Title: Entanglement harvesting near black holes

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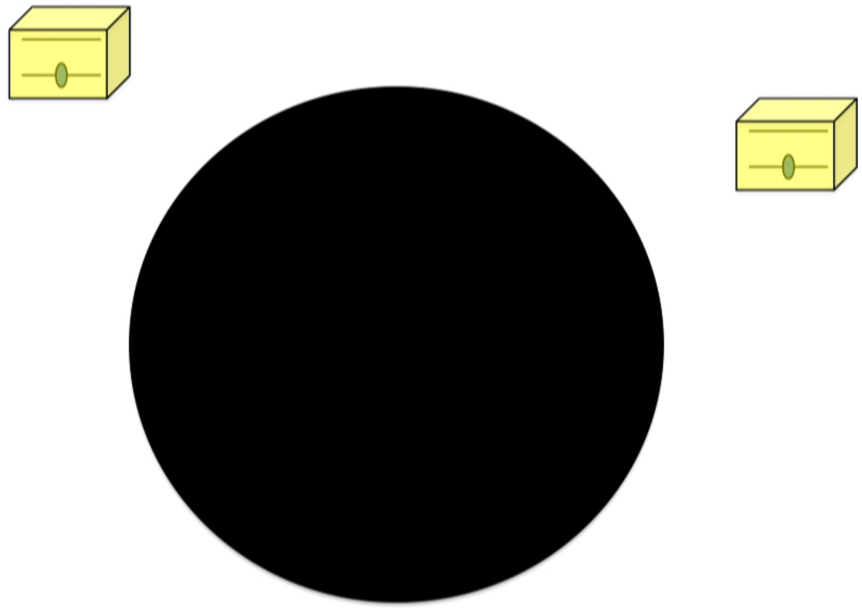
Abstract: <p>Although entanglement harvesting was first posited over 25 years ago, it is only in recent years that this phenomenon has been the subject of active study. The basic idea of entanglement harvesting is to transfer correlations from the vacuum of some quantum field to a pair of detectors. The result provides a new probe of the structure of spacetime via quantum correlations. I shall describe recent work on some of the first results in harvesting entanglement in curved spacetime, in particular anti de Sitter spacetime and black holes.</p>

Harvesting Entanglement Near Black Holes



Robert B. Mann
L. Henderson R. Hennigar K. Ng A. Smith J. Zhang
E. Martin-Martinez

Entanglement Harvesting

- Extracting correlations from the vacuum

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- Uncorrelated detectors can become correlated after a finite time depending on their
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  - Separation
  - State of motion

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  - Rangefinding
  - Quantum Key Distribution
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Brown/Donnelly/Kempf/RBM/Martin-Martinez NJP16 (2014)105020

Salton/RBM/Menicucci NJP17 (2015) 035001

Ralph/Walk NJP17 (2015) 063008

Pozas-Kerstjens /Martin-Martinez PRD94 (2016) 064074

A Brief History of Entanglement Harvesting

- 1991: Valentini: uncorrelated atoms that are spacelike separated can become correlated via QED vacuum fluctuations Valentini PLA153(1991) 321
- 2003: Reznik rediscovers and quantifies this effect Reznik FndPhy 33 (2003) 167
- 2009: VerSteeg/Menicucci: investigate non-local correlations between detectors in de Sitter spacetime → first curved-spacetime study

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- 2013: Sustainable Harvesting → entanglement farming — Martin-Martinez /Brown/Donnelly PRA88 (2013) 052310
- 2017: Harvesting outside of black holes — Henderson/Hennigar/RBM/Smith/ Zhang (2018) 1712.10018

Quantum Detectors

Vacuum

$$S = \frac{m_0}{2}\int d\tau\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] - \int d^4x\sqrt{-g}\,\frac{1}{2}\left(\nabla\Phi(x)\right)^2 + S_I$$

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detector

Cavity

$$\hat{H}=\Omega_d\hat{a}_d^\dagger\hat{a}_d+\frac{dt}{d\tau}\sum_n\omega_n\hat{a}_n^\dagger\hat{a}_n+H_I$$

Quantum Detectors

S-Y Lin, B.L.Hu PRD73 (2006) 124018
PRD76 (2007) 064008

$$S_I = \lambda_0 \int d\tau \int d^4x Q(\tau)\Phi(x)\delta^4\left(x^\mu - z^\mu(\tau)\right)$$

Vacuum

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detector　field　interaction

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detector field interaction

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E.G. Brown, E. Martin-Martinez, N. Menicucci, RBM PRD87 (2013) 084062
D. Bruschi, A. Lee, I Fuentes J. Phys A46 (2013) 165303

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detector — field — interaction

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Provide an operational means of probing the quantum character of spacetime

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Hot Accelerating Detectors?

$$T = \frac{a}{2\pi}\left(\frac{\hbar}{k_B c}\right)$$

S.A. Fulling PRD7 (1973) 2850 P.C.W. Davies J Phys A8 (1975) 609 W. G. Unruh PRD14 (1976) 3251

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  - Geometric Methods + Bogoliubov transformations
  - Eternally accelerating qubit coupled to a quantum field

B. deWitt in *General Relativity: An Einstein Centenary Survey* (CUP 1980)

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- Limitations
  - Highly idealized: eternal uniform acceleration, unbounded system, perturbative, model-dependent, …
- What we would like and need to know
  - Finite time and distance effects (cavities, switching)
  - Boundary conditions
  - Non-perturbative effects; non-equilibrium effects
  - Entanglement, Non-locality of correlations

Detector Response Outside Black Holes

- BTZ Black holes
  - Static and Rotating
- Schwarzschild Black Holes
- Schwarzschild AdS Black Holes
- All for various boundary conditions, detector trajectories

Hodgkinson/Louko PRD86 (2012) 064031

Hodgkinson/Louko/Ottewill PRD89 (2014) 104002

Ng/ Hodgkinson/Louko/RBM/ Martin-Martinez PRD90 (2014) 064003

$$H_{\text{int}} = c\chi(\tau)\mu(\tau)\phi(x(\tau))$$

$$P(E) = c^2 \left|\langle 0_d | \mu(0) | E \rangle\right|^2 \mathcal{F}(E)$$

$$\mathcal{F}(E) = \Re\left[\int_{-\infty}^{\infty} du\,\chi(u)\int_0^{\infty} ds\,\chi(u-s)e^{-iEs}G^{+}(u,u-s)\right]$$

$$\frac{d\mathcal{F}}{d\tau}(E;M,\ell,\ldots) = \frac{1}{4} + 2\Re\left[\int_0^{\Delta\tau} ds\,e^{-iEs}G^{+}(\tau,\tau-s)\right]$$

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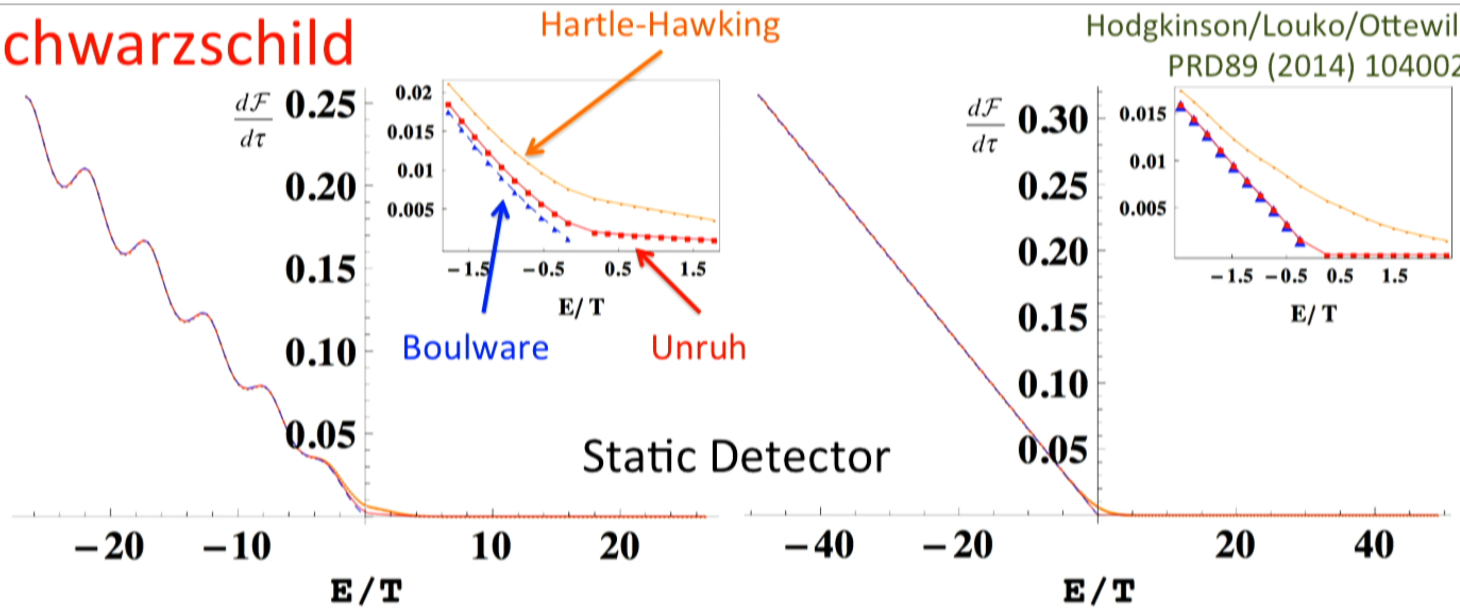
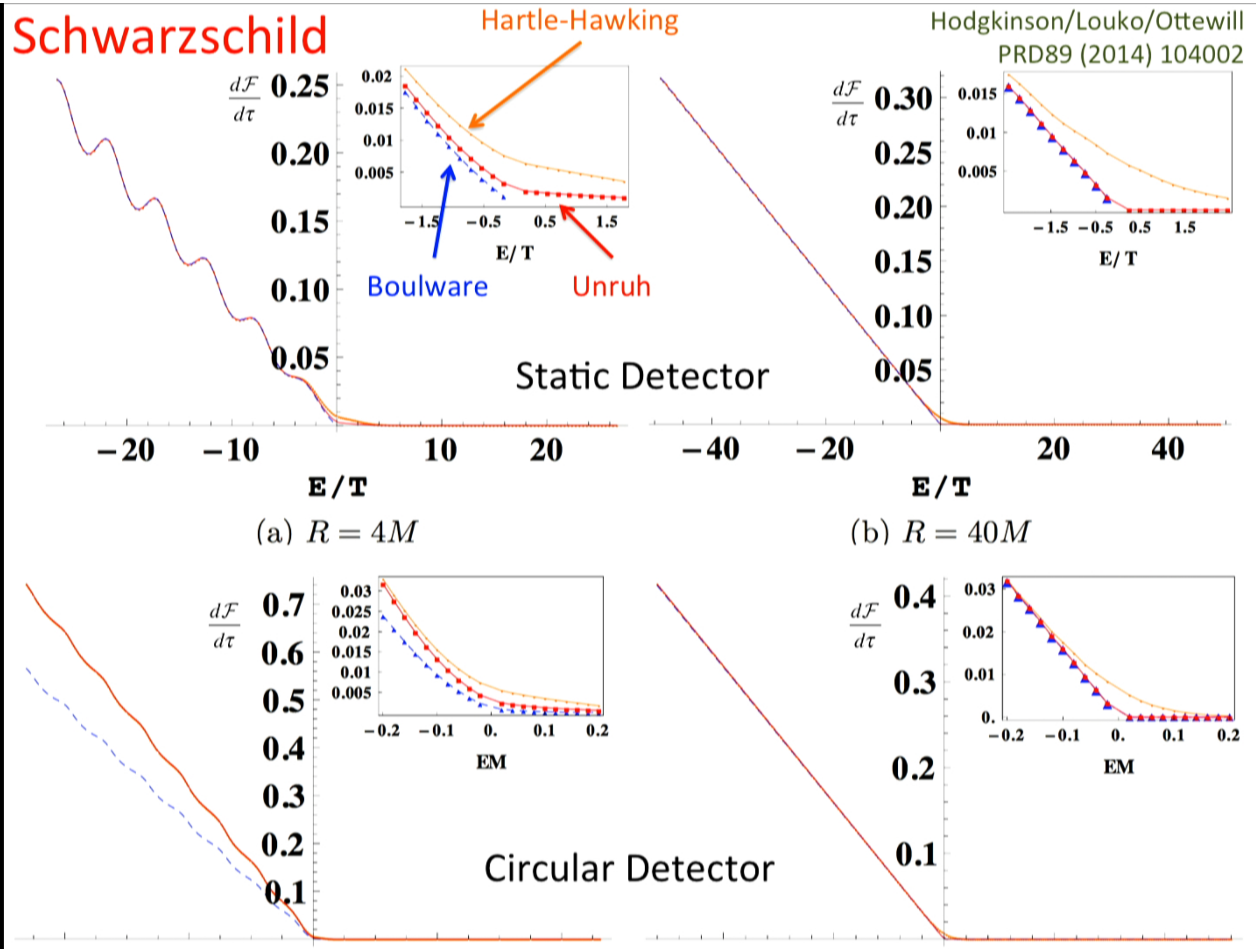
Detector Response Rate

Schwarzschild



(a) $R = 4M$ (b) $R = 40M$



Schwarzschild
Hartle-Hawking
Hodgkinson/Louko/Ottewill
PRD89 (2014) 104002
Boulware
Unruh
Static Detector
Circular Detector
E/T
(a) $R = 4M$
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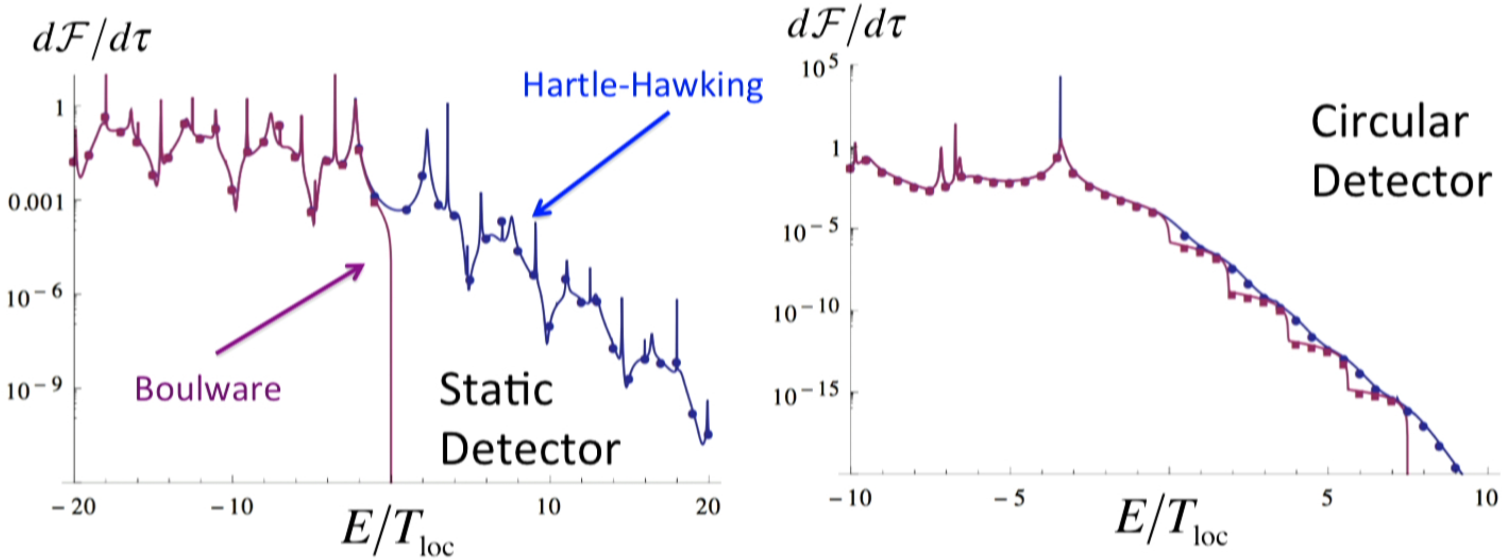
EM

Detector Response in Schwarzschild-AdS

Ng/ Hodgkinson/Louko/RBM/Martin-Martinez
PRD90 (2014) 064003



- Spikes due to Quasinormal mode resonances
- Visible only when black hole is much smaller than AdS length
- Peaks become higher and sharper as black hole size decreases

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- Single Detectors have sensitivity to spacetime geometry and topology

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- Can more be learned from Detector correlations?
- Flat Spacetime
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Pozas-Kerstjens/Martin-Martinez
PRD92 (2015) 064042

Harvesting in Flat Spacetime

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- Flat Spacetime
  - 2 Static Detectors
  - 2 Accelerating Detectors
  - Detectors in Identified Minkowski Space

Pozas-Kerstjens/Martin-Martinez
PRD92 (2015) 064042

Salton/RBM/Menicucci
NJP17 (2015) 035001

Harvesting Formalism

$$S = -\int d^4x\sqrt{-g}\left[R + \frac{1}{2}\partial_\mu \Phi(x)\partial^\mu \Phi(x) - \xi R\Phi^2(x)\right]$$

$$+\int d\tau \left\{\frac{m_0}{2}\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] + \sum_D \lambda_D \int d^4x Q_D(\tau)\Phi(x)\delta^4\left(x^\mu - z_D^\mu(\tau)\right)\right\}$$

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switcher

$$\chi_D = \exp\left(-\frac{(\tau-\tau_D)^2}{2\sigma_D^2}\right)$$

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switcher

monopole operator

$$\chi_D = \exp\left(-\frac{(\tau-\tau_D)^2}{2\sigma_D^2}\right)$$

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$$U = \mathcal{T}e^{-i\int dt\left[\sum_D \frac{d\tau_D}{dt} H_{ID}(\tau_D)\right]}$$

$$H_{ID}(\tau) = \chi_D(\tau)\left[e^{i\Omega_D\tau}\sigma_D^+ + e^{-i\Omega_D\tau}\sigma_D^-\right]\Phi[z_D(\tau)]$$

switcher — monopole operator

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$$\rho_{ij} := \mathrm{Tr}_\Phi(U|\Psi\rangle_i\langle\Psi|_i U^\dagger) = \begin{pmatrix} 1-P_A-P_B & 0 & 0 & X \\ 0 & P_B & C & 0 \\ 0 & C^* & P_A & 0 \\ X^* & 0 & 0 & 0 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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$$P_D = \lambda^2 \int_{-\infty}^{\infty} d\tau_D \int_{-\infty}^{\infty} d\tau_{D'}\, \chi_D(\tau_D)\chi_{D'}(\tau_{D'}) e^{-i\Omega_D(\tau_D - \tau_{D'})} W\left(x_D(\tau_D), x_D(\tau_{D'})\right) \quad D = A, B$$

$$C = \lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dt' \frac{d\tau_A}{dt} \frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A - \Omega_B\tau_B)} W\left(x_A(t), x_B(t')\right)$$

$$X = -\lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' \Big[\frac{d\tau_A}{dt'} \frac{d\tau_B}{dt} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_B\tau_B + \Omega_A\tau_A)} W\left(x_A(t'), x_B(t)\right) + \frac{d\tau_A}{dt} \frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A + \Omega_B\tau_B)} W\left(x_B(t'), x_A(t)\right) \Big]$$

