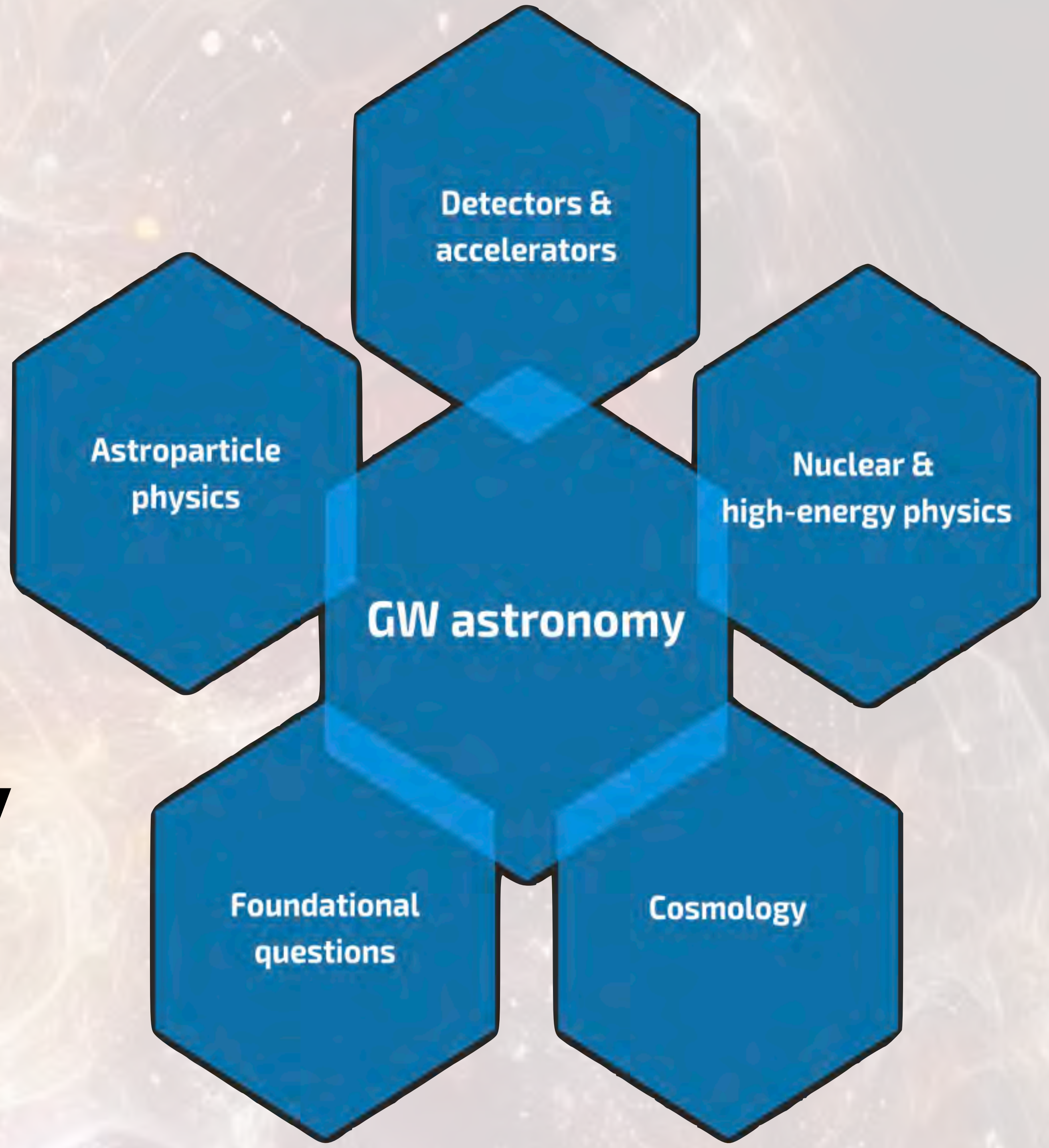
Bottom-Up Cross-Cutting Workshop
“JENAS Initiative: Gravitational Wave Probes of Fundamental Physics”

12–16 Feb 2024
Sapienza University of Rome



Quantum Spacetime in the Sky

from the horizon to the vacuum

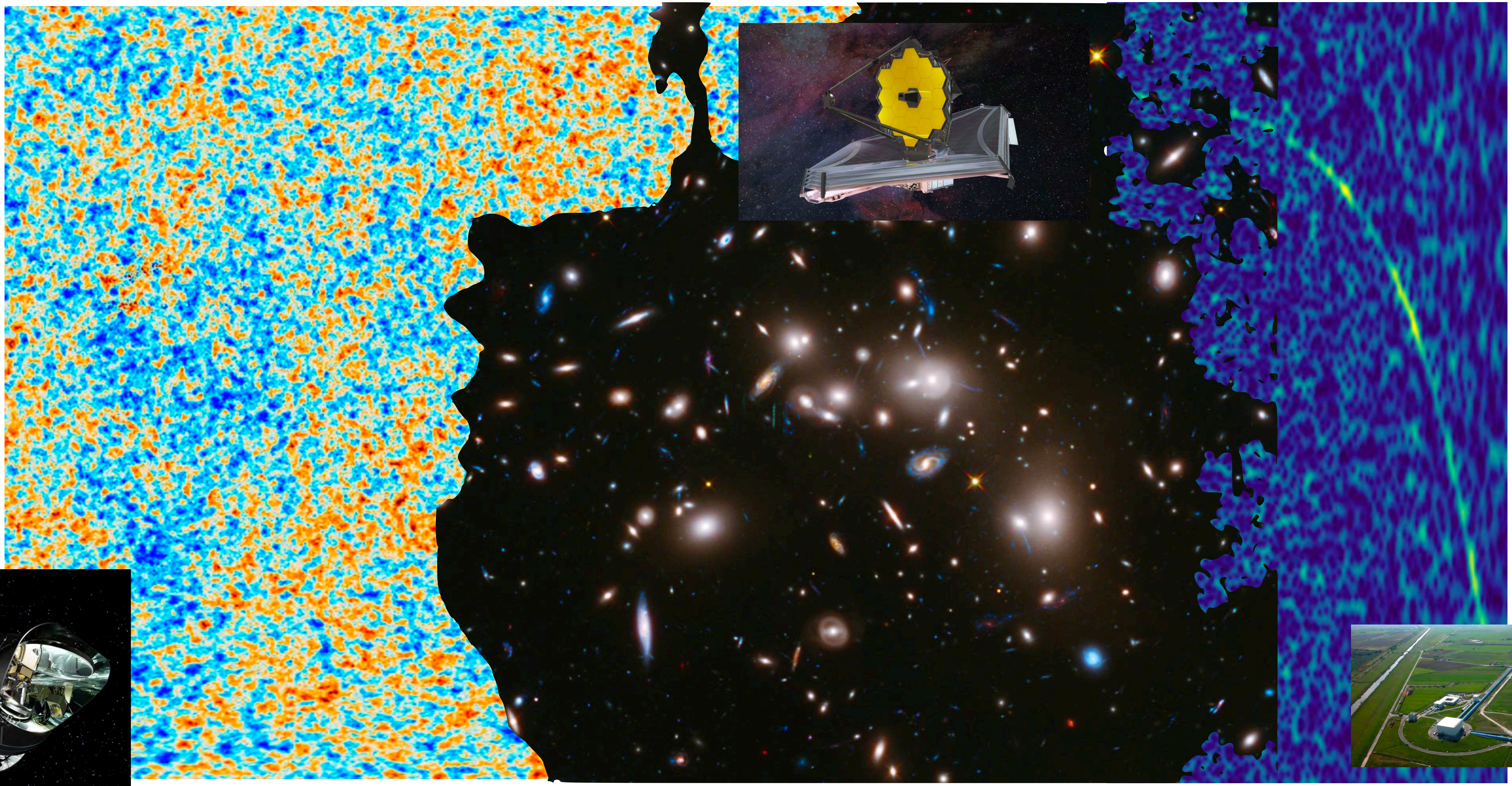
Niayesh Afshordi

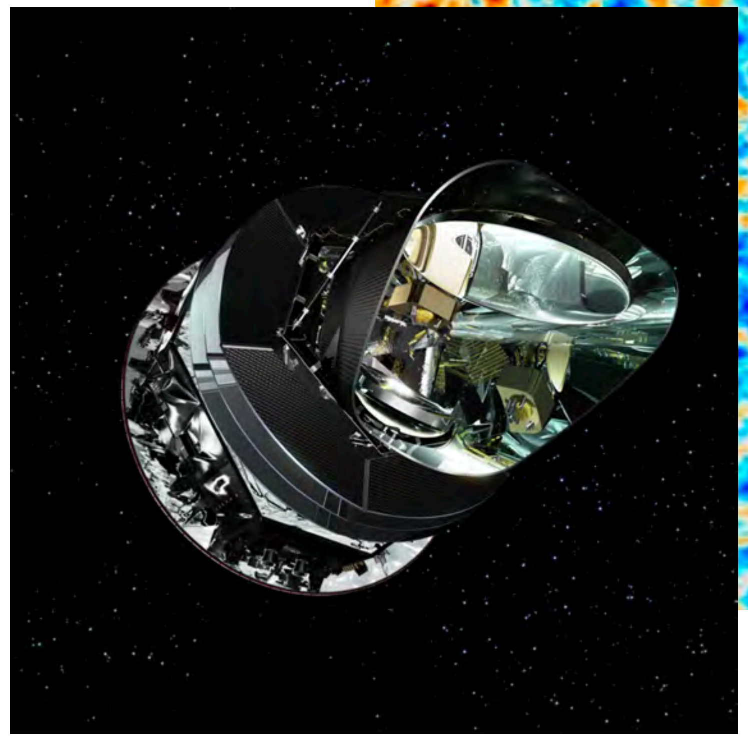
UNIVERSITY OF WATERLOO

WATERLOO CENTRE FOR ASTROPHYSICS

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

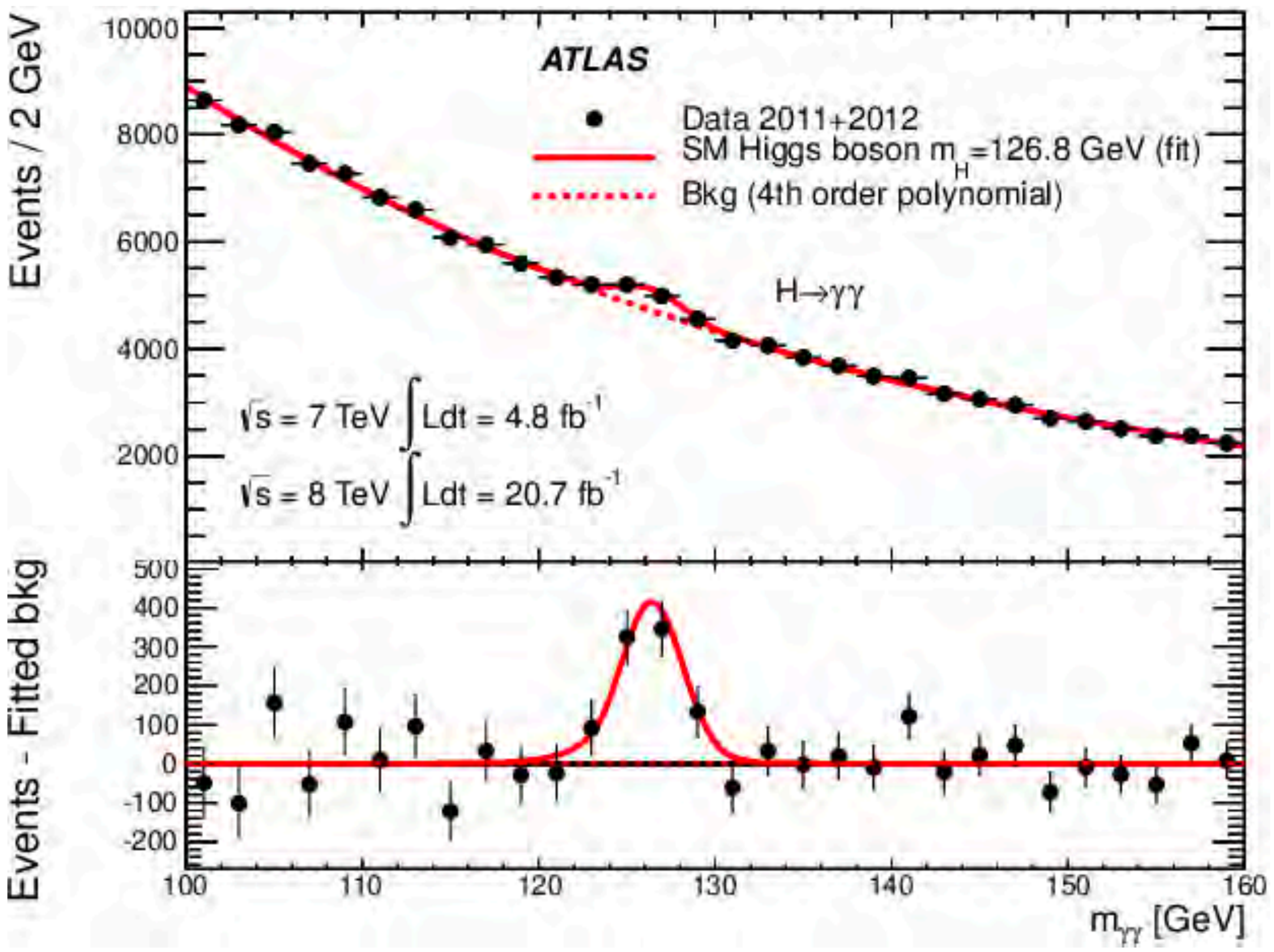
Our cosmic pictures, more beautiful than ever

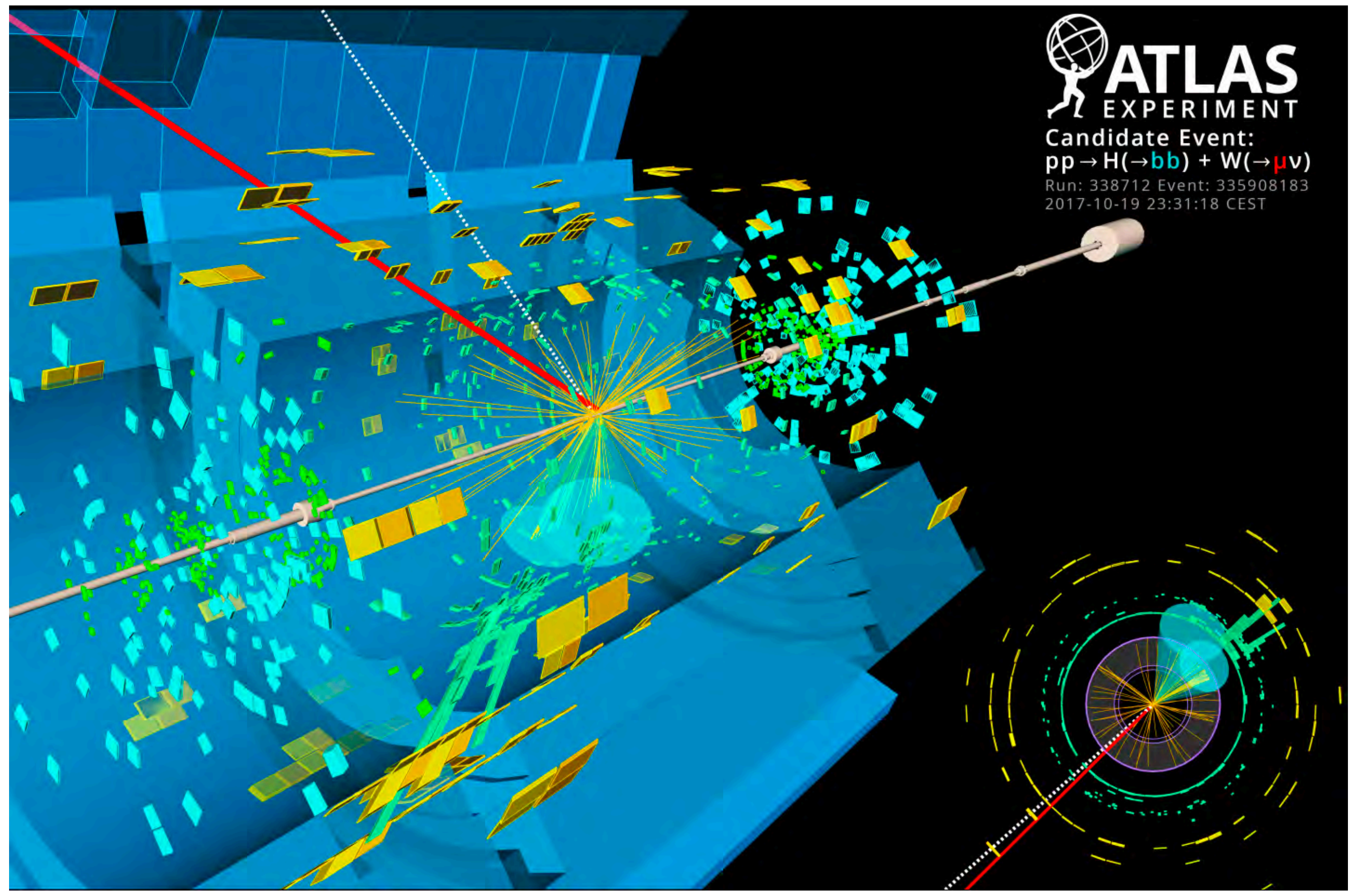


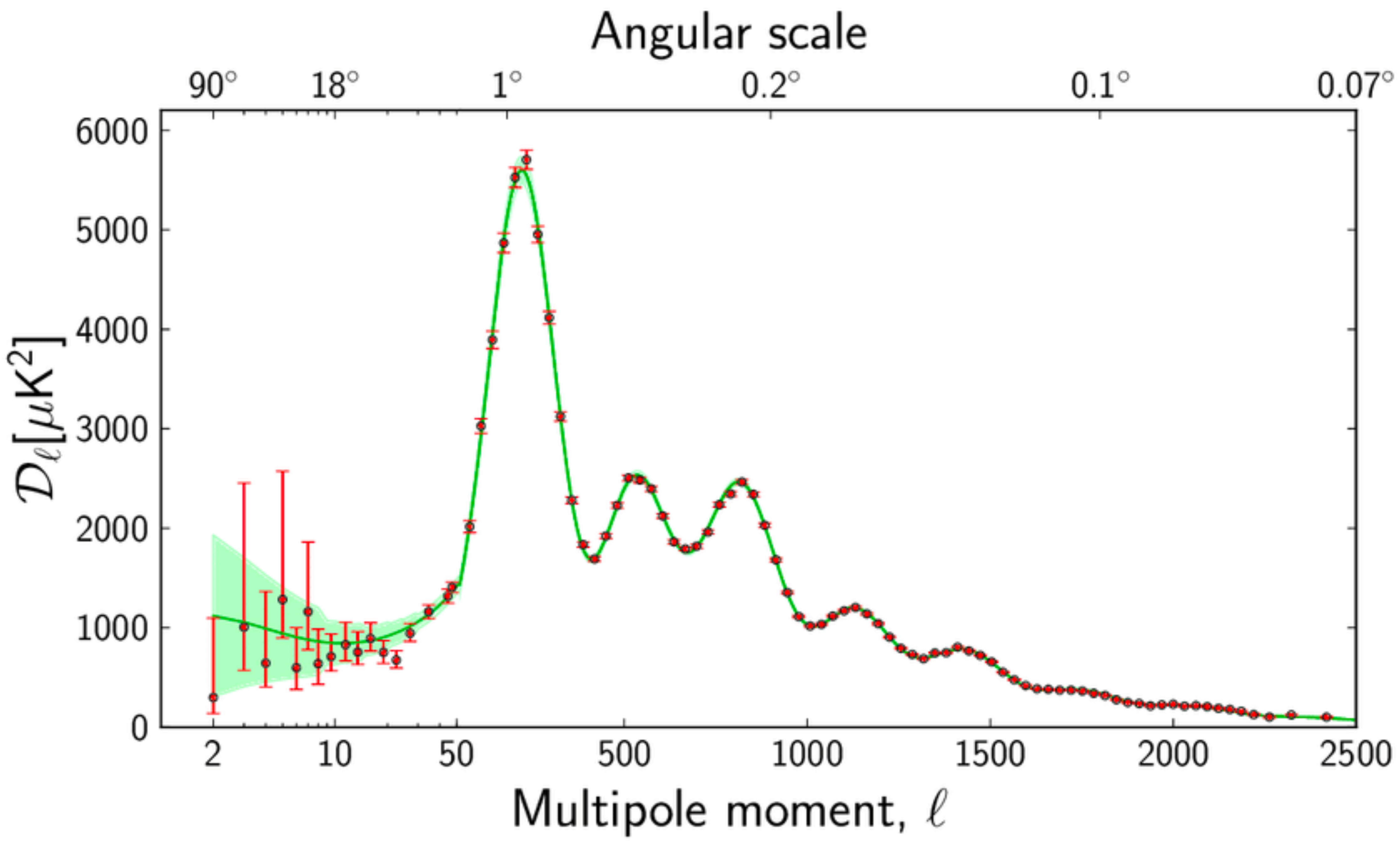


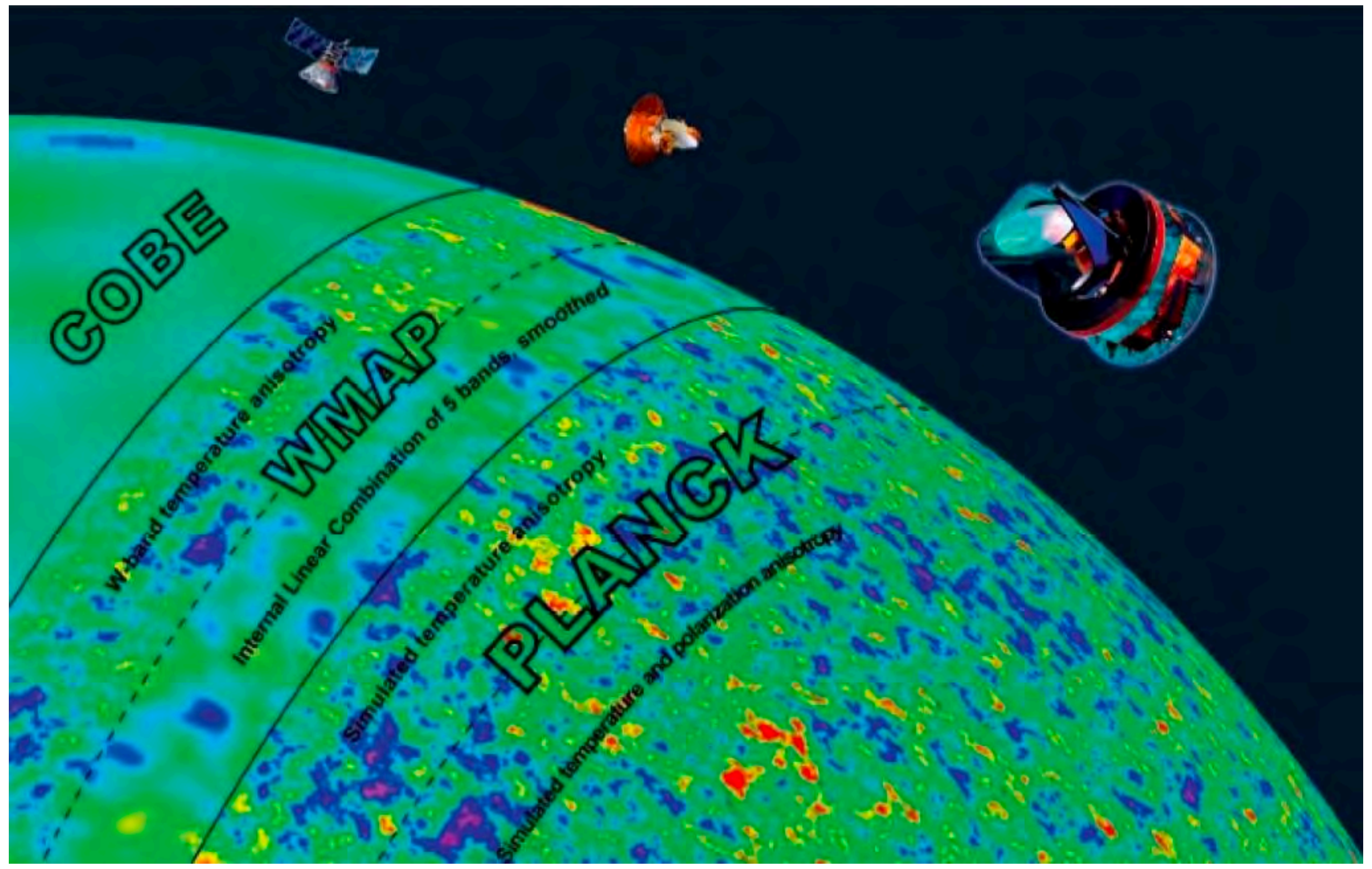
@Planck **@JWST** **@LIGO/Virgo**

and most complete, from smallest to largest scales

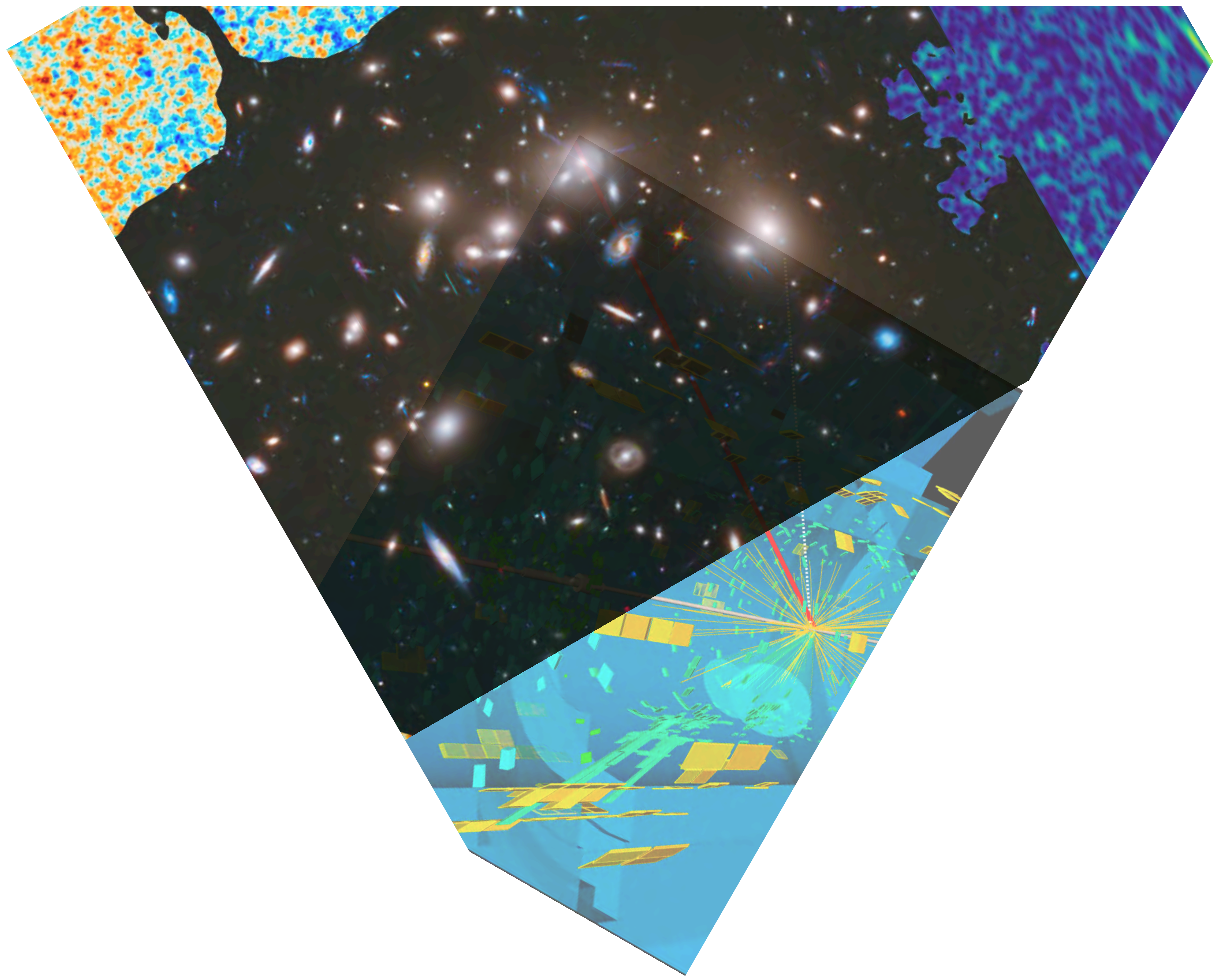








Yet, the Big Picture is surrounded by mysteries



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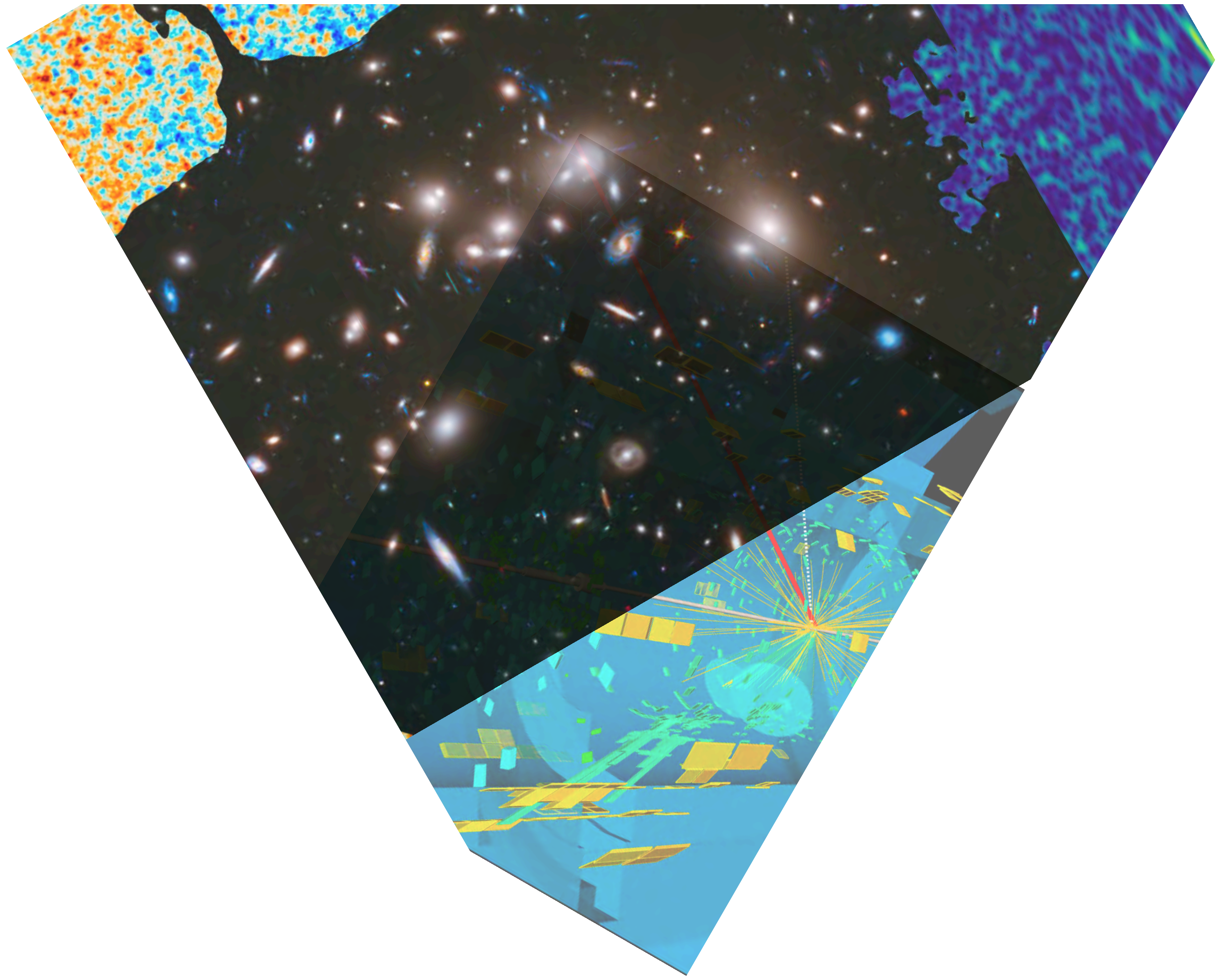
Nature of Quantum Vacuum?



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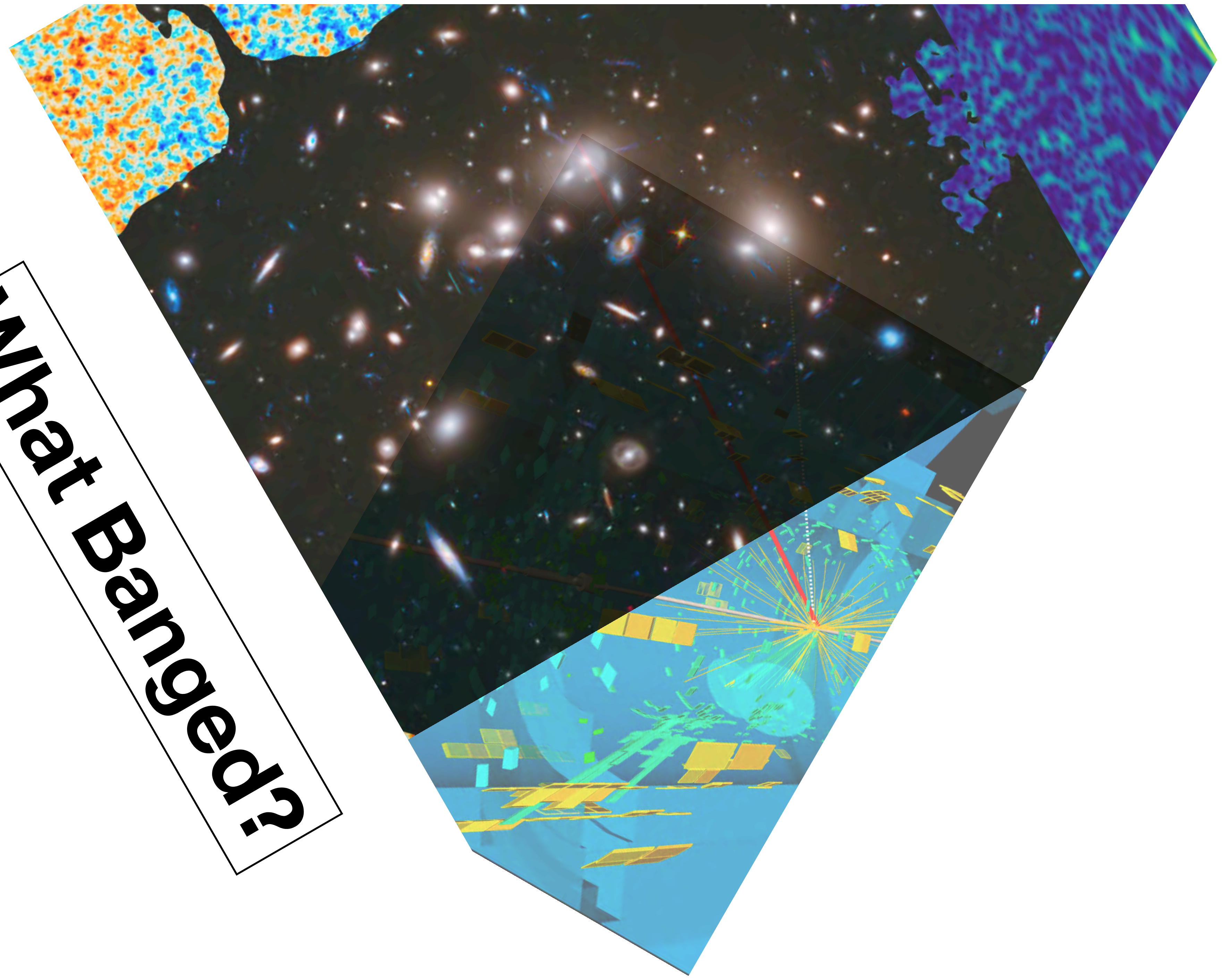
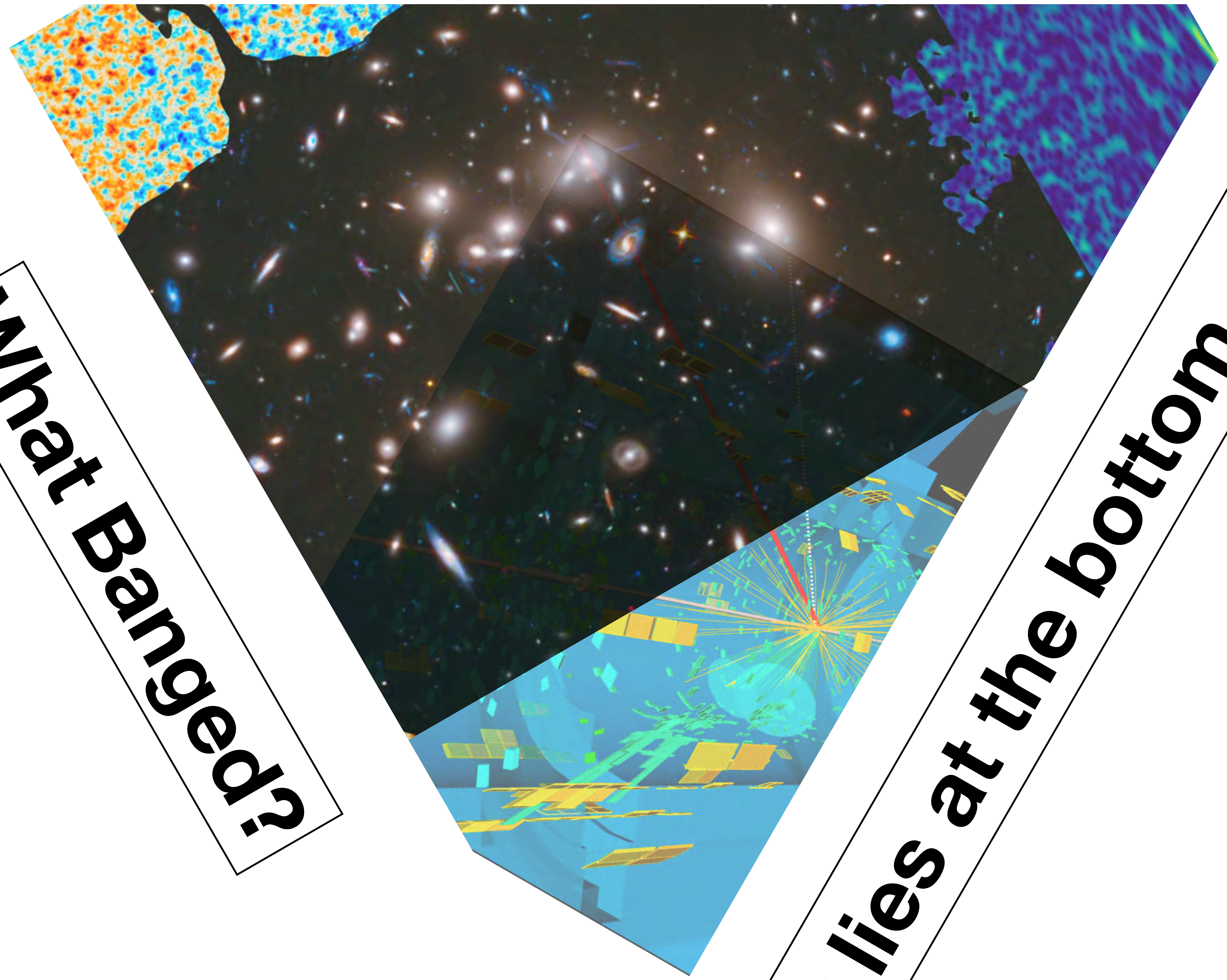


What Banged?

