Quantum Technology in Space

& A Deep Dive on Space-based Quantum Networks

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ACT Workshop - Fundamental Physics Matters
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Quantum Technology in Space

- Quantum information as a resource

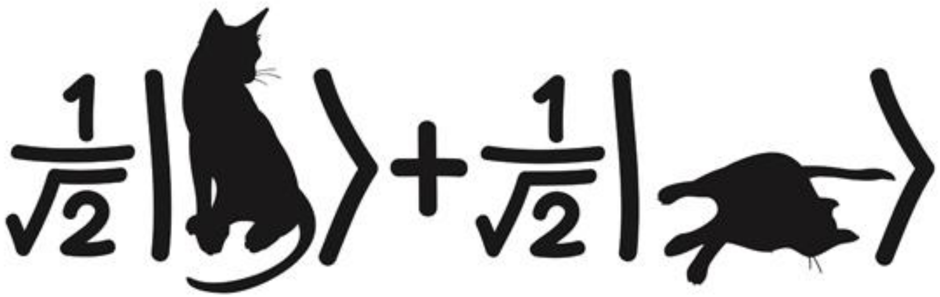
- From the lab into space
  - Quantum Sensing/Metrology
  - Quantum Computing
  - Quantum Communication

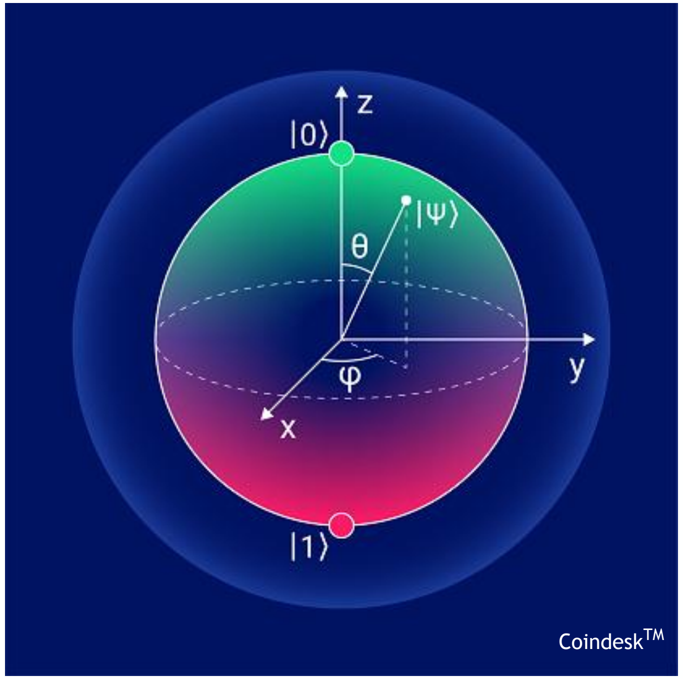
- Space-based global Quantum Networks
  - ACT research: Entanglement-distribution via satellite-based global network

Quantum Information as a resource

- **Spooky** and **mysterious** field of physics
- **Max Planck** in **1900: Light** consists of **quantized energy packets**
- Challenge our imagination and intuition, and offer exciting possibilities for **technological advancements (1st quantum revolution: transistor, laser, atomic clock)**

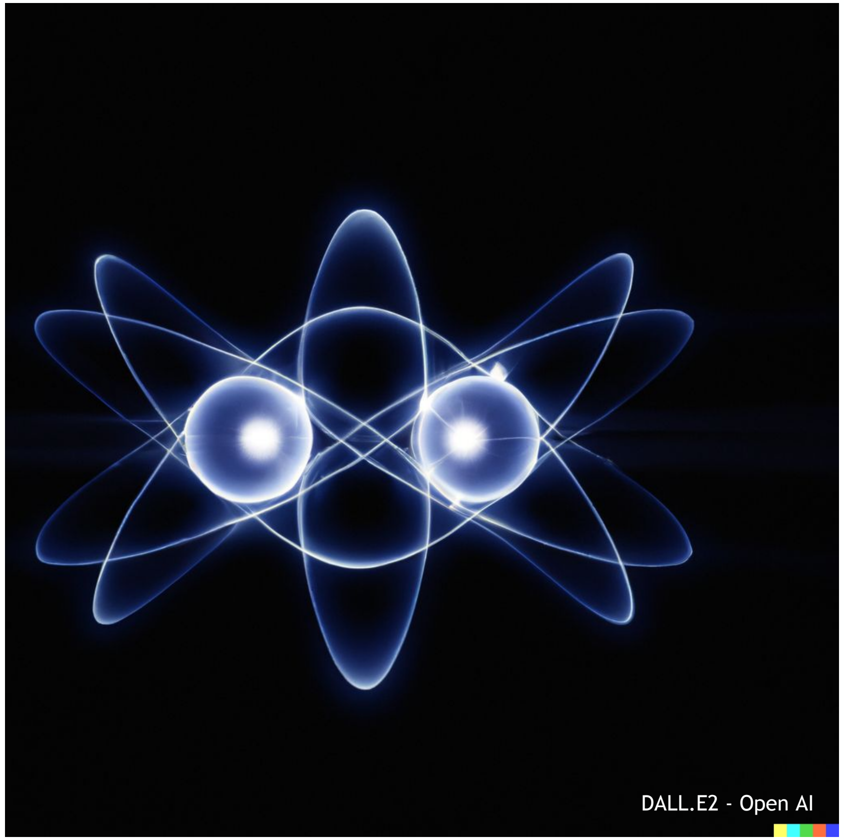
- **Quantum information** as a resource (**2nd quantum revolution**)
- Information encoded into quantum systems
  - **Superposition**
  - **Entanglement**
  - **Threat:** Noise/decoherence





From lab into space

- **Scientific** and **technological** progress in the last decades and **hype**
    - Increasing ability to manipulate **physical systems** **at quantum level** in large systems
    - Generate and sustain entanglement outside the lab
- Novel quantum technologies are emerging in a number of sectors, namely **sensing** and **measuring**, **computing** and **communication**
- Three key quantum technologies:
    - **Quantum sensing** —> sense/detect quantum information
    - **Quantum computing** —> process quantum information
    - **Quantum communication** —> transfer quantum information

