ICELAND NEAR HORIZON

NOT SO COLD

MIDNIGHT 01/06/2026

Probing Quantum Gravity in Extremely Cold Horizons

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34TH NORDIC NETWORK MEETING ON STRINGS, FIELDS & BRANES

REYKJAVÍK, 3 JUNE 2026

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN

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

Love at First Loop

w/ Pablo Cano, Marina David, Stefano Trezzi

to appear

Can we observe large quantum fluctuations of the spacetime geometry?

Can we probe quantum gravity near the horizon of a black hole?

This requires a breakdown of semiclassical QFT

in curved space

Typically studied near singularities, not outside

large black holes

The gigantic scale challenge

For a solar-mass black hole:

Schwarzschild horizon: $r_H \sim 3$ km

Planck length: $\ell_P \sim 10^{-33}$cm

$$\ell_P / r_H \sim 10^{-38}$$

This alone explains why horizon-scale quantum-gravity is hard to find

The gigantic scale challenge

Large fluctuations when specific heat is small, $C = O(1)$

$$C \sim T\, r_H \left(\frac{r_H}{\ell_P}\right)^2$$

Schwarzschild BH: $T\, r_H \sim 1$ $C \gg 1$

Near extremality as a magnifying glass

Large fluctuations when specific heat is small, $C = O(1)$

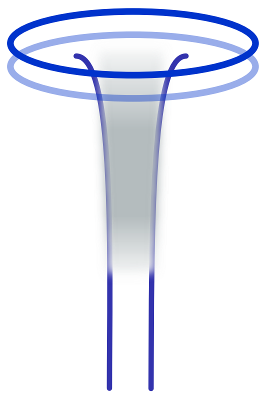
$$C \sim T\, r_H \left(\frac{r_H}{\ell_P}\right)^2$$

Schwarzschild BH:	$T\, r_H \sim 1$	$C \gg 1$
Near extremal BH:	$T\, r_H \ll 1$	arbitrarily small $C \searrow O(1)$

Near extremality as a magnifying glass

Near extremality, black holes have *large but tractable* quantum fluctuations of a geometric mode

The length of the throat has large quantum variance



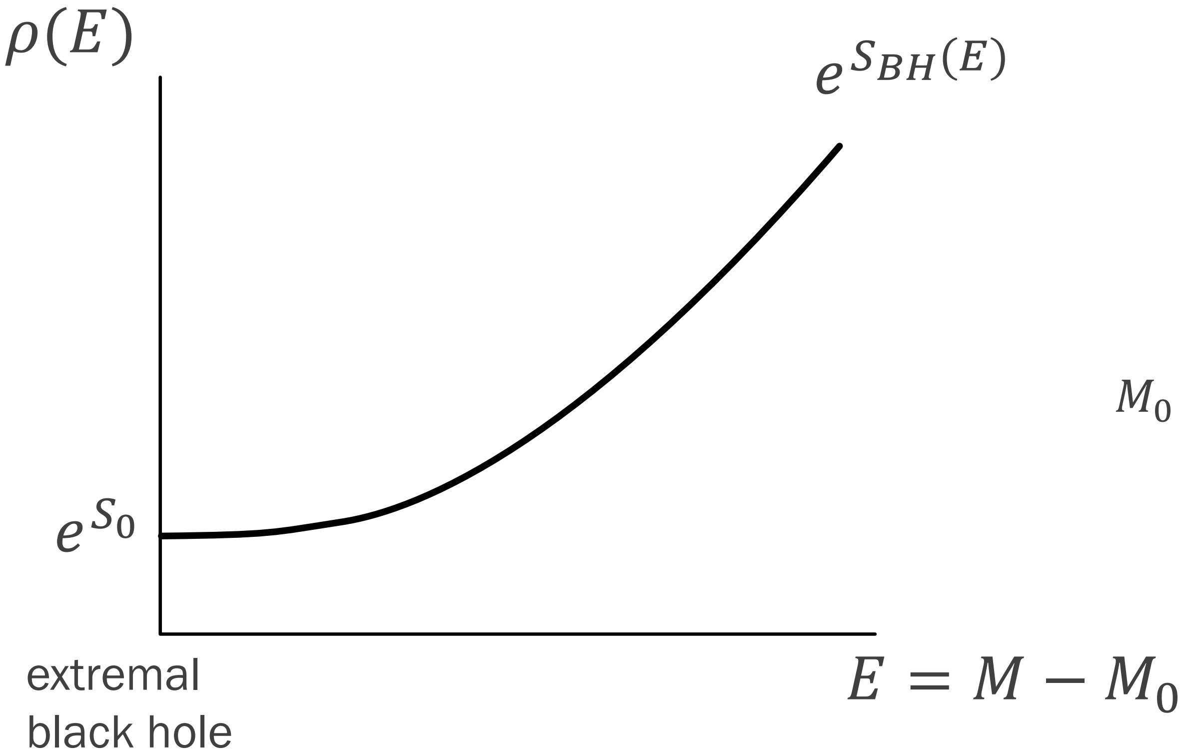
curvature remains small

Near extremality as a magnifying glass

This is the best controlled mechanism by which quantum horizon physics can evade conventional decoupling

