Black Holes as Catalytic Vacuum Converters

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hep-th/0605047/PRD

cf Arkani-Hamed, Schuster, Toro

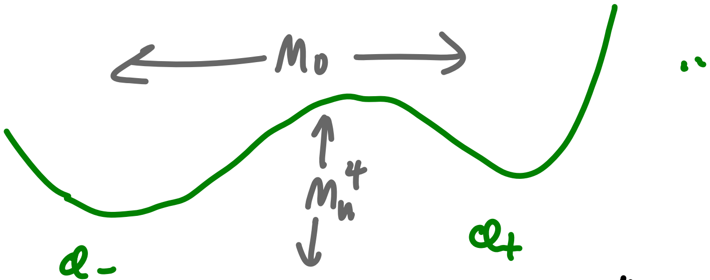
Aguirre, Banks, Dine, Johnson, Shomer

Motivating Questions:

Any chance to probe observationally?

- Λ stimulated study of <u>metastable</u> dS backgrounds in string theory (BP, GKP, ES, MSS, KKLT, ...)
  ↳ want to know fastest processes causing their population & decay
- Generic Black holes Hawking radiate.
  ↳ what is endpoint, and what role does UV string theory play?

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



Consider regime where all relevant scales $\ll M_{KK}, M_s, M_p$

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

with $M_u \ll M_0$ (weakly coupled)

<u>Tunneling</u> from $\varphi_+ \to \varphi_-$ can be exponentially suppressed: $\Gamma/\mathrm{vol} \sim m_\varphi^4 \, e^{-(M_0^4/M_u^4)}$

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

e.g. Ferrara Kallosh Strominger ... GIJT

- Attractor black holes

$$S = \int d^4x\sqrt{-G}\left(M_p^2 R - 2(\partial\phi)^2 - f_{ab}\left(\frac{\phi}{\check{M}_0}\right)F^a_{\mu\nu}F^{b\mu\nu} - U(\phi)\right)$$

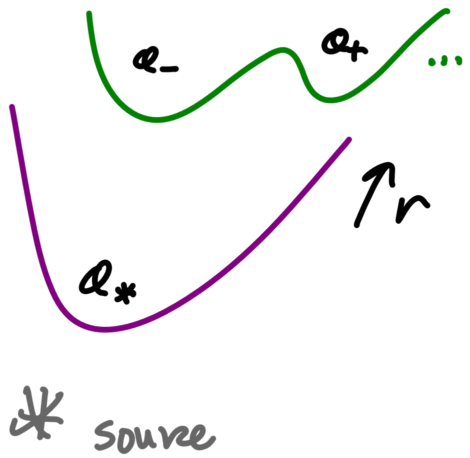
- Moduli-dependent masses

$$\int d^4x\sqrt{-G}\left(-2(\partial\phi)^2 + i\bar{\Psi}\not{D}\Psi + \check{f}\left(\frac{\phi}{\check{M}_0}\right)m_\psi\bar{\Psi}\Psi - U(\phi)\right)$$

$m_\psi < \check{M}_0$ (weak)

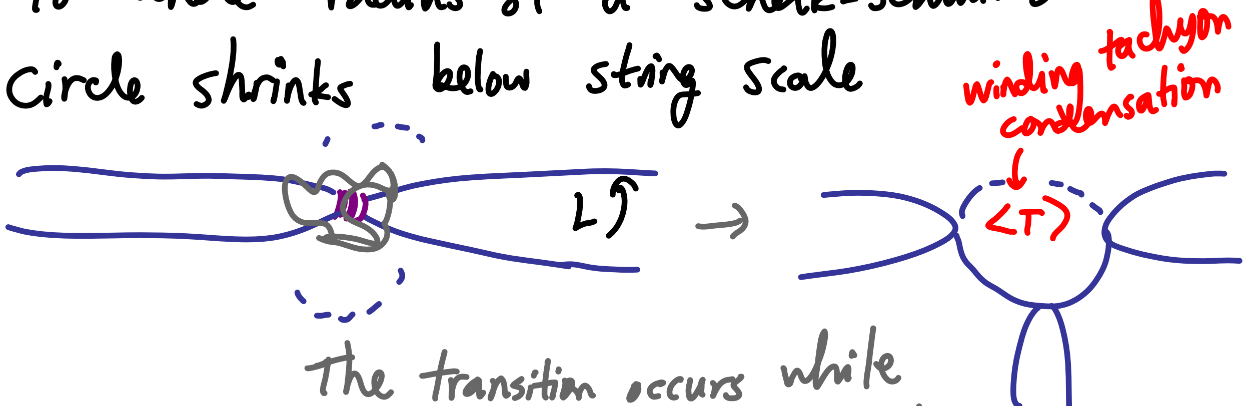
$\check{M}_0 > M_0 \rightarrow$ radiatively stable.

