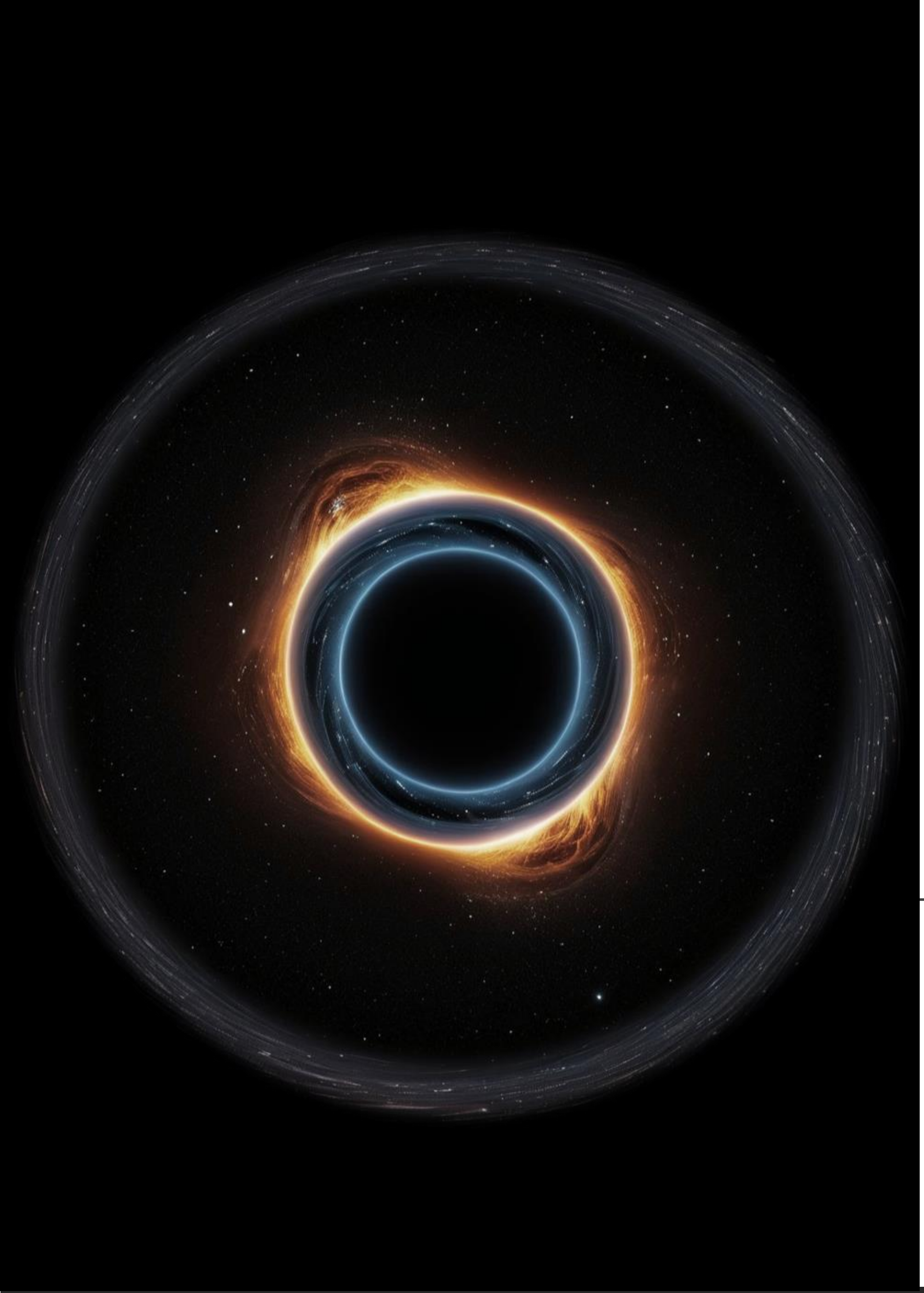


Quantum Cross-Section of Near-extremal Black Holes

ROBERTO EMPARAN ICREA+ICCUB

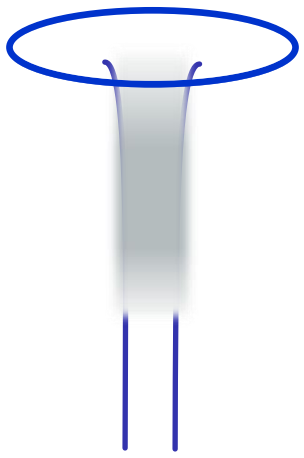
STRING THEORY AS A BRIDGE

ROMA, 17 FEBRUARY 2025

Can we observe large quantum fluctuations of the spacetime geometry?

