



Учреждение Российской  
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Физический институт  
им. П.Н. Лебедева РАН



RQC

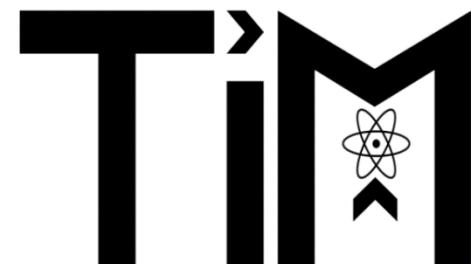
Russian  
Quantum  
Center

# Квантовые вычисления на ионах

Ilya Semerikov

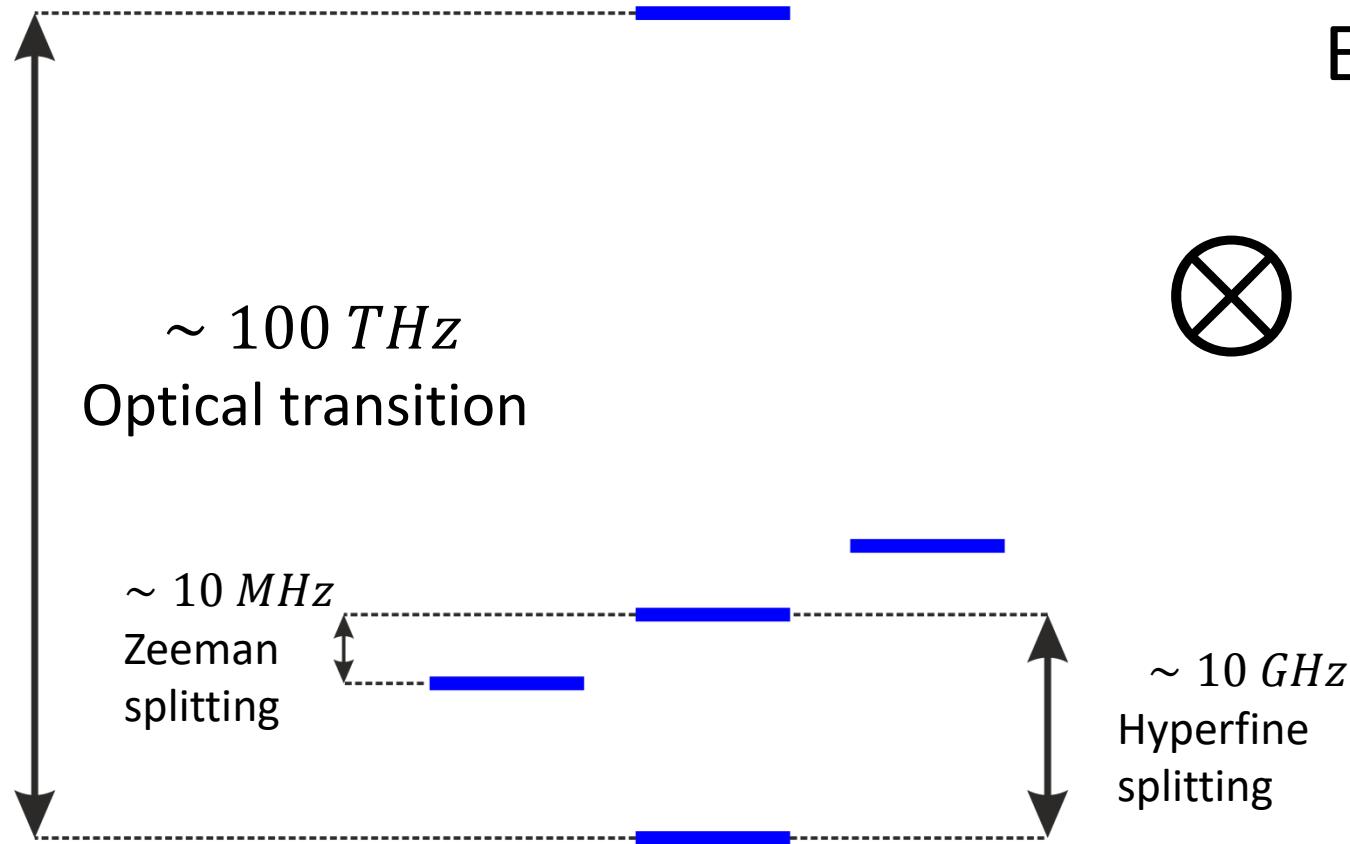
Ilya Zalivako, Alexander Borisenko, Mikhail Aksenov, Andrey Korolkov

Nikolay Kolachevsky, Ksenia Khabarova

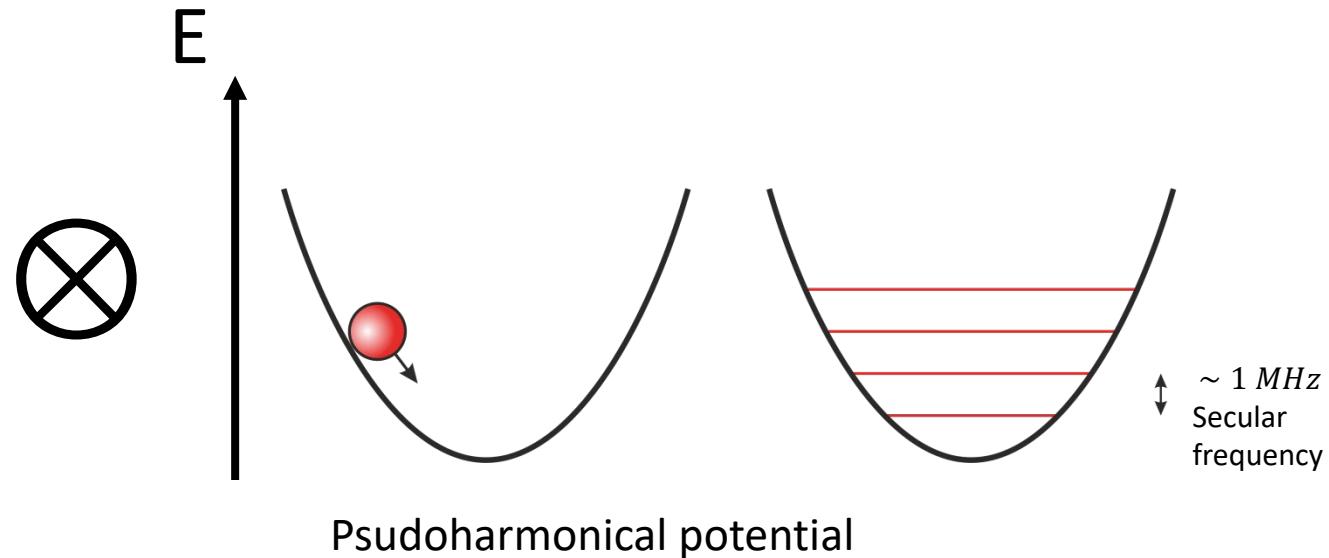


# Ion qubits

## Electronic states



## Motional states

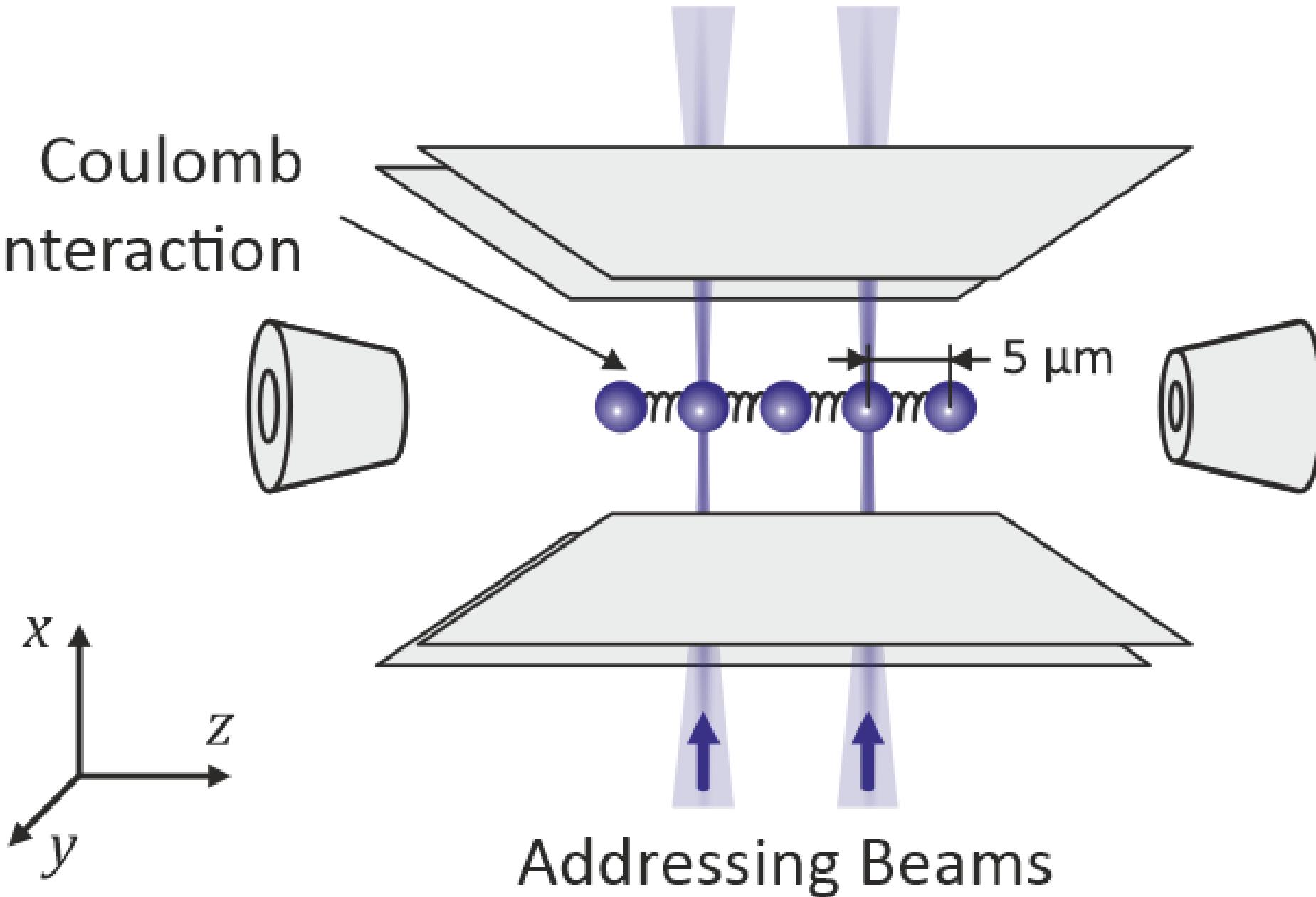


$$E = h\nu_{sec} \left( n + \frac{1}{2} \right)$$

$$\nu_{sec} \sim 1 \text{ MHz}$$

# Principles of ion quantum computer

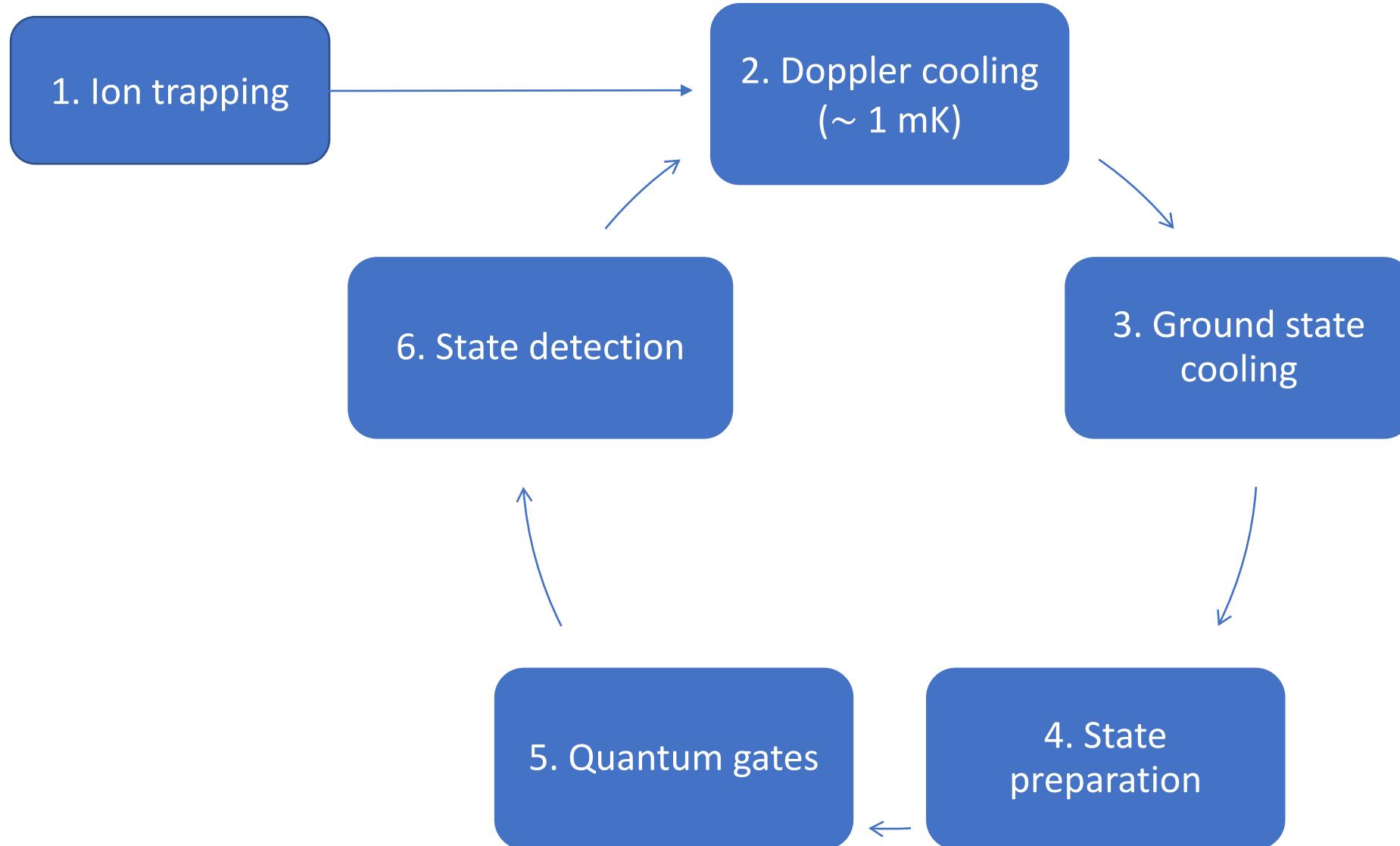
Coulomb  
Interaction



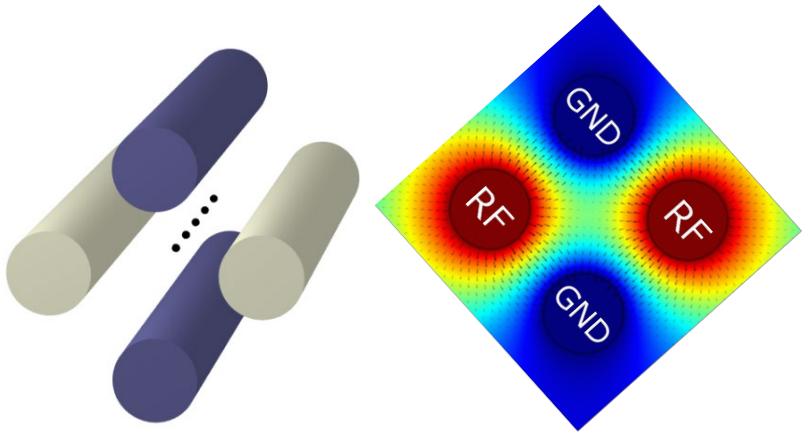
# Outline

- Ion quantum computer workflow and our progress
- Leaders of the field
- Challenges in ion quantum computation and our proposals
  - Ion addressing
  - Nonlocal entanglement
  - Ground state cooling of large ion crystals
  - Ion heating

# Ion quantum computer workflow



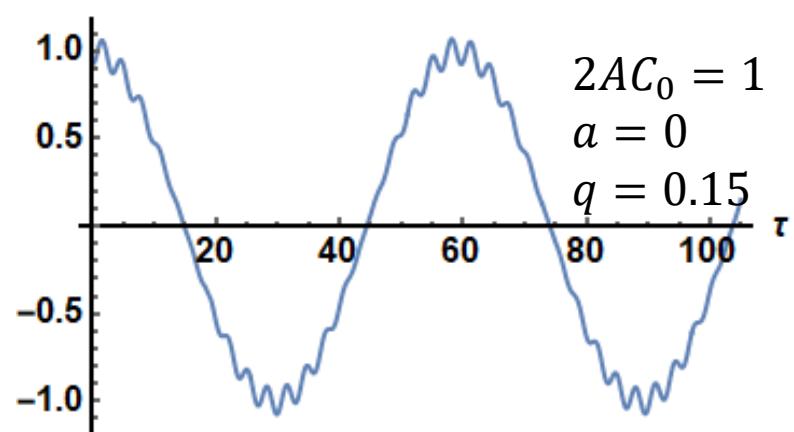
# 1. Ion trapping: Paul trap



$$E_x = \frac{\kappa_x \Phi_0}{r_0^2} x; E_y = -\frac{\kappa_y \Phi_0}{r_0^2} y; E_z = 0$$

$$\Phi_0 = U_{dc} - V_{ac} \cos \omega t$$

$$x(t) = 2AC_0 \cos(\Omega_{sec}t) \left( 1 - \frac{q}{2} \cos \omega t \right)$$



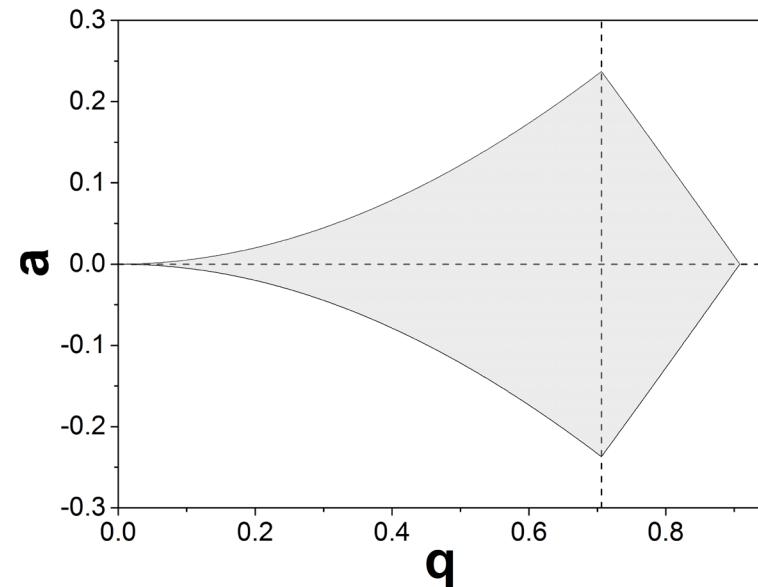
$$\tau = \frac{\omega}{2} t; a = \frac{4eU_{dc}}{m\omega^2 r_0^2}; q = \frac{2eV_{ac}}{m\omega^2 r_0^2}$$

$$\Omega_{sec} = \frac{\omega}{2} \sqrt{a + \frac{q^2}{2}} \quad (\text{при } |a|, |q| \ll 1)$$

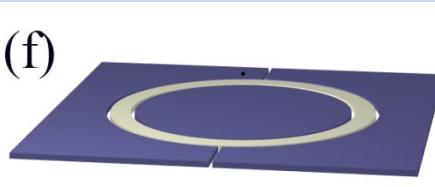
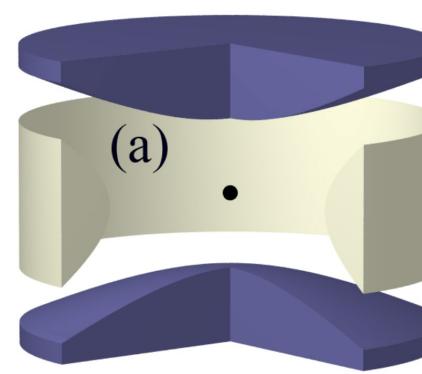
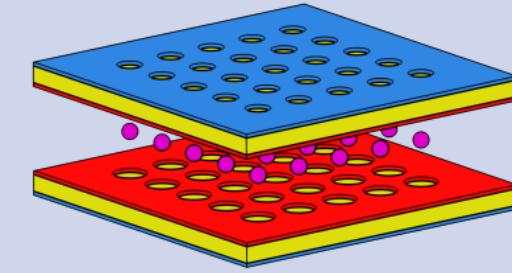
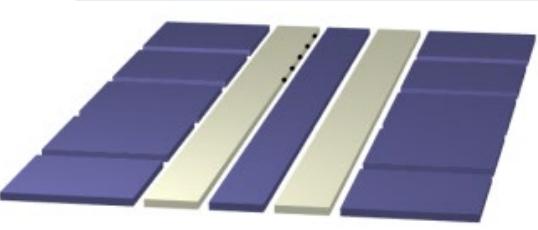
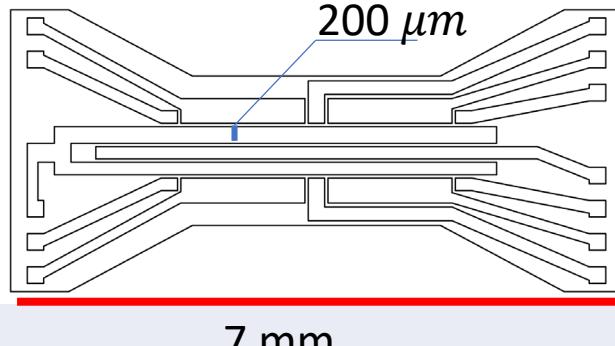
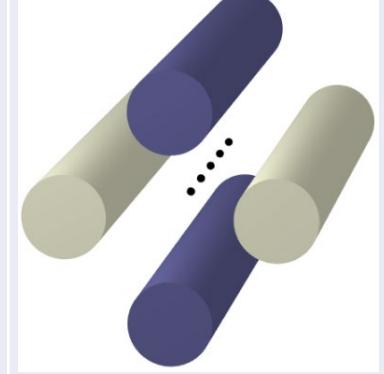
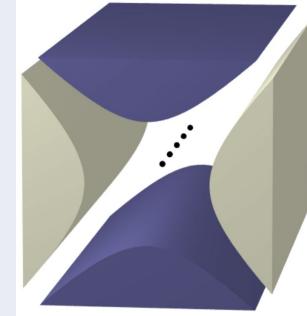
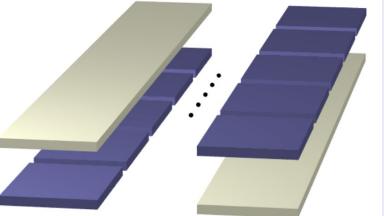
$$\frac{d^2x(\tau)}{d\tau^2} + (a - 2q \cos 2\tau)x = 0$$

$$\frac{d^2y(\tau)}{d\tau^2} - (a - 2q \cos 2\tau)y = 0$$

*Secular frequency*  $\Omega_{sec} \sim 1 \text{ MHz}$   
*Trap depth*  $\sim 1 \text{ eV}$

