Big crunch singularities in AdS and relevant deformations of CFT’s

Vlad Vaganov

Fields, Gravity & Strings Group
Center for Theoretical Physics of the Universe
Institute for Basic Science
Seoul, Korea

5th January, 2017, ICTS, USTC
Based on

1510.03281, “Probing crunching AdS cosmologies”
1512.07184, “Quasinormal modes and holographic correlators in a crunching AdS geometry”

+ ongoing..

with **S. Prem Kumar** *(Swansea University)*
Some previous work

0406134 [hep-th] “Towards a big crunch dual” Hertog, Horowitz
0503071 [hep-th] “Holographic description of AdS cosmologies” Hertog, Horowitz
0712.4180 “On the Quantum Resolution of Cosmological Singularities using AdS/CFT” Craps, Hertog, Turok
0807.1517 “Gauge theories with time dependent couplings and their cosmological duals” Trivedi, Narayan, Nampuri, Das, Awad
1012.0274 “Vacuum decay into anti de Sitter space” Maldacena
1102.3015 “AdS crunches, CFT falls and cosmological complementarity” Barbon, Rabinovici
1210.7244 “Entanglement entropy in de Sitter space” Maldacena, Pimentel
1404.2309 “Holographic signatures of cosmological singularities” Engelhardt, Hertog, Horowitz
1509.07509 “Holographic consequences of a No Transmission Principle” Engelhardt, Horowitz
1512.05761 “Cosmological singularities encoded in IR boundary correlations” Bzowski, Hertog, Schillo
Background and motivation

General setup

Examples from known deformations of CFT’s

AdS$_4$/CFT$_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary
Main theme:

Toy models in holography to address (potential) resolution of cosmological singularities by string theory

Secondary themes:

- QFT in de Sitter spacetime
- Nonequilibrium dynamics of strongly driven interacting QFT’s
Precedent:

- Subtle signals of black hole singularity encoded in large $N$ thermal correlators.
- Is black hole singularity resolved by stringy ($\alpha'$) corrections or quantum ($g_s$) effects?
Our focus:

- Spacelike cosmological curvature singularity of FRW type, **big crunch**.
- Cuts all the way across the asymptotically global AdS spacetime.
- Time-dependent supergravity solutions dual to a CFT deformed by a relevant operator.
- The field theory lives on de Sitter spacetime.
- There is an equivalent point of view where the field theory lives on the Einstein static universe but the relevant couplings are time-dependent and diverge at finite time.
Other toy models:

- CFT’s on de Sitter deformed by marginal multi-trace operators (Horowitz/Hertog 2004, Craps/Hertog/Turok 2007).
- Dilaton deformations of $\text{AdS}_5 \times S^5$ dual to $\mathcal{N} = 4$ on Minkowski with time-dependent coupling (Trivedi et al. 2006-2009)
- Examples in higher-spin AdS/CFT dualities.
- AdS black holes.
- ...
Outline:

- Examples and generic features of such gauge-gravity dual pairs.
- Potential holographic QFT signatures of bulk gravity singularity.
- Compare and contrast to thermal QFT/AdS black holes.
- Eventually hope to understand such singularities from QFT perspective.
Plan

Background and motivation

General setup

Examples from known deformations of CFT's

AdS$_4$/CFT$_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary
Background and motivation

General setup

Examples from known deformations of CFT’s

AdS$_4$/CFT$_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary

- Start with Euclidean CFT on $S^d$ dual to empty Euclidean AdS

$$ds^2 = d\xi^2 + \sinh^2(\xi)d\Omega_d^2$$

- Deform the CFT by a relevant operator (mass terms)

$$\mathcal{L}_{S^d} = \mathcal{L}_{CFT} + \frac{1}{2}m^2\varphi^2$$
Euclidean instanton

