Entangled Qubit Sources for Quantum Secure Communication and Imaging

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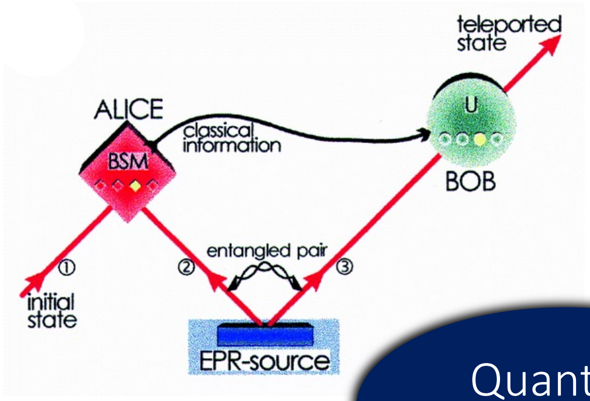
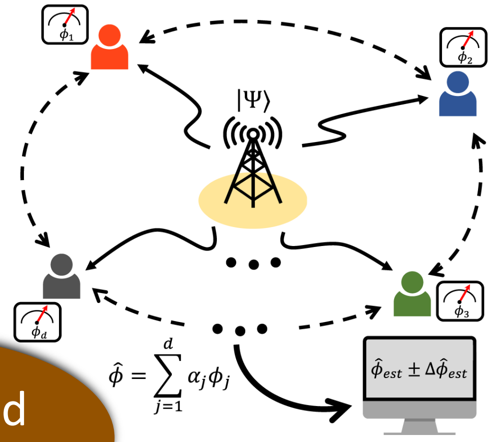
ISQIC-2025, TCG CREST





Quantum Randomness

Quantum Teleportation

Distributed Sensing

Quantum Repeater

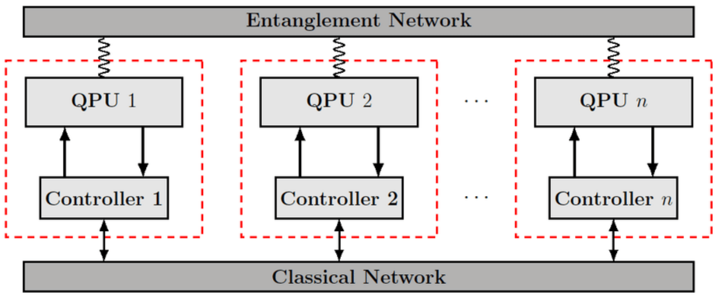
Quantum Communication Technologies

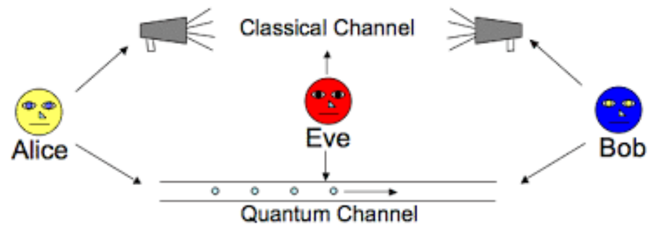
Quantum Internet

Distributed Computing

Quantum key distribution

Clock Synchronization

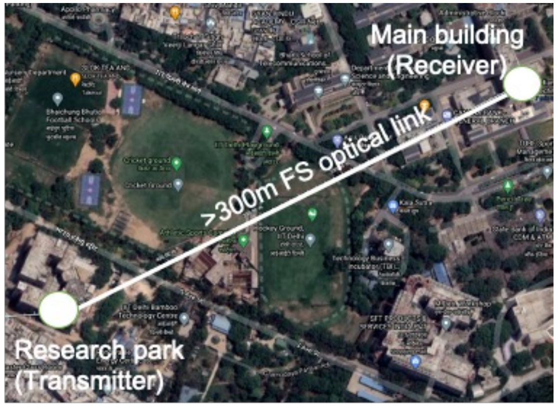




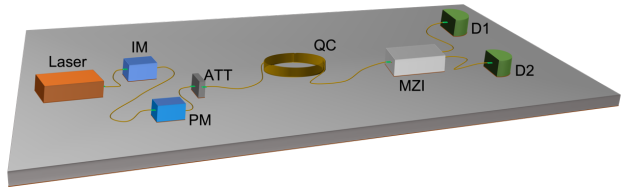
Myriad of Applications of Quantum Communication

Free space Quantum tech.(Partial Coherence, QKD, quantum imaging)

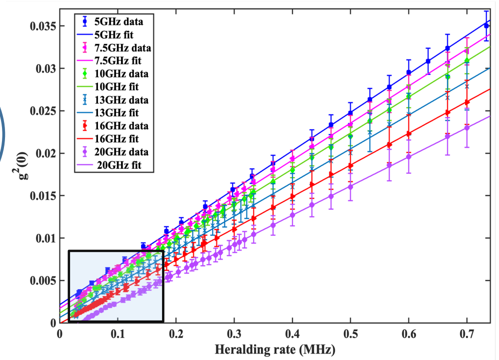
Fiber based QKD (Telecom compliant, DPS, BBM92, Quantum Networks)



Quantum Technology activities at EQUIP-IITD



Single photons, entangled photons (Bright, high rate and high purity)

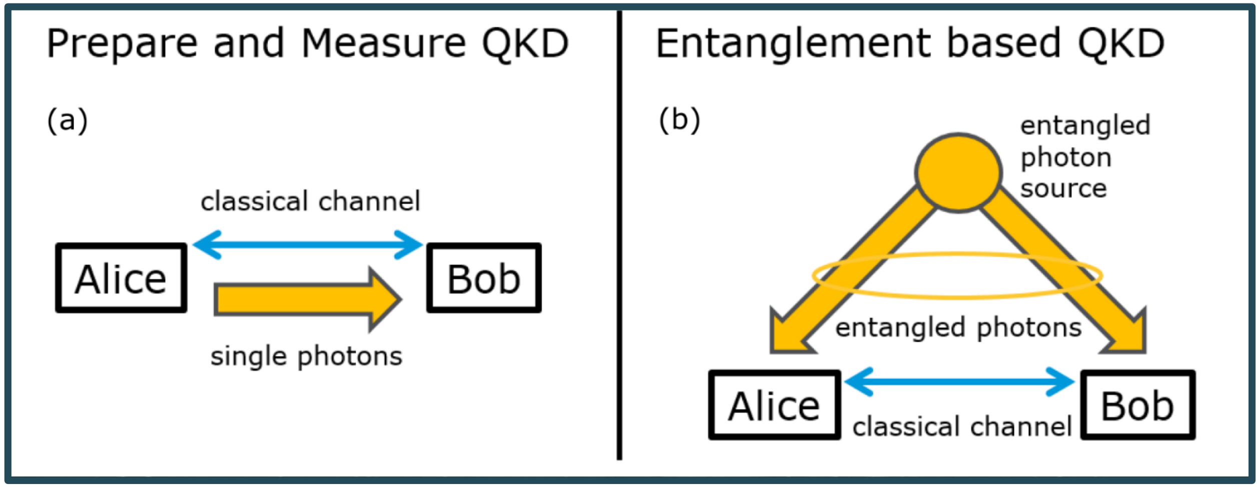


SNSPD development (PNR detectors)

OL 49, 1381 (2024)

ISQIC-2025, TCG CREST

Phy. Scr. 98, 65115 (2023)



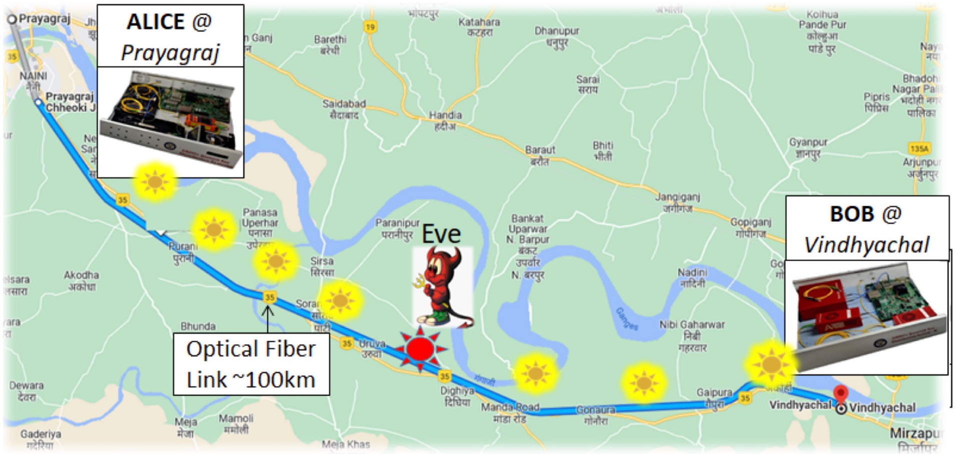
Property	Prepare and Measure QKD	Entanglement QKD
Channel	Fibre and Free-space	Fibre and Free-space
Length (between nodes)	100km	Can be more
Source	Weak coherent pulses	True quantum (SPDC)
Key rate at 50km	In 10-100kbps	In 5-50 kbps
Security of QKD	Good	Higher (entanglement distribution)
Type of Nodes	Trusted (Secure) Nodes	Can Lead to Trusted Node-free
Hacking	Need countermeasures	Even hacked source produces secure keys
Protocols	DPS, BB84, COW	E91, BBM92
Future Applications	QKD	QKD, Quantum Teleportation, Sensing, Absolute Metrology, Repeaters, etc.

DPS QKD demonstrations on commercial grade fiber

(Innovations in design and optimization of parameters)

2022

Intercity QKD for 100km fiber

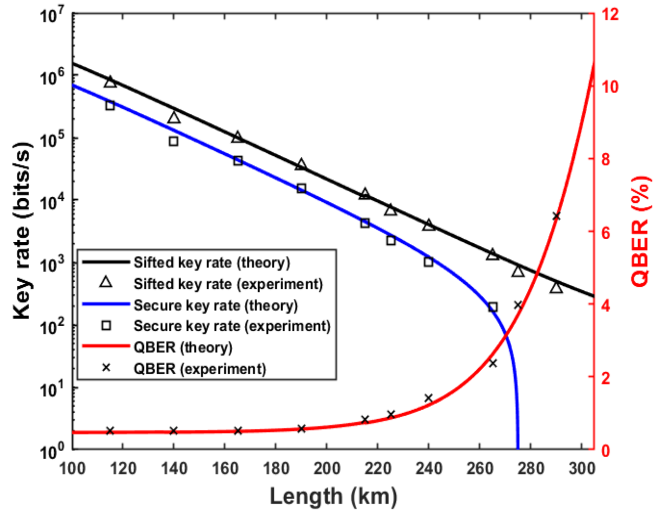


Fiber optic link distance: 100 km
Optical loss: 25-26 dB
Tx (Alice): Prayagraj
Rx (Bob): Vindhyanchal

QBER: Less than 9%
Sifted key rate: Up to 10 kbps

2023

Trusted node free QKD for 380km fiber

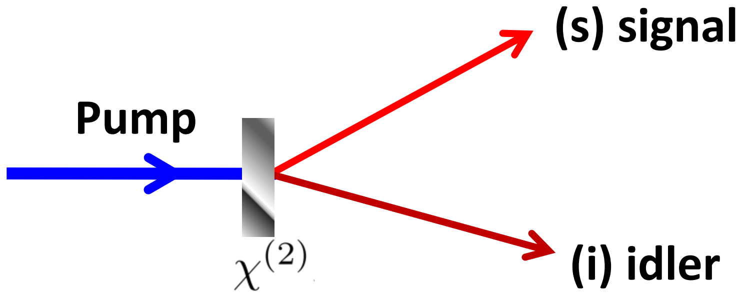


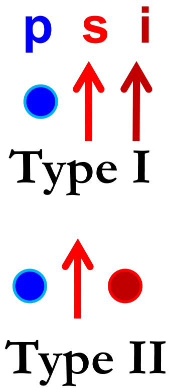
Experiment	Clock rate	QBER	Secure KR	Channel length	Year
Wang et al.[28]	2 GHz	3.45%	N.A.[a]	260 km	2012
Diamanti et al.[31]	1 GHz	3.40%	166 bps	100 km	2006
Takesue et al.[30]	10 GHz	> 4%	12.1 bps	200 km	2007
Takesue et al.[30]	1 GHz	> 2.3%	17 kbps	105 km	2007
Zhang et al.[42]	2 GHz	3%	1.3 Mbps	10 km	2009
Shibata et al.[b33]	1 GHz	2.93%	0.03 bps	336 km	2014
This work[c]	2.5 GHz	1.48% (2.36%)	0.11 bps (192.7 bps)	380 km (265 km)	2023

