Jet Propulsion Laboratory
California Institute of Technology

Quantum Optics in Cislunar Space

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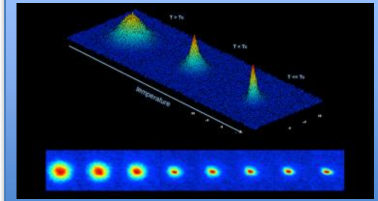
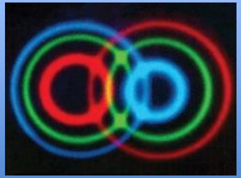
Motivation

Quantum Theory explains "Atomic Scale" physics



JPL BEC & AI



Quantum Entanglement:
Multiple particles,
one wavefunction

Recent experimental results prove quantum wavefunctions can extend 1000+ km

1

Testing the Bell inequality on frequency-bin entangled photon pairs using time-resolved detection

XIANXIN GUO, YEFENG MEI, AND SHENGWANG DU*

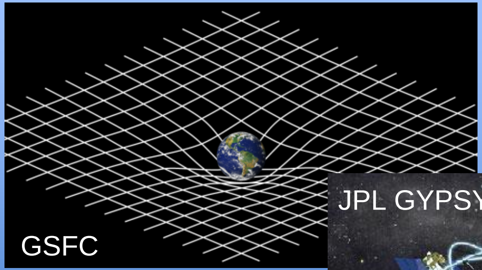
2

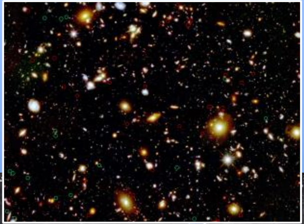
Satellite-based entanglement distribution over 1200 kilometers

Juan Yin,[1,2] Yuan Cao,[1,2] Yu-Huai Li,[1,2] Sheng-Kai Liao,[1,2] Liang Zhang,[2,3]

2016 & 2017

Classical Physics/General Relativity explains "Large Scale" physics





Open Questions in Science:

- Does propagation through a changing gravitational potential result in a measurable change to an entangled quantum state?
- If a change in the quantum state is measured, what does that tell us about spacetime?

3

Space QUEST mission proposal: Experimentally testing decoherence due to gravity

ISS Mission proposal (arXiv:1703.08036v2 [quant-ph] 26 Apr 2017)

Quantum Fidelity and Coherence

Entangled State Production Rate = R pairs/s

Path-A

Multiple Measures of Particle A ~ Matrix ρ_1

Path-B

Multiple Measures of Particle B ~ Matrix ρ_2

R > received flux

Compute Fidelity[7]

$$F(\rho_1, \rho_2) = \left(\mathrm{Tr}\left\{\sqrt{\sqrt{\rho_1}\rho_2\sqrt{\rho_1}}\right\}\right)^2$$

There are formal relationships between coherence and fidelity[8, 9]

Interaction with environment along Path-B drives an *averaging* of the matrix ρ_2

Leading to reduced Fidelity

"environment"

Uncertainty effects[4,5]
Clock precision[6]
Scattering

Gravity?
Other sources?

4. Karolyhazy F, Nuovo Cimento 52 39 (1966)
5. Gambini R, Porto R and Pullin J, Phys. Rev. Lett. 93 240401 (2004)
6. Altepeter, JB, Jeffrey, ER, and Kwiat, PG, Photonic State Tomography
7. Liu, C.L., Zhang, DJ., Yu, XD. et al. Quantum Inf Process 16: 198. (2017)
8. Streltsov, A, et al, Physical Review Letters 115, 020403 (2015)
9. Anastopoulos and B L Hu, Class. Quantum Grav. 30 165007 (2013)

Models for Gravity-Induced Quantum Decoherence

Propagate using Hamiltonian containing gravitational and vacuum interactions; treat as linearized perturbations from weak gravitational fields and relative velocity << c

$$\rho_t(p, p') = \exp\left[-\frac{i}{2m_R}(p^2 - p'^2)t - \frac{4\pi G\Theta}{9m_R^2}(p^2 - p'^2)^2 t\right]\rho_0(p, p')$$ [9]

