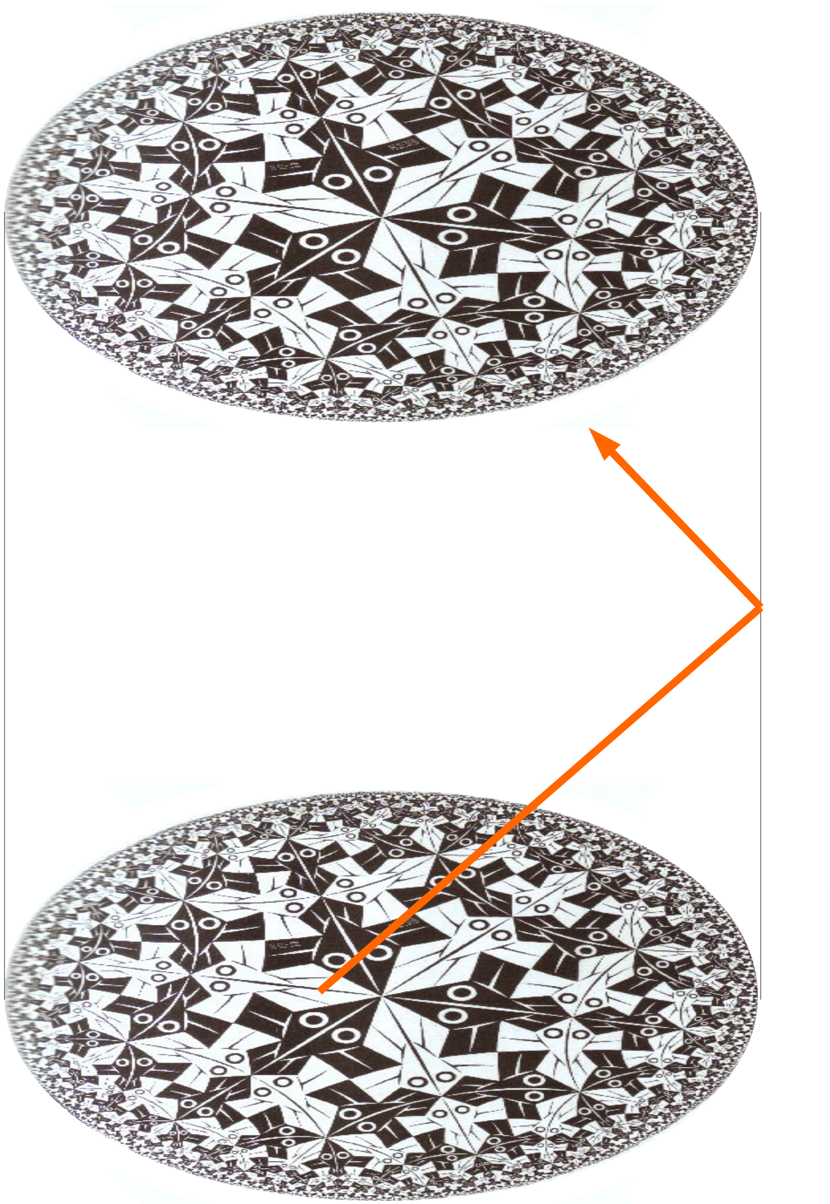
The Case **AGAINST** Information Loss

Aron Wall
(IAS)

Argument #1: AdS/CFT



Anti-de Sitter

DUALITY

string/M-theory on asymptotically | nongravitational gauge theory

$$AdS_{d+1} \times F \iff CFT_d$$

↓ | ↓

classical GR $\iff$ large N colors strong coupling

The "Dictionary"

string theory on AdS	conformal gauge theory
$l_{\text{planck}}/L_{AdS} \to 0$	$N_{\text{colors}} \to \infty$
$l_{string}/L_{AdS} \to 0$	strong coupling limit
$\lim_{z\to 0}[z^{\Delta}\,\phi_{\text{bulk}}]$	single trace $\mathcal{O}$ of dim Δ
action of saddle w/ b.c.	partition function w/ sources
BLACK HOLE	deconfined thermal phase
$S_{BH} = A/4G\hbar$	$S_{\text{thermal}} = -tr(\rho \ln \rho)$

- CFT evolution is unitary because it is an ordinary quantum field theory with a known Hamiltonian,

even in situations dual to formation & evaporation of black holes!

