Blackhole Disappearance

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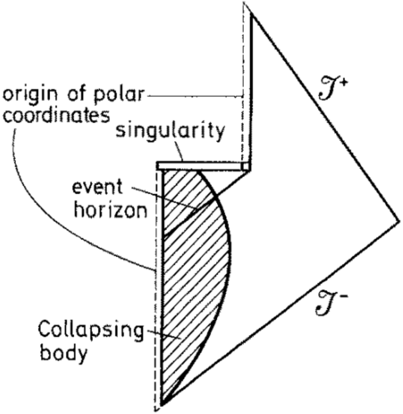
What really happens at the end of evaporation?



The Penrose diagram of a black hole which evaporates and leaves only empty space is shown in Fig. 5. The horizontal line marked "singularity" is really a region where the radius of curvature is of the order the Planck length. The matter that runs into this region might reemerge in another universe or it might even reemerge in our universe through the upper vertical line thus creating a naked singularity of negative mass.

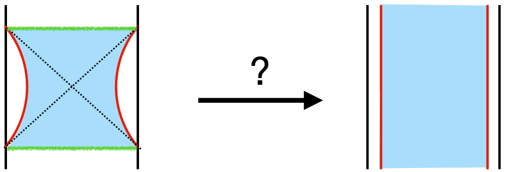
[Hawking, '75]

- Lots of activities in the '90s on BH evaporation in solvable 1+1d models
  - Callan-Giddings-Harvey-Strominger (CGHS)
  - Russo-Susskind-Thorlacius (RST)
- Results remain largely inconclusive
- In this talk, I will try to provide a new perspective taking advantage of newer developments on BH physics in the field
- We will focus on JT gravity for better control and making use of existing technologies

The Maldacena-Qi model

- consider a modification of JT gravity that admits both **black holes** and **AdS_2**
- start from the BH solution, couple the system to a bath and let evaporate

Q: how does the system find its ground state (AdS_2)?



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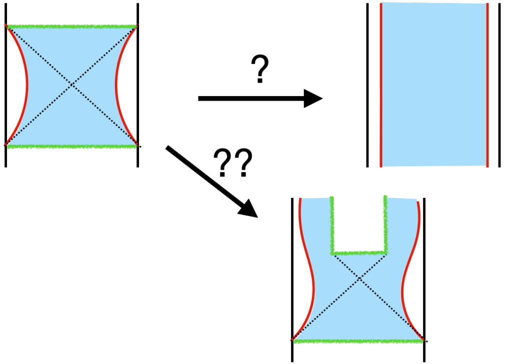


Outline

- Review of JT gravity + matter
- BH evaporation in JT + matter
- Wormholes
- In progress

Review of JT gravity + matter

JT gravity

- 1+1d EH gravity with dilaton

$$S_{JT} = \frac{1}{16\pi G}\int_M \sqrt{g}\phi(R+2) + \frac{1}{8\pi G}\int_{\partial M}\sqrt{h}\phi(K-1) + S_0\chi$$

- dilaton EOM: $R = -2 \Rightarrow$ locally AdS_2 everywhere
- Einstein Eqs:

$$-e^{2\omega}\partial_\pm(e^{-2\omega}\partial_\pm\phi) = 8\pi G T_{\pm\pm}$$
$$2\partial_+\partial_-\phi + e^{2\omega}\phi = 16\pi G T_{+-}$$

- conformal factor $ds^2 = -e^{2\omega(x^+,x^-)}dx^+dx^-$
- unless specified I will work at the disk level where $S_0 \to \infty$

AdS$_2$ coordinate systems

- global

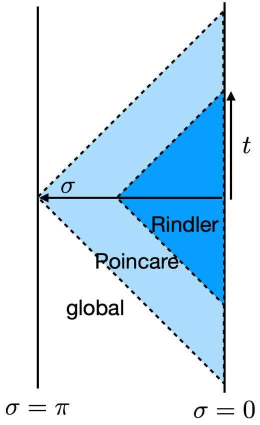
$$ds^2 = \frac{-dt^2 + d\sigma^2}{\sin^2\sigma}, \quad \sigma \in [0, \pi]$$

- Poincare

$$ds^2 = \frac{-dT^2 + dZ^2}{Z^2}, \quad Z \in [0, \infty)$$

- Rindler

$$ds^2 = -\sinh^2\rho d\tau^2 + d\rho^2, \qquad \rho = [0, \infty)$$
$$= \frac{4(-r^2 d\tau^2 + dr^2)}{(1-r^2)^2}, \qquad r \in [0, 1]$$



boundary conditions

- The only dynamics in JT gravity comes from the boundary term $\int_{\partial M}\sqrt{h}\phi(K-1)dx$
- asymptotic boundary defined by

$$\phi = \phi_b = \frac{\phi_r}{\epsilon}, \quad ds^2 = -\frac{du^2}{\epsilon^2}$$