Yet, the Big Picture is surrounded by mysteries

Nature of Quantum Vacuum?

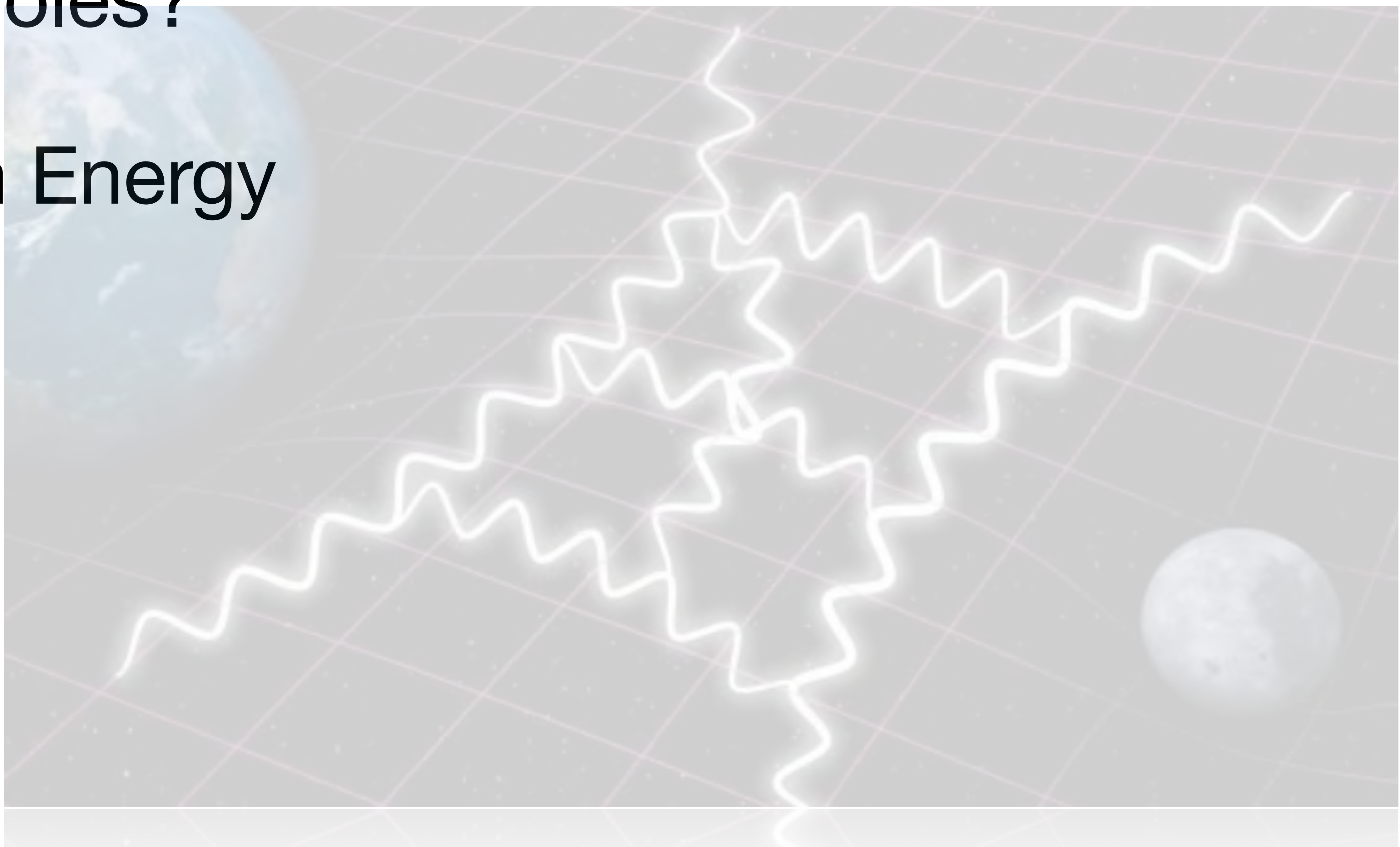


What Banged?

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”?



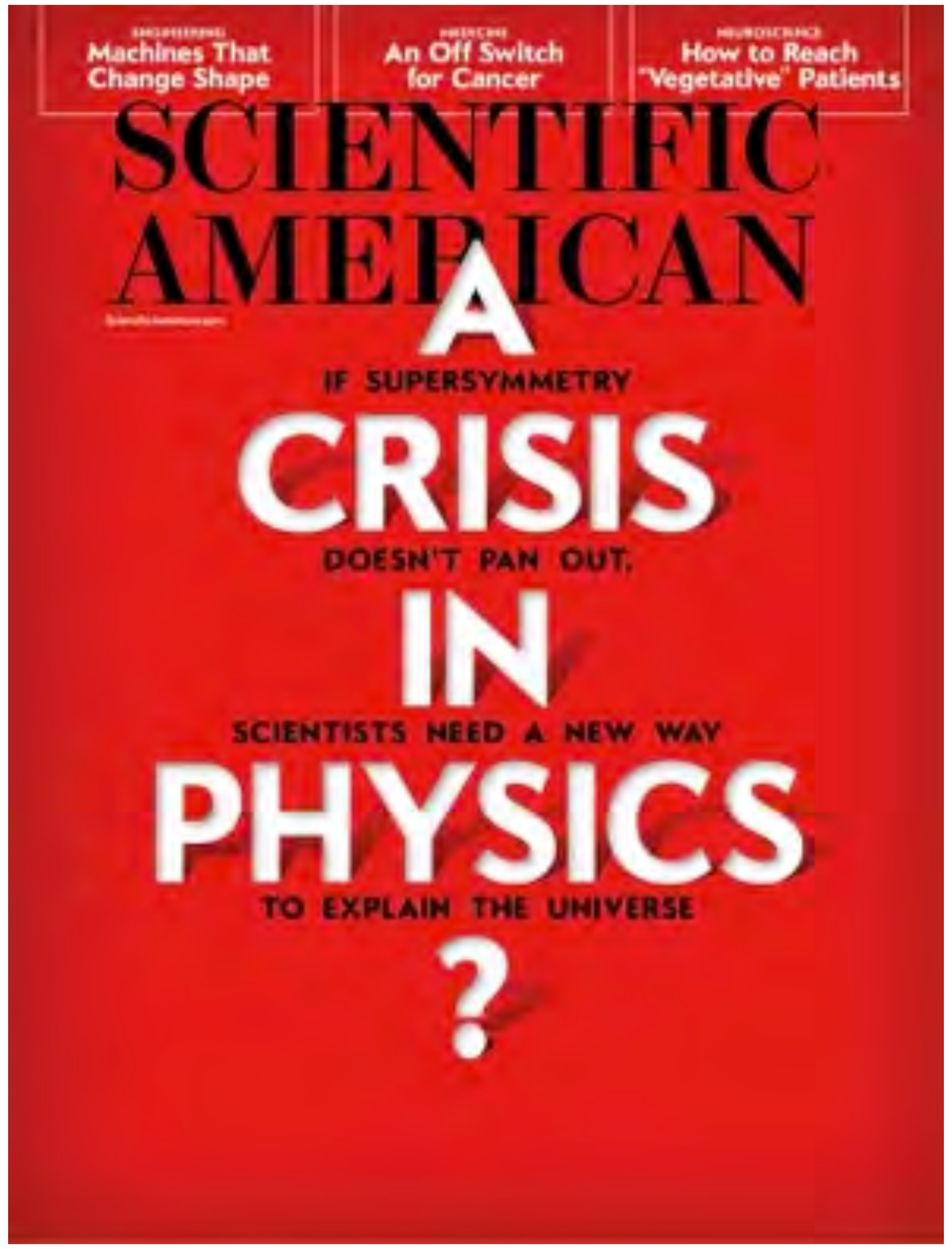
Quantum Gravity Zoo

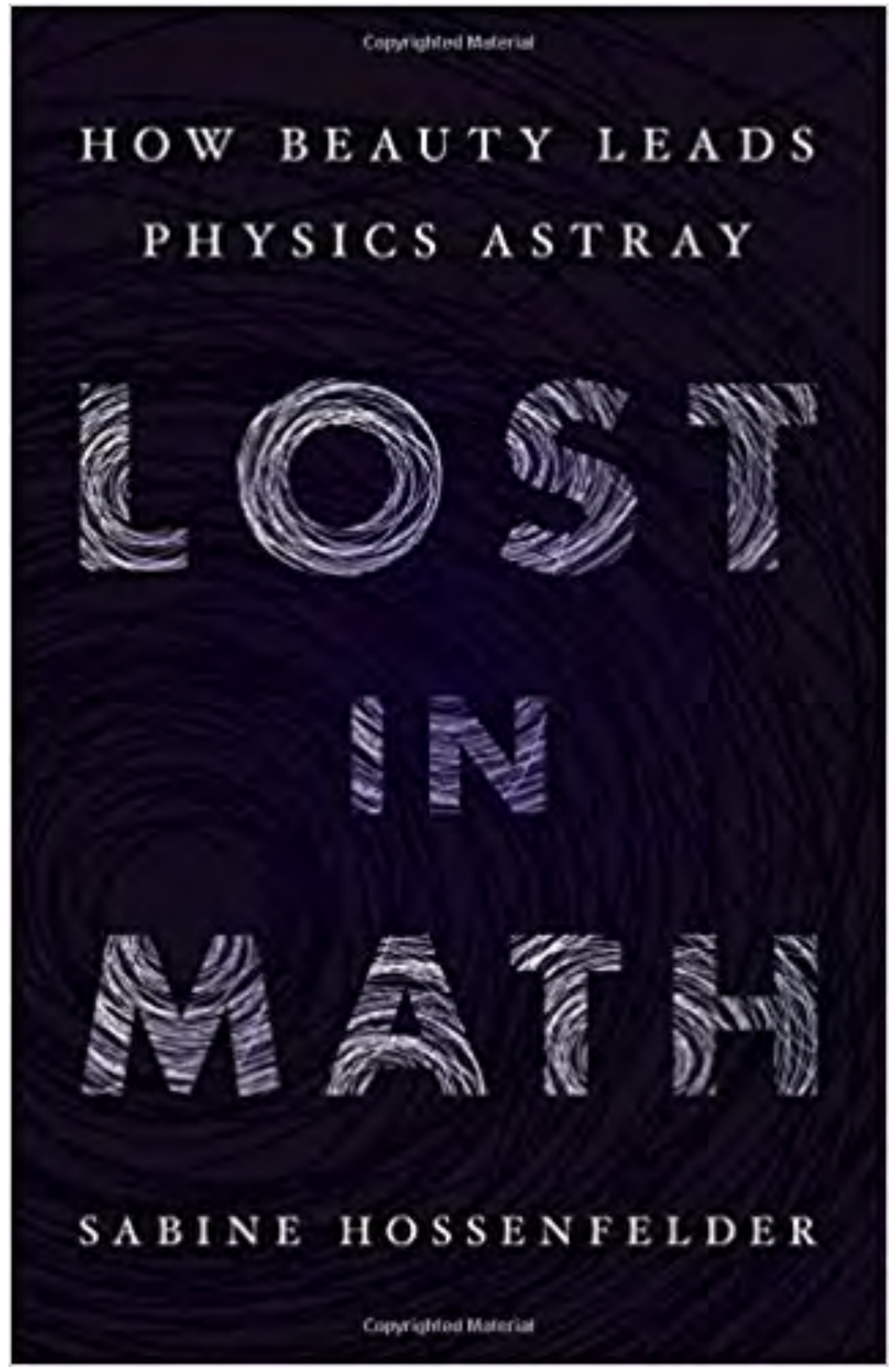
Too much of a good thing?

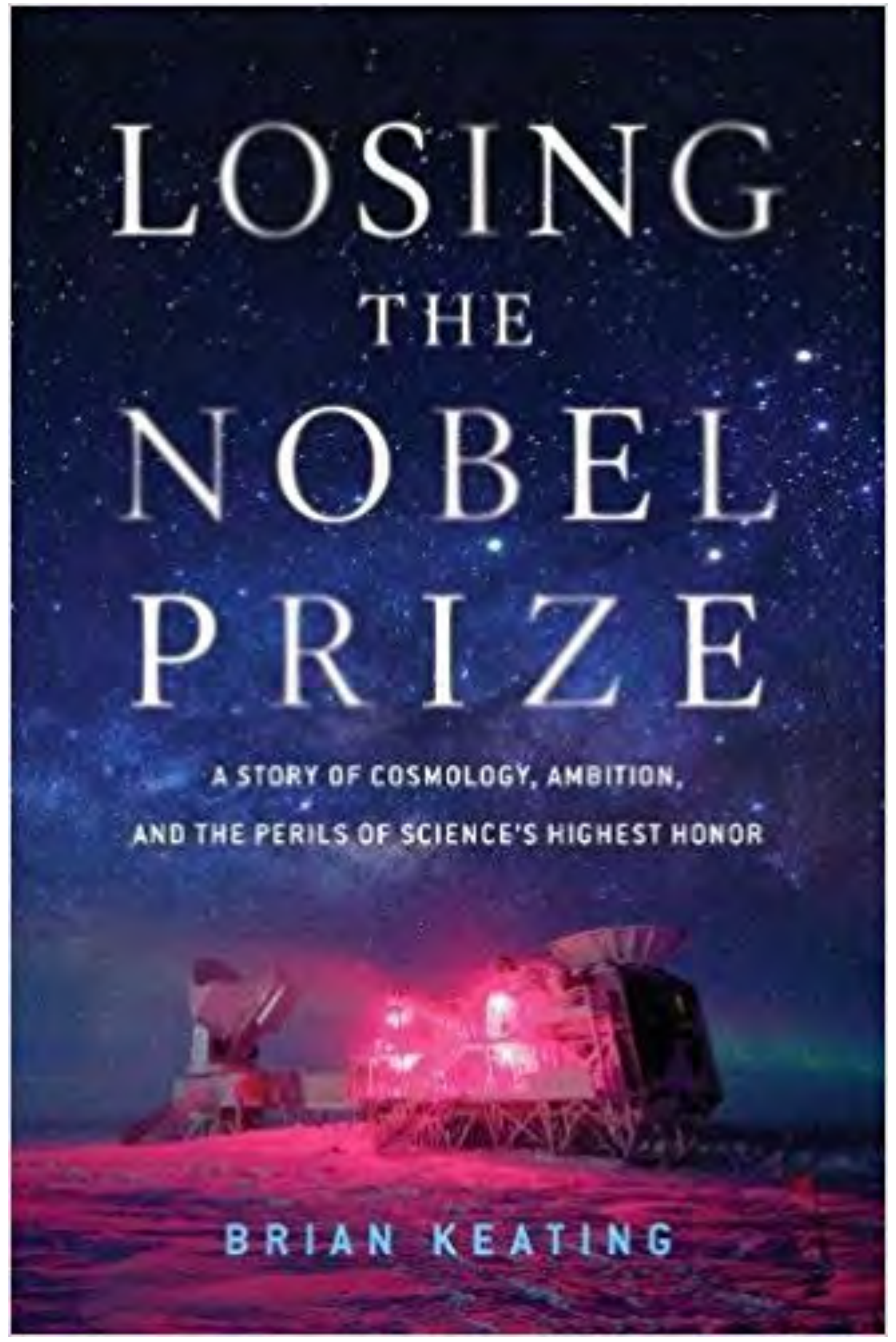
- String Theory and Holography
- Loop Quantum Gravity and Spin Foams
- Asymptotic Safety
- Causal Dynamical Triangulation
- Causal Sets
- Horava-Lifshitz gravity
- …

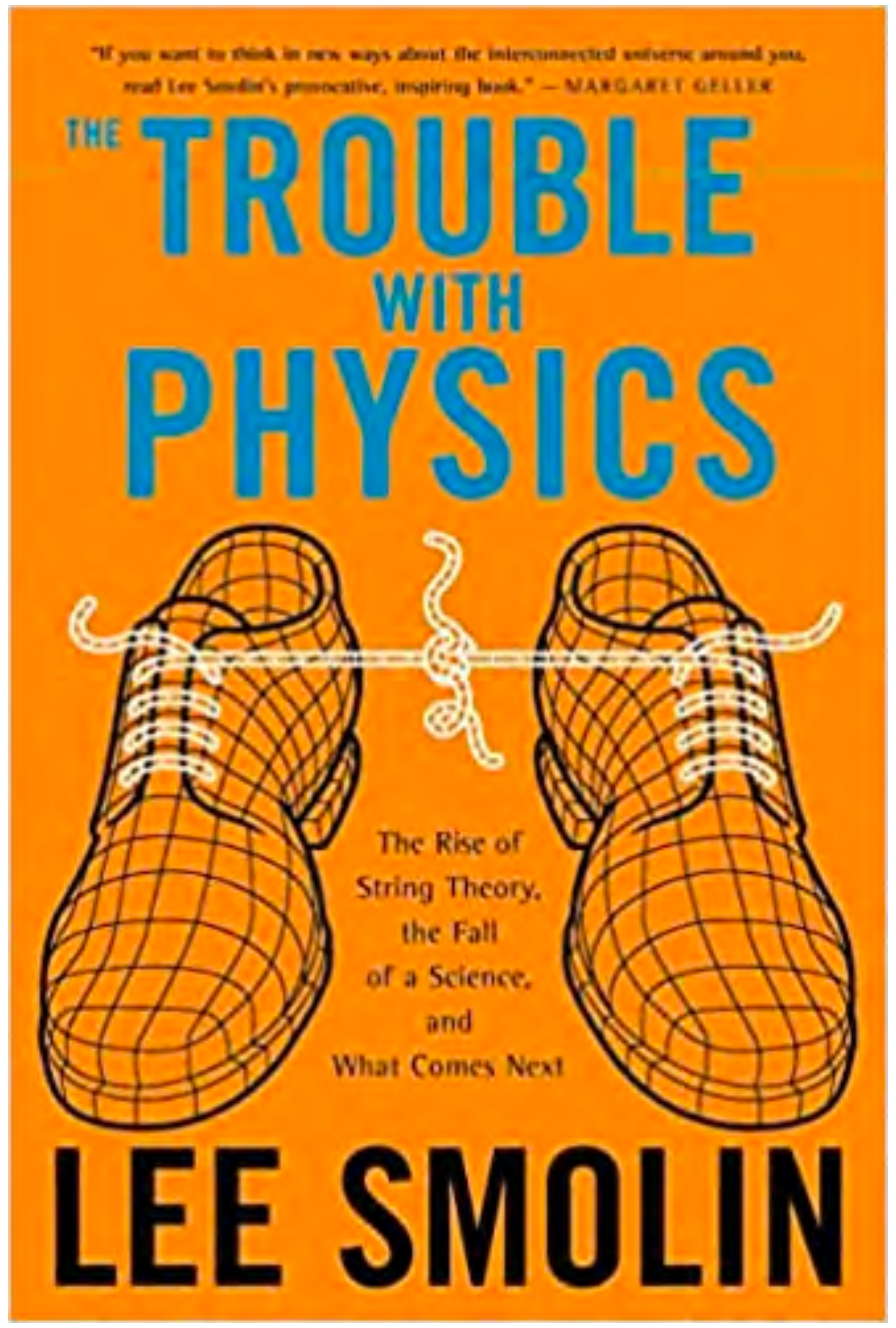
Olena Shmahalo/Quanta Magazine

Crisis and Desperation?

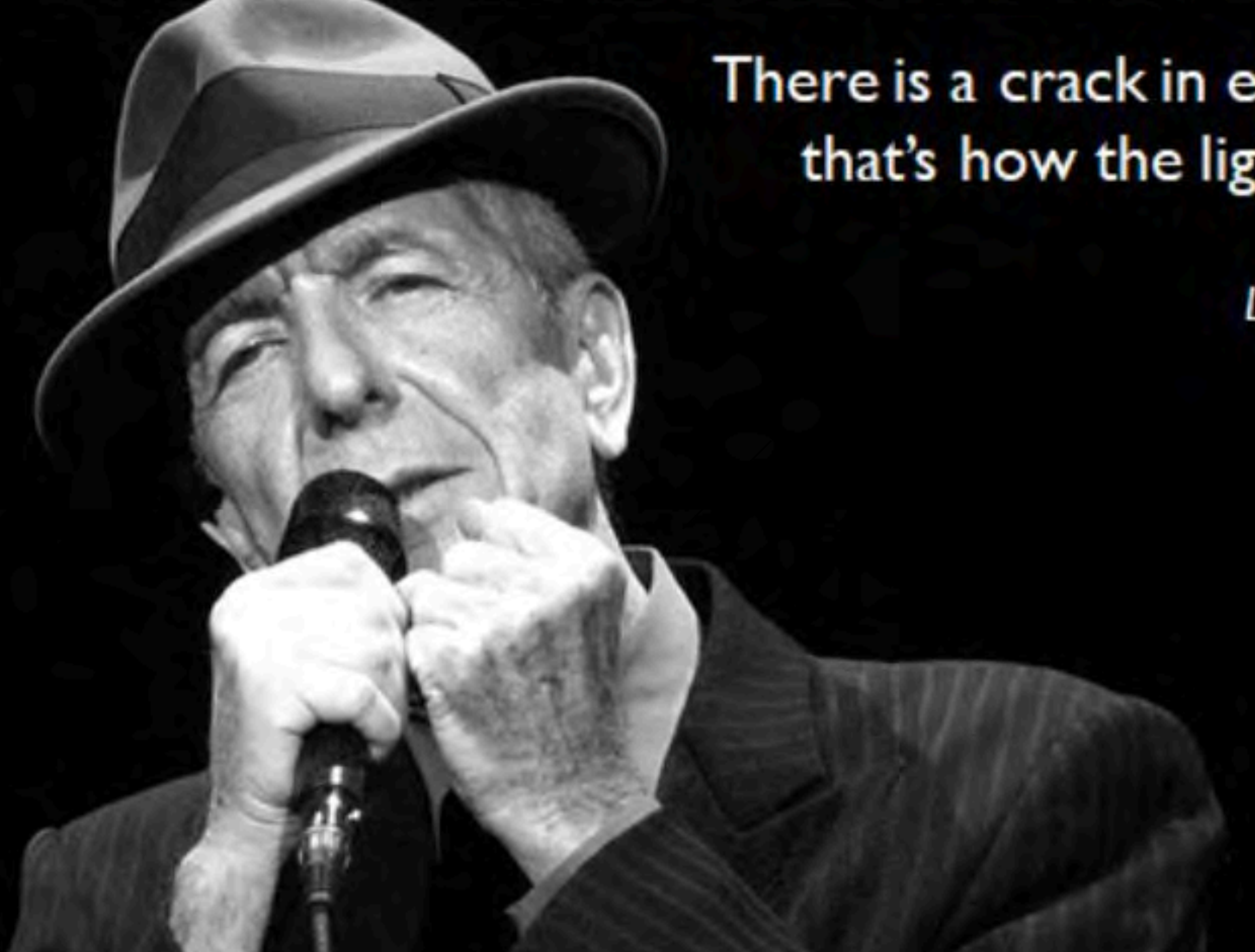








50 years in theoretical wasteland!



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

Leonard Cohen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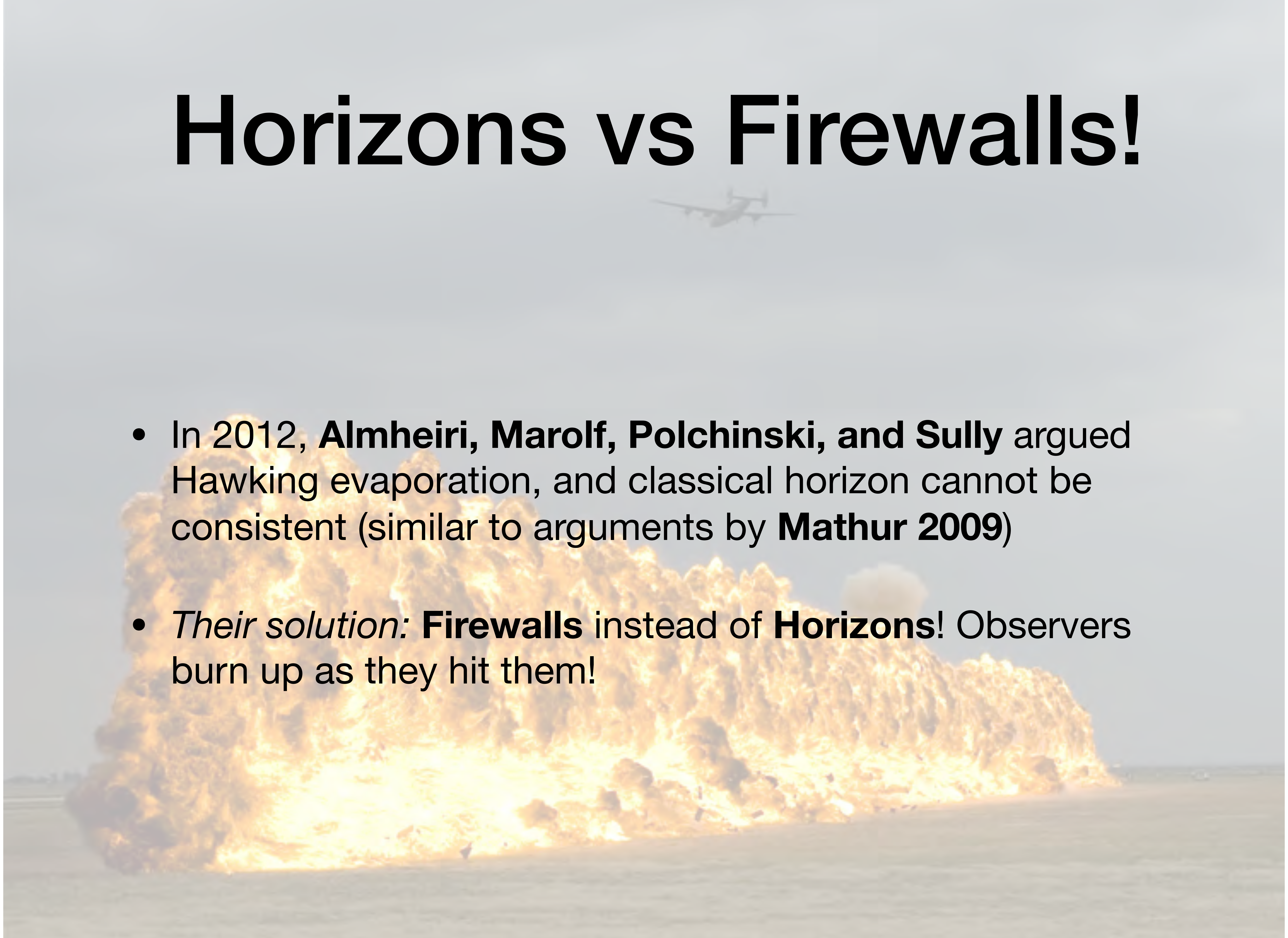
Quantum Gravity at the Horizon

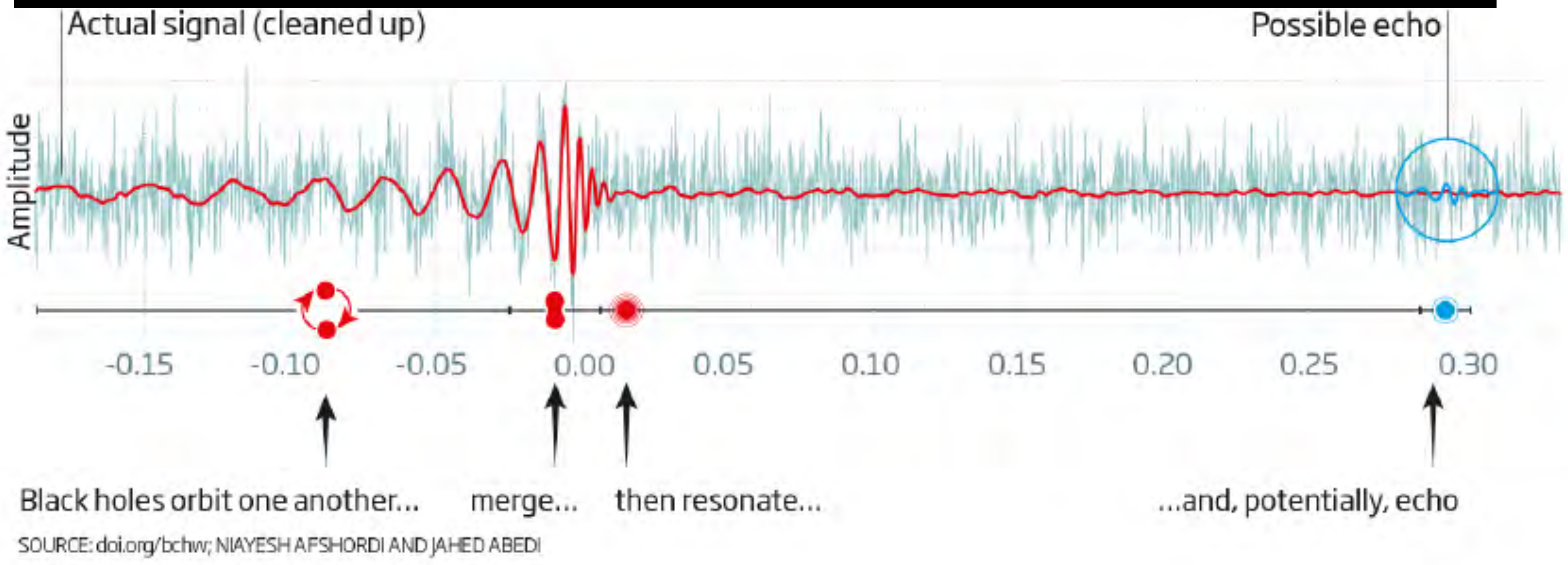


Horizons vs Firewalls!

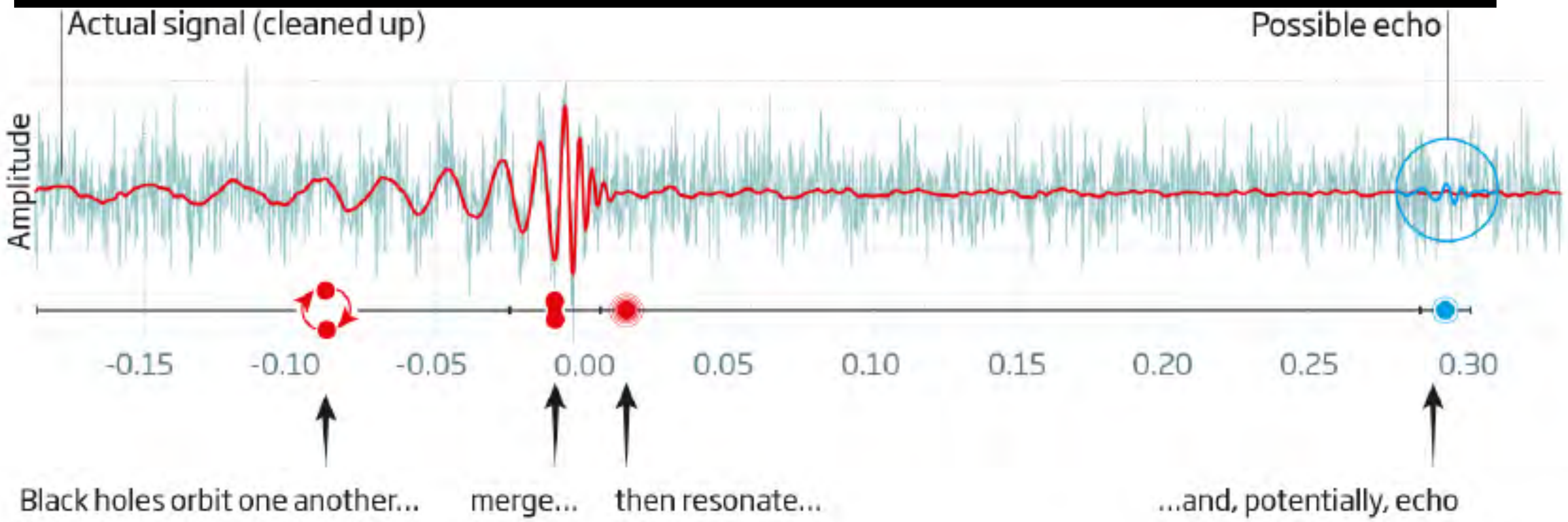
- In 2012, **Almheiri, Marolf, Polchinski, and Sully** argued Hawking evaporation, and classical horizon cannot be consistent (similar to arguments by **Mathur 2009**)

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

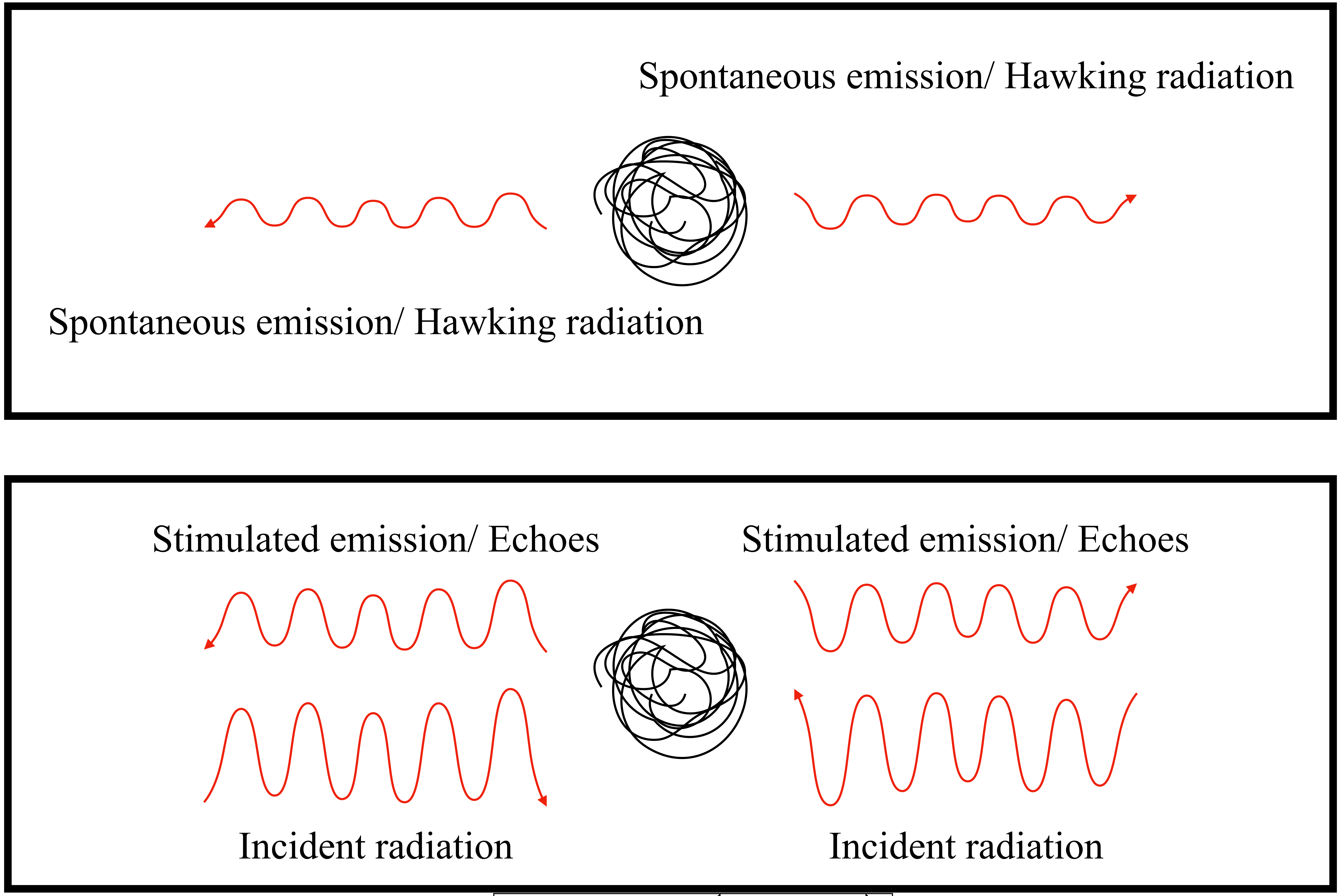
Gravitational Waves from firewalls?



