Singularities, Black Holes, and Attractor Explosions

- G. Horowitz & ES

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↔ Arkani-Hamed, Dimopoulos, Schuster, Toro

How do black holes explode?

- Information flow
- Singularity
- Endpoint(s)
- production & signatures?

This is an arena where string theory (or at least a complete theory of gravity) should matter.

This talk: Two aspects of string theory configuration space affect BH evolution

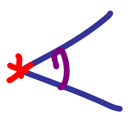
I. Closed String Tachyons
singularity, info, endpoints

II. Multiple vacua
endpoints

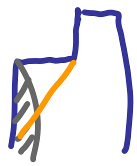
I. Quasilocal tachyons and black holes

G. Horowitz & ES

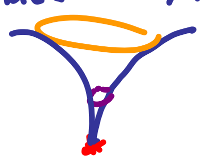
In string theory, several types of GR singularities are replaced by a phase of closed string tachyon condensate $\langle T \rangle$.



orbifolds , ... ,



black holes/branes



e.g. spacetimes containing 1-cycles with AP boundary conditions have winding strings with mass²

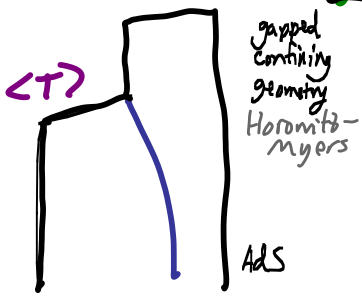
$$M_T^2 = -m_s^2 + L^2 m_s^4$$

↖ worldsheet Casimir energy

$$\rightarrow \langle T \rangle \propto \mu e^{\kappa X^0}$$

cf Horowitz review talk

Examples of quasilocal tachyon condensation:



time-dependently induced confinement

gravity / QFT

↙ ↳ mass gap

<T> replaces region dual to QFT IR

AdS/CFT on Coulomb branch

shell of D3-branes — Kraus, Larsen, Trivedi '98

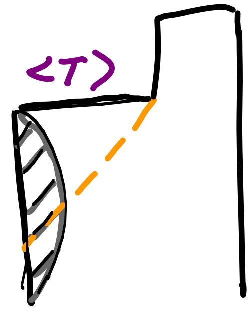
$$ds^2 = H^{-\frac{1}{2}}\left(-dt^2 + d\vec{x}^2\right) + H^{\frac{1}{2}}\left(dr^2 + r^2 d\Omega_5^2\right)$$

$$H(r) = \begin{cases} \frac{\ell^4}{r^4} & r > R \\ \frac{\ell^4}{R^4} & r < R \end{cases} \quad (R \ll L)$$

← Scherk-Schwarz cylinder

Compactify $X_1 = X_1 + L$ with AP boundary conditions for Fermions. Roll shell to origin → cylinder shrinks slowly

Black holes



e.g.
- BTZ
- wrapped black strings

cf Horowitz '05 Black string → bubble of nothing

→ of interest to understand $\langle T \rangle$ phase.

$\langle T \rangle = \hat{T} \mu e^{\kappa X^0}$ ⇒ time-dependent background,

so no a priori preferred vacuum state.

Simplest choice: Euclidean vacuum, related to spatial Liouville theory by Wick rotation. Strominger/Takayanagi '03 McGreevy/ES '05

- Calculate occupation #s of particles in bulk → $N_\omega = \frac{1}{e^{\frac{2\pi\omega}{\kappa}} \pm 1}$

- Calculate partition function (quantum correction to stress-energy) → $\mathrm{Re}(Z) = -\frac{\ln \mu}{\kappa} \hat{Z}_{free}$

  ↖ not $\delta(0) = \mathrm{Vol}(X^0)$

These calculations in the Euclidean vacuum reproduce behavior (behaviour) expected from several points of view

