# Multi-mode optical quantum memory for quantum processing and communication

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ITMO UNIVERSITY

KQC

## Key problems of quantum information technologies

1. *Quantum communication at large distances (more than 1000 km)*
2. *Quantum computer creation*



*Photons are ideal carriers of quantum information*





*Photon quantum memory*

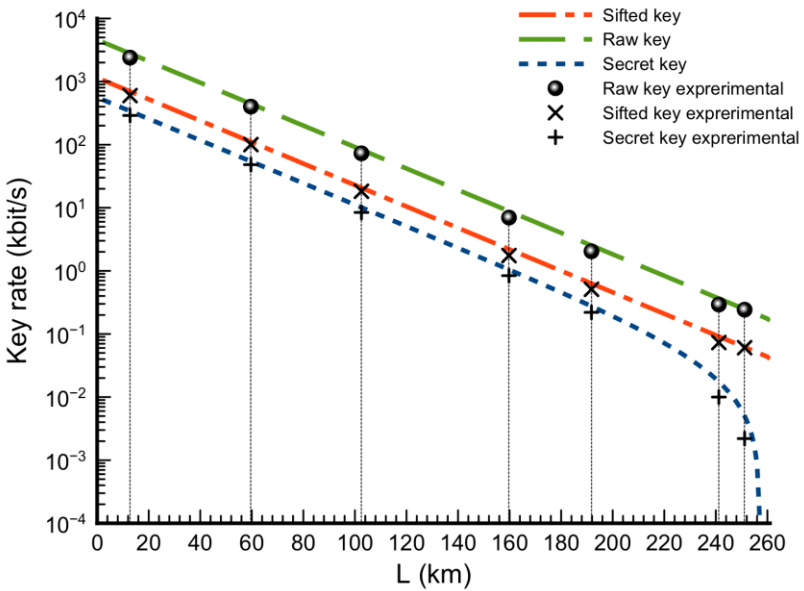


*Quantum processing with photon qubits*

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KQC 2014

# *Limitations of quantum key distribution systems*




The largest distance in quantum communications is 307 km[1]
1Tbit/s pulse repetition rate quantum system will produce only 0,001 bit/s on the distance 1000 km. The fastest quantum communication system provide only 10 Gbit/s today.

1. B. Korzh, C. Ci Wen Lim, R. Houlmann et al, Nature Photonics 9, 163–168

## Quantum communication at large distances

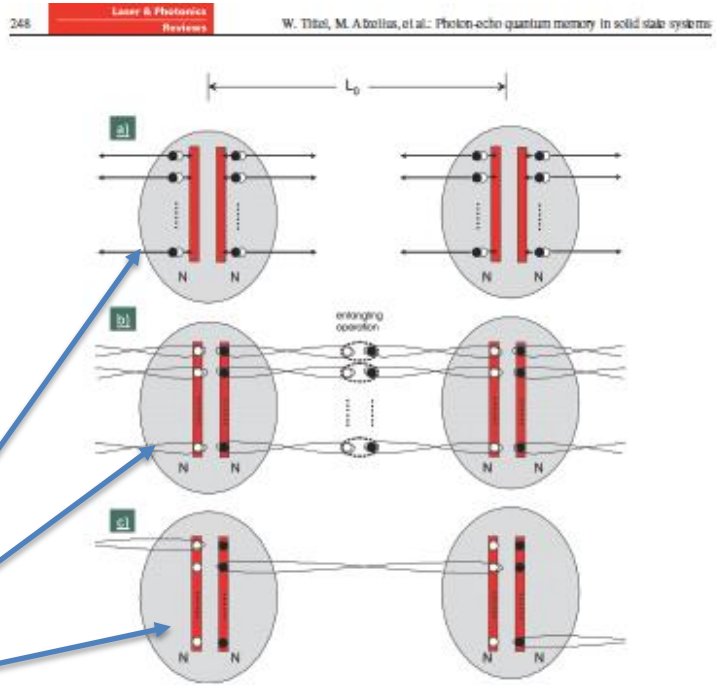
**Combination of quantum teleportation with quantum memory can provide creation of scalable schemes:**

- ✓ **for quantum computations (P.Kok, et al, RMP, 79 135 (2007),**
- ✓ **quantum repeaters (H.-J., Briegel, et.al, PRL, 81, 5932 (1998))**
- ✓ **quantum networks (H.J. Kimble, Nature 453, 1023 (2008).**

**The distribution of entangled states to large distances is more efficient when multi-qubit quantum memory is used**

C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden, and N. Gisin, Phys. Rev. Lett. 98 , 190503 (2007).

**Multi-qubit quantum memory for quantum repeaters (N.Sangouard et.al, RMP, 83, 33 (2011).**




**Multi-qubit quantum memories:**

## Quantum memory reviews

[1]. Lvovsky Alexander I., Sanders Barry C., Tittel Wolfgang. Optical quantum memory //Nat. Photonics.- **2009**. - dec. - Vol. 3, no. 12. - Pp. 706-714.
[2]. Hammerer Klemens, Sorensen Anders S., Polzik Eugene S. Quantum interface between light and atomic ensembles //Rev. Mod. Phys.- **2010**. - Apr. - Vol. 82. - Pp. 1041-1093.
[3]. Quantum memories / Simon, C., Afzelius, M., Appel, J. et al. //*Eur. Phys. J. D.*- **2010**. - Vol. 58, no. 1. - Pp. 1-22.
[4]. Photon-echo quantum memory in solid state systems / W. Tittel, M. Afzelius, T. Chaneliere et al. //*Laser & Photonics Reviews*.- **2010**. - Vol. 4, no. 2. - Pp. 244-267..
[5]. Prospective applications of optical quantum memories / F. Bussieres, N. Sangouard, M.Afzelius et al. // *J. Mod. Opt.*- **2013**. - oct. - Vol. 60, no. 18. - Pp. 1519-1537.
[6]. *K. Heshami, D.G. England, P.C. Humphreys et al.* Quantum memories: emerging applications and recent advances. - **2015**. - 11. - preprint.http://arxiv.org/abs/1511.04018.

