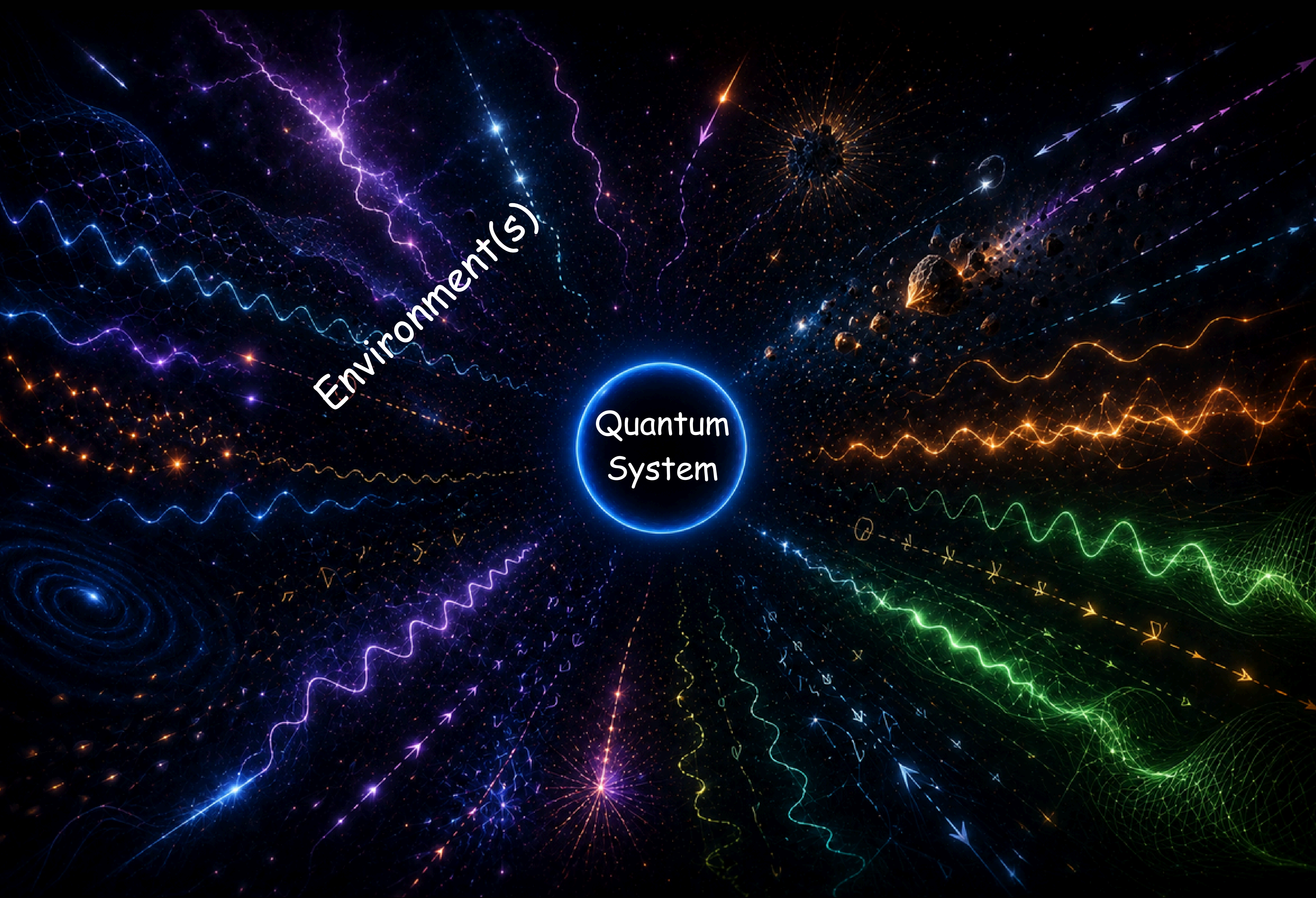
Imprints of different descriptions of (quantum) gravity on gravitational decoherence models

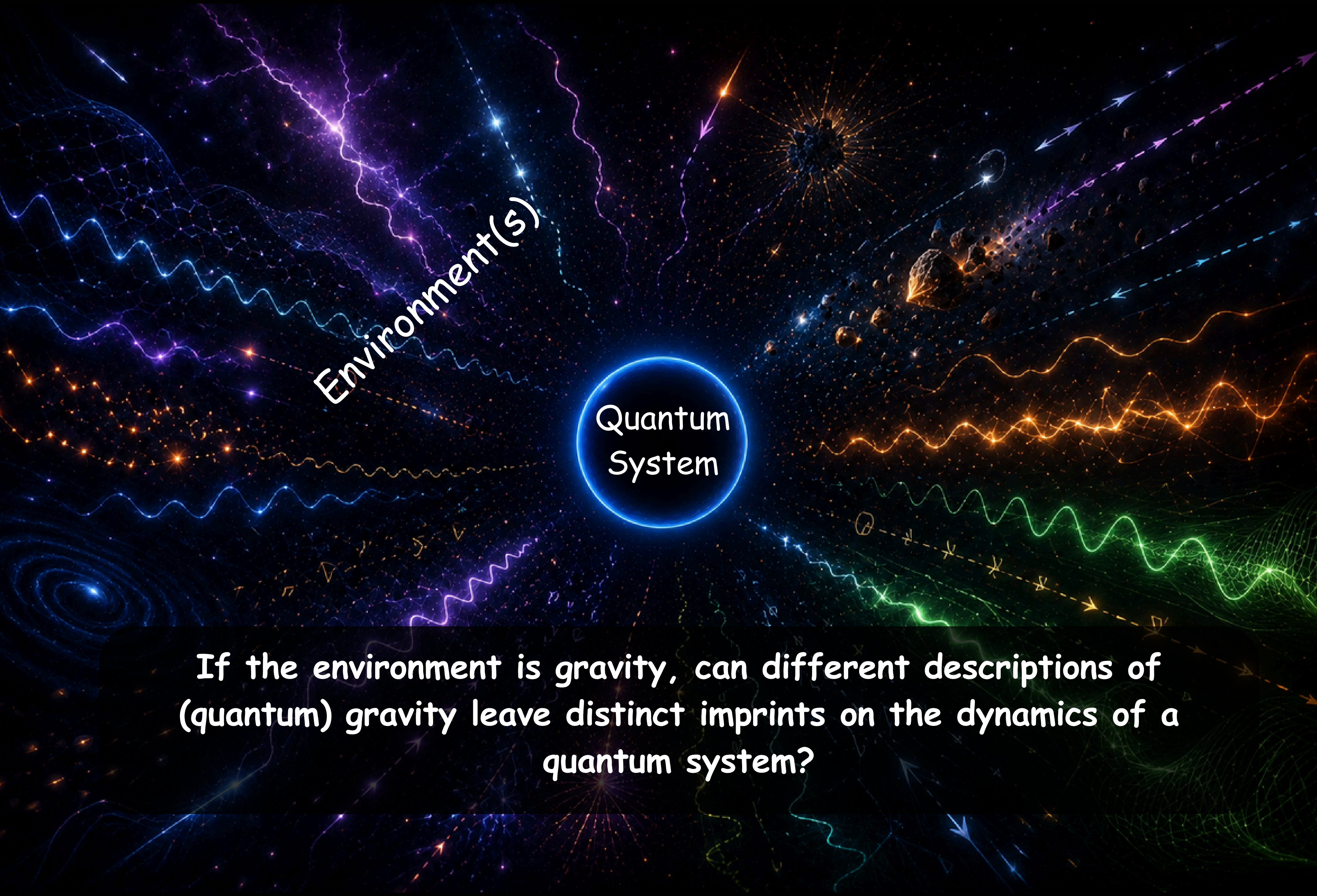
Max Joseph Fahn

(*Università di Bologna and INFN Sezione di Bologna)*

FAU² Workshop: Quantum Gravity Meets Quantum Information – Foundations, Frameworks and Frontiers

