Recent progress in theoretical physics based on quantum information theory @ YITP
March 2nd 2021 (JST)

Can we probe the microstates of spacetime?

Naritaka Oshita
(Perimeter Institute)

Role of gravitational entropy in cosmology

Gregory, Moss, NO (2020) 2003.04927

Gregory, Moss, NO, Patrick (2020) 2007.11428

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What is the origin of gravitational entropy?

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BH spectroscopy and CFT thermal state

Ongoing work

Could the total entropy decrease?

YES

(non-equilibrium situations)

Jarzynski equality

Jarzynski (1997)

non-equilibrium paths

$$e^{-\beta\Delta F} = \langle e^{-\beta W} \rangle$$

inverse temperature

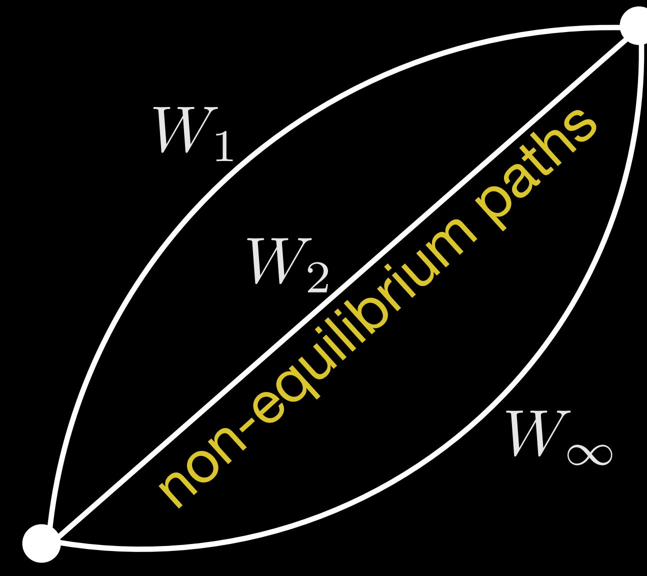
free energy

work

$$\Updownarrow$$

$$\langle e^{-\Delta S} \rangle = 1$$

Entropy (B) - Entropy (A)



equilibrium state B

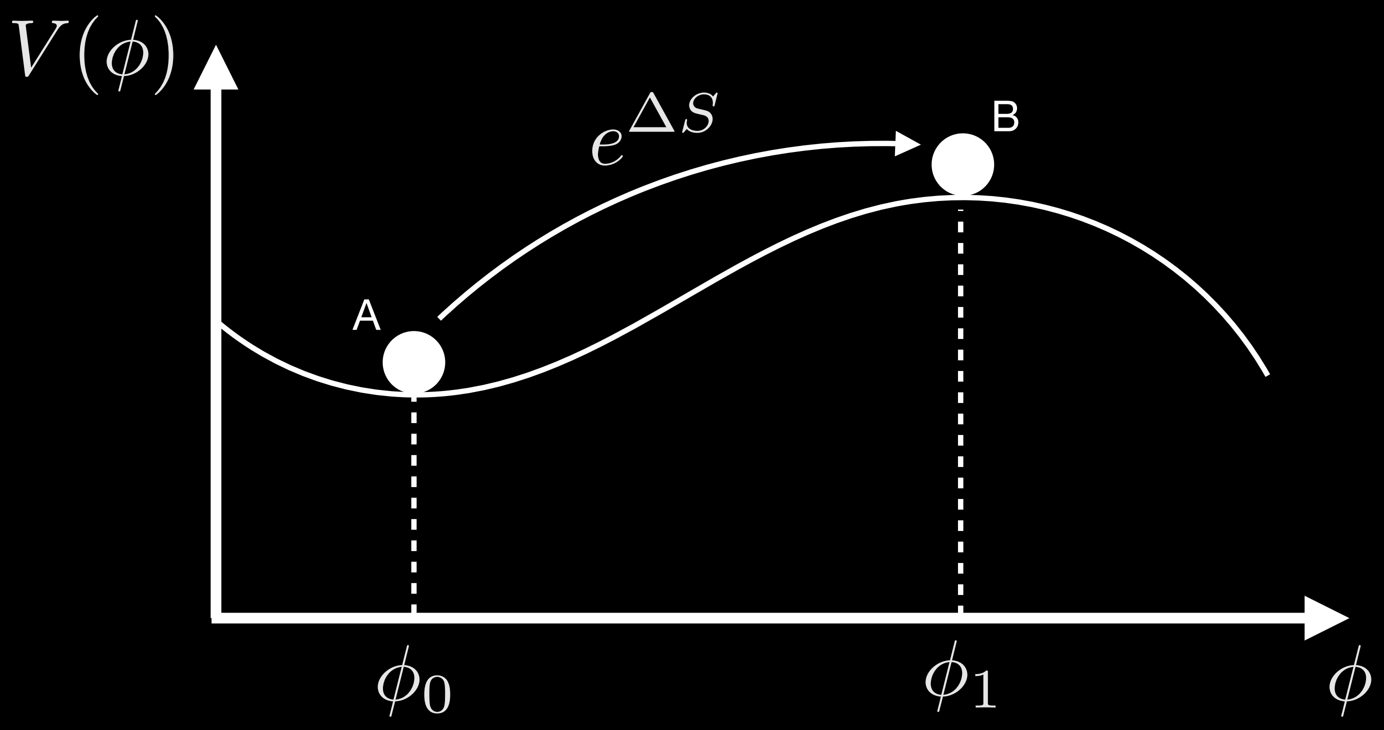
non-equilibrium paths

equilibrium state A

Entropy decreases with small probability!

$$p \sim e^{\Delta S} \ll 1 \ (\Delta S < 0)$$

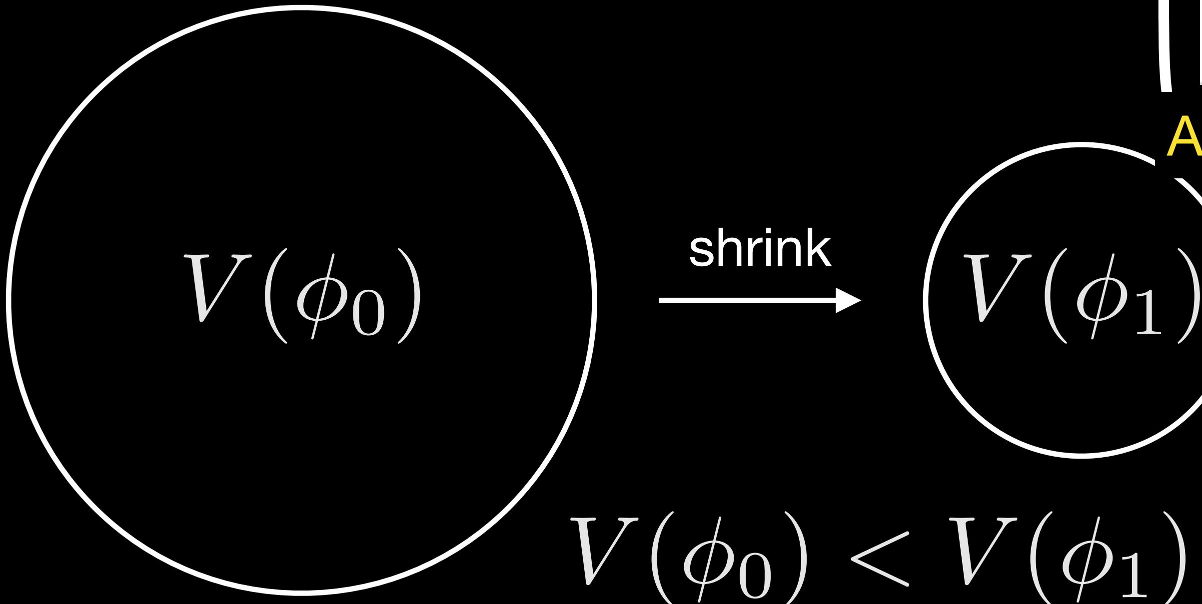
Cosmological horizon is no exception!



Hawking-Moss transition

Hawking and Moss (1982)

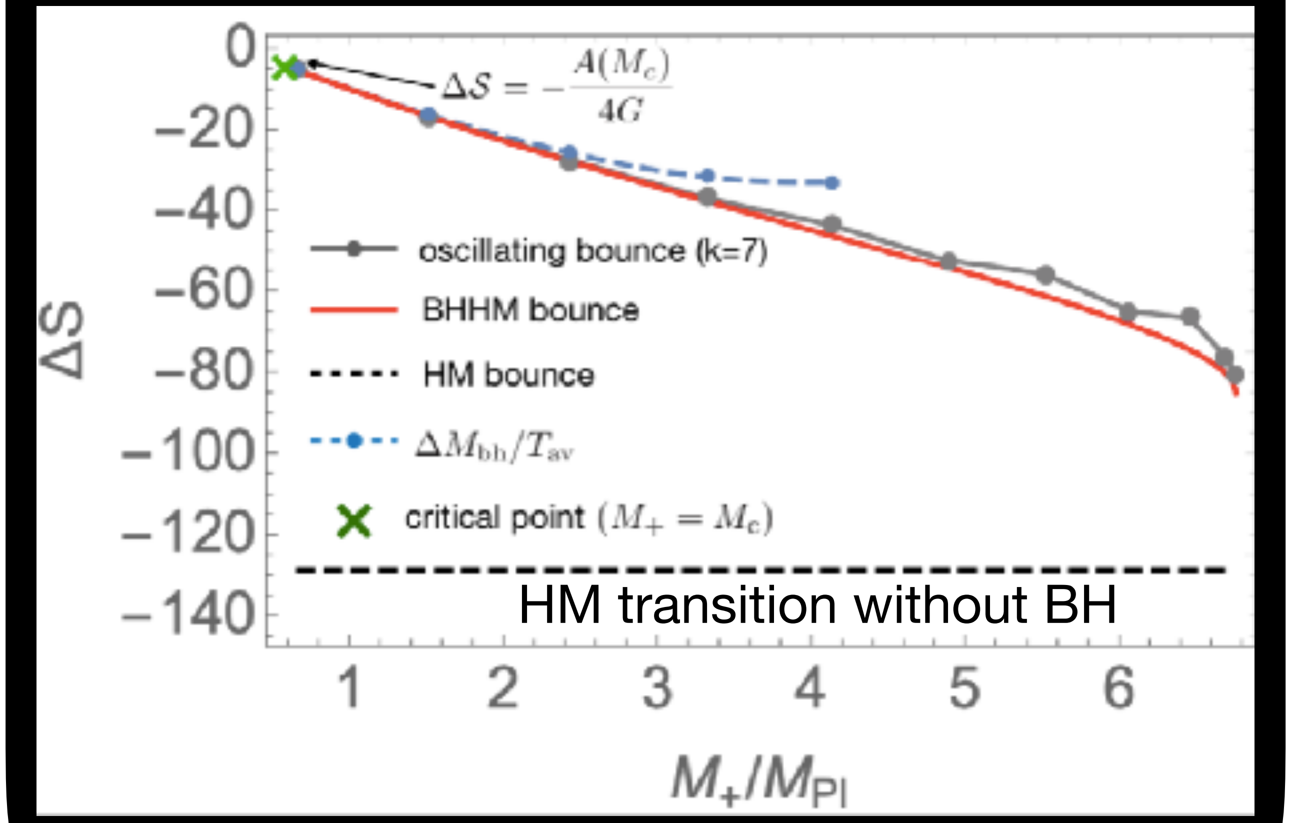
cosmological horizon



$$V(\phi_0) < V(\phi_1)$$

What if a black hole is involved?