In the worldsheet path integral $\int DX^0 D\tilde{X}\, e^{iS}\, \pi V$, the integrand has semiclassical action

de Alwis, Schimmrigk, Polchinski '89

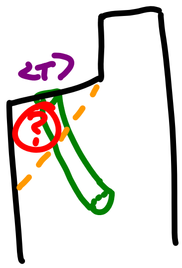
$$S \to S_0 + \int d^2\sigma\, \mu^2 e^{2kX^0}\, \hat{T}(\tilde{X})$$

$\hat{T}(\tilde{X})$: relevant in worldsheet matter sector

$\int d^2\sigma\, \mu^2 e^{2kX^0}$: cf mass^2 of relativistic particle in analogue QFT

Strominger '02

} suggest degrees of freedom becoming heavy in $\langle T \rangle$ phase.



* What about other states? What happens to a particle/string sent into the $\langle T \rangle$ phase?

A priori, challenge for bulk spacetime unitarity

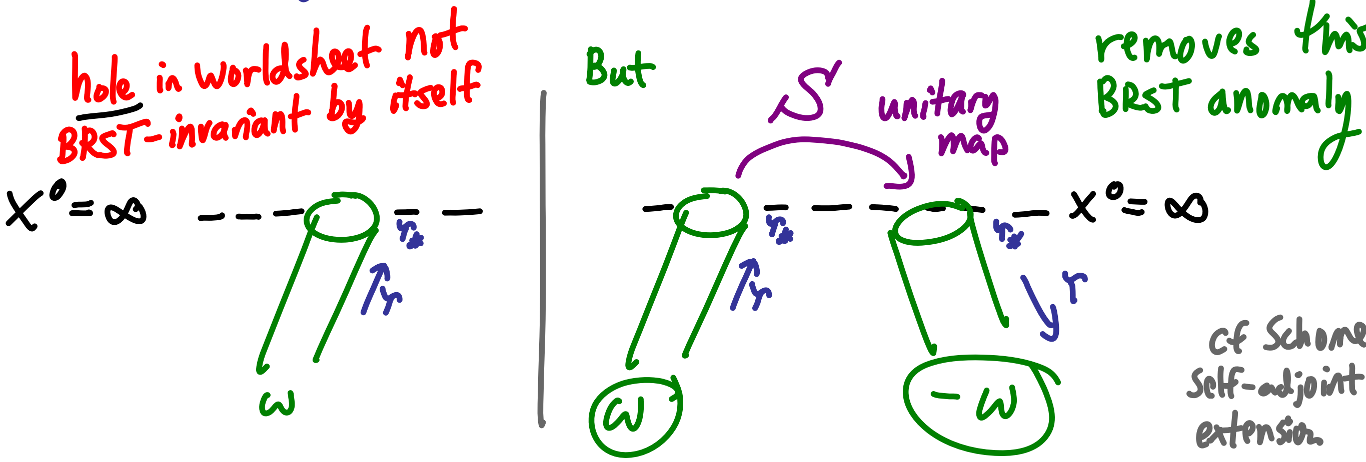
- Worldsheet path integral has saddle point classical solution with single string stuck in $\langle T \rangle$ phase

- Analogue QFT with $m^2(X^0, \vec{X}) = f(\vec{X})\, \mu e^{2kX^0}$ has the property that particles get stuck and wavepackets stop expanding in massive region
- $\langle T \rangle \rightarrow$ all modes massing up, including gravity multiplet, so back reaction caused by massive source is suppressed.

However, these features do not survive in the full string theory, for 2 reasons

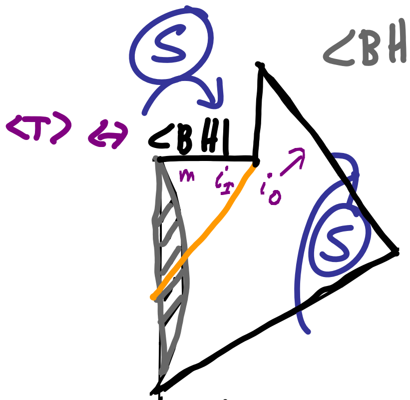
① BRST invariance (decoupling of Q_B - trivial modes)

