FLUCTUATIONS NEAR A COLD HORIZON
(ICELAND MIDNIGHT)

Observing Quantum Gravity at Macroscopic Horizon Scales

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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

Love at First Loop

w/ Pablo Cano, Marina David, Stefano Trezzi

to appear

Why discuss horizon-scale quantum gravity?

Quantum-mechanical description of black holes demands O(1) modifications where EFT breakdowns are not expected, since all local, diff-invariant quantities are well behaved

Why discuss horizon-scale quantum gravity?

Is it possible at all?

Does it require radically new physics?

Why discuss horizon-scale quantum gravity?

Is it possible at all?

Yes

Does it require radically new physics?

No

The gigantic scale challenge

Expected size of quantum gravity effects at horizon is

$$(\ell_P/r_H)^2 \ll 1$$

For stellar-mass BH this is $\sim 10^{-76}$

This alone explains why horizon-scale quantum-gravity phenomenology is hard

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: $T\, r_H \sim 1$ $C \gg 1$: Tiny fluctuations

The gigantic scale challenged

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 $C \searrow O(1)$

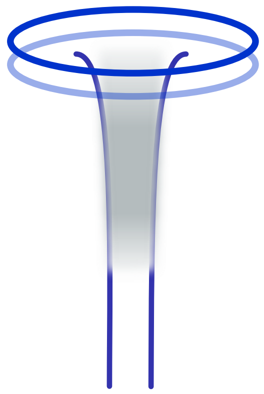
The gigantic scale challenged

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

Near extremality as a magnifying glass

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

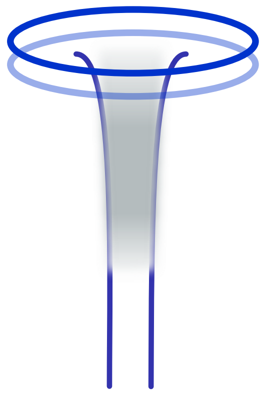
The length of the throat has large quantum variance



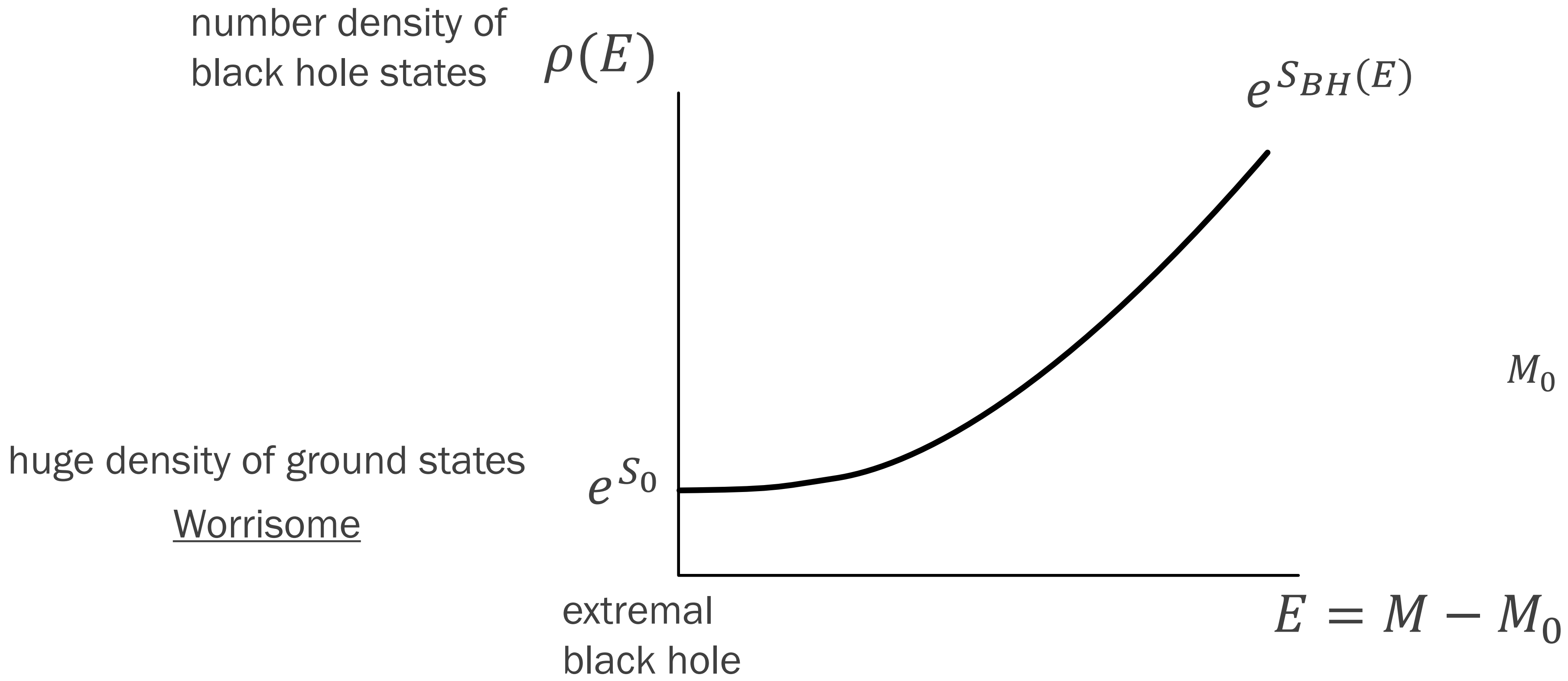
curvature remains small

Quantum trouble shooting

These effects resolve some longstanding puzzles in the quantum physics of black holes



