University *of Ljubljana*
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Quantum Memory with Hot Cesium Atoms

Seminar I – 1st year, 2nd cycle

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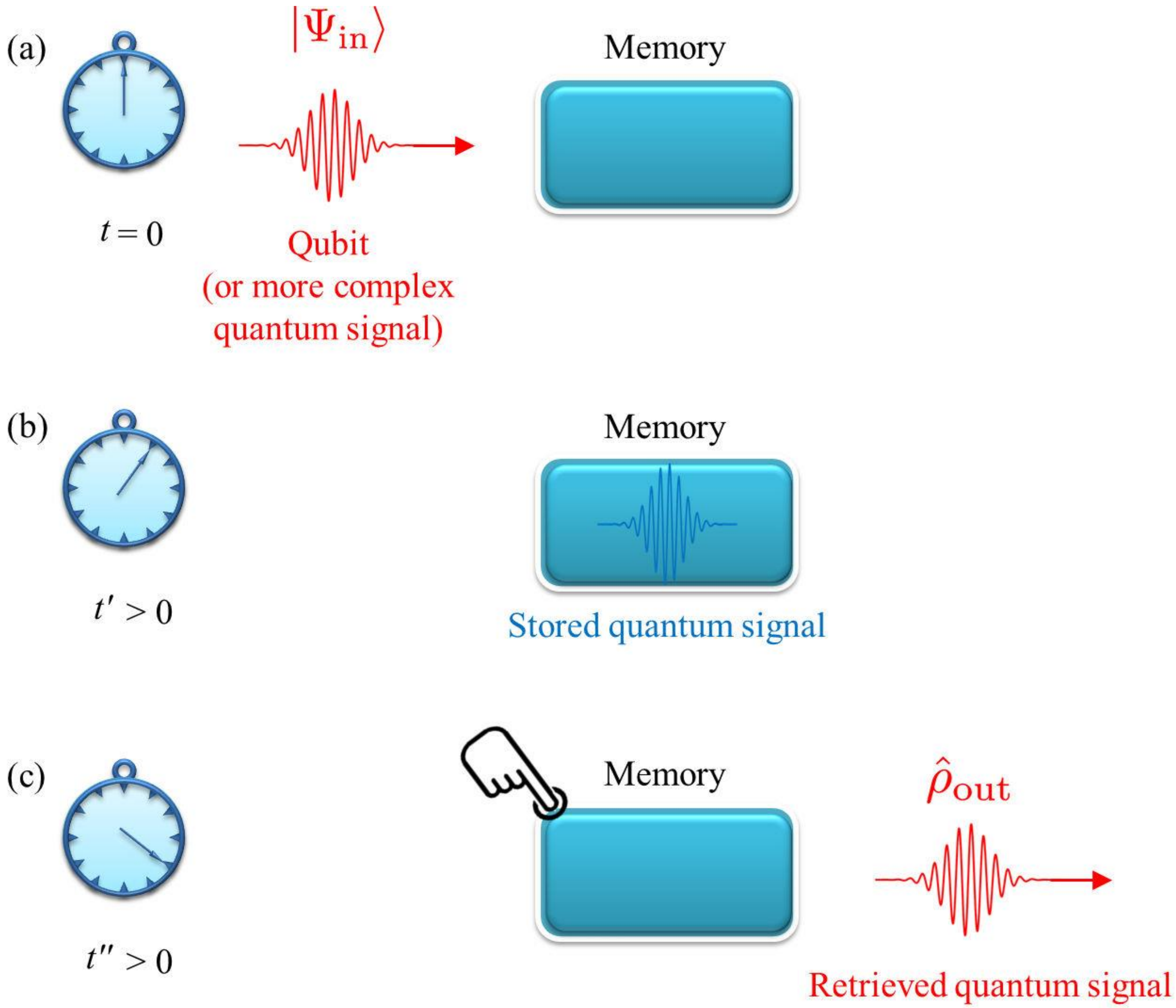
Why do we need quantum memory?

