Title: Quantum Black Hole Seismology

Speakers: Naritaka Oshita

Collection: Echoes in Southern Ontario

Date: February 24, 2020 - 9:30 AM

URL: http://pirsa.org/20020085

Echoes in Southern Ontario @ Perimeter Institute, 24th, February, 2020

Quantum Black Hole Seismology

Naritaka Oshita
(Perimeter Institute, JSPS fellowship)

Collaborators:
Niayesh Afshordi (PI, UW), Daichi Tsuna (U of Tokyo, LIGO), Qingwen Wang (PI, UW)

N.O., D. Tsuna, and N. Afshordi (2020), arXiv: 2001.11642
Q. Wang, N.O., and N. Afshordi (2019), arXiv: 1905.00446
N.O., Q. Wang, and N. Afshordi (2019), arXiv: 1905.00464
N.O. and N. Afshordi (2018), arXiv: 1807.10287

Quantum BHs

Thermal excitation of quantum fields around a BH

→ Hawking radiation

→ BH information loss paradox

→ stretched horizons, quantized BH area etc…

Quantum BHs has been discussed mainly in the theoretical side.
There are several predictions & conjectures in the literature.

Quantum BHs

Thermal excitation of quantum fields around a BH

→ Hawking radiation

→ BH information loss paradox

→ stretched horizons, quantized BH area etc…

Quantum BHs has been discussed mainly in the theoretical side.
There are several predictions & conjectures in the literature.

How we can observationally probe the quantum properties of BH ?

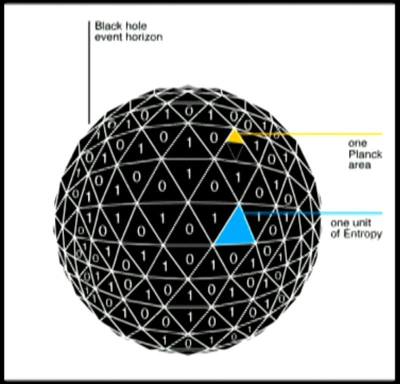
How about Hawking radiation ?

$M = M_\odot$

$$T_H \sim 10^{-6}\ \mathrm{K} \ll T_{\mathrm{CMB}} \simeq 2.7\ \mathrm{K}$$

How about the Planck size structure of space?

To reach the Planck scale with a particle accelerator, its size should be comparable to the solar system.

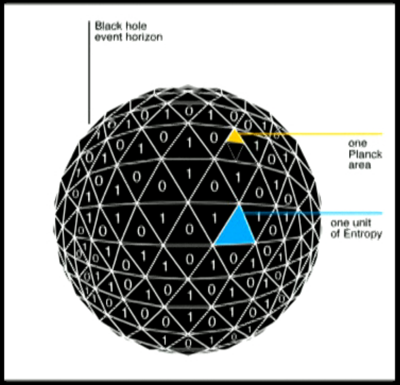


How about Hawking radiation ?

$$T_H \sim 10^{-6}\ \mathrm{K} \ll T_{\mathrm{CMB}} \simeq 2.7\ \mathrm{K}$$

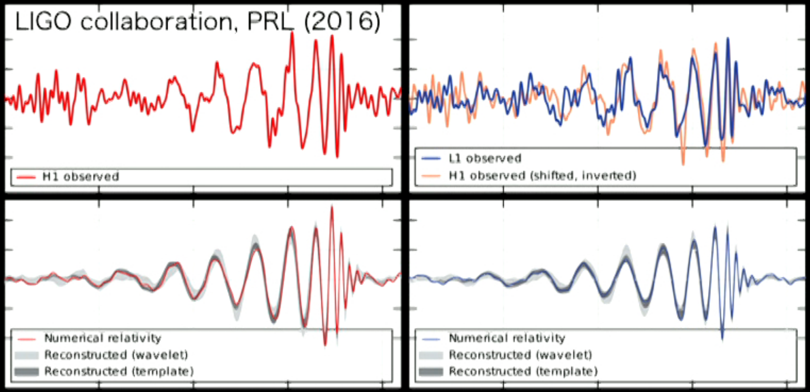
How about the Planck size structure of space?

To reach the Planck scale with a particle accelerator, its size should be comparable to the solar system.

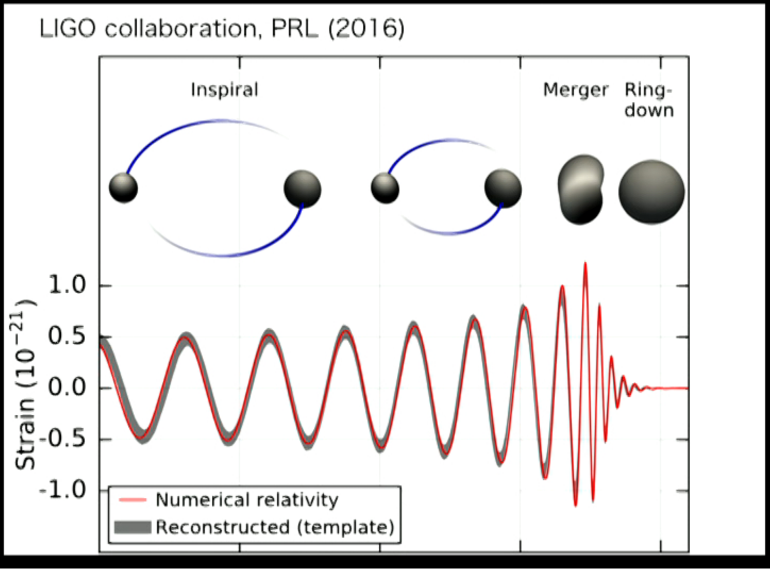


Ringdown GWs tell us about the horizon structure.

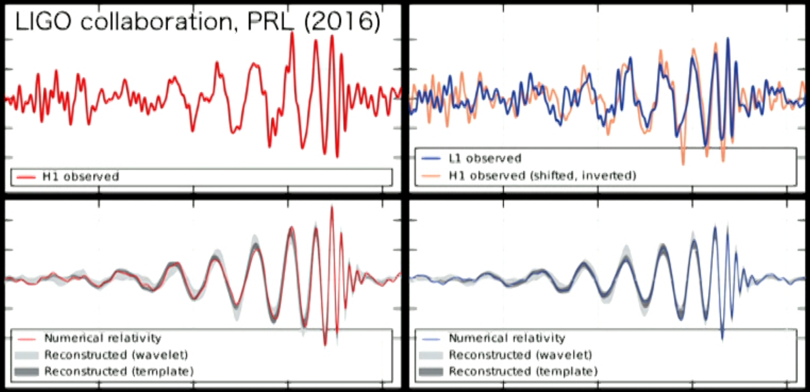
GWs from a BH binary


LIGO collaboration, PRL (2016)

GW150914
(the first detection of GWs by LIGO)

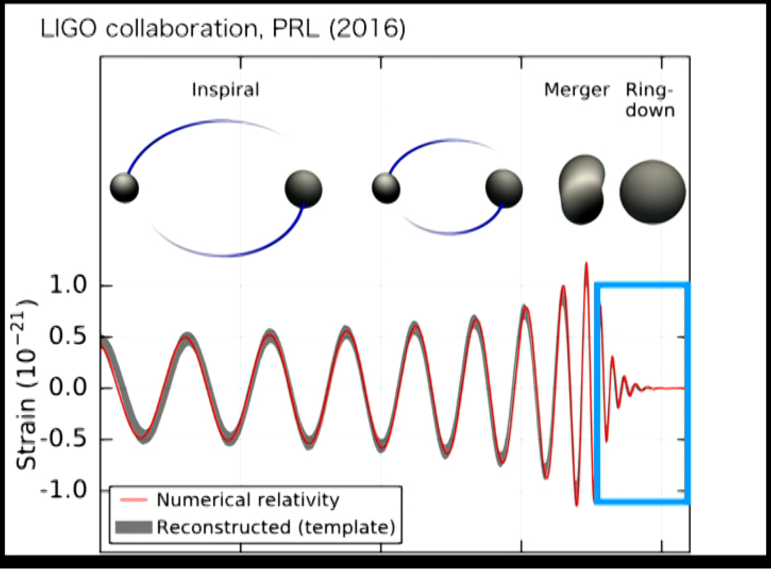

LIGO collaboration, PRL (2016)

GWs from a BH binary



LIGO collaboration, PRL (2016)

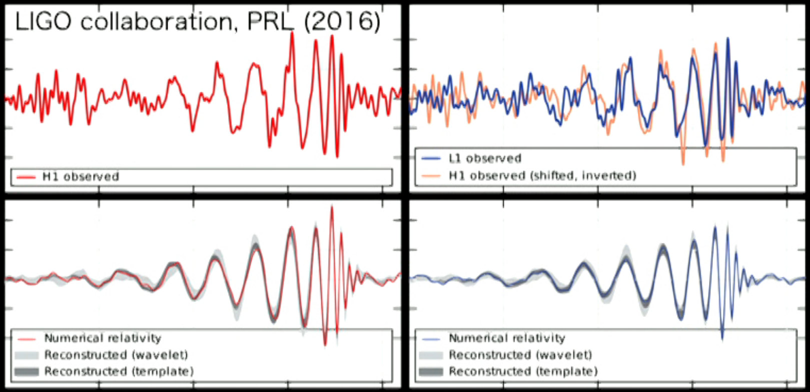
GW150914
(the first detection of GWs by LIGO)



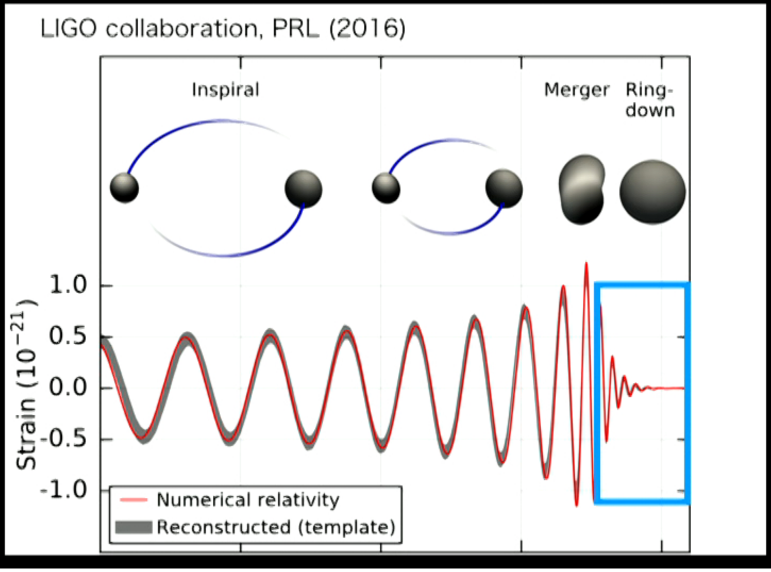
LIGO collaboration, PRL (2016)

- ringdown GWs consists of quasi-normal modes (QNMs)

GWs from a BH binary


LIGO collaboration, PRL (2016)

GW150914
(the first detection of GWs by LIGO)

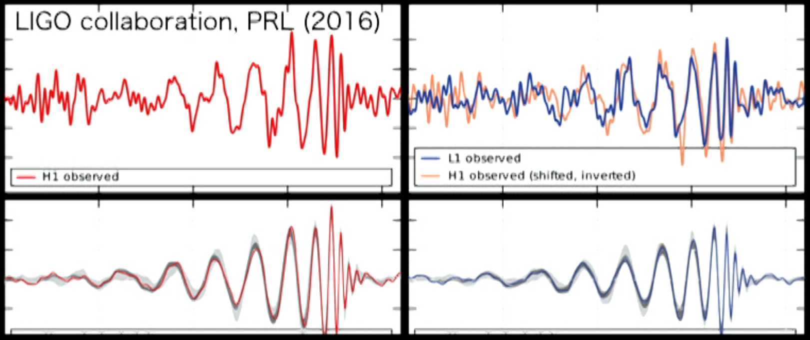

LIGO collaboration, PRL (2016)

- ringdown GWs consists of quasi-normal modes (QNMs)
- QNMs depends only on its mass and angular momentum

⬇

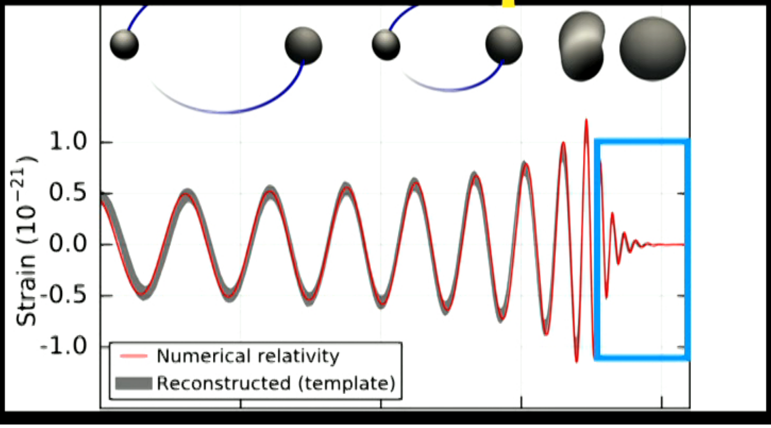
observation of ringdown GWs is useful to test gravity theories.

GWs from a BH binary



GW150914
(the first detection of GWs by LIGO)

ringdown GWs may be useful to test quantum gravity

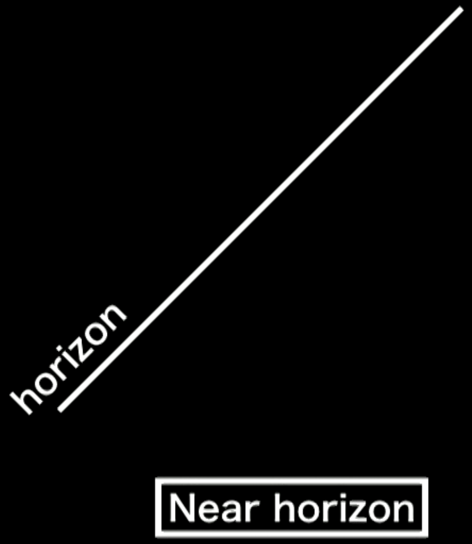


- QNMs depends only on its mass and angular momentum

observation of ringdown GWs is useful to test gravity theories.

Hawking radiation is observer-dependent.

