Title: TBA

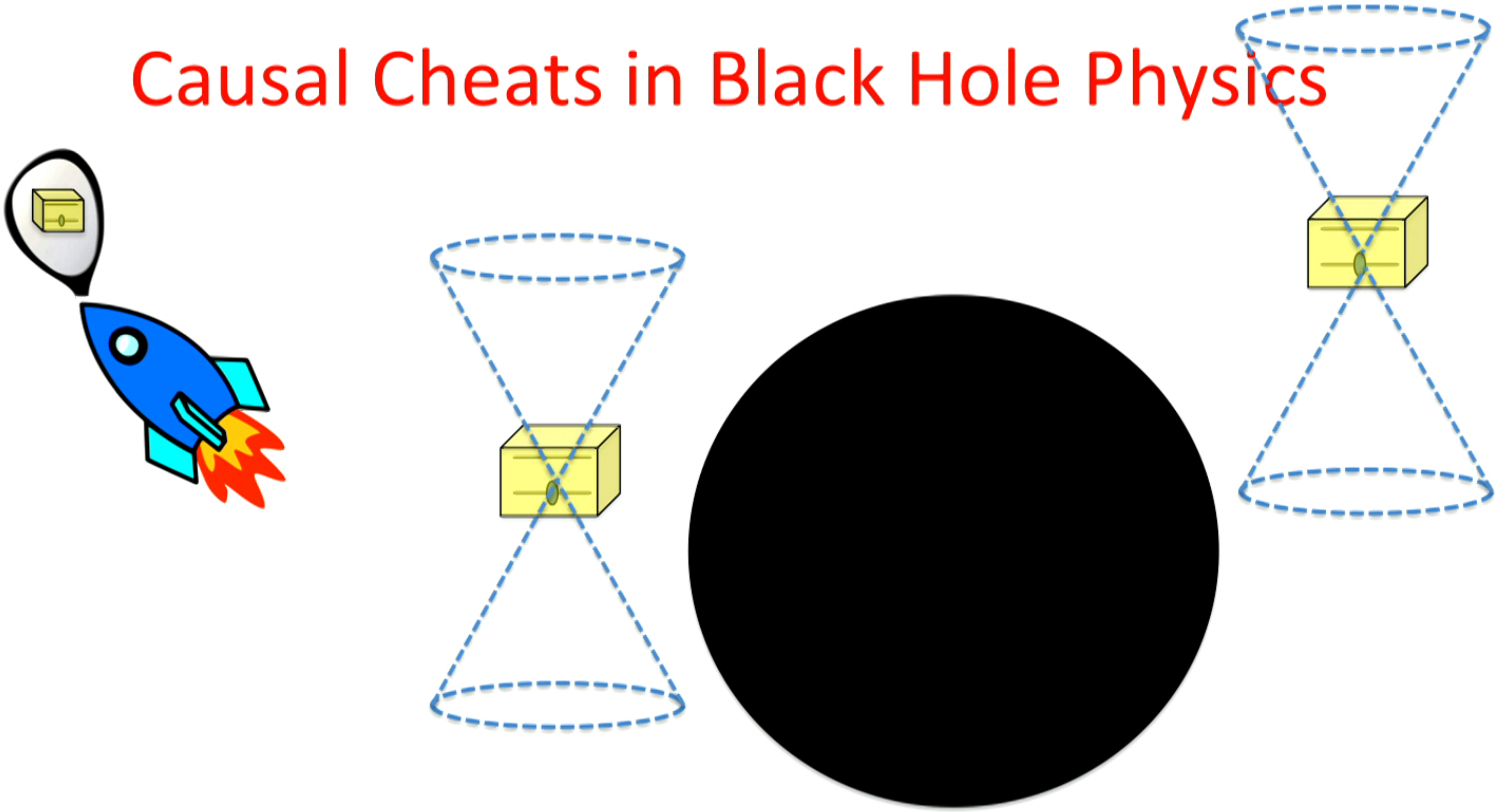
Speakers: Robert Mann

Collection: Indefinite Causal Structure

Date: December 12, 2019 - 11:20 AM

URL: http://pirsa.org/19120040

Causal Cheats in Black Hole Physics

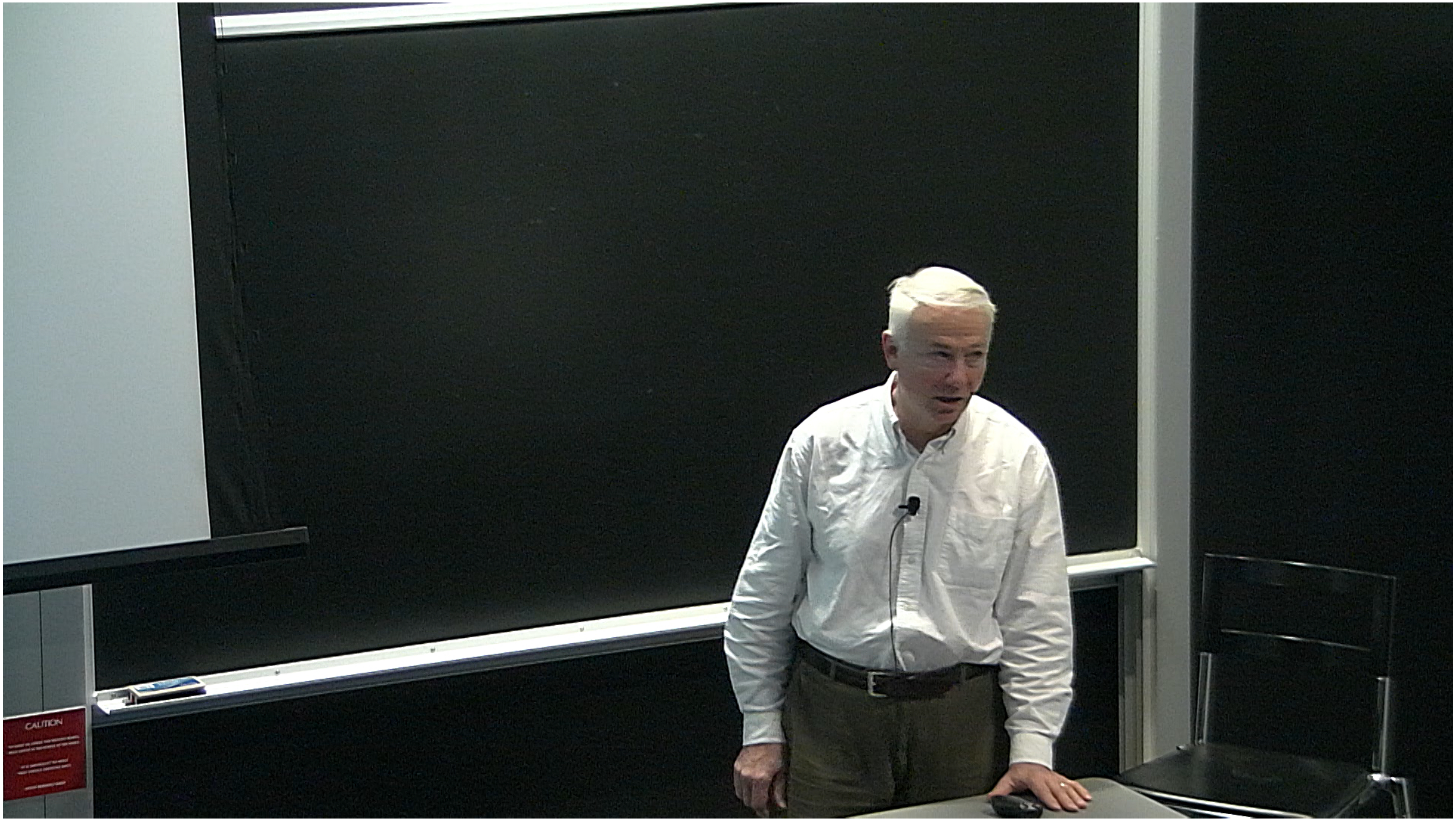


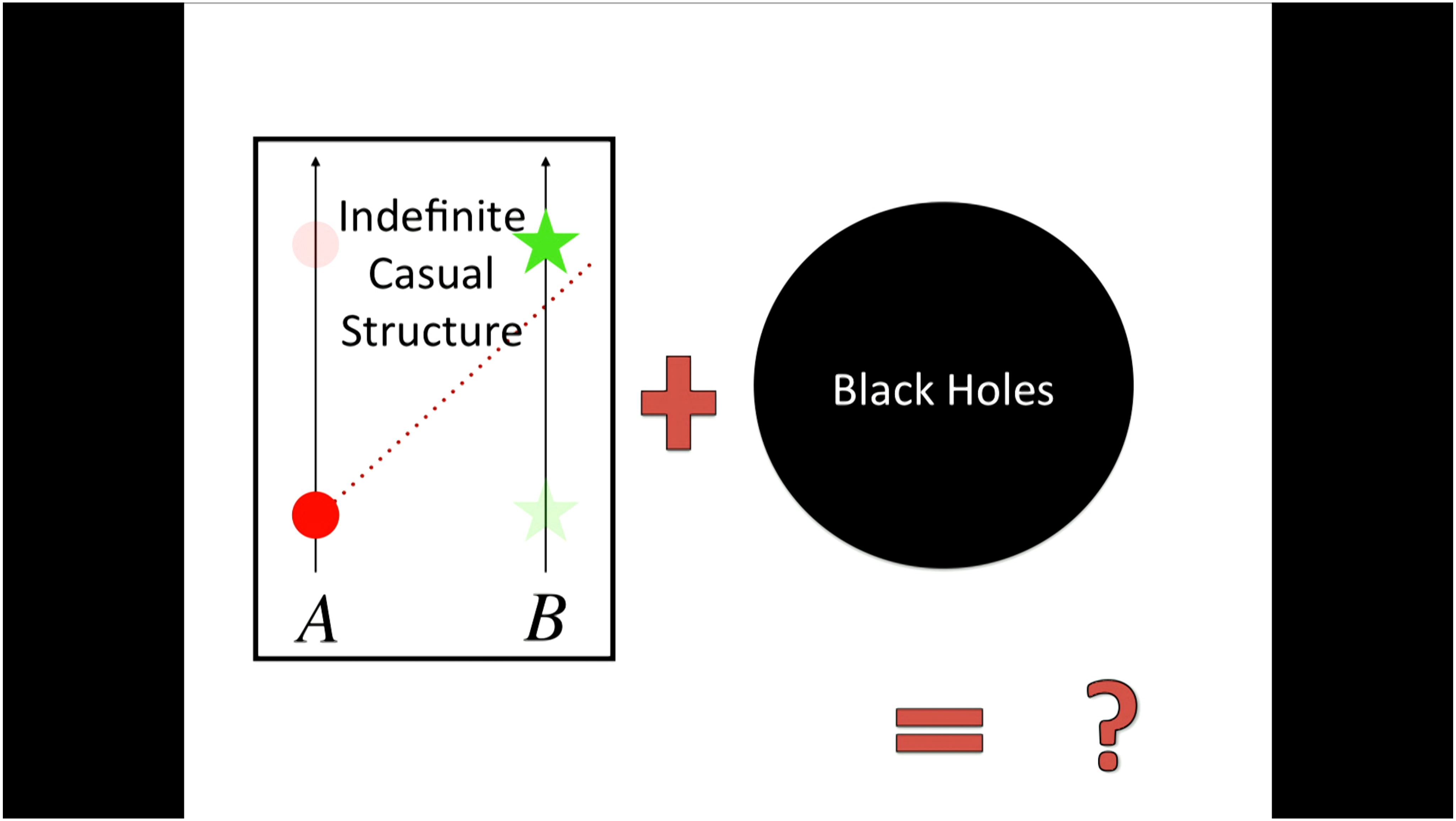
Robert B. Mann

W. Cong L. Henderson R. Hennigar K. Ng A. Smith E. Tjoa J. Zhang

E. Martin-Martinez A. Belenchia C. Brukner C. Budroni E. Castro-Ruiz

M. Zych



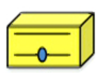

Indefinite
Casual
Structure
A
B
Black Holes
?

Causal Structure, Quantum Vacuum, and Black Holes

- Causal Structure
  - Particle Interactions and Decays
  - Information transfer and Signalling
  - Black Holes
- Black Holes
  - Hot `quantum vacuum' around black holes
  - Information paradox as black hole evaporates
- Quantum Vacuum
  - Noisy: Field Fluctuations and Correlations

Quantum Detectors

- Model systems that couple to quantum fields
  - Qubits, harmonic oscillators, Gaussian systems, …
  - Operational (only?) way to (empirically) learn about
    - Temperature, Entropy, Correlations, …
    - entanglement, mutual information, information paradox,…
    - Quantum gravity



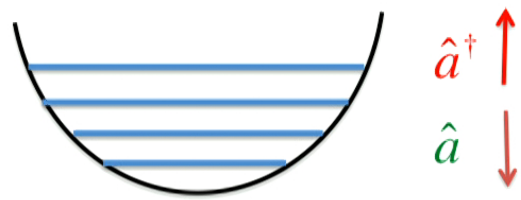
UdW (qubit)

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

Density Matrix

$$\rho = \sum_l p_l |\psi_l\rangle\langle\psi_l|$$

Harmonic Oscillator



Covariance Matrix

$$\sigma \equiv \begin{pmatrix} \langle \hat{q}^2 \rangle & \langle \hat{q}\hat{p} + \hat{p}\hat{q} \rangle \\ \langle \hat{q}\hat{p} + \hat{p}\hat{q} \rangle & \langle \hat{p}^2 \rangle \end{pmatrix}$$

Quantum Detectors

Vacuum

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

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

Action

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

Quantum Detectors

Vacuum

S-Y Lin, B.L.Hu PRD73 (2006) 124018
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$$S_I = \lambda_0 \int d\tau \int d^4 x Q(\tau)\Phi(x)\delta^4\left(x^\mu - z^\mu(\tau)\right)$$

Action

interaction

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

interaction

Cavity

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

$$H_I = \lambda(\tau)(\hat{a}_d e^{-i\Omega\tau} + \hat{a}_d^\dagger e^{i\Omega\tau})\sum_n \left(\hat{a}_n u_n[x(\tau),t(\tau)] + \hat{a}_n^\dagger u_n^*[x(\tau),t(\tau)]\right)$$

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

Detector Formalism

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

$$+\int d\tau\left\{\frac{m_0}{2}\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] + \sum_D \lambda_D \underbrace{\int d^4x Q_D(\tau)\Phi(x)\delta^4\left(x^\mu - z_D^\mu(\tau)\right)}_{H_{ID}(\tau) = \chi_D(\tau)\left[e^{i\Omega_D\tau}\sigma_D^+ + e^{-i\Omega_D\tau}\sigma_D^-\right]\Phi[z_D(\tau)]}\right\}$$

switcher

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

Detector Formalism

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

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

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

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

switcher

monopole operator

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

$$\sigma_D^+:=|1_D\rangle\langle 0_D|=|e_D\rangle\langle g_D|$$

$$\sigma_D^+:=|0_D\rangle\langle 1_D|=|g_D\rangle\langle e_D|$$

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

switcher

monopole operator

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$$\rho_{AB}:=\mathrm{Tr}_\Phi\left(U|\Psi\rangle\langle\Psi|U^\dagger\right)=\begin{pmatrix}1-P_A-P_B & 0 & 0 & X\\ 0 & P_B & C & 0\\ 0 & C^* & P_A & 0\\ X^* & 0 & 0 & E\end{pmatrix}$$

Initial State
$|\Psi\rangle=|0\rangle_A|0\rangle_B|0\rangle_\Phi$

$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle \qquad \tau_D = \gamma_D t$$

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

$$W(\tau - i/T_{\mathrm{KMS}}, \tau') = W(\tau', \tau)$$

KMS Field temperature

$$R = \frac{P(\Omega)}{P(-\Omega)} \qquad T_{\mathrm{EDR}} = -\frac{\Omega}{\log R}$$

Detector temperature

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

Local excitations

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

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

$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle \qquad \tau_D = \gamma_D t$$

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

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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

$$W(x,x') := \langle 0|\phi(x)\phi(x')|0\rangle \qquad \tau_D = \gamma_D t$$

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

$$W(\tau - i/T_{\text{KMS}}, \tau') = W(\tau', \tau)$$ KMS Field temperature

$$R = \frac{P(\Omega)}{P(-\Omega)} \qquad T_{\text{EDR}} = -\frac{\Omega}{\log R}$$ Detector temperature

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Concurrence

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

Cheat #1: Unfamiliar Unruh Effects

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

Cheat #1: Unfamiliar Unruh Effects

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

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

Fuentes-Schuller/Mann PRL95 12404 (2005) Alsing/Fuentes-Schuller/ Mann/Tessier PRA74 032326 (2006)

- A cold vacuum to one observer is a hot vacuum to another
- Quantum entanglement between one pair of observers is degraded entanglement between another pair
- Causally inaccessible region with *eternally accelerating detectors* ➔ thermality and entanglement degradation
- How necessary is this idealization?
  - Finite time and distance effects (cavities, switching)
  - Boundary conditions
  - Non-perturbative effects; non-equilibrium effects
  - Causal structure (or lack therof)
  - Topological features

Oscillating Vacuum Detectors

$$S = -\int d^4x\sqrt{-g}\,\frac{1}{2}\partial_\mu\Phi(x)\partial^\mu\Phi(x)$$

J. Doukas, S-Y Lin, B. Hu, RBM
JHEP **1311** (2013) 119

$$+\int d\tau\left\{\frac{m_0}{2}\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] + \lambda_0\int d^4x\,Q(\tau)\Phi(x)\delta^4\left(x^\mu - z^\mu(\tau)\right)\right\}$$

Do oscillating detectors get hot?
And how?

Effective Temperature

$$T_{\text{eff}}(\tau) = \left[\frac{k_B}{\hbar\Omega_r}\ln\left(\frac{U(\tau)+\hbar/2}{U(\tau)-\hbar/2}\right)\right]^{-1}$$

Uncertainty Function

$$U(\tau) \equiv \sqrt{\langle\hat{P}^2(\tau)\rangle\langle\hat{Q}^2(\tau)\rangle - \langle\hat{Q}(\tau),\hat{P}(\tau)\rangle^2}$$

Oscillating Vacuum Detectors

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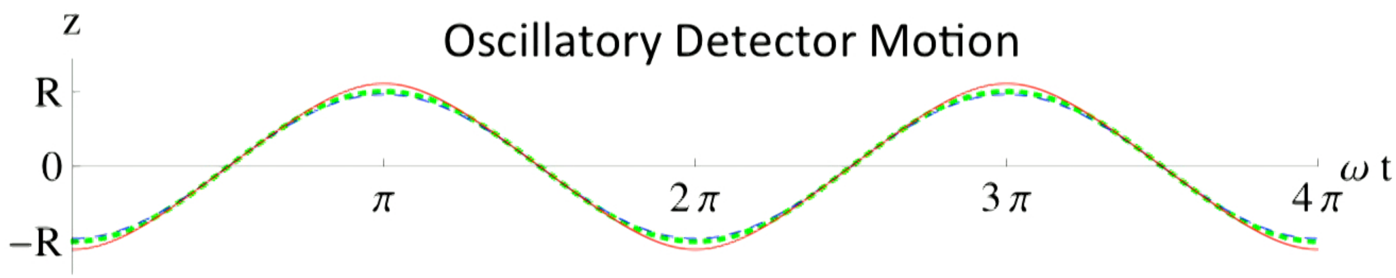
Uncertainty Function

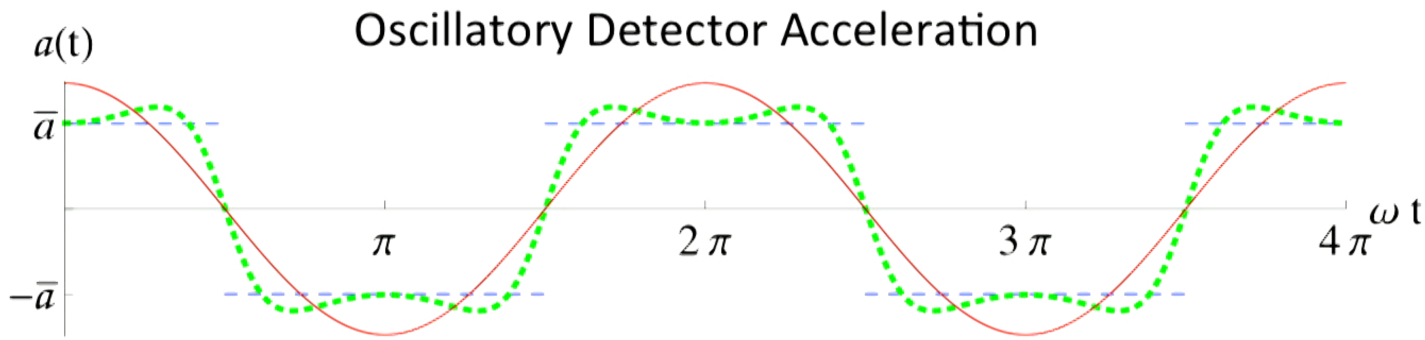
$$U(\tau) \equiv \sqrt{\langle\hat{P}^2(\tau)\rangle\langle\hat{Q}^2(\tau)\rangle - \langle\hat{Q}(\tau),\hat{P}(\tau)\rangle^2}$$

$$\mathrm{v}_{ij}(\tau) = \langle\hat{R}_i(\tau),\hat{R}_j(\tau)\rangle$$

Covariance matrix

$$\hat{R}_i(\tau) = \left(\hat{Q}(\tau),\hat{P}(\tau)\right)$$





Sinusoidal Motion

SM $z^{\mu}_{\mathrm{SM}}(t) = \left(t, 0, 0, -R\cos\omega t\right)$

Chen-Tijima (Sinusoidal Acc'n)

