Kwiat

Quantum Information

Group

SEAQUE

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Illinois Quantum Information Science & Technology Center (IQUIST)
University of Illinois Urbana-Champaign

JPL

ILLINOIS

NASA

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SEAQUEing the Final Frontier

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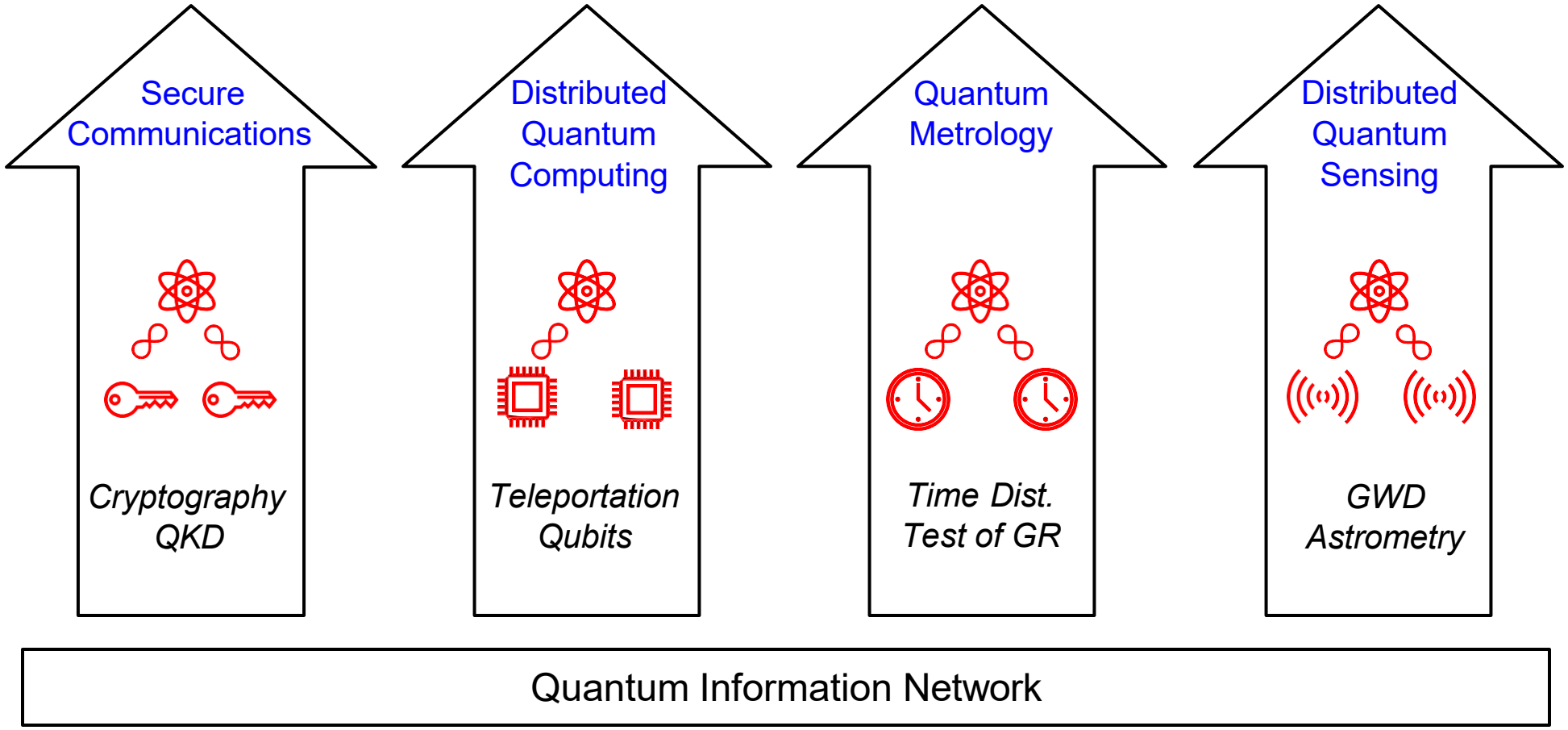
Need for Quantum Space Network



Why (Quantum needs) Space?

Optical Fiber ~ e^{-r} (limited range: 100km fiber = 99% loss)

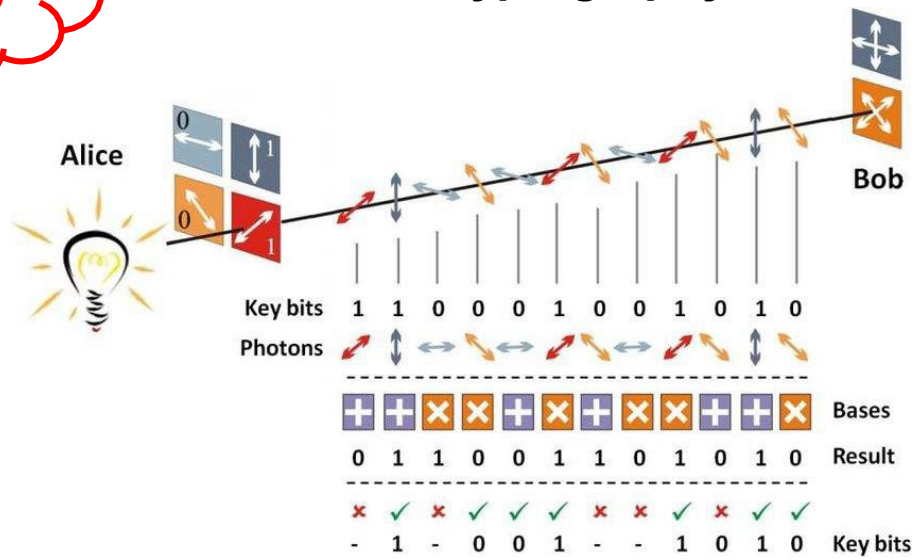
Free-Space Optical Link ~ $1/r^2$ (intercontinental range to deep space)

