SAPIENZA
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What can low energy quantum systems teach us about space and time?

Andrea Di Biagio

Advisors: Giovanni Montani and Carlo Rovelli

Tutor: Leonardo Gualtieri

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Albanesi, S. and Allocca, A. and Altin, P. A. and Amato, A. and Anand, C. and Anand, S. and Ananyeva, A. and Anderson, S. B. and Anderson, W. G. and Andrade, T. and Andres, N. and Andri{\'c}, T. and Angelova, S. V. and Ansoldi, S. and Antelis, J. M. and Antier, S. and Appert, S. and Arai, K. and Araya, M. C. and Areeda, J. S. and Ar{\`e}ne, M. and Arnaud, N. and Aronson, S. M. and Arun, K. G. and Asali, Y. and Ashton, G. and Assiduo, M. and Aston, S. M. and Astone, P. and Aubin, F. and Austin, C. and Babak, S. and Badaracco, F. and Bader, M. K. M. and Badger, C. and Bae, S. and Baer, A. M. and Bagnasco, S. and Bai, Y. and Baird, J. and Ball, M. and Ballardin, G. and Ballmer, S. W. and Balsamo, A. and Baltus, G. and Banagiri, S. and Bankar, D. and Barayoga, J. C. and Barbieri, C. and Barish, B. C. and Barker, D. and Barneo, P. and Barone, F. and Barr, B. and Barsotti, L. and Barsuglia, M. and Barta, D. and Bartlett, J. and Barton, M. 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F. and Franke, A. and Frasca, S. and Frasconi, F. and Frederick, C. and Freed, J. P. and Frei, Z. and Freise, A. and Frey, R. and Fritschel, P. and Frolov, V. V. and Fronz{\'e}, G. G. and Fulda, P. and Fyffe, M. and Gabbard, H. A. and Gabella, W. and Gadre, B. U. and Gair, J. R. and Gais, J. and Galaudage, S. and Gamba, R. and Ganapathy, D. and Ganguly, A. and Gaonkar, S. G. and Garaventa, B. and Garc{\'i}a, F. and {Garc{\'i}a-N{\'u}{\~n}ez}, C. and {Garc{\'i}a-Quir{\'o}s}, C. and Garufi, F. and Gateley, B. and Gaudio, S. and Gayathri, V. and Gemme, G. and Gennai, A. and George, J. and George, R. N. and Gerberding, O. and Gergely, L. and Gewecke, P. and Ghonge, S. and Ghosh, Abhirup and Ghosh, Archisman and Ghosh, Shaon and Ghosh, Shrobana and Giacomazzo, B. and Giacoppo, L. and Giaime, J. A. and Giardina, K. D. and Gibson, D. R. and Gier, C. and Giesler, M. and Giri, P. and Gissi, F. and Glanzer, J. and Gleckl, A. 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J. and Hanson, J. and Harder, T. and Hardwick, T. and Haris, K. and Harms, J. and Harry, G. M. and Harry, I. W. and Hartwig, D. and Haskell, B. and Hasskew, R. K. and Haster, C.-J. and Haughian, K. and Hayes, F. J. and Healy, J. and Heidmann, A. and Heidt, A. and Heintze, M. C. and Heinze, J. and Heinzel, J. and Heitmann, H. and Hellman, F. and Hello, P. and {Helmling-Cornell}, A. F. and Hemming, G. and Hendry, M. and Heng, I. S. and Hennes, E. and Hennig, J. and Hennig, M. H. and Hernandez, A. G. and Vivanco, F. Hernandez and Heurs, M. and Hild, S. and Hill, P. and Hines, A. S. and Hochheim, S. and Hofman, D. and Hohmann, J. N. and Holcomb, D. G. and Holland, N. A. and {Holley-Bockelmann}, K. and Hollows, I. J. and Holmes, Z. J. and Holt, K. and Holz, D. E. and Hopkins, P. and Hough, J. and Hourihane, S. and Howell, E. J. and Hoy, C. G. and Hoyland, D. and Hreibi, A. and Hsu, Y. and Huang, Y. and H{\"u}bner, M. T. and Huddart, A. D. and Hughey, B. and Hui, V. and Husa, S. and Huttner, S. H. and Huxford, R. and {Huynh-Dinh}, T. and Idzkowski, B. and Iess, A. and Ingram, C. and Isi, M. and Isleif, K. and Iyer, B. R. and JaberianHamedan, V. and Jacqmin, T. and Jadhav, S. J. and Jadhav, S. P. and James, A. L. and Jan, A. Z. and Jani, K. and Janquart, J. and Janssens, K. and Janthalur, N. N. and Jaranowski, P. and Jariwala, D. and Jaume, R. and Jenkins, A. C. and Jenner, K. and Jeunon, M. and Jia, W. and Johns, G. R. and {Johnson-McDaniel}, N. K. and Jones, A. W. and Jones, D. I. and Jones, J. D. and Jones, P. and Jones, R. and Jonker, R. J. G. and Ju, L. and Junker, J. and Juste, V. and Kalaghatgi, C. V. and Kalogera, V. and Kamai, B. and Kandhasamy, S. and Kang, G. and Kanner, J. B. and Kao, Y. and Kapadia, S. J. and Kapasi, D. P. and Karat, S. and Karathanasis, C. and Karki, S. and Kashyap, R. and Kasprzack, M. and Kastaun, W. and Katsanevas, S. and Katsavounidis, E. and Katzman, W. and Kaur, T. and Kawabe, K. and K{\'e}f{\'e}lian, F. and Keitel, D. and Key, J. S. and Khadka, S. and Khalili, F. Y. and Khan, S. and Khazanov, E. A. and Khetan, N. and Khursheed, M. and Kijbunchoo, N. and Kim, C. and Kim, J. C. and Kim, K. and Kim, W. S. and Kim, Y.-M. and Kimball, C. and {Kinley-Hanlon}, M. and Kirchhoff, R. and Kissel, J. S. and Kleybolte, L. and Klimenko, S. and Knee, A. M. and Knowles, T. D. and Knyazev, E. and Koch, P. and Koekoek, G. and Koley, S. and Kolitsidou, P. and Kolstein, M. and Komori, K. and Kondrashov, V. and Kontos, A. and Koper, N. and Korobko, M. and Kovalam, M. and Kozak, D. B. and Kringel, V. and Krishnendu, N. 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Lopez and Lorenzini, M. and Loriette, V. and Lormand, M. and Losurdo, G. and Lott, T. P. and Lough, J. D. and Lousto, C. O. and Lovelace, G. and Lucaccioni, J. F. and L{\"u}ck, H. and Lumaca, D. and Lundgren, A. P. and Lynam, J. E. and Macas, R. and MacInnis, M. and Macleod, D. M. and MacMillan, I. a. O. and Macquet, A. and Hernandez, I. Maga{\~n}a and Magazz{\`u}, C. and Magee, R. M. and Maggiore, R. and Magnozzi, M. and Mahesh, S. and Majorana, E. and Makarem, C. and Maksimovic, I. and Maliakal, S. and Malik, A. and Man, N. and Mandic, V. and Mangano, V. and Mango, J. L. and Mansell, G. L. and Manske, M. and Mantovani, M. and Mapelli, M. and Marchesoni, F. and Marion, F. and Mark, Z. and M{\'a}rka, S. and M{\'a}rka, Z. and Markakis, C. and Markosyan, A. S. and Markowitz, A. and Maros, E. and Marquina, A. and Marsat, S. and Martelli, F. and Martin, I. W. and Martin, R. M. and Martinez, M. and Martinez, V. A. and Martinez, V. and Martinovic, K. and Martynov, D. V. and Marx, E. 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W. and Richardson, L. and Riemenschneider, G. and Riles, K. and Rinaldi, S. and Rink, K. and Rizzo, M. and Robertson, N. A. and Robie, R. and Robinet, F. and Rocchi, A. and Rodriguez, S. and Rolland, L. and Rollins, J. G. and Romanelli, M. and Romano, R. and Romel, C. L. and {Romero-Rodr{\'i}guez}, A. and {Romero-Shaw}, I. M. and Romie, J. H. and Ronchini, S. and Rosa, L. and Rose, C. A. and Rosell, M. J. B. and Rosi{\'n}ska, D. and Ross, M. P. and Rowan, S. and Rowlinson, S. J. and Roy, S. and Roy, Santosh and Roy, Soumen and Rozza, D. and Ruggi, P. and {Ruiz-Rocha}, K. and Ryan, K. and Sachdev, S. and Sadecki, T. and Sadiq, J. and Sakellariadou, M. and Salafia, O. S. and Salconi, L. and Saleem, M. and Salemi, F. and Samajdar, A. and Sanchez, E. J. and Sanchez, J. H. and Sanchez, L. E. and {Sanchis-Gual}, N. and Sanders, J. R. and Sanuy, A. and Saravanan, T. R. and Sarin, N. and Sassolas, B. and Satari, H. and Sauter, O. and Savage, R. L. and Sawant, D. and Sawant, H. L. and Sayah, S. and Schaetzl, D. and Scheel, M. and Scheuer, J. and Schiworski, M. and Schmidt, P. and Schmidt, S. and Schnabel, R. and Schneewind, M. and Schofield, R. M. S. and Sch{\"o}nbeck, A. and Schulte, B. W. and Schutz, B. F. and Schwartz, E. and Scott, J. and Scott, S. M. and {Seglar-Arroyo}, M. and Sellers, D. and Sengupta, A. S. and Sentenac, D. and Seo, E. G. and Sequino, V. and Sergeev, A. and Setyawati, Y. and Shaffer, T. and Shahriar, M. S. and Shams, B. and Sharma, A. and Sharma, P. and Shawhan, P. and Shcheblanov, N. S. and Shikauchi, M. and Shoemaker, D. H. and Shoemaker, D. M. and ShyamSundar, S. and Sieniawska, M. and Sigg, D. and Singer, L. P. and Singh, D. and Singh, N. and Singha, A. and Sintes, A. M. and Sipala, V. and Skliris, V. and Slagmolen, B. J. J. and {Slaven-Blair}, T. J. and Smetana, J. and Smith, J. R. and Smith, R. J. E. and Soldateschi, J. and Somala, S. N. and Son, E. 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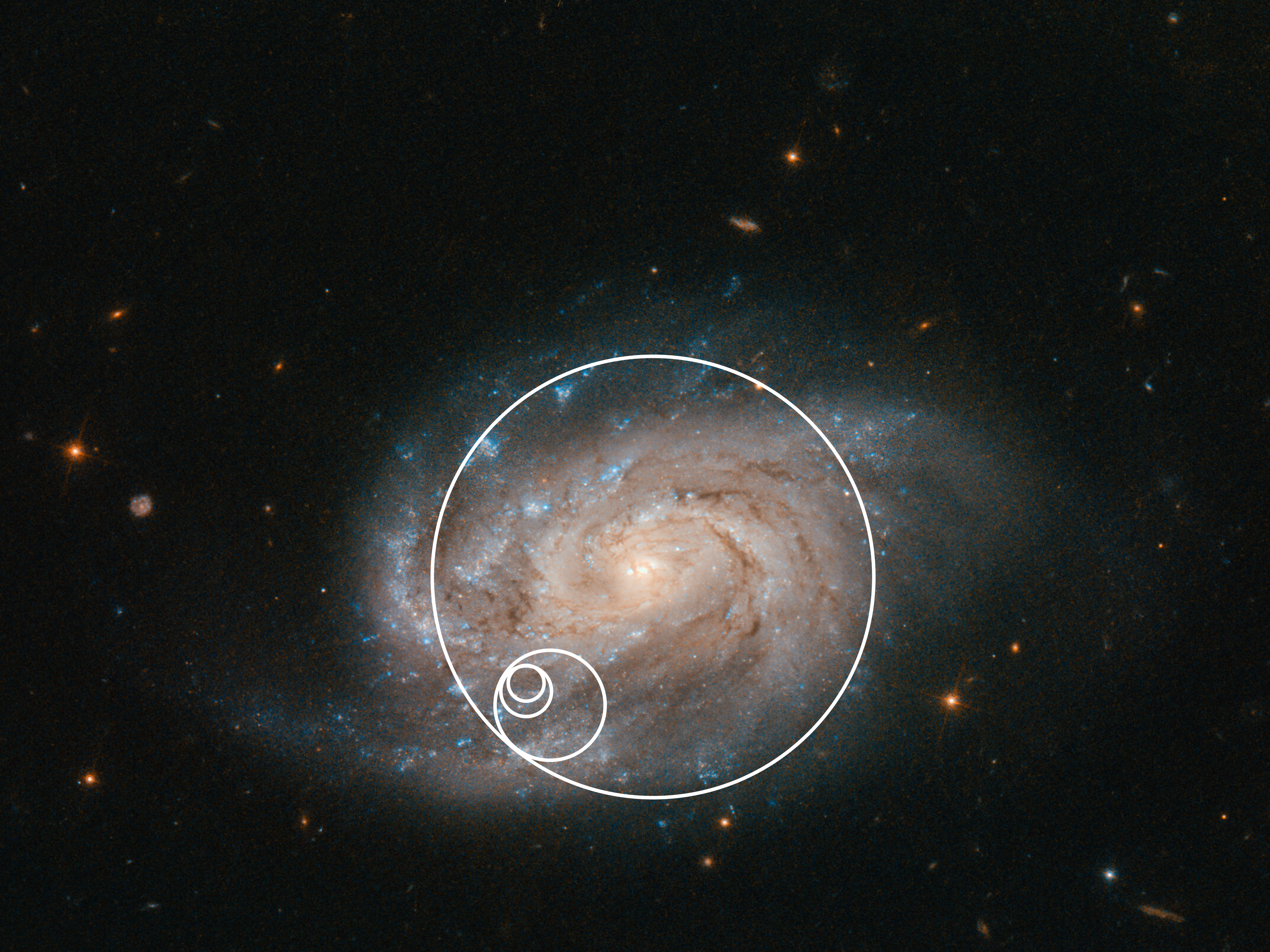
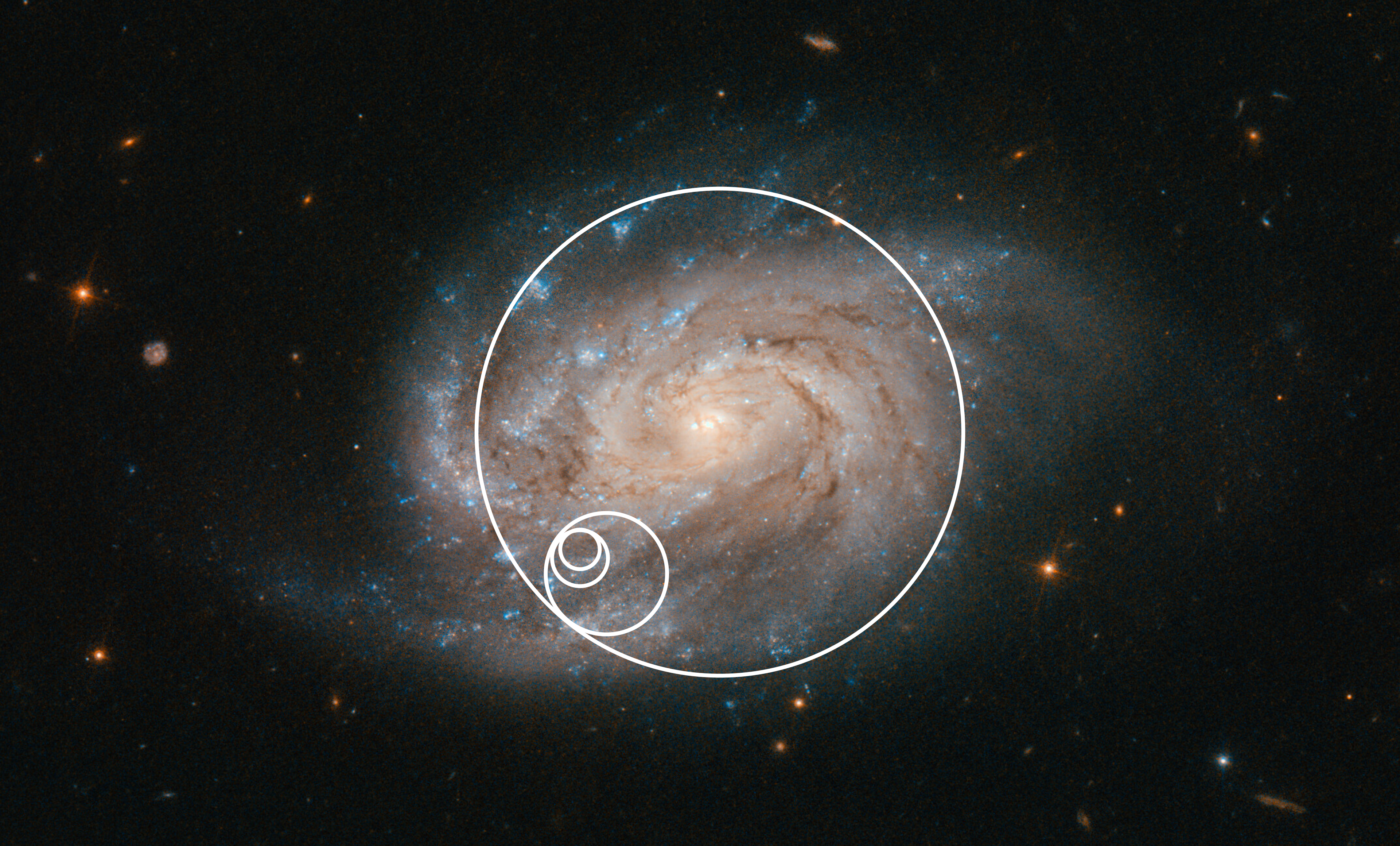
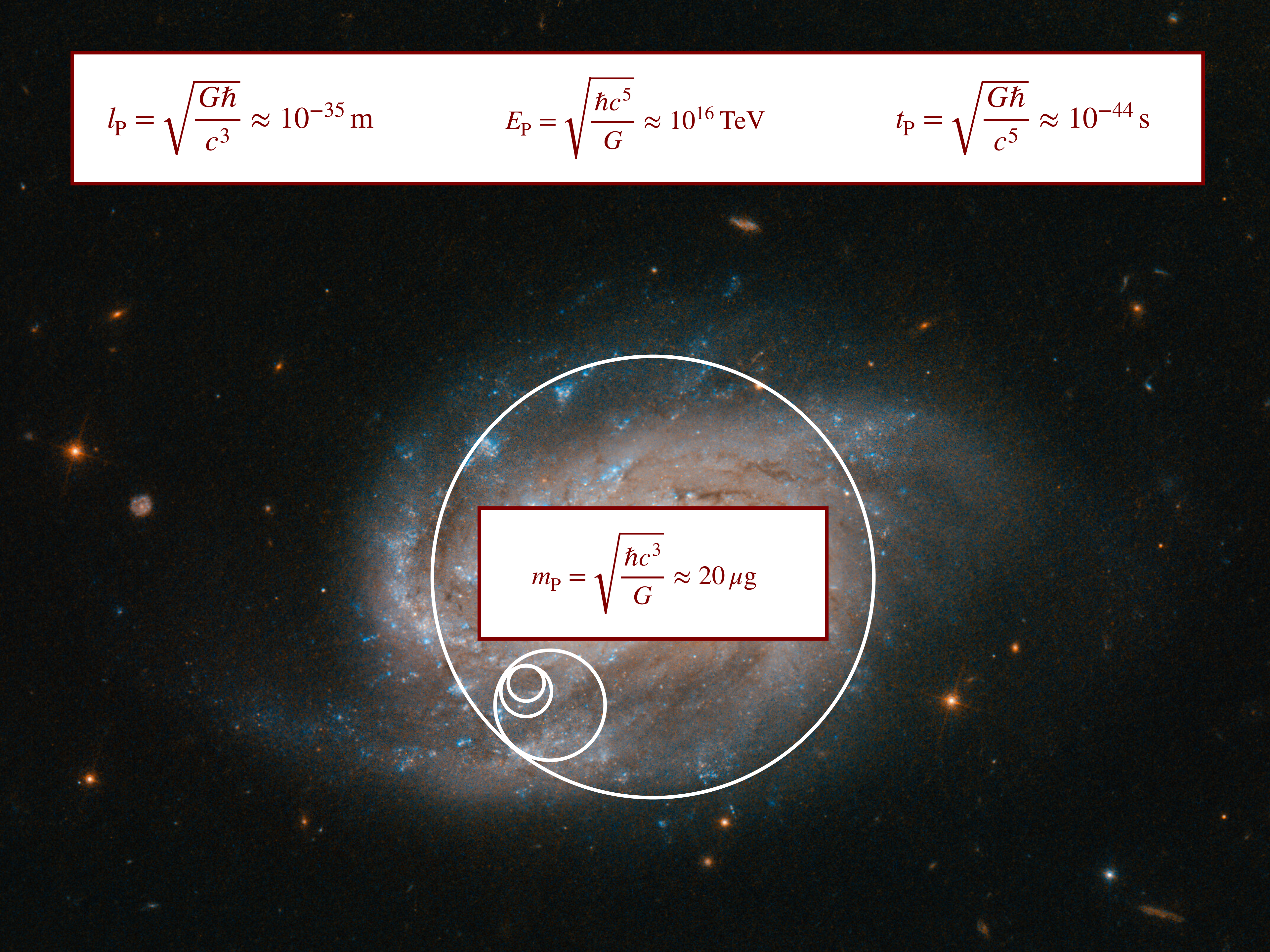


