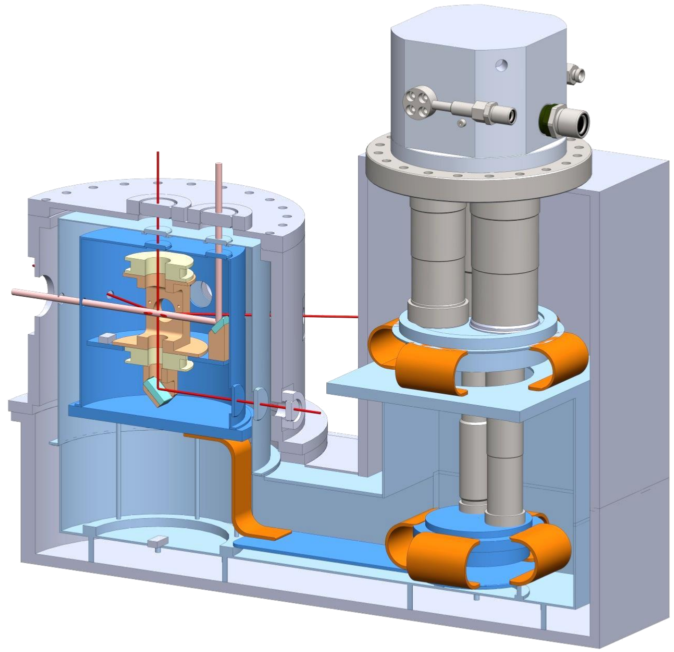
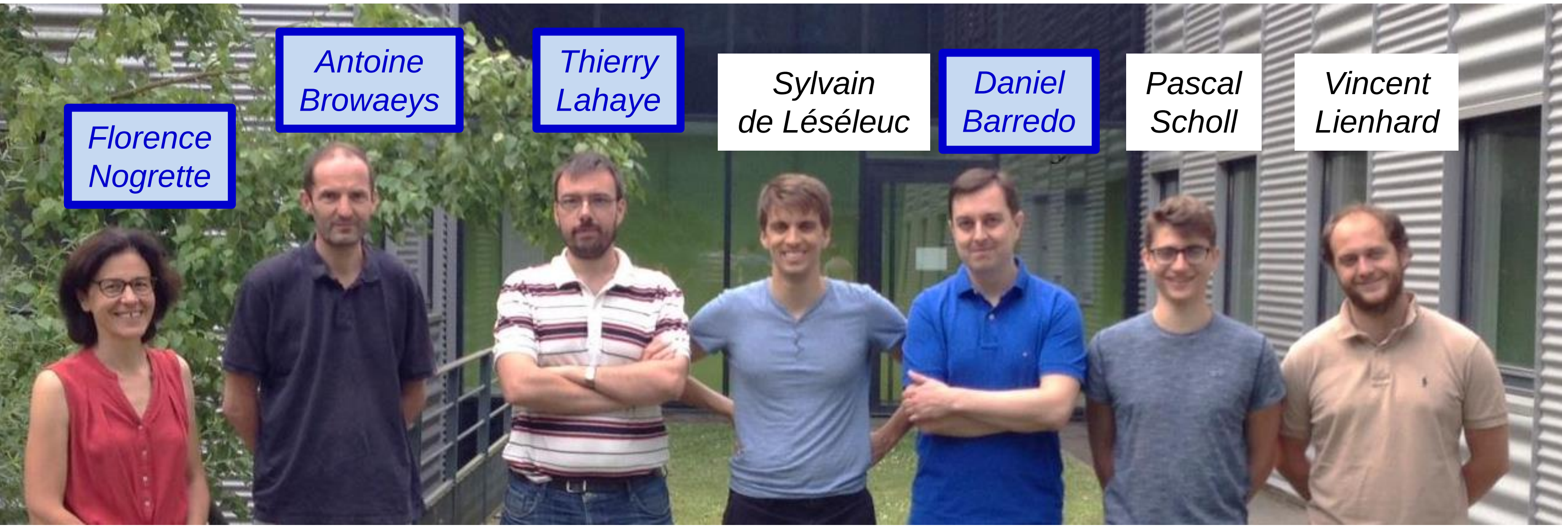
# *Single atoms with 6000 s trapping times in optical tweezer arrays at 4 K*

**Thierry Lahaye**
*Laboratoire Charles Fabry*
*CNRS & Institut d'Optique, Palaiseau, France*



**Cryogenic ion trapping day**, 19 October 2021

# The Rydberg team in Palaiseau




Hannah Williams

Guillaume Bornet

Kai-Niklas Schymik

Sara Pancaldi

***Collaboration with***
Julien Paris

MYCRYOFIRM CRYOGENIC SOLUTIONS

**https://atom-tweezers-io.org/**

***Funding:*** SIRTEQ, îledeFrance, AGENCE NATIONALE DE LA RECHERCHE ANR, QUANTUM FLAGSHIP, PASQuanS

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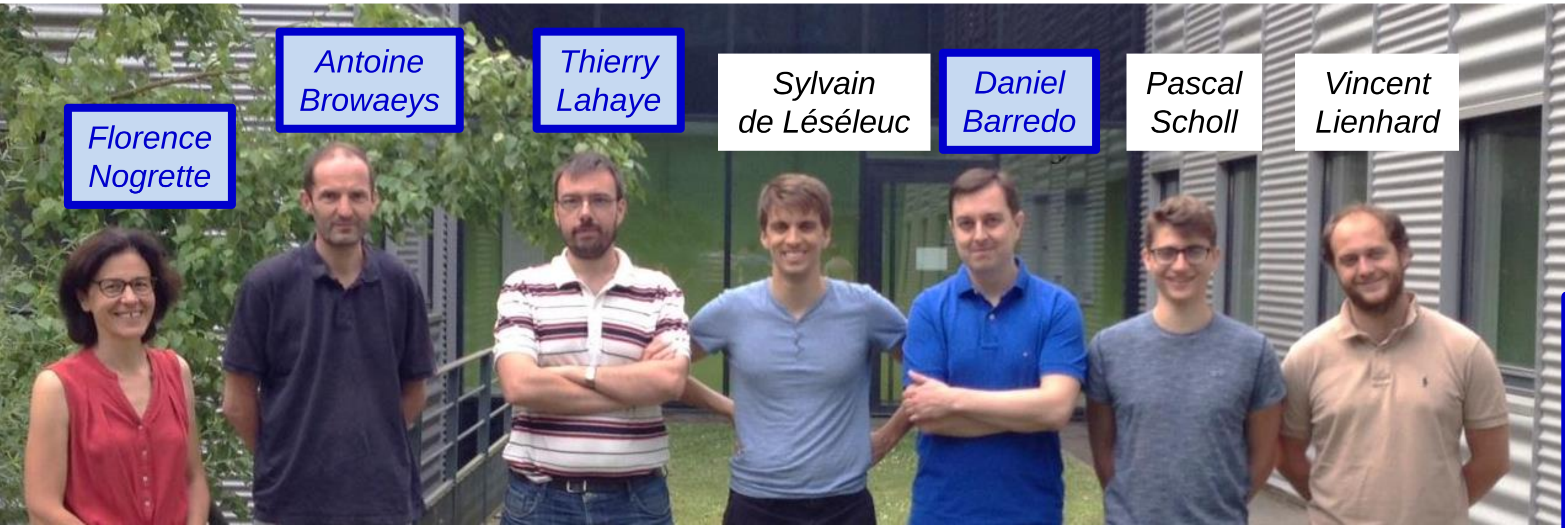


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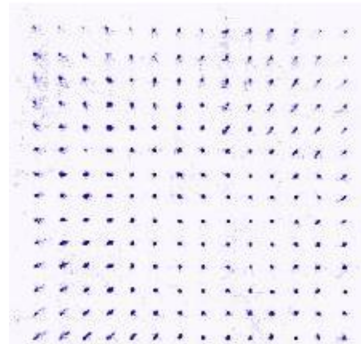
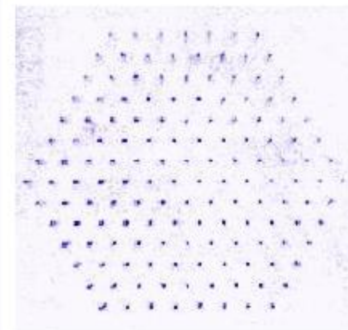
# *Arrays of single Rydberg atoms*

- **Arrays of single atoms with arbitrary geometries**

Up to > 200 atoms
Spacing: a few microns





- **Strong interactions via Rydberg excitation**

$U / h$ ~ 1 to 10 MHz for $R$ ~ 5 µm

Lifetime 100s of µs

***Implement spin models***

Ising (vdW interactions)

$$\hat{H} \sim \sum_{i,j} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)}$$

XY (resonant dipole-dipole interaction)

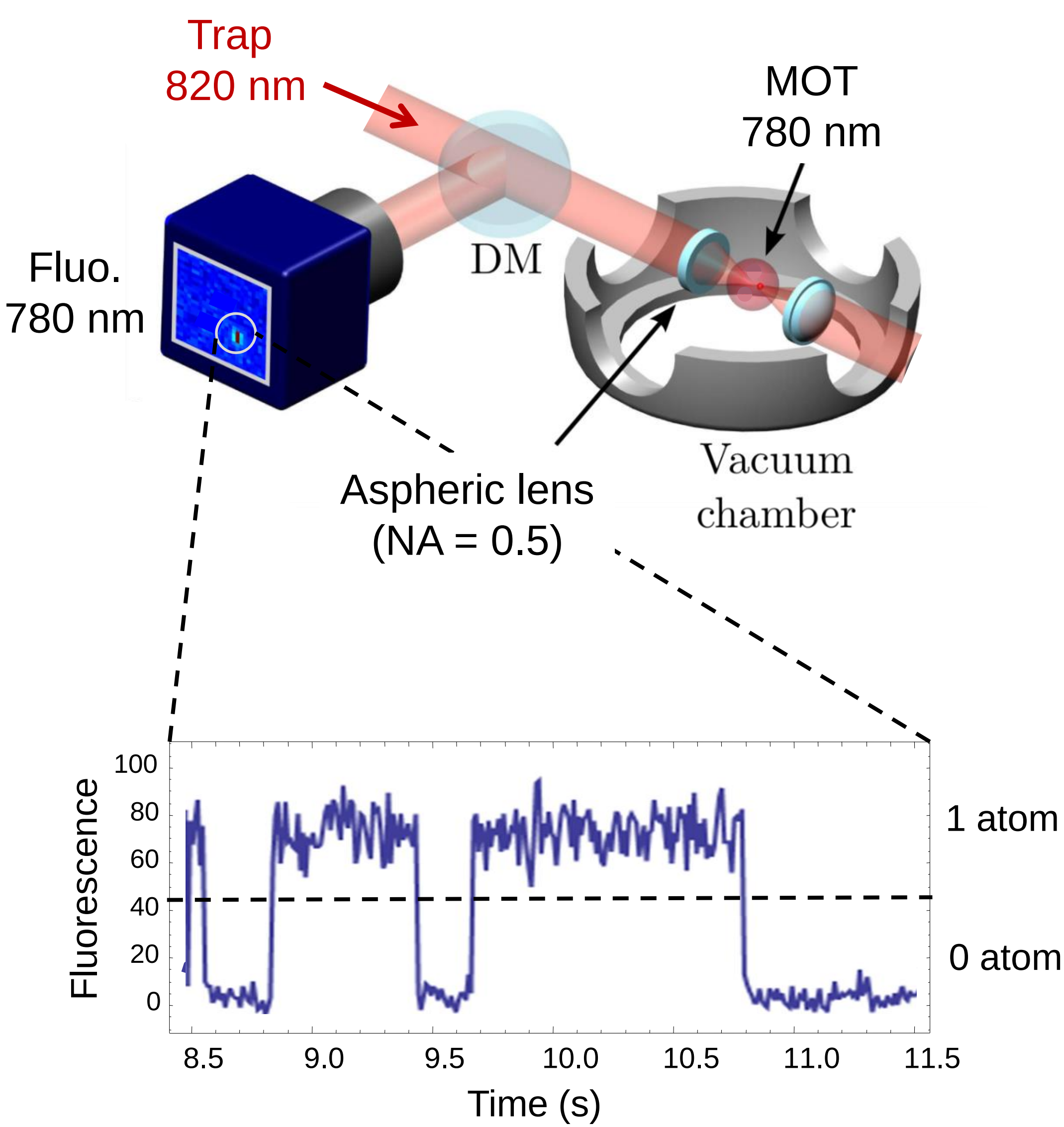
$$\hat{H} \sim \sum_{i,j} J_{ij} \sigma_+^{(i)} \sigma_-^{(j)}$$