Hawking effect

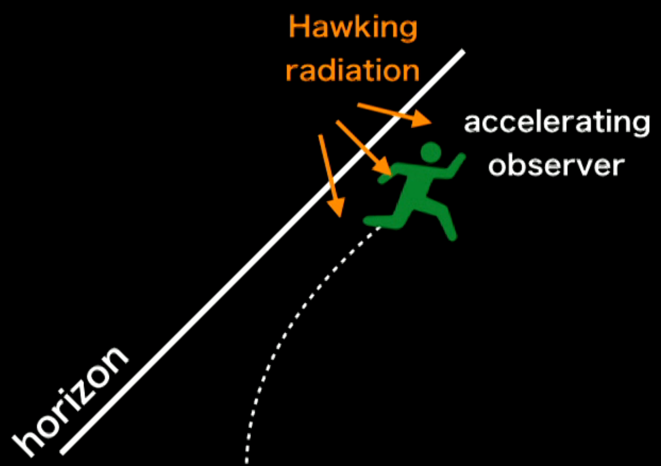


Unruh effect

Hawking radiation is observer-dependent.

Hawking effect

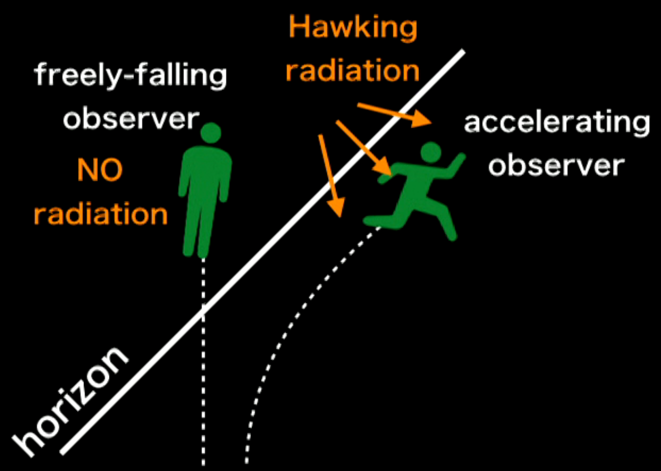
Unruh effect



Near horizon

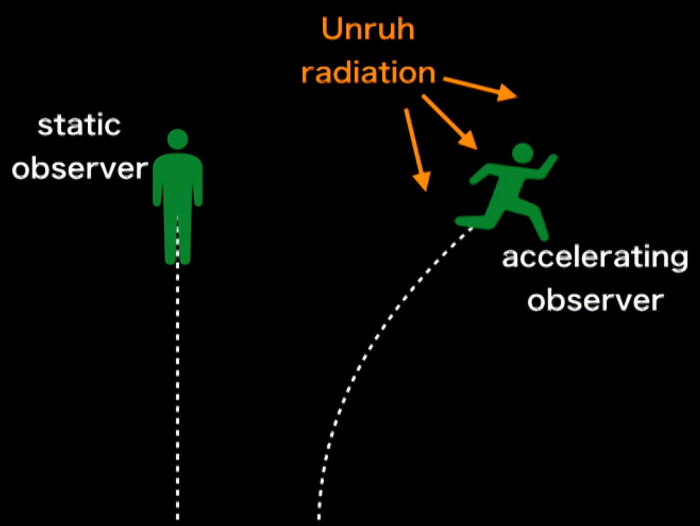
Hawking radiation is observer-dependent.

Hawking effect



Near horizon

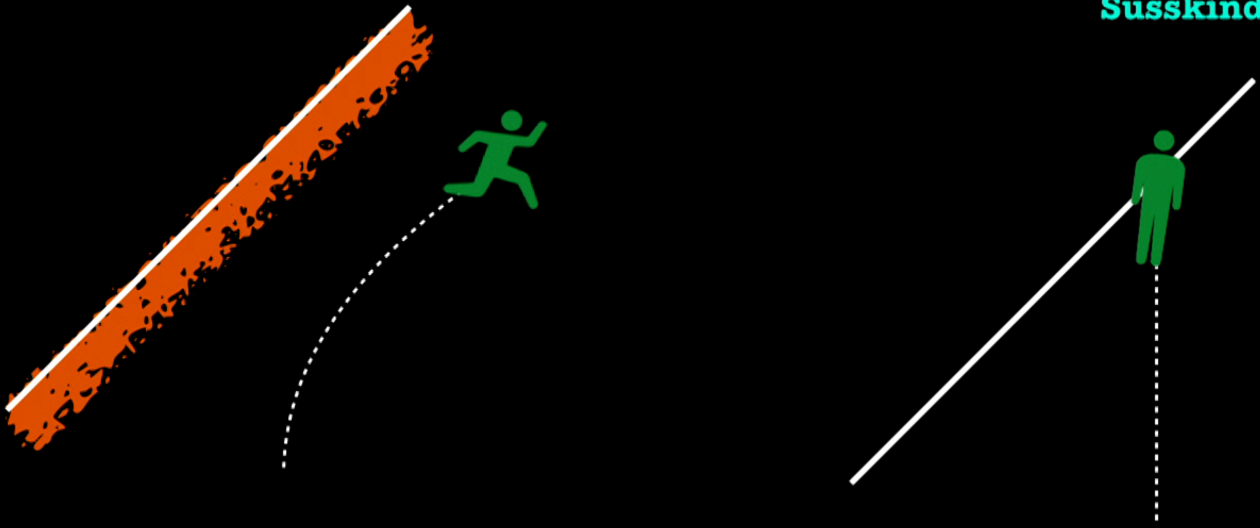
Unruh effect



Minkowski space

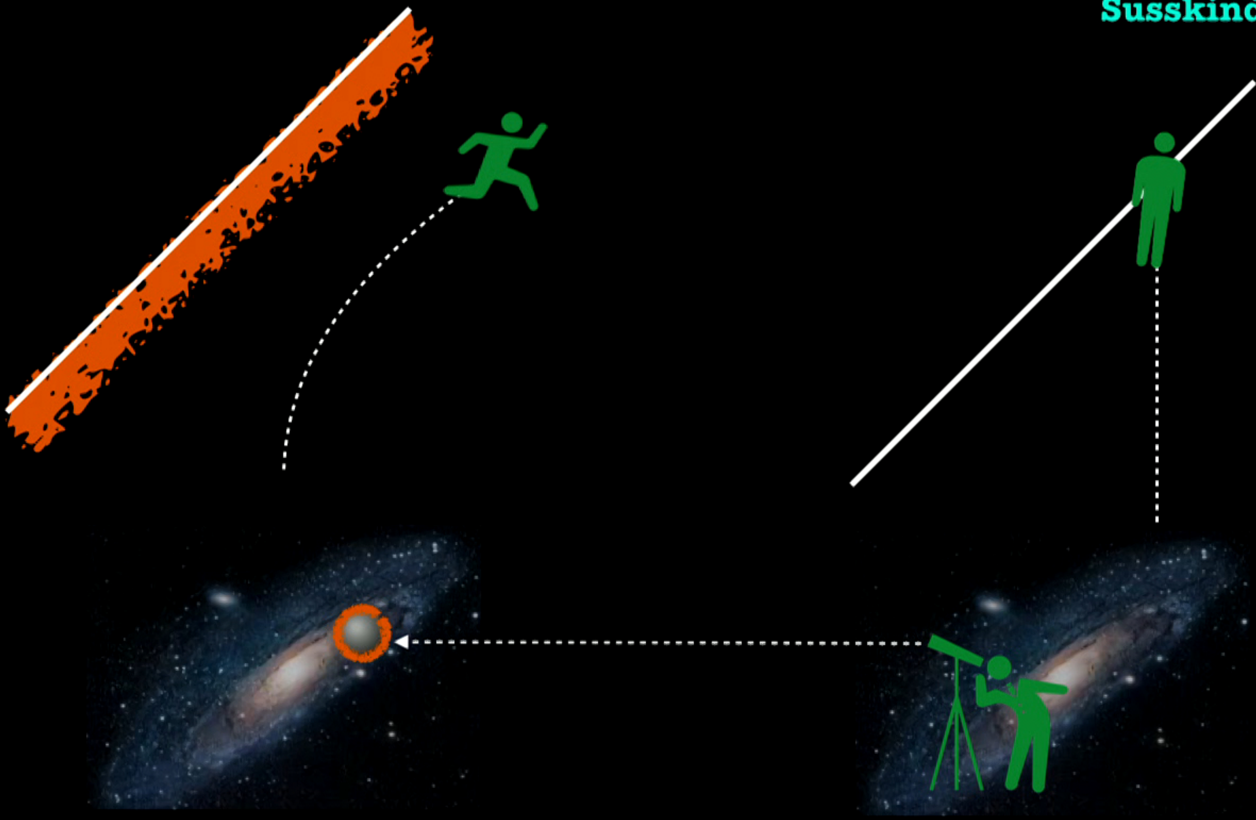
stretched horizon is observer-dependent

Susskind+ (1993)



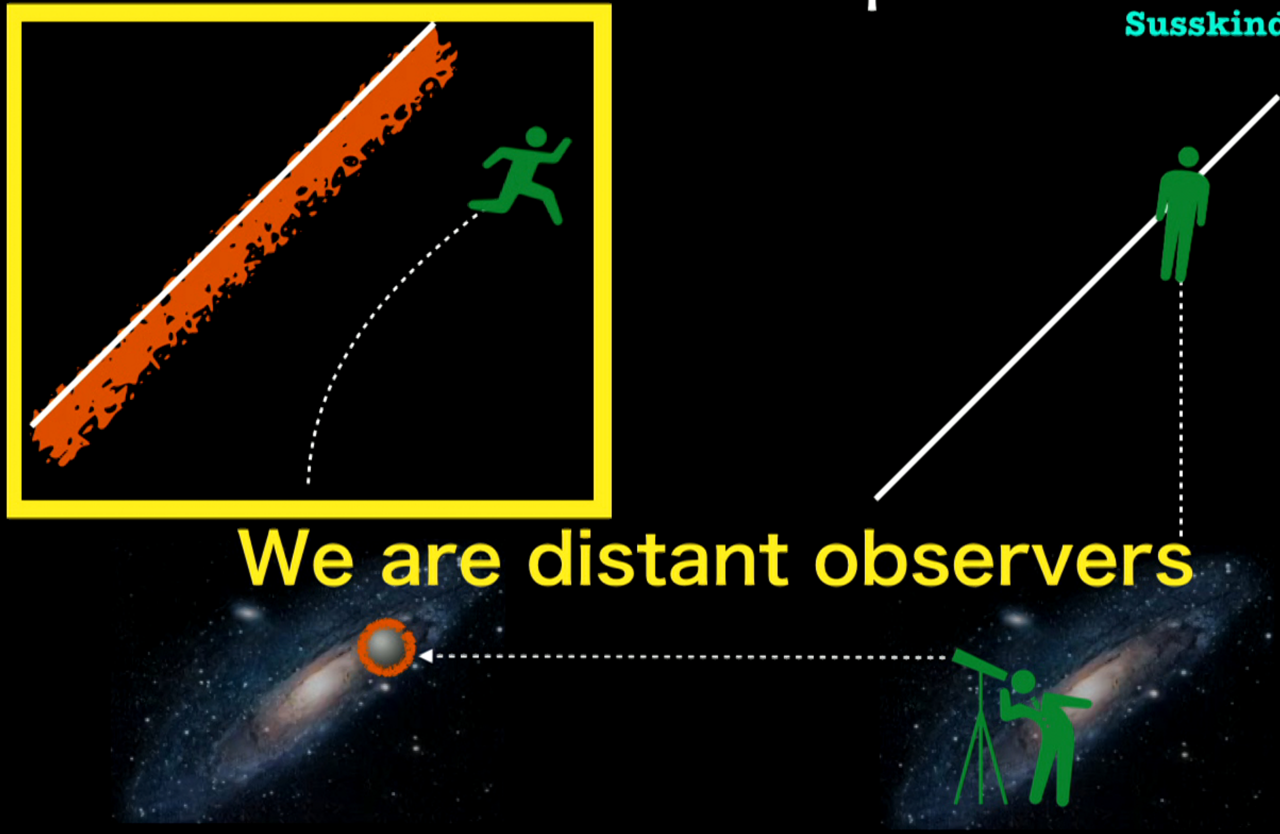
stretched horizon is observer-dependent

Susskind+ (1993)



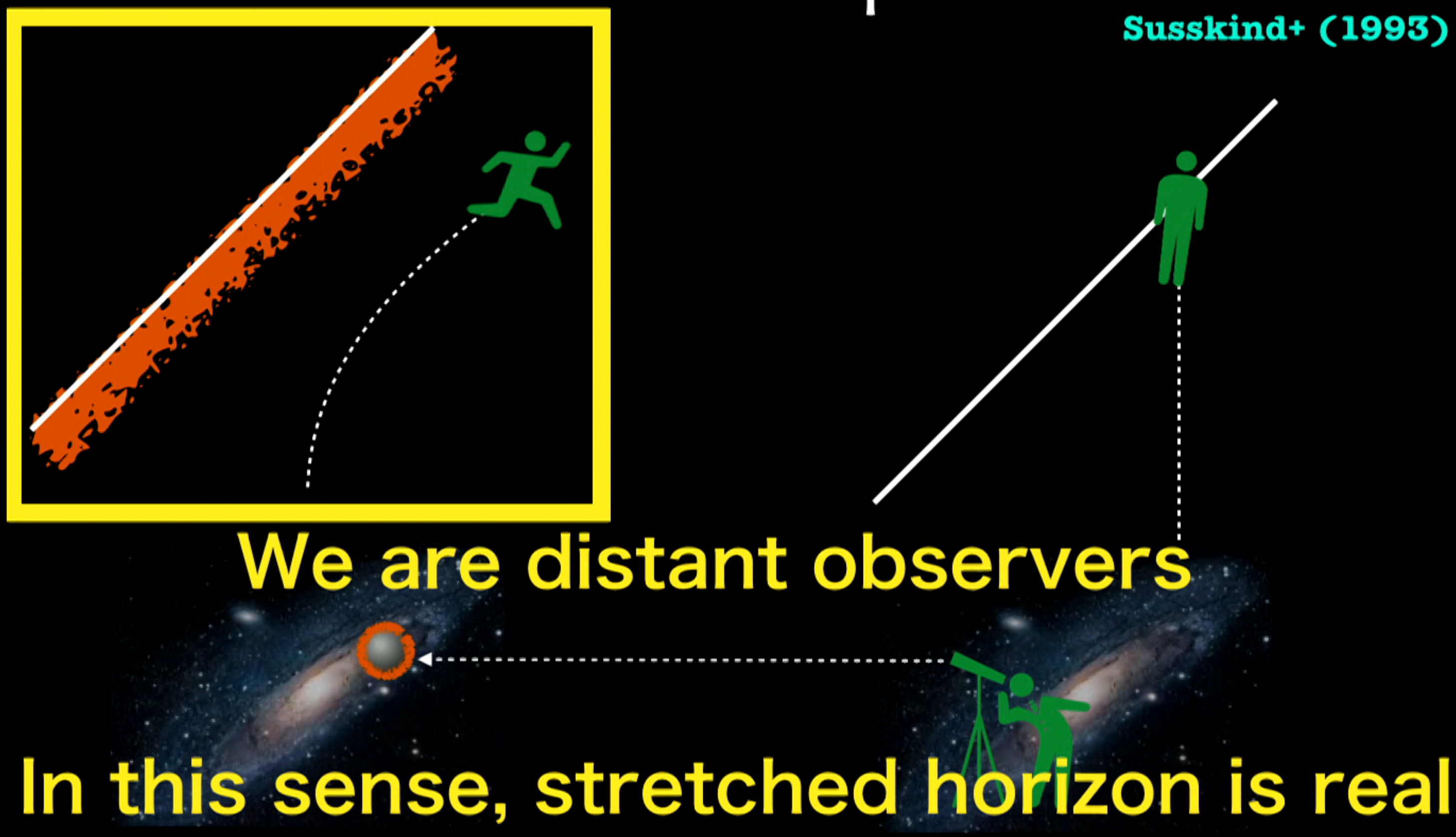
stretched horizon is observer-dependent

Susskind+ (1993)