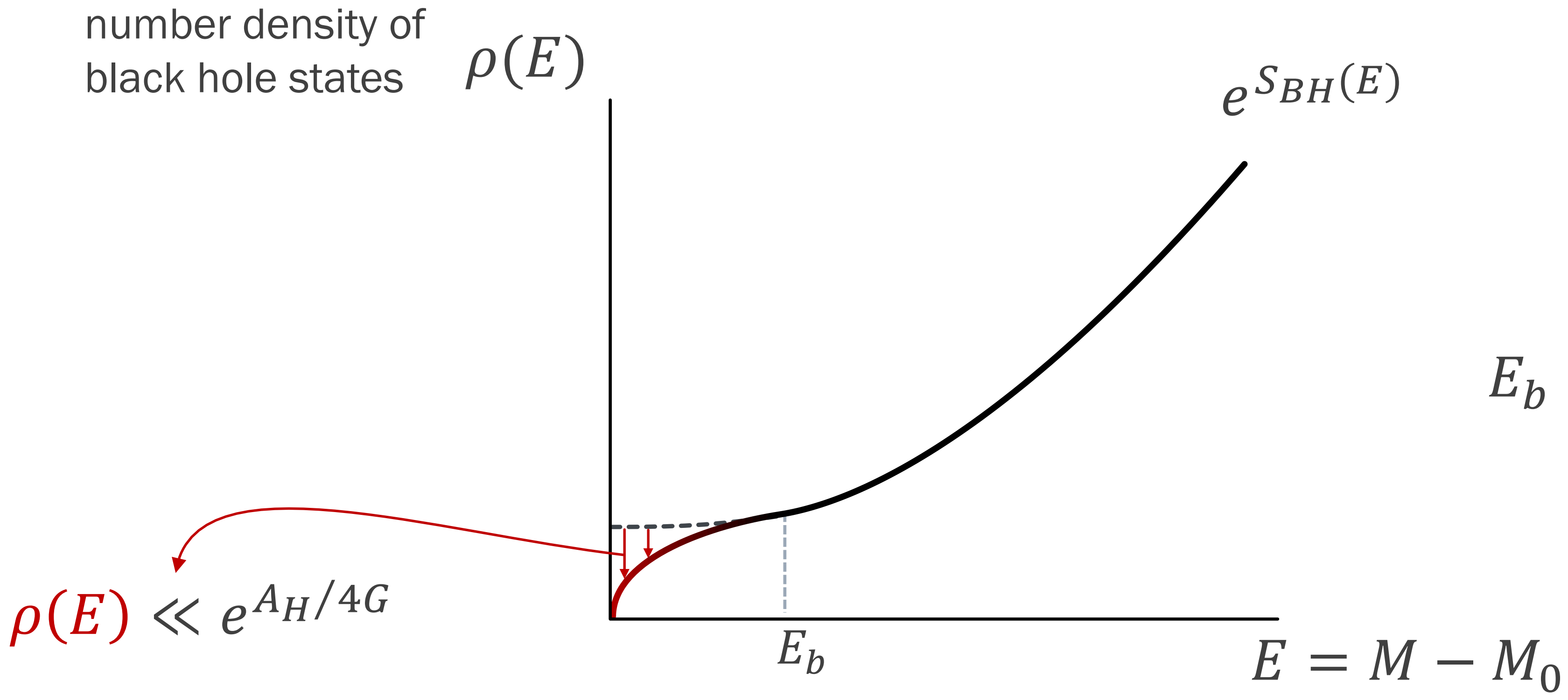
The spectre of Bekenstein & Hawking



M_0 = extremal bh mass

Quantum Black Hole spectrum*

*non-supersymmetric



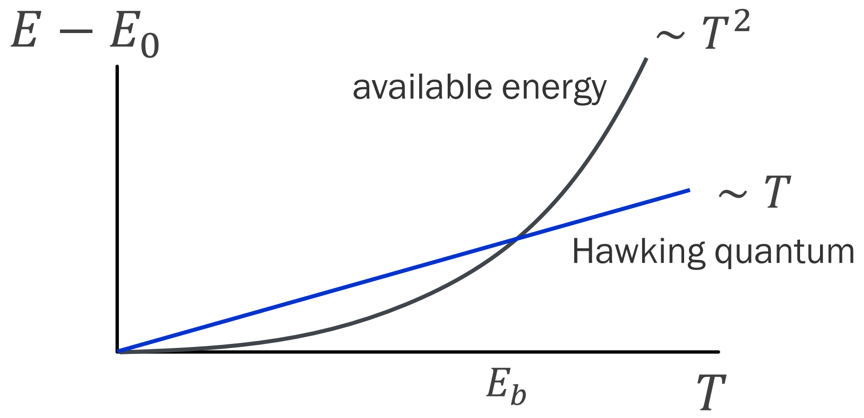
Iliesiu+Turiaci 2020

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

Breakdown 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

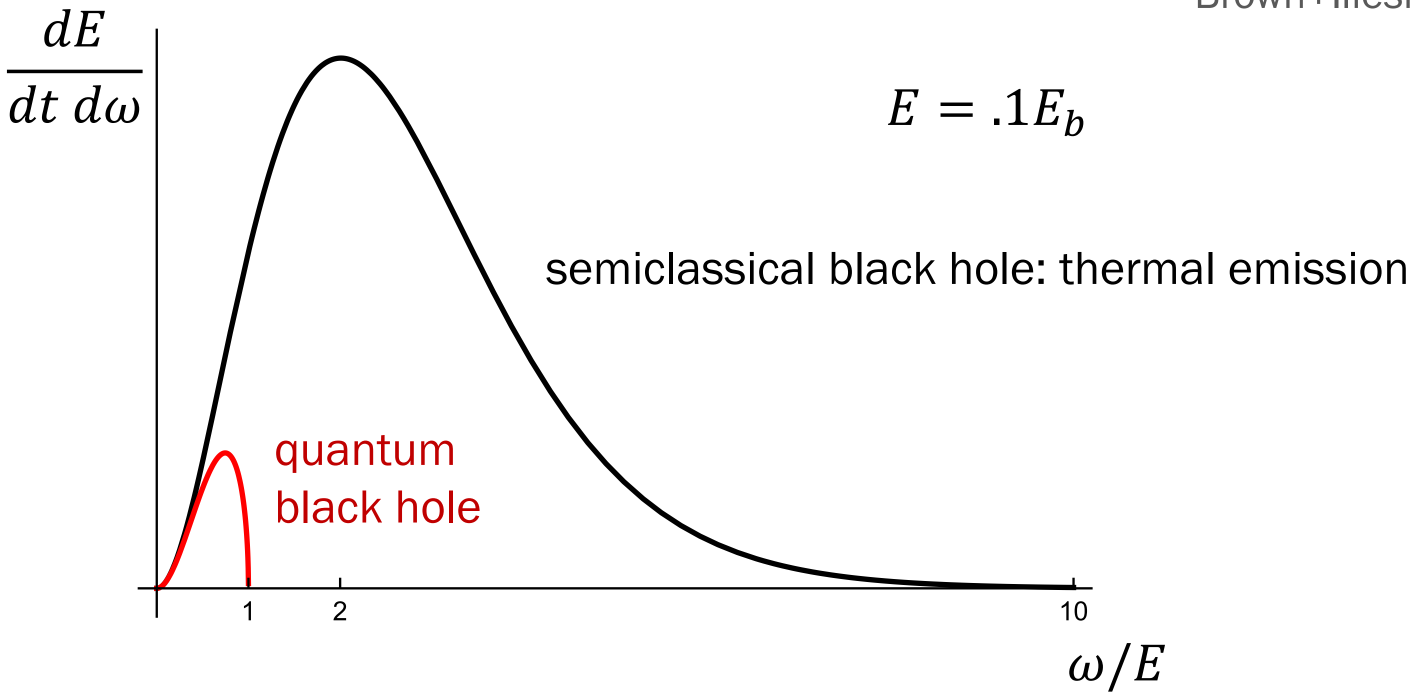
$$E_b = \frac{\pi}{r_h S_0}$$

$\Rightarrow$ *Semiclassical thermodynamics breaks down*

Preskill+Schwarz+Shapere+Trivedi+Wilczek

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.*

No state w/ $M = Q$: energy is lifted

A lesson

But don’t throw <u>*all*</u> classical extremal black hole results

in the trash just yet

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

