A reversible quantum memory for OAM encoded qubits

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A. Nicolas, L. Veissier, L.Giner, E. Giacobino, D. Maxein, and J. Laurat
Nature Photonics (accepted), arXiv:1308.0238 (2013)

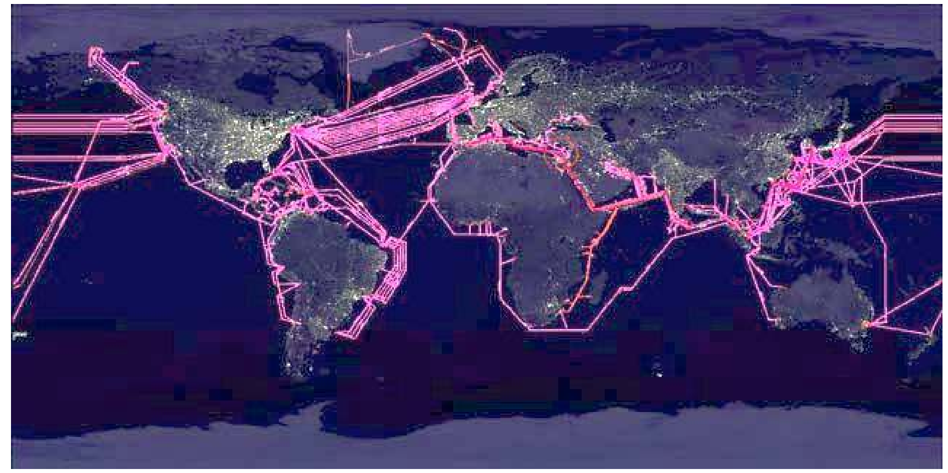
For QIPA2013 participants and their internal use.

From classical to quantum networks

For QIPA2013 participants and their internal use.

Classical Information Network

Nodes



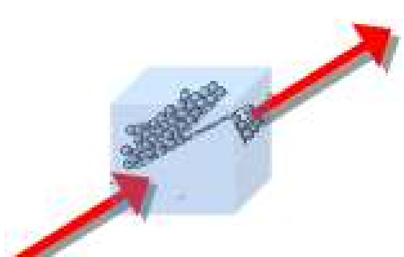
Channels

Equivalent for Quantum Information Processing ?

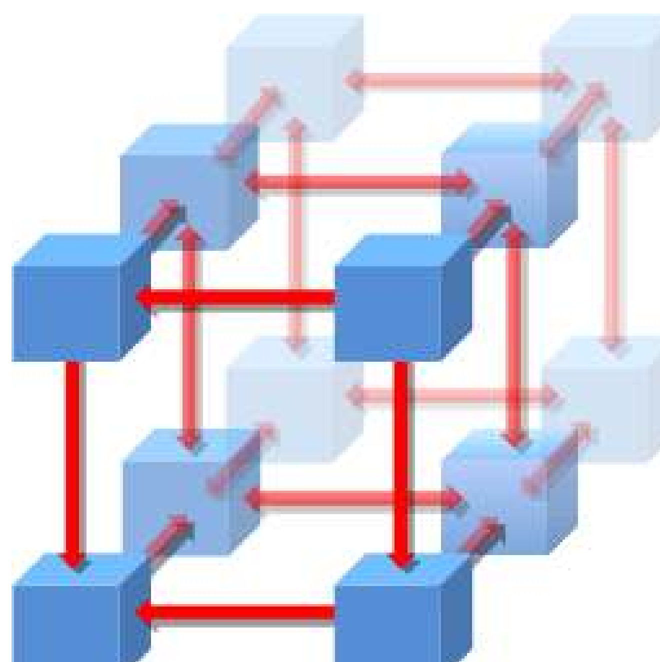
- Distributed quantum computing, "quantum internet"
- Quantum cryptography

Quantum Information Network

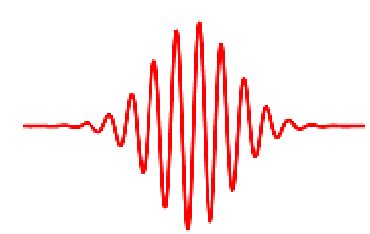
Quantum nodes
process & store states



e.g. atoms



Quantum channels
distribute quantum states

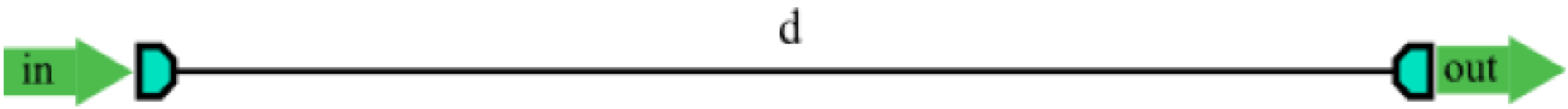


e.g. single photons

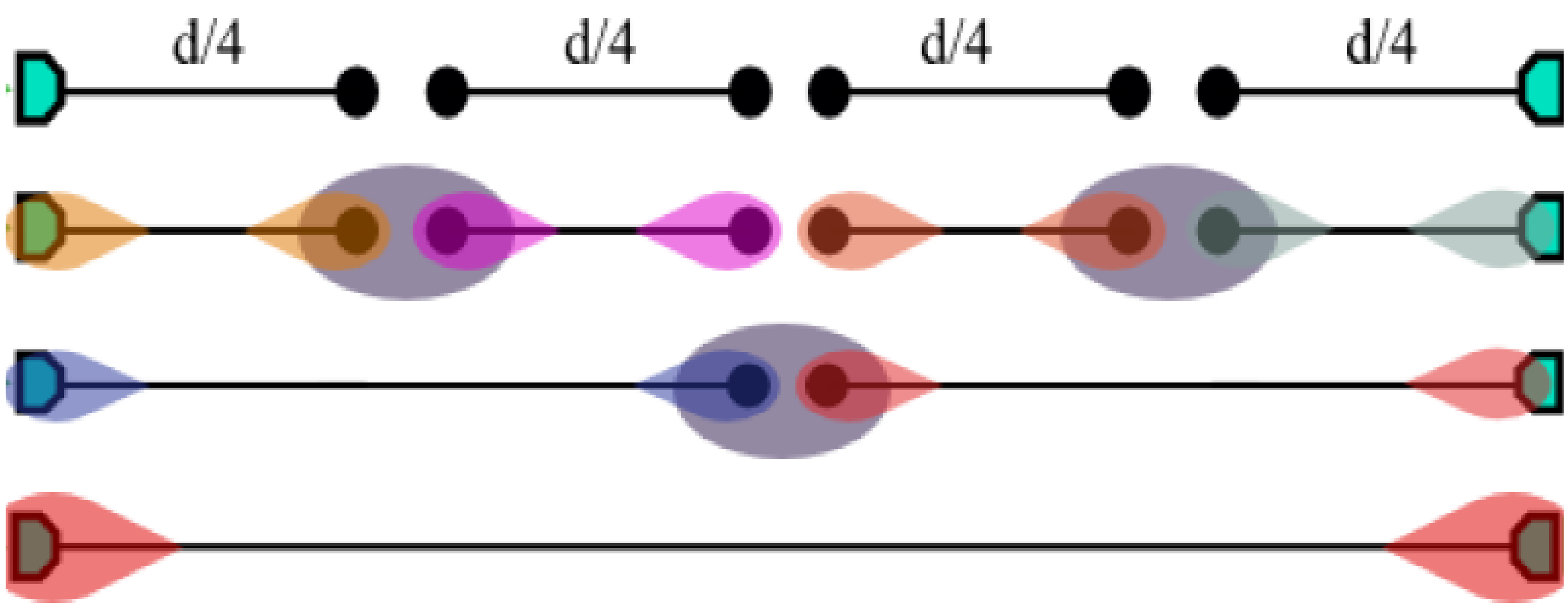
[Kimble, Nature, **453**, 1023 (2008)]

Specific challenges of a quantum link

For QIPA2013 participants and their internal use.



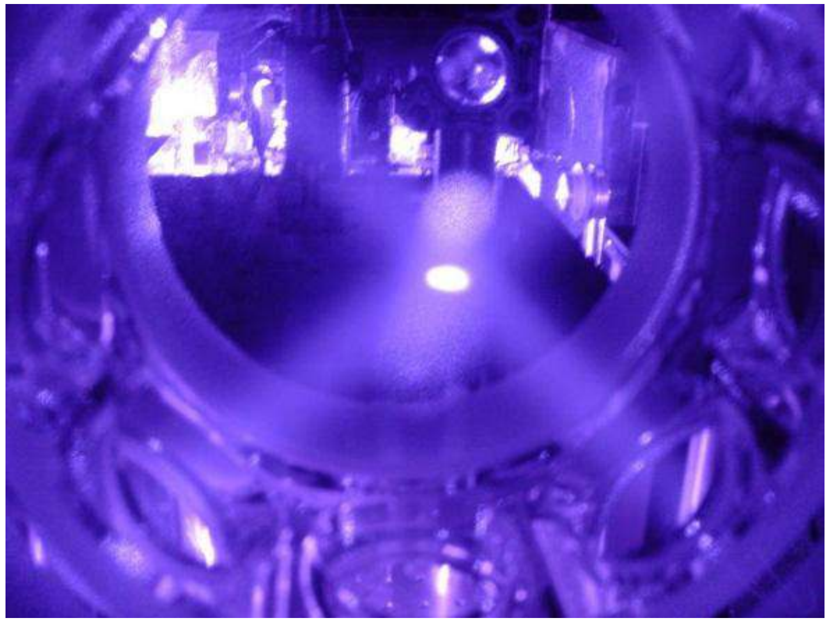
- Losses: direct transmission of states infeasible $> \sim 100$ km
- No-cloning-theorem: amplification not possible
- Approach: split distance and use "Quantum Repeaters"
- Distribute basic resource: entanglement

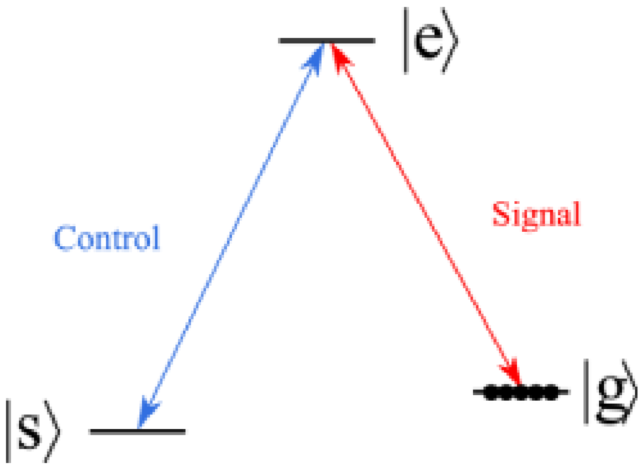


- Gain only if each segment works asynchronously
  $\rightarrow$ need for Quantum Memories

Light-matter interface: EIT memory

For QIPA2013 participants and their internal use.



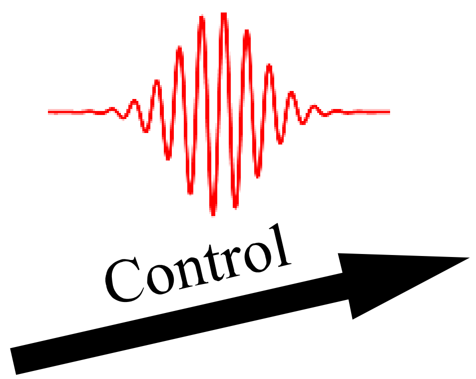


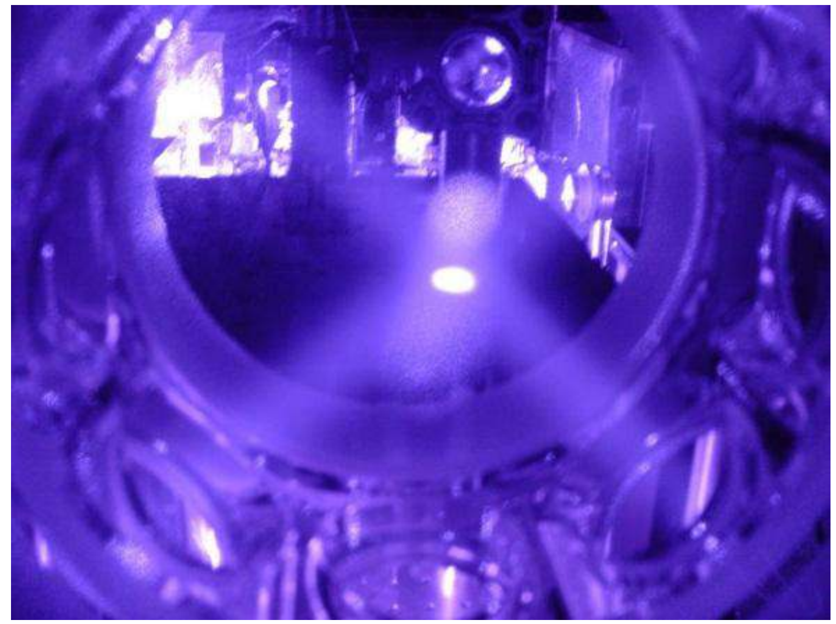
Light-matter interface: EIT memory

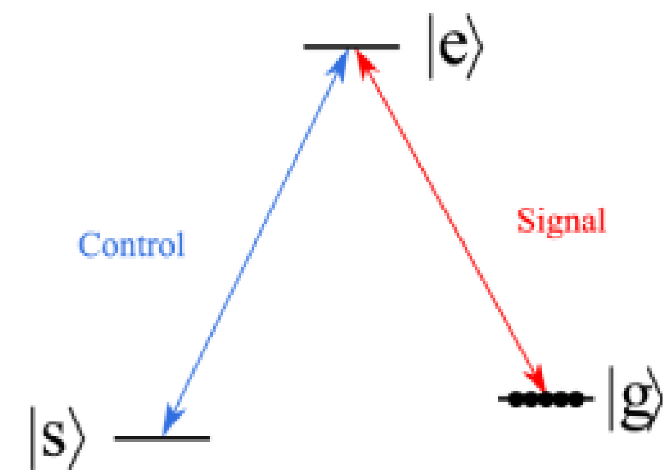
For QIPA2013 participants and their internal use.

