Experimental quantum optics for quantum information technologies

Juan Rafael Álvarez

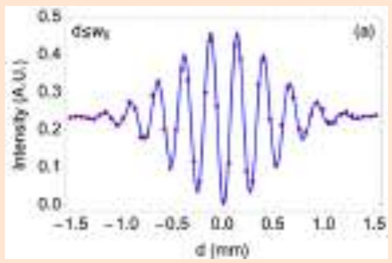
Séminaire ICE - 04/09/2025

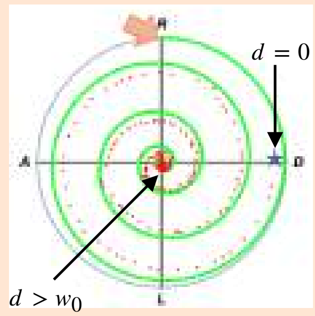
About me

Universidad de los Andes Colombia

2011-16 Bachelor

A. Valencia





Spatial structuring of light: J. Opt. **18** 125201 (2016)
Tunable dephasing: Opt. Ex. **26**, 9 11940 (2018)

Active collaboration on decoherence control:

Sci. Rep. **15**, 31258 (2025)

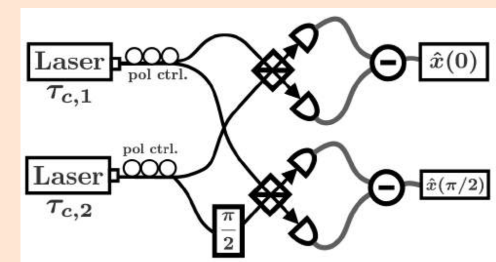
Photonics master 2016-18

IQOQI Vienna (2017)

Internship: Satellite QKD (R. Ursin)
Miniaturization and deployment

ICFO Barcelona (2018)

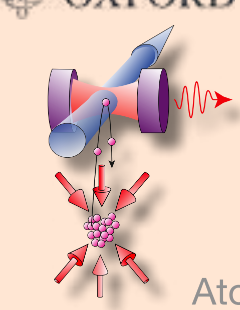
Random number generator with telecom
Opt. Ex. **28** (4), 5538 (2020)
J.P. Torres

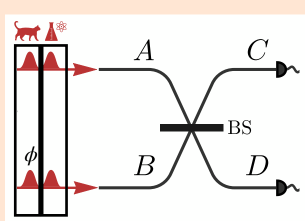


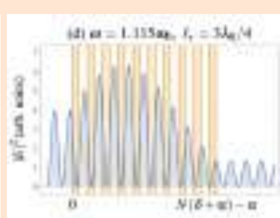
Atomic and Laser Physics - DPhil (2018-23)

A. Kuhn

University of Oxford







Photon feedback: J. Phys. B **55** 054001 (2022)
Atom state preparation: J. Phys. B **56** 205003 (2023)

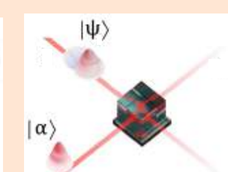
Secondment

S. Guérin

Multilayer cavity: *Appl. Phys. Lett.* **118**, 154002 (2021)
Photon dynamics: arXiv 2410.06379

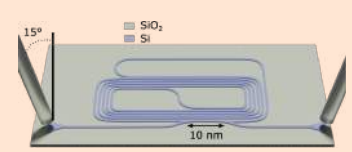
Postdoc (2023-24)

C2N cnrs université PARIS-SACLAY



P. Senellart
D. Fioretto

Laser-single photon bunching: arXiv:2504.12111
Wigner of single photon: *In preparation*
QKD with quantum dot source: *In preparation*



High-dimensional QKD with frequency bin: arXiv:2507.00972

N. Belabas

Intention of this seminar

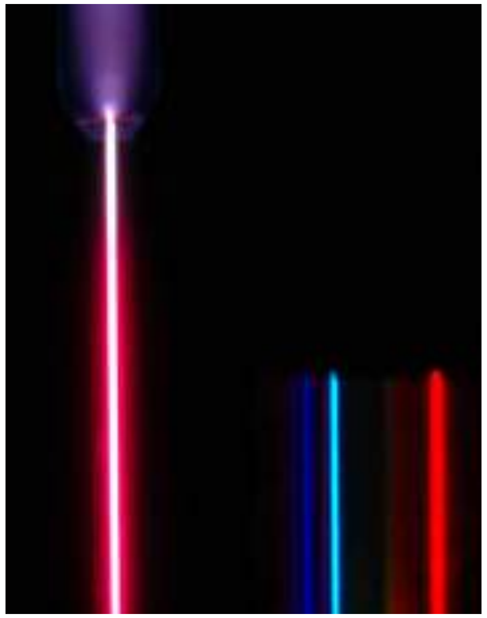
Experimental quantum optics for quantum information technologies

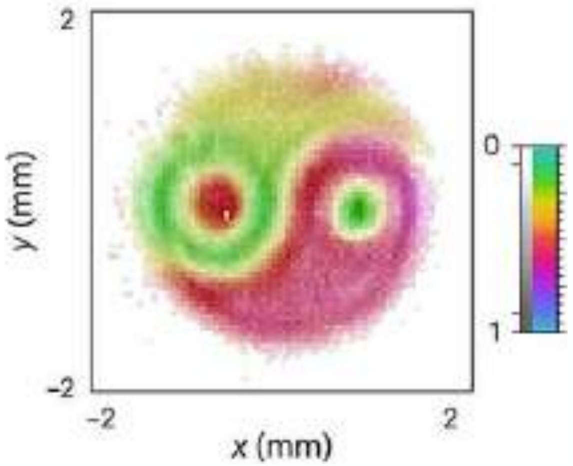
- Tutorial on quantum optics:
  How to generate quantum light?
  How can quantum light help us process/transmit information?

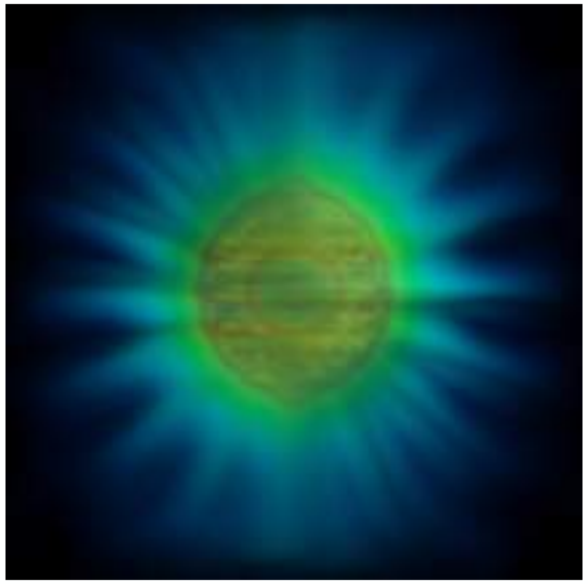
- Some of my recent results on the field
  (with different degrees of freedom of light)

- How will this be continued during my research in Telecom Paris

Why quantum photonics?







Speed of light - $c = 299\,792\,458 \text{ m/s}$

Fibre infrastructure globally deployed - Fibered and free space

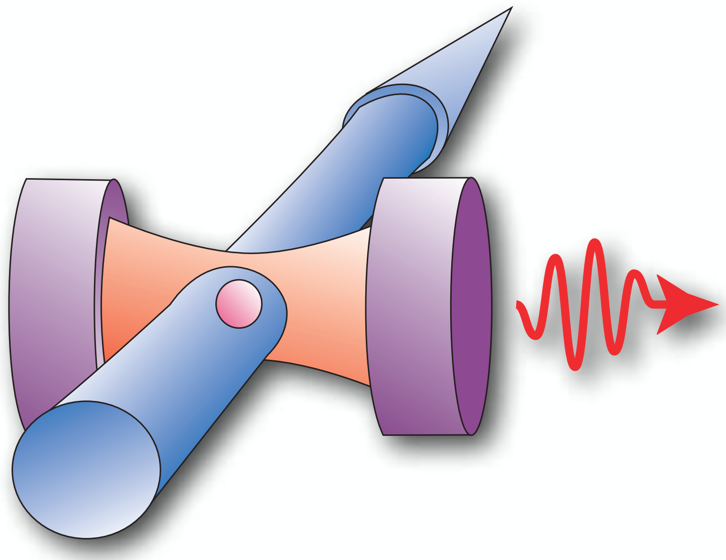
Low environmental interaction

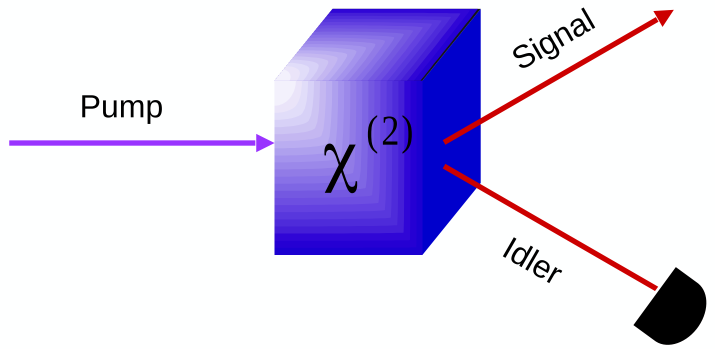
Many different ways to encode information (degrees of freedom)

Little to none cryogenic requirements (only in detection)

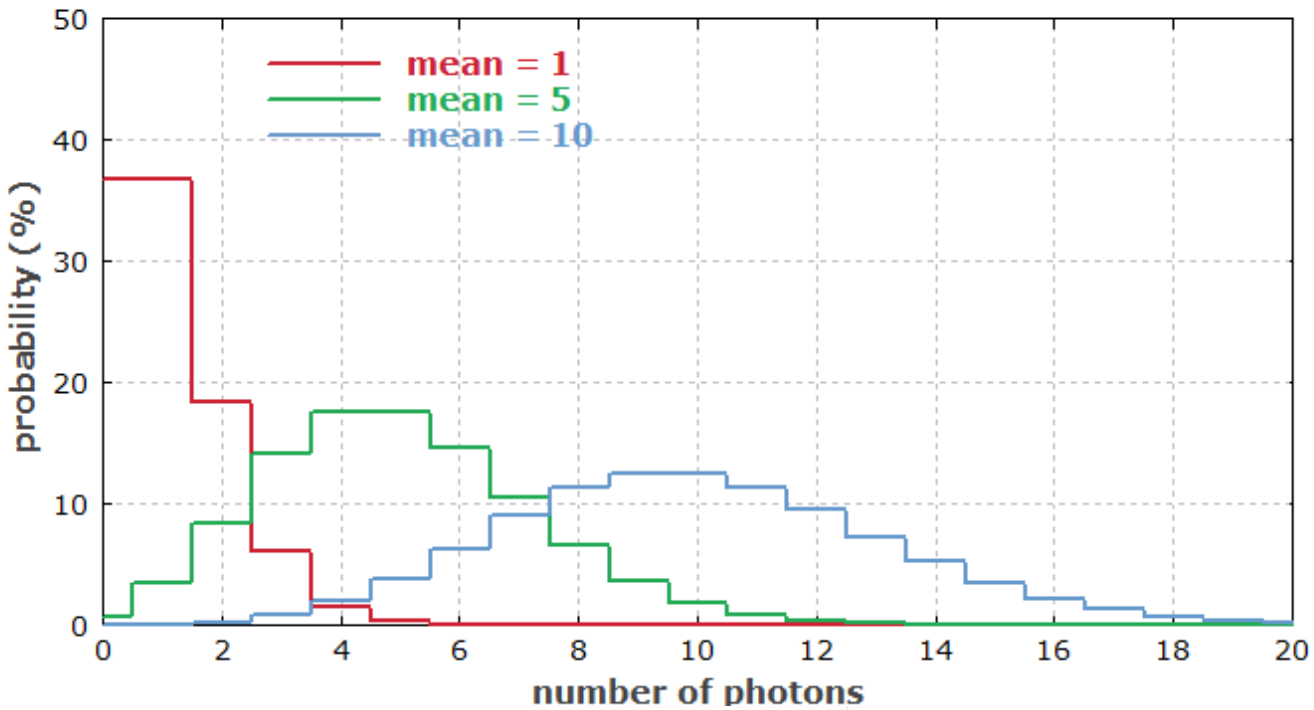
Quantum superposition and quantum entanglement

How to generate quantum light?





Attenuating a laser: Weak coherent states

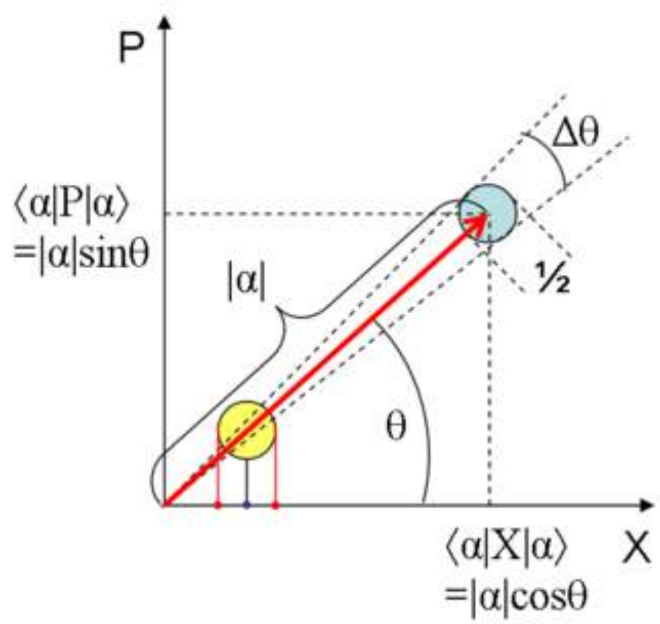


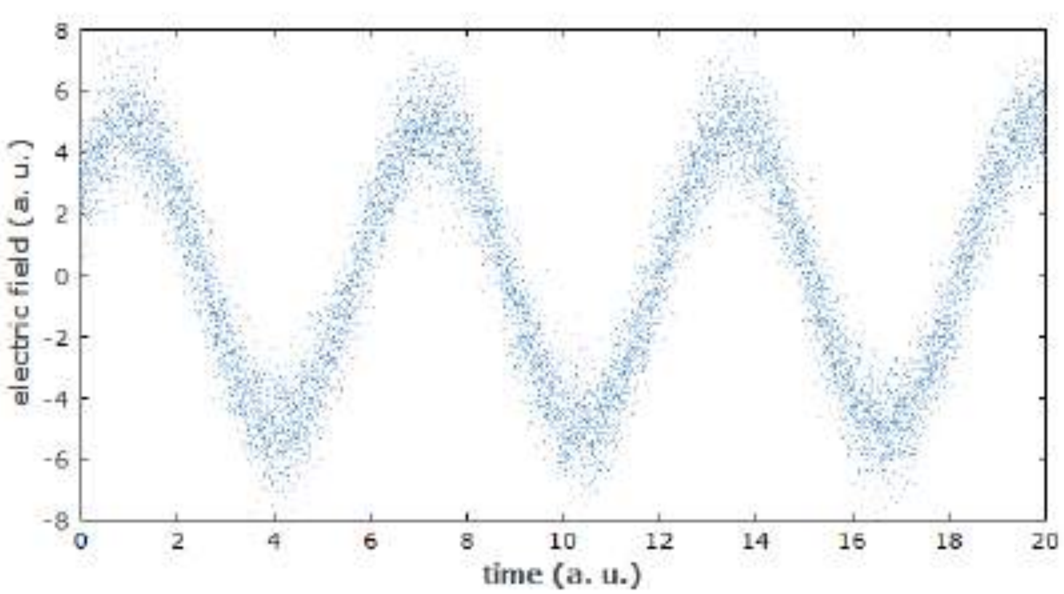
$$P(n) = \langle n \rangle^n \frac{\exp(-\langle n \rangle)}{n!}$$

RP Photonics

$$|\alpha\rangle = \sum_{n=0} \alpha^n \frac{e^{\frac{-|\alpha|^2}{2}}}{\sqrt{n!}} |n\rangle$$

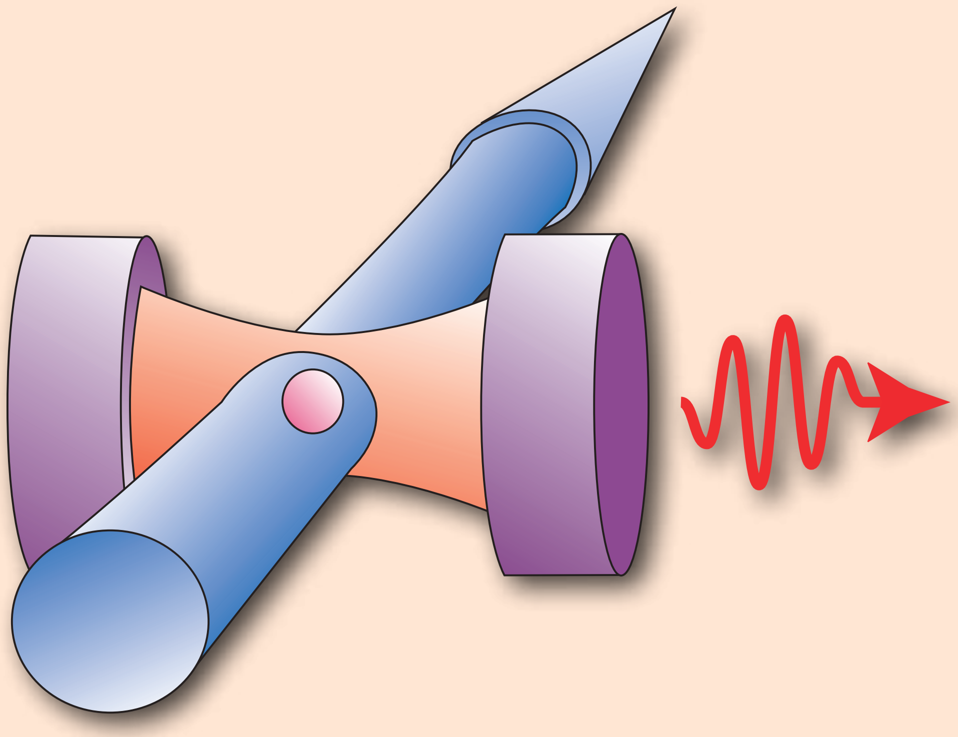
Well defined
phase evolution





Generating quantum light

Atom in a high finesse cavity - cavity QED



A. Kuhn's group - Oxford

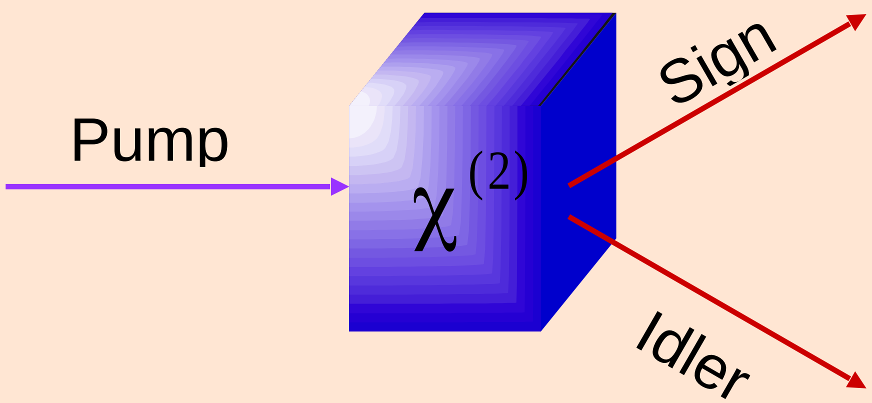
Purcell effect:

Directional emission of single photons.

Emission is accelerated by the cavity.

