Is the Black Hole Still There When We Look?

Observing Quantum Gravity in Extremely Cold Horizons

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THE DYNAMICS OF BH MERGERS AND GW GENERATION

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Based on

Quantum Cross-section of Near-extremal Black Holes

JHEP 04 (2025) 122 • e-Print: 2501.17470

Quantum Transparency of Near-extremal Black Holes

w/ Stefano Trezzi

JHEP 10 (2025) 023 • e-Print: 2507.03398

Can we observe large quantum fluctuations of the spacetime geometry?

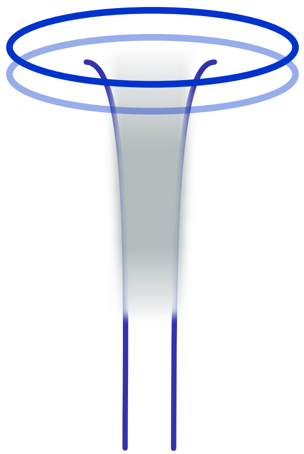
This requires a breakdown of semiclassical QFT

in curved space

Typically studied near (naked) singularities

Near extremality, black holes have large but tractable quantum fluctuations

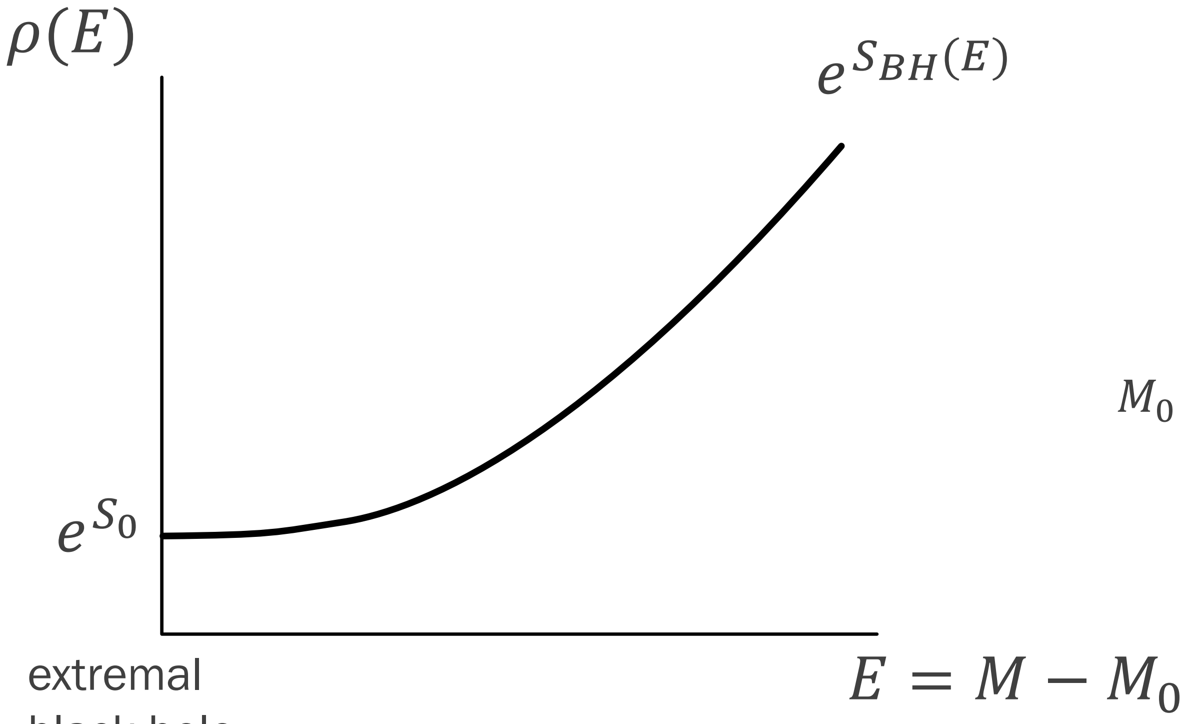
The length of the throat has large quantum variance