# *Outline*

1. ***Tweezer arrays and Rydberg atoms***
2. ***Cryogenic setup***
3. ***Cryogenic trapping of single atoms***

## *1. Tweezer arrays & Rydberg atoms*

# Single atoms in optical tweezers

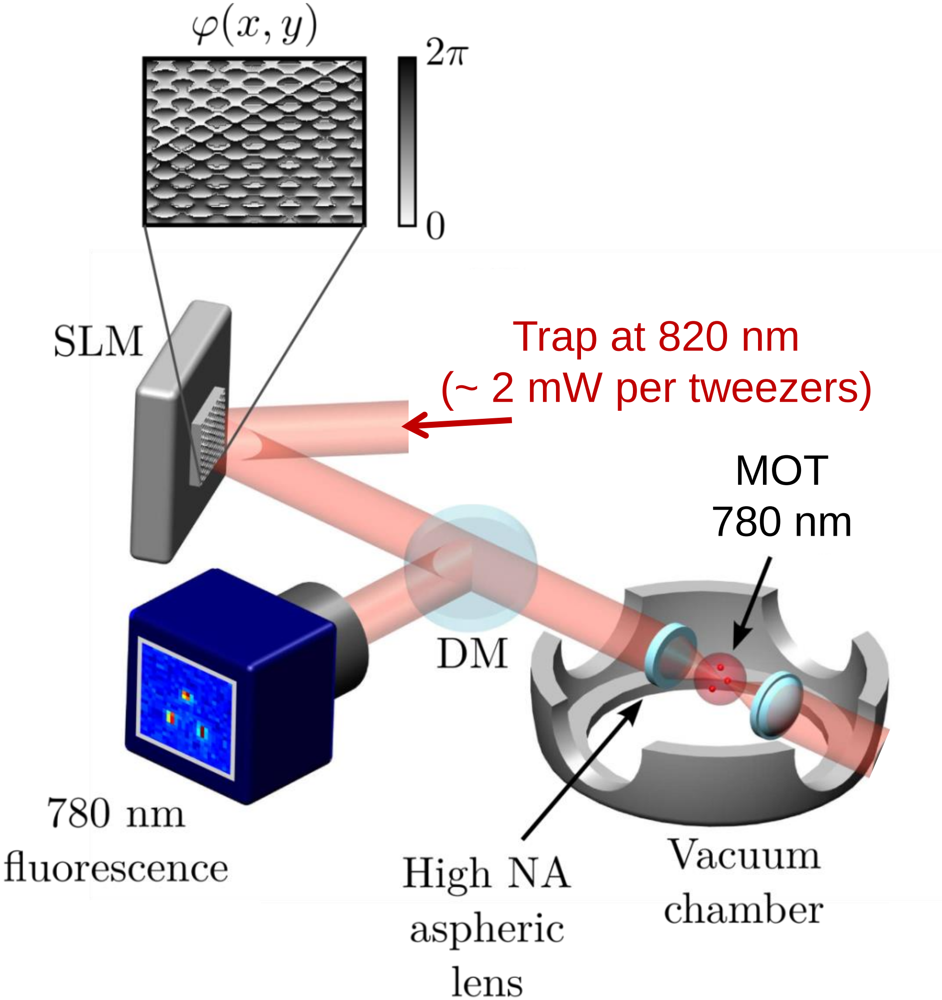


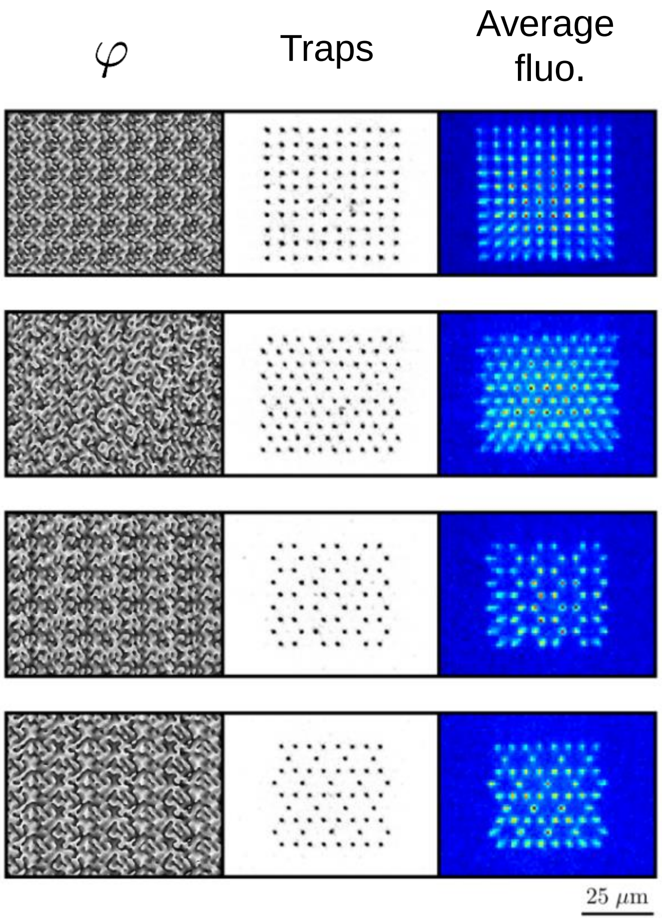

- 1 µm waist optical tweezers loaded from MOT
- At most one atom due to light-assisted collisions
- 50% loading probability:

  ***Non-deterministic single-atom source!***

Schlosser *et al.*, Nature 2001

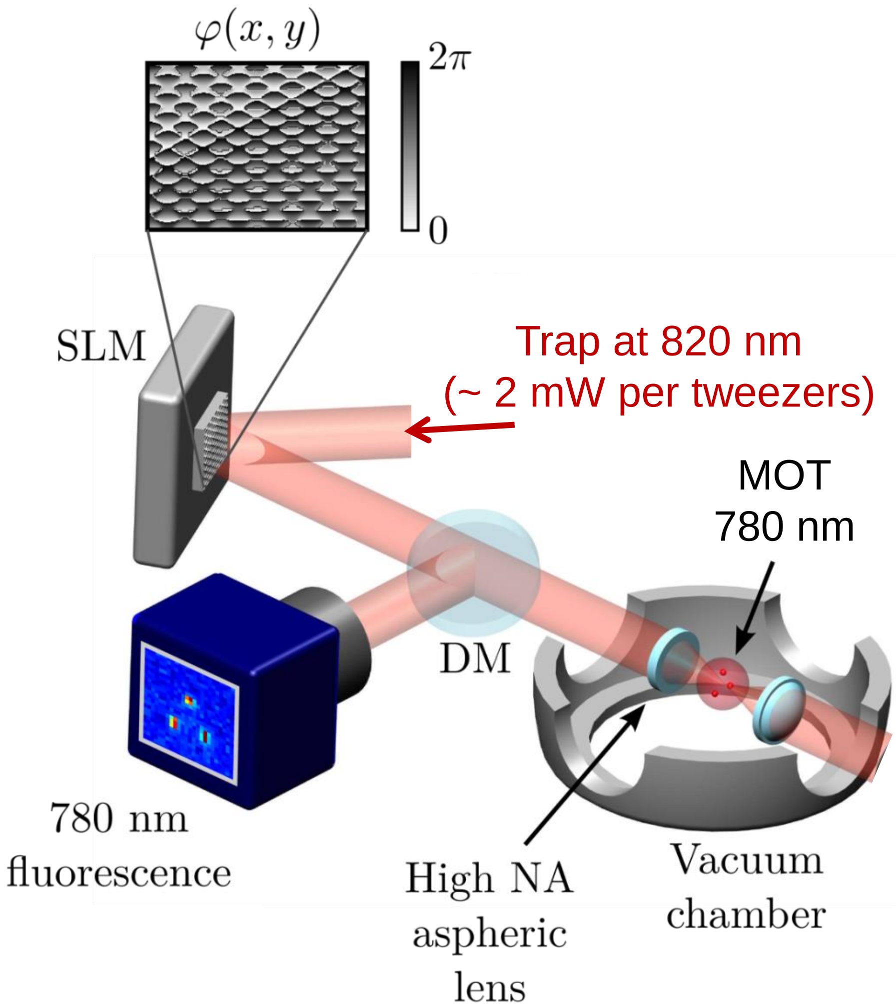
# Arrays of single atoms

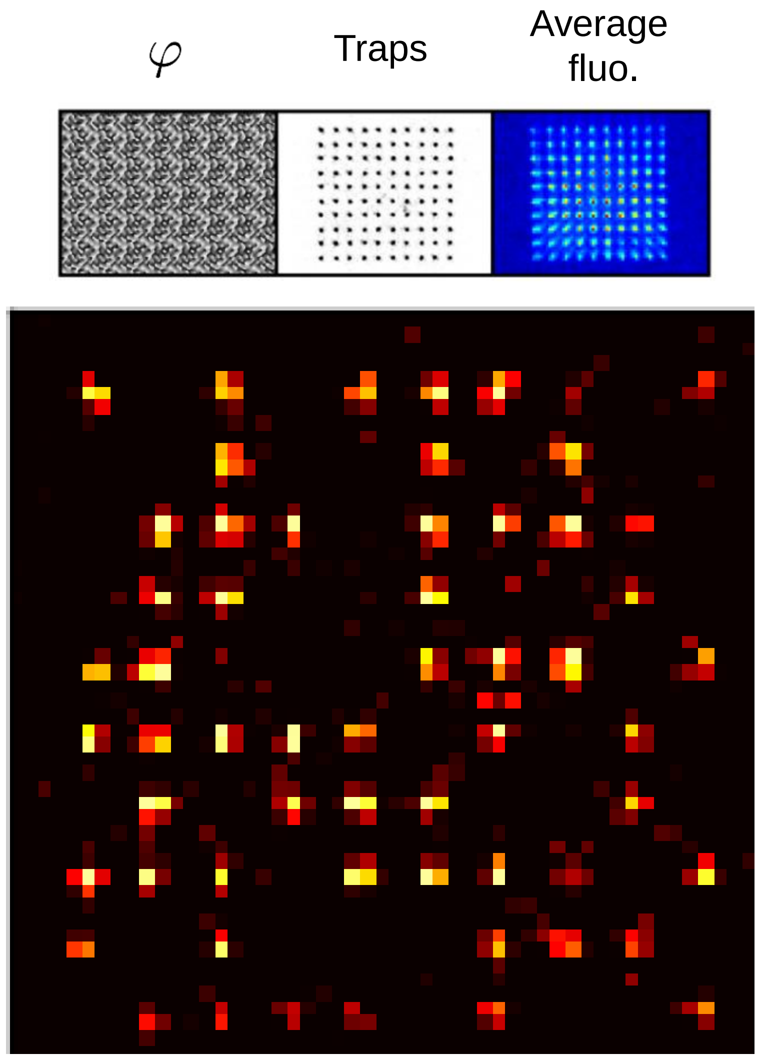



Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

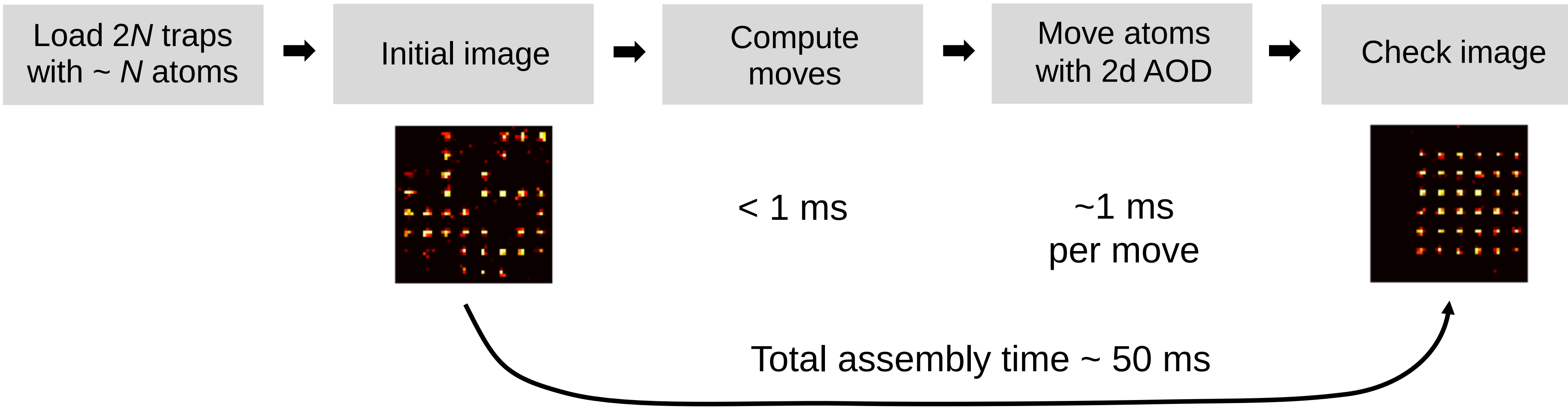
# Arrays of single atoms

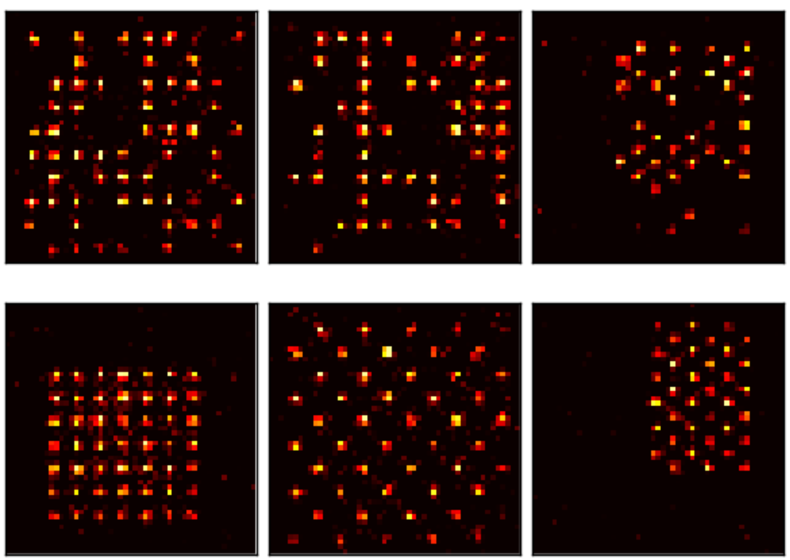



Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

# *Atom-by-atom assembly*



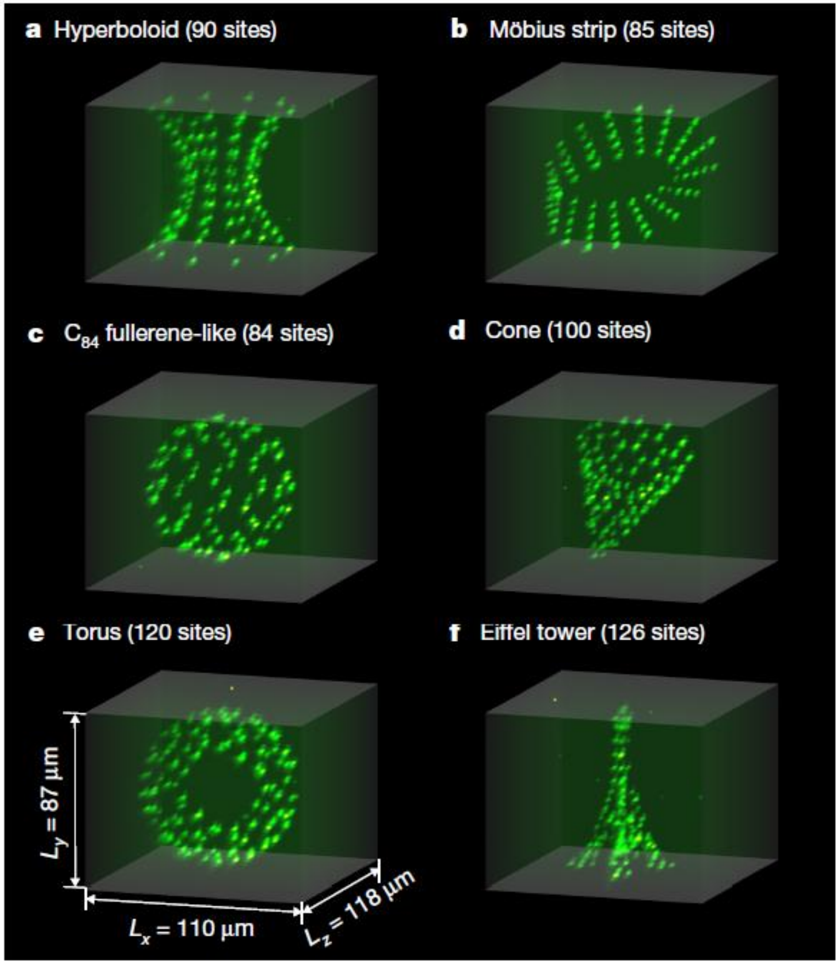



- Fully loaded arrays up to 50 atoms
- 98% filling fraction
- Rep. rate up to ~ 4 Hz

Barredo *et al.*, Science **354**, 1021 (2016)

See also:
Endres *et al.*, Science **354**, 1024 (2016)
Kim *et al.*, Nature Comm. **7**, 13317 (2016)

# *Extension to 3D arrays*

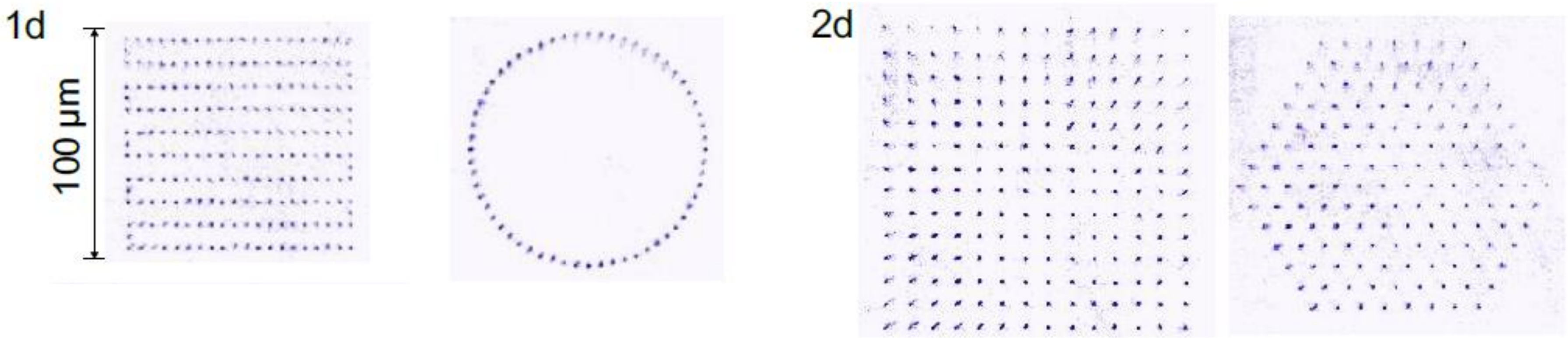



Barredo *et al.*, Nature **561**, 79 (2018)

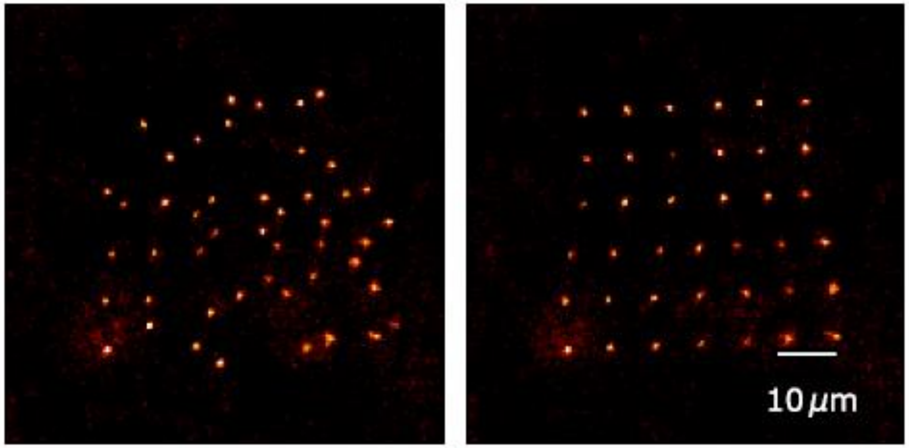
# *Recent improvements*

Improved assembler algorithms
K.-N. Schymik *et al.*, Phys. Rev. A **102**, 063107 (2020)

- ***Up to > 200 atoms***




- ***Geometries not limited to a regular array***



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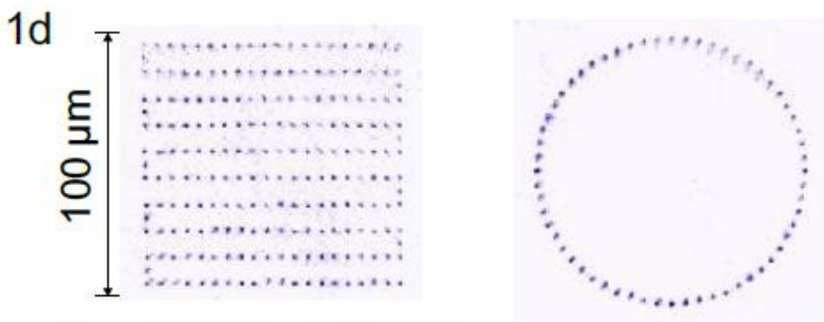


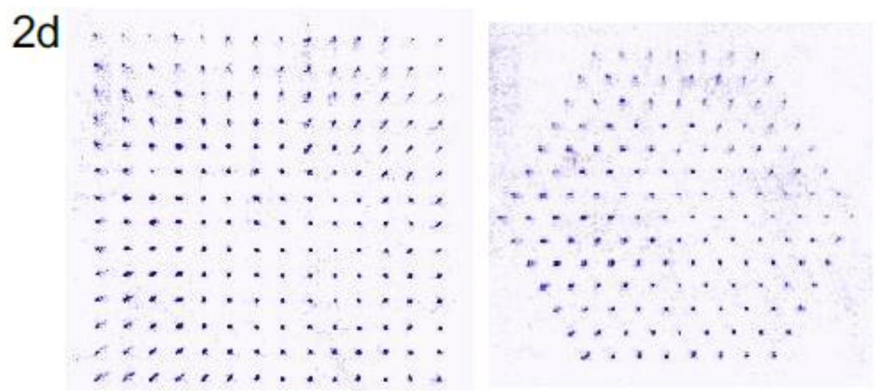


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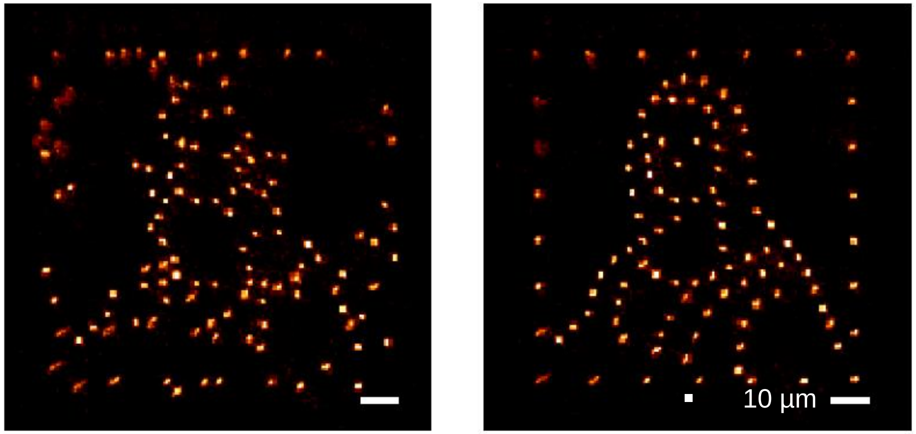
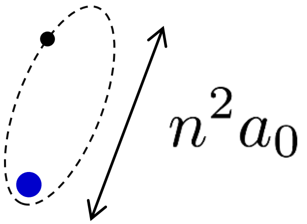


# Rydberg atoms

Large principal quantum number: $n \gg 1$

$n \sim 50 - 100$



Exaggerated properties:

Electric dipole $\langle nS| \, d \, |nP\rangle \sim n^2$

Lifetime $\tau \sim n^3$ (100s of μs)

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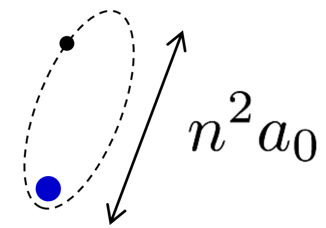


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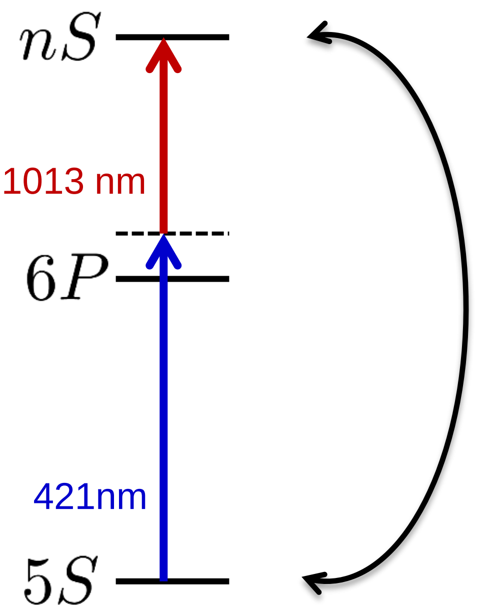
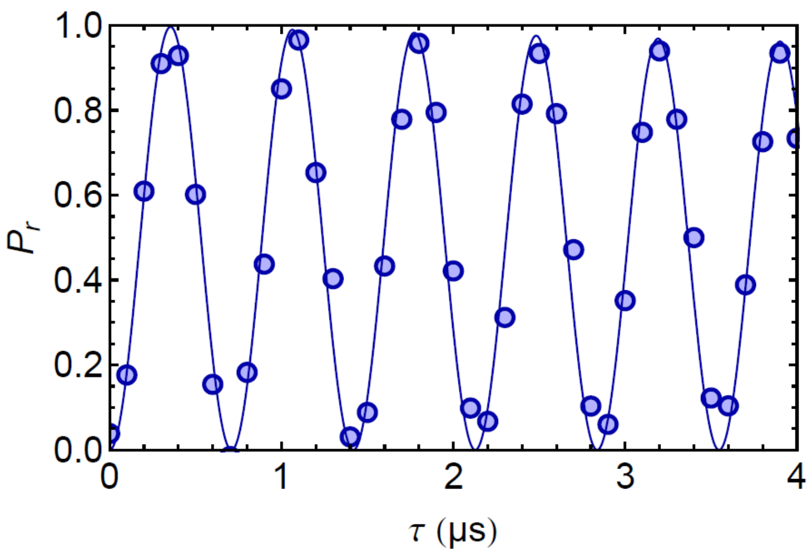



*5S – nS* Rabi oscillations



# *Why go cryogenic?*

***Rydberg state lifetime***

$\tau \propto n^3 (200\ \mu\mathrm{s}$ at $n\ = 80)$ has two (roughly equal) contributions:

- Radiative decay to low-lying states (independent of $T$)
- BBR-induced transitions to neighboring Rydberg states (scales as $T^4$)

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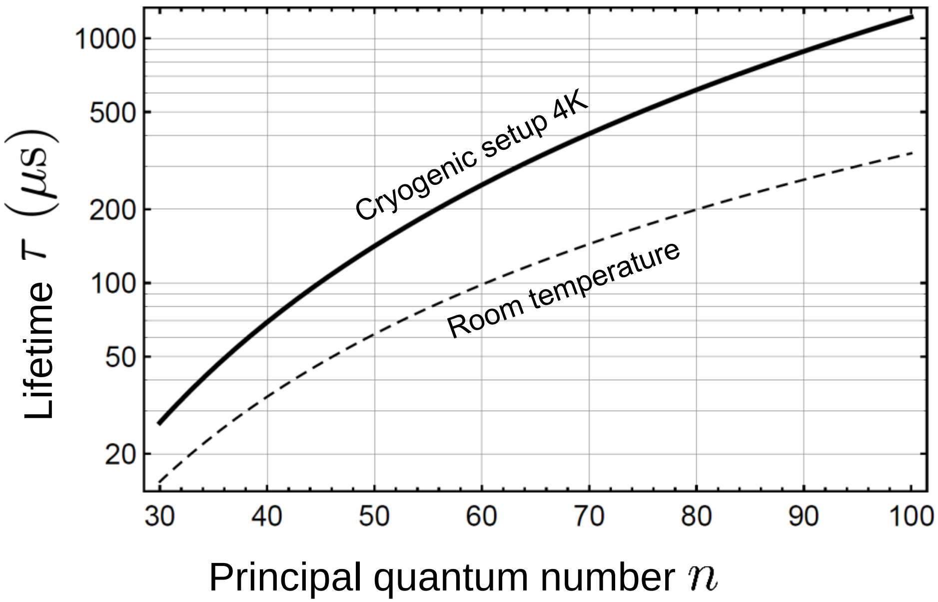

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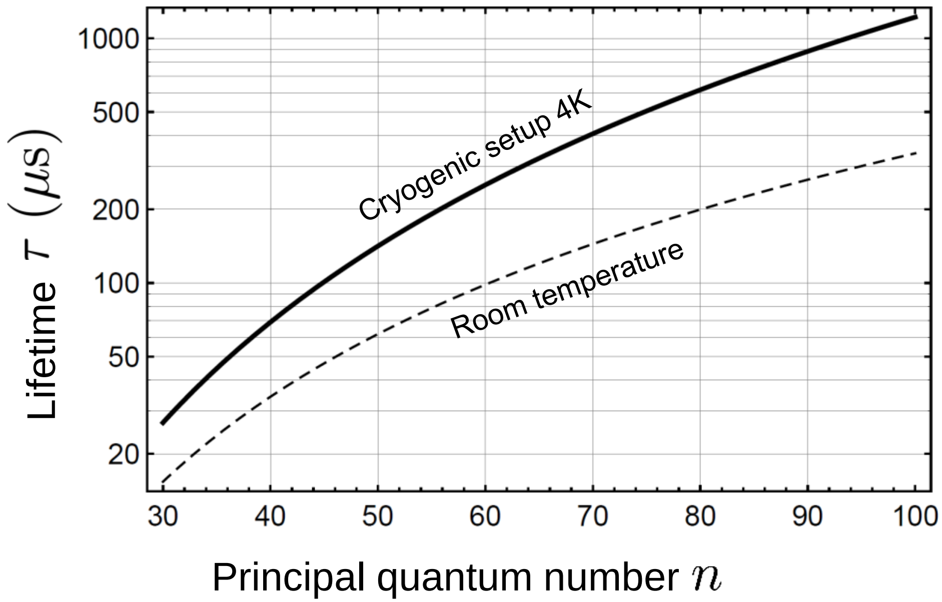
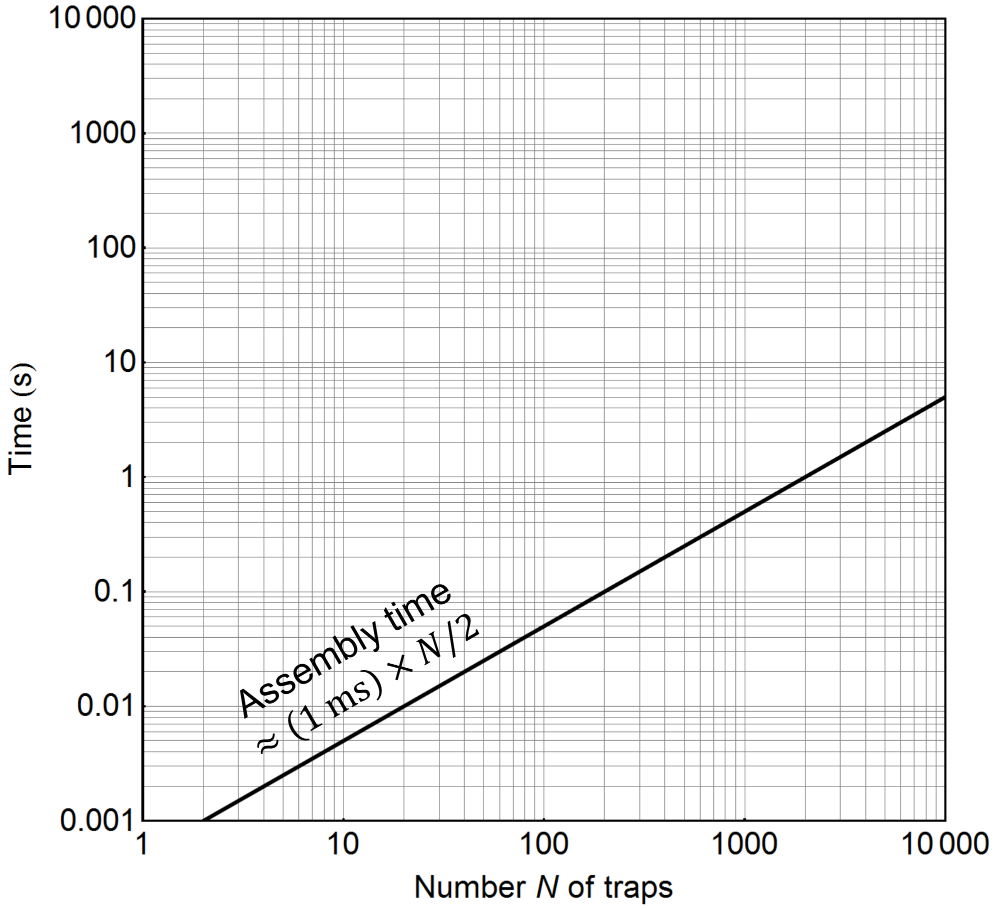



***Nice gain of 2-3, but not enough to bother with a cryogenic setup*** **;-)**
***Note:*** circular Rydberg states have tens of ms of lifetime below 1K

# *Why go cryogenic?*

***The real reason: scaling up the atom number !!!***



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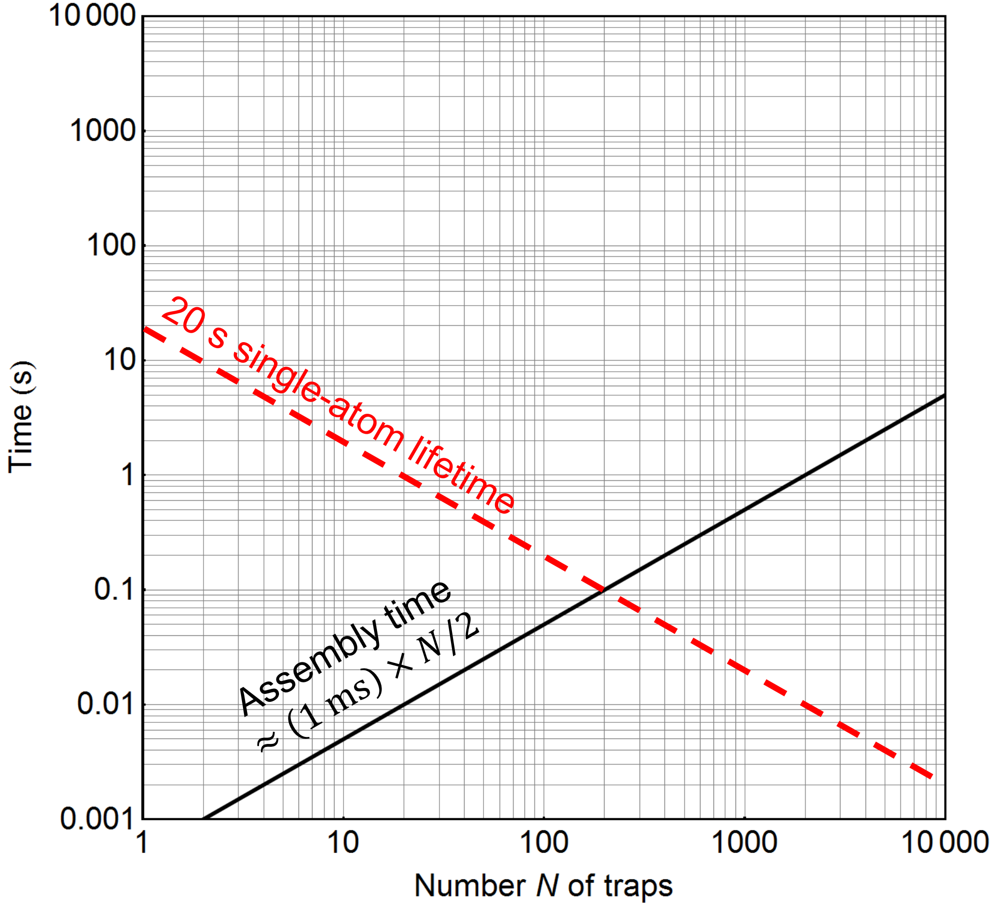

