High rate quantum sources and hybrid networks at JPL and Caltech

Boris Korzh

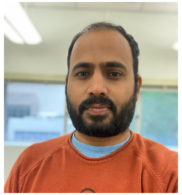
13th Dec 2023

Jet Propulsion Laboratory
California Institute of Technology

Caltech

INQNET-JPL team

Maria Spiropulu



Raju Valivarthi

Dr. Andrew Mueller (Caltech APh)

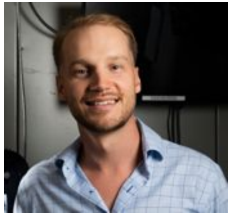
Samantha Davis (Caltech Ph)

Prathwiraj Umesh (Visiting PhD student)

Lautaro Narvaez

JPL members

Matt Shaw



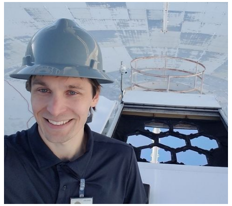
Boris Korzh

Ioana Craiciu

Andrew Beyer

Sean Meenehan

Alex Lohrmann



Jason Allmaras

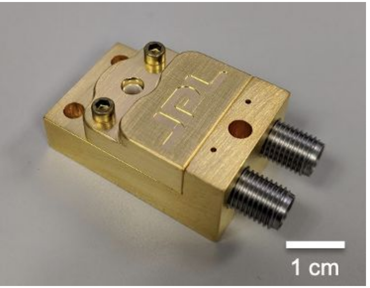
Dan Shanks

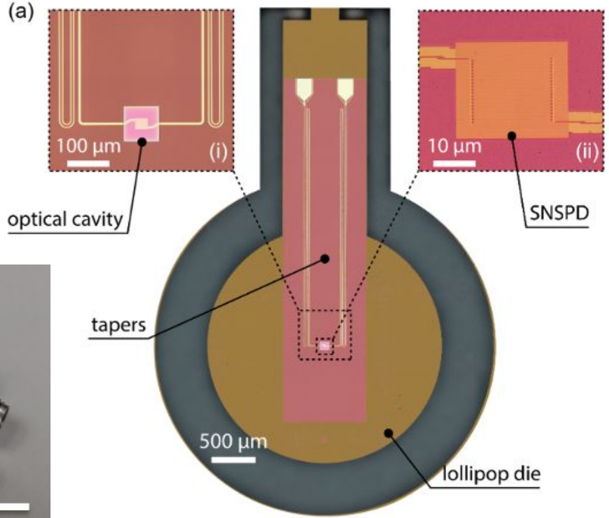
Key Collaborators

JPL’s superconducting nanowire detectors optimized for quantum communication

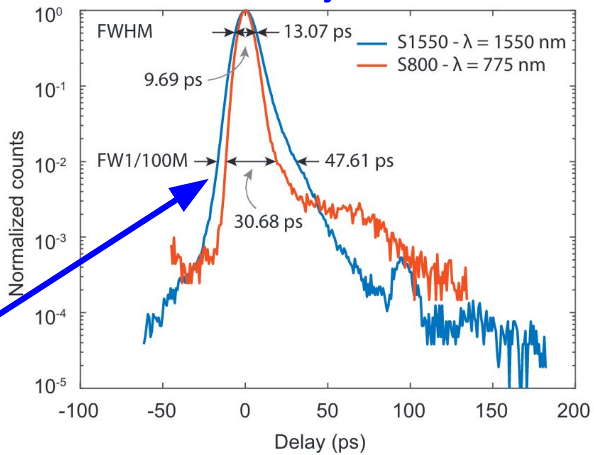
- Telecom operation achieving **low-jitter** (Δt), **high-efficiency** (η) and **low-noise** (D), simultaneously.
- Optimizes key figure-of-merit for quantum communication [1]:

$$H = \frac{\eta}{\Delta t D}$$



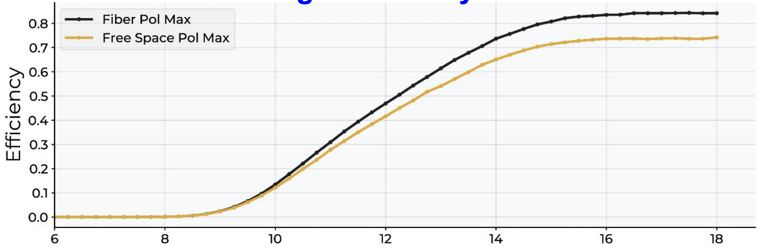


Low jitter

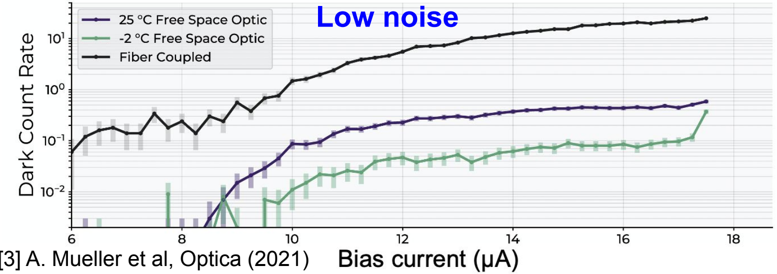


Enables >10 GHz clock rate

High efficiency



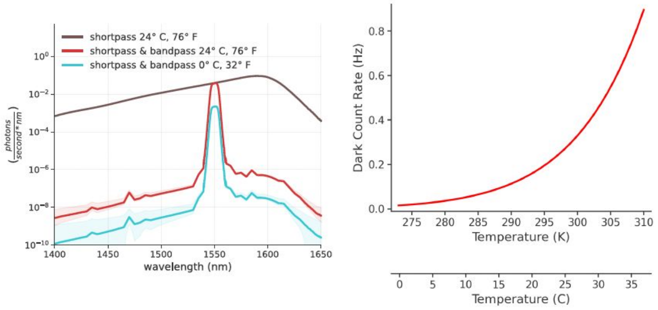
Low noise



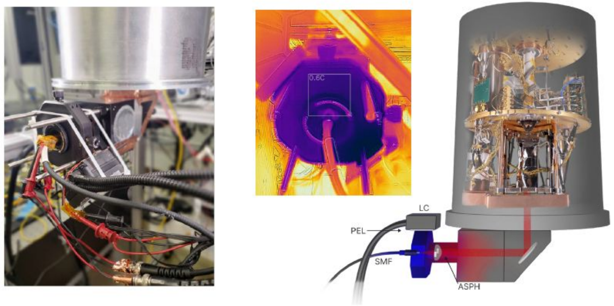
[1] R. Hadfield, *Nat. Photonics* **3**, 696 (2009)
[2] M. Colangelo, B. Korzh et al, *PRApplied* **19**, 044093 (2023)
[3] A. Mueller et al, Optica (2021)

