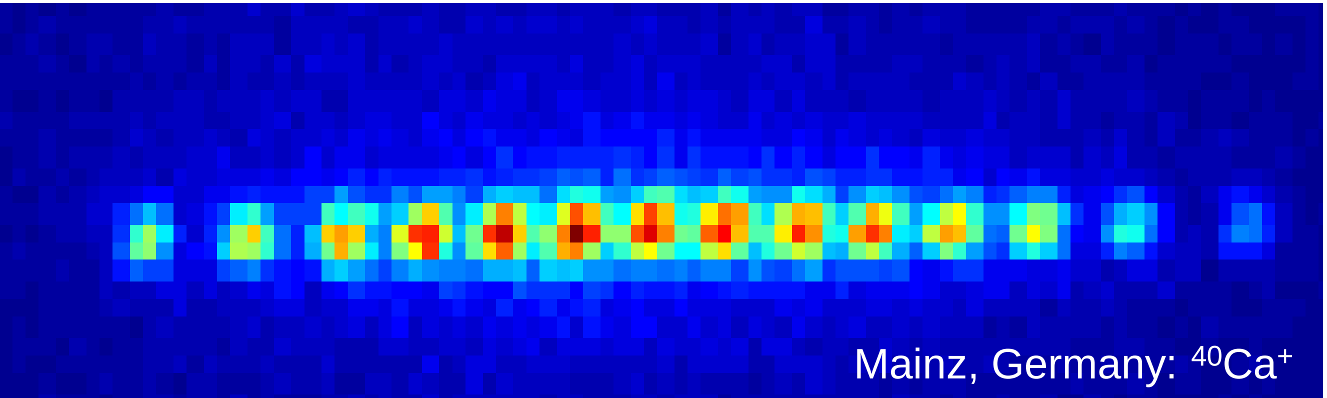
Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Rydberg excitations for fast entangling operations
- Quantum thermodynamics, heat engines, phase transitions
- Implanting single ions for a solid state quantum device



www.quantenbit.de

F. Schmidt-Kaler

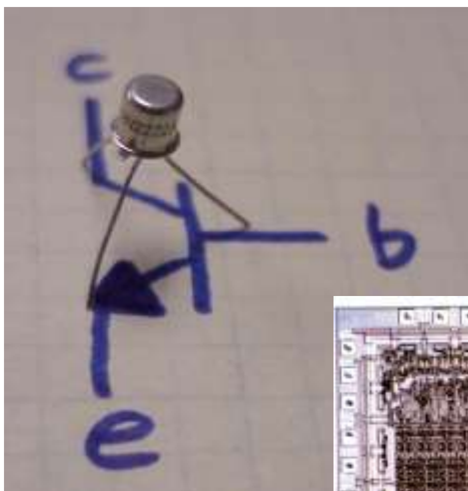
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

History of classical information processing

Wheels: 1671
Gottfried Leibnitz

Relais: Konrad Zuse Z1
1937 Berlin

Transistor:
Lilienfeld / 1925
Mataré, Welker / 1942
Shockley, Brattain / 1945

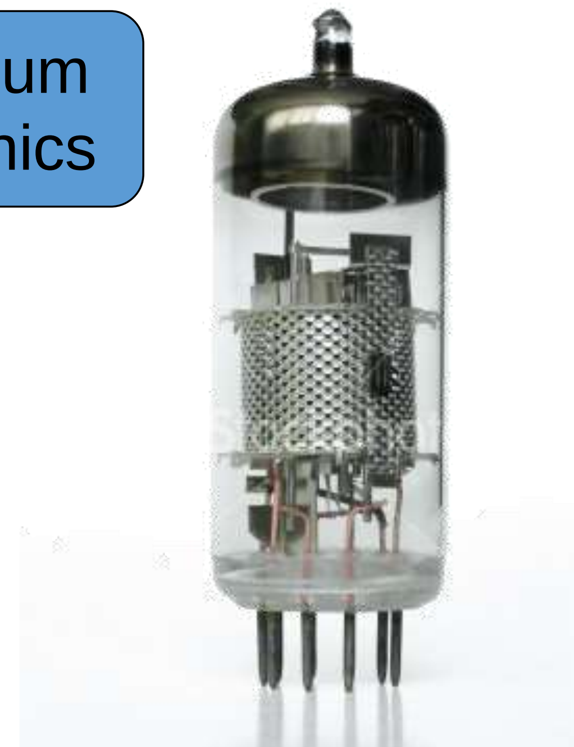


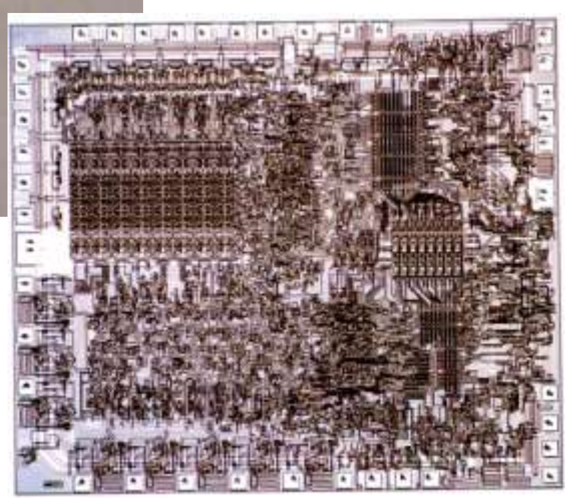
Mechanical computing

semiconductor electronics

in vacuum electronics

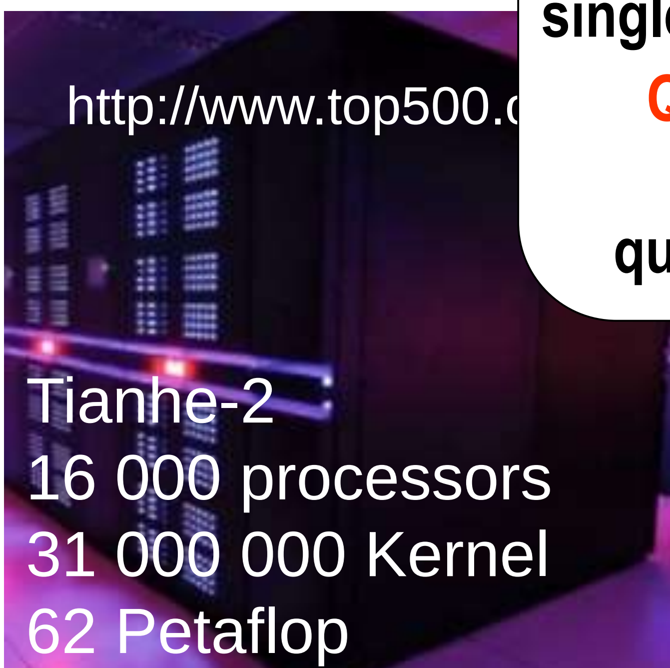
Electron tube:
Femming / 1904





Processor:
Intel 8080
/ 1974

Digital Information processing

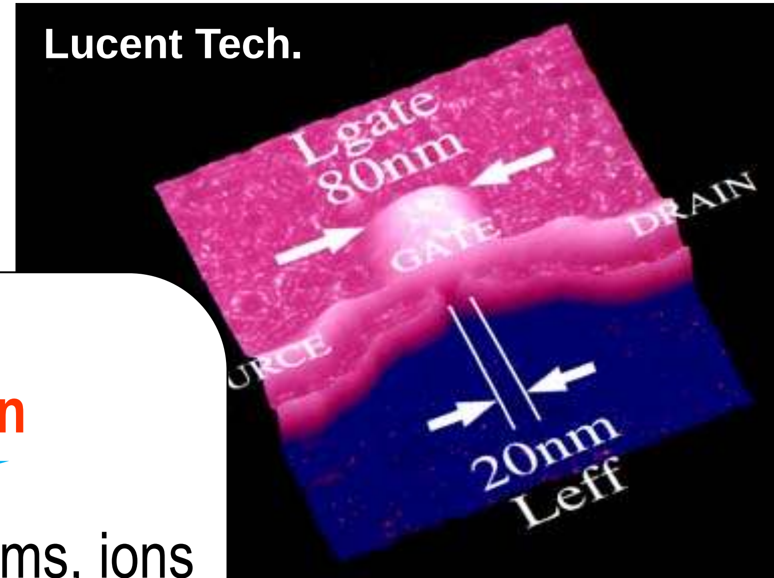


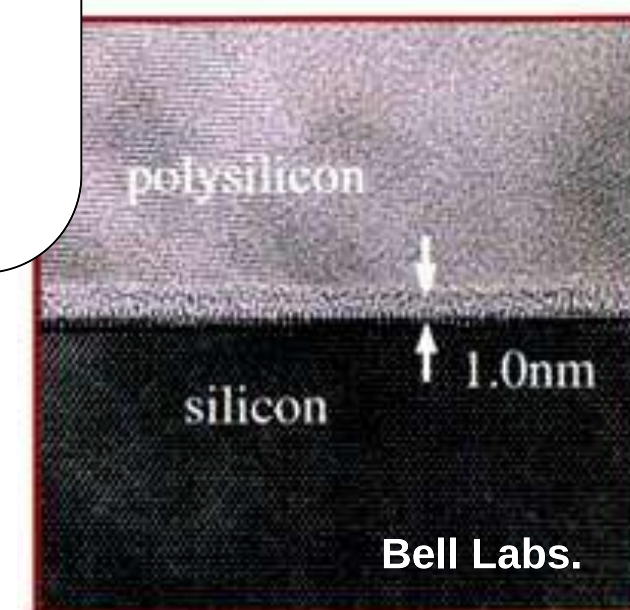
Miniaturization

single electrons, atoms, ions

Quantum effecs

quantum advantage



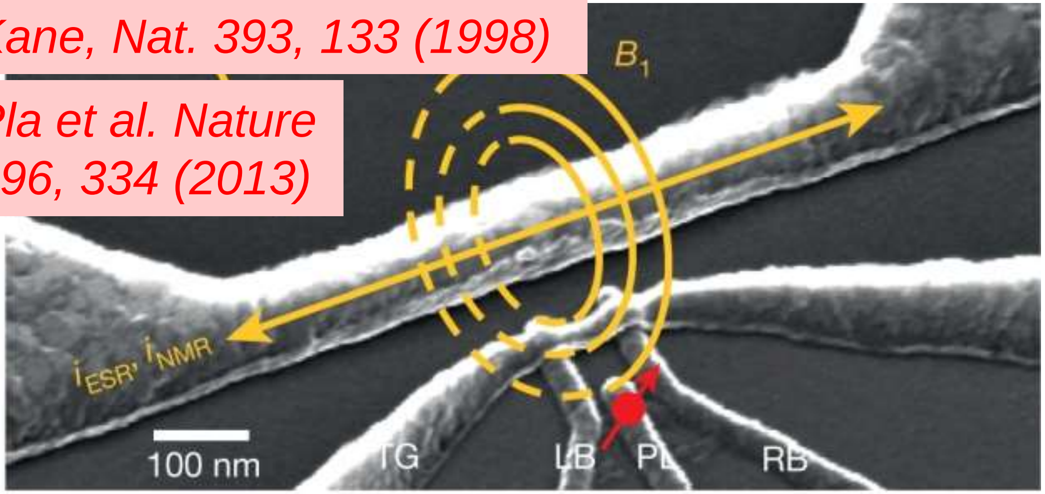


…enter the beauty of solid state physics

Single P-ion qubit devices in Silicium – Kane proposal

Kane, Nat. 393, 133 (1998)

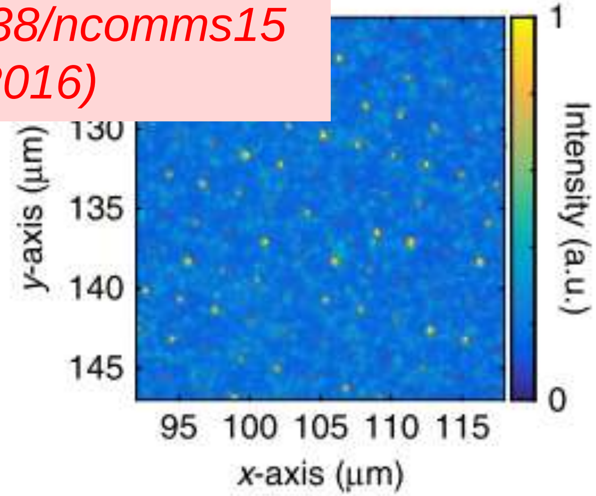
Pla et al. Nature 496, 334 (2013)

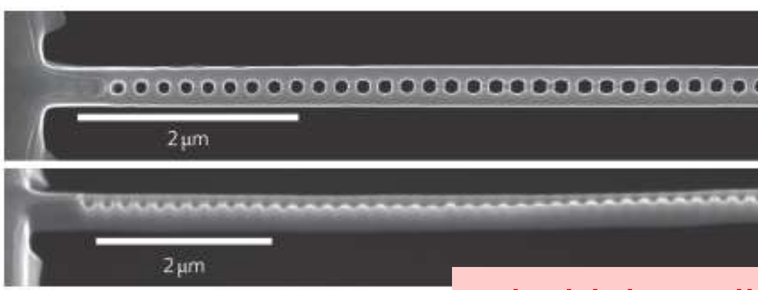


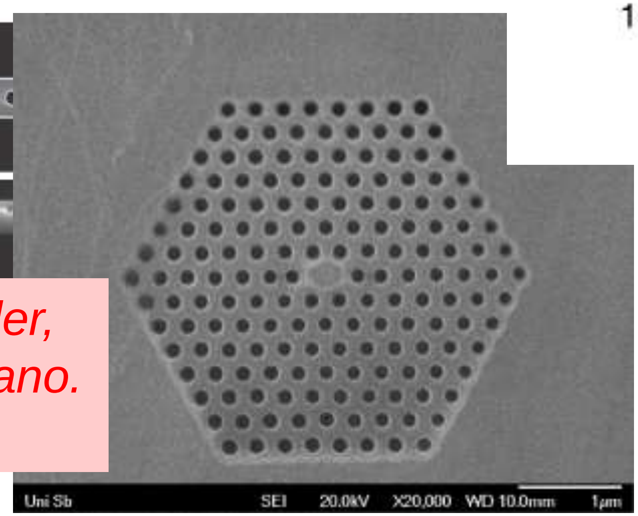
NV, SiV, Pr, …

Implant patterns

Schröder, Lukin et al. Nat. Comm. 10.1038/ncomms15376 (2016)







Diamond

functional nanostructures

Riedrich-Möller, et al., Nat. Nano. 7, 69 (2011)

Jelezko, Wrachtrup et al. Nat. Phys. 9, 139 (2013)

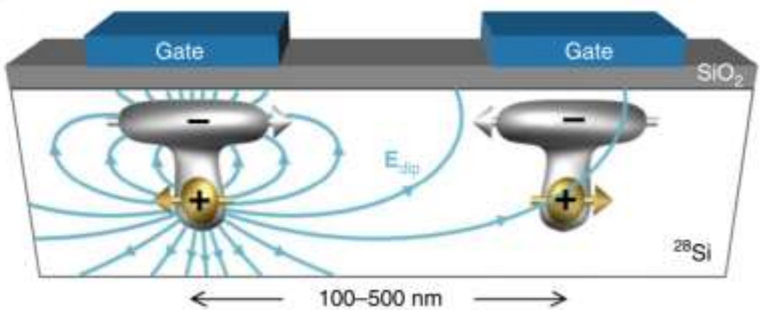
Single donor-based architecture

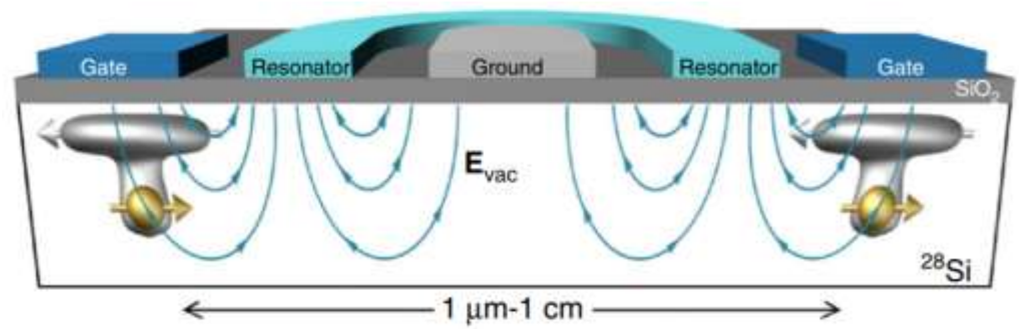
CENTRE FOR
QUANTUM COMPUTATION &
COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Silicon quantum processor with robust short & long-distance qubit couplings, P-ions in Si,

Kane, Nature 393, 133 (1998)

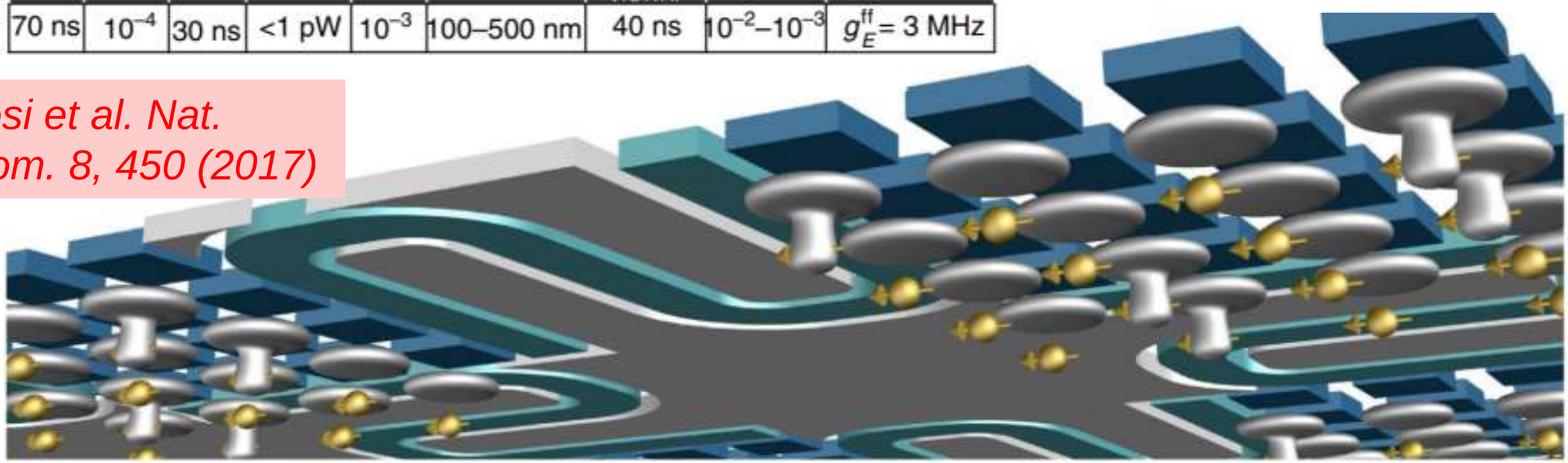
Pla et al. Nature 496, 334 (2013)





z-gates		*x*(*y*)-gates			2-qubit $\sqrt{iSWAP}$ gates			Photonic link
τ_π	Error	$\tau_{\pi/2}$	Power	Error	Distance	$\tau_{\sqrt{iSWAP}}$	Error	Coupling
70 ns	10^{-4}	30 ns	<1 pW	10^{-3}	100–500 nm	40 ns	10^{-2}–10^{-3}	g_E^{ff}= 3 MHz

Tosi et al. Nat. Com. 8, 450 (2017)



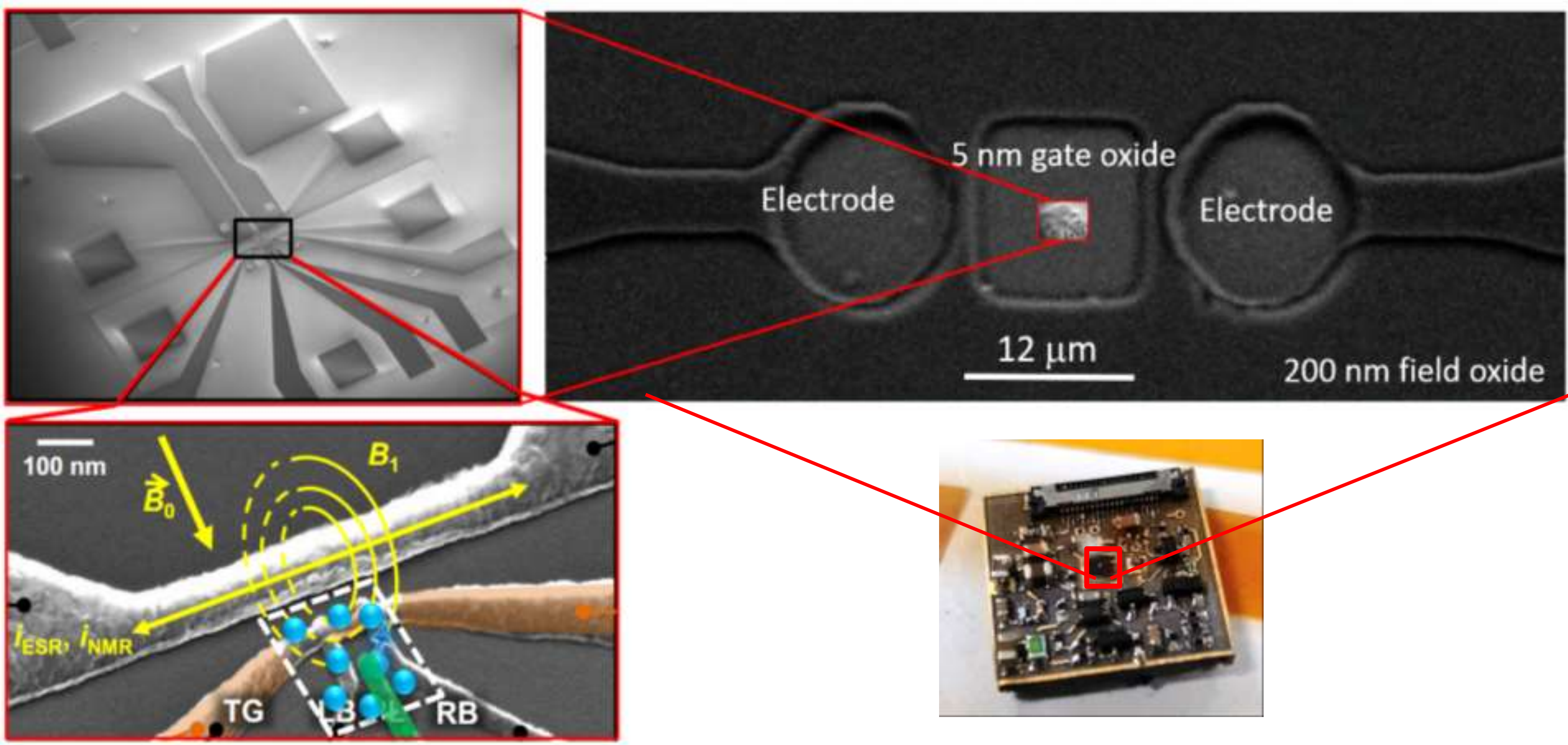
Single donor-based architecture

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Silicon quantum processor with robust short & long-distance qubit couplings, P-ions in Si,

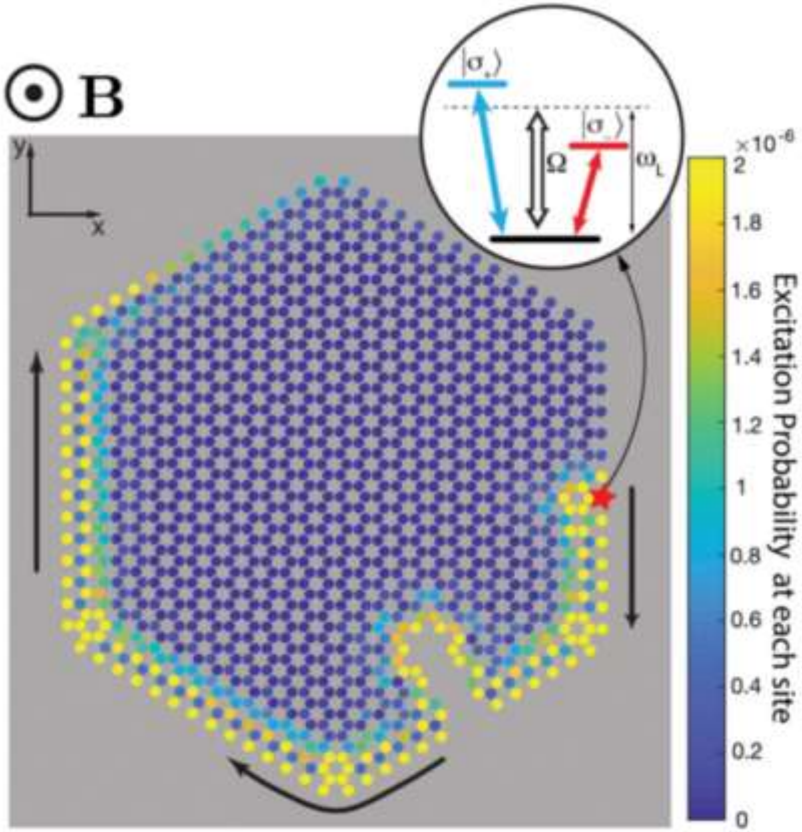
Pla et al. Nature 496, 334 (2013)

…… zoom in further …..