- A **qubit** is basic unit of quantum information – a two-state quantum-mechanical system.
- Two good examples:
  - **electron** (spin),
  - **photon** (polarization).
- **Quantum communication**: exchange of qubits between multiple participants.
- **Quantum key distribution** (QKD) safety protocol → **ultimately safe**.
- Problem: Signal attenuation.
- Solution: Quantum repeaters.

Definition of **quantum memory**

Quantum memory is a device that enables the storage of quantum information and its later retrieval.



Requirements: key parameters

- **Fidelity** quantifies how closely the retrieved quantum state matches the input state.
- **Efficiency** represents the energy ratio between retrieved and input states.
- **Memory time** refers to the duration over which a quantum state remains faithfully stored.
- **Multimodal capacity** – number of elementary quantum states a memory can store in parallel.
- **Wavelength –** telecom wavelengths $(\lambda = 1.3 \text{ to } 1.5\,\mu\text{m})$ desired.
- **Signal-to-noise ratio**

Quantum memory protocols

Single quantum emitter-based memories:

- single atoms in cavities,
- individual trapped ions,
- nitrogen-vacancy centers (NVC) in diamonds,
- quantum dots.

Ensemble-based memories:

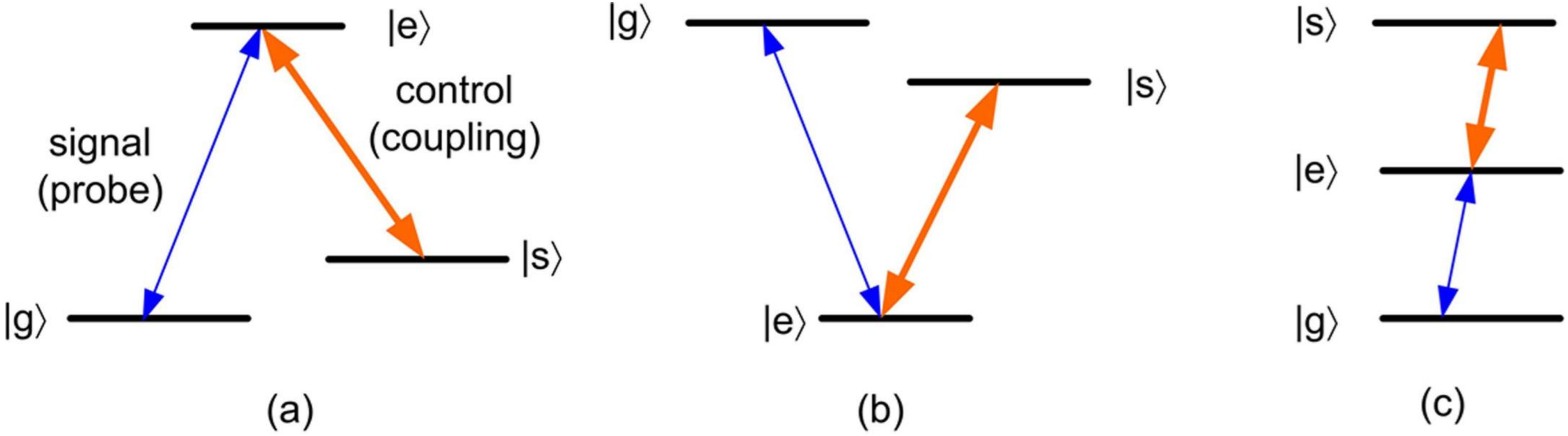
- cold or ultra-cold atomic gases,
- hot atomic vapors,
- rare-earth-doped crystals,
- microcavity coupled NVC ensembles.

Decoherence

- **Decoherence**, the loss of quantum coherence, is the primary obstacle for quantum memories and quantum information systems. It primarily limits storage times.