## Special editions of journals devoted to quantum memory

[1]. Quantum memory (editors: Jean-Louis Le Gouet, Sergey Moiseev), J. Phys. B: At. Mol. Opt. Phys.- 2012. - Vol. 45. - Pp. 120201-124021.
[2]. Focus on Quantum memory (editors: Brennen Gavin, Giacobino Elisabeth, Simon Christoph), New J. Phys.- 2015. - Vol. 17. - P. 050201.
[3]. Special Issue CFP: Quantum Memory (editors: Nunn Joshua, Sussman Ben, Acosta Victor), Journal of Modern Optics. – 2016. – (in press).

## *Quantum communication on large spatial distances*

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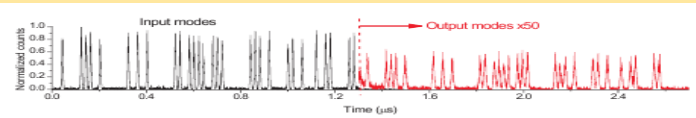
- ✓ **Quantum repeater (H.-J., Briegel, et.al, PRL, 81, 5932 (1998)**
- ✓ **Multi-qubit quantum memory for quantum repeaters (N.Sangouard et.al, RMP, 83, 33 (2011).**

## *Quantum communication on large spatial distances*

- ✓ **Quantum repeater (H.-J., Briegel, et.al, PRL, 81, 5932 (1998)**
- ✓ **Multi-qubit quantum memory for quantum repeaters (N.Sangouard et.al, RMP, 83, 33 (2011).**

**Experiments on multi-mode photon echo quantum memory on rare-earth ions in crystals :**

**Photon Echo QM with atomic frequency comb (AFC)**
I.Usmani, M.Afzelius, H.de Riedmatten, and N.Gisin, Nat.Comm.**1**,1 (2010).




**Quantum storage of entangled broadband light fields (AFC):**
C.Clausen, et.al.,**Nature 469**, 508 (12 January 2011).
E. Saglamyurek, et.al., **Nature 469**, 512-515 (12 January 2011).
**Quantum storage of 1060 temporal light modes:**
M. Bonarota, J.-L. Le Gouet, and T. Chaneliere, NJP **13** (2011) 13013

**Gradient Echo M:**
**Record quantum efficiency - 69 %**
**is demonstrated in solid state medium:**
- M. P. Hedges et al., **Nature** (London) 465, 1052 (2010).

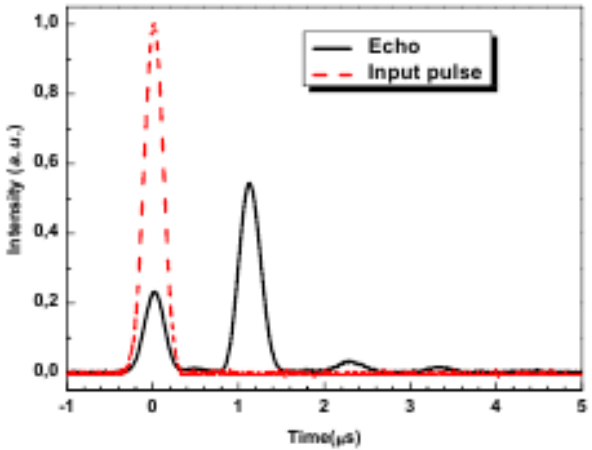
## Experiments on photon echo QM in cavity :

**Fabry-Perot cavity (0.05 % Pr3+ : Y2SiO5):**

**Sabooni M., Li Q., Kroll S and Rippe L. Phys. Rev. Lett. 110 133604 (2013)** (QE=58%)

**Sabooni M., Kometa S.T., Thuresson A., Kroll S. and Rippe L. New Journal of Physics 15, 035025 (2013).**

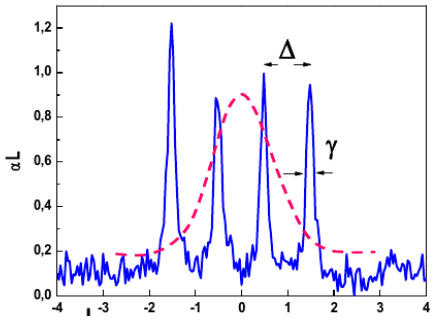
**P. Jobez, I. Usmani, N. Timoney, C. Laplane, N. Gisin, M. Afzelius. New Journal of Physics 16, 083005 (2014)** (QE=53%)




**Rephasing (reemission) time:** $t_r = 1/\Delta$

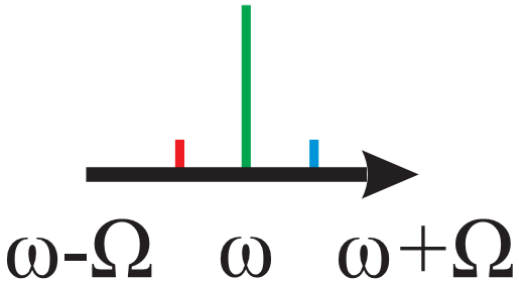
**Finesse f=Δ/γ=4.5**

Возможное время жизни квантовой памяти – 6 часов M. Zhong, M. P. Hedges, R. L. Ahlefeldt, J. G. Bartholomew, S. E. Beavan, S. M. Wittig, J. J. Longdell, and M. J. Sellars, Nature 517, 177 (2015).