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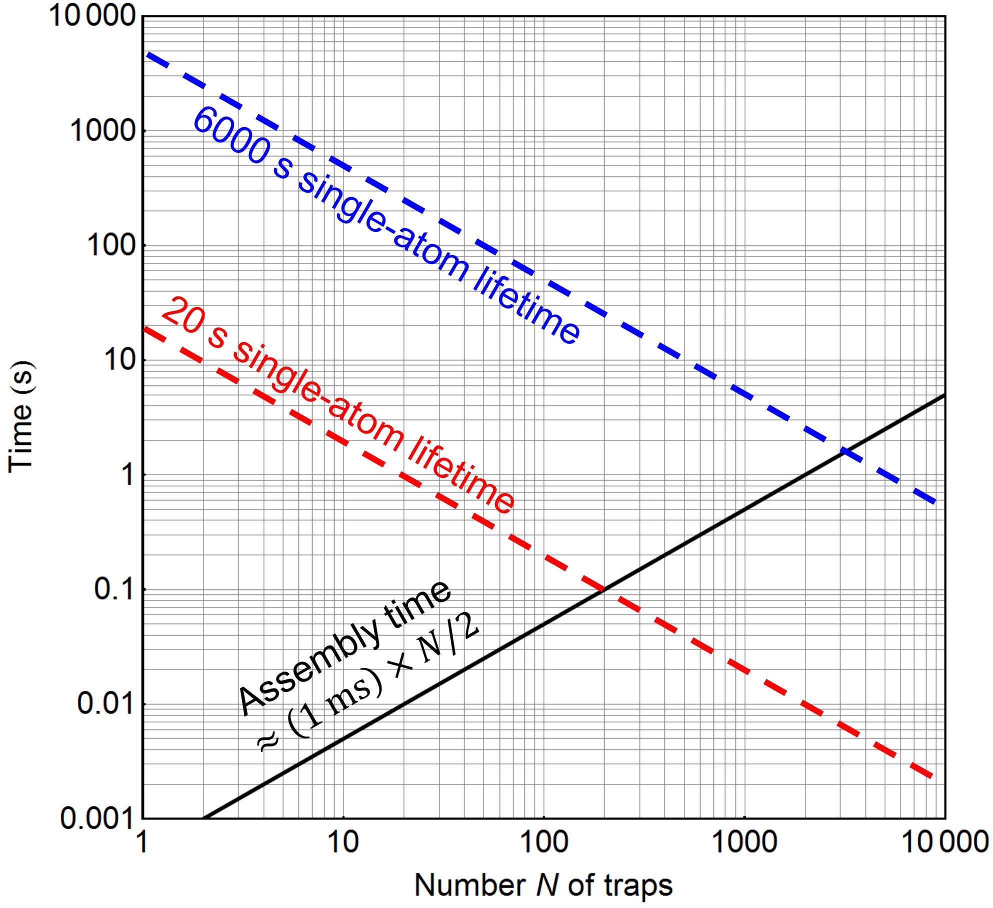
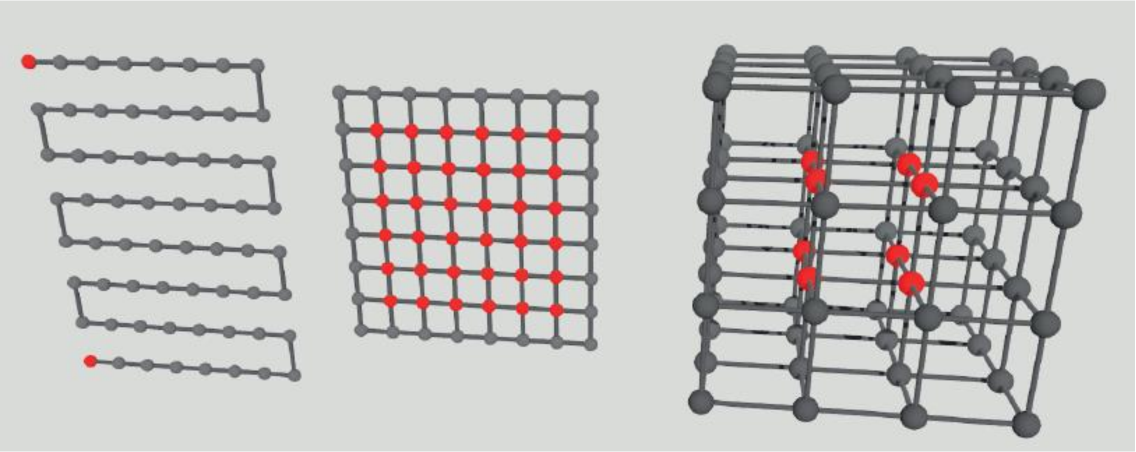


***Q: You already have a 200-spin quantum simulator. Why would you need 2000 spins?***

# *Who cares about 200 vs 2000 atoms?*

***In 2D and 3D, you have lots of boundaries vs bulk***

$N = 64$

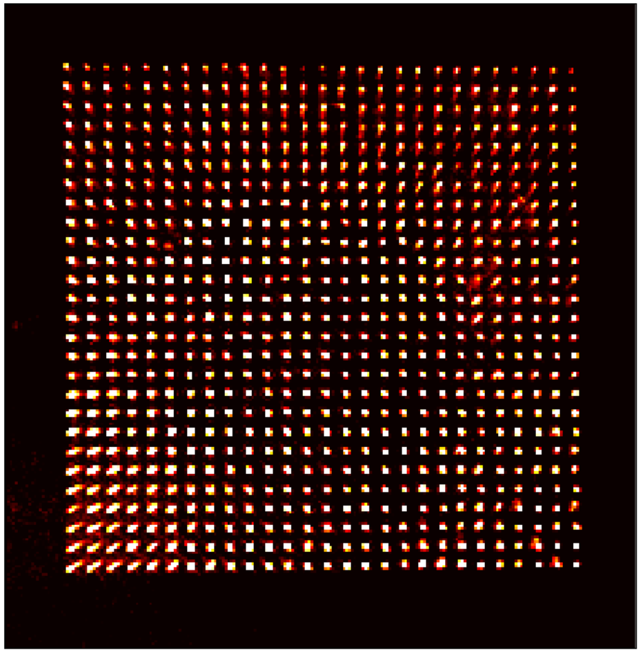


| | 1D | 2D | 3D |
|---|---|---|---|
| $N_{\text{bulk}}$ | 62 | 36 | 8 |
| $N_{\text{boundary}}$ | 2 | 28 | 56 |
| Bulk fraction | 97% | 56% | 13% |

# *Who cares about 200 vs 2000 atoms?*

***In 2D and 3D, you have lots of boundaries vs bulk***

$$N = 729 = 27^2 = 9^3$$



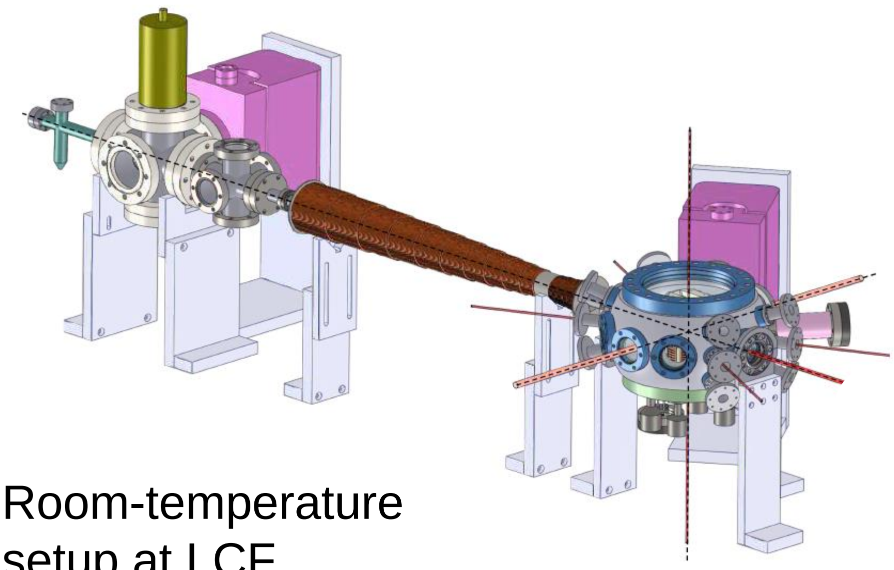
| | 1D | 2D | 3D |
|---|---|---|---|
| $N_{\text{bulk}}$ | 727 | 625 | 343 |
| $N_{\text{boundary}}$ | 2 | 104 | 386 |
| Bulk fraction | 99.7% | 86% | 47% |

## *2. Cryogenic setup*

K. N. Schymik *et al.*, Phys. Rev. Applied **16**, 034013 (2021)

# *Keep things as 'simple' as possible*

Build the "same" setup as the room-T one…



Room-temperature setup at LCF

Commercial closed-cycle optical access cryostat: OptiDry from MyCryoFirm

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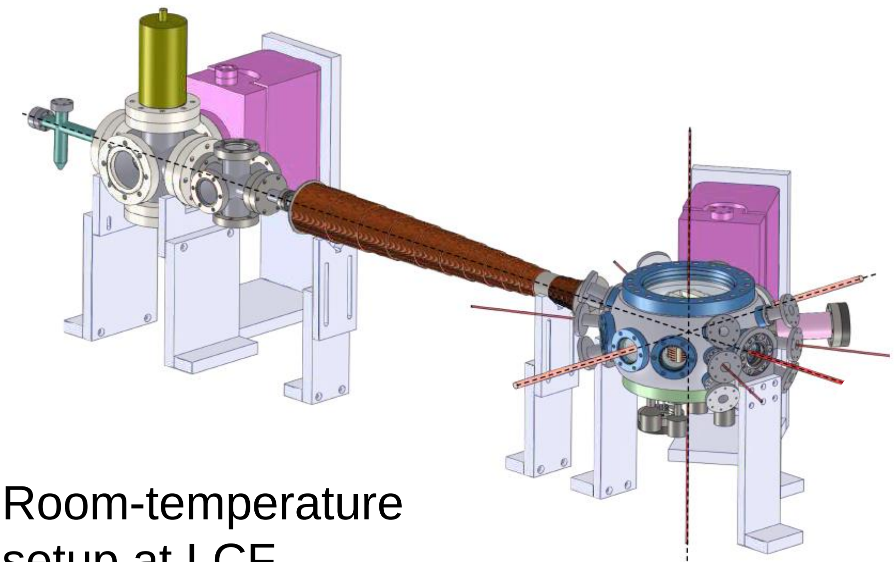