Θ: "textures of spacetime" [9]

The underlying configuration of spacetime – has **not** been measured

Θ: 0 → no decoherence due to gravity; "Minkowski spacetime is the ground state of quantum gravity"

Θ > 0 → "Gravity is a hydrodynamic theory", coarse-grained structure of arbitrary length scale may exist in spacetime

9. Anastopoulos and B L Hu, Class. Quantum Grav. 30 165007 (2013)

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Models for Gravity-Induced Decoherence

- Deutsch's theory[10]: curved spacetime may contain closed time like lines
  - A particle can interact with a future version of itself
- Ralph and Pienaar developed framework to measure resultant decoherence sending entangled light 'along the well' in the Schwarzschild metric[11]

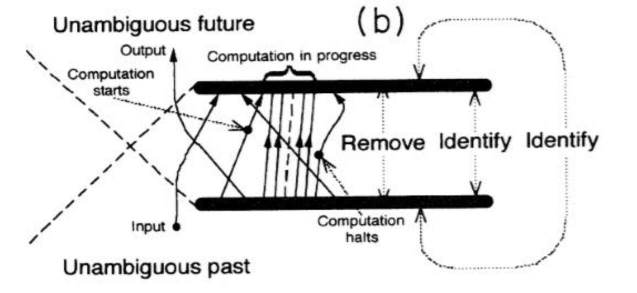
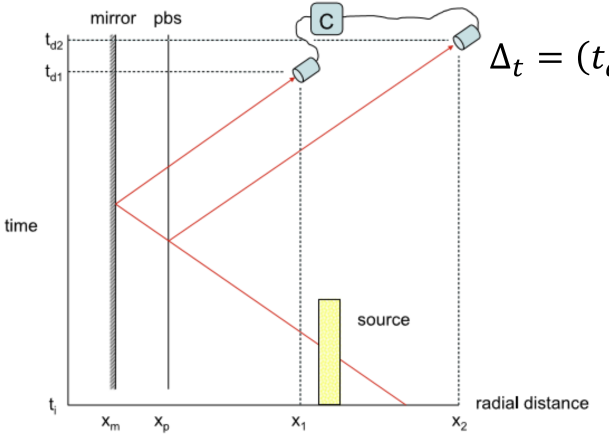


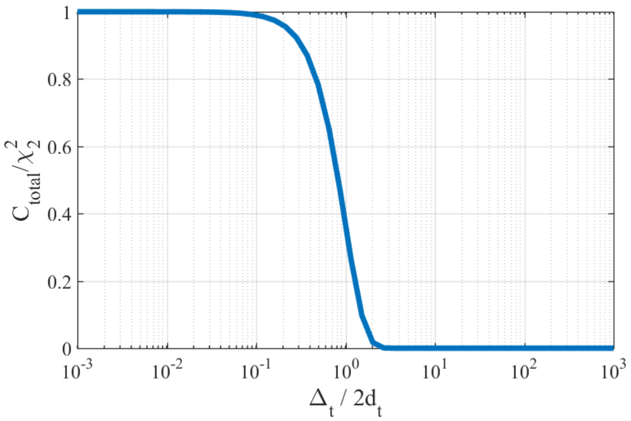
FIG. 7. (a) How to compute anything in no time? (b) Space-time implementation of Fig. 7(a).