curvature remains small

The spectre of Bekenstein & Hawking

number density of black hole states



huge density of ground states

Worrisome

extremal black hole

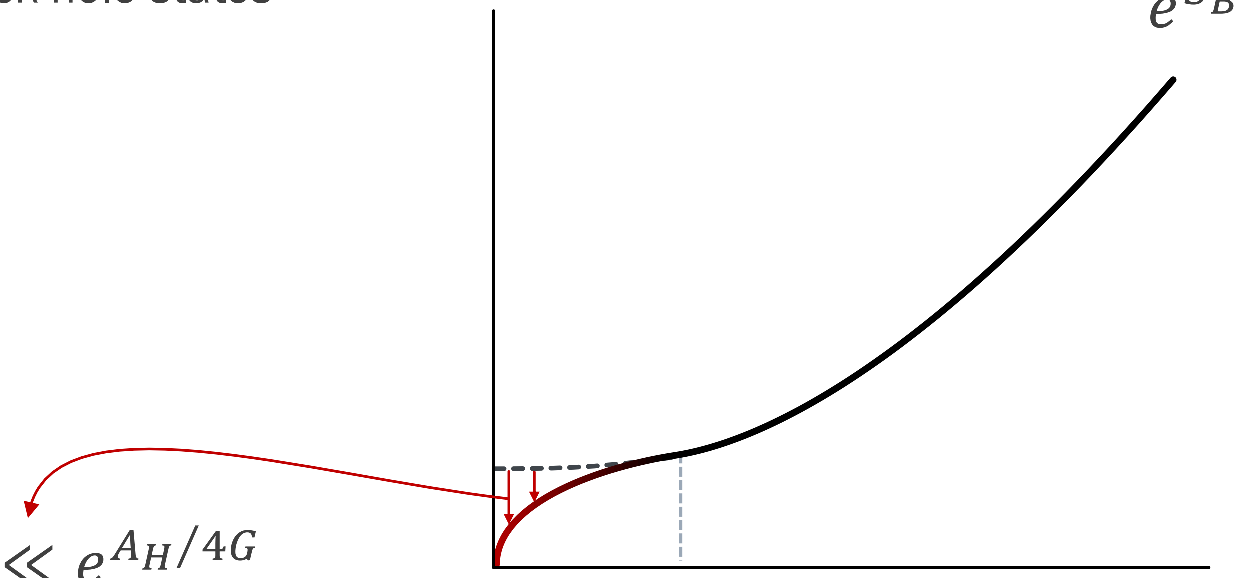
M_0 = extremal bh mass

Quantum Black Hole spectrum*

*non-supersymmetric

number density of black hole states $\rho(E)$

Iliesiu+Turiaci 2020

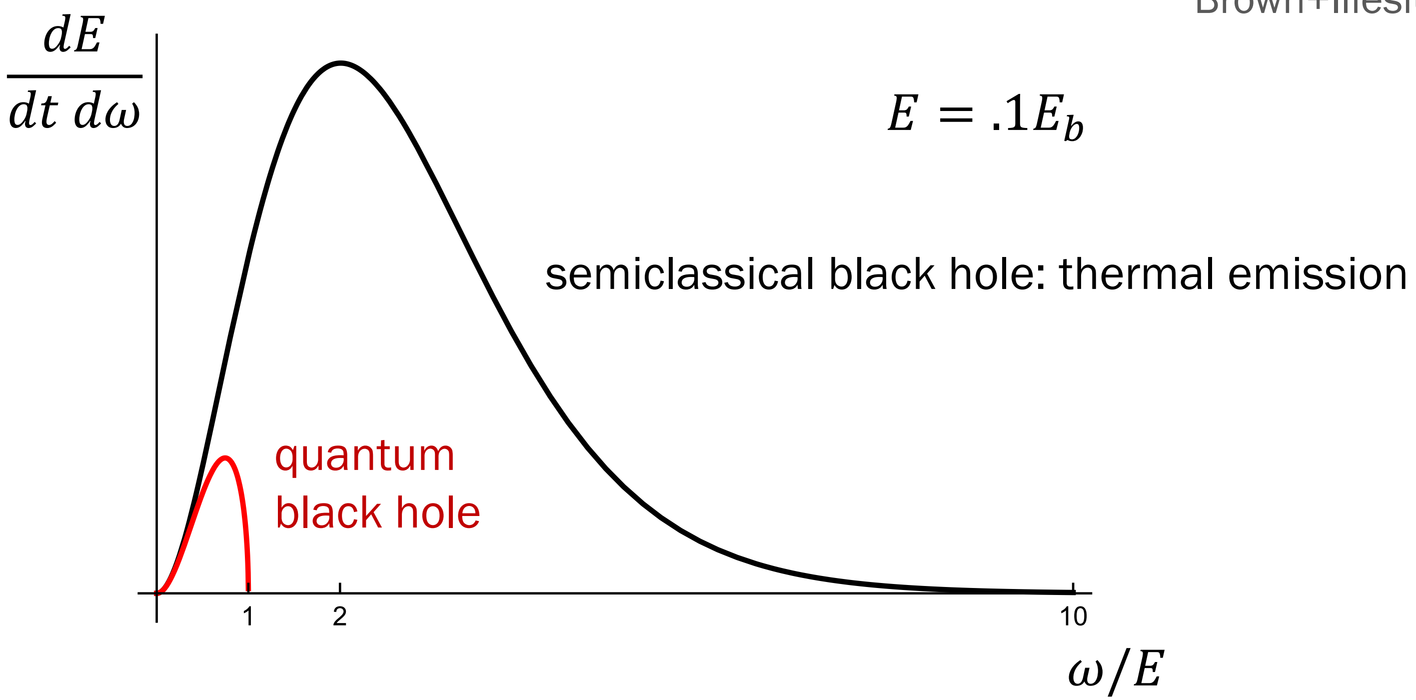


$\rho(E) \ll e^{A_H/4G}$

$$E_b \sim \frac{1}{r_h S_{\text{ext}}}$$

Hawking emission: suppressed

Brown+Iliesiu+Penington+Usatyuk



Quantum Black Hole: non-thermal emission

A lesson

The Classical limit $\hbar \to 0$ of Quantum Gravity, and

the Zero-temperature limit $T \to 0$ of Black Holes

do not commute

When $\hbar \neq 0$ (no matter how small), physics at $T \to 0$ is drastically different than first $\hbar \to 0$, then $T \to 0$

A lesson

The *classical extremal black hole* in GR textbooks is an artifact of the wrong order of limits

How can an external observer probe this large quantum object?

A reality check

How cold is extremely cold?

A reality check

$E_b \sim \frac{1}{r_h S_0}$ wavelength $\lambda_b \sim r_h S_0$

For any astro-ph black hole $r_h > \mathrm{km}$

Easily $\lambda_b \sim r_h S_0 \sim 10^{83}\mathrm{mm} \sim 10^{54}$ Hubble radius

$T \sim 10^{-83} K$

A reality check

Observations would require $\sim 10^{64}$ years,

which is impractical

Observing this large quantum object

A fundamental question of principle,

examined through thought experiments

Shining light on the Black Hole

Send a wave to the black hole

Measure the absorption cross-section

Shining light on the Black Hole

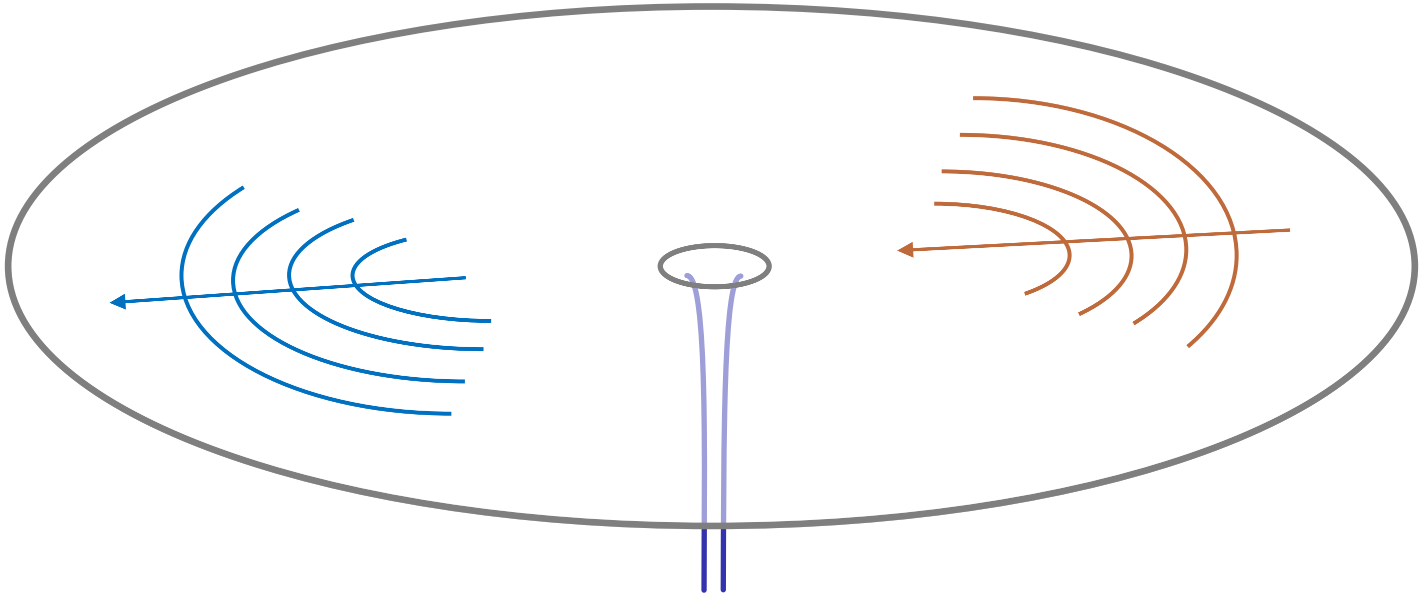
Throwing geodesic photons is not good

1. May destroy the long quantum throat

2. Only probe local geometry of the throat – not strongly fluctuating

Light rays on quantum black hole produce a classical image

Softly probe the mouth of the throat



Low-frequency scalar field scattering

- Dominated by s-wave: probe homogeneous fluctuations
- Small energy absorption: quantum throat preserved

