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Technologies quantiques émergentes

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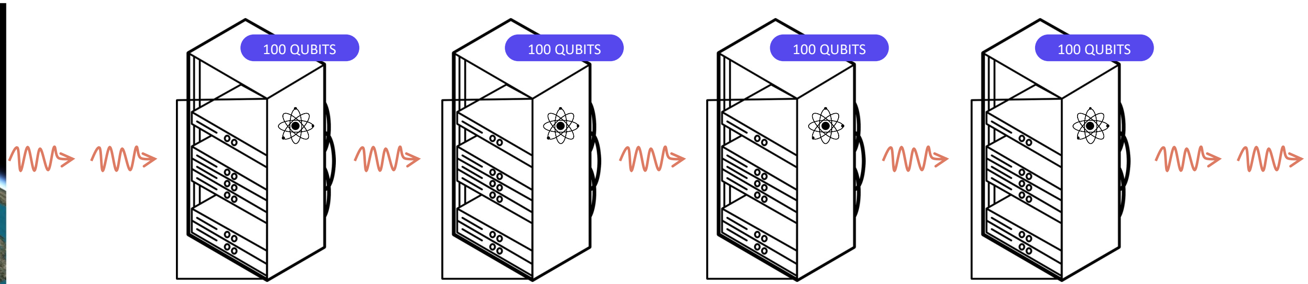
23 février 2026

Interfaces et mémoires quantique: vers un « internet » quantique ?

Communications quantiques : pourquoi ?

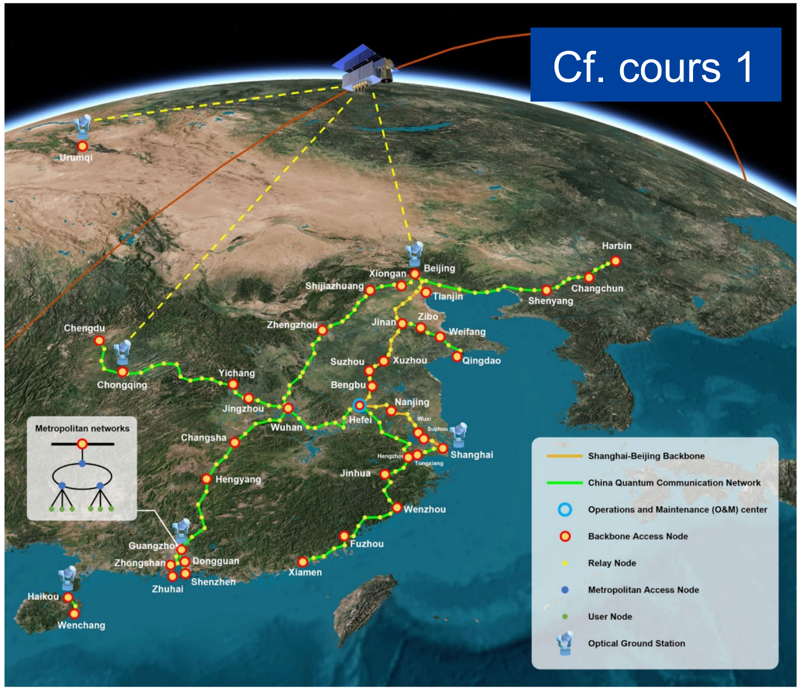
npj Quantum Information 11, 137 (2025)



ordinateur
capteur

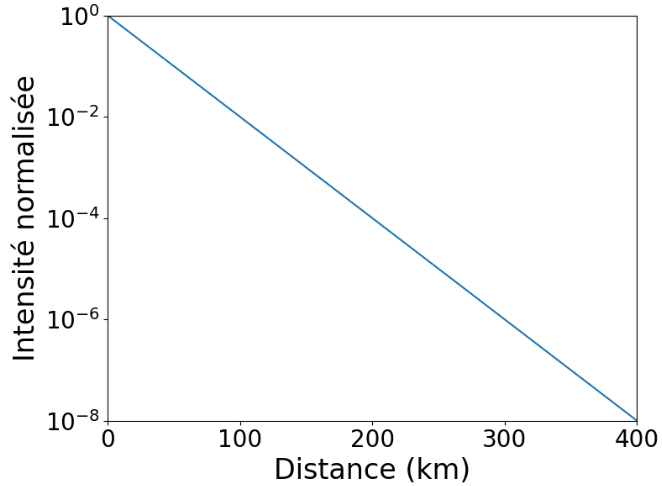
Communications quantiques : défis

Exemple de l'échange de clé cryptographique



npj Quantum Information 11, 137 (2025)

Pertes fibres optiques



Probabilité de succès de transfert d'une information sur un essai

$$P_{\mathrm{dir}}(L) = p_0 \, e^{-L/L_{\mathrm{att}}}$$

Réseaux quantiques : défis

npj Quantum Information 11, 137 (2025)

Erreurs :
- Perte du photon
- Fluctuation de la polarisation
- Fluctuation de la phase

Théorème de non-clonage

Transformation (nécessairement **unitaire**) U telle que

$$U(|\psi\rangle \otimes |0\rangle) = |\psi\rangle \otimes |\psi\rangle$$

Deux états normalisés différents $|\psi\rangle$et $|\phi\rangle$

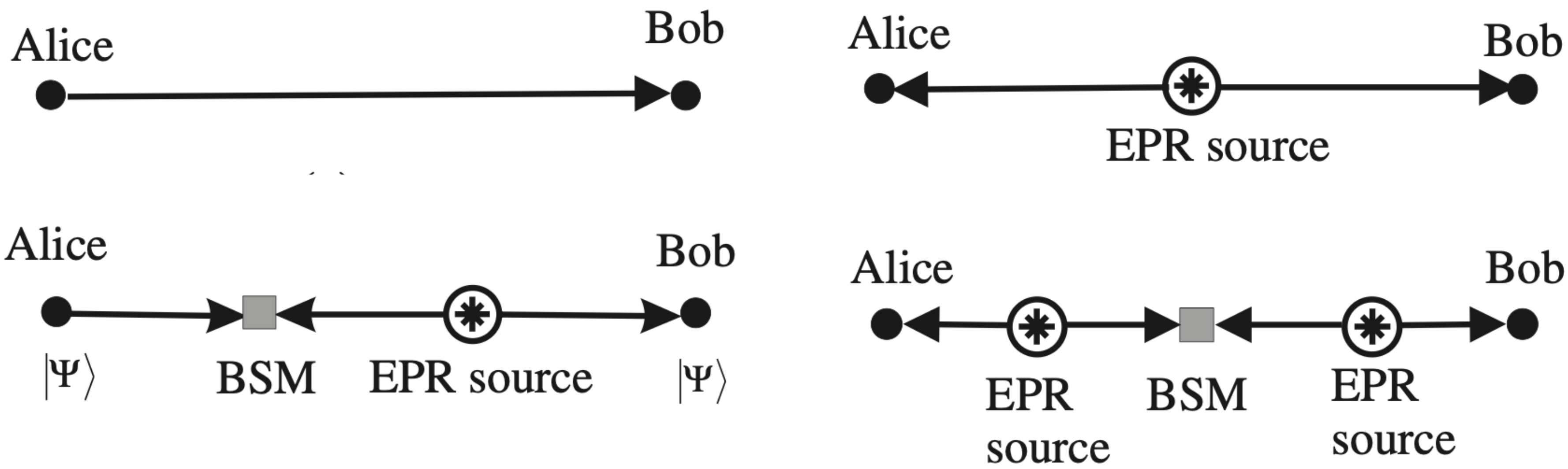
$$U(|\psi\rangle |0\rangle) = |\psi\rangle |\psi\rangle$$

$$U(|\phi\rangle |0\rangle) = |\phi\rangle |\phi\rangle$$

Conservation produits scalaires. $\langle\psi|\phi\rangle = \langle\psi|\phi\rangle^2$

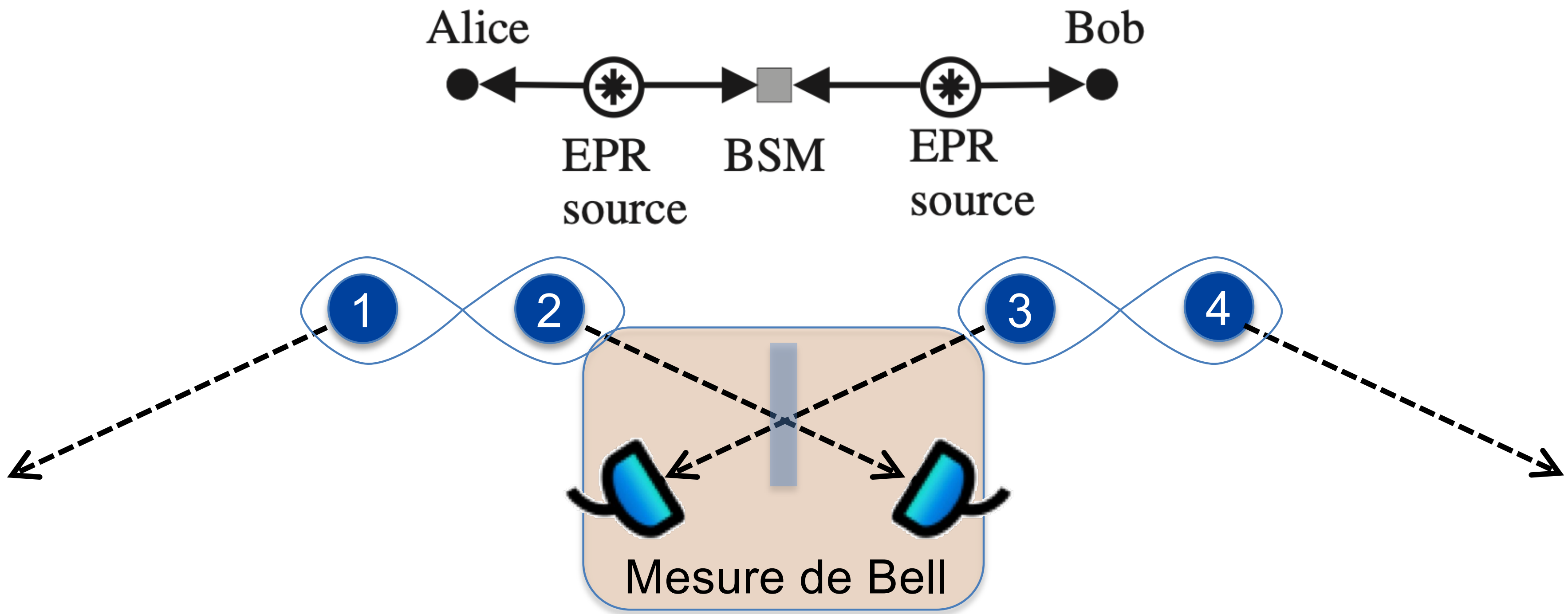
=> $|\psi\rangle$et $|\phi\rangle$ orthogonaux ou identiques !

Communications quantiques : augmenter la distance ?



Quantum relays for long distance quantum Cryptography
Journal of Modern Optics, *52*(5), 735–753 (2007)

Communications quantiques : augmenter la distance ?



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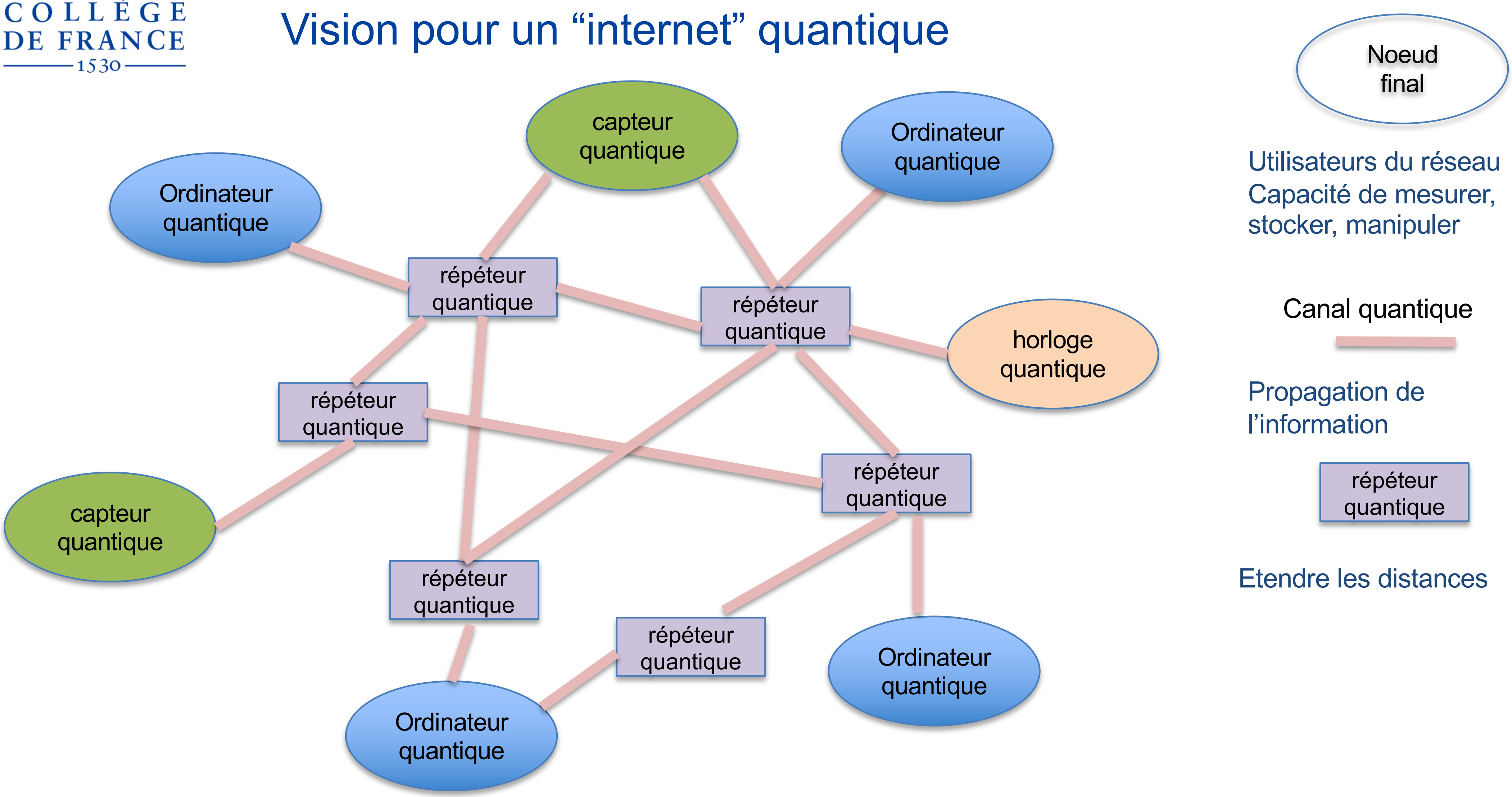
Vision pour un “internet” quantique



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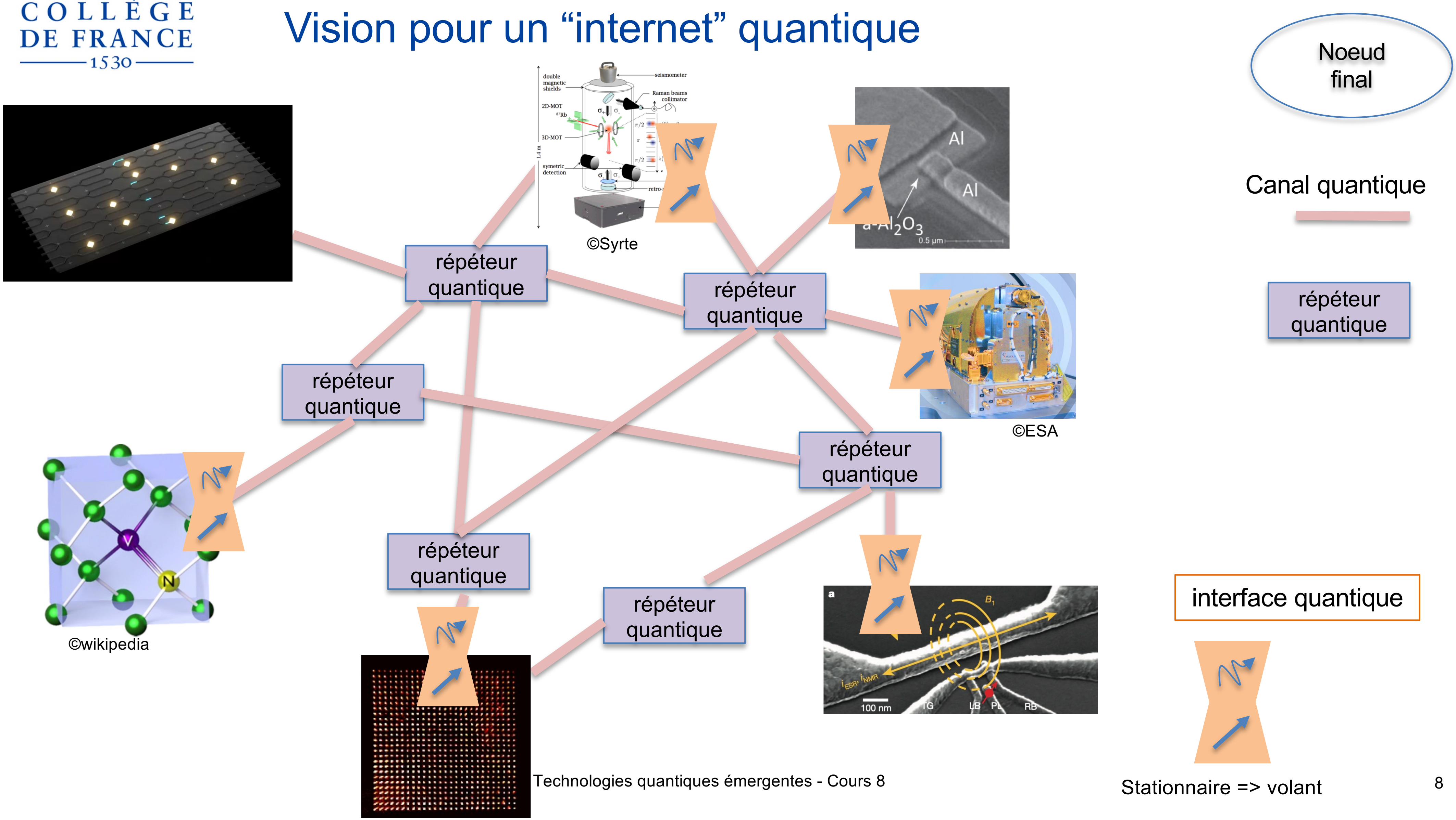

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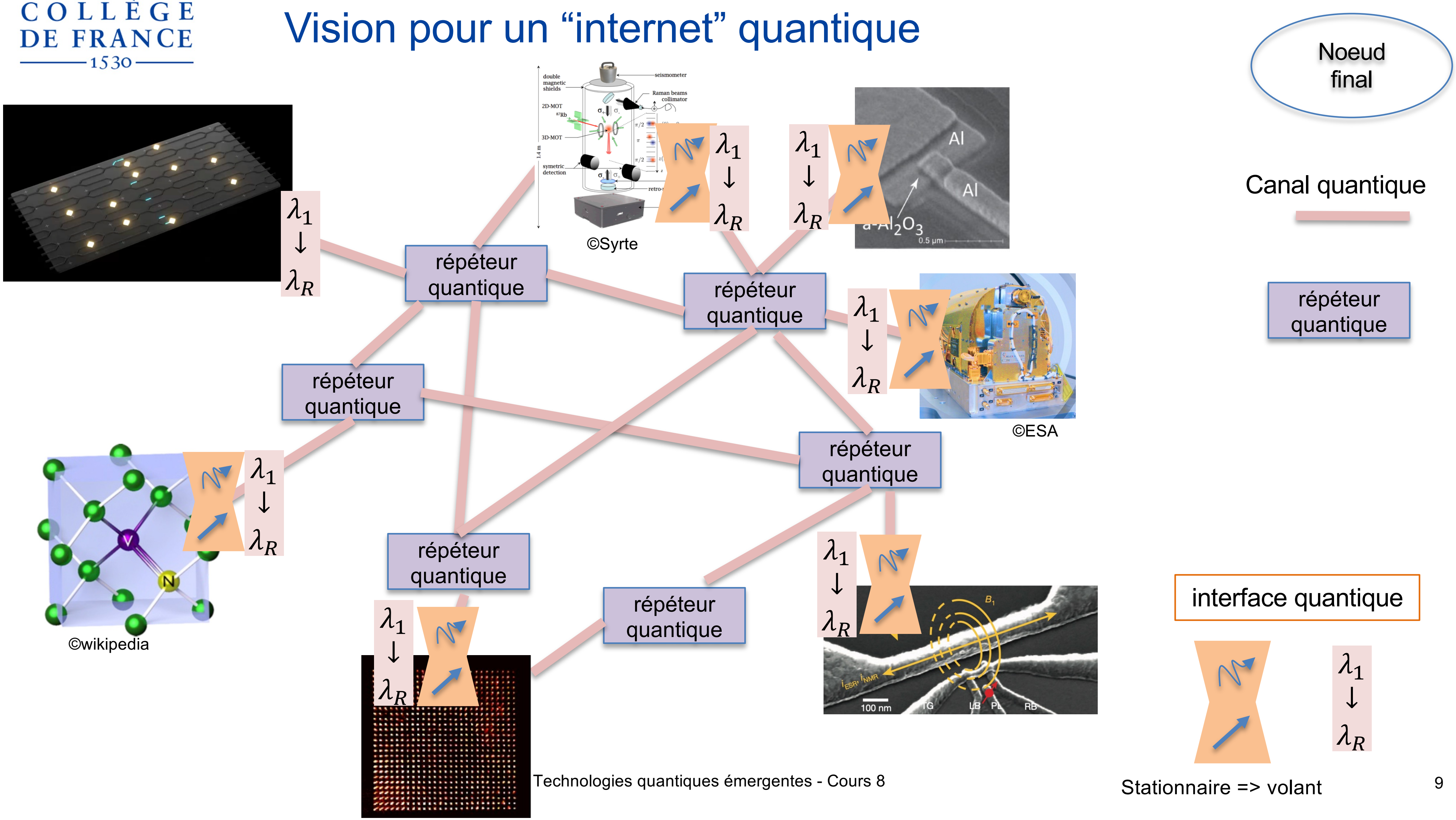
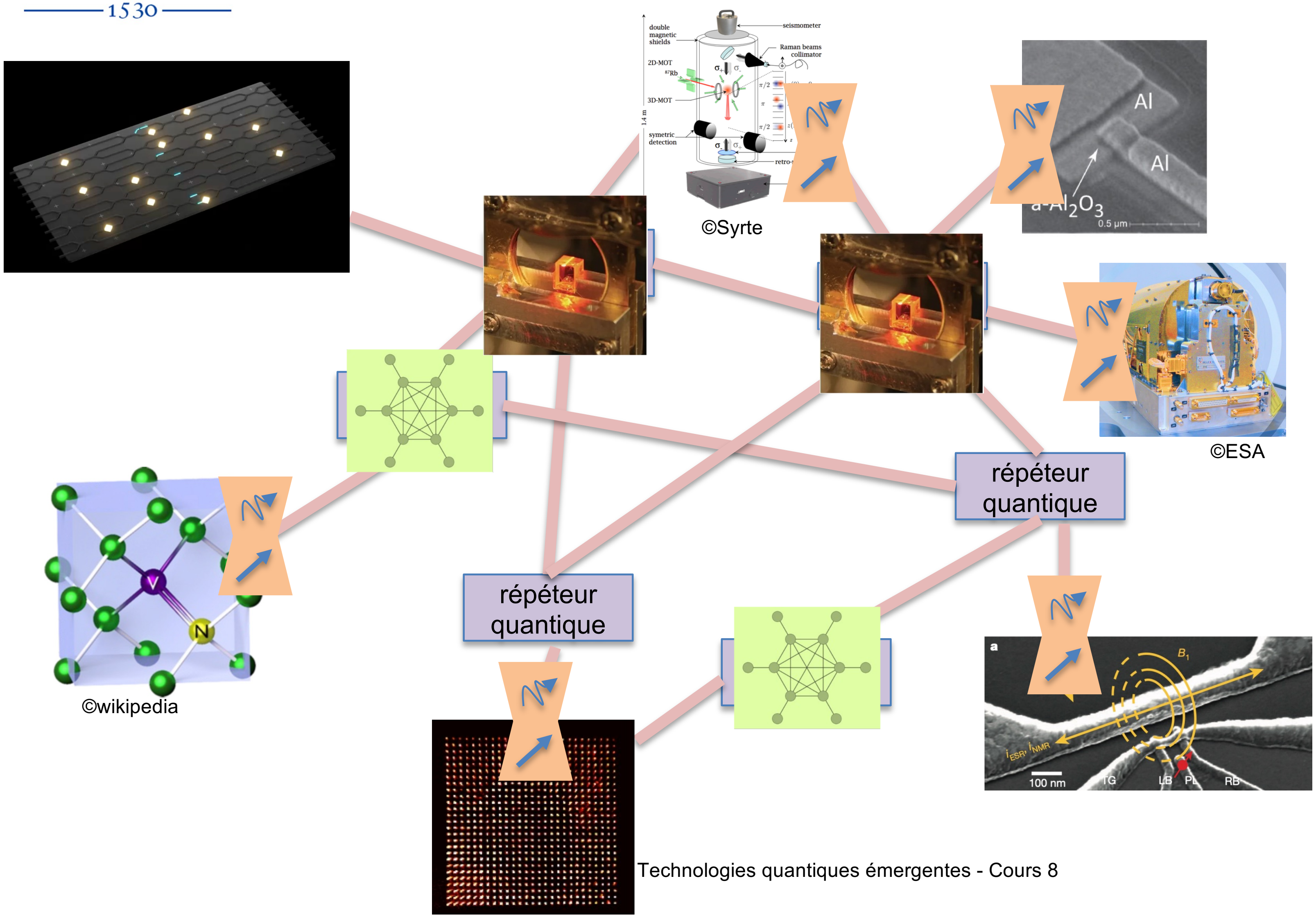
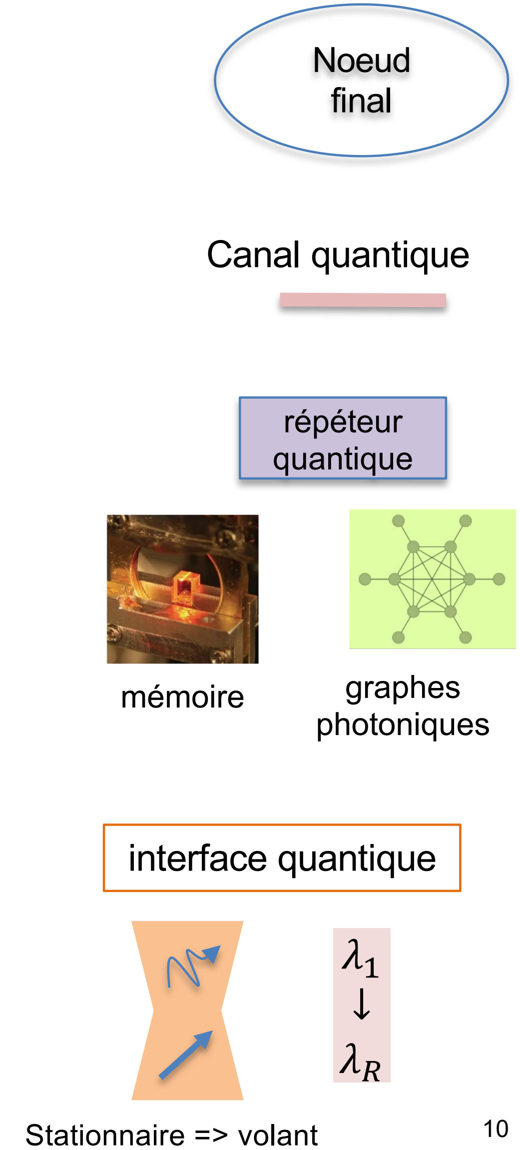


