strings, symmetries and holography

Discrete'08
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THE ROLE OF SYMMETRY PRINCIPLES IN THE CONSTRUCTION OF STRING THEORY WAS NEVER UNDERESTIMATED

Examples of the ever higher symmetry fugue

- String Field Theory
- Topological Field Theory
- String Duality
- . . .

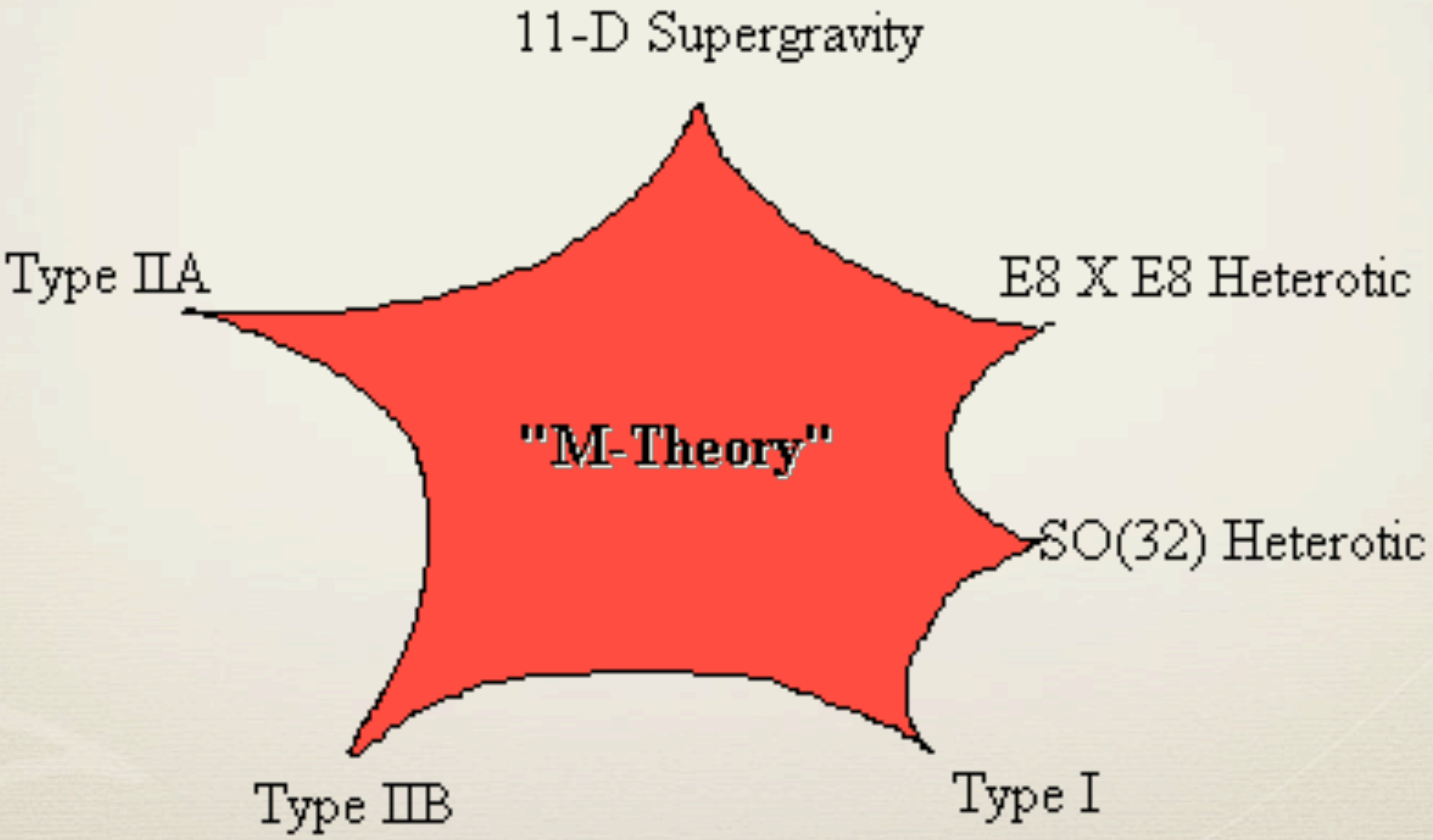
SUPERSYMMETRY
is the

éminence grise

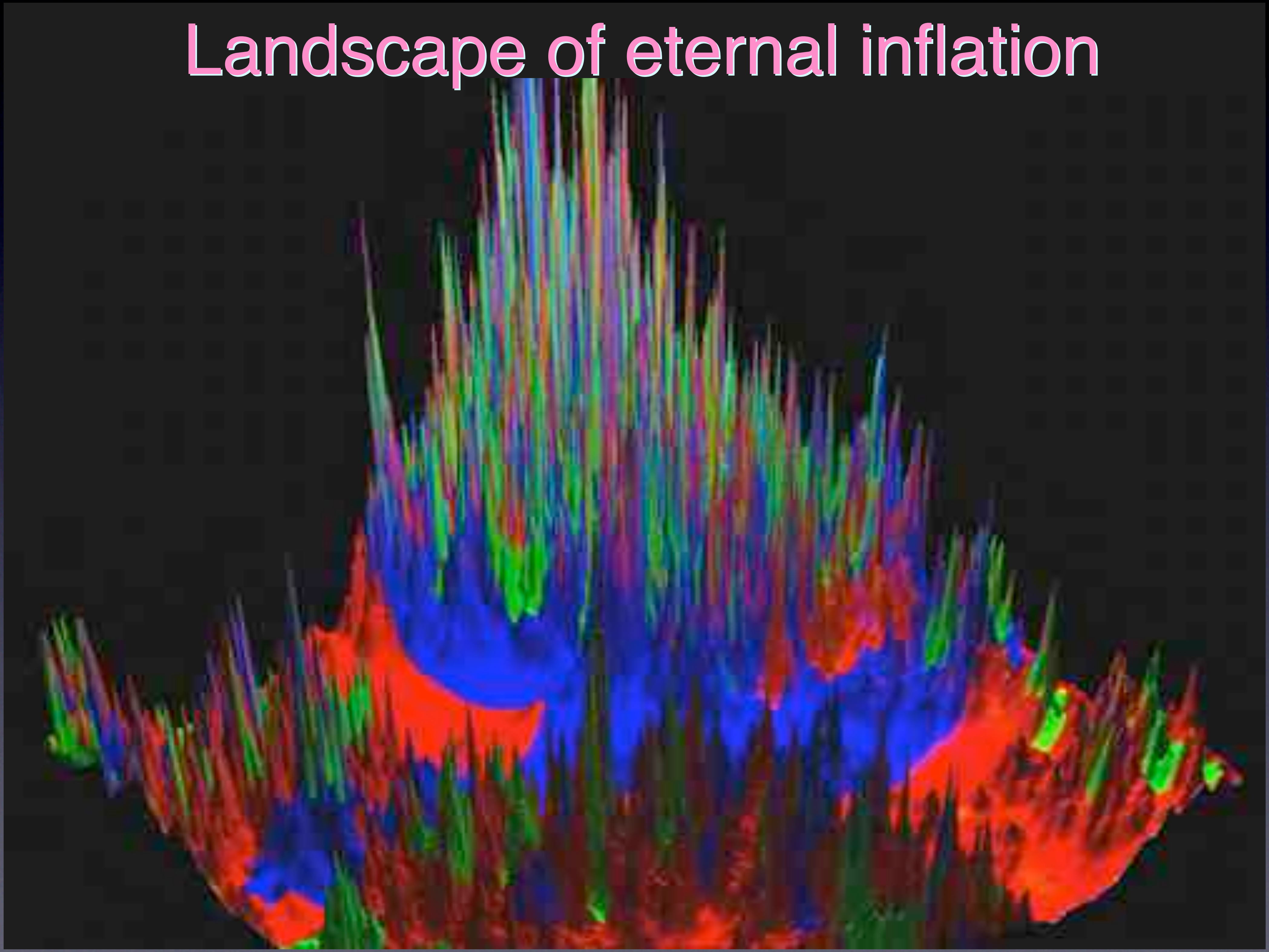
behind most well-established facts
in string-M-theory

according to taste, this leads
us to...

A glimpse of heaven...



…OR A VISION OF HELL…



One conspicuous feature of “vintage string theory” is the absence of GLOBAL symmetries

Banks & Dixon

- Global continuous symmetries are gauged by construction
- Discrete symmetries are in practice residuals of spontaneously broken gauge symmetries

A baby version of this property already occurs in Kaluza-Klein theory

Let G be the isometry group of some compact manifold K_G of size L

The effective Lagrangian on R^4 obtained
by integrating out K_G realizes
the symmetry group G in low-energy effective
theory

However, as soon as $G_N > 0$, the mixed metric component is a G-gauge field on R^4

$$\mathcal{L}_{\mathrm{eff}} \sim \frac{1}{G_{\mathrm{N}}}\left(R + |d\phi|^2\right) + \frac{1}{g_{\mathrm{YM}}^2}|F|^2$$

$$A^i_\mu \sim g_{\mu i}$$

$$\phi \sim \log(L^2/G_{\mathrm{N}})$$

$$g_{\mathrm{YM}}^2 \sim G_{\mathrm{N}}/L^2$$

Moduli fields

String theory generalizes this mechanism

- Typically, one gets $G_L \times G_R$ for generic L
- When $L \sim \ell_s$ symmetry can be enhanced at special points in the moduli space of compactifications ($E_8 \times E_8$ of Heterotic string is a particular case of this)
- Discrete symmetries arise as spontaneously broken gauge symmetries around these points (example T-duality)
- On D-branes, also find gauged SU(N) from N Chan-Paton factors

Ironically, AdS/CFT brings back the global symmetries, but it puts them "at the outer limits of the world"