This includes recent results on “violations of the 3rd law”

Quantum fluctuations near extremality

This does not need String theory, Holography, or any UV Quantum Gravity

It is *conventional* quantum physics *consistently applied* to a very light fluctuation mode – IR Quantum Gravity

A reality check

How cold is extremely cold?

A reality check

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

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

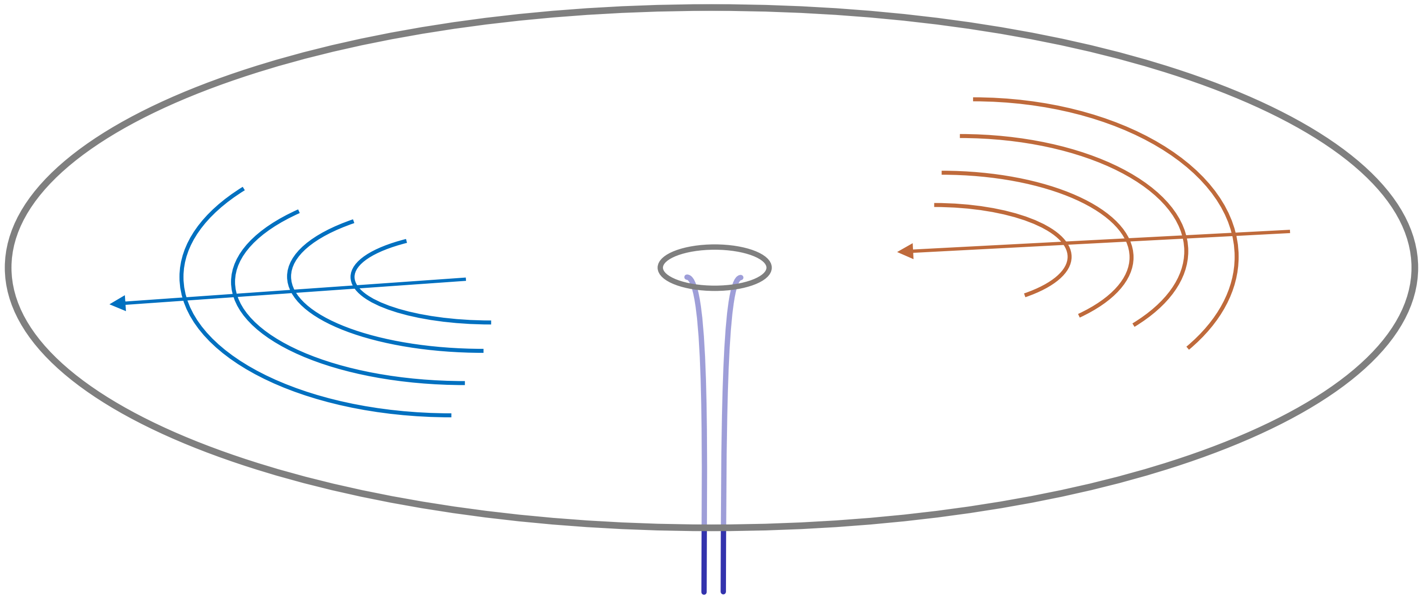
$$T \sim 10^{-83} K$$

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 <u>enhance transitions</u> between individual states

Late-time correlations are enhanced in quantum black hole

What we also find

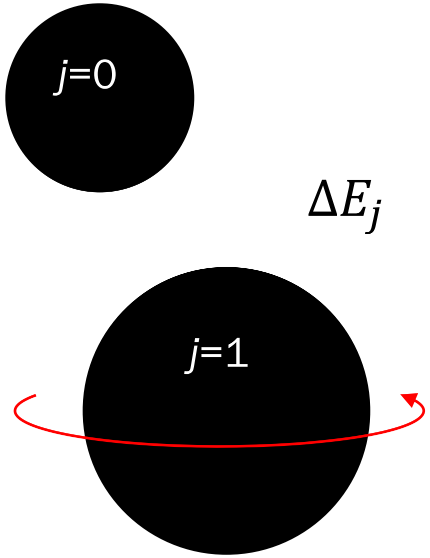
Near-extremal black holes are **transparent** to