$$l_\mathrm{P} = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35}\,\mathrm{m} \qquad E_\mathrm{P} = \sqrt{\frac{\hbar c^5}{G}} \approx 10^{16}\,\mathrm{TeV} \qquad t_\mathrm{P} = \sqrt{\frac{G\hbar}{c^5}} \approx 10^{-44}\,\mathrm{s}$$



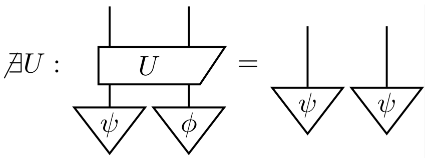


$$l_{\mathrm{P}} = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35}\,\mathrm{m} \qquad E_{\mathrm{P}} = \sqrt{\frac{\hbar c^5}{G}} \approx 10^{16}\,\mathrm{TeV} \qquad t_{\mathrm{P}} = \sqrt{\frac{G\hbar}{c^5}} \approx 10^{-44}\,\mathrm{s}$$

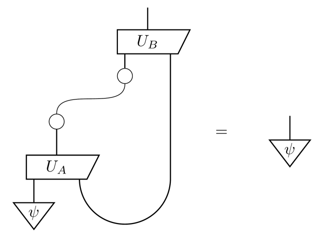
$$m_{\mathrm{P}} = \sqrt{\frac{\hbar c^3}{G}} \approx 20\,\mu\mathrm{g}$$

Quantum Information and Foundations

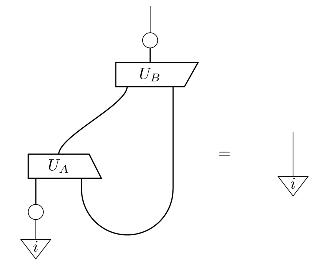
QI: Information-processing capabilities afforded by quantum systems



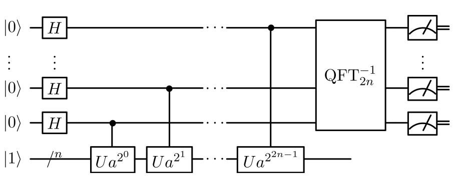
No-cloning theorem



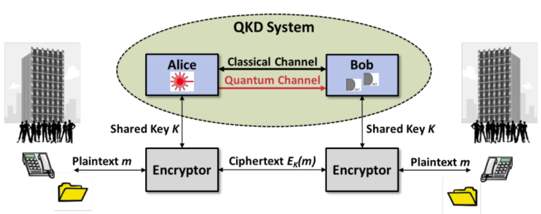
Quantum Teleportation



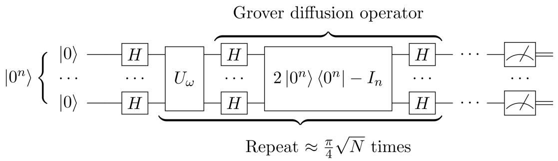
Superdense coding



Shor's algorithm



Quantum key distribution



Grover's algorithm

By Bender2k14 - Own work.

commons.wikimedia.org/w/index.php?curid=34319883

Mailloux *et.al.*

By Fawly - Own work

ommons.wikimedia.org/w/index.php?curid=106362482

Quantum Information and Foundations

QF: study of the counterintuitive properties of QM

Quantum Information and Foundations

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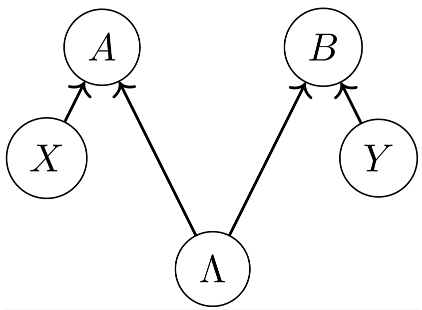
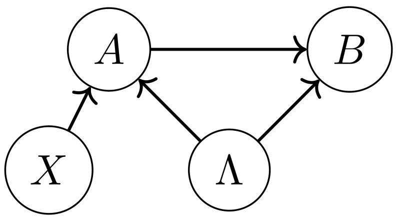
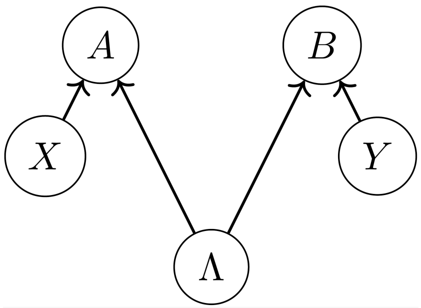


Violation of causal inequalities



Quantum Information and Foundations

QF: study of the counterintuitive properties of QM



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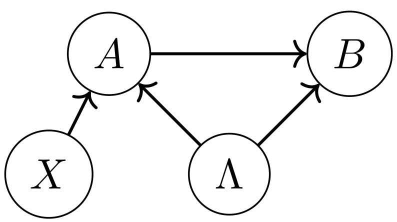
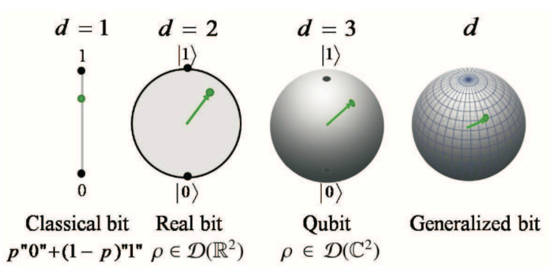
2. **Local tomography.** The state of a composite system is fully characterised by the statistics of measurements performed on the subsystems.
3. **Equivalence of subspaces.** Systems that carry the same amount of information have isomorphic state spaces.
4. **Symmetry.** Any pure state can be reversibly transformed into any other pure state.
5. **All measurements are allowed.** Every mathematically well defined effect on a system carrying one bit corresponds to a possible measurement.

Violation of causal inequalities

Reconstructions of quantum theory from physical principles

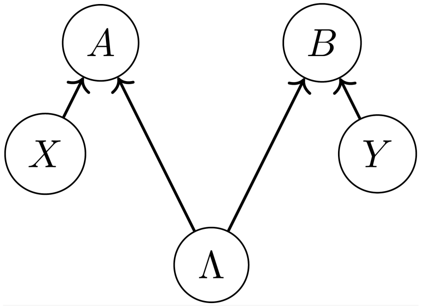




Dakic and Brukner

Quantum Information and Foundations

QF: study of the counterintuitive properties of QM



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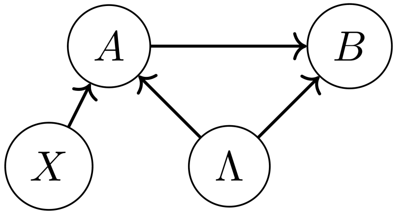
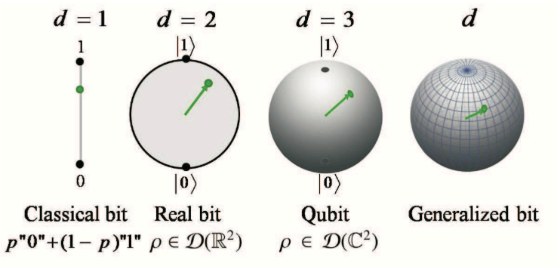
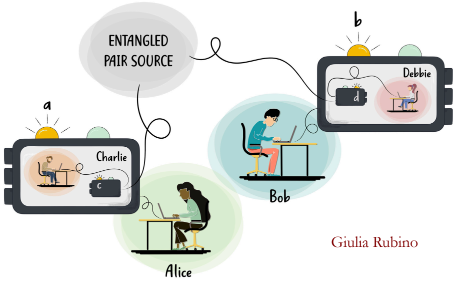
Reconstructions of quantum theory from physical principles

Interpretations of quantum theory





Dakic and Brukner



Giulia Rubino

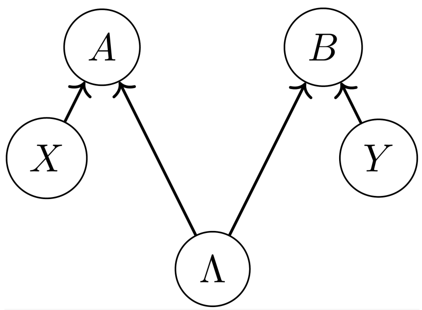
Quantum Information and Foundations

Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons

Marissa Giustina, Marijn A. M. Versteegh, Sören Wengerowsky, Johannes Handsteiner, Armin Hochrainer, Kevin Phelan, Fabian Steinlechner, Johannes Kofler, Jan-Åke Larsson, Carlos Abellán, Waldimar Amaya, Valerio Pruneri, Morgan W. Mitchell, Jörn Beyer, Thomas Gerrits, Adriana E. Lita, Lynden K. Shalm, Sae Woo Nam, Thomas Scheidl, Rupert Ursin, Bernhard Wittmann, and Anton Zeilinger

Phys. Rev. Lett. **115**, 250401 – Published 16 December 2015

)f QM



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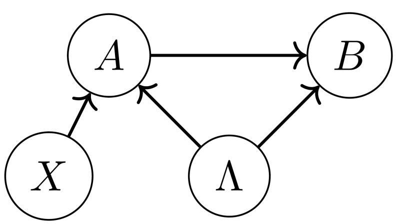
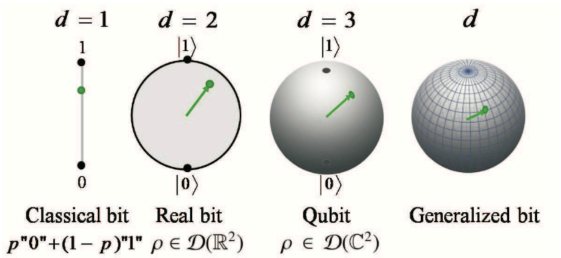
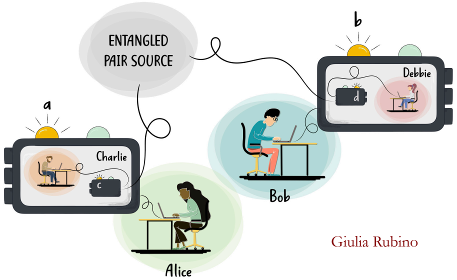


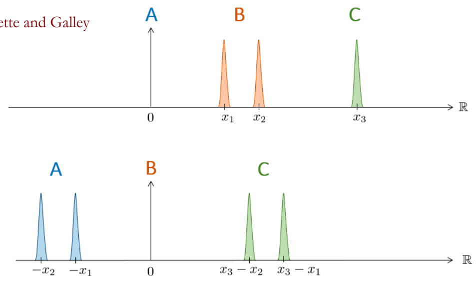


Dakic and Brukner

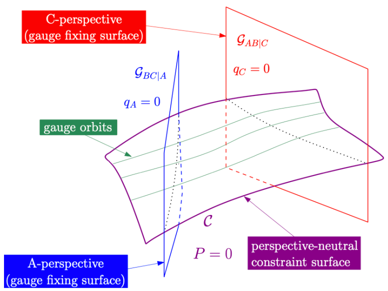


Giulia Rubino

de la Hamette and Galley



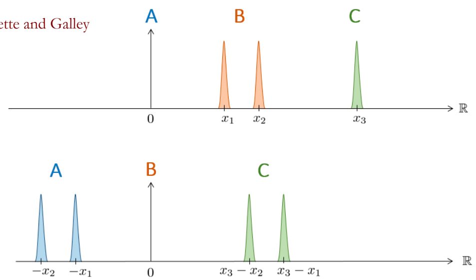
Quantum Reference Frames



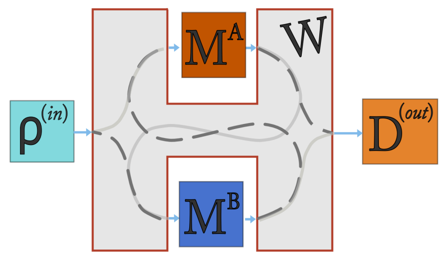
Vanrietvelde, Höhn, Giacomini, Castro-Ruiz

QI and Spacetime

de la Hamette and Galley

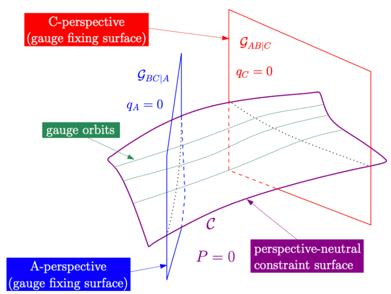


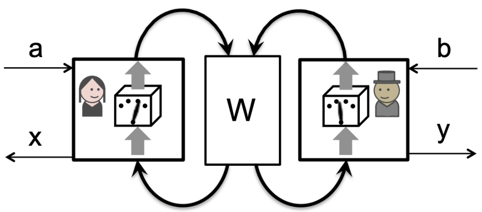
Rubino et.al.



Quantum Reference Frames

Indefinite causality



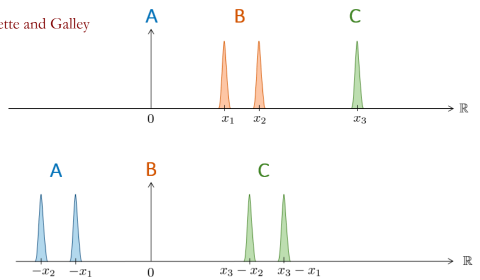


Oreshkov, Costa, Brukner

Vanrietvelde, Höhn, Giacomini, Castro-Ruiz

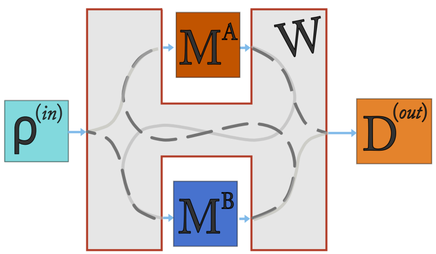
QI and Spacetime

de la Hamette and Galley



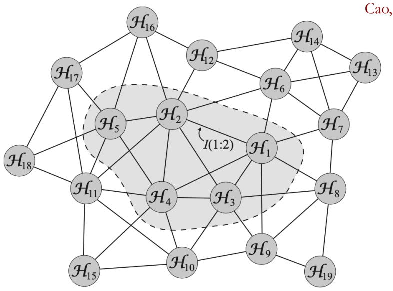
Quantum Reference Frames

Rubino et.al.

