Probing Spacetime through Relativistic Quantum Information

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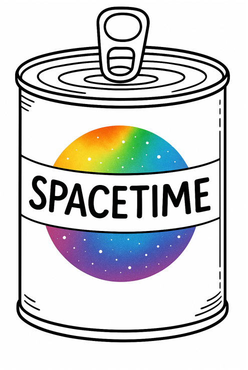
1. Motivation: intro to RQI
2. Methodology: UdW detector and interaction
3. Our recent progress: magic harvesting in AdS and CFT
4. Summary

Motivation



- **Holography:**
  - "The World as a hologram" ('t Hooft 1993 [1], Susskind 1994 [2])
  - Anti-de Sitter/conformal field theory correspondence (Maldacena 1997 [3]; Gubser, Klebanov, Polyakov 1998 [4]; Witten 1998 [5])
- **Open Question:**
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  - How can we probe the nature of spacetime in an operational manner that complements the holographic picture ?

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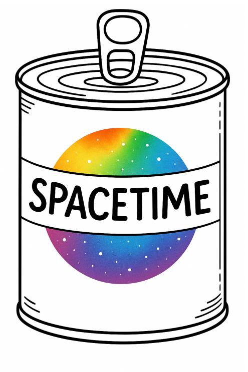

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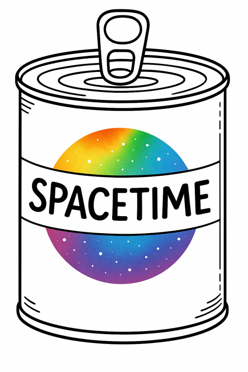

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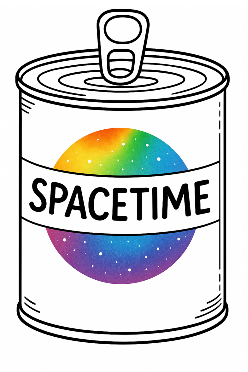

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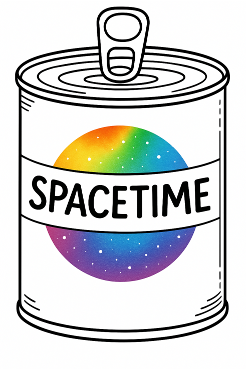

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RQI helps!

What is Relativistic Quantum Information?

- **Definition:** Relativistic Quantum Information (RQI) studies quantum information in relativistic settings, e.g., when spacetime is curved or observers are non-inertial.
- **Theoretical foundations:**
  - General Relativity (GR)
  - Quantum Field Theory (QFT) in curved spacetime
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- **Representative phenomena:**
  - Unruh effect (Fulling 1973, Davies. 1975, Unruh1976 [6, 7, 8])
  - Entanglement harvesting (Valentini 1991; Reznik, Retzker, Silman 2003 [9, 10, 11, 12])
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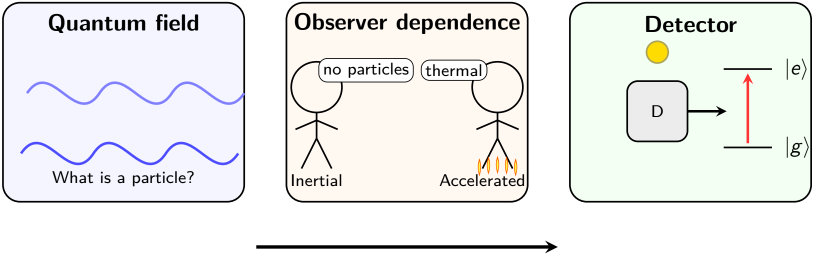
Why do we need particle detectors?



- No unique notion of particles in curved spacetime
- Different observers ⇒ different particle content
- **A particle = what a particle detector detects [13, 14]**

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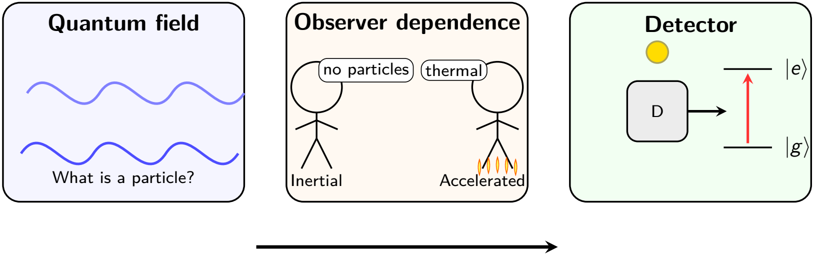