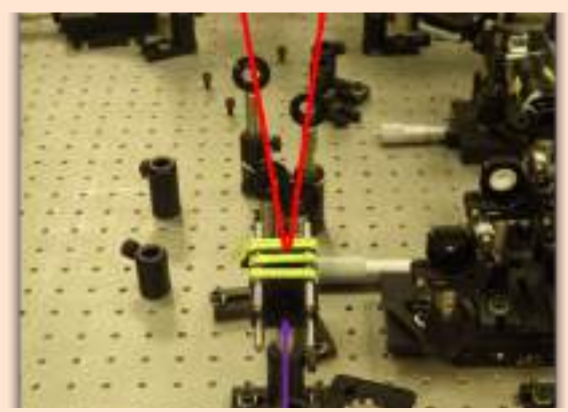
Photon pair sources

Phase matching and energy conservation

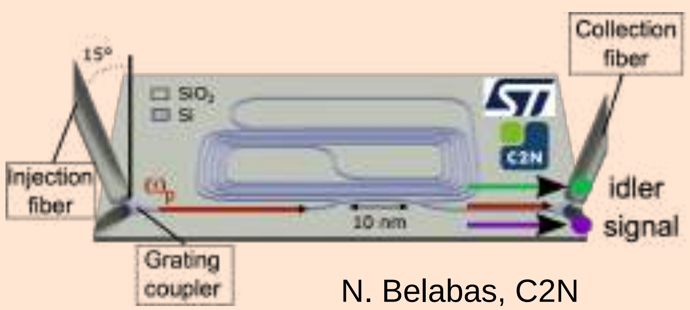


$$\vec{k}_s + \vec{k}_i = \vec{k}_p$$

$$\omega_s + \omega_i = \omega_p$$



A. Valencia, Uniandes



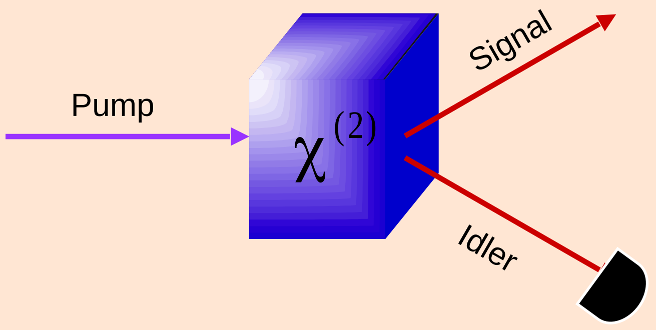
N. Belabas, C2N

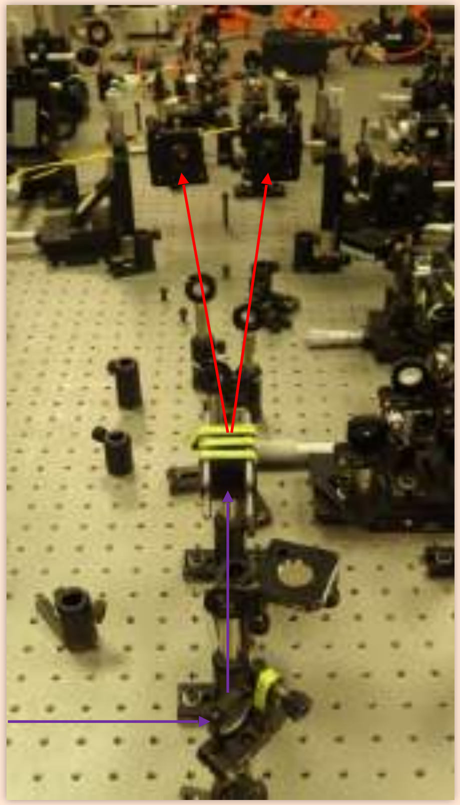
Bulk
Nonlinear crystal

Integrated
Silicon resonators

Generating quantum light

Heralded single photons

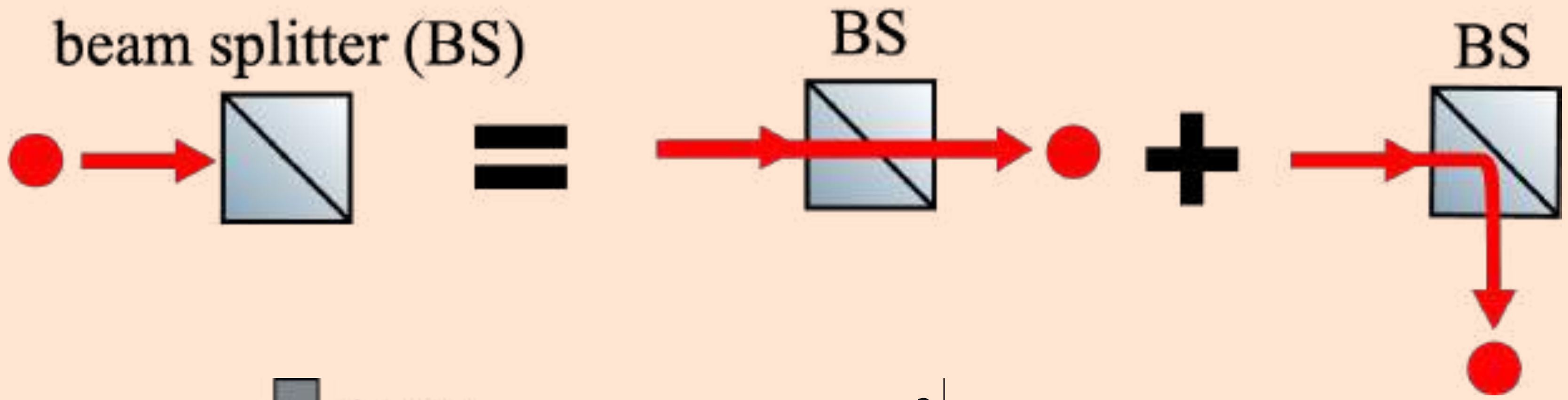


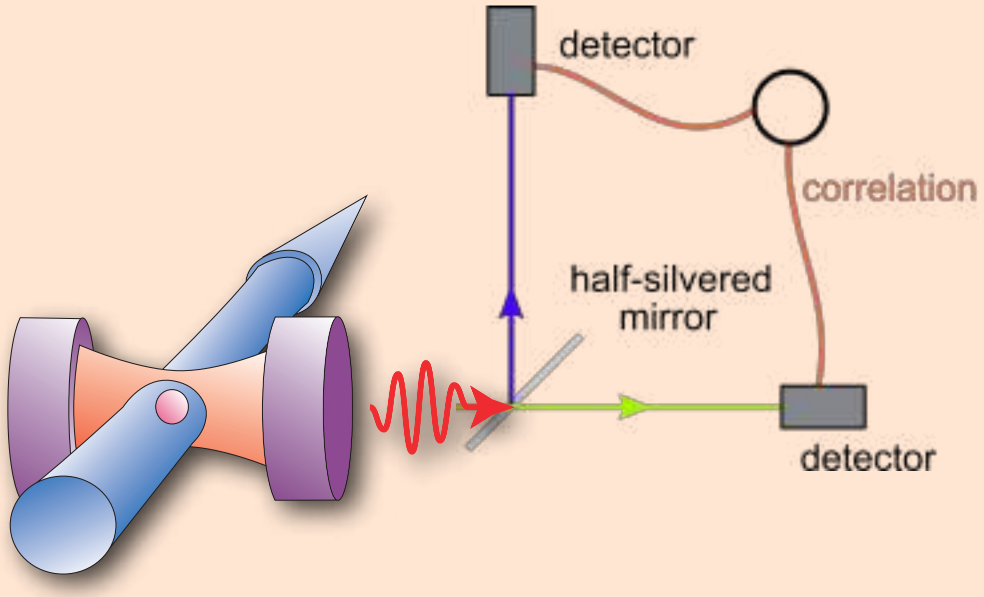


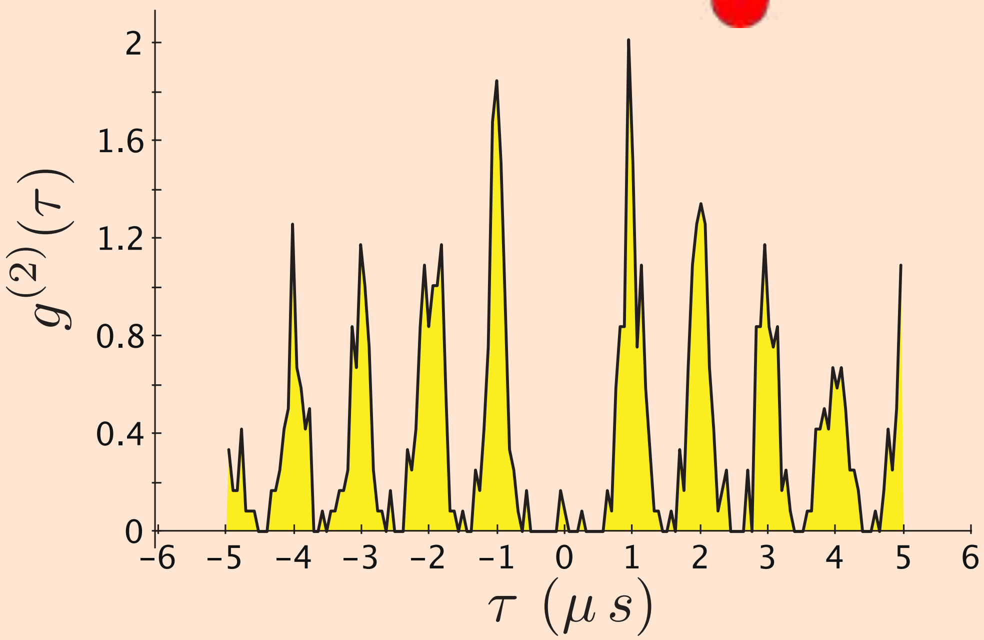
Credit: A. Valencia, Uniandes - Bogotá, Colombia

Heralded single photon:
The arrival of a photon from the pair heralds the presence of another

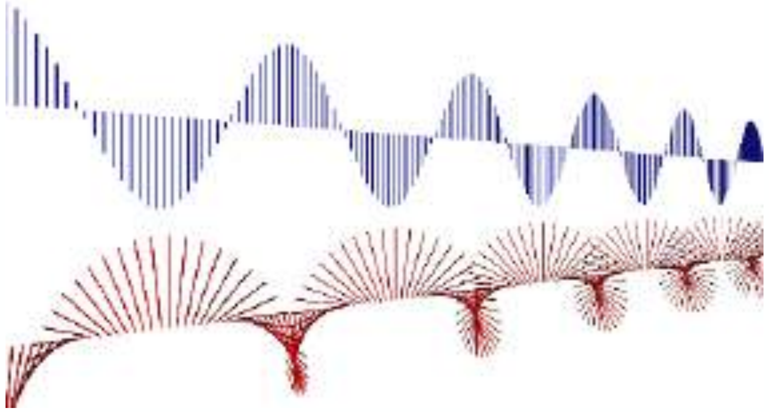
Second order correlation function - $g^{(2)}(0)$

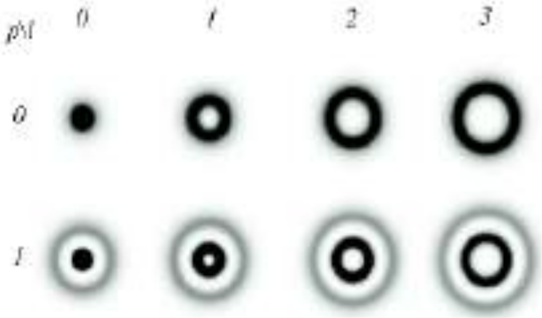


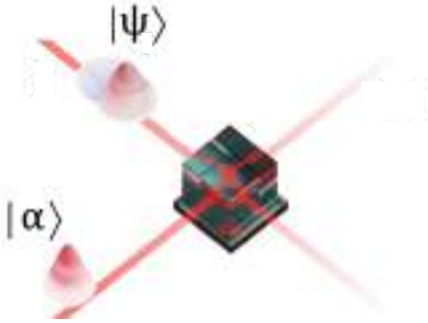




What can you do with quantum light for quantum information technologies?



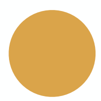




Two paradigms in quantum information technologies

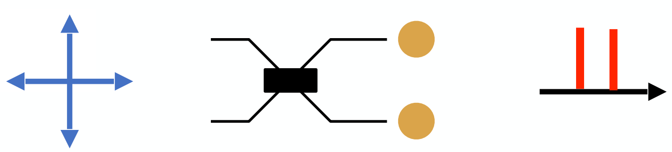
Discrete variable (DV)

Single photons as particles



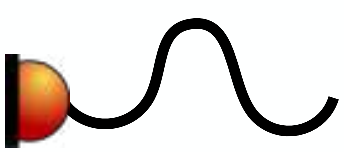
$|1\rangle$

Encoding of information in different degrees of freedom:



Polarization, path, time bin

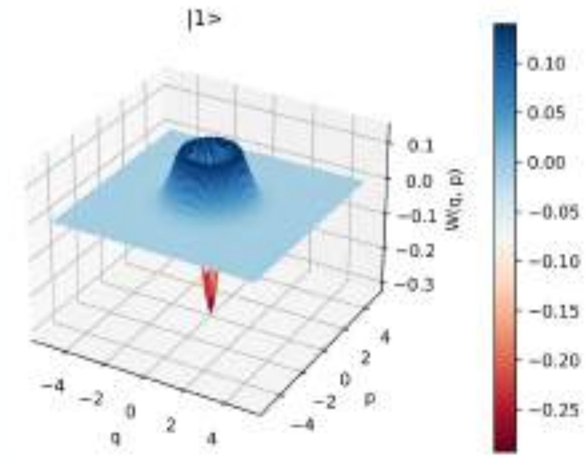
Single photon detection



Continuous variable (CV)

Quantum states as fields

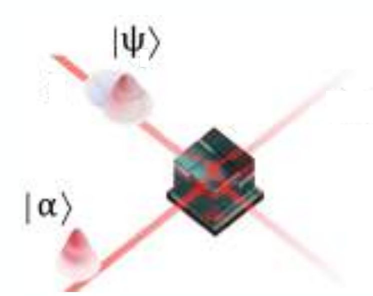
$|1\rangle$



Encoding of information in quadratures (p, q)

Representation in distribution functions (e.g., Wigner function)