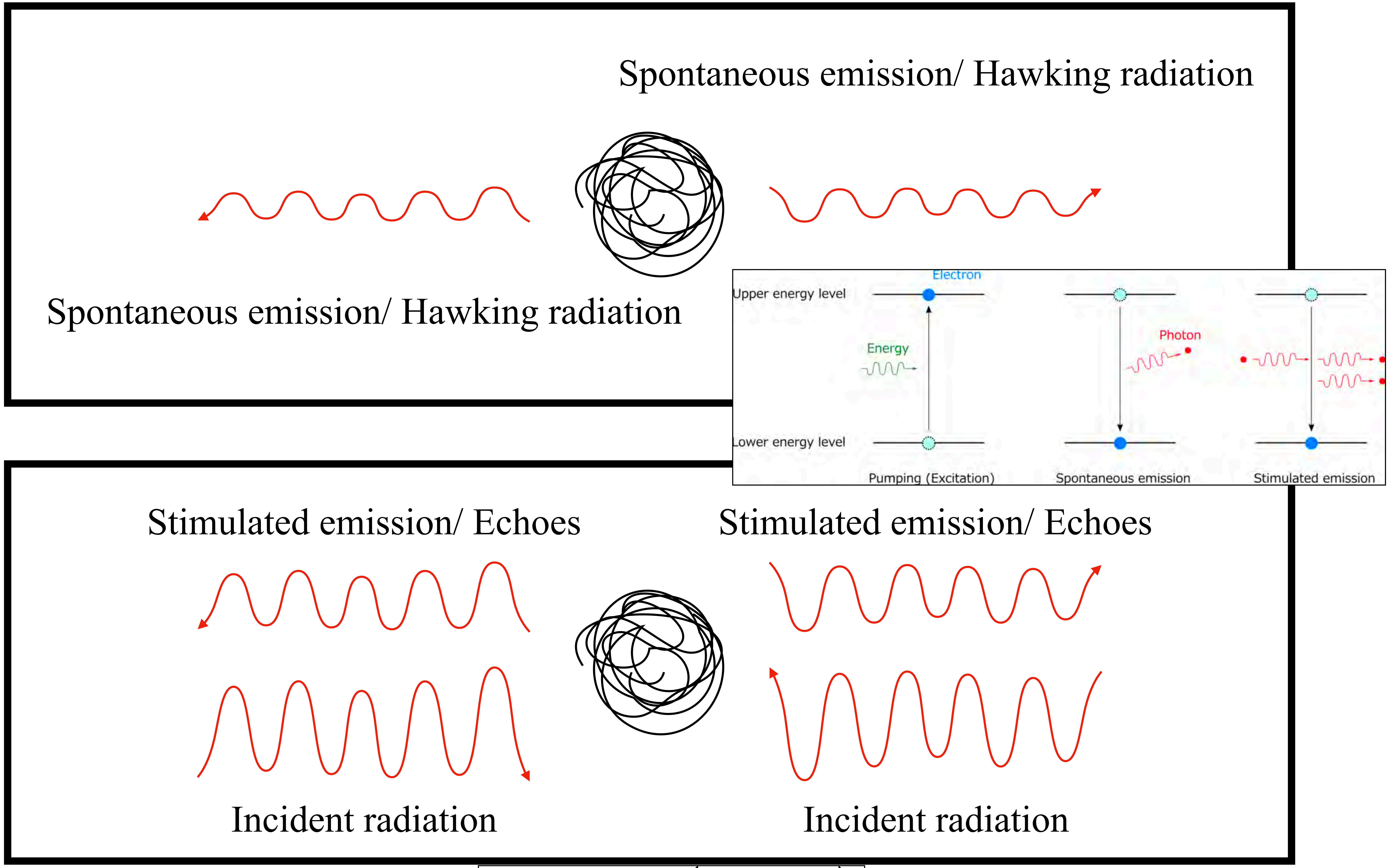
Gravitational Waves from firewalls?



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



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



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

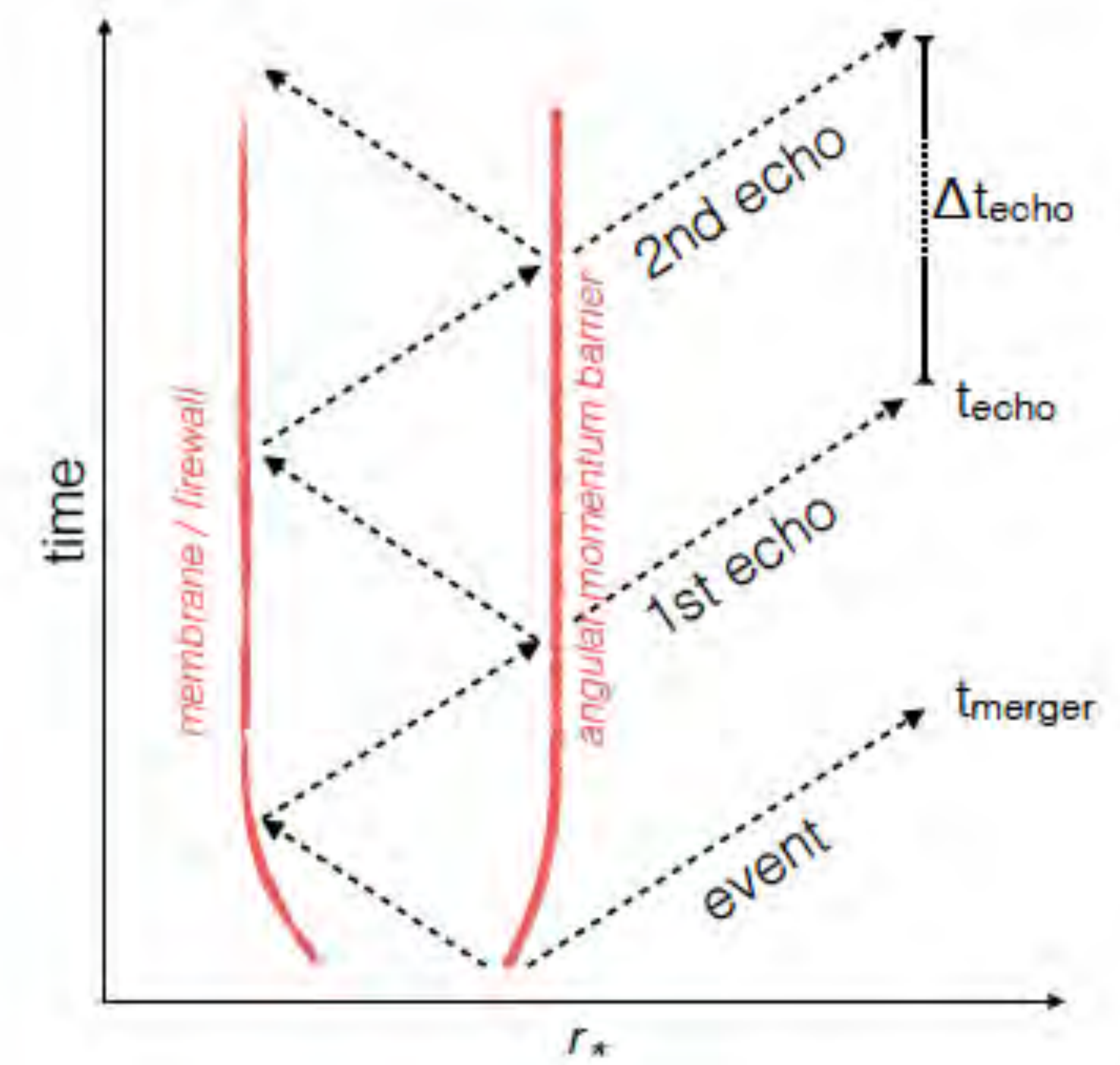
From Planck to LIGO!

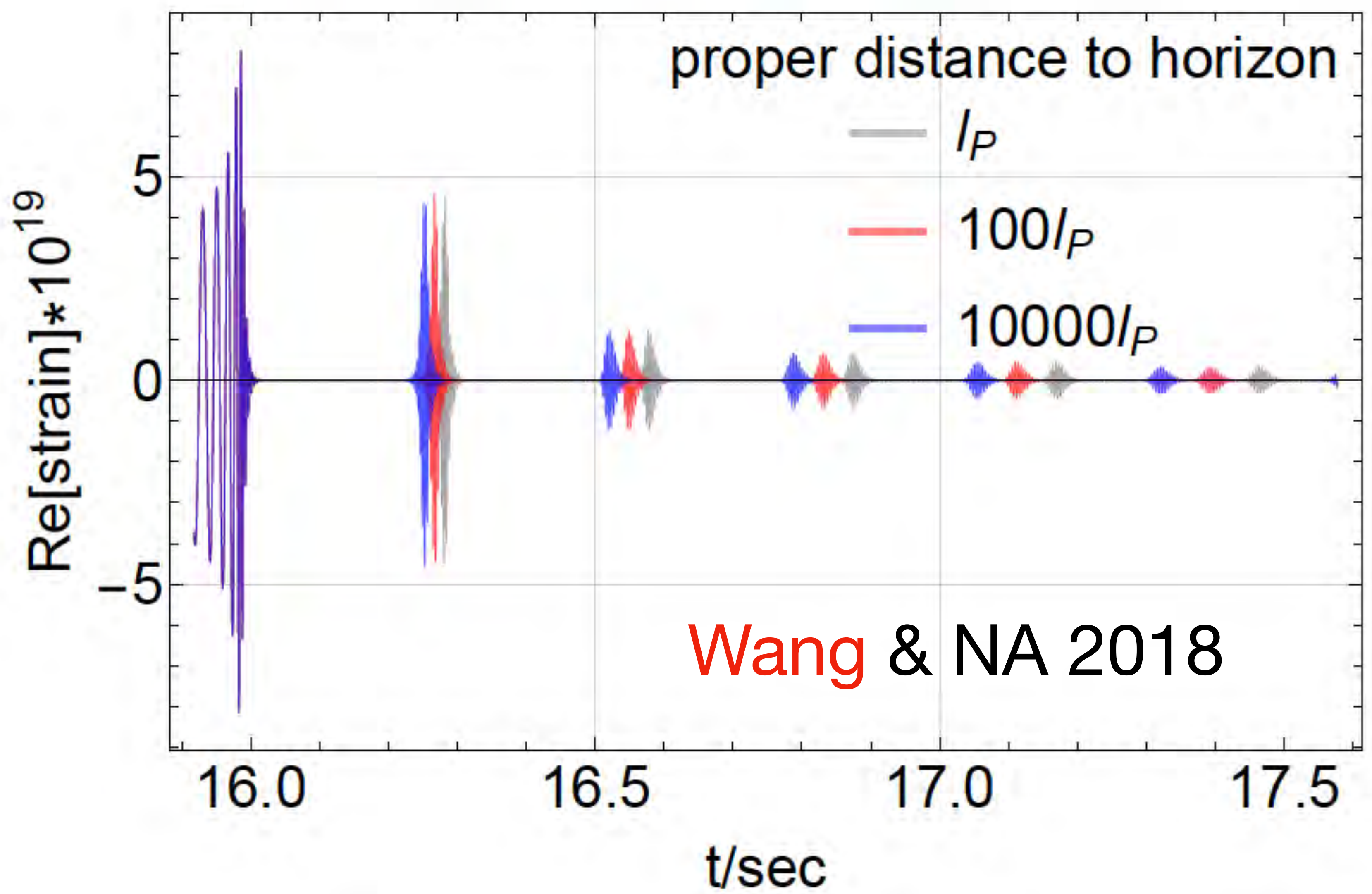
- Quantum effects within a Planck length of horizon

- "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)*

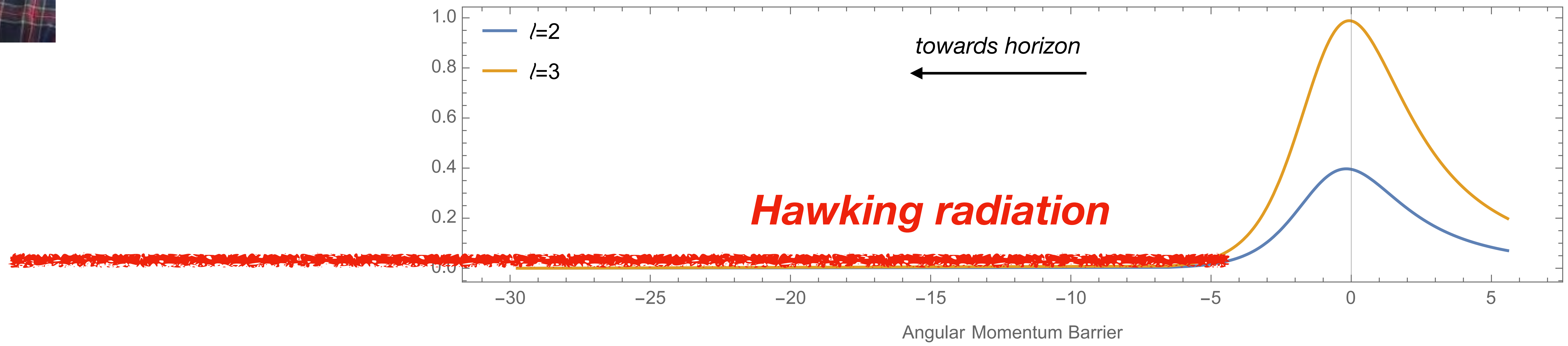




Finite Entropy of Hawking radiation

➡ Echoes *(Oshita & NA 2023)*

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



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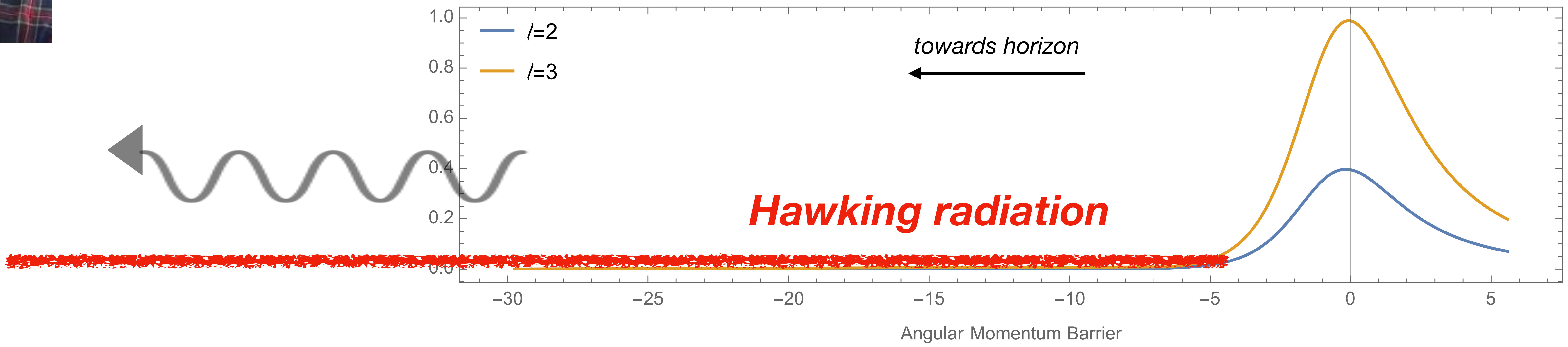

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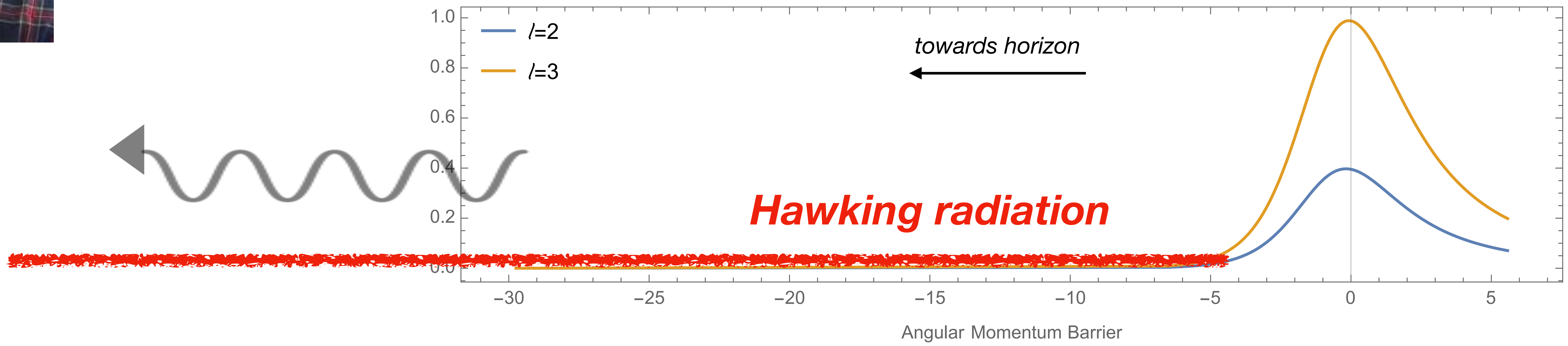
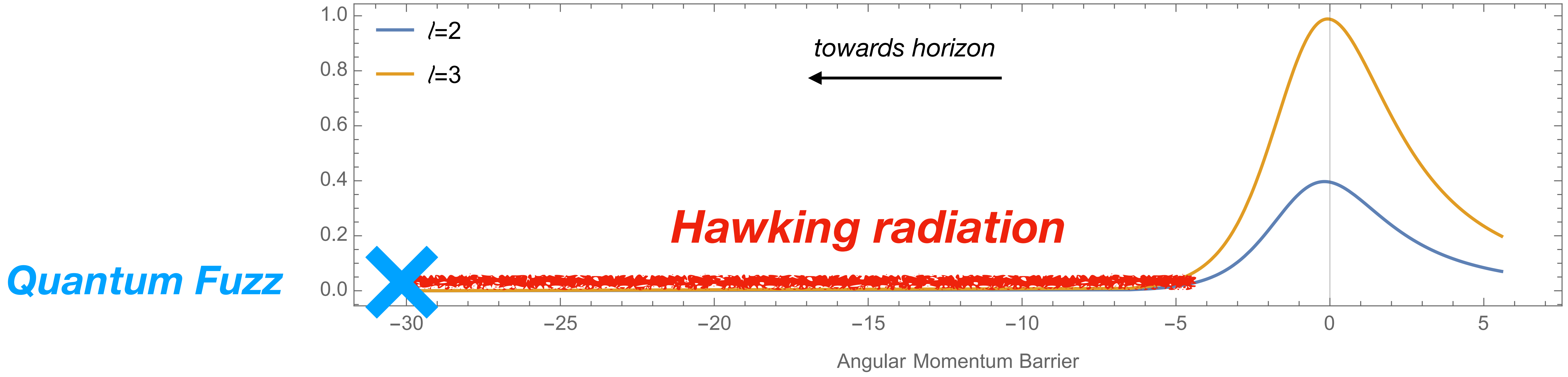


- Finite Entropy & Echoes: $t_{\rm echo} = \dfrac{\ln\left[\text{Entropy}/\ell(\ell+1)\right]}{2\pi \times \text{Hawking Temperature}}$



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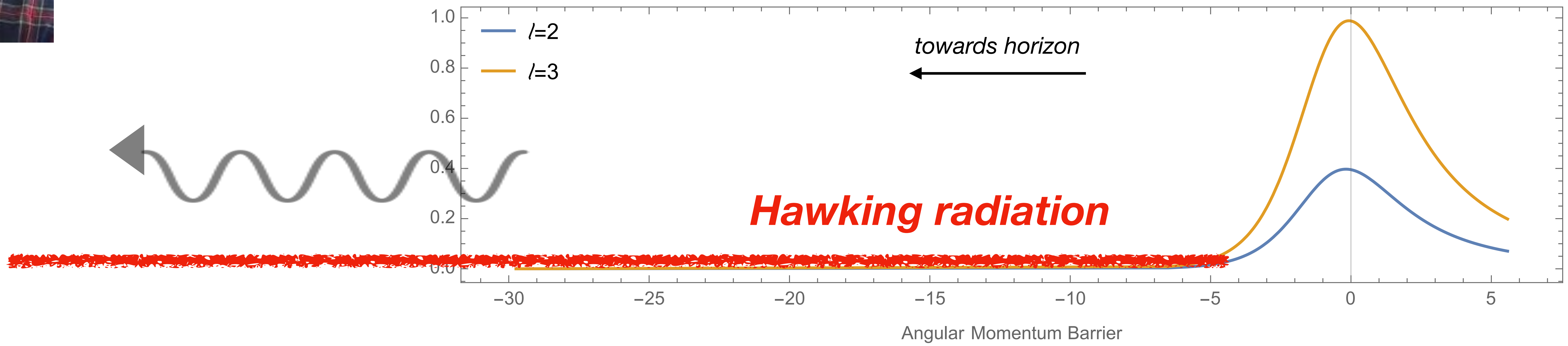

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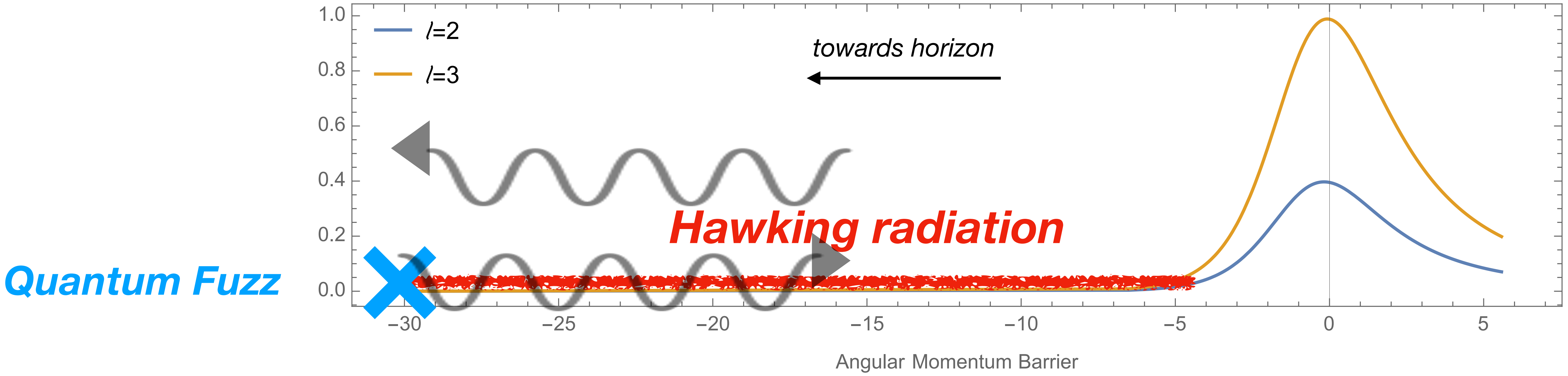
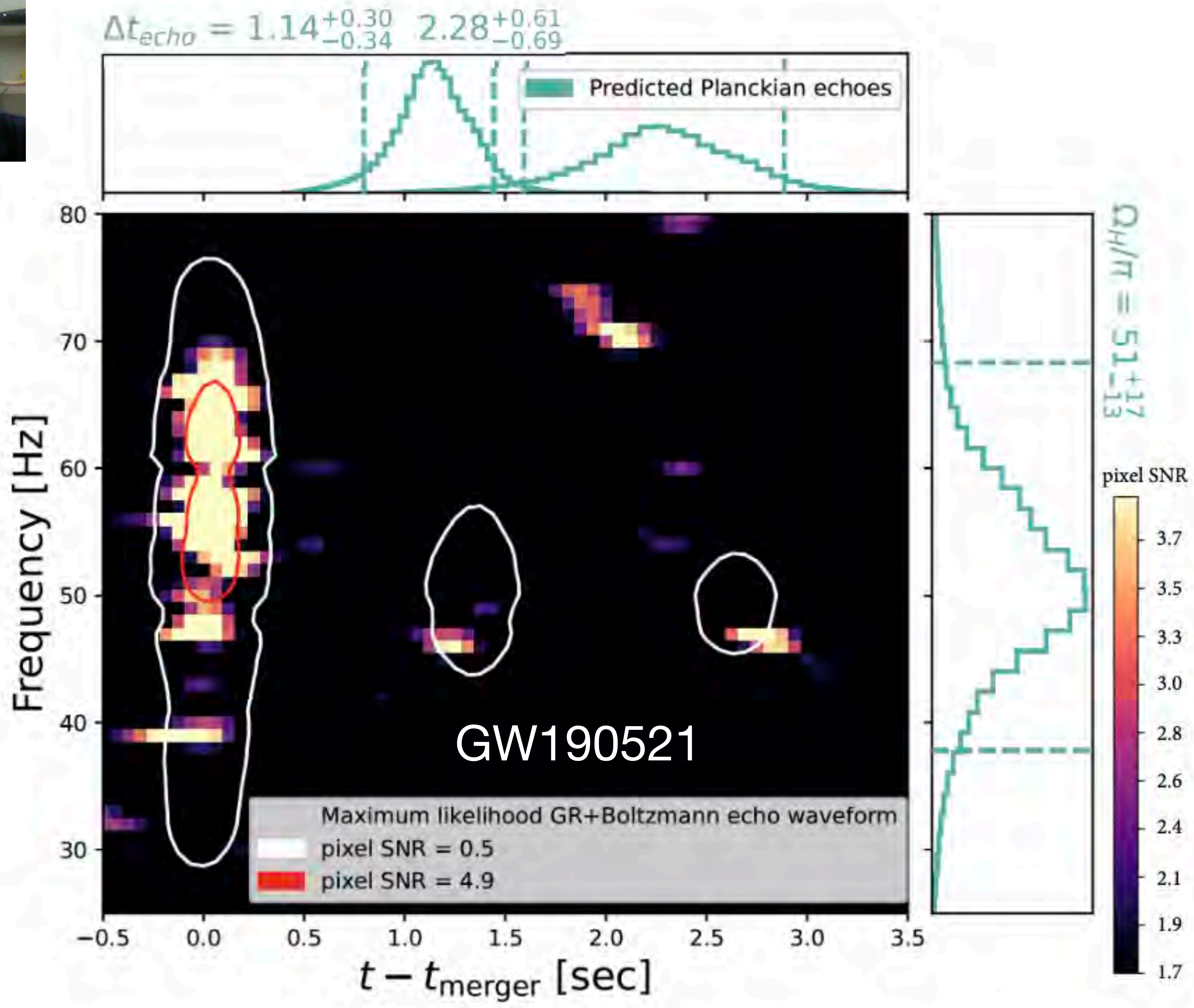
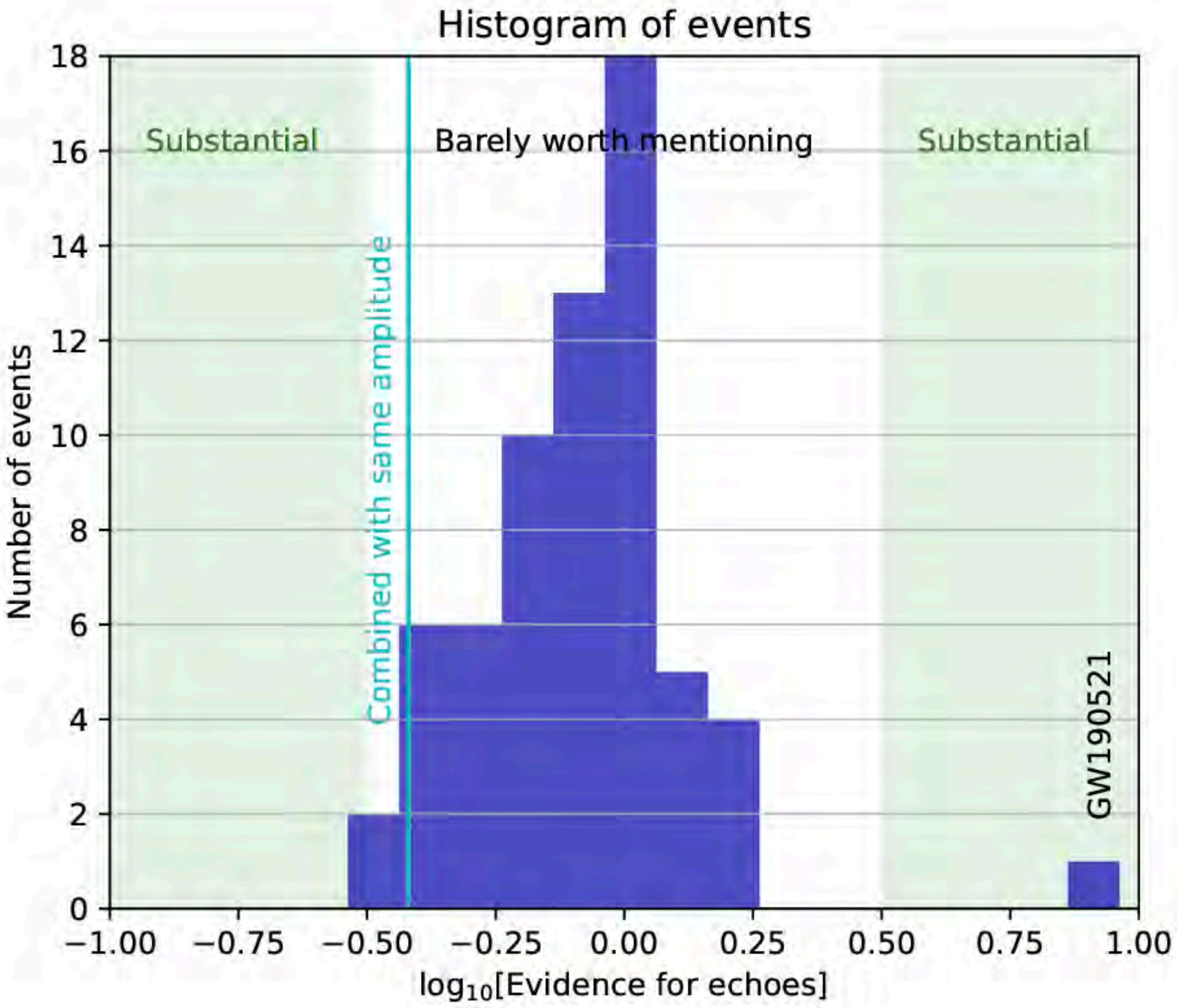


Are there echoes in LIGO data?

- Abedi, Longo & NA 2023

Abedi 2023

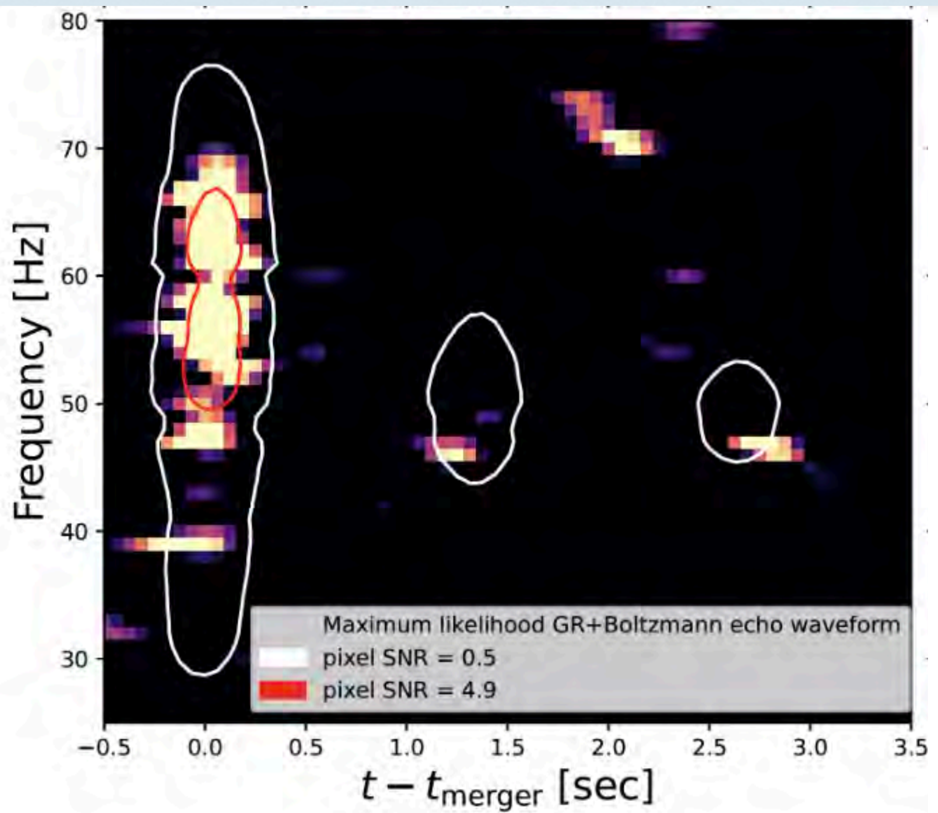


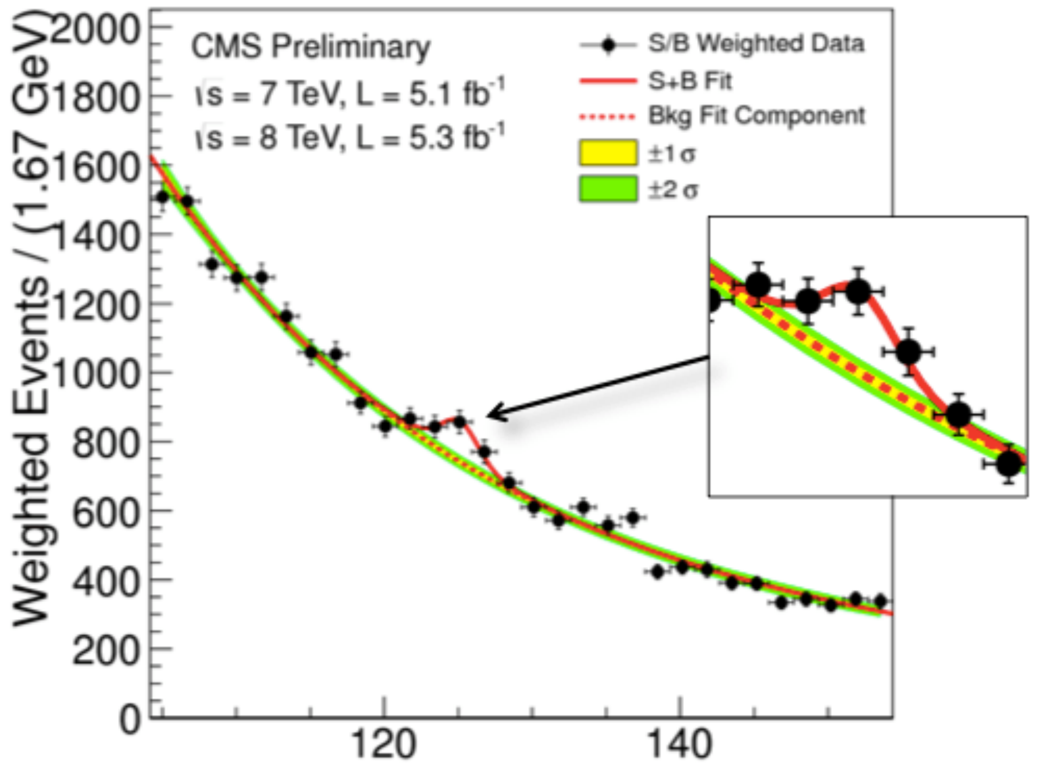


Echoes to *LIGO*	Higgs to *LHC*

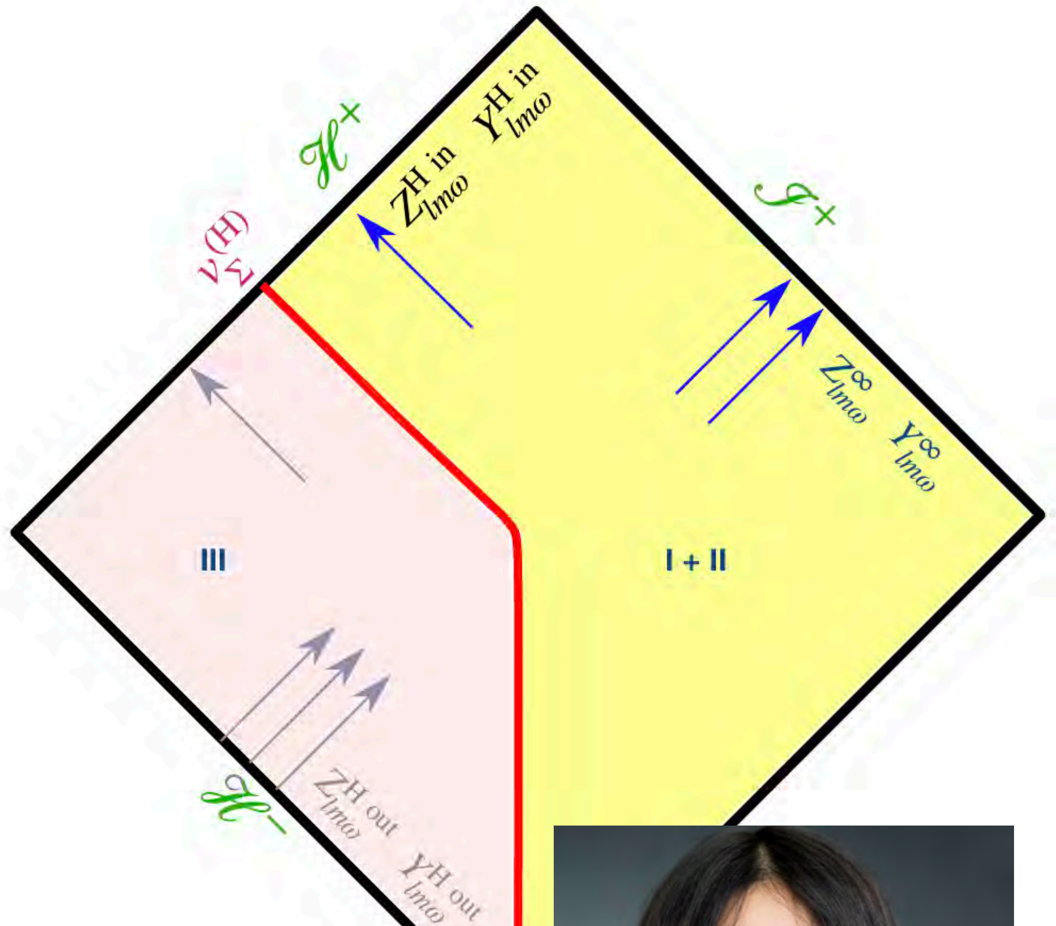
- Unitarity
- (Perturbative) Effective Field Theory
- Holographic Entropy ↔️ Diffeomorphism sym.