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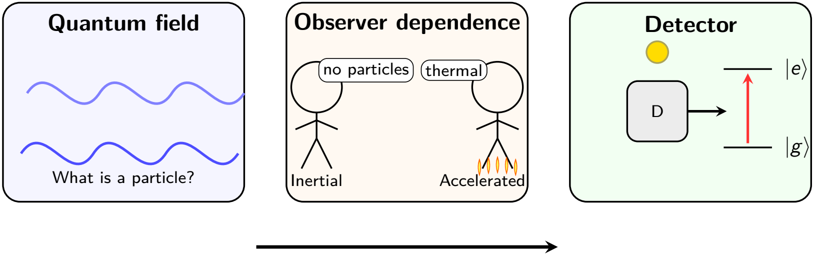

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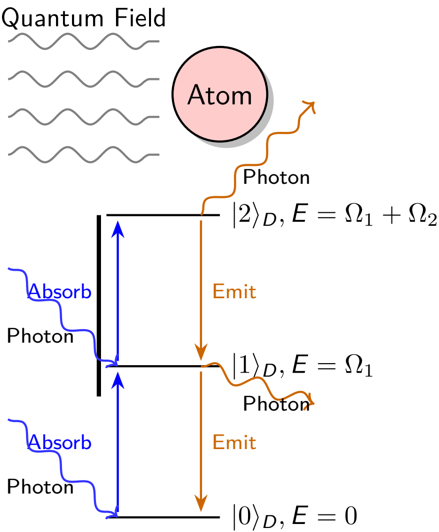
Qutrit Unruh-DeWitt detector



- This qutrit quantum system (Lima, Patterson, Tjoa, Mann 2023 [15]) is described by

$$\hat{H}_{\text{free}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Omega_1 & 0 \\ 0 & 0 & \Omega_1 + \Omega_2 \end{bmatrix}. \quad (1)$$

- The qutrit state transitions are characterized by the monopole operator

$$\hat{\mu}(\tau) = 2^{-1/2}\left(|1\rangle_D {}_D\langle 0| e^{i\Omega_1 \tau} + |2\rangle_D {}_D\langle 1| e^{i\Omega_2 \tau} \right) + \text{H.c.} \quad (2)$$

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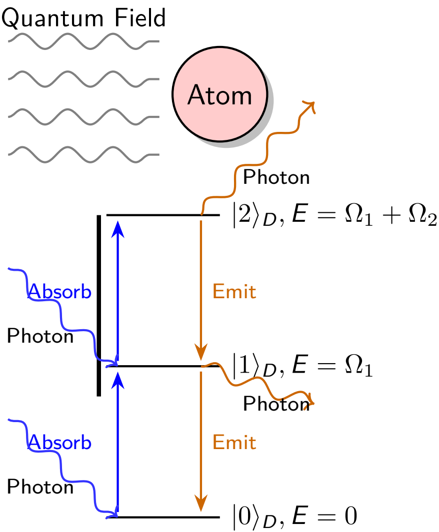

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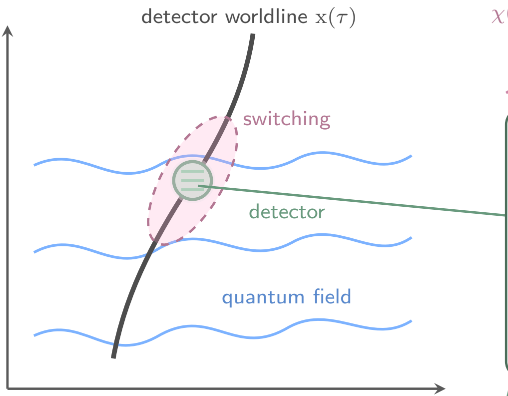
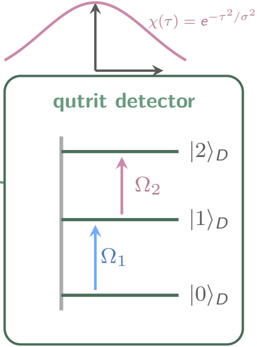
Detector–Field Interaction

