Aspects of de Sitter Quantum Gravity

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Consider Euclidean path integrals in the presence of a positive cosmological.

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- Include the effects of matter fields in the gravitational path integral.

- Direct evaluation in 4D gravity, in situations when there is a relation to 2D models.

$$\mathcal{Z} = \int_{\mathcal{M}} \underbrace{\mathcal{D}g}_{\text{Geometries}} \, \underbrace{\mathcal{D}\phi_i}_{\text{Fields}} \, e^{\overbrace{-S_E(g,\phi_i)}^{\text{Action for gravity+fields}}}$$

Focus

Consider Euclidean path integrals in the presence of a positive cosmological.

- Include the effects of matter fields in the gravitational path integral.
- Direct evaluation in 4D gravity, in situations when there is a relation to 2D models.

There will be no use of holography. Providing examples to argue that

- exact results for the path integral are possible in de Sitter,
- new features arise when quantum gravity is coupled to matter.

Outline

I. dS_3 quantum gravity coupled to matter

II. Quantum corrections for near-extremal black holes in dS_4

dS_3 quantum gravity coupled to matter

Advance methods in Chern-Simons to explore quantum gravity

Based on...

2001.09998
AC, Sabella-Garnier, Zukowski

2302.12281+2304.02668
AC, Coman, Fliss, Zukowski

2407.09608
Bourne, AC, Fliss

Einstein-Hilbert: Metric, curvature

$$Z_{matter}[g_{\mu\nu}] = \int D\phi \, e^{-S_{matter}[\phi, g_{\mu\nu}]} = \det(-\nabla^2 + m^2 \ell^2)^{-1/2}$$

$$\langle Z_{matter}[M] \rangle_{grav} = \int (D g_{\mu\nu})_M \, e^{-S_{EH}[g_{\mu\nu}]} Z_{matter}[g_{\mu\nu}]$$

Today: massive scalar field for simplicity

Today: Fixed topology, 3D gravity

Einstein-Hilbert: Metric, curvature

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$$\langle Z_{matter}[M] \rangle_{grav} = \int (Dg_{\mu\nu})_M \, e^{-S_{EH}[g_{\mu\nu}]} Z_{matter}[g_{\mu\nu}]$$

Chern-Simons: Gauge connections

$$\log(Z_{matter}[g_{\mu\nu}]) = \frac{1}{4} \mathbb{W}_j[A_L, A_R]$$

$$\langle \mathbb{W}_j \rangle_{grav} = \int DA_{L/R} e^{ik_L S[A_L] + ik_R S[A_R]} \mathbb{W}_j[A_L, A_R]$$

Wilson Spool

dS_3 Quantum Gravity

$$\log(Z_{scalar}[g_{\mu\nu}]) = \frac{1}{4}\mathbb{W}_j[A_L, A_R]$$

$$\langle \mathbb{W}_j \rangle_{grav} = \int DA_{L/R}\, e^{ik_L S[A_L] + ik_R S[A_R]}\, \mathbb{W}_j[A_L, A_R]$$

Focus mainly on massive fields coupled to dS_3 gravity. **Why dS_3?**

- We can use the full power of SU(2) Chern-Simons theory.

  [Carlip 1992; AC, Lashkari, Maloney 2011; Anninos, Denef, Law, Sun 2022]

- Make predictions for G_N corrections without the aid of holography.

How to couple matter to 3D gravity
via the Chern-Simons formulation?

Step 1: cast Euclidean dS_3 gravity in Chern-Simons language

Step 2: describe particles and fields in a group theoretic language

Step 3: incorporate step 2 into Chern-Simons path integral

Step 1: cast Euclidean dS_3 gravity in Chern-Simons language

- Gauge group: $SU(2) \times SU(2)$ leads to dS_3 Euclidean Gravity, $\Lambda = \frac{1}{\ell^2} > 0$
- Action: $-ik_L S_{CS}[A_L] - ik_R S_{CS}[A_R] = I_{EH}[g_{\mu\nu}] - i\delta\, I_{GCS}[g_{\mu\nu}]$
- Couplings: $k_L = \delta + i\,\frac{\ell}{4G_N}\,, \quad k_R = \delta - i\,\frac{\ell}{4G_N}$
- Dictionary: $A_L = i\left(\omega^a + \frac{e^a}{\ell}\right)L_a, \qquad A_R = i\left(\omega^a - \frac{e^a}{\ell}\right)\bar{L}_a$