The strings impinge on $X^0 = \infty$ at finite $\tau \equiv \tau_*$



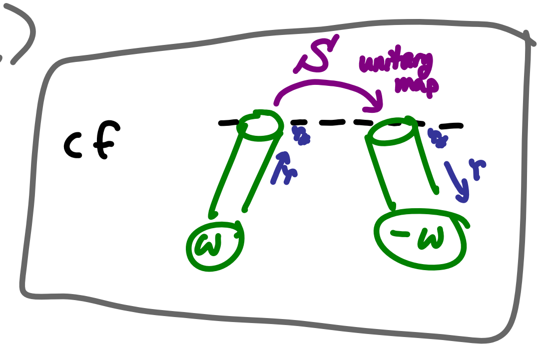
cf Schomerus self-adjoint extension

This suggests microphysical realization of the "Black Hole Final State" Horowitz/Maldacena



$$\langle BH|\psi\rangle = \underbrace{|i\rangle_0 S^{im} \langle m|}_{\text{unitary}}\psi_m\rangle$$

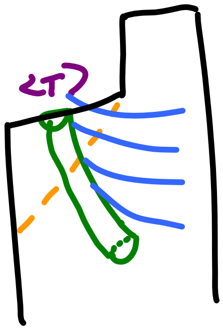
$$|\psi\rangle = |\psi\rangle_m \otimes \sum |i\rangle_I \otimes |i\rangle_0$$



At linearized level, $\langle BH| = S^{mi} \langle m| \otimes \langle i|_I$

- S^{mi} ← unitary matrix
- $\langle m|$ ← matter
- $\langle i|_I$ ← inner Hawking

② Dynamics :



Infalling string sources fields (e.g. gravitational field).

This field gets heavy in the <T> phase as well.

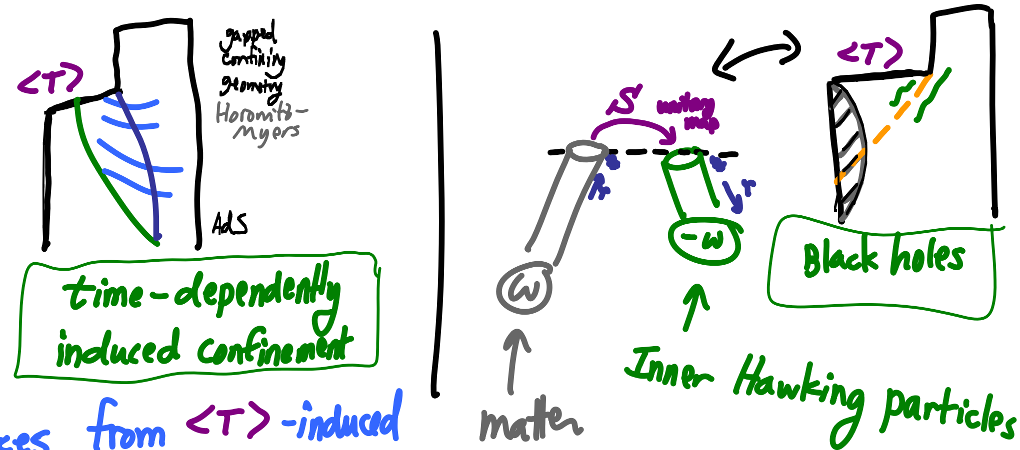
In QFT analogue $m^2(x^0,\vec{x}) = f(\vec{x}) M^2(x^0) + m_0^2$

$$E = m_0^2 \lambda^2 M(x^0) \cos^2\left(\int^{x^0} M(t')\,dt'\right) \times \int d^{d-1}x\, f(|\vec{x}|) \left(\int \frac{d^{d-1}\vec{k}}{(2\pi)^{d-1}} \frac{e^{i\vec{k}\cdot\vec{x}}}{\omega_{\vec{k}}^{3/2}}\right)^2$$

→ forces out configurations sourcing the heavy fields

e.g. gravitational fld ⇒ $\Sigma\omega = 0$

Altogether, BRST invariance & forces in the problem provide concrete indications of direct mechanism for unitarity.