$$\Delta_t = (t_{d1} - t_{d2}) + (\tau_2 - \tau_1) \approx M ln({}^{x_1}/_{x_2})$$

$$\tau(t, t_d) = \int_t^{t_d} ds$$

$$C_{\text{total}} = |\chi_2|^2 e^{-\frac{\Delta_t^2}{2d_t^2}}.$$

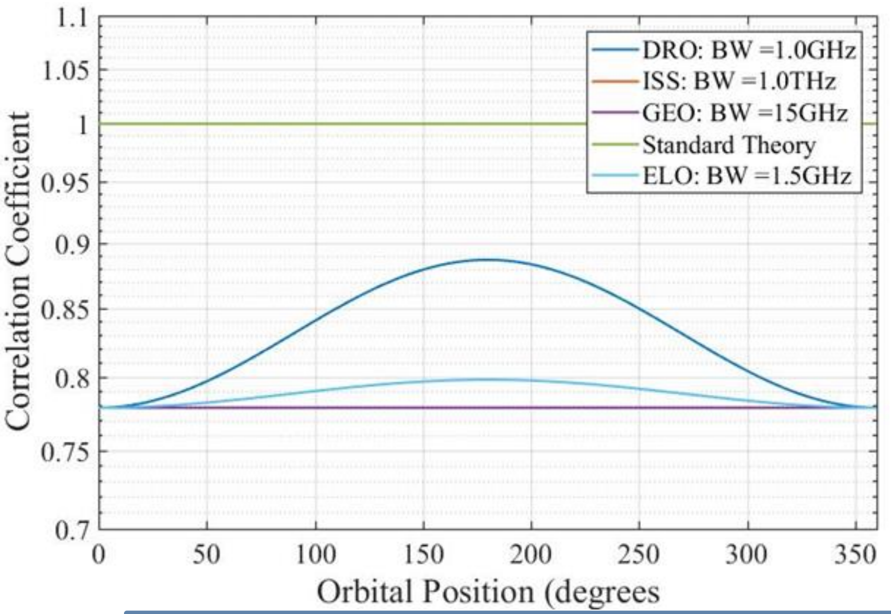


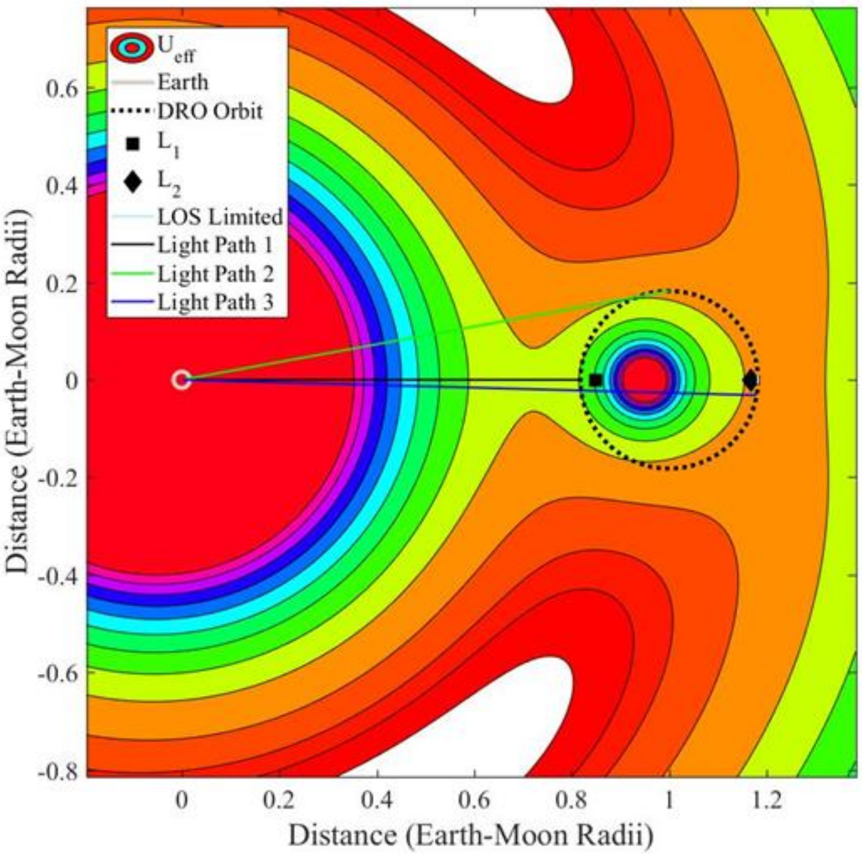
10. Deutsch, D, Physical Review D, 44, 10 (1991)
11. Ralph, TC and Pienaar, J, New Journal of Physics, 16 085008 (2014)