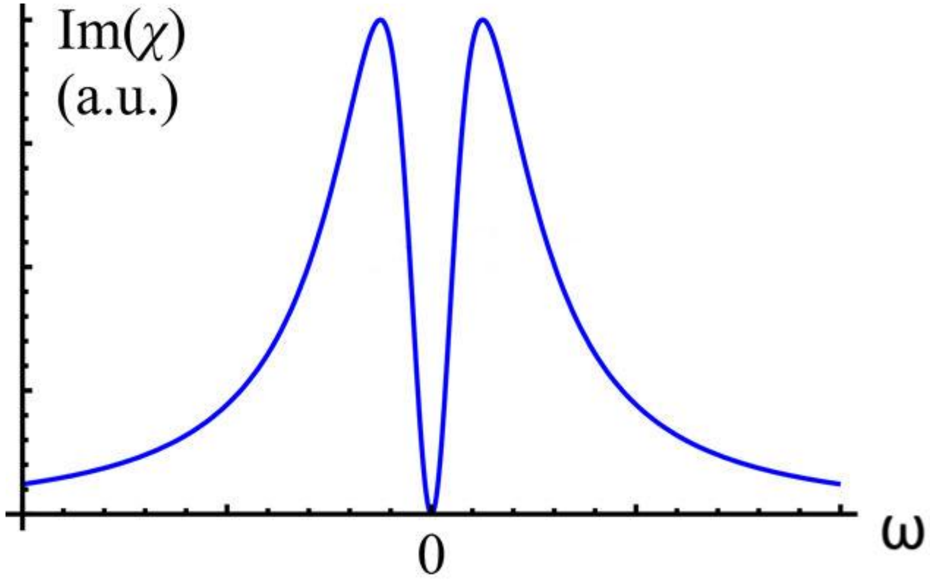
- This process transforms pure quantum states into classical (non-quantum) mixture states, rendering them useless for quantum purposes.

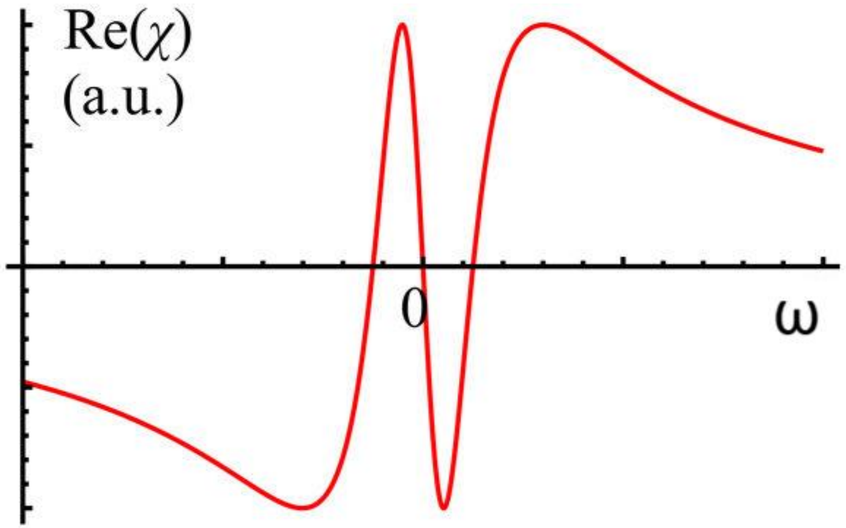
Electromagnetically induced transparency



EIT occurs in some media when a light beam, that should normally be absorbed, is instead transmitted.
We name states: ground |g⟩, excited |e⟩, and storage |s⟩.
In **lambda system** (a) transition |g⟩ → |s⟩ is dipole forbidden.

Slow light





From complex refractive index

$$n = n' + in'',$$

we obtain the real part of refractive index:

$$n' = 1 + \frac{1}{2}\mathrm{Re}\chi(\omega)$$

From Kramers-Kronig relations + theory of Rabi oscillations:

$$\chi(\omega) = g^2 N \frac{\gamma_{gs} + i\omega}{(\gamma_{ge} + i\omega)(\gamma_{gs} + i\omega) + |\Omega|^2}$$

$|\Omega|^2$ proportional to control beam intensity

Real part of electric susceptibility χ determines the refractive properties, imaginary part determines the absorption in the medium!