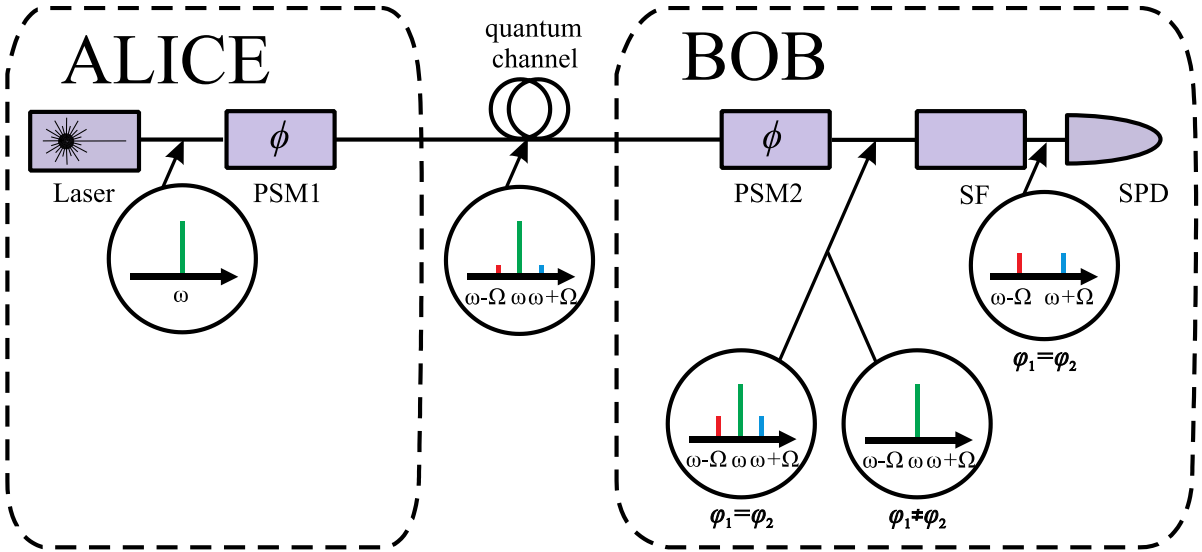
# *Subcarrier quantum communication. Scheme and spectrum of photonic qubits:*

- **Quantum channel is formed at sidebands of an optical carrier as a result of phase modulation**
- **The optical properties of light at subcarriers are set by modulation parameters used by Alice and Bob**
- **Each pair of subcarriers can operate as a separate quantum channel**




$$E = Ae^{i\omega t} + iAa \cdot \cos\left(\frac{\varphi_a - \varphi_b}{2}\right) \cdot \left(e^{i\left((\omega+\Omega)t+\frac{\varphi_a+\varphi_b}{2}\right)} + e^{i\left((\omega-\Omega)t+\frac{\varphi_a+\varphi_b}{2}\right)}\right)$$

# *Subcarrier quantum communication. Scheme and spectrum of photonic qubits:*




Principle scheme of a Subcarrier wave QKD system (SCW QKD)[1,2]


1. Jean-Marc Merolla, Yuri Mazurenko et al. //Phys. Rev. Let. V.82, 8, 1656-1659 (1999)
2. Gleim A. V. et al. Secure polarization-independent subcarrier quantum key distribution in optical fiber channel using BB84 protocol with a strong reference //Optics Express. – 2016. – Т 24. – №. 3. – С. 2619-2633.

## *Subcarrier Wave QKD advantages*

- **Interferometric stability not affected by distance**
- **Compliance with existing telecommunication lines**
- **Spectral efficiency up to 40% compared to 4% for modern QKD[1]**
- **Broad multiplexing capabilities**
- **Maximum distance limited only by detector properties**
- **Persistent against natural conditions**
- **Modulation frequency (i.e. bitrate) not limited by the system architecture**

1. J. Mora, A. Ruiz-Alba, J. Capmany el al. // Opt. Lett. 37, 2031-2033 (2012).

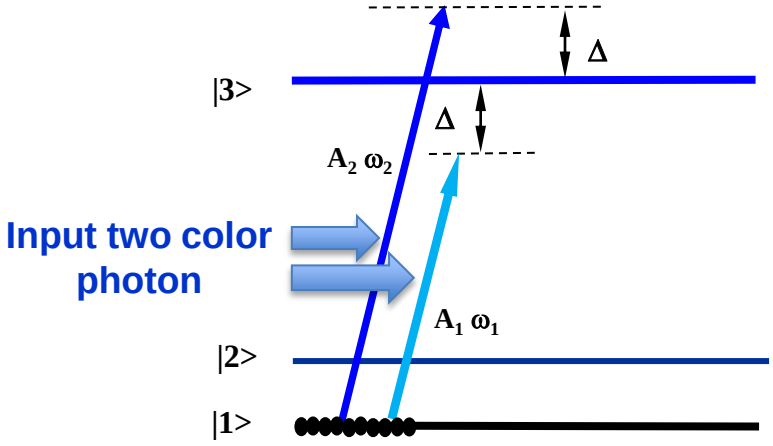
# Off-resonant Raman Echo Quantum Memory:

S. A. Moiseev and G. H'etet et. al., 2008 LASPHYS Workshop (Trondheim, Norway, 2008).
G. H´etet *et al., Opt. Lett.* 33, 2323 (2008);
J. L. Le Gouet and P. R. Berman, Phys. Rev. A 80, 012320 (2009).
S. A. Moiseev and E. S. Moiseev, in *Proceedings of the NATO Workshop: "Quantum Cryptography and Computing," edited* by R. Horodecki, S. Ya. Kilin, and J. Kowalik (IOS Press,Amsterdam, 2010), p. 212.
S. A. Moiseev and W. Tittel, New Journal of Physics 13, 063035 (2011); E. S. Moiseev, and S. A. Moiseev. New Journal of Physics 15 (2013) 105005.
Xiwen Zhang, Alexey Kalachev, and Olga Kocharovskaya. Phys. Rev. A 90, 052322