Transitioning from point-like Earth to the N-Body system

First Order Evaluation:

- Linear sum of point-like sources (Earth-Sun-Moon-Jupiter)
- Flying qubit is in its own inertial frame
- Critical boundary is surface where orbital angular momentum and lunar gravity is equal to earth gravity (not the Lagrange points)
- An independent test of the Equivalence Principle





Open question: how do points of inflection in the field line of sight affect the mechanism of decoherence?

N-Body System

[13]

Next Order Evaluation:

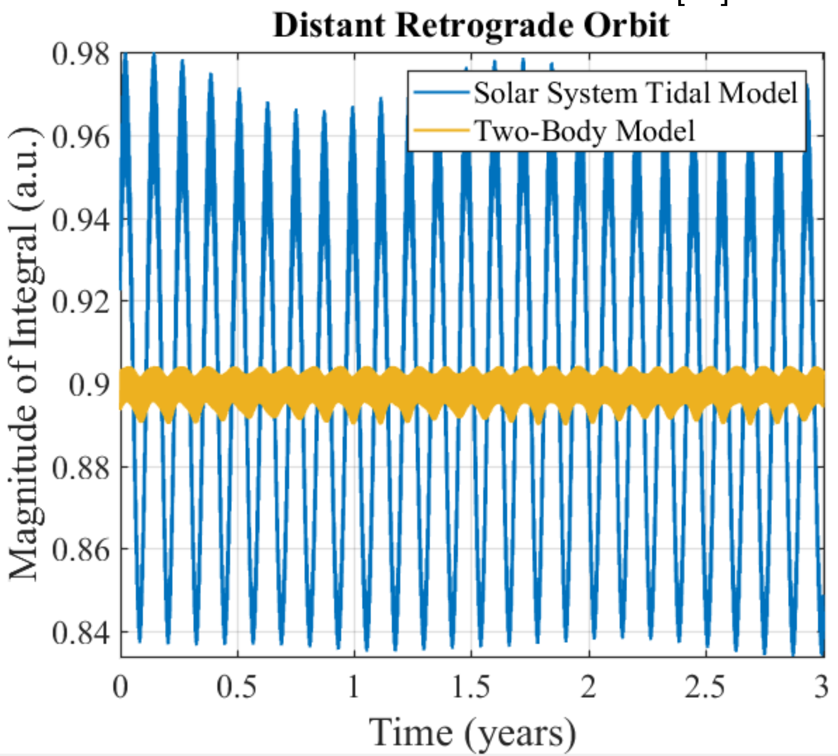
- Rework integration outside of “event formalism” symmetric-shell framework
- N-body numerical solution will have off-diagonal terms
- Potential to test alternative gravity theories
    - Replace earth Schwarzschild radius with n-body effective Schwarzschild radius per PPN[12]

$$\tau(t, t_d) = \int_t^{t_d} \mathrm{d}s \qquad \mathrm{d}s^2 = g_{\mu\nu}\, \mathrm{d}x^\mu\, \mathrm{d}x^\nu,$$

$$g_{00} = 1 - 2\alpha \sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|} + 2\beta\left(\sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\right)^2 + 2\alpha' \sum_i \sum_{j\neq i} \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\frac{m_j}{|\boldsymbol{r}_i-\boldsymbol{r}_j|}$$
$$+ \frac{\chi}{c^2}\sum_i \frac{m_i(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{a}_i}{|\boldsymbol{r}-\boldsymbol{r}_i|} - \frac{4\alpha''}{c^2}\sum_i \frac{m_i v_i^2}{|\boldsymbol{r}-\boldsymbol{r}_i|} + \frac{\alpha'''}{c^2}\sum_i \frac{m_i\{(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{v}_i\}^2}{|\boldsymbol{r}-\boldsymbol{r}_i|^3}$$