J. Callas, JPL

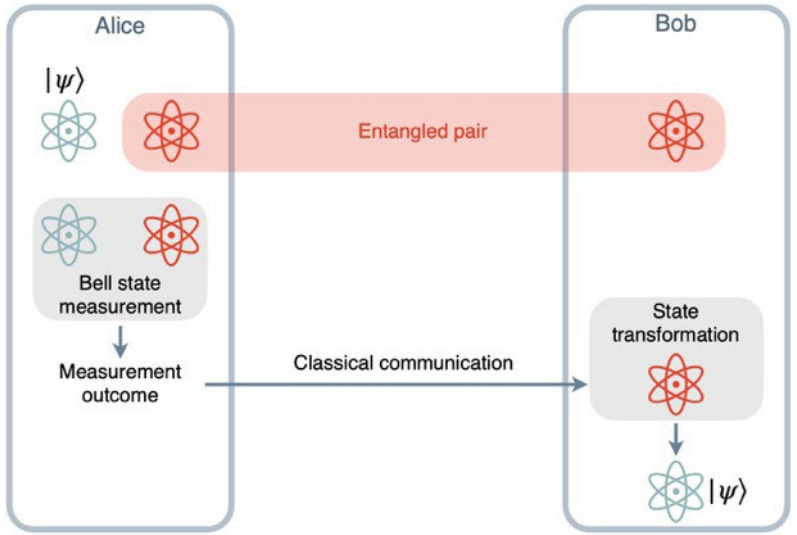
Quantum Space Network Applications

Technology

Quantum Cryptography



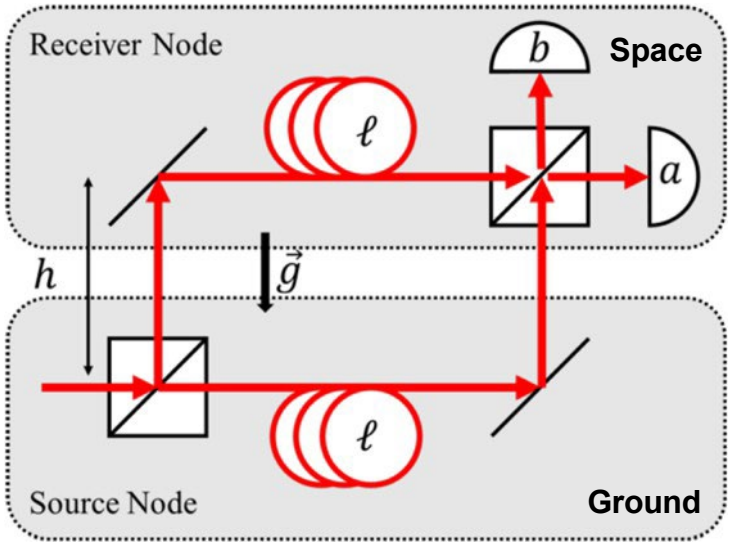
Quantum Teleportation



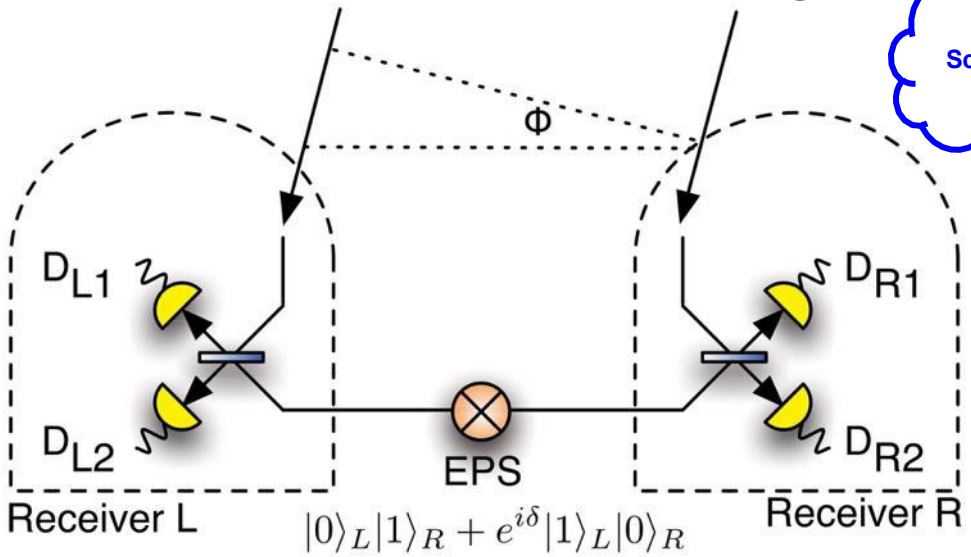
Technology

Science

Quantum Metrology

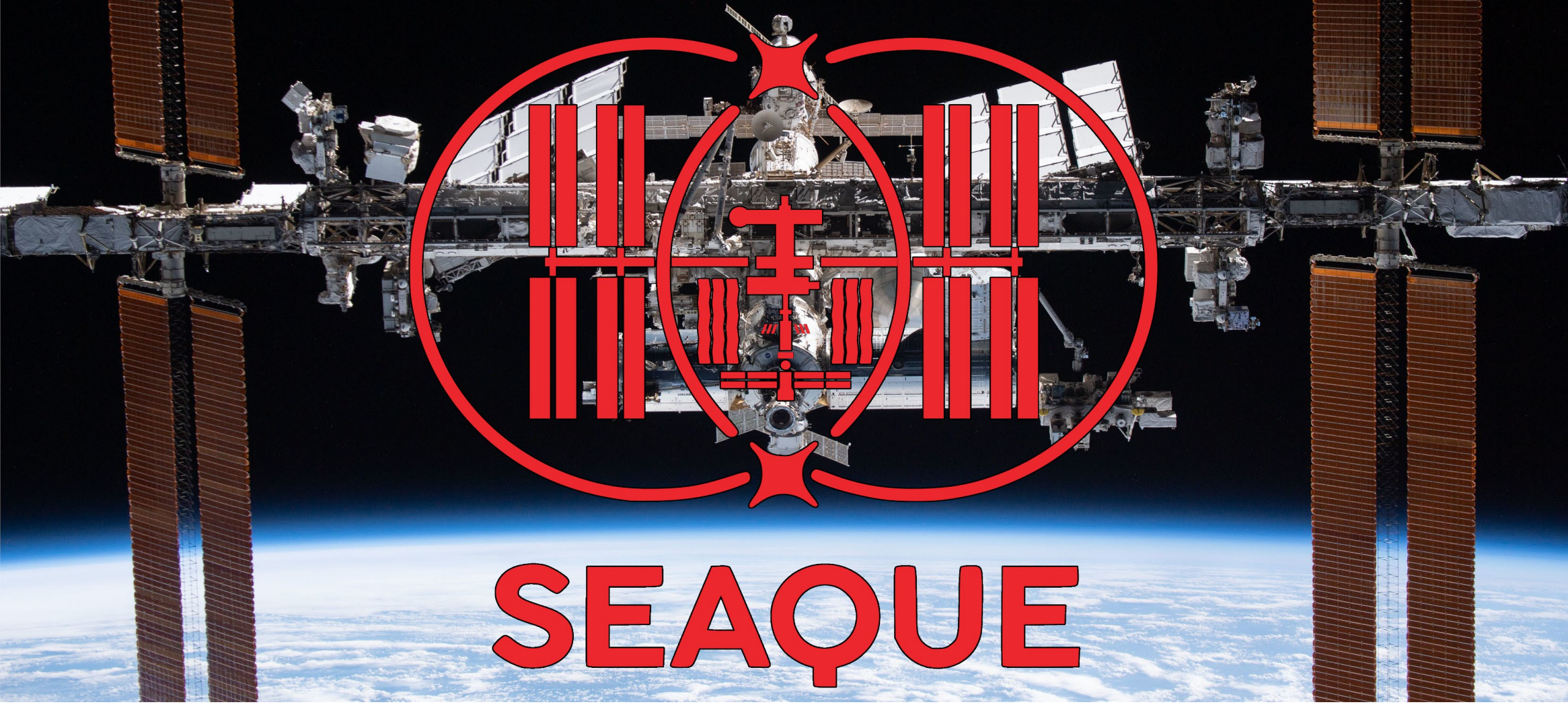


Distributed Quantum Sensing



Science

J. Callas, JPL


SEAQUE

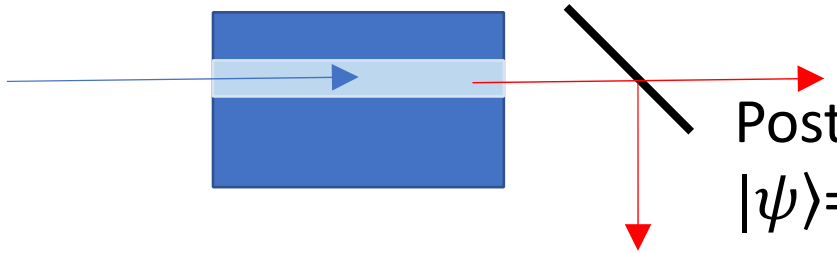
Space Entanglement and Annealing QUantum Experiment

SEAQUE

SEAQUE Goals	Impact
Create and verify <u>entanglement in space</u> • Quantum state tomography • Bell inequality violation	• Never-before flown integrated waveguide source • Demonstrate single element tomography *"Exploration"*
Combat <u>radiation damage</u> with "self-healing" through thermal & laser <u>annealing</u>	• Increase lifetime of quantum payloads • Learn about annealing repeatability *"Know before you go"*

SEAQUE Entanglement Source – lowest SWaP

PPKTP waveguide, Type II
405nm → 810 nm (H) + 810 nm (V)

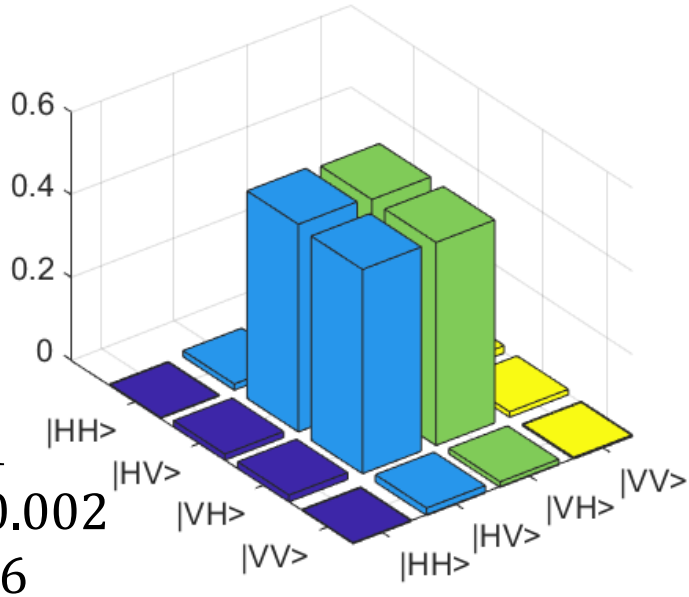


Postselected state:
$|\psi\rangle = |H\rangle|V\rangle + |V\rangle|H\rangle$

Fiber-In/Fiber-Out Timing Compensated SPDC Module
WDC-K0405-P40P85ABC
SN: 22012061