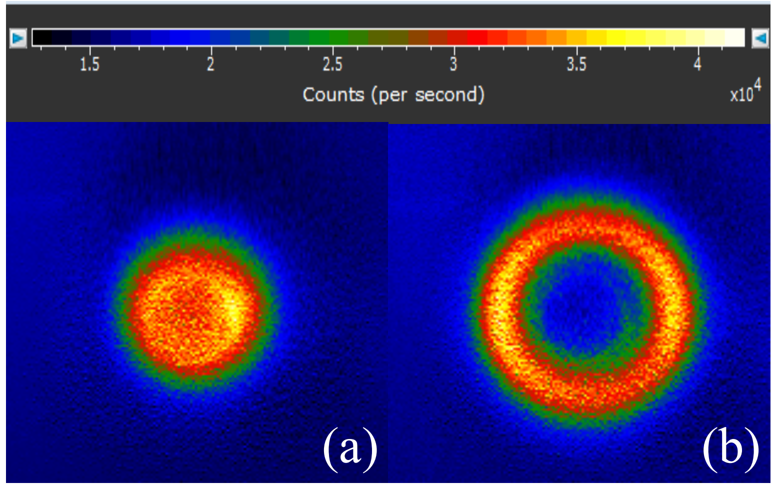
Light Quest Continues

N. Pathak, S. Chaudhury, Sangeeta, **B. Kanseri,**
Scientific Reports 13, 15868 (2023)

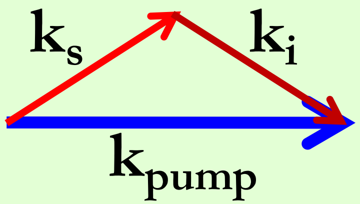
Spontaneous Parametric Down Conversion



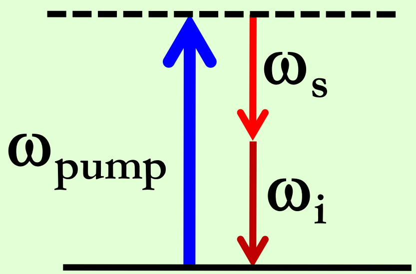




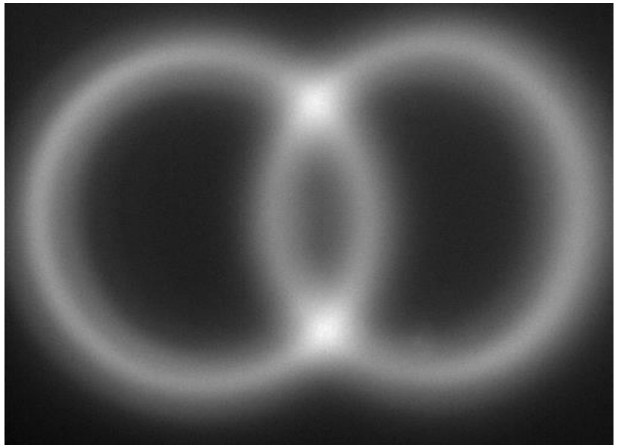
Type I



Momentum Conservation



Energy Conservation



Type II

Alain Aspect John F. Clauser Anton Zeilinger

The Nobel Prize in Physics 2022

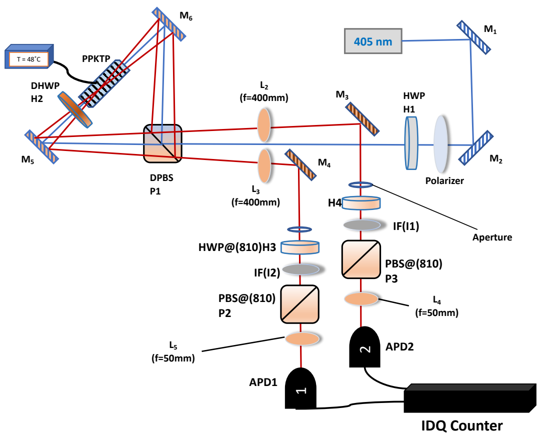
Entanglement and its applications

Entangled Photon Sources

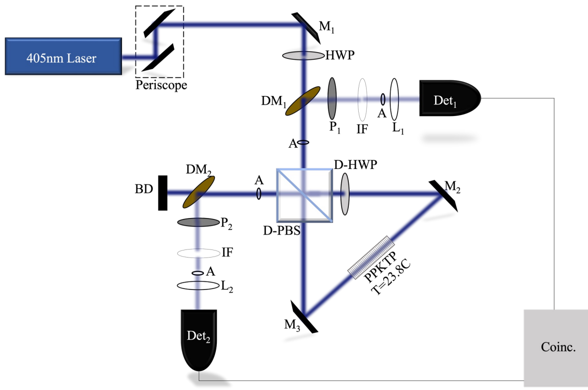
NIR wavelength @810nm
Using PPKTP

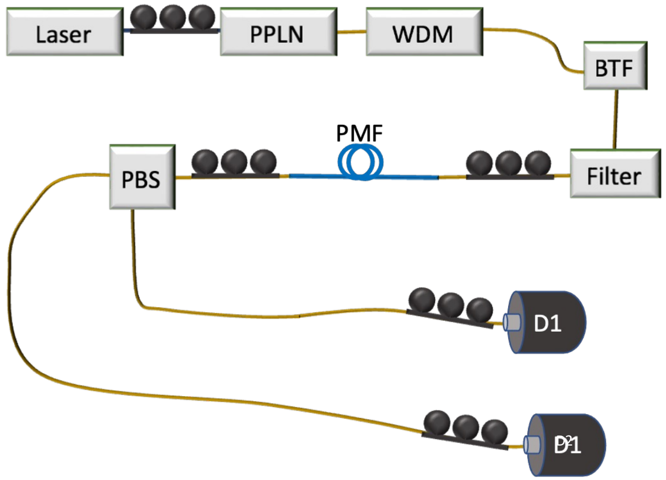
All-guided wave @1550nm
Using PPLN

1. Type 0 scheme



2. Type II scheme





Av. Visibility > 87%

Bell violation :

S~2.60±0.02

Av. Visibility > 88%

Bell violation :

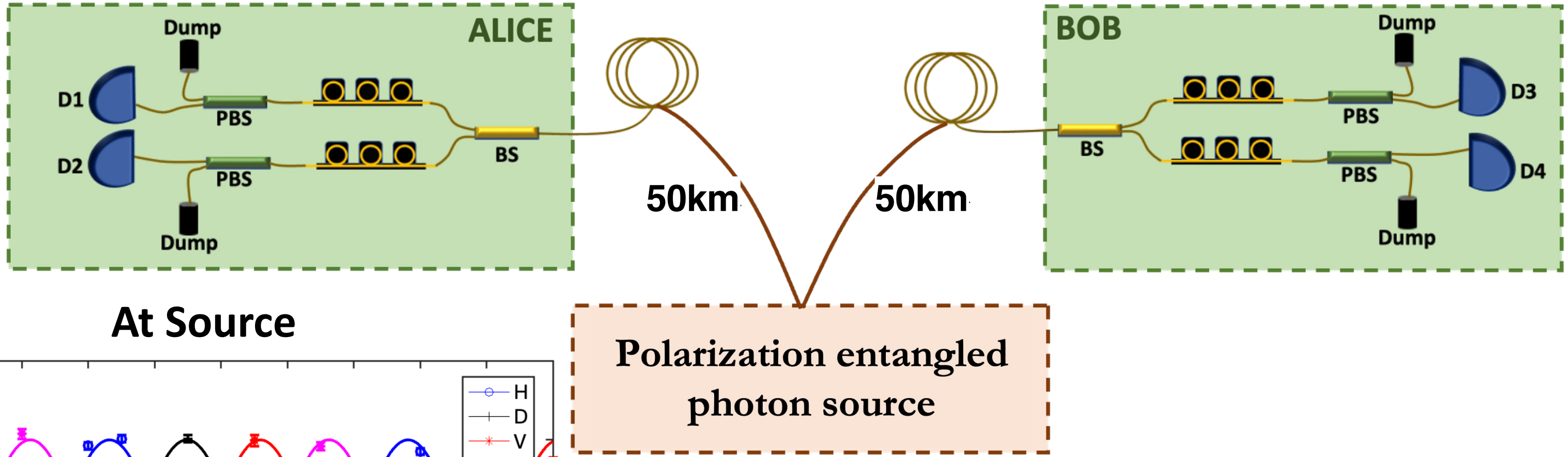
S~2.61±0.05

Av. Visibility > 92%

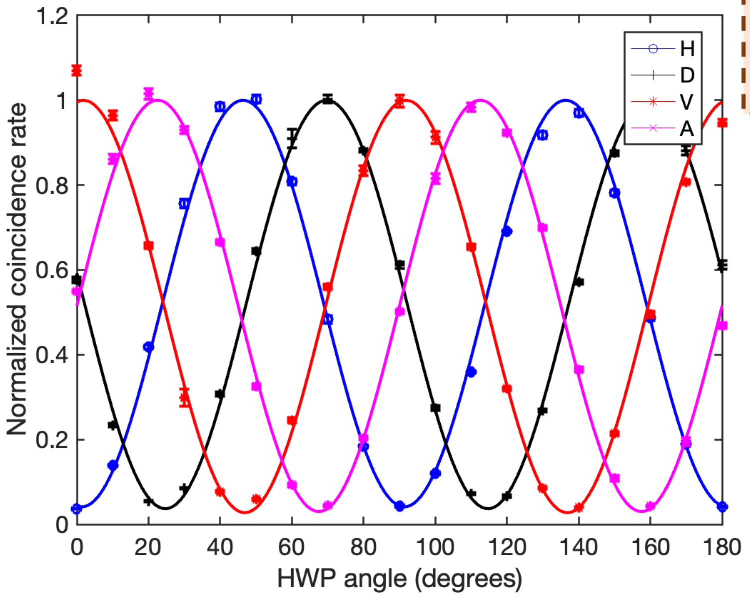
Bell violation :

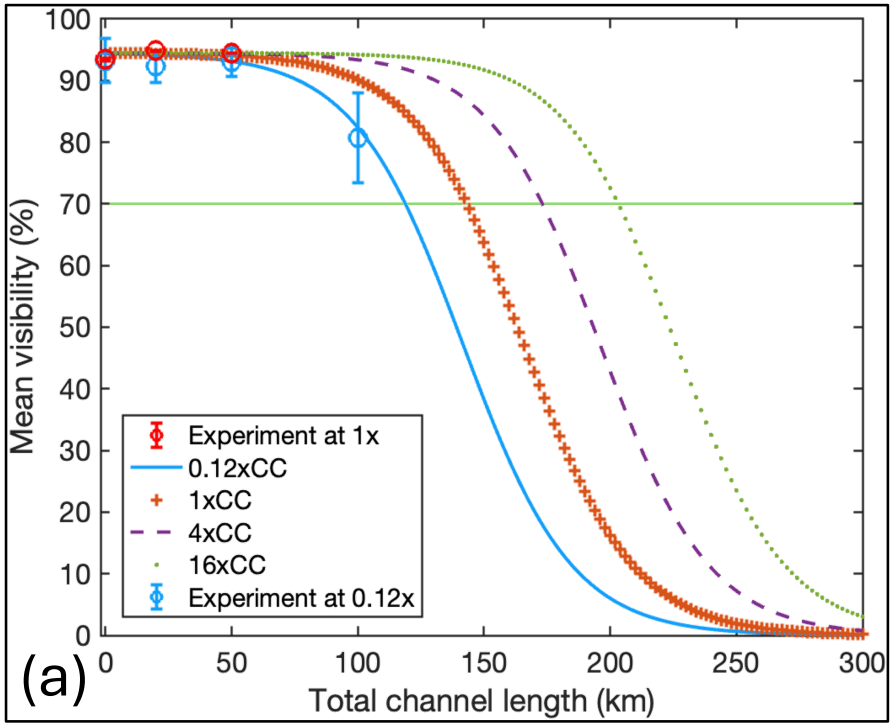
S~2.71±0.03

Fibre entanglement distribution and QKD in lab



At Source

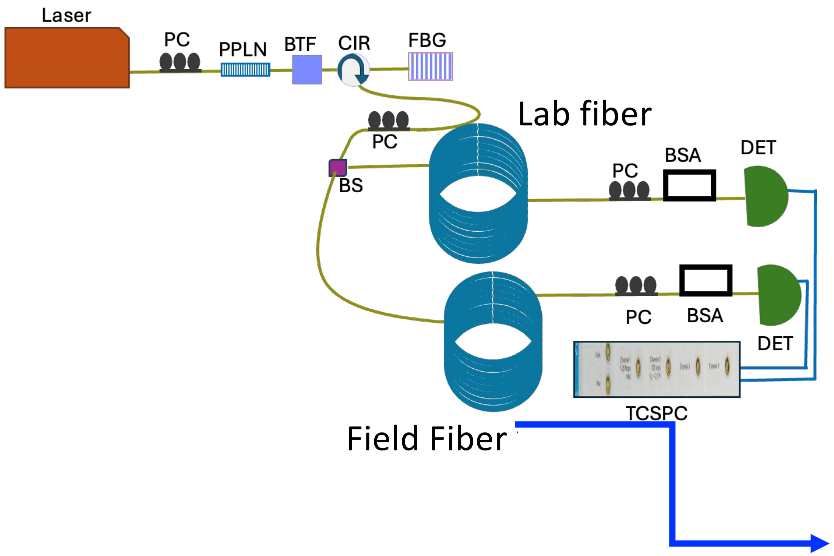


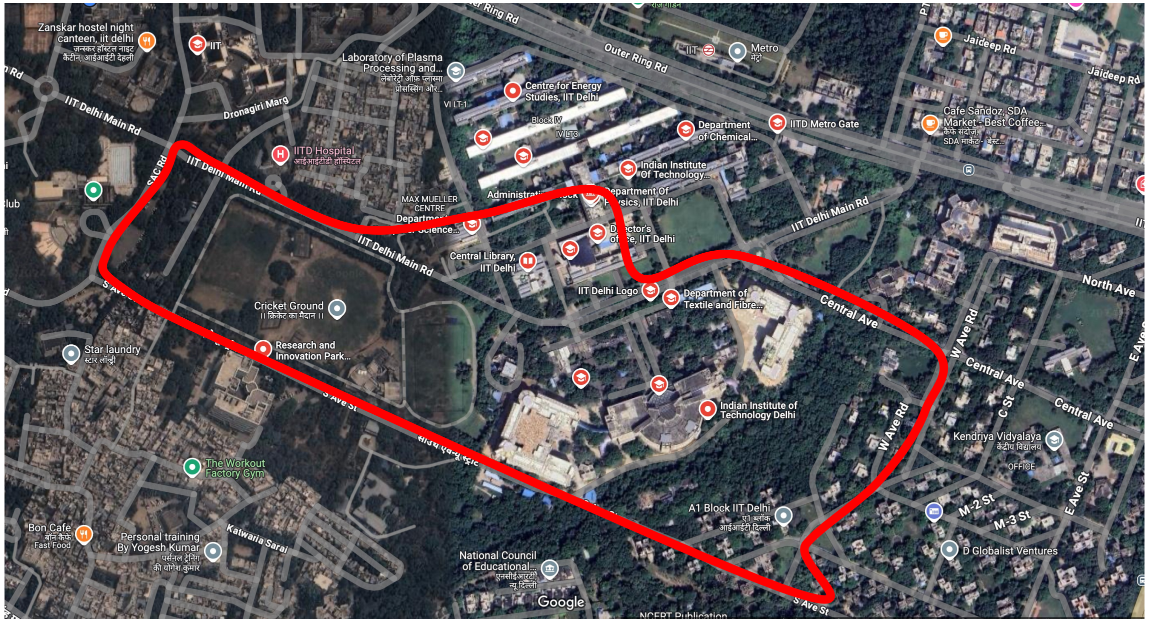


Length (km)	QBER %	Coin Rate (Ps)	Secure KR (kbps)
0	3.29	31.1 k	10.51
20	2.58	10.56 k	3.45
50	2.77	3.10 k	1.43

