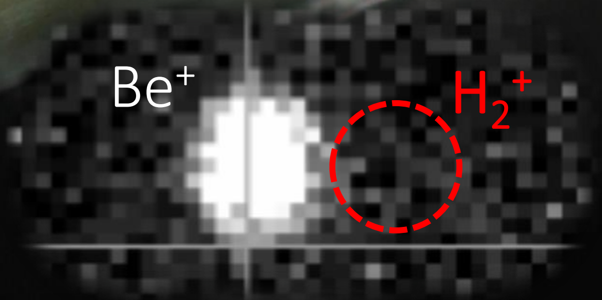
Towards quantum control and spectroscopy of a single hydrogen molecular ion



N. Schwegler, D. Holzapfel, J. P. Home, D. Kienzler

Trapped Ion Quantum Information Group, ETH Zurich

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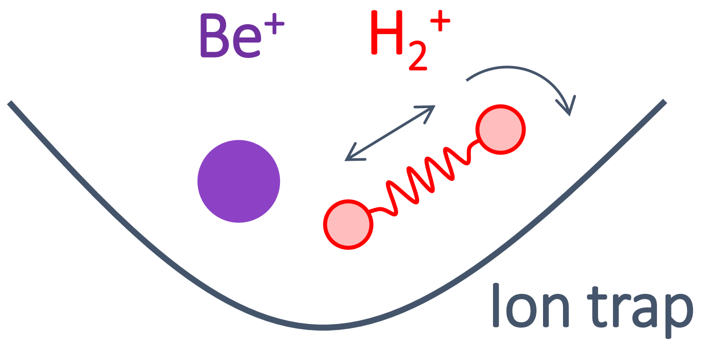
Searching for New Physics at the Quantum Technology Frontier

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

FNSNF

Motivation



- H_2^+: simplest molecule

  Theory H2+, D2+, and HD+ (10^{-12}) : V. I. Korobov et al. 2017 (10.1103/PhysRevLett.118.233001)
- Rotation and vibration give access to fundamental constants …
  - **Proton-to-electron mass ratio** (and its potential drift in time)

    HD^+ ensemble:

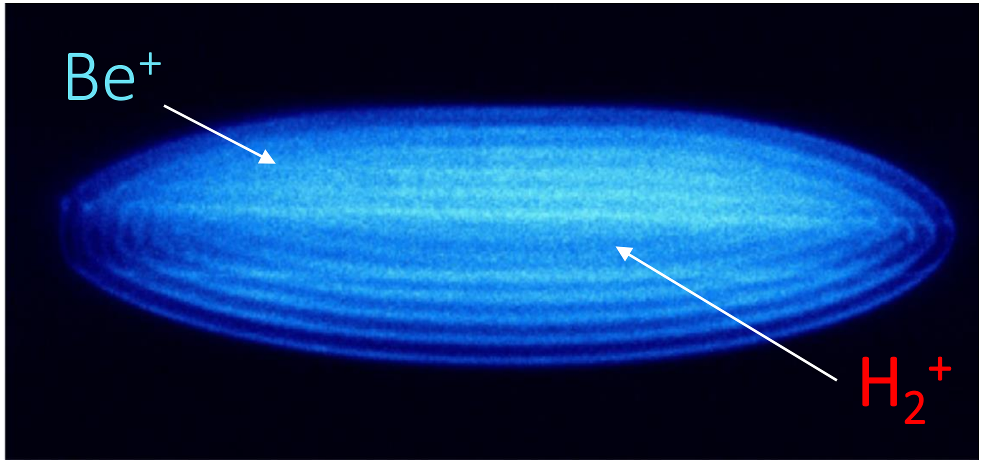
    m_p/m_e (10^{-12})
    - *S. Patra et al. 2020 (10.1126/science.aba0453)*
    - *I. V. Kortunov et al. 2021 (10.1038/s41567-020-01150-7)*
  - **Proton charge radius**
  - **Rydberg constant**

  Measure in same setup with enough transitions

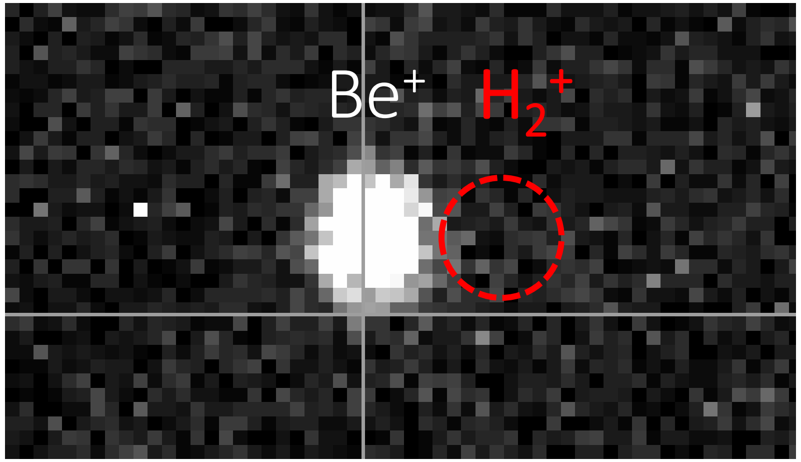
  J.-Ph. Karr et al. 2016 (10.1103/PhysRevA.94.050501)
- … or theory test

  Probing QED, fifth force: e.g. M. Germann et al. 2021 (10.1103/PhysRevResearch.3.L022028)

- Why **single** trapped H2+?
  - clean system
  - lower temperatures suppress Doppler shift
  - reduce negative effects from oscillating trapping potential



H_2^+ ensemble: J. Schmidt et al. 2020 (https://doi.org/10.1103/PhysRevApplied.14.024053)

