Bridge QG Work Group 3: Low-energy gravitational effects in quantum systems

Lin-Qing Chen
Institute for Quantum Optics and Quantum Information (IQOQI), Vienna
Department of Physics, University of Vienna

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Theoretical descriptions:

- Theoretical formulations for low-energy gravitational table top experiments
- Models of gravity-induced decoherence
- Novel effects of how quantum systems behave in gravity/quantum gravity

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- Quantum clocks
- Process matrix, causal modeling
- Resource theory

— Theoretical formulation & application in quantum spacetime

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Big questions:

- Is gravity quantized, what constitutes a quantum signature of gravity?
- Can we design new protocols for testing the (quantum) nature of gravity?
- What is the role of observers in quantum gravity?
- Can we probe the compatibility of the fundamental assumptions in gravity & quantum physics?

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As theorists, we need to foster closer dialogue and collaborations with experimentalists. Many concepts and open questions in this subfield are connected with the high energy quantum gravity community.

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  Using optical levitation combined with quantum ground-state cooling techniques, experimentalists can control the quantum trajectory of a 10^-18 kg nanoparticle (towards 10^-12 kg in a few years)

[Quantum control of a nanoparticle optically levitated in cryogenic free space , F. Tebbenjohanns, M. Mattana, *et al.* ***Nature*** 2021]

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- Delocalised quantum source: 10^-16 kg optically levitated nanoparticle delocalised over several nanometers, on timescales of milliseconds.

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- Preparing massive quantum states in large superposition

[Quantum superposition of molecules beyond 25 kDa, Y.Fein, P. Geyer, et al. ***Nature Physics*** 2019],
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More information see Catalina's talk tomorrow!

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- When the two regimes close, experimental advancement will reach a point that we could measure physical effect of gravitational field generated by quantum matter source - an observational window for the genuine low energy quantum gravity effect!

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[E.T. Jaynes and F.W. Cummings, Comparison of quantum and semiclassical radiation theories with application to the beam maser, Proceedings of the IEEE **51** (1963) 89.
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- 1973 Clauser sent single photons through two interferometers, to test the violation of Cauchy-Schwarz inequality. This is considered the first test that really differentiated the classical and quantum field-theoretic predictions for the photoelectric effect.

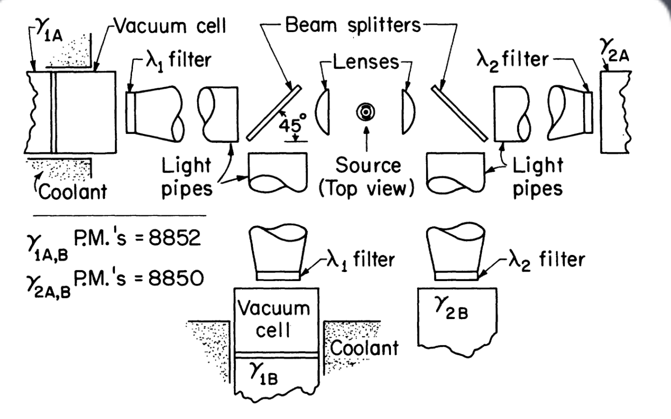

FIG. 2. Schematic diagram of our apparatus.

[J.F. Clauser, Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect, Phys. Rev. D **9** (1974) 853.]

The Gravity-Induced-Entanglement experiment (BMV)

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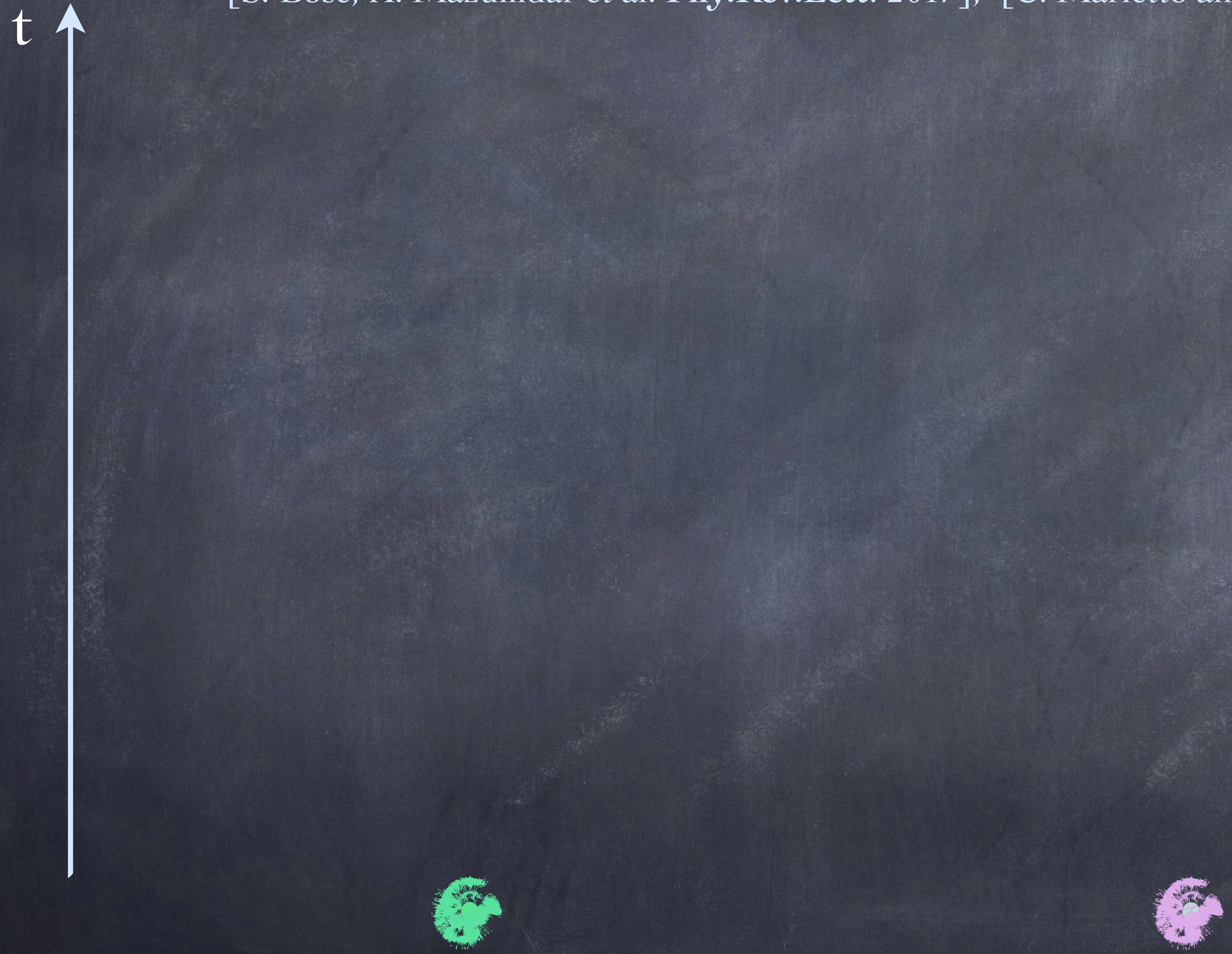