[Acucharro & Townsend; Witten]

Step 1: cast Euclidean dS_3 gravity in Chern-Simons language

Background S^3 connections

$$a_L = i\, L_1 d\rho + i(\sin\rho\, L_2 - \cos\rho\;\; L_3)(d\varphi - d\tau)$$
$$a_R = -i\bar{L}_1 d\rho - i(\sin\rho\, \bar{L}_2 + \cos\rho\, \bar{L}_3)(d\varphi + d\tau)$$

Holonomies

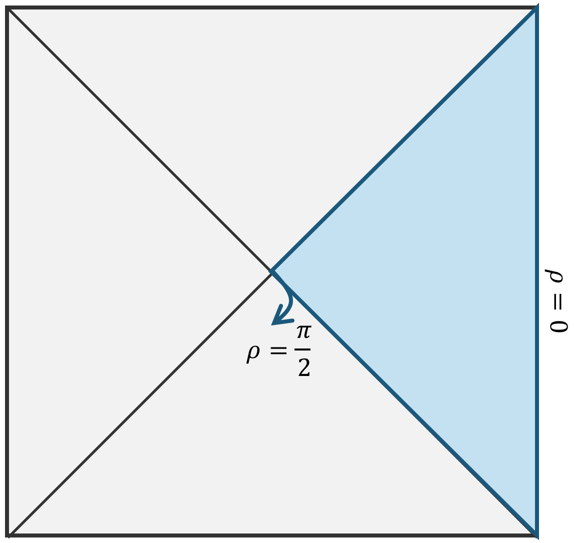
$$P\exp\oint_\gamma \; a_{L/R} \sim e^{2\pi i\, L_3 h_{L/R}}$$

For a cycle γ that wraps horizon at $\rho = \frac{\pi}{2}$

$$\boxed{\begin{aligned} h_L &= 1 \\ h_R &= -1 \end{aligned}}$$

Geometry: Static Patch

$$ds^2 = \ell^2(\cos^2\rho\;\; d\tau^2 + \sin^2\rho\;\; d\varphi^2 + d\rho^2)$$



Step 2: describe particles and fields in a group theoretic language

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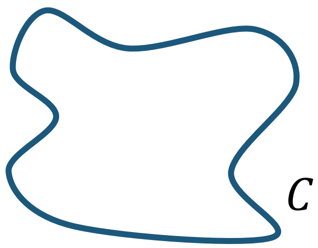
Description of **particles** in CS language: Wilson lines/loops

$$W_R(C) = \underbrace{Tr_R}_{\substack{\text{Infinite dimensional representation of G.} \\ \text{Encodes quantum numbers of the particle.}}}\left(P \exp \oint_C A\right) = \underbrace{\int DU \exp(-S(U,A)_C)}_{\text{Path integral of a massive particle.}}$$



C

[Witten 1989; Carlip 1989; Ammon, AC, Iqbal 2013; AC, Sabella-Garnier, Zukowski, 2020]

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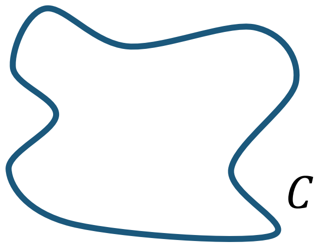

For SU(2) applied to dS_3, these representations are non-standard (complex/real casimir).

Step 2: describe particles and fields in a group theoretic language

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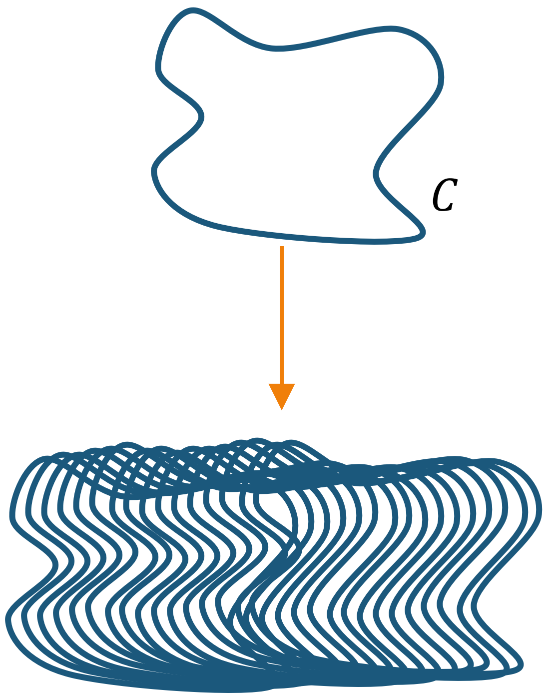