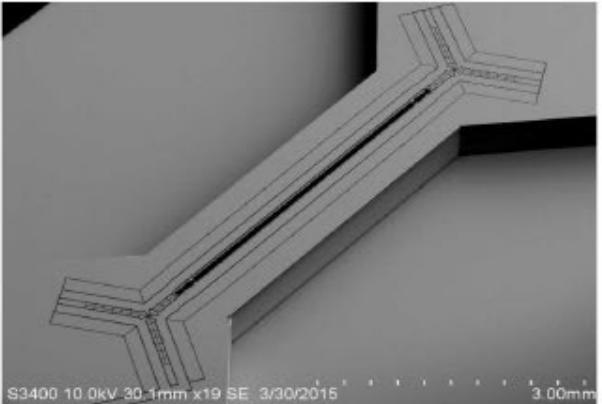


# Possible topologies and technologies

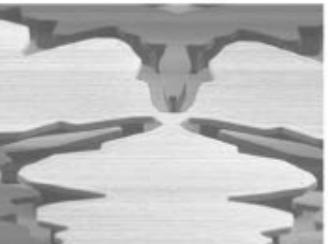
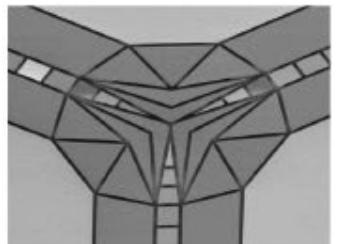
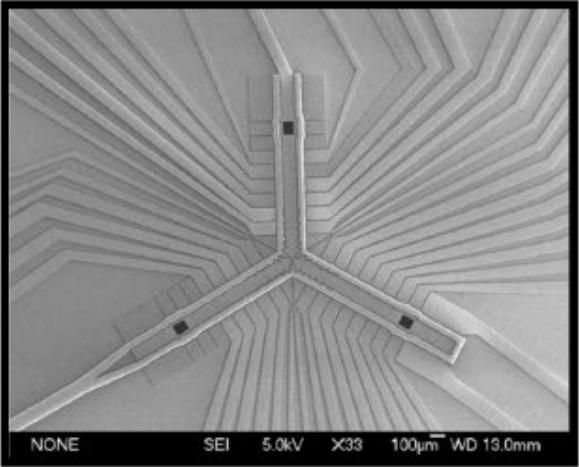
	2D	3D
Point		 
Linear	 	  

# Some of sandias traps

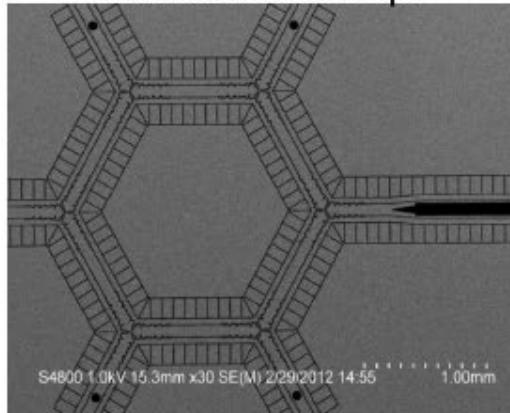
High Optical Access (HOA) trap



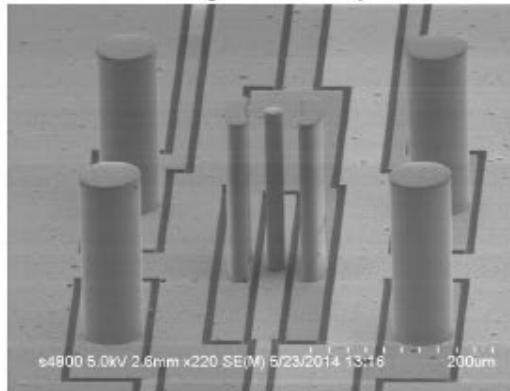
Y-junction traps



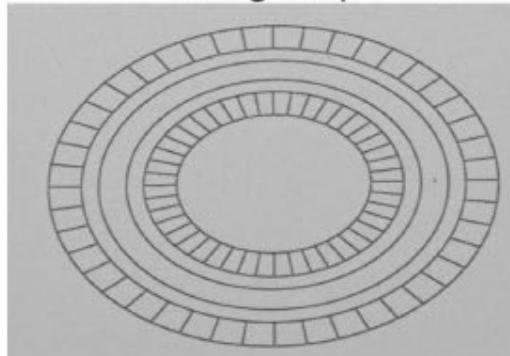
Circulator trap



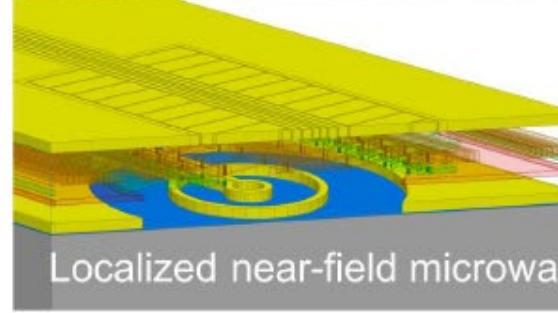
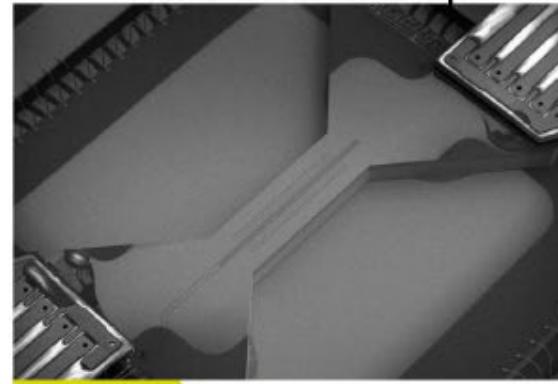
Stylus trap



Ring trap

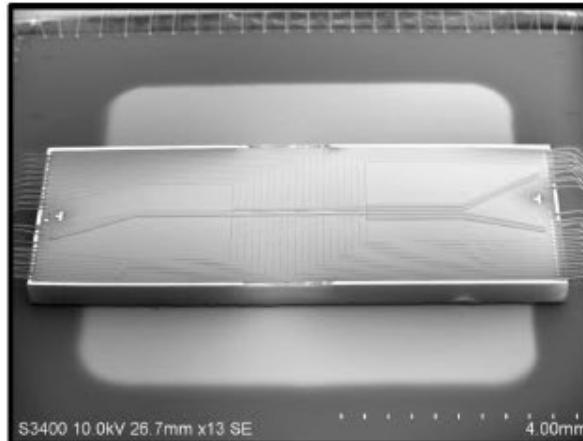


Microwave trap



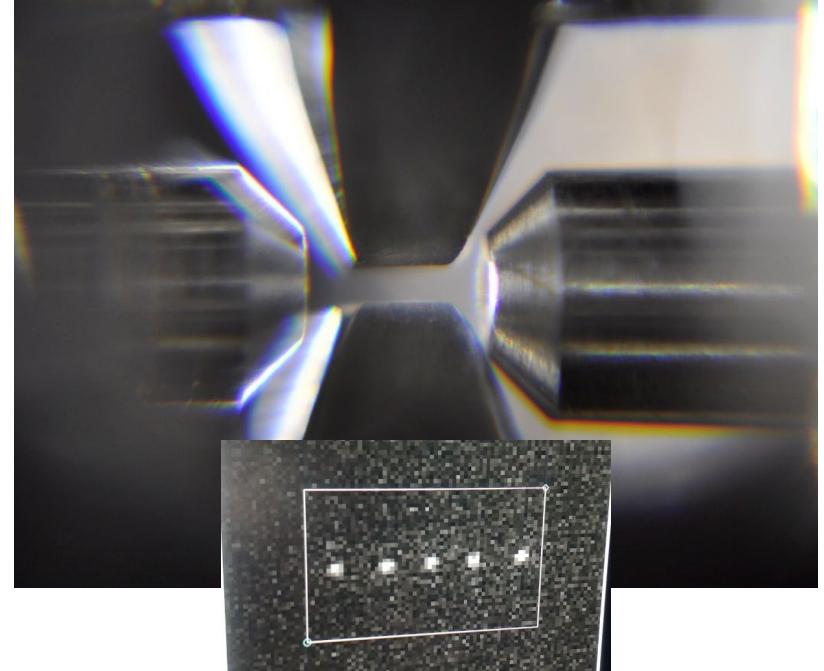
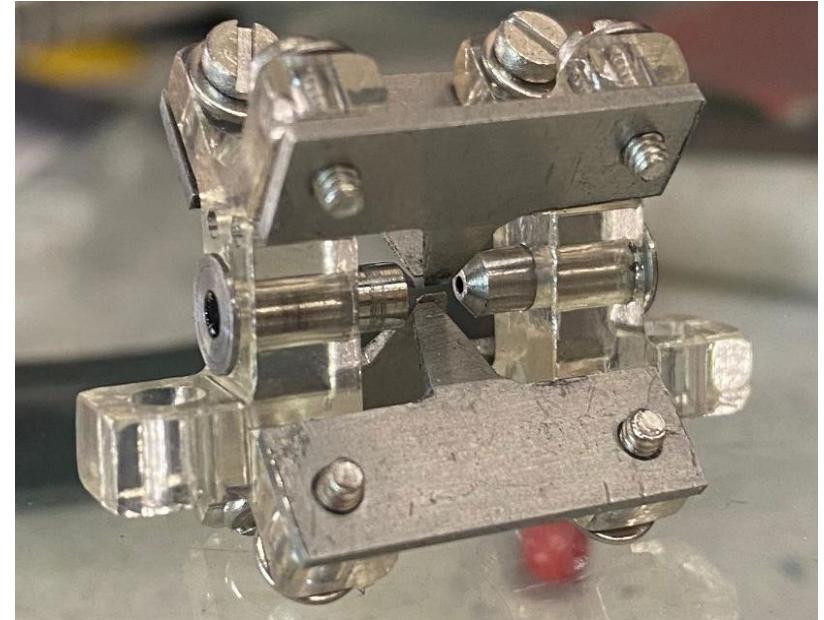
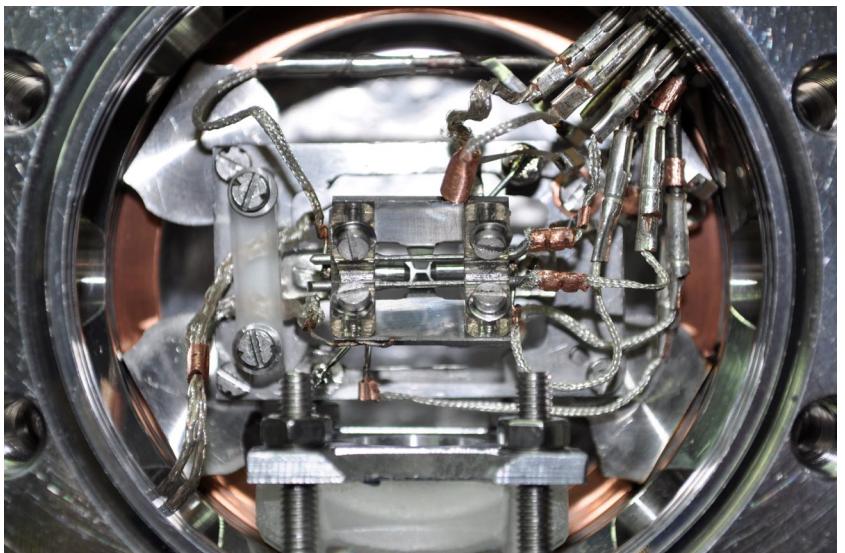
Localized near-field microwave trap

EPICS trap

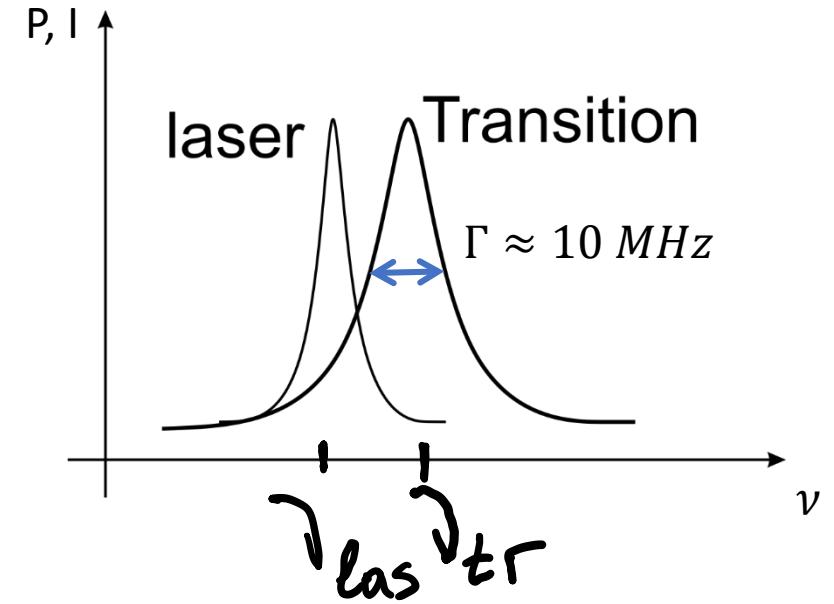
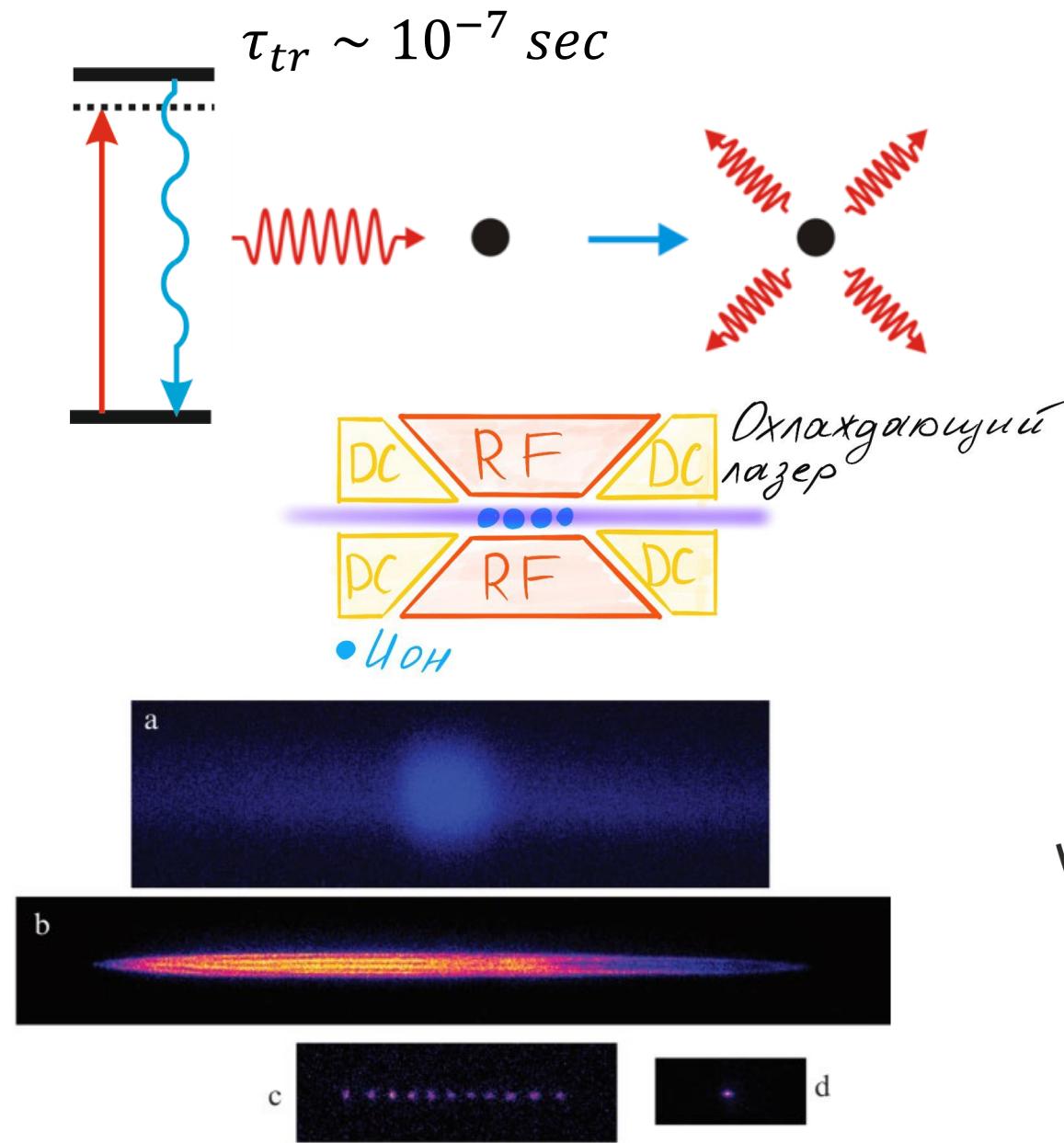


# LRC Trap gen 1

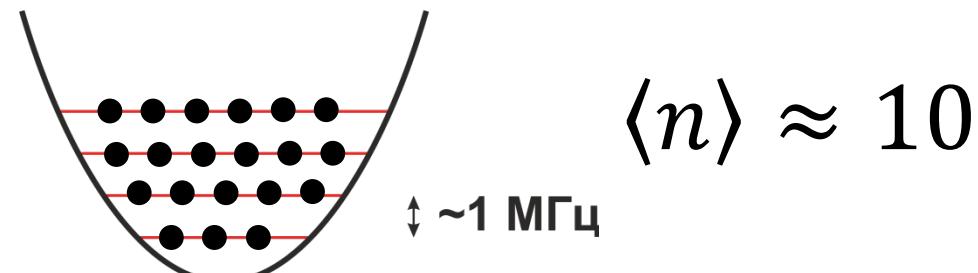
- Linear single section Paul trap
- Mo electrodes
- Zerodur dielectrics
- NA = 0,45 / 0,7
- $(\Omega_X, \Omega_Y, \Omega_Z) = 2\pi \times (1500, 1480, 450) \text{ kHz}$
- Heating rate 400 phonon/s
- Ion lifetime > 7 days (room temperature setup)
- 5 ions in the line configuration @  $\Omega_Z=300 \text{ kHz}$
- Next generation trap designed



## 2. Doppler cooling

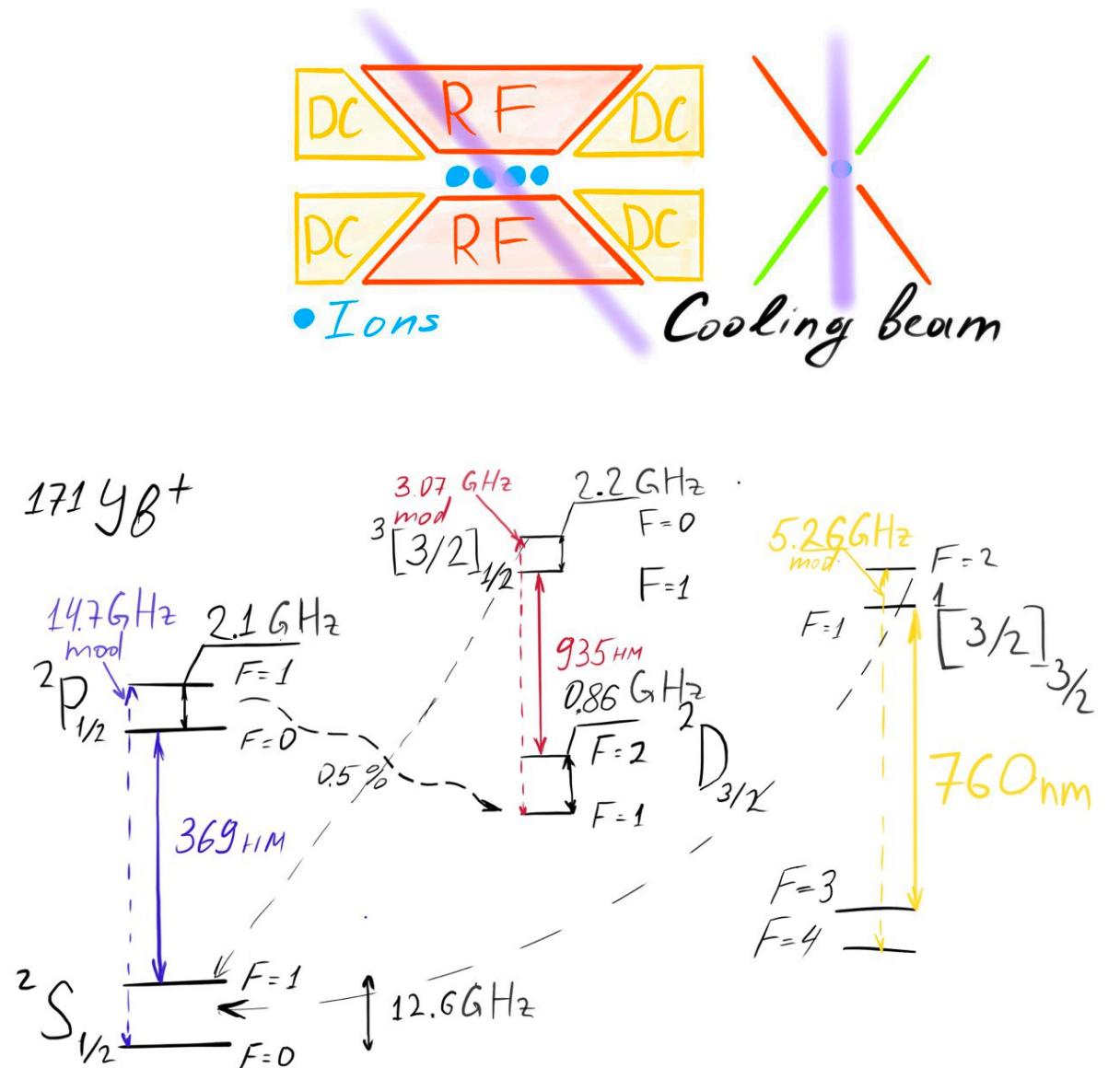
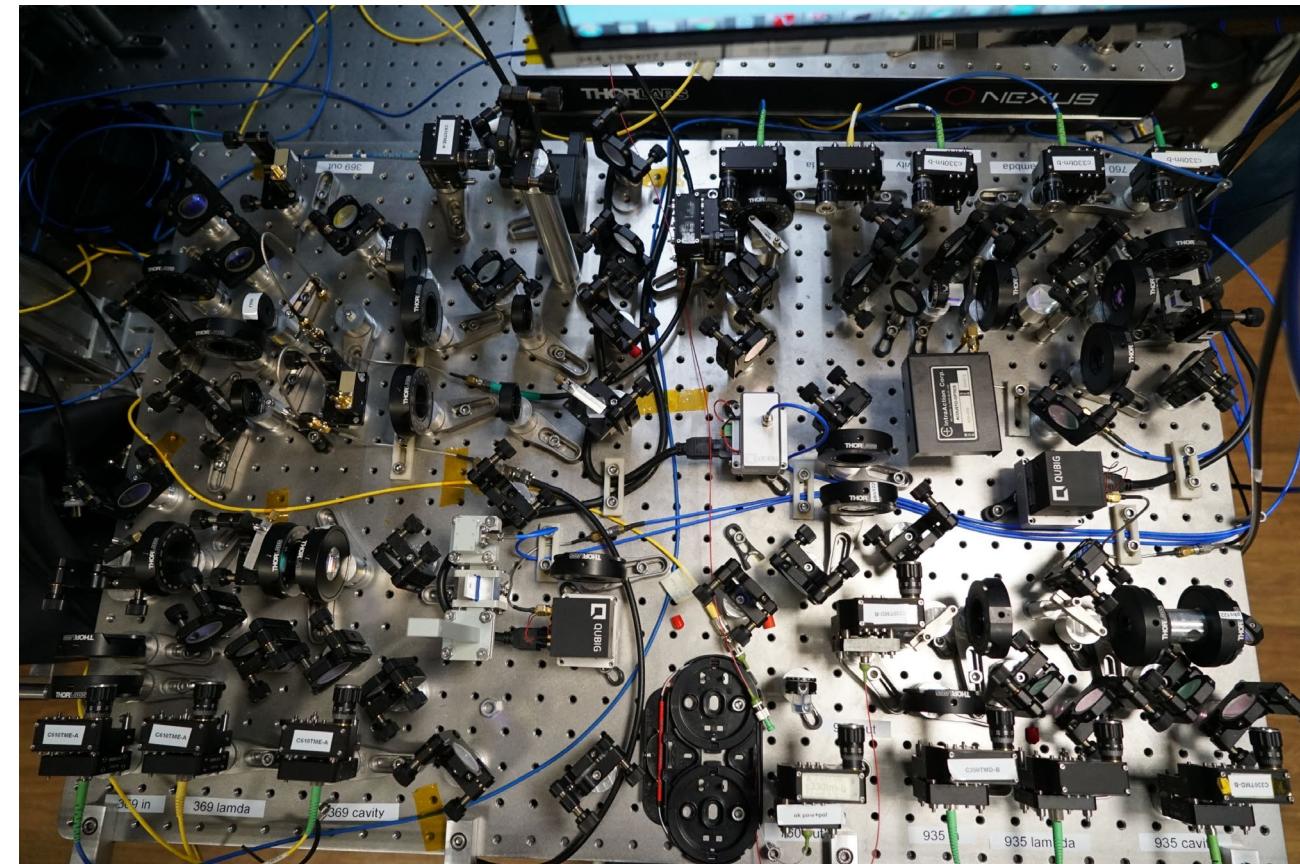