- Large $N$ dual: gravity + scalars

$$ds^2 = d\xi^2 + a^2(\xi) d\Omega_d^2, \quad \phi = \phi(\xi), \quad 0 \leq \xi < \infty$$

- Take $m$ to be small compared to inverse sphere radius

- smooth origin: $a|_{\xi \to 0} \sim \xi$ & asympt. AdS: $a|_{\xi \to \infty} \sim \sinh \xi$

- $O(d+1)$-invariant Euclidean instanton
Lorentzian exterior region

- Wick rotation \( \theta \rightarrow i t + \frac{\pi}{2} \)

\[
d\Omega_d^2 = d\theta^2 + \sin^2(\theta)\ d\Omega_{d-1}^2 \quad \rightarrow \quad -dt^2 + \cosh^2(t)\ d\Omega_{d-1}^2
\]

Deformed CFT in de Sitter (dS\(_d\)).

- Bulk dS-sliced asymptotically AdS exterior patch

\[
ds^2 = d\xi^2 + a^2(\xi) \left( -dt^2 + \cosh^2(t)\ d\Omega_{d-1}^2 \right)
\]

\( \xi = 0 \) now a horizon.
Lorentzian interior region

Can continue through the horizon into another region:

\[ \xi \rightarrow i\sigma , \quad t \rightarrow \chi - \frac{i\pi}{2} , \quad a \rightarrow i\tilde{a} \]

\[
\begin{align*}
    ds^2 & \rightarrow -d\sigma^2 + \tilde{a}^2(\sigma) \left( d\chi^2 + \sinh^2(\chi) d\Omega_{d-1}^2 \right) \\
\end{align*}
\]

FRW cosmology with scale factor \( \tilde{a} \) and hyperbolic spatial sections. Interior patch.
General setup

Pure AdS

- $a = \sinh \xi$, $\tilde{a} = \sin \sigma$
- Exterior coordinate patch:

$$ds^2 = d\xi^2 + \sinh^2(\xi) \left( -dt^2 + \cosh^2(t) d\Omega_{d-1}^2 \right), \quad 0 \leq \xi < \infty$$

- Interior coordinate patch:

$$ds^2 = -d\sigma^2 + \sin^2(\sigma) \left( d\chi^2 + \sinh^2(\chi) d\Omega_{d-1}^2 \right), \quad 0 \leq \sigma \leq \pi$$
Pure AdS

\[ a(\xi) \]

AdS (\( a = \sinh[\xi] \))

\[ \tilde{a}(\sigma) \]

AdS (\( \tilde{a} = \sin[\sigma] \))

\( \xi = 0 \) or \( \sigma = 0 \): horizon

\( \sigma = \pi \): "crunch" (coordinate singularity)
Deformed AdS with crunch

\[ \xi = 0 \text{ or } \sigma = 0: \text{ horizon} \]

\[ \sigma = \sigma_c < \pi: \textbf{big crunch} \text{ curvature singularity - unavoidable barring fine-tuning} \]
Penrose diagram

Pure AdS

Deformed AdS with crunch
Penrose diagram

Pure AdS

Deformed AdS with crunch
Coleman & de Luccia

- Closely related to Coleman & de Luccia (1980) false vacuum decay (e.g. Minkowski to AdS): expanding bubbles with AdS interiors.

- Deviation of scalar from AdS extremum $\rightarrow$ curvature singularity (C-dL 1980).
General setup

Conformal complementarity map

- Boundary \( dS_d \) is conformal to \( \mathbb{R}_\tau \times S^{d-1} \) (Einstein static universe = ESU).

\[
-dt^2 + \cosh^2(t) \, d\Omega_{d-1}^2 = \sec^2 \tau \left( -d\tau^2 + d\Omega_{d-1}^2 \right),
\]

\[
-\infty < t < \infty \quad \cosh t = \frac{1}{\cos \tau} \quad -\frac{\pi}{2} < \tau < \frac{\pi}{2}
\]

