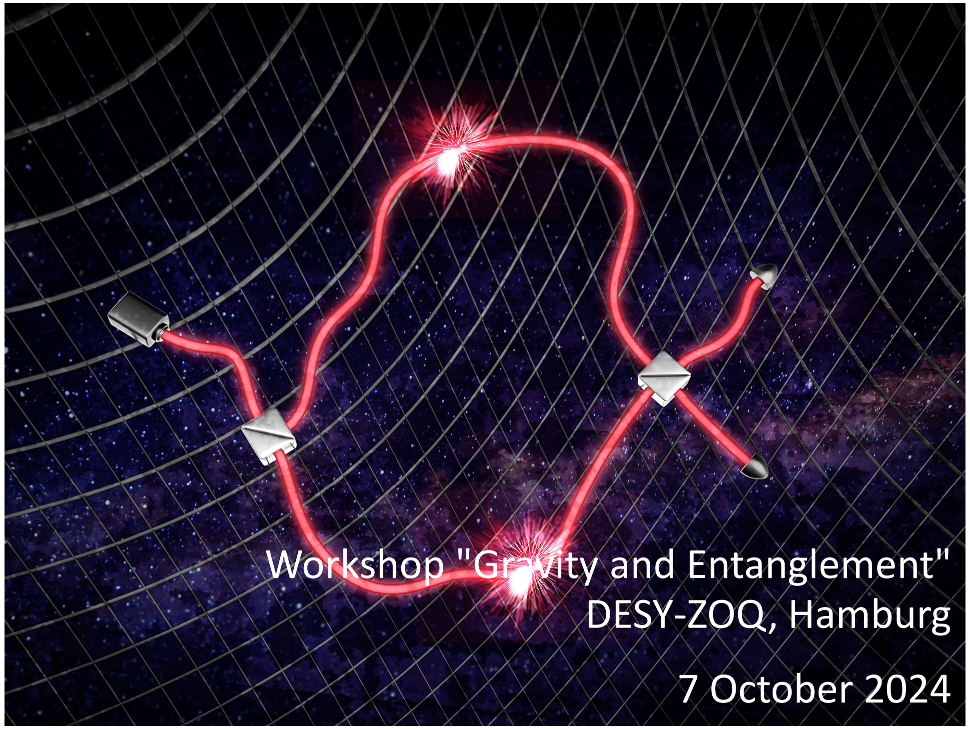
Entangled photons in the Earth's gravitational field

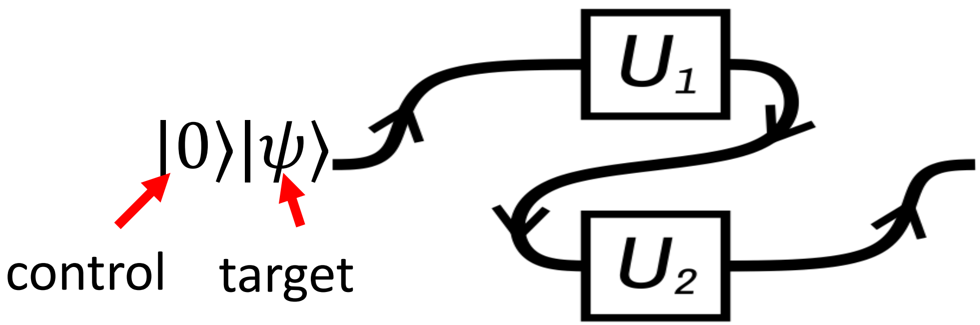
Philip Walther (University of Vienna & UniVie-ÖAW Research Network TURIS)

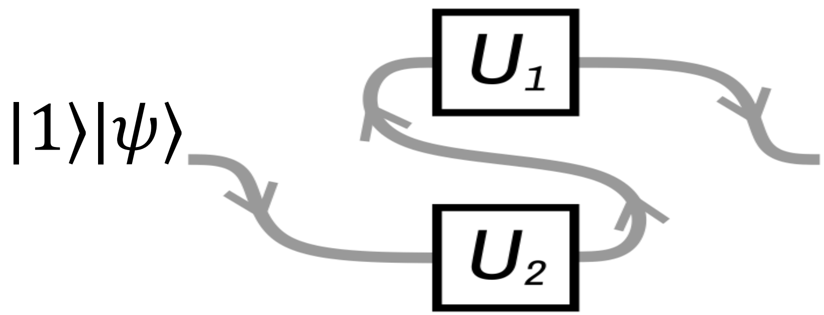


Fundamental experiments with single photons

- **Quantum Causality**
- **Quantum-Gravity Interface**
- **Probing Special Relativity with Entanglement**

Preparation of superimposed causal oders: the quantum switch





$$|0\rangle|\psi\rangle \rightarrow |0\rangle U_2 U_1|\psi\rangle$$

Gate U_1 acts before U_2

$$|1\rangle|\psi\rangle \rightarrow |1\rangle U_1 U_2|\psi\rangle$$

Gate U_2 acts before U_1

Chiribella et al, Phys. Rev. A 88, 022318 (2013)

Preparation of superimposed causal oders: the quantum switch

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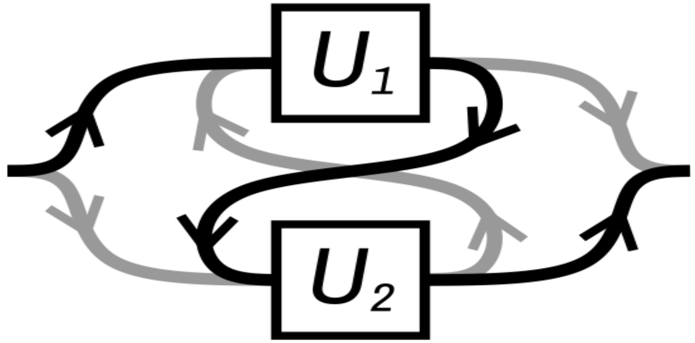
$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|\psi\rangle$



$\frac{1}{\sqrt{2}}|0\rangle U_1 U_2|\psi\rangle + \frac{1}{\sqrt{2}}|1\rangle U_2 U_1|\psi\rangle$

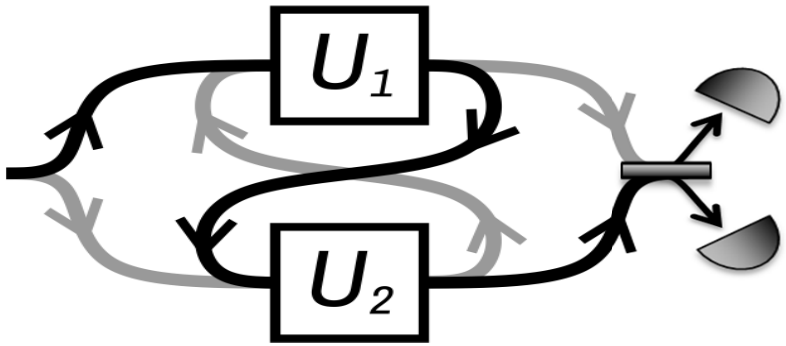
Gate U_1 acts before U_2 *and* U_2 acts before U_1

Chiribella et al, Phys. Rev. A 88, 022318 (2013)

What is it good for?

Given $\boldsymbol{U_1}$ and $\boldsymbol{U_2}$, the task is to distinguish whether they *<u>commute or anti-commute.</u>*

$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|\psi\rangle$$



anticommutator

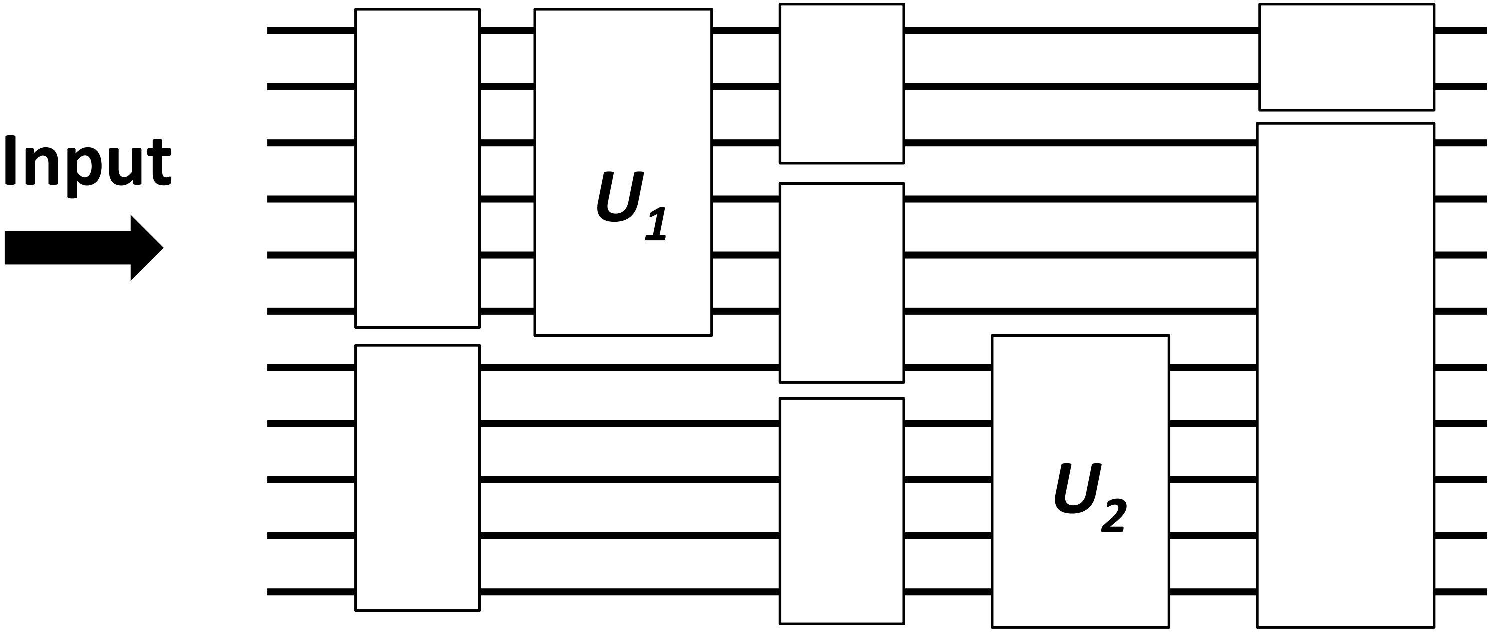
$$\frac{1}{2}|0\rangle\{U_1, U_2\}|\psi\rangle + \frac{1}{2}|1\rangle[U_1, U_2]|\psi\rangle$$

commutator

Chiribella et al, Phys. Rev. A 88, 022318 (2013)

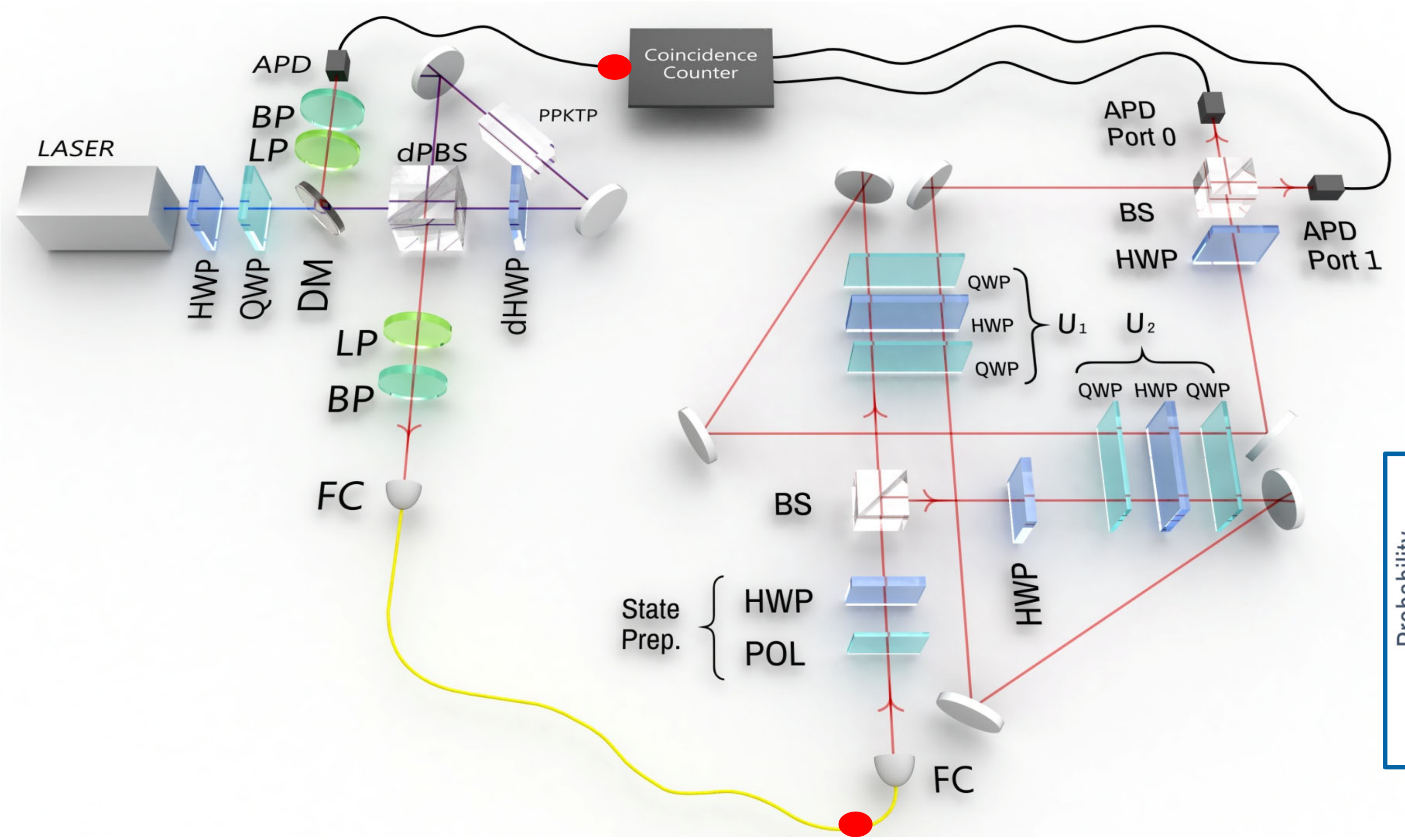
Causal orders for quantum computers

standard quantum algorithm



➡ **Fixed order of quantum computer gates**

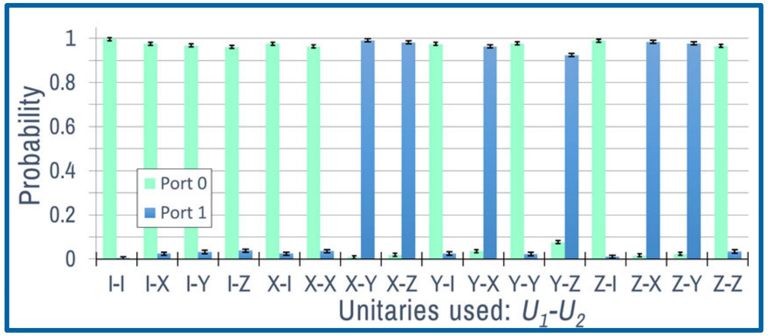
The actual setup



Surpassing regular QC

average success rate:

0.976 ± 0015



Procopio, Moqanaki, Araujo, Costa, Calafell, Dowd, Hamel,Rozema, Brukner, Walther
Nature Communication 6, 8913 (2015)

Rubino, Rozema, Feix, Araújo, Zeuner, Procopio, Brukner, Walther
Science Advances 3, e1602589 (2017)

Experimental Indefinte Causal Order

RESEARCH ARTICLE | QUANTUM INFORMATION

Experimental verification of an indefinite causal order

Giulia Rubino[1,*], Lee A. Rozema[1], Adrien Feix[1,2], Mateus Araújo[1,2], Jonas M. Zeuner[1], Lorenzo M. Procopio[1], Časlav B...
+ See all authors and affiliations

Science Advances 24 Mar 2017:
Vol. 3, no. 3, e1602589
DOI: 10.1126/sciadv.1602589

Quantum
the open journal for quantum science
PAPERS PERSPECTIVES

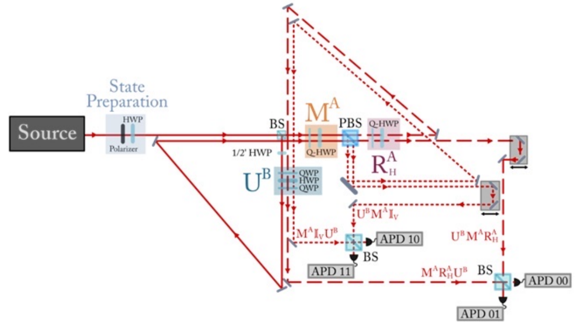
Experimental entanglement of temporal order

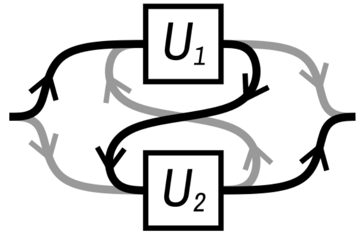
Giulia Rubino[1,2], Lee A. Rozema[1], Francesco Massa[1], Mateus Araújo[1,3], Magdalena Zych[4], Časlav Brukner[1,3], and Philip Walther[1]

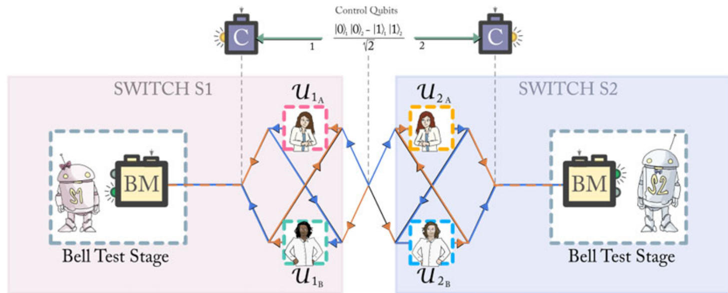
200 Vol. 10, No. 2 / February 2023 / Optica Research Article
OPTICA

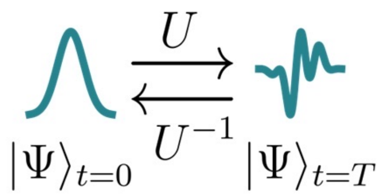
Demonstration of universal time-reversal for qubit processes

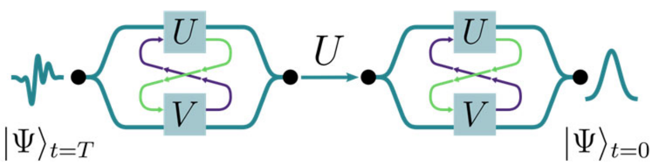
P. Schiansky,[1,3,†] T. Strömberg,[1,†] D. Trillo,[2] V. Saggio,[1] B. Dive,[2] M. Navascués,[2] and P. Walther[1,4]











Experimental aspects of indefinite causal order in quantum mechanics
L. A. Rozema, T. Strömberg, H. Cao, B.H. Liu, PW, Nature Review Physics 6, 483 (2024)

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Experiments at the interface of quantum physics and gravity

TURIS' big open question:

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How does gravity act on quantum systems ?

<u>more specifically:</u>

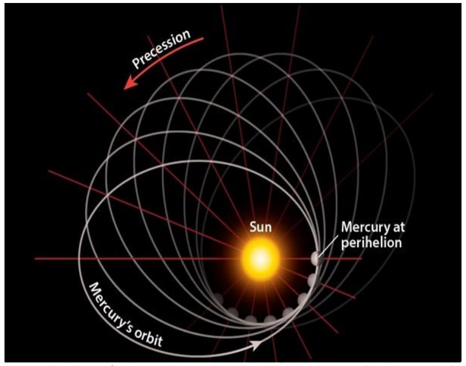
How does gravity act on massless quantum systems,

including quantum entanglement?

The four «classical» tests of General Relativity

1) Mercury perihelion precession

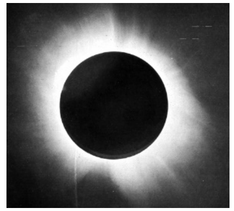
1859 *(Urbain Le Verrier)* & 1882 *(Simon Newcombe):*
anomalous precession of the perihelion of Mercury orbital plane

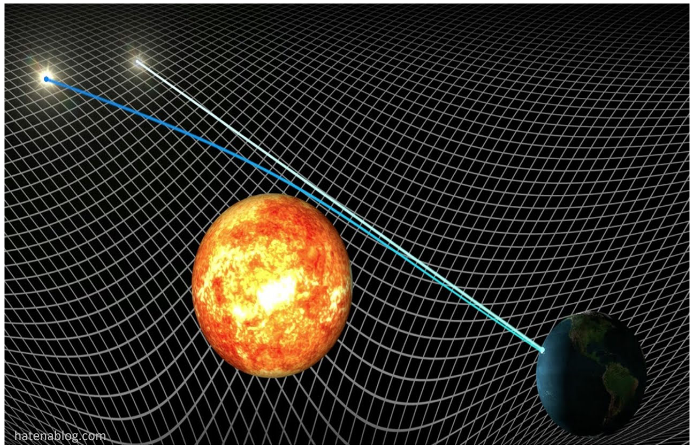


A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919.

By Sir F. W. Dyson, *F.R.S., Astronomer Royal, Prof.* A. S. Eddington, *F.R.S., and Mr.* C. Davidson.

Philosophical Transactions of the Royal Society. **220A** (571–581): 291–333.



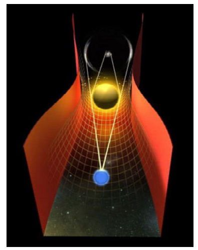


2) Light bending

1919 *(Sir Arthur Eddington), Brazil & South Africa:*
total solar eclipse to confirm doubling of the deflection angles (1,75” VS 0,87”)

2009 *(Fomalont et al.):*
gravitational lensing observerd via strong radio signals from astrophysical sources (i.e. quasars).

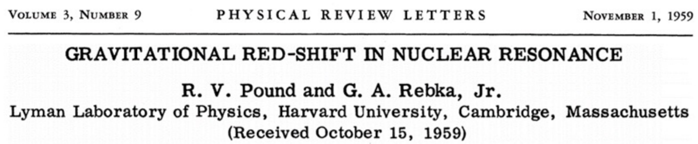
$$\gamma = 0{,}9998 \pm 0,0003\,,\ (\gamma_{GR} = 1)$$



The four «classical» tests of General Relativity

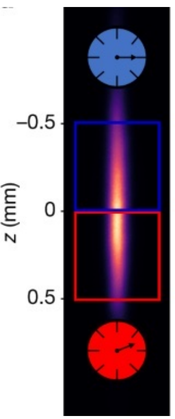
3) Gravitational redshift

$$\nu_r = \nu_e\left(1 - \frac{gh}{c^2}\right)$$


VOLUME 3, NUMBER 9 PHYSICAL REVIEW LETTERS NOVEMBER 1, 1959

GRAVITATIONAL RED-SHIFT IN NUCLEAR RESONANCE

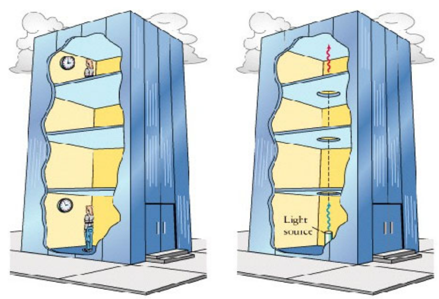
R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received October 15, 1959)

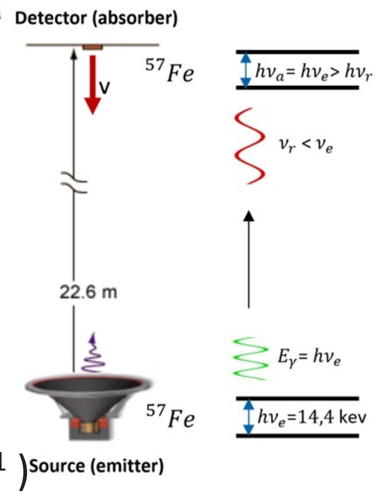


1959 *(Pound and Rebka)* & 1964 *(Pound and Snider):*
relative frequency shift of light emitted-absorbed at different heigh

1972 *(Hafele and Keating):*
four Cs-atomic clocks on plane show time dilation with 9% accuracy

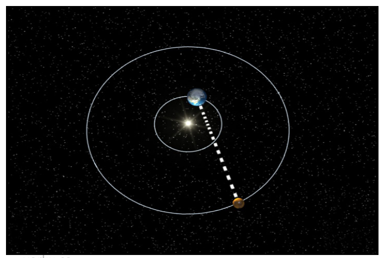
2022 *(Jun Ye group):*
Sr atoms enable to detect gravitational-redshift at millimeter scale (clock uncertainty 7.6×10^{-21})

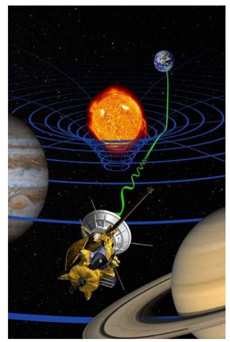




4) Shapiro Delay

1967 *(Irwin Shapiro):*
radio signals of roundtrip Earth-Venus show time delay of 200 µs


yorku.ca


NASA/JP

The first quantum test of gravity

Matter-wave interferometry using neutrons

(the «famous» COW-experiment)

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

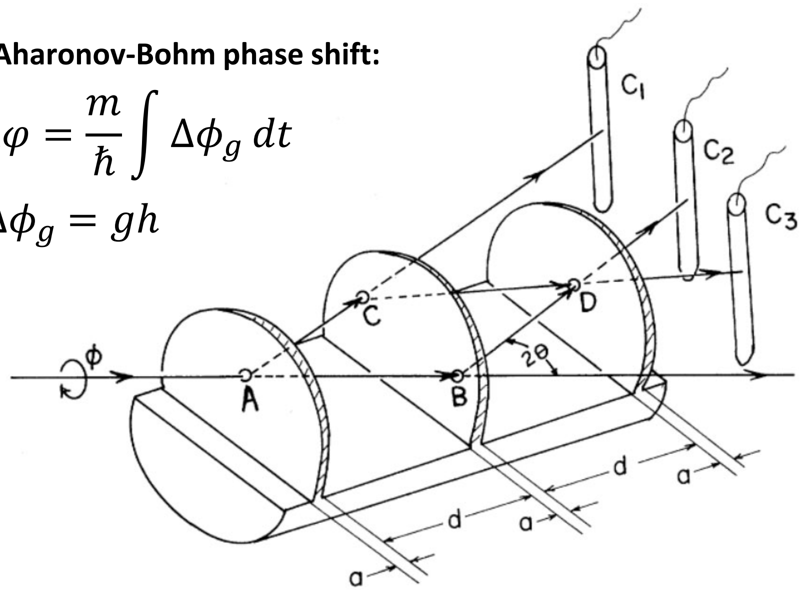
S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

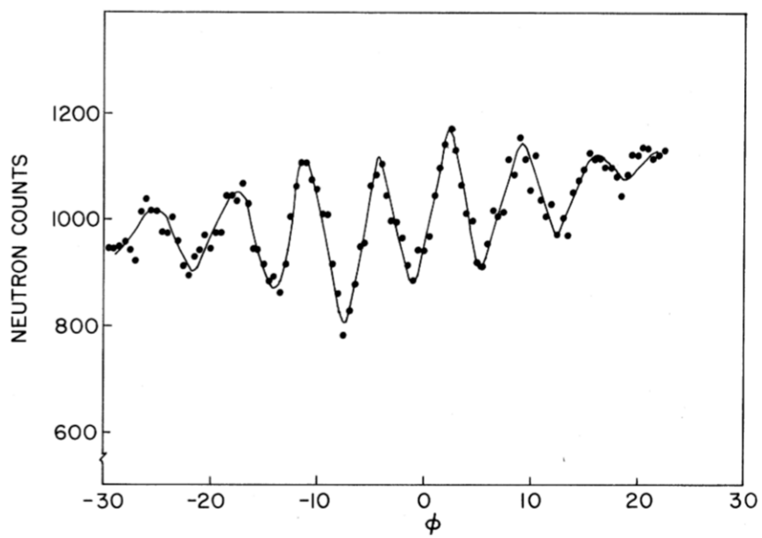
Aharonov-Bohm phase shift:

$$\Delta\varphi = \frac{m}{\hbar}\int \Delta\phi_g \, dt$$

$$\Delta\phi_g = gh$$



Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.



