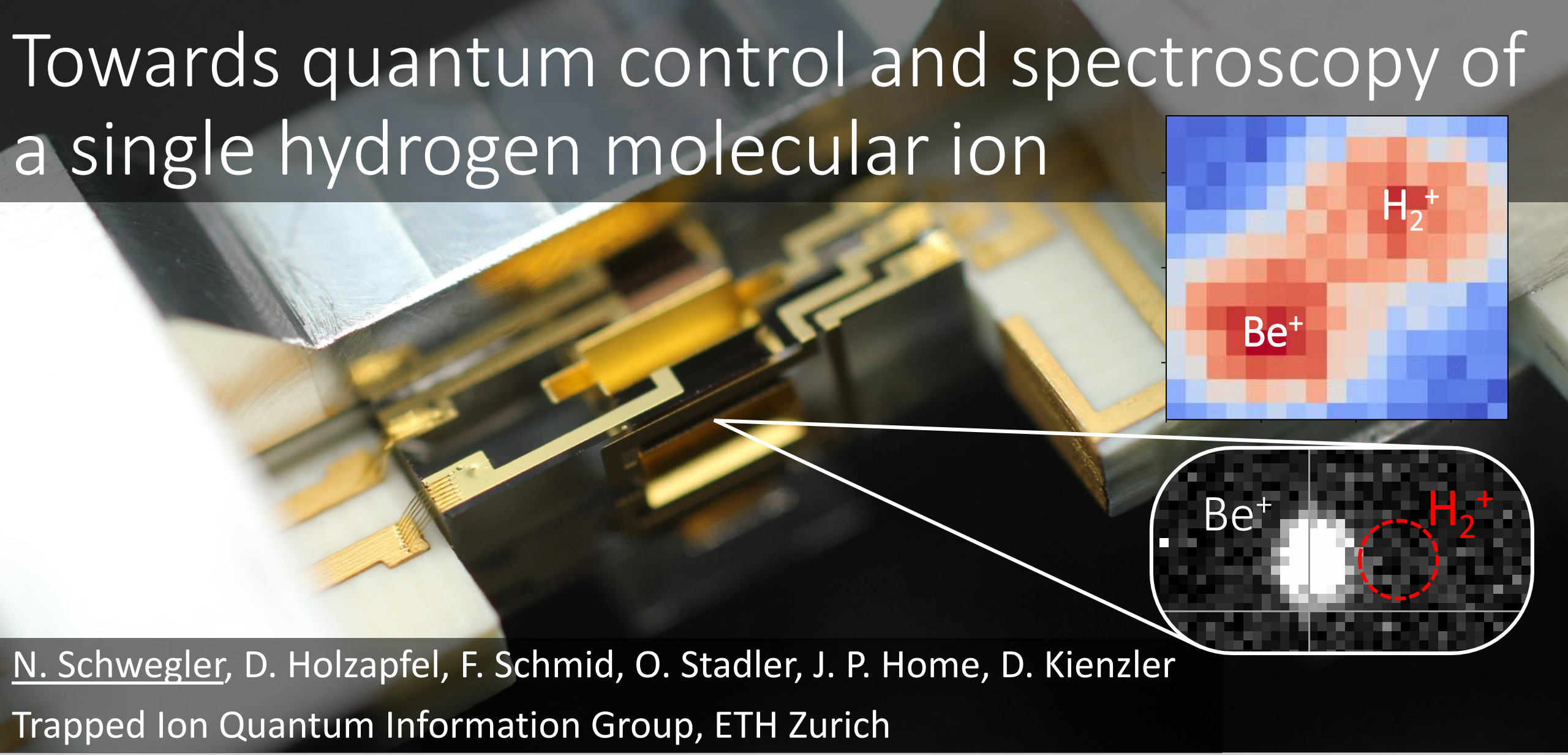
Towards quantum control and spectroscopy of a single hydrogen molecular ion



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Eidgenössische Technische Hochschule Zürich
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04.07.2023

Searching for New Physics at the Quantum Technology Frontier

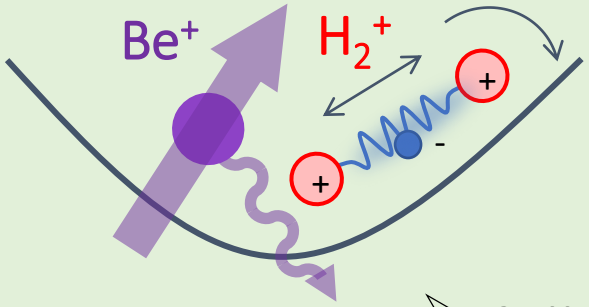
Motivation

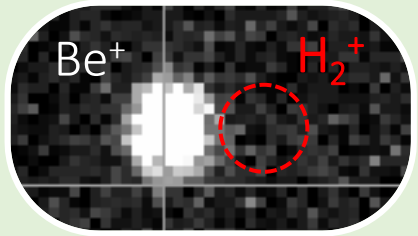
H_2^+ simplest (stable) molecule:

- ab-initio theory [1]
- fundamental constants (proton-electron mass ratio, proton charge radius, Rydberg constant) [2]

[1] V. I. Korobov et al. 2017 (DOI: 10.1103/PhysRevLett.118.233001)
[2] J.-P. Karr et al. 2016 (DOI: 10.1088/1742-6596/723/1/012048)

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





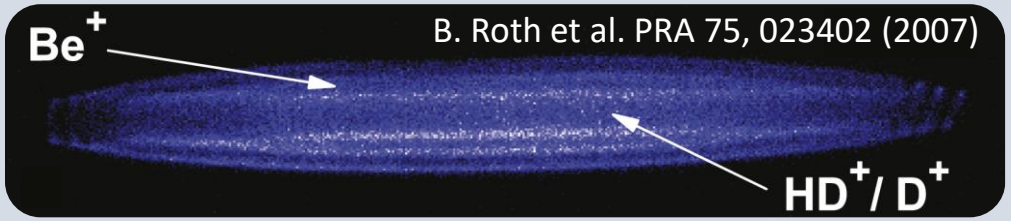
- sympathetic **cooling**
- non-destructive **readout**
- **state-preparation**

$\Delta f/f \sim 10^{-17}$

S. Schiller et al. Phys. Rev. Lett. 113, 023004 (2014)
J.-P. Karr et al. J. Phys. Conf. Ser. 723 012048 (2016)

HD^+ Ensembles

$\Delta f/f \sim 10^{-12}$



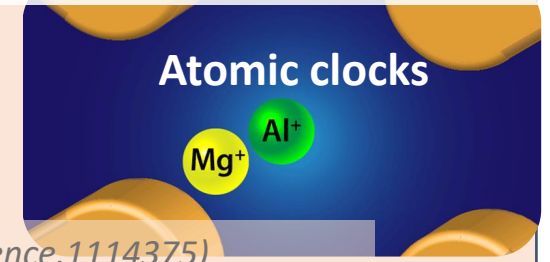
m_p/m_e [1, 2], **Probing QED, fifth force** [3]

[1] S. Patra et al. Science 369, 6508 (2020)
[2] I. V. Kortunov et al. Nature Phys. 17, 569-573 (2021)
[3] M. Germann et al. 2021 (10.1103/PhysRevResearch.3.L022028)

