The DLCZ Protocol

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Presentation Plan

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  - Pros and Cons of QC
  - The DLCZ Protocol's Idea
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Motivation – Quantum Communications

- Transmitted information is a quantum state
- Quantum bit – qubit: 0/1 --> $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle,\ |\alpha|^2 + |\beta|^2 = 1$
  - Stern-Gerlach, polarizing beam splitter (PBS)

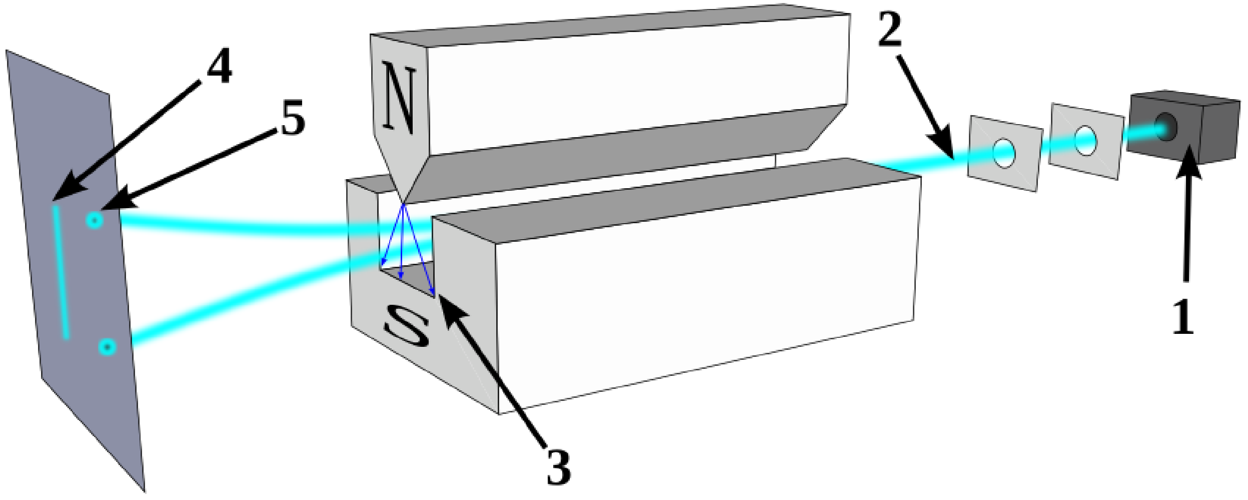
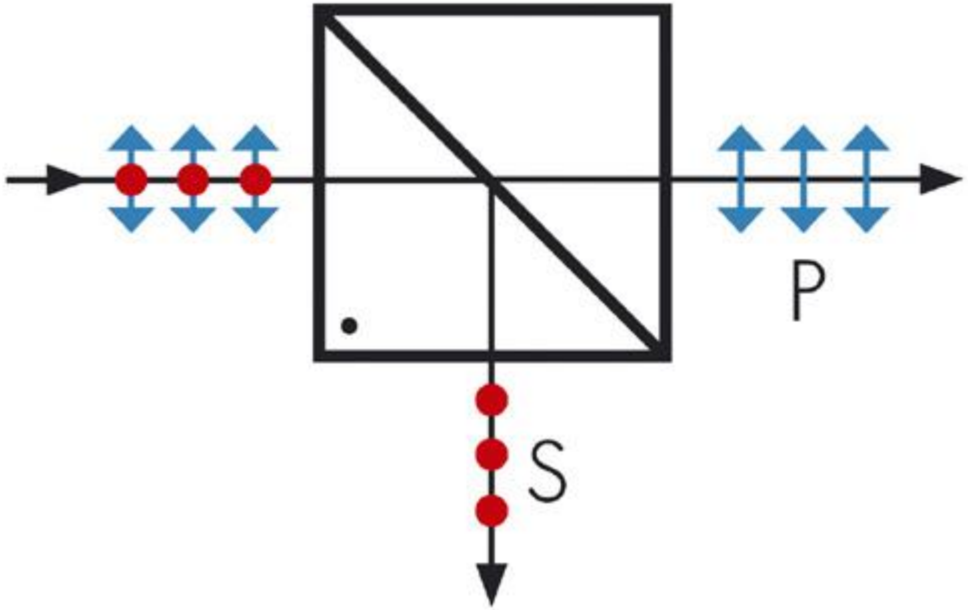


Fig. 1: Stern-Gerlach experiment

Fig. 2: polarizing beam splitter



Motivation – Quantum Communications

- Quantum key distribution (QKD)
  - Bennet-Brassard 1984 (BB84)