Near extremality, black holes have large but controllable quantum fluctuations

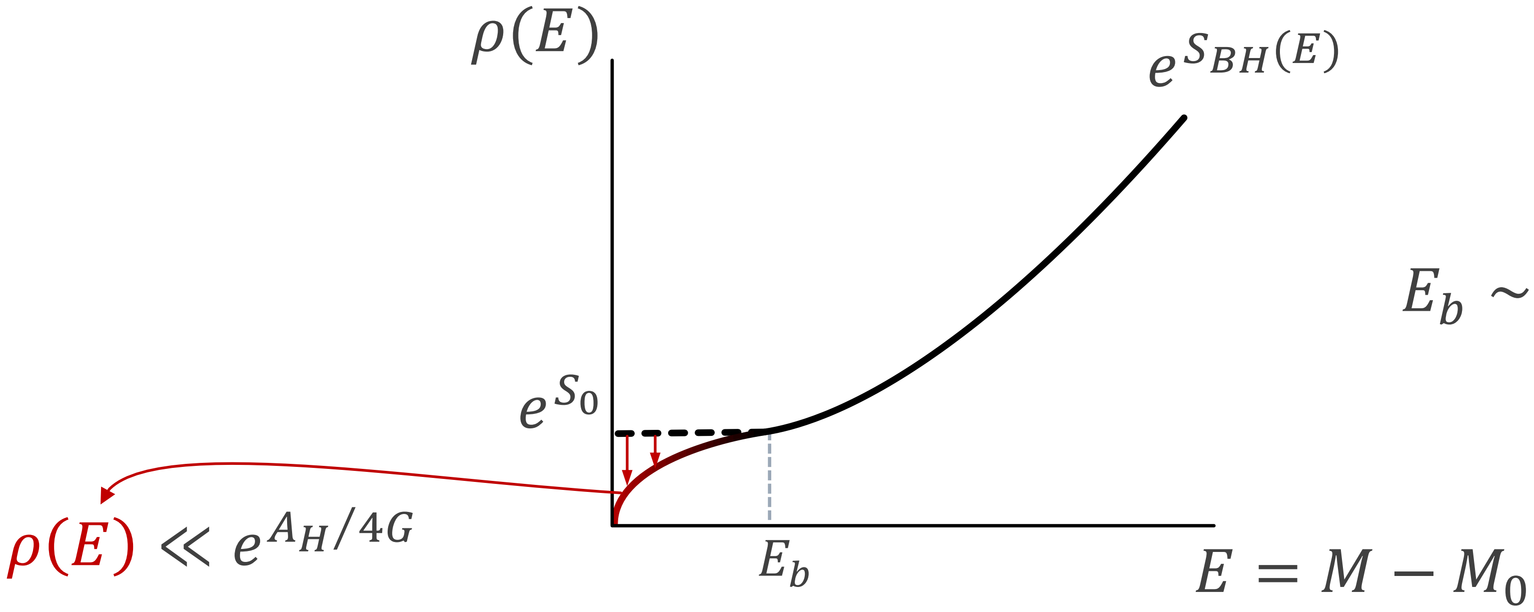
The length of the throat has large quantum variance



curvature remains small

Quantum fluctuations drastically reduce the density of states

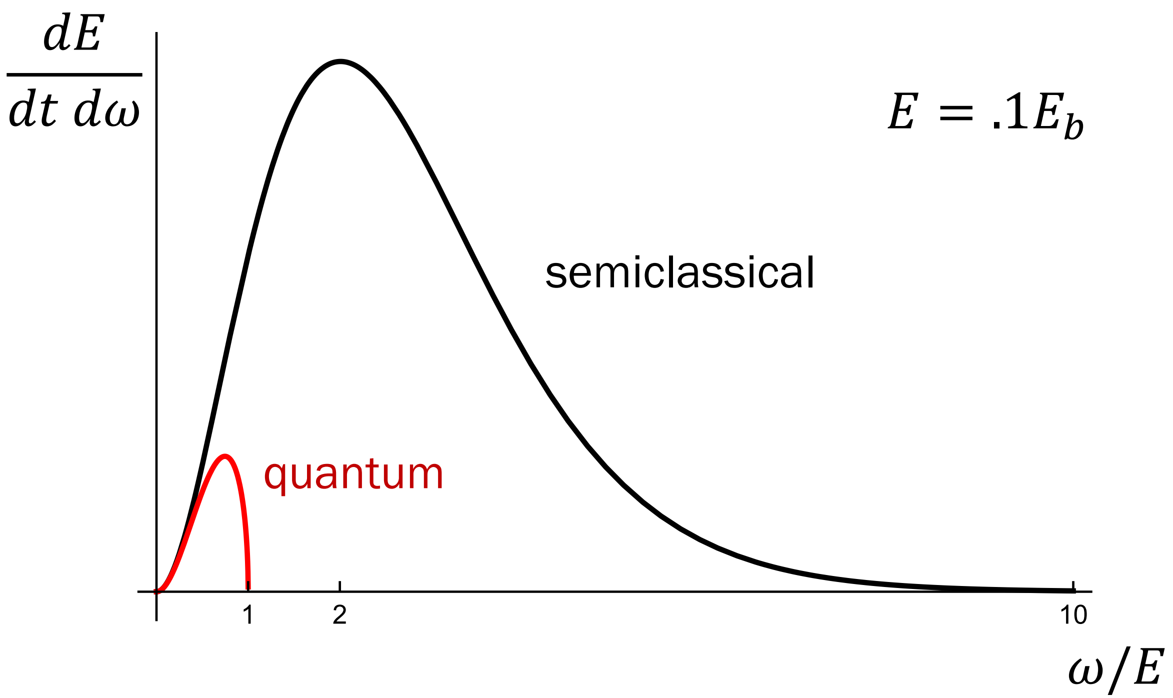
Iliesiu+Turiaci



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

Hawking emission is suppressed

Brown+Iliesiu+Penington+Usatyuk



How can an external observer probe this large quantum object?