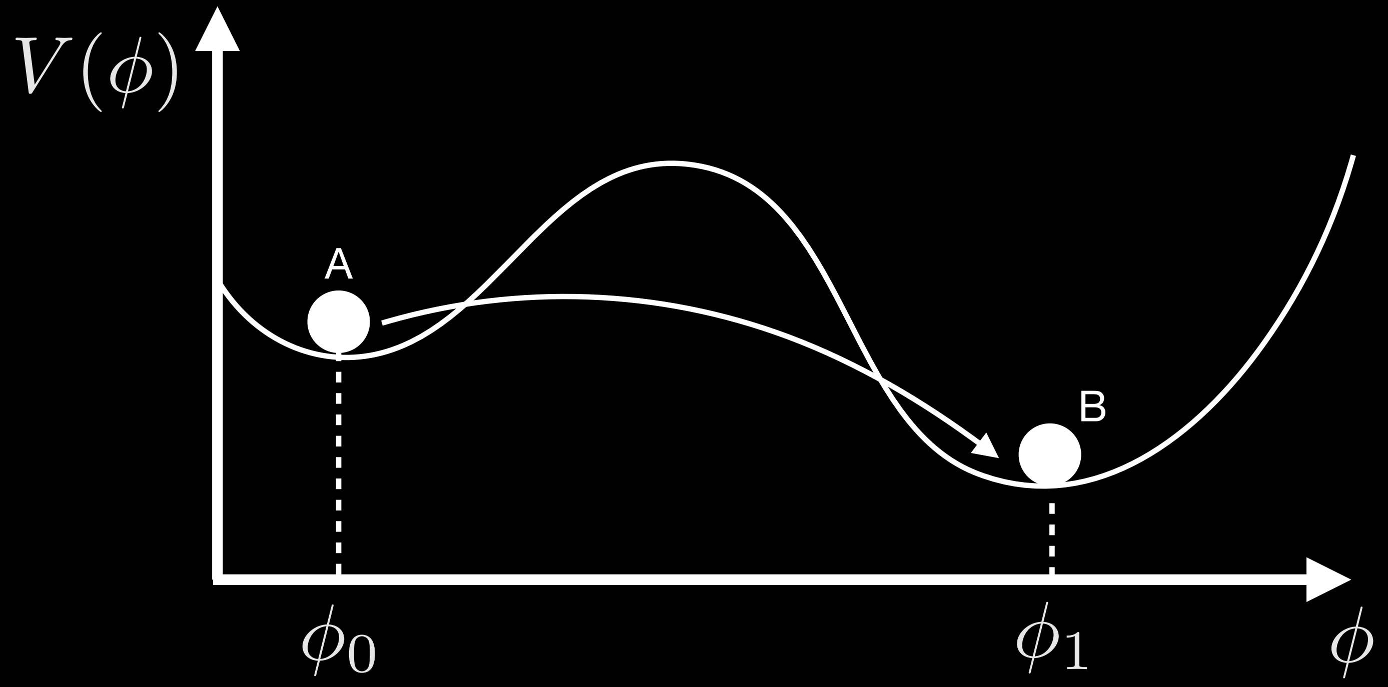
Gregory, Moss, NO (2020)



A BH behaves like a catalyst for vacuum transition!!

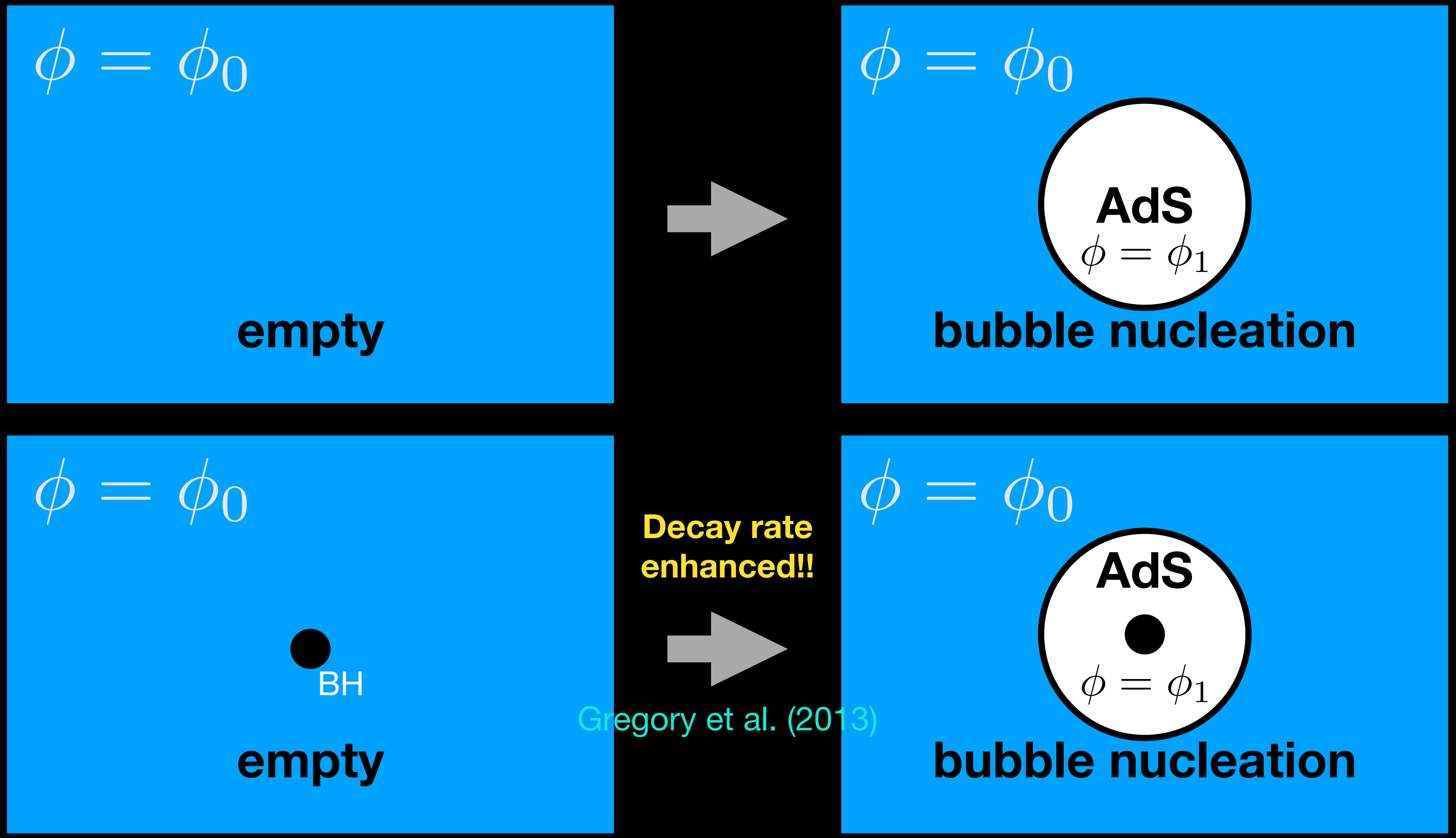
Bekenstein Hawking entropy decreases!

$$\Delta S < 0$$



Coleman-de Luccia tunneling

Coleman and de Luccia (1980)



Decay rate enhanced!!

Gregory et al. (2013)

Running coupling

$$V = \frac{1}{4}\lambda_{\rm eff}(\phi)\phi^4$$

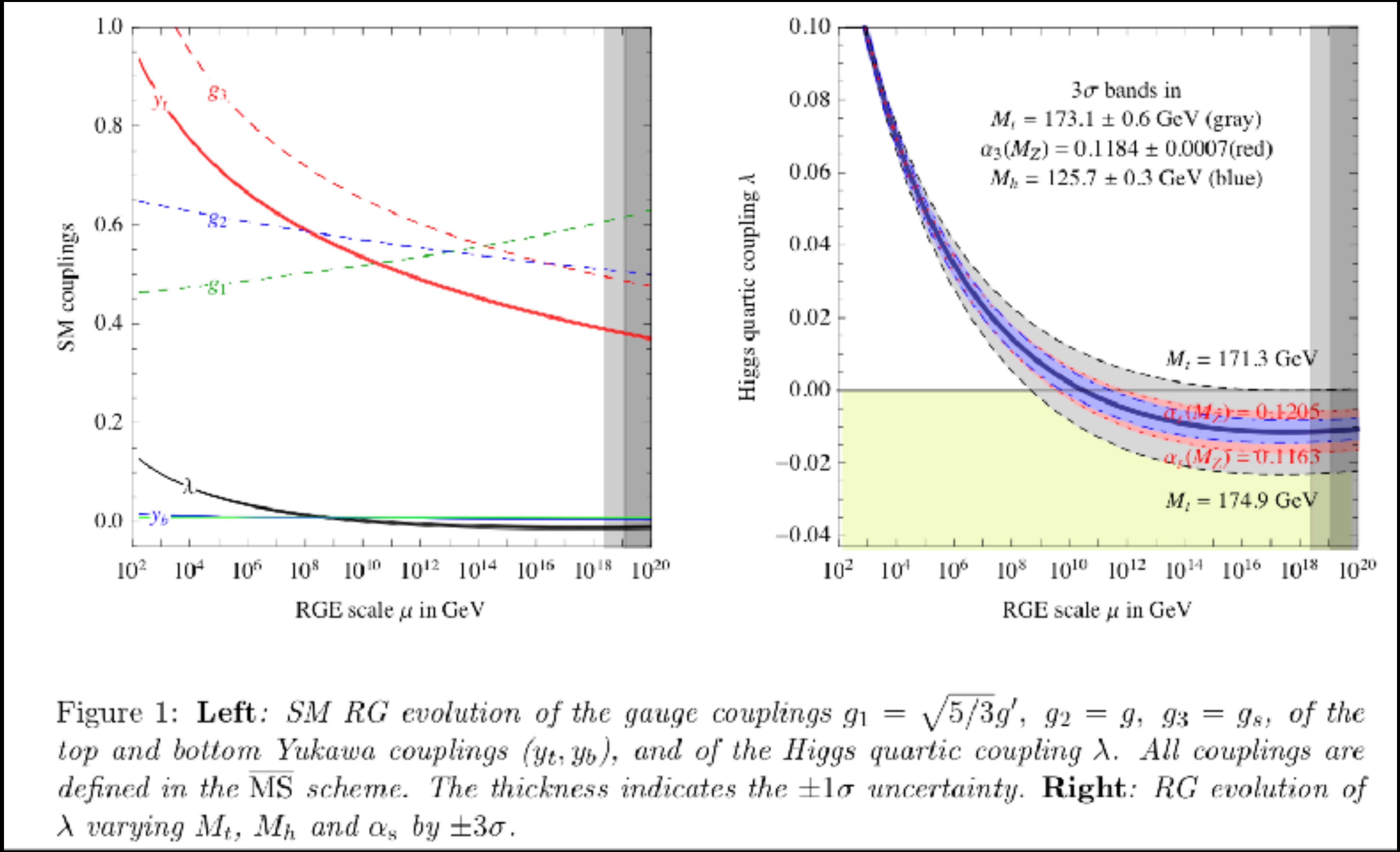


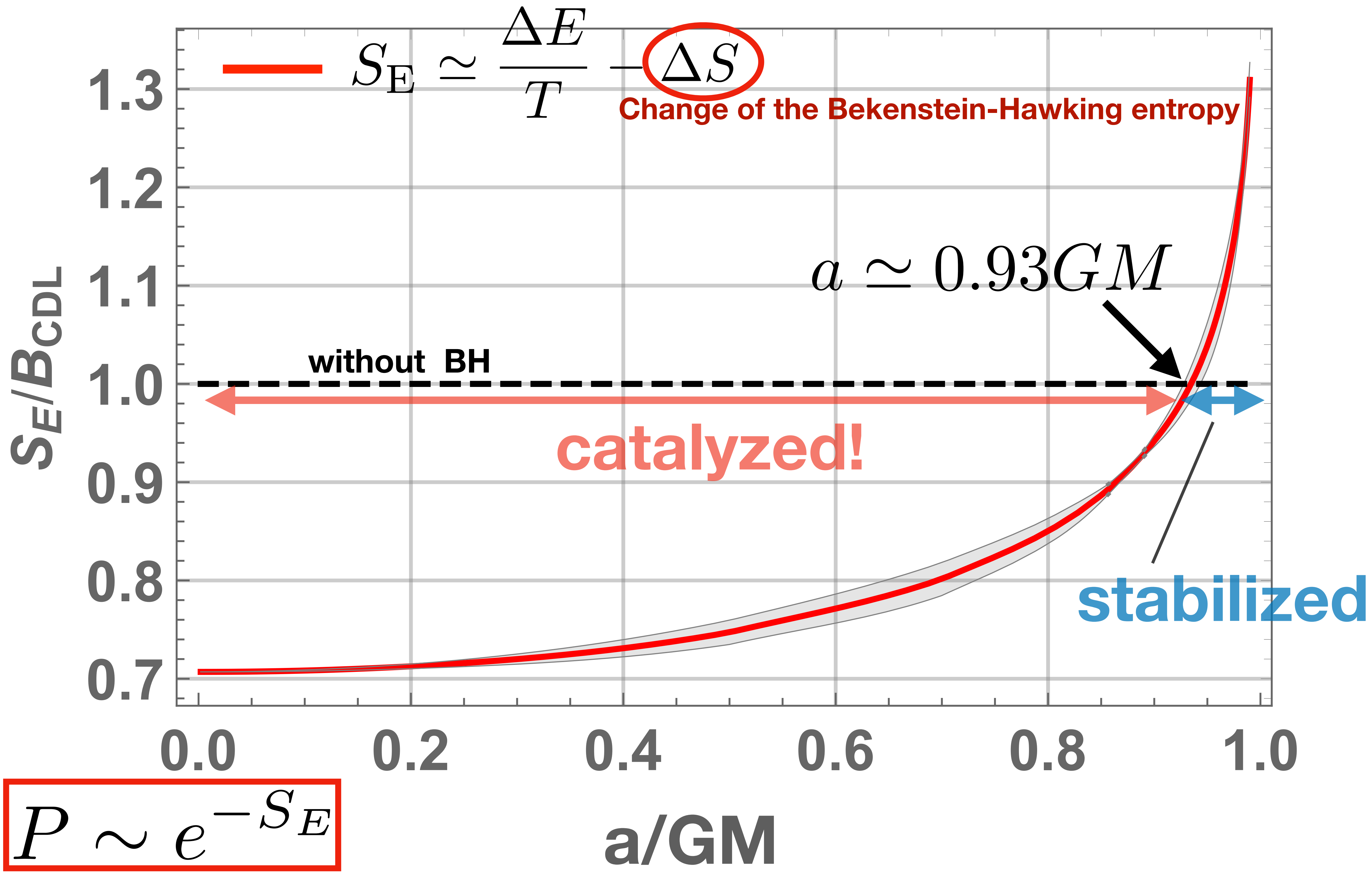
Figure 1: **Left**: *SM RG evolution of the gauge couplings* $g_1 = \sqrt{5/3}g'$, $g_2 = g$, $g_3 = g_s$, *of the top and bottom Yukawa couplings* (y_t, y_b), *and of the Higgs quartic coupling* λ. *All couplings are defined in the* $\overline{\rm MS}$ *scheme. The thickness indicates the* $\pm 1\sigma$ *uncertainty.* **Right**: *RG evolution of* λ *varying* M_t, M_h *and* α_s *by* $\pm 3\sigma$.

