Rydberg atoms in ultracold gases – from electron to ion impurities

Quantum 2021: Dynamics and local control of impurities in complex quantum environments

September 14th, 2021

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Universität Stuttgart
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IQST

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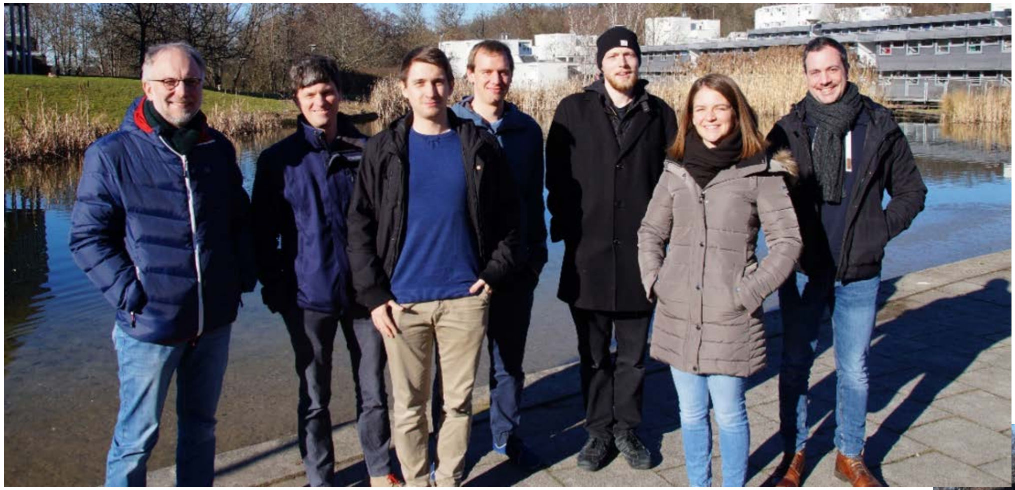
Deutsche Forschungsgemeinschaft DFG

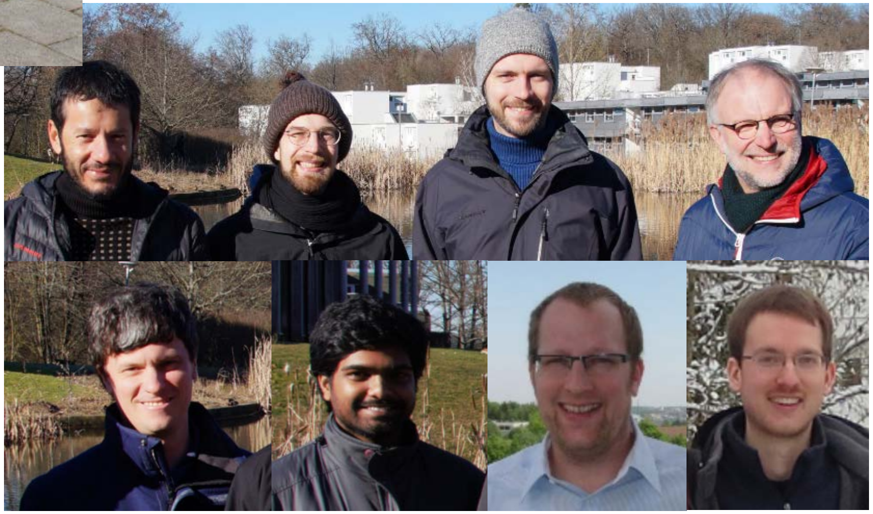
Carl Zeiss Stiftung

Baden-Württemberg Stiftung
WIR STIFTEN ZUKUNFT

Our Rydberg Teams



(from left to right) Tilman Pfau, Florian Meinert, Thomas Dieterle, Moritz Berngruber, Christian Hölzl, Muamera Basic, Felix Engel



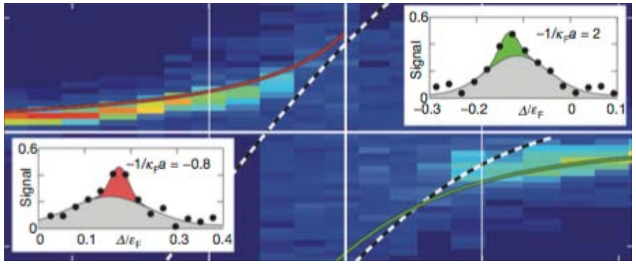
(from left to right) Oscar Herrera-Sancho, Christian Veit, Nicolas Zuber, Tilman Pfau, Florian Meinert, Viraatt Anasuri, Robert Löw, Thomas Schmid

Recent theory support:

Peter Schmelcher
Krzysztof Jachymski
Michal Tomza
Michal Tarana
Georg Raithel

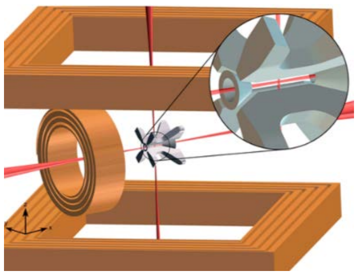
Single impurities immersed in ultracold gases …

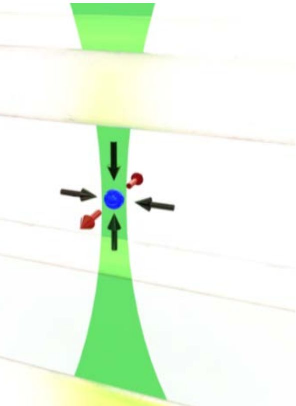
… ensembles of neutral impurities in BEC/Fermi gases



Schirotzek *et al.*, PRL 102, 230402 (2009)
Kohstall *et al.*, Nature 485, 615 (2012)
Jorgensen *et al.*, PRL 117, 055302 (2016)
Hu *et al.*, PRL 117, 055301 (2016)
…

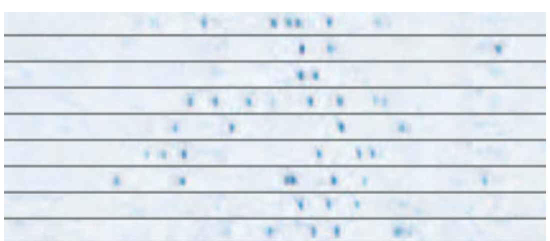
… charged impurities (ions)

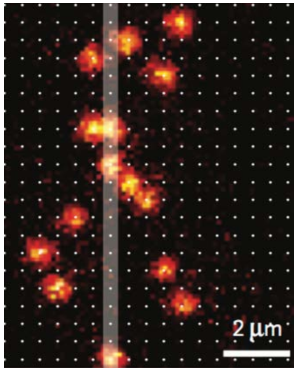




Zipkes *et al.*, Nature 464, 388 (2010)
Schmidt *et al.*, PRL 105, 133202 (2010)
T. Huber *et al.*, Nat. Commun. 5, 5587 (2014)
…

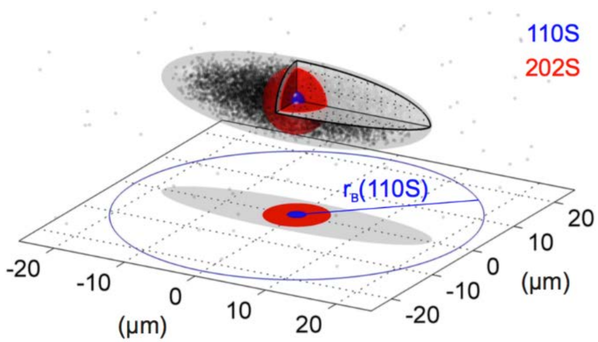
… single spin impurities in lattice and bulk systems





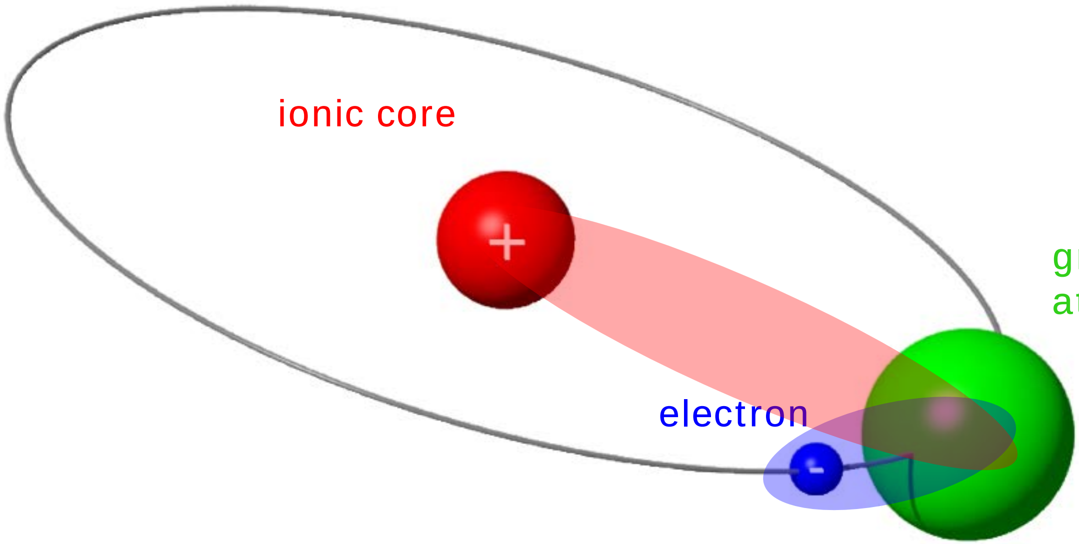
Fukuhara et al, Nat. Phys. 9, 235 (2013)
Hohmann *et al.*, PRL 118, 263401 (2017)
Schmidt *et al.*, PRL 121, 130403 (2018)