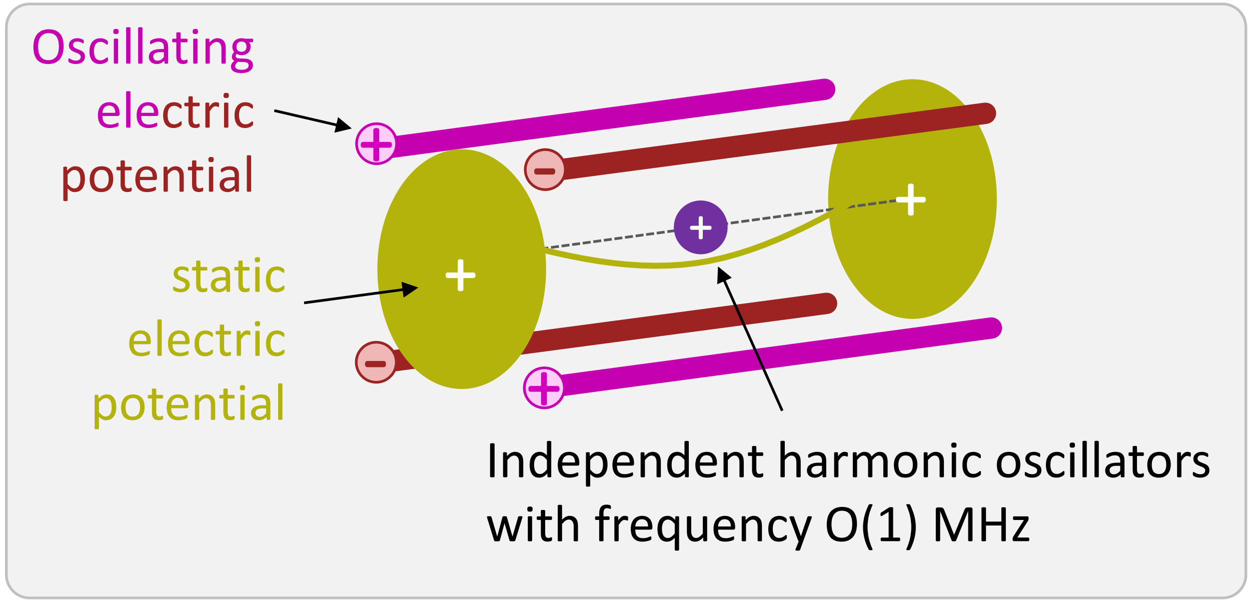


our setup

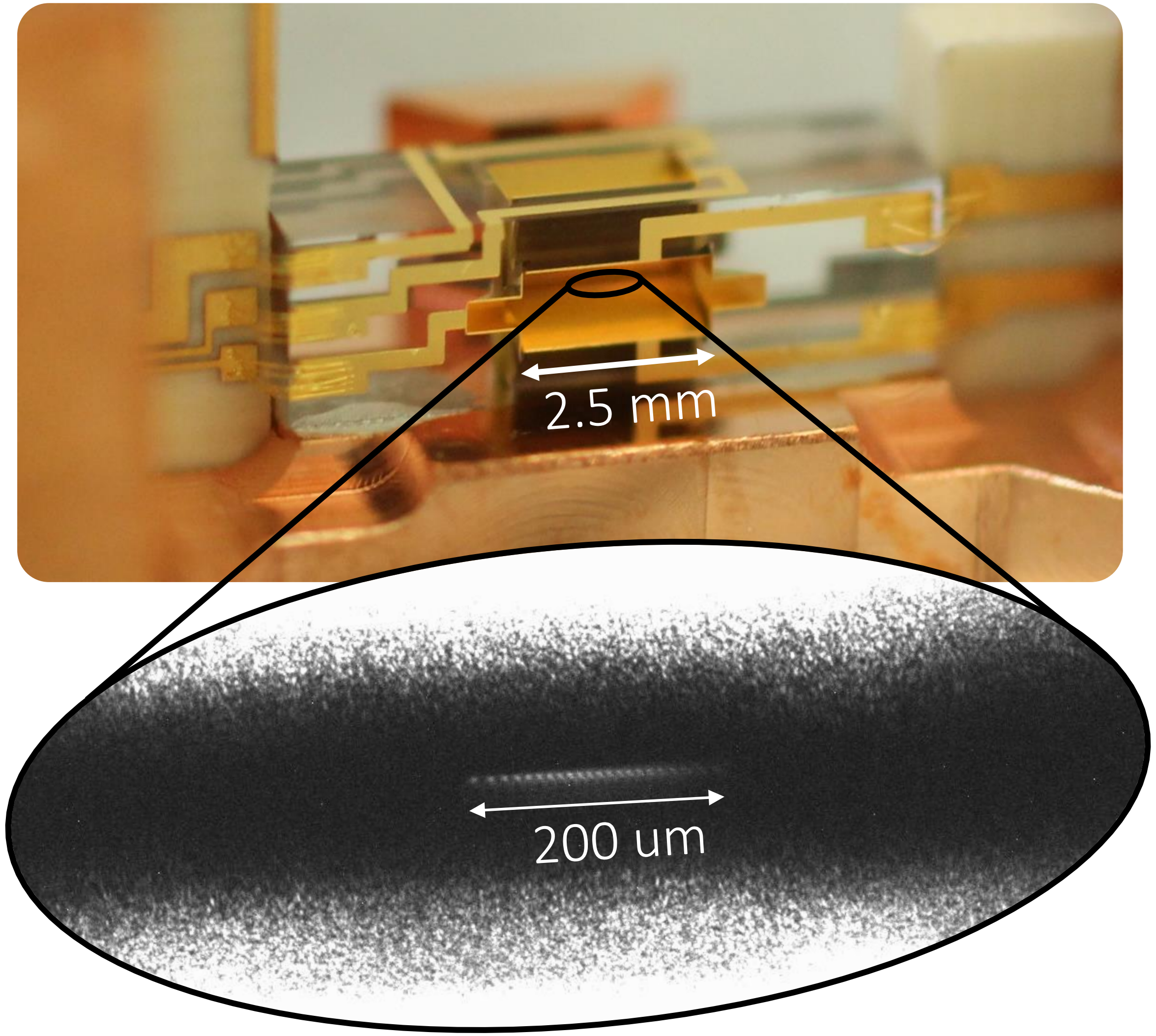
Single HD+: Ch. Wellers et al. 2021 (10.1080/00268976.2021.2001599)