Degrassi et al. (2013)

The Higgs self-coupling can be negative at high energies.

BH catalyzing effect and the Higgs metastability

NO, Ueda, Yamaguchi (2019)



$$P \sim e^{-S_E}$$

$r_s = 10^3 \ell_\mathrm{Pl},\ H = 1 \times 10^{-4} M_\mathrm{Pl}, \Sigma = 1.5 \times 10^{-5} M_\mathrm{Pl}\ \ \Sigma / M_\mathrm{Pl} = 1.3 \times 10^{-5}$

Higgs metastability and PBHs

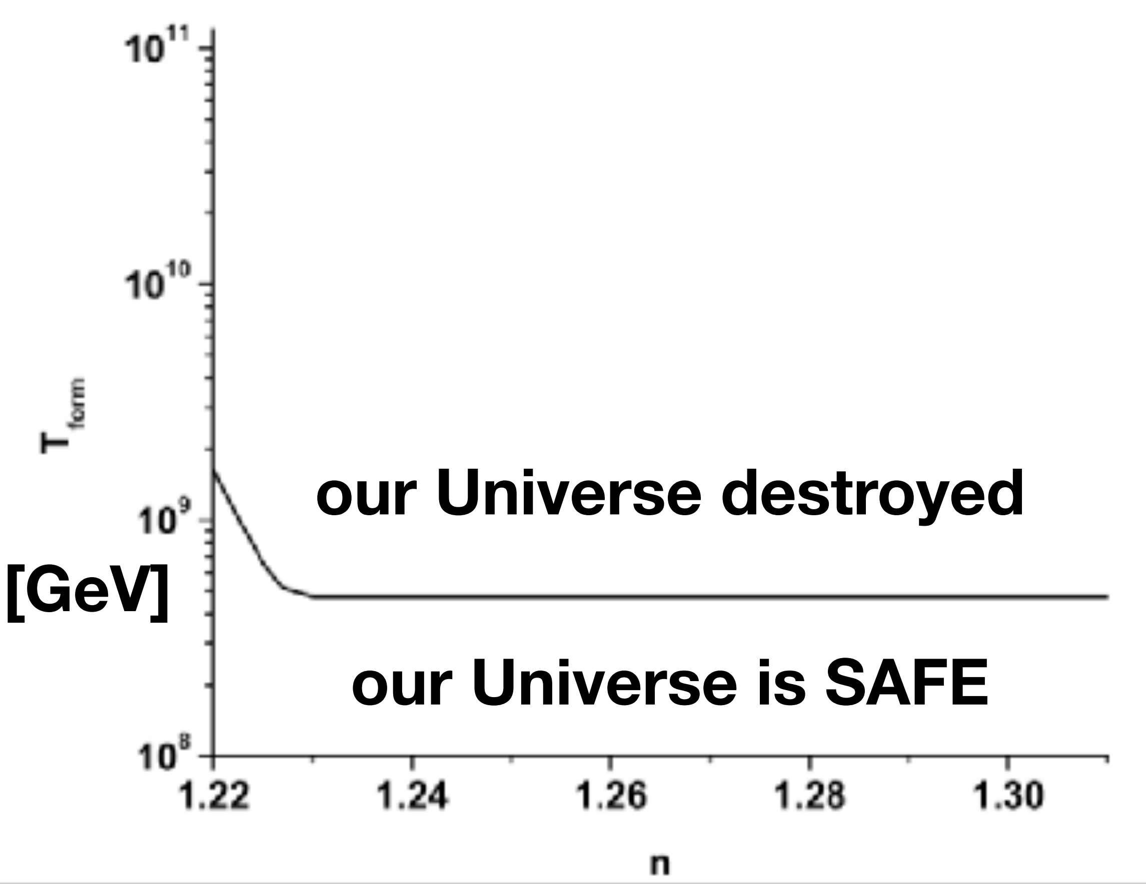
Higgs potential

Dai et al. (2019)

$$V = \frac{1}{4}\lambda_{\rm eff}(\phi)\phi^4 \qquad \lambda_{\rm eff} = \lambda_* + b\left(\ln\frac{\phi}{M_{\rm Pl}}\right)^2 + c\left(\ln\frac{\phi}{M_{Pl}}\right)^4$$

$$\lambda_* = -0.004 \qquad b = 1.5\times10^{-5} \qquad c = 0$$

PBHs (spectral index of the density fluctuations, mass, temp.)



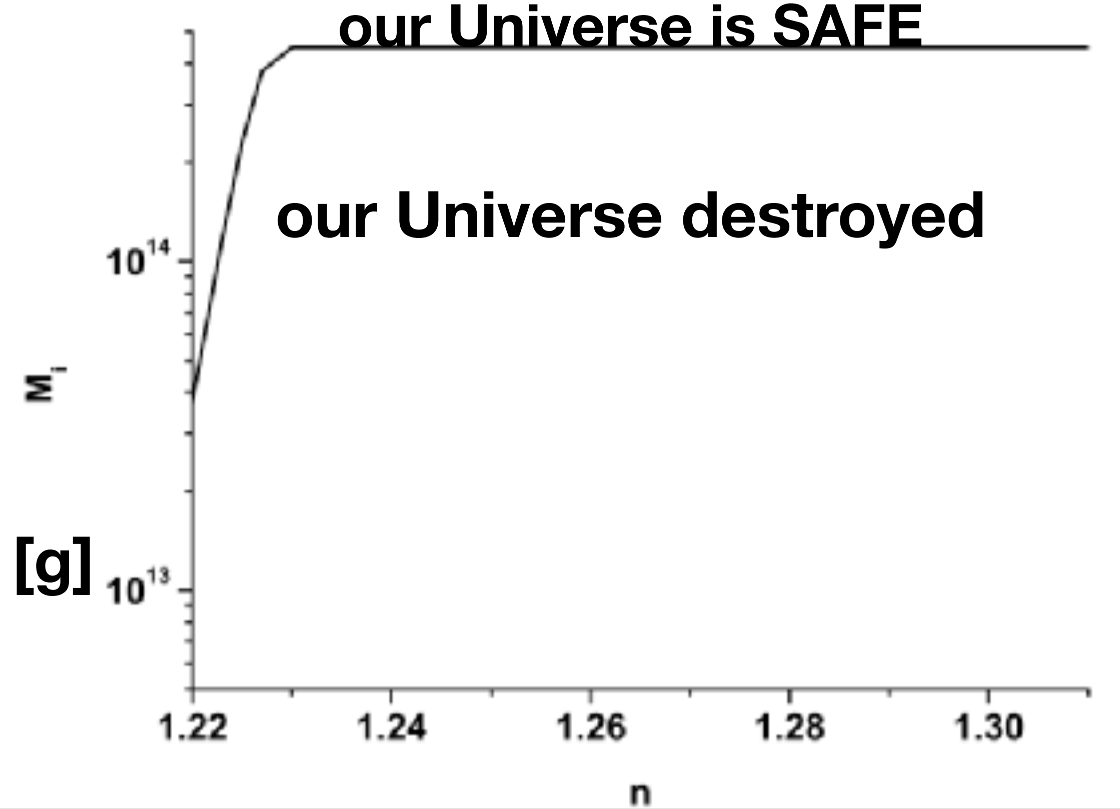
(temperature at the formation time)

[GeV]

our Universe destroyed

our Universe is SAFE

(spectral index)



(Mass of PBH)

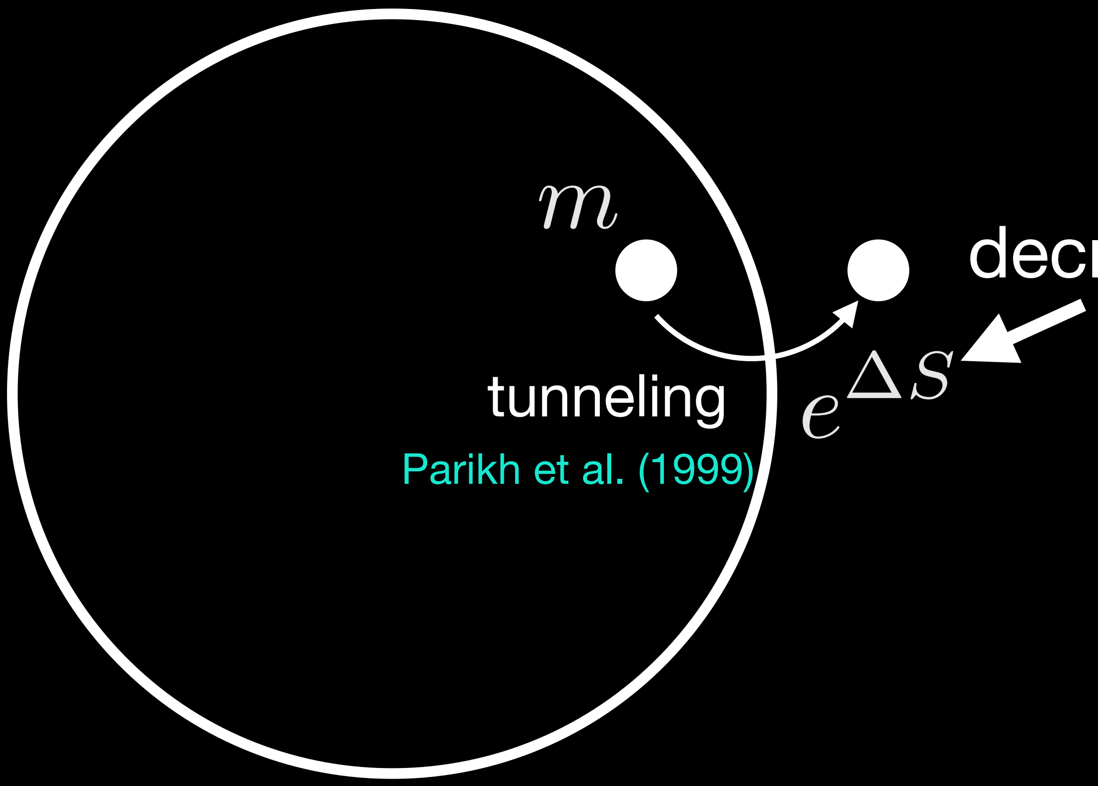
[g]

our Universe is SAFE

our Universe destroyed

(spectral index)

Hawking radiation



m

decrement of the Bekenstein-Hawking entropy

$e^{\Delta S}$

tunneling

Parikh et al. (1999)

What we can learn

quantum mechanics in gravity

non-equilibrium statistical mechanics

[Jarzynski equality]

transition probability $p \sim e^{\Delta S}$

gravitational entropy plays an important role in phenomenology

Constraints on cosmological models and the parameters of the (beyond) Standard Model

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BH spectroscopy and CFT thermal state

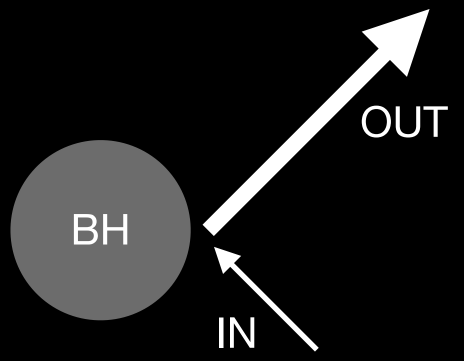
Ongoing work

1. microstructure which breaks the Lorentz symmetry

(e.g. Horava-Lifshitz quantum gravity)

Superradiance of Primordial Black Holes (PBHs)

NO, Afshordi, Mukohyama (2021)



amplification in scattering process

2. microstructure which is an ensemble of two level systems

GW echoes from BH ringing (late-time GW signal from binary black hole merger)

NO, Wang, Afshordi (2019)