Optical Characterization

Pump Wavelength	404.88 nm
Pair Rate	25 MHz/mW (power in input fiber)
2-Photon Visibility	95% with 3 nm filter
Module Degeneracy Temperature	45.1°C



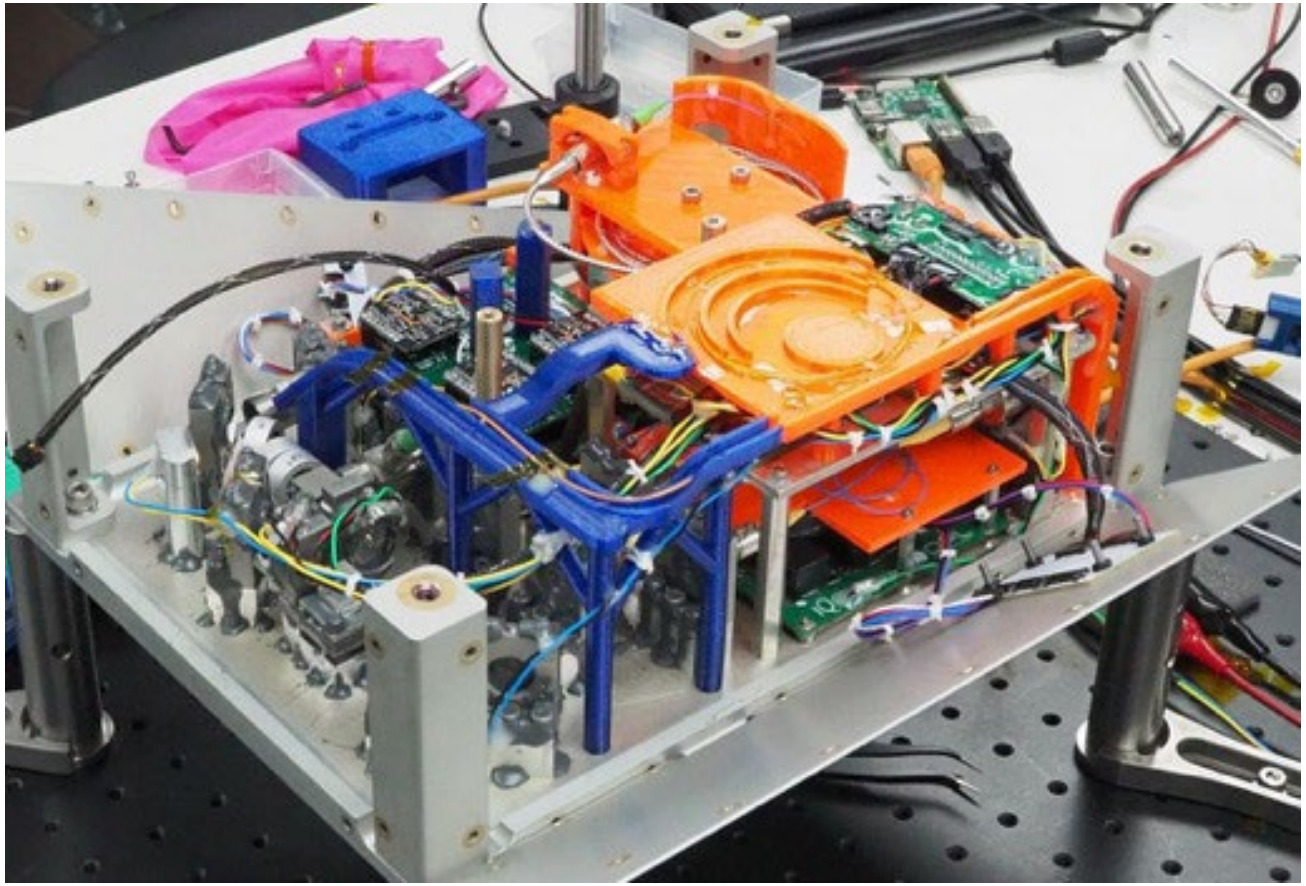
Fidelity: 0.991 ± 0.001
Concurrence: 0.984 ± 0.002
Bell Test: 2.758 ± 0.006

AdvR

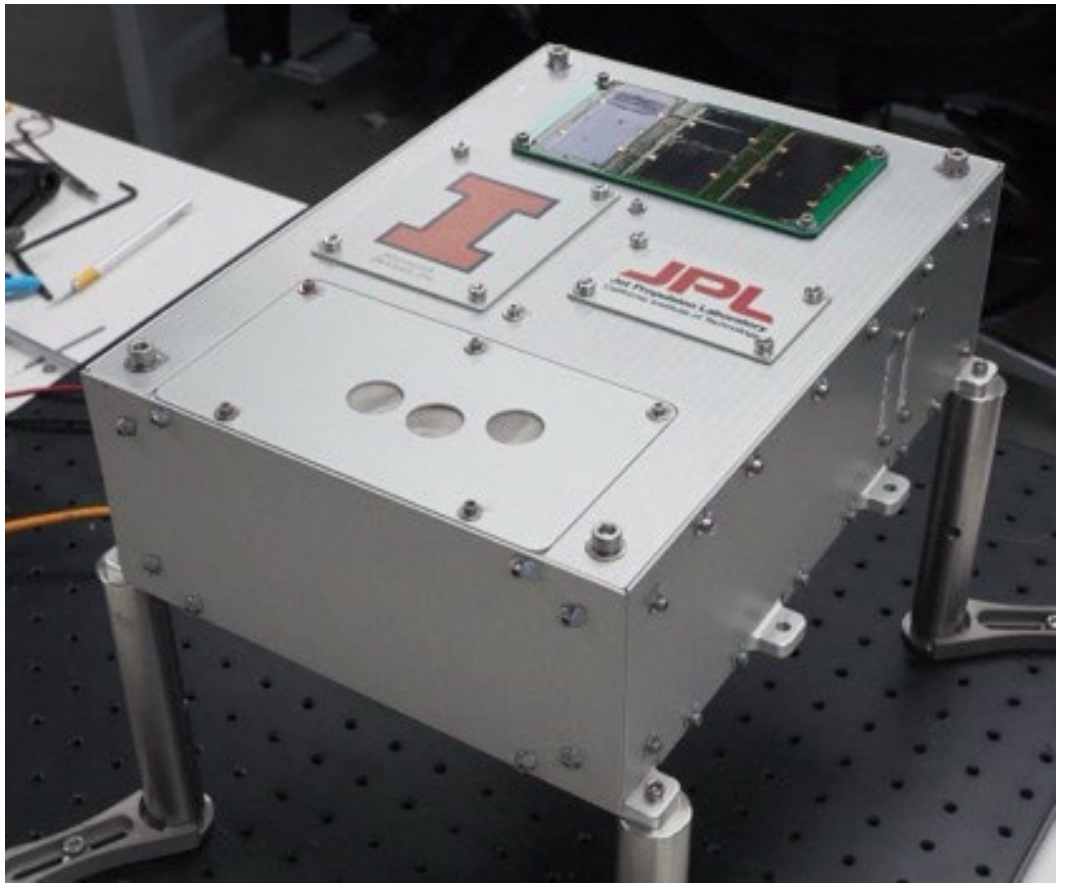
"Commercialization"

Space Entanglement and Annealing QUantum Experiment

Flight System (10x20x30cm):