… mesoscopic Rydberg impurities



Balewski *et al.*, Nature 502, 664 (2013)
Camargo *et al.*, PRL 120, 083401 (2018)

Electron-atom and ion-atom interaction



perturbative electron-atom Born-Oppenheimer potential
(e.g. for isolated *S*-states)

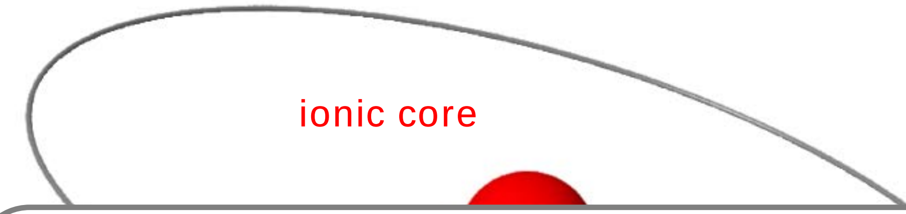
$$U_e(R) = \langle \Psi_e | V_e | \Psi_e \rangle = 2\pi a_s(k) |\Psi_e(R)|^2$$

ion-atom polarization potential

$$U_i(R) = -\frac{C_4}{2R^4}$$

V. Bendkowsky et al., Nature 458, 1005 (2009)
C.H. Greene et al., Phys. Rev. Lett. 85, 2458 (2000)

Electron-atom and ion-atom interaction

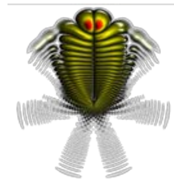


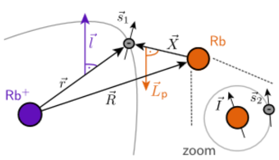
state

K. S. Kleinbach, F. Meinert, F. Engel, W. J. Kwon, R. Löw, T. Pfau, and G. Raithel,
Phys. Rev. Lett. **118**, 223001 (2017).

F. Engel, T. Dieterle, F. Hummel, C. Fey, P. Schmelcher, R. Löw, T. Pfau, and F. Meinert,
Phys. Rev. Lett. **123**, 073003 (2019).

M. Deiß, S. Haze, J. Wolf, L. Wang, F. Meinert, C. Fey, F. Hummel, P. Schmelcher and J. Hecker Denschlag,
Phys. Rev. Research **2**, 013047 (2020).





in collaboration with P. Schmelcher group

perturb
Born-Op
(e.g. fo

$$U_e(R) = \langle \Psi_e | V_e | \Psi_e \rangle$$
$$= 2\pi a_s(k) |\Psi_e(R)|^2$$

tential

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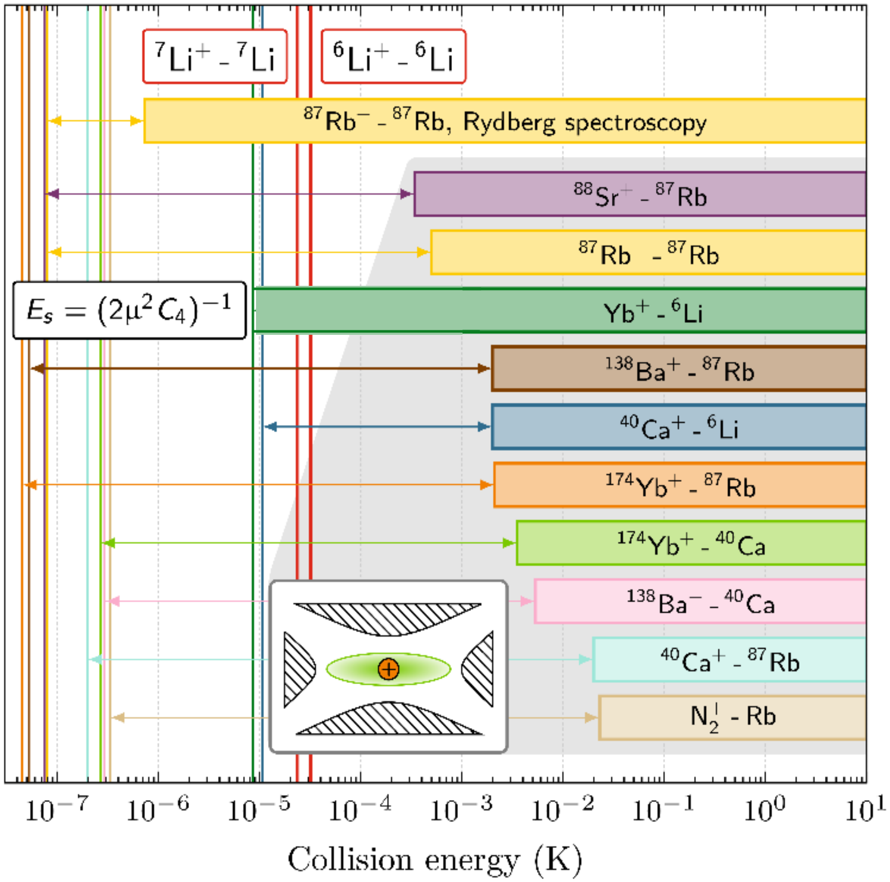
V. Bendkowsky et al., Nature 458, 1005 (2009)
C.H. Greene et al., Phys. Rev. Lett. 85, 2458 (2000)

Cold ion-atom interaction – State of the art

$E^\star \sim (2\mu^2 C_4)^{-1}$ *s*-wave limit



T. Schmid et al., Phys. Rev. Lett. 120, 153401 (2018)

Cold Langevin collisions in hybrid traps

- micromotion in Paul traps
- ~ mK collision energies
- lower *E** with light atoms

M. Tomza et al., Rev. Mod. Phys. 91, 035001 (2019)
M. Cetina et al., Phys. Rev. Lett. 109, 253201 (2009)

J. Joger et al., Phys. Rev. A 96, 030703 (2017)
T. Feldker at al., Nat. Phys. 16, 413 (2020)

R. Saito et al., Phys. Rev. A 95, 032709 (2017)

Optical traps for ions

A. Lambrecht et al., Nat. Photonics 11, 704 (2017)

Light Ion-Molecule Collisions (H_2)

P. Allmendinger et al., J. Chem. Phys. 145, 244316 (2016)

Cold ion-atom interaction – State of the art

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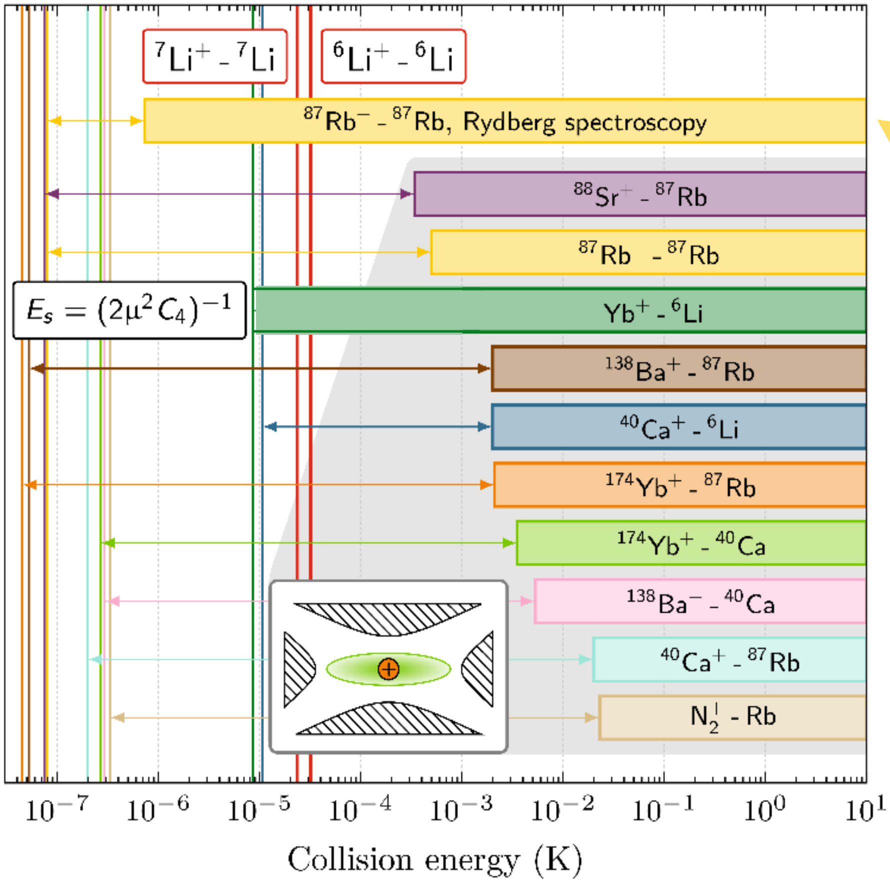