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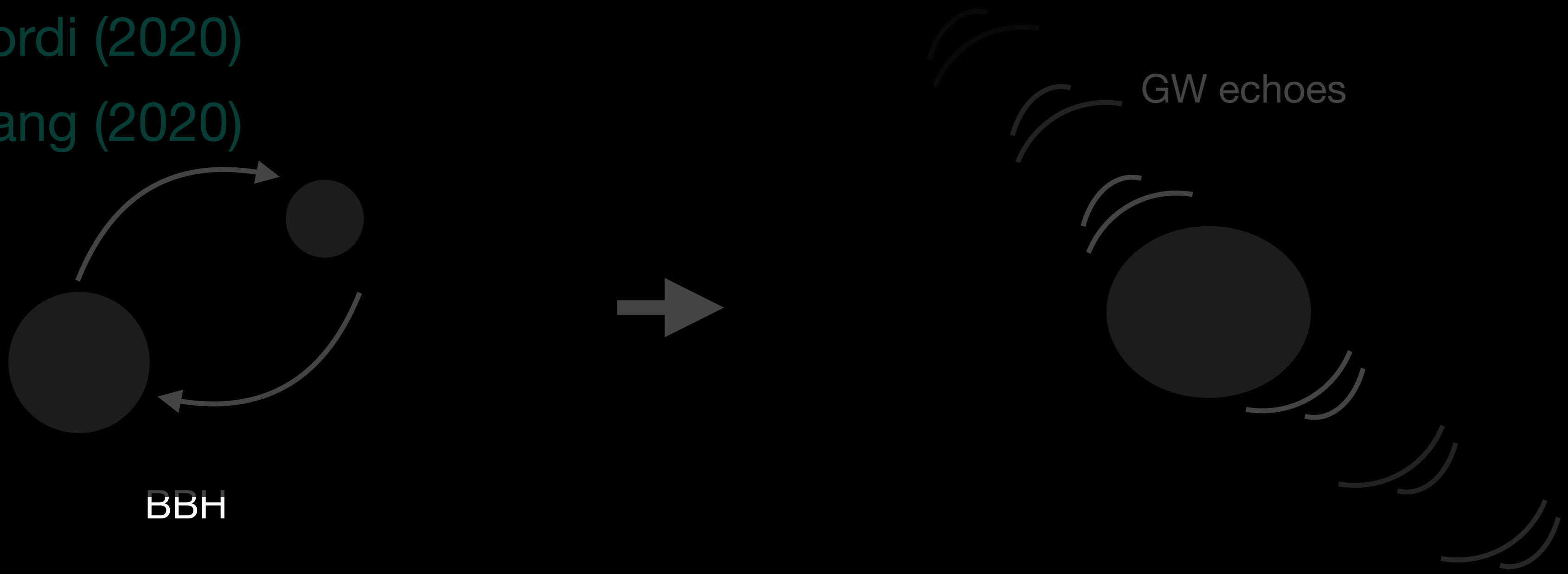


Lifshitz scaling

Anisotropy between space and time

$$x \to bx \quad t \to b^z t$$

Applying this to quantum gravity theory,
it becomes a renormalizable theory in a power-counting level.

Horava (2009)

Afterwards, the renormalizability of the (projectable) Horava-Lifhshitz gravity was performed!

Barvinsky et al. (2015)

dispersion relation in the Horava-Lifshitz quantum gravity

GR at high energy

$$\omega^2 = k^2$$

HL at high energy

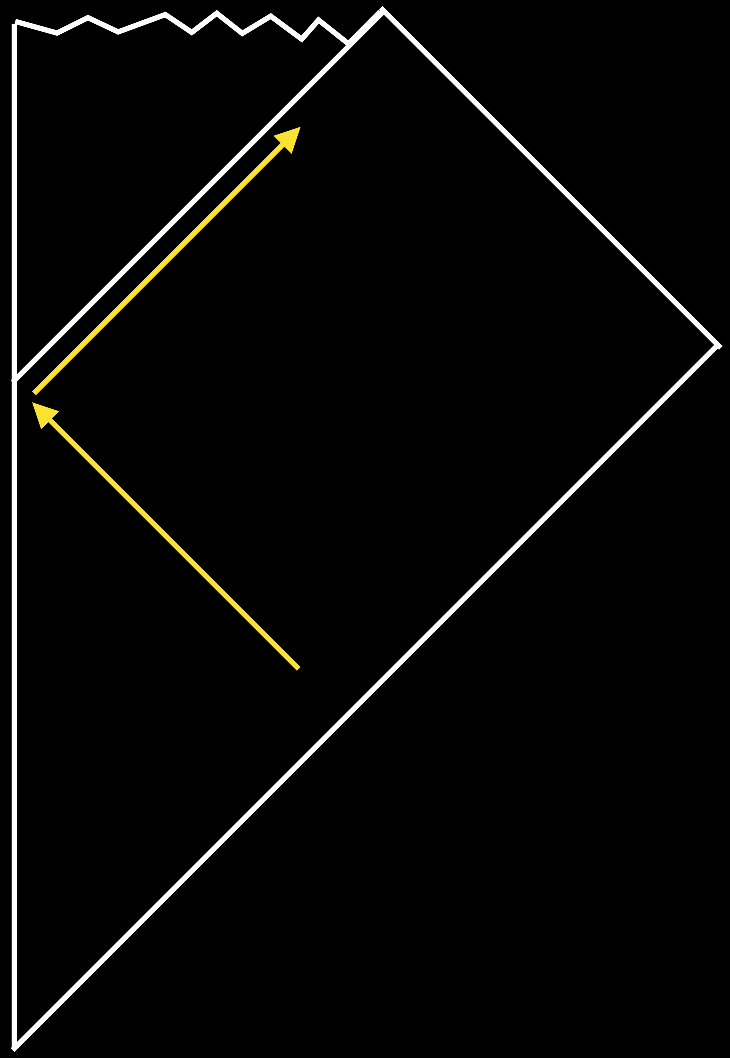
$$\omega^2 = \Xi_6 k^6 + \Xi_4 k^4 + k^2 \qquad \Xi_4 \equiv \frac{\mathcal{O}(1)}{M_{\rm HL}^2} \qquad \Xi_6 \equiv \frac{\mathcal{O}(1)}{M_{\rm HL}^4}$$

HL quantum gravity is consistent with observational cosmology!!

1. HL gravity solves the Horizon problem in cosmology
and leads to the scale-invariant perturbations
(alternative to inflation)
Mukohyama (2009), Kiritsis et al. (2009)

2. HL gravity has no Hamiltonian constraint
→ cold dark matter as integration constant Mukohyama (2009)

Lifshitz scaling and Hawking radiation



Hawking radiation

||

Scattering around a BH

$$N(\omega) = \frac{\Gamma(\omega)}{e^{(\omega-\mu)/T} - 1}$$

μ : chemical potential

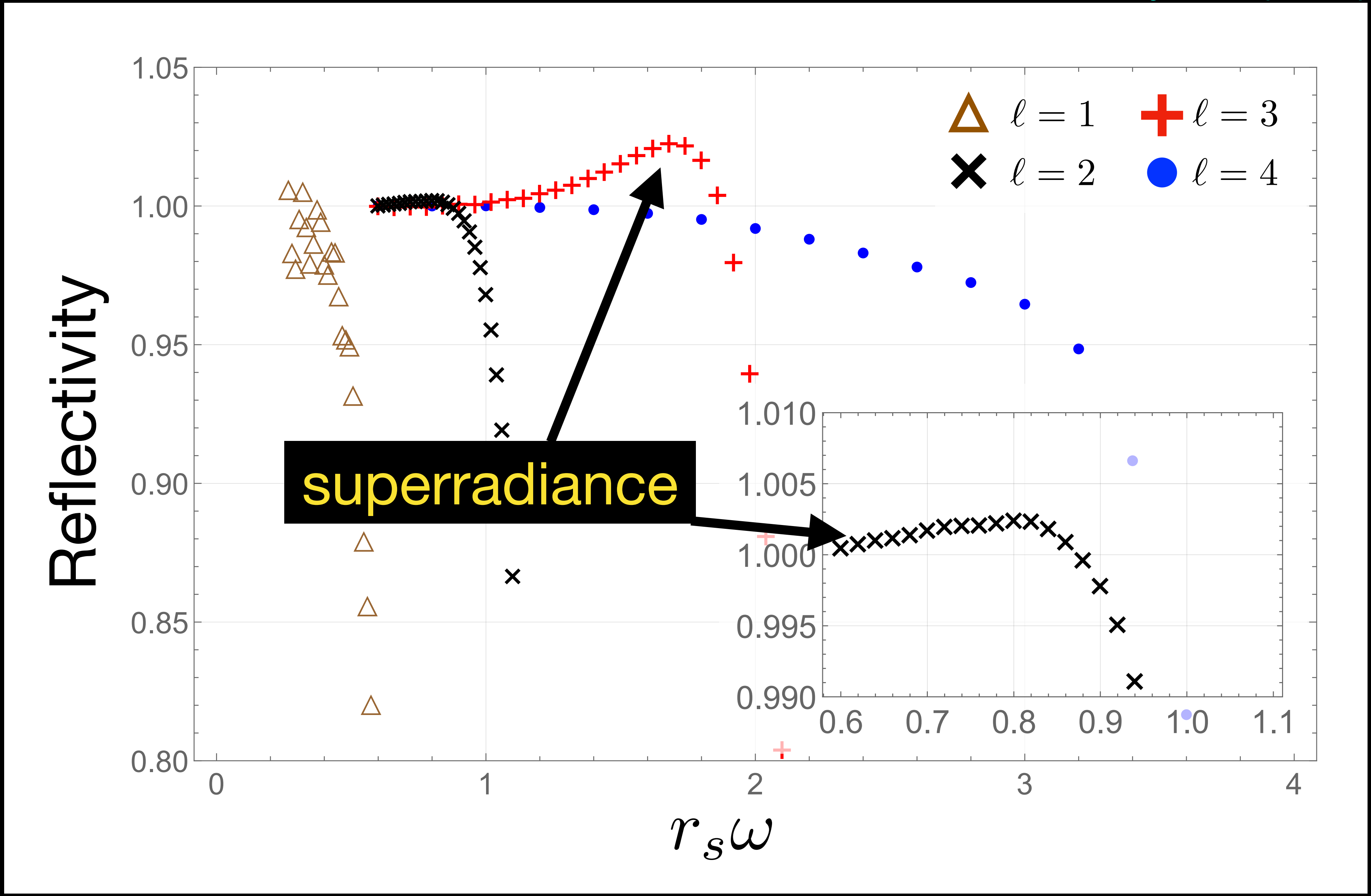
greybody factor

determined by the reflectivity of a BH

superradiance around a Schwarzschild BH

$$\left[-\Xi_6\Delta^3+\Xi_4\Delta^2+\Box\right]\psi(t,r)=0$$

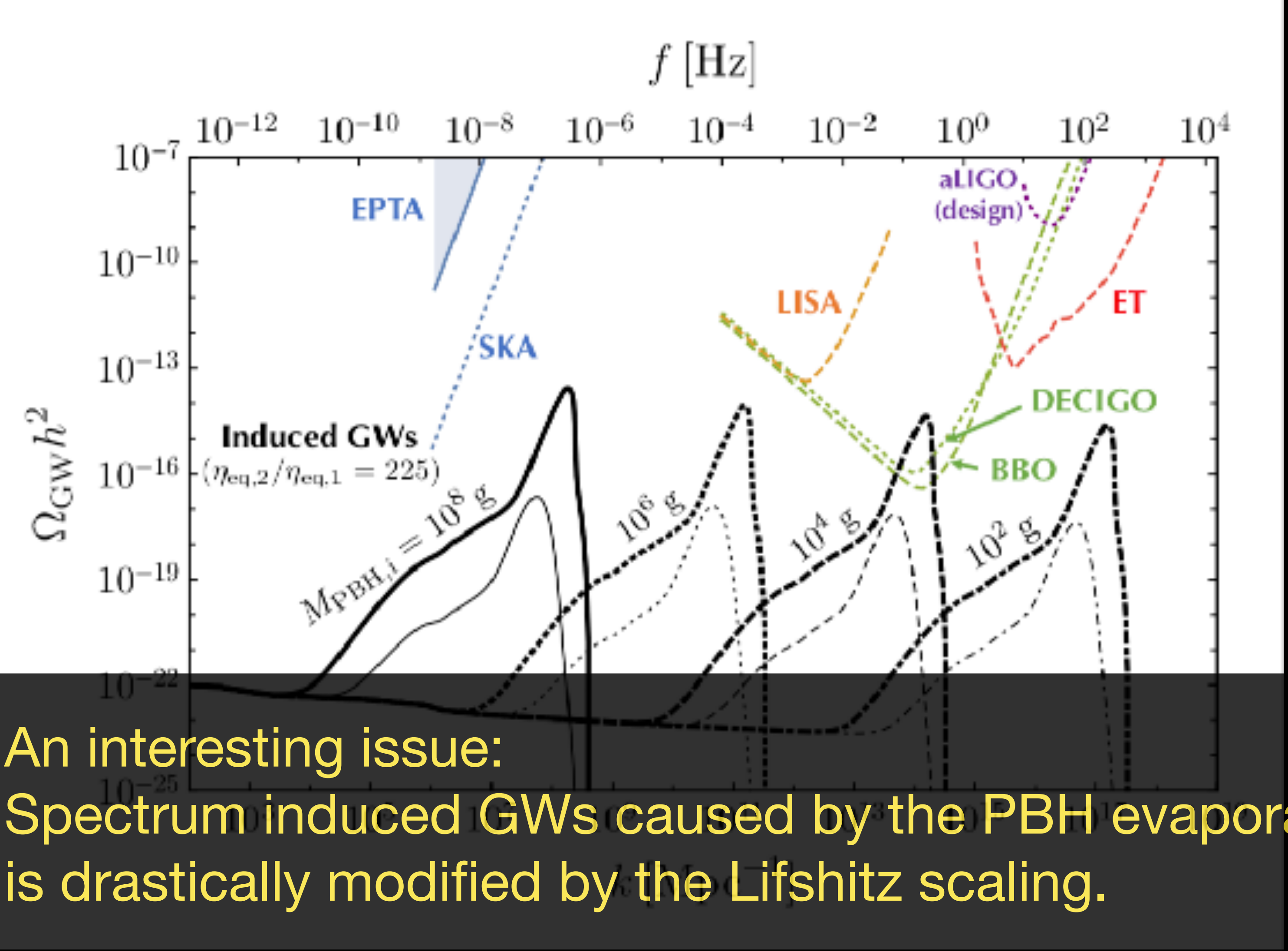
NO, Afshordi, Mukohyama (2021)



superradiance

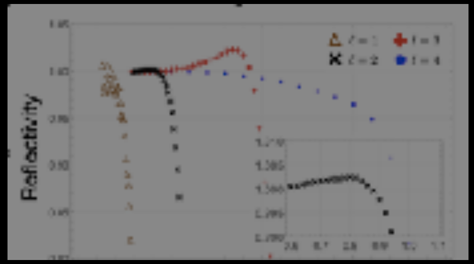
Future observations to probe Lifshitz scaling