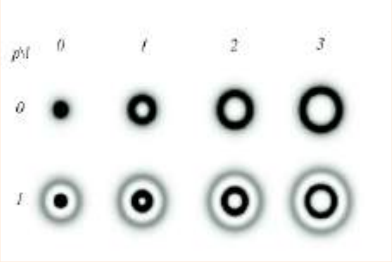
Homodyne detection

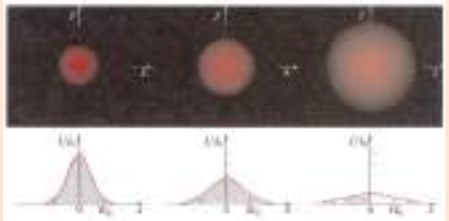


Degrees of freedom of light

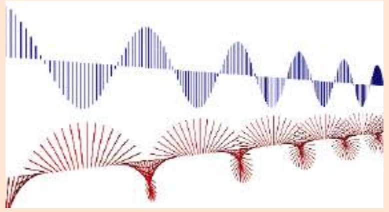
Time - frequency

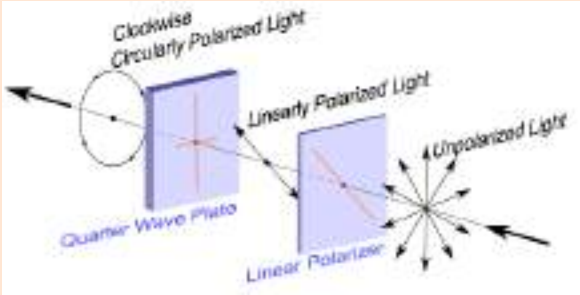
Position – Transverse momentum



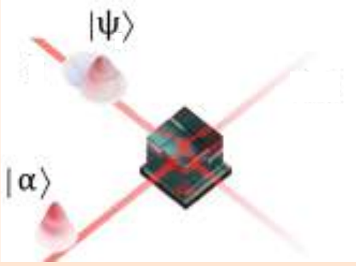


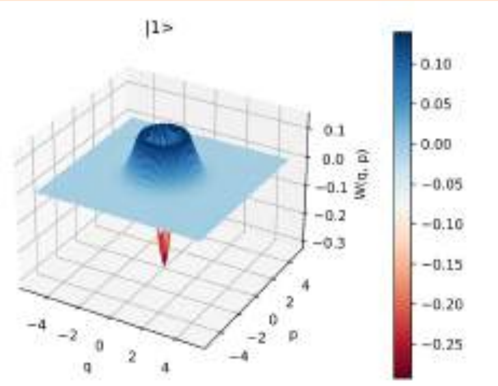
Polarisation





Quadratures of the electromagnetic field

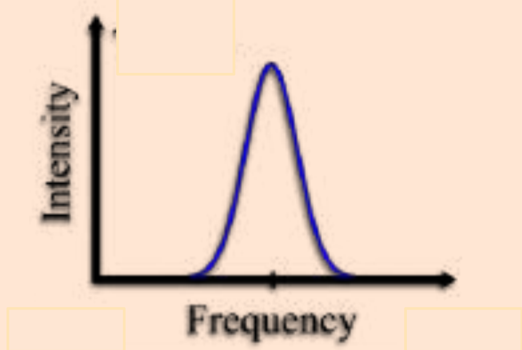




Characterization mechanisms for different degrees of freedom

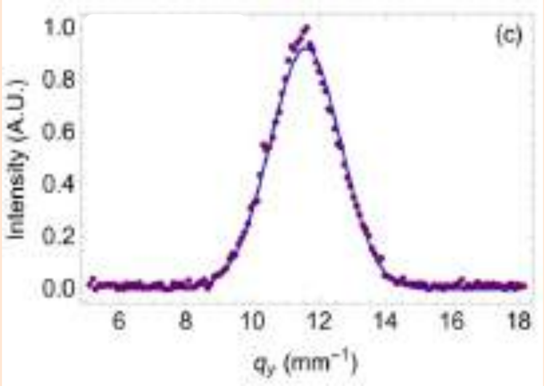
Time - frequency

Single photons ◄ • • • • Monochromator



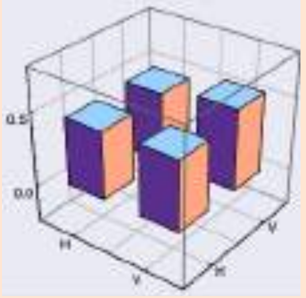
Position – Transverse momentum

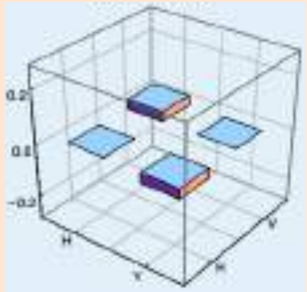
Single photons ◄ • • • • 2-f system



Polarisation

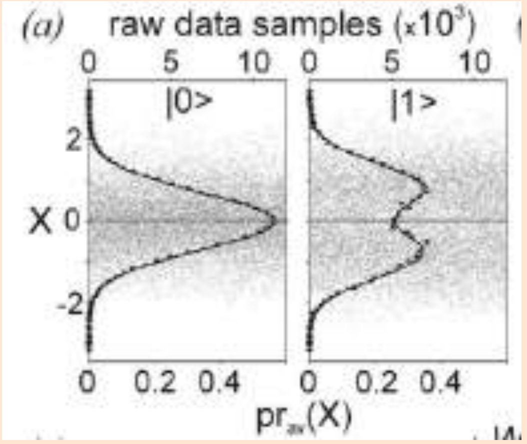
Single photons ◄ • • • • QWP and HWP



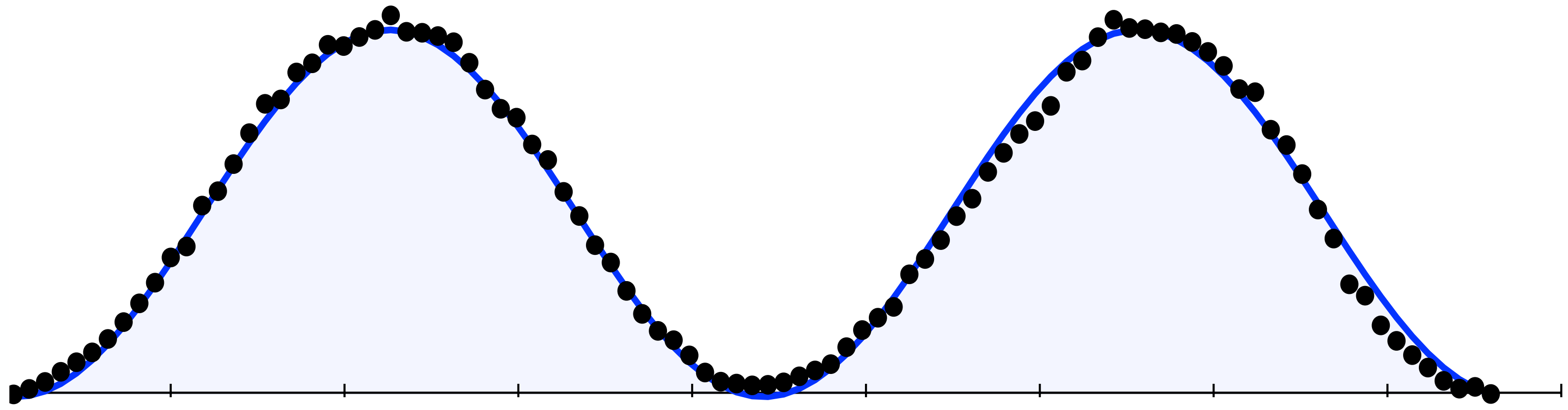


Quadratures of the electromagnetic field

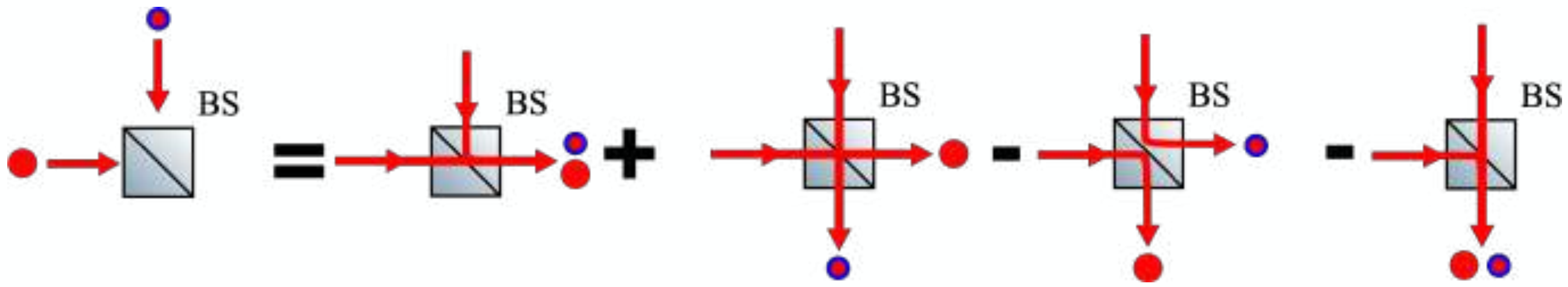
Single photons ◄ • • • • Homodyne

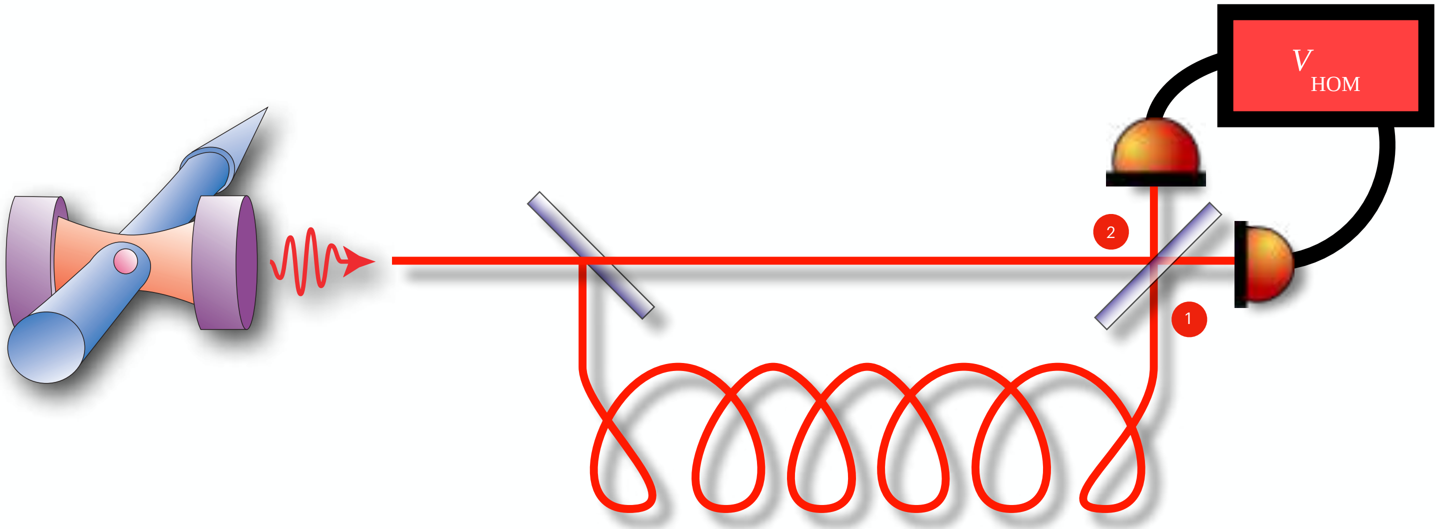


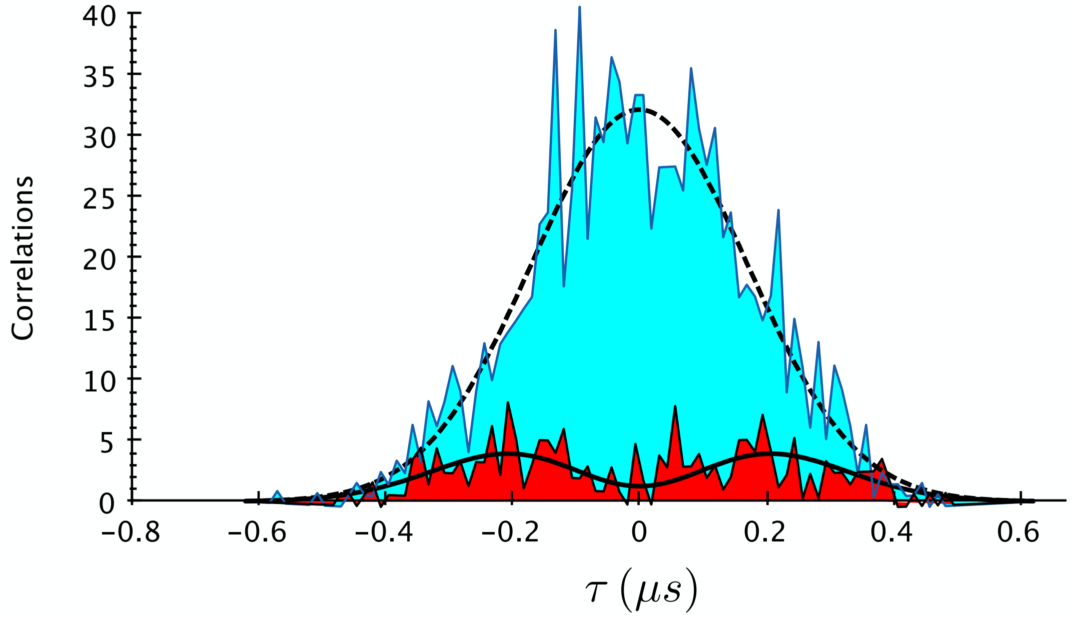
Temporal degree of freedom: time-bin encoding



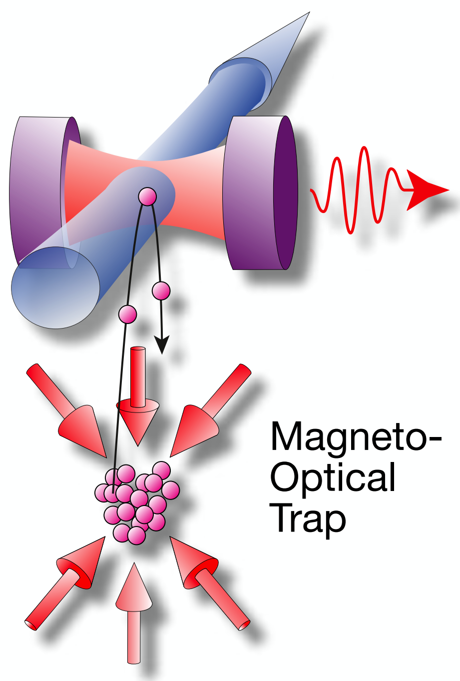
Two-photon interference:
Two identical photons *bunch* at the same output of a beam splitter.