Quantum Logic Spectroscopy

$\Delta f/f < 10^{-18}$

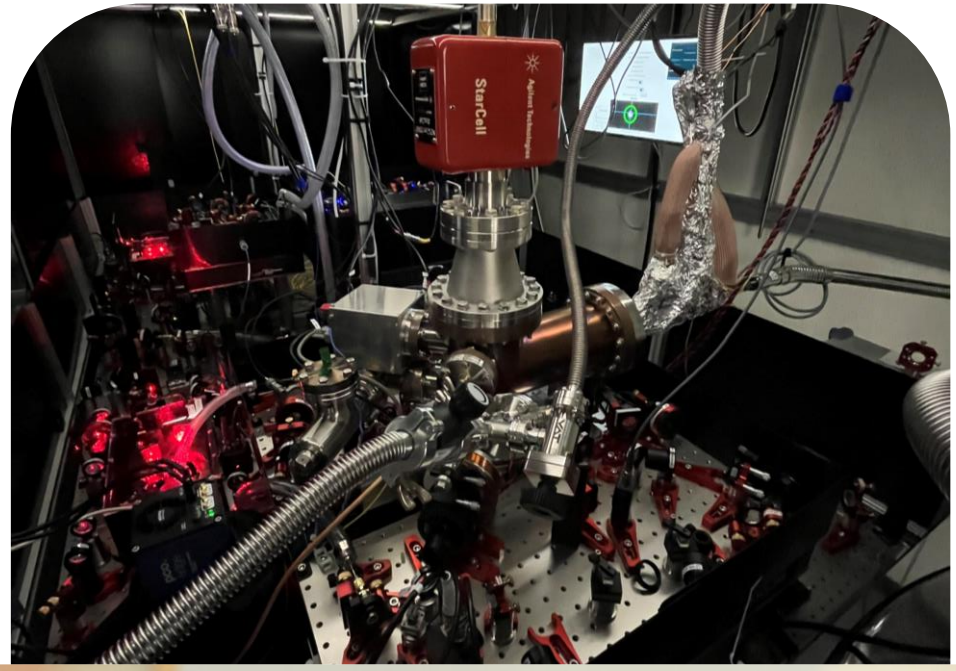
Al^+ [1,2], MgH^+ [3], CaH^+ [4], N_2^+ [5]



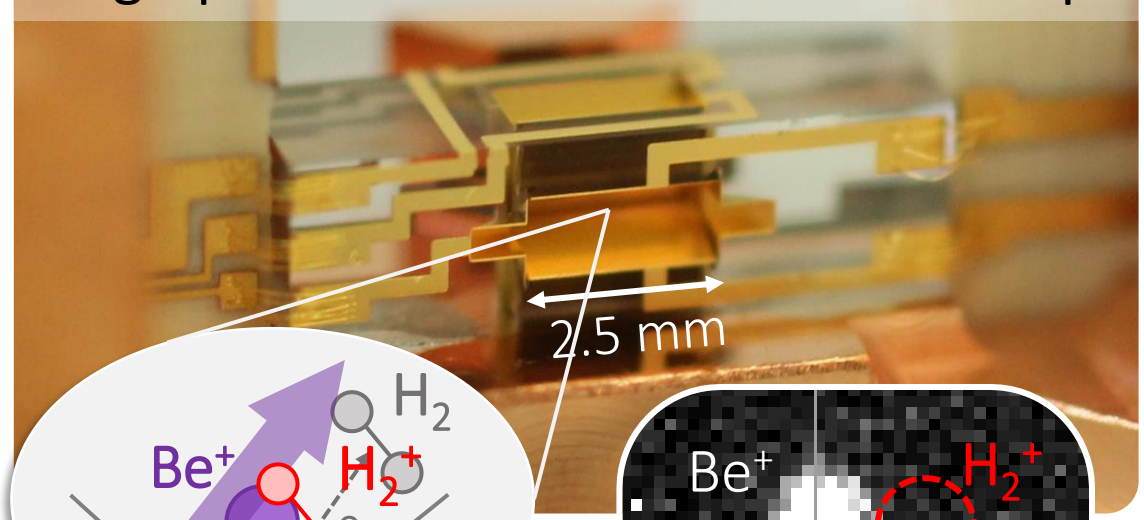
[1] P. O. Schmidt et al. 2005 (DOI: 10.1126/science.1114375)
[2] S. M. Brewer et al. 2019 (DOI: 10.1103/PhysRevLett.123.033201)
[3] F. Wolf et al. 2016 (DOI: 10.1038/nature16513)
[4] C.-W. Chou et al. 2017 (DOI: 10.1038/nature22338)
[5] M. Sinhal et al. 2021 (DOI: 10.2533/chimia.2021.291)

Apparatus

- "tabletop" experiment (~few m^3)



High-precision micro-fabricated ion trap



<u>Linear Paul trap:</u>

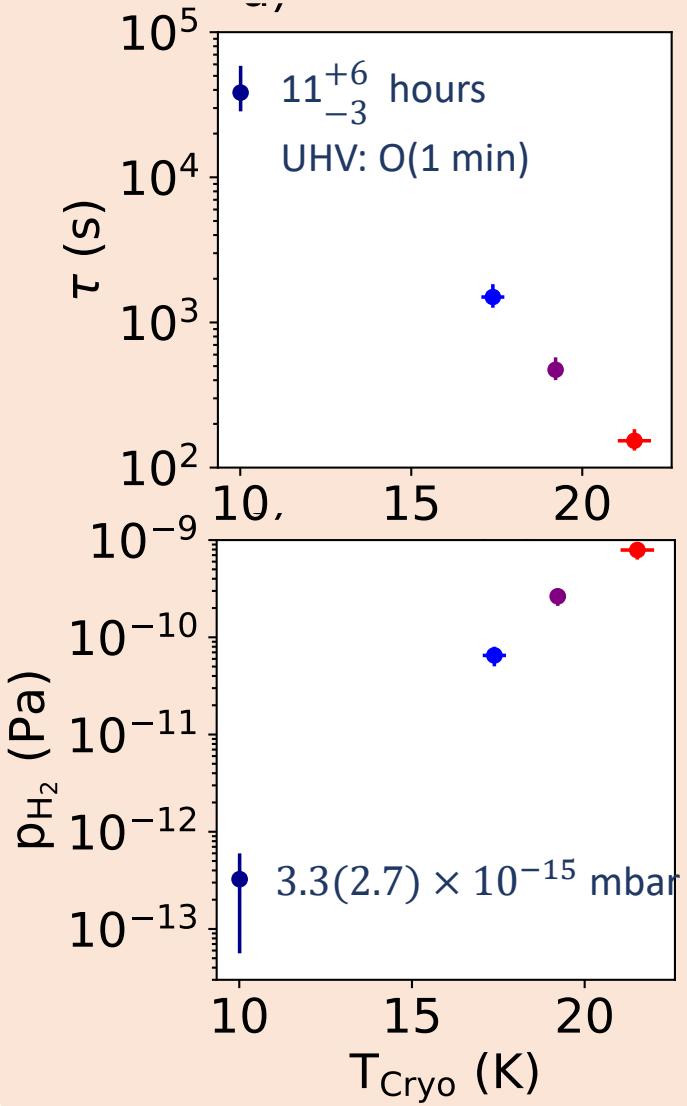
- Trap a charged particle
- ➢ particle motion: **harmonic oscillators** with frequency O(1 MHz)

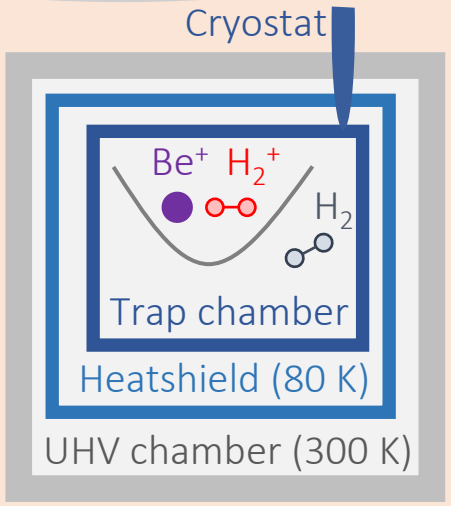
<u>Loading procedure:</u>

- Trap single Be^+ (photo-ionization)
- **Electron impact ionization** of background H_2