[Inomata et al. (2020)]



An interesting issue:
Spectrum induced GWs caused by the PBH evaporation
is drastically modified by the Lifshitz scaling.

Evaporation of PBHs



changes the evaporation rate

induce curvature perturbations

induce GW

Observation of DECIGO / BBO

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(e.g. Horava-Lifshitz quantum gravity)

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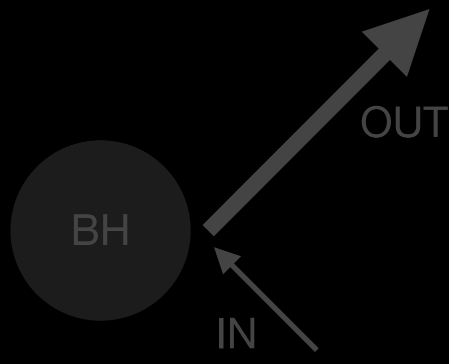

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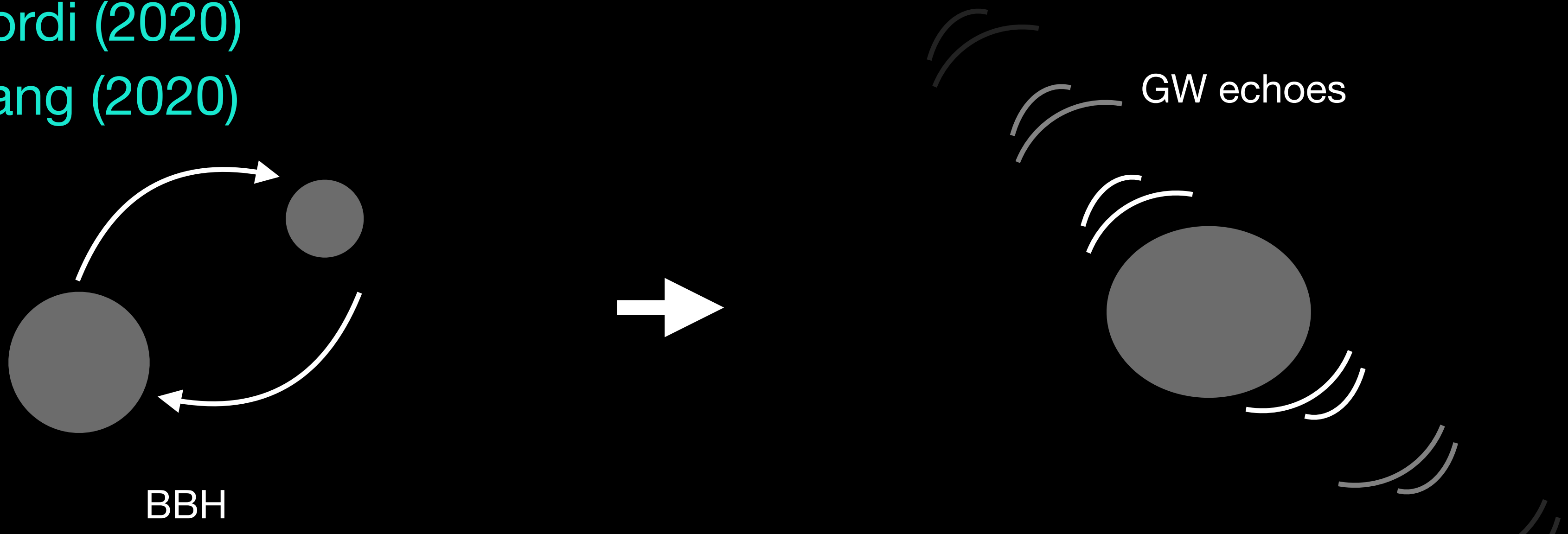
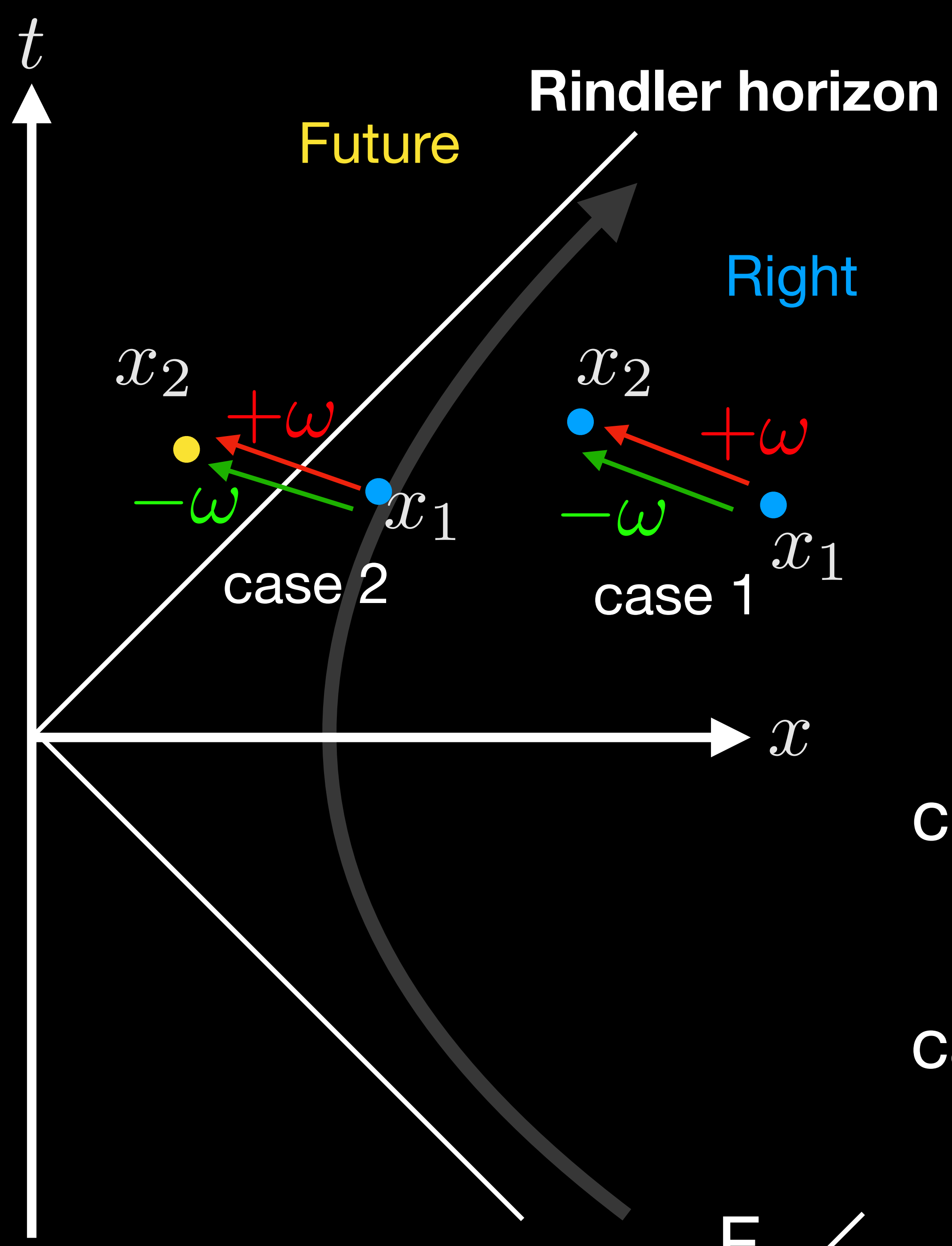


Thermality of horizon

Padmanabhan (2019)

