Fundamental Physics with LISA

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New/Improved Tests of Fundamental Physics with LISA

- Classical gravity and cosmology
  - Validity of GR
  - Alternative theories of gravity
  - Classical/primordial Black holes
  - Dark cosmology
- Quantum gravity
  - Fine structure of spacetime
  - Quantum black holes
  - Early/quantum cosmology
- Astroparticle physics
  - ΛCDM and dark matter

And much more…

Living Reviews in Relativity (2022)25:4
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WHITE PAPER

New horizons for fundamental physics with LISA

K. G. Arun · Enis Belgacem · Robert Benkel · Laura Bernard · Emanuele Berti · Gianfranco Bertone et al. *[full author details at the end of the article]*

Received: 17 February 2022 / Accepted: 26 April 2022

Abstract
The Laser Interferometer Space Antenna (LISA) has the potential to reveal wonders about the fundamental theory of nature at play in the extreme gravity regime, where the gravitational interaction is both strong and dynamical. In this white paper, the Fundamental Physics Working Group of the LISA Consortium summarizes the current topics in fundamental physics where LISA observations of gravitational waves can be expected to provide key input. We provide the briefest of reviews to then delineate avenues for future research directions and to discuss connections between this working group, other working groups and the consortium work package teams. These connections must be developed for LISA to live up to its science potential in these areas.

Keywords LISA · Gravitational waves · Fundamental physics · Tests of general relativity

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Check for updates

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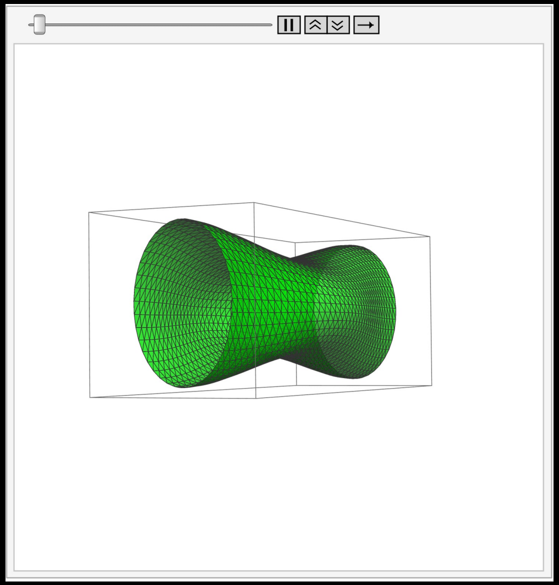
Testing GR and Alternative Gravity

Some Alternative Gravity Tests

Classical GR

- Propagating tensor modes with two polarizations: $h_{\mu\nu} = e^{+}_{\mu\nu} h_{+} + e^{\times}_{\mu\nu} h_{\times}$
- Usual (perturbative) quantization $\Longrightarrow$ massless spin-2 gravitons



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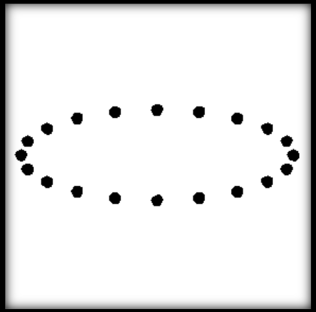