SEAQUE payload



Launch Day: November 4th, 2024

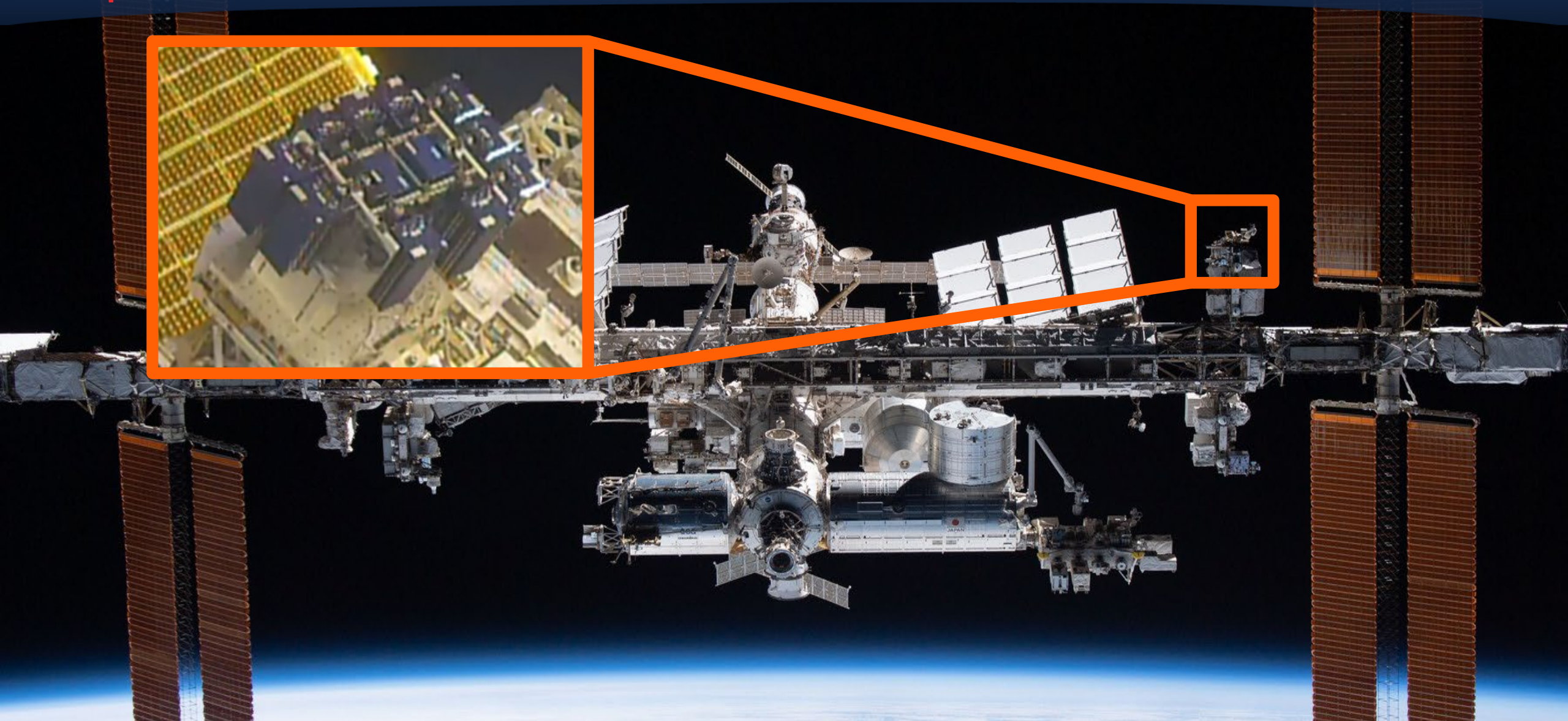
- Launched provider:

AEGIS AEROSPACE

- Kennedy Space Center FL
- Space-X Dragon Resupply Mission CRS-31

SEAQUE

MISSE Platform



SEAQUE

Mounted on ISS

SEAQUE History

- Sept. 2021: SEAQUE started
- June, 2024: Payload delivered to Aegis Aerospace
- Nov. 4, 9:30 pm ET: launch on SpaceX CRS-31
- Nov. 26: SEAQUE ‘power-on’…..

Fidelity = 97-99%

$S = 2.6 \pm 0.01 >> 2 \geq S_{\text{local realism}}$

“And there was much rejoicing…”

- Highest ‘quantumness’ of any space experiment to date!
- Many more tests, detector annealing, etc.
- Will return to Earth in 2026

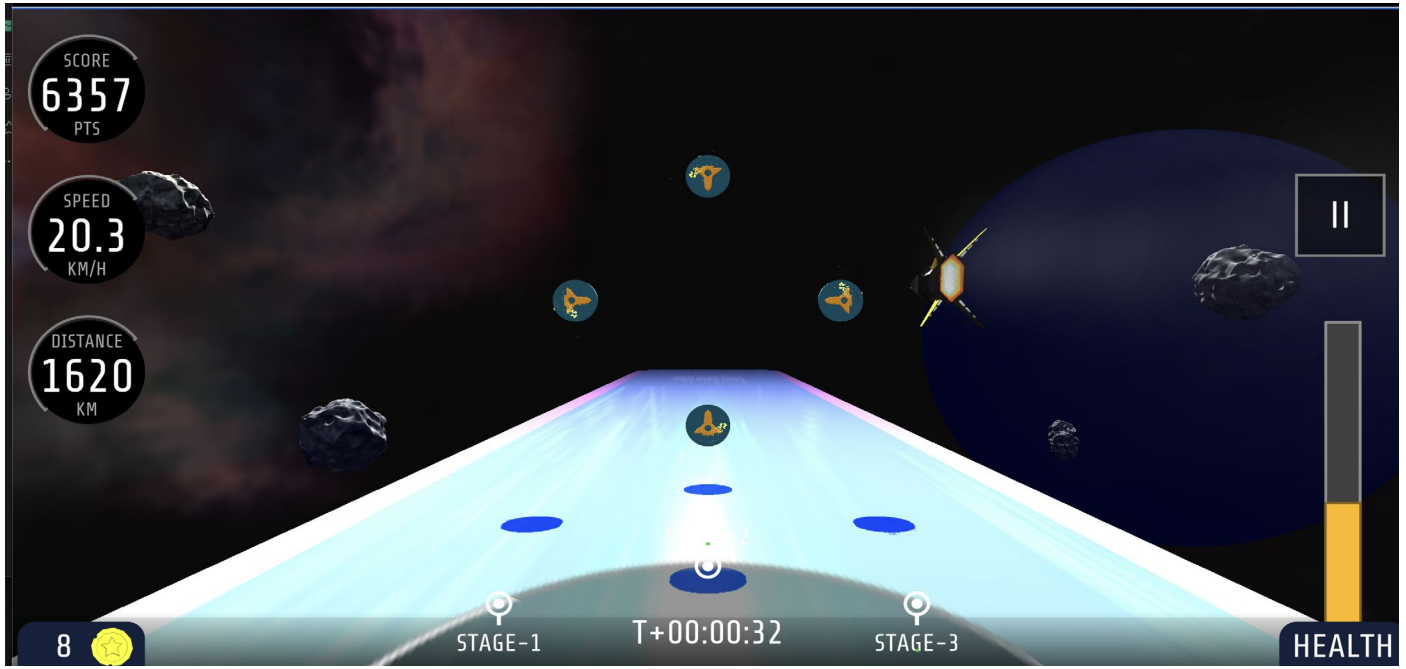
S = 2.70! (4 hours ago)

Outreach: Public Bell Test (@ Quantum Jubilee)

Quantum Satellite Game

- Decisions in the game are mapped to LC settings for a Bell violation
- Connect the public audience to entangled measurement
- Browser game for easy accessibility

- Successful Bell tests run using the public random data during the “Quantum Jubilee”
- Result from audience choices: **2.69 ± 0.16**



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  - Subash Sachidananda
  - Ankush Sharma
  - Daniel Pardo Suárez

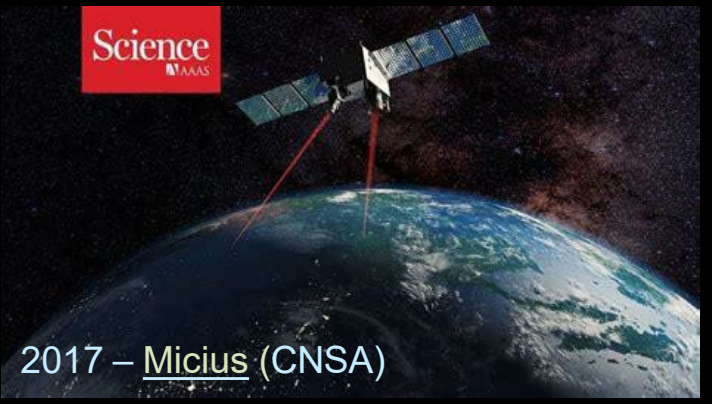
- Prof. Thomas Jennewein
  - Joanna Krynski
  - Noura Bayat
  - Nigar Saltana
  - Paul Godin
  - Zhenwen Wang