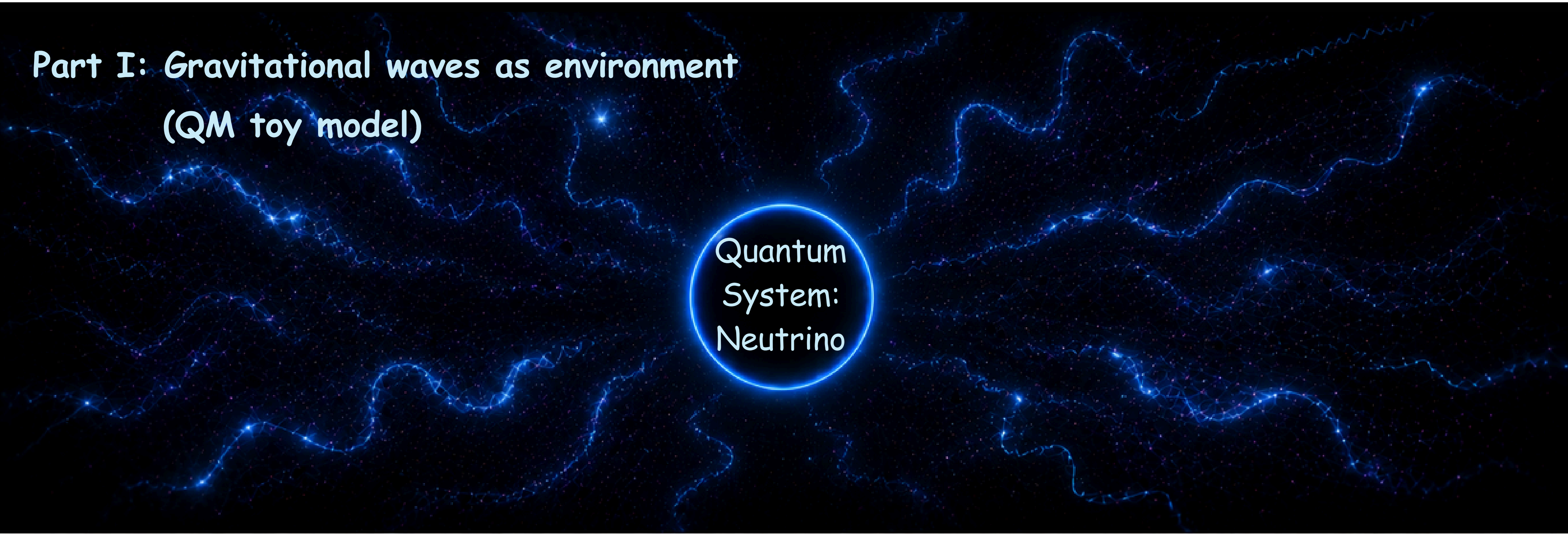
Erlangen, 08.07.2026


Environment(s)
Quantum
System

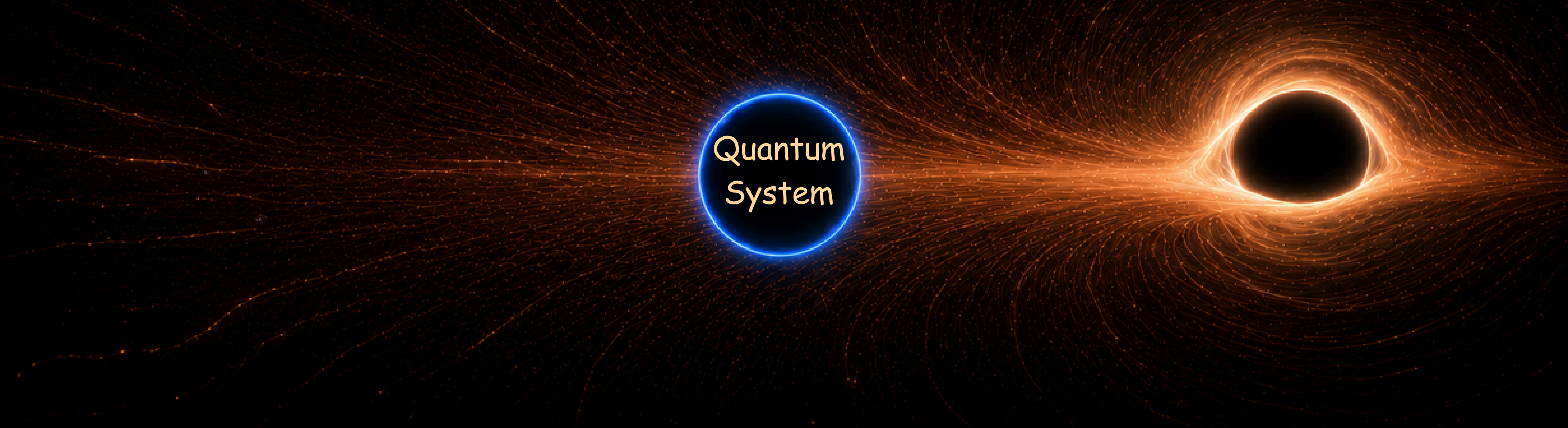

Environment(s)
Quantum System
If the environment is gravity, can different descriptions of (quantum) gravity leave distinct imprints on the dynamics of a quantum system?

Overview of the talk

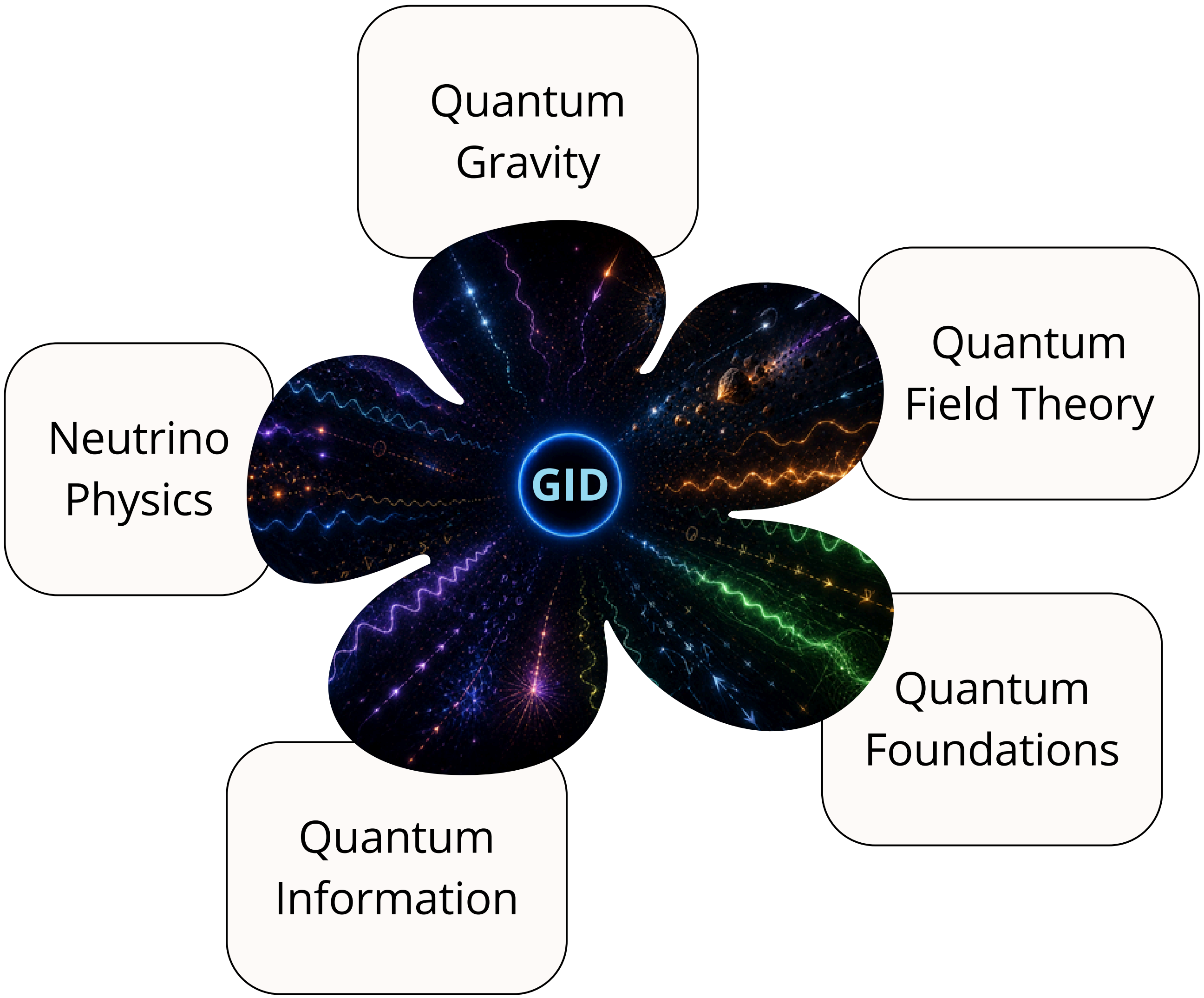
Part I: Gravitational waves as environment
(QM toy model)



Part II: Horizon and quantum field as environment



Location in the physics landscape



Gravitationally induced decoherence…

- as playground for distinct signatures of QG theories
- as contribution to better understand fundamental processes in nature

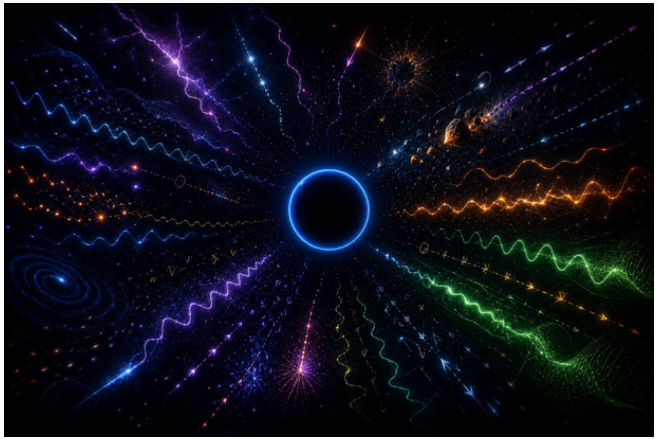
This talk: Neutrino oscillations & effects of black holes/Hawking radiation

Dynamics of open quntum systems

How to derive the imprints of the environment?

Dynamics of the full system:

$$\frac{\partial \rho(t)}{\partial t} = -\frac{i}{\hbar}[H(t), \rho(t)]$$



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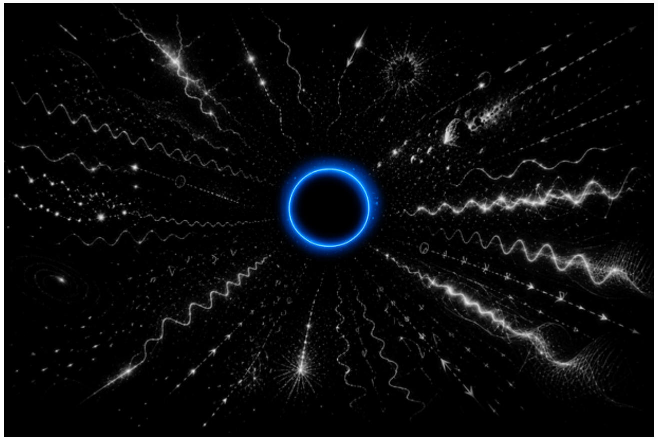
Dynamics of the quantum system of interest:
"Master equation"

$$\frac{\partial \rho_S(t)}{\partial t} = -\frac{i}{\hbar}[H_S(t)+H_{add}(t), \rho_S(t)]+\mathcal{D}[\rho_S(t)]$$

Lindblad form

$$\mathcal{D}[\rho_S(t)] = \sum_j c_j \left(L_j\, \rho_S(t)\, L_j^\dagger - \frac{1}{2}\left\{ L_j^\dagger L_j, \rho_S(t) \right\} \right)$$



