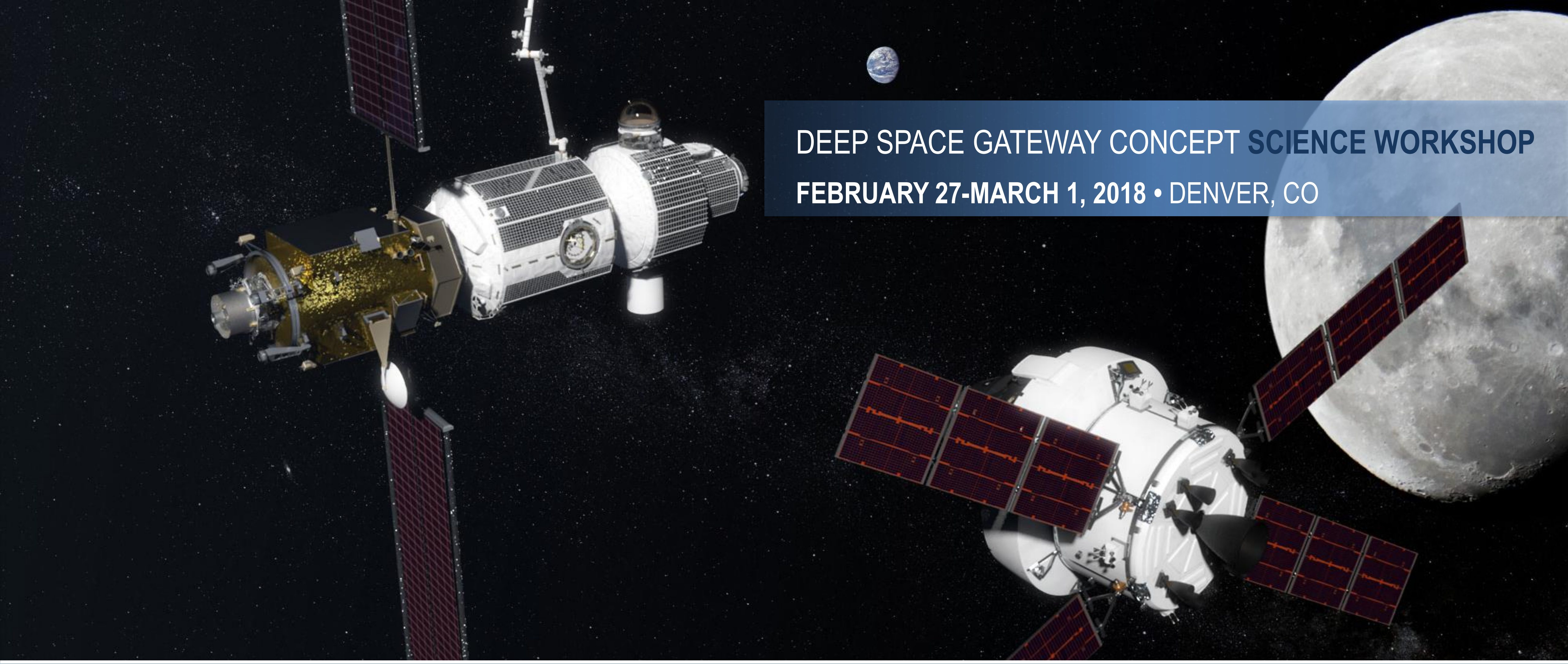

Deep Space Quantum Link

February 27, 2018

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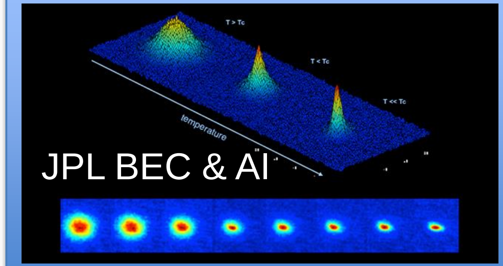
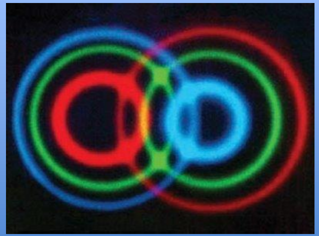
Motivation