Description of **fields** in CS language: …

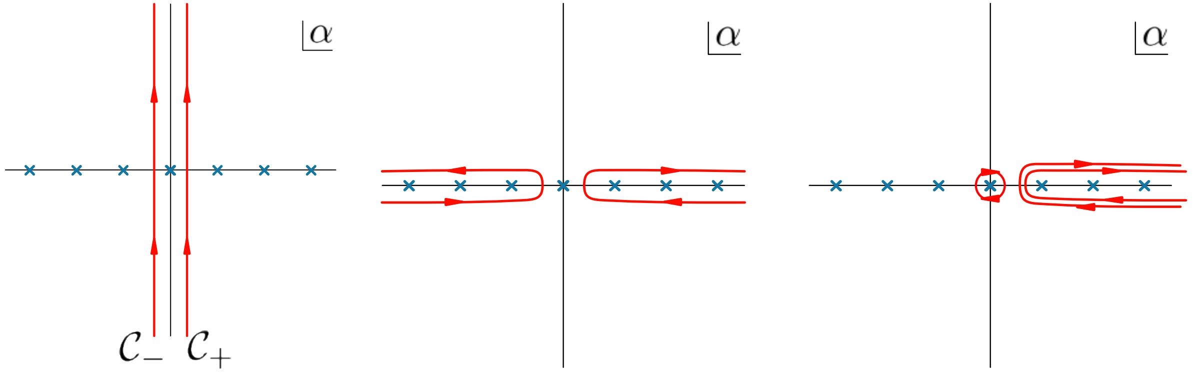
$$\log\det(-\nabla^2 + m^2\ell^2) \sim \sum_n \frac{1}{n} \text{``}\mathrm{Tr}_j(Pe^{\frac{n}{2\pi}\oint A})\text{''}$$

Step 2: describe particles and fields in a group theoretic language

Description of **fields** in CS language: Wilson spool. Derivation relies on a group theoretic understanding of one-loop determinants.
For massive scalar fields

$$\mathbb{W}_j[A_L, A_R] = i \int_{\mathcal{C}} \frac{d\alpha}{\alpha} \frac{\cos\frac{\alpha}{2}}{\sin\frac{\alpha}{2}} \mathrm{Tr}_j(P e^{\frac{\alpha}{2\pi}\oint A_L}) \mathrm{Tr}_j(P e^{-\frac{\alpha}{2\pi}\oint A_R})$$

where $\mathcal{C} = \mathcal{C}_+ \cup \mathcal{C}_-$



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This expression can be taken off-shell for the metric: A_L and A_R appear in a simple way!

Step 3: incorporate step 2 into Chern-Simons path integral

Einstein-Hilbert: Metric, curvature

$$Z_{matter}[g_{\mu\nu}] = \int D\phi \, e^{-S_{matter}[\phi, g_{\mu\nu}]} = \det(-\nabla^2 + m^2\ell^2)^{-1/2}$$

$$\langle Z_{matter}[M]\rangle_{grav} = \int (Dg_{\mu\nu})_M \, e^{-S_{EH}[g_{\mu\nu}]} Z_{matter}[g_{\mu\nu}]$$

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$$\log(Z_{matter}[g_{\mu\nu}]) = \frac{1}{4}\mathbb{W}_j[A_L, A_R]$$

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There are three things to keep in mind:

- Level is complex: $k = \delta - i\frac{\ell}{4G_N}$
- Background connection is not trivial.
- Assure that exact results are compatible with the non-standard representations

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We adapted exact methods to incorporate these tweaks:

- Abelianisation [Blau-Thompson]
- Supersymmetric Localization [Kapustin-Willet-Yaakov]