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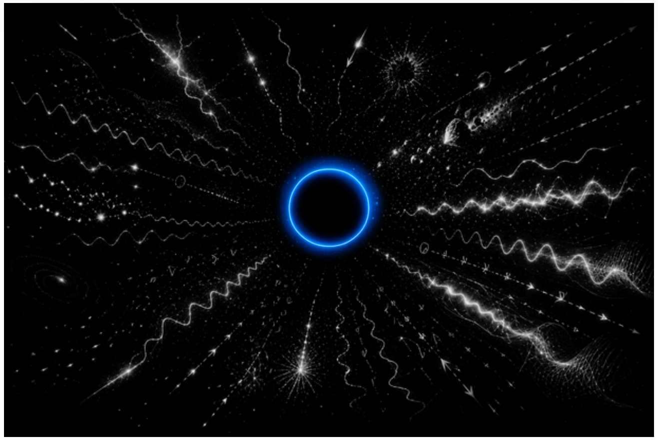


New processes in an open quantum system:

- Energy shifts / renormalisations
- Dissipation
- **Decoherence** $\longrightarrow$ Damping of off-diagonal elements of $\rho_S(t)$
  $\rightarrow$ less/no interference

Part I

QM toy models for a neutrino in an environment of gravitational waves

Based on work with

- A. Domi, T. Eberl, K. Giesel, L. Hennig, U. Katz, R. Kemper, M. Kobler [**arXiv:2403.03106**]
- R. Ferrero, K. Giesel and R. Kemper **[arXiv:2605.25936]**
- R. Ferrero, K. Giesel and R. Kemper **[in preparation]**

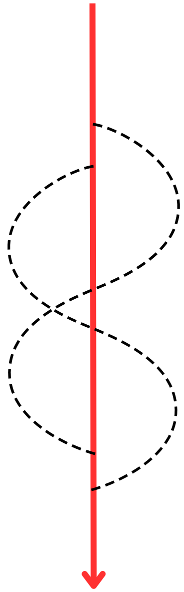
Why neutrinos?

- Three flavours, weak interaction in flavour basis

propagation and coupling to gravity in mass basis

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \xleftrightarrow[\text{unitary transformation}]{U} \begin{pmatrix}\nu_{m_1}\\ \nu_{m_2}\\ \nu_{m_3}\end{pmatrix}$$

→ Probability to measure a specific flavour state oscillates (caused by interference of different mass eigenstates)



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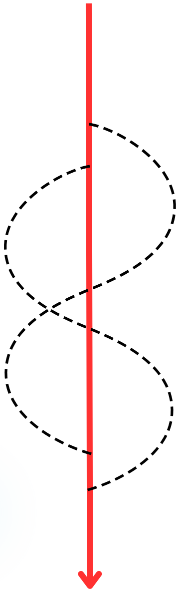

→ Probability to measure a specific flavour state oscillates (caused by interference of different mass eigenstates)

Gravitationally induced decoherence is expected to modify these oscillations

- Phenomenological quantum mechanical models
  See e.g. [Lisi, Marrone, Montanino, 2000], [Benatti, Floreanini 2000], [Coelho, Mann 2017], [Gomes, Gomes, Peres 2023], ...
- Microscopic quantum mechanical model: Resolution of the phenomenological parameters
  [D'Esposito, Gubitosi 2023], [Domi, Eberl, MJF, Giesel, Hennig, Katz, Kemper, Kobler 2024]

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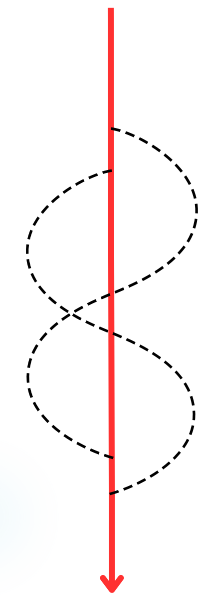

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Effect of different quantisations of the gravitational environment in this toy model on the oscillations?

Here: One step from Schrödinger towards polymer quantisation

Quantum mechanical toy model

[Domi, Eberl, MJF, Giesel, Hennig, Katz, Kemper, Kobler 2024]

Hamiltonian in Schrödinger quantisation, inspired by [Xu, Blencowe 2022]

$$H = H_S \otimes 1_\mathcal{E} + 1_S \otimes \underbrace{\left[\frac{1}{2}\sum_{i=1}^{N}\left(p_i^2 + \omega_i^2 q_i^2\right)\right]}_{H_\mathcal{E}} - \underbrace{H_S \otimes \sum_{i=1}^{N} g\, q_i}_{H_\text{int}}$$

Neutrino Hamiltonian

N harmonic oscillators

Schrödinger quantisation

Linear in the q_i

In a field theory with linearised gravity:

$$g \int d^3x\, T^{\mu\nu}(x) \otimes \delta h_{\mu\nu}(x)$$

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Main assumptions for derivation of a master equation:

- interaction is perturbation to uncoupled dynamics
- environment in thermal state with temperature β^{-1}
- continuum limit in the environment $\rightarrow$ effective coupling constant η

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→ Lindblad master equation for the neutrino:

$$\frac{\partial \rho_S(t)}{\partial t} = -\frac{i}{\hbar}[H_S(t), \rho_S(t)] + \mathcal{D}[\rho_S(t)]$$

Solution (in eigenbasis of H_S):

$$\rho_{ij}(t) = \rho_{ij}(0)\; e^{-\frac{i}{\hbar}(E_i - E_j)t - \Gamma_0 \cdot (E_i - E_j)^2 t} \qquad \Gamma_0 = \frac{2\eta^2}{\beta\hbar^3}$$

→ Damping of the off-diagonal elements (decoherence)

Polymer quantisation-inspired modification of the environment

A glimpse of polymer quantisation in quantum mechanics:

- Inspired by loop quantisation
- Based on quantisation of the Weyl algebra (i.e. relations between $U_{\mu_0} = e^{i\mu_0 q}, V_\beta = e^{i\beta p}$)
- Not both q and p exist together → replace one by a combination of Weyl elements
- Not unitarily equivalent to Schrödinger quantisation

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Toy model in ***Schrödinger quantisation*** *with* ***Weyl element in interaction****:*

[MJF, Ferrero, Giesel, Kemper 2026]

$$q_i \to \frac{1}{\mu_0}\sin\left(q_i \mu_0\right) = \frac{1}{2i\mu_0}\left(U_{\mu_0,i} - U^\dagger_{\mu_0,i}\right), \quad U_{\mu_0,i} := e^{i\mu_0 q_i}$$

$$H = H_S \otimes 1_\mathcal{E} + 1_S \otimes \underbrace{\left[\frac{1}{2}\sum_{i=1}^{N}\left(p_i^2 + \omega_i^2 q_i^2\right)\right]}_{H_\mathcal{E}} \underbrace{- H_S \otimes \sum_{i=1}^{N} \frac{g}{2i\mu_0}\left(U_{\mu_0,i} - U^\dagger_{\mu_0,i}\right)}_{H_\text{int}}$$

Imprint of the chosen model on the decoherence in neutrino oscillations

[MJF, Ferrero, Giesel, Kemper 2026]

→ Derivation of Lindblad master equation, additional assumption: $\mu_0' := \frac{\mu_0}{g} \ll \sqrt{\frac{\pi\beta\hbar}{8\eta^2}} =: (\mu_0')_{\max}$

Solution: $\rho_{ij}(t) = \rho_{ij}(0)\, e^{-\frac{i}{\hbar}(E_i - E_j)t - \Gamma_{\mu_0}\cdot(E_i - E_j)^2 t}$

$$\Gamma_{\mu_0} = \frac{2\eta^2}{\beta\hbar^3} \sum_{\ell=0}^{\infty} \left(-\frac{4\eta^2 (\mu_0')^2}{\pi\beta\hbar} \right)^{\ell} \varphi_\ell$$

Previous model with position coupling: $\Gamma_0 = \frac{2\eta^2}{\beta\hbar^3}$

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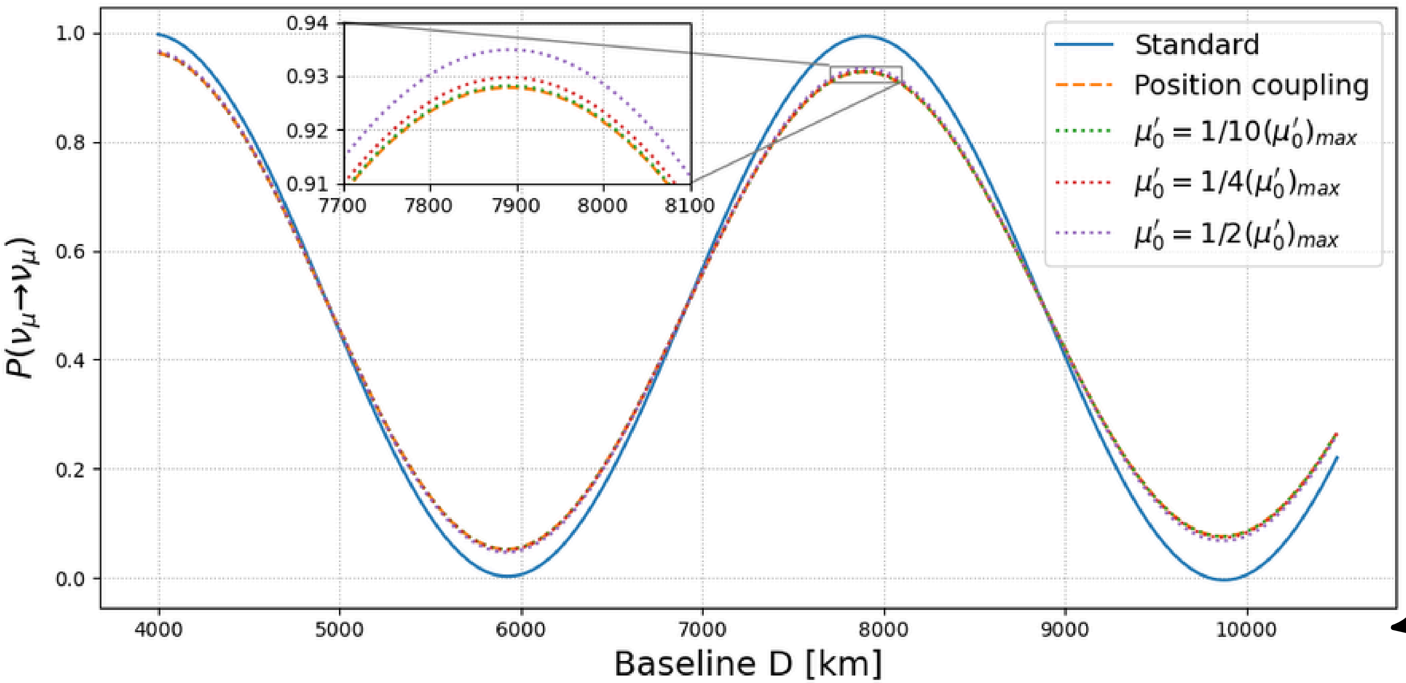