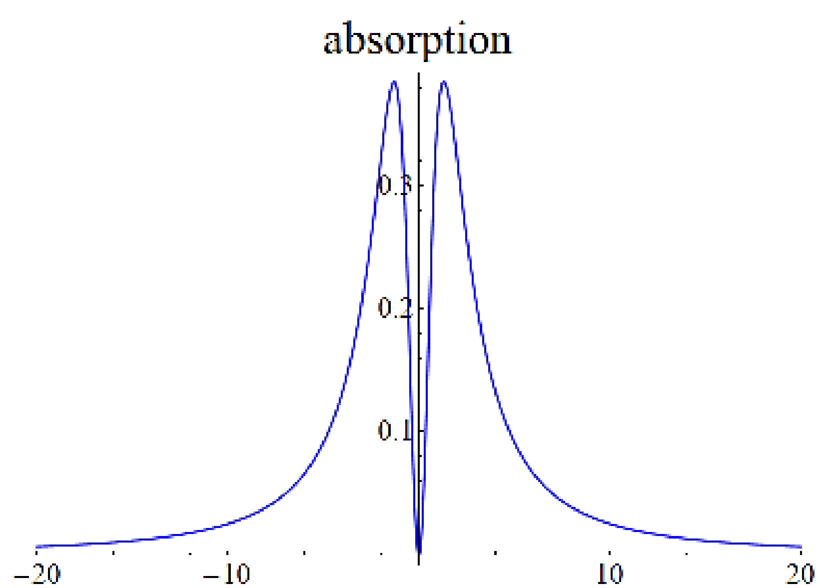
Signal pulse,

< 1 photon

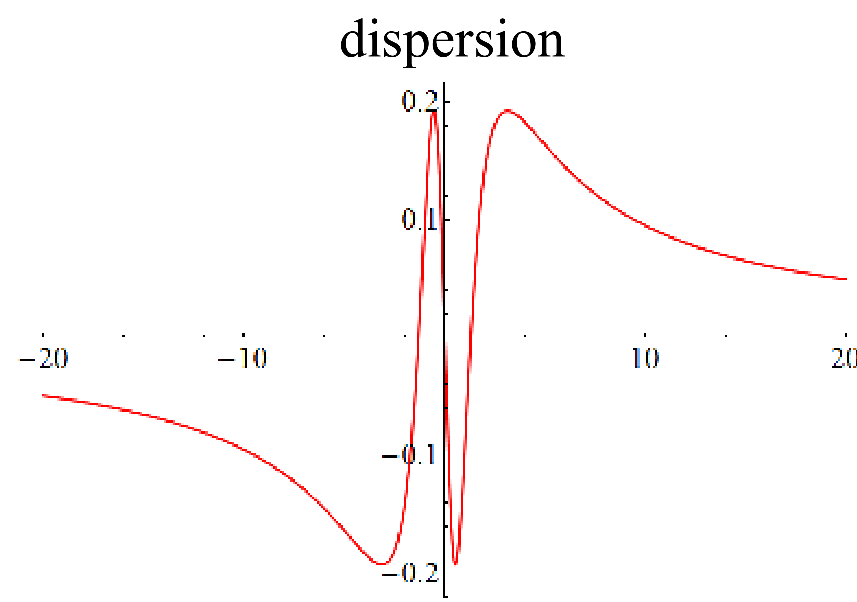








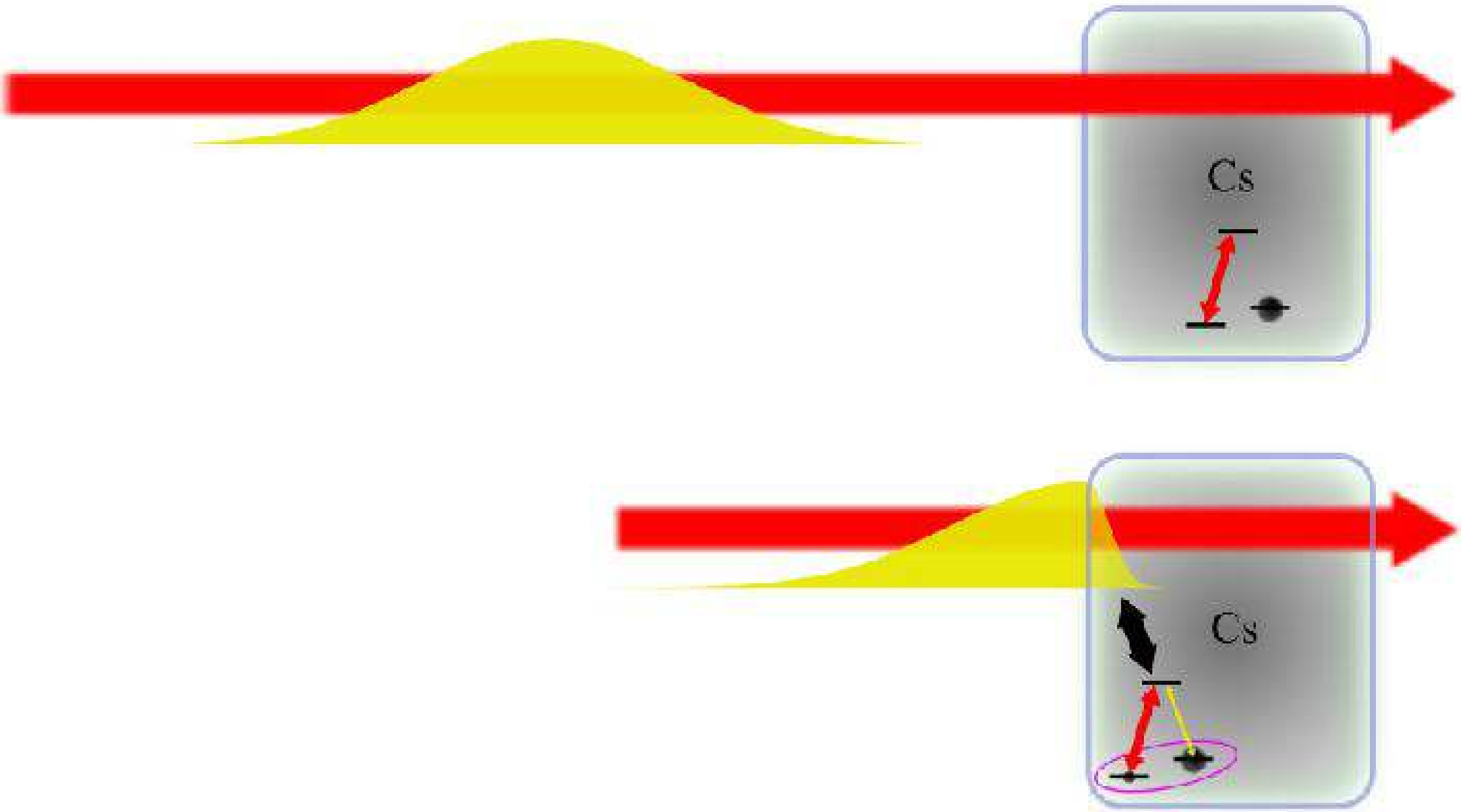
Transparency



… and slow light

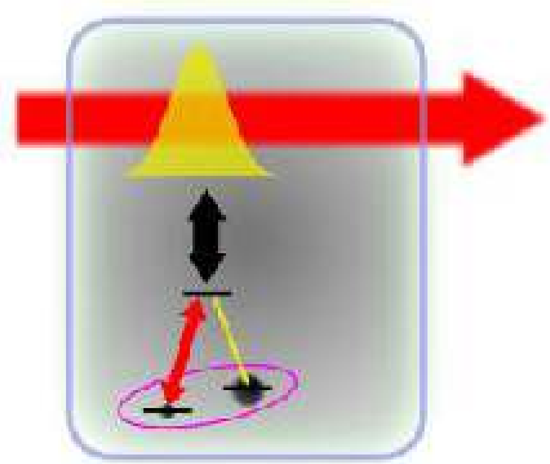
Slowing down the light pulse

For QIPA2013 participants and their internal use.



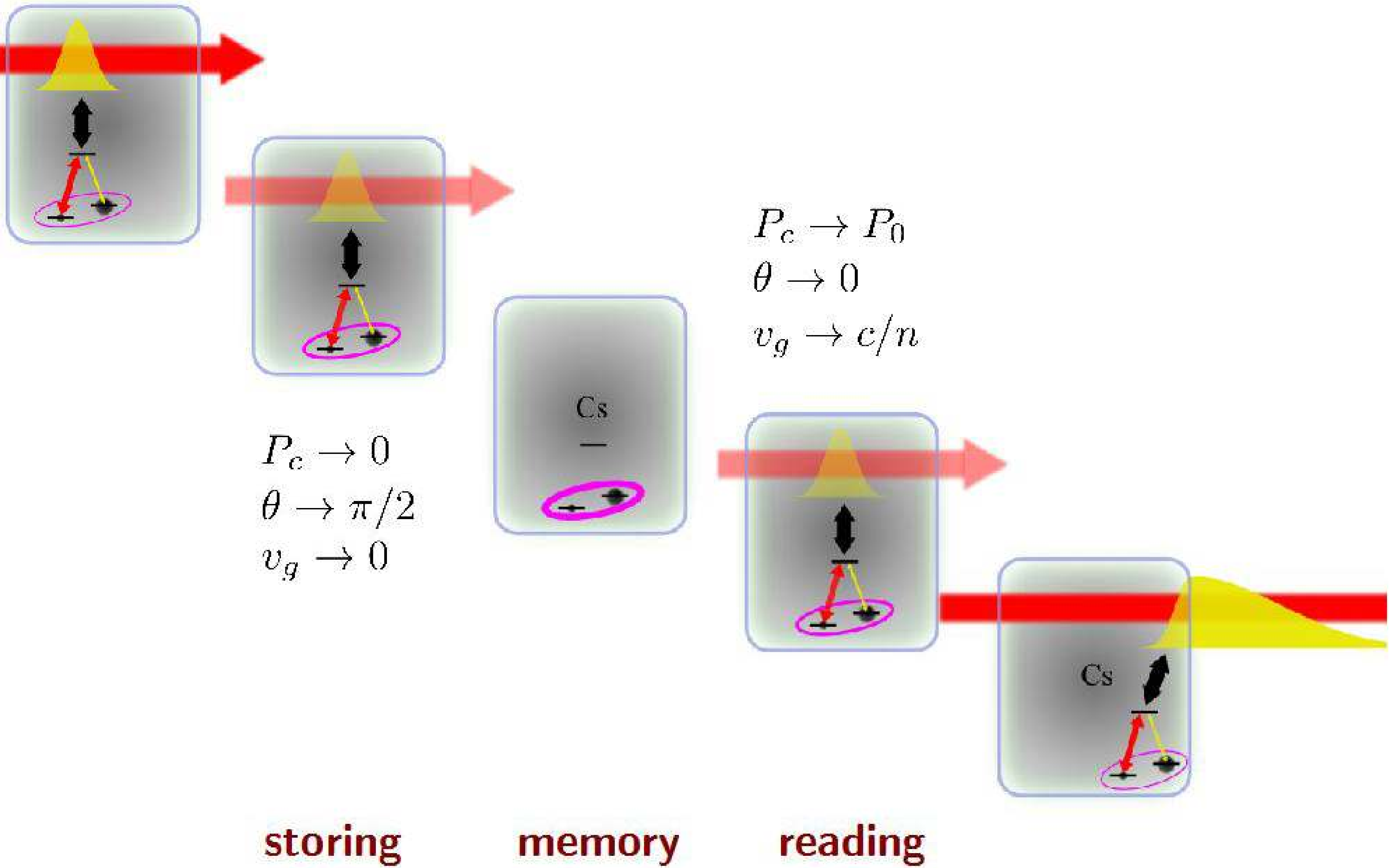
free propagation

slow light



... and storing it

For QIPA2013 participants and their internal use.

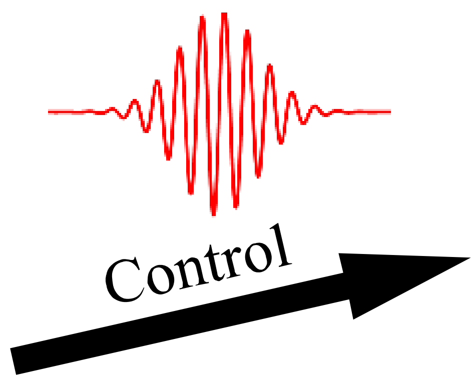


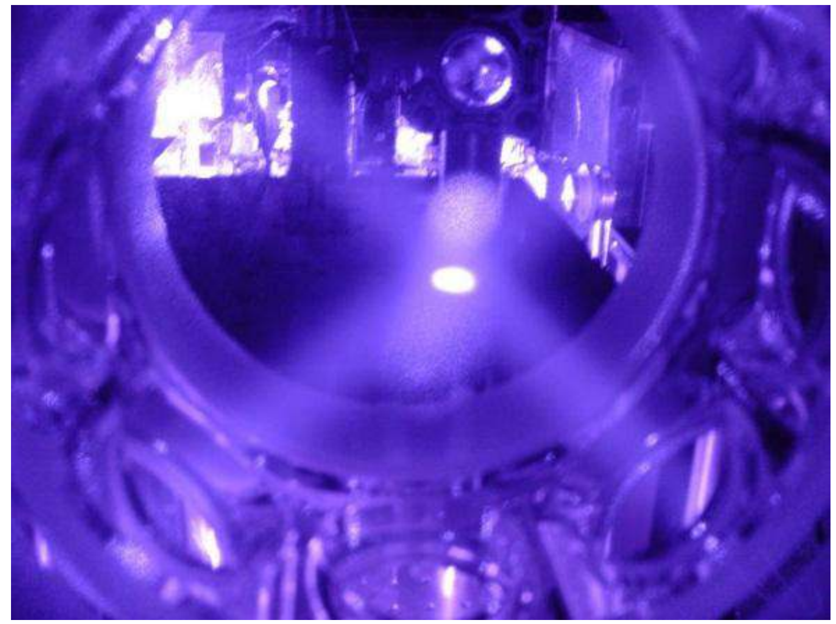
Memory measurement

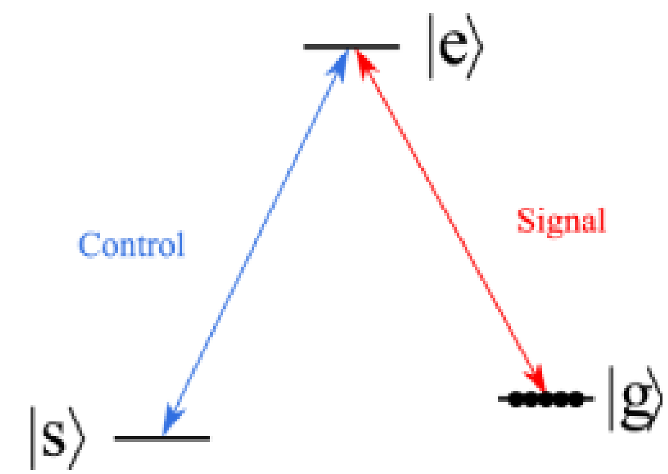
For QIPA2013 participants and their internal use.

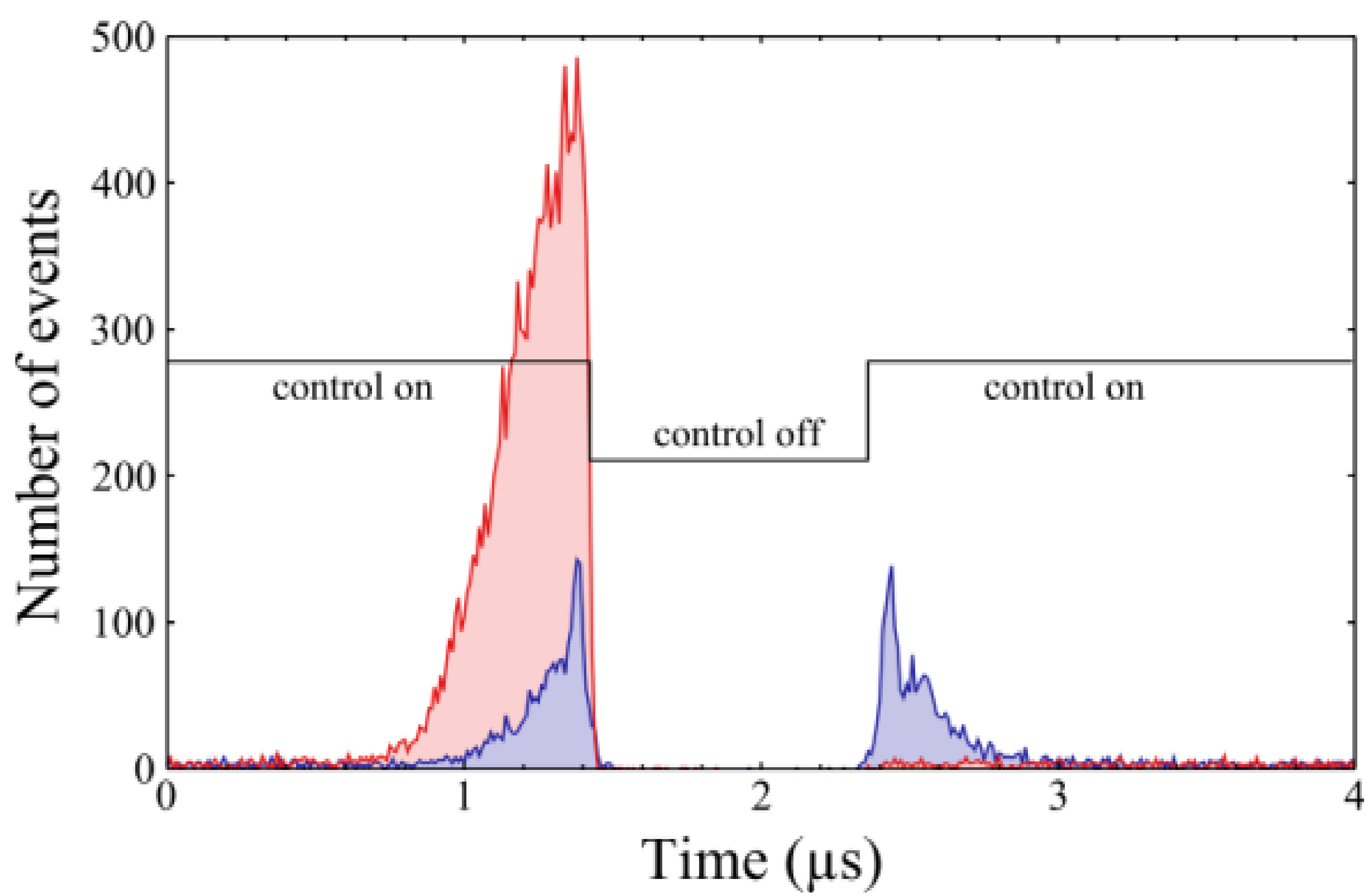
Signal pulse,

< 1 photon



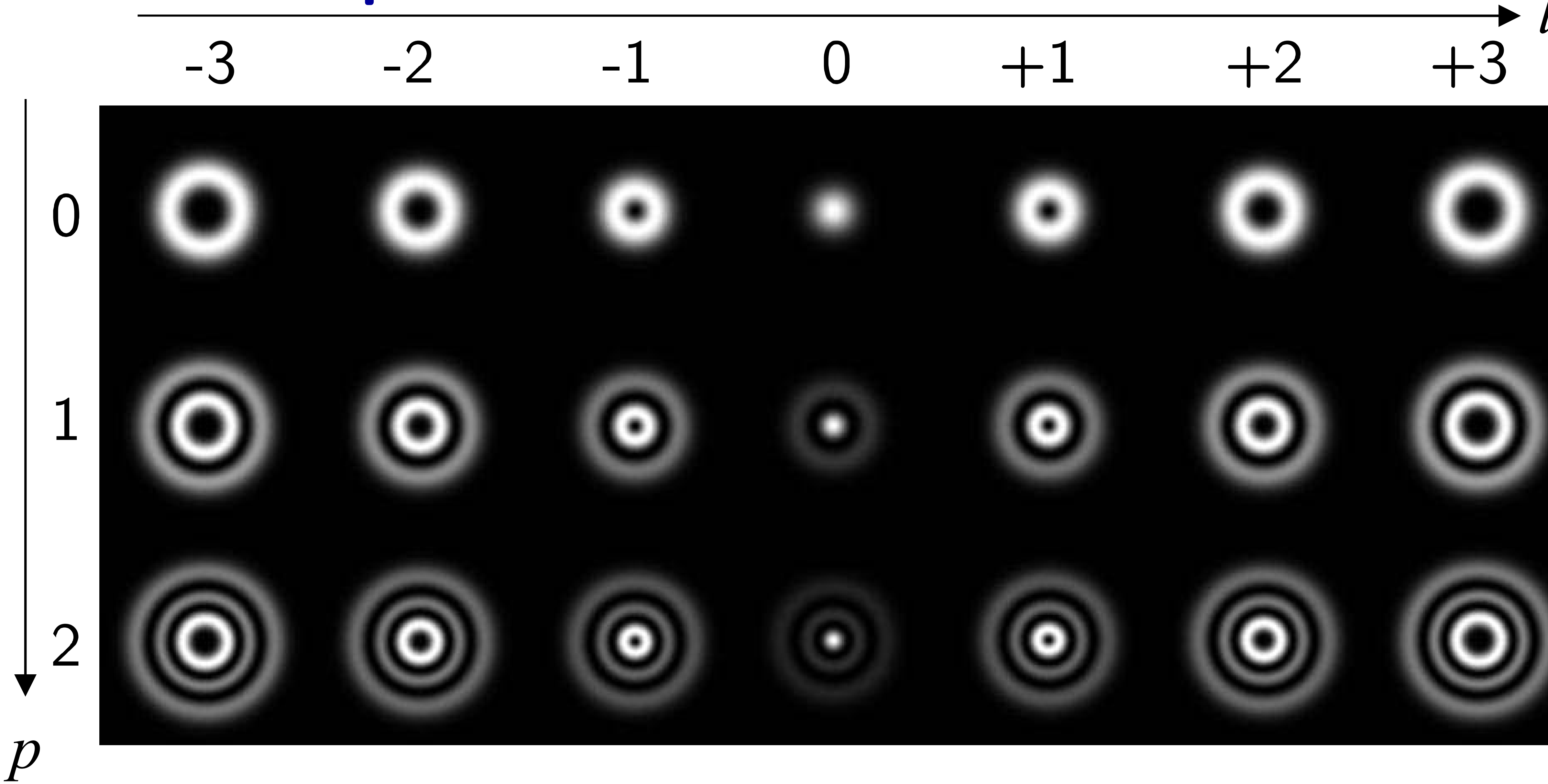






Laguerre-Gaussian modes

A basis for spatial modes ...