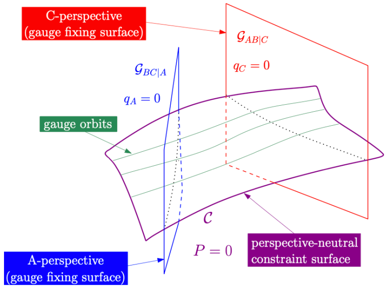


Indefinite causality

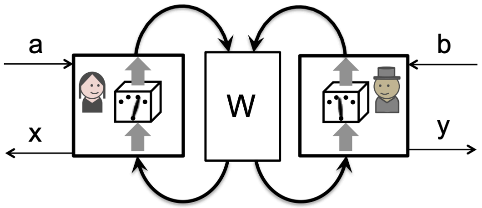
Cao, Carrol, Michalakis



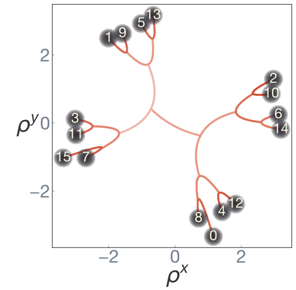
Geometry from entanglement



Vanrietvelde, Höhn, Giacomini, Castro-Ruiz



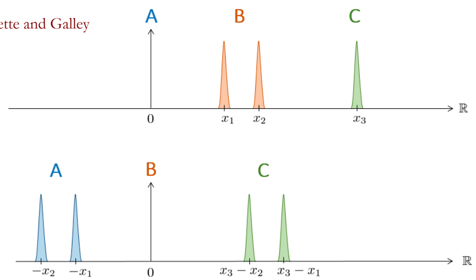
Oreshkov, Costa, Brukner



Periwal *et.al.*

QI and Spacetime

de la Hamette and Galley



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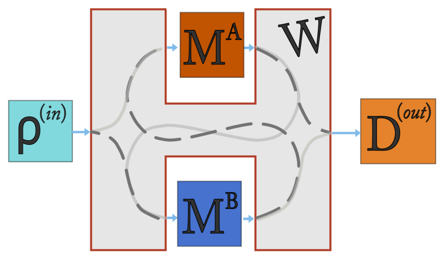

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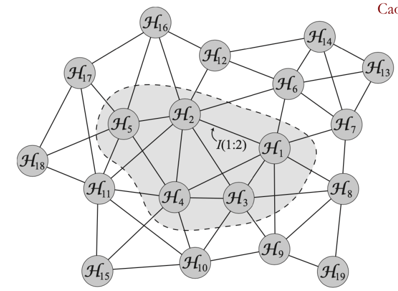

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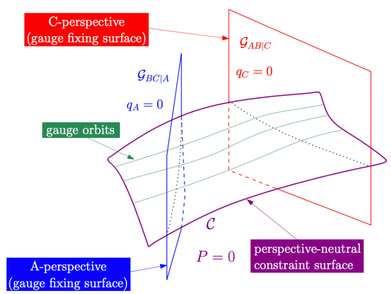

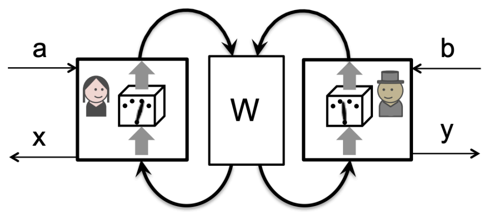

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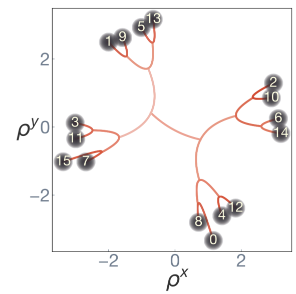

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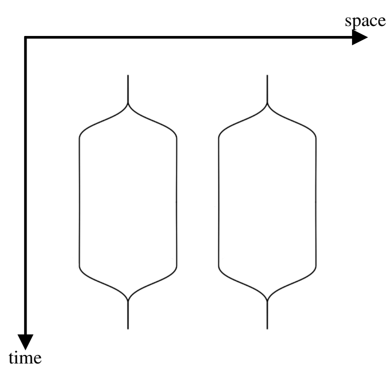
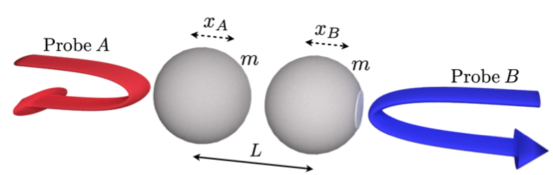
Vanrietvelde, Höhn, Giacomini, Castro-Ruiz



Low energy tests of quantum gravity!



Krisnanda *et.al.*

Plan

- **Part I: Quantum gravity (and beyond) in the lab**
- **Part II: Conceptual investigations**

Plan

- Part I: Quantum gravity (and beyond) in the lab
  - Gravitationally Mediated Entanglement (GME)
  - Optical Simulation of a GME experiment
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GME

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C. Marletto and V. Vedral
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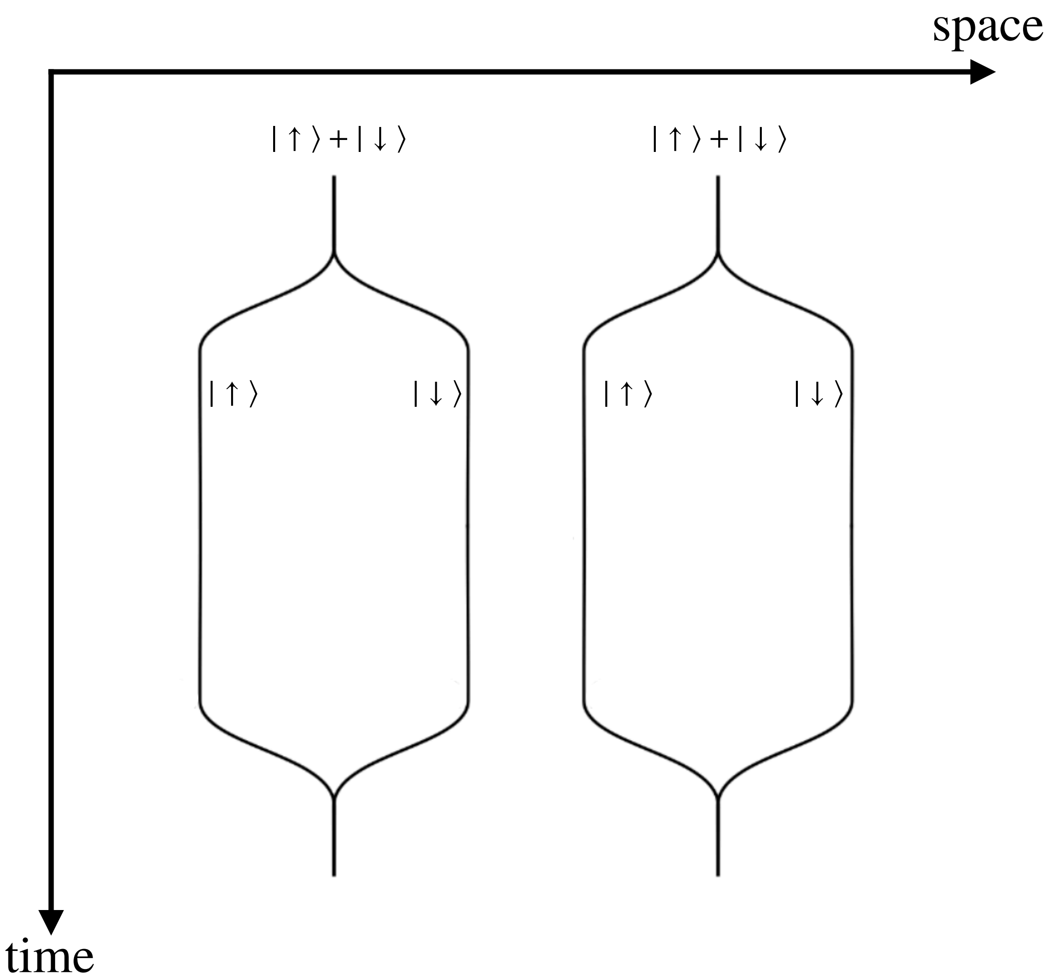


Preparation

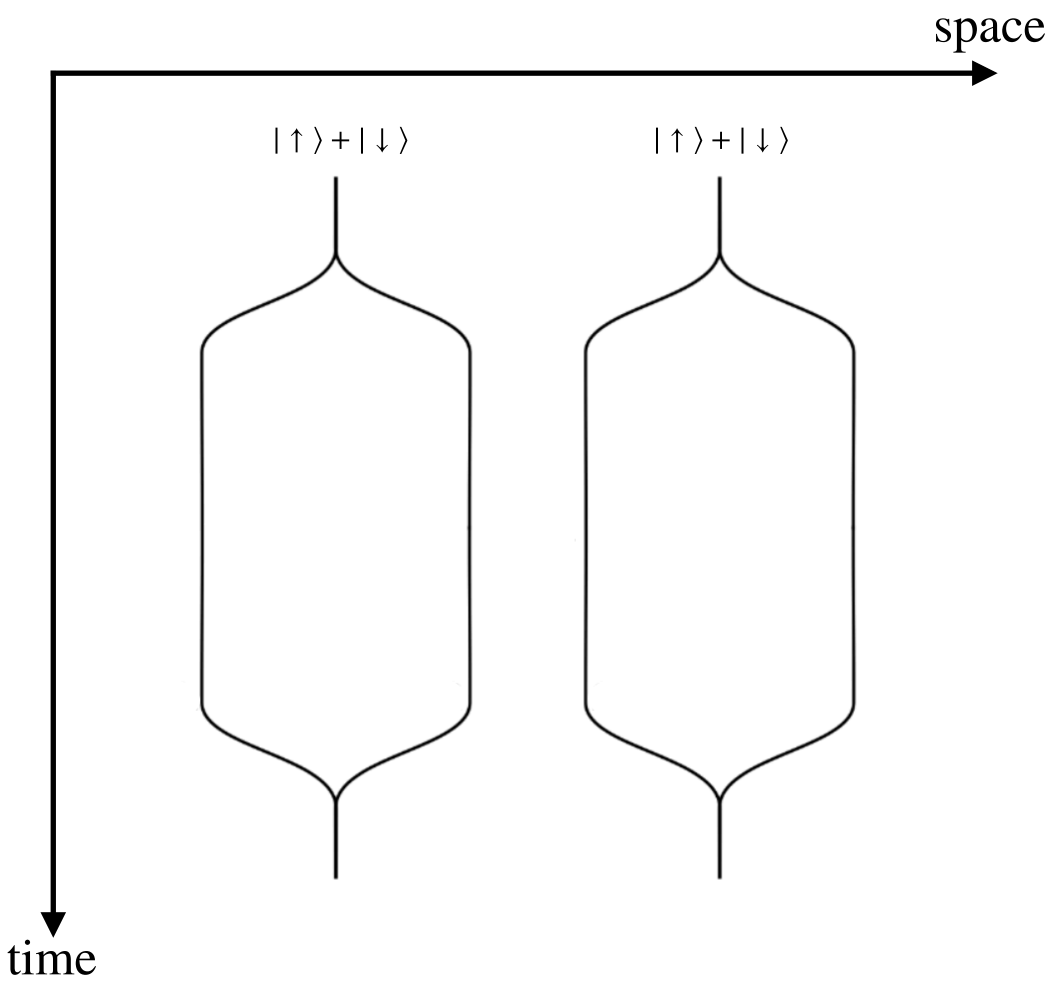
Superposition

Free Fall

Recombination

Measurements

GME



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$$\left(|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle\right)|g_{CC}\rangle$$

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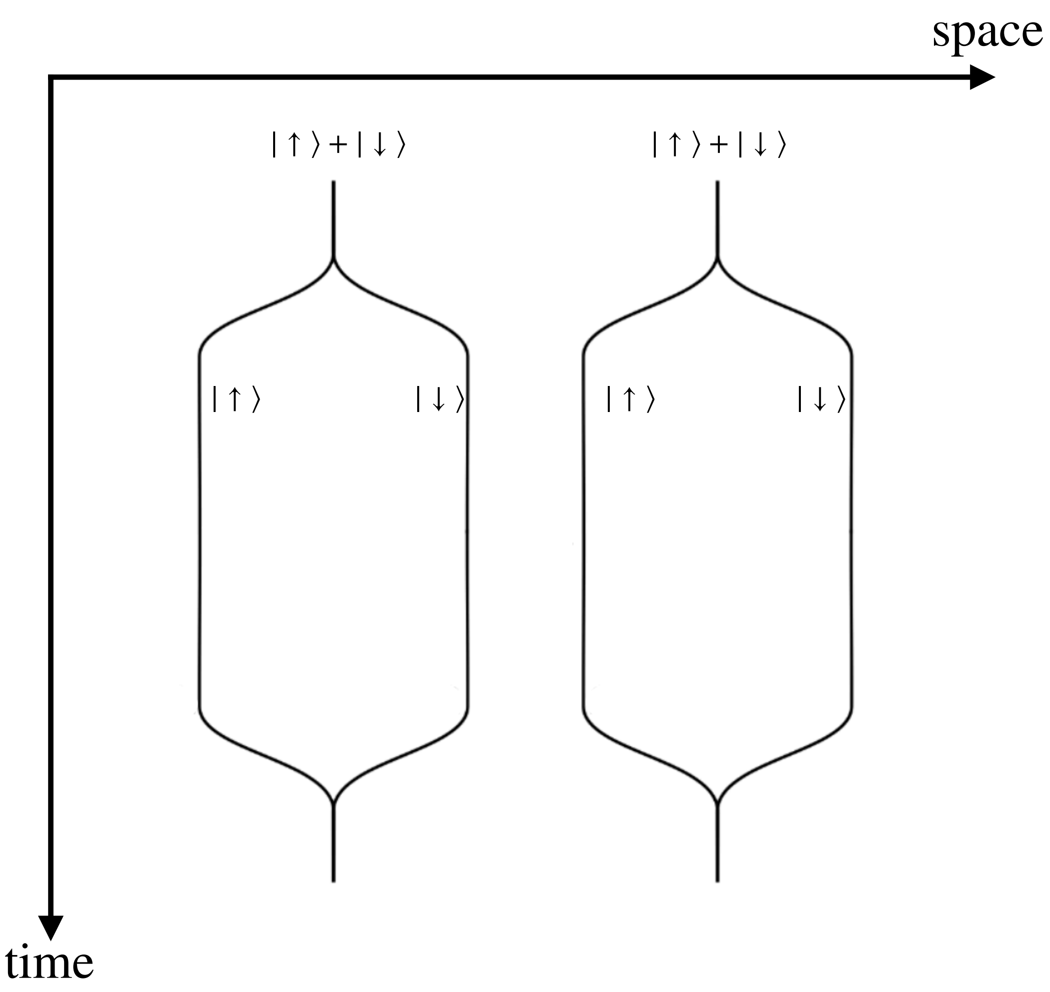

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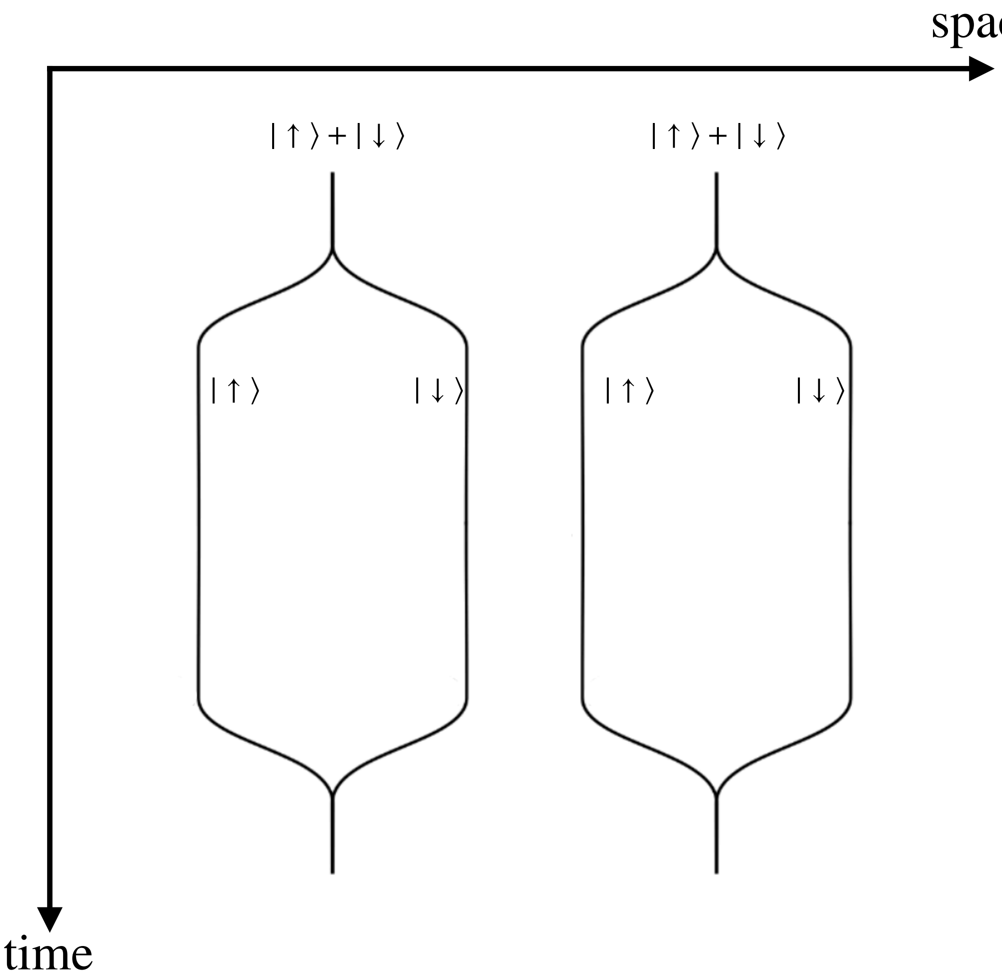

