



Observing Quantum Gravity at Macroscopic Horizon Scales

ROBERTO EMPARAN ICREA+ICCUB

PUZZLES IN THE QUANTUM GRAVITY LANDSCAPE

GRAZ, 18 SEPTEMBER 2026

In recent years we've learned about a new regime
of Quantum Gravity

Quantum Gravity becomes macroscopic without
Planckian curvature

Extremely cold black holes are not semiclassical
objects with small quantum corrections

They are genuine quantum systems

They have quantum fluctuations of order one,
even if the horizon curvature is arbitrarily small

These fluctuations can be isolated, and are
described by an exactly solvable quantum
mechanical system

No need of UV quantum gravity

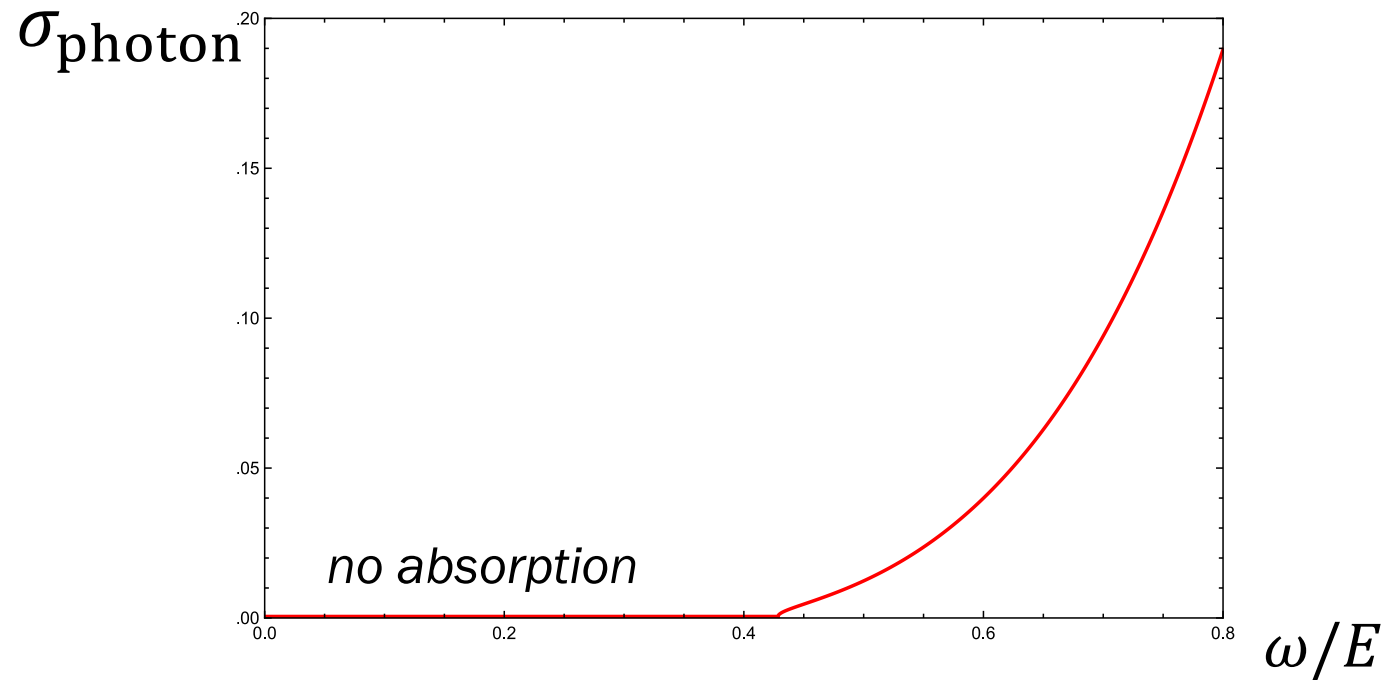
This overturns the widespread expectation that Quantum Gravity becomes important only when the curvature approaches the Planck scale

It also upends how we should think about –and
teach– what an extremal black hole is,
and what it is not

The quantum nature of black holes shows up in
observable quantities (in principle)

Extremely cold black holes become transparent to light

RE+Trezzi 2025



Black holes that *don't* absorb light

Big Question

Can black holes behave like ordinary quantum systems?