The spectre of Bekenstein & Hawking

number density of black hole states



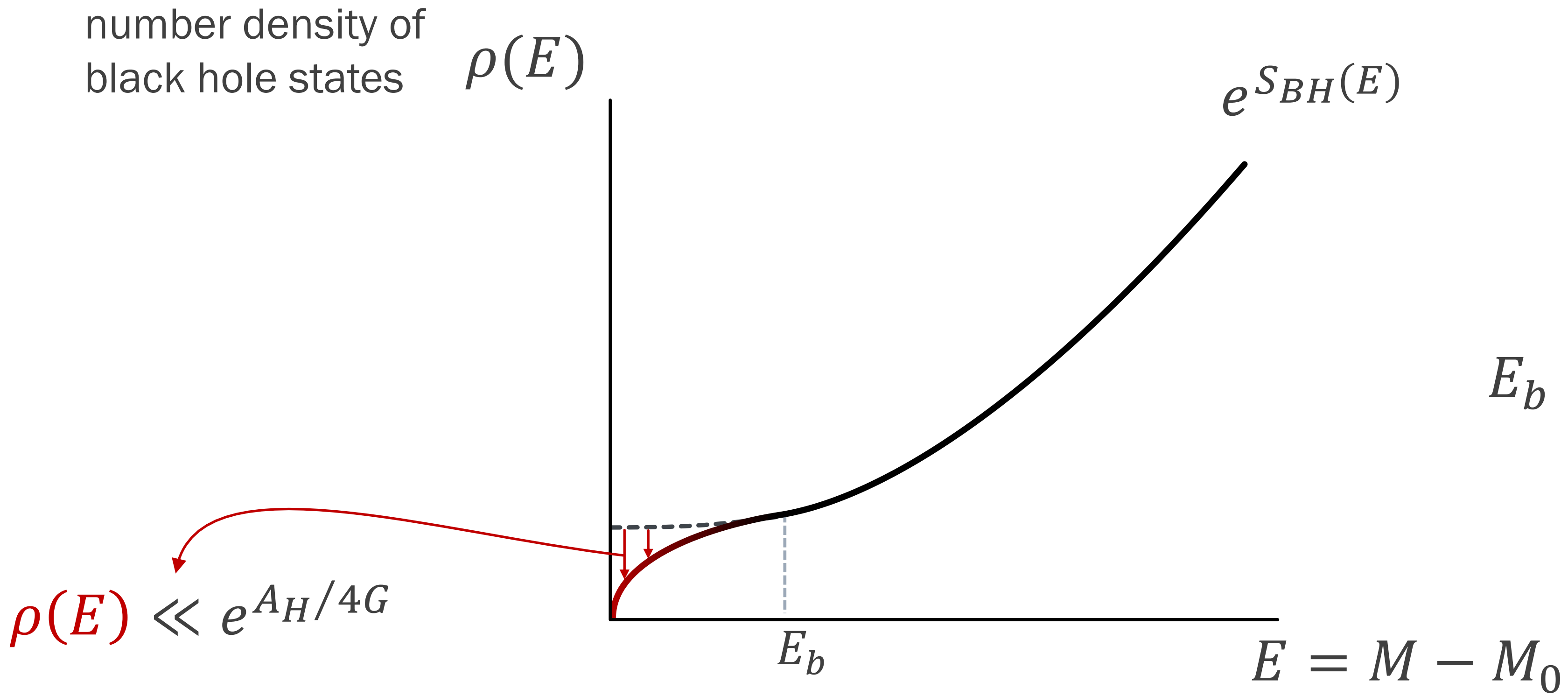
M_0 = extremal bh mass

huge density of ground states

<u>Worrisome</u>

Quantum Black Hole spectrum*

*non-supersymmetric

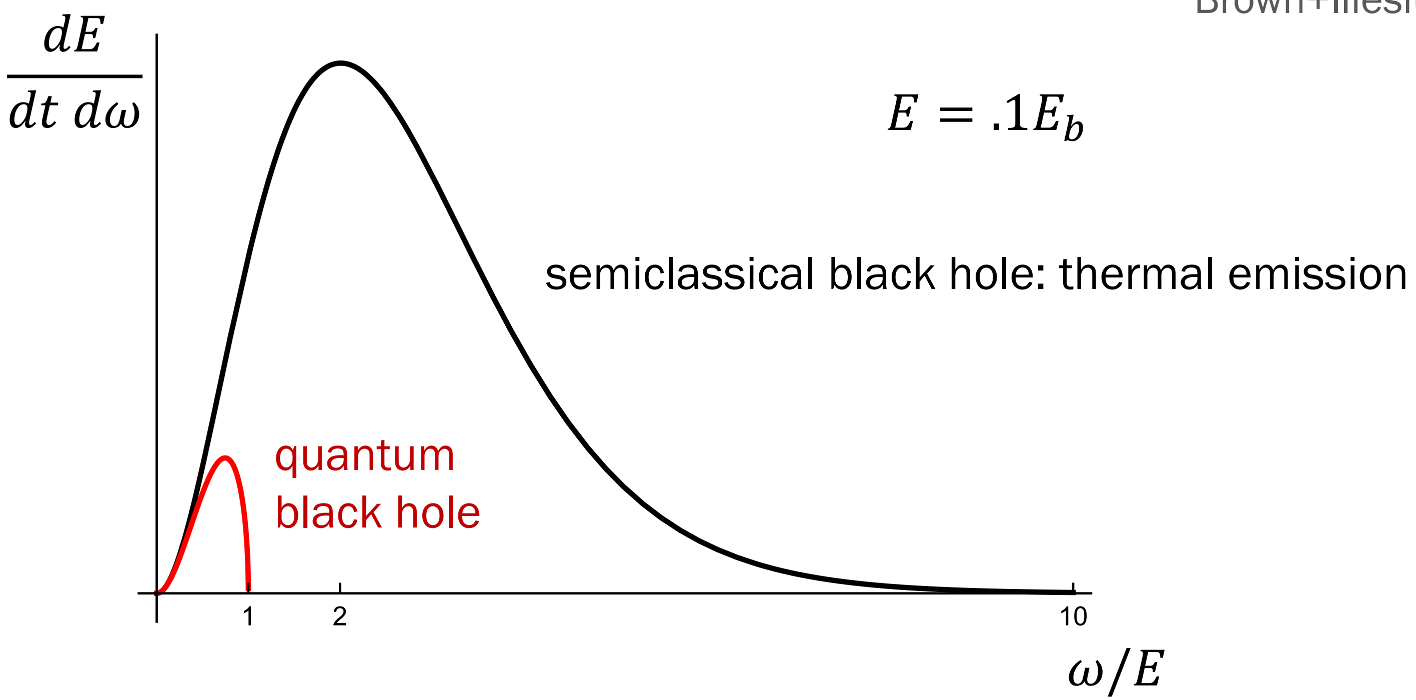


Iliesiu+Turiaci 2020

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

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 $T \to 0$

eg $\Delta S \sim \hbar \log T$

A lesson

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

A lesson

Supersymmetric extremal black holes exist, but are

highly quantum objects

Non-supersymmetric extremal black holes *do not exist*

A lesson

But don’t throw *all* classical extremal black hole results

in the trash just yet

Reconsider them at small $T \neq 0, \hbar \neq 0$

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

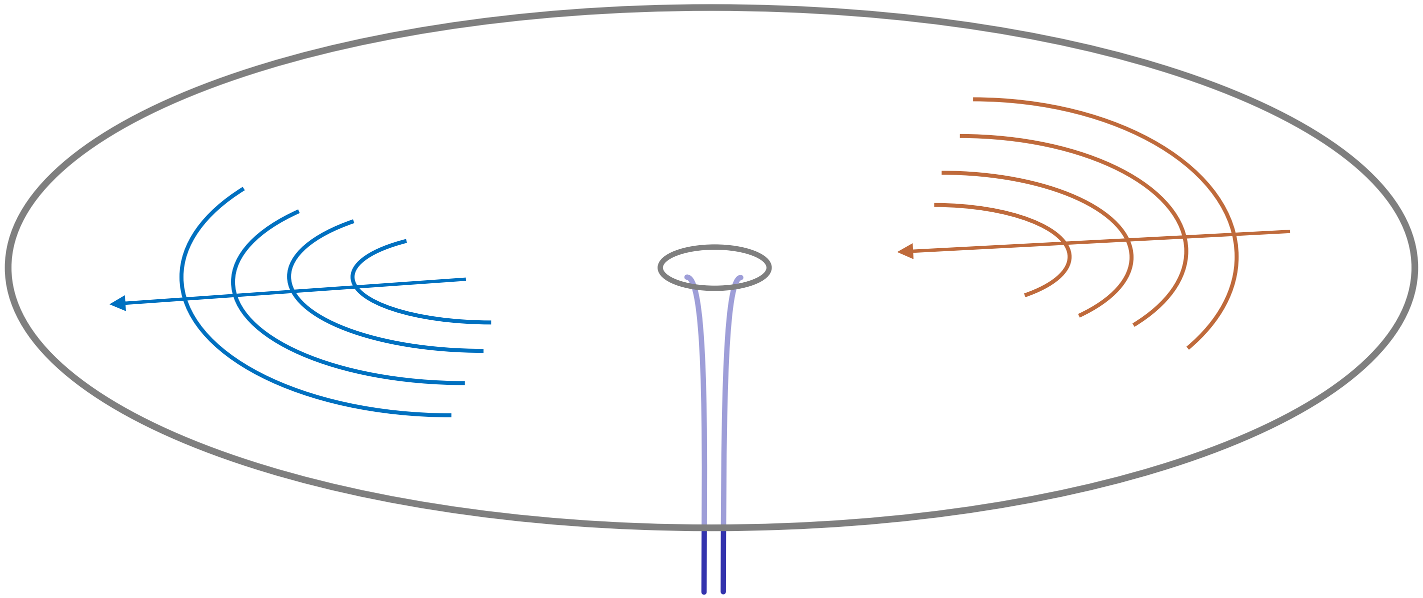
$T \sim 10^{-83} K$

Shining light on the Black Hole