- *remnants* that store large amounts of info not possible, since finite # of states below any given energy @ finite N

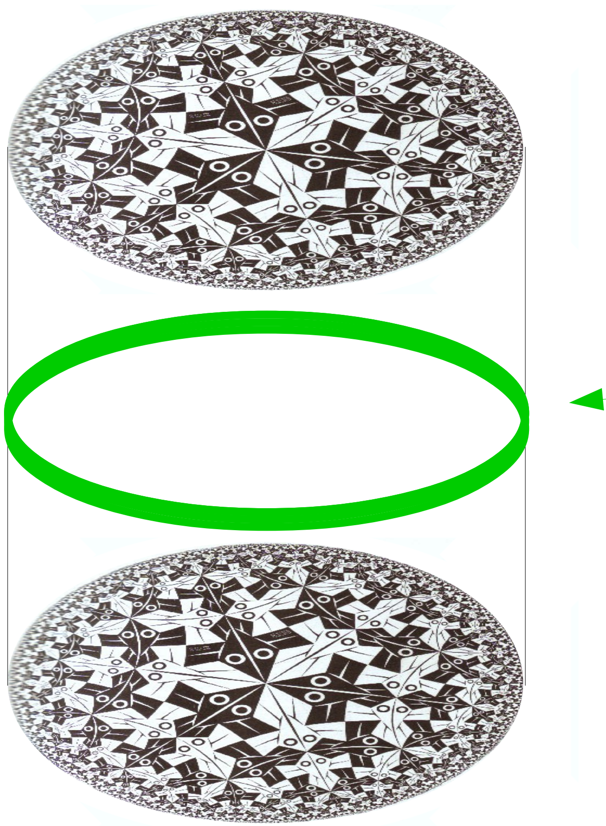
- many nontrivial checks confirm the duality

but could it be violated nonperturbatively in 1/N (i.e. $\hbar$)?
also, could a non-stringy QG theory avoid info loss?

Argument #2: Boundary Unitarity (Marolf)

assume asymptotically AdS, but do *NOT* assume AdS/CFT
(instead we will be *proving* that something like it must hold)

[a asymptotically flat argument exists, but is more subtle.]



argument concerns the set of all quantities that are measurable on the boundary at a given time t:

$$\mathcal{A}_{t,\Delta t}$$

allow a small "thickness" Δt to avoid worries about smearing operators in time...

basic principles of physics will now imply that the info that falls into a black hole remains accessible on the boundary...

Axiom #1: $\mathcal{A}_{t,\Delta t}$ is an *algebra of operators* [QFT]

- vector subset of operators A, B... in global Hilbert space

- closed under addition (vector space): A + B

- closed under multiplication (algebra): AB

- and reasonable limits thereof (C* algebra)

These assumptions are totally standard in AQFT when describing the set of all measurable quantities in a region

Axiom #2: the Hamiltonian is measurable at boundary [GR]

$$H \in \mathcal{A}_{t,\Delta t}$$

In ANY **diffeomorphism-invariant** *theory of gravity (not just GR), the total energy is a pure boundary term (the ADM energy).*

Gauge symmetry implies that H = 0 locally, up to a total derivative that arises when the diffeo vector ξ *does not vanish on the boundary.*

The ADM energy is obtained from the case where ξ *limits to a time translation on the boundary.*

Axiom #3: The Hamiltonian generates time translations [QM]

a) H is a self adjoint operator

b) for all $\mathcal{O}$, $[H, \mathcal{O}] = i \frac{d\mathcal{O}}{dt}$ (Heisenberg picture)

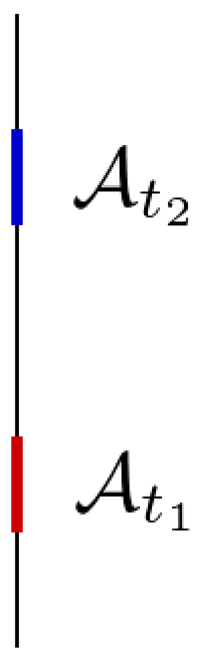
These rules are simply the **definition** *of the Hamiltonian in QM, which always exists if there is a time-translation symmetry acting on the complete Hilbert space.*

(the identification of this with the previous H is related to the exact equivalence of gravitational and inertial energy in GR.)

Axioms 1-3 imply that the boundary evolves unitarily!