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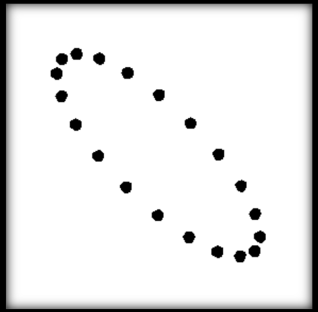
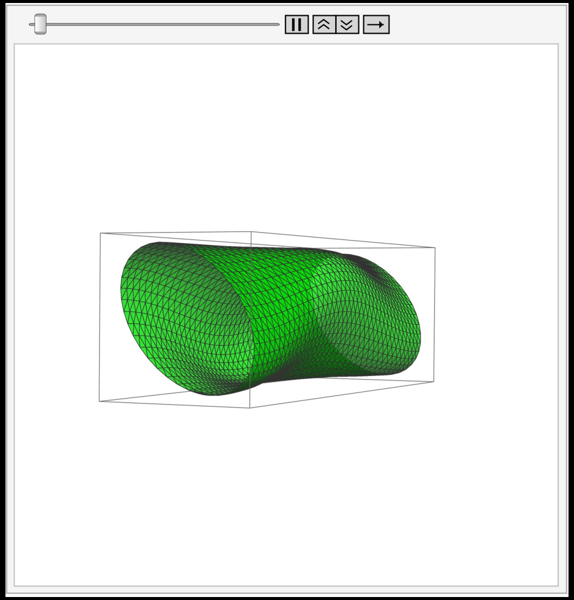




Some Alternative Gravity Tests

Alternative gravity

- Modification to $+$, $\times$ polarizations
- New modes: scalar, vector - might be massive

Example: $S = \int \sqrt{-g} f(R) d^4 x$

Wave decomposed as: $h_{\mu\nu}(t,x) = h_+(t - x/c)e^+_{\mu\nu} + h_\times(t - x/c)e^\times_{\mu\nu} + h_f\left(t - \frac{x}{c}\frac{v_G}{c}\right)e^s_{\mu\nu}$

Massive scalar mode propagating with group velocity $v_G \neq c$ and a <u>modified dispersion relations</u>

Some Alternative Gravity Tests

In general on FLRW background in transverse traceless gauge, in Fourier space

$$\ddot{h}_{ij}(k,t) + [3H(t) + \Gamma(k,t)]\dot{h}_{ij}(k,t) + \left[c_T^2(t)k^2 + D(k,t)\right] h_{ij}(k,t) = 0$$