$$T_{min} \sim 1 \text{ mK}$$
$$\lambda = 369 \text{ nm (Yb)}$$



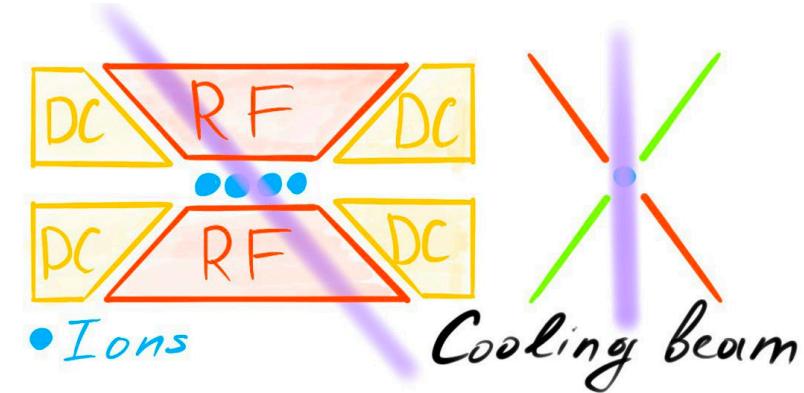
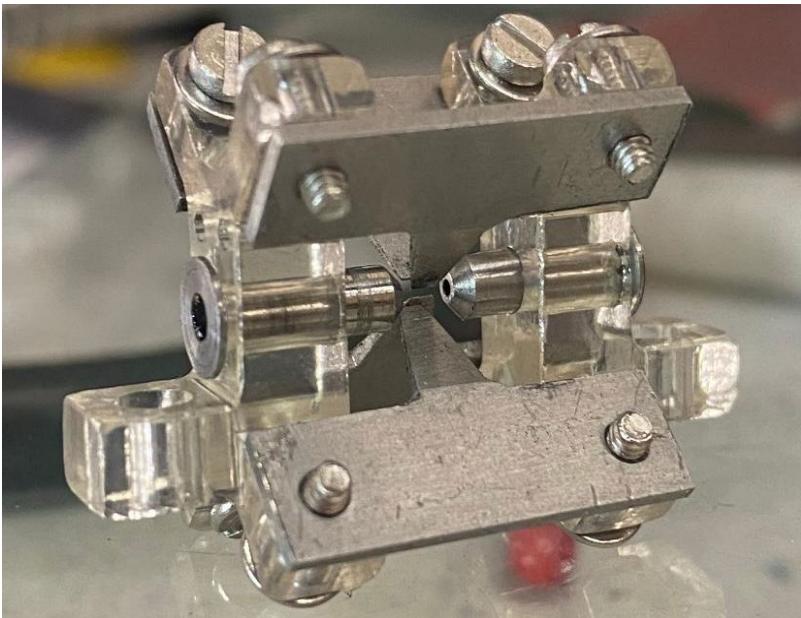
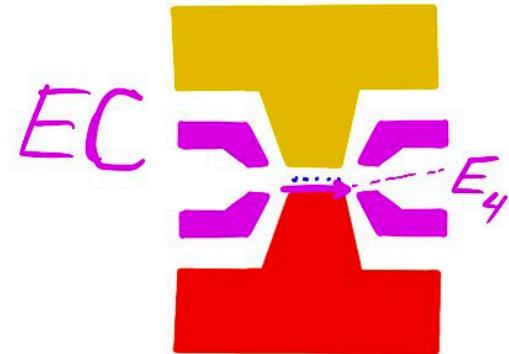
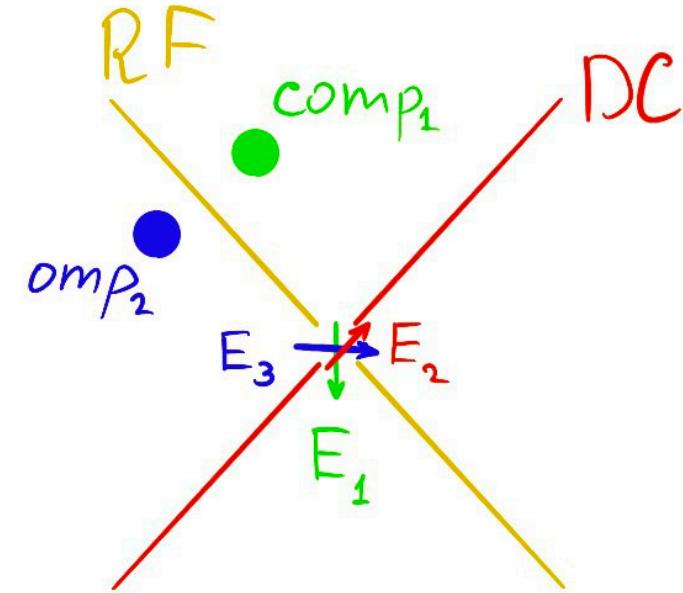
# LRC doppler cooling

- Single cooling beam
- Measured temp  $T=1.5 T_{Dop} \approx 1 mK$
- Applying DC on green electrodes splits radial secular frequencies
- $\langle n_{meas} \rangle \approx 15$



90 cm

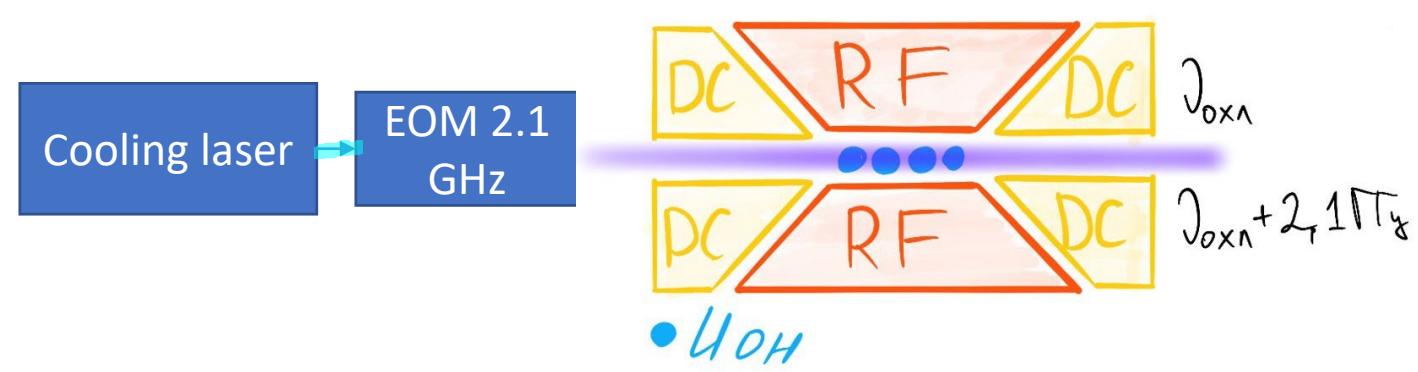
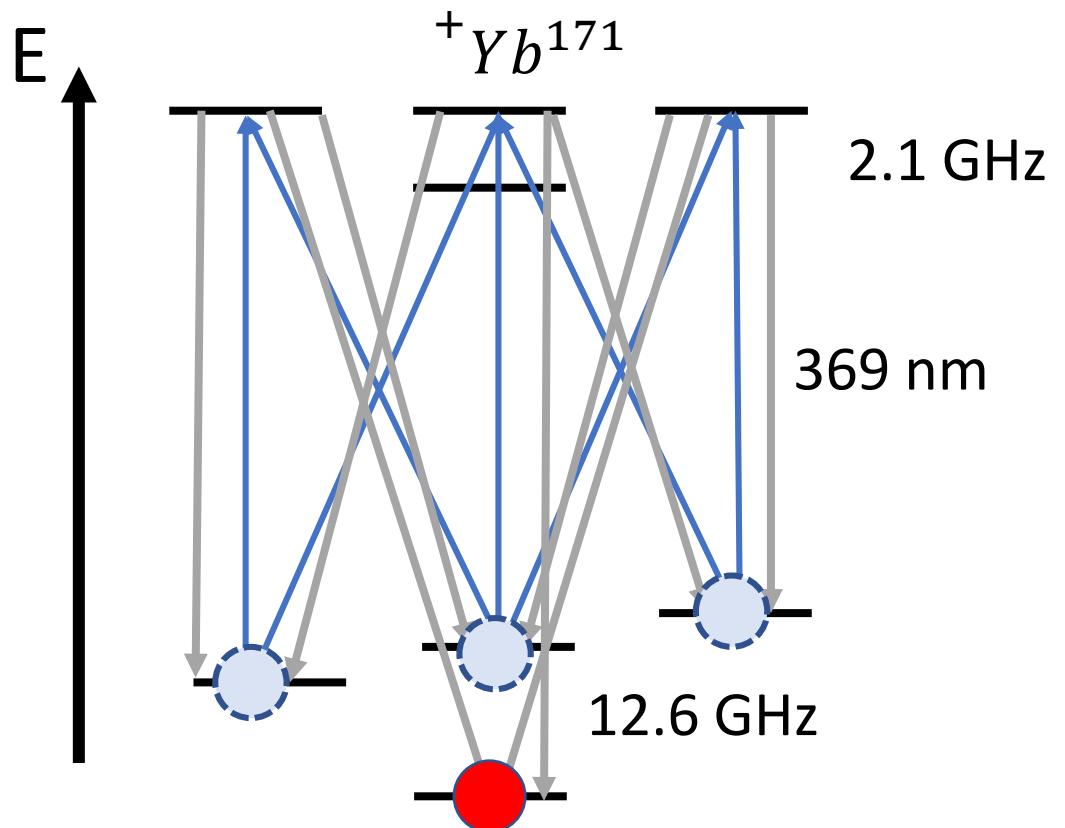
# Stray electric field compensation



- 3 types of micromotion detection:
1. Lowering RF potential
  2. Adding  $\Omega_{sec}$  to  $\omega_{RF}$
  3. Synchronous detection

4 degrees of freedom involved

## 4.State preparation



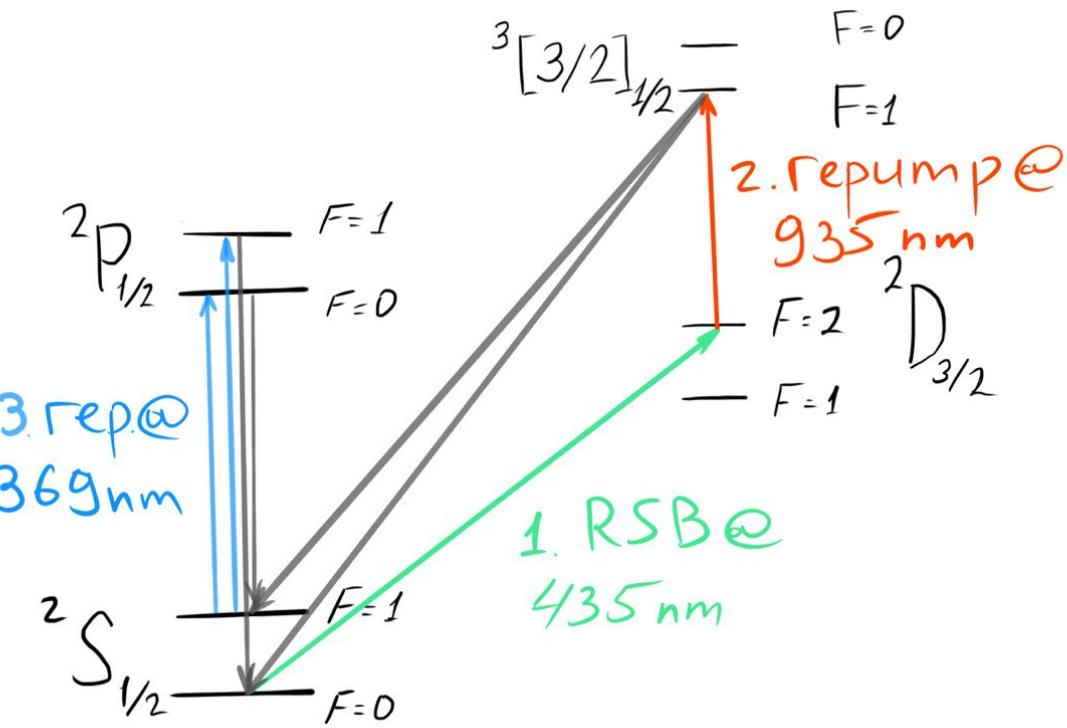
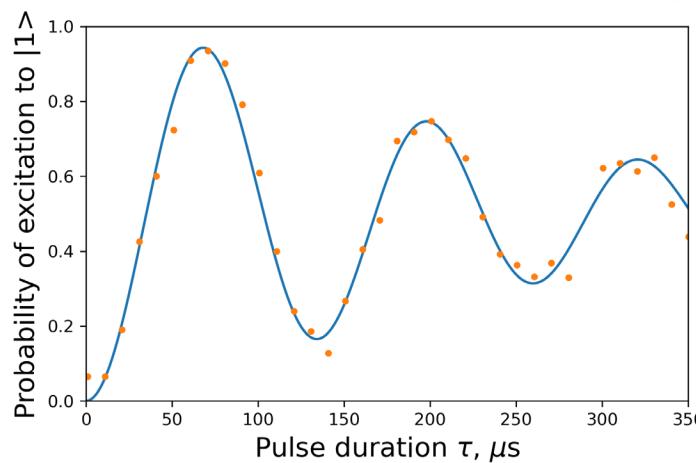
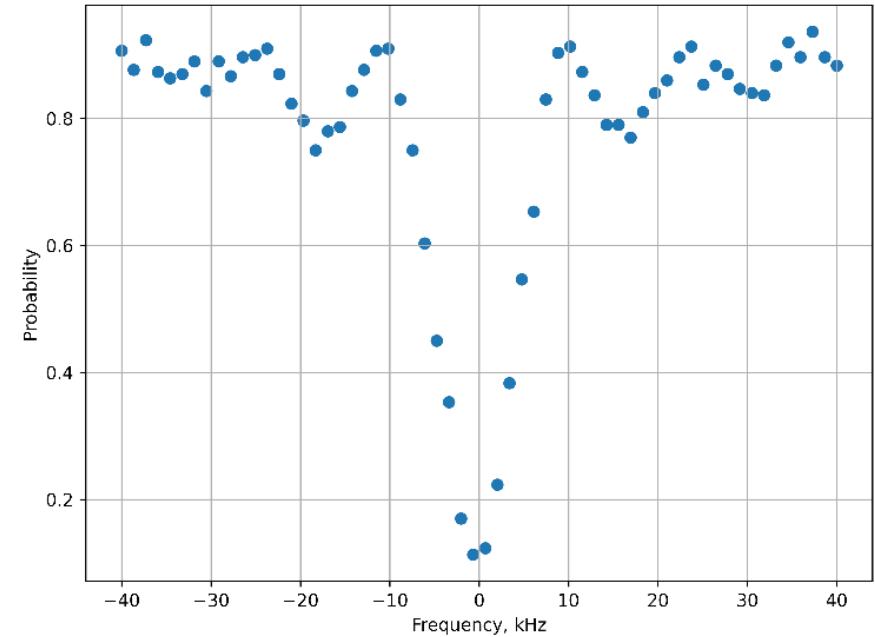
- + Single optical field
- +  $T_{prep} \approx \frac{1}{\Gamma} < 1 \mu\text{s}$
- + Only Doppler laser involved

# 5. Single qubit operations

$$\Omega(n, n') = \Omega_0 e^{\frac{-\eta^2}{2}} \sqrt{\frac{n!}{n'!}} \eta^{n'-n} L_n^{n'-n}(\eta^2); n' > n$$

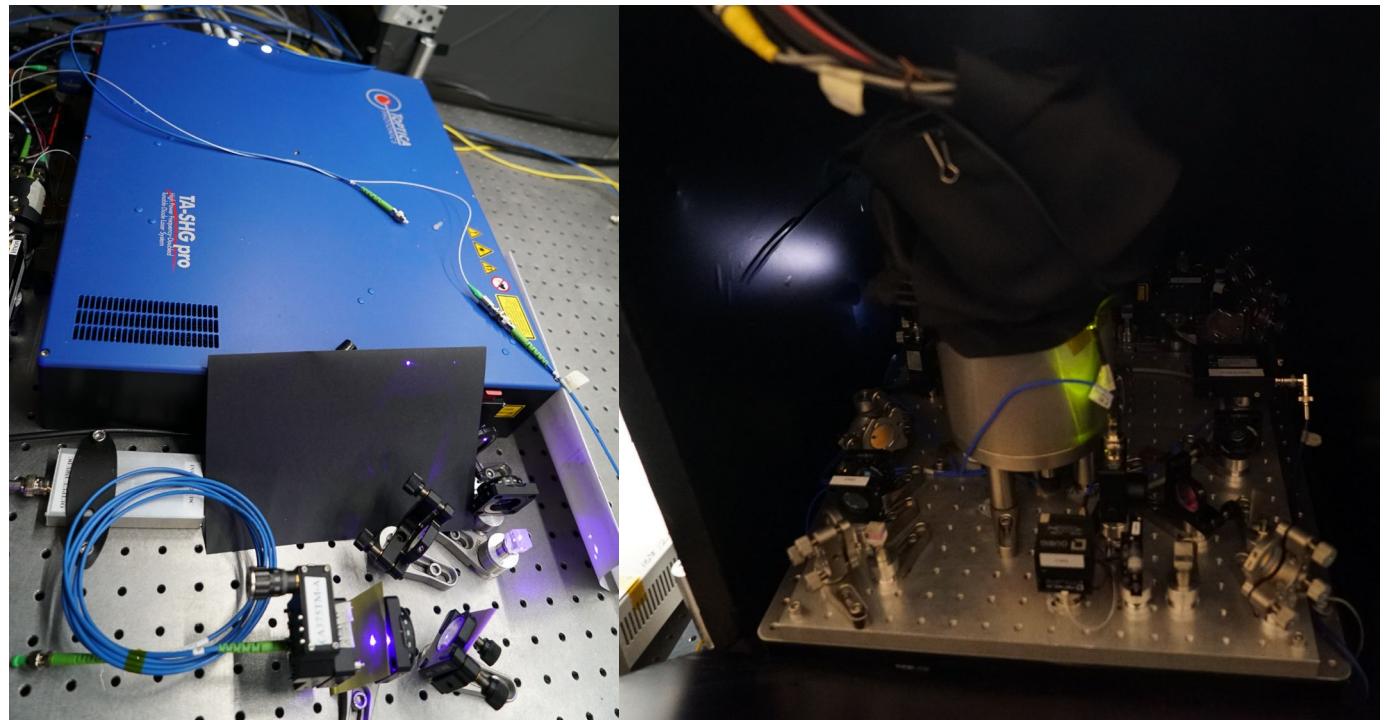
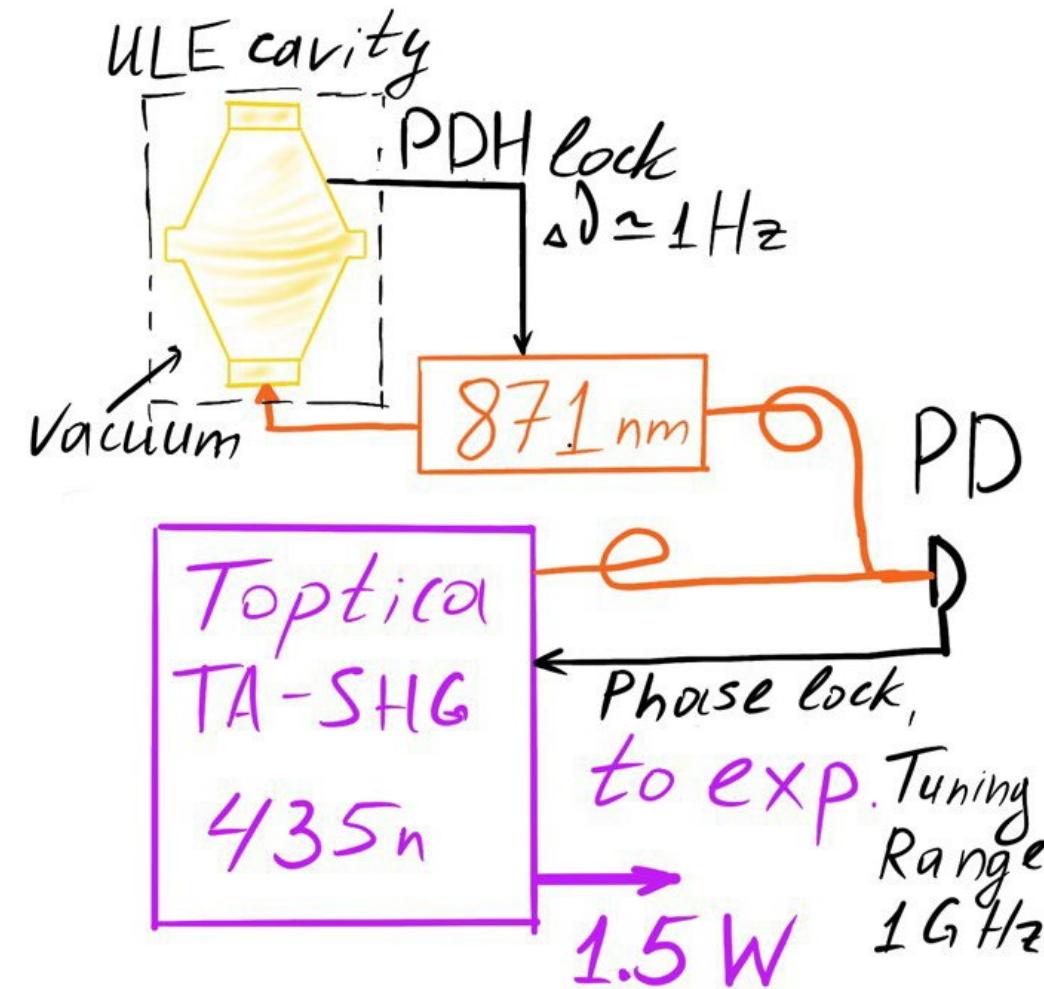
$$P(n) = \frac{n_0^n}{(n_0 + 1)^{n+1}}$$