Vision pour un “internet” quantique





Interfaces et mémoires quantiques

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Primitives des répéteurs quantiques

Interfaces et mémoires quantiques
à 1 spin

Mémoires quantiques
à ensemble de spins

Conversion de fréquence quantique

Distribuer l'intrication

Mesures de Bell

Téléportation, transfert d'intrication

Ondes de spins

Séminaire Pr. Tracy Northrup

Primitives des répéteurs quantiques

Mesures de Bell

Téléportation, transfert d’intrication

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Etats à deux qubits : états de Bell

Cf. cours 2

Définition

Etats maximalement intriqués à deux photons

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|H_A H_B\rangle + |V_A V_B\rangle)$$
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|H_A H_B\rangle - |V_A V_B\rangle)$$
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|H_A V_B\rangle + |V_A H_B\rangle)$$
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|H_A V_B\rangle - |V_A H_B\rangle).$$

Matrices densité dans la base

$$|H_A H_B\rangle,\ |H_A V_B\rangle,\ |V_A H_B\rangle,\ |V_A V_B\rangle$$

$$\rho_{\Phi^+} = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}$$

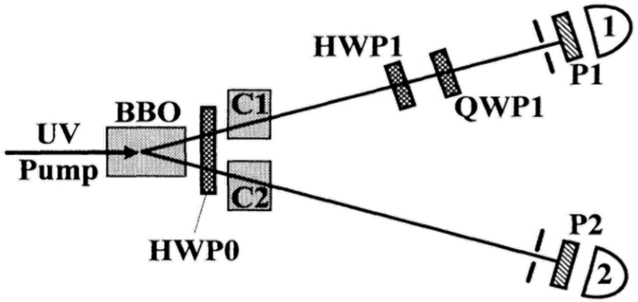
$$\rho_{\Psi^-} = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Etats de Bell : génération par conversion de fréquence

$\omega_p = \omega_s + \omega_i$

$k_p = k_s + k_i$

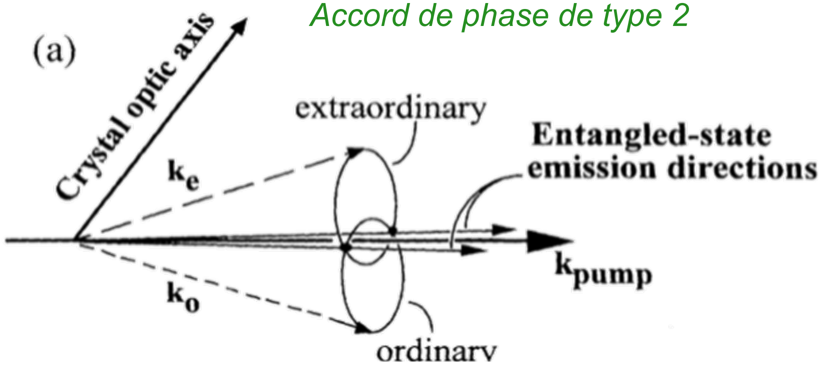
Cf. cours 4

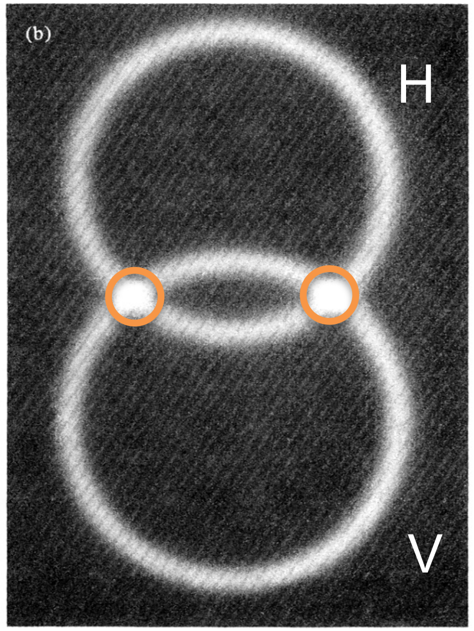


$$\hat{H}_{\text{int}} = \hbar g \left(\hat{a}_p \, \hat{a}_s^\dagger \hat{a}_i^\dagger + \hat{a}_p^\dagger \hat{a}_s \hat{a}_i \right)$$

$$|\psi\rangle = \left(1 - \frac{|\eta|^2}{2}\right) |0_s, 0_j\rangle + \eta \, |1_s, 1_j\rangle + \eta^2 \, |2_s, 2_j\rangle$$

Accord de phase de type 2





$$|\psi\rangle = \frac{|H_1, V_2\rangle + e^{i\alpha} |V_1, H_2\rangle}{\sqrt{2}}$$

Phys. Rev. Lett. 75, 4337-4341 (1995).

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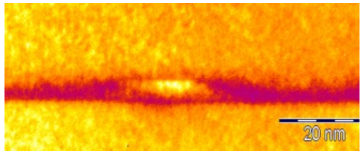
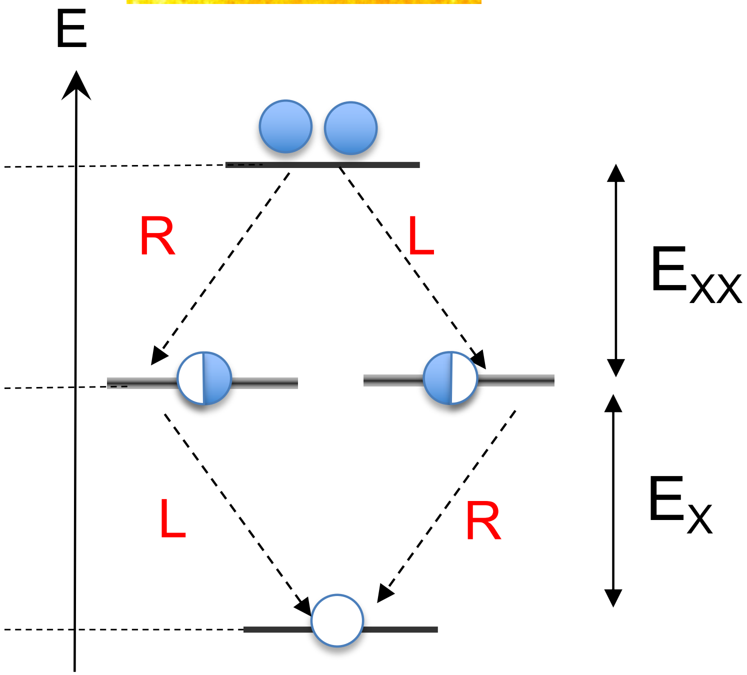
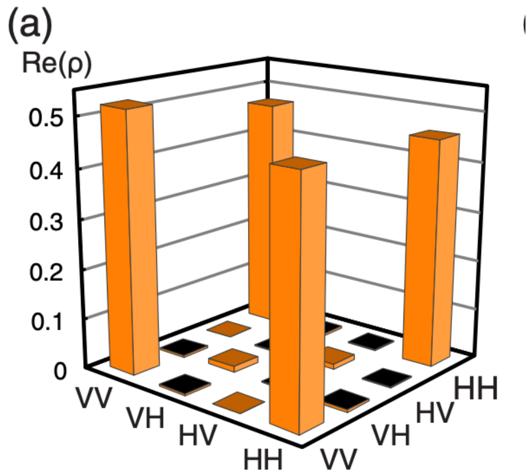
Cf. cours 4

Etats de Bell : cascade radiative d'une boite quantque

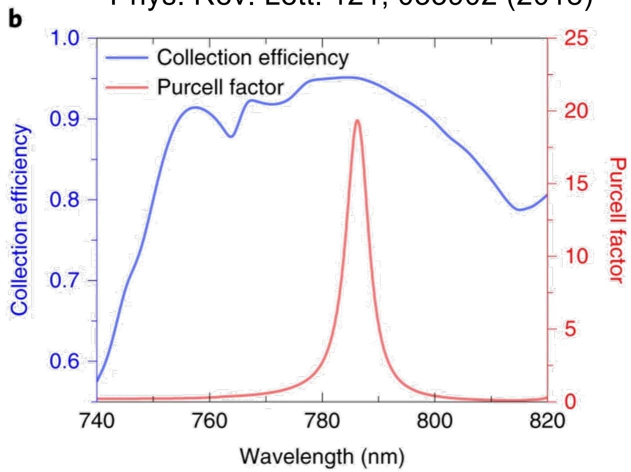




$$|\psi_+\rangle = \frac{|R_{XX}L_X\rangle + |L_{XX}R_X\rangle}{\sqrt{2}}$$



Phys. Rev. Lett. 121, 033902 (2018)

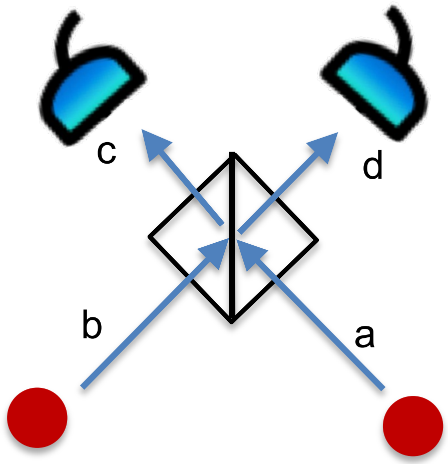


Nat. Nano. 14, 586–593 (2019)

Opération centrale pour les réseaux : mesure de Bell

Mesure de Bell

mesure conjointe à deux qubits dans la base des états de Bell, permettant la discrimination partielle de ces états intriqués.



Etat à deux photons

$$|\psi\rangle = \alpha|HH\rangle + \beta|HV\rangle + \gamma|VH\rangle + \delta|VV\rangle$$

$$|HH\rangle = \frac{1}{\sqrt{2}}(|\Phi^+\rangle + |\Phi^-\rangle)$$

$$|HV\rangle = \frac{1}{\sqrt{2}}(|\Psi^+\rangle + |\Psi^-\rangle)$$

$$|VH\rangle = \frac{1}{\sqrt{2}}(|\Psi^+\rangle - |\Psi^-\rangle)$$

$$|VV\rangle = \frac{1}{\sqrt{2}}(|\Phi^+\rangle - |\Phi^-\rangle)$$

$$a^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

$$|\psi\rangle = \frac{\alpha+\delta}{\sqrt{2}}|\Phi^+\rangle + \frac{\alpha-\delta}{\sqrt{2}}|\Phi^-\rangle + \frac{\beta+\gamma}{\sqrt{2}}|\Psi^+\rangle + \frac{\beta-\gamma}{\sqrt{2}}|\Psi^-\rangle$$

Opération centrale pour les réseaux : mesure de Bell

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Mesure de Bell

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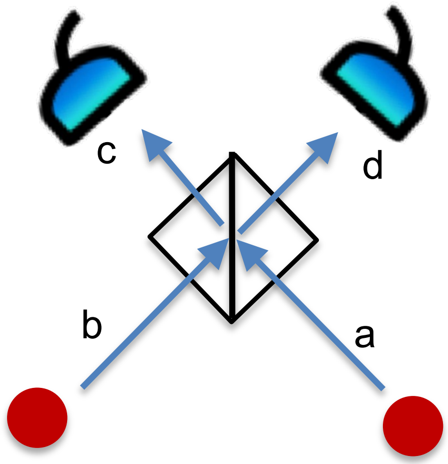


Etat à deux photons

$$|\psi\rangle = \alpha|HH\rangle + \beta|HV\rangle + \gamma|VH\rangle + \delta|VV\rangle$$

$$|HH\rangle = \frac{1}{\sqrt{2}}(|\Phi^+\rangle + |\Phi^-\rangle)$$

$$|HV\rangle = \frac{1}{\sqrt{2}}(|\Psi^+\rangle + |\Psi^-\rangle)$$

$$|VH\rangle = \frac{1}{\sqrt{2}}(|\Psi^+\rangle - |\Psi^-\rangle)$$

$$|VV\rangle = \frac{1}{\sqrt{2}}(|\Phi^+\rangle - |\Phi^-\rangle)$$

$$a^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

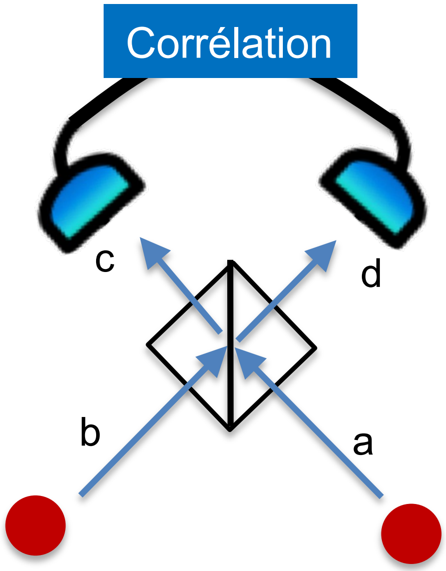
$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

Opération centrale pour les réseaux : mesure de Bell

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger b_V^\dagger - a_V^\dagger b_H^\dagger)|0\rangle.$$

$$a_H^\dagger b_V^\dagger - a_V^\dagger b_H^\dagger \rightarrow \frac{1}{2}\left[(c_H^\dagger c_V^\dagger - c_V^\dagger c_H^\dagger) - (c_H^\dagger d_V^\dagger - c_V^\dagger d_H^\dagger) + (d_H^\dagger c_V^\dagger - d_V^\dagger c_H^\dagger) - (d_H^\dagger d_V^\dagger - d_V^\dagger d_H^\dagger)\right]$$

$$|\Psi^-\rangle \rightarrow \frac{1}{\sqrt{2}}(c_V^\dagger d_H^\dagger - c_H^\dagger d_V^\dagger)|0\rangle.$$



⇒ Sortie sur deux chemins différents

$$a^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

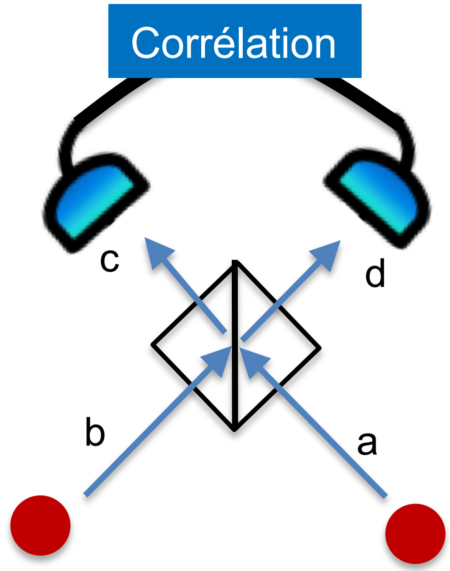
$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

Opération centrale pour les réseaux : mesure de Bell

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger b_V^\dagger + a_V^\dagger b_H^\dagger)|0\rangle$$

$$a_H^\dagger b_V^\dagger + a_V^\dagger b_H^\dagger \to \frac{1}{2}\left[(c_H^\dagger c_V^\dagger + c_V^\dagger c_H^\dagger) - (\cancel{c_H^\dagger d_V^\dagger} + \cancel{c_V^\dagger d_H^\dagger}) + (\cancel{d_H^\dagger c_V^\dagger} + \cancel{d_V^\dagger c_H^\dagger}) - (d_H^\dagger d_V^\dagger + d_V^\dagger d_H^\dagger)\right]$$

$$|\Psi^+\rangle \to \frac{1}{\sqrt{2}}(c_H^\dagger c_V^\dagger - d_H^\dagger d_V^\dagger)|0\rangle$$



⇒ Sortie sur même chemin avec polarisation orthogonale

$$a^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \to \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

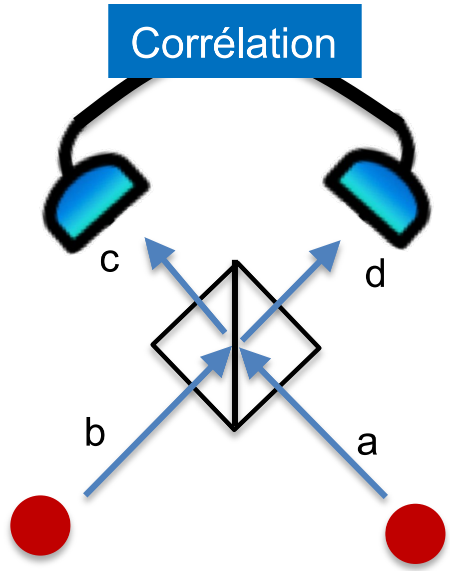
$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

Opération centrale pour les réseaux : mesure de Bell

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger b_H^\dagger \pm a_V^\dagger b_V^\dagger)|0\rangle.$$

$$|\Phi^{\pm}\rangle \rightarrow \frac{1}{2\sqrt{2}}\left[c_H^{\dagger 2} \pm c_V^{\dagger 2} - (d_H^{\dagger 2} \pm d_V^{\dagger 2})\right]|0\rangle$$

⇒ Sortie sur même chemin avec même polarisation



$$a^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

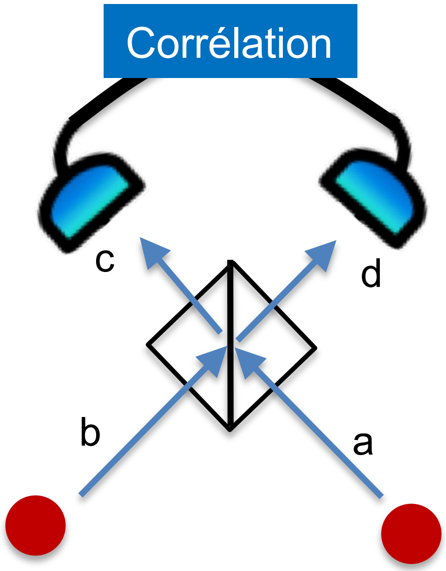
Opération centrale pour les réseaux : mesure de Bell

$$|\Psi^-\rangle \rightarrow \frac{1}{\sqrt{2}}(c_V^\dagger d_H^\dagger - c_H^\dagger d_V^\dagger)|0\rangle$$

Double clic c&d → Annonce $|\Psi^-\rangle$

$$|\Psi^+\rangle \rightarrow \frac{1}{\sqrt{2}}(c_H^\dagger c_V^\dagger - d_H^\dagger d_V^\dagger)|0\rangle$$

Sortie sur même chemin avec polarisation orthogonale



$$a^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

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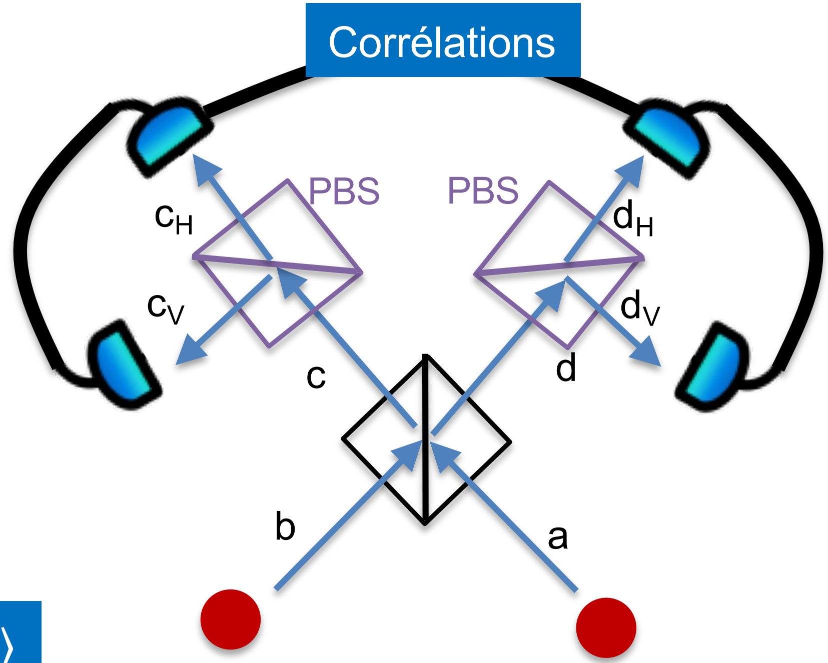
Opération centrale pour les réseaux : mesure de Bell



$$|\Psi^-\rangle \rightarrow \frac{1}{\sqrt{2}}(c_V^\dagger d_H^\dagger - c_H^\dagger d_V^\dagger)|0\rangle$$