Interaction Hamiltonian: $\hat{H}_{\text{int}}(\tau) = \lambda\, \chi(\tau)\, \hat{\mu}(\tau) \otimes \hat{\phi}(x(\tau))$



λ: coupling strength

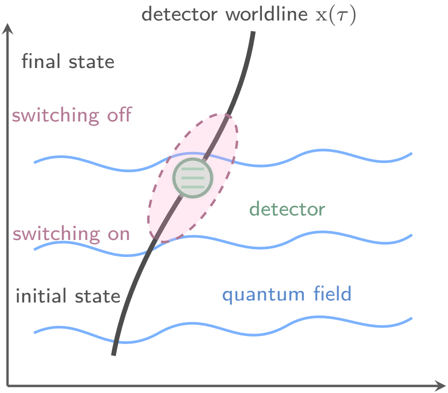
$\chi(\tau)$: switching function



$\hat{\mu}(\tau)$: monopole operator

$\hat{\phi}[x(\tau)]$: quantum field evaluated along the detector worldline $x(\tau)$

Final state



- Consider initial state

$$|\Psi_i\rangle = |0\rangle_D \otimes |0\rangle \tag{3}$$

- Evolution operator:

$$U = \mathcal{T} \exp\left[-i \int d\tau \hat{H}_{\text{int}}(\tau)\right]$$

- Final state is $|\Psi_f\rangle = U|\Psi_i\rangle$. Detector's final state:

$$\rho_D = \text{tr}_\phi \left[U |\Psi_i\rangle \langle \Psi_i| U^\dagger \right]. \tag{4}$$

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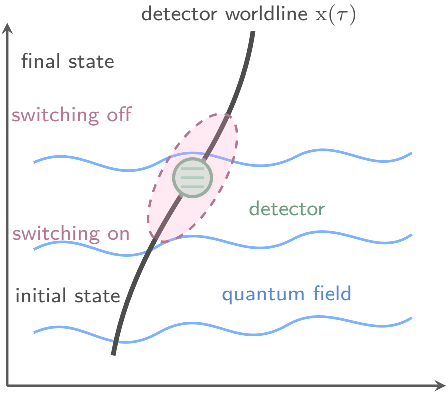

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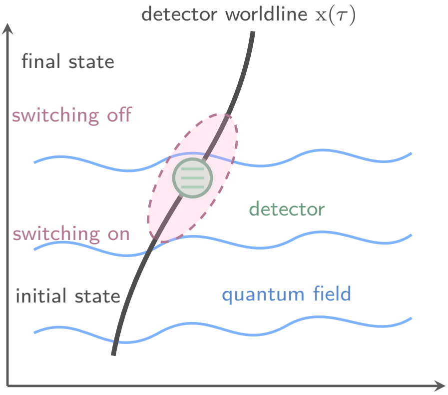

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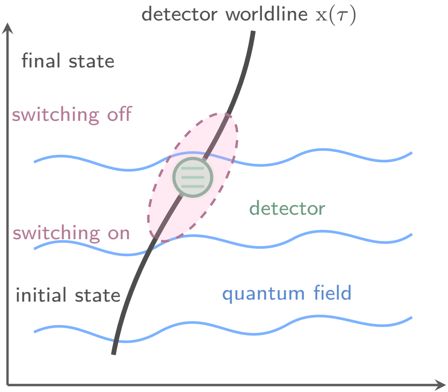

- Detector's final state [15]:

$$\hat{\rho}_{\mathcal{D}} = \begin{bmatrix} 1-q & 0 & \beta^* \\ 0 & q & 0 \\ \beta & 0 & 0 \end{bmatrix}, \quad (5)$$

- q: excitation probability to the first excited state $|1\rangle_D$
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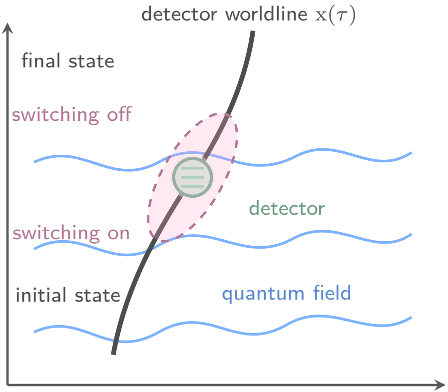