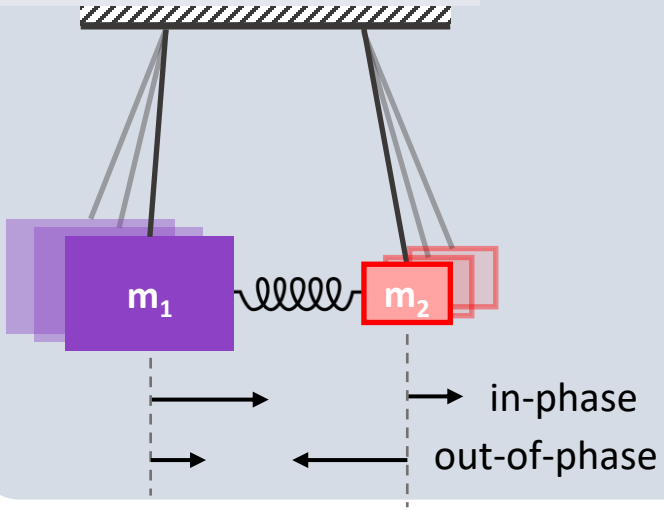
Chemical reaction

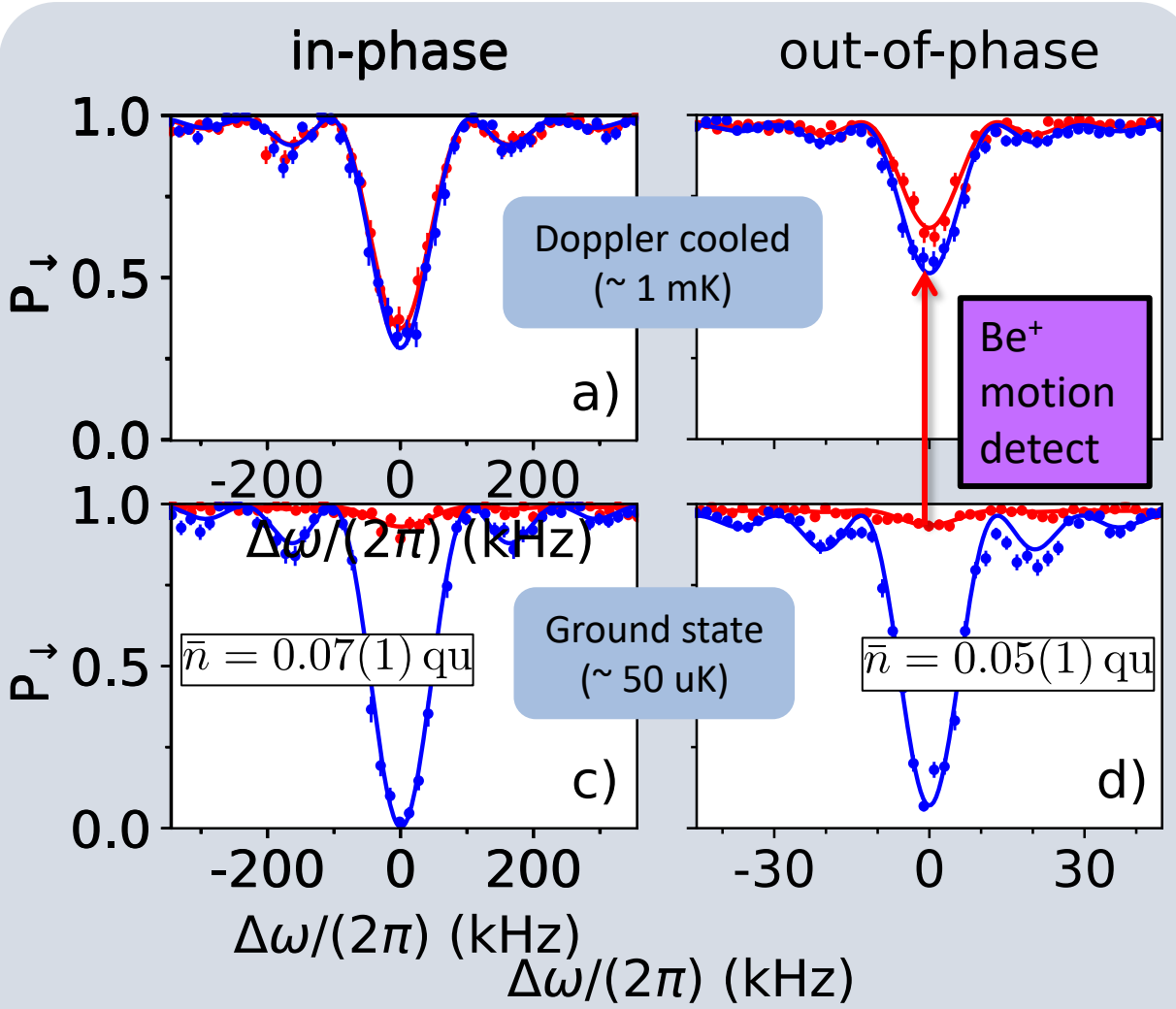
$H_2^+ + H_2 \rightarrow H_3^+ + H$





Ground-state cooling



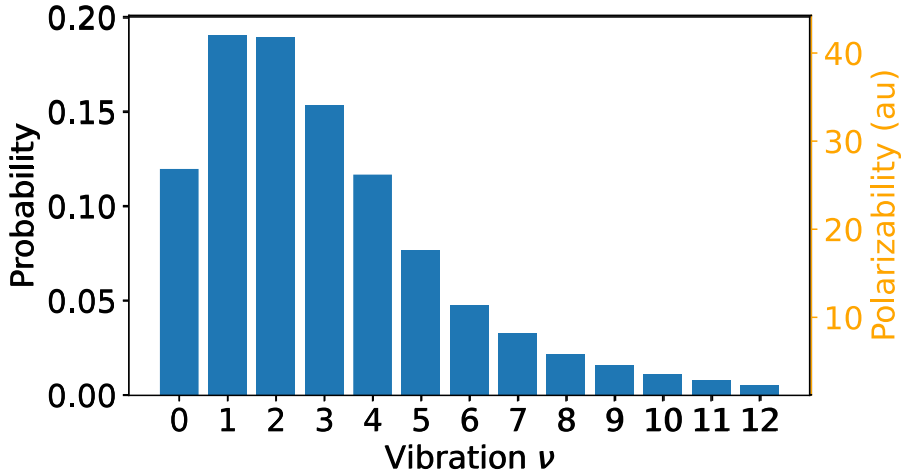


- Resolved sideband cooling
- stimulated Raman transition on Be⁺ (313 nm)

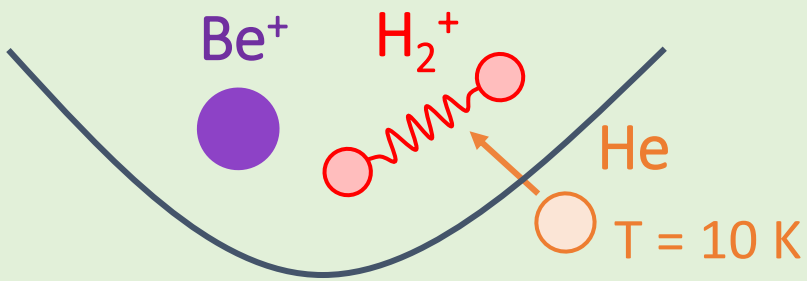
N. Schwegler et al. 2022 (DOI: 10.48550/arXiv.2212.06456)