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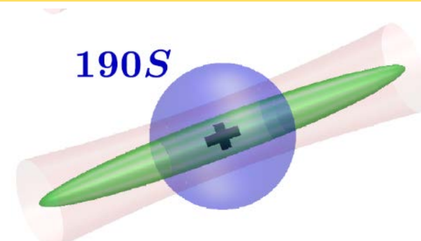
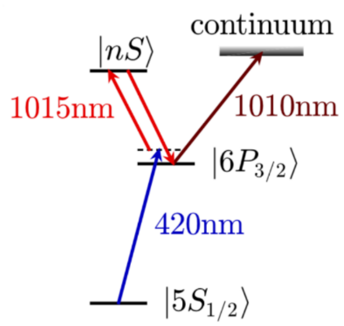


Ion-atom interaction
inside a Rydberg orbit
at sub-μK temperatures

K. S. Kleinbach, F. Engel, T. Dieterle, R. Löw, T. Pfau, and F. Meinert
Phys. Rev. Lett. **120**, 193401 (2018)

Rydberg impurities … from electrons to ions

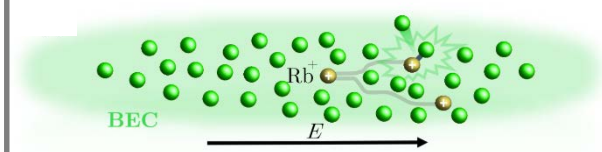


Low-energy ions from single Rydberg atoms

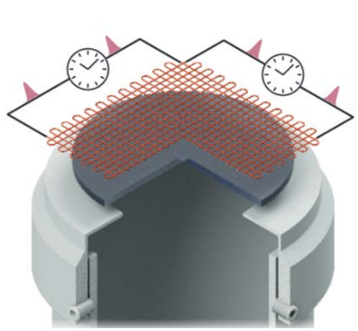
C. Veit, N. Zuber, O. A. Herrera-Sancho, V. S. V. Anasuri, T. Schmid, F. Meinert, R. Löw, and T. Pfau
Phys. Rev. X **11**, 011036 (2021)

T. Dieterle, M. Berngruber, C. Hölzl, R. Löw, K. Jachymski, T. Pfau, and F. Meinert
Phys. Rev. Lett. **126**, 033401 (2021)

Ionic transport through a BEC

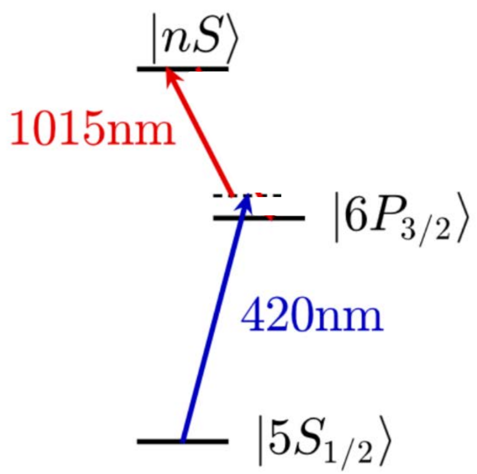


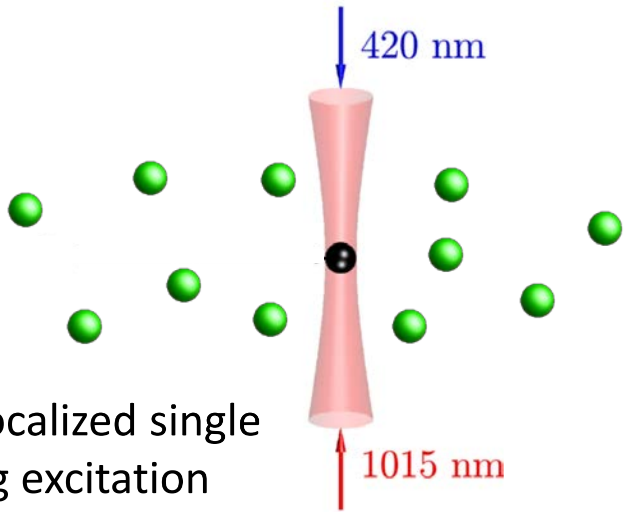
High-resolution imaging



Low-energy ions from single Rydberg atoms

Making a single slow ion from
an ultracold gas





spatially localized single
Rydberg excitation

rapid near-threshold „V-type“
two-photon ionization
(excess energy < 10 µK)

F. Engel, T. Dieterle, T. Schmid, C. Tomschitz, C. Veit,
N. Zuber, R. Löw, T. Pfau, and F. Meinert,
Phys. Rev. Lett. 121, 193401 (2018)

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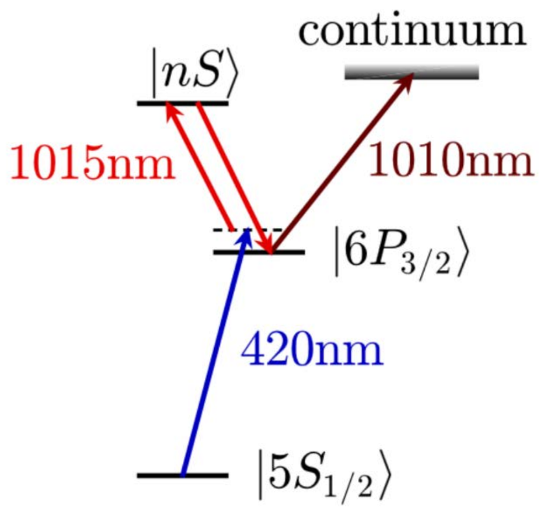

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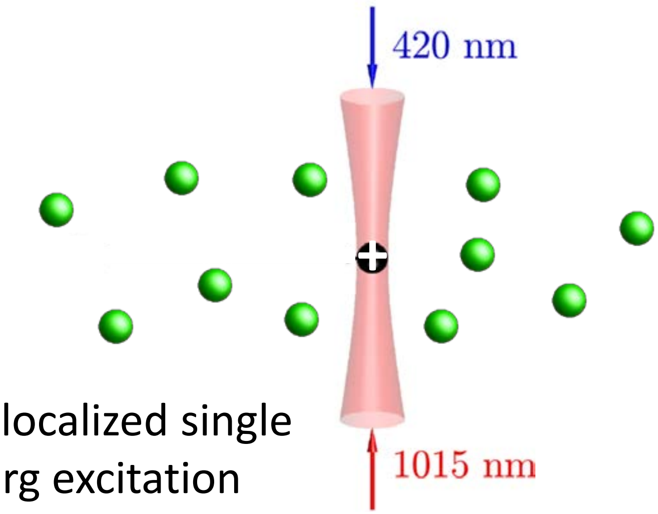

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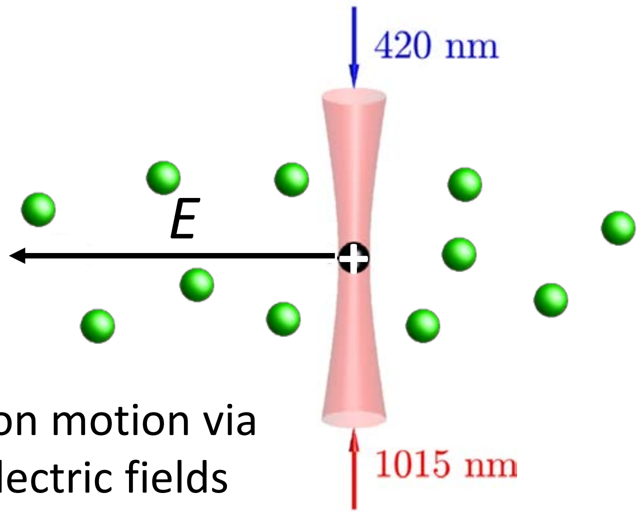
Probing the ion motion via Rydberg blockade