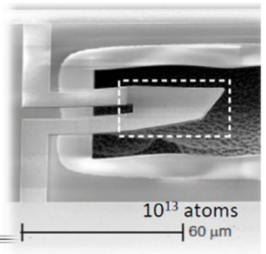
Experiments at the gravity-quantum interface

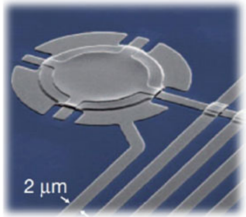
Quantum optomechanics....

Nature **464**, 697-703 (2010)

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]





Nature **475**, 359-363 (2011)

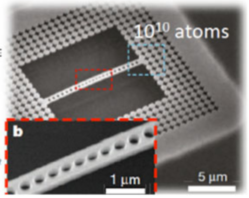
Sideband cooling of micromechanical motion to the quantum ground state

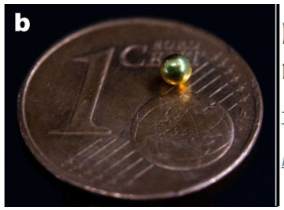
J. D. Teufel, T. Donner, Dale Li, J. W. Harlow, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, K. W. Lehnert & R. W. Simmonds

Nature **478**, 89-92 (2011)

Laser cooling of a nanomechanical oscillator into its quantum ground state

Jasper Chan, T. P. Mayer Alegre, Amir H. Safavi-Naeini, Jeff T. Hill, Alex Krause, Simon Gröblacher, Markus Aspelmeyer & Oskar Painter

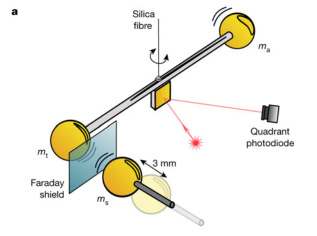




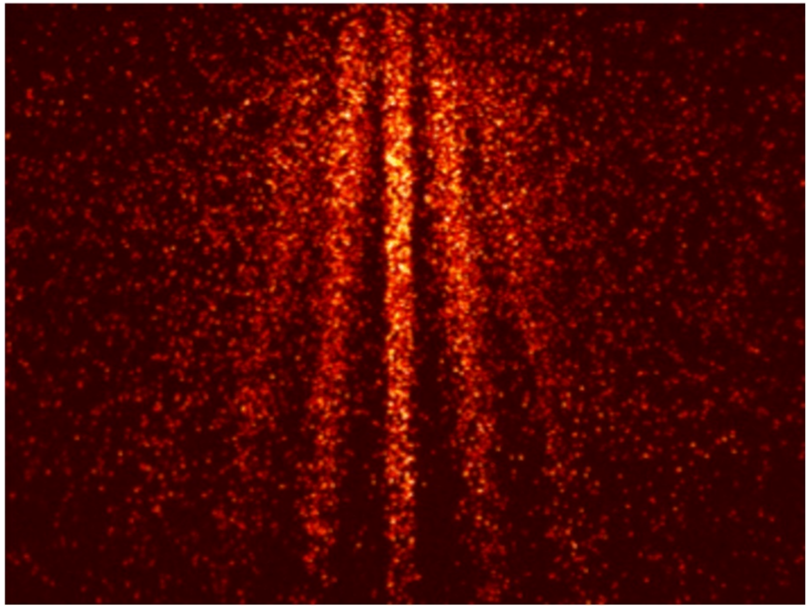
Measurement of gravitational coupling between millimetre-sized masses

Tobias Westphal, Hans Hepach, Jeremias Pfaff & Markus Aspelmeyer

Nature **591**, 225–228 (2021) | Cite this article



...Quantum matter waves



Experiments at the gravity-quantum interface

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TURIS

How does gravity act on massless quantum systems, including quantum entanglement?

And what was done so far?

	Classical physics	*Quantum mechanics*
Newtonian gravity	17^{th}- 19^{th} century	Neutrons (COW) Atoms/BEC
General relativity	Classical test of GR Time dilation with clocks	**Photonic quantum systems**

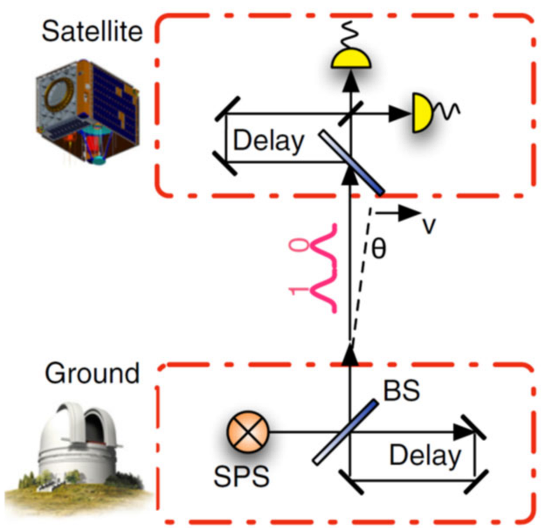
Experimental concepts with single photons

Satellite-based missions

IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. 29 (2012) 224011 (44pp) doi:10.1088/0264-9381/29/22/224011

Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities

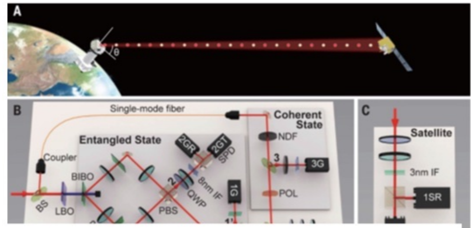
David Rideout[1,2,3], Thomas Jennewein[2,4], Giovanni Amelino-Camelia[6], Tommaso F Demarie[7], Brendon L Higgins[2,4], Achim Kempf[2,3,4,5], Adrian Kent[3,8], Raymond Laflamme[2,3,4], Xian Ma[2,4], Robert B Mann[2,4], Eduardo Martín-Martínez[2,4,5], Nicolas C Menicucci[3,9], John Moffat[3], Christoph Simon[10], Rafael Sorkin[3], Lee Smolin[3] and Daniel R Terno[7]



Science — REPORTS
Cite as: P. Xu et al., Science 10.1126/science.aay5820 (2019).

Satellite testing of a gravitationally induced quantum decoherence model

Ping Xu[1,2*], Yiqiu Ma[3*], Ji-Gang Ren[1,2*], Hai-Lin Yong[1,2], Timothy C. Ralph[4], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Xuan Han[1,2], Hui-Nan Wu[1,2], Wei-Yang Wang[1,2], Feng-Zhi Li[1,2], Meng Yang[1,2], Feng-Li Lin[5], Li Li[1,2], Nai-Le Liu[1,2], Yu-Ao Chen[1,2], Chao-Yang Lu[1,2], Yanbei Chen[3], Jingyun Fan[1,2†], Cheng-Zhi Peng[1,2†], Jian-Wei Pan[1,2†]



PHYSICAL REVIEW LETTERS 133, 020201 (2024)

Single-Photon Interference over 8.4 km Urban Atmosphere: Toward Testing Quantum Effects in Curved Spacetime with Photons

Hui-Nan Wu,* Yu-Huai Li,* Bo Li, Xiang You, Run-Ze Liu, Ji-Gang Ren, Juan Yin, Chao-Yang Lu, Yuan Cao, Cheng-Zhi Peng, and Jian-Wei Pan

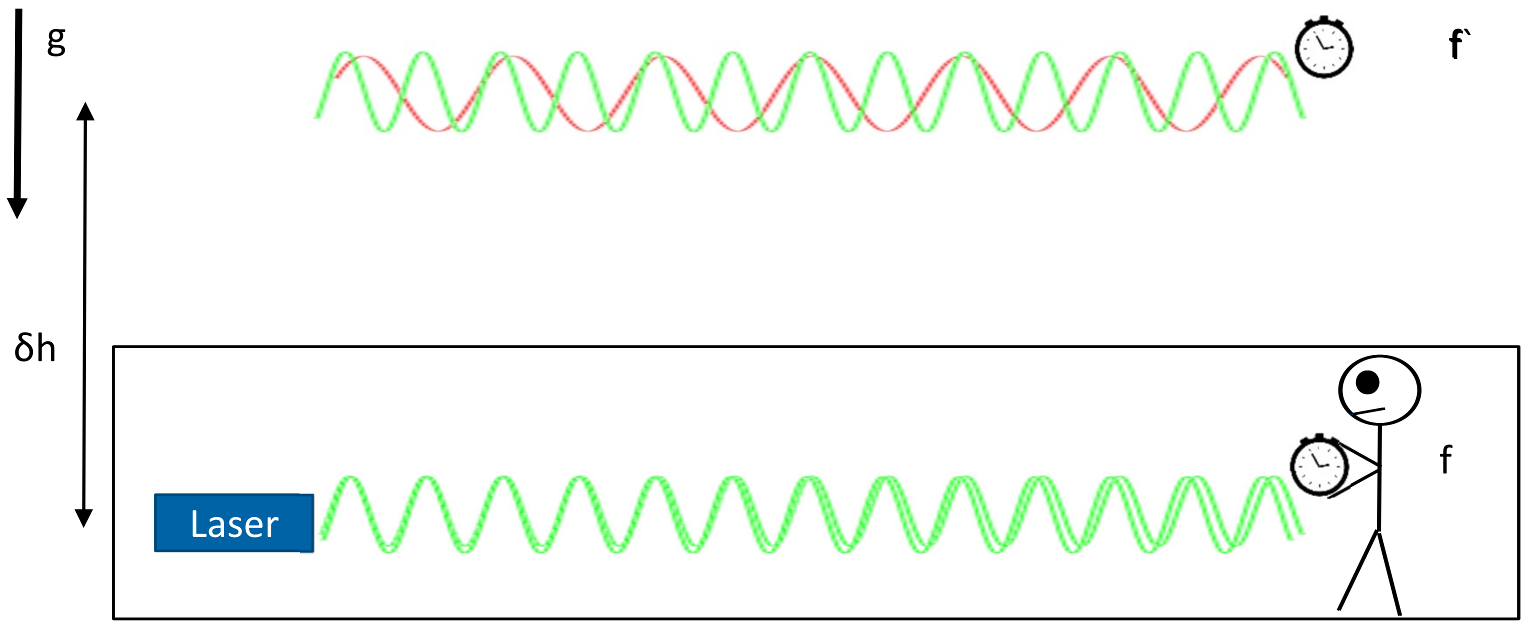
Table-top experiments

IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. 29 (2012) 224010 (18pp) doi:10.1088/0264-9381/29/22/224010