Send a wave to the black hole

Measure the absorption cross-section

Softly probe the mouth of the throat



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

What we also find

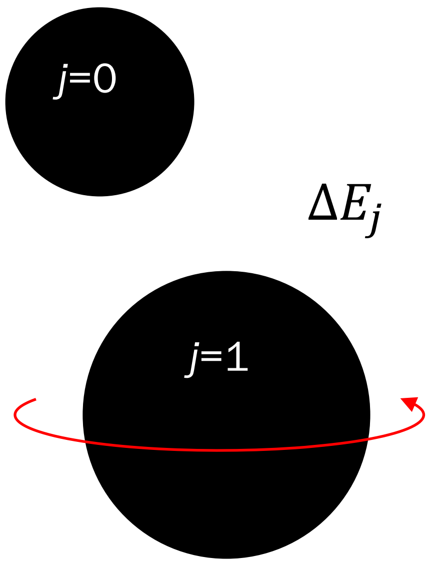
Near-extremal black holes are **transparent** to

electromagnetic and *gravitational* radiation

below a frequency threshold

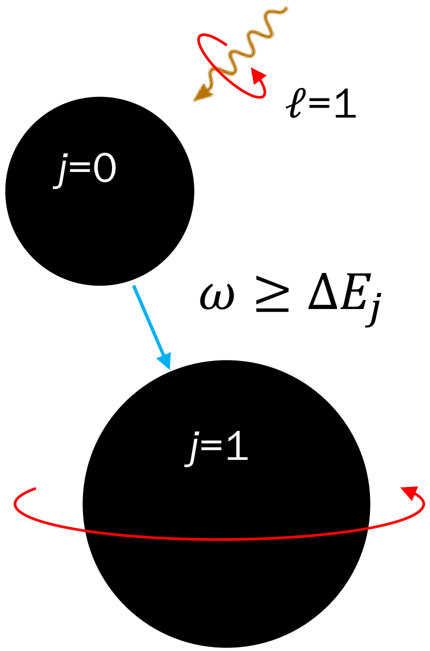
How come *transparent* black holes?

- 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



Finding Love at first loop

Tidal deformability

Set up a static deforming field far from the black hole

Measure the deformation of the geometry around the black hole

Stress-strain linear response coeffs = **Love numbers**

Measurable from inspiral in binaries

Finding Love at first loop

Love numbers vanish for classical Schwarzschild & Reissner-Nordström black holes

We find that quantum fluctuations induce non-zero deformability in near-extremal black holes