Ion trap

Linear Paul trap



High-precision micro-fabricated ion trap

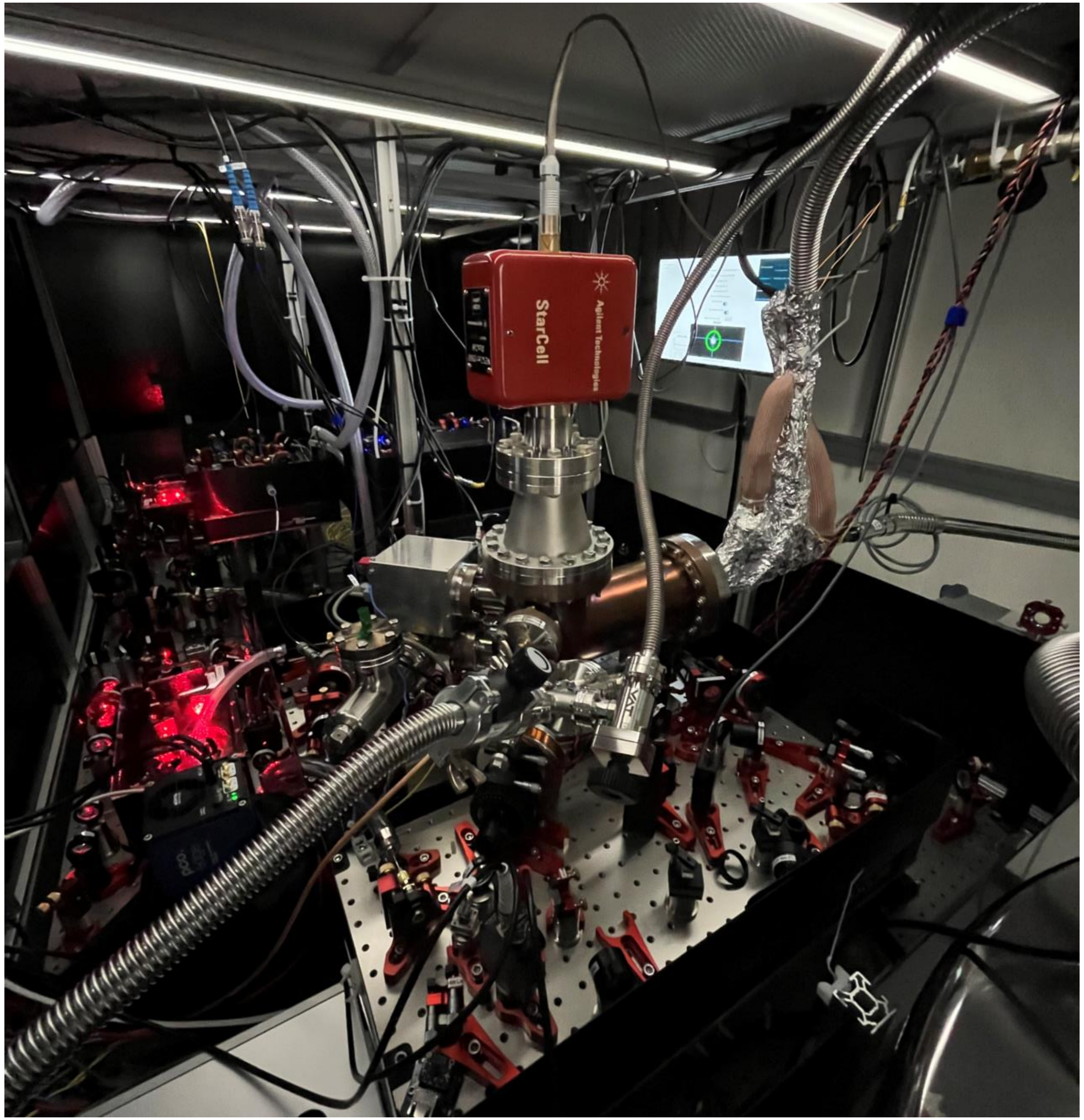


- “tabletop” experiment (~few m^3)
- subgroup of *Trapped Ion Quantum Information* group:
  - ➢ Benefit from knowhow (complex control system, trap fabrication, cryostat, shared lasers, …)

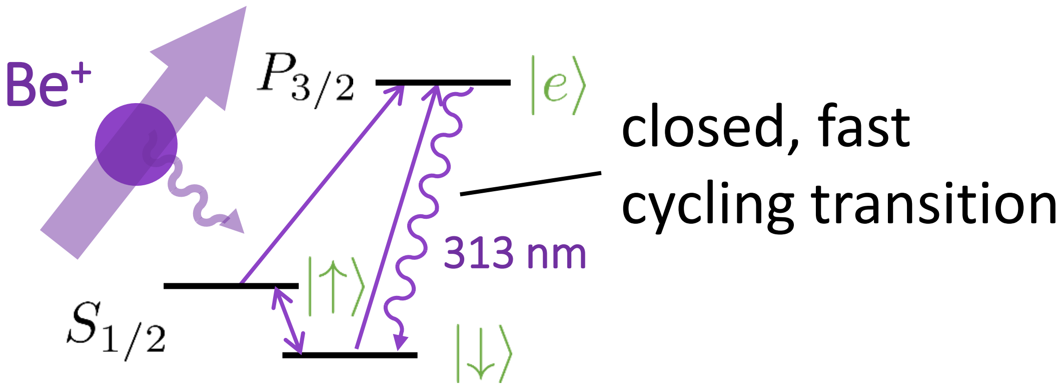
- Challenge: Reactions with background gas limit lifetime:

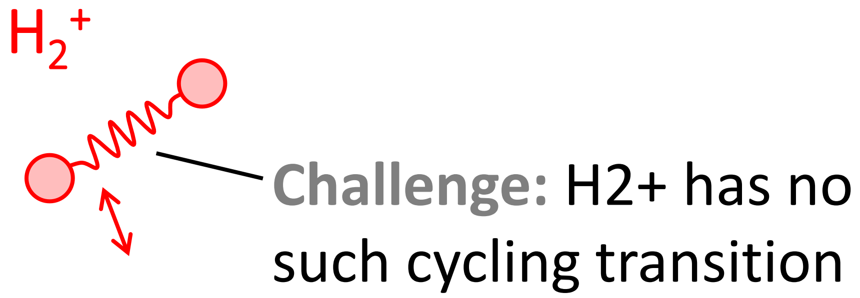
$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

- ➢ Ultra-High-Vacuum chamber
- ➢ trap cooled to ~10 K with liquid helium flow cryostat



Quantum control





- ✓ 1. laser cool ion motion
- ✓ 2. electronic state preparation
- ✓ 3. state-dependent fluorescence readout
- ✓ 4. coherent control

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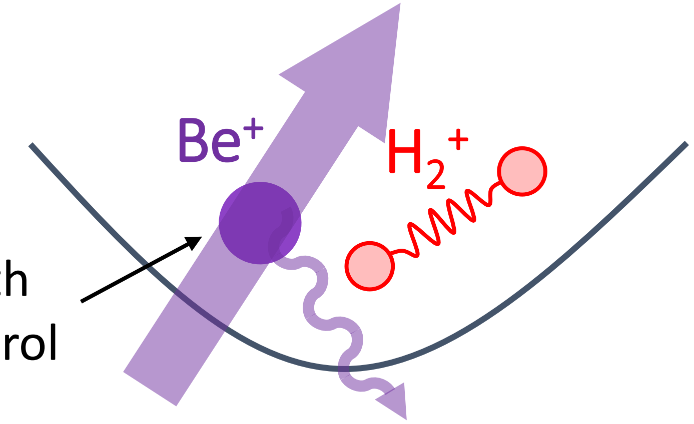
➢ **Solution**: Co-trap Be+ and H2+

Quantum control

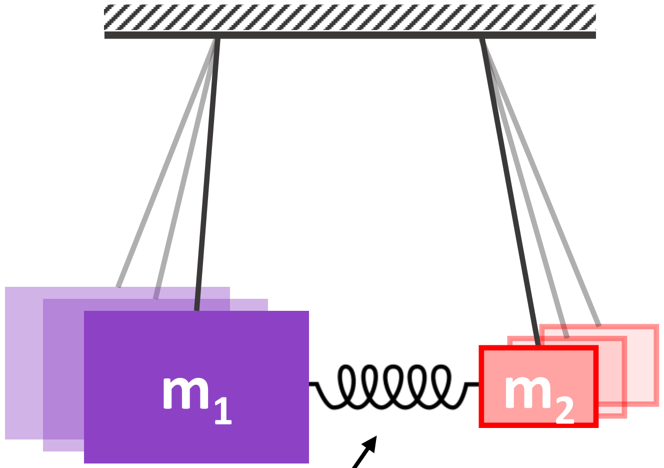
Two ion crystal

lightest ion with
high-level control



1. sympathetic cooling of translational motion (groundstate)