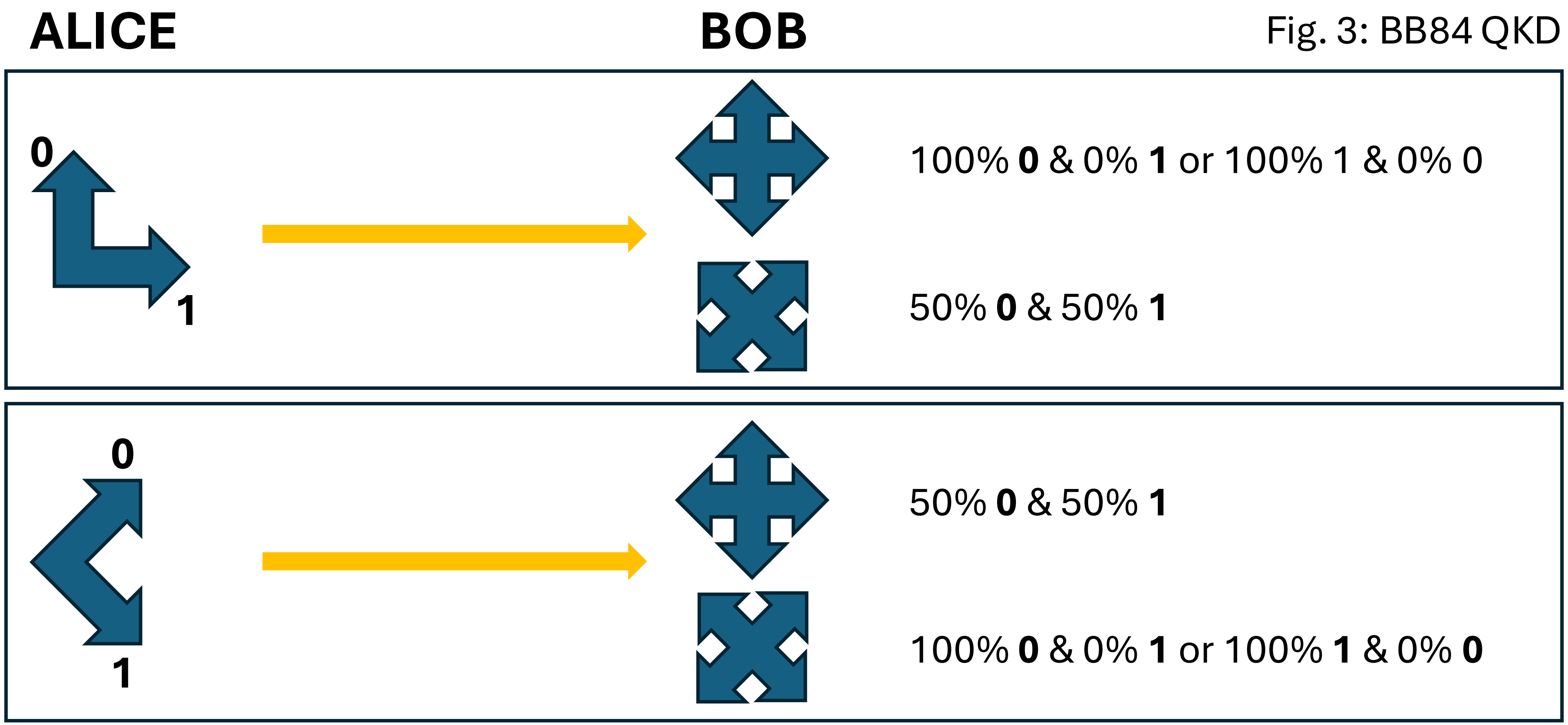


Fig. 3: BB84 QKD

Motivation – Quantum Communications

- Quantum state teleportation

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B\right)$$

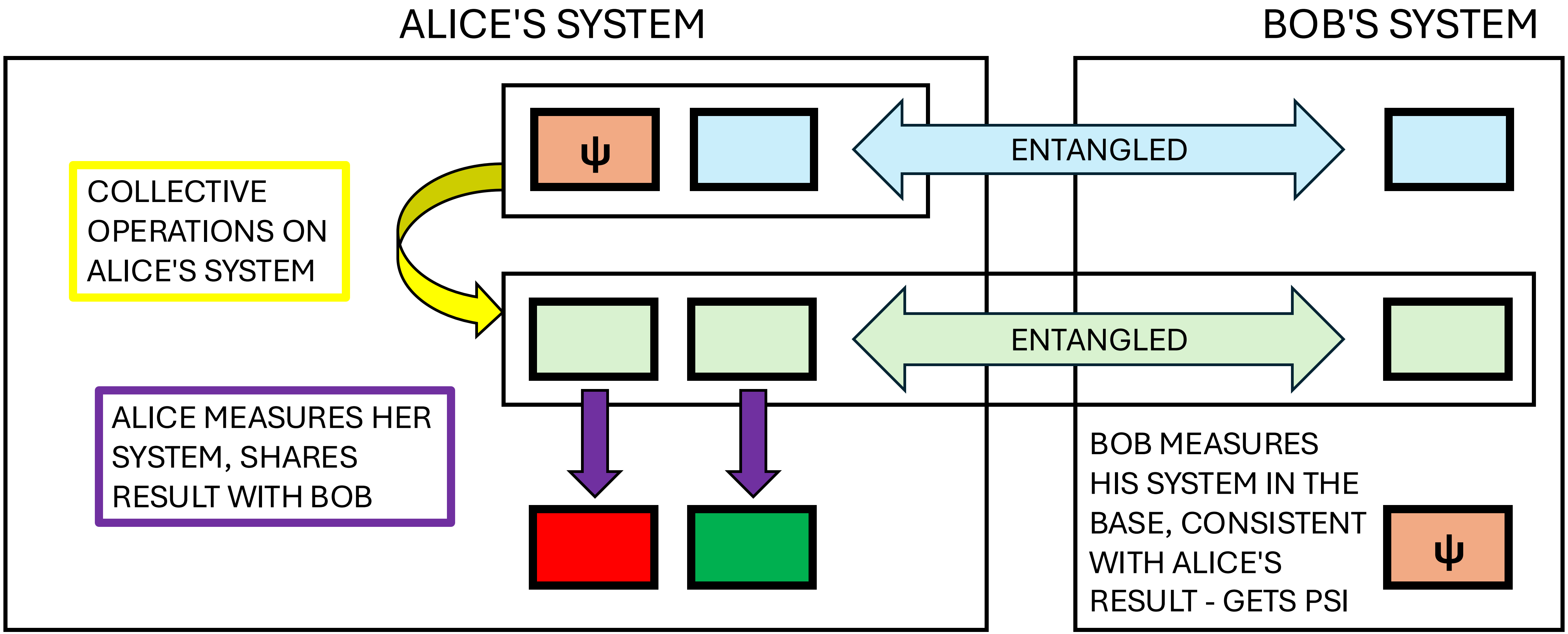


Fig. 4: Quantum state teleportation

Motivation – Pros and Cons of Quantum Comm.

- Perfect security (QKD)
- Transmission of quantum states (quantum computing, internet)
- Quantum decoherence
  - Bottleneck on distance

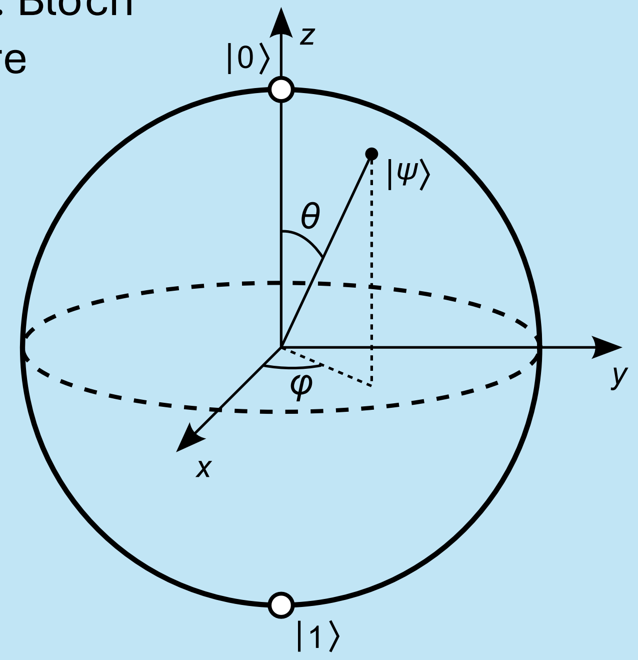
$$|\psi\rangle = \sum_n c_n |n\rangle; \quad \sum_n |c_n|^2 = 1$$

