FAU² WORKSHOP · QUANTUM GRAVITY MEETS QUANTUM INFORMATION

Reduced Quantum-Reference-Frame Channels for Open Quantum Systems

Paolo Luppi

University of Milan

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

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BridgeQG

Viktoria Kabel

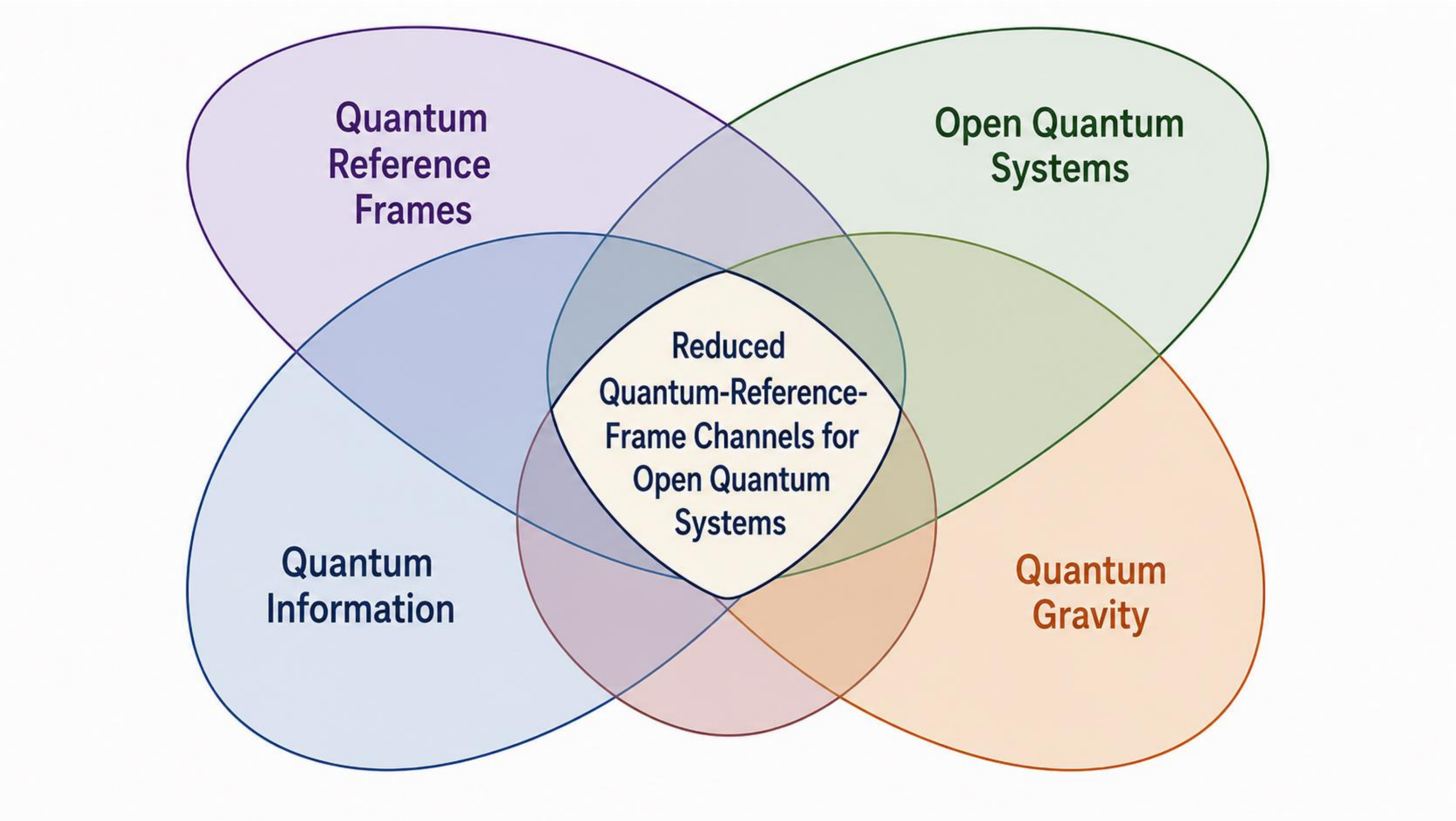
(ETH)

Flaminia Giacomini

(University of Rome Tor Vergata)

Andrea Smirne

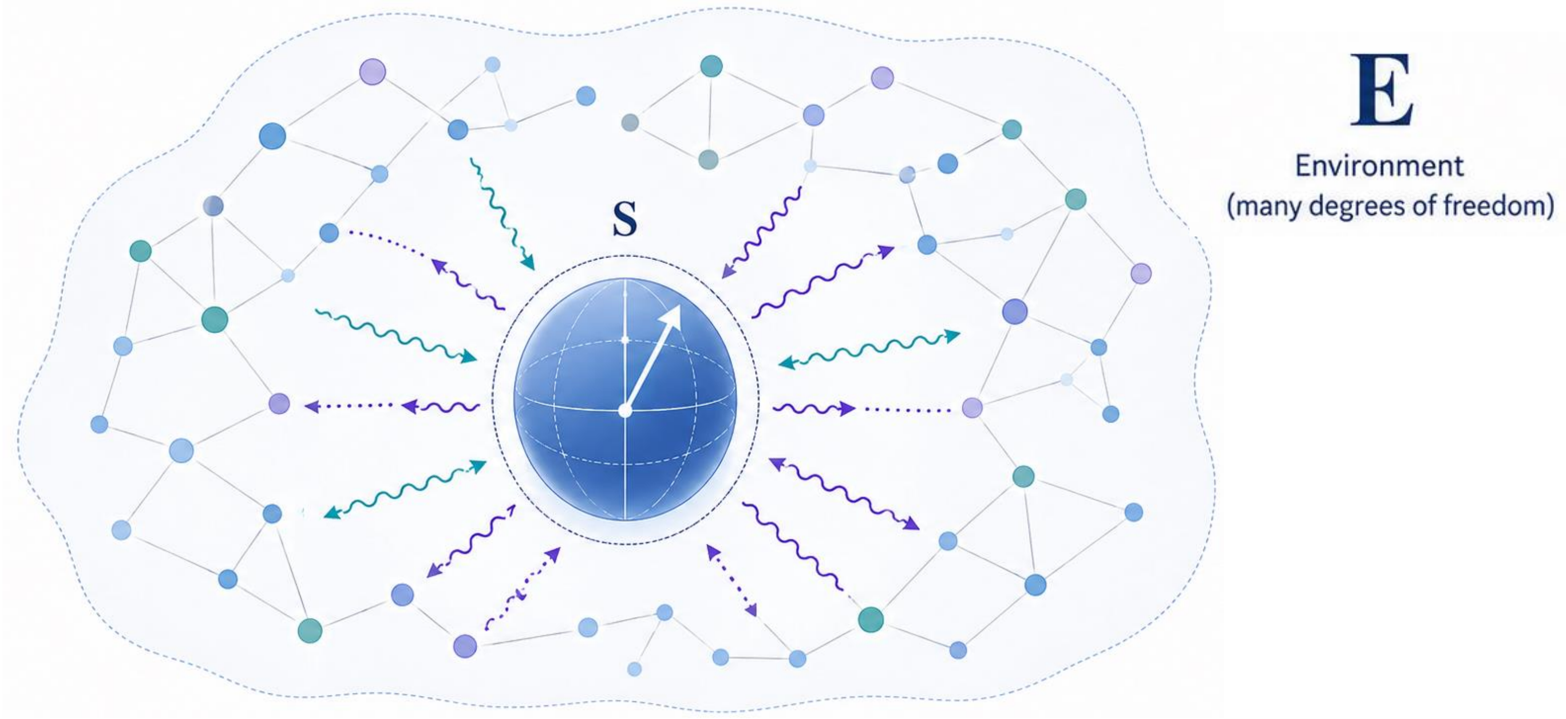
(University of Milan)