- Can talk about theory on de Sitter or the theory on the ESU. The Lagrangians of the two theories are related as

\[
\mathcal{L}_{dS_d} = \mathcal{L}_{CFT} + \frac{1}{2} m^2 \phi^2
\]

\[
\mathcal{L}_{\mathbb{R}_\tau \times S^{d-1}} = \mathcal{L}_{CFT} + \frac{1}{2} \frac{m^2}{\cos^2 \tau} \phi^2
\]

General setup

Conformal complementarity map

- Bulk geometry in dS slicing:

\[ ds^2 = d\xi^2 + a^2(\xi) \left( -dt^2 + \cosh^2(t) d\Omega_{d-1}^2 \right) \]

- Bulk geometry in global slicing:

\[ ds^2 = \Lambda^2 \left( \frac{\cos \psi}{\cos \tau} \right) ds_{AdS}^2 \]

\[ ds_{AdS}^2 = \sec^2(\psi) \left( -d\tau^2 + d\psi^2 + \sin^2(\psi) d\Omega_{d-1}^2 \right) , \quad 0 \leq \psi < \frac{\pi}{2} \]

- \( \Lambda = 1 \) at AdS boundary, \( \Lambda = 0 \) at crunch singularity.
Aside: comparison to AdS black hole
Comparison to AdS black hole

<table>
<thead>
<tr>
<th>AdS-Schw black hole</th>
<th>AdS crunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 boundaries</td>
<td>1 boundary</td>
</tr>
<tr>
<td>Singularity curved inward</td>
<td>Singularity curved outward</td>
</tr>
<tr>
<td>Static</td>
<td>Time-dependent</td>
</tr>
<tr>
<td>$\mathbb{R} \times O(d)$ symmetry</td>
<td>$O(d,1)$ symmetry</td>
</tr>
<tr>
<td>Vacuum solution</td>
<td>Requires supergravity fields</td>
</tr>
<tr>
<td>CFT in thermal state</td>
<td>Deformation of CFT Lagrangian</td>
</tr>
<tr>
<td>Boundary $\mathbb{R} \times S^{d-1}$</td>
<td>Boundary $dS_d$ or $\mathbb{R}_\tau \times S^{d-1}$ related by complementarity map</td>
</tr>
</tbody>
</table>
Background and motivation

General setup

Examples from known deformations of CFT’s

AdS$_4$/CFT$_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary
Examples from known deformations of CFT’s

**Examples: AdS$_5$/CFT$_4$**  (Kumar-VV (to appear))

Within $\mathcal{N} = 8$ gauged supergravity in 5d

- $\mathcal{N} = 4$ SYM + equal masses for 3 adjoint chiral multiplets ($\mathcal{N} = 1^*$ on $\mathbb{R}^4$): **GPPZ 2-scalar truncation** (Girardello/Petrini/Porrati/Zaffaroni 1999).

- $\mathcal{N} = 1^*$ on $S^4$: **BEKOP 10-scalar truncation** (Bobev/Elvang/Kol/Olson/Pufu 2016)

- $\mathcal{N} = 4$ SYM + mass for adjoint hypermultiplet ($\mathcal{N} = 2^*$ on $\mathbb{R}^4$): **Pilch-Warner 2-scalar truncation** (Pilch/Warner 2000)

- $\mathcal{N} = 2^*$ on $S^4$: **BEFP 3-scalar truncation** (matching localization results) (Bobev/Elvang/Freedman/Pufu 2013)
Examples: AdS$_4$/CFT$_3$

Within $\mathcal{N} = 8$ gauged supergravity in 4d


- M2-brane CFT ($k = 1$ ABJM) + mass term ($\Delta = 1$ operator): Papadimitriou-Skenderis 1-scalar truncation (Papadimitriou/Skenderis 2004)

- M2-brane CFT ($k = 1$ ABJM) + mass term preserving $\mathcal{N} = 2$ SUSY on $S^3$: Freedman-Pufu 3-scalar truncation (Freedman/Pufu 2013)