Low-frequency scalar field scattering

- Measure absorption cross section
- Benchmark: universal classical value for $\omega \to 0$

$$\sigma_{abs} = A_H$$

Unruh
Gibbons+Das+Mathur

Low-frequency scalar field scattering

$$\sigma_{abs} = A_H = 4G \log \rho(E)$$

Absorption cross-section as measure of number of absorbing states

in semiclassical regime

What can we expect?

Quantum fluctuations make $\rho(E) \ll e^{A_H/4G}$

Surely, then, in the quantum regime

$$\sigma_{abs} \ll A_H$$

?

What we find

Quantum fluctuations make $\rho(E) \ll e^{A_H/4G}$

In the quantum regime

$$\sigma_{abs} > A_H > 4G \log \rho(E)$$

Quantum BH looks larger the closer to extremality

Why $\sigma_{abs} > A_H$ if fewer BH states?

Quantum effects enhance transitions between individual states

Late-time correlations are enhanced in quantum black hole

(power-law decay in time, instead of exponential)

What we also find

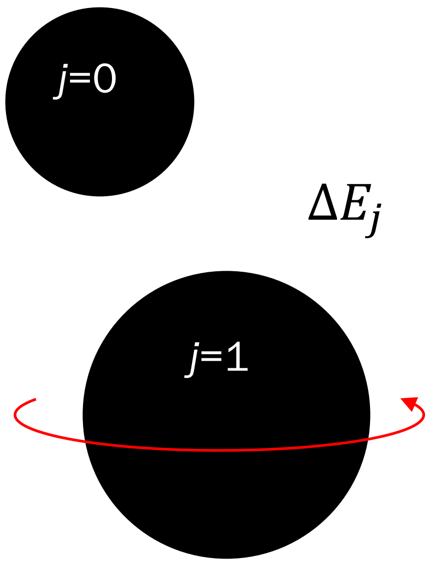
Near-extremal black holes are **transparent** to

electromagnetic and *gravitational* radiation

below a frequency threshold

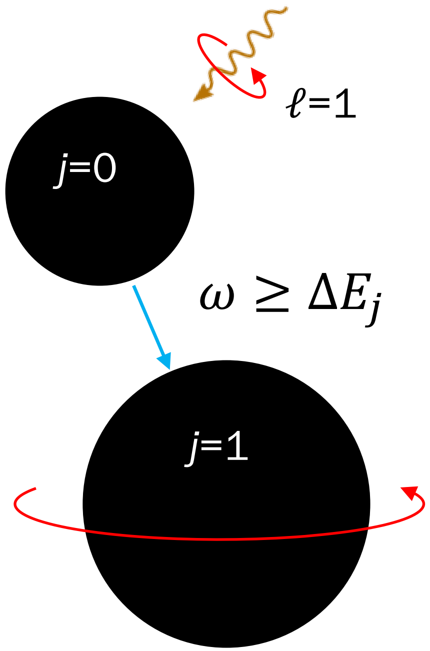
How come *transparent* black holes?

- Black hole angular momentum j is quantized
- Rotational energy creates an energy gap $\Delta E_j = \frac{Gj(j+1)}{2r_h^3}$



How come *transparent* black holes?

- Black hole angular momentum j is quantized
- Rotational energy creates an energy gap $\Delta E_j = \frac{Gj(j+1)}{2r_h^3}$
- Photons & gravitons carry spin: must supply enough energy to bridge this gap – to set the black hole rotating, $\omega \geq \Delta E_j$
- No absorption if frequency below threshold ⇒ Transparency



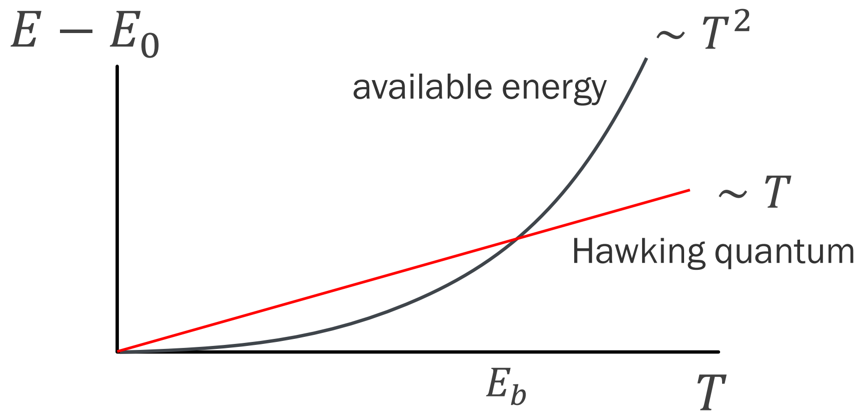
Quantum Deep Throats

HAVE FUZZY MOUTHS

Near extremality

Semiclassical black hole energy (mass)

$$E(T) = E_0 + 2\pi^2 \frac{T^2}{E_b} + O(T)^3$$



$T \lesssim E_b$: too little energy available to emit a single quantum

$$E_b = \frac{\pi}{r_h S_0}$$

⇒ *Semiclassical thermodynamics breaks down*

Preskill+Schwarz+Shapere+Trivedi+Wilczek

Near extremality

QFT in curved spacetime breaks down

even if curvatures are small

Quantum gravity important at low temperatures

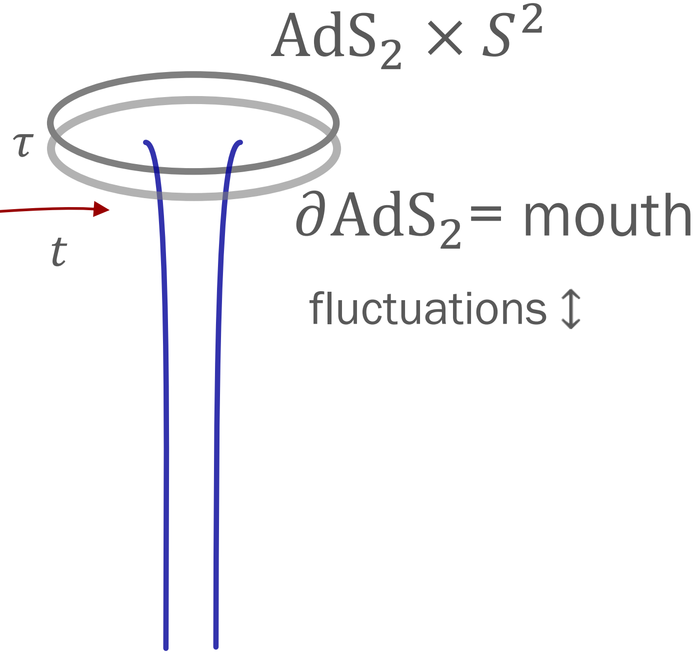
Throat theory

Maldacena+Stanford+Yang
Stanford+Witten
Mertens+Turiaci+Verlinde
Yang,...