- Let $\{T(u), Z(u)\}$ be the "boundary trajectory" in Poincare coordinate

$$Z(u) = \epsilon T'(u) + O(\epsilon^2)$$

- Extrinsic curvature

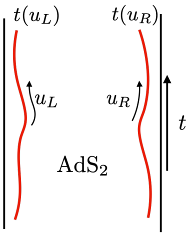
$$K = 1 + \epsilon^2\{T(u), u\} + O(\epsilon^4)$$

- Schwarzian derivative

$$\{f(z), z\} \equiv \frac{f'''}{f'} - \frac{3}{2}\left(\frac{f''}{f'}\right)^2$$

JT gravity: boundary particle formalism

$$S_{JT} = \frac{\phi_r}{8\pi G} \int du \, \{T(u), u\}$$

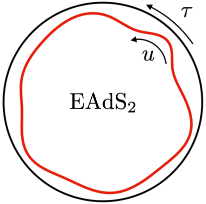


- single gravitational D.O.F. $T(u)$: reparametrization mode

  bulk coordinate time T $\longleftrightarrow$ boundary physical time u

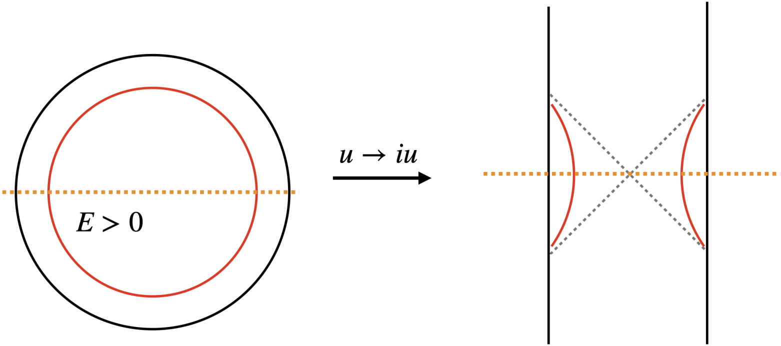
- $H = -\frac{\phi_r}{8\pi G}\{T(u), u\}$ Hamiltonian (ADM energy)
- EOM of the system: energy conservation

$$-\frac{\phi_r}{8\pi G}\partial_u H = \partial_u\{T(u), u\} = \partial_\mu K = 0$$