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



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

Depending on parameters, this can happen perturbatively → faster than tunneling cf Horowitz : bubble of nothing catalyzed classically when charged wrapped black string Hawking decays to where radius of a Scherk-Schwarz circle shrinks below string scale



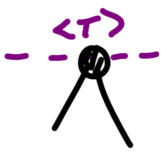
The transition occurs while system weakly curved, weakly coupled, & way before correspondence point. → ⟨T⟩ bubble constitutes a new endpoint for Hawking decay.

Closed String Tachyon condensation: lightning summary

$\langle T \rangle = \hat{T} \mu e^{\kappa X^0}$ ⇒ 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, Schomerus, ... McGreevy / ES '05, ..., NRS '06



- Calculate occupation #s of particles in bulk → $N_\omega = \dfrac{1}{e^{\frac{2\pi\omega}{\kappa}} \pm 1}$
- Calculate partition function (quantum correction to stress-energy) → $\mathrm{Re}(Z) = -\frac{\ln \mu}{\kappa} \hat{Z}_{free}$ ← not $\delta(0) = \mathrm{Vol}(X^0)$

⇒ full worldsheet calculations of basic quantities agree with expectation that $\langle T \rangle$ lifts closed strings → "nothing"

Usually microphysics is difficult to access :

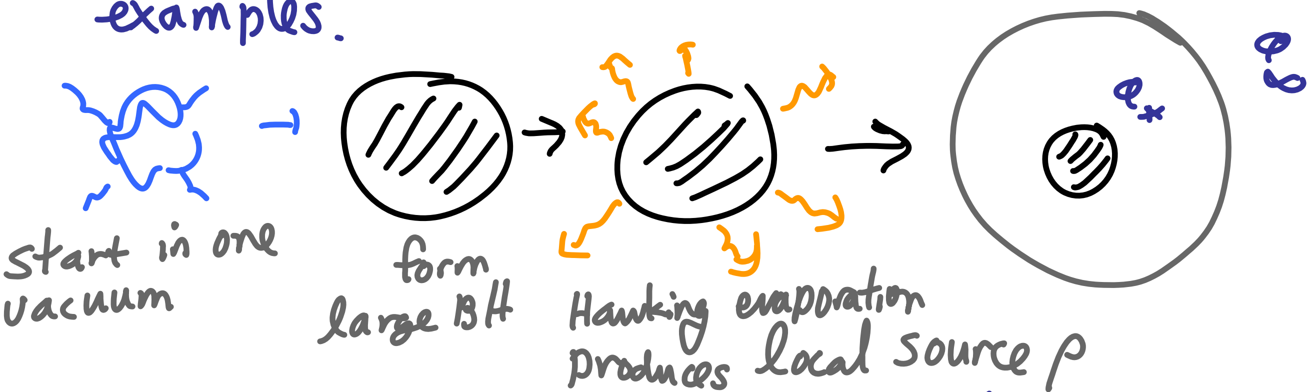
- high energy
- hidden behind horizon

} both in the case of black holes

e.g. "Standard" extrapolation of Hawking effect would yield small burst of radiation + elementary particle(s)

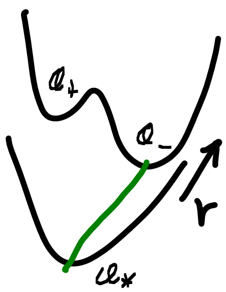
Horowitz's example, assuming we metastabilize the circle in bulk, exhibits a case where the endpoint is so dramatic as to rule out the background. → How general ?

Compact objects (including black holes) catalyze vacuum bubble production in a large class of examples.



