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Probing new physics with open quantum systems

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YOUNGST@RS - Quantum Sensing for Fundamental Physics,
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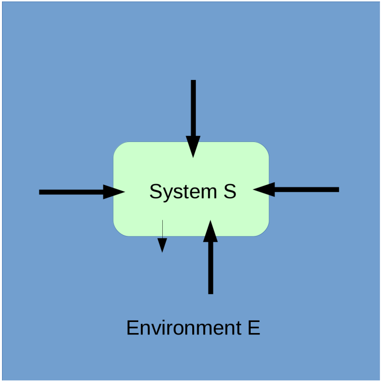
ATOMINSTITUT

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

Open quantum systems



- Realistic quantum systems are not isolated $\rightarrow$ surrounded by environments
- Examples: thermal bath, electromagnetic field, gravity, scalar field,...

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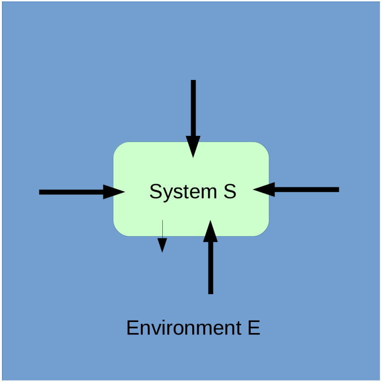

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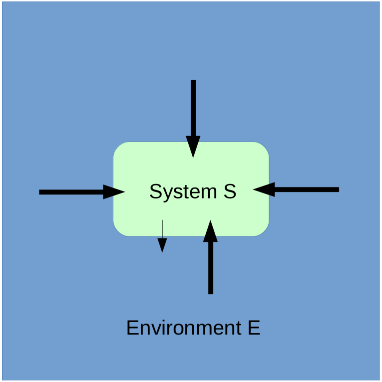

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- Examples: thermal bath, electromagnetic field, gravity, scalar field,...

Reduced density matrix

- Consider system scalar field ϕ with environment scalar field χ
- Combination of system and environment: $\hat{\rho}_{\phi\chi}(t)$
- Assume $\hat{\rho}_{\phi\chi}(0) = \hat{\rho}_{\phi}(0) \otimes \hat{\rho}_{\chi}(0)$
- Reduced density matrix: $\hat{\rho}_{\phi}(t) = \mathrm{Tr}_{\chi}\hat{\rho}_{\phi\chi}(t)$
- Project into single-particle momentum basis:

$$\rho_{\phi}(\mathbf{p}, \mathbf{p}'; t) := \langle \mathbf{p} | \hat{\rho}_{\phi}(t) | \mathbf{p}' \rangle$$

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Phys.Rev.D 107 (2023) 1, 016005

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$$

$$
\times \int_{\mathbf{x}\mathbf{x}'\mathbf{y}\mathbf{y}'} e^{-\mathrm{i}(\mathbf{p}\cdot\mathbf{x}-\mathbf{p}'\cdot\mathbf{x}')+\mathrm{i}(\mathbf{k}\cdot\mathbf{y}-\mathbf{k}'\cdot\mathbf{y}')} \partial_{x^0,E^\phi_{\mathbf{p}}} \partial^*_{x^{0\prime},E^\phi_{\mathbf{p}'}} \partial^*_{y^0,E^\phi_{\mathbf{k}}} \partial_{y^{0\prime},E^\phi_{\mathbf{k}'}}
$$

$$
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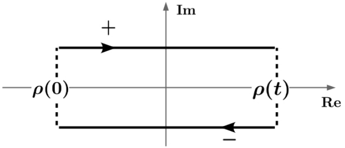
$$\widehat{\mathcal{F}}[\phi;t] = \left\langle \exp\left\{\mathrm{i}\left(\widehat{S}_{\chi,\mathrm{int}}[\chi;t] + \widehat{S}_{\mathrm{int}}[\phi,\chi;t]\right)\right\}\right\rangle_\chi$$

Schwinger-Keldysh closed time path:



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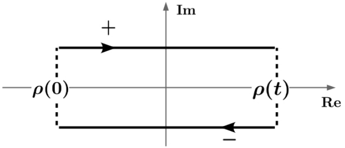