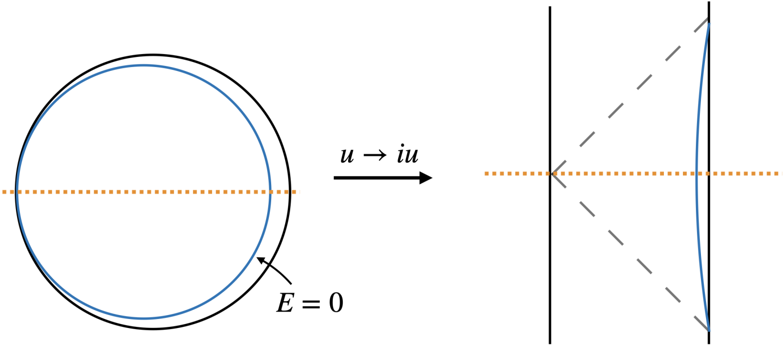
Solution: Blackholes

$$H = -\frac{\phi_r}{8\pi G}\{T(u), u\} > 0$$



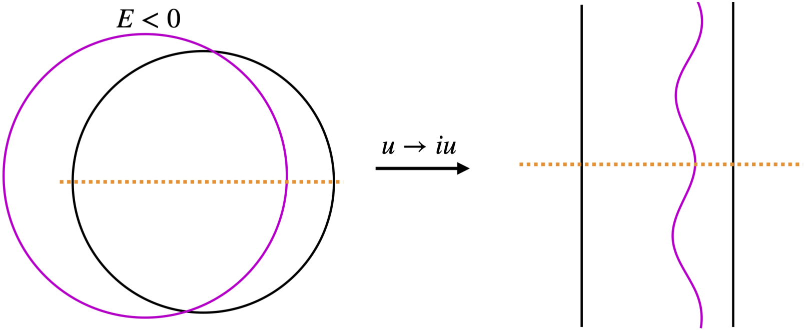
Solution: Poincare vacuum

$$H = -\frac{\phi_r}{8\pi G}\{T(u), u\} = 0$$



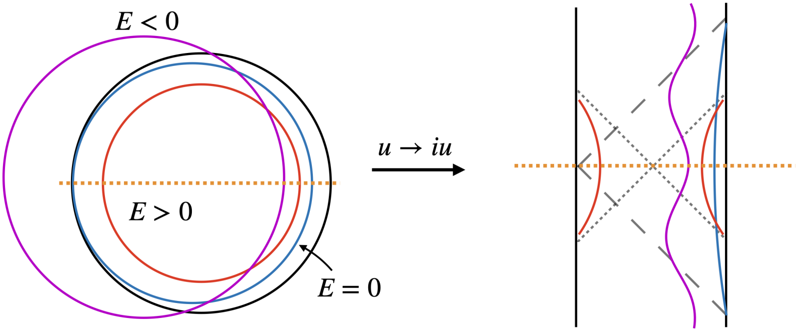
Solution: Eternal traversable Wormholes

$$H = -\frac{\phi_r}{8\pi G}\{T(u), u\} < 0$$



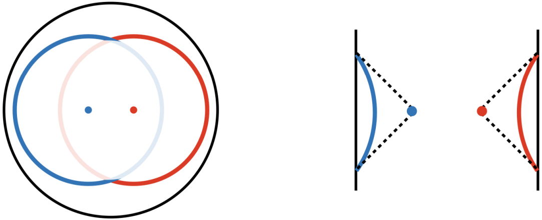
Solution: the comparison

$$\partial_u H = -\frac{\phi_r}{8\pi G}\partial_u\{T(u), u\} = 0$$



Are all combination of solutions, solutions?

For example, is



a valid solution?

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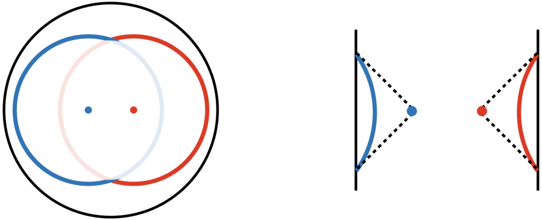


a valid solution?

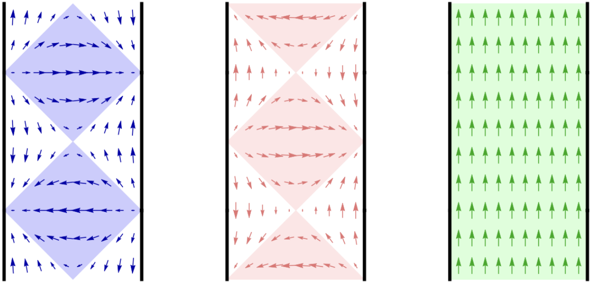
No, because the global $SL(2)$ charge is not conserved!

SL(2) charges

- $PSL(2;\mathbb{R})$: Global isometry group for AdS_2

$$T(u) \to \frac{a + bT(u)}{c + dT(u)}, \quad ad - bc \neq 0$$

- three generators: (Adapted from Lin-Maldacena-Zhao)



$\hat{B}$: "boost", $\hat{P}$: "momentum", $\hat{E}$: "global energy"

SL(2) charges

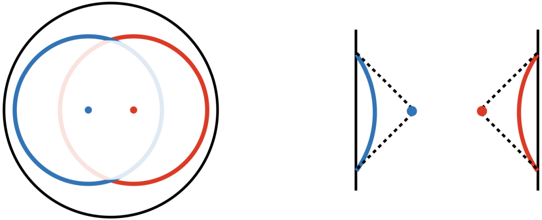
- in terms of the reparametrization mode (similar expression for the left):

$$Q_R^- = \frac{\phi_r}{8\pi G}\left(\frac{T'''}{T'^2} - \frac{T''^2}{T'^3}\right)$$
$$Q_R^0 = \frac{\phi_r}{8\pi G}\left(\frac{TT'''}{T'^2} - \frac{TT''^2}{T'^3} - \frac{T''}{T'}\right)$$
$$Q_R^+ = \frac{\phi_r}{8\pi G}\left(\frac{T^2T'''}{T'^2} - \frac{T^2T''^2}{T'^3} - \frac{2TT''}{T'} + 2T'\right)$$

$$B_R = Q_R^0, \quad P_R = \frac{1}{2}(Q_R^+ - Q_R^-), \quad E_R = \frac{1}{2}(Q_R^+ + Q_R^-)$$

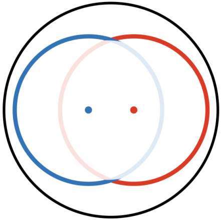
- This is a gauge symmetry: combined solutions must have trivial charges

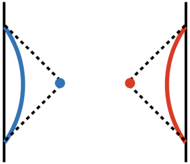
$$\vec{Q}_L + \vec{Q}_R = 0$$



$$\vec{Q}_L = \sqrt{H}(-\cosh\alpha, 0, -\sinh\alpha), \quad \vec{Q}_R = \sqrt{H}(\cosh\alpha, 0, -\sinh\alpha)$$

$$\vec{Q}_L + \vec{Q}_R = \sqrt{H}(0, 0, -2\sinh\alpha) \neq 0$$





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$$\vec{Q}_L + \vec{Q}_R = \sqrt{H}(0, 0, -2\sinh\alpha) \neq 0$$