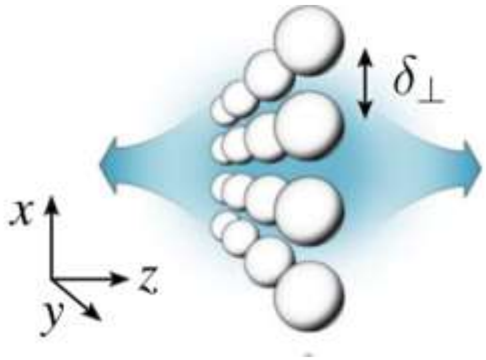
Proposal: Quantum simulation with atomic emitters

Perczel et al. PRL 119, 023603 (2017)



- Rare earth emitters in honey comb structure
- subwavelength spacing
- Protection againts imperfections and noise
- Topological edge states
- Propagating in unidirectional mode

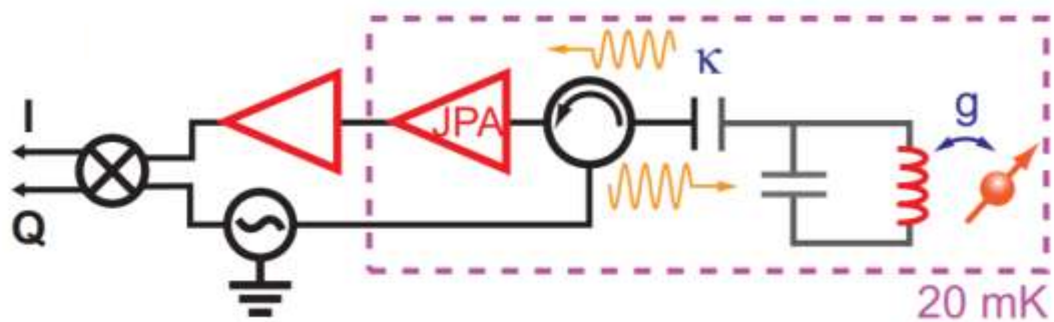
Guimond, et al, PRL 122, 093601 (2019)

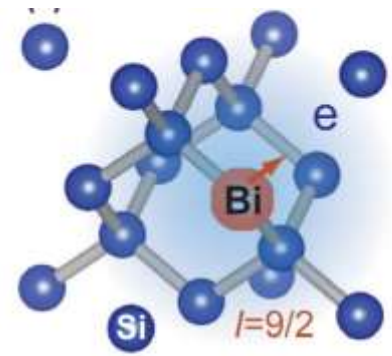


- Super/sub radiant states from array

Proposal: Hybrid single donor-based architecture

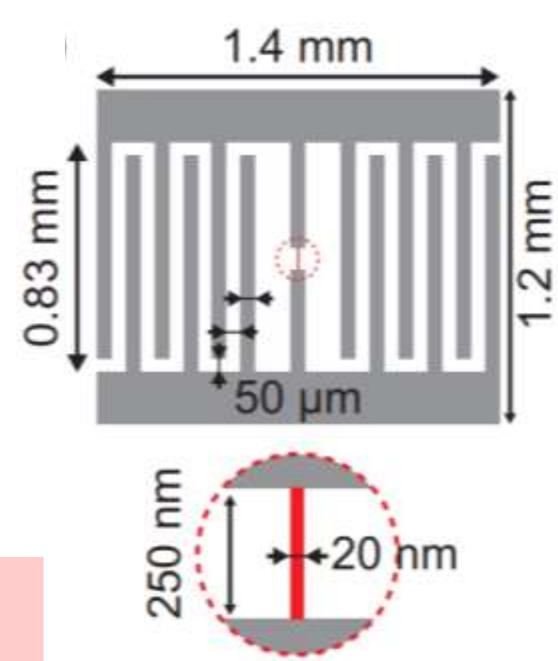
Interfacing single donors, e.g. Bi, to superconducting circuits





Join:

- Scalable architecture of superconducting qubits
- Long coherence times of single donors



Kurizki et al.
PNAS 112, 3866 (2015)

Haika et al. PRA
95, 022306 (2017)

Single donor-based architectures

- Silicon quantum processor with robust short & long-distance qubit couplings, P-ions in Si
- large single photon emitter structures for quantum simulation with e.g. REI, NV's, SiV's …
- Interfacing single donors, e.g. Bi, Er, NV … to superconducting circuits

Pla et al. Nature 496, 334 (2013)

Haika et al. PRA 95, 022306 (2017)

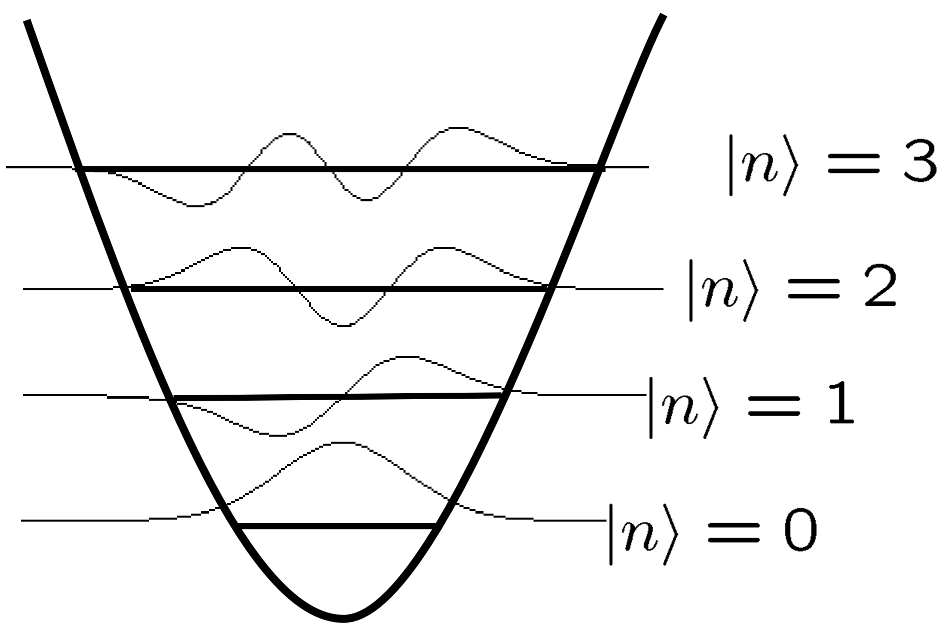
Perczel et al. PRL 119, 023603 (2017)

Challenges:

- implant arrays of single donor atoms
- with technological interesting ions, e.g. P, REI, .. pure
- in 5…15nm depth with <10nm accuracy
- with respect to gate electrodes

Cold ions source for microscopy and impantation

- Load and cool, eventually extract, single ions directly
- Trapping of all charged particles, with large range of *m/q*
- Doppler cooling, eventually cooling to quantum mechanical ground state, Heisenberg uncertainty relation $\Delta p_x \, \Delta x \geq \hbar/2$

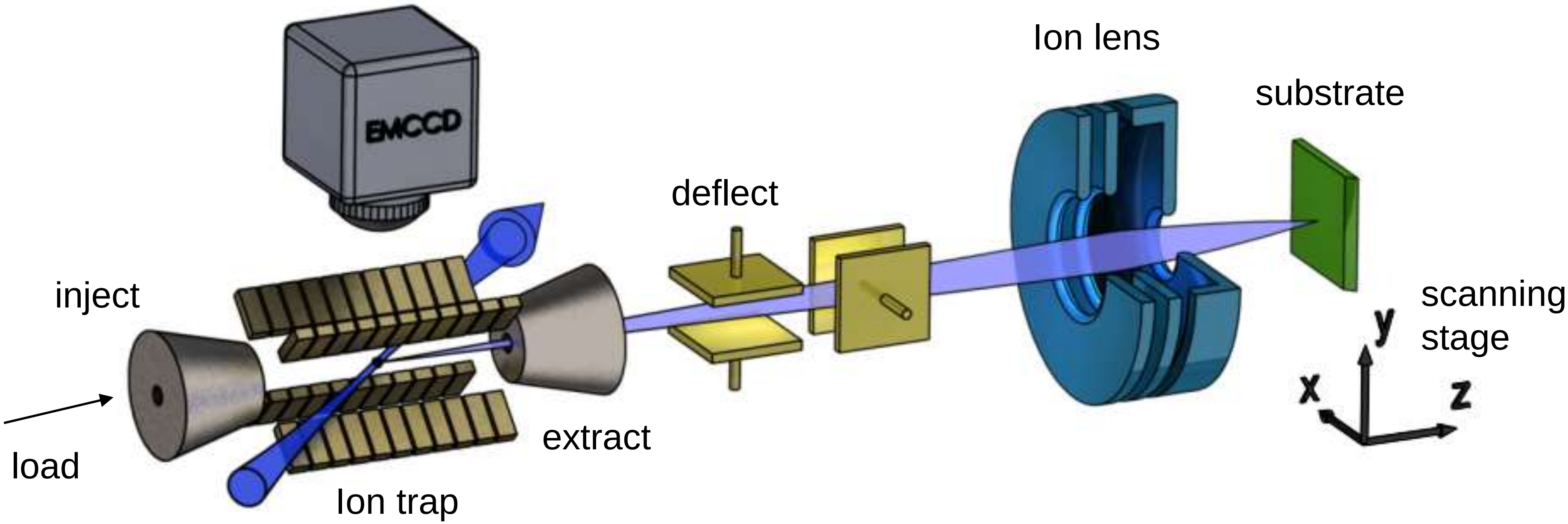


$\Delta x_{n=0} \sim 5\ldots10\text{nm}$

Paul trap as deterministic source - features

- top-down method
- deterministically single ion
- various doping ion species

- low energies (0eV… 6keV… 20keV)
- nm resolution
- low throughput

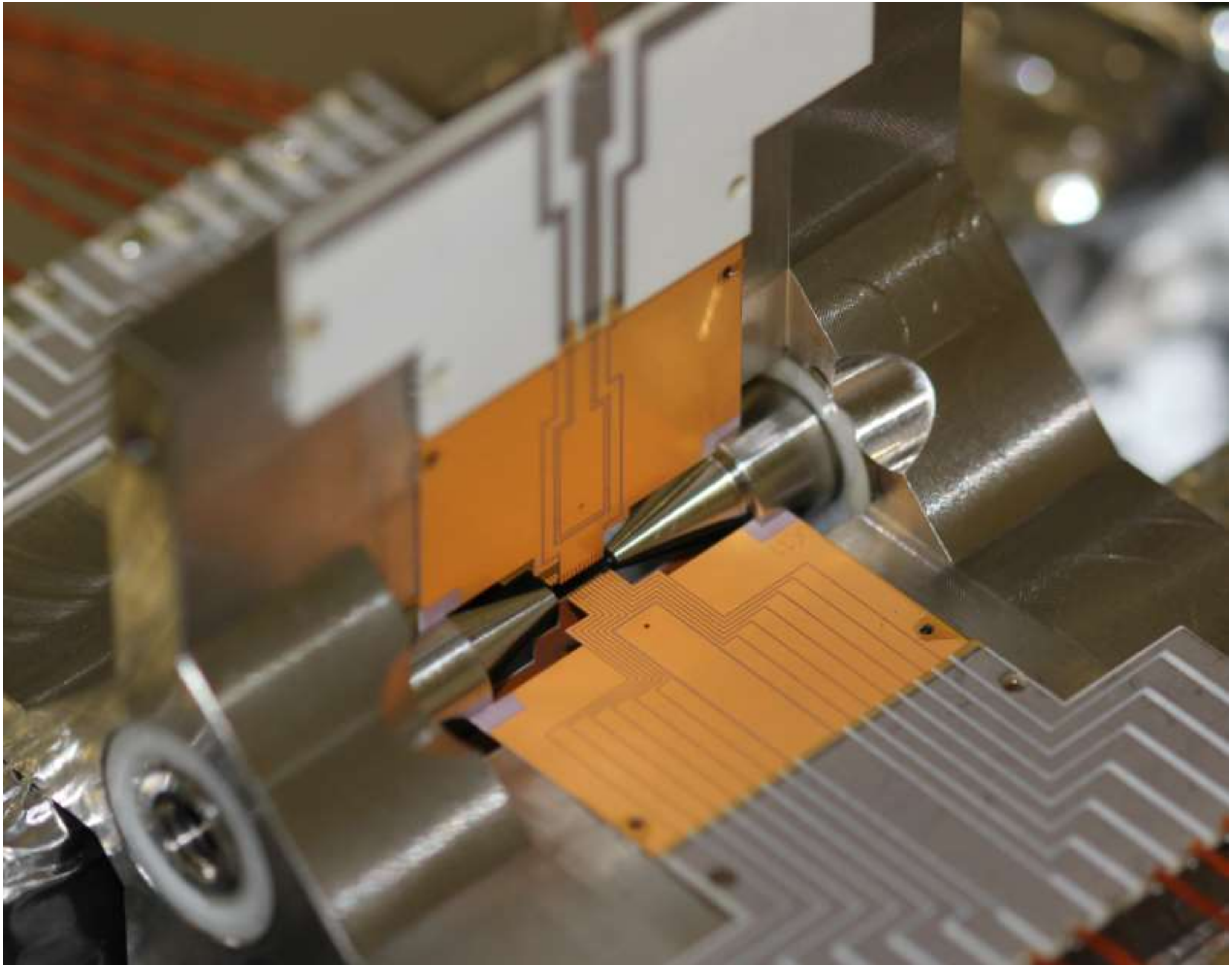


Jakob et al, PRL 117, 043001 (2016)

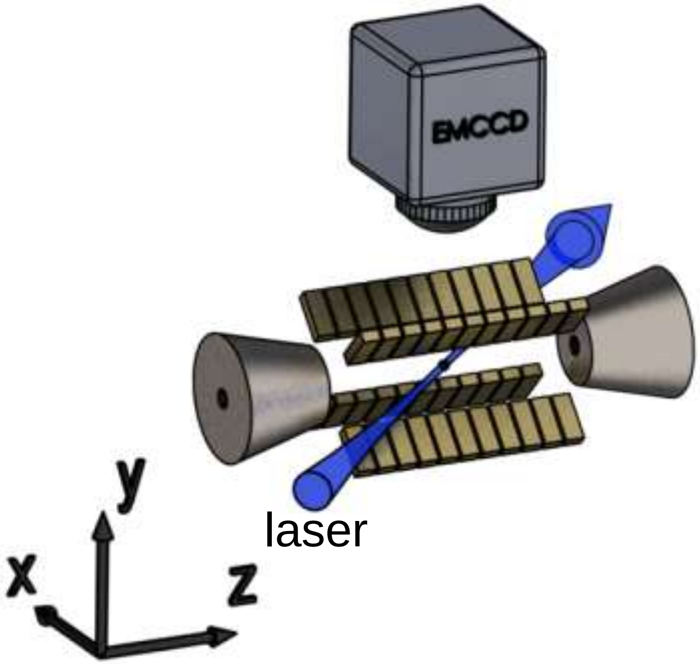
Schnitzler, et al., PRL 102, 070501 (2009)

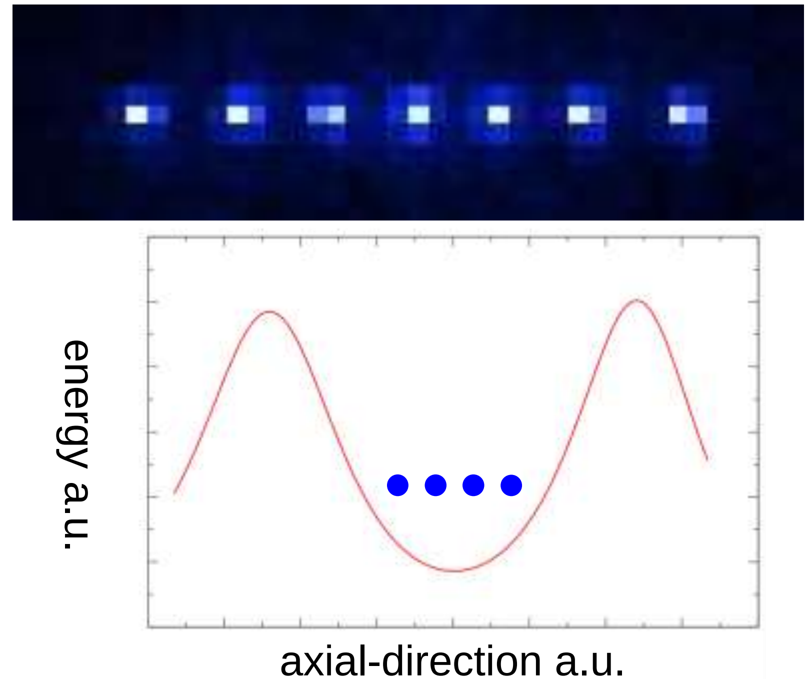
Meijer et al, Appl. Phys. A (2006) 83: 321