- Information paradox
- Extremely cold black holes

Both point toward **horizon-scale quantum effects**

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 $\sim 10^{-76}$

Horizon-scale quantum-gravity phenomenology *is hard*

Large fluctuations when specific heat is small, $C = \frac{dE}{dT} = O(1)$

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

Schwarzschild BH: $T r_H \sim 1$ $C \gg 1$: Tiny fluctuations

Large fluctuations when specific heat is small, $C = \frac{dE}{dT} = O(1)$

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

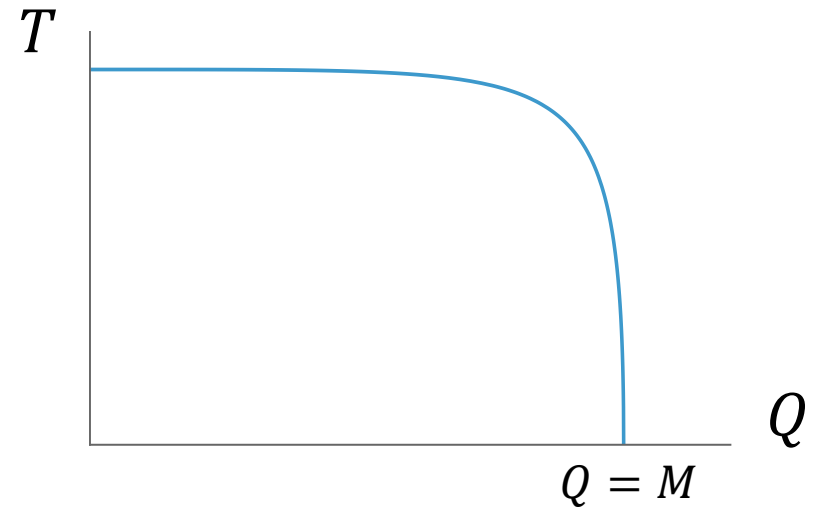
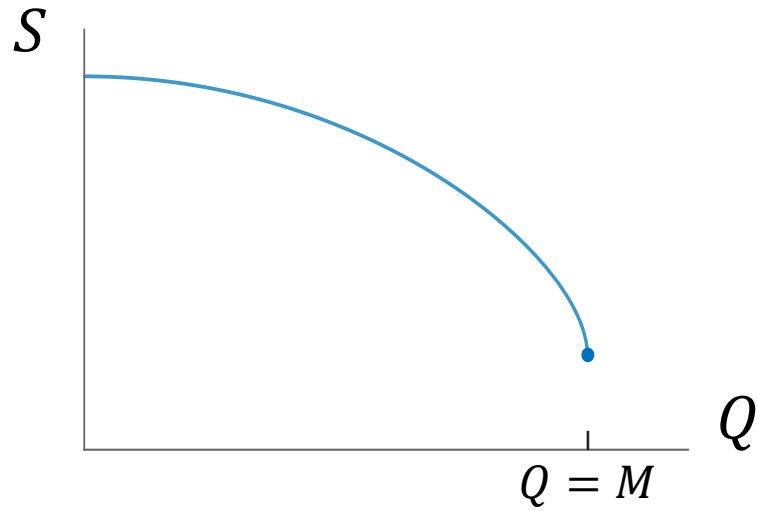
Schwarzschild BH: $T r_H \sim 1$ $C \gg 1$

Near extremal BH: $T r_H \ll 1$ arbitrarily small

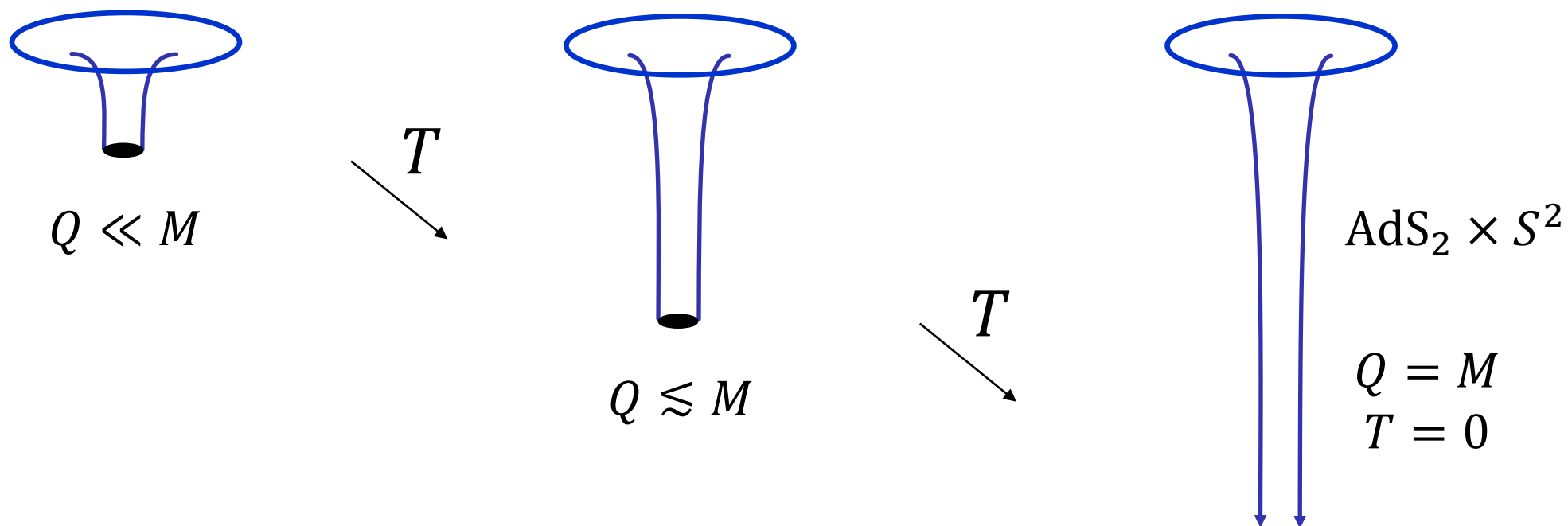
Conventional decoupling fails in
extremely cold black holes