## Experiments:

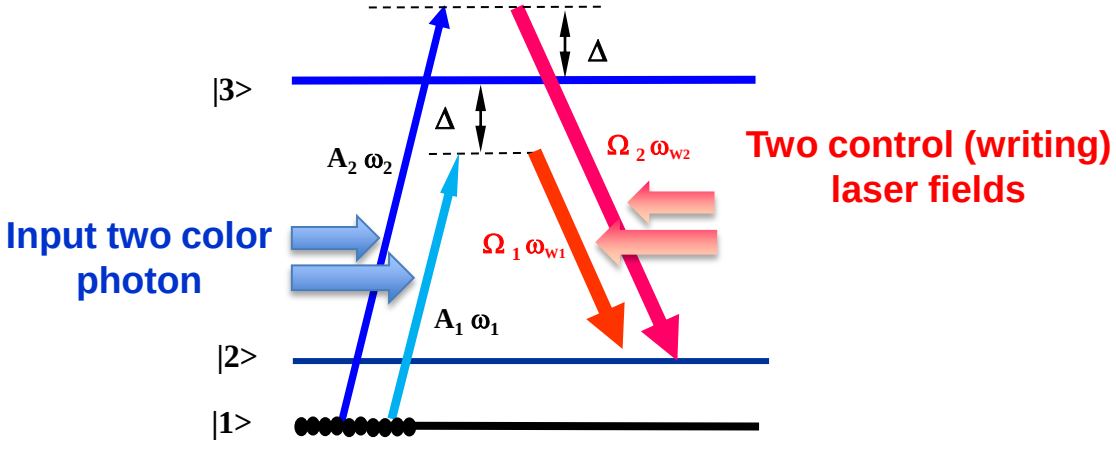
M. Hosseini *et al., Nature (London) 461,* 241 (2009).
M. Hosseini, B. M. Sparkes, P. K. Lam, and B. C. Buchler, Nature Commun.1,1, (2011) (quantum efficiency 87 %).

# Two-color off-resonant Raman echo QM



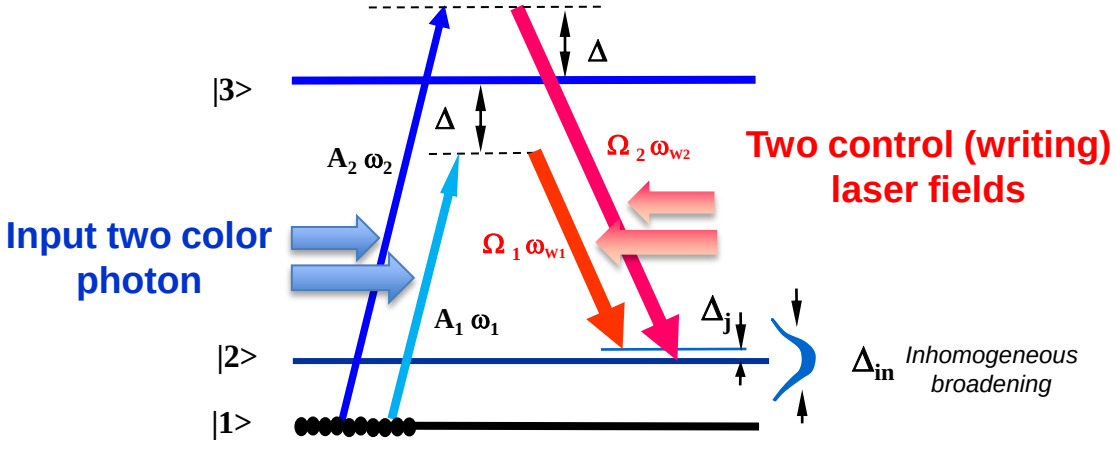

## Spectral symmetric case

# Two-color off-resonant Raman echo QM




## Spectral symmetric case

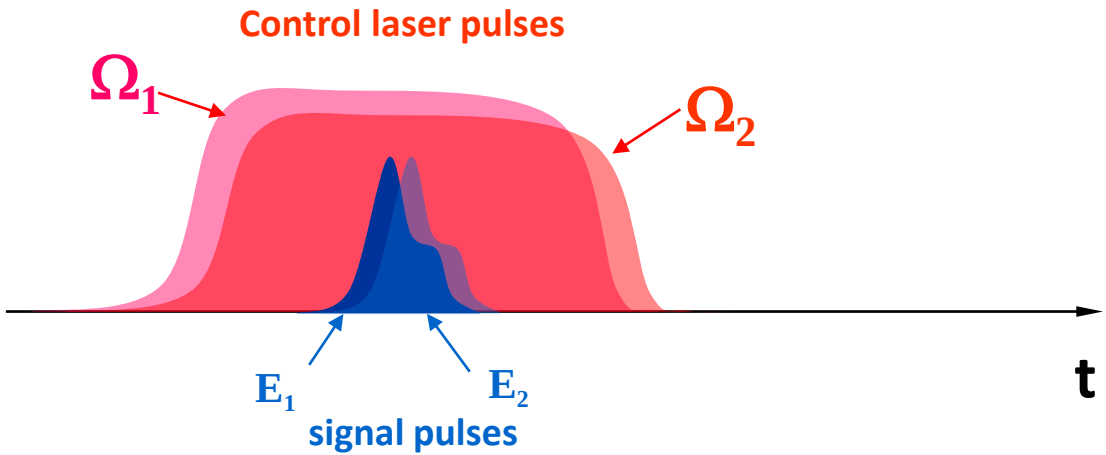
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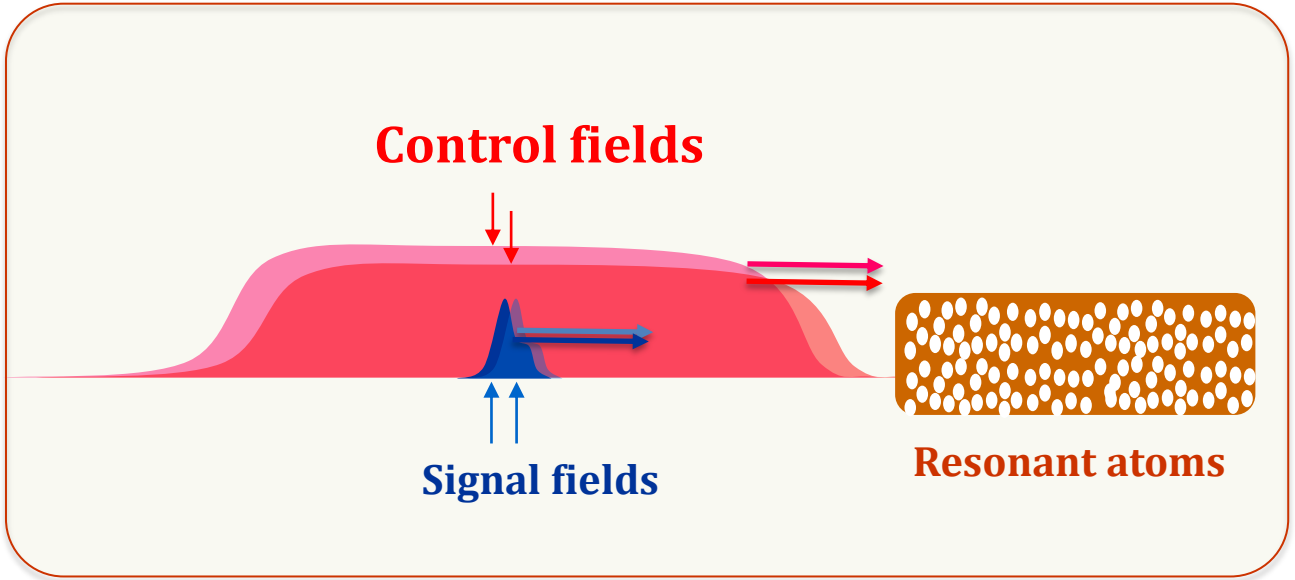