➡ Double clic c&d ➡ Annonce $|\Psi^-\rangle$

$$|\Psi^+\rangle \rightarrow \frac{1}{\sqrt{2}}(c_H^\dagger c_V^\dagger - d_H^\dagger d_V^\dagger)|0\rangle$$

➡ Double clic c_H& c_V ou d_H& d_V

➡ Annonce $|\Psi^+\rangle$

$$|\Phi^\pm\rangle \rightarrow \frac{1}{2\sqrt{2}}\left[c_H^{\dagger 2} \pm c_V^{\dagger 2} - (d_H^{\dagger 2} \pm d_V^{\dagger 2})\right]|0\rangle$$

$$a^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger + d^\dagger) \quad b^\dagger \rightarrow \frac{1}{\sqrt{2}}(c^\dagger - d^\dagger)$$

➡ Sortie sur même chemin avec même polarisation

$$|\psi\rangle = \alpha'|\Phi^+\rangle + \beta'|\Phi^-\rangle + \gamma'|\Psi^+\rangle + \delta'|\Psi^-\rangle$$

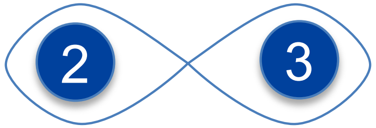
Discrimition des deux états de Bell $|\Psi^-\rangle$ et $|\Psi^+\rangle$

Téléportation quantique : protocole

Alice : qubit à téléporter

$$| \psi_1 \rangle = \alpha \mid H_1 \rangle + \beta \mid V_1 \rangle$$

Bob: paires de photons intriqués



$$|\psi_{23}\rangle = \frac{|H_2 V_3\rangle - |V_2 H_3\rangle}{\sqrt{2}}$$

$$|\Psi\rangle_{123} = \alpha \frac{|H_1 H_2 V_3\rangle}{\sqrt{2}} - \alpha \frac{|H_1 V_2 H_3\rangle}{\sqrt{2}} + \beta \frac{|V_1 H_2 V_3\rangle}{\sqrt{2}} - \beta \frac{|V_1 V_2 H_3\rangle}{\sqrt{2}}$$

$$| \psi_1 \rangle \otimes | \psi_{23} \rangle = \frac{1}{2} [| \Psi^- \rangle_{12} (\alpha \mid H \rangle + \beta \mid V \rangle)_3 + | \Psi^+ \rangle_{12} (\alpha \mid H \rangle - \beta \mid V \rangle)_3$$
$$+ | \Phi^- \rangle_{12} (\beta \mid H \rangle + \alpha \mid V \rangle)_3 + | \Phi^+ \rangle_{12} (\beta \mid H \rangle - \alpha \mid V \rangle)_3]$$

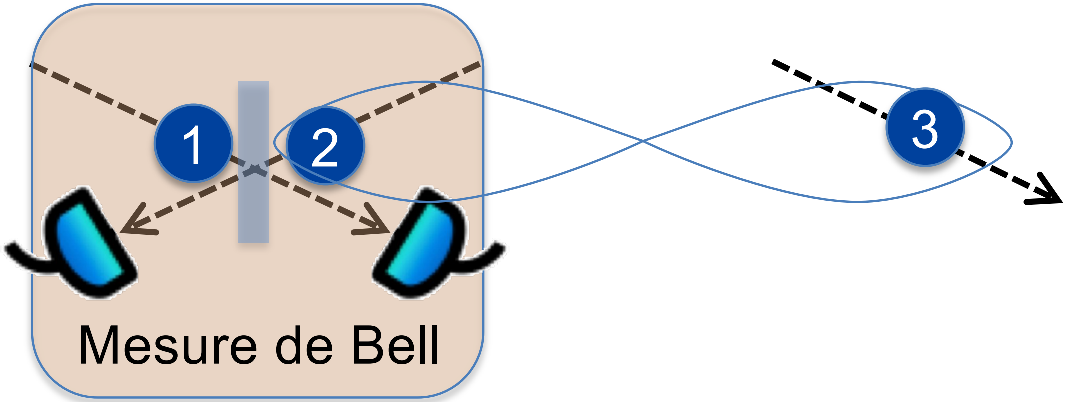
Téléportation quantique : protocole

Alice : qubit à téléporter

$$|\psi_1\rangle = \alpha\,|H_1\rangle + \beta\,|V_1\rangle$$

Bob: paires de photons intriqués

$$|\psi_{23}\rangle = \frac{|H_2V_3\rangle - |V_2H_3\rangle}{\sqrt{2}}$$



$$|\psi_1\rangle \otimes |\psi_{23}\rangle = \frac{1}{2}[|\Psi^-\rangle_{12}(\alpha\,|H\rangle + \beta\,|V\rangle)_3 + |\Psi^+\rangle_{12}(\alpha\,|H\rangle - \beta\,|V\rangle)_3$$
$$+|\Phi^-\rangle_{12}(\beta\,|H\rangle + \alpha\,|V\rangle)_3 + |\Phi^+\rangle_{12}(\beta\,|H\rangle - \alpha\,|V\rangle)_3]$$

Qubit transféré du photon 1 au photon 3

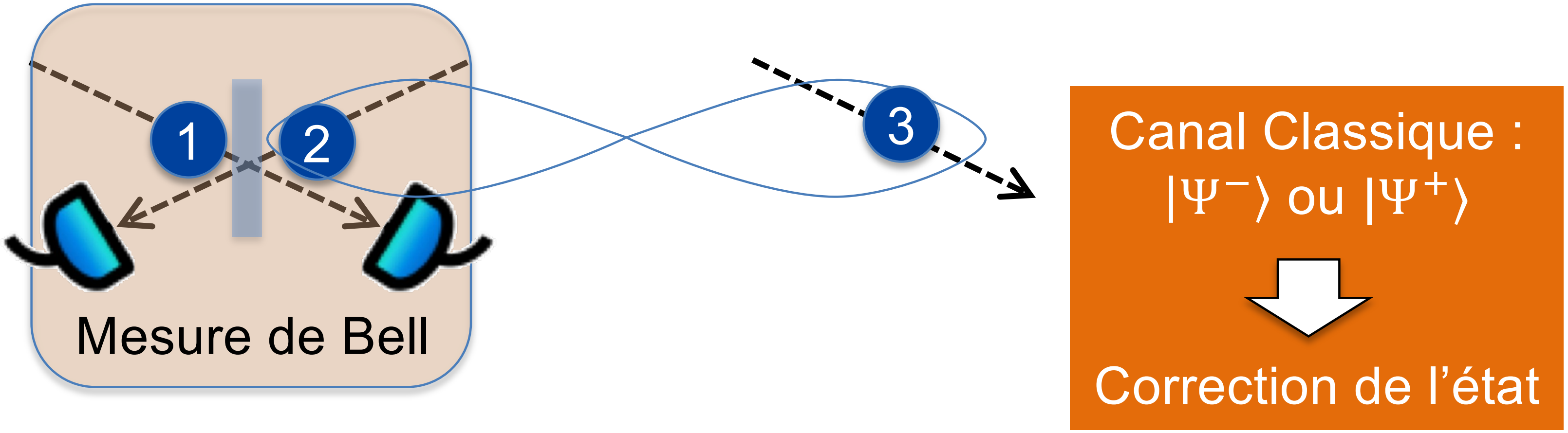
Téléportation quantique : protocole

Alice : qubit à téléporter

$$|\psi_1\rangle = \alpha\,|H_1\rangle + \beta\,|V_1\rangle$$

Bob: paires de photons intriqués

$$|\psi_{23}\rangle = \frac{|H_2V_3\rangle - |V_2H_3\rangle}{\sqrt{2}}$$

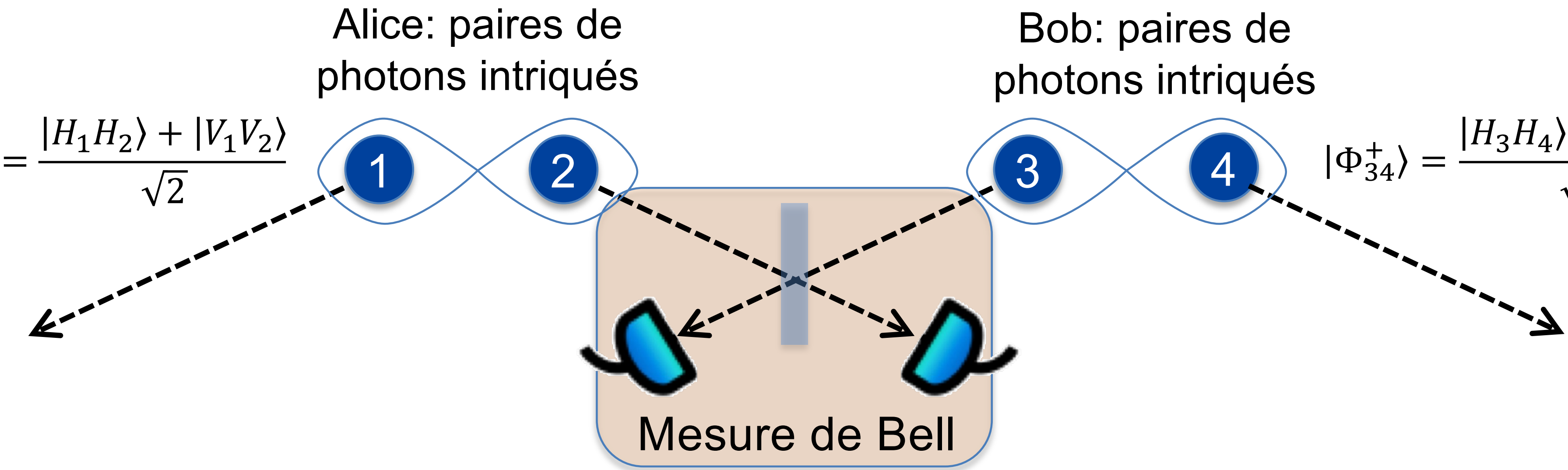


$$|\psi_1\rangle \otimes |\psi_{23}\rangle = \frac{1}{2}[|\Psi^-\rangle_{12}(\alpha\,|H\rangle + \beta\,|V\rangle)_3 + |\Psi^+\rangle_{12}(\alpha\,|H\rangle - \beta\,|V\rangle)_3$$
$$+ |\Phi^-\rangle_{12}(\beta\,|H\rangle + \alpha\,|V\rangle)_3 + |\Phi^+\rangle_{12}(\beta\,|H\rangle - \alpha\,|V\rangle)_3]$$

Qubit transféré du photon 1 au photon 3 avec correction de phase

Transfert d'intrication : protocole

$$|\Phi_{12}^{+}\rangle = \frac{|H_1H_2\rangle + |V_1V_2\rangle}{\sqrt{2}} \qquad |\Phi_{34}^{+}\rangle = \frac{|H_3H_4\rangle + |V_3V_4\rangle}{\sqrt{2}}$$



$$|\Phi^{+}\rangle_{12}|\Phi^{+}\rangle_{34} = \frac{1}{2}(|\Phi^{+}\rangle_{23}|\Phi^{+}\rangle_{14} + |\Phi^{-}\rangle_{23}|\Phi^{-}\rangle_{14} + |\Psi^{+}\rangle_{23}|\Psi^{+}\rangle_{14} + |\Psi^{-}\rangle_{23}|\Psi^{-}\rangle_{14})$$

Intrication des photons 1 et 4 après mesure de 2 et 3 dans $|\Psi^{-}\rangle_{23}$

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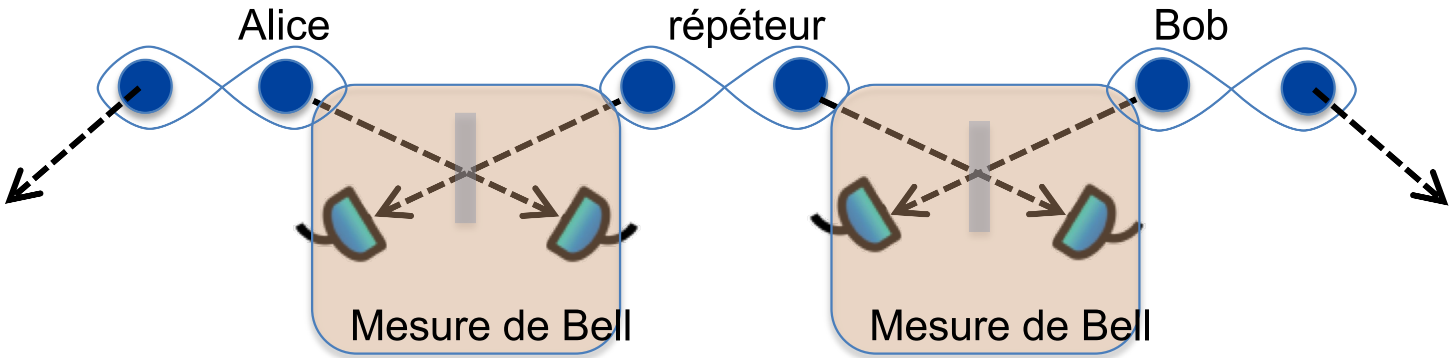
Transfert d'intrication photonique : quel gain en distance ?



$$p(\ell) = p_0\, e^{-\ell/L_{\text{att}}}$$

On découpe L en N segments : $\ell = L/N$.

Condition de succès sur un essai synchrone :

- les N liens élémentaires réussissent *simultanément*
- les $N-1$ mesures de Bell (swappings) réussissent

$$P(L,N) = p(\ell)^N p_{BSM}^{N-1}$$

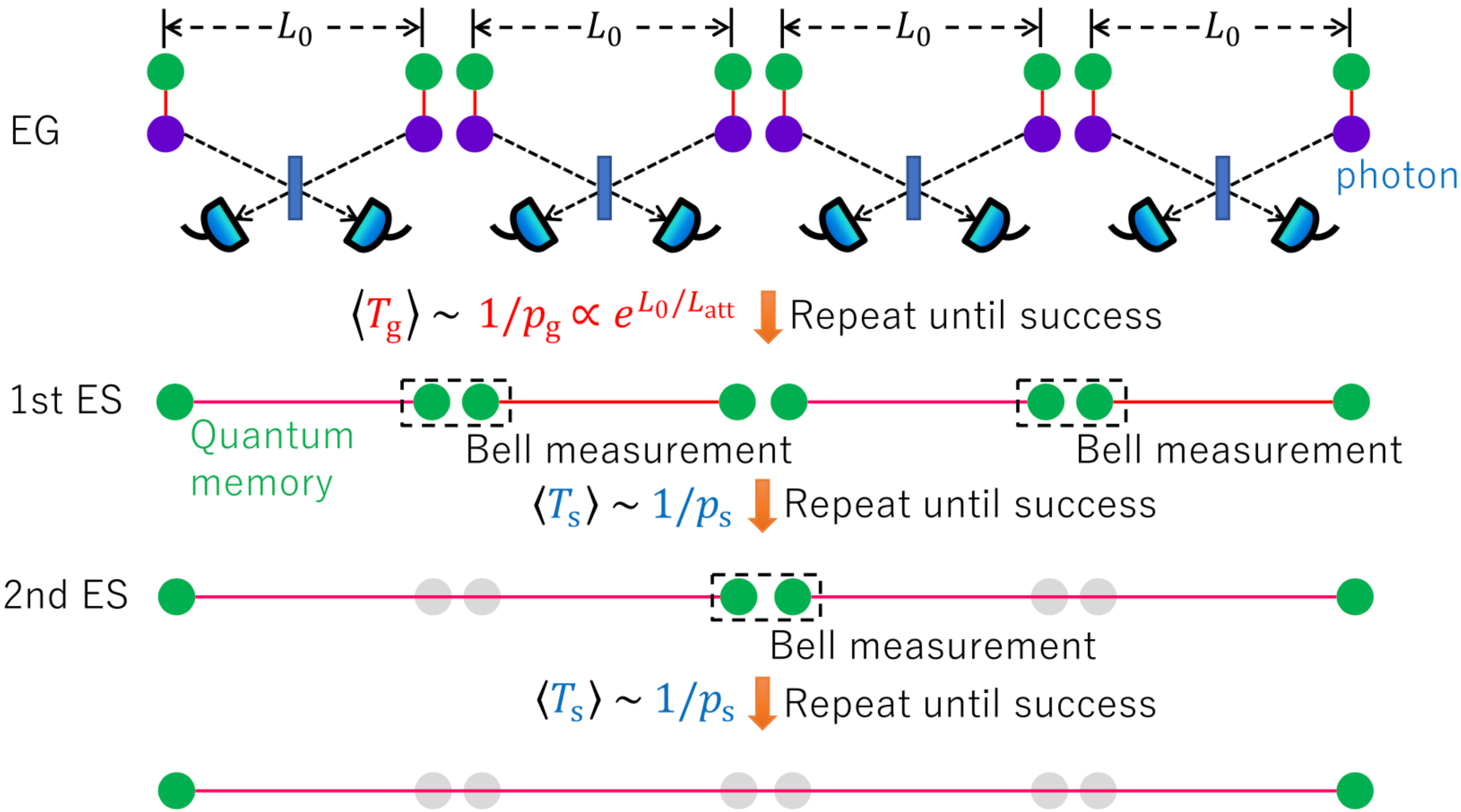
Probabilité de succès de transfert d'une information sur un essai "synchrone"

$$P(L,N) = p_0^N e^{-L/L_{att}} p_{BSM}^{N-1}$$

Mémoires quantiques nécessaires pour étendre la distance

Journal of Modern Optics, *52*(5), 735–753 (2007)

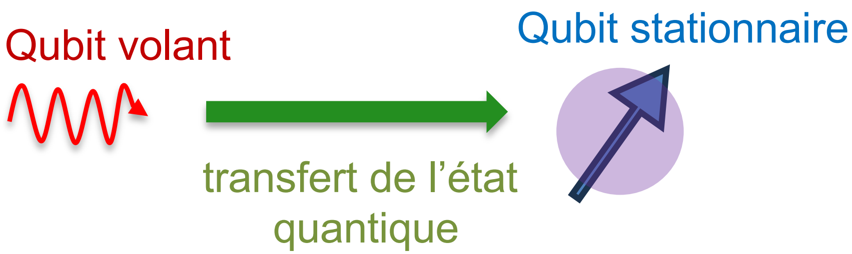
Exemple d'architecture de répéteurs quantiques

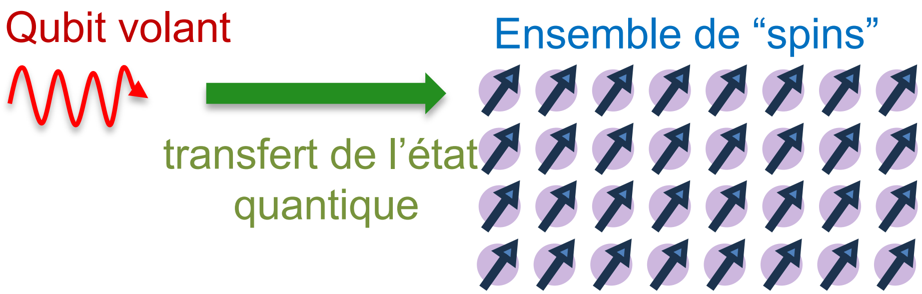


Rev. Mod. Phys. 95, 045006 (2023)

Mémoires et interfaces quantiques

Mémoire : stocker l’information





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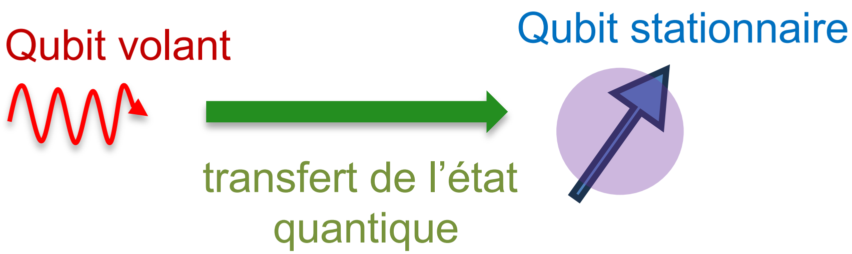
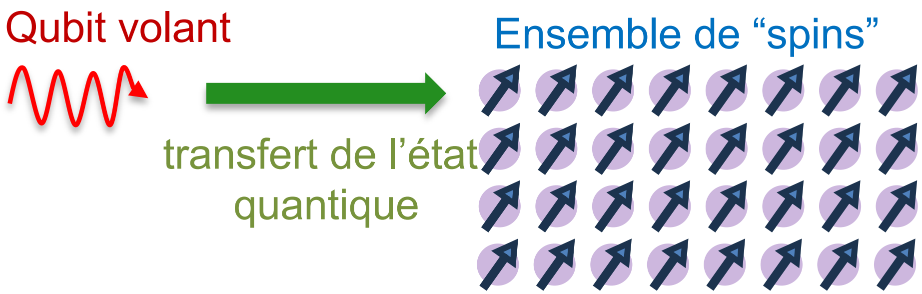
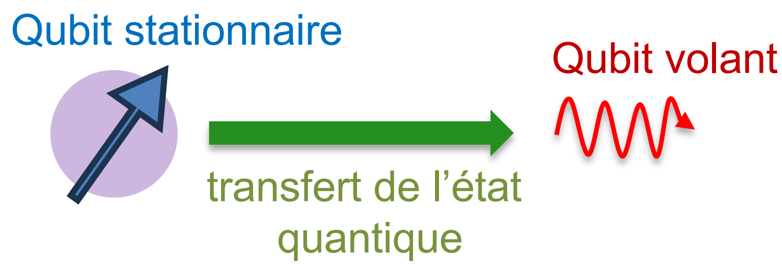
Mémoires et interfaces quantiques

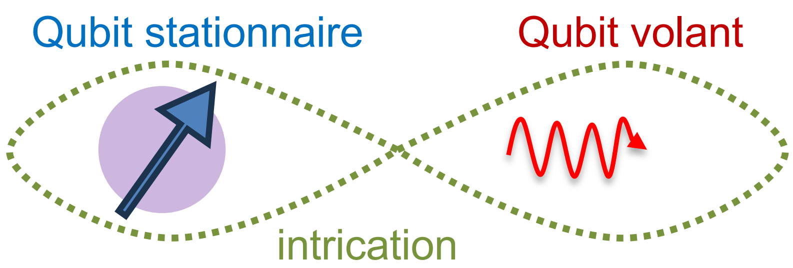
Mémoire : stocker l'information





Interface : distribuer l'intrication





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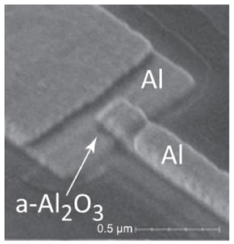
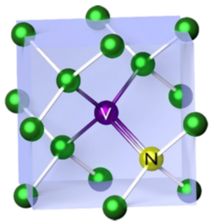
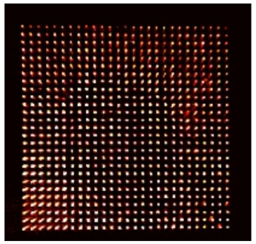
DE FRANCE
1530

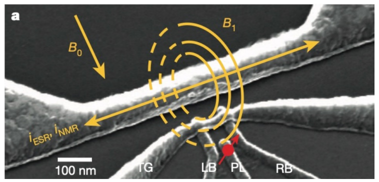
Interfaces et mémoires quantiques à un spin*

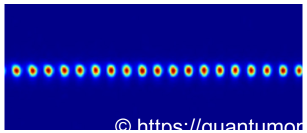
(*) spin au sens qubit de matière: atome, ions, boite quantique, centre coloré, qubit supra-conducteur etc