We are distant observers

stretched horizon is observer-dependent



Susskind+ (1993)

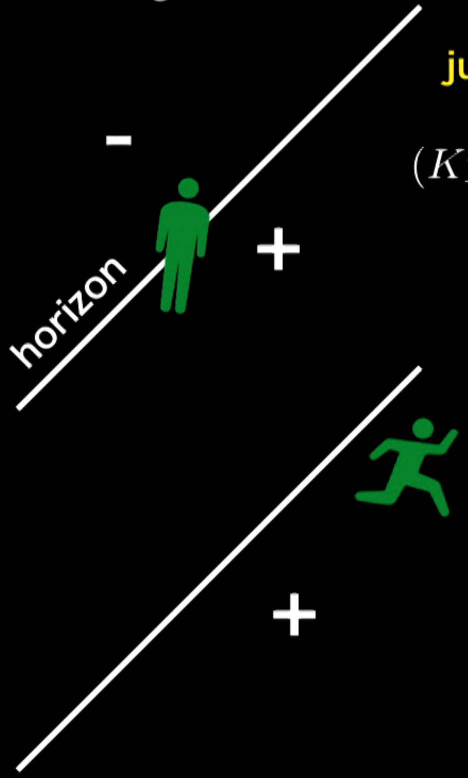
We are distant observers

In this sense, stretched horizon is real !!

membrane paradigm

K. Thorne+ (1986)

According to a distant observer, BH horizons behave like **viscous fluid**.



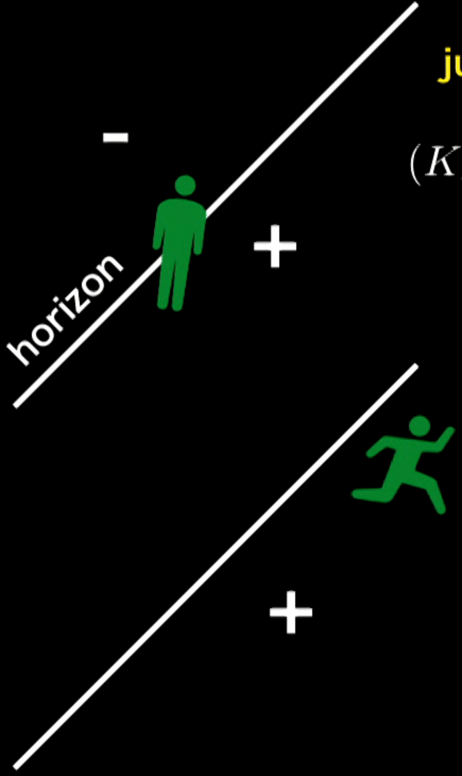
junction between the interior and exterior

$$(K_{+}^{AB} - K_{+}h^{AB}) - (K_{-}^{AB} - K_{-}h^{AB}) = 8\pi T^{AB} = 0$$

membrane paradigm

K. Thorne+ (1986)

According to a distant observer, BH horizons behave like **viscous fluid**.



junction between the interior and exterior

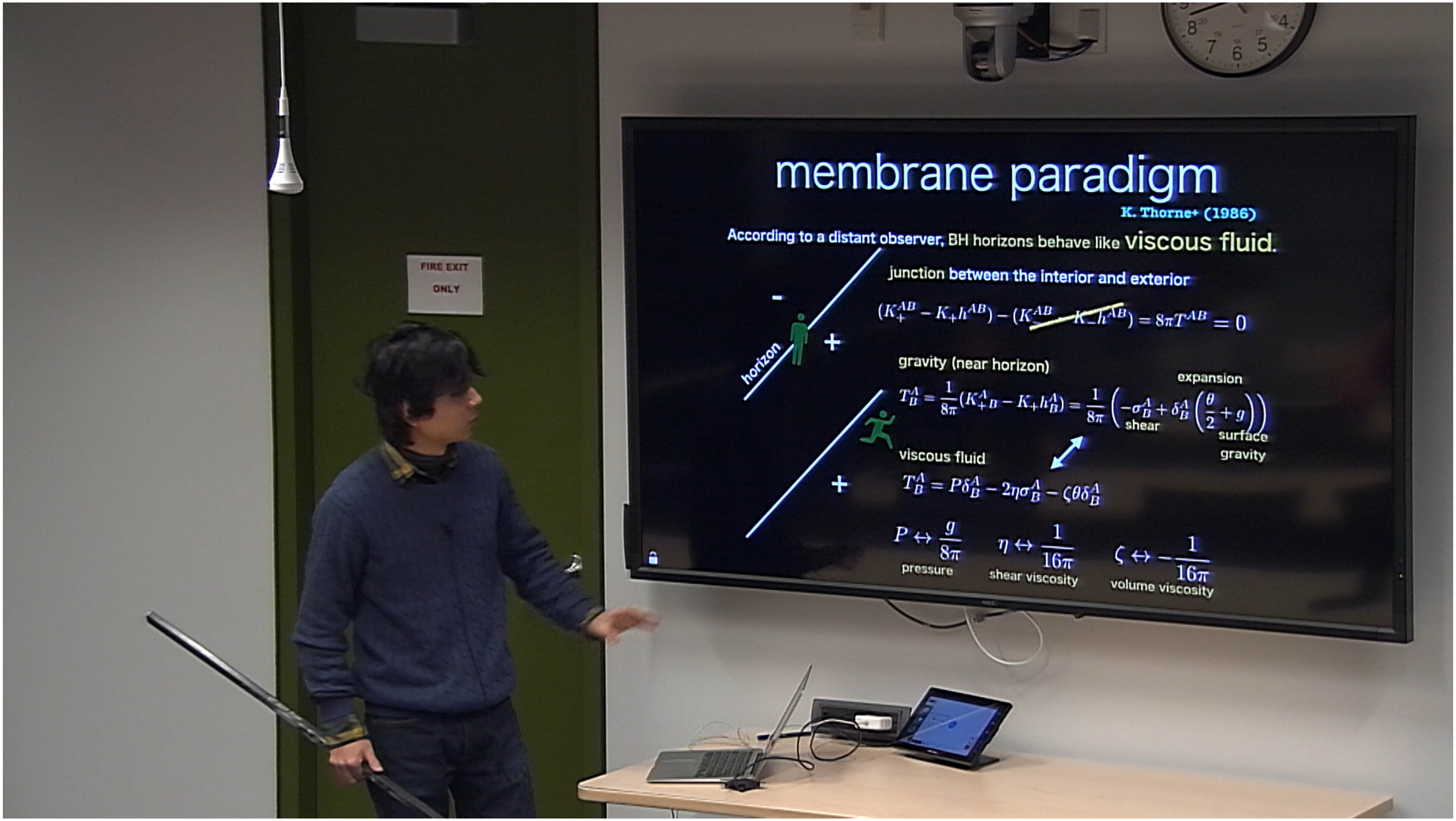
$$(K_+^{AB} - K_+ h^{AB}) - (\cancel{K_-^{AB} - K_- h^{AB}}) = 8\pi T^{AB} = 0$$

gravity (near horizon)

$$T^A_B = \frac{1}{8\pi}(K^A_{+B} - K_+ h^A_B) = \frac{1}{8\pi}\left(\underset{\text{shear}}{-\sigma^A_B} + \delta^A_B\left(\overset{\text{expansion}}{\frac{\theta}{2}} + \underset{\text{surface gravity}}{g}\right)\right)$$

viscous fluid

$$T^A_B = P\delta^A_B - 2\eta\sigma^A_B - \zeta\theta\delta^A_B$$



membrane paradigm

K. Thorne+ (1986)

According to a distant observer, BH horizons behave like **viscous fluid.**

junction between the interior and exterior

$$(K_+^{AB} - K_+ h^{AB}) - (\cancel{K_-^{AB} - K_- h^{AB}}) = 8\pi T^{AB} = 0$$

gravity (near horizon)

$$T^A_B = \frac{1}{8\pi}(K_+{}^A{}_B - K_+ h^A_B) = \frac{1}{8\pi}\left(\underset{\text{shear}}{-\sigma^A_B} + \delta^A_B\left(\overset{\text{expansion}}{\frac{\theta}{2}} + \underset{\text{surface gravity}}{g}\right)\right)$$

viscous fluid

$$T^A_B = P\delta^A_B - 2\eta\sigma^A_B - \zeta\theta\delta^A_B$$

$$\underset{\text{pressure}}{P \leftrightarrow \frac{g}{8\pi}} \qquad \underset{\text{shear viscosity}}{\eta \leftrightarrow \frac{1}{16\pi}} \qquad \underset{\text{volume viscosity}}{\zeta \leftrightarrow -\frac{1}{16\pi}}$$

Modeling viscous membrane

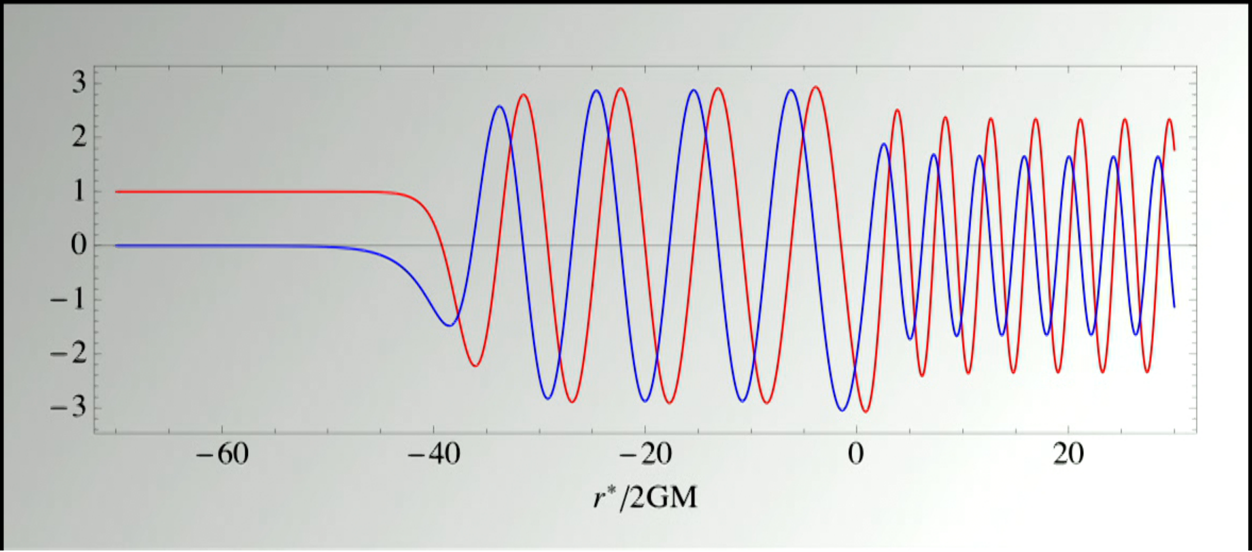
viscosity

blue-shifted frequency

classical general relativity

$$\left[-i\frac{\gamma\Omega}{E_{\mathrm{Pl}}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

Planck energy



Modeling viscous membrane

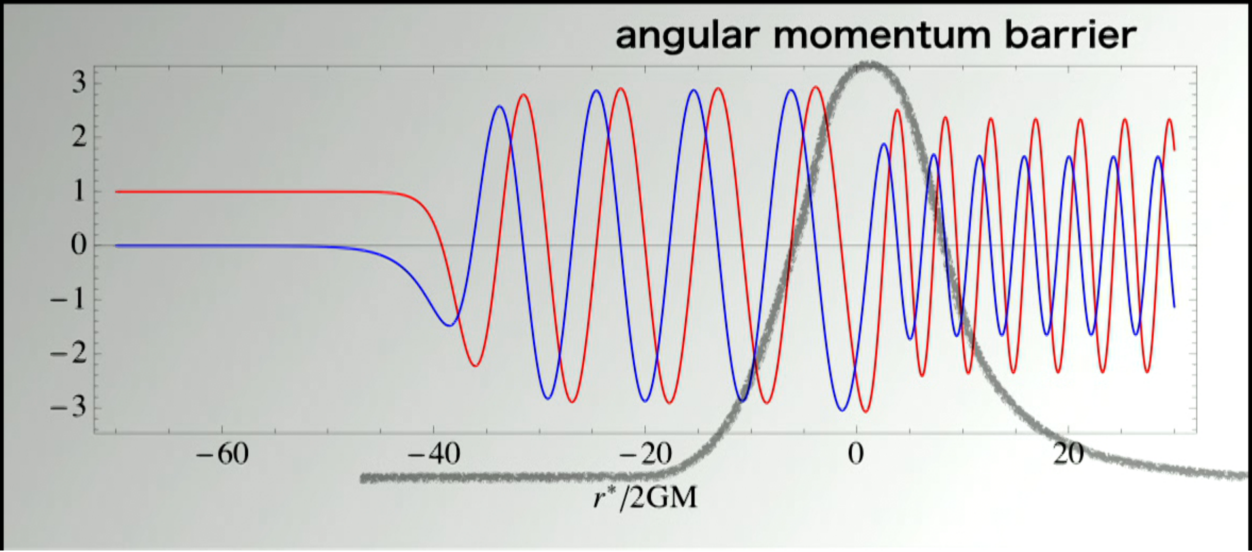
viscosity

blue-shifted frequency

classical general relativity

$$\left[-i\frac{\gamma\Omega}{E_{\rm Pl}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