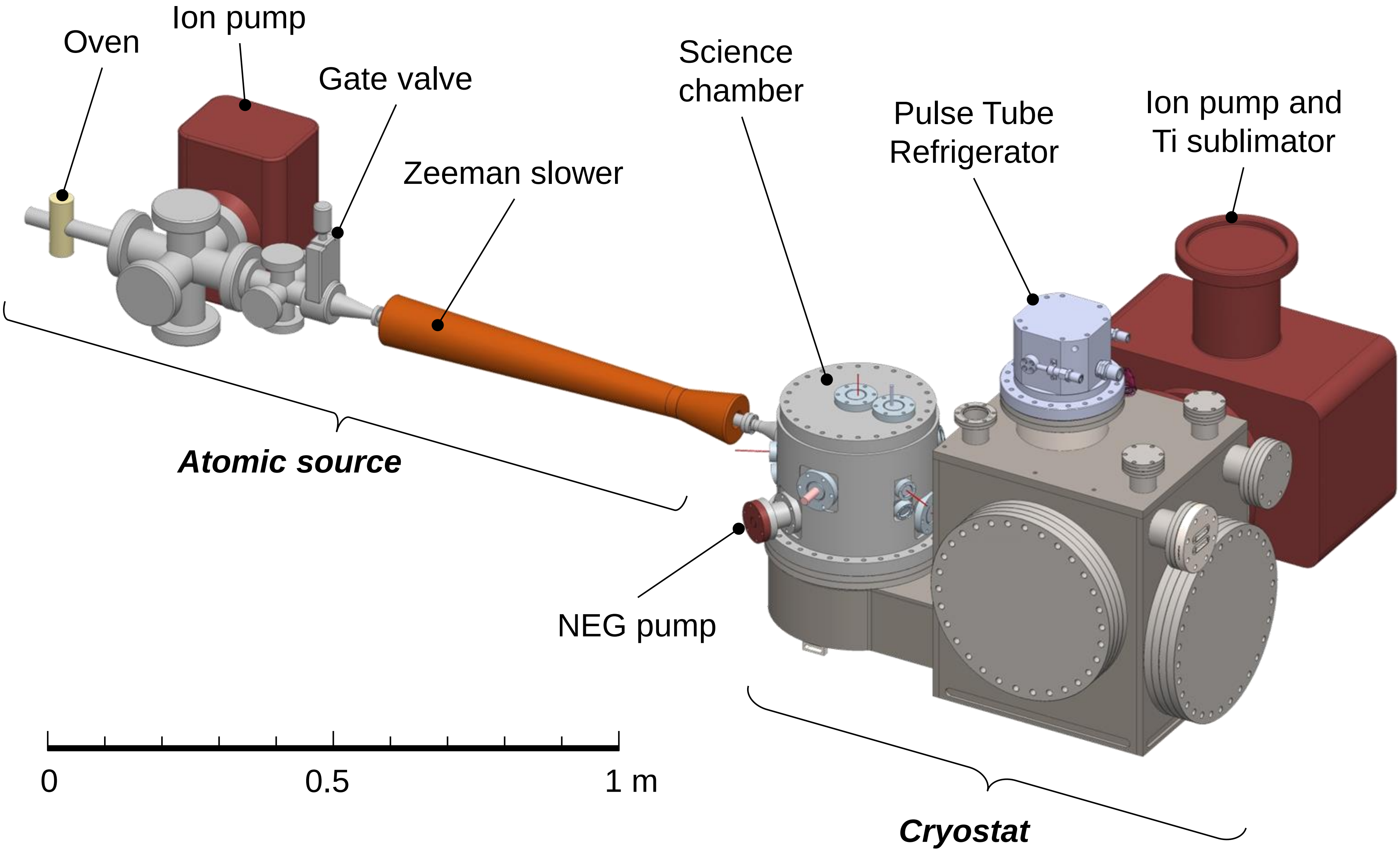
Room-temperature setup at LCF

Commercial closed-cycle optical access cryostat: OptiDry from MyCryoFirm

→ *Basically a UHV-compatible version of OptiDry:*

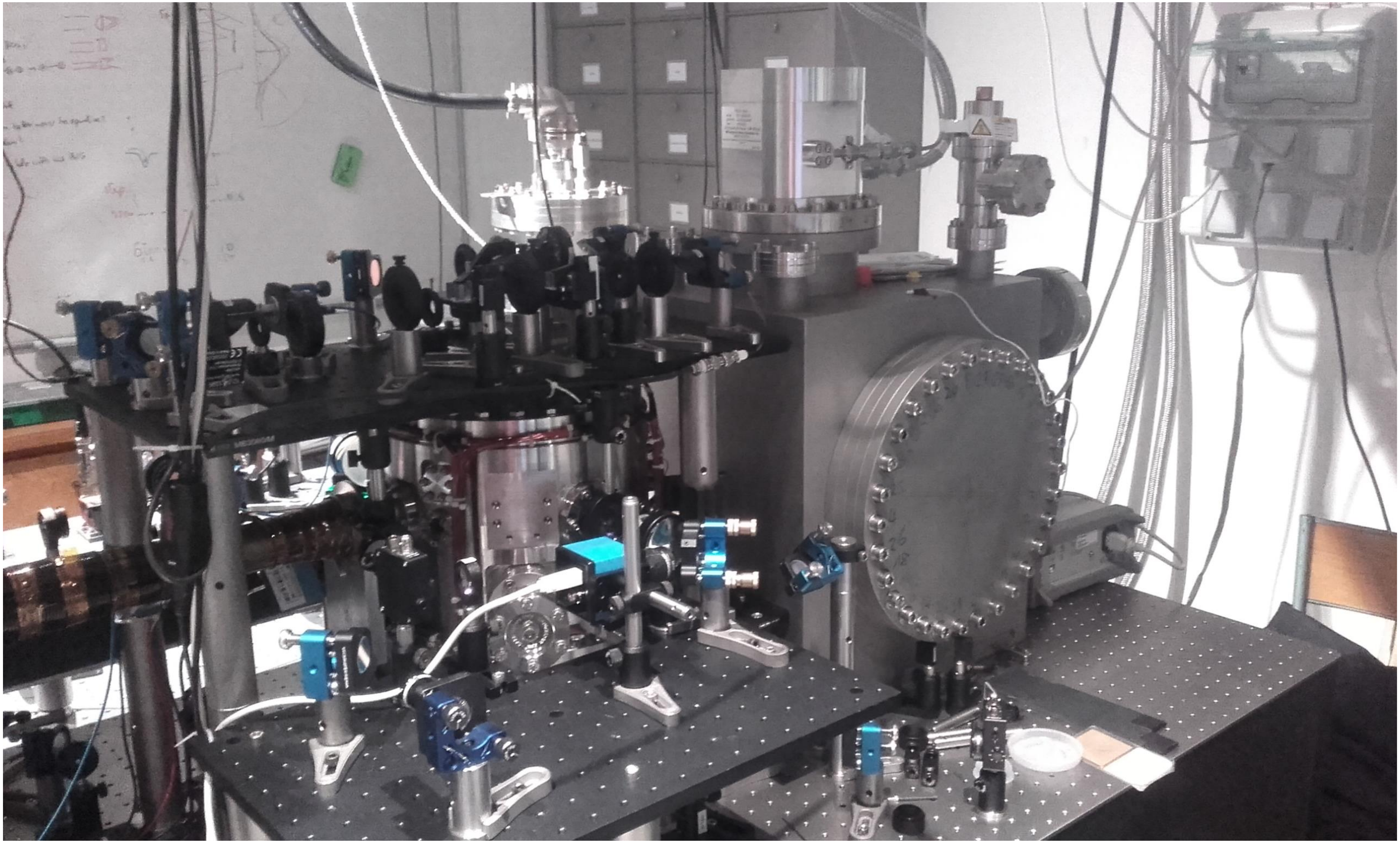
- Only CF vacuum fittings
- No polymers, no adhesives…
- But no bake-out (would require to remove pulse-tube, too complex)

# The merger

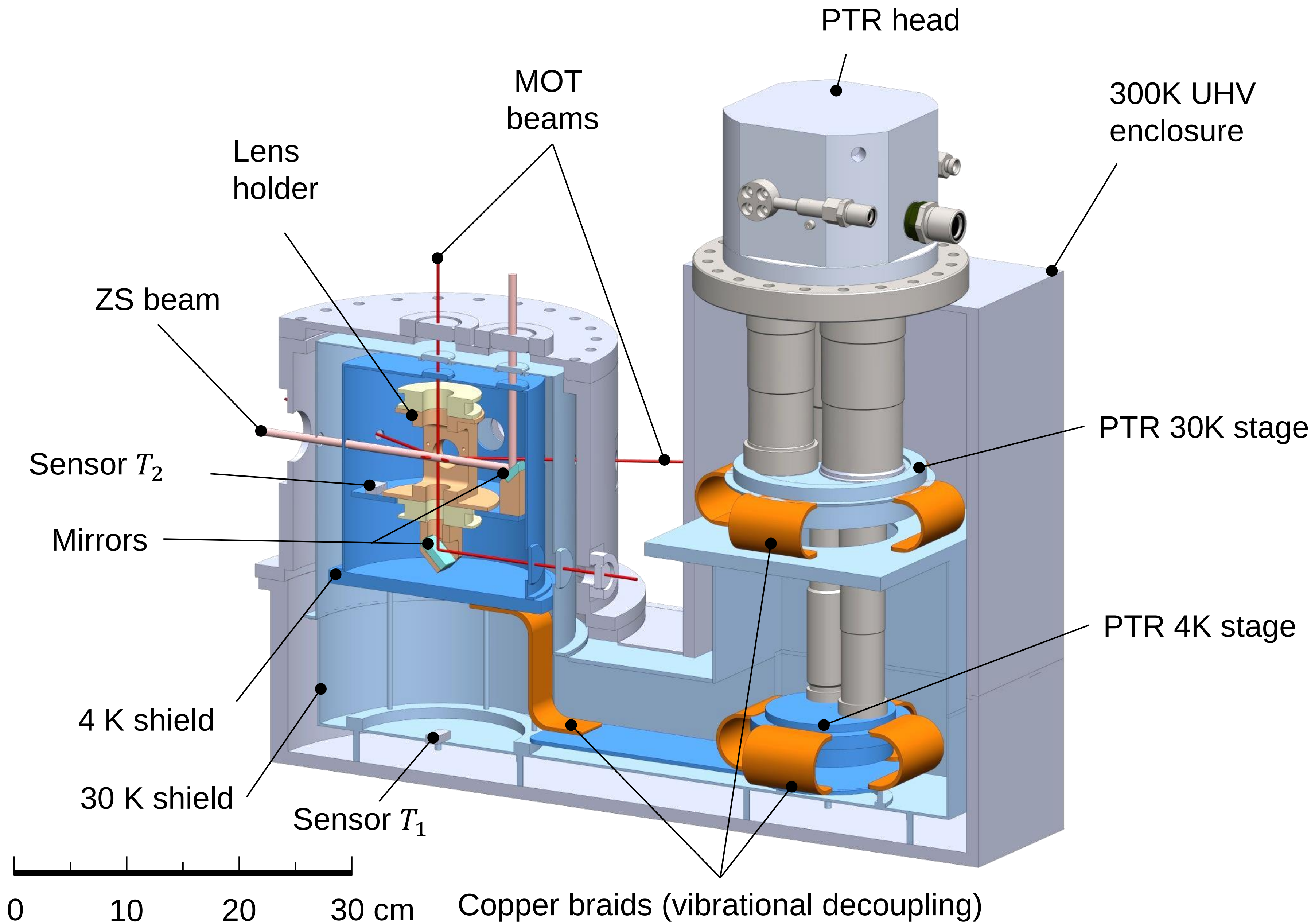


Oven
Ion pump
Gate valve
Zeeman slower
Science chamber
Pulse Tube Refrigerator
Ion pump and Ti sublimator
Atomic source
NEG pump
Cryostat
0
0.5
1 m