Field test of entanglement-based fiber QKD

Underground fiber within IITD campus





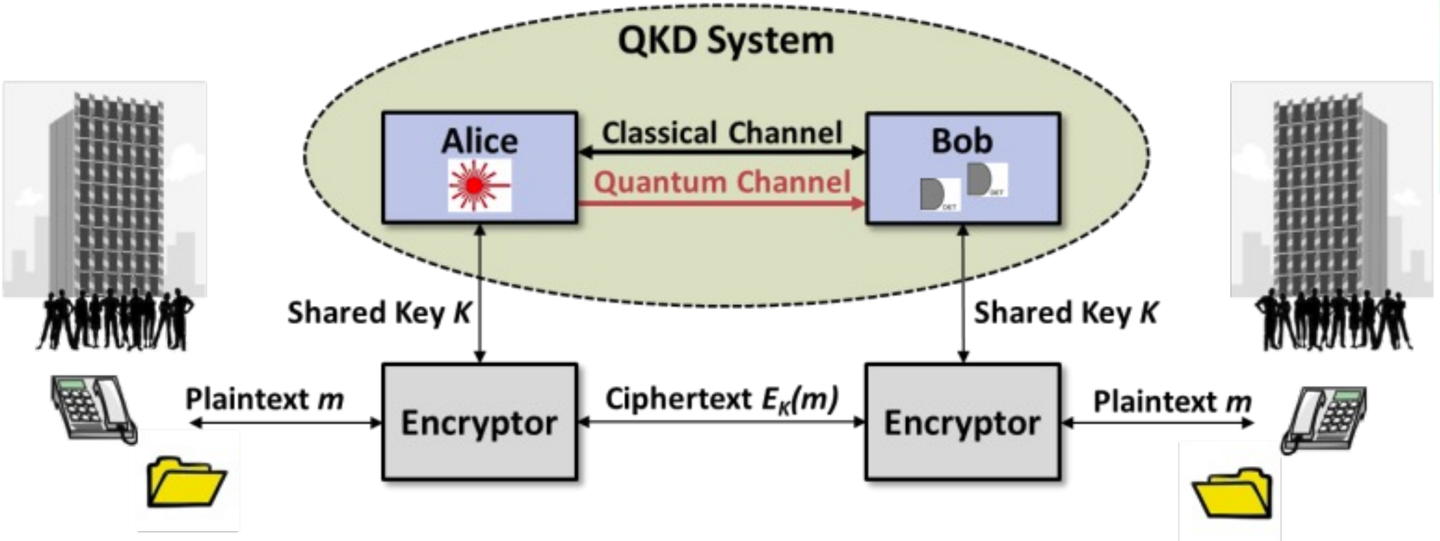
Total length:
Field: 7.8 km
Lab spool : ~10 km
Total Loss: -6.5dB + (-4.5dB)

Key rate achieved so far: 2kbps, QBER<3%

Entanglement based QKD is compatible with field deployed telecom grade fiber

Nishant et al, Frontiers in optics (2024)

Need to co-propagate signals through the same fiber

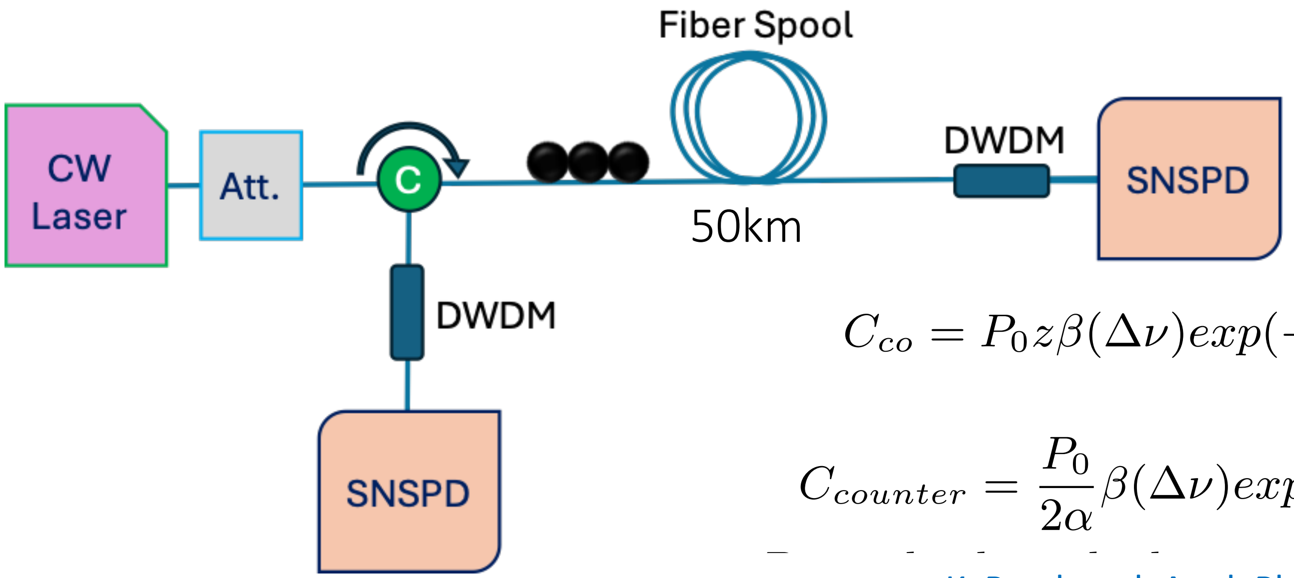


Multiplexing of quantum and classical signals in same fiber:
Both signals pass through identical ambient conditions

Compensation of polarization and time delay fluctuations
High precision clock synchronization
Reduced infrastructure cost and increased bandwidth

Both quantum channels must be in C band for reduced losses and use of same off-the-shelf components

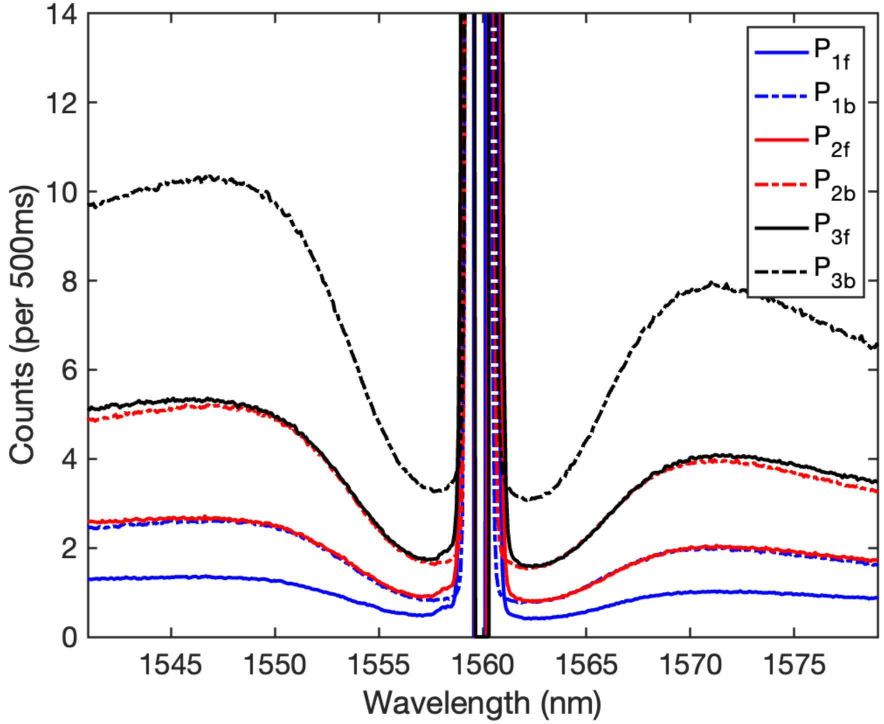
Forward and Backward Raman Scattering in Fiber

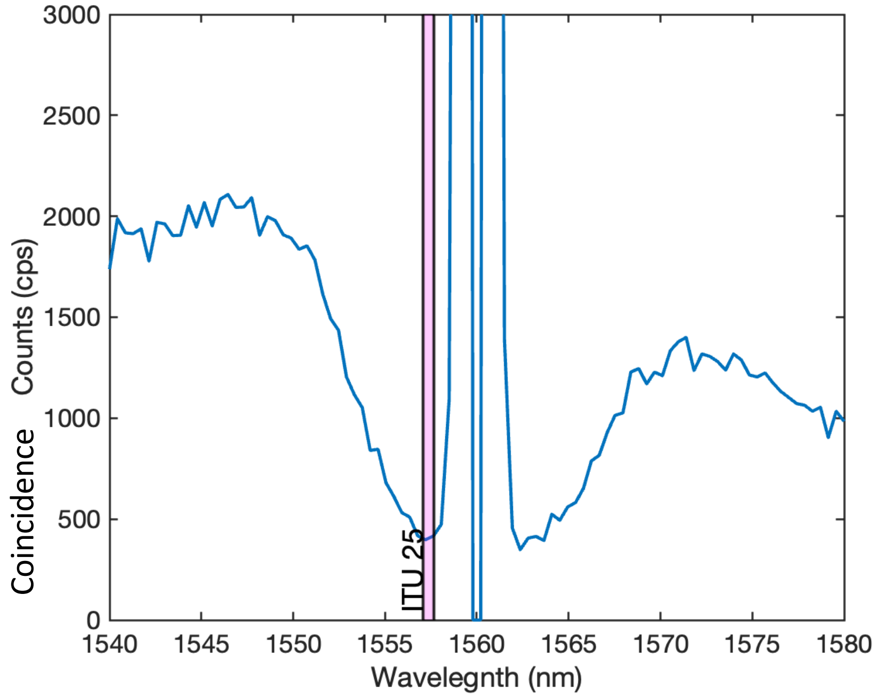


$$C_{co} = P_0 z \beta(\Delta\nu) exp(-\bar{\alpha} z) \eta_d \frac{\tau}{h\nu}$$

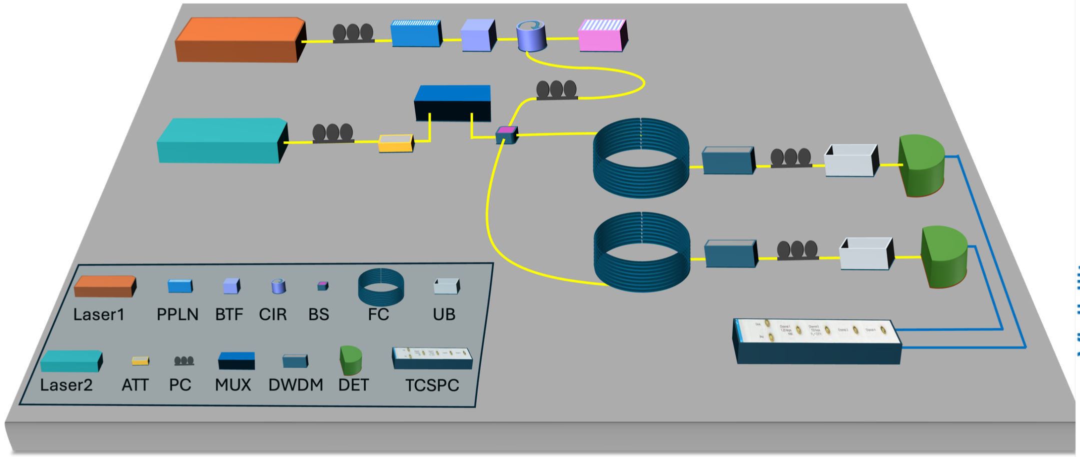
$$C_{counter} = \frac{P_0}{2\alpha} \beta(\Delta\nu) exp(-\bar{\alpha} z) \eta_d \frac{\tau}{h\nu}$$