Hubble rate

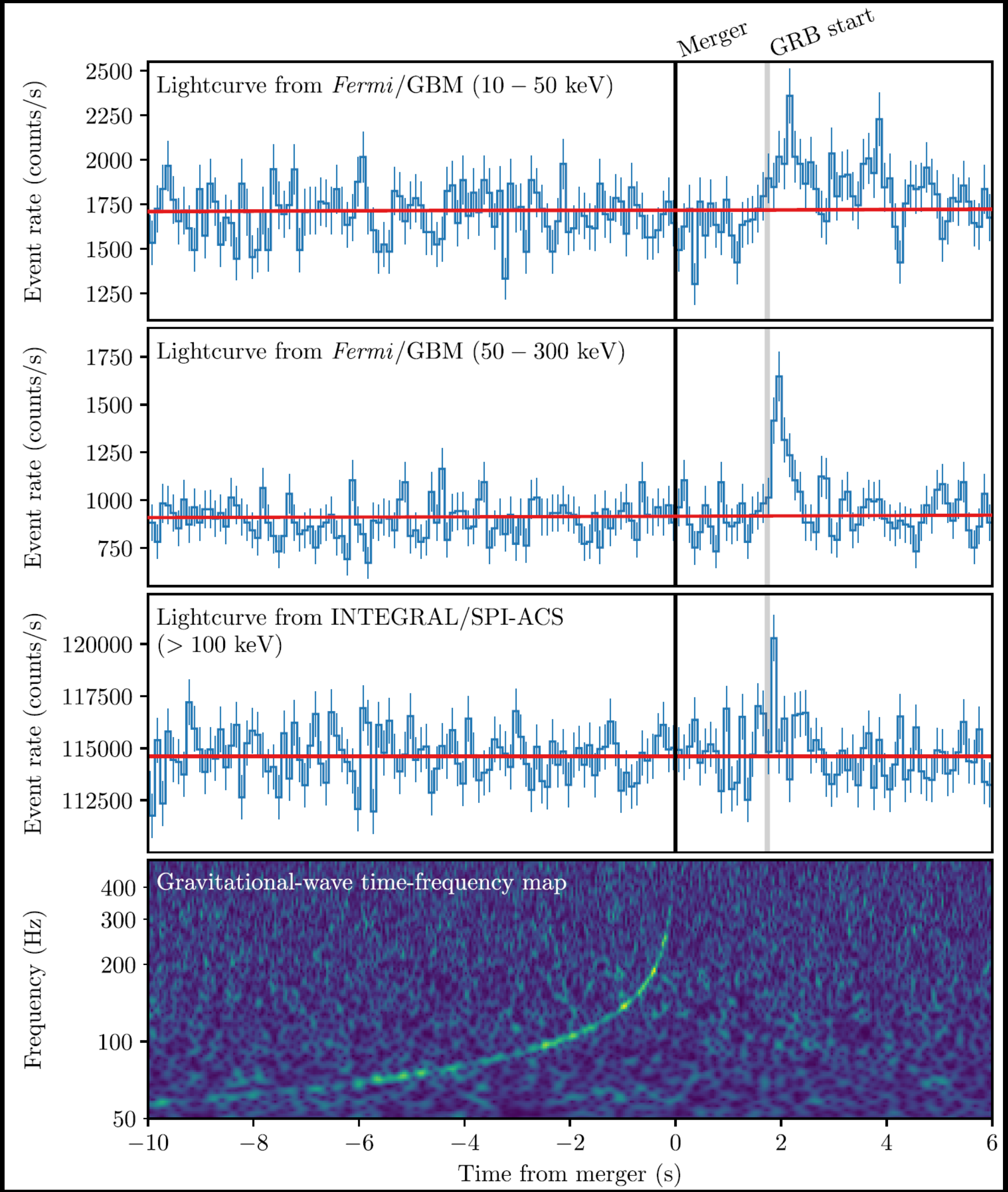
Amplitude damping

Propagation speed of GW

Modification of dispersion relation

By putting bound on these parameters, LISA will rule out/limit different alternative theories of gravity

[Barausse et al. 2020; Ezquiaga 2021; Ezquiaga and García-Bellido 2018]



August 17, 2017:

- A NS-NS inspiral GW170817 observed by the LIGO and Virgo detectors
- $1.74 \pm 0.05\,\mathrm{s}$ later the GRB 170817A was observed independently by Fermi gamma-ray laboratory
- Using
  - luminosity distance of GW signal,
  - the time delay between the GW and GRB,

Speed of GWs was constrained to:

$$-3 \times 10^{-15} c < v_g - c < +7 \times 10^{-16} c$$

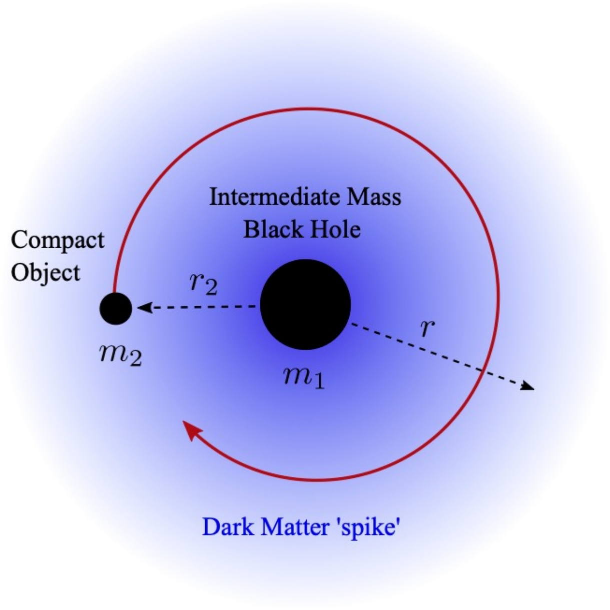
LISA will be able to significantly strengthen this bound