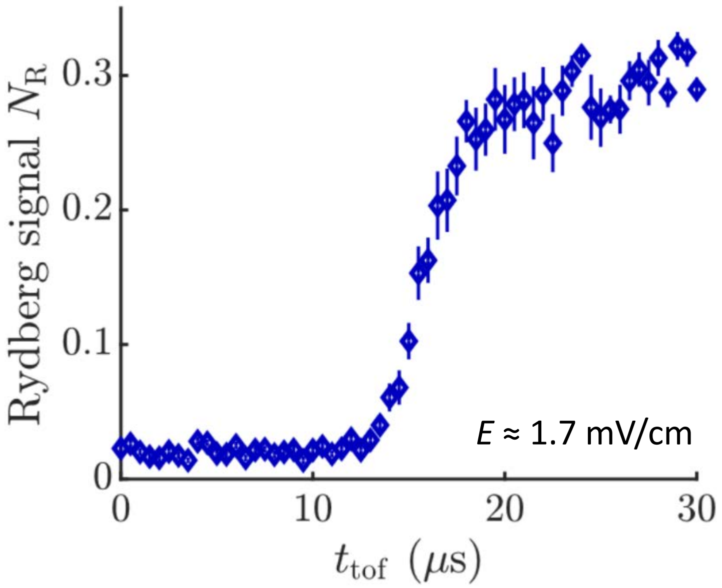


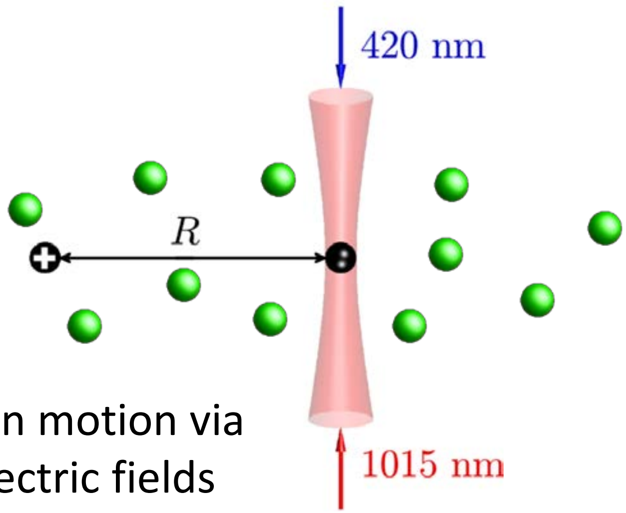
control ion motion via
small electric fields

F. Engel, T. Dieterle, T. Schmid, C. Tomschitz, C. Veit,
N. Zuber, R. Löw, T. Pfau, and F. Meinert,
Phys. Rev. Lett. 121, 193401 (2018)

Probing the ion motion via Rydberg blockade

second Rydberg excitation at the ion's initial position





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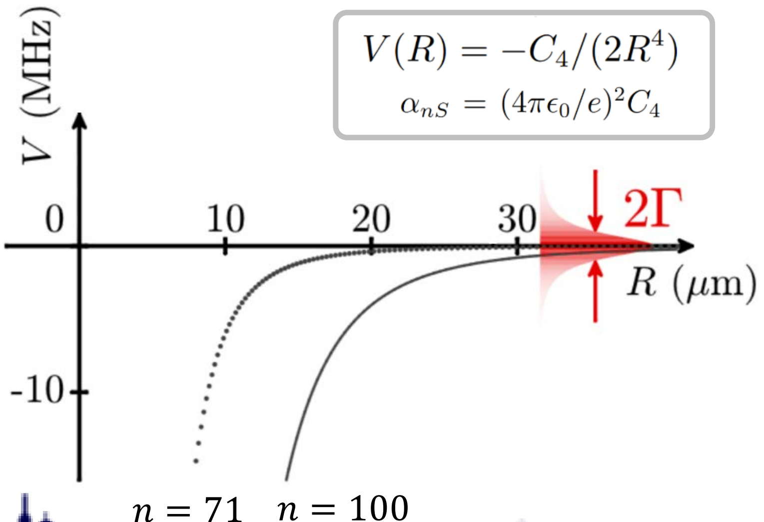
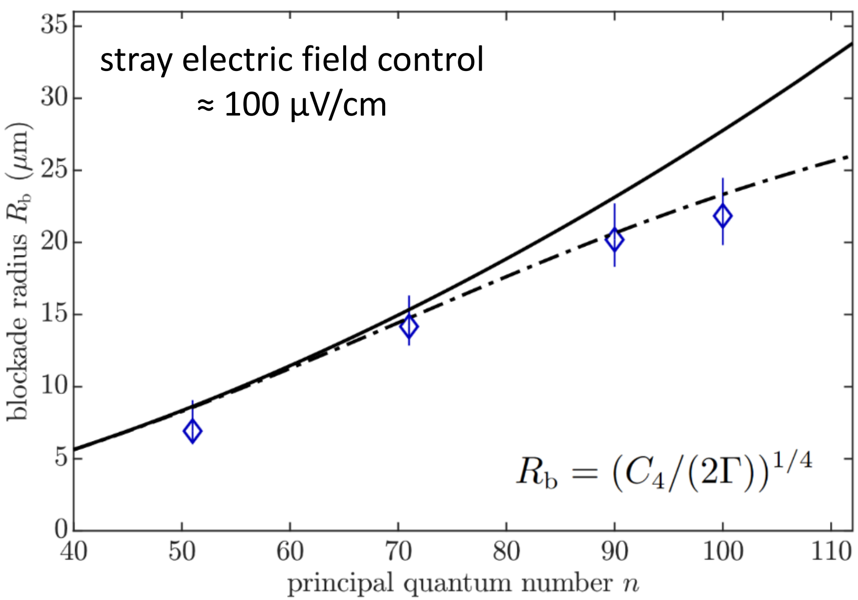
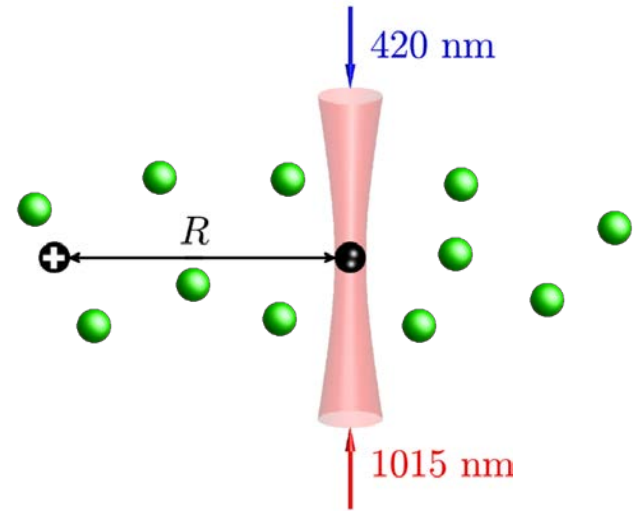


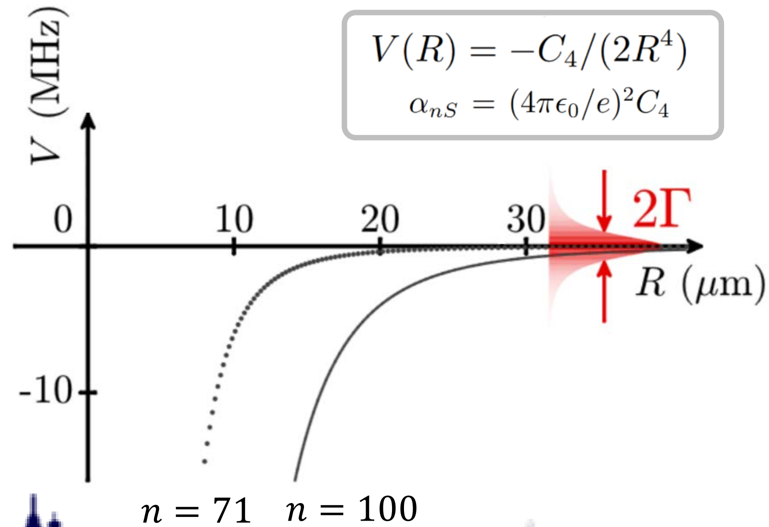
F. Engel, T. Dieterle, T. Schmid, C. Tomschitz, C. Veit, N. Zuber, R. Löw, T. Pfau, and F. Meinert, Phys. Rev. Lett. 121, 193401 (2018)