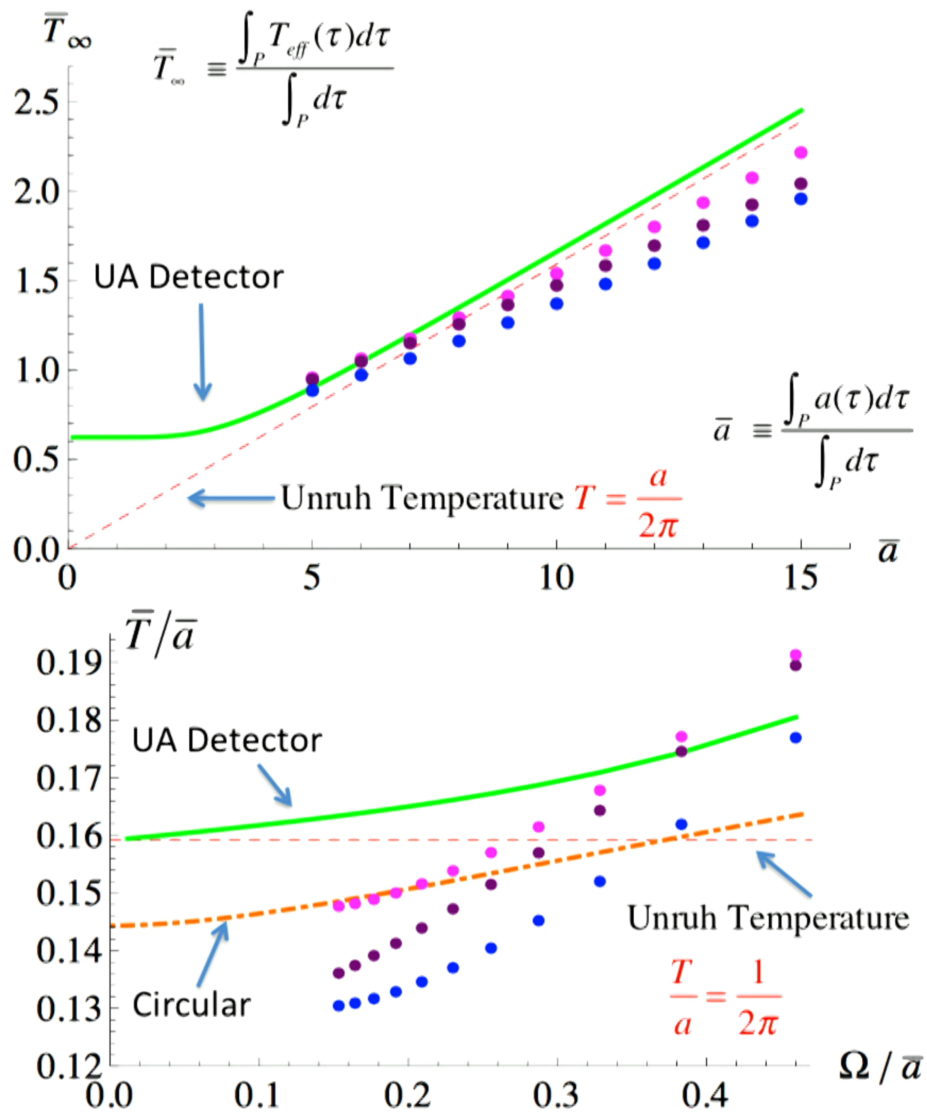
CT $z^{\mu}_{\mathrm{CT}}(t) = \left(t, 0, 0, -\frac{1}{\omega}\sin^{-1}\frac{2a_0\cos\omega t}{\sqrt{1+4a_0^2}}\right)$

Alternating Uniform Acceleration

$$z^{\mu}_{\mathrm{AUA}}(\tau) =$$

$$\left(\frac{1}{a}\left[\sinh a\left(\tau - \frac{n\tau_p}{2}\right) + 2n\sinh\frac{a\tau_p}{4}\right], 0, 0, \frac{(-1)^n}{a}\left[\cosh a\left(\tau - \frac{n\tau_p}{2}\right) + \left\{(-1)^n - 1\right\}\cosh\frac{a\tau_p}{4}\right]\right)$$

Results



CT worldline

SM worldline

AUA worldline

$$\omega = 20$$

$$\gamma \equiv \lambda_0^2 / 8\pi m_0 = 0.01$$

$$\Omega \equiv \sqrt{\Omega_r^2 - \gamma^2} = 2.3$$

$$\Lambda = -\ln \frac{\hbar\Omega_R}{E_{\text{cutoff}}} = 20$$

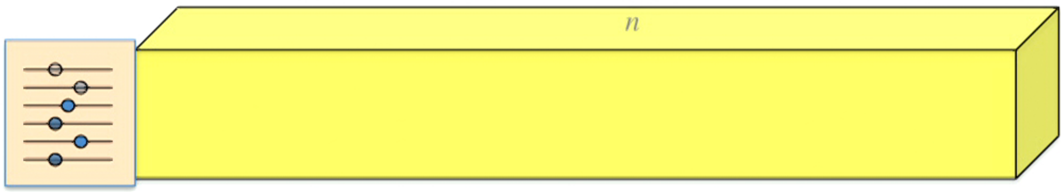
Cavity Detectors

W. Brenna, E.G. Brown, E. Martin-Martinez, RBM PR**D88** (2013) 064031

Ahmadi/Lorek/Checinska/Smith/ RBM /Dragan PRD**93** (2016) 124031

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

$$+ \lambda(\tau)(\hat{a}_d e^{-i\Omega\tau} + \hat{a}_d^\dagger e^{i\Omega\tau}) \sum_n \left(\hat{a}_n u_n[x(\tau),t(\tau)] + \hat{a}_n^\dagger u_n^*[x(\tau),t(\tau)] \right)$$

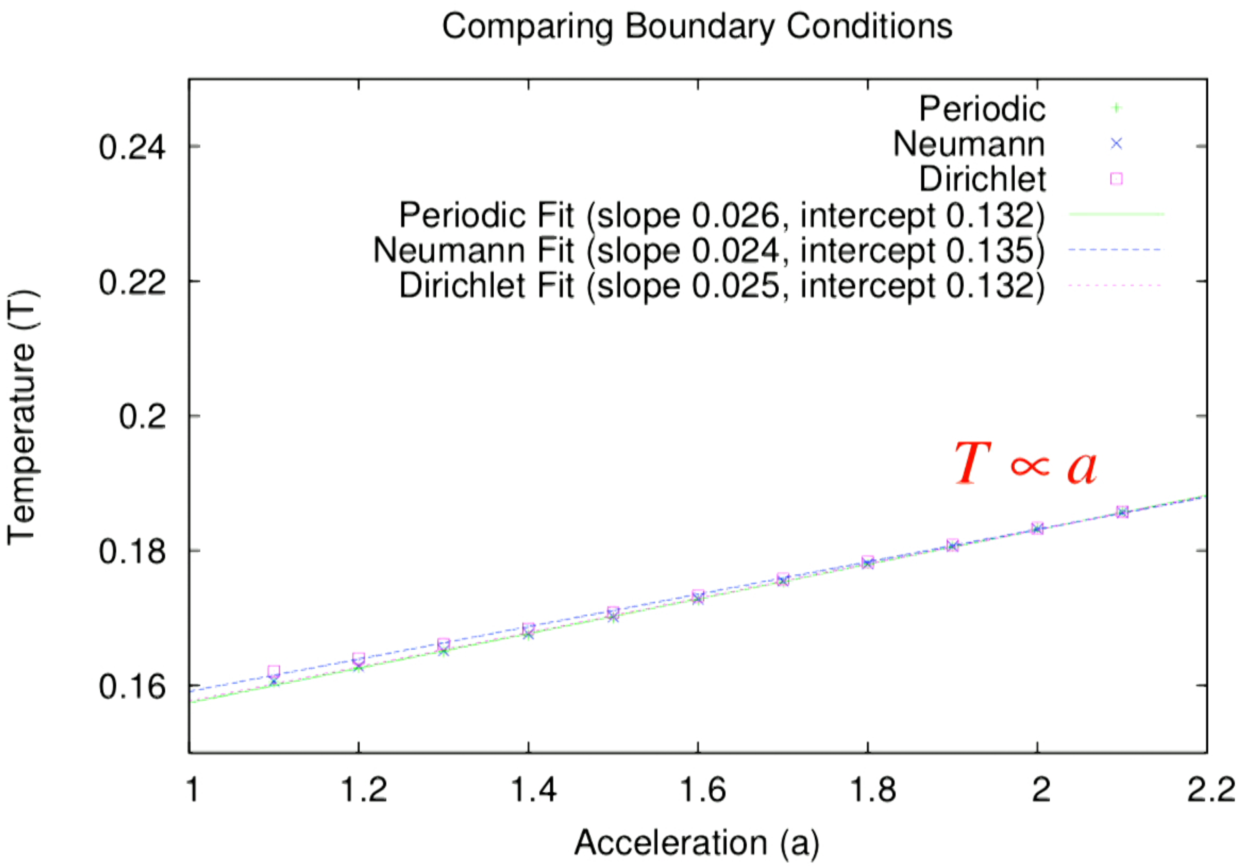


Brown/Martin-Martinez/ Menicucci/ RBM PRD87 (2013) 084062

D. Bruschi, A. Lee, I Fuentes J. Phys A46 (2013) 165303

- Non-perturbative formalism
  - Switching Effects can be smoothed out
  - Can avoid acausal signalling to desired accuracy

Results

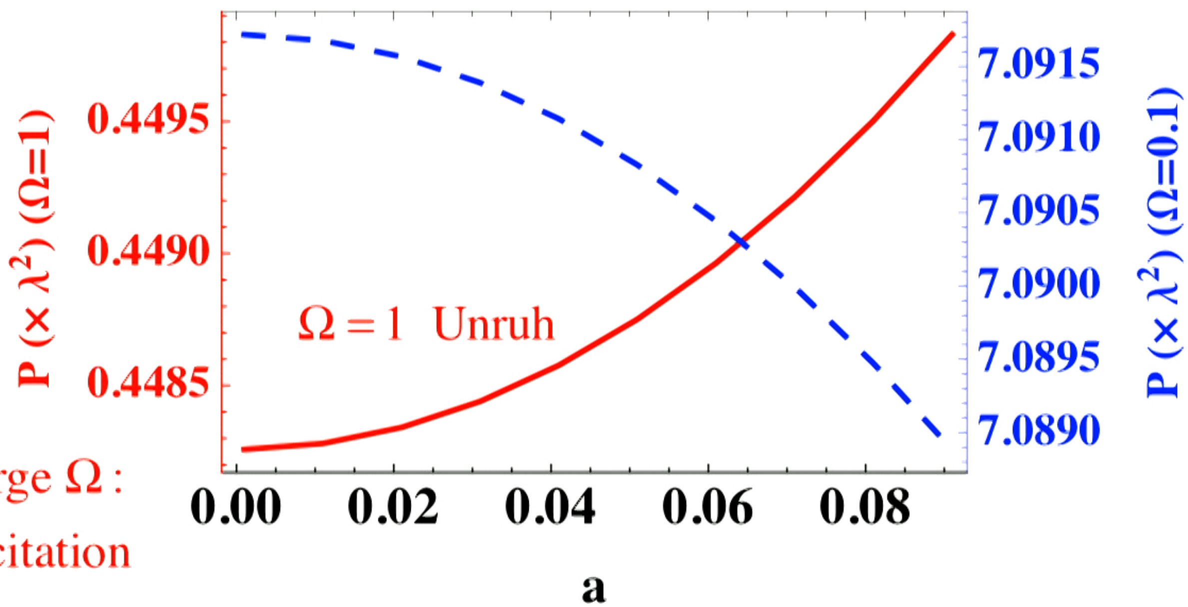


- Temperature ~ Acceleration ~ Gravity
- But the slope is wrong

$$T \neq \frac{a}{2\pi}$$

Smaller accelerations?

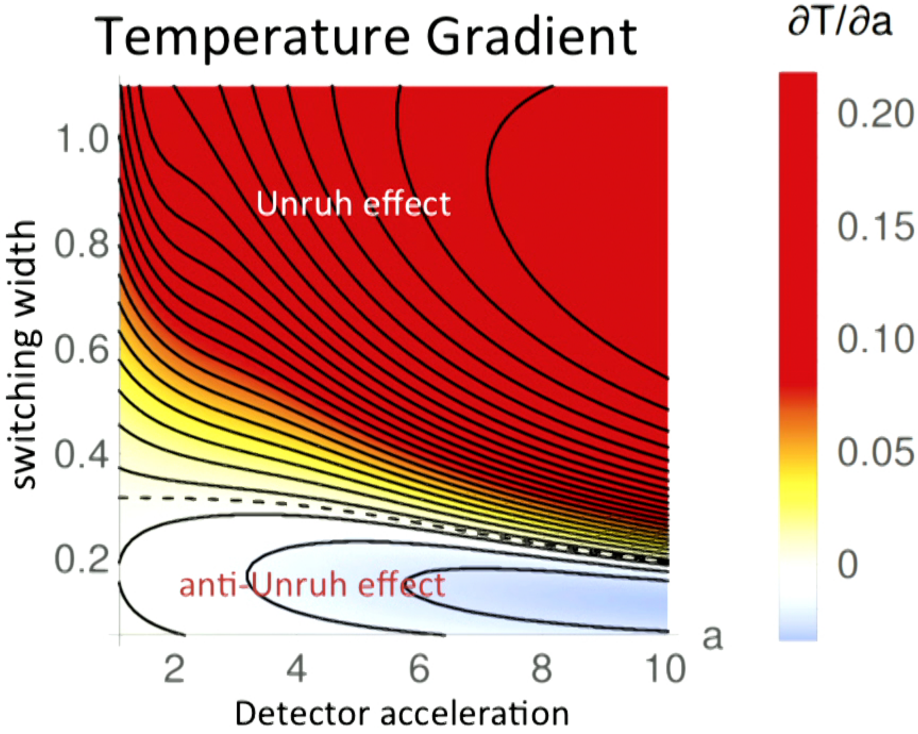
W. Brenna,
E. Martin-Martinez, RBM
PLB**757** (2016) 307



$L = 200$

$\sigma = 0.4$

Large Ω: excitation increases with a



Not a transient effect!

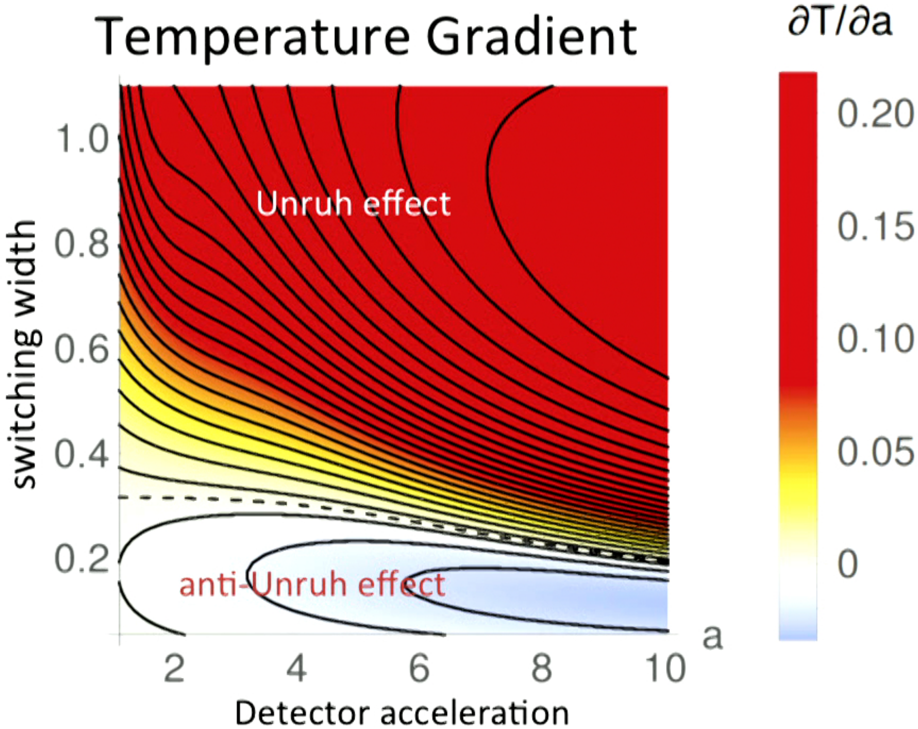
L. Garay, E. Martin-Martinez, J. Ramon
PRD**94** (2016) 3104048

$$W(\tau - i/T_{\mathrm{KMS}}, \tau') = W(\tau', \tau)$$

Field Temperature

$$R = \frac{P(\Omega)}{P(-\Omega)}$$ Excitation Detector Ratio

$$T_{\mathrm{EDR}} = -\frac{\Omega}{\log R}$$ Detector Temperature



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Field Temperature

$$R = \frac{P(\Omega)}{P(-\Omega)}$$ Excitation Detector Ratio

$$T_{\rm EDR} = -\frac{\Omega}{\log R}$$ Detector Temperature

Weak AU effect $\frac{dP(\Omega)}{dT} < 0$

- Can persist even for infinite interaction time
- Detector clicks less often as temperature increases

Strong AU effect

$T_{\rm EDR} \downarrow$ as $T_{\rm KMS} \uparrow$

- Thermalized detectors
- Recorded detector temperature decreases as KMS Field temperature increases