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$$|\uparrow\uparrow\rangle|g_{LL}\rangle + |\uparrow\downarrow\rangle|g_{LR}\rangle + |\downarrow\uparrow\rangle|g_{RL}\rangle + |\downarrow\downarrow\rangle|g_{RR}\rangle$$

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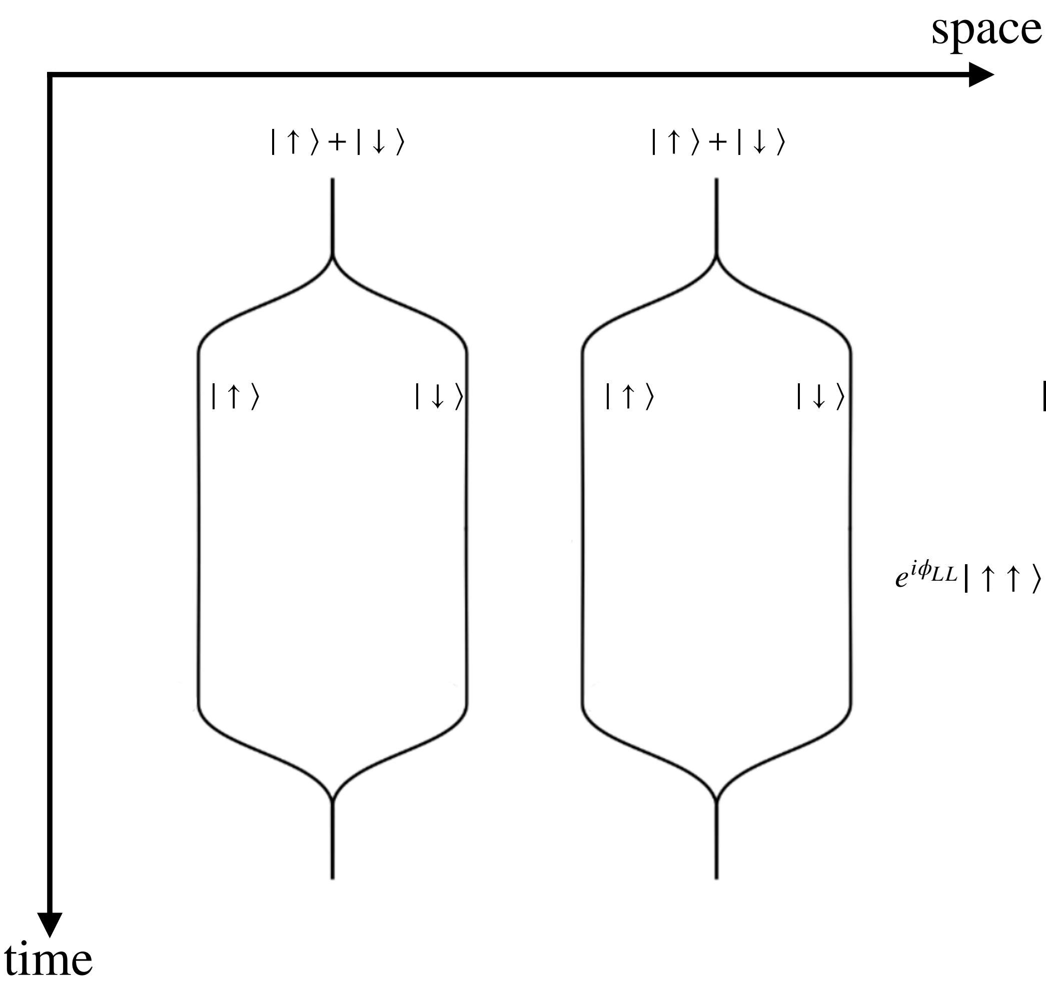

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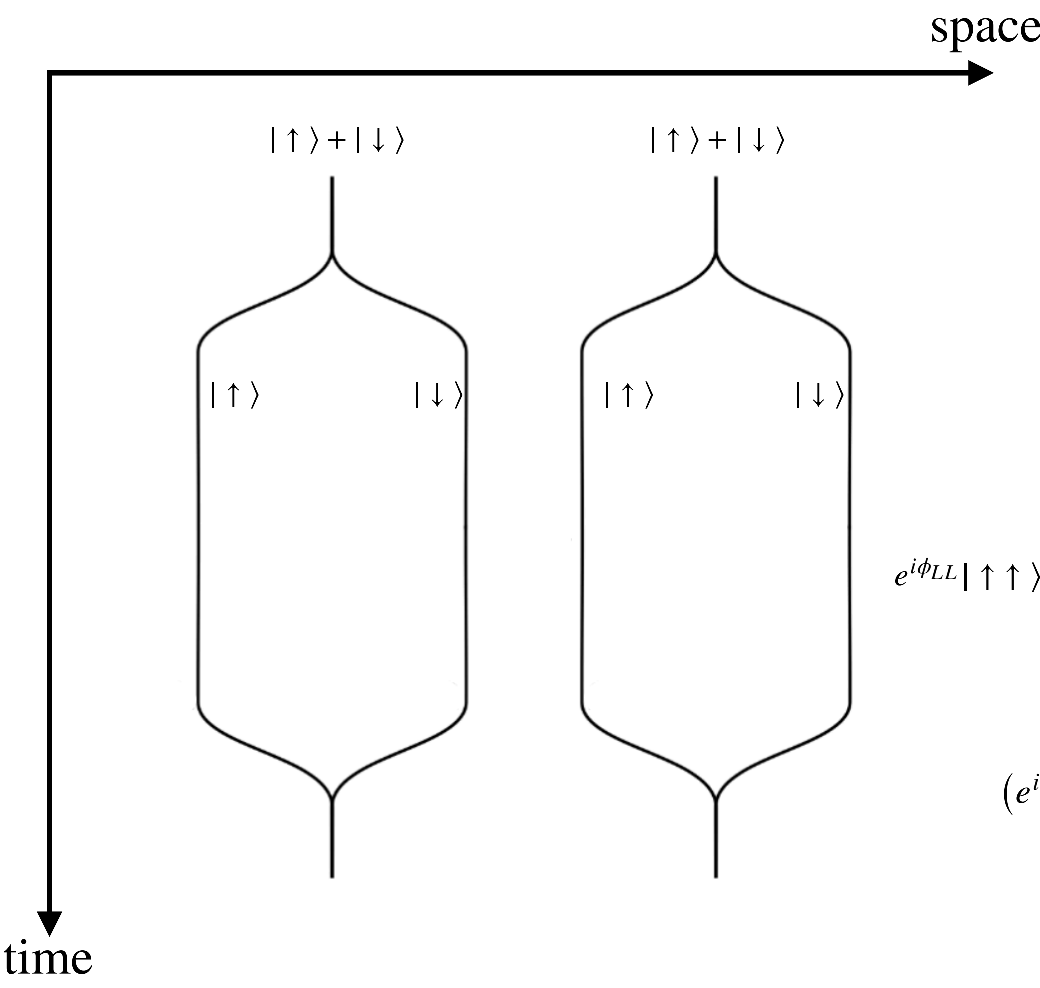

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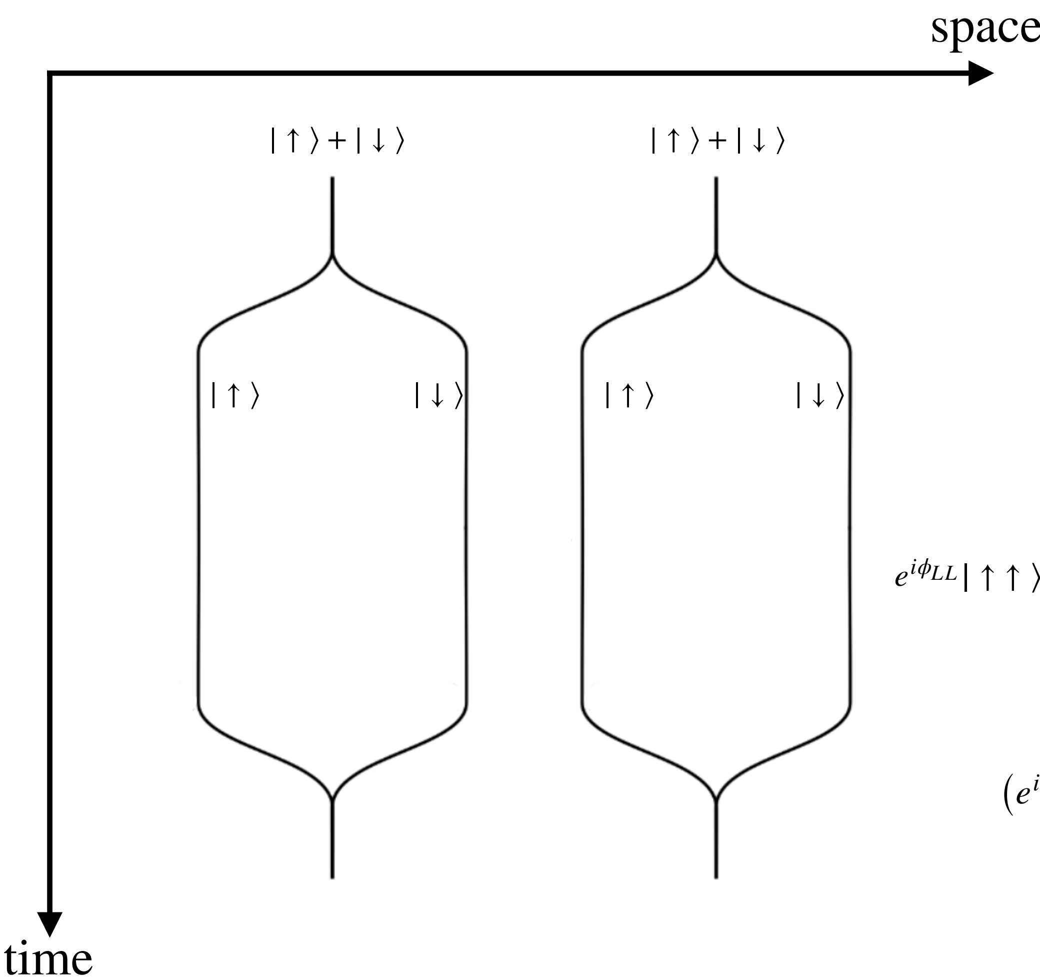
Recombination

$$\big(e^{i\phi_{LL}}|\uparrow\uparrow\rangle + e^{i\phi_{LR}}|\uparrow\downarrow\rangle + e^{i\phi_{RL}}|\downarrow\uparrow\rangle + e^{i\phi_{RR}}|\downarrow\downarrow\rangle\big)|g_{CC}\rangle$$

Measurements



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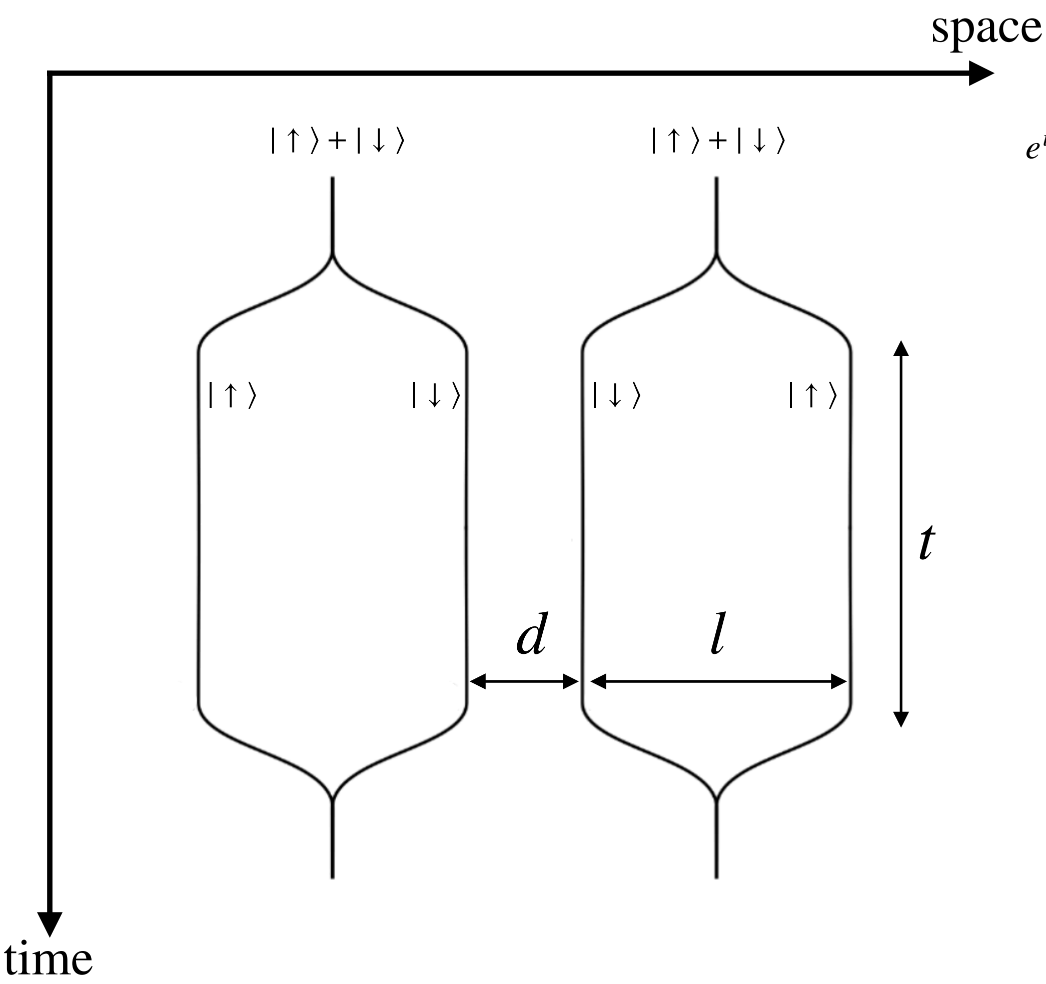
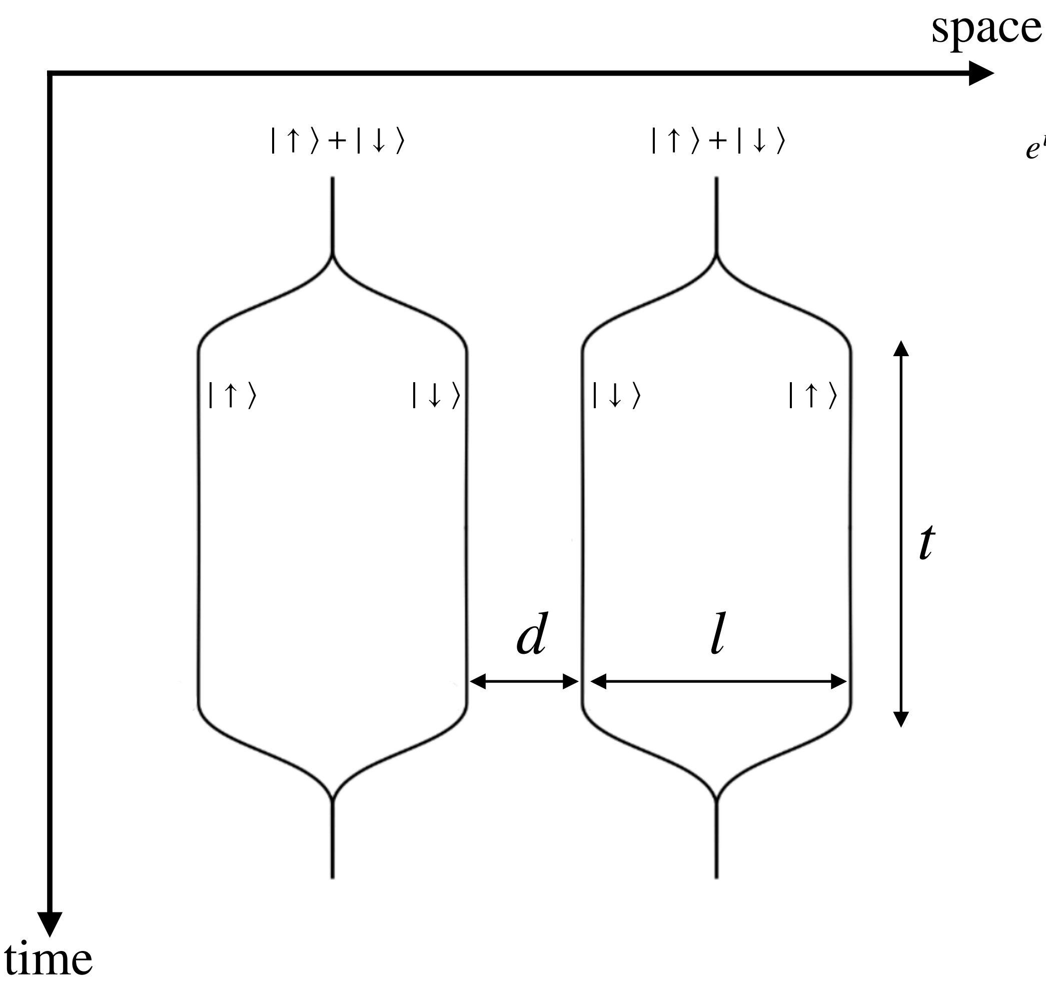