H_2^+ internal states

Vibration after loading

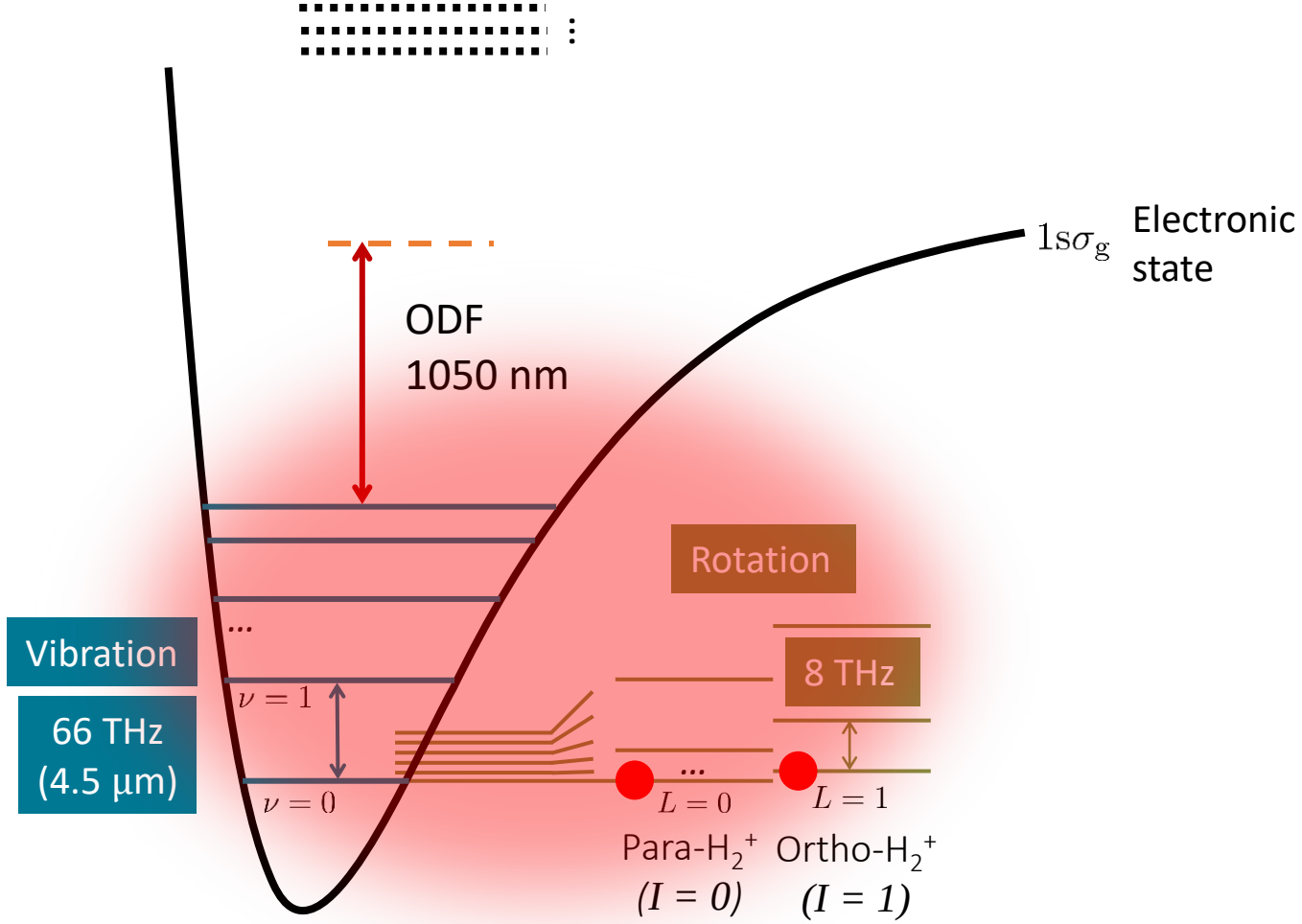


J. P Karr et al. Appl Phys B 107:1043–1052 (2012)
S. Schiller et al 2014 (https://doi.org/10.1103/PhysRevA.89.052521)



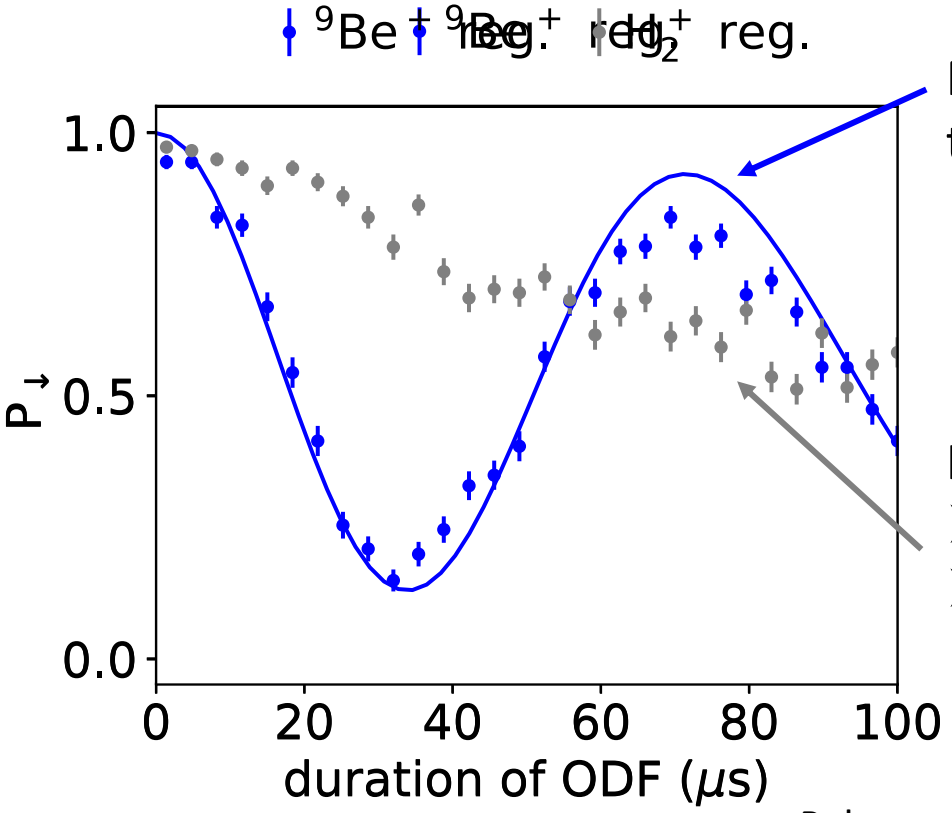
Buffer gas cooling

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



- Loading para/ortho random
- homonuclear: (almost) no rovibrational decay
- measure polarizability with optical dipole force
  - ➢ 1050 nm far-detuned Raman beams

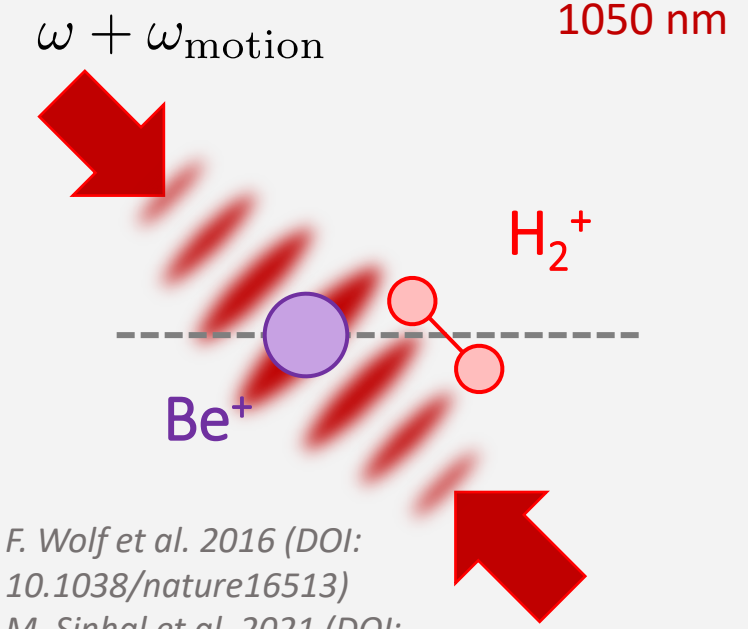
Optical dipole force



Motional excitation (proportional to polarizability)

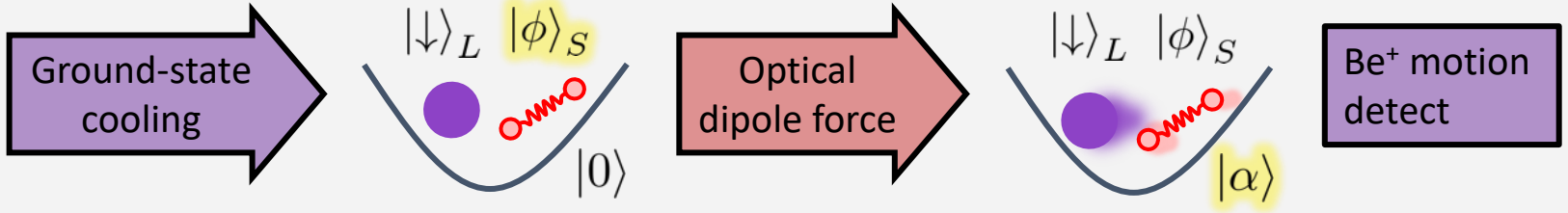
High mass-mismatch (9:2)