electromagnetic and *gravitational* radiation

below a frequency threshold

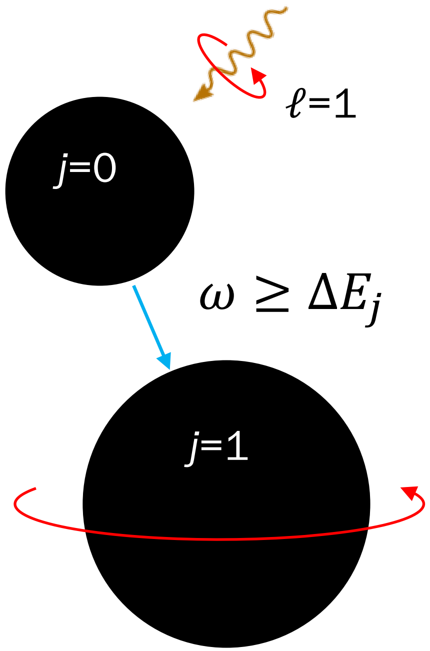
How come *transparent* black holes?

- 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 $\Delta E_j = \frac{G j(j+1)}{2 r_h^3}$
- 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 black hole

Measure the deformation of geometry around lack 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

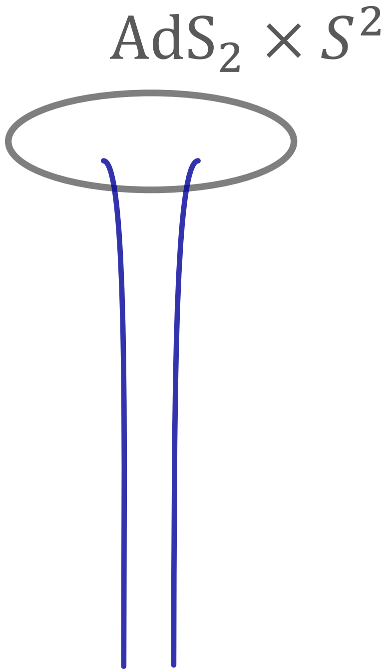
Quantum Deep Throats

HAVE FUZZY MOUTHS

The AdS_2 throat and enhanced IR physics

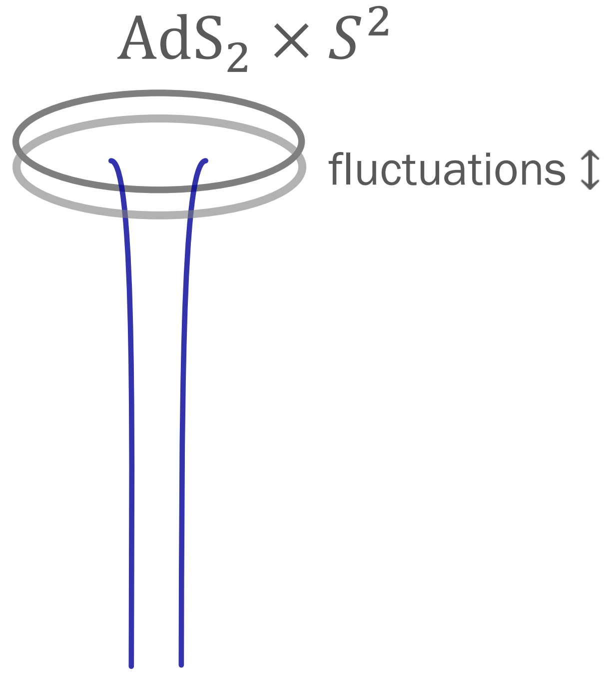
- A long near-horizon throat develops as $T \to 0$
- Two scales: throat width and throat length

(or horizon radius and surface gravity)



The AdS_2 throat and enhanced IR physics

- A long near-horizon throat develops as $T \to 0$
- Two scales: throat width and throat length
- Large quantum fluctuations of a soft geometric mode: nearly-zero-mode of reparametrization of the throat "Schwarzian mode"



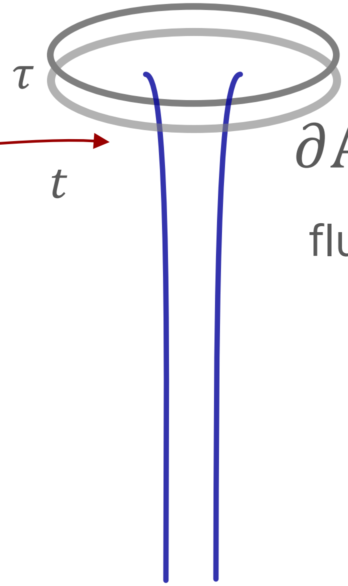
Throat theory

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:

nearly-zero-mode of reparametrizations
of the throat

Gravitational partition function at small T

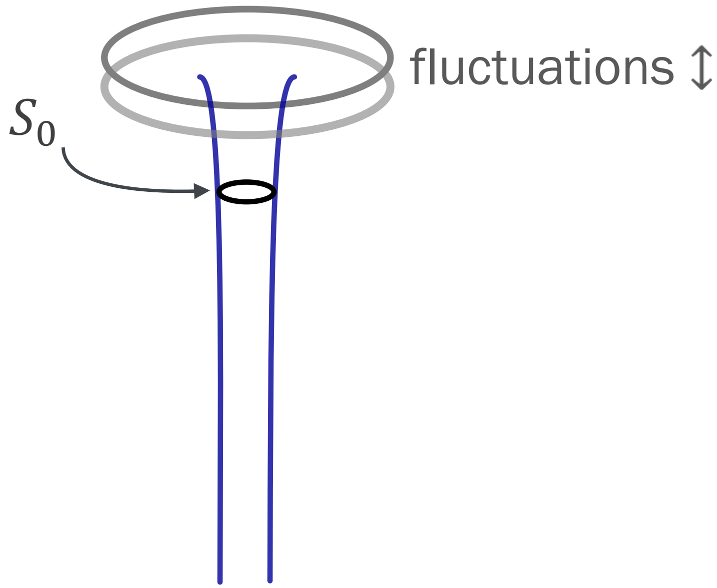
$$Z(T) = e^{-I_{\text{bh}}(T)} \times \overbrace{\det(\mathrm{Q})^{-1/2}}^{\text{one-loop det}}$$