Probing the ion motion via Rydberg blockade

Blockade radius of a single ion







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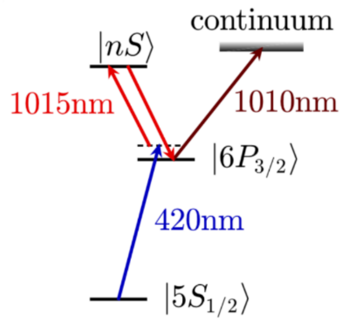
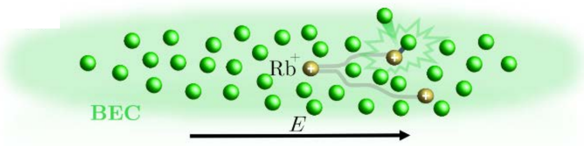
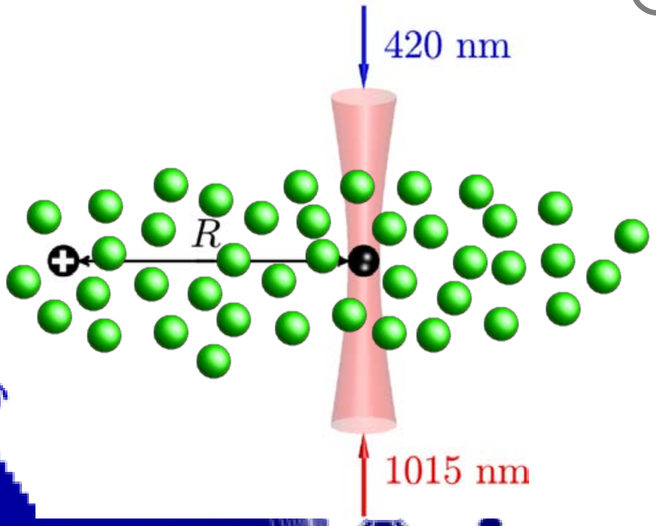
Rydberg impurities ... from electrons to ions



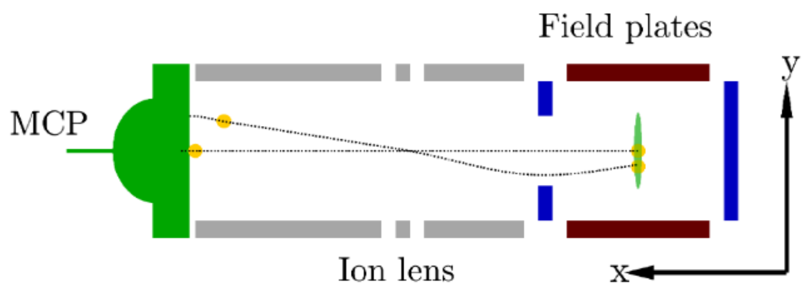
Low-energy ions from single Rydberg atoms

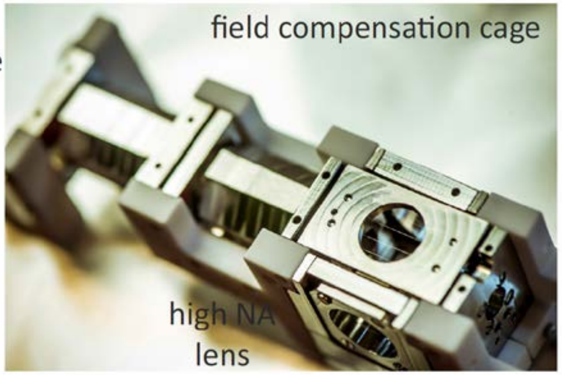
Ionic transport through a BEC

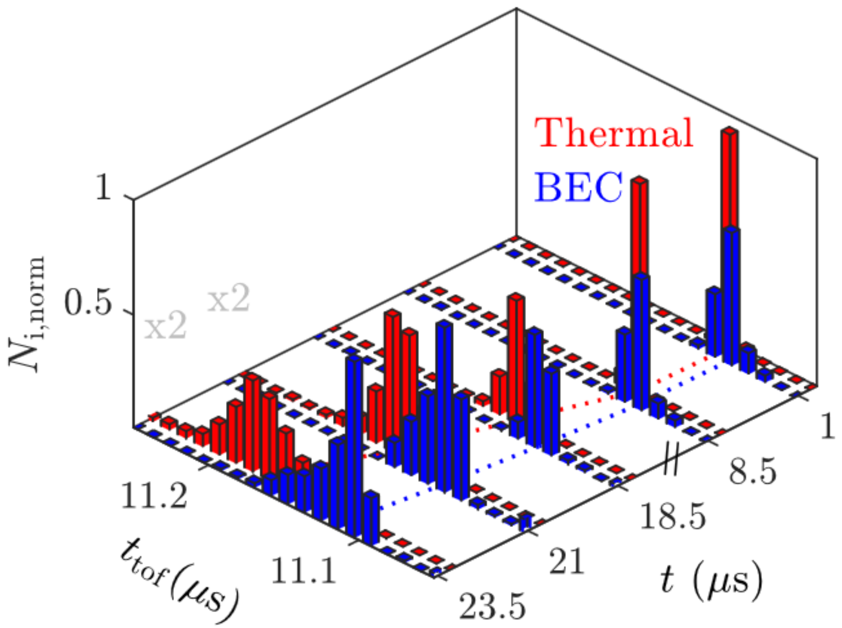




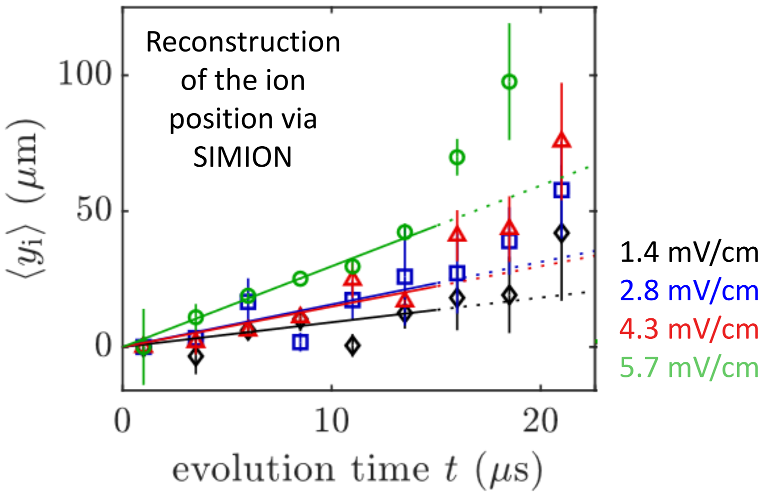
Ionic transport through a BEC



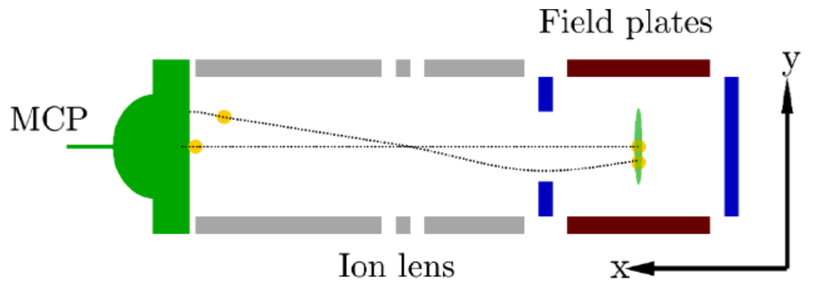


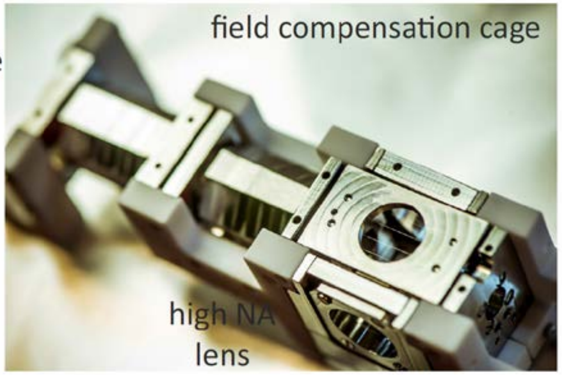


Delay in the time-of-flight to the detector signifies frequent ion-atom collisions