$E^{\text{kin}} = 4\,GeV$

$\beta^{-1} = 0.9\,K$

$\eta = 10^{-8}\,s$

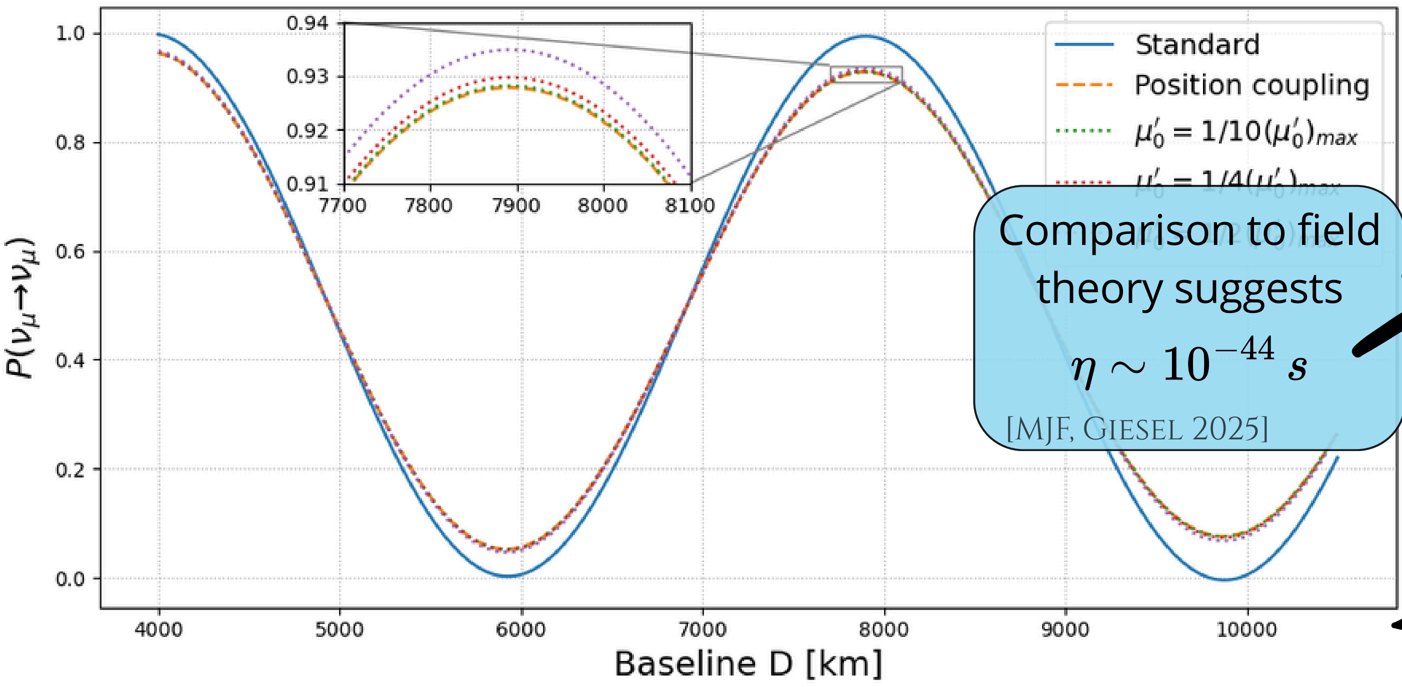
Typical baselines for atmospheric neutrinos

Next steps

- **Polymer quantisation:**

$$H = H_S \otimes 1_{\mathcal{E}} + 1_S \otimes \underbrace{\left[\frac{1}{2}\sum_{i=1}^{N}\left(p_i^2 + \omega_i^2 q_i^2\right)\right]}_{H_{\mathcal{E}}} \underbrace{- H_S \otimes \sum_{i=1}^{N} \frac{g}{2i\mu_0}\left(U_{\mu_0,i} - U_{\mu_0,i}^{\dagger}\right)}_{H_{\text{int}}}$$

- **Enhance size of the effect:**



Comparison to field theory suggests

$\eta \sim 10^{-44}\, s$

[MJF, Giesel 2025]

$E^{\text{kin}} = 4\, GeV$

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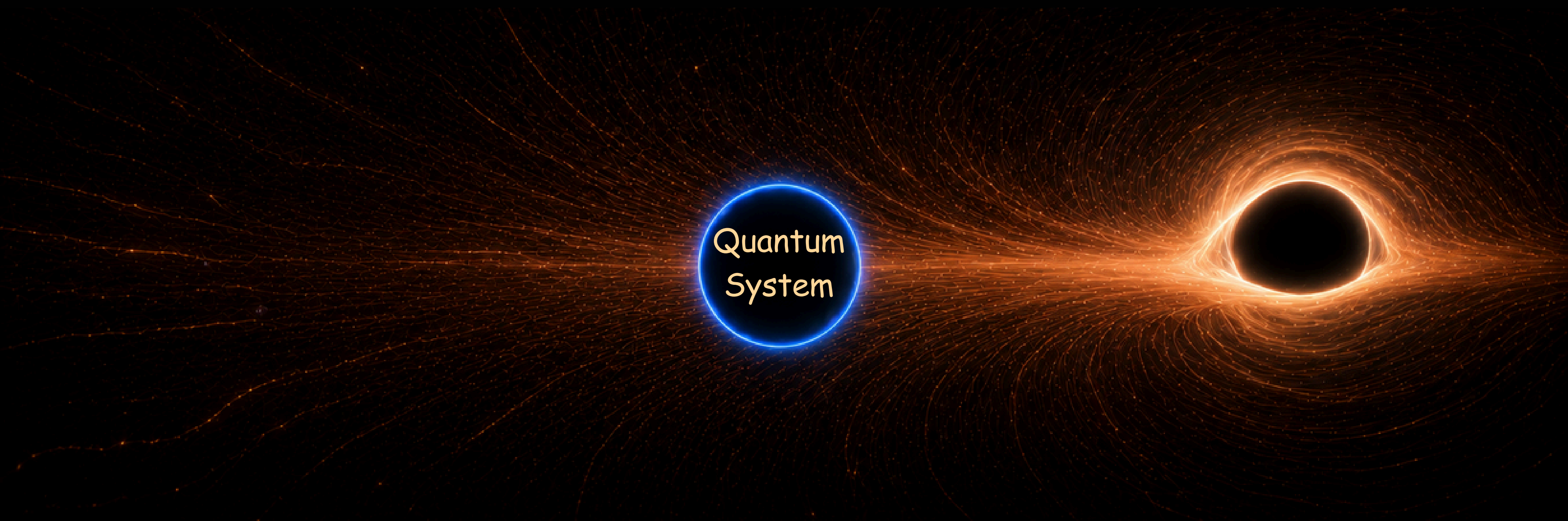
Typical baselines for atmospheric neutrinos

Part II

Decoherence induced by horizons with classical and quantum geometries

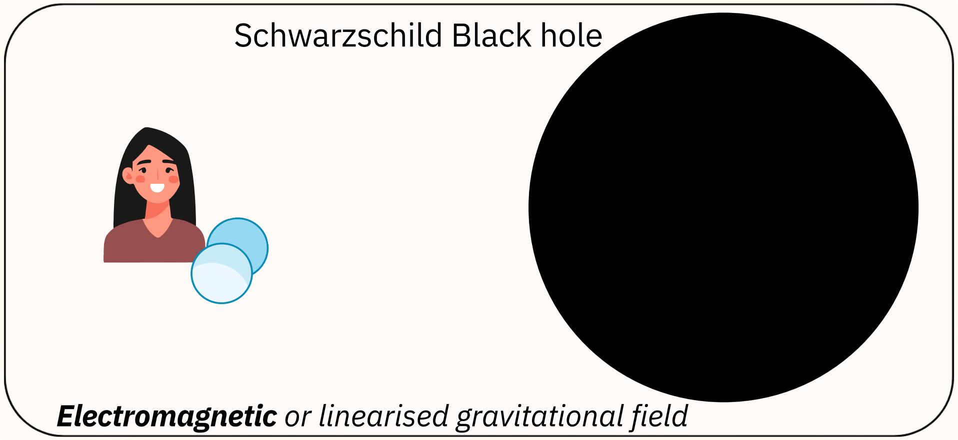


BASED ON WORK WITH A. PESCI

- **[ARXIV:2507.16911]**
- **[ARXIV:2507.18709]**
- **[ARXIV:2605.19588]**

The model

[Danielson, Satishchandran, Wald 2022], [Danielson, Satishchandran, Wald 2023], [Gralla, Wei 2024]
[Wilson-Gerow, Dugad, Chen 2024], [Danielson, Satishchandran, Wald 2024]