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

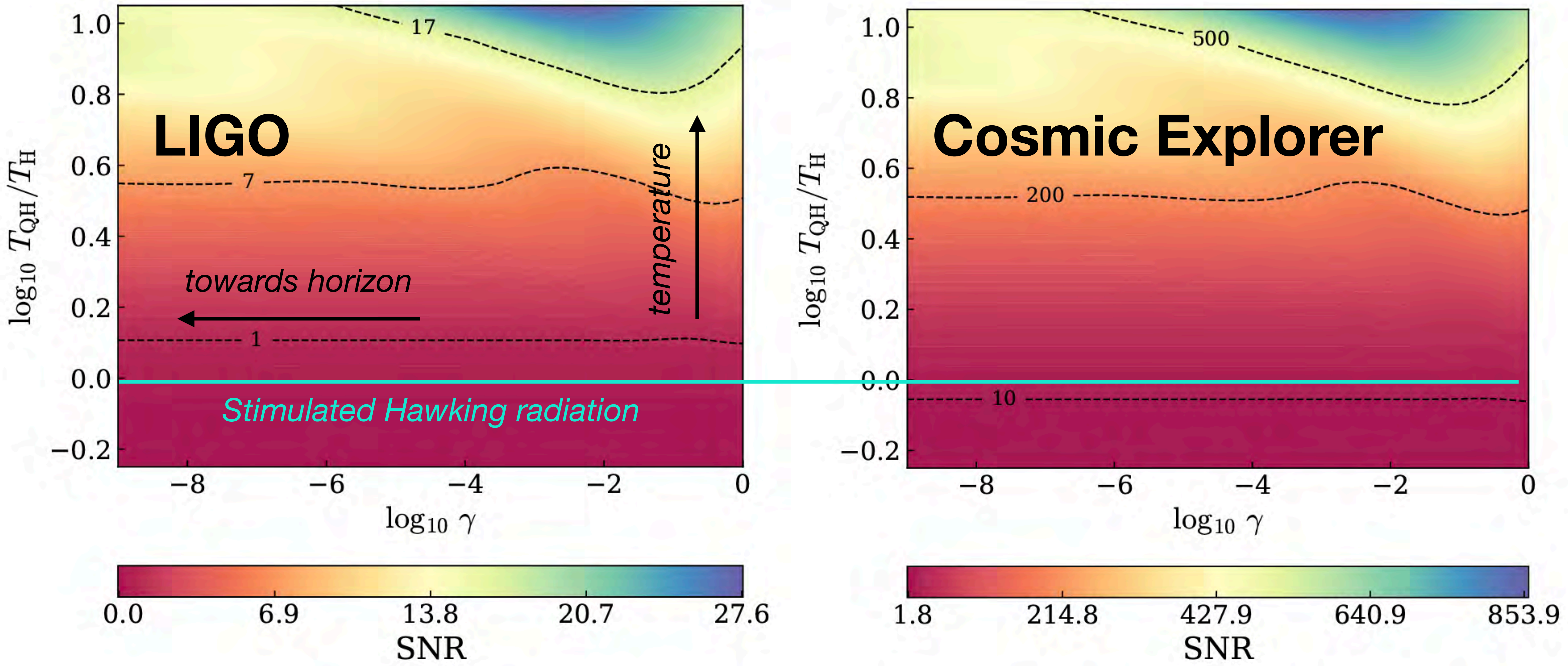




Future is bright!



- Echoes in "numerical relativity"?
- Hybrid PPN+Teukolsky with matching (Qingwen Wang's PhD thesis)



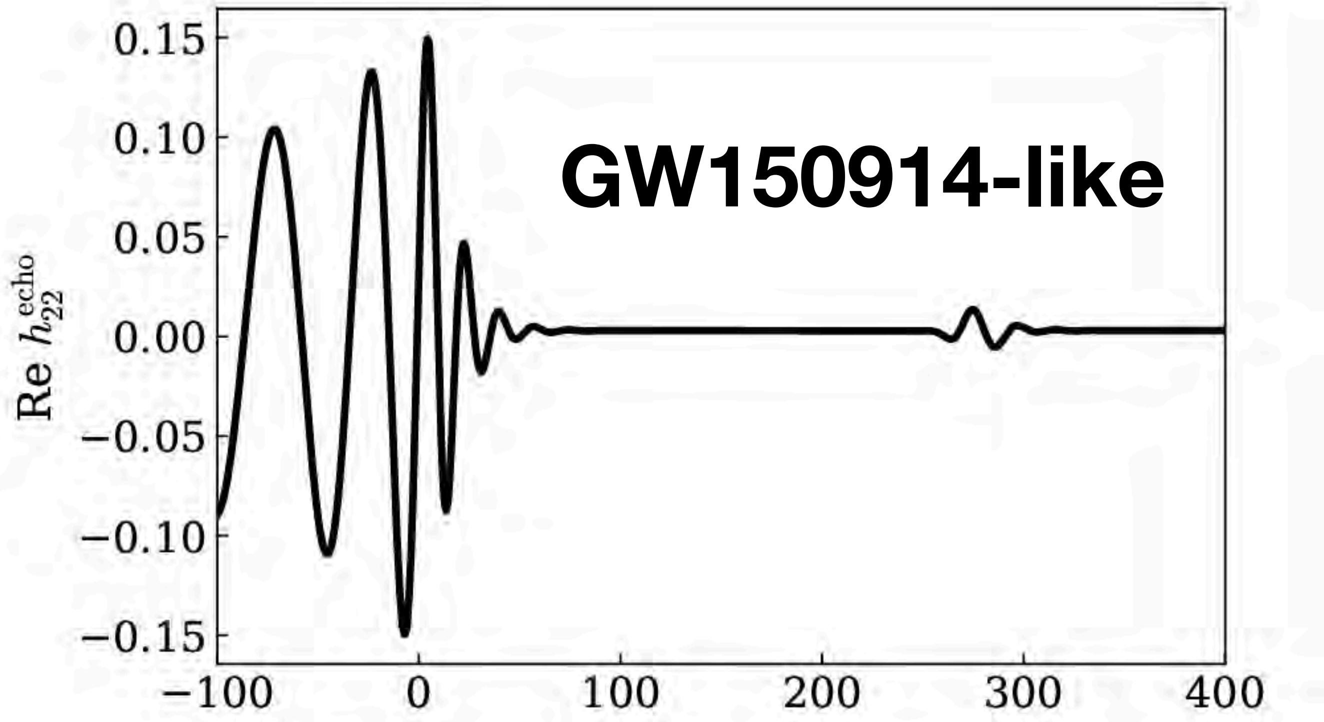


FIG. 11. The echo emitted by SXS:BBH:0207, following the main GW. Here we set $v_\Sigma^{(H)} = -13, \Delta v = 2/\kappa = 8, \gamma = 10^{-15}$, and $T_{QH} = T_H$.

arXiv > gr-qc > arXiv:2203.03174

General Relativity and Quantum Cosmology

[Submitted on 7 Mar 2022]

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

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

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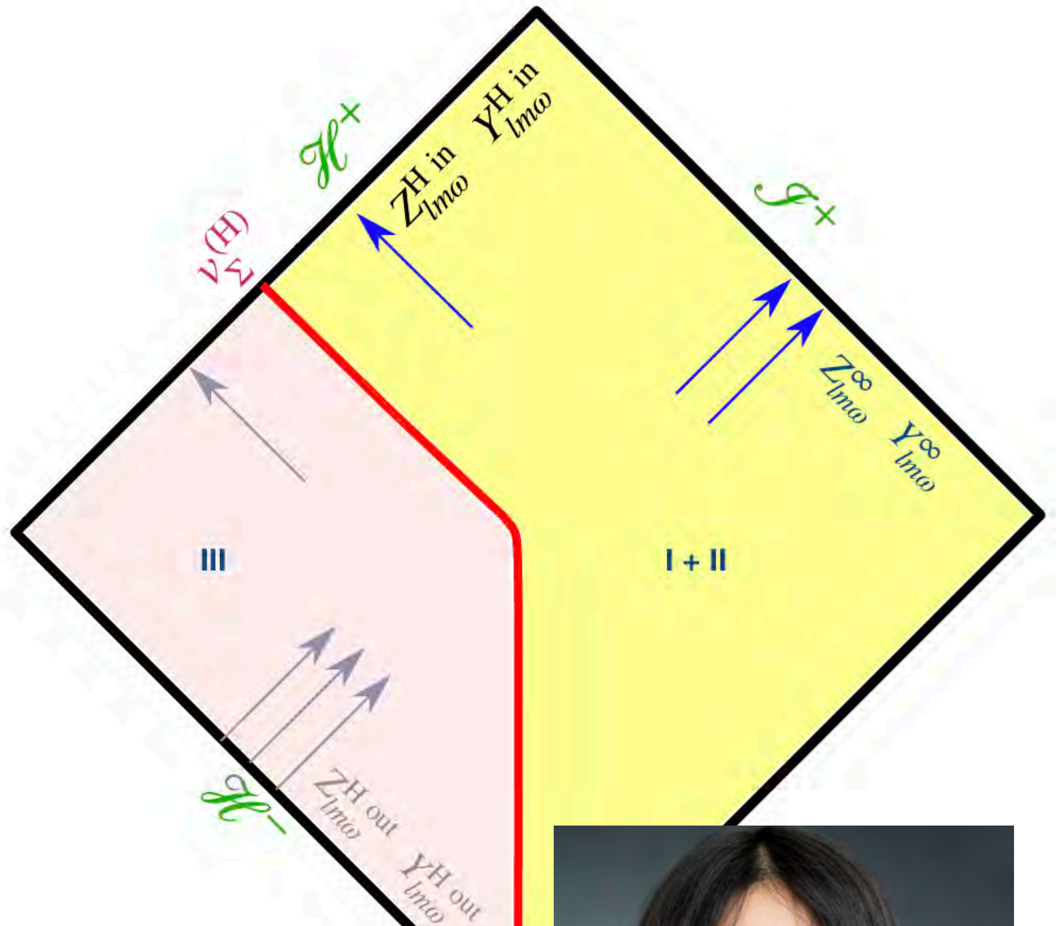

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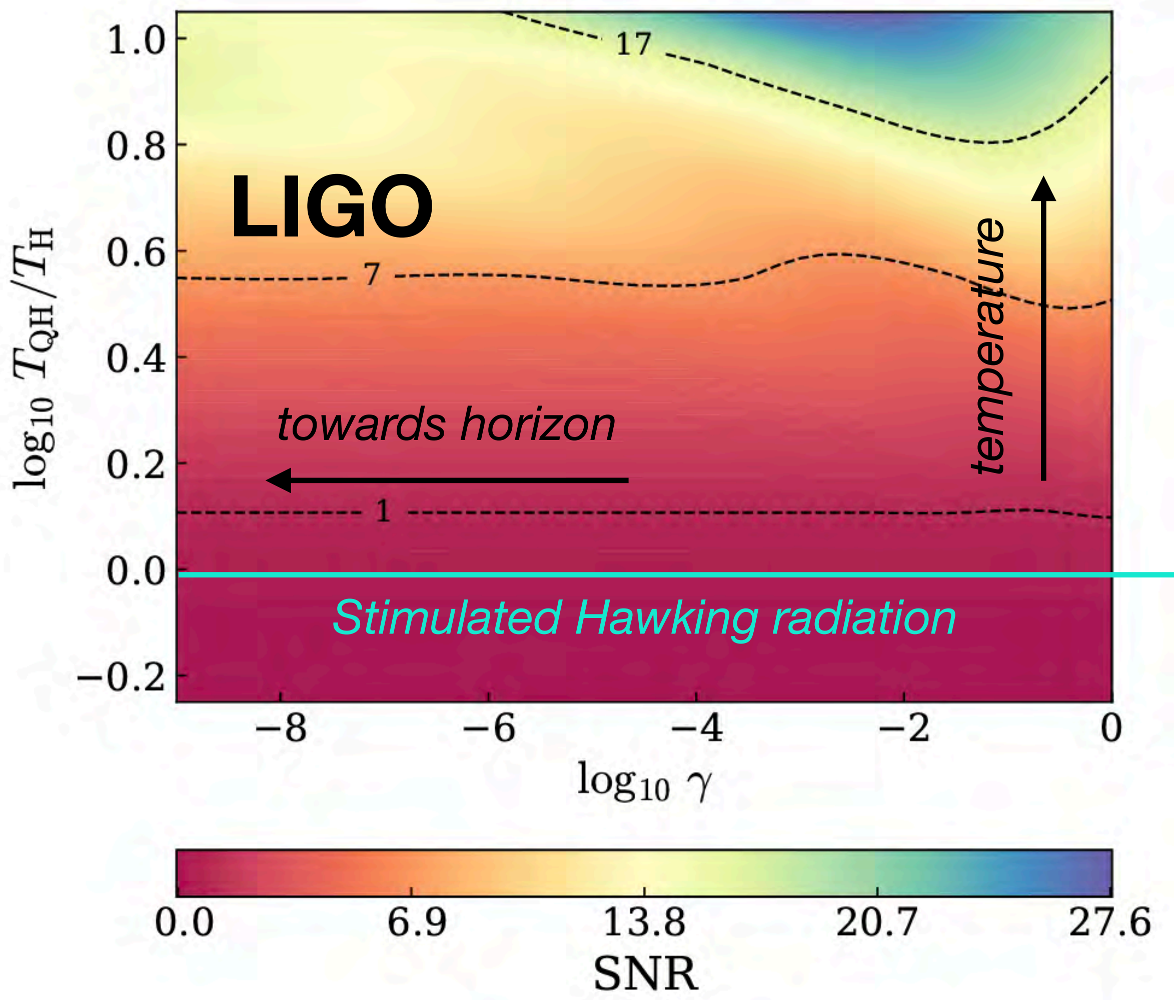

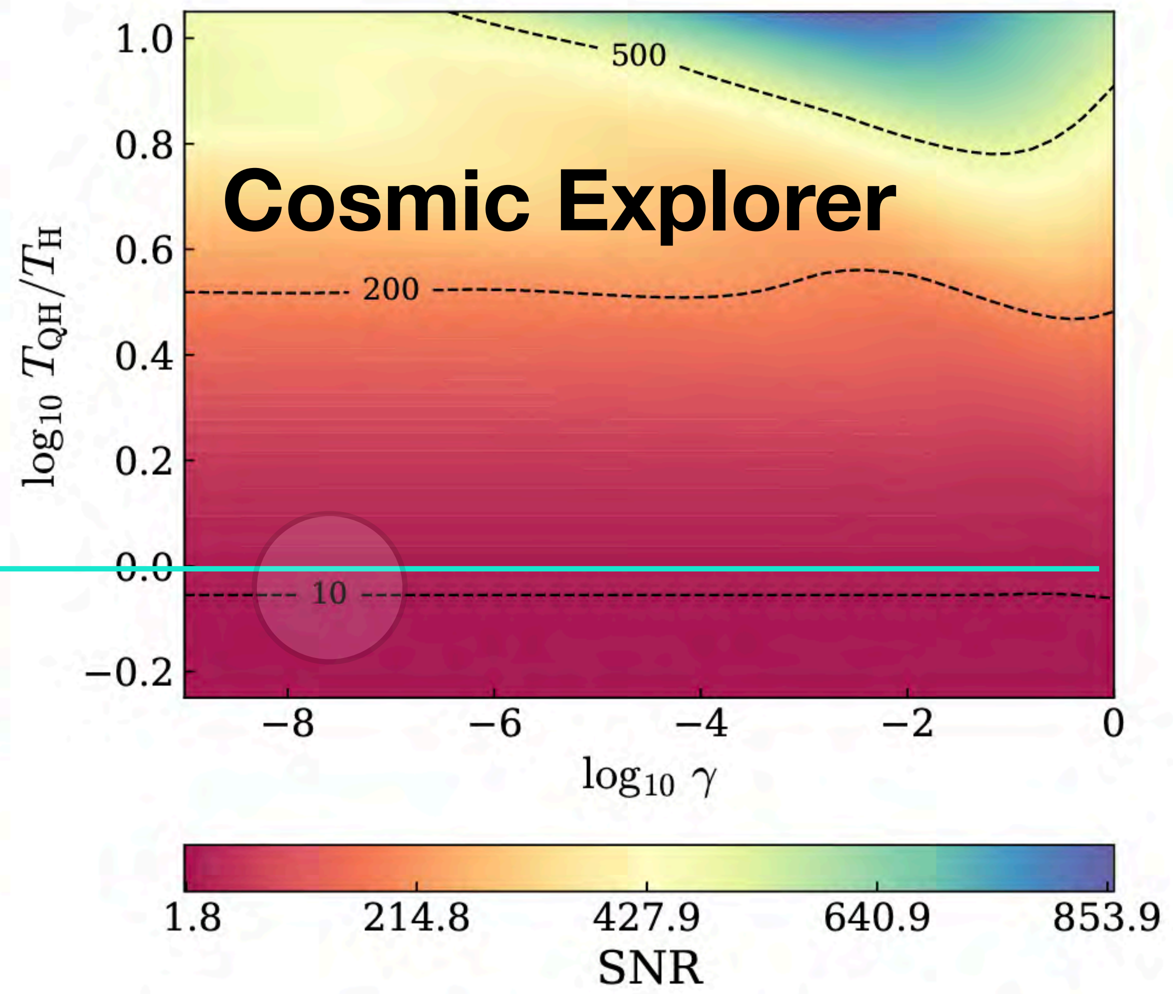

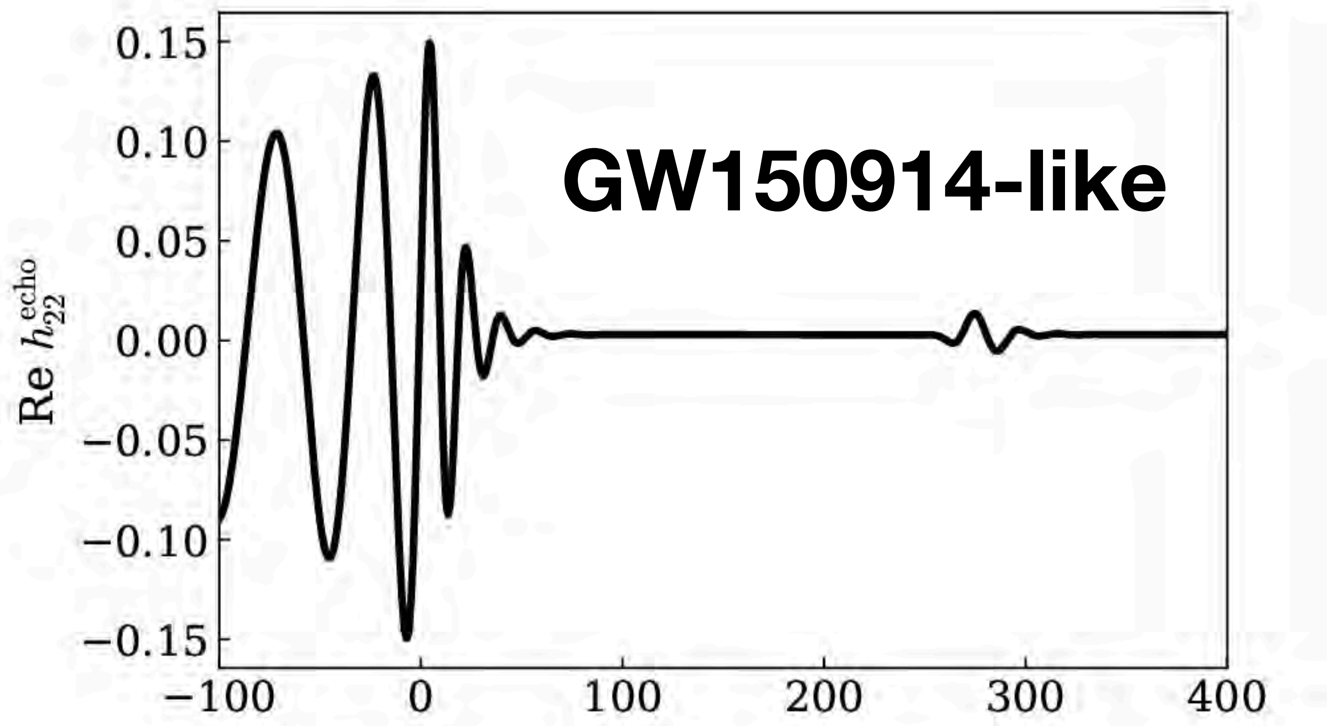

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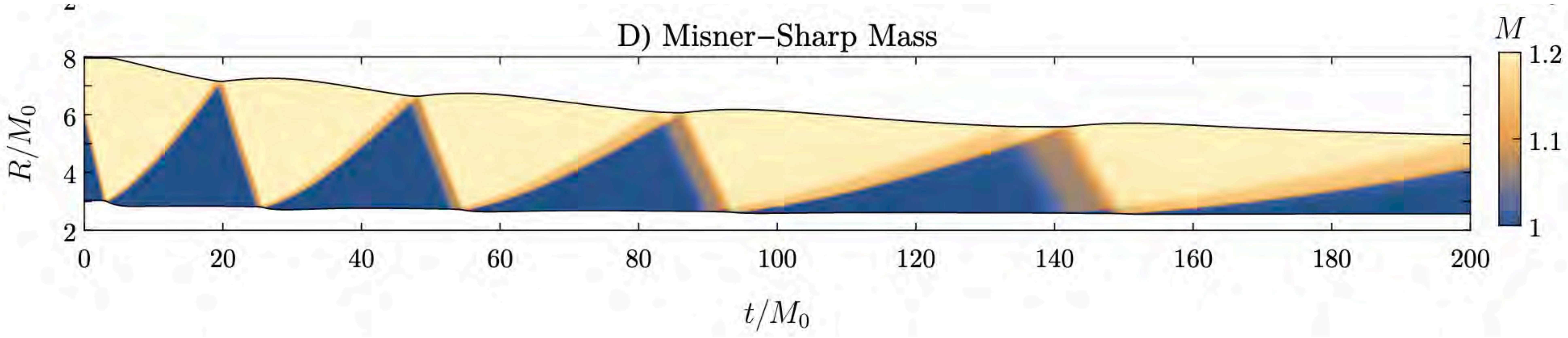
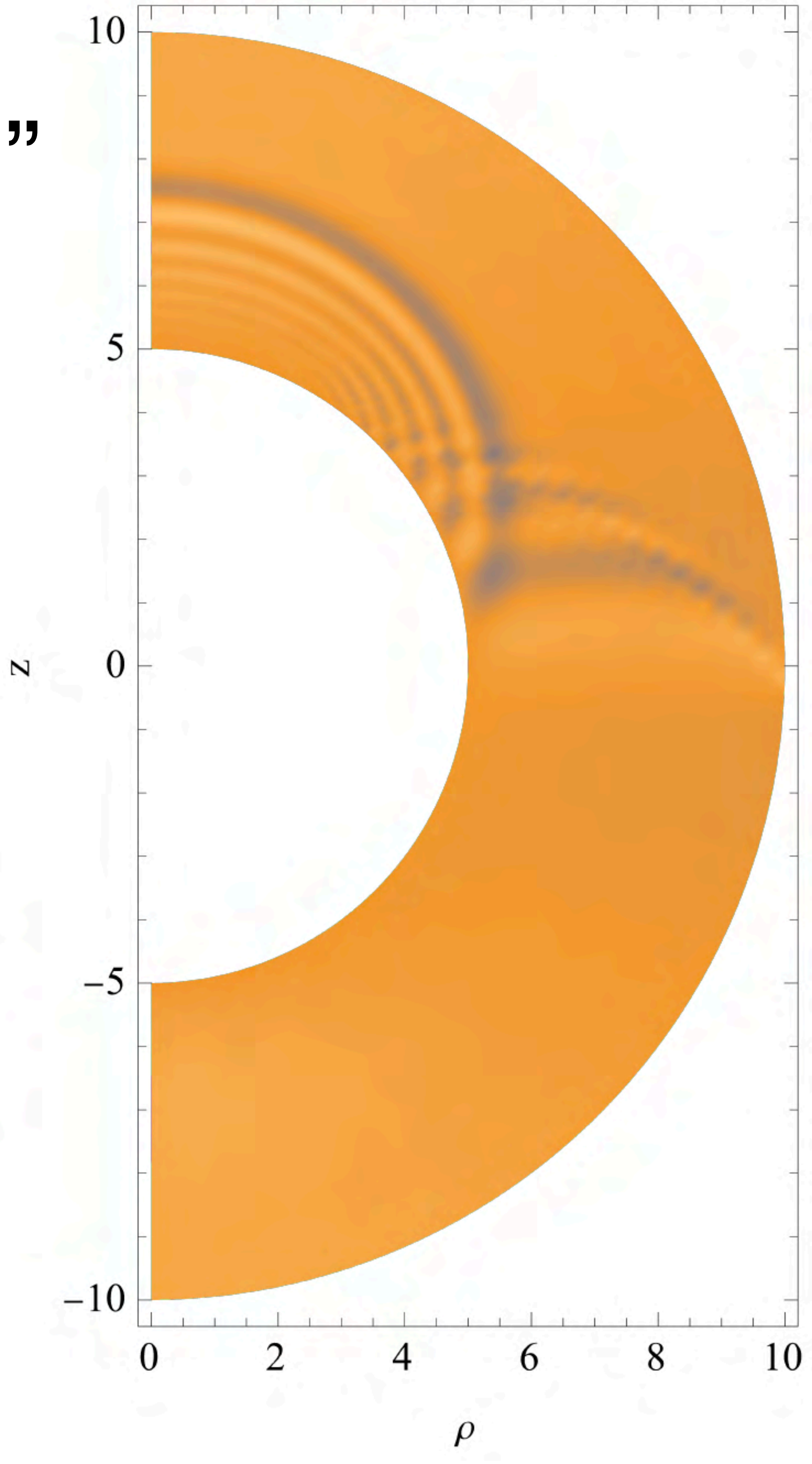
Black Hole Echoes in Numerical Relativity

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

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





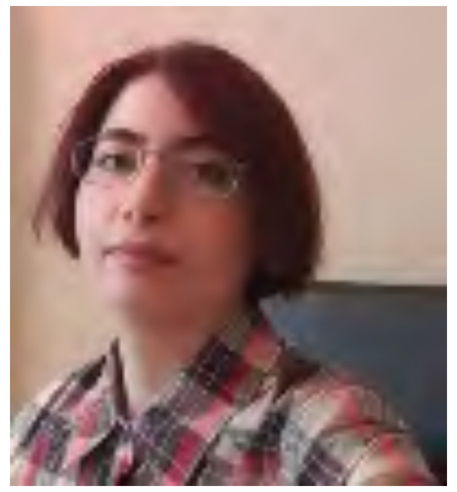
Can we image Quantum Black Holes? *the case of q-metric*

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

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

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

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

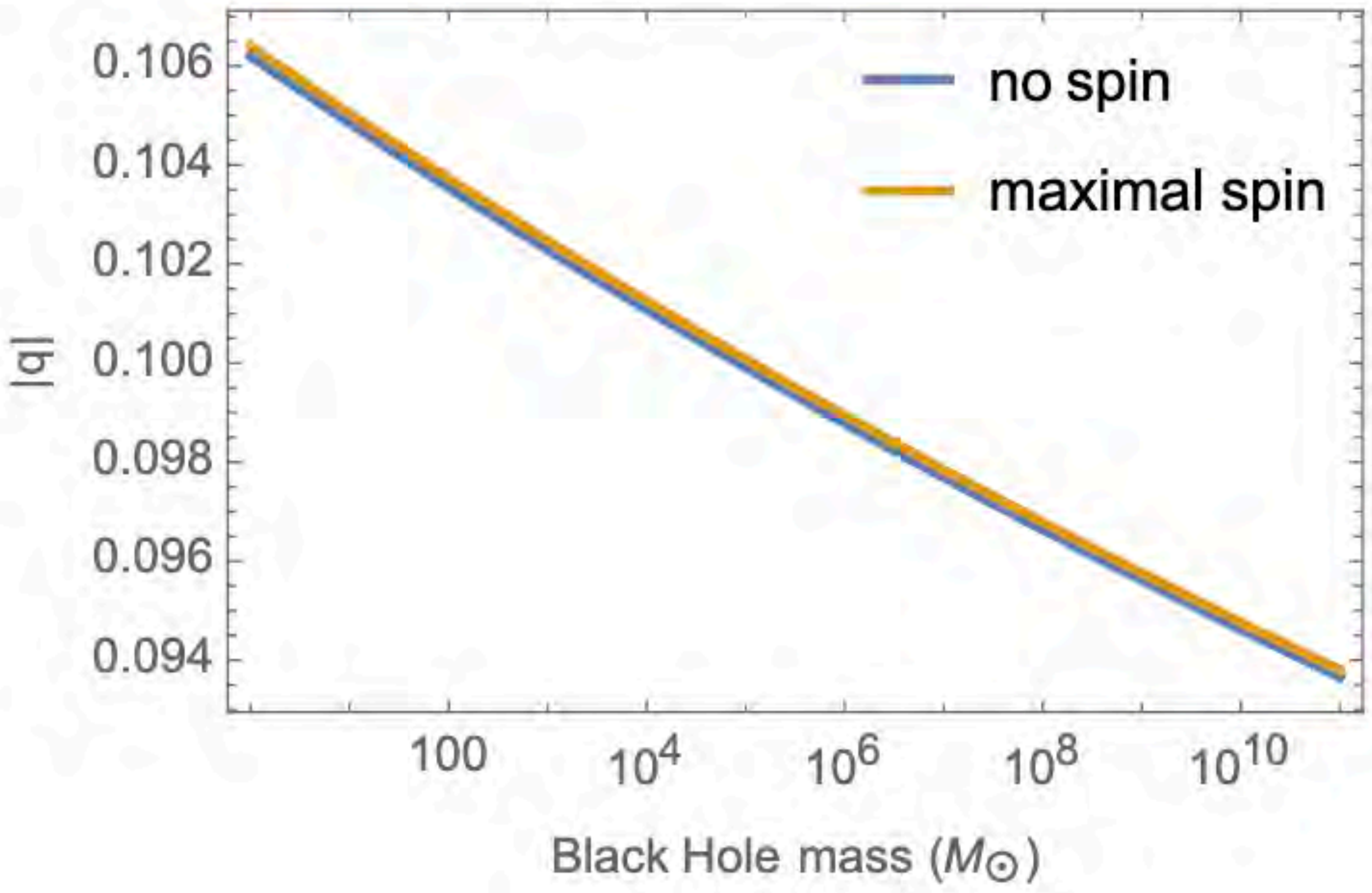


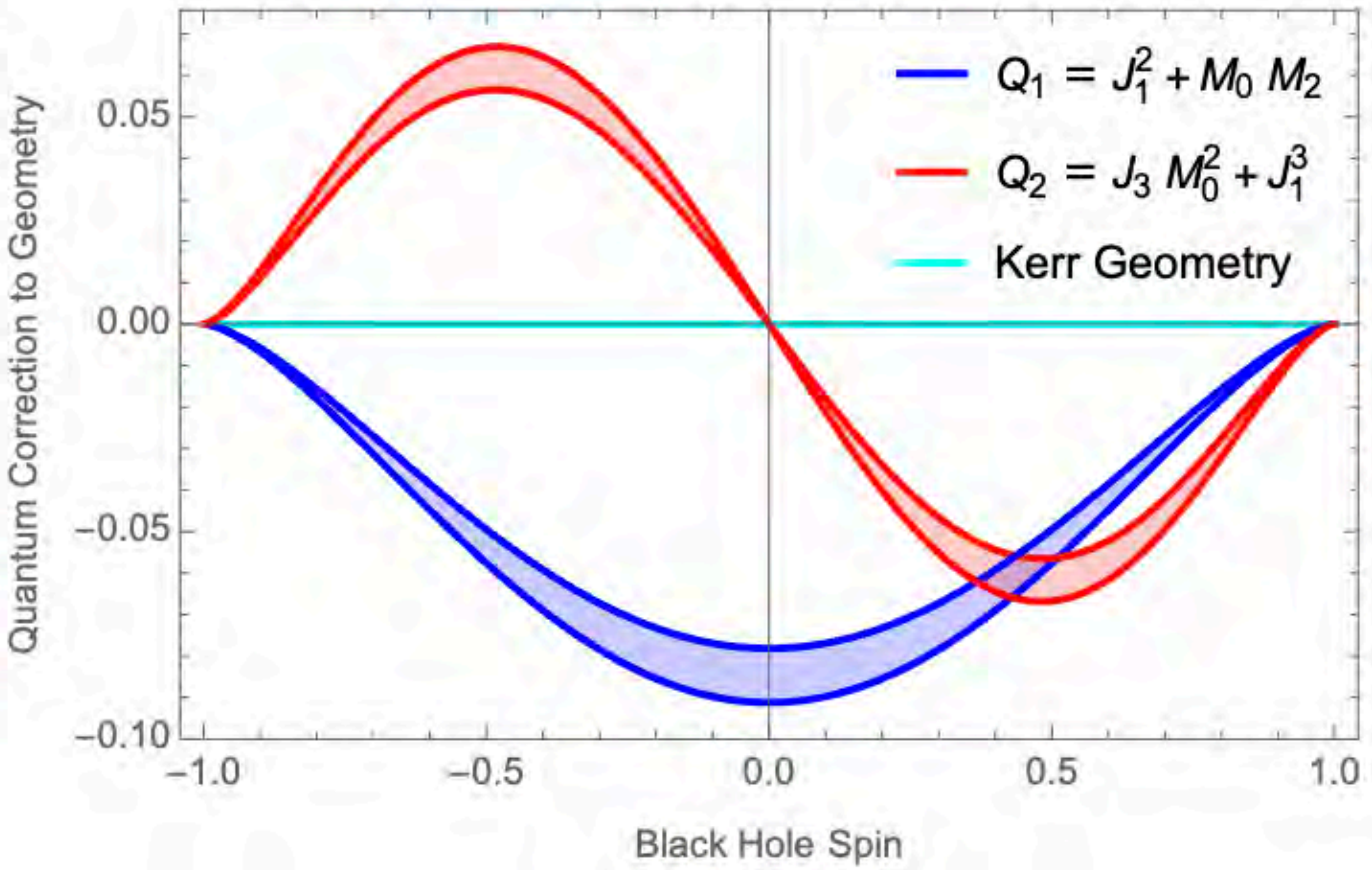
Imaging Quantum Black Holes?

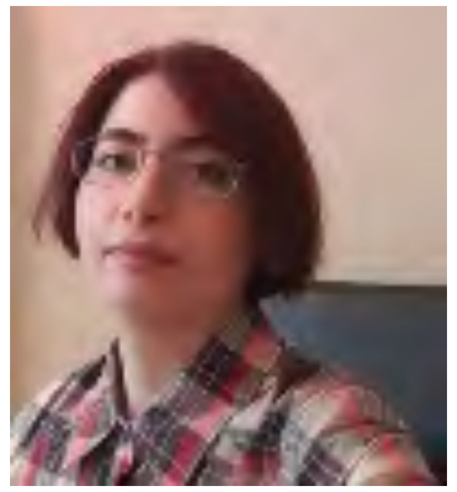
Faraji, NA, et al. (in prep.)