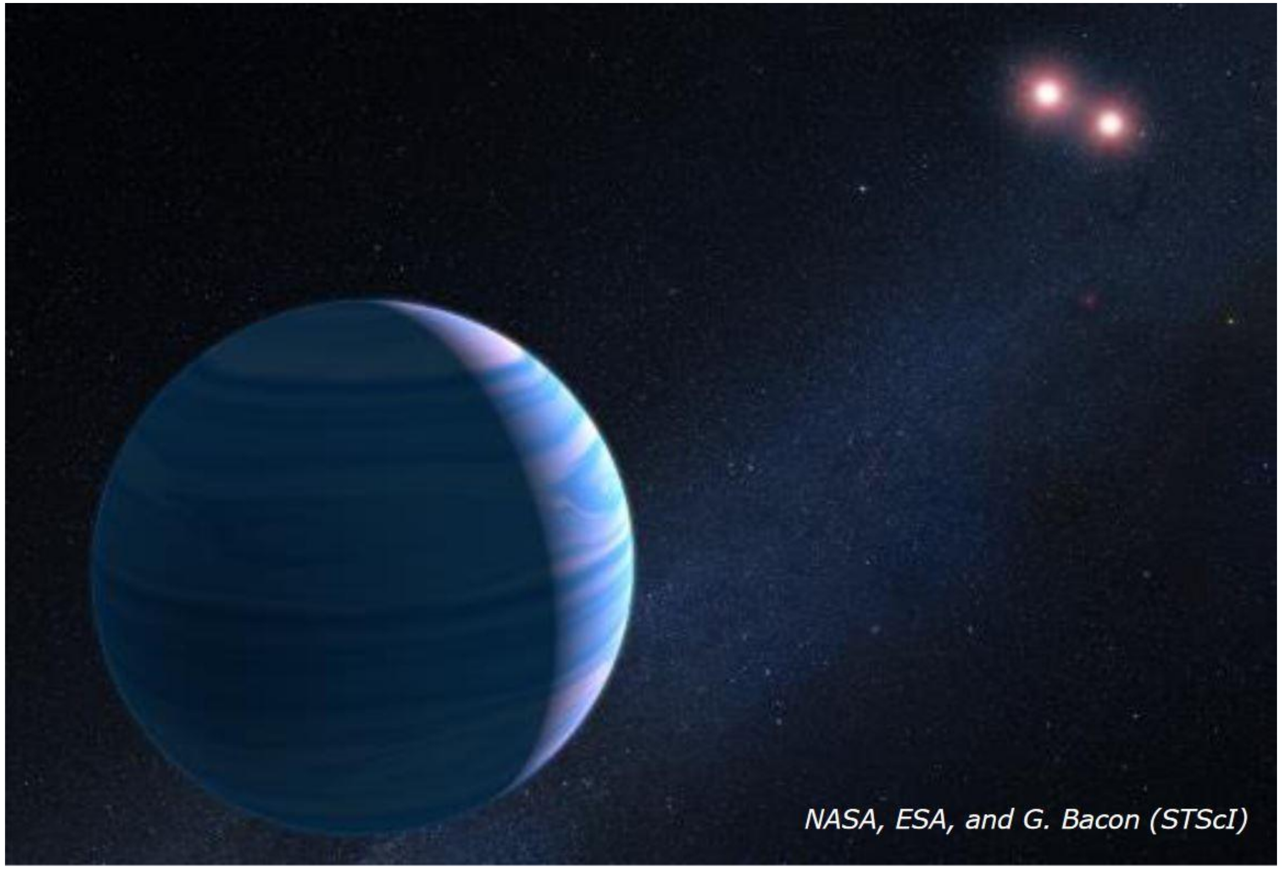


Quantum Sensing & Metrology:

sense or detect quantum information

Quantum Sensing/Metrology

- A new generation of **sensors** and **clocks** of **unprecedented accuracy** with **quantum systems** as **probes**
- Quantized energy levels: using **quantum coherence** to measure a physical quantity, or entanglement to improve measurements beyond classical sensors
- New sensors for **acceleration**, **rotation**, and **gravitational** and **magnetic** fields, improved **atomic clocks** and new methods of **imaging**
- Applications are very varied:
  - Geodesy
  - Time and frequency transfer
  - Navigation
  - **"Superresolution" in astronomy**
  - Fundamental tests of general relativity



Rehacek, J. and Hradil, Z. and Stoklasa, B. and Paur, M. and Grover, J. and Krzic, A. and Sanchez-Soto, L.L., "Multiparameter Quantum Metrology of Incoherent Point Sources: Towards Realistic Superresolution", Phys. Rev. A 96, no. 6 (2017)

Rehacek, J. and Hradil, Z. and Koutny, D. and Grover, J. and Krzic, A. and Sanchez-Soto, L., "Optimal measurements for quantum spatial superresolution", Phys. Rev. A 98, no. 1: 012103 (2018)

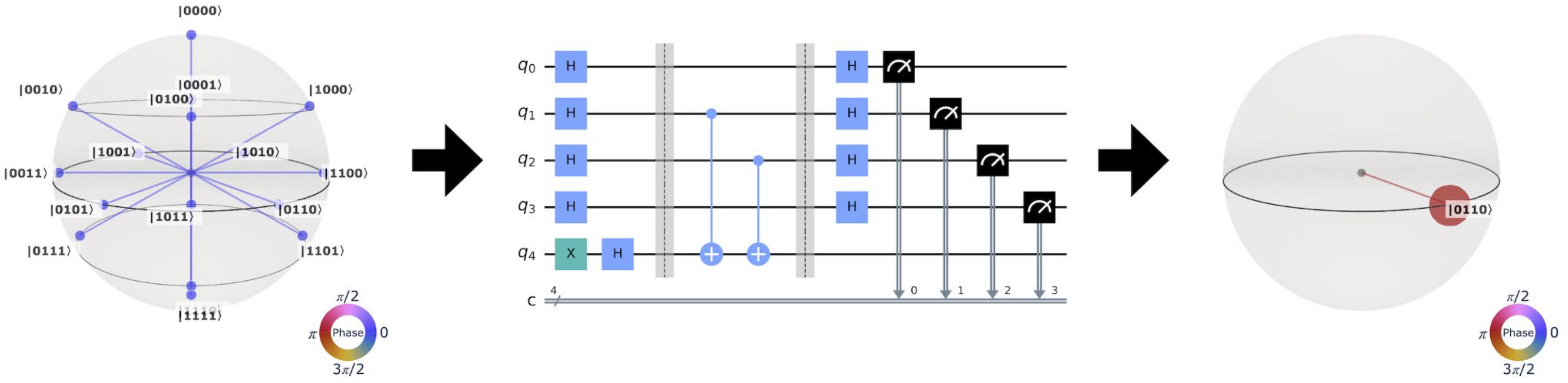
Quantum Computing:

process quantum information

Quantum Computing

- Early 1990s: theoretical work on improved efficiency of specific **computational tasks** using quantum carriers of information (**qubits**) and **processing** them based on quantum physical laws
  - **Prime factorization:** (common encryption scheme, RSA)
- Significant progress regarding **initialization, processing** and **read-out** of qubits in **atomic**, **photonic** and **solid state** systems
- **Low near-term space relevance** (**NISQ**): trajectory optimization, mission organization, materials and structure optimisation
- **ACT** collaboration with **PSI/ETH Zurich (QC Hub)**