If $\mathcal{O}(t)$ is a family of operators related by time translation symmetry, then you can solve for one time in terms of other times:

$$\mathcal{O}(t_1) = e^{iH(t_1-t_2)}\mathcal{O}(t_2)e^{-iH(t_1-t_2)}$$



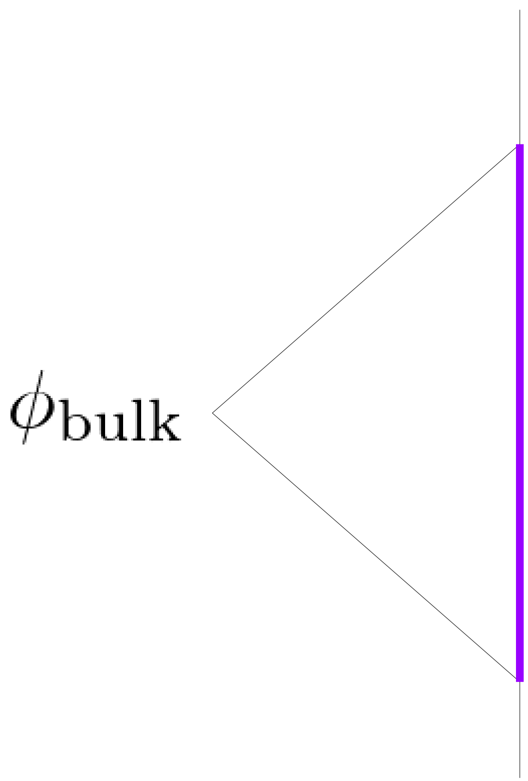
anything that can be measured at t_1 can also be measured at t_2,

because H and $\mathcal{O}(t_2)$ are in the algebra and the r.h.s. is just a limit of sums & products of those...

hence no info can be lost from the boundary (unless it was *never* on the boundary)

Axiom #4: There are other nontrivial operators in the algebra that can be excited to form a black hole [AdS QFT]

e.g. the boundary value of a scalar field $\phi(t) \in \mathcal{A}_{t,\Delta t}$



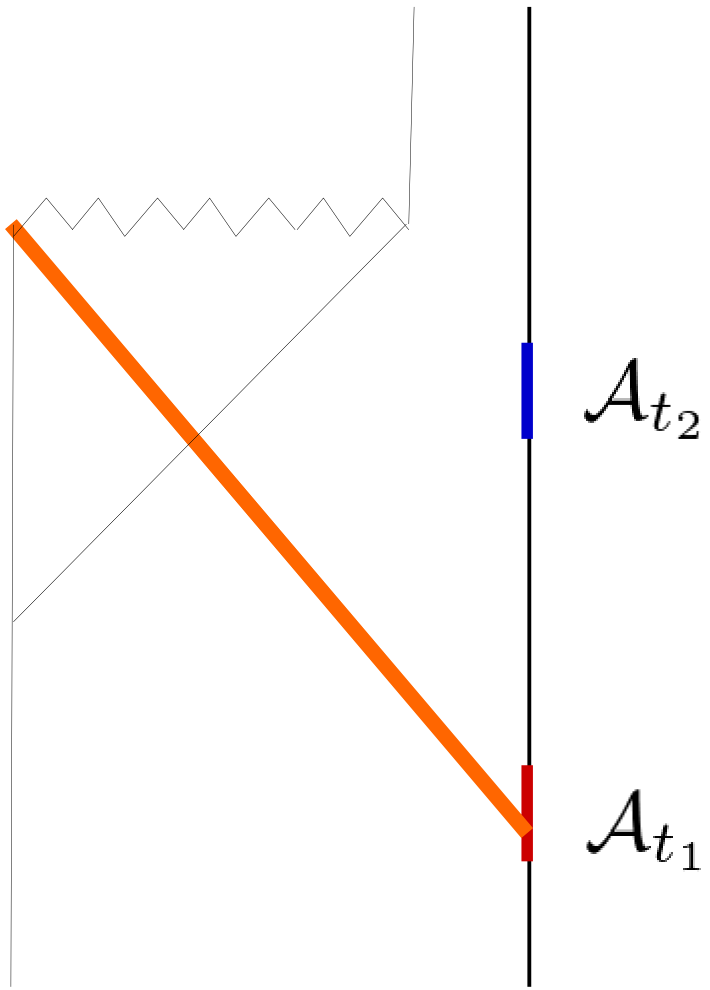
it is known how to solve for a field (outside of any horizons) in terms of integrals of boundary limiting values ϕ_{bulk}

sideways Cauchy problem subtle but basically OK

Hamilton-Kabat-Lifschytz-Lowe (free fields)
interacting case done perturbatively in 1/N
(should be good near infinity)

note we just need ***some*** *nontrivial field operator,*
(other than vacuum symmetry generators like H)
on a small boundary interval