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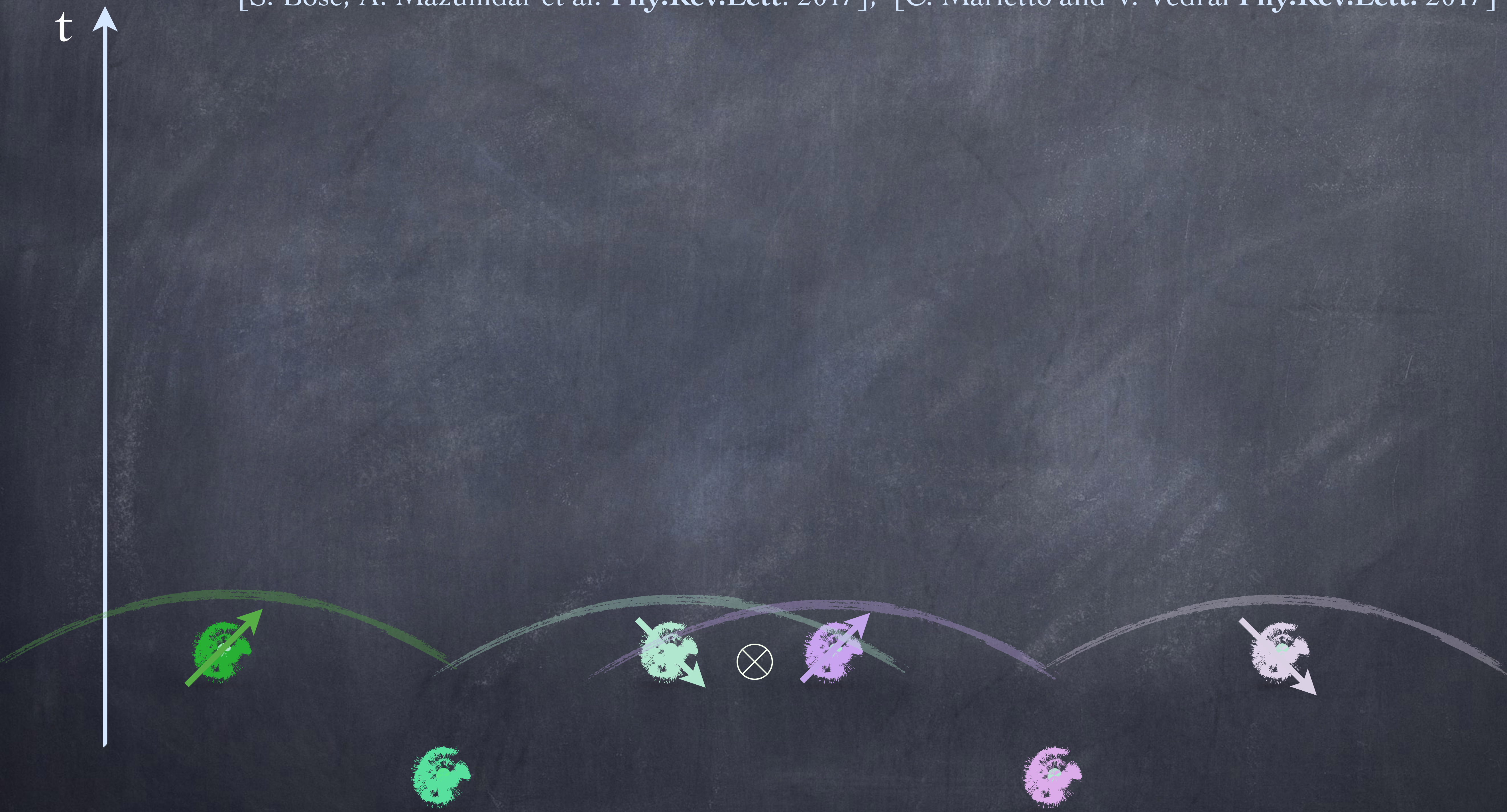

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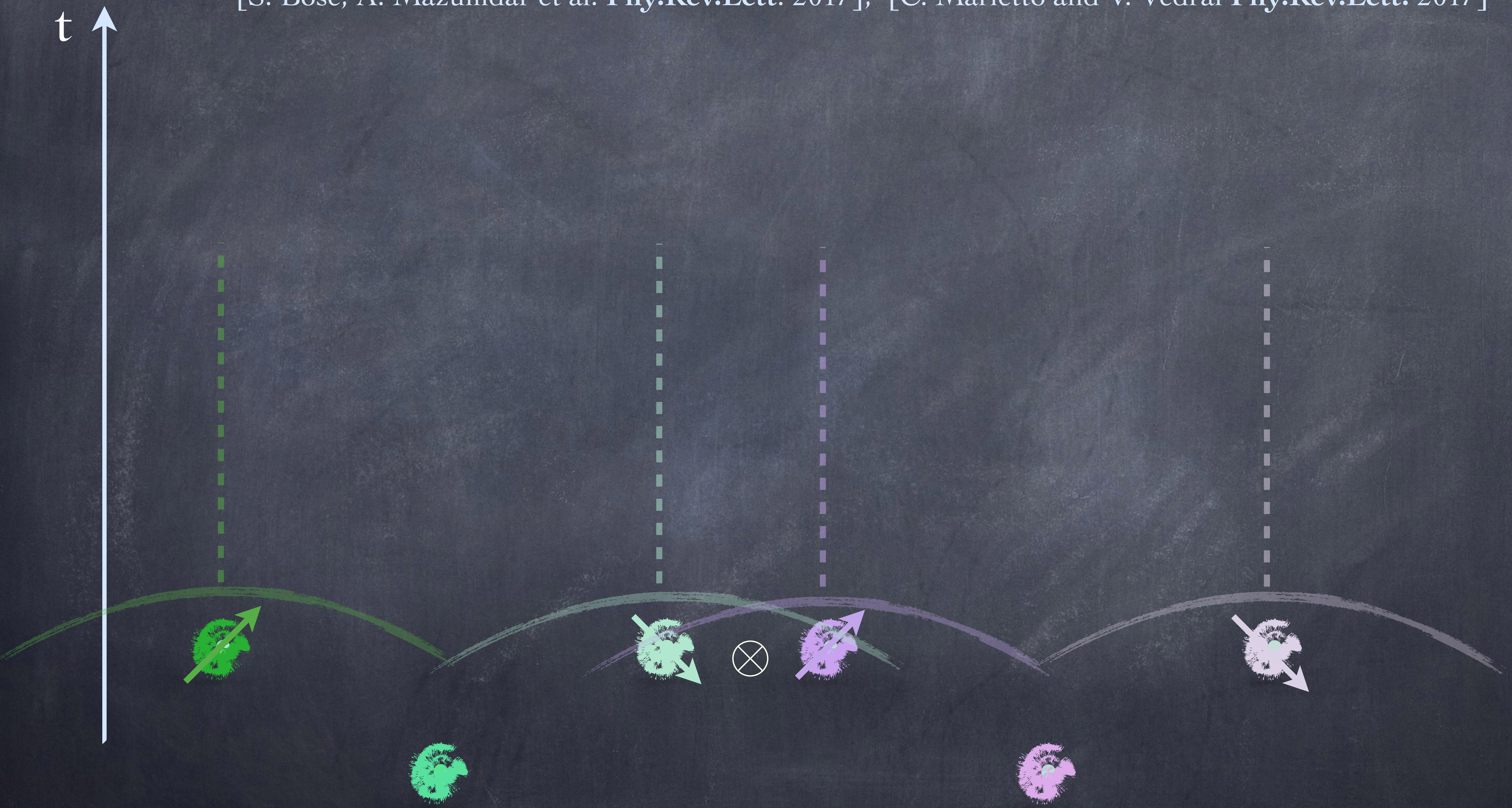