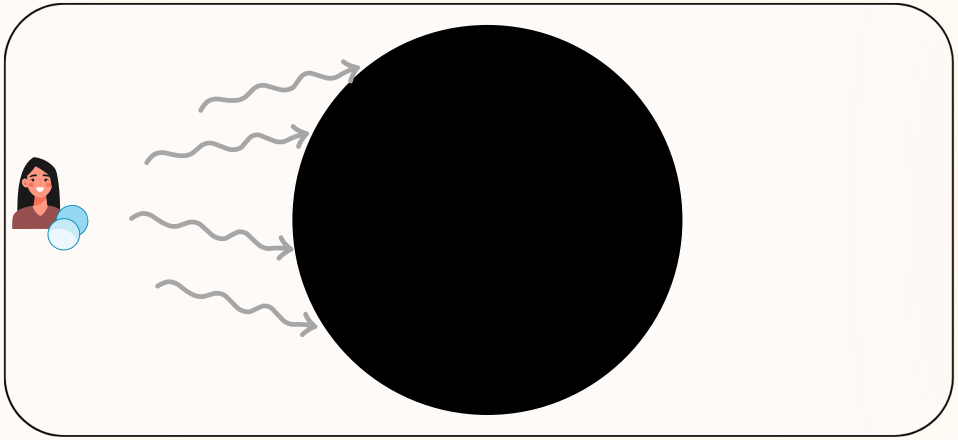
How does the presence of the horizon influence A's superposition?

motivated by [Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer 2018]
[Baym, Ozawa 2009], [Mari, De Palma, Giovannetti 2016]

Global vs. local approach

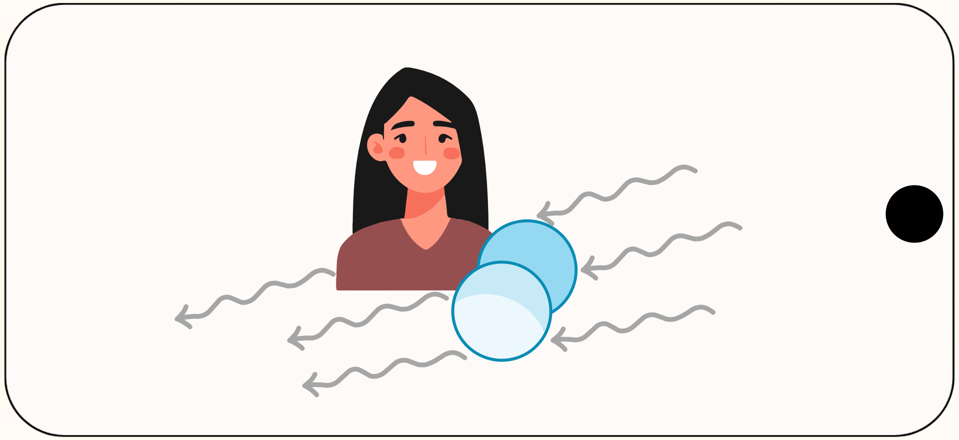
Global point of view: Radiation through horizon

[Danielson, Satishchandran, Wald 2022],
[Danielson, Satishchandran, Wald 2023], [Gralla, Wei 2024]



Local point of view: Field vacuum in Alice's lab

[Wilson-Gerow, Dugad, Chen 2024],
[Danielson, Satishchandran, Wald 2024],
[MJF, Pesci 2025], [Li, Man, Wang 2026]



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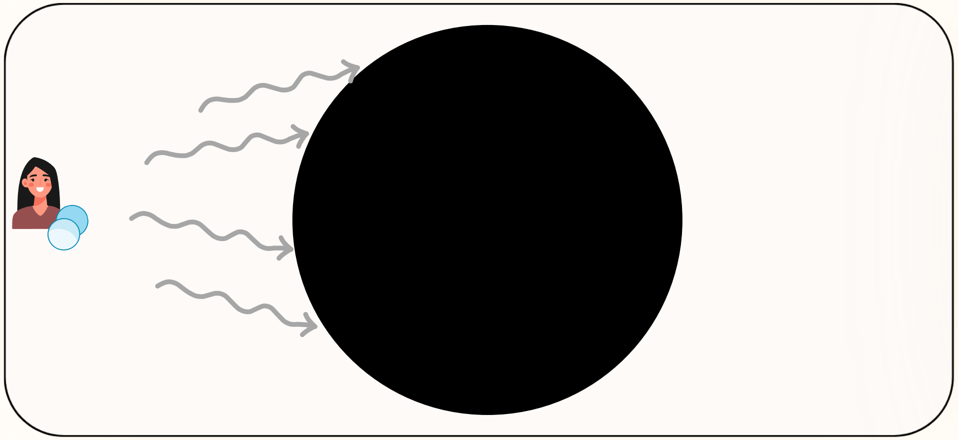

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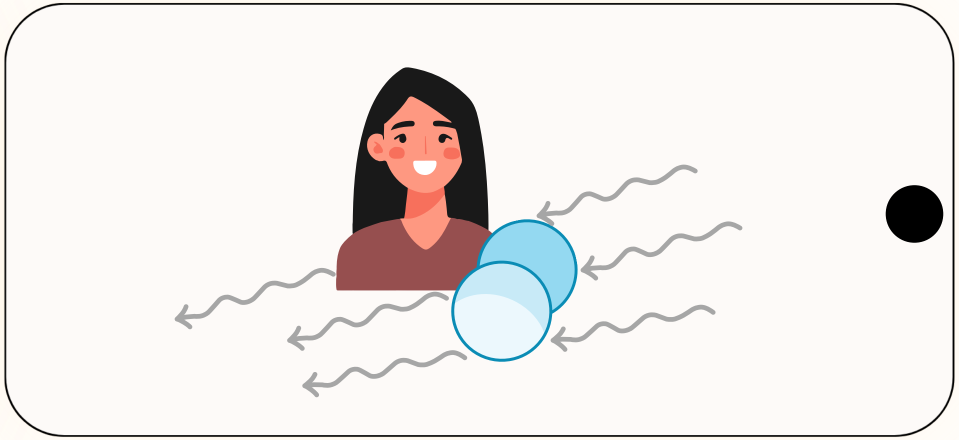

Hamiltonian in for local point of view:

$$H = H_S \otimes 1_{\mathcal{E}} + 1_S \otimes H_{\mathcal{E}} + H_{\text{int}}$$

A's spatial superposition

Electromagnetic field in vacuum in Schwarzschild spacetime

Coupling superposition – electromagnetic field

A's protocol

[Danielson, Satishchandran, Wald 2022], [Danielson, Satishchandran, Wald 2023], [Gralla, Wei 2024]
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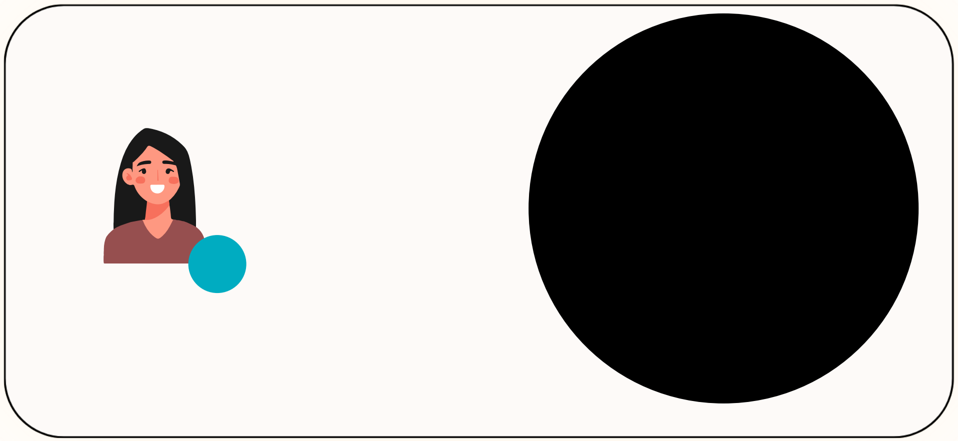
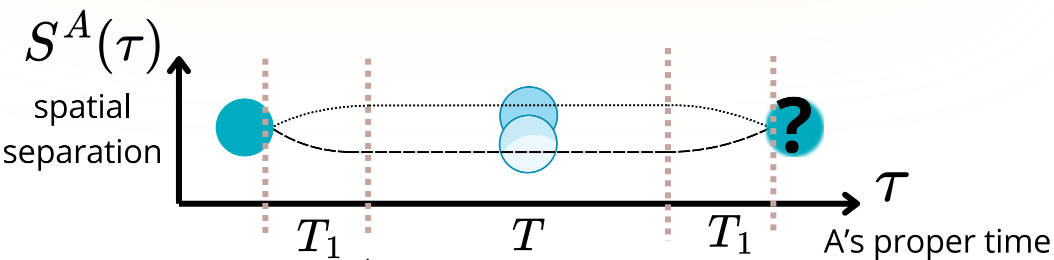




$T \gg T_1$

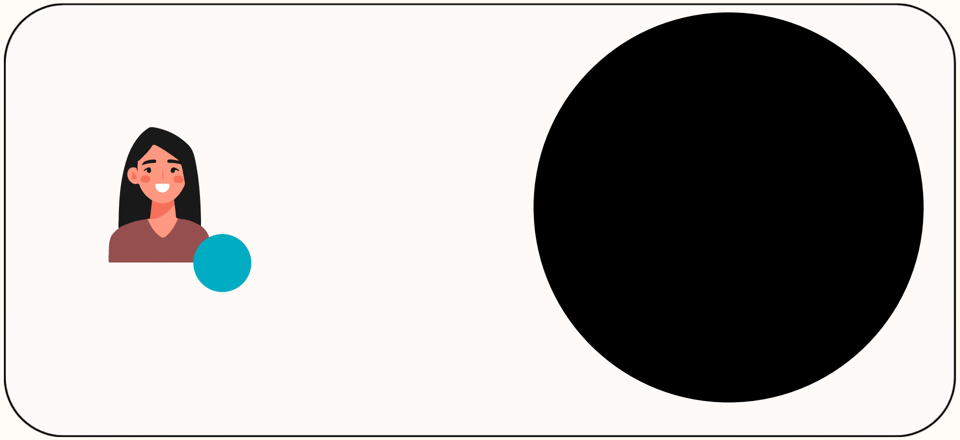
$$|\psi\rangle = \alpha|U\rangle + \beta|L\rangle$$