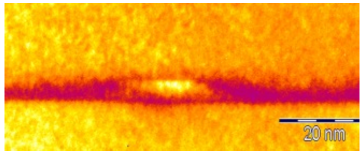






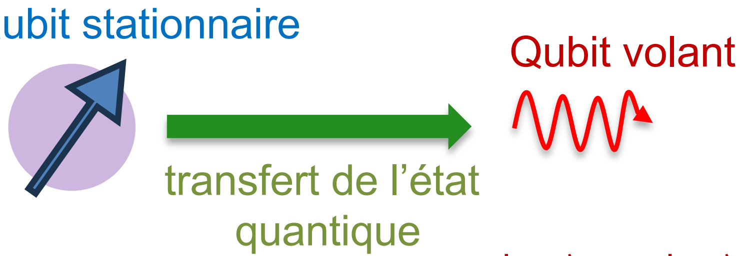






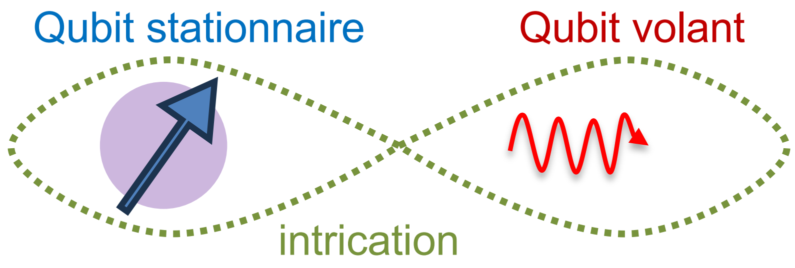
Interface quantique

Fonctions recherchées



$|\psi_S\rangle = \alpha|0_S\rangle + \beta|1_S\rangle$

$|\psi_V\rangle = \alpha|0_V\rangle + \beta|1_V\rangle$



$$|\Psi\rangle = \frac{|0_S 0_V\rangle + |1_S 1_V\rangle}{\sqrt{2}}$$

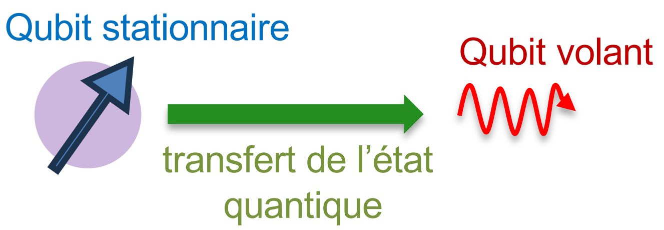
$|\psi_V\rangle = \alpha|0_V\rangle + \beta|1_V\rangle$

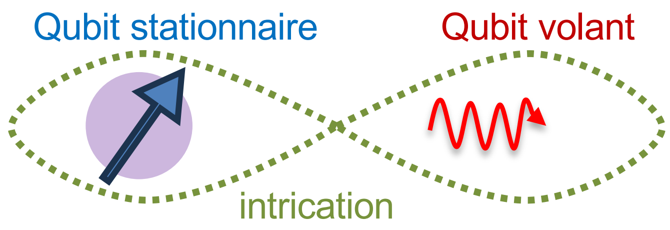
$|\psi_S\rangle = \alpha|0_S\rangle + \beta|1_S\rangle$

Interfaces quantiques

Métriques

- Fidélité du transfert, de l'intrication

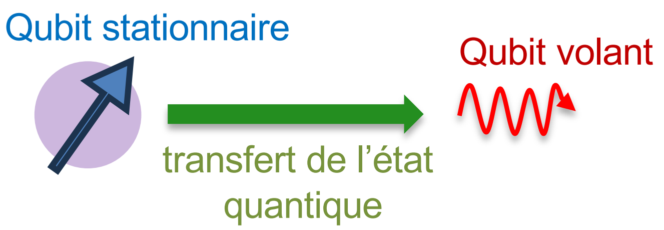


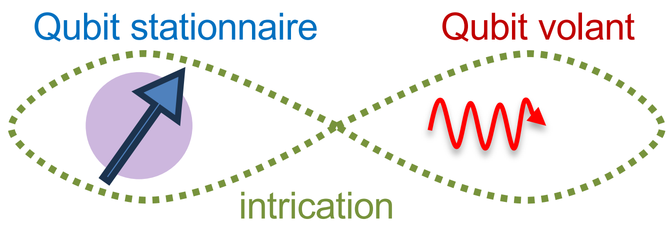


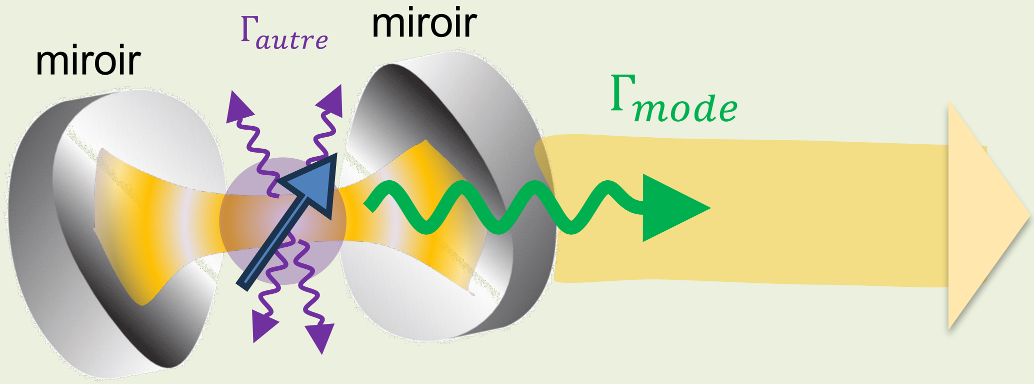
Interfaces quantiques

Métriques

- Fidélité du transfert, de l'intrication
- Efficacité







Fraction émise dans le mode de cavité

$$\beta = \frac{\Gamma_{mode}}{\Gamma_{mode} + \Gamma_{autre}}$$

Cf. cours 4

E. M. Purcell - Phys. Rev. 69, 681 (1946)

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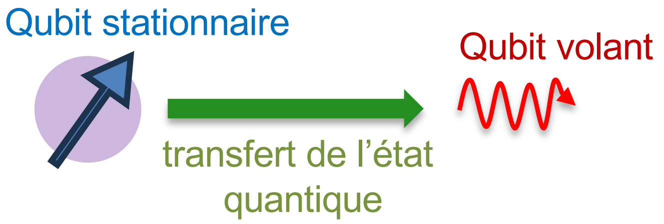
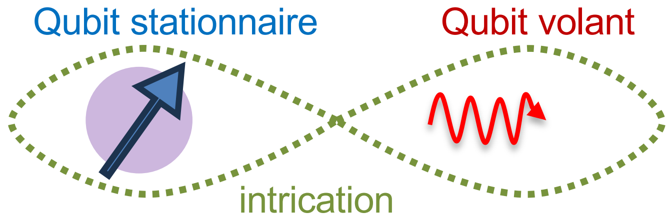
Interfaces quantiques

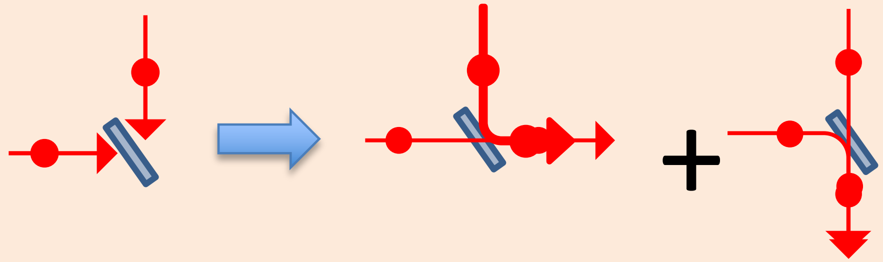
Métriques

- Fidélité du transfert, de l'intrication
- Efficacité
- Indiscernabilité des photons





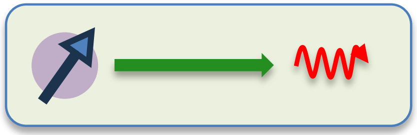
Cf. cours 5

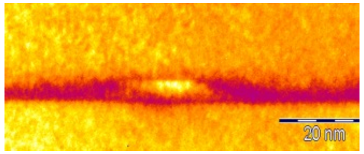


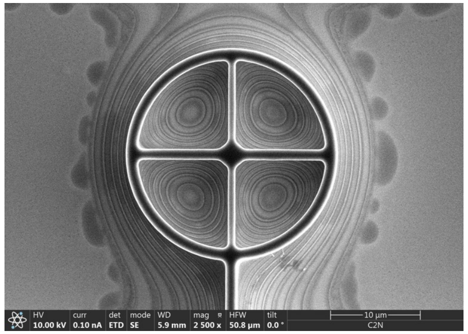
indiscernabilité pour mesure de Bell

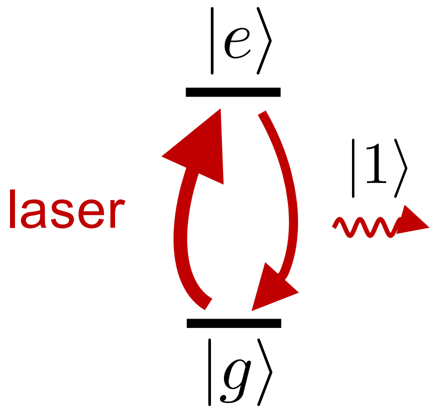
$$|\psi_{\text{in}}\rangle = \hat{a}_a^\dagger\,\hat{a}_b^\dagger\,|0\rangle \;\Longrightarrow\; |\psi_{\text{out}}\rangle = \frac{-i}{2}\left((\hat{a}_c^\dagger)^2 + (\hat{a}_d^\dagger)^2\right)|0\rangle = \frac{-i}{\sqrt{2}}\left(\,|2,0\rangle + |0,2\rangle\,\right)$$

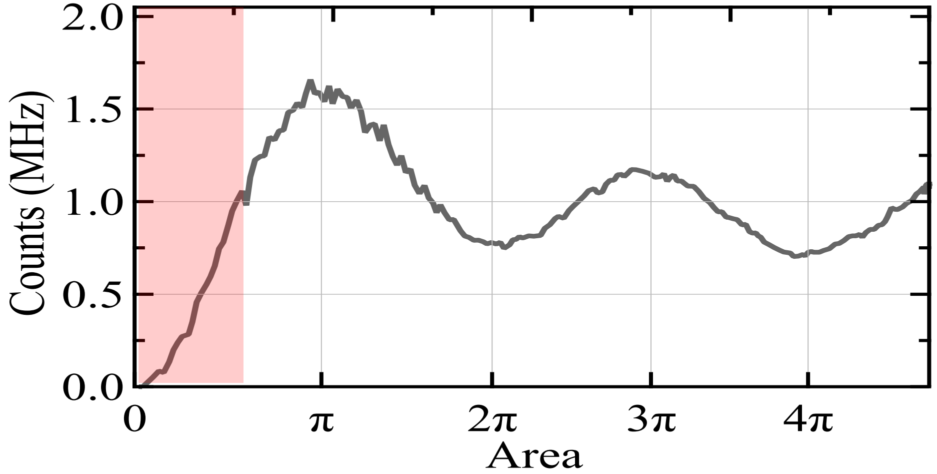
Transfert de l'information quantique : stationnaire vers volant



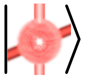








Etat atomique

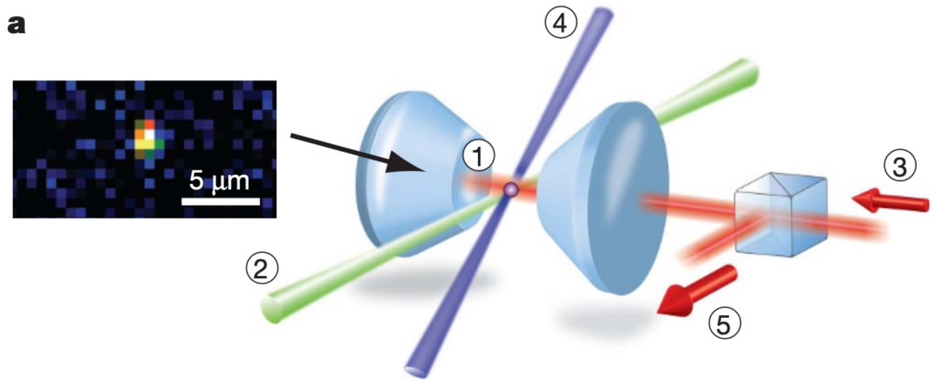
$|$$\rangle = c_g|g\rangle + c_e|e\rangle$ →

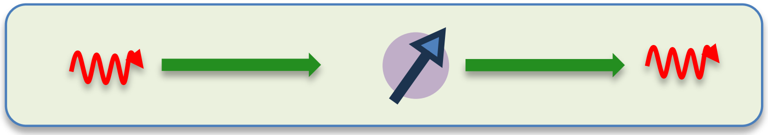
Photonic state

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

Nature Photonics 13, 803 (2019)

Transfert de l'information : volant - stationnaire - volant

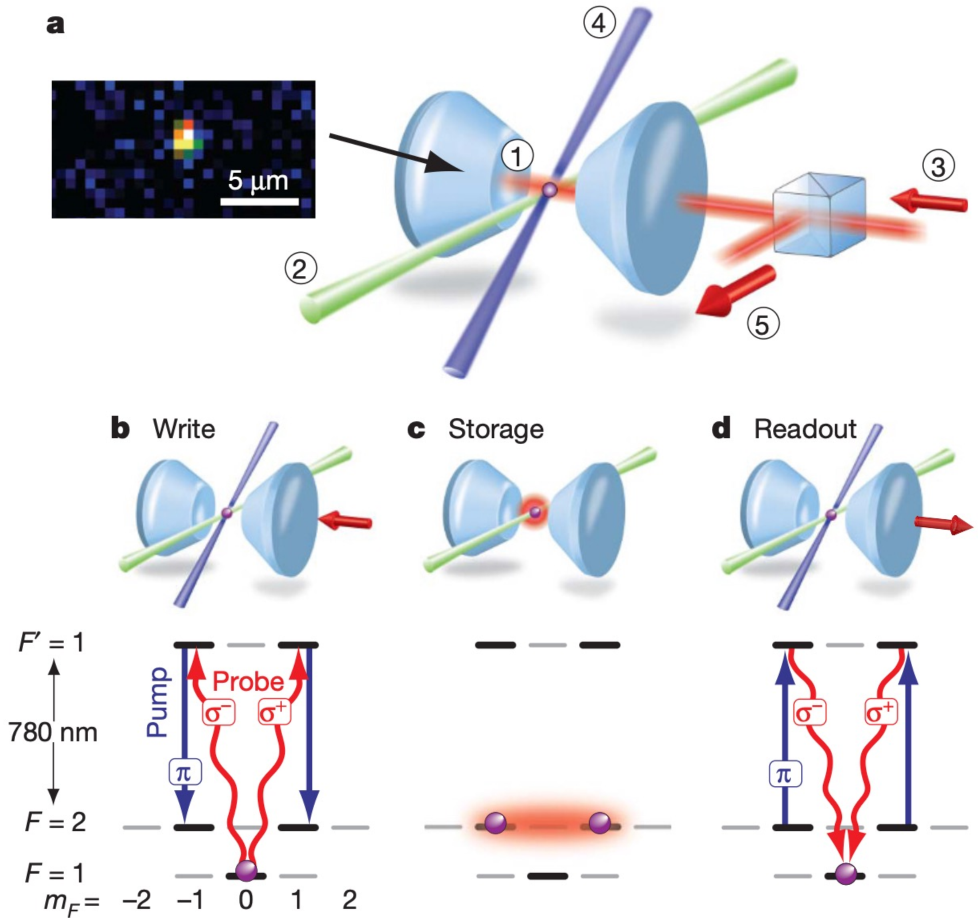


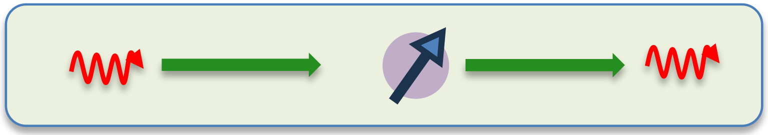


Nature volume 473, 190–193 (2011)

Phys. Rev. Lett. 98, 063601 (2007)

Transfert de l'information : volant - stationnaire - volant

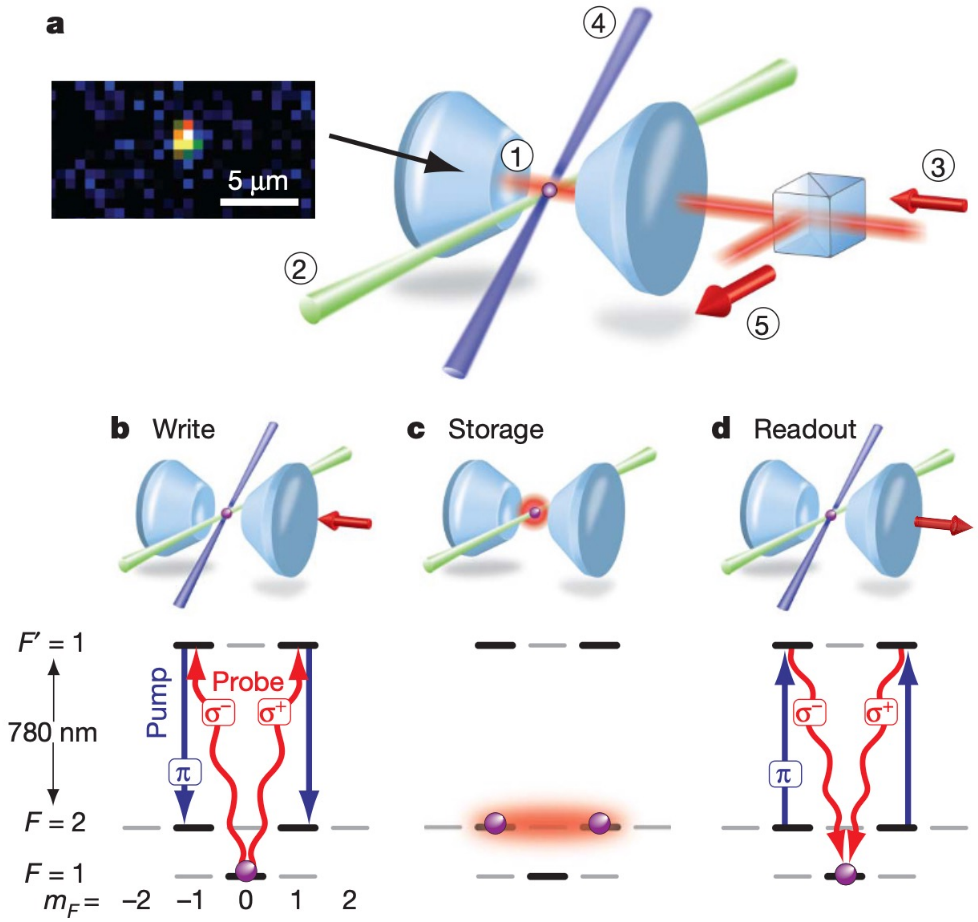


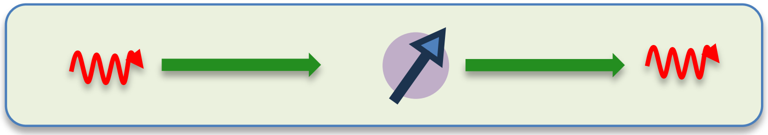


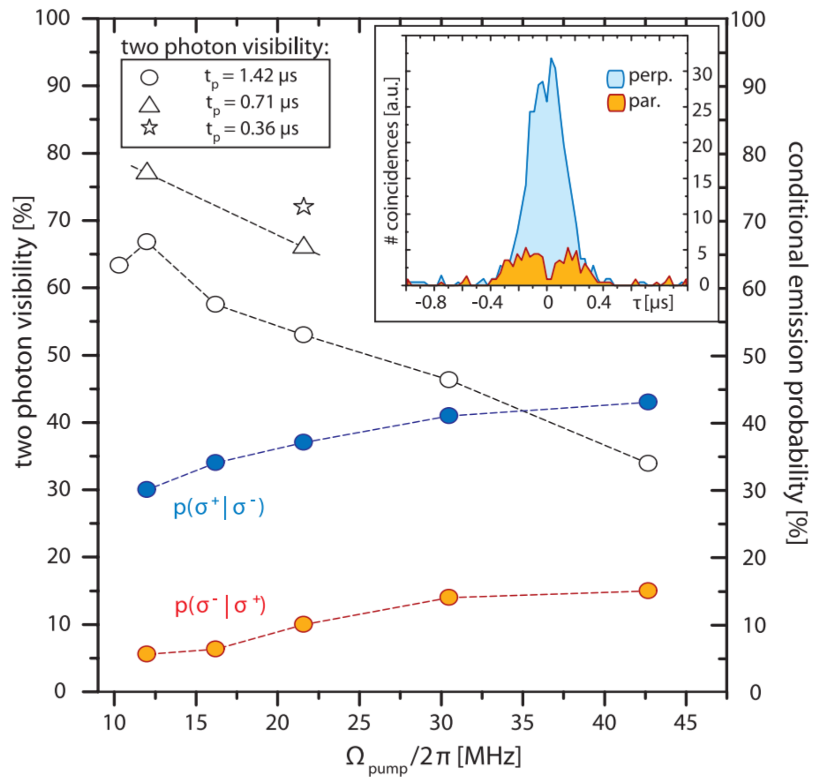
Nature volume 473, 190–193 (2011)

Phys. Rev. Lett. 98, 063601 (2007)

Transfert de l'information : volant - stationnaire - volant







Nature volume 473, 190–193 (2011)

Phys. Rev. Lett. 98, 063601 (2007)

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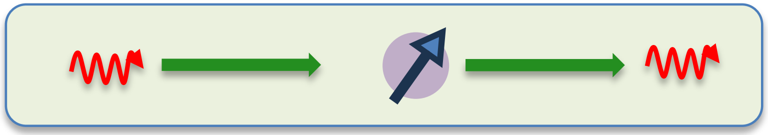
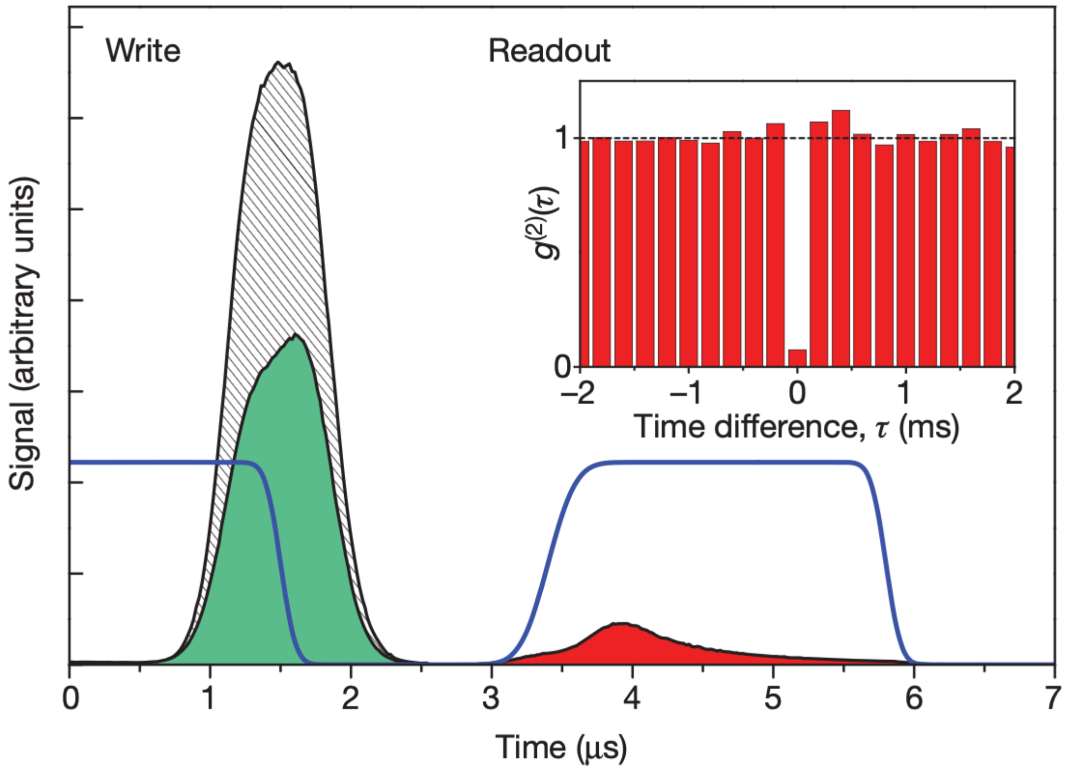
Transfert de l'information : volant - stationnaire - volant