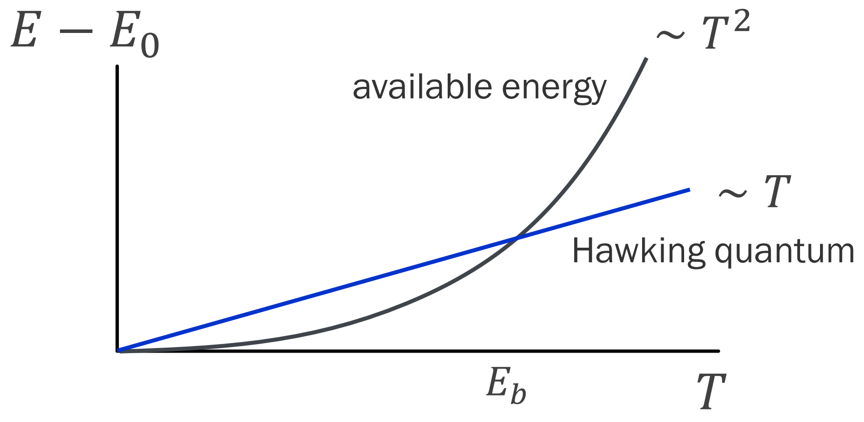
Quantum Deep Throats

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

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

$\Rightarrow$ *Semiclassical thermodynamics breaks down*

Preskill+Schwarz+Shapere+Trivedi+Wilczek

Near extremality

QFT in curved spacetime breaks down
even if curvatures are small

But we can still control the physics

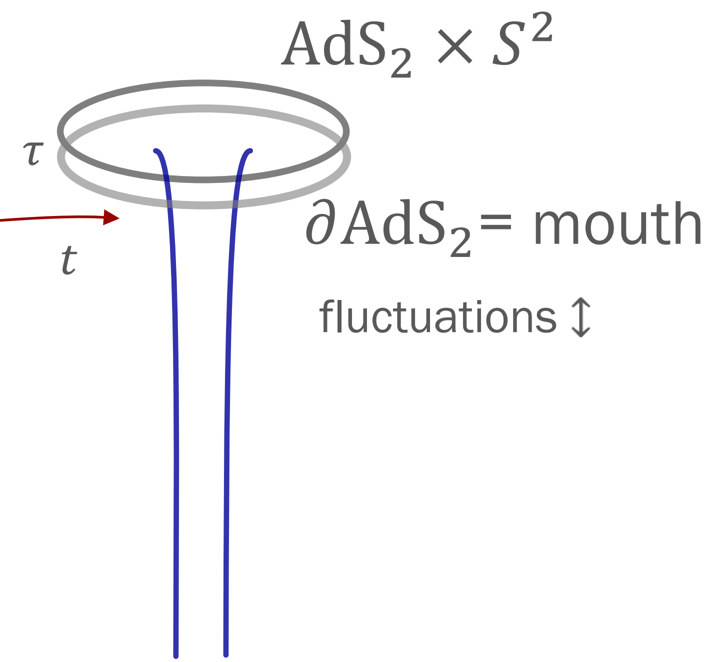
Throat theory

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

Throat KK reduction ⟶ 2D JT-dilaton gravity ⟶ 1D 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

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

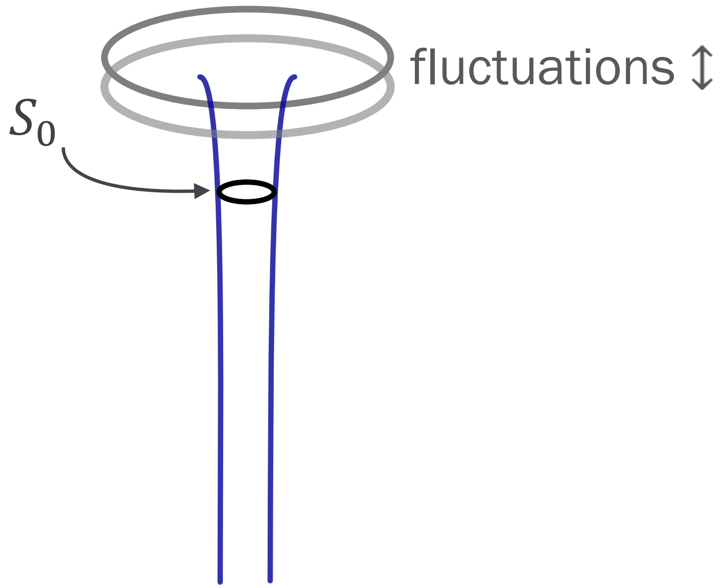
$$= e^{S_0 + 2\pi^2 \frac{T}{E_b}} \left(\frac{T}{E_b}\right)^{3/2}$$

semiclassical Gibbons-Hawking

quantum fluctuations of throat

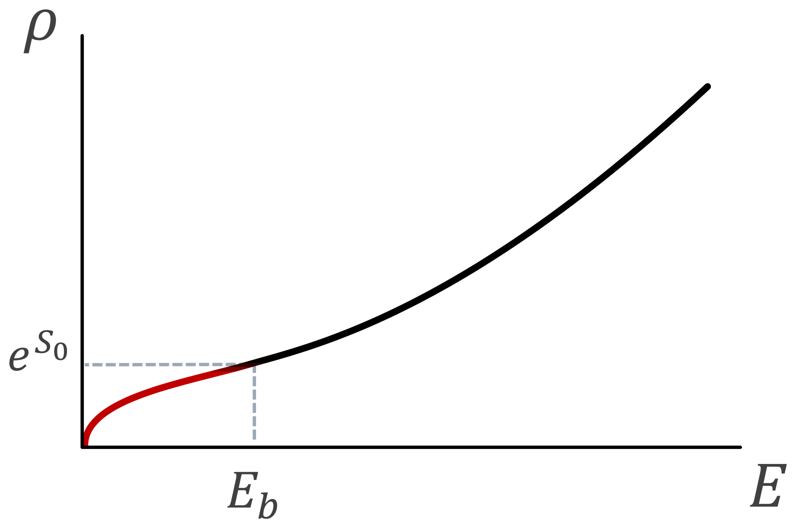
⇓

large effect when $T \lesssim E_b$



Density of states near extremality

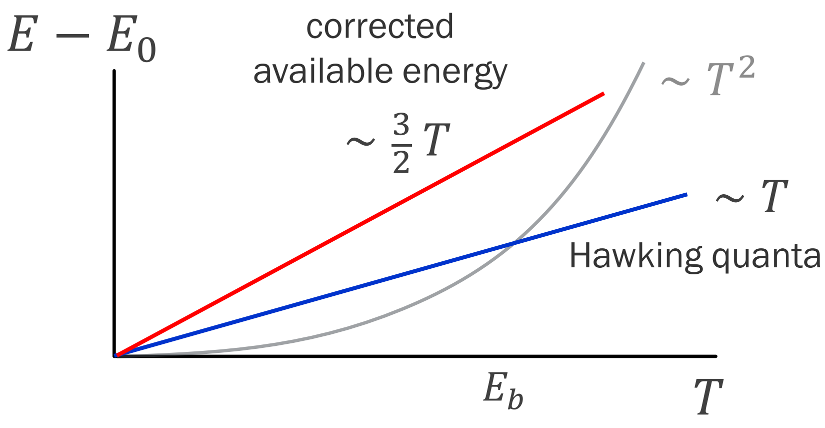
$$\rho(E) = e^{S_0} \sinh\left(2\pi\sqrt{2E/E_b}\right)$$

