Open Quantum Systems for Cosmological Observers

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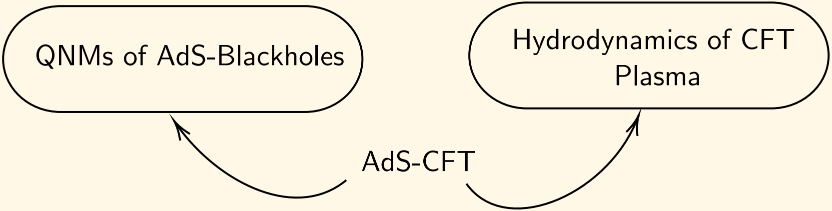
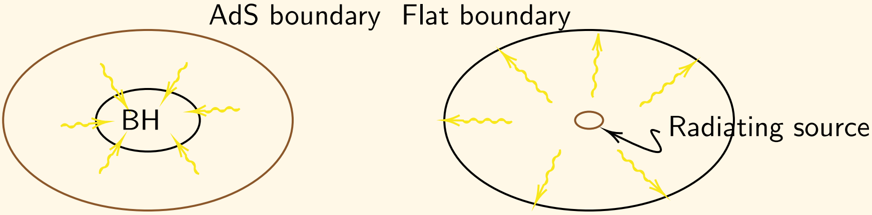
The Schwinger-Keldysh family



Does this connect to the self-force problem?

[Goldberger and Rothstein, 2006]

Son-Starinets vs Dirac-Detweiler-Whiting

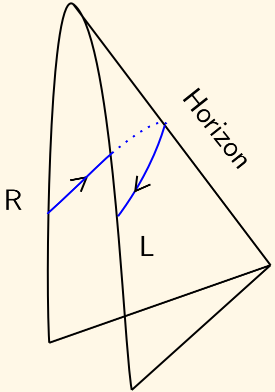


Son-Starinets prescription:
Ingoing BCs at horizon.
Extrapolate to the boundary.
Subleading behaviour
gives fluid retarded propagators.

DDW prescription:
Outgoing BCs at the flat boundary.
Extrapolate back to the source.
Subleading behaviour encodes
the self-force.

But what about the fluctuations?

Schwinger-Keldysh Holograms



The SK contour in the AdS boundary can be filled in with a smooth bulk geometry. One sources each side separately and computes the on-shell action on this geometry: open dynamics of fluid probes

[Skenderis and van Rees, 2009], [Glorioso et al., 2018], [Chakrabarty et al., 2020], [Jana et al., 2020], [Ghosh et al., 2020], [Loganayagam et al., 2020], [He et al., 2022]

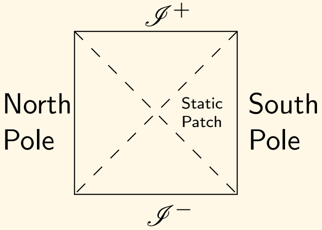
Is there a similar construction for the self-force?

Yes, but one needs a horizon!

The natural setting for this analogy is then in de Sitter, not flat spacetime.

dS geometry

- de Sitter can be thought of as a sphere contracting and then expanding in time.



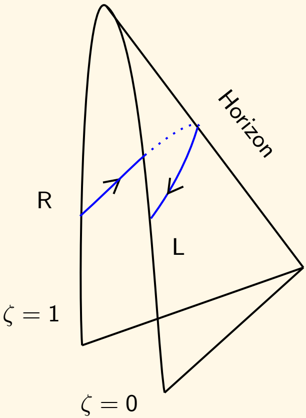
- Static patch metric in the outgoing Eddington-Finkelstein co-ordinates centered about the observer:

$$ds^2 = -(1-r^2)du^2 - 2dudr + r^2 d\Omega_{d-1}^2 \tag{1}$$

- The source is thickened to a time-like tube $S_{r_c}^{d-1} \times \mathbb{R}_u$ carrying radiative multipole moments. r_c acts as a regulator.

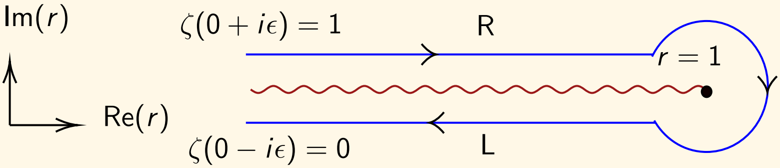
dS-SK geometry

- Inspired by a similar prescription for AdS black holes, we give a dS-SK geometry. This geometry can be thought of as doubling the static patch and joining it smoothly at the horizon. Now we have two copies of the worldline sourced by two distinct sources.



dS-SK geometry

- This geometry is obtained by complexifying the radial co-ordinate and considering a hypersurface in the complexified space-time.