* including uncharged examples : Mechanism for decay even if no source initially present

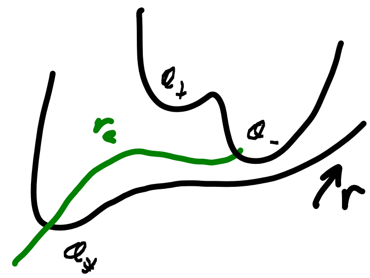
3 Simple cases: r_c = radius at which $\partial_\phi \rho \sim \partial_\phi U$



Case I

↓

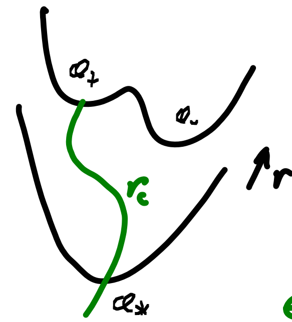
ϕ sits in minimum $\forall r$



Case II

↓

bubble of "false" vacuum forms; stays only while ρ present



Case III

Bubble of lower energy forms, and explodes out if $r_c > R_c$

where R_c = critical Coleman-de Luccia bubble

$$R_c^3 (\Delta U) = R_c^2 (\text{wall tension})$$

(Also could explode more generally since have more pressure.)

a) Charged case

Attractor (Charged) Black Holes:

Ferrara Kallosh Strominger
Goldstein et al
Sen ...

$$S = \int d^4x \sqrt{-G}\left(M_p^2 R - 2(\partial\phi_i)^2 - \hat{f}_{ab}\left(\frac{\phi_i}{M_p}\right) F_{\mu\nu}{}^a F^{b\mu\nu} - \mathcal{U}(\phi)\right)$$

$$F^a = Q^a \sin\theta\, d\theta \wedge d\phi$$

weak gravity

$$\frac{1}{r^2\sin\theta}\partial_\mu\left(r^2\sin\theta\,\partial^\mu\phi\right) = \left(\frac{\partial_\phi V_{eff}}{r^4} + \partial_\phi \mathcal{U}\right)$$

with $V_{eff} \sim \hat{f}_{ab}\left(\frac{\phi}{M_p}\right) Q^a Q^b$

$$\mathcal{U}_{tot} = \frac{V_{eff}}{r^4} + \mathcal{U}$$

Once the outer horizon $r_h = \frac{M}{M_p^2} + \sqrt{\frac{M^2}{M_p^4} - \frac{Q^2}{M_p^2}}$ shrinks below $r_c \sim \sqrt{Q}/M_u$, a bubble forms.

This can happen while the BH is still very non-extremal $\frac{M_c}{M_p} \gg Q$, far from a correspondence point where it would cross over to constituents

(e.g. branes + strings Susskind; Horowitz/Polchinski)

Thermo. Quantities when BH spits out bubble:

Temperature $T_c \sim \frac{1}{r_c} \sim \frac{u}{\sqrt{Q}}$

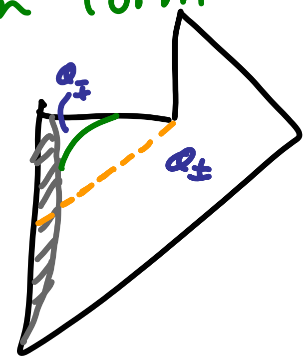
Entropy $S_c \sim Q \frac{M_p^2}{M_u^2} \gg Q^2$

If there is a microscopic statistical description of BH thermodynamics, it should contain information about other vacua.

Does the charge matter? Moduli are generically sourced by uncharged densities as well.

Schwartschild case: 3 ways bubbles can form

① outside in collapse ② inside



☆ ③ outside, catalyzed by massive Hawking decay products.

★ ③ Massive Hawking particles seed bubbles

Consider model like

$$M_U^4 f\left(\frac{\phi}{M_0}\right)$$
$$\uparrow$$
$$S = \int d^4x \sqrt{-G} \left(-\frac{1}{2}(\partial\phi)^2 + i\bar{\Psi}\not{D}\Psi + f\left(\frac{\phi}{M_0}\right) m_\Psi \bar{\Psi}\Psi - U(\phi) \right)$$

where ϕ modulates mass of particle Ψ of mass $\sim m_\Psi$.

Whatever went into forming the BH, once its temperature increases to $T \sim m_\Psi$, it starts emitting Ψ's by the Hawking process.