$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

$$\phi_{LR} = \frac{Gm^2}{d+2l}\frac{t}{\hbar} \qquad \phi_{RR} = \frac{Gm^2}{d+l}\frac{t}{\hbar} = \phi_{LL}$$

$$\phi_{RL} = \frac{Gm^2}{d}\frac{t}{\hbar}$$

GME



$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

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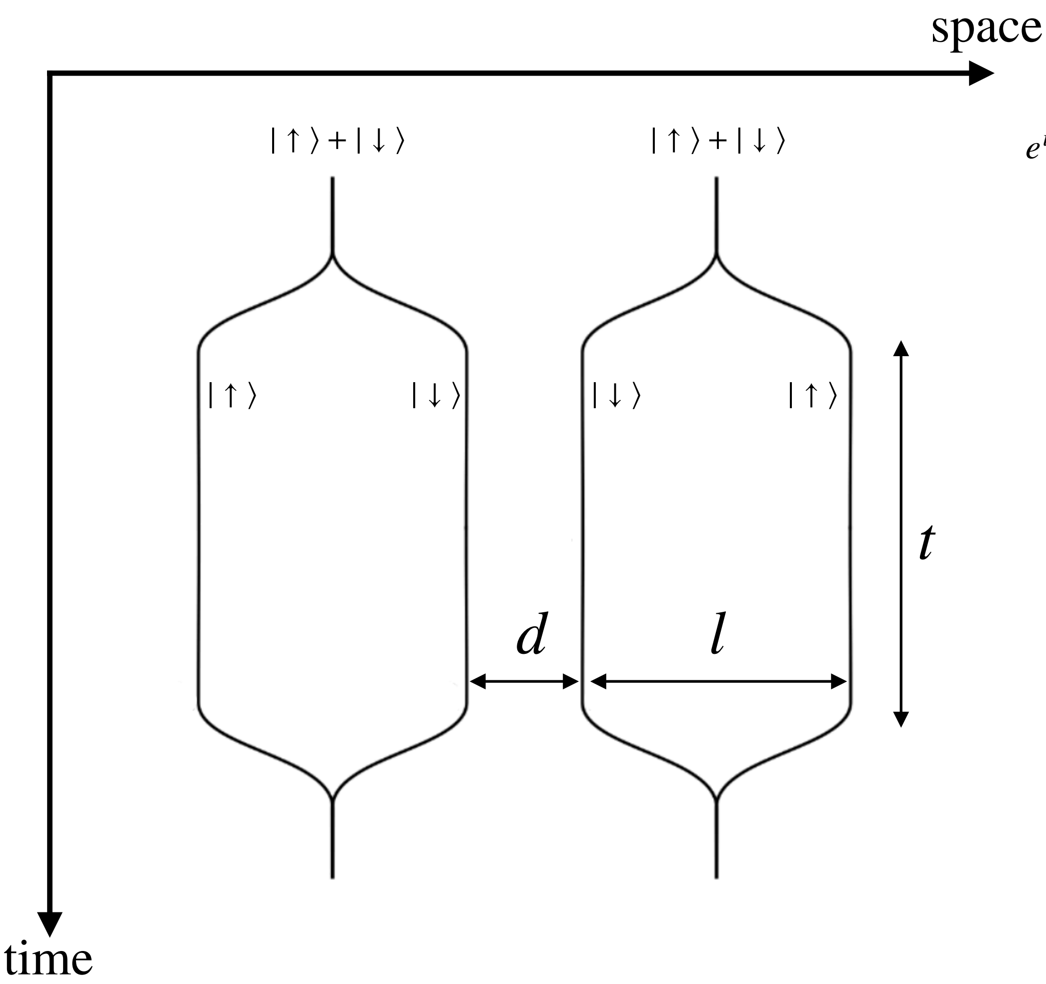
$$\phi_{RL} = \frac{Gm^2}{d}\frac{t}{\hbar}$$

$$m \approx 10^{-14}\mathrm{kg} \approx 10^{-6} m_{\mathrm{P}}$$

$$t \approx 1\mathrm{s} \qquad d \approx 200\mu\mathrm{m} \qquad l \approx 250\mu\mathrm{m}$$

$$\implies \Delta\phi = \phi_{RL} + \phi_{LR} - 2\phi_{LL} \approx 1$$

GME



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A prediction of linearised quantum gravity.

Not explainable in terms of semi-classical gravity $\qquad G_{\mu\nu} \propto \langle \hat{T}_{\mu\nu} \rangle$

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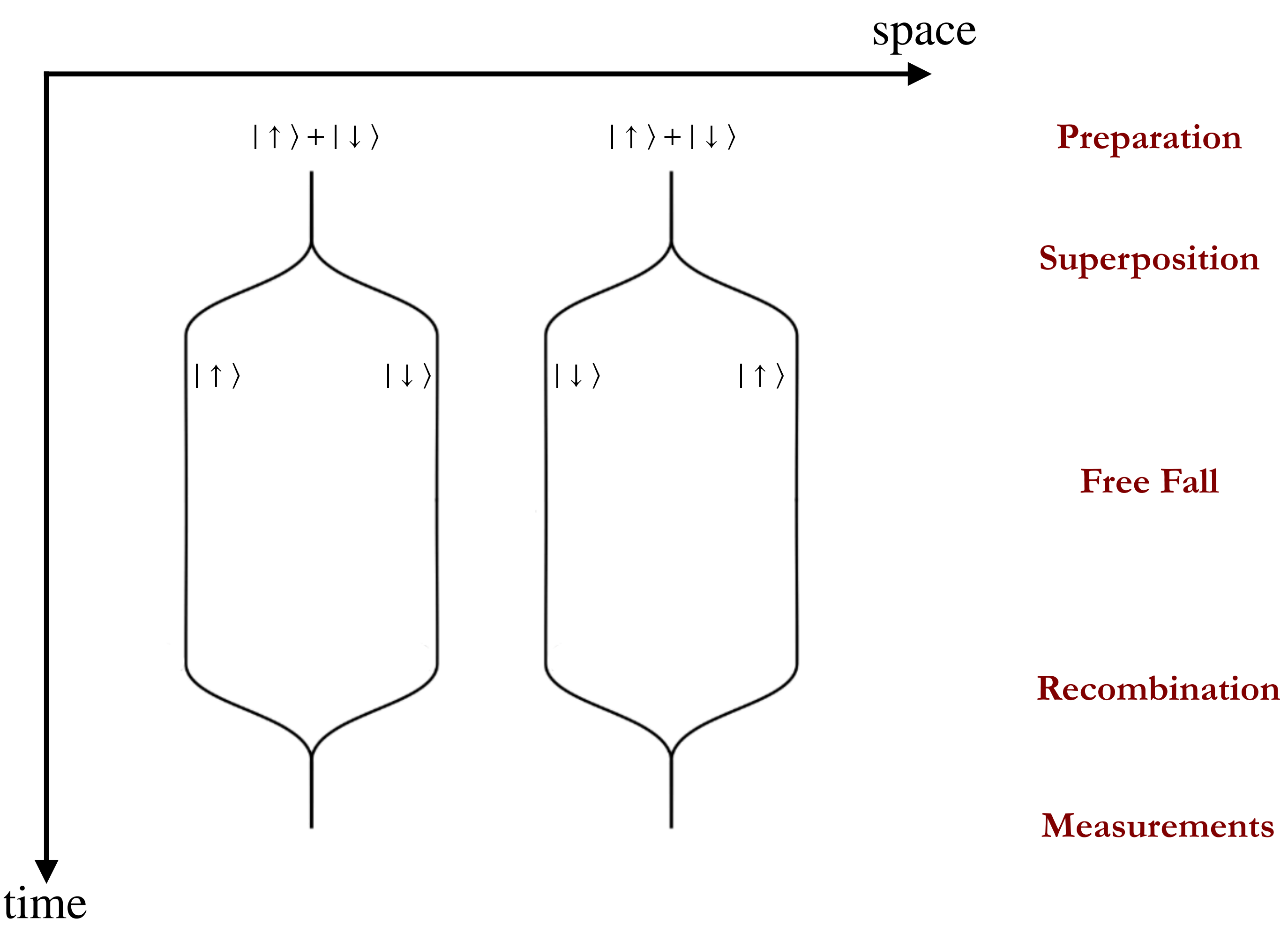
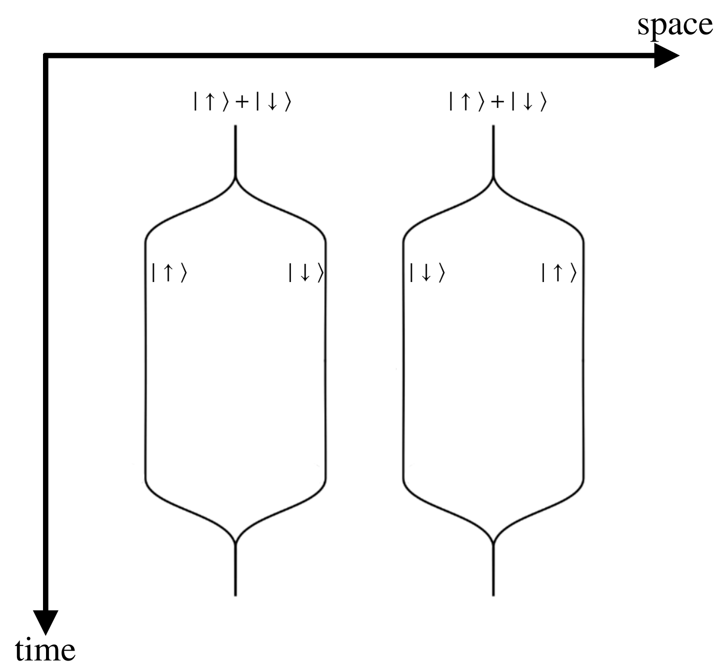
Simulating GME



$$\mathbb{C}^2 \otimes \mathbb{C}^4 \otimes \mathbb{C}^2 = \mathscr{H}_{\text{spin}_A} \otimes \mathscr{H}_{\text{geometry}} \otimes \mathscr{H}_{\text{spin}_B}$$

Quantum Circuit



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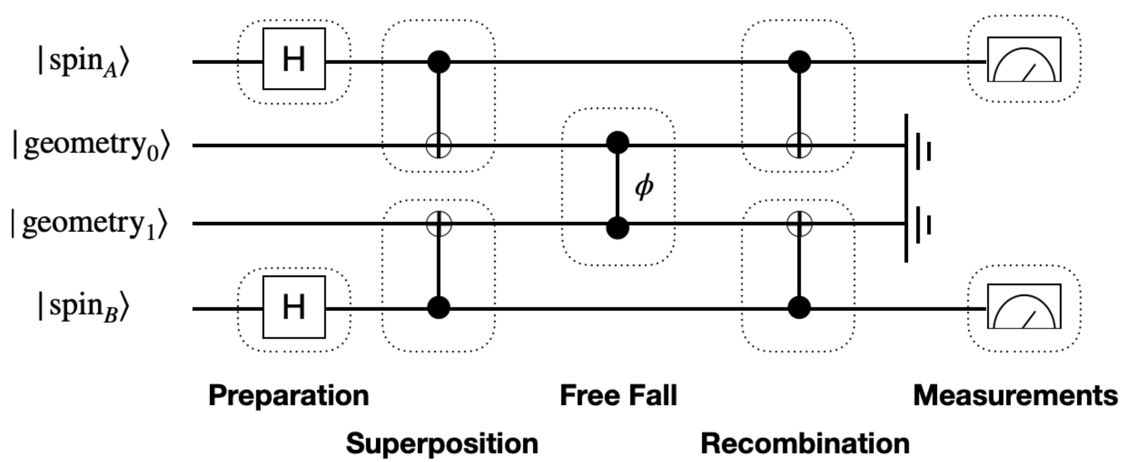
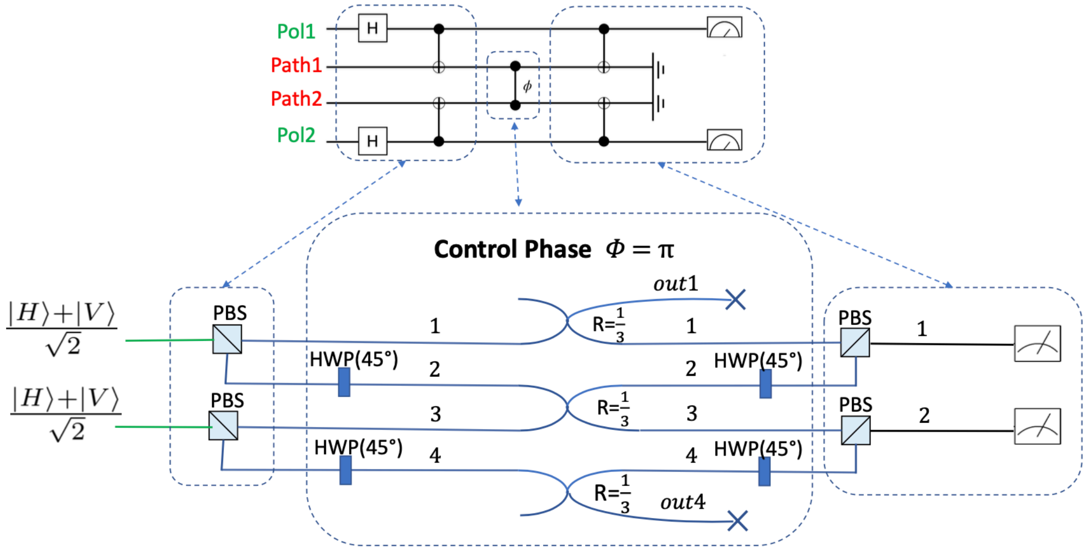
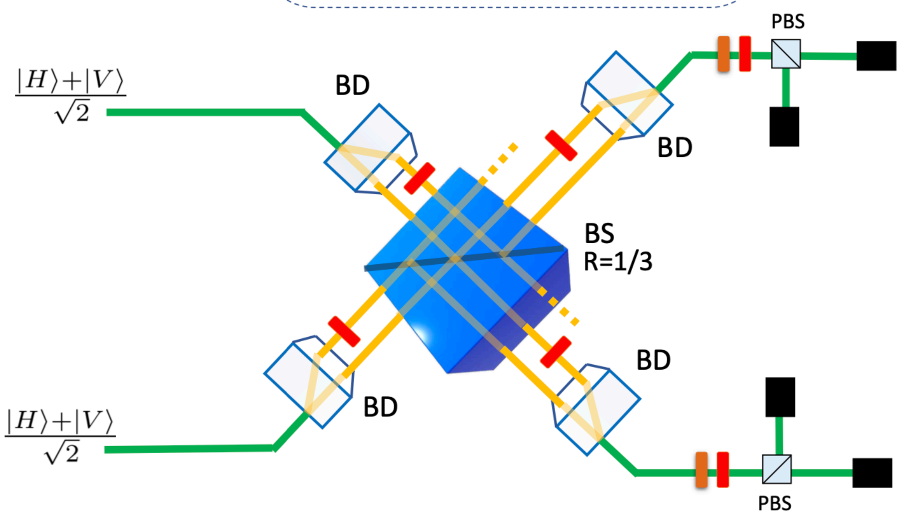