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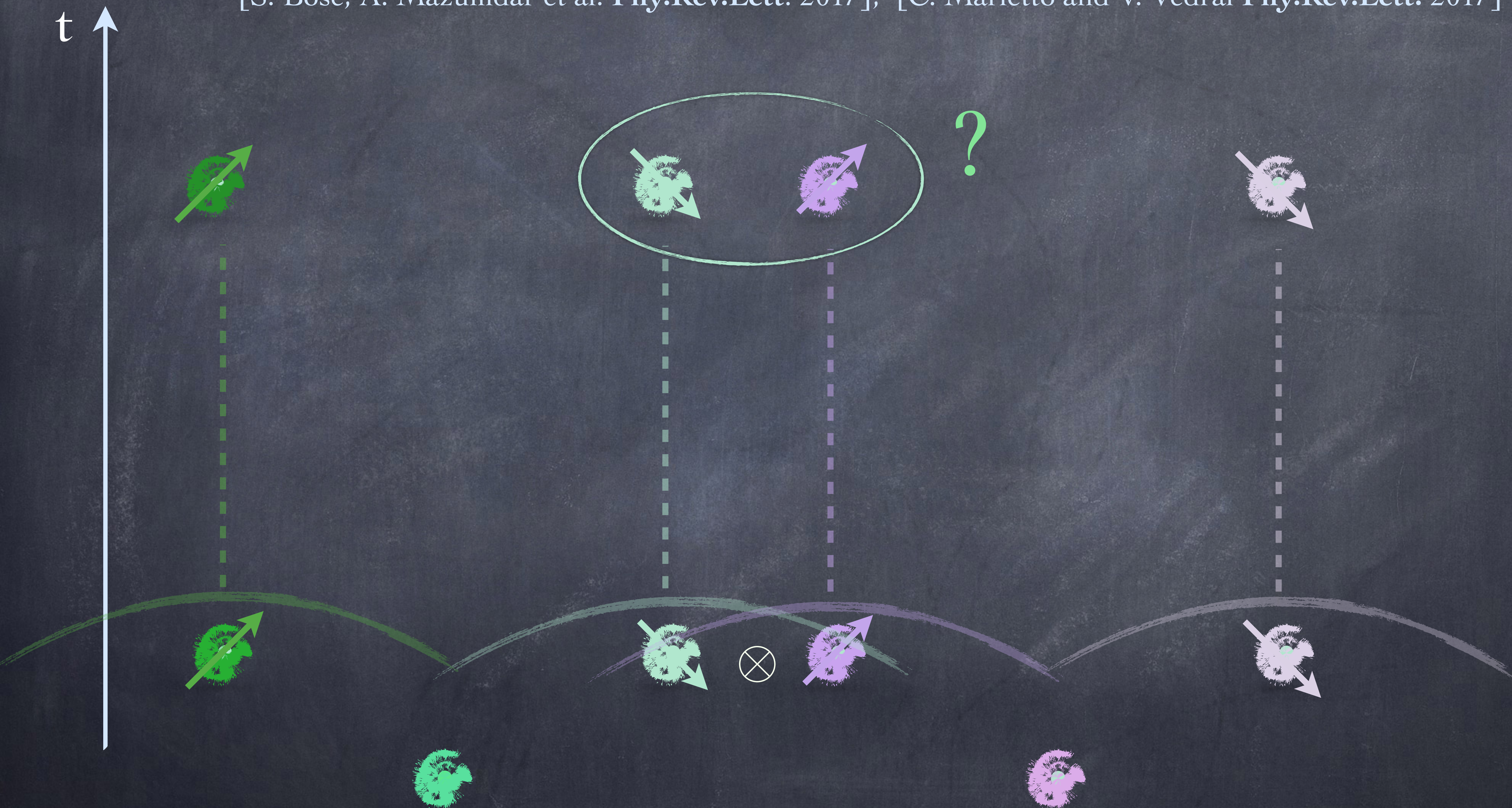