Planck energy



Modeling viscous membrane

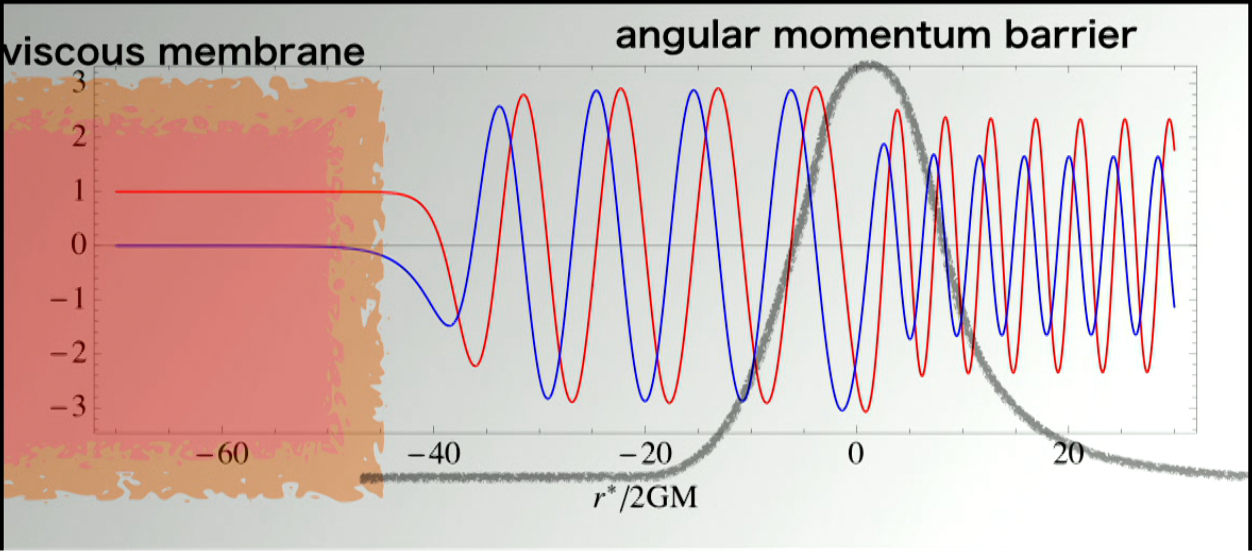
viscosity

blue-shifted frequency

classical general relativity

$$\left[-i\frac{\gamma\Omega}{E_{\rm Pl}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

Planck energy



Modeling viscous membrane

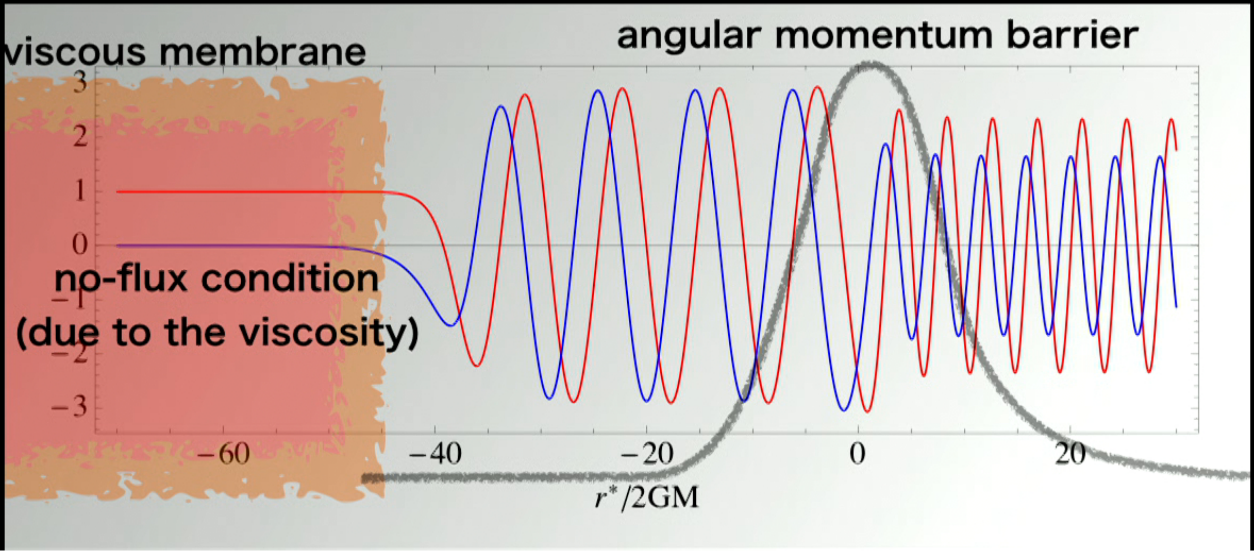
viscosity

blue-shifted frequency

classical general relativity

$$\left[-i\frac{\gamma\Omega}{E_{\mathrm{Pl}}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

Planck energy



Modeling viscous membrane

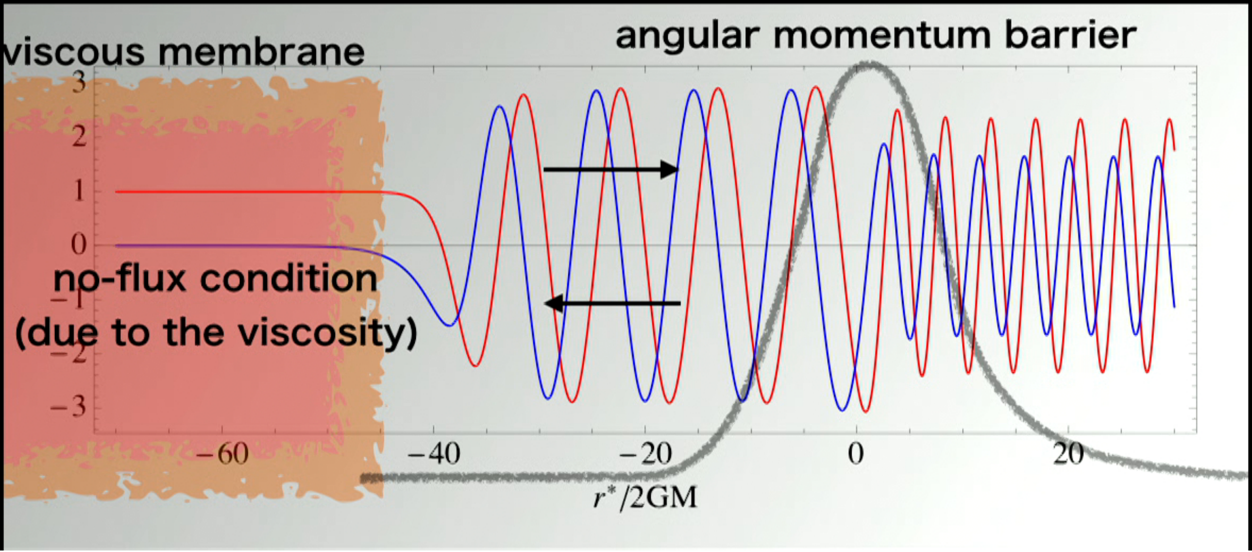
viscosity

blue-shifted frequency

classical general relativity

$$\left[-i\frac{\gamma\Omega}{E_{\rm Pl}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

Planck energy



no-flux condition (due to the viscosity)

Boltzmann reflection from the membrane

$$\left[-i\frac{\gamma\Omega}{E_{\mathrm{Pl}}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

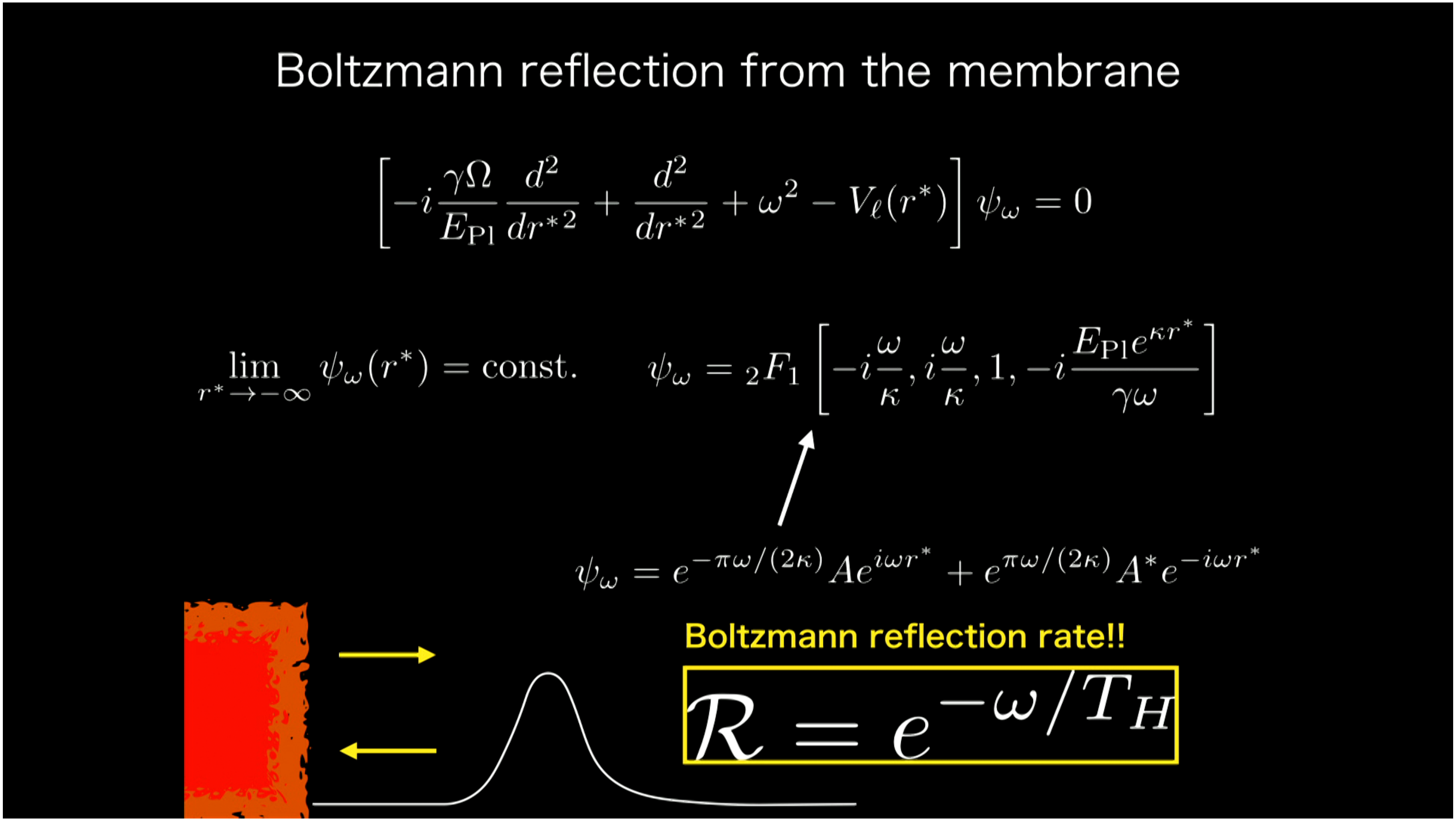
$$\lim_{r^*\to-\infty}\psi_\omega(r^*)=\mathrm{const.}\qquad \psi_\omega={}_2F_1\left[-i\frac{\omega}{\kappa},i\frac{\omega}{\kappa},1,-i\frac{E_{\mathrm{Pl}}e^{\kappa r^*}}{\gamma\omega}\right]$$

Boltzmann reflection from the membrane

$$\left[-i\frac{\gamma\Omega}{E_{\mathrm{Pl}}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

$$\lim_{r^*\to-\infty}\psi_\omega(r^*)=\mathrm{const.}\qquad \psi_\omega={}_2F_1\left[-i\frac{\omega}{\kappa},i\frac{\omega}{\kappa},1,-i\frac{E_{\mathrm{Pl}}e^{\kappa r^*}}{\gamma\omega}\right]$$

$$\psi_\omega=e^{-\pi\omega/(2\kappa)}Ae^{i\omega r^*}+e^{\pi\omega/(2\kappa)}A^*e^{-i\omega r^*}$$



Boltzmann reflection from the membrane

$$\left[-i\frac{\gamma\Omega}{E_{\rm Pl}}\frac{d^2}{dr^{*2}}+\frac{d^2}{dr^{*2}}+\omega^2-V_\ell(r^*)\right]\psi_\omega=0$$

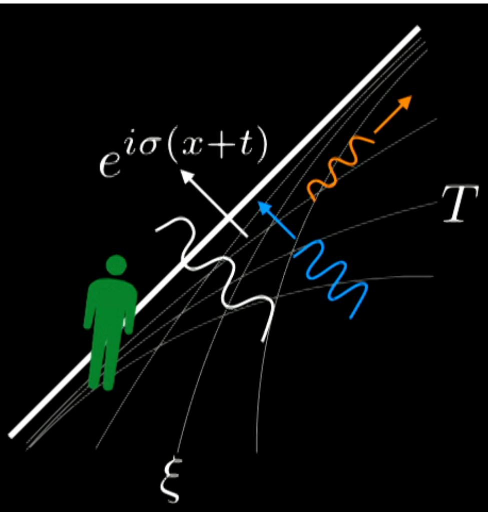
$$\lim_{r^*\to-\infty}\psi_\omega(r^*)=\text{const.}\qquad\psi_\omega={}_2F_1\left[-i\frac{\omega}{\kappa},i\frac{\omega}{\kappa},1,-i\frac{E_{\rm Pl}e^{\kappa r^*}}{\gamma\omega}\right]$$

$$\uparrow$$

$$\psi_\omega=e^{-\pi\omega/(2\kappa)}Ae^{i\omega r^*}+e^{\pi\omega/(2\kappa)}A^*e^{-i\omega r^*}$$

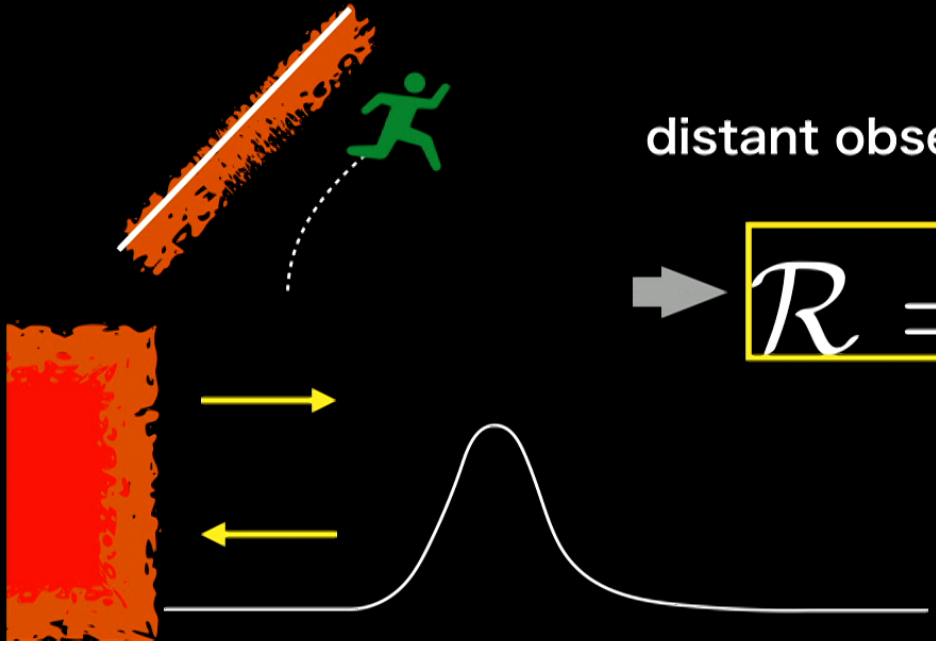
Boltzmann reflection rate!!