## Spectral symmetric case

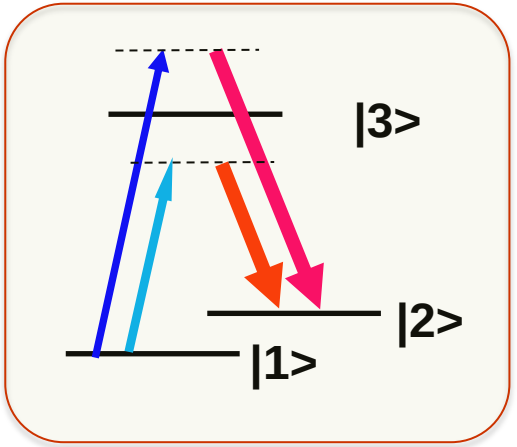
# Temporal Scheme

$\delta t_{\Omega} > \delta t_{signal}$



# 1. FREE SPACE SPATIAL SCHEME



## Light-atoms equations (absorption stage)

**Weak light fields**

$$\hat{P}_{11} \cong 1, \hat{P}_{22} \cong 0$$

**Large spectral detunings from optical transition**

$$(\Delta_{in} / \Delta_1 << 1; \Delta_{in} / \Delta_1 << 1 \quad \delta\omega_s / \Delta_1 << 1, \delta\omega_s / \Delta_2)$$

$$\frac{\partial}{\partial Z} E_1(\tau, Z) = i \frac{\beta_1}{2\Delta_1} \{E_1(\tau, Z) / g_1 + \Omega_1 \left\langle \hat{R}_{12}^j \right\rangle\}, (1w)$$

$$\frac{\partial}{\partial Z} E_2(\tau, Z) = i \frac{\beta_2}{2\Delta_2} \{E_2(\tau, Z) / g_2 + \Omega_2 \left\langle \hat{R}_{12}^j \right\rangle\}, (2w)$$

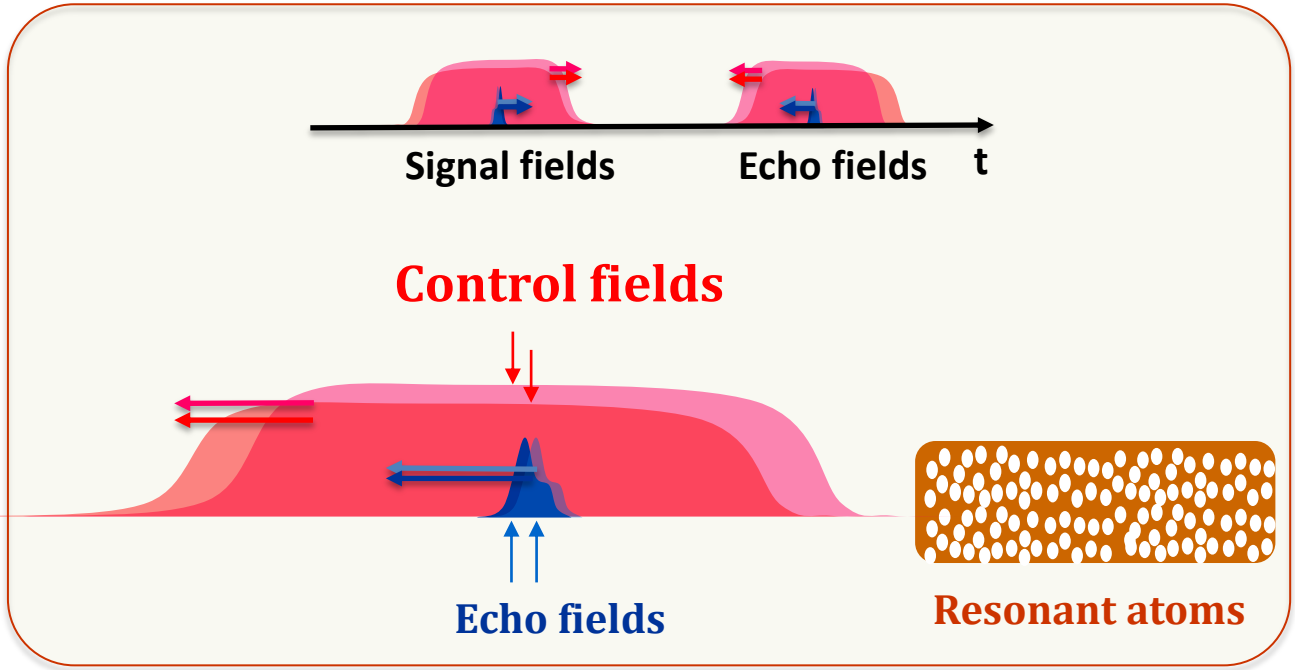
$$\frac{\partial}{\partial \tau} \hat{R}_{12}^j(\tau) = -i\{\Delta_j - \frac{|\Omega_1|^2}{\Delta_1} - \frac{|\Omega_2|^2}{\Delta_2}\} \hat{R}_{12}^j(\tau) + i\{\frac{\Omega_1^* g_1 E_1(\tau, Z_j)}{\Delta_1} + \frac{\Omega_2^* g_2 E_2(\tau, Z_j)}{\Delta_2}\}. (3w)$$