Assumptions:

- Opening (and closing) adiabatically
  → radiation going to infinity negligible
- No decoherence from other surroundings

Black hole with classical horizon geometry

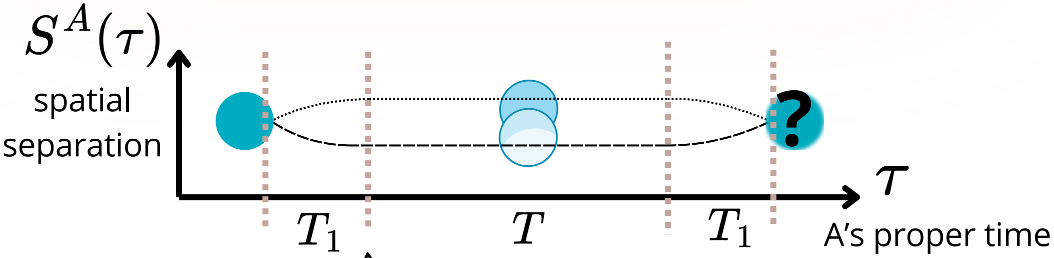
[Danielson, Satishchandran, Wald 2022], [Danielson, Satishchandran, Wald 2023], [Gralla, Wei 2024]
[Wilson-Gerow, Dugad, Chen 2024], [Danielson, Satishchandran, Wald 2024]



- Solution of master equation → density matrix of A's particle:

$$\rho_S(T_F) \approx \begin{pmatrix} |\alpha|^2 & \alpha^* \beta\, e^{-\mathbb{D}(T)} \\ \alpha\beta^*\, e^{-\mathbb{D}(T)} & |\beta|^2 \end{pmatrix}$$

$$\mathbb{D}(T) \geq 0$$



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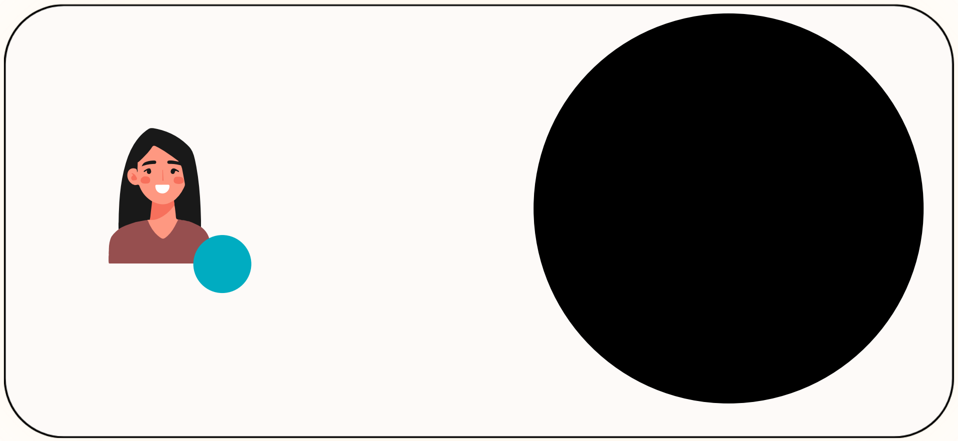

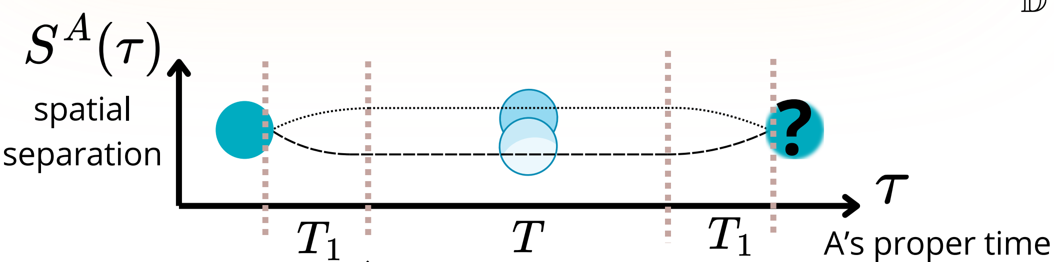

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$$\mathbb{D}(T) \geq 0$$

- Decoherence functional (electromagnetic case):

$$\mathbb{D} = \frac{q^2}{2} \int_{-\infty}^{\infty} d\tau\, d\tau'\; S^A(\tau)\; S^B(\tau') \langle \{ E_A(\tau, X), E_B(\tau', X) \} \rangle_0$$

Electric field quantised on Schwarzschild background

Unruh vacuum or Hartle-Hawking vacuum

Black hole with classical horizon geometry

[Danielson, Satishchandran, Wald 2022], **[Danielson, Satishchandran, Wald 2023]**, [Gralla, Wei 2024]
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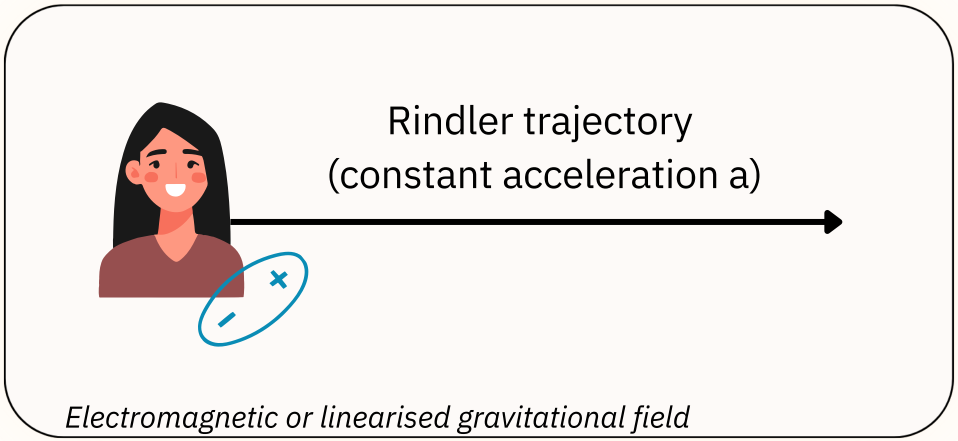

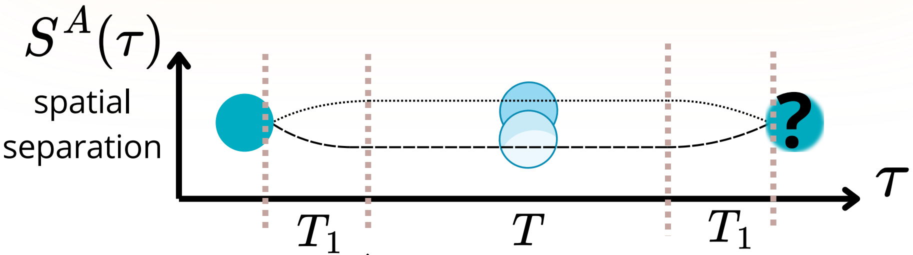

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Electric field quantised on Schwarzschild background

Unruh vacuum or Hartle-Hawking vacuum

- Rindler analogue:

$$\mathbb{D} = \frac{q^2}{2}\int_{-\infty}^{\infty} d\tau\, d\tau'\; S^A(\tau)\; S^B(\tau')\langle\{E_A(\tau, X(\tau)), E_B(\tau', X(\tau'))\}\rangle_0$$

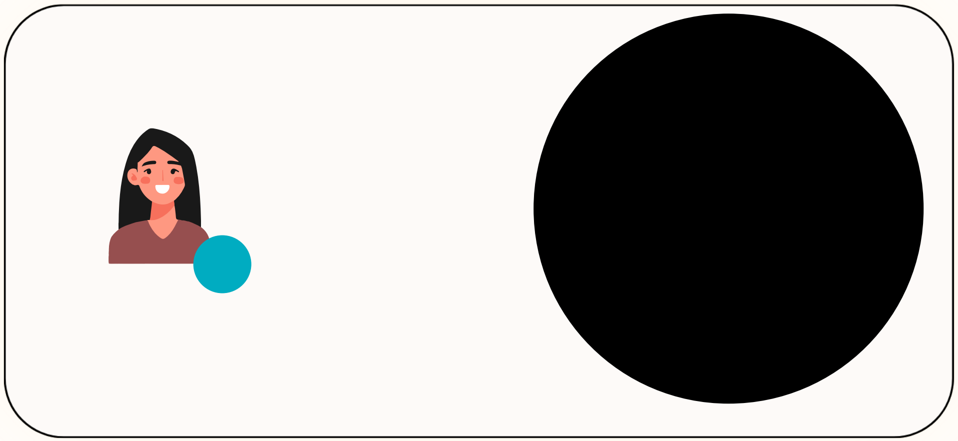
Electric field quantised on **Minkowski** background

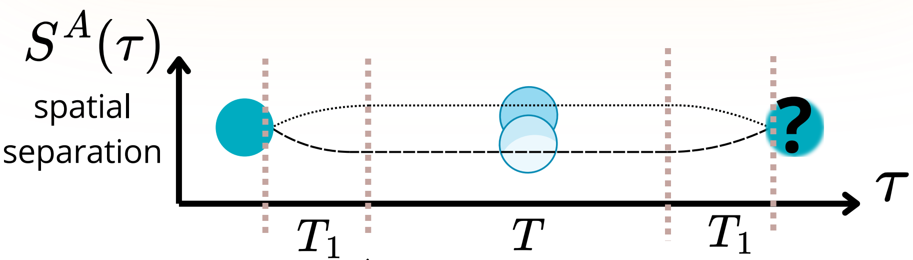
Rindler coordinates

Minkowski vacuum

Black hole with classical horizon geometry

[DANIELSON, SATISHCHANDRAN, WALD 2022], [DANIELSON, SATISHCHANDRAN, WALD 2023], [GRALLA, WEI 2024]
[WILSON-GEROW, DUGAD, CHEN 2024], [DANIELSON, SATISHCHANDRAN, WALD 2024]