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$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle$$

$$\tau_D = \gamma_D t$$

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Local excitations

$$C = \lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dt' \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A-\Omega_B\tau_B)} W\big(x_A(t), x_B(t')\big)$$

Local correlations

$$X = -\lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' \Big[\frac{d\tau_A}{dt'}\frac{d\tau_B}{dt} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_B\tau_B+\Omega_A\tau_A)} W\big(x_A(t'), x_B(t)\big) + \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A+\Omega_B\tau_B)} W\big(x_B(t'), x_A(t)\big) \Big]$$

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Local correlations

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Non-Local correlations

$$\rho = \begin{pmatrix} 1-P_A-P_B & 0 & 0 & X \\ 0 & P_B & C & 0 \\ 0 & C^* & P_A & 0 \\ X^* & 0 & 0 & 0 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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$$C = \lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dt' \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A-\Omega_B\tau_B)} W\big(x_A(t), x_B(t')\big)$$

Local correlations

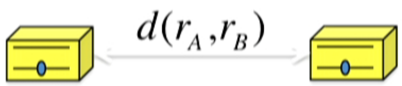
$$X = -\lambda^2 \int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' \Big[\frac{d\tau_A}{dt'}\frac{d\tau_B}{dt} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_B\tau_B+\Omega_A\tau_A)} W\big(x_A(t'), x_B(t)\big) + \frac{d\tau_A}{dt}\frac{d\tau_B}{dt'} \chi_A(\tau_A)\chi_B(\tau_B) e^{-i(\Omega_A\tau_A+\Omega_B\tau_B)} W\big(x_B(t'), x_A(t)\big)\Big]$$

Non-Local correlations

Concurrence

$$\mathcal{C} = 2\mathcal{N} = \max\{0, |X| - \sqrt{P_A P_B}\} + \mathcal{O}(\lambda^4)$$

Harvesting with Static Detectors



Pozas-Kerstjens/
Martin-Martinez
PRD92 (2015) 064042

Switching Width

$$\sigma_A = \sigma_B = T$$

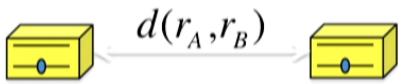
Switching Displacement

$$\tau_A - \tau_B = \Delta$$

Detector Gap

$$\Omega_A = \Omega_B = \Omega$$

Harvesting with Static Detectors



Switching Width
$\sigma_A = \sigma_B = T$

Pozas-Kerstjens/
Martin-Martinez

PRD92 (2015) 064042

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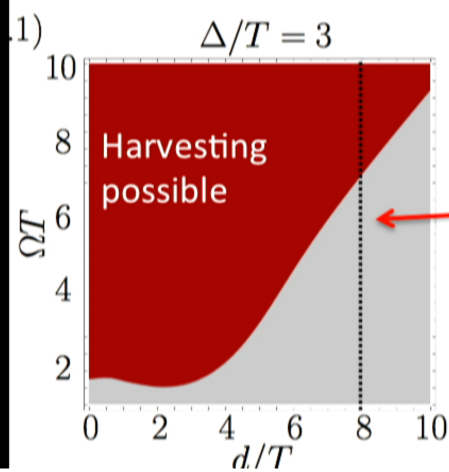
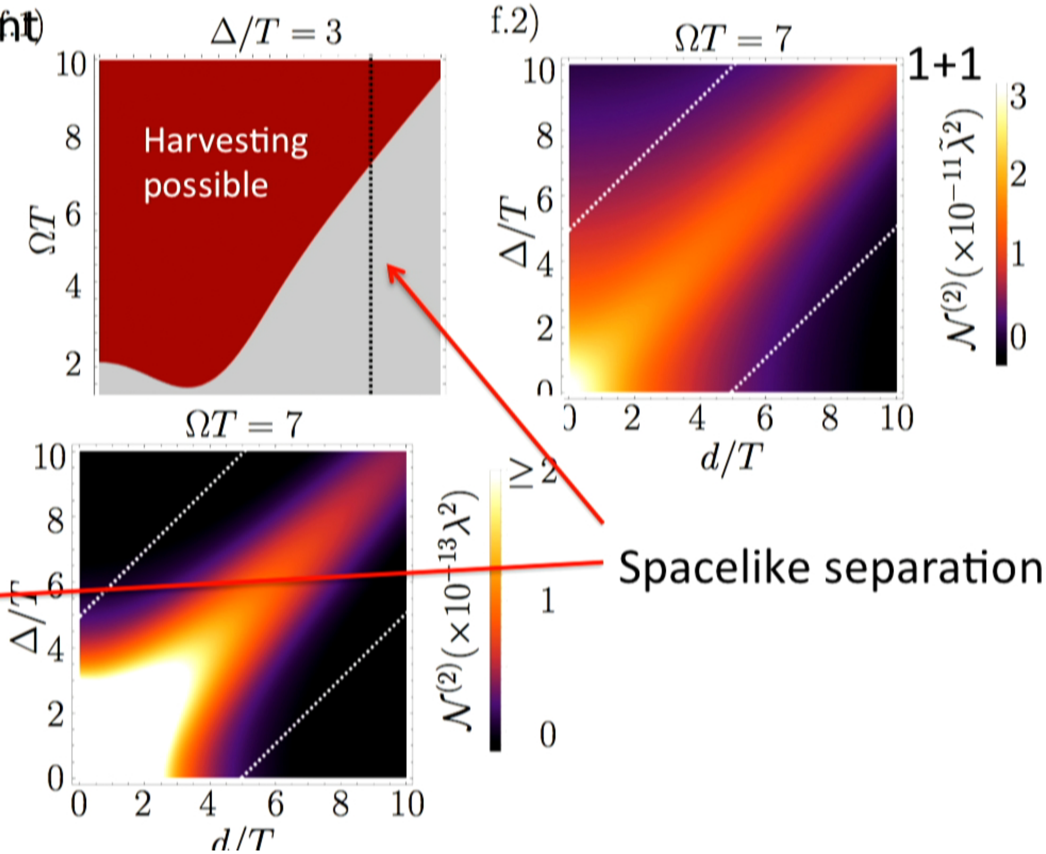
3+1





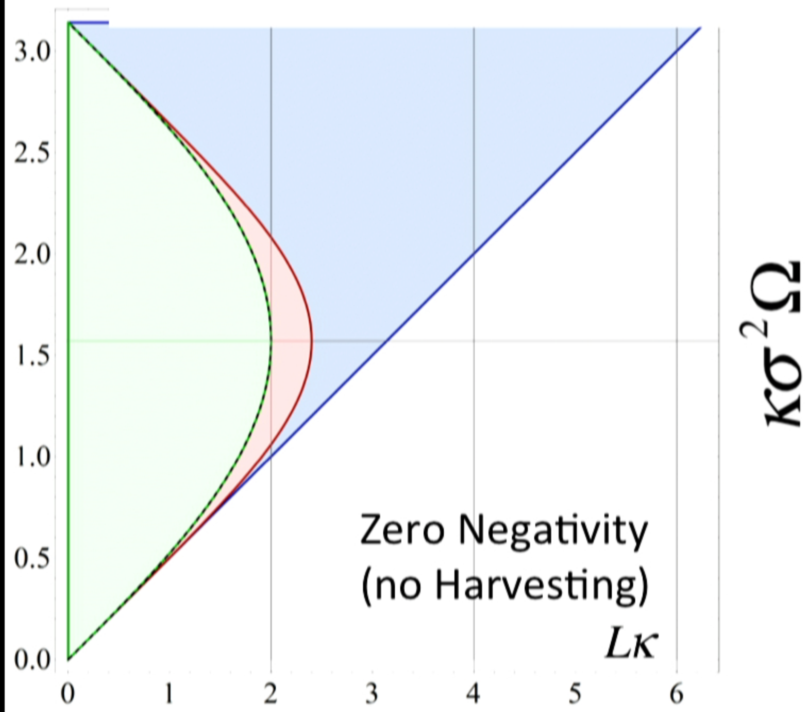
General Features

- Entanglement
  - Decreases with increasing separation
  - Increases with increasing gap
  - Weak dependence on spacetime dimension
  - Harvesting Possible at spacelike separation

General Features

- Entanglement
  - Decreases with increasing separation
  - Increases with increasing gap
  - Weak dependence on spacetime dimension
  - Harvesting Possible at spacelike separation
- Other features studied
  - Pointlike vs. finite size
  - Sudden switching vs. Gaussian Switching

Harvesting with Accelerating Detectors



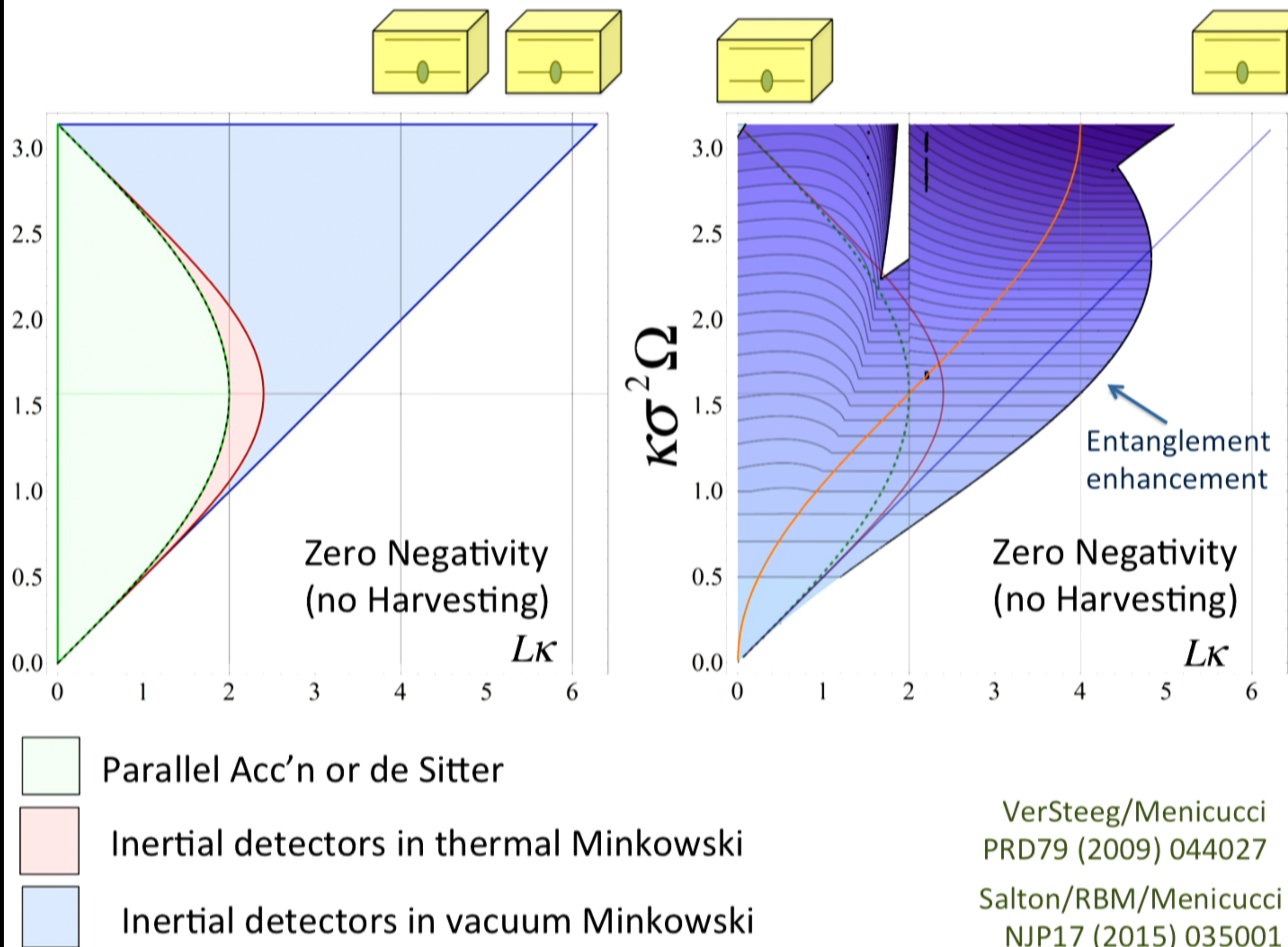
Parallel Acc'n or de Sitter

Inertial detectors in thermal Minkowski

Inertial detectors in vacuum Minkowski

VerSteeg/Menicucci
PRD79 (2009) 044027

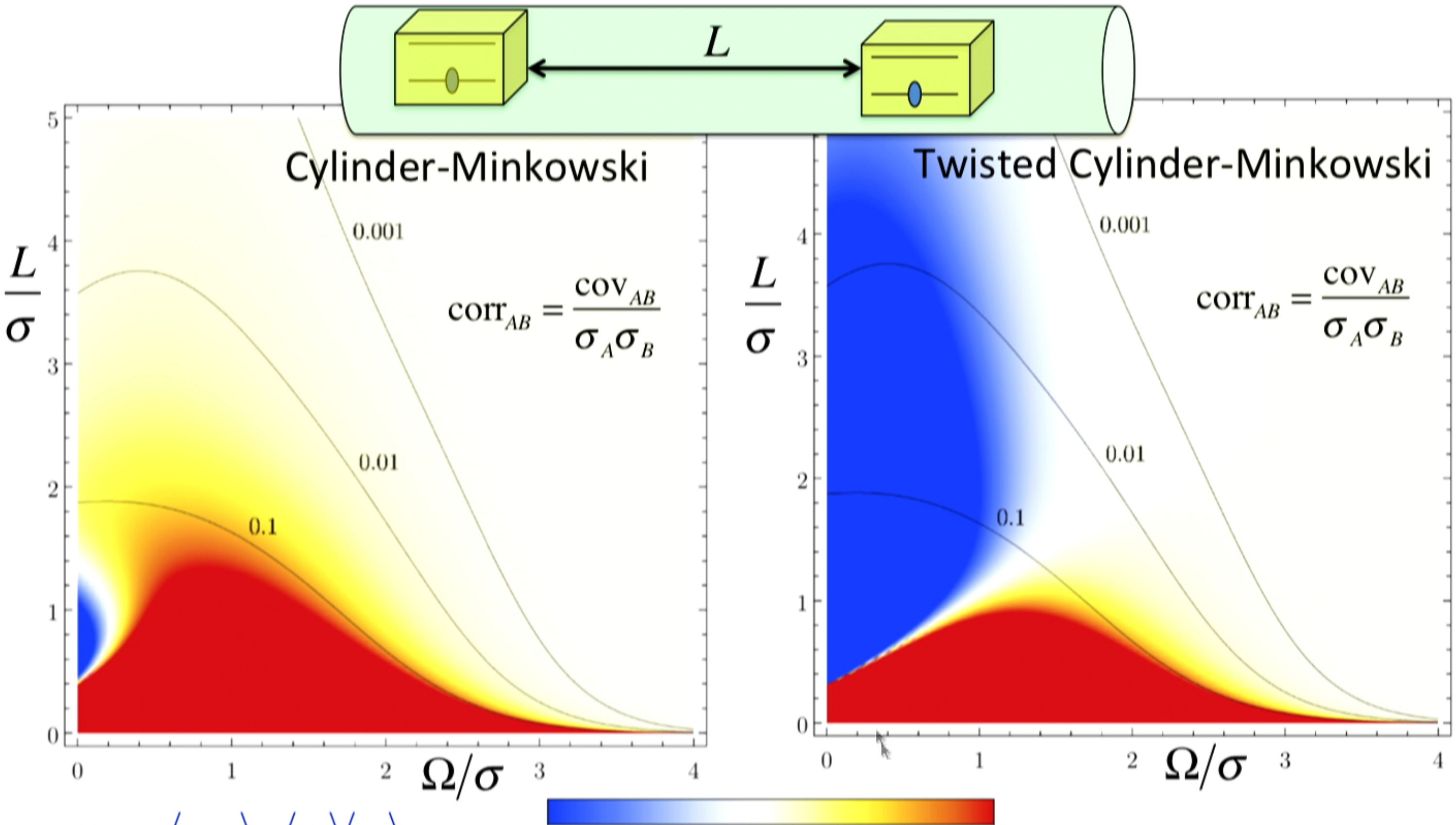
Salton/RBM/Menicucci
NJP17 (2015) 035001



VerSteeg/Menicucci
PRD79 (2009) 044027

Salton/RBM/Menicucci
NJP17 (2015) 035001

Harvesting as a Probe of Topology



$\mathrm{cov}_{AB} = \langle r_A r_B \rangle - \langle r_A \rangle \langle r_B \rangle$

$\sigma_A^2 = \mathrm{cov}_{AA} \qquad r \in \{0,1\}$

Martin-Martinez /Smith/Terno PRD93 (2016) 044001

Harvesting in Curved Spacetime

- De Sitter spacetime
  - Correlations distinct from thermal case

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VerSteeg/Menicucci
PRD79 (2009) 044027

- Anti de Sitter spacetime
  - Single detector: thermal response above threshold
  - Harvesting: ??????

Jennings
CQG 27 (2010) 205005

$$T = \frac{\sqrt{a^2\ell^2 - 1}}{2\pi\ell}$$

Harvesting in Curved Spacetime

- De Sitter spacetime

  VerSteeg/Menicucci
  PRD79 (2009) 044027

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  Jennings
  CQG 27 (2010) 205005

  – Single detector: thermal response above threshold $T = \frac{\sqrt{a^2\ell^2 - 1}}{2\pi\ell}$
  – Harvesting: ??????
- Black Holes
  – Single detector
    - response correlated with BH QNMs
    - sensitive to (hidden) topology
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VerSteeg/Menicucci PRD79 (2009) 044027

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Jennings CQG 27 (2010) 205005

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  - Single detector
    - response correlated with BH QNMs
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  - Harvesting: ??????