Optics Simulation





Two-photon scheme:

spins $\rightarrow$ polarisation

geometry $\rightarrow$ path

Entanglement witness

separable $\implies$ $W \geq 0$

$$W^{\exp} = -0.514(2)$$

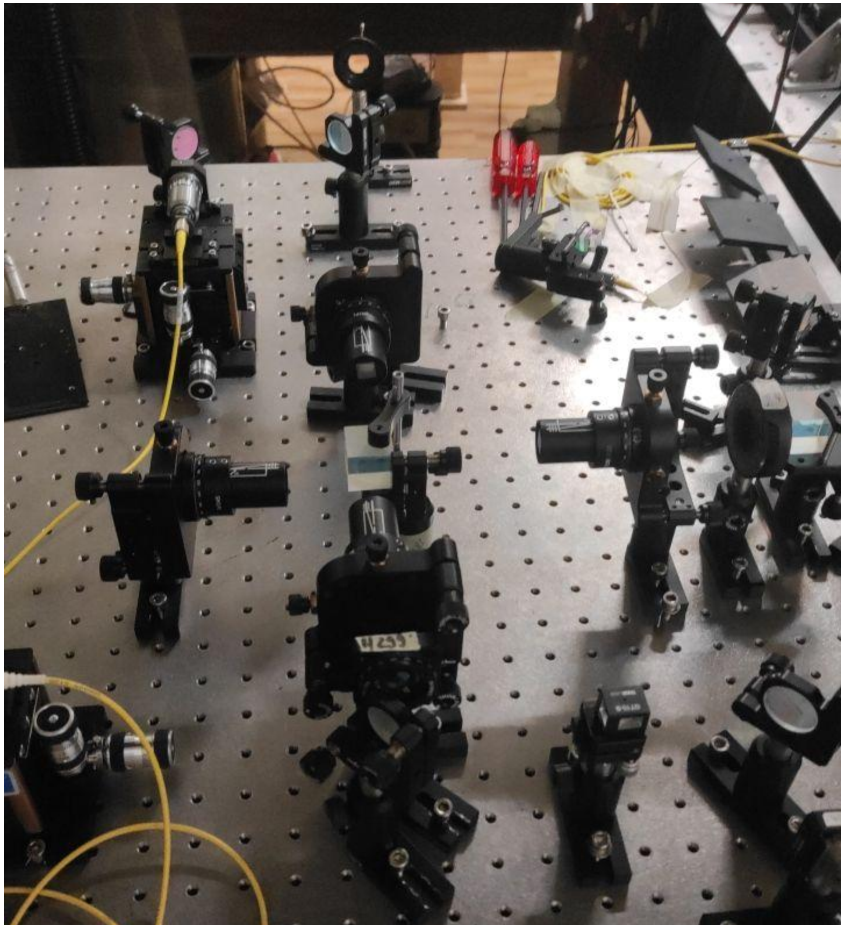
CHSH inequality violation

classical bound $S \leq 2$

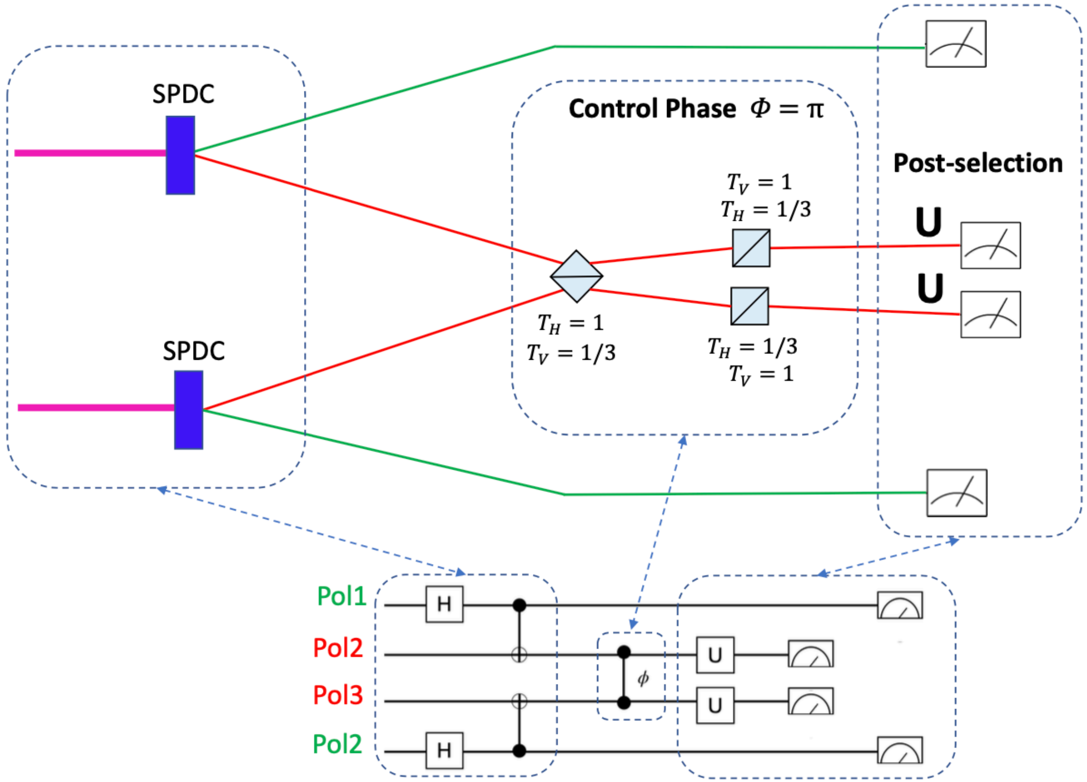
$$S^{\exp} = 2.401(15)$$

Optics Simulation

Optics Simulation



Four-photon scheme: Each qubit mapped to photon path



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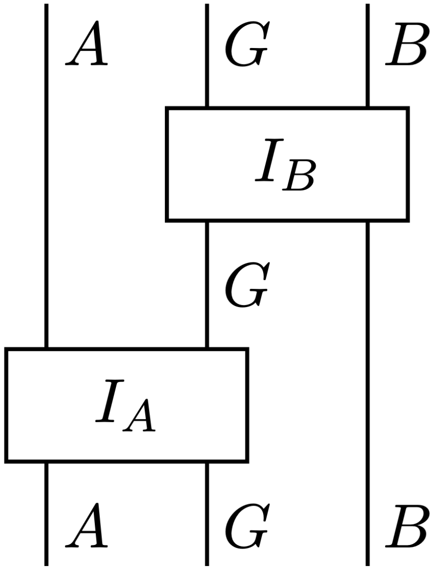
LOCC

Local Operations and Classical Communication cannot create entanglement.

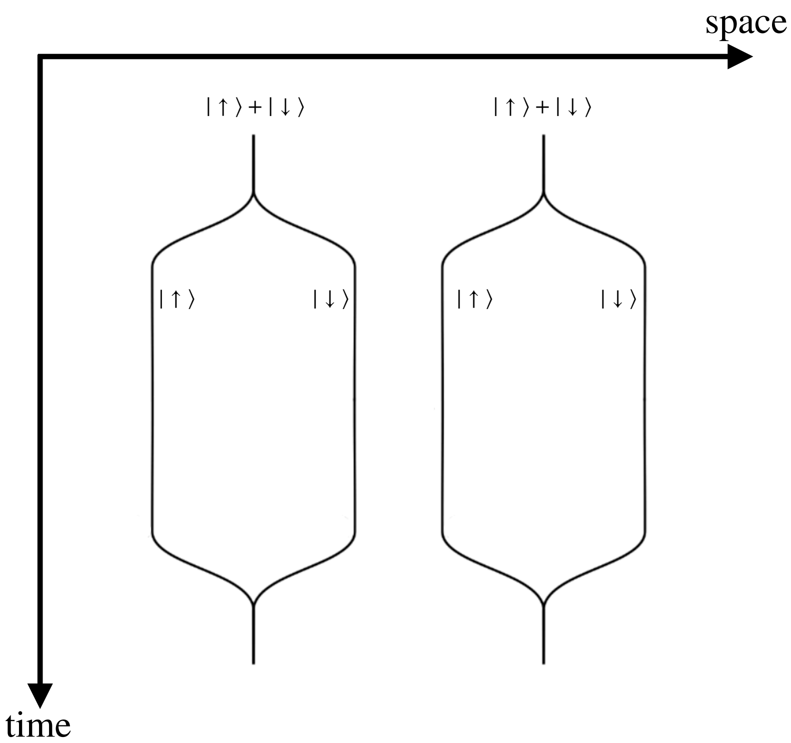


"If A and B get entangled by interacting only with G, then G cannot be classical."

Formalised in QI and GPTs.

The experiment can rule out a class of theories.

Instantaneous interaction?



Extant derivations of the effect made use of the static approximation.

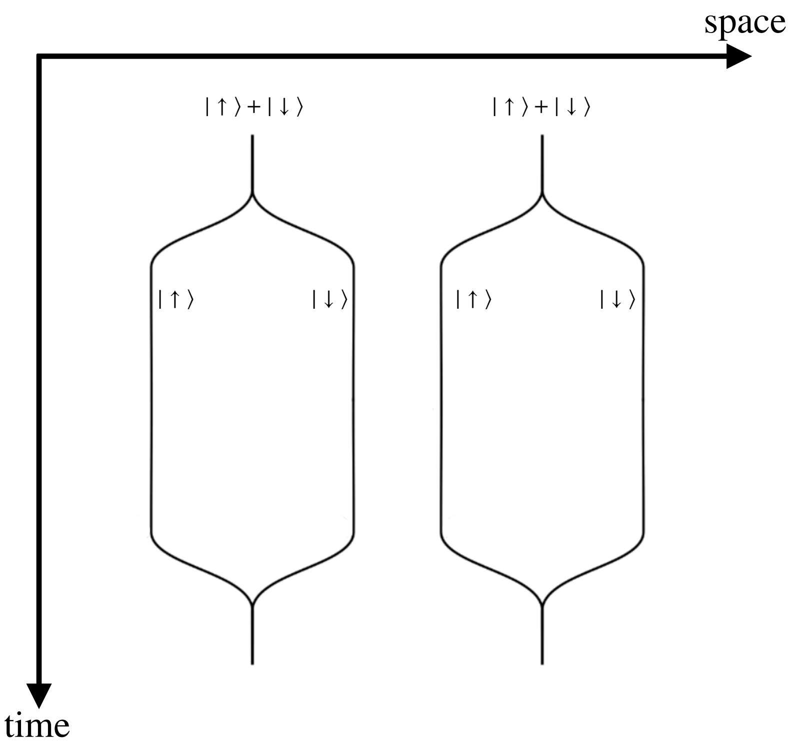
In that case, the effect can be explained by a direct interparticle interaction:

$$\hat{H}_{\text{int}} = -\frac{G m_A m_B}{|\hat{x}_A - \hat{x}_B|}$$

We make use of the path-integral formulation of QM to compute the phases developed during the experiment.

Path Integral

$$Z \propto \int \mathscr{D}x_1 \mathscr{D}x_2 \mathscr{D}F \; e^{iS\left[x_1, x_2, F[x_1, x_2]\right]/\hbar}$$



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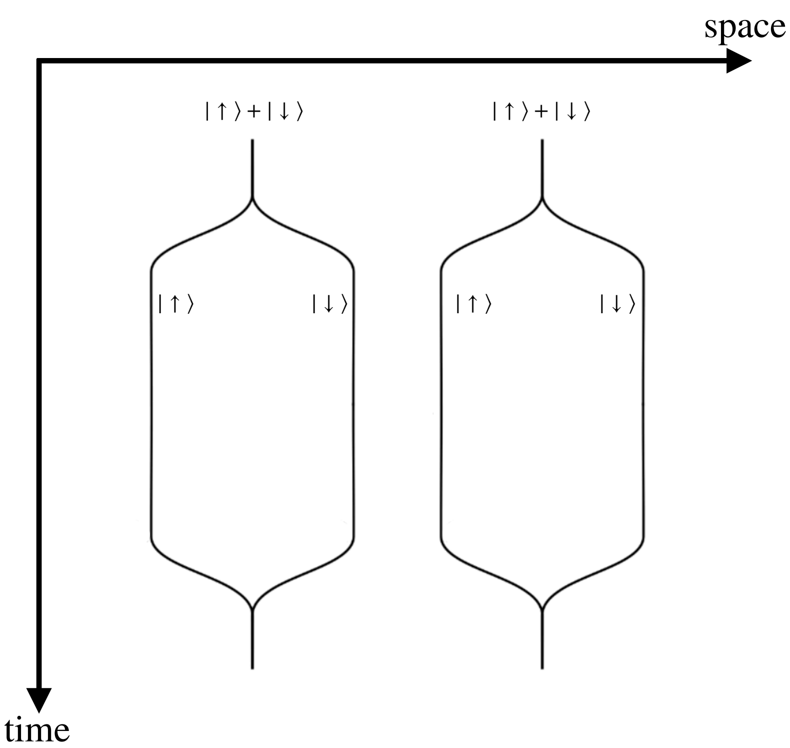

Assume the paths of the particles is imposed by the interaction with an external field.

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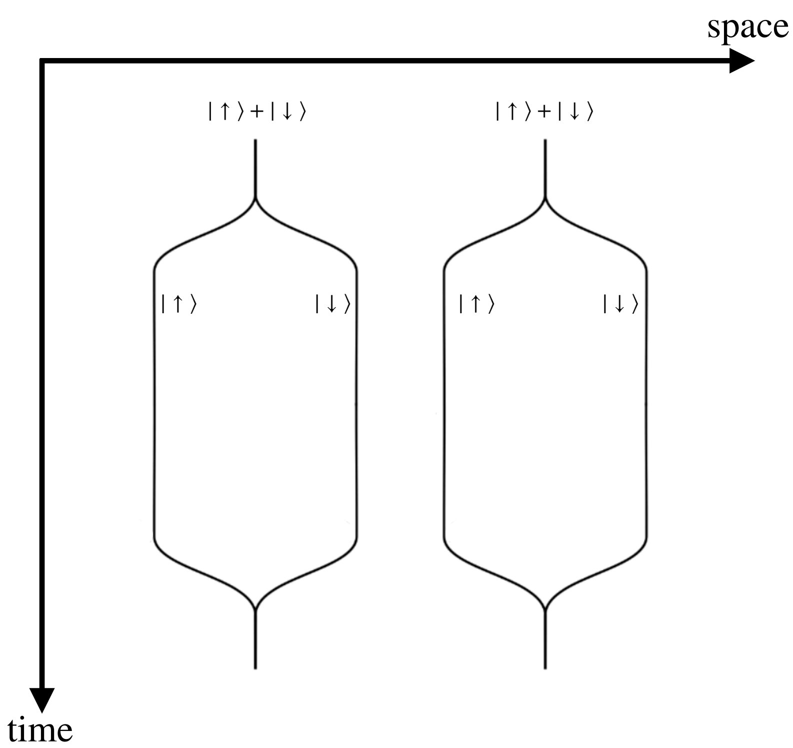

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Stationary phase approximation.

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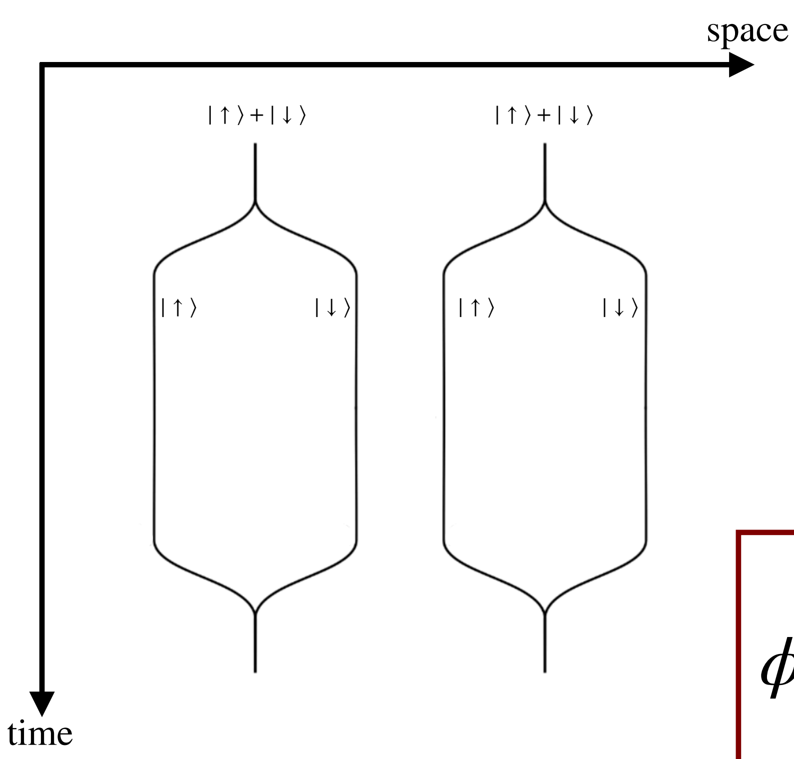

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$$\phi(s_1, s_2) = \frac{iS^{\mathrm{os}}\left[x_1^{s_1}, x_2^{s_2}, F[x_1^{s_1}, x_2^{s_2}]\right]}{\hbar}$$

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- Phases are actions, have the same symmetries

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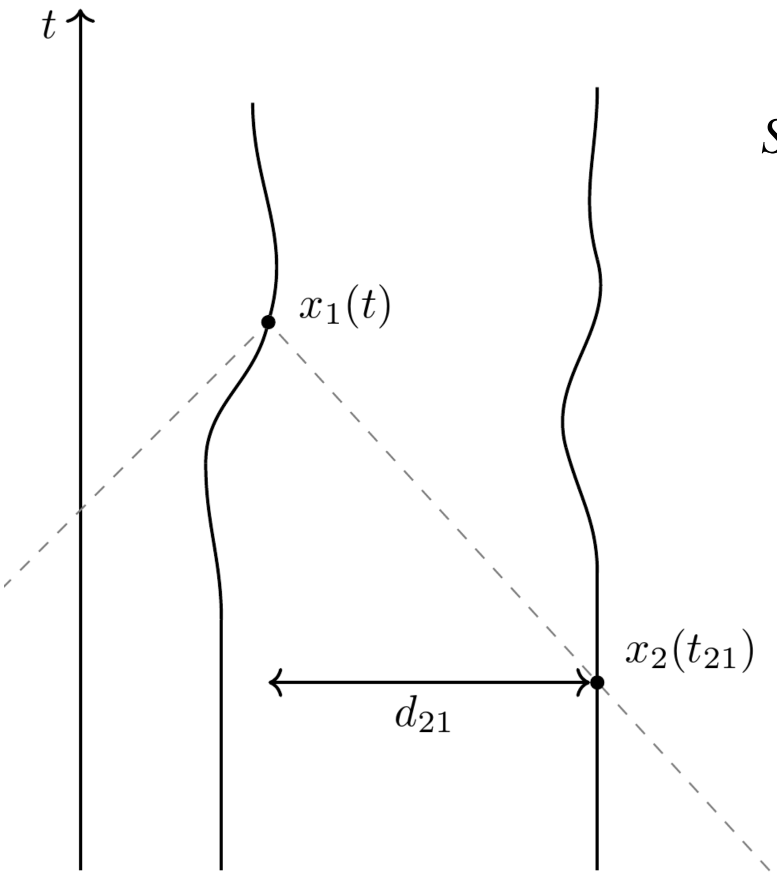
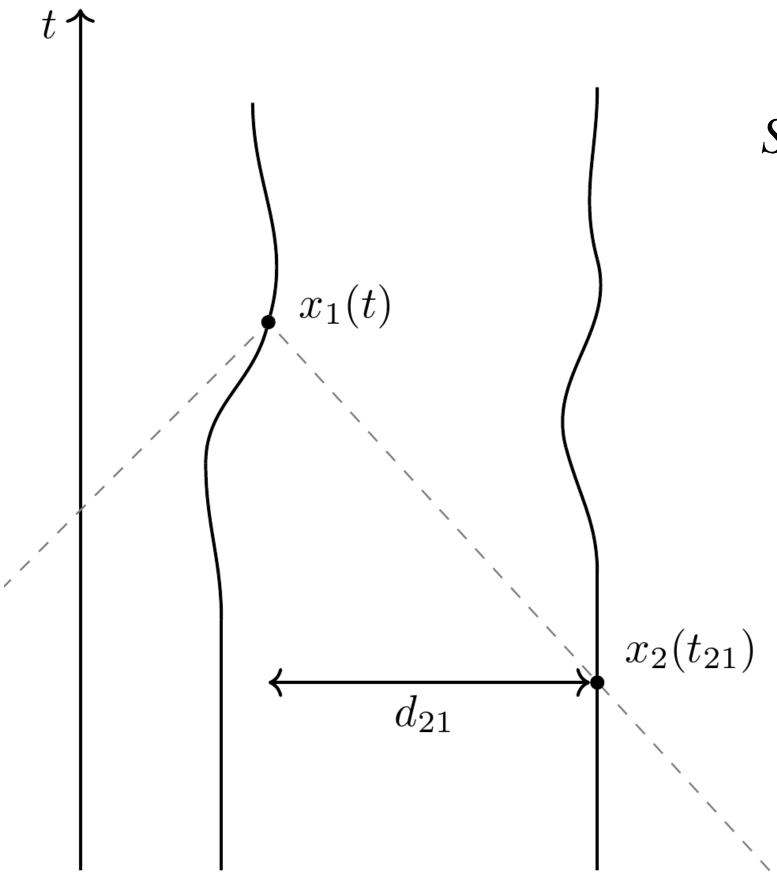
- Phases are actions, have the same symmetries
- Gauge-invariant + Lorentz covariant (manifestly local)
- Can be computed for arbitrary particle trajectories.