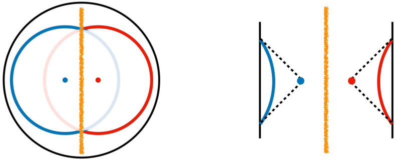
- However, extra charges can be compensated by adding matter:

$$\vec{Q}_L + \vec{Q}_R + \vec{Q}_M = 0$$

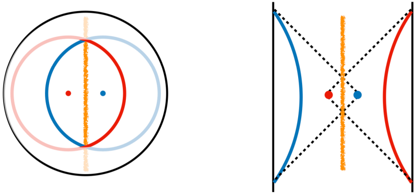
$$\Rightarrow \quad \vec{Q}_M = (0, 0, E) = \sqrt{H}(0, 0, 2\sinh\alpha)$$

solutions: JT+matter

- $E > 0$: Partially Entangled Thermal States (PETS) [Goel-Lam-Turiaci-Verlinde]



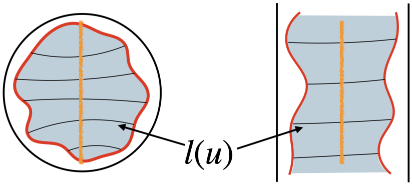
- $E < 0$: traverable BHs



JT gravity: 1d QM formalism [Harlow-Jafferis, Gao-Jafferis-Kolchmeyer]

- classical phase space of JT gravity:
  - ADM energy H
  - (sum of) boundary time $\delta = t_L + t_R$
- or equivalently, can be expressed in terms of the renormalized length between boundaries ℓ and its canonical conjugate p_ℓ

$$d\omega = d\delta \wedge dH = d\ell \wedge dP_\ell$$

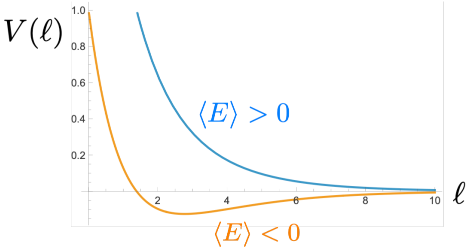


- can solve for H in terms of ℓ and P_ℓ

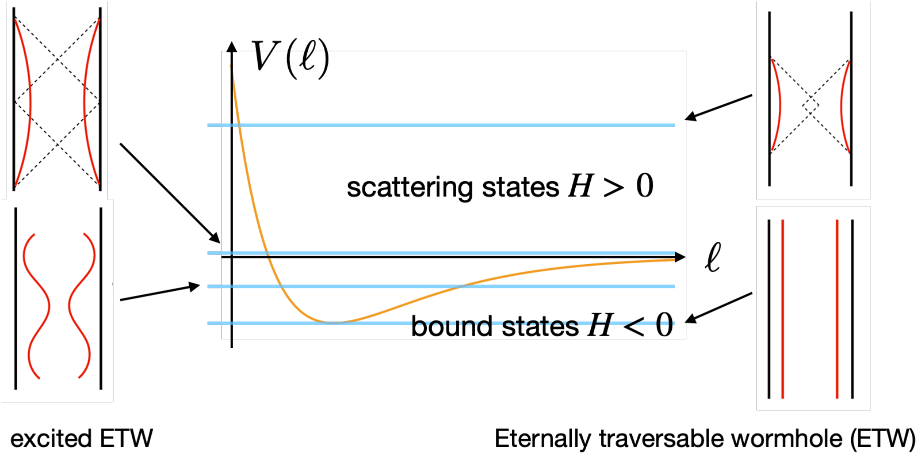
$$H_L = \frac{1}{2}(P_\ell + P)^2 + (E+B)e^{-\ell/2} + 2e^{-\ell}$$
$$H_R = \frac{1}{2}(P_\ell - P)^2 + (E-B)e^{-\ell/2} + 2e^{-\ell}$$

- work in symmetric configuration $B = P = 0$ and do canonical quantization
  $\Rightarrow$ 1d QM on a Morse potential

$$H = H_L + H_R = (\hat{P}_\ell)^2 + 2\langle E \rangle e^{-\ell/2} + 4e^{-\ell}$$

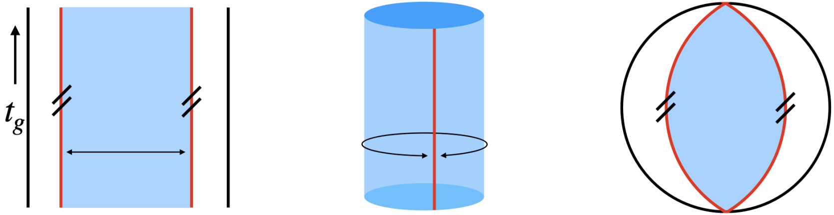


Classical solutions for $\langle E \rangle < 0$



An exemplary construction

- Many constructions to achieve negative E to stablize a traversable BH, e.g.
  - via double trace deformation $S_{int} = \int O_L O_R dx$ [Gao-Jafferis-Wall]
  - via explicit coupling $S_{int} = \int \frac{t_L' t_R'}{\cos^2(\frac{t_L - t_R}{2})} du$ [Maldacena-Qi]
  - via turing on a imaginary source of massless scalar field [(Garcia-Garcia)-Godet]
- Here we propose an alternative option by adding a bulk CFT with periodic b.c.