PURE STATE

$$\rho = \sum_j p_j \, |\psi_j\rangle\langle\psi_j| \, ; \quad \sum_j p_j = 1$$

DENSITY MATRIX

Fig. 5: Bloch sphere



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|a\rangle + e^{i\theta}|b\rangle)$$

$$\rho = \frac{1}{2}\begin{bmatrix} 1 & e^{-i\theta} \\ e^{i\theta} & 1 \end{bmatrix}$$

DECOHERENCE

$$\rho = \begin{bmatrix} 1/2 & 0 \\ 0 & 1/2 \end{bmatrix}$$

The Protocol's Goal

- Quantum communications channel, where preparation time scales only polynomially with distance
- Quantum repeater

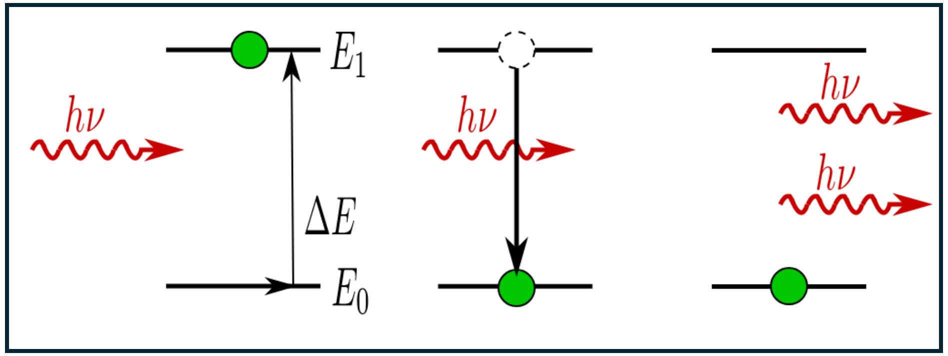


Fig. 6: No cloning!