Global current
of boundary CFT

bulk gauge field

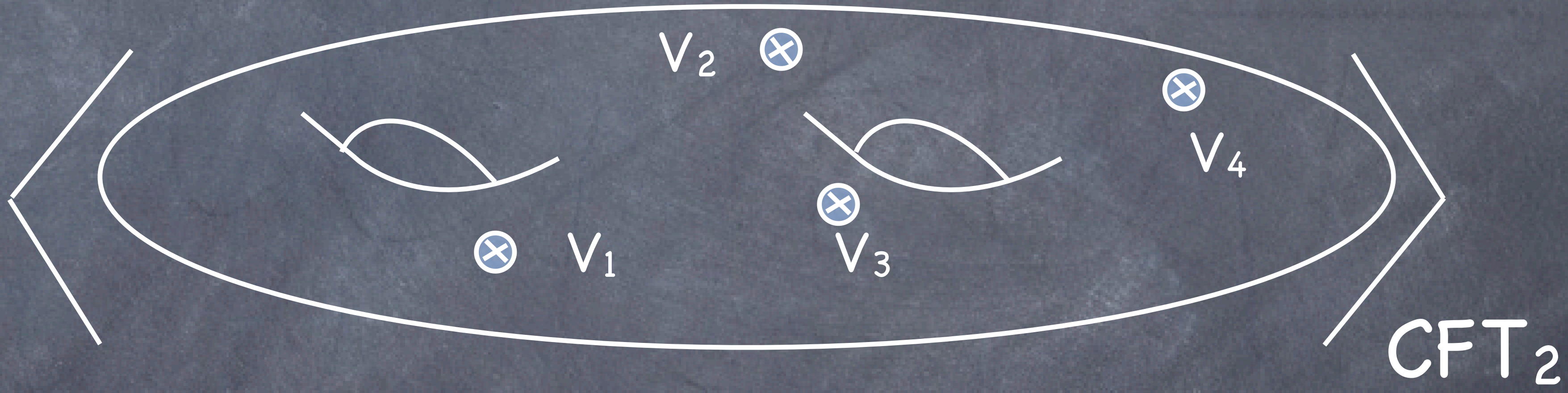
$$\left\langle e^{\int J\cdot A_\partial} \right\rangle_{\mathrm{CFT}} = e^{-I_{\mathrm{bulk}}(A\to A_\partial)}$$

classical source of CFT current operator = boundary value of bulk gauge field

This is a nonperturbative generalization of an old mantra of perturbative string theory

A symmetry of the S-matrix is a global symmetry of the 2-dim worldsheet theory

$S_{(1,2)\to(3,4)} =$



But the vertex operators V_i create gauge particles in spacetime

All these formal niceties are OK for exact symmetries specified in the UV regime but...

what about accidental global symmetries in the IR?

The are broken by irrelevant operators, at least...

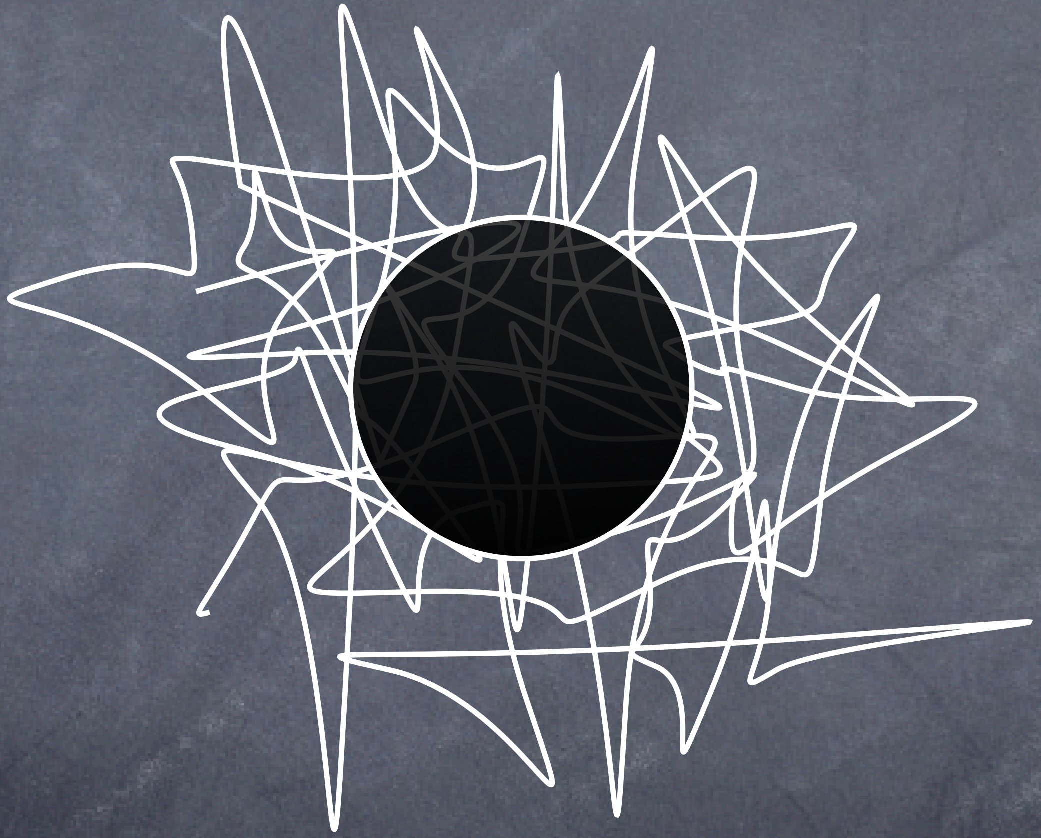
$$\Delta \mathcal{L}_{\mathrm{eff}} \sim \frac{1}{(M_{\mathrm{Planck}})^n}\, \mathcal{O}_{n+4}$$

Induced by strings or...

perhaps microscopic black holes...