PART I

Setup: open quantum systems and quantum reference frames

Open Quantum Systems (OQSs)



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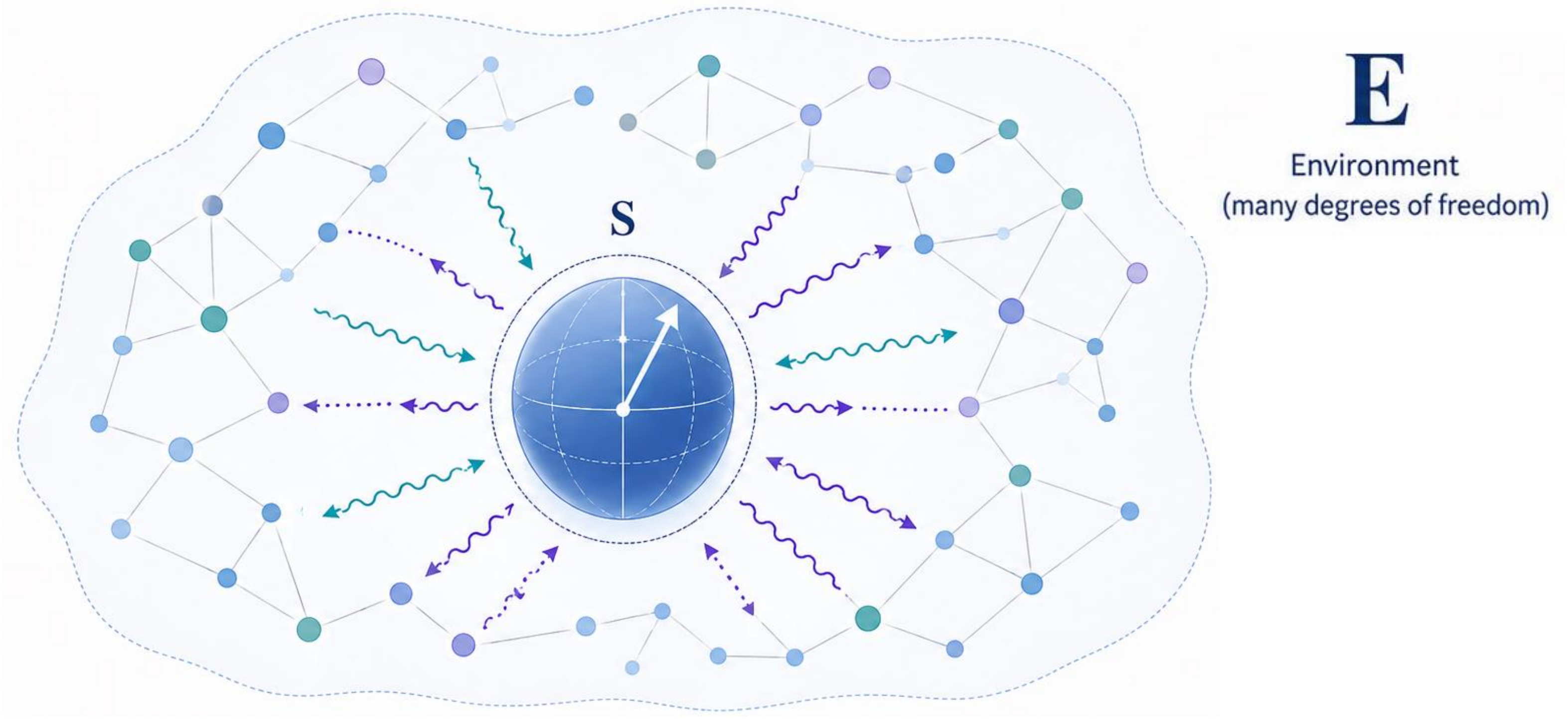

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Total **global unitary evolution**:

$$\rho_{SE}(t) = U(t)\,\rho_S(0) \otimes \rho_E(0) U^{\dagger}(t)$$

Nonunitary

System evolution:

$$\rho_S(t) = Tr_E\,[U(t)\,\rho_S(0) \otimes \rho_E(0) U^{\dagger}(t)] = \Phi_t \rho_S(0)$$