- traversability is supported by the negative Casimir energy

$$E_{CFT} = \int \sqrt{g} \langle T_{ab} \rangle \xi^a \xi^b dx^2 \sim \langle T_{tt} \rangle = -\frac{c}{16\pi}$$

Ground state solution

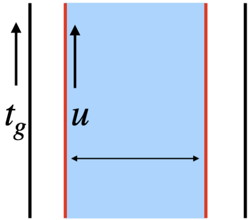
- solution determined by balancing the charge

$$\vec{Q}_L = \vec{Q}_R = (0, 0, -\langle T_{tt} \rangle)$$

$$\Rightarrow t(u) = -\frac{\langle T_{tt} \rangle}{2} u, \quad T(u) = \tan \frac{t(u)}{2}$$

- energy

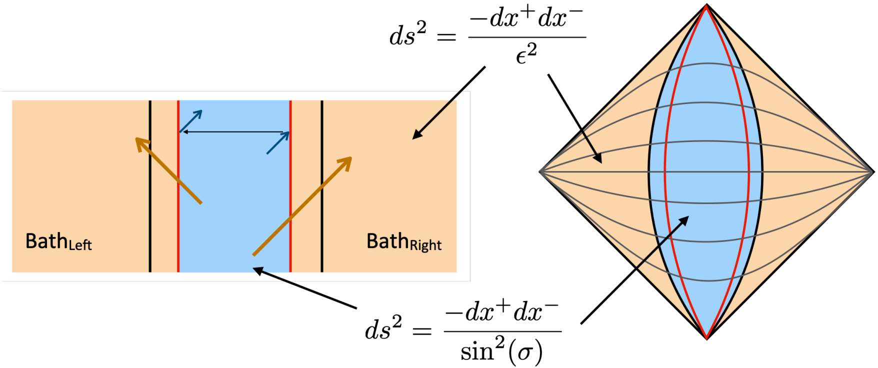
$$H = -\frac{\phi_r}{8\pi G} \{ T(u), u \} = -\frac{\phi_r}{8\pi G} \left(\frac{\langle T_{tt} \rangle}{2} \right)^2$$



BH evaporation in JT + matter

Evaporation

- Achieved by adding a bath CFT with transparent boundary condition [Almheiri-Engelhardt-Marolf-Maxfield, Almheiri-Hartman-Maldacena-Shaghouian-Tajdini]



$$ds^2 = \frac{-dx^+dx^-}{\epsilon^2}$$

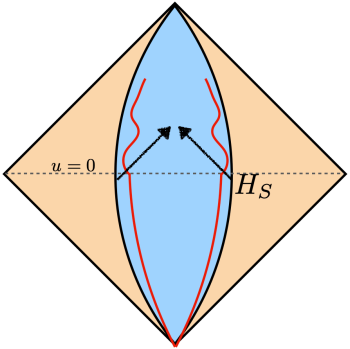
$$ds^2 = \frac{-dx^+dx^-}{\sin^2(\sigma)}$$

- Create a BH from the ETW by throwing in some shockwave, then let evaporate

- EOM: energy balance condition at the asymptotic boundaries

$$-\frac{\phi_r}{8\pi G}\{T_{L/R}(u),u\} = (T_{++} - T_{--})_{bdy}$$

- sources for $T_{\pm\pm}$, focusing on the right bdy:
  - shockwave
$$T^S_{++} = H_S\delta(x), \quad T^S_{--} = 0$$
  - line CFT (given by Weyl anomaly in the blue region)
$$T^B_{++} = 0, \quad T^B_{--} = -\frac{c_B}{24\pi}\{t(u),u\}$$



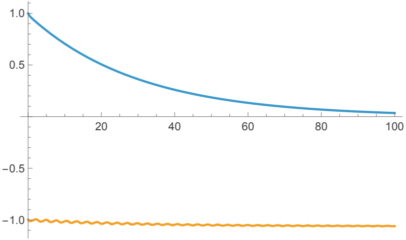
EOM of reparametrization mode $t(u)$ in global coordinate

$$-\frac{\phi_r}{8\pi G}\{\tan(t(u)/2),u\} = -\frac{c_B}{24\pi}\{t(u),u\} + H_S\delta(u), \quad (u > 0)$$

Numerics

See drastically different behavior depending on the sign of $H_0 + H_S$

- $H_0 + H_S > 0$: BH is formed in the bulk
  decays to *Poincare vacuum* $H = 0$
- $H_0 + H_S < 0$: no BH is formed (ETW becomes excited)
  settles down to a ETW with lower energy $H < 0$



The system does not always find its true ground state!