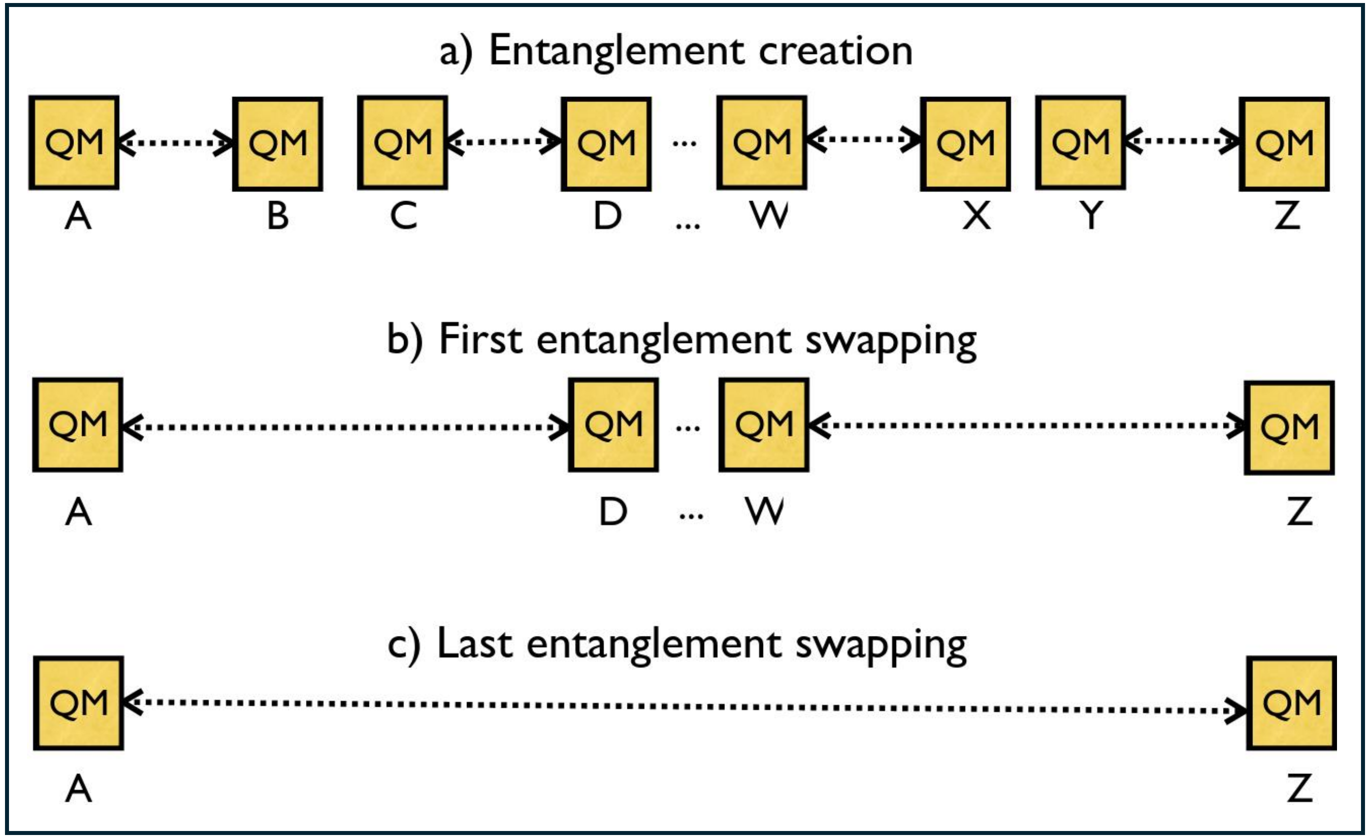


Fig. 7: DLCZ protocol scheme

Breakdown - Quantum Memory

- Writing photonic states into atomic states

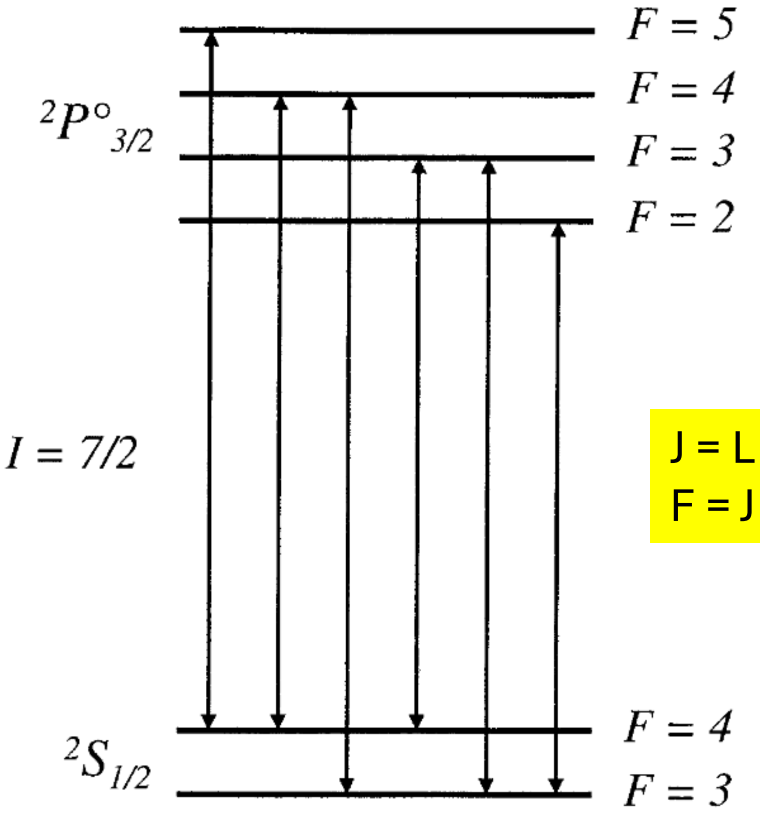
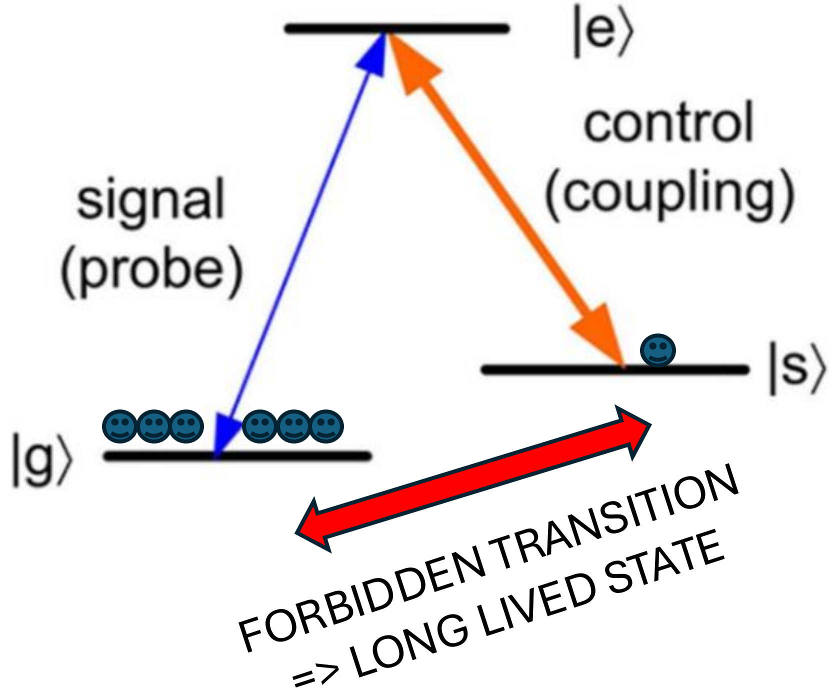


Fig. 8: Cs hyperfine D_2 transitions

J = L + S fine splitting
F = J + I hyperfine spl.