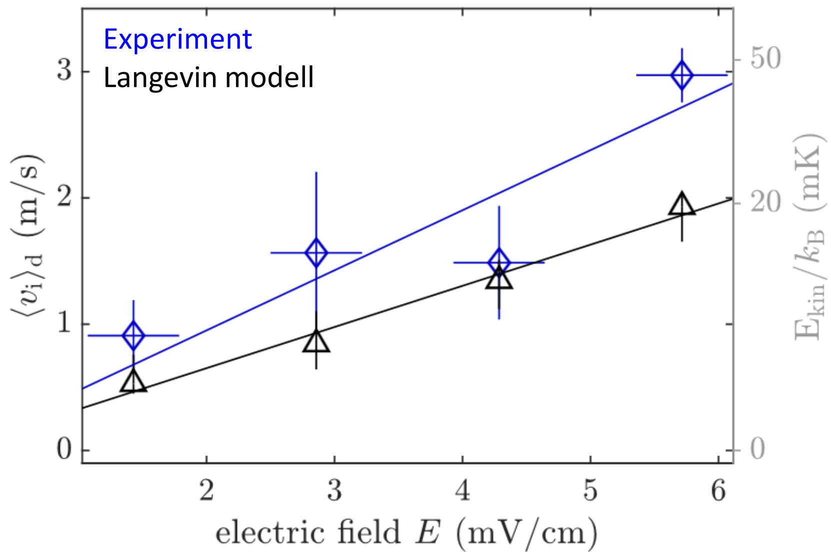


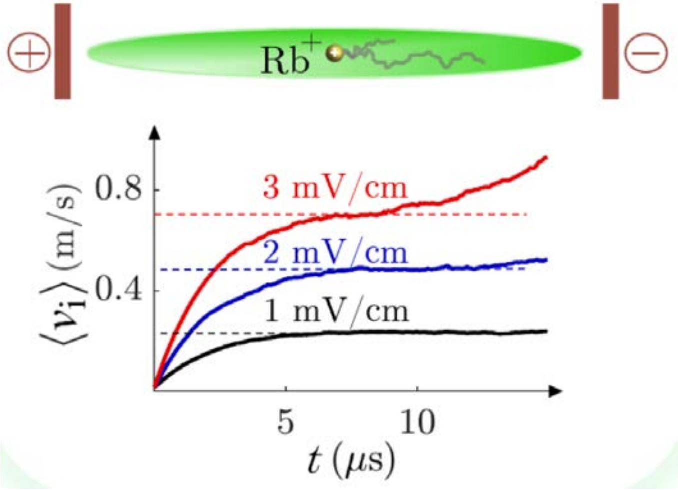
Ionic transport through a BEC





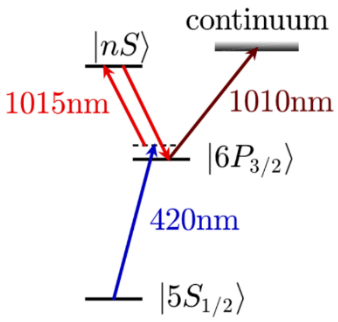
Diffusive transport and ion mobility





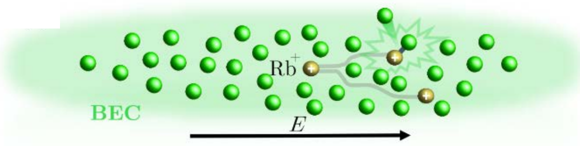
T. Dieterle, M. Berngruber, C. Hölzl, R. Löw, K. Jachymski, T. Pfau, and F. Meinert
arXiv:2007.00309 (2020)

Rydberg impurities ... from electrons to ions

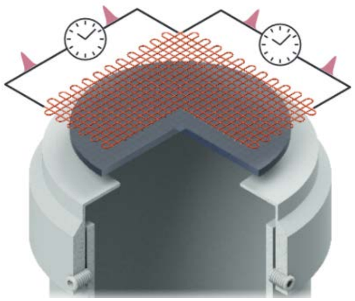


Low-energy ions from single Rydberg atoms

Ionic transport through a BEC



High-resolution imaging



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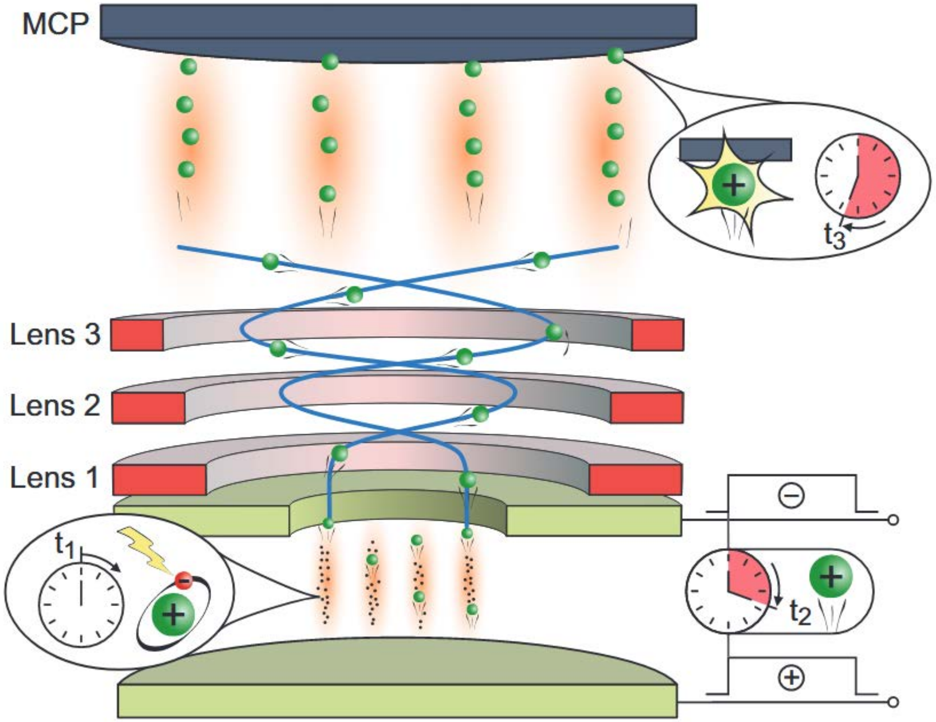
Phys. Rev. X **11**, 011036 (2021)

A new quantum gas microscope
our pulsed ion microscope

Benefits of ion microscope to observe and control single atoms

- imaging of ground state atoms,
  Rydbergs & (ultracold) ionic impurities
- High time resolution (<100 nsec)
- High spatial resolution (<200nm)
- probing of dynamic processes
- 3D-imaging (large depth of field)
- Very good E-Field control: **free cold ions**

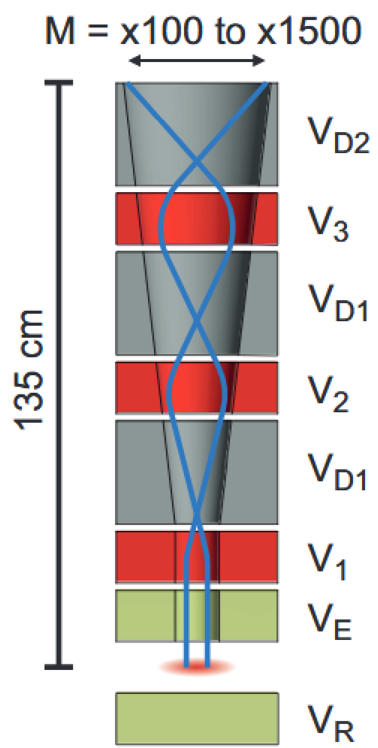


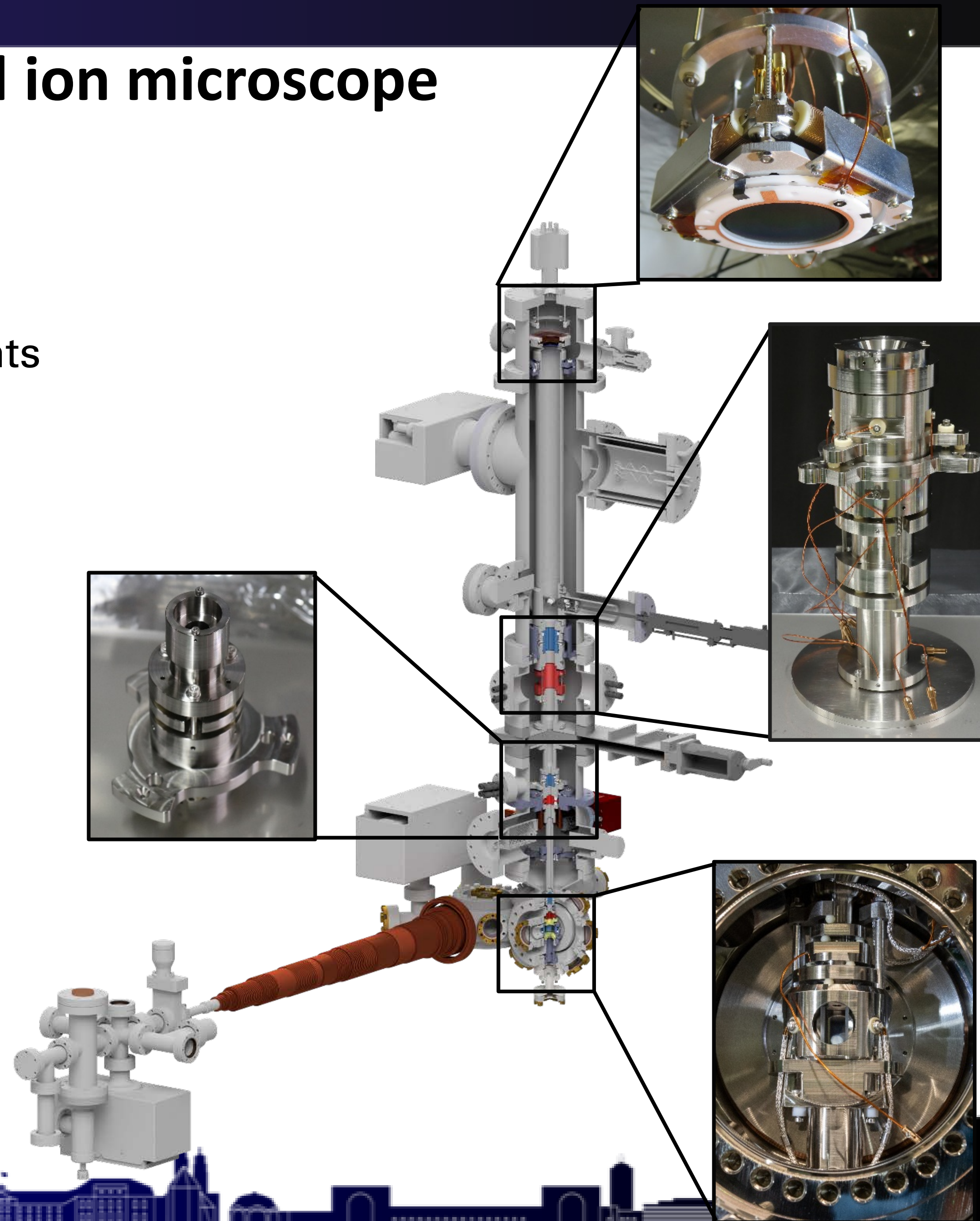
C. Veit et al. Phys. Rev. X **11**, 011036 (2021)