- weakly cooled H_2^+ radial modes
- dephasing of signal (Debye-Waller)

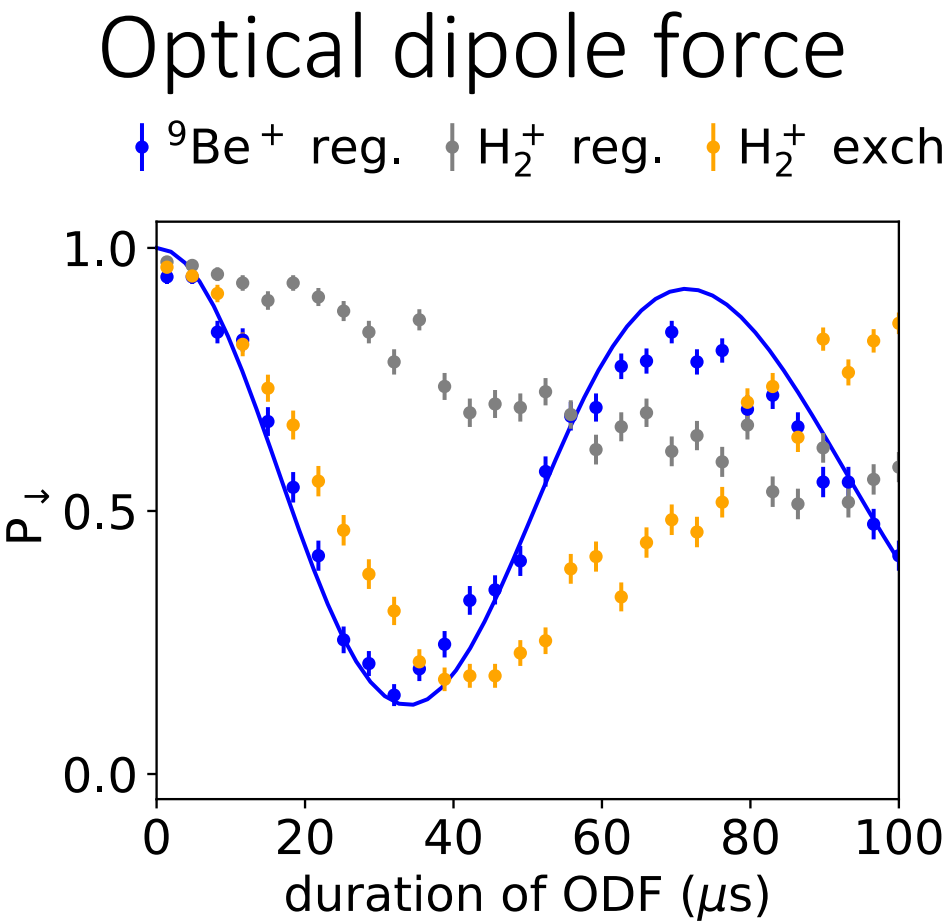


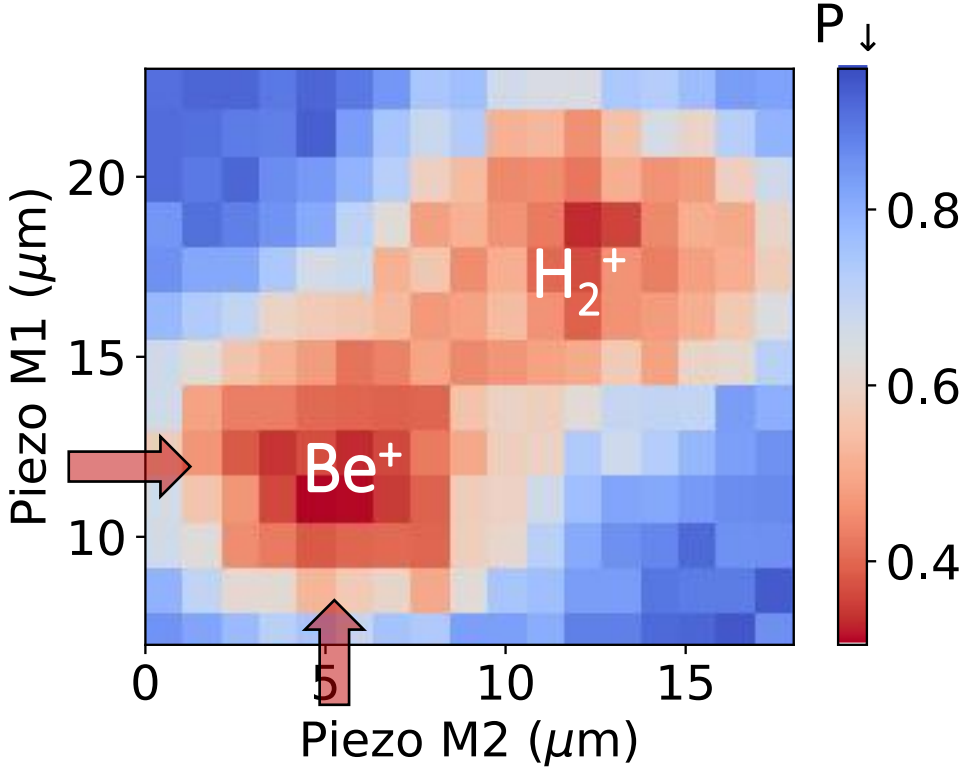
F. Wolf et al. 2016 (DOI: 10.1038/nature16513)
M. Sinhal et al. 2021 (DOI: 10.2533/chimia.2021.291)