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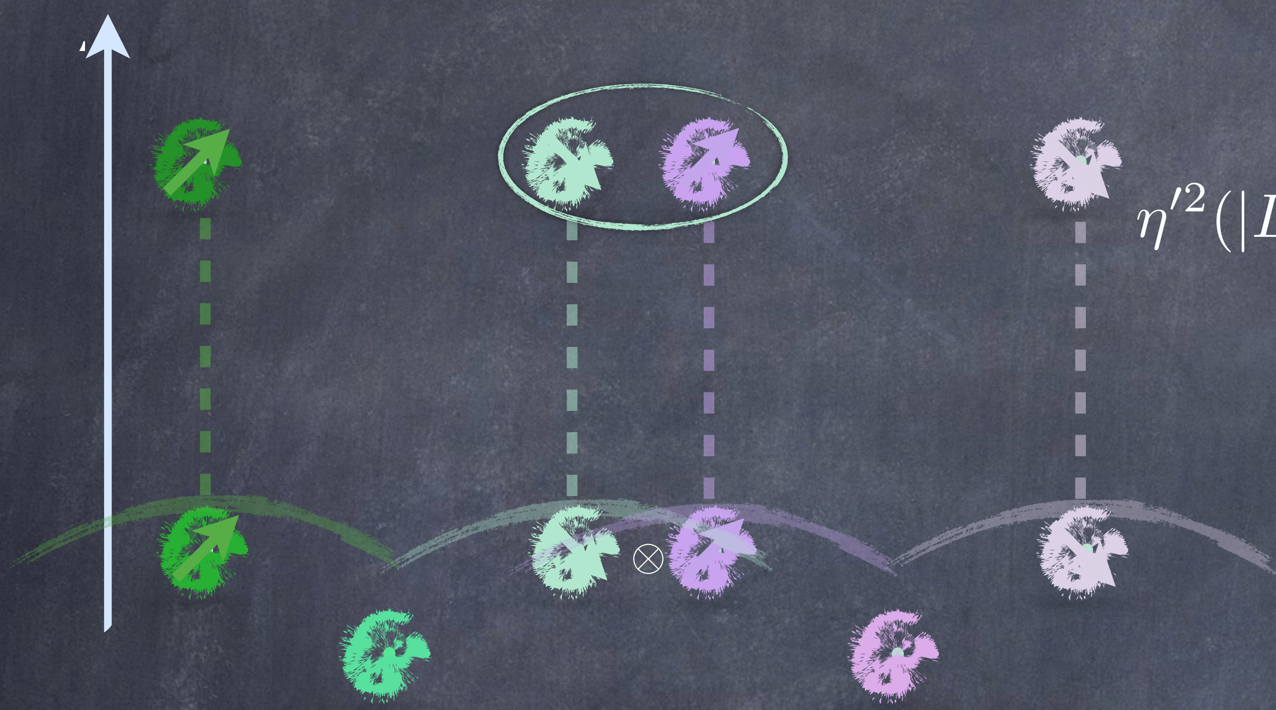

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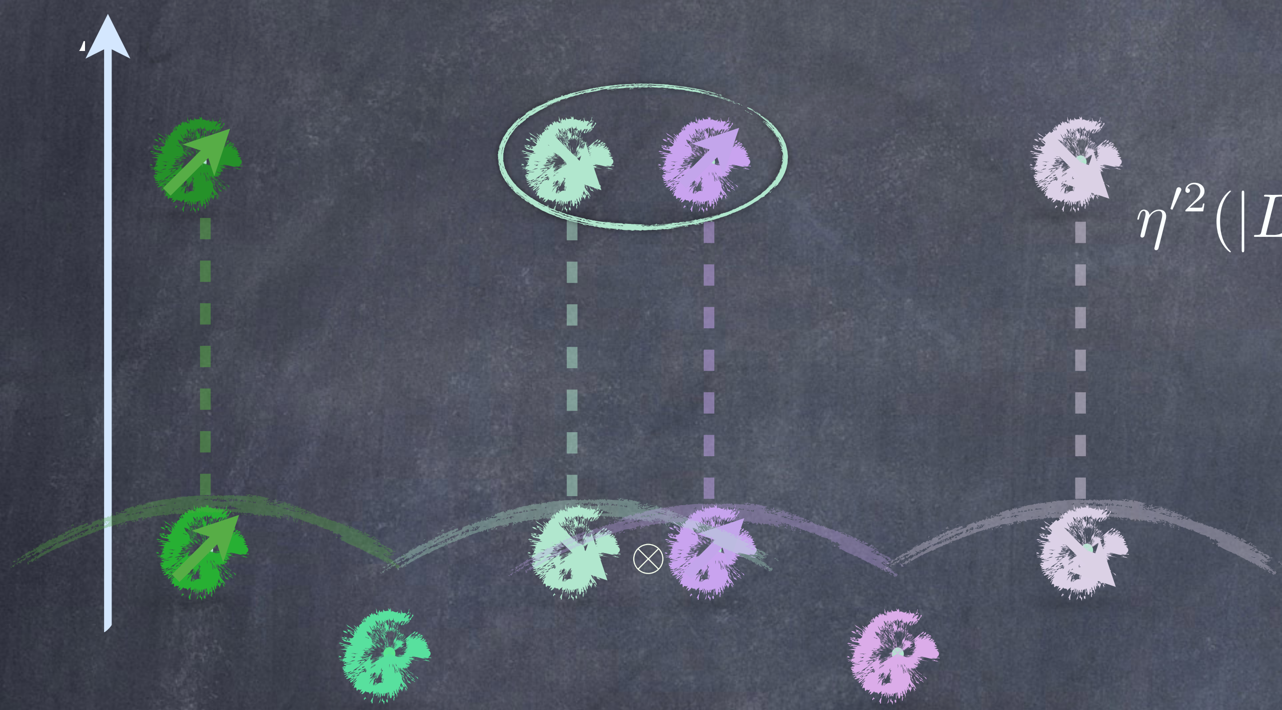

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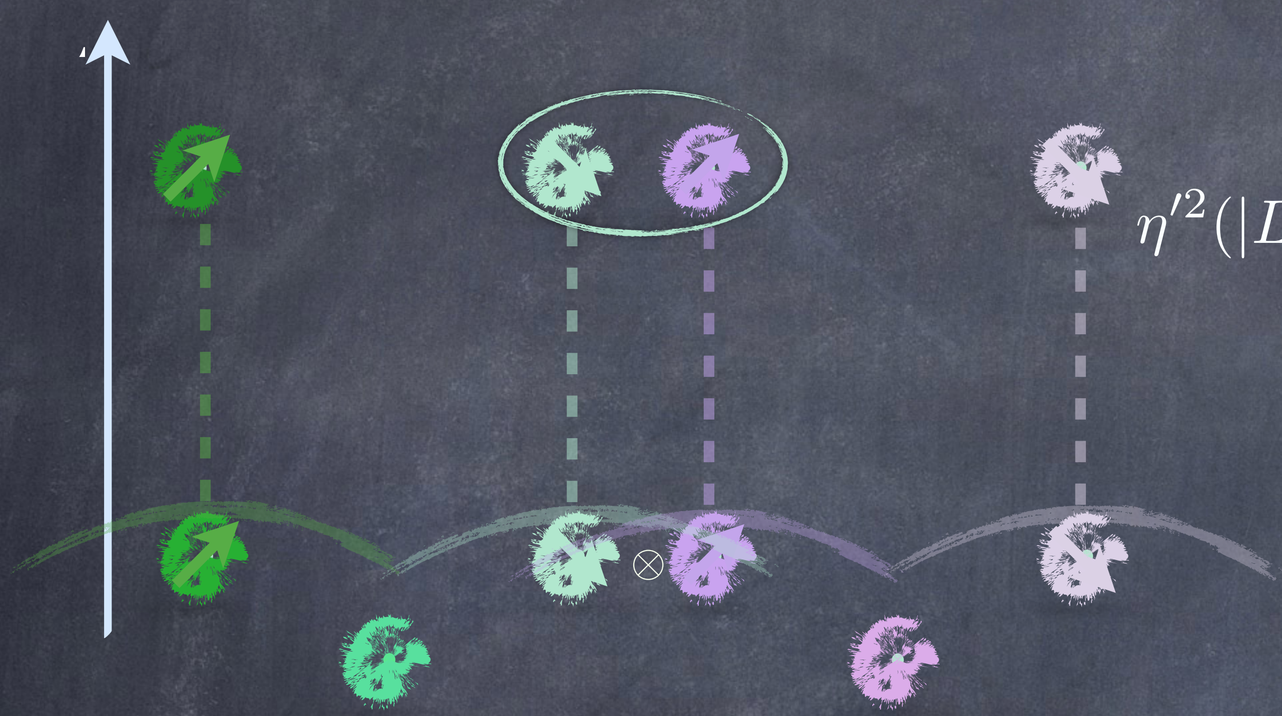