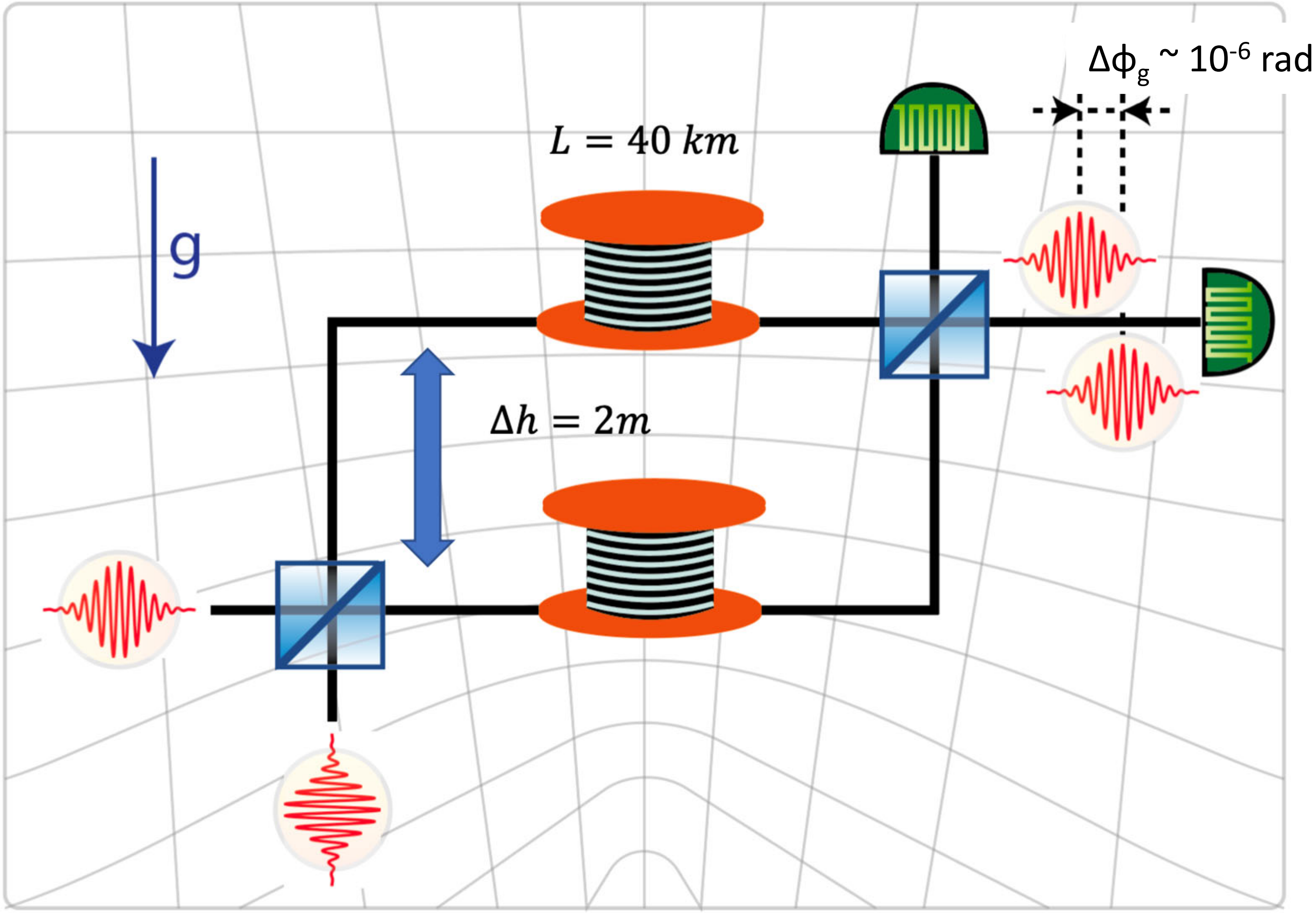
General relativistic effects in quantum interference of photons

Magdalena Zych[1], Fabio Costa[1], Igor Pikovski[1], Timothy C Ralph[2] and Časlav Brukner[1,3]

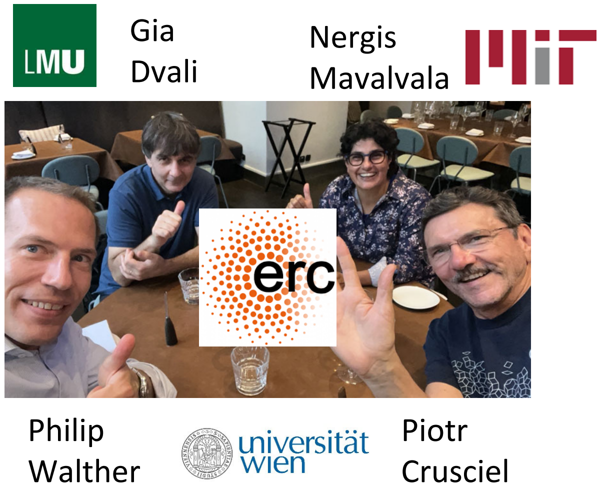
Clocks at different heights in a gravit. field



Interferometic phase-shift due to hight difference



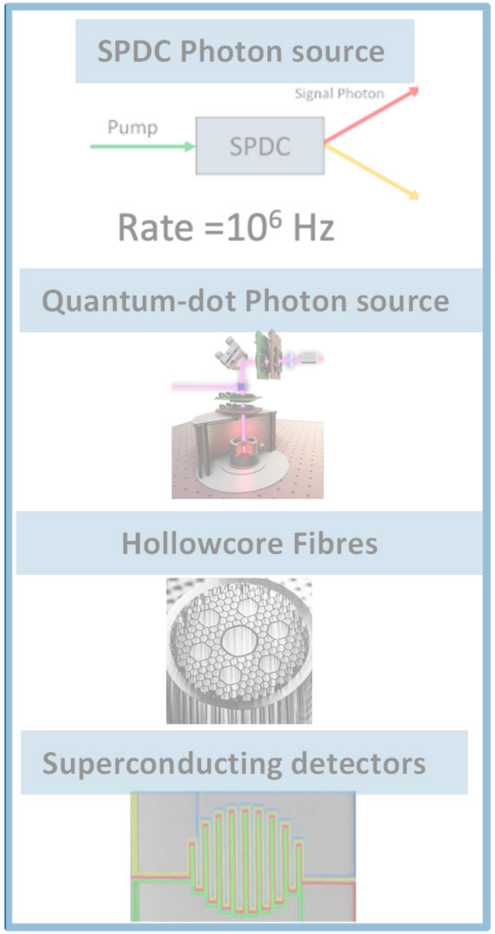
$\Delta f/f = 10^{-16}$

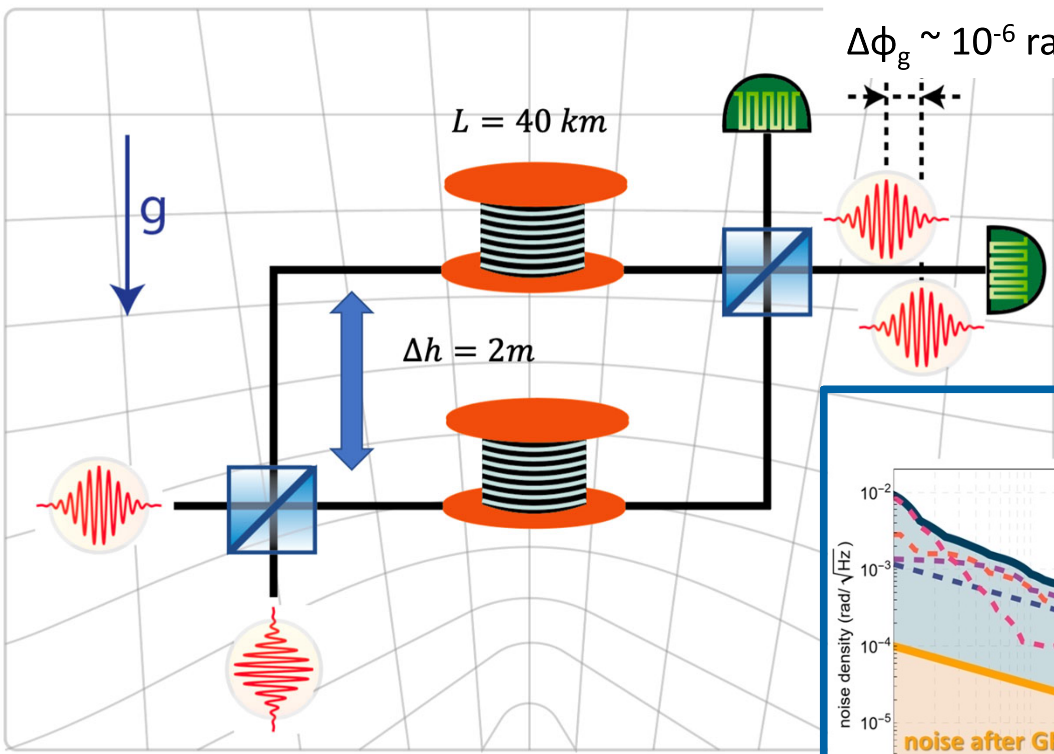


Gravitationally induced phase shift on a single photon
Hilweg, Massa, Martynov, Mavalavala, Walther, New J. Phys. 19, 033028 (2017)

Measuring space-time curvature using maximally path-entangled quantum states
Mieling, Hilweg, Walther, Physical Review A 106, L031701 (2022)

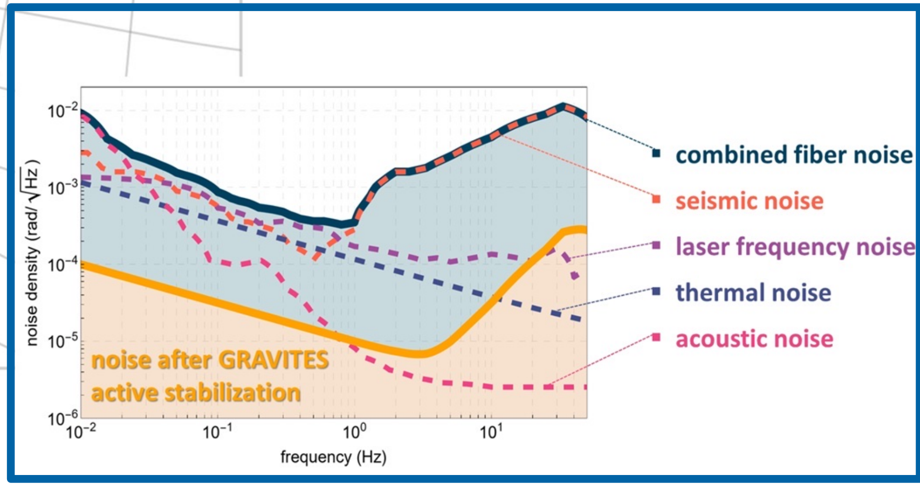
Interferometic phase-shift due to height difference





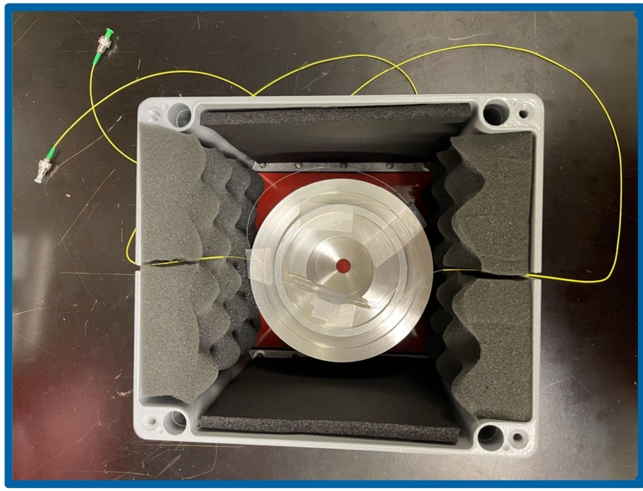
$\Delta\phi_g \sim 10^{-6}$ rad → $$\Delta\phi_g = \frac{2\pi n g L \Delta h}{\lambda c^2}$$

Limits and prospects for long-baseline optical fiber interferometry
C. Hilweg, D. Shadmany, P. Walther, N. Mavalvala, V. Sudhir,
Optica 9, 1238 (2022)



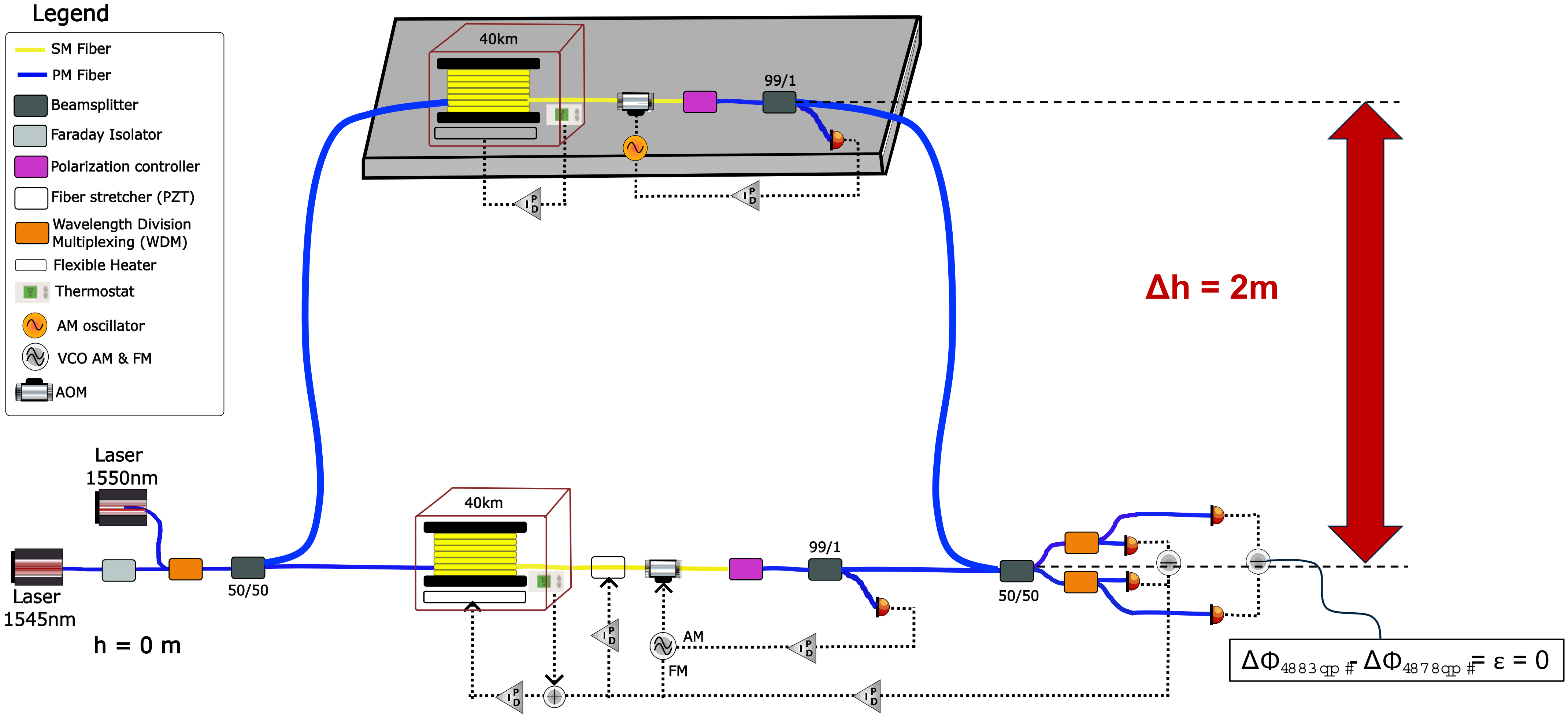
Passive noise stabilization in the city of Vienna