Segmented linear Paul trap



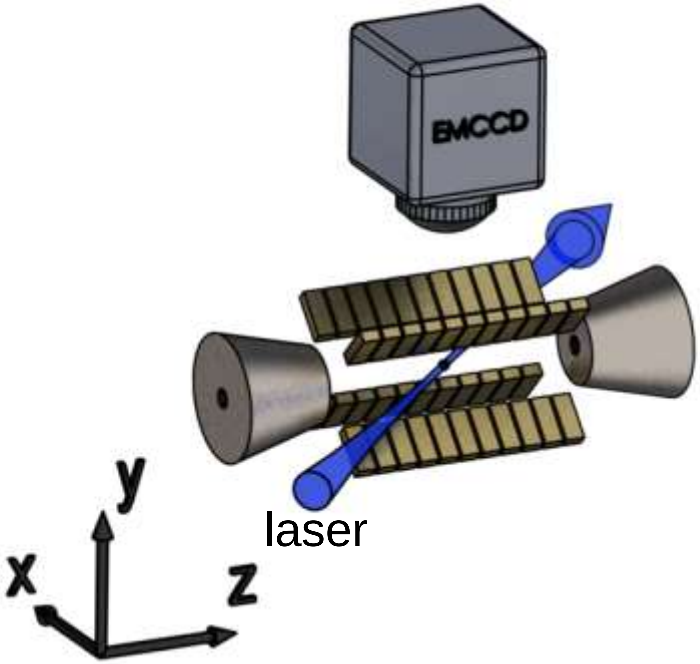
Loading and Cooling of Ca^+ Ions



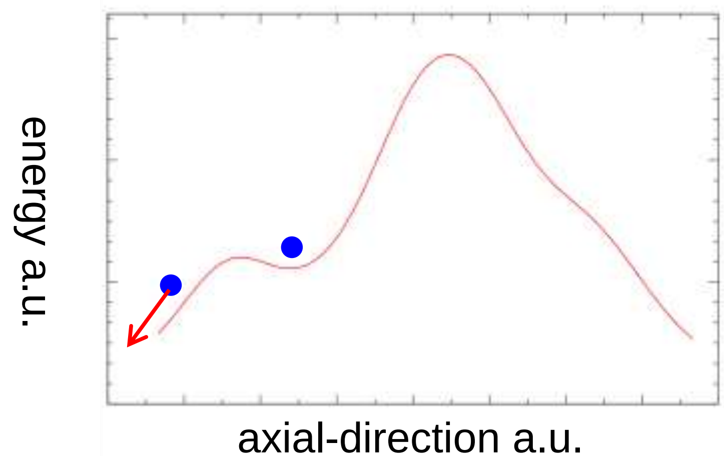


string of ions

Loading and Cooling of Ca^+ Ions

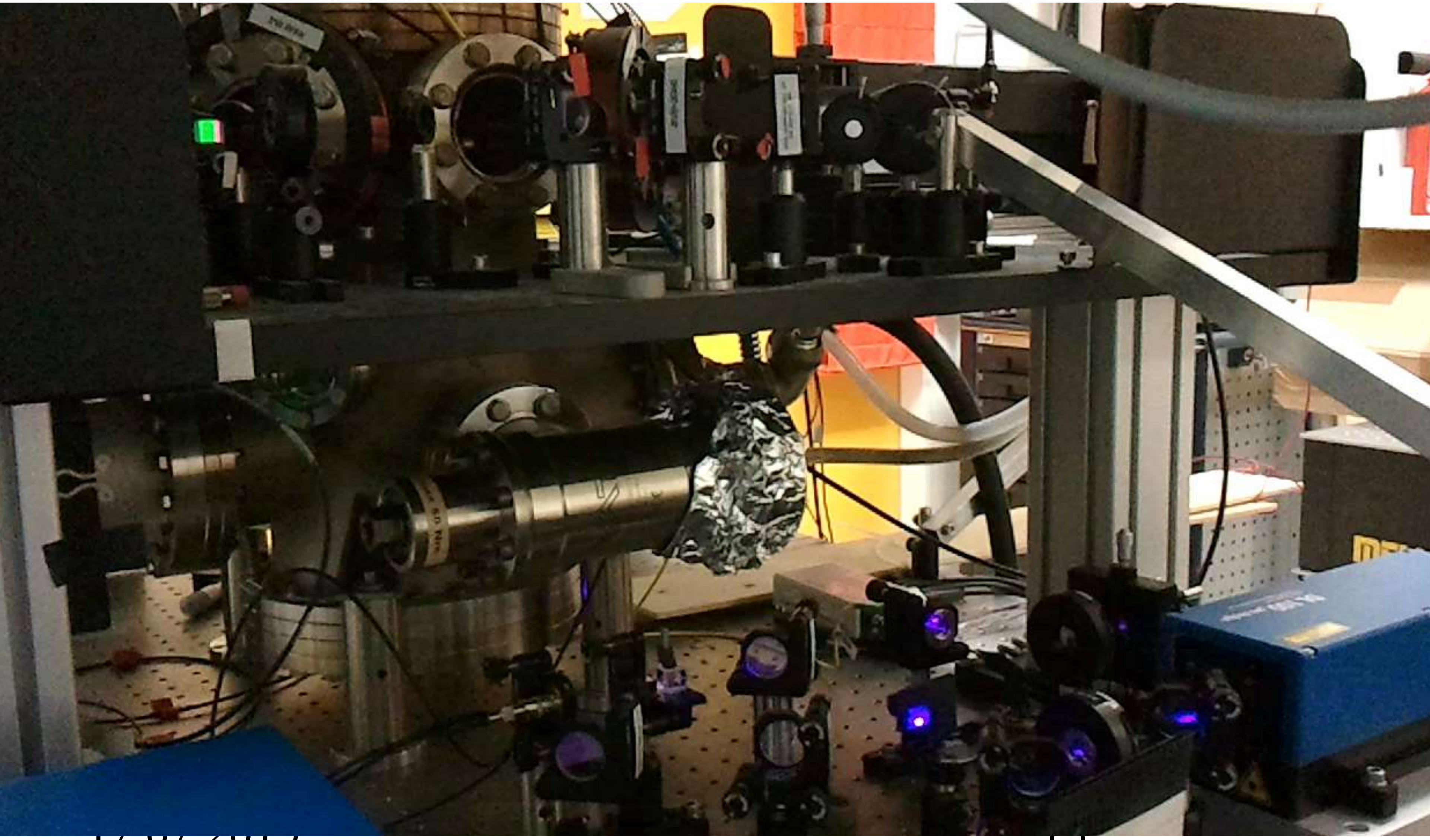


potential is shaped to force excess ions to leave the trap

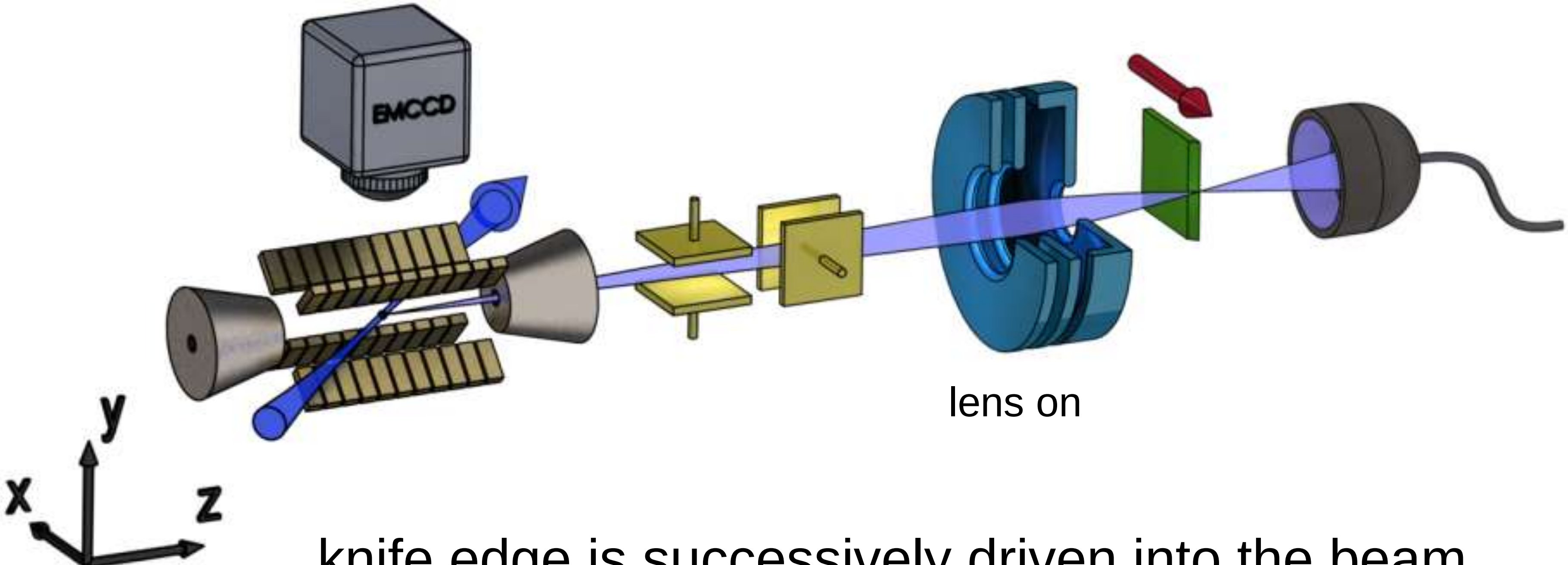


exacly one ion is trapped

Automatic Extraction of Ions



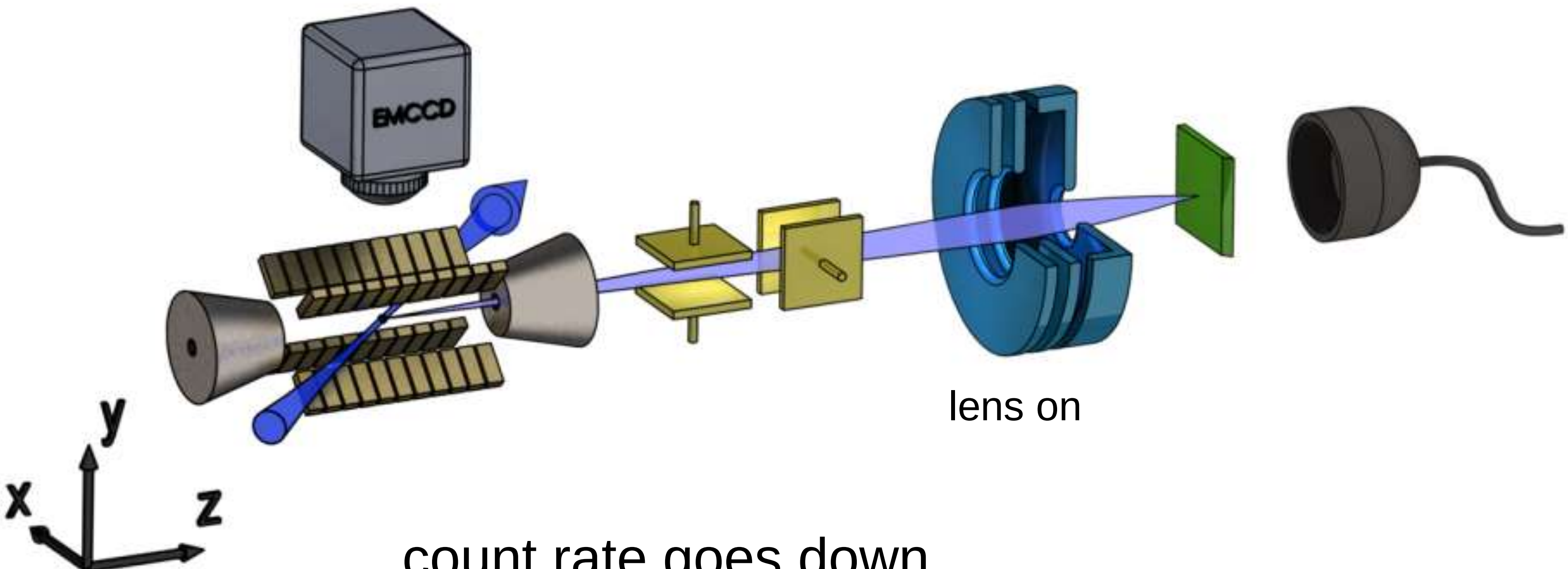
Beam profiling



lens on

knife edge is successively driven into the beam

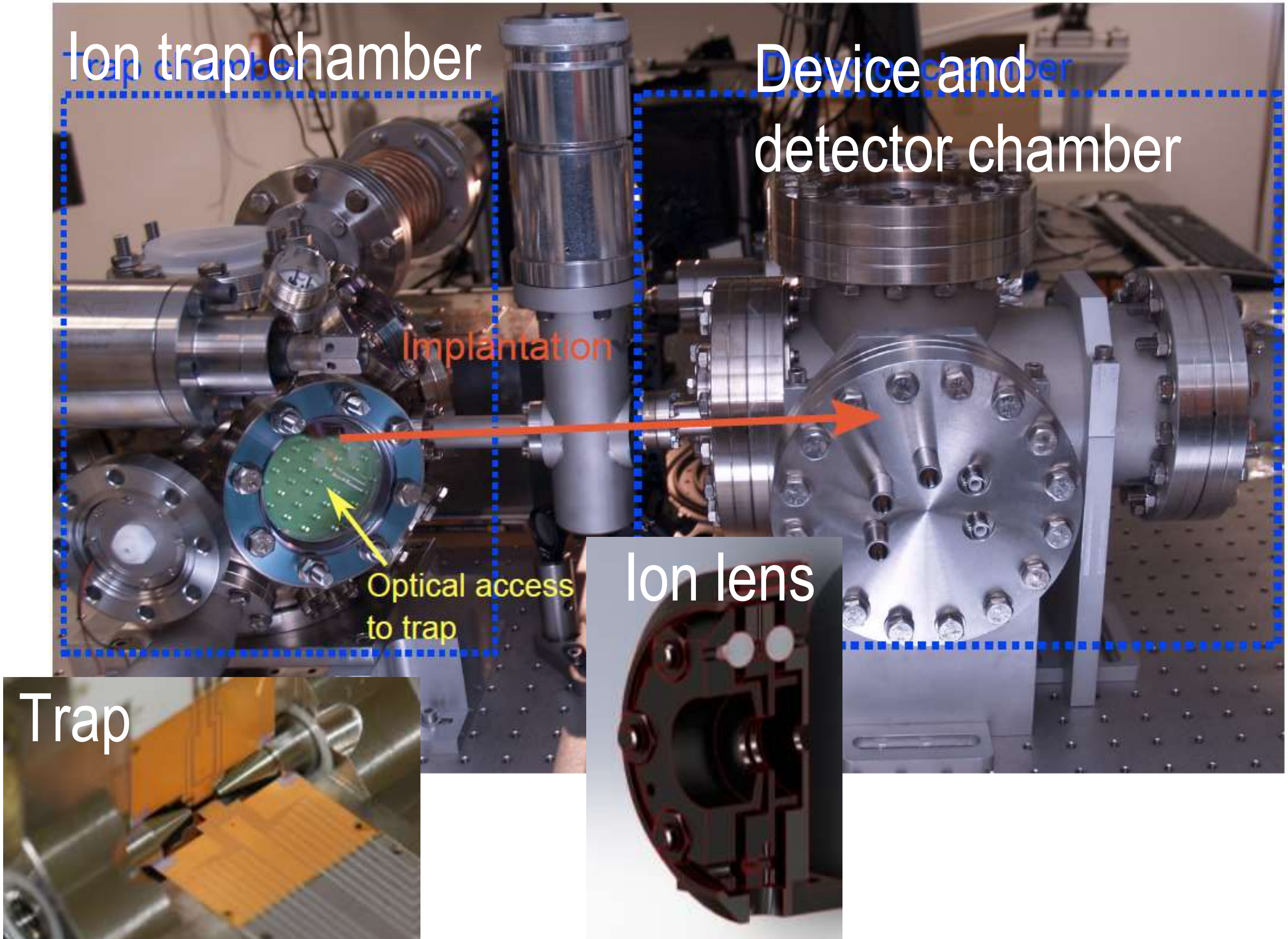
Beam profiling



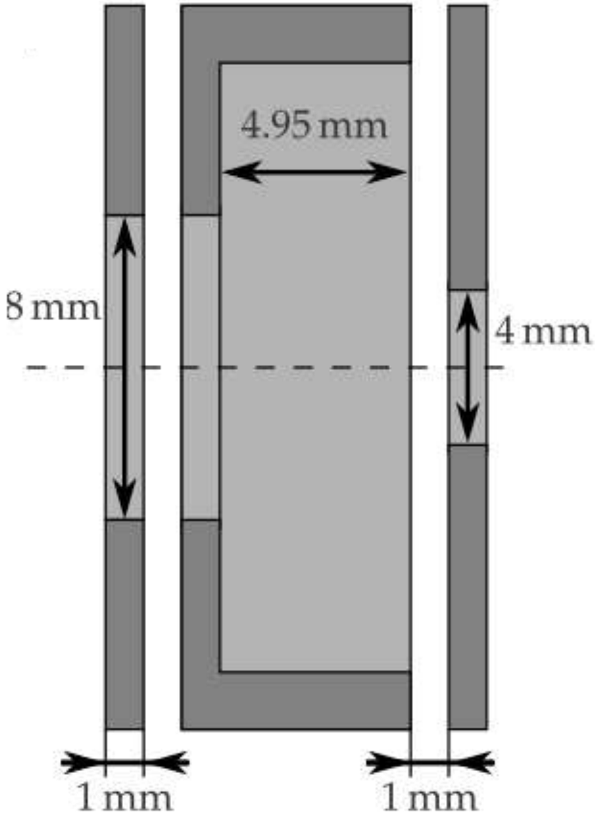
lens on

count rate goes down
revealing the beam cross section

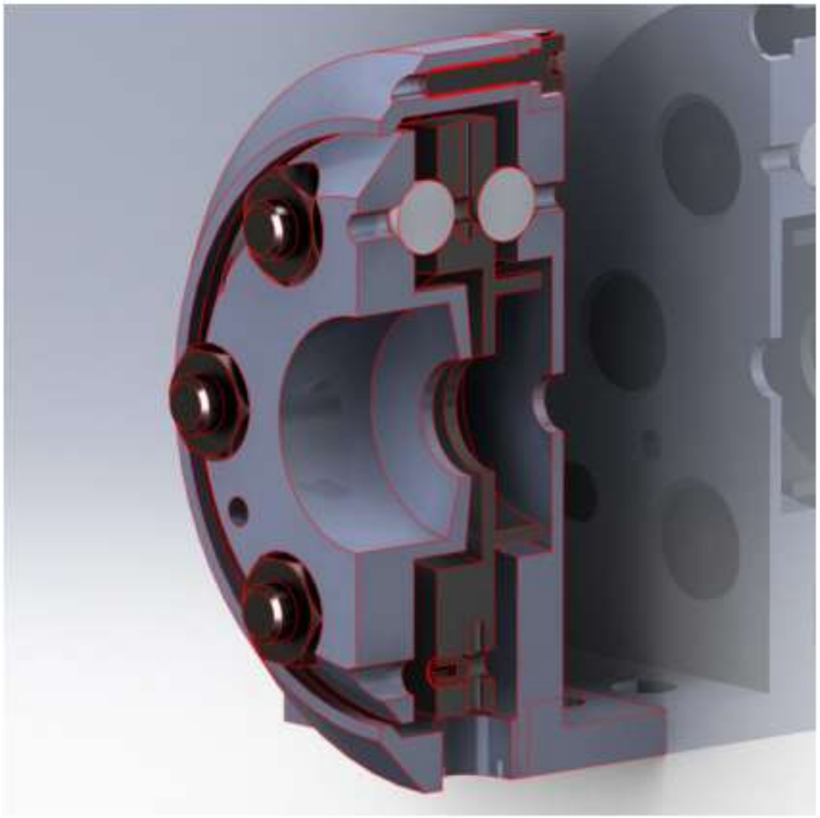
Complete experimental setup



Electrostatic Einzel-lens

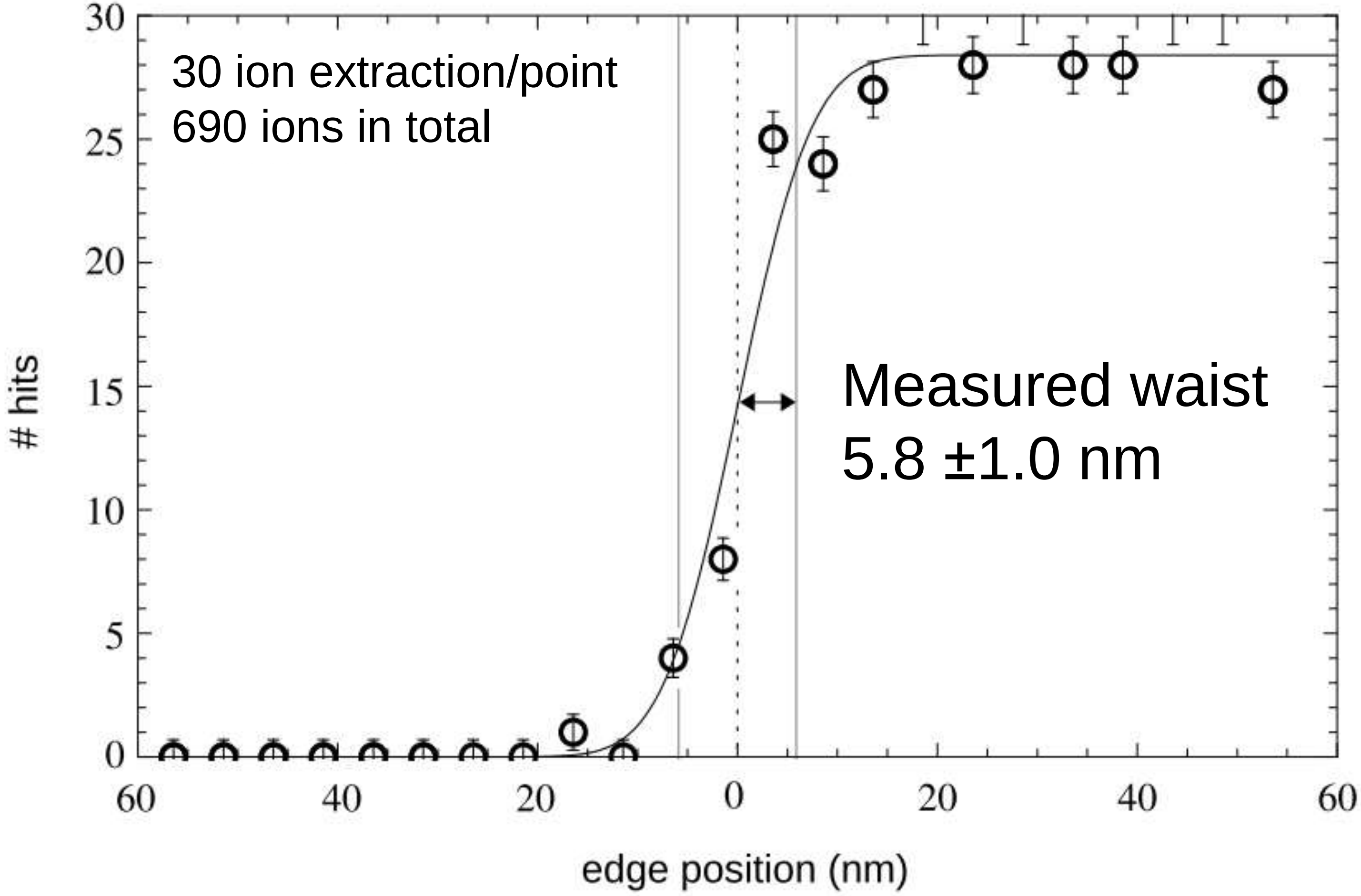


$f \cong 12mm$



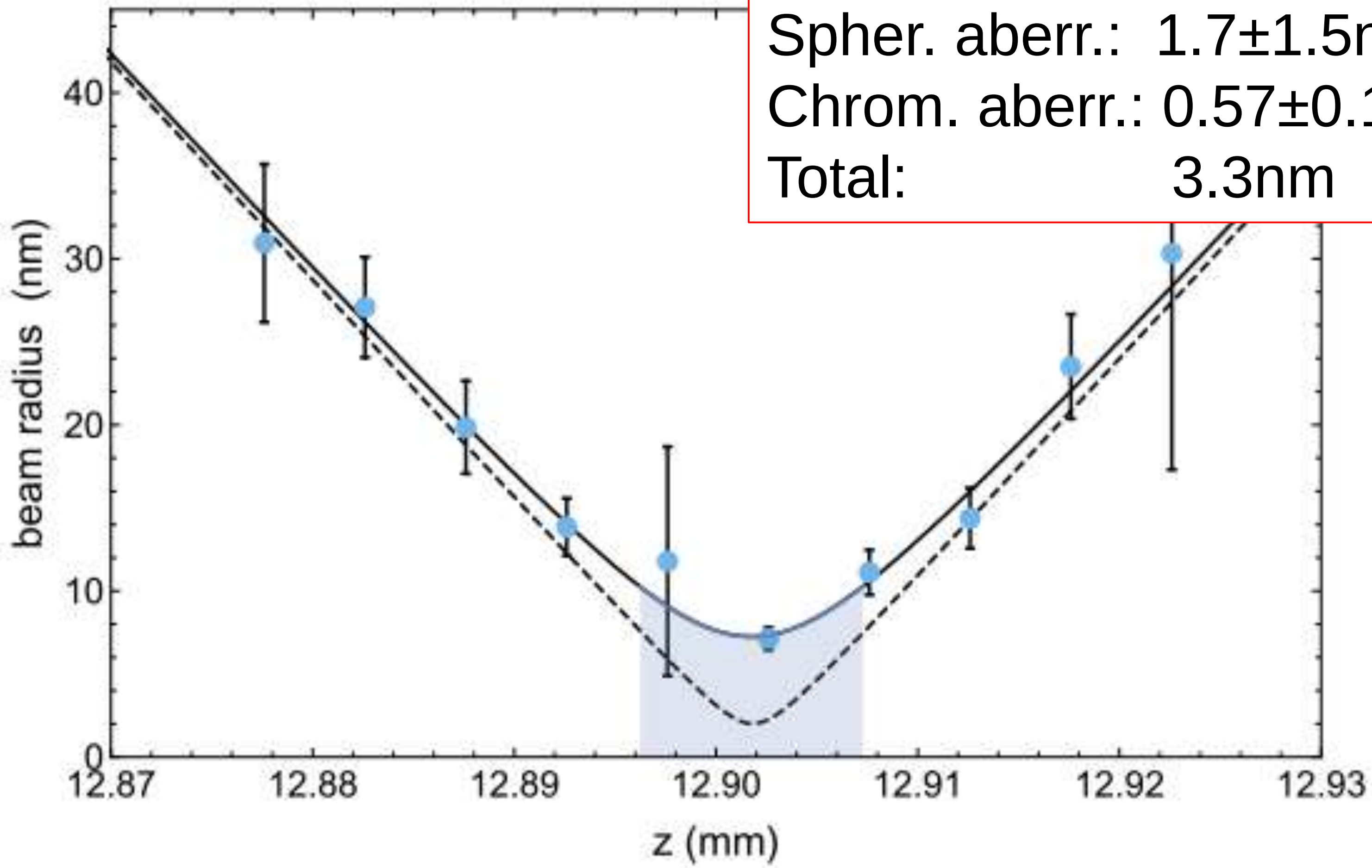
Lens characterization
G. Jakob, PhD (2017)

Beam profiling - result



Jakob et al, PRL 117, 043001 (2016)

Beam profiling - result



Source size: 2.1nm
Spher. aberr.: 1.7±1.5nm
Chrom. aberr.: 0.57±0.17nm
Total: 3.3nm

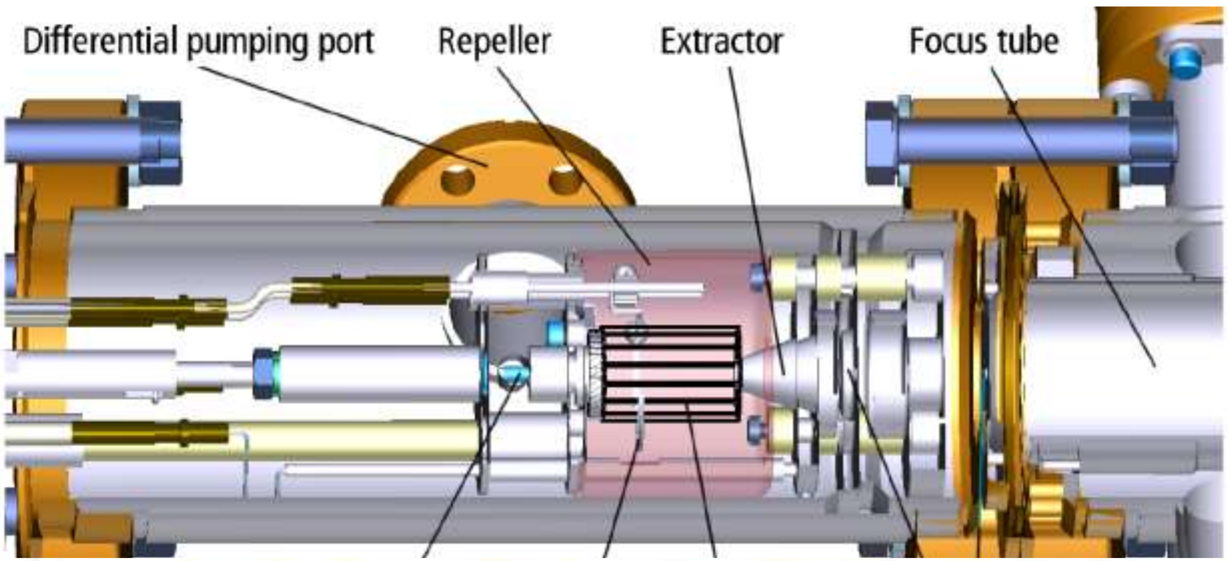
Determined source size $\sigma_x = \sigma_y \cong$ 50nm, but vibrations limit spot

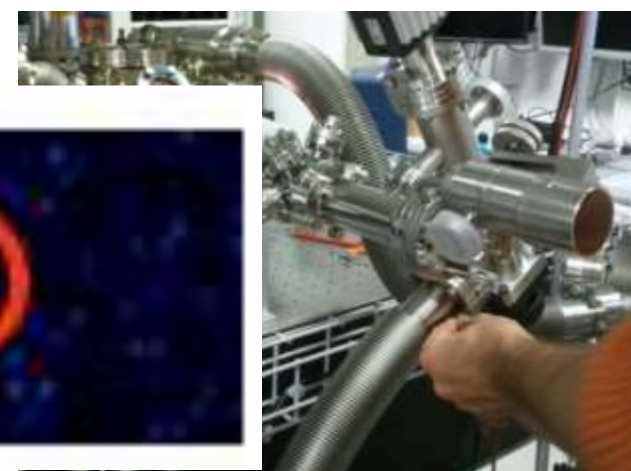
Universal deterministic ion source

- Extending to more ion species
- Combinations of ion species

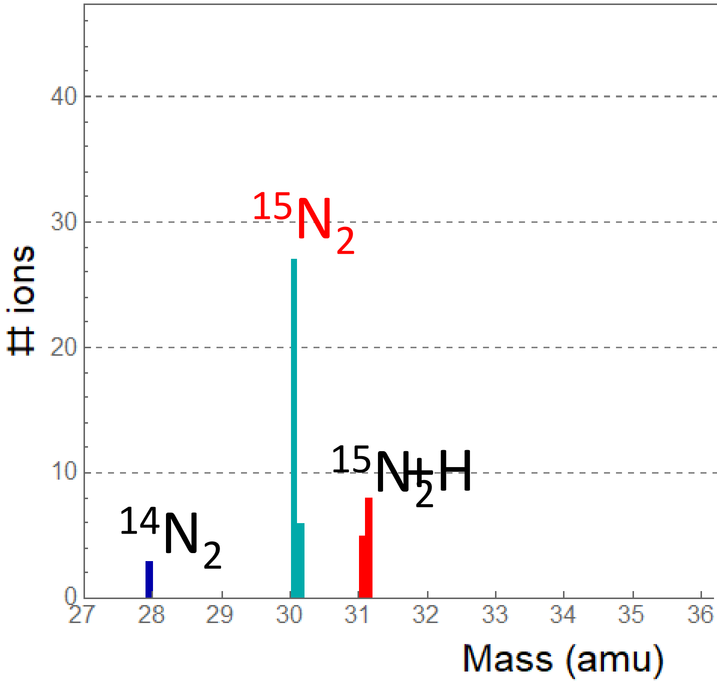
- Gas targets
- Laser ablation of solid targets
- Wien filter and ToF identification

Nitrogen N_2^+,
Praseodymium,
Argon,
Xenon,
Cerium,
Phosphorous,
Bismut



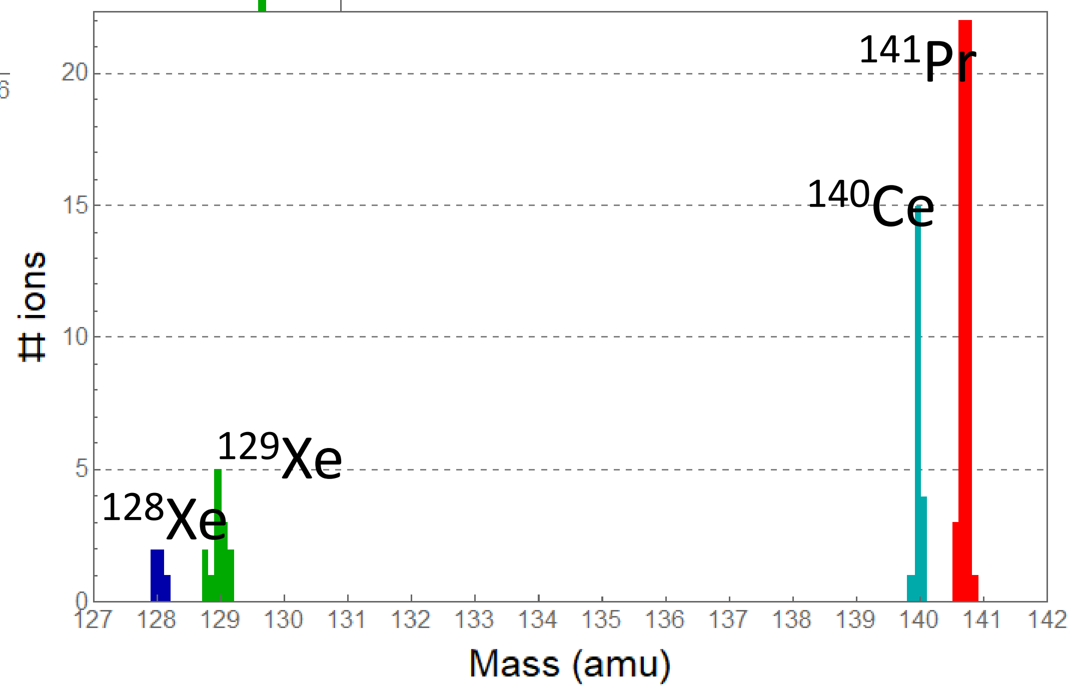


TOF data identifying doping ions



6keV acceleration

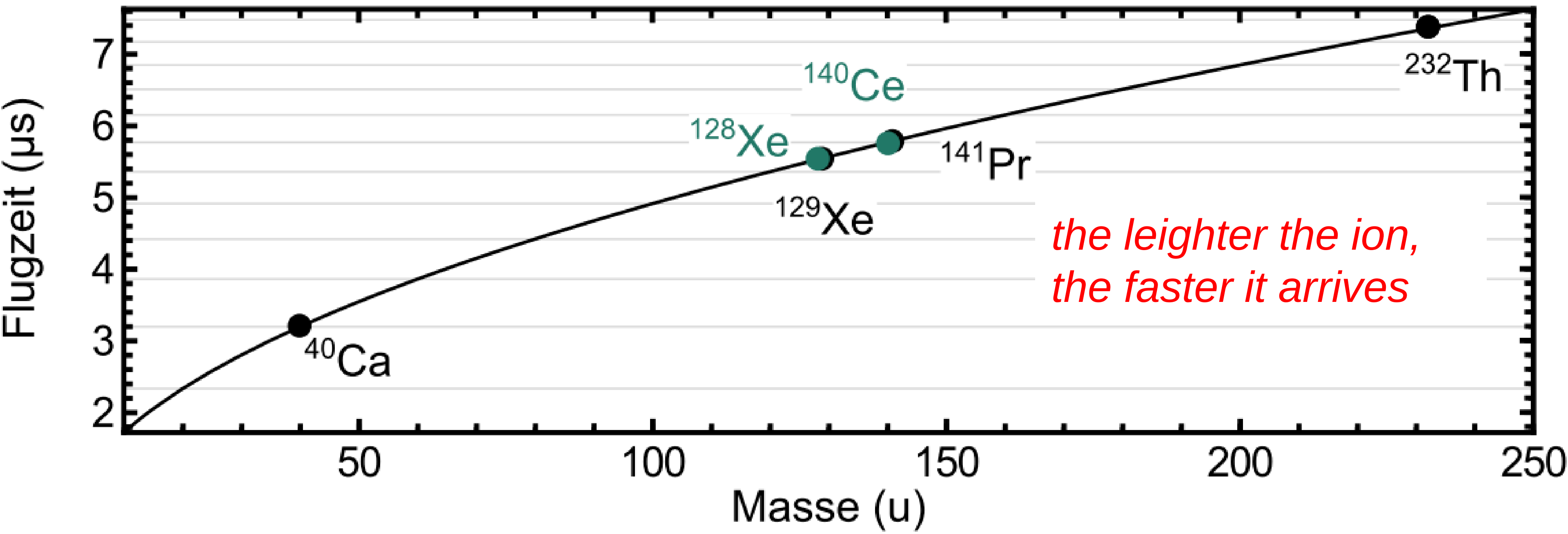
the leighter the ion, the faster it arrives



Deflect the Ca^+ away later to get only Pr^+

Groot-Berning et al, PRA 99, 023420 (2019)