Exact formula

$$S_h = \frac{G}{c^4}\int dt \left(\frac{m_1 m_2 V_{1\mu\nu}(t)\bar{V}_2^{\mu\nu}(t_{21})}{|\,d_{21}(t)\,| - d_{21}(t)\cdot v_2(t_{21})/c} + 1 \leftrightarrow 2 \right)$$

Gravitational phases



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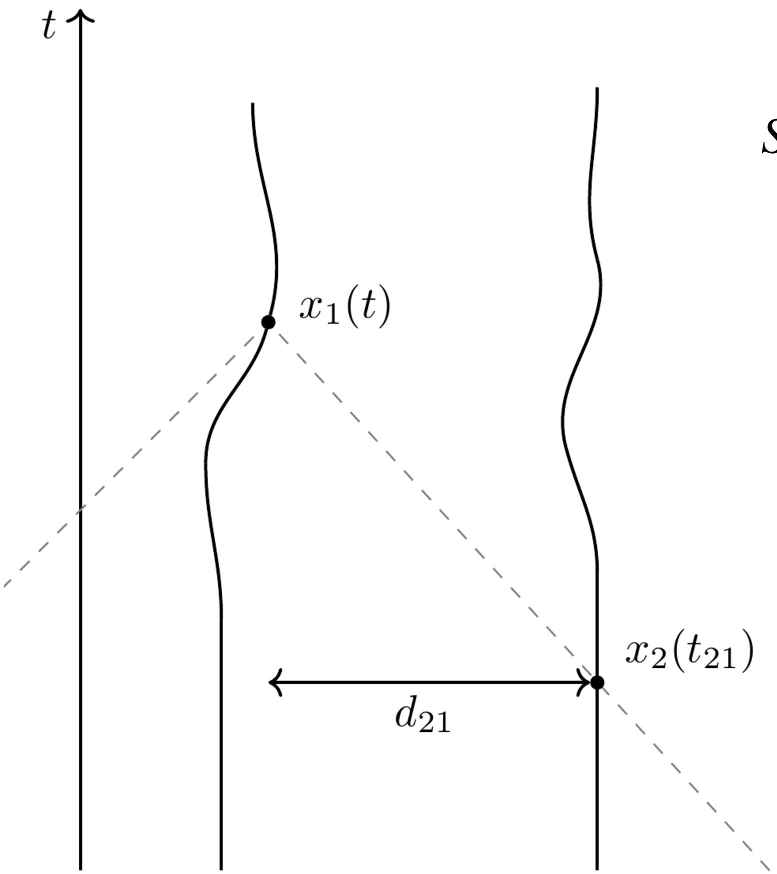
Small velocities

$$S_h = \frac{G}{2}\int dt \left(\frac{m_1 m_2}{|d_{21}(t)|} + \frac{m_1 m_2}{|d_{12}(t)|} \right)$$

Gravitational phases



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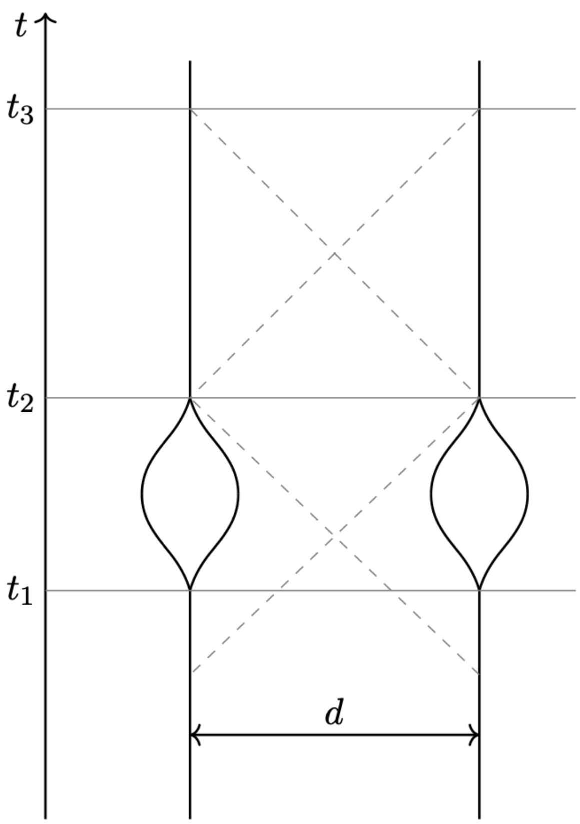
Newtonian

$$S_F = \int dt \;\frac{G m_1 m_2}{|\,d(t)\,|}$$

Observable effects



$$\phi(s_1, s_2) = \frac{G}{2\hbar}\int dt\left(\frac{m_1 m_2}{|d_{21}(t)|} + \frac{m_1 m_2}{|d_{12}(t)|}\right)$$

If superposition happens in spacelike separated regions $\implies$ no entanglement!

Signal of the superposition needs time to propagate casually between masses.

Signal of the superposition needs time to propagate casually between masses.

Smaller deviations due to retarded interaction could be measured in electron interferometry—for the EM case!

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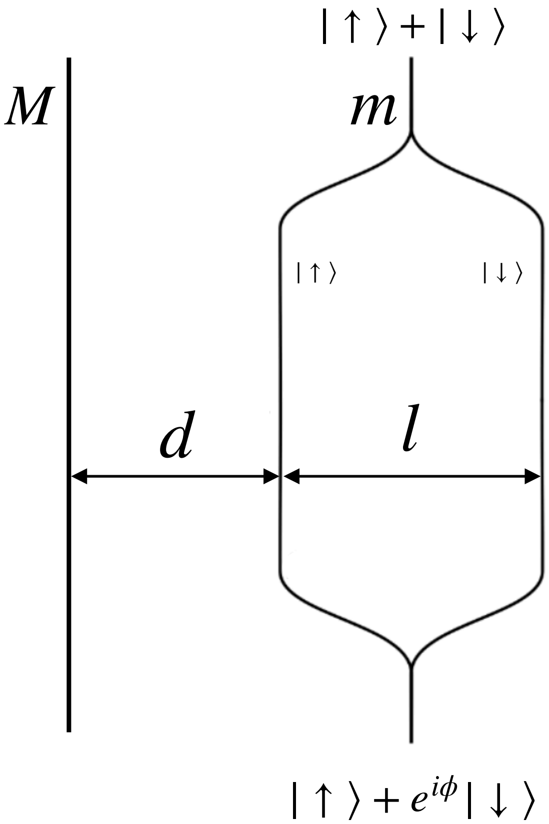
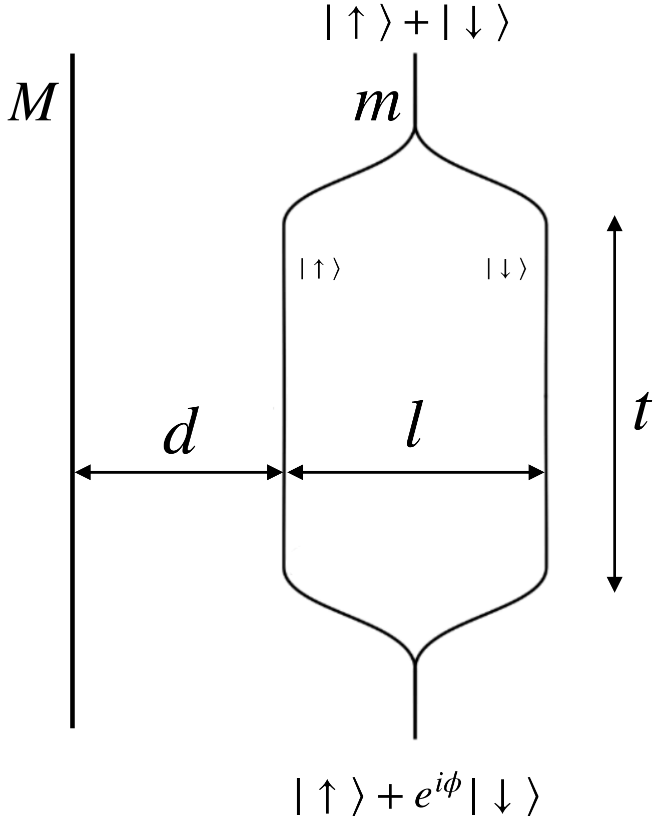


$|\uparrow\rangle + |\downarrow\rangle$
M
m
$|\uparrow\rangle$
$|\downarrow\rangle$
d
l
t
$|\uparrow\rangle + e^{i\phi}|\downarrow\rangle$

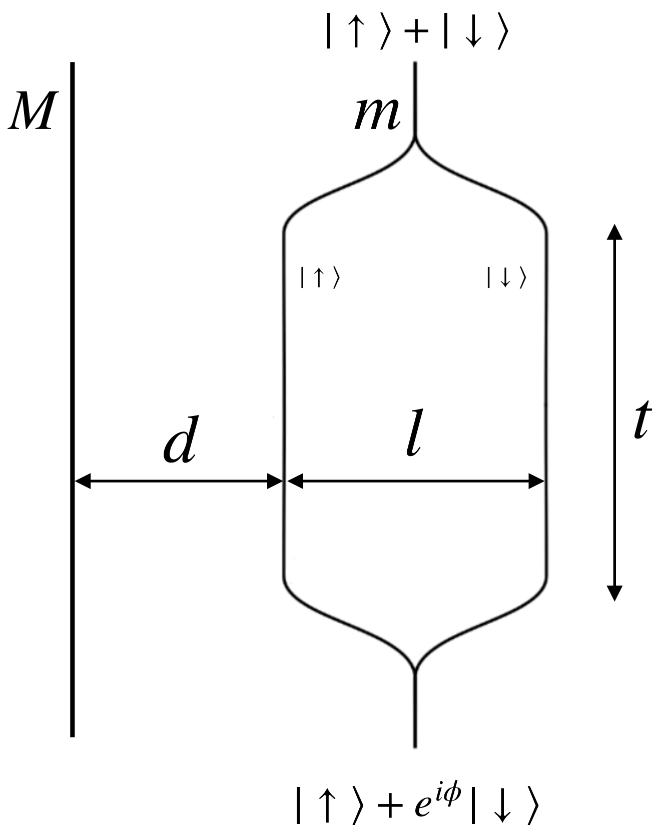
Setup



Time dilation

$$\tau(r) = \sqrt{|g_{00}(r)|}\,t = \sqrt{1 - \frac{2GM}{r}}\,t \approx \left(1 - \frac{GM}{r}\right) t$$

Setup



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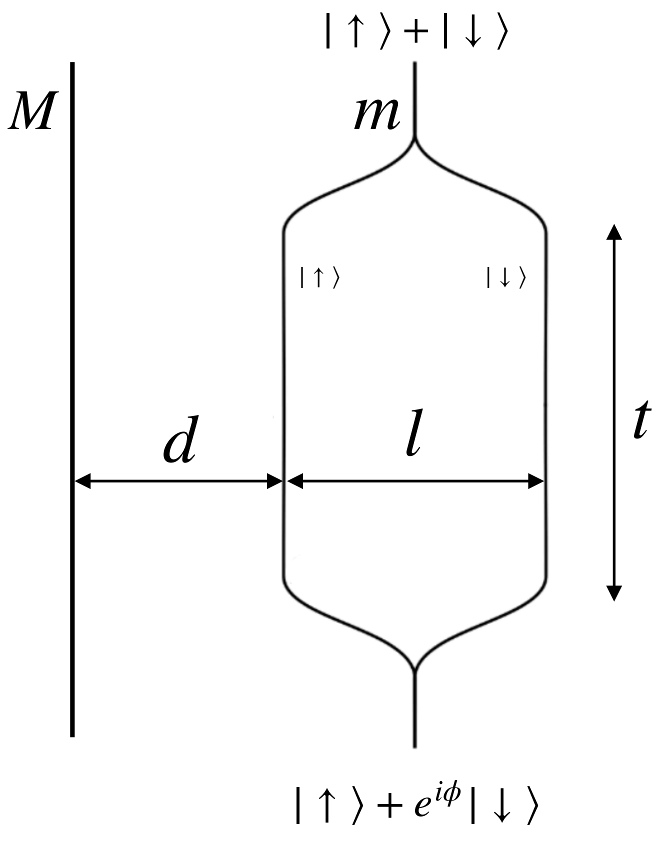
Phases due to proper time differences

$$\phi = \frac{mc^2}{\hbar}\delta\tau = \frac{m}{m_P}\frac{\delta\tau}{t_P}$$

Setup



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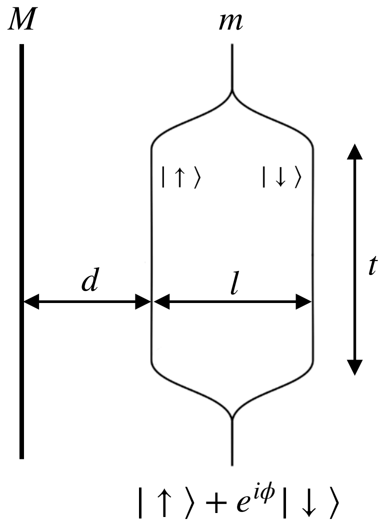
$$\delta\tau = \frac{GM}{c^2}\frac{l}{d(d+l)}t$$

Hypothesis



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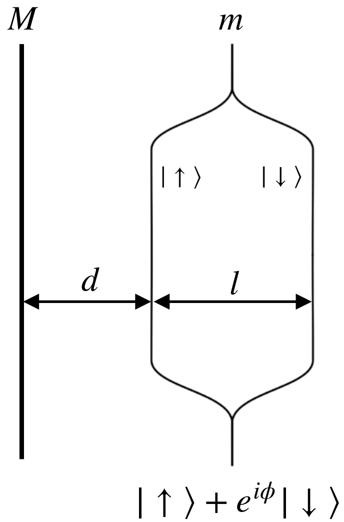
Hypothesis



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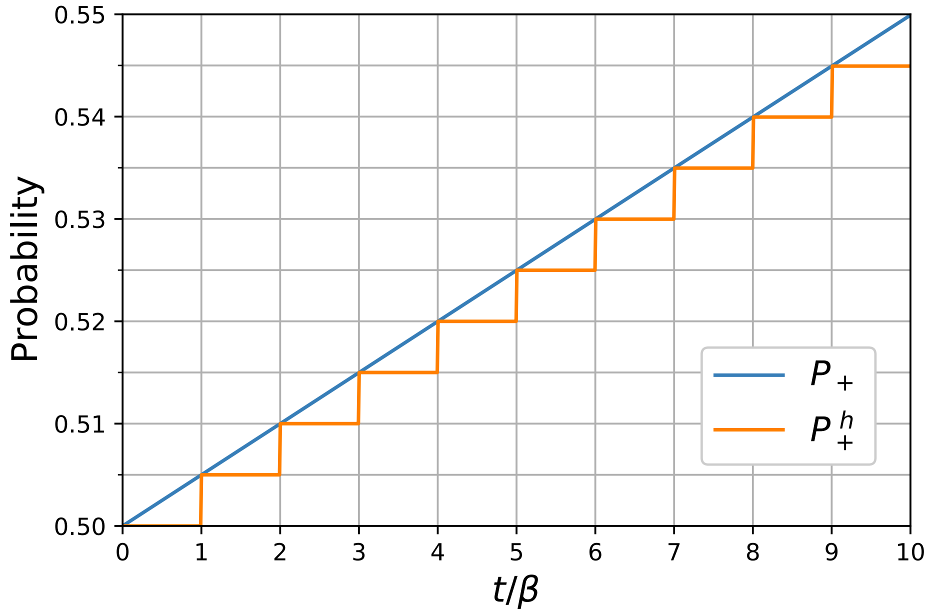
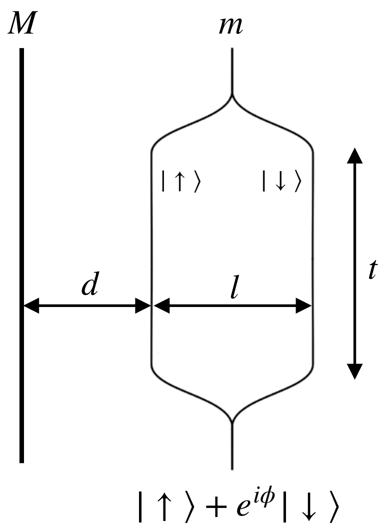