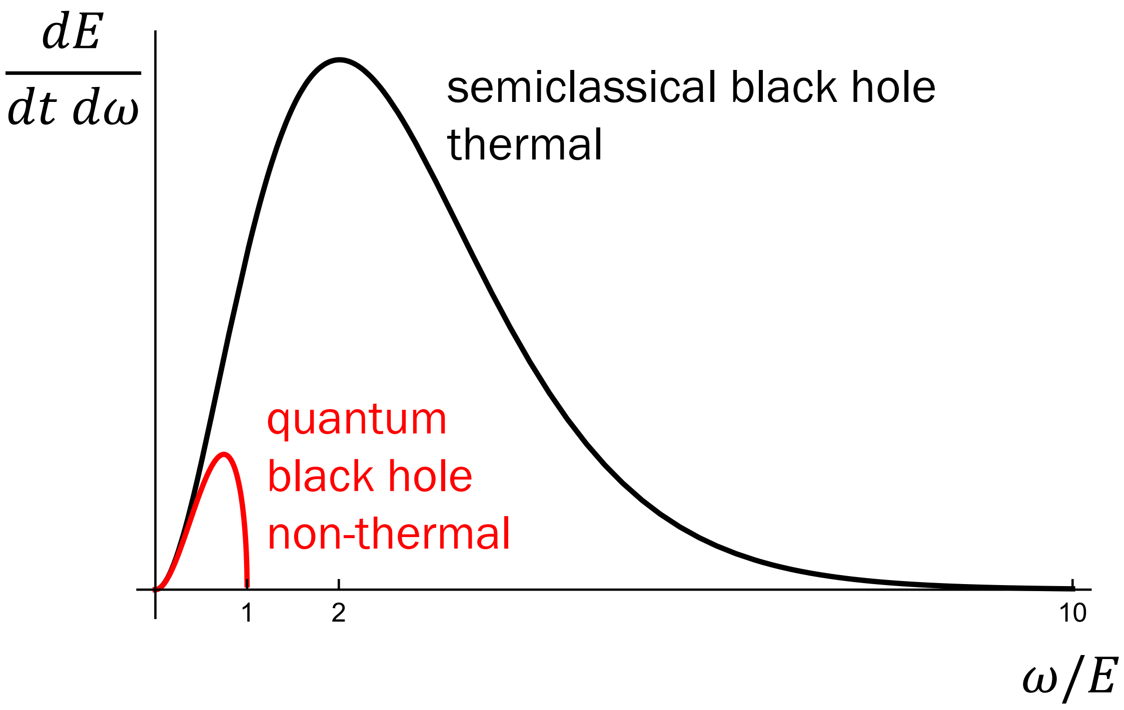


$$E_b = \frac{\pi}{r_h S_0}$$

$$E = M - M_0$$

Radiation near extremality



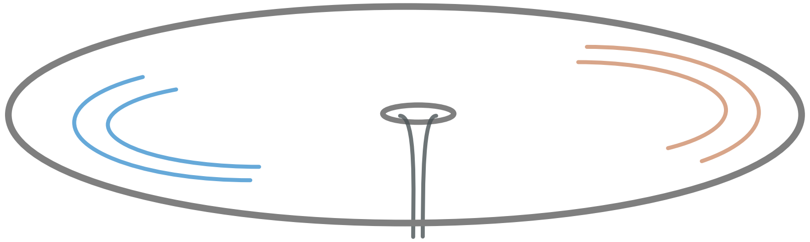


Is the Black Hole Still There When We Look?

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

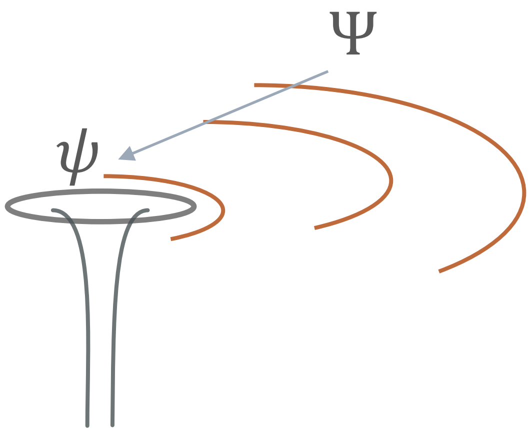
$$E_b = \frac{\pi}{r_h S_0} \qquad M = M_0 + E_i$$

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



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

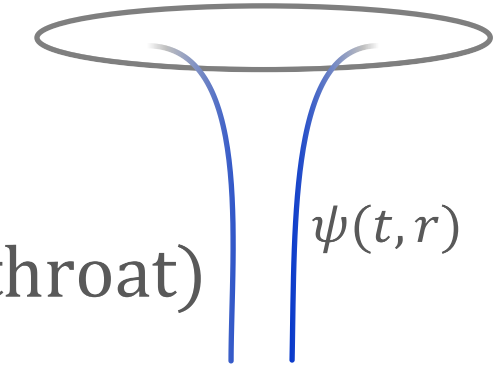
$\mathcal{O}_\Delta(t)$: response operator

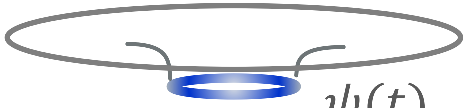
Brown+Iliesiu+Penington+Usatyuk

Quantum Throat

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

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

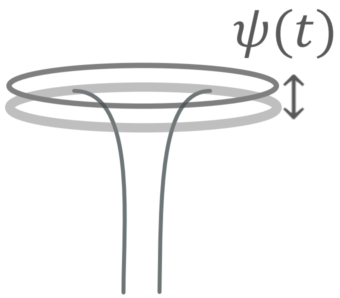




$|E\rangle$ state of Schwarzian theory

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:

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

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

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

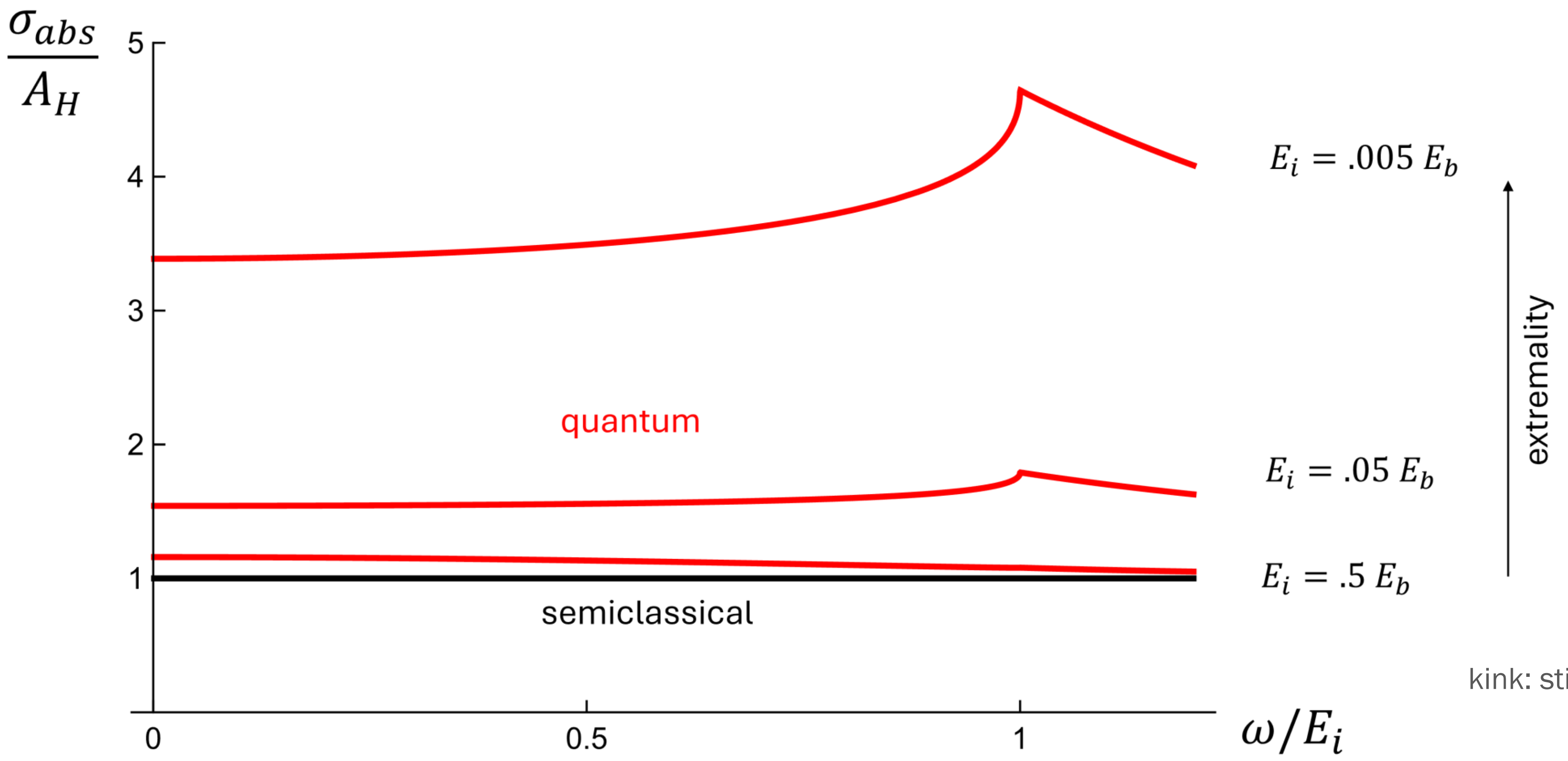
known from Schwarzian theory

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: $E_i \gg \omega, E_b$ $\quad \sigma_{abs} \to A_H$