Ng/Hodgkinson/Louko/Mann/Martin-Martinez PRD 90 (2014) 064003

Ng/Mann/Martin-Martinez PRD 96 (2017) 0850043

Smith/Mann CQG 31 (2014) 082001

Anti de Sitter Spacetime

$$\sum_{J=1}^{D-1} X_J^2 - T_1^2 - T_2^2 = -\ell^2$$

$$ds^2 = -dT_1^2 - dT_2^2 + \sum_{J=1}^{D-1} dX_J^2$$

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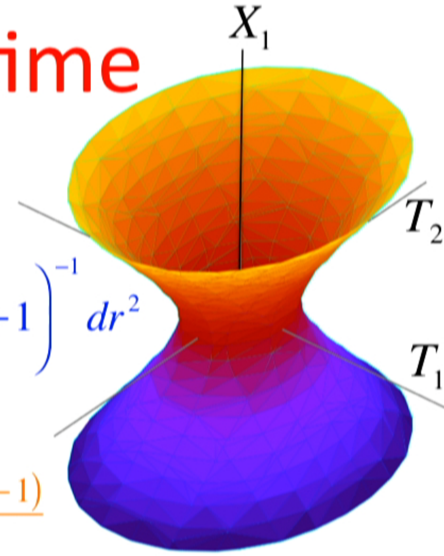
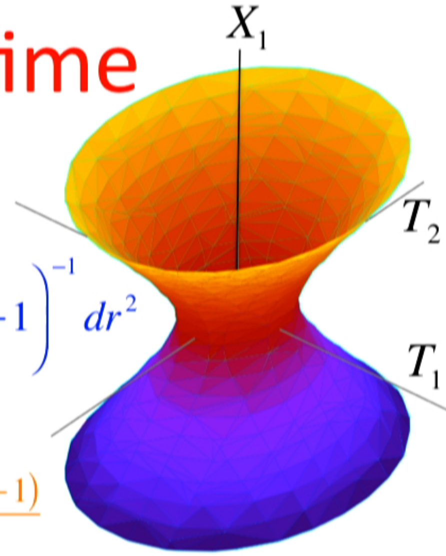
$$\Lambda = -\frac{(D-2)(D-1)}{2\ell^2}$$



Anti de Sitter Spacetime



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Hyperboloid in flat spacetime²

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Conformal coupling

$$W_{AdS}^{(\zeta)}(x,x') = \frac{1}{4\pi\ell\sqrt{2}}\left(\frac{1}{\sqrt{\sigma_\epsilon(x,x')}} - \frac{\zeta}{\sqrt{\sigma_\epsilon(x,x')+2}}\right)$$

2+1

Geodesic length

Anti de Sitter Spacetime

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Hyperboloid in flat spacetime[2]

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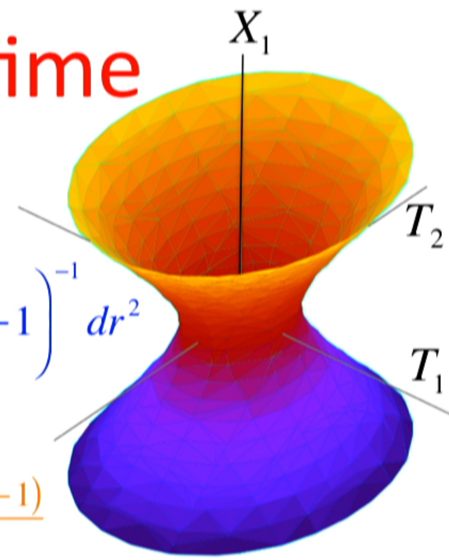

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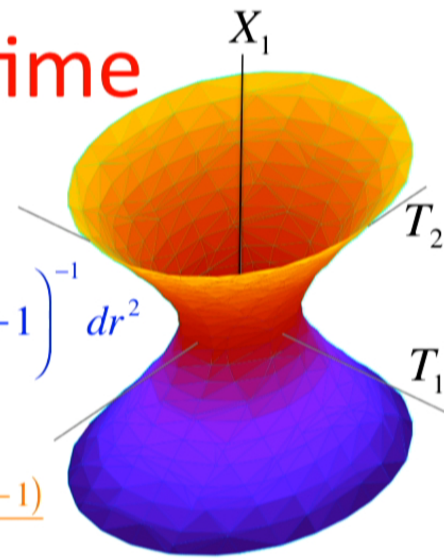
Geodesic length

$$W_{AdS}^{(\zeta=1)}(x,x') = \sum_{\omega=0}^{\infty}\sum_{lm}\frac{1}{2\omega}e^{-i\omega(t-t')}\varphi_{\omega lm}(x)\bar{\varphi}_{\omega lm}(x') \quad 3+1$$

Sum over modes

$$\Phi_{\omega lm}(t,x) = \frac{1}{\sqrt{2\omega}}e^{-i\omega t}\varphi_{\omega lm}(x)$$

Anti de Sitter Spacetime



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Conformal coupling

$$W_{AdS}^{(\zeta)}(x,x') = \frac{1}{4\pi\ell\sqrt{2}}\left(\frac{1}{\sqrt{\sigma_\epsilon(x,x')}} - \frac{\zeta}{\sqrt{\sigma_\epsilon(x,x')+2}}\right) \qquad 2+1$$

Geodesic length

$\zeta = 1$ (Dirichlet)

$\zeta = 0$ (Transparent)

$\zeta = -1$ (Neumann)

$$W_{AdS}^{(\zeta=1)}(x,x') = \sum_{\omega=0}^{\infty}\sum_{lm}\frac{1}{2\omega}e^{-i\omega(t-t')}\varphi_{\omega lm}(x)\bar{\varphi}_{\omega lm}(x') \qquad 3+1$$

Sum over modes

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Harvesting in Anti de Sitter Space

2+1: Henderson/Hennigar/Smith/Zhang/RBM 1712.10018
3+1 Ng/Martin-Martinez/RBM (to appear)

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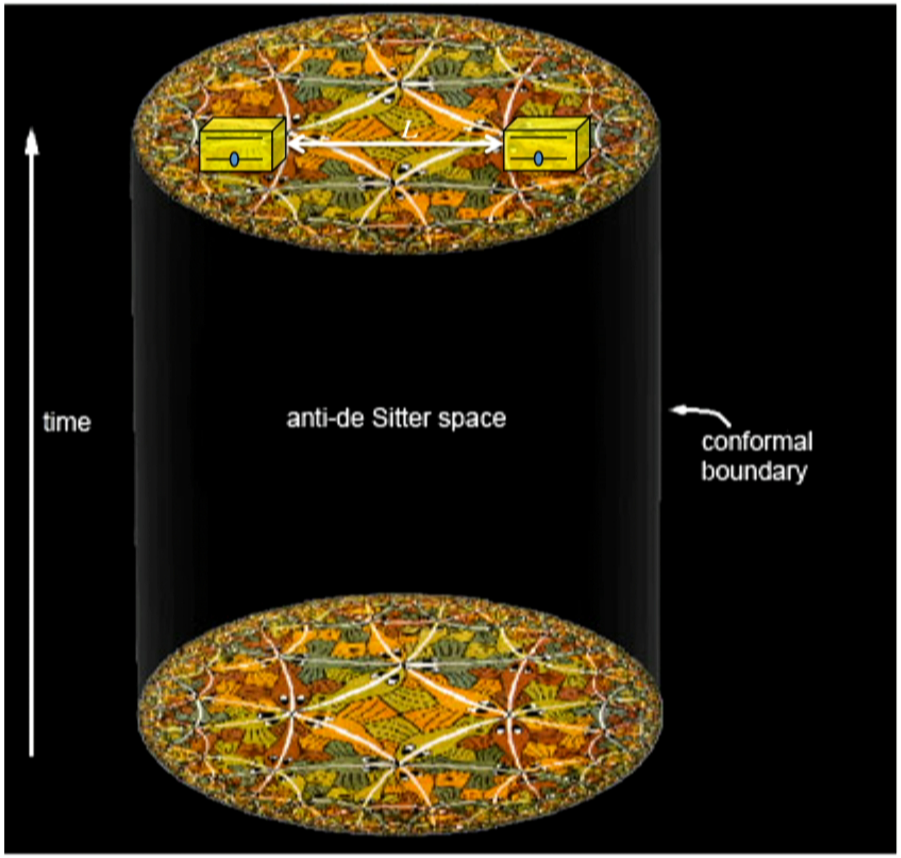


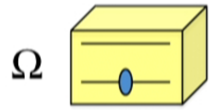
2+1 vs 3+1

	2+1	3+1
Constant Curvature	Yes	Yes
Conformally Flat	Yes	Yes
Conformally Coupled Scalar	Yes	Yes
Wightmann Function	Explicit Function of Geodesic length	Sum over Modes
Huygens Principle	No	Yes
Black Hole	From identifying AdS	Not identifying AdS

Results in 2+1 AdS

Henderson/Hennigar/
Smith/Zhang/RBM
(to appear)

$$ds^2 = -\left(\frac{r^2}{\ell^2}+1\right)dt^2 + \left(\frac{r^2}{\ell^2}+1\right)^{-1} dr^2 + r^2 d\phi^2$$



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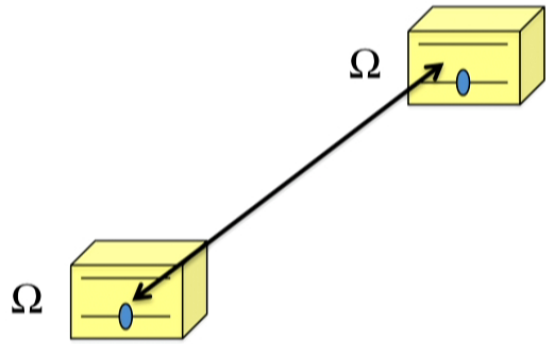

Results in 2+1 AdS

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Switching Width

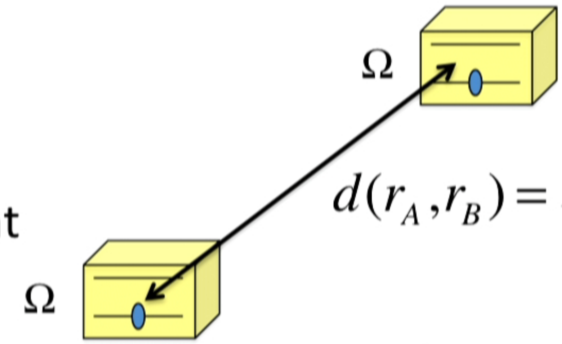
$$\sigma_A = \sigma_B = \sigma$$

Switching Displacement

$$\tau_A = \tau_B = 0$$

Detector Gap

$$\Omega_A = \Omega_B = \Omega$$



$$d(r_A, r_B) = \ell \ln\left[\frac{r_B + \sqrt{r_B^2 + \ell^2}}{r_A + \sqrt{r_A^2 + \ell^2}}\right]$$