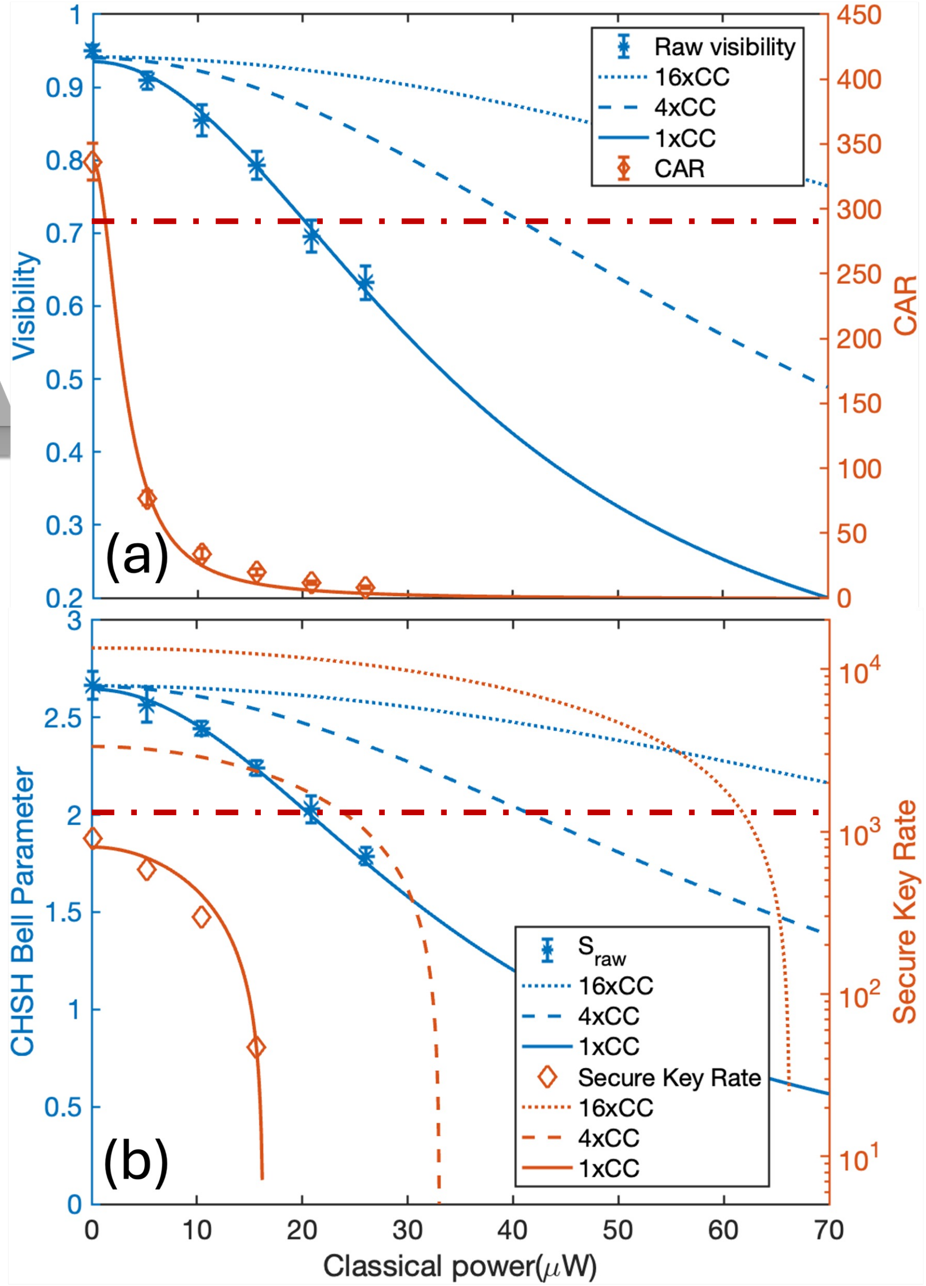
K. Patel et al, Appl. Phys. Lett. 104 (2014)





Coexistence of C Band Quantum & Classical Signals





S>2 for $P_{classical}$ ≈ -16.82 dBm

SKR ~175bps for powers −20.0 dBm

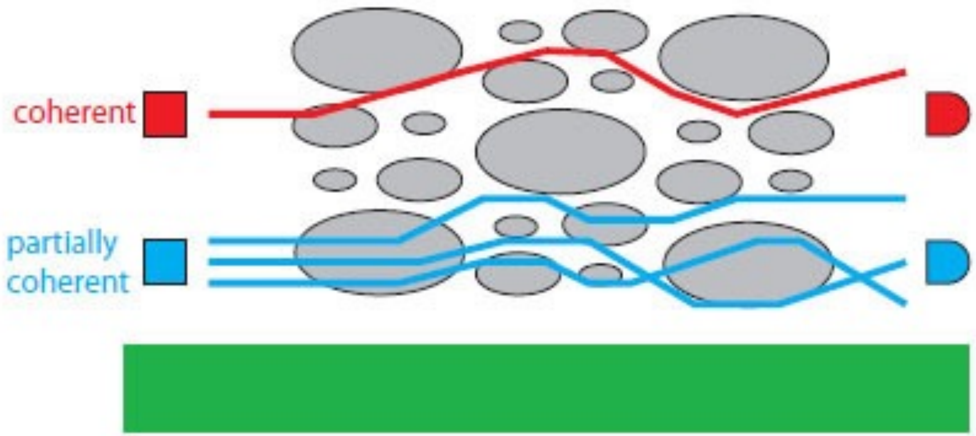
Up to -12.2 dBm classical power can be propagated simultaneously with entanglement based QKD leading to multiple classical channels with standard internet traffic

21 dB higher than standard classical comm. power requirement

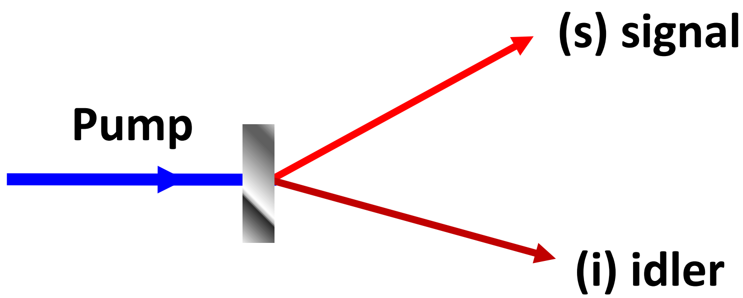
N. Pathak, A, Dulta, and **B. Kanseri, Submitted (2024)**

Motivation for using partial coherence

Application of partially coherent (spatially) photons for free-space quantum communication and imaging/sensing

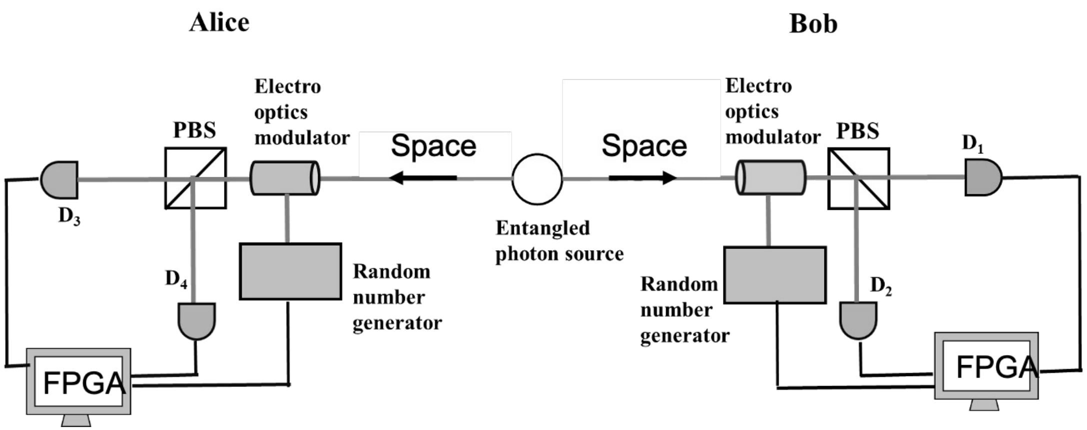


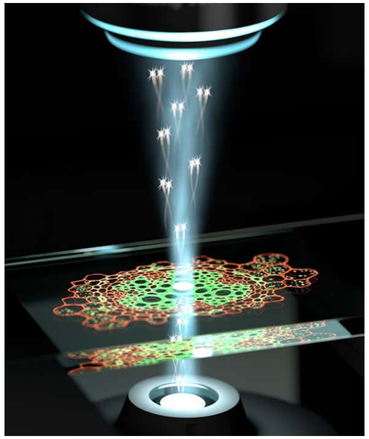
Gbur et al, J. Opt. Soc. Am. A 19, 1592 (2002),



SPDC for quantum state generation

Partial coherence for resistance to losses





"The detection probability of the two-photon field is higher, and thus less susceptible to turbulence, if the field is produced by a partially coherent pump beam."

Qiu et al, Appl. Phys. B 108, 683 (2012), New Scientist, 9 June 2021

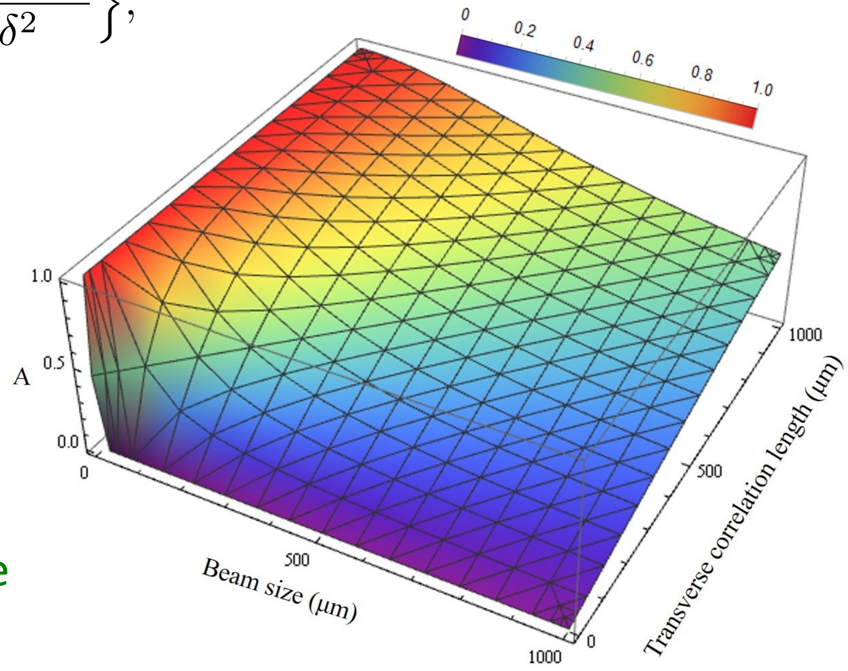
Partially-coherent optical beam

Gaussian Schell Model pump beam (Spatial coherence)

$$\langle V^*(\mathbf{r})V(\mathbf{r}')\rangle \propto \exp\left\{-\frac{(\mathbf{r}+\mathbf{r}')^2}{8\sigma_0^2}\right\}\exp\left\{-\frac{(\mathbf{r}-\mathbf{r}')^2}{2\delta^2}\right\},$$

$$A = \frac{\delta}{2\sigma_0}$$

$$0 \leq A \leq 1$$



(Incoherent) $0 \leq \mathrm{DOC} \leq 1$ (Fully coherent)

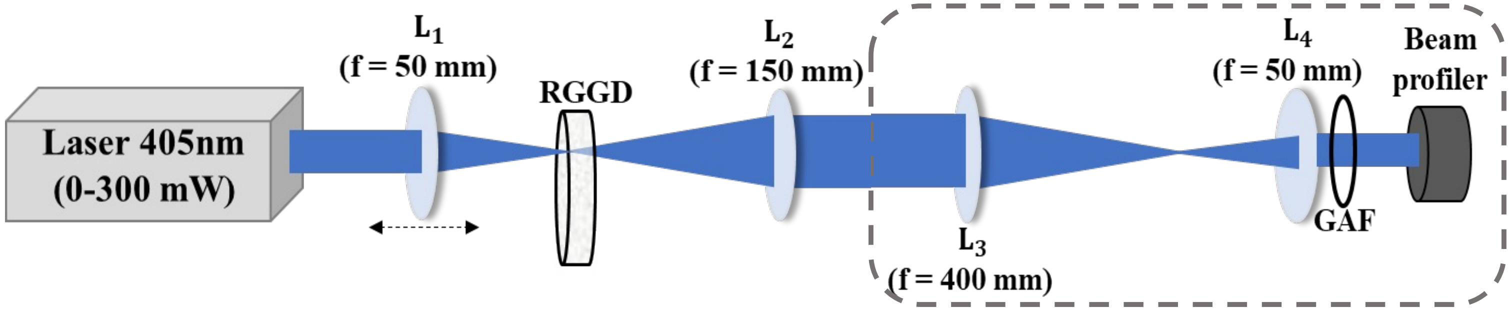
Intermediate values of *A* refer to partial coherence

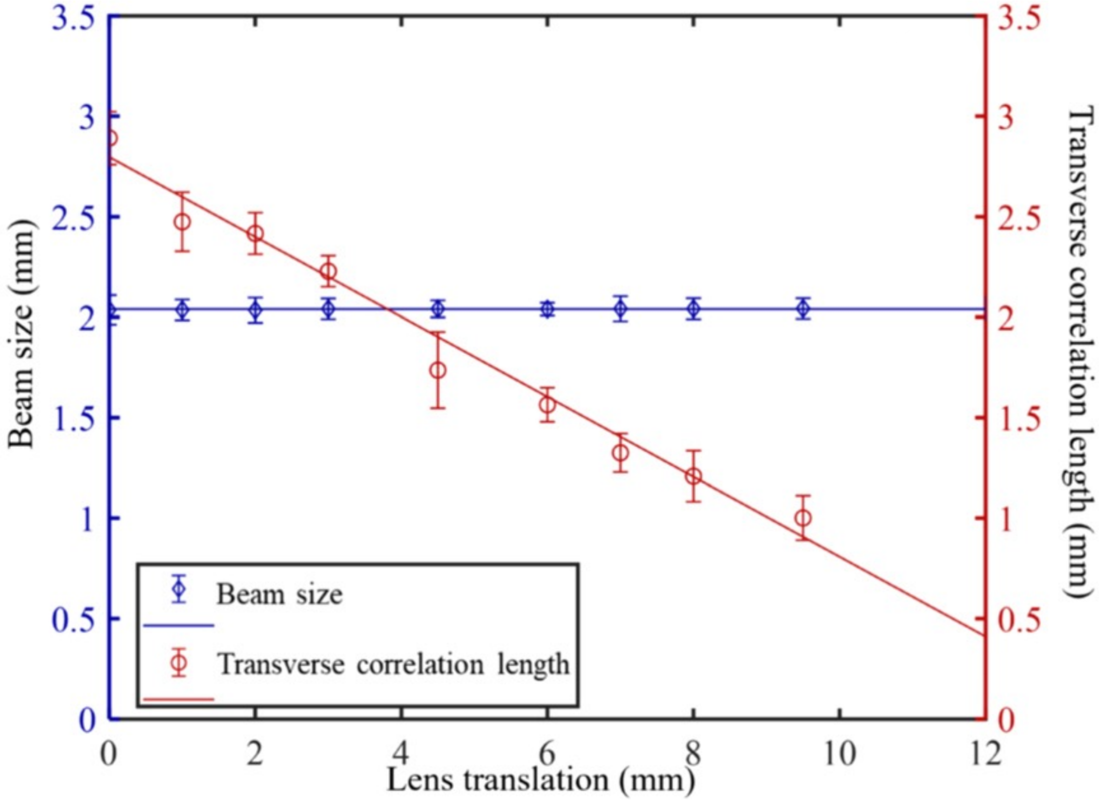
Applications of optical coherence:

Astrophysics, optical communication, data encoding and transmission, imaging (optical coherence tomography), and microscopy, beam propagation in random media, beam shaping, quantum optics and information

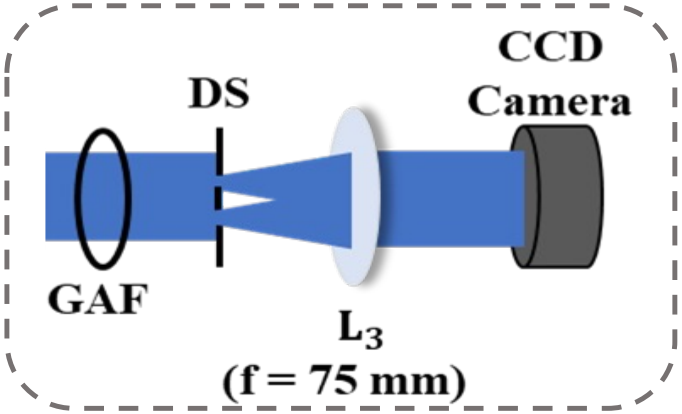
Optical Coherence and Quantum Optics, L. Mandel and E. Wolf (1995)

Generation and characterization of GSM pump beam



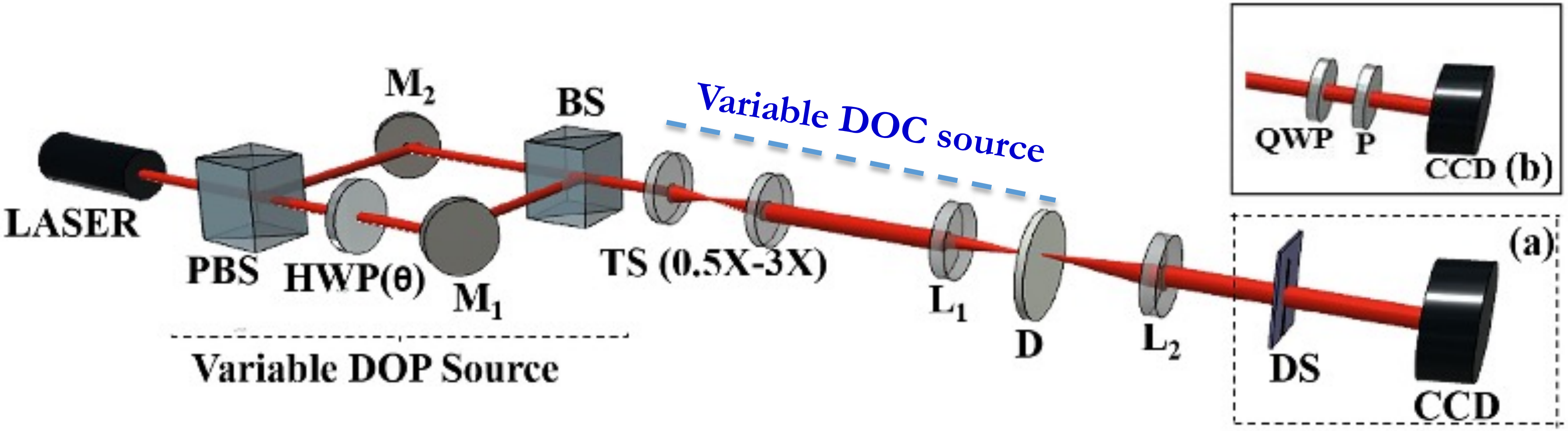


RGGD: Rotating ground glass diffuser
GAF: Gaussian amplitude filter
DS: Double slit

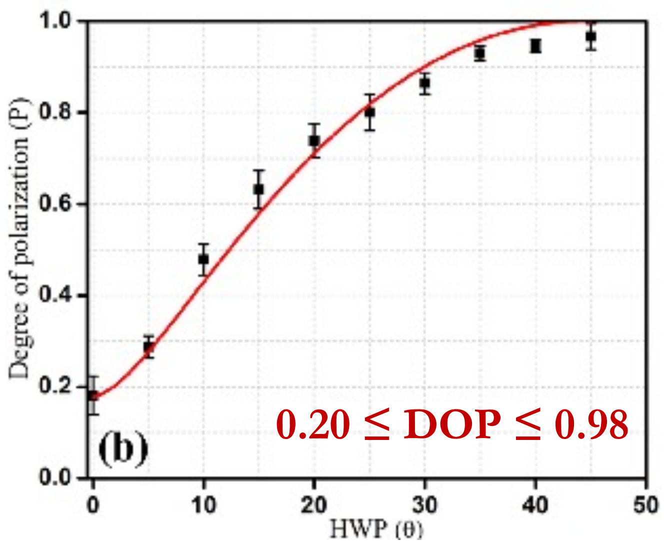


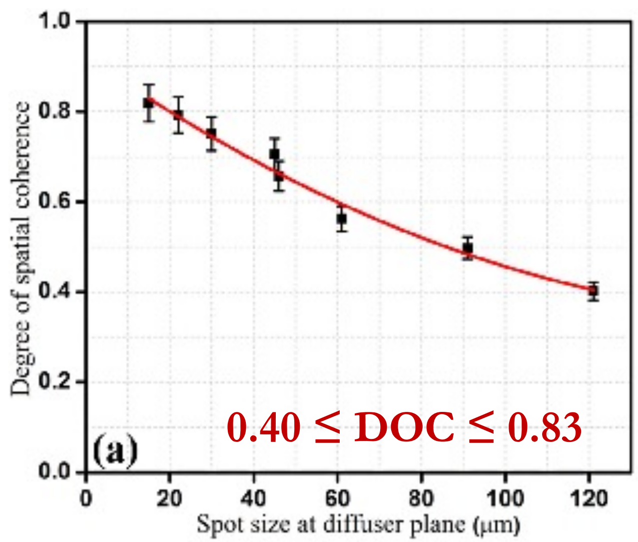
P. Sharma, S. Rao and B. Kanseri, **Physica Scripta 98, 65115 (2023)**

Tunable polarization and partial coherence source



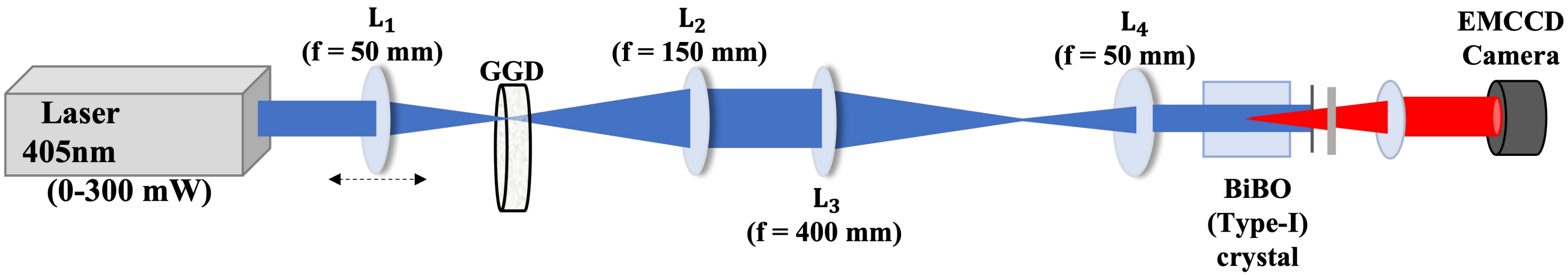
Use of van-Cittert Zernike theorem for DOC tunability



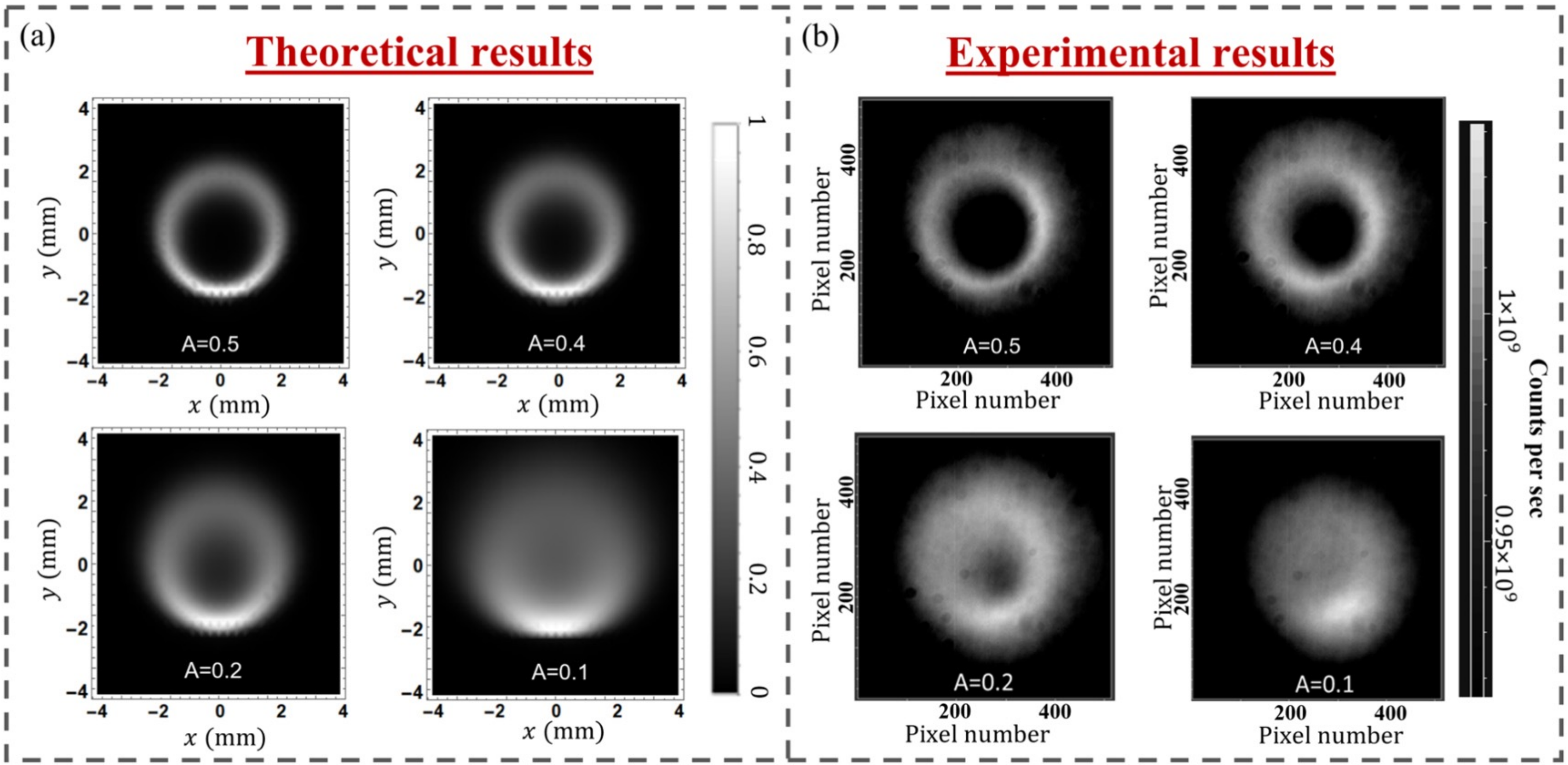


B. Kanseri, H. Kumar, **Optik 206, 163747 (2020)**

Experimental Results: Biphoton Profiles



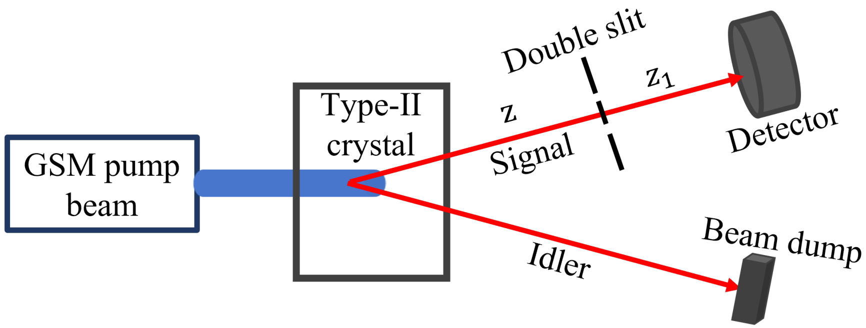
Type I non-collinear

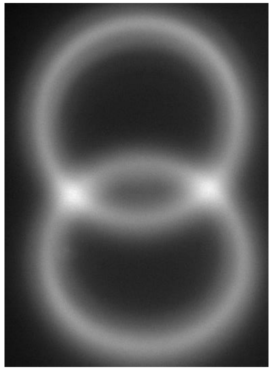


B. Kanseri and P. Sharma, **JOSA B 45, 4815 (2020)**

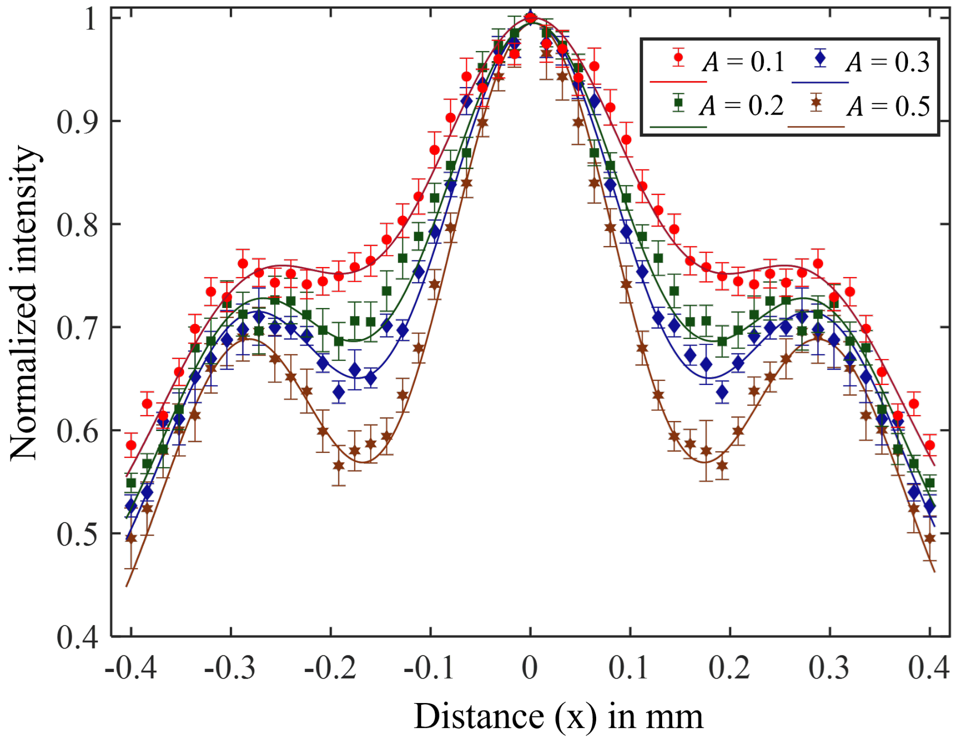
P. Sharma, S. Rao and B. Kanseri, **Physica Scripta 98, 65115 (2023)**