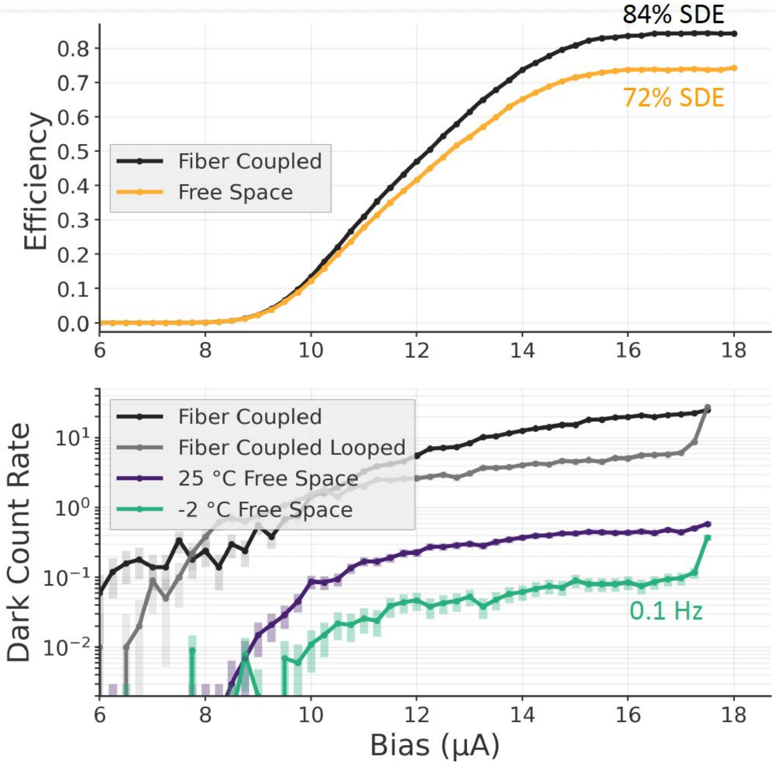
Free-space coupled photon detectors

Strong dependence of **room temperature** on **dark count rate**



Apply mild cooling to surface imaged onto detector

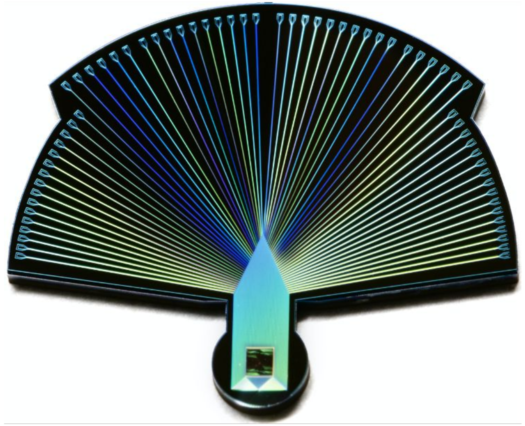




[3] A. Mueller, B. Korzh et al, Optica 8, 1586 (2021)

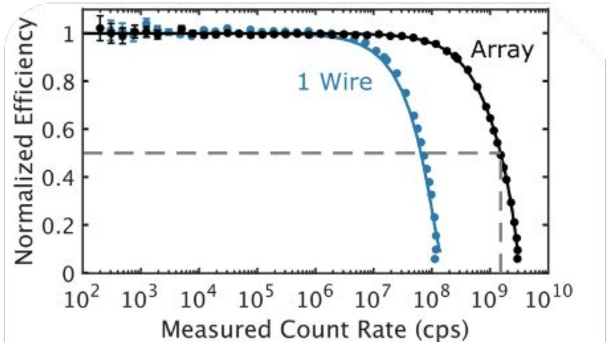
Other capabilities for future Advanced Quantum Networks

- High count rates
- Photon number resolution



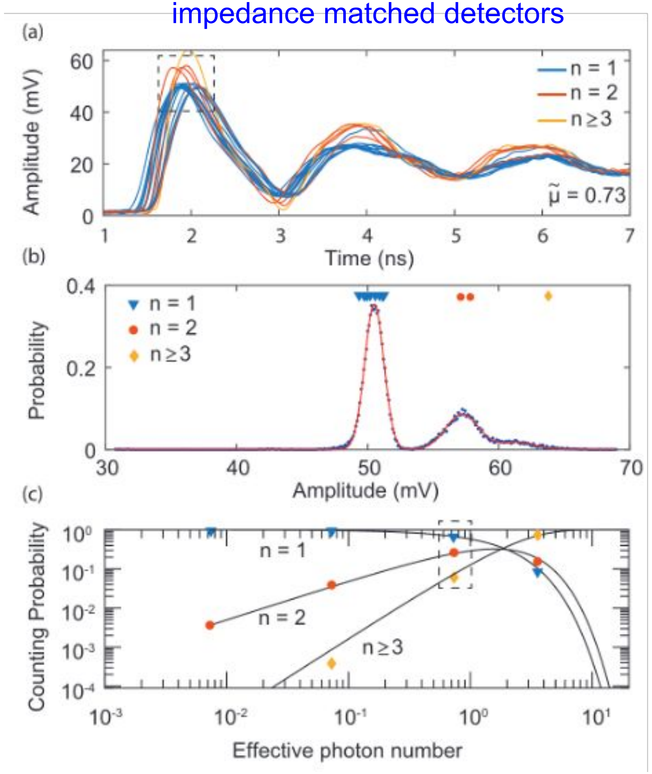
Performance Enhanced Array for Counting Optica Quanta (PEACOQ)

Normalized efficiency versus count rate



1.5 Gcps maximum count rates - pathway towards low-jitter at high rates

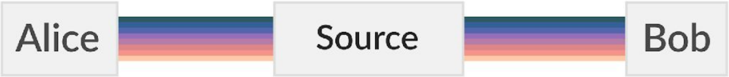
Photon-number resolution with impedance matched detectors



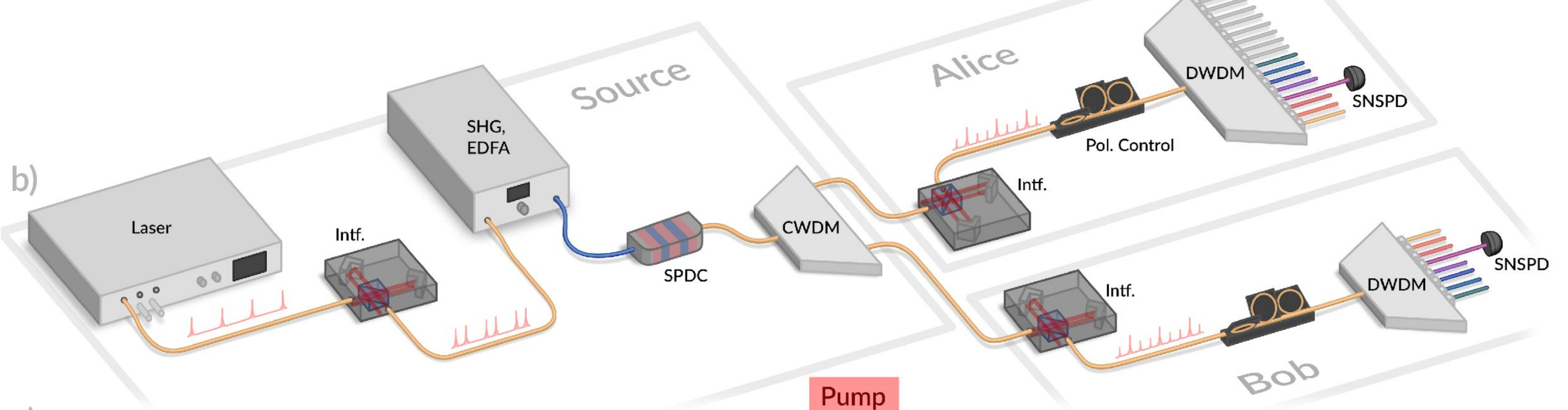
I. Craiciu, B. Korzh et al ***Optica*** **10** 183 (2023)