Hartle & Hawking (1976)
Path integral approach



Amplitude of propagation with E=ω from x1 to x2

$$A(\omega) = \int d\tau G(\tau) e^{-i\omega\tau}$$

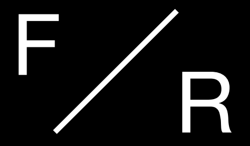
Feynman propagator

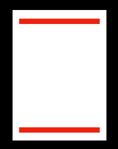
case 1 $A(\omega) = A(-\omega)$

case 2 $|A(\omega)|^2 / |A(-\omega)|^2 = \exp\left[-\omega / T(a)\right]$

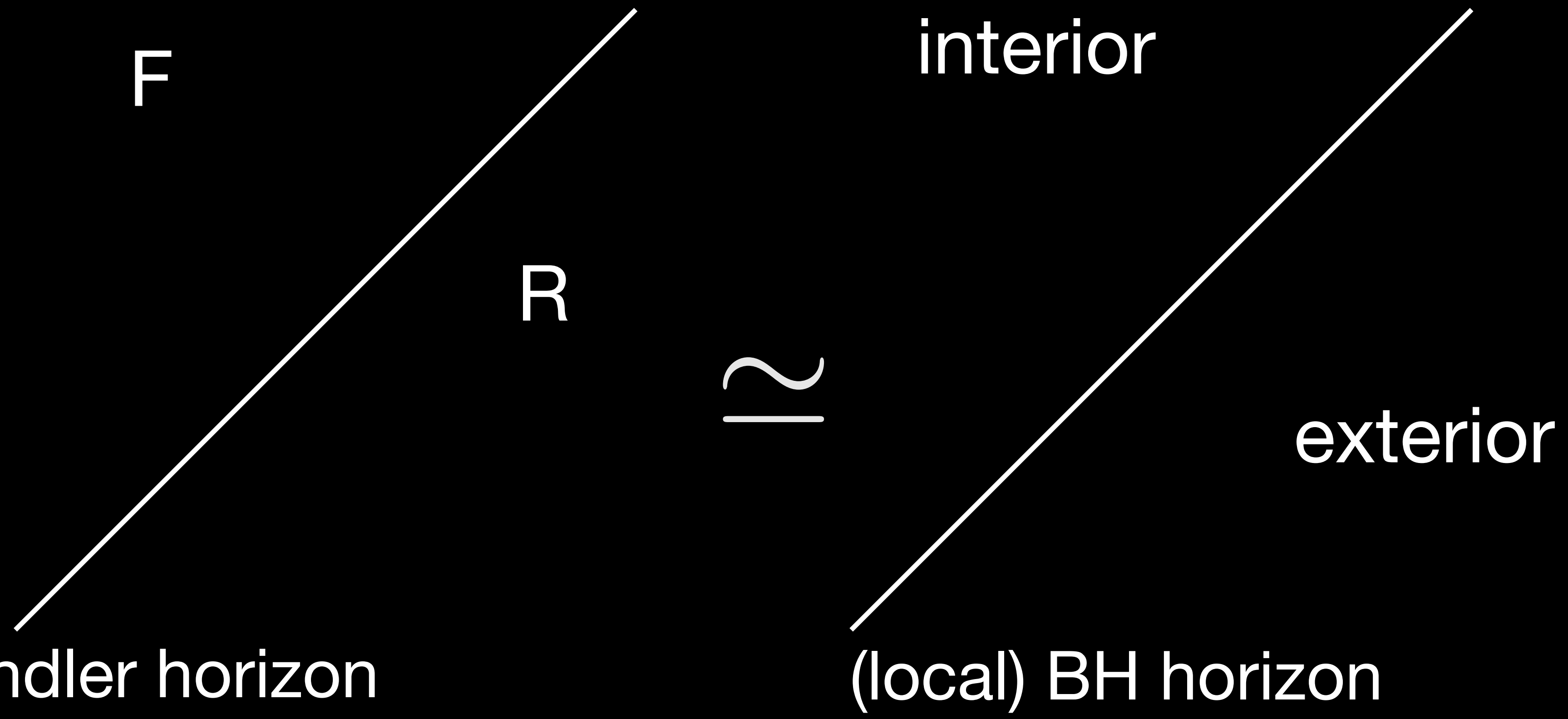
Boltzmann factor

$$T(a) \equiv \frac{a}{2\pi}$$





Lindler horizon $\simeq$ a two-level system



F

R

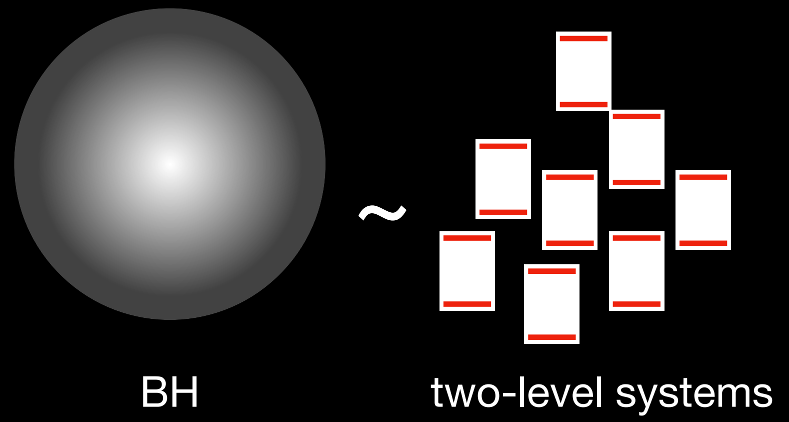
interior

$\simeq$

exterior

Rindler horizon

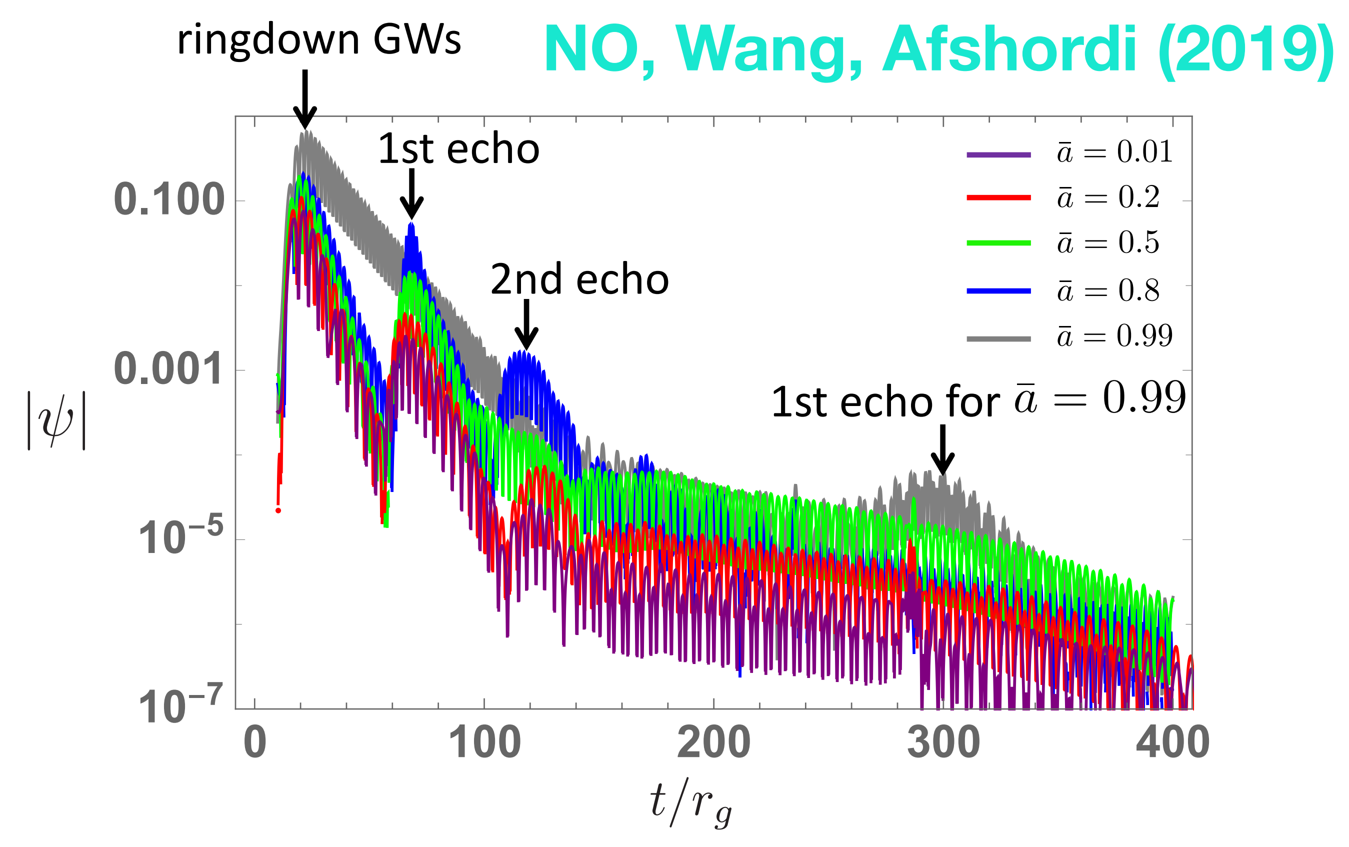
(local) BH horizon



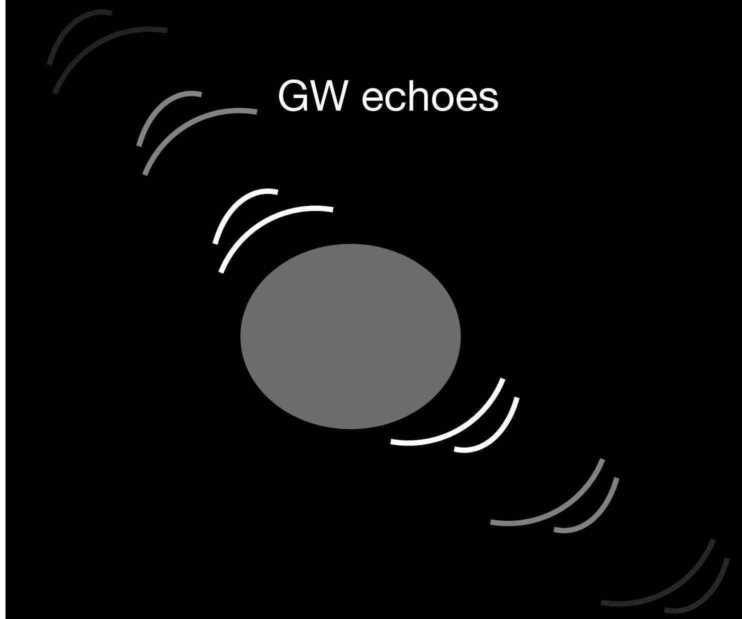
What if a BH horizon has its Boltzmann reflectivity?

GW echoes at late time

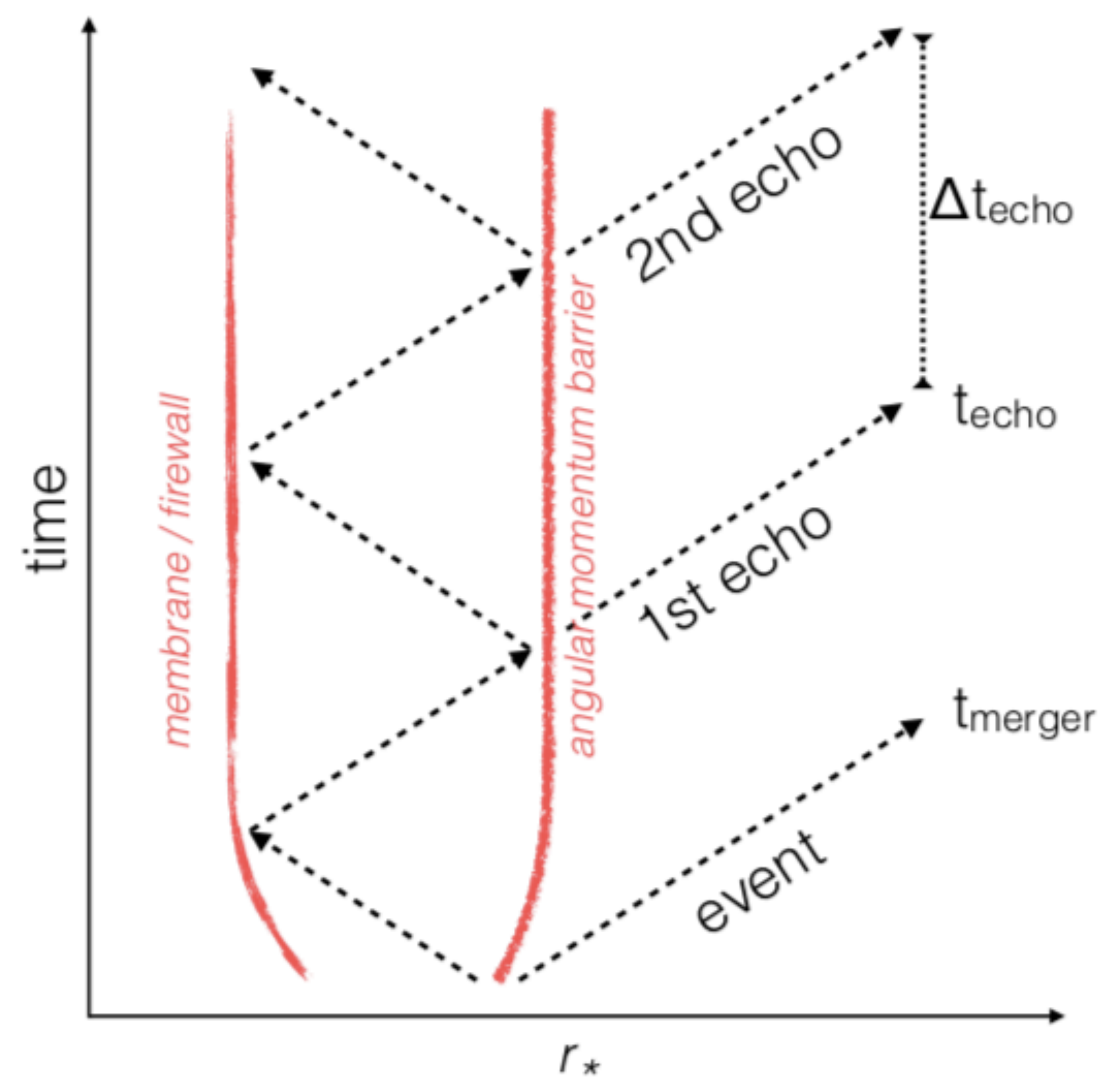
※ similar idea was out in 2019
[Gravitational wave echoes from black hole quantization]
Cardoso et al. (2019)



NO, Wang, Afshordi (2019)



Mechanism of GW-echo emission

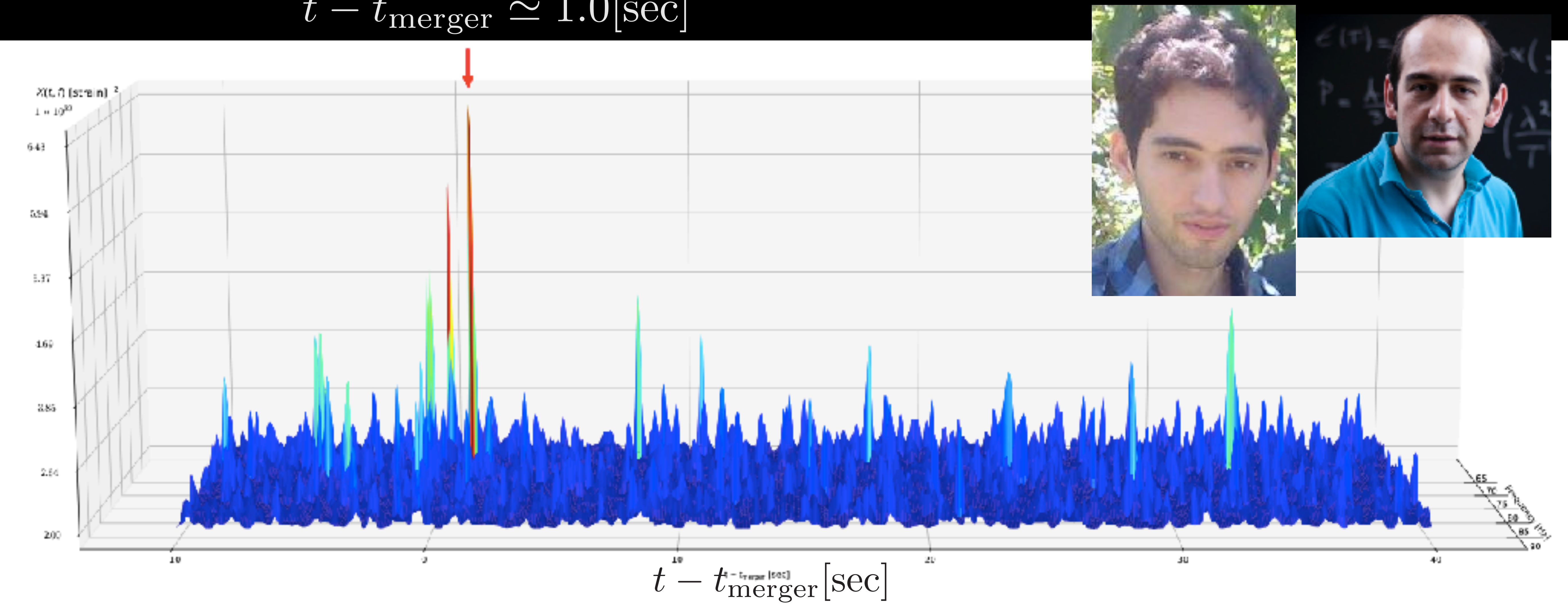


Abedi & Afshordi (2016)

Tentative detection of GW echoes

Abedi and Afshordi (2018)

$t - t_{\rm merger} \simeq 1.0[\rm sec]$



$t - t_{\rm merger}[\rm sec]$

Figure 4: A 3d rendition of Fig. (3) within our echo search frequency range $f = 63 - 92$ Hz, showing that our tentative detection of echoes at $f_{\rm peak} = 72\ (\pm 0.5)$ Hz and $t - t_{\rm merger} \simeq 1.0$ sec clearly stands above noise.