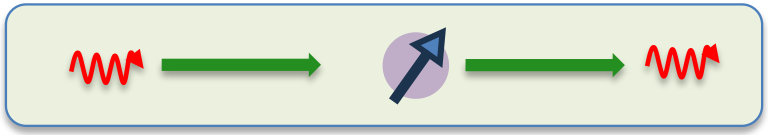


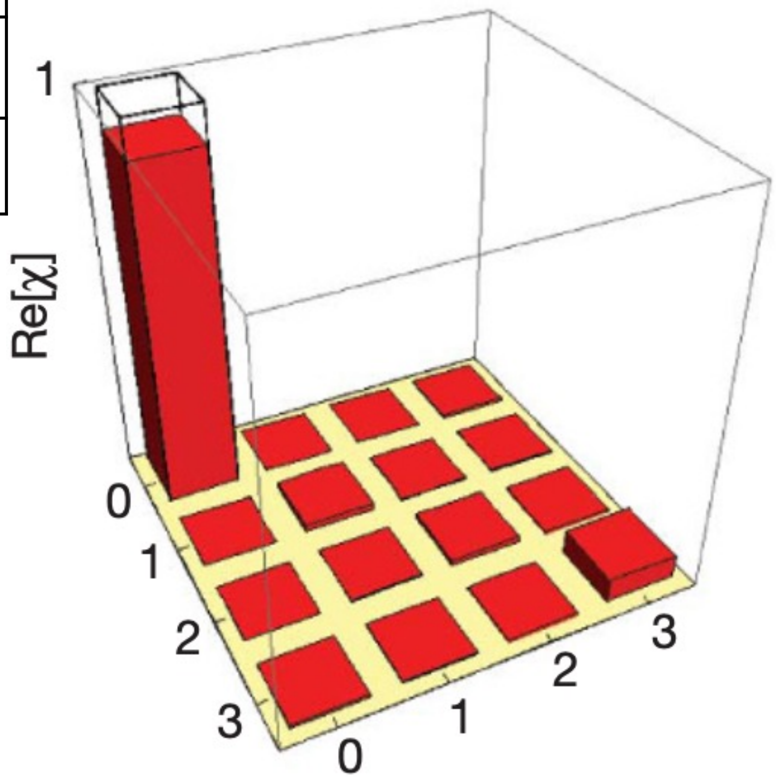


Nature volume 473, 190–193 (2011)

Transfert de l'information : volant - stationnaire - volant

0	I
1	σ_x
2	σ_y
3	σ_z





Tomographie du transfert d'information
(process tomography)

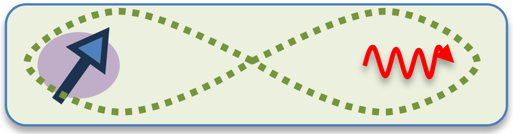
$$\mathcal{E}(\rho) = \sum_{m,n=0}^{3} \chi_{mn}\,\sigma_m \rho \sigma_n^\dagger$$

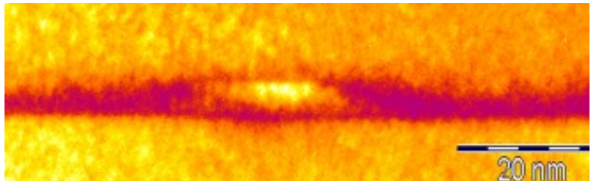
Erreurs

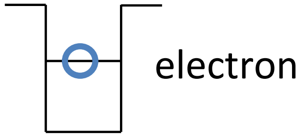
σ_x → flip dans la base H/V
σ_y → rotation complexe
σ_z → déphasage entre |R⟩ et |L⟩

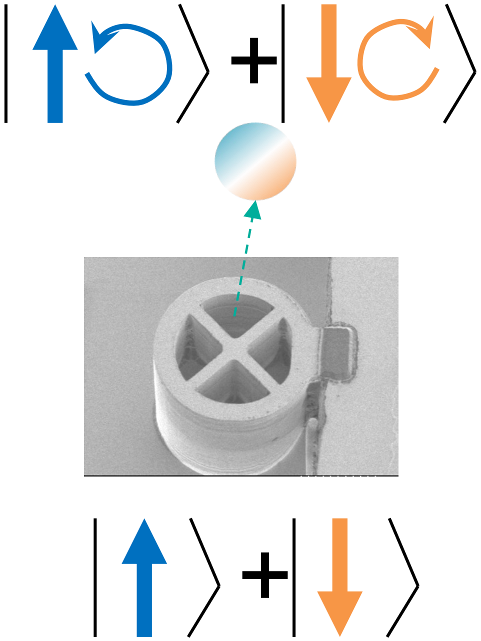
Nature volume 473, 190–193 (2011)

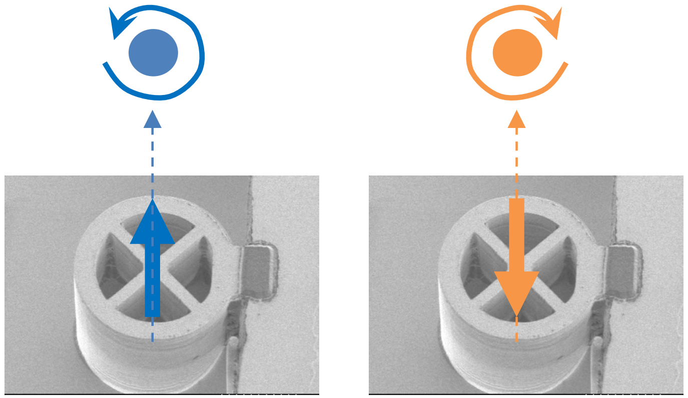
Interfaces : qubit spin dans une boite quantique - photon

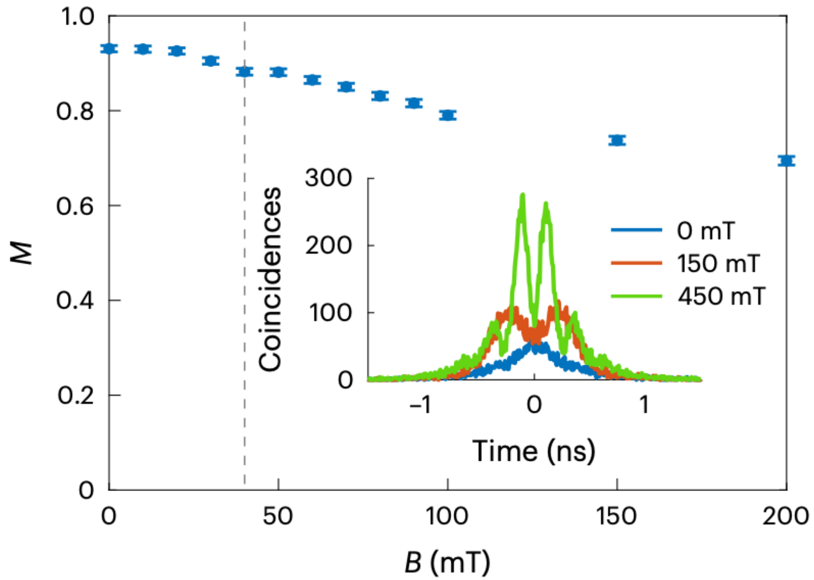












Cf. cours 5

Nature Photonics 17, 582 (2023)

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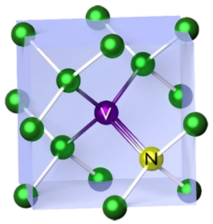
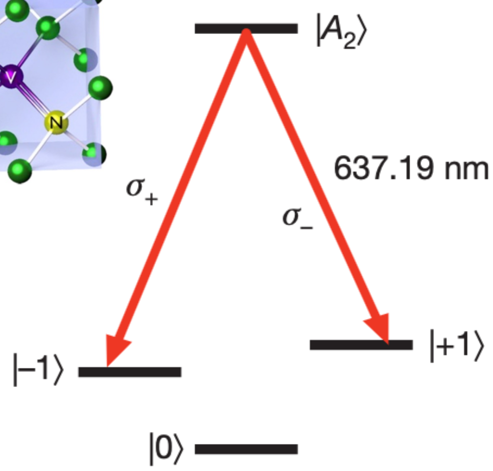
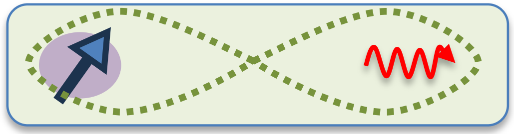
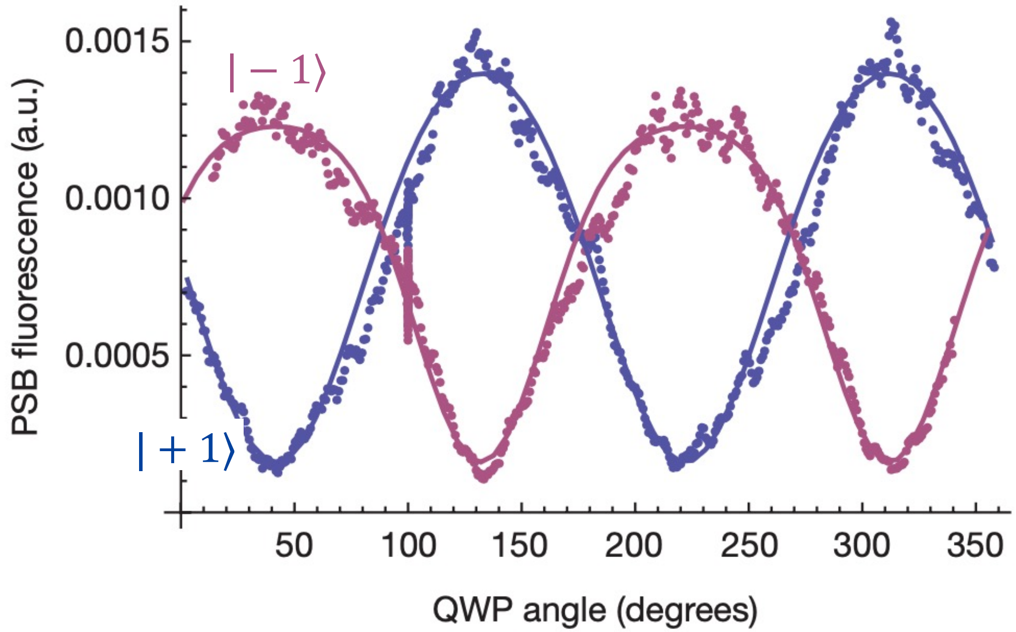
Interfaces : intrication spin-photon – centre NV









A_2 Etat intriqué entre spin et moment orbital

$$|A_2\rangle = \frac{1}{\sqrt{2}}(|E_-\rangle|+1\rangle + |E_+\rangle|-1\rangle)$$

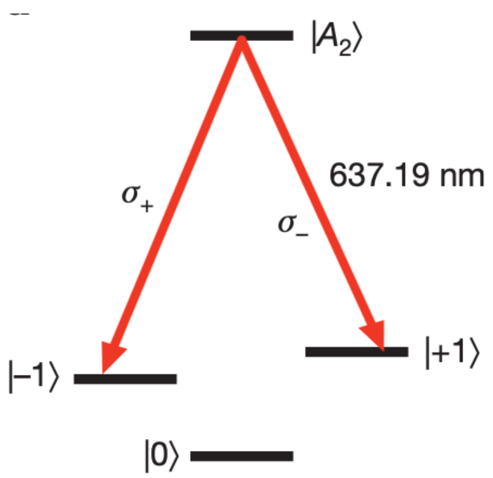
émission

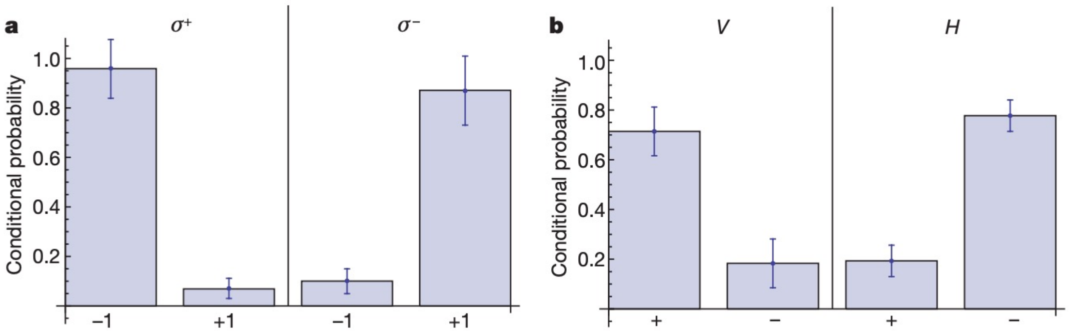
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\sigma_-\rangle|+1\rangle + |\sigma_+\rangle|-1\rangle)$$

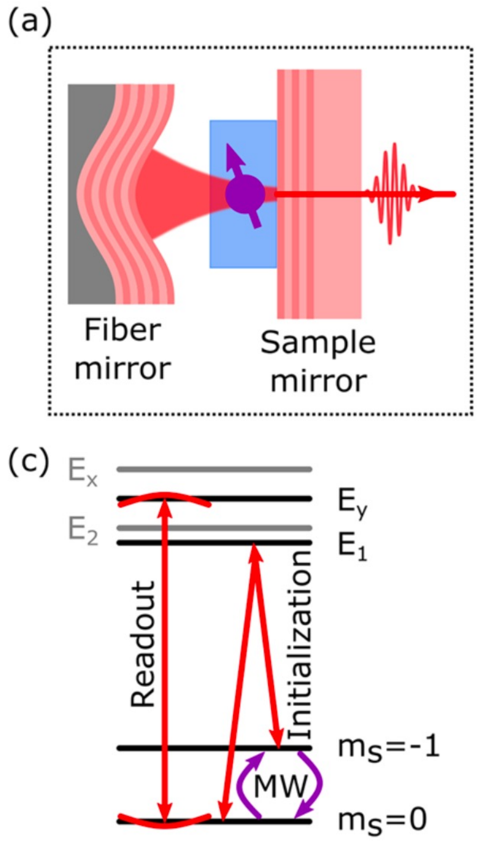
Nature 466, 730–734 (2010)

COLLÈGE DE FRANCE 1530

Interfaces : intrication spin-photon – centre NV







Nature Communications 16, 11680 (2025)

Nature 466, 730–734 (2010)

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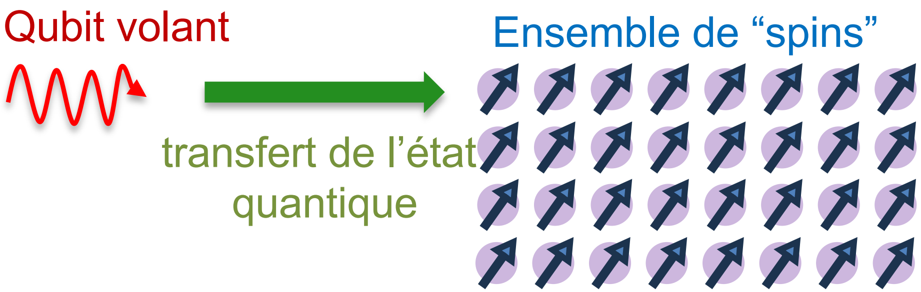
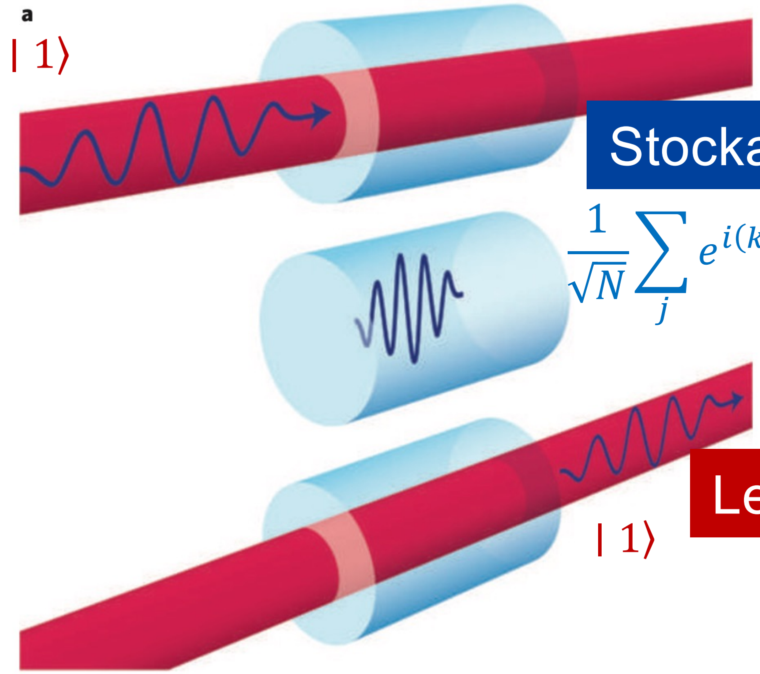
Mémoires quantiques à ensemble de spins



Mémoire quantique : excitation collective

$| G \rangle = | g_1 g_2 \ldots g_N \rangle$

Ecriture



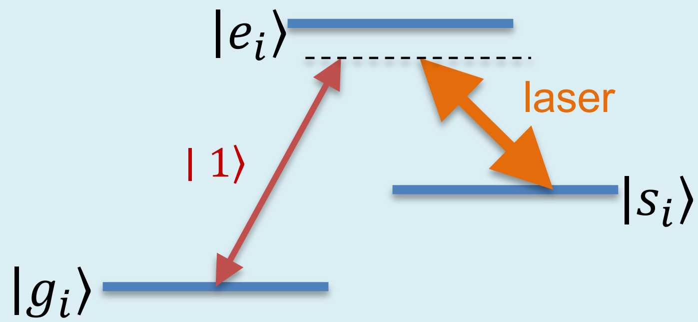
Stockage "onde de spins"

$$\frac{1}{\sqrt{N}} \sum_j e^{i(k_s - k_c) z_j} \left| g \ldots s_j \ldots g \right\rangle$$

Lecture

$| G \rangle = | g_1 g_2 \ldots g_N \rangle$

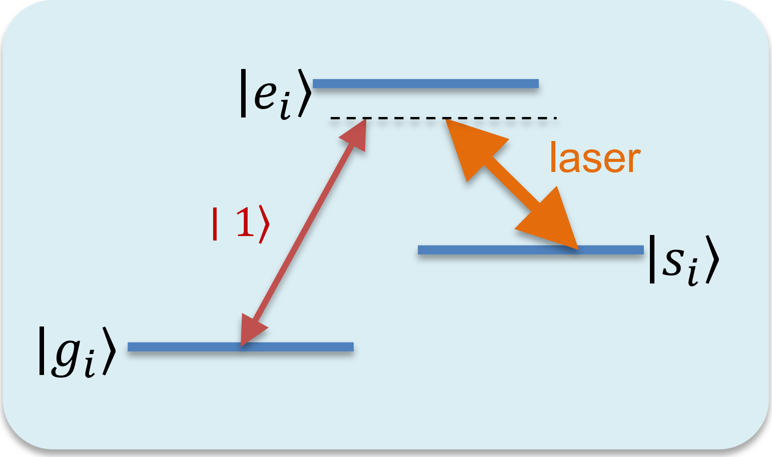
Mémoire :
N>>1 systèmes en "lambda"



Nature Photonics 3, 706–714 (2009)

Rev. Mod. Phys. 82, 1041 (2010)

Mémoire quantique : excitation collective



En representation d'interaction (cf. cours 6)

$$H = \hbar \sum_{j=1}^{N} [g\ e^{ik_s z_j}\ \hat{a}\ |e_j\rangle\langle g_j| + \Omega_c(t)\ e^{ik_c z_j}\ |e_j\rangle\langle s_j| + h.c.]$$

dans le sous-espace à **une excitation totale** :

$$|\psi(t)\rangle = c_p(t)\,|1\rangle\,|G\rangle + \sum_j c_{e_j}(t)\,|0\rangle\,|e_j\rangle + \sum_j c_{s_j}(t)\,|0\rangle\,|s_j\rangle$$

$|G\rangle = |g_1 g_2 \dots g_N\rangle \qquad |e_j\rangle = |g_1 \dots e_j \dots g_N\rangle \qquad |s_j\rangle = |g_1 \dots s_j \dots g_N\rangle$

Equation de Schrödinger

$$\dot{c}_p = -ig \sum_j e^{ik_s z_j} c_{e_j}$$

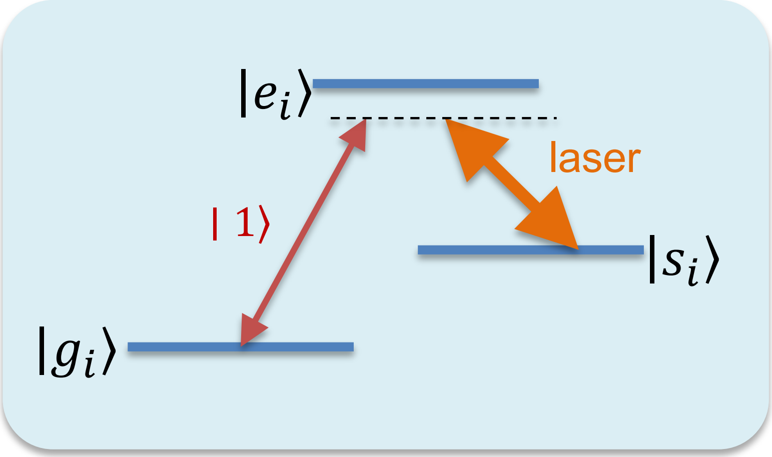
$$\dot{c}_{e_j} = -i\Delta c_{e_j} - ig e^{-ik_s z_j} c_p - i\Omega_c(t) e^{-ik_c z_j} c_{s_j}$$

$$\dot{c}_{s_j} = -i\Omega_c^*(t) e^{ik_c z_j} c_{e_j}$$

$$P(t) = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{ik_s z_j} c_{e_j}(t)$$

$$S(t) = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(k_s - k_c) z_j} c_{s_j}(t)$$

Mémoire quantique : excitation collective



$$P(t) = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{ik_s z_j} c_{e_j}(t) \qquad S(t) = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(k_s - k_c) z_j} c_{s_j}(t)$$

$$|\psi(t)\rangle = c_p(t)\,|1\rangle\,|G\rangle + P(t)\,|0\rangle\,|E_{\text{coll}}\rangle + S(t)\,|0\rangle\,|S_{\text{coll}}\rangle.$$

$$|E_{\text{coll}}\rangle = \frac{1}{\sqrt{N}} \sum_j e^{ik_s z_j}\,|e_j\rangle \qquad |S_{\text{coll}}\rangle = \frac{1}{\sqrt{N}} \sum_j e^{i(k_s-k_c)z_j}\,|s_j\rangle$$

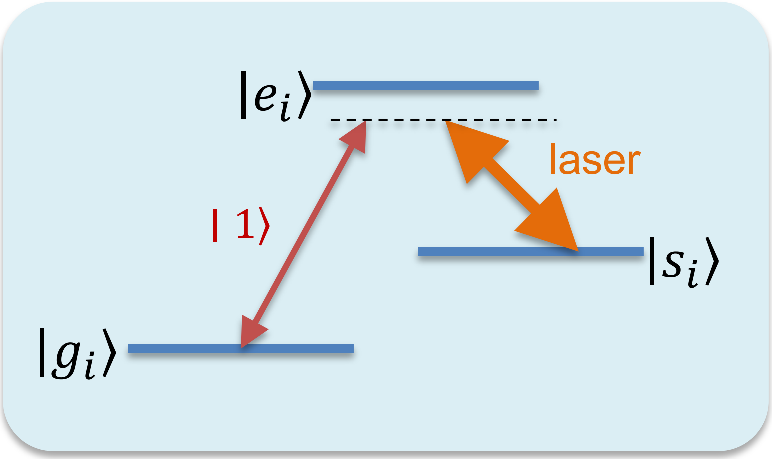
$$\dot{c}_p = -ig\sqrt{N}\,P$$
$$\dot{P} = -i\Delta P - ig\sqrt{N}\,c_p - i\Omega_c(t)S$$
$$\dot{S} = -i\Omega_c^*(t)P$$

$$\dot{P} = P = 0 \Rightarrow \begin{cases} g\sqrt{N}\,c_p + \Omega_c S = 0 \\ \tan\theta(t) = \dfrac{g\sqrt{N}}{\Omega_c(t)} \end{cases}$$