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Many researchers contributed to the discussion in the last 7 years: Anastopoulos, Aspelmeyer, Barker, Belenchia, Bengyat, Bhatar, Blencowe, Bose, Brukner, Carney, Castro-Ruiz, Chen, Christodoulou, Cooper, Di Biagio, Galley, Geraci, Hackermüller, Howl, Hu, Huggett, Iyer, Kent, Kim, Krisnanda, Lami, Linneman, Liu, Mahesh, Marletto, Marshman, Martín-Martínez, Mazumdar, Milburn, Morley, Müller, Mummery, Naik, Pal, Paterek, Paternostro, Pedernales, Perche, Pitalúa-García, Plenio, Qvarfort, Rovelli, Schneider, Schut, Selby, Serafini, Sillanpää, Tam, Taylor, Toros, Ulbricht, Vedral, Wald, Yant etc.

Questions for the low energy table-top experiment

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- For the GIE experiment, the only element of gravitational theory required is the Newton potential. As a non-local potential, it evades the assumption of LOCC, and therefore one cannot conclude the non-classicality of gravity.
- However, if one further assumes that the entanglement is mediated by a local field, then observing GIE would rule out classical local field descriptions of gravity (such as classical general relativity).

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→ Main approaches:

1)Model the protocol as a QFT process then take Newtonian limit;

E.g. [D. Carney 2022, S.Bose, A Mazumdar, M.Schut, M.Toros 2022]

2) Path-integral approach;

[M.Christodoulou, A. Di Biagio, M.Asepelmeyer, C.Brukner, C.Rovelli, R.Howl 2023]

3) Solving the quantum states of gravitational field

[LQ Chen, F.Giacomini, C.Rovelli 2023, LQ Chen, F.Giacomini 2024]

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- We need to search for more general statement: characterising non-classicality in a theory-independent way using General Probability Theory for gravity experiments.

[T.Galley, F.Giacomini, J.Selby 2020, 2023]

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- Further reads on the state of the art:

  Review: Massive quantum systems as interfaces of quantum mechanics and gravity, S. Bose, I. Fuentes, A. Geraci, et al. Rev. Mod. Phys. 97, 015003 2025

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Quantum Reference Frames

- Early developments:

The idea of including a reference frame to make coherent superpositions across different charge superselection sectors physically possible; Connecting superselection rules with the presence or absence of a reference system.

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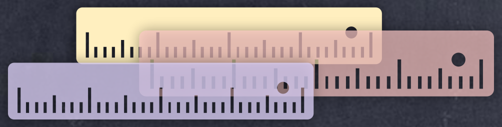

Different Formalisms of Quantum Reference Frames

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- **Quantum information approach of QRF**

What information can be encoded and inferred without accessing to an external QRF? Using symmetries to "average out" external correlations through G-twirling $\int_G dg\hat{U}(g)[\cdot]\hat{U}^\dagger(g)$ (incoherent group averaging operation)

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- **Operational approach of QRF**

In the presence of symmetries, "invariantising" positive operator-valued measures (POVMs) to obtain a space of relative observables. The relational formalism was also developed into relativistic measurement theory.

[T. Miyadera, L. Loveridge, and P. Busch, 2016, 2017, 2018, T. Miyadera and L. Loveridge 2020, J. Glowacki, L. Loveridge, and J. Waldron 2024]
[C. J. Fewster, D. W. Janssen, L. D. Loveridge, K. Rejzner, and J. Waldron 2024]

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- **Perspective/foundational approach**

  What it means to have a reference frame associated to a quantum system? Relational observables and states of other systems relative to a particular quantum reference frame's perspective, and transformation between perspectives.

  [F. Giacomini, E. Castro-Ruiz, C. Brukner 2019, AC de la Hamette, T. Galley 2020, F. Giacomini 2021, L. Apadula, E. Castro-Ruiz, C. Brukner, 2024 etc.]

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  Using the methods of gauge theory quantisation (reduced and Dirac quantisation); encompassing all frame perspectives at once and can consistently reduce to each one.

  [A. Vanrietvelde, P. A. Hohn, F. Giacomini, and E. Castro-Ruiz 2020, P.Hohn, A. Smith, and M. Lock 2021, de la Hamette, T. D. Galley, P. A. Hohn, L. Loveridge, M. P. Muller 2022, Ahmad, T. Galley, P. Höhn, M.Lock, A.Smith, 2022 etc]

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  Equivalent for ideal frame

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Harp and Violin, Georges Braque, Paris

The Perspective approach of quantum reference frames

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- Example: reference frame of translation

Article | Open access | Published: 30 January 2019

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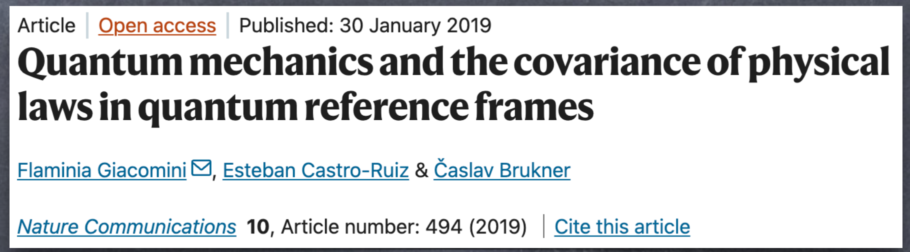

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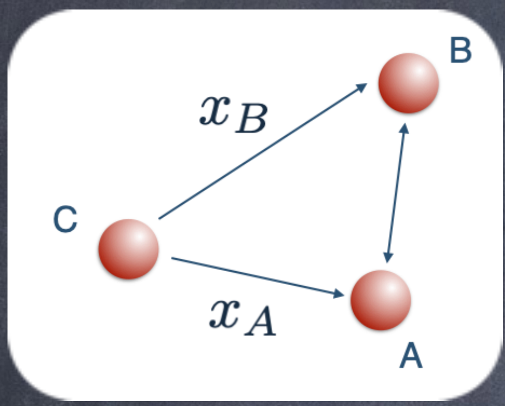