Tr_E partial trace of *E: an average over the environment's degrees of freedom.*

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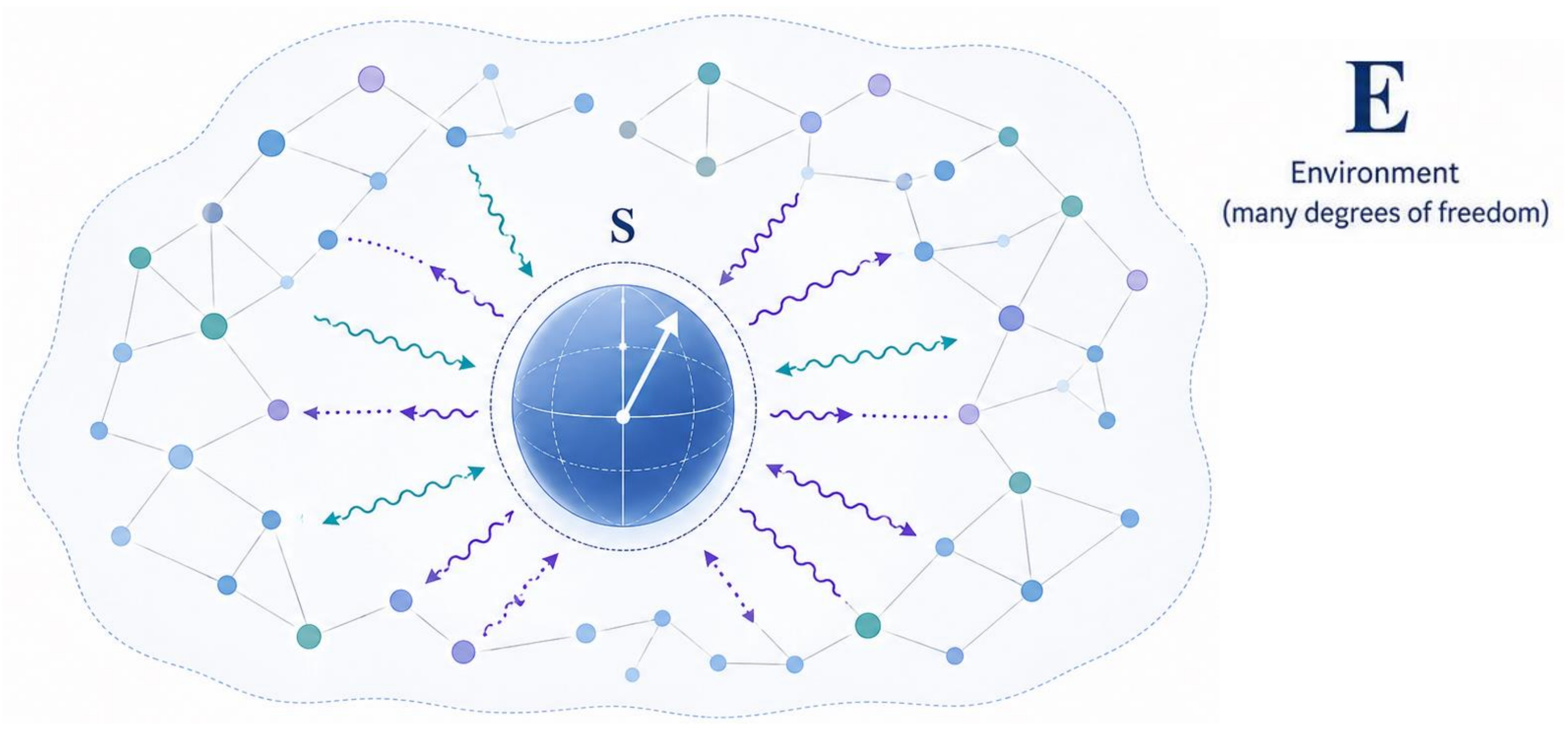

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A **quantum dynamical map** Φ_t is:

- Completely positive ($\Phi_t \otimes \mathbb{I}$ is positive);
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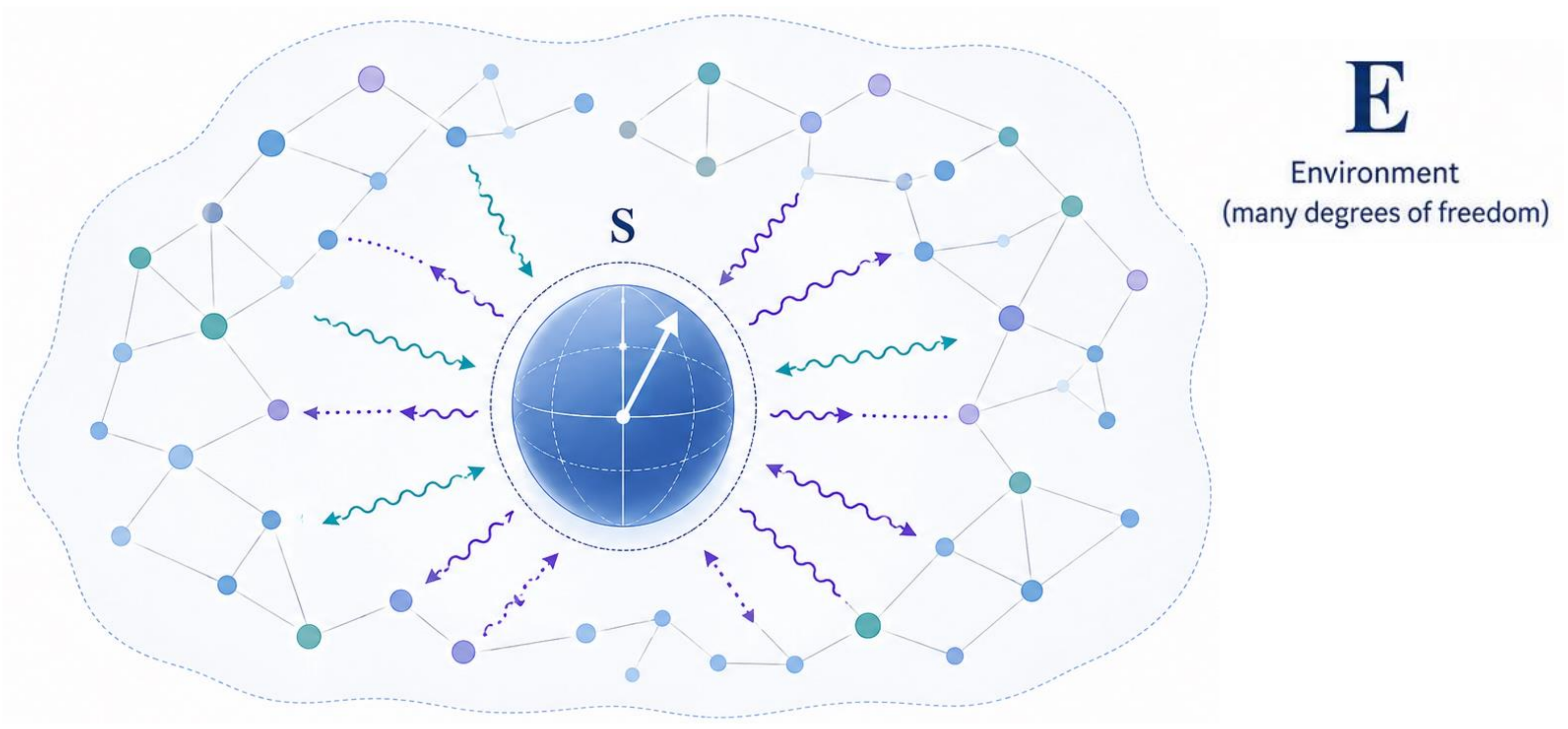