See also
Nat. Phys. **4**, 949 (2008, Ott)
Phys. Rev. Lett. **107**, 103001 (2011, Raithel)
New J. Phys. **19**, 043020 (2017, Fortágh/Günther)
arxiv:2008.08512 (2020)

Pulsed ion microscope

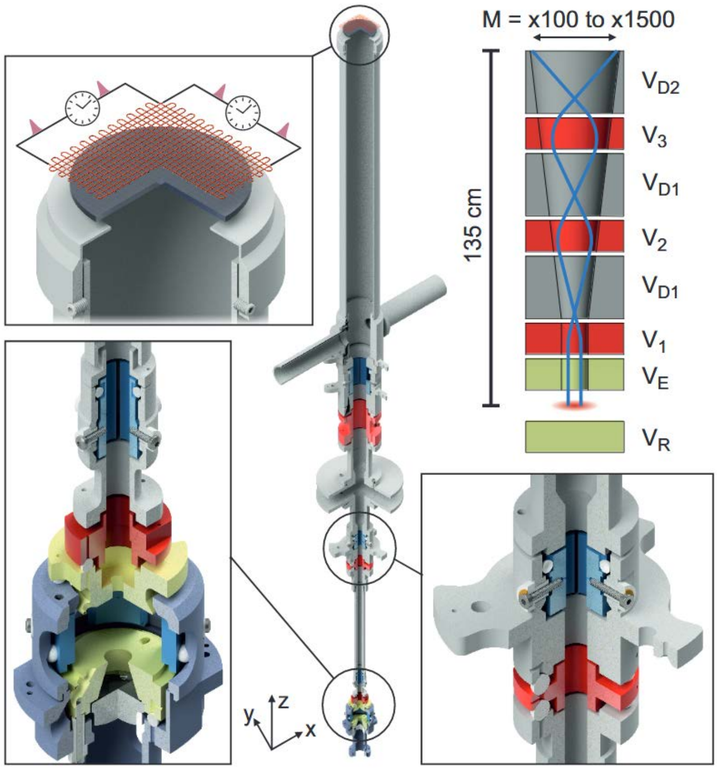
- E-field control
- 3 electro-static lenses
- quadrupole deflector elements
- delay-line detector + MPC