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$$\mathrm{LG}_p^l = E_0 \frac{w_0}{w(z)} e^{-\left(\frac{r}{w(z)}\right)^2} e^{-ik\frac{r^2}{2R(z)}} \left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|} e^{il\phi} \mathrm{L}_p^{|l|}\left(\frac{2r^2}{w(z)^2}\right) e^{i(2p+|l|+1)\zeta(z)}$$

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Laguerre-Gaussian modes

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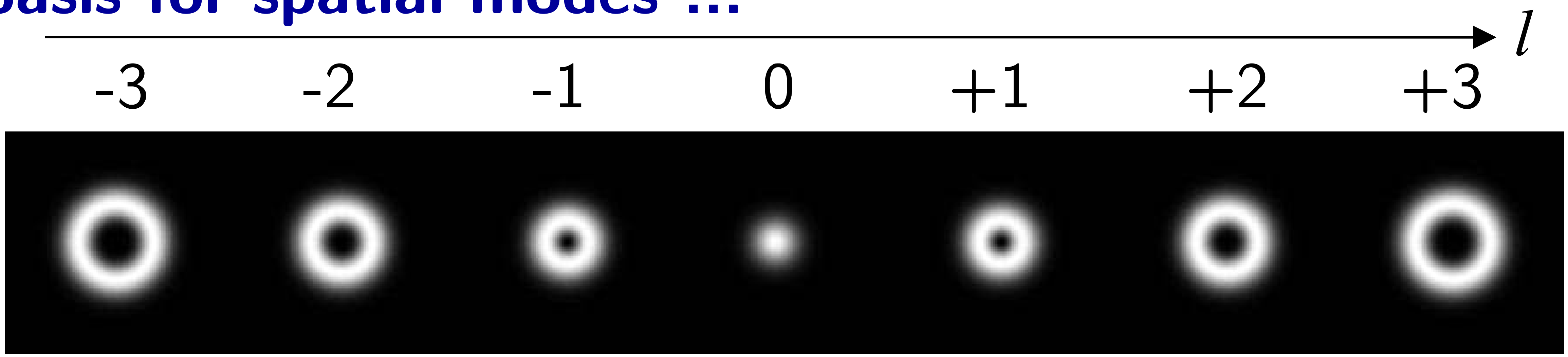
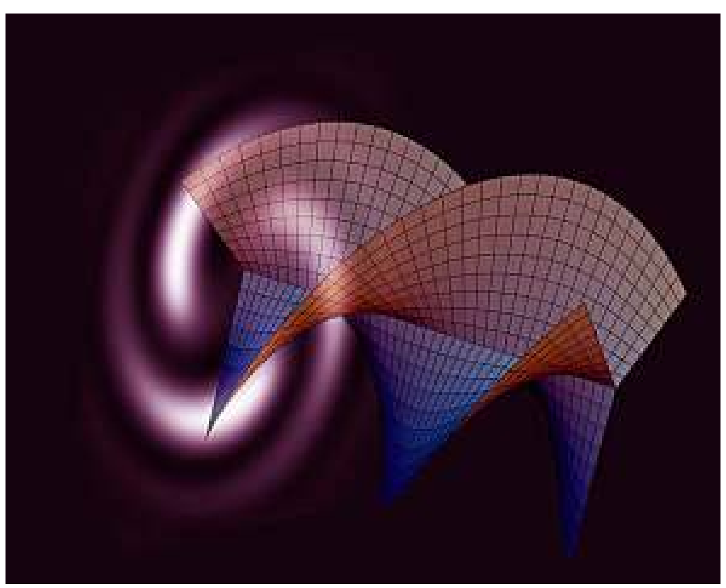
A basis for spatial modes ...



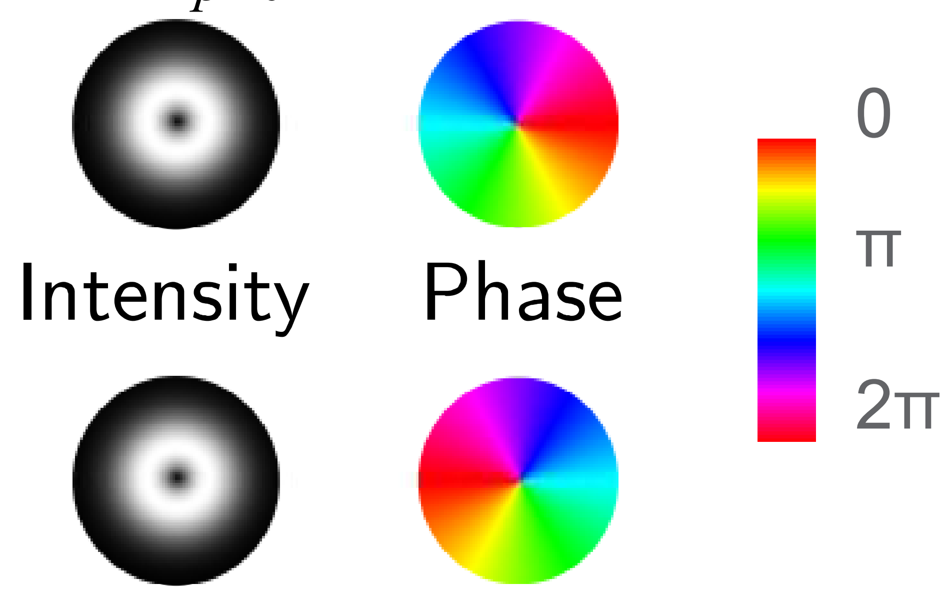
... carrying orbital angular momentum



(picture from M. Padgett)

$$\mathrm{LG}_{p=0}^{l=+3}$$

$$\mathrm{LG}_{p=0}^{l=+1} = \mathrm{LG}^{+1} = \mathrm{R}$$



$$\mathrm{LG}_{p=0}^{l=-1} = \mathrm{LG}^{-1} = \mathrm{L}$$

Single photons with OAM

For QIPA2013 participants and their internal use.

- Each photon carries this orbital angular momentum of $l \times \hbar$
  Mair *et al.*, Nature **412**, 313 (2001)

- How much information can a single photon carry?
  - Polarization states: e.g. H, V => 1 qubit
  - OAM: $l =$ ... -3, -2, -1, 0, +1, +2, +3, ... => $\log_2 n$ qubit
    infinite-dimensional Hilbert space for information encoding
  - Potential use in quantum information science, e.g.:
    Langford *et al.*, Phys. Rev. Lett. **93**, 040501 (2005): quantum bit commitment
    Molina-Terriza *et al.*, Phys. Rev. Lett. **94**, 040501 (2005): quantum coin tossing
    Dada *et al.*, Nature Phys. **7**, 677 (2011): high-dimensional entanglement

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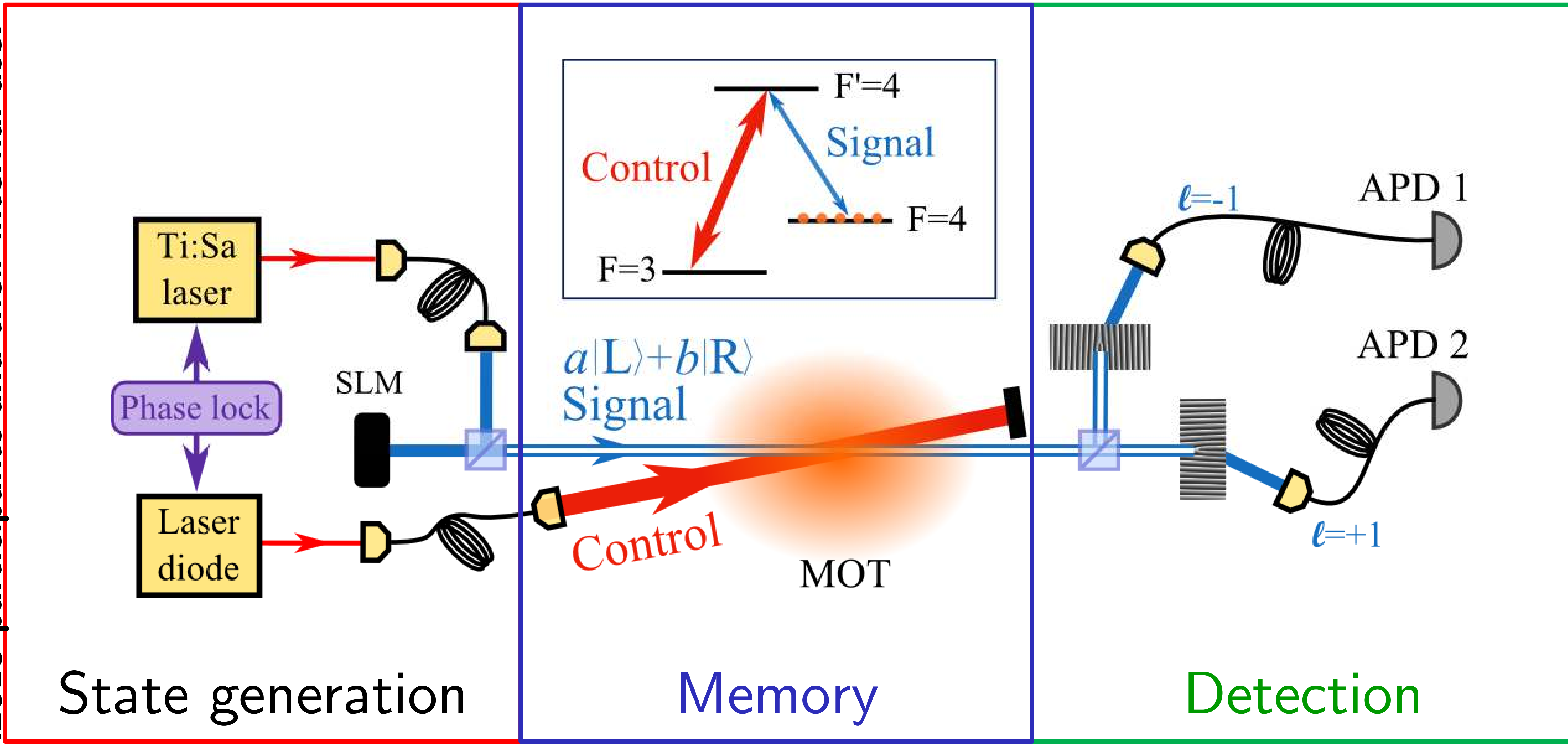
- OAM-light-matter interactions, but no reversible qubit storage yet:
  Inoue *et al.*, Phys. Rev. A **74**, 053809 (2006) (DLCZ entanglement)
  Pugatch *et al.*, Phys. Rev. Lett. **98**, 203601 (2007) (bright light)
  Moretti *et al.*, Phys. Rev. A **79**, 023825 (2009) (bright light)
  Ding *et al.*, arXiv e-print 1305.2675 (2013) (single photon level)

Experimental setup



For QIPA2013 participants and their internal use.

Experimental setup

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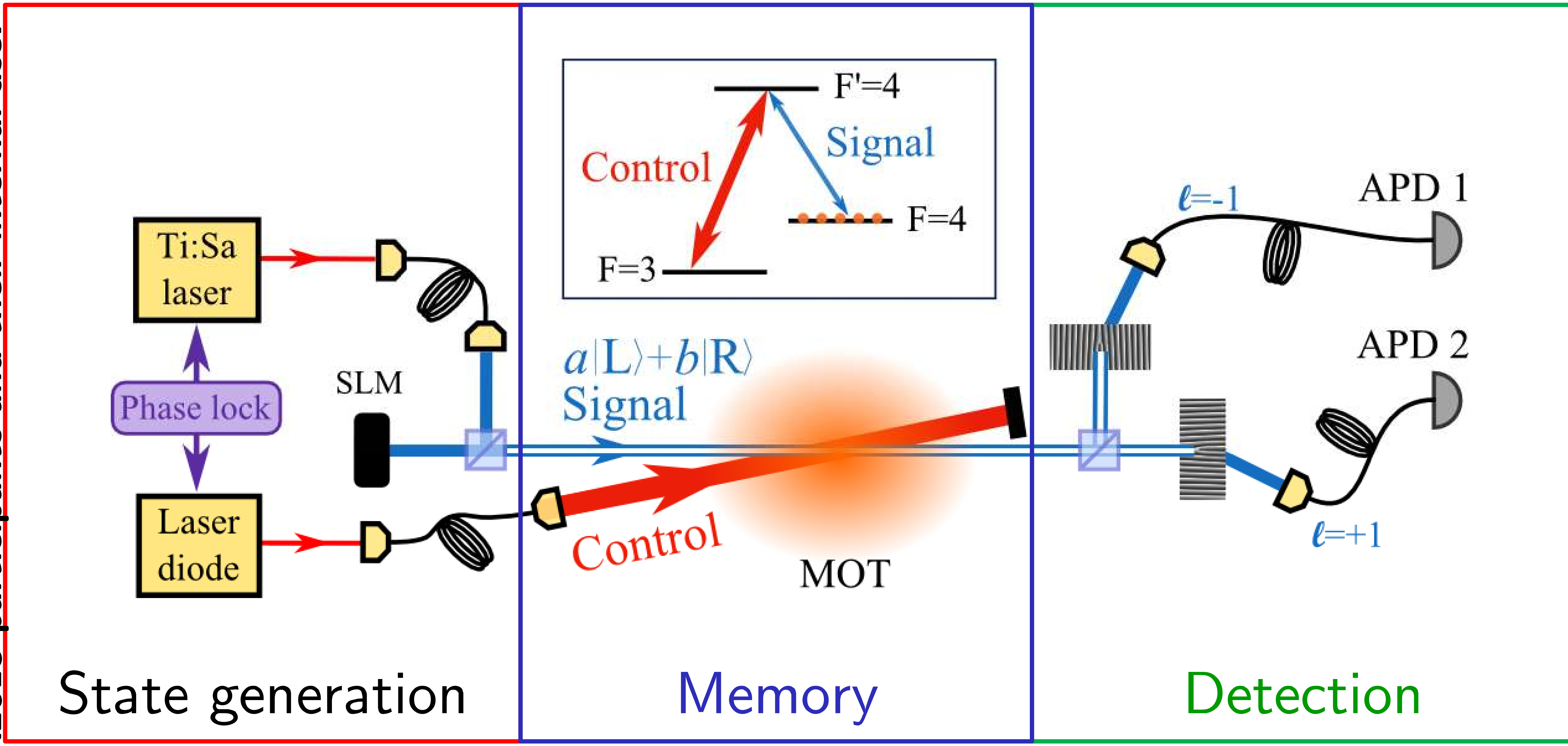
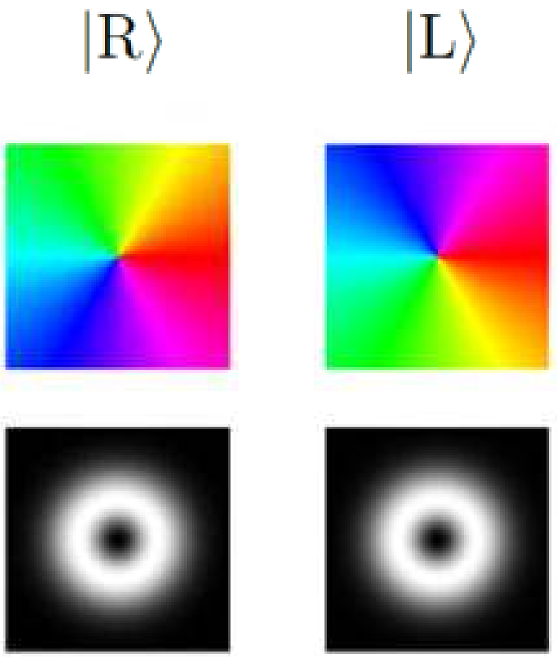


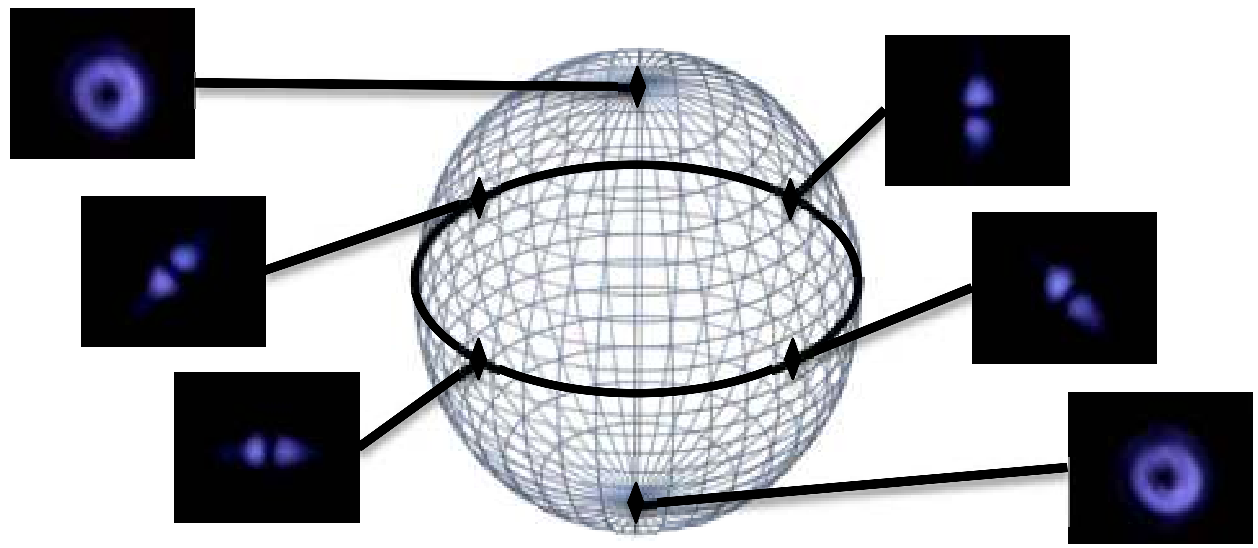
- Phase and frequency locking between Ti:Sapphire laser and external-cavity diode laser at 9.2 GHz
- Signal: very weak coherent pulse (< 1 photon per pulse)

Single photons with OAM

For QIPA2013 participants and their internal use.