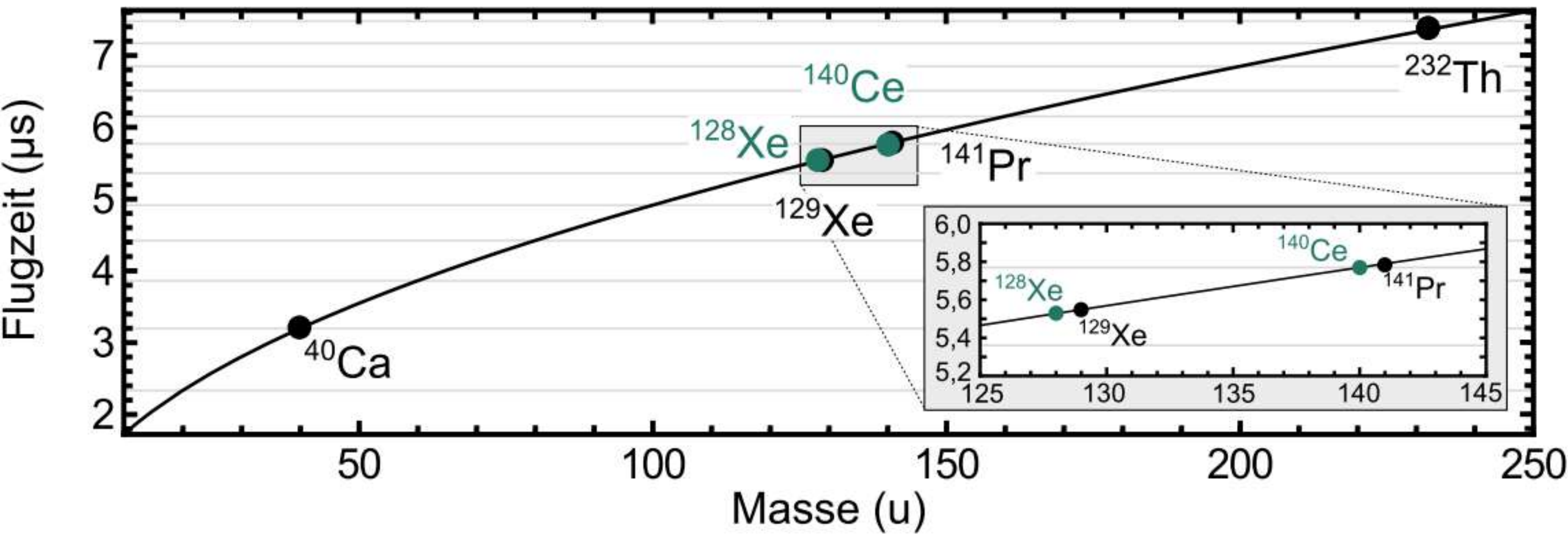
TOF data identifying doping ions



Luis Ortiz *K. Groot-Berning* *F. Stopp*

Groot-Berning et al,
PRA 99, 023420 (2019)

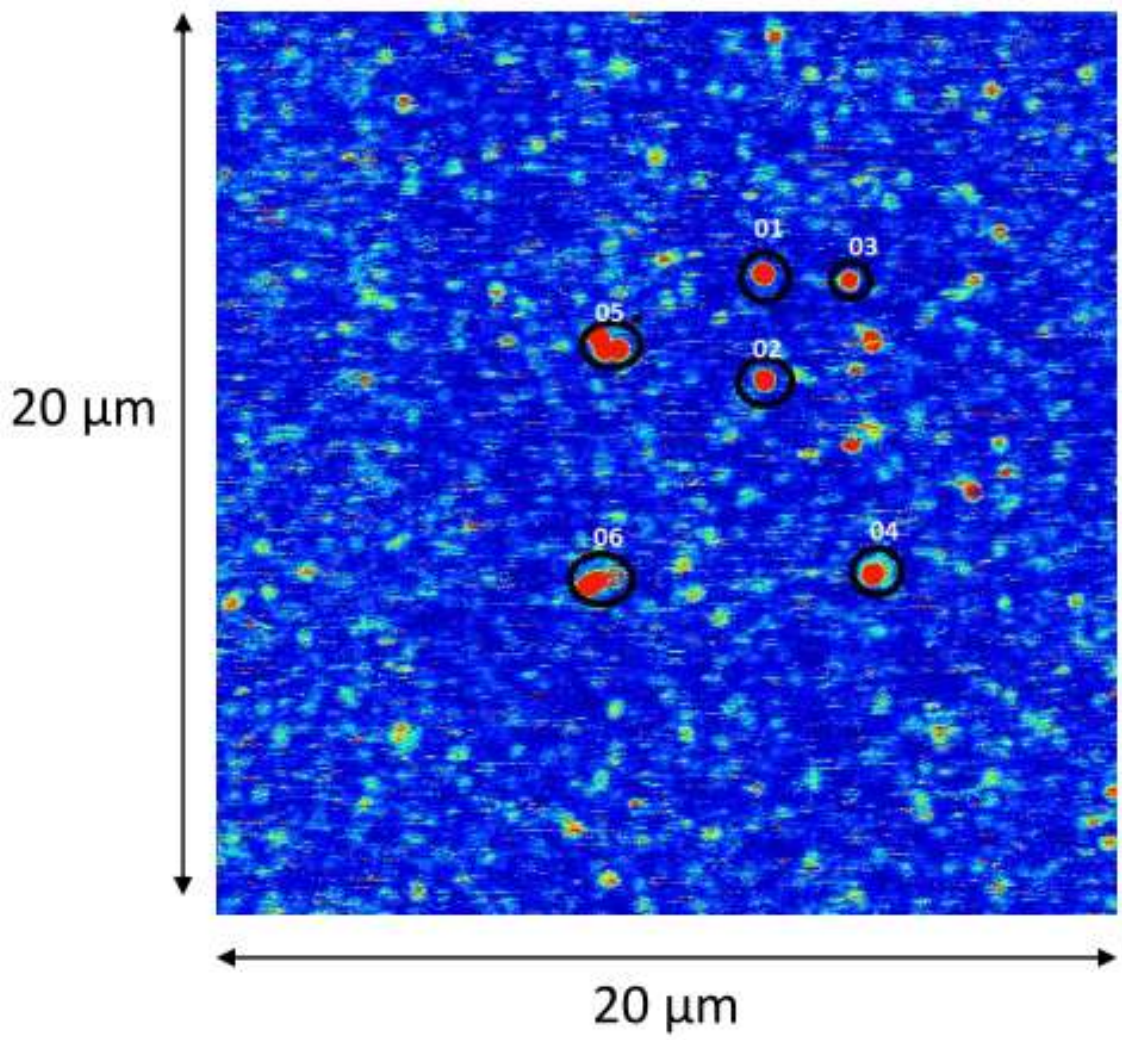
TOF data identifying doping ions



Luis Ortiz *K. Groot-Berning* *F. Stopp*

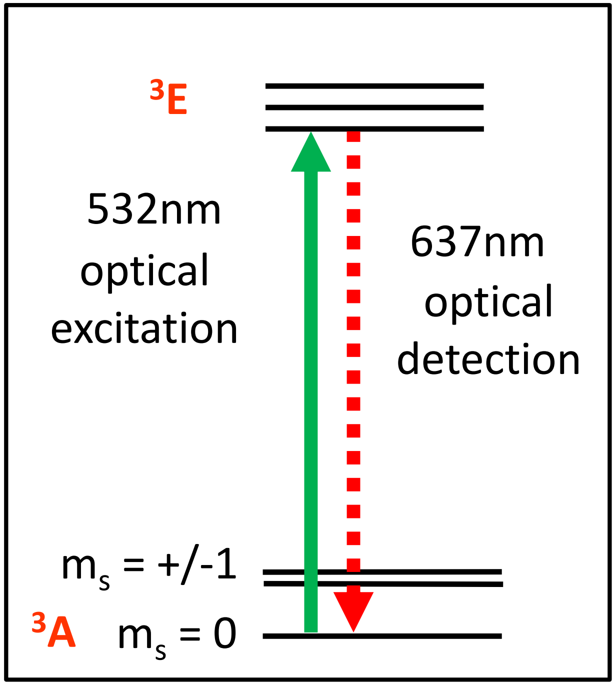
Groot-Berning et al, PRA 99, 023420 (2019)

Single ion doping with Nitrogen molecular ions



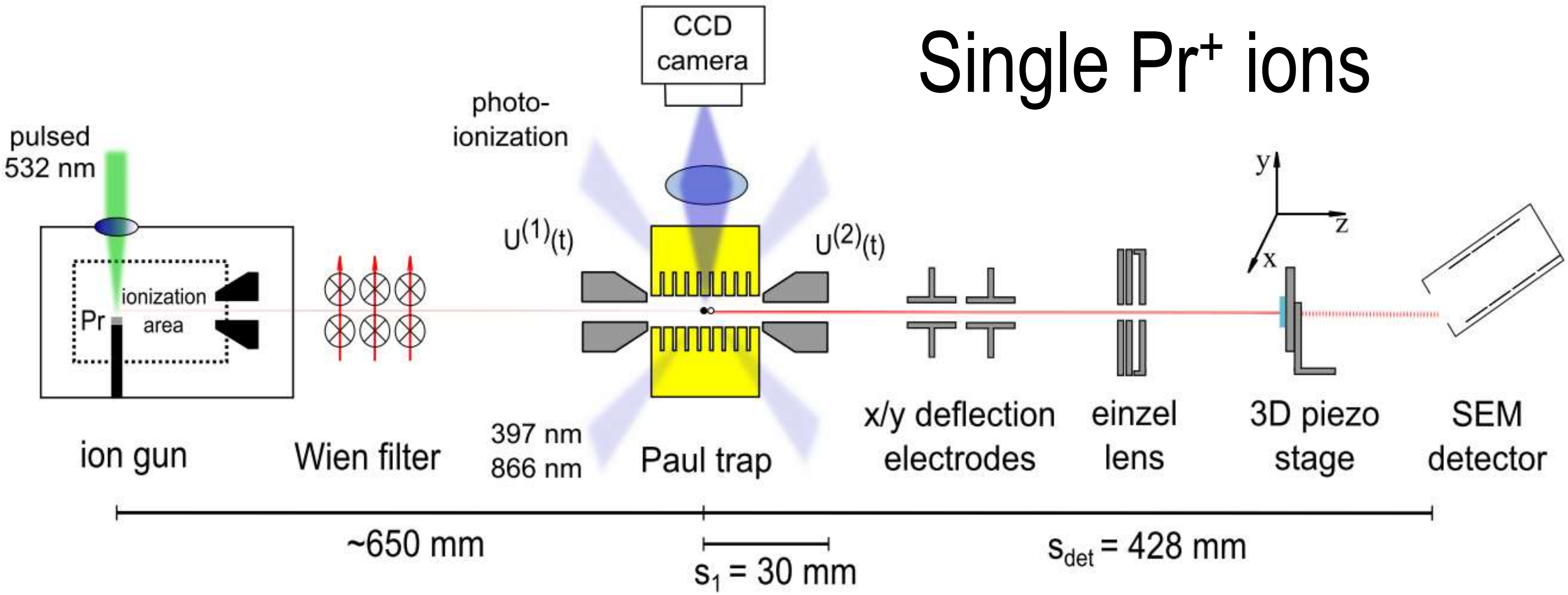
- $^{15}N_2^+$ ions implanted from isotopically pure gas sample @6keV
- NV centers observed
- 0.6% yield

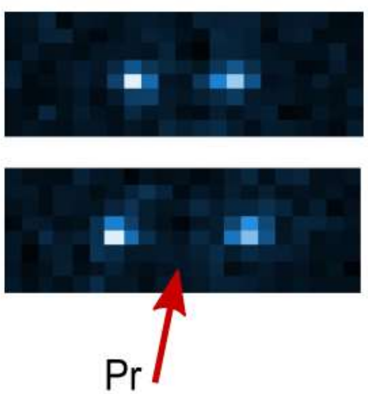
- NV- centers
- Nuclear species identified from ODMR resonance

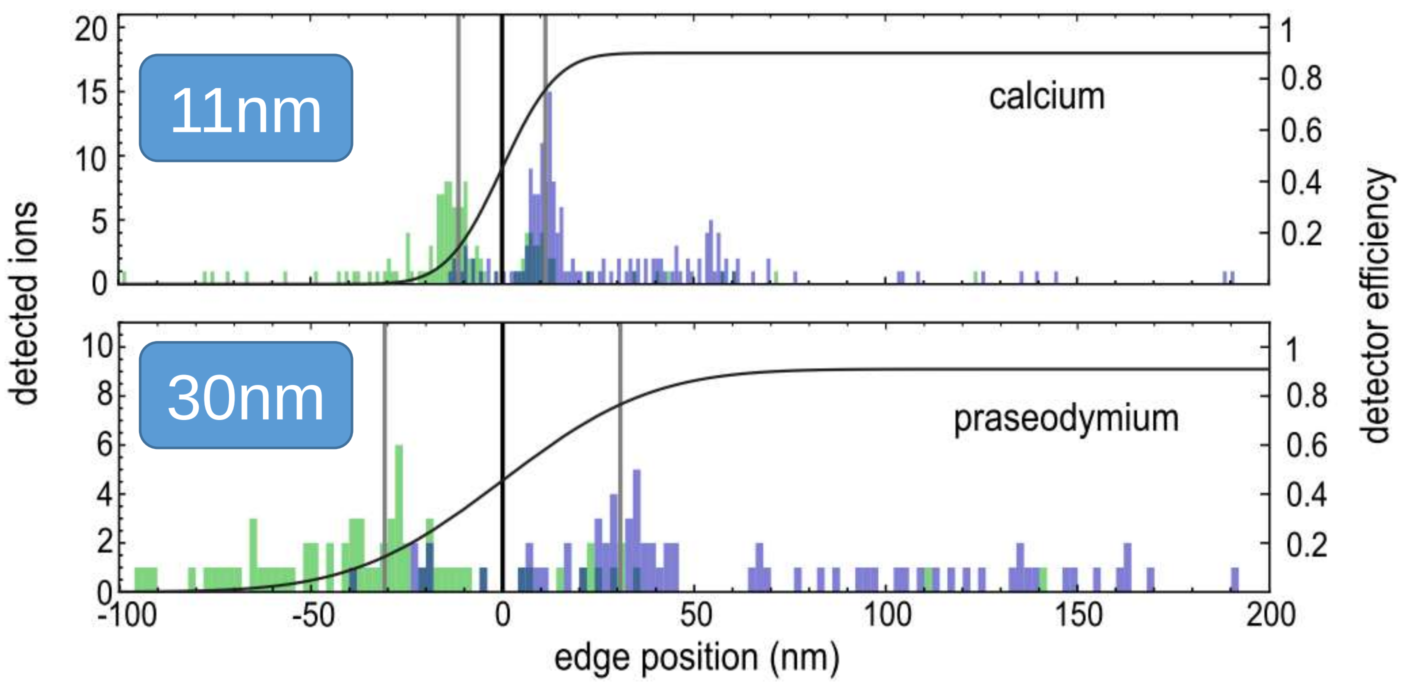


with F. Jelezko @ Ulm

Single Pr^+ ions

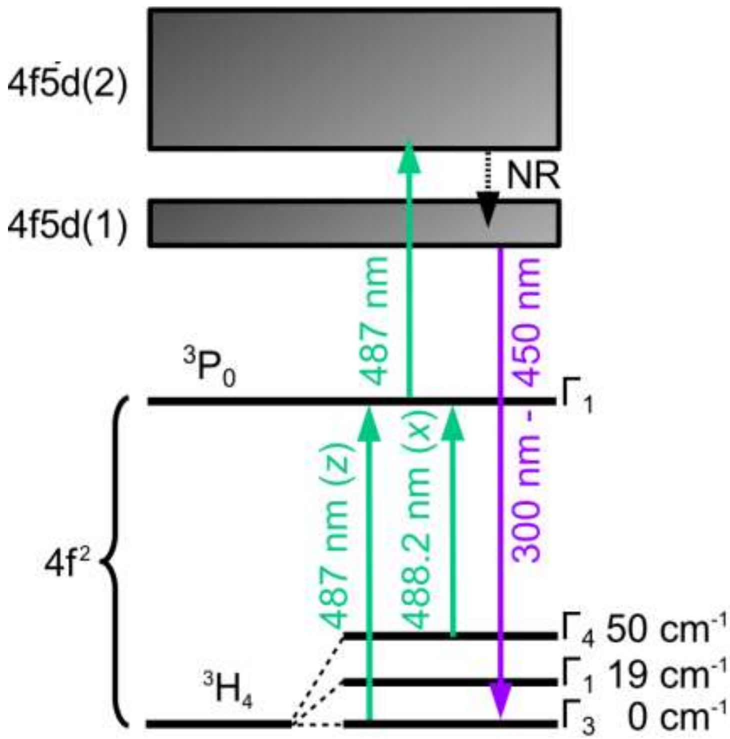


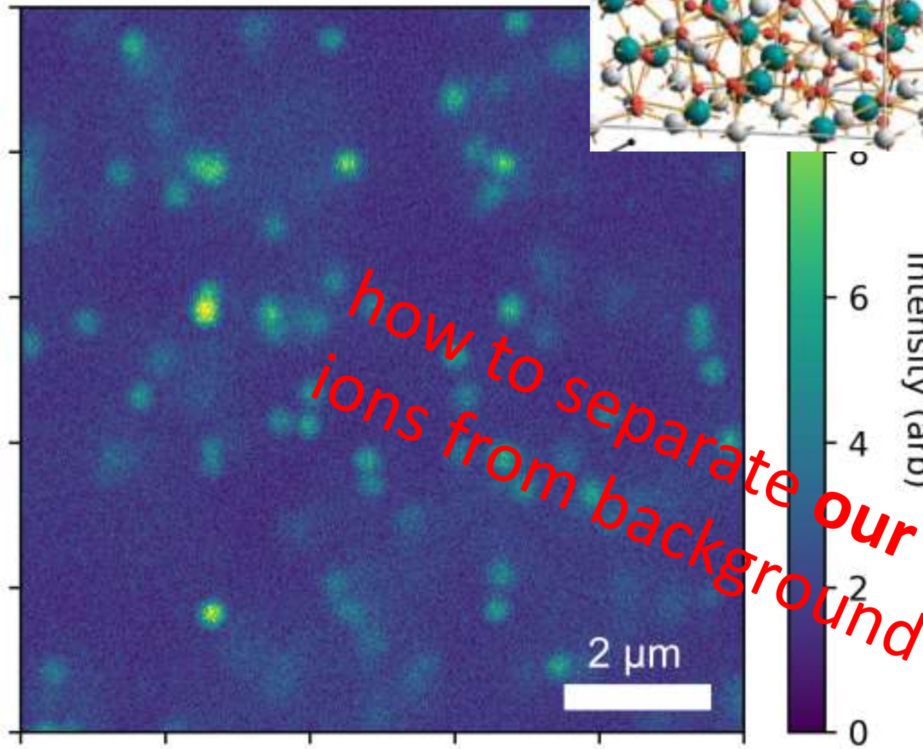


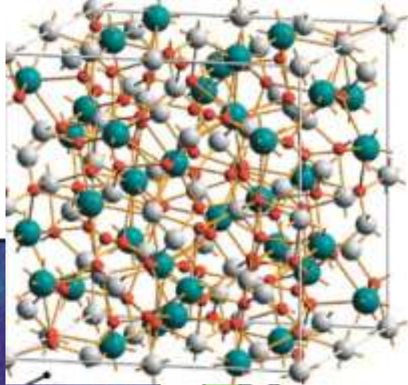


Confocal 2-photon microscope for Pr^{3+}

- shooting pattern into YAG
- anneal 1min @ 1200°C







how to separate **our** ions from background?

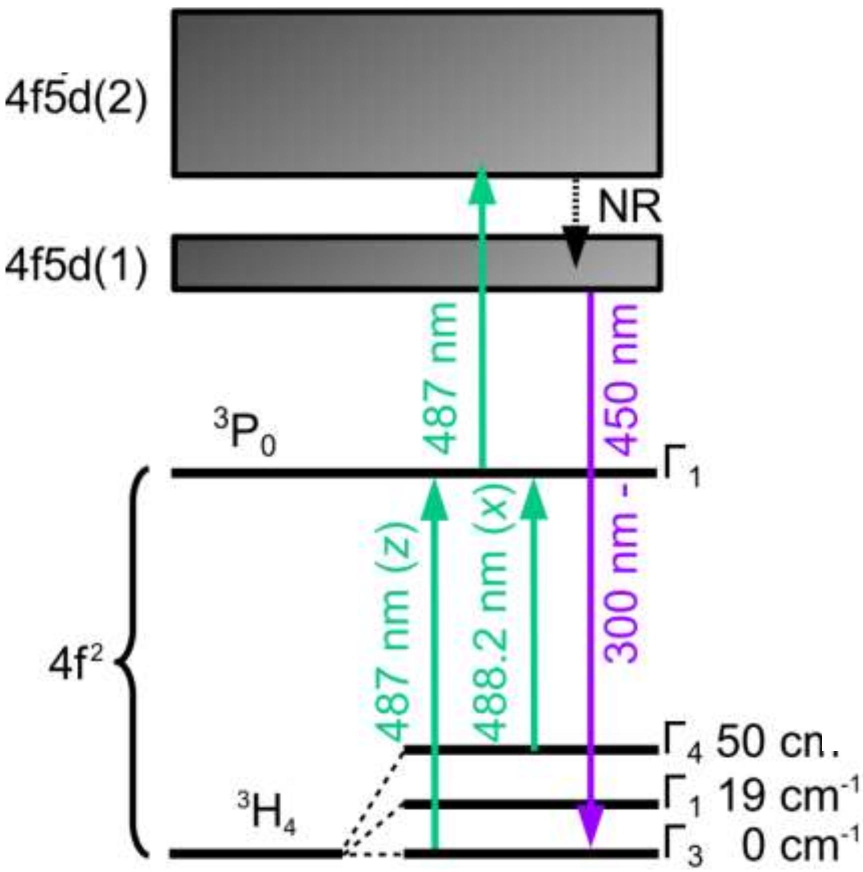
with R. Kolesov, J. Wrachtrup @ Stuttgart

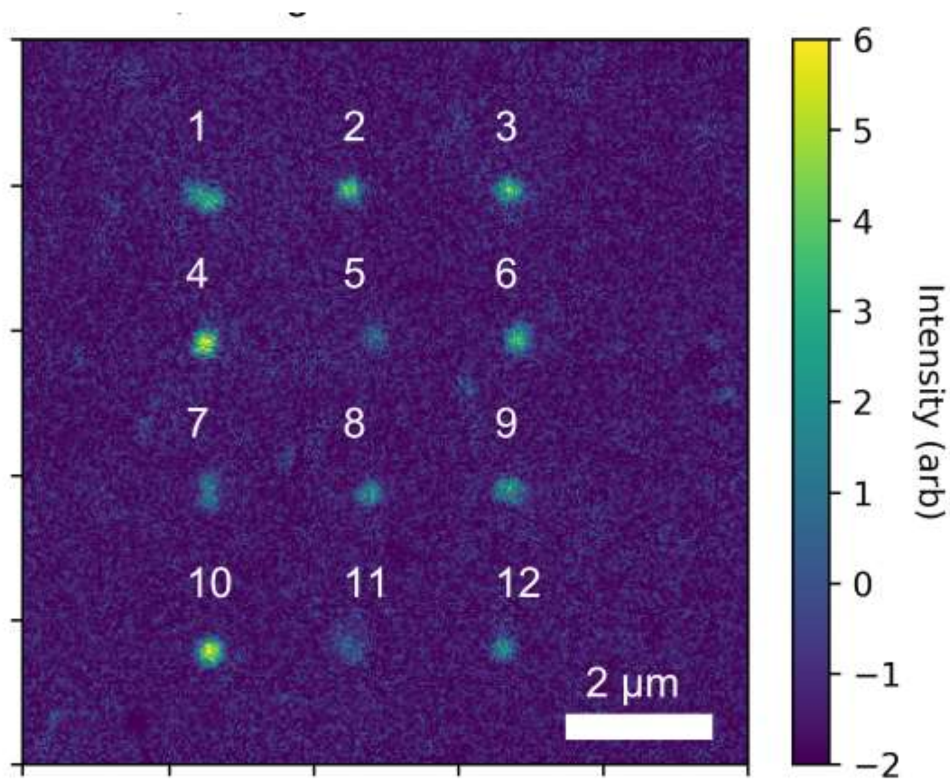
Kornher et al, Appl. Phys. Lett. 108, 053108 (2016)

Groot-Berning et al, arXiv:1902.05308

Confocal 2-photon microscope for Pr^{3+} ions in YAG

University of Stuttgart
3. Physikalisches Institut

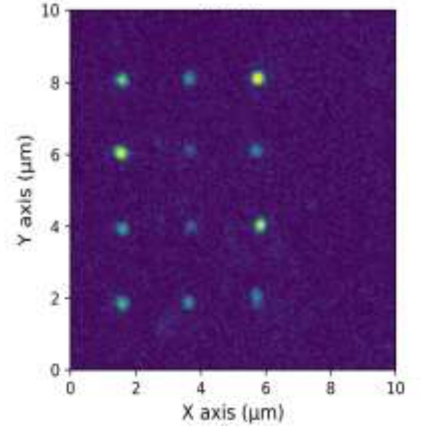




Kornher et al, Appl. Phys. Lett. 108, 053108 (2016)