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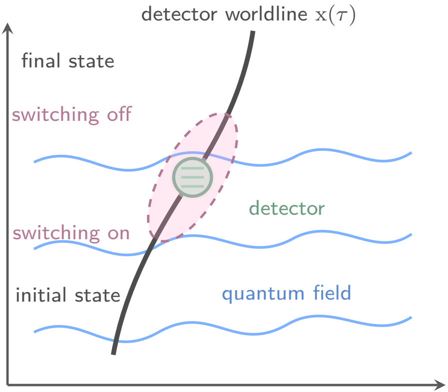

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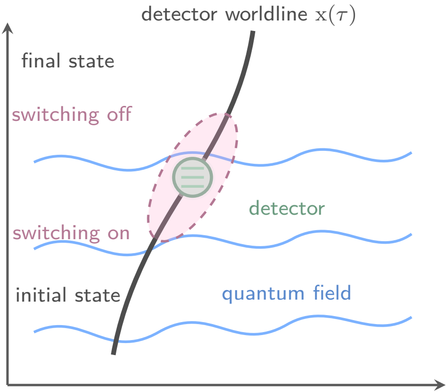

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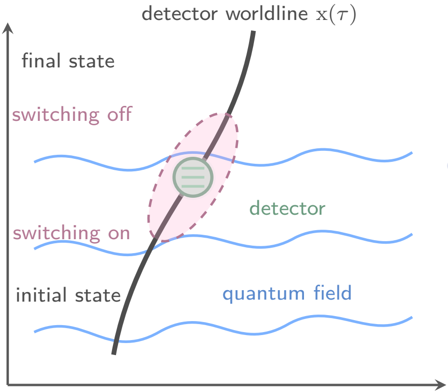

- Excitation probability

$$q = \frac{\lambda^2}{2} \int d\tau d\tau' \chi(\tau)\chi(\tau') e^{-i\Omega_1(\tau-\tau')} \mathcal{W}(\tau,\tau')$$

- Coherence

$$\beta = -\frac{\lambda^2}{4} \int d\tau d\tau' \chi(\tau)\chi(\tau') \Big[\Theta(\tau-\tau') e^{i(\Omega_1\tau'+\Omega_2\tau)} \mathcal{W}(\tau,\tau') + \Theta(\tau'-\tau) e^{i(\Omega_1\tau+\Omega_2\tau')} \mathcal{W}(\tau',\tau)\Big]$$

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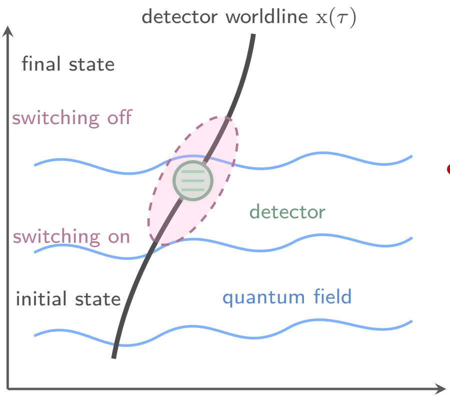

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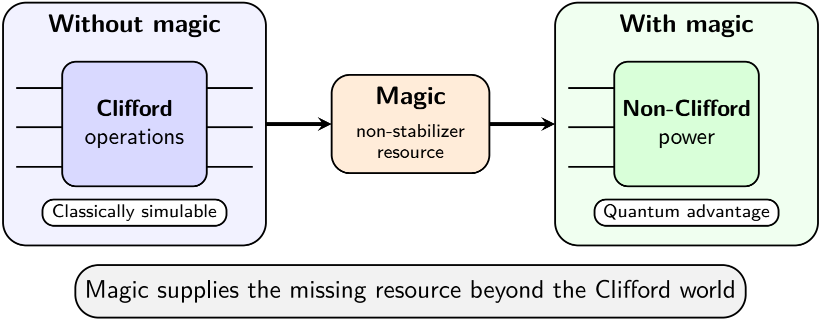

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- Magic provides the missing non-Clifford resource
- Enables quantum computational advantage [18, 19, 20]