- We consider the basis states |R> and |L>:





Bloch sphere of superpositions

$$|\Psi\rangle = \alpha|R\rangle + \beta|L\rangle$$

Single photons with OAM

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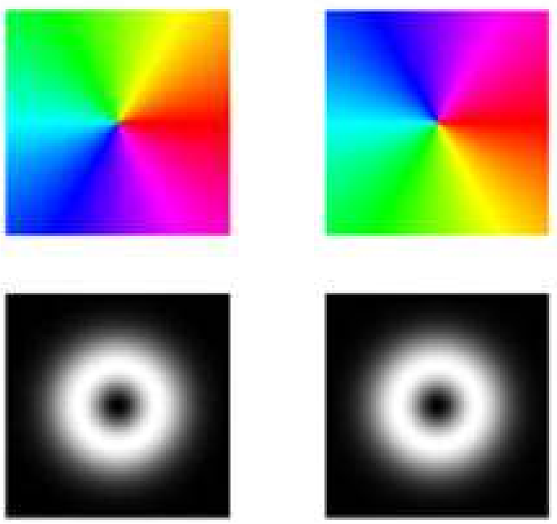
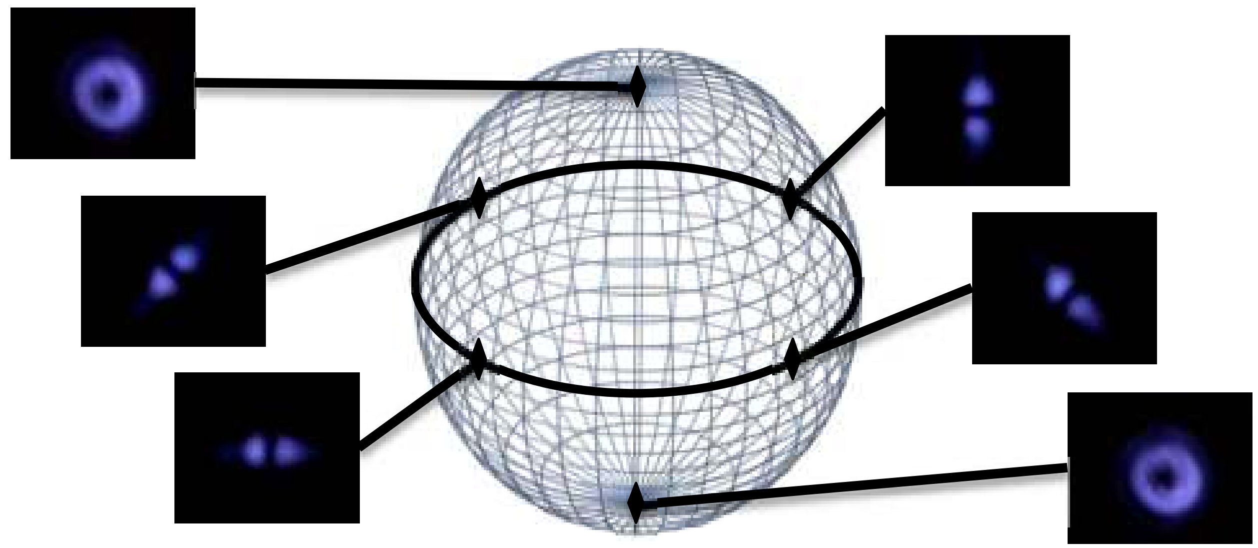
- We consider the basis states |R> and |L>:

$|\mathrm{R}\rangle$ $|\mathrm{L}\rangle$

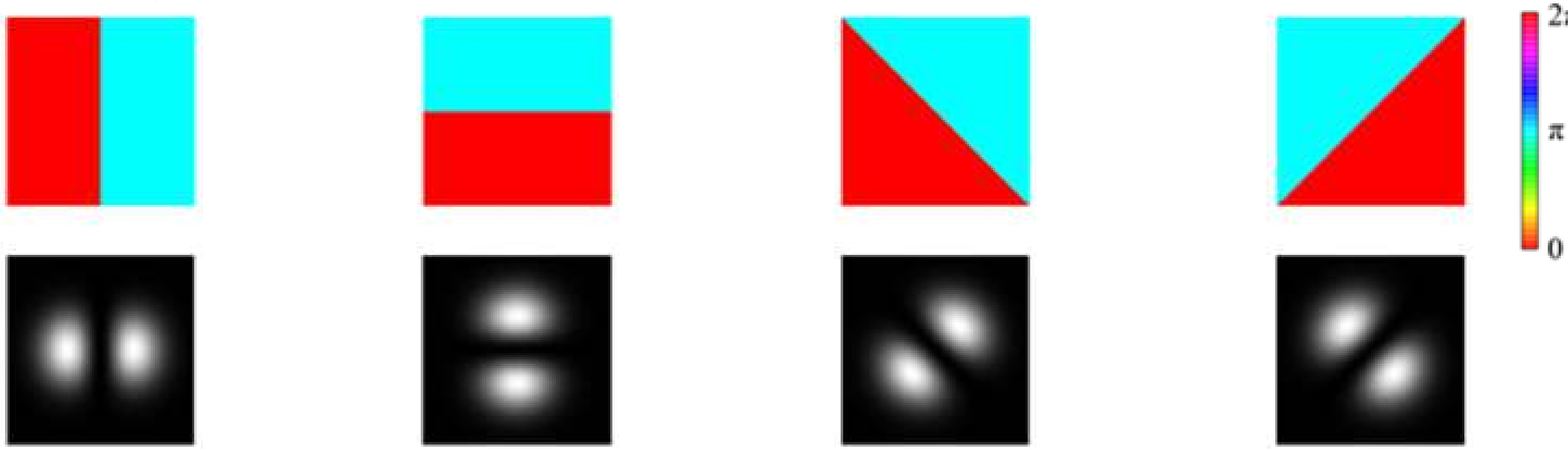




Bloch sphere of superpositions $|\Psi\rangle = \alpha|R\rangle + \beta|L\rangle$

•Equal-amplitude superpositions: |H>, |V>, |D>, and |A>:

$$|\mathrm{H}\rangle = \frac{|\mathrm{R}\rangle + |\mathrm{L}\rangle}{\sqrt{2}} \quad |\mathrm{V}\rangle = \frac{|\mathrm{R}\rangle - |\mathrm{L}\rangle}{\sqrt{2}} \quad |\mathrm{D}\rangle = \frac{|\mathrm{R}\rangle + i\,|\mathrm{L}\rangle}{\sqrt{2}} \quad |\mathrm{A}\rangle = \frac{|\mathrm{R}\rangle - i\,|\mathrm{L}\rangle}{\sqrt{2}}$$



Generation of "twisted photons"

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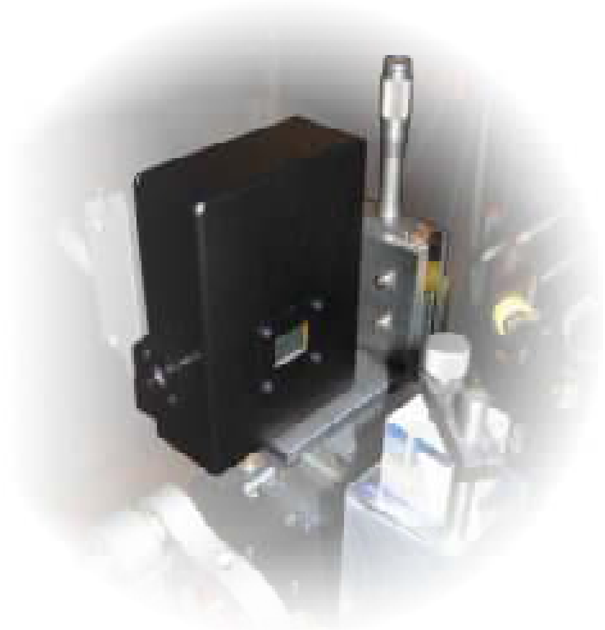
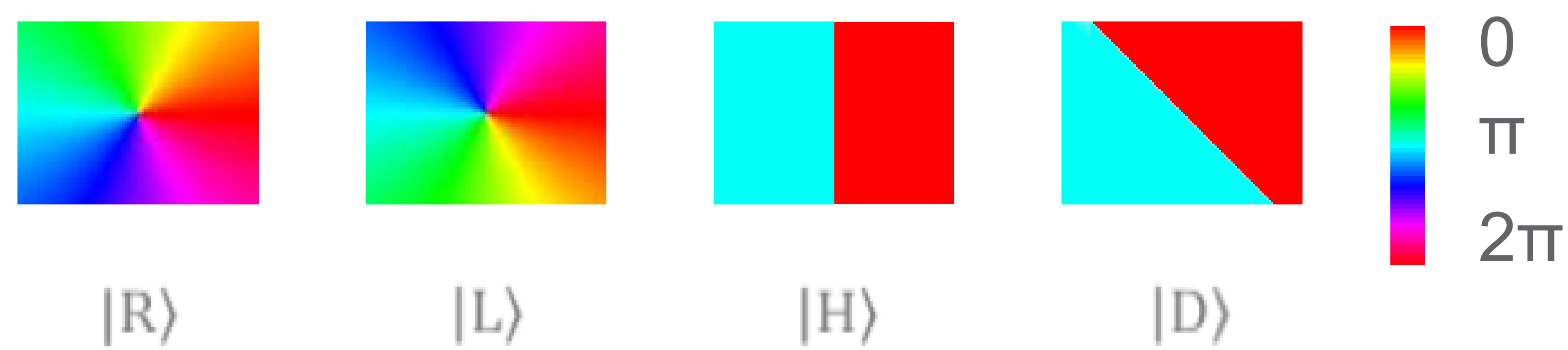


SLM and assistance provided by M. Padgett and D. Tasca.

Spatial light modulator (SLM):

- Imposing a programmable phase from point to point ("LCD for the phase")
- Desired phase patterns:



Results not perfect:

- 79% in the desired LG mode, 64% for HG modes due to intrinsic mode overlap
- The rest (higher order radially excited modes) are lost for detection.

Detection in the single-photon regime

- Bright light & basis state: imaging and interferogramm

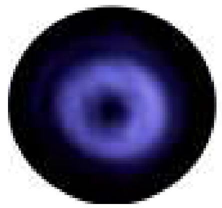
 +  => LG^{+1}

Image Interference

For QIPA2013 participants and their internal use.

Detection in the single-photon regime

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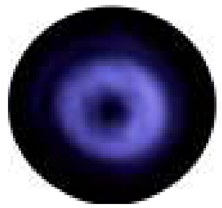
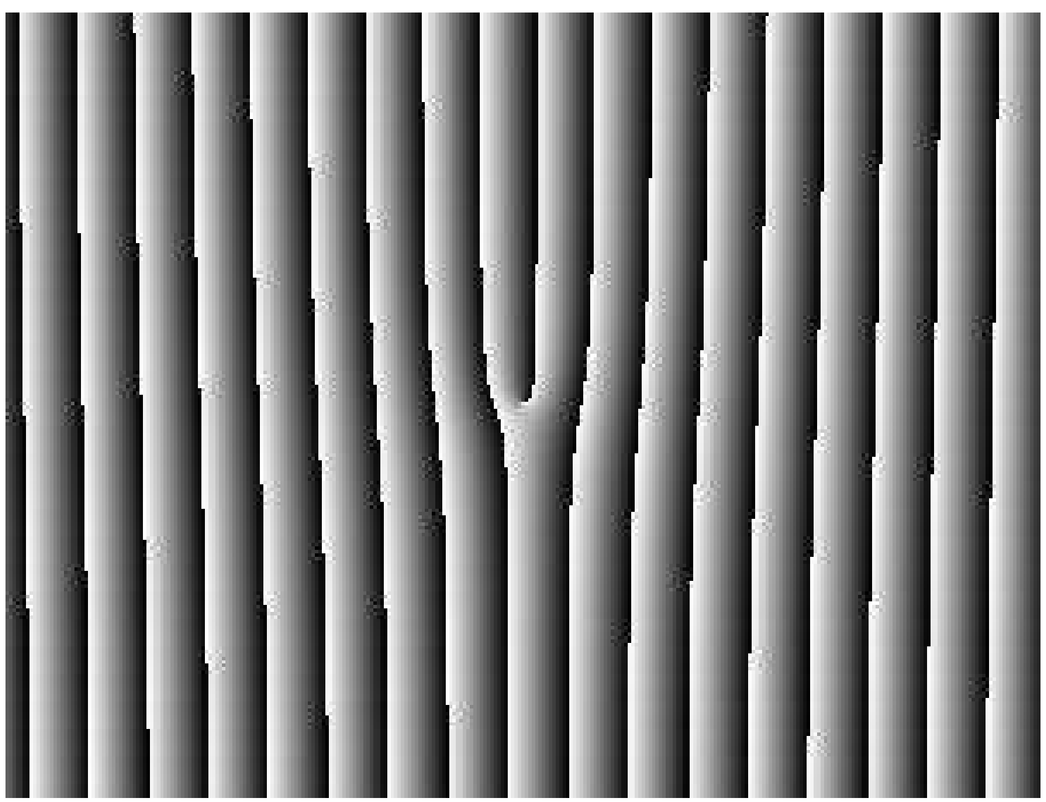
 +  => LG^{+1}

- Single photon regime: mode transformation & filtering



Phase holograms :

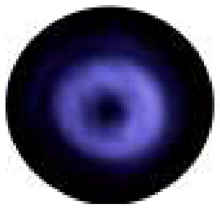
- Diffract the beam
- Add (or subtract) one OAM unit

  ➔ mode conversion

Detection in the single-photon regime

For QIPA2013 participants and their internal use.