Black holes cool down w/ charge & spin

Fixed M



Cooling creates a long throat

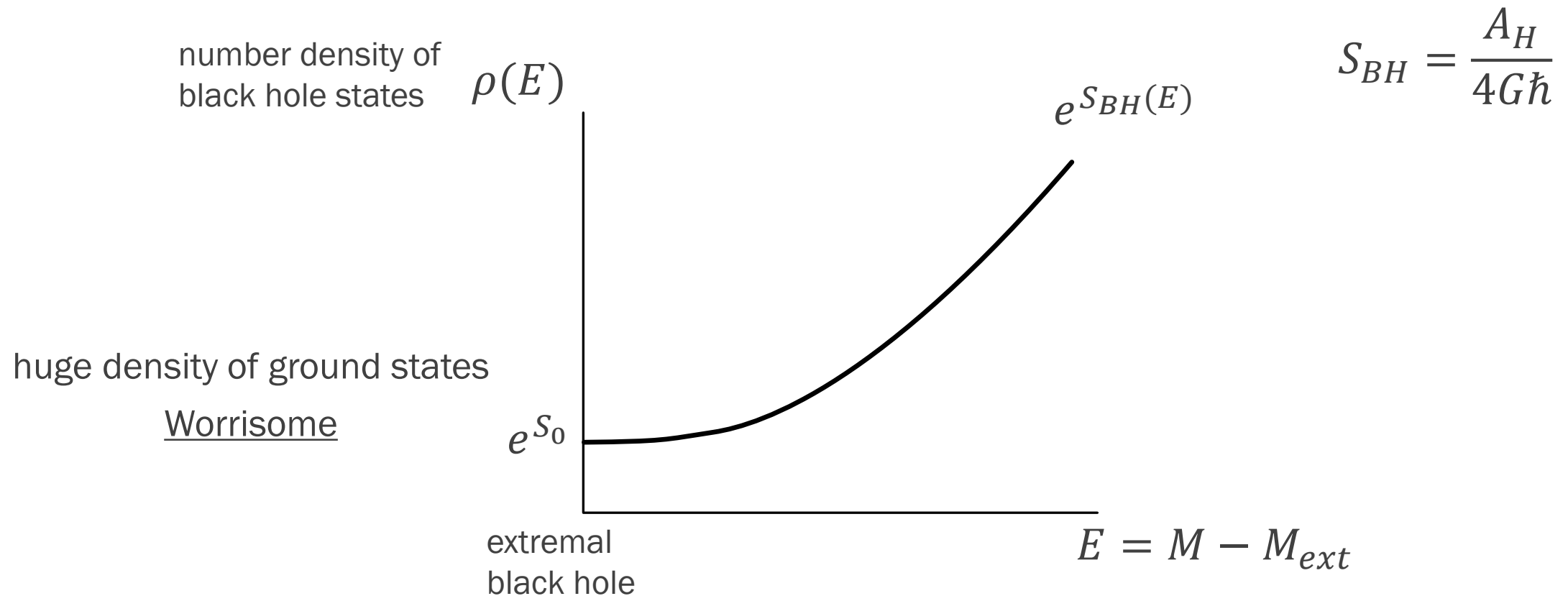


Throat becomes arbitrarily long, while area remains finite

Black hole thermodynamics at low temperature
appears inconsistent with ordinary quantum
mechanics

- Huge extremal entropy
- Non-thermality near extremality

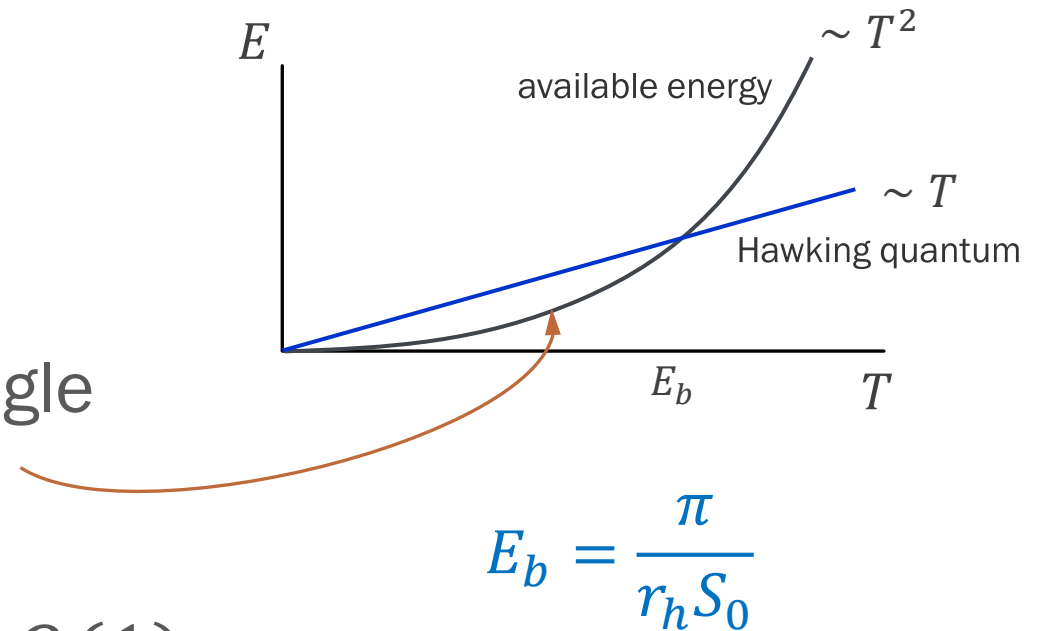
Puzzle #1: Extremal entropy



Puzzle #2: Near-extremal thermality

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

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



This happens when Specific heat is $O(1)$

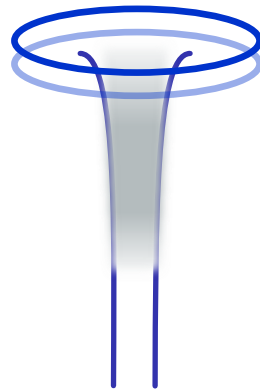
Can we describe these black holes quantum mechanically
without invoking unknown UV physics?

Can we describe these black holes quantum mechanically
without invoking unknown UV physics?