$T \gg T_1$

$|\psi\rangle = \alpha|U\rangle + \beta|L\rangle$

- Evaluation of decoherence:

$$\mathbb{D} = \frac{q^2}{2}\int_{-\infty}^{\infty} d\tau\, d\tau'\; S^A(\tau)\; S^B(\tau')\langle\{E_A(\tau,X), E_B(\tau',X)\}\rangle_0$$

$$\propto \int_0^{\infty} d\Omega\; \tilde{S}^A(\Omega)\; \tilde{S}^B(\Omega)\; W_{AB}(\Omega)$$

$$\approx q^2 d^2\, T\, W_{AB}(\Omega = 0)$$

Black hole with classical horizon geometry

[DANIELSON, SATISHCHANDRAN, WALD 2022], [DANIELSON, SATISHCHANDRAN, WALD 2023], [GRALLA, WEI 2024]
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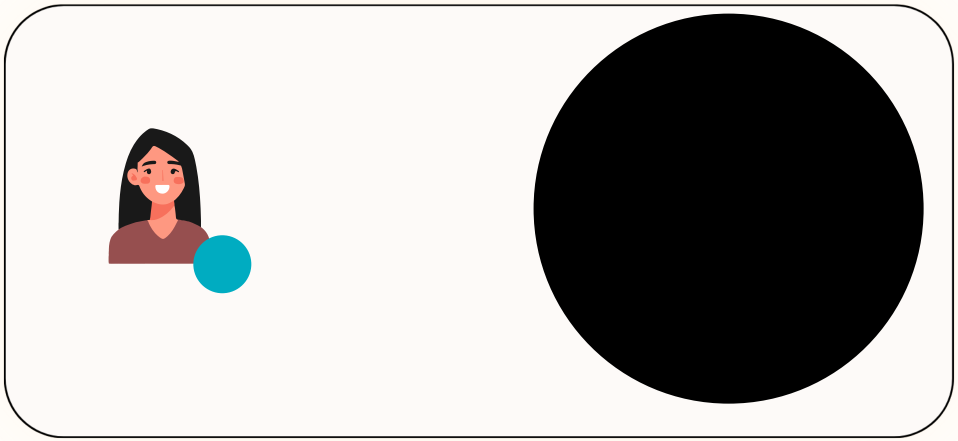

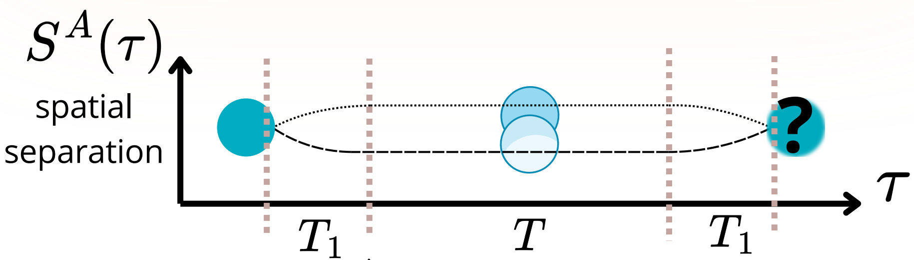

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- Decoherence mainly due to the very low frequency field modes

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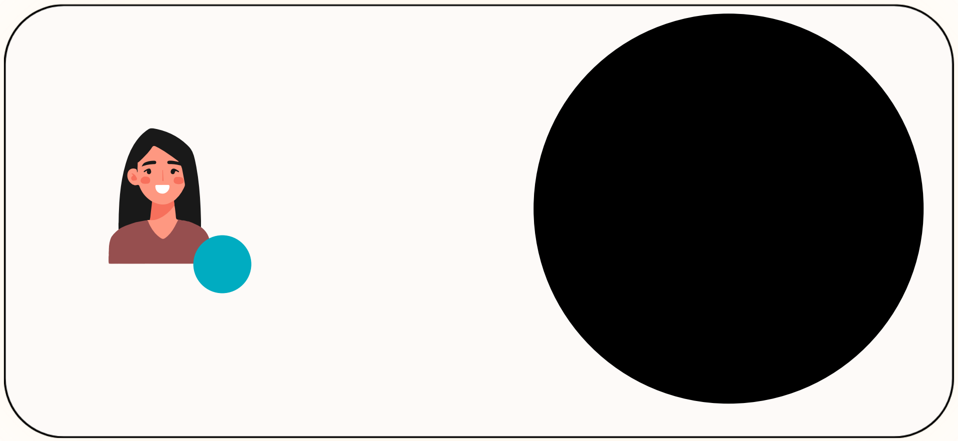
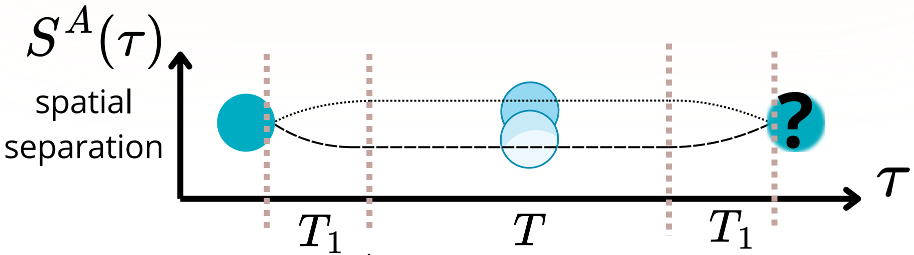
$$\rho_S(T_F) \approx \begin{pmatrix} |\alpha|^2 & \alpha^*\beta\, e^{-\gamma T} \\ \alpha\beta^*\, e^{-\gamma T} & |\beta|^2 \end{pmatrix}$$

→ Mere presence of the black hole induces decoherence on A's superposition

Black hole with classical horizon geometry

[Danielson, Satishchandran, Wald 2022], [Danielson, Satishchandran, Wald 2023], [Gralla, Wei 2024]
[Wilson-Gerow, Dugad, Chen 2024], [Danielson, Satishchandran, Wald 2024]





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Is the decoherence induced by the horizon on A's superposition sensitive to whether the horizon obeys classical or quantum geometry?

Implementation of a quantum horizon geometry

[MJF, Pesci 2025], [MJF, Pesci 2025]

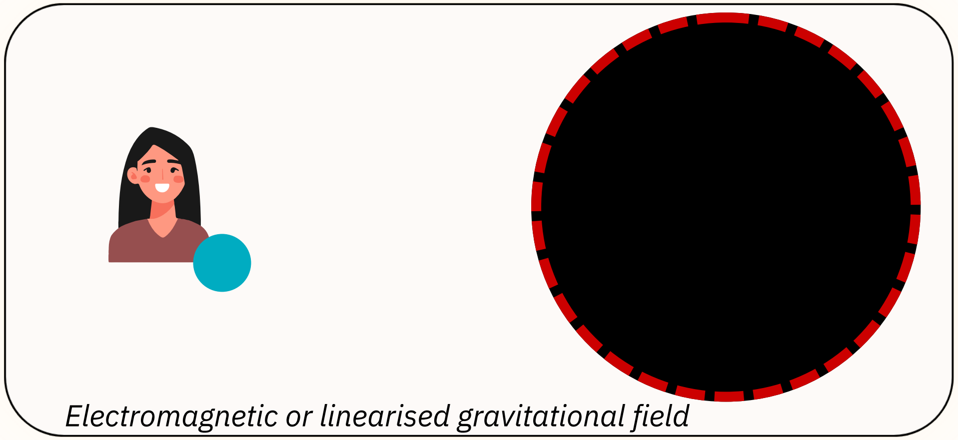
Motivation:

- Spacetime itself might be quantum
- Possible existence of a minimal length in spacetime

Effective implementation:

- Assumption of a minimal area gap A_0
- Different proposals for its size, mostly order of the Planck length squared

[Bekenstein 1974], [Hod 1998], [Maggiore 2008], [Barbero, Lewandowski, Villasenor 2009], [Krishnendu, Perri, Chakraborty, Pesci 2025], [Pesci 2025], ...



Implementation of a quantum horizon geometry

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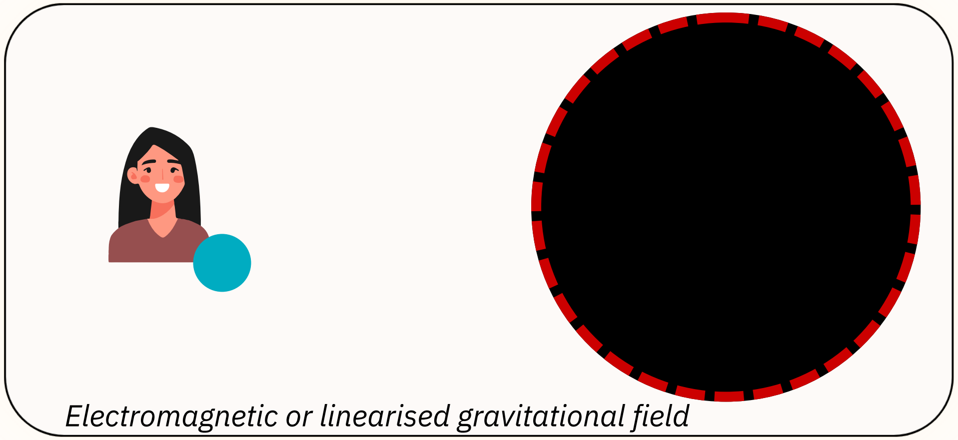
[BEKENSTEIN 1974], [HOD 1998], [MAGGIORE 2008], [BARBERO, LEWANDOWSKI, VILLASENOR 2009], [KRISHNENDU, PERRI, CHAKRABORTY, PESCI 2025], [PESCI 2025], ...