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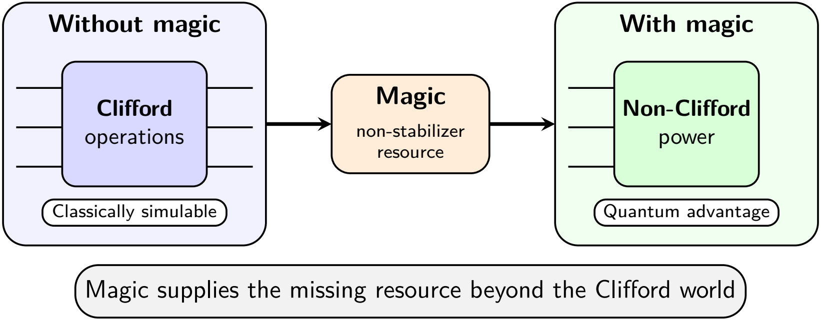

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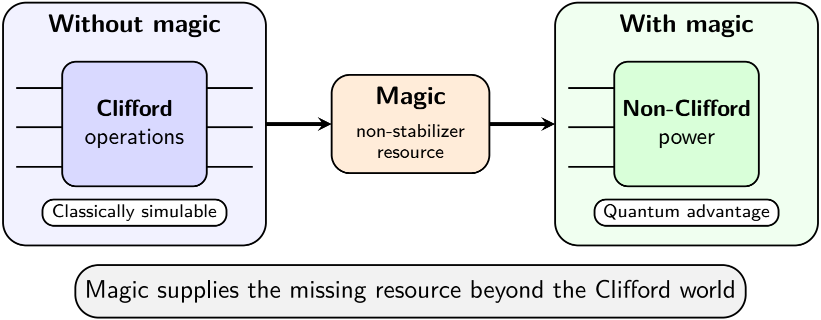

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What is Magic?

- We adopt mana Magic(Veitch, Mousavian, Gottesman, Emerson 2013 [21])—a well-established and operationally significant measure—to quantify magic.
- In the interaction picture of the energy eigenbasis, mana $M(\hat{\rho})$ is determined by the elements q and β of the detector (Nyström, Pranzini, and Keski-Vakkuri 2024 [22])

$$M(\hat{\rho}) = \ln\Big[1 - q + \frac{1}{3}\Big(|q - \mathcal{Re}(\beta) - \sqrt{3}\ \mathcal{Im}(\beta)| + |q + 2\ \mathcal{Re}(\beta)| + |q - \mathcal{Re}(\beta) + \sqrt{3}\ \mathcal{Im}(\beta)|\Big)\Big] . \quad (6)$$

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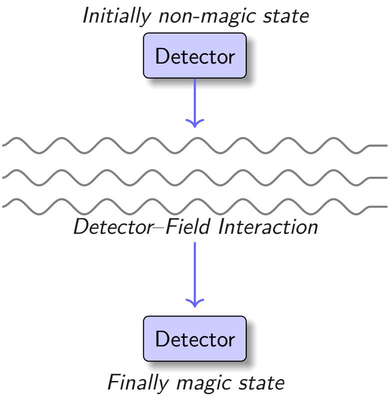

Magic harvesting protocol in flat spacetime (Nyström, Pranzini, and Keski-Vakkuri 2024 [22])

- **Initial state**: no magic

$$M = 0 \tag{7}$$

- Detector–Field Interaction Hamiltonian

$$\hat{H}_{\text{int}}(\tau) = \lambda\chi(\tau)\hat{\mu}(\tau) \otimes \hat{\phi}(\mathrm{x}(\tau)) \tag{8}$$

- **Final state**: non-zero magic

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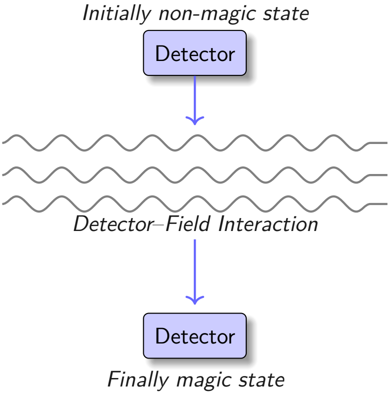

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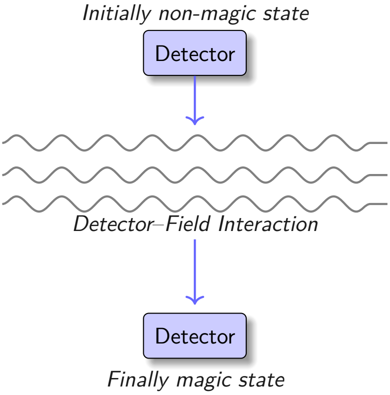