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✓ Path integral on S^3
✓ Wilson Loops on S^3
✓ Wilson Spool on S^3

Results

Massive spinning fields coupled to dS_3 quantum gravity

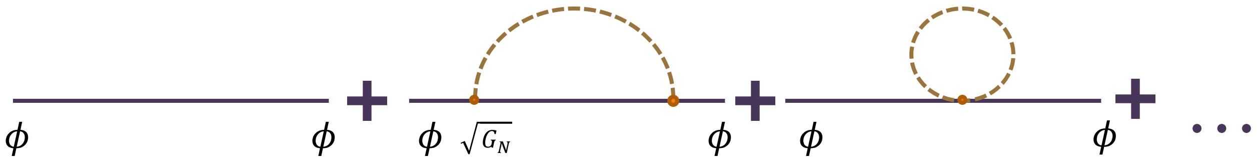
$$\frac{\langle \log Z_{matter}[S^3]\rangle_{grav}}{\mathcal{Z}_{grav}[S^3]} = \log Z_{matter}[S^3] + \sum_{m=1}^{\infty}\left(\frac{G_N}{\ell}\right)^{2m}(\log Z)_{2m}$$

Mass renormalization: $\ell^2 m^2 = (s-1)^2 + \mu^2$

$$\boxed{\mu_R = \mu + \left(-\frac{48}{5}\mu^3 + \left(\frac{24}{\pi} - \frac{16\pi}{3} + 32\pi^2 s^2\right)\mu^2\right)e^{-2\pi\mu}\left(\frac{G_N}{\ell}\right)^2 + \cdots}$$

Presenting $\mu \gg 1$ limit.
Exact results in references.

Concrete predictive statement about how dynamical gravity renormalizes field



Field on a fixed curved background

One-loop corrections

Higher loops

Results

Massive spinning fields coupled to dS_3 quantum gravity

$$\frac{\langle Z_{matter}[S^3]\rangle_{grav}}{\mathcal{Z}_{matter}[S^3]} = Z_{grav}[S^3] + \sum_{m=1}^{\infty}\left(\frac{G_N}{\ell}\right)^{2m}(Z_{grav})_{2m}$$

Renormalization G_N: integrate out massive field

$$\boxed{G_N = G_{N,R}\left(1+\left(\frac{16\pi}{5}\mu^5-\left(8-\frac{16\pi^2}{9}+\frac{32\pi^2}{3}s^2\right)\mu^4\right)e^{-2\pi\mu}\left(\frac{G_{N,R}}{\ell}\right)^2+\cdots\right)}$$

Presenting $\mu \gg 1$ limit.
Exact results in references.

We have introduced a new object: the Wilson spool.

- Allows us to incorporate matter fields in the Chern-Simons formulation of 3D gravity.

- Tested at $G_N \to 0$, where the Wilson spool reproduces the one-loop determinant of massive spinning fields.

$$\begin{aligned}\log(Z_{matter}[S^3]) &= \log\det(-\nabla^2 + m^2\ell^2)^{-\frac{1}{2}} \\ &= \frac{1}{4}\mathbb{W}_j[a_L, a_R]\end{aligned}$$

- We can also make predictions for quantum corrections, without the aid of holography.

Overview

dS_3 gravity

✓ Massive spinning fields in S^3 via CS theory

🛠 One-loop determinants on Lens Spaces via CS theory [wip Bourne, AC, Fliss, Law]

🛠 Mass renormalization in metric formulation (2-loops)

AdS_3 gravity

✓ One-loop determinants on rotating BTZ via CS theory

🛠 One-loop determinants on handlebodies via CS theory [wip Bourne, Fliss, Knighton]

