

# Rydberg excited Calcium Ions for quantum interactions

Innsbruck – Mainz – Nottingham

**Igor Lesanovsky**



# Outline

1. **The R-ION consortium** – Who are we?
2. **Goals** – What are we doing and why?
3. **Physics** – State of the art (cold ions and atoms)
4. **Challenge** – Why is this difficult?
5. **Status** – Current exp. & theo. developments?
6. **Future**

# The R-ION Consortium

## Experiment

**Prof. Ferdinand Schmidt-Kaler**

*University of Mainz/Germany*

Expert in experimental trapped  
Ion physics

**Prof. Jochen Walz**

*University of Mainz/Germany*

Expert in experimental laser  
physics and spectroscopy

## Theory

**Prof. Peter Zoller**

*University of Innsbruck/Austria*

Expert in quantum information  
theory and cold atoms physics

**Dr. Igor Lesanovsky**

*University of Nottingham/UK*

Expert in theoretical atomic  
physics and spin systems

# The R-ION Consortium



**Kick-off meeting at Überglingen/Germany 23.08.-25.08.11**

# The R-ION Consortium

## Funding period

August 2011

July 2014



## Requested funds

- six postdoc years for theory
- six postdoc years for experiment
- 200 kEUR for consumables
- 70 kEUR travel and subsistence

## Aims

- explore and understand fundamental properties of a new platform for quantum information processing and for quantum simulations

# The R-ION Consortium

Follow us on the web: [www.nottingham.ac.uk/~ppziwl/rion](http://www.nottingham.ac.uk/~ppziwl/rion)



The screenshot shows a Firefox browser window with the address bar displaying [www.nottingham.ac.uk/~ppziwl/rion/index.php](http://www.nottingham.ac.uk/~ppziwl/rion/index.php). The website content includes the R-ION logo (a red sphere with a blue ring and the text 'R-ION ++'), the tagline 'Rydberg excited Calcium Ions for Quantum Interactions', and logos for funding partners: FWF (Der Wissenschaftsfonds), EPSRC (Pioneering research and skills), PT-DLR, and chist-era. A navigation bar at the bottom contains links: HOME, THE CONSORTIUM, WORK PACKAGES, PUBLICATIONS, and CONTACT. The main content area has a heading 'Welcome to the website of the R-ION consortium' followed by sections for 'Funding' and 'Mission statement'. The 'Funding' section states that the consortium receives support from EPSRC, FWF, PT-DLR, and CHIST-ERA. The 'Mission statement' section describes the goal of implementing quantum information processing with trapped cold ions. A 'LATEST NEWS' sidebar on the right lists three updates: a paper in Physical Review Letters (11.01.2012), a presentation at the COHERENCE ITN meeting (30.11.2011), and a presentation at the QIPC 2011 conference (05.09.2011).

**R-ION**  
Rydberg excited Calcium Ions for Quantum Interactions

**FWF**  
Der Wissenschaftsfonds.

**EPSRC**  
Pioneering research and skills

**PT-DLR**

**chist-era**

HOME THE CONSORTIUM WORK PACKAGES PUBLICATIONS CONTACT

## Welcome to the website of the R-ION consortium

### Funding

The R-ION consortium receives the funding support of [EPSRC](#), [FWF](#) and [PT-DLR](#) in the framework of the ERA-NET [CHIST-ERA](#).

### Mission statement

Trapped cold ions are among the most advanced systems to implement quantum information processing. In current experiments entanglement of the qubits, represented by long lived internal atomic states, is achieved via quantum control of the (collective) motion of the ion crystal. Instead, we propose an unprecedented experimental program supported by theory, where the huge dipole moments associated with Rydberg excited ions are the basis of extremely strong spin-dependent long range interactions, and thus exceptionally fast entangling operations as basic building blocks for quantum computing and

### LATEST NEWS

**11.01.2012** Our paper [Electronically Excited Cold Ion Crystals](#) has appeared in Physical Review Letter. Check out the [Publications](#) page.

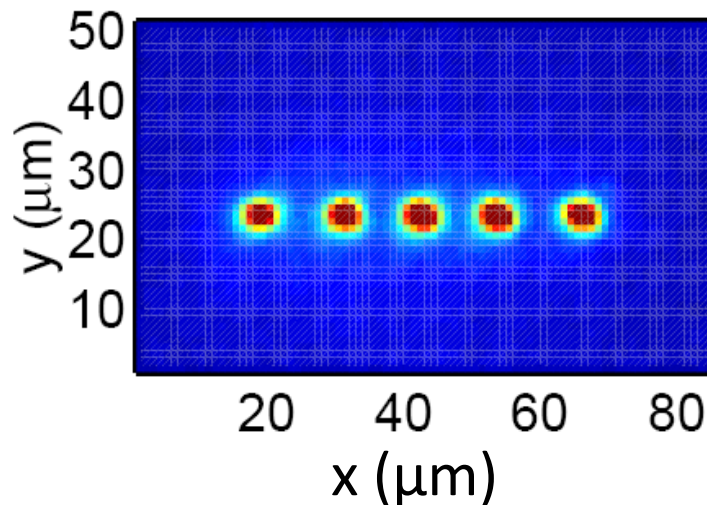
**30.11.2011** The R-ION project was presented at the Kick off meeting of the [COHERENCE](#) ITN at Heidelberg/Germany.