Fig. 9: Lambda (Λ) scheme



Breakdown – Spontaneous Raman Transition

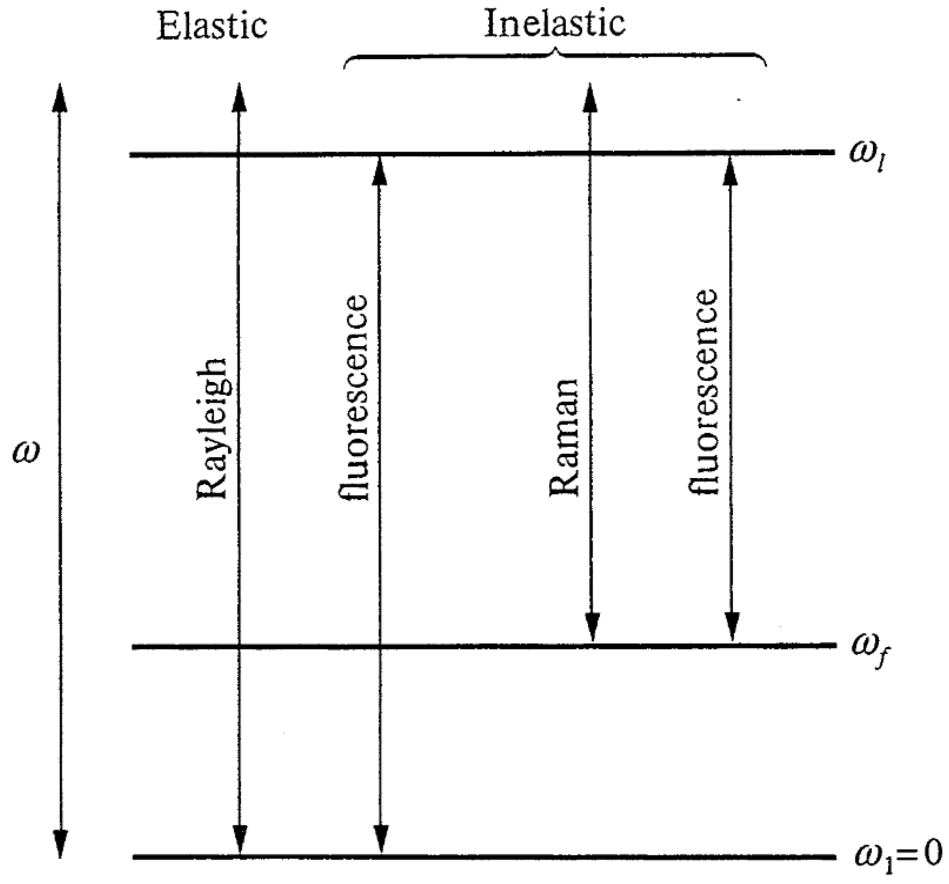


Fig. 10: Types of transitions

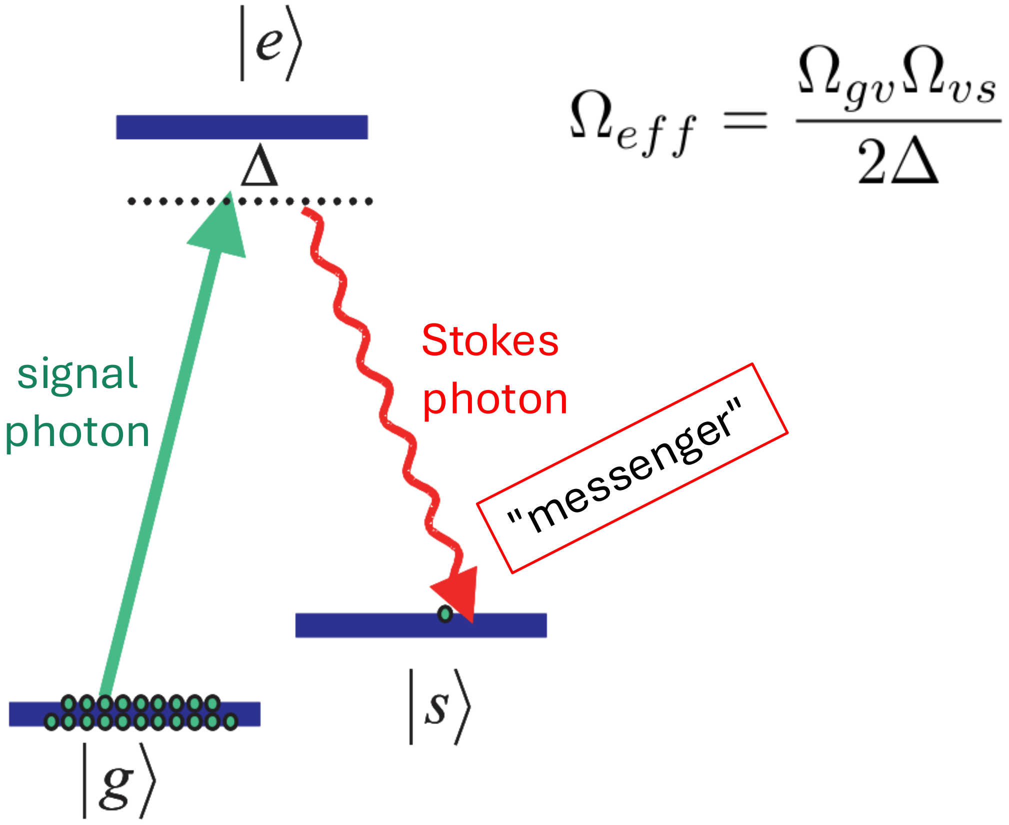
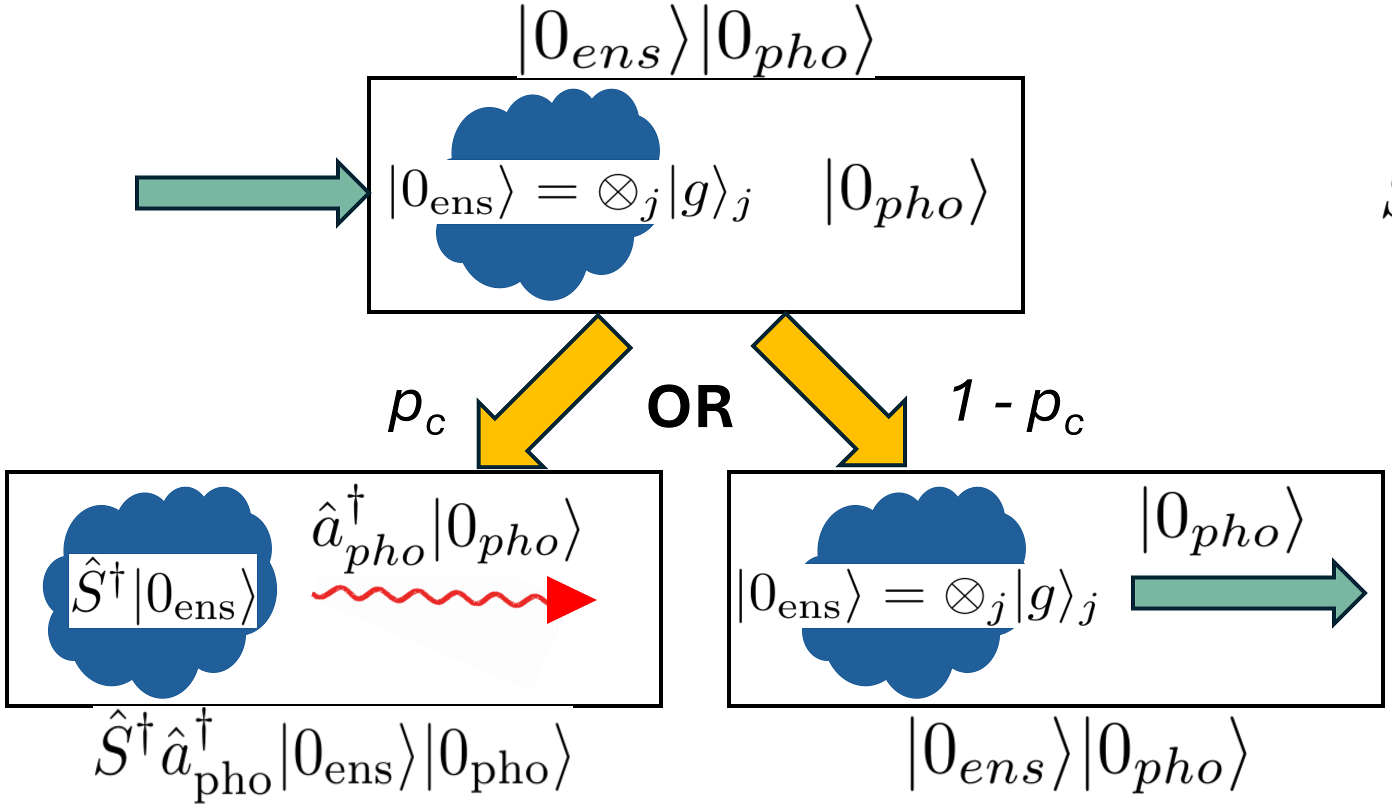