Improving rates: High Rate Entanglement Generation

a)



b)



c)

Pump Laser

ITU Channel	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Wavelength (nm)	1555.75	1554.94	1554.13	1553.33	1552.52	1551.72	1550.92	1550.12	1549.32	1548.51	1547.72	1546.92	15546.12	15545.32

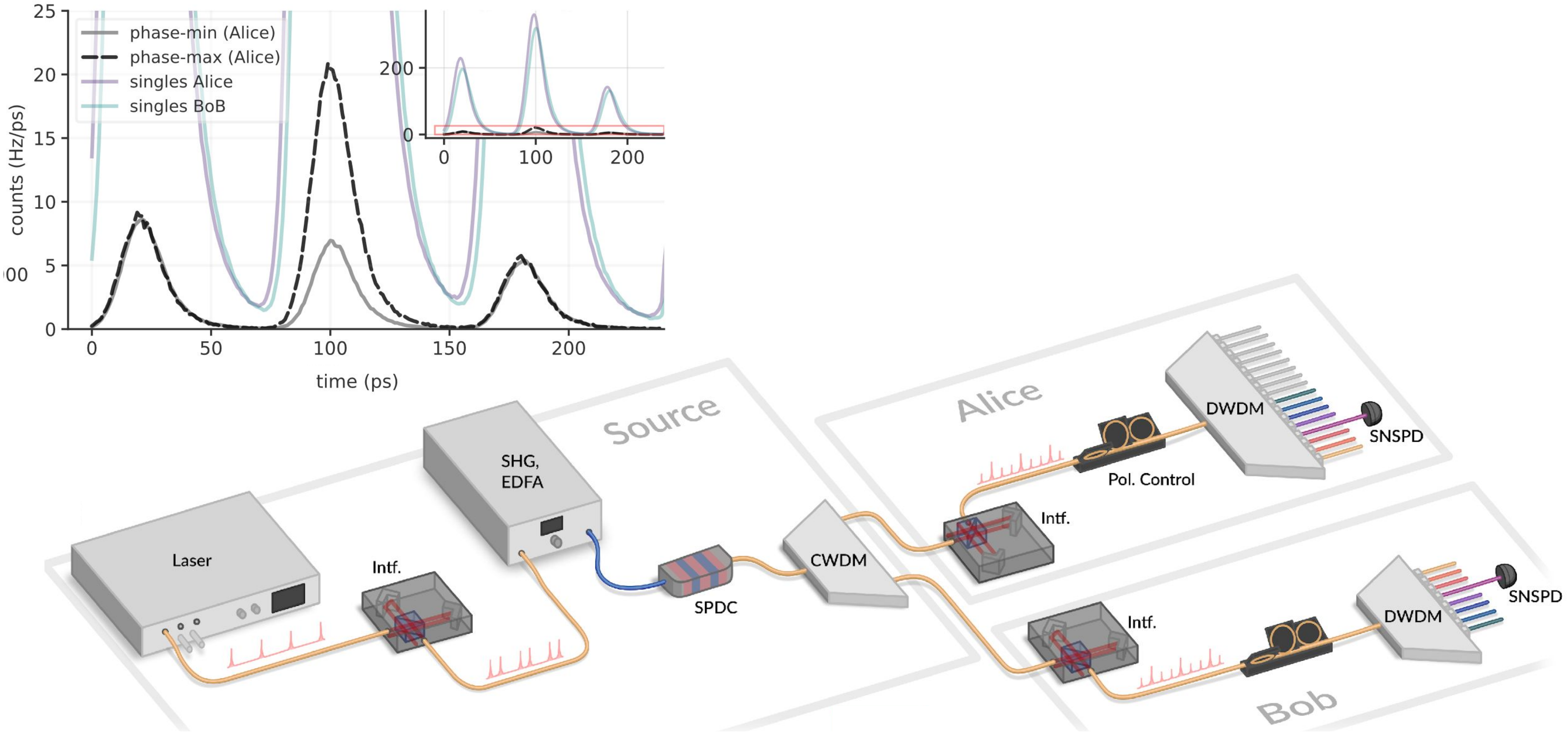
ITU Channel	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Wavelength (nm)	1544.53	1543.73	1542.94	1542.14	1541.35	1540.56	1539.77	1538.98	1538.19	1537.40	1536.61	1535.82	1535.04	1534.25

ITU Channel	55	56	57	58	59	60	61	62	63	64	65	66	67
Wavelength (nm)	1533.47	1532.68	1531.90	1531.12	1530.33	1529.55	1528.77	1527.99	1527.22	1526.44	1525.66	1524.89	1524.11