**05.09.2011** The R-ION project will be presented at the [QIPC 2011 - Conference](#) at ETH Zurich in September, ETH Zurich, September 5 - 9, 2011

# Physics

**Rydberg** excited   for

- project merges two disjointed fields



# Physics – trapped Ions

## Paul trap

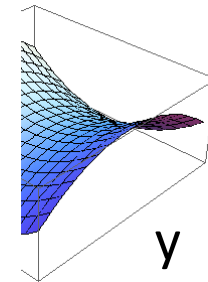
- ions are trapped with electric fields (static and time-dependent)

$$V_{\text{Paul}}(r, t) = e\alpha \cos(\omega t)[x^2 - y^2] +$$

trapping
anti-trapping

$t=t_0$

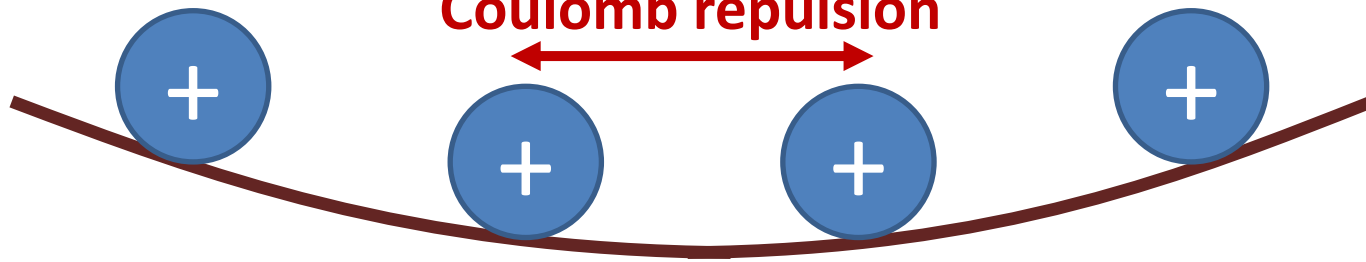
Trapping an ion ...



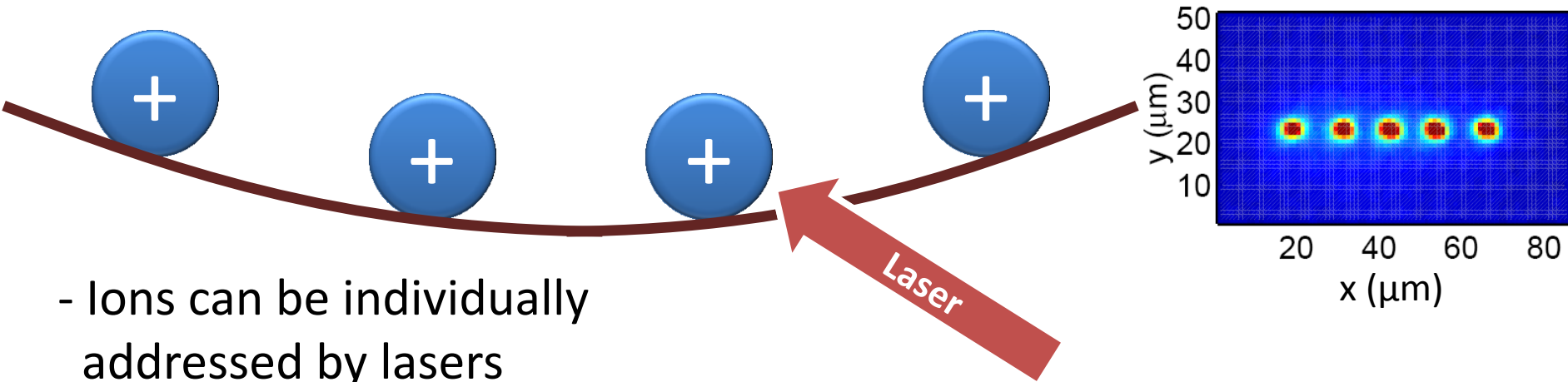
- oscillating field
- linear crystal at low temperatures

dependent) potential  
element and low

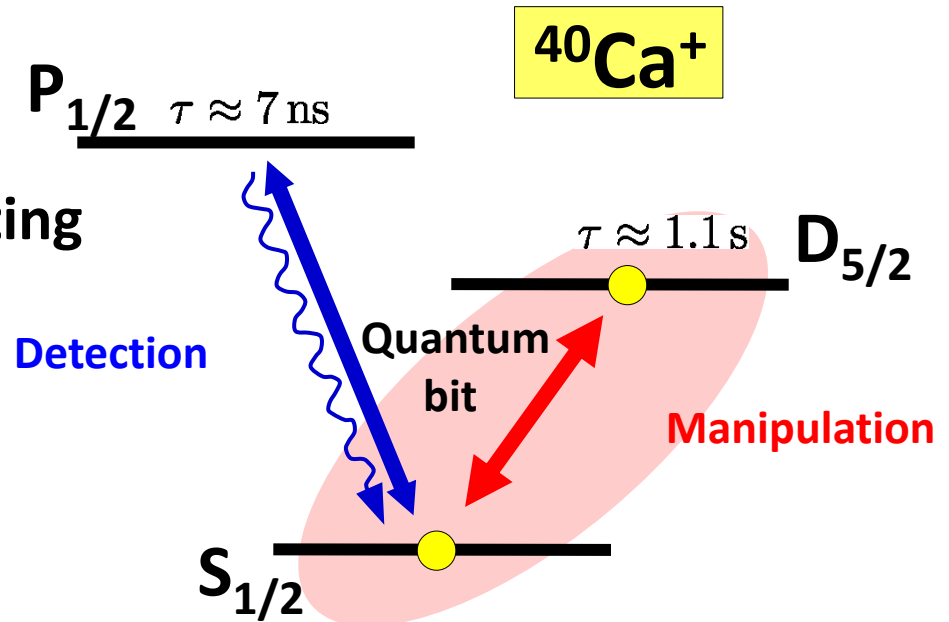
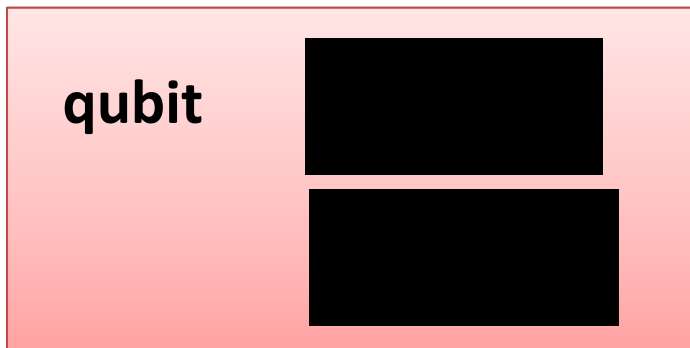
Coulomb repulsion