Near-extremal BHs in dS_4

Limitations of 2D models and pathologies of de Sitter

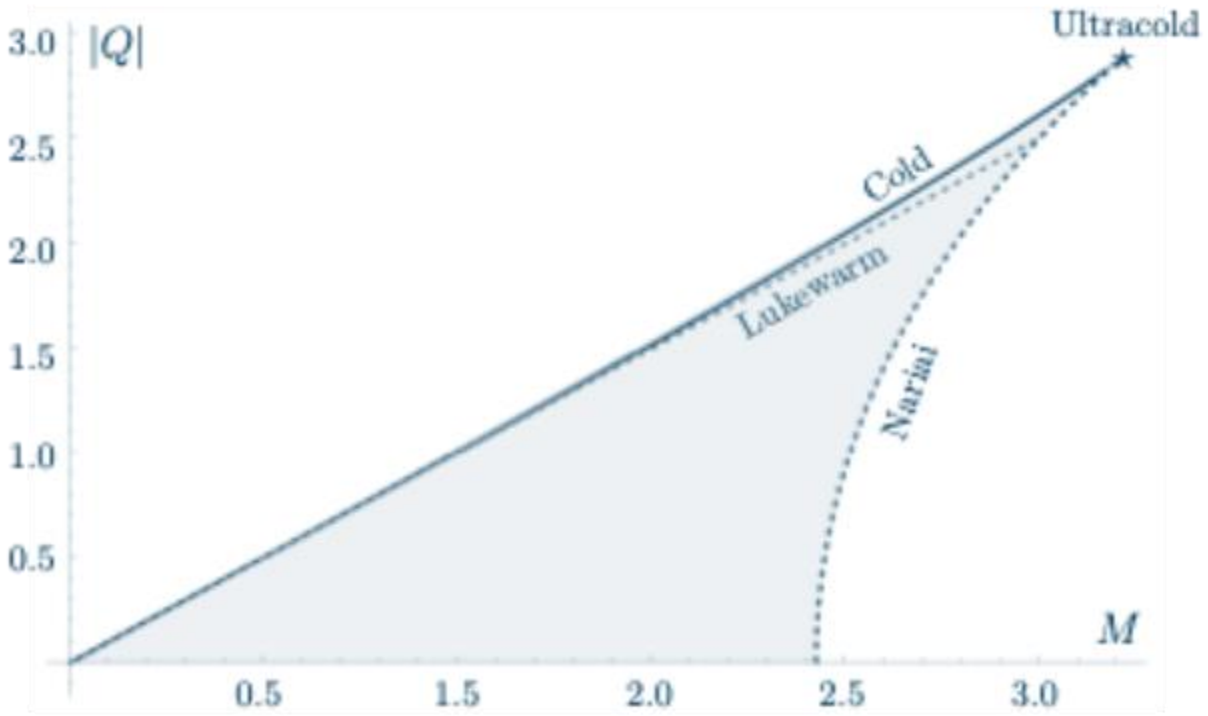
[to appear M. Blacker, AC, W. Sybesma, C. Toldo]

Charged BHs in dS_4

Einstein-Maxwell + positive c.c.

$$S_E = \frac{1}{16\pi G_N} \int d^4x \sqrt{g} \left(R - 2\Lambda - F_{\mu\nu} F^{\mu\nu} \right)$$