Model: Coupled harmonic oscillator

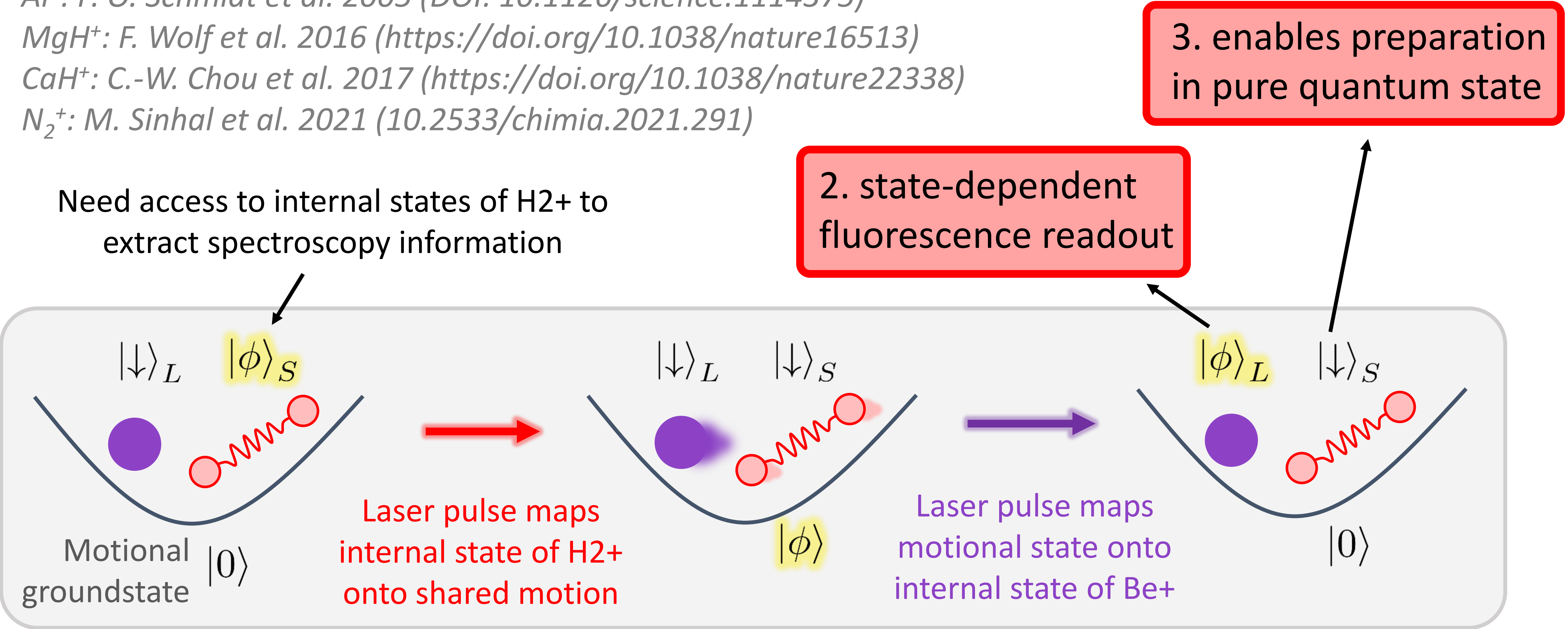


Coupling extends quantum control from Be+ to H2+

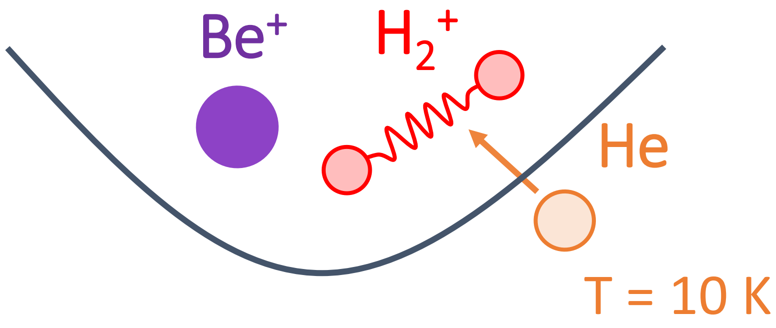
Readout and state preparation using "quantum logic spectroscopy":

- non-destructive (keep H2+)
- Quantum Non-Demolition (QND) measurement.

Al^+: P. O. Schmidt et al. 2005 (DOI: 10.1126/science.1114375)
MgH^+: F. Wolf et al. 2016 (https://doi.org/10.1038/nature16513)
CaH^+: C.-W. Chou et al. 2017 (https://doi.org/10.1038/nature22338)
N_2^+: M. Sinhal et al. 2021 (10.2533/chimia.2021.291)



Proposed experiment sequence



slow (O(10) minutes),
do once

proposed by S. Schiller et al. 2017
(https://doi.org/10.1103/PhysRevA.95.043411)

1. Co-trap Be+ and H2+
2. Helium buffer gas cools H2+ to rovibrational groundstate
3. Prepare H2+ in pure quantum state (hyperfine level)
4. Do spectroscopy experiments

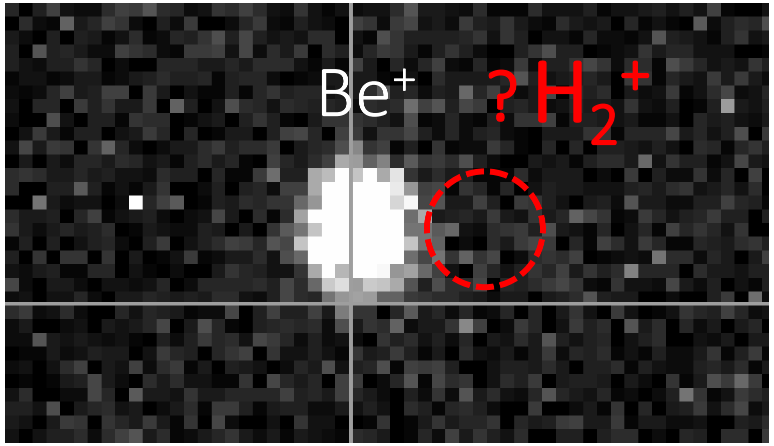
"Quantum Logic Spectroscopy"
Fast, do many times to gather statistics:
1 shot = 1 bit = 1 probe time (e.g. for 10 ms for 100 Hz linewidth) + ~20 ms overhead

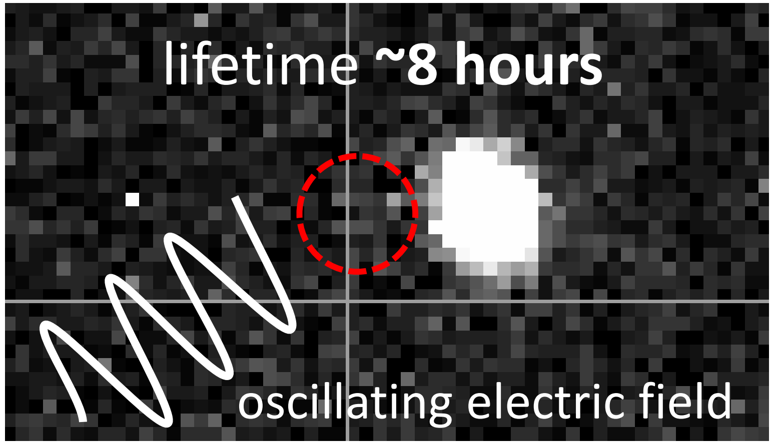
convenient to have non-destructive readout and long lifetimes