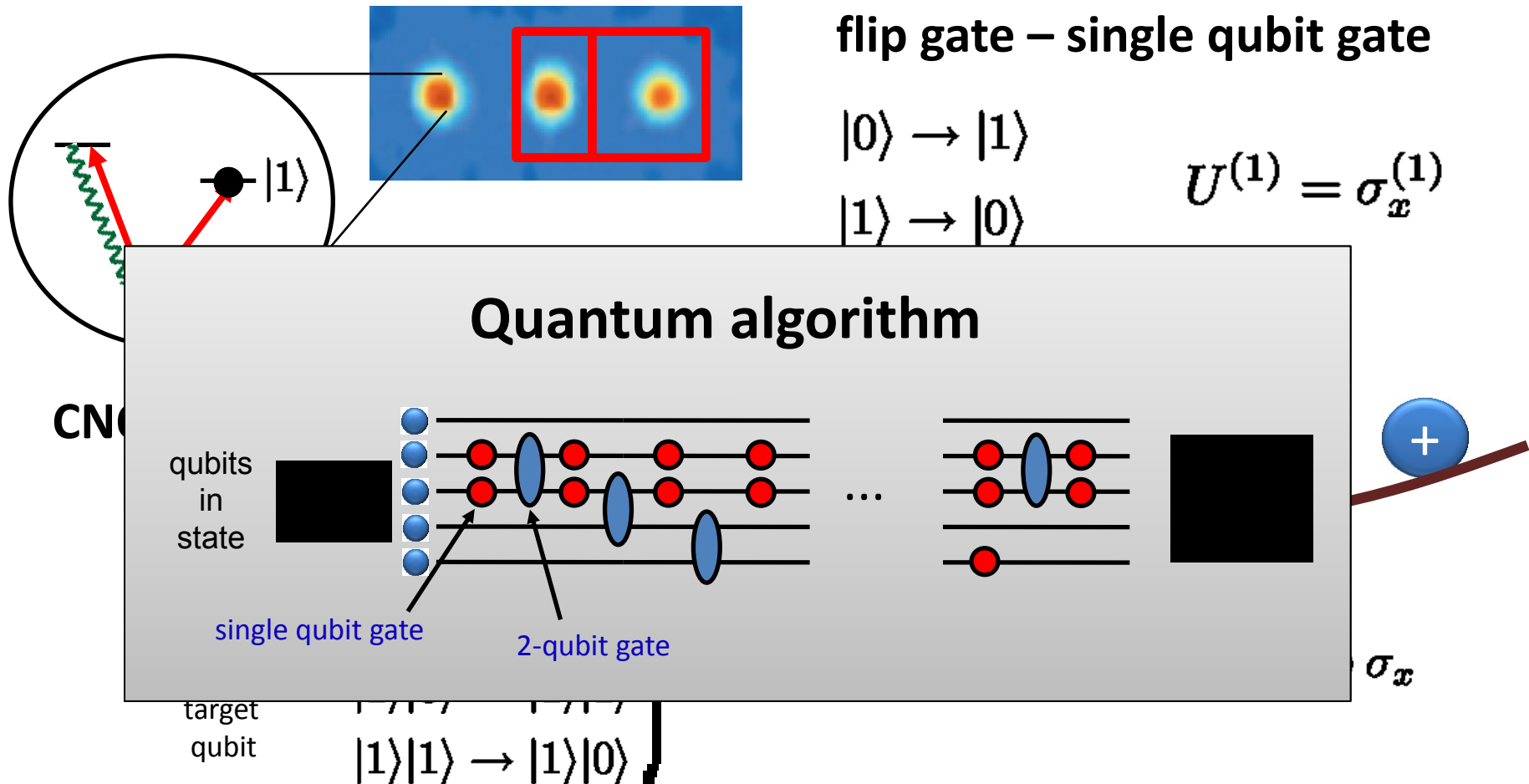
# Physics – trapped ions



- Ions can be individually addressed by lasers
- internal states can be manipulated and selectively excited
- application: **Quantum Computing**



# Quantum interactions – quantum gates



- two qubit gates possible because ions can **interact via vibrational modes of the ion crystal**

# Trapped ions

- individually addressable
- decoupled from environment (**can be trapped for days !!**)

- single-qubit gates with fidelity > 99% possible

- two-qubit gates with high efficiency

Applications

- universal

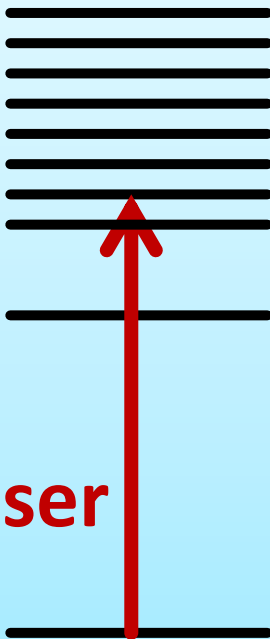
- precision

- universal

- universal

(see

**Laser**

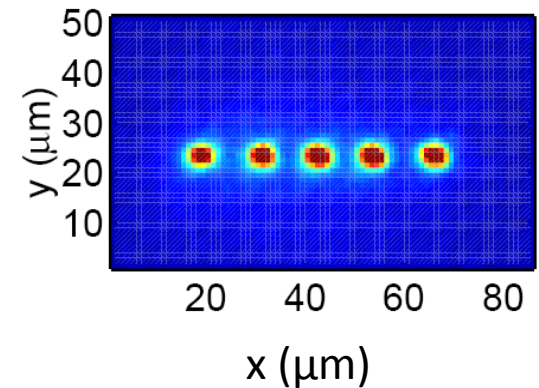


ts

computer

ulator

eland, Monroe...)