Solution sans excitation dans les états $|e_i\rangle$

$$|D(t)\rangle = \cos\theta(t)\ |1\rangle\,|G\rangle - \sin\theta(t)\ |0\rangle\,|S_{\text{coll}}\rangle$$

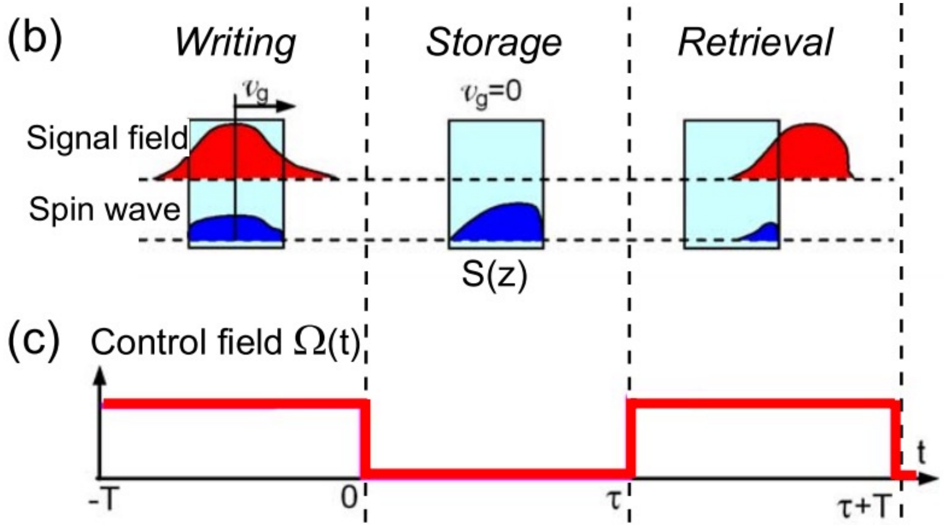
Mémoire quantique : excitation collective



$$\dot{c}_p = -ig\sqrt{N}\,P$$
$$\dot{P} = -i\Delta P - ig\sqrt{N}\,c_p - i\Omega_c(t)S$$
$$\dot{S} = -i\Omega_c^*(t)P$$

$$\dot{P} = P = 0 \Rightarrow \begin{cases} g\sqrt{N}\,c_p + \Omega_c S = 0 \\ \tan\theta\,(t) = \dfrac{g\sqrt{N}}{\Omega_c(t)} \end{cases}$$

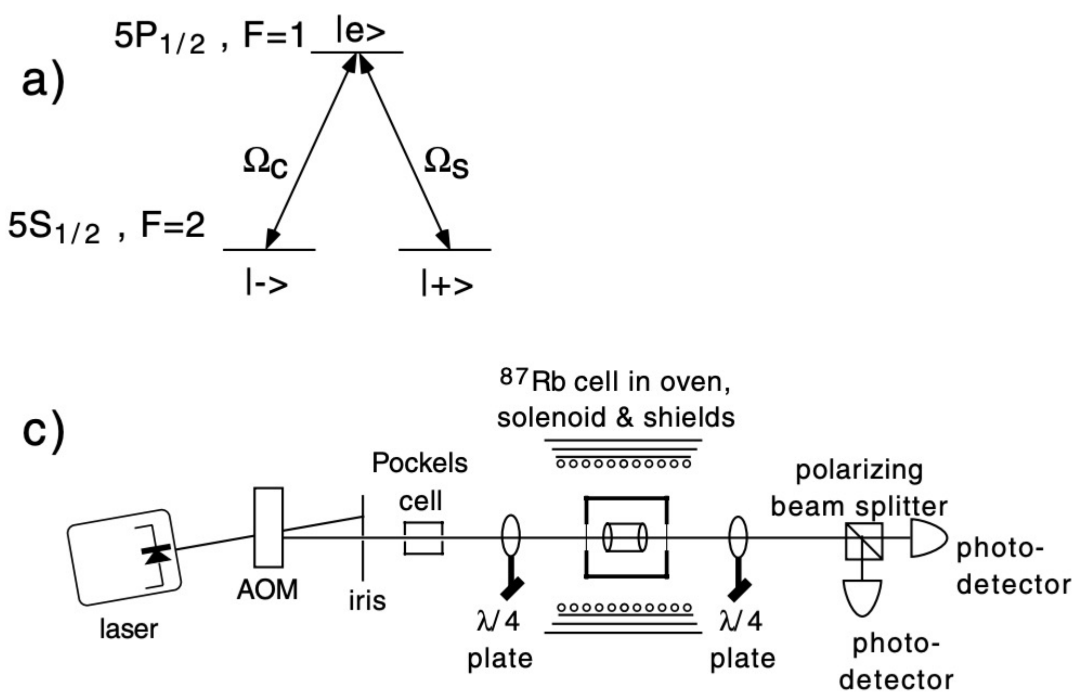
Phys. Rev. A 78, 023801 (2008)

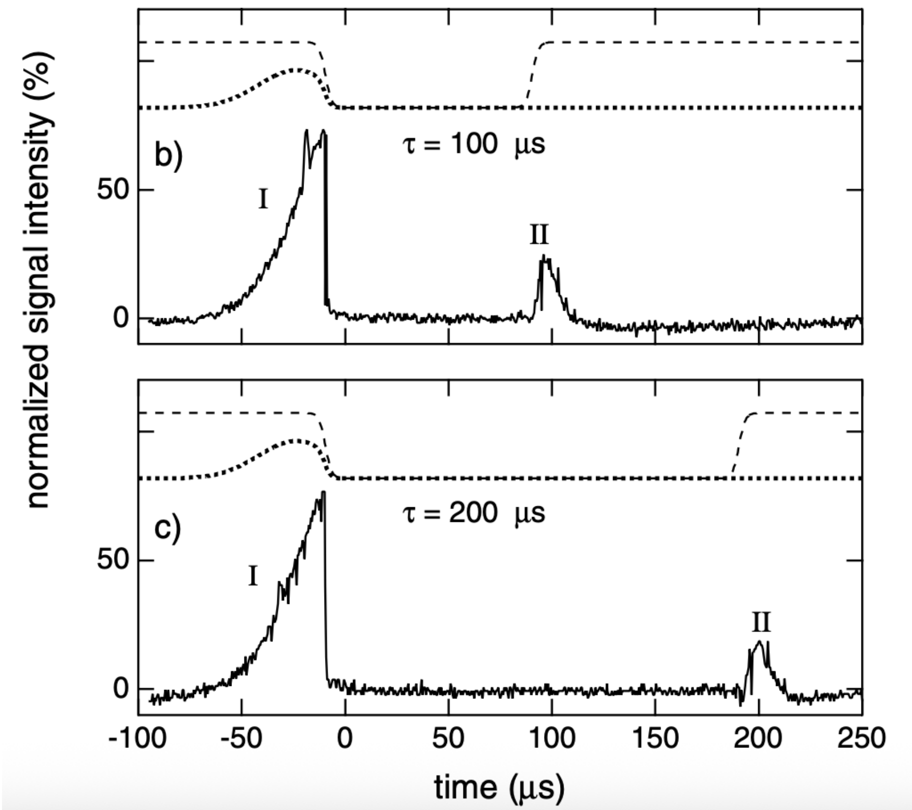


On contrôle les paramètres pour obtenir

$$|\,D(t)\rangle = \cos\theta(t)\ \ |\,1\rangle\,|\,G\rangle - \sin\theta(t)\ \ |\,0\rangle\,|\,S_{\text{coll}}\rangle$$

Mémoire quantique basée sur ensemble d'atomes





Phys. Rev. Lett. 86, 783 (2001)

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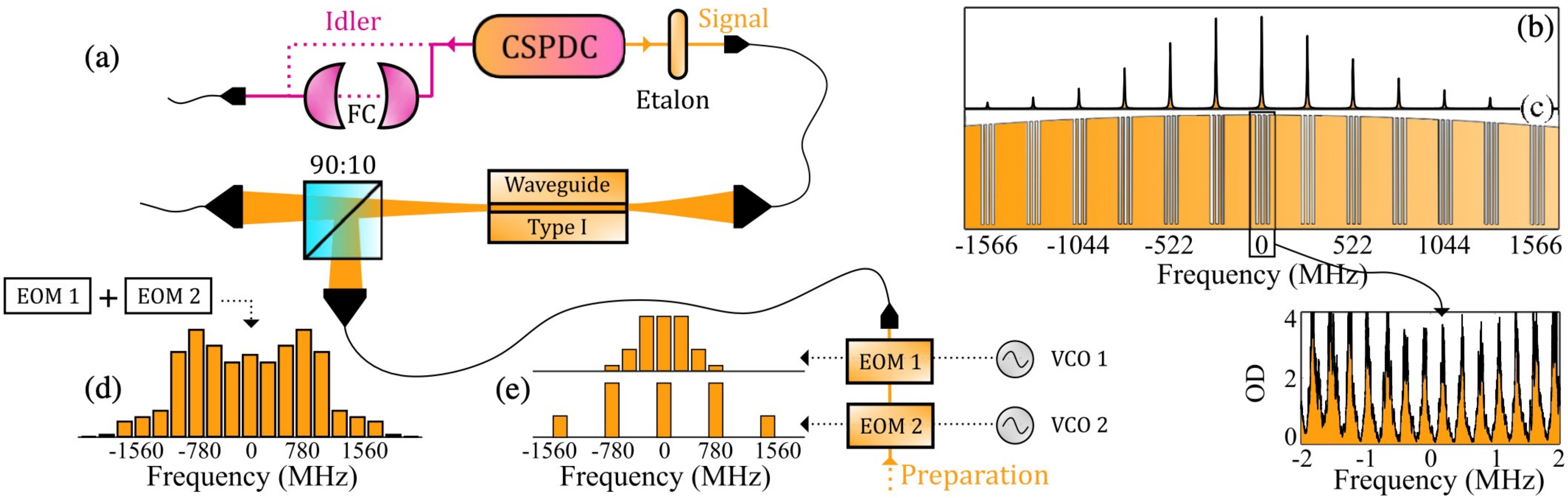
Mémoire quantique basée sur ensemble d'atomes

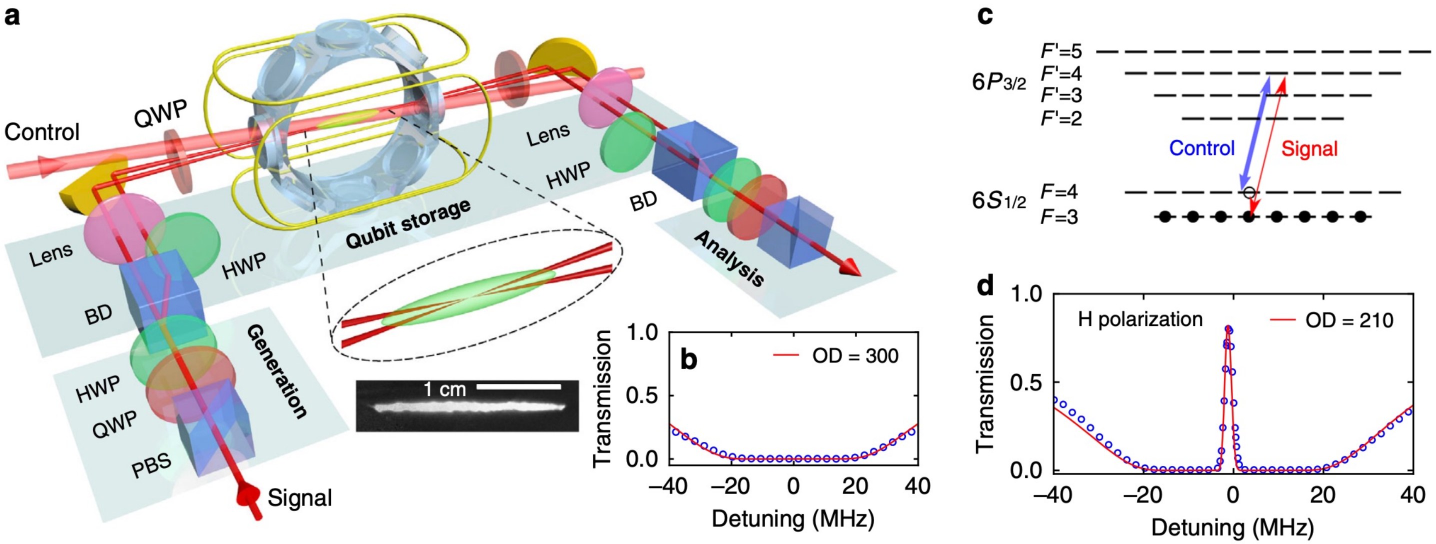


- ➢ Mémoire quantique intégrée : guide d'onde dope au ions de terre rares
- ➢ Multiplexage en fréquence

Phys. Rev. Lett. 123, 080502 (2019)

Mémoire quantique commerciale

Atomes de césium



Weling

Nature Communications 9, 363 (2018)

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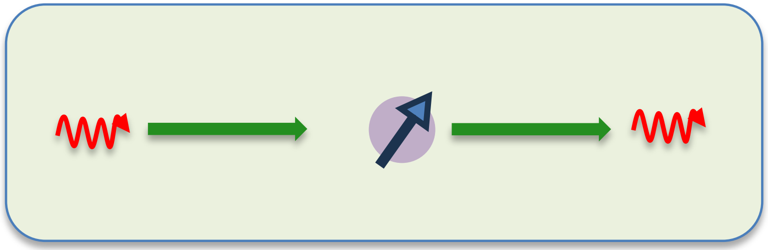
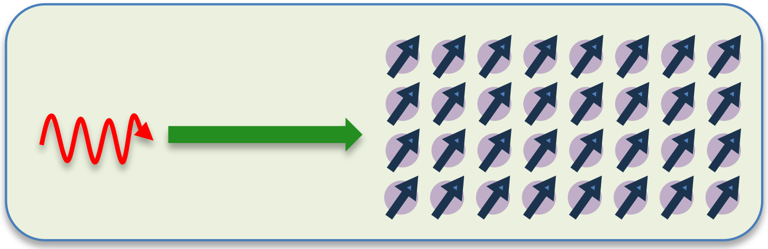
Avantages et défis pour les deux approches





Atome unique	Ensemble
cavité haute finesse	fonctionne en espace libre
mise en place complexe	vapeur chaude possible
excellent contrôle individuel	Bruit Raman
Logique locale	Pas d'opérations locales

Conversion de fréquence quantique

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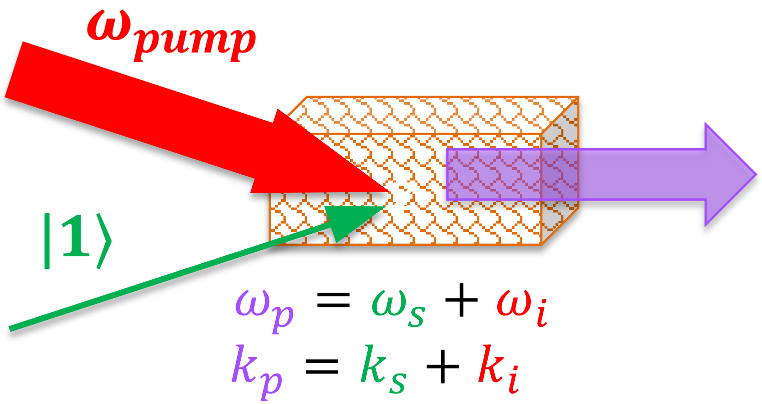
Problématique : réseau hétérogène

	Exemples typiques	Couplage optique (λ)	Couplage micro-ondes / RF (f)
Supraconducteurs	transmon, fluxonium	—	~4–6 GHz
Ions piégés	$^{171}Yb^{+}$ hyperfin $^{40}Ca^{+}$ optique $^{88}Sr^{+}$ optique	lecture: 369.5 nm qubit optique : 729 nm qubit optique 674 nm	qubit hyperfin12.6 GHz
Atomes neutres – Rydberg	^{87}Rb (et Cs)	780 nm + ~480 nm	qubit hyperfin : ~6.8 GHz (^{187}Rb)
Qubits de spin	Si/SiGe, donneurs	—	dizaines de GHz
Centres colorés diamant	NV^{-}	ZPL : 637 nm (excitation souvent 532 nm)	
	SiV^{-}	ZPL : ~738 nm	
boites quantiques III–V	InAs/GaAs	~900–1000 nm	
photons	Sources annoncées	1550 nm	
Terres rares	Er^{3+}	~1.54 μm	

Conversion de fréquence quantique



$$P^{\mathrm{NL}}(t) = \frac{\varepsilon_0 \chi^{(2)}}{4} \Big[E_1^2 e^{-i2\omega_1 t} + E_2^2 e^{-i2\omega_2 t} + 2E_1 E_2 e^{-i(\omega_1+\omega_2)t} + 2E_1 E_2^* e^{-i(\omega_1-\omega_2)t} + \left(|E_1|^2 + |E_2|^2\right) + \text{c.c.} \Big]$$

Equation d'onde avec source non-linéaire

$$\nabla^2 \mathbf{E} - \frac{n^2}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2 \mathbf{P}^{\mathrm{NL}}}{\partial t^2}$$

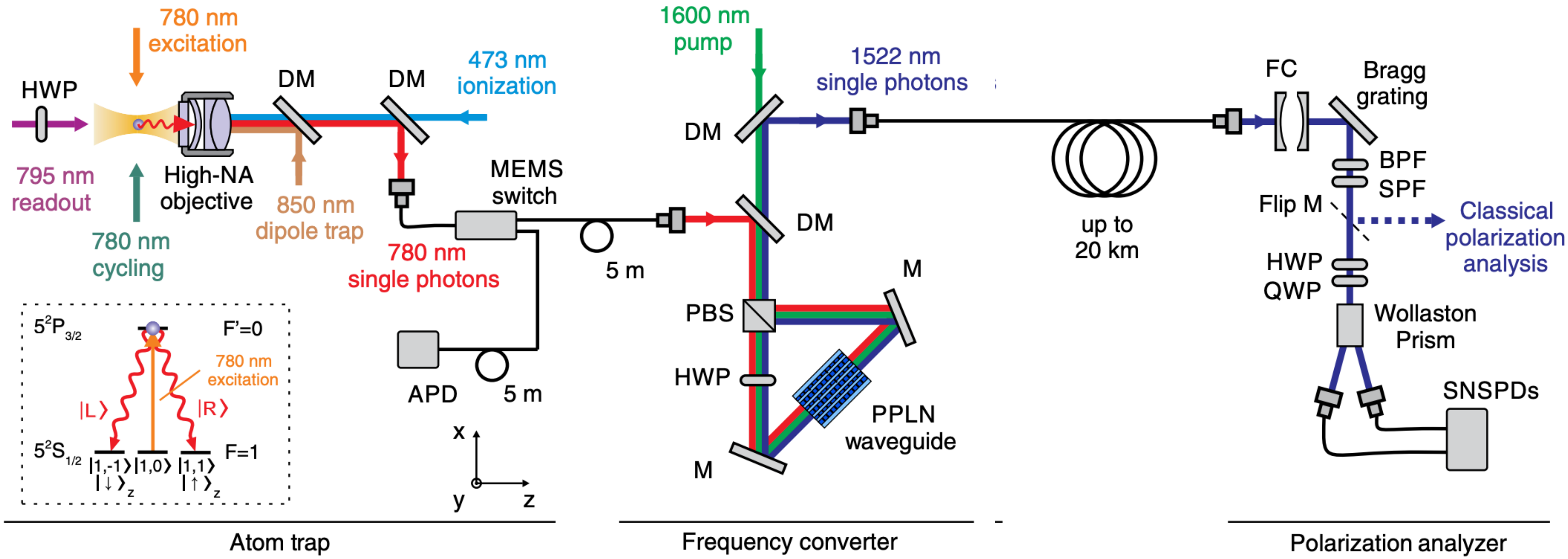
$$\mathbf{P}^{\mathrm{NL}}(t) = \varepsilon_0 \chi^{(2)} \mathbf{E}^2(t)$$

$$E(t) = \frac{1}{2} E_1 e^{-i\omega_1 t} + \frac{1}{2} E_2 e^{-i\omega_2 t} + \text{c.c.}$$

Fréquences générées

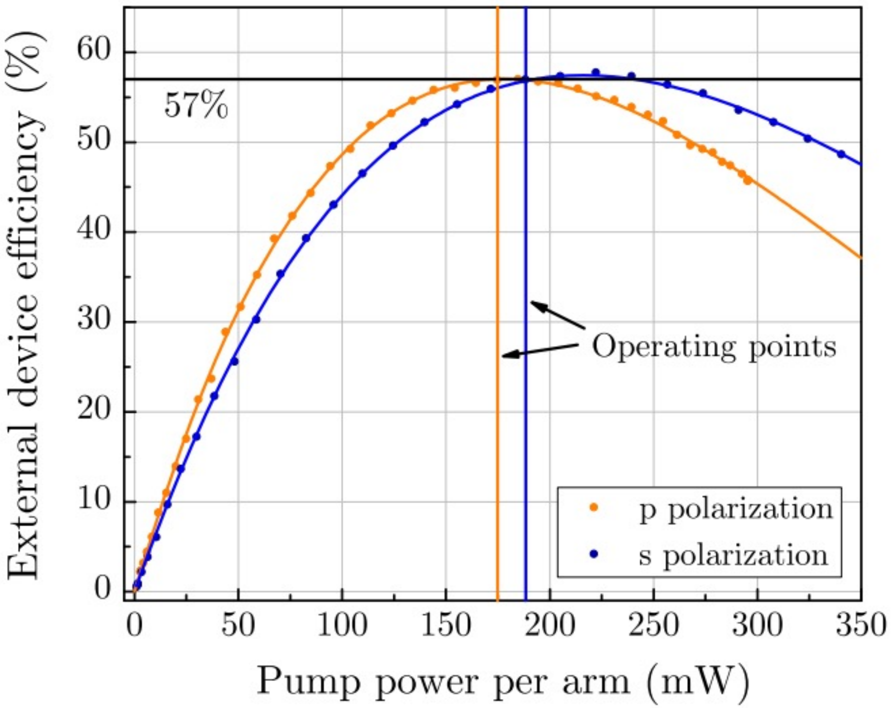
- $2\omega_1,\ 2\omega_2$: secondes harmoniques
- $\omega_1 + \omega_2$: somme de fréquences
- $\omega_1 - \omega_2$: différence de fréquences

Conversion de fréquence: optique vers optique



Phys. Rev. Lett. 124, 010510 (2020)

Conversion de fréquence: optique vers optique



	(A)	(B)	(C)	(D)
Fiber length	20 km	10 km	50 m	5 m
Wavelength	1522 nm	1522 nm	1522 nm	780 nm
Readout delay	102 μs	51 μs	51 μs	51 μs
Fidelity (%)	78.5 ± 0.9	84.3 ± 0.9	88.0 ± 0.8	89.7 ± 0.7
S (CHSH)	2.12 ± 0.05	2.37 ± 0.04	2.41 ± 0.03	2.49 ± 0.03
SNR	25.1	23.2	32.3	934.2

PHYSICAL REVIEW LETTERS 124, 010510 (2020)