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

$\Downarrow$

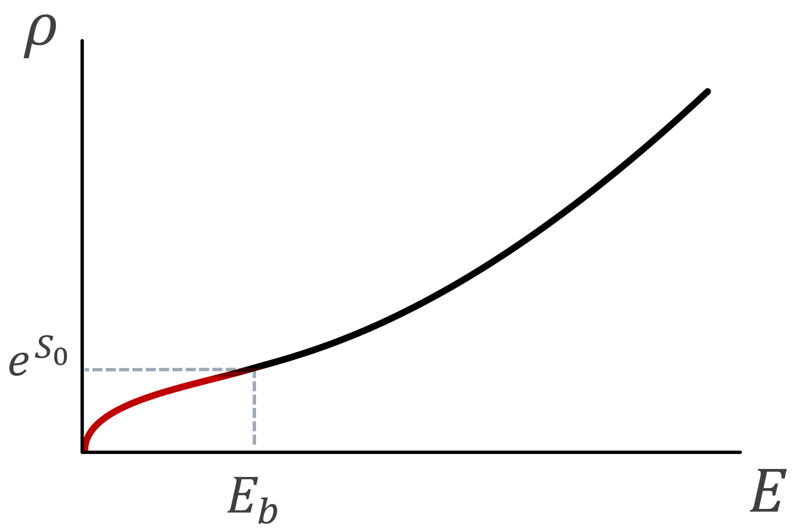
large effect when $T \lesssim E_b$

ensemble inequivalence



Density of states near extremality

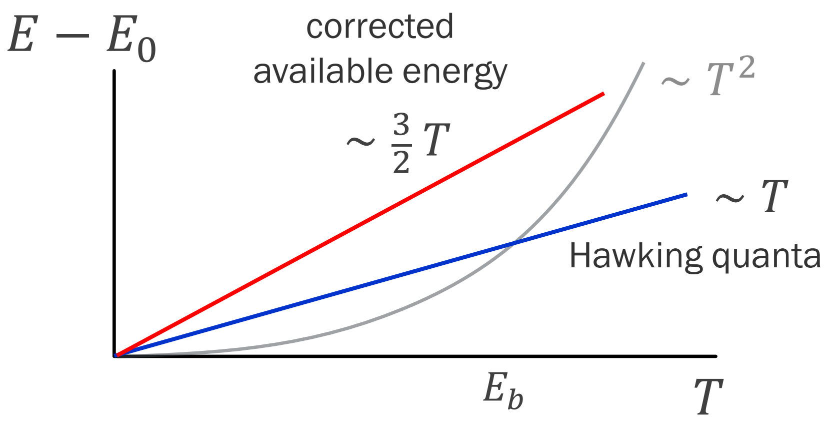
$$\rho(E) = e^{S_0} \sinh\left(2\pi\sqrt{2E/E_b}\right)$$

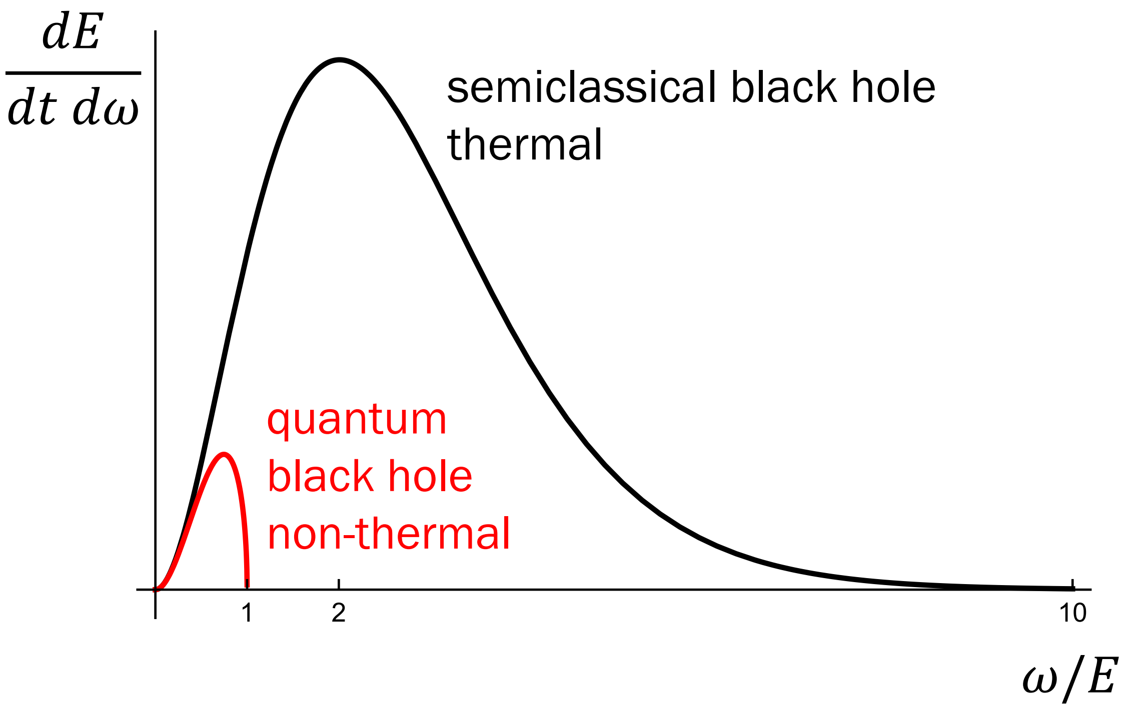


$$E_b = \frac{\pi}{r_h S_0}$$

$$E = M - M_0$$

Radiation near extremality



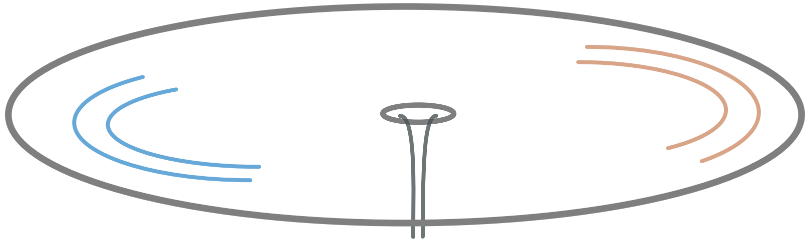


Is the Black Hole Still There When We Look?