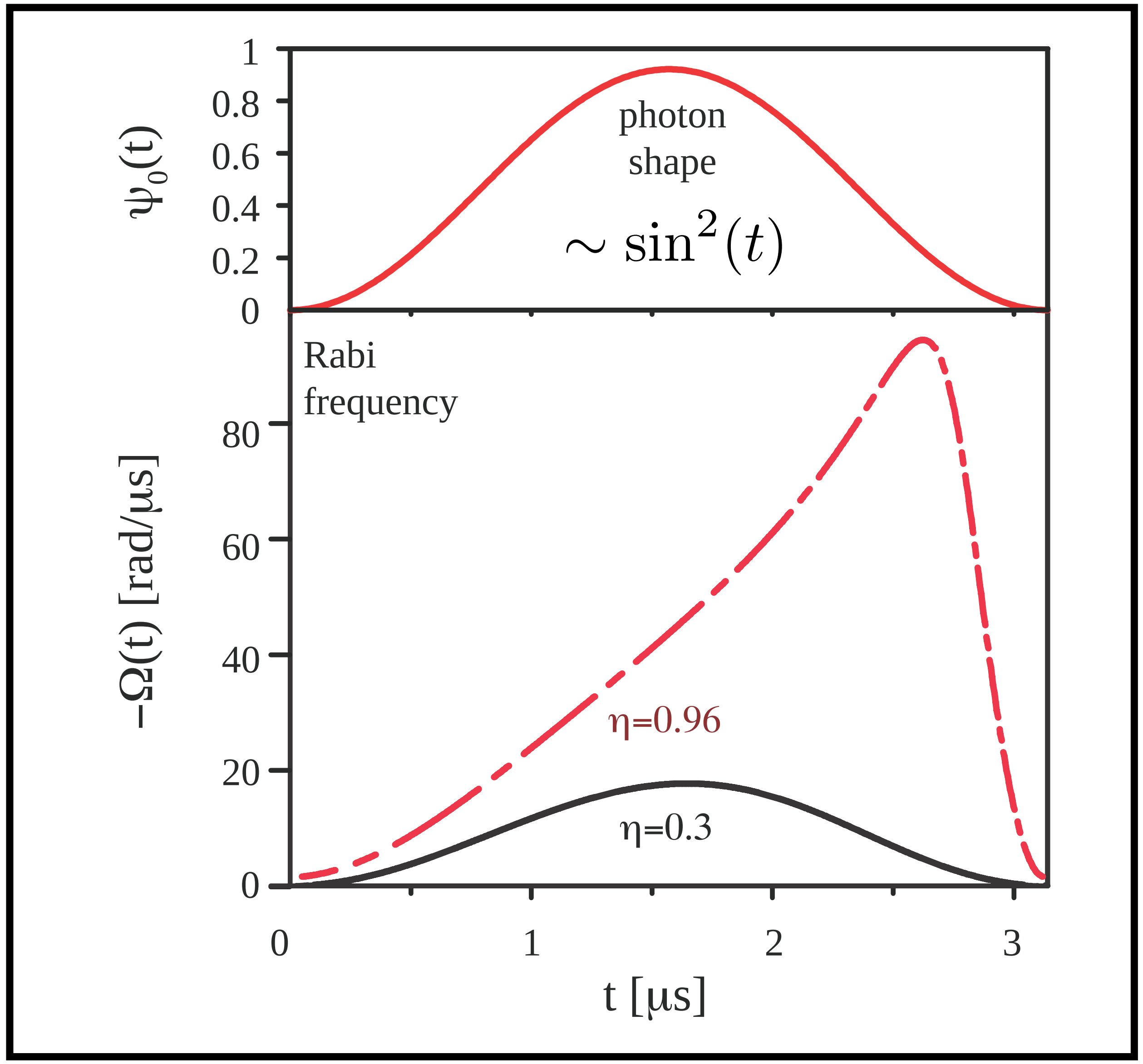


Time-bin encoding with atoms



Neutral ^{87}Rb

Tailored time-bin encoding



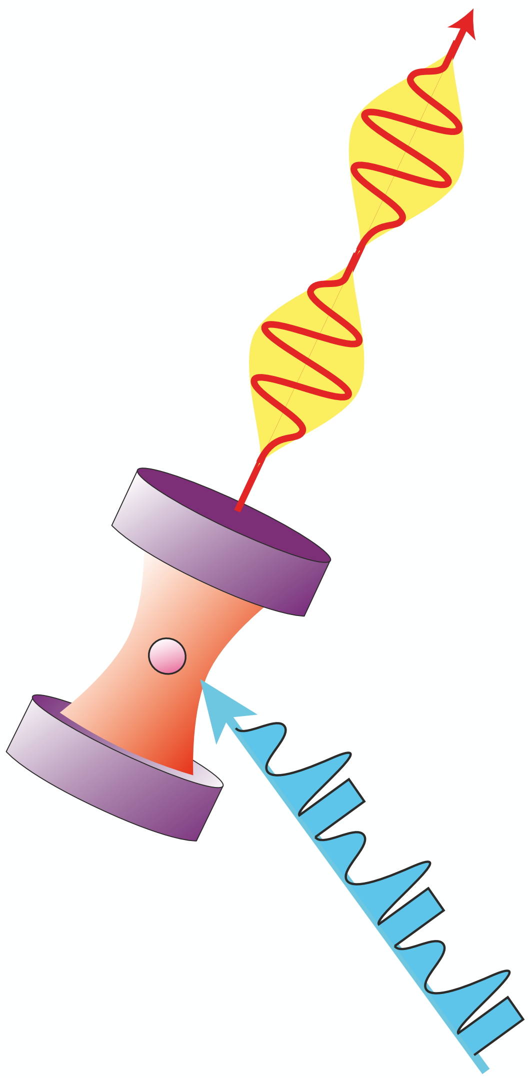
O. Barter

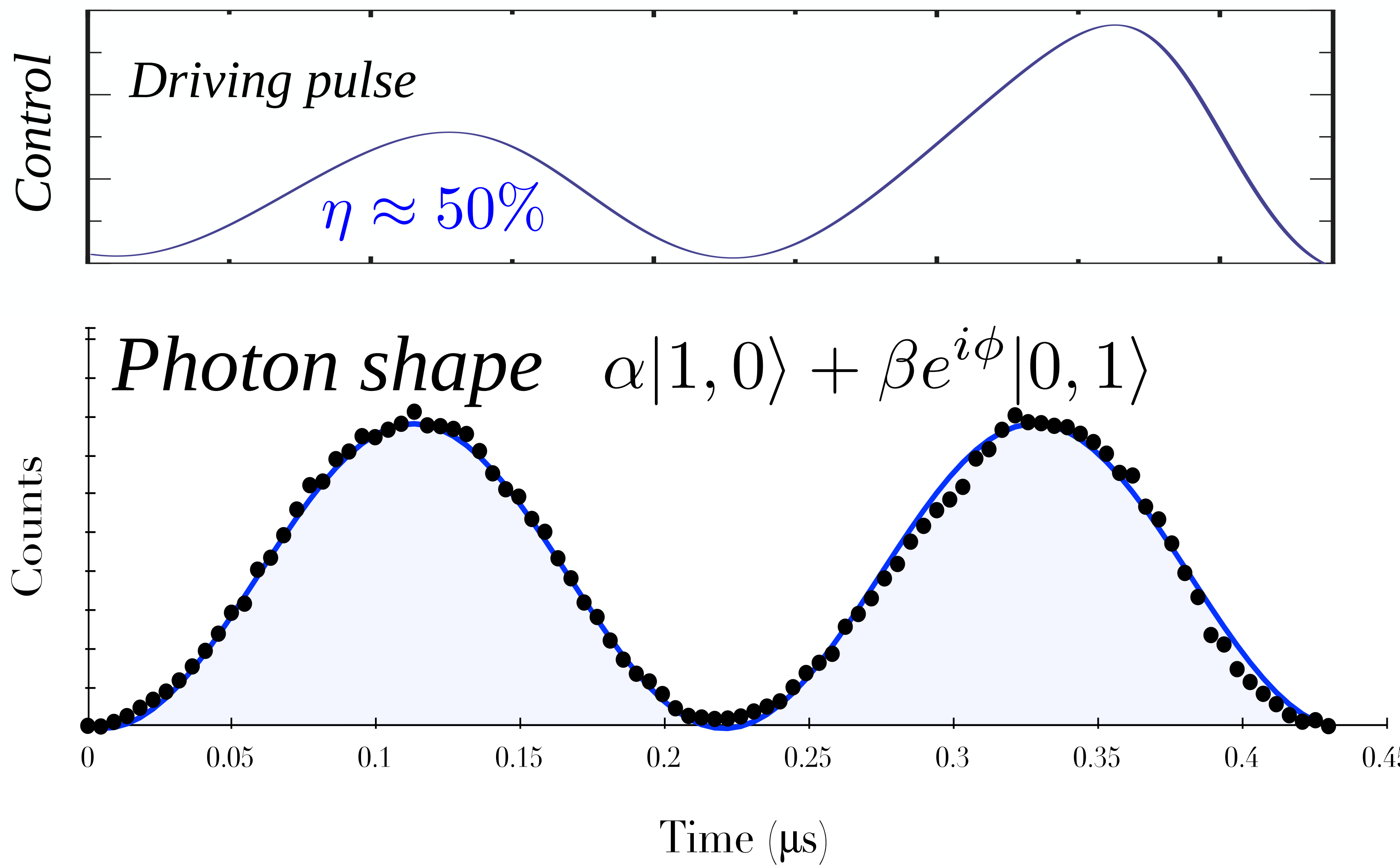
T. Barrett

A. Kuhn

G. Vasilev et al. New J. Phys. **12**, 063024 (2010)
J. Dilley et al. Phys. Rev. A **85**, 023834 (2012)

Time-bin encoding with atoms





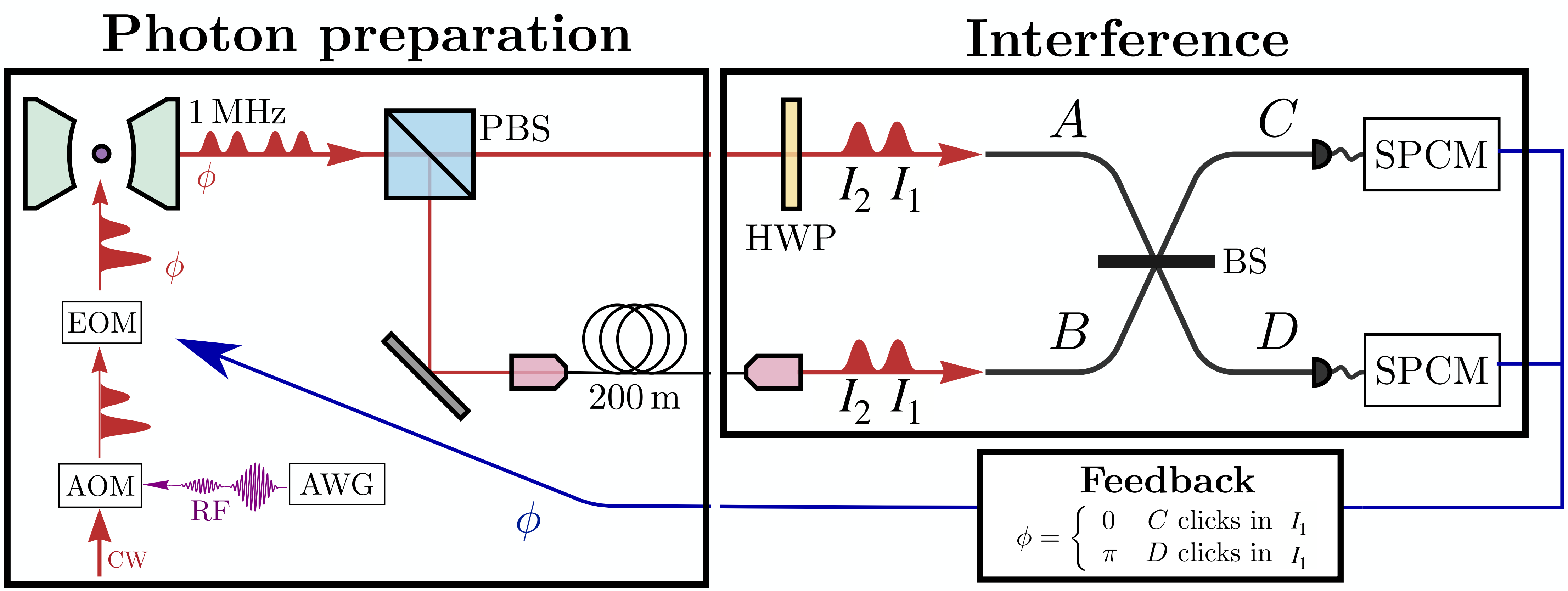

O. Barter

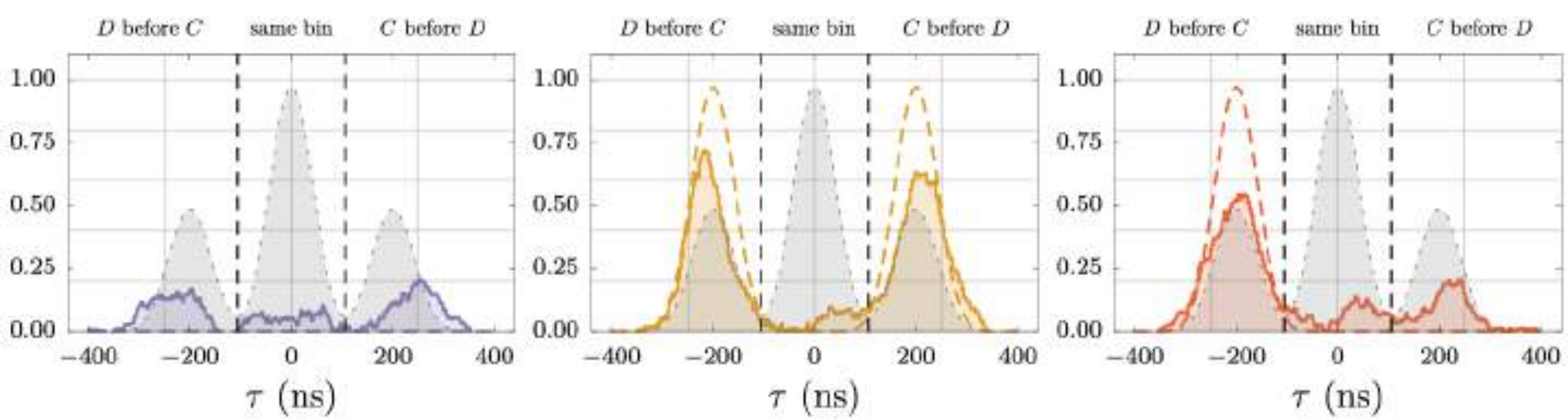

T. Barrett


A. Kuhn

P. Nisbet et al., New J. Phys. **15**, 053007 (2013)

Feedback on quantum interference






O. Barter

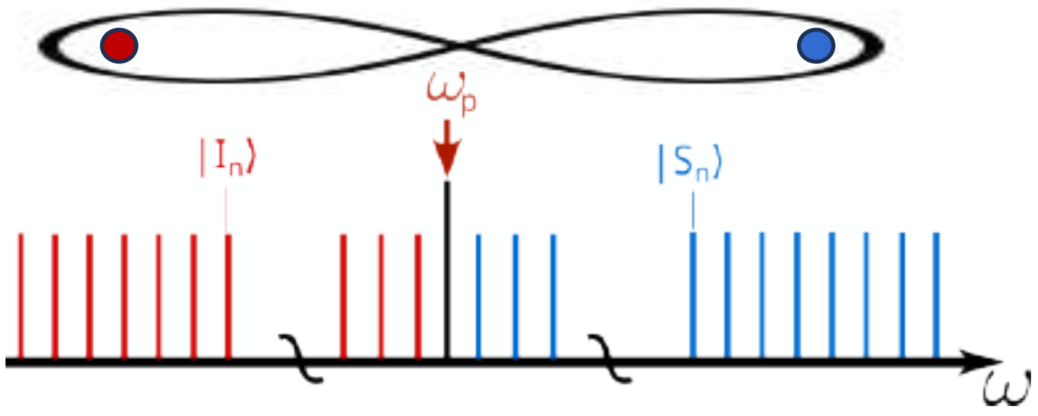

T. Barrett


A. Kuhn

Total latency of feedback:
97 ± 0.2 ns

J.R.A. et al. J. Phys. B **55** 054001 (2022)

Frequency degree of freedom: high dimensional QKD network

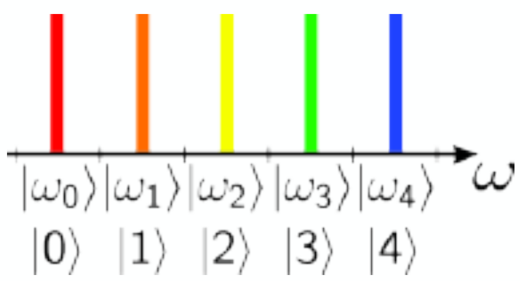


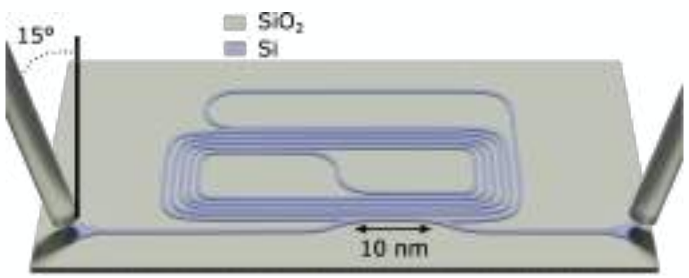
Frequency bin encoding

Robust to environmental noise

Adequate for both free space and fibered distribution

Potential to encode multi-dimensional states





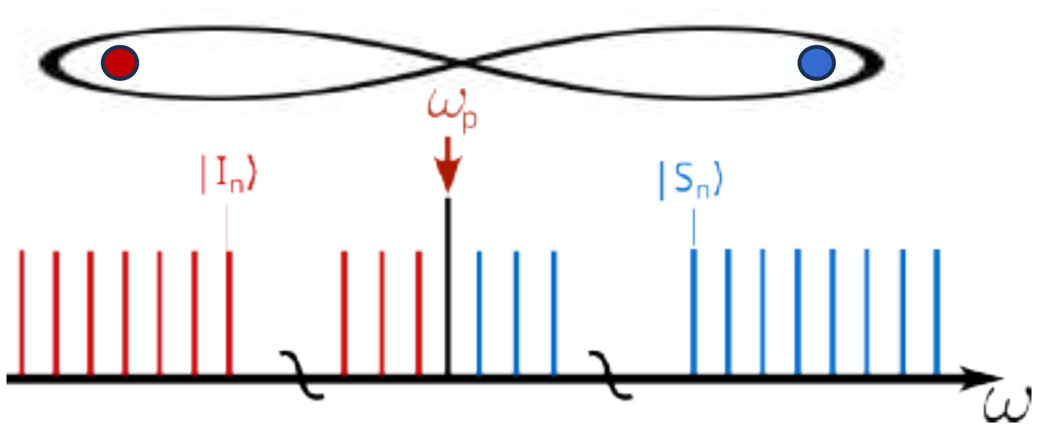
Adv. Photonics **6** (3), 036003 (2024)

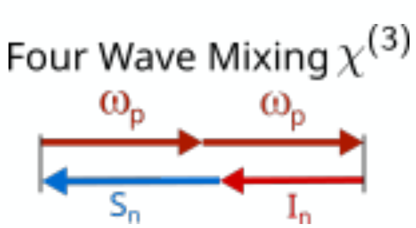
Brightness:
48M pairs.s^{-1}.GHz^{-1}.mW^{-2}

Quality factor:
3.10^5

FSR = 21 GHz

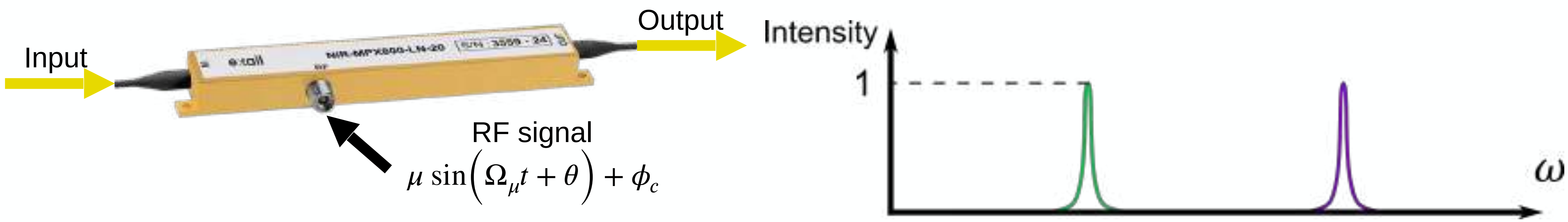
$$|\Psi\rangle \propto \sum_n e^{i\alpha_n} |I_n, S_n\rangle$$





Simultaneous manipulation of multiple channels - **Off-the-shelf devices**

Electro-Optical Modulation - Bin mixing

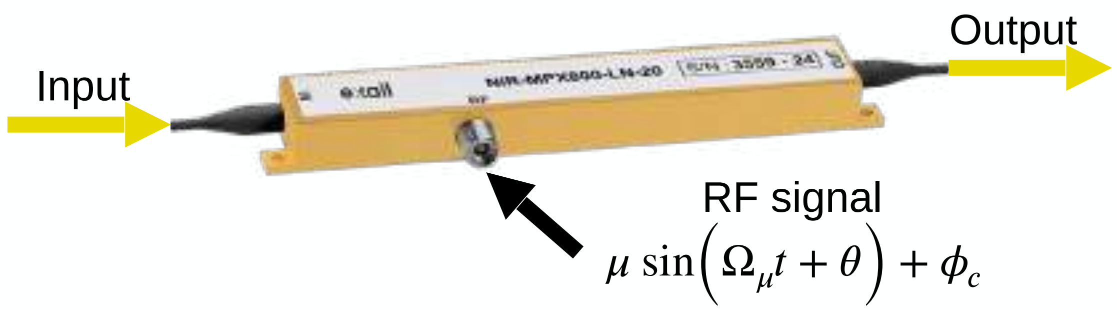


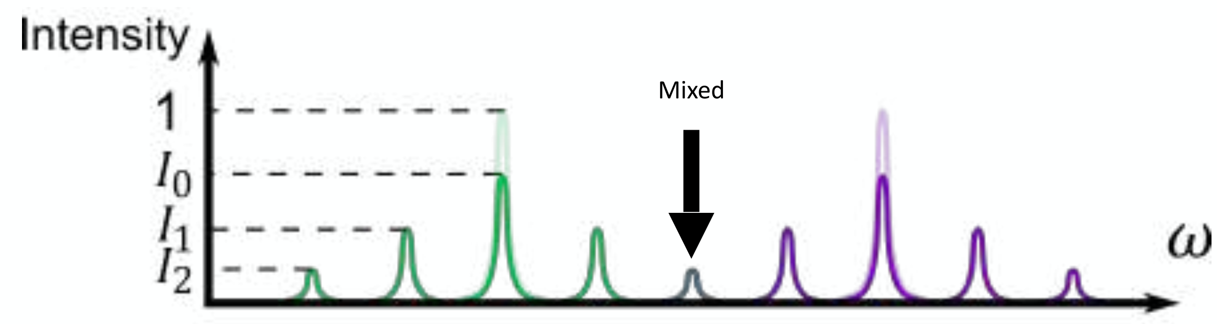
Lukens J. et al., Optica, Vol. 4, No. 1 (2017)

Frequency bin encoding

Simultaneous manipulation of multiple channels - **Off-the-shelf devices**

Electro-Optical Modulation - Bin mixing



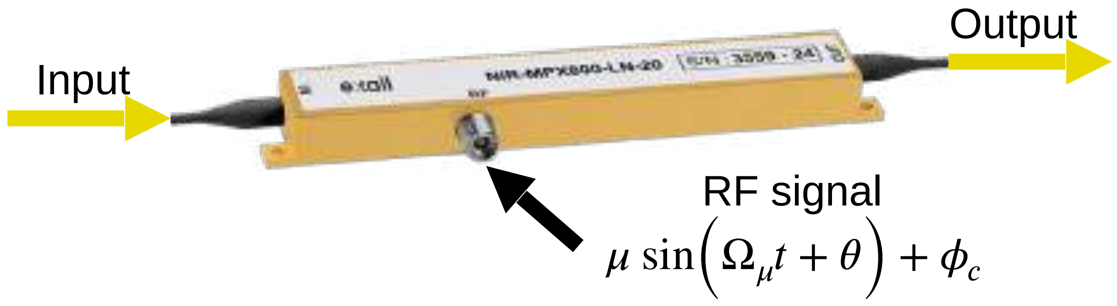


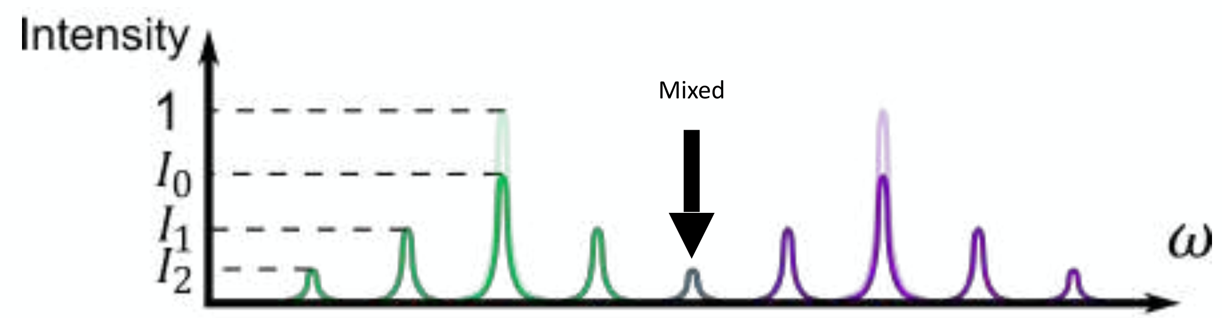
Lukens J. et al., Optica, Vol. 4, No. 1 (2017)

Frequency bin encoding

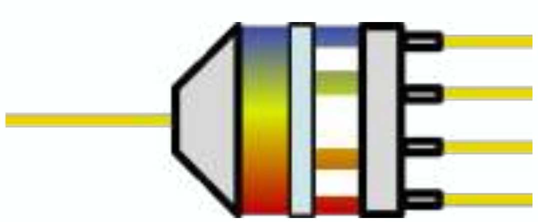
Simultaneous manipulation of multiple channels - **Off-the-shelf devices**

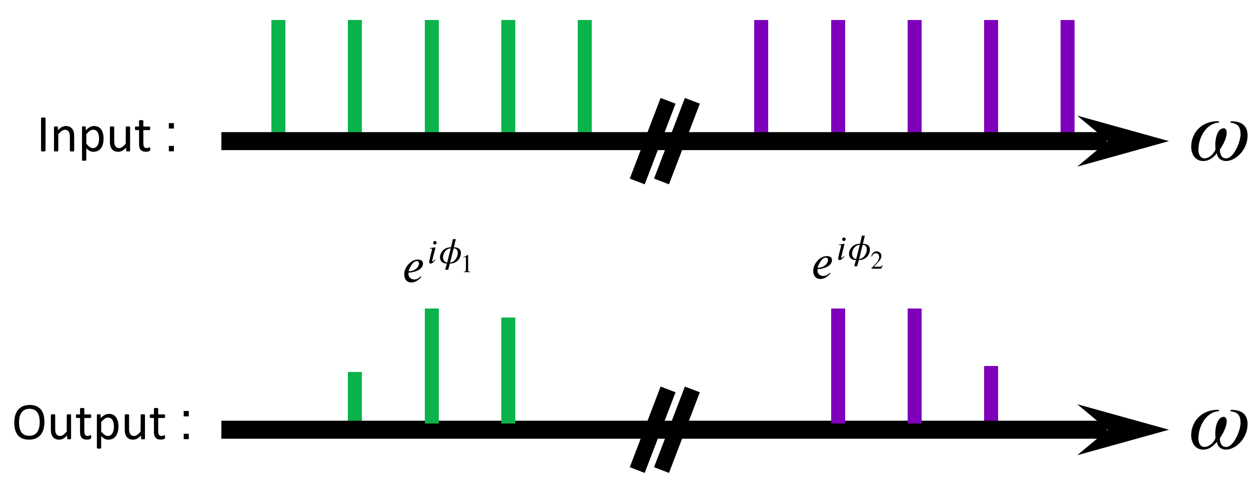
Electro-Optical Modulation - Bin mixing





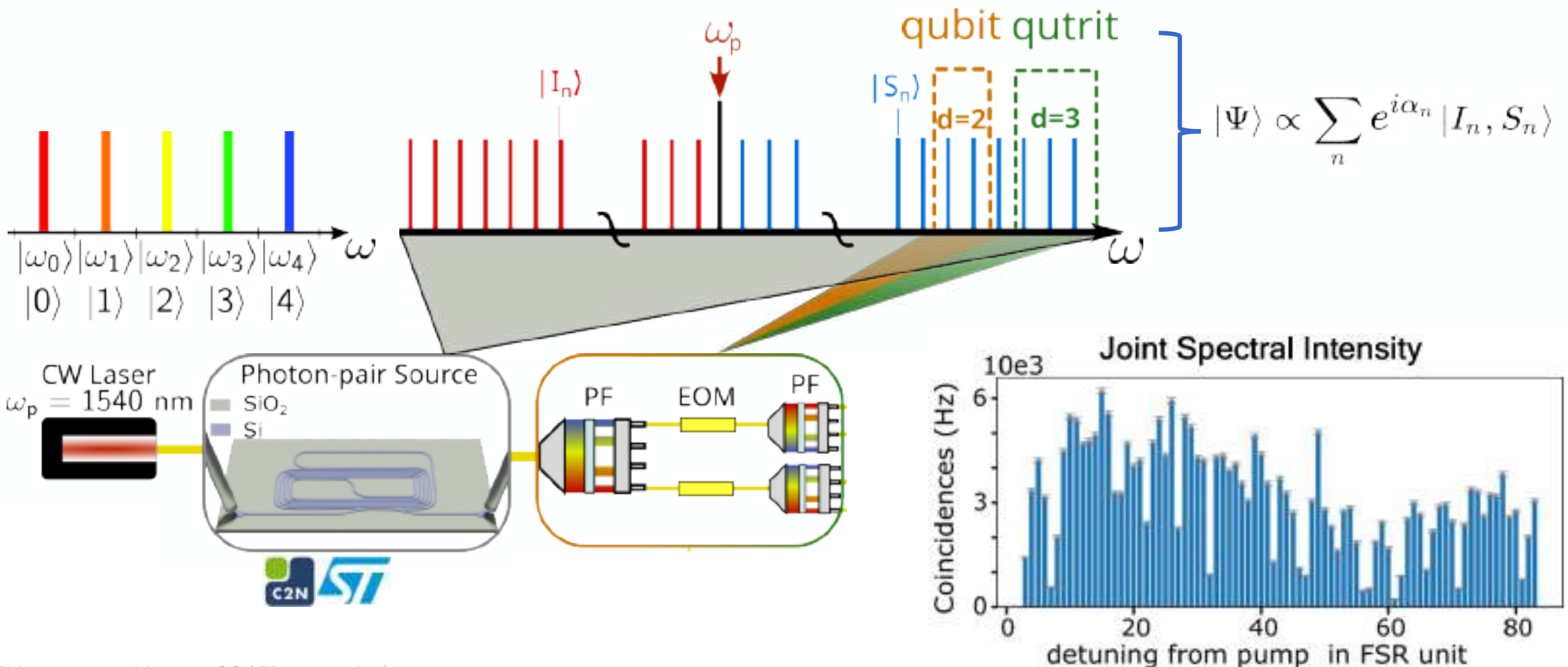
Programmable filter - Attenuation and phase shifting





Lukens J. et al., Optica, Vol. 4, No. 1 (2017)