BOEING

- Makan Mohageg
- Jay Lowell

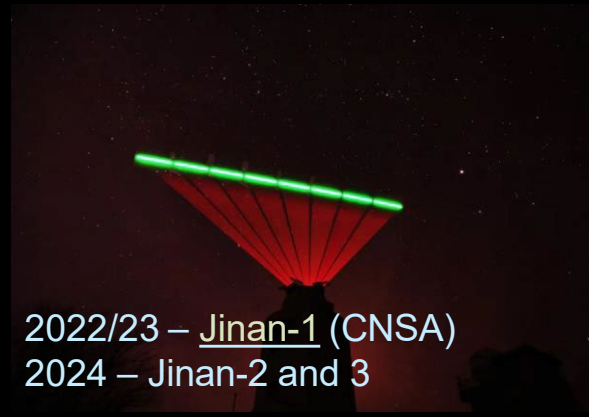
AdvR

Quantum Networking Space Missions

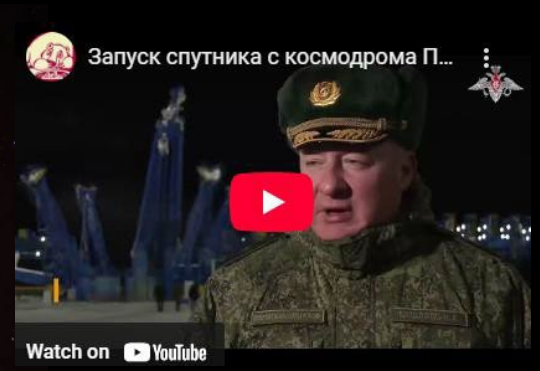


2017 – Micius (CNSA)

2020 – SPOOQY-1 (Singapore)

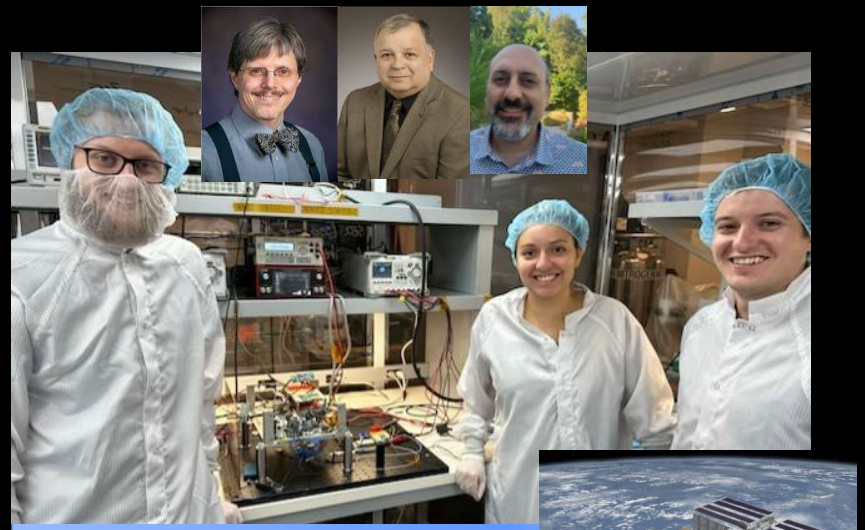


2022/23 – Jinan-1 (CNSA)
2024 – Jinan-2 and 3

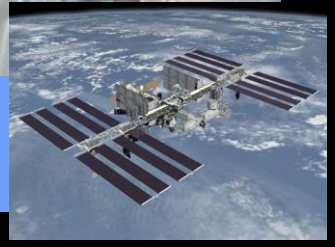


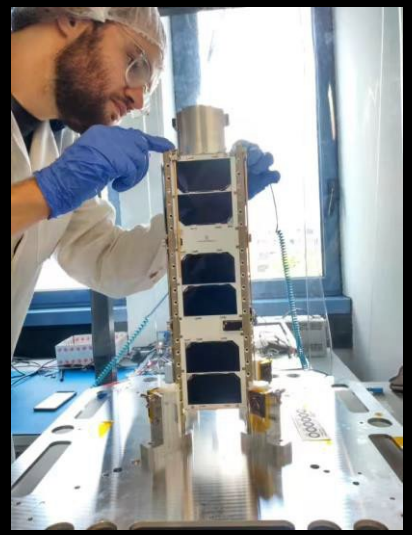
2023 – Vector (Russia)
– not confirmed

2024 – QUBE (Germany)

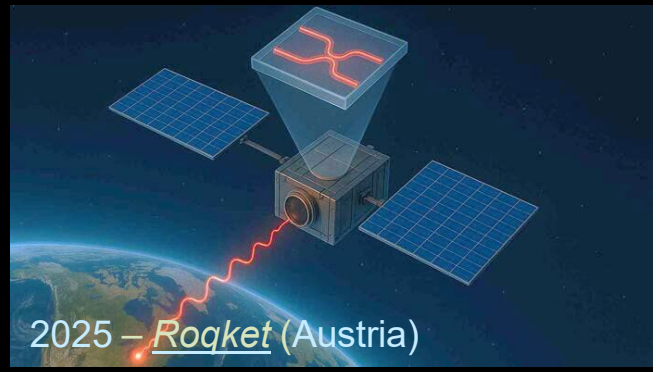


2024 – SEAQUE (USA)





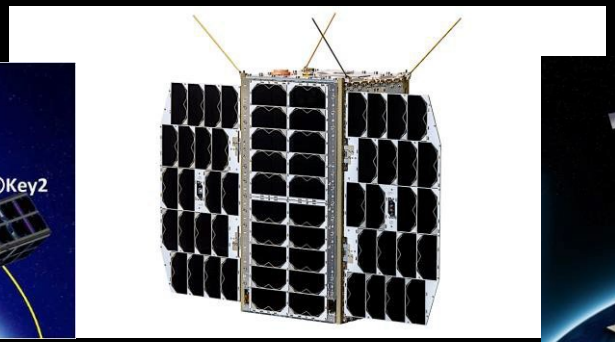
2025 – QUICK³ (Germany)



2025 – Roqket (Austria)

Planned Quantum Networking Space Missions

Nanobob (France, 2026)



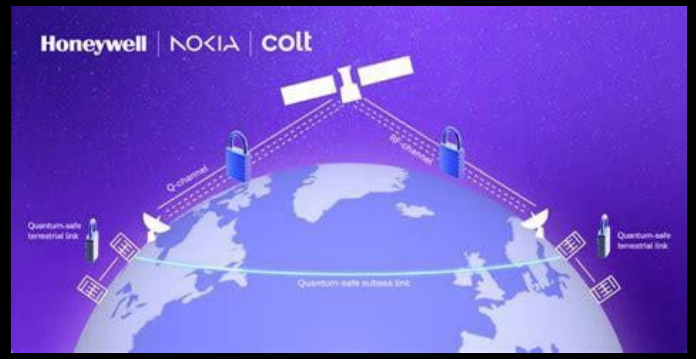
SPEQTRAL-1 & SPEQTRE (Singapore & UK, 2026)

QEYSsat (Canada, 2026)

Q4S (Boeing + HRL, 2026)

QUBE-II (Germany, *2028*)

ROKS (UK, *2028*)



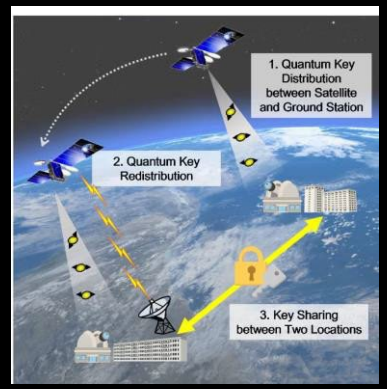
Two Unnamed QKD Missions (Honeywell, Nokia, and Colt, 2027 & 2028)

SAGA (ESA, *2029*)

LEO net➔
MEO relay
GEO relay

CNSA
CHINA NATIONAL SPACE ADMINISTREATION

JAXA/NICT QKD (*2030*)



GEO-QKD, (Spain. *2030*)

Eagle-1 (ESA, *2028*)