$$g_{0k} = \frac{4\Delta}{c}\sum_i \frac{m_i(\boldsymbol{v}_i)_k}{|\boldsymbol{r}-\boldsymbol{r}_i|} + \frac{4\Delta'}{c}\sum_i \frac{m_i\{(\boldsymbol{r}-\boldsymbol{r}_i)\cdot\boldsymbol{v}_i\}(\boldsymbol{r}-\boldsymbol{r}_i)_k}{|\boldsymbol{r}-\boldsymbol{r}_i|^3}$$

$$g_{kl} = -\left(1 + 2\gamma\sum_i \frac{m_i}{|\boldsymbol{r}-\boldsymbol{r}_i|}\right)\delta_{kl},$$



Brans-Dicke or Nordtvedt spacetime would yield *measurably* different results than Einstein GR

12. B Breen J. Phys. A: Math. Nucl. Gen. 6 150 (1973)
13. https://ssd.jpl.nasa.gov/horizons.cgi

Feasibility

Source Production Rate R ~ 10^5 ph/s[14]

Divergence Div ~ -310 dB

Transmitter Gain Tx ~ 121 dB[15]

Receiver Gain Rx ~ 146 dB [16]

T = duration of flyby ~ 6 hours

N = number of datum to perform tomography

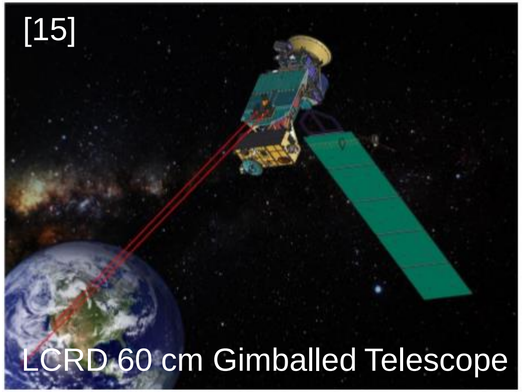
→ Requires clock stability of $\sigma_y^2 < 2 \cdot 10^{-14}$ @ 1 s

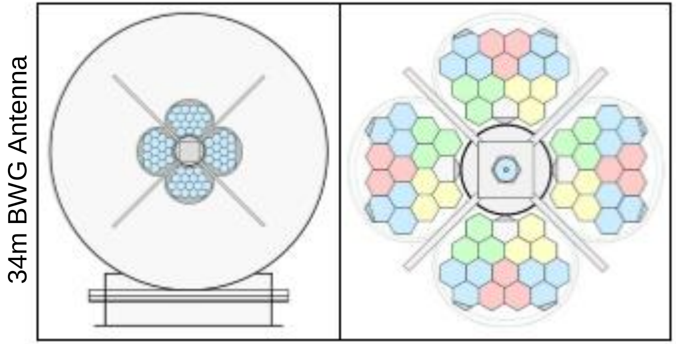
N < 10^((Tx + Rx + Div + Eff)/10) * R * T

N < 10^((121+146 - 310 - 10)/10) * 10^5 * 6*3600

N < 10,800 [sufficient to perform tests to 6σ confidence]

Enabling Technologies:





[16]: JPL large area ground receivers for deep space optical communication

Summary

- We do not know if quantum coherence is coupled to gravity
- We do not know if there is fine structure or texture in curved spacetime
- We do not know if time forms closed loops in the presence of mass
- **Addressing these questions experimentally will open new doors for fundamental physics, and influence the practical design of planned quantum communication networks and satellite links**

- Earth-orbiting missions to distribute entangled photon pairs to two different gravitational potentials could validate existence of this type of coupling
- **Moon-orbiting missions will unambiguously determine the detailed nature of the coupling; test the equivalence principle; and potentially test alternative metric theories**

[17]

References

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14. arXiv:1803.05171v1 [quant-ph] 14 Mar (2018)
15. https://www.nasa.gov/mission_pages/tdm/lcrd/overview.html
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17. https://images.nasa.gov/details-as11-44-6551.html

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