Magic harvesting protocol in flat spacetime (Nyström, Pranzini, and Keski-Vakkuri 2024 [22])

- **Initial state**: no magic

$$M = 0 \tag{7}$$

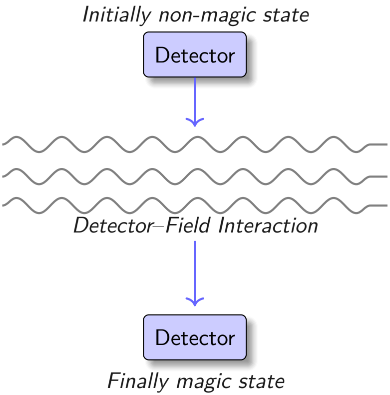
- Detector–Field Interaction Hamiltonian

$$\hat{H}_{\text{int}}(\tau) = \lambda \chi(\tau) \hat{\mu}(\tau) \otimes \hat{\phi}(\mathrm{x}(\tau)) \tag{8}$$

- **Final state**: non-zero magic

$$M \neq 0. \tag{9}$$

Related works



Related works

- Harvesting of stabilizer Rényi entropy in Minkowski spacetime (Cepollaro, Cusumano, Hamma, Lo Giudice and Odavić 2024 [23])
- Harvesting of contextuality in Minkowski spacetime: (LeMaitre 2025 [24]; Lima, Preciado-Rivas, and Srivastava 2025 [25])
- Entanglement harvesting in CFT (Wurtz, Lima, Myers, and Martín-Martínez 2026 [26])

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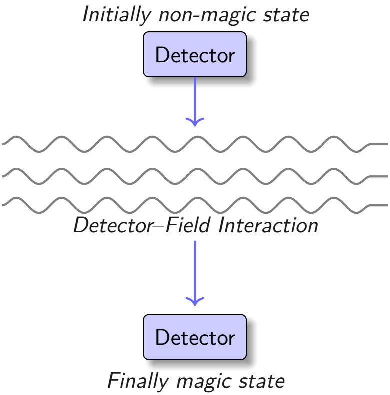

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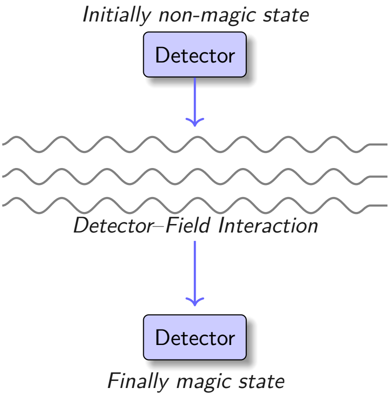

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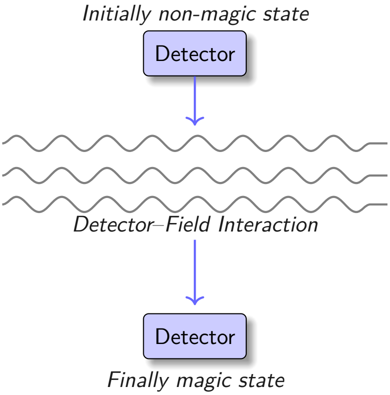

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- Conformal field theories are magical (White ,Cao, Swingle 2020 [27])
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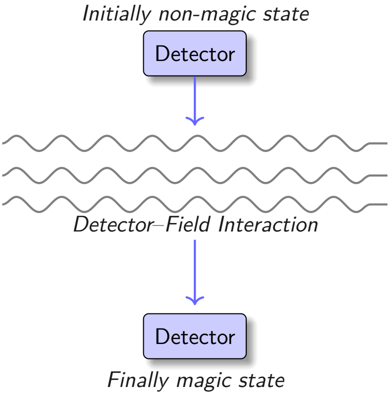

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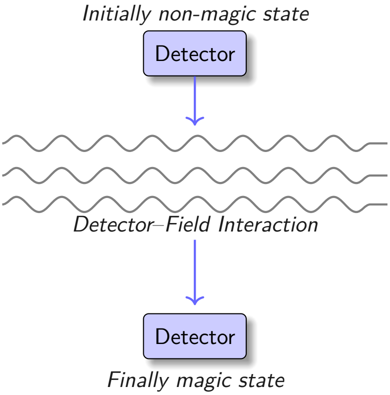

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Magic harvesting in AdS and CFT

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AdS spacetime

- Consider a static detector in $D = d + 1$-dimensional AdS spacetime with coordinates $(t, r, \theta_1, \theta_2, \ldots, \theta_{d-1})$,

$$ds^2 = -\left(1 + r^2/\ell^2\right) dt^2 + \frac{dr^2}{1 + r^2/\ell^2} + r^2 d\Omega_{d-1}^2 \,, \qquad (10)$$

where ℓ is the AdS radius, and the curvature is $\mathcal{R} = -\frac{d(d+1)}{\ell^2}$.