Quantum circuit



Qiskit™

Superposition of all possibilities

Computation driven interference

Solution

Quantum Communication:

transfer quantum information

Quantum Communication

- Transmission of information at **macroscopic distances** → **quantum communication**
- Light (photons) is the carrier, exploiting phenomena such as **photon entanglement**
- Information transfer **cryptographically secured** by laws of quantum physics: **no-cloning theorem** does not allow for the **copying/amplification** of quantum states
- Creative solutions!
  - Entanglement swaps + quantum memories = quantum repeaters

Quantum Communication

- Allows for **distributed** quantum computing (either by transferring information from one computer to another)
- Enhances quantum sensing metrology via **time/frequency transfer**
- Quantum Key Distribution (QKD) provides **security guaranteed** by the laws of quantum physics

At ESA:

- Space-based component of Quantum Communication Infrastructures **EuroQCI**, known as **SAGA (I+II)** (Security And cryptoGrAphic mission, QKD)
- SES Techcom S.A. (LU) to develop **QUARTZ** (Quantum Cryptography Telecommunication System): a robust, scalable and commercially-viable satellite-based **QKD system for use in geographically-dispersed networks**


SES, ESA and Nico E.N.

Towards a global quantum network

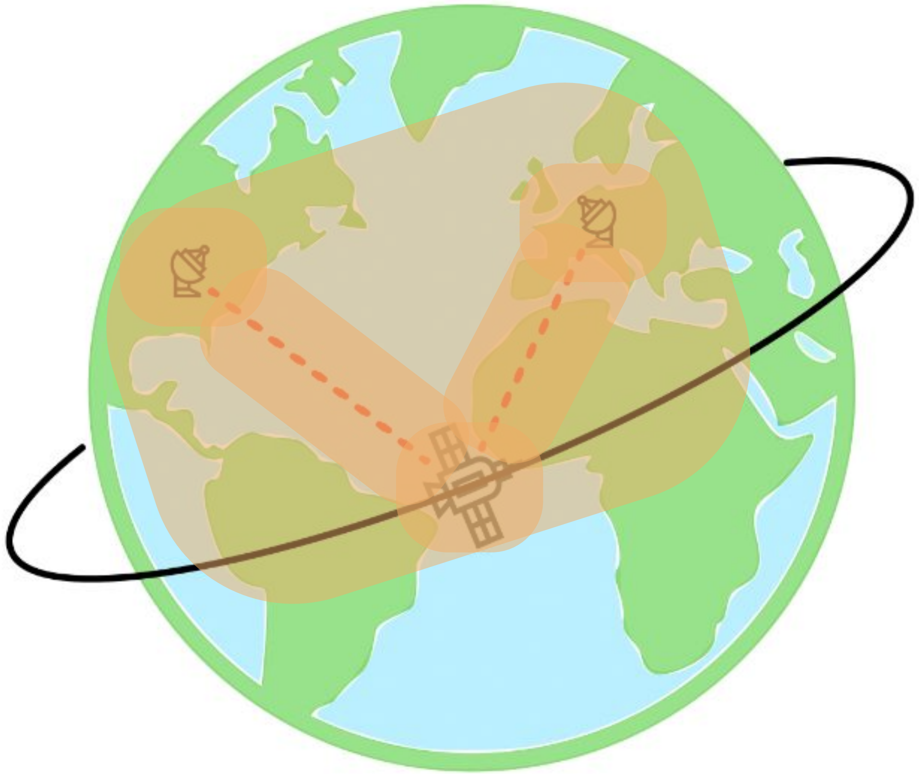
- Goal: to distribute quantum systems over global distances via:
  - Fibres → exponential loss
  - Free space → quadratic loss
- Loss = bad (no-cloning theorem)
- Satellite quantum network provides perfect solution

Research Goals:

- Simulate an entanglement distribution scheme via a quantum global network
- Create a modular simulation which can be used to optimize/analyze various parameters (telescope specifications, number of satellites, sensitivity to various parameters, etc.)

The Building Blocks

1. Node: generate & store entanglement
2. Link: model channel
3. Network: design protocol



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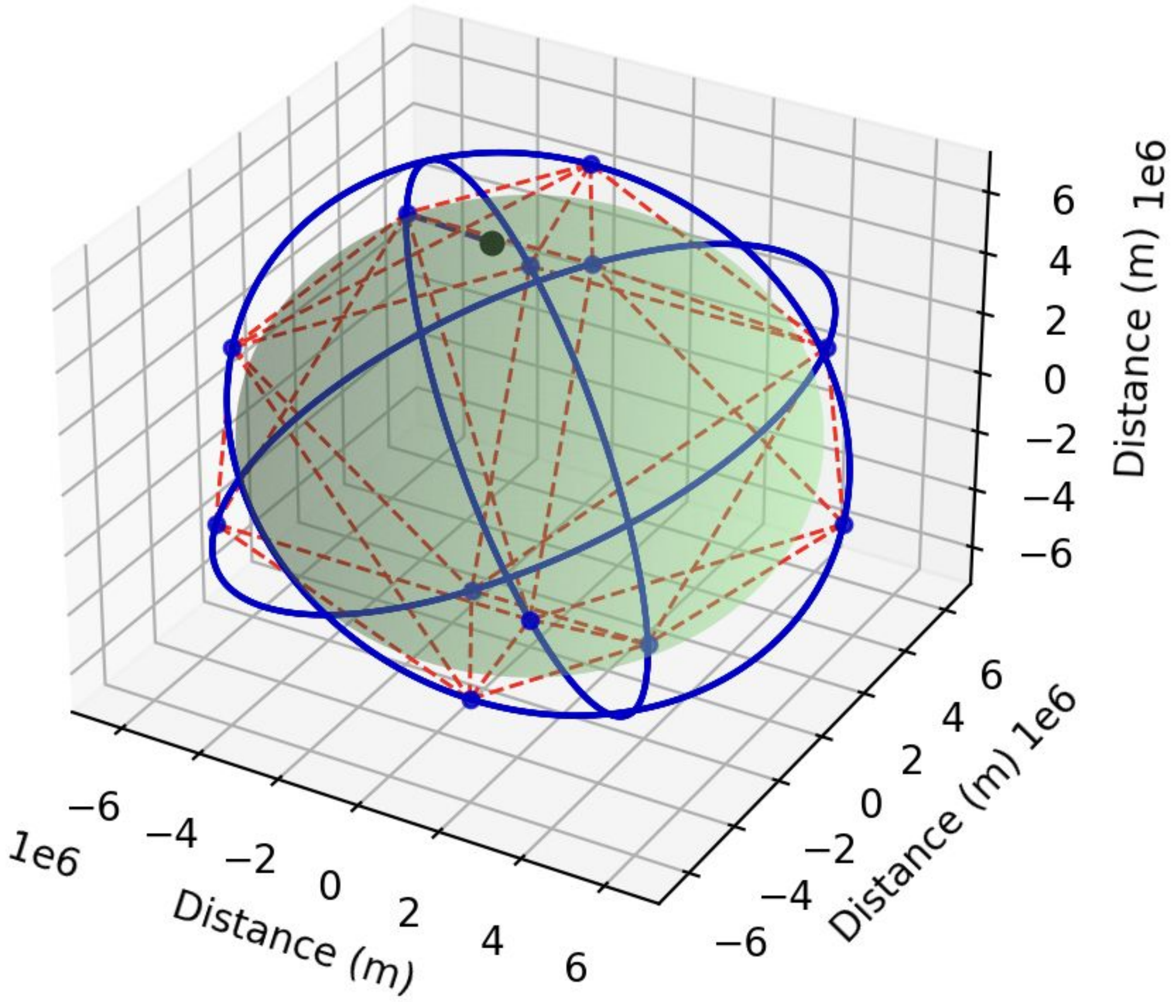
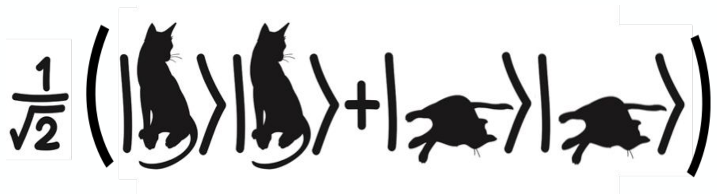