AdS$_3$/CFT$_2$ examples..
Construction

- For each truncation, $S^d$-sliced Euclidean "ungapped" solution is constructed numerically. Start with smooth b.c. at origin and integrate out to AdS boundary.
- Typically find bounded mass deformation $|m| < |m_{\text{crit}}|$.
- Continuation to dS$_d$-sliced exterior region of the Lorentzian geometry is trivial as profiles depend only on radial coordinate.
- FRW interior region is obtained by integrating analytically continued equations inward from the horizon.
Near-singularity behaviour  (Kumar-VV (to appear))

- In each case, find crunch at $\sigma = \sigma_c < \pi$ and $\tilde{a}_{\text{max}} < 1$:

![Graph showing $\tilde{a}$ versus $\sigma$ with different curves for $\Phi_0=0.3$, $\Phi_0=1.0$, and $\Phi_0=1.5$.]

- Power law scaling as $\sigma \to \sigma_c$ (supergravity not reliable)

$$\tilde{a}(\sigma) \sim (\sigma_c - \sigma)^\gamma$$

- Generically $\gamma = 1/d \iff$ scalar potential terms are negligible. Non-generic $\gamma$ also possible but depends on potential.

- BEFP $\mathcal{N} = 2^*$ example ($d = 4$) has two branches of solution

$$\tilde{a} \sim (\sigma_c - \sigma)^{1/4} \text{ (generic)}, \quad \tilde{a} \sim (\sigma_c - \sigma)^{1/7} \text{ (non-generic)}$$

5th January, 2017, ICTS, USTC
Background and motivation

General setup

Examples from known deformations of CFT’s

**AdS$_4$/CFT$_3$ analytical example**

Holographic probes: geodesics, correlators, entanglement entropy

Summary
1-scalar truncation of $\mathcal{N}=8$ gauged supergravity in 4 dimensions.

$$S_{\text{truncated}} = \int d^4x \sqrt{g_4} \left[ -\frac{1}{2\kappa^2} R + \frac{1}{2} \partial_\mu \Phi \partial^\mu \Phi + V_{2/3}(\Phi) \right]$$

$$V_{2/3} = -\frac{3}{\kappa^2 L^2} \cosh \left( \sqrt{\frac{2}{3}} \kappa \Phi \right)$$

AdS$_4$ maximum at $\Phi = 0$ with $M_\Phi^2 = -2/L^2$.
(in window $M_{BF}^2 < M^2 < M_{BF}^2 + 1$)

Two possible quantizations: $\Phi$ dual to $\Delta = 2$ (Dirichlet b.c.)
or $\Delta = 1$ (Neumann b.c.) CFT operator.
AdS$_4$/CFT$_3$ analytical example

- Exact smooth Euclidean solution with $S^3$ slices (Papadimitriou 2007):

\[
ds^2 = \left(1 - f(u)^2\right) \left[\frac{du^2}{u^2(1 + u^2)} + \frac{1}{u^2} d\Omega_3^2\right]
\]

\[
\Phi = \sqrt{6} \tanh^{-1} f, \quad f(u) = \frac{f_0 u}{\sqrt{1 + u^2 + u\sqrt{1 + f_0^2}}}
\]

- Boundary asymptotics: $\Phi \sim \alpha u + \beta u^2 + \ldots$

$\alpha = f_0, \beta = -f_0 \sqrt{1 + f_0^2}$.

- View $\beta$ as a mass deformation ($\Delta = 1$ operator) of M2-brane CFT and $\alpha$ as its VEV (Neumann b.c.).
Lorentzian continuation shows (analytically) FRW crunch with \( \ddot{a}(\sigma) \sim (\sigma_c - \sigma)^{1/3} \) as \( \sigma \to \sigma_c \) (generic scaling).