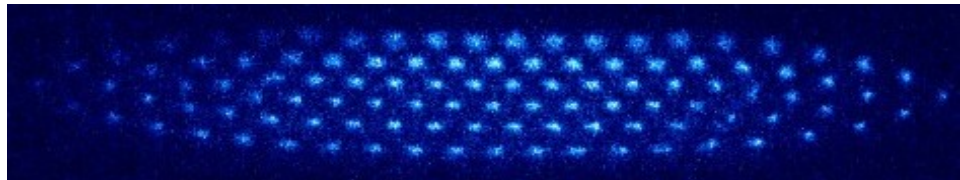
„Pr

- **sc**

- scalability required to do „serious“ quantum computation

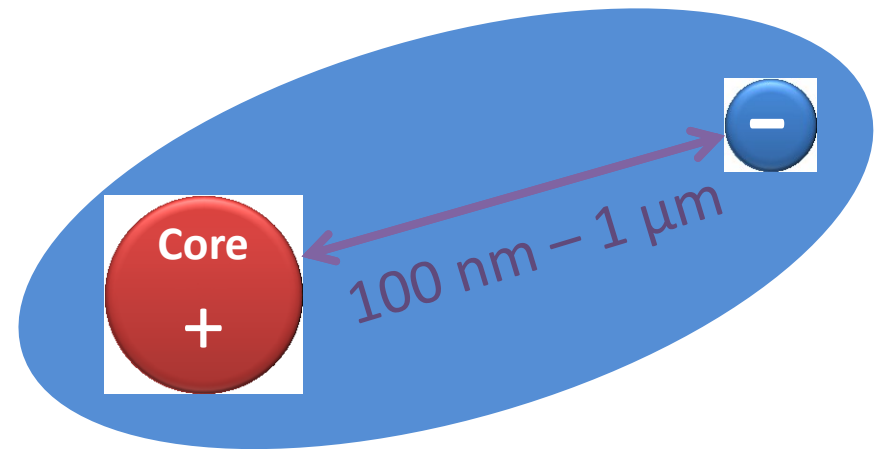
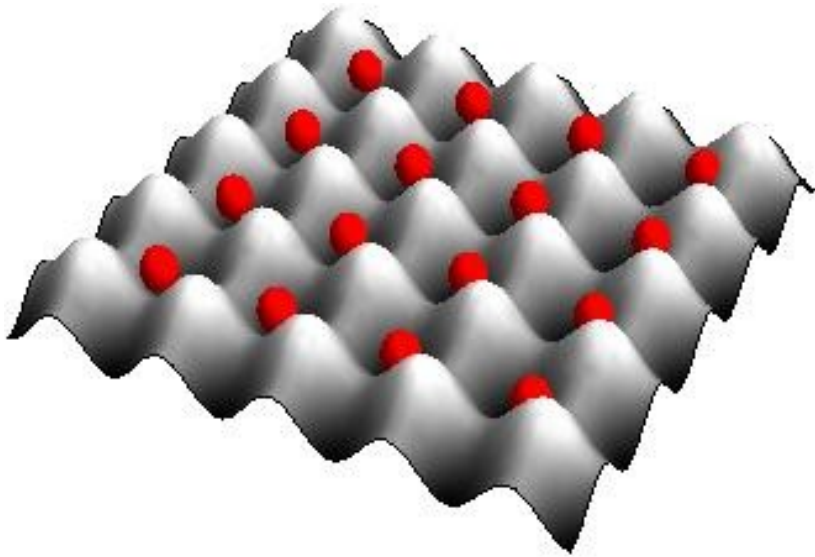
- problem: interactions rely on structure of

vibrational modes (which need to be addressed by the laser)



# Physics – Rydberg atoms

 excited **Calcium Ions** for  
**quantum interactions**



# Ultra cold **ground state** atoms

Bloch et al., RMP 80, 885 (2008)

- provide a universal toolbox for the study of many-particle problems
  - great ability to **control the interatomic interactions**
  - almost **arbitrary shapes of external confinement** realizable
- allows us to gain new insights into questions of condensed matter physics

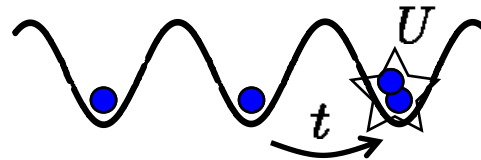
## Prototypical problem

?

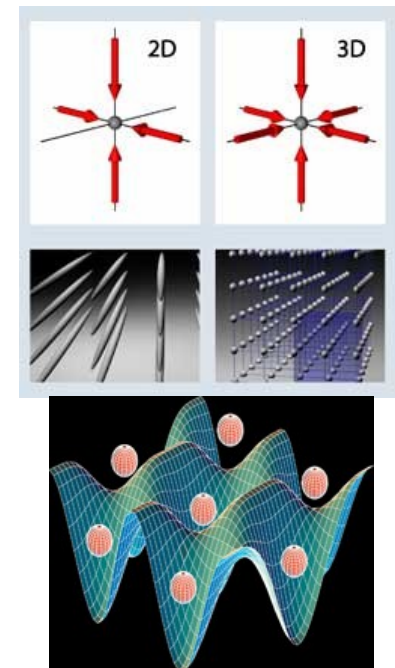
### Model Hamiltonian

$$H = -t \sum_{\langle i,j \rangle} (b_i^\dagger b_j + b_j^\dagger b_i) + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1) - \mu \sum_i \hat{n}_i$$