Analytics: The $SL(2)$ charges formalism

- Schwarzian EOM is a 4th order ODE

$$\partial_u\{T(u),u\} \sim T_{++} - T_{--}, \quad \{T,u\} = \frac{T'''}{T'} - \frac{3}{2}\left(\frac{T''}{T'}\right)^2$$

- initial conditions $\{T(0), T'(0), T''(0), T'''(0)\}$
- can be expressed in terms of $T(0)$ + three $SL(2)$ charges by inverting the definition

$$\begin{aligned} Q^- &= \left(\frac{T'''}{T'^2} - \frac{T''^2}{T'^3}\right) \\ Q^0 &= \left(\frac{TT'''}{T'^2} - \frac{TT''^2}{T'^3} - \frac{T''}{T'}\right) \\ Q^+ &= \left(\frac{T^2T'''}{T'^2} - \frac{T^2T''^2}{T'^3} - \frac{2TT''}{T'} + 2T'\right) \end{aligned} \longrightarrow \begin{aligned} T' &= \frac{1}{2}(E+P) - TB + \frac{T^2}{2}(E-P) \\ \frac{T''}{T'} &= T(E-P) - B \\ \left(\frac{T''}{T'}\right)' &= T'(E-P) \end{aligned}$$

- we have traded the (ungauged) phase space $\{T, T', T'', T'''\} \longrightarrow \{T, B, P, E\}$

EOM in the charges formalism

- Hamiltonian given by quadratic Casimir of $SL(2)$

$$H = -\frac{\phi_r}{8\pi G}\{T, u\} = \frac{1}{2}(B^2 + P^2 - E^2)$$

- Four 1st order ODEs
  - one dynamical EOM

$$\partial_u H = T_{++} - T_{--}$$

  - three "kinematic constraints" form the consistency condition between charges

$$2T' = (E + P) - 2TB + T^2(E - P)$$
$$0 = B'^2 + P'^2 - E'^2$$
$$T^2 = (E' + P')/(E' - P')$$

- Static solution

$$T(u) = \sqrt{\frac{P+E}{P-E}}\frac{\sqrt{1-\frac{B}{ck}}e^{ku} - \sqrt{1+\frac{B}{ck}}}{\sqrt{1-\frac{B}{ck}} + \sqrt{1+\frac{B}{ck}}e^{ku}}, \quad c^2 = \frac{\phi_r}{8\pi G}, \ k^2 = 2H$$

Adiabatic approximation

$$T(u) = \sqrt{\frac{P+E}{P-E}} \frac{\sqrt{1-\frac{B}{ck}}e^{ku} - \sqrt{1+\frac{B}{ck}}}{\sqrt{1-\frac{B}{ck}} + \sqrt{1+\frac{B}{ck}}e^{ku}}$$

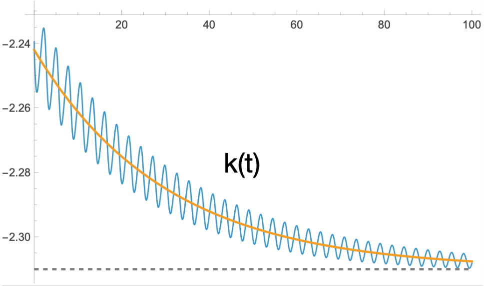
- promote B, P, E to be time dependent and assume $B', P', E' \ll B, P, E$
- consistent with small c_B limit
- dynamical EOM

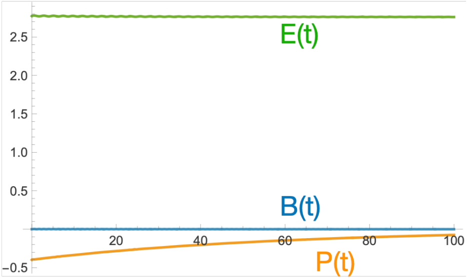
$$k^2 \equiv 2H = B^2 + P^2 - E^2,$$
$$-k' = \frac{c_b k}{48\pi}\left(1 + \frac{k^2(P^2-E^2)}{(kP\cosh(ku) - BE\sinh(ku) - E\sqrt{P^2-E^2})^2}\right)$$

$H_0 + H_S < 0$

- universal behavior at small coupling
- breaks into slow and fast mode $k \sim k_f(u) + k_s(u)$

$$k_s(u) = \frac{1}{2}\left[\left(E_{0+} + \sqrt{-2H_{0+}}\right) - e^{\frac{c_B}{24\pi}u}\left(E_{0+} - \sqrt{-2H_{0+}}\right)\right]$$