new precision lab – decoupled ground floor

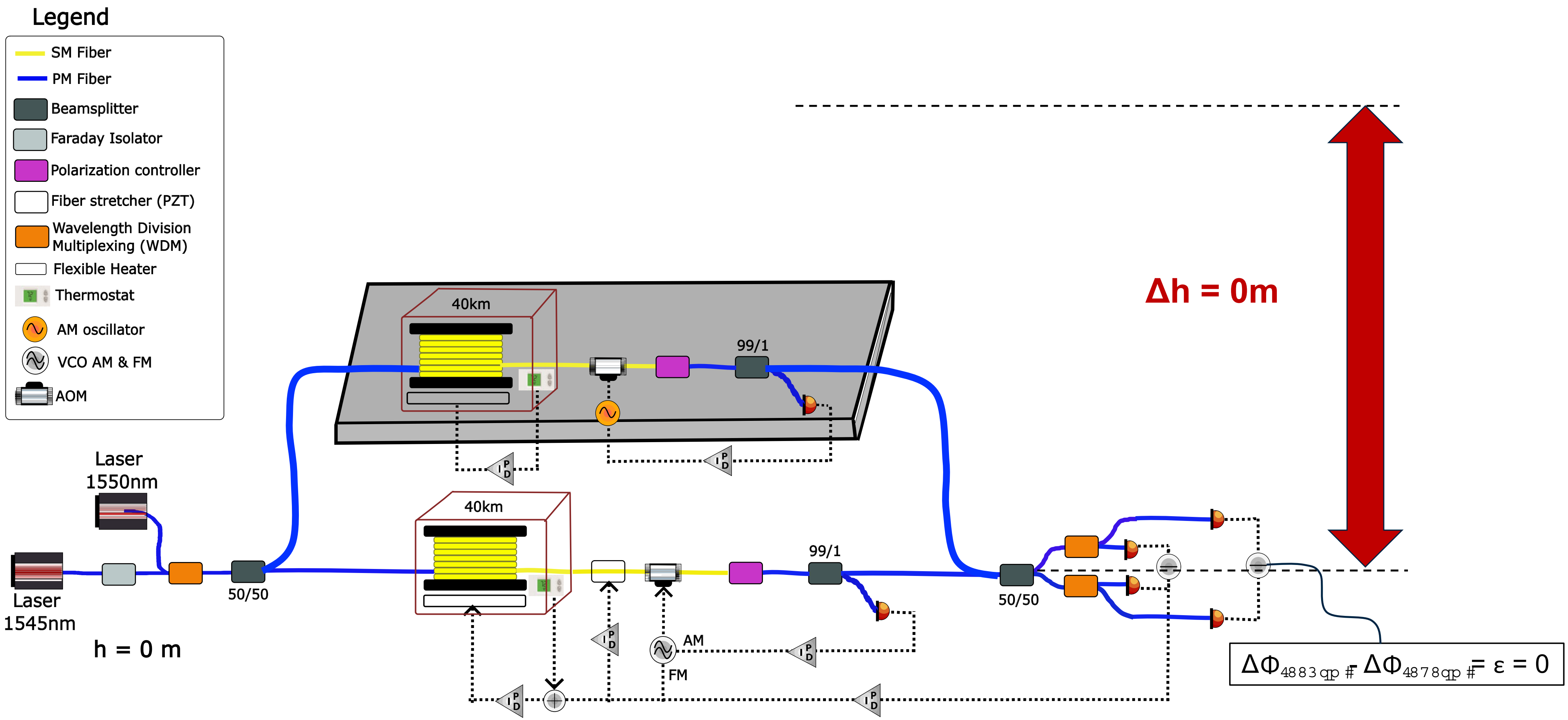


Vibration insensitive spool

Differential measurements



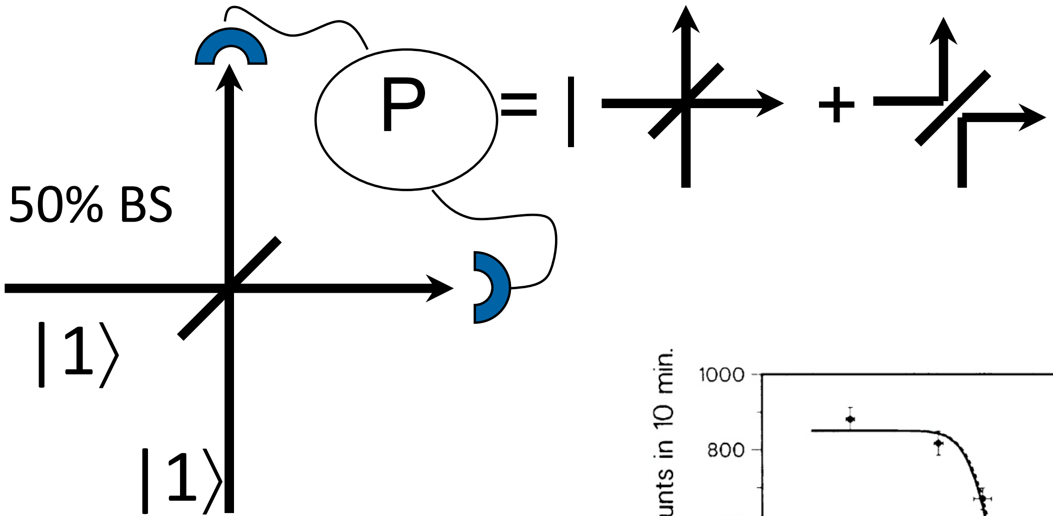
Differential measurements



From superposition to quantum entanglement

Tutorial: Boson behaviour of photons

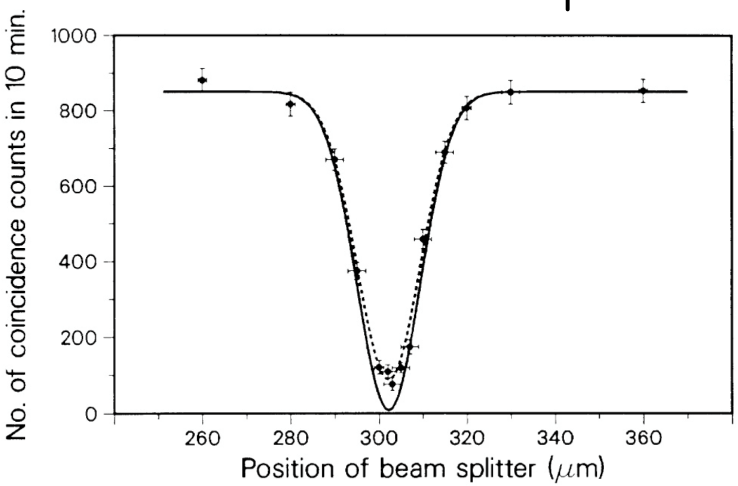
Hong-Ou-Mandel effect



$$= |\, t.t + r.r \,|^2$$

$$= \left| \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} + \frac{i}{\sqrt{2}} \cdot \frac{i}{\sqrt{2}} \right|^2 = 0$$

$|20\rangle - |02\rangle$



Hong, Ou, Mandel, PRL 59, 2044 (1987)

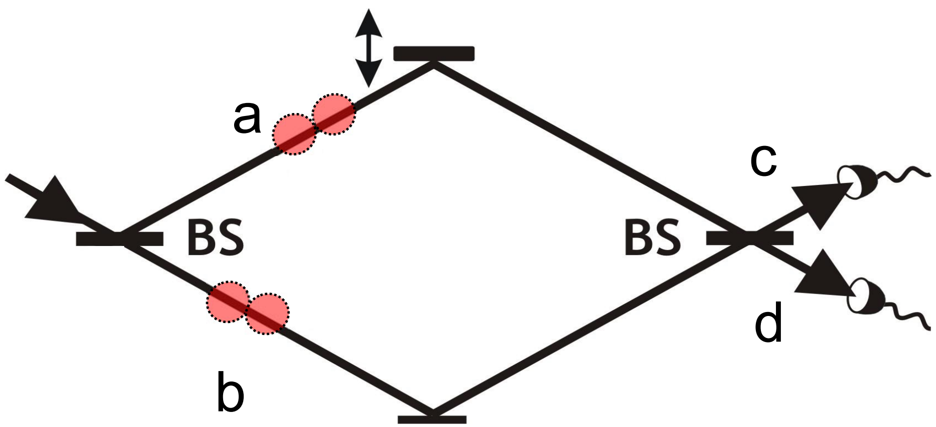
Gravity effects on quantum entanglement

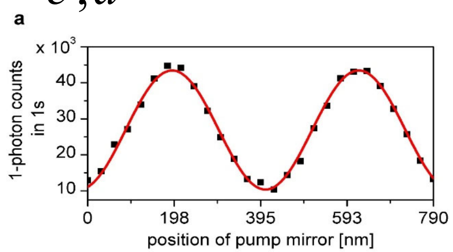
Path-entangled photon pairs

- Mach-Zehnder setup
- *N*-input particles (photons) are propagating either along mode a *or* b
- $|N\rangle_a|0\rangle_b$ or $|0\rangle|N\rangle_b$ which is called N00N-state
- Oscillation of interference fringes is proportional to *N*

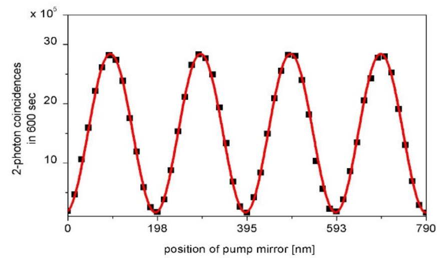
$$\frac{1}{\sqrt{2}}\left(|N\rangle_a|0\rangle_b + e^{iN\Delta\varphi}|0\rangle_a|N\rangle_b\right)$$

$$P_{c,d} \propto 1 \pm \cos(N\Delta\varphi)$$





$$\frac{1}{\sqrt{2}}\left(|1\rangle_a|0\rangle_b + e^{i\Delta\varphi}|0\rangle_a|1\rangle_b\right)$$



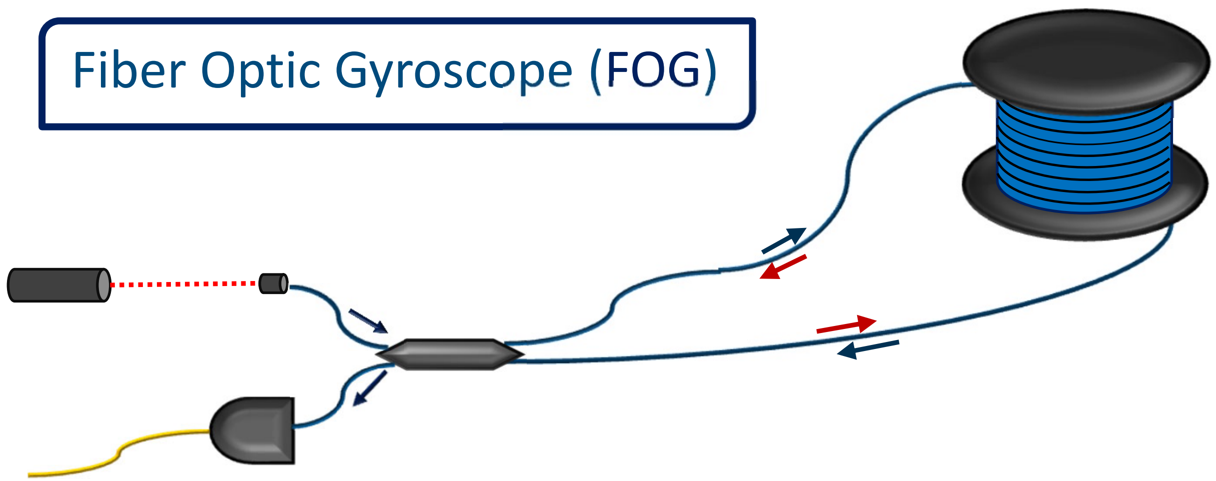
$$\frac{1}{\sqrt{2}}\left(|2\rangle_a|0\rangle_b + e^{i2\Delta\varphi}|0\rangle_a|2\rangle_b\right)$$