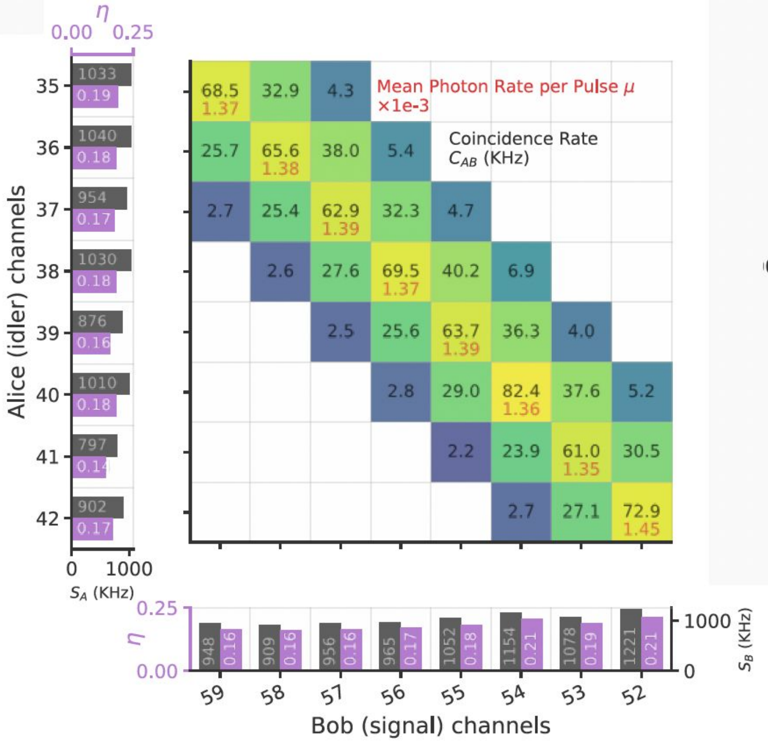
16 ch. DWDM

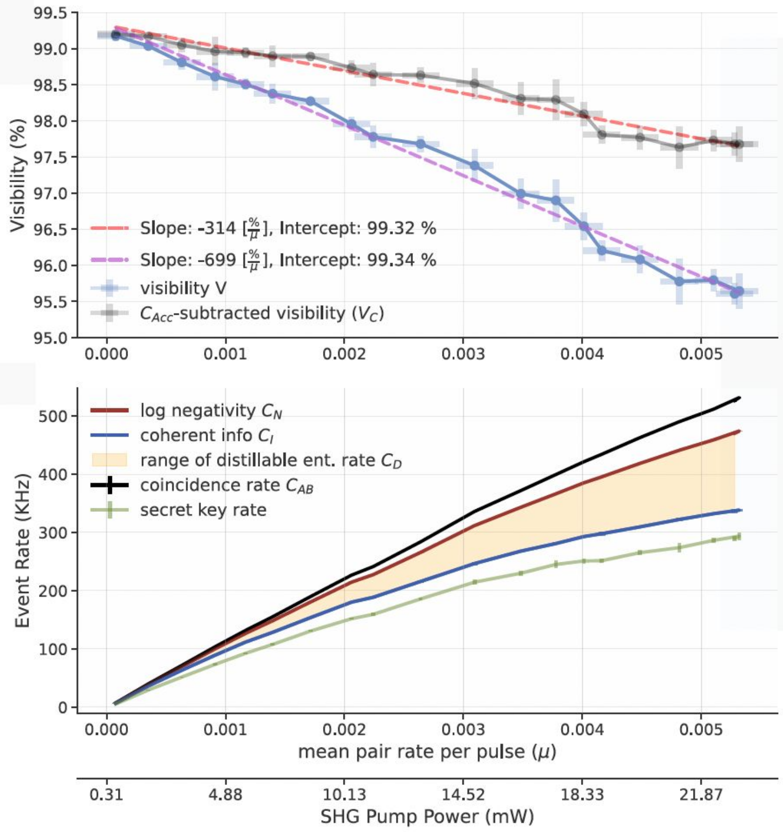
8 ch. DWDM

Time Bin Entanglement

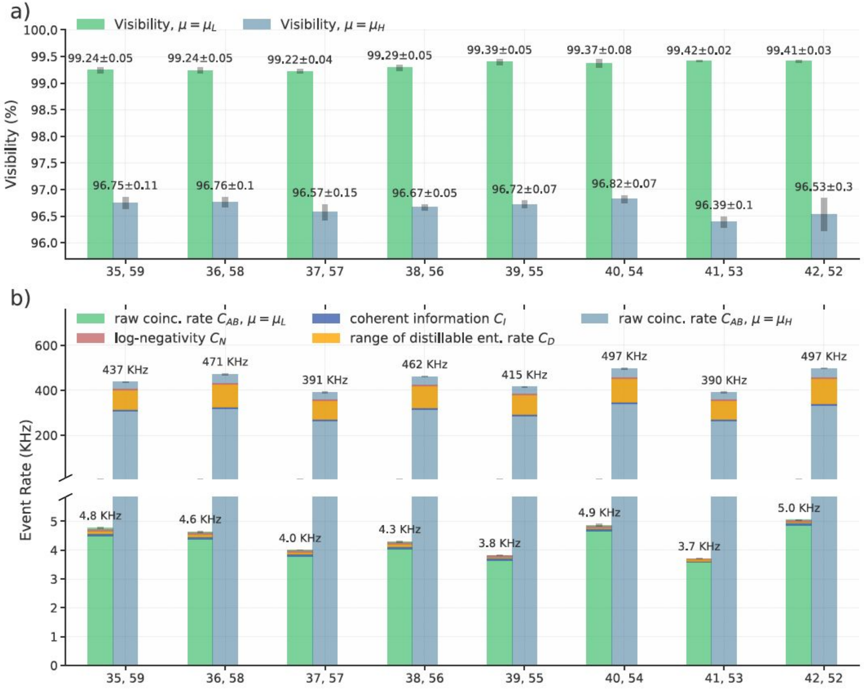


Rates and visibilities





Overview of entanglement source

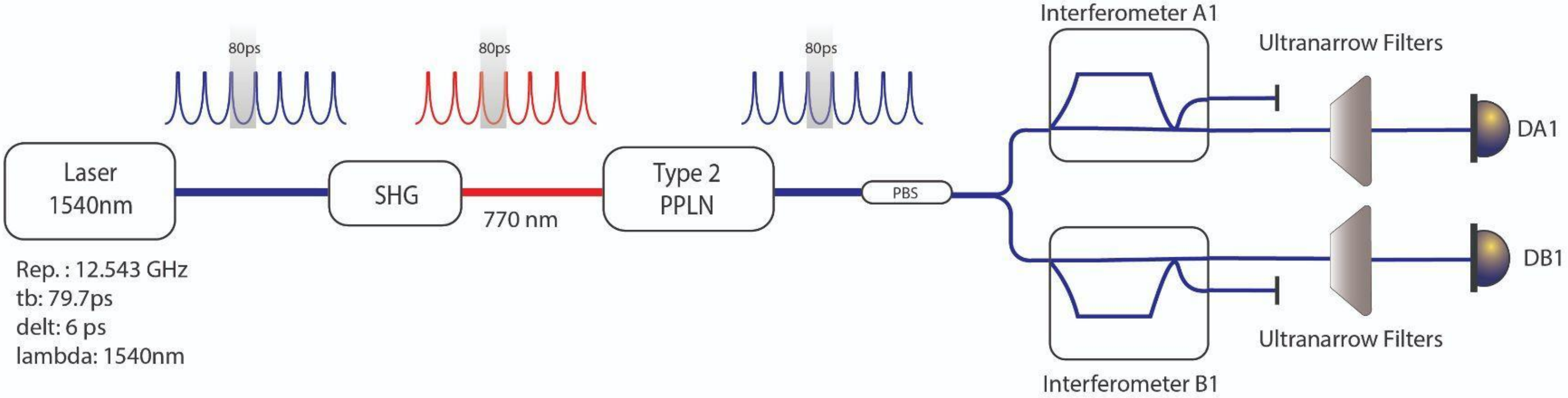


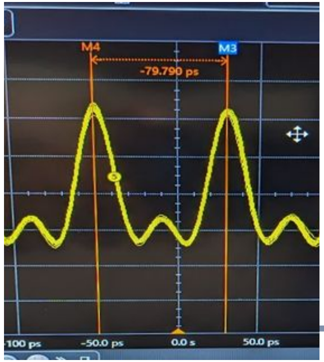
3.55e6 coincidences/s
Across 8 multiplexed pairs