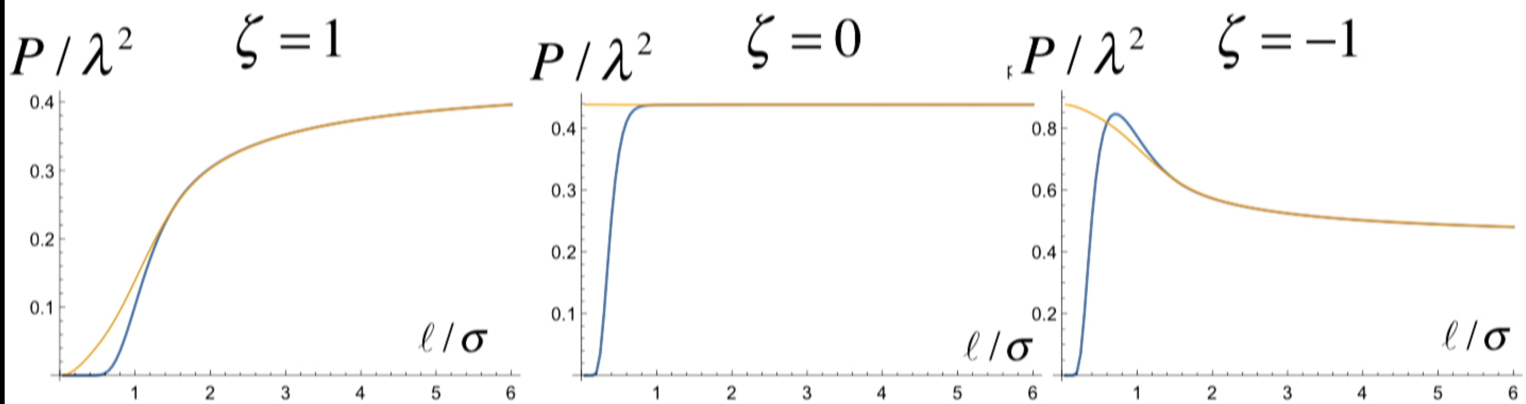
Detector Separation

$d(0,r_B)/\sigma = 1$

Detector Excitation

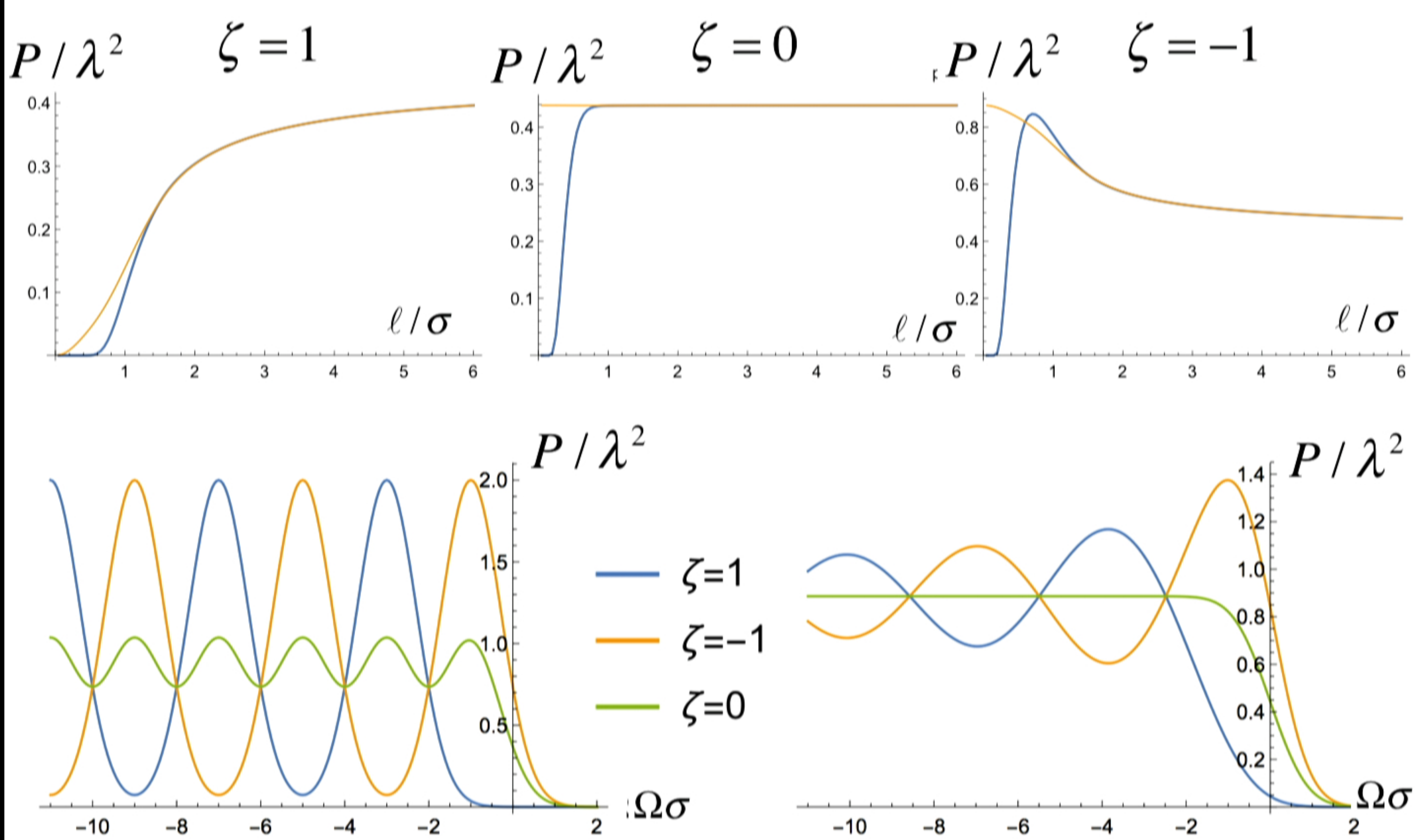
P_A

P_B

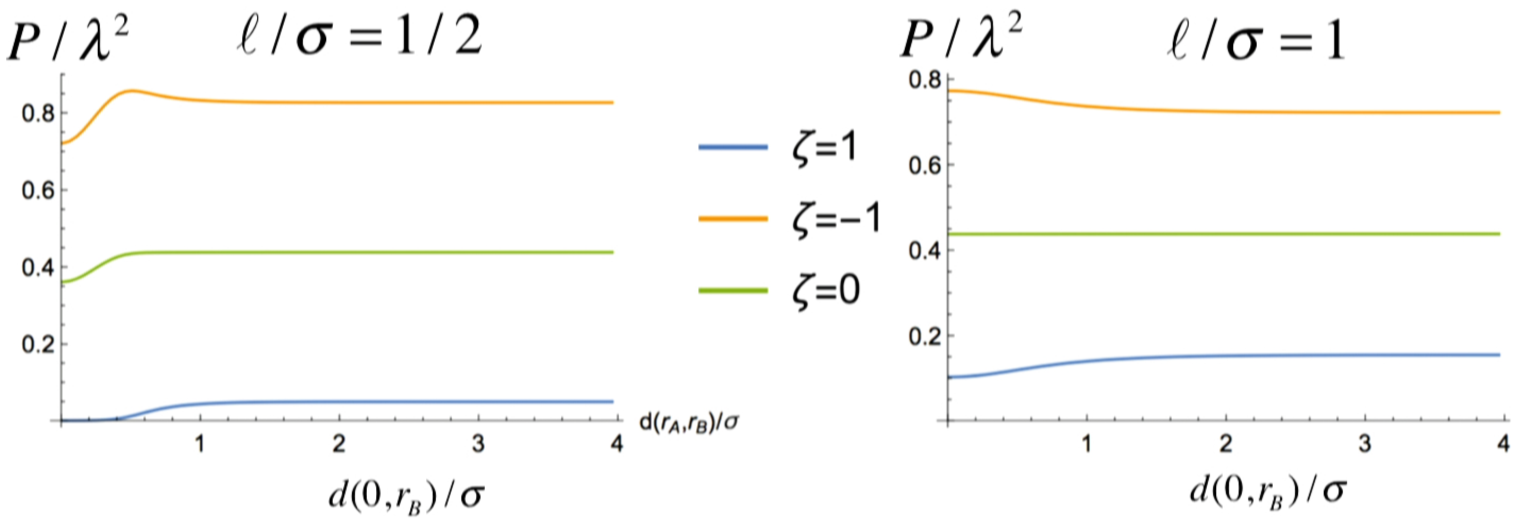


$d(0, r_B)/\sigma = 1$

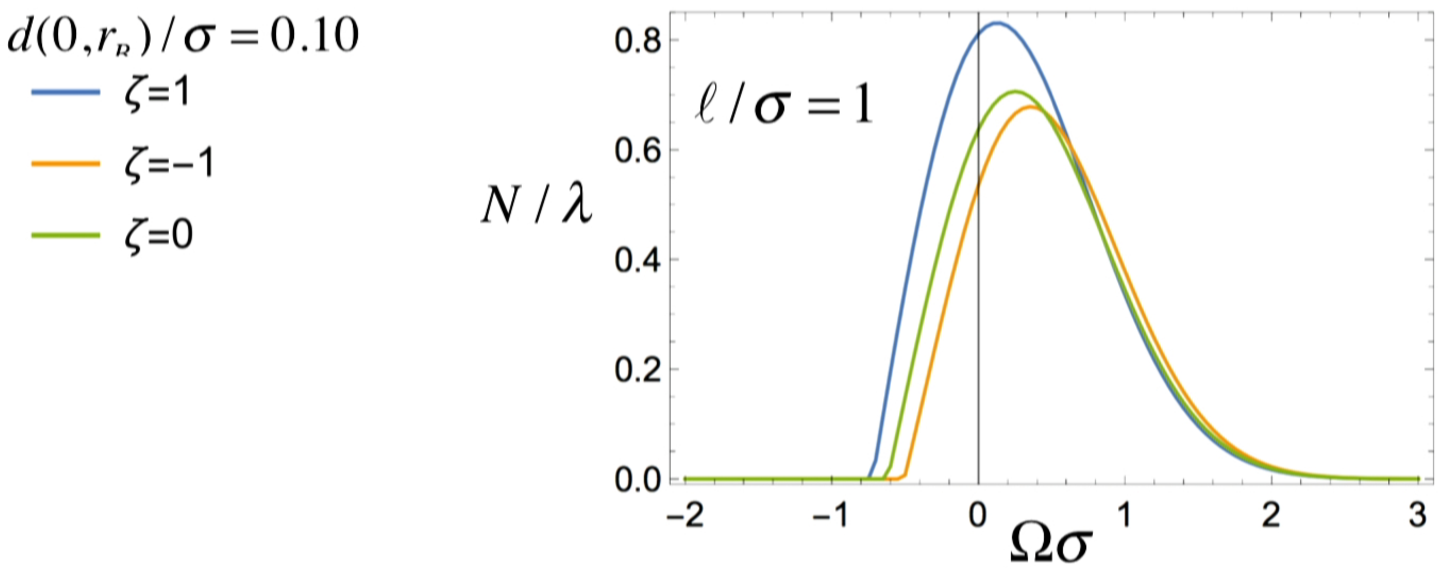
Detector Excitation



$$\Omega\sigma = 0.01$$

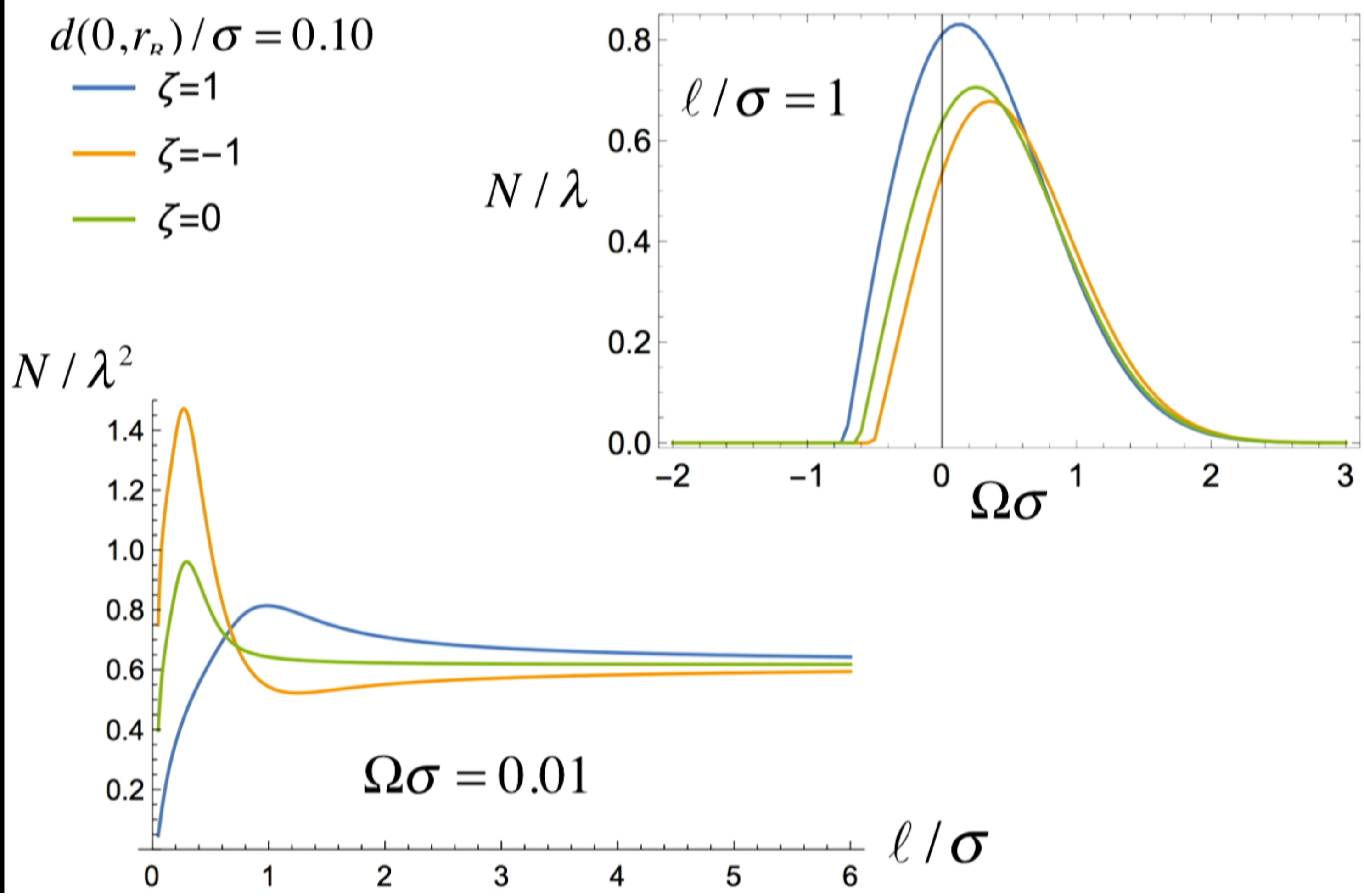


Negativity

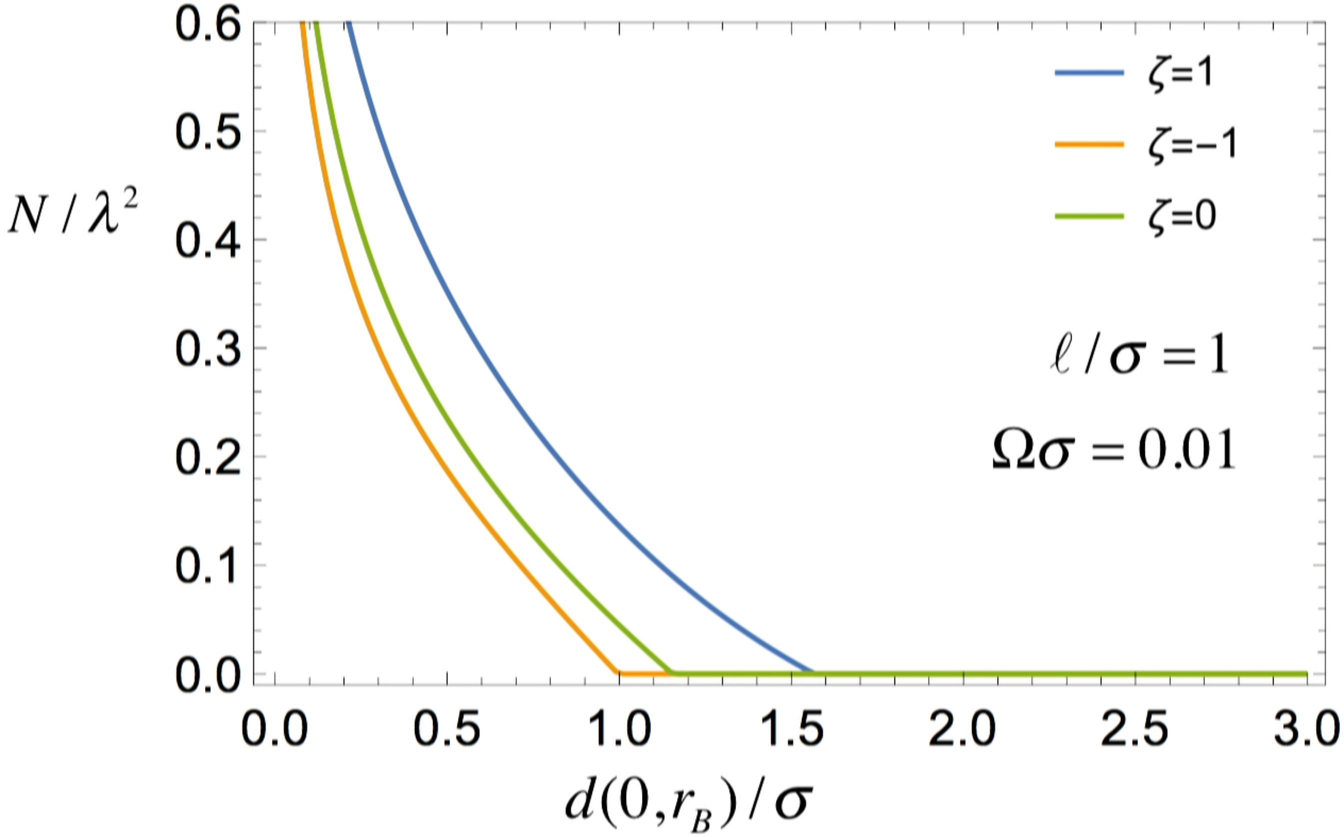


$d(0,r_R)/\sigma = 0.10$
ζ=1
ζ=−1
ζ=0
$\ell/\sigma = 1$
N/λ
0.8
0.6
0.4
0.2
0.0
−2
−1
0
1
2
3
$\Omega\sigma$

Negativity

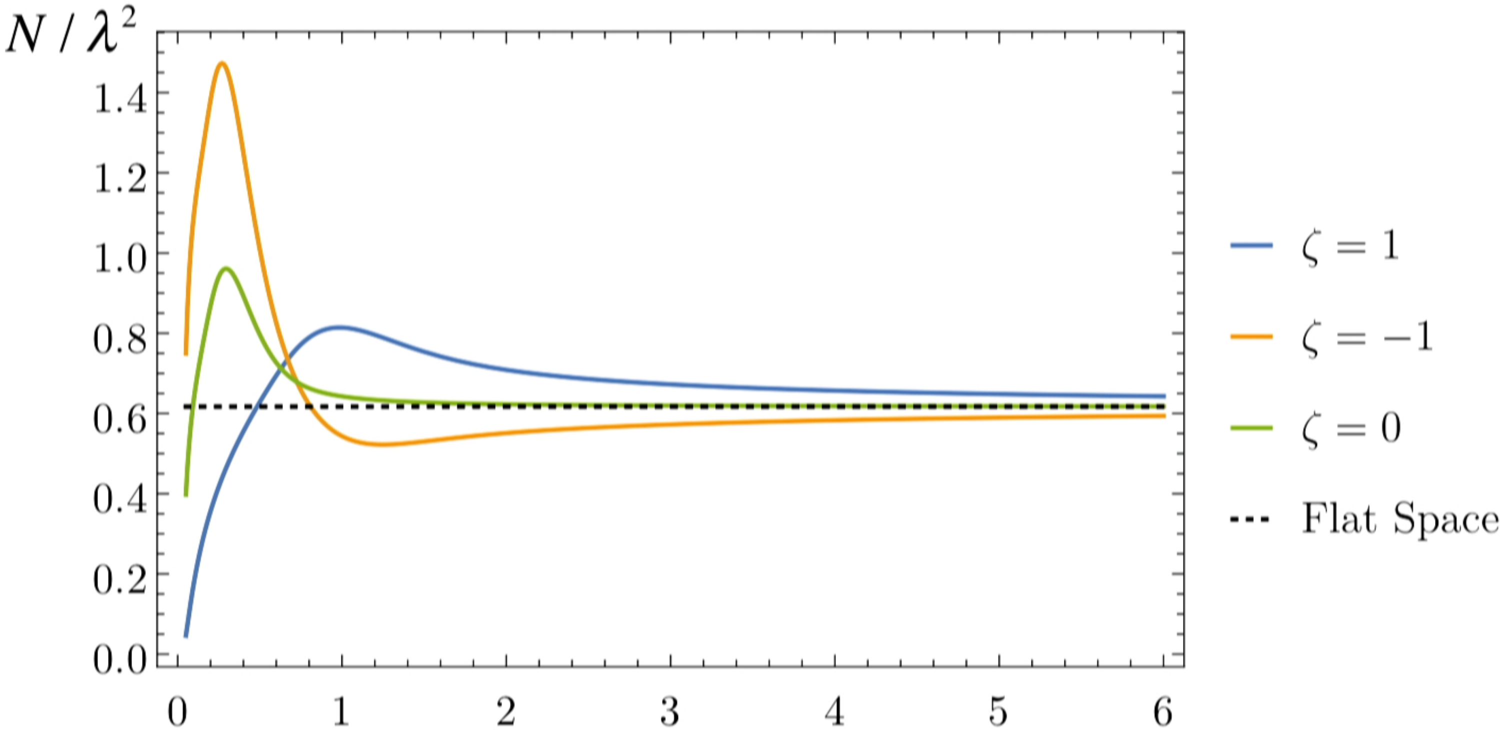


$d(0,r_B)/\sigma = 0.10$
ζ=1
ζ=−1
ζ=0
N/λ
$\ell/\sigma = 1$
0.8
0.6
0.4
0.2
0.0
−2
−1
0
1
2
3
$\Omega\sigma$
N/λ^2
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$\Omega\sigma = 0.01$
0
1
2
3
4
5
6
ℓ/σ



N/λ^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$d(0,r_B)/\sigma$
ζ=1
ζ=−1
ζ=0
$\ell/\sigma = 1$
$\Omega\sigma = 0.01$

Flat Space Limit



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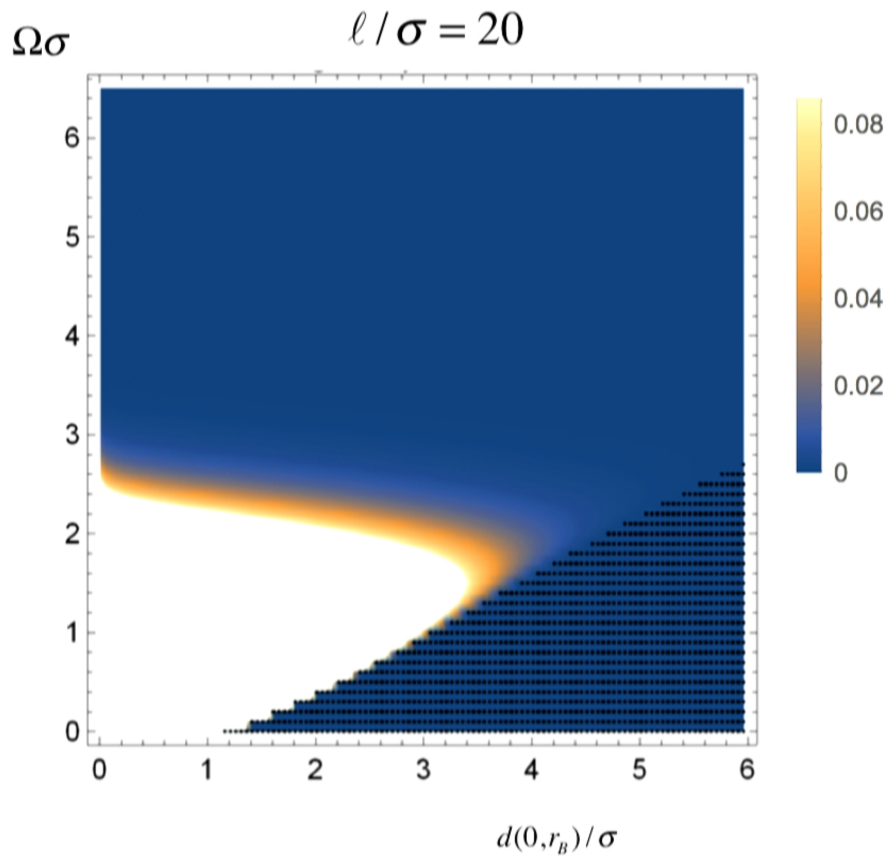
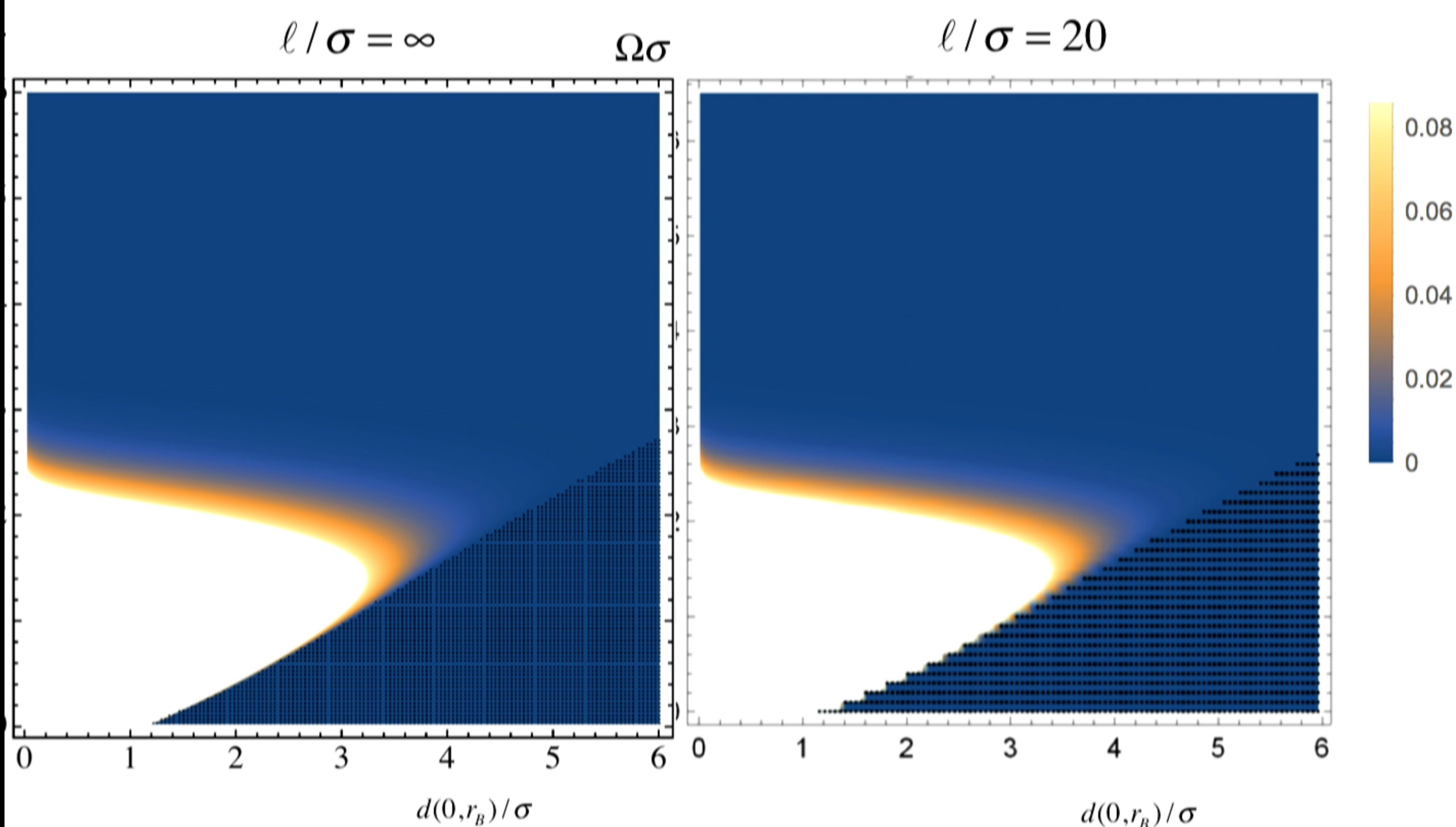
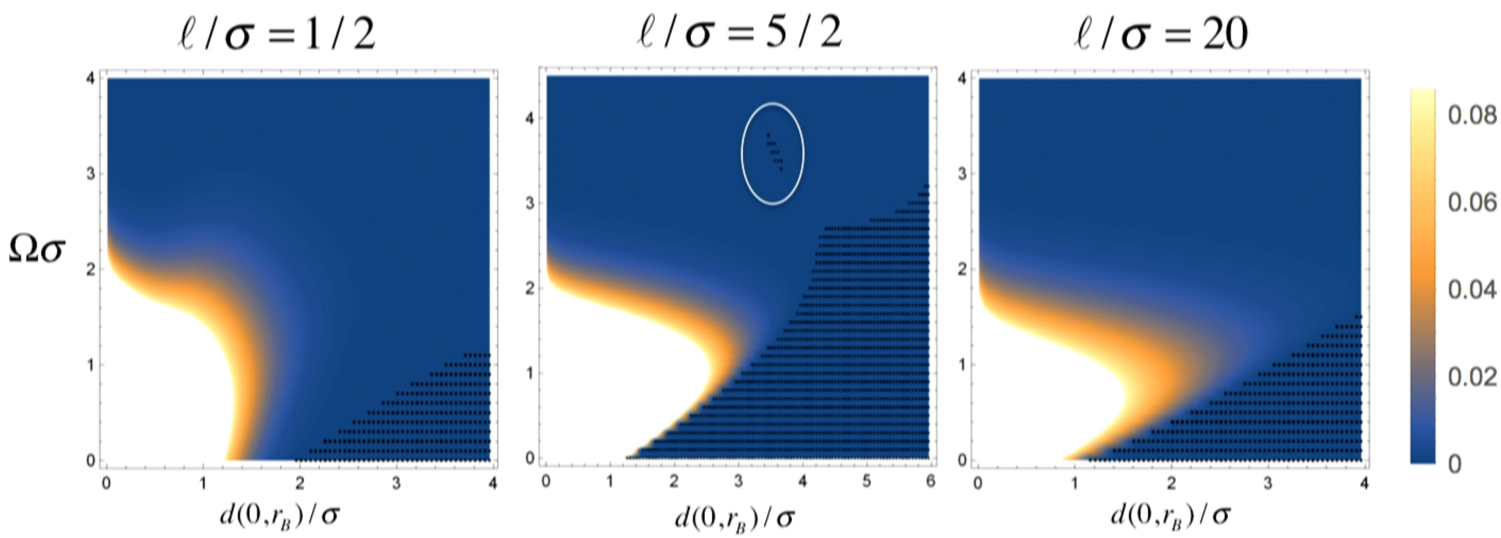