$$Rabi(t) = \sum_{n=0}^{n=\inf} P(n) * \sin^2(\Omega(n, n) * t/2)$$



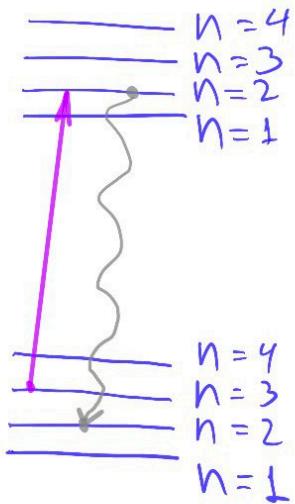
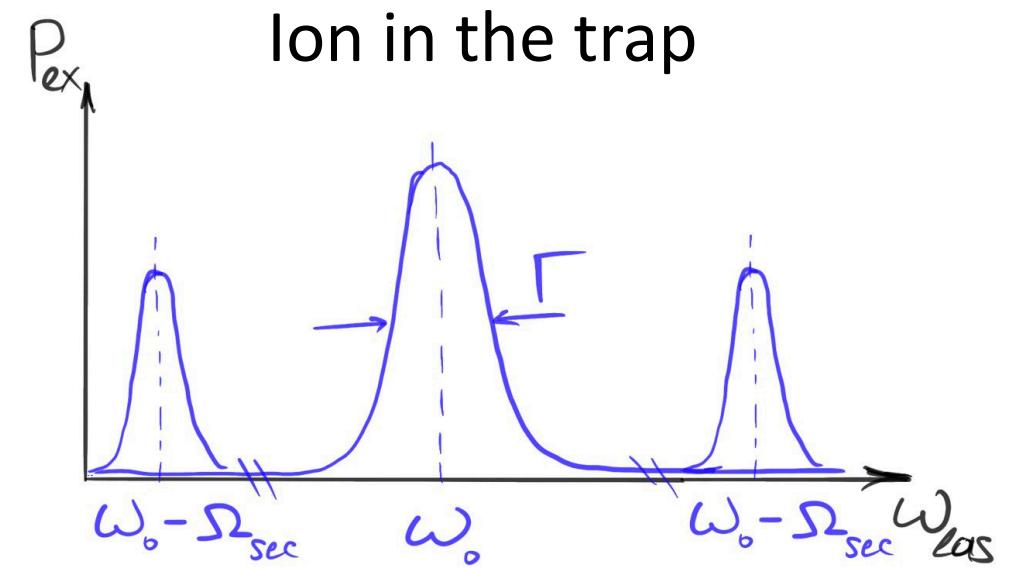
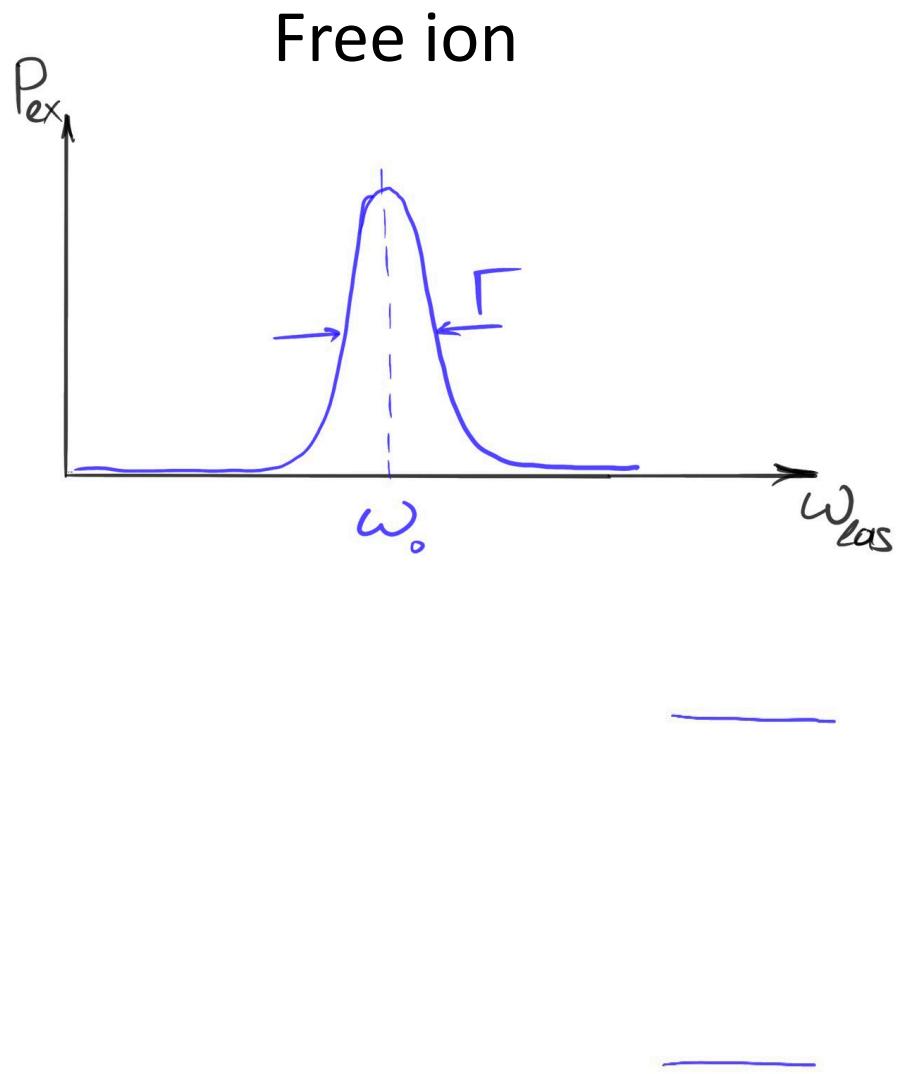
**F>0.95,  
Coherence time up to 3 ms**

# Laser for quadrupole transition in $^{171}Yb^+$



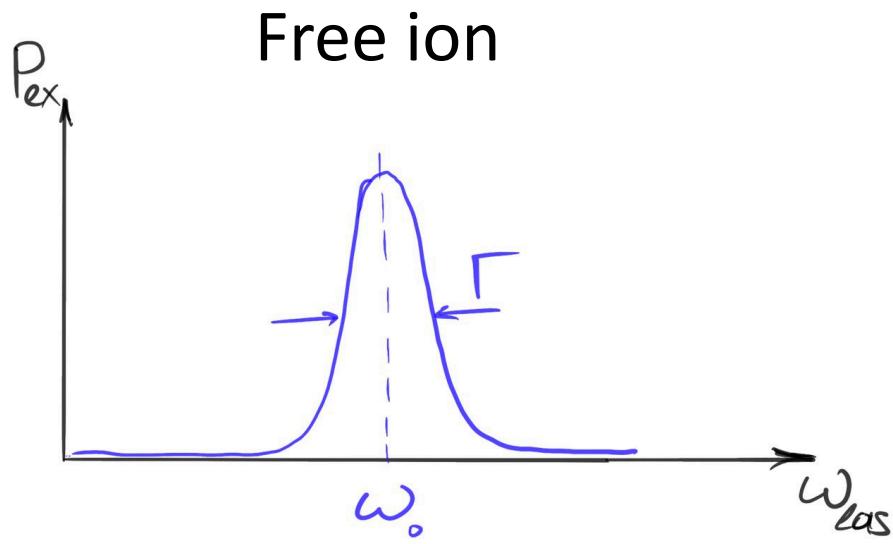
- 1.5 W output power @ 435 nm
- 1 Hz stable linewidth
- Fast tuning over 1 GHz
- All day operation without relock
- Same laser for optical and RF qubit

### 3. Ground state cooling (GSC)

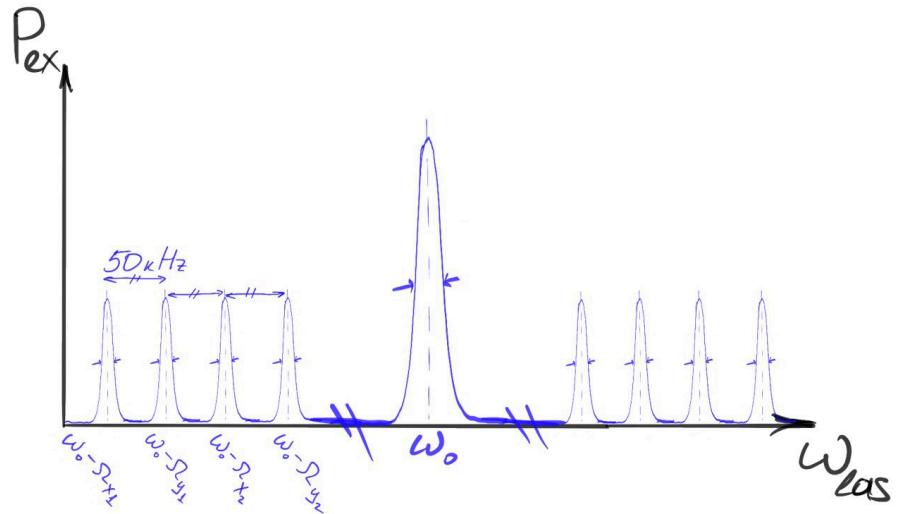


$$N_{\text{puls}} = 10 - 30 = \\ = 10 - 30 \mu\text{s}$$

# GSC of radial modes for 2 ions



Two ions in the trap, radial modes



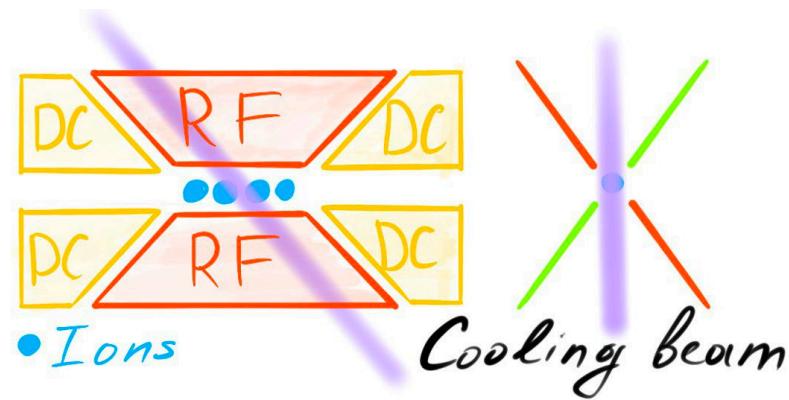
2 ions

$$\Omega_x \neq \Omega_y$$

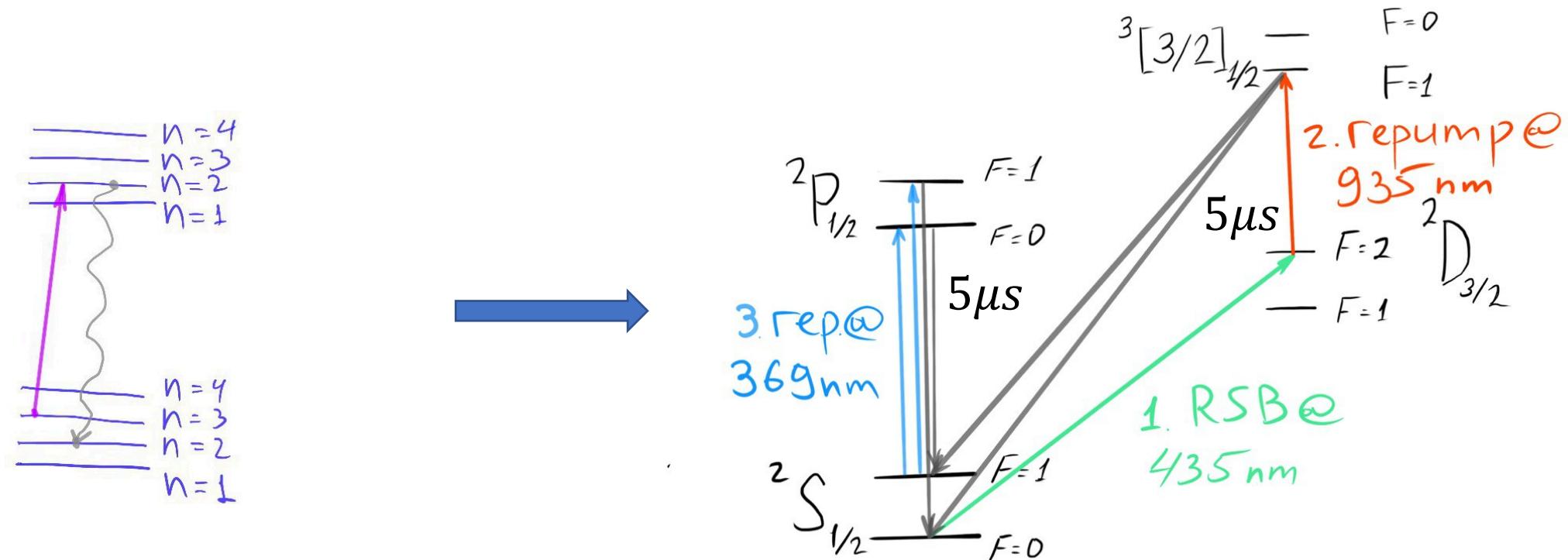
$$\Omega_{x1} \neq \Omega_{x2}$$

$$N_{\text{puls}} = 30 \rightarrow N_{\text{puls}} = 120, \\ \tau_{\text{cool}} = 30 \mu\text{s} \rightarrow \tau_{\text{cool}} = 120 \mu\text{s}$$

$$\tau_{\text{cool}} = 900 - 3000 \mu\text{s}$$



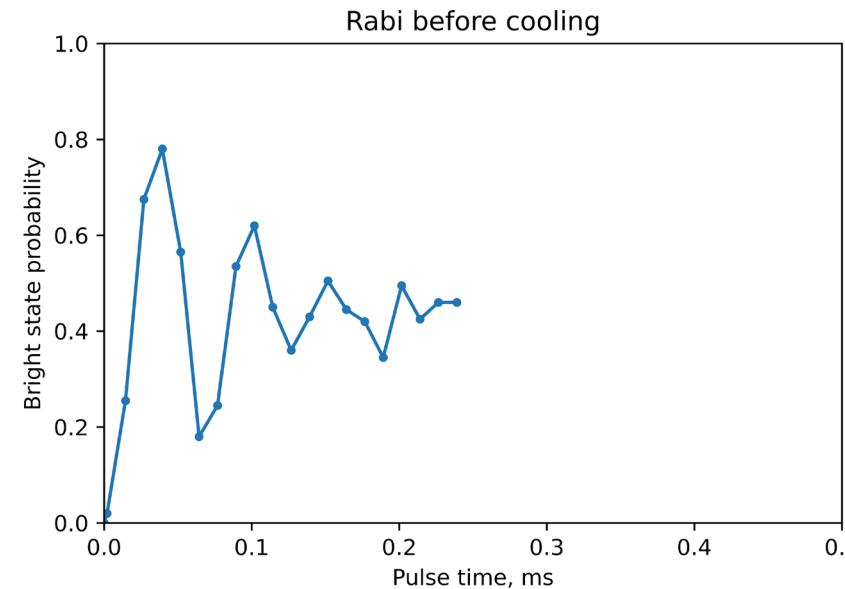
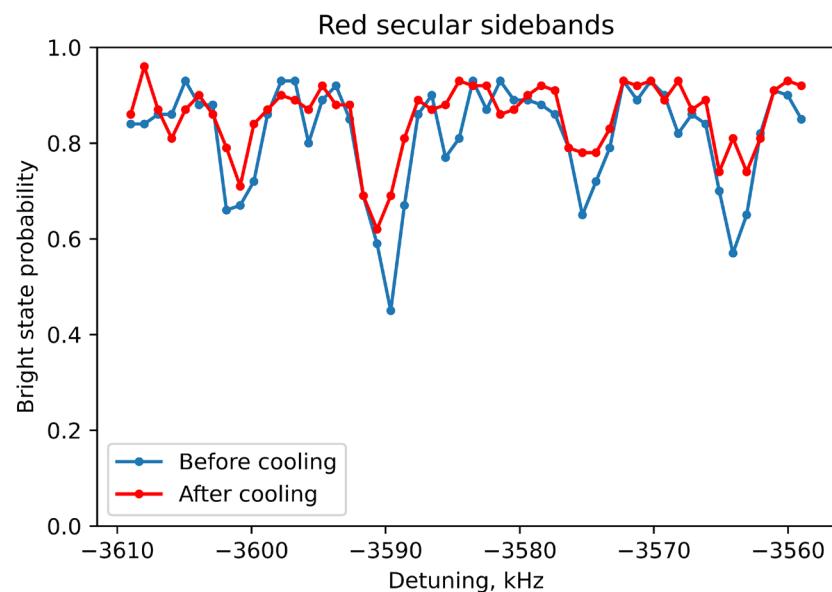
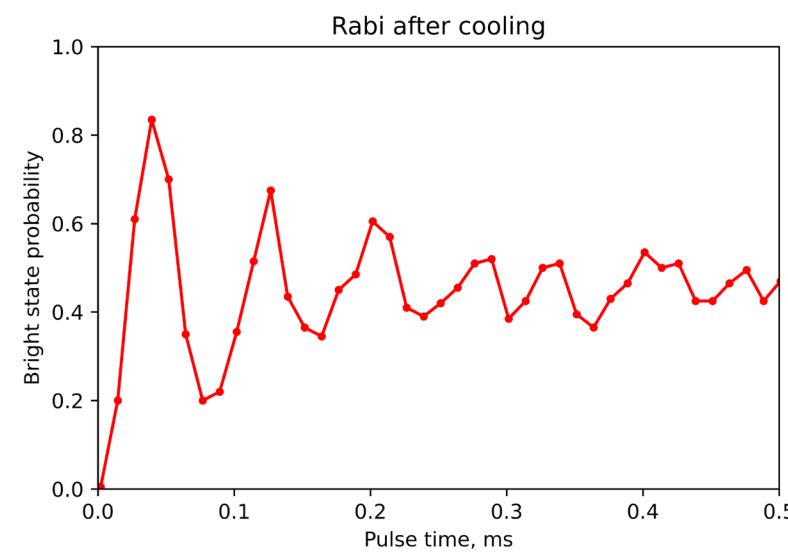
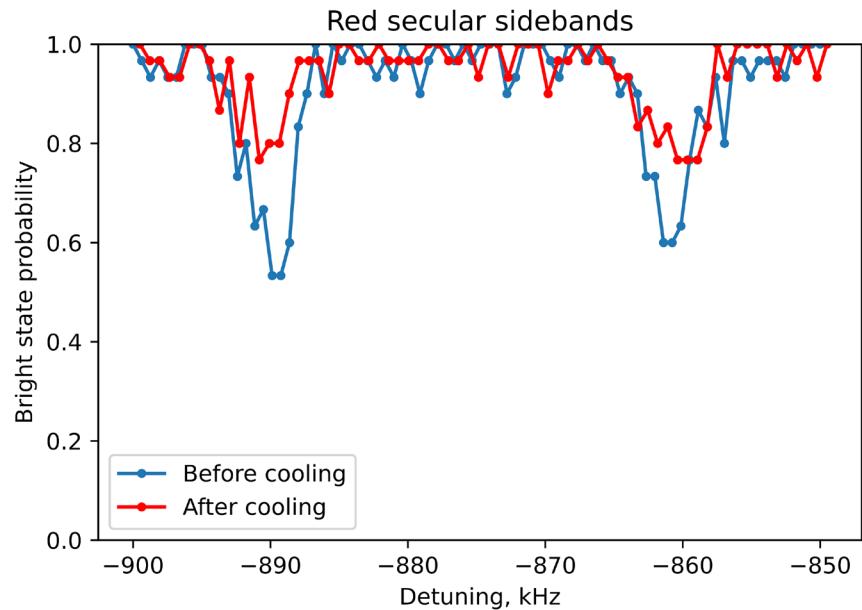
# Real implementation of GSC



$$N_{puls} = 120$$

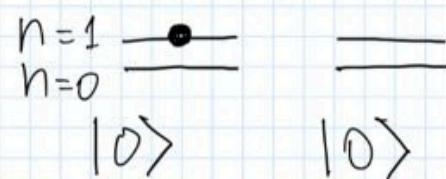
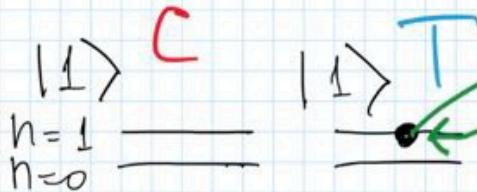
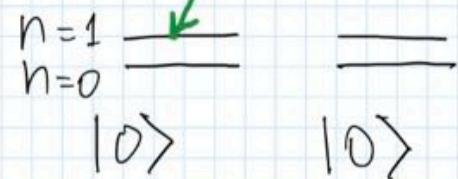
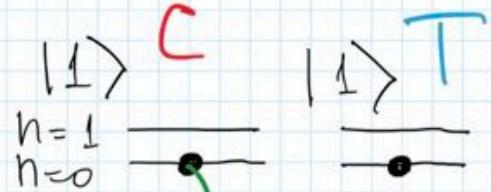
$$\tau_{cool} = 900 - 3000 \mu s \rightarrow \tau_{cool} = 2100 - 4300 \mu s$$