… which actually match one another…

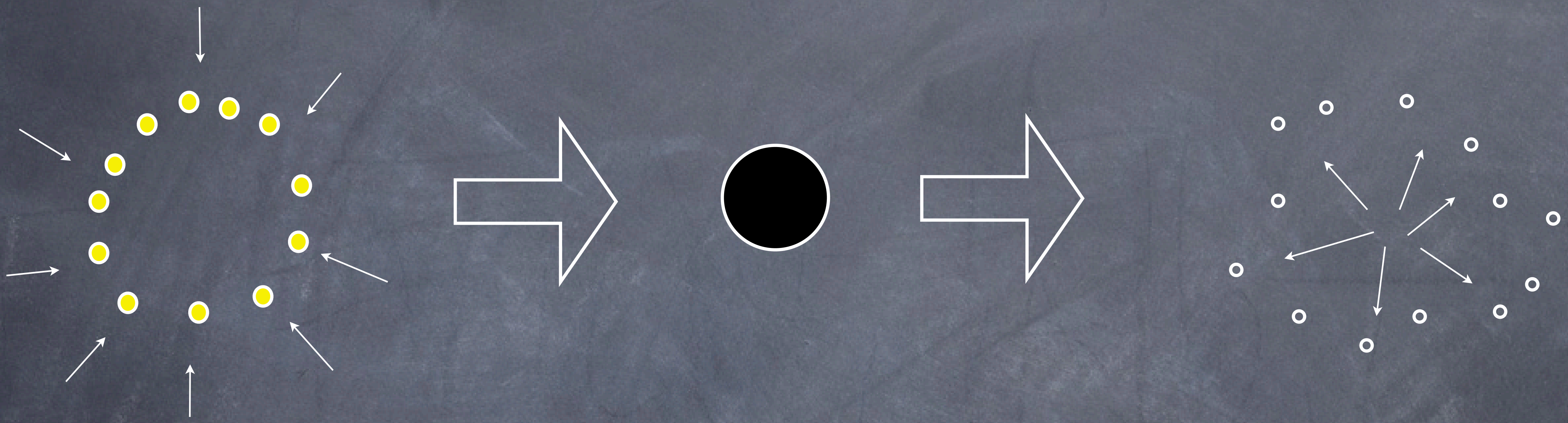
Bowick, Veneziano,
Susskind, Horowitz, Polchinski, Damour



$S_{\rm bh} \sim S_{\rm string}$ precisely when $R_{\rm bh} \sim \ell_s$

$T_{\rm Hag} \sim T_{\rm Haw}$

Black holes destroy any global charges



Charge Q
collapsing

Black Hole with
no classical Q-hair

$Q \sim 0$
evaporation
products

Conversely, gauge charges are measurable by fluxes at infinity, and are part of the Hole's "hair"

- If the charged states have a gap m_Q then Q-charged particles cannot come out until very late, when $M_{bh} \sim m_Q$
- Even then... thermal rates are equal for particles and antiparticles. So the net Q ~ 0
- Hence, a macroscopic Q can only come out if a Planck mass particle exists with arbitrarily large value of Q: a **Q-remnant**

WE HAVE SIMPLY RESTATED THE INFORMATION PARADOX, FOR THE PARTICULAR CASE OF THE Q-CHARGE QUANTUM NUMBER

However, the macroscopic black hole argument poses a greater challenge to ungauged charge non-conservation, because it folds it into the information paradox...

While apparently staying well within the IR domain!

Question:

How fast can we “decode” the initial Q ?

The answer depends on how LOCAL is
the probe used to
“measure” Q

THE INFORMATION PARADOX

Hawking

$$S : \mathcal{H}_{\rm in} \to \mathcal{H}_{\rm out} \otimes \mathcal{H}_{\rm sing}$$