From $\boldsymbol{C}$ to $\boldsymbol{A}$: $x_A \mapsto -q_C$

$$x_B \mapsto q_B - q_C$$

Inspired by the translation operator: $e^{\frac{i}{\hbar}\alpha\hat{p}_B}|x\rangle_B = |x-\alpha\rangle_B$

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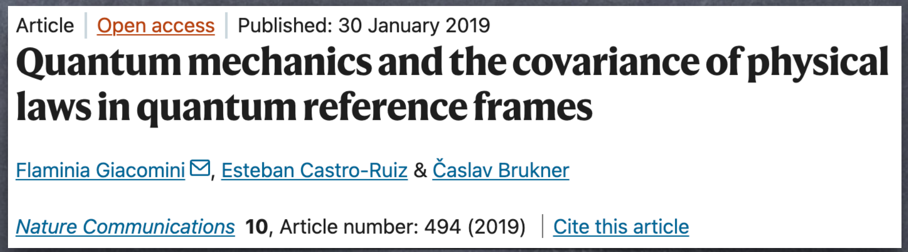

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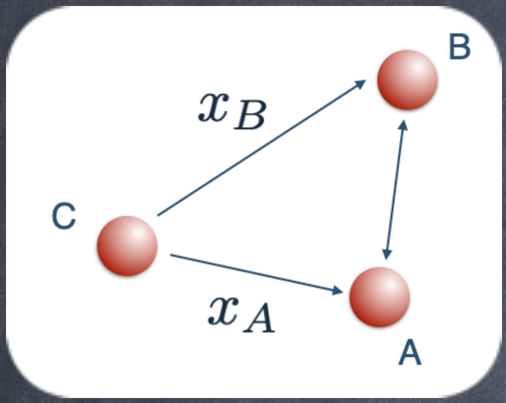

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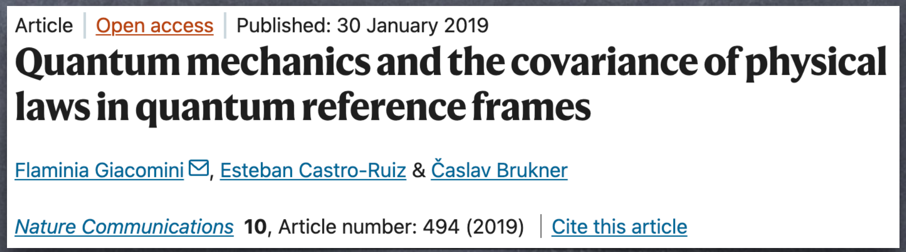

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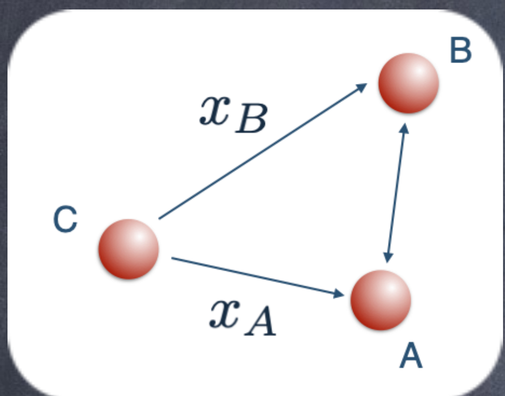

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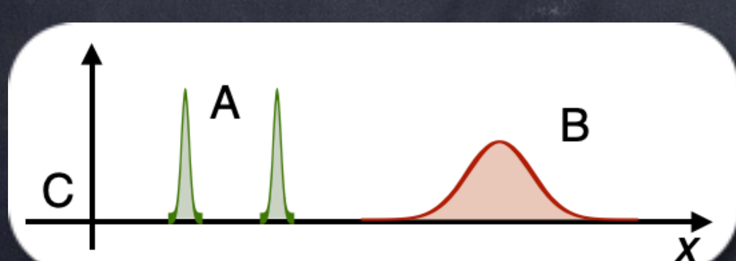
- Perspective transformation of the quantum state: $\rho^{(A)}_{BC} = \hat{S}_x \rho^{(C)}_{AB} \hat{S}^\dagger_x$



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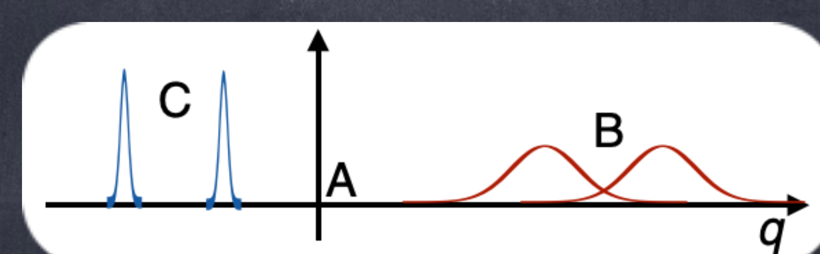

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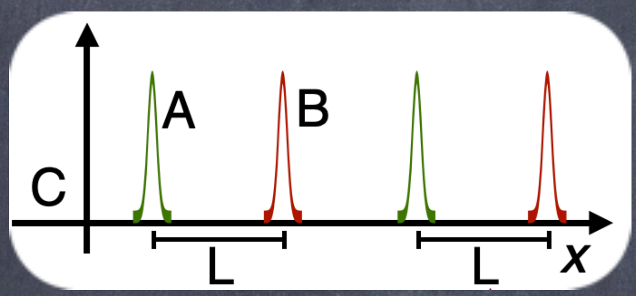

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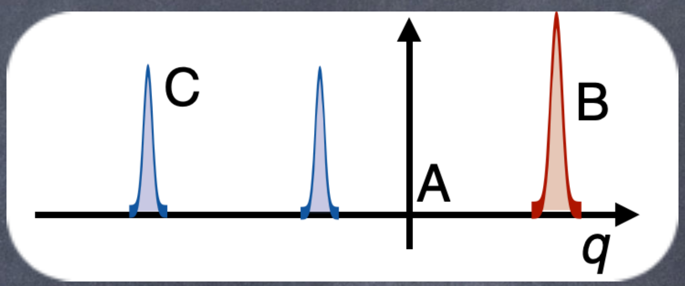