We find regime for which the force from the Ψ particles beats that from moduli potential,

$$|\partial_\phi \rho_\Psi| > |\partial_\phi \mathcal{U}|$$

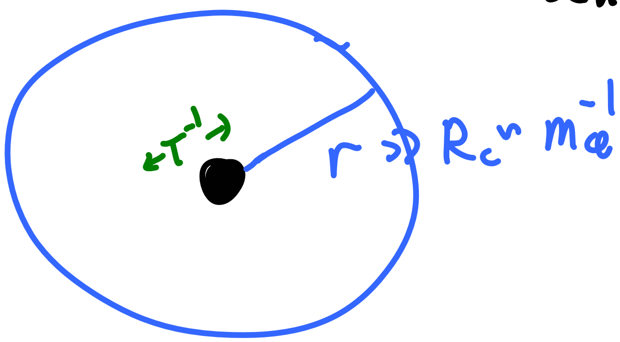
for long enough time to kick ϕ across barrier $\phi_+ \to \phi_-$ within a volume $\gg R_c^3$ in a self-consistent mean field treatment;

ϕ particles alone would not suffice.

Hawking:

$$\frac{dN}{dt} = \frac{\sigma v^2 E^2 dE}{\left(e^{E/T} \pm 1\right) 2\pi^2} = 4\pi r^2 \underbrace{n(r)}_{\text{number density}} v \qquad r \gg \frac{1}{T}$$

(v: velocity)



Non-relativistic regime $v \ll 1$ $\quad \sigma \sim \frac{1}{T^2 v^2}$

Relativistic regime $v \simeq 1$ $\quad \sigma \sim \frac{1}{T^2} \sim R_{schw}^2$

In non-relativistic regime,

$$n_\psi(r) = \frac{\dot{N}}{4\pi r^2 v} \sim \frac{1}{4\pi r^2} \int_{m_\psi}^{m_\psi + \frac{1}{2} m_\psi v^2 \sim T} \frac{1}{T^2 v^2} v \, f^2 \, dE$$

$$\rho_\psi(r) \sim m_\psi n_\psi(r) \sim \frac{m_\psi^4 v}{T^2 r^2}$$

$$\rho_\psi \Big|_{R_c \sim m_\phi^{-1}} \sim M_u^4 \, v \frac{m_\psi^2}{M_0^2}$$

$$\left(m_\phi \sim \frac{M_u^2}{M_0} \sim \frac{1}{R_c} \right)$$

⇒ Force from ψ particles beats those from moduli potential $U(\phi)$ if

$$\boxed{v\, m_\psi^2 \geq M_0 \tilde{M}_0}$$

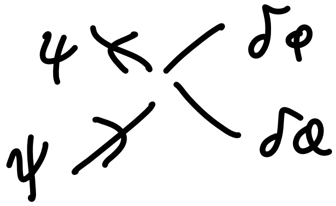
[Same condition with $v=1$ arises for force condition in relativistic regime as well]

Self-consistency checks + conditions:

1) $L_\psi \sim \frac{1}{n_\psi^{1/3}} << m_\phi^{-1}$ Compton wavelength

so mean field treatment OK

2) ρ_ψ is in place long enough to kick ϕ a distance M_0 (across barrier)

3) 

annihilation negligible

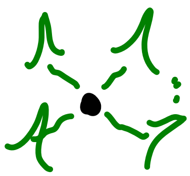
↳ $\frac{v^3 M_p^2 M_u^4}{\hat{M}_0^4 M_0^2} << 1$

- The BH also produces ϕ particles $\delta\phi$.

  These don't produce <u>this</u> effect themselves:

$$\frac{M_u^4}{M_0} = m_\phi^2 \not> M_0^2$$

- Even if $\delta\phi$ particles thermalized at $T_{eff} \sim \rho_{\delta\phi}^{1/4}$ (they're too weakly coupled), $T_{eff} \ll$ Energy of critical bubble for $M_u^3 \ll M_0^3 (M_0/M_p)^{1/4} \Rightarrow$ exponential suppression

- 
  Free $\delta\phi$'s have interparticle spacing $L_{\delta\phi} \gg k^{-1}$ 

  so not coherent over volume R_c^3

Applications

1) Population of landscape:

e.g. solar mass $10^{65} \ll e^{10^{120}}$

$$\left(\tau_{\substack{BH\\ decay}} \sim \frac{M_{BH}^3}{M_p^4} \right) \ll \tau_{tunneling}$$

so with above field content & structure formation, can populate landscape faster than by tunneling.

2) population of the desert:

At the same time, favor lighter particles (FSPs)

$M_\psi(Q)$ decreases in process (cf moduli trapping KLLMMS)

favors e.g. broken global symm. or unbroken gauge symm.

cf ISS example.