↑ forces from <T>-induced mass help evacuate <T> region.

This would be a good arena in which to develop full worldsheet descriptions of consistent states.

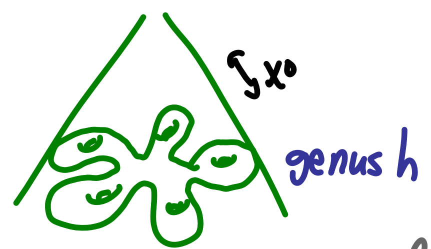
Remark: In <T> examples, the singularity is ultimately replaced by a phase with no light modes

Also expected for positively curved spaces (e.g. S^n) Polyakov '92 mass gap

Is this general? I expect not in the cosmological case: consider compact negatively curved spaces

$$\left(c-2\right) \sim \frac{2h}{V}$$ for Riemann surface follows ES '05 Phys. Rev. D

from Weyl anomaly, modular invariance → π_1 + Selberg trace, goes supercritical rather than subcritical as V decreases.



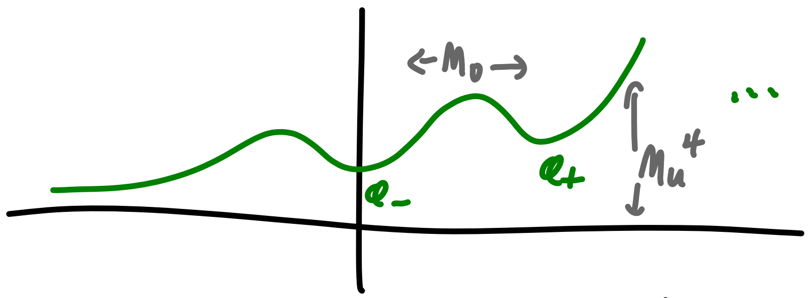
cf also Craps et al null singularity

→ Rich zoology of examples

II. Attractor Explosions :

D. Green, ES, D. Starr

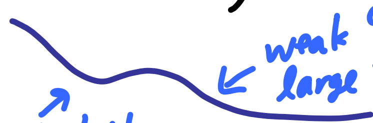
Moduli φ in string compactifications are generically lifted by a complicated moduli potential $\mathcal{U}(\varphi)$.



BP '00
GKP ; ES '01
MSS '02
KKLT '03
...

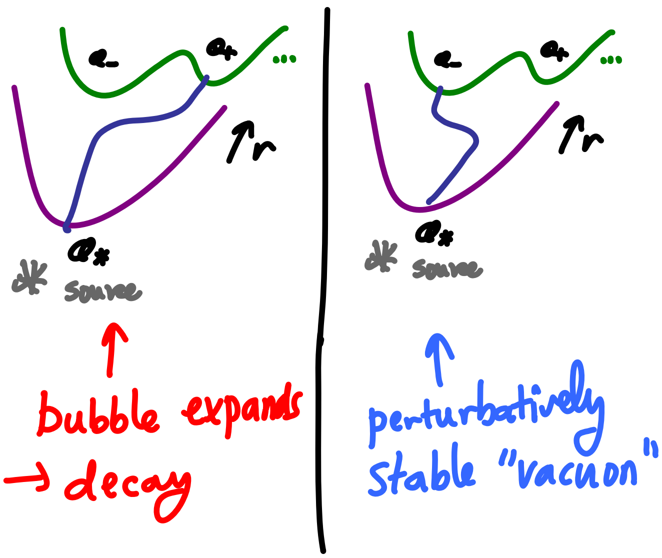
Parameterize $\mathcal{U}(\varphi) \sim M_u^4 \, f\left(\frac{\varphi}{M_0}\right)$

e.g. dilaton/volume runaway



ϕ modulate particle masses + couplings $\Rightarrow$ ϕ is also sourced by local densities $\rho(x;\phi)$