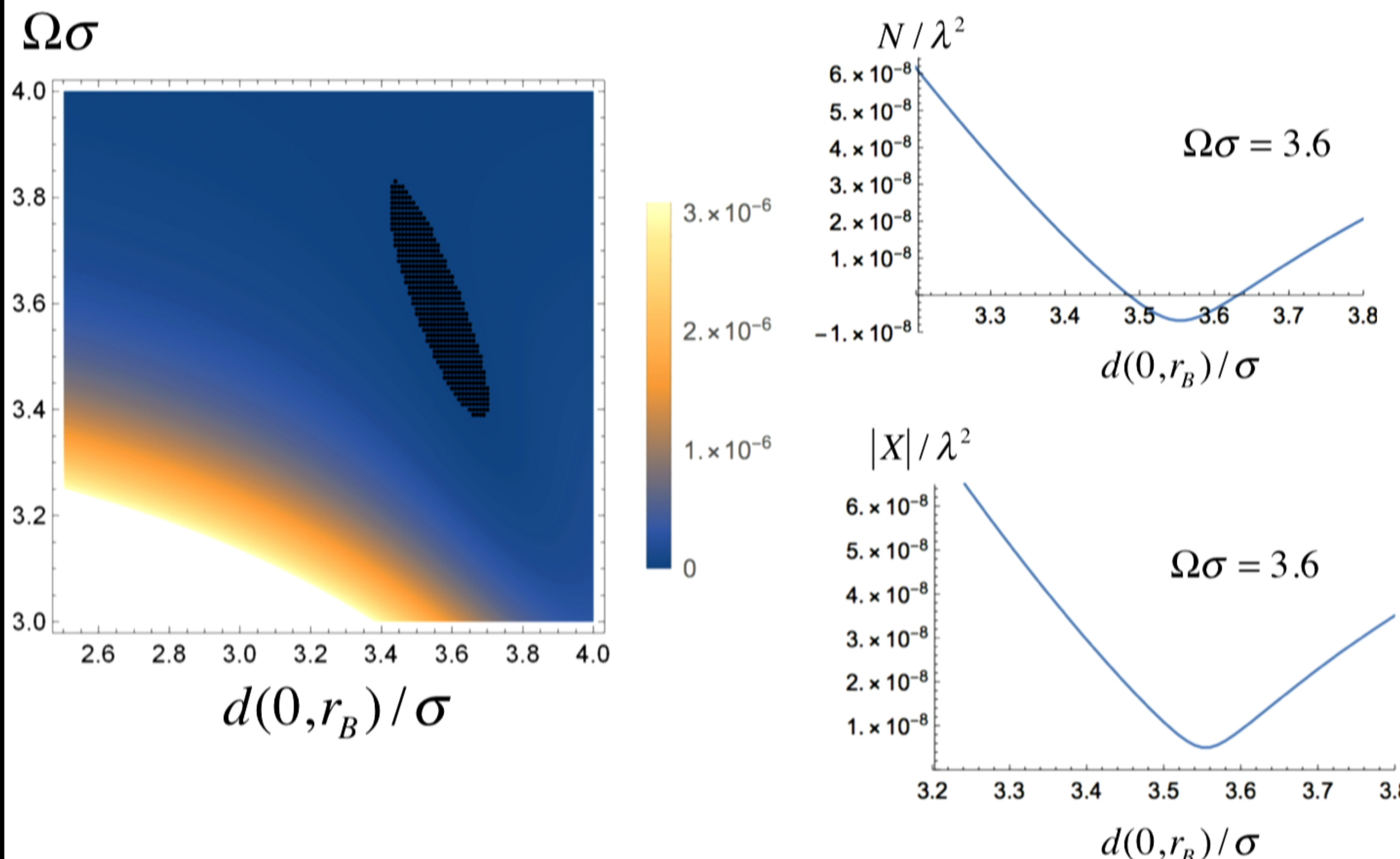
Flat Space Limit



Negativity $\zeta = 1$

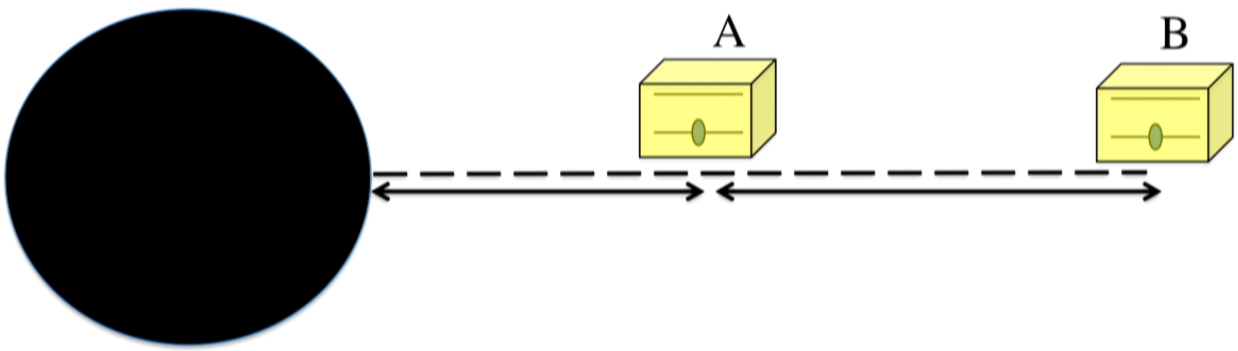


The Dead Zone $\ell/\sigma = 5/2$



Harvesting Near Black Holes

Henderson/Hennigar/Smith/Zhang/RBM
1712.10018

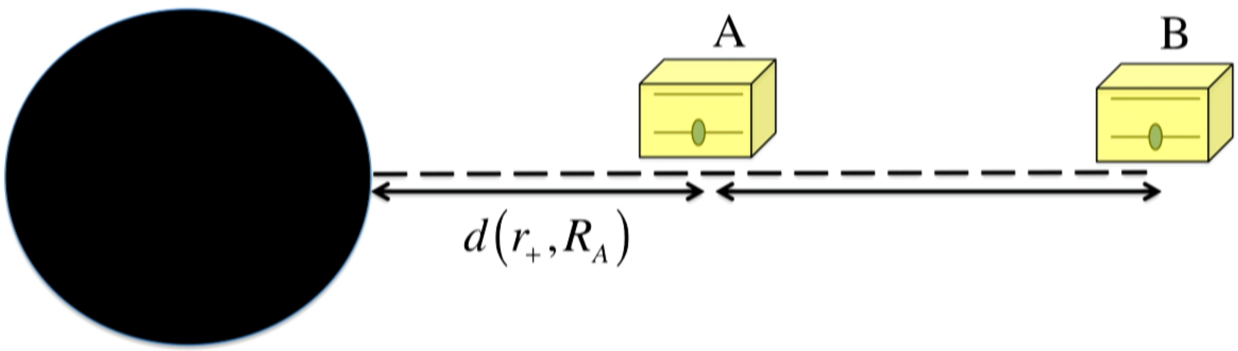


$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2$$

$$f(r) = \left(\frac{r^2}{\ell^2} - M\right)$$

Harvesting Near Black Holes

Henderson/Hennigar/Smith/Zhang/RBM
1712.10018



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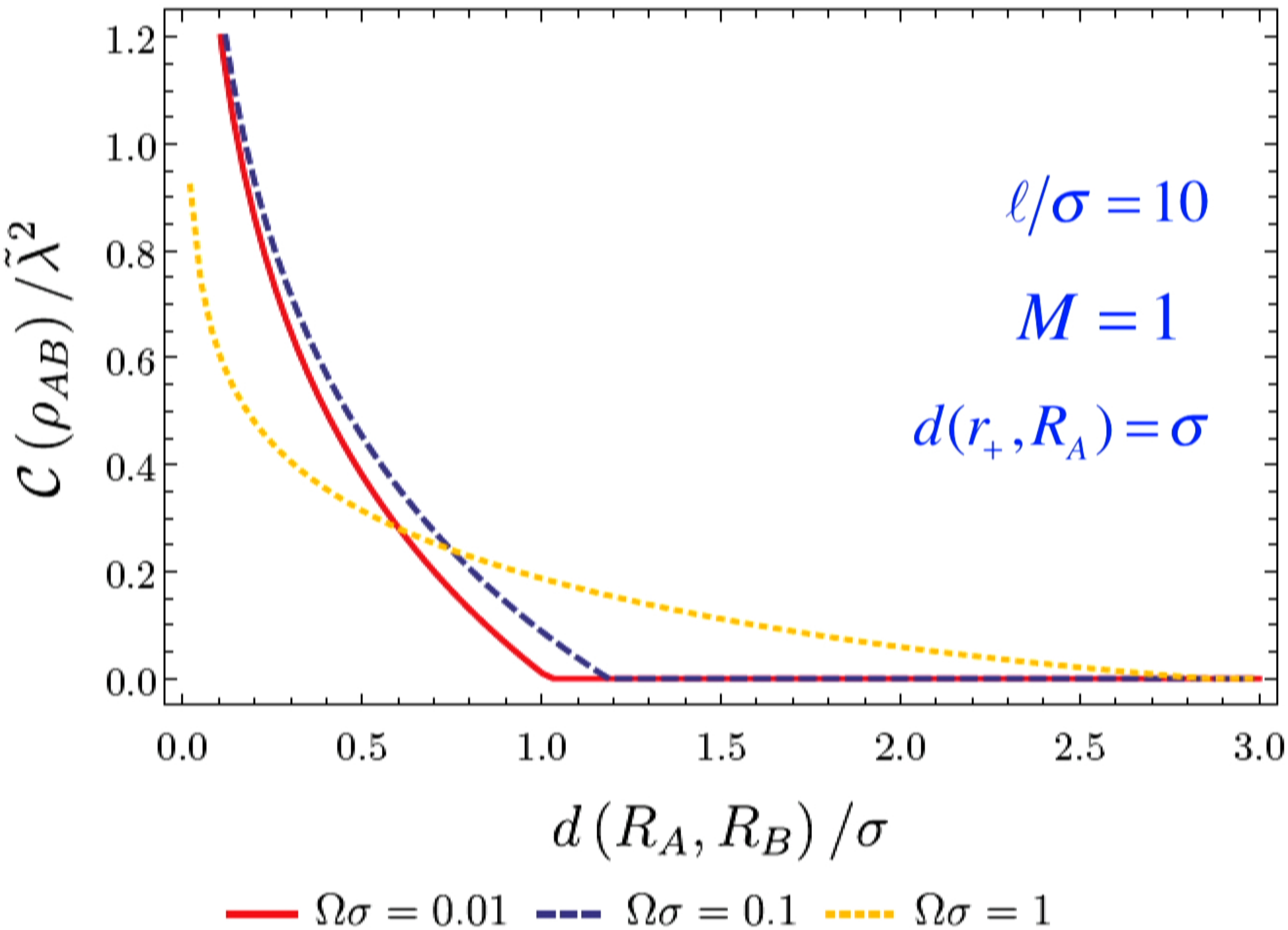
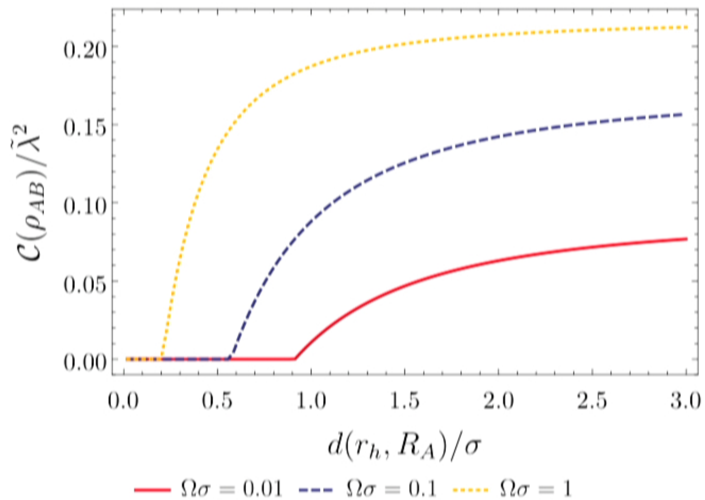
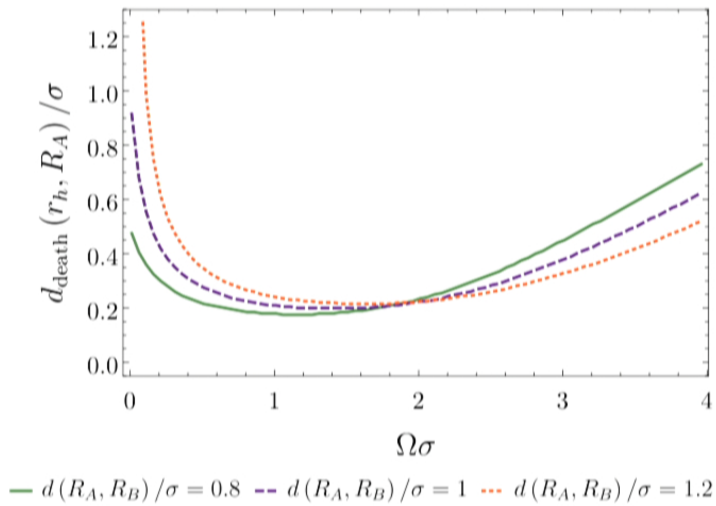
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2$$



1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\mathcal{C}(\rho_{AB})/\tilde{\lambda}^2$
$\ell/\sigma = 10$
$M = 1$
$d(r_+, R_A) = \sigma$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$d(R_A, R_B)/\sigma$
$\Omega\sigma = 0.01$
$\Omega\sigma = 0.1$
$\Omega\sigma = 1$