A frequency-bin entangled QKD network



[Kues et. al, Nature 2017] up to d=4

[Lu et. al, Nature Com 2022] up to d=7

[Cabrejo et. al, Laser&Photonics Rev 2023] d=7

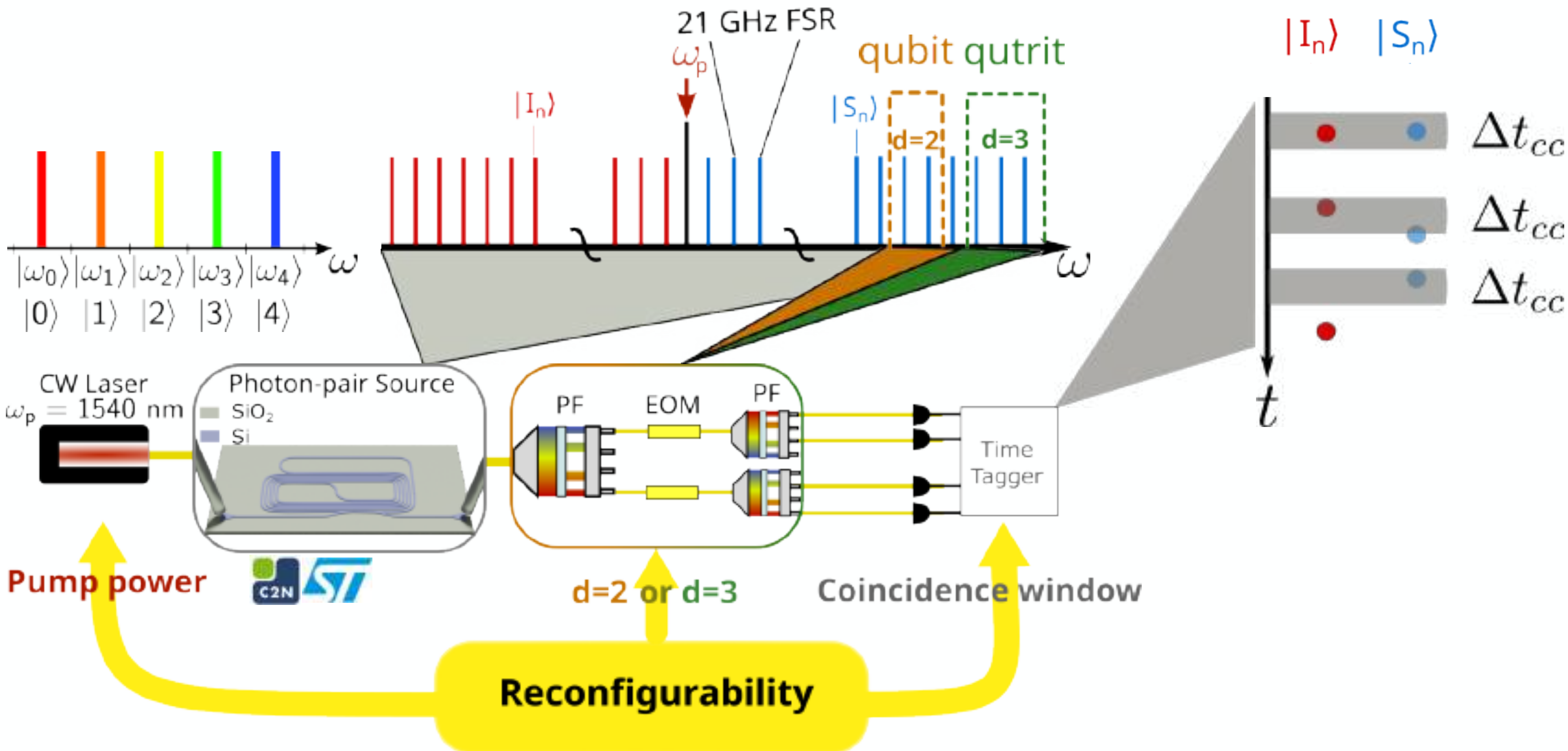
Antoine Henry

George Crisan

N. Belabas

G. Crisan el al., arXiv:2507.00972

A frequency-bin entangled QKD network



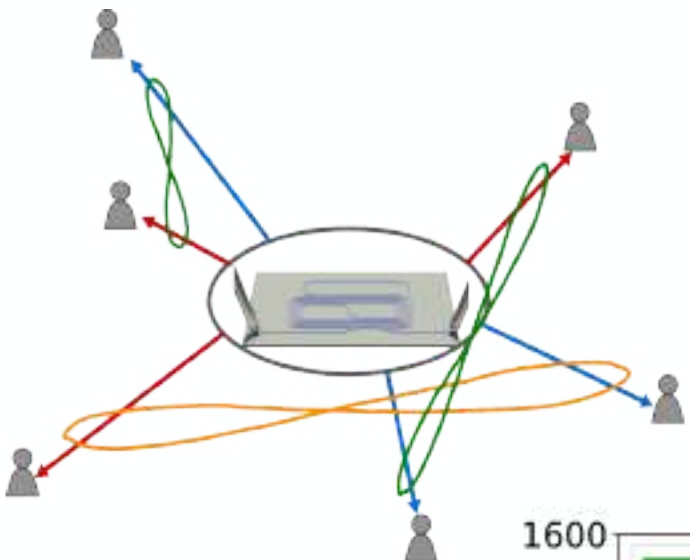
Antoine Henry

George Crisan

N. Belabas

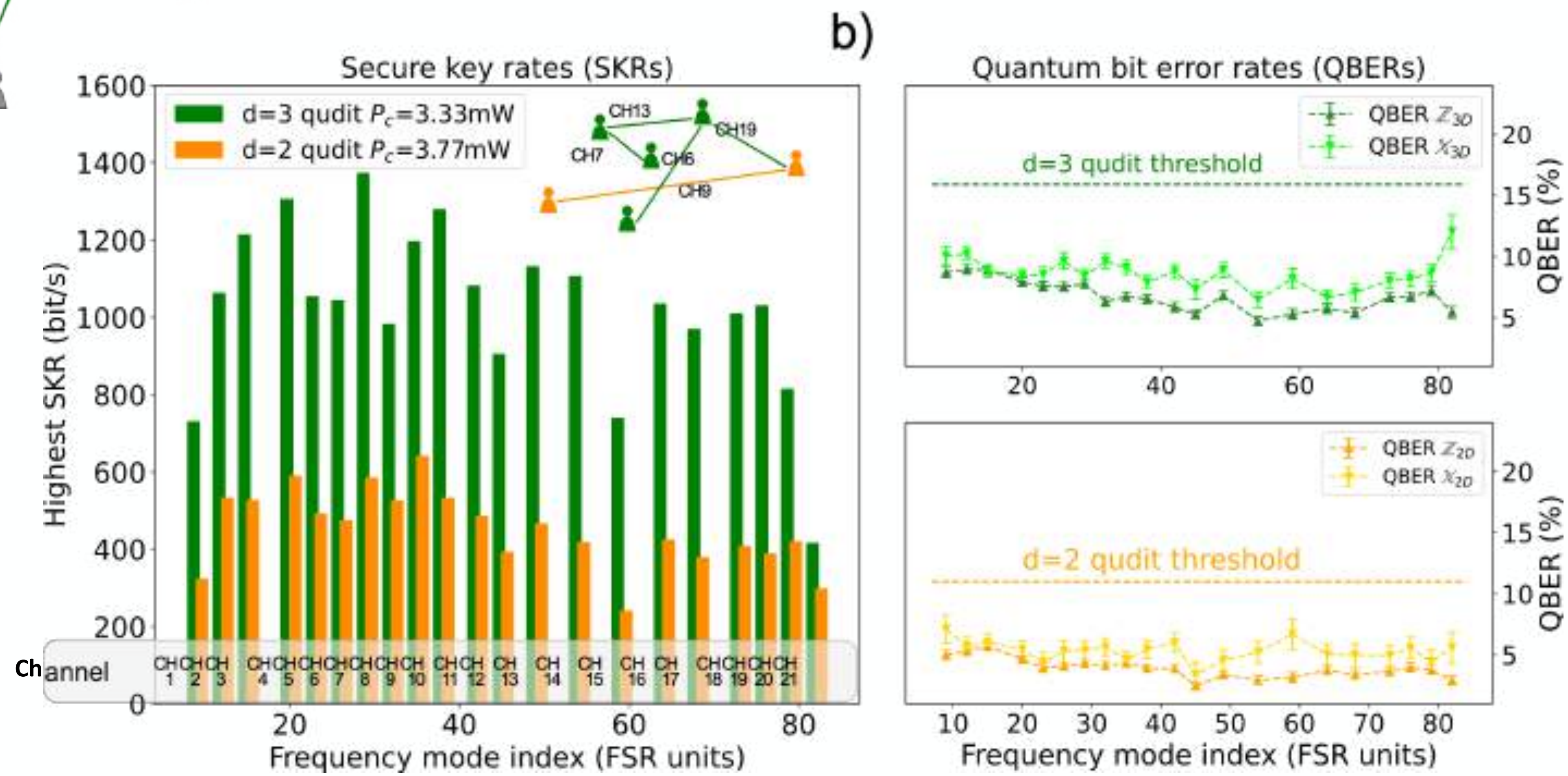
G. Crisan el al., arXiv:2507.00972

A frequency-bin entangled QKD network



Secret Key Rate

$$SKR \geq \frac{1}{2} R_{raw} \times [log_2(d) - H_d(e) - f(e)H_d(e)]$$



Antoine Henry

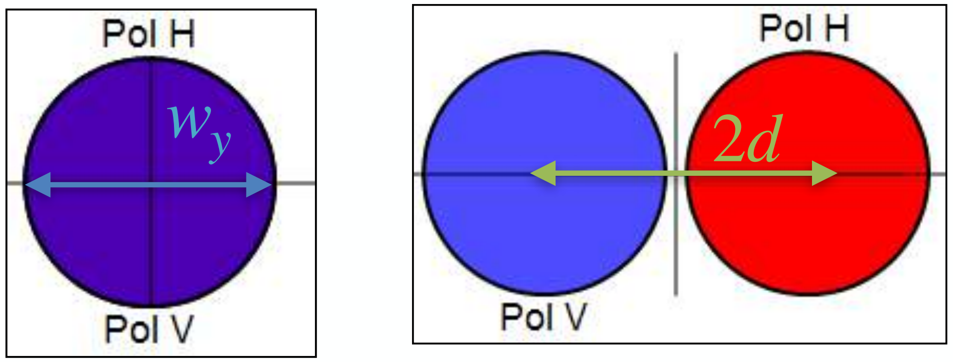
George Crisan

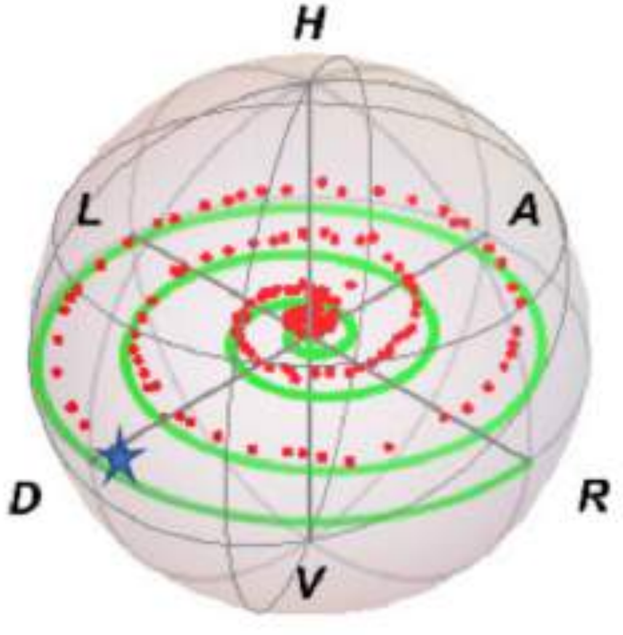
N. Belabas

G. Crisan el al., arXiv:2507.00972

Spatial and polarization degrees of freedom:

Using decoherence for quantum communications

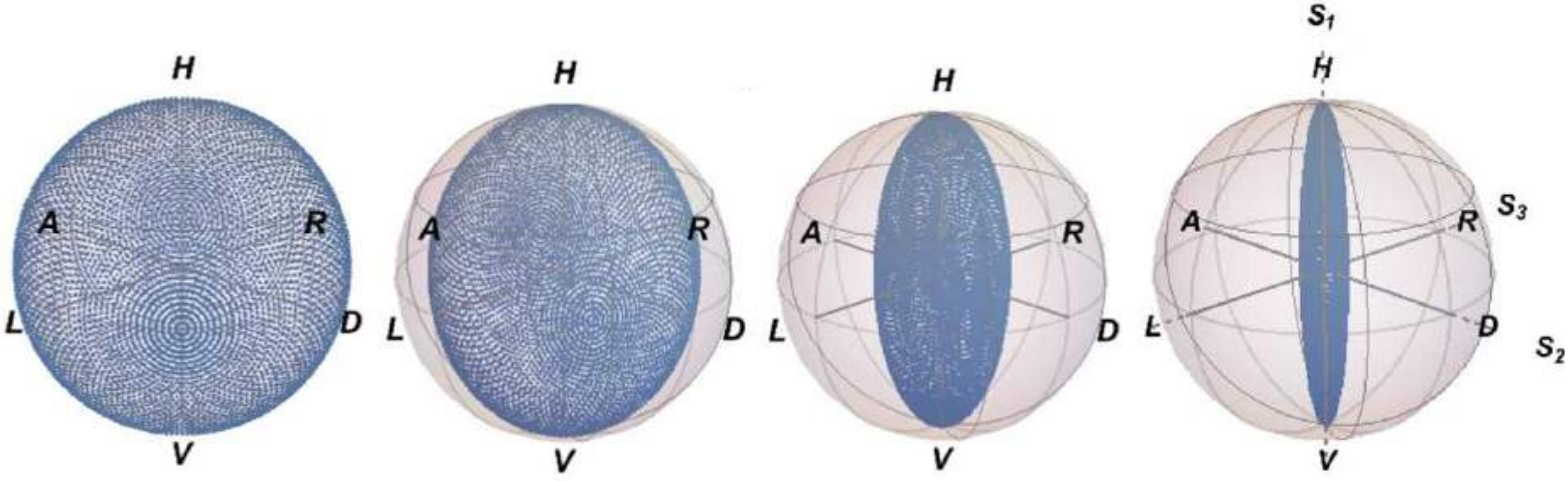




Decoherence:

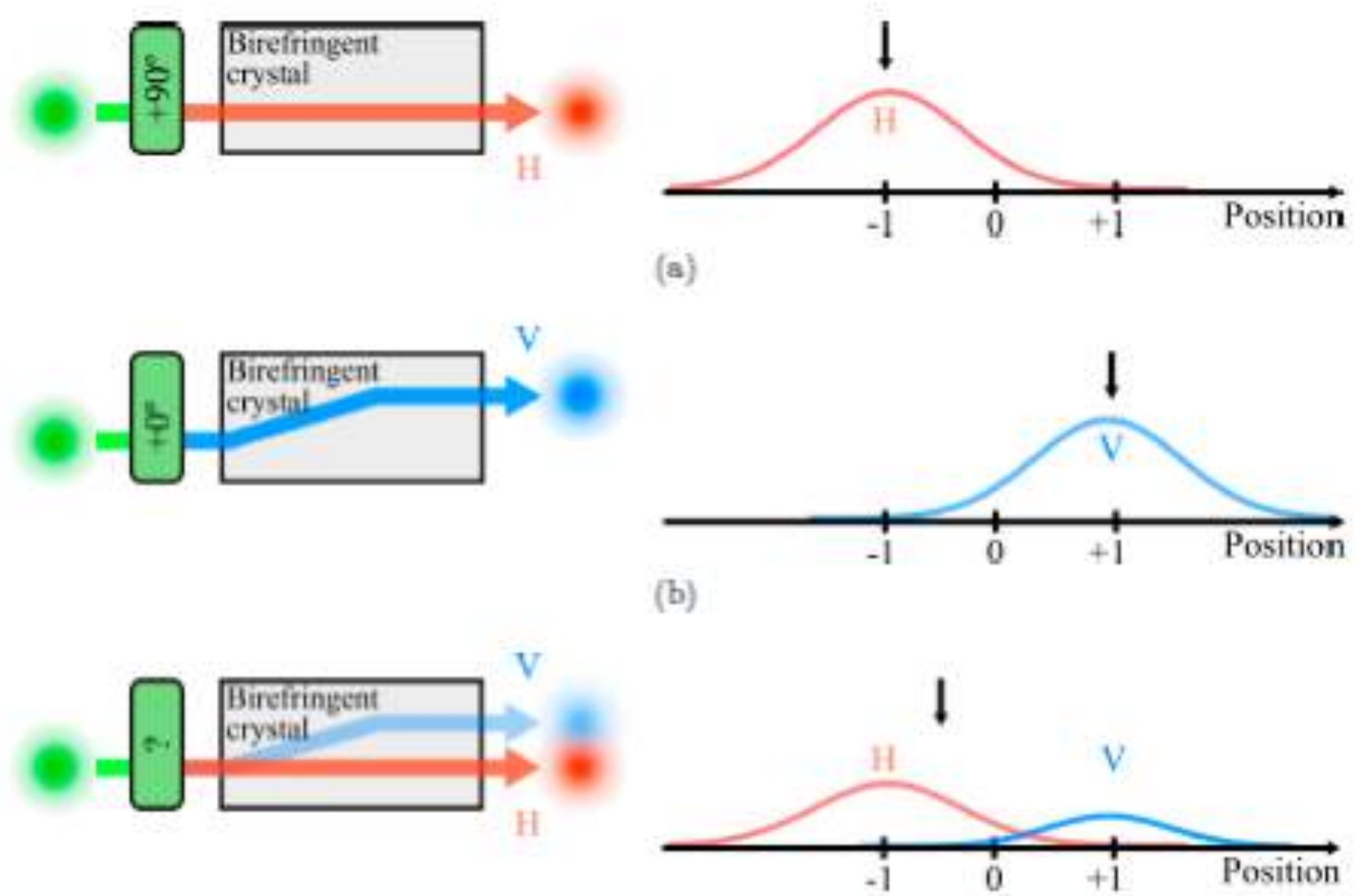
Loss of quantum superposition → Bloch sphere shrinking

Assumed detrimental to quantum information



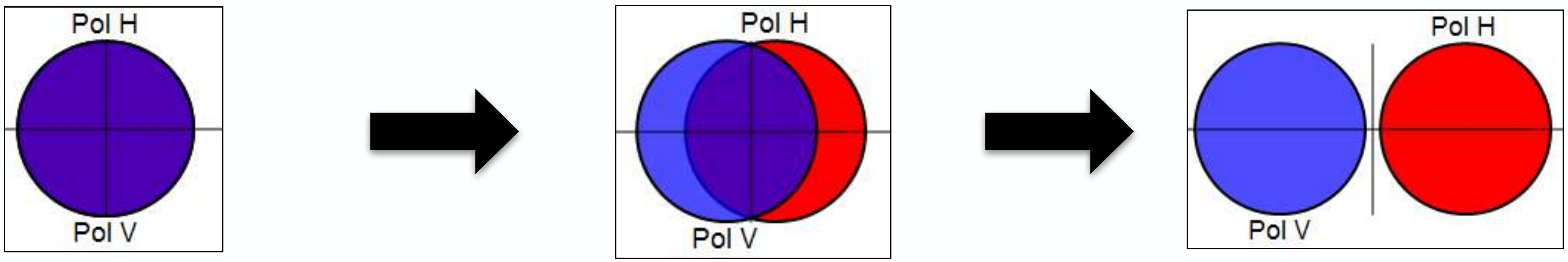
Coupling different degrees of freedom:

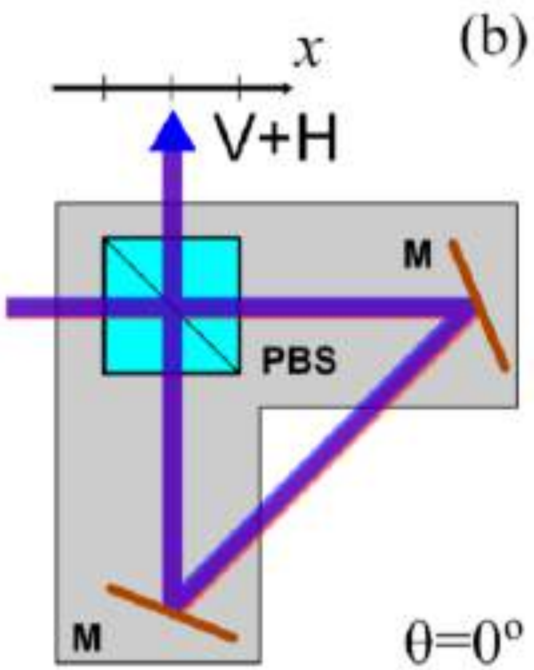
Birefringence:
Naturally couples spatial distribution and polarization