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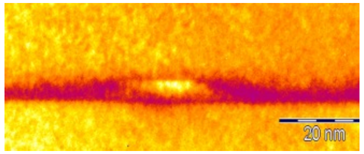
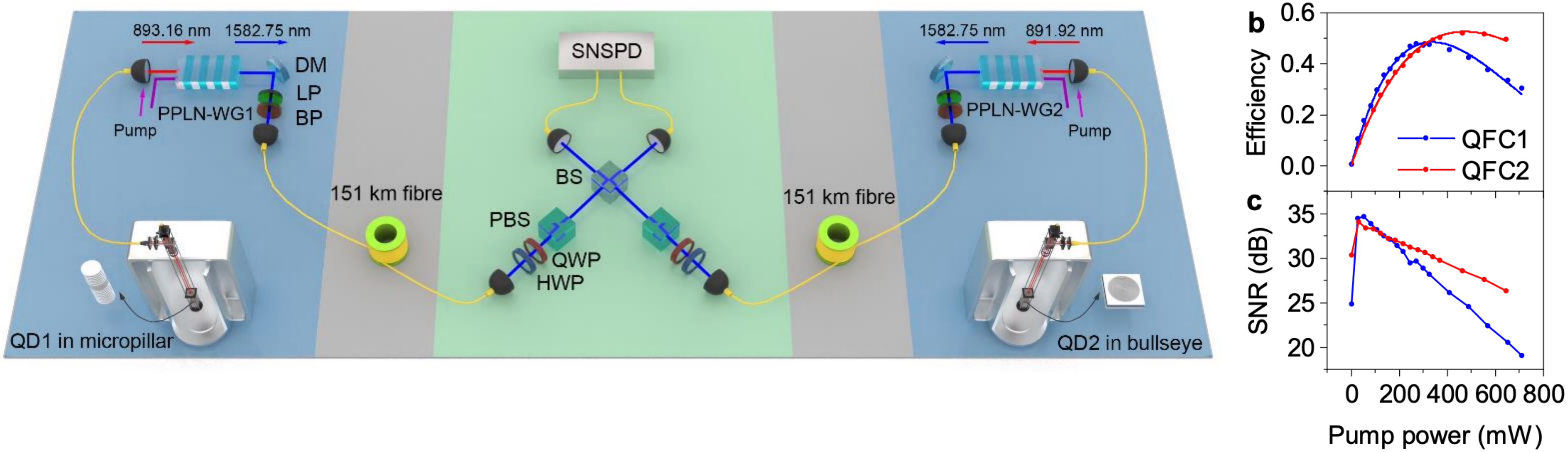
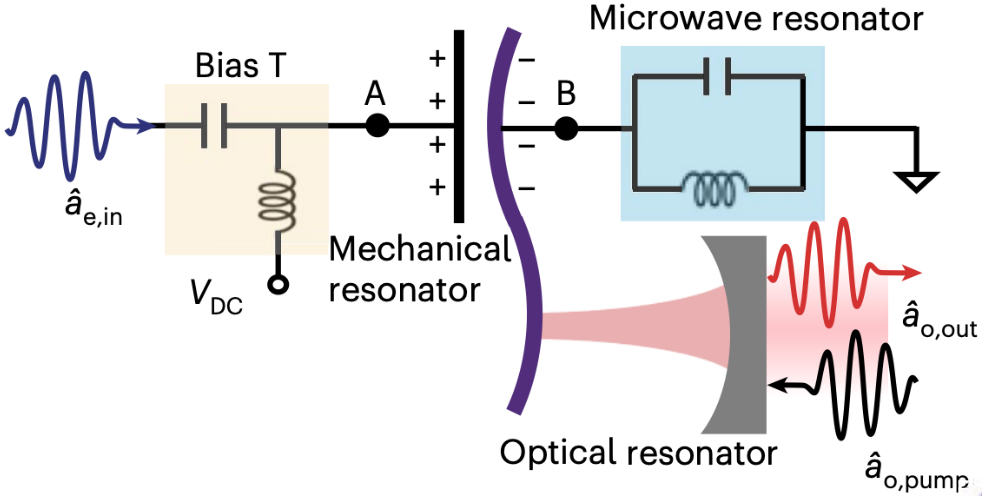
Conversion de fréquence: optique vers optique

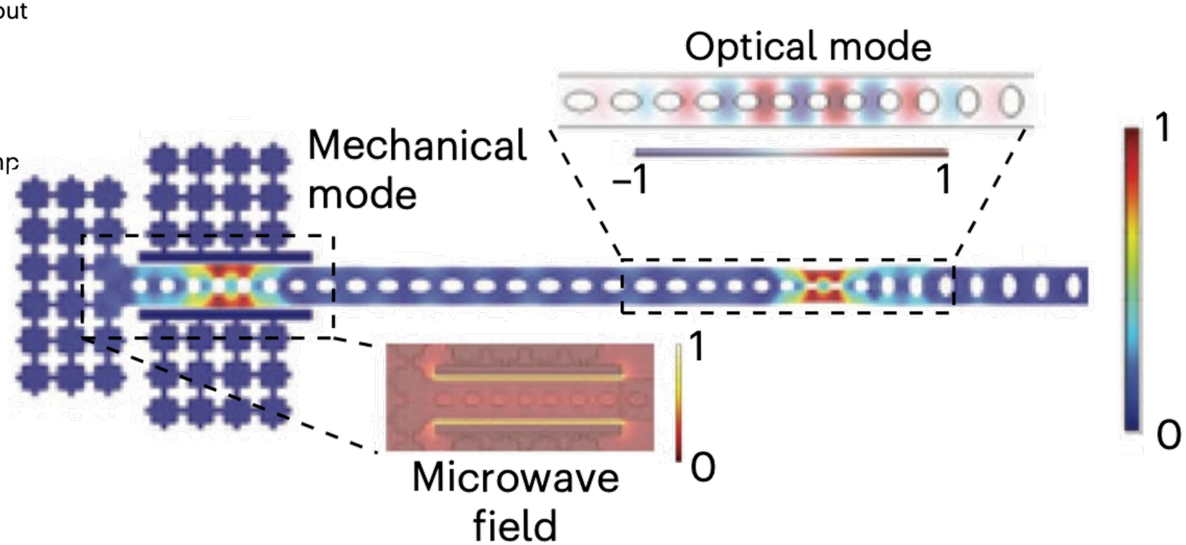




Advanced Photonics, 4, 066003 (2022)

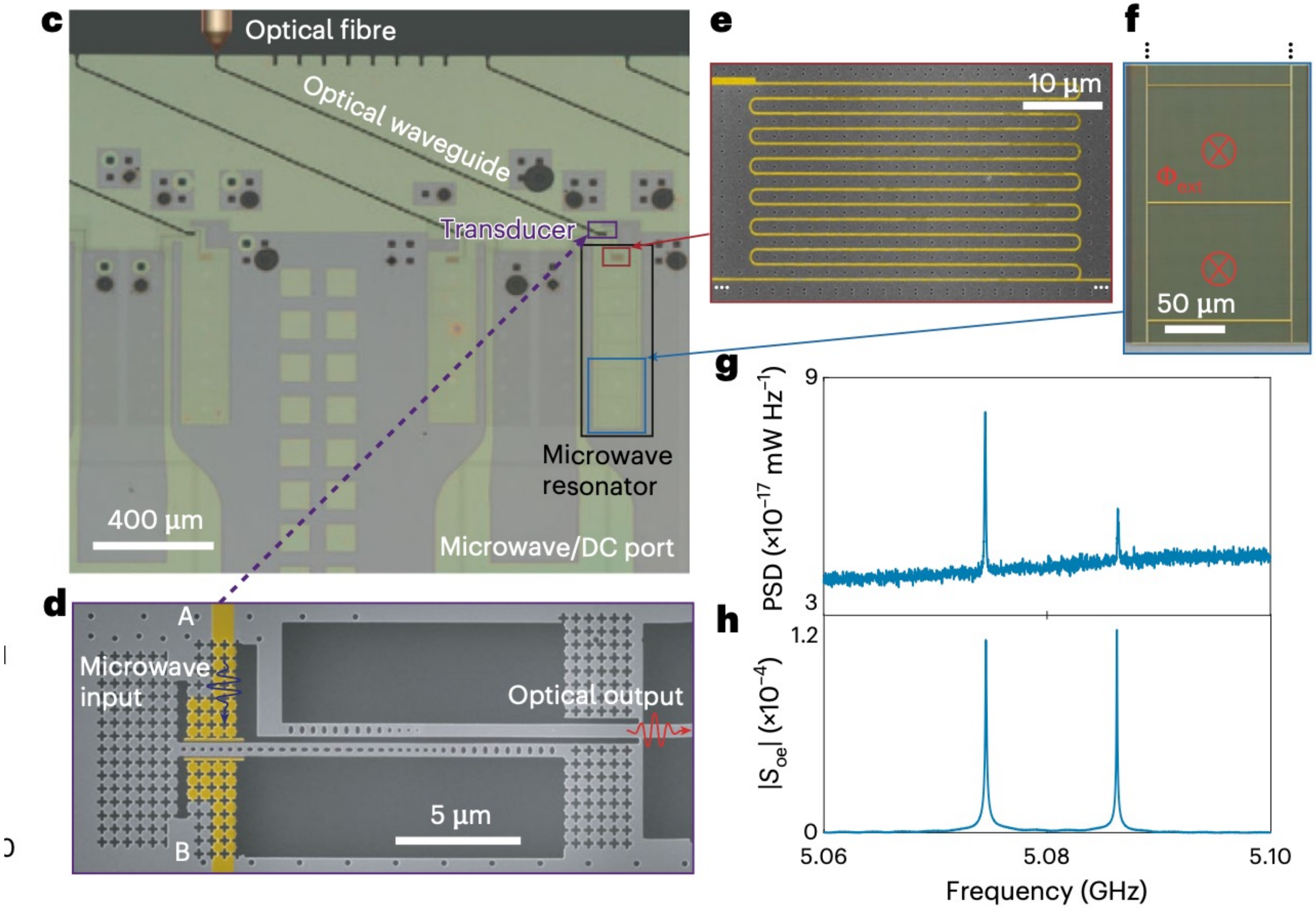
Conversion de fréquence: micro-onde vers optique





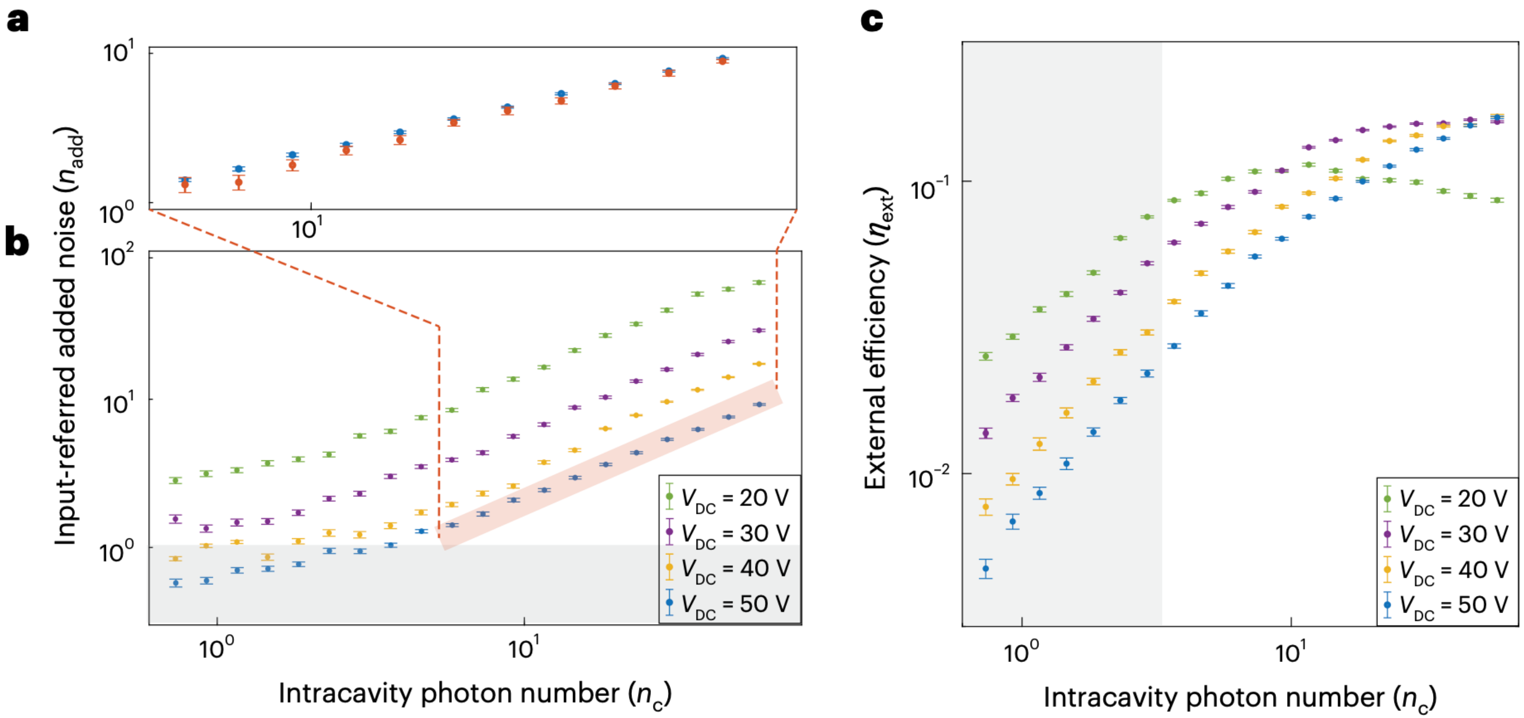
Nature Nanotechnology 20, 602–608 (2025)

Conversion de fréquence: micro-onde vers optique



Nature Nanotechnology 20, 602–608 (2025)

Conversion de fréquence: micro-onde vers optique

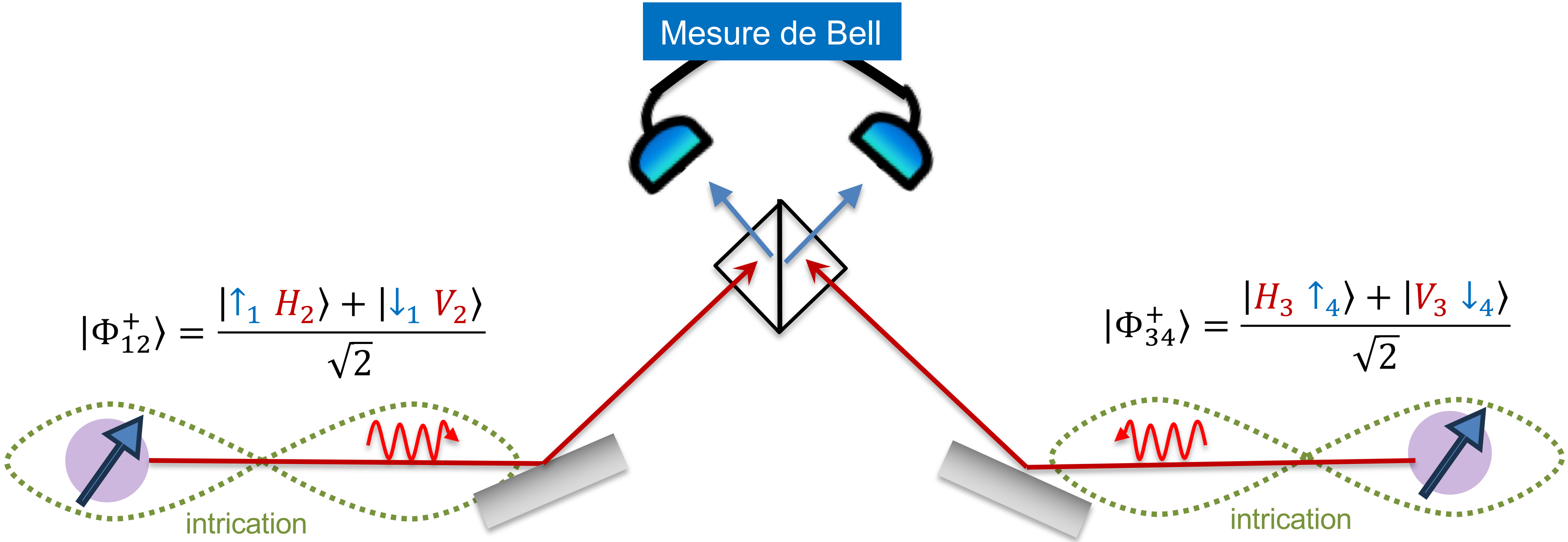


Transduction optimale vers 2-3% d'effficacité

Nature Nanotechnology 20, 602–608 (2025)

Distribuer l'intrication

Intriquer deux atomes/spins à distance



$$|\Phi_{12}^{+}\rangle = \frac{|\uparrow_1 H_2\rangle + |\downarrow_1 V_2\rangle}{\sqrt{2}}$$

$$|\Phi_{34}^{+}\rangle = \frac{|H_3 \uparrow_4\rangle + |V_3 \downarrow_4\rangle}{\sqrt{2}}$$

$$|\Phi^+\rangle_{12}\,|\Phi^+\rangle_{34} = \frac{1}{2}\left(|\Phi^+\rangle_{23}\,|\Phi^+\rangle_{14} + |\Phi^-\rangle_{23}\,|\Phi^-\rangle_{14} + |\Psi^+\rangle_{23}\,|\Psi^+\rangle_{14} + |\Psi^-\rangle_{23}\,|\Psi^-\rangle_{14}\right)$$

Intrication des spins 1 et 4 après mesure des photons 2 et 3 dans $|\Psi^-\rangle_{23}$

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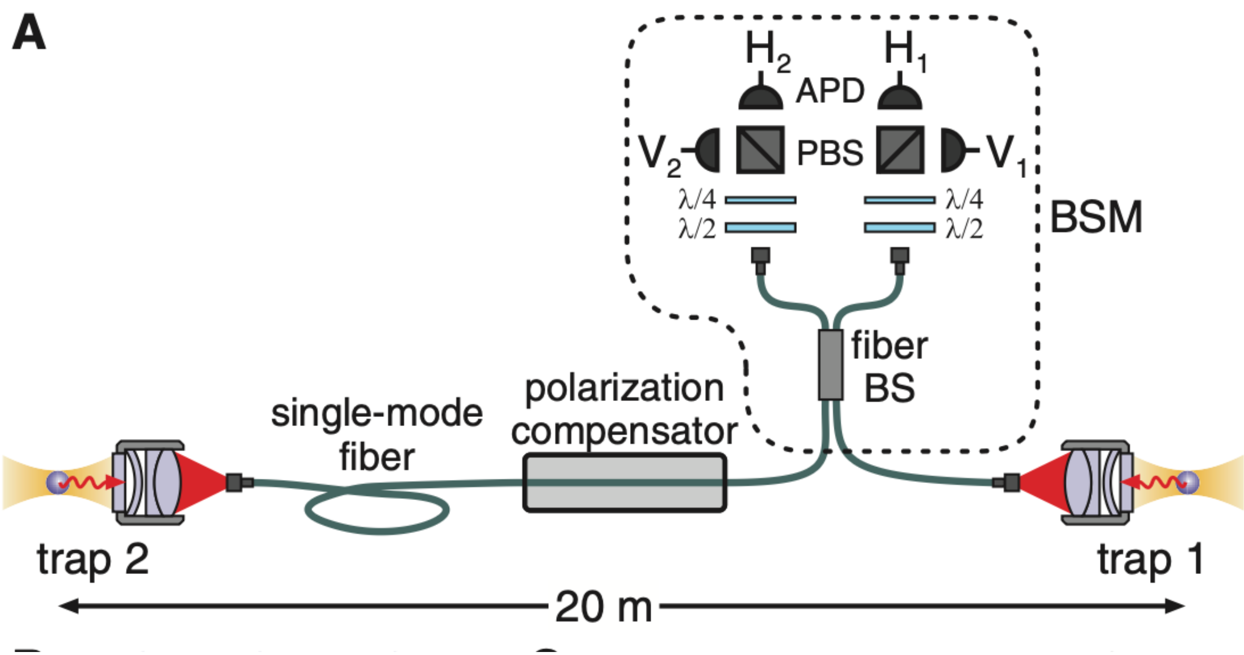
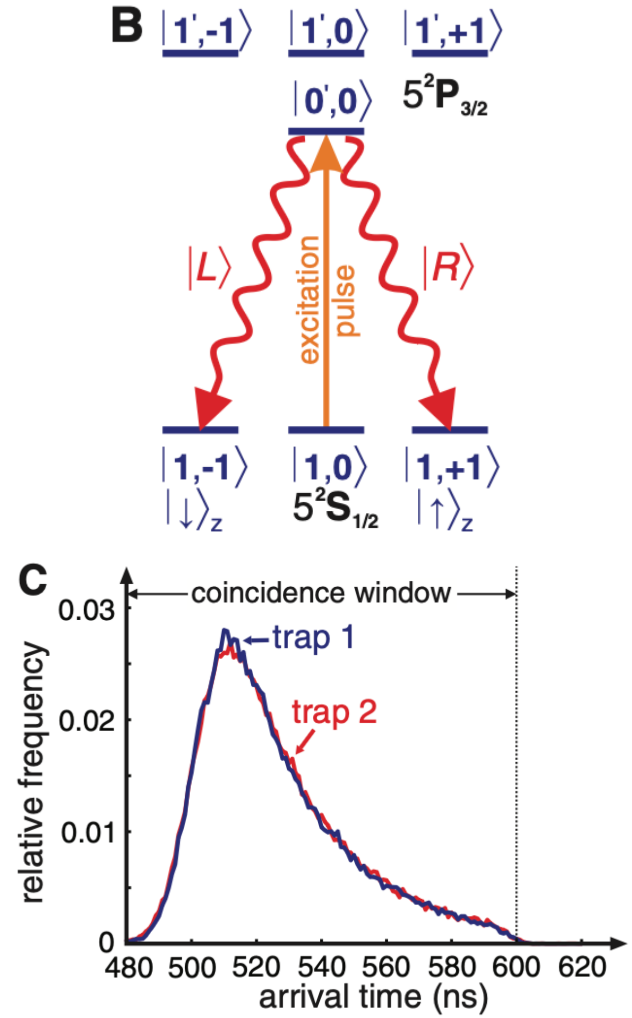
Intrication de deux ions piégés à distance

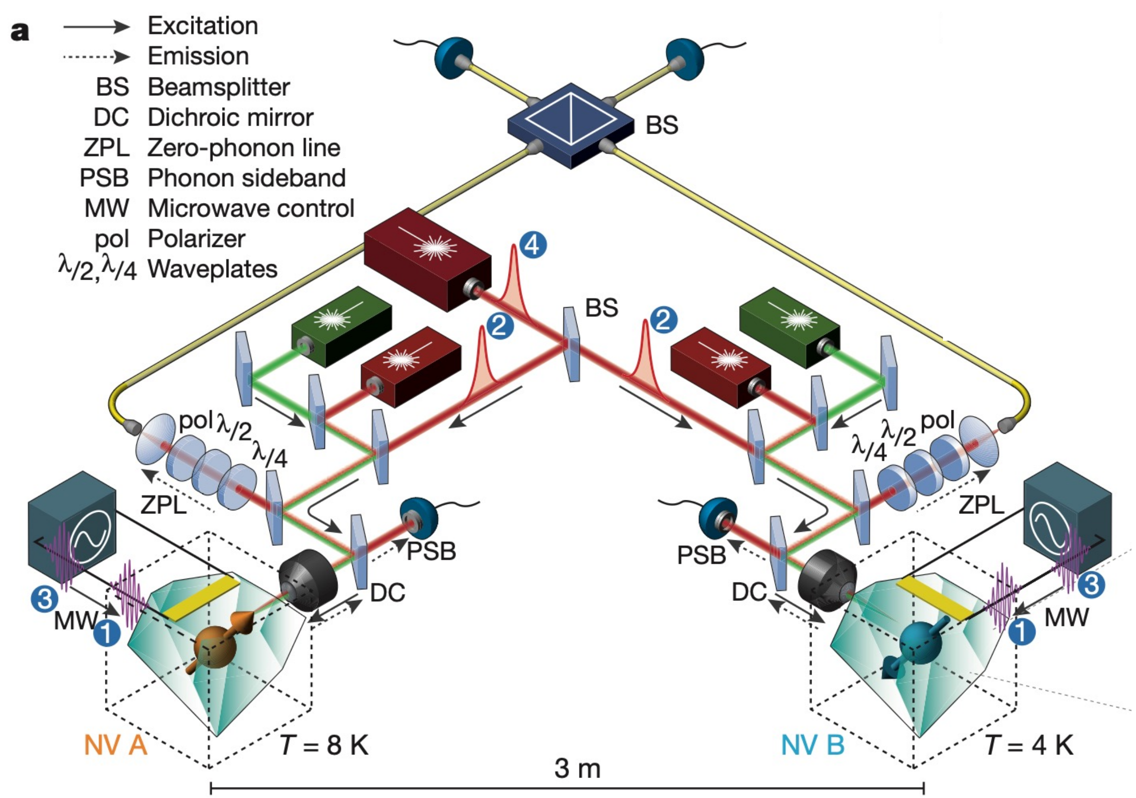




Fidélité atome-atome ~81%

Intrication toutes les ~106 secondes

Intrication de deux centres NV



$$|\Psi\rangle_{tot} = \frac{1}{2}(|\uparrow_A\uparrow_B\rangle\,|\,1_A 1_B\rangle + |\uparrow_A\downarrow_B\rangle\,|\,1_A 0_B\rangle + |\downarrow_A\uparrow_B\rangle\,|\,0_A 1_B\rangle + |\downarrow_A\downarrow_B\rangle\,|\,0_A 0_B\rangle)$$