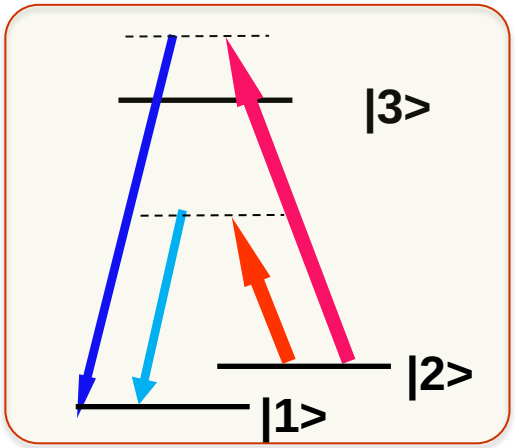
$\tau = t - Z / \upsilon_g, z = Z.$

**ν=1 – 1-st signal field**

**ν=2 – 2-nd signal field**

# 1.FREE SPACE SPATIAL SCHEME (echo emission)



# Light-atoms equations (echo emission stage)

$$-\frac{\partial}{\partial Z}E_{1e}(\tilde{\tau},Z)=i\frac{\beta_1^{'}}{2\Delta_1^{'}}\{E_{1e}(\tilde{\tau},Z)/g_1^{'}+\Omega_1^{'}\left\langle\hat{R}_{12}^{j}\right\rangle\},(1w)$$

$$\tilde{\tau}=t+Z/\upsilon_g,z=Z.$$

$$-\frac{\partial}{\partial Z}E_{2e}(\tilde{\tau},Z)=i\frac{\beta_2^{'}}{2\Delta_2^{'}}\{E_{2e}(\tilde{\tau},Z)/g_2^{'}+\Omega_2^{'}\left\langle\hat{R}_{12}^{j}\right\rangle\},(2w)$$

$$\frac{\partial}{\partial\tilde{\tau}}\hat{R}_{12}^{j}(\tilde{\tau})=i\{\Delta_j^{'}+\frac{|\Omega_1^{'}|^2}{\Delta_1^{'}}+\frac{|\Omega_2|^2}{\Delta_2}\}\hat{R}_{12}^{j}(\tilde{\tau})+i\{\frac{\Omega_1^{'*}g_1^{'}E_{1e}(\tilde{\tau},Z_j)}{\Delta_1^{'}}+\frac{\Omega_2^{'*}g_1^{'}E_{2e}(\tilde{\tau},Z_j)}{\Delta_2^{'}}\}.(3w)$$

**ν=1 – 1-st echo field; ν=2 – 2-nd echo field**

## Properties of the efficient echo emission (perfect quantum memory):

### Spectral symmetric case :

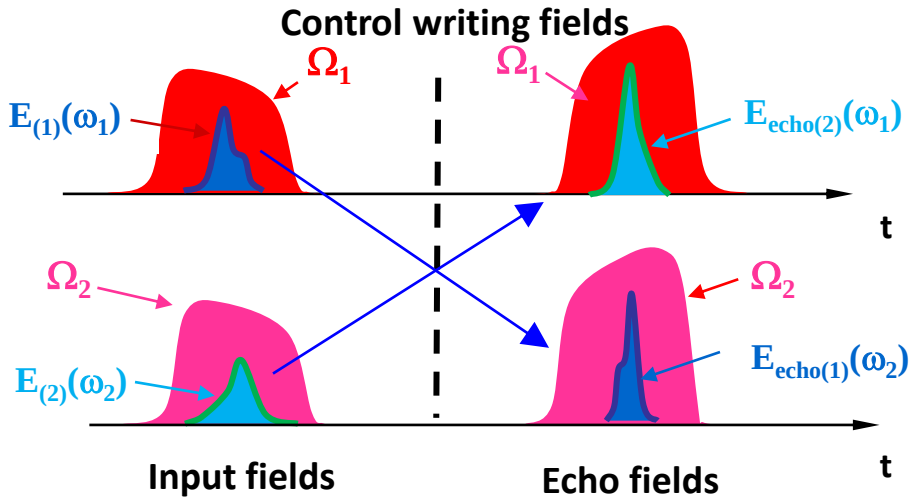
Spectral detunings: $\Delta_1 = -\Delta_2,\ \Delta_1^{'} = -\Delta_1,\ \Delta_2^{'} = \Delta_1$