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

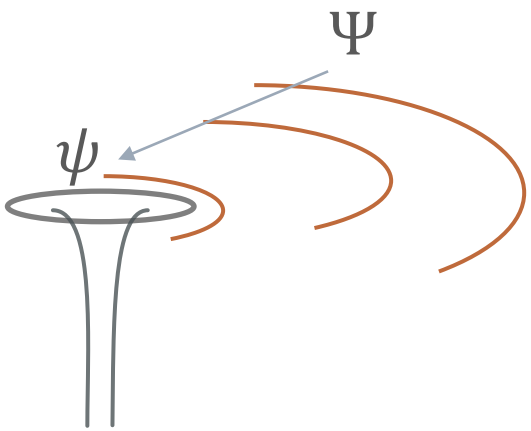
$$E_b = \frac{\pi}{r_h S_0} \qquad\qquad M = M_0 + E_i$$

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$_2$



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

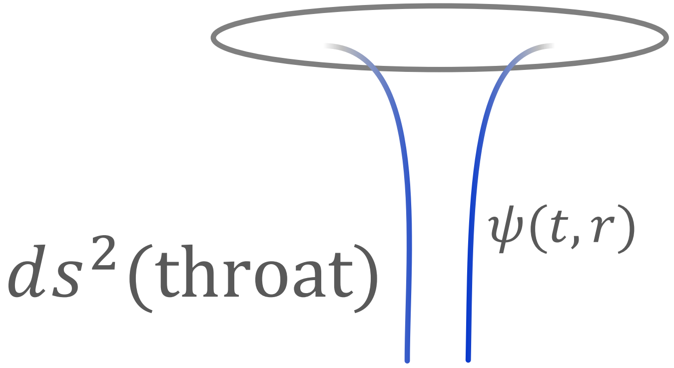
$\mathcal{O}_\Delta(t)$: response operator