3) Probe / Constrain the landscape?

Small primordial BHs can be dangerous

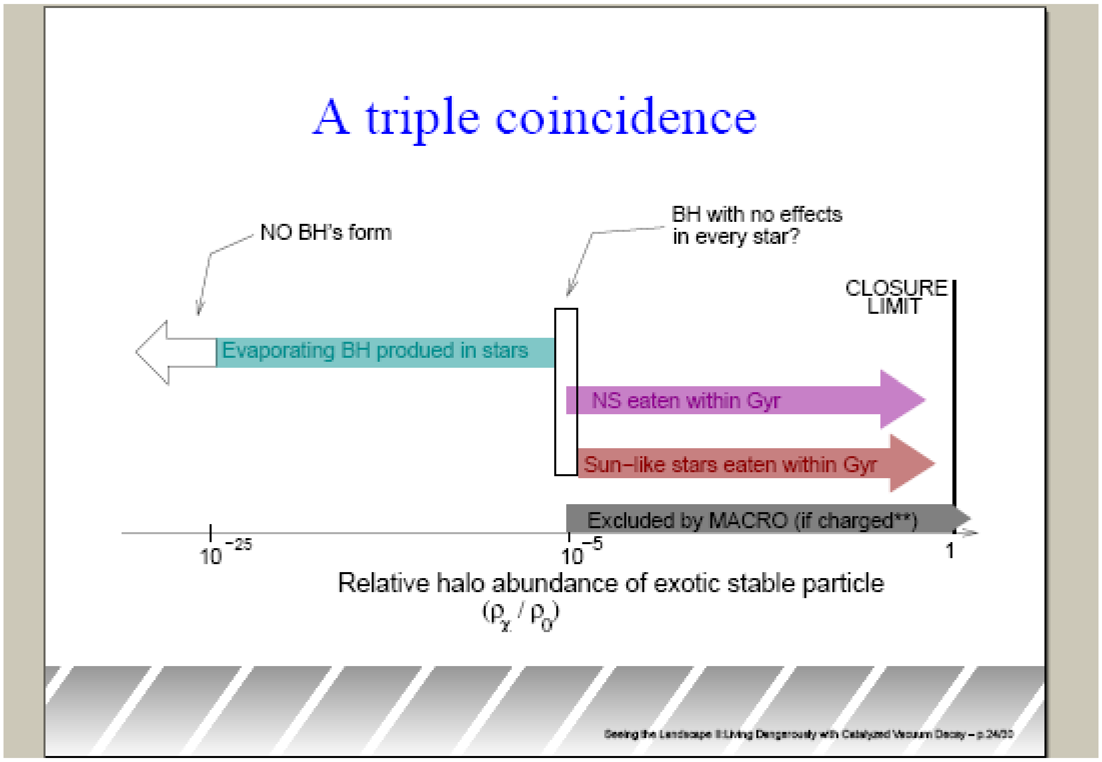
Arkani-Hamed, Schuster, Toro; Dimopoulos

- For $\frac{\Omega_{exotic}}{\Omega_{DM}} > 10^{-20}$ density of SM-interacting exotics, can get trapped in stars, fall to center, and form small BHs that evaporate. Cf Gould et al

- Other mechanisms for small BHs (some hybrid inflation models G-BLW...)

Evidence for small BHs having evaporated in our causal past would constrain / rule out classes of string models otherwise difficult to test.

From Schuster / Toro Trieste June '06



Alternatively, Preliminary work raises possibility of narrow window where an experimental observation of an exotic charged particle would suggest selection effect + multiverse

From Schuster / Toro Trieste June '06

A triple coincidence

The mass of black hole that. . .

- . . . evaporates in $< 10^{10}$ yrs in vacuum
- . . . eats a neutron star in $\sim 10^{9}$ yrs
- . . . accretes in 10^{6} yrs at current flux limits

. . . could be many orders of magnitude apart!
Instead, they're on top of each other...
and **close to flux at which suns get eaten by accreted black holes**.

Conclusion is more interesting than it had to be!

Summary

- Compact objects source vacuum bubbles (static or exploding depending on parameters)
- BH evaporation can produce vacuum bubbles seeded by Hawking decay products in Schwarzschild case.
- Applications to populating/probing/constraining the landscape.