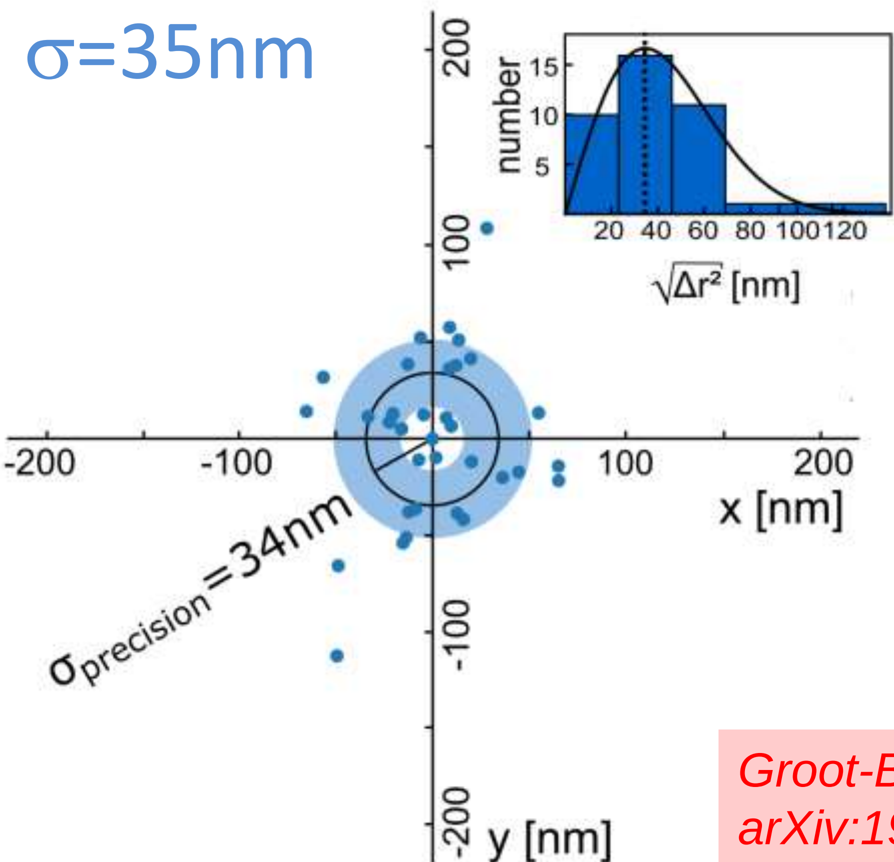
Groot-Berning et al, arXiv:1902.05308

Determination of impantation spot size



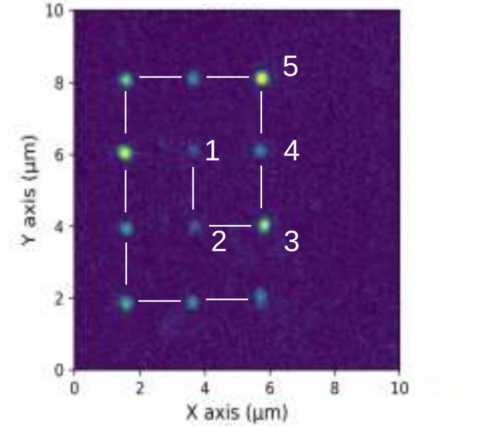
- Optical confocal image resolution
- Fit observed fluorescence spots
- precision

σ=35nm



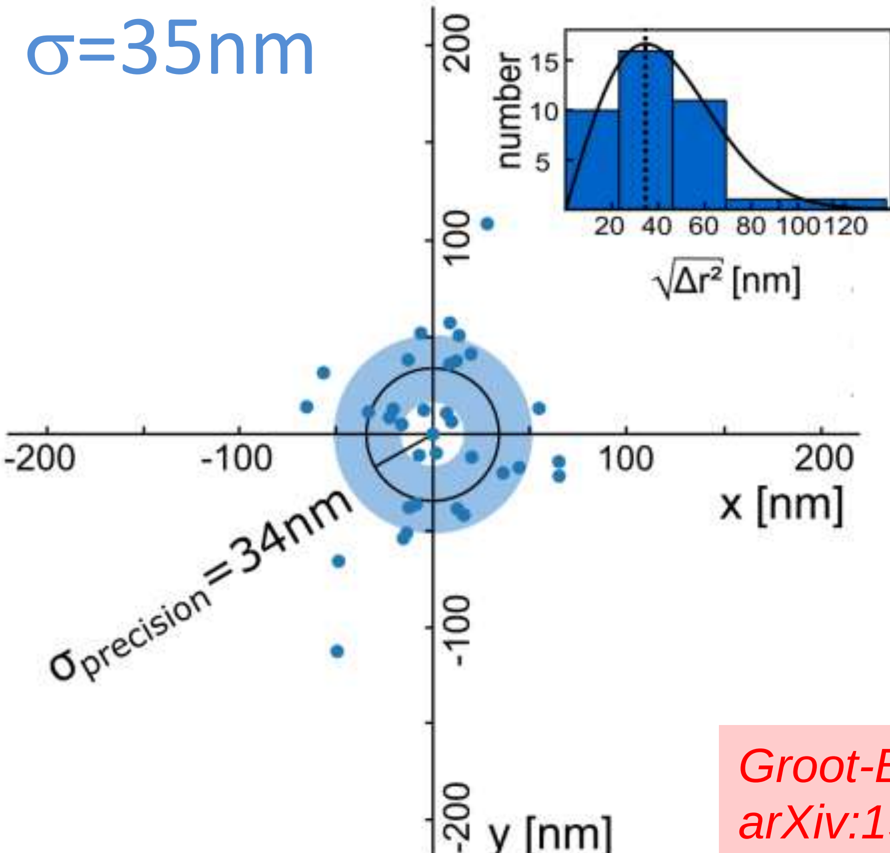
Groot-Berning et al, arXiv:1902.05308

Determination of impantation spot size

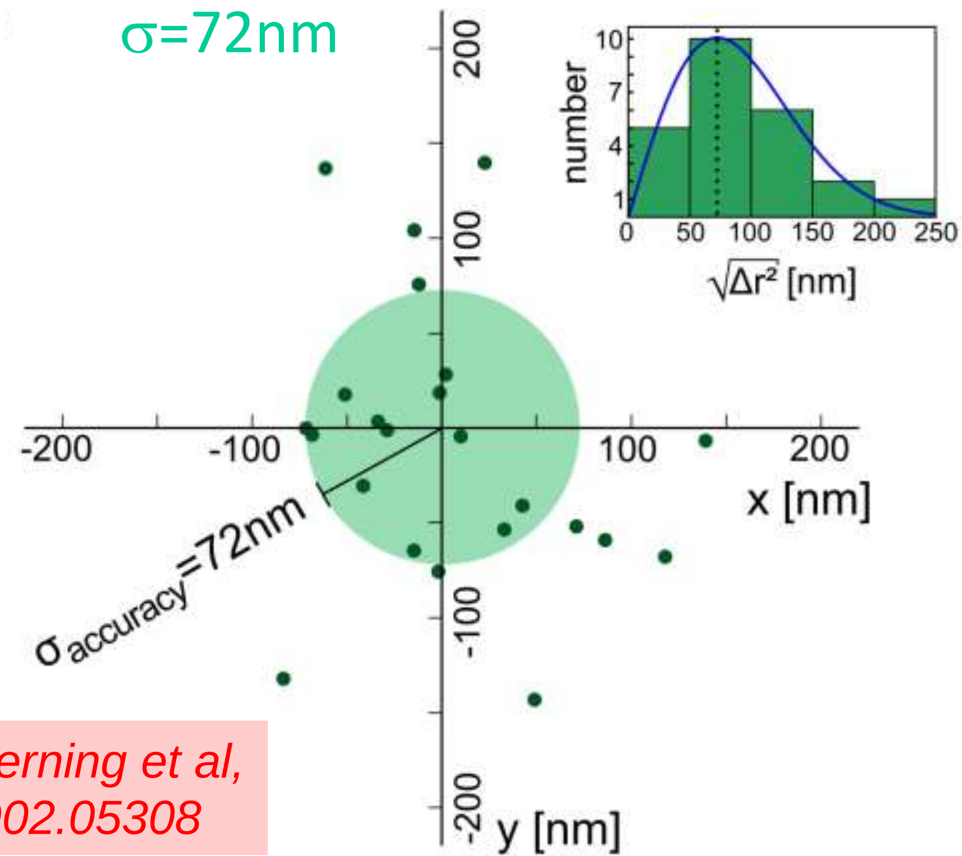


- Optical confocal image resolution
- Fit observed fluorescence spots
- precision / accuracy

σ=35nm



σ=72nm



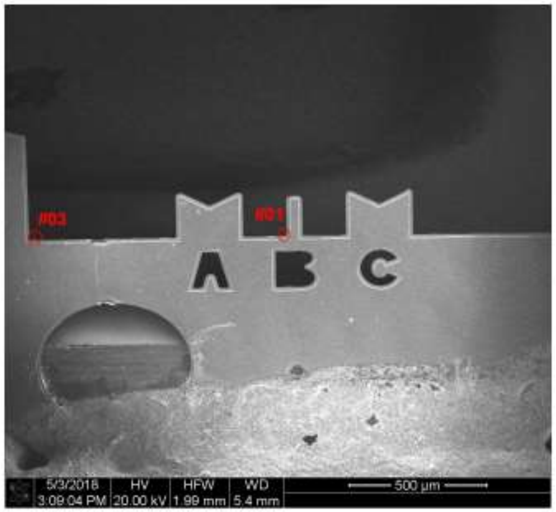
Groot-Berning et al, arXiv:1902.05308

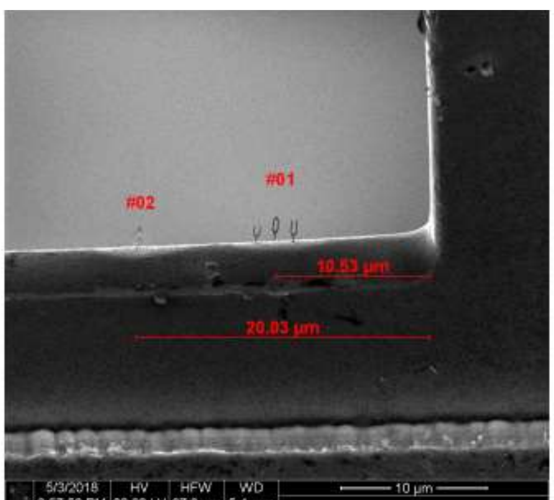
Single ion microscopy

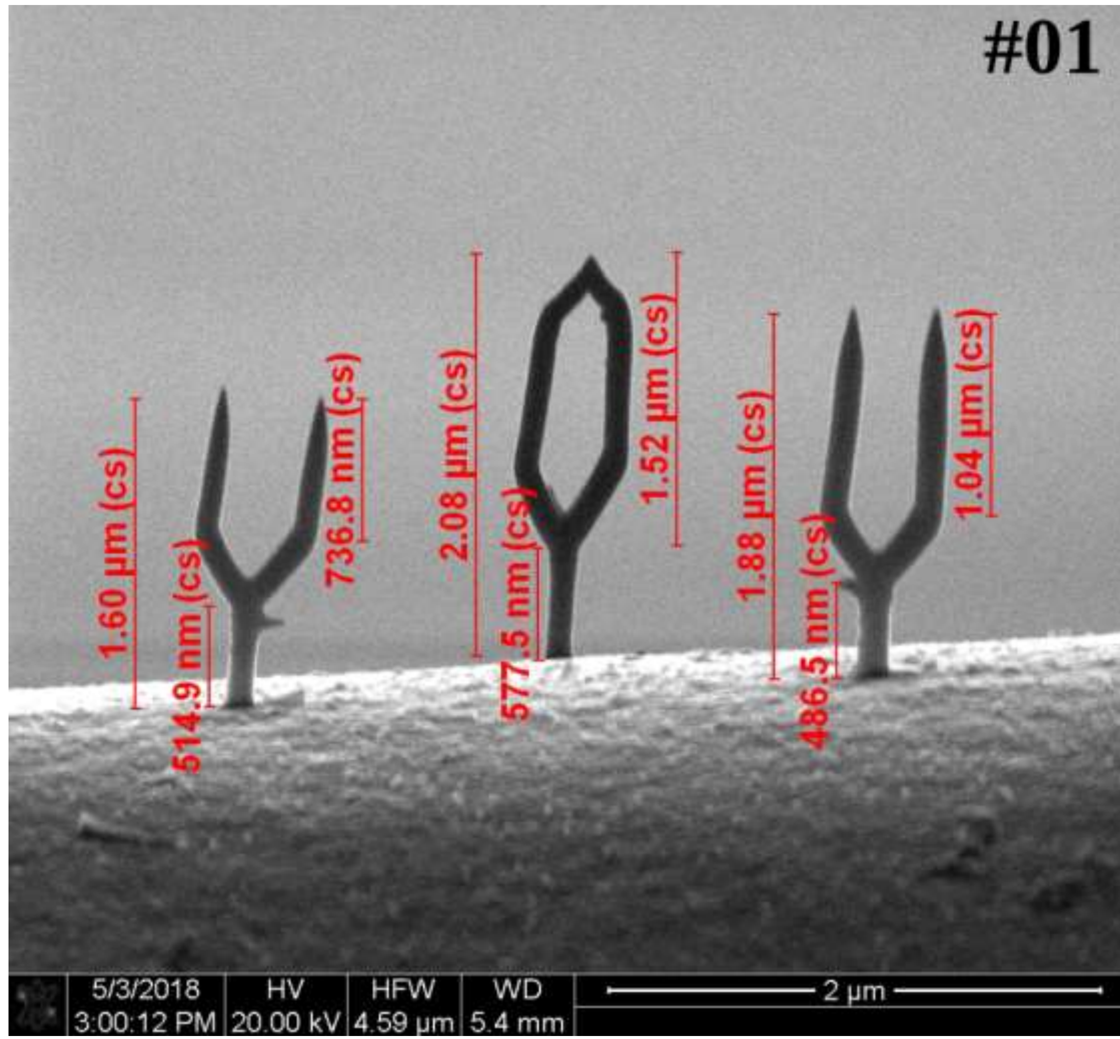
with C. Henkel, Folman, Keller, Huth

Focus a single ion beam into a structure

Precursor $HCo_3Fe(CO)_{12}$



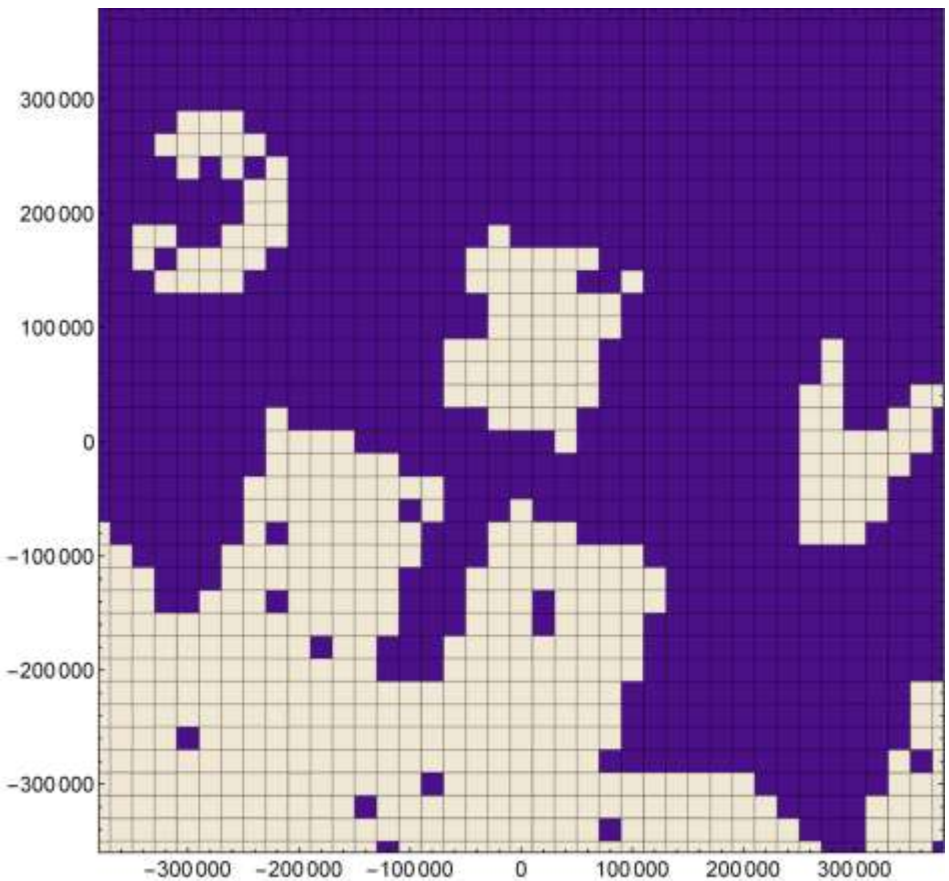




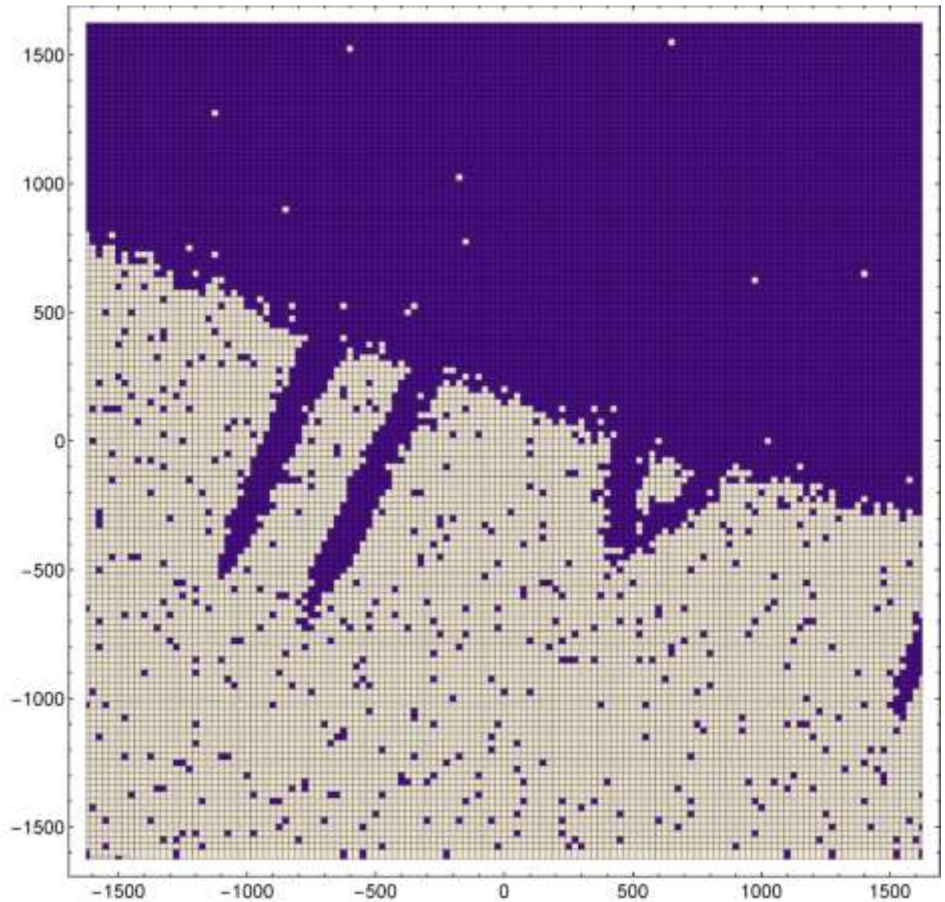
Single ion microscopy

single ion transmission image

Ca+ ions @6keV

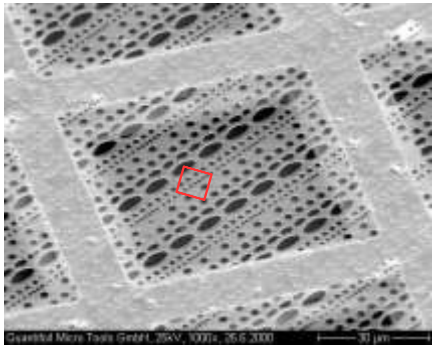


Single ion, 20µm pixel size



Single ion, 25nm pixel size

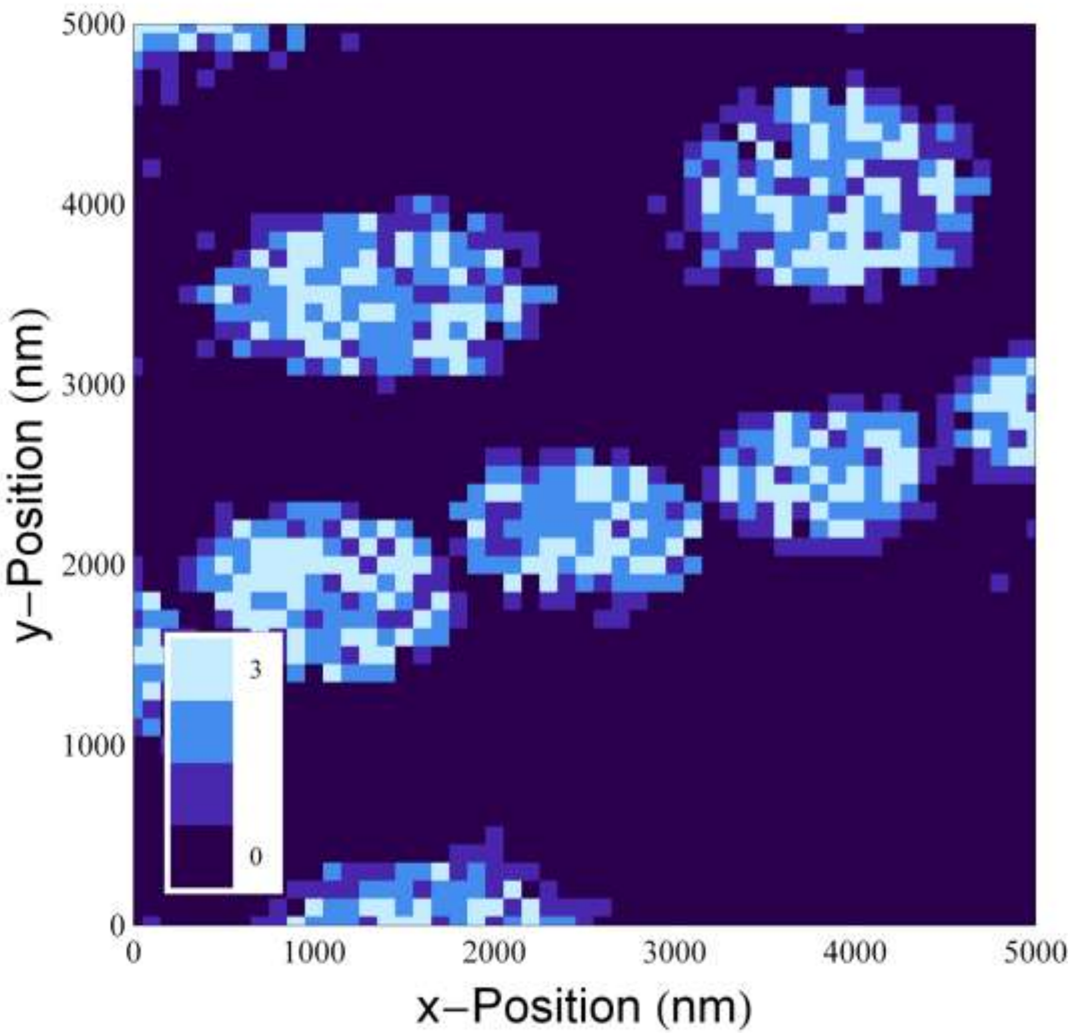
Carbon foil transmission sample



3 ions per pixel

Resolution here: (100x100) nm²

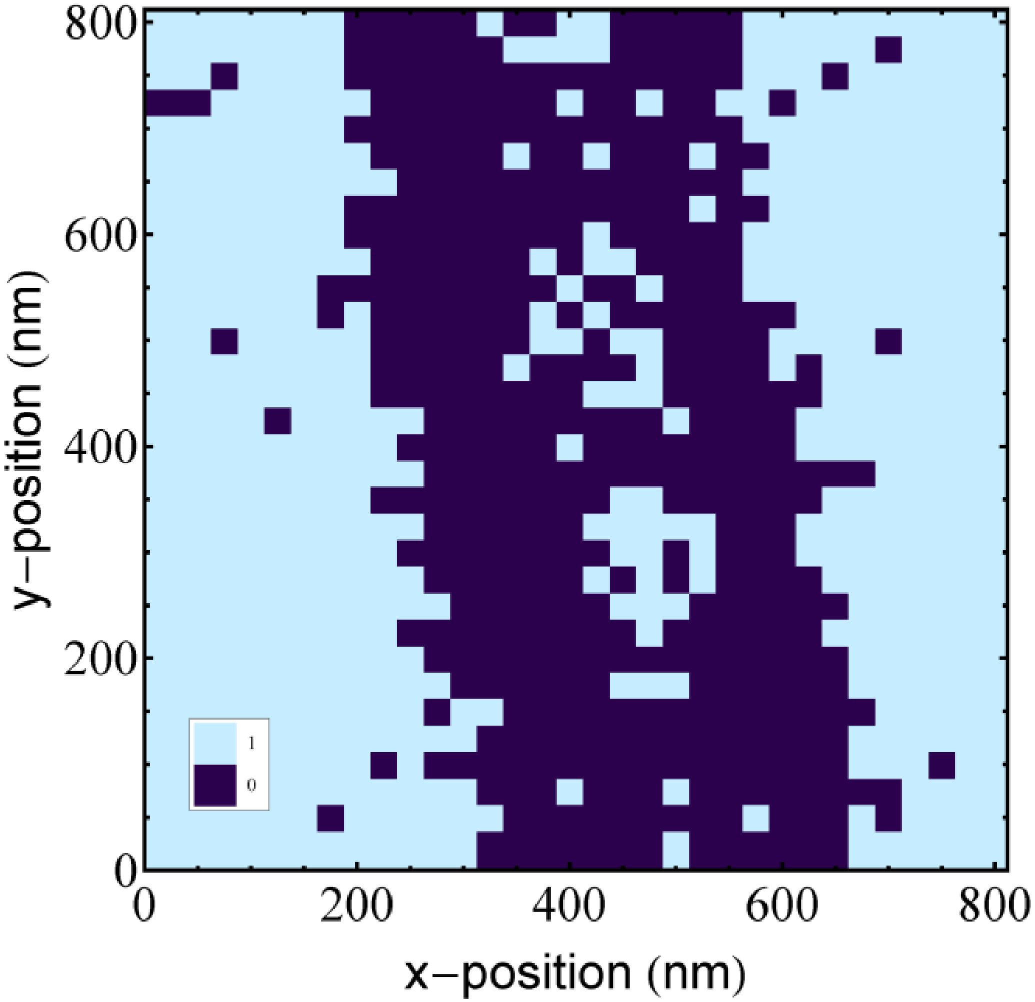
gating by the extraction of the detector
→ supression of dark counts



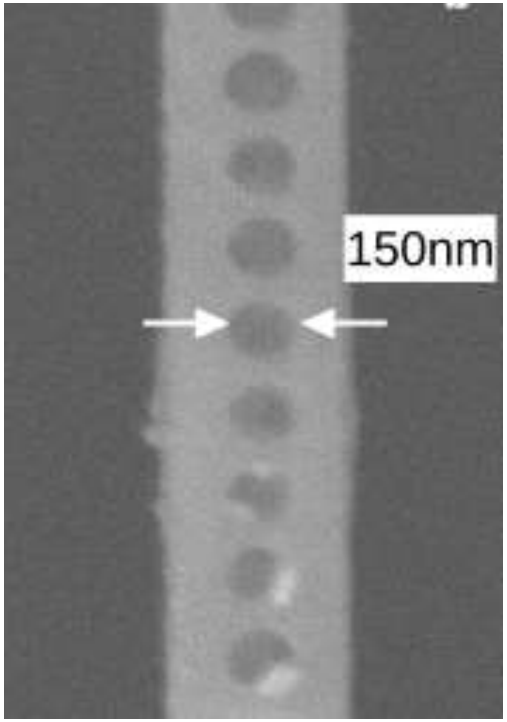
imaging with single particle exposure avoids sample charging or damage