Through Hawking radiation?

- Create a charged black hole
- Let it evaporate until close to extremality
- Detect its radiation

Brown+Iliesiu+Penington+Usatyuk

Through Hawking radiation?

That's painfully slow!

Quantum evaporation timescale diverges as $\hbar \to 0$

(plus radiation is suppressed near extremality)

Classically probing a quantum black hole

Classical formation: collapse

Classical observation: wave scattering – shine a light

Classical formation: collapse

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

Shine a light

Send a wave to the black hole

Measure the absorption cross-section

It is quick

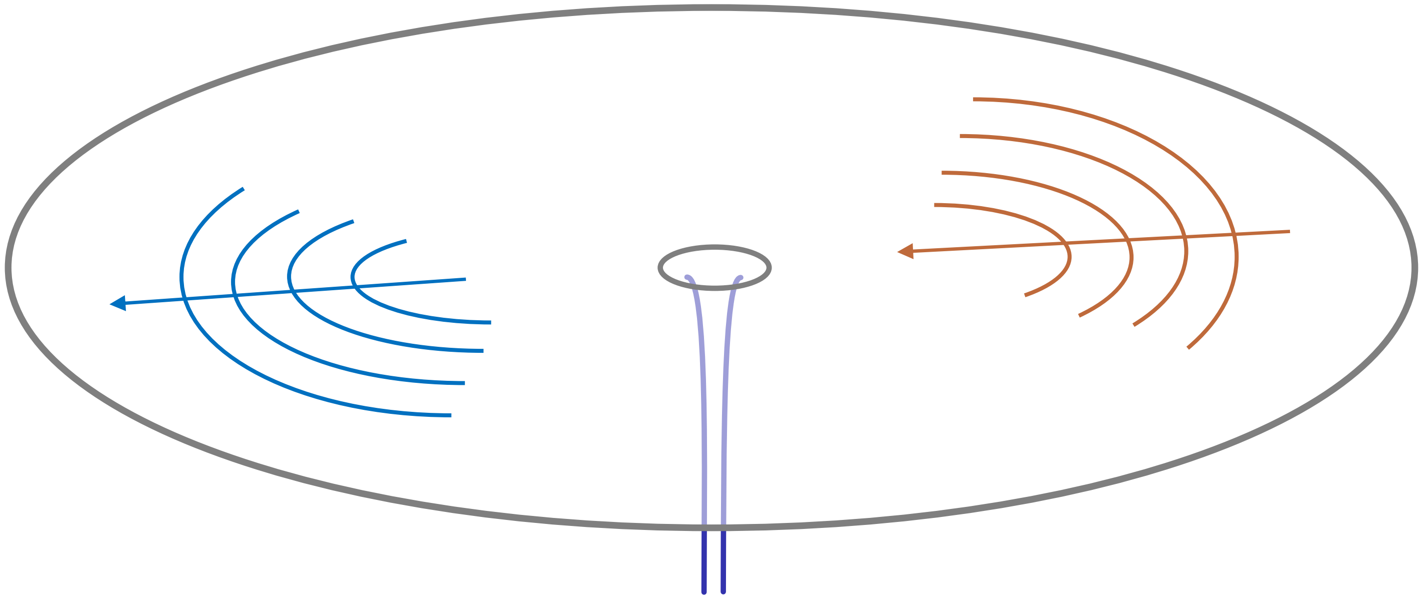
Shine a light

Throwing geodesic photons is not good

1. May destroy the long quantum throat
2. Only probe local geometry of the throat – not strongly fluctuating

Shining 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

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

larger the closer to extremality

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

Because quantum effects:

1. Enhance absorption transitions between individual states

   late-time correlations are enhanced in quantum black hole

2. Suppress stimulated emission

   fewer lower-energy states

Quantum Throats

HAVE FUZZY MOUTHS

Near extremality

Semiclassical black hole energy (mass)

$$E(T) = E_0 + 2\pi^2 \frac{T^2}{E_b} + O(T)^3 \qquad E_b = \frac{\pi}{r_h S_0}$$

$T \lesssim E_b$: semiclassical thermodynamics breaks down

Too little energy available to emit a single quantum

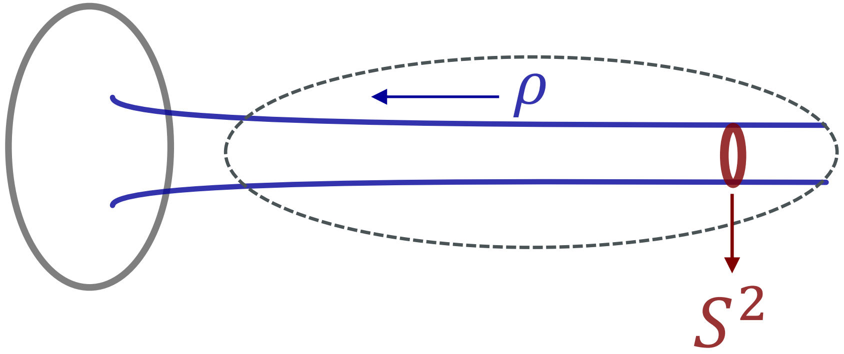
Preskill+Schwarz+Shapere+Trivedi+Wilczek