Cheat #2: The Anti-Hawking Effect

- 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

field

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

switch

monopole operator

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

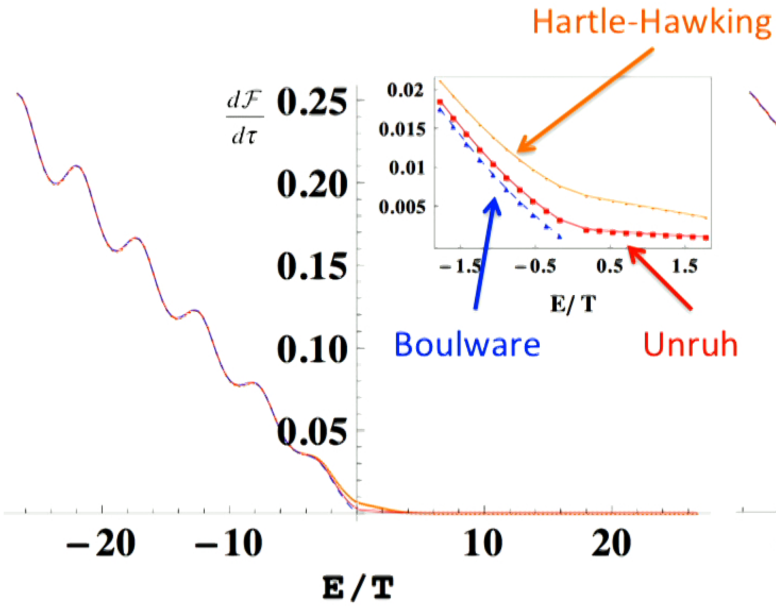
Wightman function

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

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

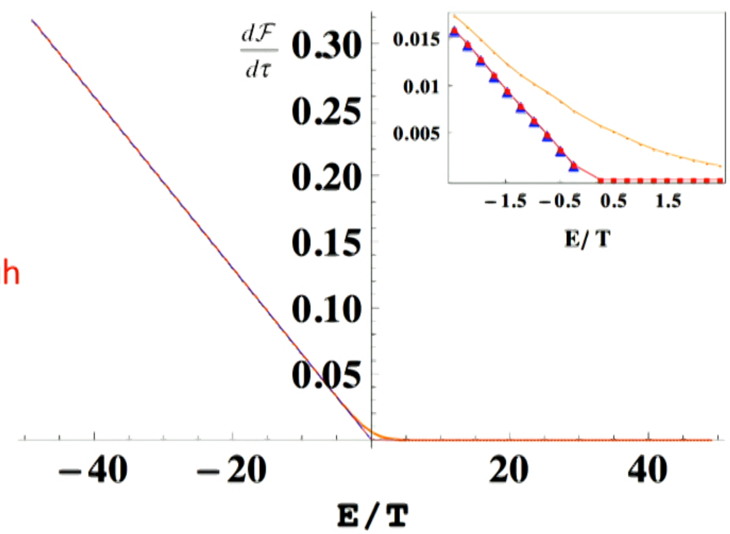
Detector Response: Schwarzschild

Hodgkinson/Louko/Ottewill
PRD89 (2014) 104002



(a) $R = 4M$

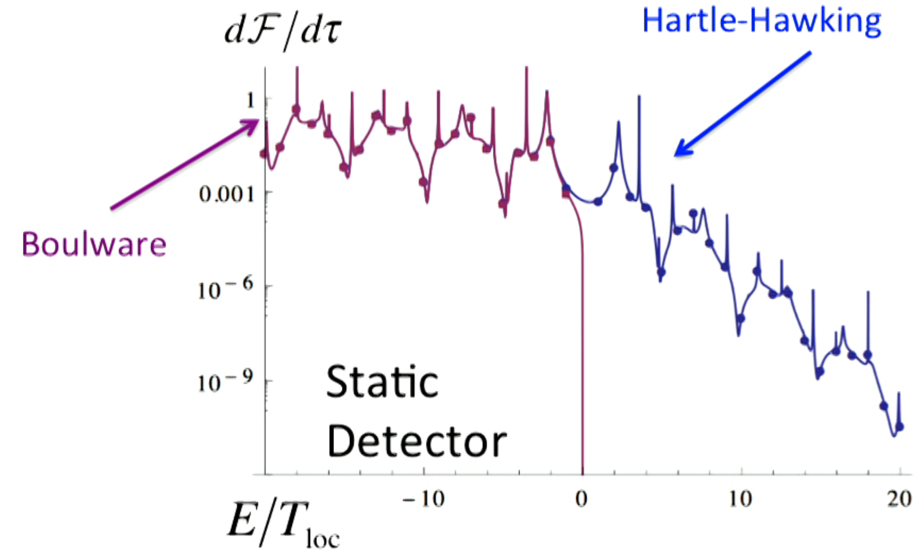
Static Detector



(b) $R = 40M$

Detector Response: Schwarzschild-AdS

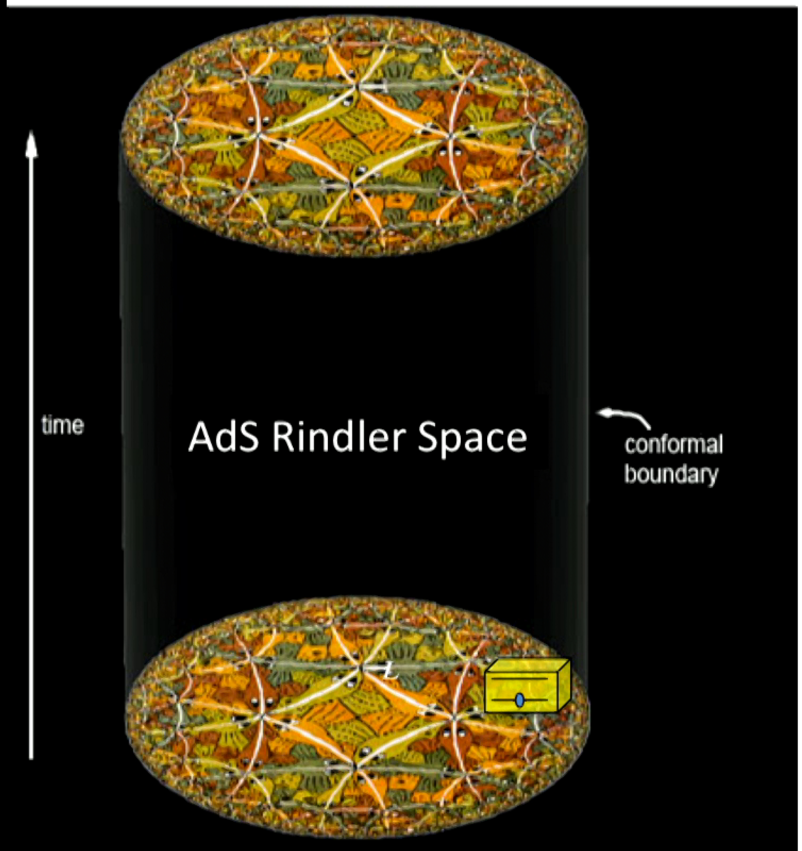
Ng/ Hodgkinson/Louko/RBM/Martin-Martinez
PRD90 (2014) 064003

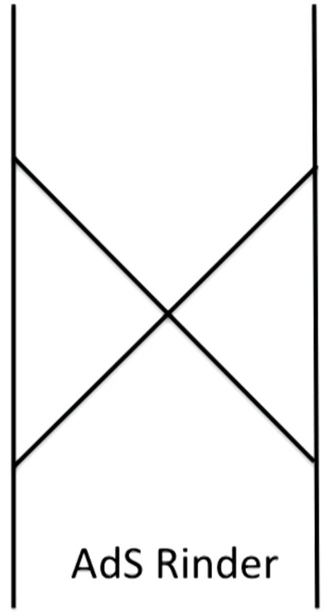


- Spikes due to Quasinormal mode resonances
- Visible only when black hole is much smaller than AdS length
- Peaks become higher and sharper as black hole size decreases
- Detectors provide (empirical) information about the quasinormal modes of the black hole!

The anti-Hawking Effect

Henderson/Hennigar/
Smith/Zhang/RBM
1911.02977





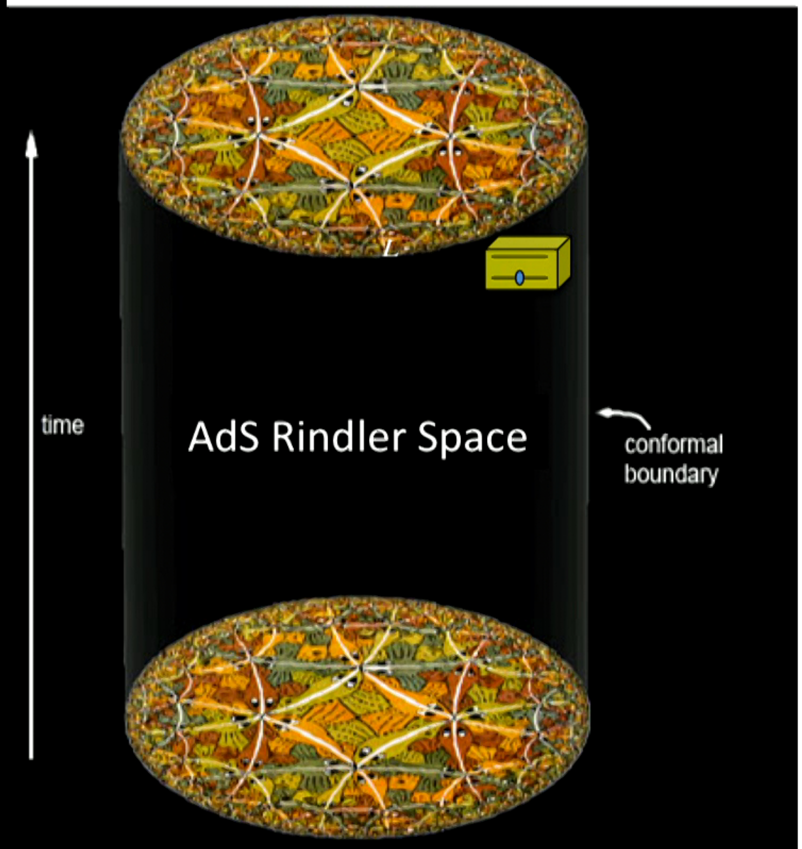
$$f(r)=\left(\frac{r^2}{\ell^2}-1\right)$$

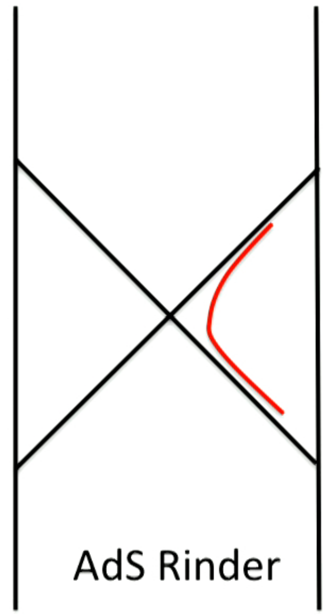
$$ds^2=-f(r)dt^2+\frac{dr^2}{f(r)}+r^2dx^2$$

$$x\in\mathbf{R}$$

The anti-Hawking Effect

Henderson/Hennigar/
Smith/Zhang/RBM
1911.02977





$$f(r) = \left(\frac{r^2}{\ell^2} - 1\right)$$

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

$$x \in \mathbf{R}$$

Accelerating detector in AdS gets hot above a certain threshold acceleration

$$T_{\mathrm{KMS}} = \frac{\sqrt{a^2\ell^2 - 1}}{2\pi\ell}$$

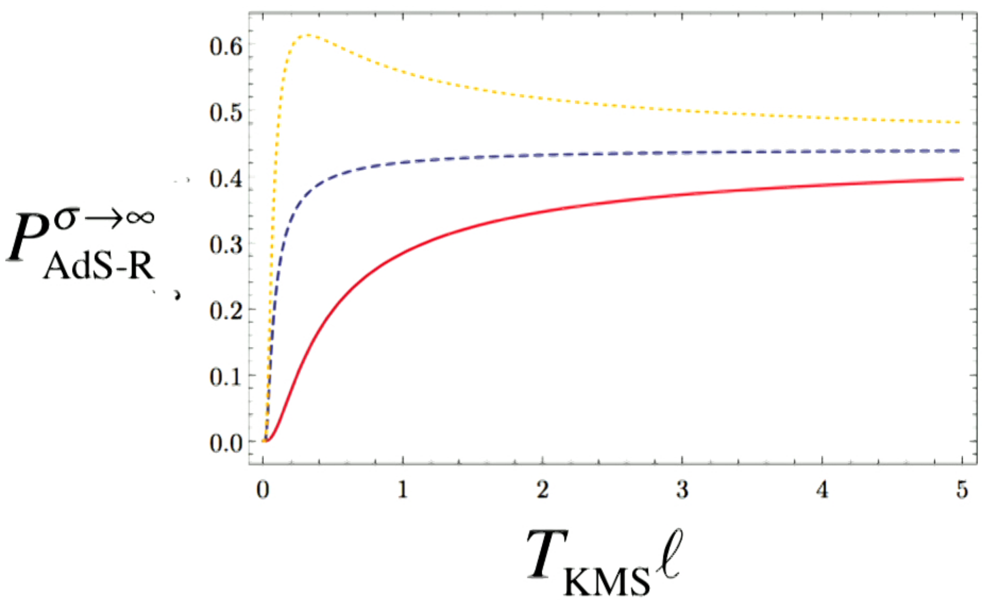
Jennings
CQG**27** (2010)
205005

AdS Rindler Response Function

Henderson/Hennigar/Smith/Zhang/RBM
1911.02977

$$P_{\text{AdS-R}} = \frac{\sqrt{\pi}}{4} - \frac{i}{4\sqrt{\pi}} \mathrm{PV}\int_{-\infty}^{\infty} dz \frac{e^{-z^2/(2\pi T_{\text{KMS}}\sigma)^2} e^{-i\Omega z/(\pi T_{\text{KMS}})}}{\sinh z} - \frac{\zeta}{2\sqrt{2\pi}} \mathrm{Re}\int_0^{\infty} dz \frac{e^{-z^2/(4\pi T_{\text{KMS}}\sigma)^2} e^{-i\Omega z/(2\pi T_{\text{KMS}})}}{\sqrt{1+8\pi^2\ell^2 T_{\text{KMS}}^2 - \cosh z}}$$

$$P_{\text{AdS-R}}^{\sigma\to\infty} = \frac{\sqrt{\pi}}{4}\left[1-\tanh\left(\frac{\Omega}{2\,T_{\text{KMS}}}\right)\right]\left\{1-\zeta P_{-\frac{1}{2}+\frac{i\Omega}{2\pi T_{\text{KMS}}}}\left(1+8\pi^2\ell^2 T_{\text{KMS}}^2\right)\right\}$$



$\varsigma = 1$ Dirichlet

$\varsigma = 0$ Transparent

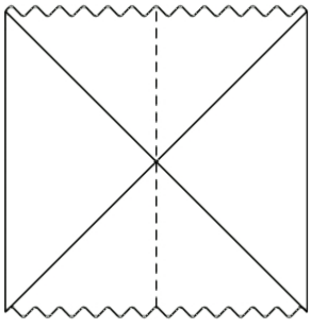
$\varsigma = -1$ Neumann

$$T_{\text{KMS}} = \frac{\sqrt{a^2\ell^2 - 1}}{2\pi\ell}$$

$$a = R_D/\ell$$

BTZ Black Hole

Henderson/Hennigar/Smith/Zhang/RBM
1911.02977



$$T_{\mathrm{BTZ}} = \frac{\sqrt{\ell^2 M}}{2\pi}$$

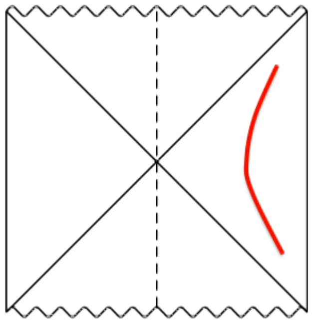
AdS with Identification

$$f(r) = \left(\frac{r^2}{\ell^2} - M\right) \qquad \phi \in (0, 2\pi)$$

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

BTZ Black Hole

Henderson/Hennigar/Smith/Zhang/RBM
1911.02977



$$T_{\rm BTZ} = \frac{\sqrt{\ell^2 M}}{2\pi}$$

$$a = {}^{R_D}\!/_{\ell}$$

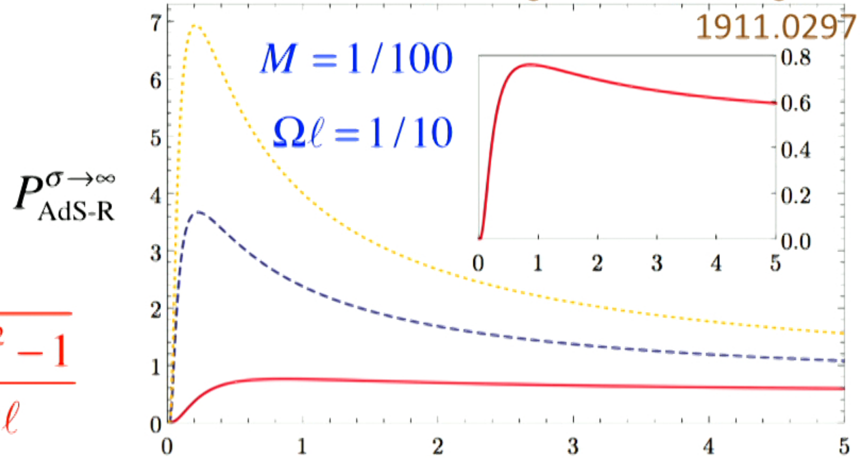
$$T_{\rm KMS}^{\rm local} = \frac{\sqrt{a^2\ell^2 - 1}}{2\pi\ell}$$

AdS with Identification

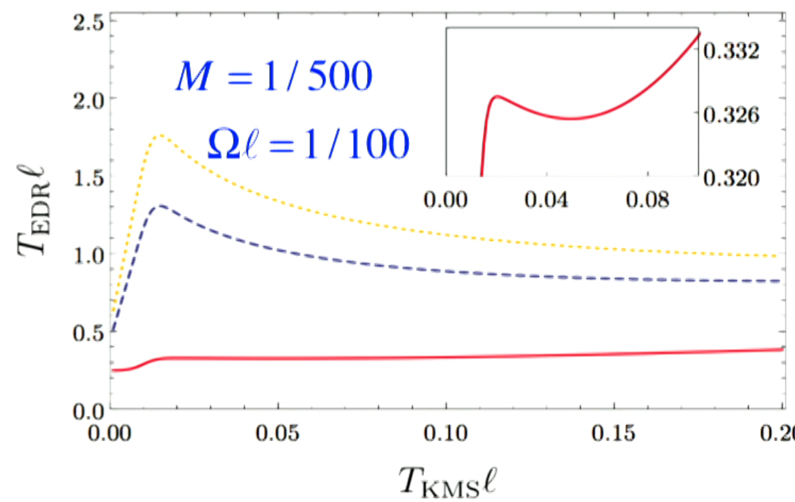
$$f(r) = \left(\frac{r^2}{\ell^2} - M\right) \qquad \phi \in (0, 2\pi)$$

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

$$W_{\rm BTZ}(x,x') = \sum_{n=-\infty}^{\infty} W_{\rm AdS_3}(x, \Gamma^n x')$$



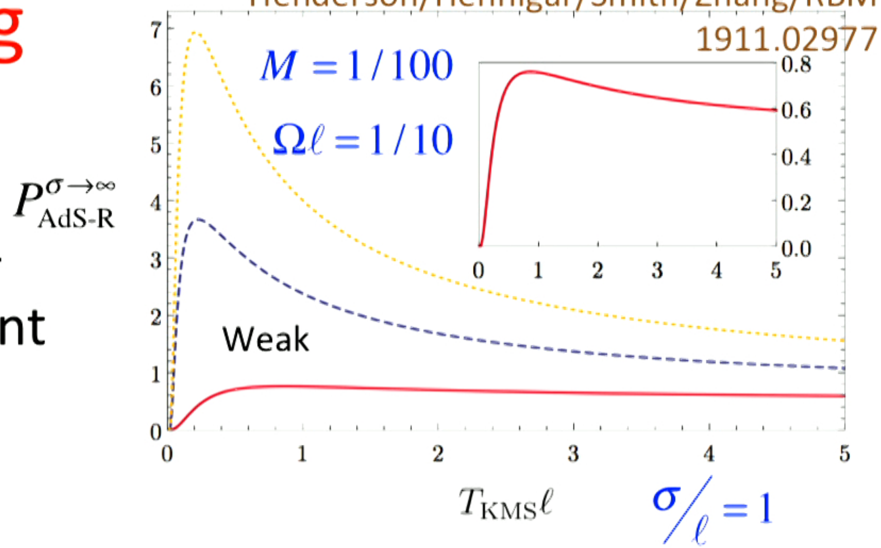
$\sigma/\ell = 1$

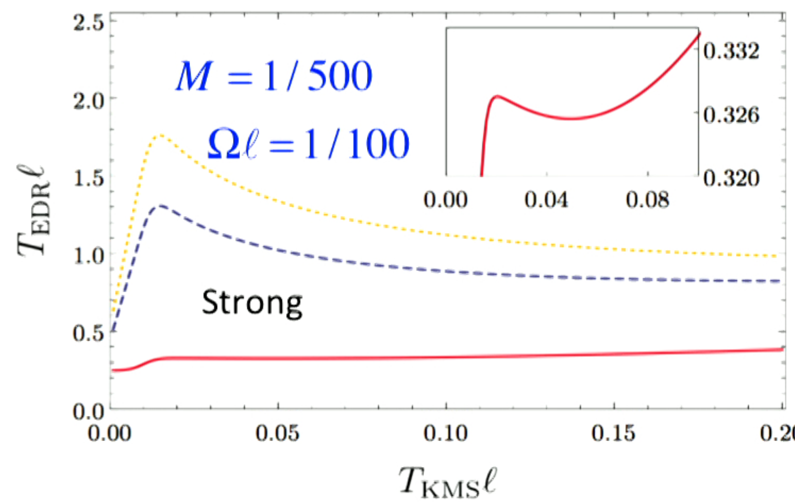


The anti-Hawking Effect

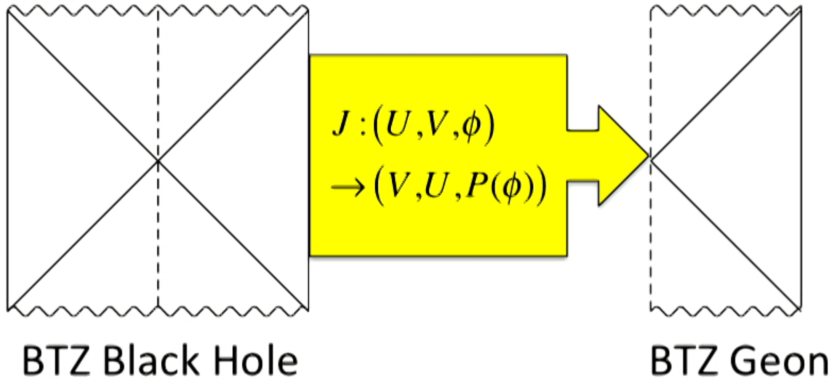
- Weak and Strong anti-Hawking effects present for all boundary conditions
- Small mass effect: expected behaviour occurs for large mass
- Detailed balance satisfied over range of parameters considered

Henderson/Hennigar/Smith/Zhang/RBM
1911.02977





Cheat #3: Looking Inside Black Holes



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

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

$$=\frac{\ell^2\left[4\mathrm{d}U\mathrm{d}V-M(1-UV)^2\,d\phi^2\right]}{(1+UV)^2}$$

Louko Lect.Notes Phys. 541:188 (2000)
Louko/RBM/Marolf CQG22 (2005) 1451

- No classical way of distinguishing these spacetimes
- Topological features hidden behind horizon
- Can a UdW detector `look' inside a black hole?