Quantum absorption $\sigma_{abs} > A_H$

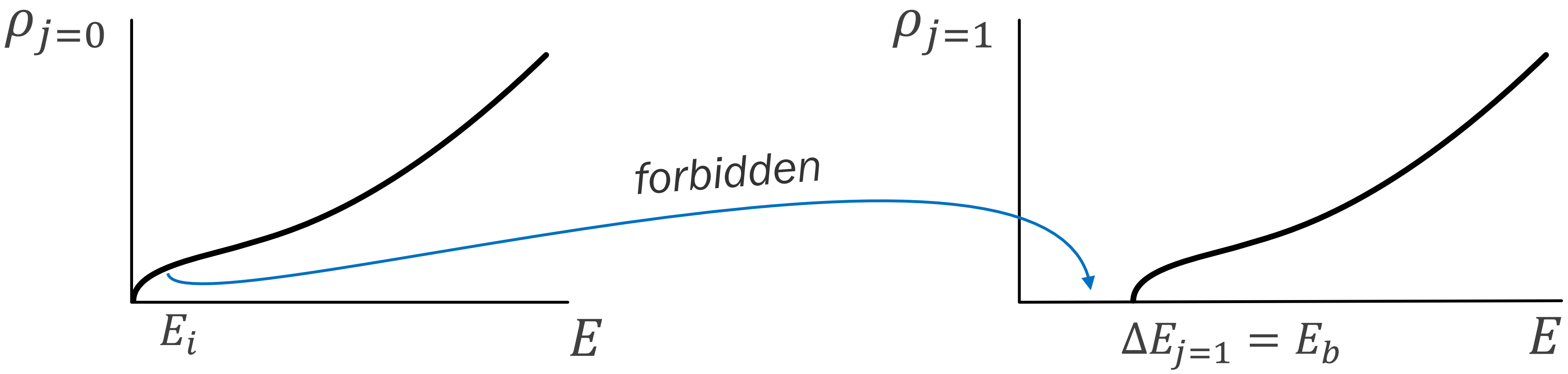


kink: stimulated emission stops

Photon & Graviton absorption

Spinless BH $\longrightarrow$ Spinning BH: gapped

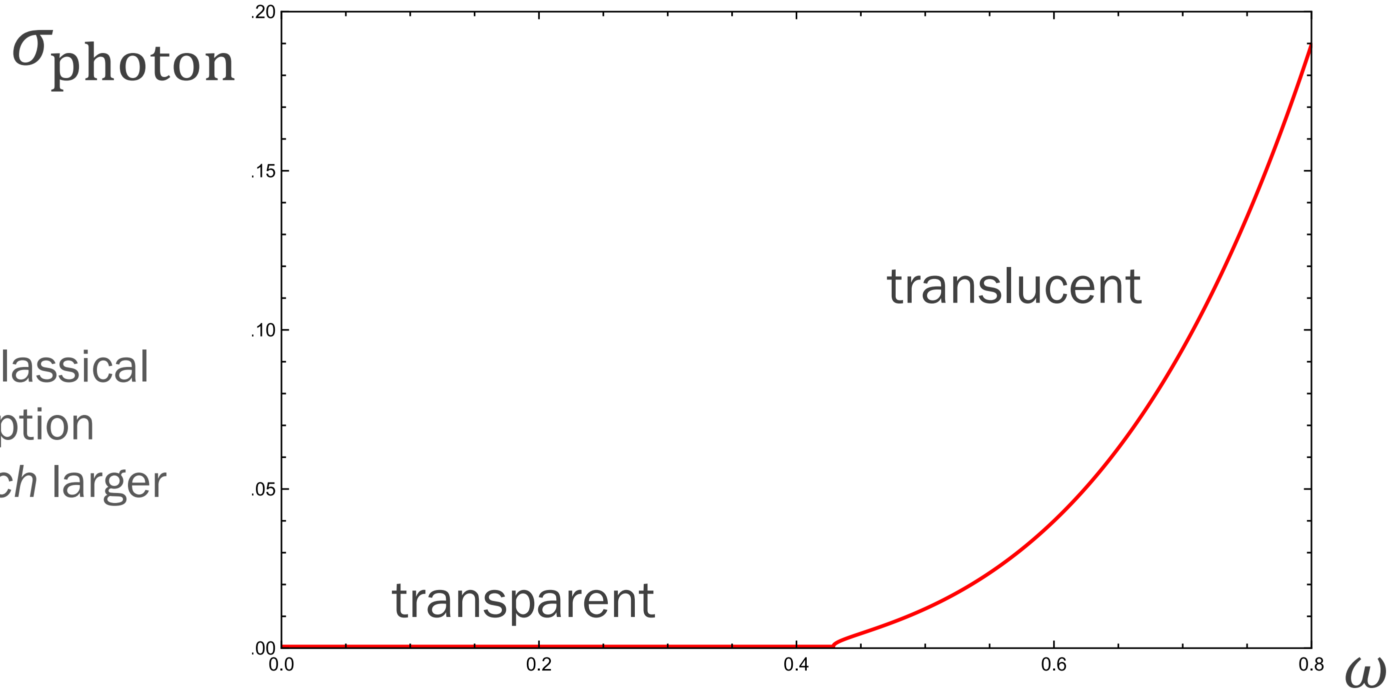
$$\Delta E_j = \frac{G\, j(j+1)}{2 r_0^3}$$



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

w/ Stefano Trezzi

Black Hole Transparency & Translucency



semiclassical
absorption
is *much* larger

w/ Stefano Trezzi

Quantum Love

To appear

w/ P Cano+M David+S Trezzi

Love numbers: linear response coefficients

Real part of retarded two-point function at zero frequency

More generally, also dynamic and dissipative Love numbers

Quantum Schwarzian 2-pt function yields non-zero Love numbers for all multipoles

Probing further

- Decoherence induced by black holes — Danielson+Satishchandran+Wald

  Transparent black holes *do not decohere* — 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 do behave like genuine quantum systems

Near zero temperature: like systems in the lab

- $S \to 0$ as $T \to 0$ (without supersymmetry)
- Spectrum, absorption & emision, deformability, 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

Non-zero Love numbers

are distinct signatures of quantum gravity near a horizon

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

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

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

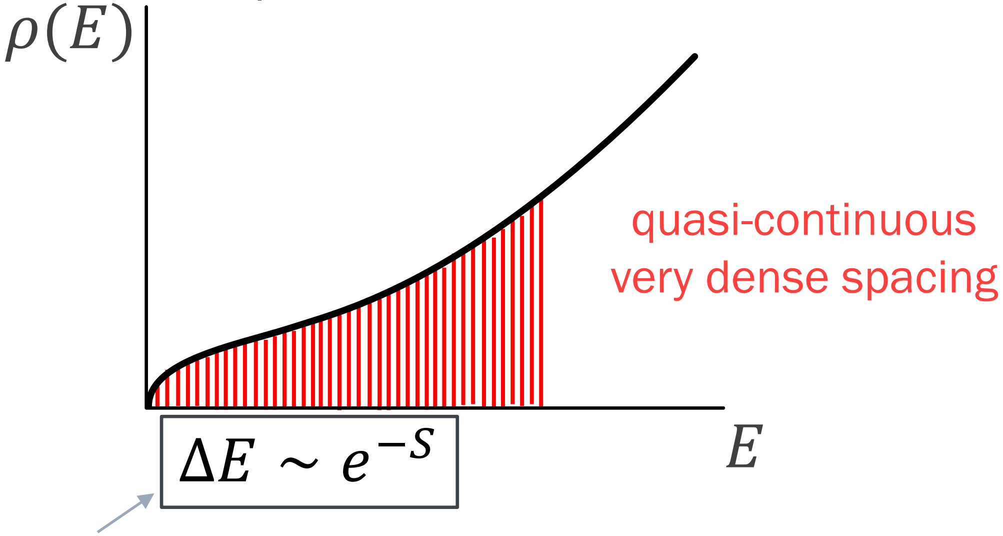
$$= -\Gamma_{abs}(-\omega)$$

Total absorption rate per mode:

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

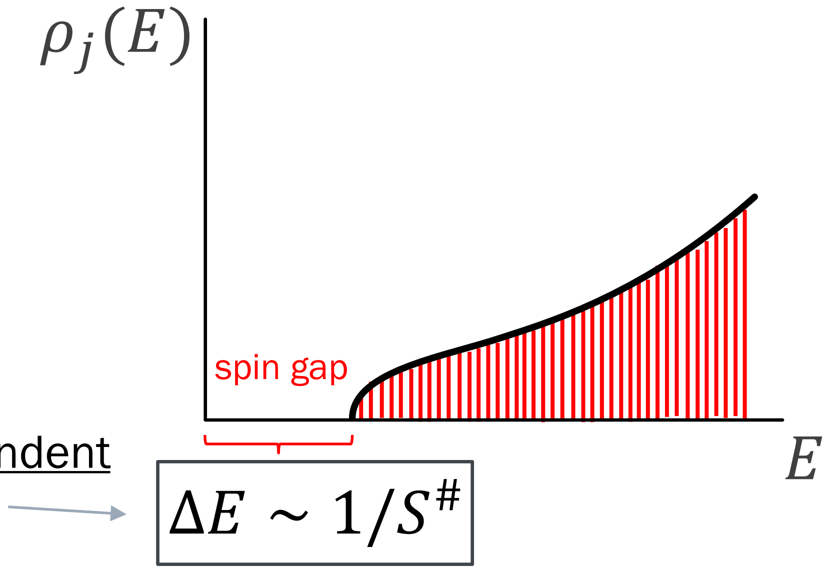
Quantum Black Hole Spectrum

Spinless Black Hole



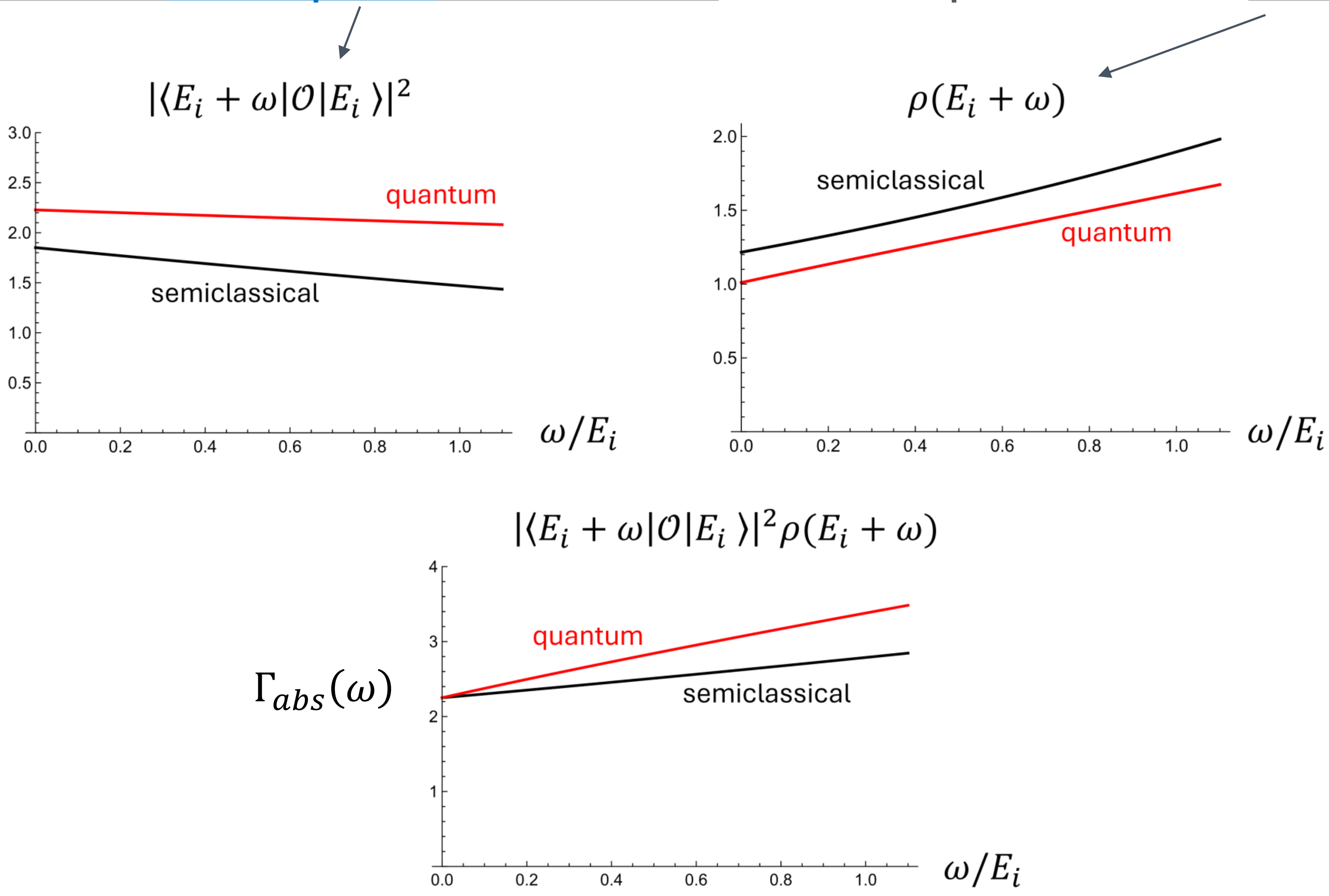
requires detailed UV microscopics
(string theory)

Spinning Black Hole



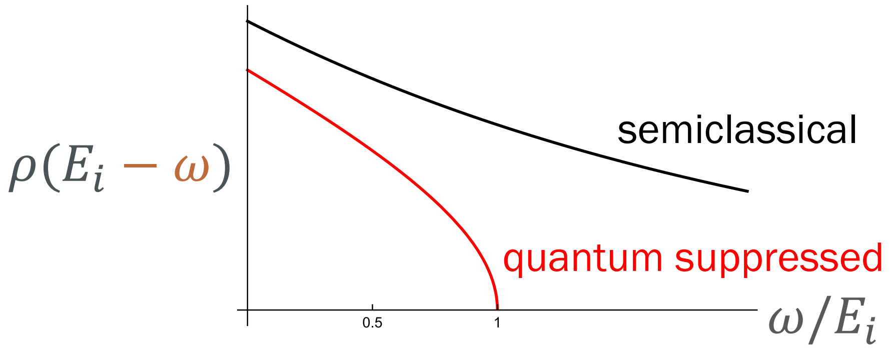
calculable UV-independent
quantized gravity

Enhanced absorption transitions overcompensate for fewer states



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