- The trajectory parameterized by the proper time τ is $(\gamma = \sqrt{\ell^2 + R^2})$

$$x(\tau) = \{t = \frac{\tau \ell}{\gamma},\ r = R,\ \theta_i = \Theta_i\}. \qquad (11)$$

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AdS spacetime

- The Wightman function for our purposes is given by (Decanini, Folacci 2006, 2008; Jennings 2010; Saharian 2020 [30, 31, 32, 33])

$$\mathcal{W}(\tau, \tau') = \frac{\Gamma(d-1)}{(4\pi)^{d/2}\Gamma(\frac{d}{2})} \left[i\, 2\gamma \sin\left(\frac{\tau - \tau' - i\epsilon}{2\gamma} \right) \right]^{1-d}. \quad (12)$$

- d $(d \geq 2)$ is the spatial dimension
- Γ represents the Gamma function
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Analytic results of transition and coherence for qutrit in AdS_{d+1}!

- The diagonal element q is

$$q = 2\alpha \sum_{n=0}^{\infty} \frac{\Gamma(d+n-1)}{\Gamma(n+1)} e^{-\frac{\sigma^2}{2}(\Omega+\Omega_n)^2} \tag{13}$$

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  where $U(a,b,c)$ is the Tricomi confluent hypergeometric function.

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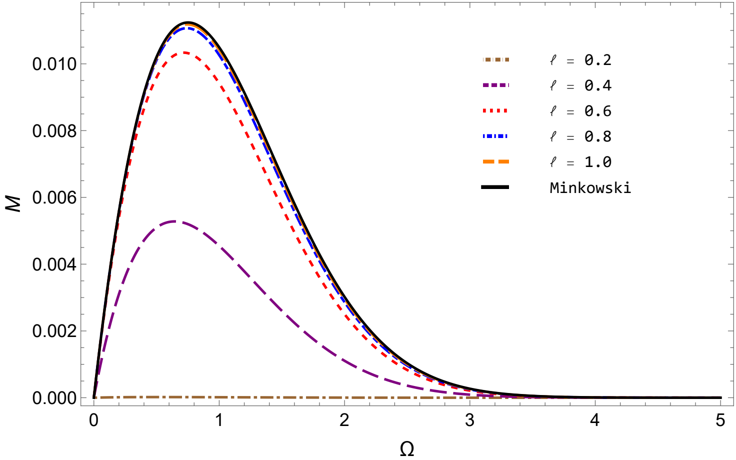
Magic Harvesting in AdS



Dependence on the AdS_4 radius ℓ
(Yang, Bhattacharya, Zhang, and Mann 2025 [34])

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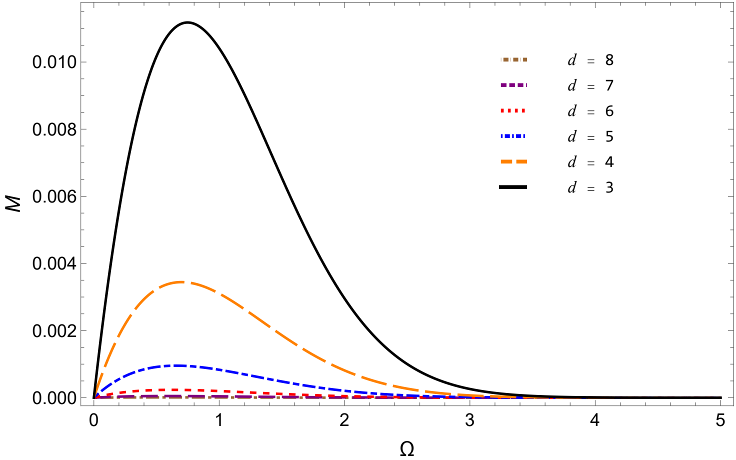
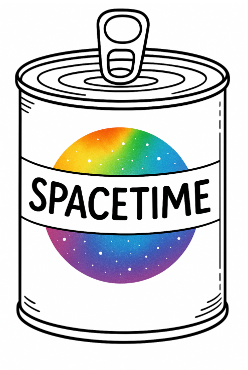