GW170817

binary neutron star mergers

tentative detection of GW echoes with 4.2σ

Third generation of GW detectors

Abedi, Afshordi, NO, Wang (2020)

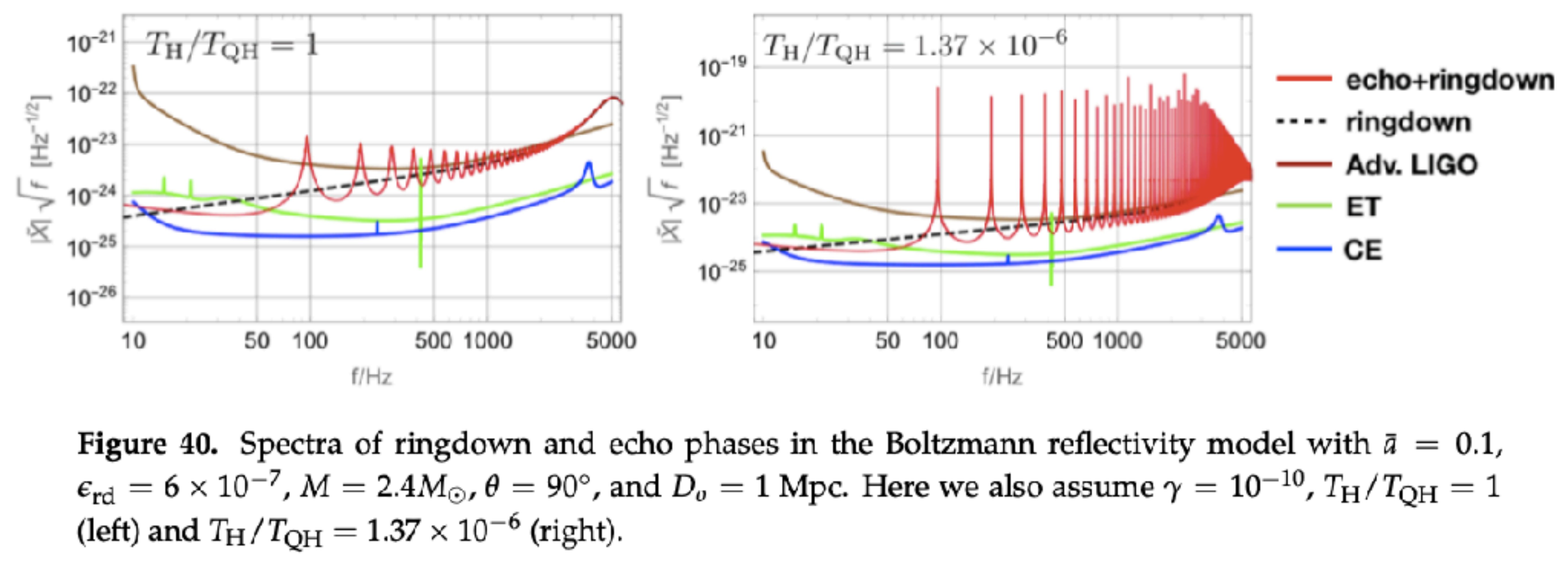
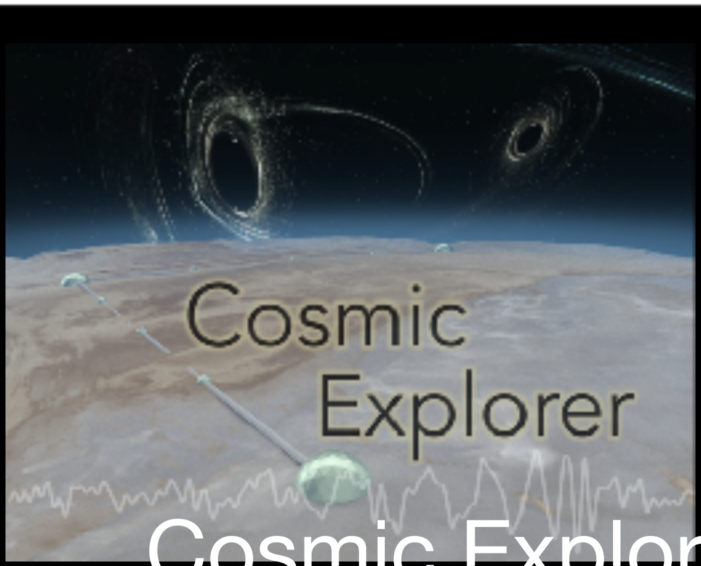
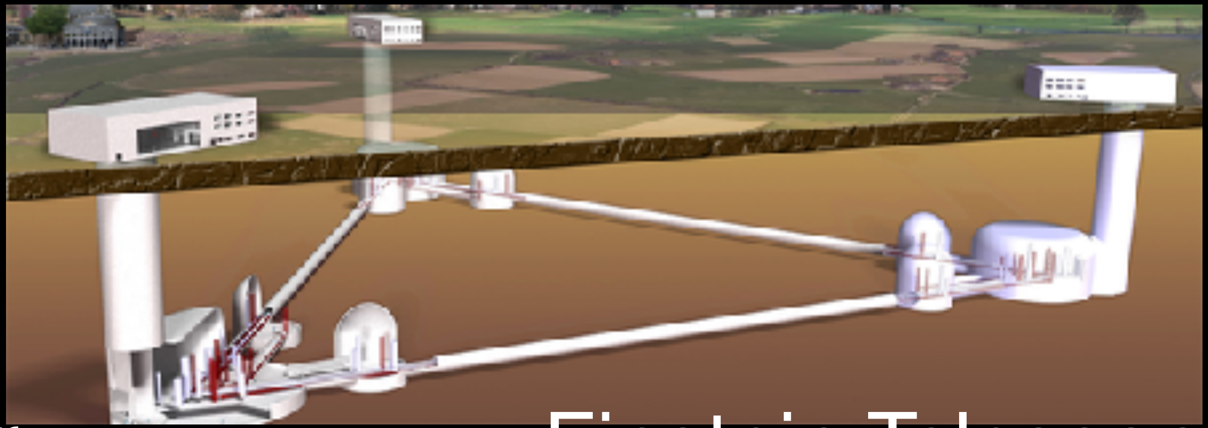


Figure 40. Spectra of ringdown and echo phases in the Boltzmann reflectivity model with $\bar{a} = 0.1$, $\epsilon_{\rm rd} = 6 \times 10^{-7}$, $M = 2.4 M_\odot$, $\theta = 90°$, and $D_o = 1$ Mpc. Here we also assume $\gamma = 10^{-10}$, $T_{\rm H}/T_{\rm QH} = 1$ (left) and $T_{\rm H}/T_{\rm QH} = 1.37 \times 10^{-6}$ (right).

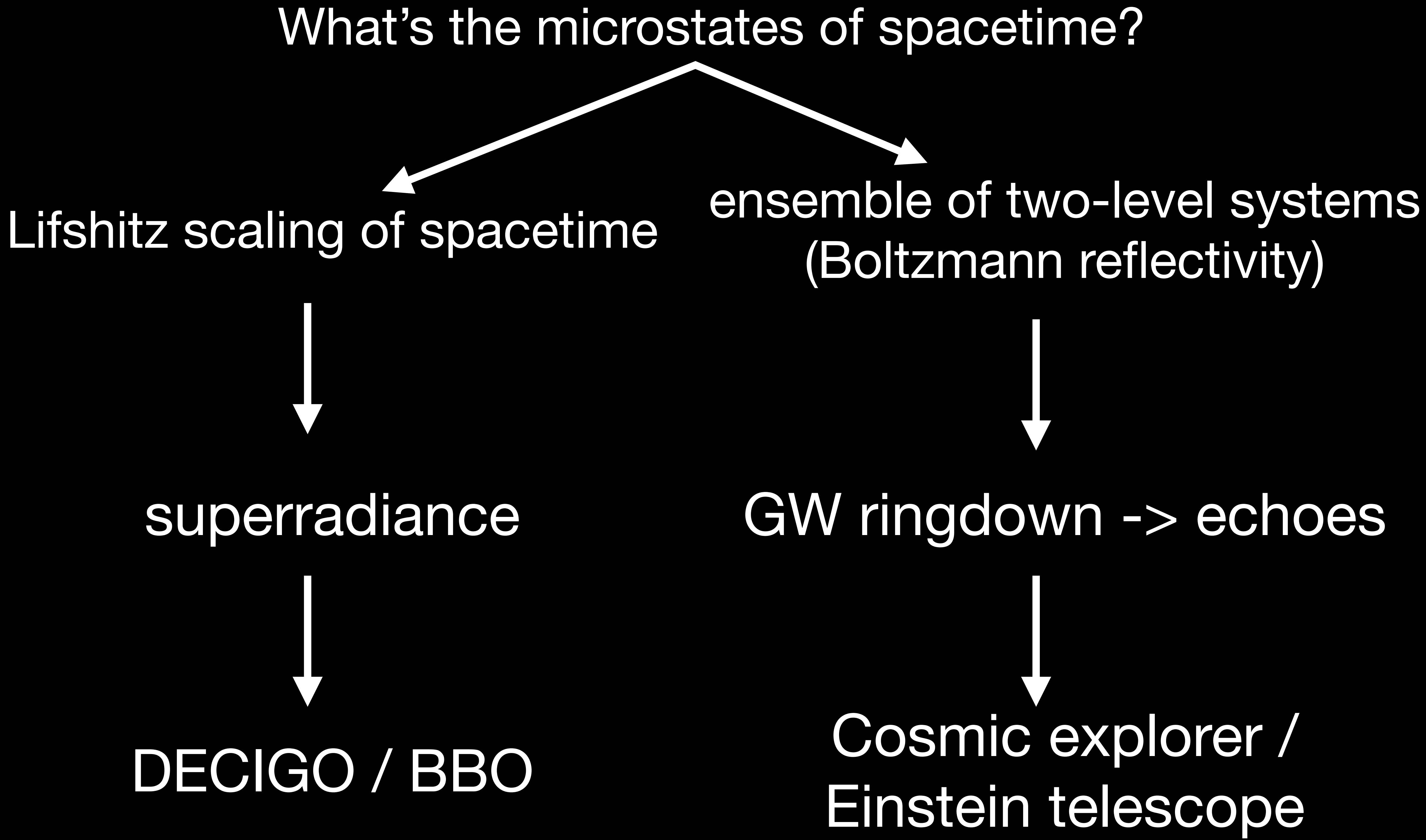


Cosmic Explorer



Einstein Telescope

$$|R|^2 = e^{-|\omega|/T_{\rm QH}}$$



What’s the microstates of spacetime?