Smith/RBM CQG**31** (2014) 082001

$$W^{(\zeta)}(x,x')=\frac{1}{4\pi}\left(\frac{1}{\sqrt{\Delta X^2(x,x')}}-\frac{\zeta}{\sqrt{\Delta X^2(x,x')+4\ell^2}}\right)$$

$$G_{\mathrm{BTZ}}(x,x')=\sum_n G_A^{(\zeta)}\left(x,\Lambda^n x'\right) \qquad G_{\mathrm{geon}}(x,x')=\sum_{m\in\{0,1\}} G_{\mathrm{BTZ}}^{(\zeta)}\left(x,J^m x'\right)$$

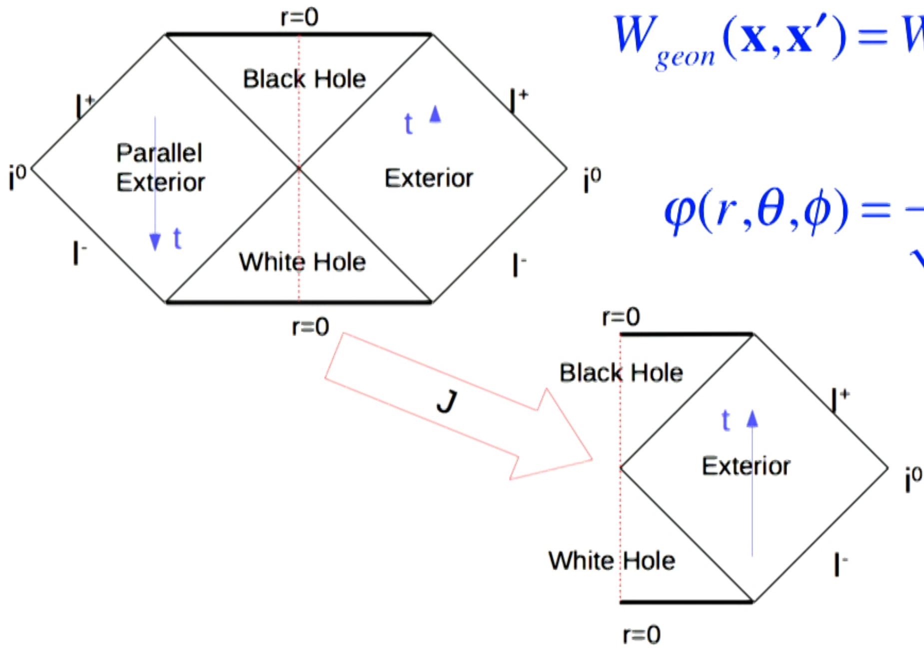
Schwarzschild Geon

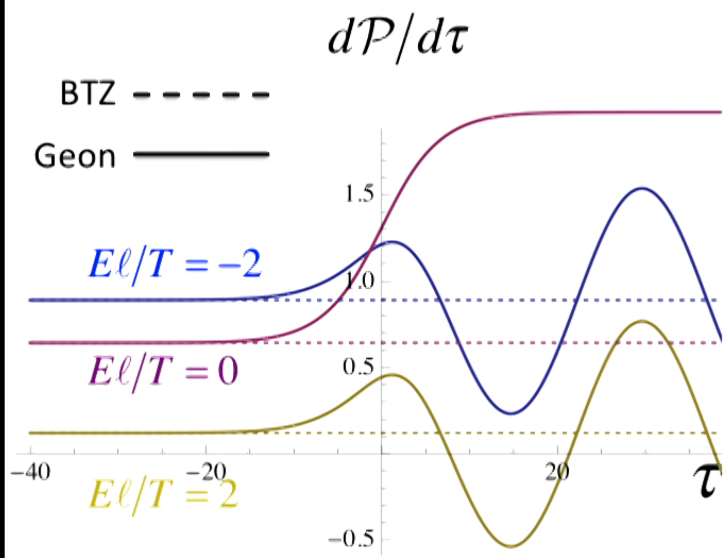
Ng/RBM/Martin-Martinez
PRD**96** (2017) 085004

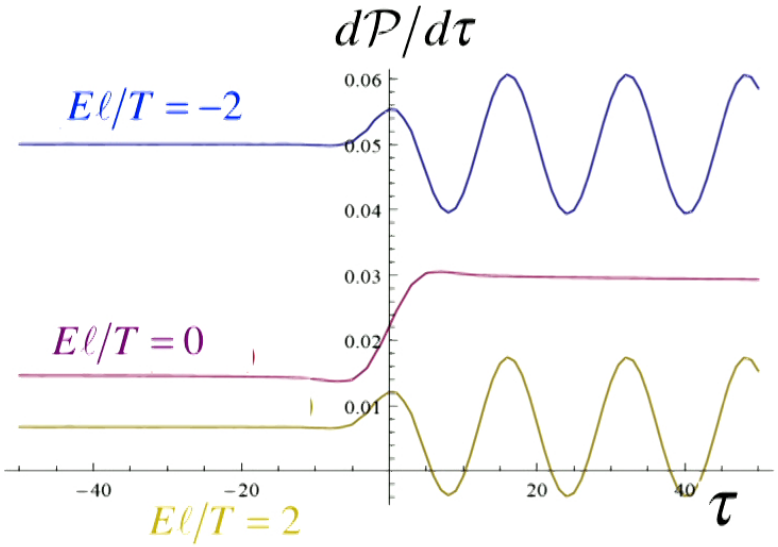
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\theta^2 + \sin^2\theta d\phi^2 \qquad f(r) = \left(1 - \frac{2M}{r}\right)$$

$$W_{geon}(\mathbf{x},\mathbf{x}') = W_{BH}(\mathbf{x},\mathbf{x}') + W_{BH}(\mathbf{x},J(\mathbf{x}'))$$

$$\varphi(r,\theta,\phi) = \frac{1}{\sqrt{4\pi\omega}} e^{-i\omega t} R_{\omega l}^{\mathrm{up,in}}(r) Y_{lm}(\theta,\phi)$$







BTZ Geon

Smith/RBM CQG31 (2014) 082001

Schwarzschild Geon

Ng/RBM/Martin-Martinez
PRD 96 (2017) 085004

- Time dependence due to indefinite sign of Killing vector at origin
- Distinction vanishes at large distances and at past/future infinity

$$\frac{d\mathcal{P}}{d\tau}(E) = \frac{d\mathcal{P}}{d\tau}_{\text{BTZ}}(E) + \Delta\frac{d\mathcal{P}}{d\tau}(E,\tau)_{\text{geon}}$$

Cheat #4: The Entangling Power of (anti) de Sitter Space

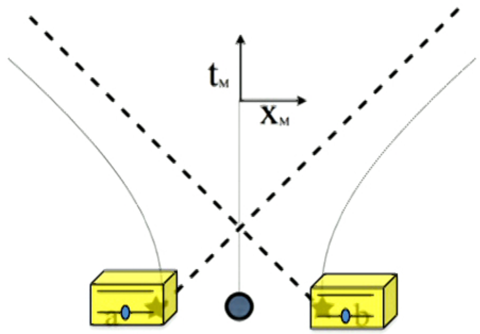
- Single detector in de Sitter Spacetime

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

Gibbons/Hawking
PRD (1979)

- Cannot distinguish from a heat bath at the same T
  But 2 detectors can extract vacuum entanglement
- Entanglement in de Sitter space differs from entanglement in a heat bath!

Ver Steeg/Menicucci
PRD**79** (2009) 044027



Cheat #4: The Entangling Power of (anti) de Sitter Space

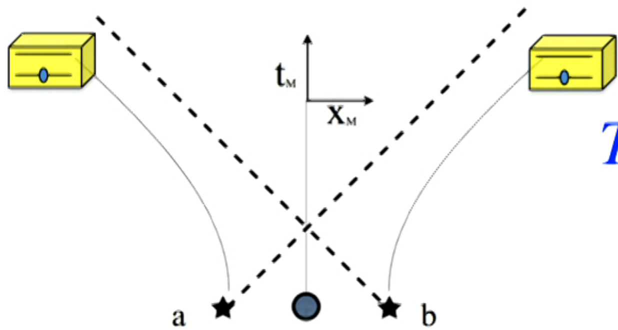
- Single detector in de Sitter Spacetime

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

Gibbons/Hawking PRD (1979)

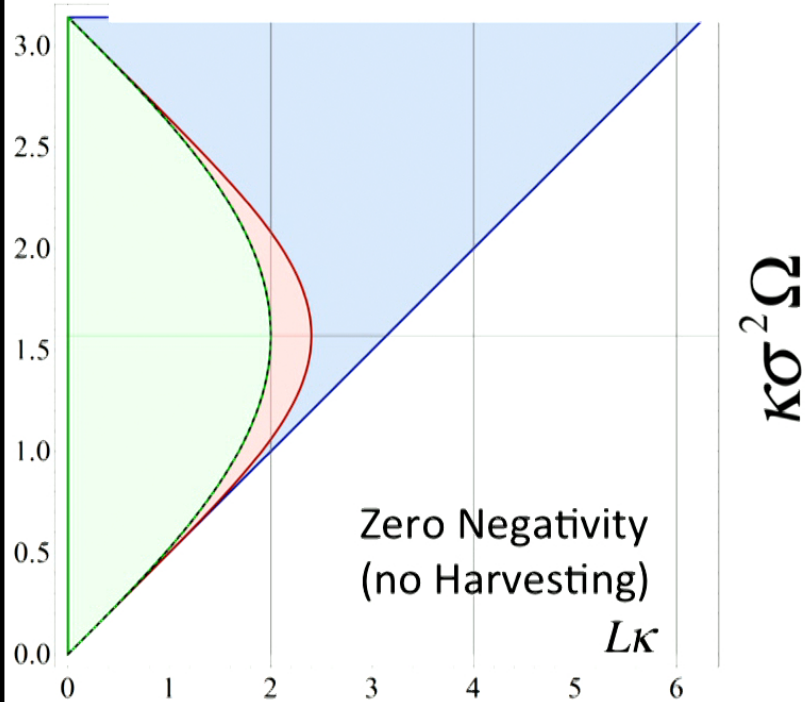
- Cannot distinguish from a heat bath at the same T But 2 detectors can extract vacuum entanglement
- Entanglement in de Sitter space differs from entanglement in a heat bath!

Ver Steeg/Menicucci PRD**79** (2009) 044027



$$T = \frac{1}{2\pi\ell}$$

Entangling Accelerating Detectors



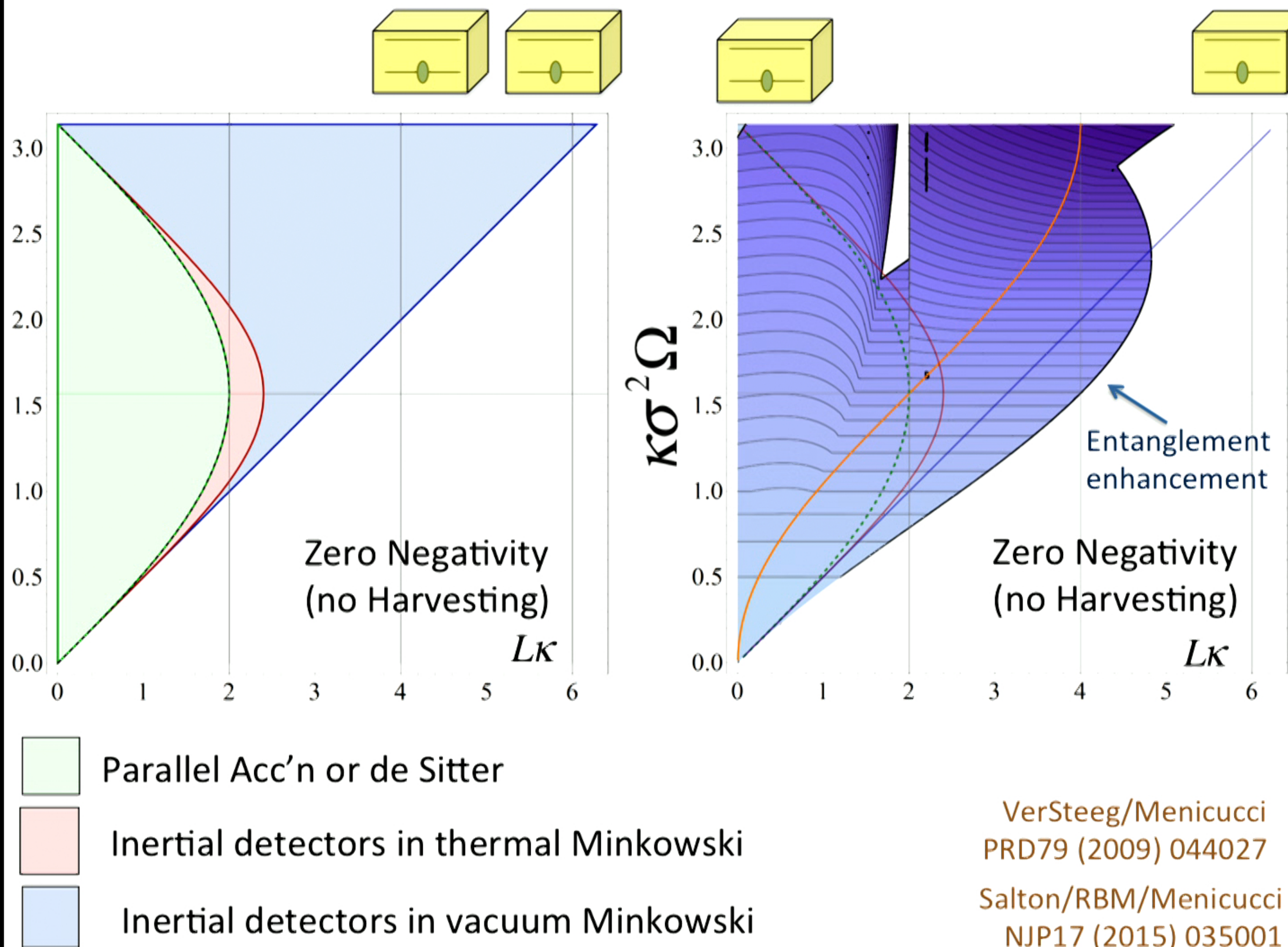
Parallel Acc'n or de Sitter

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

Entanglement Harvesting

- Extracting correlations from the vacuum
- Uncorrelated detectors can become correlated after a finite time depending on their
  - Energy gaps
  - Separation
  - State of motion
- Applications (in principle)
  - Seismology
  - Rangefinding
  - Quantum Key Distribution
  - Extraction from Atoms
  - Graphene
- Very little is known about extraction in curved spacetime

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; PRD95 (2017) 105009

Martin-Martinez/Sanders NJP 18 (2016) 043031

Richter/Tercas/Omar/de Vega PRA96 (2017) 053612

Huang/Tian NPB 923 (2017) 458

Rodríguez-Camargo/Svaiter/Menezes Ann.Phys. 396 (2018) 266

Trevison/Yamaguchi/Hotta PTEP10 (2018) 103A03

Ardenghi PRD98 (2018) 045006

Onoe/Ralph 1901.11144

Harvesting in Flat Spacetime

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

- Entanglement with Static Detectors
  - Decreases with increasing separation
  - Increases with increasing gap
  - Weak dependence on spacetime dimension
  - Harvesting Possible at spacelike separation
- Flat Spacetime in Other contexts
  - 2 Accelerating Detectors
  - Detectors in Identified Minkowski Space

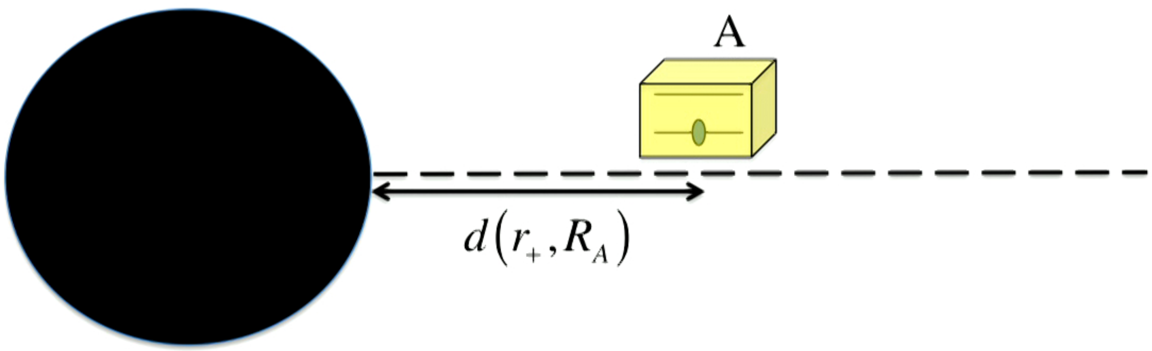
Salton/RBM/Menicucci
NJP17 (2015) 035001

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

Cheat #5: Harvesting Entanglement Near Black Holes

2+1 Black Hole

Henderson/Hennigar/RBM/Smith/
Zhang CQG 35 (2018) 21LT02



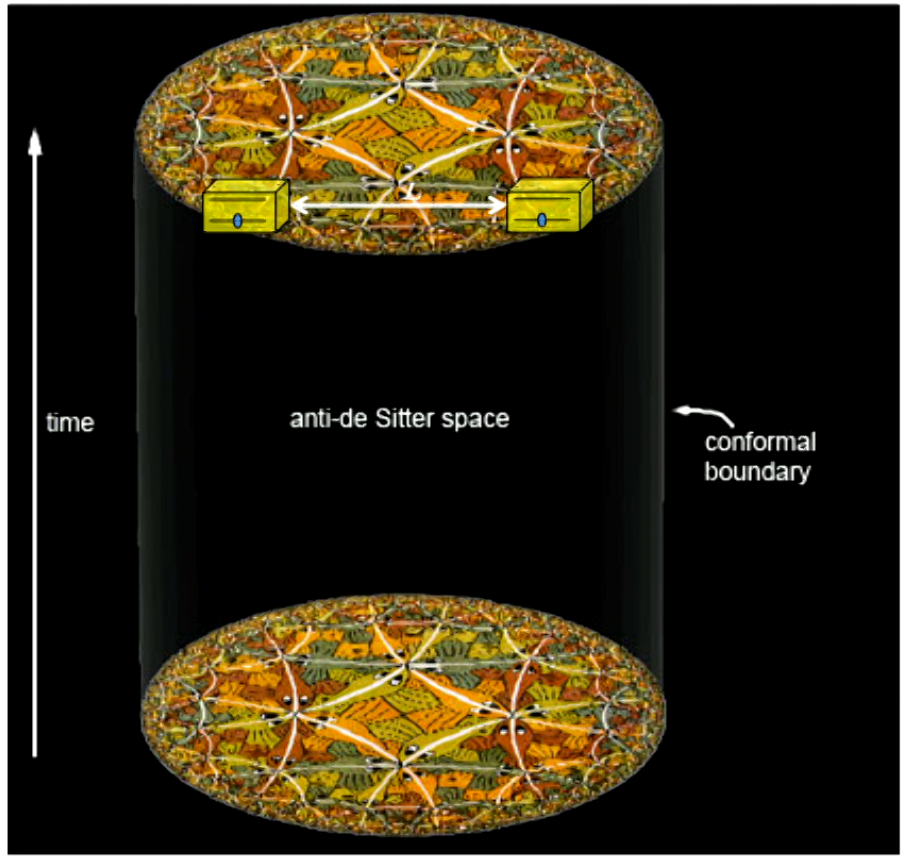
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2$$