Quantum Theory explains "Atomic Scale" physics





Quantum Entanglement:
Multiple particles,
one wavefunction

Recent experimental results prove quantum wavefunctions can extend 1000+ km

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

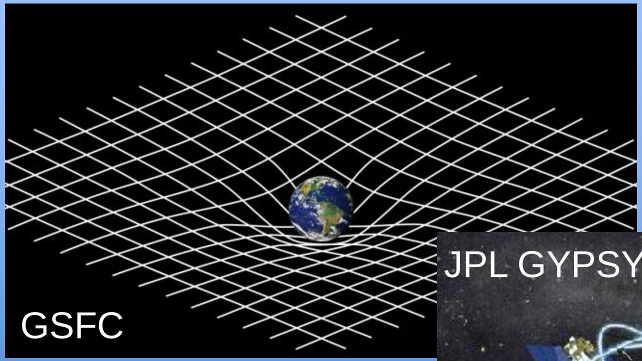
Xianxin Guo, Yefeng Mei, and Shengwang Du*

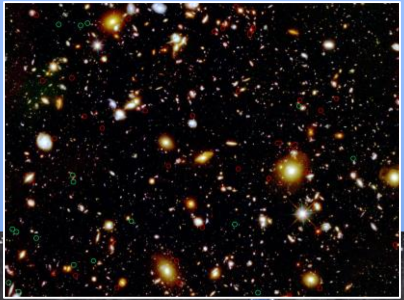
Satellite-based entanglement distribution over 1200 kilometers

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?

Space QUEST mission proposal: Experimentally testing decoherence due to gravity

ISS Mission proposal (ESA, 2017)

Instrument Function Statement and Gateway Usage

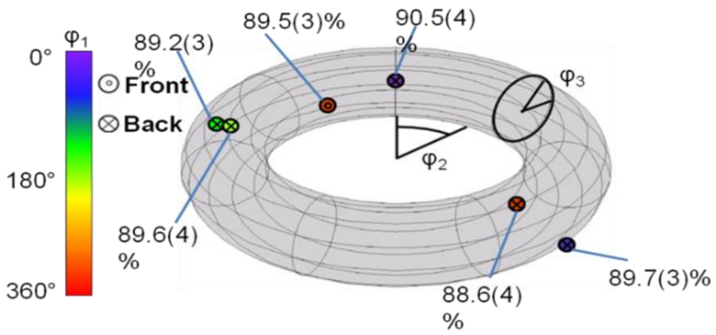
STATEMENT	INSTRUMENT/CONCEPT DETAILS
FUNCTION STATEMENT • **Are quantum wave functions nonlocal at deep-space lengths?** • **Does spacetime contain closed time-like curves?** • **Does operation *beyond* L1 result in re-coherence of quantum light?**	1. High repetition rate, low bandwidth entangled photon source 2. Classical optical channels for pointing, acquisition, and tracking; beam director 3. Optical bench and single photon detector system 4. Ground station (user facility) 5. Instrument will perform quantum key distribution demonstration 6. Instrument will provide classical optical communication channel
WHY IS THE GATEWAY THE OPTIMAL FACILITY FOR THIS INSTRUMENT/ RESEARCH? • Operation *at* Lagrange Points enables measurement “at infinity” from perspective of potential energy—maximum sensitivity • Allows causality loophole free Bell’s inequality measurement • Potential crew interaction to remove “freedom of choice” loophole • Only platform near Earth-Moon Lagrange point, allows unambiguous testing	(see table below)

Model	Predicted Effect	Measurement System
Special Relativity	Time dilation	Spectroscopy
General Relativity, classical light	Time dilation and redshift	Global Positioning System
General Relativity – QM Deutsch Model, entangled photons	**Decoherence of entanglement**	**Deep Space Quantum Link**