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

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







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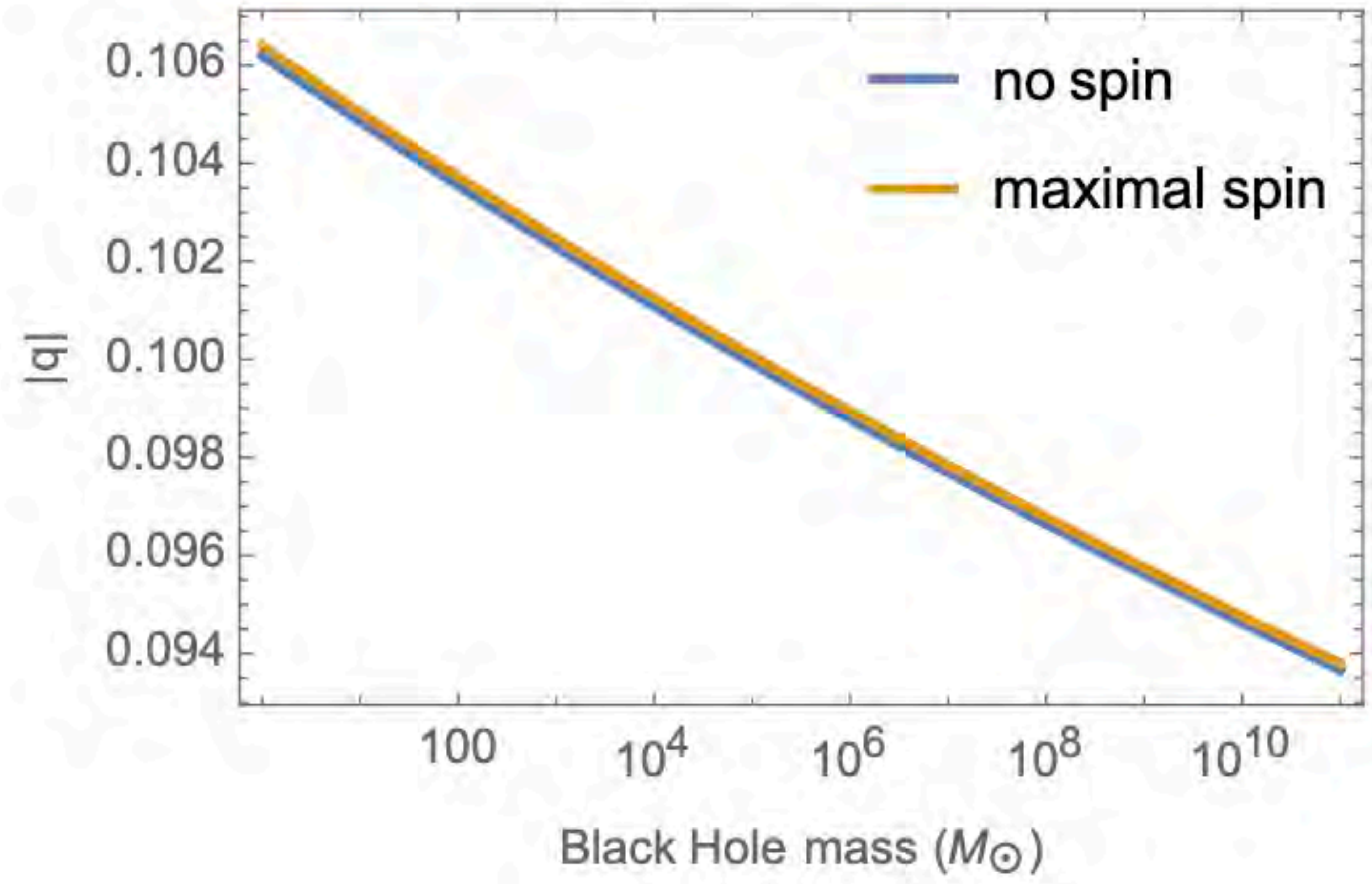
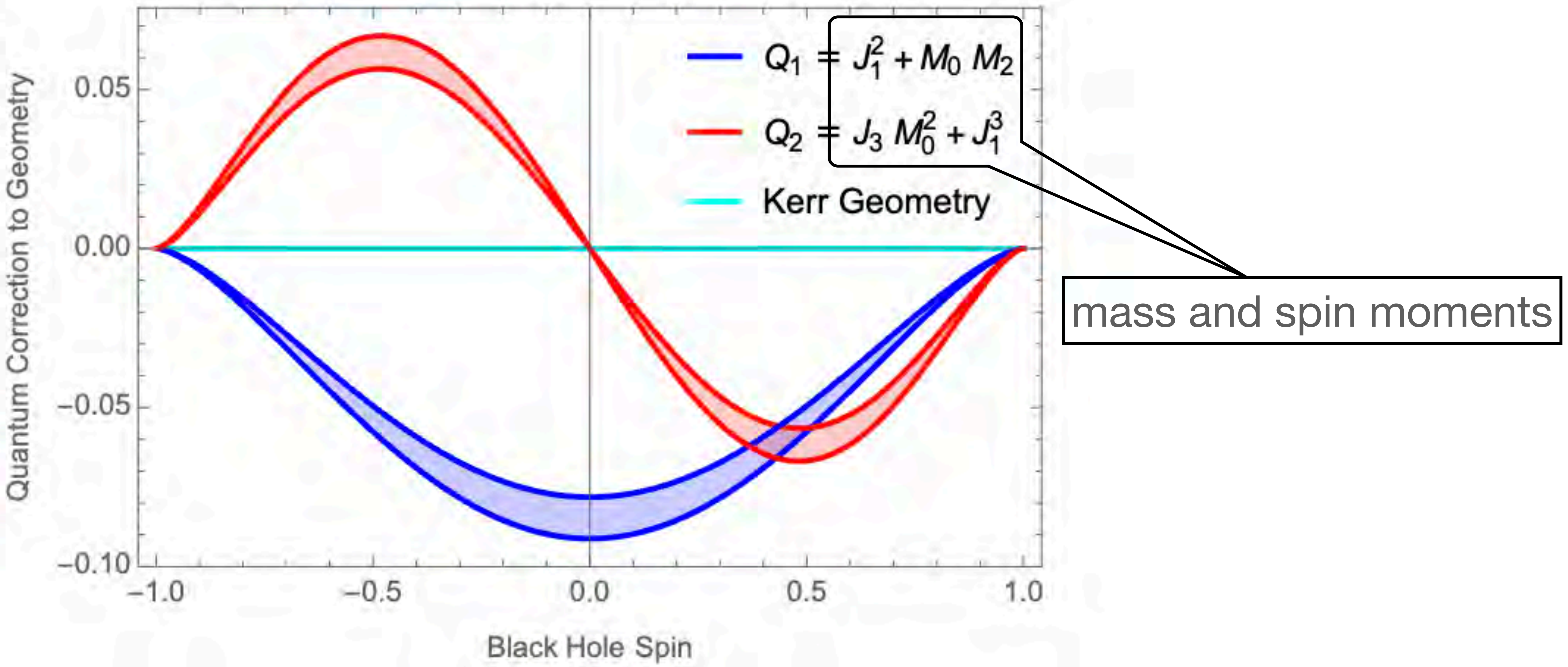




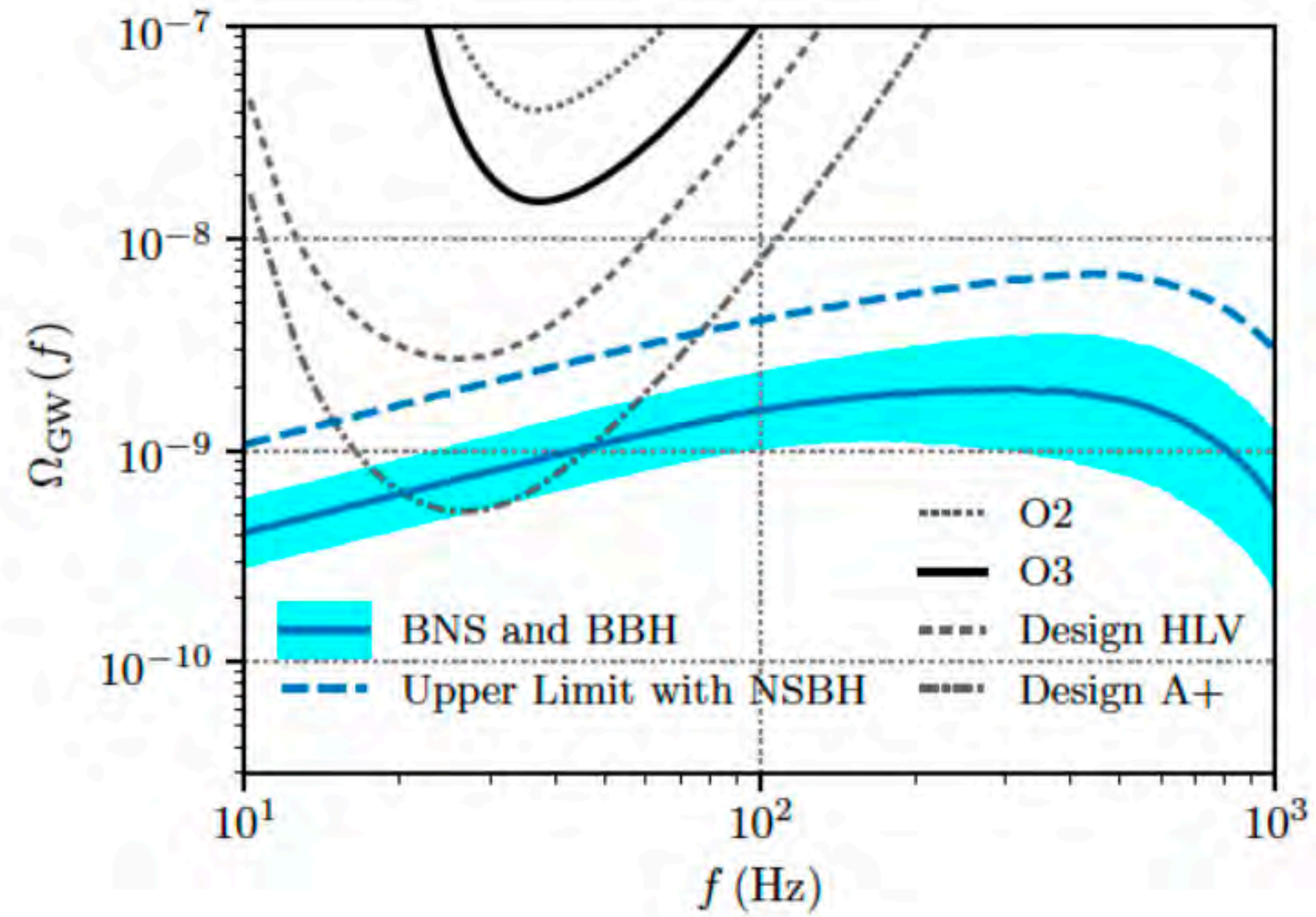
When we fail to see anything

Subthreshold: what if we cannot detect the events?

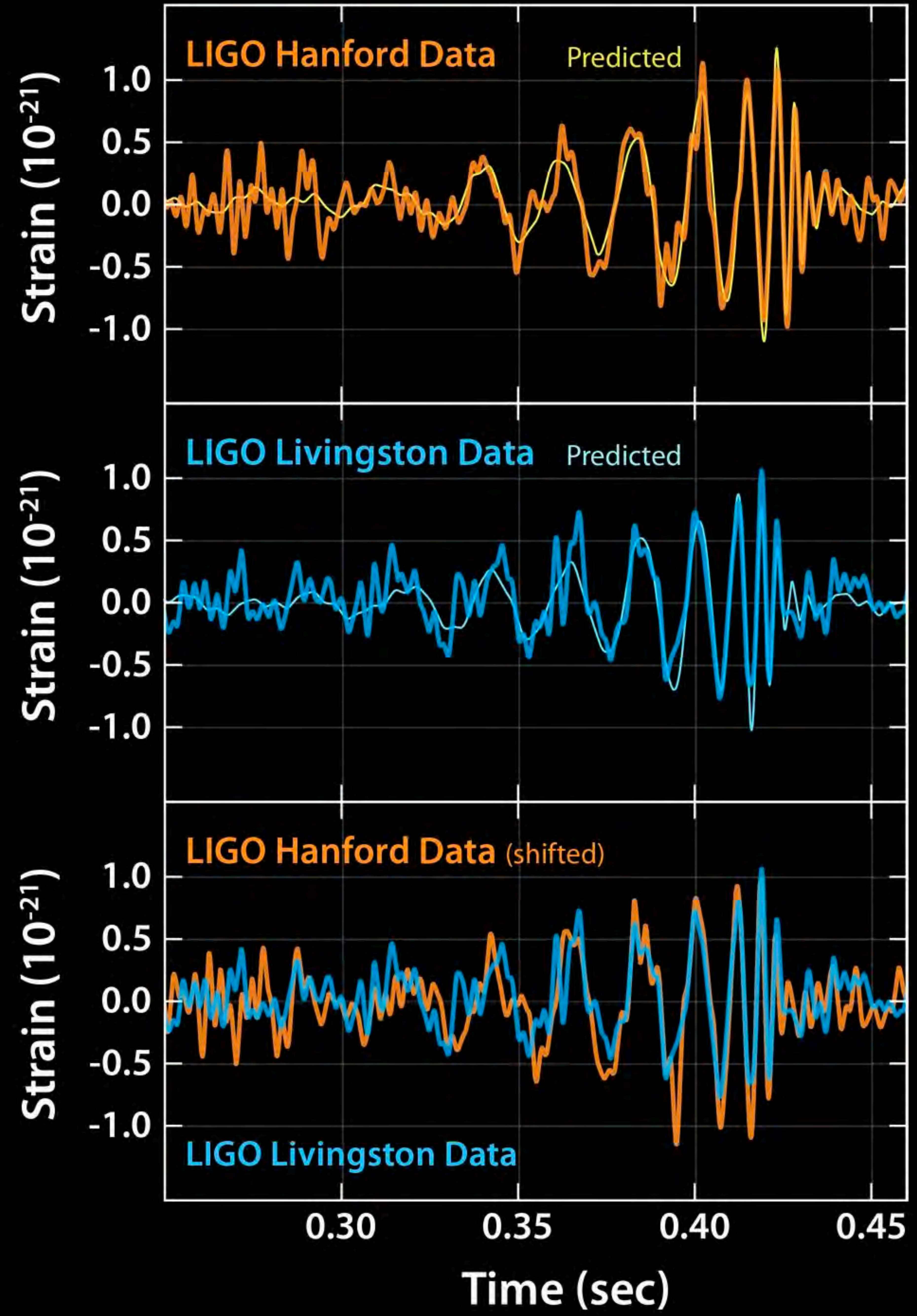
Detecting the Stochastic Gravitational Wave background (SGWB) by

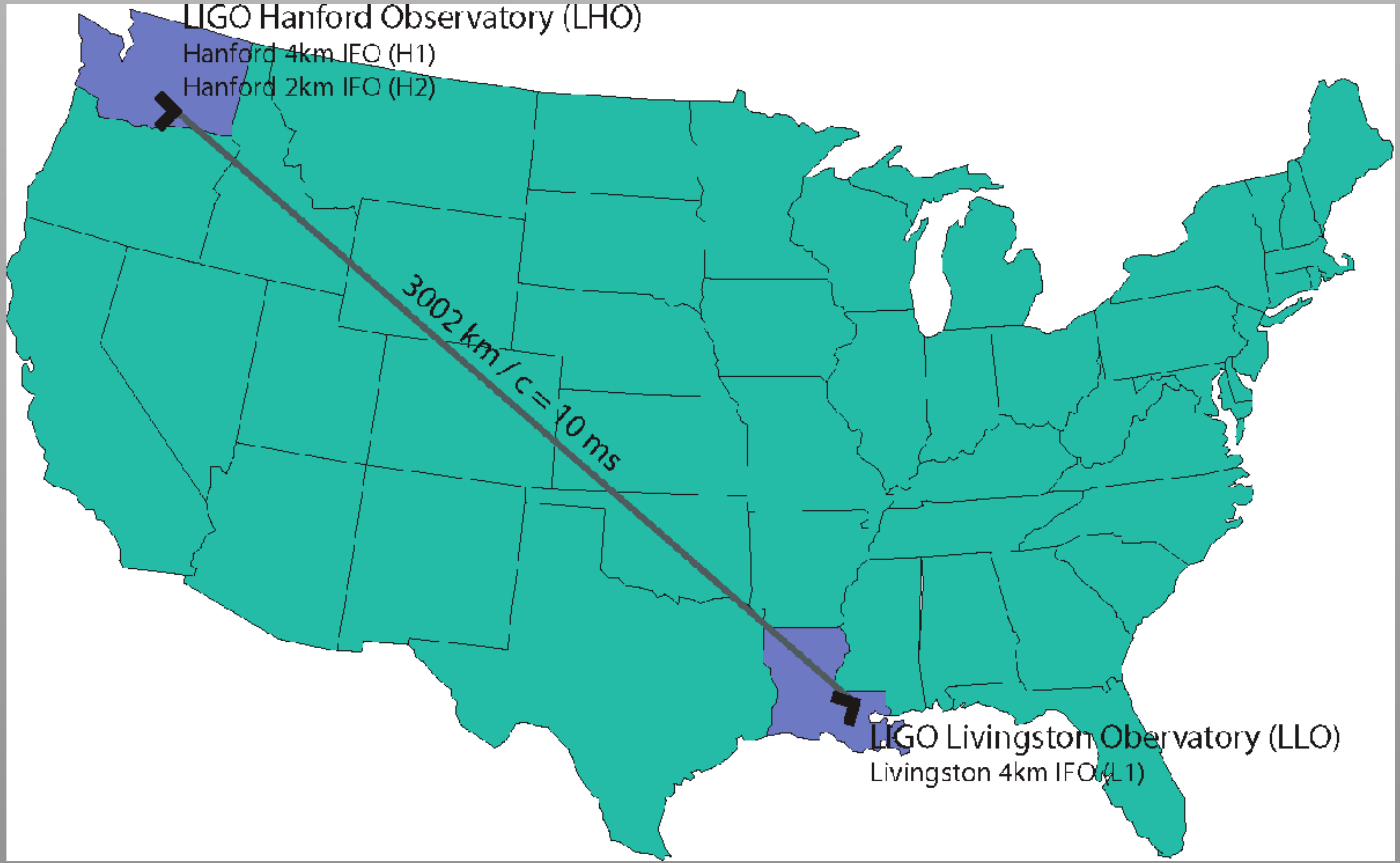
detector signal cross-power spectrum

Time-delay between detectors (± 10 msec) kills signal at frequency > 30 Hz (for unknown sky position)

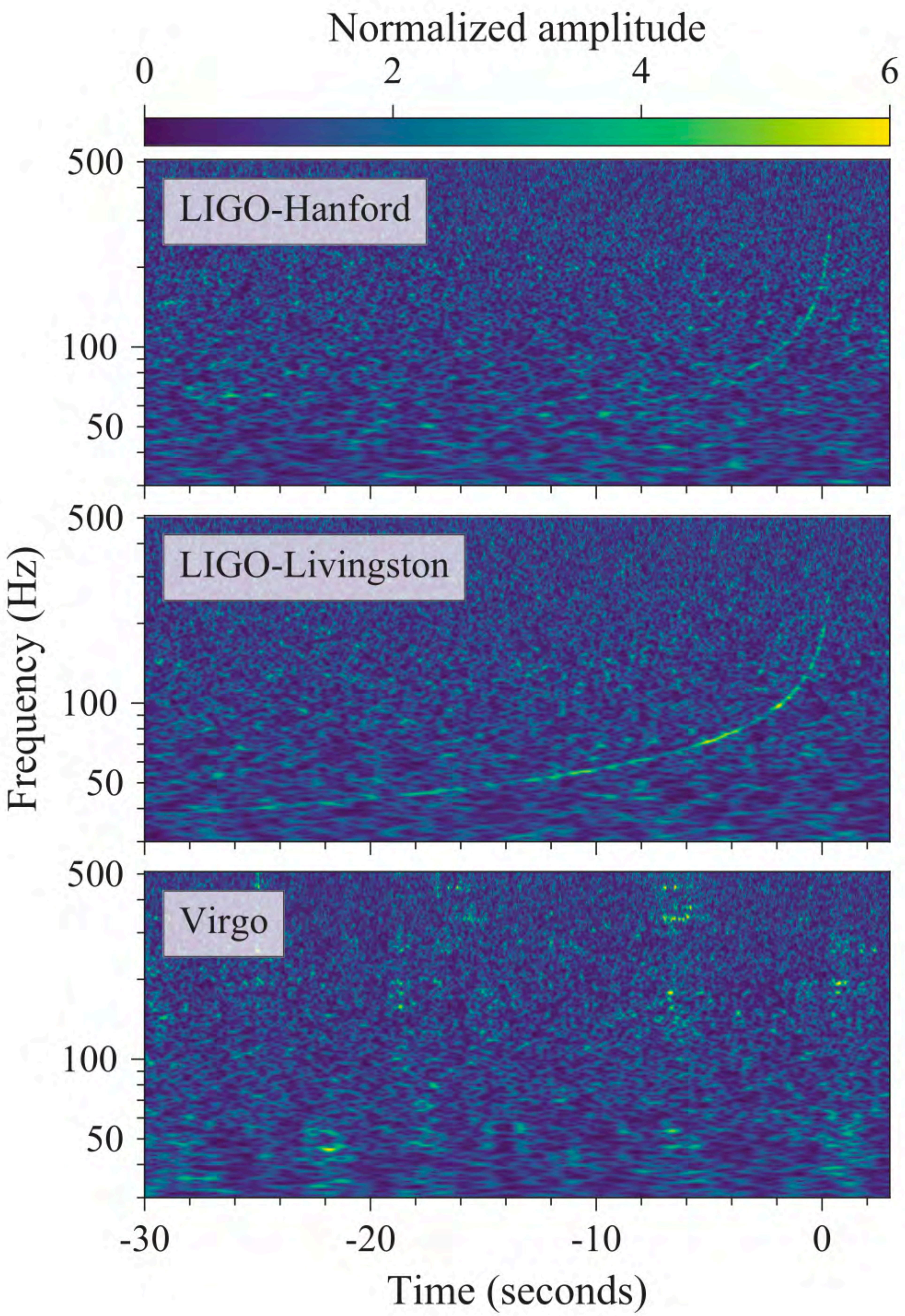


Abbott, et al, 2021


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


LIGO Hanford Observatory (LHO)
Hanford 4km IFO (H1)
Hanford 2km IFO (H2)
3002 km / c = 10 ms
LIGO Livingston Obervatory (LLO)
Livingston 4km IFO (L1)

Note that spectrograms remain correlated on much longer times



Signal beyond power spectrum

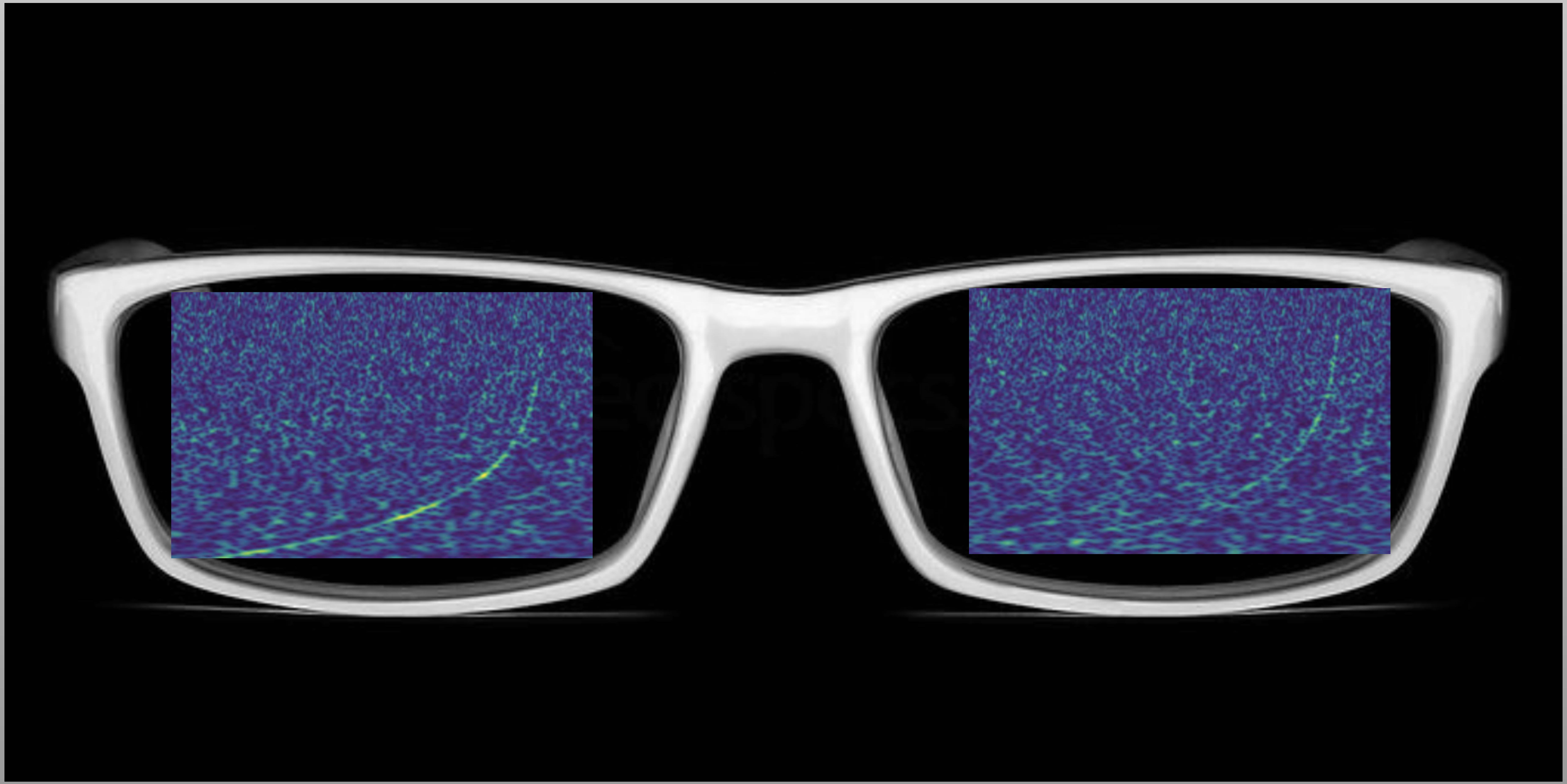
The temporal dependence of the signal is not captured *only* by the power spectrum

A new method:

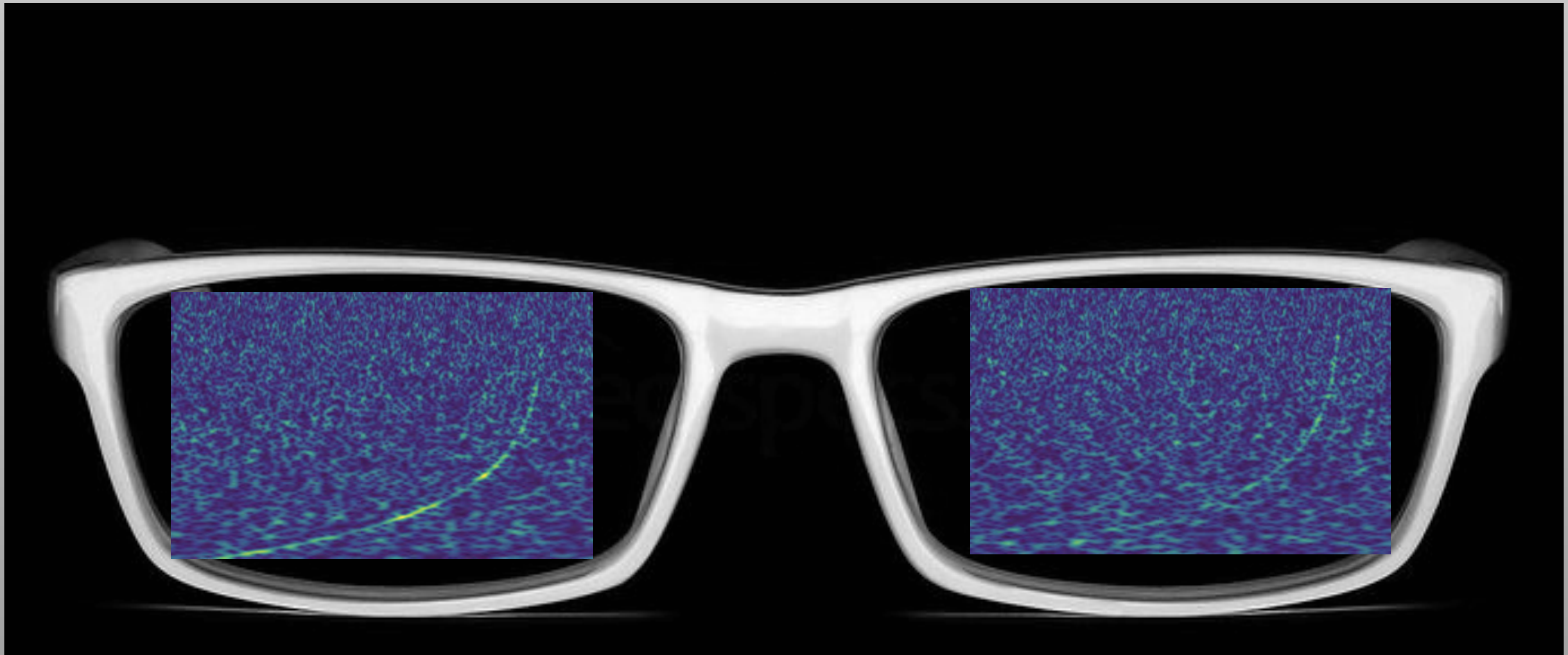
SpeCS: Spectrogram Correlated Stacking

Dey, Longo, Mukherjee & NA 2023

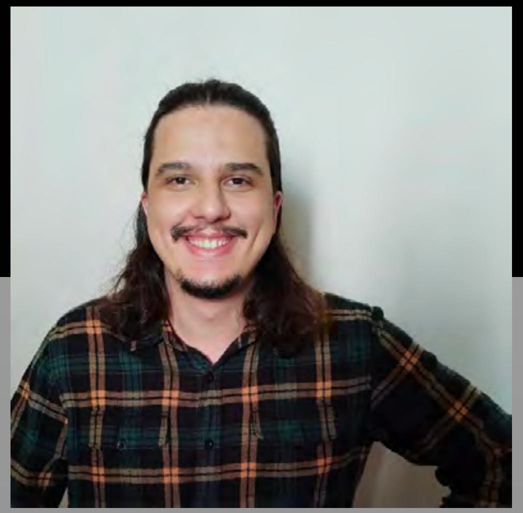
SpeCS: Spectrogram Correlated Stacking



SpeCS: Spectrogram Correlated Stacking



Ramit Dey (Western)

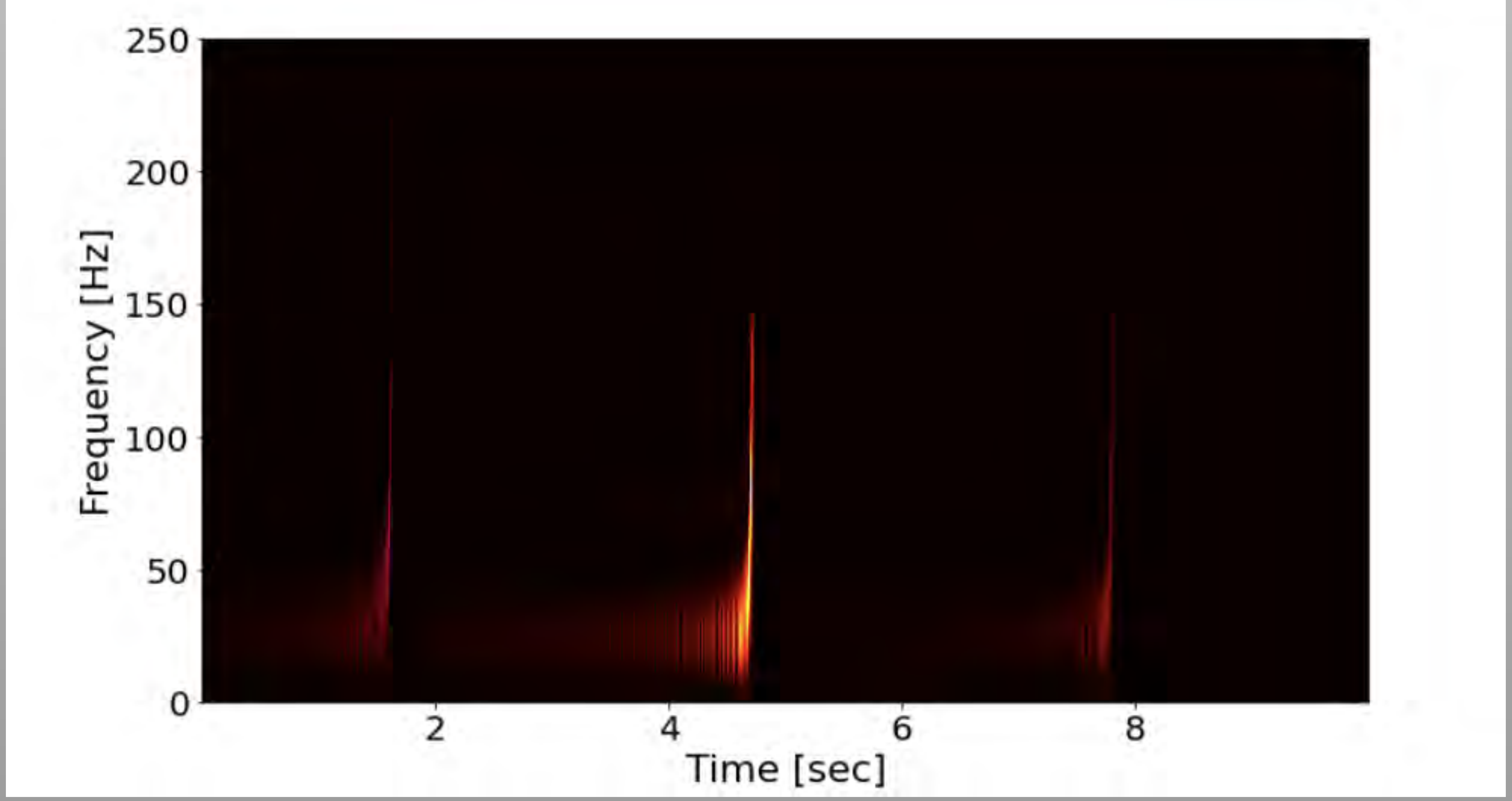


Luis Longo (UABC, Brazil)

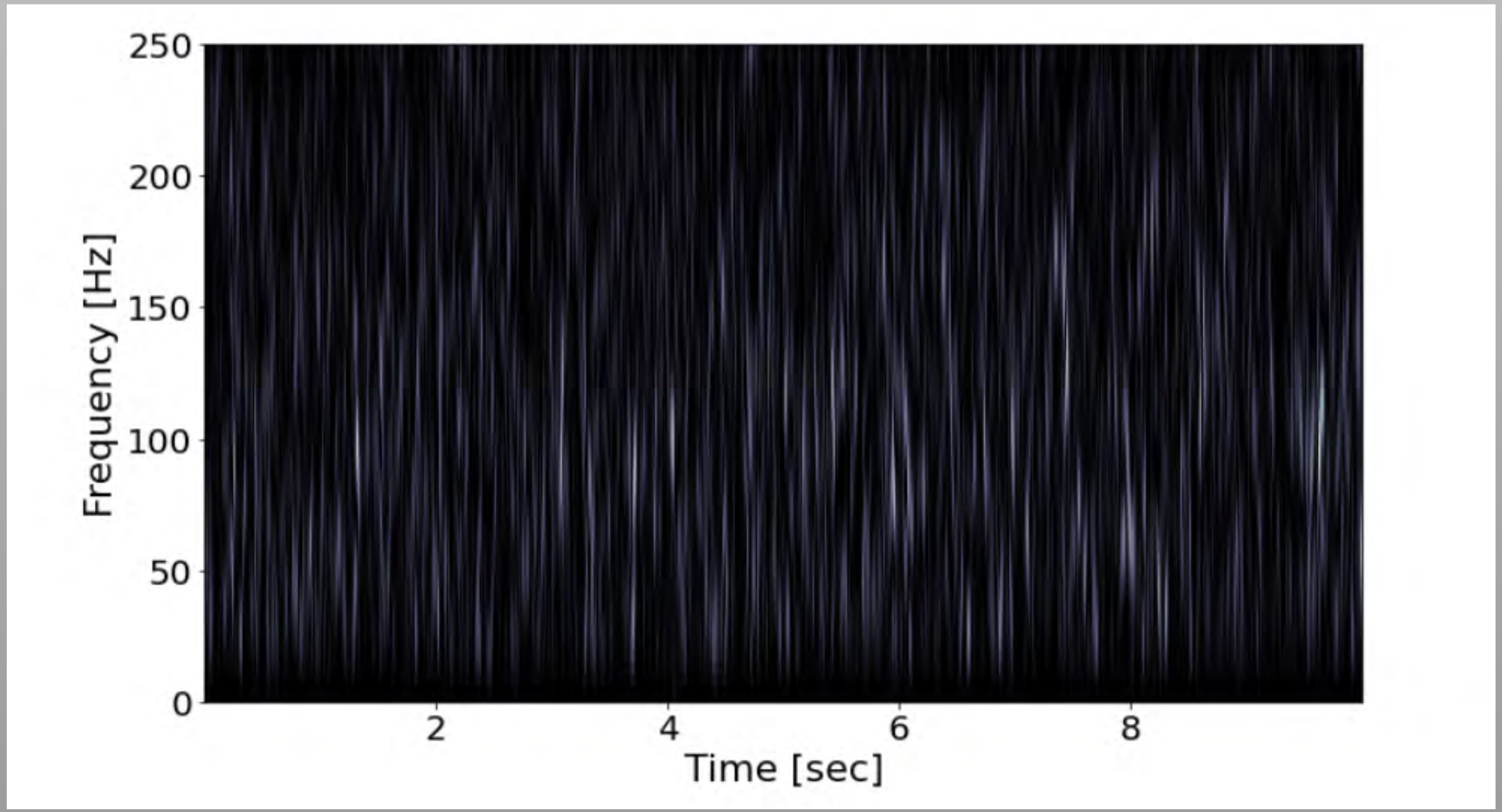
Suvodip Mukherjee (TIFR, India)