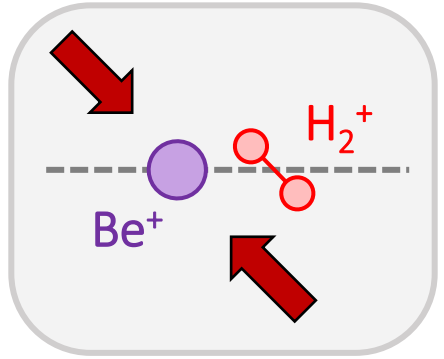
Pulse sequence



Optical dipole force

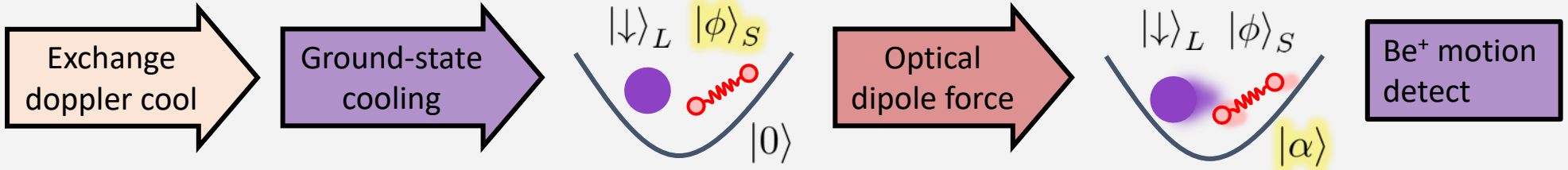






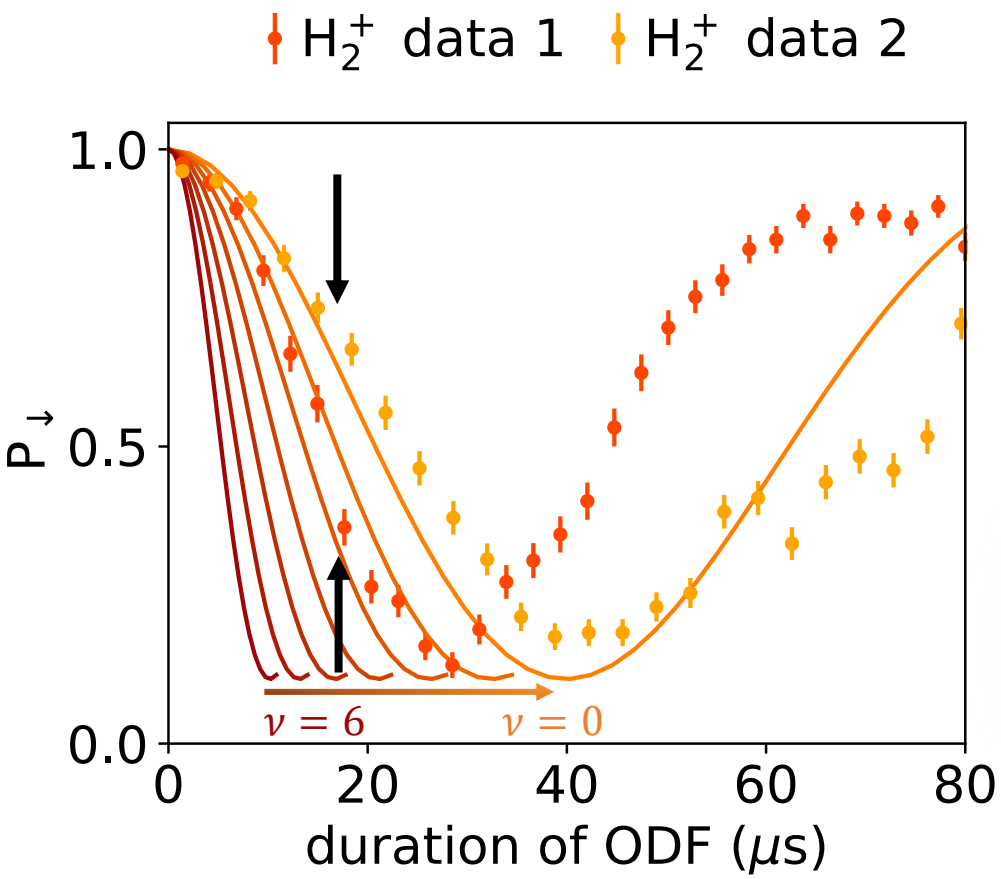
Poster Session: Fabian Schmid

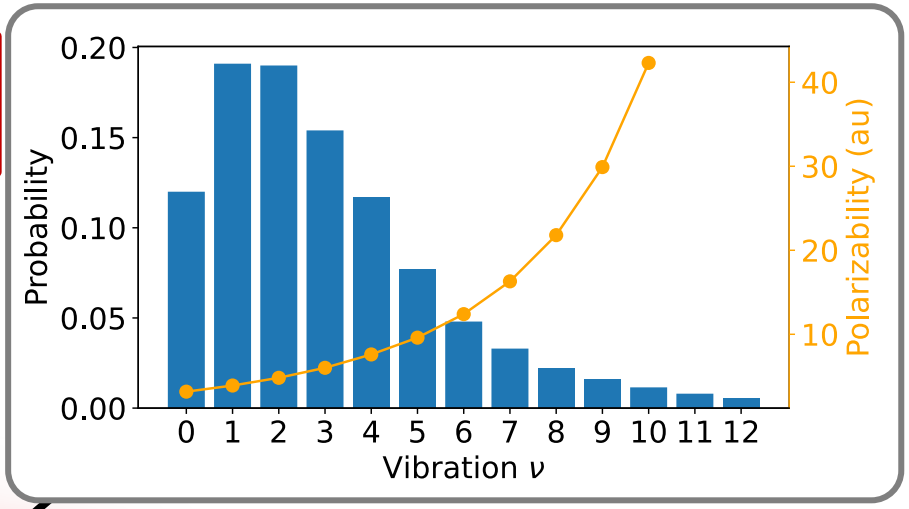
Pulse sequence

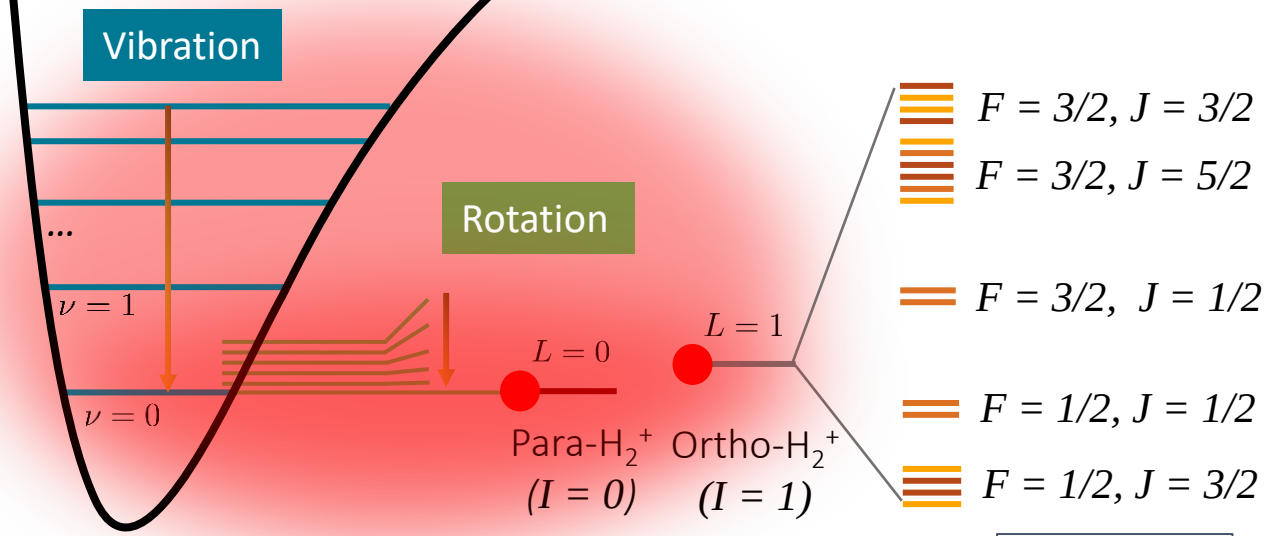


Polarizability measurement

Preliminary







$F = I + 1/2$
$J = F + L$

Complications: finite He pressure, drifts after loading

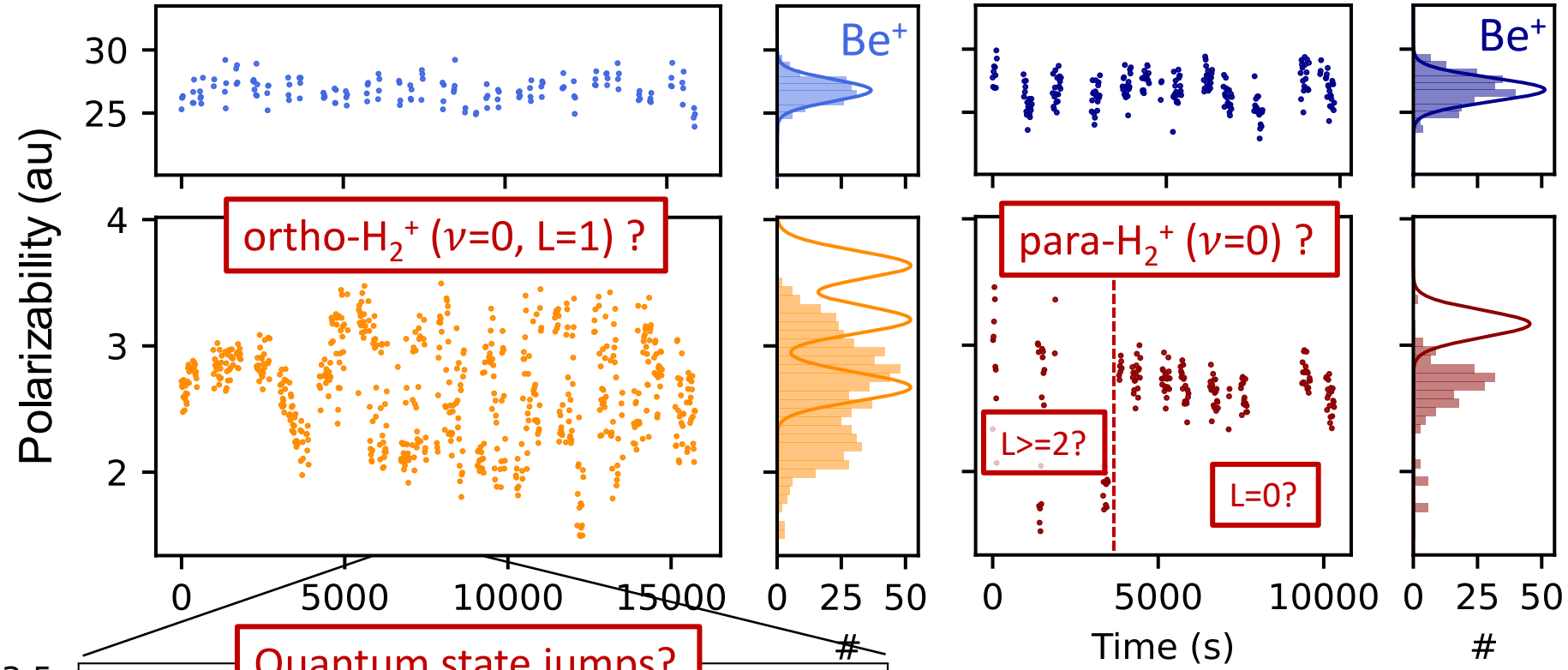
- Vibrational state cooled ($v < 2$)
- Expect rotational cooling on same timescale