Basic Instrument Parameters

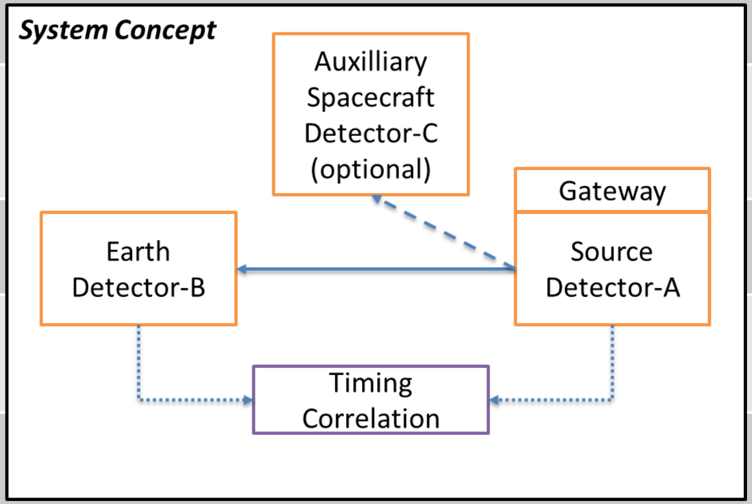
PARAMETER	INSTRUMENT ESTIMATE & ANY COMMENTS:
MASS (KG)	190 – 220 kg estimate
VOLUME (M)	1 m^3 estimate
POWER (W)	300 – 400 W estimate
THERMAL REQUIREMENTS	Minimal. Power budget includes allocation for detector cooling
DAILY DATA VOLUME	Health and status data only; experimental data to be transmitted on the self contained PAT system; majority of data generated on ground station
CURRENT TRL	TRL 3+ : Systems representative of all major subassemblies have been deployed on spacecraft
WAG COST & **BASIS**	WAG estimates and other parameters are based on comparisons to similar-to quantum physics packages to be deployed on spacecraft and ISS
DURATION OF EXPERIMENT	12-36 months estimate
OTHER PARAMETERS	

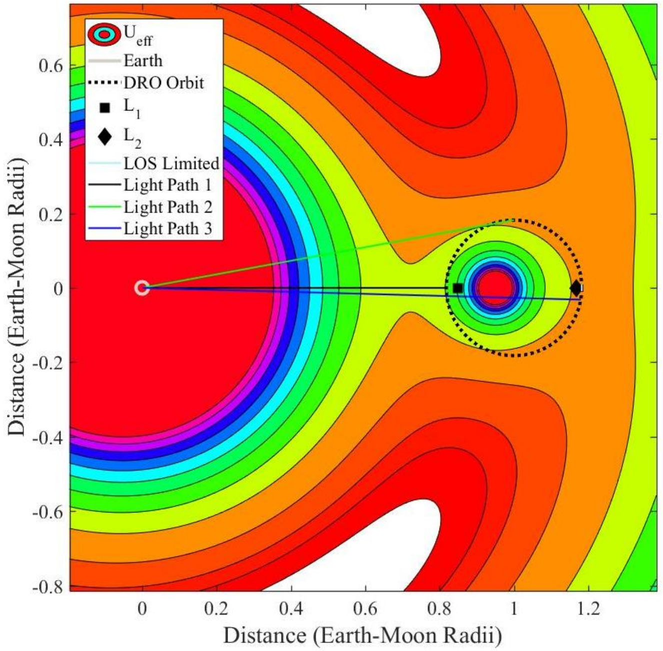
Basis of Estimates: "Quantum Teleportation from Space" NASA program: Super Dense Teleportation of Hyper-Entangled Photons From ISS to Ground Station