Note ~ *italic* ~ estimated date

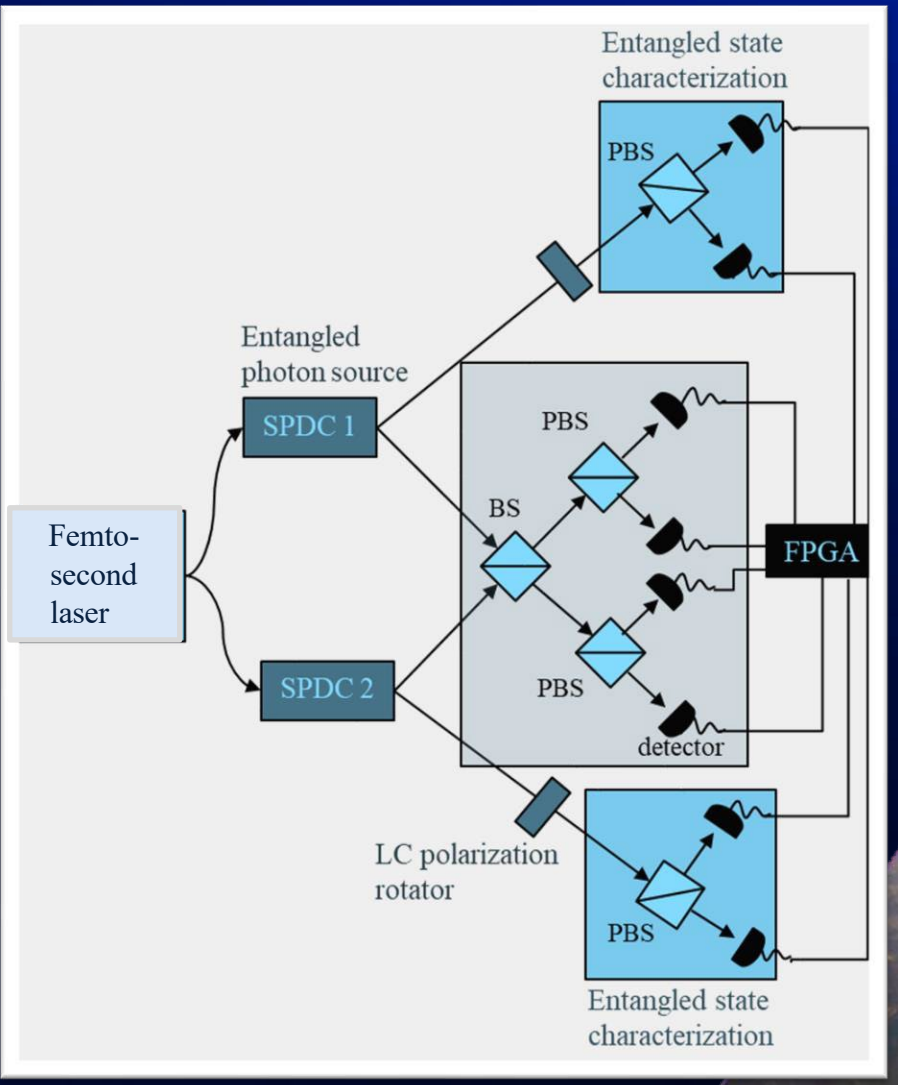
Opportunities for New Physics

- Most of the existing/planned experiments are focused on quantum key distribution (only secure communication)
- Distributing *entanglement* is enabling for
  - Fundamental science
  - Secure communication tasks, e.g., encryption, position verification, multi-party computations, …
  - ‘Blind’ quantum computing
  - Distributed quantum computing
  - Distributed quantum sensing
  - …

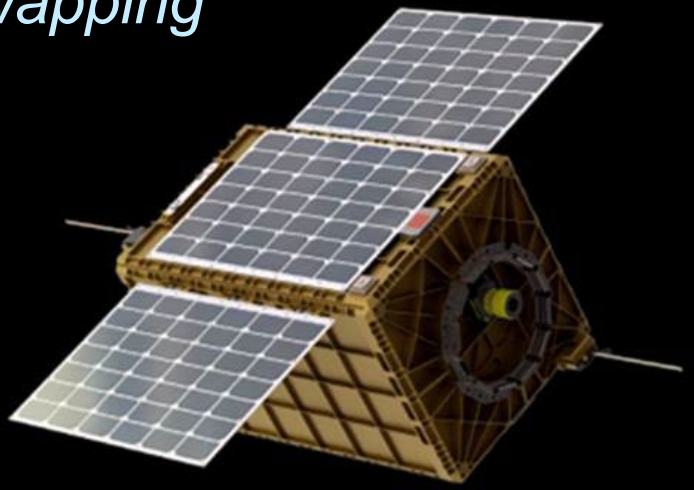
Q4S

Satellite quantum entanglement swapping

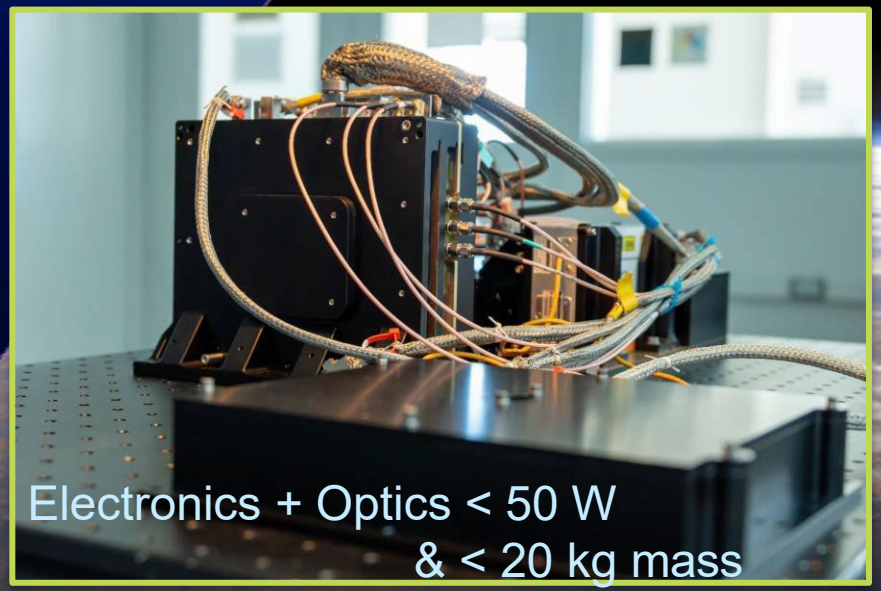
Boeing · HRL · UIUC



Q4S enables space-based quantum networking systems for distributed quantum computing, quantum sensing, and communications



Q4S is on-track for launch into LEO orbit in 2026



Electronics + Optics < 50 W
& < 20 kg mass

www.boeing.com/quantum

Opportunities for New Physics

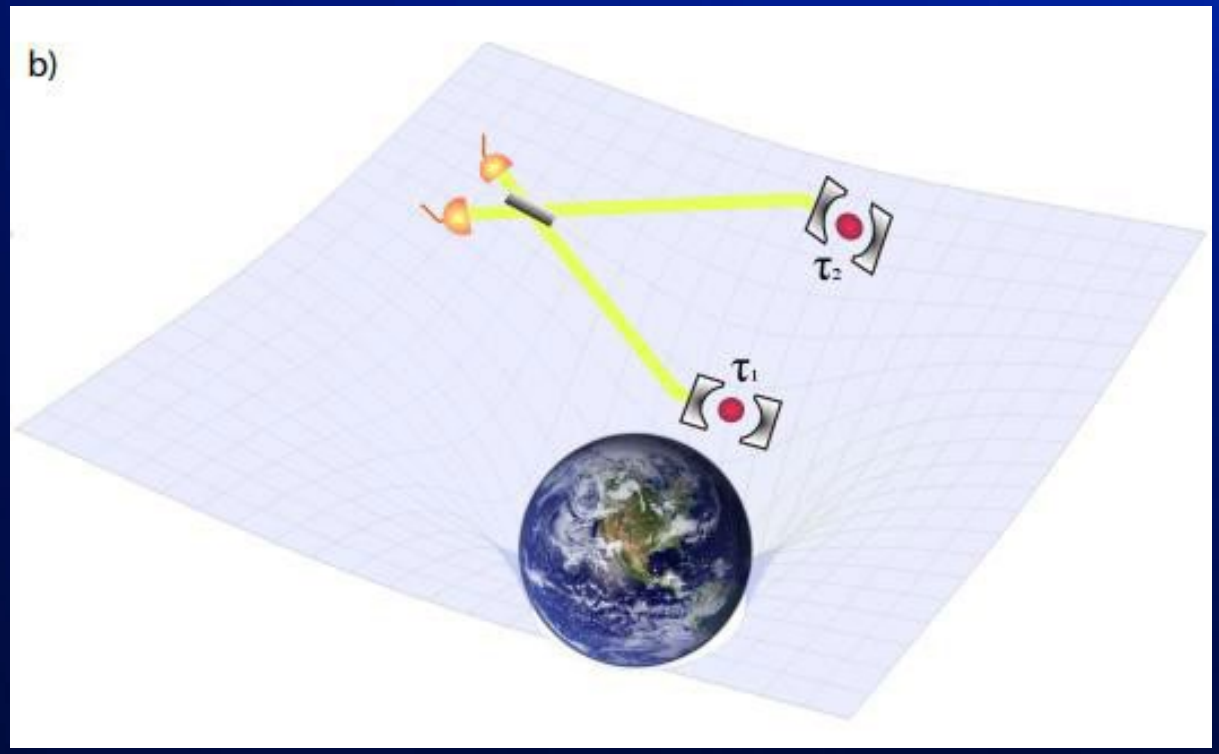
- Most of the existing/planned experiments are focused on quantum key distribution (only secure communication)
- Distributing *entanglement* is enabling for
  - Fundamental science
  - Secure communication tasks
  - ‘Blind’ quantum computing
  - Distributed quantum computing
  - Distributed quantum sensing
  - …