Shape of the crunch (solid blue) and maximal expansion slice (dashed)

\[
\begin{align*}
\sigma &= 0 & f_0 &= 0 \\
\sigma &= 0.02 & f_0 &= 0.02 \\
\sigma &= 10 & f_0 &= 10
\end{align*}
\]

Small deformations: crunch is almost null.
Large deformations: crunch is horizontal; Penrose diagram close to a square (like BTZ).
Background and motivation

General setup

Examples from known deformations of CFT’s

$\text{AdS}_4/\text{CFT}_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary
Geodesics and correlators

- What QFT observables know about the crunch?
- Start with two-point correlation functions.
- First consider geodesic limit:

\[
\langle \psi | \mathcal{O}_\Delta(x_1) \mathcal{O}_\Delta(x_2) | \psi \rangle \sim e^{-\Delta \cdot S_{\text{reg}}(x_1, x_2)}.
\]

Scaling dimension \( \Delta \to \infty \).

\( S_{\text{reg}} \): regulated length of bulk geodesic connecting \( x_1 \) and \( x_2 \).

- Geodesic limit \( \equiv \) WKB limit of wave equation for a probe scalar.
Aside: probing AdS black hole

(Fidkowski/Hubeny/Kleban/Shenker 2003)
Aside: probing AdS black hole

(Fidkowski/Hubeny/Kleban/Shenker 2003)
Bouncing geodesics (Shenker et al 2003)

- Spacelike geodesics compute analytically continued Wightman functions in thermal CFT

\[ G_{12}(t) \equiv \langle \mathcal{O}_1(0) \mathcal{O}_2(t) \rangle_{\text{HH}} = \langle \mathcal{O}_1(0) \mathcal{O}_1(t - i\beta/2) \rangle_{\text{HH}} \]

for operators with \( \Delta \gg 1 \).

HH = Hartle-Hawking / thermofield double state.

- High-energy spacelike geodesics going from one boundary to the other bounce off the singularity.

- Implies singularity in correlator, as a function of complex time \( t \), on an unphysical sheet.
Frequency space thermal correlators (Festuccia/Liu 2005)

- Solve wave equation for probe scalar of mass $m_\varphi$ dual to CFT operator of dimension $\Delta = d^2 + \sqrt{d^2/4 + m_\varphi^2}$ in the WKB limit $\omega \to \infty$, $\Delta \to \infty$, $u \equiv \omega/\Delta$ fixed.
- Coincides with geodesic equation upon identifying conserved "energy" of geodesic $E = iu$.
- Exponential decay of frequency-space Green’s functions along imaginary axis:

$$G_{12}(\omega) \sim e^{-2i\omega z_c}, \quad \omega \to -i\infty, \quad \text{Re}(\omega) = 0$$

$z_c = \int_0^\infty \frac{dr}{f(r)}$ complex tortoise coordinate of BH singularity.

$z_c$: complex Schwarzschild time it takes for a radial null geodesic to go from the AdS boundary to the singularity.

$z_c$: WKB turning point behind the horizon for large imaginary $\omega$. 

Holographic probes: geodesics, correlators, entanglement entropy

**Quasinormal modes**

- $z_c$ determines angle made by high frequency quasinormal modes:

  \[
  \frac{\text{Im} (\omega_n)}{\text{Re} (\omega_n)} = \pm \frac{\text{Im} (z_c)}{\text{Re} (z_c)}
  \]

- Has been argued from a pure high frequency "eikonal" limit \equiv null rays bouncing around the BH Penrose diagram $\longrightarrow$ UV singularities of correlator (commutator?) in complex time $\longrightarrow$ asymptotic quasinormal modes (Amado-Hoyos 2008).
Probing AdS crunches