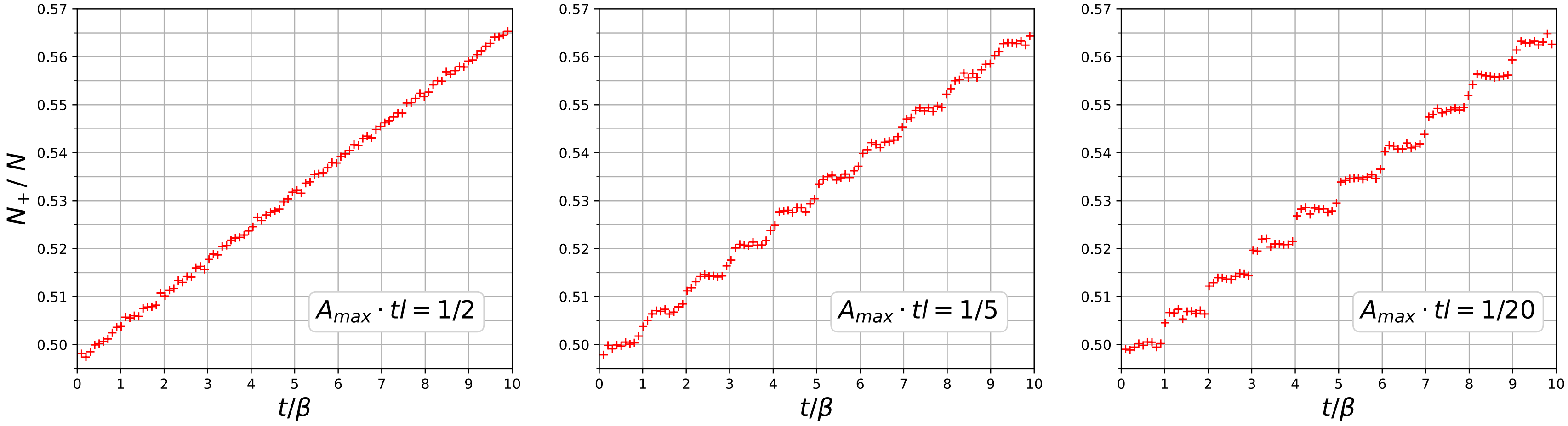
$$\delta\tau = \left\lfloor \frac{t}{\beta} \right\rfloor t_P$$

Results



Parameter	Value	Uncertainty
m	3×10^{-10} kg	10^{-12} kg
M	3×10^{-9} kg	10^{-11} kg
t	10^{-1} s	10^{-4} s
l	10^{-7} m	10^{-9} m
d	$[17, 54]$ cm	10^{-2} cm
A	$\leq 4 \times 10^{-10}$ kg m^{-2}	

$$T \approx 4 \text{ K} \qquad P \approx 10^{-18}\text{Pa}$$



Plan

- Part I: Quantum gravity (and beyond) in the lab
- Part II: Conceptual investigations

Plan

- Part II: Conceptual investigations
  - The arrow of time in operational formulations of QT
  - The relational interpretation of QM.

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Tensions

Operational formulations of QM are strongly time-oriented.

Quantum states are associated with the past of a system.

Probabilities are about future results.

In tension with time-reversal symmetry of the rest of fundamental physics.

An issue for the reconstructions of quantum mechanics.

Resolution

Does quantum uncertainty imply time orientation?

Resolution

Does quantum uncertainty imply time orientation?

No.

Resolution

Does quantum uncertainty imply time orientation?

No.

Then why are certain formulations of quantum theory time-oriented?

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Then why are certain formulations of quantum theory time-oriented?

They are designed to describe the interaction of macroscopic thermodynamical systems with quantum systems.

Resolution

Does quantum uncertainty imply time orientation?

No.

Then why are certain formulations of quantum theory time-oriented?

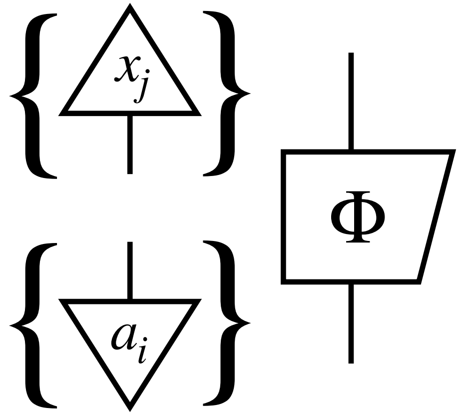
They are designed to describe the interaction of macroscopic thermodynamical systems with quantum systems.

We remember the past, but not the future.

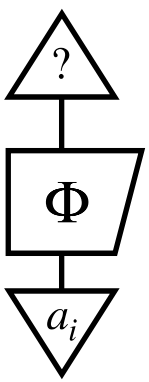
Two games

Measurement

Preparation

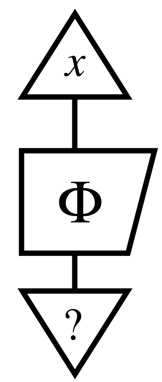


Evolution



$$P_{pre}(x \,|\, a, \Phi)$$

$$P_{post}(a \,|\, x, \Phi)$$



Prediction

Postdiction

Inference Symmetry

A process Φ is **inference symmetric** if:

$$P_{pre}(x_j \,|\, a_i, \Phi) = P_{post}(a_i \,|\, x_j, \Phi)$$

for any choice of bases.

A kind of passive time-reversal symmetry.

Unitary evolution is inference symmetric.

Quantum channels are not inference symmetric.

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$$P_{pre}(x_j | a_i, \Phi) = P_{post}(a_i | x_j, \Phi)$$

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A kind of passive time-reversal symmetry.

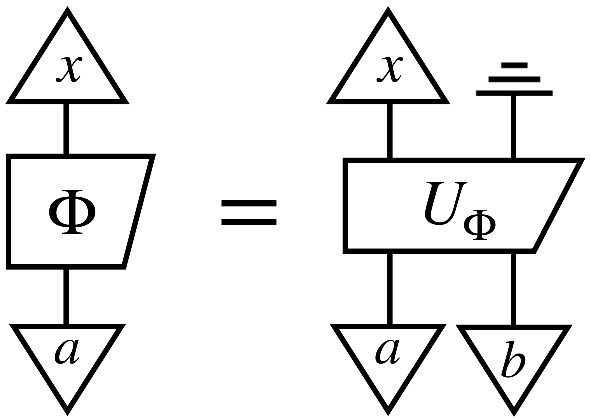
Unitary evolution is inference symmetric.

Quantum channels are not inference symmetric.

The inference asymmetry of quantum channels is understood as an asymmetry in the inference data.

Purification

$$P_{pre}(x\,|\,a,\Phi) =$$



$$= P_{pre}(x\,|\,ab, U_\Phi)$$

$$P_{post}(a\,|\,x,\Phi) = P_{post}(a\,|\,xb, U_\Phi)$$

Why the asymmetry?

Time-asymmetry due to the users of QM.

QI is about correlations established between agents.

The agent is not explicitly modelled by the theory, but *represented* in the mathematical objects in the theory.

Plan

- Part II: Conceptual investigations
  - The arrow of time in operational formulations of QT
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Map of Madness

	ψ-Ontic	ψ-Epistemic
Type-I (intrinsic realism)	Bohmian mechanics[10,11] Many worlds[12,13] Modal[14,15] Bell's "beables"[16] Collapse theories*[17,18]	Einstein[19] Ballentine[20] Consistent histories[21,22] Spekkens[23]

	About knowledge	About belief
Type-II (participatory realism)	Copenhagen[24,25] Wheeler[26,27] Relational[28,29] Zeilinger[3,30] No "interpretation"[31] Brukner[32]	QBism[33–35]

+ objective collapse models: Penrose-Diósi, GRW...

arXiv:1509.04711 (quant-ph)

[Submitted on 15 Sep 2015 (v1), last revised 23 Nov 2016 (this version, v2)]

Interpretations of quantum theory: A map of madness

Adán Cabello

Interpretations of quantum mechanics:

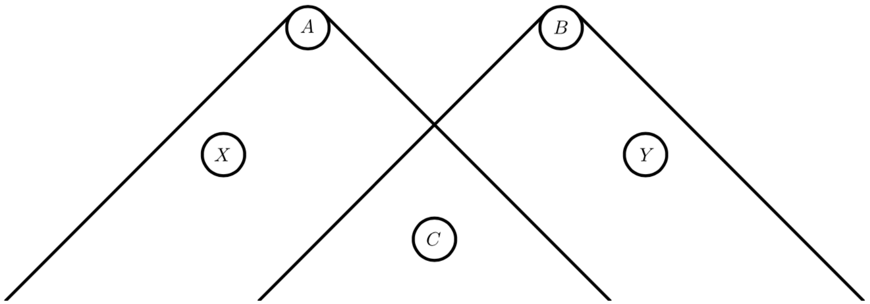
- Surprisingly different pictures of the world
- Designed to give the same predictions (except for objective collapse)
- But experimental metaphysics *can* put constraints on them.

No-Go theorems

Put constraints on various features of an interpretation.

Bell's 1967 theorem says QM is incompatible with:

- Relativistic causality
- Reichenbach's principle of decorrelating explanation
- No Superdeterminism



$$P(ab|c) = P(a|c)P(b|c)$$

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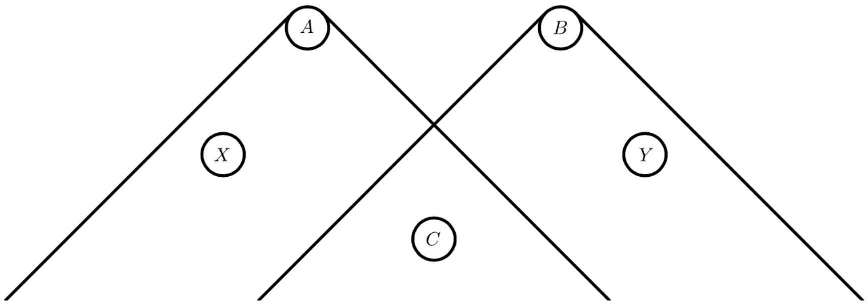


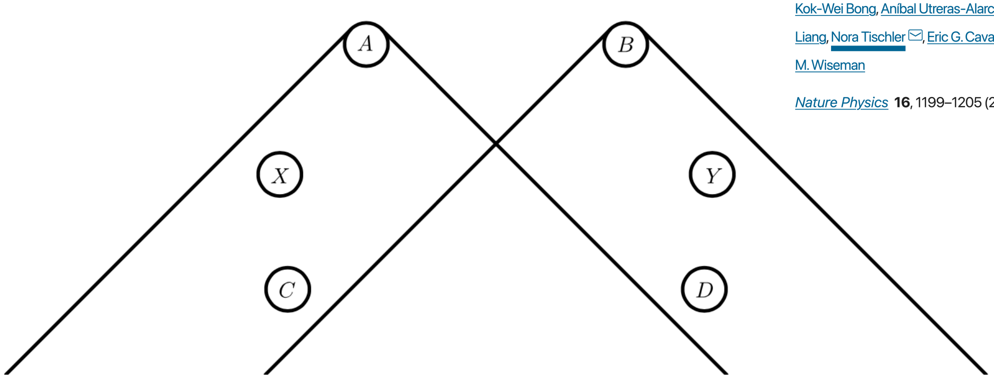
$$P(ab|c) = P(a|c)P(b|c)$$

Implicit assumption: Absoluteness of observed events

No-Go theorems

Recent theorem by Bong *et.al.* shows that QM is incompatible with

- Locality
- No Superdeterminism
- **Absoluteness of observed events**

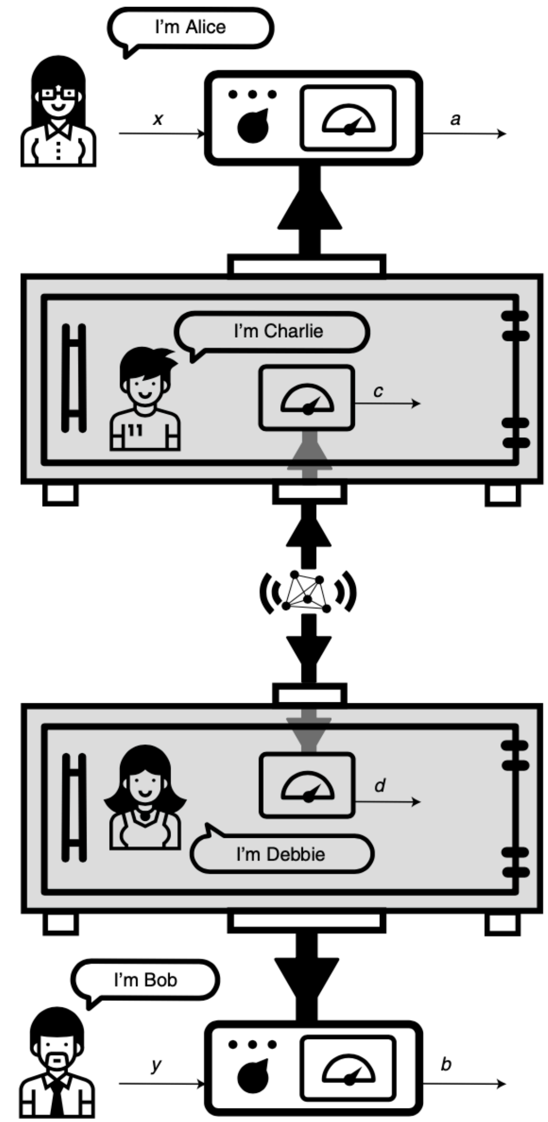


Article | Published: 17 August 2020

A strong no-go theorem on the Wigner's friend paradox

Kok-Wei Bong, Aníbal Utreras-Alarcón, Farzad Ghafari, Yeong-Cherng Liang, Nora Tischler, Eric G. Cavalcanti, Geoff J. Pryde & Howard M. Wiseman

Nature Physics **16**, 1199–1205 (2020) | Cite this article



Relational Quantum Mechanics is an interpretation of QM that embraces the relativity of facts.

In RQM, facts are relations established between two systems.

What is a fact relative to a given system might not be a fact relative to another.

"Wigner's facts are not necessarily his friend's facts"

Facts can happen relative to *any* physical system.

How does the classical world emerge from the world of relative facts?

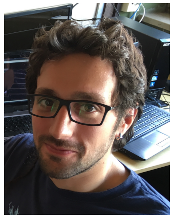
To what extent the relativity of facts is analogous with special relativity?

How can objectivity be achieved when facts are not shared?

Plan

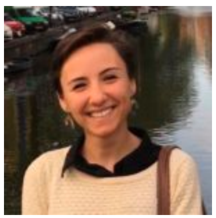
- Part I: Quantum gravity (and beyond) in the lab
  - Gravitationally Mediated Entanglement (GME)
  - Optical Simulation of a GME experiment
  - Computing the phases from first principles
  - An experiment to test the discreteness of time
- Part II: Conceptual investigations
  - The arrow of time in operational formulations of QT
  - The relational interpretation of QM.

Collaborators



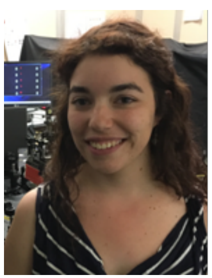
Davide Poderini

Emanuele Polino



Beatrice Polacchi

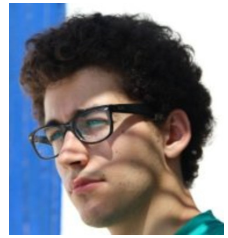
Fabio Sciarrino



Iris Agresti

Gonzalo Carvacho

Photonic Implementation of Quantum Gravity Simulators



Pierre Martin-Dussaud

[Submitted on 16 Jul 2020 (v1), last revised 31 Jan 2022 (this version, v4)]

An experiment to test the discreteness of time 2007.08431

Open Access | Published: 27 February 2021

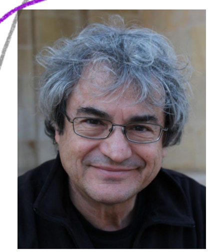
Stable Facts, Relative Facts

Foundations of Physics **51**, Article number: 30 (2021)

[Submitted on 7 Oct 2021] 2202.03368

Relational Quantum Mechanics is about Facts, not States: A reply to Pienaar and Brukner

Marios Christodoulou



Carlo Rovelli

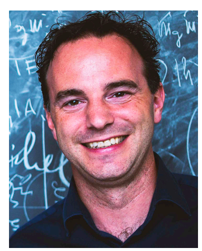
Pietro Donà

The arrow of time in operational formulations of quantum theory

2021-08-09, volume 5, page 520

arXiv:2010.05734v2

https://doi.org/10.22331/q-2021-08-09-520



Markus Aspelmeyer

Časlav Brukner

Richard Howl

[Submitted on 7 Feb 2022] 2202.03368

Locally mediated entanglement through gravity from first principles

Thank you!