Walther et al.
Nature 429, 158 (2004)

1st generation experiments: measurement of Earth‘s rotation using entanglement

Optical gyroscope – Sagnac interferometry

(Greek: ***gyros*** - rotation, ***skopeein*** - to observe)

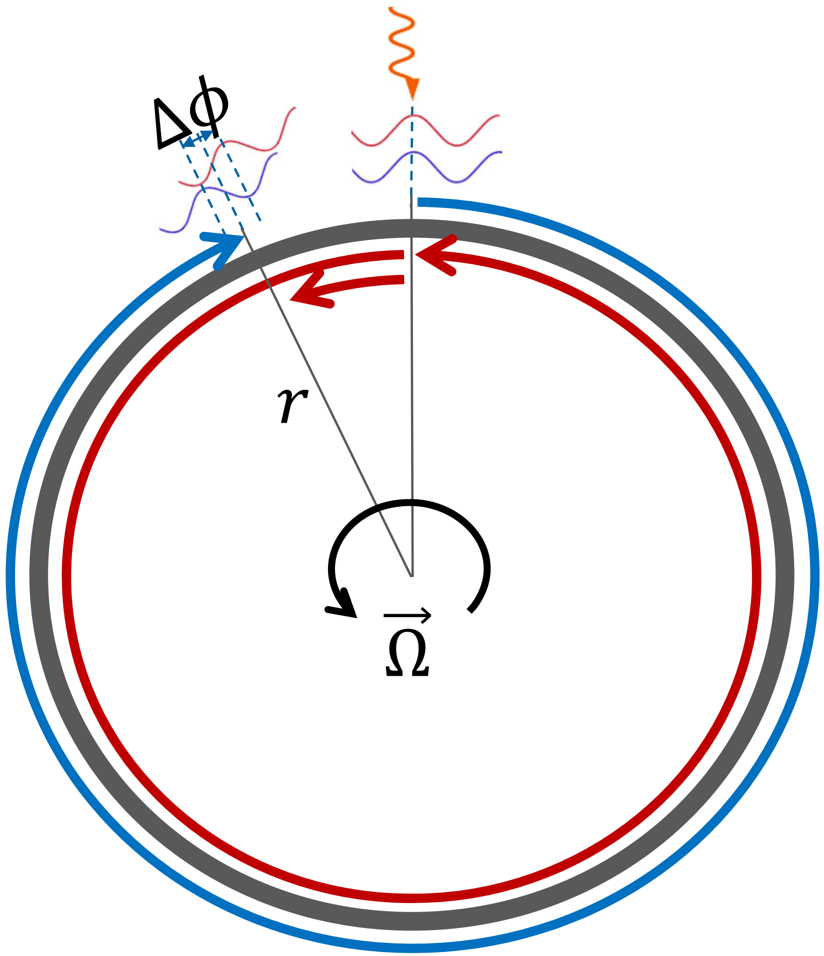


Sagnac interferometry

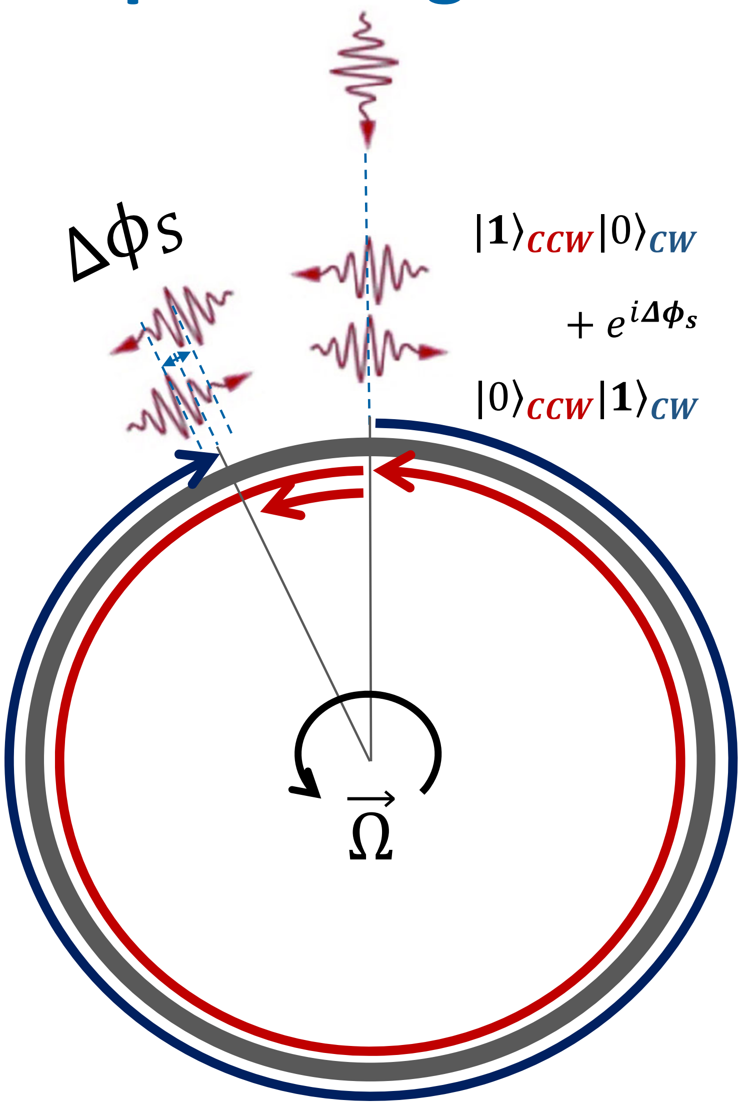
$$\Delta t = \frac{4\,\vec{\Omega}\cdot\vec{A}}{c^2}$$

↓

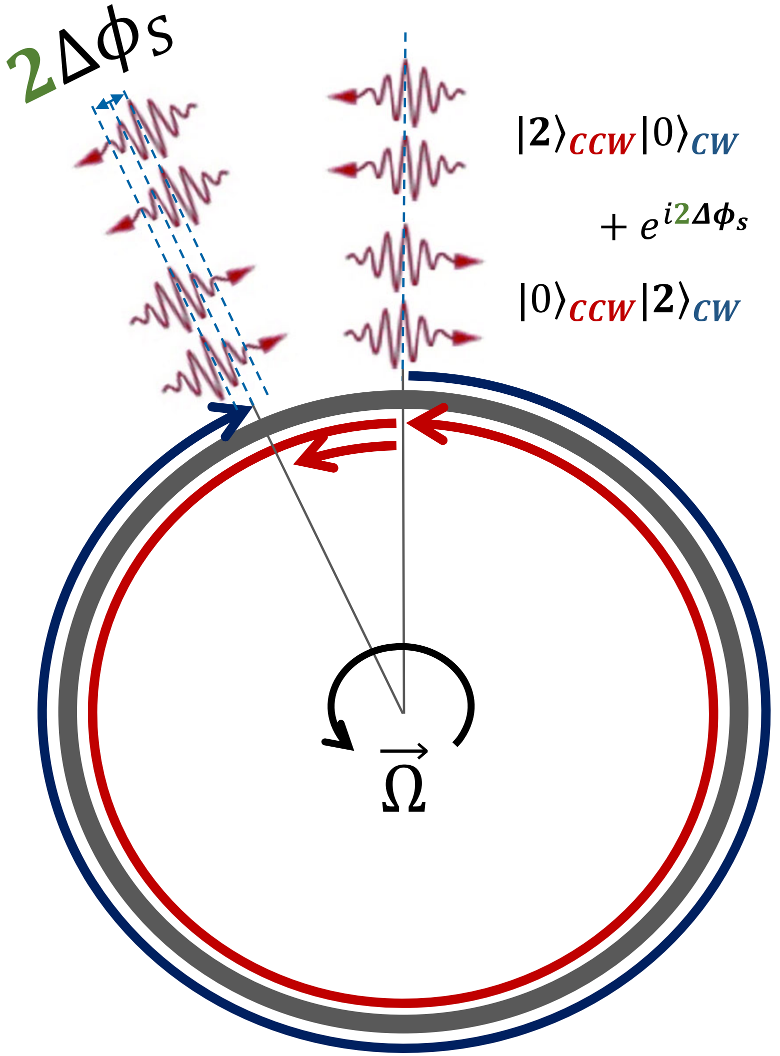
$$\Delta\phi = \frac{8\pi\,\vec{\Omega}\cdot\vec{A}}{\lambda\,c}$$



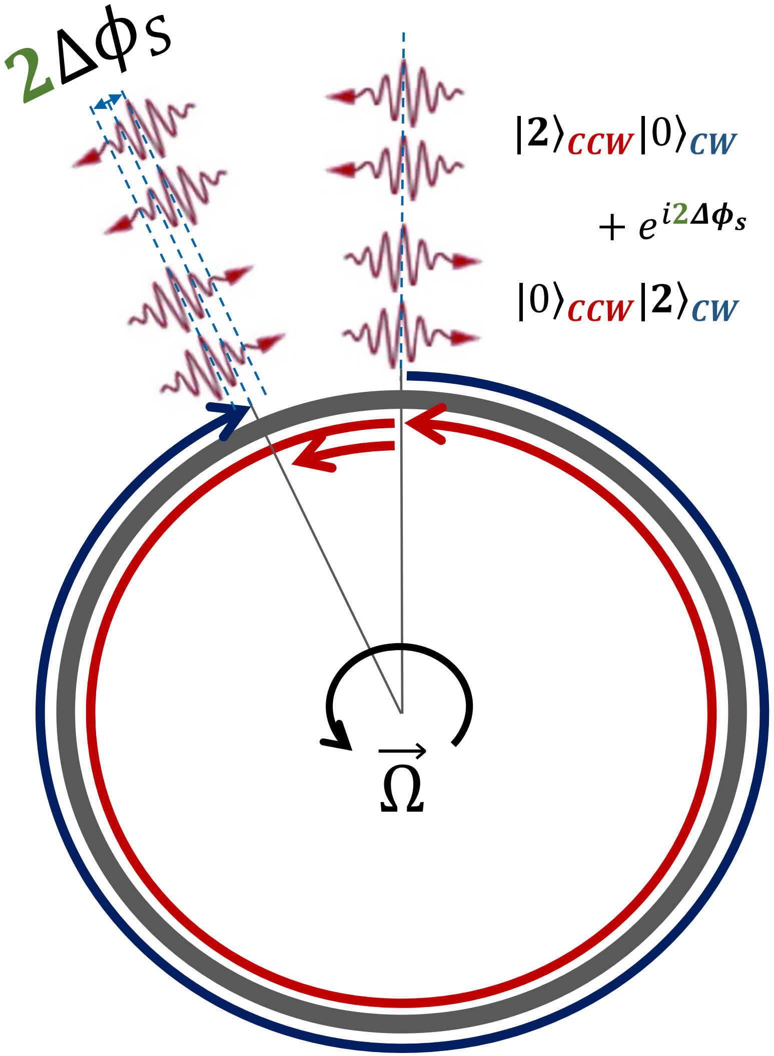
Optical Sagnac effect – single photons



Optical Sagnac effect – two photons N00N state



Optical Sagnac effect – two photons N00N state

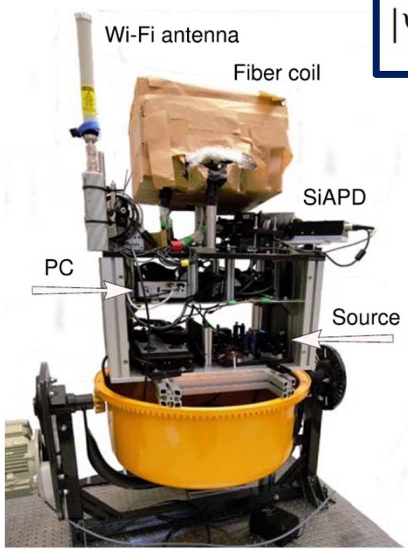


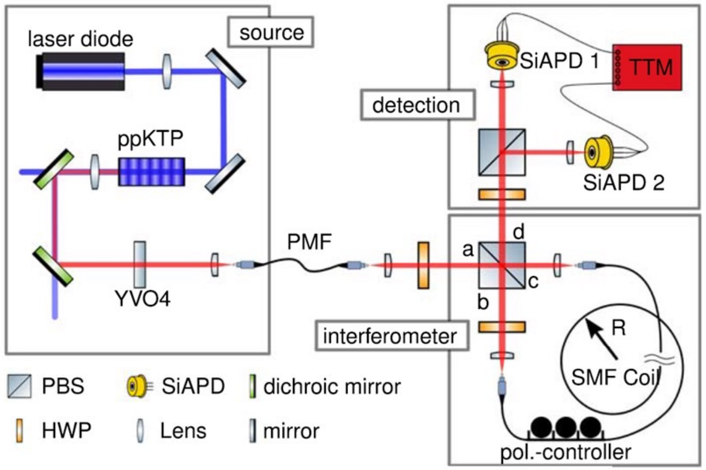
New Journal of Physics Volume 21, May 2019