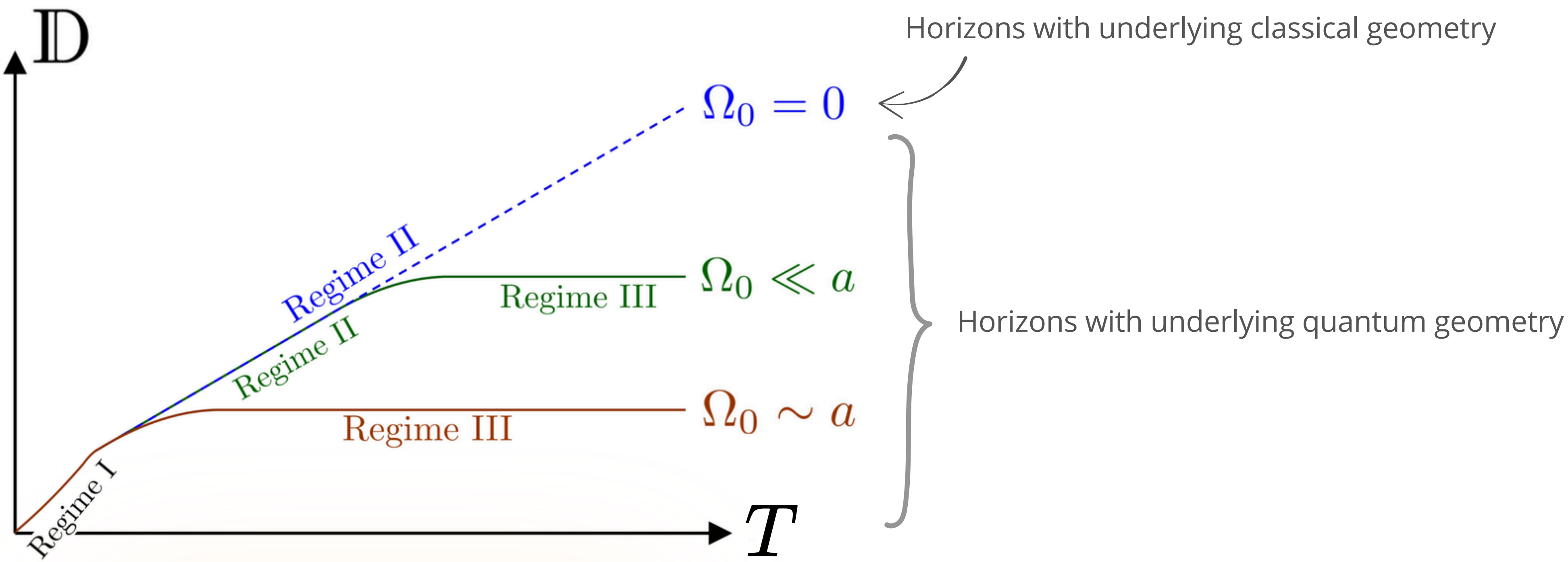
→ Minimal frequency required to "enter" the horizon, $\Omega_0 \propto A_0$
[KRISHNENDU, PERRI, CHAKRABORTY, PESCI 2025], [PESCI 2025]

$$\mathbb{D} = \frac{q^2}{2}\int_{-\infty}^{\infty} d\tau\, d\tau'\; S^A(\tau)\; S^B(\tau')\langle\{E_A(\tau,X), E_B(\tau',X)\}\rangle_\Omega = \frac{q^2}{2}\int_{\Omega_0}^{\infty} d\Omega\; \tilde{S}^A(\Omega)\; \tilde{S}^B(\Omega)\; W_{AB}(\Omega)$$

Very low frequency modes excluded

Comparison of decoherence from horizons with classical and quantum geometries

[MJF, Pesci 2025], [MJF, Pesci 2025]

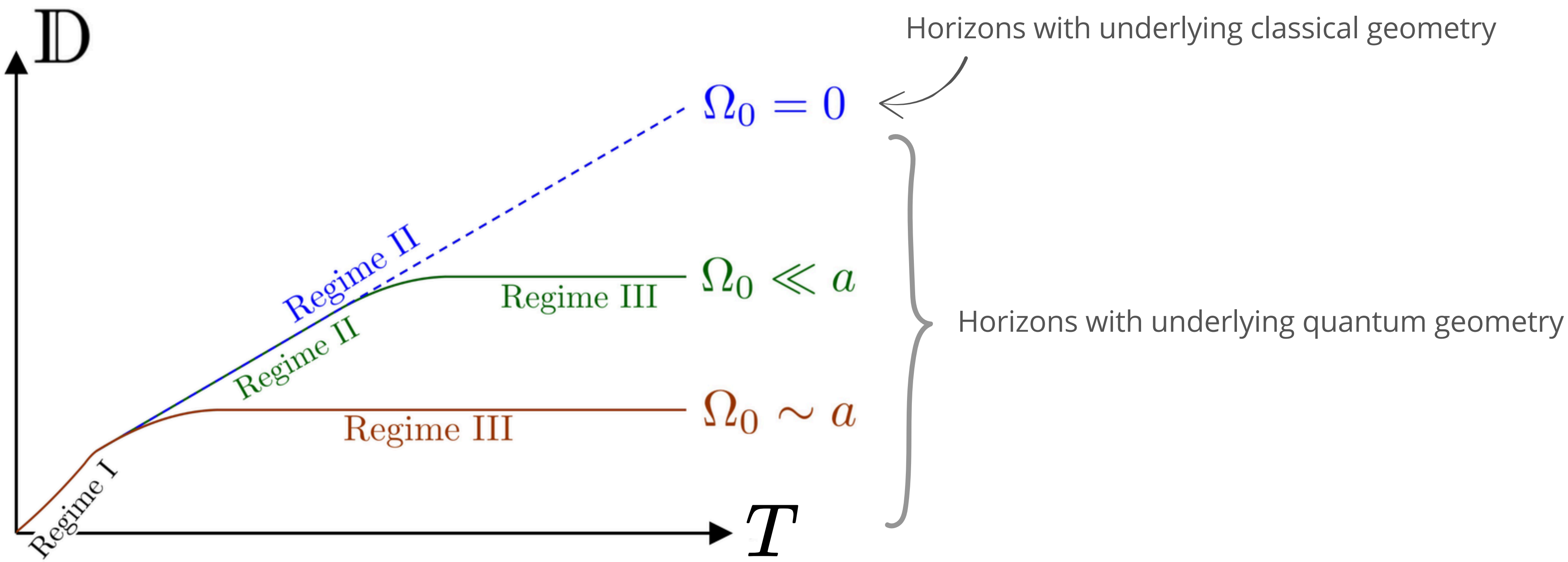


- Regime I: Quadratic increase in T
- Regime II: Linear increase in T
- **Regime III: Saturation**

Sketch source: Fahn, Pesci; Phys. Rev. D, 2025 DOI:10.1103/279x-zgl1

Comparison of decoherence from horizons with classical and quantum geometries

[MJF, Pesci 2025], [MJF, Pesci 2025]



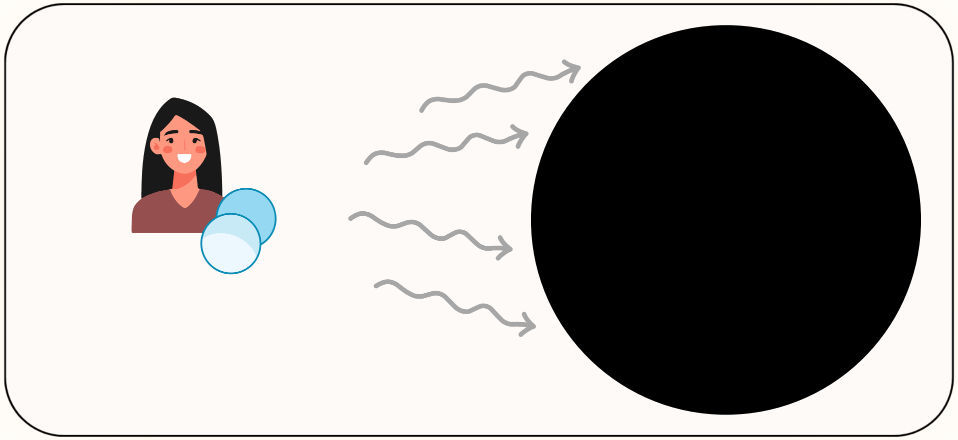
Order of magnitude of the saturation value negligibly small for $A_0 \sim l_p^2$

→ if there is a minimal area gap of the Planck length squared,
then the black hole only causes negligible decoherence on A's superposition

→ Fundamentally different decoherence behaviour compard to classical horizon geometry

Sketch source: Fahn, Pesci; Phys. Rev. D, 2025 DOI:10.1103/279x-zgl1

Next steps: A flux through the horizon?



Entangling photons:

- Finite amount of entropy
- Arbitrarily small energy

[Kudler-Flam, Penington 2025]

Tension with BH thermodynamics?

[MJF, Pesci 2026]

Possible resolution:

Entangling photons ≠ flux through the horizon, but static energy density on the horizon?

→ change of decoherence behaviour

Summary

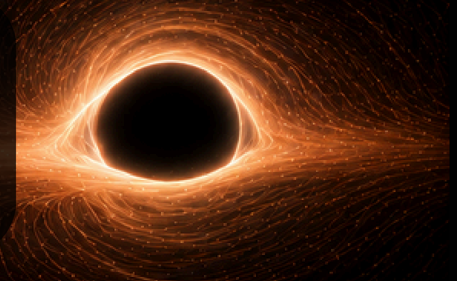
Part I: Gravitational waves as environment (QM toy model)

- GID changes neutrino oscillation pattern (in the toy model)
- Schrödinger quantisation with position interaction vs. Weyl interaction: perturbative change of decoherence pattern (for small μ_0)

  → what happens for polymer quantisation?

Part II: Decoherence induced by horizons with classical and quantum geometries

- Horizons with classical horizon geometries unavoidably decohere spatial superpositions
- Quantum horizon geometries: Decoherence can differ significantly (in particular for $A_0 \sim l_p^2$)



→ **Gravitationally induced decoherence effects differ depending on the formulation of quantum gravity in the two discussed scenarios.**