$$\boxed{\mathcal{R}=e^{-\omega/T_H}}$$



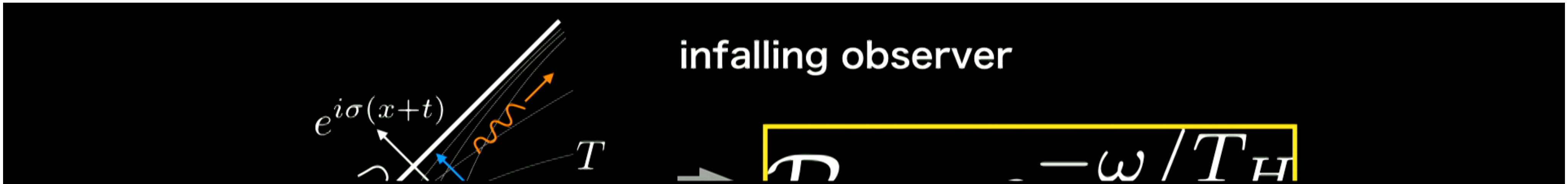
infalling observer

$$\boxed{\mathcal{R} = e^{-\omega/T_H}}$$

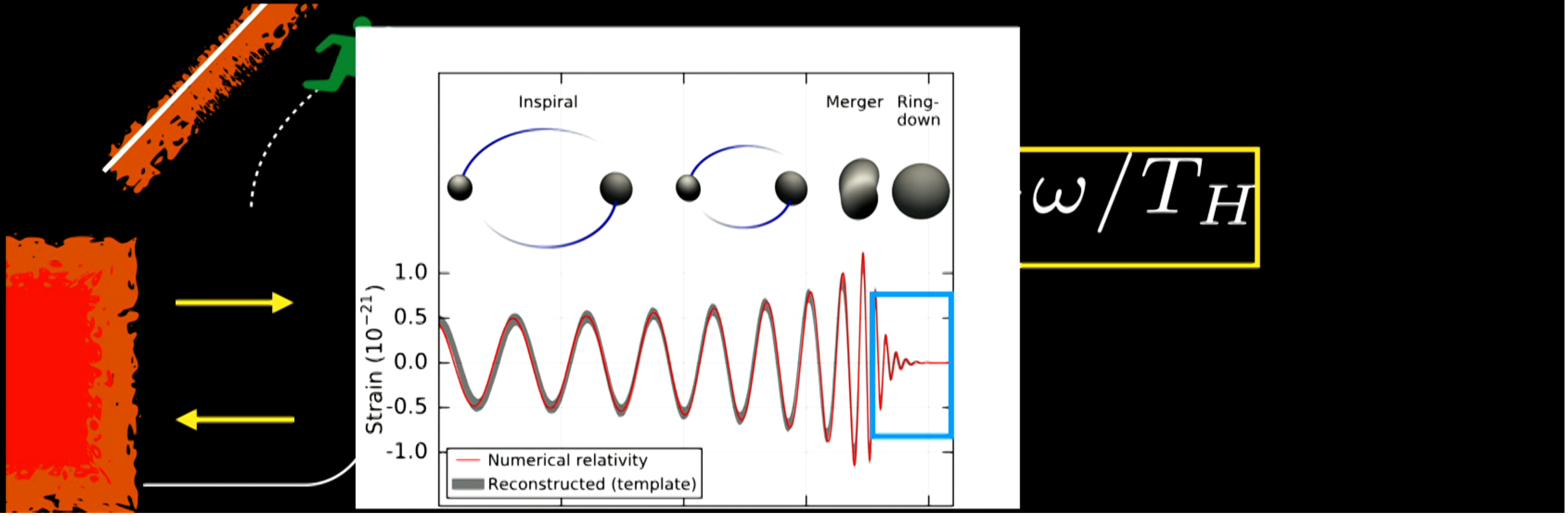


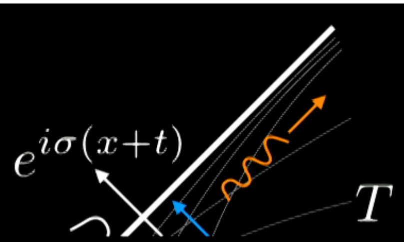
distant observer

$$\boxed{\mathcal{R} = e^{-\omega/T_H}}$$



How is the ringdown GWs modified??

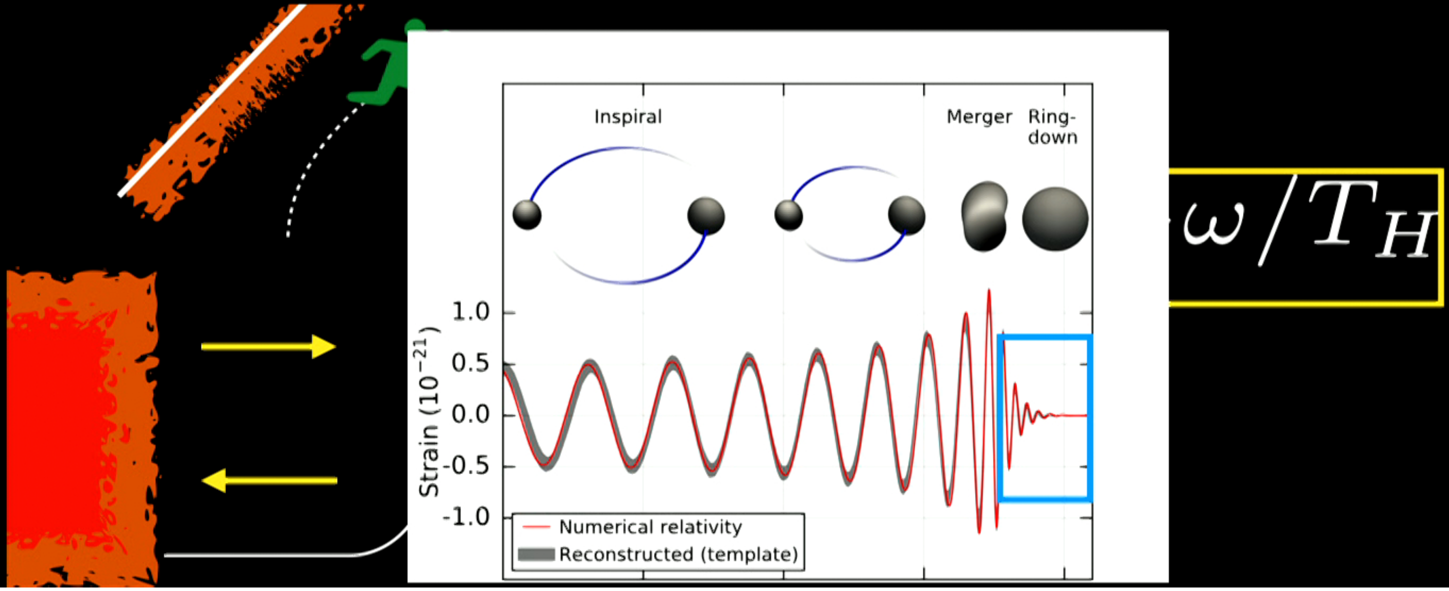




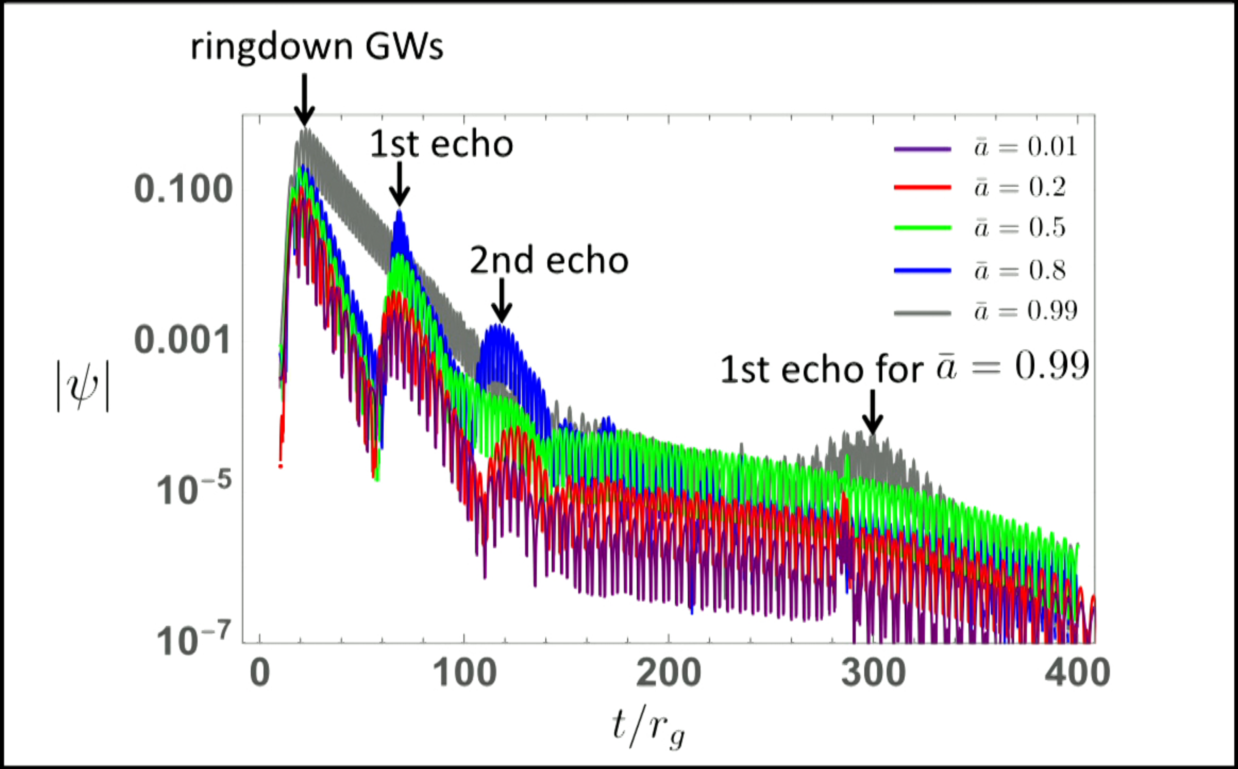
infalling observer

$-\omega/T_H$

How is the ringdown GWs modified??



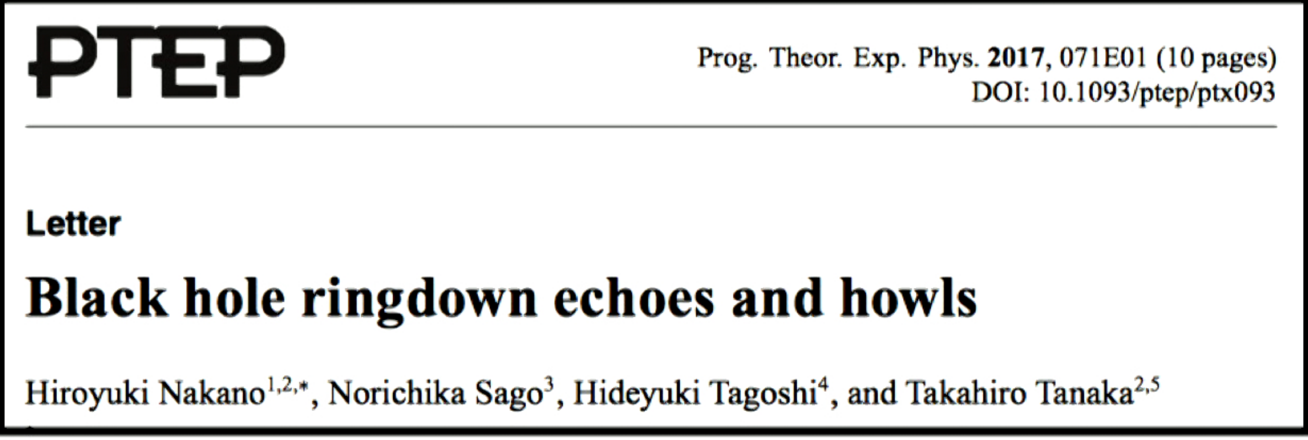
Echoes from a quantum BH



Superradiance

Superradiance may cause the instability of ringdown GWs.

H. Nakano+ (2017)



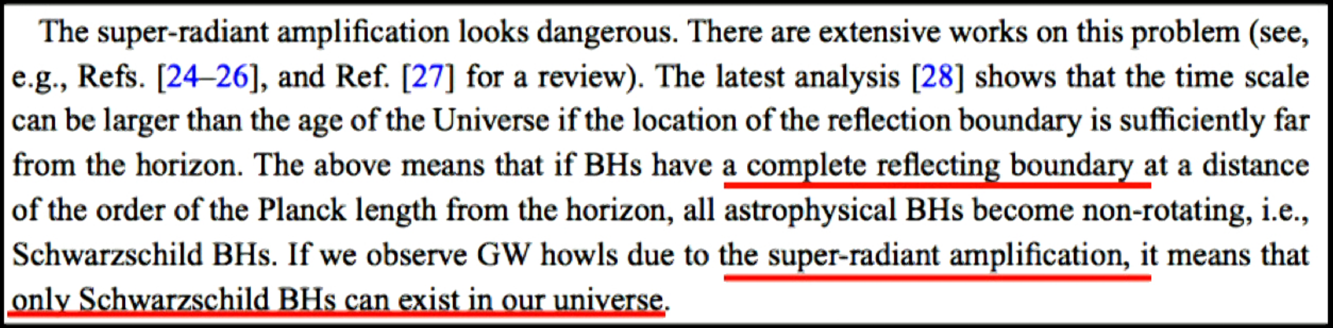
PTEP

Prog. Theor. Exp. Phys. **2017**, 071E01 (10 pages)
DOI: 10.1093/ptep/ptx093

Letter

Black hole ringdown echoes and howls

Hiroyuki Nakano[1,2,*], Norichika Sago[3], Hideyuki Tagoshi[4], and Takahiro Tanaka[2,5]

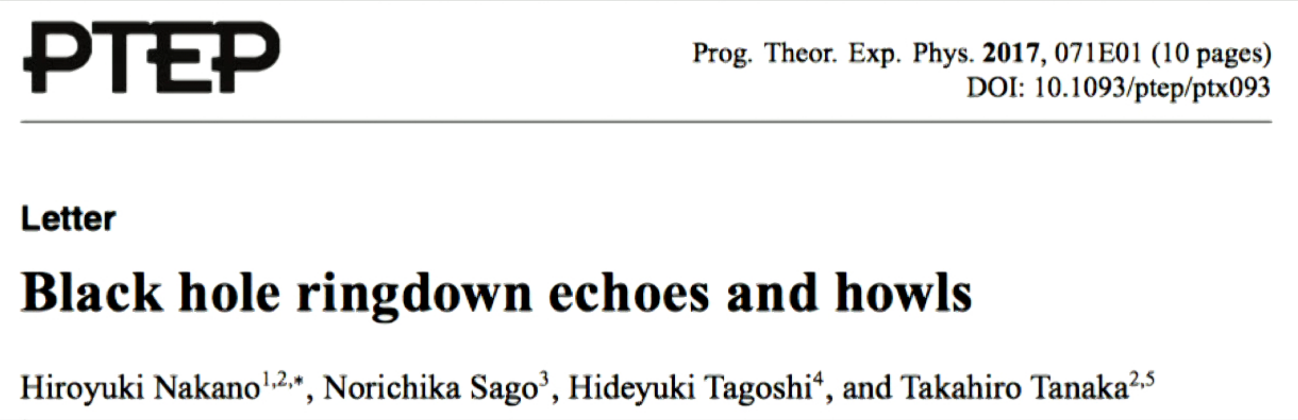


The super-radiant amplification looks dangerous. There are extensive works on this problem (see, e.g., Refs. [24–26], and Ref. [27] for a review). The latest analysis [28] shows that the time scale can be larger than the age of the Universe if the location of the reflection boundary is sufficiently far from the horizon. The above means that if BHs have a complete reflecting boundary at a distance of the order of the Planck length from the horizon, all astrophysical BHs become non-rotating, i.e., Schwarzschild BHs. If we observe GW howls due to the super-radiant amplification, it means that only Schwarzschild BHs can exist in our universe.