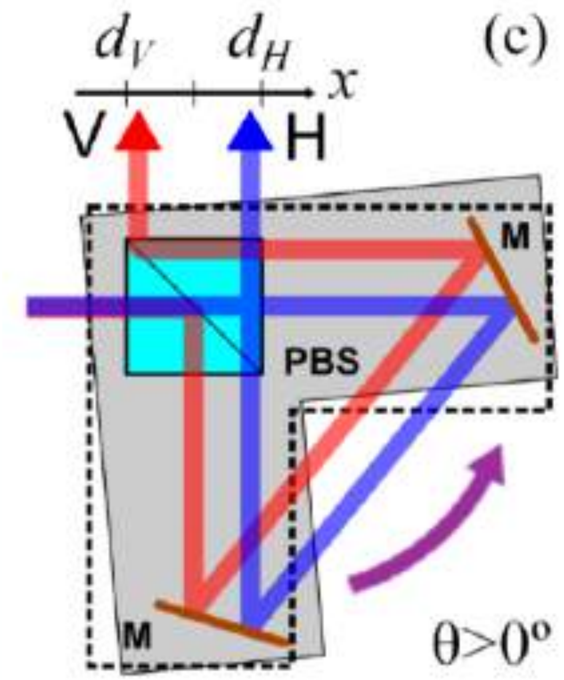


Tunable beam displacement (TBD)

Tunable birefringence



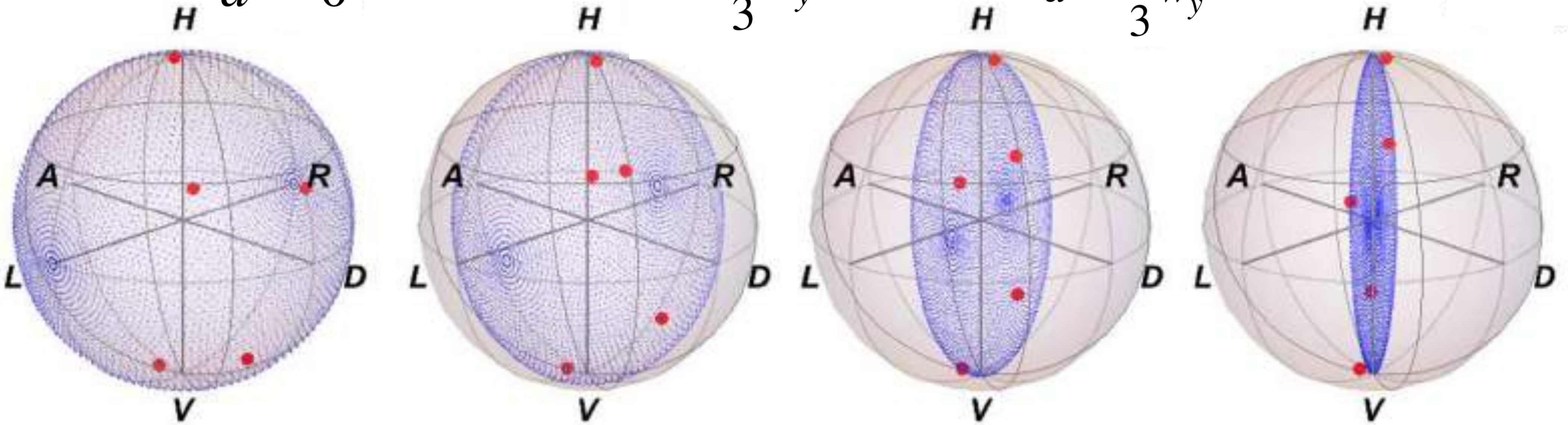




L.J. Salazar-Serrano *et al.*, Rev. Sci. Instrum. **86**, 033109 (2015)

Controllable dephasing channel

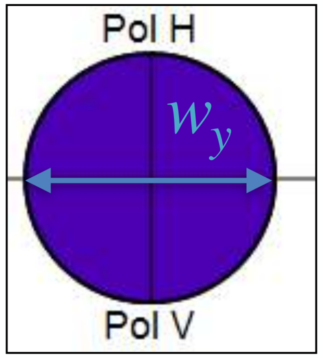
$d = 0$ $\quad d = \frac{1}{3} w_y$ $\quad d = \frac{2}{3} w_y$ $\quad d = w_y$

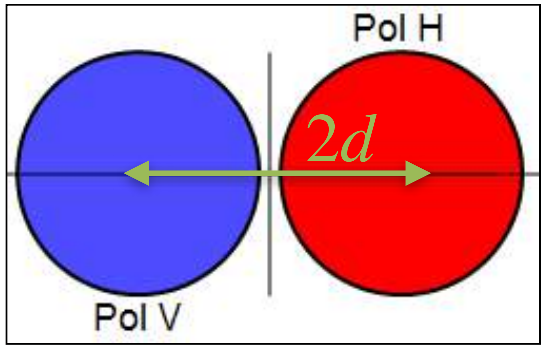


A. Valencia

D.F. Urrego

No dephasing.



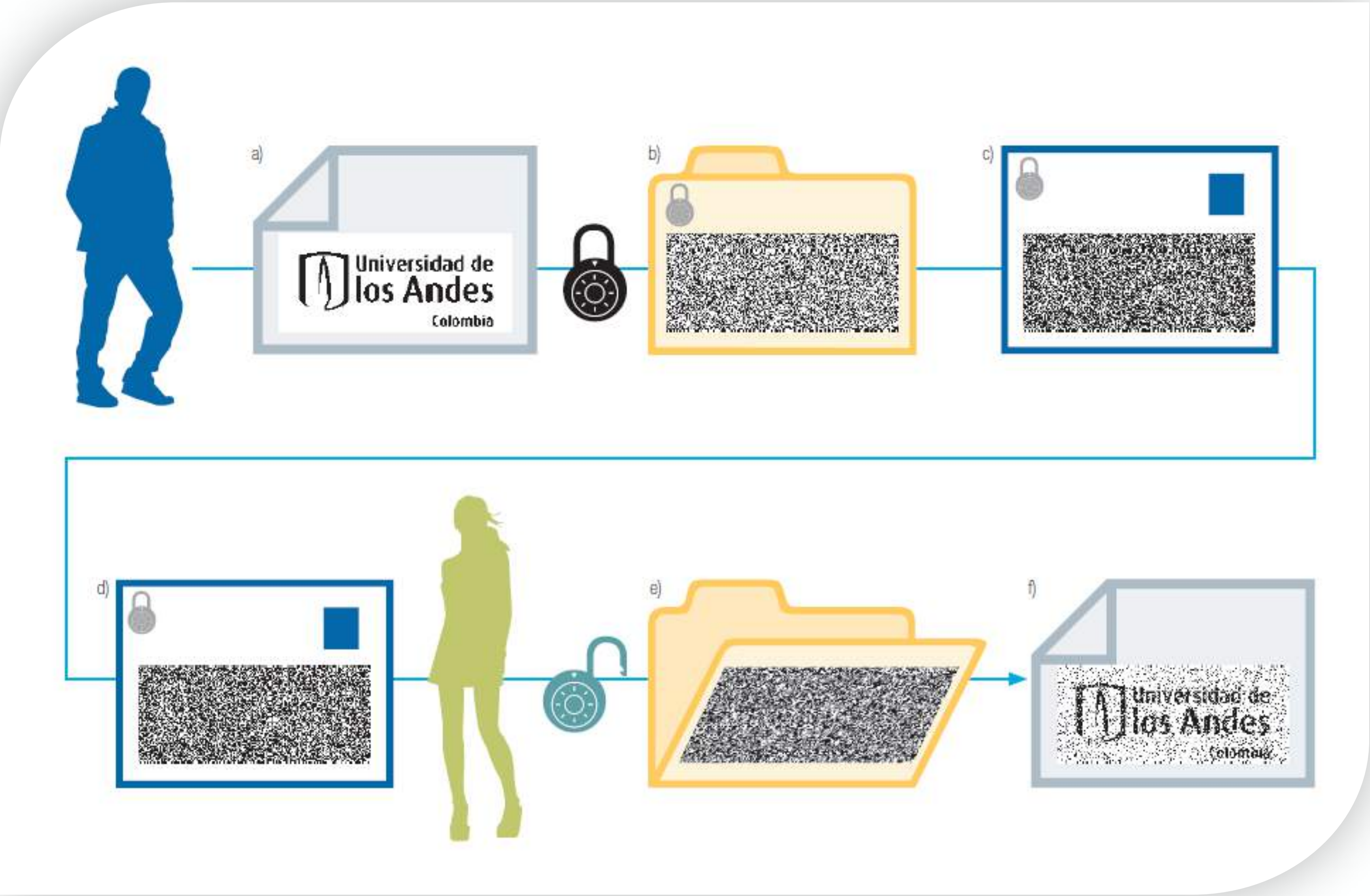


Full dephasing

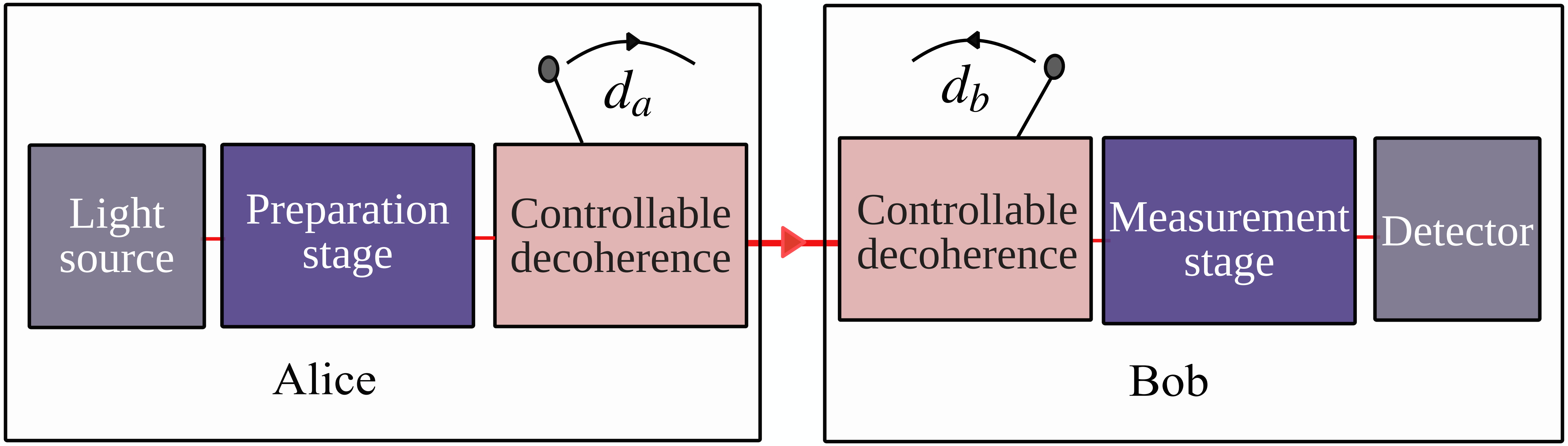
D. F. Urrego, <u>J.R.A.</u>, *et al.*, Opt. Expr. **26** (9), 11940 (2018)

QKD - BB84

- One-time pad encryption
- Ciphertext created by hashing with key, key also used to decode (with XOR)
- Ability to detect Eve's presence.
- Physical security: provided by no-cloning theorem.
- **Goal: Reduce the amount of information Eve can obtain.**

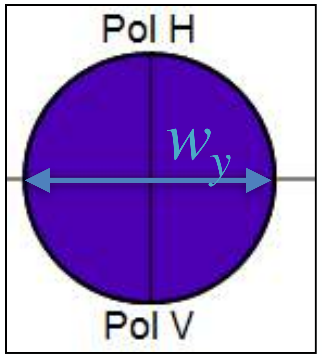


Decoherence-assisted mechanism on prepare and measure QKD



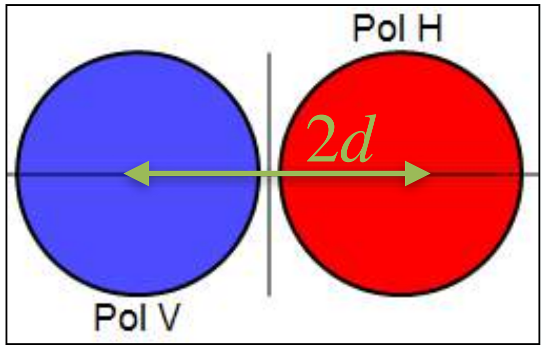
D.R. Sabogal, D.F. Urrego, **J.R.A.** et al., Sci. Rep. **15**, 31258 (2025)

Theoretical improvements to security



$\gamma_0 = 1$

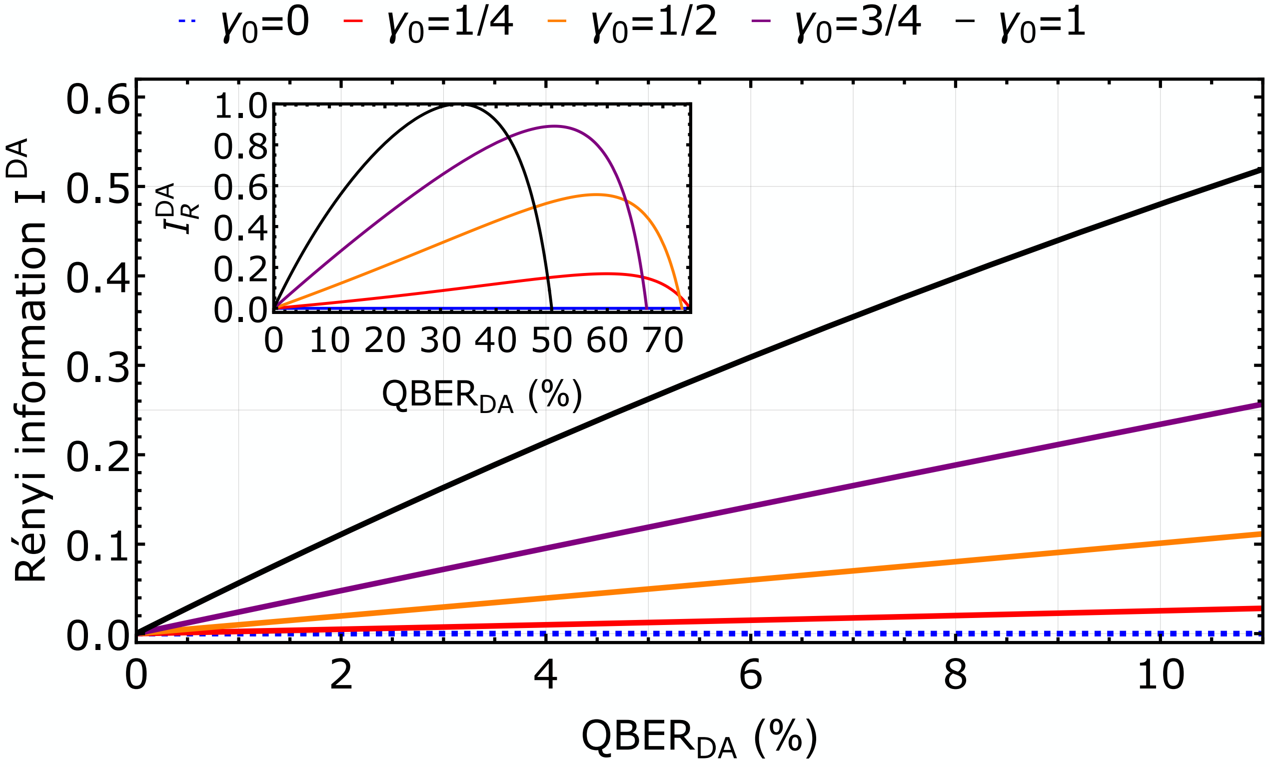
No decoh.



$\gamma_0 = 0$

Full decoherence

Reduced Renyi information with higher decoherence



J. P. Torres

D.F. Urrego

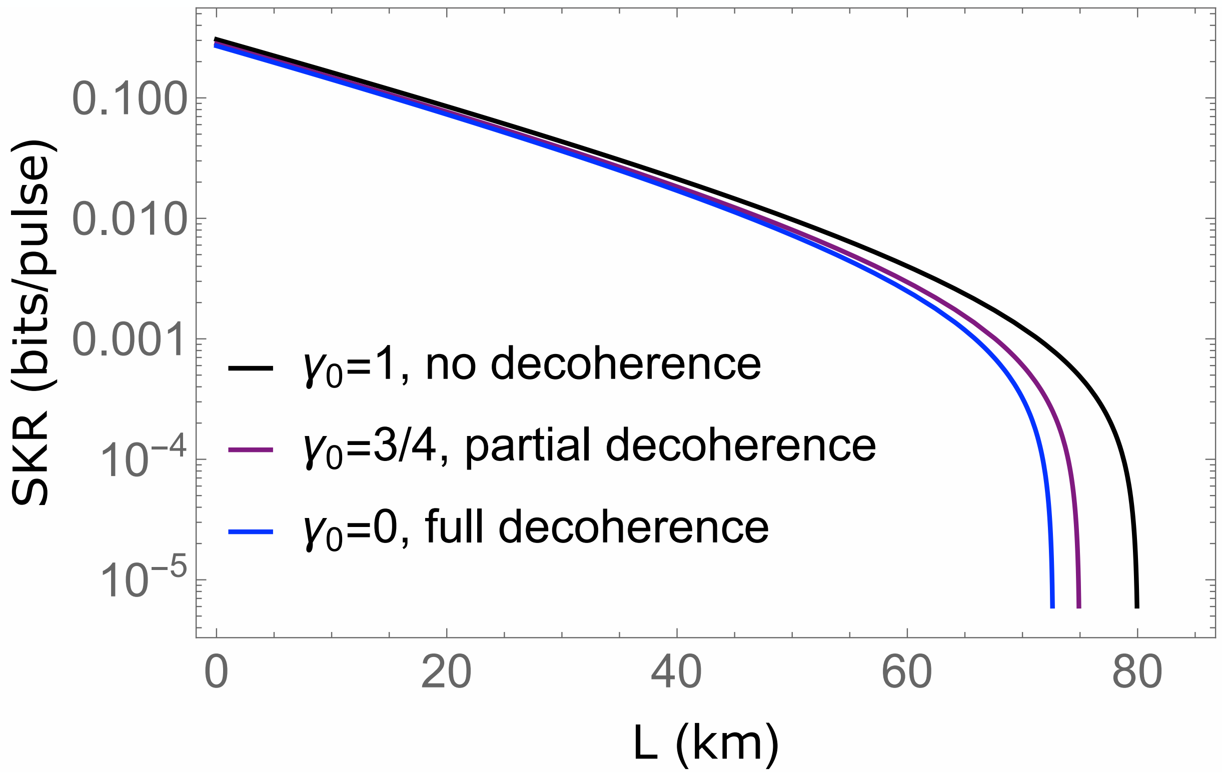
$$\mathrm{QBER}_{HV} = S^2/2 = P_e \quad , \qquad \mathrm{QBER}_{DA} = \frac{1}{4}\left(3 - \gamma_0^4\right)S^2.$$

D.R. Sabogal, D.F. Urrego, **J.R.A.** et al., Sci. Rep. **15**, 31258 (2025)

Estimated secret key rate

(only contrasting decoherence-assisted with standard BB84)

$$\mathrm{SKR} < \frac{\eta}{2}\left(1 - H_2\left(\mathrm{QBER}_{HV}\right) - H_2\left(\mathrm{QBER}_{DA}\right)\right),$$



$$\mathrm{QBER}_{HV}(L) = Q_0 + \zeta L$$

$$\mathrm{QBER}_{DA}(L) = 1/2 * (3 - \gamma_0^4) * Q_0 + \zeta L$$

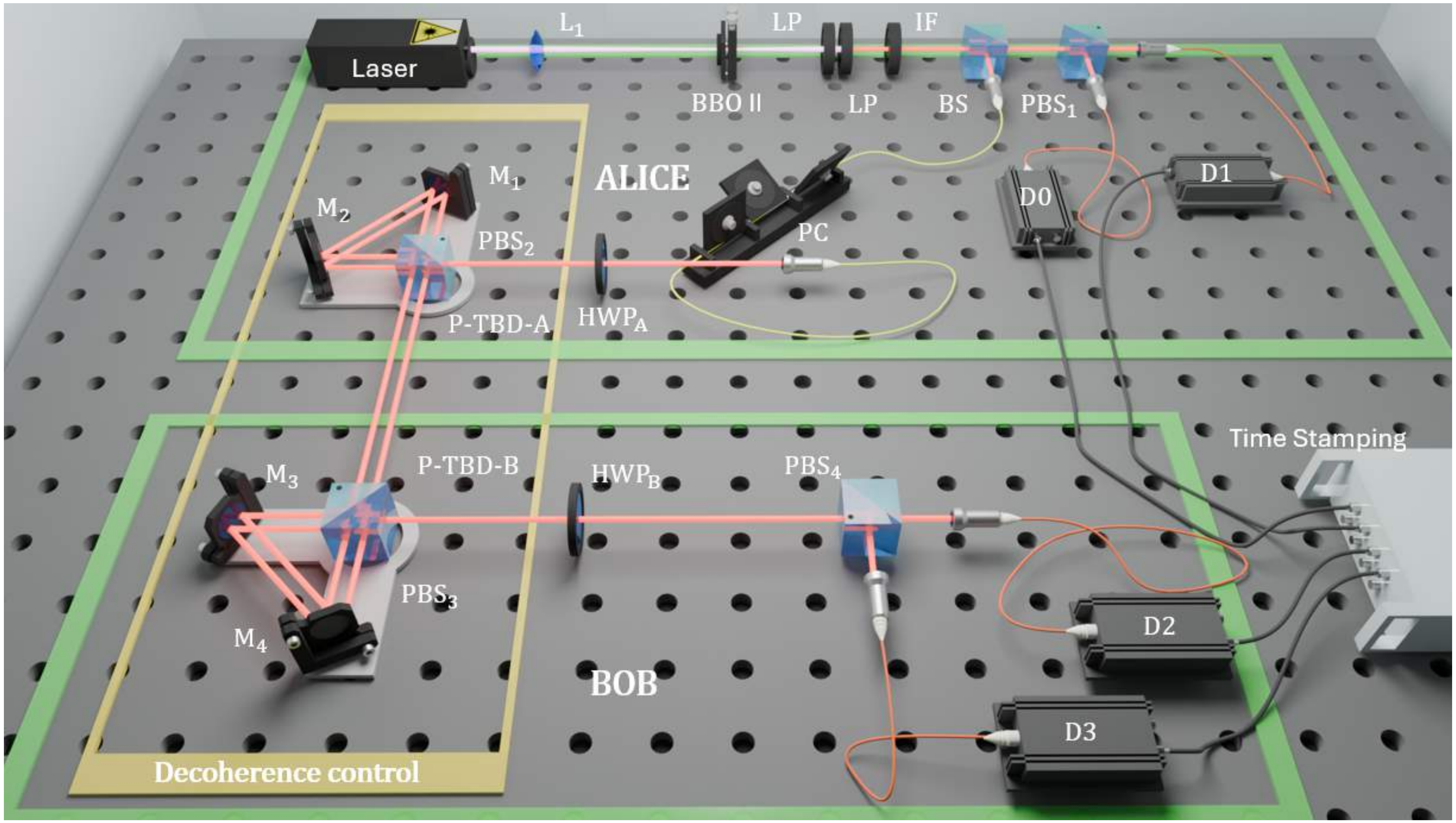
$$\eta = 10^{-\alpha L/10},$$
$$\alpha = 0.2\ \mathrm{dB/km},$$
$$Q_0 = 0.03,$$
$$\zeta = 0.001\ \mathrm{km}^{-1}$$

Small distance trade off compared with high Renyi information loss

D.R. Sabogal, D.F. Urrego, **J.R.A.** et al., Sci. Rep. **15**, 31258 (2025)

Experimental implementation

QKD with heralded single photons: with and without decoherence



A. Valencia

D.F. Urrego

D.R. Sabogal

QBER $= 3.9\ \%$ with 5 keys of 1000 bits. QBER $= 7.38\ \%$ with keys of 1000 bits.