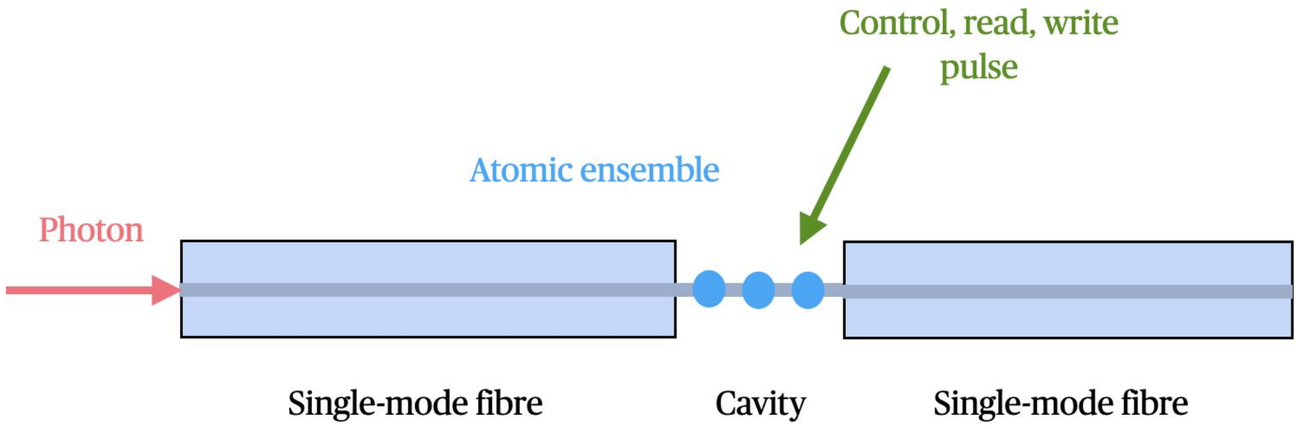
1. Node

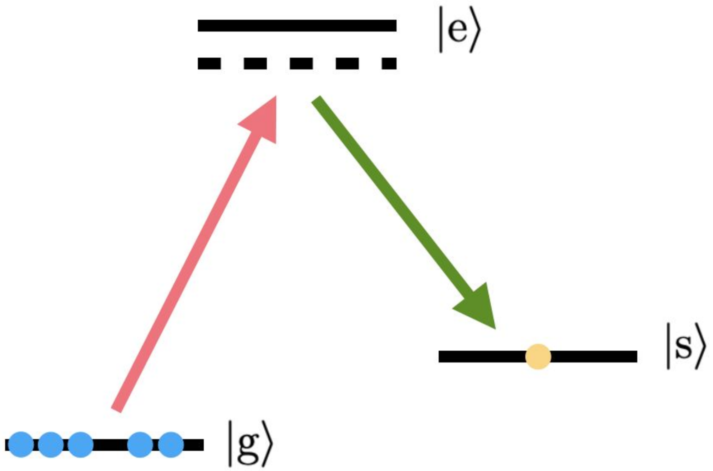
- Generate entanglement via entangled photon pair source



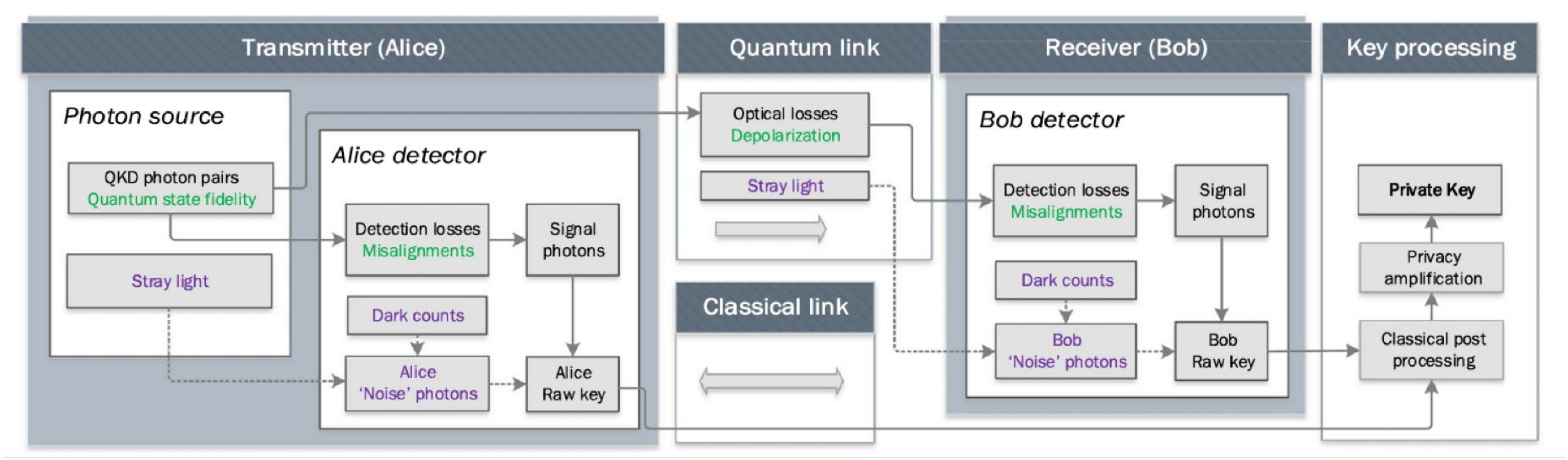
$$\frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$$