Lifshitz scaling of spacetime

superradiance

DECIGO / BBO

ensemble of two-level systems
(Boltzmann reflectivity)

GW ringdown -> echoes

Cosmic explorer /
Einstein telescope

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BH spectroscopy and CFT thermal state

Ongoing work

BH spectroscopy and CFT thermal state

$$\left[\frac{\partial^2}{\partial r^{*2}} + \omega^2 - V(r)\right]\psi_\omega(r^*) = 0$$

Boundary condition

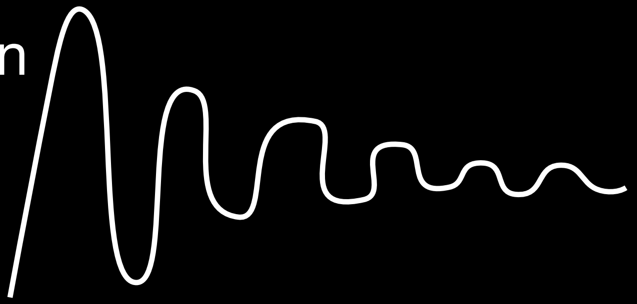
$$\psi_\omega(r^*) \begin{cases} \to \exp\left(-i\omega_n r^*\right) & (r^* \to -\infty) \\ \to \exp\left(+i\omega_n r^*\right) & (r^* \to +\infty) \end{cases}$$

Nunez et al. (2003)

Poles of the retarded correlators of the thermal $\mathcal{N}=4$ SYM theory operators ⟷ ω_n: nth-quasinormal mode (QNM) frequency

testable!!

Dissipation for quasiparticle excitations in the finite temperature gauge theory ⟷ GW ringdown

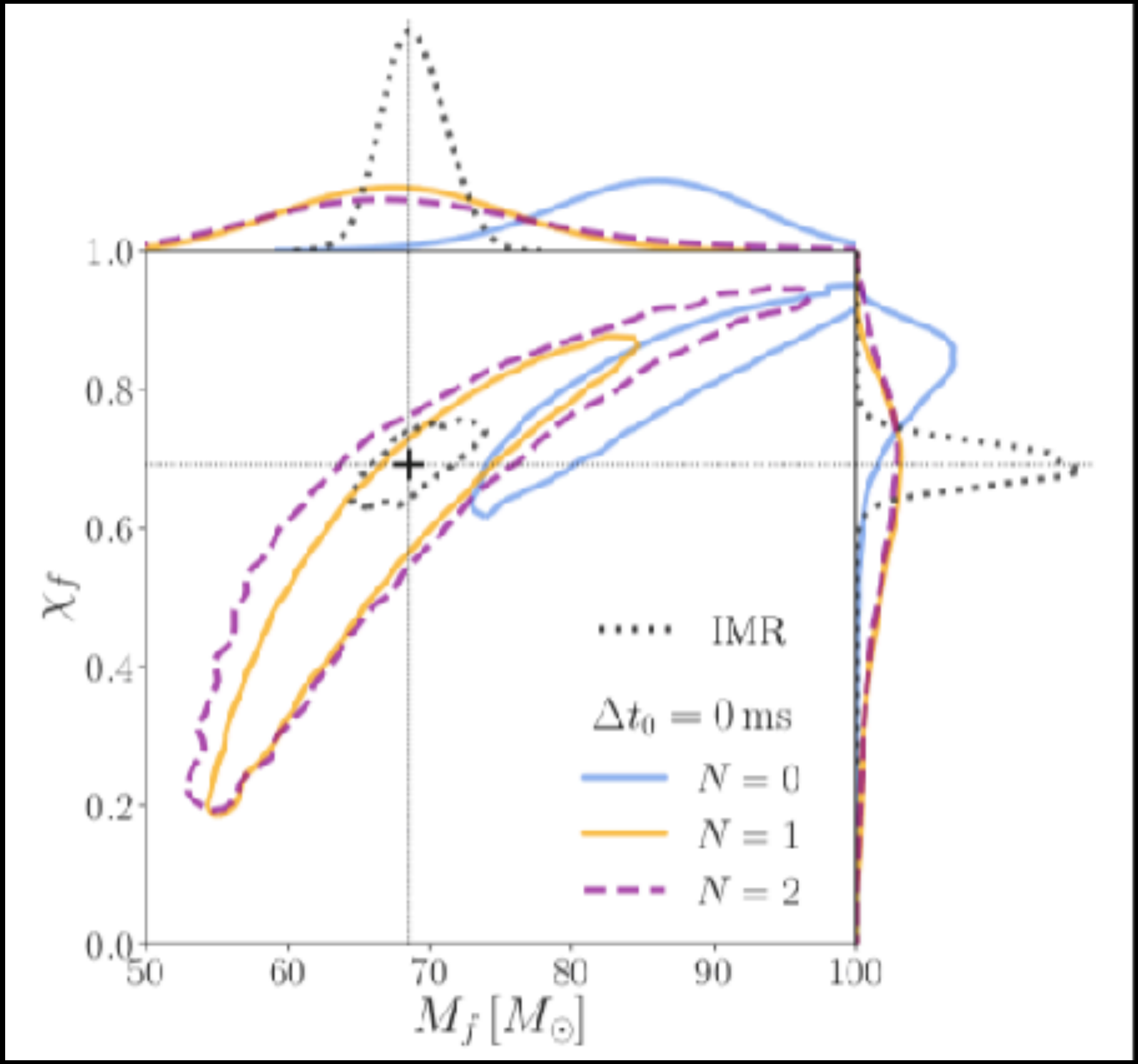


$$e^{-i\omega_n t} = \underset{\text{dissipation}}{e^{\mathrm{Im}[\omega_n]t}}\,\underset{\text{oscillation}}{e^{-i\mathrm{Re}[\omega_n]t}}$$

Testing the no-hair theorem with GW150914

Isi et al. (2019)

QNM frequency depends on the mass and spin only!!! (no-hair theorem)



QNMs are characterized by

1. frequency ω_n
2. Excitation factor B_n

(quantify the ease-of-excitation of QNMs)

CFT | Bulk

Ease-of-excitation of quasiparticles in thermal gauge theory? ↔ B_n for 5d Kerr-AdS

Role of gravitational entropy in cosmology

Phase transition or tunneling process in strong gravity
=> decay rate is governed by the change of Bekenstein-Hawking entropy

gravitational entropy plays an important role for putting constraints on cosmological models and Standard Model.

What is the origin of gravitational entropy?

Future GW observations (ET, CE, DECIGO, BBO,….)
are very important to probe the microstructure of spacetime

BH spectroscopy and CFT thermal state

no-hair nature of QNMs is testable

QNM frequencies <==> dissipation of quasiparticles in thermal gauge theory

QNM excitation factors <==> ease-of-excitation of quasiparticles
in thermal gauge theory??

Why superradiance?

[NO, Afshordi, Mukohyama (2021)]

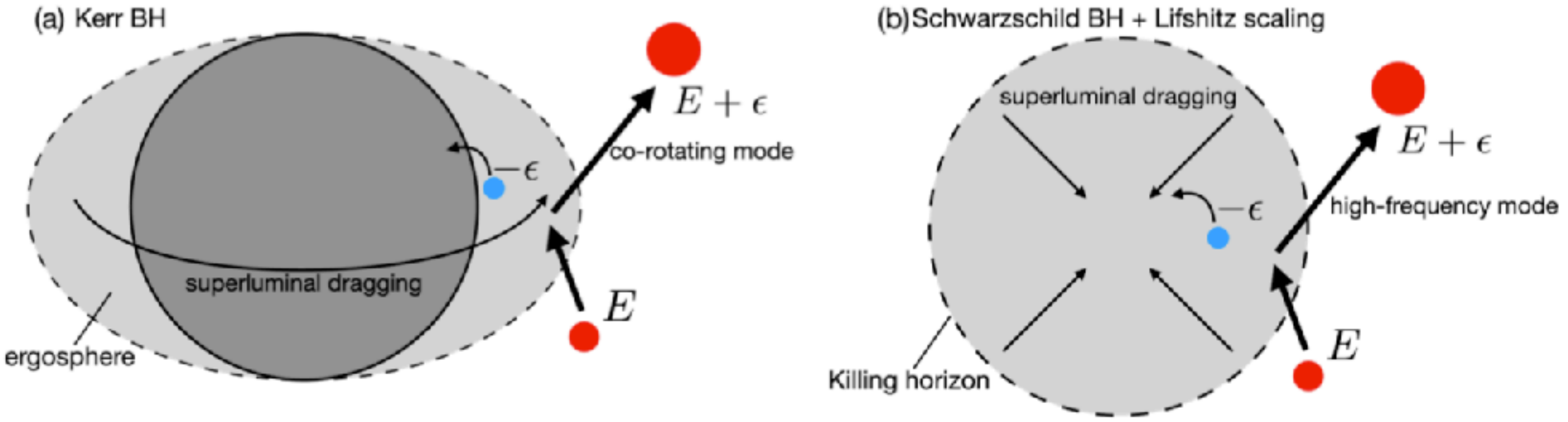
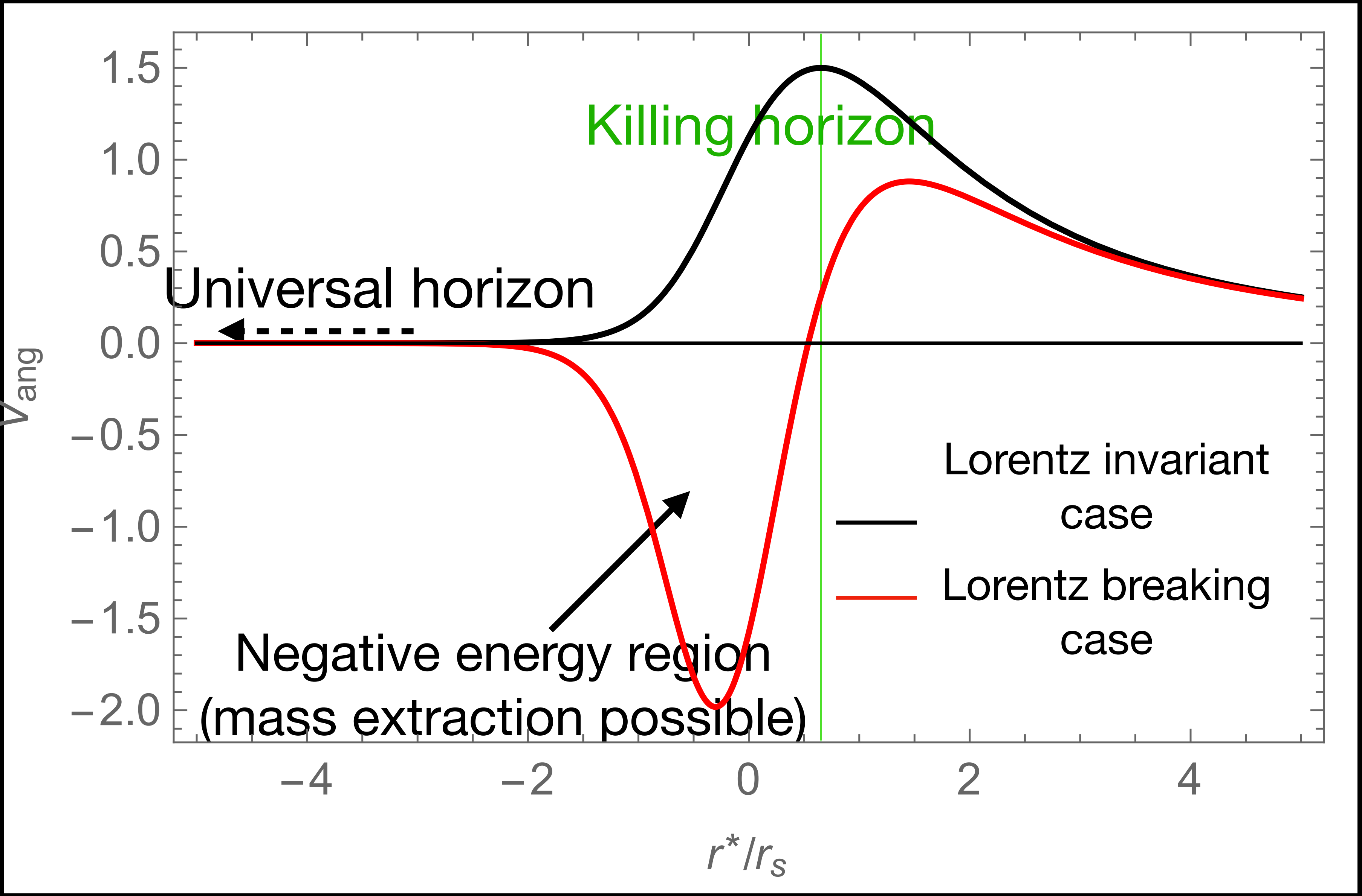


Figure 1. A schematic picture showing the superradiant scattering around (a) a Kerr black hole and (b) Schwarzschild black hole with a Lifshitz field. The negativity of energy is allowed in the region where spacetime is superluminally dragged such as the ergosphere of a Kerr black hole or the interior of Killing horizon of a Schwarzschild black hole. Therefore, modes leaving from such a region can carry out additional positive energy to infinity while leaving negative energy there. This is nothing but the superradiance effect.

Why superradiance? -What causes the SR?-

$$\Xi_4 = 0.1 \quad \Xi_6 = 0.01 \quad c_\chi = 0$$



Kerr spacetime: positive (rotational) energy extraction at ergosphere

Schwarzschild with the Lifshitz scaling: Positive (mass) energy extraction near the horizon