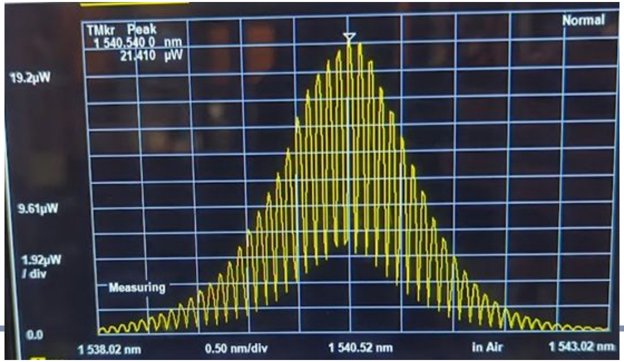
Up to 99.3% entanglement visibility
At μ = 5.6e-5

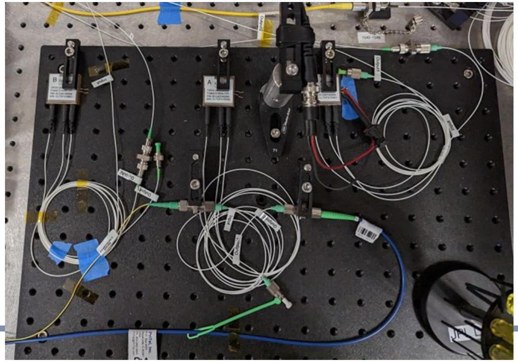
2.46 – 3.25 Mebits/s
μ = 5.0e-3, V ≃ 96.6%

High dim. source









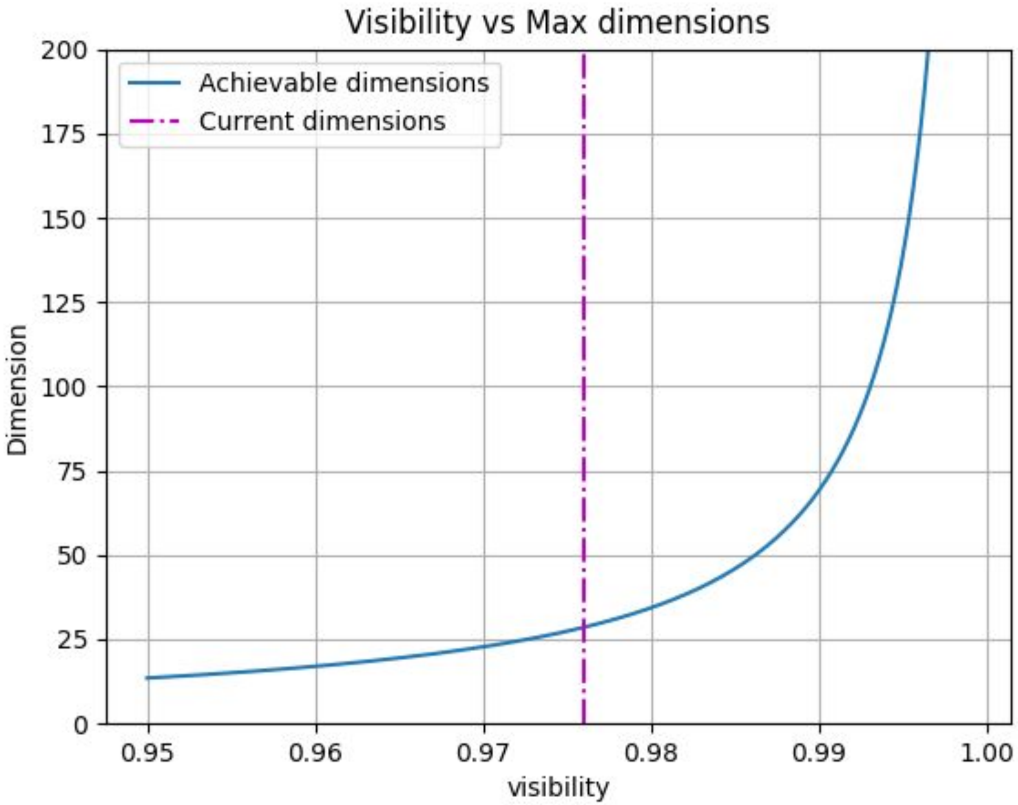
Results

inqnet

- Current interferometer visibility: 98.8%
- Estimated entanglement visibility: >97.5%
- # dimensions: approx 29
- Estimated increase in the secret key rate: Order of higher magnitude compared to current two dimensional entanglement sources

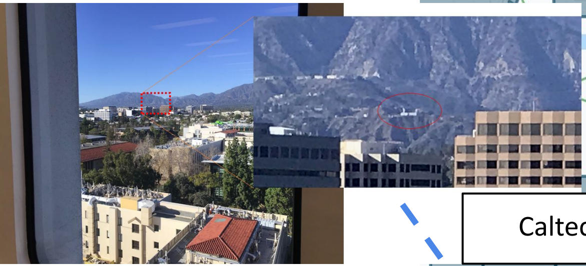
Future steps:

- Increasing entanglement visibility to >99%
- Entanglement distribution over fiber and free space links
- Readily operable time-bin or frequency bin entanglement source