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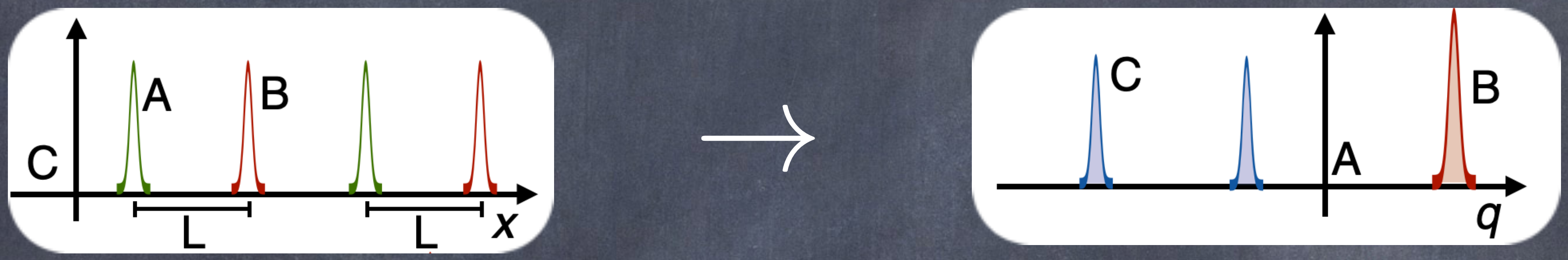

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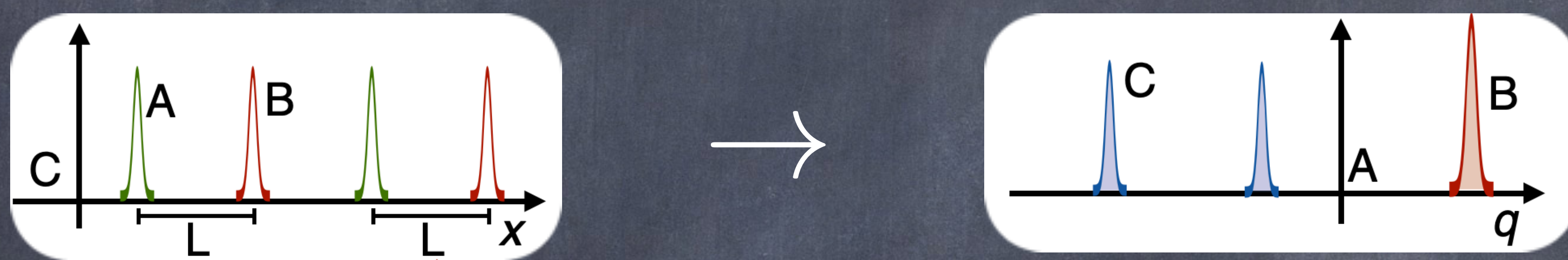

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The basis of QRF which diagnoses the observable we are using the frame for.

Quantum reference frames for quantum spacetime

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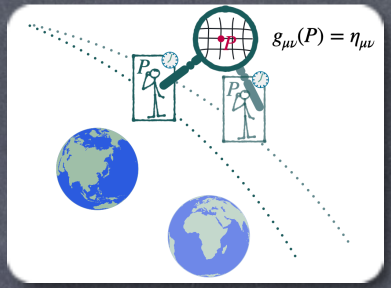

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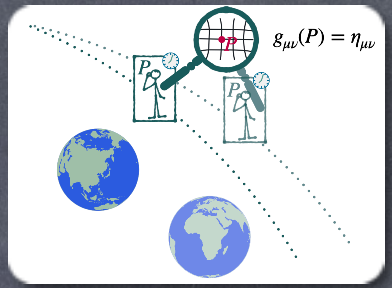

- Relating physics in definite v.s. indefinite metric

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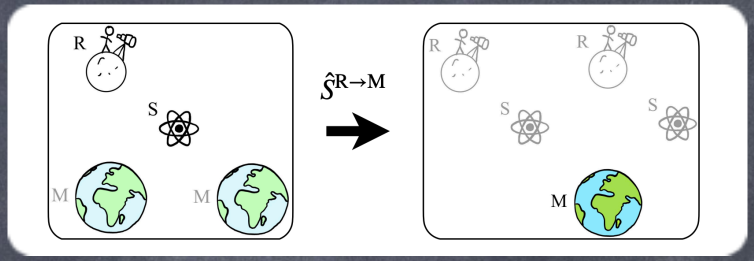

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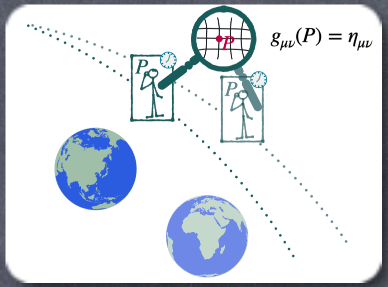

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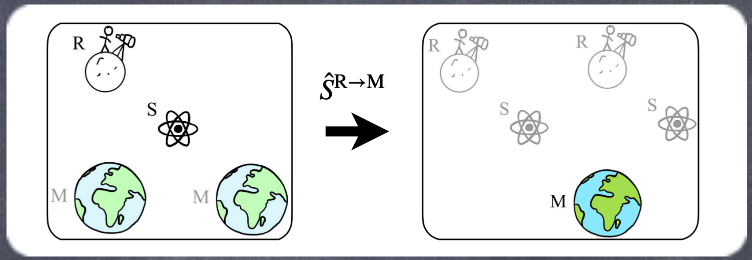

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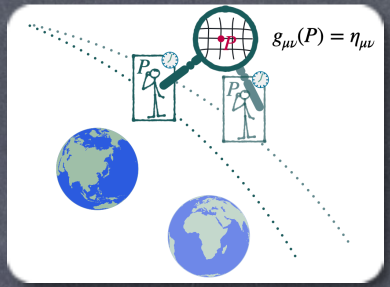

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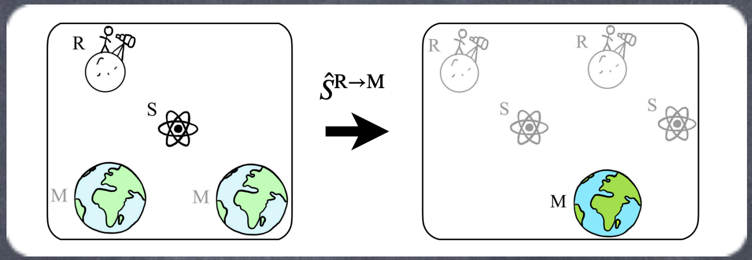

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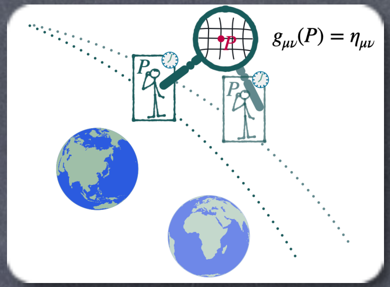

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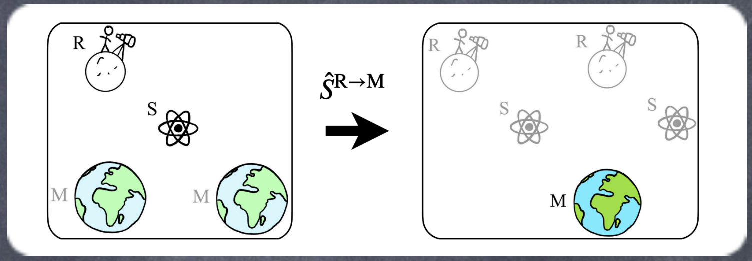