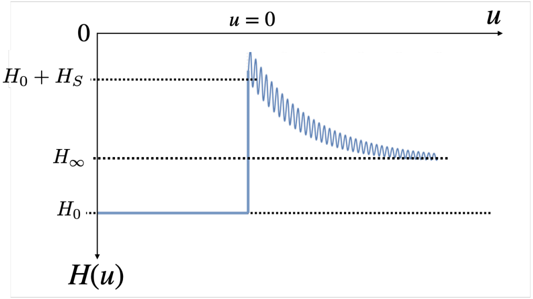


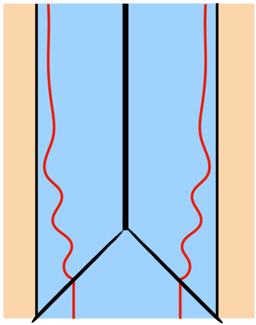


$H_0 + H_S < 0$

- settles down to eternal traversable wormhole
- final state energy

$$H_\infty = (E_{0+} + \sqrt{-2H_{0+}})^2$$



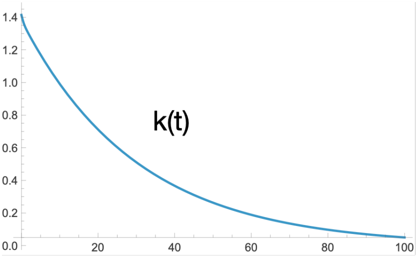


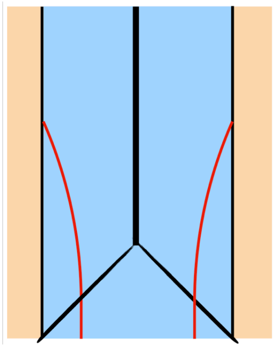
$H_0 + H_S > 0$

- adiabatic solution:

$$k(u) = k_0 \exp\left[\frac{-c_B}{48\pi}\left(u + \frac{\tanh(k_0 u)}{k_0}\right)\right]$$

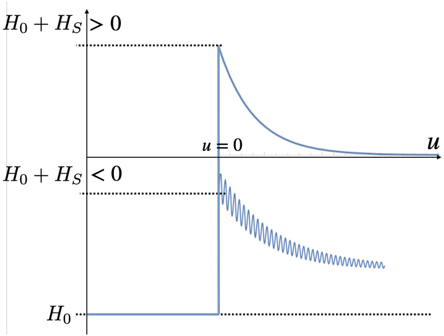
- energy approaches 0 at late time (Poincare Vacuum)





Recap

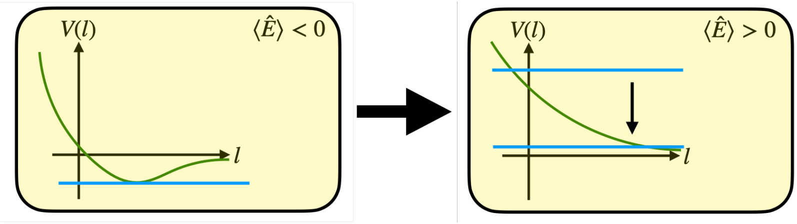
If the energy starts out positive, it remains positive



The system doesn't find its true ground state!

in terms of the 1d QM potential:

- insertion of shockwave turns the matter E charge positive
- not enough E charge is emitted back to the bath through evaporation
- system stuck at the false ground state $H = 0$



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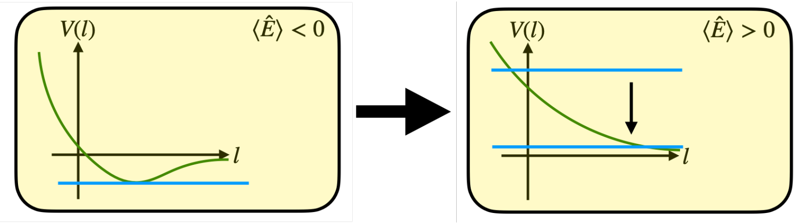
- not enough E charge is emitted back to the bath through evaporation
- system stuck at the false ground state $H = 0$



However, non-perturbative effects (wormhole) can lead to large changes of charges

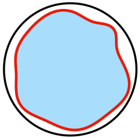
Wormholes

JT Wormholes

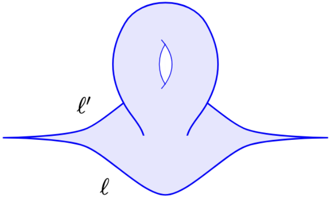
- corrections to JT path integral for finite S_0

$$S_{EH} = S_0 \left(\int_M d^2x \sqrt{g} R + 2 \int_{\partial M} dx K \right) = S_0 \chi$$

- manifests in GPI as contribution from higher genus topology

$Z_{JT} =$  $+e^{-2S_0}$  $+\cdots$

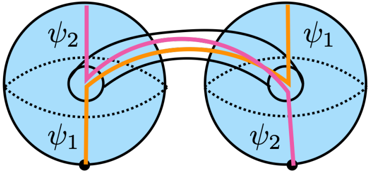
- introduce nontrivial inner product to wavefunctions [Iliesiu-Levin-Lin-Maxfield-Mezei]

$\overline{\langle \ell' | \ell \rangle} = \delta(\ell - \ell') +$ 

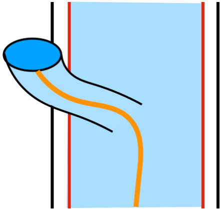
$+ \; O(e^{-4S_0})$

Wormholes violate global symmetry

- charges can exit through wormholes, violating global $SL(2)$ symmetry
- $|\psi_1\rangle, |\psi_2\rangle$ different charges $\rightarrow \overline{\langle \psi_1 \mid \psi_2 \rangle} = 0$