Near extremality

Quantum effects are important at

low temperatures

Near-extremal throat geometry



near-extremality & near throat

$$ds^2 = -(\rho^2 - \rho_+^2)dt^2 + \frac{d\rho^2}{\rho^2 - \rho_+^2} + r_0^{\,2} d\Omega_2 + \cdots$$

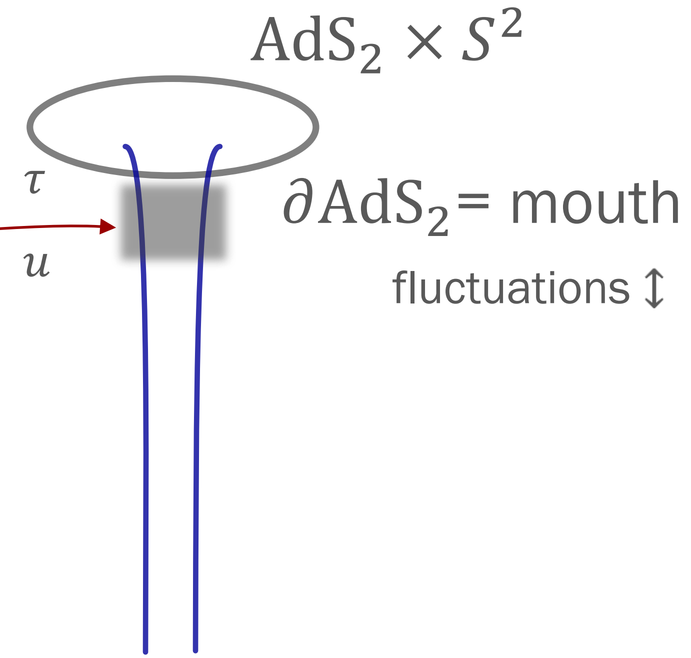
$$\underbrace{-(\rho^2 - \rho_+^2)dt^2 + \frac{d\rho^2}{\rho^2 - \rho_+^2}}_{\mathrm{AdS}_2} \quad \underbrace{r_0^{\,2} d\Omega_2}_{S^2}$$

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

Throat KK reduction ⟶ 2-dim dilaton JT gravity in AdS_2

⟶ 1-dim Schwarzian theory $\partial \mathrm{AdS}_2$

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



Schwarzian theory:

- spherical homogeneous mode
- fluctuations in height of mouth
- exactly quantized

Gravitational partition function at small T

one-loop det

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

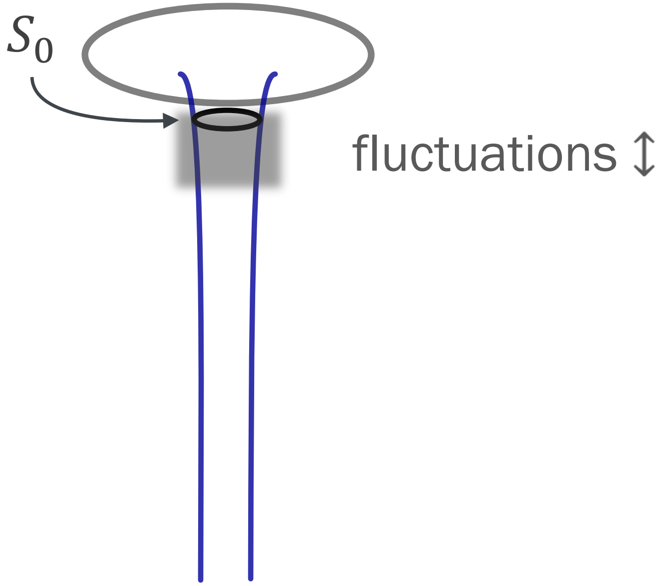
$$= e^{S_0 + 2\pi^2 \frac{T}{E_b}} \left(\frac{T}{E_b}\right)^{3/2}$$