Dependence on the AdS_{d+1} dimensionality d
(Yang, Bhattacharya, Zhang, and Mann 2025 [34])

Holographic setup



- Consider a conformal field theory in d dimension defined on the Lorentzian cylinder, whose line element is

$$ds_b^2 = -d\tau^2 + R^2\, d\Omega_{d-1}^2. \qquad (17)$$

- Introducing a radial cutoff at $r = r_c$ and performing a Weyl rescaling of the induced metric, we have the below relation as $r_c \to \infty$,

$$ds_b^2 = \omega^2 \frac{\ell^2}{r_c^2}\, ds_{\text{AdS}}^2\Big|_{r=r_c}, R = \omega\ell, \tau = \omega t. \qquad (18)$$

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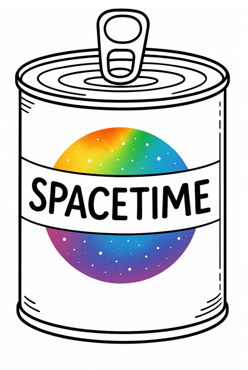

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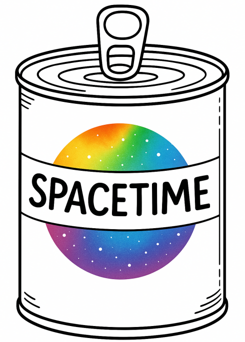

- Field/operator correspondence

$$\hat{\phi} \longleftrightarrow \hat{\mathcal{O}} \tag{19}$$

- The scaling dimension Δ can be related to the effective bulk mass $m_{\text{eff}}^2 := m^2 + \xi\mathcal{R}$ through (Gubser, Klebanov, Polyakov; Witten 1998 [4, 5, 35])

$$m_{\text{eff}}^2 \ell^2 = \Delta(\Delta - d). \tag{20}$$

- For a conformally massless scalar field,

$$\Delta_+ = \frac{d+1}{2}, \qquad \Delta_- = \frac{d-1}{2} = d - \Delta_+. \tag{21}$$

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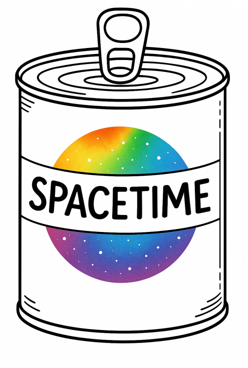

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Final state: qutrit in CFT

Analytic results of transition and coherence for qutrit in CFT!

- The diagonal element q is

$$q = \frac{1}{2}\lambda^2 \pi \sigma^2 C_\Delta R^{-2\Delta} \sum_{n=0}^{\infty} \binom{2\Delta + n - 1}{n} \times \exp\left[-\frac{\sigma^2}{2} \left(\Omega + \frac{\Delta + n}{R} \right)^2 \right], \tag{22}$$

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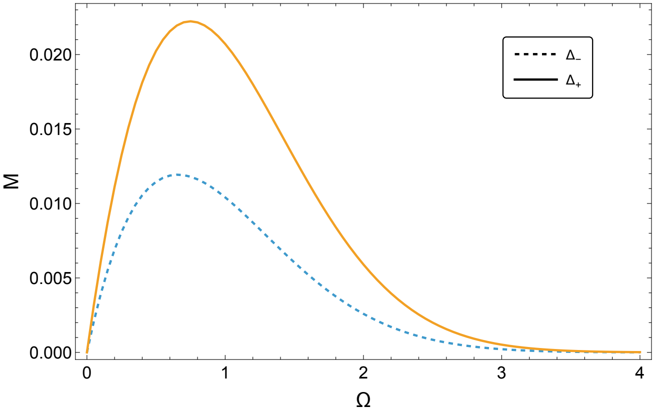

Dependence on the CFT_3 scaling dimension $\Delta_{\pm}$
(Zhang, Yang, Bhattacharya, and Mann 2026 [36])

Summary

Magic is the "rabbit" we pull out of the hat called "vacuum". And in my research, I'm just trying to see if the hat has any hidden bunnies for us to harvest.

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