Yes

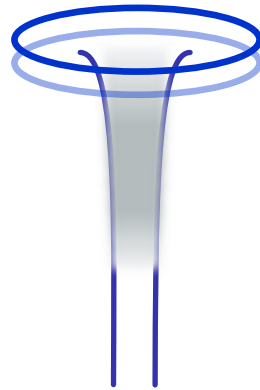
The throat itself becomes a quantum system

Around 2016 it became clear that the dynamics of near-AdS₂ throats can be isolated and quantized consistently



Two scales: throat width and length

or, horizon radius and surface gravity



Quantum Black Hole entropy



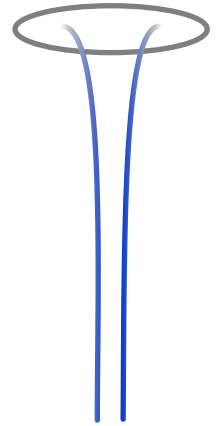
$$S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H$$

Quantum Black Hole entropy

$$S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \# \log T$$

Fluctuations at scale $\sim r_H$: $\log A_H \ll A_H/\ell_P^2$

Fluctuations at scale $\sim 1/T$
Can be large if T small



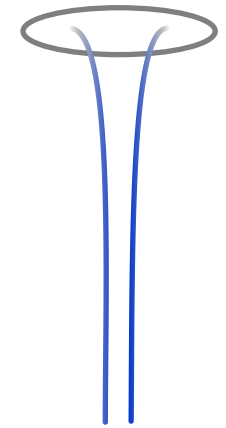
Quantum Black Hole entropy

$$S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \# \log T$$

Fluctuations at scale $\sim r_H$: $\log A_H \ll A_H/\ell_P^2$

Fluctuations at scale $\sim 1/T$
Can be large if T small

are calculable: IR Quantum Gravity
= quantized GR around a black hole



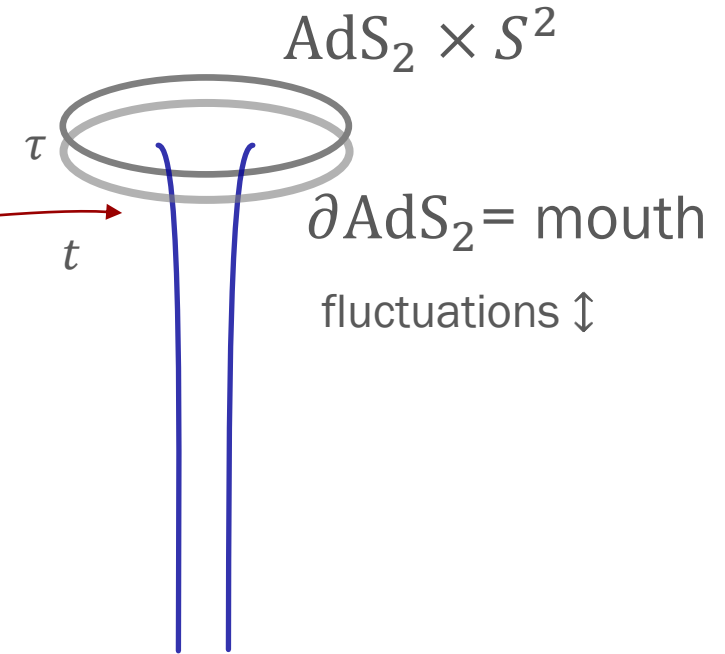
Throat theory

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

Throat KK reduction $\rightarrow$ 2D JT-dilaton gravity $\rightarrow$ 1D Schwarzian theory at ∂AdS_2

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

semiclassical extremal



Schwarzian theory:

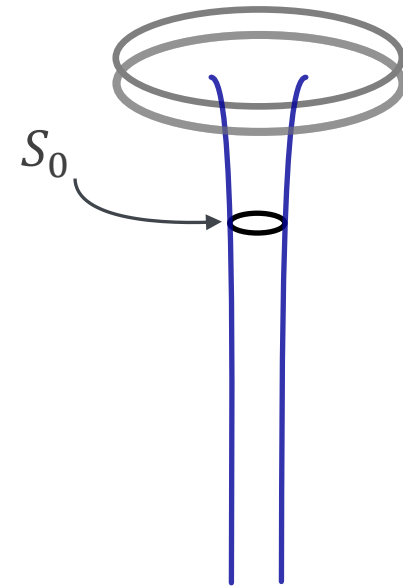
nearly-zero-mode of reparametrizations
of the throat

Gravitational partition function at small T

$$Z(T) = e^{-I_{\text{bh}}(T)} \times \text{one-loop det}(\mathbf{Q})^{-1/2}$$
$$= e^{\underbrace{S_0 + 2\pi^2 \frac{T}{E_b}}_{\text{semiclassical Gibbons-Hawking}}} \underbrace{\left(\frac{T}{E_b}\right)^{3/2}}_{\text{quantum fluctuations of throat}}$$