external (time-dependent) control  
of the Hamiltonian parameters

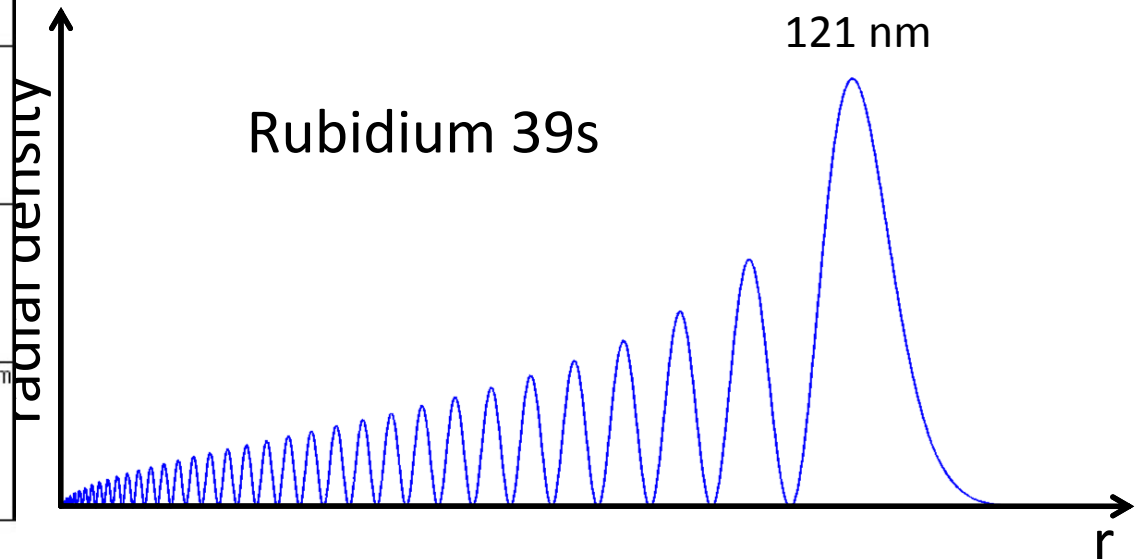
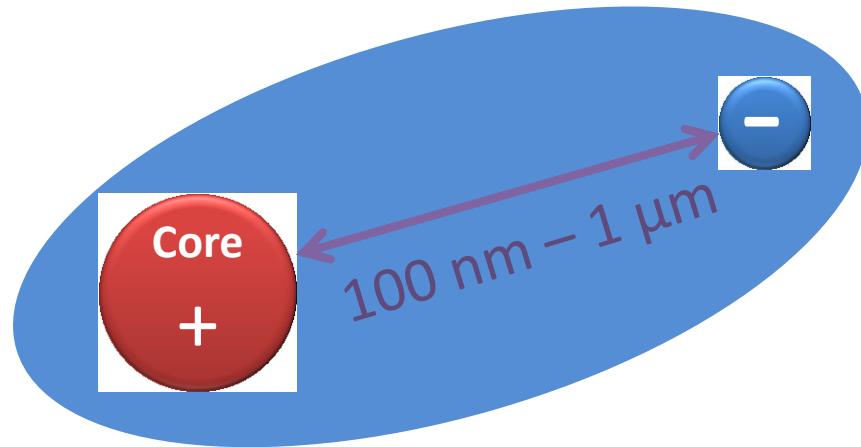


### Lattices of light



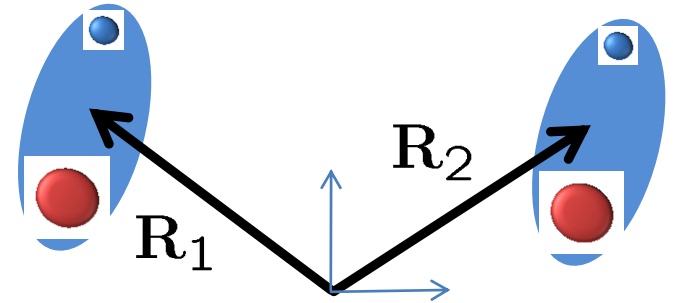
# Atoms in Rydberg states

|            |  |     |  |           |  |        |  |               |  |     |  |           |  |        |  |  |  |
|------------|--|-----|--|-----------|--|--------|--|---------------|--|-----|--|-----------|--|--------|--|--|--|
|            |  |     |  |           |  |        |  |               |  |     |  |           |  |        |  |  |  |
| beryllium  |  | 4   |  | <b>Be</b> |  | 9.0122 |  | magnesium     |  | 12  |  | <b>Mg</b> |  | 24.305 |  |  |  |
| calcium    |  | 20  |  | <b>Ca</b> |  | 40.078 |  | strontium     |  | 38  |  | <b>Sr</b> |  | 87.62  |  |  |  |
| barium     |  | 56  |  | <b>Ba</b> |  | 137.33 |  | radium        |  | 88  |  | <b>Ra</b> |  | [226]  |  |  |  |
| scandium   |  | 21  |  | <b>Sc</b> |  | 44.956 |  | yttrium       |  | 39  |  | <b>Y</b>  |  | 88.906 |  |  |  |
| titanium   |  | 22  |  | <b>Ti</b> |  | 47.867 |  | zirconium     |  | 40  |  | <b>Zr</b> |  | 91.224 |  |  |  |
| luteceium  |  | 71  |  | <b>Lu</b> |  | 174.97 |  | hafnium       |  | 72  |  | <b>Hf</b> |  | 178.49 |  |  |  |
| lawrencium |  | 103 |  | <b>Lr</b> |  | [262]  |  | rutherfordium |  | 104 |  | <b>Rf</b> |  | [261]  |  |  |  |



# Atoms in Rydberg states

- hydrogen-like
- simple level structure
- **long lifetime**  $\tau / n^{3...5}$  ( $\tau \sim 100 \mu\text{s}$ )
- large displacement between charges



Rydberg atoms via van-der-Waals or dipole-dipole interaction

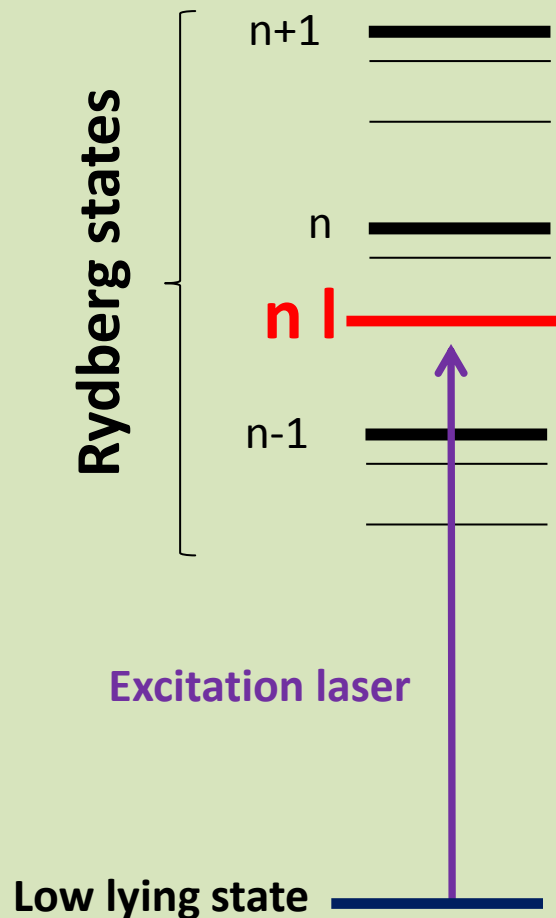
$$V_{\text{vdW}} = \frac{C_6}{|\mathbf{R}_1 - \mathbf{R}_2|^6}$$

$$V_{\text{dd}} \approx \frac{\mathbf{d}_1 \cdot \mathbf{d}_2}{|\mathbf{R}_1 - \mathbf{R}_2|^3}$$