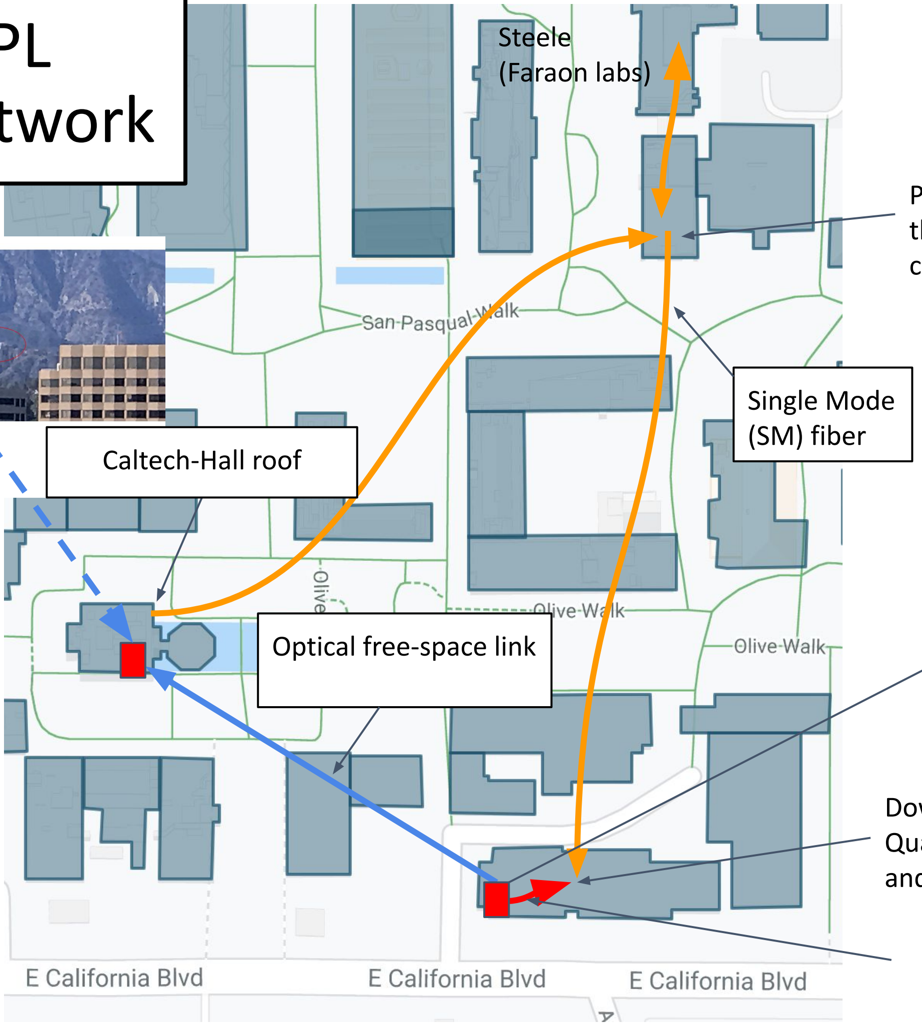


Caltech-JPL Quantum Network

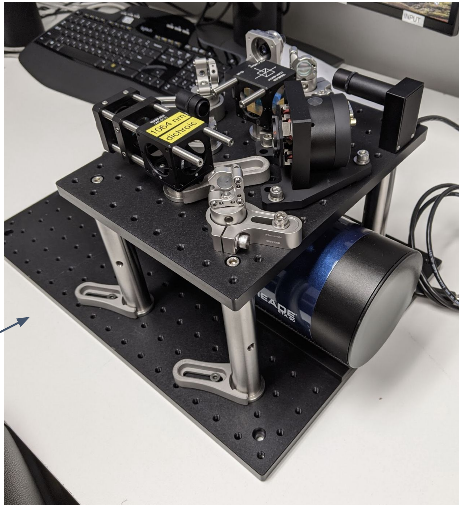
Line-of-sight from JPL



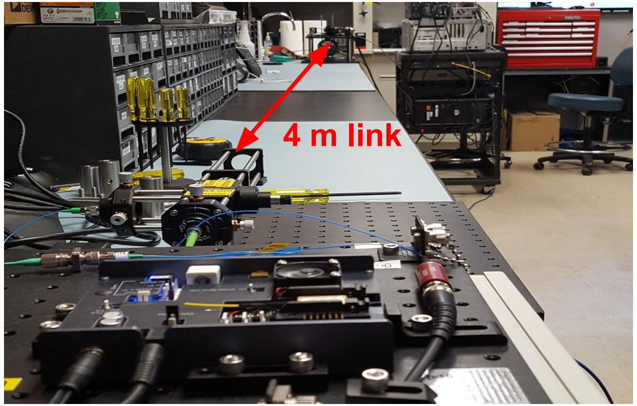
View from roof of Caltech Hall to the roof of Downs-Lauritsen building - 160 m link.

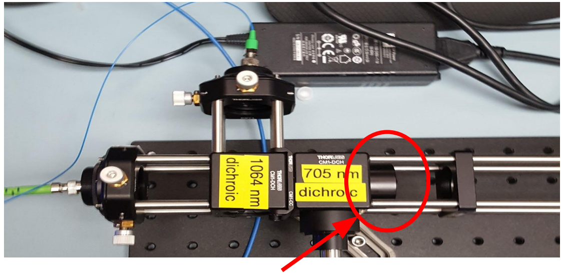


Optical telescope assembly for signal collection, alignment and coupling into SM fiber for transmission to detectors



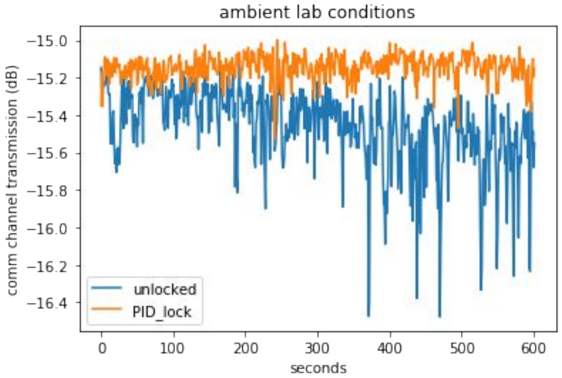
Benchtop tests at Caltech

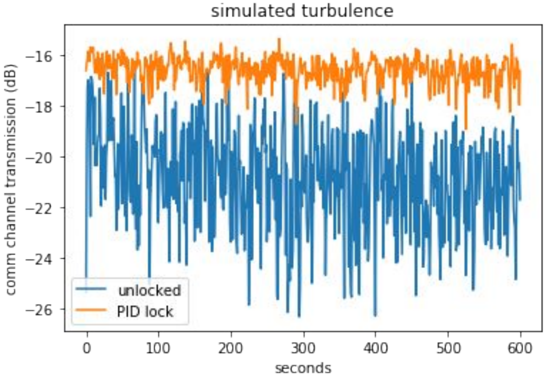




transmit through 60 mm achromat instead of telescope, due to ~40x reduced link distance

simulated turbulence (uncontrolled): fan of hot air directed at beam path



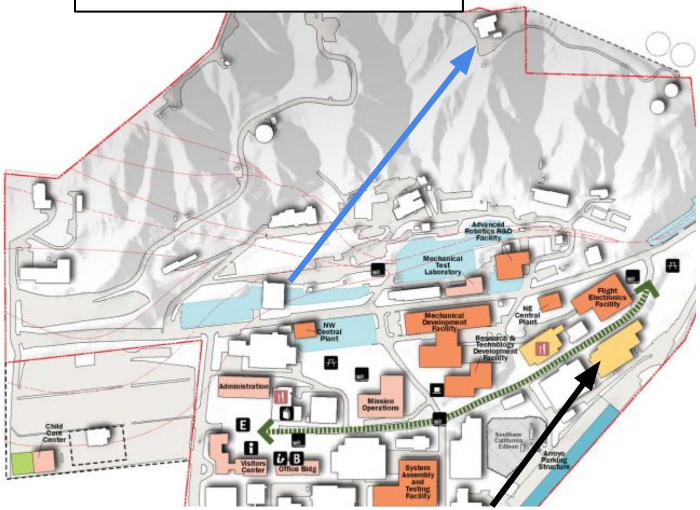


- Aperture loss of -8.5 dB, receiver fiber coupling of -6.5 dB (vs. ideal -4 dB)
- FSM-locked signal stable to within ±0.5-1 dB, consistent with expectations

