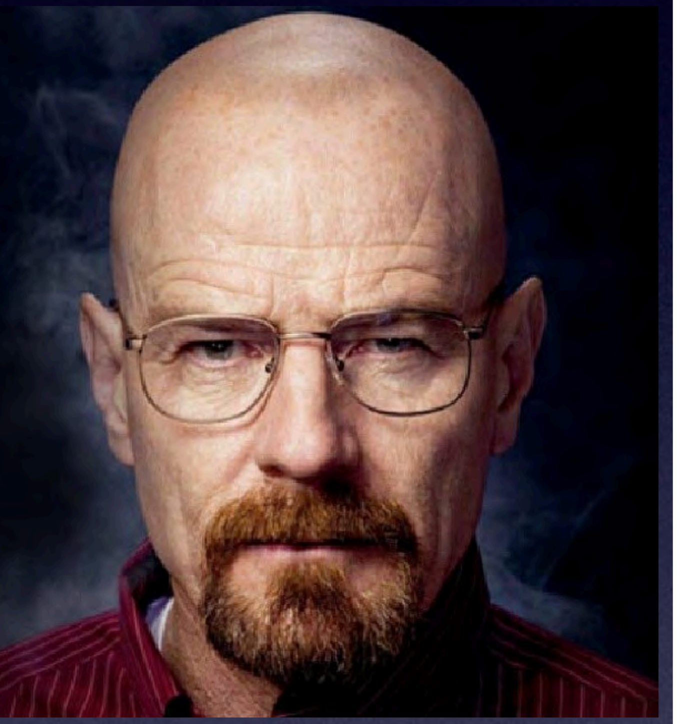
Journal of High Energy Physics **2020**, Article number: 136 (2020) | Cite this article

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.

Heisenberg vs. Einstein Microscopes

Heisenberg vs. Einstein Microscopes

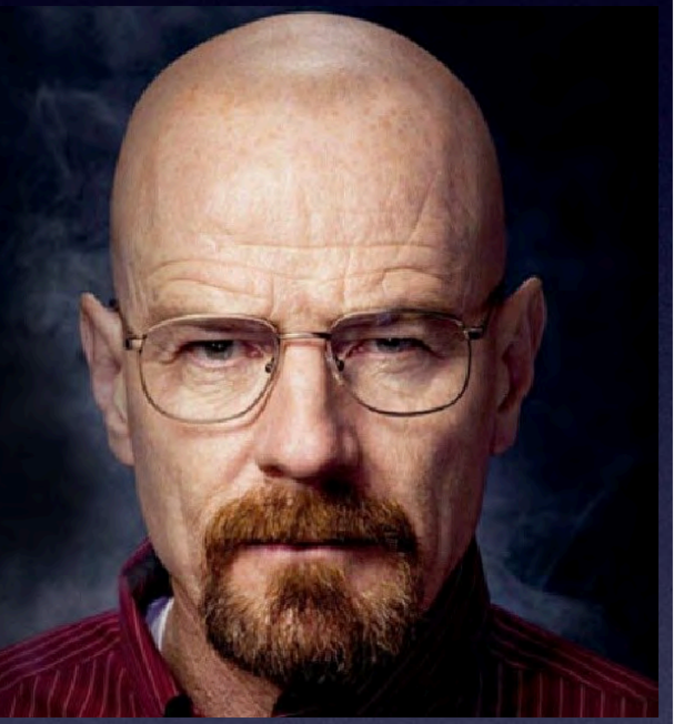


- Higher energy

➡ Shorter wavelength

➡ *Better resolution*

Heisenberg vs. Einstein Microscopes



- Higher energy

➡ Shorter wavelength

➡ *Better resolution*

- Higher energy

➡ Bigger black holes

➡ *Worse resolution*