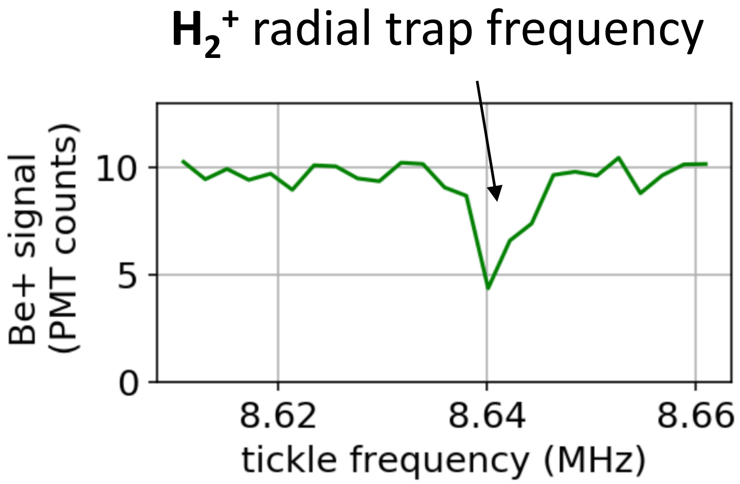
Current state

- Load Be+ (photo-ionization laser) and Be+ control
- Load H2+ (electron impact ionization)
- Implementing control over H2+ (cool to motional groundstate, first steps towards quantum logic spectroscopy and buffer gas cooling)

➢ **First goal: microwave spectroscopy of the hyperfine sub-levels of H2+ prepared in rovibrational groundstate**

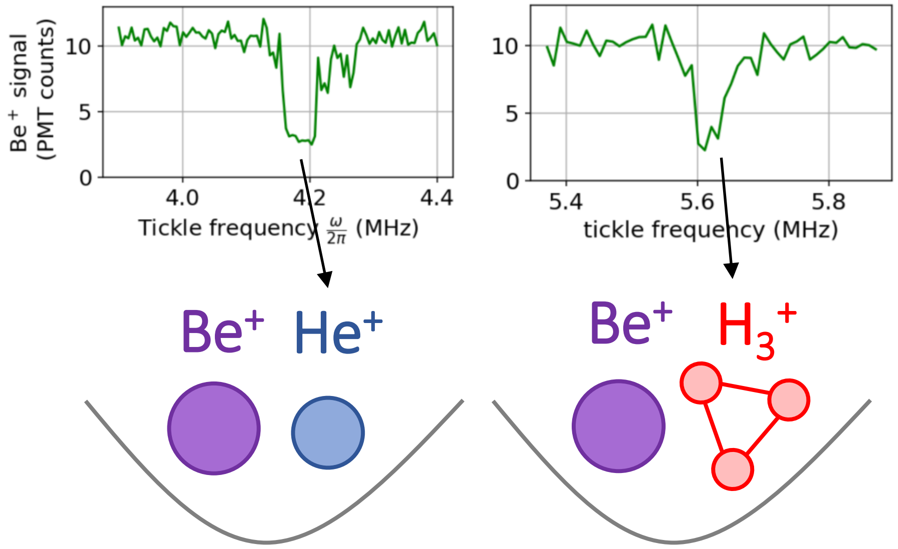




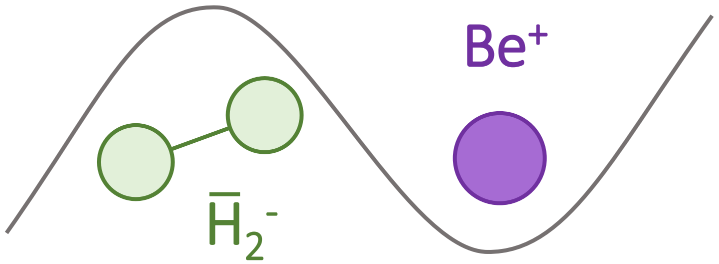


Future possibilities / dreams

- Apparatus and techniques applicable to other light (molecular) ions.