Towards Partially Coherent Qubits



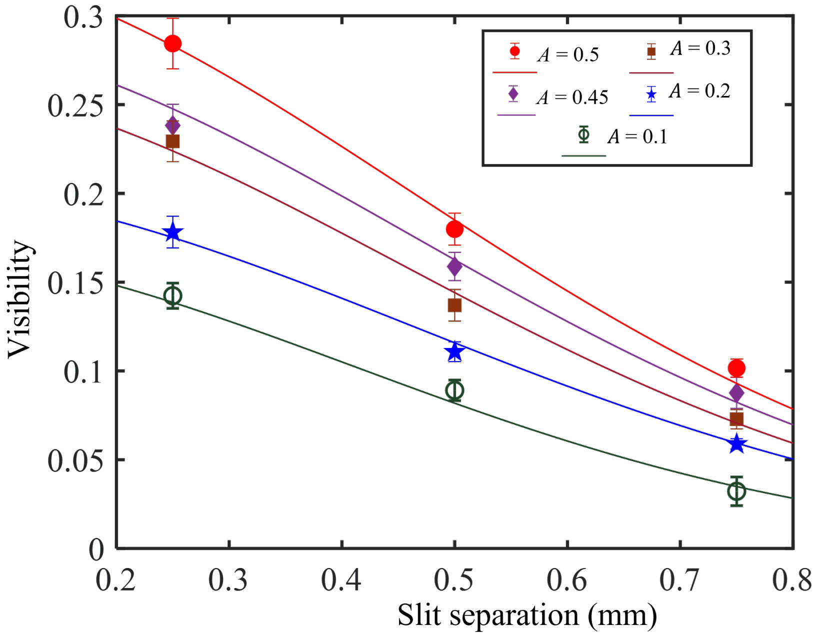


Type II SPDC Biphoton Profile

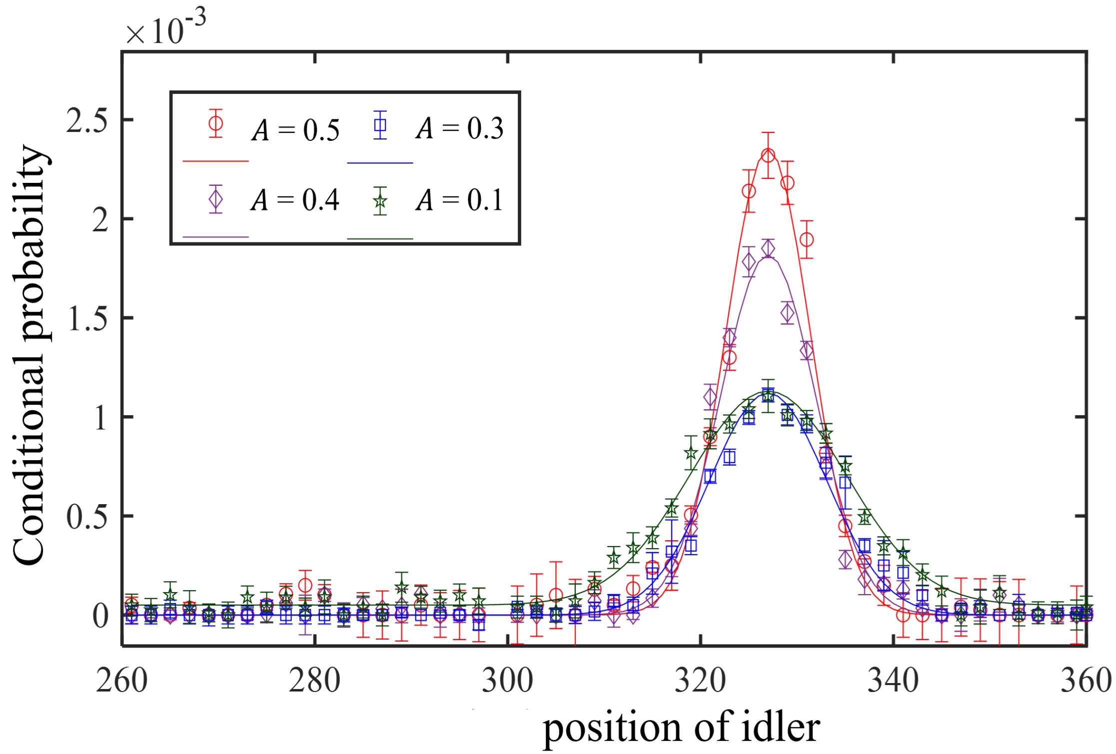


Double-slit interference using signal beam of single photons

P. Sharma, S. Rao and B. Kanseri, **Physica Scripta 98, 65115 (2023)**



Interference visibility



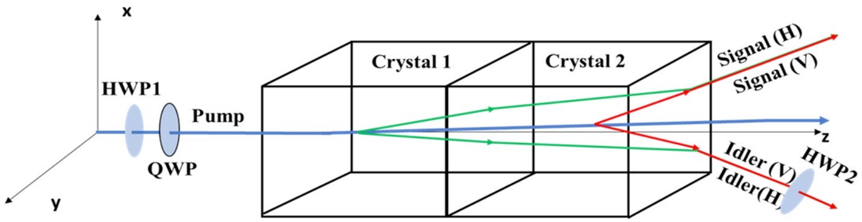
Conditional probability distribution

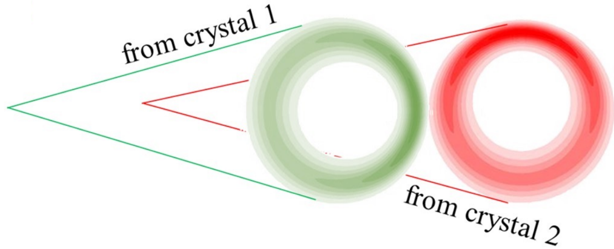
Transfer for spatial coherence properties in SPDC process from pump to down converted photons

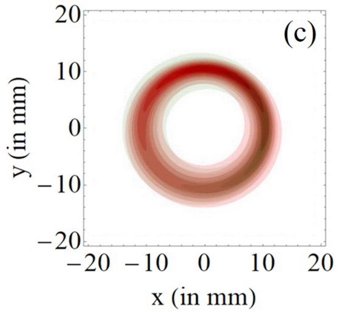
Demonstrates double-slit interference with single-photons is affected by partial spatial coherence of photons

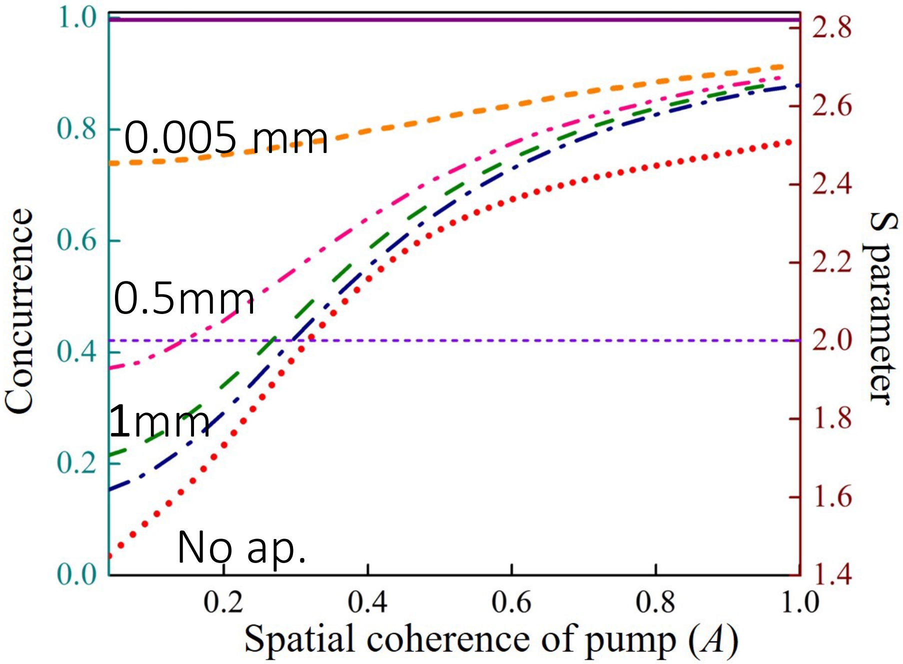
P. Sharma, S. Rao and B. Kanseri, **Physica Scripta 98, 65115 (2023)**

Effect of partially coherent pump on Entanglement

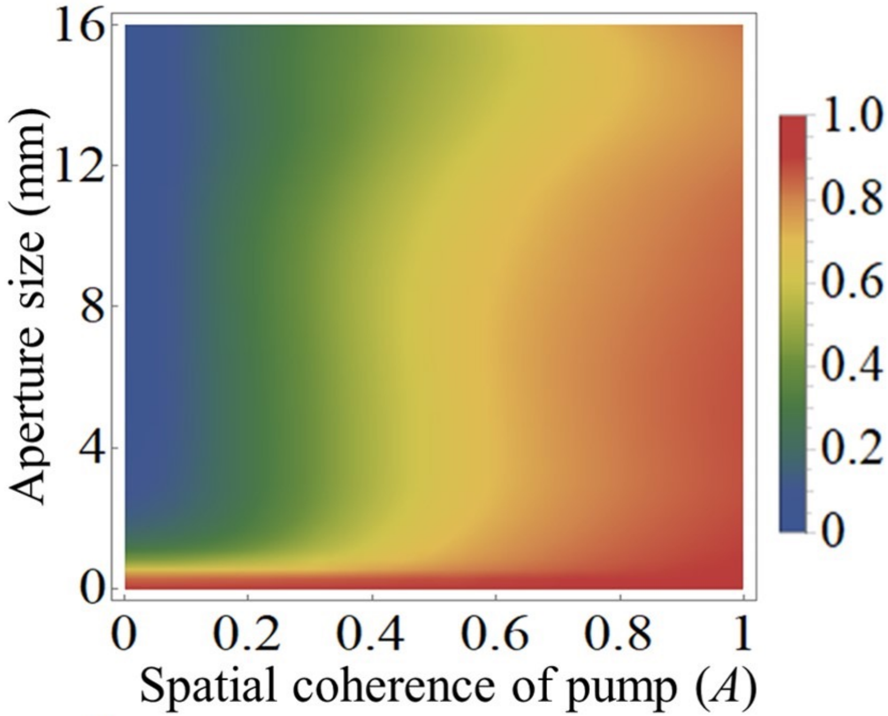


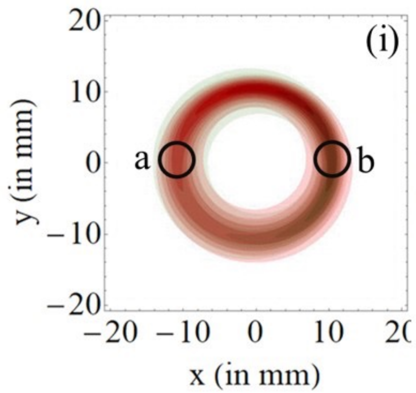


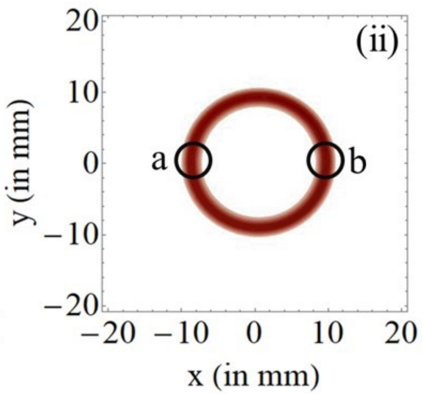




Concurrence $C = \left|\langle\Psi^*|\sigma_y \otimes \sigma_y|\Psi\rangle\right|.$