- Bright light & basis state: imaging and interferogramm

 +  => LG^{+1}

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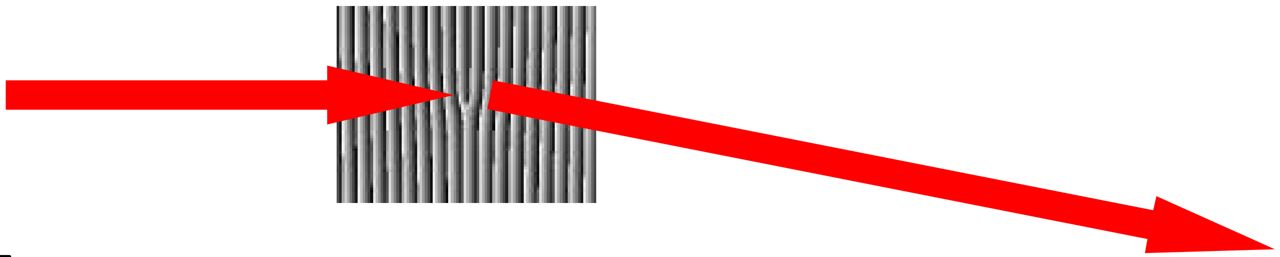
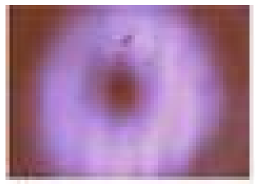
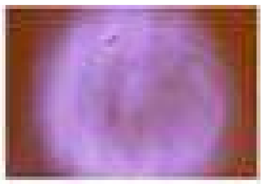


$|l=+1\rangle$ $|l=+2\rangle$

$|l=-1\rangle$ $|l=0\rangle$

80% diffraction efficiency

Detection in the single-photon regime

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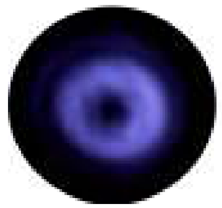 +  => LG^{+1}

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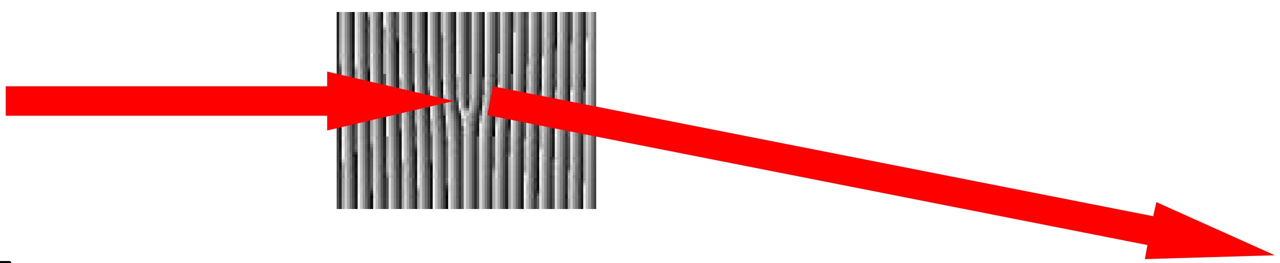

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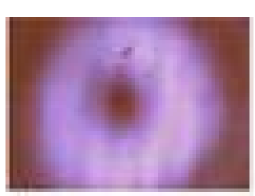
 

Fiber: single mode selection

80% diffraction efficiency

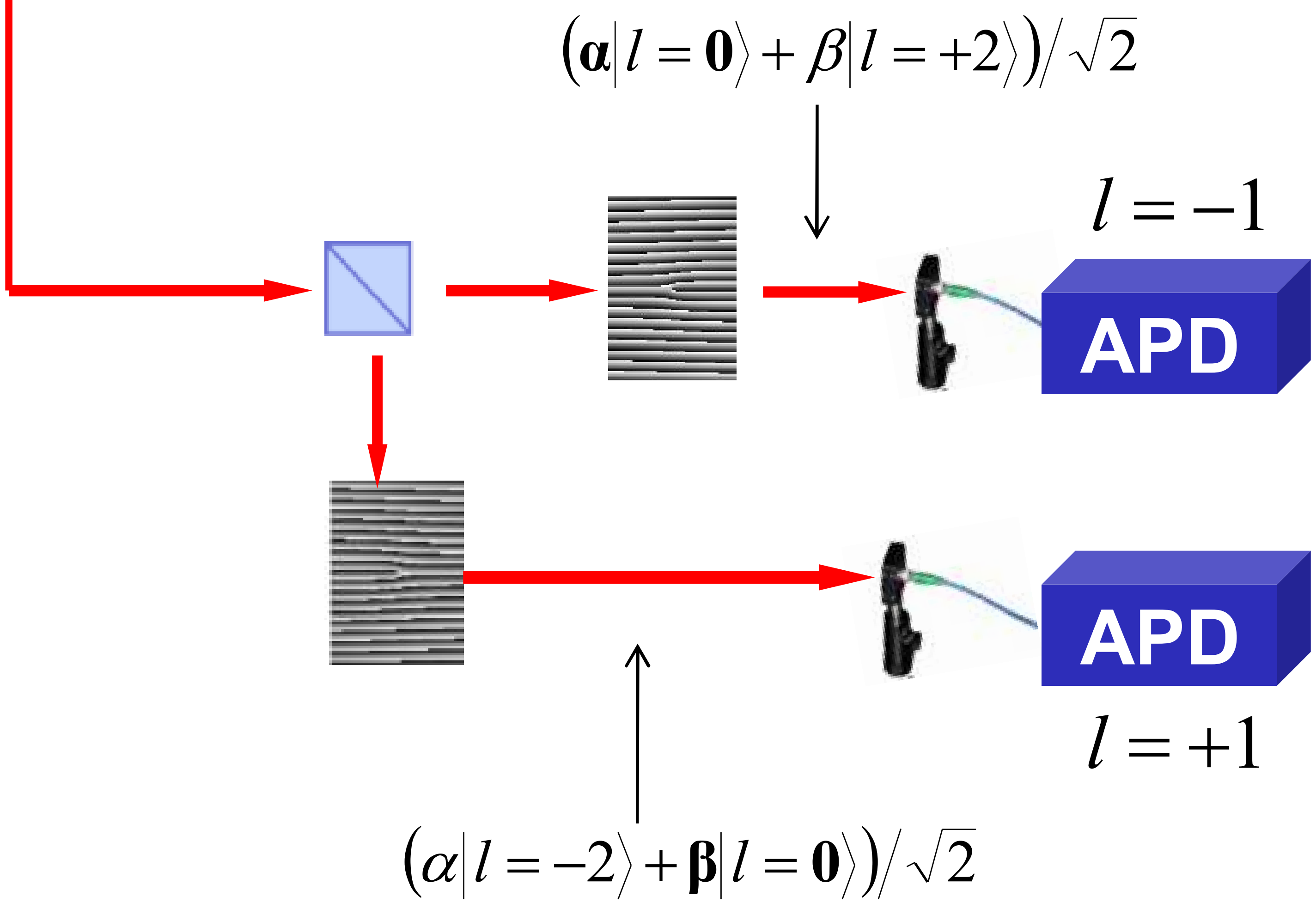
80% coupling, < 1% cross talk

For QIPA2013 participants and their internal use.

Detection setup

Input mode
from memory

$$|\Psi\rangle = \alpha|L\rangle + \beta|R\rangle$$



Count rate

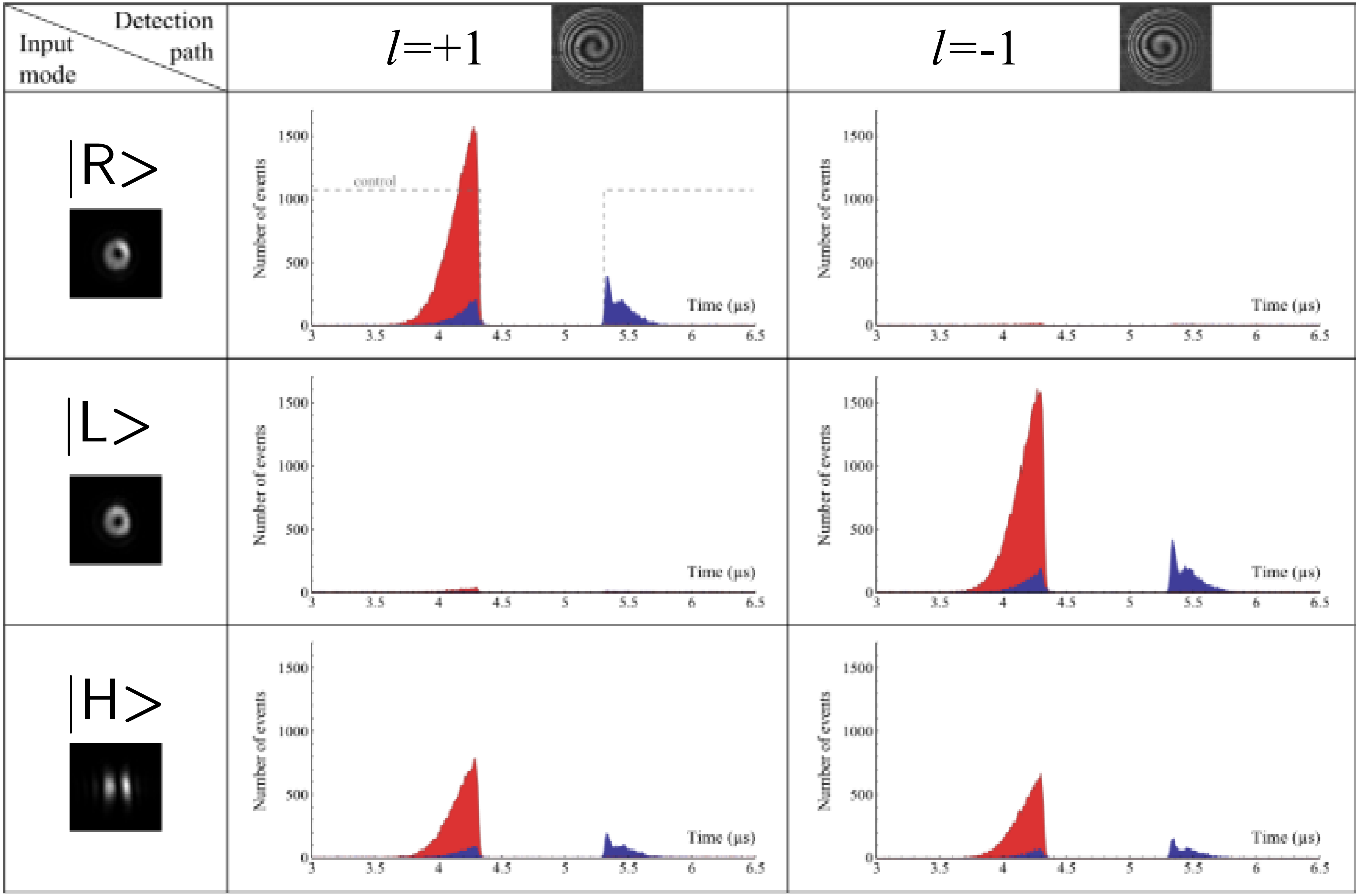
$|\alpha|^2/2$

$|\beta|^2/2$

Forked holograms provided
by A. Zeilinger and R. Fickler.

For QIPA2013 participants and their internal use.

Experimental results



➔ Storage efficiency $\eta = 16 \pm 2\%$

L. Veissier et al., Opt. Lett. **38**, 712 (2013)

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Experimental results

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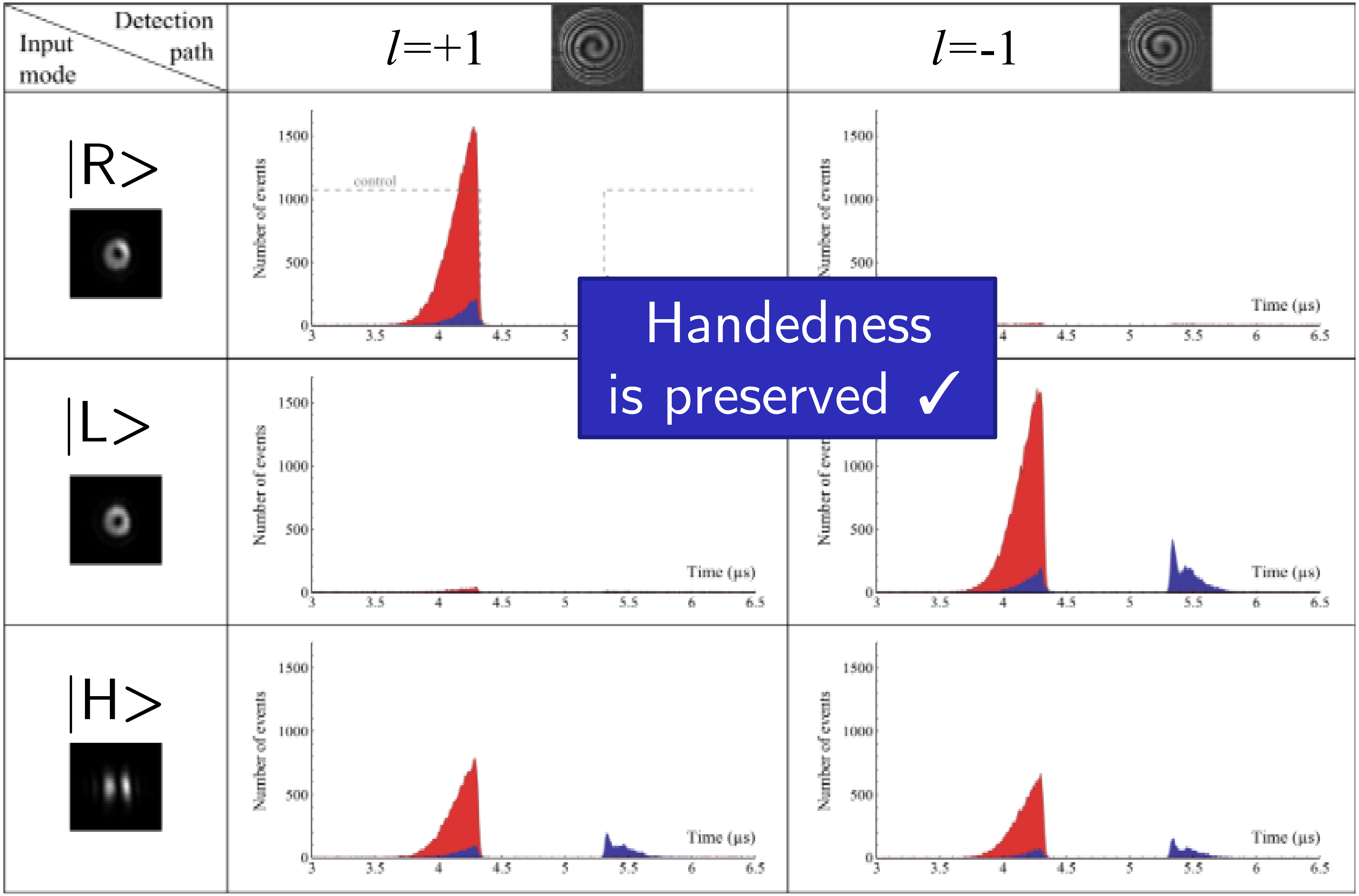

Handedness is preserved ✓

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Experimental results

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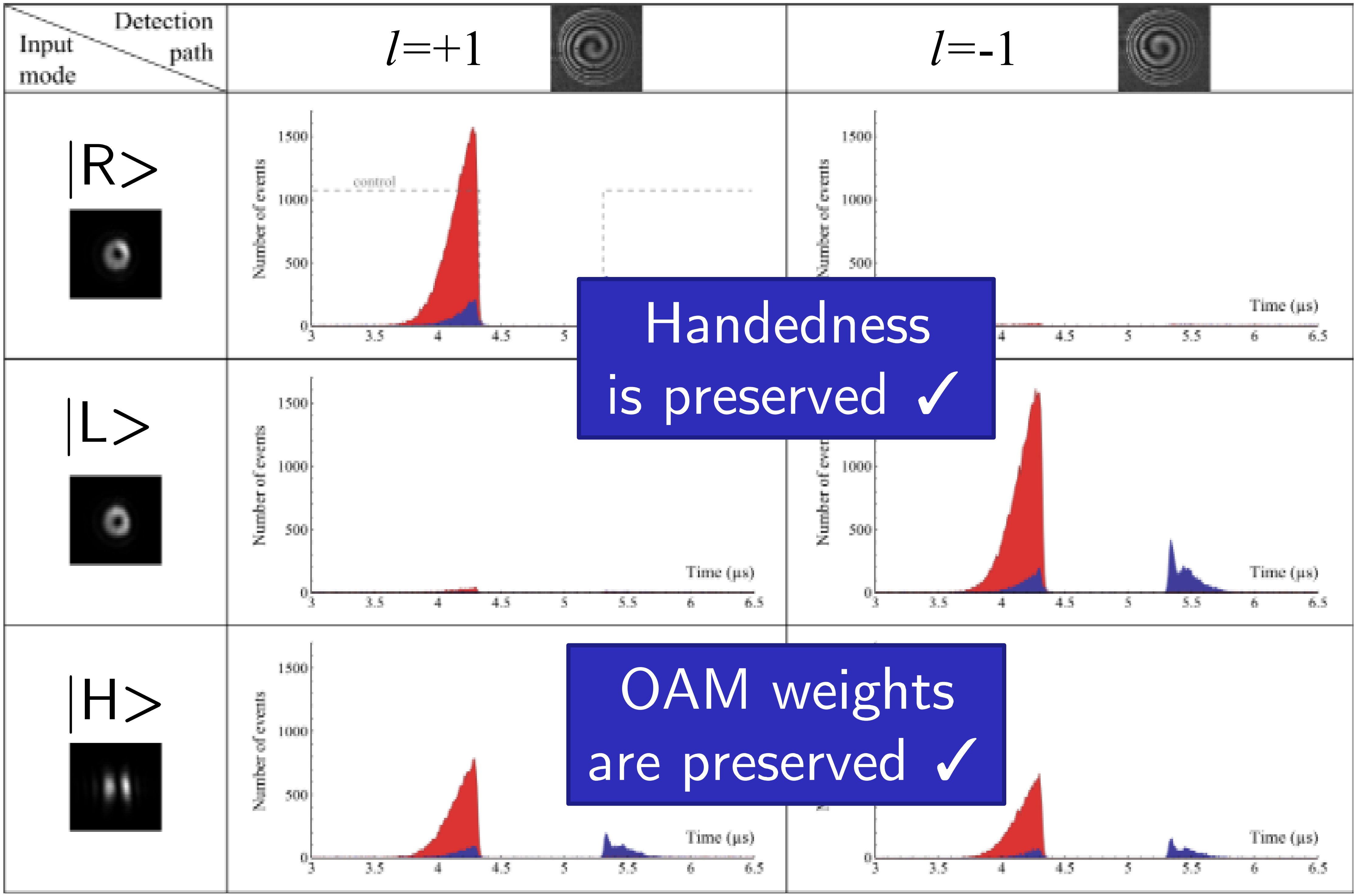