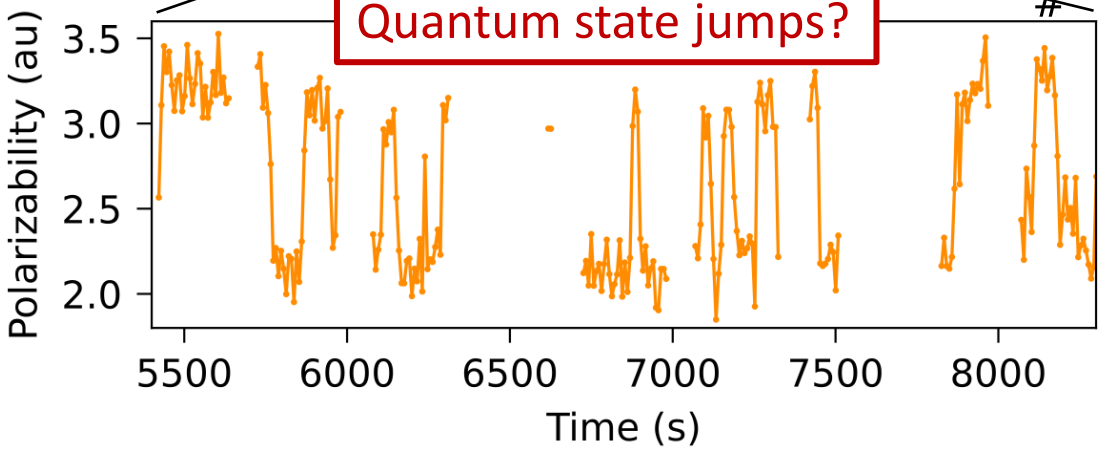
➢ In groundstate?

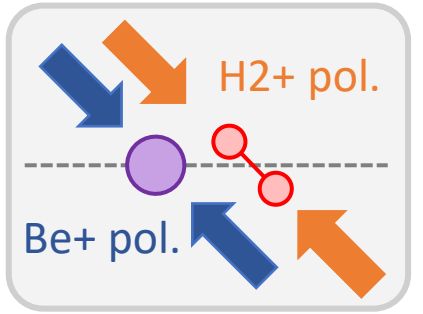
S. Schiller et al 2014 (https://doi.org/10.1103/PhysRevA.89.052521)

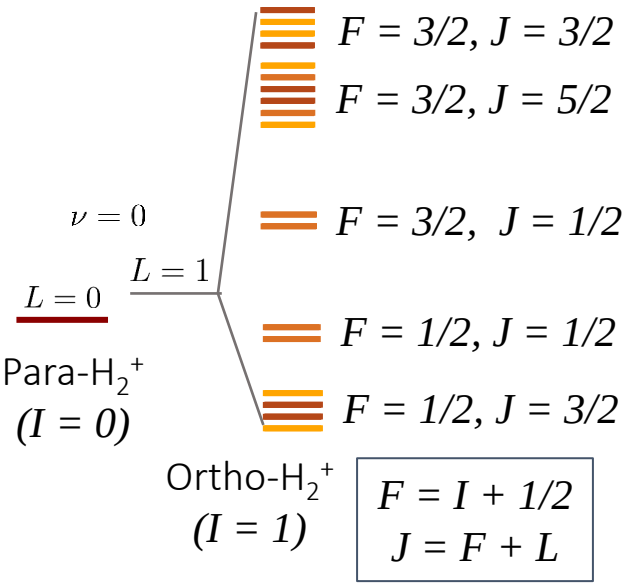
Fluctuations in H_2^+ polarizability

Preliminary





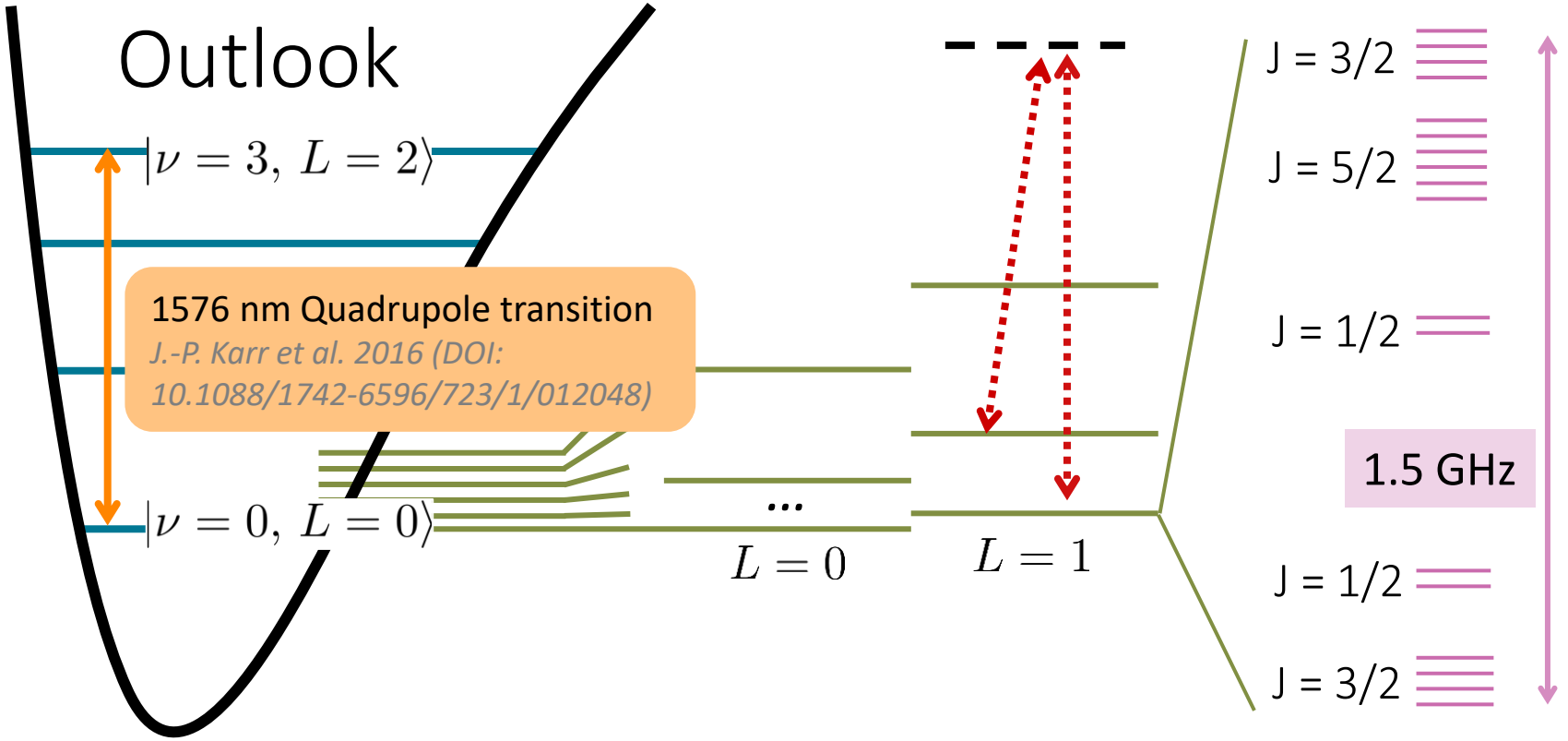




Possible explanation:

- He collision-induced transitions between hyperfine levels in ortho-H_2^+

Outlook



L = 1 (Ortho-H_2^+)

- Prepare pure hyperfine state
- Hyperfine spectroscopy

CaH+ C.-W. Chou et al. 2017 (DOI: 10.1038/nature22338)

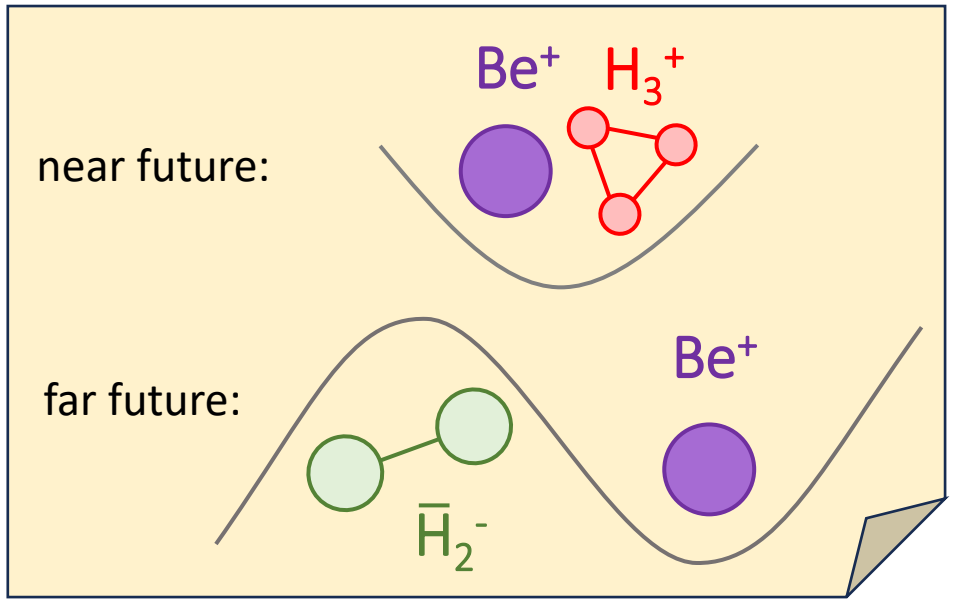
L = 0 (Para-H_2^+)

- 1576 nm laser system under construction
- Fiber link to Swiss Federal Institute of Metrology

D. Husmann et al. 2021 (DOI: 10.1364/OE.427921)

- Raman spectroscopy of rotational transitions (~THz) with frequency comb

CaH+ C.-W. Chou et al. 2020 (DOI: 10.1126/science.aba3628)



Team

Molecules “Sub-group”

PI	PhD students		Post-doc
Daniel Kienzler	Nick Schwegler	David Holzapfel	Fabian Schmid

He

Master students:
Björn Jósteinsson,
Oliver Stadler

Be^+

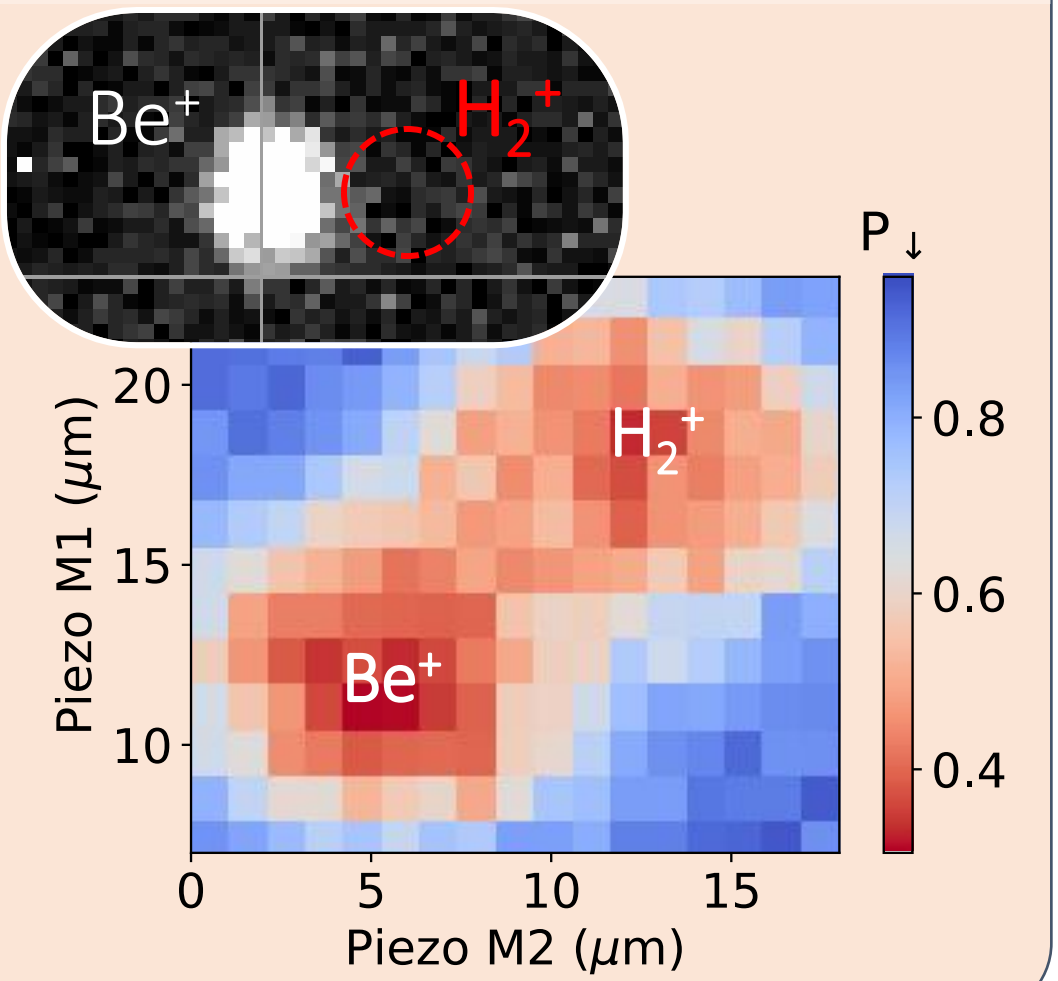
H_2^+

Jonathan Home

Trapped ion quantum information group

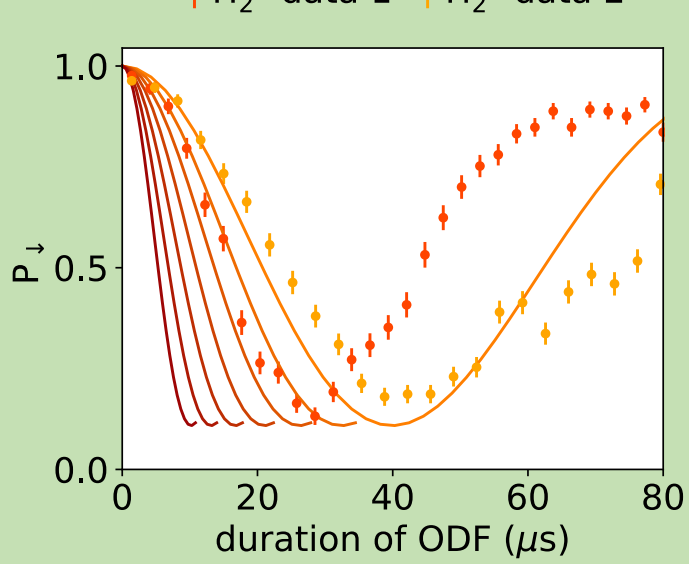
Summary - Thank you for your attention!

Polarizability measurement



H_2^+ buffer-gas cooling

Preliminary



H_2^+ quantum state jumps?

Preliminary