Phase velocity:

$$v_{\mathrm{p}} = \frac{\omega}{k} = \frac{c}{n'}$$

Group velocity:

$$v_{\mathrm{g}} = \frac{\partial \omega}{\partial k} = \frac{c}{n' + \omega \frac{\partial n'}{\partial \omega}}$$

By using equations from previous slide, we can evaluate the derivative, which gives us new expression for group velocity:

$$v_g = \frac{c}{1 + g^2 N / |\Omega|^2}$$

Increasing the atomic density N or decreasing control beam intensity $|\Omega|^2$ will reduce the group velocity of the signal beam.

This has been demonstrated theoretically and practically (also in our lab). Said phenomenon is called the **slow light**.

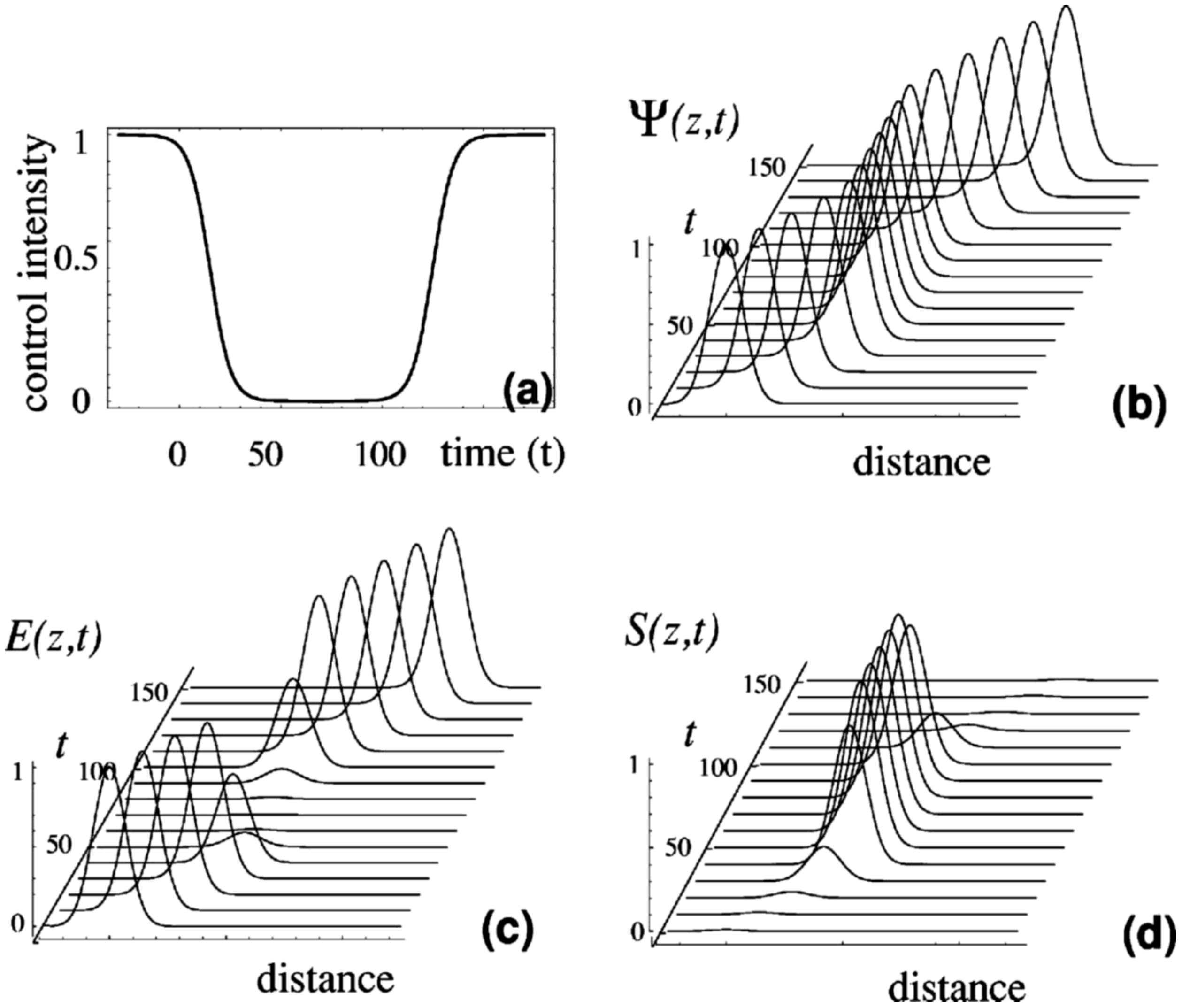
Stored light: Dark-state polariton description