- Store photons in a quantum memory



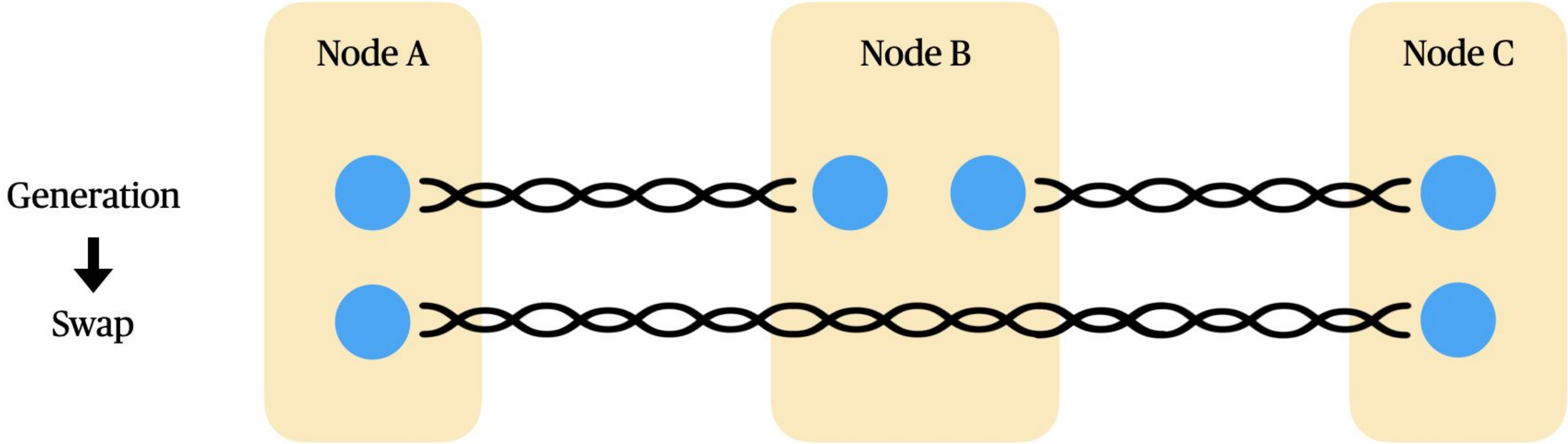


2. Link

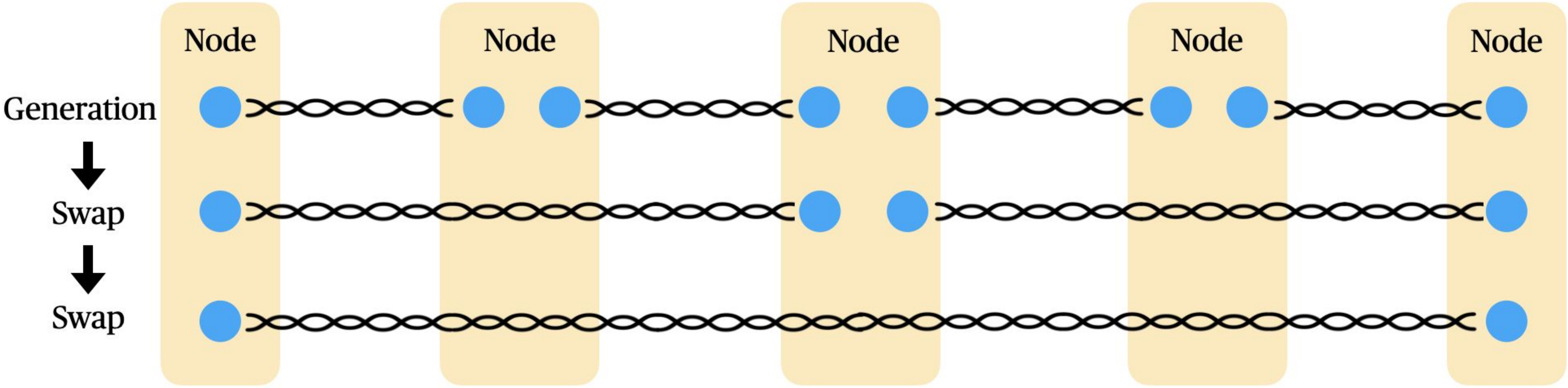


Loss in a quantum communication system. Green shows loss which affects fidelity of quantum state (visibility) and purple shows loss which from accidental counts (sources of unwanted photons)
(Bedington et al. Progress in satellite quantum key distribution. npj Quantum Inf 3, 1-13 (2017))