Single ion microscopy

Structure of Diamond sample
(single Ca^+ ion microscope)



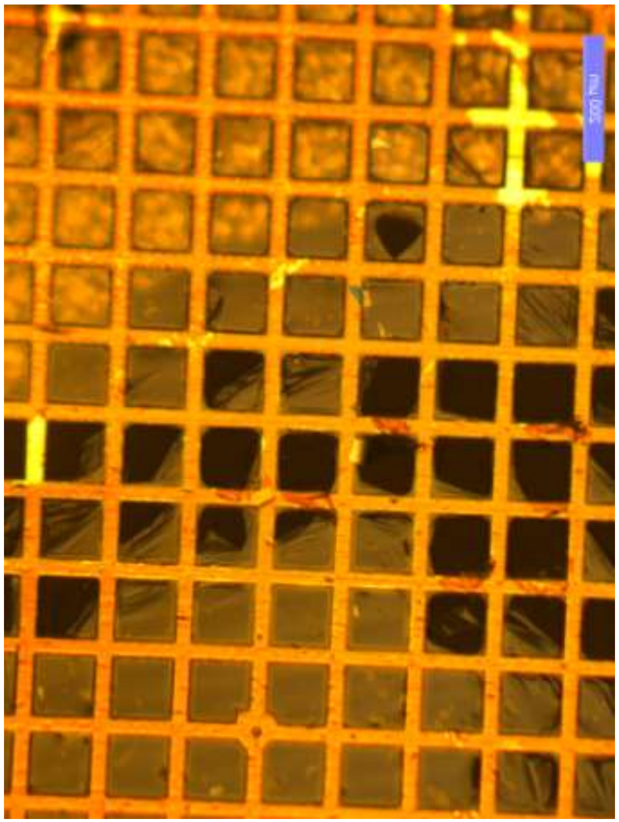
Photonic Diamond Structure
(electr. microscope)



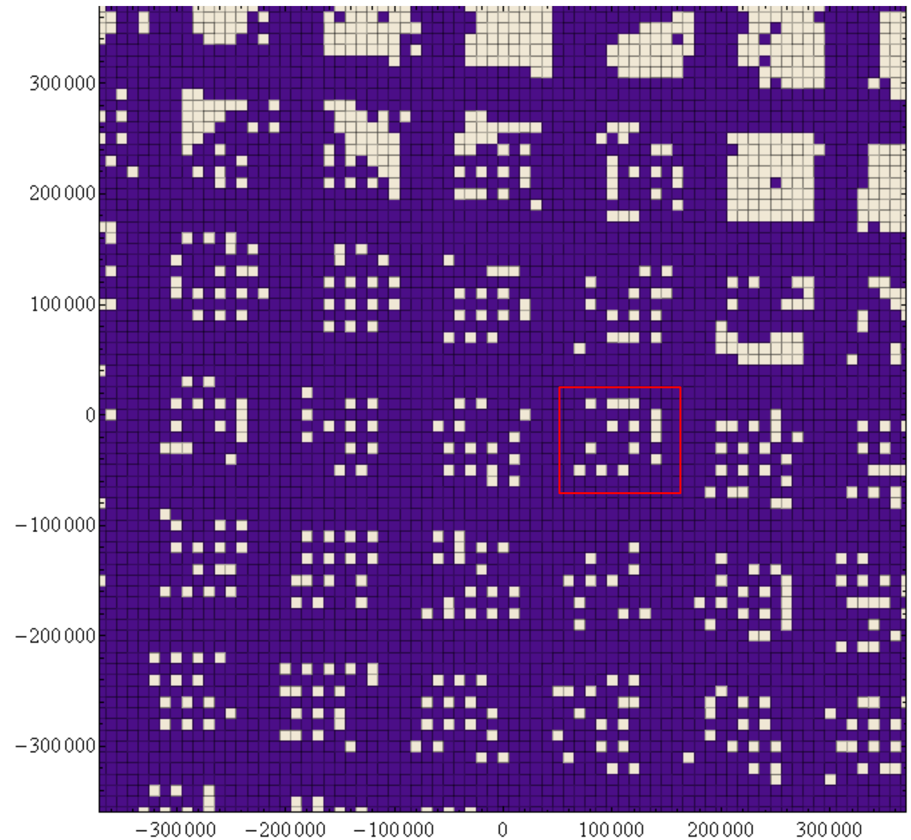
Probe: Riedrich-Möller, et al., Nat. Nano. 7, 69 (2011)

Single ion microscopy – semitransparent sample

with Jannik Meyer @Wien



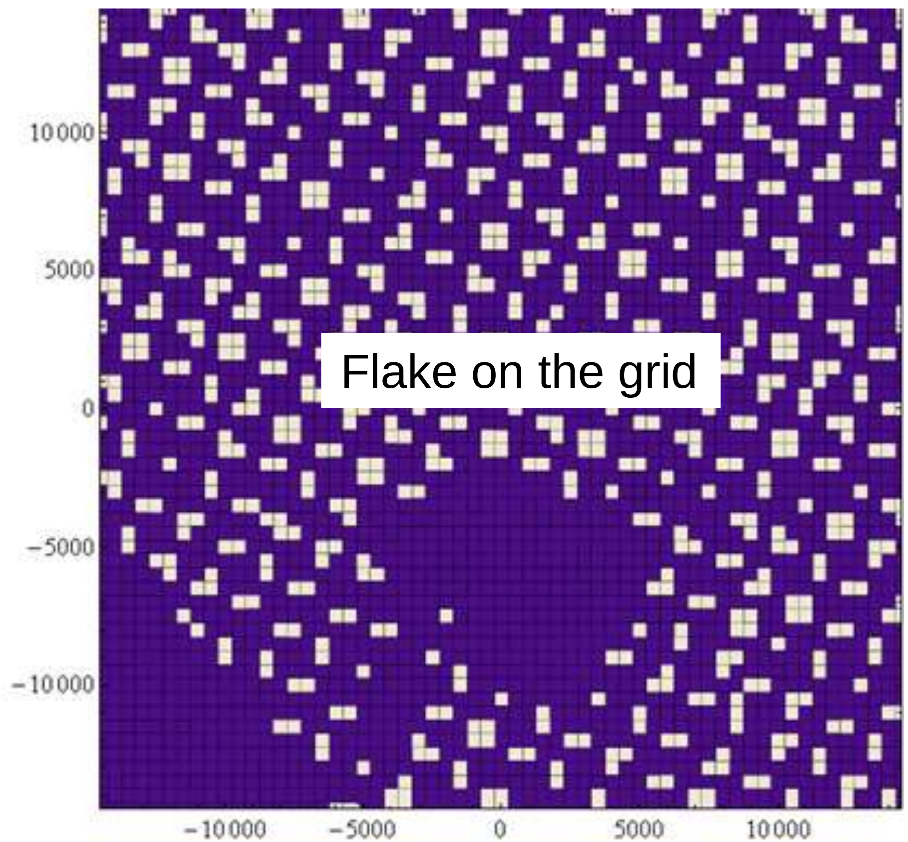
TEM quantifoil grid with graphene



Single ion 10μm pixel size

Single ion microscopy – semitransparent sample

with Jannik Meyer @Wien



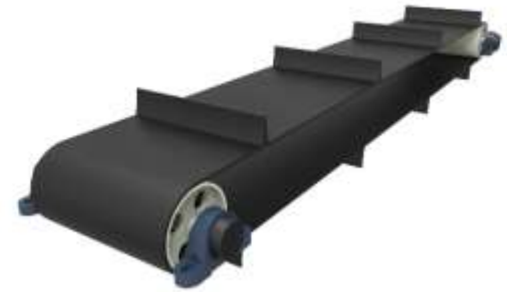
Single ion 500nm pixel size

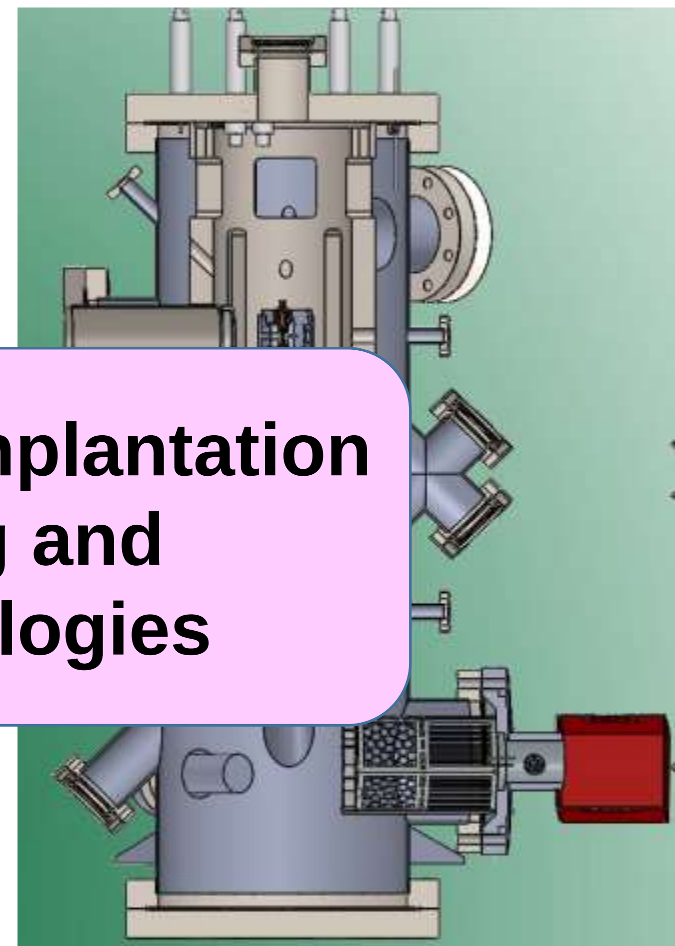
Ca+ ions @3keV
Single layer graphene T=8.5%
Double layer graphene T=0.69%

From ToF:
Δv/v reduced by 1% and spread increased by x36

Second generation setup

- Compact & high mech. stability
- Aiming for < 2 nm
- Modular design
- kHz-rate reloading from „reservoir“ trap segment
- Species: Phosphor, Cerium, Bismuth...
- Fast changing probes with lock





Applications of single ion implantation in quantum computing and nanostructuring technologies

The team

Coll.: Folman, Retzker, Wrachtrup, Meijer, Lesanowski, Hennrich, Zanthier, Lutz, Budker, Walz, Plenio, Jelezko, Calarco, Jamieson, Blatt

BMBF QLinkX

www.quantenbit.de

RySQ

iRyd

DFG Deutsche Forschungsgemeinschaft

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY

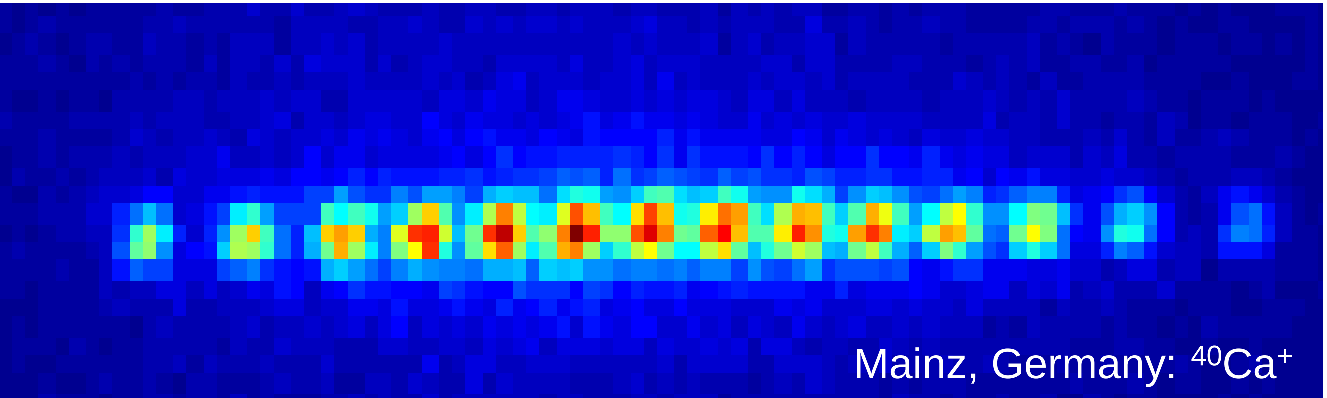
VolkswagenStiftung

QUANTUM FLAGSHIP

FUNDING OPPORTUNITIES from the FUTURE & EMERGING TECHNOLOGIES scheme

Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Rydberg excitations for fast entangling operations
- Quantum thermodynamics, heat engines, phase transitions
- Implanting single ions for a solid state quantum device



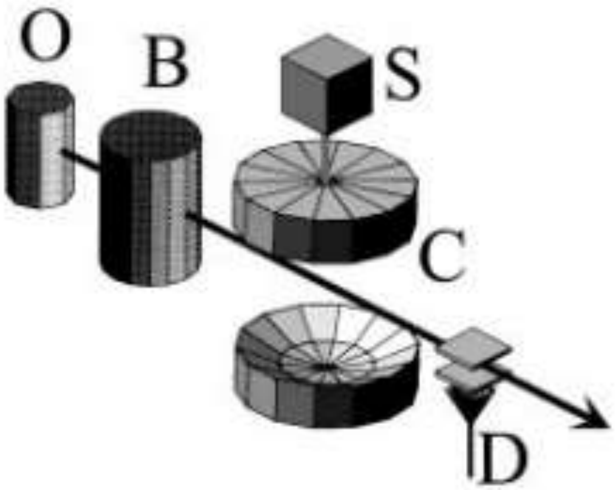
www.quantenbit.de

F. Schmidt-Kaler

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Rydberg atoms and cavities

Giant dipole, long lifetime – strong coupling regime
& realization of Jaynes-Cummings Hamiltonian

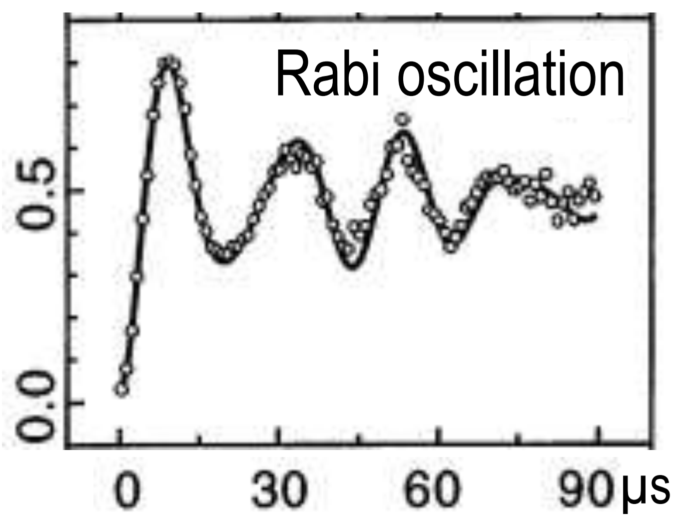


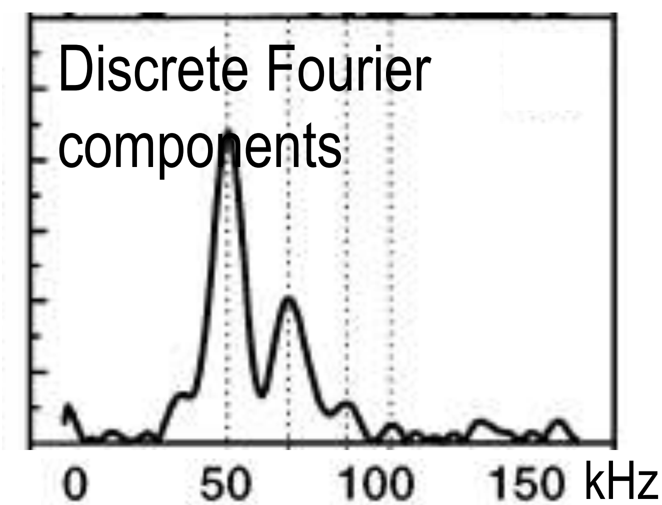
Raimond, Brune, Haroche, RMP 73, 565 (2001)

Haroche, Raimond, Exploring the Quantum

Rydberg atom serves as electric field sensor

Direct evidence of cavity field quantization



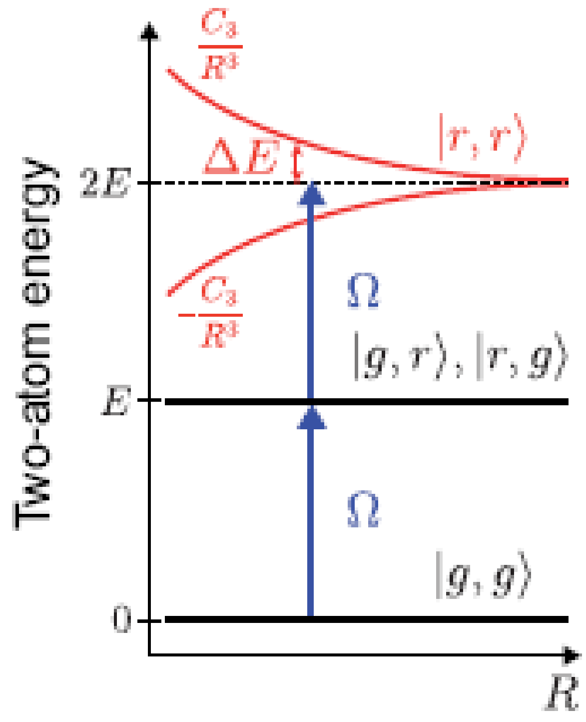


Brune, Schmidt-Kaler, Maali, Dreyer, Hagley, Raimond, Haroche, Phys. Rev. Lett. 76, 1800 (1996)

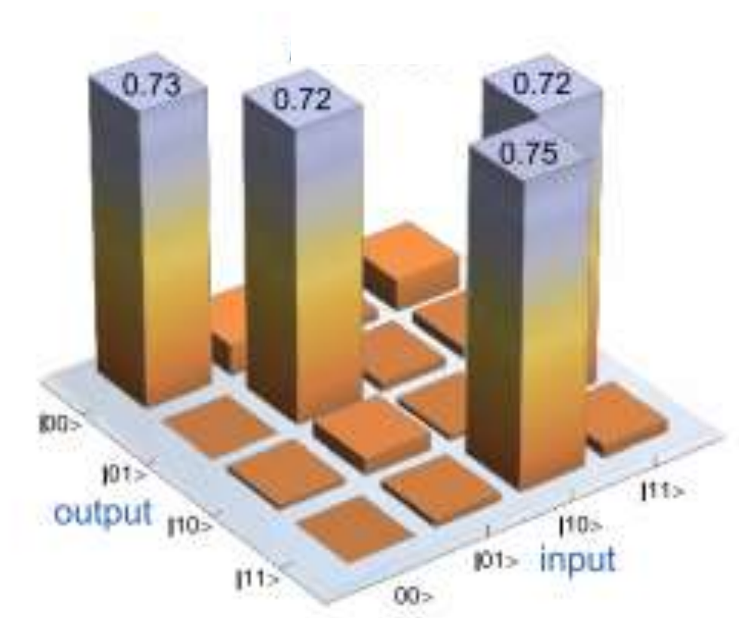
Entangling individual neutral atoms

Tailoring the dipole-blockade

Lukin, Fleischhauer, Cote, Duan, Jaksch, Cirac, Zoller, PRL 87, 037901 (2001)



C-NOT gate between two atoms held in optical tweezer

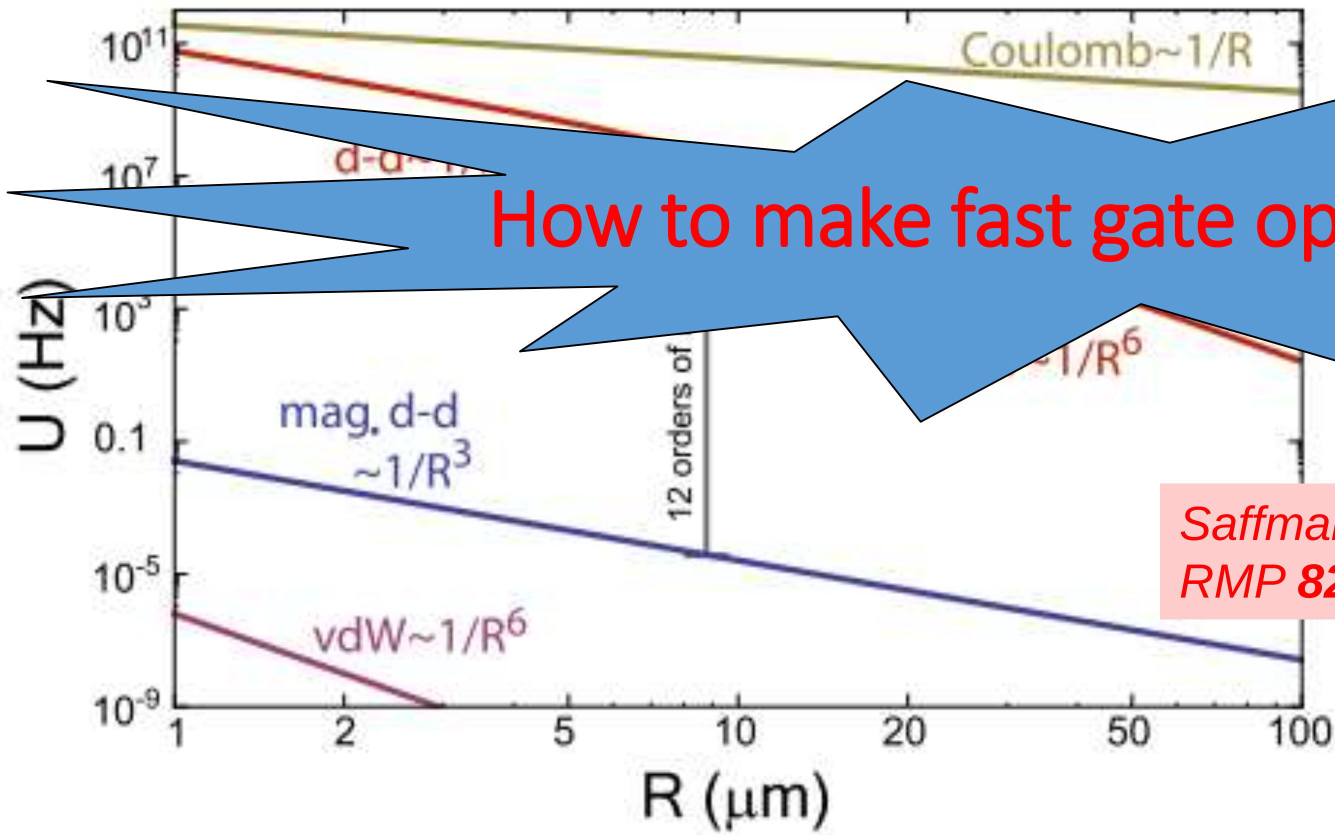


Saffman, Walker, Mölmer, RMP ***82****, 2313 (2010)*

Isenhower, Urban, Zhang, Gill, Henage, Johnson, Walker, Saffman, PRL 104, 010503 (2010)

Wilk, Gaëtan, Evellin, Wolters, Miroshnychenko, Grangier, Browaeys, PRL 104, 010502 (2010)

Making two or more atoms/ions/spins interact…



How to make fast gate operations ?