Throat KK reduction ⟶ 1-dim Schwarzian theory at $\partial \mathrm{AdS}_2$

$$I = \beta M_0 - S_0 - \frac{1}{E_b}\int_0^\beta dt\ \mathrm{Sch}(\tau, t)$$

semiclassical extremal



Schwarzian theory:

- spherical mode
- fluctuations in height of mouth

Gravitational partition function at small T

one-loop det

$$Z(T) = e^{-I_{\mathrm{bh}}(T)} \times \det(\mathrm{Q})^{-1/2}$$

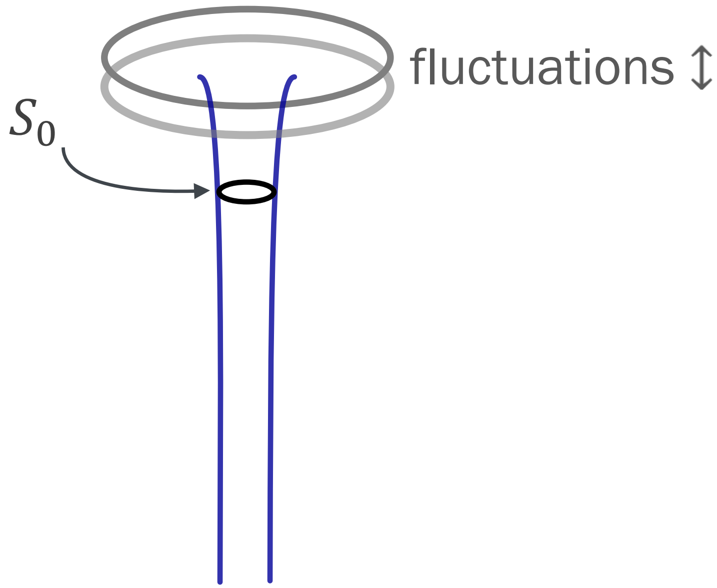
$$= \underbrace{e^{S_0 + 2\pi^2 \frac{T}{E_b}}}_{\text{semiclassical Gibbons-Hawking}} \underbrace{\left(\frac{T}{E_b}\right)^{3/2}}_{\text{quantum fluctuations of throat}}$$

semiclassical Gibbons-Hawking

quantum fluctuations of throat

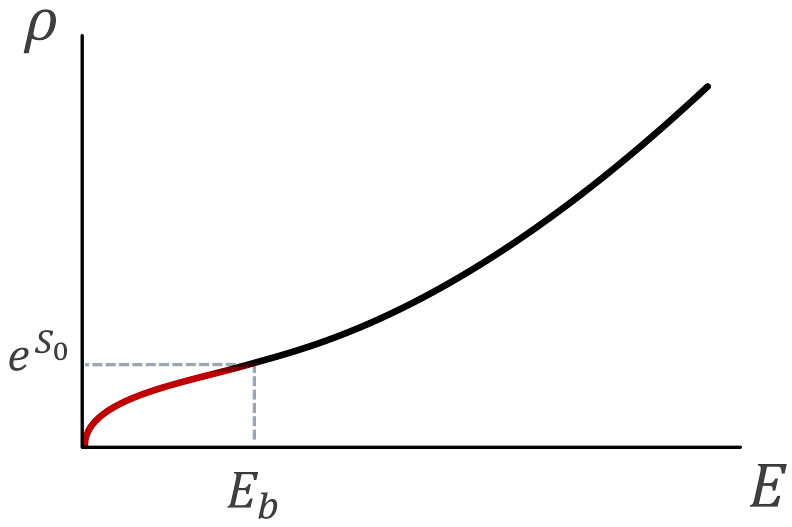
⇓

large effect when $T \lesssim E_b$



Density of states near extremality

$$\rho(E) = e^{S_0} \sinh\left(2\pi\sqrt{2E/E_b}\right)$$



$$E_b = \frac{\pi}{r_h S_0}$$

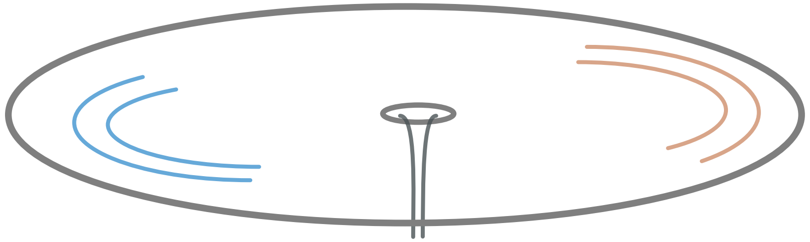
$$E = M - M_0$$

Is the Black Hole Still There When We Look?

SEEN, NOT SEEN

Also: Biggs 2503.0251

Wave scattering



Send a wave into a near-extremal black hole

parametrized by E_b and energy E_i above extremality

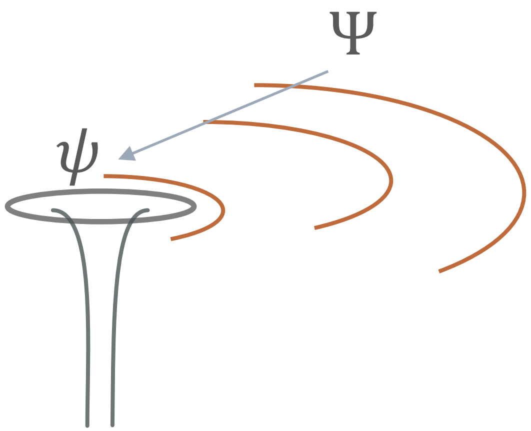
$$E_b = \frac{\pi}{r_h S_0} \qquad\qquad M = M_0 + E_i$$