semiclassical Gibbons-Hawking

quantum fluctuations of throat

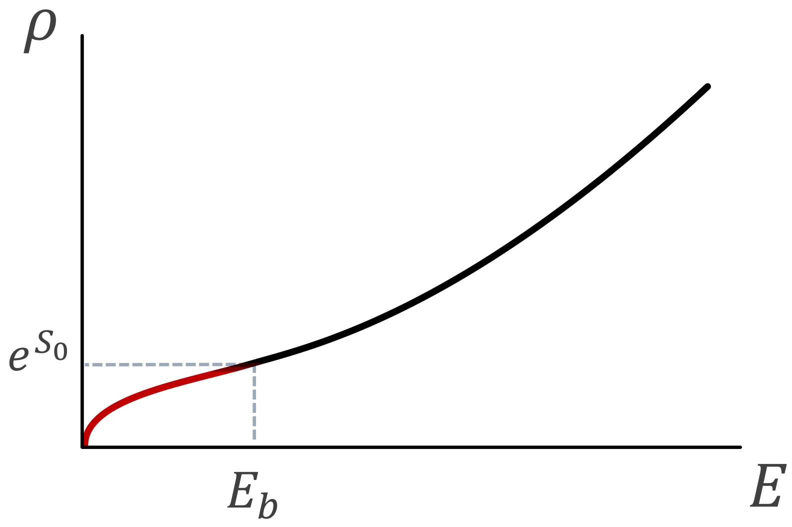
⇓

large effect when $T \lesssim E_b$



Density of states near extremality

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



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

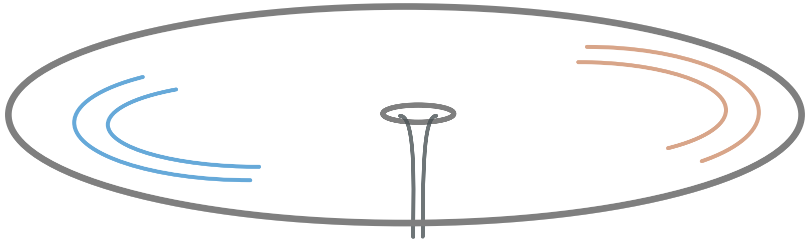
$$E = M - M_0$$

Quantum absorption

TO SEE OR NOT TO SEE

Also: Anna Biggs upcoming work

Wave scattering



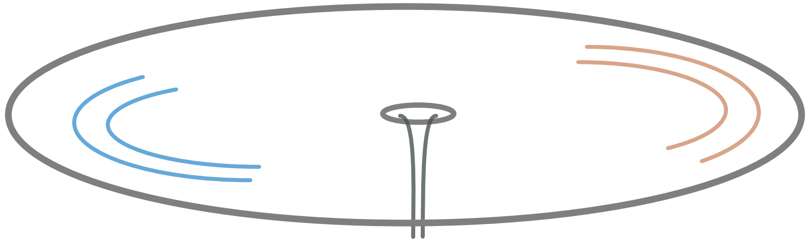
Send a wave of minimally coupled scalar field

into a near-extremal black hole

parametrized by E_b and initial energy E_i above extremality

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

Classical wave



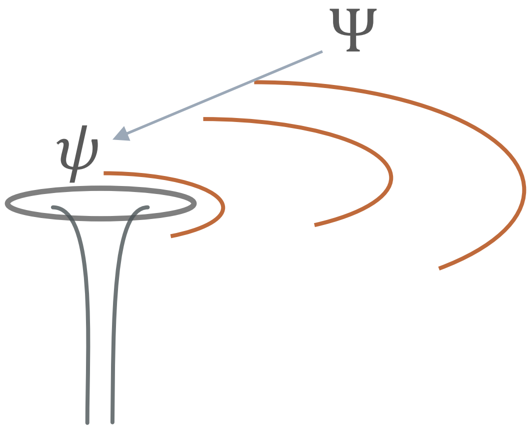
- Large occupation number $\langle N_\omega \rangle \gg 1$
- Low frequency $\omega \ll 1/r_h$
- Restrict to s-wave

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 throat: <u>**source**</u> for the field in AdS_2

$$\Psi(t,r) = \psi(t)\, r^{\Delta-1} + O(r^{-\Delta}) \qquad \Delta = 1$$

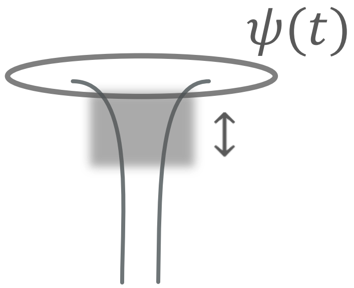


In the boundary theory

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

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

Brown+Iliesiu+Penington+Usatyuk



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

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

$$H_I(t) = e^{-i\omega t}\psi_0\, \mathcal{O}(t)$$

It 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)

Transition rates: Fermi rules

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

from matching

$$E_f = \begin{cases} E_i + \omega & : \text{absorption} \\ E_i - \omega & : \text{emission} \end{cases} \qquad |\psi_0|^2 = \langle N_\omega\rangle \frac{r_+^2\omega}{\pi^2}$$

Neglect spontaneous emission: $N_\omega + 1 \simeq N_\omega \;\Rightarrow\; \mathcal{T}_{i\to f} \propto \langle N_\omega\rangle$

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:

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

From rates to cross-section

Total absorption rate:

$$\frac{d\langle N\rangle}{dt} = -\int \frac{d\omega}{2\pi}\, P_{abs}(\omega)\langle N_\omega\rangle$$

$P_{abs}(\omega)$ = "greybody factor"= $2\pi(\Gamma_{abs} - \Gamma_{emit})$

Optical theorem:

$$\sigma_{abs} = \frac{\pi}{\omega^2} P_{abs} = \frac{2\pi^2}{\omega^2}(\Gamma_{abs} - \Gamma_{emit})$$

Schwarzian absorption

$$\sigma_{abs} = \frac{A_H}{\omega}\left(|\langle E_i + \omega|\mathcal{O}|E_i\rangle|^2 \rho(E_i+\omega) - |\langle E_i - \omega|\mathcal{O}|E_i\rangle|^2 \rho(E_i-\omega)\right)$$

Schwarzian theory:

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

2-pt function

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

Near-extremal absorption

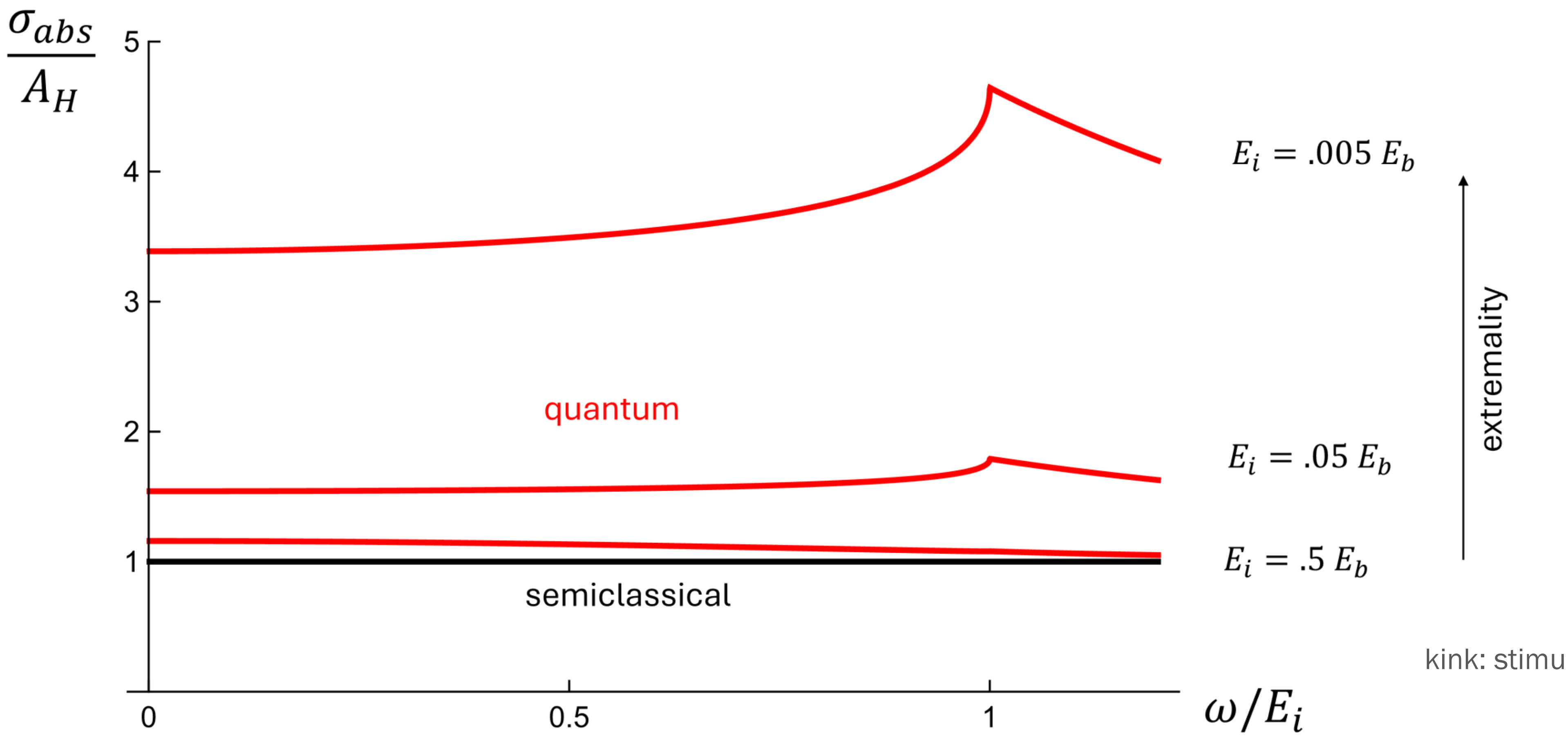
$$\sigma_{abs} = A_H \left(\frac{\sinh(2\pi\sqrt{2(E_i+\omega)/E_b})}{\cosh\left(2\pi\sqrt{2(E_i+\omega)/E_b}\right) - \cosh(2\pi\sqrt{2E_i/E_b})} + (\omega \to -\omega) \right)$$