Dark Matter

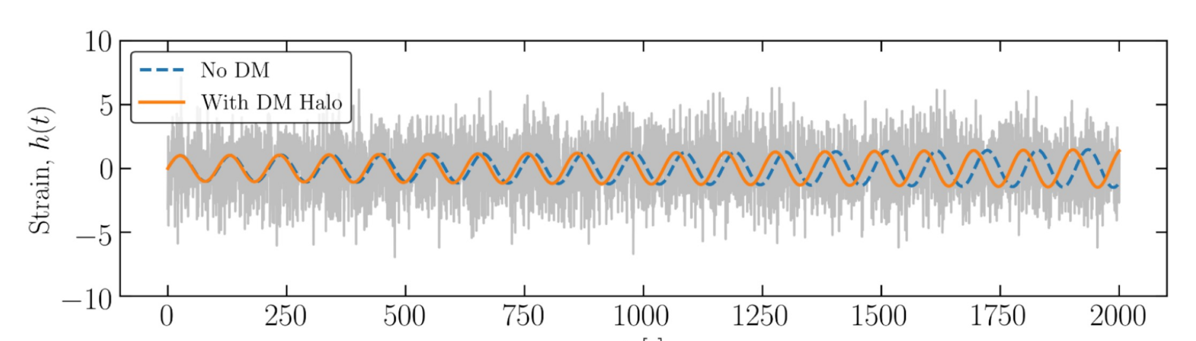
Particle Nature of Dark Matter

Various ways LISA can provide crucial info about dark matter (DM)…

A promising method: DM spike around BH



- DM spikes modifies the dynamics of the system
- GW pattern gets modified, yields precise information about DM profile, **picked up by LISA**
- Crucial info about the particle nature of DM



[Courtesy of B. J. Kavanagh]

More detail: Diego Montalvo's talk in lightning session

[Kavanagh et al 2020; Coogan et al. 2022; Becker, Sagunski, Prinz, SR 2022]

Quantum Structure of Spacetime

Illusive Spacetime

Many in quantum gravity community:

- Continuous spacetime may be an illusion
- More fundamental quantum/discrete substrate under spacetime giving rise to it?
  - Solution to the problem of singularities?

What is the fine structure of spacetime?

Is it fundamentally discrete?

LISA can help us in shedding light on this!

Spacetime Structure and LISA

- Quantum gravity/spacetime theories modify the metric
  - Effective metric or effective perturbations
- Modification of the production and propagation of GWs