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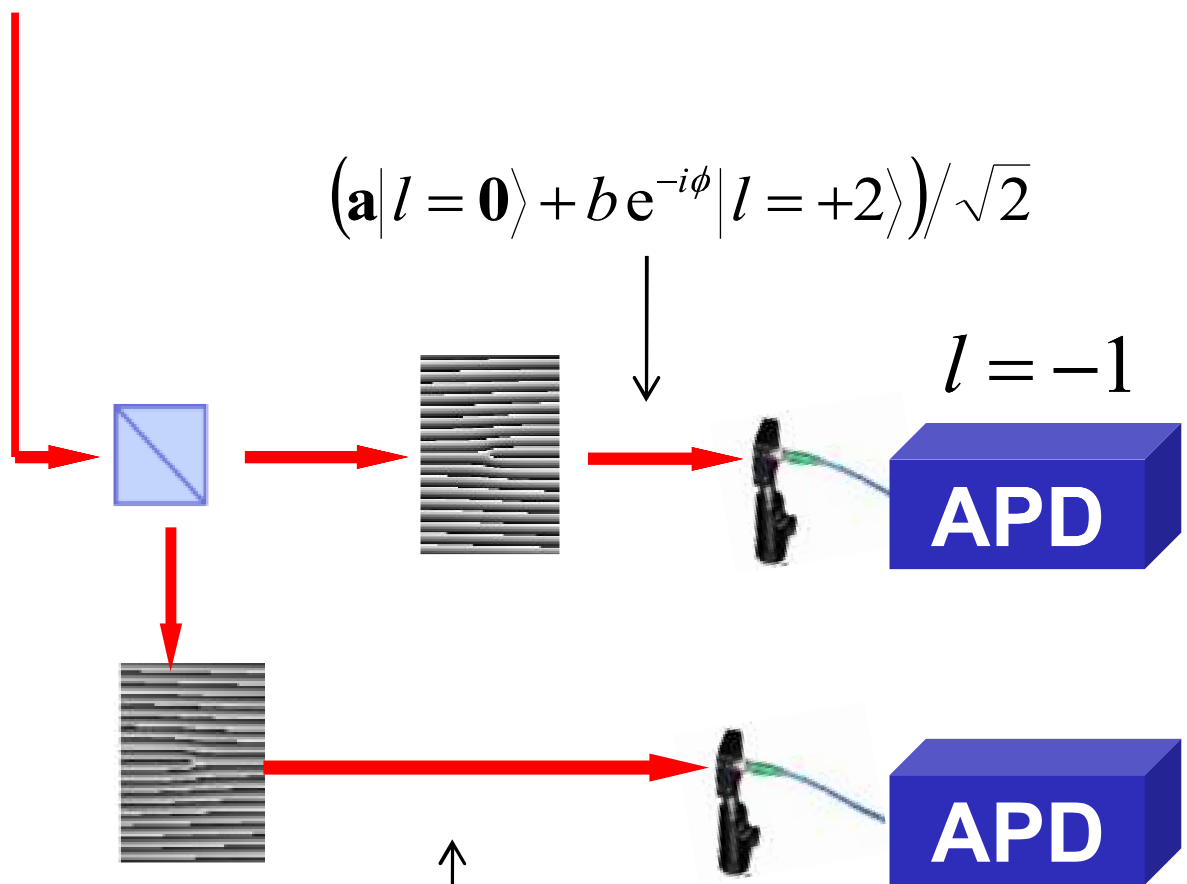
Measuring the coherences

Input mode from memory

$$|\Psi\rangle = a|L\rangle + b\,e^{-i\phi}|R\rangle$$

$$\left(\mathbf{a}|l=\mathbf{0}\rangle + b\,e^{-i\phi}|l=+2\rangle\right)/\sqrt{2}$$



Count rate

$l=-1$: $|a|^2/2$

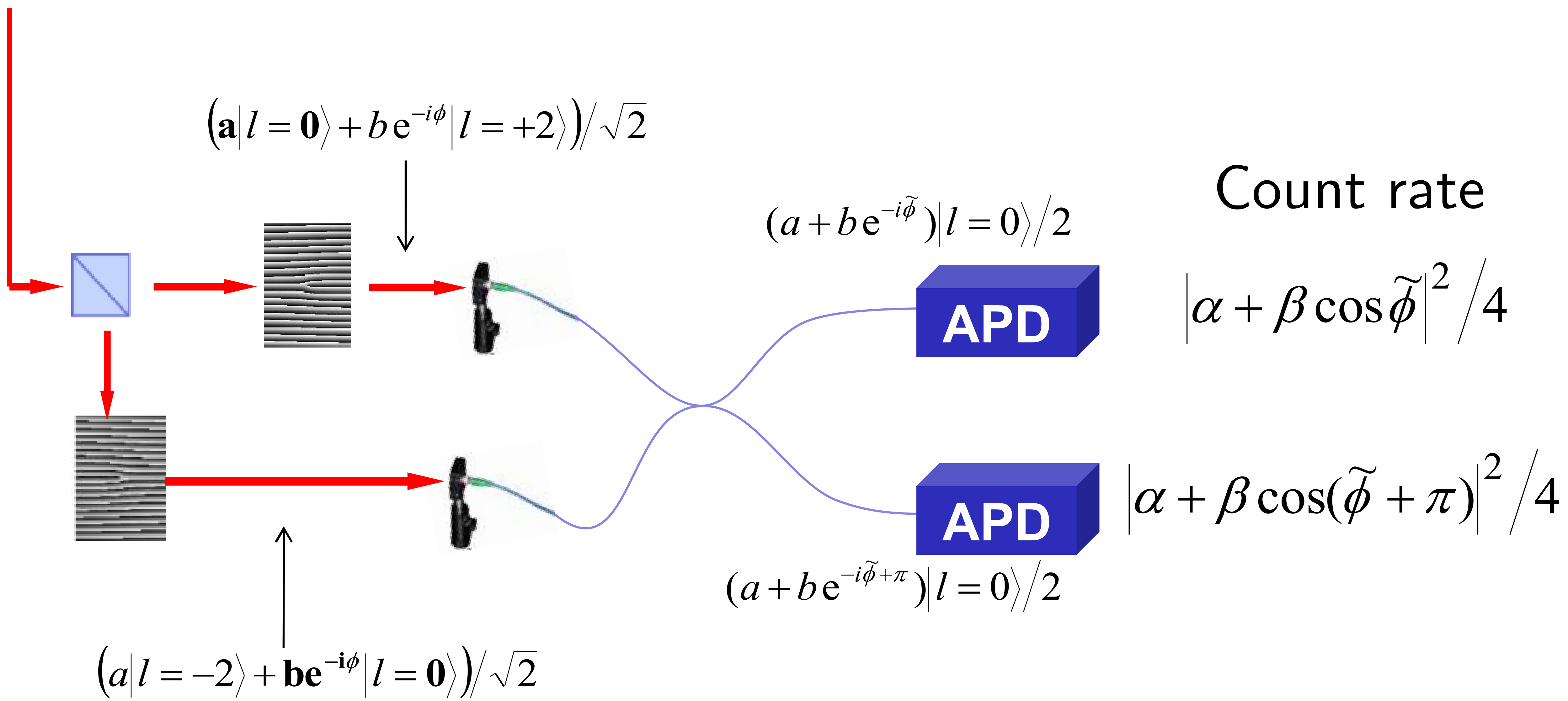
$l=+1$: $|b|^2/2$

$$\left(a|l=-2\rangle + \mathbf{b}e^{-i\phi}|l=\mathbf{0}\rangle\right)/\sqrt{2}$$

For QIPA2013 participants and their internal use.

Measuring the coherences

Input mode from memory $|\Psi\rangle = a|L\rangle + b\,\mathrm{e}^{-i\phi}|R\rangle$



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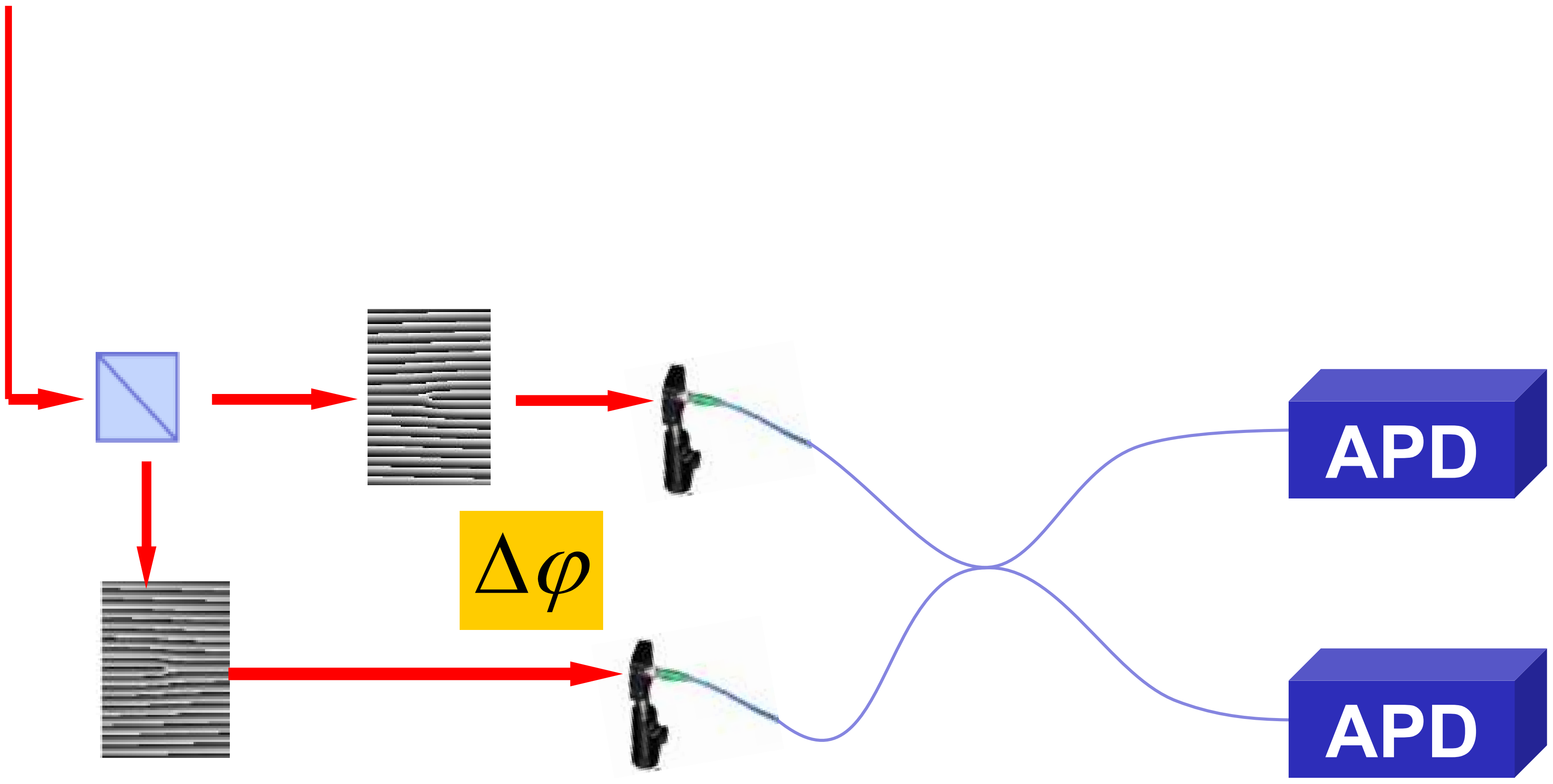

$$|\alpha + \beta\cos\tilde{\phi}|^2/4$$

$$|\alpha + \beta\cos(\tilde{\phi} + \pi)|^2/4$$

$$\tilde{\phi} = \phi + \Delta\varphi$$

Measuring the coherences

For QIPA2013 participants and their internal use.

Input mode from memory

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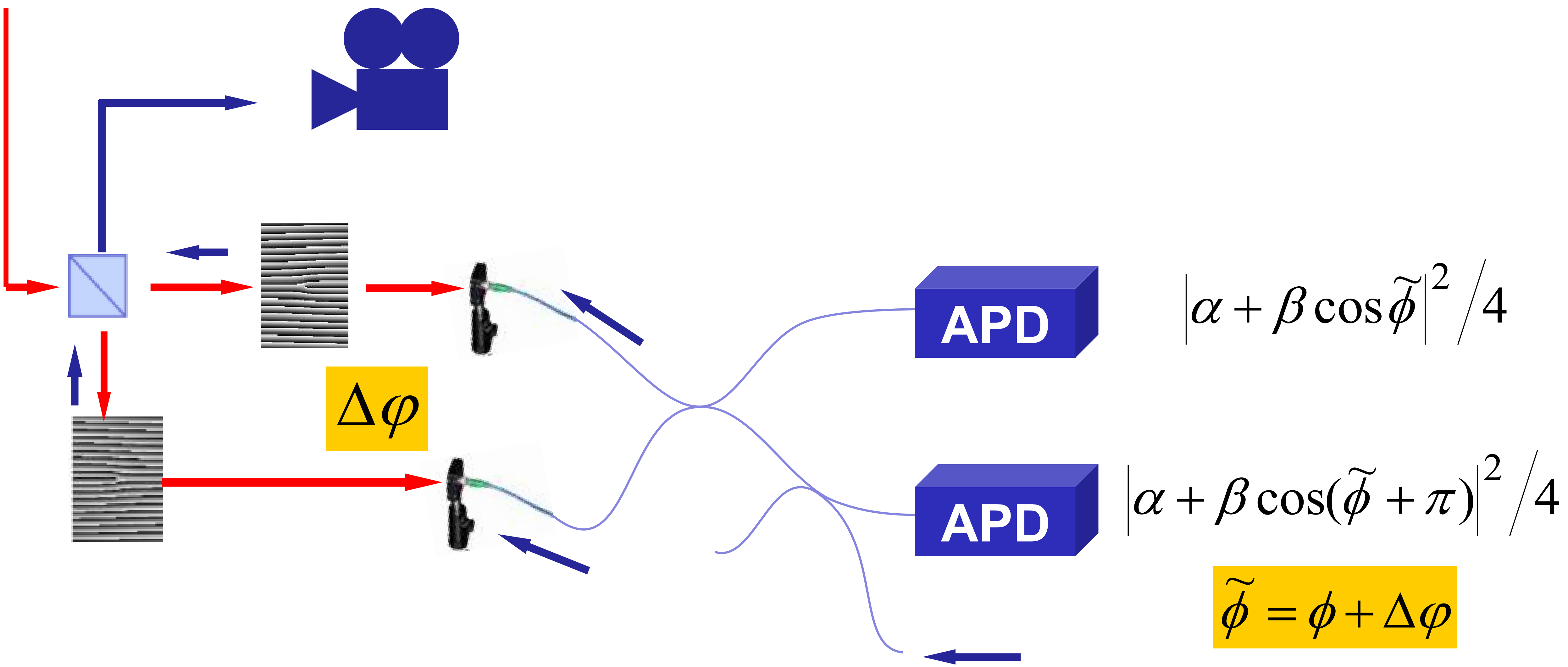
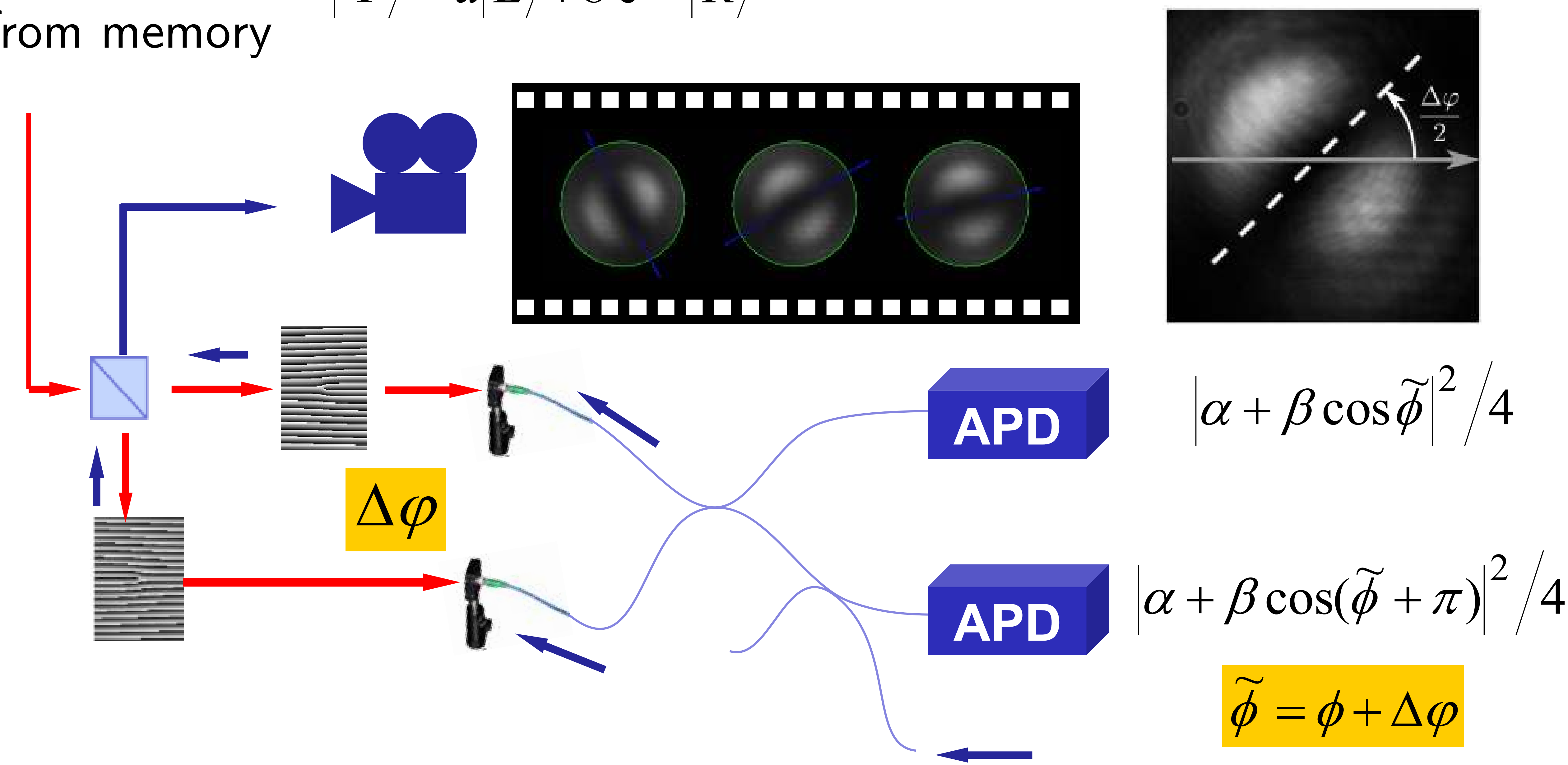


Measuring the coherences

For QIPA2013 participants and their internal use.