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

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

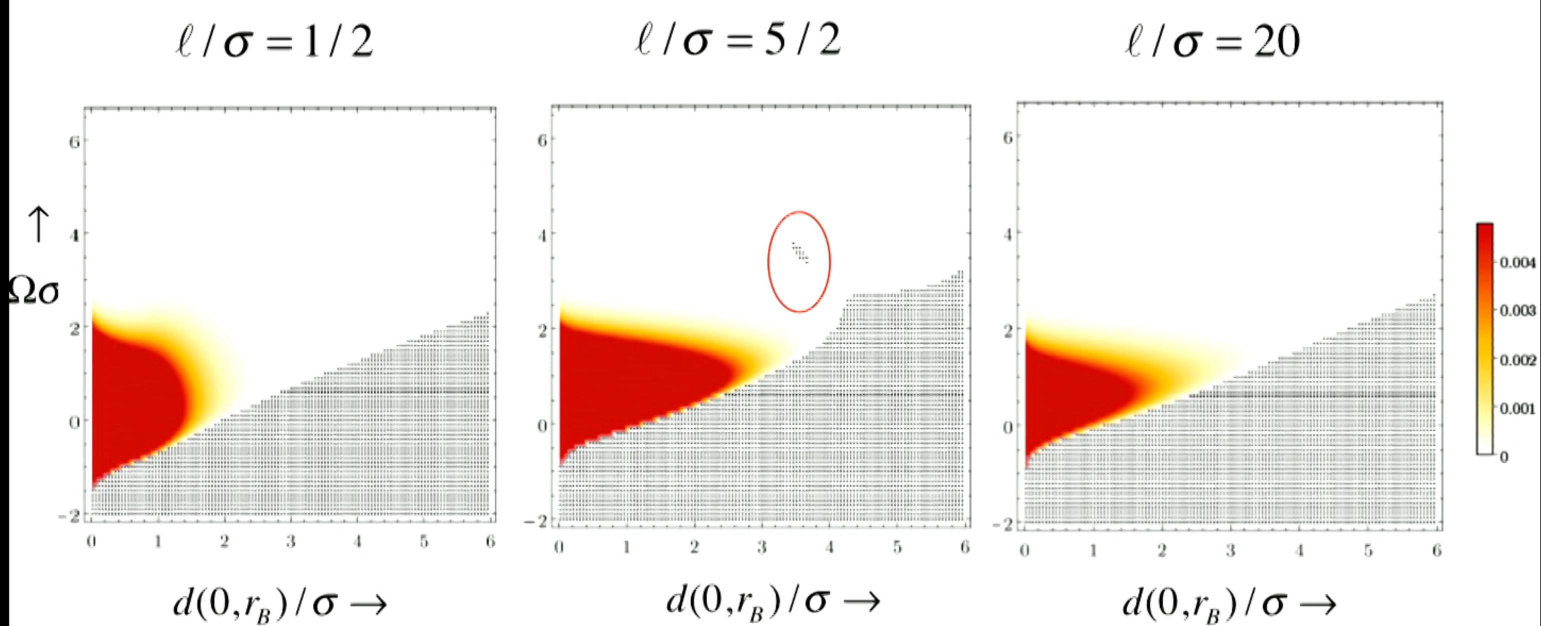
Harvesting in Anti de Sitter Space

2+1: Henderson/Hennigar/Smith/Zhang/RBM 1809.06862 (JHEP)
3+1: Ng/Martin-Martinez/RBM PRD98 (2018) 125005

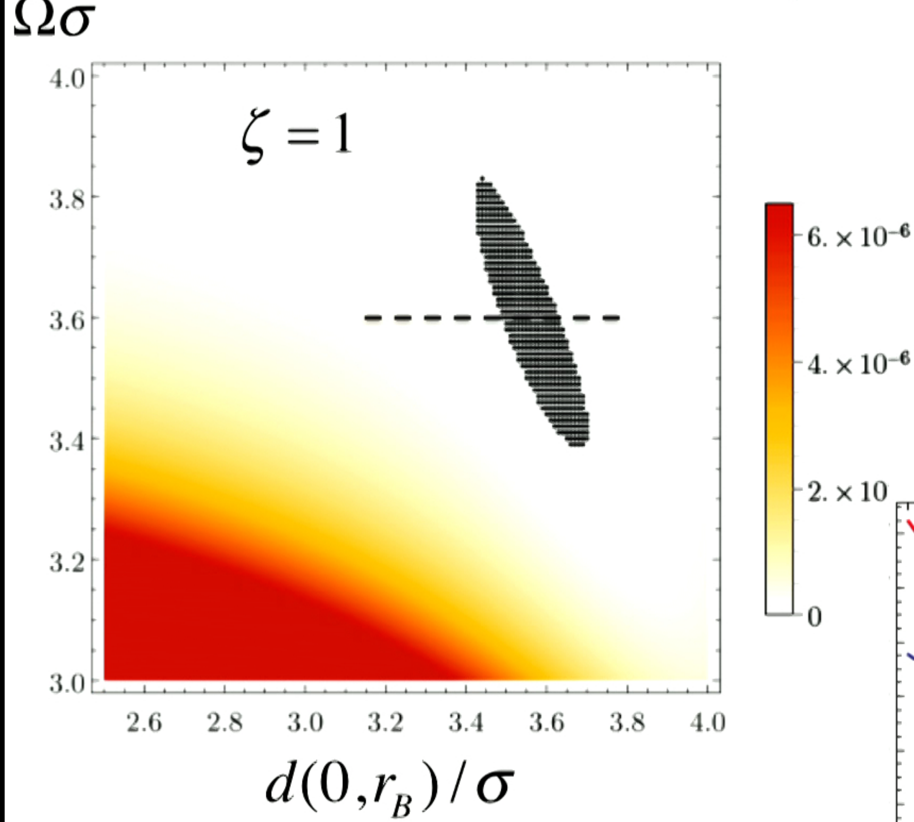


AdS: Concurrence vs. Separation and Gap

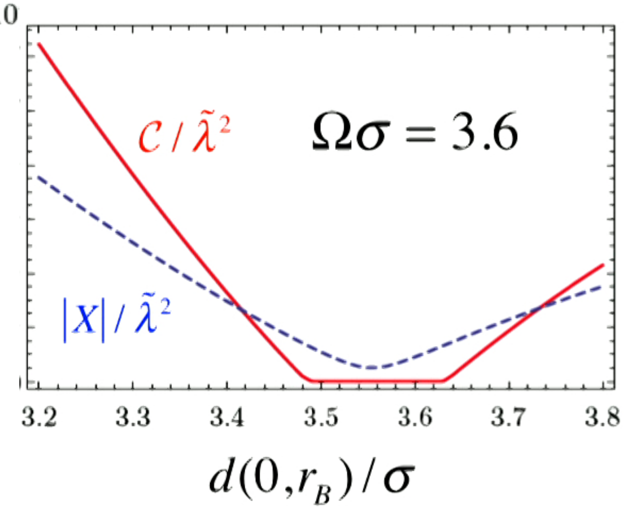
$\zeta = 1$



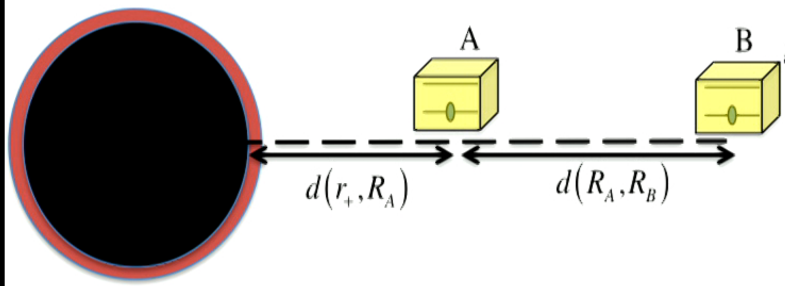
AdS: Island of Separability $\ell / \sigma = 5/2$

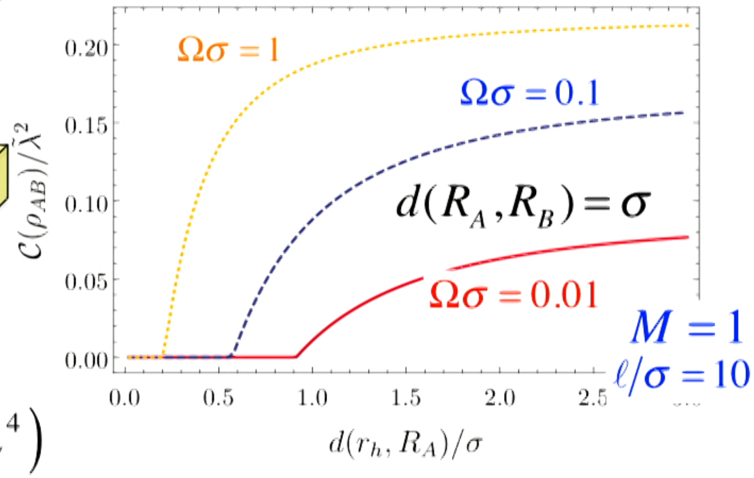


Appears for all boundary conditions

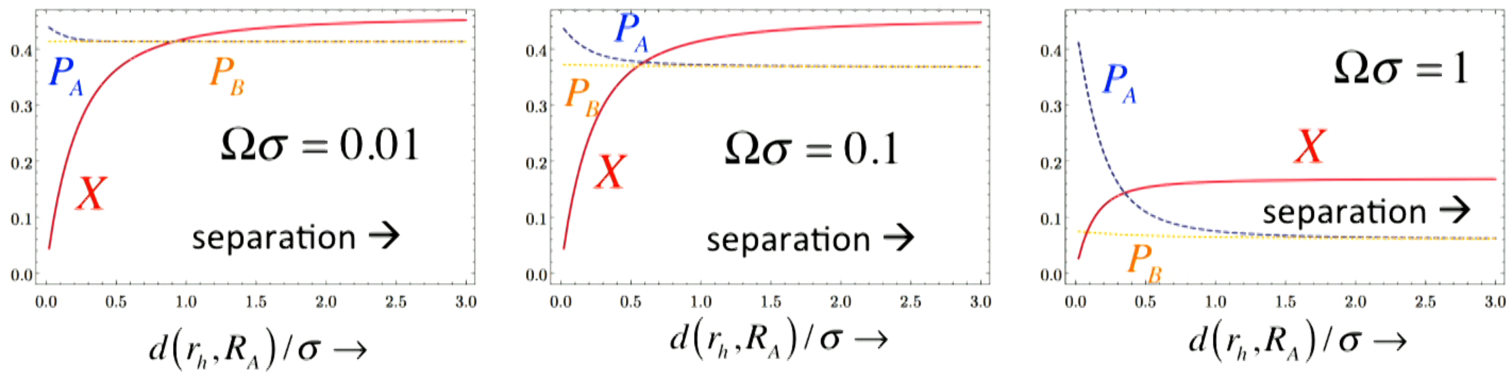


Black Hole Entanglement Inhibition



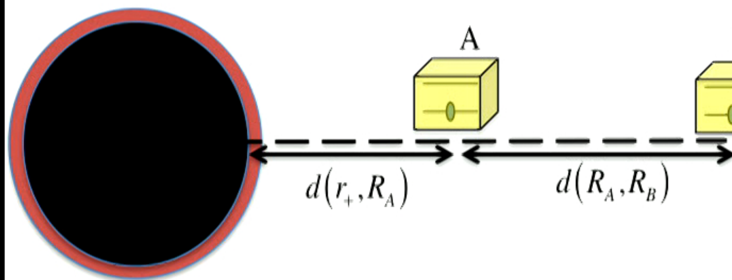


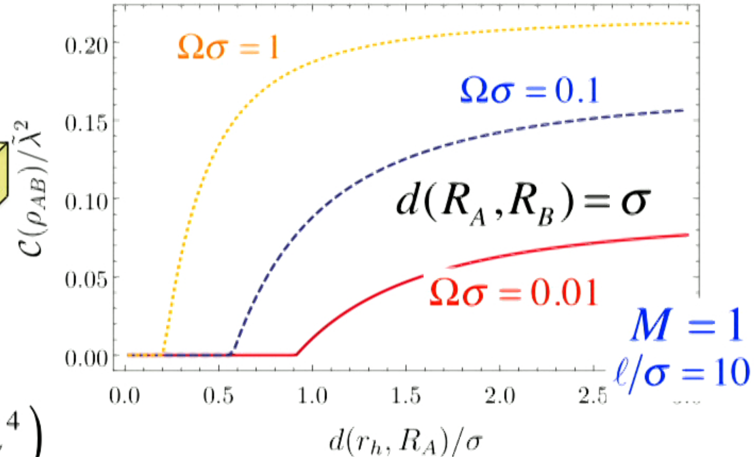
Recall: $\mathcal{C} = \max\{0, |X| - \sqrt{P_A P_B}\} + \mathcal{O}(\lambda^4)$



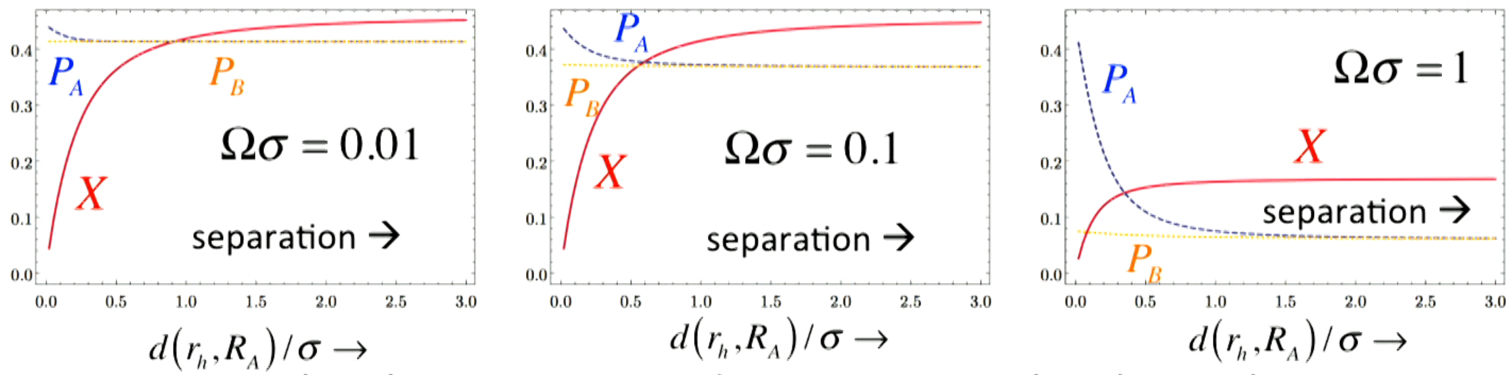
Henderson/Hennigar/RBM/Smith/
Zhang CQG 35 (2018) 21LT02

Black Hole Entanglement Inhibition





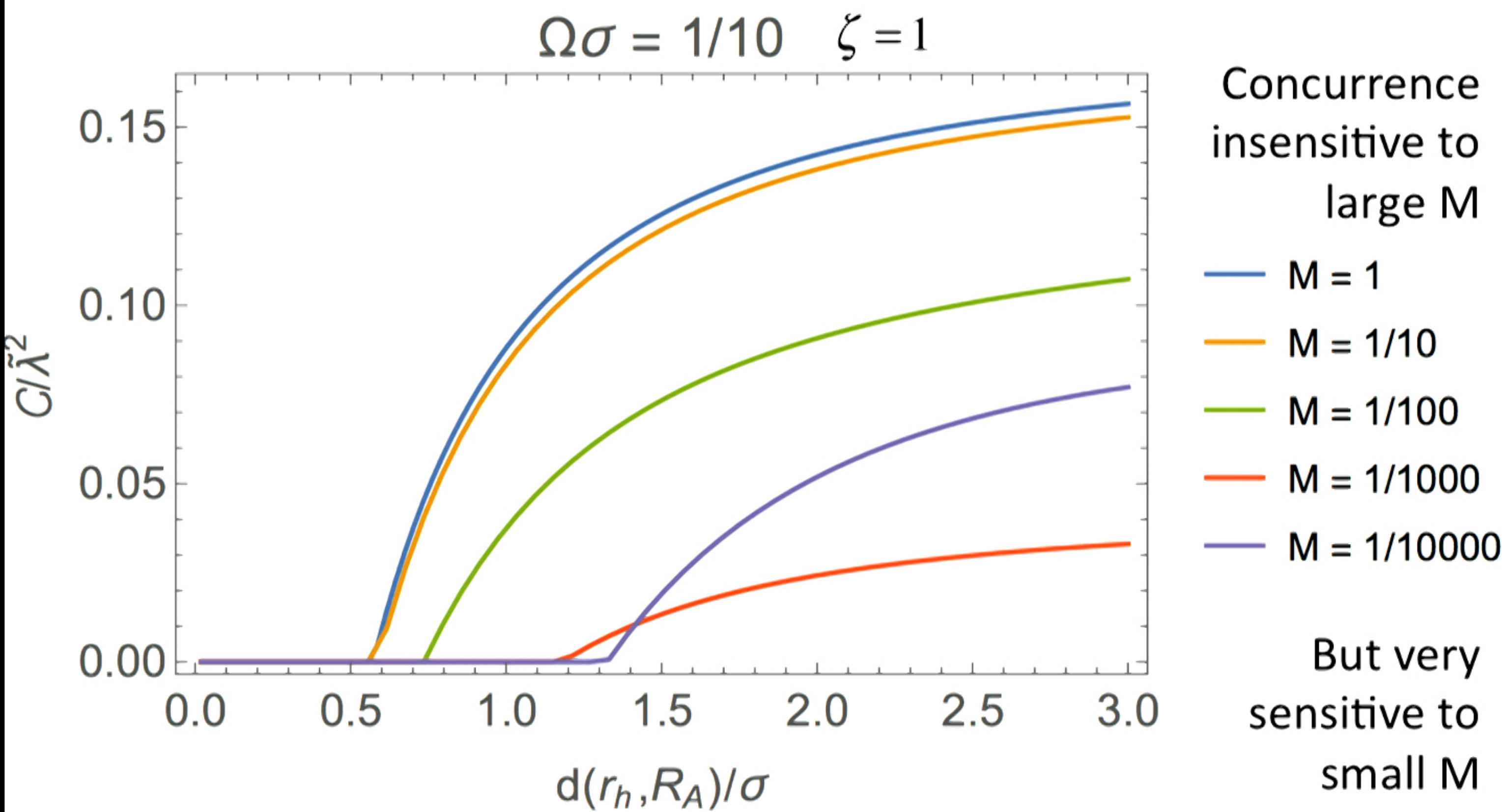
Recall: $\mathcal{C} = \max\{0, |X| - \sqrt{P_A P_B}\} + \mathcal{O}(\lambda^4)$



- Increasing local excitations vs decreasing non-local correlation
  - Hawking radiation → excitation probability rises
  - Redshift effects → erode correlations

Henderson/Hennigar/RBM/Smith/ Zhang CQG 35 (2018) 21LT02

Inhibition: Mass Dependence

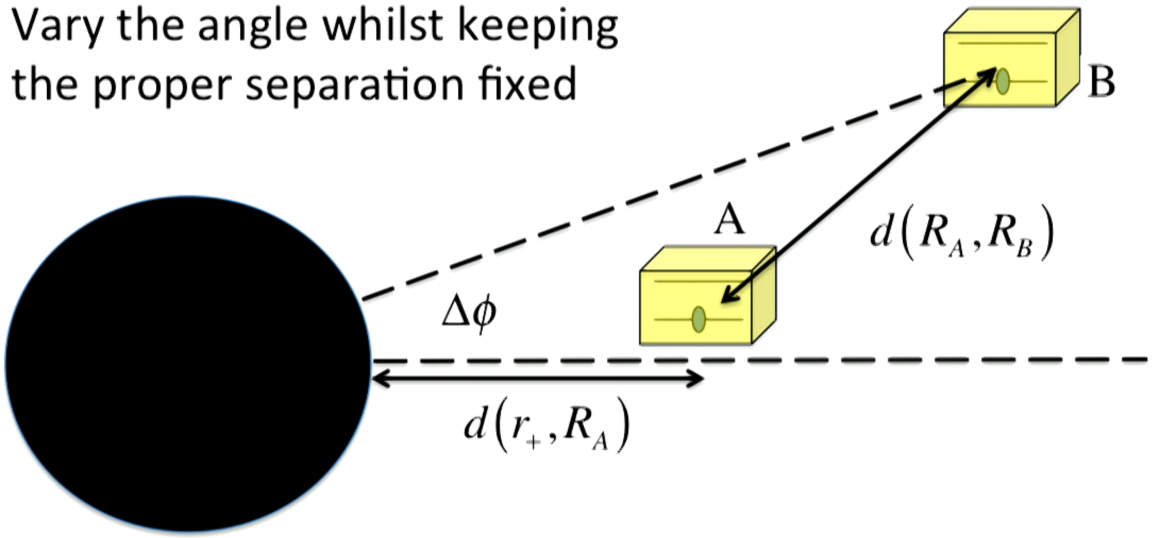


Concurrence insensitive to large M

But very sensitive to small M

Inhibition: Angular Dependence

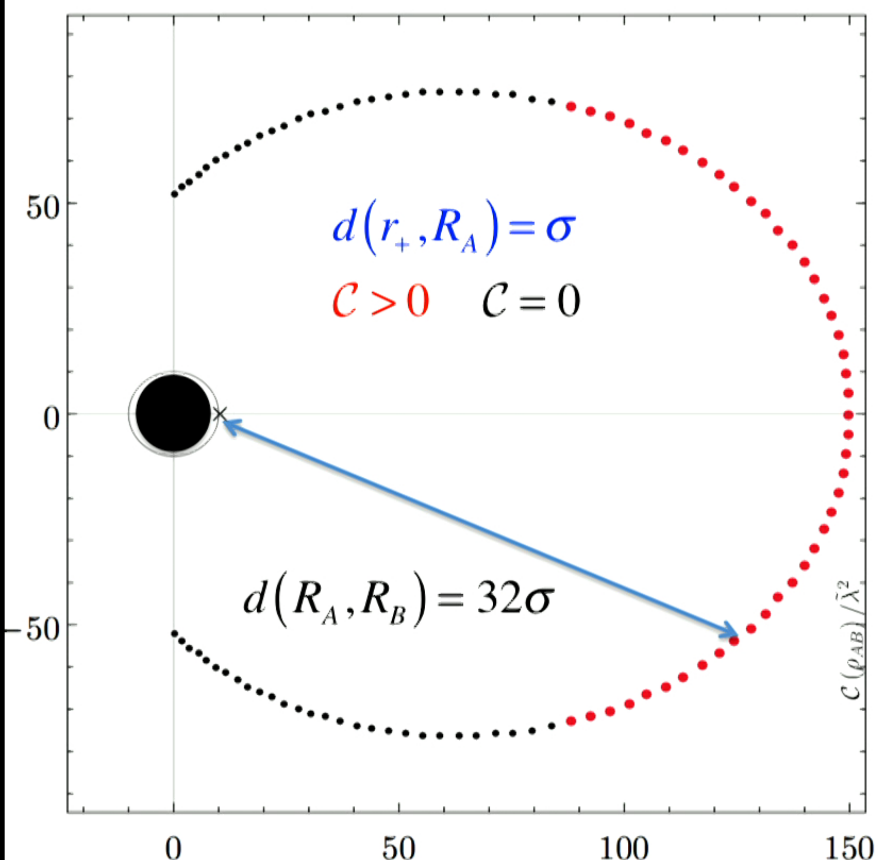
Vary the angle whilst keeping the proper separation fixed