- Comparison matter vs. anti-matter: quantum logic spectroscopy with anti-H2-

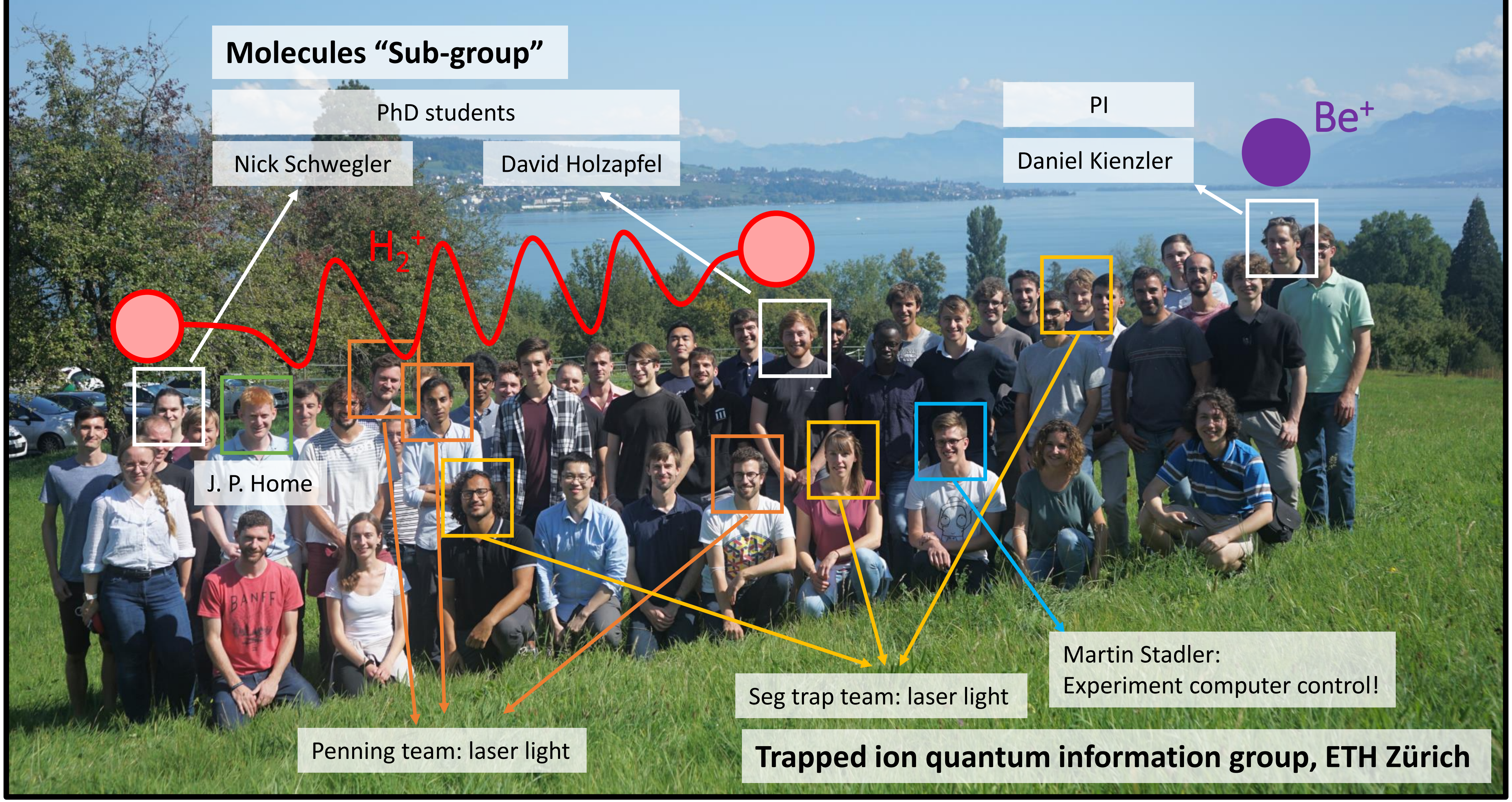


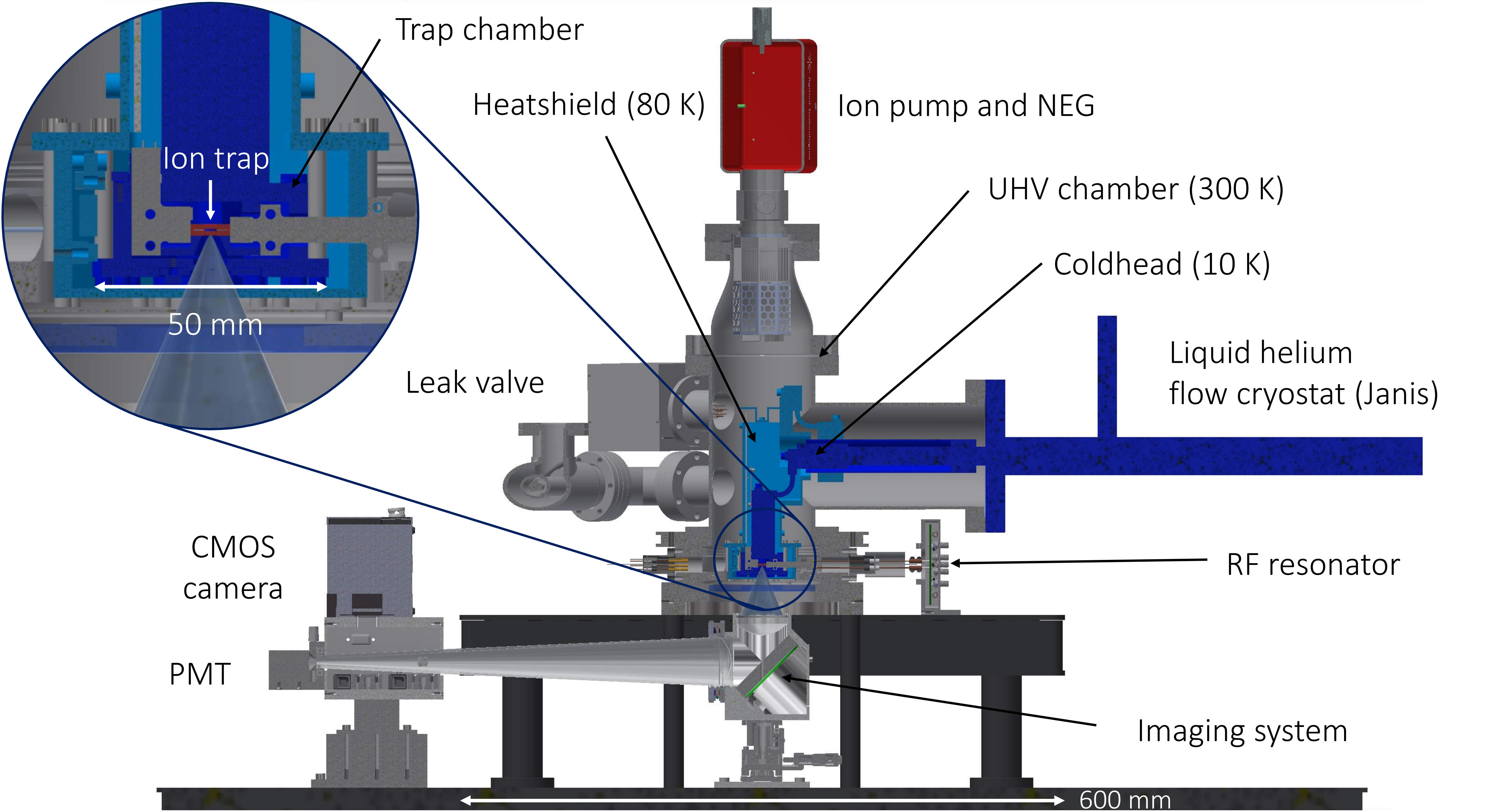
modifications to the trap required to co-trap positive and negative charges.

Team

FNSNF

ETH zürich

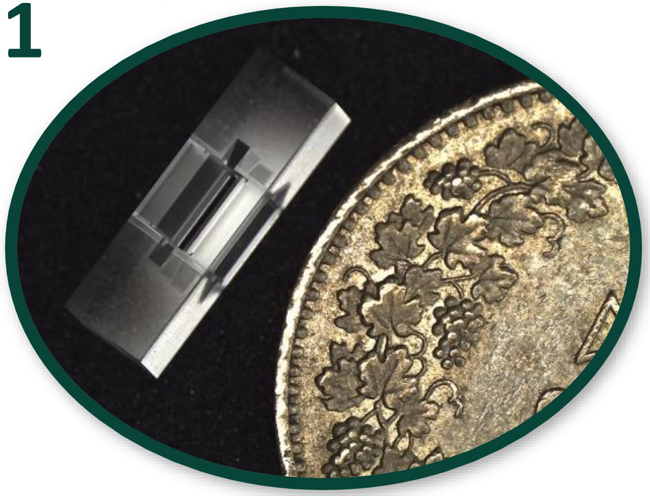




Trap chamber
Heatshield (80 K)
Ion pump and NEG
Ion trap
50 mm
UHV chamber (300 K)
Coldhead (10 K)
Liquid helium
flow cryostat (Janis)
Leak valve
CMOS
camera
RF resonator
PMT
Imaging system
600 mm