Information is not lost into the black hole



excite fields at t_1 to form BH,
these fields carry info to the inside

at any later moment of time t_2
(even before the BH evaporates)
the information is still available
in principle, and can be measured
by a complicated experiment

Summary of Assumptions

#1: exists an *algebra of operators* $\mathcal{A}_{t,\Delta t}$. [QFT]

#2: $H \in \mathcal{A}_{t,\Delta t}$ [GR]

#3: a) H is a self adjoint operator

b) for all $\mathcal{O}$, $[H,\mathcal{O}] = i\frac{d\mathcal{O}}{dt}$ [QM]

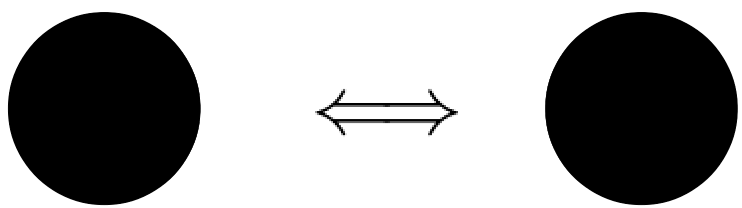
#4: exist nontrivial operators in $\mathcal{A}_{t,\Delta t}$ that can be used to form black hole [AdS QFT]

Argument #3: Too Many Species!

Suppose the information does *not* escape to infinity.

In that case the info trapped inside a BH can be larger than A/4G

These states can be distinguished in principle by means of a “swap test”

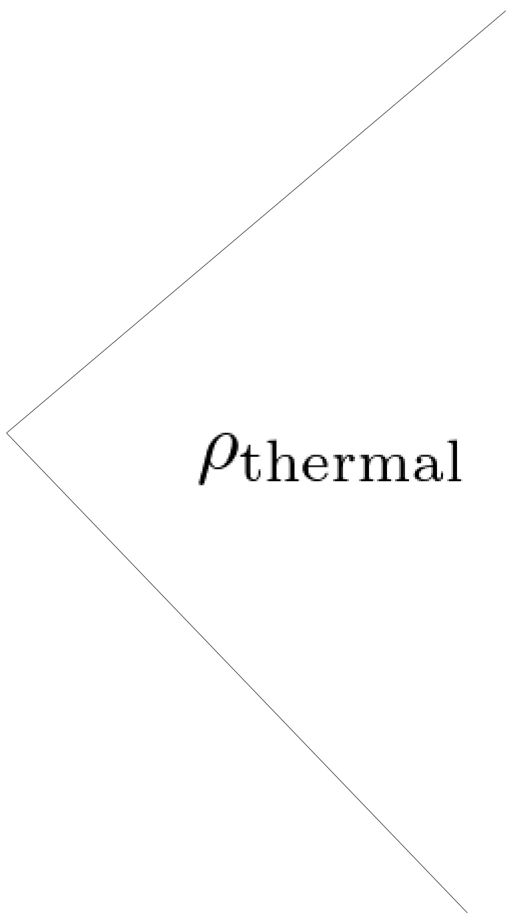


step #1: form additional “test” BH

step #2: do interference experiment to check if BH's behave like identical bosons or fermions.

But if they do count as different “species”, they should appear with infinite state-counting enhancement in pair production

Problem even in vacuum state...



“Unruh effect”: the vacuum in a spacetime “Rindler wedge” region is exactly thermal (flat space limit of Hawking effect)

That means that distinguishable particles MUST appear with a degeneracy factor associated with their number N of internal states.

Otherwise Hawking radiation won't be exactly thermal & you can violate BH thermo.

Hence infinitely many black holes in vacuum.

Causes infinite renormalization of 1/G and other very bad things...

Violation of Effective Field Theory for observers who fall across horizon

Fundamental Theory

↓

Effective Field Theory

the more *fundamental* theory that controls when the EFT is valid, not the other way around!

Could be discontinuous phase transition (e.g. hydrodynamics of fluid water abruptly changes when it freezes to ice).

Phase transition might be modelled by Q error correcting code...