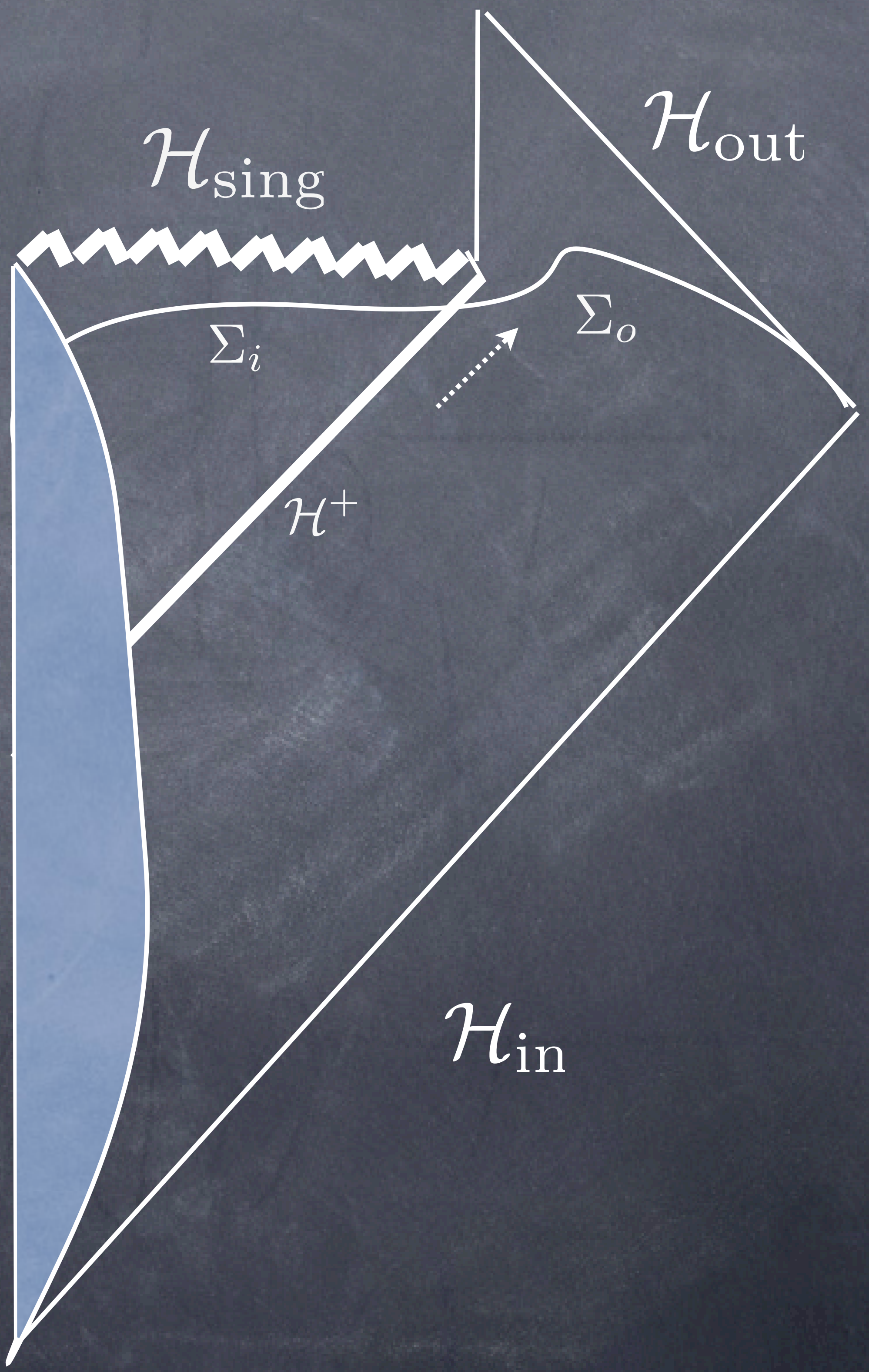
unitarily, unlike

$$\$: \mathcal{H}_{\rm in} \to \mathcal{H}_{\rm out}$$

which treats the singularity inclusively

Implied by QFT locality

$$\left[\mathcal{O}_{\Sigma_i}, \mathcal{O}_{\Sigma_o}\right] = 0$$



The “nice slice” $\Sigma_i \cup \Sigma_o$ intersects all infalling matter AND most Hawking radiation while remaining weakly curved in Planck units

Expansion parameter of low-energy QFT:

$$\lambda_{\rm eff} = \frac{G}{R_s^2} \sim \frac{1}{S} \ll 1$$

where S is the black-hole entropy

The scenario called “Black Hole complementarity” claims that it is QFT locality that must yield

‘t Hooft, Susskind, Verlinde^2

$$\left[\mathcal{O}_{\Sigma_i}, \mathcal{O}_{\Sigma_o}\right] \neq 0$$

after all...

But... just how serious is this violation of locality?

If information comes back, it requires at least a time t_{bit} of O(evaporation time)

$$t_{\text{bit}} \sim t_{\text{ev}} \sim \frac{R_s^3}{G} \sim R_s\, S \sim \frac{R_s}{\lambda_{\text{eff}}}$$

$$\Downarrow$$

Information retrieval is NONPERTURBATIVE in the low-energy QFT expansion parameter λ_{eff}

No Hair arguments give damping effects of order

$$e^{-t\,T_H}$$

with T_H the Hawking temperature of $O(1/R_s)$

Information restoration should come from effects of order

$$\boxed{e^{-t_{\text{bit}}\,T_H} \sim e^{-S} \sim e^{-1/\lambda_{\text{eff}}}}$$

FULLY NONPERTURBATIVE IN λ_{eff} !!

So far, it has been difficult to go beyond these general remarks, even in two-dimensional toy models

One needs a non-perturbative definition the system, capable of revealing tiny effects of order e^{-S}