- Radial bulk geodesic connects spatially antipodal points on boundary \( dS_d \).
- Conserved "energy" along radial geodesic: \( \mathcal{E} = a(\xi)^2 \dot{t} \).
- \( \mathcal{E} = iu \) where \( u = \omega / \Delta \) is the rescaled frequency of de Sitter harmonic.
- Correlator can depend only on the de Sitter invariant embedding distance

\[
Z_{12} = - \sinh t_1 \sinh t_2 + \cosh t_1 \cosh t_2 \cos (\phi_1 - \phi_2) \\
= - \cosh (t_1 + t_2) \text{ for antipodal points} \\
\leq -1
\]
Geodesics do not probe the crunch

- Geodesics connecting antipodal points exist only for $\mathcal{E} < \tilde{a}_{max}$.
- Geodesics with $\mathcal{E} > \tilde{a}_{max}$ "fall" into crunch.
- Geodesics do not probe the crunch

Imploding space pulls geodesics into crunch (Hubeny 2004) Related to crunch being curved outward

Maximal expansion slice "barrier" (Engelhardt/Wall 2013)

Similar observation holds for entanglement entropy (Maldacena-Pimentel 2012)
Branch cut in frequency-space correlator \(^{(Kumar-VV)}\)

- No geodesics with \(\mathcal{E} > \tilde{a}_{\text{max}}\) corresponds to branch cut in frequency-space retarded correlator.

- Merger of discrete set of quasinormal modes.
Late time geodesics (Kumar-VV)

- Late time geodesics hug the maximal FRW expansion slice $\tilde{a}_{\text{max}}$.
- Correlator in $dS_d$ ($t_1 + t_2 \to \infty$)

$$\langle O_\Delta(t_1, 0) O_\Delta(t_2, \pi) \rangle_{dS} \sim e^{-\tilde{a}_{\text{max}}(t_1 + t_2)} \Delta, \quad (\Delta \gg 1)$$

large super-horizon sized separations in de Sitter ($Z_{12} \to -\infty$).
- Correlator in ESU frame ($\tau_{1,2} \to \pi/2$)

$$\langle O_\Delta(\tau_1, 0) O_\Delta(\tau_2, \pi) \rangle_{ESU} \sim (\frac{\pi}{2} - \tau_1)^{\tilde{a}_{\text{max}} - 1} \Delta \quad (\frac{\pi}{2} - \tau_2)^{\tilde{a}_{\text{max}} - 1} \Delta$$

- ESU correlator is singular ($\tilde{a}_{\text{max}} < 1$) and factorises $\rightarrow$ diverging condensates?
Beyond geodesics

- Correlators in geodesic/WKB limit probe only as far as the maximal FRW expansion slice.
- To probe crunch need to go beyond geodesic limit.
- Solve full wave equation in the bulk.
- Use AdS$_4$/CFT$_3$ analytical example.
Wave equation in AdS$_4$/CFT$_3$ example (Kumar-VV)

- Use tortoise coordinate $z$

  
  \[
  z = \sinh^{-1} u, \quad f_0 = \text{cosech } z_0, \\
  ds^2 = a^2(z) \left( dz^2 - dt^2 + \cosh^2 t \, d\Omega_2^2 \right), \\
  a^2(z) = \sinh^{-2} z - \sinh^{-2}(z + z_0)
  \]

- Exterior dS-sliced patch: $0 < z < \infty$ and $t \in \mathbb{R}$.

- Interior FRW patch: $z = -i\pi/2 + w$, $t = i\pi/2 + \chi$, with $w, \chi \in \mathbb{R}$.

  Crunch at $z_c = -i\pi/2 - z_0/2$. 

Singular potential

- Radial part of wave equation of probe bulk scalar mass $m_\phi$ in Schrödinger form

$$- \psi''(z) + V(z) \psi(z) = \omega^2 \psi(z),$$

$$V(z) = \frac{m_\phi^2 + 2}{\sinh^2 z} - \frac{m_\phi^2 - 2}{\sinh^2(z + z_0)} - \frac{1}{\sinh^2(2z + z_0)}.$$ 

- $V_{WKB} = m^2 a^2$ regular at crunch (dashed curve).