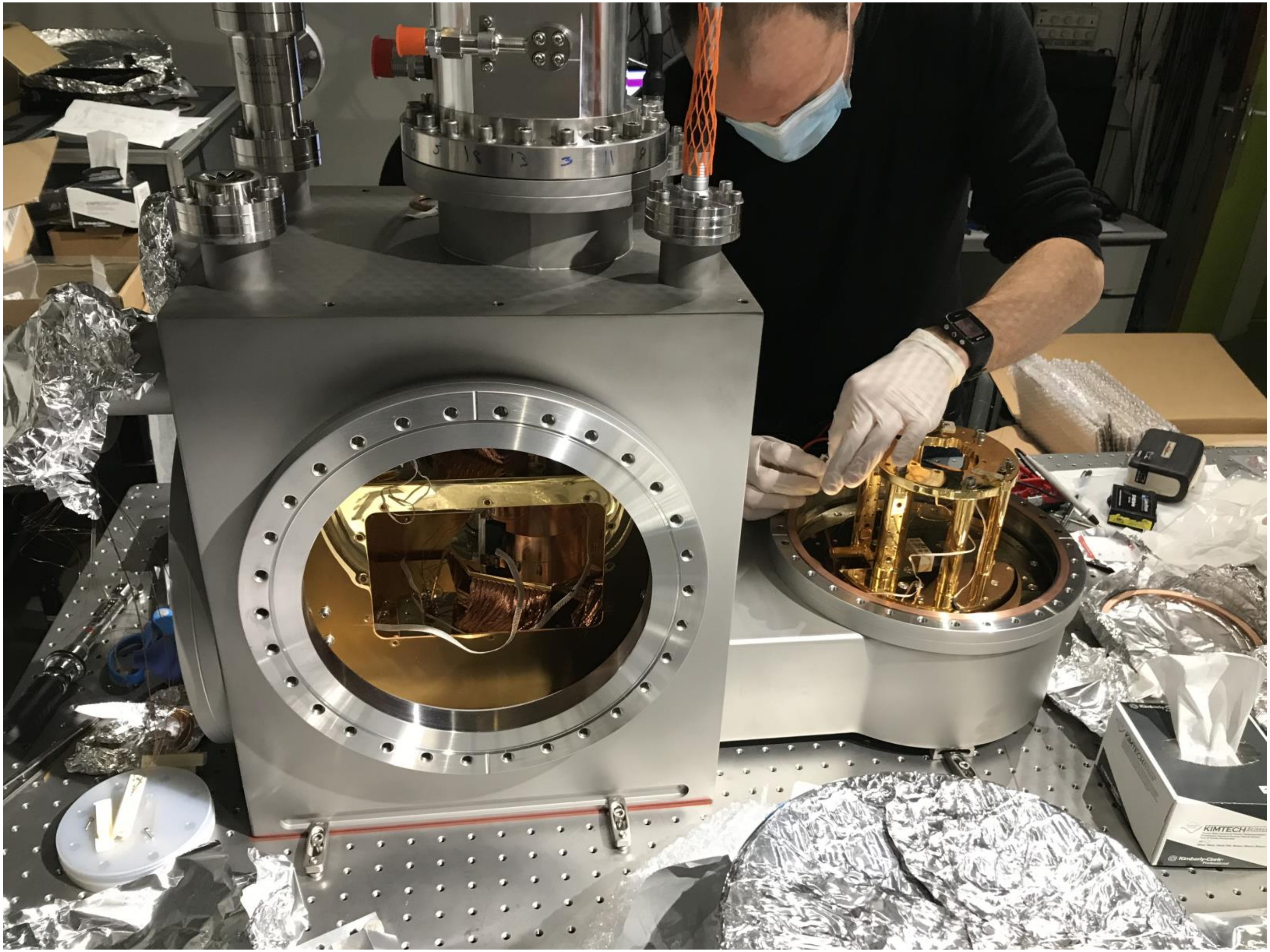
# For real in the lab



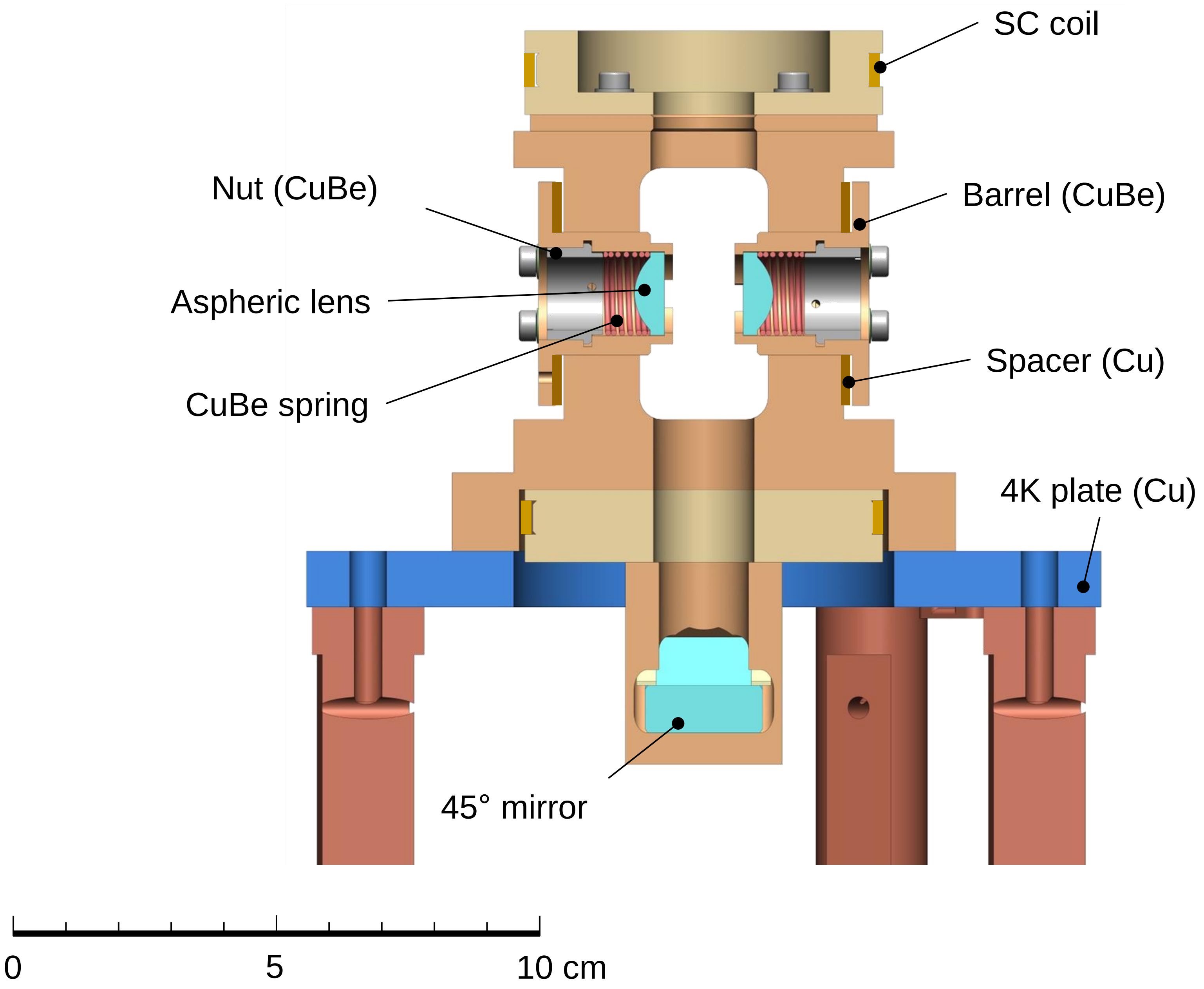
# *The guts of the cryo*



# *The cryostat during assembly*



# *The lens holder*



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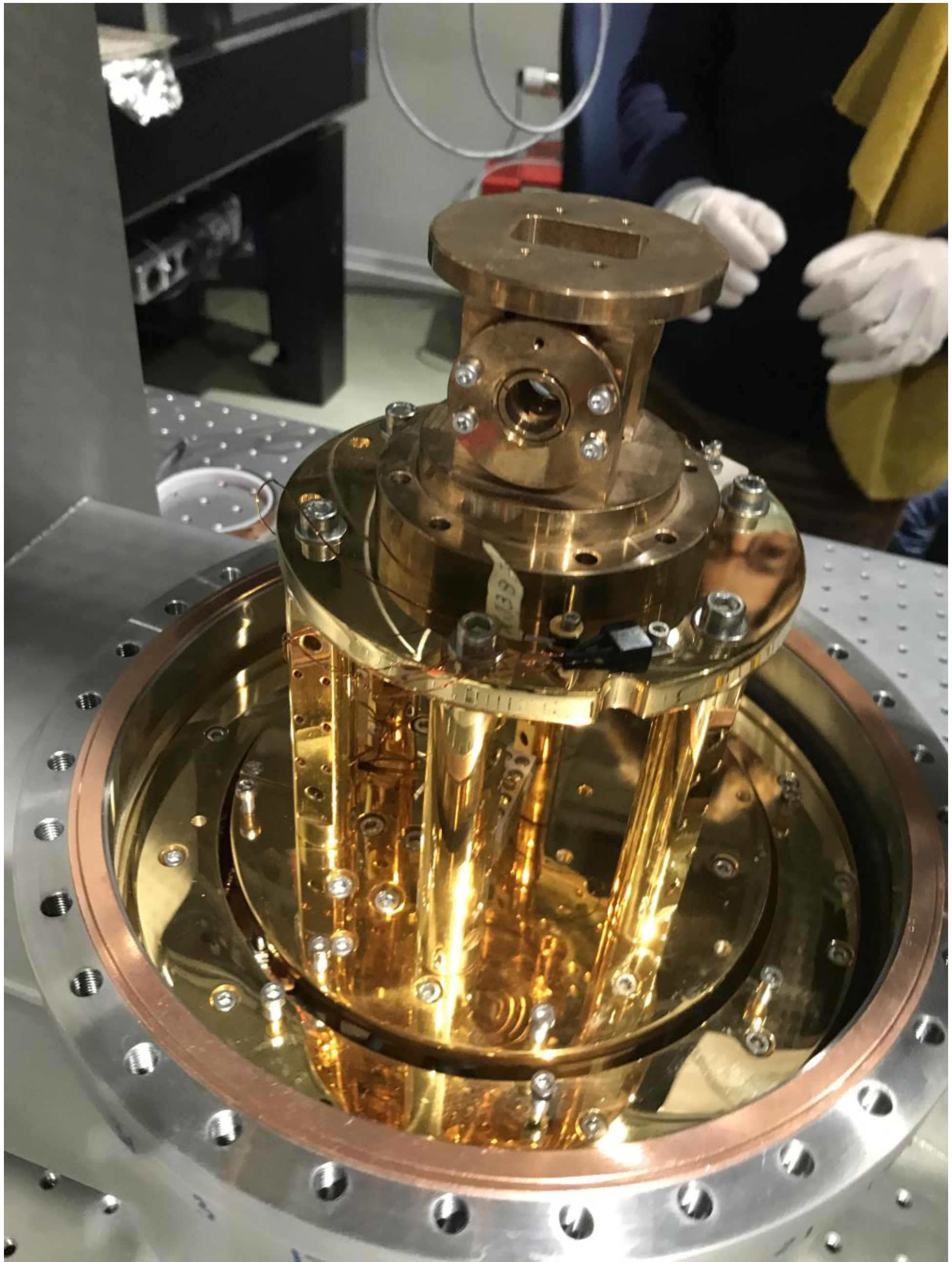


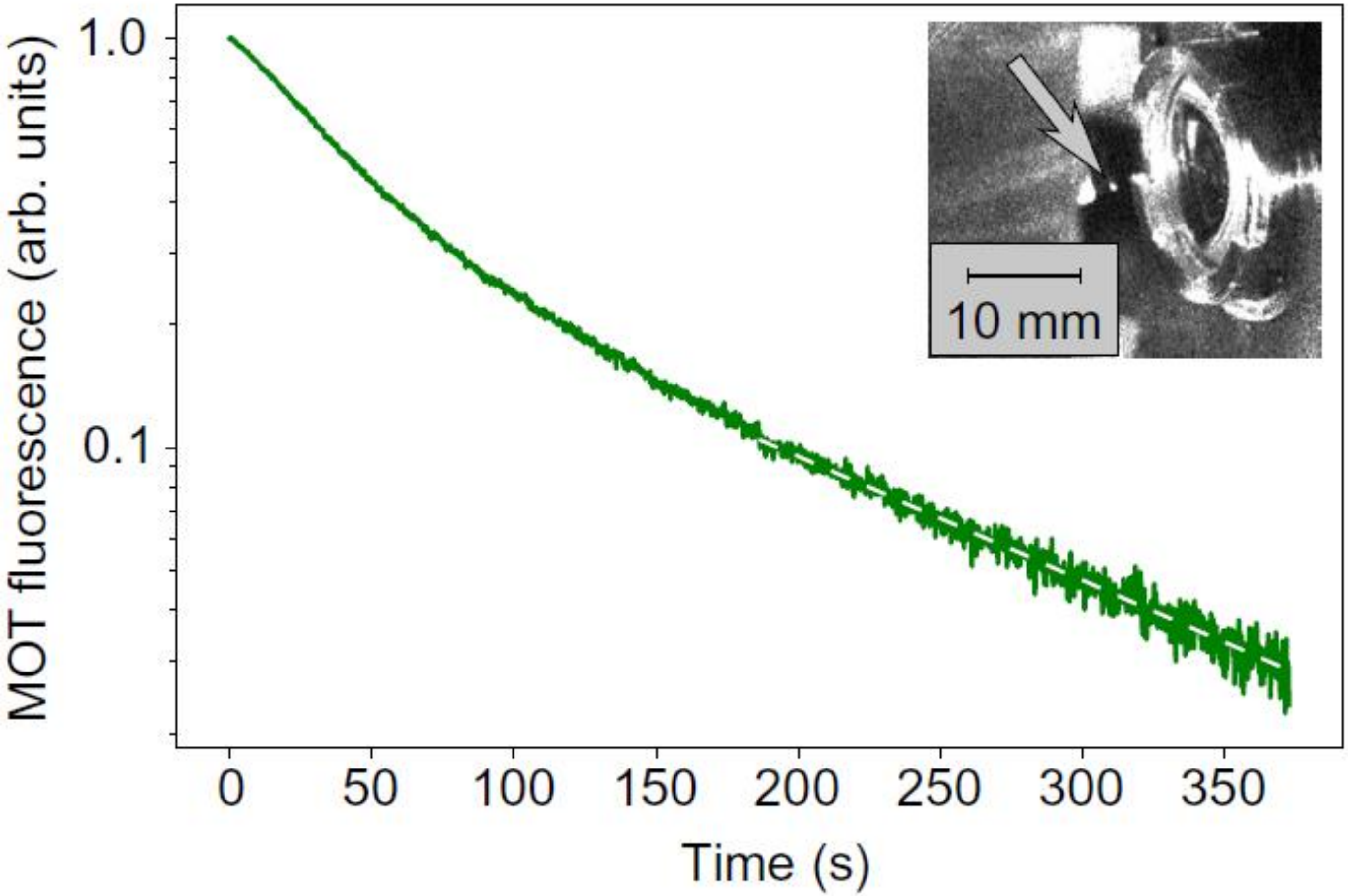
# *Cryostat performance*

- Vibrations at the atoms' position ~ 10 nm r.m.s.
- Temperature increase when applying heat load $\sim 4\ \mathrm{K/W}$