Implementation of SpeCS on injections

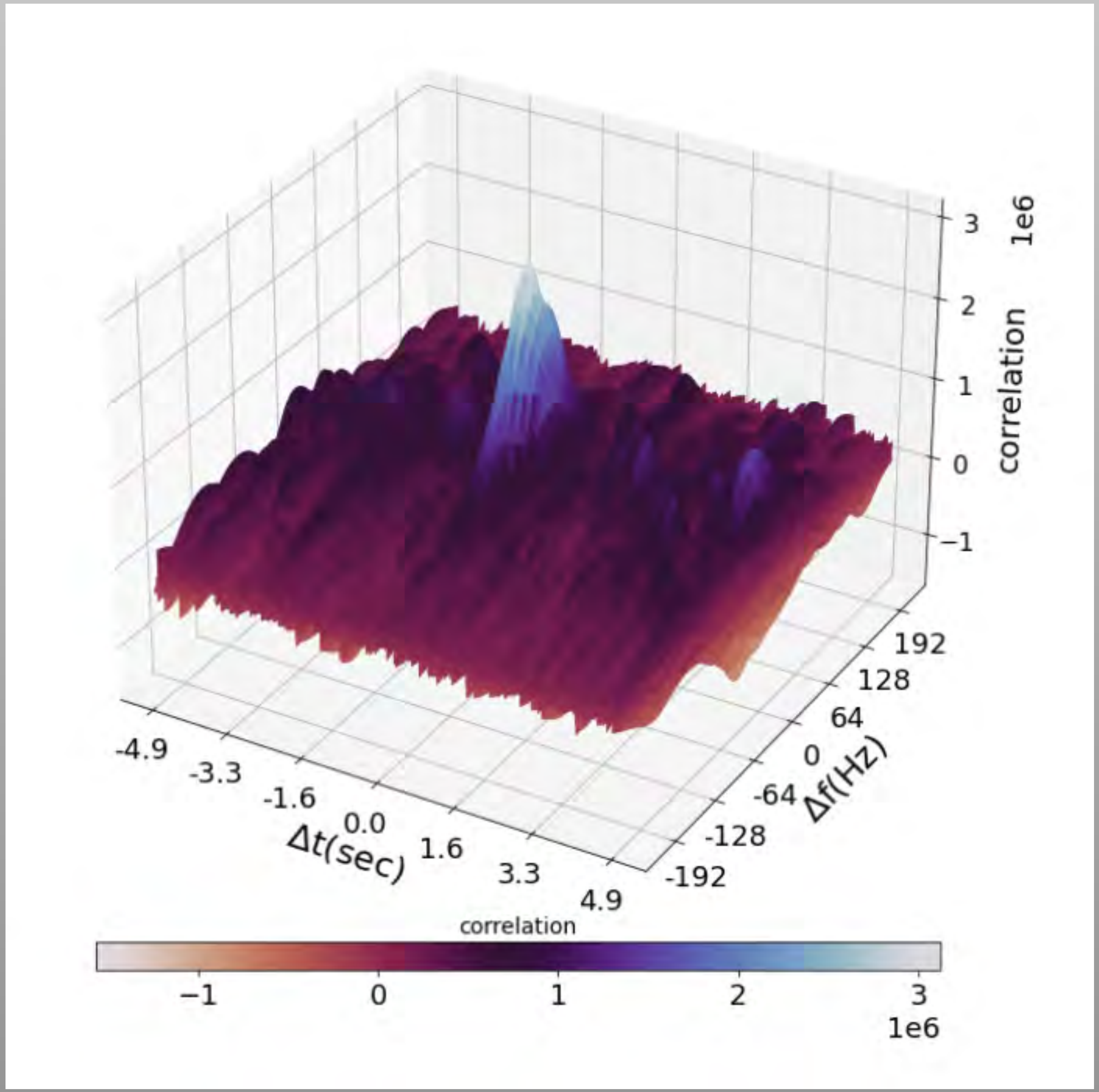
signal



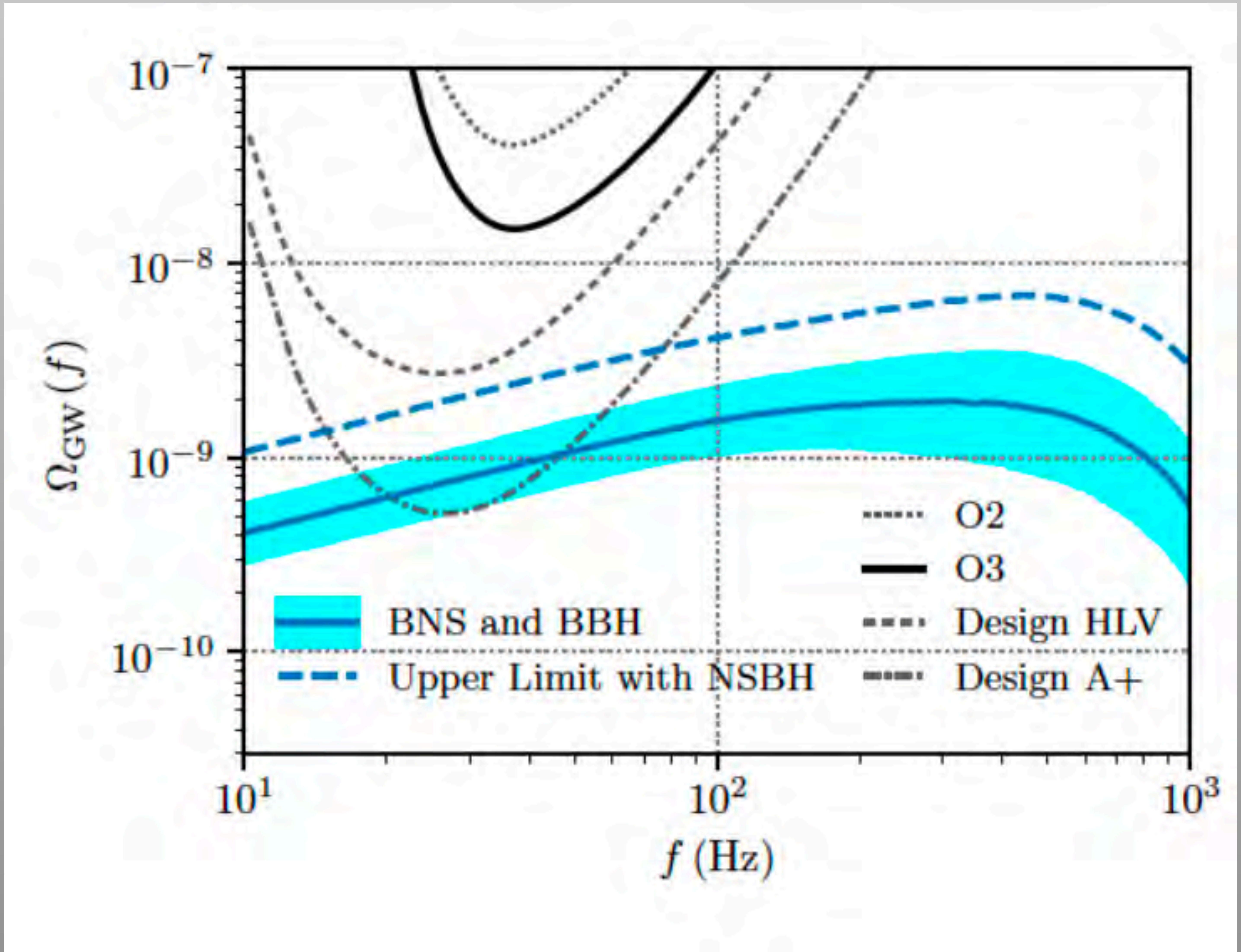
noise



SpeCS: Results on the injections



SpeCS improves (astrophysics) SNR by ×8



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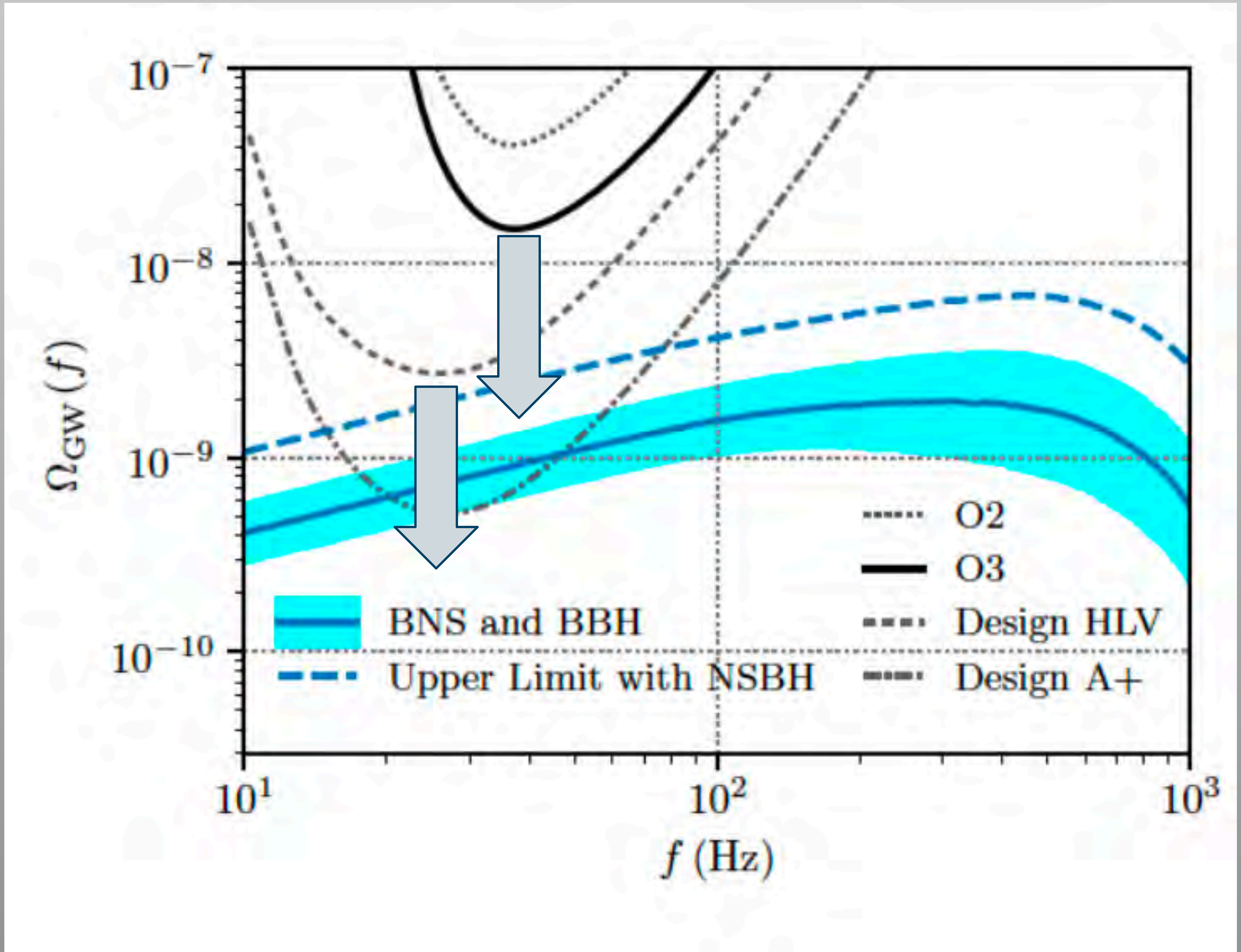
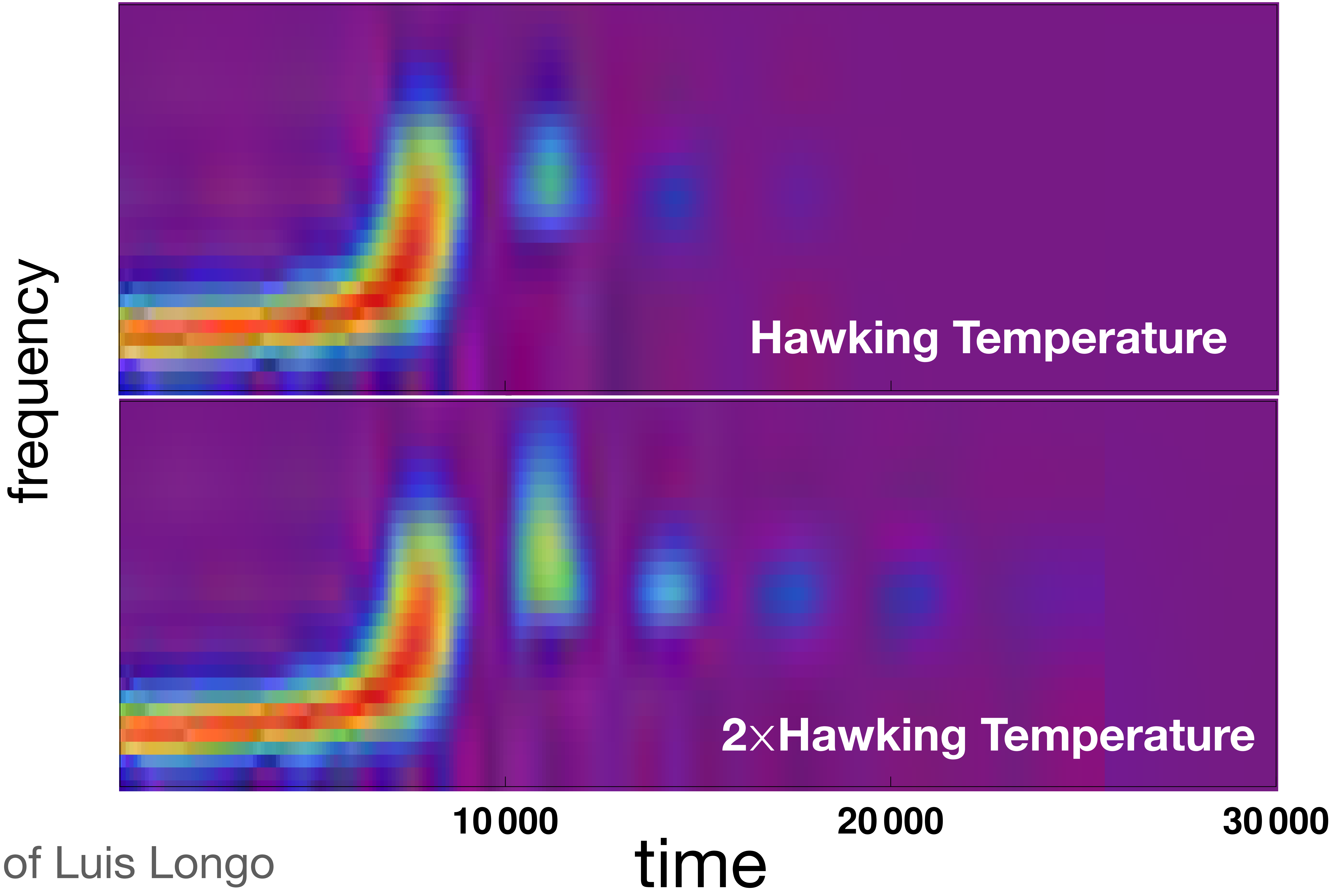


Can we see echoes in SpeCS?



Courtesy of Luis Longo

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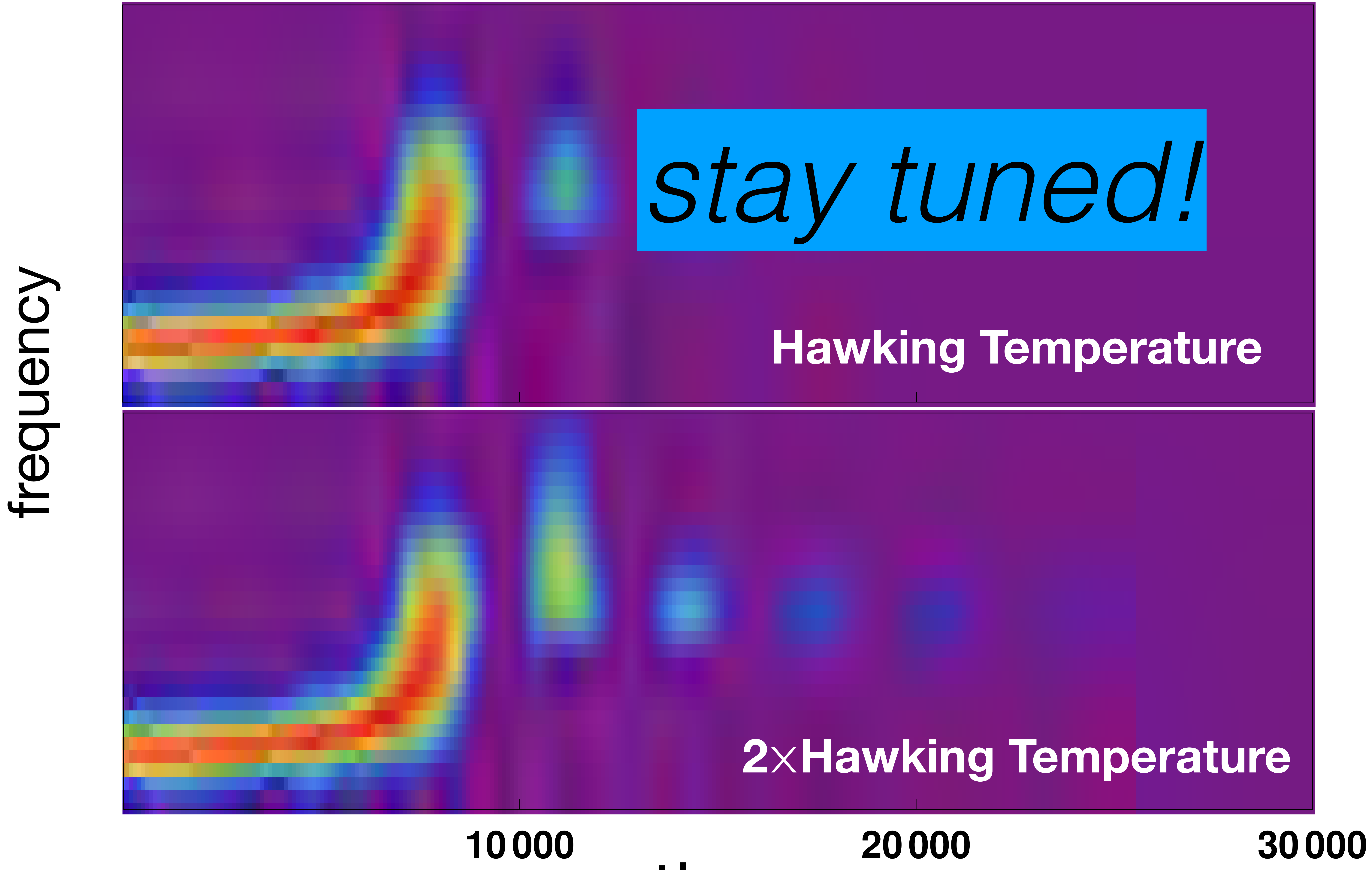


Courtesy of Luis Longo

Quantum Gravity in the vacuum

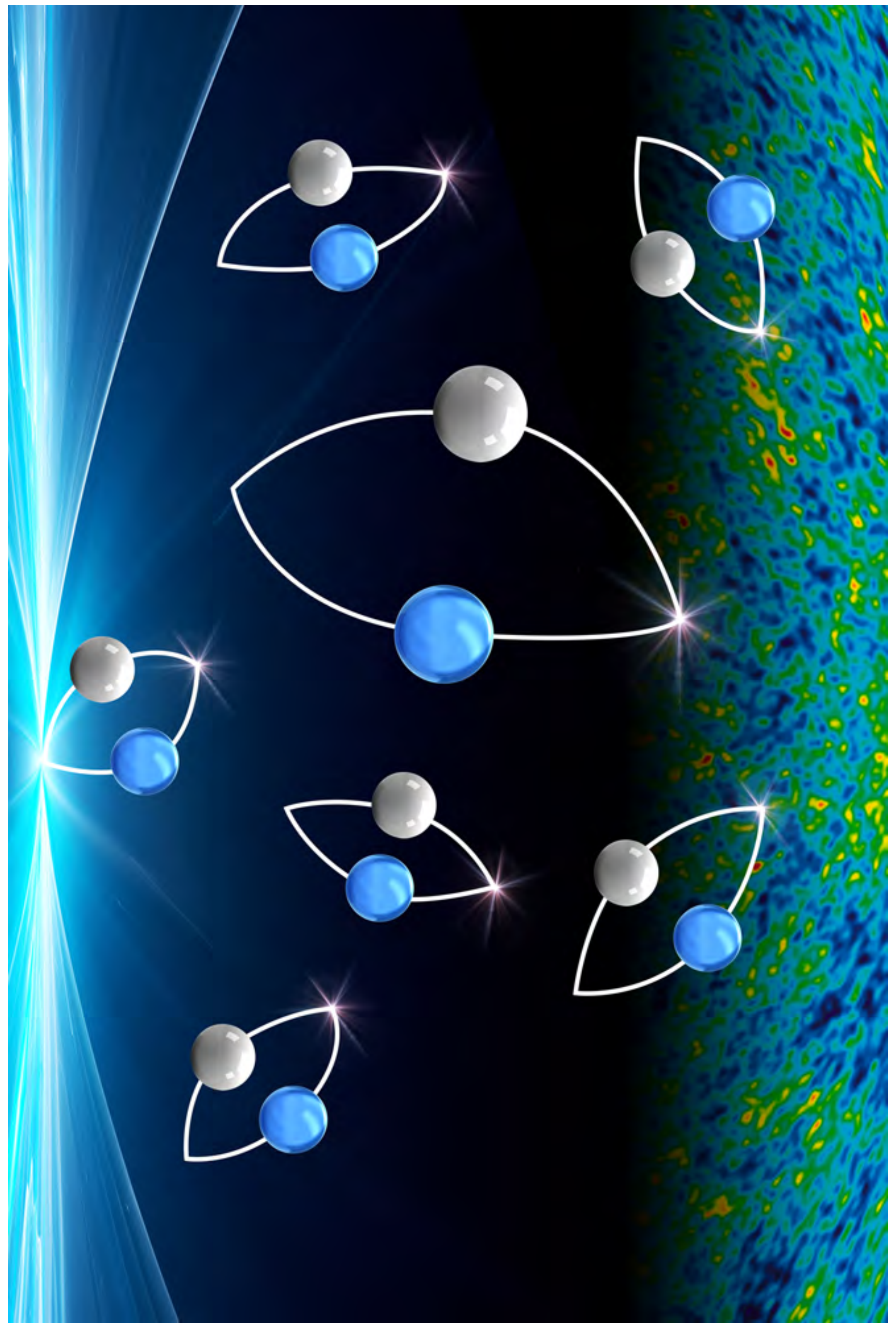
Remember the Cosmological Constant Problem?

- Why is the Quantum Vacuum, made out of heavy particles, so light?!

$$\rho_{vac} = (7.1 \pm 0.9) \times 10^{-27}\ kg/m^3$$

- when Quantum Mechanics predicts an energy density of

$$\rho_{QM} \sim 10^{33}\ kg/m^3$$



Gravity vs *Quantum*: A Tale of Two Vacua

- In General Relativity: $G_{\mu\nu} = 0$

  → Minkowski, black holes, gravitational waves

- In Quantum Field Theory, $\min \mathscr{H}\{\phi, \psi_a, A_\mu\}$

$$\langle T_{\mu\nu} \rangle \sim \pm M^4 g_{\mu\nu} \quad , \quad \langle T_{\mu\nu}(k) T_{\alpha\beta}(-k) \rangle_c \sim \frac{M^5}{\sqrt{k^2}}$$

- What happens when you try to solve: $G_{\mu\nu} = \kappa T_{\mu\nu}$?

(NA & Nelson 16; Wang, Zhu & Unruh 19; Carlip 19)

Now meet the Cosmological non-Constant Problem!

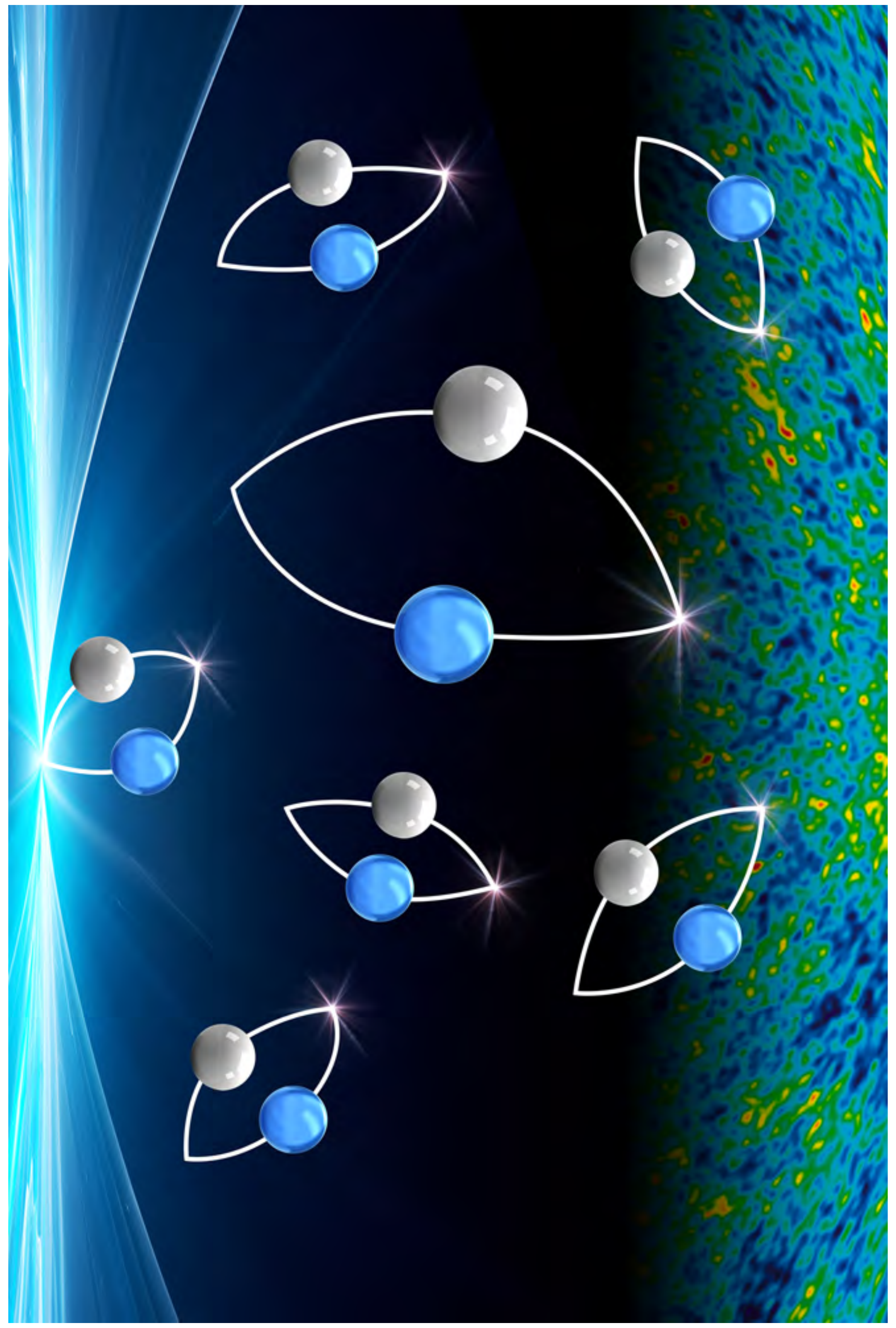
- Even if you cancel the mean vacuum density, its fluctuations can still gravitate

$$\delta\rho_{QM} \sim \pm 1\ kg/m^3 \left(\frac{L}{1\ \mathrm{km}}\right)^{-3/2} \left(\frac{\mathrm{mass}}{173\ \mathrm{GeV/c^2}}\right)^{5/2}$$

- This leads to fluctuations in length, using Einstein gravity

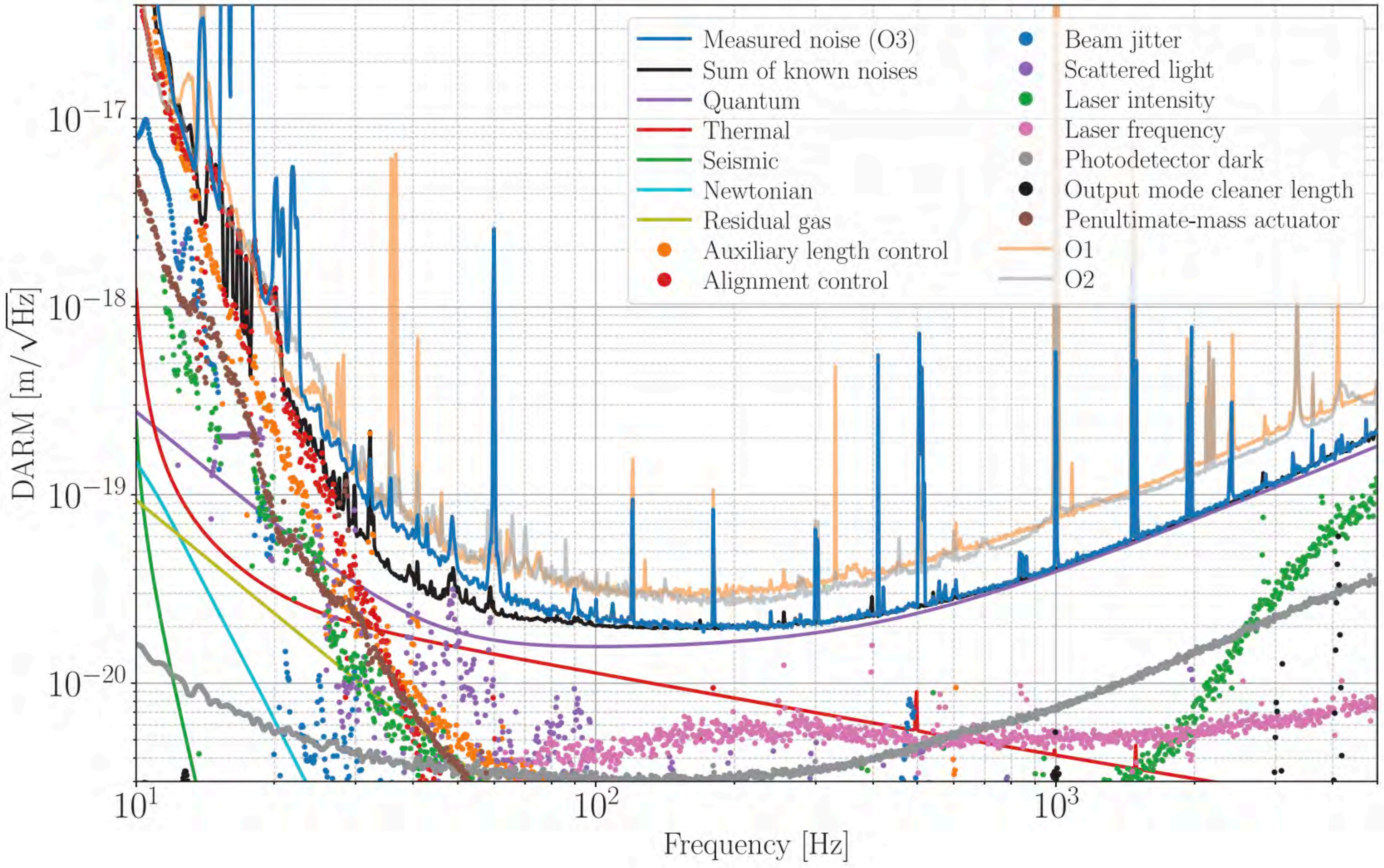
$$\delta L \sim (10^{-20}\ \mathrm{km}) \left(\frac{L}{1\ \mathrm{km}}\right)^{5/4} \left(\frac{\mathrm{mass}}{173\ \mathrm{GeV/c^2}}\right)^{5/2} \left(\frac{f}{1\ \mathrm{Hz}}\right)^{-1/4}$$

NA & Nelson 16; NA, Kim & Nelson 17

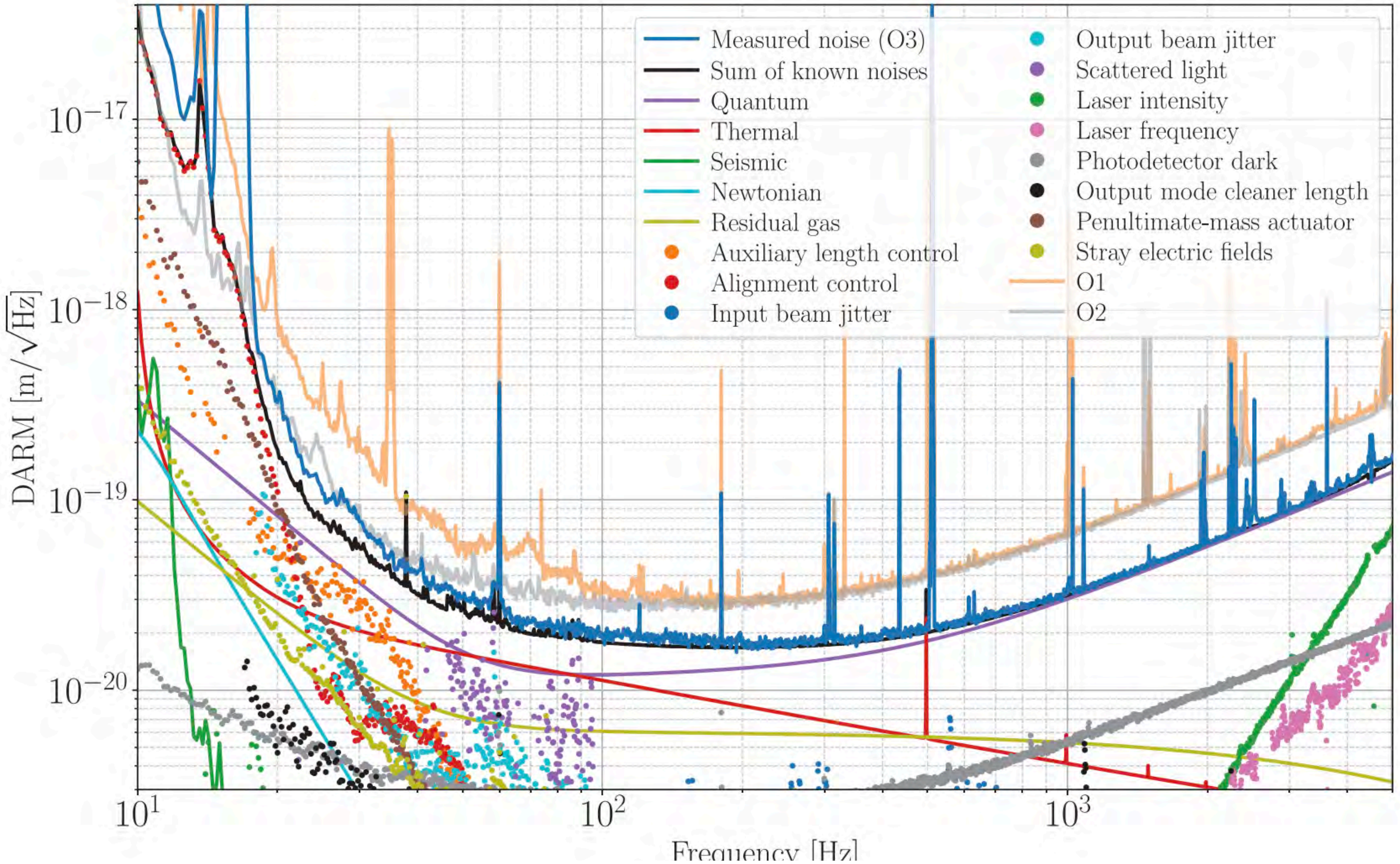


PHYSICAL REVIEW D **102**, 062003 (2020)

Sensitivity and performance of the Advanced LIGO detectors in the third observing run



Hanford

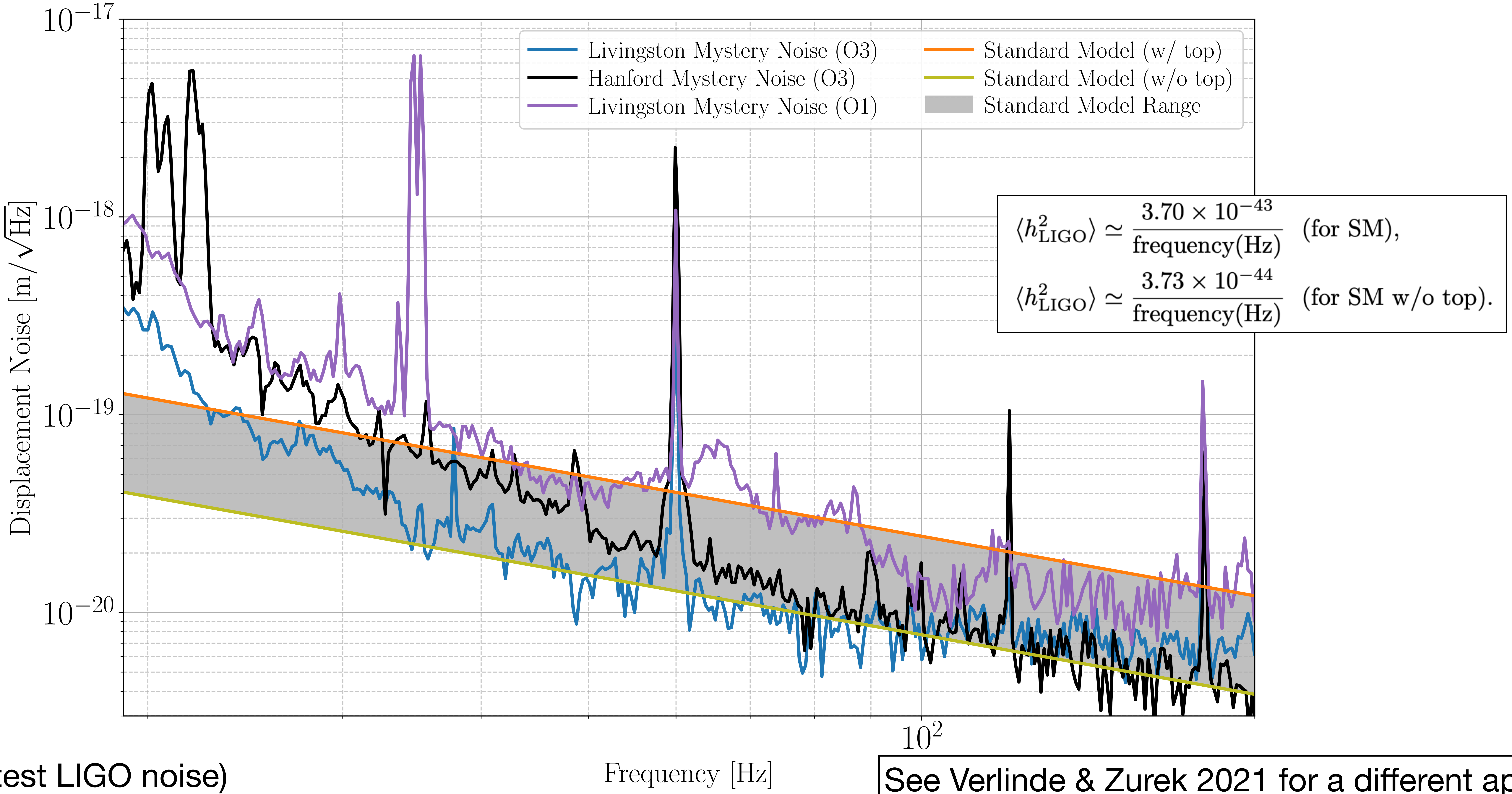


Livingston

PHYSICAL REVIEW D **102**, 062003 (2020)

Sensitivity and performance of the Advanced LIGO detectors in the third observing run

Is LIGO "Mystery Noise" the gravity of fluctuating quantum vacuum?