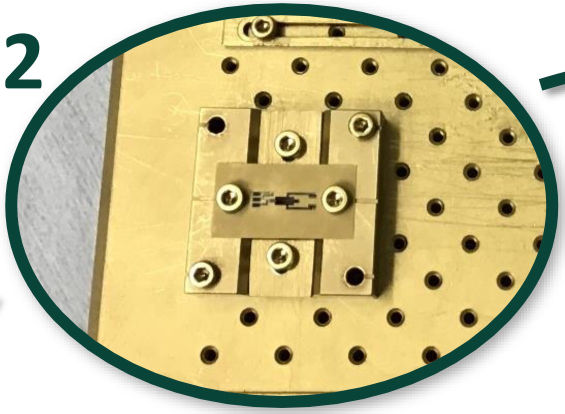
Trap Fabrication in 4 steps

1



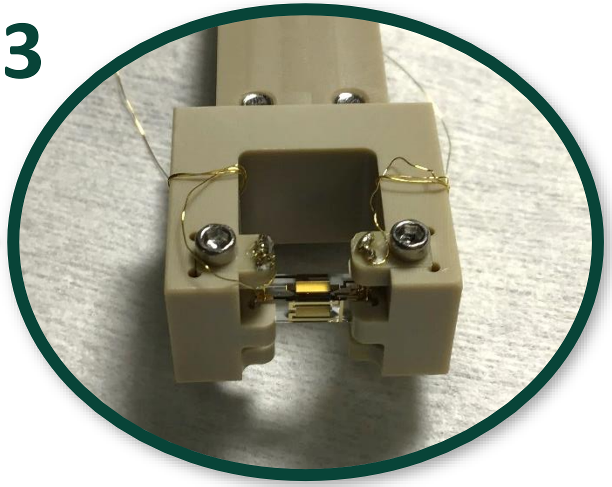
Femtoprint sample

2



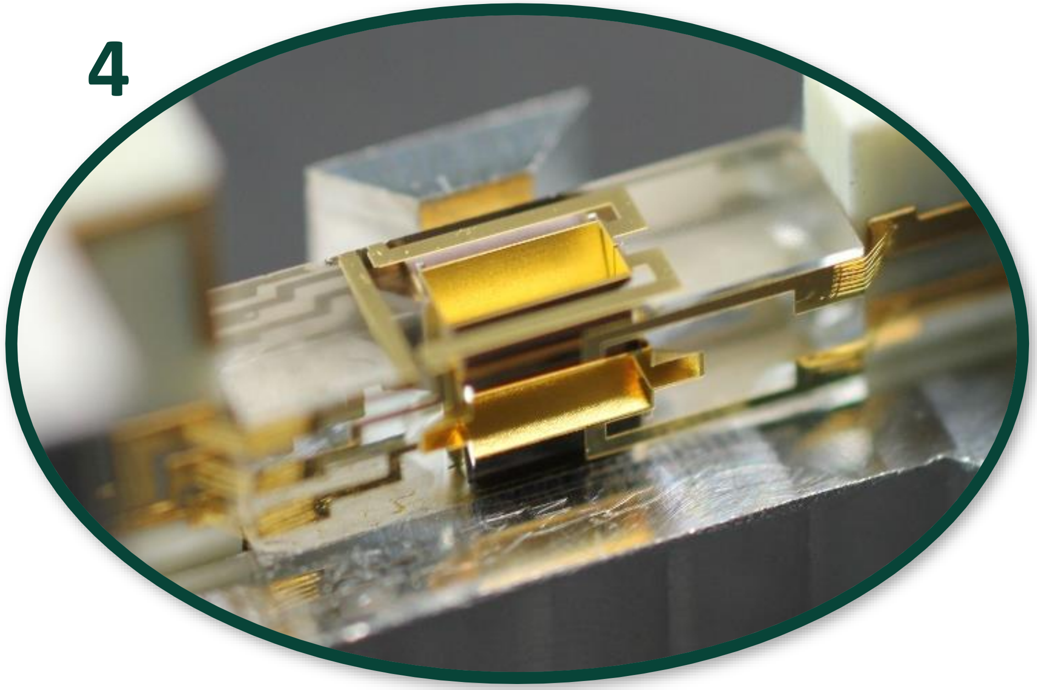
Electron beam evaporation of gold (100 nm)

3



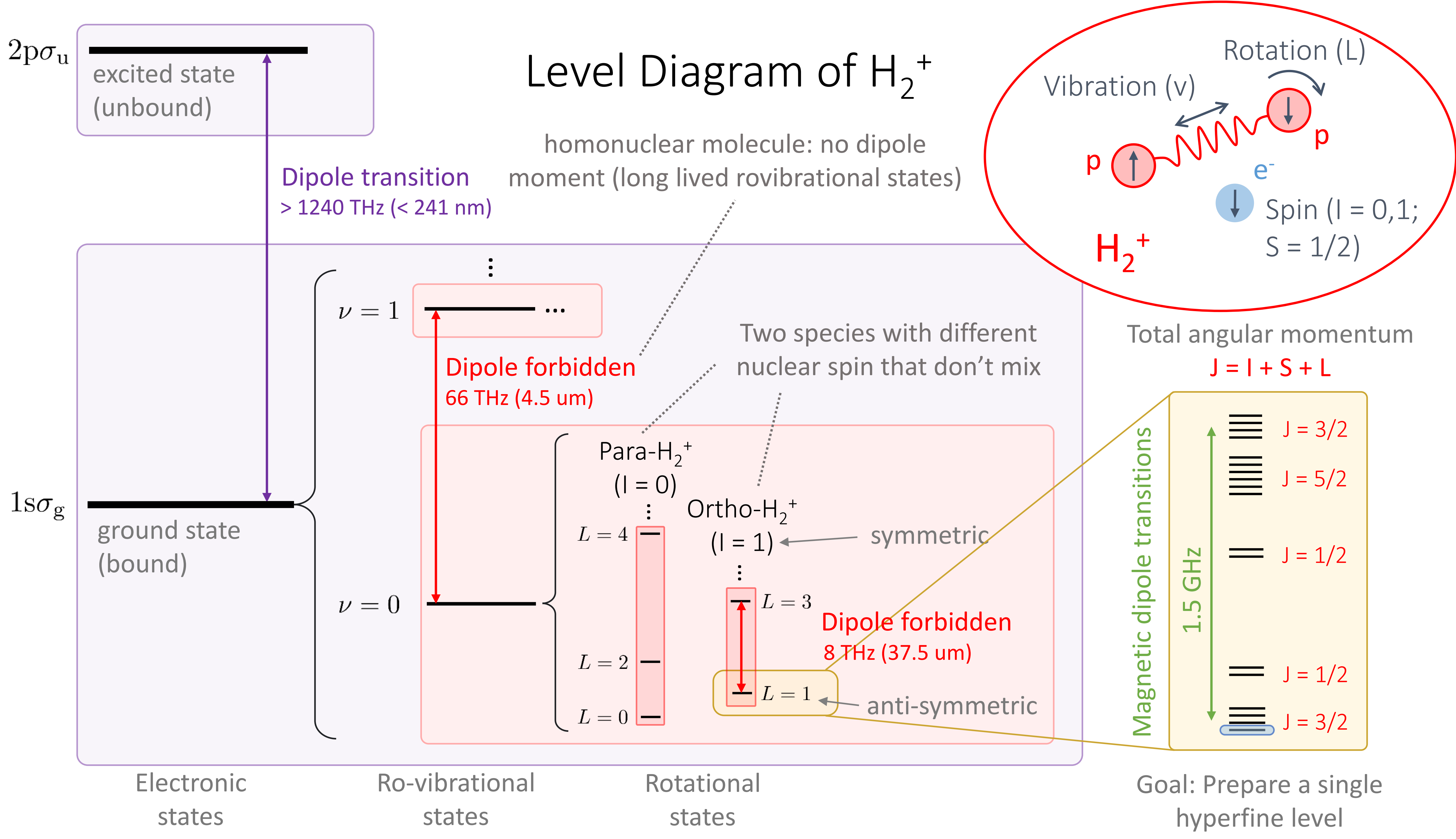
Gold electroplating (5 um)