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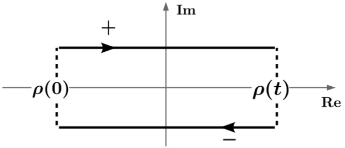

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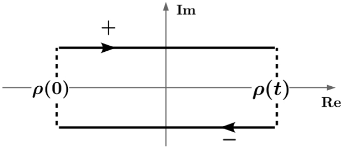

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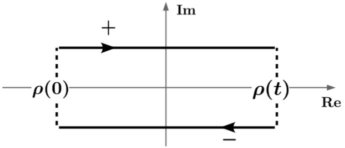

Example: dilatons with Damour-Polyakov mechanism

- Motivated by string theory and schalar-tensor theories
- Screening mechanism to circumvent fifth force constraints
- $\mathcal{L} = -(\partial X)^2 - V_0\, e^{-\lambda X/m_{\rm Pl}} + \frac{A_2}{2m_{\rm Pl}^2} T^{\nu}{}_{\nu} X^2$ with $X = X_0 + \chi$
- VEV: $X_0 = \frac{m_{\rm Pl}}{\lambda} W\left(-\frac{\lambda^2 V_0}{A_2 T^{\nu}{}_{\nu}}\right)$ with $W(x) = \sum_{n=1}^{\infty} \frac{(-n)^{n-1}}{n!} x^n$
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Eur.Phys.J.C 83 (2023) 8, 767

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- Open quantum dynamical effects could affect interference pattern in atom interferometer

- Rough approximation of cold atom:
  - Real scalar ϕ since dilaton only couples to mass density
  - Ignore all ϕ-loops since atoms are complex composite objects
  - Restrict to single-particle subspace since atoms are cold

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- Rough approximation of cold atom:
  - Real scalar ϕ since dilaton only couples to mass density
  - Ignore all ϕ-loops since atoms are complex composite objects
  - Restrict to single-particle subspace since atoms are cold

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- Compute reduced density matrix elements $\rho_\phi(\mathbf{p}, \mathbf{p}'; t)$
- Extract frequency shift $\Delta u := M \frac{A_2}{4m_{\rm Pl}^2} \left[X_0^2 + \Delta_{zz}^{\rm F(T\neq 0)} \right] v^2$
  - M: cold atom's mass (rubidium-87)
  - $v := \frac{||\mathbf{p}| - |\mathbf{p}'||}{M}$ non-relativistic speed difference of two atom states
  - Thermal part of the dilaton Feynman propagator:

$$\Delta_{xx}^{\rm F(T\neq 0)} = \frac{T^2}{2\pi^2} \int_{m/T}^{\infty} d\xi \frac{\sqrt{\xi^2 - (\frac{m}{T})^2}}{e^{\xi} - 1}$$

with dilaton mass m and temperature T

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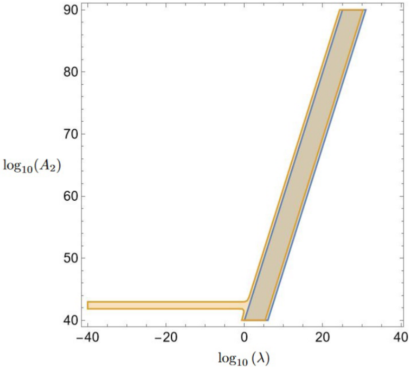

- $V_0 = 1\,(\text{MeV})^4$
- $u(P, T_2; P, T_1)$ (blue) and $u(P, T_3; P, T_1)$ (orange); $P = 9.6 \times 10^{-10}$ mbar (hydrogen);

$T_1 = 0.5 \times 10^{-3}$ K, $T_2 = 100$ K, and $T_3 = 500$ K

Conclusions

- New first principle-based formalism for computing reduced density matrices
- Open quantum dynamical effects could lead to new constraints on new physics

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- Compare two measurements:

$$|\Delta u(P_a, T_b) - \Delta u(P_c, T_d)| =: u(P_a, T_b; P_c, T_d) \geq \Delta u_{\text{min}}$$

  - P: Gas pressure in vacuum chamber (affects φ_0)
  - Choose rubidium-87 atoms with $M = 87 m_u$
  - $v = 50$ mm/s
  - $\Delta u_{\text{min}} \approx 10^{-8}$ Hz