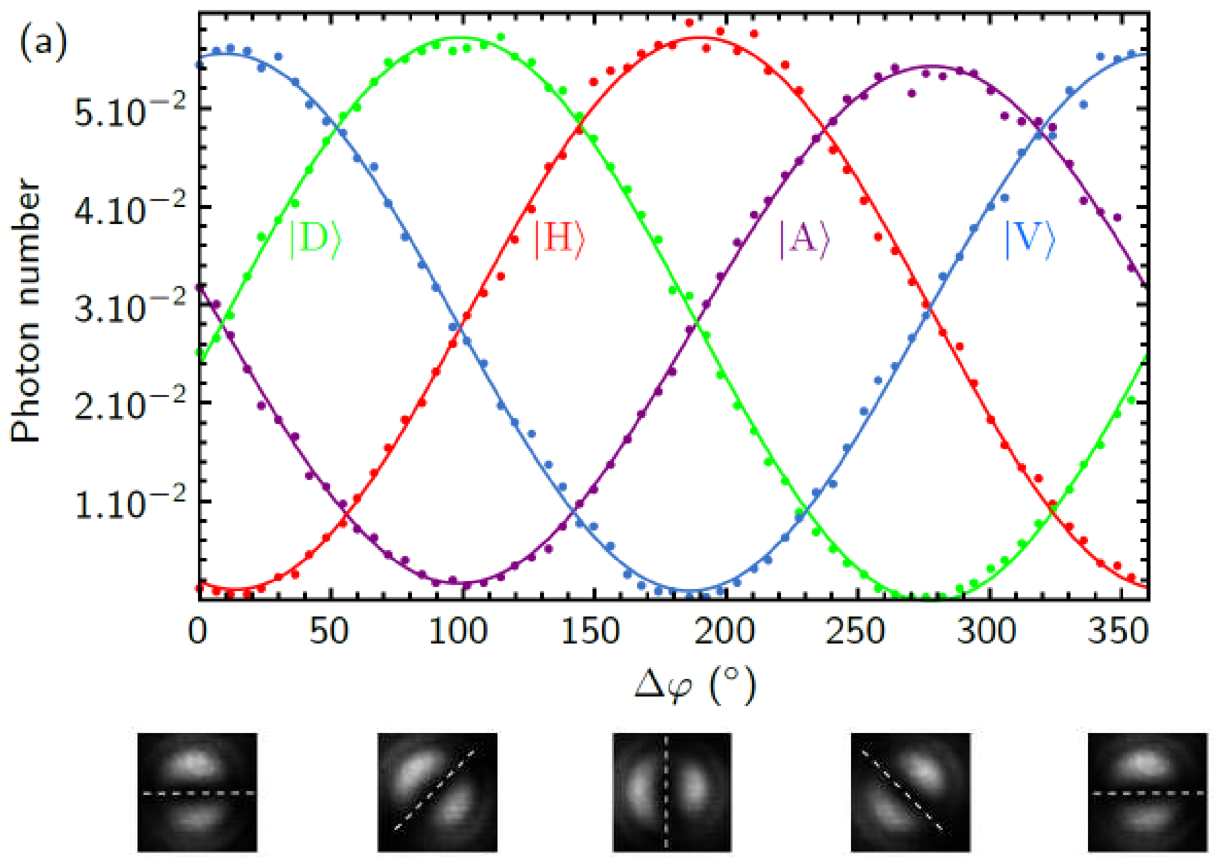
Input mode
from memory

$$|\Psi\rangle = a|L\rangle + b\,e^{-i\phi}|R\rangle$$



- Image every 100 ms, determine interferometer phase
- Timestamp: Correlate with the APD count rates

Interferometer measurements



0.6 photons/pulse

Phase bins of 6°

Average visibility: 95.8%

For QIPA2013 participants and their internal use.

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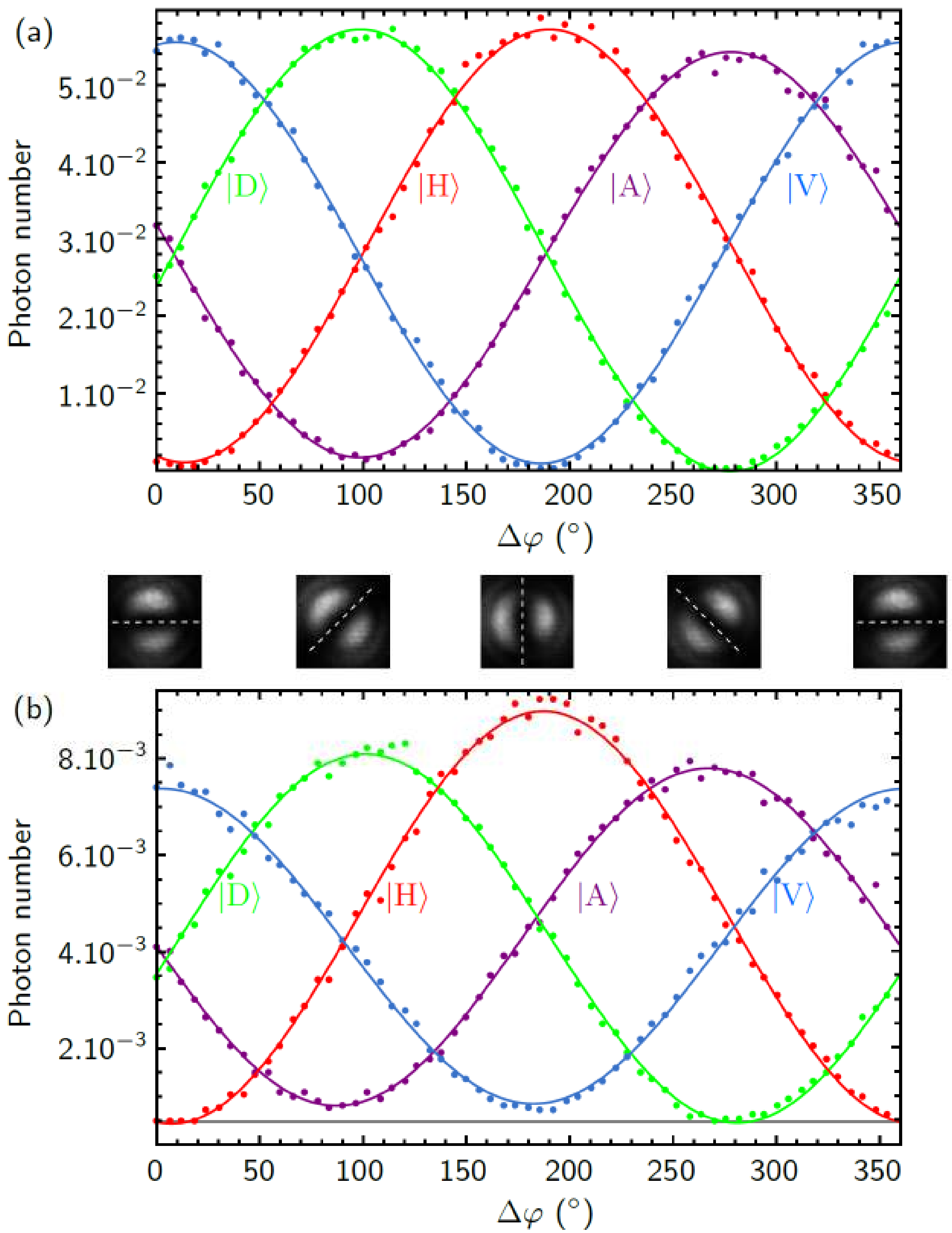

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Average visibility: 85.1%

Background-corrected: 95.7%

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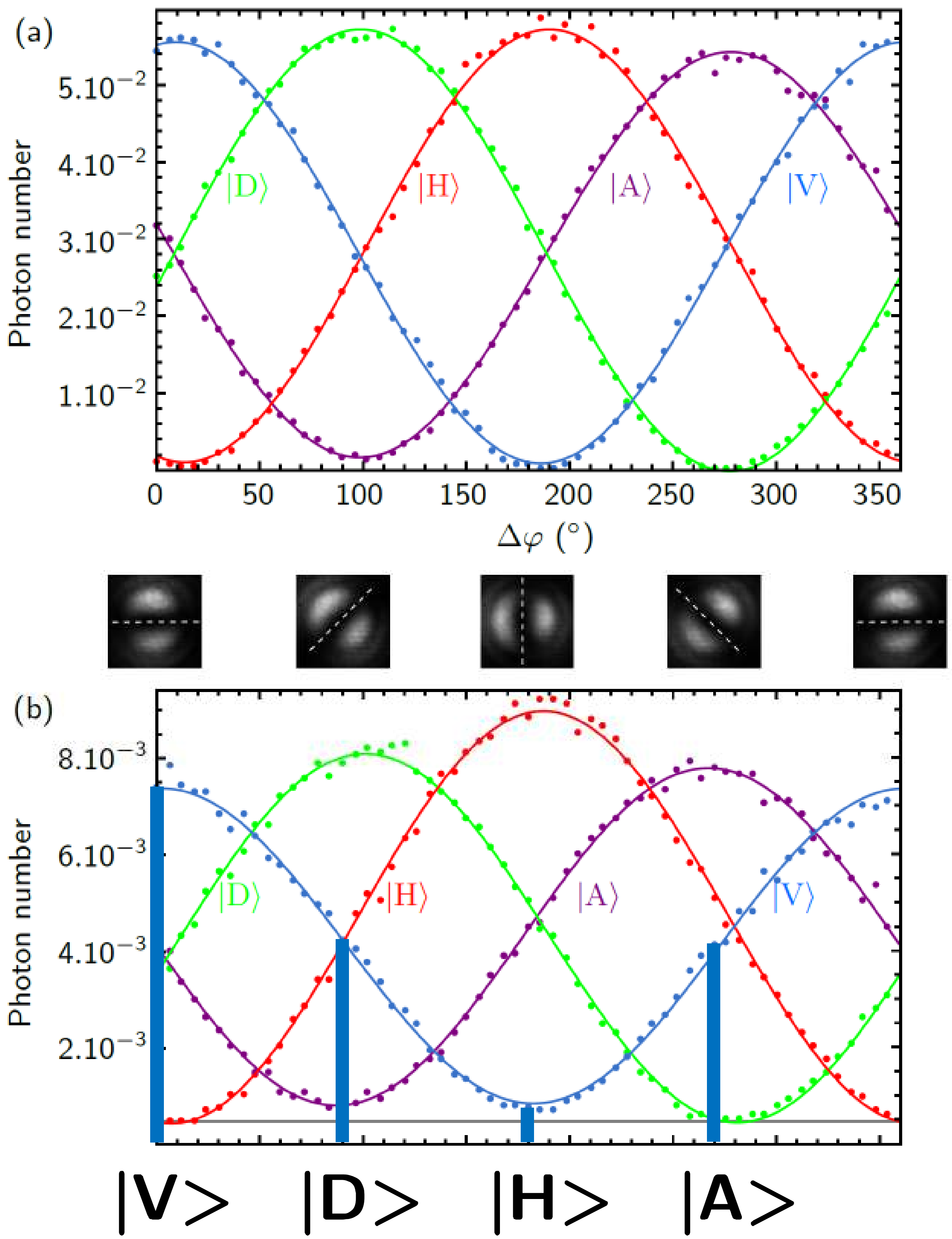

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Quantum state tomography

For QIPA2013 participants and their internal use.

Measurements:

- j=H,V,D,A at the phase

$$\Delta\varphi = \pi - \phi_j^{th}$$

- for j=R,L: no interferometer

p_j relative probability for j

Stokes parameters

$$\begin{cases} S_1 = & (p_{\rm R} - p_{\rm L}) \\ S_2 = & (p_{\rm H} - p_{\rm V}) \\ S_3 = & (p_{\rm D} - p_{\rm A}) \end{cases}$$

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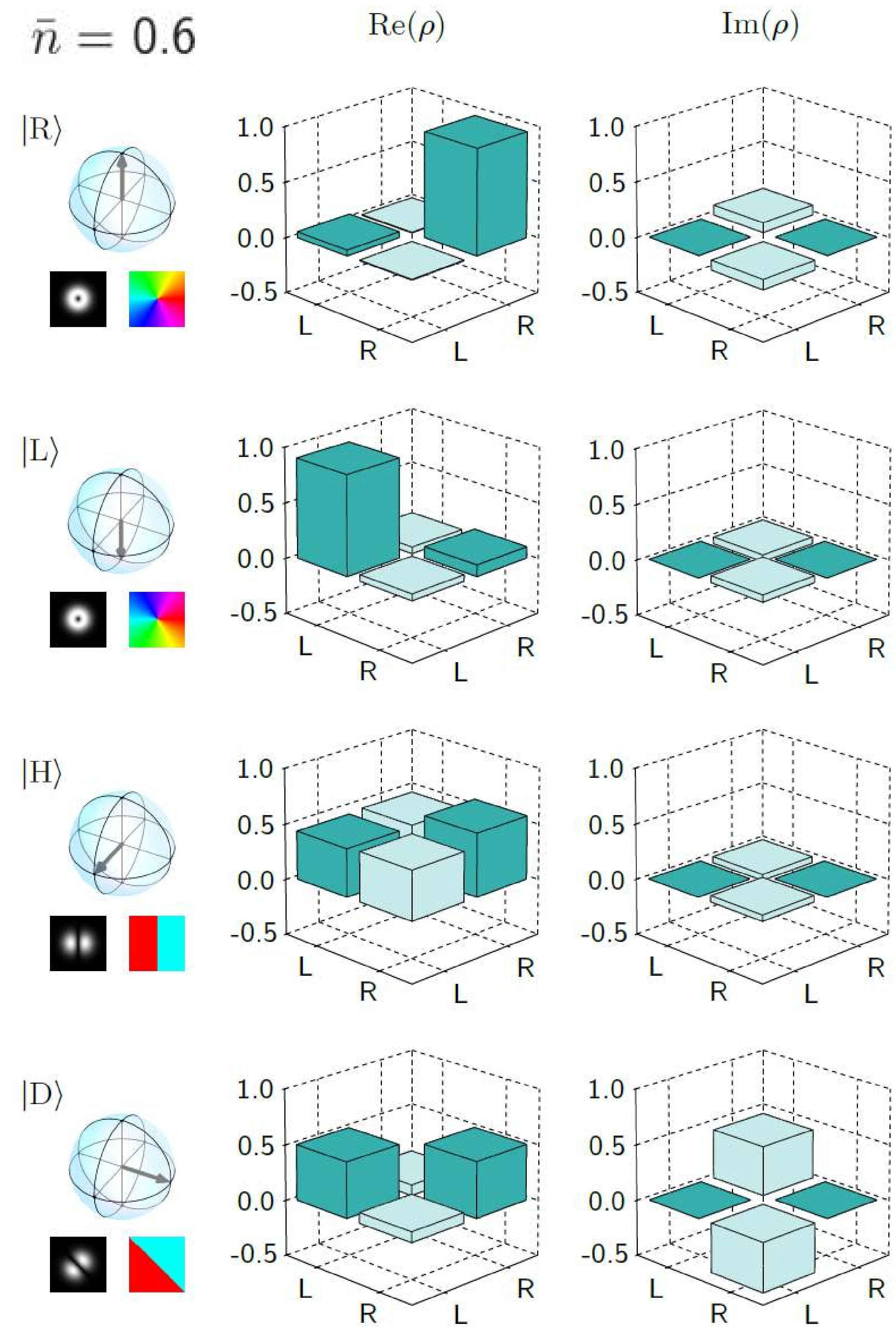
$$\longrightarrow \quad \hat{\rho} = \frac{1}{2}\begin{pmatrix} 1+S_1 & S_2 - iS_3 \\ S_2 + iS_3 & 1 - S_1 \end{pmatrix}$$



Classical benchmarking

For QIPA2013 participants and their internal use.