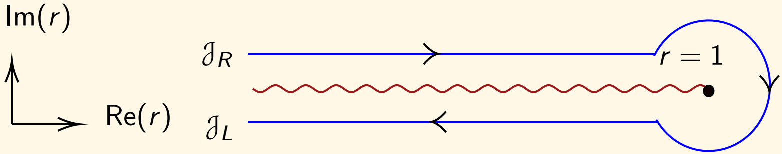


- This geometry can be thought of as being parameterised by a co-ordinate ζ analogous to the tortoise co-ordinate:

$$\zeta(r) = -\frac{1}{i\pi}\int_{0-i\epsilon}^{r}\frac{dr'}{1-r'^2} = \frac{1}{2\pi i}\ln\left(\frac{1-r}{1+r}\right) \tag{2}$$

Outgoing and ingoing solutions

- Our motivation for the geometry comes from the the fact that boundary to bulk propagators have a branch cut singularity.
  - The outgoing modes are analytic functions in r times $e^{-i\omega u}$.
  - The incoming modes have a branch cut between $r = 1$ and $r = -1$.
- Thus we can source the fields separately on two sides of the contour which doubles the observer.



Prescription

Self-force Influence Phase
= On-shell action on the dS-SK geometry

- This implies that the boundary value of the renormalised conjugate field encodes the self-force and is consistent with the Dirac-Detweiler-Whiting prescription.
- One can think of this as a de Sitter version of the GKPW prescription.

On Shell Action

- We solve for various fields in the geometry in the frequency domain of u and a spherical harmonic expansion.
- Given scalar solutions we can substitute them back into the action to obtain the following on-shell action(regularised):

$$S_{\text{on-shell}} = -\sum_{\ell,\vec{m}} \int \frac{d\omega}{2\pi} K_{\text{Out}}(\omega,\ell)\ \mathcal{J}_a^* \left[\mathcal{J}_r + \left(n_\omega + \frac{1}{2}\right)\mathcal{J}_a\right] \tag{3}$$

$$\mathcal{J}_r = \frac{\mathcal{J}_L + \mathcal{J}_R}{2}, \qquad \mathcal{J}_a = \mathcal{J}_R - \mathcal{J}_L, \qquad n_\omega = \frac{1}{e^{2\pi\omega} - 1}$$

K_{out} is the wordline retarded propagator defined as the boundary value of the renormalised conjugate field.

- This action satisfies constraints arising from bulk unitarity and the fluctuation-dissipation theorem (KMS).

[Loganayagam and Shetye, 2024, Loganayagam and Shetye, 2025]

Long time expansion and fluctuations

- In the long time limit, we have

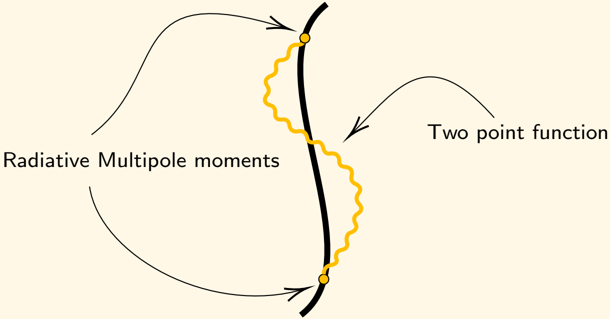
$$K_{\text{Out}} = K_{\text{Out}}|_{\omega=0} - i\ \omega\ \tau_{dS} + \dots \tag{4}$$

- This τ_{dS} controls both the lifetime of a particular multipole moment as well as the Hawking "noise" through the FD relations.

Table: τ_{dS} (Massless KG scalar)

$\mu = \frac{d}{2}$	$\ell = 1$	$\ell = 2$	$\ell = 3$	$\ell = 4$	$\ell = 5$
$d = 3$	4	1	$\frac{64}{225}$	$\frac{4}{49}$	$\frac{256}{11025}$
$d = 4$	$\frac{9\pi^2}{16}$	1	$\frac{25\pi^2}{1024}$	$\frac{1}{16}$	$\frac{441\pi^2}{262144}$
$d = 5$	$\frac{64}{9}$	1	$\frac{256}{1225}$	$\frac{4}{81}$	$\frac{16384}{1334025}$
$d = 6$	$\frac{225\pi^2}{256}$	1	$\frac{1225\pi^2}{65536}$	$\frac{1}{25}$	$\frac{3969\pi^2}{4194304}$