Superradiance

Superradiance may cause the instability of ringdown GWs.

H. Nakano+ (2017)



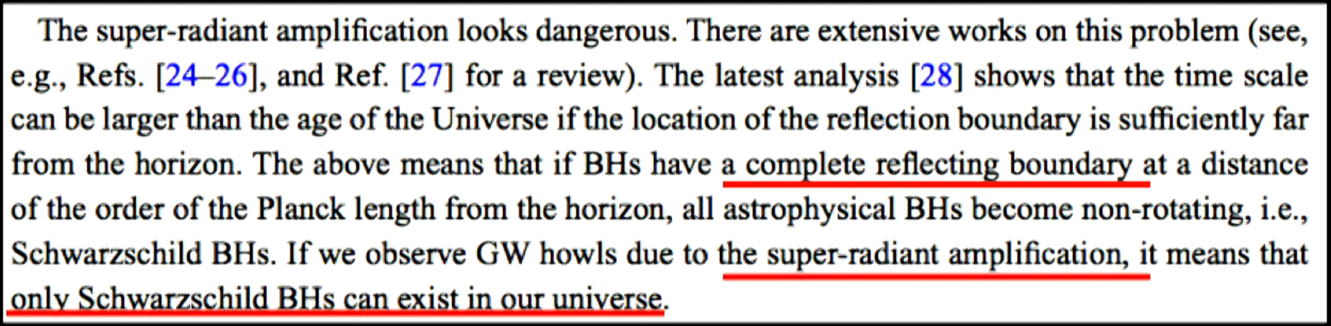
PTEP

Prog. Theor. Exp. Phys. **2017**, 071E01 (10 pages)
DOI: 10.1093/ptep/ptx093

Letter

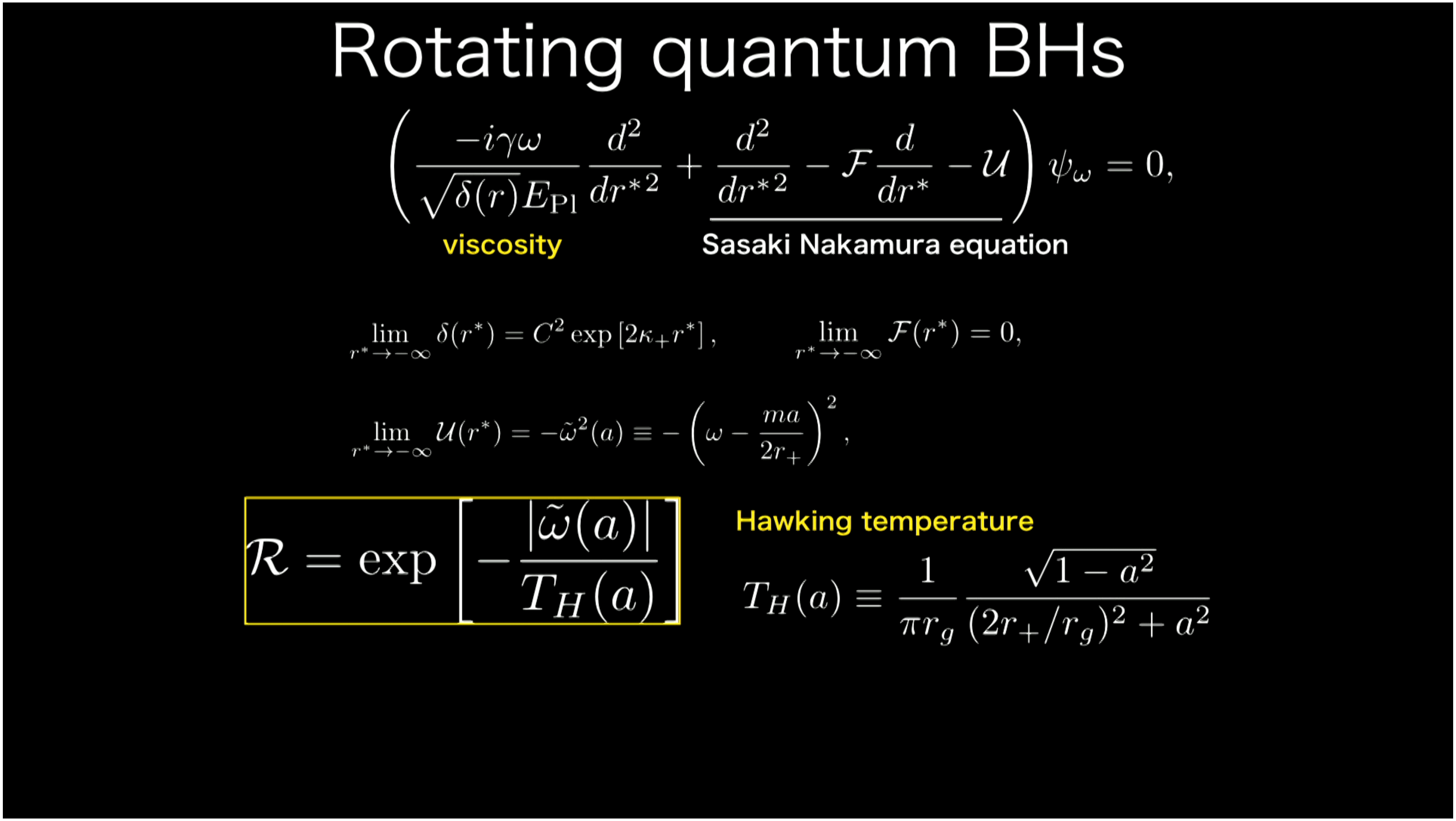
Black hole ringdown echoes and howls

Hiroyuki Nakano[1,2,*], Norichika Sago[3], Hideyuki Tagoshi[4], and Takahiro Tanaka[2,5]



The super-radiant amplification looks dangerous. There are extensive works on this problem (see, e.g., Refs. [24–26], and Ref. [27] for a review). The latest analysis [28] shows that the time scale can be larger than the age of the Universe if the location of the reflection boundary is sufficiently far from the horizon. The above means that if BHs have a complete reflecting boundary at a distance of the order of the Planck length from the horizon, all astrophysical BHs become non-rotating, i.e., Schwarzschild BHs. If we observe GW howls due to the super-radiant amplification, it means that only Schwarzschild BHs can exist in our universe.

We should confirm NO instability !



Rotating quantum BHs

$$\left(\frac{-i\gamma\omega}{\sqrt{\delta(r)}E_{\mathrm{Pl}}}\frac{d^2}{dr^{*2}} + \underline{\frac{d^2}{dr^{*2}} - \mathcal{F}\frac{d}{dr^*} - \mathcal{U}}\right)\psi_\omega = 0,$$

viscosity

Sasaki Nakamura equation

$$\lim_{r^*\to-\infty}\delta(r^*) = C^2\exp\left[2\kappa_+ r^*\right], \qquad \lim_{r^*\to-\infty}\mathcal{F}(r^*) = 0,$$

$$\lim_{r^*\to-\infty}\mathcal{U}(r^*) = -\tilde{\omega}^2(a) \equiv -\left(\omega - \frac{ma}{2r_+}\right)^2,$$

$$\boxed{\mathcal{R} = \exp\left[-\frac{|\tilde{\omega}(a)|}{T_H(a)}\right]}$$

Hawking temperature

$$T_H(a) \equiv \frac{1}{\pi r_g}\frac{\sqrt{1-a^2}}{(2r_+/r_g)^2 + a^2}$$

Rotating quantum BHs

$$\left(\underset{\text{viscosity}}{\frac{-i\gamma\omega}{\sqrt{\delta(r)}E_{\rm Pl}}\frac{d^2}{dr^{*2}}}+\underline{\frac{d^2}{dr^{*2}}-\mathcal{F}\frac{d}{dr^*}-\mathcal{U}}\right)\psi_\omega=0,$$

viscosity Sasaki Nakamura equation

$$\lim_{r^*\to-\infty}\delta(r^*)=C^2\exp\left[2\kappa_+r^*\right],\qquad \lim_{r^*\to-\infty}\mathcal{F}(r^*)=0,$$

$$\lim_{r^*\to-\infty}\mathcal{U}(r^*)=-\tilde{\omega}^2(a)\equiv-\left(\omega-\frac{ma}{2r_+}\right)^2,$$

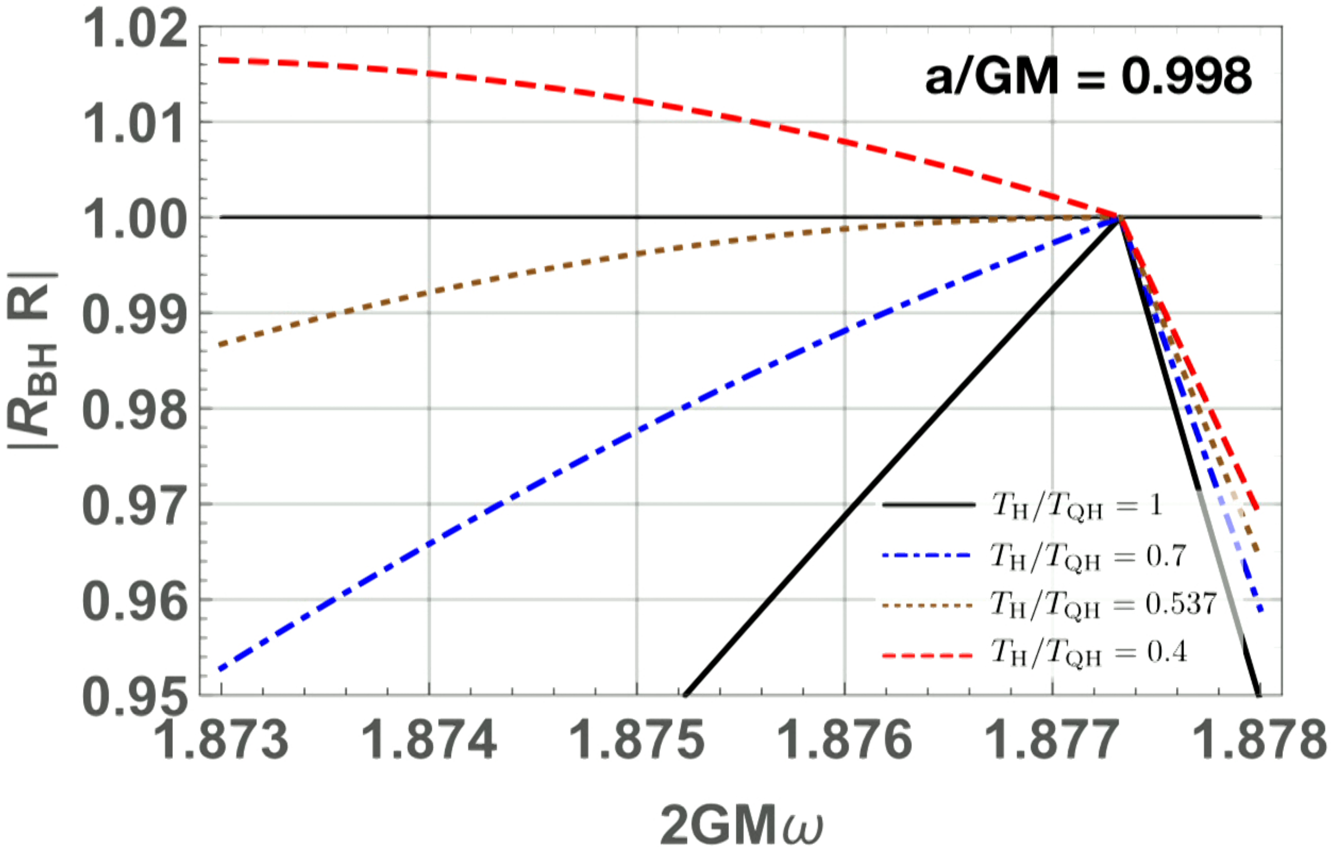
$$\boxed{\mathcal{R}=\exp\left[-\frac{|\tilde{\omega}(a)|}{T_H(a)}\right]}$$