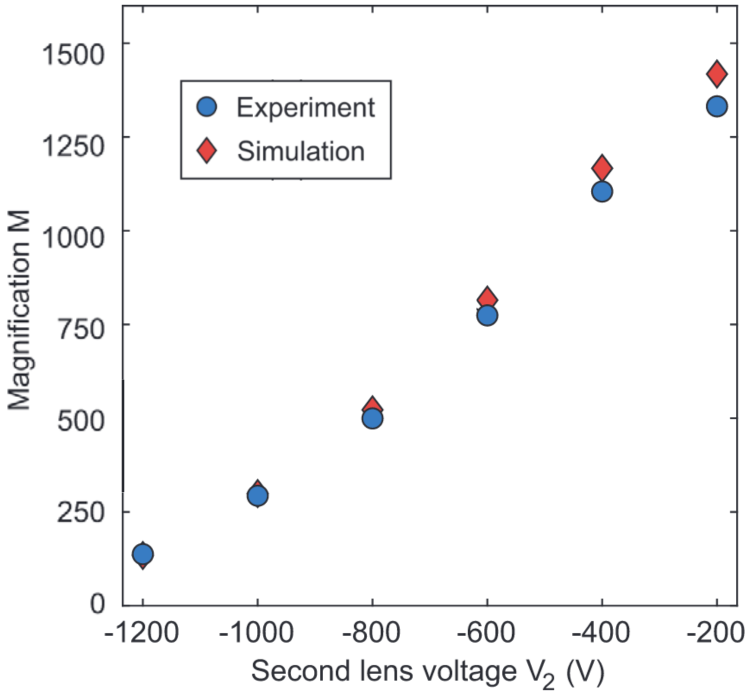
Ion optics

- E-field control + 3 electro-static lenses
- delay-line detector

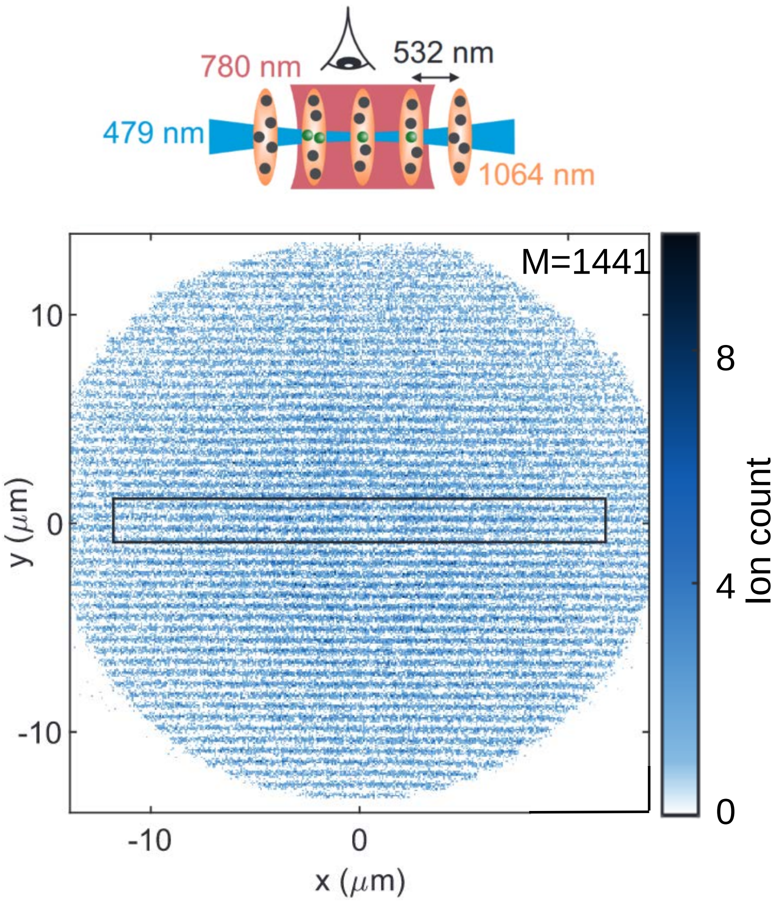


Magnification

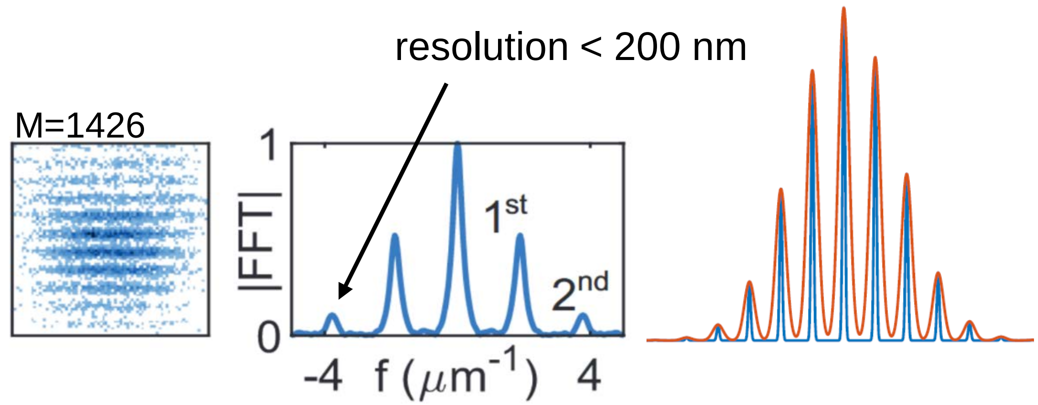
- tuning of M via lens voltages



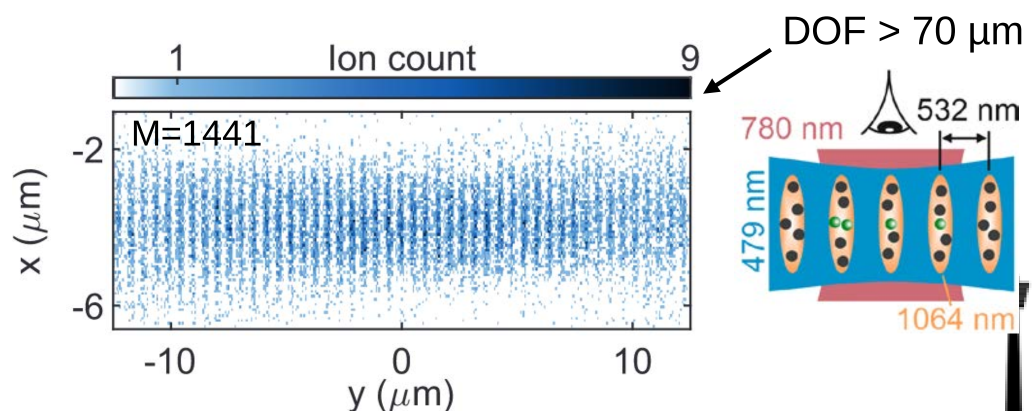
Field of view



Resolution



Depth of field



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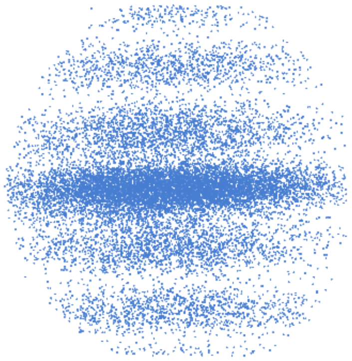
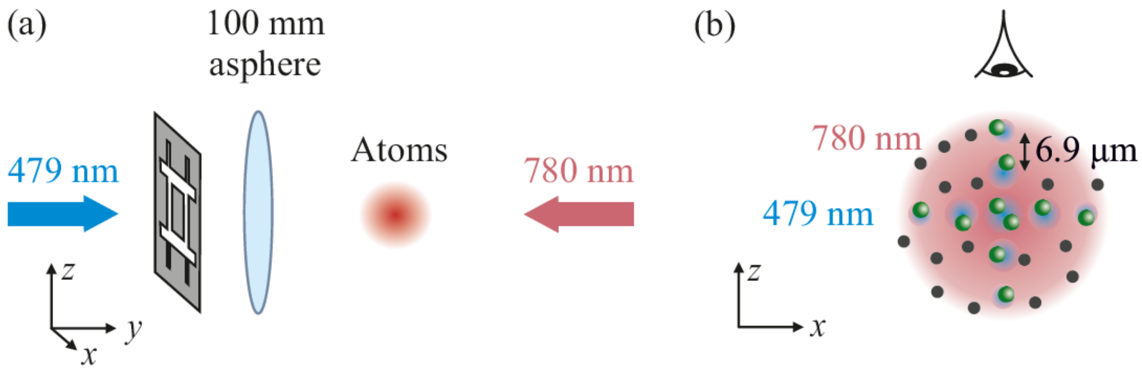
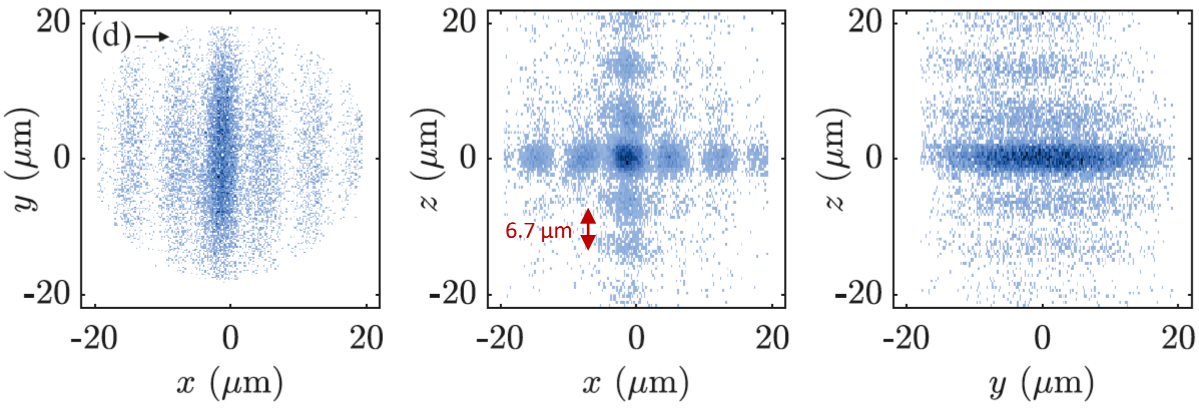


3D imaging – pulsed operation mode

- 3D imaging via TOF information
- 2D-diffraction pattern
- expected achievable resolution <1µm





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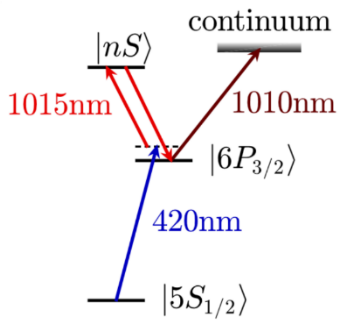
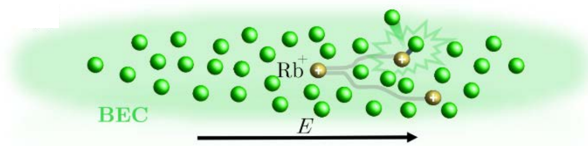
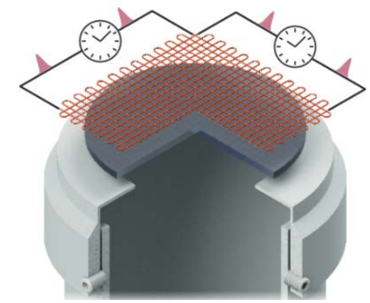


Single
low-energy ions



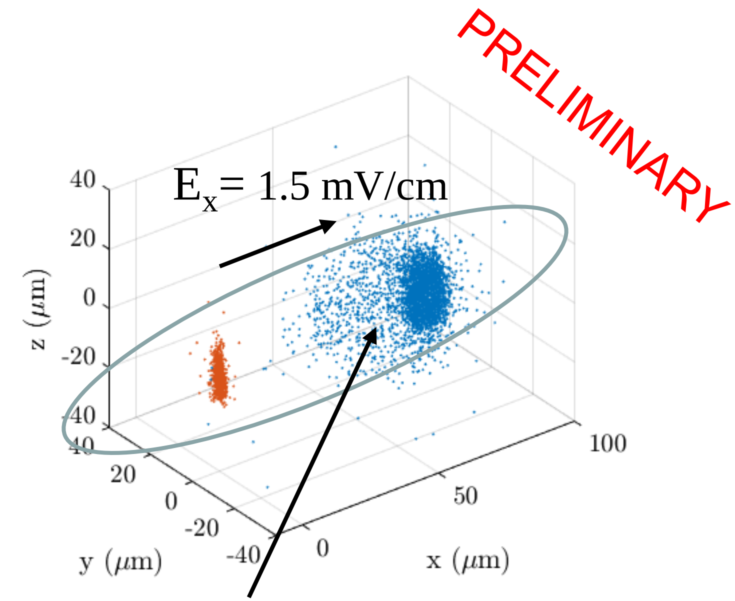
Diffusive ion transport
in a BEC



Ion microscopy

What‘s next?

- microscopy of ionic transport
- quantum regime of ion-atom scattering
- ionic polarons
- bosonic and fermionic bath
- …



Scattering halo of a single Langevin collision
under the microscope
(30 µs TOF)