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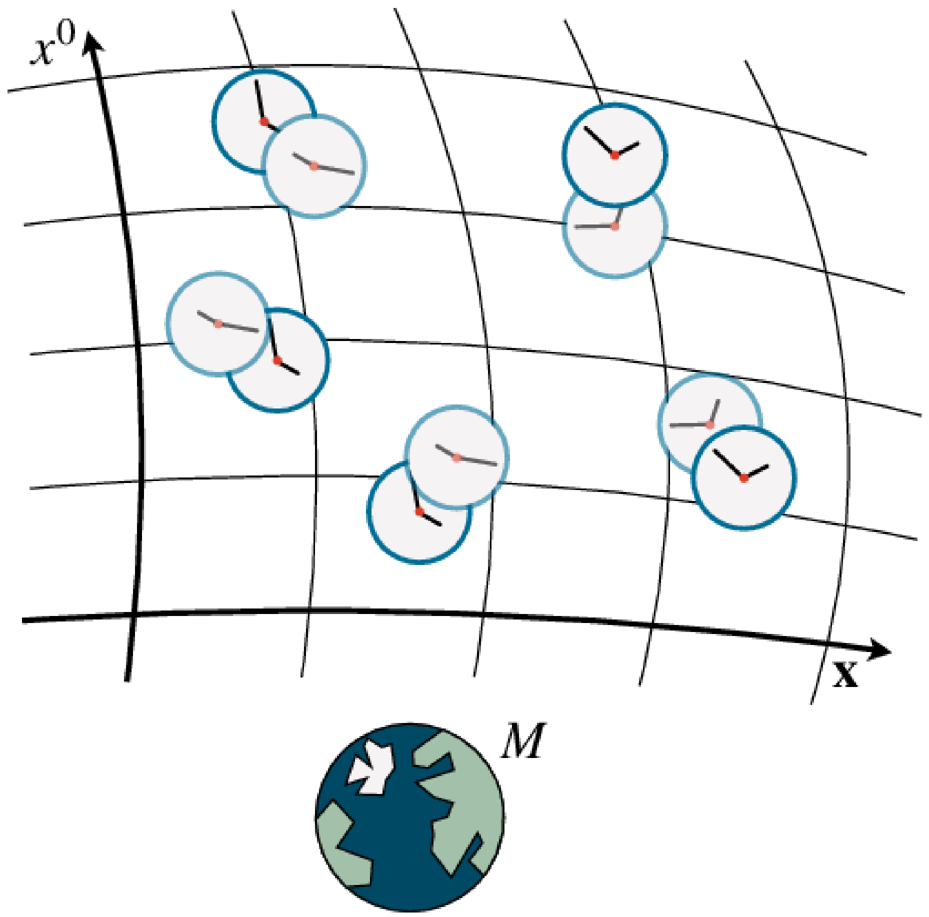
New effects such as **decoherence, dissipation** and **memory effects.**

Quantum Reference Frames (QRFs)

A **reference frame** is **physical** and therefore can be **quantum**.

Time in quantum mechanics: In quantum gravity there is no absolute time; QRFs let us define dynamics relative to quantum clocks.



F.Giacomini "Spacetime Quantum Reference Frames and superpositions of proper times" in Quantum

Gauge fixing: In background-free quantum theories, choosing a reference frame is effectively a gauge fixing: QRFs provide a fully quantum and operational way to implement and transform between different gauge choices.

OQSs and QRFs?

How do open **quantum system dynamics** change under QRFs transformations?

Which features of the **open-system** dynamics remain **invariant** under a change of QRF?

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QRFs can themselves be noisy, correlated, or degraded.

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Can **decoherence** drive the transition **from quantum to classical reference frames**?

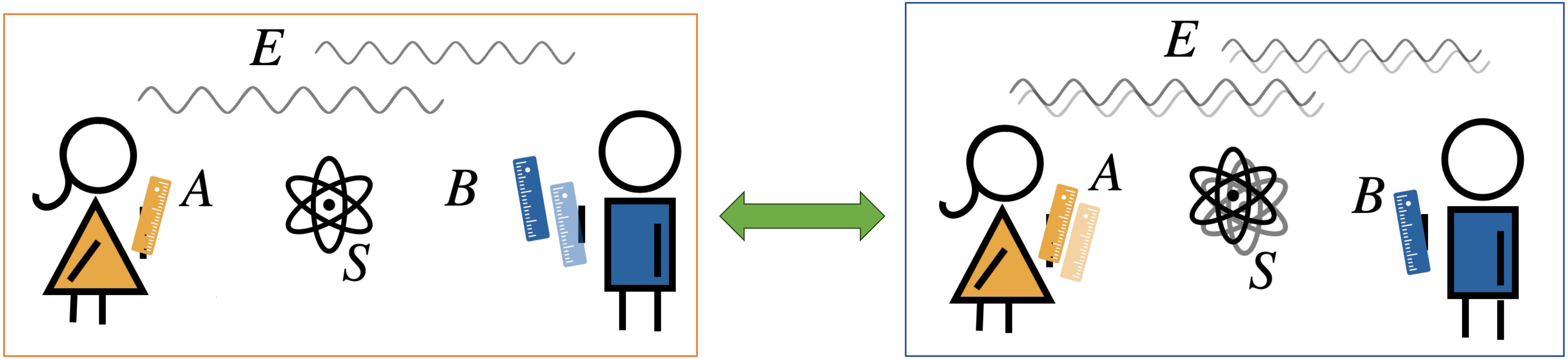
In **broader gravity-related settings**, questions about information loss further motivate a consistent treatment of open quantum systems without relying on an external classical frame.