4

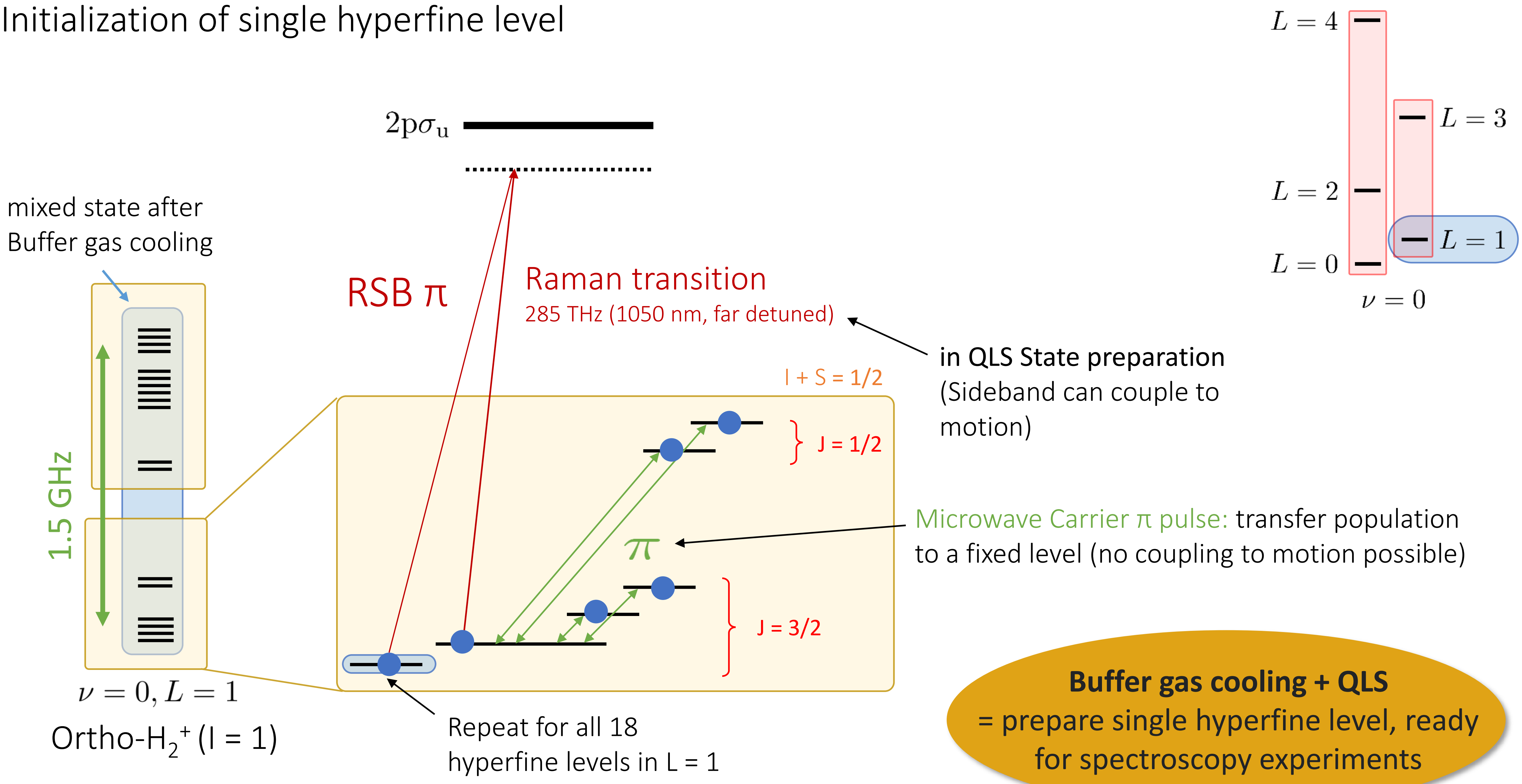


Glue trap and wirebond

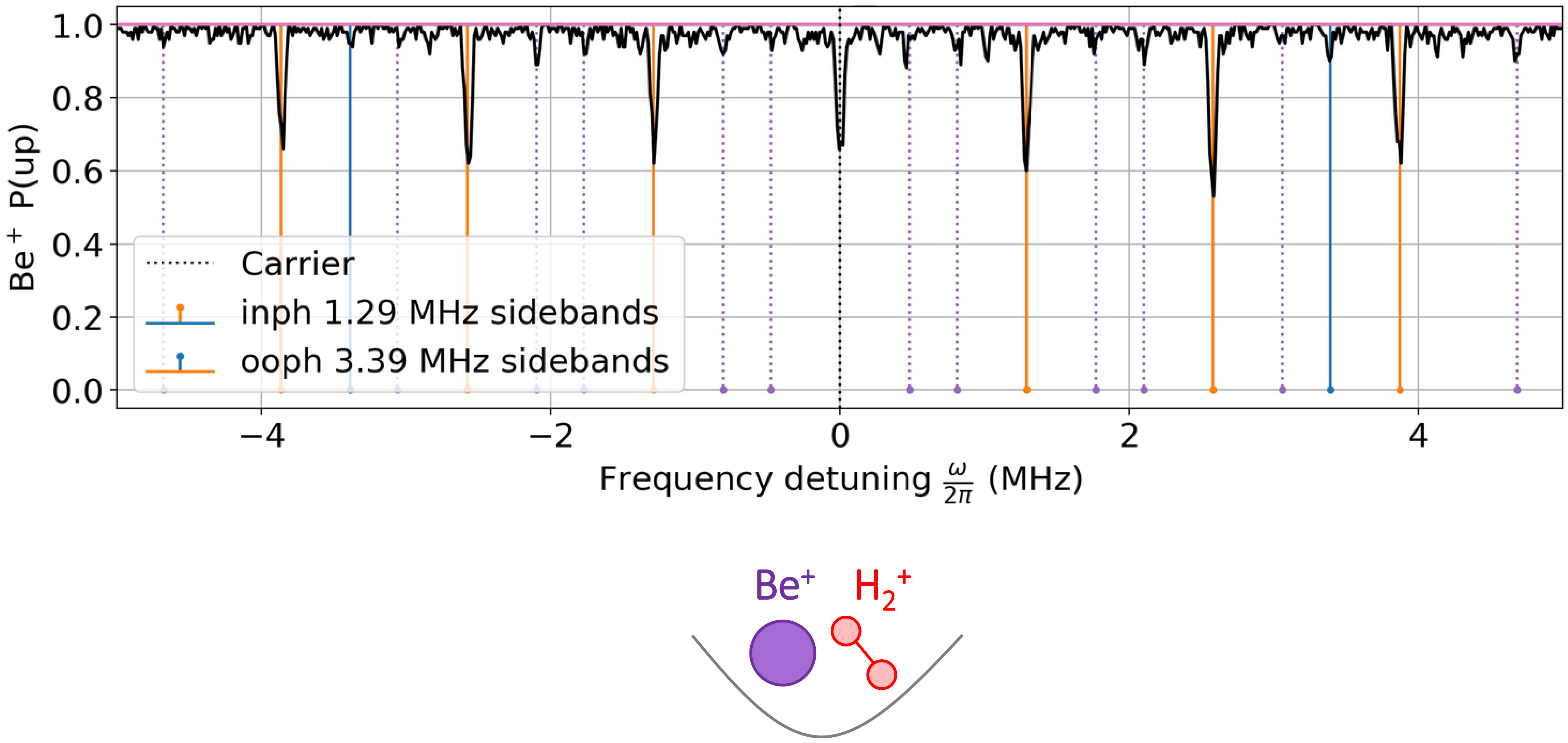
Level Diagram of H_2^+



Initialization of single hyperfine level



Buffer gas cooling + QLS
= prepare single hyperfine level, ready
for spectroscopy experiments



1.0
0.8
0.6
0.4
0.2
0.0
Be$^+$ P(up)
−4
−2
0
2
4
Frequency detuning $\frac{\omega}{2\pi}$ (MHz)
Carrier
inph 1.29 MHz sidebands
ooph 3.39 MHz sidebands
Be$^+$
H_2^+