Hawking temperature

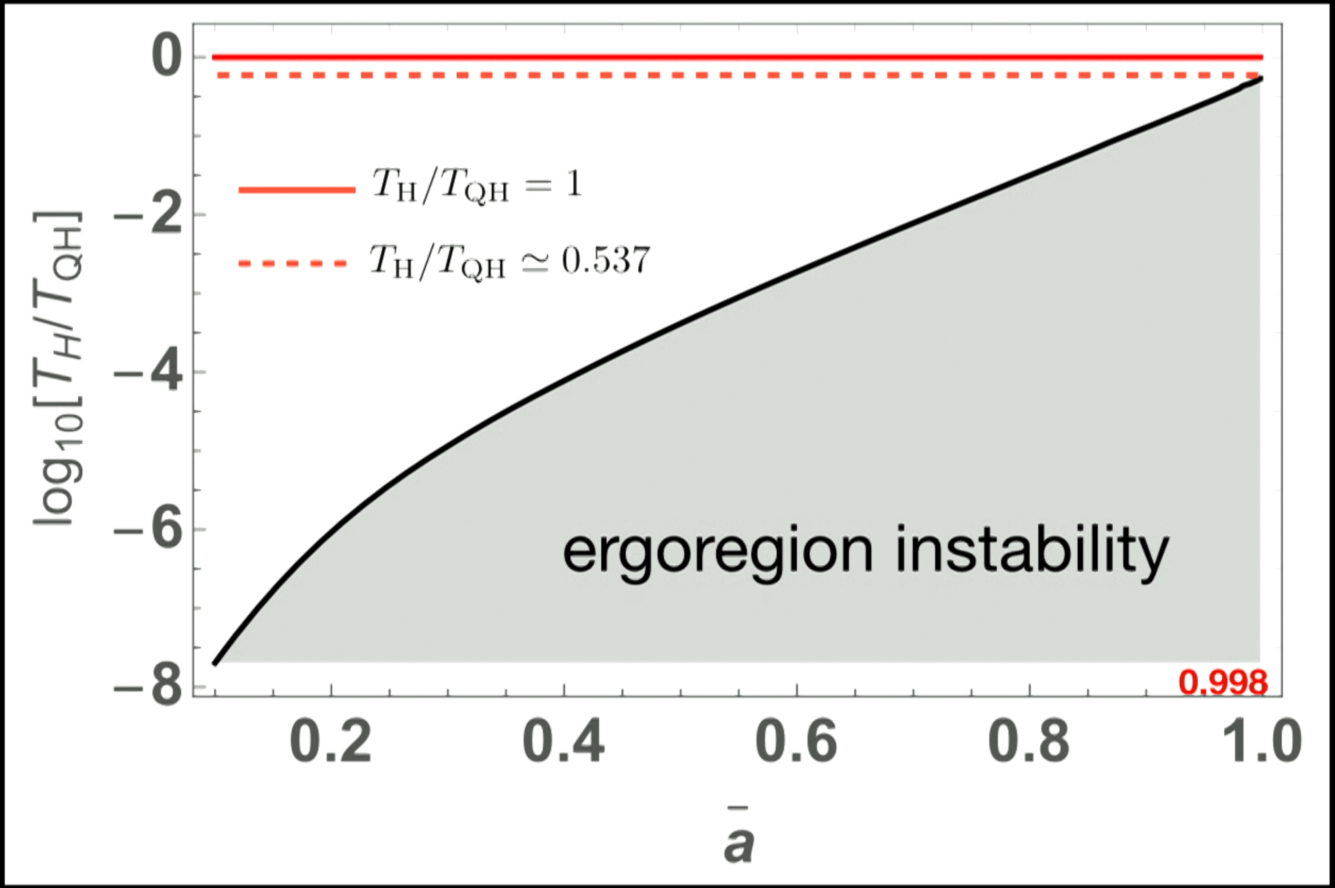
$$T_H(a)\equiv\frac{1}{\pi r_g}\frac{\sqrt{1-a^2}}{(2r_+/r_g)^2+a^2}$$

In the extreme limit (a -> 1), the temperature becomes zero.

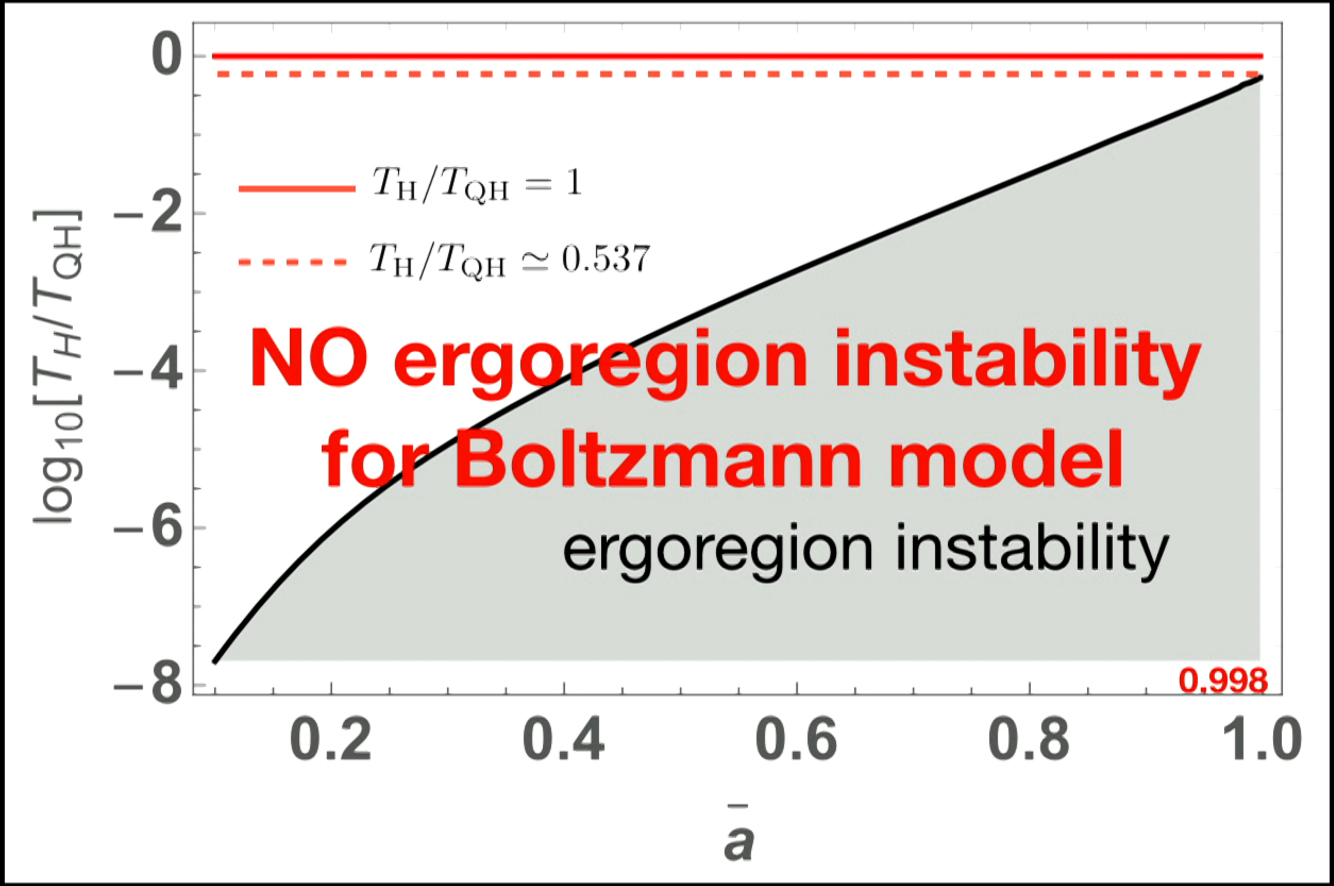
$\mathcal{R}\to 0$ except for $\omega=\dfrac{ma}{2r_+}$


a/GM = 0.998
|R_BH R|
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
1.873
1.874
1.875
1.876
1.877
1.878
2GMω
T_H/T_QH = 1
T_H/T_QH = 0.7
T_H/T_QH = 0.537
T_H/T_QH = 0.4

$$|\mathcal{R}_{\rm wall}|^2 = \exp\left[-\frac{|\tilde{\omega}|}{T_{\rm QH}}\right]$$

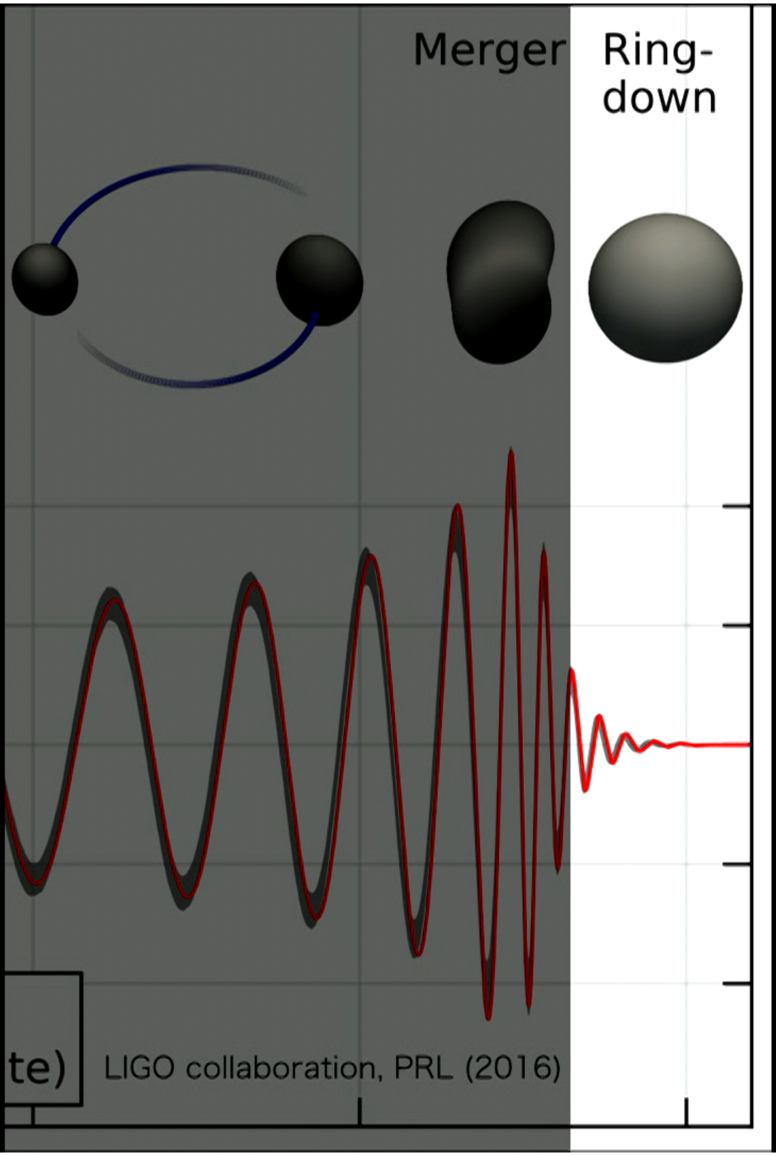


$$|\mathcal{R}_{\rm wall}|^2 = \exp\left[-\frac{|\tilde{\omega}|}{T_{\rm QH}}\right]$$



NO ergoregion instability for Boltzmann model

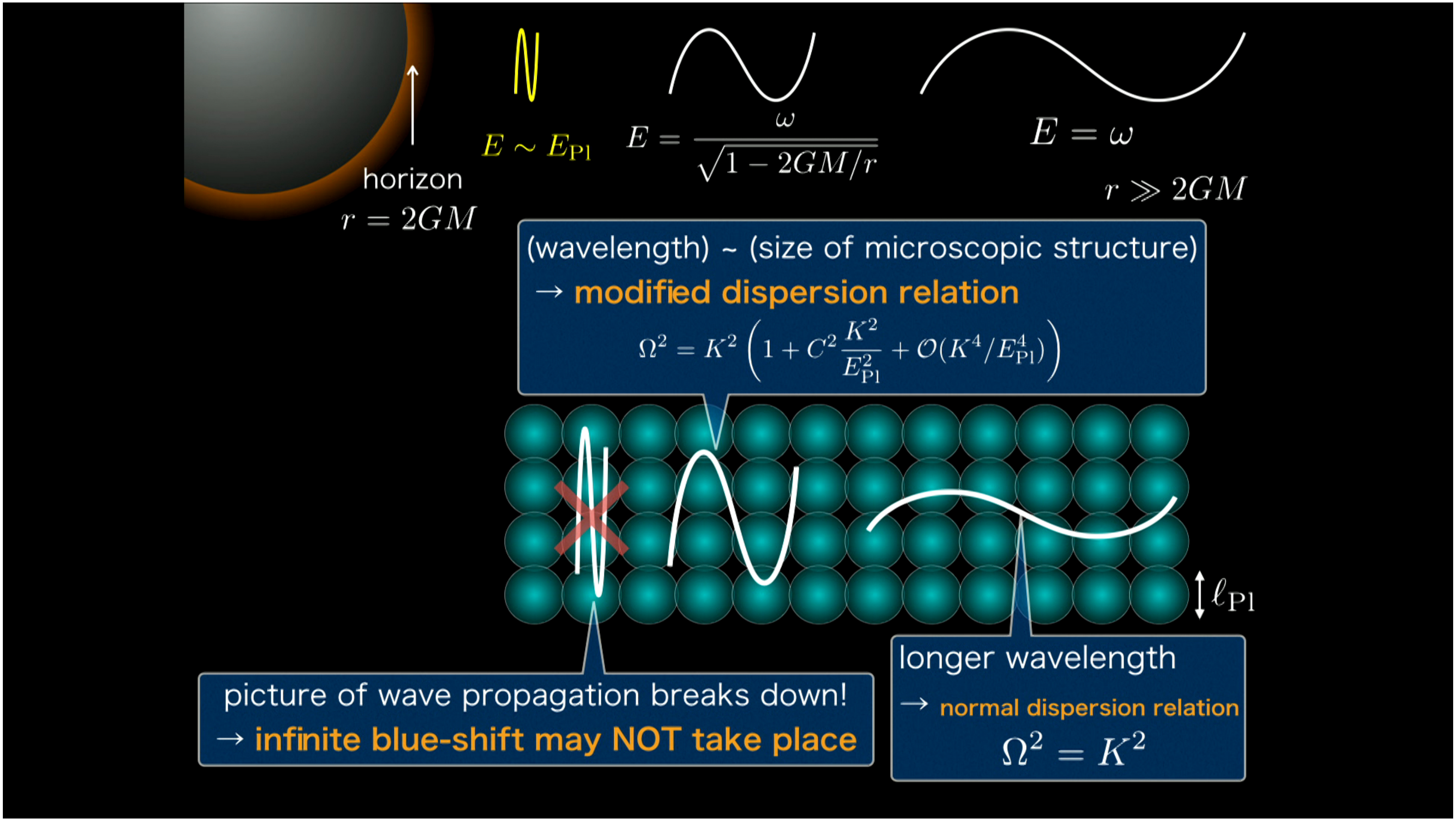
What’s NEXT?



LIGO collaboration, PRL (2016)

Is it possible to test the candidates of **quantum gravity** with **ringdown** ??

(e.g., **loop quantum gravity**
Horava-Lifshitz gravity,
causal dynamical triangulation)



horizon

$r = 2GM$

$E \sim E_{\mathrm{Pl}}$

$$E = \frac{\omega}{\sqrt{1 - 2GM/r}}$$

$$E = \omega$$

$r \gg 2GM$

(wavelength) ~ (size of microscopic structure)

→ **modified dispersion relation**

$$\Omega^2 = K^2 \left(1 + C^2 \frac{K^2}{E_{\mathrm{Pl}}^2} + \mathcal{O}(K^4/E_{\mathrm{Pl}}^4)\right)$$

ℓ_{Pl}

picture of wave propagation breaks down!