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

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

Encompassing the Hole

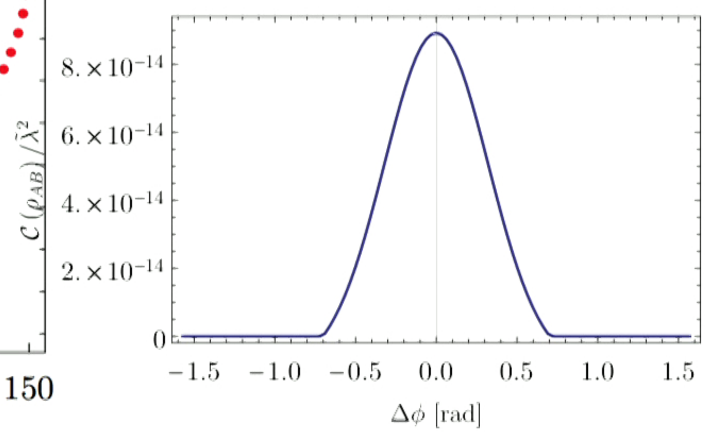


$$\Omega\sigma = 5.5$$

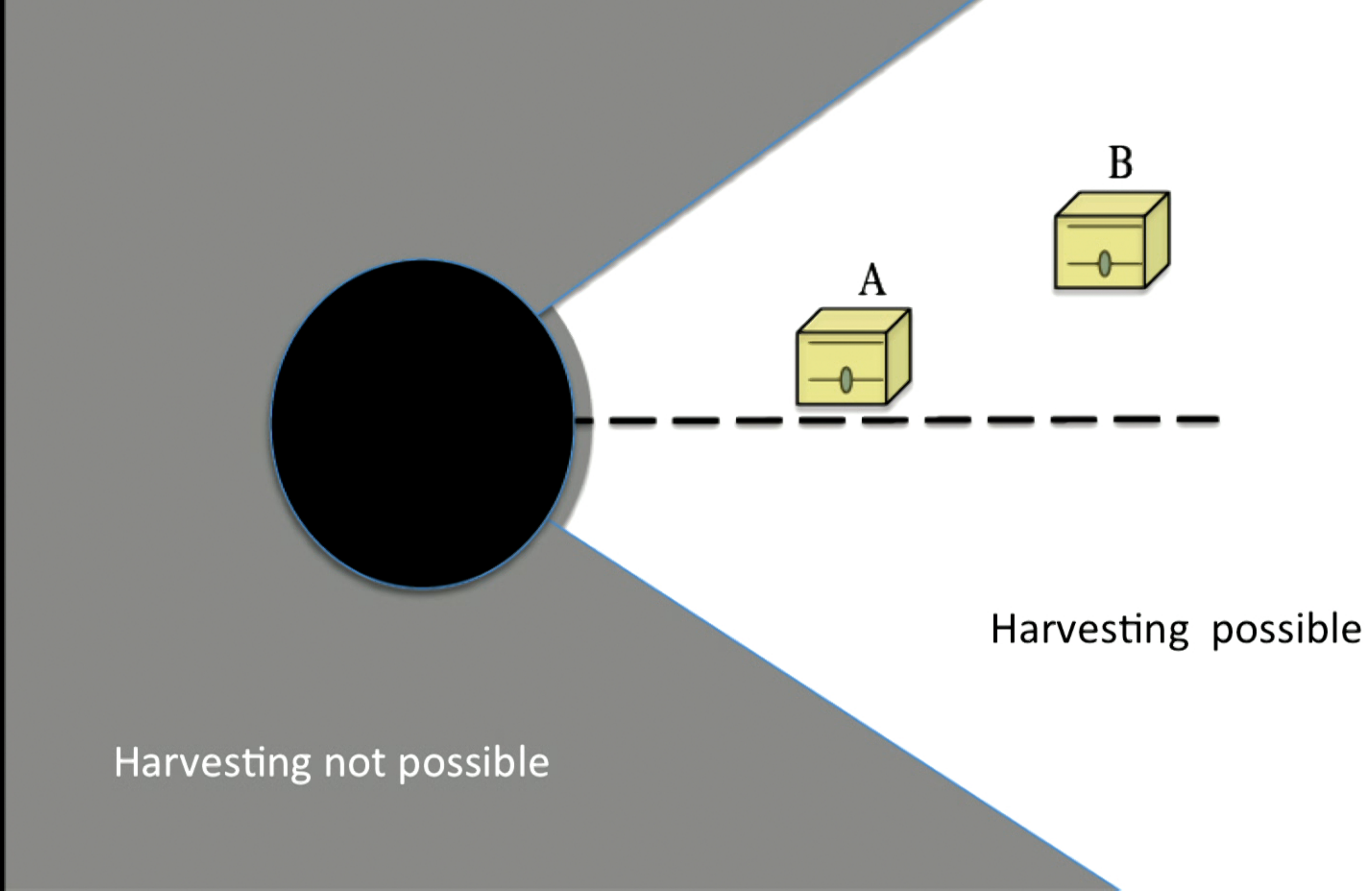
$$M = 1 \qquad \ell = 10\sigma$$

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

$$d(R_A, R_B) = 32\sigma$$

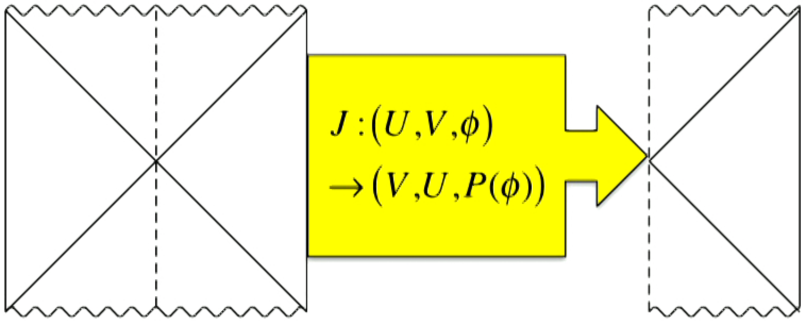


The Entanglement Shadow of a Black Hole



Geon Entanglement

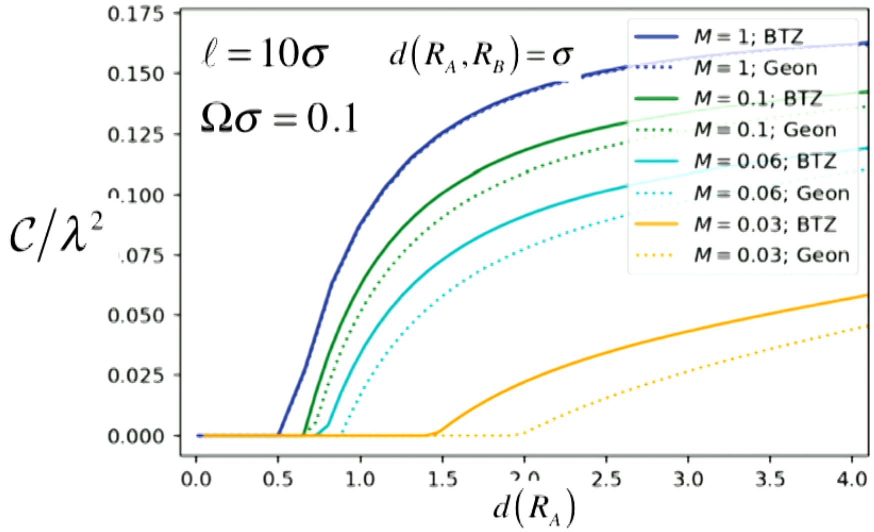
Ding/Henderson/RBM
(in progress)



BTZ Black Hole

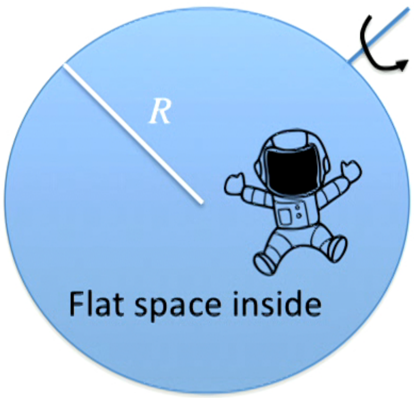
BTZ Geon

- Geon Entanglement Shadow is larger than its black hole counterpart
- Effect more prominent for smaller mass

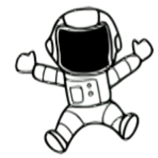


Cheat #6: Equivalence Principle

Ng/Martin-Martinez/
RBM PRD**94** (2016) 104041



$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 - \frac{4Ma\sin^2\theta}{r}dt\,d\phi + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$



Flat space everywhere

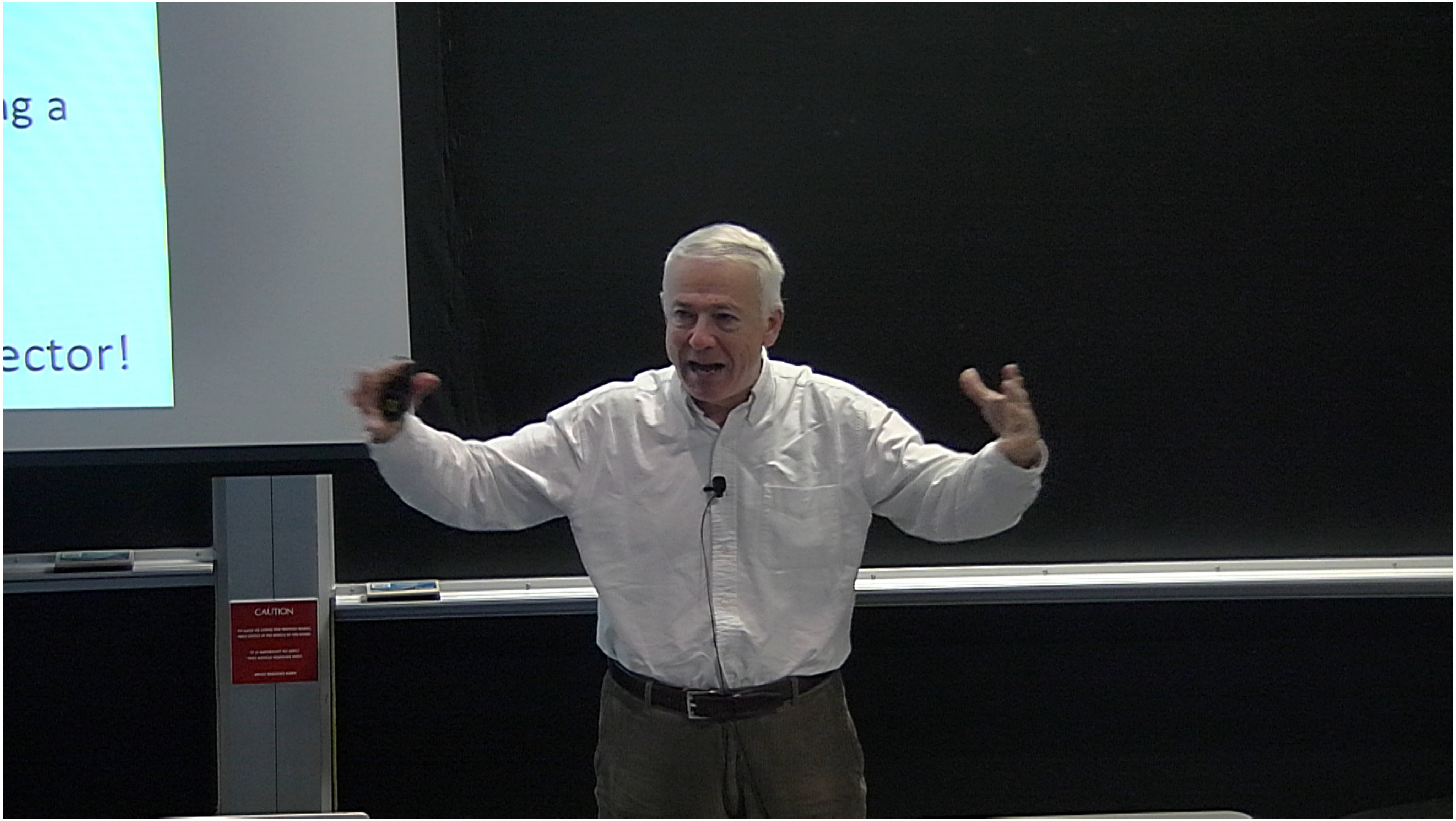
- Q: Can an astronaut determine if

  (a) they are in a hollow shell or flat space without sending a signal to the shell?

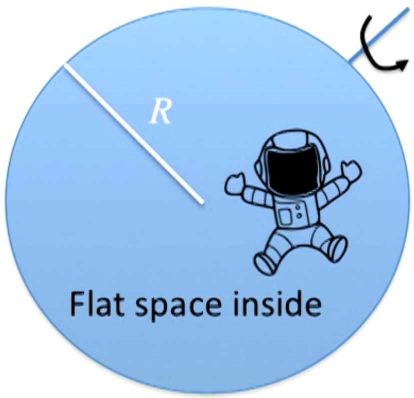
  (b) if the shell is rotating?

- A: Classically no

  Quantum mechanically yes – with a UdW detector!


ng a
ector!
CAUTION

Cheat #6: Equivalence Principle



$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 - \frac{4Ma\sin^2\theta}{r}dt\,d\phi + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

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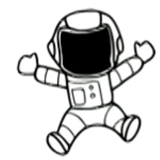
RBM PRD**94** (2016) 104041



- Q: Can an astronaut determine if

  (a) they are in a hollow shell or flat space without sending a signal to the shell?

  (b) if the shell is rotating?

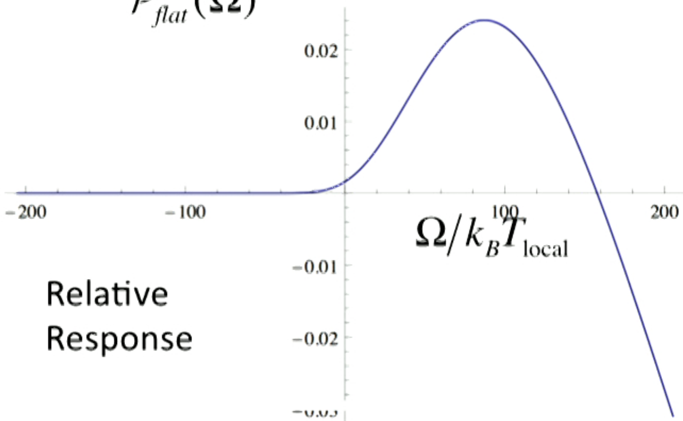
- A: Classically no

  Quantum mechanically yes – with a UdW detector!

Static Shell

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

$$\frac{\mathcal{P}_{shell}(\Omega) - \mathcal{P}_{flat}(\Omega)}{\mathcal{P}_{flat}(\Omega)}$$



Relative Response

$$\mathcal{P}_{shell}(\Omega = 0)$$

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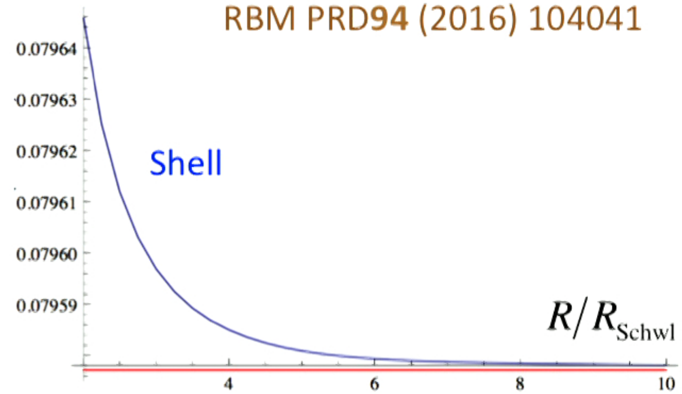


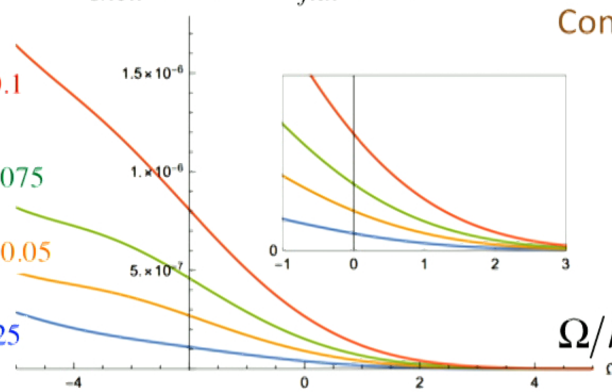
Flat space

Rotating Shell

- Offset detector from centre of sphere
- Order a^2 effects difficult to separate out

$$\mathcal{P}_{shell}(\Omega) - \mathcal{P}_{flat}(\Omega)$$

Cong/Bicak/Kubiznak/ RBM (in progress)



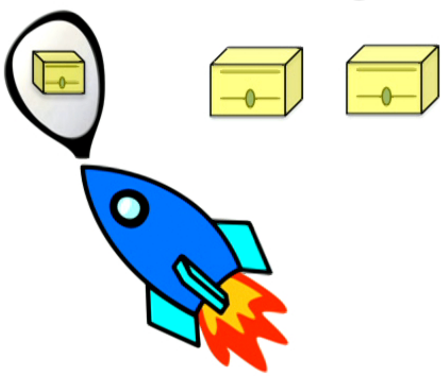
Response Difference

$\Omega/k_B T_{\text{local}}$

Cheat #7: Accelerating Mirrors

Cong/Tjoa/RBM 1810.07359 (JHEP)

- First study of Harvesting with moving boundary conditions
- Prelude to Harvesting near collapsing matter
- Main results
  - Entanglement inhibition near moving mirror
  - Entanglement enhancement in some regimes



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

$$+\left\{\begin{array}{l} \sum\limits_D \lambda_D \int d^4x Q_D(\tau)\Phi(x)\delta^4\left(x^\mu - z_D^\mu(\tau)\right) \\ \sum\limits_D \lambda_D \int d^4x Q_D(\tau)\left(u\bullet\nabla\Phi(x)\right)\delta^4\left(x^\mu - z_D^\mu(\tau)\right) \end{array}\right.$$