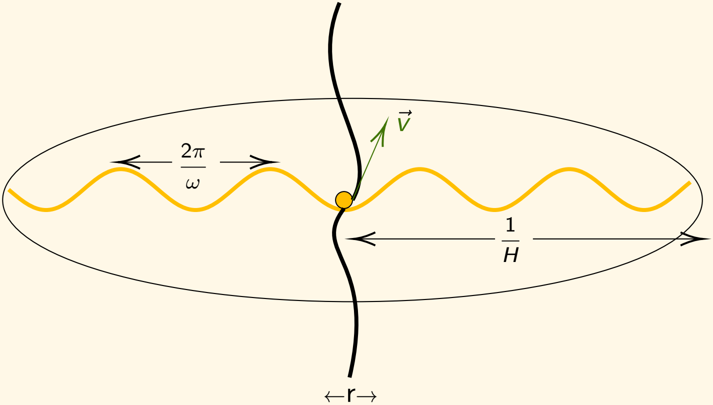
Radiation reaction force on a particle



- Radiative multipole moments: source distribution smeared to account for appropriate time delays.
- Two point function: How radiative multipole moment at some point of time affects the multipole moment at a later time.

RR Force on a particle

$$\underbrace{v \ll 1,\ \omega r \ll 1,\ \text{small } \ell,}_{\text{flat space PN expansion}}\ \underbrace{rH \ll 1,\ \omega \gg H}_{\text{Curvature Expansion}}$$



ALD in de Sitter

For electromagnetic fields, the self-force is given by:

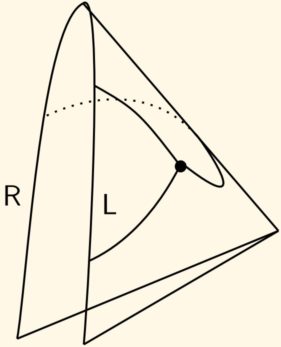
$$
\begin{aligned}
f_3^{\mu} &\equiv \frac{2P^{\mu\nu}}{3!!}\left\{-a_\nu^{(1)}\right\} \ , \\
f_5^{\mu} &\equiv \frac{P^{\mu\nu}}{5!!}\left\{-4a_\nu^{(3)} + 10\,(a\cdot a)\,a_\nu^{(1)} + 30\,(a\cdot a^{(1)})\,a_\nu\right\} - H^2\frac{16P^{\mu\nu}}{5!!}\left\{a_\nu^{(1)}\right\} \ , \\
f_7^{\mu} &\equiv \frac{2P^{\mu\nu}}{7!!}\Big\{-3a_\nu^{(5)} + 21\,(a\cdot a)\,a_\nu^{(3)} + 105\,(a\cdot a^{(1)})\,a_\nu^{(2)} + 112\,(a\cdot a^{(2)})\,a_\nu^{(1)} + \frac{287}{3}\,(a^{(1)}\cdot a^{(1)})\,a_\nu^{(1)} \\
&\qquad +63\,(a\cdot a^{(3)})\,a_\nu + 140\,(a^{(1)}\cdot a^{(2)})\,a_\nu + O(a^5)\Big\} \\
&\quad + H^2\frac{P^{\mu\nu}}{7!!}\left\{300a_\nu^{(3)} - 2445\,(a\cdot a)\,a_\nu^{(1)} - 855\,(a\cdot a^{(1)})\,a_\nu\right\} - H^4\frac{960P^{\mu\nu}}{7!!}\left\{a_\nu^{(1)}\right\} \ .
\end{aligned}
\tag{5}
$$

[Galakhov, 2008]

We are in the process of getting similar expressions for linearised gravity.

Interactions

One can also take into account non-linearities in the bulk fields by dS-SK versions of Witten diagrams. [Jana et al., 2020]



Summary

- We provide a geometric prescription to compute the open effective action for de Sitter radiation reaction.
- This action describes the physics of radiation-reaction and Hawking fluctuations as seen by the source.
- We performed several checks on the computation to ensure agreement with known and expected physics.
- The presence of a geometric saddle that 'fills in' the bulk for the boundary SK contour is arguably a holographic feature in itself. [Anninos et al., 2012, Nakayama, 2012]
- This provides us with data analogous to the fluid-gravity correspondence regime of AdS-CFT on the black hole side, which is interpreted as transport coefficients of the CFT plasma.

Outlook

- Upcoming work: influence phase for linearised gravitational perturbations.
- Interactions: non-linear RR force.
- Extension to time-dependent geometries, questions in cosmology, etc.