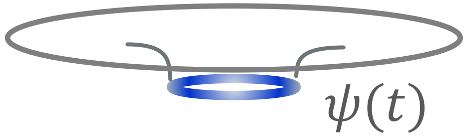
Brown+Iliesiu+Penington+Usatyuk

Quantum Throat

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

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

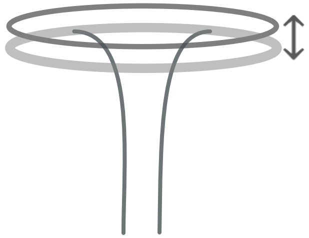




$|E\rangle$ state of Schwarzian theory

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

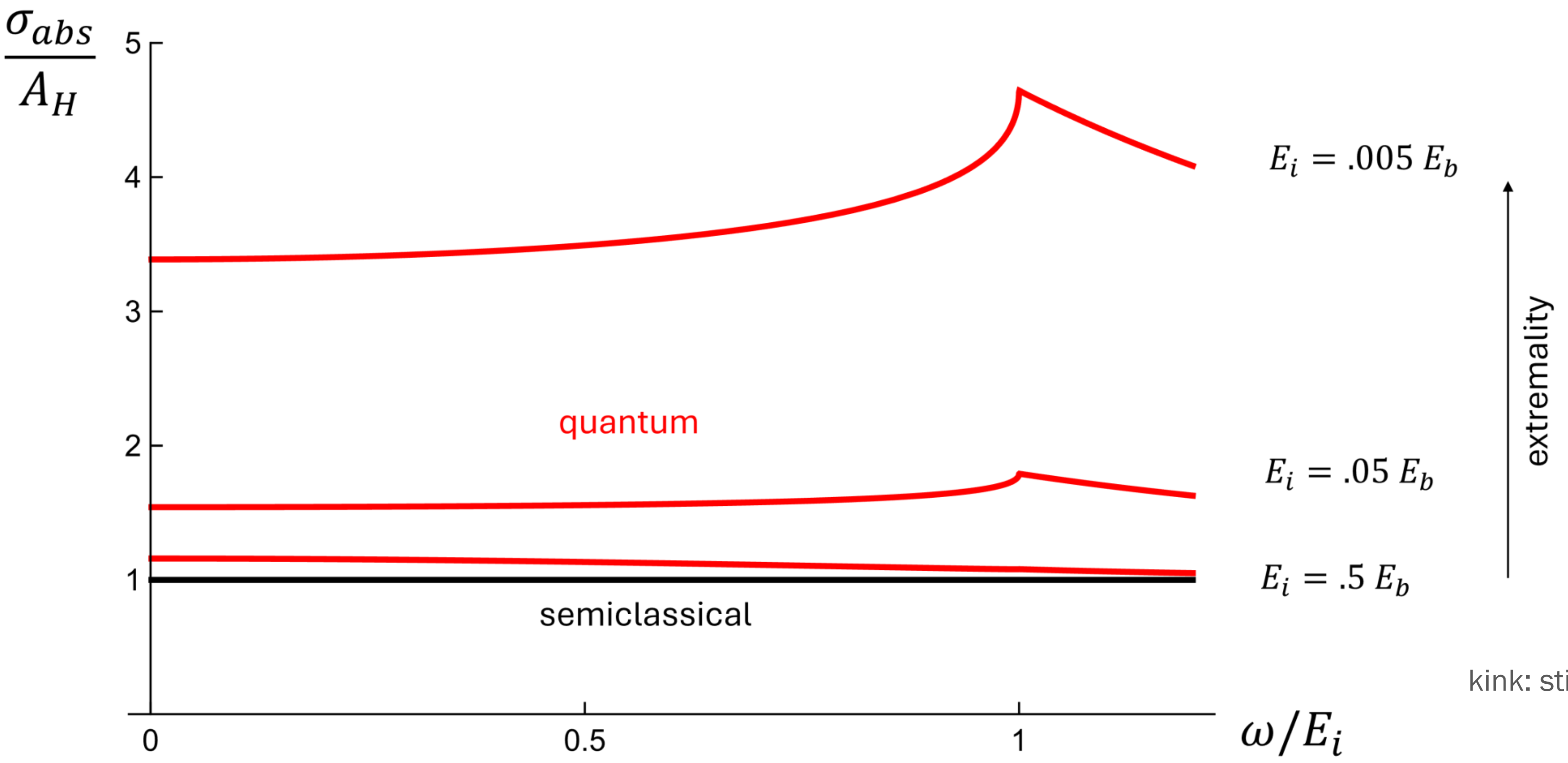
known from Schwarzian theory

Near-extremal absorption: s-wave

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

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

Quantum absorption $\sigma_{abs} > A_H$

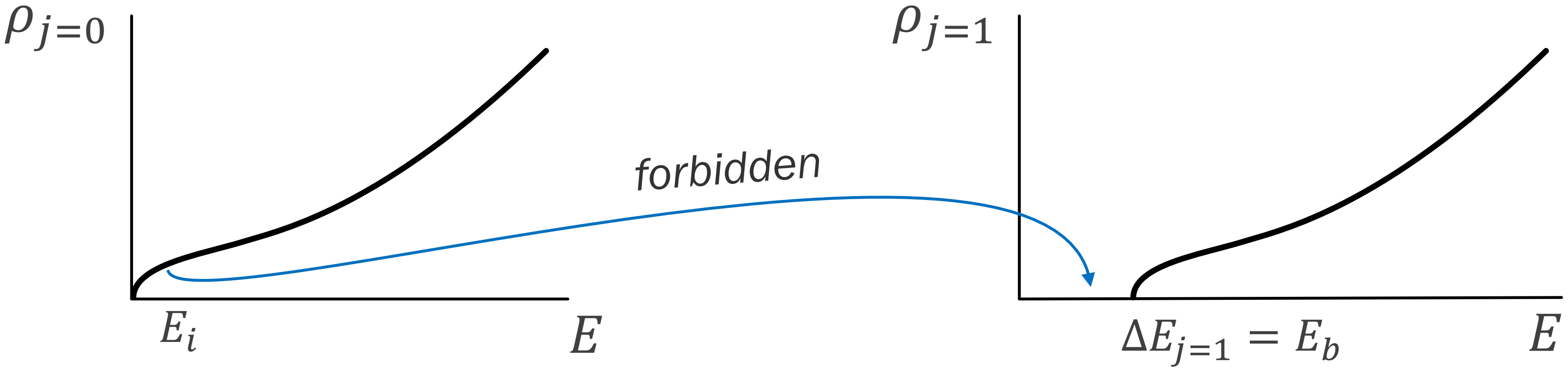


kink: stimulated emission stops

Photon & Graviton absorption

Spinless BH $\longrightarrow$ Spinning BH: gapped

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

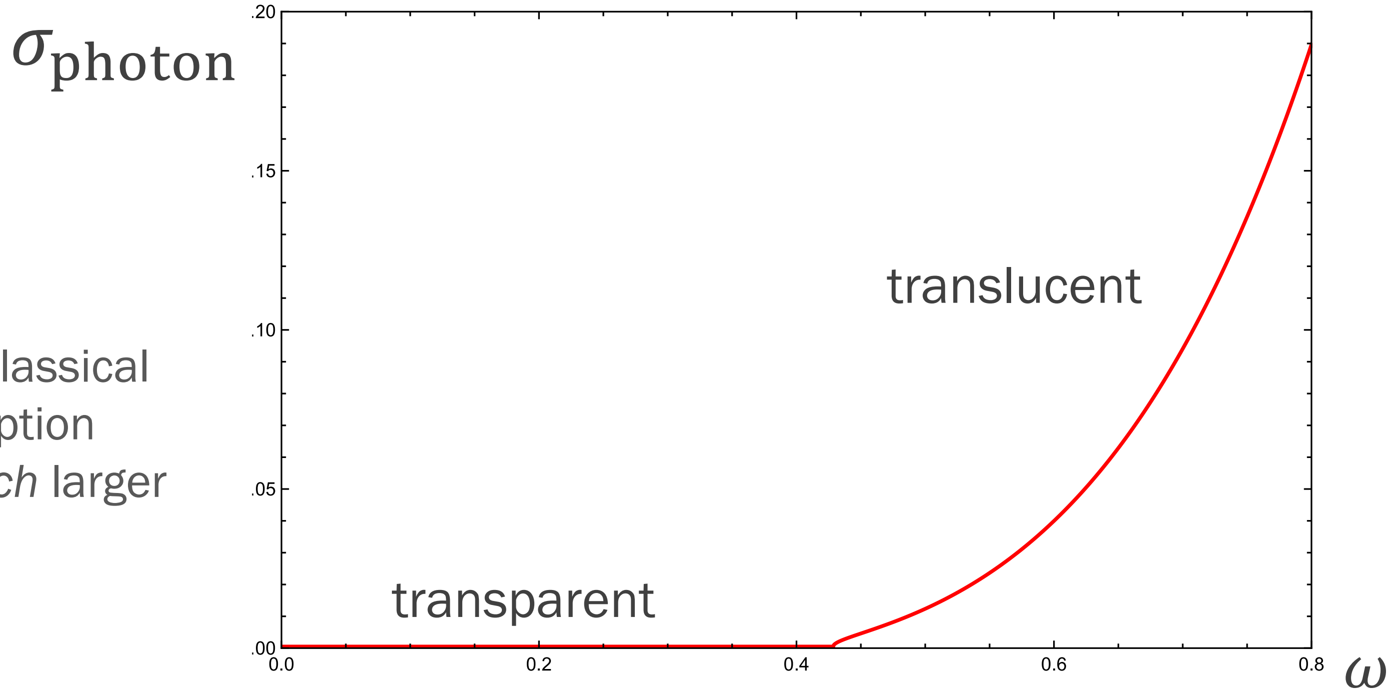


$\omega + E_i < \Delta E_{j=1}$ Transparent

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

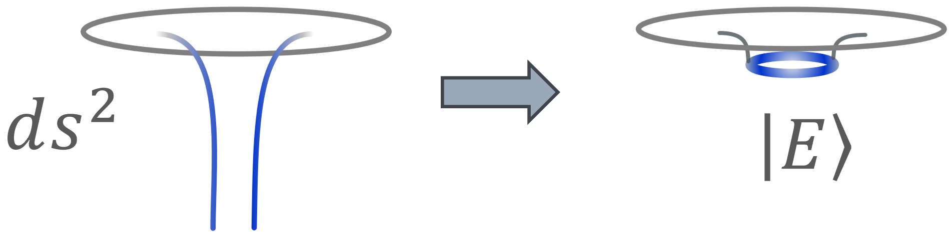
Do Black Holes behave like ordinary quantum systems?

Unitarity Paradoxes

Near-Zero-Temperature Paradoxes

Questions

- What does this picture



say about the **infalling observer and the BH interior?**

Questions

- Can quantum gravity effects be parametrically enhanced near the horizon in **other settings**?
- If the BH is a very quantum object – can we do **quantum experiments** with it?
- Description of (non-BPS) **lowest energy state** w/ fixed Q?