- interaction strength of MHz achievable over a distance of several ten micrometers
- interaction is state-dependent

# Rydberg atoms as (pseudo)spins

## Energy level spectrum



$$\Delta \quad \quad \quad |\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$\Omega$

$$|\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

## Hamiltonian

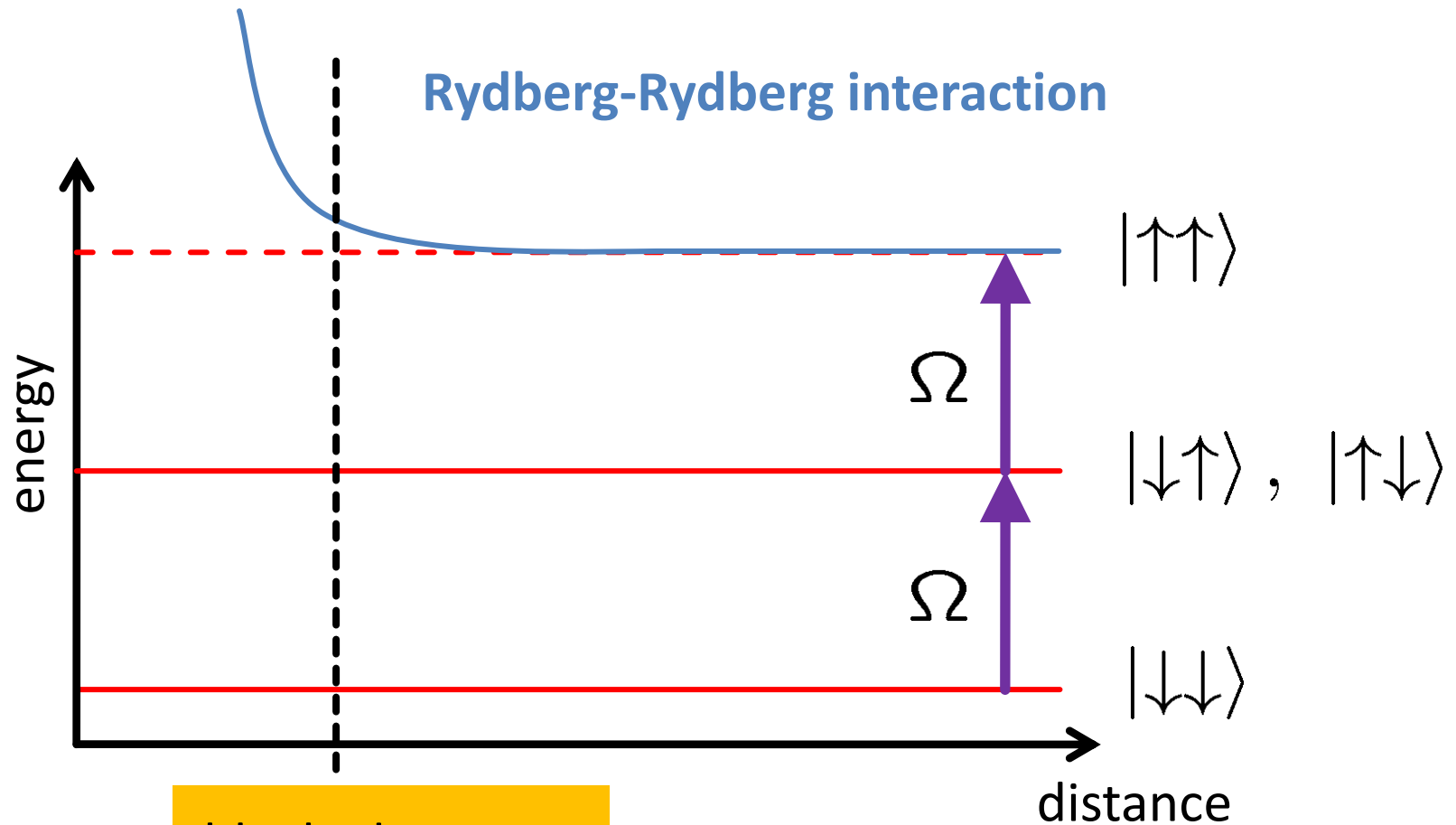
$$H = \text{Rabi frequency} \sigma_x + \text{Detuning} n$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad n = \frac{1}{2} [\sigma_z + 1] = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