**η - Scaling factor (0< η<∞)** $\Delta_j^{'} = -\eta\Delta_j, \tilde{\tau}\eta = -\tau,$

**Control field amplitudes:** $\Omega_{1,2}^{'} = -\sqrt{\eta}\Omega_{1,2},$

**Echo field amplitudes:** $E_{1e,2e}(\tilde{\tau}, Z) = -\sqrt{\eta}E_{1,2}(\tau, Z)$

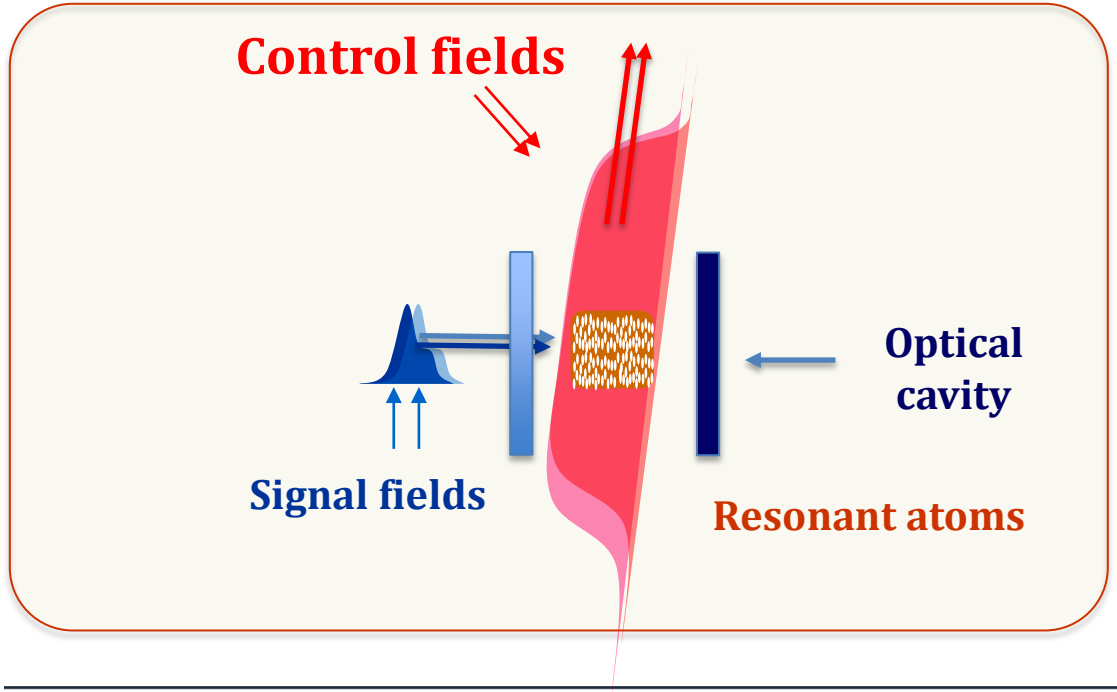
# Temporal and frequency properties of echo fields

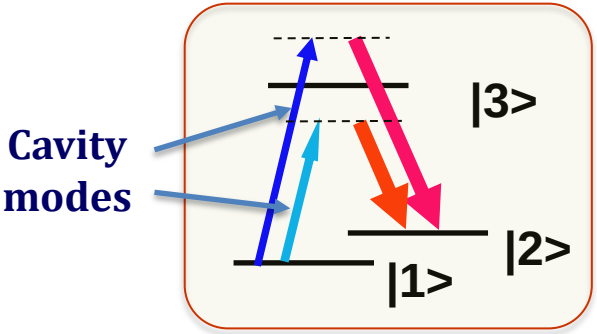



*(Swapping of two-color field )*

*+ temporal compression/decompression)*

# 1. IMPEDANCE MATCHING TWO-COLOR RAMAN ECHO SCHEME



# Light-atoms equations (input-output approach)

$$\frac{d}{d\tau}E_{c,1}(\tau) = -(i\delta_1 + \tfrac{1}{2}\gamma_1)E_{c,1}(\tau) + i\frac{\Omega_1}{\Delta_1}\left\langle g_1^j \hat{R}_{12}^j \right\rangle + \sqrt{\gamma_1}E_{in,1}(\tau), (1w)$$

$$\frac{d}{d\tau}E_{c,2}(\tau) = -(i\delta_2 + \tfrac{1}{2}\gamma_2)E_{c,2}(\tau) + i\frac{\Omega_2}{\Delta_2}\left\langle g_2^j \hat{R}_{12}^j \right\rangle + \sqrt{\gamma_2}E_{in,2}(\tau), (2w)$$

$$\frac{d}{d\tau}\hat{R}_{12}^j(\tau) = -i\{\Delta_j - \frac{|\Omega_1|^2}{\Delta_1} - \frac{|\Omega_2|^2}{\Delta_2}\}\hat{R}_{12}^j(\tau) + i\{\frac{\Omega_1 (g_1^j)^* E_{c,1}(\tau)}{\Delta_1} + \frac{\Omega_2 (g_2^j)^* E_{c,2}(\tau)}{\Delta_2}\}. (3w)$$

$\left\langle g_{1,2}^j \hat{R}_{12}^j \right\rangle = \sum_{j=1}^{N} g_{1,2}^j \hat{R}_{12}^j, \quad g_{1,2}^j = g(\vec{r}_j)\exp\{i\vec{K}_{1,2}\vec{r}_j\},$ **c,1 – 1-st cavity mode field; c,2 – 2-nd cavity mode field**

# Light-atoms equations (input-output approach)

$$\frac{d}{d\tau}E_{c,1}(\tau) = -\tfrac{1}{2}\gamma E_{c,1}(\tau) + iNg\frac{\Omega_1}{\Delta_1}\int d\Delta G(\Delta/\Delta_{in})\hat{R}_{12}(\tau,\Delta) + \sqrt{\gamma_1}E_{in,1}(\tau), (1w)$$

$$\frac{d}{d\tau}E_{c,2}(\tau) = -\tfrac{1}{2}\gamma E_{c,2}(\tau) + iNg\frac{\Omega_2}{\Delta_2}\int d\Delta G(\Delta/\Delta_{in})\hat{R}_{12}(\tau,\Delta) + \sqrt{\gamma}E_{in,2}(\tau), (2w)$$

$$\frac{d}{d\tau}\hat{R}_{12}(\tau,\Delta) = -i(\Delta + \frac{1}{T_2})\hat{R}_{12}(\tau,\Delta) + ig\{\frac{\Omega_1 E_{c,1}(\tau)}{\Delta_1} + \frac{\Omega_2 E_{c,2}(\tau)}{\Delta_2}\}. (3w)$$