Near-extremal absorption

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

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

Quantum absorption $\sigma_{abs} > A_H$



kink: stimulated emission stops

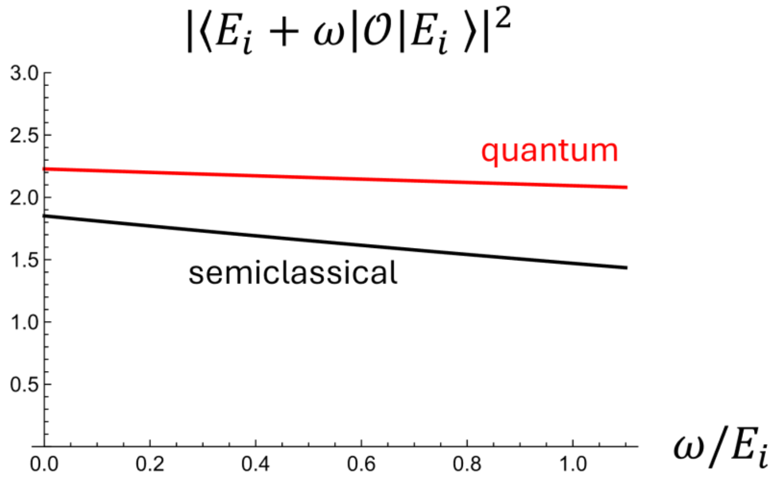
Quantum absorption $\sigma_{abs} > A_H$

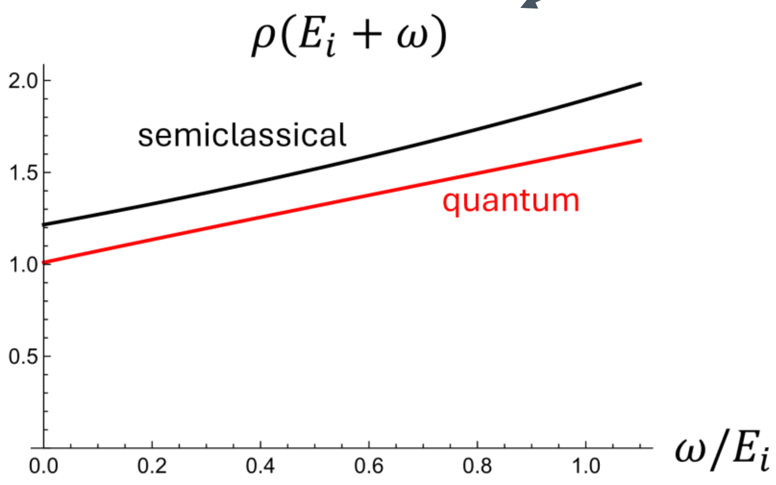
Since $\rho(E) < e^{A_H/4G} = e^{S_0}$

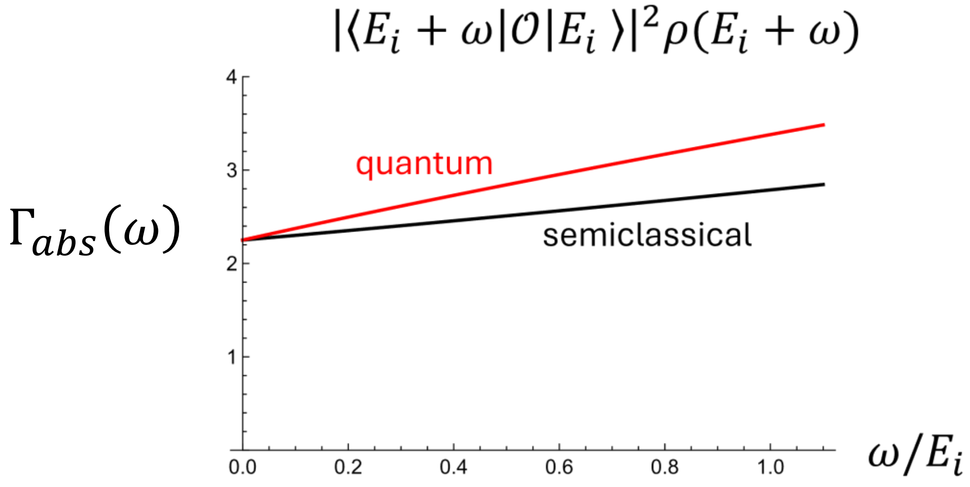
$$\sigma_{abs} > 4GS_0 > 4G \log \rho(E_i)$$

Density of states grossly underestimates the absorption near extremality

Enhanced absorption transitions overcompensate for fewer states

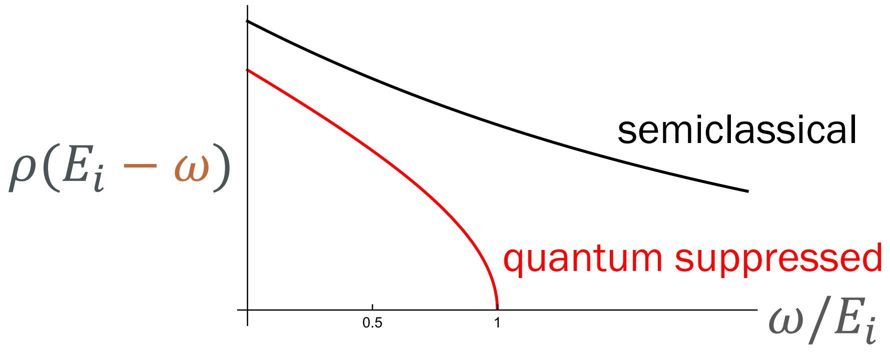






Stimulated emission is suppressed: many fewer final states

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



Generality & universality

- Higher dimensions, other black holes: just change A_H and E_b in σ_{abs}
- Valid for static near-extremal black holes in Einstein-Hilbert gravity + matter (no susy)