large effect when $T \lesssim E_b$

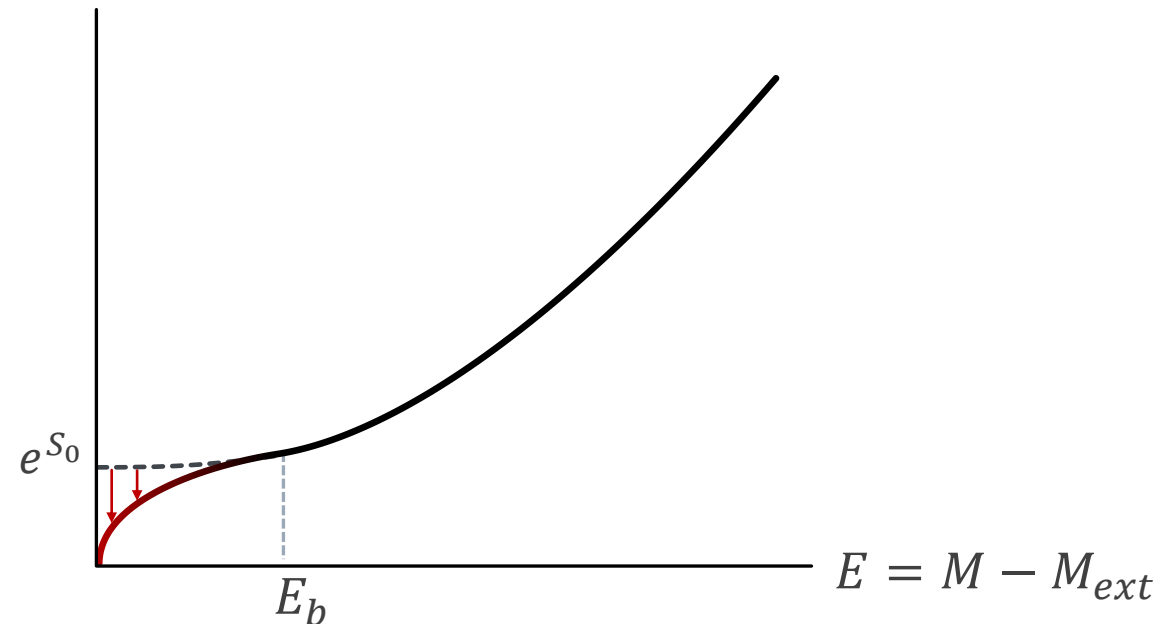
ensemble inequivalence



A genuine quantum spectrum

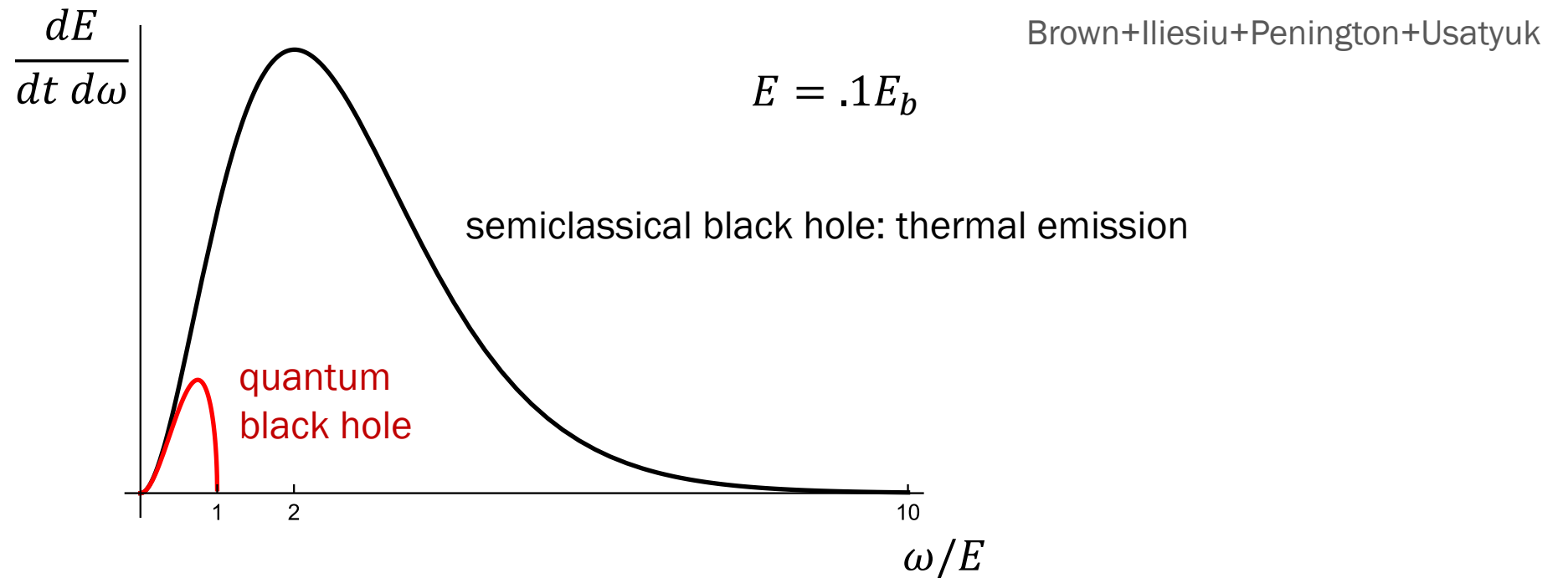
$$\rho(E) = e^{S_0} \sinh \left(2\pi \sqrt{2E/E_b} \right)$$

Iliesiu+Turiaci 2020



Huge semiclassical ground-state degeneracy disappears

Hawking emission: suppressed



Quantum Black Hole: non-thermal emission

Biggs

A lesson

*The Classical limit $\hbar \rightarrow 0$ of Quantum Gravity, and
the Zero-temperature limit $T \rightarrow 0$ of Black Holes
do not commute*