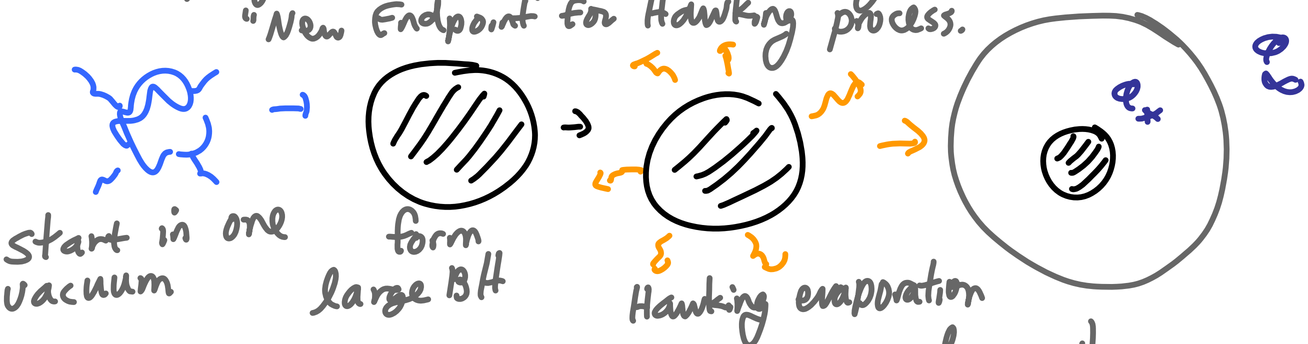
Generically both effects are present $\nabla^2\phi = -\partial_\phi \mathcal{U} - \partial_\phi \rho$



Accumulation of source density ρ can kick ϕ into the basin of attraction of a different metastable minimum of $\mathcal{U}$

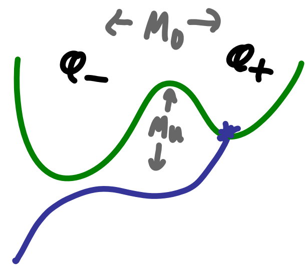
Compact objects (including black holes) catalyze vacuum bubble production:

- large set of examples generalizing Horowitz's "New Endpoint" for Hawking process.

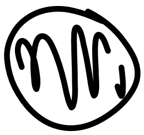


* including uncharged examples where the density ρ_* in produced massive particles catalyzes a bubble.

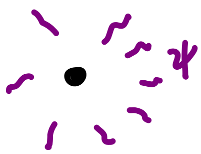
e.g. Schwarzschild case:



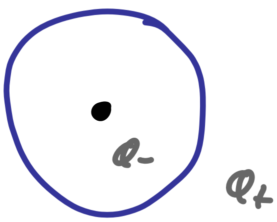
$$S = \cdots + \int d^4x\, f\left(\frac{\varphi}{\check{M}_0}\right) m_\psi \bar{\psi}\psi$$



① Form large BH in φ_+ vacuum

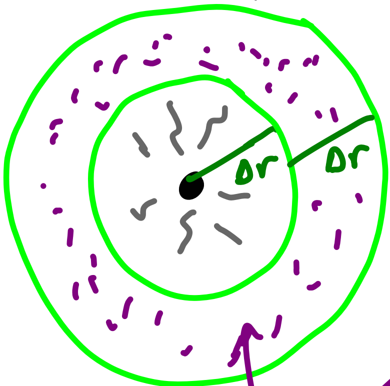


② Hawking evaporation proceeds, increasing temperature T until T crosses the threshold $T = m_\psi$ for producing massive ψ particles



③ For $M_p \gg \check{M}_0 \gtrsim m_\psi \gtrsim M_0 \gtrsim M_u$, find ρ_ψ catalyzes bubble of φ_- well before hit correspondence point.