# Rydberg blockade

## Two atoms

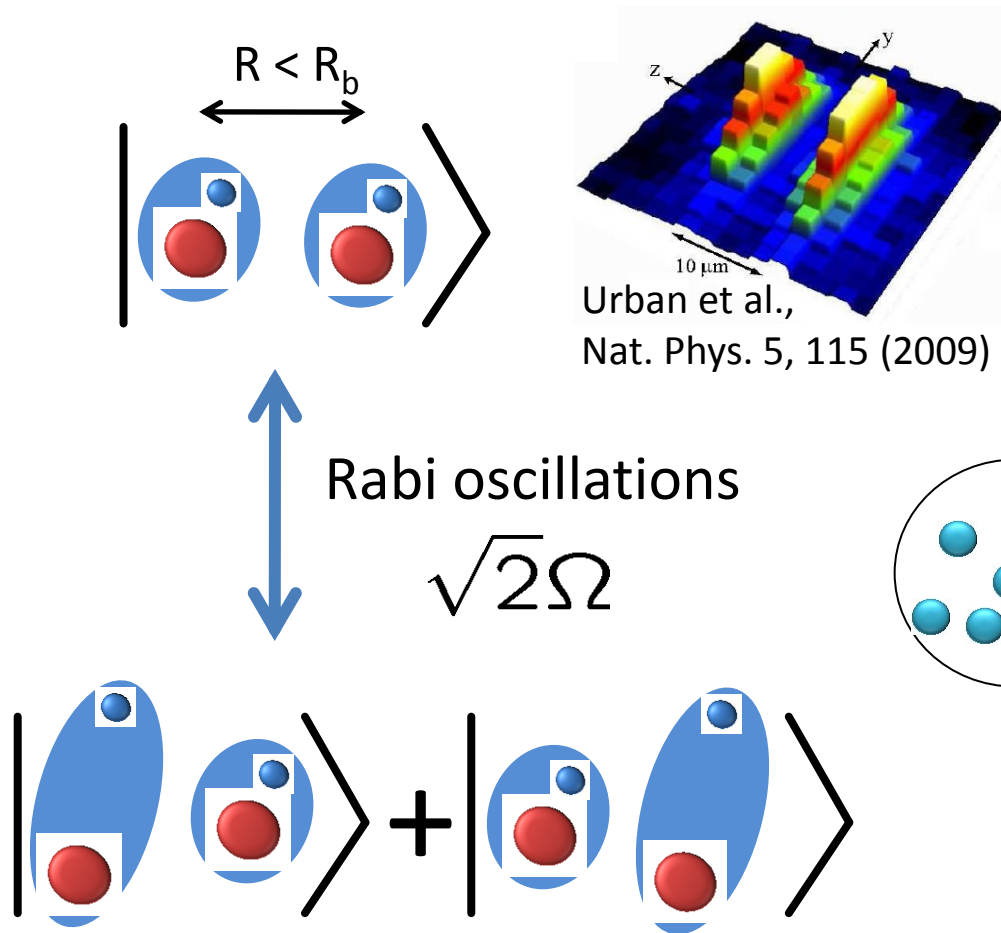
D. Jaksch et al., PRL 85, 2208 (2000)  
M. Lukin et al., PRL 87, 037901 (2001)



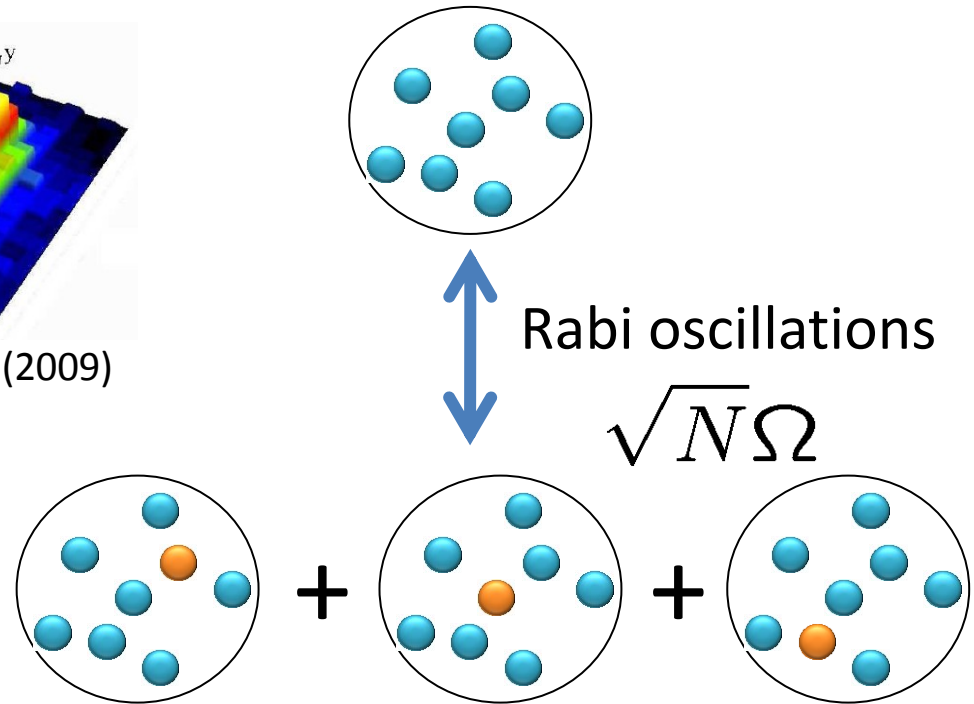
blockade  
radius  $\gg 10\ \mu\text{m}$

# Interacting Rydberg Atoms

## Two blockaded atoms



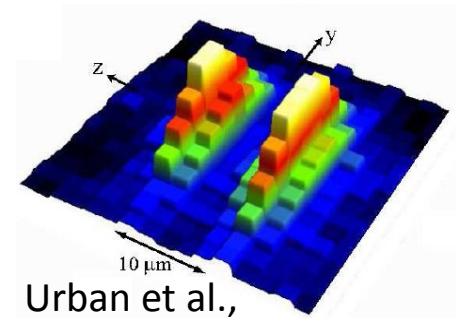
## N blockaded atoms



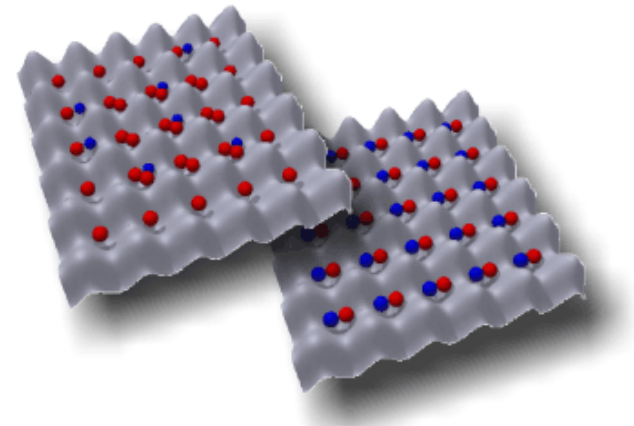
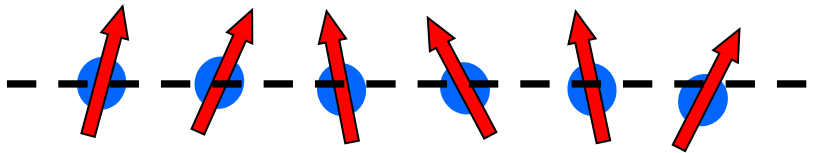
**Entangled states can be easily created**