| Test condition | Temperature (K) |
| --- | --- |
| No wiring, windows replaced by Cu plugs | 3.2 |
| No wiring, windows and hole for atomic beam | 3.3 |
| With Cu Wiring for SC coils | 4.2 |
| With 1A current flowing | 4.3 |
| With 1.5 W of trap laser | 5.5 |

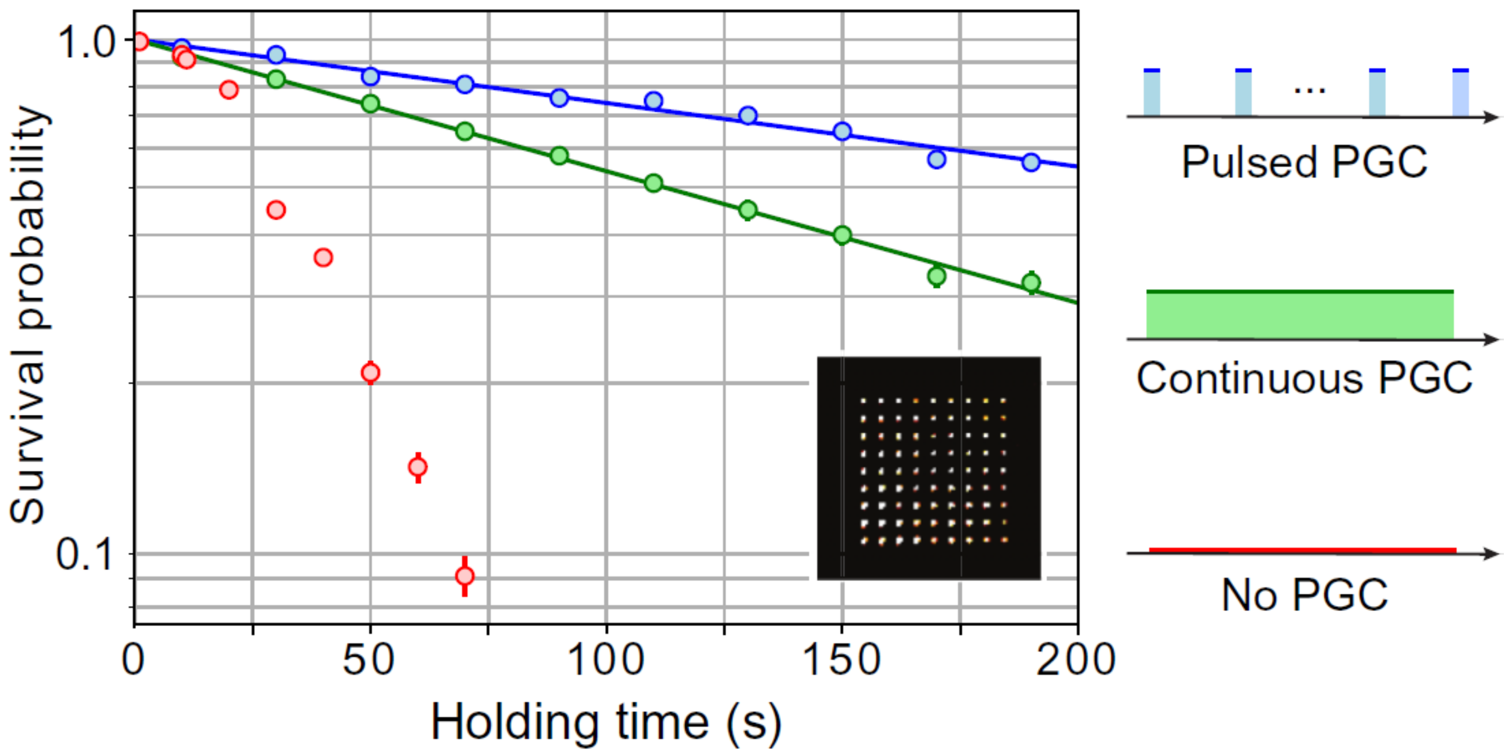
## *2. Cryogenic trapping of single atoms*

# First things first: a MOT



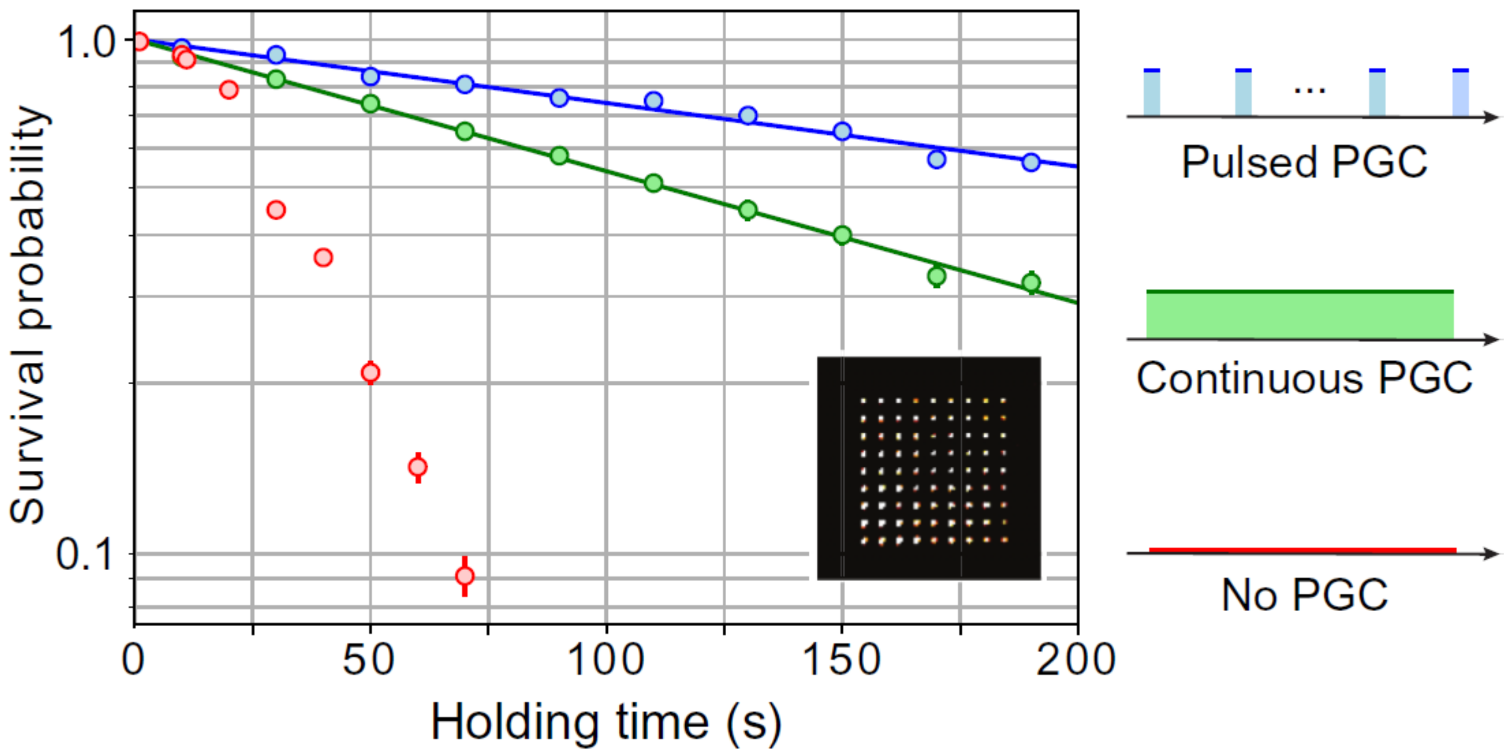

$1/e$ decay time: $\tau = 140\ s$

# *Single atoms in tweezers*




$1/e$ decay time with pulsed PGC: $\tau = 335\ s$

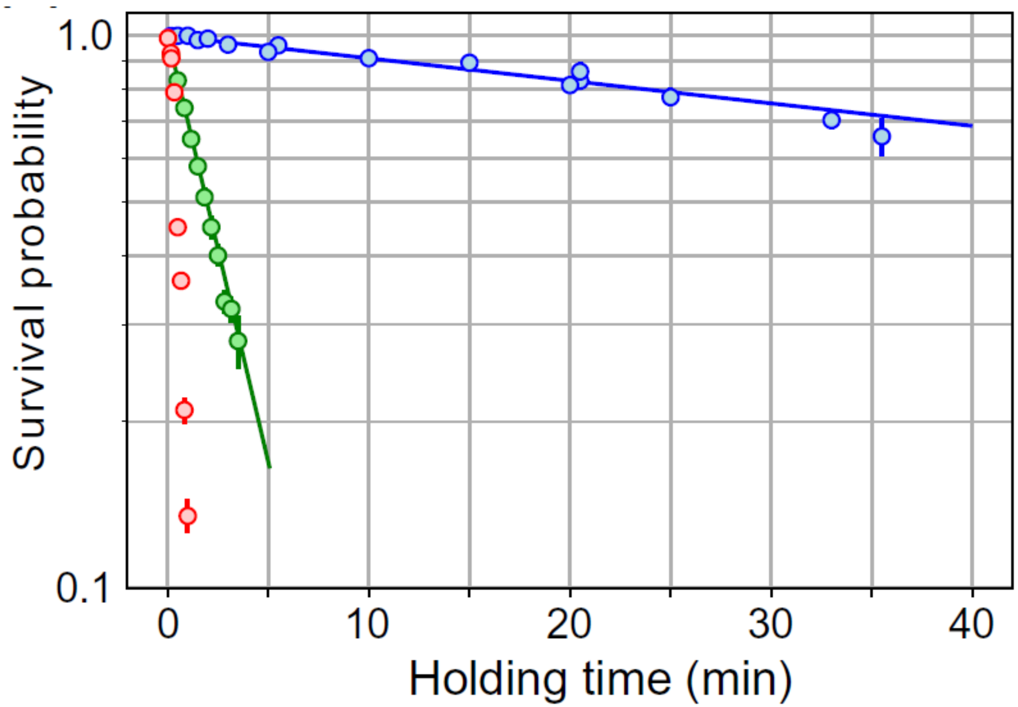
# *Single atoms in tweezers*




$1/e$ decay time with pulsed PGC: $\tau = 335\ \mathrm{s}$

***But there was a (rather big) leak in our ion pump!***

# *After fixing the leak*




$1/e$ decay time with pulsed PGC: $\tau = 6050\ s$

# *Conclusion*

✓ ***Cryogenic arrays of atoms in optical tweezers with 6000 s lifetime***

→ ***Next steps:***

- Large assembled arrays at 4K (270 atoms: done, 350: in progress)
- Rydberg excitation, see Rydberg lifetime increase due to BBR reduction
- Large-scale quantum simulation in 2d and 3d!

***Thanks for your attention!***