A natural candidate: AdS/CFT

AdS_{d+1} / CFT_d

Maldacena
Gubser & Klebanov & Polyakov
Witten

AdS_{d+1}
quantum
gravity

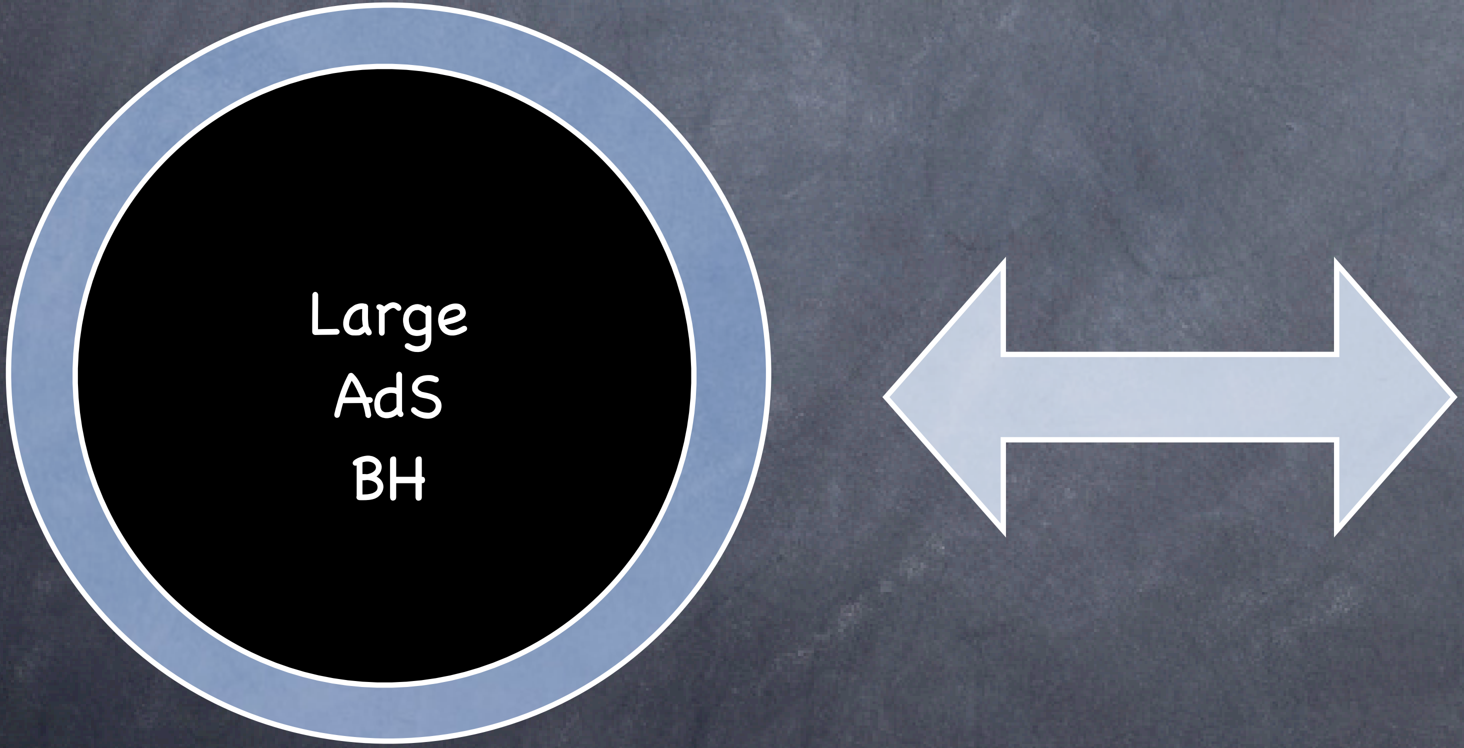
=
defined!

S^d
conformal
field
theory

$$\frac{R^{d-1}}{G} = N^2 \sim \text{central charge}$$

Large AdS black holes with temperature T>> 1/R are stable, $C_v > 0$, and are dual to the standard thermal state of the Yang-Mills plasma

$$\Omega(E) \propto \exp[\, N^2 (RE)^{3/4} \,]$$



$$\rho_T = \frac{e^{-H/T}}{\mathrm{Tr}\left(e^{-H/T}\right)}$$

Can we rephrase the information paradox for a large AdS black hole in terms of some property of

ρ_T ?

This was proposed by Maldacena, and later further analyzed by:

Susskind et al
Birmingham, Sachs, Solodhukin
Barbon, Rabinovici
Kleban, Porrati, Rabadan
Hawking
...

MAIN IDEA: study time structure of correlation functions of the global charge operator

$$G(t) = \mathrm{Tr}\left[\rho_T \, Q(t) \, Q(0)\right]$$

Local operator on CFT
boundary operator on AdS

It measures the damping of a generic perturbation as in no-hair set ups

Gravitational calculation to leading order in λ_{eff} yields QUASINORMAL behavior

$\Gamma \sim T$ in general (horizon diffusion)

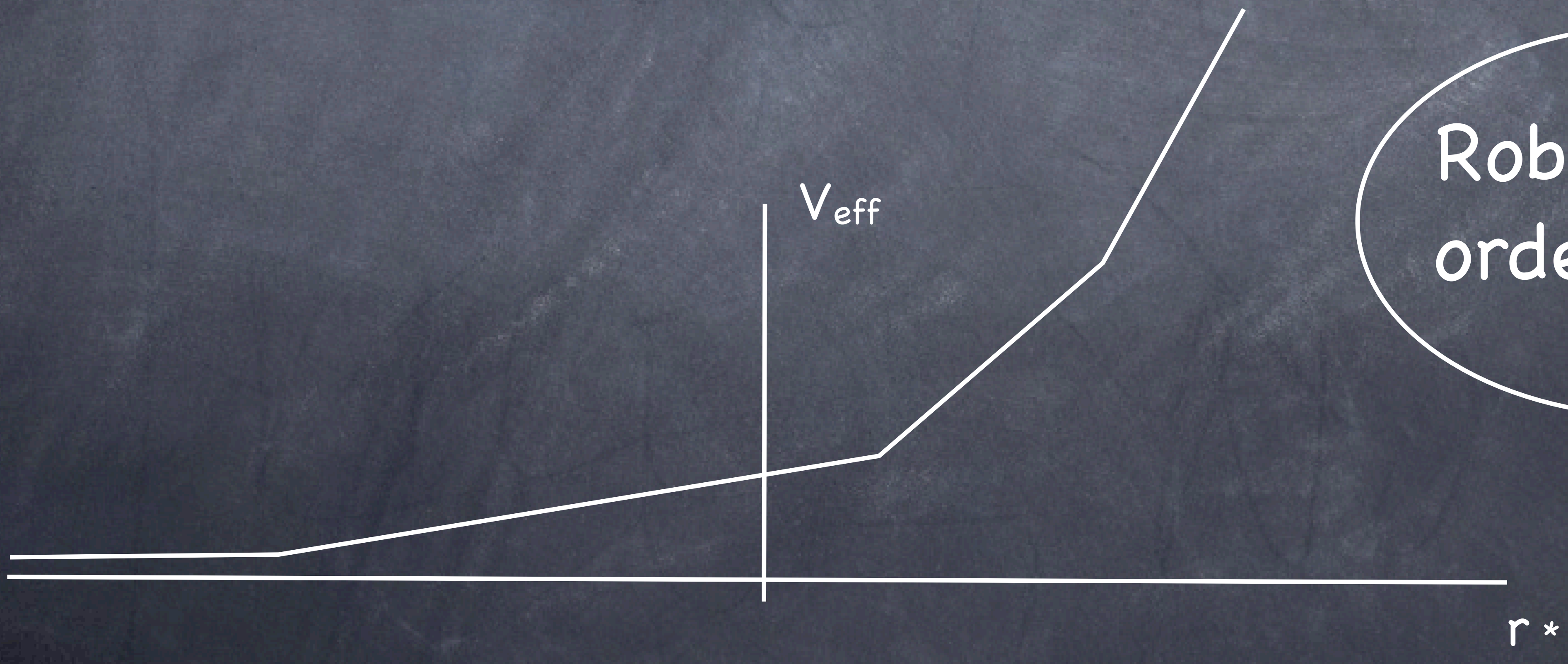
Infinite time average vanishes!