Full potential (solid curve) is singular: $V \sim -\frac{1}{4} (z - z_c)^{-2}$
Results

- Solve full wave equation in exterior dS patch with infalling b.c. at horizon.
- Determines frequency-space retarded correlator via Son-Starinets.
- Exact solution for $m_\phi = 0$ and arbitrary deformation $f_0$.
- Numerical determination of quasinormal poles for arbitrary $m_\phi$ and $f_0$. 

5th January, 2017, ICTS, USTC
Correlator for $\Delta = 3$ operator

- Focus on probes dual to scalar operators that fit spectrum of M2-brane CFT (Aharony et al 1999)

$$m^2_\varphi = \frac{1}{4}k(k - 6), \quad \Delta = \frac{k}{2}, \quad k = 2, 3, \ldots .$$

- Exact result for $\Delta = 3$ operator

$$G_R(\omega)|_{\Delta=3} = -2(\omega^2 + 1) \partial_z \ln \left( P_{1/2}^{i\omega/2} [\coth(2z + z_0)] \right)|_{z=0}$$

- $f_0 \to 0$ (pure dS-sliced AdS$_4$): regular (no poles).
- small $f_0 \ll 1$: infinite set of quasinormal poles at $\omega_n \simeq -2n i, n = 1, 2, \ldots$ with residues scaling as $f_0^{2n}$.
- infinite deformation $f_0 \to \infty$: quasinormal poles at $\omega_n = -(2n + 1) i, n = 1, 2, \ldots$. 
Infinite deformation limit

- In the infinite deformation limit $f_0 \to \infty$, scalar operators of all dimensions have the same quasinormal poles and correlators.
- Quasinormal poles at $\omega_n = -(2n + 1)i$, $n = 1, 2, \ldots$.
- Same as BTZ and its higher dimensional "topological AdS BH" generalisations.
- Penrose diagram of AdS crunch becomes a square in infinitely deformed limit (same as BTZ).
Quasinormal poles for $\Delta = 5/2$ operator

For $\Delta = 5/2$ operator quasinormal poles move into complex plane as $f_0$ increases

- $f_0 = 0.37$
- $f_0 = 1.026$
- $f_0 = 1.033$
Quasinormal poles for $\Delta = 5/2$ operator
Holographic probes: geodesics, correlators, entanglement entropy

**Quasinormal poles for $\Delta = 5/2$ operator**

Angle made by line of poles correlated with $z_c$

Empirically observe

$$\frac{\text{Im}(\omega_n)}{\text{Re}(\omega_n)} \sim \frac{2}{z_0} = \frac{2 \text{Im}(z_c)}{\pi \text{Re}(z_c)}, \quad n \gg 1, \ f_0 \gg 1$$
In a nutshell

- Geodesics do not probe the crunch.
- Beyond geodesic limit, in AdS$_4$/CFT$_3$ example, no obvious probe of crunch.
- Hints that shape of crunch in Penrose diagram is connected to analytic structure of quasinormal poles.
- Much remains to be understood: possible instabilities, simplicity of infinite deformation limit, genericity.
Background and motivation

General setup

Examples from known deformations of CFT’s

$\text{AdS}_4$/CFT$_3$ analytical example

Holographic probes: geodesics, correlators, entanglement entropy

Summary
Believed that the QFT evolution on $\mathbb{R} \times S^{d-1}$ is singular at $\tau = \pi/2$ when the time-dependent mass $m^2 / \cos^2 \tau$ diverges. Genuine sickness?

Little intuition for how strongly interacting field theories with time-dependent divergent couplings behave.

de Sitter QFT evolution appears to be well-defined for all times. Should be equivalent to the ESU picture, so what does the singularity mean in de Sitter?

Study simple toy QFT’s to get insight.