D.R. Sabogal, D.F. Urrego, **J.R.A.** et al., Sci. Rep. **15**, 31258 (2025)

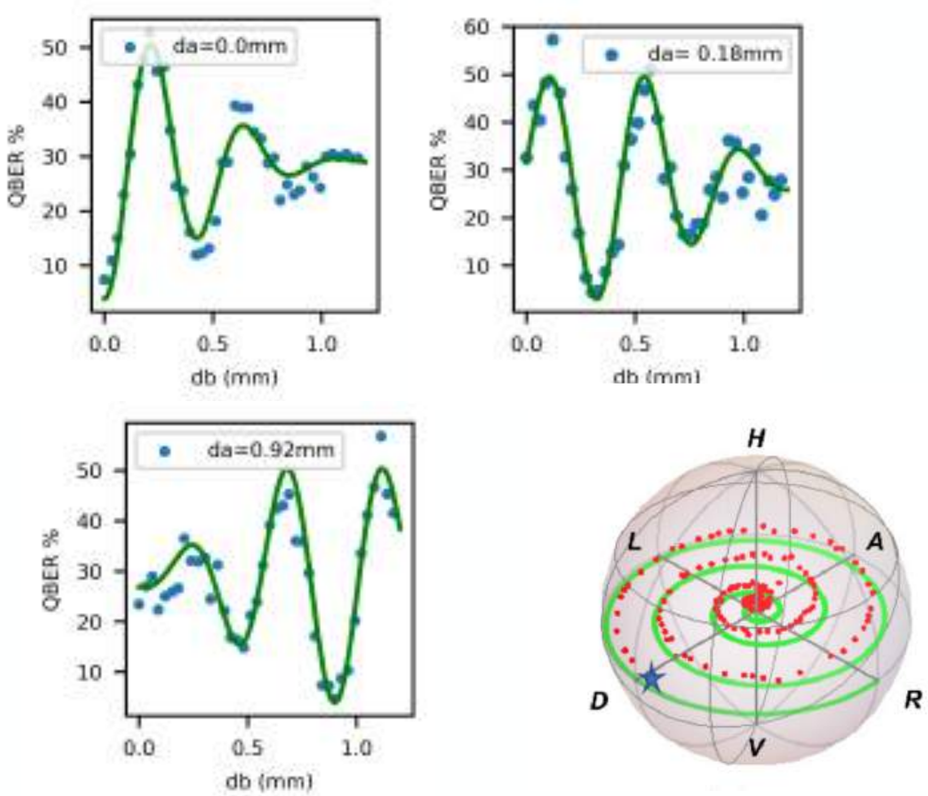
Experimental implementation

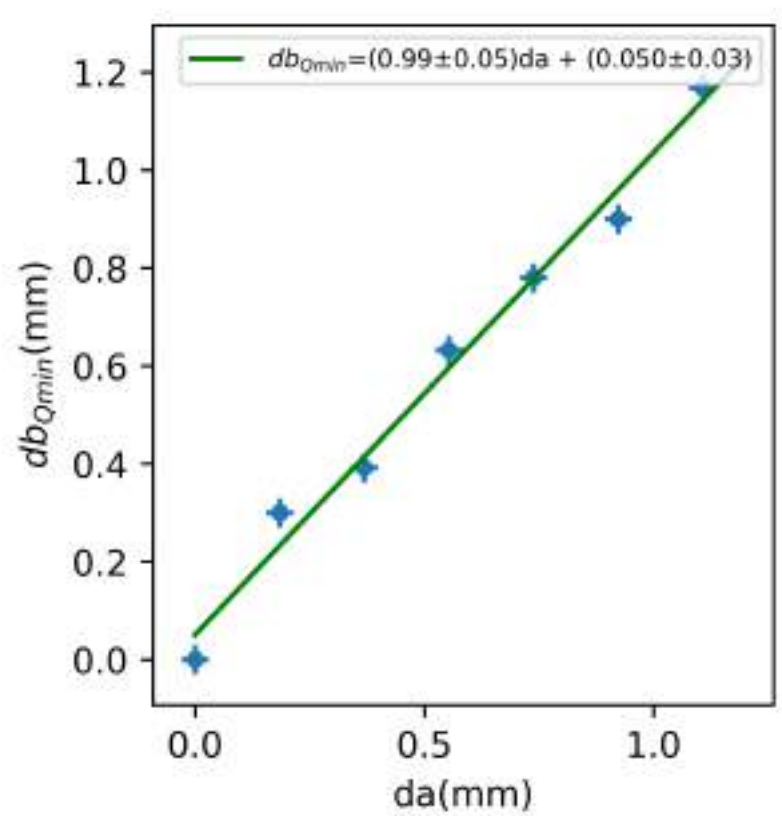
QKD with heralded single photons with decoherence

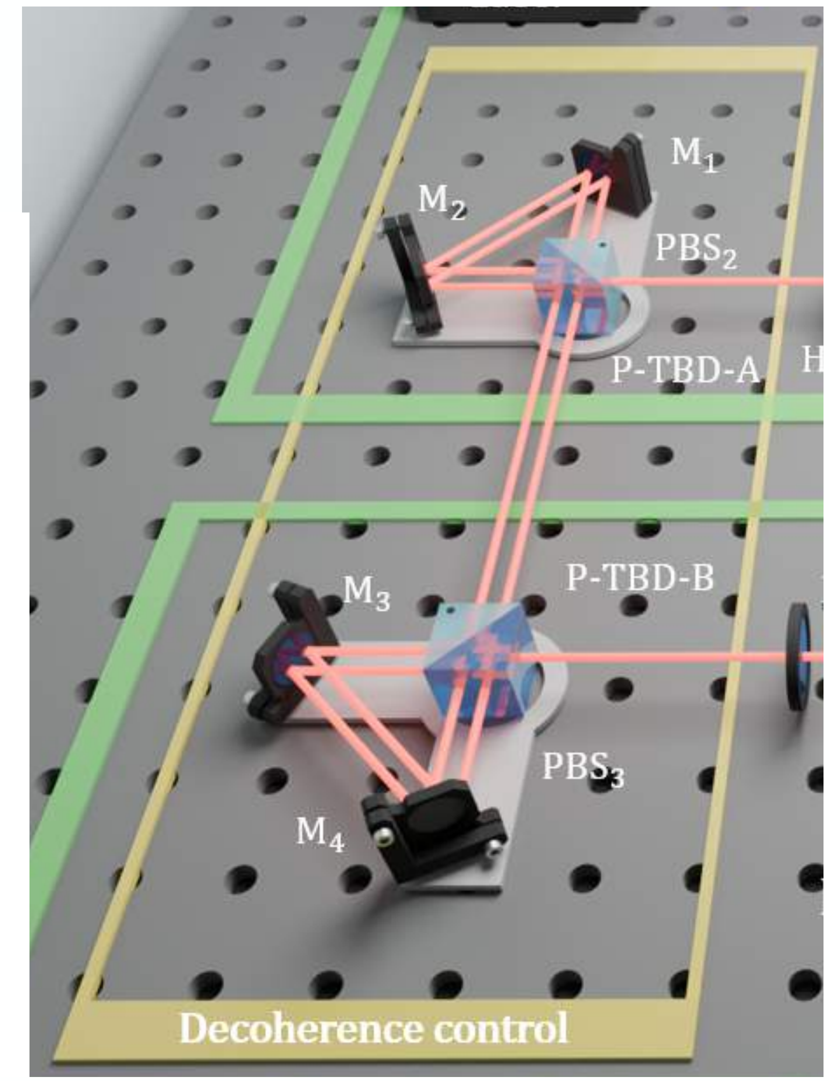
Decoherence assisted method using Tunable Beam Displacers:

$$\mathrm{QBER}\left(d_a, d_b\right) = \frac{1}{4}\left\{1 - \exp\left[-2\frac{(d_a - d_b)^2}{w^2}\right]\cos[2q_0(d_a - d_b)]\right\}.$$

1000 bits/ key



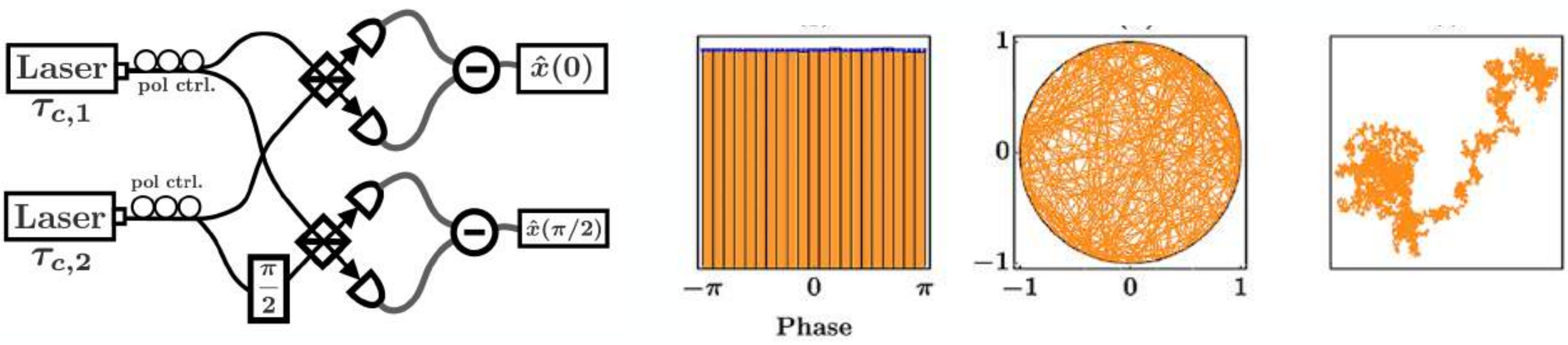




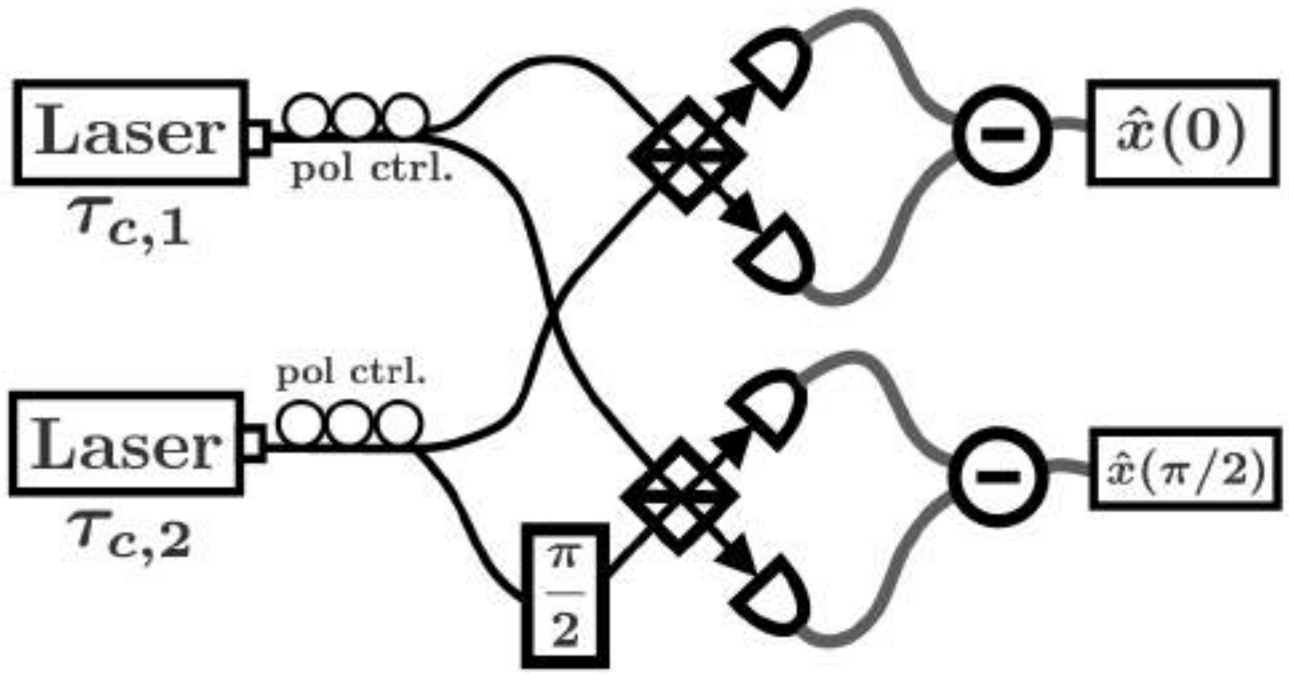
D.R. Sabogal, D.F. Urrego, **J.R.A.** et al., Sci. Rep. **15**, 31258 (2025)

Continuous variable degrees of freedom:

Generating random numbers from phase noise



Interfering two coherent states: Random number generation of quantum origin



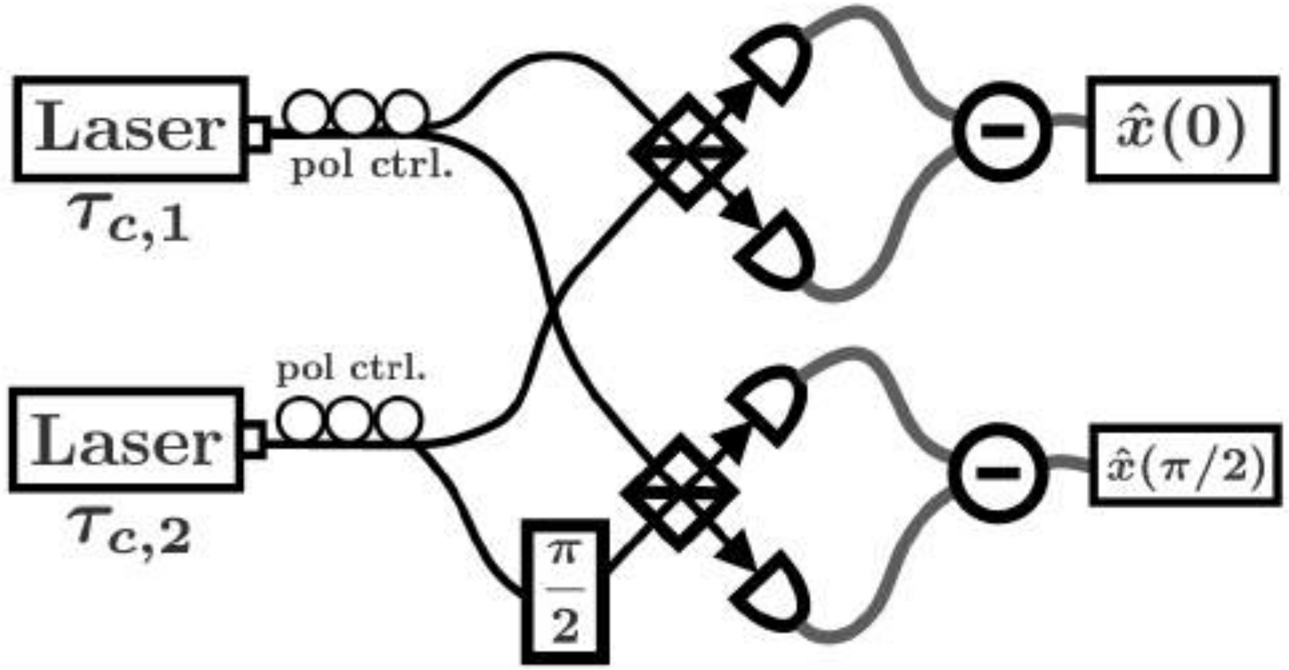
J.R.A. et al. Opt. Ex. **28** (4), 5538 (2020)


S. Sarmiento

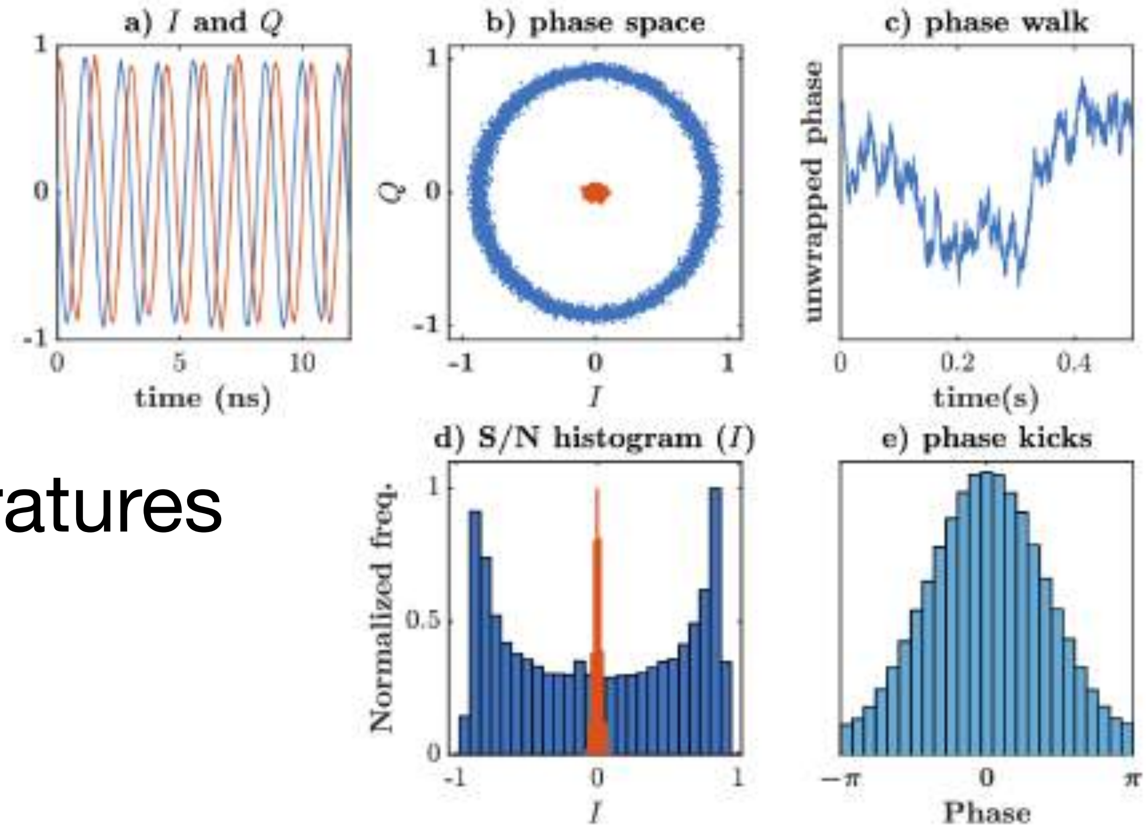

J. P. Torres


J. Lazaro


J.M. Gené



J.R.A. et al. Opt. Ex. **28** (4), 5538 (2020)