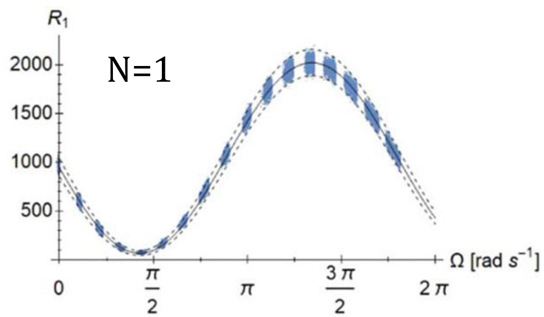
Entanglement-enhanced optical gyroscope

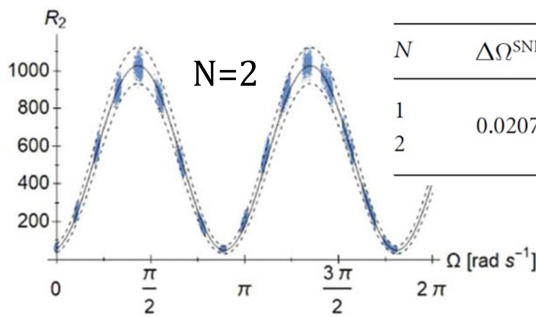
M. Fink, F. Steinlechner, J. Handsteiner, J. P. Dowling, T. Scheidl and R. Ursin

$$|\Psi^{d}(N)\rangle = \frac{1}{\sqrt{2}}(|N_{H}, 0_{V}\rangle - e^{iN(\phi_{S}(\Omega)+\phi_{0})}|0_{H}, N_{V}\rangle)$$









N	$\Delta\Omega^{SNL}$		$\Delta\Omega_{min}$
1	0.0207	$\ngtr$	0.025(0)
2		$>$	0.018(9)

Experimental scheme – fiber loop frame

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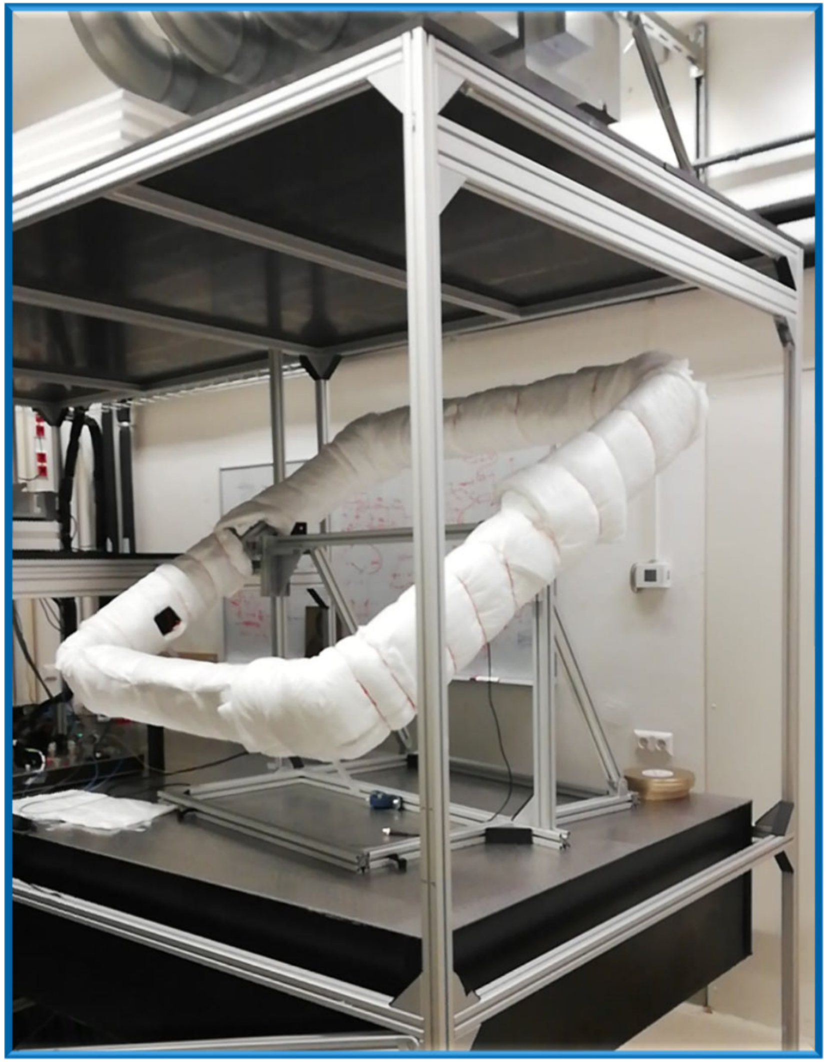
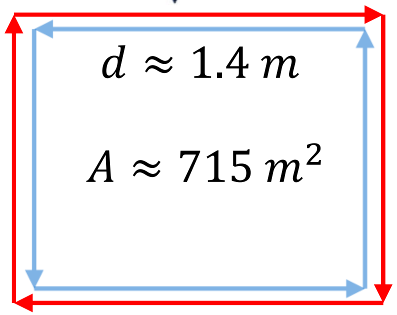


Experimental Scale factor calibration

$$\Delta\phi_E = \frac{8\pi \vec{A}\cdot\vec{\Omega}_E}{\lambda\, c}$$

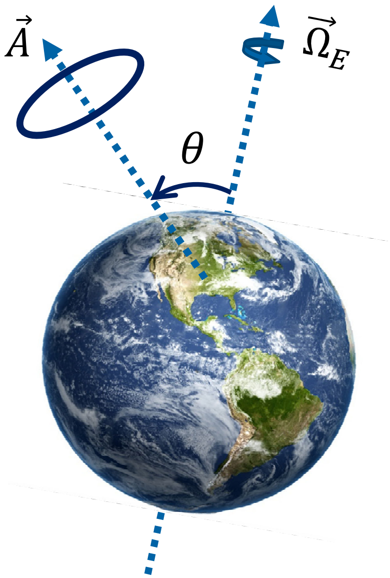
$$\Delta\phi_E = S\,\Omega_E \cos(\theta + \theta_0)$$