# GSC intermediate results

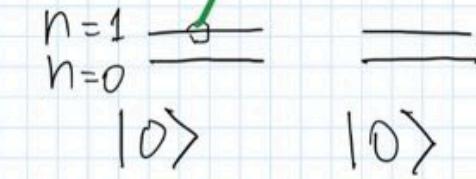
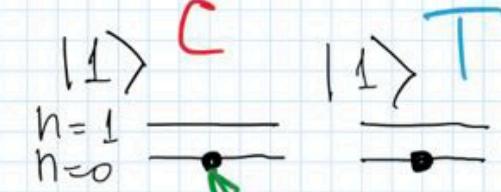


# Cirac Zoller

CZ gate orig. proposal



AUX



$$|1, n=0, 1, n=0\rangle \rightarrow |0, n=1, 1, n=1\rangle$$

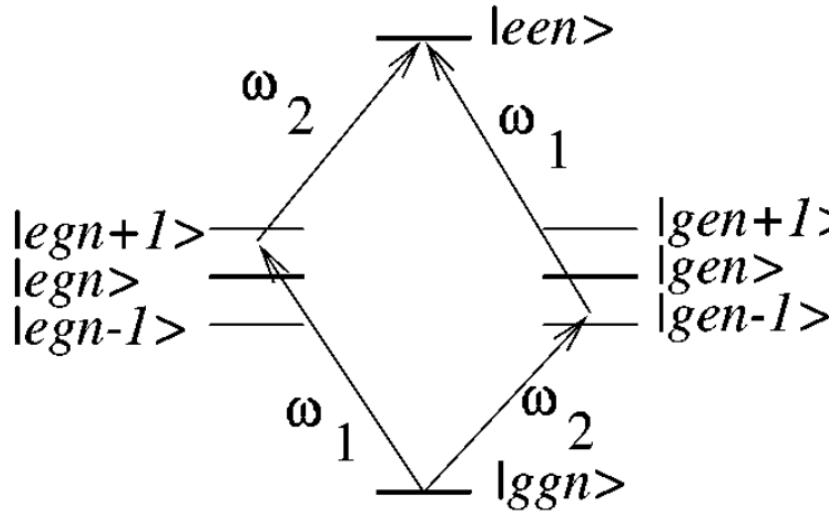
$$-|1, n=0, 1, n=0\rangle$$



$$U_{\text{phase}} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{vmatrix}$$

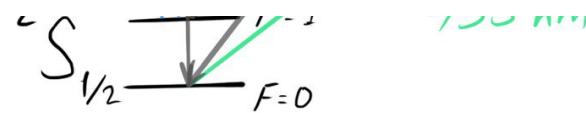
# 4. MS Gate general

(b)



$$XX(\chi_{i,j}) = \exp[i\chi_{i,j}\sigma_x^i\sigma_x^j] =$$

$$\begin{bmatrix} \cos(\chi_{ij}) & 0 & 0 & -i \sin(\chi_{ij}) \\ 0 & \cos(\chi_{ij}) & -i \sin(\chi_{ij}) & 0 \\ 0 & -i \sin(\chi_{ij}) & \cos(\chi_{ij}) & 0 \\ -i \sin(\chi_{ij}) & 0 & 0 & \cos(\chi_{ij}) \end{bmatrix} \quad (5.21)$$

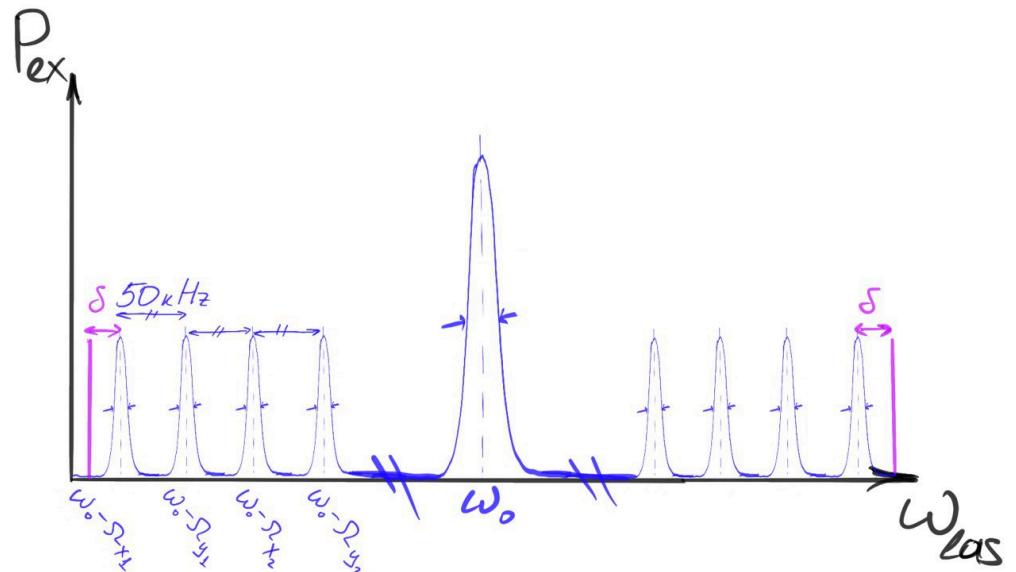


$$\Omega_{rabi} < 50 \text{ kHz}$$

$$\eta\Omega_{rabi} = \frac{\delta}{4}$$

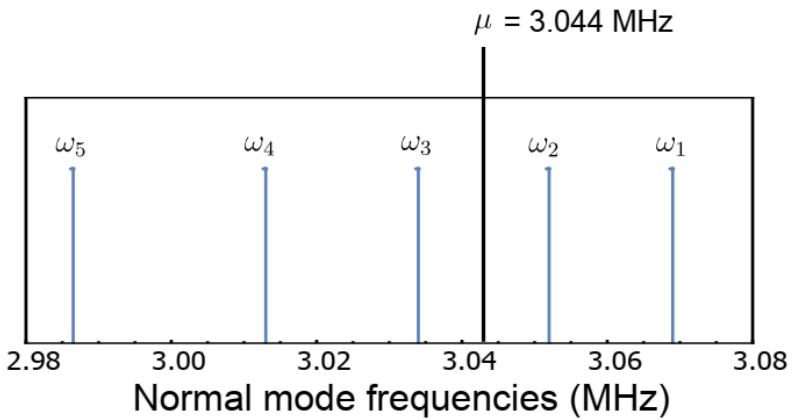
$$\eta = 0.06;$$

$$\tau_{gate} = \frac{2\pi}{\delta} = \frac{2\pi}{4\eta\Omega_{rabi}} > 3 \text{ ms}$$

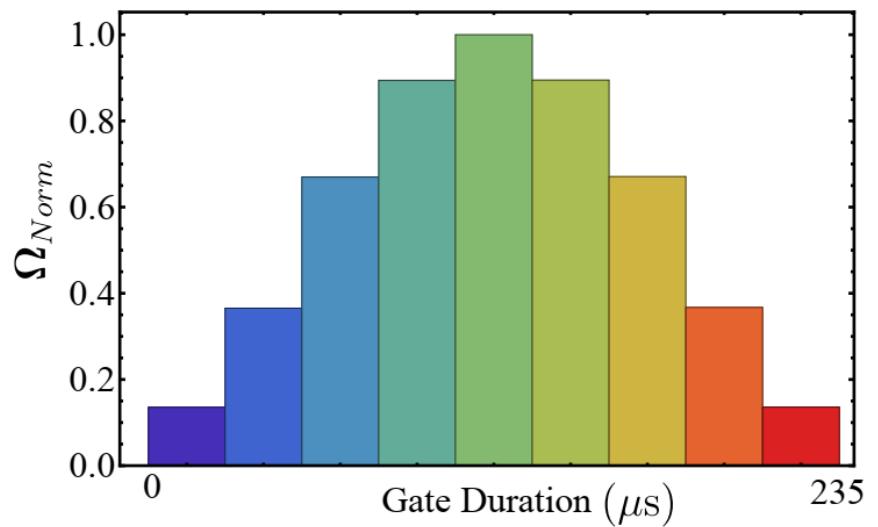


# Two qubit operation on ion string

b)

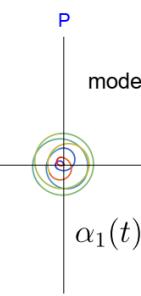


c)

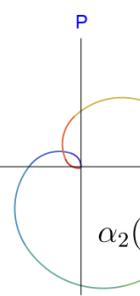


Shantanu Debnath  
PhD thesis

d)



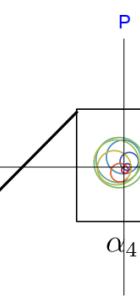
e)



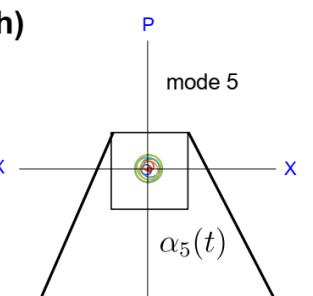
f)



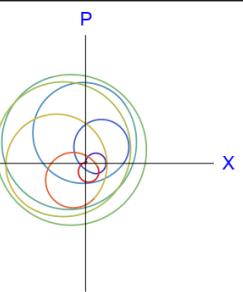
g)



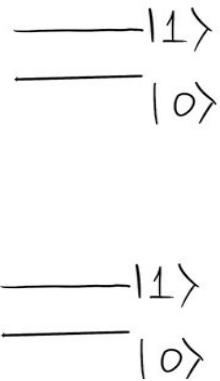
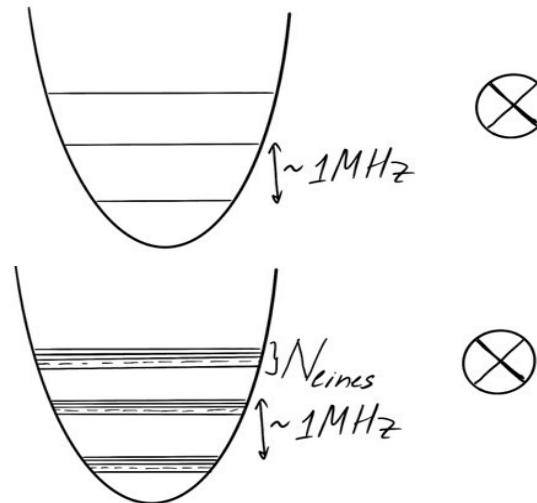
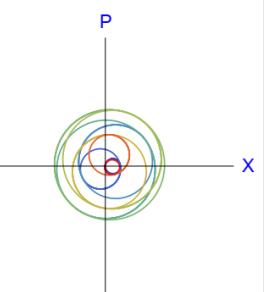
h)



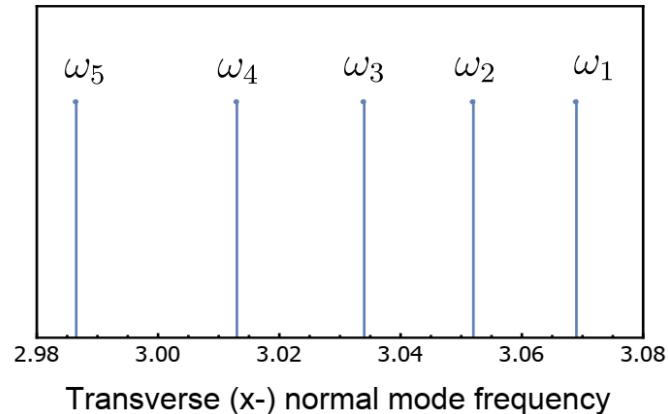
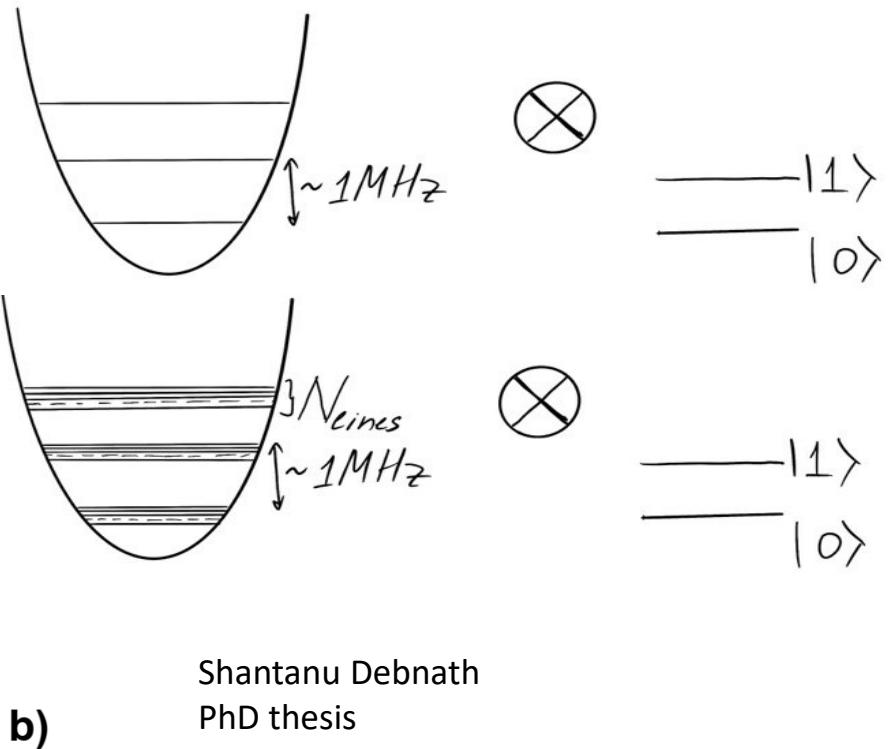
i)



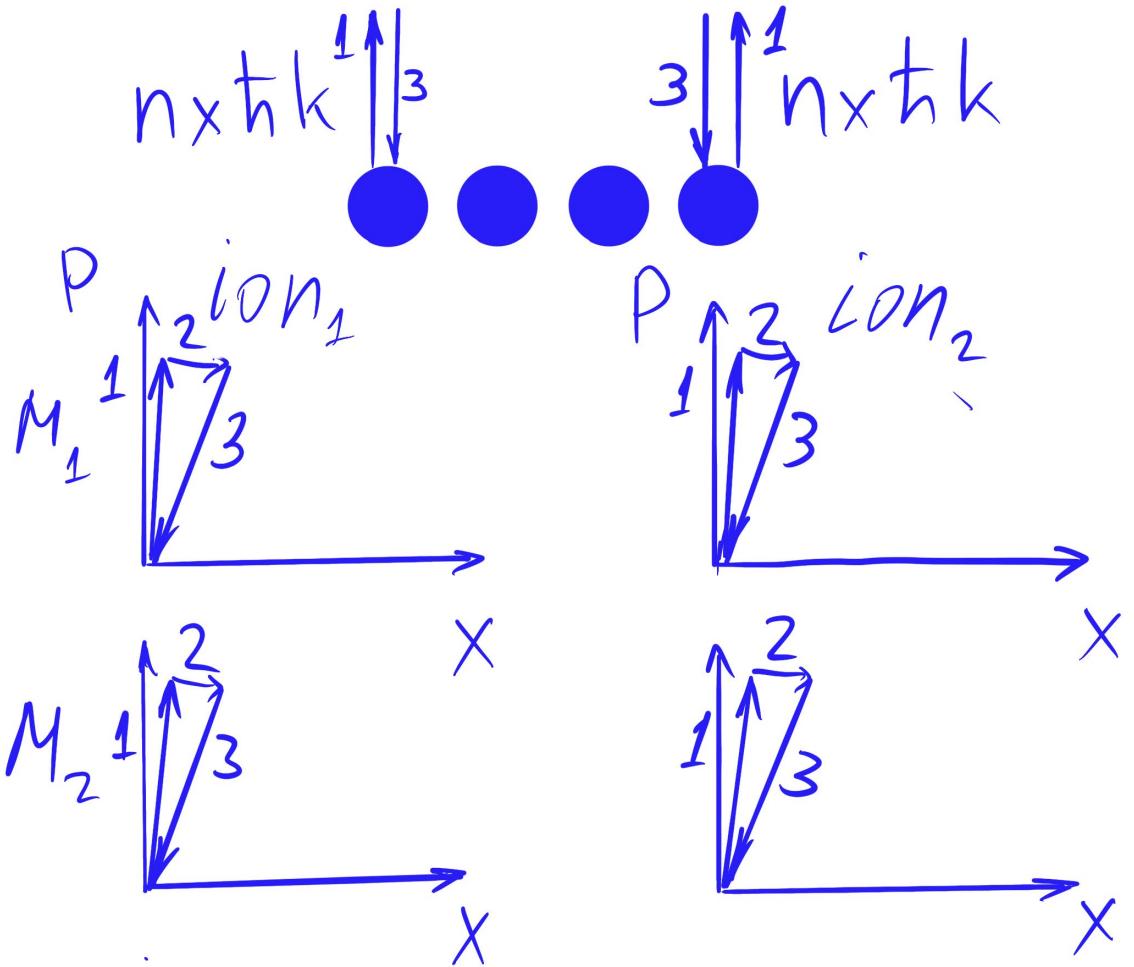
j)



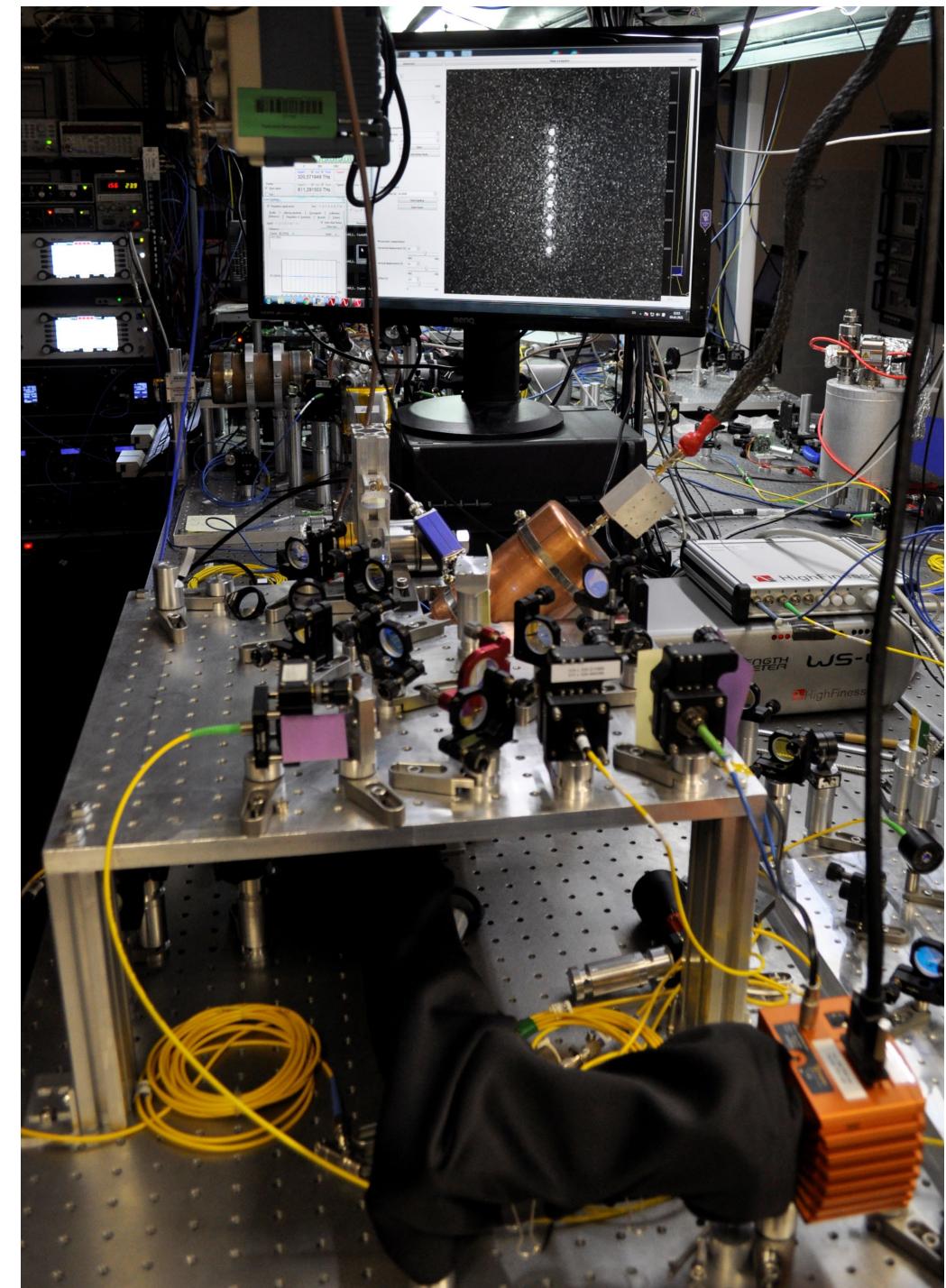
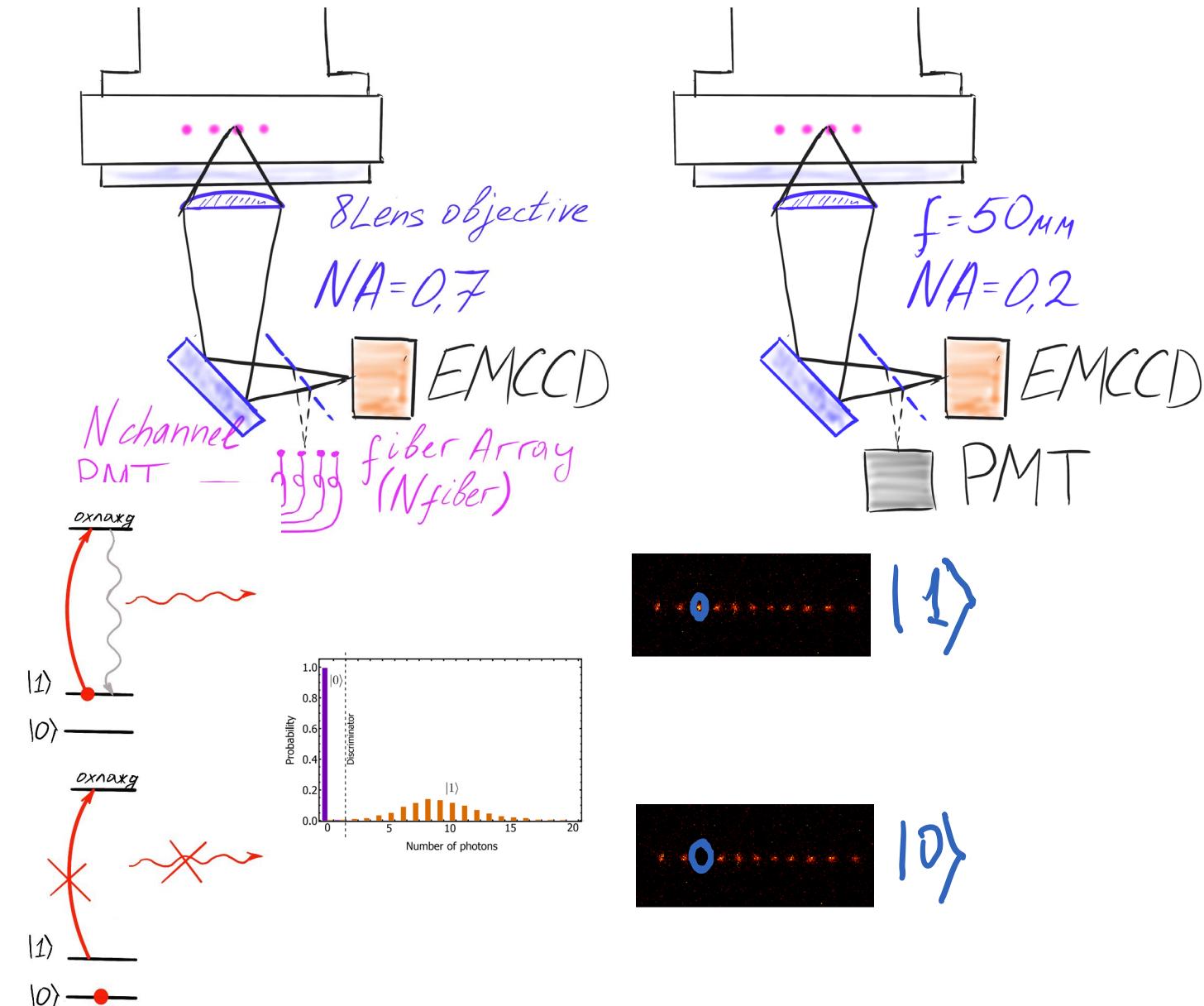
# Fully non-adiabatic gate