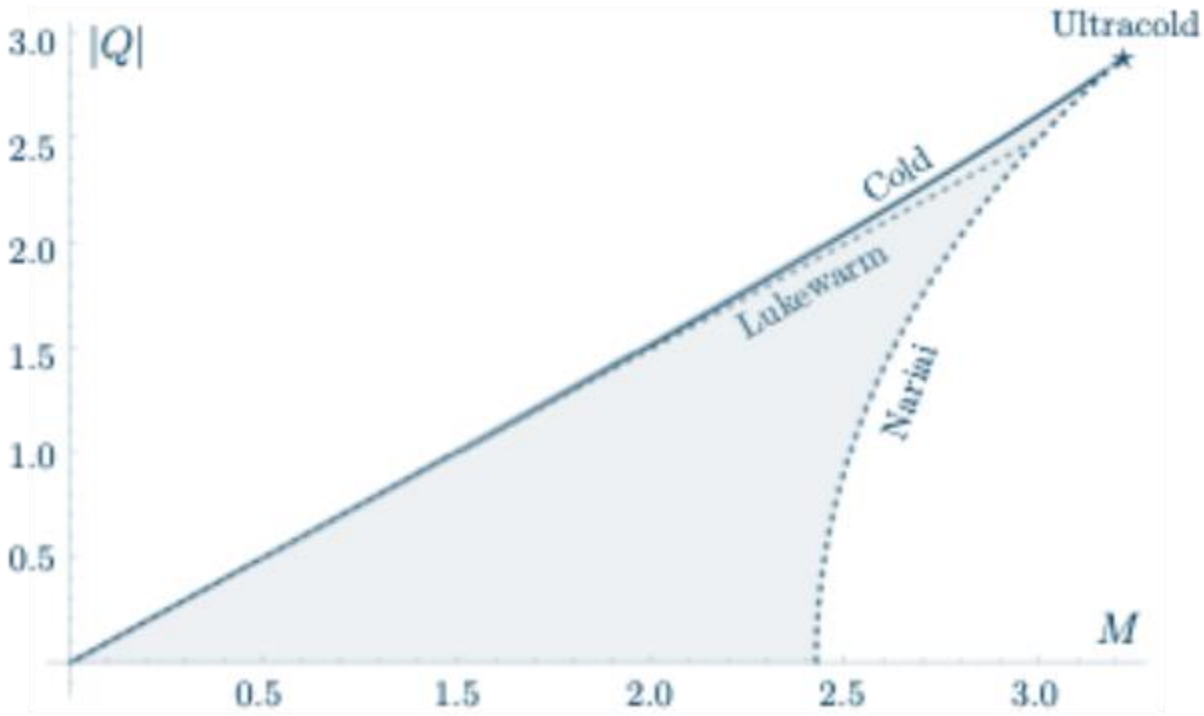
M: “mass”
Q: charge



Charged BHs in dS_4

Extremal limits:

- Cold branch, $r_+ = r_-$, $AdS_2 \times S^2$
- Nariai, $r_c = r_+$, $dS_2 \times S^2$
- Ultracold, $r_c = r_+ = r_-$, $Mink_2 \times S^2$



More details, see e.g., 2212.14356 [AC, Mariani,Toldo]

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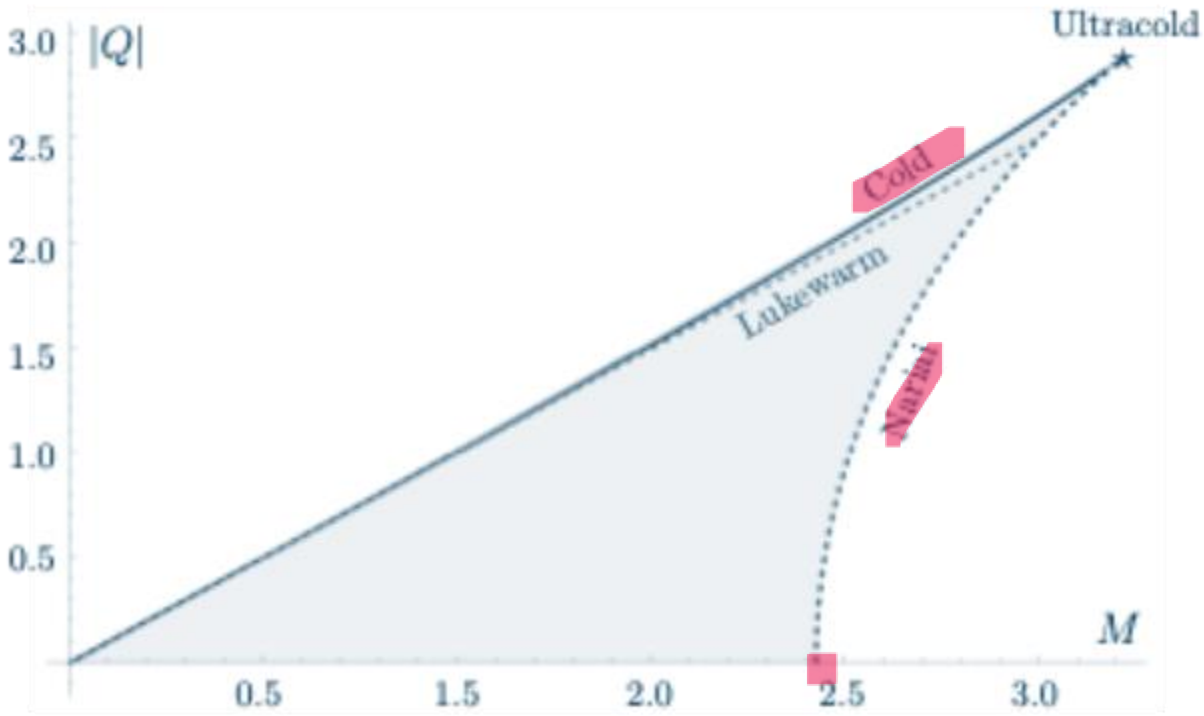