Example: certain model inspired by loop quantum gravity

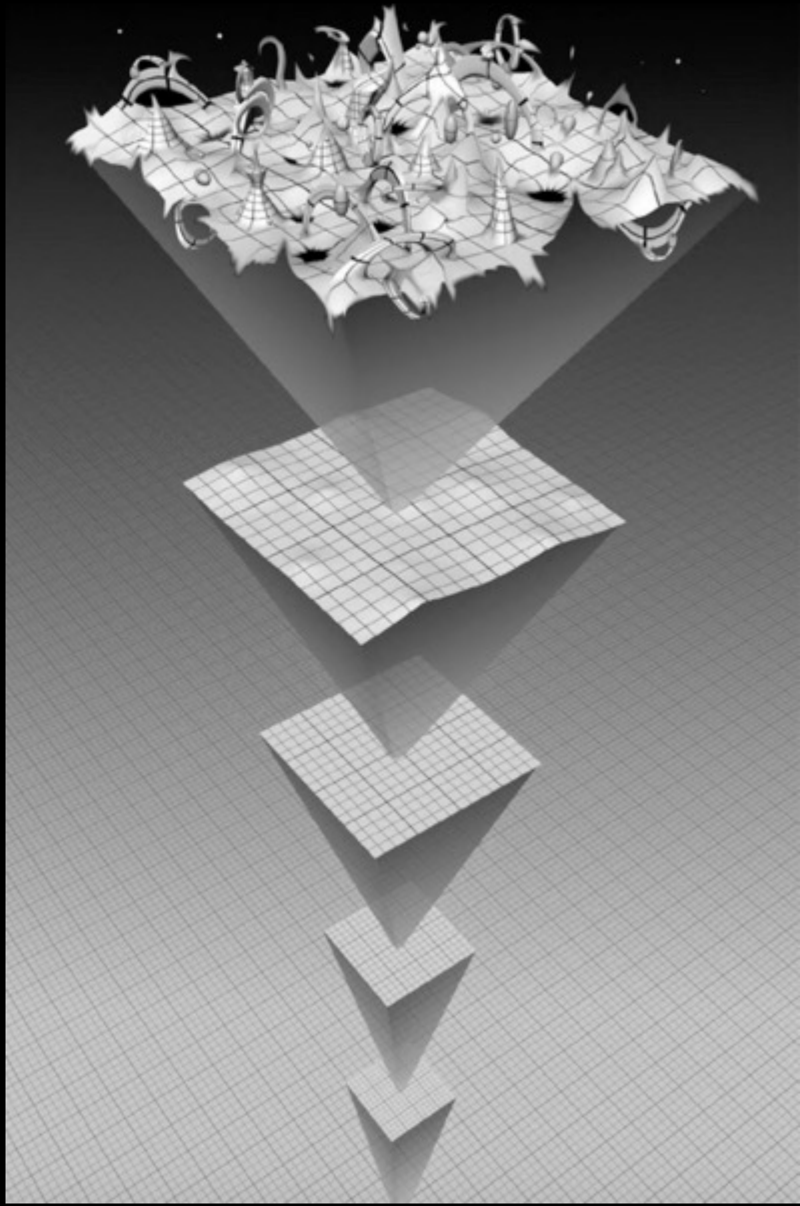
$$h_{+,\mathbf{k}}(t) = h_l \left[(1 - F(\mu, k)) \cos\left(k\sqrt{1 - 4F(\mu, k)}\, t \right) - \frac{1}{2} F(\mu, k) \cos\left(3k\sqrt{1 - 4F(\mu, k)}\, t \right) + \cdots \right]$$

Amplitude modification

Higher harmonics

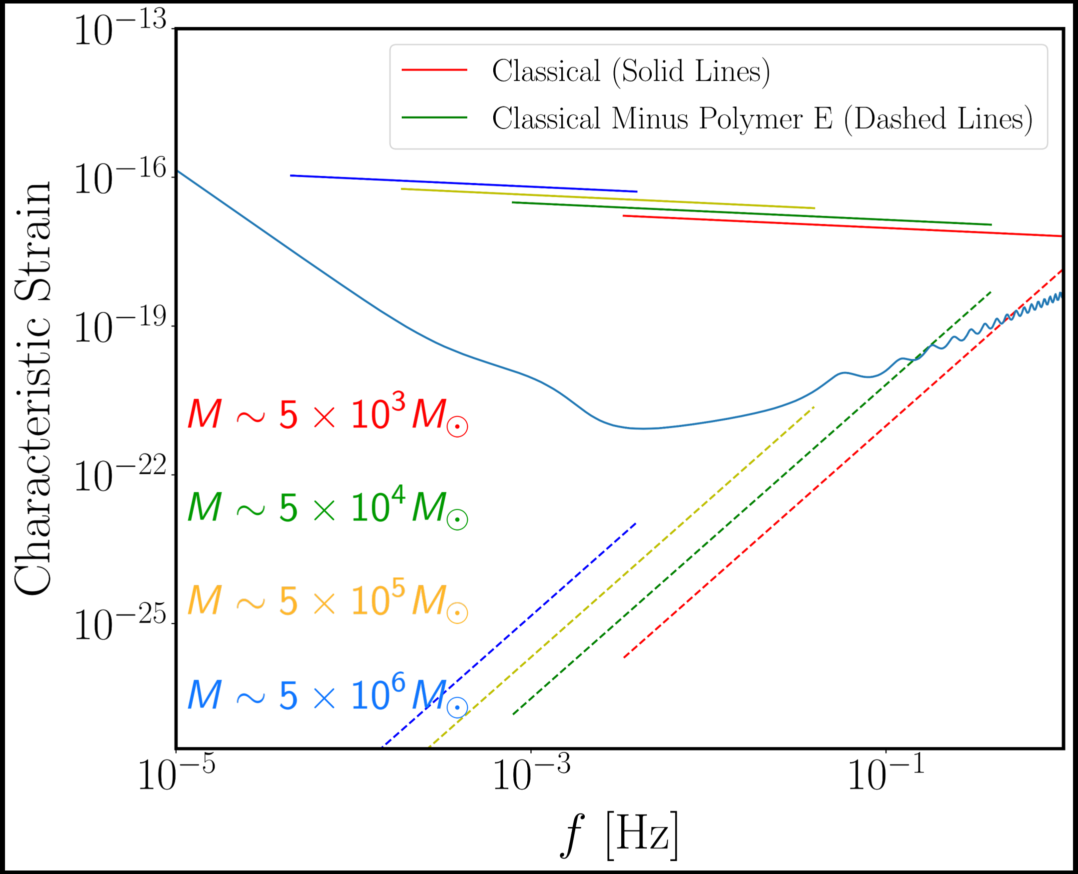
Dispersion & propagation speed modification