Fidelity with the ideal state

$$\mathcal{F} = \langle\psi|\,\hat{\rho}\,|\psi\rangle$$

Averaged fidelities ($\bar{n}$=0.6):

- raw fidelity: 92.5±2%
- corrected fidelity: 98.8±1%

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Specht *et al.*, Nature **473**, 190 (2011)

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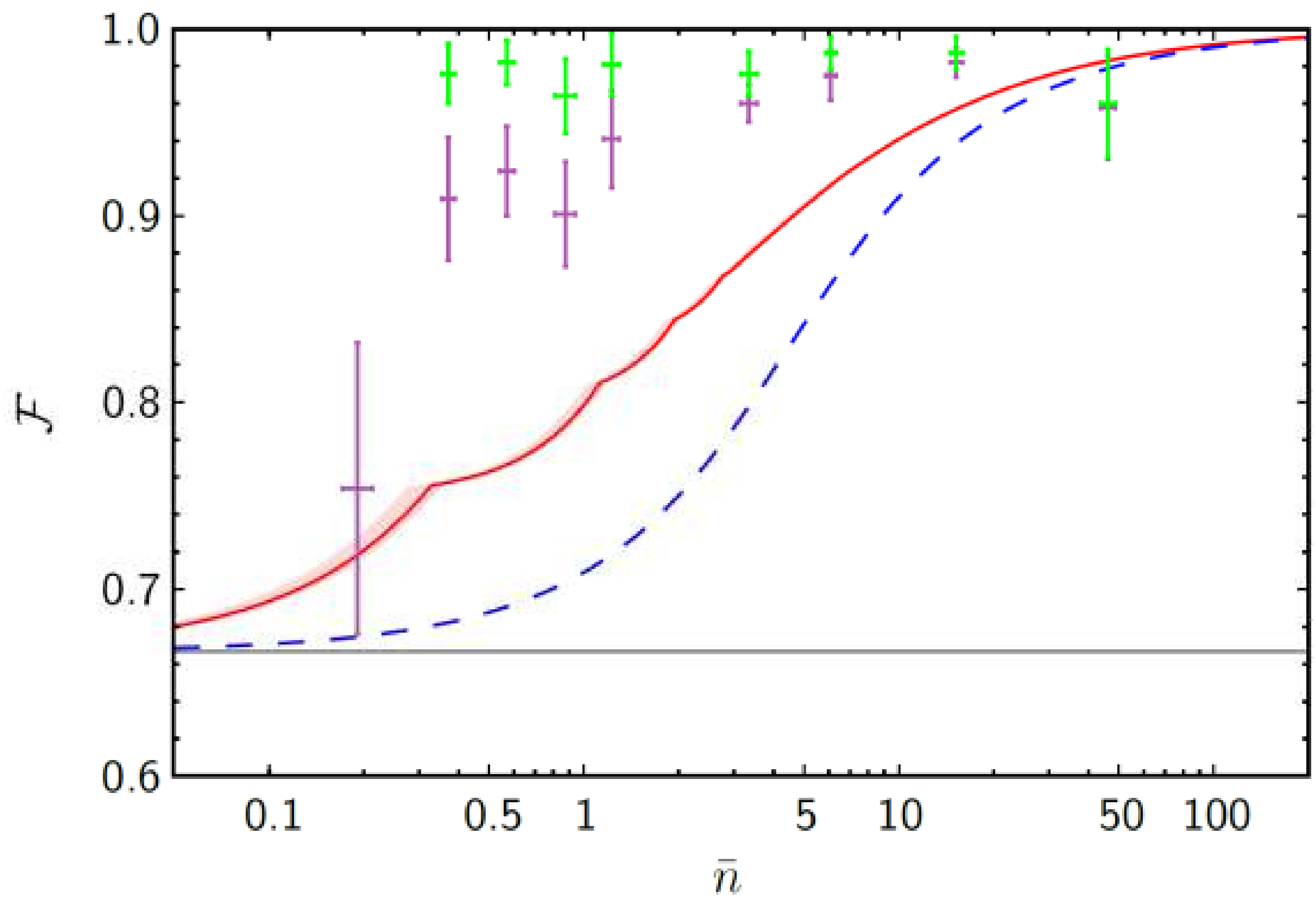
- higher for coherent state
- better strategy for η < 1

➔ higher classical bound



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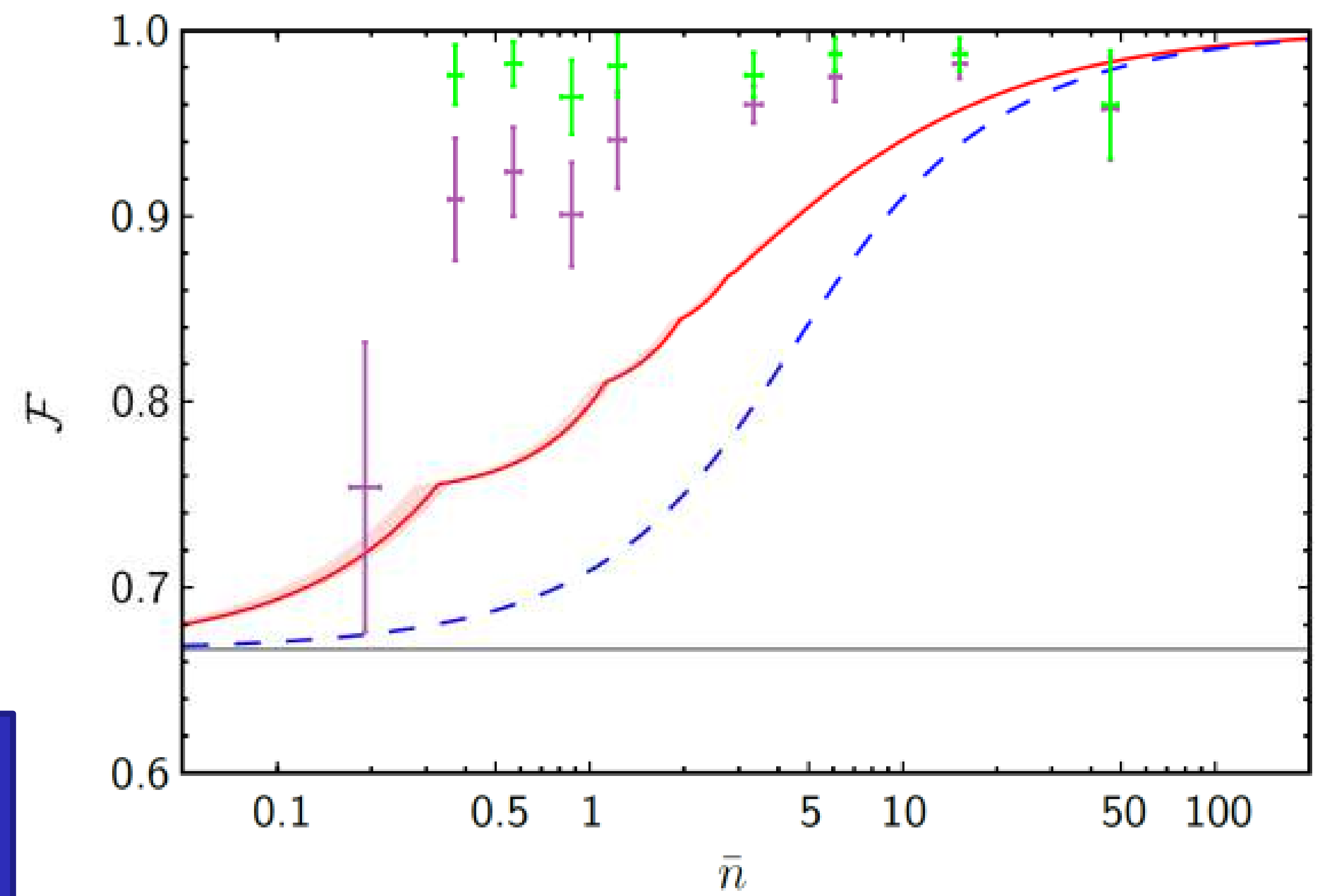


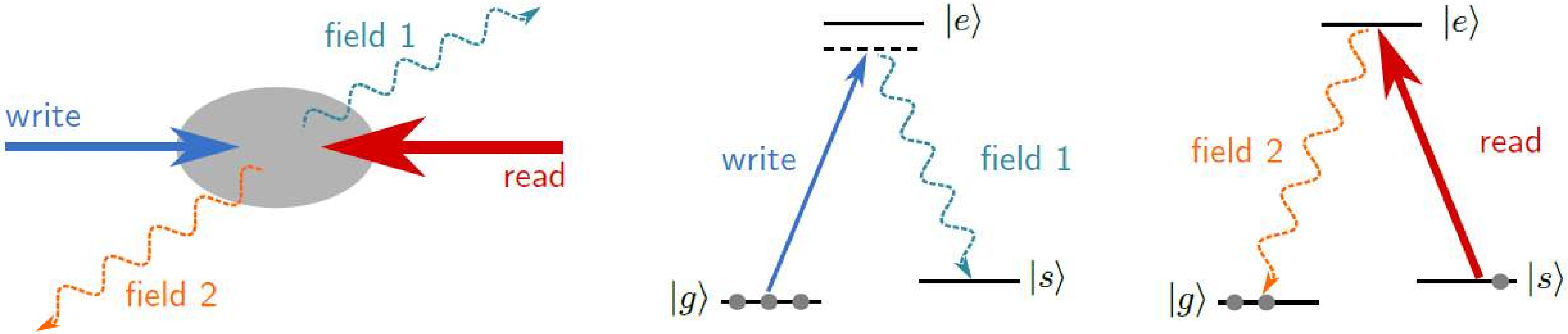
Our memory operates in the quantum regime ✓

Outlook

For QIPA2013 participants and their internal use.

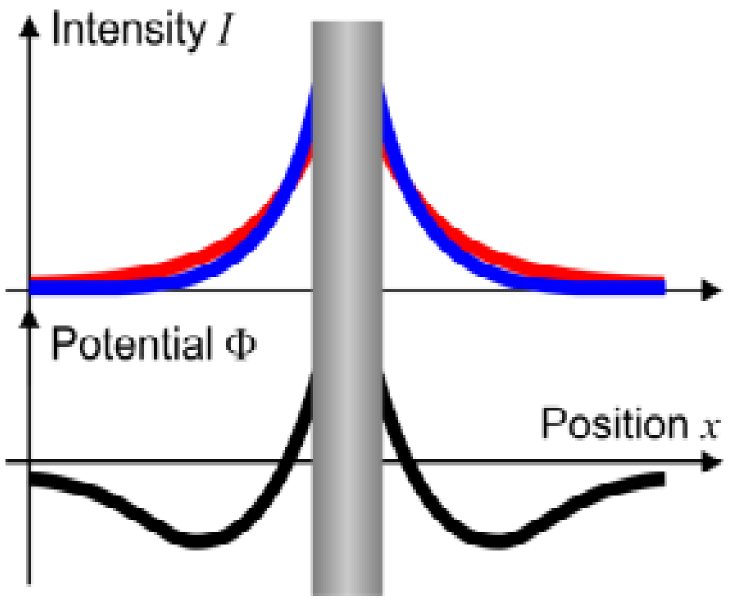
Alternative memory schemes: DLCZ

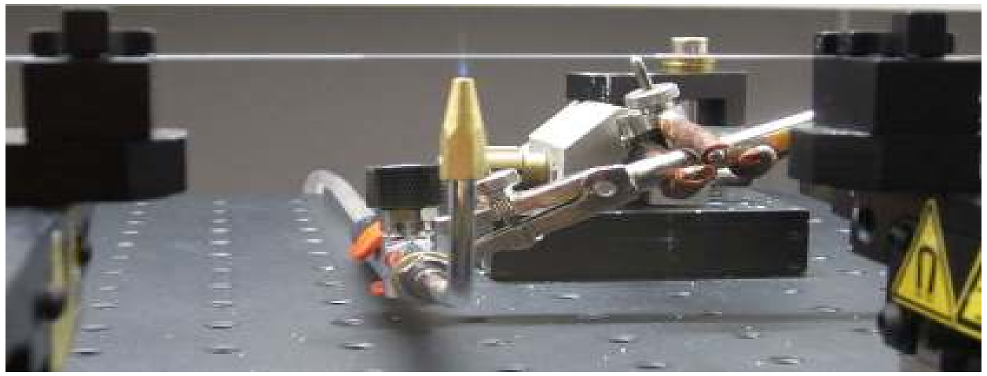
Duan et al, Nature **414**, 413 (2001)

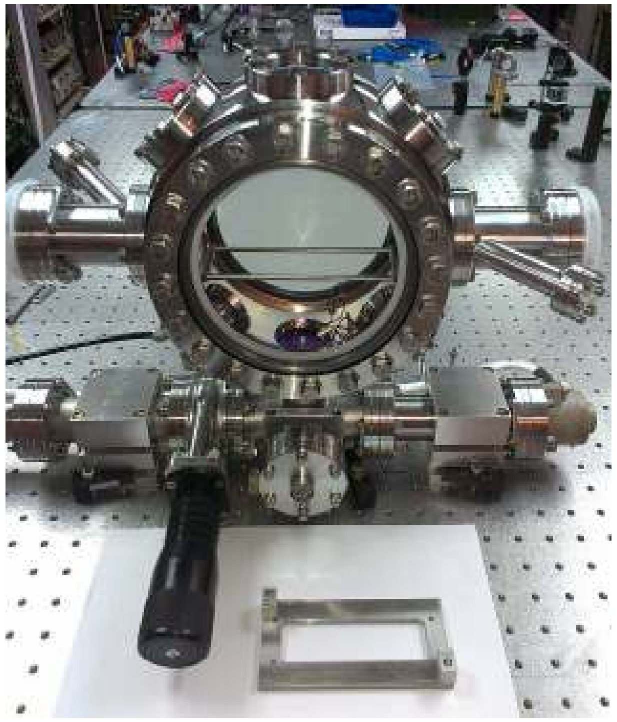


- Characterization in continuous variables: homodyne detection

Improved coupling: Nanofibers







- High integrability
- Higher optical densities than in free-space experiments

The Laboratoire Kastler Brossel

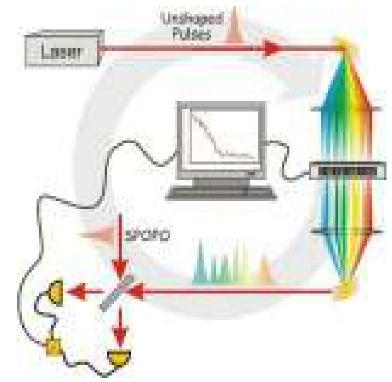
For QIPA2013 participants and their internal use.

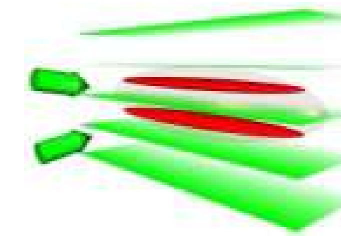
Laboratoire Kastler Brossel
Physique quantique et applications

UPMC SORBONNE UNIVERSITÉS

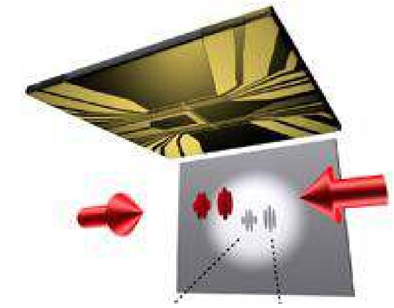
Quantum physics and applications

Quantum frequency combs

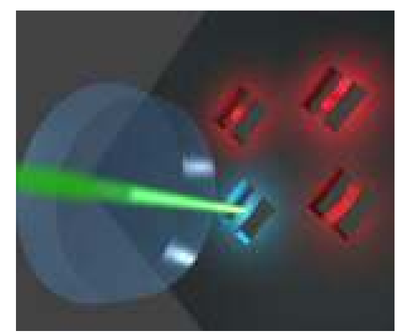




2D quantum gases

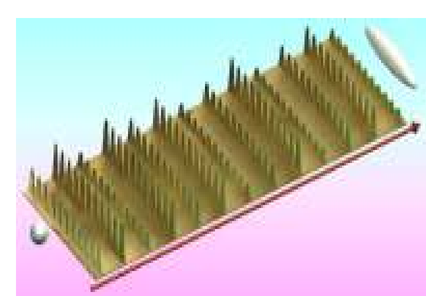


Atom chip systems

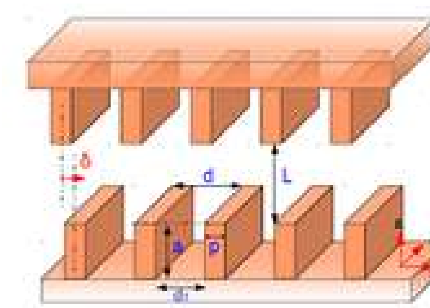


Opto-mechanical couplings

Proton radius determination



Complex systems & quantum chaos



Quantum fluctiations and relativity

The Team

For QIPA2013 participants and their internal use.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Julien Laurat
Principal Investigator


Dominik Maxein
Postdoc

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Nanoquint

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IUF

ERA-Net Chist-ERA
QScale
Chistera-qscale.eu

Summary

For QIPA2013 participants and their internal use.

- EIT-based optical memory for OAM states
- Employing multimode nature of the medium
- Full state tomography of retrieved states
  & comparision with classical benchmark
  → "quantumness" of the memory

L. Veissier *et al.*, Opt. Lett. **38**, 712 (2013)
A. Nicolas *et al.*, Nature Phot. (accepted), arXiv:1308.0238 (2013)