→ **infinite blue-shift may NOT take place**

longer wavelength

→ **normal dispersion relation**

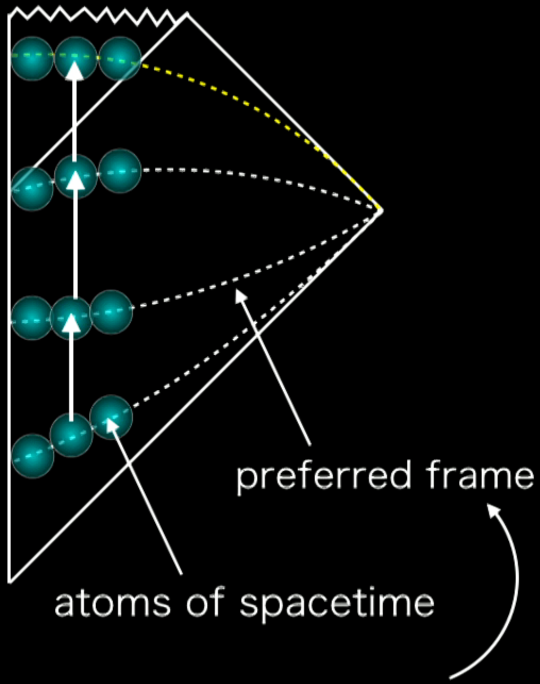
$$\Omega^2 = K^2$$

space has a special length (Planck length)

↓

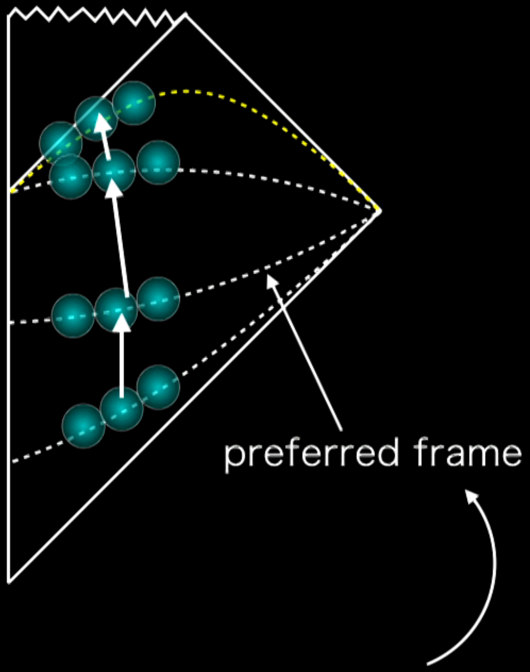
Lorentz symmetry is broken → preferred frame may exist

infalling atoms



Kruskal coordinate
(freely falling observer)

atoms stuck at horizon



Schwarzschild coordinate
(distant & static observer)

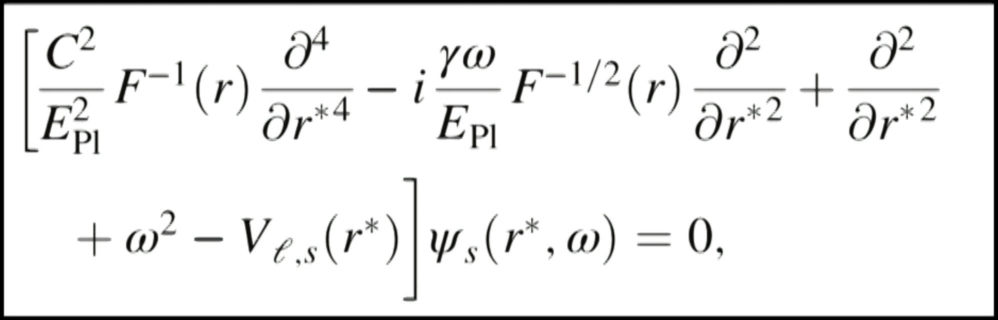
model

dispersion relation

$$\Omega^2 = K^2\left(1 + C^2\frac{K^2}{E_{\rm Pl}^2}\right)$$

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

$$f(r) \equiv 1 - \frac{2GM}{r}$$

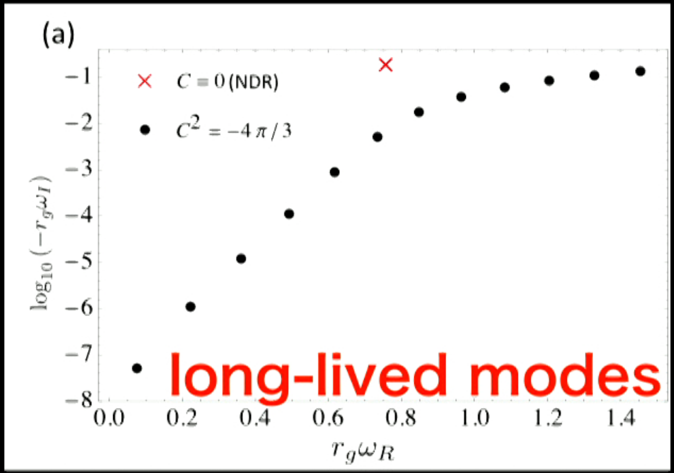


$$\left[\frac{C^2}{E_{\rm Pl}^2}F^{-1}(r)\frac{\partial^4}{\partial r^{*4}} - i\frac{\gamma\omega}{E_{\rm Pl}}F^{-1/2}(r)\frac{\partial^2}{\partial r^{*2}} + \frac{\partial^2}{\partial r^{*2}} + \omega^2 - V_{\ell,s}(r^*)\right]\psi_s(r^*,\omega) = 0,$$

N.O. and Afshordi (2018)

QNMs with modified DRs

N.O. and Afshordi (2018)

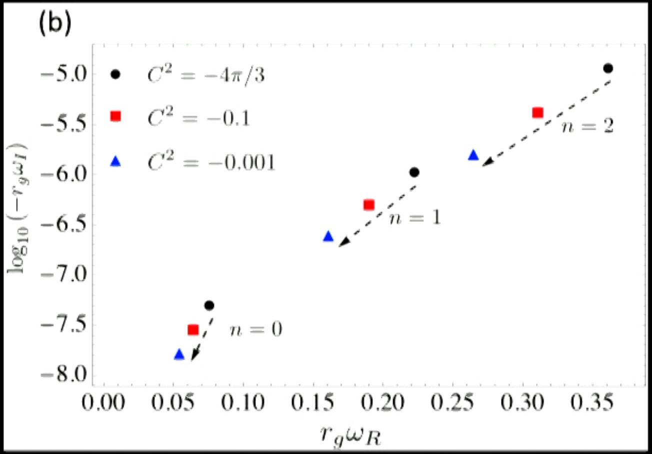


long-lived modes

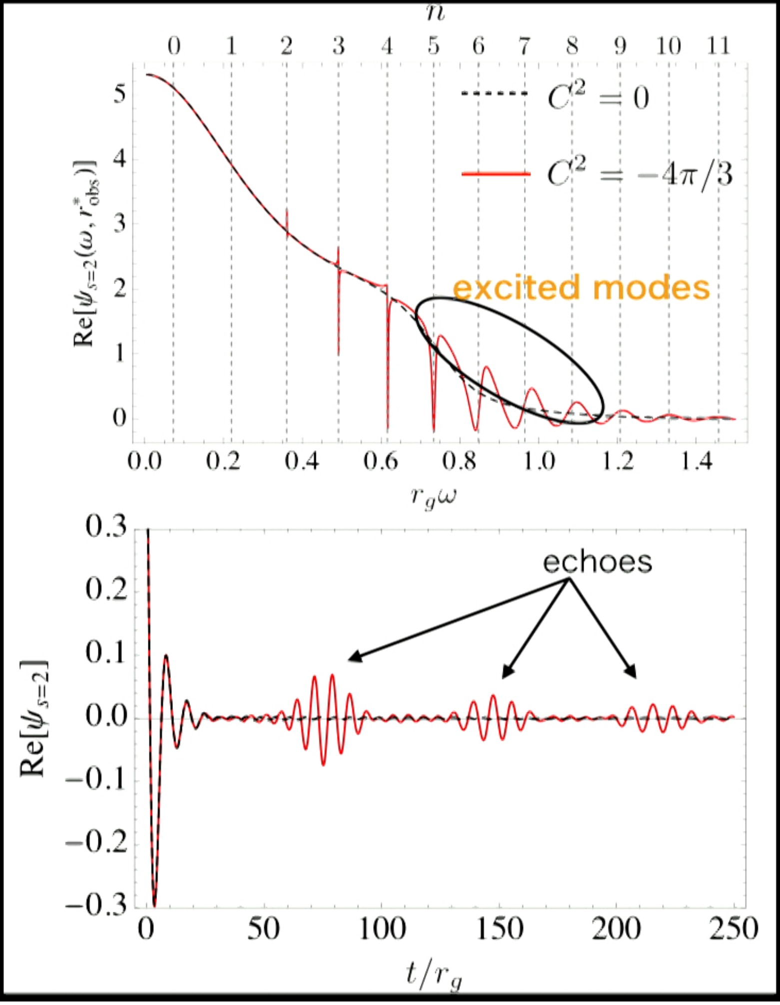
smaller microstructure

⇕

more long-lived QNMs

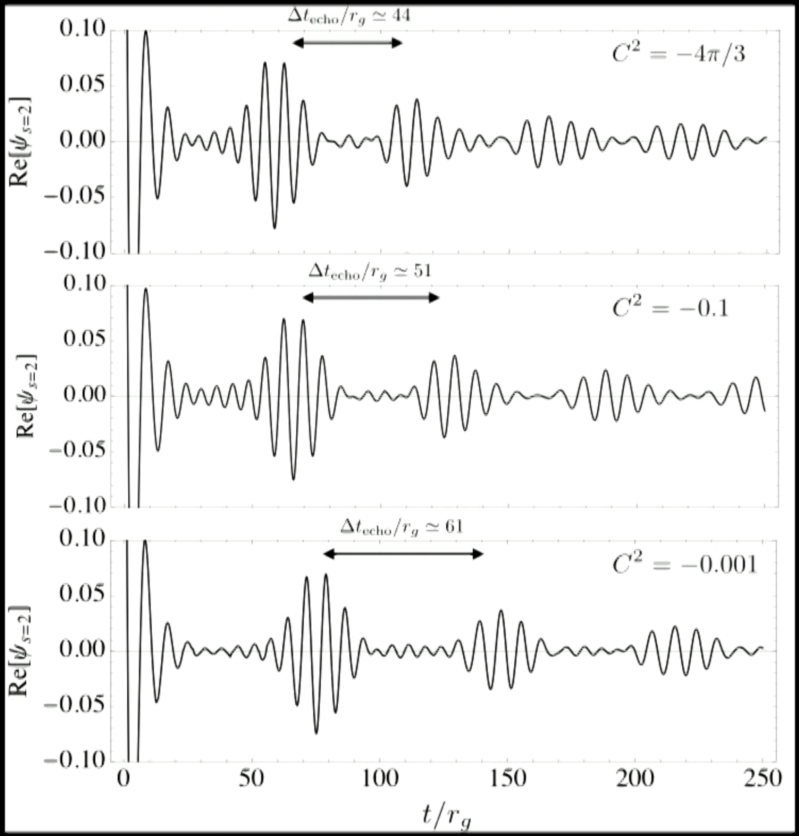


Supporting evidence of atoms of spacetime
- echoes from a black hole -

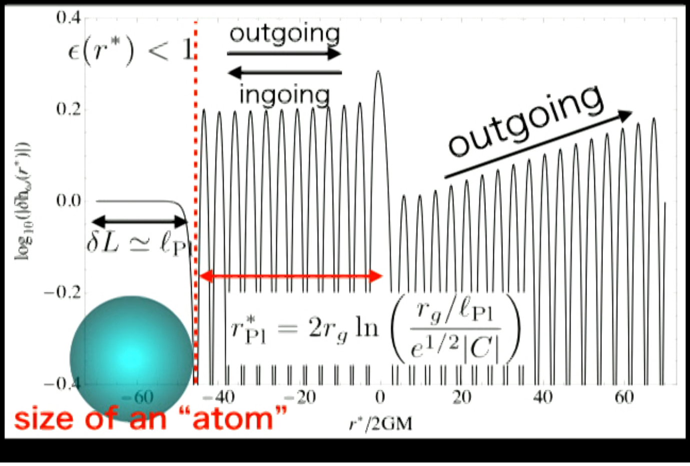


N.O. and Afshordi (2018)

Supporting evidence of atoms of spacetime
- echoes from a black hole -



$$\Delta t_{\rm echo} \equiv 4 r_g \ln\left(\frac{r_g/\ell_{\rm Pl}}{e^{1/2}|C|}\right)$$



Horava Lifshitz Gravity

Renormalizable gravitational theory

proven for projectable case [A. O. Barvinsky+ (2016)]

low-energy limit

- GR recovered
- 2 + 1 D.O.F.

scalar (khronon)

two graviton polarizations

high-energy

- Lorentz breaking theory
- superluminal

Horava Lifshitz Gravity

Renormalizable gravitational theory

proven for projectable case [A. O. Barvinsky+ (2016)]

dynamics of khronon tells us the preferred frame

khronon field on Schwarzschild space
-> new horizon structure!!

- **Lorentz breaking theory**
- **superluminal**

- **2 + 1 D.O.F.**

scalar (khronon)

two graviton polarizations

khronon field and universal horizon

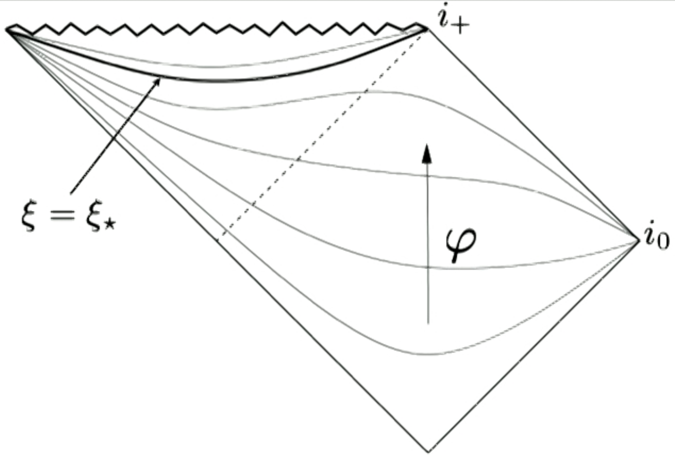


Figure 2: The leaves of constant khronon field (thin solid lines) superimposed on the upper half of the Penrose diagram of the Schwarzschild black hole. The thick solid line shows the universal horizon.

$$\xi \equiv \frac{r_s}{r}$$

D. Blas+ (2011)

superluminal modes inside the Killing horizon can escape to infinity