- Theoretic studies started
- Article is in review at NJP



# 6. State readout

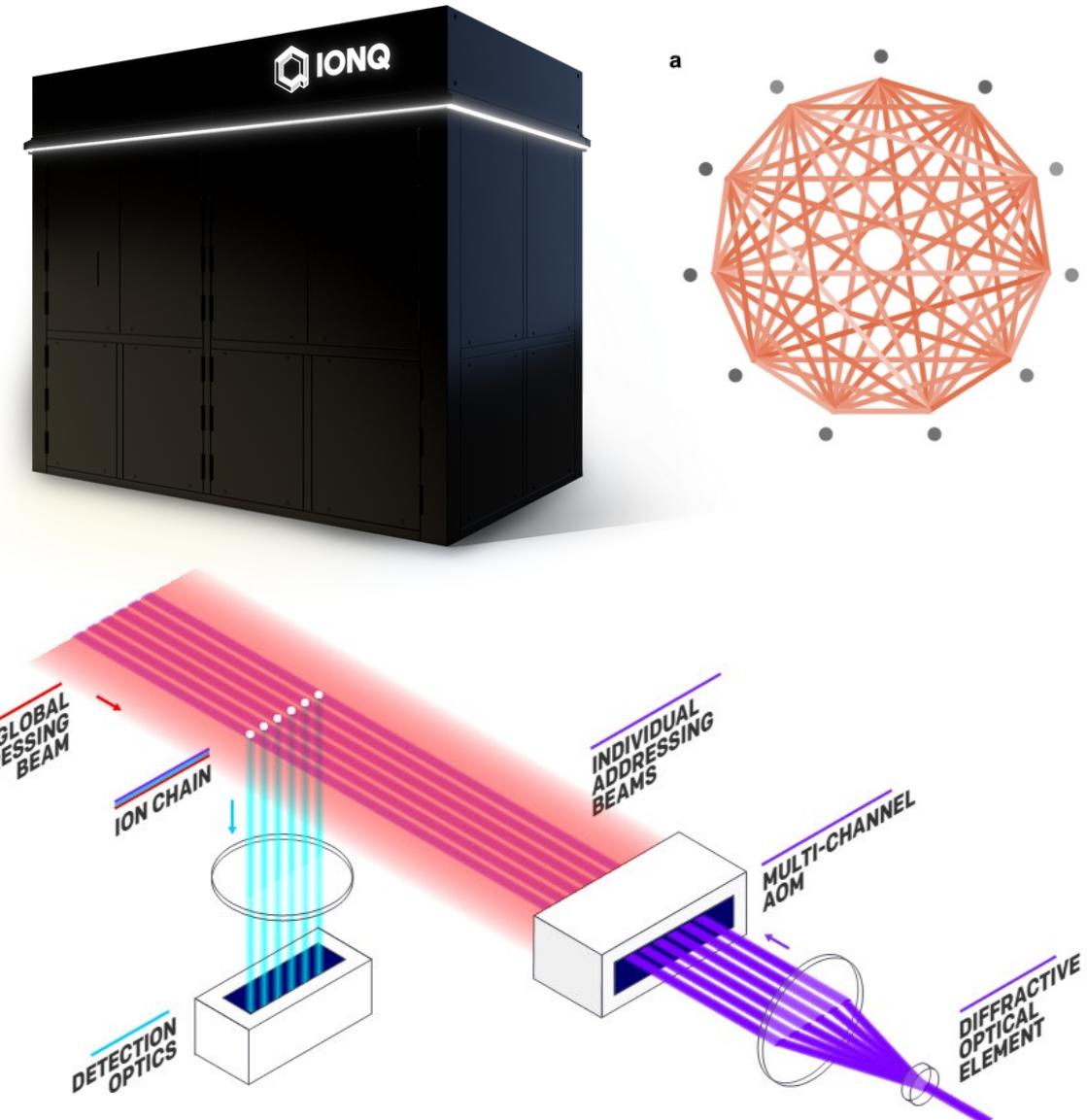


	Ions	Neutral Atoms	Superconducting circuits
Scalability	Universal QC— <b>32</b> qubits (each pair is entangled)	Simulators — <b>256</b> qubit	Universal QC ~ <b>51</b> qubits
Coherence time $\tau_{coh}$	Minutes	Seconds	Milliseconds
Two qubit operation $\tau_{op}$	<b>~ 100 <math>\mu</math>s</b>	<b>~ 100 ns</b>	<b>~10 ns</b>
Fidelity	<b>99.996%</b> single qubit <b>99.9%</b> two qubit	<b>99.6%</b> single qubit <b>97.4%</b> two qubit	<b>99.92 %</b> single qubit <b>99.4%</b> two qubit
$\tau_{coh}/\tau_{op}$	Up to <b><math>10^9</math></b>	Up to <b><math>10^7</math></b>	Up to <b><math>10^4</math></b>
Main challenge	<b>Transferring properties from small to big system</b>	<b>Improving two qubit fidelity</b>	<b>Improving coherence time</b>

# Leaders in the field

## IonQ 32-qubit quantum computer

- 32 RF qubits in  $^{171}\text{Yb}^+$
- Each-to-each two-qubit entanglement
- Parallel two-qubit operations
- Mean single qubit fidelity  $F_{\text{single}} > 99\%$  (benchmarked with 11 qubits)
- Mean two-qubit fidelity  $F_{\text{two-qubit}} > 98\%$  (benchmarked with 11 qubits)
- Benchmarked with algorithms: Deutsch–Jozsa, Bernstein–Vazirani, Hidden shift, QFT, error correction
- Cloud access

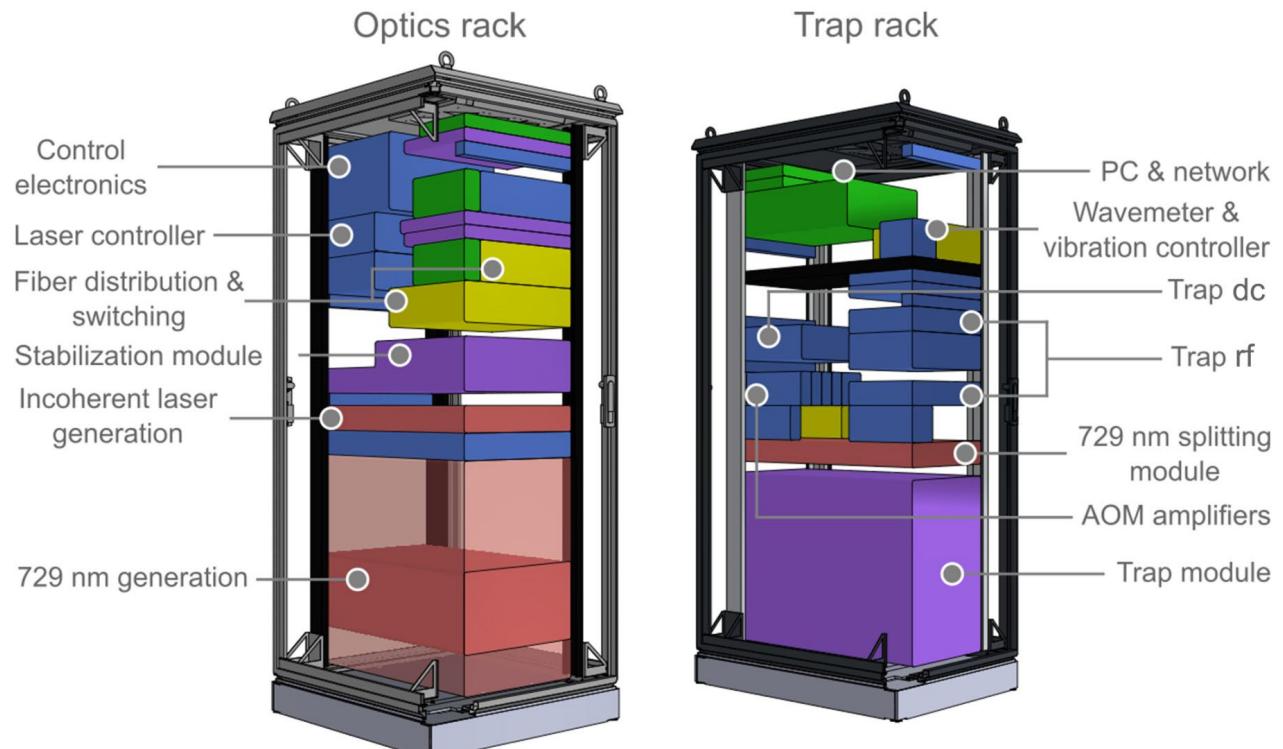
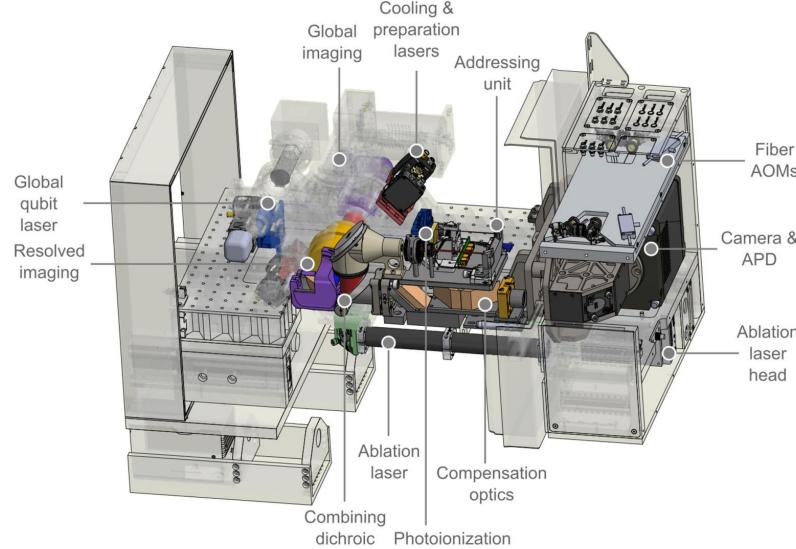


Wright, K., Beck, K. M., Debnath, S., Amini, J. M., Nam, Y., Grzesiak, N., ... & Kim, J. (2019). Benchmarking an 11-qubit quantum computer. *Nature communications*, 10(1), 1-6.

# Leaders in the field

## Compact transportable ion QC demonstrator by AQT

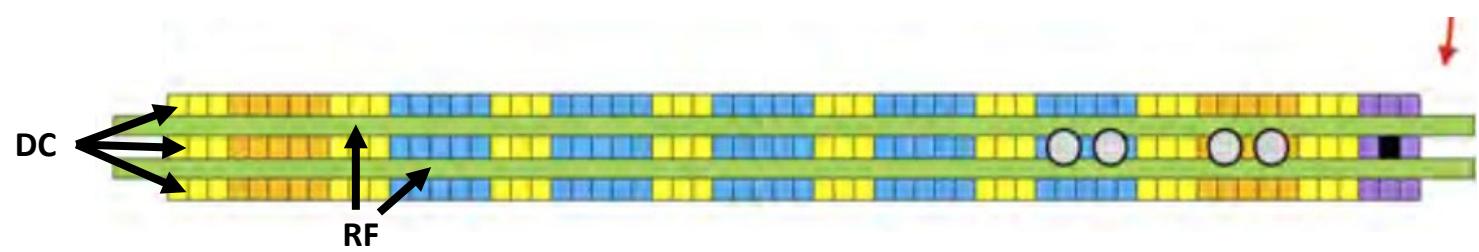
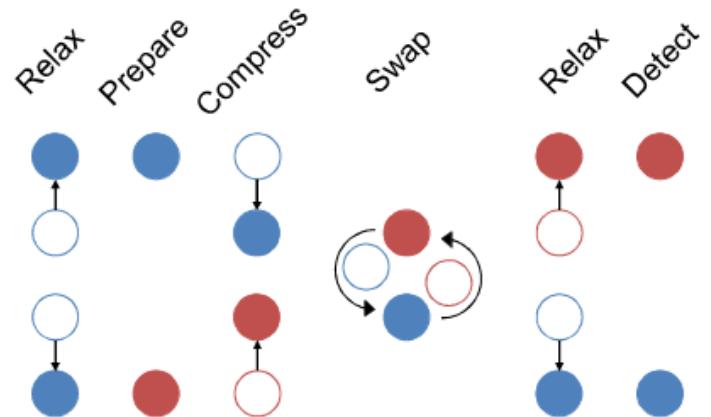
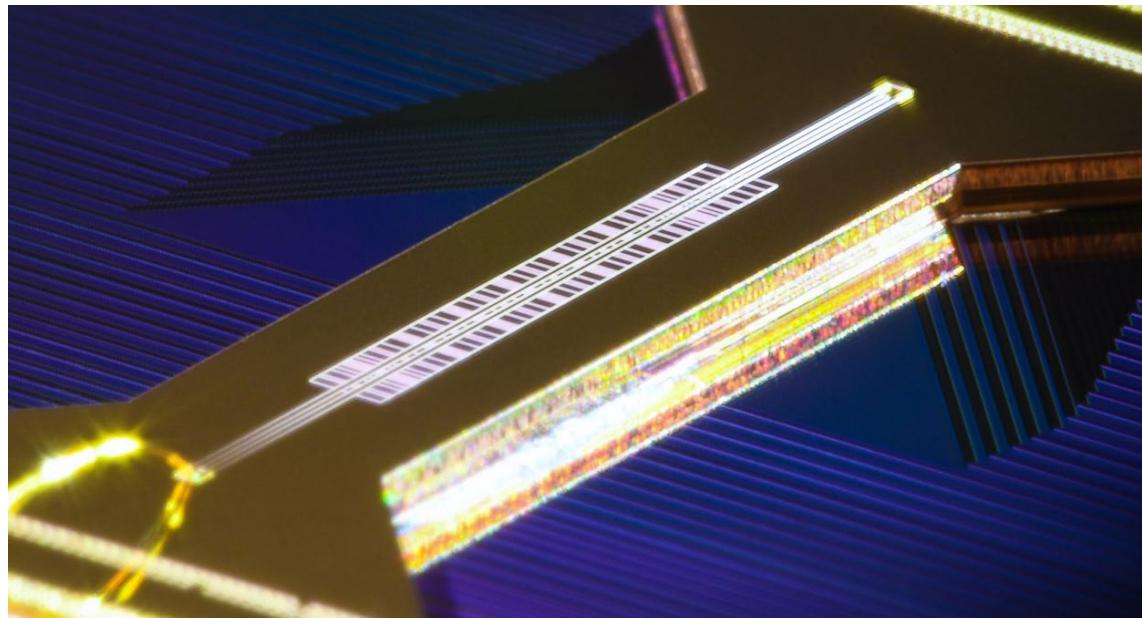
- Ca<sup>+</sup> optical qubit
- Compact transportable system with 1.7 x 1 m<sup>2</sup> footprint
- 24 qubits GHZ state demonstrated
- Two-qubit operations with 10 ion quantum register with fidelities of 97-99%
- Single-qubit gate fidelity 99.86%



# Leaders in the field

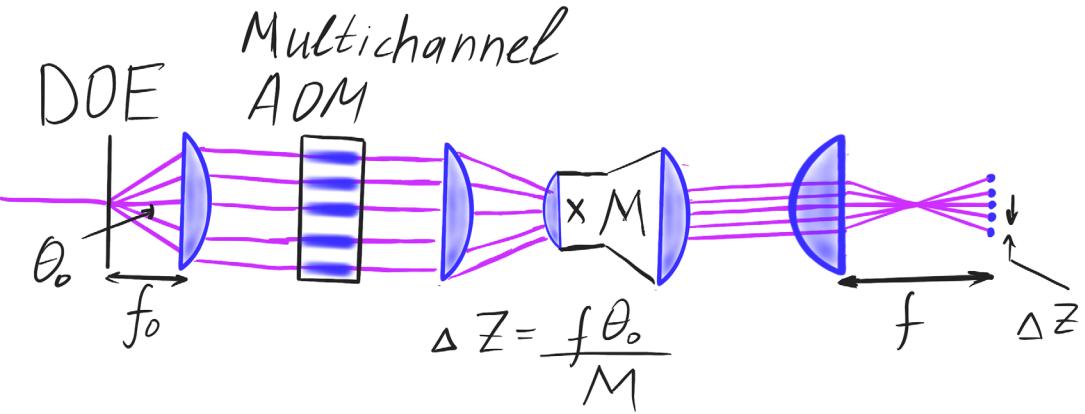
## Honeywell H1 CCD quantum computer

- **10 qubits**
- Surface trap at 12 K
- **5 quantum processing zones** (blue)
- **2 storing zones** (orange)
- **8 auxiliary** (yellow)
- **198 DC electrodes**
- Parallel operations in separate zones
- Qubit in **Yb<sup>+</sup>**, sympathetic cooling with **Ba<sup>+</sup>**
- Single-qubit gate fidelity **99.9 %**
- Two-qubit gate fidelity **99 %**



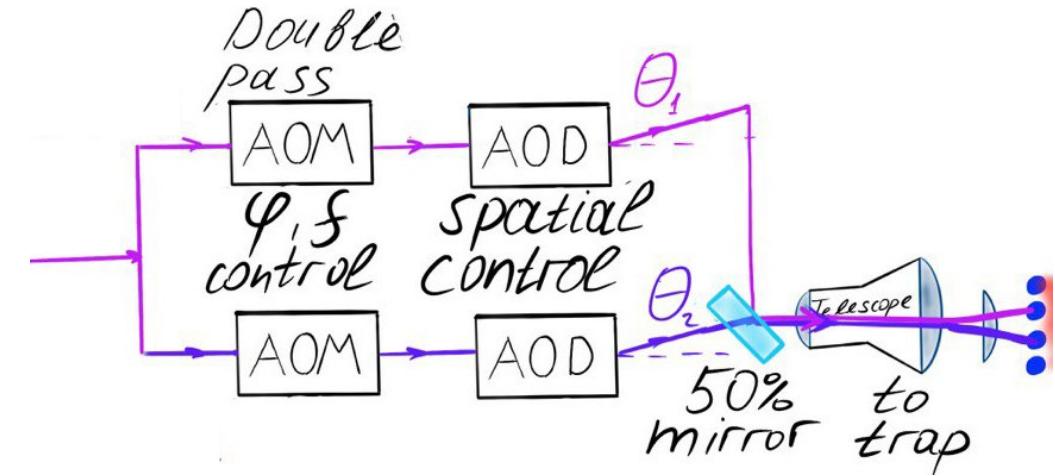
# Individual ion addressing

- Multichannel AOM



- Number of addressed ions is limited with number of channels
- Higher crosstalk
- Channels are equidistant
- + Deep UV options are available (for RF qubit manipulation via strong dipole transitions)

- Optical deflector



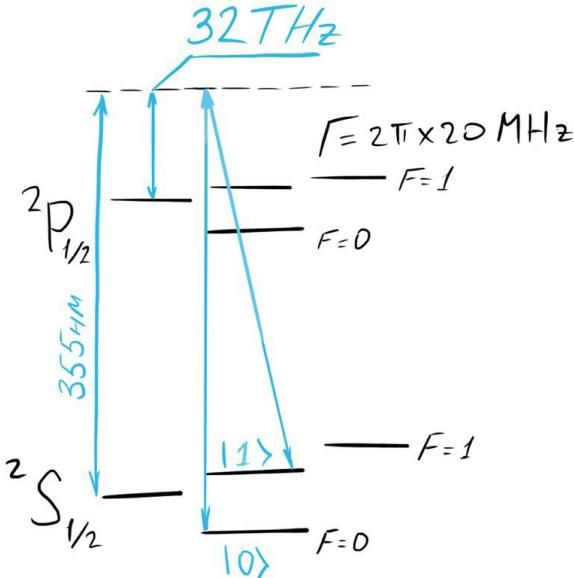
$$N_{ions} = \frac{\pi}{4} \Theta_{max} d_0$$

RF qubit manipulation via strong dipole transitions are limited

With  $TeO_2$  AOMs  $N_{ions} \sim 500$  (@435 nm)

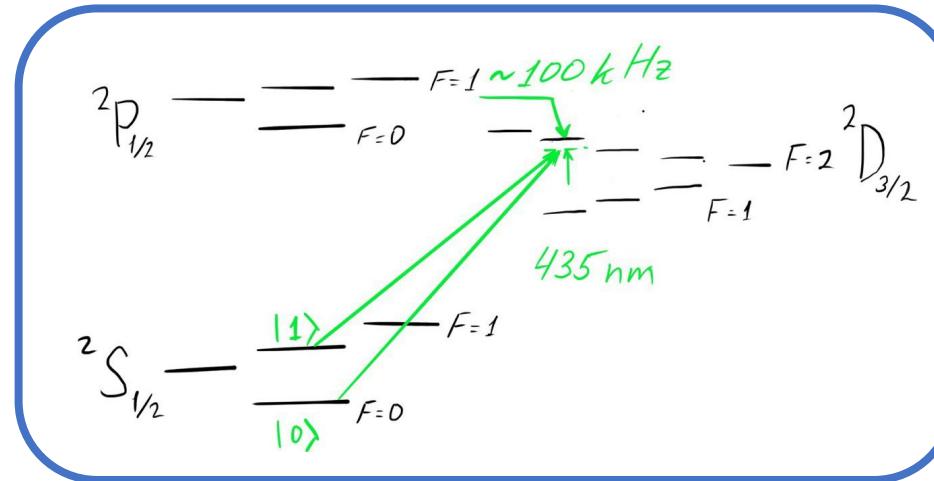
With  $SiO_2$  or saphire AOMs  $N_{ions} \sim 5$  (@355 nm)