$$\boxed{L = \overline{G(t)}_{\text{grav}} = 0}$$

L=0 follows from the continuous spectrum of normal modes around the large AdS black hole

Effective potential in Regge-Wheeler coordinates

$$\left(-\frac{d^2}{dr_*^2}+V_{\text{eff}}(r_*)\right)\varphi_\omega=\omega^2\,\varphi_\omega$$



Robust to all orders in λ_{eff}

Nonperturbatively, on the CFT side, the spectrum is discrete, with density of states Ω(E) = exp(S)

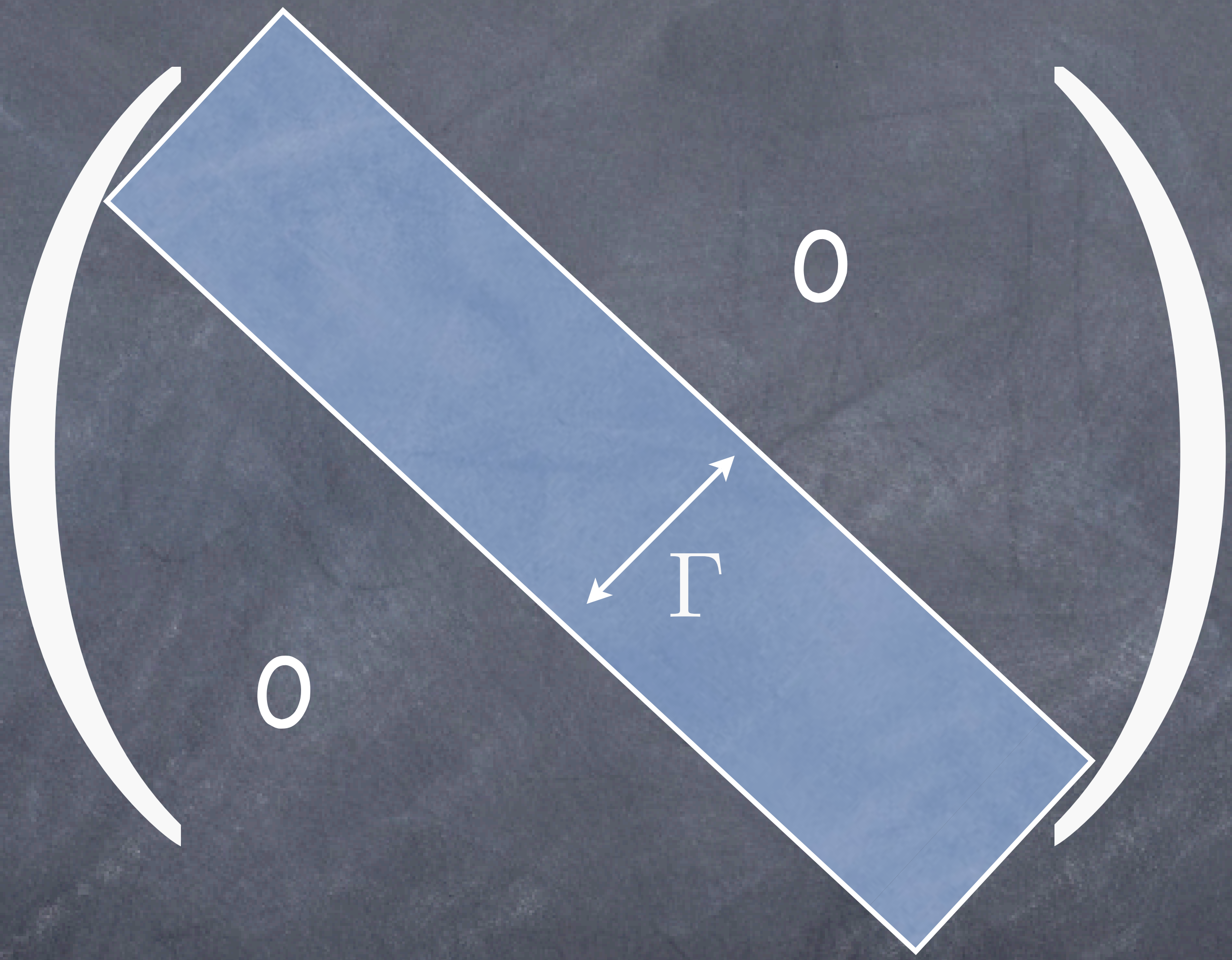
$$\Downarrow$$

$$G(t) = \frac{1}{Z(T)} \sum_{n,m} |Q_{nm}|^2 e^{-E_n/T} e^{i(E_n - E_m)t}$$

is quasiperiodic in time

The matrix of Q is a banded random matrix in the energy basis

Q_{nm} =



with nonzero entries of size $|Q_{nm}|^2 \propto e^{-S}$

This implies that G(t) has Poincaré recurrences after time of order

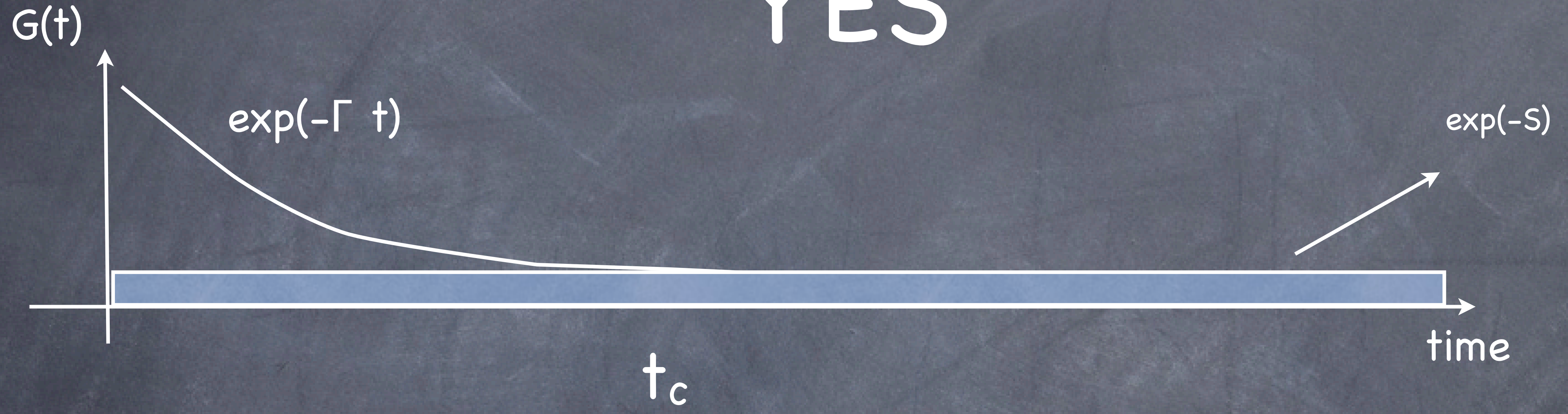
$$\boxed{t_{rec} = \Gamma^{-1} \ \exp(S)}$$

Time average: $L = e^{-S}$

OK!!

Can we identify the $\boxed{t_{\text{bit}}}$ time scale in the correlator?

YES



Consider the time scale t_c where the quasinormal behavior becomes DOMINATED by the time-average noise

$$t_c \sim \Gamma^{-1} S \sim t_{\text{bit}}$$

In this way, we have succesfully identified on the CFT side the time scale t_{bit} at which information retrieval begins

This time scale can be identified in terms of an Euclidean instanton calculation a la Gibbons-Hawking

Maldacena

But, so far there is no semiclassical understanding of the full recurrence time scale t_{rec}

Barbon & Rabinovici
Kleban, Porrati & Rabadan

SCENARIO for locality violations