Wave scattering

Propagates classically from ∞ to mouth of throat

$$\Psi(t,r) \sim c_{in} e^{-i\omega(t-r)} + c_{out} e^{-i\omega(t+r)}$$

At the mouth: <u>source</u> for the field in AdS_2



$$I = I_{Schwarzian} + \int dt\, \psi(t) \mathcal{O}_\Delta(t)$$

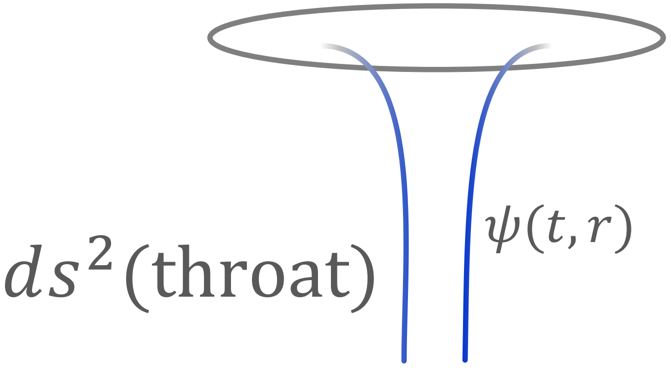
$\mathcal{O}_\Delta(t)$: response operator

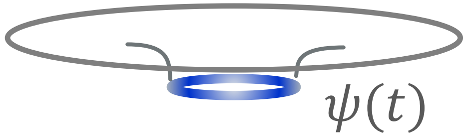
Brown+Iliesiu+Penington+Usatyuk

Quantum Throat

We replace fields propagating in the classical throat with operators coupling to the quantum Schwarzian theory

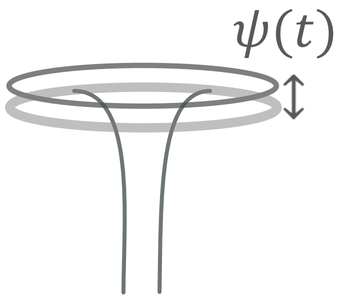
$$I = I_{Schwarzian} + \int dt\, \psi(t)\mathcal{O}_\Delta(t)$$





$|E\rangle$ state of Schwarzian theory

quantum black hole energy eigenstate



$\psi(t) = \psi_0 e^{-i\omega t}$: oscillating source excites black hole state

Induces transitions between black hole states:

$|E_i\rangle \to |E_i + \omega\rangle$: absorption

$|E_i\rangle \to |E_i - \omega\rangle$: emission (stimulated)

Fermi rule: $\mathcal{T}_{i\to f} = 2\pi \left|\langle E_f, N_f | \mathcal{O}_\Delta \psi_0 | E_i, N_i\rangle\right|^2 \rho(E_f)$

known from Schwarzian theory

Schwarzian absorption

Schwarzian theory:

density of states

$$\rho(E) = e^{S_0} \sinh(2\pi\sqrt{2E/E_b})$$

2-pt function

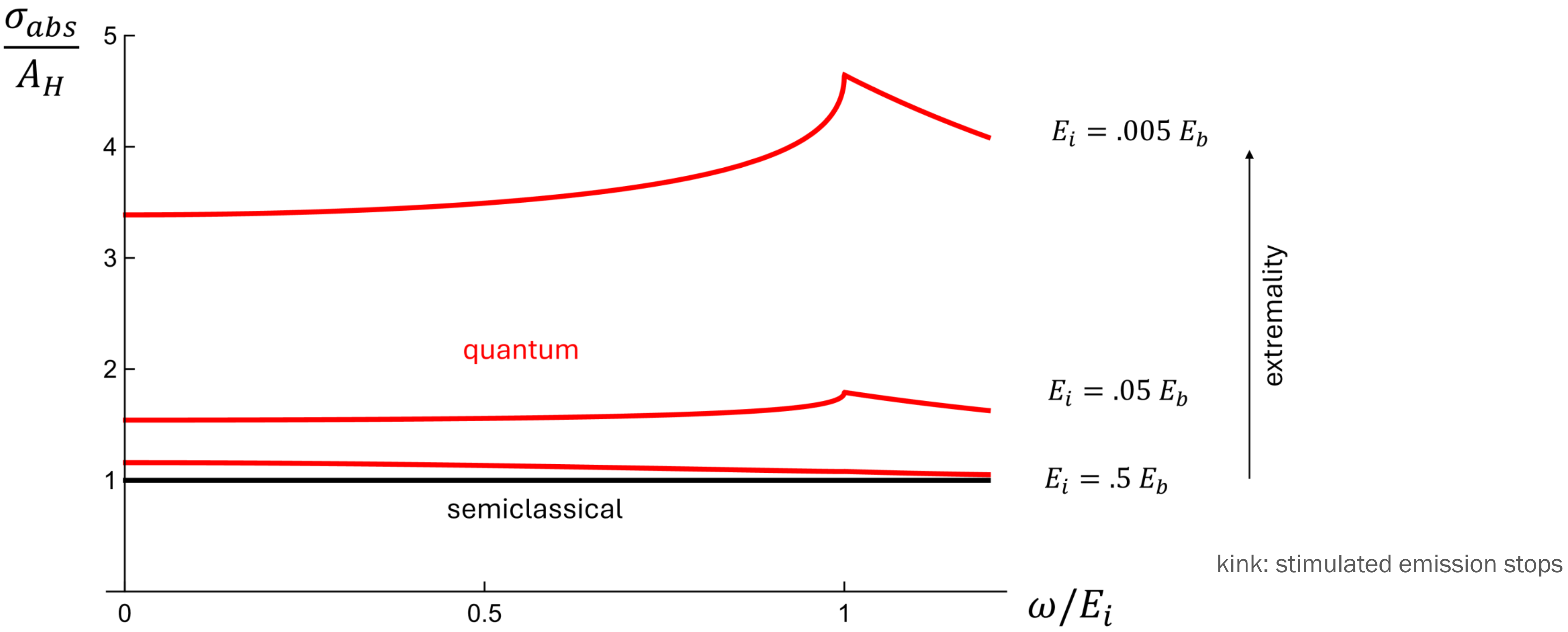
$$\left|\langle E_f|\mathcal{O}|E_i\rangle\right|^2 = e^{-S_0} \frac{E_f - E_i}{\cosh\left(2\pi\sqrt{2E_f/E_b}\right) - \cosh(2\pi\sqrt{2E_i/E_b})}$$

Near-extremal absorption: s-wave

$$\sigma_{abs} = A_H \left(\frac{\sinh(2\pi\sqrt{2(E_i+\omega)/E_b})}{\cosh\left(2\pi\sqrt{2(E_i+\omega)/E_b}\right) - \cosh(2\pi\sqrt{2E_i/E_b})} + (\omega \to -\omega) \right)$$