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Near-extremal GPI

$$\mathcal{Z} = \int_{\mathcal{M}} \mathcal{D}g\, \mathcal{D}A\, e^{-S_E(g,A)}$$

Talks Strings 2022 L. Iliesiu, 2023 A. Sen
[Iliesiu, Murthy, Turiaci; Banerjee, Saha; …]

Near-extremal GPI

$$\mathcal{Z} = \int_{\mathcal{M}} \mathcal{D}g\, \mathcal{D}A\, e^{-S_E(g,A)} = e^{-I(g_e,A_e)} \underbrace{\int_{\mathcal{M}} \mathcal{D}h\, \mathcal{D}a\, e^{-S_{(1)}(h,a)+\cdots}}_{\text{One-loop determinants}} + \cdots$$

$$g = g_{extremal} + h$$
$$A = A_{extremal} + a$$

Around near-horizon of extremal black holes, infinitely many normalizable zero modes (h^0, a^0):

$$\int_{\mathcal{M}} \mathcal{D}h^0\, \mathcal{D}a^0 = \infty$$

Talks Strings 2022 L. Iliesiu, 2023 A. Sen
[Iliesiu, Murthy, Turiaci; Banerjee, Saha; …]

Near-extremal GPI

$$\mathcal{Z} = \int_{\mathcal{M}} \mathcal{D}g\, \mathcal{D}A\, e^{-S_E(g,A)} = e^{-I(g_e+\delta g, A_e+\delta A)} \int_{\mathcal{M}} \mathcal{D}h\, \mathcal{D}a\, e^{-S_{(1)}(h,a)+\cdots} + \cdots$$

$$g = g_{extremal} + \delta g + h^0 + \delta h_T^0$$
$$A = A_{extremal} + \delta A + a^0 + \delta a_T^0$$

with $\delta g \sim O(T), \;\; \delta a \sim O(T)$

Around near-horizon of near-extremal black holes, zero modes are lifted:

$$\int_{\mathcal{M}} \mathcal{D}h^0\, \mathcal{D}a^0\;\; e^{-\lambda_h(T)\langle h^0|h^0\rangle}\, e^{-\lambda_a(T)\langle a^0|a^0\rangle} \sim T^{\#}$$

with $\lambda_{h,a}(T) \sim O(T)$

Talks Strings 2022 L. Iliesiu, 2023 A. Sen
[Iliesiu, Murthy, Turiaci; Banerjee, Saha; …]

Results

Extremal dS_4 BH	Tensor modes		Vector modes		U(1) modes		$\mathcal{Z}_{low-T}$
	$\langle h^0 \vert h^0 \rangle$	$\lambda_h(T)$	$\langle h^0 \vert h^0 \rangle$	$\lambda_h(T)$	$\langle a^0 \vert a^0 \rangle$	$\lambda_a(T)$	
$AdS_2 \times S^2$ (+,+,+,+)							
$dS_2 \times S^2$ (-,-,+,+)							
$dS_2 \times S^2$ (-,-,-,-)							
$dS_2 \times S^2$ Q=0							

dS_2 JT sector

Results

Extremal dS_4 BH	Tensor modes		Vector modes		U(1) modes		$\mathcal{Z}_{low-T}$
	$\langle h^0 \vert h^0 \rangle$	$\lambda_h(T)$	$\langle h^0 \vert h^0 \rangle$	$\lambda_h(T)$	$\langle a^0 \vert a^0 \rangle$	$\lambda_a(T)$	
$AdS_2 \times S^2$ (+,+,+,+)	+	+	+	+	+	+	$\sim T^{7/2}$
$dS_2 \times S^2$ (-,-,+,+)							
$dS_2 \times S^2$ (-,-,-,-)							
$dS_2 \times S^2$ Q=0							

$$\mathcal{Z}_{low-T} \sim \int_{\mathcal{M}} \mathcal{D}h^0\, \mathcal{D}a^0\, e^{-\lambda_h(T)\langle h^0 | h^0 \rangle}\, e^{-\lambda_a(T)\langle a^0 | a^0 \rangle} + \cdots$$