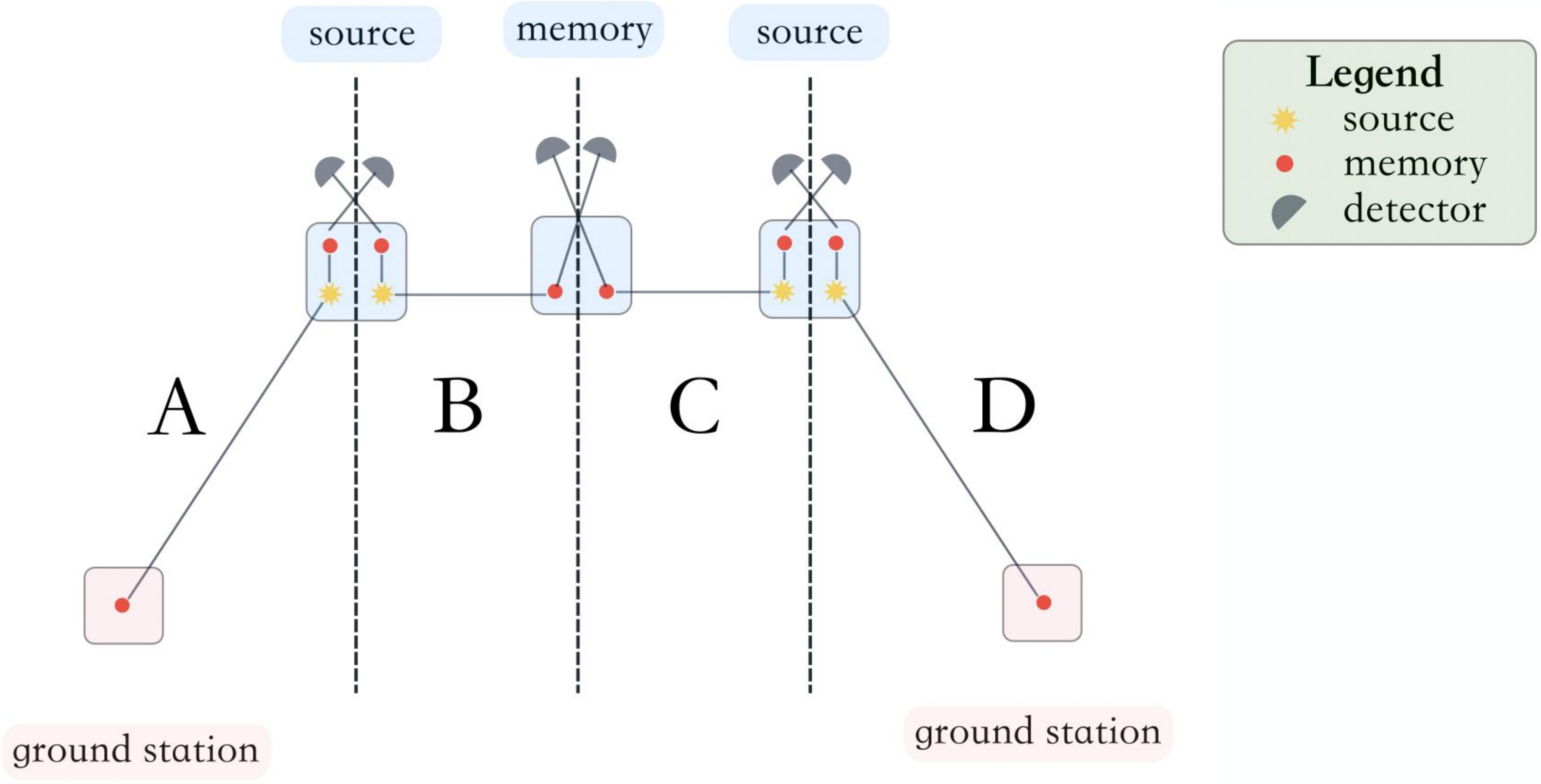
3. Network: Entanglement Swap



3. Network

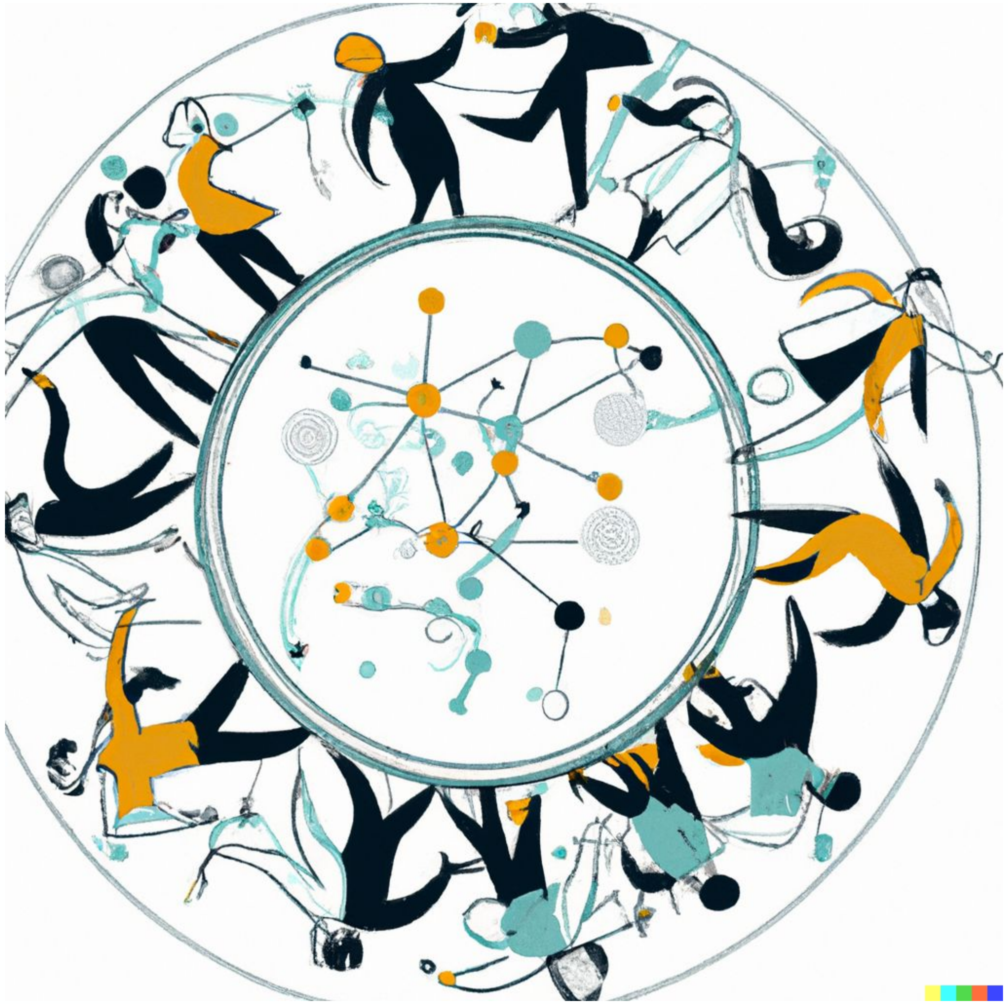


3. Network: Designing Quantum Repeater Architecture

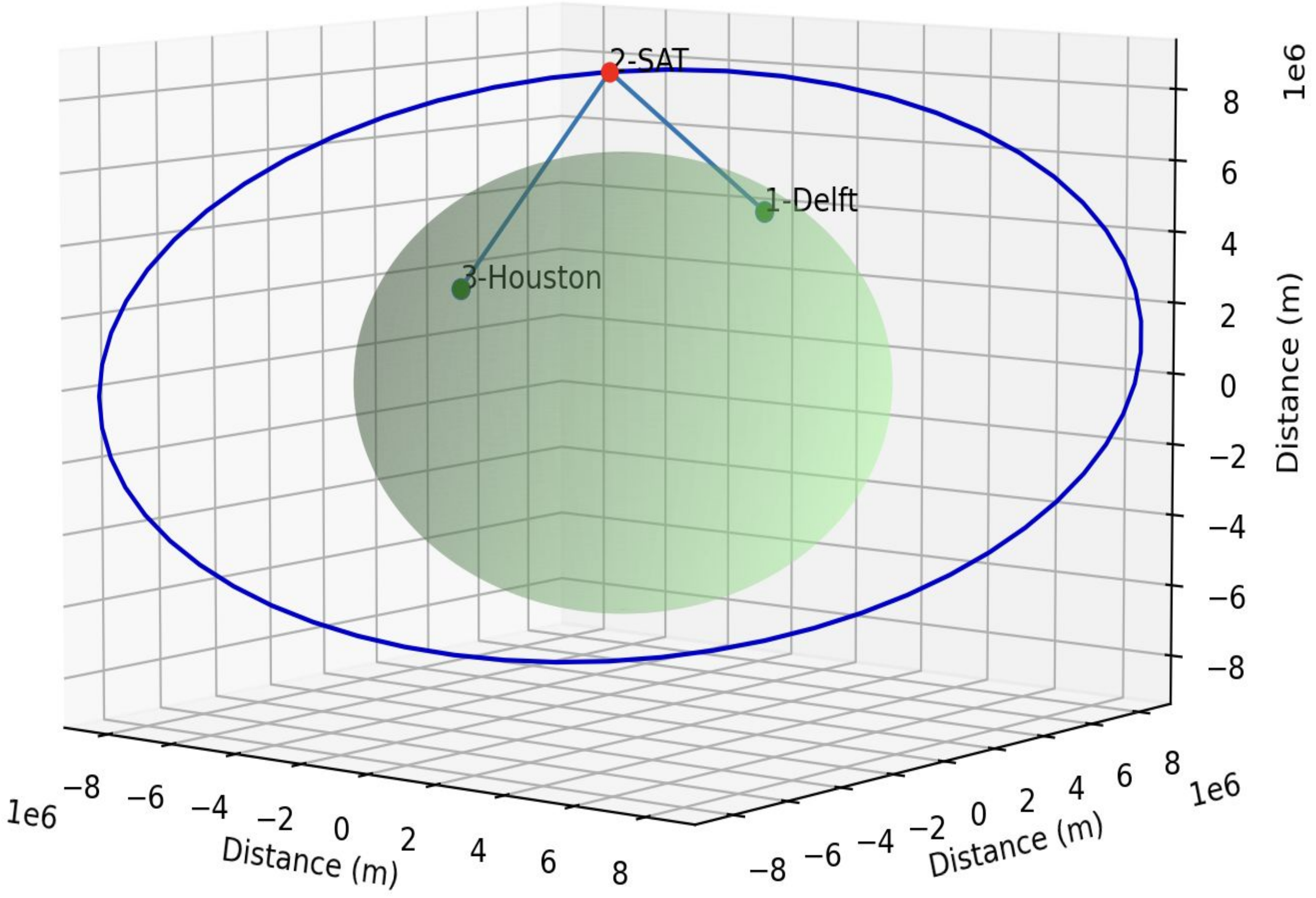