Semiclassical black hole limit: $E_i \gg \omega, E_b$ $\sigma_{abs} \to A_H$

Quantum absorption $\sigma_{abs} > A_H$



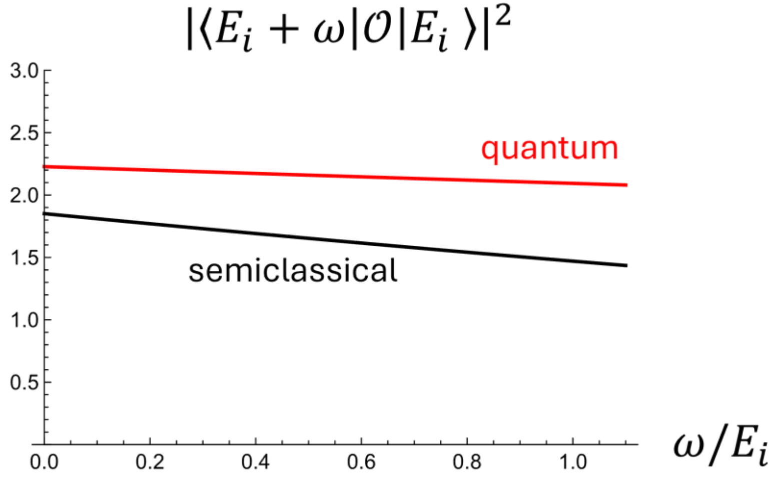
Quantum absorption $\sigma_{abs} > A_H$

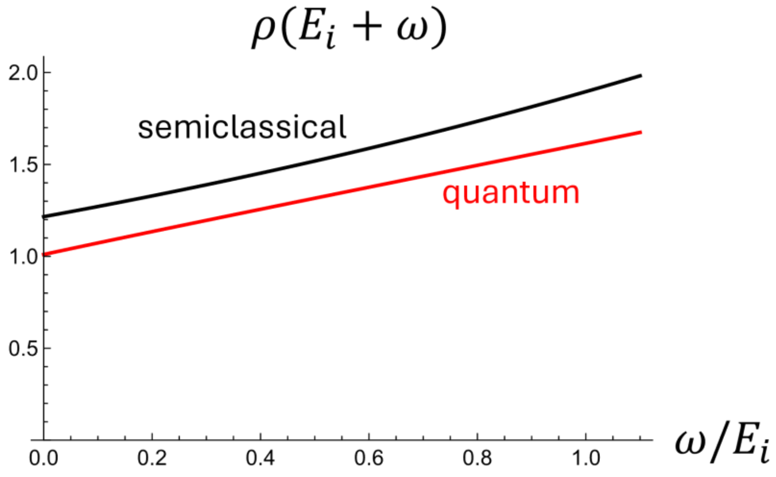
Since $\rho(E) < e^{A_H/4G} = e^{S_0}$

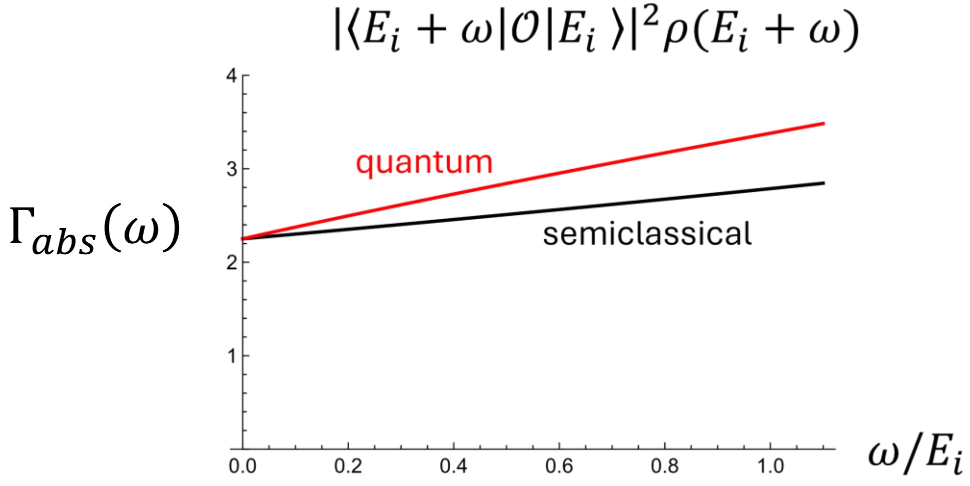
$$\sigma_{abs} > 4GS_0 > 4G \log \rho(E_i)$$