[Garcia-Chung, Mertens, SR, Tavakoli, Vargas Moniz, Parvizi, Carney, 2021 and 2022]



Spacetime Structure and LISA

Loudness of signal: coalescing of two equal-mass inspiraling BH at $z = 0.3$



[Garcia-Chung, Mertens, SR, Tavakoli, Vargas Moniz, Parvizi, Carney, 2021 and 2022]

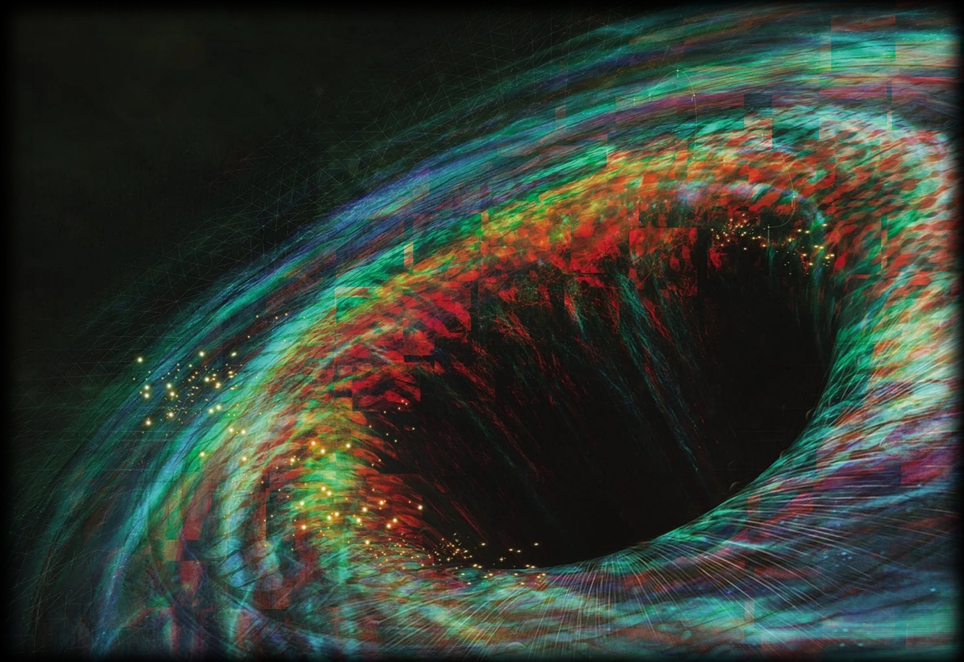
Quantum Black Hole Spectroscopy

Black Holes Spectroscopy

- Bekenstein: area of BHs an adiabatic invariant in GR $\Longrightarrow$ horizon area should be quantized
- Quantization of angular momentum $\Longrightarrow$ mass spectrum must be discrete
- BHs interaction with radiation: emit/absorb discrete values of the frequency of the waves like atoms
- GWs allow for observation of the consequences of BH area quantization for the absorption spectrum