*Saffman, Walker, Mölmer, RMP **82**, 2313 (2010)*

➡ long-range and strong:
- Coulomb interaction
- Rydberg dipoles

Join advantages for **ion trap qubits** with **Rydberg excitations and interactions**

Müller, Liang, Lesanovsky, Zoller, NJP 10, 093009 (2008)

Experimental Challenges for exciting Rydberg states in trapped ions

- Unfriedly wavelenght range 100nm…150nm

  ➡ Develop reliable and narrow VUV source @ 122nm
  few µW laser power / optimize difficult beam delivery
  Or multi-step excitation with UV

- Single / few ion crystal

  ➡ Develop electron shelving detection with
  high single-excitation detection efficiency

- Hostile high electric alternating RF field of a Paul trap

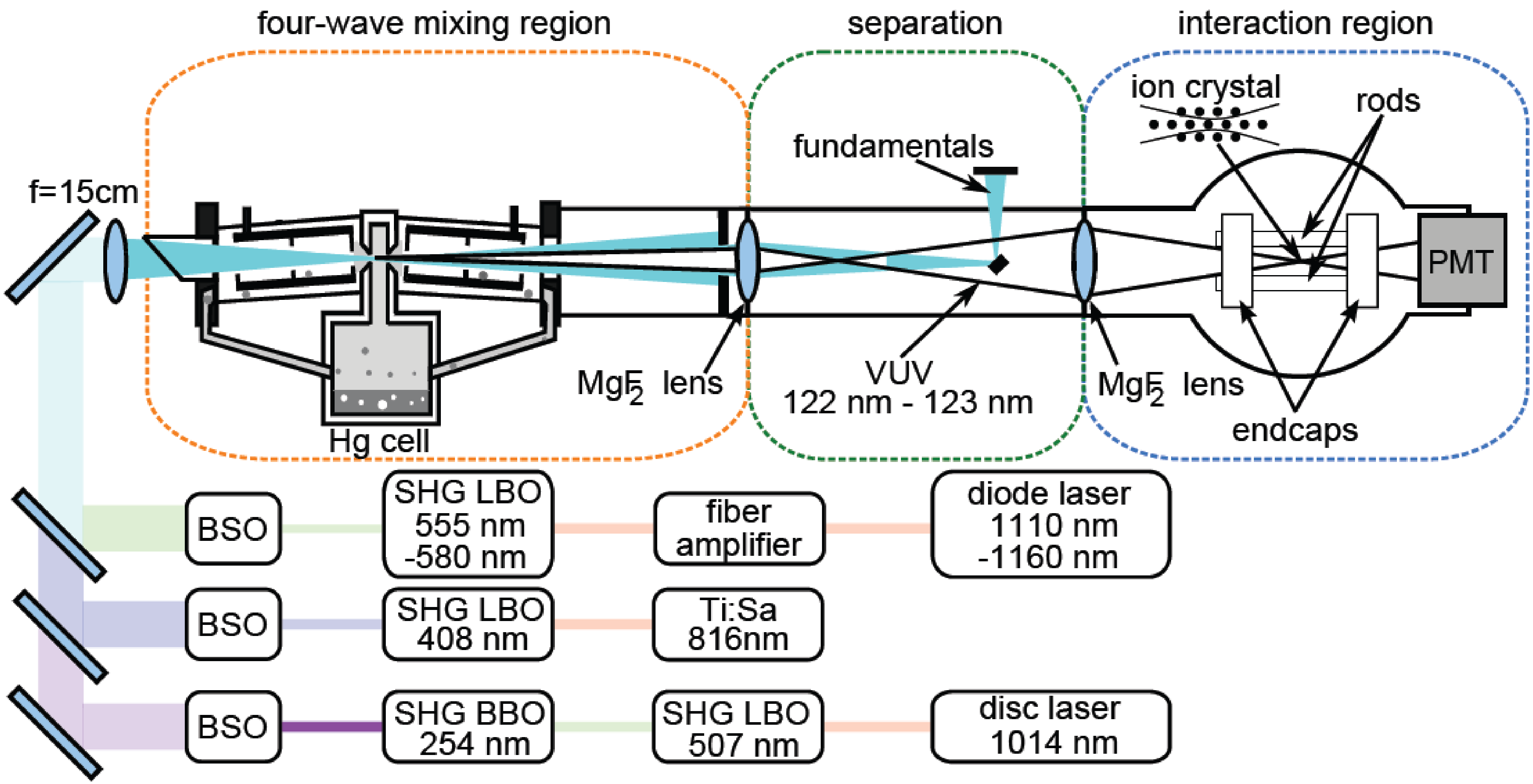
  ➡ Optimized ion trap & optimized trap operation parameters,
  compensation of electric field (micro-motion compensation)

*NJP **13** (2011) 075014*

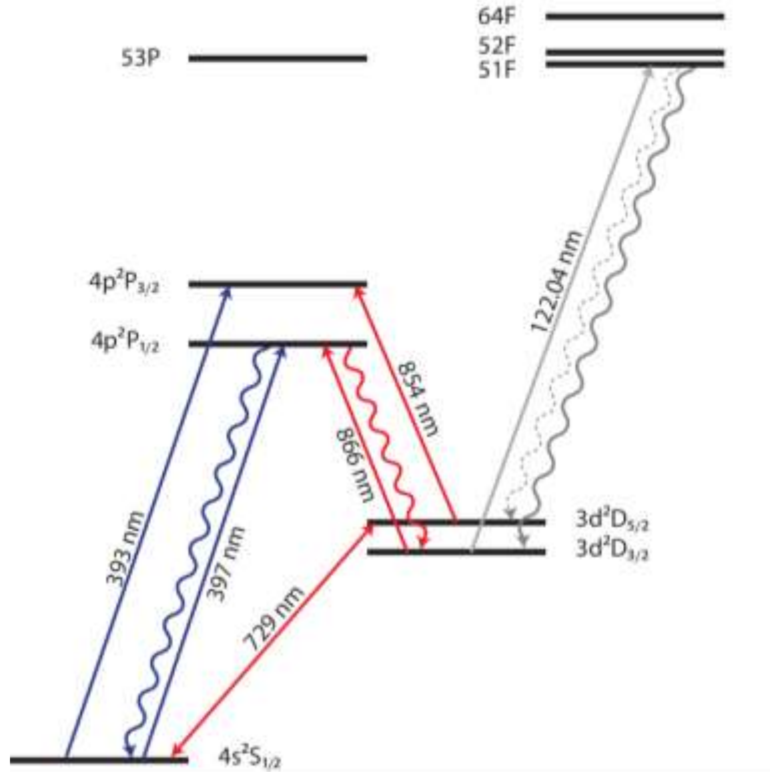
122nm four wave mixing

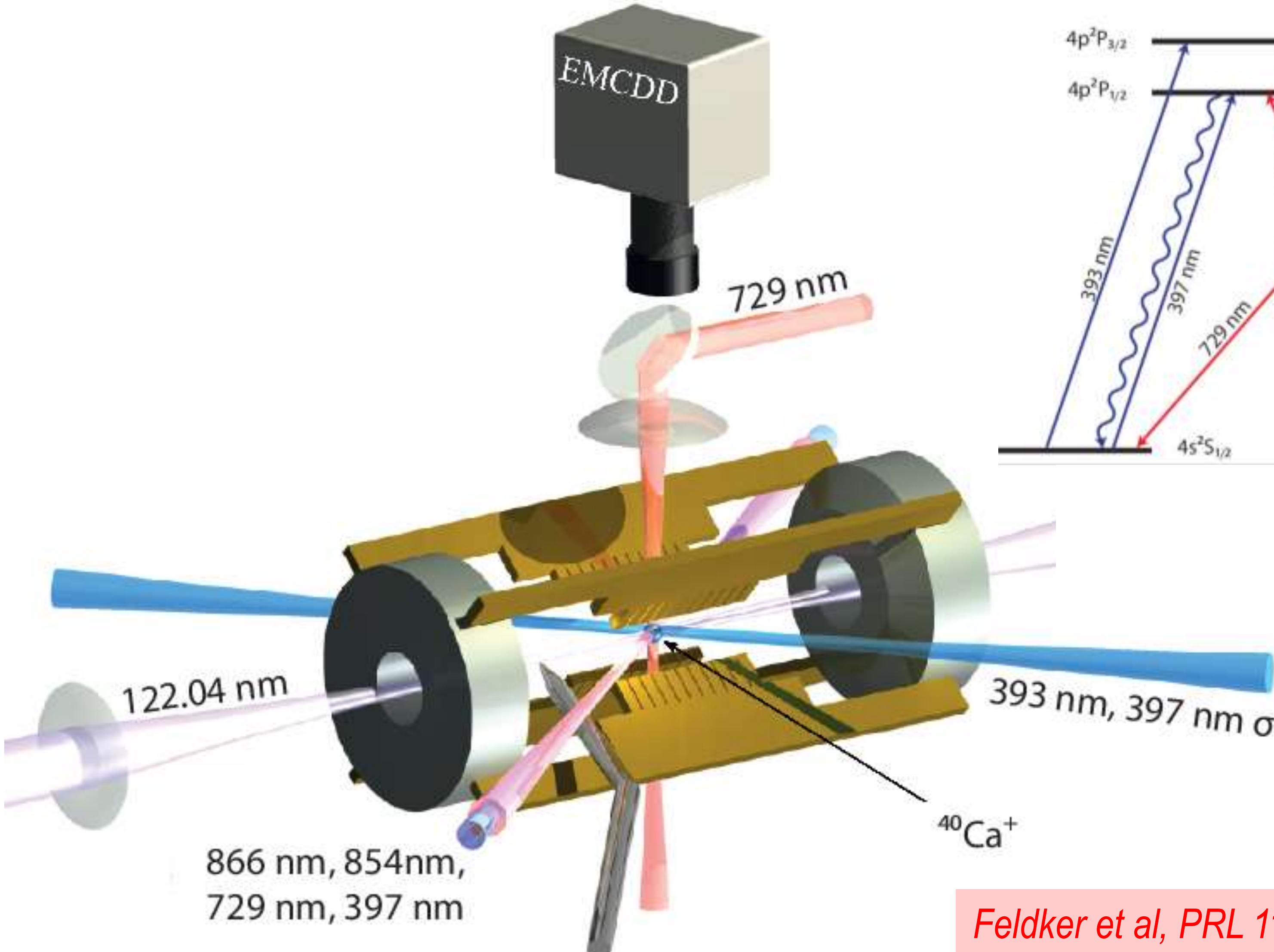
Walz et al, PRL83, 3828 (1999)
Opt. Express 17, 11274 (2009)

…laser system for anti-H spectroscopy



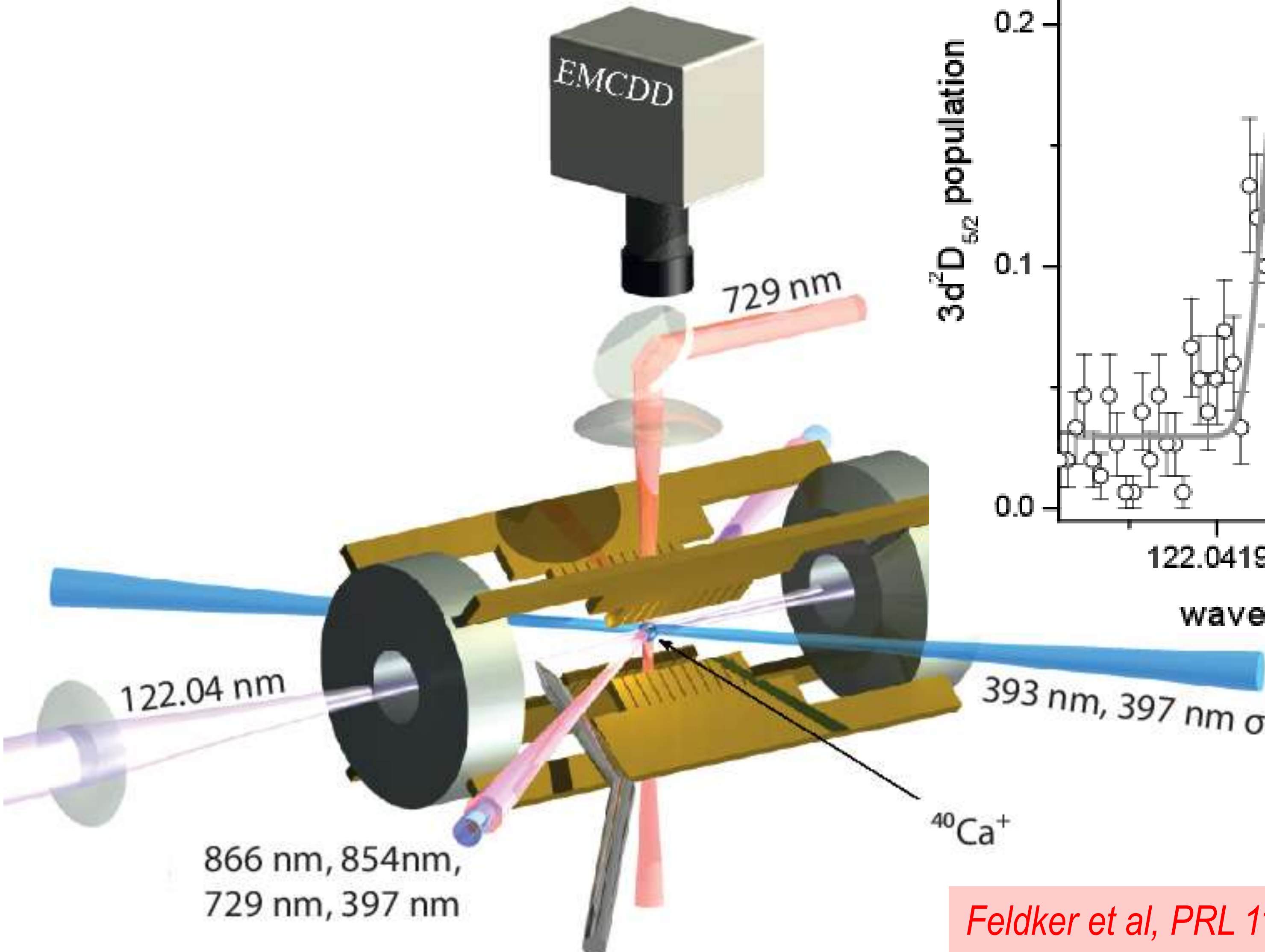
Setup & exc. scheme

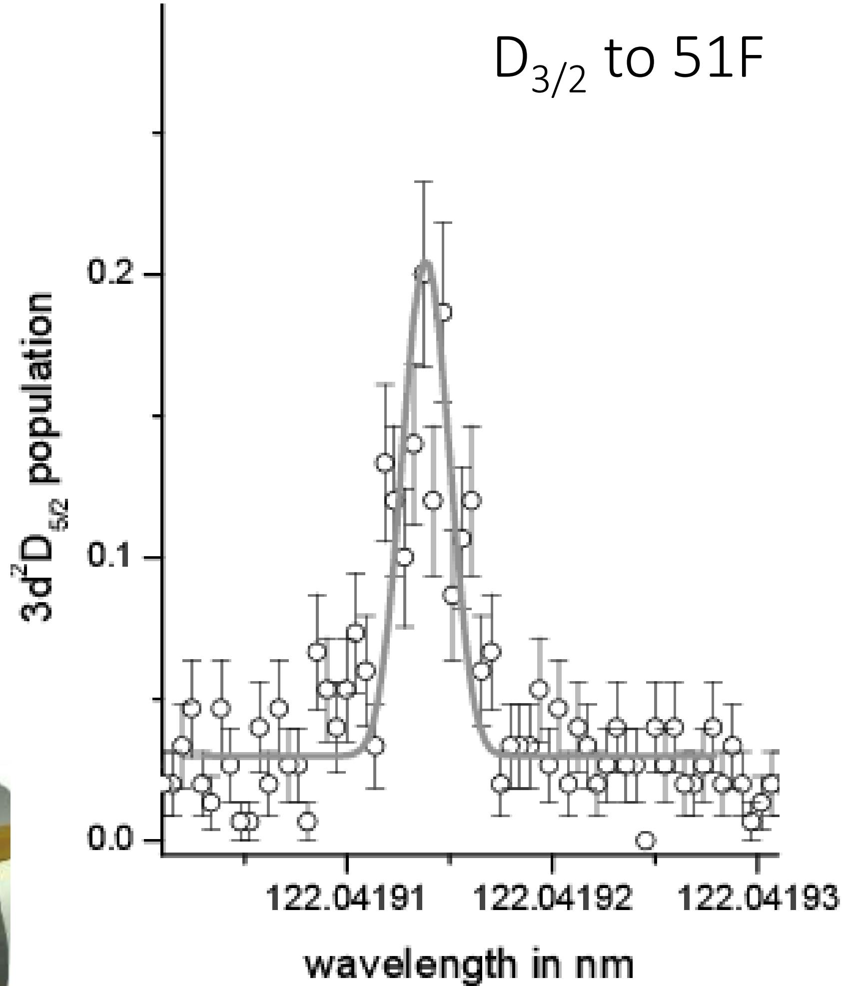




Feldker et al, PRL 115, 173001 (2015)
Schmidt-Kaler et al, NJP 13, 075014 (2011)

First Rydberg signal

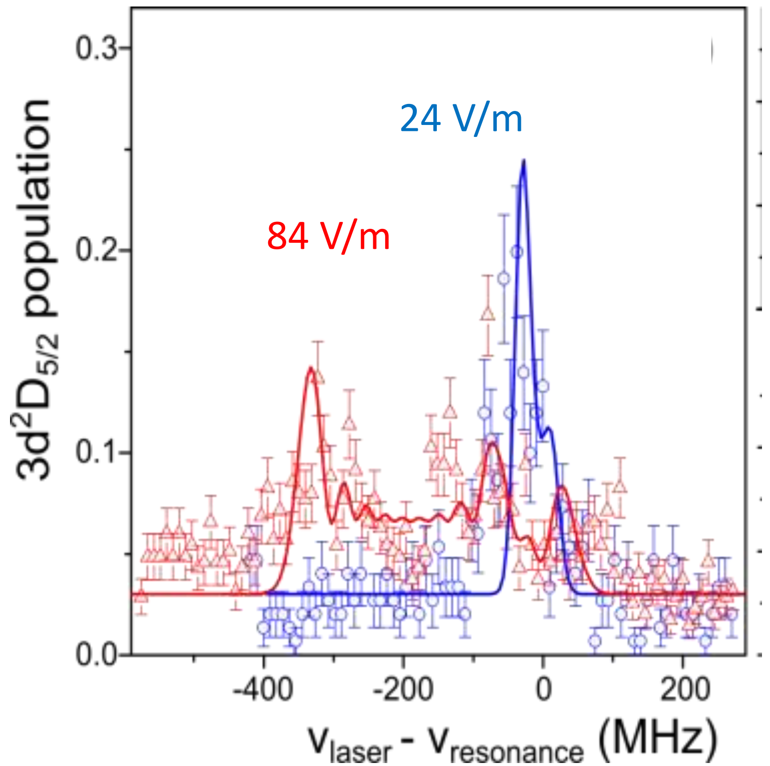




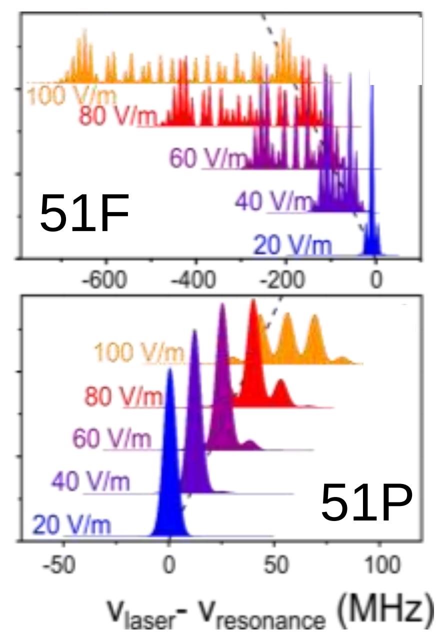
Feldker et al, PRL 115, 173001 (2015)
Schmidt-Kaler et al, NJP 13, 075014 (2011)

Line shape model

- Optimized segmented linear Paul trap
- Compensation of the electric field to position ion at center
- Single $^{40}Ca^{+}$ excitation on single photon transition in VUV near 122 nm
- < 1µW of VUV light from 4-wave-mixing
- Detecting 397 nm fluorescence



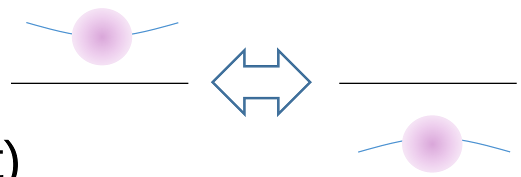
- Rydberg excitation of single ion $3D_{3/2} \rightarrow 51F$
- Large polarizability of Rydberg F-states leads to line broadening by electric field at the ion position
- Order of magnitude weaker influence for Rydberg P-states



Feldker et al, PRL 115, 173001 (2015)

Line shape model: Electric oscillating field

Uncompensated axial micro motion (from electrode misalignment)



~ 10-50 V/m depending on RF amplitude

$$\omega(t) = \omega_0 + k x_{mm} \Omega \sin \Omega t - \frac{\alpha E_{ion}^2}{2} \cos^2 \Omega t.$$

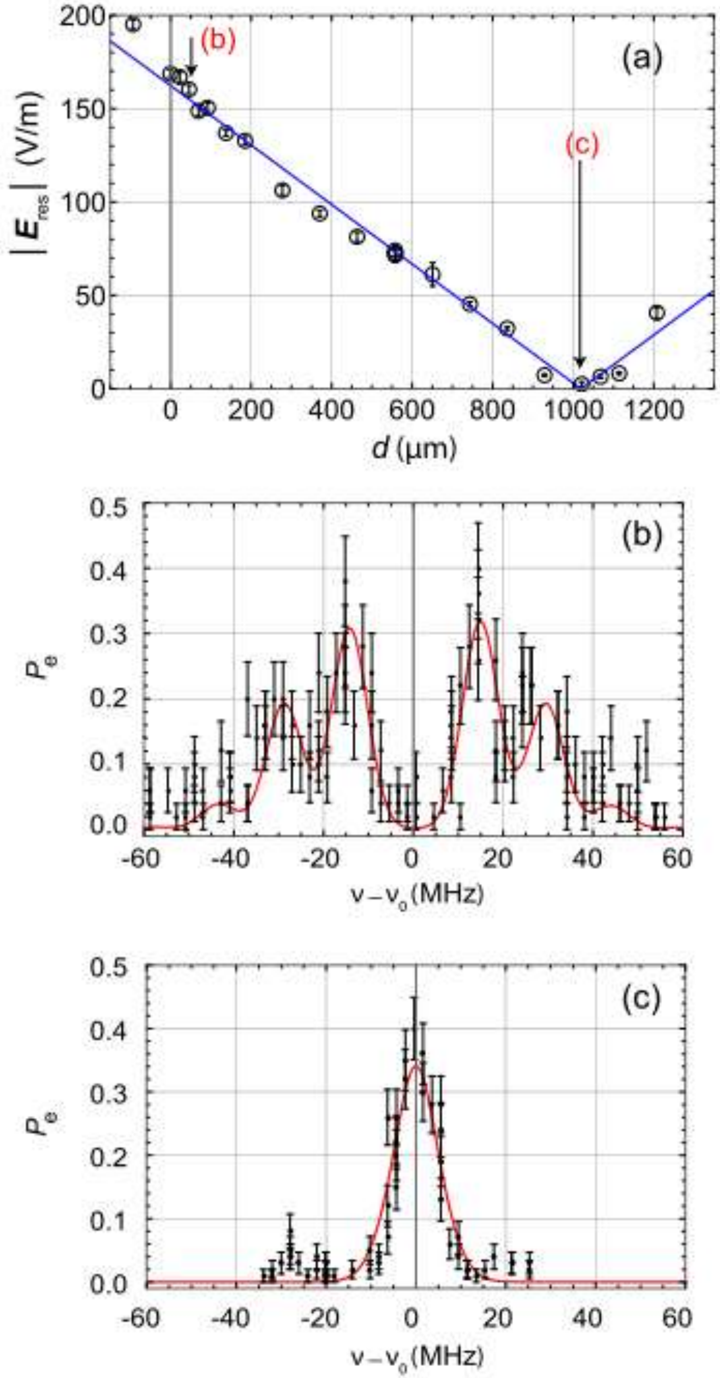
Doppler shift

Stark shift

Bessel-modulated line from periodic Stark and Doppler shift

Rydberg spectroscopy

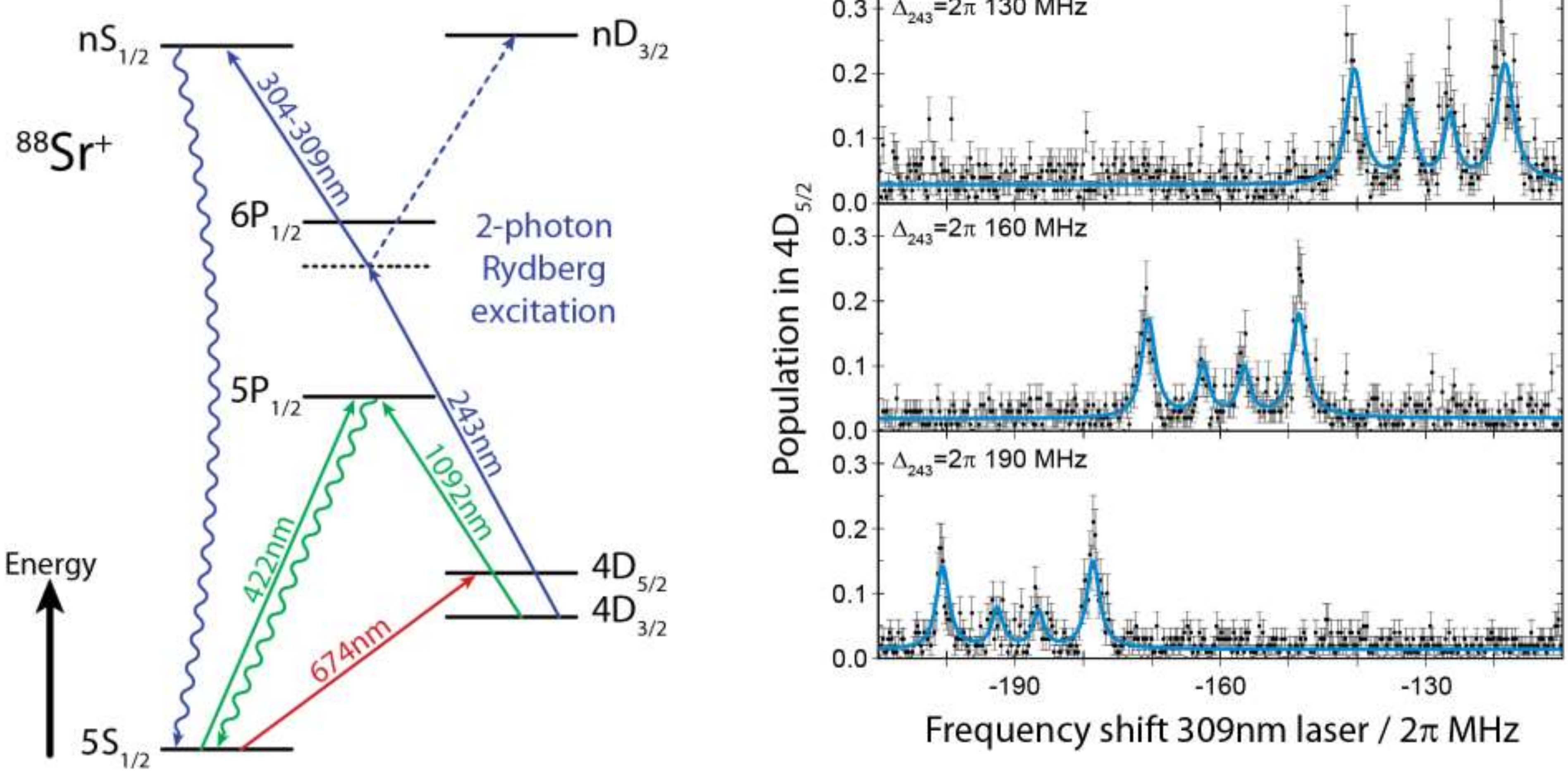
- Determine resonances, e.g. $3D_{3/2} \longrightarrow 23P_{1/2}$ at 94 807.798 8(4) cm^{-1}
- Identify levels
- Deduce quantum defects
- Measure polarizabilities
- Control E-field in the Paul trap in 3D micromotion compensation <10V/m



Mokhberi, et al, arXiv 1902.04391

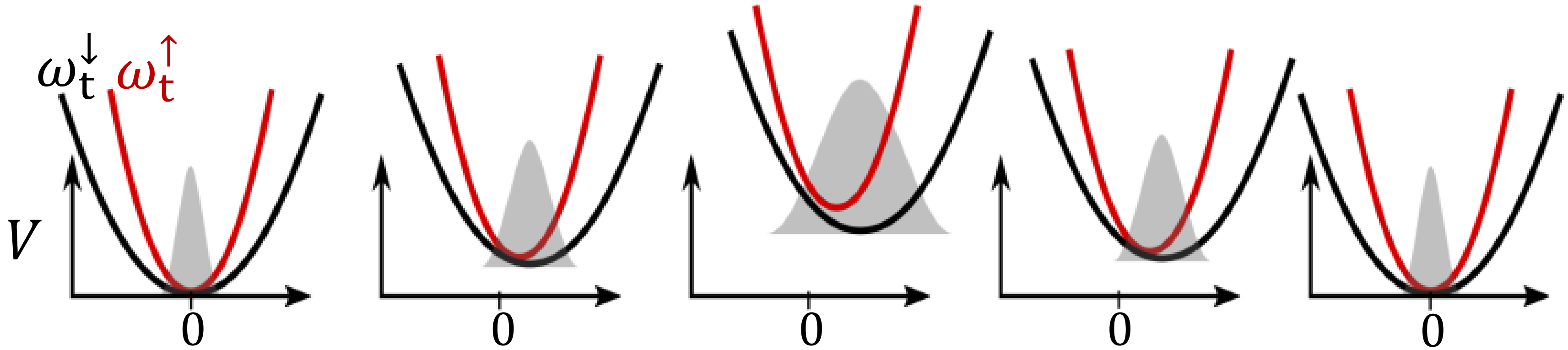
Two-photon Rydberg excitation of $25S_{1/2}$ in $^{88}Sr^+$