Phase space from field quadratures

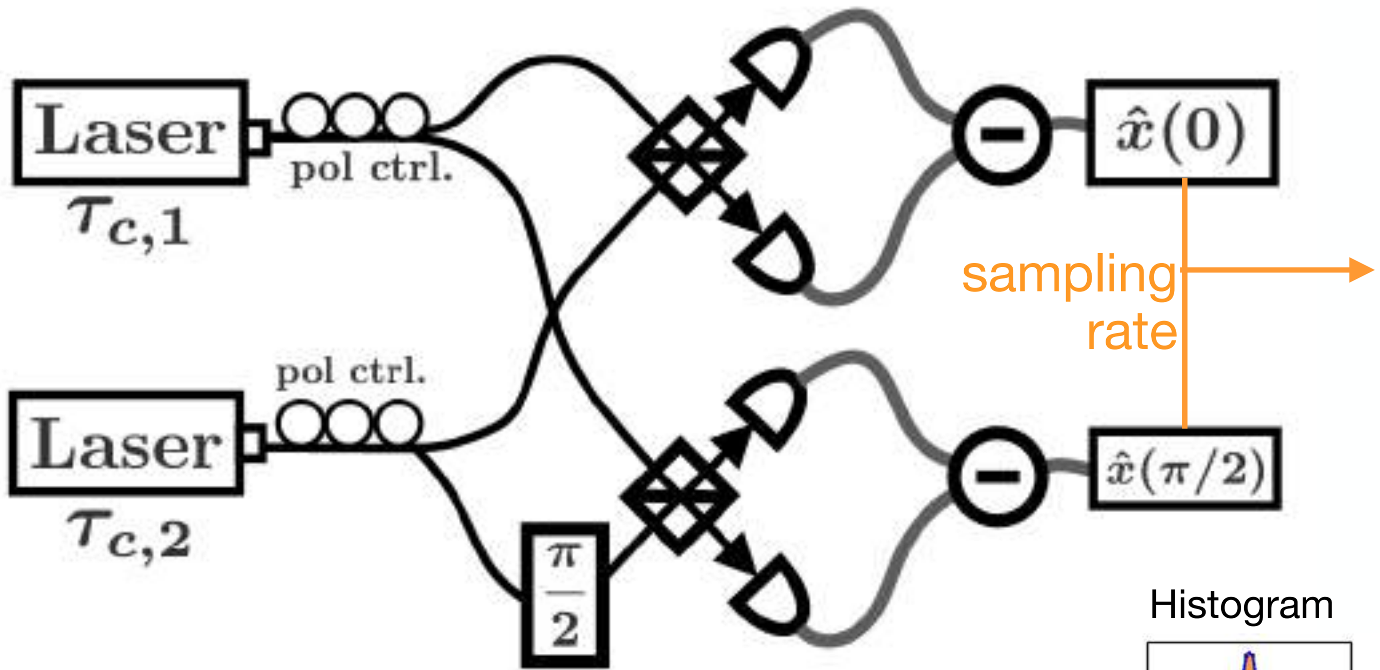

S. Sarmiento


J. P. Torres


J. Lazaro


J.M. Gené

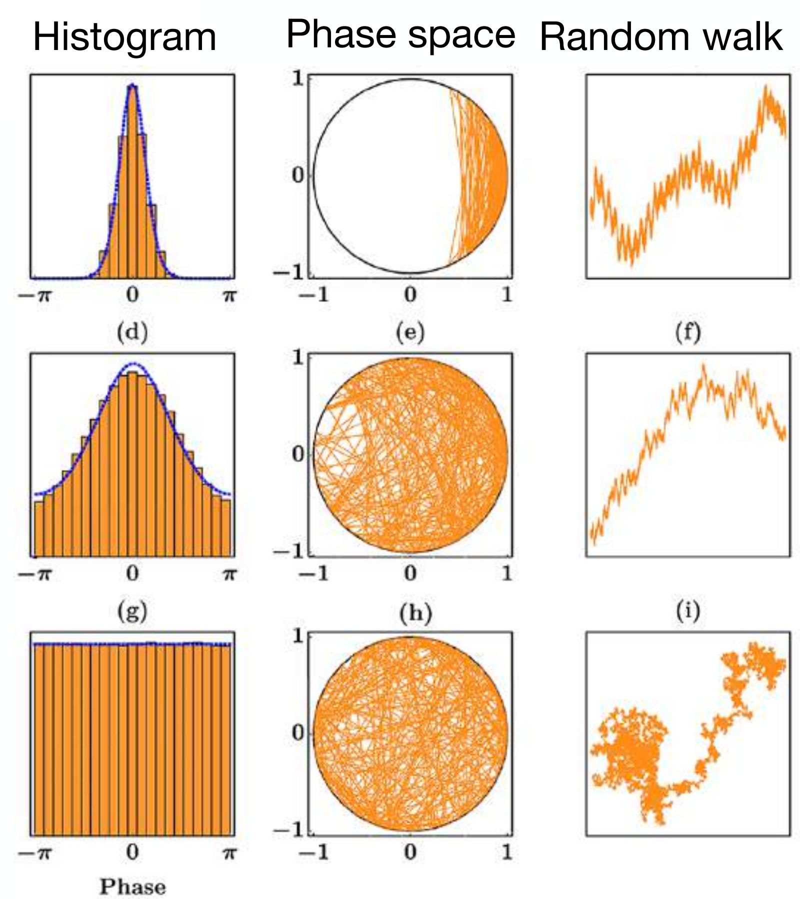
Interfering two coherent states: Random number generation of quantum origin



$$P(\xi(t) = \theta) = \frac{1}{2\pi I_0(t/\overline{\tau}_c)} \exp\left[\frac{\overline{\tau}_c}{t}\cos(\theta)\right].$$

J.R.A. et al. Opt. Ex. **28** (4), 5538 (2020)

Fast (~5Mbit/s) and off the shelf



7.81MSa/s

500kSa/s

156kSa/s


S. Sarmiento


J. P. Torres

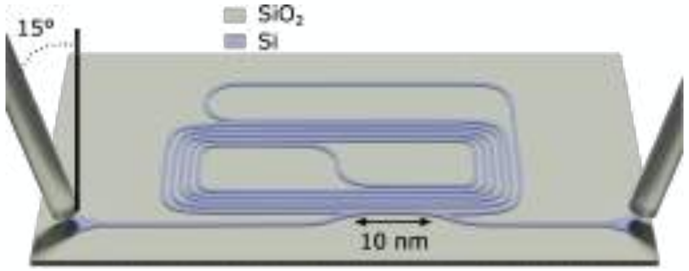

J. Lazaro


J.M. Gené

Research plan from 2025 onwards

1 Developing frequency entanglement-based **quantum networks**

Usage of **existing fiber infrastructure** between Télécom Paris and C2N



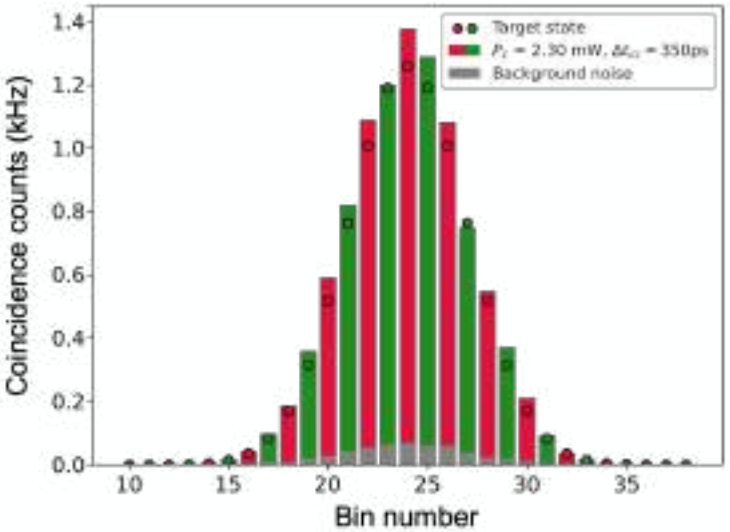
Adv. Photonics **6** (3), 036003 (2024)


J. Viatteau


N. Belabas


N. Fabre

- Multi-dimensional
- frequency entangled
- Already at Telecom wavelengths
- Compatible with off-the-shelf telecom equipment
- Novel encodings: Time-frequency GKP states

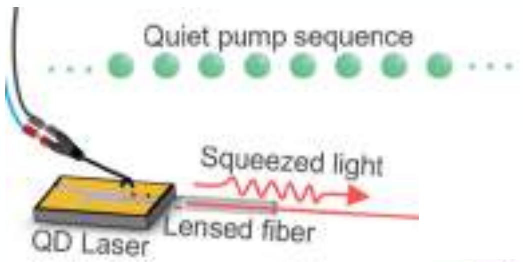


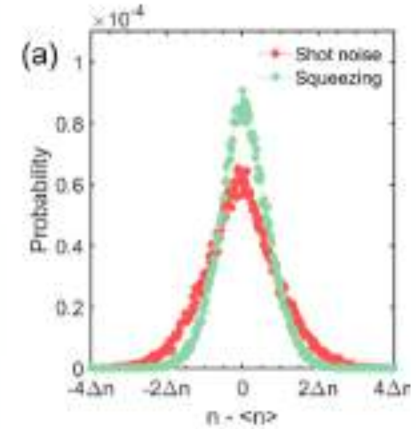
Research plan from 2025 onwards

2 Contribute to the already existing **continuous variable platforms**

Certification of squeezing and full tomography of the generated states

Electrically driven source of squeezed light without nonlinear media



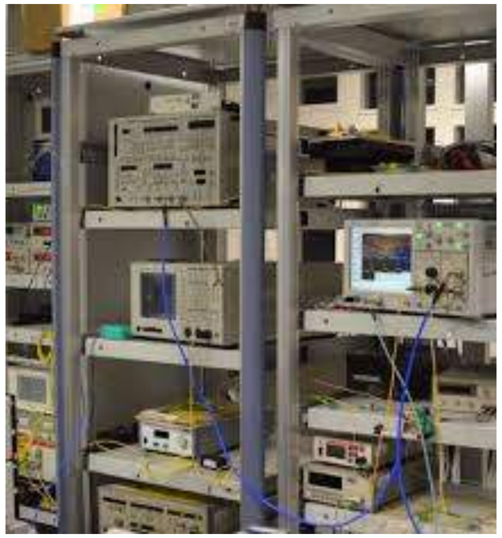


Phys. Rev. Research **6**,L032021 (2024)

 F. Grillot  H. Huang

 F. Battiston

Contribute to the development of the current CVQKD infrastructure



 R. Alleaume  S. Srivastava

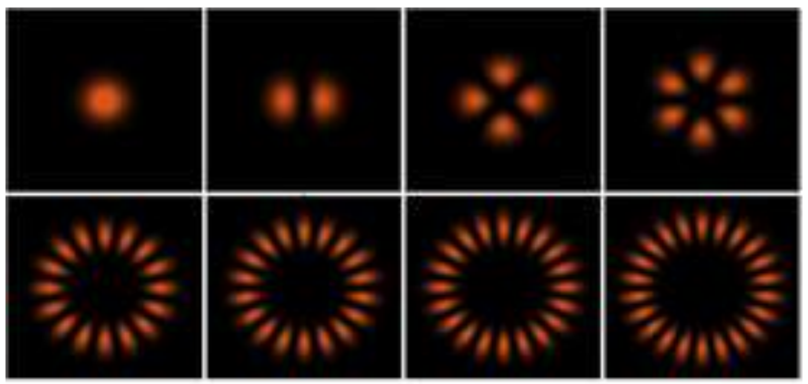
 M. Schiavon  N. Fabre

 C. Ware  T. Sharma

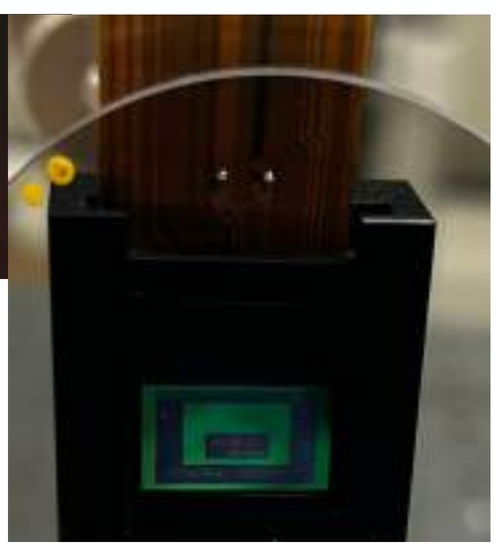
Research plan from 2025 onwards

3

Developing a **free-space** quantum communications platform



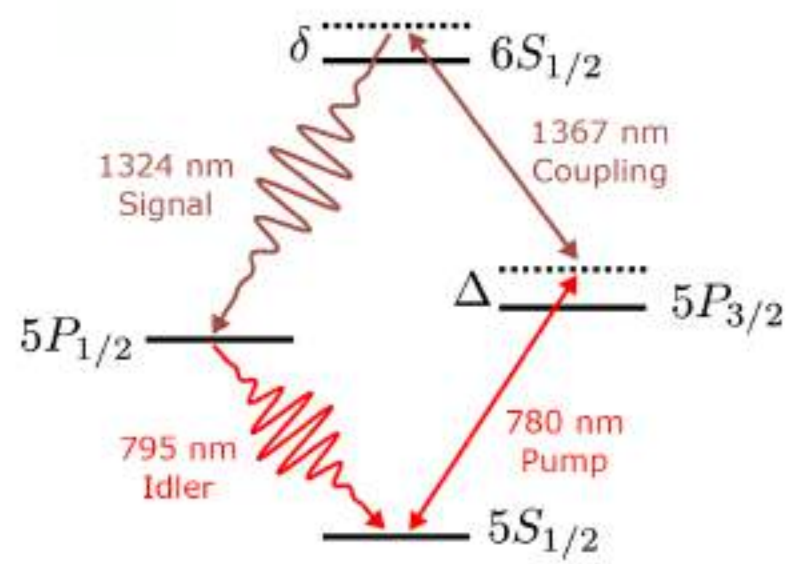
Spatial distribution of light
(with SLM)



E. DeVeyra

- Hot atomic sources:
  Naturally free space - bichromatic transitions

- Potential to use quantum memories.



M. Schiavon

Qunnect

Collaboration discussed

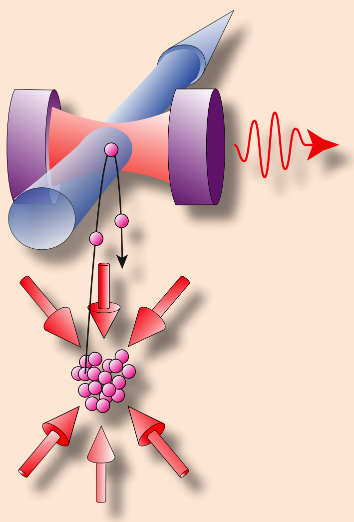
- Physical deployment
- Satellite communications

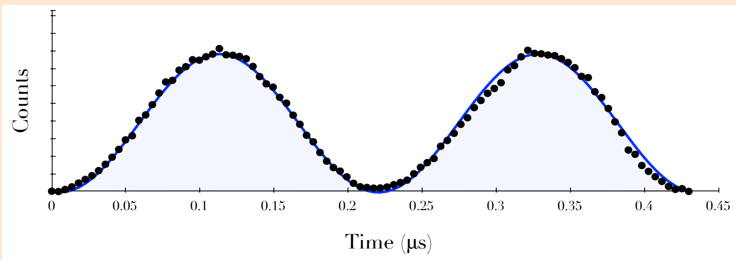
Thank you!

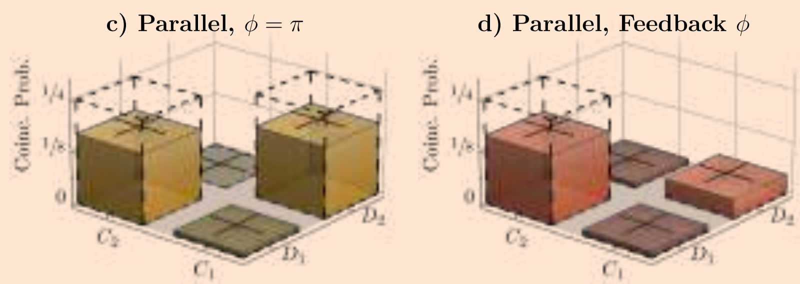
juanrafael.alvarez@telecom-paris.fr

Quantum light for quantum information technologies:

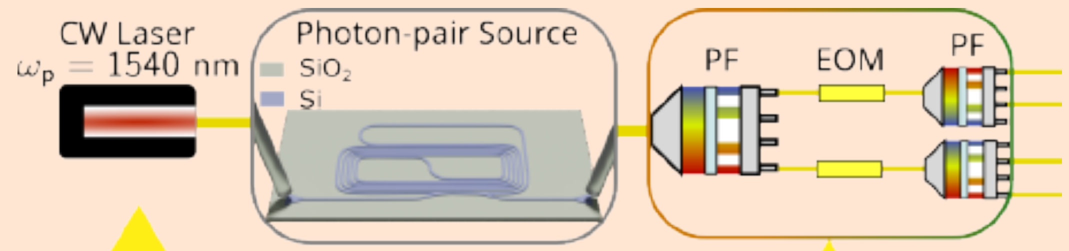
I — Time-bin encoding:
Feedback, long coherence times

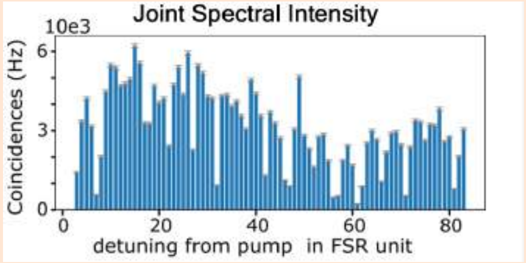




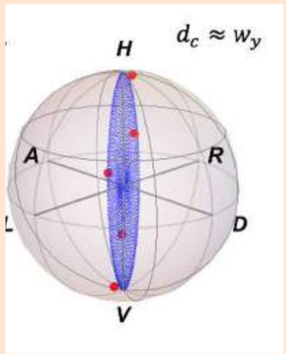


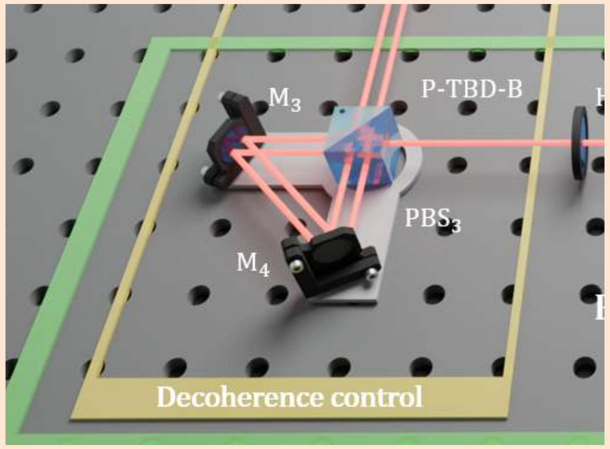
II — Frequency-bin encoding:
Multi-dimensionality, robustness, off-the-shelf devices





III — Spatial mode + polarization
Controllable dephasing channel





IV — Continuous variables
Random number generation, compatibility with telecom