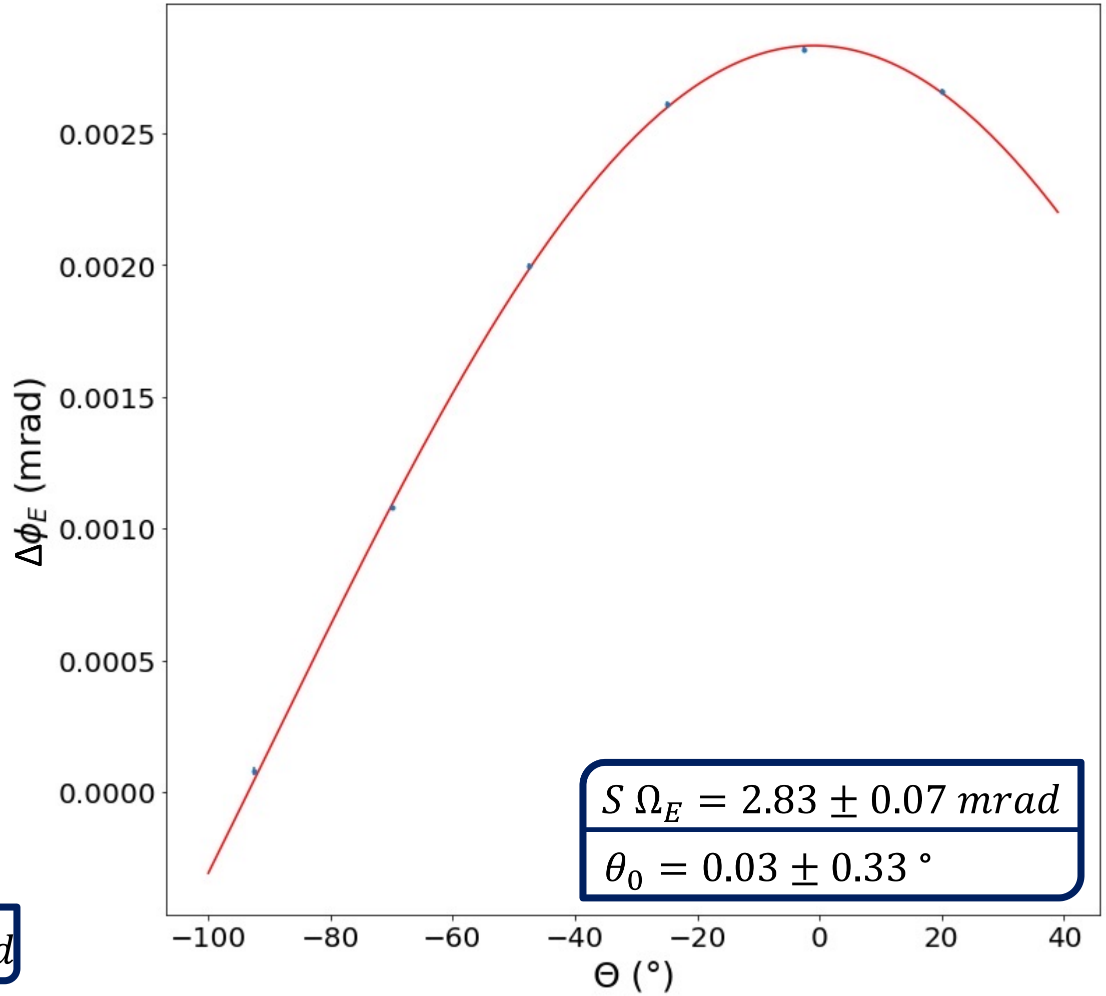
$L = 2\,km$

$$S = \frac{8\pi A}{\lambda\, c} \approx 38$$

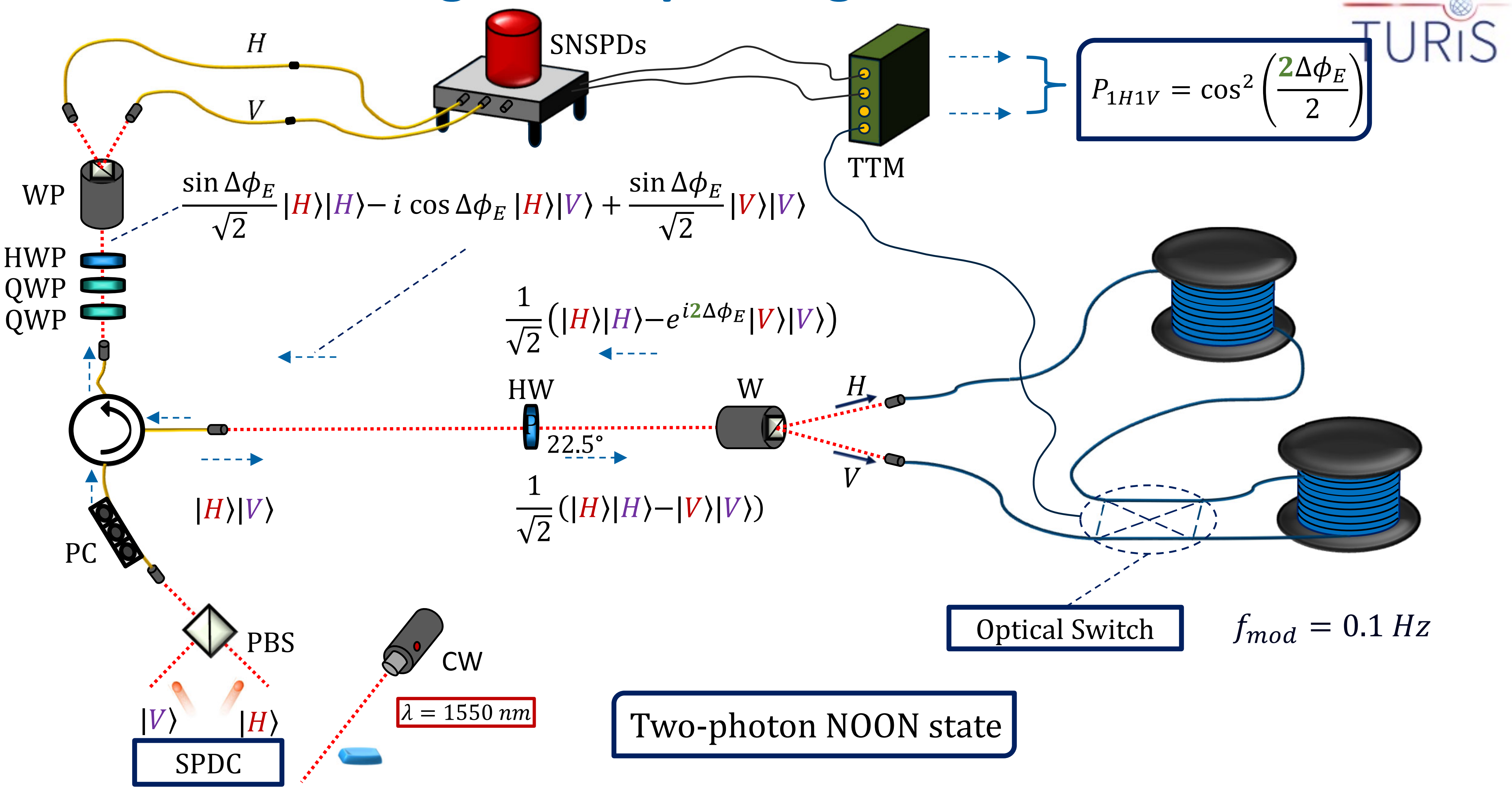
$$\Delta\phi_E \approx 2.81\,mrad$$



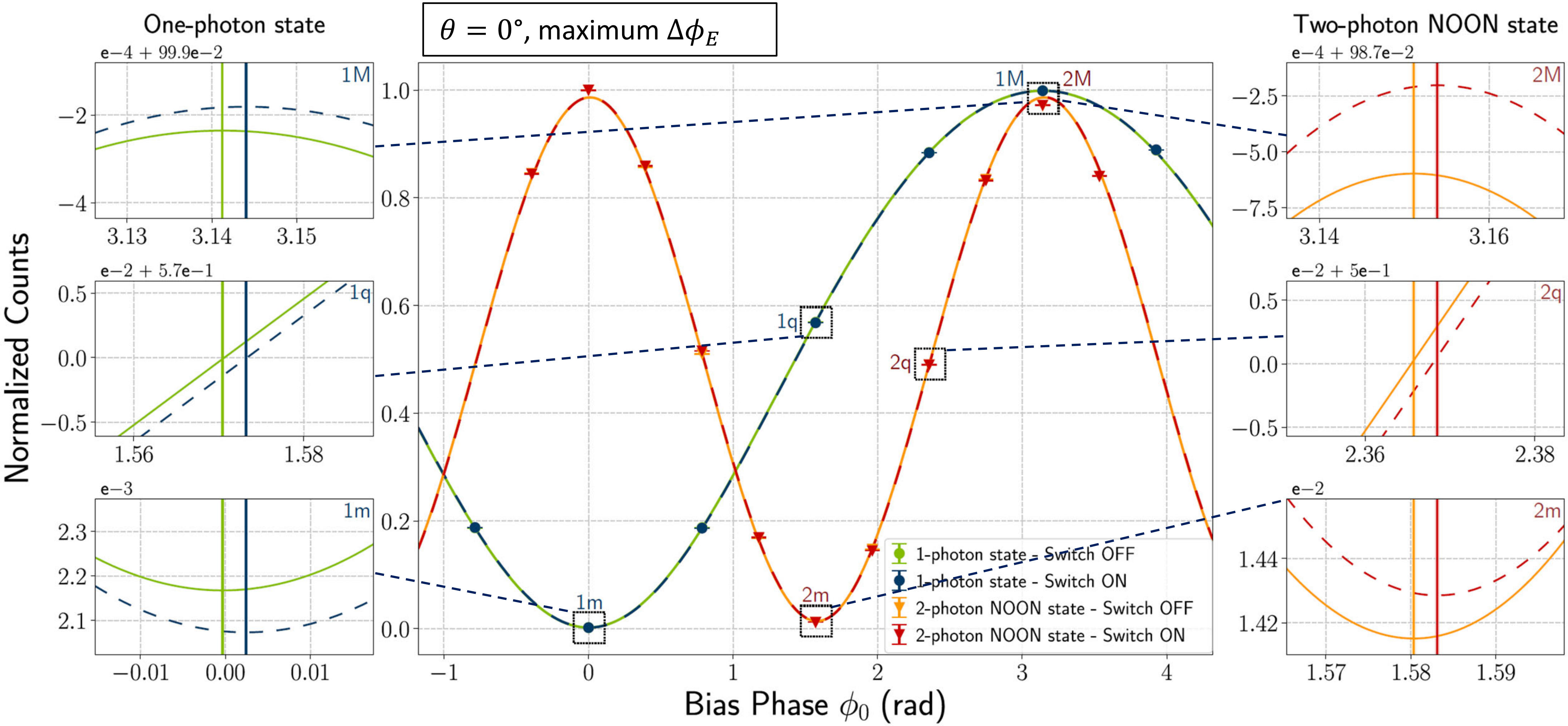
$$\Delta\phi_E^{meas} = 2.83 \pm 0.07\,mrad$$



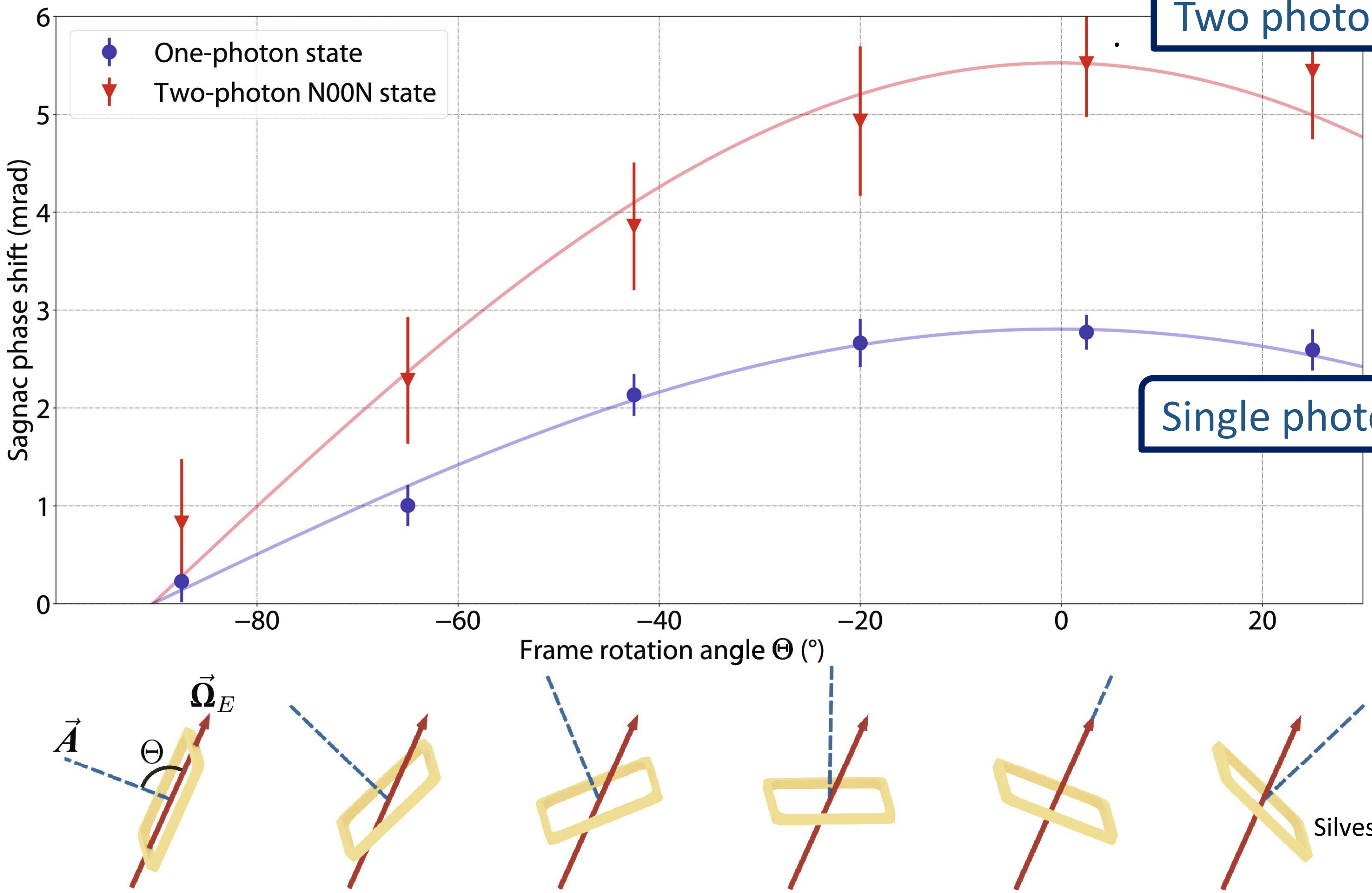
Quantum entanglement probing earth rotation



1-photon vs entangled 2-photon fringes



Quantum entanglement probing earth rotation



Two photons: $\Delta\phi_E^{(2)} = 5.51 \pm 0.54\, mrad$

1.97

Single photons: $\Delta\phi_E^{(1)} = 2.77 \pm 0.18\, mrad$

Earth's periodicity:
$24.58 \pm 1.62\, h$

Silvestri, Yu, Strömberg, Hilweg, Peterson, Walther
Science Advances 10, eadov0215 (2024)

Outlook – probing curved space time…?

PHYSICAL REVIEW RESEARCH

Frame dragging and the Hong-Ou-Mandel dip: Gravitational effects in multiphoton interference

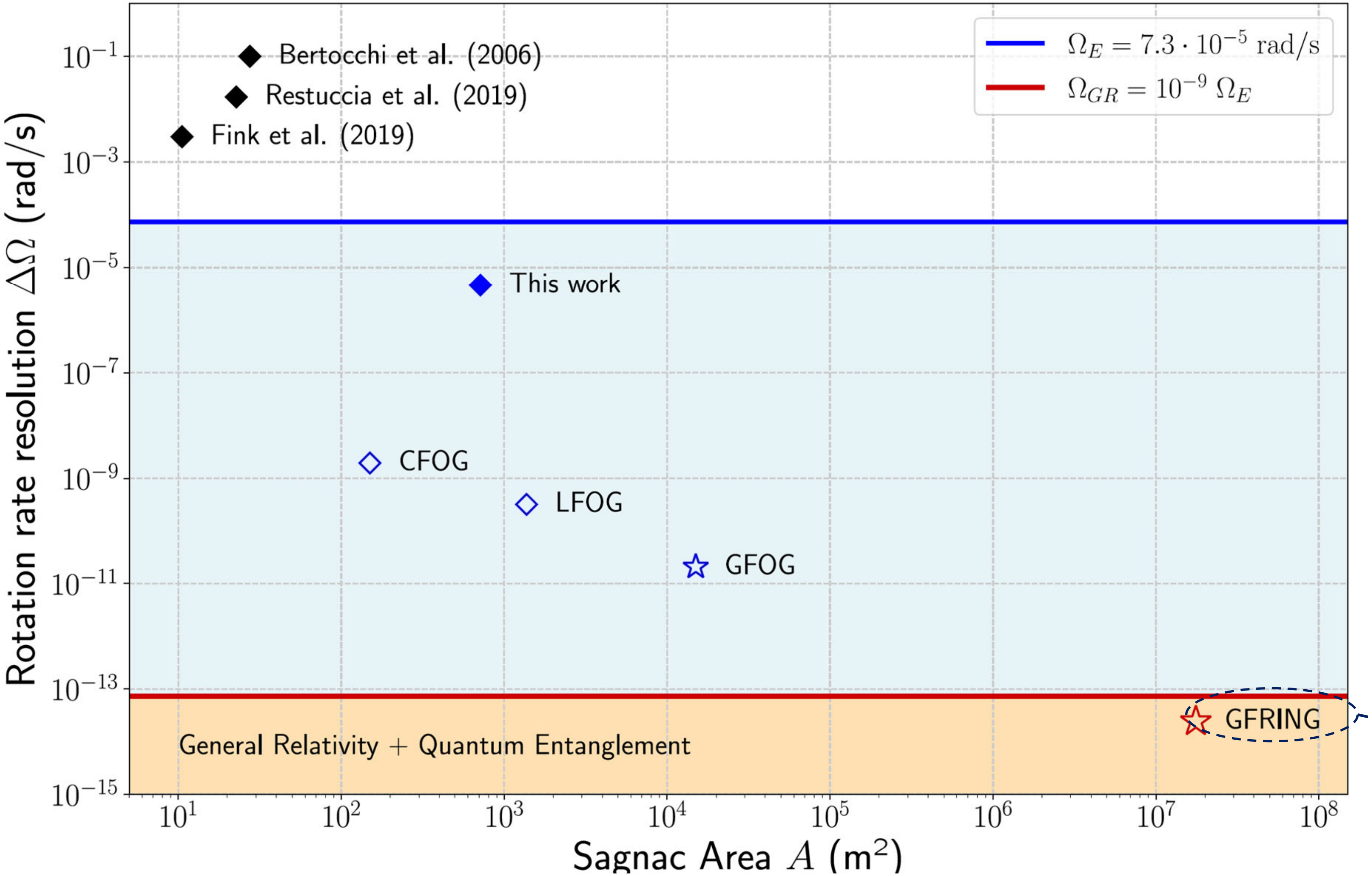
Anthony J. Brady and Stav Haldar

Phys. Rev. Research **3**, 023024 – Published 8 April 2021

$$\delta t = \underbrace{\frac{4\omega\mathcal{A}}{c^2}\cos(\theta-\alpha)}_{\text{Sagnac}} + \underbrace{\frac{4\omega\mathcal{A}}{c^2}\left(\frac{2GM}{c^2R}\sin\theta\sin\alpha + \frac{GI}{c^2R^3}(2\cos\theta\cos\alpha - \sin\theta\sin\alpha)\right)}_{\text{geodetic + Lense-Thirring}}$$

$$\Delta\phi_{Sagnac} \xrightarrow{10^{-9}} \Delta\phi_{GR}$$

Outlook – probing curved space time…?



$P = 6\ km \qquad L_f = 54\ km$

$\frac{GI}{c^2R^3}(2\cos\theta\cos\alpha - \sin\theta\sin\alpha)$

tic + Lense-Thirring

$\rightarrow \Delta\phi_{GR}$

Summary – Photonic Quantum Interferometry

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Experimental Indefinite Causal Order

- Photonic quantum switch for foundations and applications

Measurement of Earth rotation (non-inertial reference frame)

- Sagnac phase-shift using single-photons and two-photon **NOON** states

Measurement of general relativistic effects

- Gravitationally-induced phase shift acting on **entangled photons**

HORIZON 2020
ErBeStA
erc
CoQuS Complex Quantum Systems
FWF Der Wissenschaftsfonds.
QUANTERA ERA-NET Cofund in Quantum Technologies
UNIQORN Affordable Quantum Communication for Everyone
AFOSR Air Force Office of Scientific Research
Red Bull M1ND G4M3RS
QUANTUM FLAGSHIP
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Team Photonic Gravity Quantum Experiments