$$\left[\mathcal{O}_{\Sigma_i}, \mathcal{O}_{\Sigma_o}\right] = O(e^{-S})$$ for local, “small” operators

$$\left[\mathcal{O}^{(S)}_{\Sigma_i}, \mathcal{O}^{(S)}_{\Sigma_o}\right] = O(1)$$

for “large” operators $O^{(S)}$ that excite O(S) quanta

$$\mathcal{O}^{(S)} \sim \mathcal{O}_1 \mathcal{O}_2 \cdots \mathcal{O}_S$$

Indeed, we need O(S) quanta to evaporate the black hole and to measure the density matrix of the Hawking radiation

Low energy QFT is OK for times

$$t \ll t_{bit}$$

and/or for qbit observables of

$$\text{bit-size} \ll S$$

Some recent work

- Thermalization, and recurrences can be modeled in matrix quantum mechanics as a toy model of the stretched horizon Hamiltonian, confirming that quasinormality holds to all orders in the 1/N expansion
- The scrambling time scale $\boxed{t_{scram} = T^{-1} \log S}$ saturates the no-cloning theorem in black holes

Festuccia & Liu
Iizuka, Okuda & Polchinski
Sekino & Susskind
Preskill & Hayden

Summary

- Global charges are absent in the UV prescription of gravity theories
- IR accidental global charges can be decoded with $O(e^{-S})$ sensitivity, or in Poincaré times
- The understanding can be systematically improved by finding efficient computational methods for the time correlation functions

Main open questions

- Understand the scrambling time of Preskill and Hayden $t_{scram} = T^{-1} \log S$ in terms of the time correlators
- What is the precise relation between the OUT decoding operator O_Q and the initial local charge operator Q?

THANK YOU