243nm & 309nm

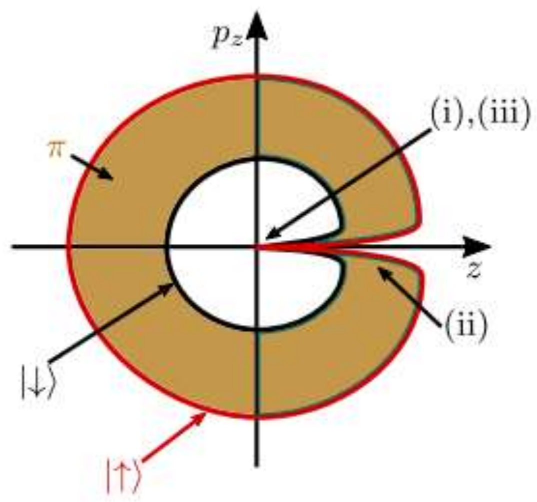


Talk by M. Hennrich, Stockholm, Thursday 16:15h

Just kicking ion crystals for entanglement



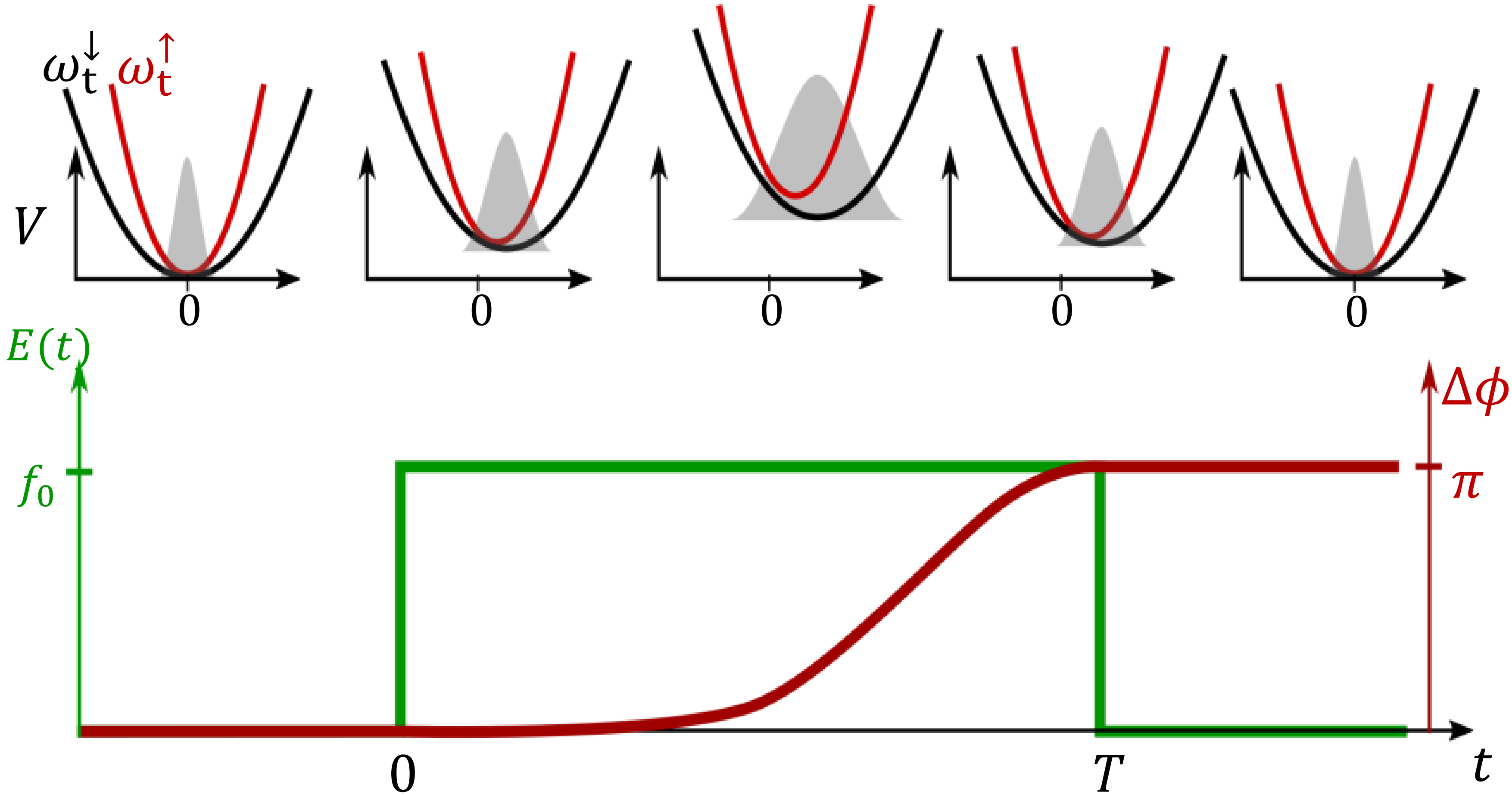
1) Excite a superposition of $D_{5/2}$ (↓) and Rydberg state (↑)
2) Apply electric kick
3) n^7 Rydberg polarizabilty results in spin-dependent potential
4) Kick back
5) Observe geometric phase



spin-dependent potential:

$$(\omega_t^{\uparrow})^2 = (\omega_t^{\downarrow})^2 + \Delta\omega_t^2, \qquad \Delta\omega_t^2 = -\frac{16\beta^2}{m}\mathcal{P}(n)$$

Just kicking ion crystals for entanglement

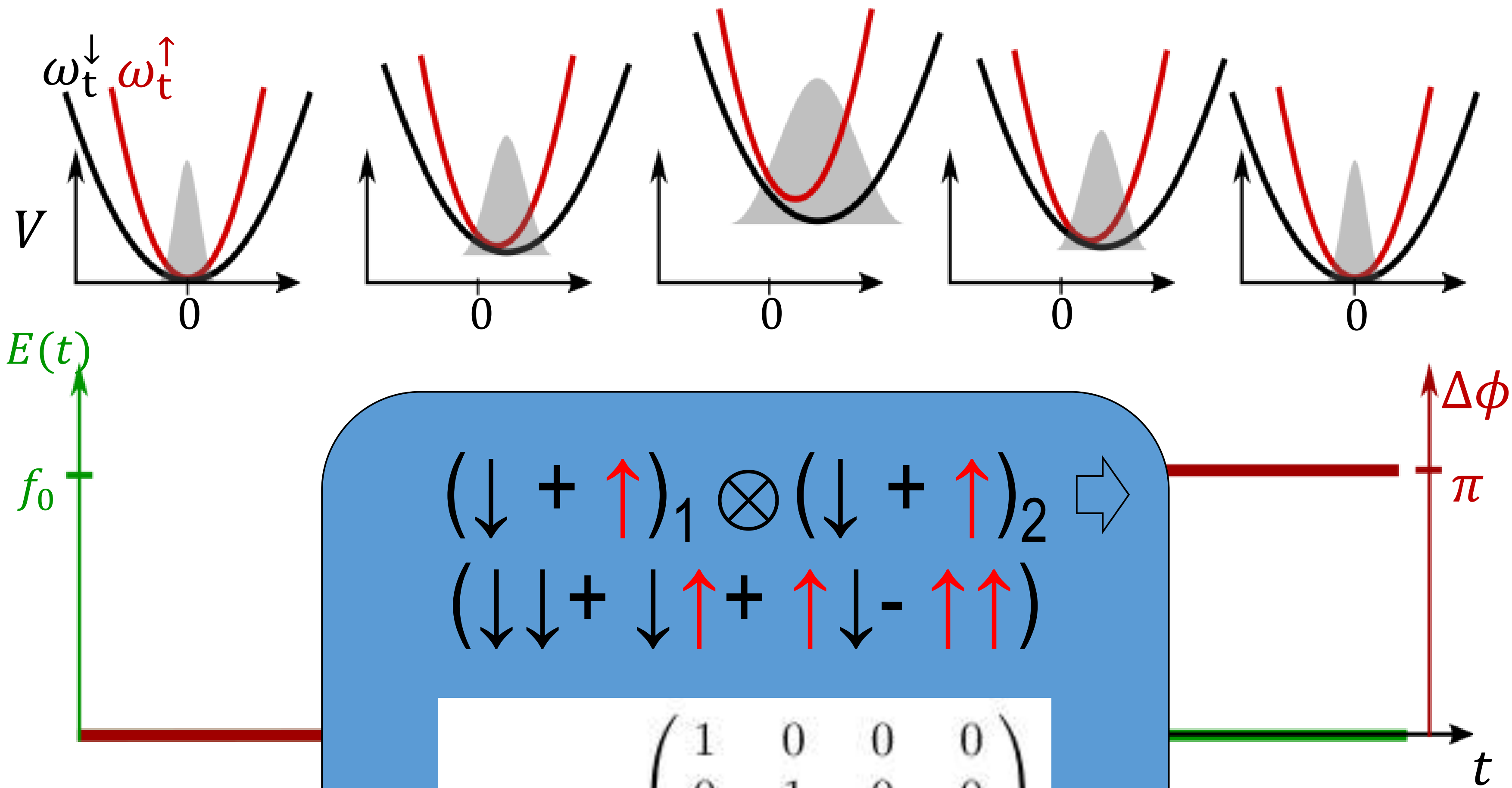


Optimize the electric electric kick by tuning:
Rydberg level *n*, Kick strength f_0
Kick duration τ

➡ Generate a π-phase gate

Vogel, Li, Mokhberi, Lesanowski, Schmidt-Kaler, arXiv:1905.05111

Just kicking ion crystals for entanglement



$(\downarrow + \uparrow)_1 \otimes (\downarrow + \uparrow)_2 \Rightarrow$

$(\downarrow\downarrow + \downarrow\uparrow + \uparrow\downarrow - \uparrow\uparrow)$

$$U_{CP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Optimize the elec… …erate a
Rydberg level *n*, … …phase gate
Kick duration τ

Vogel, Li, Mokhberi, Lesanowski, Schmidt-Kaler, arXiv:1905.05111

Trapped ion kicking

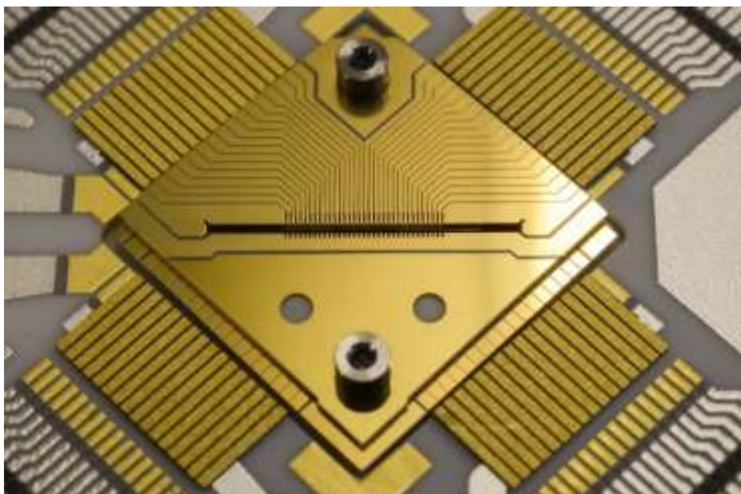
PRL **109,** 080501 (2012) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 24 AUGUST 2012

Controlling Fast Transport of Cold Trapped Ions

A. Walther, F. Ziesel, T. Ruster, S. T. Dawkins, K. Ott, M. Hettrich, K. Singer, F. Schmidt-Kaler, and U. Poschinger*

QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

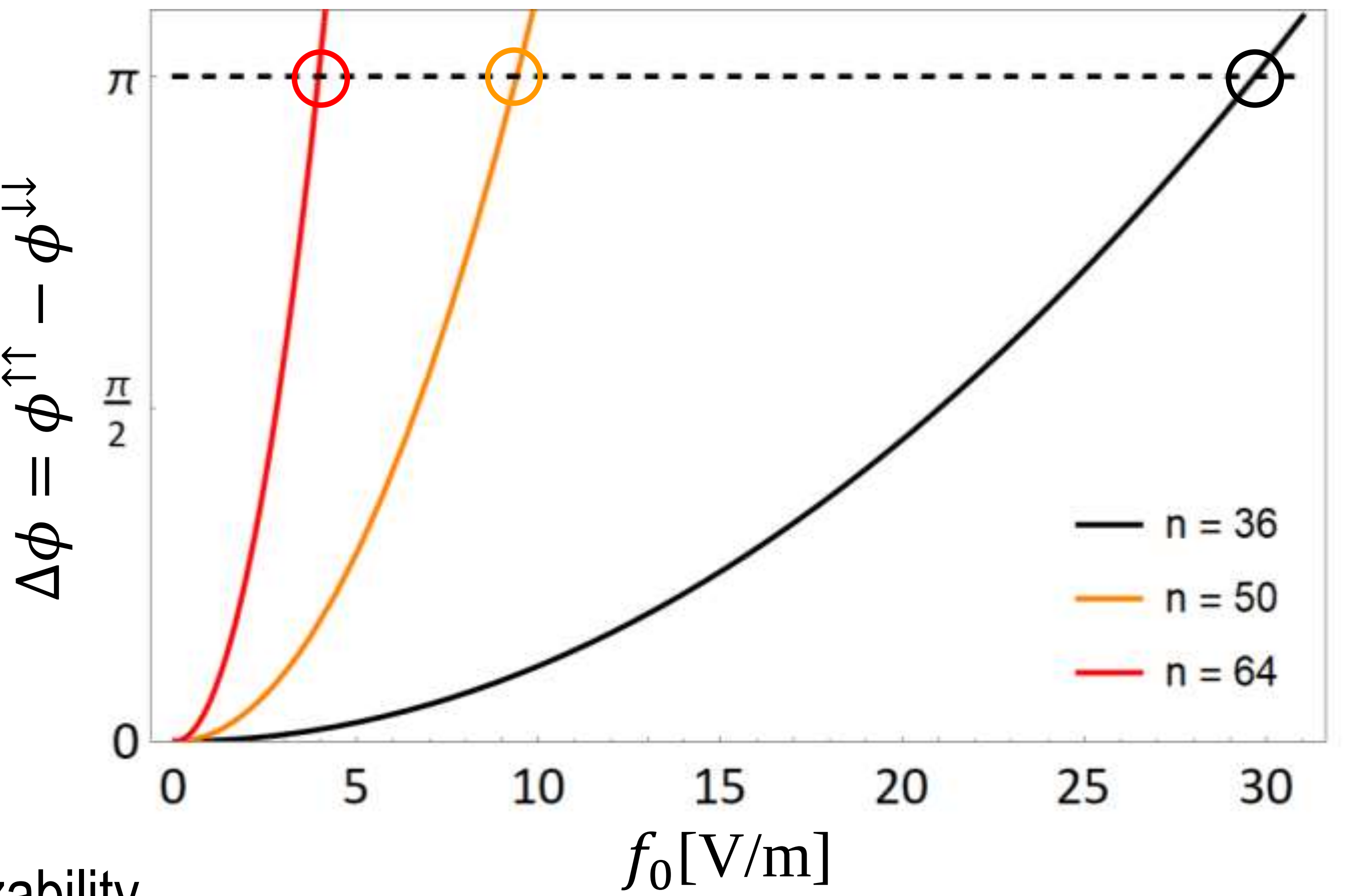
(Received 2 June 2012; published 20 August 2012)



PRL109, 080501 (2012)

PRL109, 080502 (2012)

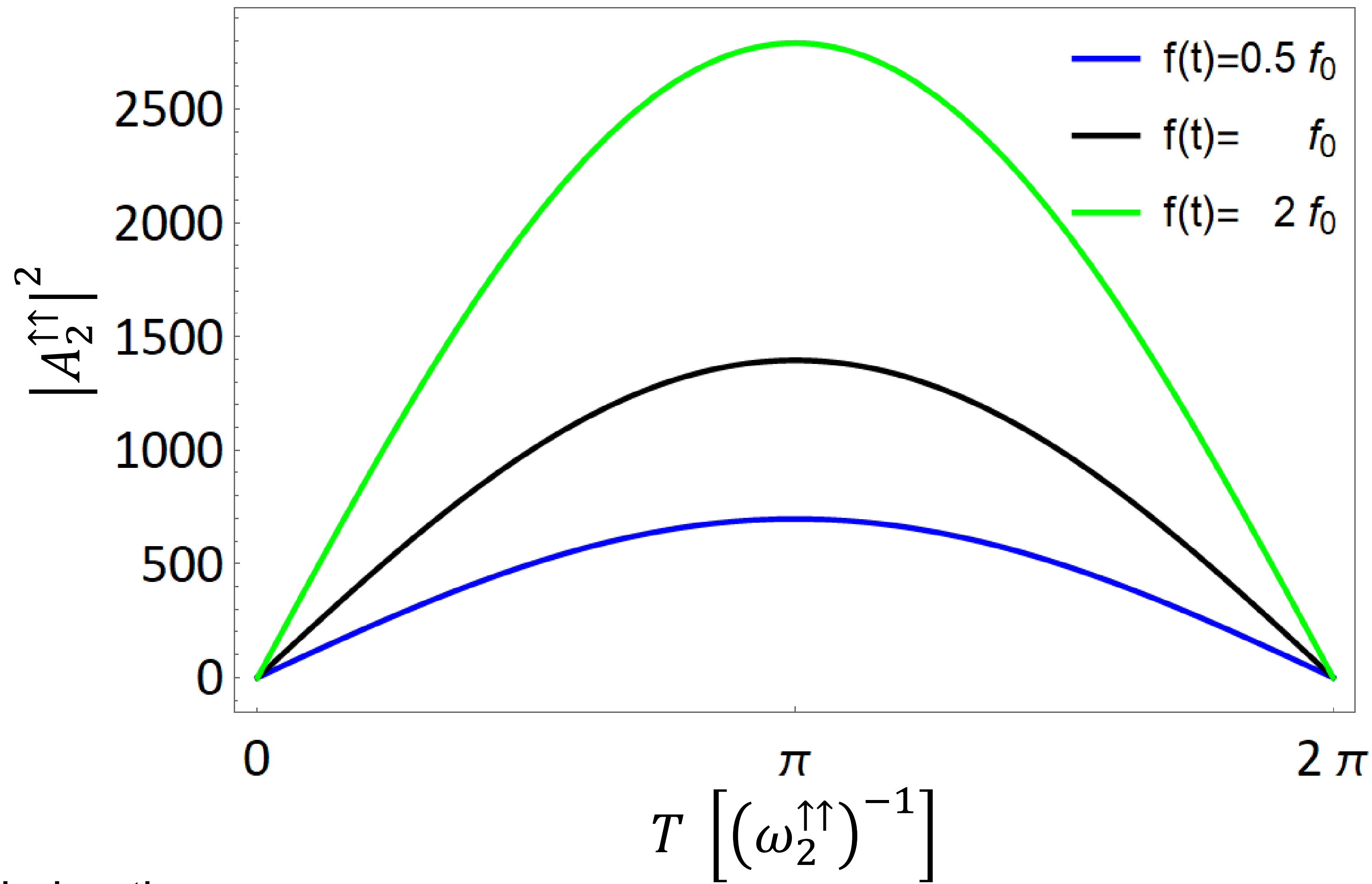
Optimize phase shift



Chose *n*, thus polarizability and kick strength f_0

Vogel, Li, Mokhberi, Lesanowski, Schmidt-Kaler, arXiv:1905.05111

Recover initial phonon number

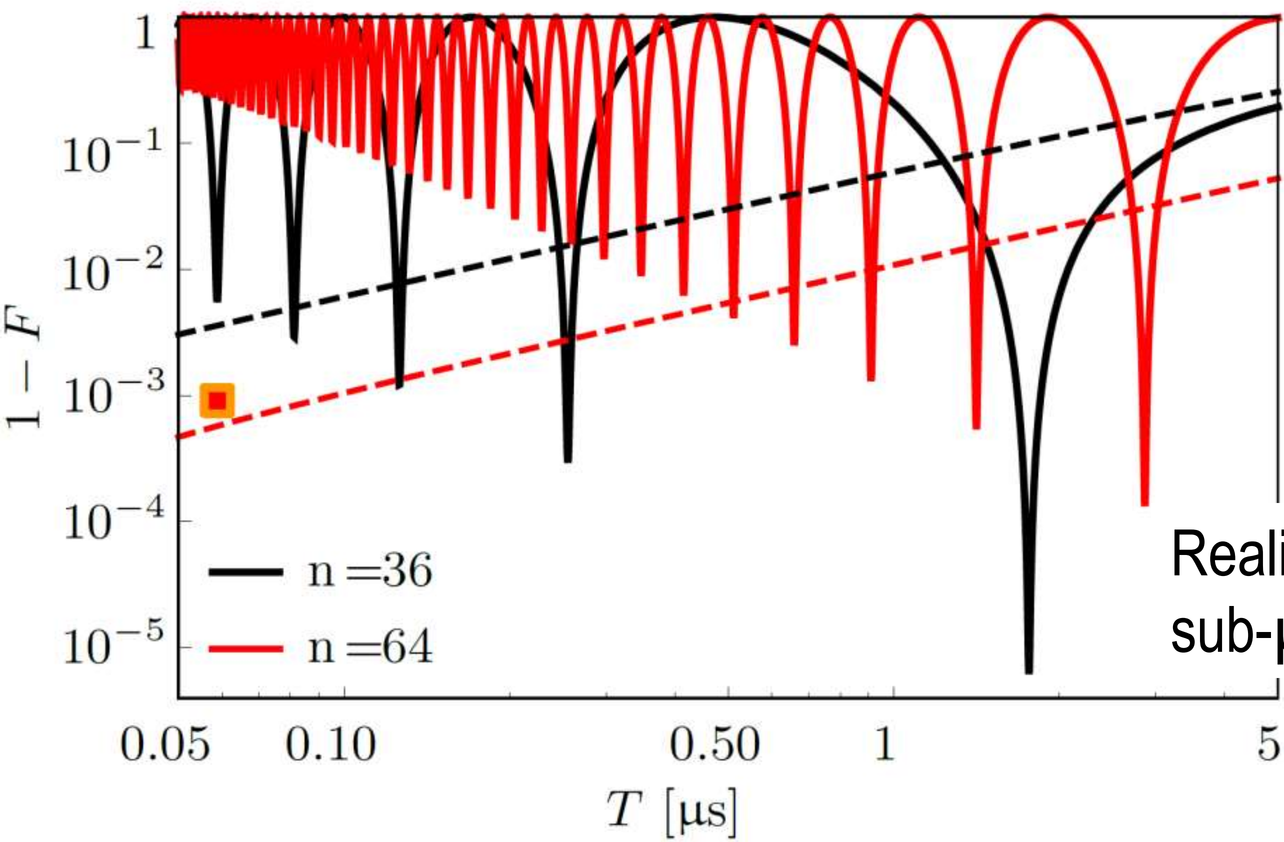


Optimize kick duration

$$\tau = 2\pi\left(\omega_2^{\uparrow\uparrow}\right)^{-1}$$

Vogel, Li, Mokhberi, Lesanowski, Schmidt-Kaler, arXiv:1905.05111

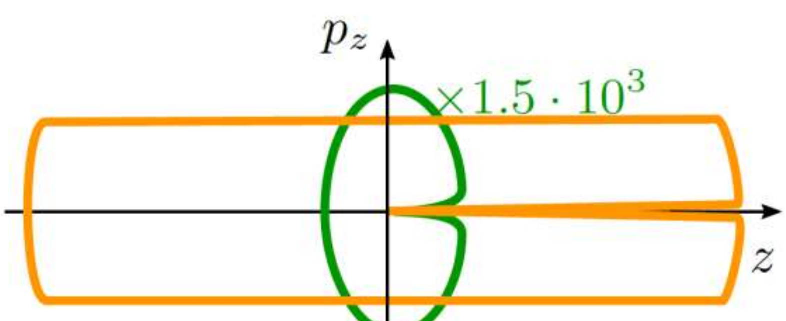
Fidelity



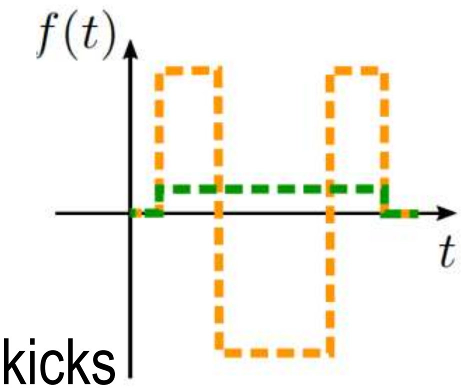
Rydberg lifetime: 65μs / 370μs

3-kick Bang-Bang control: 60ns

Realistic parameters for sub-μs entangling operation



Phase space

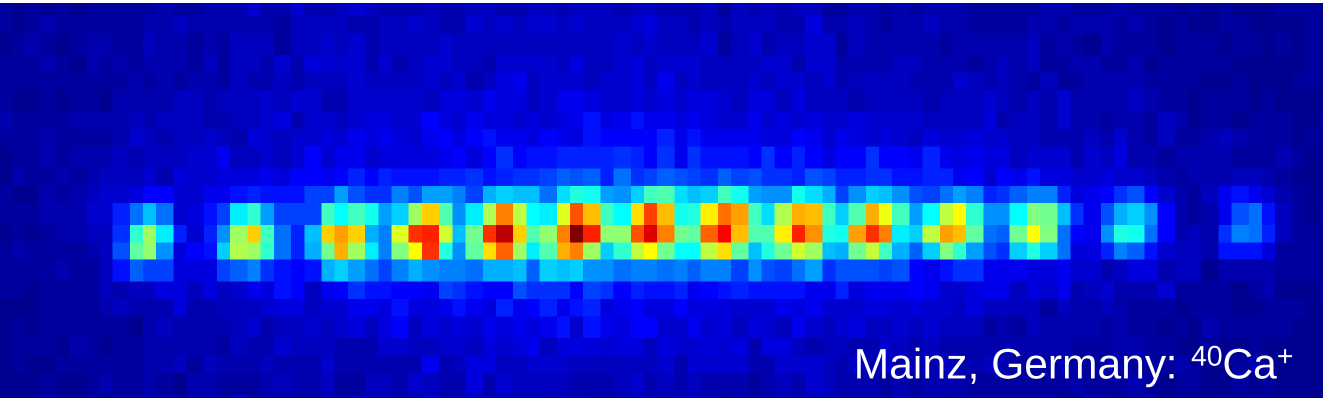


elec. kicks

See also:
Ripol, et al, PRL 91, 157901 (2003), Schäfer et al, Nat. 555, 75 (2018)

Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Rydberg excitations for fast entangling operations
- Quantum thermodynamics, heat engines, phase transitions
- Implanting single ions for a solid state quantum device



www.quantenbit.de
F. Schmidt-Kaler
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