It's a fully quantum, non-geometric macroscopic object

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 effects at horizon scales?

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 slides

Classical formation: collapse

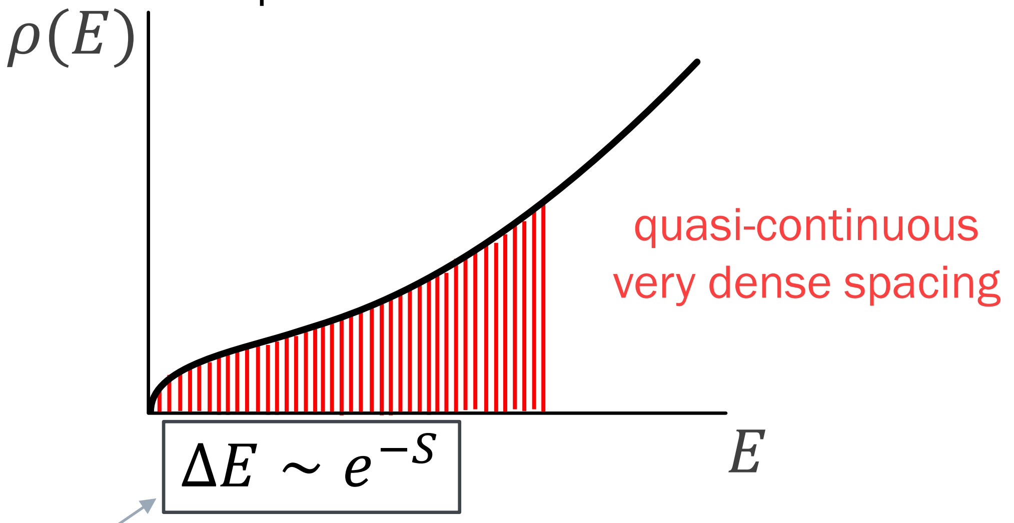
- Collapse of charged matter can be fine-tuned to land on "classical extremal black hole" in finite time Kehle+Unger

which doesn't exist!

- Correct interpretation: Can form *near-extremal* black hole within a classical timescale preparation time will be ~ $1/E_b \propto 1/\hbar$

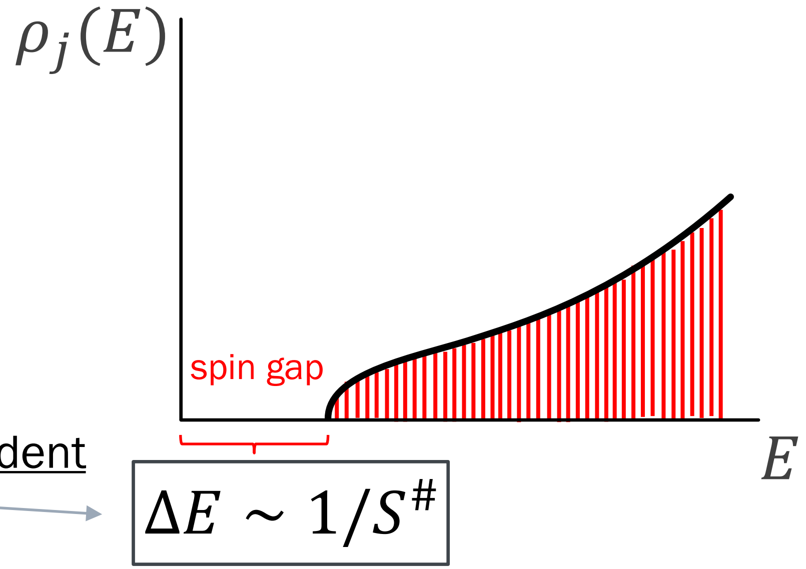
Quantum Black Hole Spectrum

Spinless Black Hole



requires detailed UV microscopics
(string theory)

Spinning Black Hole



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

Pushed Out: Charge

- Discharge: spontaneous e^+e^- pair production & charge superradiance
- Enhanced by large $\frac{q}{m} \sim 10^{21}$
- Suppressed by $m \neq 0$ when BH size is large enough

$$Q > q\left(\frac{M_{Pl}}{m}\right)^2$$

- Better if magnetically charged

Pushed Out: Spin

- Spontaneous spin superradiance: massless, fast power-law decay
- Emission of one superradiant photon drives BH away from quantum near-extremality
- No observational chance

Questions

- What’s the quantum fate of **Aretakis**’ and other on-horizon instabilities?
- How do horizon-scale quantum effects affect **dynamical critical collapse to extremality**?
- How do they relate to the **large tidal effects** near extremality?