Conclusion

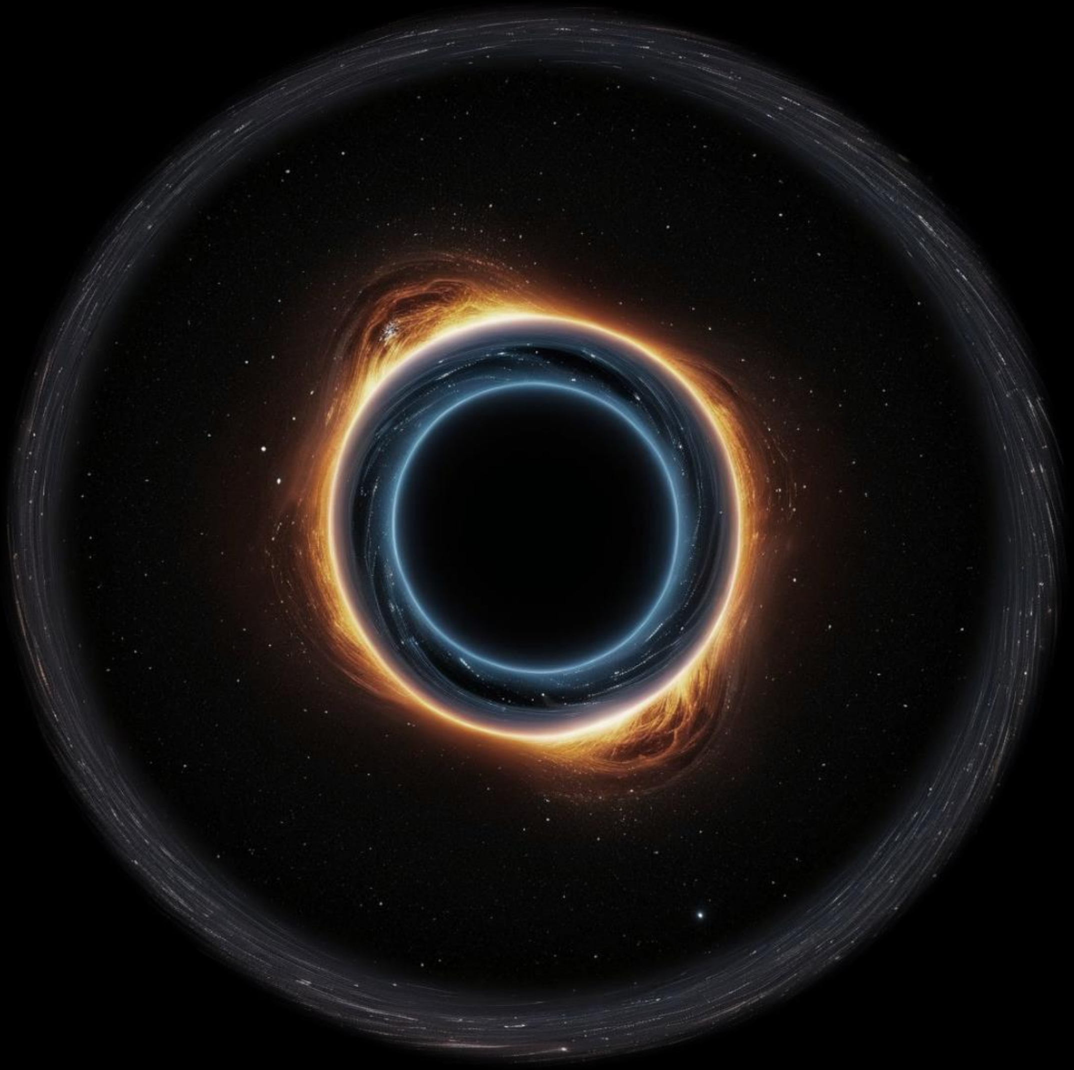
Can we observe large quantum fluctuations of the spacetime geometry?

Yes

Conclusion

Classical experiments can explore the quantum regime of near-extremal black holes

Enhanced cross-section reveals large quantum fluctuations of the throat



Thank you

Backup material

Quantum Near extremality (w/out susy)

Charged Reissner-Nordstrom black holes

Iliesiu+Turiaci
Iliesiu+Murthy+Turiaci

Rotating Kerr & BTZ black holes

Ghosh+Maxfield+Turiaci
Kapec+Sheta+Strominger+Toldo
Rakic+Rangamani+Turiaci
Kapec+Law+Toldo
Kolanowski et al

Hyperbolic AdS black holes

RE+Magán

Near-BPS: Heydeman+Iliesiu+Turiaci+Zhao

No throat disruption

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

Not if $\langle N_\omega \rangle < \frac{1}{(\omega r_h)^2} \frac{\sqrt{E_i E_b}}{\omega}$

- Since $\omega r_h \ll 1$ we can comfortably probe the quantum regime

$$\omega, E_i < E_b$$

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

Extensions

- Near-BPS: gap in the spectrum

  Heydeman+Iliesiu+Turiaci+Zhao

  No absorption in the gap

  BPS absorption must jump the gap

- BTZ near horizon

  Greybody factors carry info about left- and right- movers — Maldacena+Strominger

  Quantum Schwarzian from CFT_2 — Ghosh+Maxfield+Turiaci

- Near-extremal Kerr?

  Kapec+Sheta+Strominger+Toldo
  Rakic+Rangamani+Turiaci
  Kapec+Law+Toldo
  Kolanowski et al

Quantum η/s?

- $\frac{\sigma_{abs}}{A_H} = 1$ implies $\frac{\eta}{s} = \frac{1}{4\pi}$
- Shear modes of the black brane worldvolume behave like minimal scalars
- Absorption = Viscous dissipation : determined by 2-point function of stress-energy

Policastro+Son+Starinets+Kovtun

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…

But this may be too naive Davison+Parnachev