How does a Planck-scale discretization

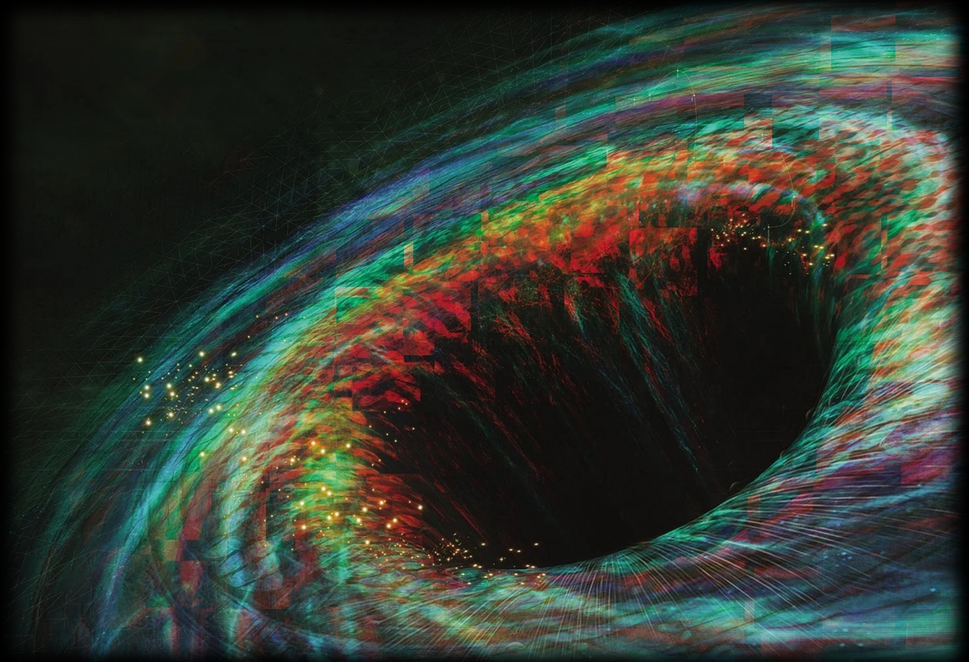
show up in low frequency GWs?



[Bekenstein and Mukhanov 1995; Agullo, Cardoso, Del Rio, Maggiore, Pullin 2021]

Black Holes Spectroscopy

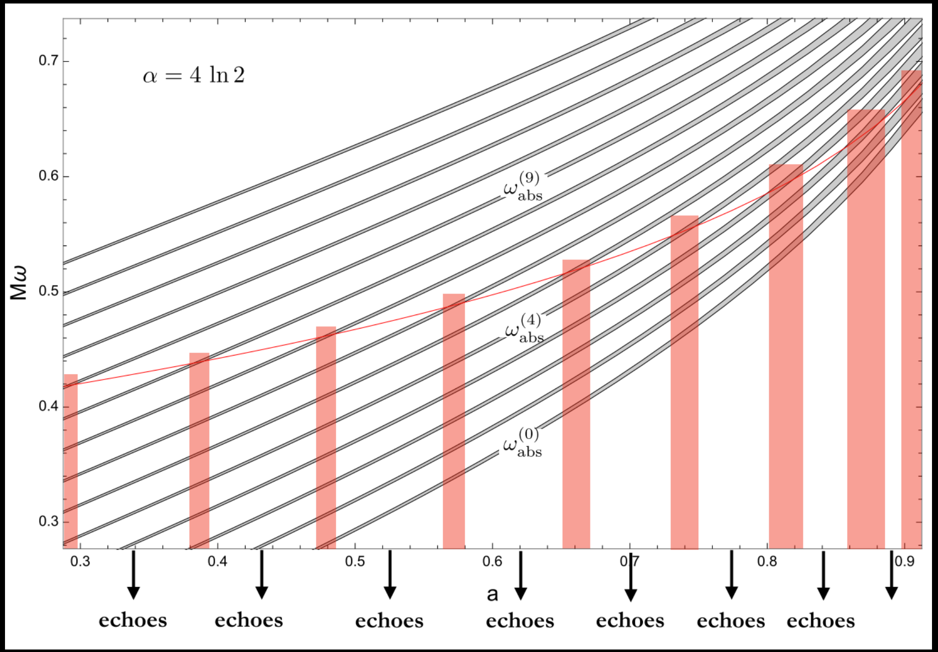
- Based on 1st law of BH mechanics $\omega_{\text{abs}} = \frac{c^3}{32\pi G}\frac{1}{M}$
- Astrophysical BHs with $M = n\, M_{\odot}$ translates Planck-scale discretization of the BH area to frequencies within the window of GW detectors $f_{\text{abs}} \approx \frac{1}{\pi n}$ kHz !
- Large BHs magnify Planck scale effects to within the window of GWs!