# Qubit options for $^{171}\text{Yb}^+$



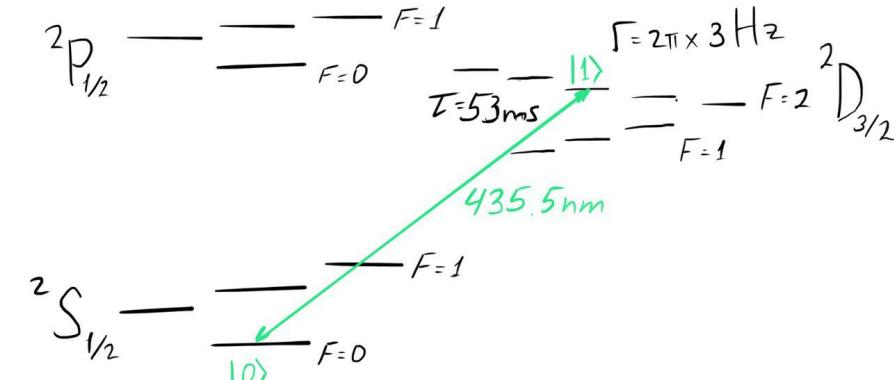
RF qubit, wide transition for Raman excitation

- + High power pulse lasers commercially available
- + Proved to work perfectly (by C. Monroe group)
- + Long coherence time
- Only multichannel AOM available for addressing



RF qubit, narrow transition for Raman excitation

- +  $\text{TeO}_2$  deflectors available for addressing
- + High power laser commercially available
- + Require 100 Hz laser

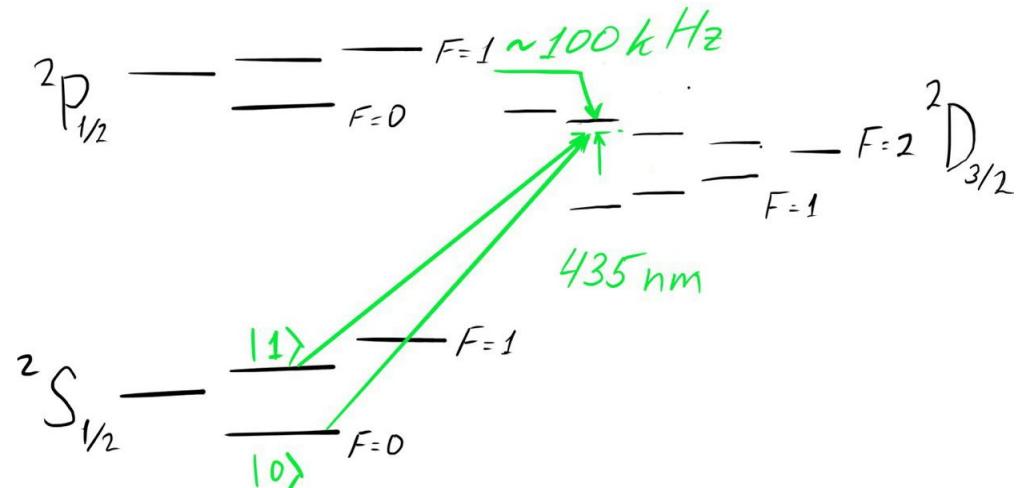
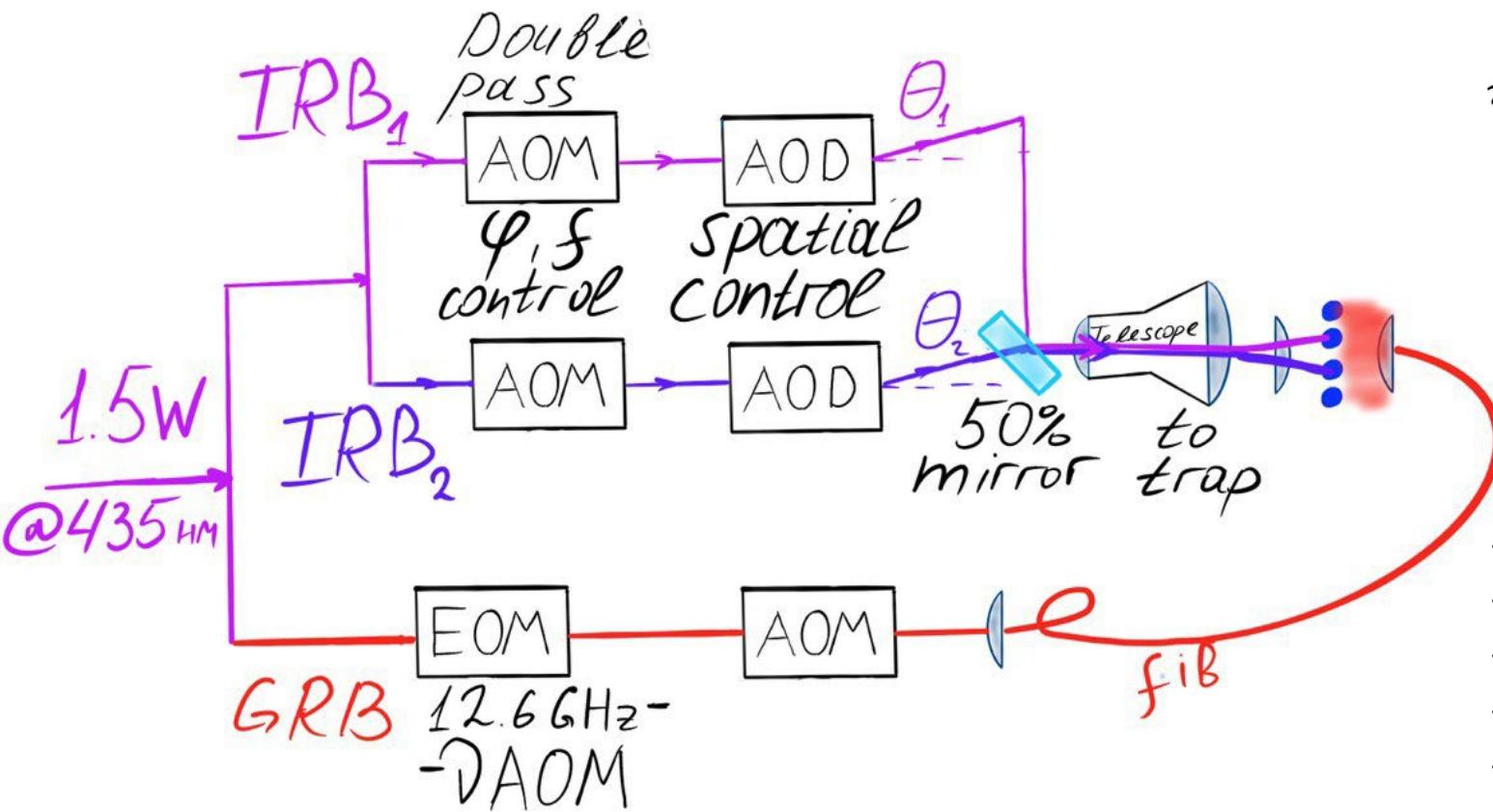


Optical qubit

- + Easier to address (single beam involved)
- Limited coherence time
- Require 1 Hz or better laser

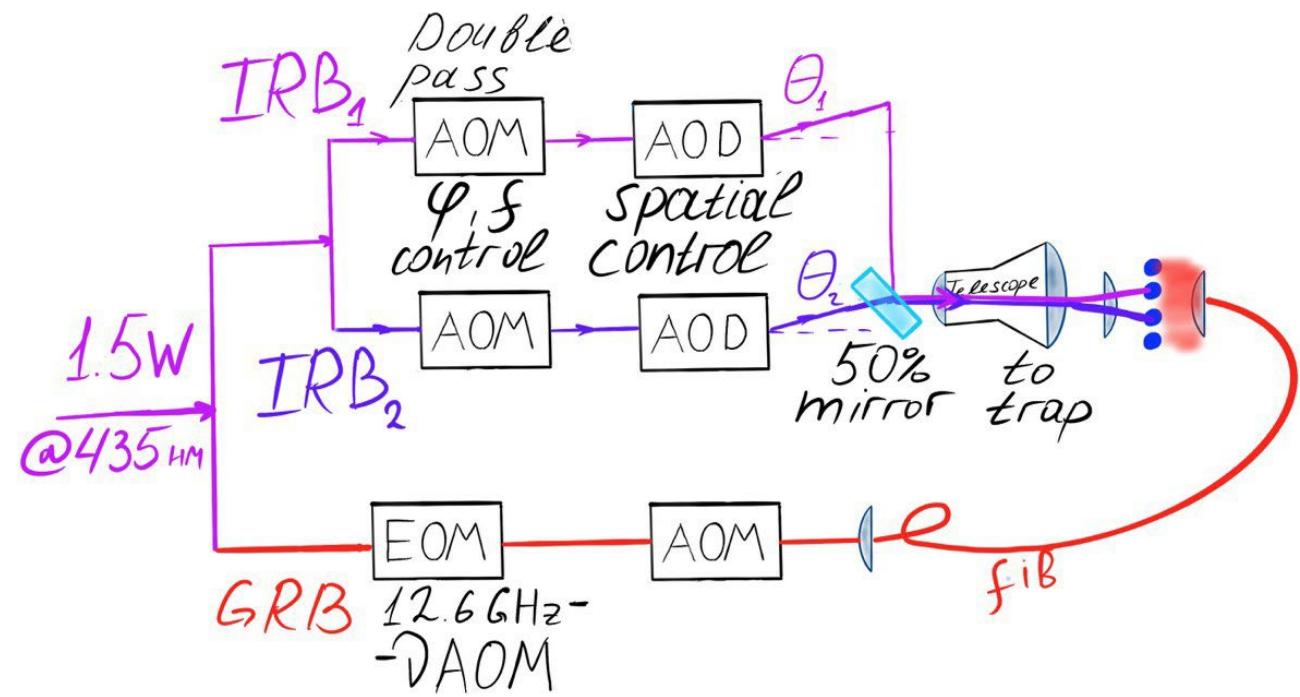
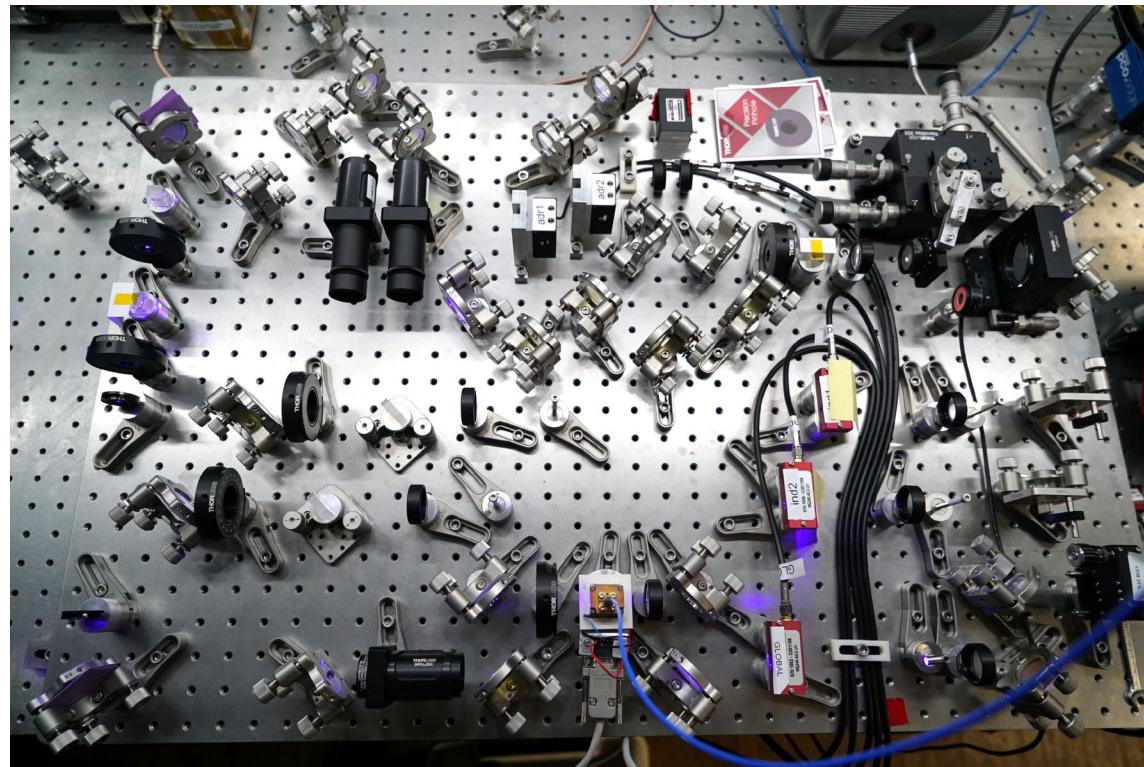
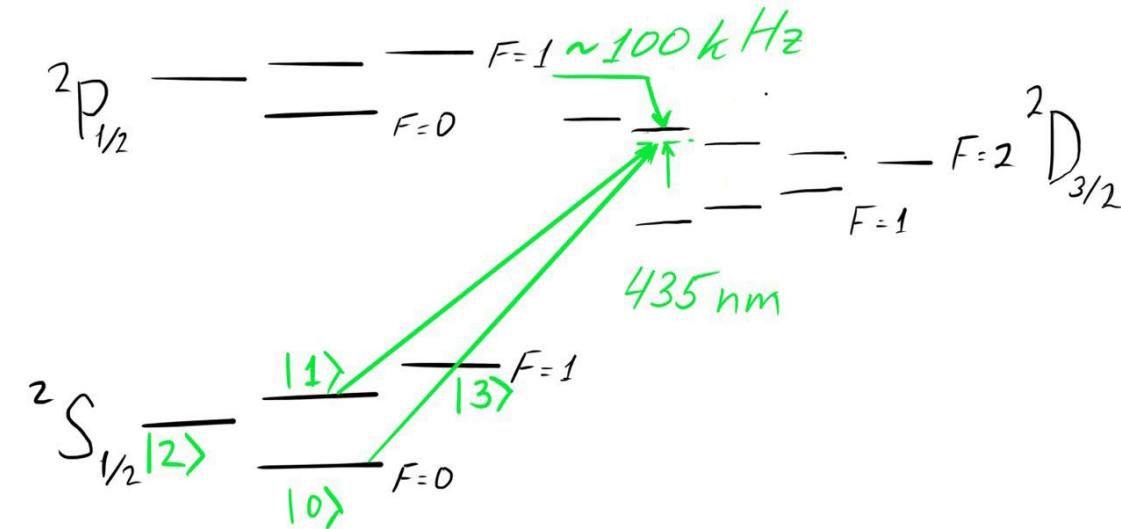
# Individual ion addressing

IRB = individual Raman beam  
GRB = global Raman beam



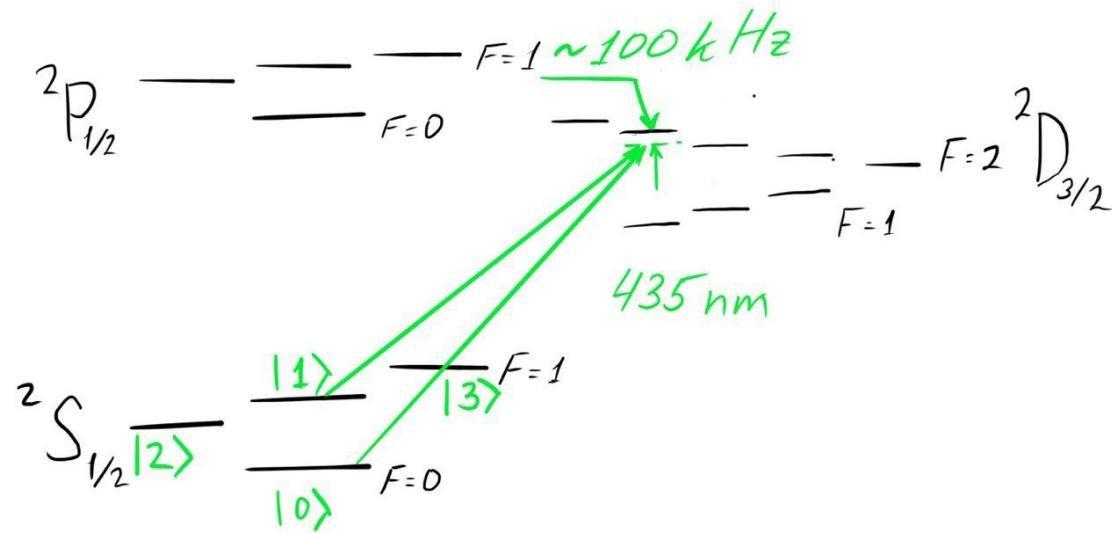
- $TeO_2$  acousto-optic deflectors
  - No parallel operations
  - + Up to 100 ions addressable
  - + Much less sensitive to addressing laser linewidth
  - + Same system for RF and optical qubits
  - + Qudits are available
  - + Same addressing system for far off resonance optical tweezer

# Individual addressing system for RF and optical qubits



- Individual addressing system for RF and optical qubit at  $^{171}\text{Yb}^+$  assembled
- $4 \mu\text{m}$  resolution at ion string achieved (measured by Rabi oscillations)
- Up to 50 ions addressable
- RF transition excitation demonstrated

# Qudits



In collaboration with A. Fedorov group

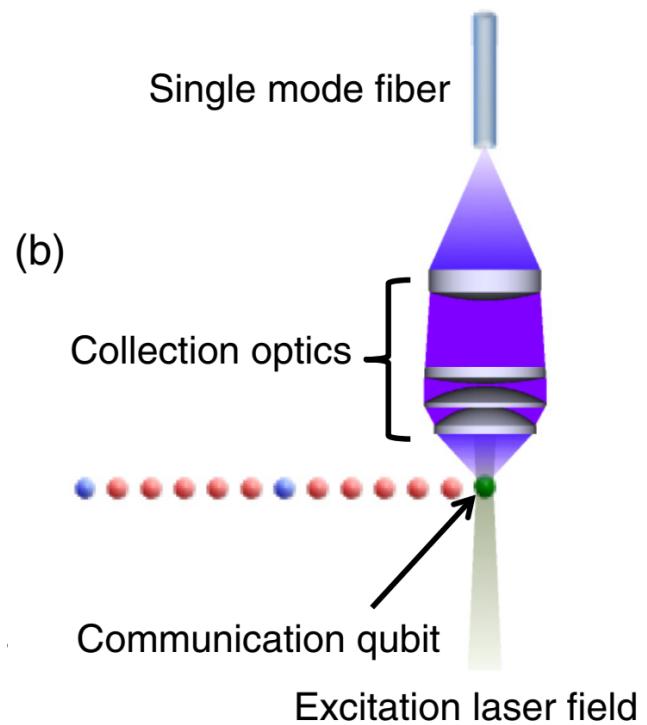
- + More qubits with 1 ion
- + Several algorithms was shown to have advantage using qudits
- Coherence time for additional levels should be lower (magnetic sensitive transition)

Kiktenko, E. O., Fedorov, A. K., Strakhov, A. A., & Man'Ko, V. I. (2015). Single qudit realization of the Deutsch algorithm using superconducting many-level quantum circuits. *Physics Letters A*, 379(22-23), 1409-1413.

Kiktenko, E. O., Nikolaeva, A. S., Xu, P., Shlyapnikov, G. V., & Fedorov, A. K. (2020). Scalable quantum computing with qudits on a graph. *Physical Review A*, 101(2), 022304.

# Non-local entanglement

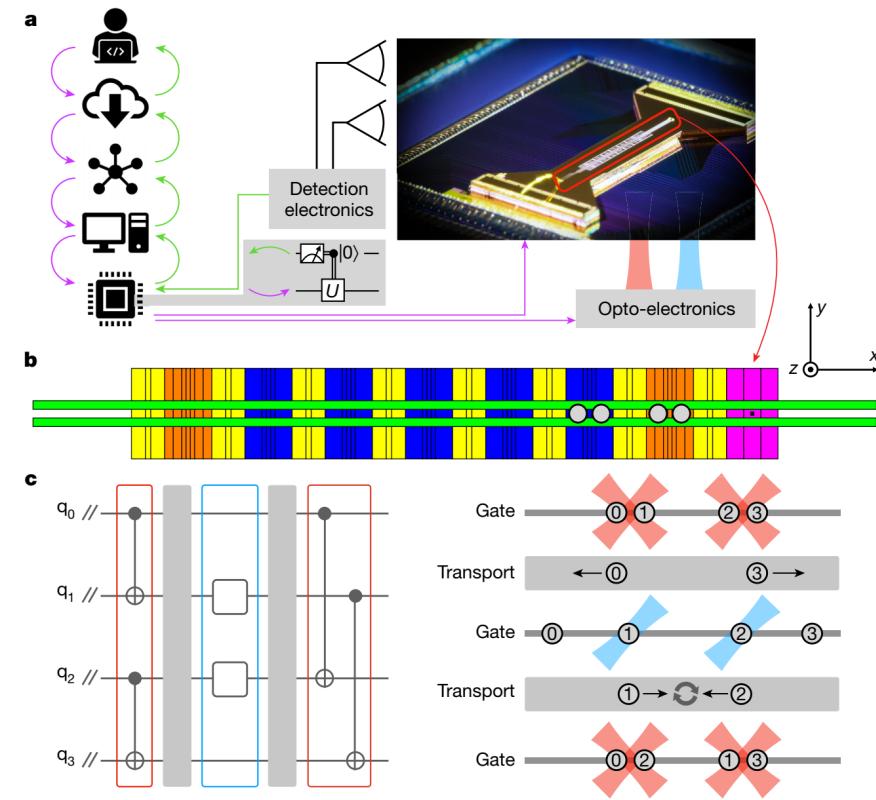
- Photonic interconnects



- High numerical aperture optics required (or even cavity)
- Slow entanglement rates
- Low fidelity

Monroe C. et al. Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects //Physical Review A. – 2014. – T. 89. – №. 2. – C. 022317.