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

$$\text{eg } \Delta S \sim \hbar \log T$$

A lesson

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

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

But don't throw all classical extremal black hole results
in the trash just yet

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

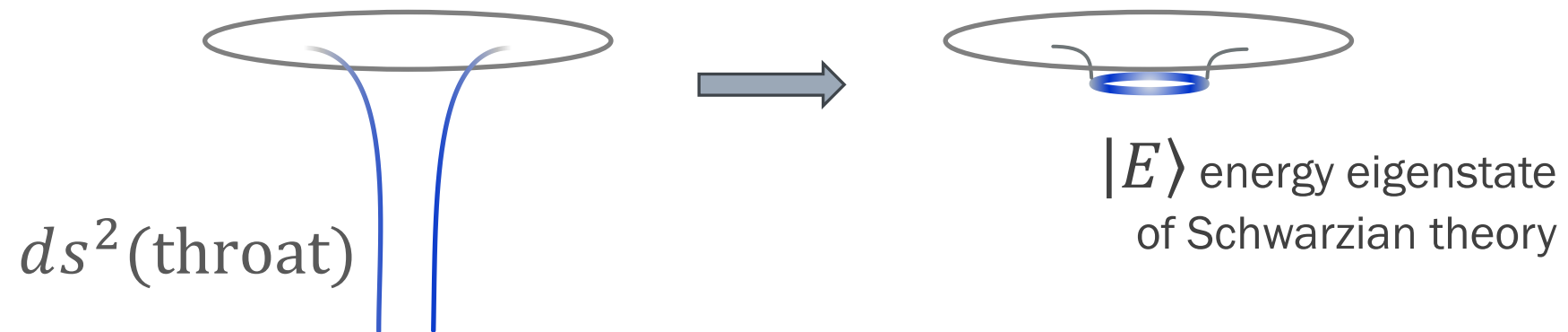
This includes recent results on “violations of the 3rd law”

This is *conventional* quantum physics *consistently*
applied to a very light fluctuation mode:

IR Quantum Gravity

Quantum Throats

Replace long classical throat with
quantum black hole energy eigenstate

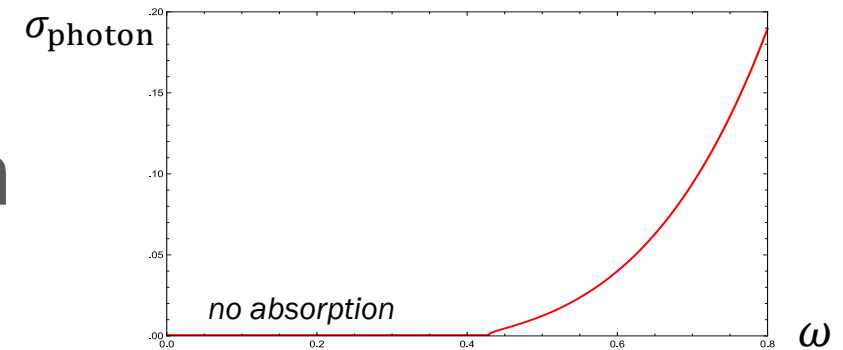


This allows us to compute scattering and absorption
as in atomic physics

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

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

Calculable large gaps in the spectrum
lead to transparency windows



The big caveat

How cold is extremely cold?

The big caveat

Astrophysical black holes are nowhere near the
extremely-cold regime

Would need $T < 10^{-83} K$

Why we still care

- Controlled quantum gravity regime
- Universal low-energy description
 - Calculable consequences

In Closing

The most surprising quantum effects of
gravity may occur not where gravity is
strongest,
but where black holes are coldest

IR-benchmarking UV Quantum Gravity

Gravitational Path Integral reliably gives

1. $S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \frac{3}{2} \log T$: w/ one-loop corrections

2.

3.

IR-benchmarking UV Quantum Gravity

Gravitational Path Integral reliably gives

1. $S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \frac{3}{2} \log T$: w/ one-loop corrections
2. Absorption/emission rates – incl near zero- T
- 3.

IR-benchmarking UV Quantum Gravity

Gravitational Path Integral reliably gives

1. $S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \frac{3}{2} \log T$: w/ one-loop corrections
2. Absorption/emission rates – incl *near zero- T*
3. Spectral statistics of black hole energy levels:
random-matrix-like (chaotic), $\Delta E \sim e^{-S}$ — from “double-cone wormhole”