Fig. 11: (coherent) Raman transition

Breakdown – Spontaneous Raman Transition



Symmetric collective atomic mode

$$\hat{S} = \sqrt{N_{\text{ens}}}^{-1} \sum_{j=1}^{N_{\text{ens}}} |g\rangle_j \langle s|$$

Probability for transition in ensemble

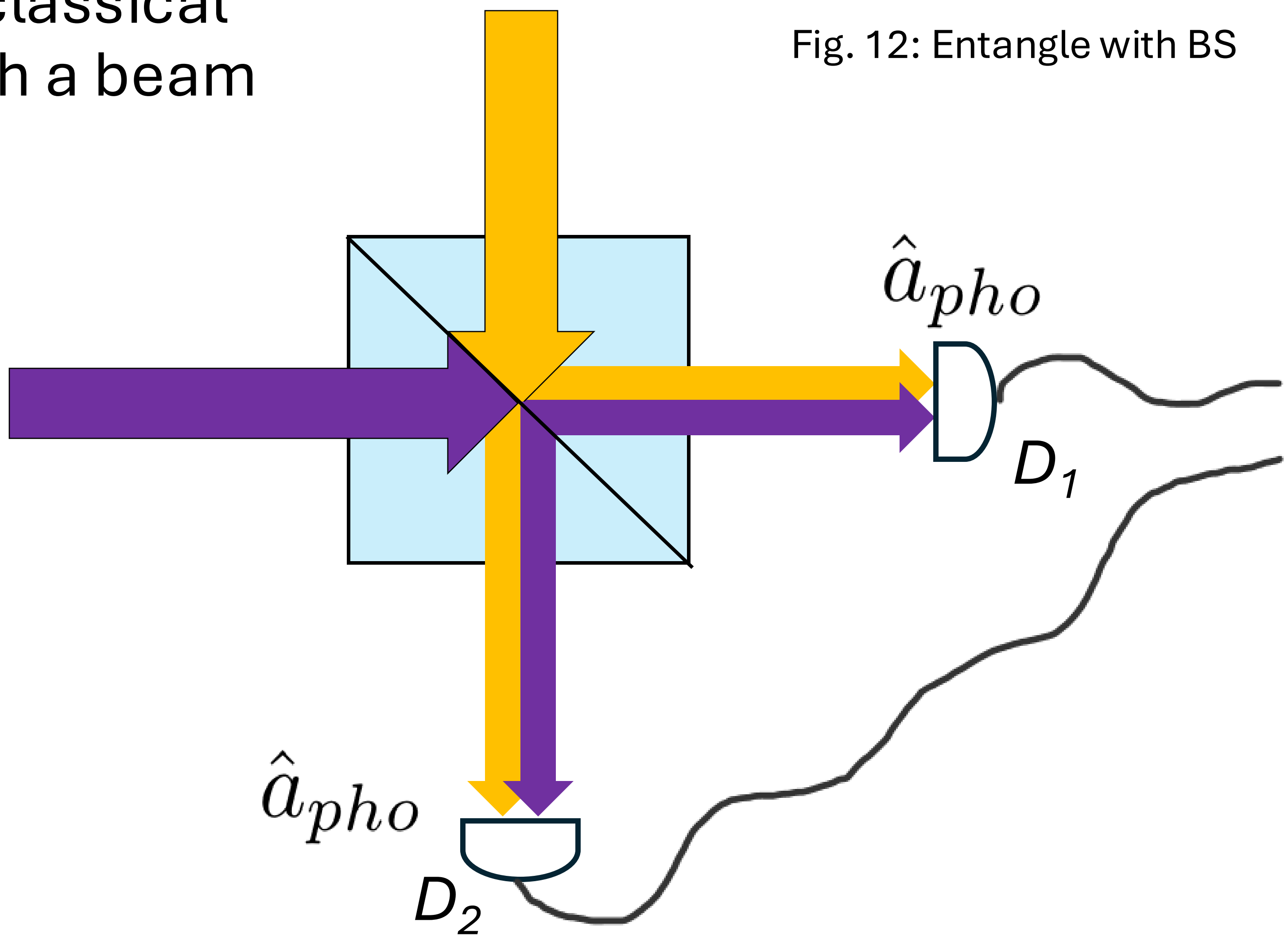
$$p_c = 4g^2 N \frac{L}{t_p c} \frac{|\Omega_p|^2}{\Delta^2}$$

$$|\Phi\rangle = |0_{\text{ens}}\rangle|0_{\text{pho}}\rangle + \sqrt{p_c}\, \hat{S}^\dagger \hat{a}^\dagger_{\text{pho}} |0_{\text{ens}}\rangle|0_{\text{pho}}\rangle + O(p_c)$$