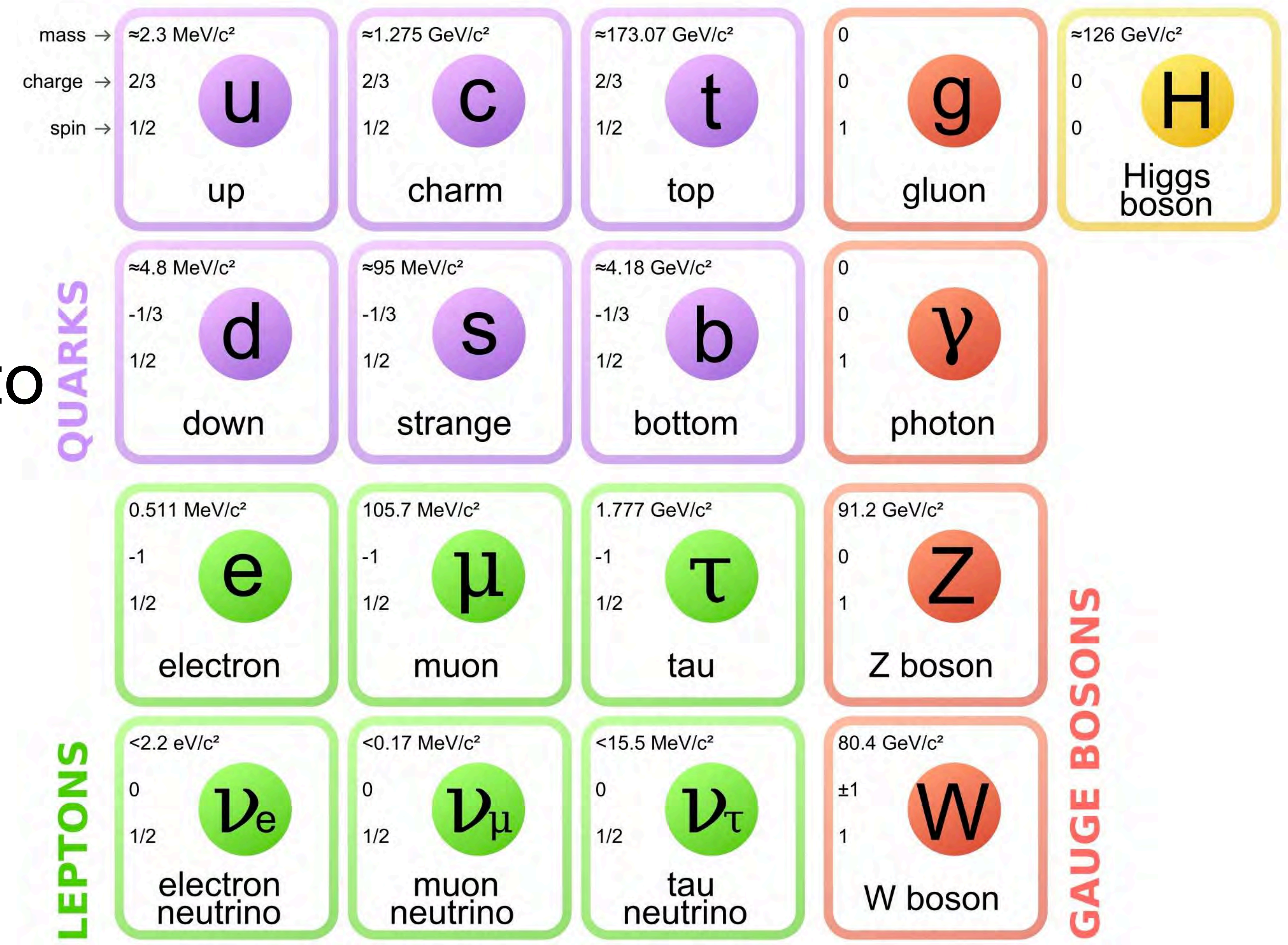
NA 2019
(updated with latest LIGO noise)

See Verlinde & Zurek 2021 for a different approach

Physics “beyond” Standard Model?

- If LIGO “Mystery” noise cannot be further reduced, then it’s likely due to top quark’s quantum vacuum

- No heavier particle than top/Higgs!



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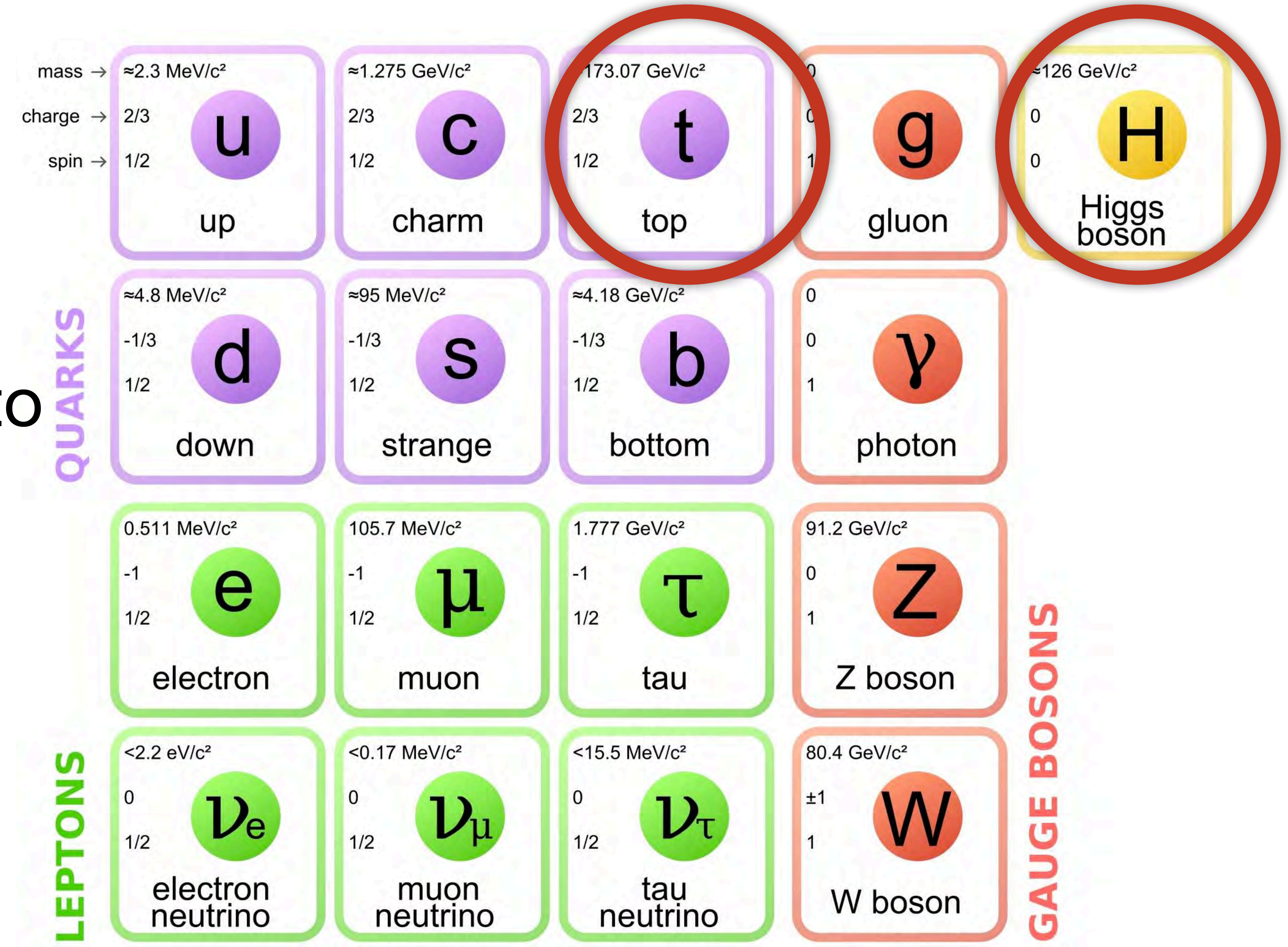
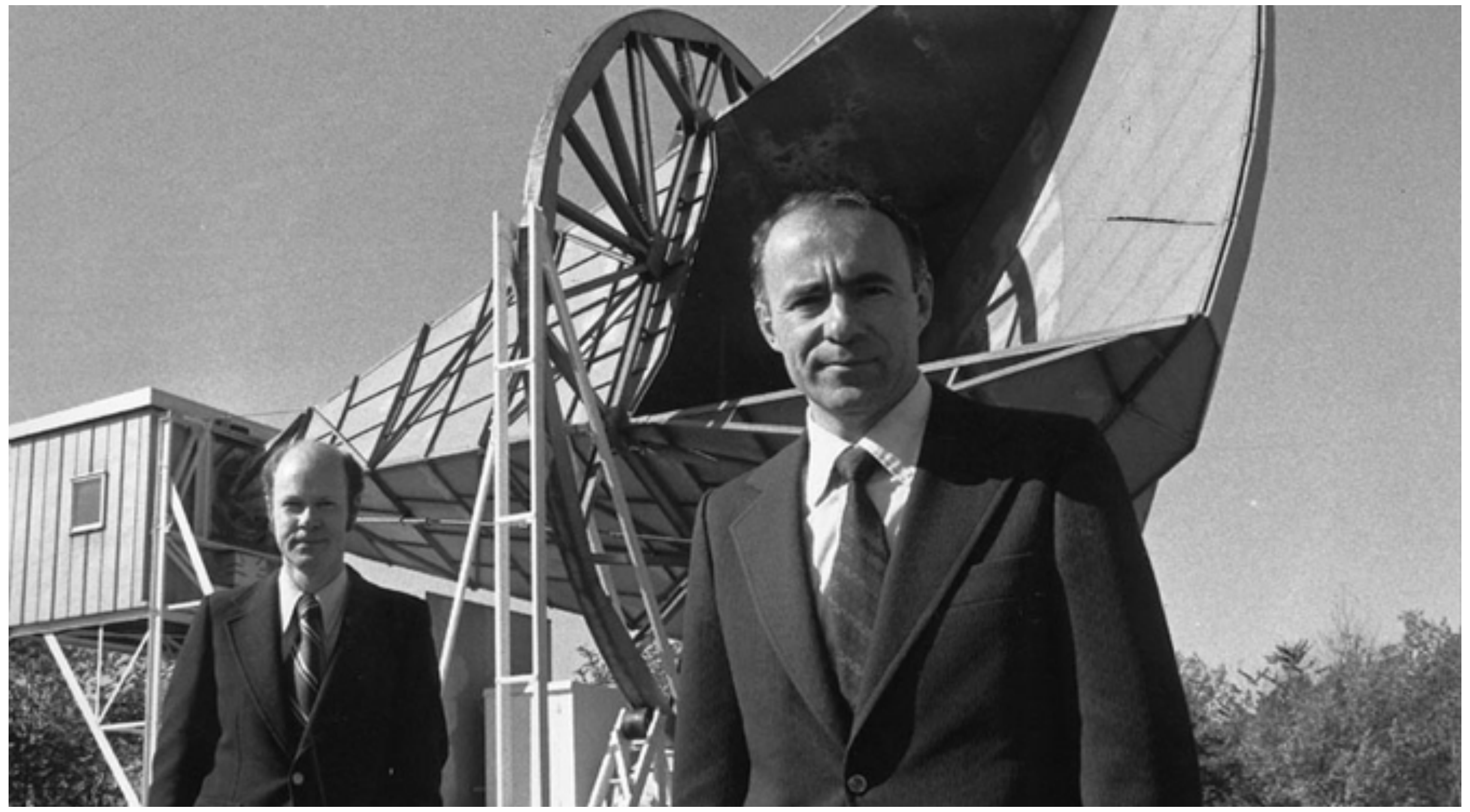
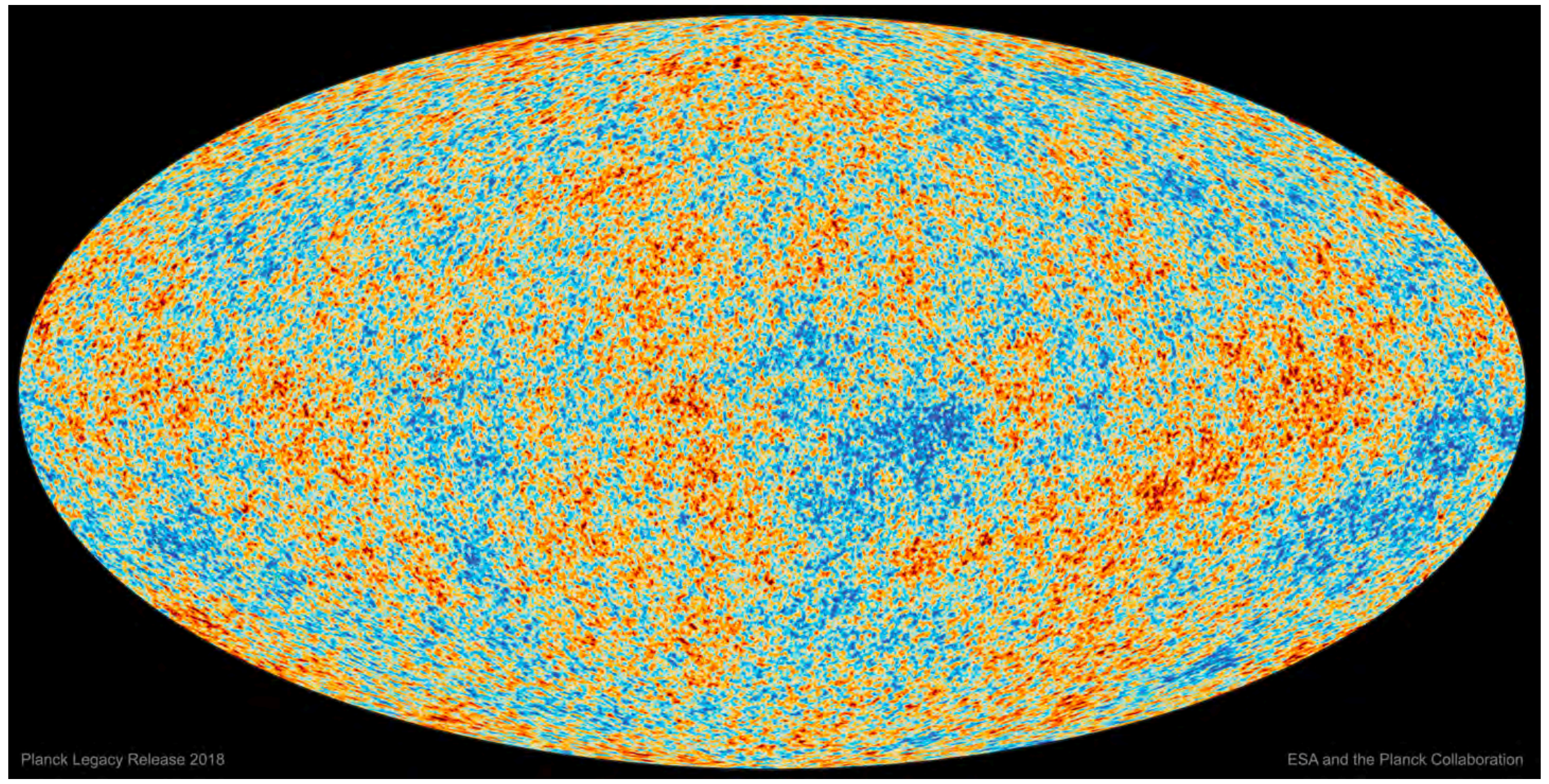
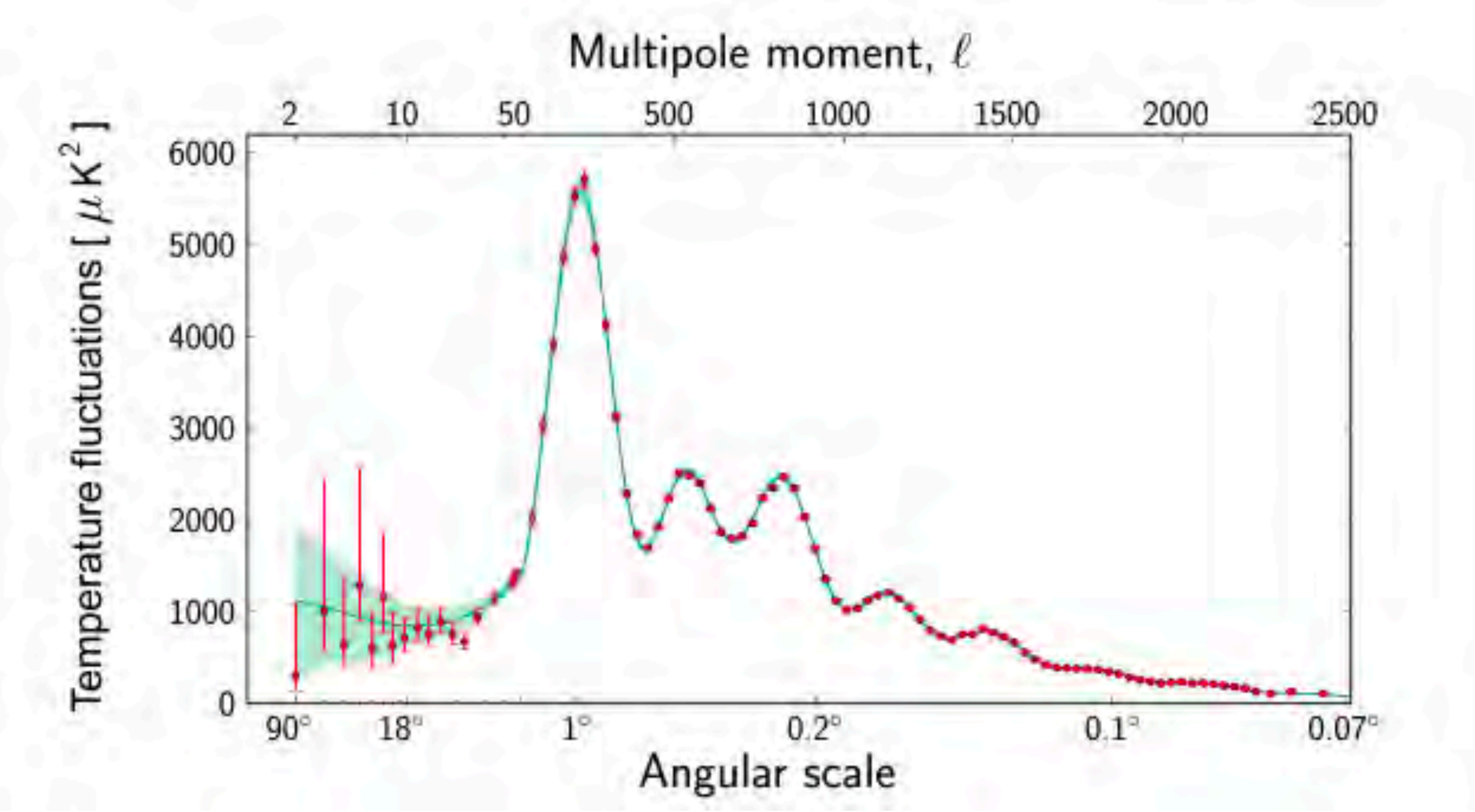


Remember that other “Mystery noise”?!







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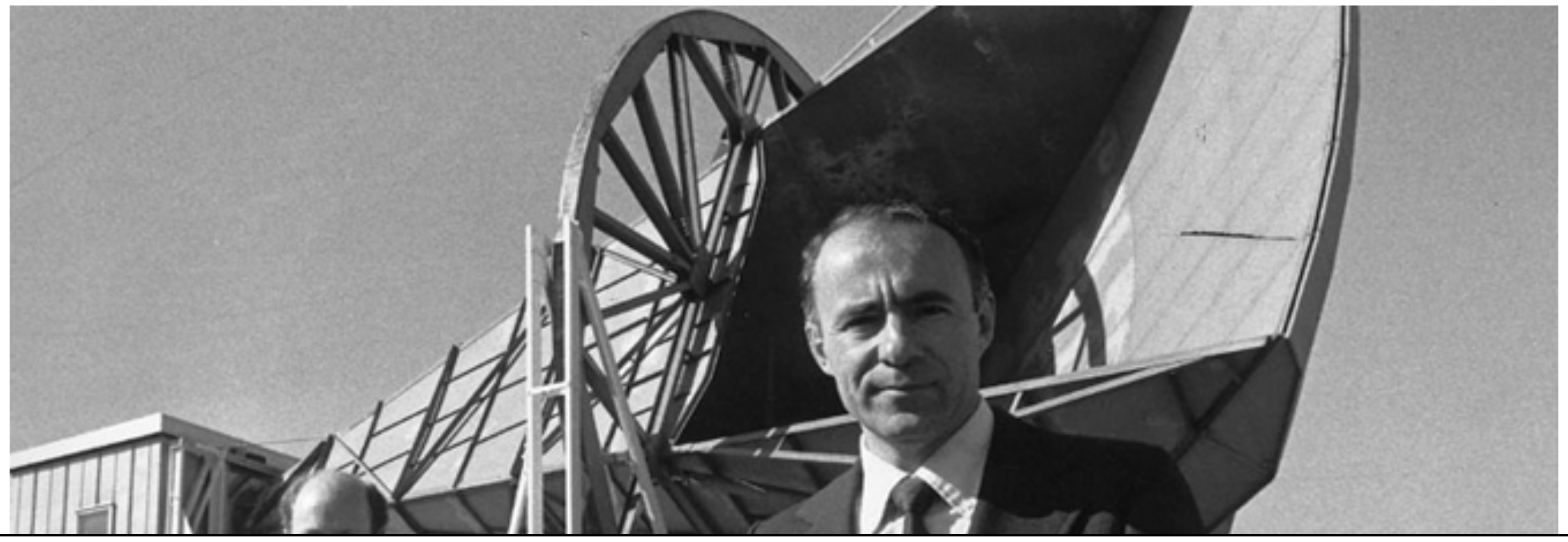
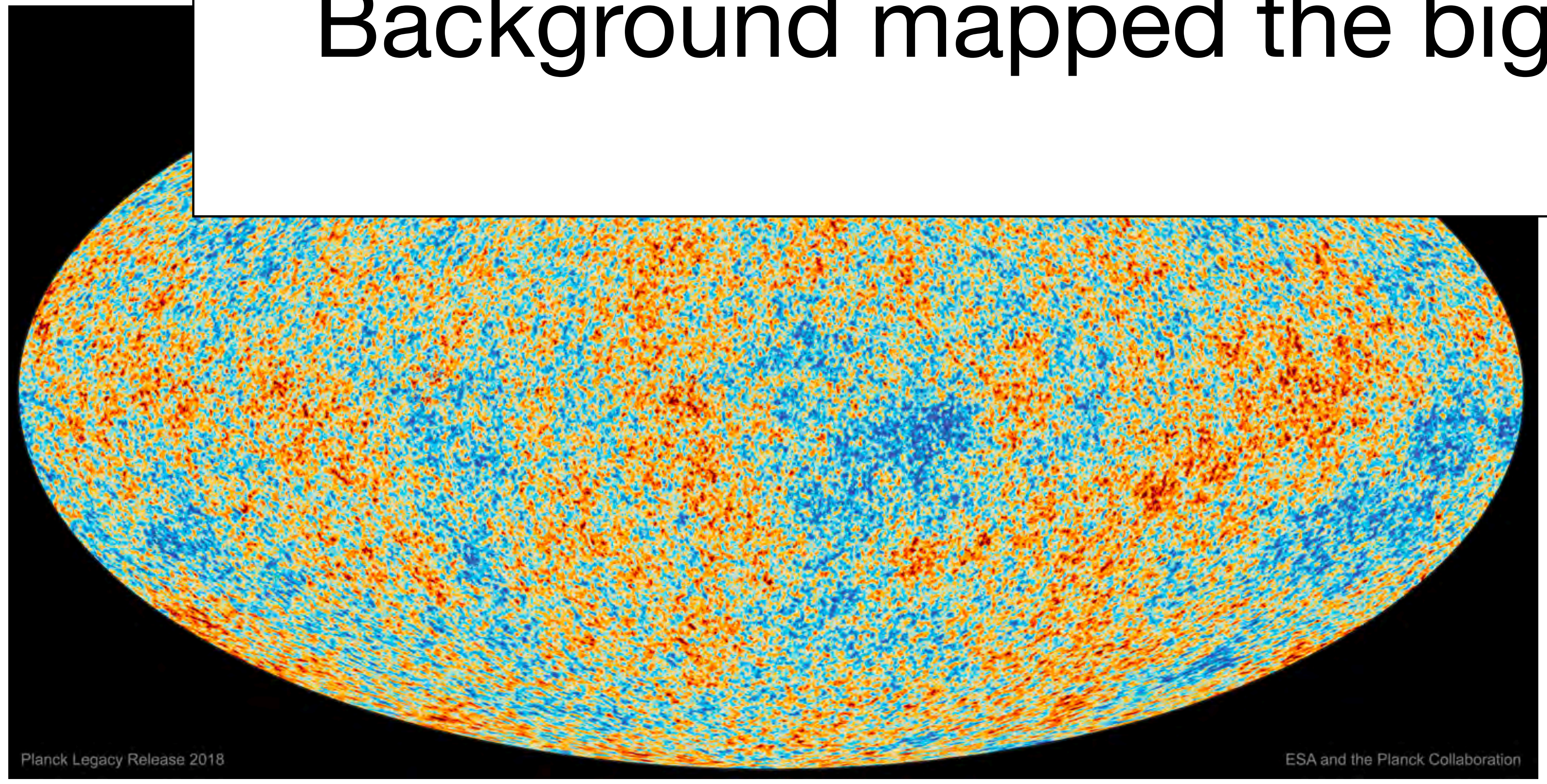
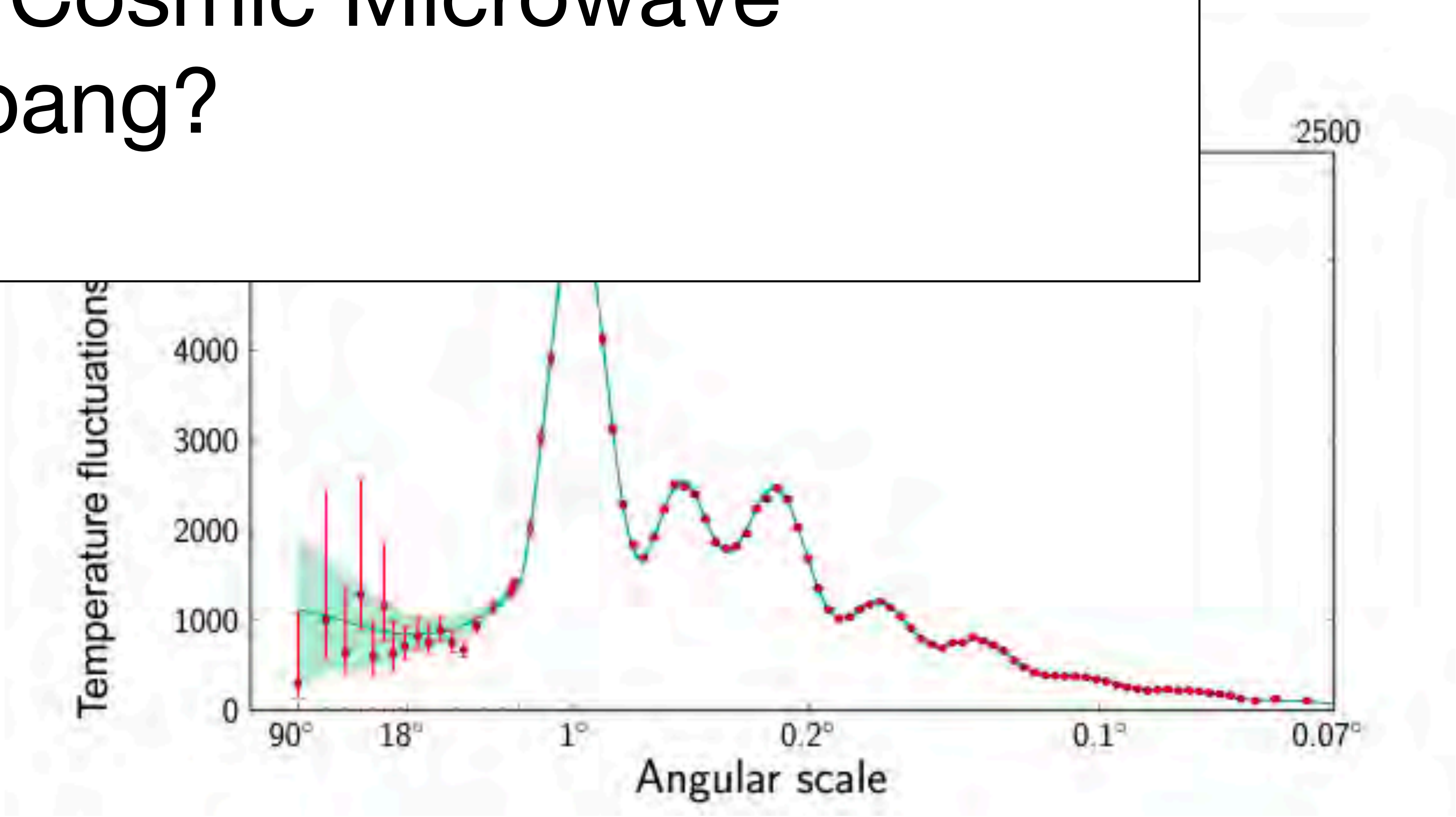


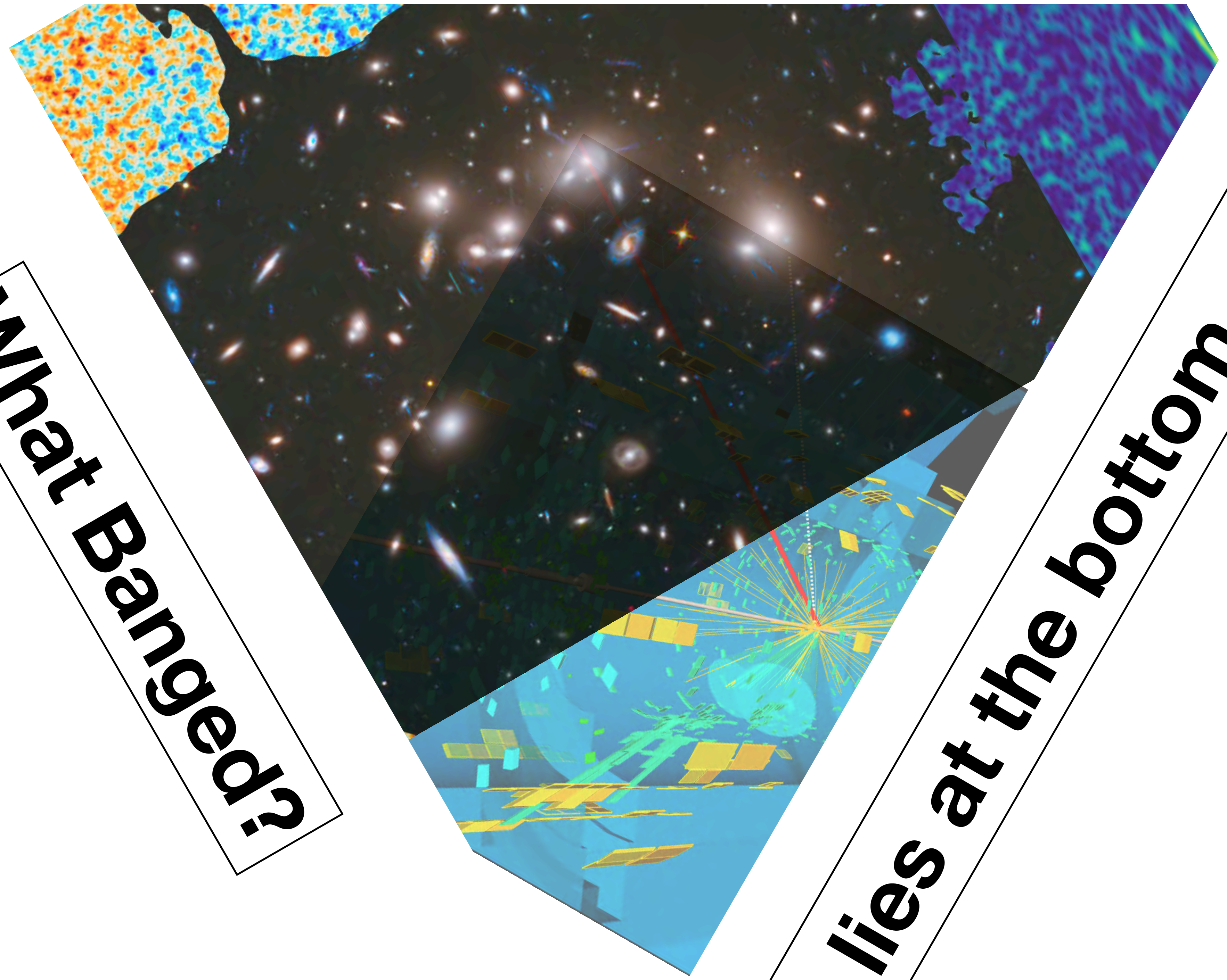
- Can Gravitational Wave “Mystery Noise" map the particle desert, the same way that the Cosmic Microwave Background mapped the big bang?





The Big Picture

Nature of Quantum Vacuum?



What Banged?

What lies at the bottom of Black Holes?

Conclusions

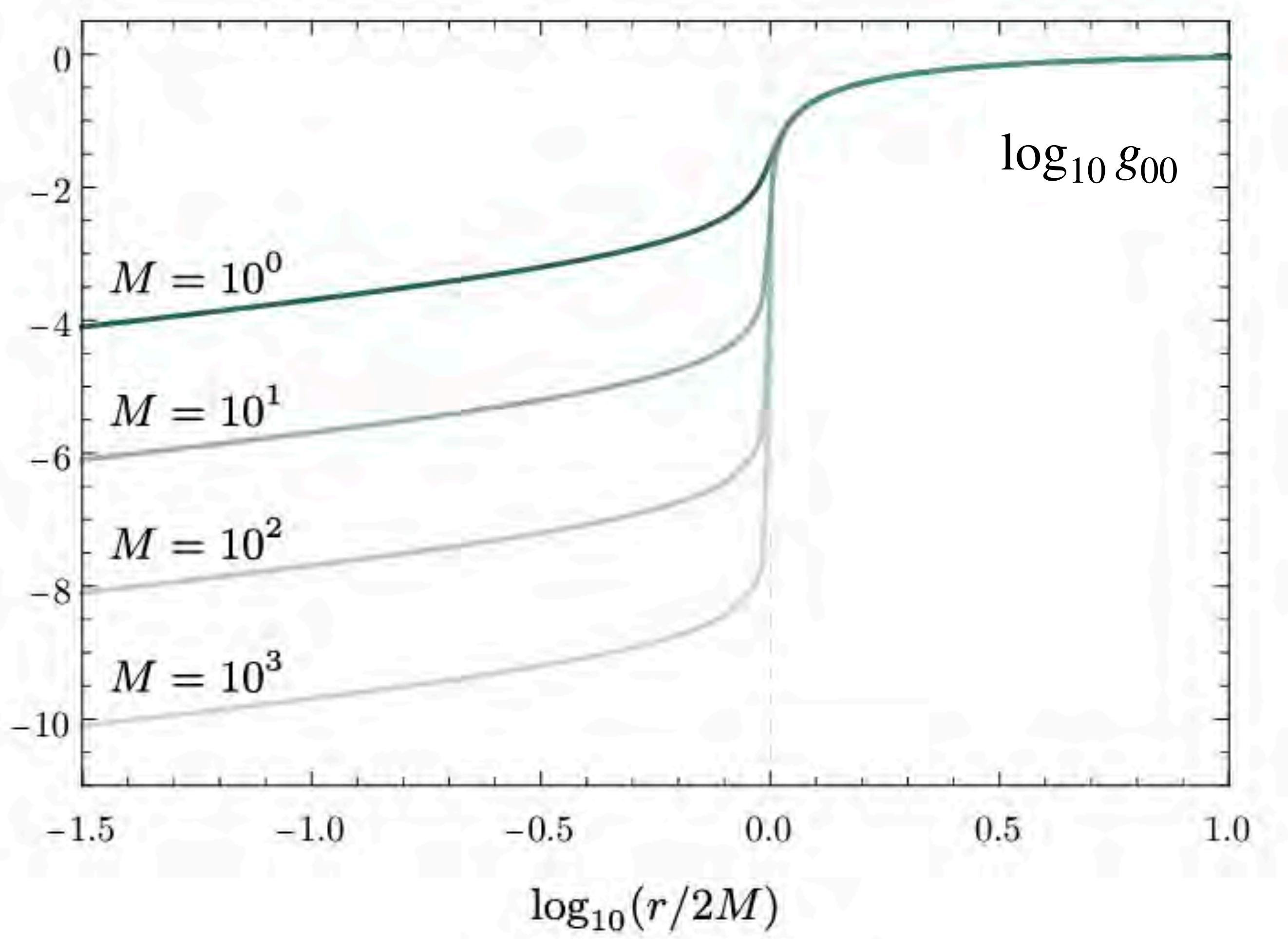
- **Echoes and Images:** probe quantum structure of BH horizons, beyond EFT *(sorry Ira!)*
- **SpeCS:** Stacking spectrograms, a novel way of detecting stochastic GW background and its underlying physics
- **Mystery Noise:** a gravitational probe of the quantum vacuum

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

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



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

CP-symmetry (RP3 geon)

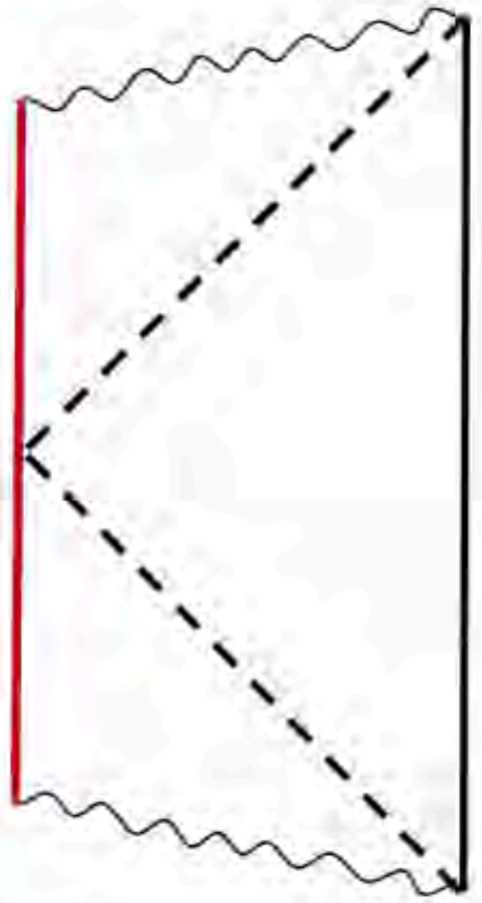


Figure 3: Penrose diagram for a $\mathbf{Z}_2$ quotient of the two-sided black hole, an example of a spacetime with the correct properties to be an disentangled microstate.