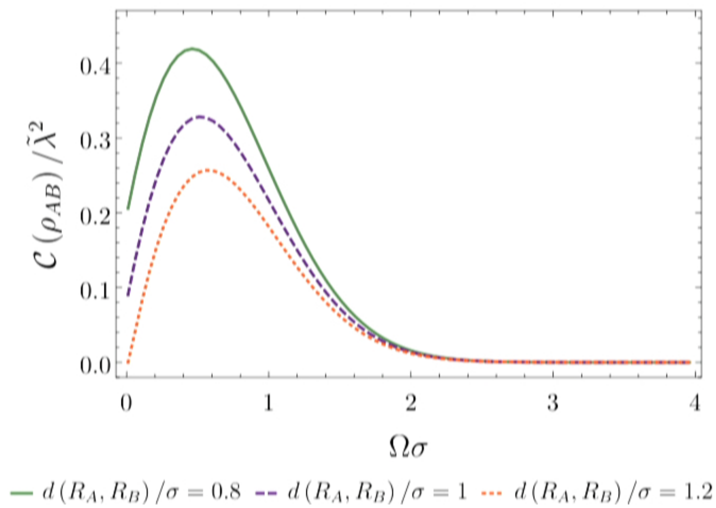
The Death Zone



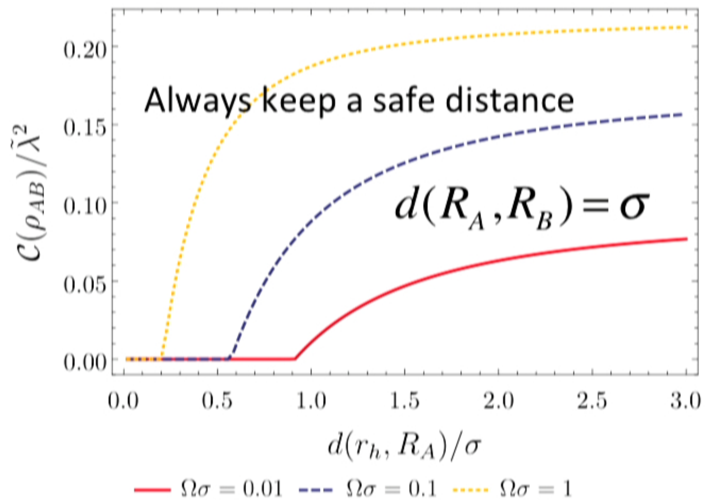


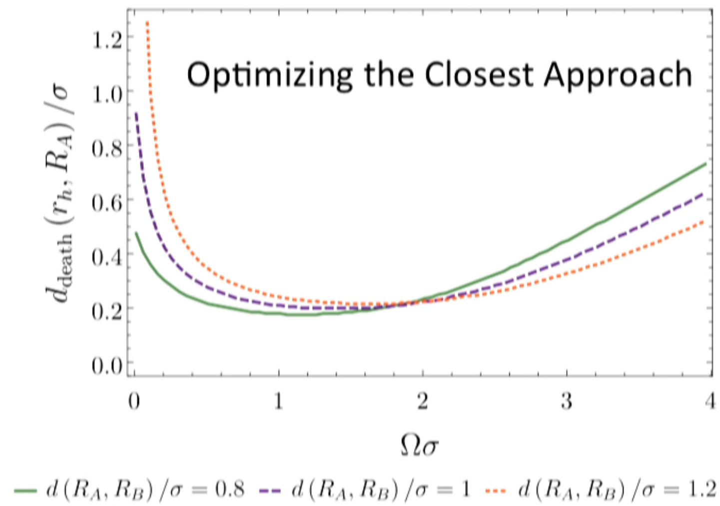
$\ell/\sigma = 10$

$M = 1$



The Death Zone





$\ell/\sigma = 10$

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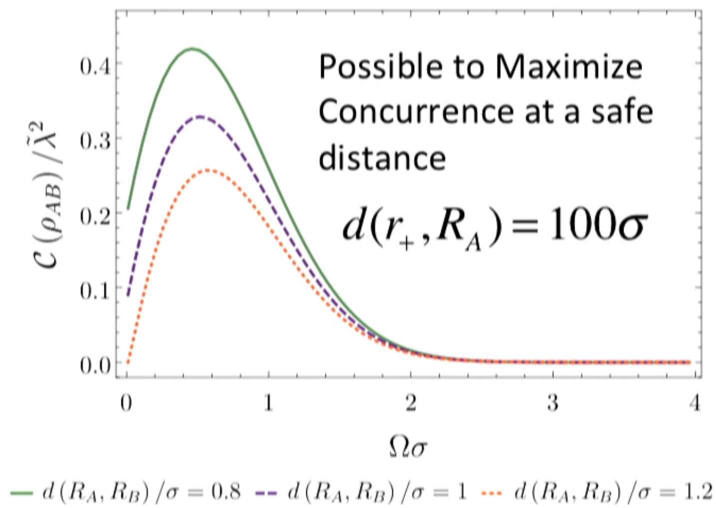
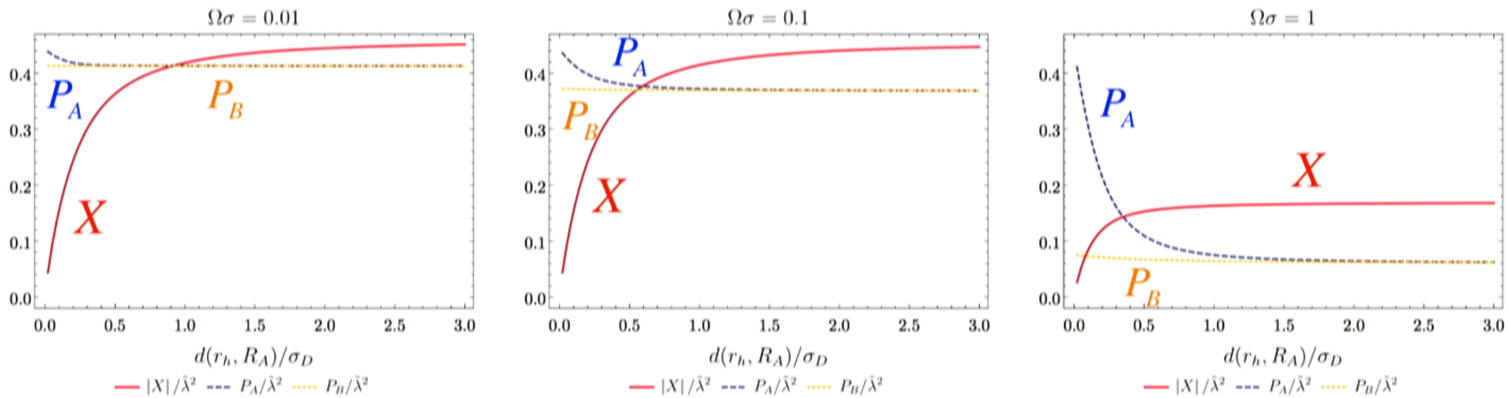


Entanglement Inhibition



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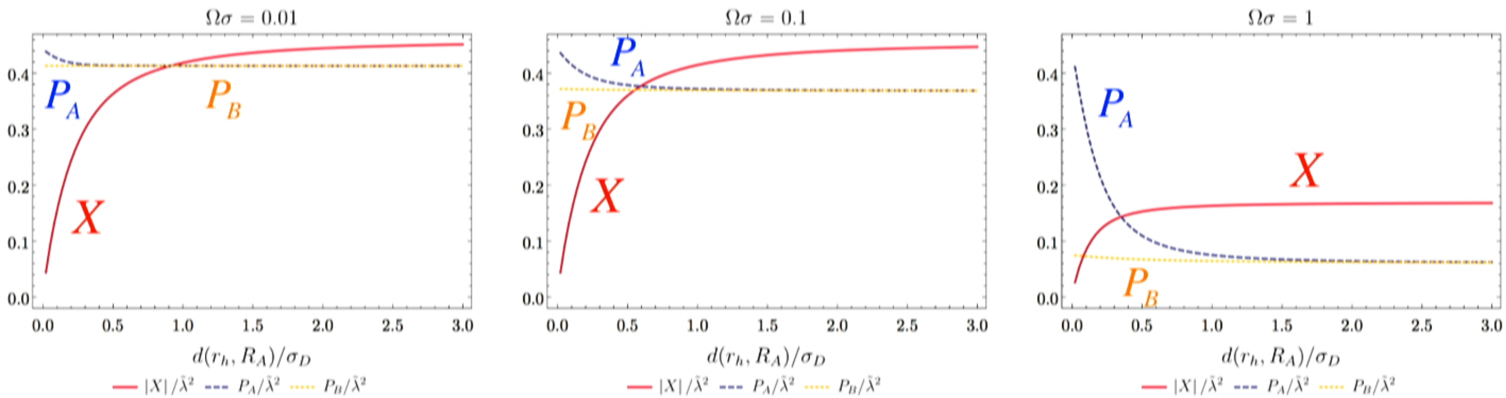
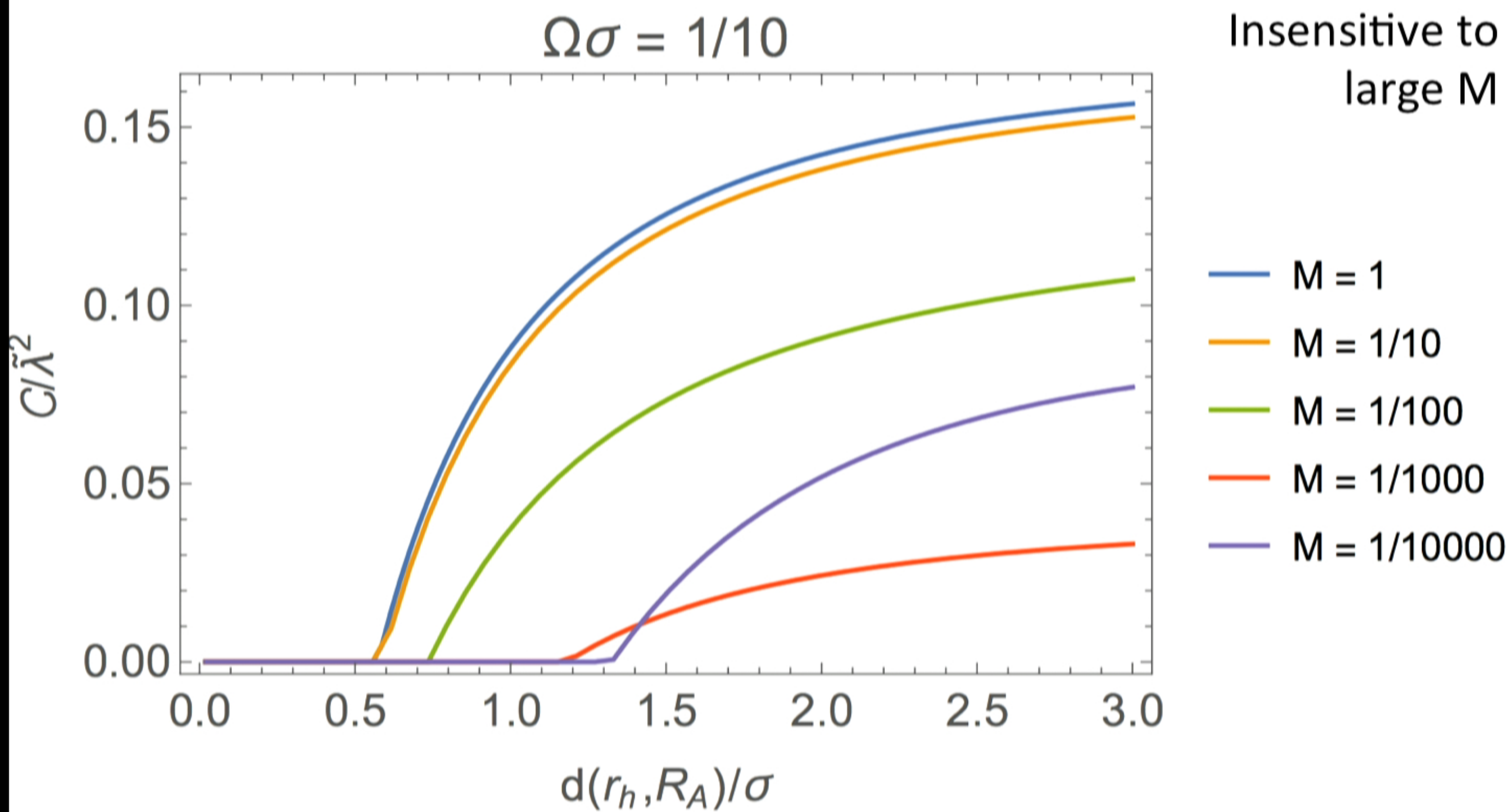


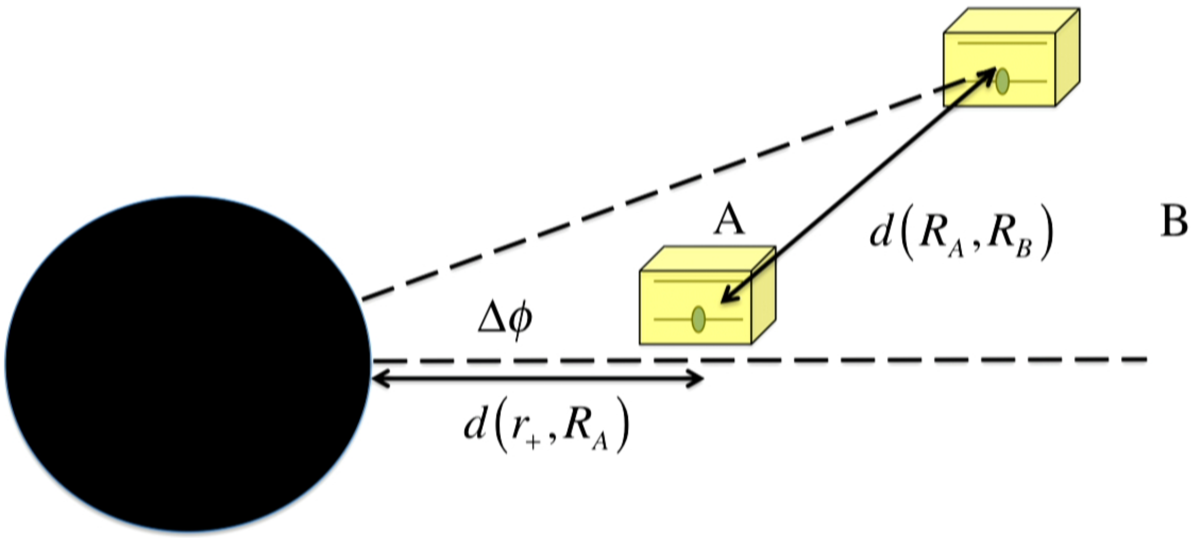
- Competition between increasing local excitations and decreasing non-local correlation
  - Hawking radiation → excitation probability rises
  - Redshift effects → erode correlations

Mass Dependence



Insensitive to large M

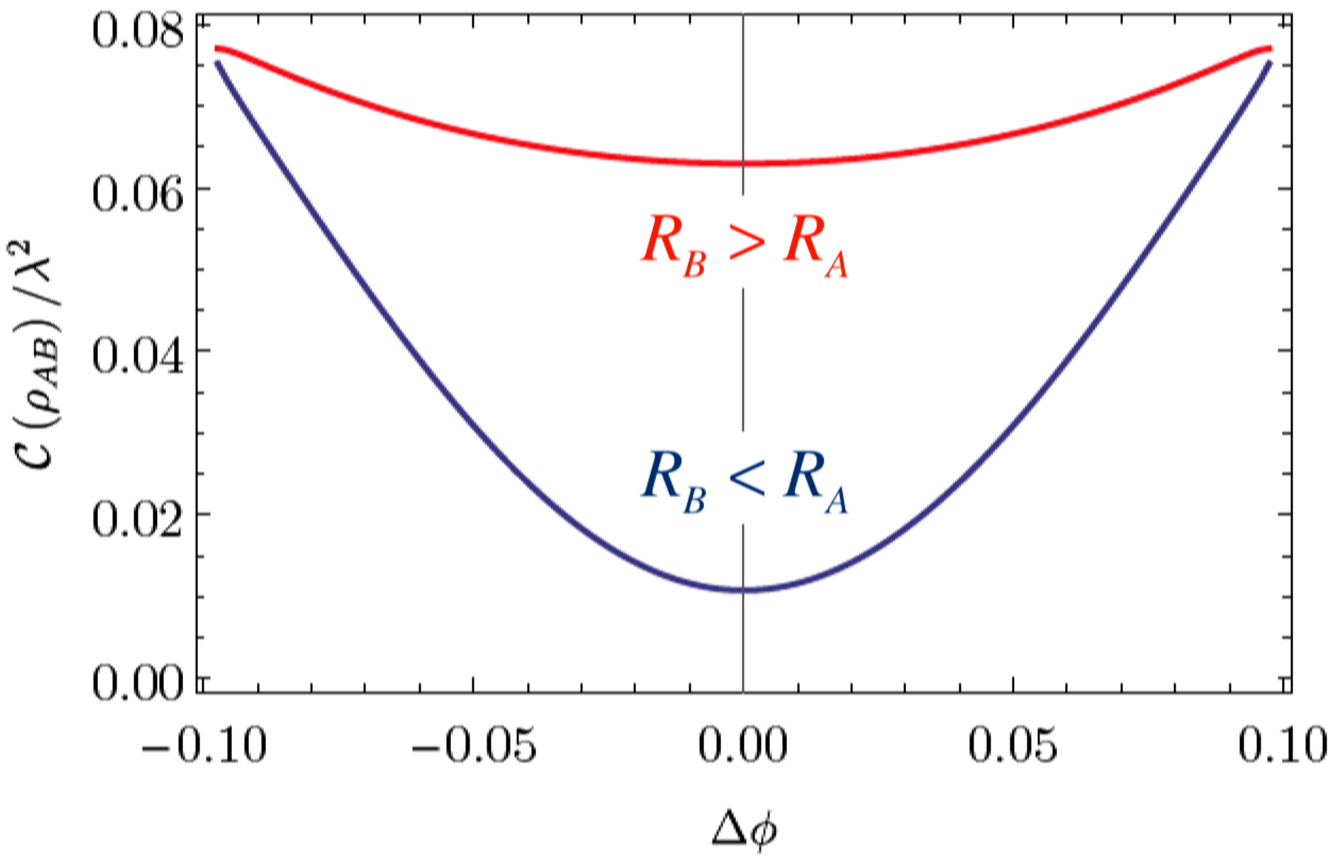
Angular Dependence



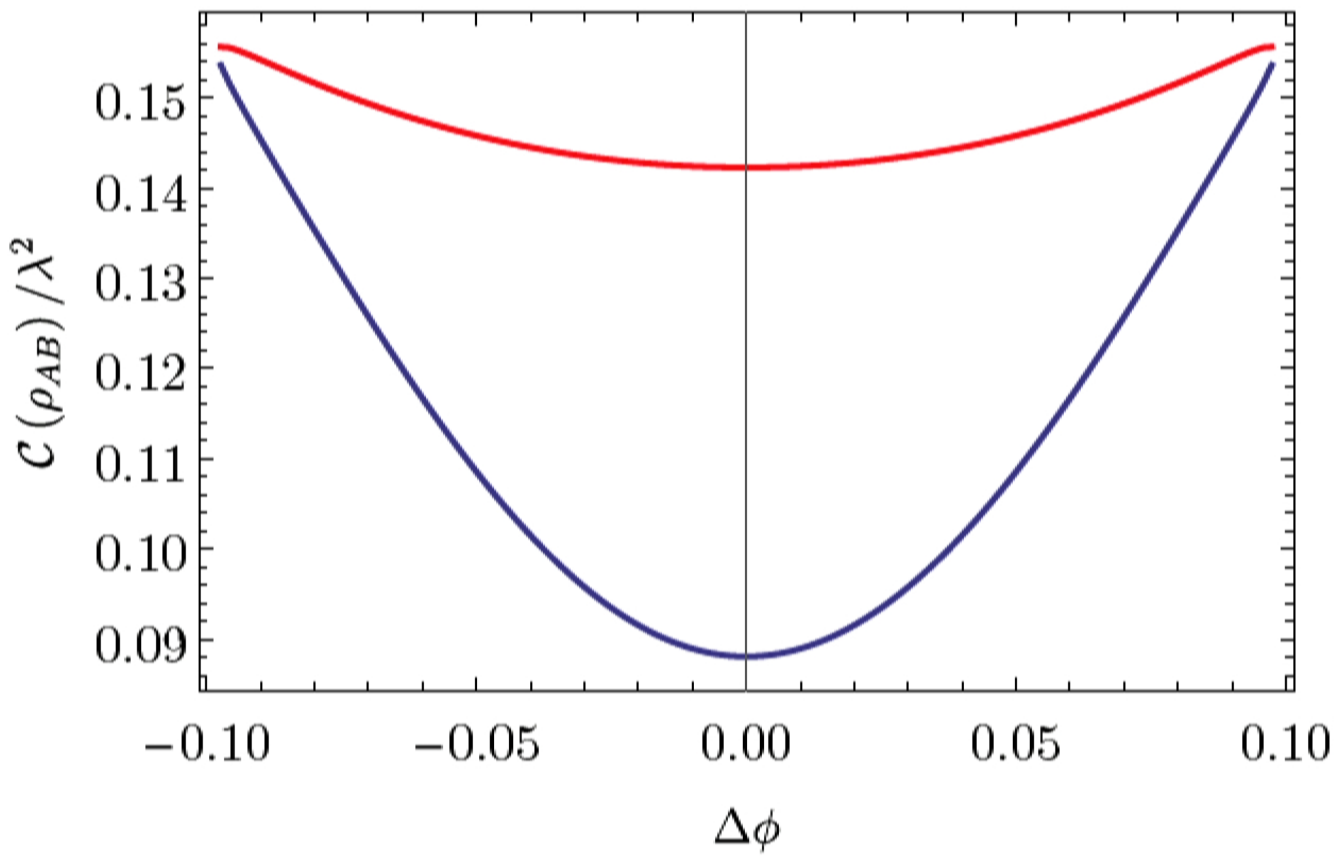
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2$$