Basic Setup

Static Mirror $p_S(u) = u$

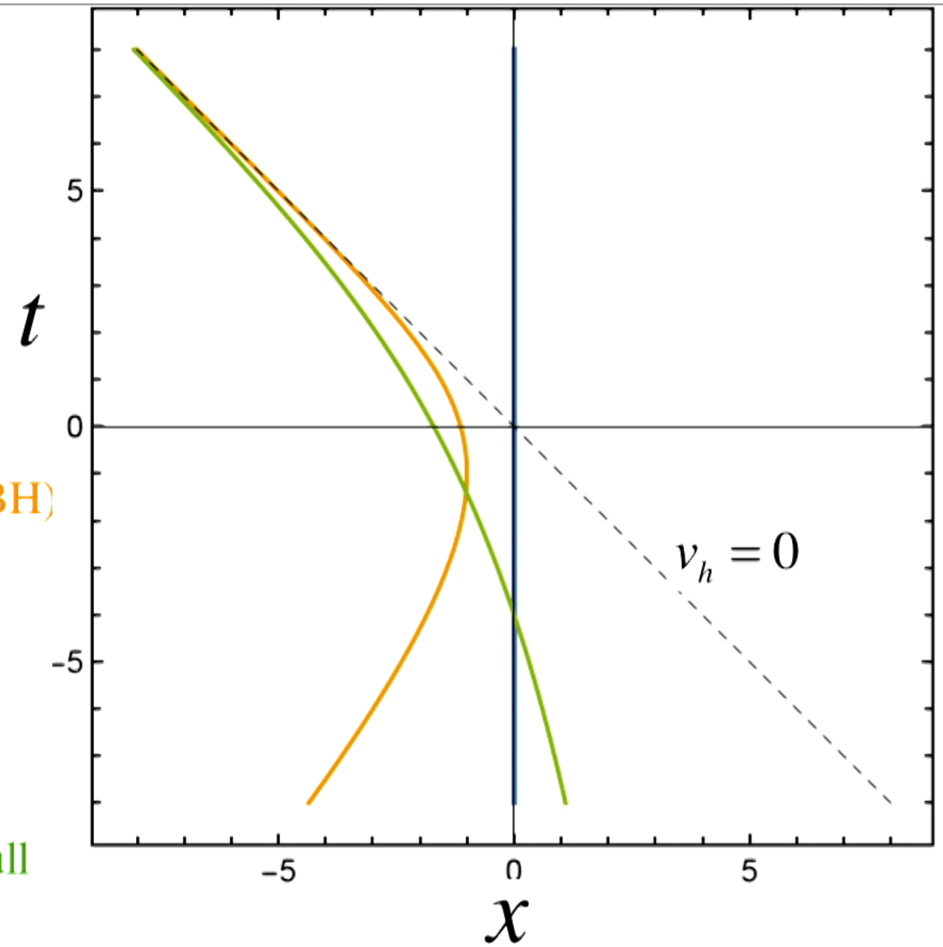
Carlitz-Willey Mirror

$$p_{CW}(u) = -\frac{e^{-\kappa u}}{\kappa} \text{(like eternal BH)}$$

BH Collapse Mirror

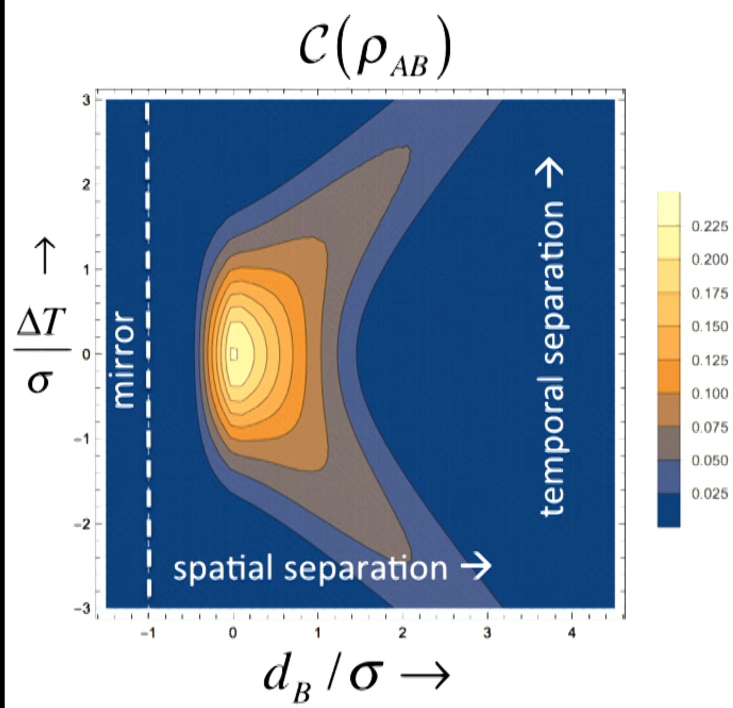
$$p_{BHC}(u) = v_H - \frac{1}{\kappa} W\left(e^{-\kappa(u - v_H)}\right)$$

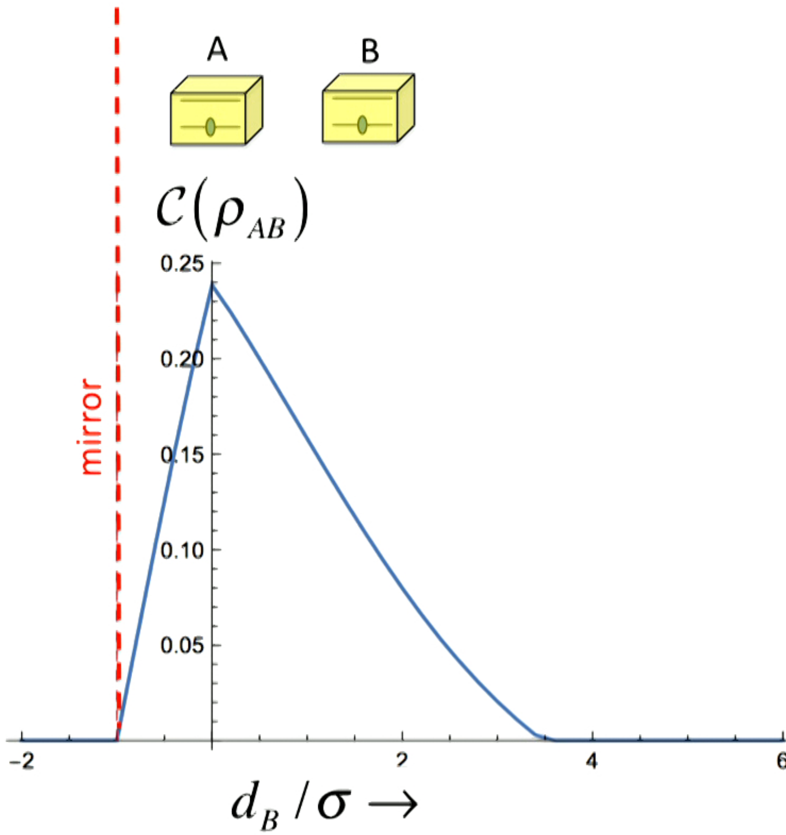
(same Bogo coefficients as null shockwave collapse)



$$W(\mathrm{x},\mathrm{x}') = -\frac{1}{4\pi} \log\left[\frac{(\epsilon + i(p(u) - p(u'))(\epsilon + i(v - v'))}{(\epsilon + i(p(u) - v')(\epsilon + i(v - p(u')))}\right.$$

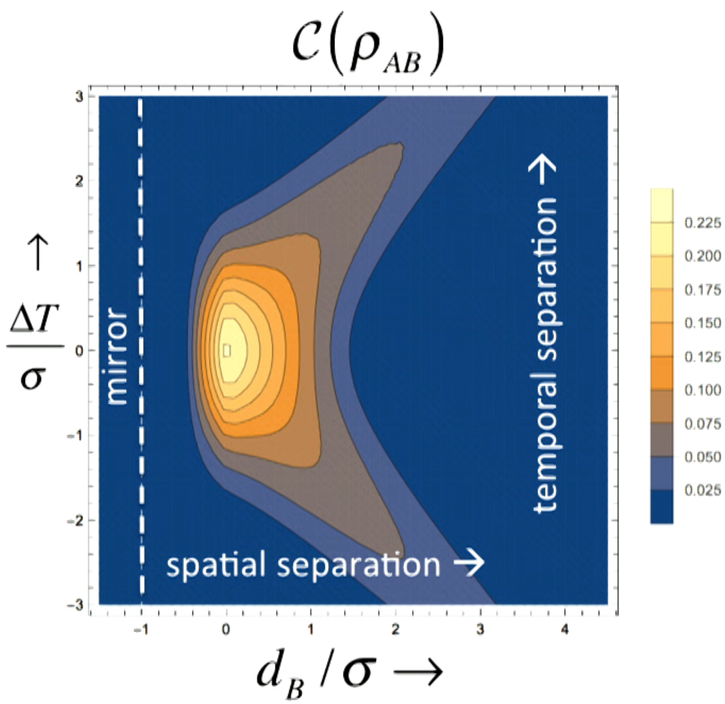
Concurrence: Static (Nearby) Mirror

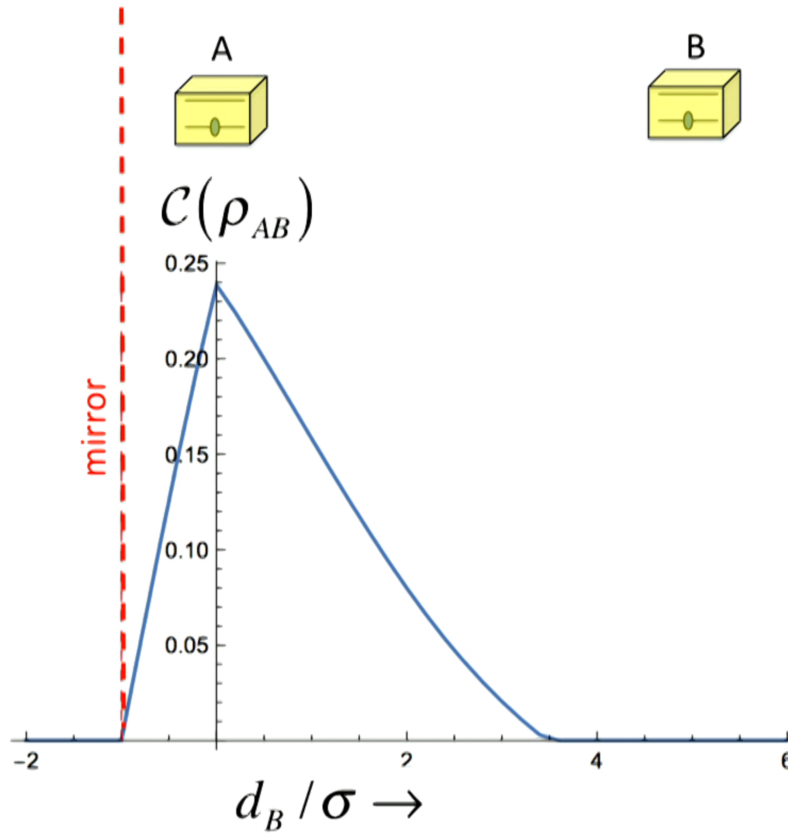




- Harvesting declines faster on the mirror side of A

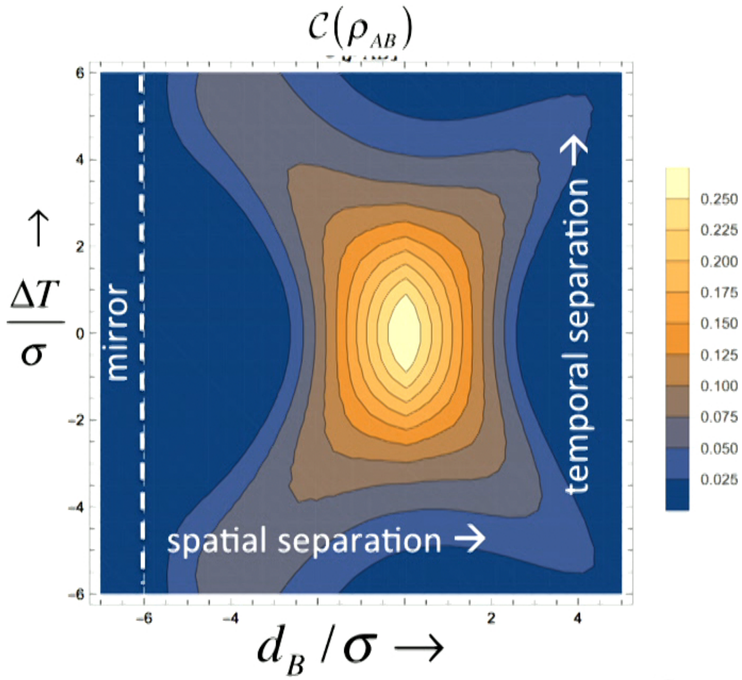
Concurrence: Static (Nearby) Mirror



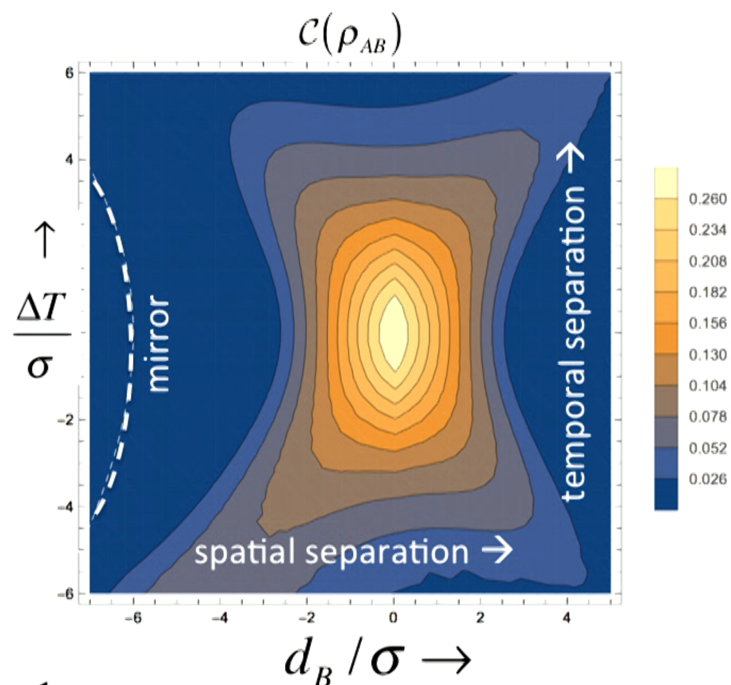


- Harvesting declines faster on the mirror side of A

Concurrence: Static vs. Eternal (CW)