(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*

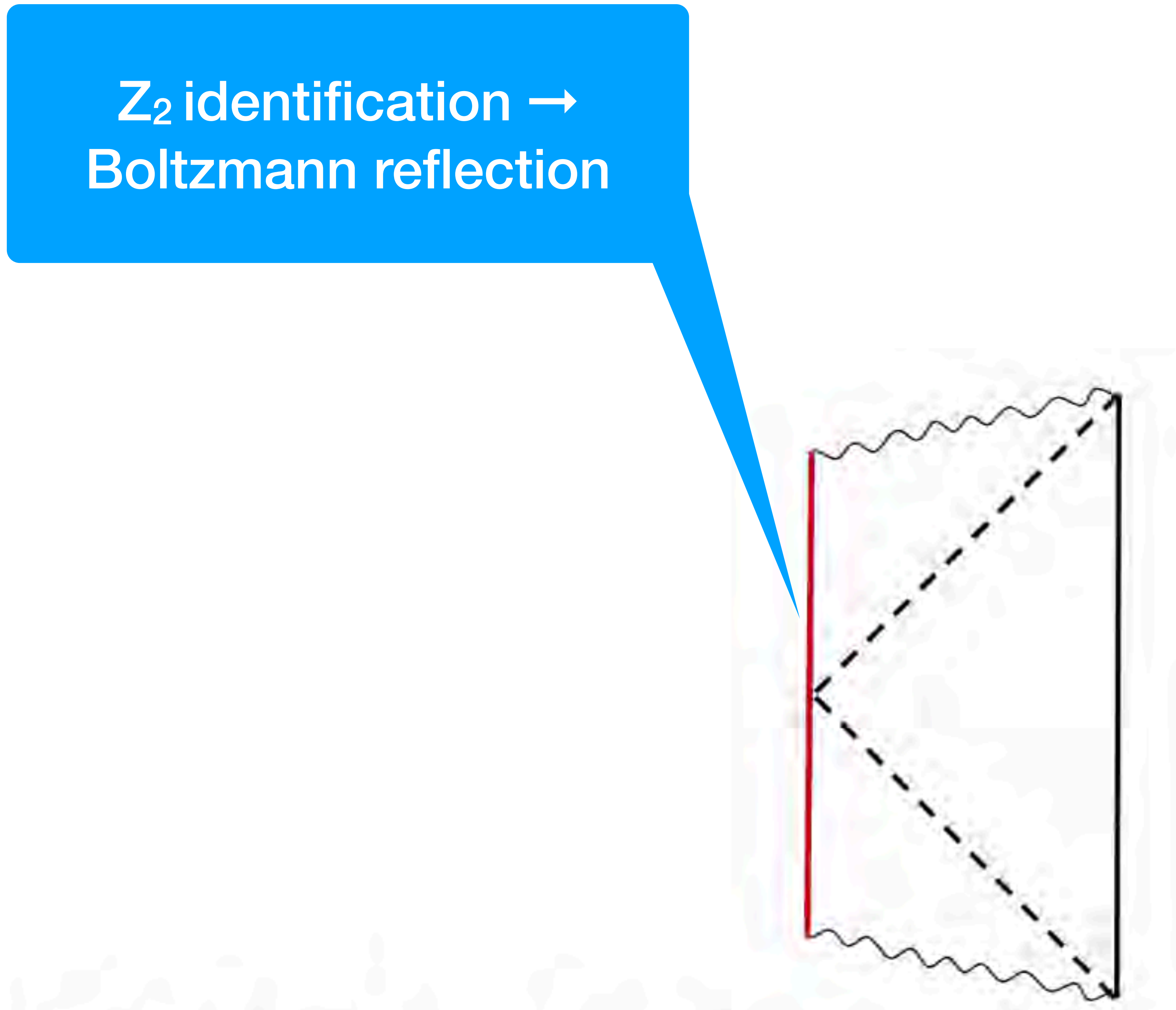
December 16, 2020

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.

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

CP-symmetry (RP^3 geon)



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

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.

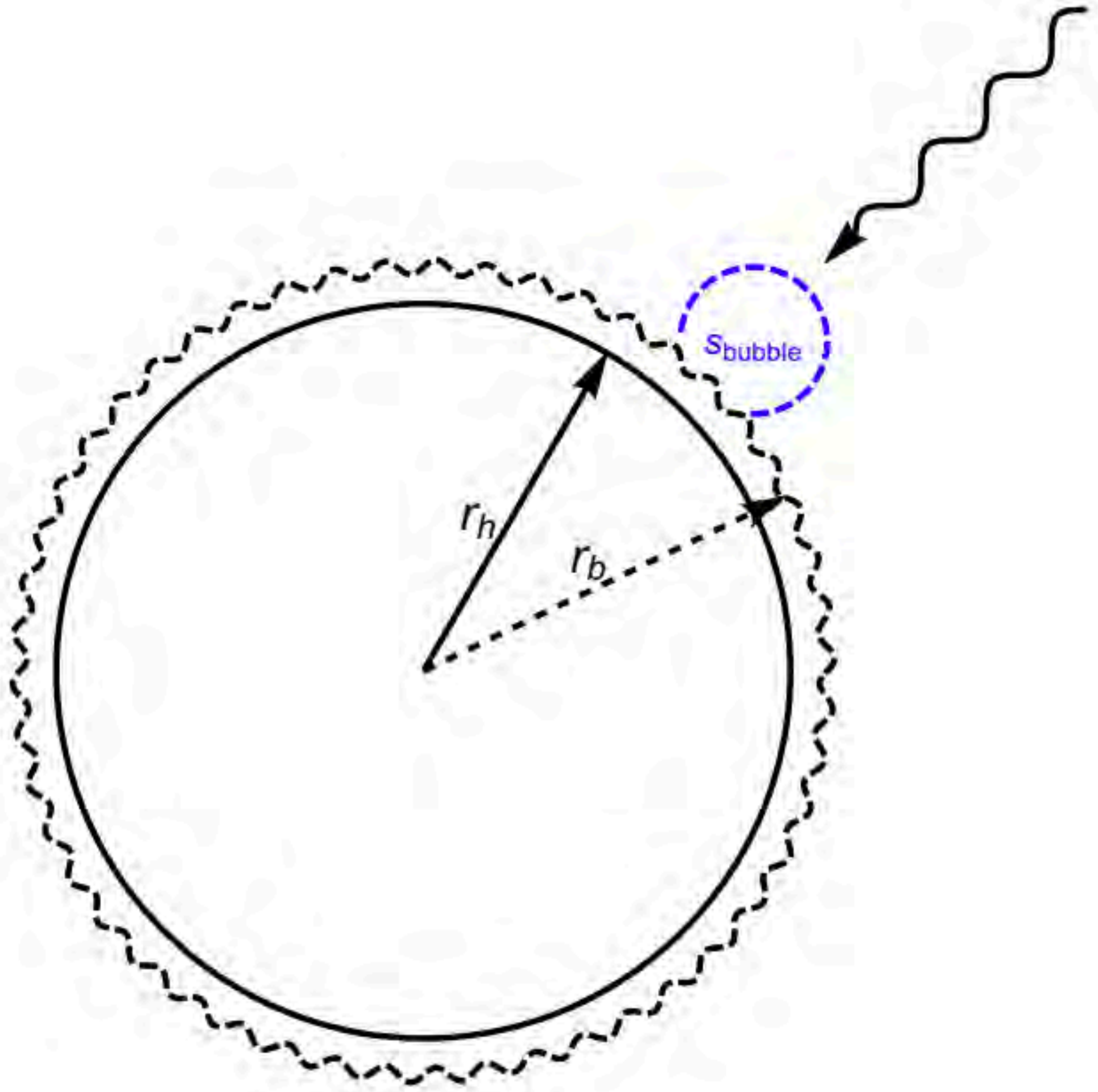
E-mail: bousso@berkeley.edu, geoffp@berkeley.edu

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.

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

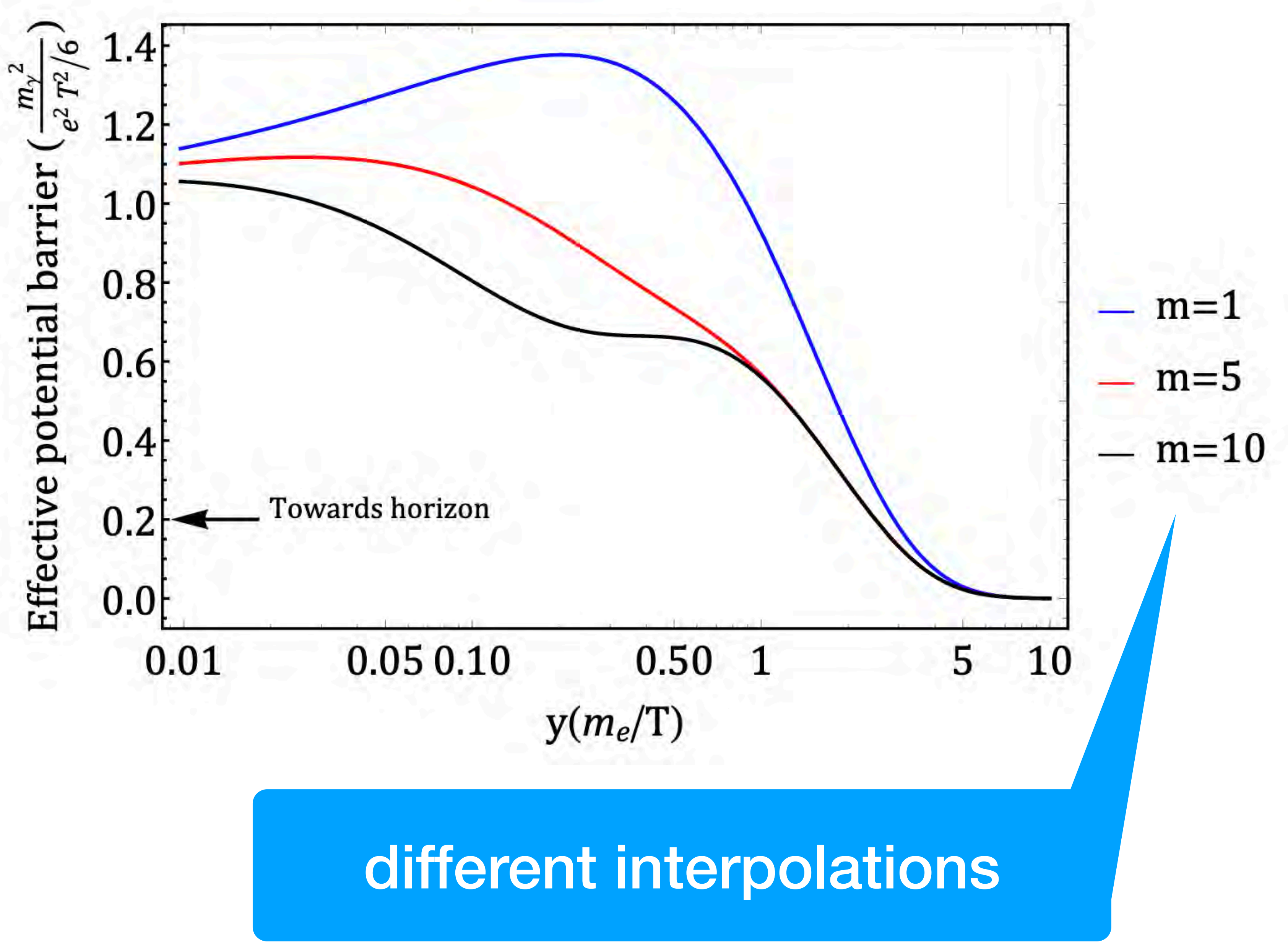
- Reflection off virtual electron-positron pairs near horizon → Boltzmann Albedo for photons

- No quantum gravity needed!

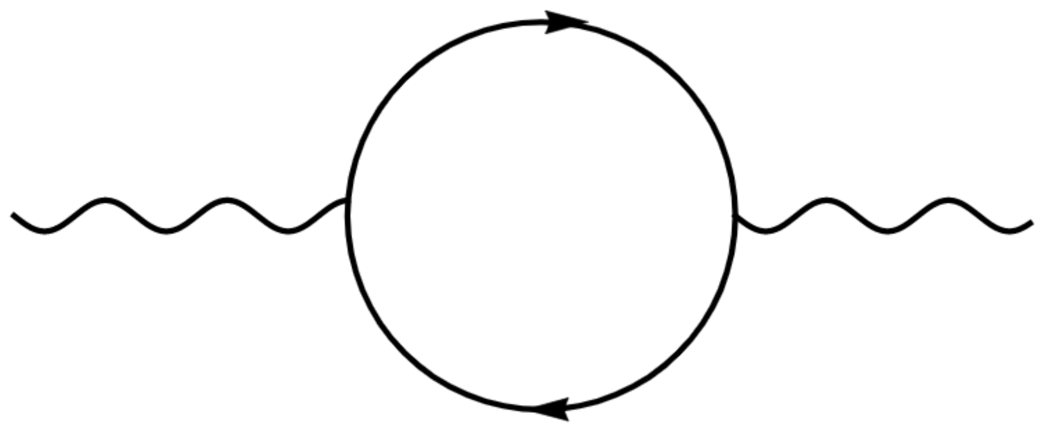


Two independent derivations

- Photon mass acquired through Hawking Plasma

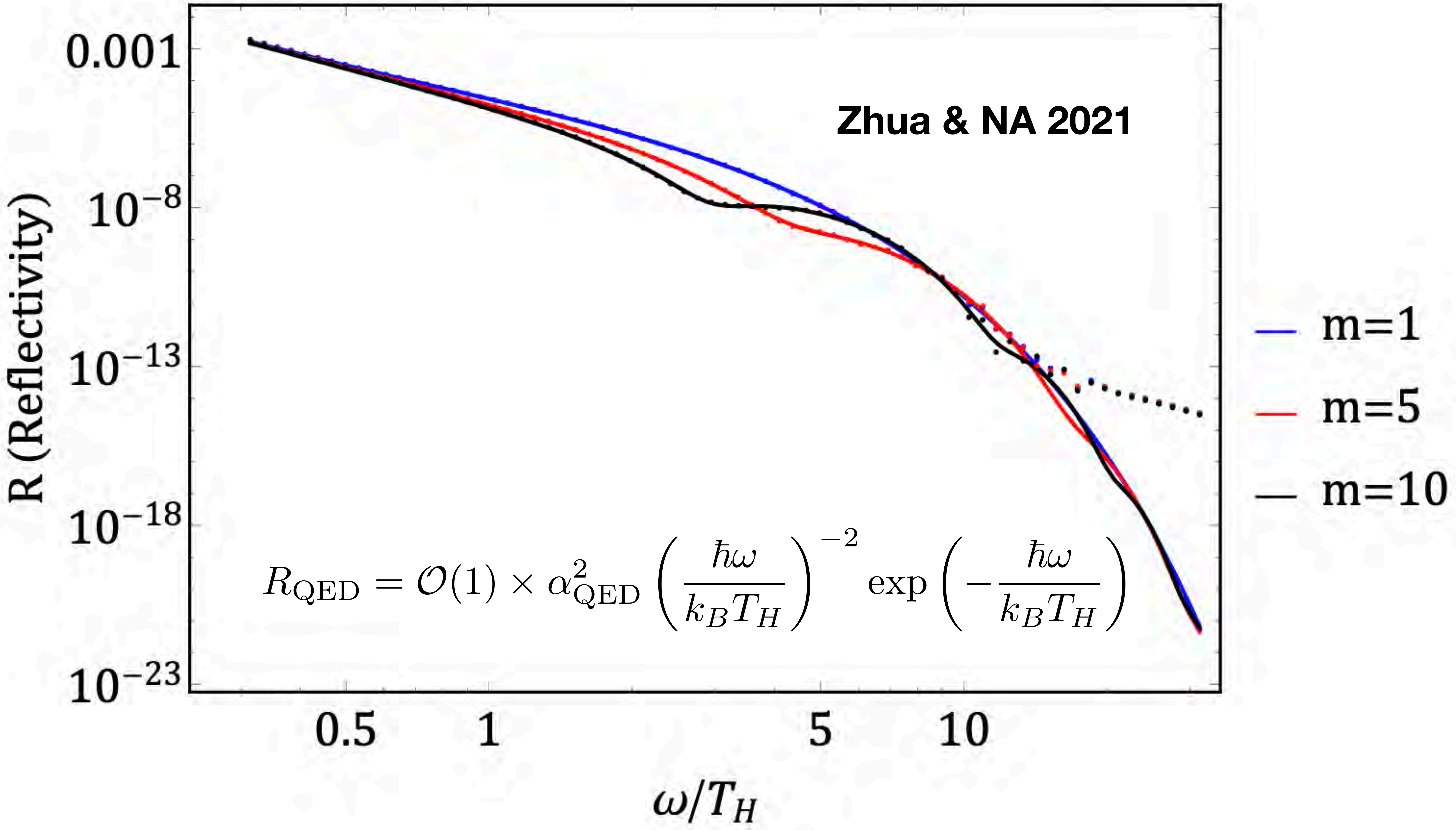


- Projecting photon 1-loop propagator from Minkowski to Rindler



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

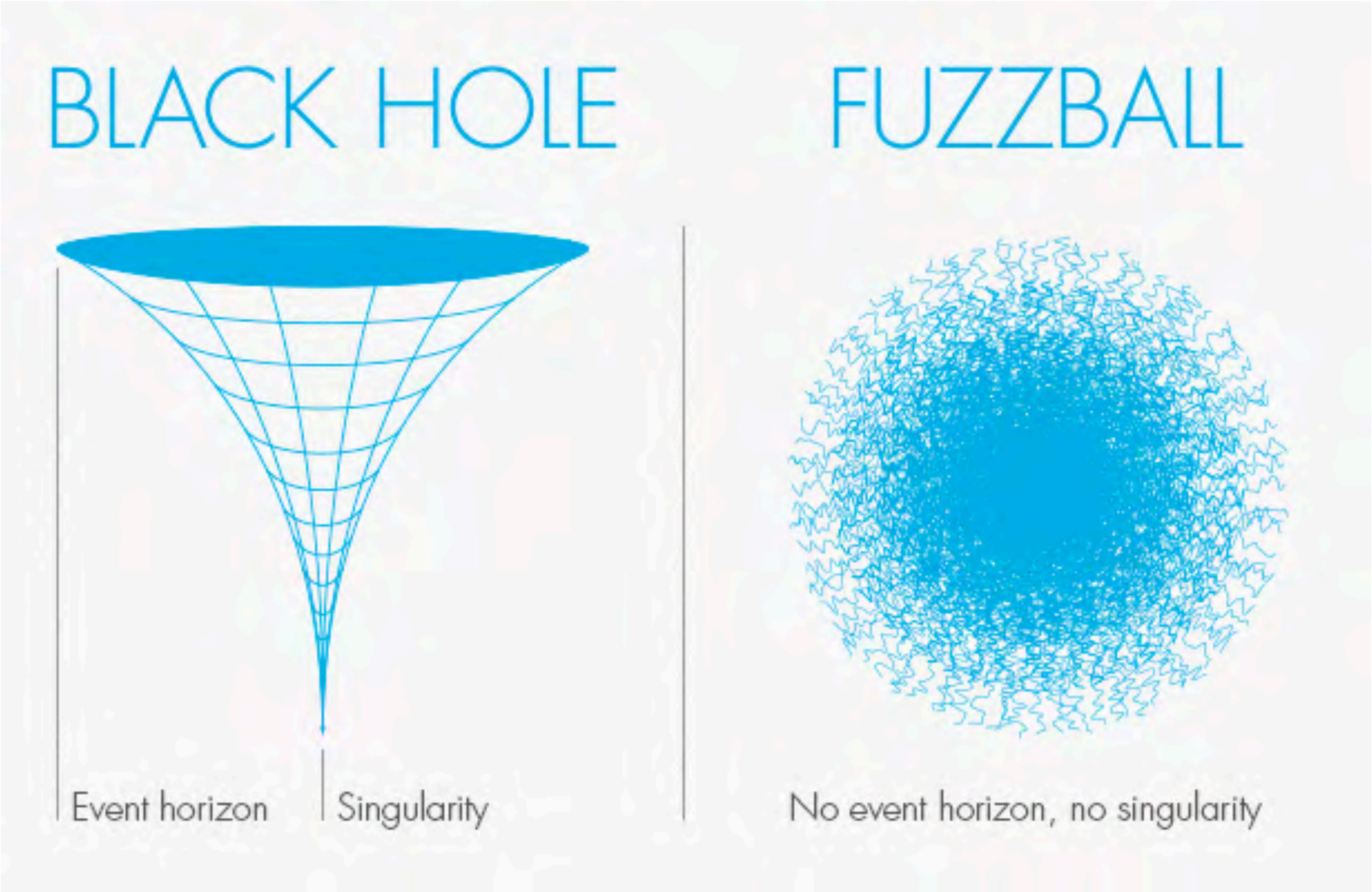
$$\pi^M(p^2) = \frac{e^2}{2\pi^2}\int_0^1 dx x(1-x) \ln\left(1 + \frac{p^2 x(1-x)}{m_e^2}\right)$$



- 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

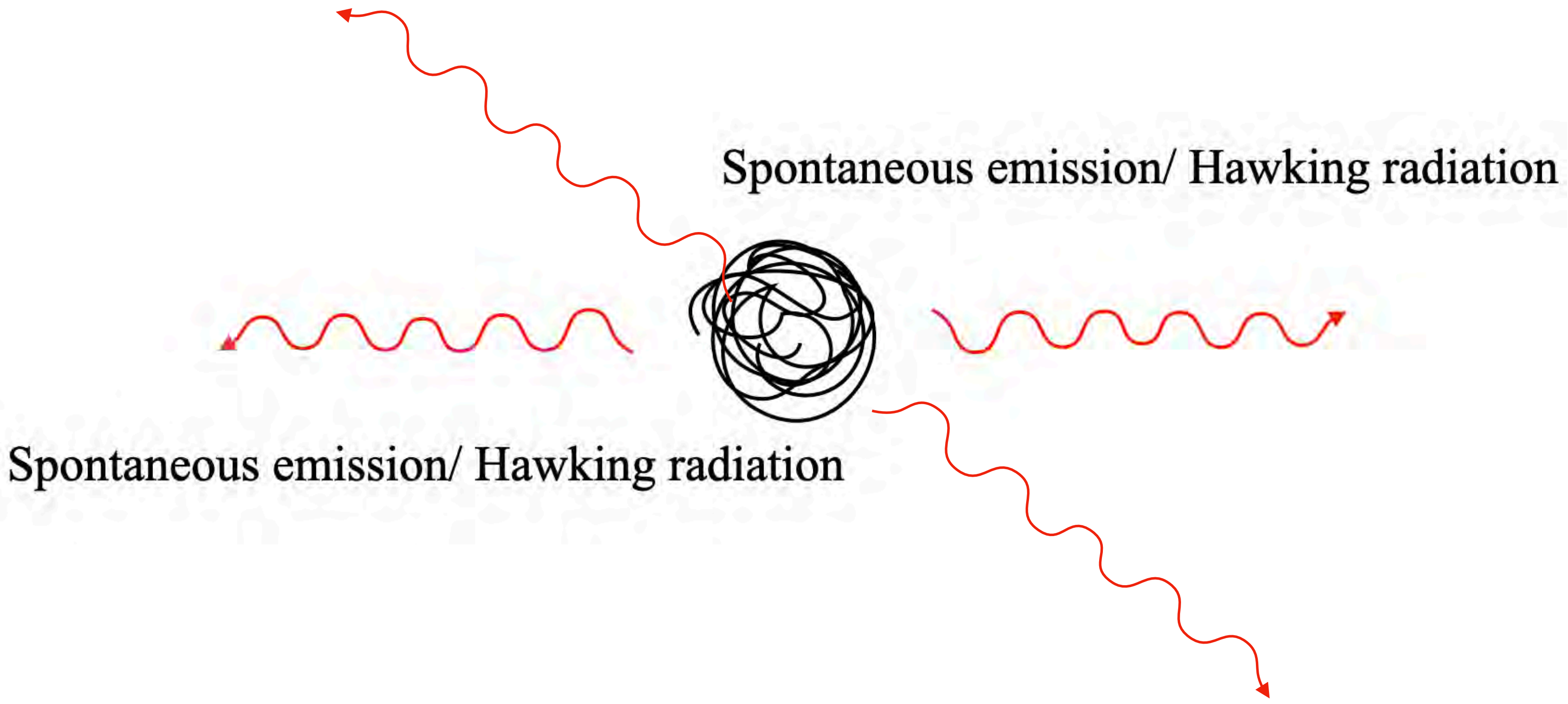
Radiation from the non-extremal fuzzball

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.

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CnC: *the upshot!*

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- Random stress fluctuations at UV scale Λ

$$\langle T_{ij}^{(V)}(\mathbf{x}) T_{kl}^{(V)}(\mathbf{y}) \rangle \sim \delta^3(\mathbf{x}-\mathbf{y})\Lambda^5$$

CnC: *the upshot!*

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$$\langle T_{ij}^{(V)}(\mathbf{x})T_{kl}^{(V)}(\mathbf{y})\rangle \sim \delta^3(\mathbf{x}-\mathbf{y})\Lambda^5$$

- Einstein eq. for anisotropic stress

$$k^2\Phi \sim M_{\rm p}^{-2}A^{ij}T_{ij}$$

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$$k^2\Phi \sim M_{\rm p}^{-2} A^{ij} T_{ij}$$

- Variance of Metric perturbations grows as distance

$$(\Delta_{\Phi}^{(V)})^2 \sim \frac{\Lambda^5}{M_p^4 k}$$

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- A UV/IR Heisenberg uncertainty relation

$$\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}^5}{M_p^4}$$

- Cosmology limits the UV scale

$$\Lambda \lesssim (M_{\rm p}^4 H_0)^{1/5} \approx 2 \text{ PeV}$$

Spectral Representation

- Most general expectation for stress correlators from *Unitarity*+*Lorentz symmetry*

$$\langle T_{\mu\nu}(x)T_{\alpha\beta}(y)\rangle = \int \frac{d^4k}{(2\pi)^4}e^{ik\cdot(x-y)}\int_0^\infty d\mu \left[\rho_0(\mu)P_{\mu\nu}P_{\alpha\beta} + \rho_2(\mu)\left(\frac{1}{2}P_{\mu\alpha}P_{\nu\beta} + \frac{1}{2}P_{\mu\beta}P_{\nu\alpha} - \frac{1}{3}P_{\mu\nu}P_{\alpha\beta}\right)\right]\theta(k^0)2\pi\delta(k^2+\mu),$$

- ρ's must positive.

$$P_{\mu\nu} \equiv \eta_{\mu\nu} - k_\mu k_\nu/k^2$$

- *Cosmological* constraints will roughly translate to

$$\int \frac{d\mu}{\sqrt{\mu}}\rho_2(\mu) \lesssim (10 \text{ TeV} - 1 \text{ PeV})^5$$

- *LIGO+Pulsar Timing* “Mystery” noise

$$\int \frac{d\mu}{\sqrt{\mu}}\rho_2(\mu) \sim (200 \text{ GeV} - 600 \text{ GeV})^5$$

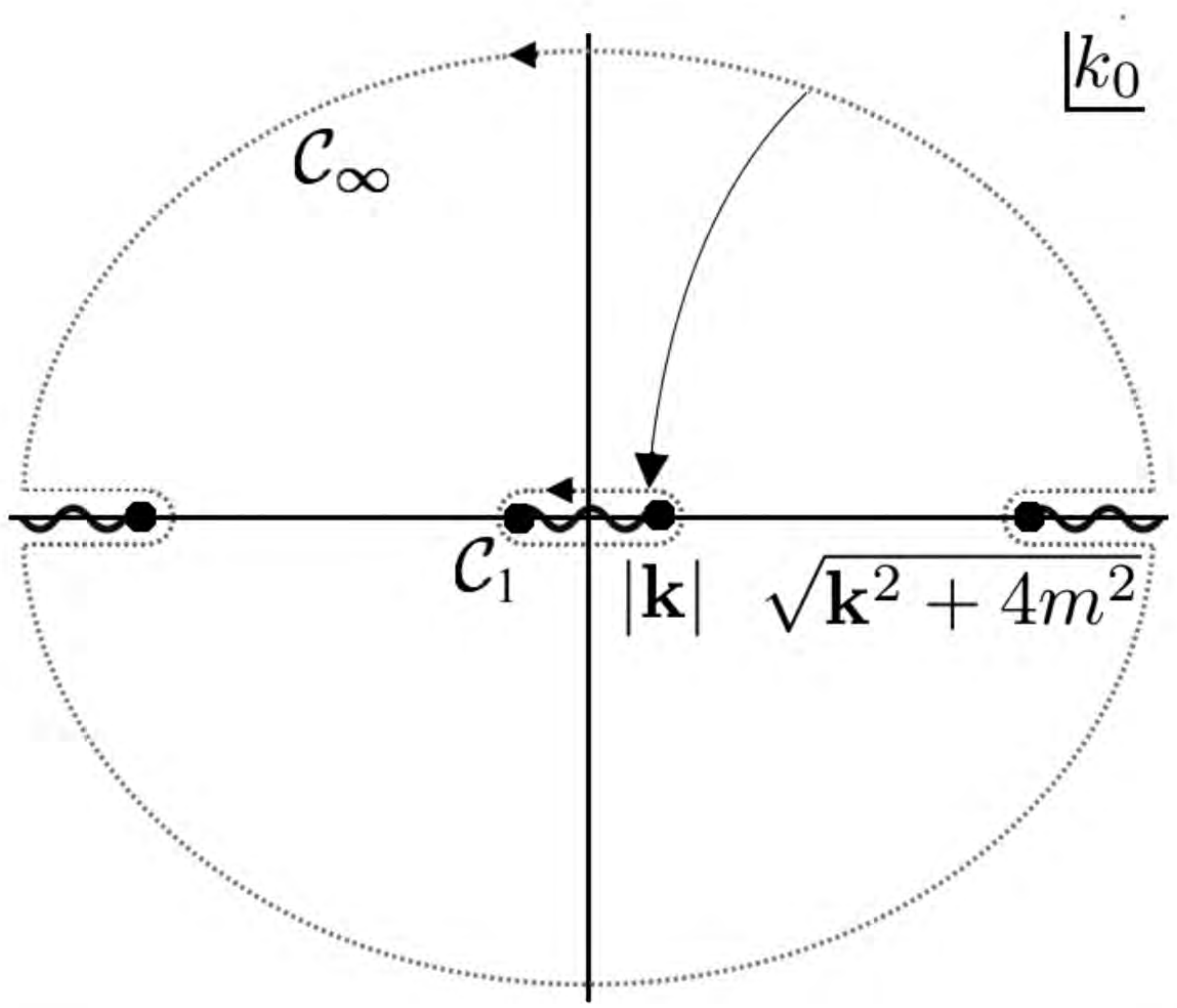
E.g., a free scalar field

$$-\mu = k_0^2 - |\mathbf{k}|^2$$

- For a weakly coupled scalar field

$$\rho_2(\mu) = \frac{\mu^2}{120\pi^2}\sqrt{\frac{1}{4} - \frac{m^2}{\mu}}\left[\frac{1}{4} - \frac{m^2}{\mu}\right]^2 \Theta(\mu - 4m^2)$$

- For large scale, real-space correlations, one can deform the contour to get *(universal for all spins)*

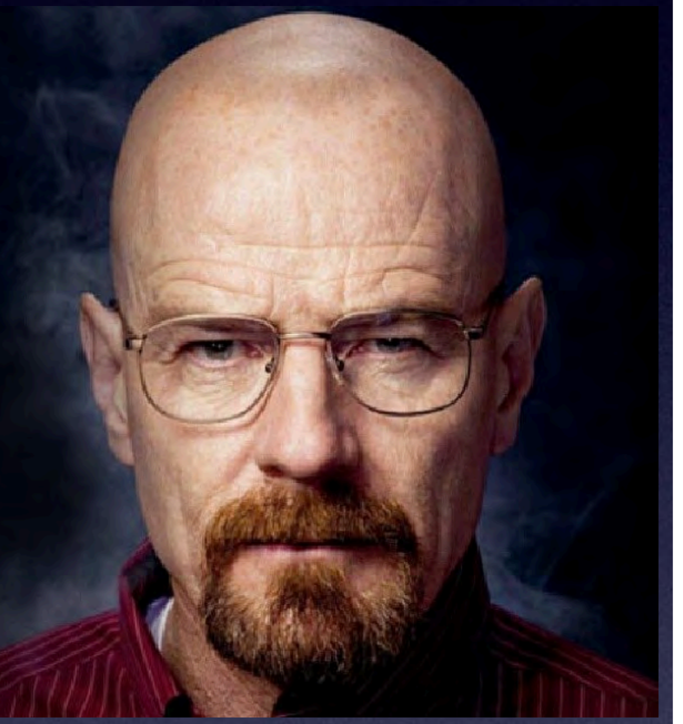


$$\rho_{2,\mathrm{eff}}(\mu) = \frac{m^5}{120\pi^2\sqrt{-\mu}}\Theta(-\mu)$$

- *Described by Poisson model*

Heisenberg vs. Einstein Microscopes

Heisenberg vs. Einstein Microscopes

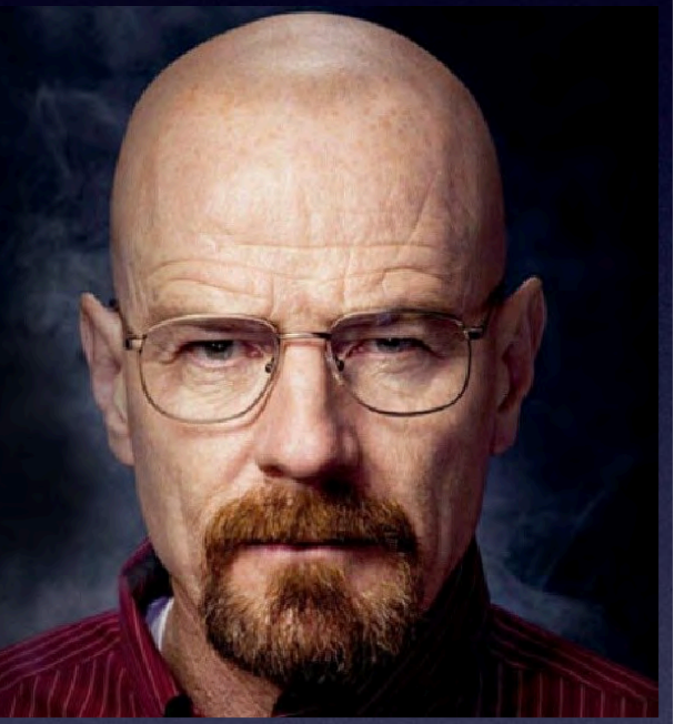


- Higher energy

➡ Shorter wavelength

➡ *Better resolution*

Heisenberg vs. Einstein Microscopes



- Higher energy

➡ Shorter wavelength

➡ *Better resolution*

- Higher energy

➡ Bigger black holes

➡ *Worse resolution*