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Extremal dS_4 BH	Tensor modes		Vector modes		U(1) modes		$\mathcal{Z}_{low-T}$
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$AdS_2 \times S^2$ (+,+,+,+)	+	+	+	+	+	+	$\sim T^{7/2}$
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$dS_2 \times S^2$ Q=0	+	-	-	-			

$$\mathcal{Z}_{low-T} \sim \int_{\mathcal{M}} \mathcal{D}h^0 \, \mathcal{D}a^0 \, e^{-\lambda_h(T)\langle h^0 | h^0 \rangle} \, e^{-\lambda_a(T)\langle a^0 | a^0 \rangle} + \cdots$$

Results

Extremal dS_4 BH	Tensor modes		Vector modes		U(1) modes		$\mathcal{Z}_{low-T}$
	$\langle h^0\|h^0\rangle$	$\lambda_h(T)$	$\langle h^0\|h^0\rangle$	$\lambda_h(T)$	$\langle a^0\|a^0\rangle$	$\lambda_a(T)$	
$AdS_2 \times S^2$ (+,+,+,+)	+	+	+	+	+	+	$\sim T^{7/2}$
$dS_2 \times S^2$ (-,-,+,+)	+	-	-	-	-	+	
$dS_2 \times S^2$ (-,-,-,-)	+	+	+	+	-	-	
$dS_2 \times S^2$ Q=0	+	-	-	-			

$$\mathcal{Z}_{low-T} \sim \int_{\mathcal{M}} \mathcal{D}h^0\, \mathcal{D}a^0\, e^{-\lambda_h(T)\left\langle h^0 \middle| h^0 \right\rangle}\, e^{-\lambda_a(T)\left\langle a^0 \middle| a^0 \right\rangle} + \cdots$$

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Extremal dS_4 BH	Tensor modes		Vector modes		U(1) modes		$\mathcal{Z}_{low-T}$
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$dS_2 \times S^2$ (-,-,+,+)	+	-	-	-	-	+	…
$dS_2 \times S^2$ (-,-,-,-)	+	+	+	+	-	-	…
$dS_2 \times S^2$ Q=0	+	-	-	-			…

$$\mathcal{Z}_{low-T} \sim \int_{\mathcal{M}} \mathcal{D}h^0 \, \mathcal{D}a^0 \, e^{-\lambda_h(T)\langle h^0 | h^0 \rangle} \, e^{-\lambda_a(T)\langle a^0 | a^0 \rangle} + \cdots$$

Overview

Near-extremal black holes in dS_4 provide a sharp lab to connect with toy models in 2D and quantify the role of extra dimensions (matter).

- Cold branch: $AdS_2 \times S^2$
- Nariai: $dS_2 \times S^2$
- Ultracold: $Mink_2 \times S^2$

Quantum corrections of dS_4 BHs display pathologies that are not present for BHs in $Mink_4/AdS_4$. Resolving them could be important for the interpretation of the Euclidean GPI in de Sitter.

Conclusions

Future Directions

I. dS_3 quantum gravity coupled to matter

Higher form symmetries in QG

$\langle \log Z_{scalar} \rangle$ versus $\log \langle Z_{scalar} \rangle$

Microscopic interpretation: edge modes within

Quantum corrections to Wilson spool in AdS_3

Future Directions

I. dS_3 quantum gravity coupled to matter

- Higher form symmetries in QG
- $\langle \log Z_{scalar} \rangle$ versus $\log \langle Z_{scalar} \rangle$
- Microscopic interpretation: edge modes within
- Quantum corrections to Wilson spool in AdS_3

II. Quantum corrections for near-extremal black holes in dS_4

- Microscopic interpretation: analytic continuations
- Ultracold limit and its ties to $Mink_2$ gravity.

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- Microscopic interpretation: edge modes within
- Quantum corrections to Wilson spool in AdS_3

II. Quantum corrections for near-extremal black holes in dS_4

- Microscopic interpretation and analytic continuations
- Ultracold limit and its ties to $Mink_2$ gravity.

Thank you!