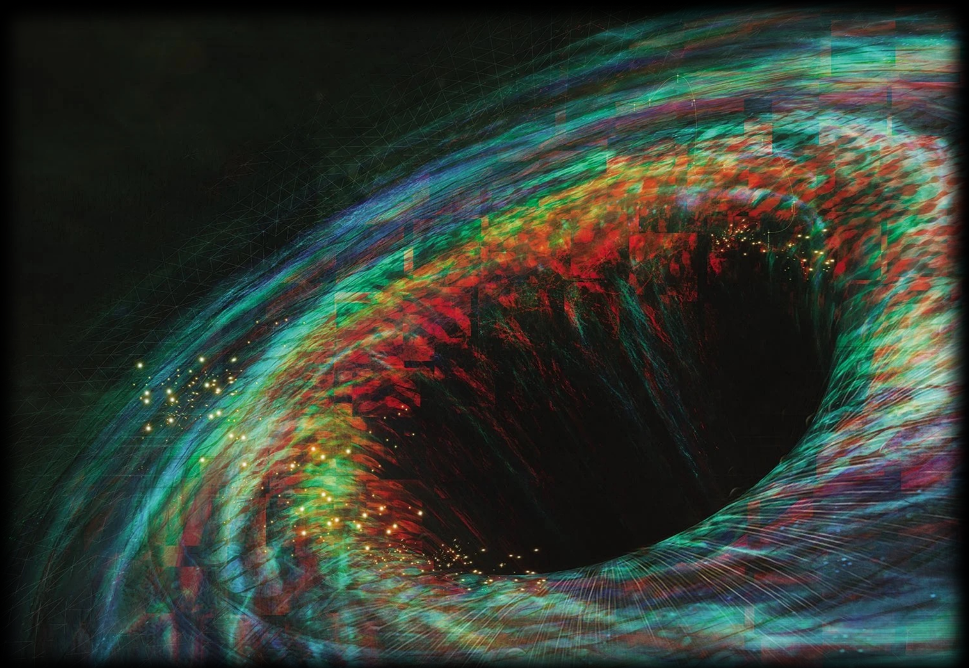


[Bekenstein and Mukhanov 1995; Agullo, Cardoso, Del Rio, Maggiore, Pullin 2021]

Black Holes Spectroscopy

- During ringdown, some energy radiates inward towards horizon
- If its frequency does not match BH mass spectrum quanta, it will radiate out
- Reaches photon ring, goes backward again, and so on…
- This produces an "echo" of GWs, carrying info about area quantization!





[Bekenstein and Mukhanov 1995; Agullo, Cardoso, Del Rio, Maggiore, Pullin 2021]

Summary

- For so long we have lacked experiments in fundamental physics (I mean quantum-gravity fundamental!)
- LISA will provide us with a crucial possibility of quantum-gravity-grade tests of fundamental physics!
- Host of tests of fundamental physics:
    - Modified gravity
    - Astro/particle physics, dark matter
    - Quantum spacetime
    - Quantum black holes
    - Quantum cosmology, and more…

- Join the journey! theory, data analysis, software, hardware, experiments,…