IR-benchmarking UV Quantum Gravity

Gravitational Path Integral reliably gives

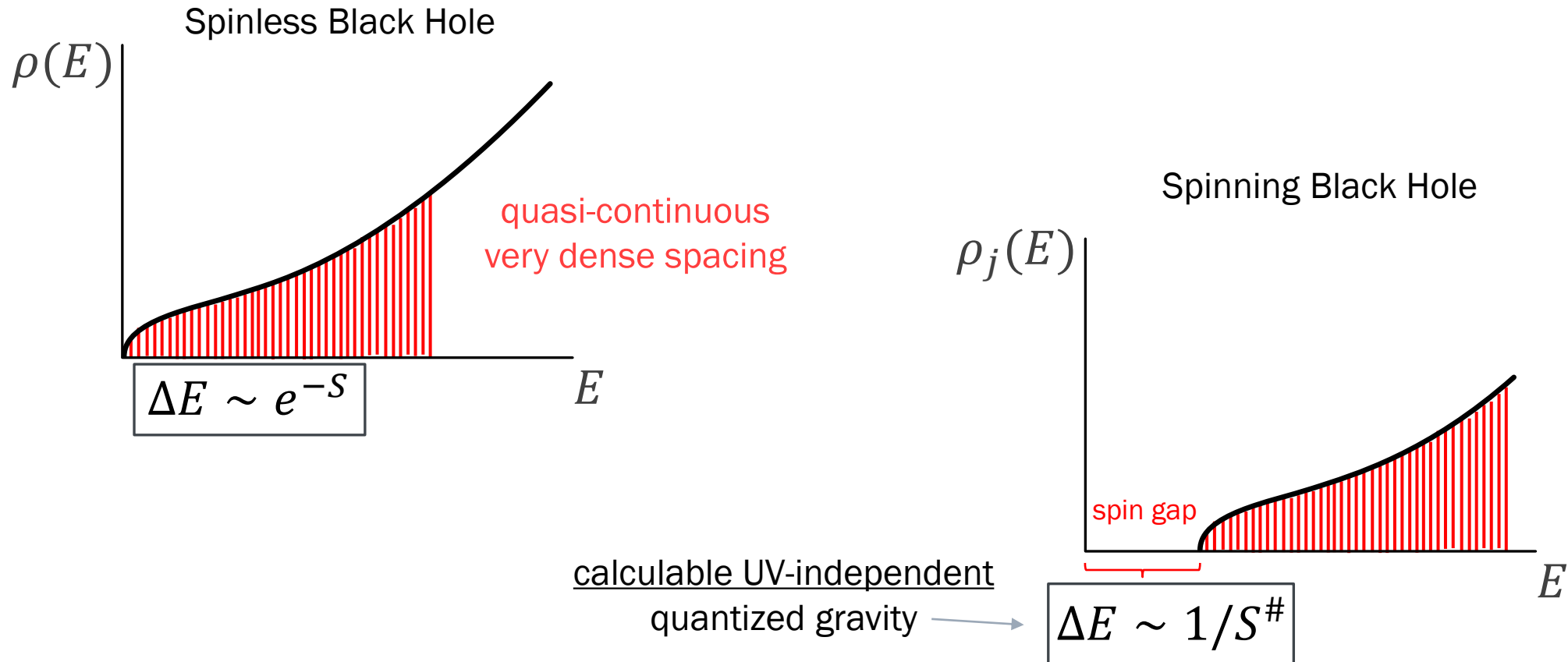
1. $S_{BH} = \frac{A_H}{4G\hbar} + \# \log A_H + \frac{3}{2} \log T$: w/ one-loop corrections
2. Absorption/emission rates – incl *near zero- T*
3. Spectral statistics of black hole energy levels:
random-matrix-like (chaotic), $\Delta E \sim e^{-S}$ — from “double-cone wormhole”

These are parameter-free. Nothing to tune



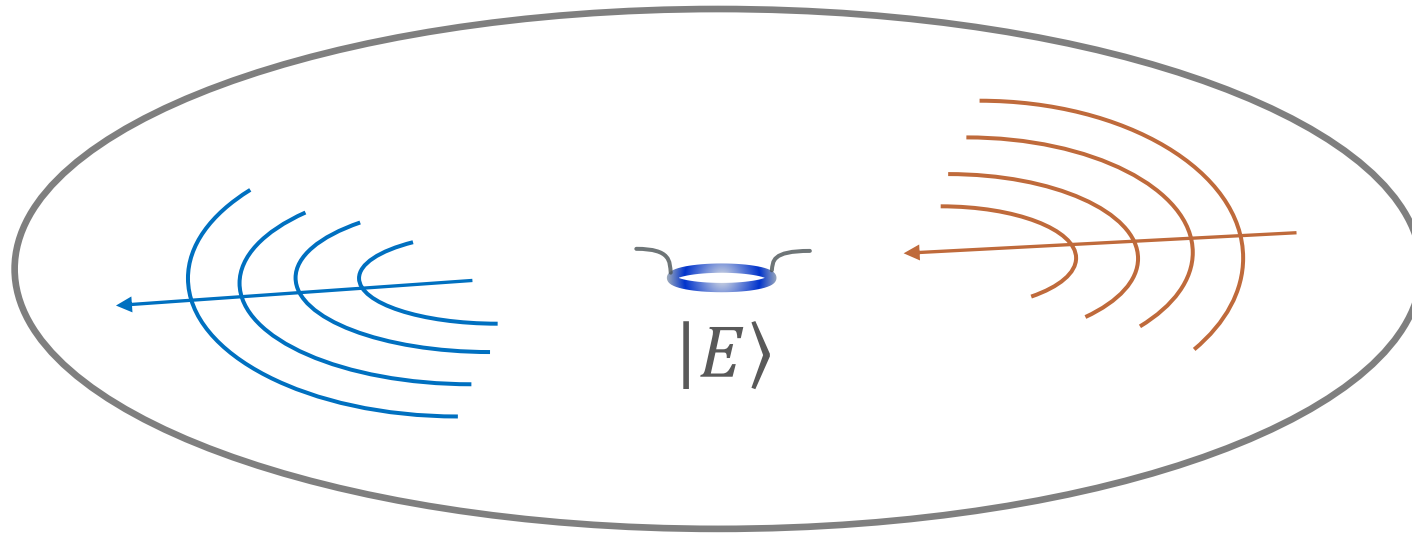
Thank you

Quantum Black Hole Spectrum



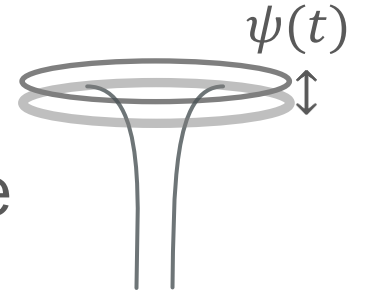
Scattering off the Quantum Black Hole

Quantum throat



Like atomic physics – but with a black hole

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



Induces transitions between black hole states:

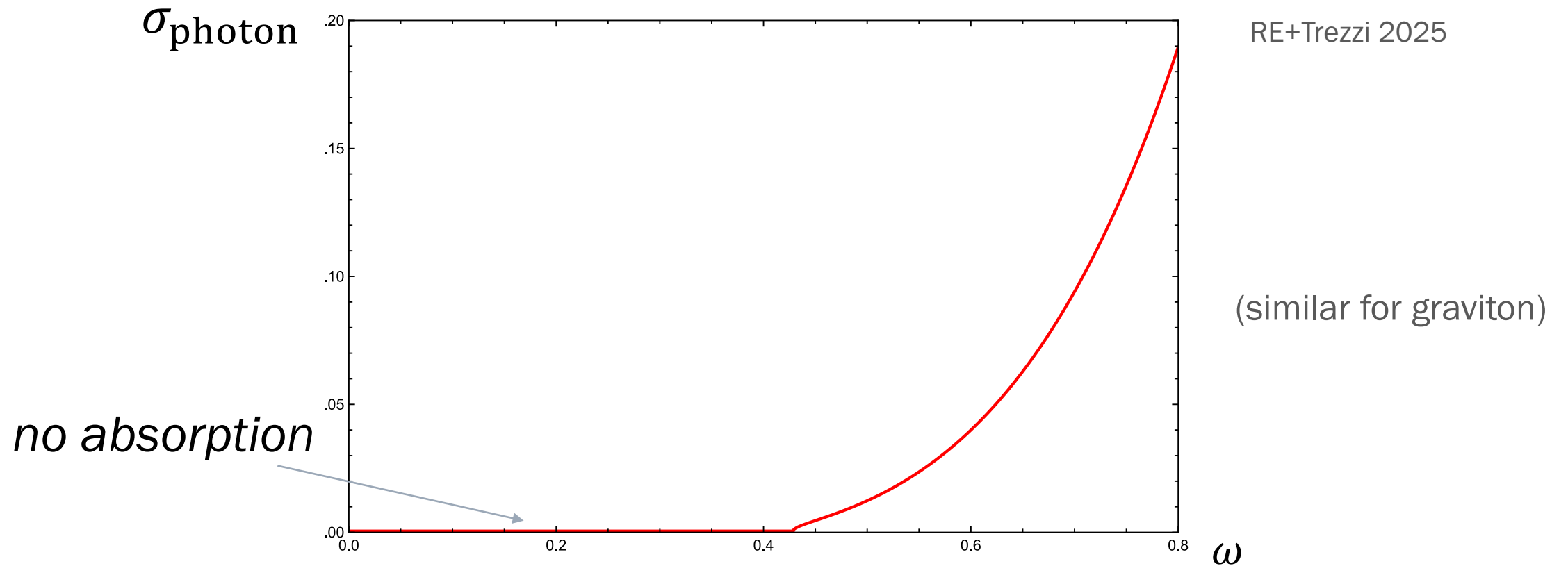
$|E_i\rangle \rightarrow |E_i + \omega\rangle$: absorption

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

Transition rates from computed using Schwarzsian theory

Fermi's Golden Rule applied to Black Hole

Photon absorption cross-section



Black holes that *don't absorb light*?

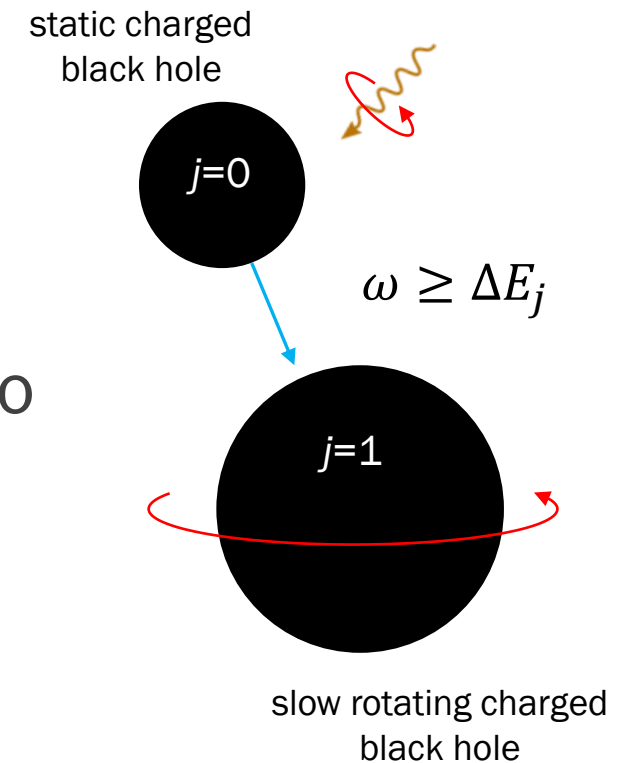
Atoms don't absorb arbitrary frequencies

Quantum black holes don't either

They have gaps in their spectrum that we can reliably
compute

The spin gap

- Black hole angular momentum j is quantized
- Rotational energy creates energy gap ΔE_j
- Photons carry spin: must supply enough energy to bridge this gap $\rightarrow \omega \geq \Delta E_j$
- No absorption if frequency below threshold



Below a threshold frequency,
extremely cold black holes are
transparent