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3. Quantum clocks

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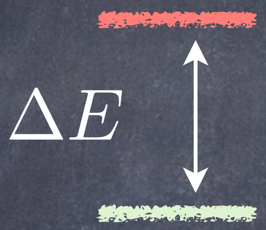

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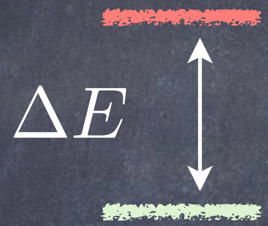

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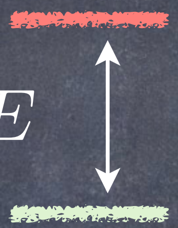

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Quantum clocks as probes of general relativistic effect

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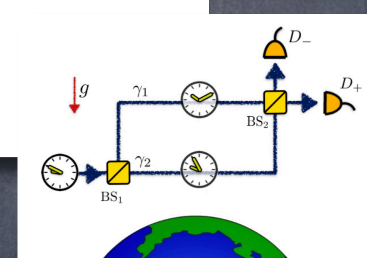
- Testing the principle of linear superposition and gravitational time dilation together.

Article | Open access | Published: 18 October 2011

Quantum interferometric visibility as a witness of general relativistic proper time

Magdalena Zych, Fabio Costa, Igor Pikovski & Časlav Brukner

Nature Communications **2**, Article number: 505 (2011) | Cite this article



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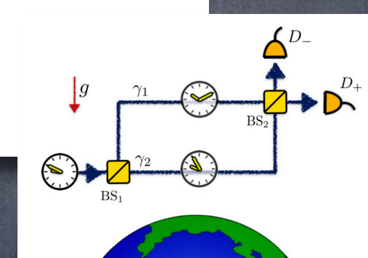

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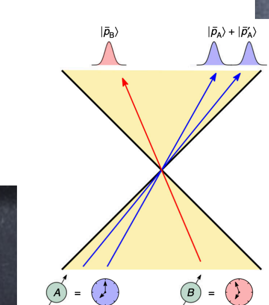
Article | Open access | Published: 23 October 2020

Quantum clocks observe classical and quantum time dilation

Alexander R. H. Smith & Mehdi Ahmadi

Nature Communications **11**, Article number: 5360 (2020) | Cite this article



A quantum correction to the time dilation observed by a clock moving in a superposition of localized momentum wave packets that has the potential to be observed in experiment.

Quantum clocks as probes of general relativistic effect

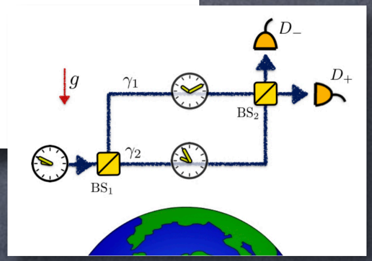
- Testing the principle of linear superposition and gravitational time dilation together.

Article | Open access | Published: 18 October 2011

Quantum interferometric visibility as a witness of general relativistic proper time

Magdalena Zych, Fabio Costa, Igor Pikovski & Časlav Brukner

Nature Communications **2**, Article number: 505 (2011) | Cite this article



Due to quantum complementarity, the visibility will drop, the path information becomes available from reading out the proper time from the clock.

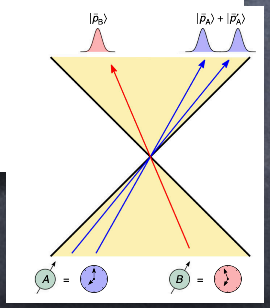
- Relativistic time dilation:

Article | Open access | Published: 23 October 2020

Quantum clocks observe classical and quantum time dilation

Alexander R. H. Smith & Mehdi Ahmadi

Nature Communications **11**, Article number: 5360 (2020) | Cite this article



A quantum correction to the time dilation observed by a clock moving in a superposition of localized momentum wave packets that has the potential to be observed in experiment.

- Experimental advancement: e.g.

Article | Published: 16 February 2022

Resolving the gravitational redshift across a millimetre-scale atomic sample

Tobias Bothwell, Colin J. Kennedy, Alexander Aeppli, Dhruv Kedar, John M. Robinson, Eric Oelker, Alexander Staron & Jun Ye

Nature **602**, 420–424 (2022) | Cite this article

Gravitating quantum clocks

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- The effects of the entanglement of quantum clocks through Newton potential

  [Castro Ruiz, Giacomini, Brukner, *2017*]

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- Quantum clocks as quantum reference frames (Perspective Neutral, Page-Wooter)

  [Giovannetti, Lloyd, Maccone, Smith, Ahmadi, Höhn, Vanrietvelde, Lock, Castro Ruiz, Giacomini, Brukner, Kirklin etc.]

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- The quantum clock/time reference frame is essential in the recent understanding of the types of von Neumann algebra in quantum field theory and perturbative quantum gravity.

  [Witten, Chandrasekaran, Longo, Penington, Fewster, Janssen, Loveridge, Rejzner, Waldron, Höhn, De Vuyst, Eccles, Kirklin etc.]

Connections with other Work Groups

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1. Operational tools: quantum reference frames, quantum clocks etc.

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- The relation between the concept of quantum reference frames with the relational observables in quantum gravity; also the potential connection with the concept of "quantum observer" explored in [Amelino-Camelia2009, Lizzi2019, Lizzi2022].

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- The reference frames on the boundary of subregion of spacetime are related to the "edge modes" and asymptotic symmetries explored in QG community, and it can be potentially related to the rich physics of the IR-triangle of gauge theory and gravity. [Strominger et al.]

  [Freidel, Donnelly, Höhn, Carrozza, Kabel, Wieland, Araujo-Regado, Sartini, Tomova etc.]

See Ana-Maria's talk!

Rich connections with other Work Groups

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- The gravity-induced decoherence models also play an important role in astrophysical observations.
- Novel ideas and protocols will come from a closer dialogue between experimentalists and theorists!

Work Group 3: Low-energy gravitational effects in quantum systems

Theoretical descriptions:

- Theoretical formulations for low-energy gravitational table top experiments
- Models of gravity-induced decoherence
- Novel effects of how quantum systems behave in gravity/quantum gravity

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Operational tools:

- Quantum reference frames
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Big questions:

- Is gravity quantized, what constitutes a quantum signature of gravity?
- Can we design new protocols for testing the (quantum) nature of gravity?
- What is the role of observers in quantum gravity?
- Can we probe the compatibility of the fundamental assumptions in gravity & quantum physics?

Thank you!