The *dark-state polariton* is a quasiparticle, a superposition of electromagnetic waves and atomic excitations.

$$\Psi(z,t) = \cos\theta E(z,t) + \sin\theta S(z,t),$$

$$\cos\theta = \frac{\Omega}{\sqrt{\Omega^2 + g^2 N}},$$

$$\sin\theta = \frac{g\sqrt{N}}{\sqrt{\Omega^2 + g^2 N}}.$$



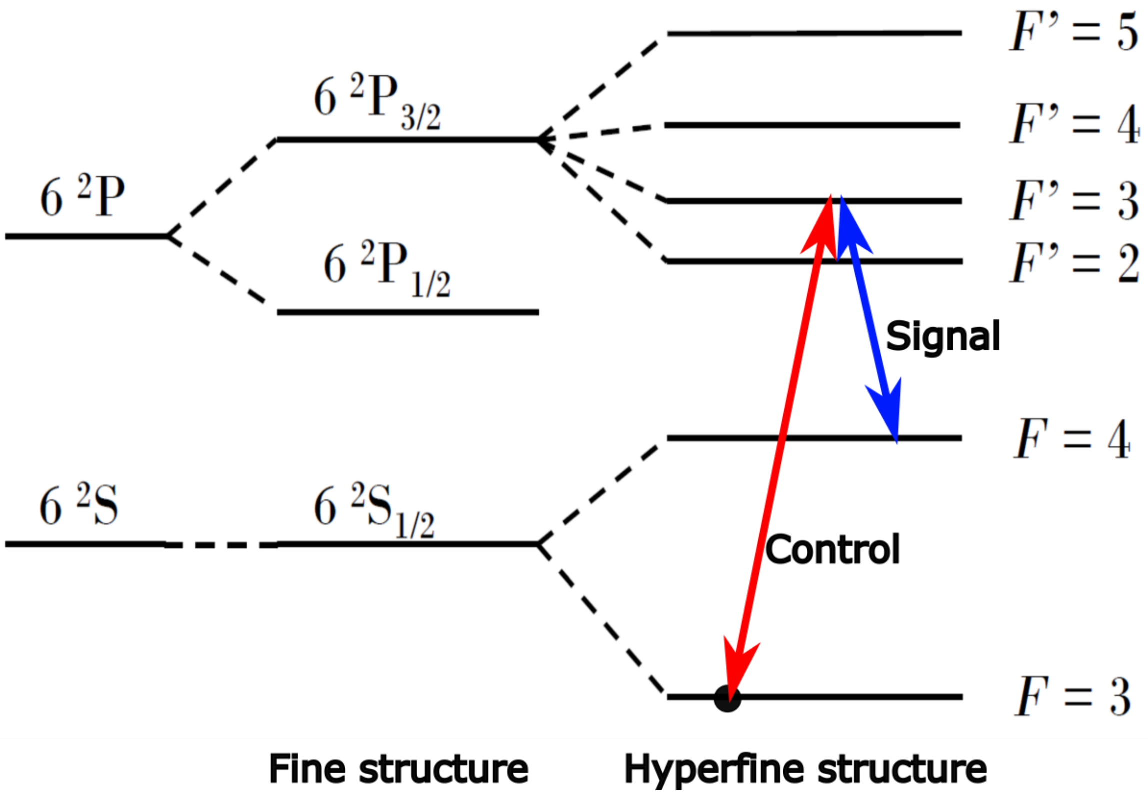
Hyperfine structure of cesium atom

- ^{133}Cs isotope
- Total el. ang. momentum (spin-orbit coupling):