PART II

The reduced QRF channel and its structure

QRF transformation

Perspectival approach



QRF transformation

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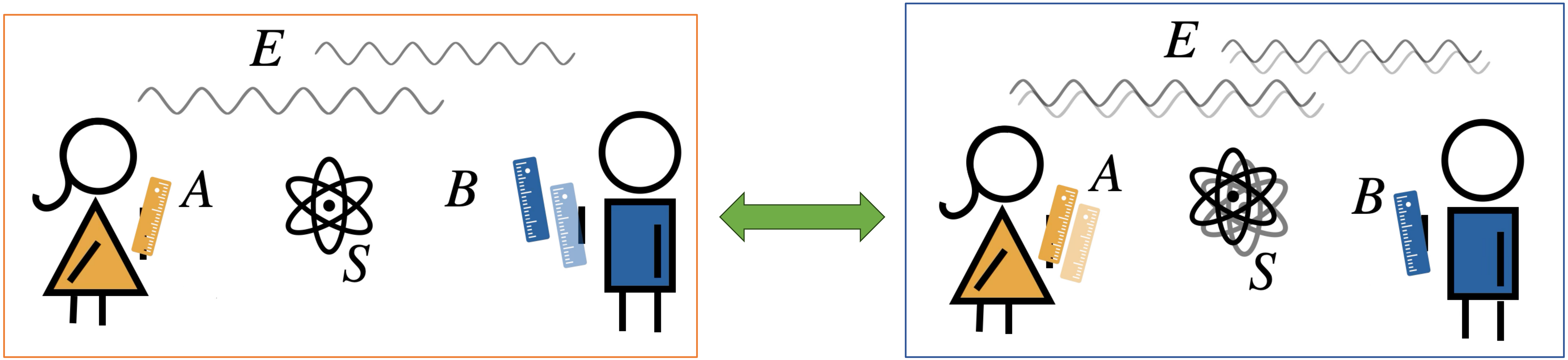

$$\rho_{SEA}^{(B)}(t) = S_{A\to B}\,\rho_{SEB}^{(A)}(t)\,S_{A\to B}^{\dagger}$$

Unitary transformation:

$$S_{A\to B} = \int dg\, |g_A^{-1}\rangle\langle g_B| \otimes V_{ES}^{\dagger}(g)$$

$\{|g\rangle\}_{\in G}$: basis states of the QRF

$V_{ES}(g)$: unitary representation

Reduced QRF channel

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$$\rho_S^{(B)}(t) = Q\left[\rho_{SEB}^{(A)}(t)\right] \coloneqq Tr_{AE}\left[S_{A\to B}\,\rho_{SEB}^{(A)}(t)\,S_{A\to B}^{\dagger}\right]$$

$Q\colon \mathcal{H}_{SEB}^{(A)} \to \mathcal{H}_S^{(B)}$ $\quad$ Q is a **CPTP** map $\quad$ Dual map $Q^{\dagger}\colon \mathcal{H}_S^{(B)} \to \mathcal{H}_{SEB}^{(A)}$

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$$\rho_S^{(B)}(t) = Q\left[\rho_{SEB}^{(A)}(t)\right] := Tr_{AE}\left[S_{A\to B}\rho_{SEB}^{(A)}(t)S_{A\to B}^{\dagger}\right]$$

$Q: \mathcal{H}_{SEB}^{(A)} \to \mathcal{H}_S^{(B)}$

Q is a **CPTP** map

Dual map $Q^{\dagger}: \mathcal{H}_S^{(B)} \to \mathcal{H}_{SEB}^{(A)}$

$$\begin{tikzcd}
\rho_{SBE}^{(A)}(0) \arrow[r, "\mathcal{U}_{SBE}^{(A)}(t)"] \arrow[d, "\mathrm{Tr}_{BE}"'] & \rho_{SBE}^{(A)}(t) \arrow[d, "\mathcal{Q}"] \\
\rho_S^{(A)}(0) \arrow[r, dashed, "\Lambda_t"'] & \rho_S^{(B)}(t)
\end{tikzcd}$$

When $\rho_{SEB}^{(A)}(0) = \rho_S^{(A)}(0) \otimes \rho_{EB}^{(A)}(0)$

$\exists$ a dynamical map:

$\Lambda_t: \rho_S^{(A)}(0) \to \rho_S^{(B)}(t)$

Block-preserving reduced QRF channels

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- Fix a PVM on S in A $\left\{P_m^{(A)}\right\}_m$ and a PVM on S in B $\left\{\tilde{P}_n^{(B)}\right\}_n$ (e.g energy projectors)

Q is **block preserving** if $\forall\, n$:

$$\boxed{Q^\dagger\left(\tilde{P}_n^{(B)}\right) = \sum_m P_m^{(A)} \otimes \Pi_{nm}^{(A)}}$$

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output block populations are insensitive to input inter-block coherences

$$p_n^{(B)}(t) = Tr_S\left[\tilde{P}_n^{(B)}\rho_S^{(B)}(t)\right]$$

$$= Tr_S\left[\tilde{P}_n^{(B)}Q(\rho_{SEB}^{(A)}(t))\right]$$

$$= Tr_S\left[Q^\dagger(\tilde{P}_n^{(B)})\rho_{SEB}^{(A)}(t)\right]$$

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$\Updownarrow$

$$\widetilde{\Delta}_S^{(B)} \circ Q = \widetilde{\Delta}_S^{(B)} \circ Q \circ \Delta_S^{(A)}$$

$\left\{\Pi_{nm}^{(A)}\right\}_n$ **POVM** on BE

Pinching maps:

$$\Delta_S^{(A)}(X) = \textstyle\sum_m P_m^{(A)} \otimes \mathbb{I}_{BE}\ X\ P_m^{(A)} \otimes \mathbb{I}_{BE}$$

$$\widetilde{\Delta}_S^{(B)}(X) = \sum_n \tilde{P}_n^{(B)}\, X\, \tilde{P}_n^{(B)}$$

Dephase first or change frame first : the output block populations are the same.

Strong preservation

$$\boxed{Q^\dagger\left(\tilde{P}_n^{(B)}\right) = P_{\pi(n)}^{(A)} \otimes \mathbb{I}_{BE}^{(A)}}$$

Output populations are a permutation of the input populations.