- CCD ion QC

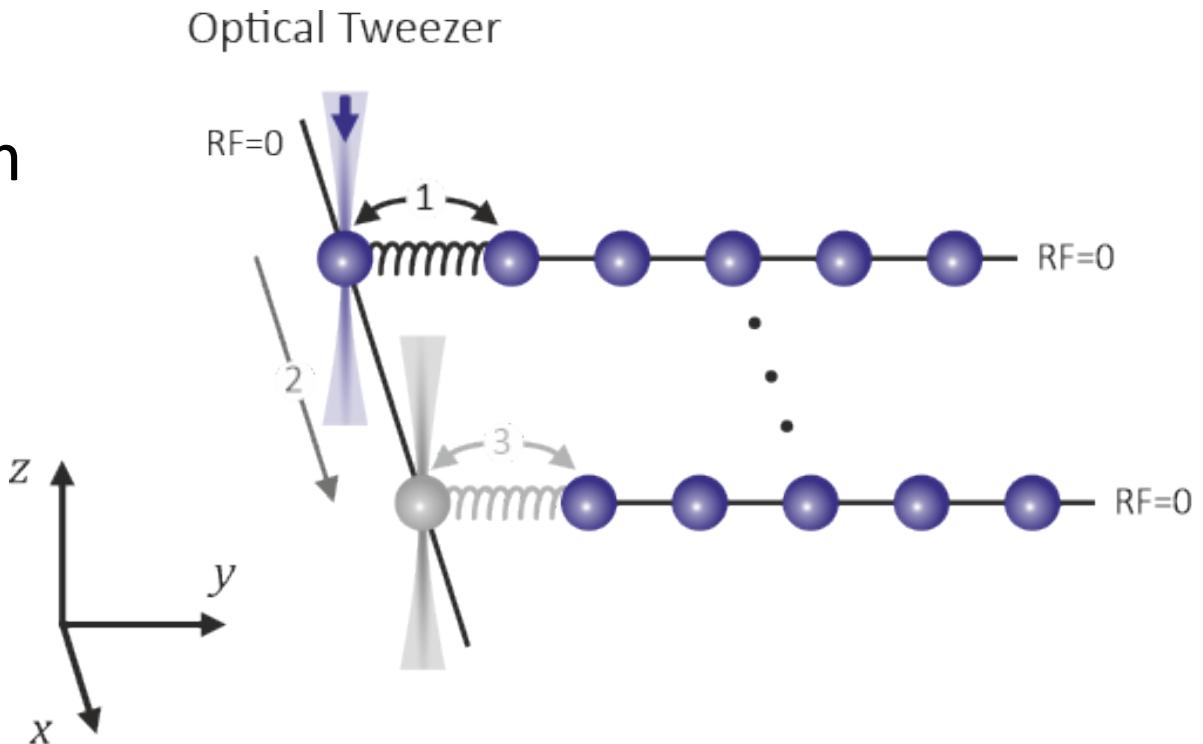


- Very tough requirements for the trap (already 200 DC electrodes) for 10 qubits
- GS cooling between operations required

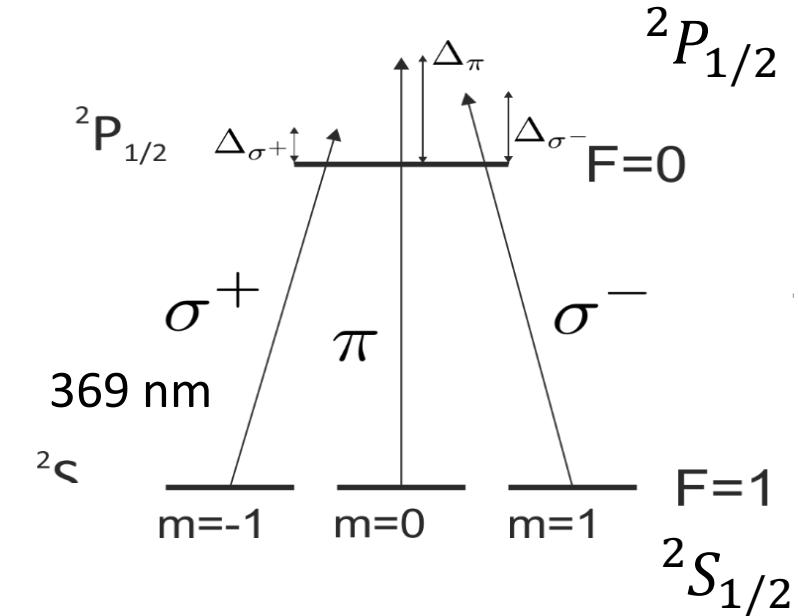
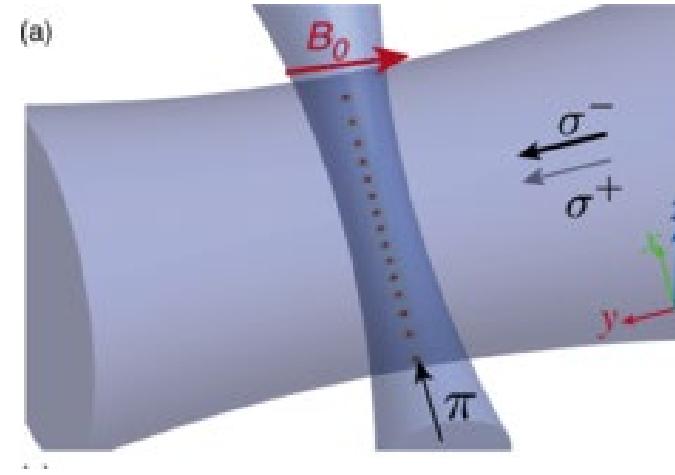
Pino J. M. et al. Demonstration of the trapped-ion quantum CCD computer architecture //Nature. – 2021. – T. 592. – №. 7853. – C. 209-213.

# Ion manipulation with optical tweezer

- Transporting ions with optical tweezer near clock transition  
(with the same addressing system as for qubit manipulation)
- + Easier trap design
- + Fast entanglement
- Large distance two-qubit gate required



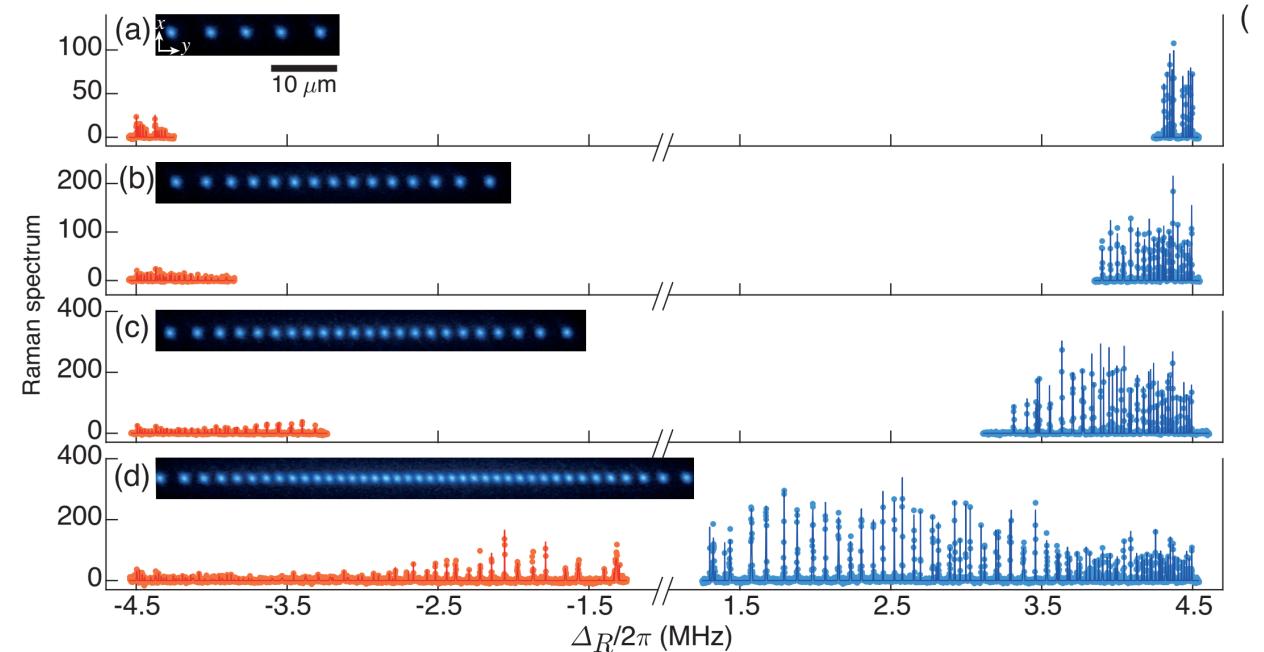
# Double EIT cooling



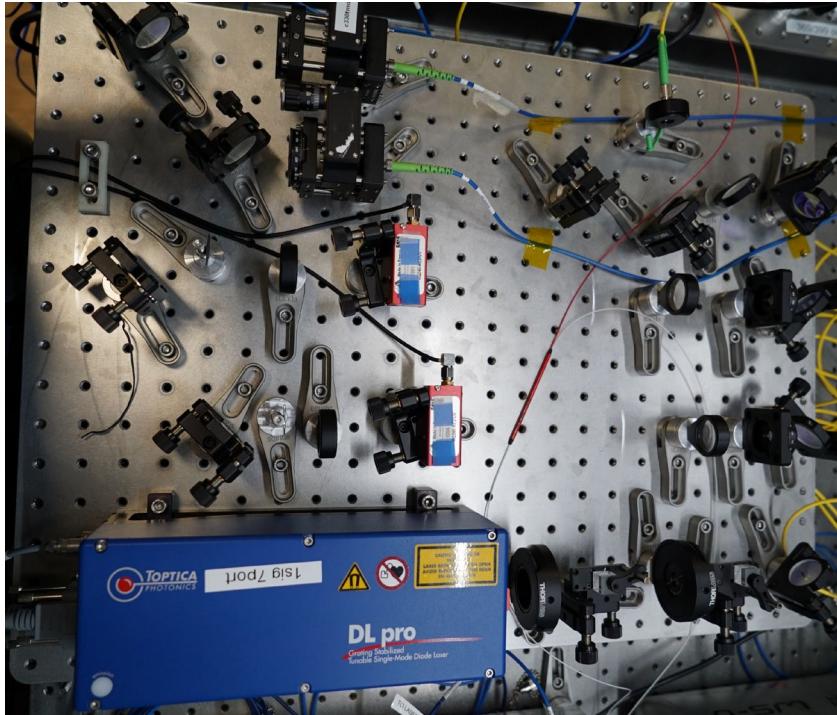
- + only 2 additional AOMs involved
- + wide ground state cooling

Semerikov, I. A., Zalivako, I. V., Borisenko, A. S., Khabarova, K. Y., & Kolachevsky, N. N. (2018). EIT Ground State Cooling Scheme of  $^{171}\text{Yb}^+$  Based on the  $2\text{S } 1/2 \rightarrow 2\text{P } 1/2$  Cooling Transition. *Journal of Russian Laser Research*, 39(6), 568-574.

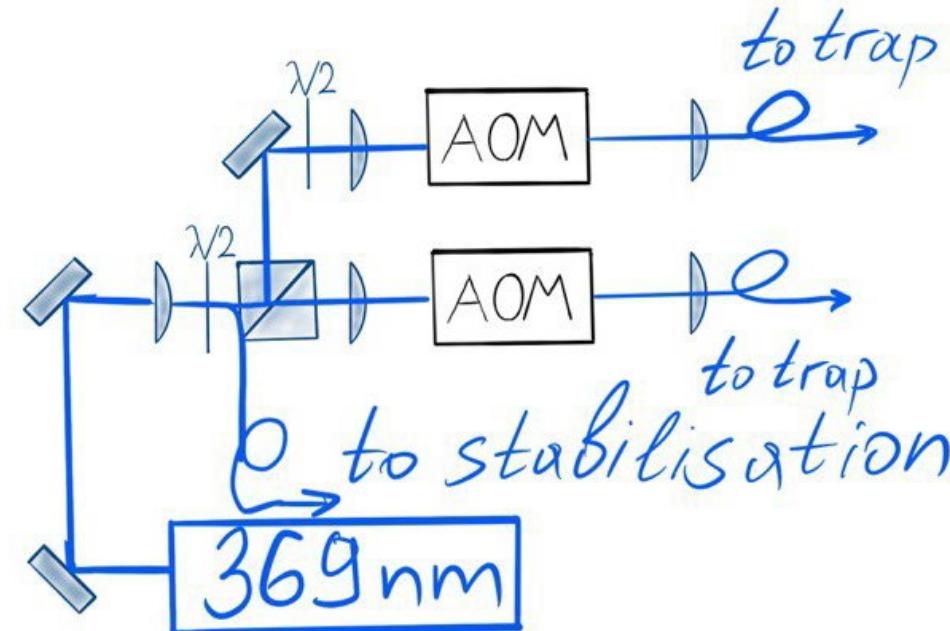
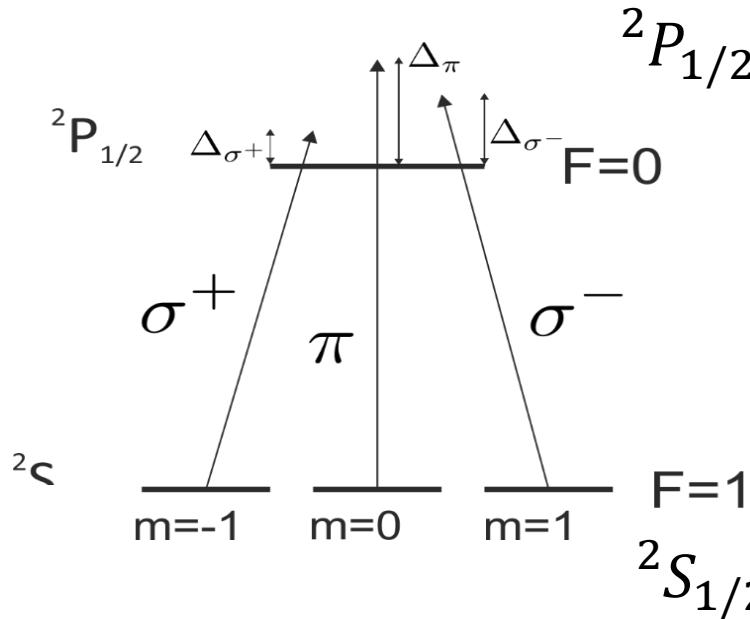
Feng, L., Tan, W. L., De, A., Menon, A., Chu, A., Pagano, G., & Monroe, C. (2020). Efficient Ground-State Cooling of Large Trapped-Ion Chains with an Electromagnetically-Induced-Transparency Tripod Scheme. *Physical Review Letters*, 125(5), 053001.



# Double EIT cooling



- Separate system for Double-EIT cooling assembled

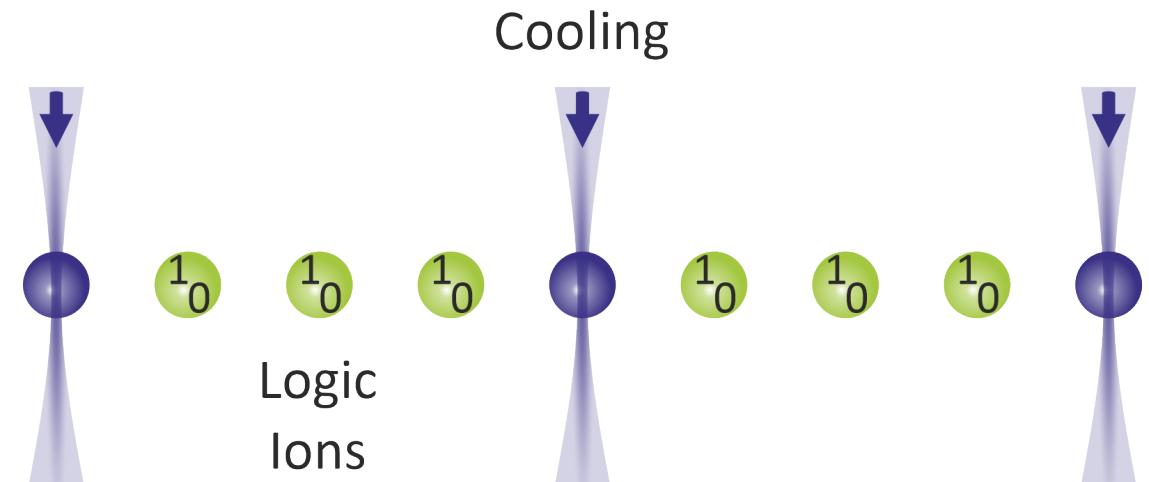


# Sympathetic cooling

Mid-circuit cooling of the chain through particular refrigerator ions

Ions of different isotope or species are usually used to prevent quantum register state perturbation.

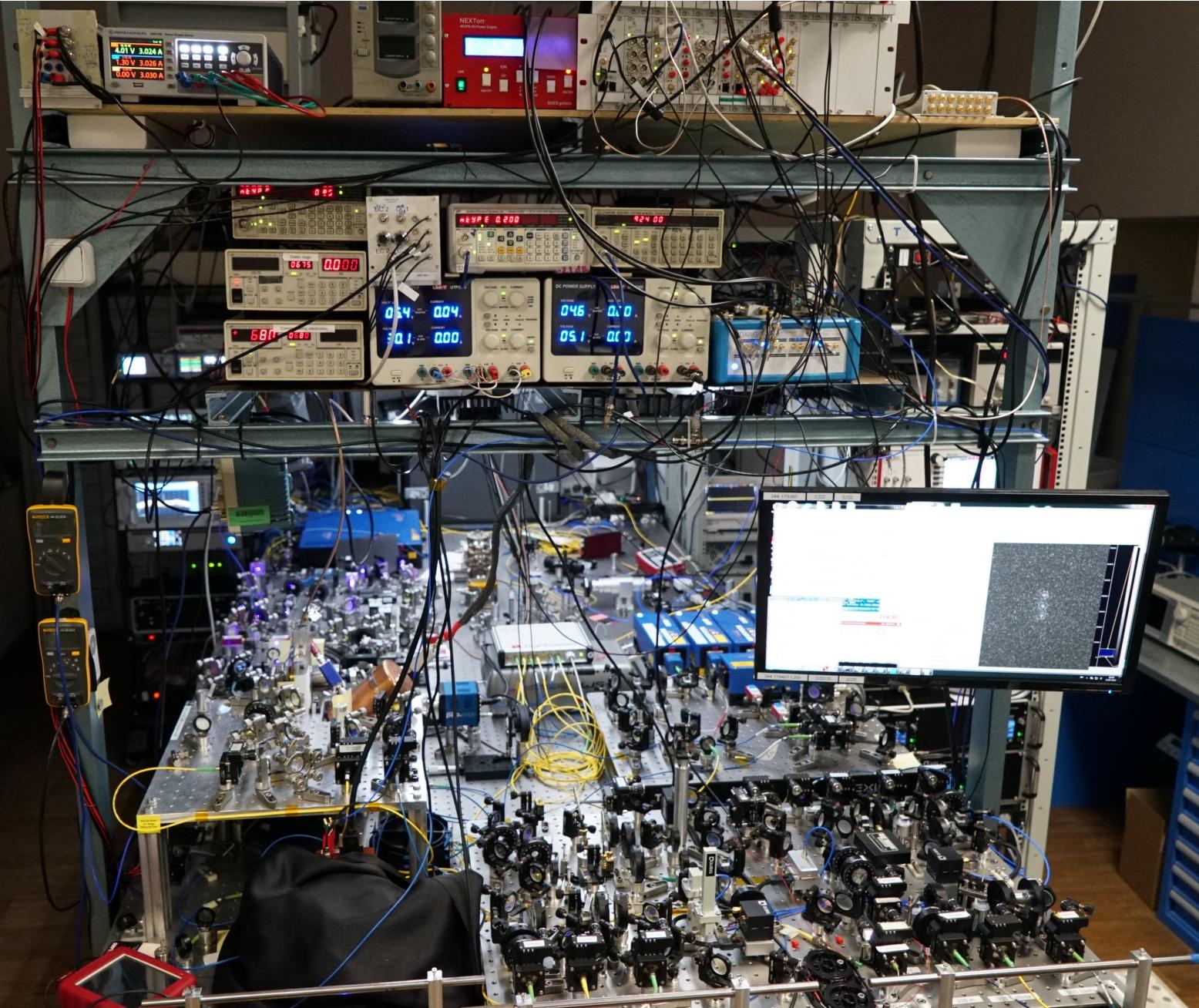
Honeywell:     $\text{Ba}^+$  coolant ions  
IonQ:             $^{172}\text{Yb}^+$  coolant isotopes



Pino, J. M., Dreiling, J. M., Figgatt, C., Gaebler, J. P., Moses, S. A., Allman, M. S., ... & Neyenhuis, B. (2021). Demonstration of the trapped-ion quantum CCD computer architecture. *Nature*, 592(7853), 209-213.

Cetina, M., Egan, L., Biswas, D., Katz, O., Noel, C., Zhu, D., ... & Monroe, C. (2021). Sympathetic Cooling in Long  $\text{Yb}^+$  Chains. *Bulletin of the American Physical Society*.

# Outlook



- We made a setup, which could be named as quantum computer
- We are in the process of understanding how does it work
- We are looking forward to test several new ideas, but before we should demonstrate simple two qubit operations.

# Our team



I. Semerikov



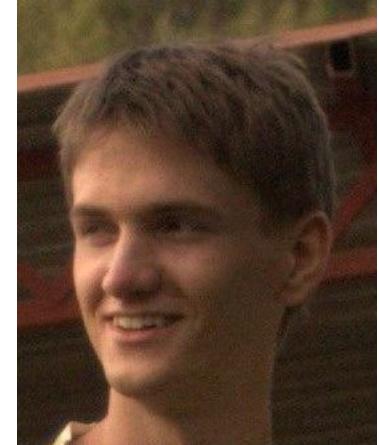
I. Zalivako



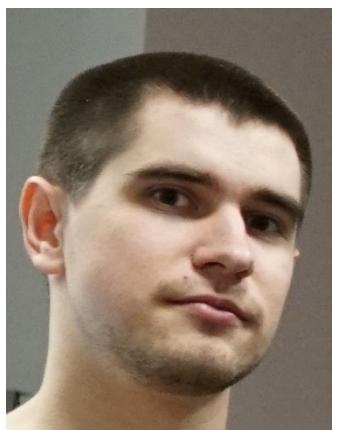
M. Aksenov



A. Borisenko



A. Korolkov



P. Sidorov



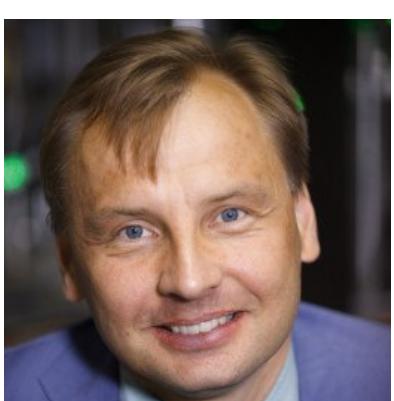
V. Smirnov



N. Semenin



K. Khabarova



N. Kolachevsky

PhD and Postdoc positions available