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

- Total atomic angular momentum (coupling of J with I):

$$\mathbf{F} = \mathbf{J} + \mathbf{I}$$

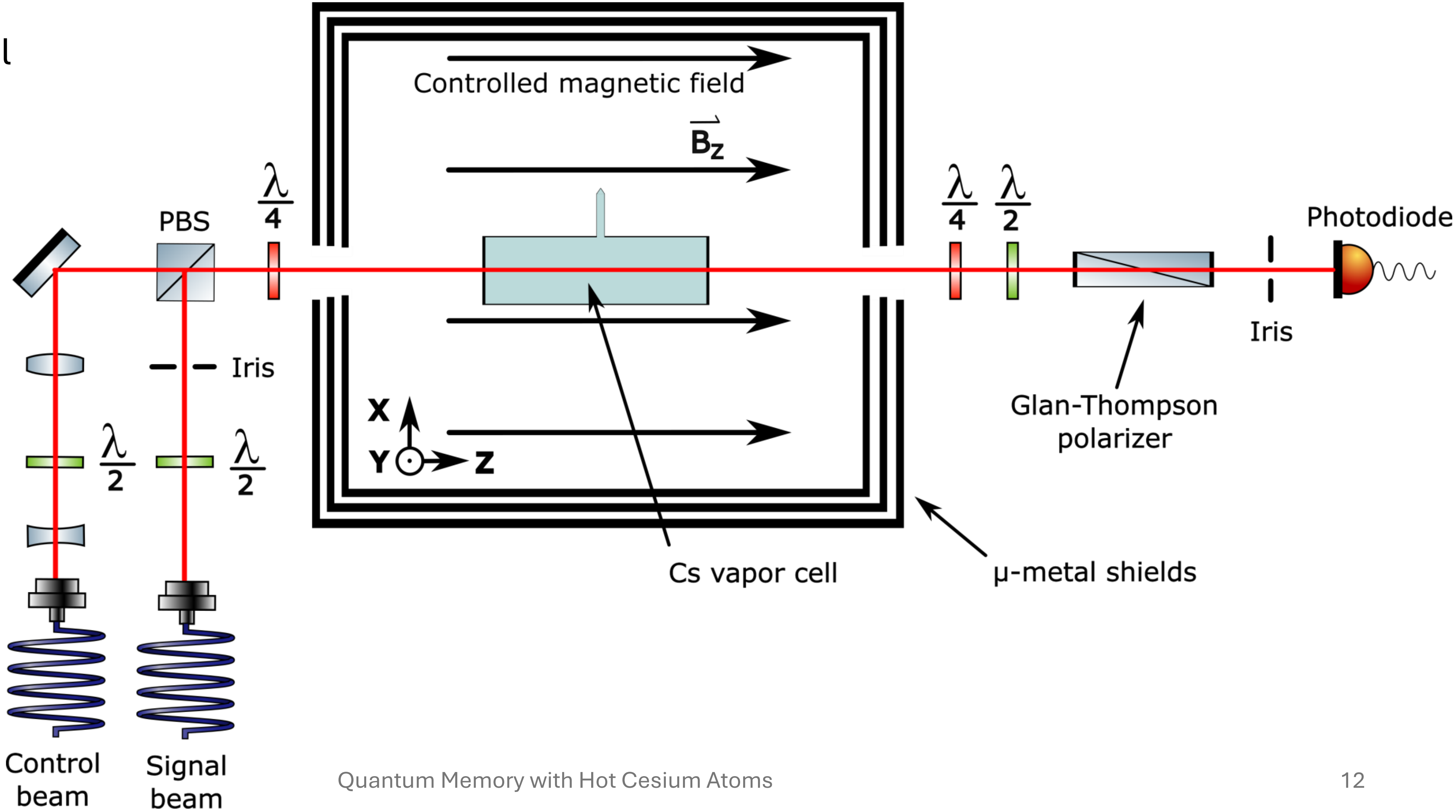


$$|g\rangle = |6S_{1/2}, F = 3\rangle,\ |s\rangle = |6S_{1/2}, F = 4\rangle,\ \text{and}\ |e\rangle = |6P_{3/2}, F' = 3\rangle$$