Breakdown – Entanglement by a BS

- Can entangle non-classical photon sources with a beam splitter

Fig. 12: Entangle with BS



The DLCZ Protocol – Entanglement Creation

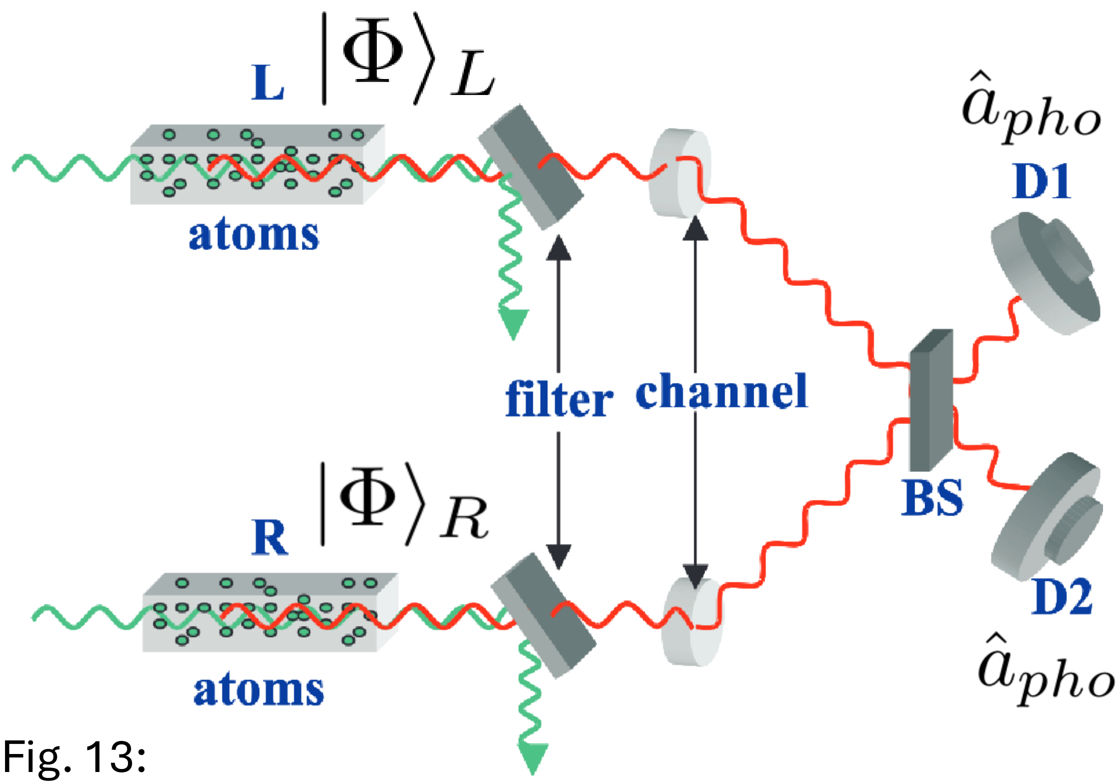


Fig. 13:
Entanglement creation

$$|\Phi\rangle = |0_{\text{ens}}\rangle|0_{\text{pho}}\rangle + \sqrt{p_c}\,\hat{S}^\dagger \hat{a}^\dagger_{\text{pho}}|0_{\text{ens}}\rangle|0_{\text{pho}}\rangle + O(p_c)$$

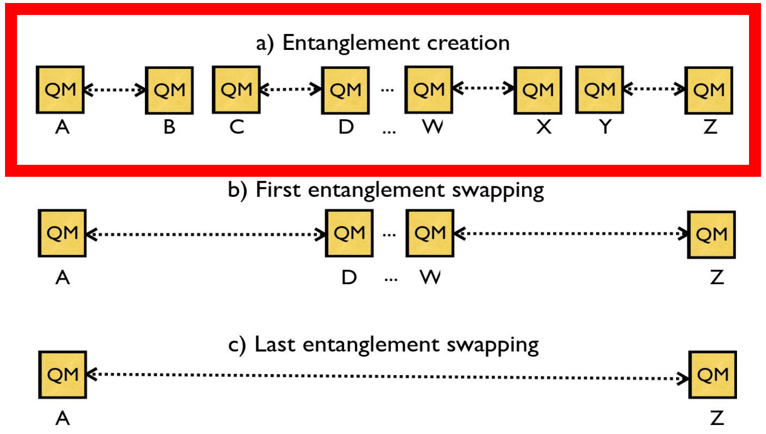
$$|\Phi\rangle_L \otimes |\Phi\rangle_R$$

$$\hat{a}_{pho,\pm} = (\hat{a}_{pho,L} \pm e^{i\zeta}\hat{a}_{pho,R})/\sqrt{2}$$

$$|\Psi_\zeta\rangle^{\pm}_{LR} = \frac{1}{\sqrt{2}}(\hat{S}^\dagger_L \pm e^{i\zeta}\hat{S}^\dagger_R)|0_{\text{ens}}\rangle_L|0_{\text{ens}}\rangle_R$$

Effectively maximally entangled state (EME):

$$\rho_{LR}(c_0,\zeta) = \frac{1}{c_0+1}(c_0\,|0_{\text{ens}}0_{\text{ens}}\rangle\langle 0_{\text{ens}}0_{\text{ens}}|_{LR} + |\Psi_\zeta\rangle\langle\Psi_\zeta|^{+}_{LR})$$



The DLCZ Protocol – Entanglement Purification

- Unfair coin flipping – binomial distr. => success $p_c N$ times
  - Must retry approx. $1/p_c$ times
- Photon loss efficiency η_p => retry $1/p_c\eta_p$ times
- Dark count probability p_{dc}
- Vacuum coef. $c_0 = p_{dc}/p_c\eta_p \ll 1$
- double excitation
  - => fidelity imperfection $\Delta F \sim p_c$
- Preparation time T ~ $\Delta t/p_c\eta_p$
- Preparation time vs. fidelity

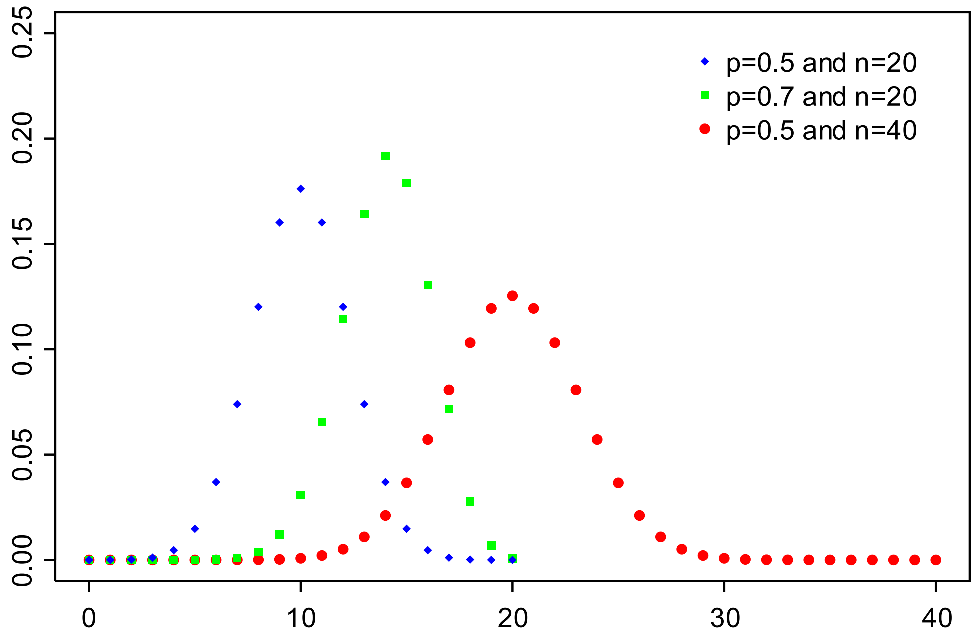


Fig. 14: Binomial distribution

The DLCZ Protocol – Entanglement Swapping

- Same as with entanglement creation, but now we send in a control beam and expect anti-Stokes