Consider period $T \in (M_\psi, M_\psi + \Delta T)$



fraction of Hawking emission into ψ's is suppressed while ψ's slow and non-relativistic

$$\rho_\psi \sim \frac{\sqrt{\frac{\Delta T}{M_\psi}}\ \Delta M}{(\Delta r)^3}$$

change in BH mass

Energy density in ψ particles

volume into which ψ particles spread

$$\Delta r \sim \bar{v}\,\Delta t \sim \sqrt{\frac{\Delta T}{M_\psi}}\ \Delta t$$

- Impose conditions:

$\partial_\varphi \rho_\psi \gg \partial_\varphi \mathcal{U}$ for long enough time $\Delta t \sim \frac{\Delta T}{M_\psi} \frac{M_p^2}{M_\psi^3}$ so that φ can be kicked across the barrier

$\Delta\varphi \gtrsim M_0$ in a volume with linear size $\Delta r \gg$ (wall thickness $\frac{M_0}{M_u^2}$ in $\mathcal{U}(\varphi)$ theory)

and with # density $n_\psi \gg \frac{1}{(\varphi \text{ Compton wavelength})^3}$

so mean field treatment of $\rho_\psi(\varphi)$ is self-consistent.

Also check self-consistency with respect to ϕ perturbations:

- check ψ's don't annihilate into $\delta\phi$'s too fast

- $m_{\delta\phi} = \frac{m_u^2}{M_0} < M_0 \rightarrow$ Produced $\delta\phi$ gas does not catalyze a bubble classically by itself

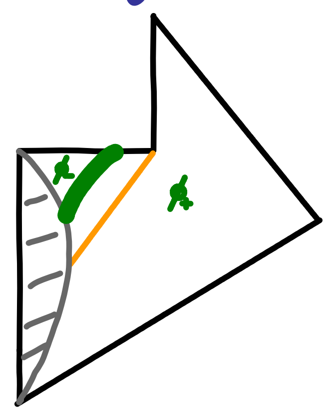
- In above window where ψ catalyzes bubble, check that ϕ fluctuations do not wash out the effect:

$k^2 \delta\phi^2 \sim \rho_{\delta\phi}$ $\quad k \sim T \sim m_\psi$ $\quad$ so $\delta\phi \sim \sqrt{\rho_{\delta\phi}} / m_\psi$

set $\delta\phi < M_0 \Rightarrow \frac{m_\psi^2}{(M_0 m_u M_p)^{4/3}} < M_0^2$

Altogether, this yields simple mechanism for vacuum bubble production. BH statistical mechanics must reproduce the explosion.

Remark: In addition to this mechanism, bubbles can be catalyzed by matter coalescing to form BH, or inside the BH once the matter becomes sufficiently dense.



Applications

- BH physics : $\gtrsim 10^{500}$ new endpoints for Hawking evaporation

$\Updownarrow$

- Landscape : mechanism for populating vacua + fastest decay mode for many metastable vacua

→ e.g. solar mass BHs $M_\odot \sim 10^{57}$ GeV

decay time $\tau \sim \frac{M^3}{M_p^4} \sim 10^{65}\,yr \ll e^{10^{120}}\,yr$

↗ catalyzed decay ↖ minimal tunneling

- Observational windows/constraints?

cf Arkani-Hamed, Dimopoulos, Schuster, Toro

vacuon production ↔ searches for exotic charged particles

Could dense structures – e.g. small BHs – be produced in our patch of the universe?

– Inflation? simple single field: no ($n_s \sim 0.95$)

...

– charged exotics may be trapped in stars and fall to center → small BHs (cf Constraints on CHAMPs)

Summary: Endpoints & Final States

Microphysics of string theory (winding tachyons, multiple metastable vacua) affect BH physics:

- Bubbles as endpoints of Hawking decay
- $\langle T \rangle$ phase replaces singularity in some BHs, massing up string modes. This leads to forces & consistency conditions constraining form of state.