Nature 497, 86–90 (2013)

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Intrication de deux centres NV

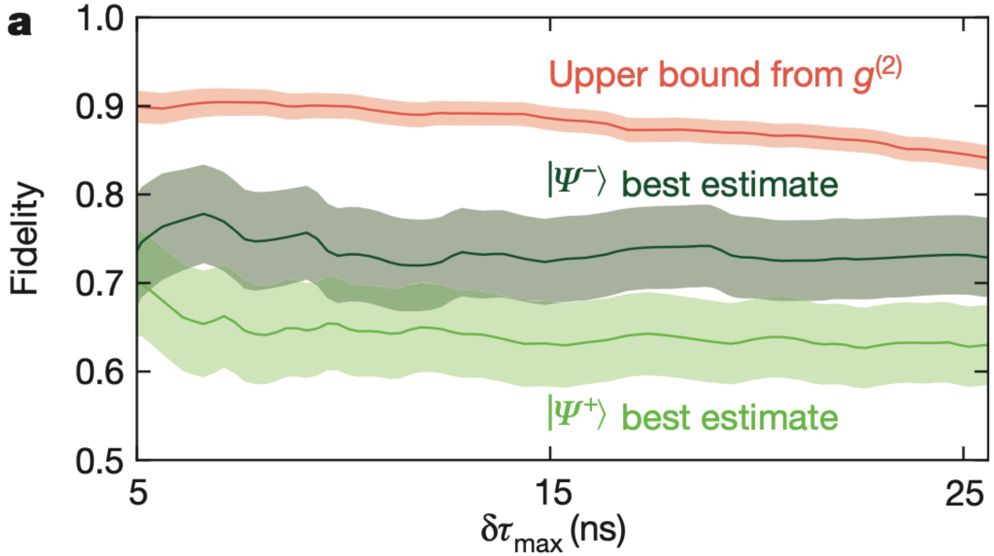
$$| \Psi\rangle_{tot} = \frac{1}{2}(|\uparrow_A\downarrow_B\rangle \,|\, 1_A 0_B\rangle + |\downarrow_A\uparrow_B\rangle \,|\, 0_A 1_B\rangle)$$

Mesure de Bell à 1 photon

Interférence (BS)

$$| \Psi\rangle_{1-\text{photon}} = \frac{1}{2\sqrt{2}}[\ |1_C 0_D\rangle(|\uparrow_A\downarrow_B\rangle + e^{-i\phi}\,|\downarrow_A\uparrow_B\rangle) \ + \ |0_C 1_D\rangle(|\uparrow_A\downarrow_B\rangle - e^{-i\phi}\,|\downarrow_A\uparrow_B\rangle)]$$

Intrication toutes les 10 minutes



Nature 497, 86–90 (2013)

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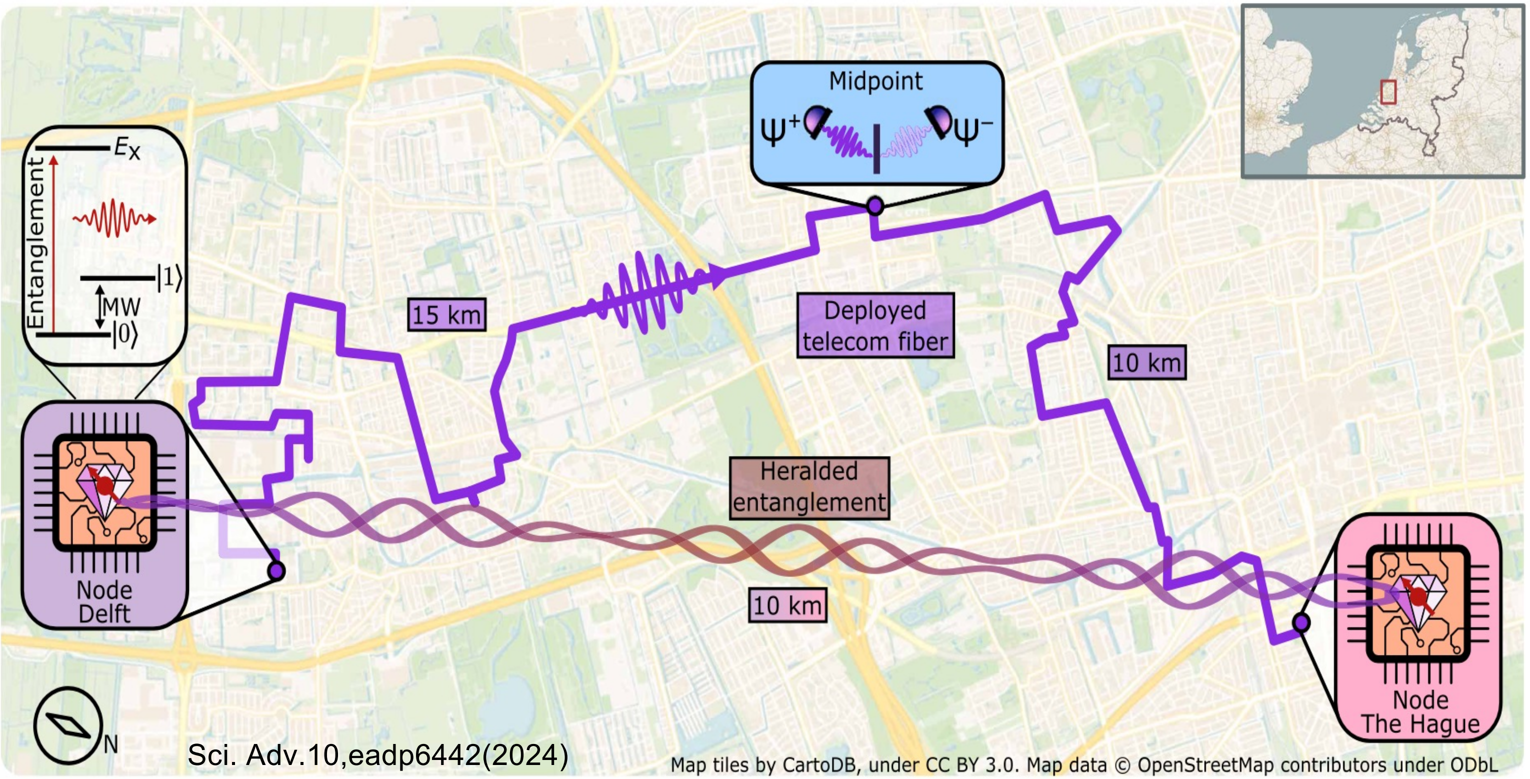
Quantum internet Alliance

https://quantuminternetalliance.org/

Quantum internet Alliance

https://quantuminternetalliance.org/



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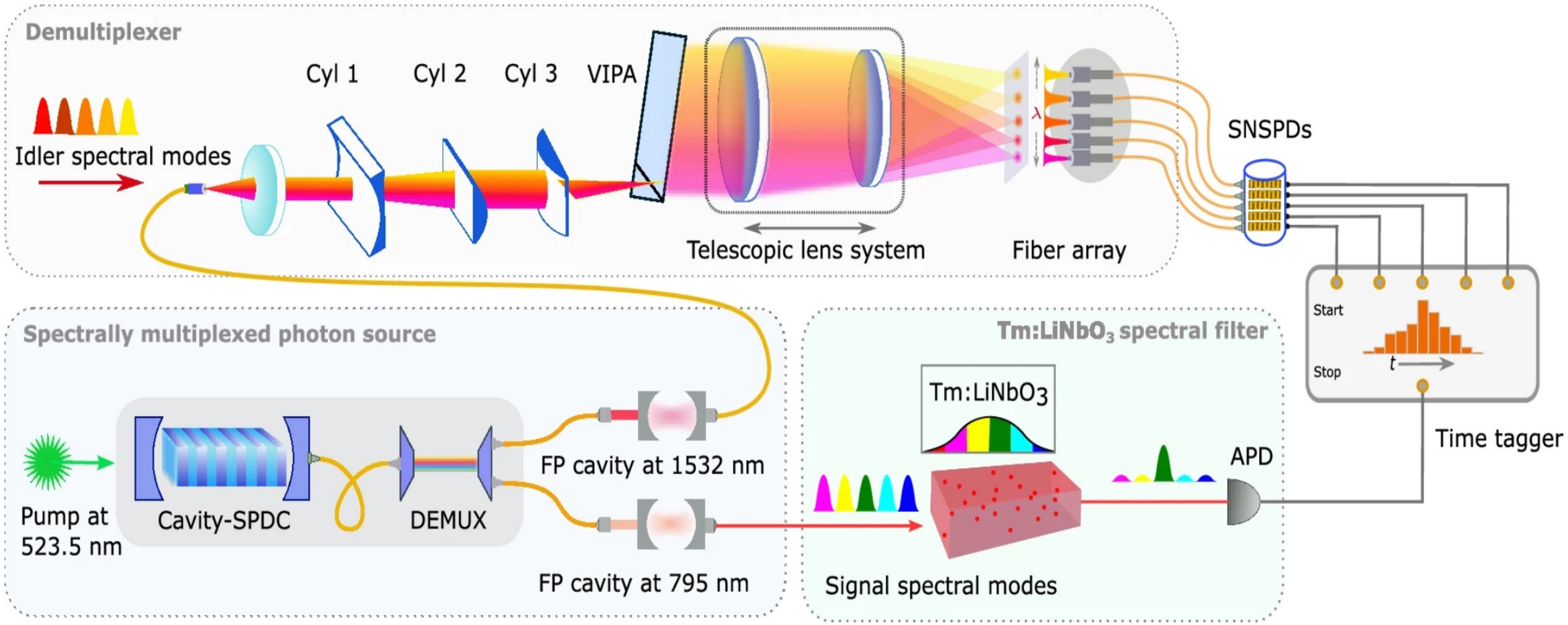
Quantum internet Alliance

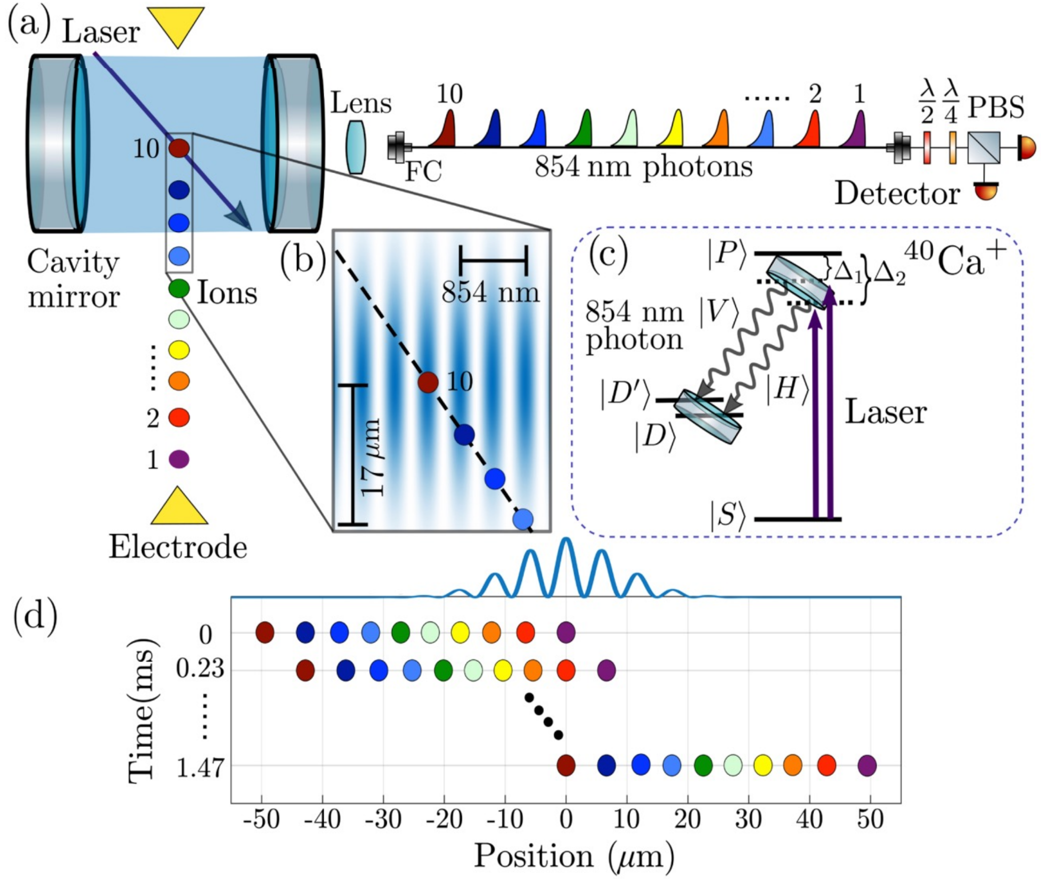
https://quantuminternetalliance.org/



npj Quantum Information 11, 3 (2025)

Quantum internet Alliance

https://quantuminternetalliance.org/



Phys. Rev. Lett.135, 080801 (2025)

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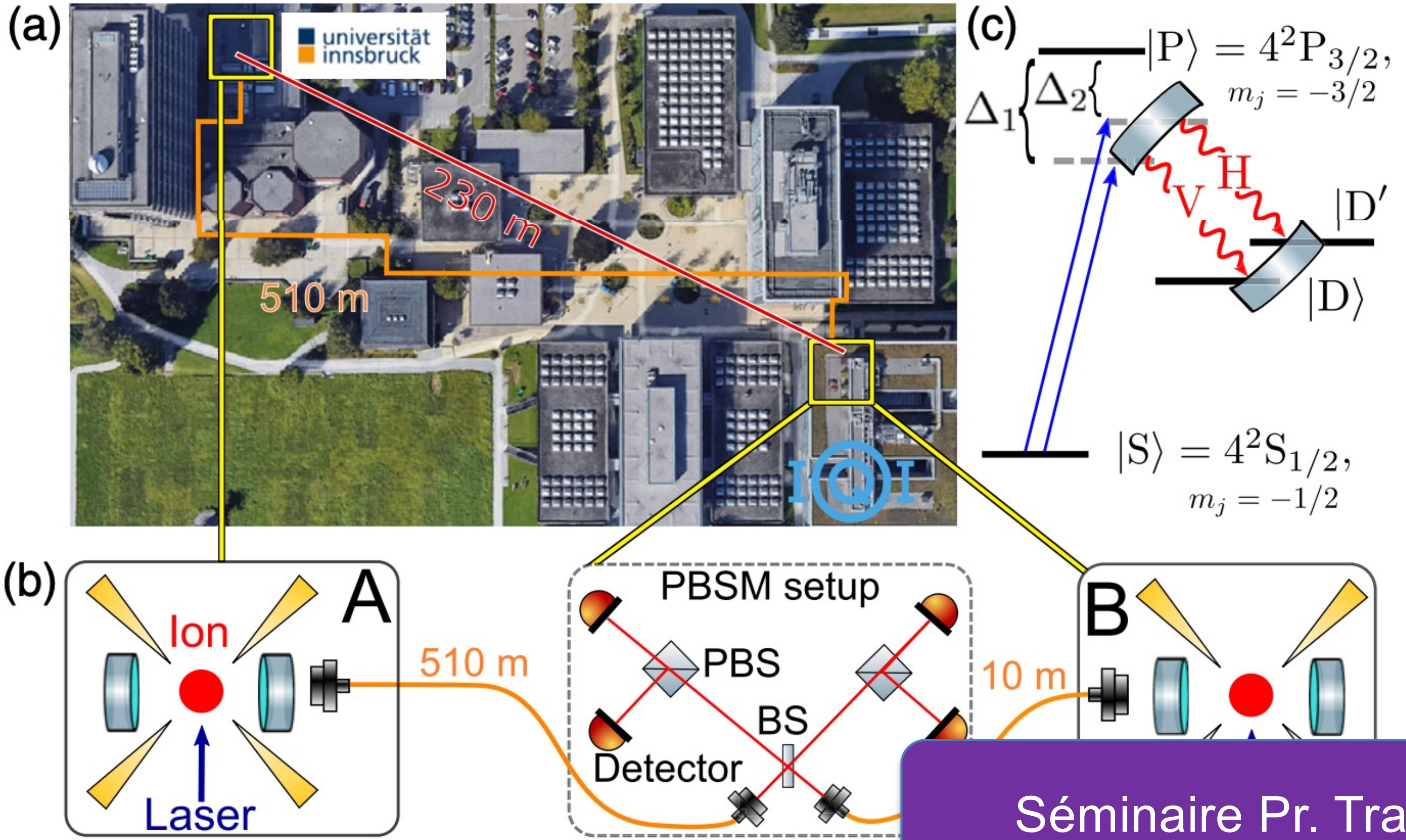
Intrication de deux ions en cavité



Séminaire Pr. Tracy Northrup

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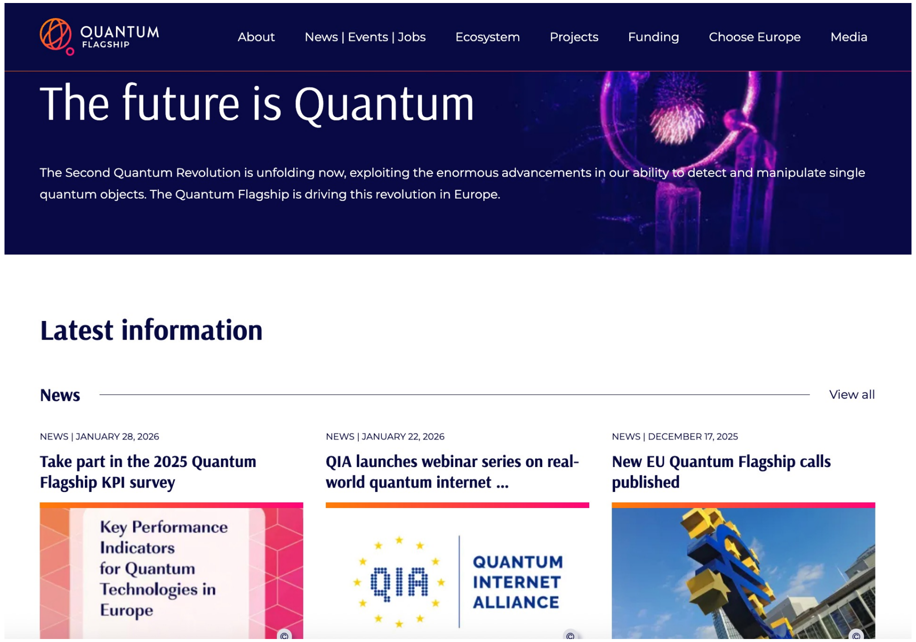
Un domaine en plein essor



https://qt.eu/

https://www.pepr-quantique.fr/

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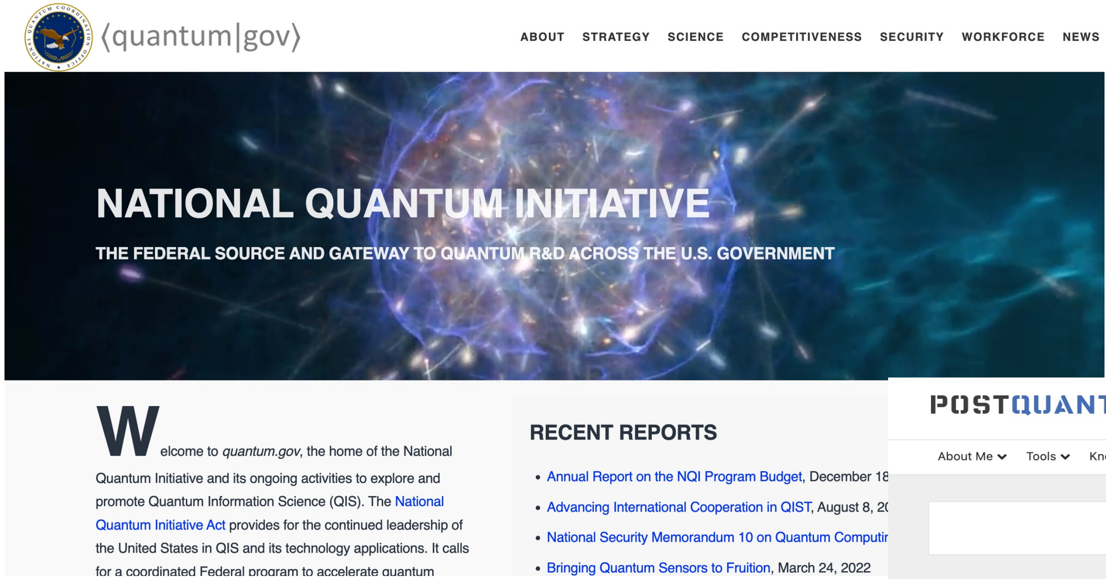
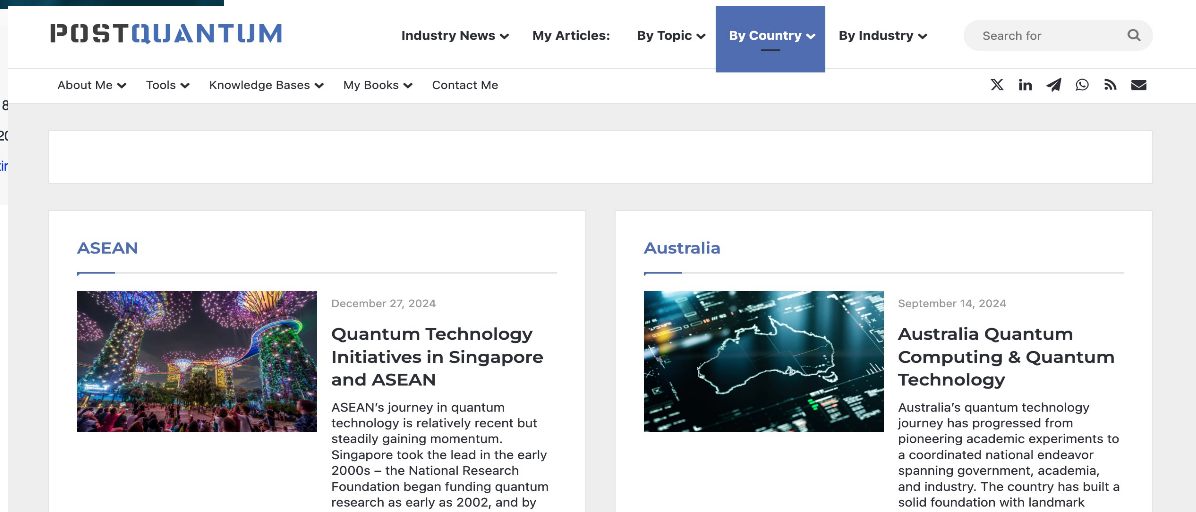
Un domaine en plein essor



https://www.quantum.gov/



https://postquantum.com/

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09:00 – 09:15 Introduction – Pr. Pascale Senellart

09:15 – 10:00 Pr. Serge Haroche – Prix Nobel de Physique 2012

Exposé introductif

10:00 – 10:45 Pr. Christine Silberhorn

Scaling Photonic Quantum Systems

10:45 – 11:15 Pause café

11:15 – 12:00 Dr. Antoine Heidmann

Listening to the universe with quantum light: quantum technologies for gravitational-wave detection

12:00 – 12:45 Dr. Adriana E. Lita

Development of Superconducting Single-Photon Detectors for Quantum Information Applications

14:15 – 15:00 Dr. Alexia Auffèves

An energetic perspective on fundamental processes in quantum optics

15:00 – 15:45 Pr. Hugues de Riedmatten

Quantum memories for Quantum Information Networks

15:45 – 16:15 Pause café

16:15 – 17:00 Dr. Anaïs Dréau

Single color centers for silicon-based quantum technologies

17:00 – 17:45 Dr. Hugo Defienne

Quantum imaging with entangled photons