Opportunities for New Physics

- Most of the existing/planned experiments are focused on quantum key distribution (only secure communication)
- Distributing *entanglement* is enabling for
  - ***Fundamental science***
  - Secure communication tasks
  - ‘Blind’ quantum computing
  - Distributed quantum computing
  - ***Distributed quantum sensing***
  - …

Testing General Relativity with Quantum Systems in Space

Matter-based tests

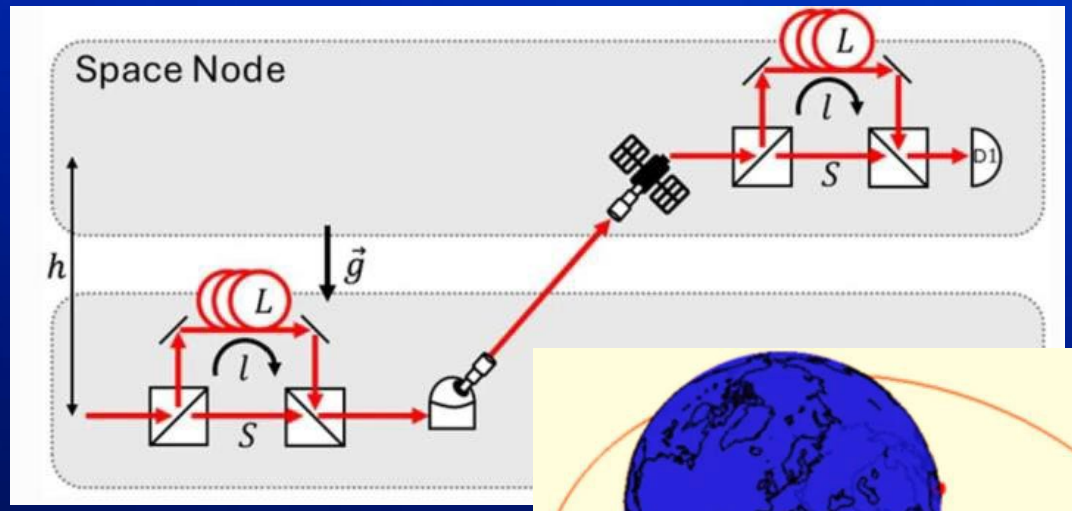


Testing quantum theory on curved space-time with quantum networks

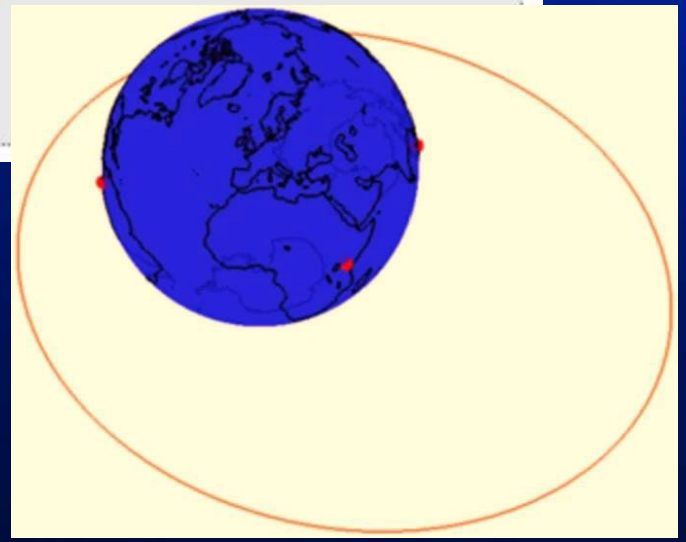
Johannes Borregaard, Igor Pikovski

https://doi.org/10.48550/arXiv.2406.19533

Photon-based tests



Deep space quantum link: measurement and mission concept



Makan Mohageg and Paul Kwiat et al. 2025
https://doi.org/10.1140/epjqt/s40507-025-00370-1

Makan Mohageg and Paul Kwiat et al. 2022

https://doi.org/10.1140/epjqt/s40507-022-00143-0

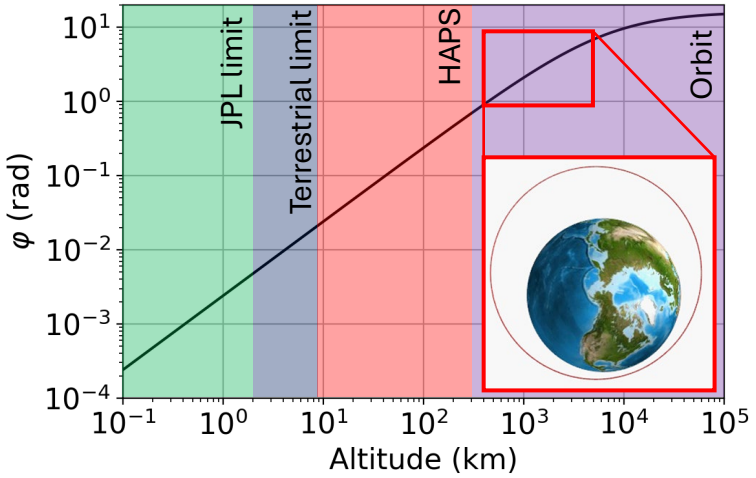
Deep Space Quantum Link Team

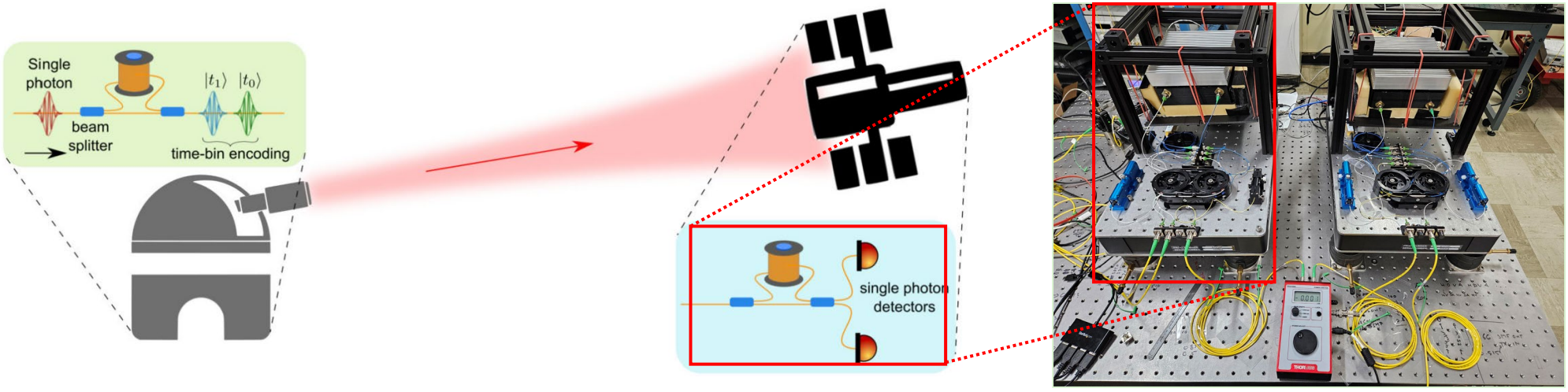
Deep Space Quantum Link (DSQL)

Gravitational redshift of quantum states of light (and beyond)

Investigators: Alexander Lohrmann (JPL), Spencer Johnson (JPL)