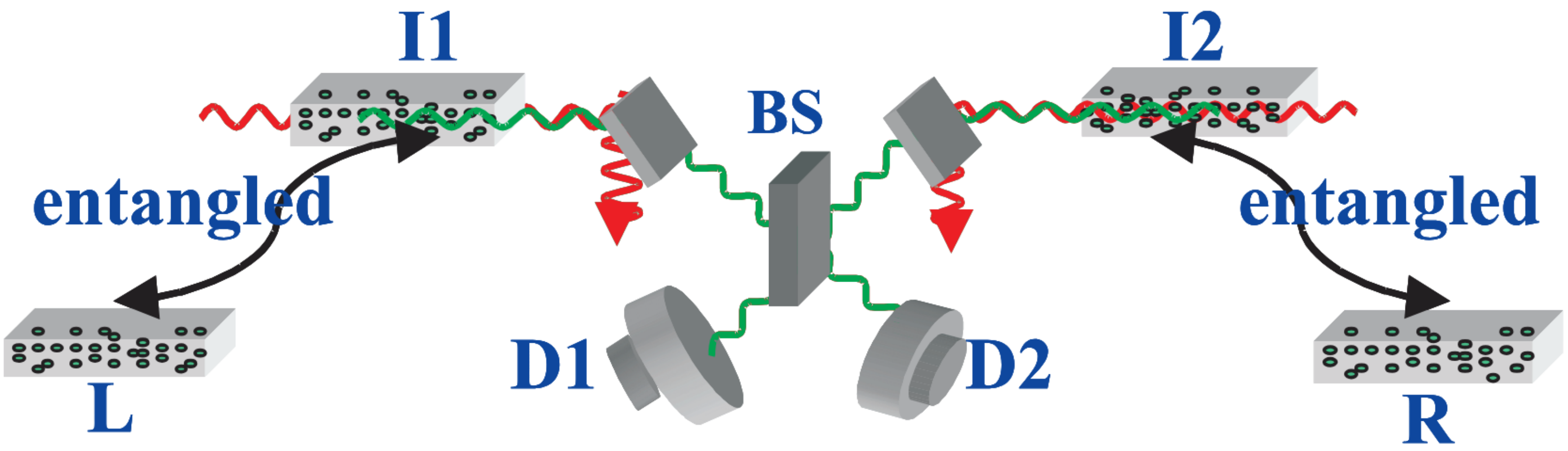
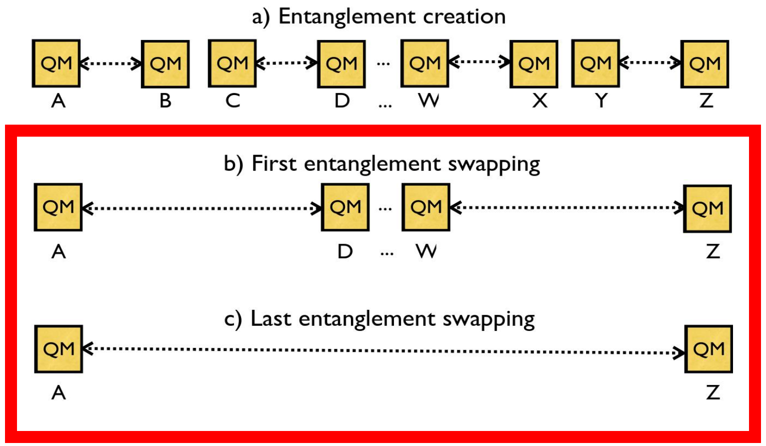


Fig. 15: Entanglement swapping



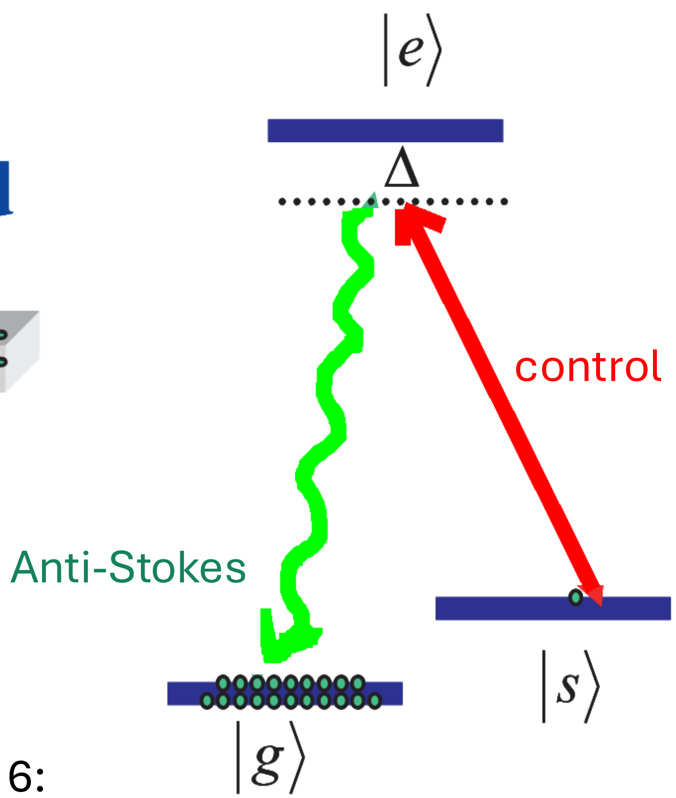


Fig. 16:
Reverse Raman transition

Conclusion

- Required quantum memory for only polynomial scaling of preparation time with distance
- Spontaneous Raman transition required as a non-classical photon source (and quantum memory)
- We can entangle Raman quantum memories pairwise by erasing Stokes/anti-Stokes source path with a beam splitter
- If entanglement does not succeed, only repeat that section
- Ensembles contribute reliability

Sources of Figures

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