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Sum of Entanglement ε and Coherence C is invariant:

$$\varepsilon^{(A)} + C^{(A)} = \varepsilon^{(B)} + C^{(B)}$$ [1]

Frame B's coherence

Frame A's coherence

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Under **strong preserving** Q channel:

$$\varepsilon^{(A)} + C_S^{(A)} = \varepsilon^{(B)} + C_S^{(B)}$$

$C_S^{(A)}$: **system**'s coherence in A

$C_S^{(B)}$: **system**'s coherence in B

System coherence and entanglement can be redistributed, but their **sum** is **invariant**.

- Invariant at the system level;
- It does not rely on a specific dynamics of *S.*

(1) C. Cepollaro et al "Sum of Entanglement and Subsystem Coherence Is Invariant under Quantum Reference Frame Transformations". In: Phys. Rev. Lett.

Classical misalignment — and how to witness its failure

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$$\rho_S^{(B)} = Q\left[\rho_{SBE}^{(A)}\right] = \int dg\, p(g) V_S^{\dagger}(g) \rho_S^{(A)} V_S(g)$$

Classical uncertainty about the parameter g

$p(g) \geq 0 \qquad \int dg\, p(g) = 1$

Perfect knowledge: $p(g) = \delta(g - g_0)$

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Random-unitary ⇒ necessarily **unital** . Holds for ideal frames with factorized preparation, no B–SE correlation, factorized action $V_{SE}(g) = V_S(g) \otimes V_E(g)$.

Perfect knowledge: $p(g) = \delta(g - g_0)$

UNITALITY WITNESS

If the original dynamics is unital but the transformed reduced dynamics is not unitaly anymore it can not be a classical misalignmenet

PART III

Pure dephasing and its operational meaning

Pure-dephasing

- A paradigmatic noise model in which populations are preserved while coherences decay;
- Dominant decoherence model in many experimental platforms;
- Arises naturally in different gravitational decoherence model. [1,2]

(1) M. P. Blencowe. “Effective Field Theory Approach to Gravitationally Induced Decoherence”. In: In *Phys. Rev. Lett*

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Pure dephasing dynamics:

$$H = H_S + H_E + H_I$$

$$H_s = \sum_n \lambda_n P_n$$

System energy projectors

$$P_n = |n\rangle\langle n|$$

$$[H_S, H_I] = 0 \longrightarrow \mathit{Controlled\ evolution}: U_{SE}(t) = \sum_n P_n \otimes U_n(t)$$

U_n: controlled unitary on *E*

System's **populations** are **constant** in time

$$p_n(t) \coloneqq Tr[P_n \rho_S(t)] = Tr[P_n \rho_S(0)] = p_n(0)$$

Only system's coherence affected.

(1) M. P. Blencowe. "Effective Field Theory Approach to Gravitationally Induced Decoherence". In: In *Phys. Rev. Lett*

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Population preservation under reduced QRF changes

A'perspective:

Pure dephasing respect to $\left\{P_m^{(A)}\right\}_m$ $\xrightarrow{\quad Q \quad}$

B'perspective:

When is it still only the coherences that dephase?

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Theorem:

Populations preserving in B $\iff$ Q is **block preserving** and **dynamical compatible**

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B's perspective:

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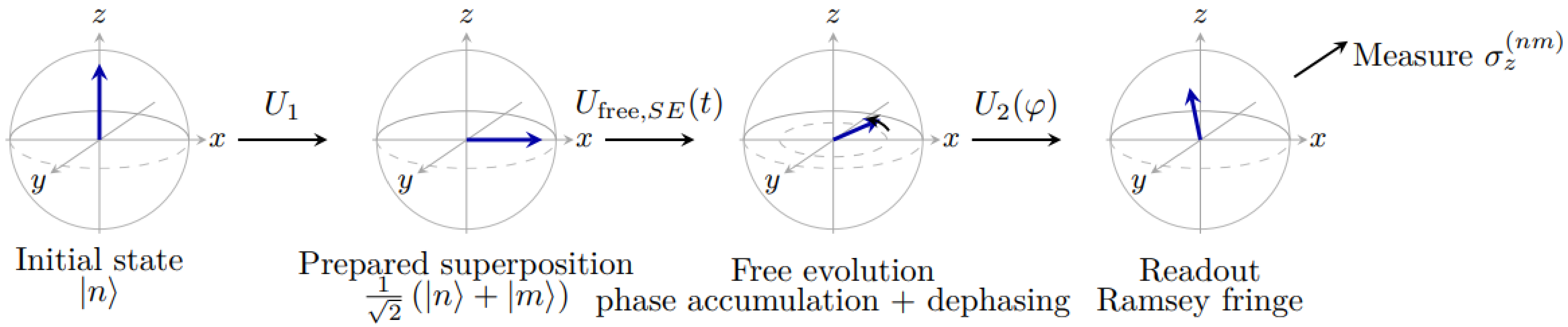
$$\gamma_{nm}^{(B)}(t) = -\frac{\mathrm{d}}{\mathrm{dt}} \ln \rho_{nm}^{(B)}(t) = \gamma_{nm}^{(A)}(t) + \underbrace{\gamma_{fr}(t)}_{\text{Frame induced decoherence}}$$

No deformation of the reference profile →
no frame-induced decoherence ($\gamma_{fr}(t) = 0$).