Density of states grossly underestimates the absorption near extremality

Enhanced absorption transitions overcompensate for fewer states







Fewer black hole states, but more efficient at absorbing radiation

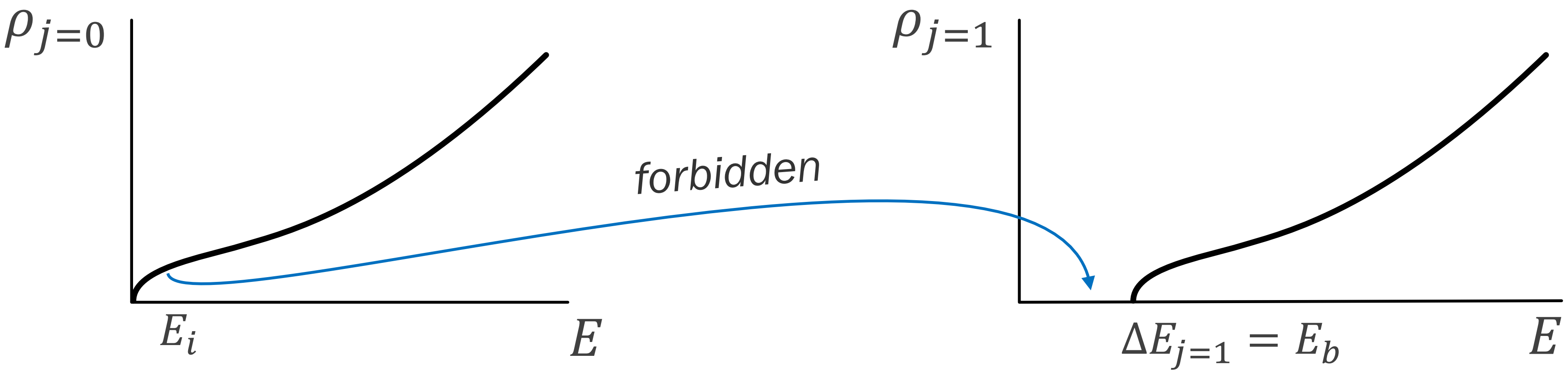
Quantum Black Hole looks larger

Quantum Spin Absorption

BLACK HOLE OUT OF SIGHT

Photon & Graviton absorption

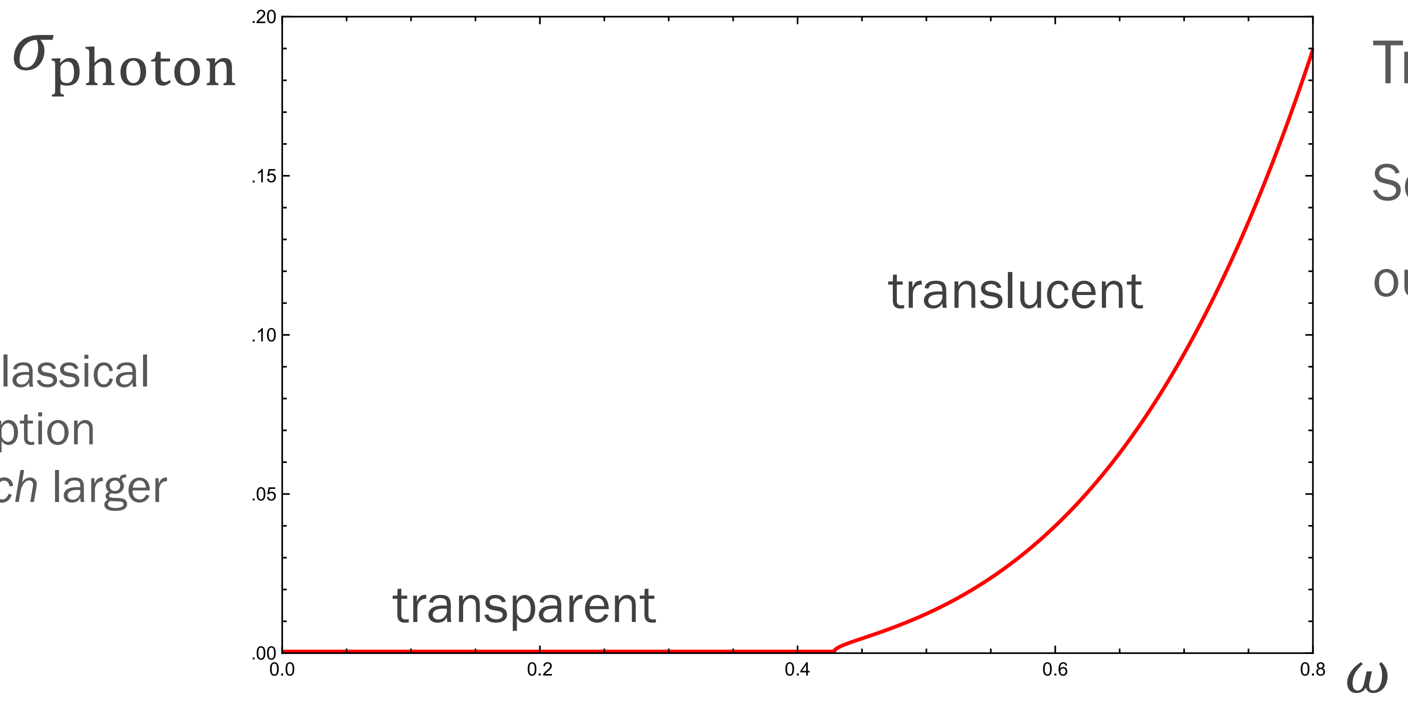
Spinless BH $\longrightarrow$ Spinning BH: gapped $\Delta E_j = \frac{G\, j(j+1)}{2r_0^3}$



$\omega + E_i < \Delta E_{j=1}$ Transparent

w/ Stefano Trezzi

Black Hole Transparency & Translucency



semiclassical absorption is *much* larger

Translucency

Scarcity of spin-absorbing states outweighs enhanced transition rates

→ suppressed absorption

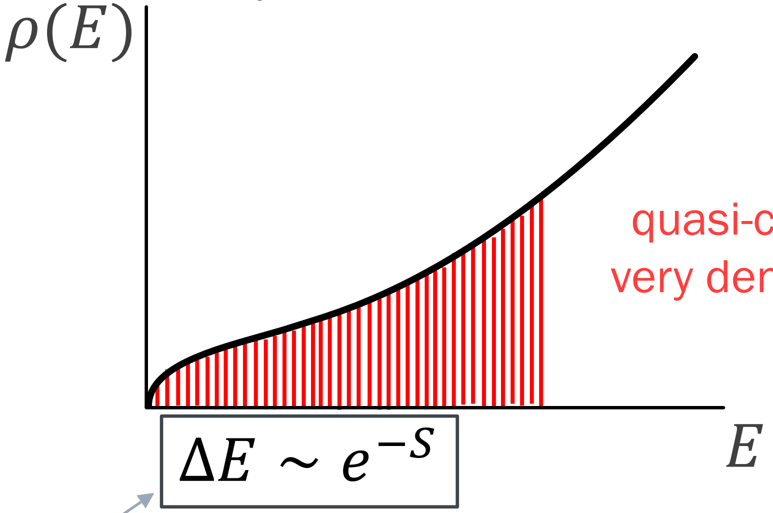
Black Hole Transparency

The Black Hole is there,

but it casts no shadow

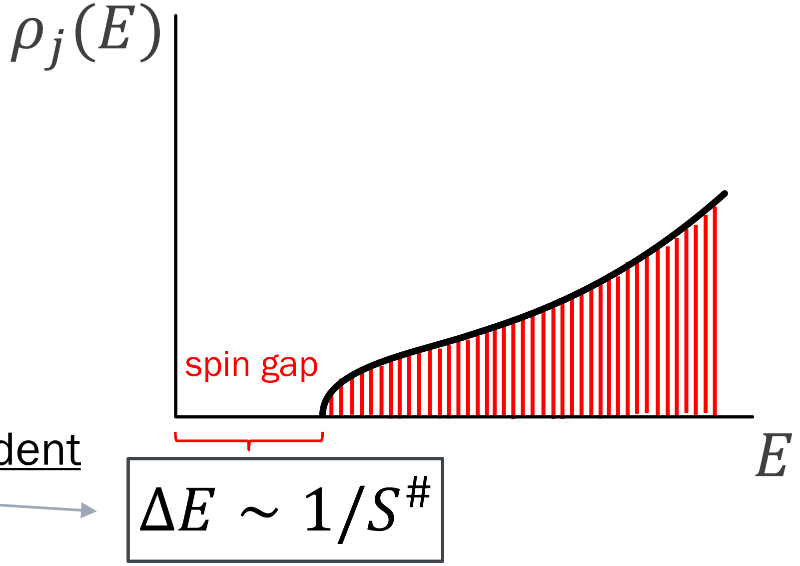
Quantum Black Hole Spectrum

Spinless Black Hole



requires detailed UV microscopics
(string theory)

Spinning Black Hole



<u>calculable UV-independent</u>
quantized gravity

Probing further

- Static probes: tidal deformability & quantum Love

  In progress
  w/ S Trezzi+P Cano+M David

- Decoherence by near-extremal black holes

  To appear A Biggs+S Trezzi

- Emission/absorption for near-BPS black holes

  Heydeman+Iliesiu+Turiaci+Zhao
  Lin+Iliesiu+Usatyuk

In Closing

Do Black Holes behave like ordinary quantum systems?