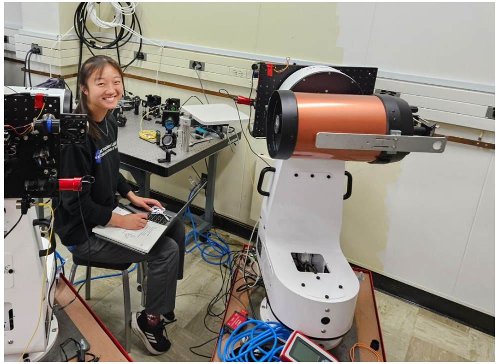
Tests at JPL

- Testbed for dynamic and static quantum optical links.
- 2x almost identical FSO terminals – first version to study impact of atmosphere (Quantum signal throughput ≈17-20 dB).
- Closed-loop pointing and tracking systems for fixed or sidereal, or TLE-based tracking.

Line of sight from Bldg. 238 to Elevated "Mesa"



Detector fabrication facility



20 cm telescope during Laboratory tracking exercise (AO correction experiment in the background)

Video (image stabilized) of ISS during closed loop tracking of a low elevation pass from rooftop of 238.

Hybrid fiber and free-space links (SoCal)

Year 1

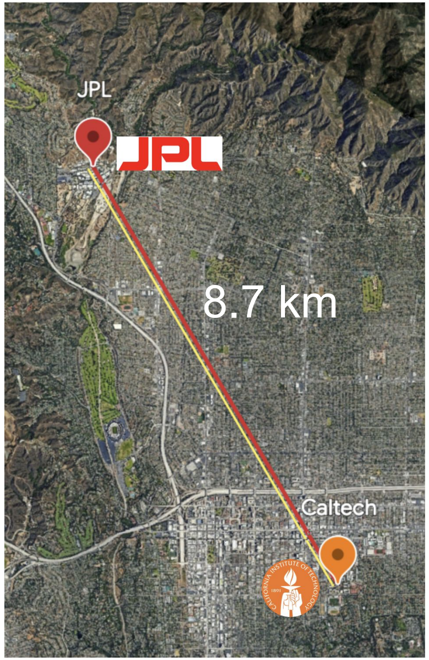
- Test free space link bldg. 238 to Mesa at JPL

Year 2

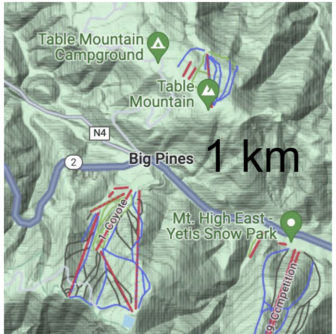
- JPL to Caltech link free-space
  - Receiver at Caltech
  - Explore AO system

Year 3

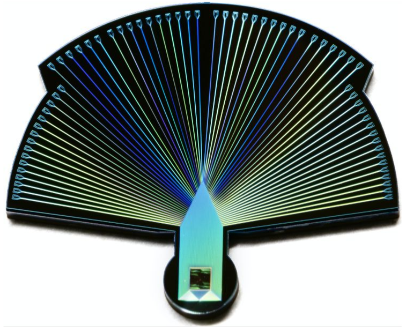
- OCTL across valley demo (2 hours from Caltech)
- Optional:
  - Potential uplink/downlink from QEYSSat (Canadian Space Agency)
  - Drone demonstration



JPL’s OCTL 1 m telescope

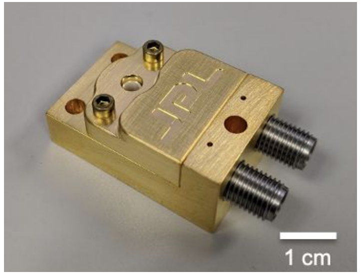


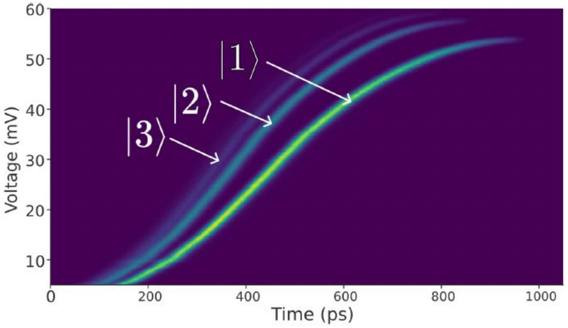
Conclusion



Deliverables: (Caltech-JPL)

1. Sources and detector for swapping between FNAL-ANL
2. Co-existence of entanglement swapping with classical communication
3. Hybrid fiber / free-space link between Caltech-JPL
4. High dimensional entanglement for more robustness to noise
5. Entanglement distillation using low jitter snspds towards error correction





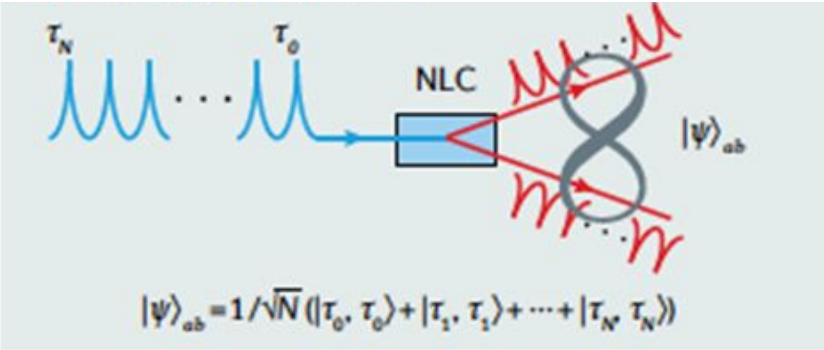
Backup

High-dimensional entanglement

High Dimensional Entanglement:

$$|\Psi_{HiDE}\rangle = \sum_{n=0}^{d-1} \frac{e^{i\phi_n^p}|nn\rangle}{\sqrt{d}}$$

d → Dimensions



Why high dimensional entanglement?

- Fundamental quantum information
- Tolerant to noise: Free space entanglement dist.
- Tolerant to loss: Fiber-based entanglement dist.
- Higher secret key rate per detection

Why time?