Static Mirror

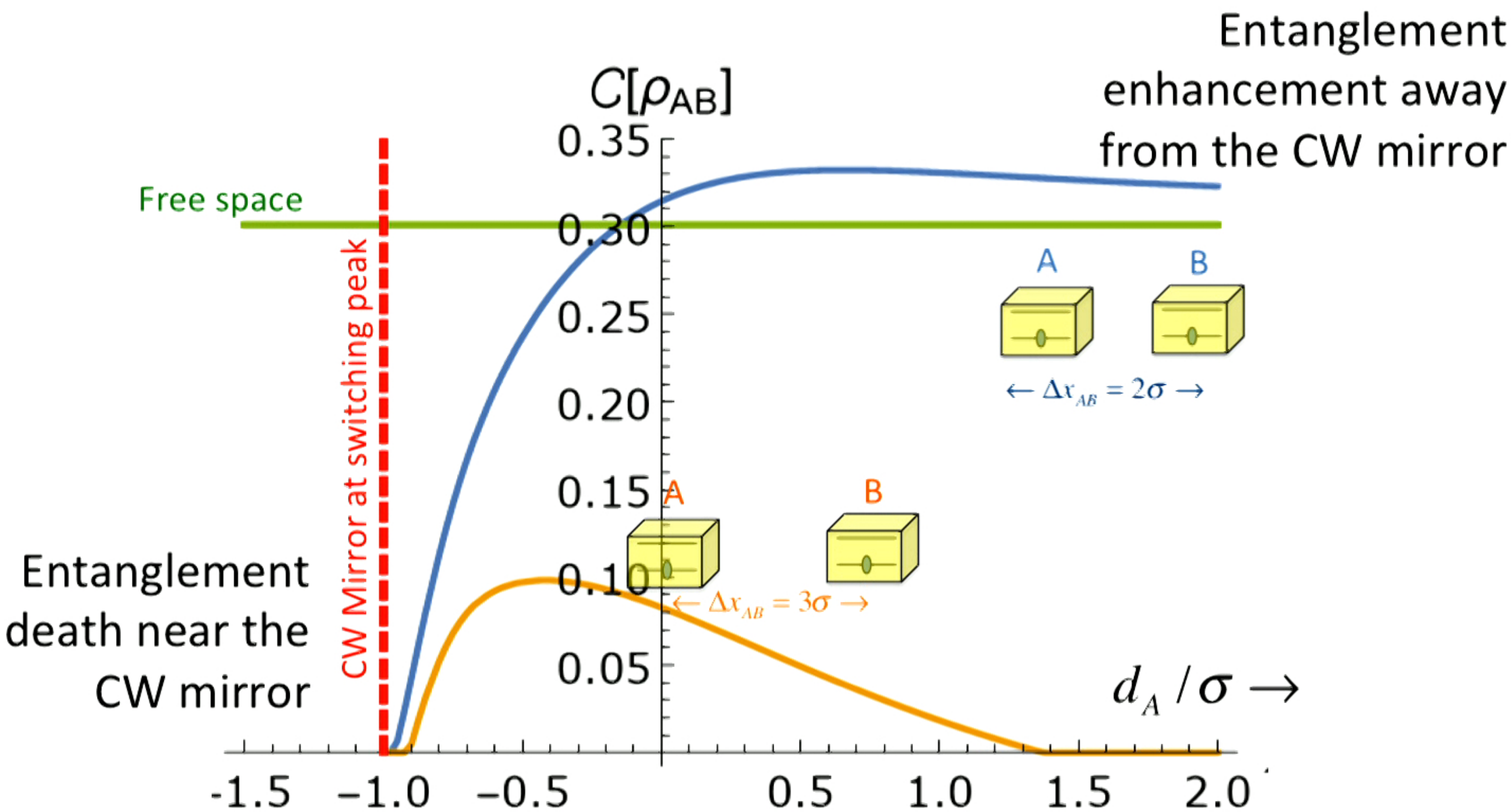


CW Mirror $\kappa\sigma = 1$

$$\Omega\sigma = 1$$

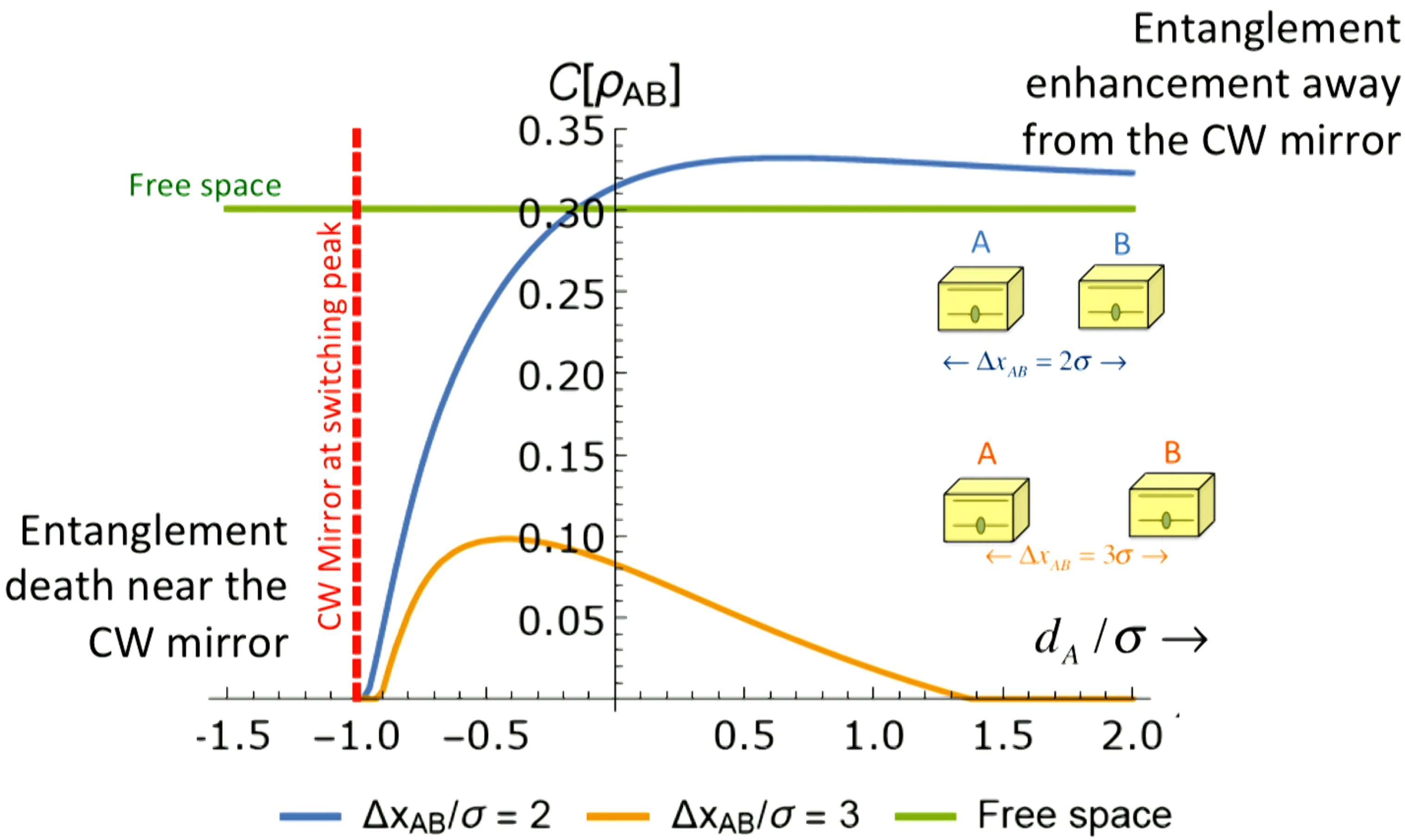
$$d_A = 6\sigma$$

Concurrence vs. Separation: CW



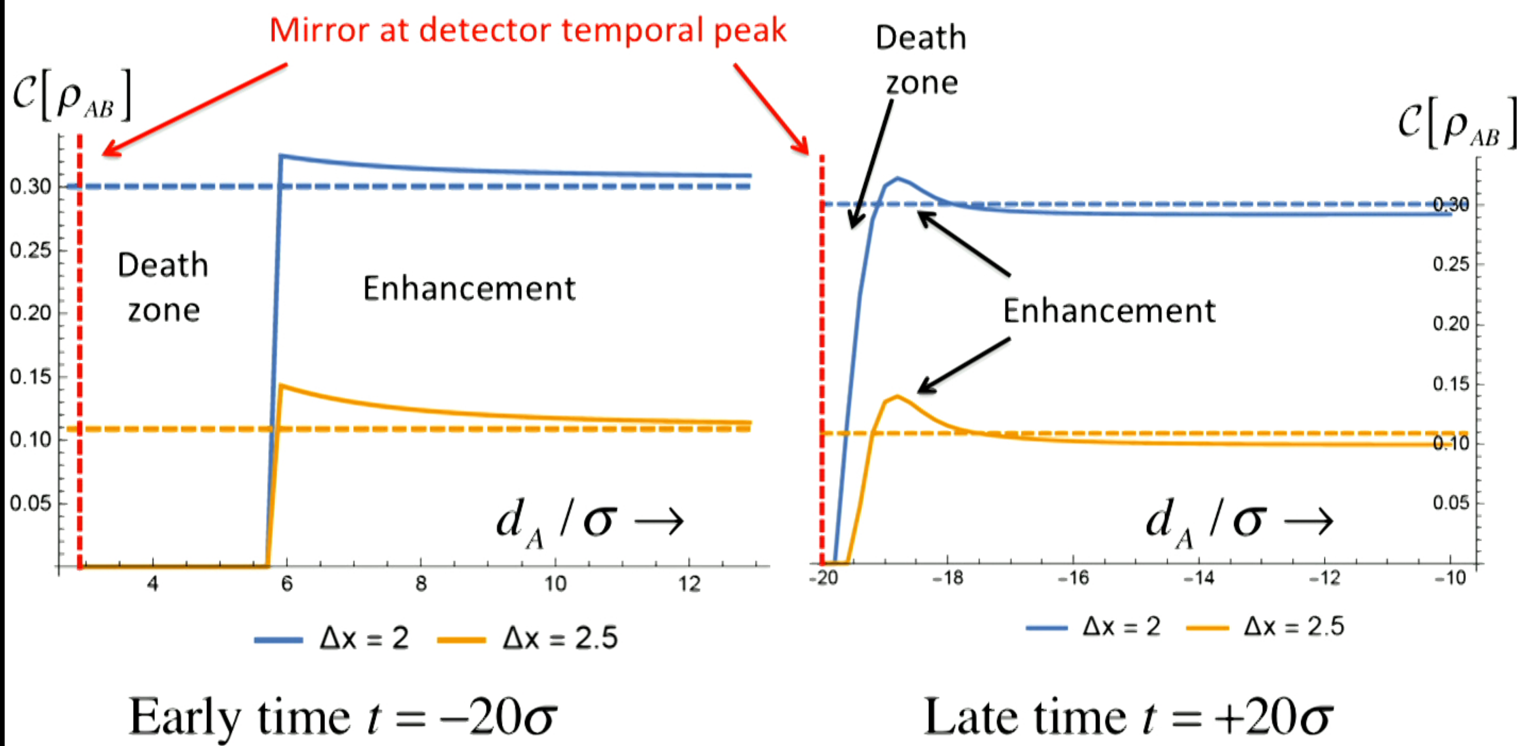
Results qualitatively the same for derivative coupling

Concurrence vs. Separation: CW

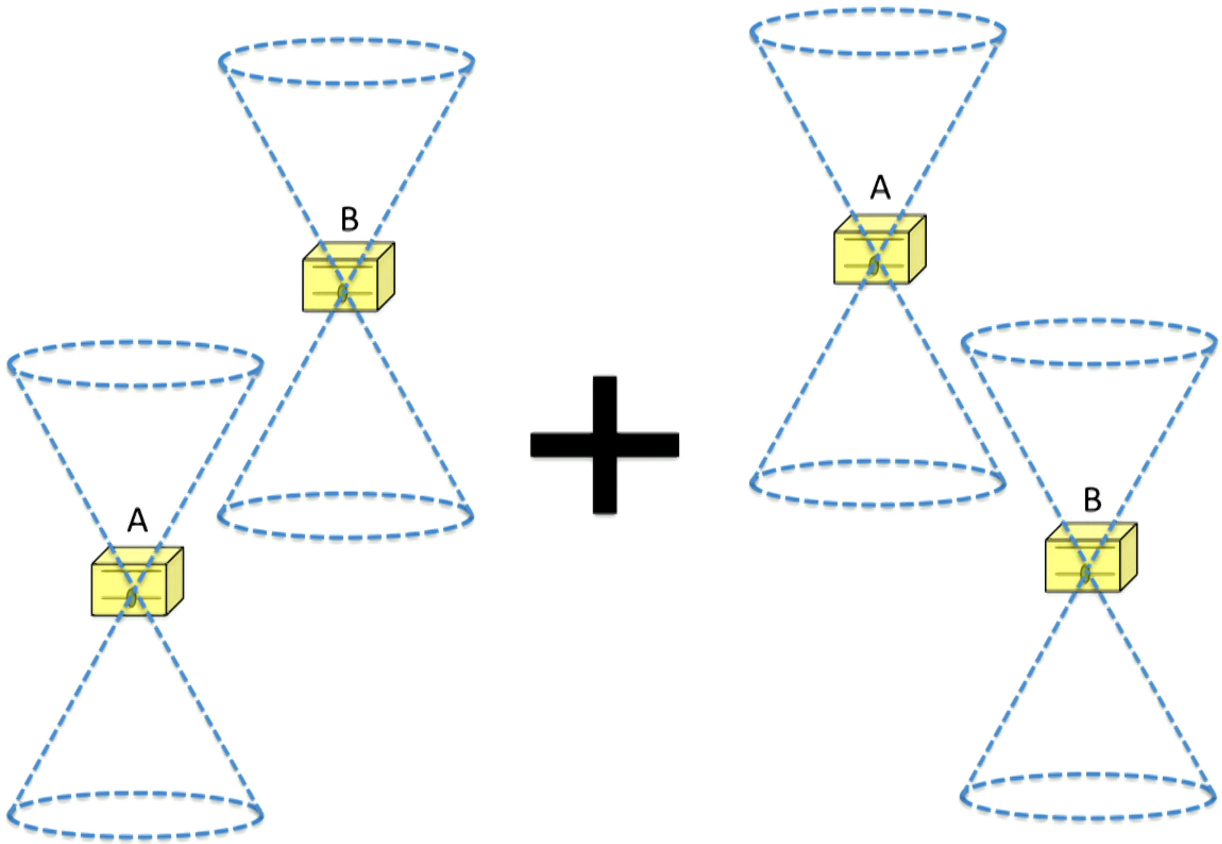


Results qualitatively the same for derivative coupling

Concurrence: BH Collapse $v_h = 0$



No more Cheats: Harvesting with Indefinite Causal Order



Causal Switch

$$\rho_{ABC} = \frac{1}{2}\sum_{ij} |0\rangle_A \langle 0| \otimes |0\rangle_B \langle 0| \otimes |0\rangle_\Phi \langle 0| \otimes |i\rangle\langle j|$$

Causal Switch

$$\rho_{ABC} = \frac{1}{2}\sum_{ij} |0\rangle_A \langle 0| \otimes |0\rangle_B \langle 0| \otimes |0\rangle_\Phi \langle 0| \otimes |i\rangle\langle j|$$

$$H = \sum_D \sum_C \lambda_D \chi_{D,i}(t)\left[e^{i\Omega_D t}\sigma^+ + e^{-i\Omega_D t}\sigma^-\right]\phi[x_D(\tau(t))] \otimes |i\rangle\langle j|$$

Hamiltonian evolution

Causal Switch

$$\rho_{ABC} = \frac{1}{2}\sum_{ij} |0\rangle_A \langle 0| \otimes |0\rangle_B \langle 0| \otimes |0\rangle_\Phi \langle 0| \otimes |i\rangle\langle j|$$

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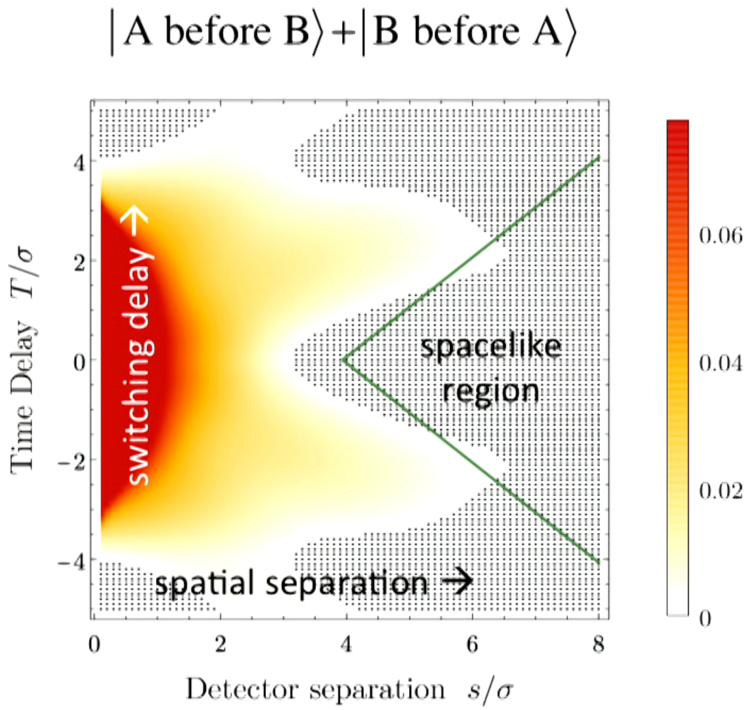
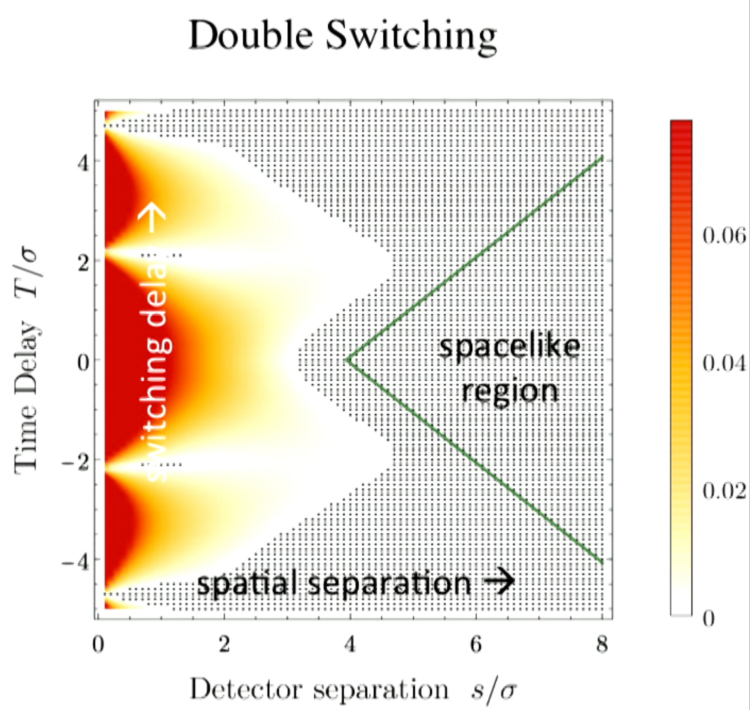
Hamiltonian evolution

$$\rho_{ABC} = \begin{pmatrix} 1 - Y_{ii} - Y_{jj}^* & 0 & 0 & M_{jj}^* \\ 0 & P_{B,ij} & L_{ABji}^* & 0 \\ 0 & L_{ABij} & P_{A,ij} & 0 \\ M_{ii} & 0 & 0 & 0 \end{pmatrix} \otimes |i\rangle\langle j| + O\left(\lambda^4\right)$$

Harvesting and (Indefinite) Temporal Order

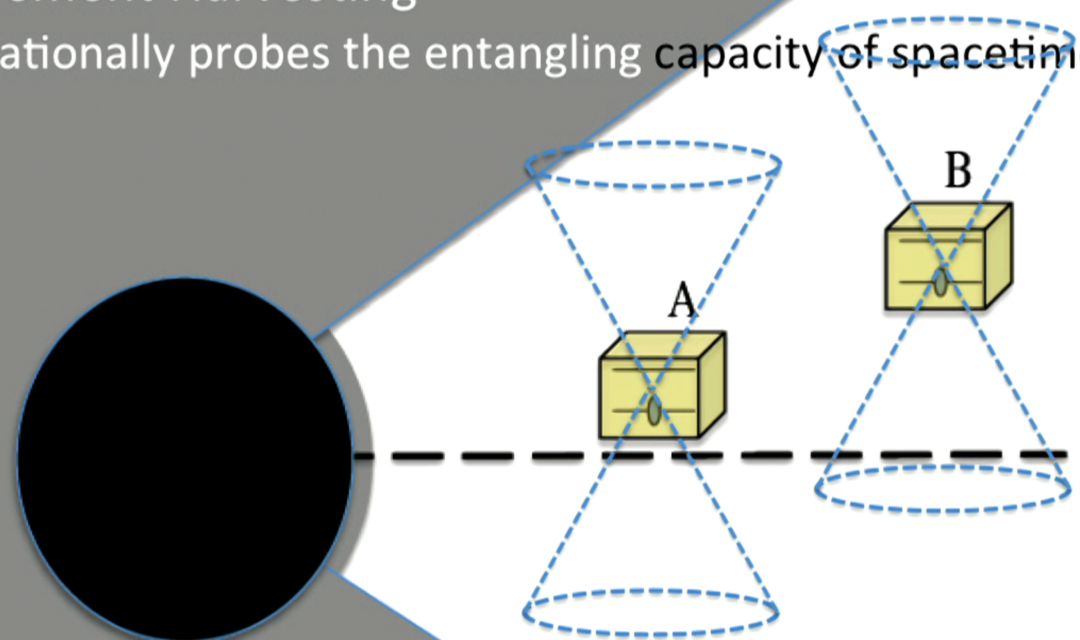
Concurrence vs. Separation and Switching Delay





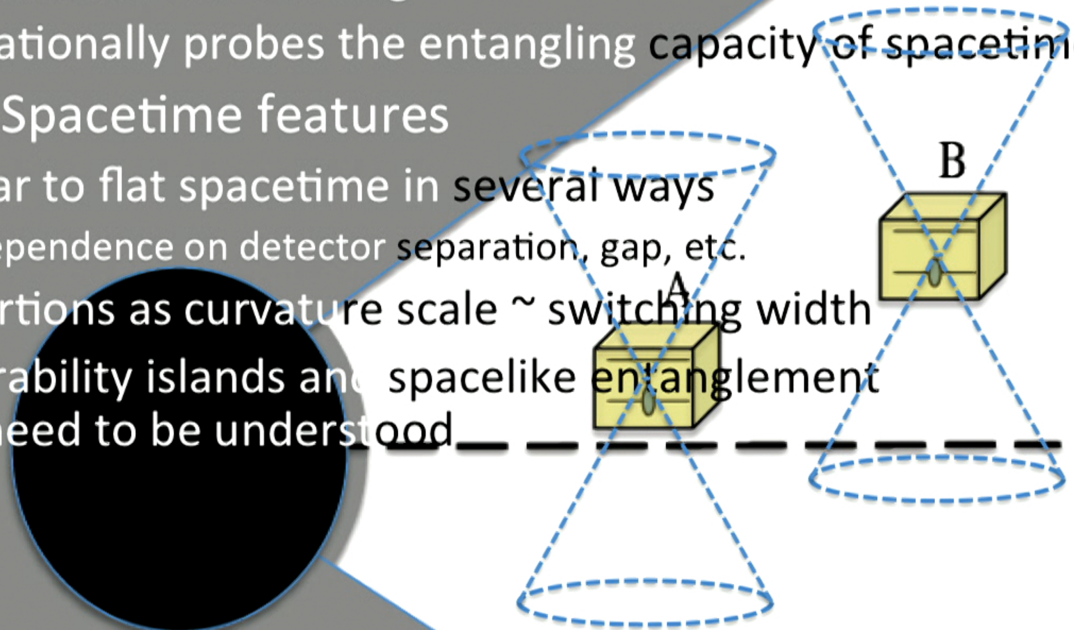
Key Lessons

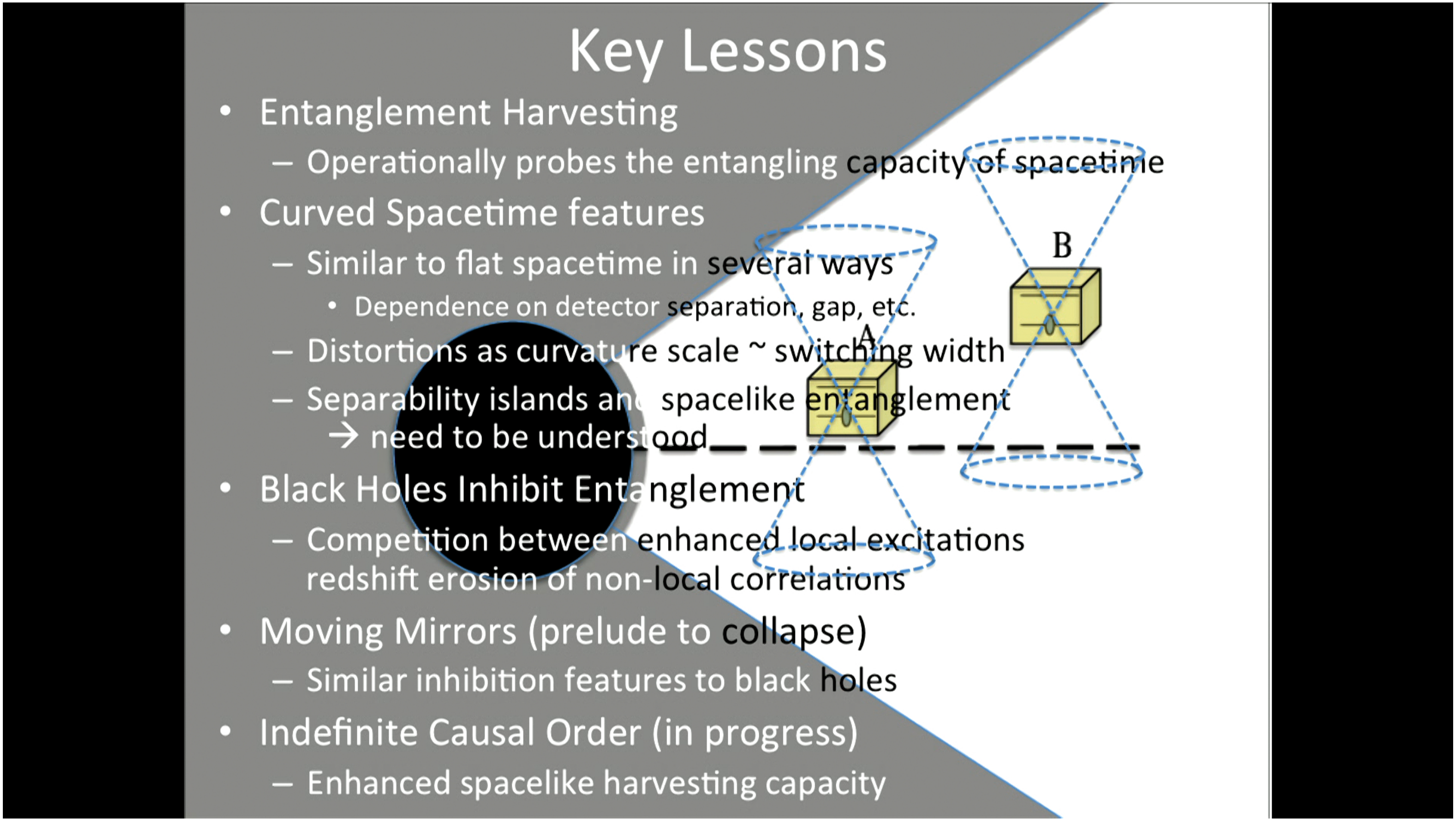
- Entanglement Harvesting
  - Operationally probes the entangling capacity of spacetime



Key Lessons

- Entanglement Harvesting
  - Operationally probes the entangling capacity of spacetime
- Curved Spacetime features
  - Similar to flat spacetime in several ways
    - Dependence on detector separation, gap, etc.
  - Distortions as curvature scale ~ switching width
  - Separability islands and spacelike entanglement
    → need to be understood




Key Lessons
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→ need to be understood
Black Holes Inhibit Entanglement
Competition between enhanced local excitations
redshift erosion of non-local correlations
Moving Mirrors (prelude to collapse)
Similar inhibition features to black holes
Indefinite Causal Order (in progress)
Enhanced spacelike harvesting capacity
A
B