The Synergy of the ACT

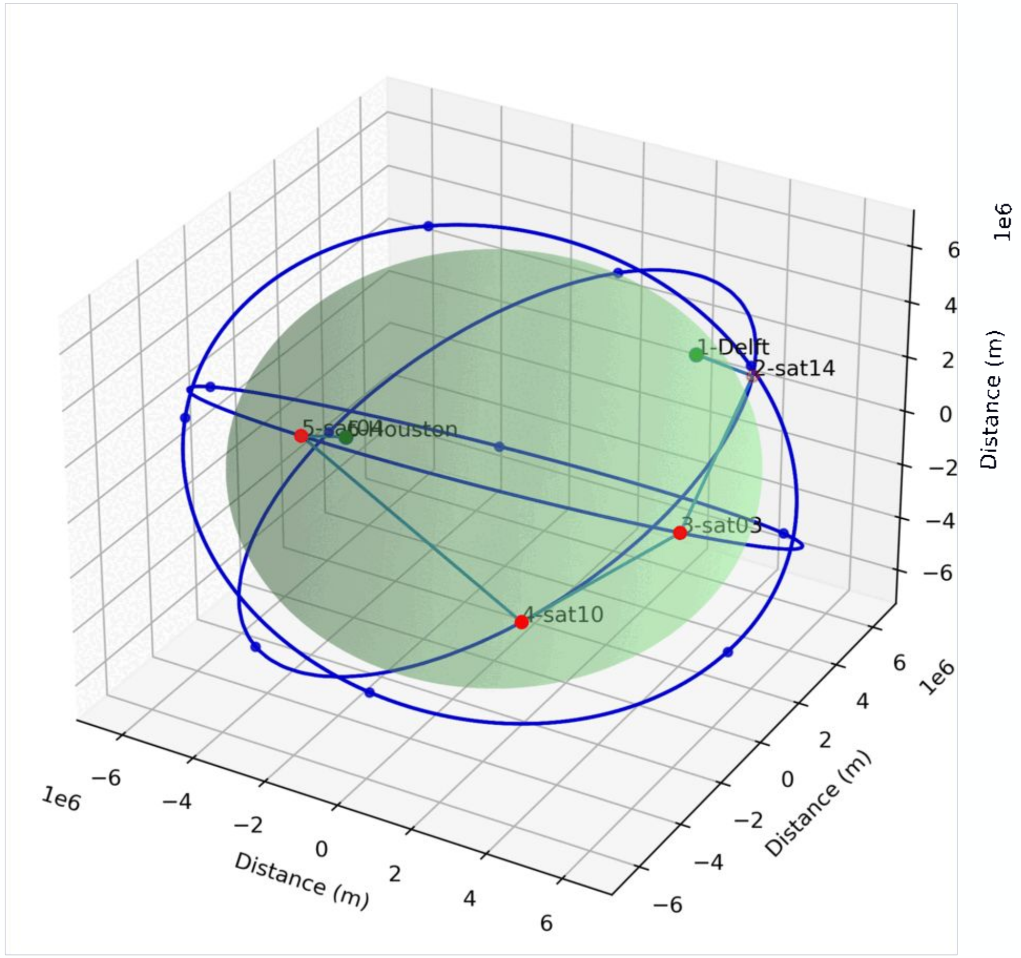
- Quantum expertise within the ACT and ESA
- External collaboration with QuTech (TU Delft)
- Orbital modeling expertise (pykep)
- Optimization expertise (pygmo)