Unitarity Paradoxes

Near-Zero-Temperature Paradoxes

In Closing

Extremely cold black holes behave like genuine quantum systems

Near zero temperature: like systems in the lab

- $S \to 0$ as $T \to 0$ (without supersymmetry)
- Spectrum, absorption & emission under quantum control

In Closing

Can we observe large quantum fluctuations of the spacetime geometry?

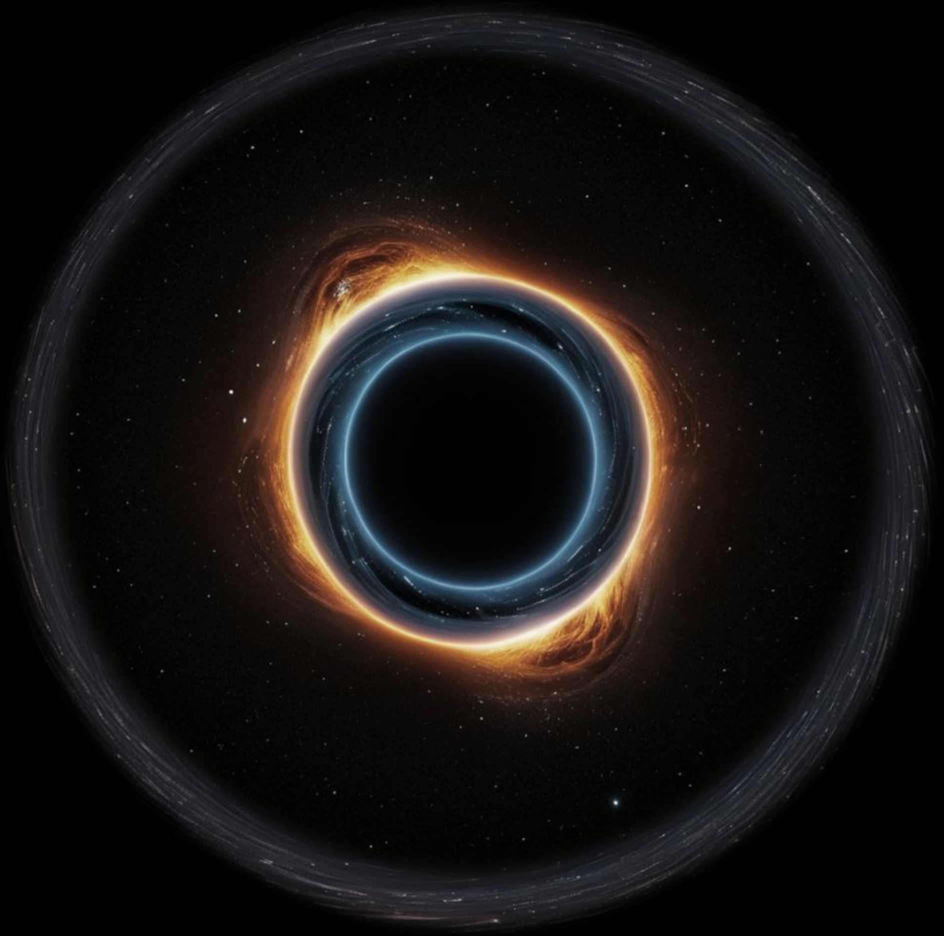
Yes

In Closing

Enhanced cross-section of scalar fields

Transparency to photons and gravitons

are distinct quantum gravity signatures



Thank you

Backup material

Classical formation: collapse

- Collapse of charged matter can be fine-tuned to land on "classical extremal black hole" in finite time

  Kehle+Unger

  which doesn't exist!

- Correct interpretation: Can form *near-extremal* black hole within a classical timescale

  preparation time will be ~ $1/E_b \propto 1/\hbar$

Absorption & emission rates

$$\Gamma_{abs}(\omega) = \langle N_\omega \rangle \frac{2r_+^2\omega}{\pi} |\langle E_i + \omega | \mathcal{O} | E_i \rangle|^2 \rho(E_i + \omega)$$

$$\Gamma_{emit}(\omega) = \langle N_\omega \rangle \frac{2r_+^2\omega}{\pi} |\langle E_i - \omega | \mathcal{O} | E_i \rangle|^2 \rho(E_i - \omega)$$

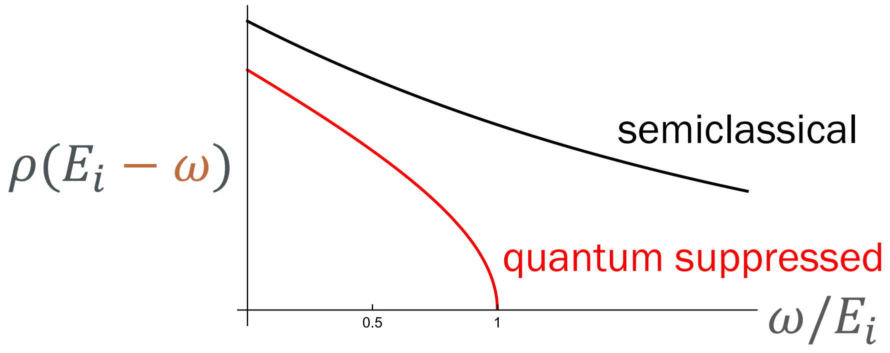
$$= -\Gamma_{abs}(-\omega)$$

Total absorption rate per mode:

$$\frac{d\langle N \rangle}{dt\, d\omega} = -\big(\Gamma_{abs}(\omega) - \Gamma_{emit}(\omega)\big)$$

Stimulated emission is suppressed: many fewer final states

$$\Gamma_{emit}(\omega) \propto |\langle E_i - \omega|\mathcal{O}|E_i\rangle|^2 \rho(E_i - \omega)$$



No throat disruption

- Does absorption become so large as to destroy the quantum throat?

  Not if $\langle N_\omega \rangle < S_0^2$

- Then we can comfortably probe the quantum regime

$$\omega, E_i < E_b$$

with $\langle N_\omega \rangle \gg 1$

Quantum η/s?

- $\left(\frac{\sigma_{abs}}{A_H}\right)_q > 1 \;\Rightarrow\; \left(\frac{\eta}{s}\right)_q > \frac{1}{4\pi}$?

Be careful:

naive hydro regime requires wavelength $\lambda > \frac{1}{T}$ $\Rightarrow$ brane length $L > \frac{1}{T}$

$\Rightarrow L\, r_h < \ell_p^2$: subPlanckian

- May still compute small quantum corrections

Pando-Zayas+Zhang

Cremonini+Li+Liu+Nian

+ others (Dec 2025)