$G(\Delta/\Delta_{in})$ – **Inhomogeneous broadening of Raman transition**

# Light-atoms equations (input-output approach)

$$\frac{d}{d\tau}E_{\Sigma}(\tau) = -\tfrac{1}{2}\gamma E_{\Sigma}(\tau) + iNg_{\Sigma}\int d\Delta G(\Delta/\Delta_{in})\hat{R}_{12}(\tau,\Delta) + \sqrt{\gamma}E_{\Sigma}^{in}(\tau), (1)$$

$$\frac{d}{d\tau}\hat{R}_{12}(\tau,\Delta) = -i(\Delta + \frac{1}{T_2})\hat{R}_{12}(\tau,\Delta) + ig_{\Sigma}E_{\Sigma}^{in}(\tau), (2)$$

$$E_{\Sigma}(\tau) = \frac{\{\frac{\Omega_1}{\Delta_1}E_{c,1}(\tau) + \frac{\Omega_2}{\Delta_2}E_{c,2}(\tau)\}}{\sqrt{\left(\frac{\Omega_1}{\Delta_1}\right)^2 + \left(\frac{\Omega_2}{\Delta_2}\right)^2}}, (3)$$

$$E_{\Sigma}^{in}(\tau) = \frac{\{\frac{\Omega_1}{\Delta_1}E_{in,1}(\tau) + \frac{\Omega_2}{\Delta_2}E_{in,2}(\tau)\}}{\sqrt{\left(\frac{\Omega_1}{\Delta_1}\right)^2 + \left(\frac{\Omega_2}{\Delta_2}\right)^2}}, (4)$$

$$g_{\Sigma} = g\sqrt{\left(\frac{\Omega_1}{\Delta_1}\right)^2 + \left(\frac{\Omega_2}{\Delta_2}\right)^2}, (5)$$

$G(\Delta/\Delta_{in})$ – **Inhomogeneous broadening of Raman transition**

# Light-atoms equations (input-output approach)

$$\frac{d}{d\tau}E_{\Sigma}(\tau) = -\tfrac{1}{2}\gamma E_{\Sigma}(\tau) + iNg_{\Sigma}\int d\Delta G(\Delta/\Delta_{in})\hat{R}_{12}(\tau,\Delta) + \sqrt{\gamma}E_{\Sigma}^{in}(\tau), (1)$$

$$\frac{d}{d\tau}\hat{R}_{12}(\tau,\Delta) = -i(\Delta + \frac{1}{T_2})\hat{R}_{12}(\tau,\Delta) + ig_{\Sigma}E_{\Sigma}^{in}(\tau), (2)$$

S. A. Moiseev. Phys.Rev.A **88**, 012304 (2013).

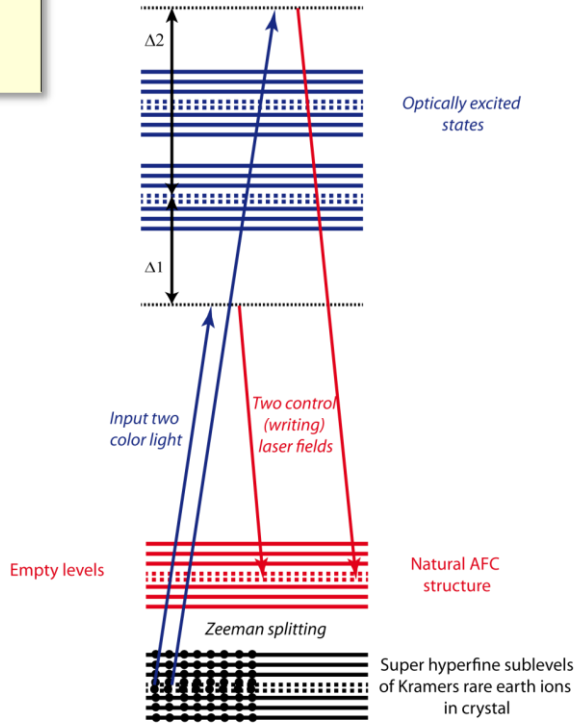
# About experimental implementation on rare-earth ions

Simplified energy levels scheme of Kramers rare earth (RE) ions ($Yb^{3+}$, $Er^{3+}$, $Nd^{3+}$) in fluorides ($CaF_2$, $LiYF_4$, $KMgF_3$), when superhyperfine interaction of RE electron with fluorine ligands ($I = 1/2$) in crystal host can form the equidistant sublevels (natural AFC structure).

Aminov, L. K., Kurkin, I. N. & Malkin, B. Z. Superhyperfine structure in the EPR spectra and optical spectra of impurity f ions in dielectric crystals: A review. *Phys. Solid State* **55,** 1343–1363 (2013).

Spectral width of natural AFC structure will allow to save optical pulses with time durations < 50 ns.

| RE ions | $Yb^{3+}$ | $Er^{3+}$ | $Nd^{3+}$ |
|---|---|---|---|
| Wavelength of optical transitions | ~970 nm | ~1540 nm<br>~ 980 nm<br>~ 790 nm | ~ 800 nm<br>~ 870 nm |



# Summary

**Off resonant Raman echo QM on rare-earth ions in QED cavity can be used for storage two color fields (two-color photonic qubit states);**

**This technique can be also used for quantum manipulation (compression/decompression, wavelength conversion), of these fields;**

**- By using different wave vectors of control laser fields, one can retrieve selectively single photon on demand (associative memory).**

**The proposed approach can be used for quantum repeaters of subcarrier optical quantum communication**

# Acknowledgements

This work was financially supported by the Russian Scientific Fund through Grant No. 14-12-01333.

# Thank you for your attention!