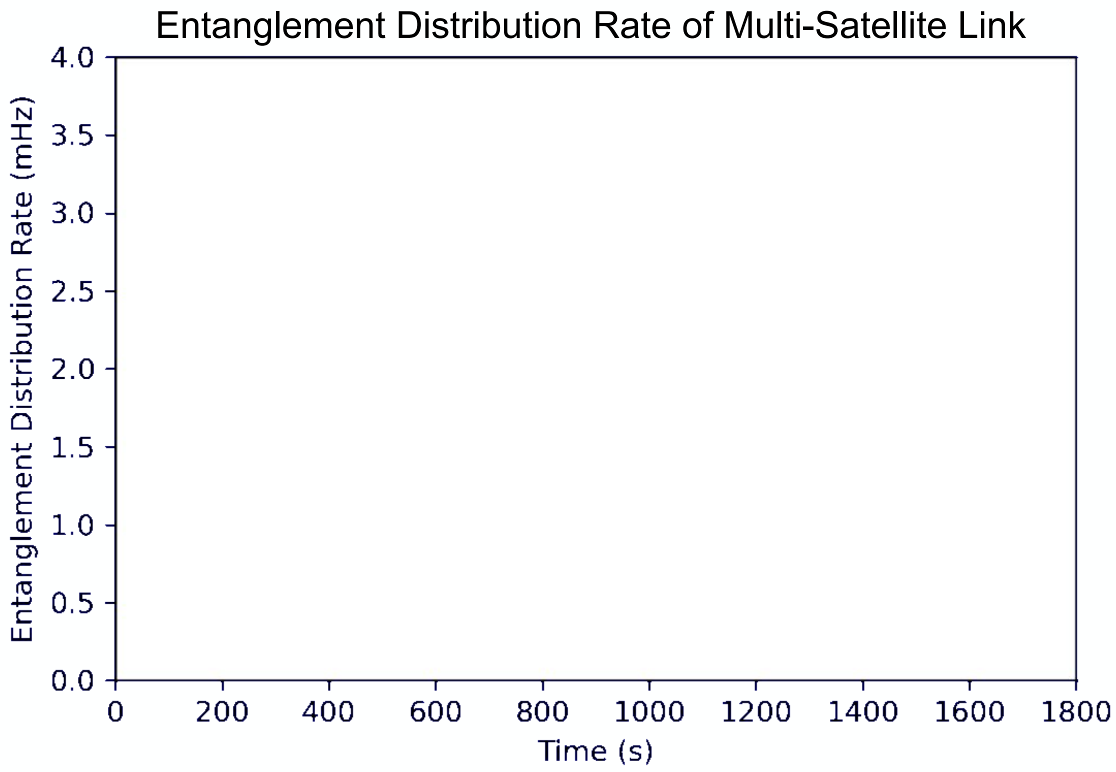


Implementable model



Simulating full multi-satellite network





Conclusion

- Many future paths forward :)

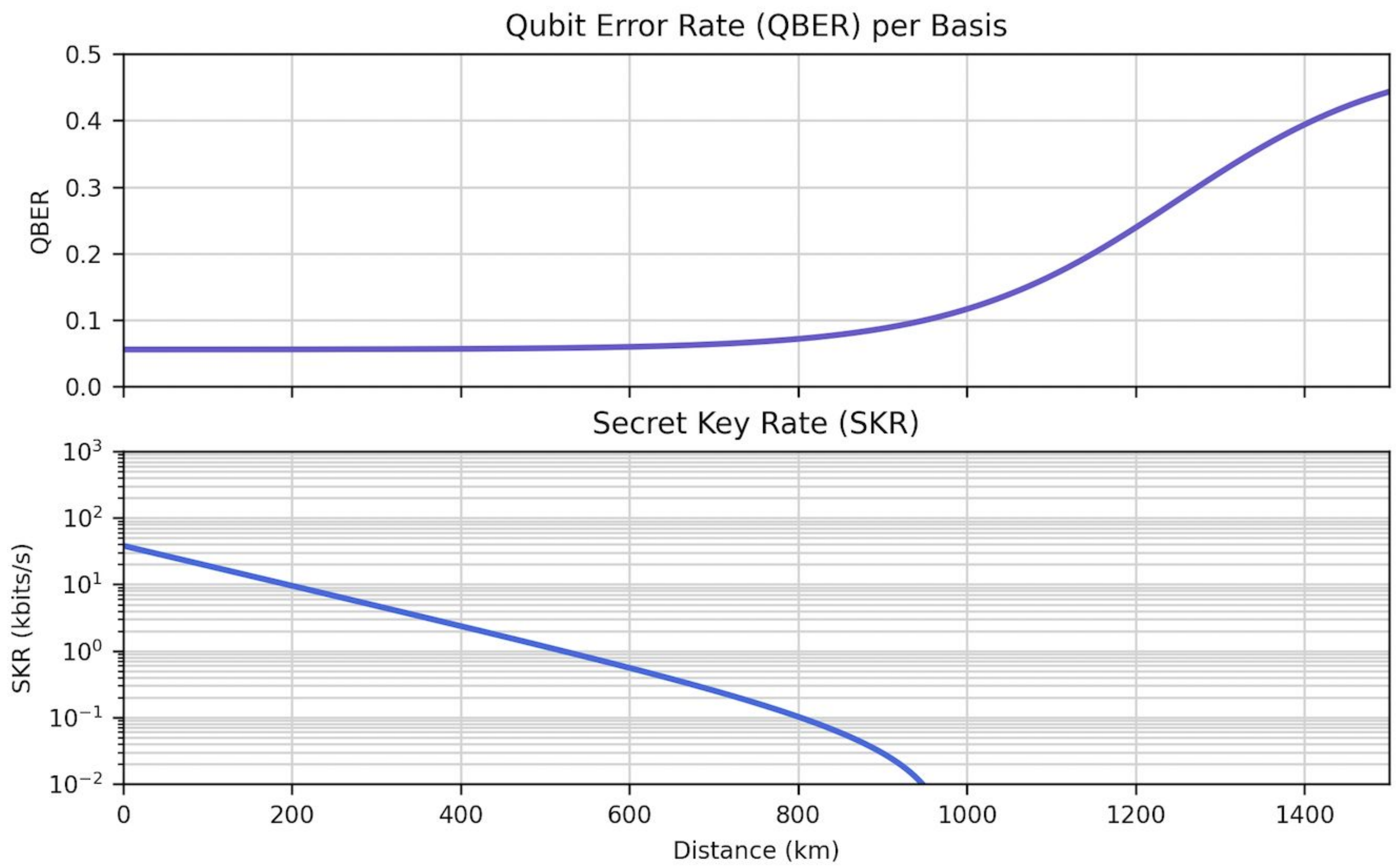
Purpose of the project:

- Understand key parameters for the fidelity & rate of a distribution network
- Find optimized network:
  - Given different applications:
    - Distributed quantum computing
    - Quantum sensing
    - QKD
  - Given different constraints:
    - Number of satellites
    - Telescope specifications
- Work *with* and *for* the scientific community via open source module
- Help facilitate future ESA satellite quantum network missions

Thank you for your attention!

Backup slides

Step 1: Quantum Key Distribution



Step 2: Validating our loss channel

- Comparison with Micius mission (Chinese QKD program)

	Micius	Our Model
Loss Channel	28 dB	23 dB
Qubit Error Rate (QBER)	4.51-8.1%	6.19%
Secret Key Rate (SKR)	~1KHz	1.057 KHz