Laboratory for cold atoms, IJS: Optical setup

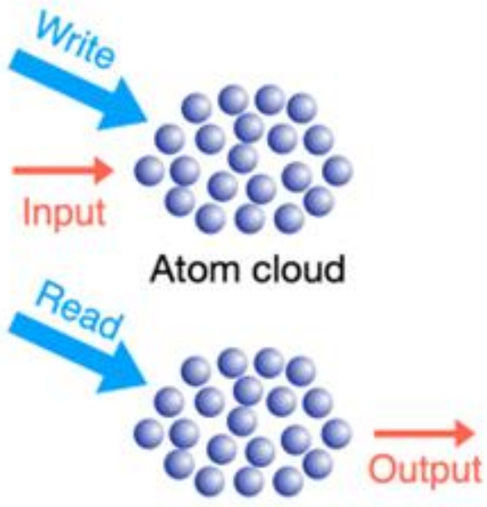
for QM with hot Cs atoms

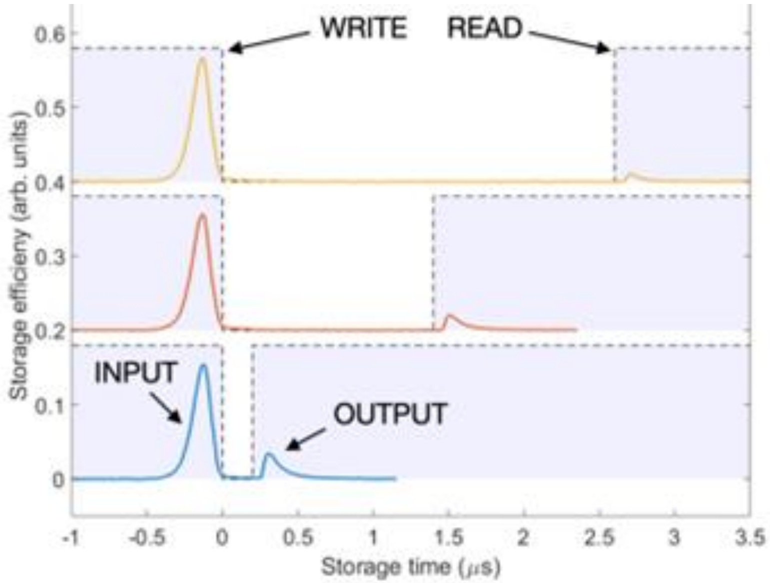
Signal and control beams are prepared using acousto-optic modulators (AOM's) to precisely match wavelengths corresponding to |g⟩ → |e⟩ and |s⟩ → |e⟩ level transitions respectively.



- AOMs are controlled by software written in python.
- After detection read signal is numerically integrated in MATLAB and the result assigned as stored light to given storage time, that we were measuring.

We fully automated this process, allowing us to be able to relatively easily change different parameters and repeat measurements.