Two Ramsey scenarios you must not conflate



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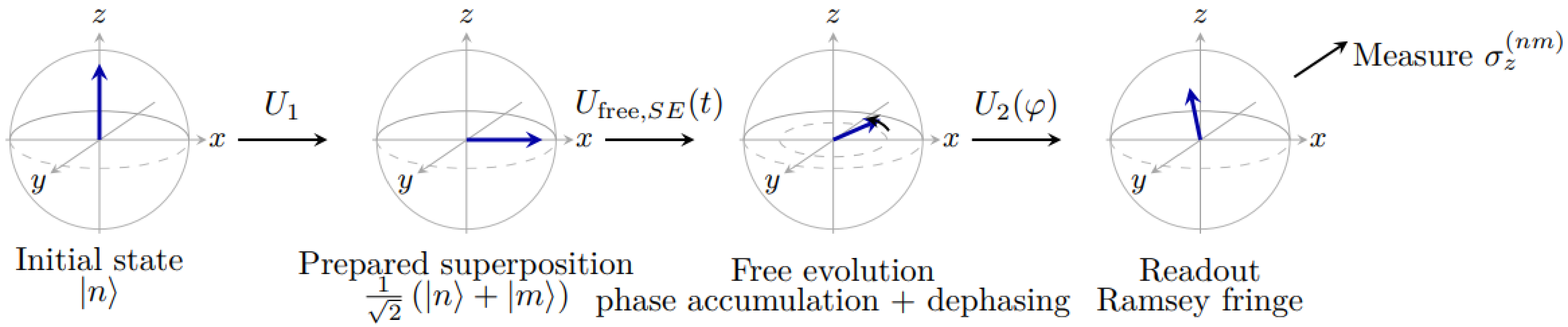
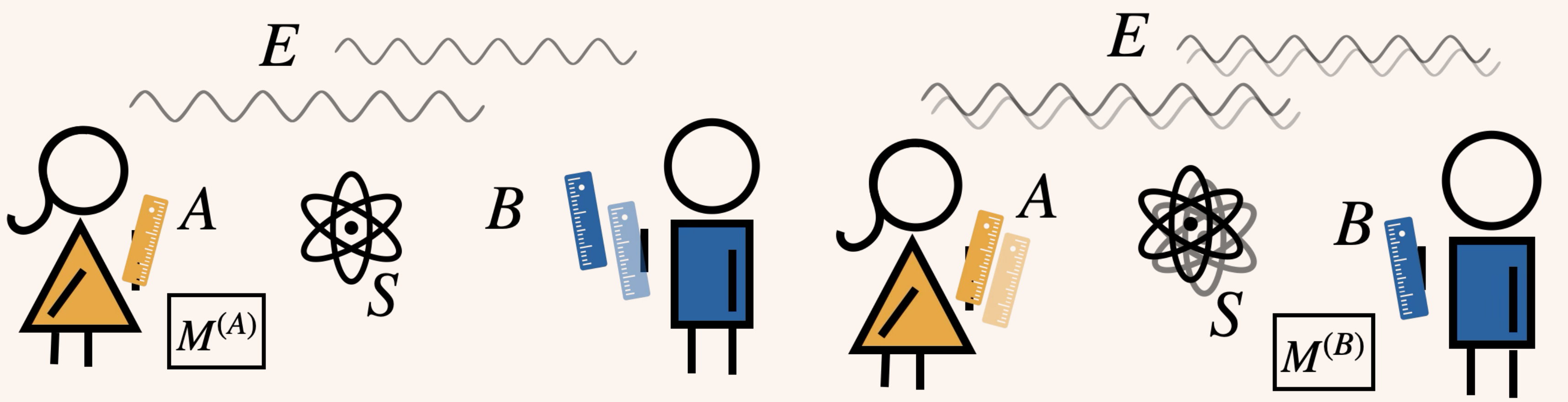


SCENARIO 1 — LOCAL RAMSEY

Each observer probes against their **own phase standard** . Inferred rates can differ by the frame factor:

$$\mathcal{V}_{nm}^{(B)}(t) = |F_{nm}(t)|\, \mathcal{V}_{nm}^{(A)}(t)$$



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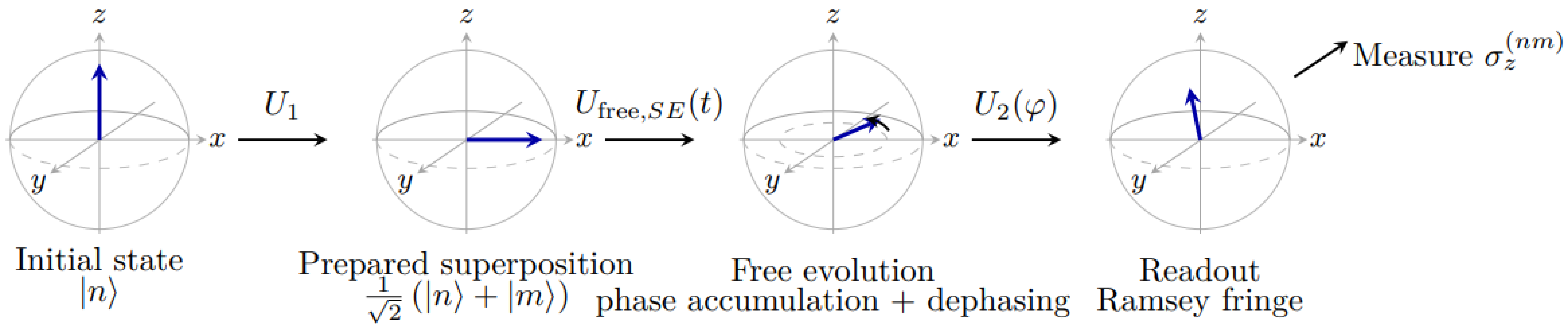

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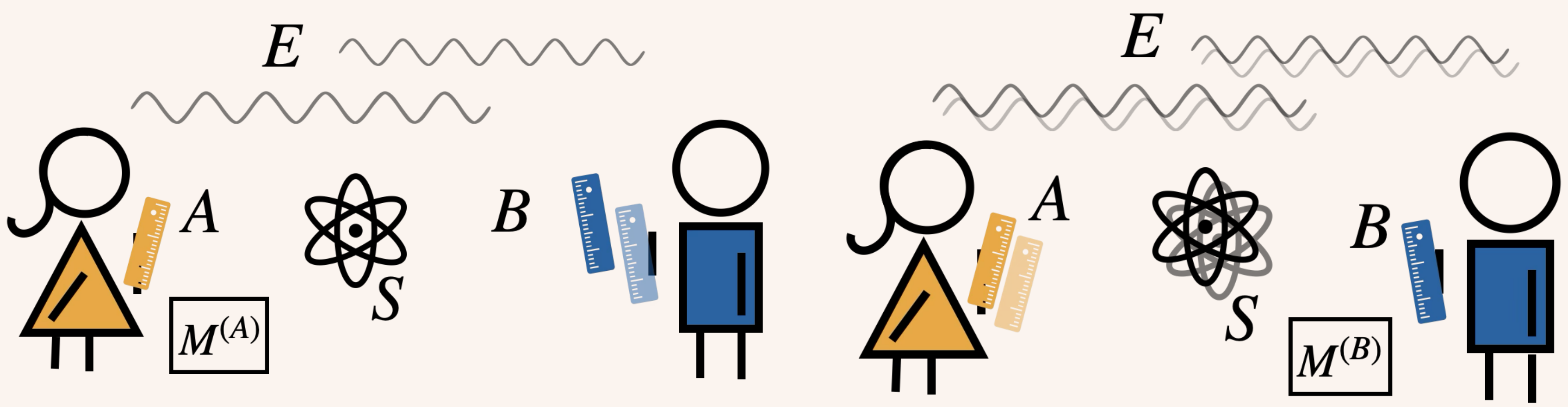