- Quantum mechanics (QM) and general relativity (GR) are incredibly successful but fundamentally incompatible
- Proposed experiment will combine gravitational redshift measurements (GR) and quantum interferometry (QM)
- Near-term objective: measure the gravitational redshift on quantum states of light on Earth (1-km altitude difference)
- Satellite links provide access to larger phase shifts and new measurements regimes

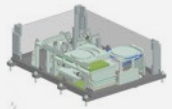




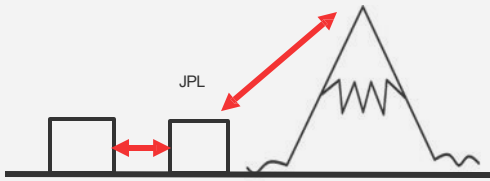
Terrestrial demonstration	LEO-to-ground redshift measurements	Quantum interference of clocks	Gravitational decoherence measurements
Ongoing	5-10 years	> 10 years	> 20 years

Quantum-to-space notional “Roadmap"

SEAQUE on ISS (2024)
Quantum entanglement in space



JPL-to-Mountain Top Gravitational Redshift (quantum field theory in curved spacetime)



Underway

Verification experiments with partner missions

SPOQC
SpeQtral-1
SpeQtre
QEYSSat

Assembly, verification and testing

Science and QC precursor experiments

Future quantum interferometry mission/OTT

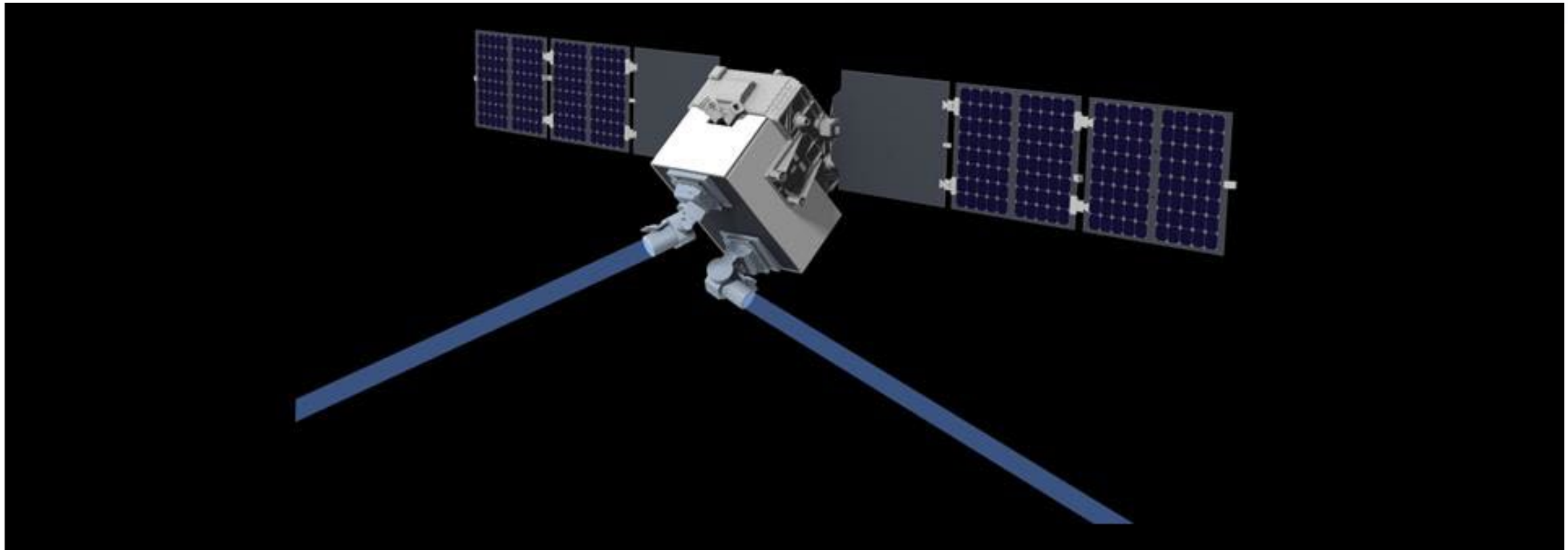
Future quantum communication mission example

Science and QC experiments

2026 2027/2028 2029 Future

QC – Quantum Communications
OTT – Optical Time Transfer

J. Callas, JPL



- **Boeing, HRL, and UIUC lead a government-funded study to architect satellites for future quantum networking missions (non-QKD)**
  - Working towards a first-of-its-kind capability demonstration
  - Accommodation of ‘hosted-payload’ rideshare or linkage to ground station discussed with sponsors
  - *This could support other government agency objectives, including tests of fundamental physics*

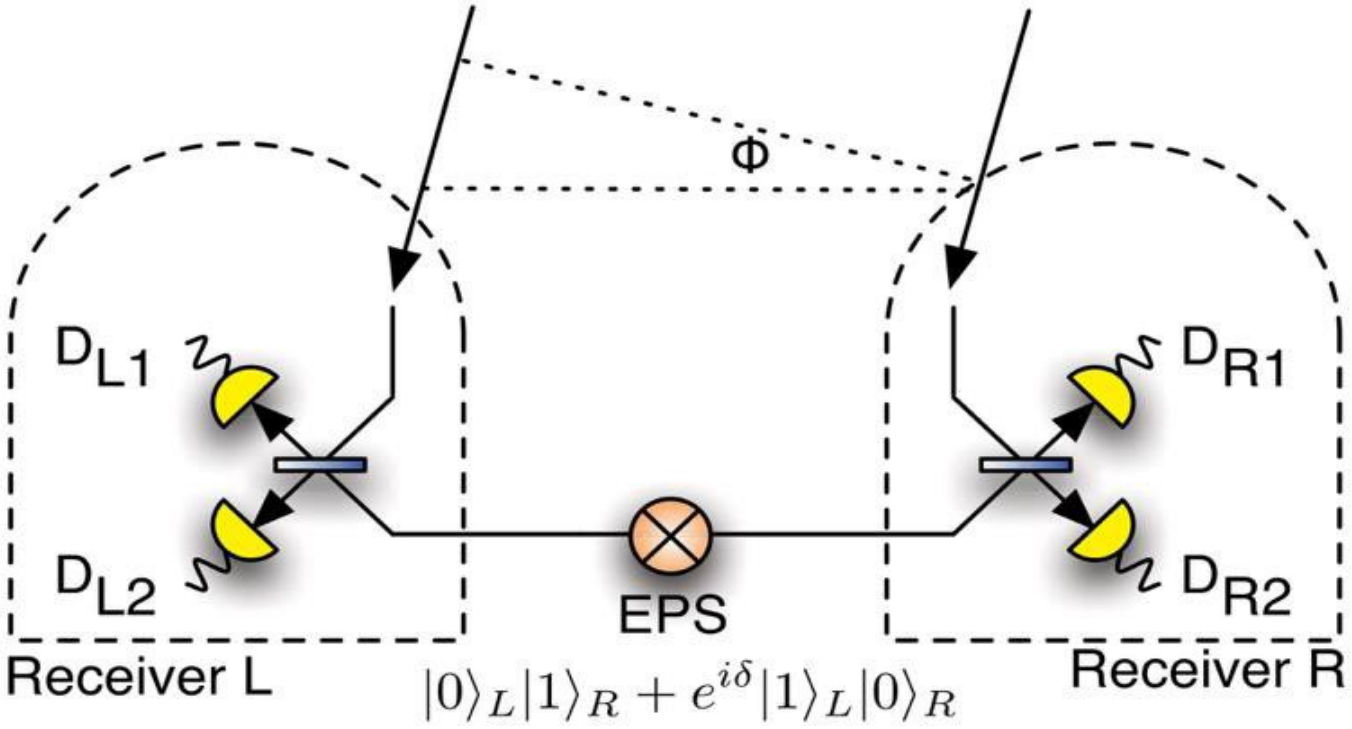
Summary takeaways

- Up/downlink quantum states of light → novel tests of QM + GR
- ***SAME*** technology to enable quantum networking in space!
  → get amazing science AND enabling quantum technologies
- Industry (and other govt) collaborations likely to be fruitful, e.g., Boeing, IonQ, …+ international!

And now for something completely different…

Crazy Bonus Idea

Quantum Telescopy



Using quantum light to couple telescopes

→enhanced resolution (~ 1/D)

→?improved astronomy

→improved earth science

→improved lunar/Mars imaging

→?ultrasensitive gravitational lensing observatory?

Start with terrestrial studies!

Gottesman, Jennewein & Croke, *PRL* **109**, 070503 (2012)