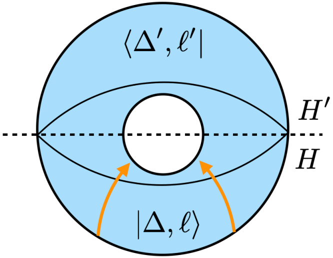
$$\overline{\langle \psi_1 | \psi_2 \rangle^2} =$$  $$+ \cdots \quad > 0$$

- Lorentzian picture: charge lost by emission of baby universe



Wormholes do not violate total energy

- while wormholes can change $SL(2)$ charges or make matter disappear, it does not change the energy

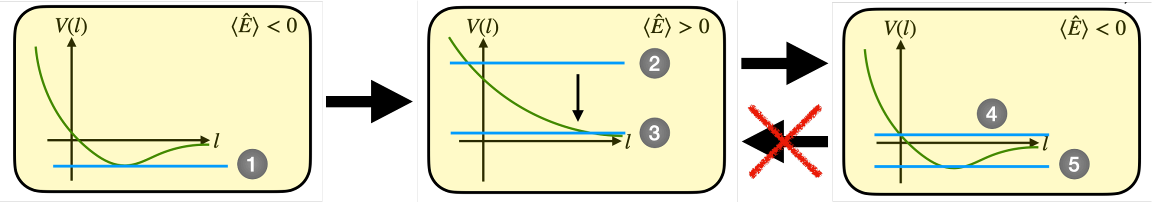


$$\langle \Delta, \ell \,|\, \Delta', \ell' \rangle \sim \delta(\ell - \ell') + O(e^{-S_0})$$
$$\langle H \,|\, H' \rangle \sim \delta(H - H')$$

- The non-conservation of charges however is enough for our purpose

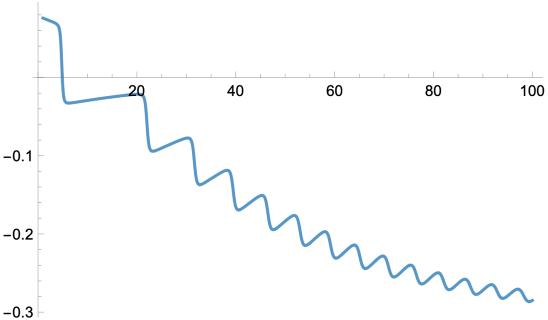
A path to complete evaporation

1. start with the ground state ($H < 0, E_{mat} < 0$)
2. throw in shock waves to form a BH ($H > 0, E_{mat} > 0$)
3. evaporation $\rightarrow$ system decays to Poincare vacuum ($H = 0, E_{mat} > 0$)
4. wormhole effect changes matter charge ($H = 0, E_{mat} < 0$)
5. system further evaporates to the original ground state ($H < 0, E_{mat} < 0$)



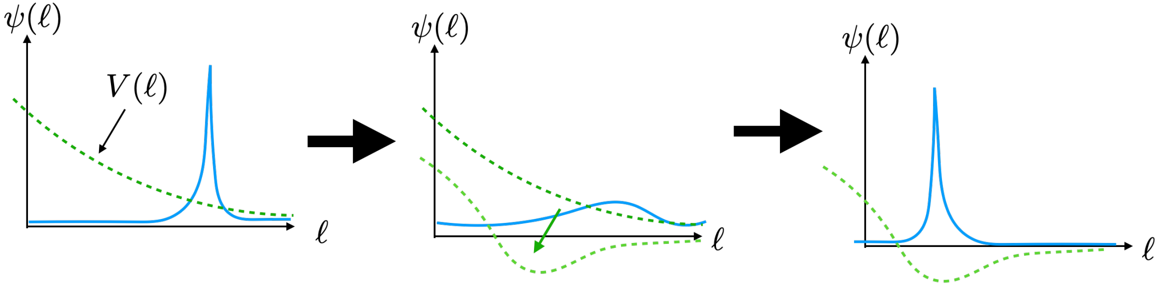
In progress

- for this to work we must show that states with $H \geq 0, E < 0$ evaporates to the true ground state
- already seen evidence in numerics, analytic analysis underway



In progress (II)

- Define JT + negative matter on non-perturbative Hilbert space
- model evaporation process by adding dissipation into the system
- solve Lindblad equation of the density matrix



More to do

- Revisit BHs in CGHS/RST model, do they also evaporate completely if shcokwave is removed?
- Quantum Schwarzian coupled to thermal bath
- Higher dimensions? BTZ?

Takeaways

- Non-perturbative effects are needed for black holes to disappear
- Global symmetry-violating wormholes provide a pathway for semi-classical evolution to reach the true ground state
- Otherwise we end up with a remnant