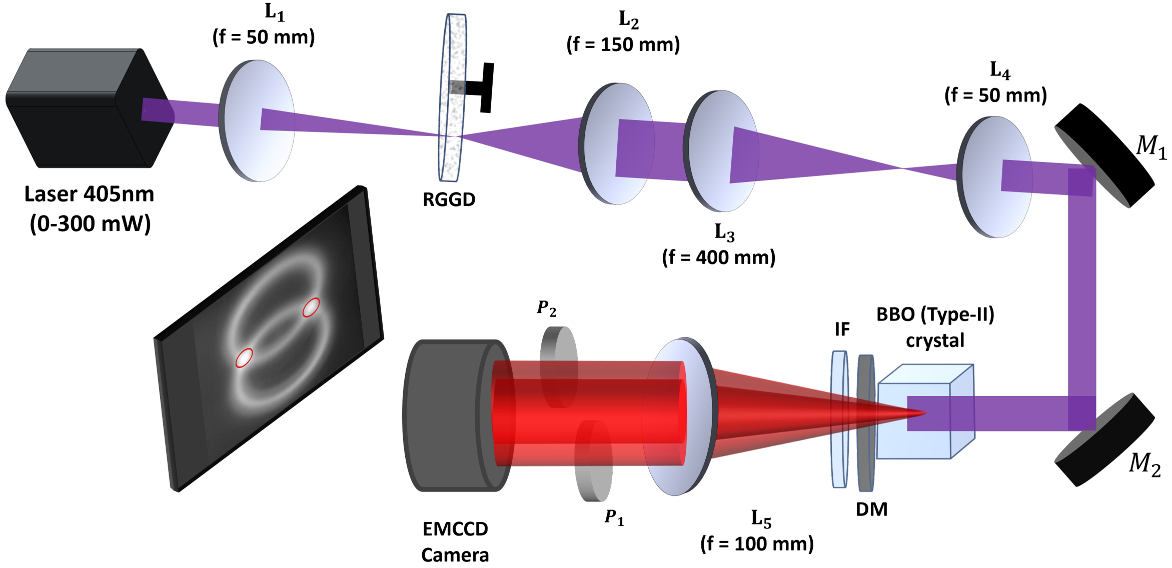


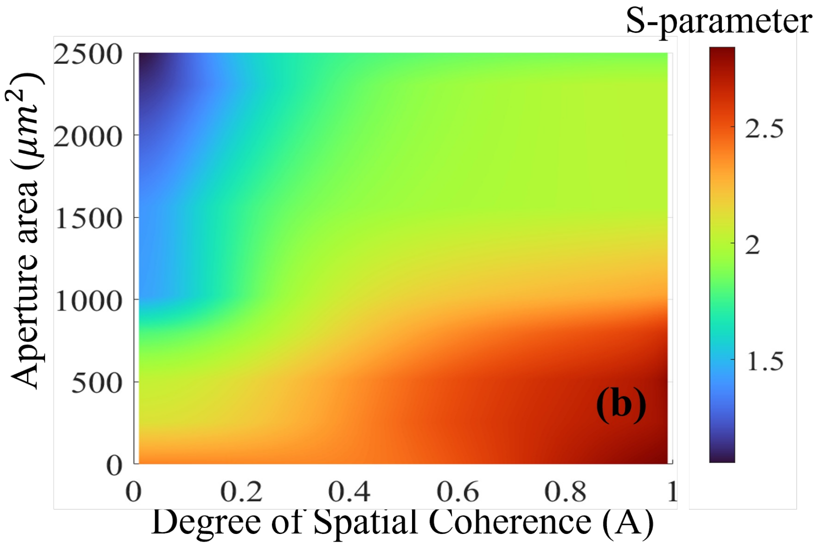


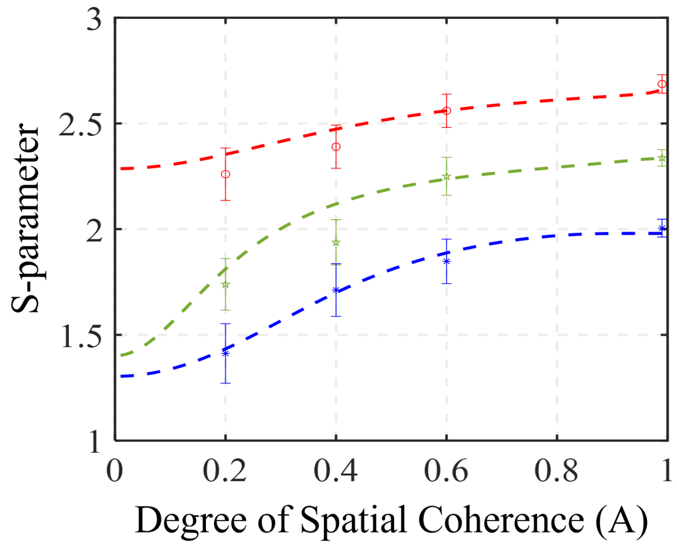
Entanglement enhanced partially coherent Qubit

PS, NKP and BK, **Results in Physics 27, 104506 (2021)**

Entanglement Recovery in Partially Coherent Qubits







Multiple spatial-mode entanglement generation and single mode detection

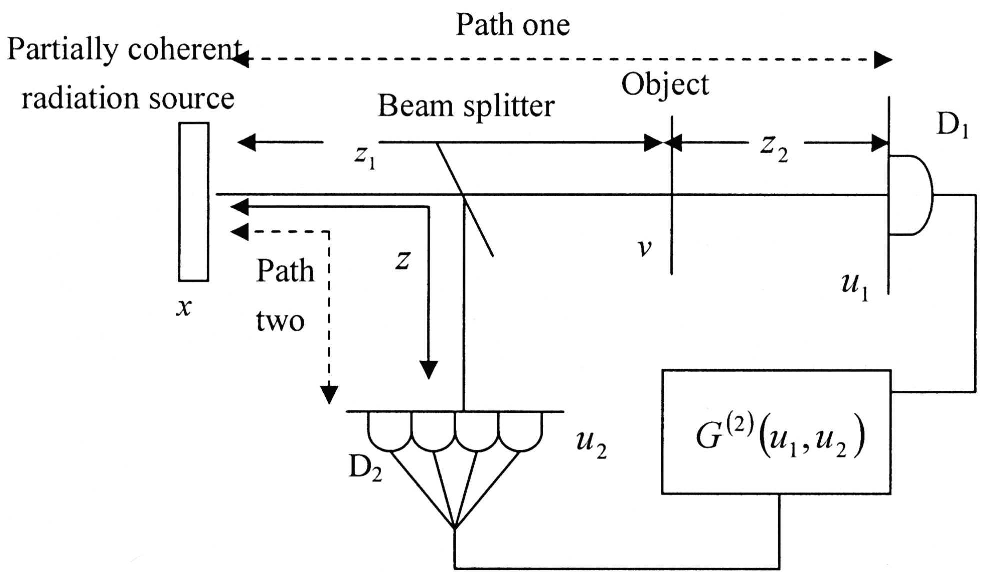
SR, PS, and BK, **Optics Letters 49, 1381-84 (2024)**

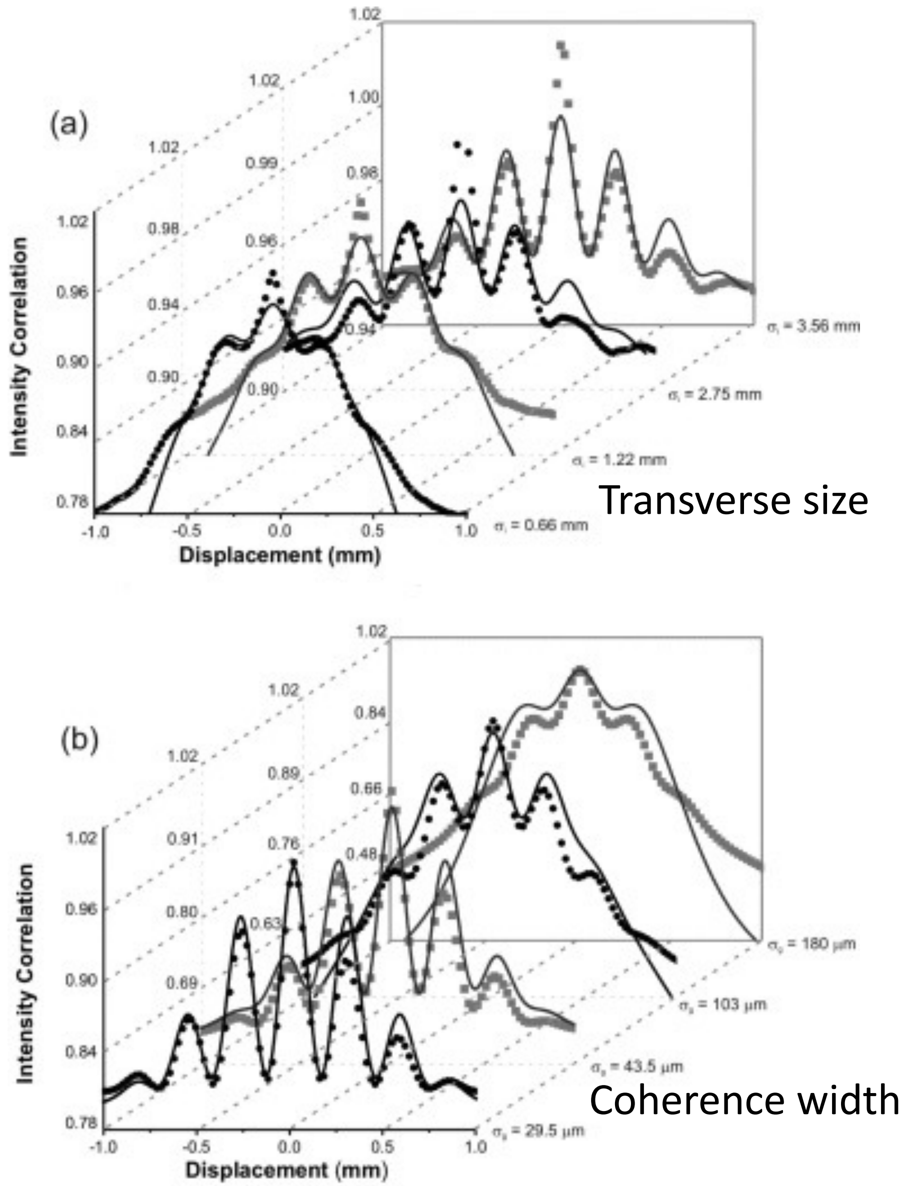
Ghost interference with partially coherent light

Fourth order correlation function:

$$G^{(2)}(u_1,u_2) = \langle E(u_1)E(u_2)E^*(u_1)E^*(u_2)\rangle$$
$$= \langle I(u_1)\rangle\langle I(u_2)\rangle + |\Gamma(u_1,u_2)|^2,$$

$$\langle E(x_1)E^*(x_2)\rangle = G_0 \exp\left[-\frac{x_1^2+x_2^2}{4\sigma_I^2} - \frac{(x_1-x_2)^2}{2\sigma_g^2}\right].$$





Visibility of pattern $V = \frac{|\Gamma_{\max}(u_1=0,u_2)|^2}{G^{(2)}_{\max}(u_1=0,u_2)}$

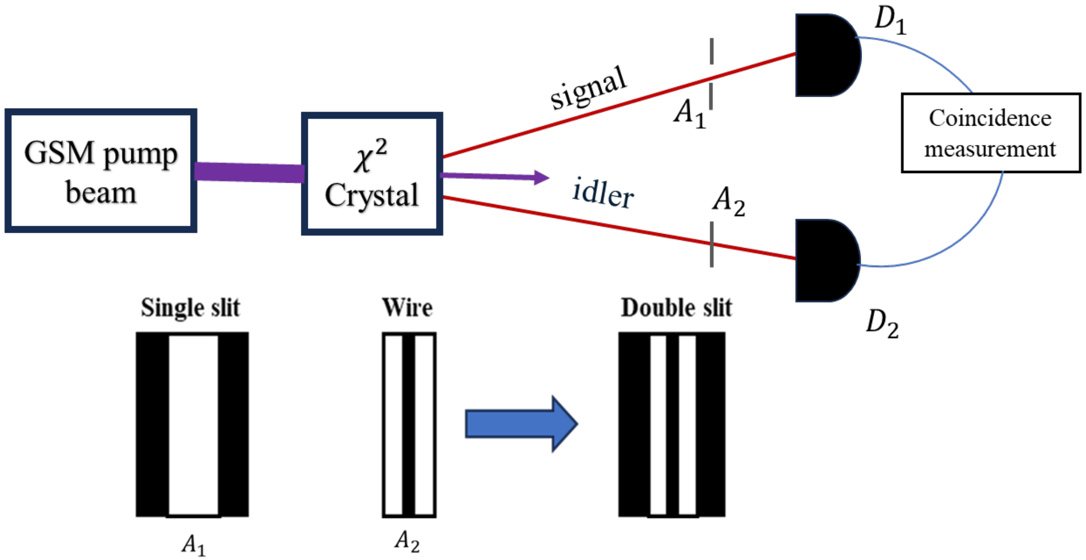
Quality of pattern: Resolution

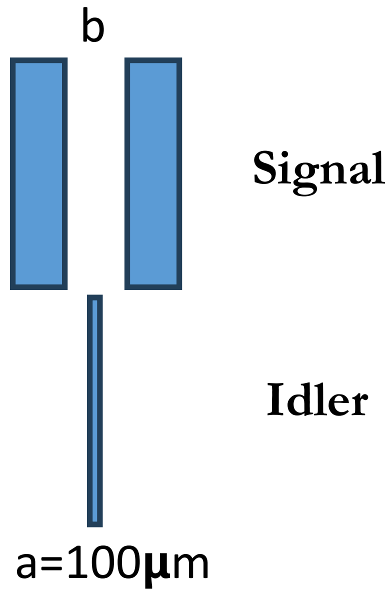
<u>A trade-off between visibility and quality</u>