- Time can be very precisely measured
    - Low jitter SNSPDs - 3ps
- Dimensions can be arbitrarily increased
- Deciding the dimensionality can be adapted in the post-processing

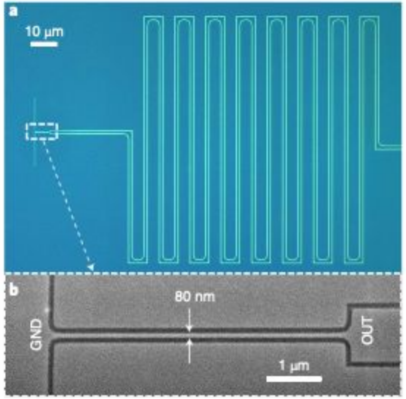
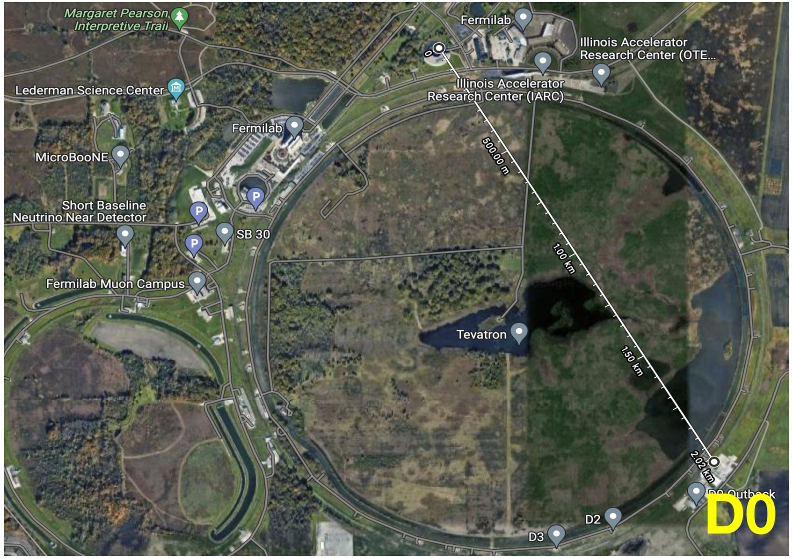
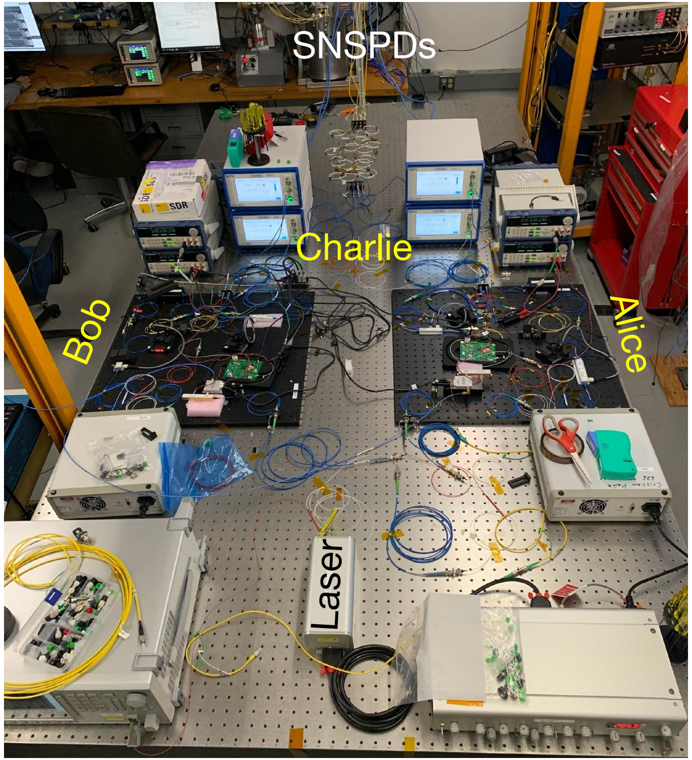


Fig. 2 | Low-jitter SNSPD. a, Optical micrograph of a representative device, inqnet

Entanglement Swapping at Fermilab

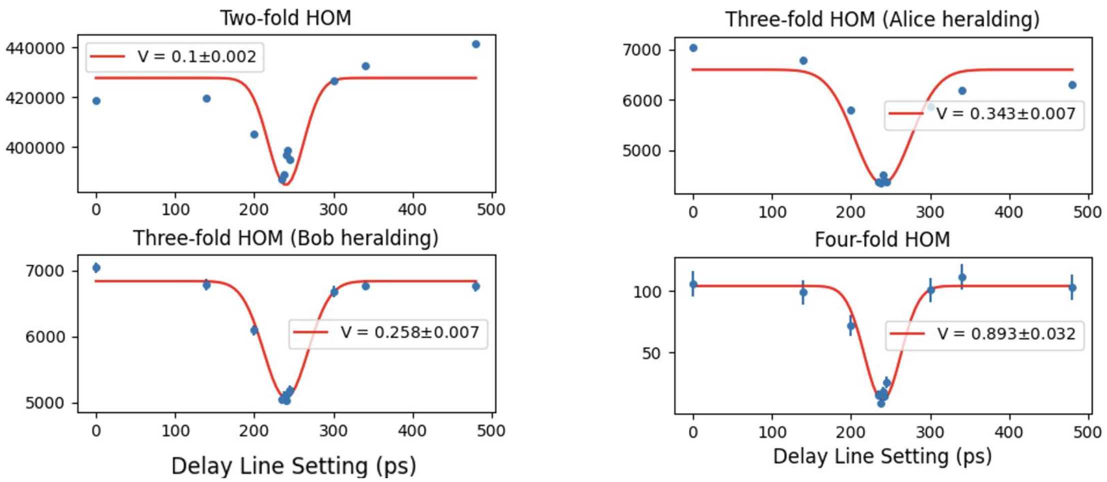
- Deployed sister testbed at Fermilab for integration in DOE's quantum internet connecting the 17 national labs

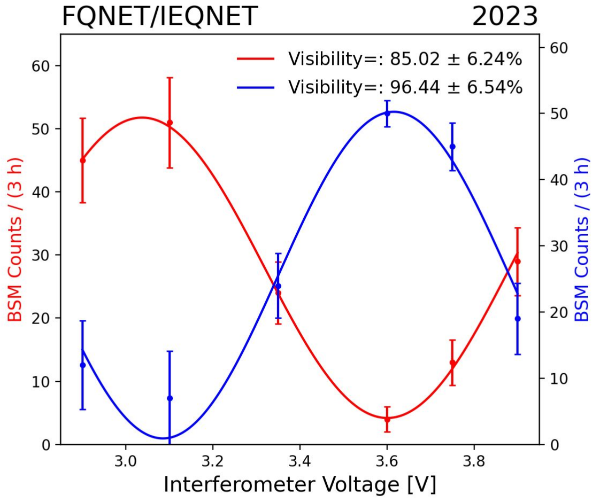




Entanglement Swapping at Fermilab

- Preliminary results





Entanglement Swapping at Fermilab

- Achieved up to 94% entanglement teleportation fidelity at D0

- Future work:
  1. Multiphoton entanglement between FCC and D0
  2. Swapping between FCC and D0
  3. Swapping between Fermilab and Argonne National Lab