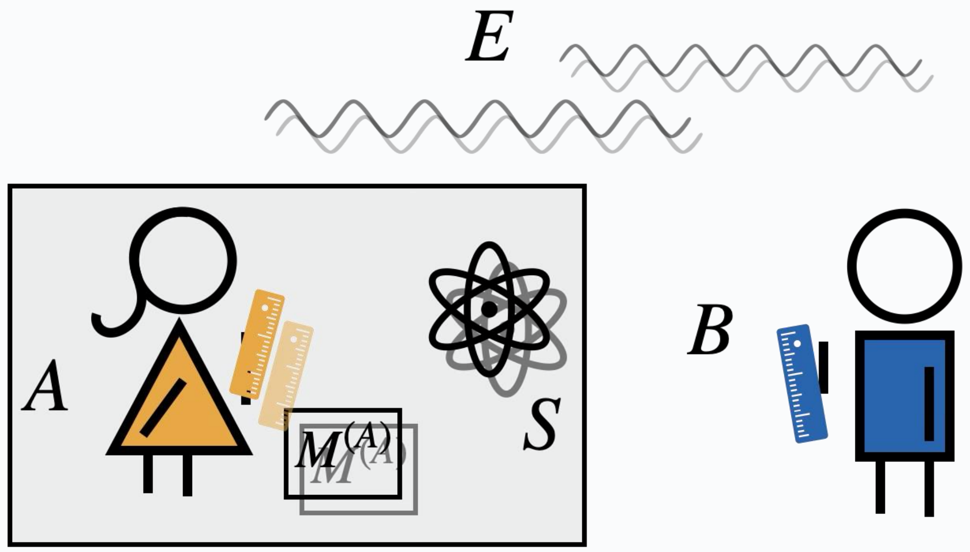
$\gamma^{(A)}_{nm}(t)$

$\gamma^{(B)}_{nm}(t) = \gamma^{(A)}_{nm}(t) + \gamma_{fr}(t)$

SCENARIO 2 — SAME INTERFEROMETER

Re-describe one physical experiment in another frame.

Transform **preparation and measurement** together ⇒ statistics are **frame-invariant** .



PART IV

IV

Case study: gravity-motivated dephasing

Energy dephasing due to a weak gravitational bath

- System S: harmonic oscillator of frequency Ω,
  $H_S = \hbar\Omega(N_S + \frac{1}{2})$
- An environment E modelling a gravitational bath;
- Energy coupling $H_{SE} = H_S \otimes B_E$ motivated by matter-graviton interaction $\propto \int d^4x\, T_{\mu\nu} h^{\mu\nu}$;
- Since $[H_S, H_{SE}] = 0$, pure dephasing dynamics

LAB-FRAME DECOHERENCE RATE

$$\Gamma_{nm}^{\mathrm{grav}}(t) = \Omega^2 (n - m)^2 \chi_{\mathrm{grav}}(t)$$

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BORN–MARKOV BENCHMARK (1)

$$\Gamma_{\mathrm{grav}}^{\mathrm{BM}}(\Delta E) = \frac{k_B T_g}{\hbar} \left(\frac{\Delta E}{E_P}\right)^2$$

T_g: effective temperature of the thermal graviton environment

$E_P = \sqrt{\frac{\hbar c^5}{G}}$ Planck energy

(1) M. P. Blencowe. “Effective Field Theory Approach to Gravitationally Induced Decoherence”. In: In *Phys. Rev. Lett*

A U(1) phase reference that spreads on the circle

$$V_s(\theta) = e^{-i\theta N_s} \qquad [V_s(\theta), H_S] = 0$$

GAUSSIAN FRAME FACTOR

$$|F_{nm}(t)| = \exp\left[-\frac{(n-m)^2}{2}\,\sigma_\theta^2(t)\right]$$

DIFFUSIVE — MARKOVIAN

$$\sigma_\theta^2(t) = \sigma_\theta^2(0) + \Gamma_B\, t$$

BALLISTIC — SHOT-TO-SHOT

$$\sigma_\theta^2(t) = \sigma_\theta^2(0) + \kappa_B\, t^2$$

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Same $(n-m)^2$ scaling — two different origins

$$\gamma_{nm}^{(B)}(t) = \underbrace{(n-m)^2\,\Omega^2\,\dot{X}_{\mathrm{grav}}(t)}_{\text{gravity-induced}} + \underbrace{\frac{(n-m)^2}{2}\,\dot{\sigma}_\theta^2(t)}_{\text{reference-induced}}$$

THE CAUTIONARY TALE

A quadratic-in-gap visibility decay is **not** a unique signature of gravitational decoherence — a degrading phase reference can **mimic, mask, or renormalize** it.

Summary

Reduced QRF channels:

- Describe the effective transformation of the accessible system after a QRF change;
- Provide the natural framework to compare open-system dynamics across reference frames.

Structure preservation

- Block-preservation identifies which population–coherence structures survive a QRF change;
- For pure dephasing, **block preservation + dynamical compatibility** are necessary and sufficient to preserve populations.

Operational implications:

- The observed decoherence rate splits into: an **environmental** contribution and a **reference-induced** contribution;
- A degrading quantum reference can mimic signatures usually attributed to gravitational decoherence.

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- For pure dephasing, **block preservation + dynamical compatibility** are necessary and sufficient to preserve populations.

Operational implications:
- The observed decoherence rate splits into: an **environmental** contribution and a **reference-induced** contribution;
- A degrading quantum reference can mimic signatures usually attributed to gravitational decoherence.

Outlook

- Beyond pure dephasing: general open-system dynamics;
- Non-ideal quantum reference frames as a resource?
- Open quantum systems in relativistic quantum reference frames.

Thank you!

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