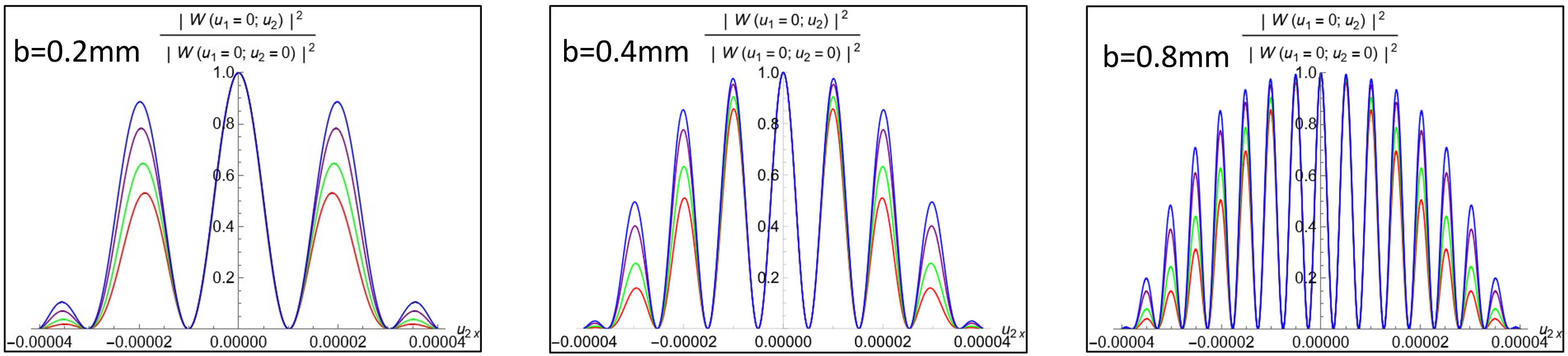
Y. Cai et al, Optics Letters 23, 2716 (2004)
I. Vidal et al, Optics Letters 34, 1450 (2009)

Nonlocal interference with partially coherent qubits

Effect of unknown object is acquired by measuring the intensity correlations



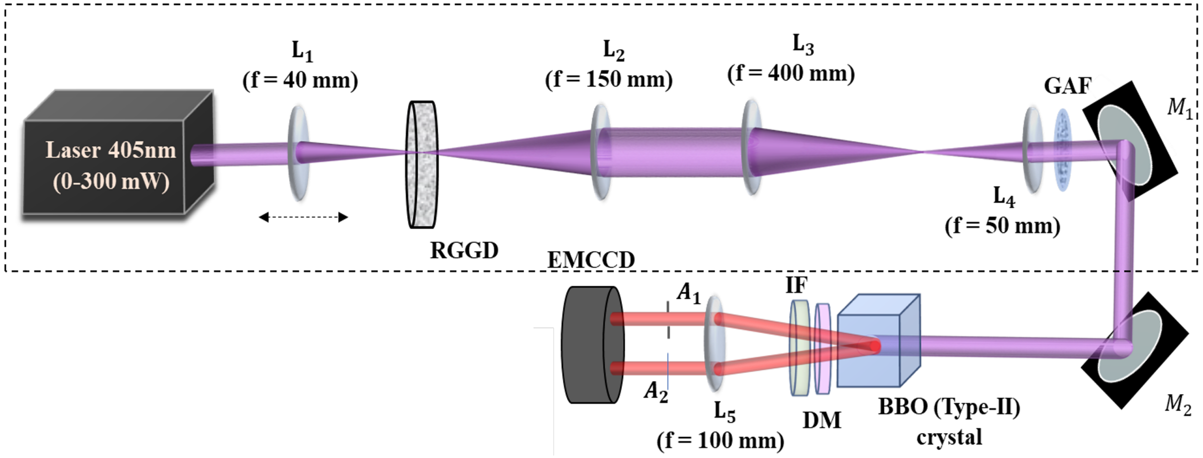


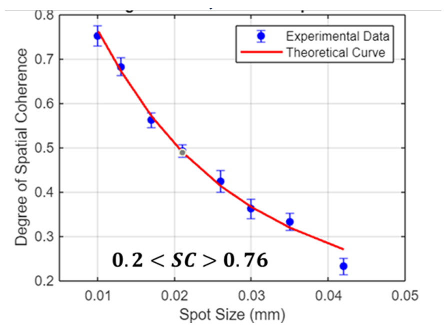


A=0.99, 0.65, 0.4, 0.1

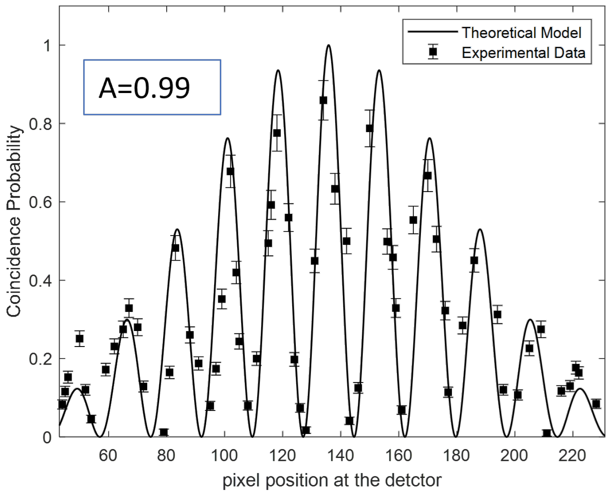
SR, and BK, **Submitted (2024)**

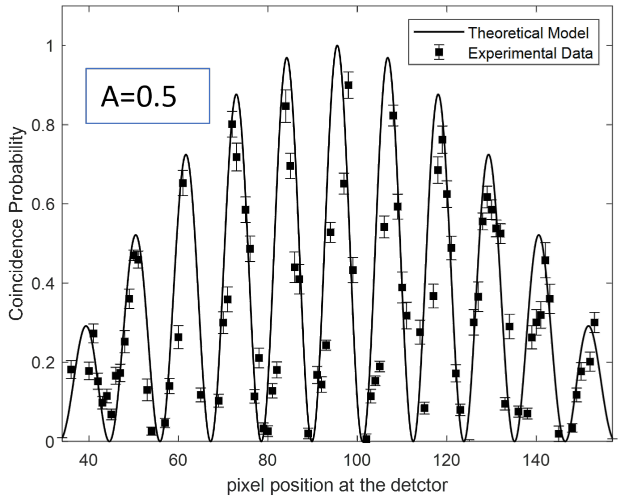
Nonlocal interference with partially coherent qubits

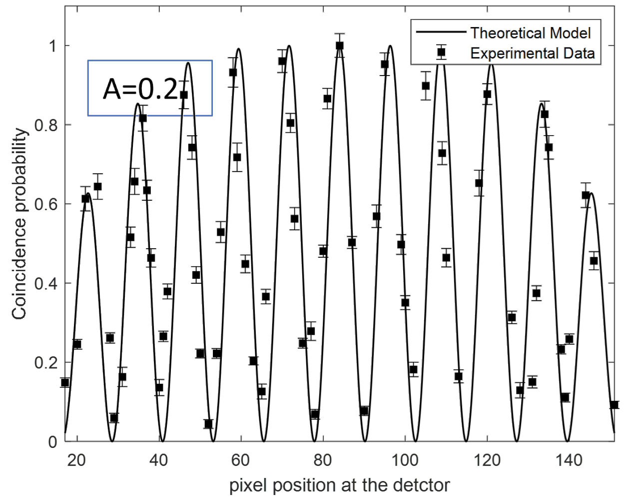




DS parameters:
b=0.55mm, a=0.1mm







We can achieve high visibility and quality simultaneously with partial coherence features

Exploring Applications in Quantum Imaging

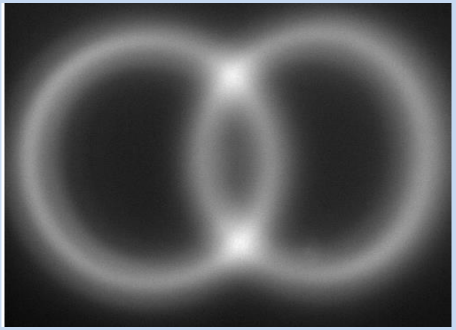
SR, and BK, **Submitted (2024)**

Towards Trusted Node-Free Hybrid Quantum Secure Communication Networks (TAHQEECAT)

Hybrid QKD and Network Architecture

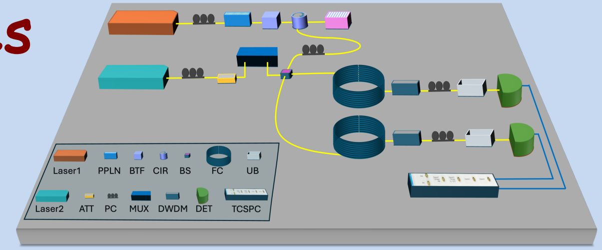
Way forward to Quantum Internet

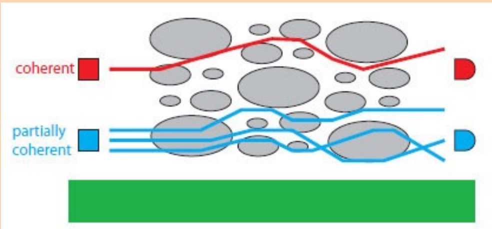
Summary



Entangled photon sources

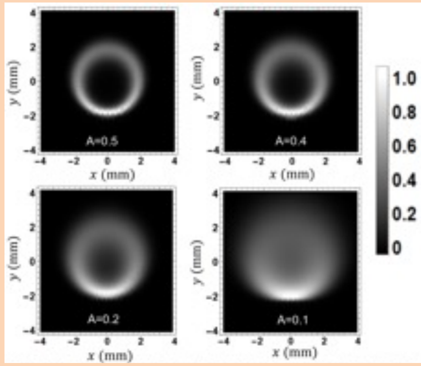
Fibre based QKD in field

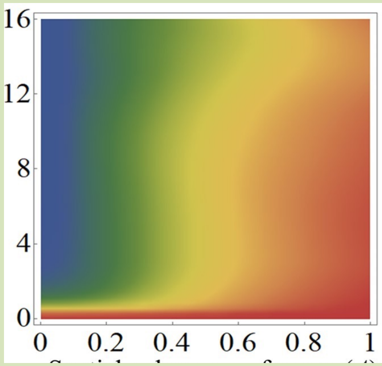




Partially coherent qubit

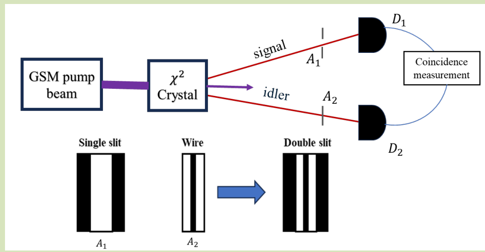
Coherence and entanglement





Recovery of entanglement

Application: Quantum Imaging

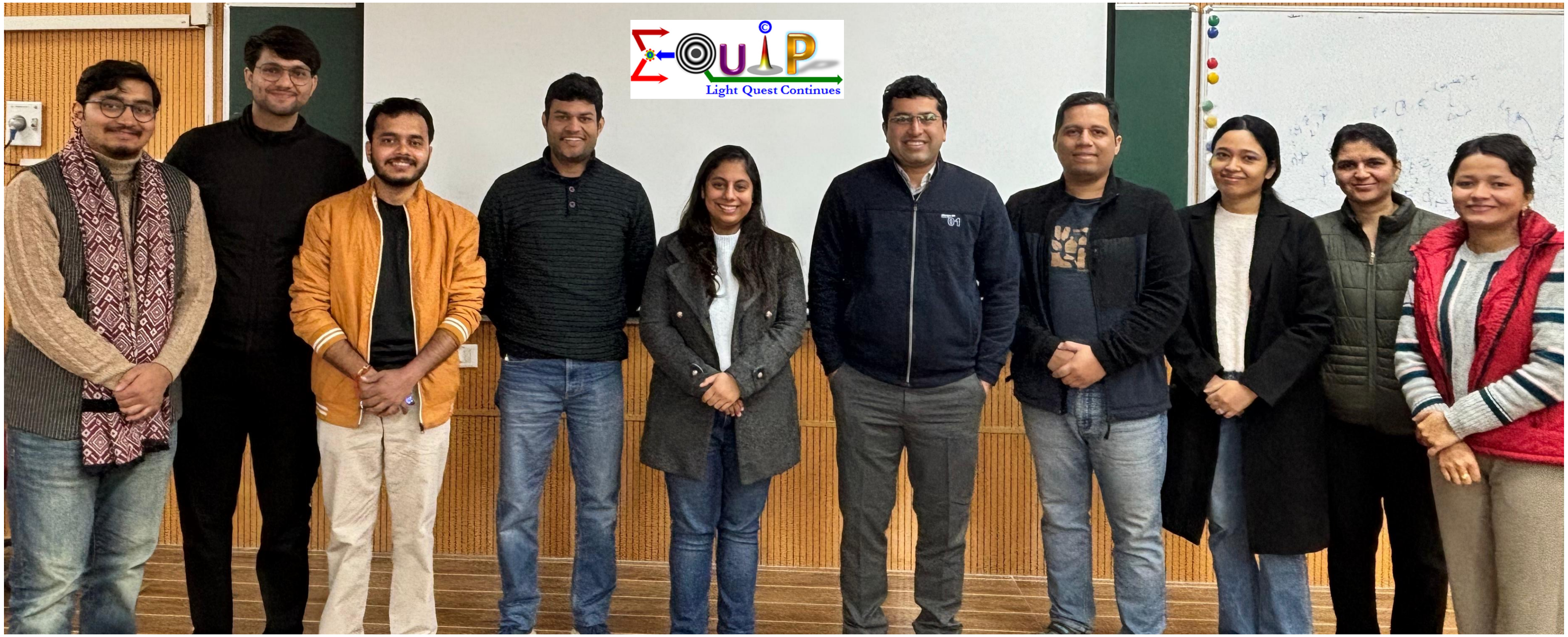


Department of Sciences & Technology
Government of India

National Quantum Mission

Institution of Eminence

Experimental Quantum Interferometry and Polarization (EQUIP) group



Group Leader: Dr. Bhaskar Kanseri

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Light Quest Continues

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