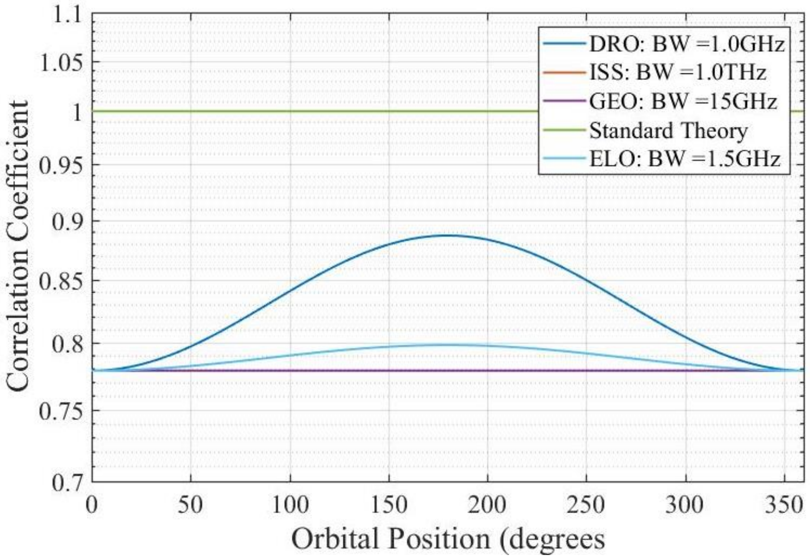
Instrument Gateway Usage

USAGE	INSTRUMENT REQUIREMENTS & COMMENTS
ORBIT CONSIDERATIONS	(optimal) DRO, (acceptable) NRHO, HALO, ELO, (limiting) LLO orbit limits line-of-sight to earth
FIELD OF VIEW REQUIREMENTS	Requires line-of-sight to earth ground station or relay
REQUIRES USE OF AIRLOCK	None
CREW INTERACTION REQUIRED?	Crew can be involved in Bell Test to address "randomness" factors in quantum measurement
WILL ASTRONAUT PRESENCE BE DISRUPTIVE?	No
DOES THE INSTRUMENT PRESENT A RISK TO THE CREW	No
OTHER CONSUMABLES REQUIRED	None
SPECIAL SAMPLE HANDLING REQUIREMENTS	None
NEED FOR TELEROBOTICS?	None
OTHER REQUIREMNTS OF THE GATEWAY?	





DSG Advantage: Testing at different points along the DSG orbit modulates the expected signal, eliminating the measurement ambiguity inherent with earth-orbiting spacecraft.



Ideal Measurement Scenario

References and Status of Work in this Field

- **Theoretical Framework:** New Journal of Physics 16 (2014) 085008 doi:10.1088/1367-2630/16/8/085008
- **Theoretical Framework:** arXiv:1309.3088v3 [quant-ph] 26 Apr 2014
- **ISS Mission Proposal (ESA):** arXiv:1703.08036v2 [quant-ph] 26 Apr 2017
- **Space-Based Bell Test (China):** Optica 4 (4) (2017) https://doi.org/10.1364/OPTICA.4.000388
- **Space-Based QKD (China)**: Science 358 (2017)
- **Satellite QKD Review Article:** Nature Quantum Information (2017) doi:10.1038/s41534-017-0031-5
- **Entangled Photon Source:** Phys. Rev. A 89 062320 (2014)
- **Space-Based QKD (Germany):** Optica 4, 611 (2017)

- **"Quantum Teleportation from Space Station" and "Quantum Teleportation from Space" (JPL, MIT-LL, ORNL, NAS, UIUC, Hampshire College, Duke University & NASA HQ (SCAN Office))**
- Superdense Teleportation and Quantum Key Distribution for Space Applications, IEEE ICSOS 978-1-5090-0281-8 (2015)
- Superdense Teleportation for Space Applications, Quantum Information and Computation XII, SPIE (2014)

Backup/Additional Information: Comparison of recent and proposed missions

	Space QKD (Erlangen/ TESAT) 2017	"Quantum Satellite" China National Space Administration 2016	QTS/QTSS (JPL/ MIT LL/ UIUC/ Hampshire/ Duke) Proposed	SPACE QUEST (ESA) Proposed	Deep Space Quantum Link (JPL) Proposed
Experiment	QKD	QKD, Bell's Test, Teleportation	Superdense teleportation	Bell's test, gravity-QM coupling	Bell's test, gravity-QM coupling
Source Location	GEO Satellite	LEO Satellite	ISS or other LEO	Ground telescope facility	DSG
Source Configuration	CV-QKD, Number States	Time-Polarization entanglement	Hyper entangled (polarization, time) photons	Time-Energy or Time-Polarization entanglement	Time-Energy or Time-Polarization entangled; potential for multiple high efficiency sources
Receiver	Ground telescope network	Pair of ground telescopes	Ground telescope facility	ISS Module	Ground telescope

- Atmospheric turbulence effects ground-to-space link more than a space-to-ground link
- Effects of Doppler shift on quantum measurement have been experimentally determined by JPL + UIUC team

As of writing, 4 funded and 6 proposed space missions for quantum communication (3 commercial, 6 foreign government, 1 NASA)