$$f(r) = \left(\frac{r^2}{\ell^2} - M\right)$$

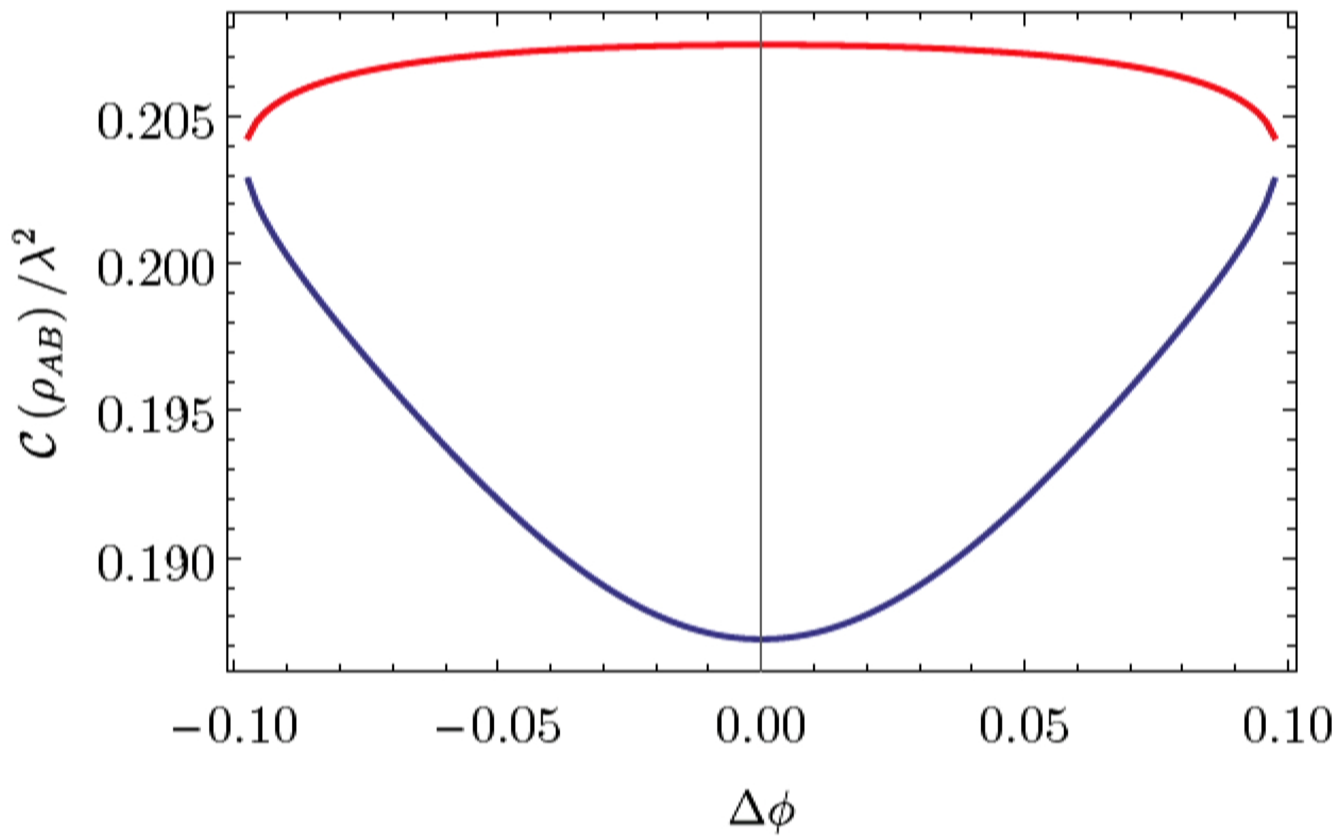
$\Omega\sigma = 0.01$ $M = 1$ $\ell = 10\sigma$ $d(r_+, R_A) = \sigma$ $d(R_A, R_B) = \sigma$



$\Omega\sigma = 0.1$ $M = 1$ $\ell = 10\sigma$ $d(r_+, R_A) = \sigma$ $d(R_A, R_B) = \sigma$

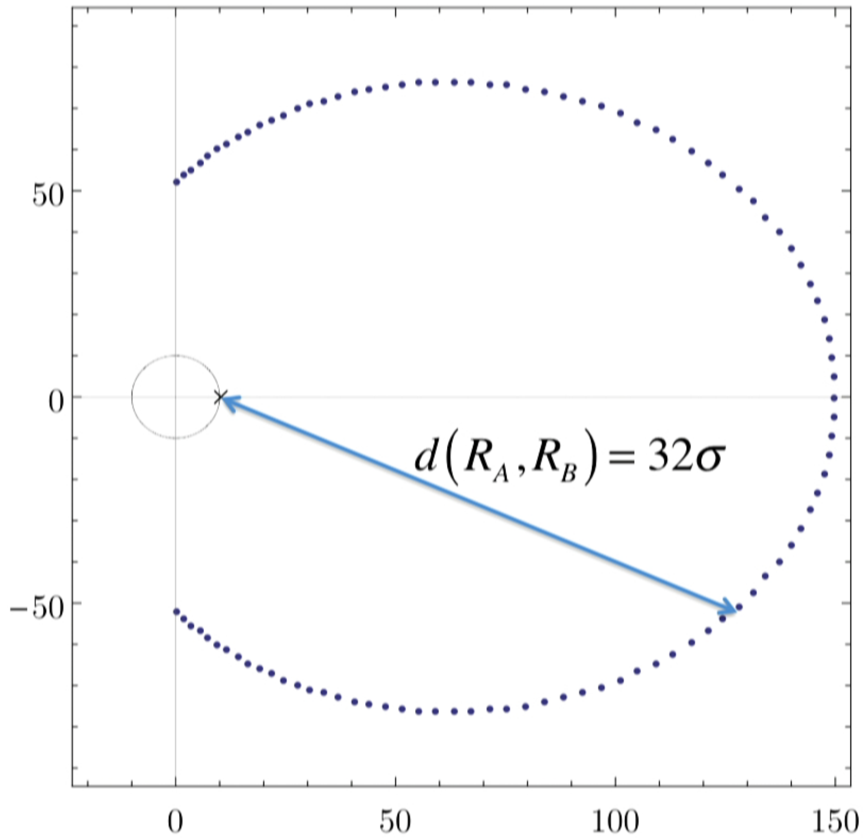


$\Omega\sigma = 1.0 \qquad M = 1 \qquad \ell = 10\sigma \qquad d(r_+, R_A) = \sigma \qquad d(R_A, R_B) = \sigma$

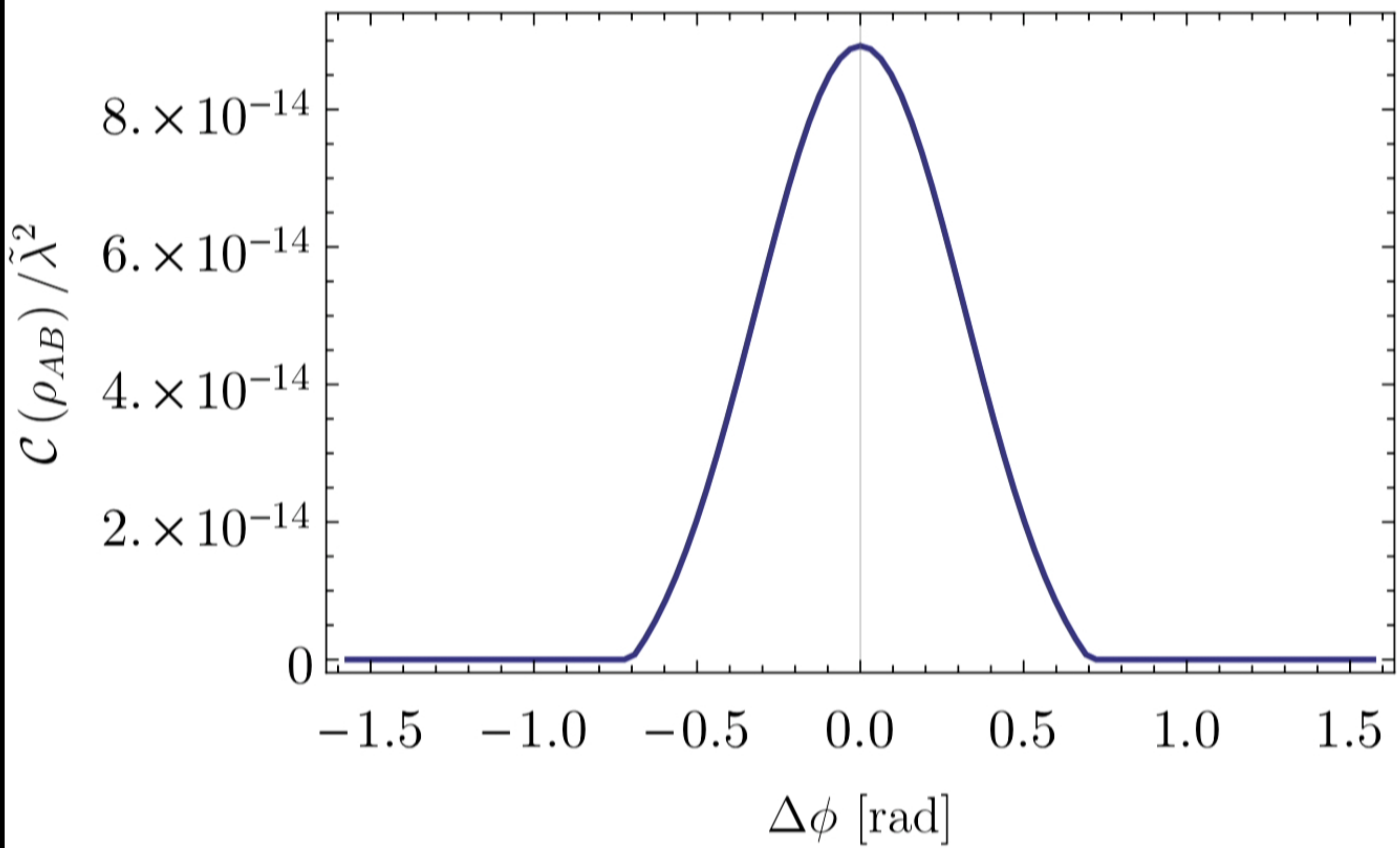


Encompassing the Hole

$d\left(r_+, R_A\right) = \sigma$



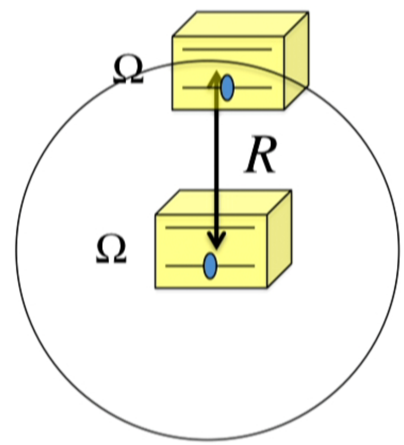
$\Omega\sigma = 5.5$ $M = 1$ $\ell = 10\sigma$ $d(r_+, R_A) = \sigma$ $d(R_A, R_B) = 32\sigma$



Results in 3+1 AdS

Ng/Mann/
Martin-Martinez
(to appear)

$$ds^2 = -\left(\frac{r^2}{\ell^2}+1\right)dt^2 + \left(\frac{r^2}{\ell^2}+1\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)$$



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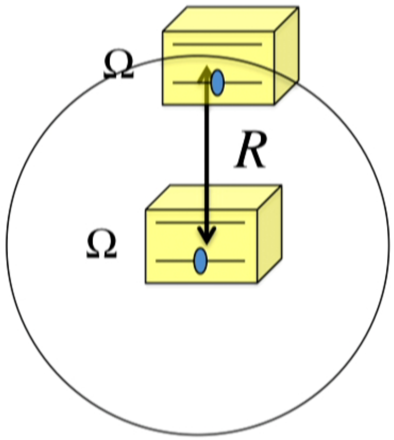

$$r = R$$
$$\theta = \pi / 2$$
$$t = \tau$$
$$\phi = \tau / \ell$$

Geodesic circular orbit: redshift and angular velocity are completely independent of radius

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Switching Displacement

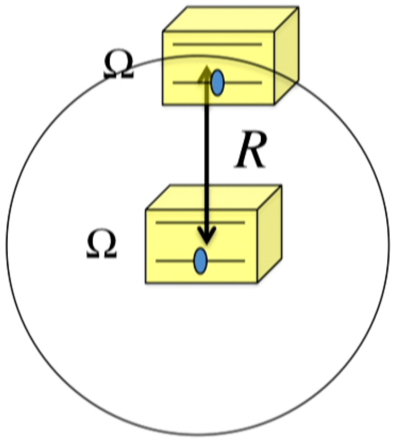
$\tau_A = 0 \quad \tau_B = \Delta\tau$

Switching Width

$\sigma_A = \sigma_B = \sigma$

Detector Gaps

$\Omega_A = \Omega_B = \Omega$



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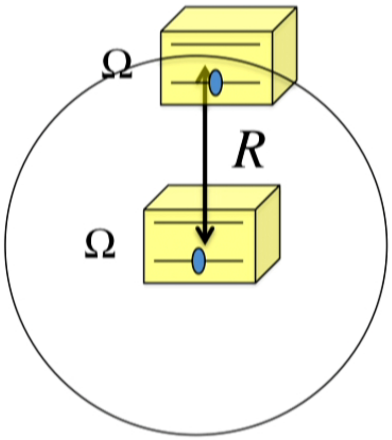
Calibrated wrt coordinate time



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Geodesic circular orbit: redshift and angular velocity are completely independent of radius

Correlation Relations

For Spacelike Separated Detectors

For any detector motion!

$$X = -\frac{1}{2}\left[C_{BA}(-\Omega_B,\Omega_A)+C_{AB}(-\Omega_A,\Omega_B)\right]$$

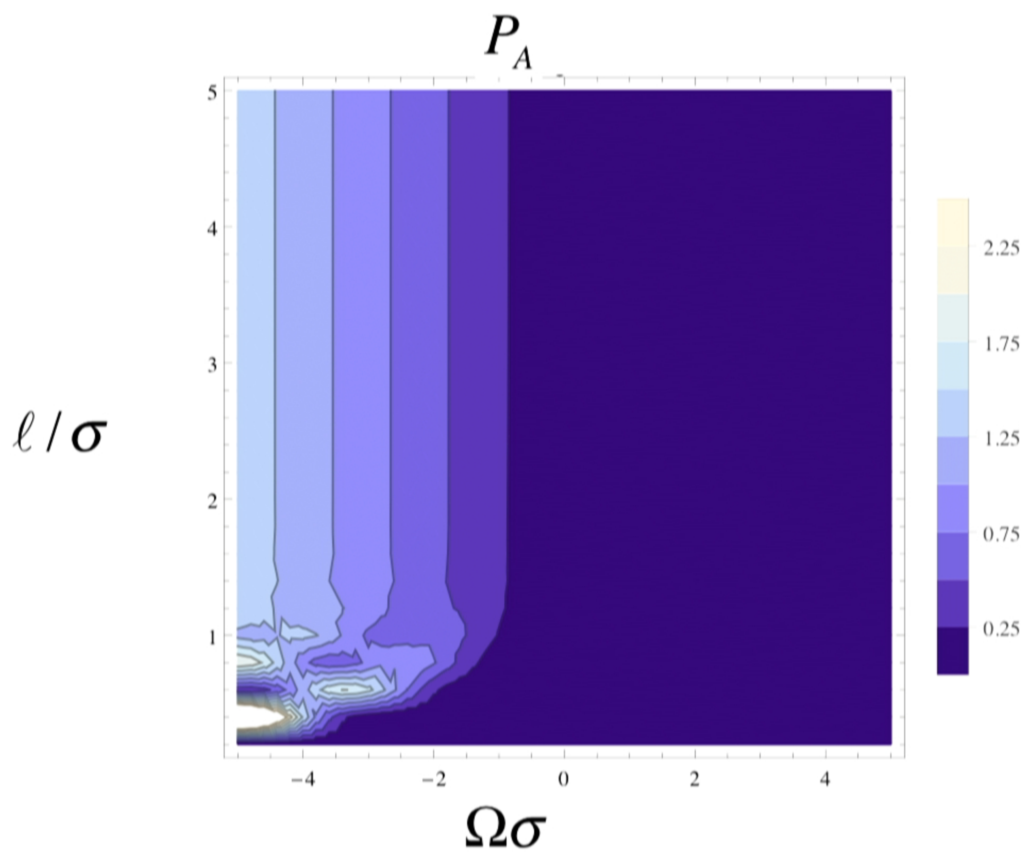
Non-local Correlations

Local Correlations

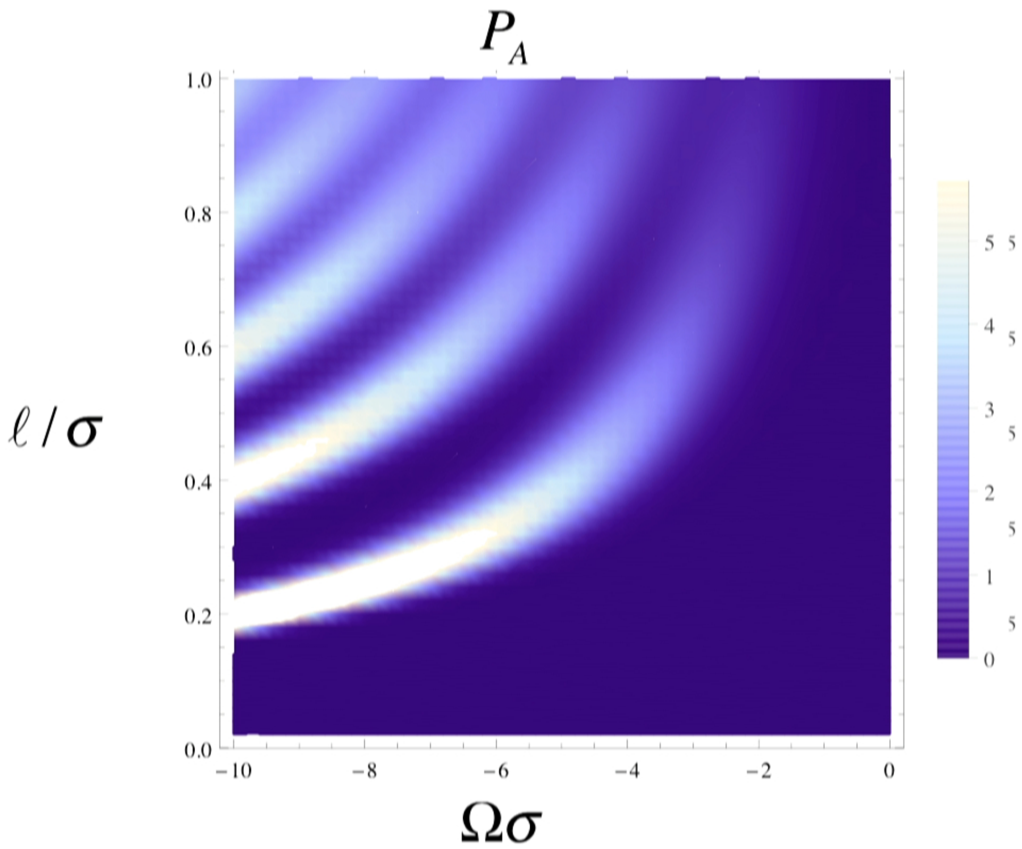
$$C_{AB} = \lambda^2 \sum_n \frac{\pi}{2n+2}\varphi_{2n+2}(x_B)\varphi_{2n+2}(x_A)\hat{\chi}^*_B(2n+2+\Omega_B)\hat{\chi}_A(2n+2+\Omega_A)$$

$$X = \lambda^2 \sum_n \frac{\pi}{2n+2}\varphi_{2n+2}(x_B)\varphi_{2n+2}(x_A)\hat{\chi}^*_B(2n+2+\Omega_B)\hat{\chi}_A(2n+2+\Omega_A)$$