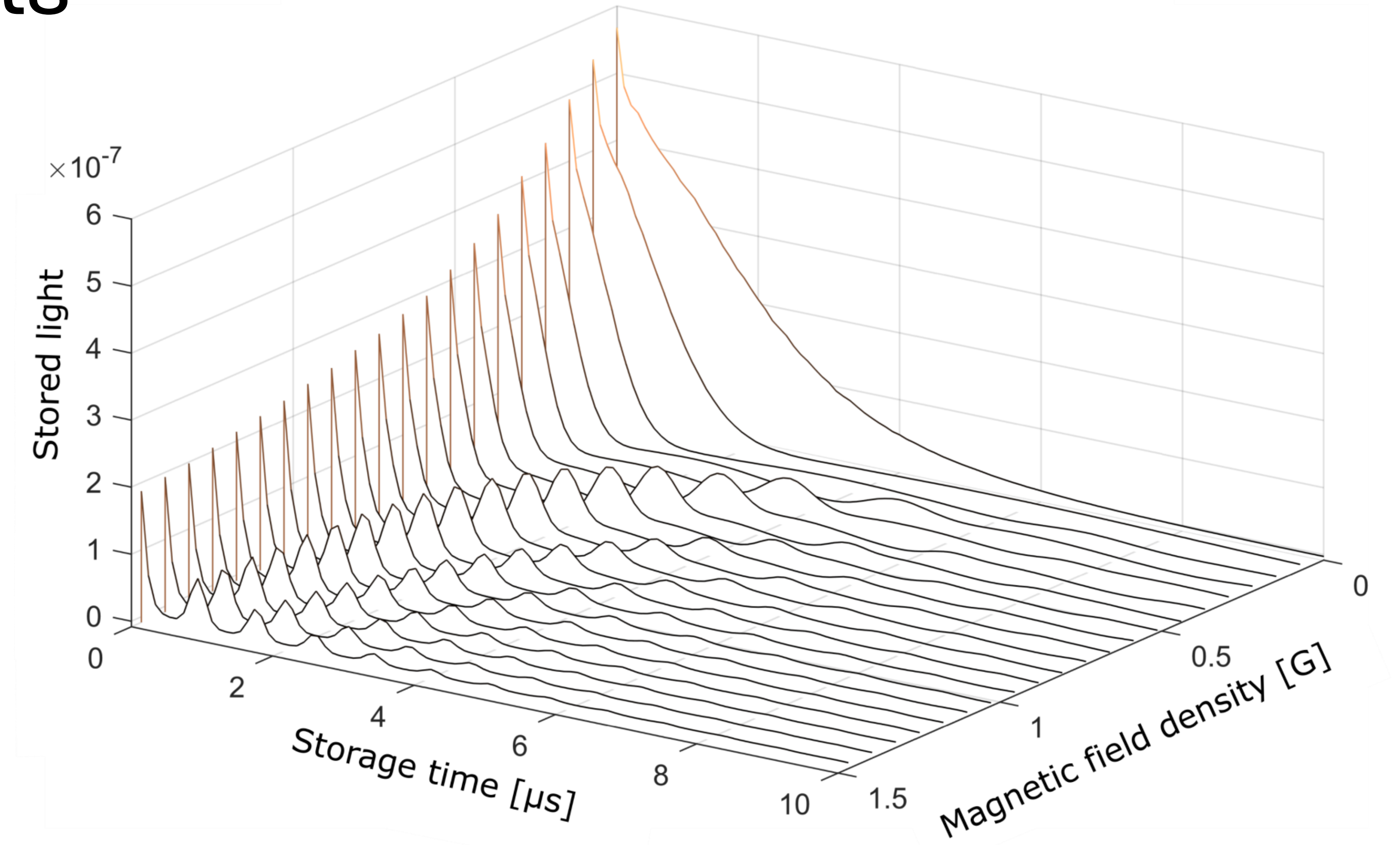




Measurements

We measure the influence of various parameters:

- magnetic field,
- partial pressure of buffer gas,
- cell coating,
- …



State of the art

- A room-temperature quantum memory using warm rubidium vapor, that performs a high-fidelity retrieval (95%) at storage time of **160 μs for single-photon** operations and up to **1 ms for classical-level light** by suppressing atomic diffusion. Done by *Qunnect Inc.*

- Research group from *Weizmann Institute of Science* set **a record 1 second storage time QM** on room temperature Cs vapor, achieved by exploiting a decoherence-free subspace, overcoming spin-exchange collision limitations and surpassing previous techniques by two orders of magnitude.

Conclusion

- Theoretical background of QM and EIT was explained.
- *Laboratory for cold atoms* at *Jožef Stefan Institute* showed successful demonstration of slowing and storing of the light in both cold Cs atoms in magneto-optical trap (MOT) (storage times of **more than 400 μs**) and hot Cs atoms (best currently achieved storage times of **5 μs**).

- State of the art research instills hope, that this results can be greatly improved in future, which is also the main objective of our future endeavours.

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Thank you!