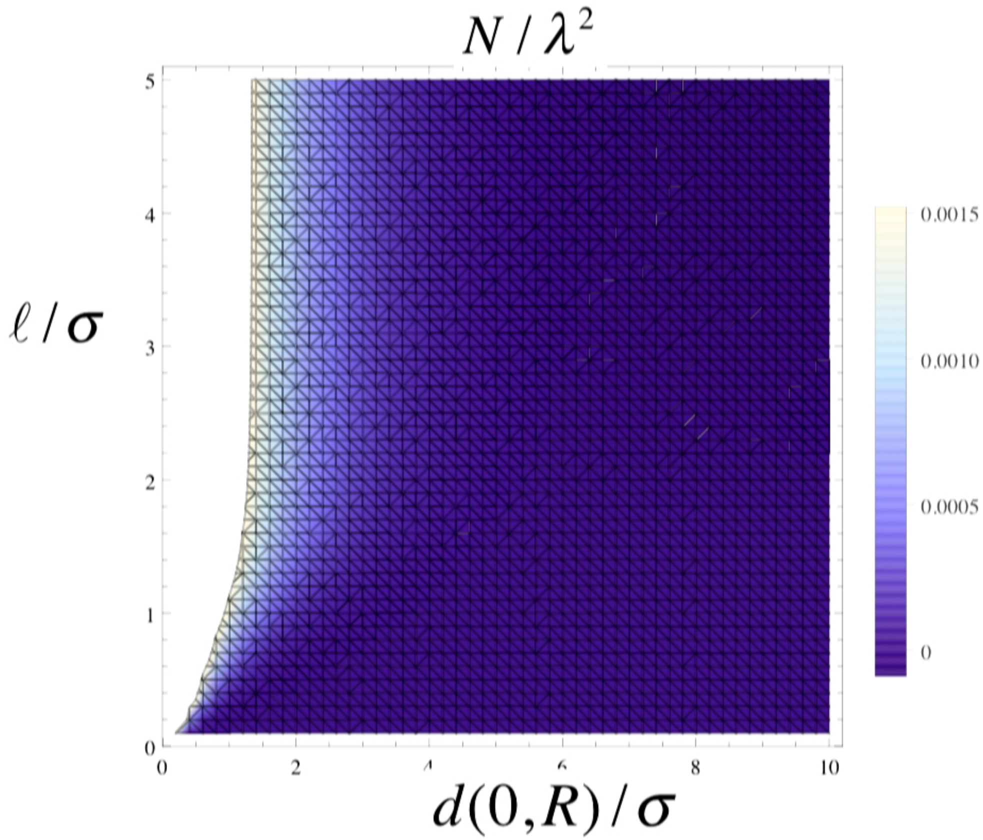
Detector Excitation



Detector Excitation



Negativity



$\Omega\sigma = 2$

Negativity

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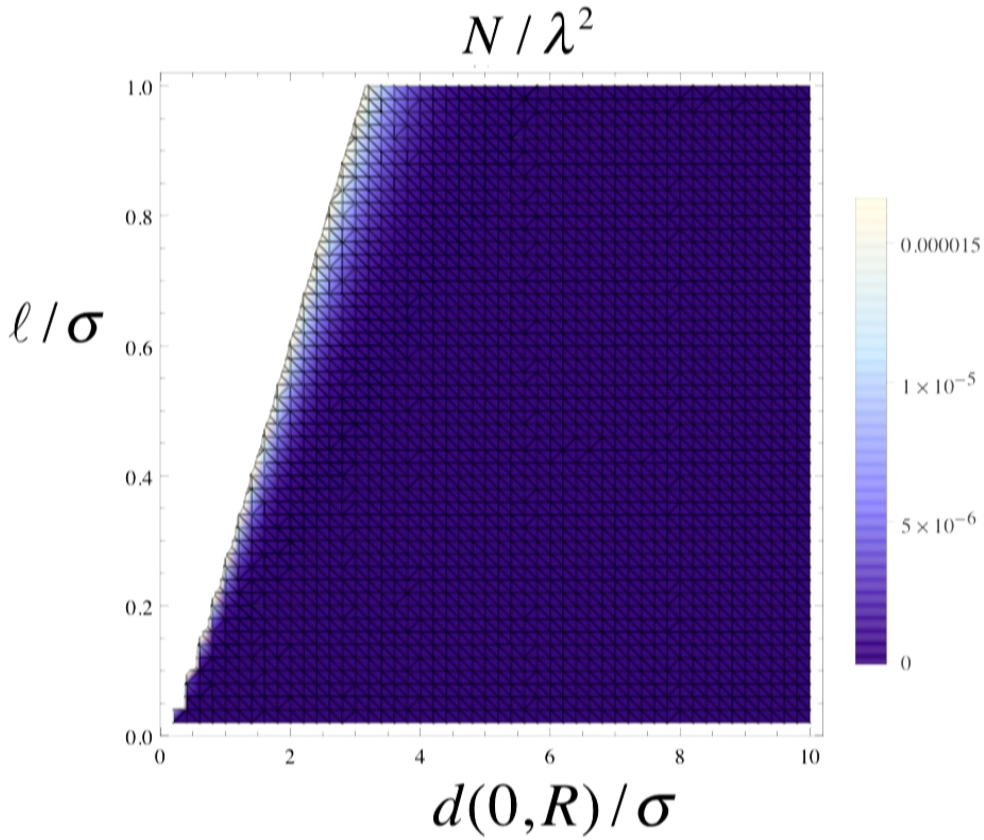
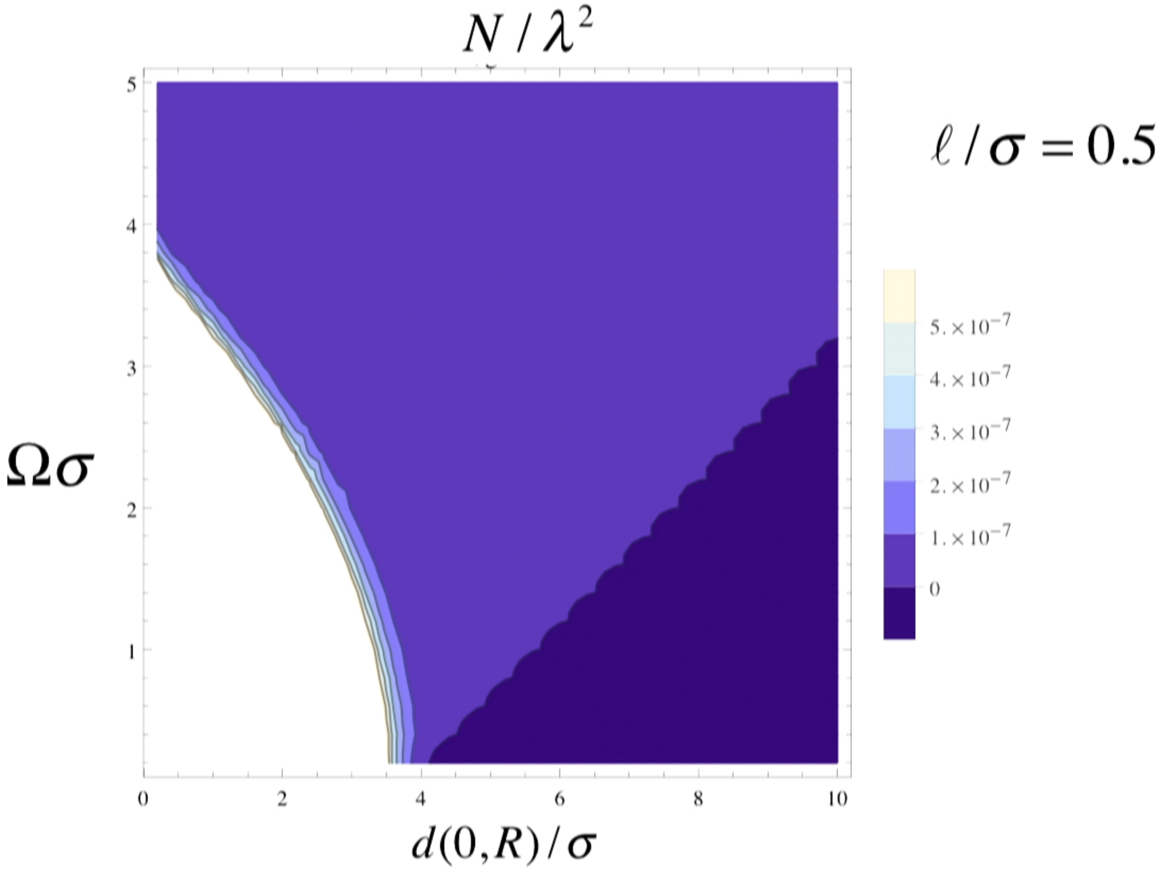
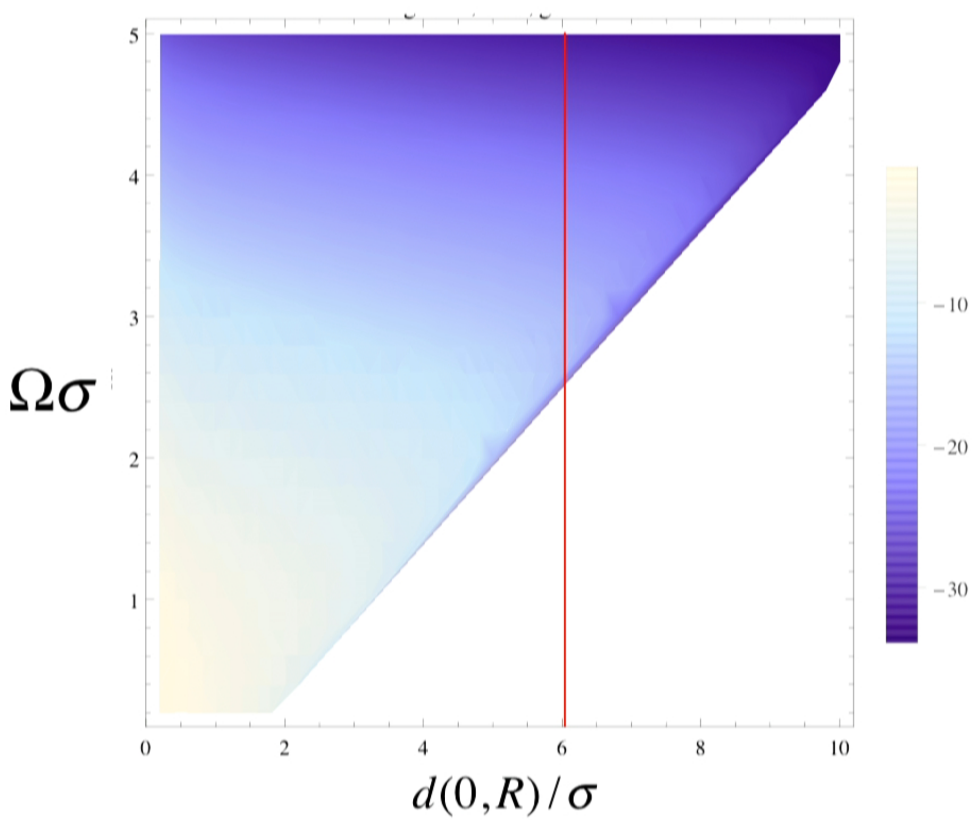


Gap Dependence

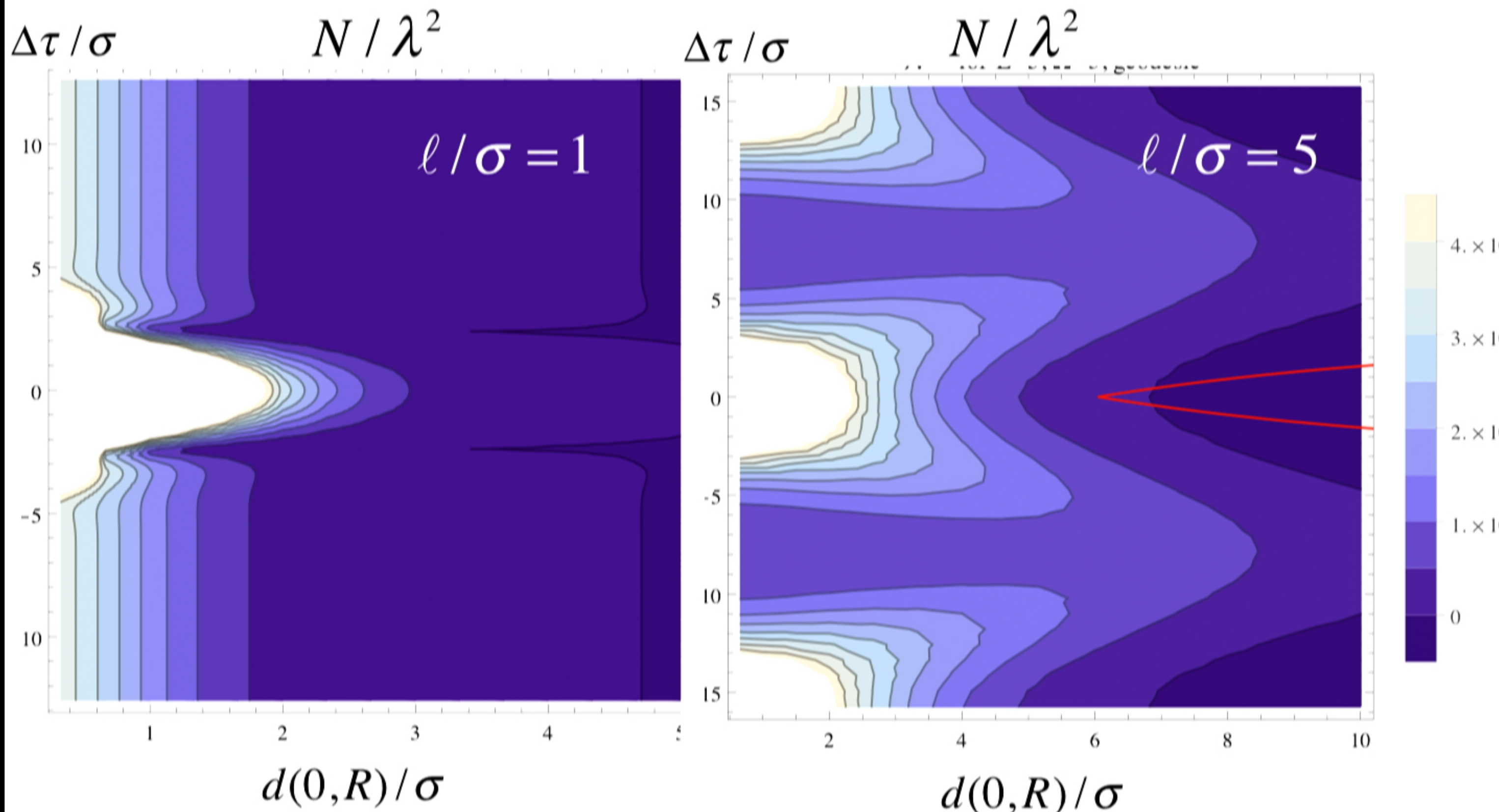


Gap Dependence

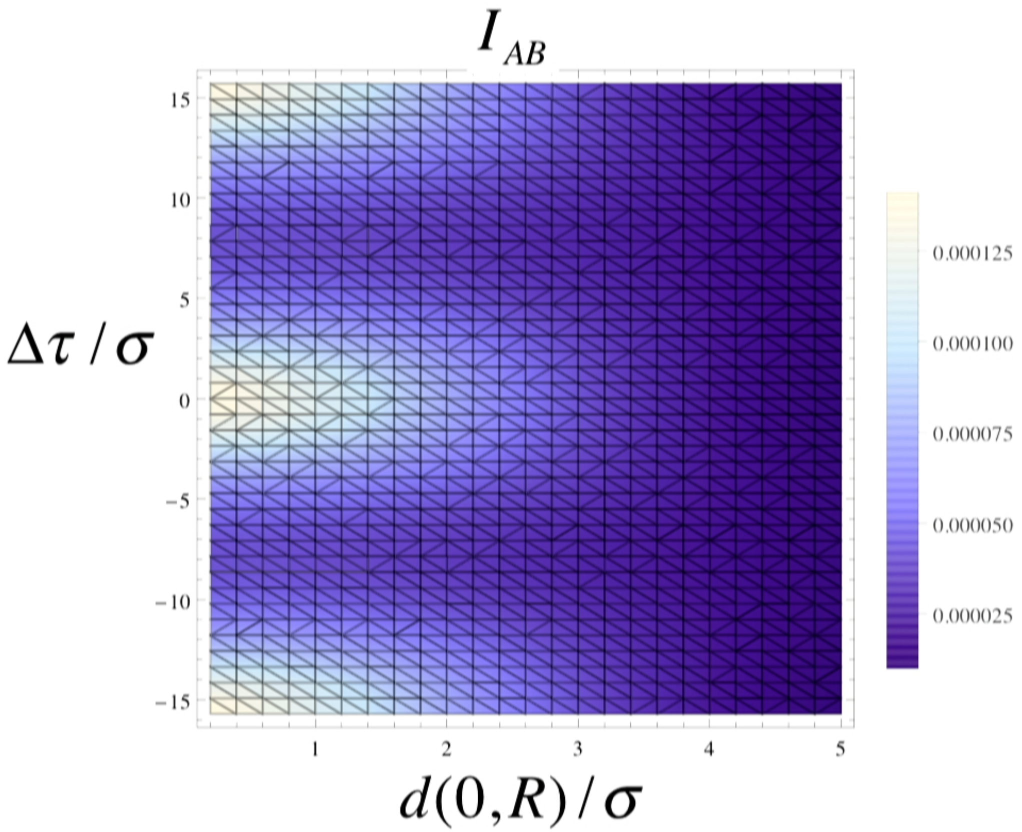


Time-Shift Dependence

$\Omega\sigma = 3$



Mutual Information



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- Black Holes Inhibit Entanglement
  - Competition between enhanced local excitations and and redshift erosion of non-local correlations