# Rydberg Atoms

- Rydberg states offer **strong and fast interactions**
- gates do not rely on vibrational modes
- **interaction** can be switched **on and off**
- intrinsically **scalable approach**
- **trapping over long times difficult**



Urban et al.,  
Nat. Phys. 5, 115 (2009)



- implementation of quantum information processing schemes
- quantum simulation of strongly interacting spin systems
- cold atoms compete with ions

# The goal of R-ION

Join advantages of **trapped ions**

- trapped, localized qubits
- near unity detection efficiency
- quantum gate operations with 99% fidelity
- state and process tomography

with **Rydberg excitations and interactions**

- Rydberg blockade mechanism
- long range interactions
- fast gate operation
- independent of vibrational modes

... a new approach towards a robust scalable quantum computer  
... to simulate quantum many-body systems in the lab

# The Challenges

$$E_n = -\frac{1}{2} \frac{Z^2}{n^2}$$

Experimental  
d coherence  
122 nm wa  
violet VUV)  
- need to co

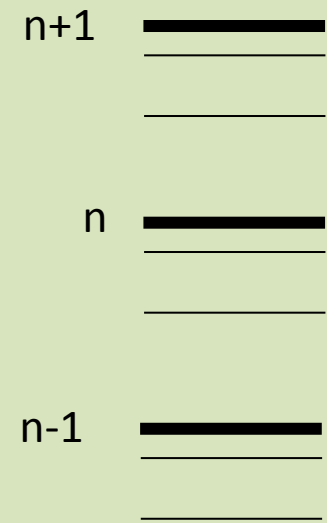
|               |                                         |                                            |
|---------------|-----------------------------------------|--------------------------------------------|
|               | scandium<br>21<br><b>Sc</b><br>44.956   | titanium<br>22<br><b>Ti</b><br>47.867      |
|               | yttrium<br>39<br><b>Y</b><br>88.906     | zirconium<br>40<br><b>Zr</b><br>91.224     |
| 57-70<br>✱    | lutetium<br>71<br><b>Lu</b><br>174.97   | hafnium<br>72<br><b>Hf</b><br>178.49       |
| 89-102<br>✱ ✱ | lawrencium<br>103<br><b>Lr</b><br>[262] | rutherfordium<br>104<br><b>Rf</b><br>[261] |

## Theoretical

- need to be
- of Rydberg
- need to kn
- need to un
- between R

## Energy level spectrum

Rydberg states



Ground state

# Structure of proposed research

## WP2 – Detection of the Rydberg excitation with trapped $\text{Ca}^+$ ions

- trap design
- producing laser light at target wavelength
- understanding the atomic physics
- perform actual Rydberg excitation

## WP3 – Rydberg- Rydberg interaction in trapped $\text{Ca}^+$ ions

- blockade experiment in crystal
- theory of Rydberg-Rydberg interaction
- implement quantum logic gates

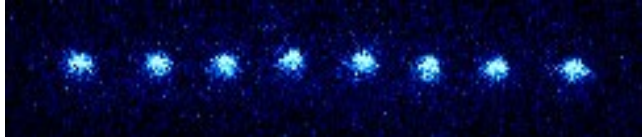
## WP4 – Quantum Simulation and Quantum Information

- representation and simulation of spin Hamiltonians
- quantum information processing in larger crystals

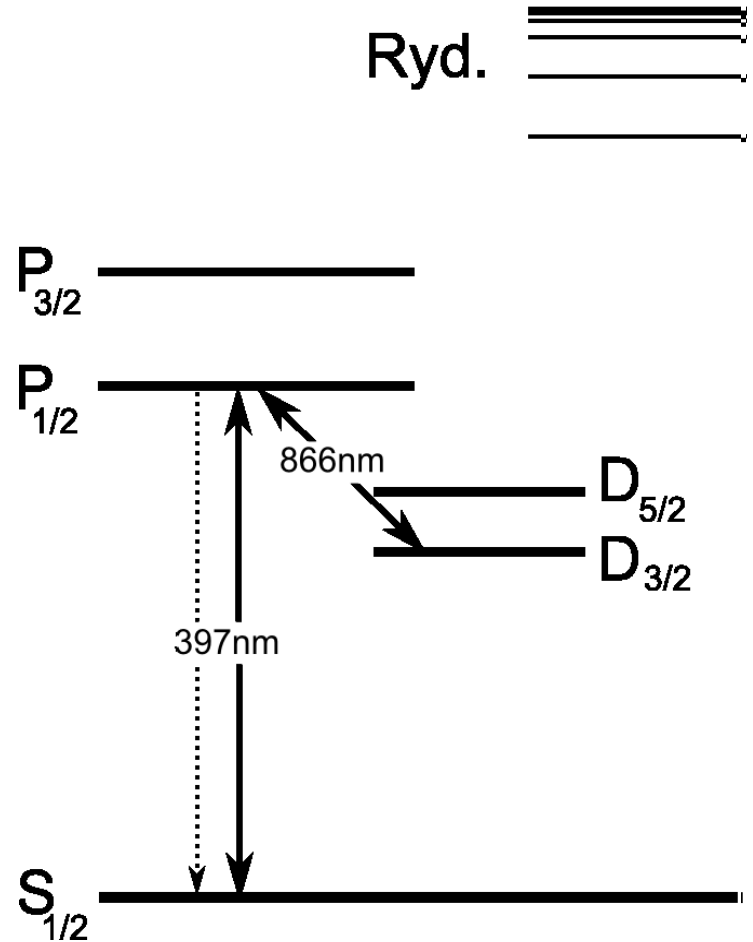
**Can one excite trapped Rydberg ions ?  
If yes, what can one do with them?**

# Experiment

# Experimental sequence

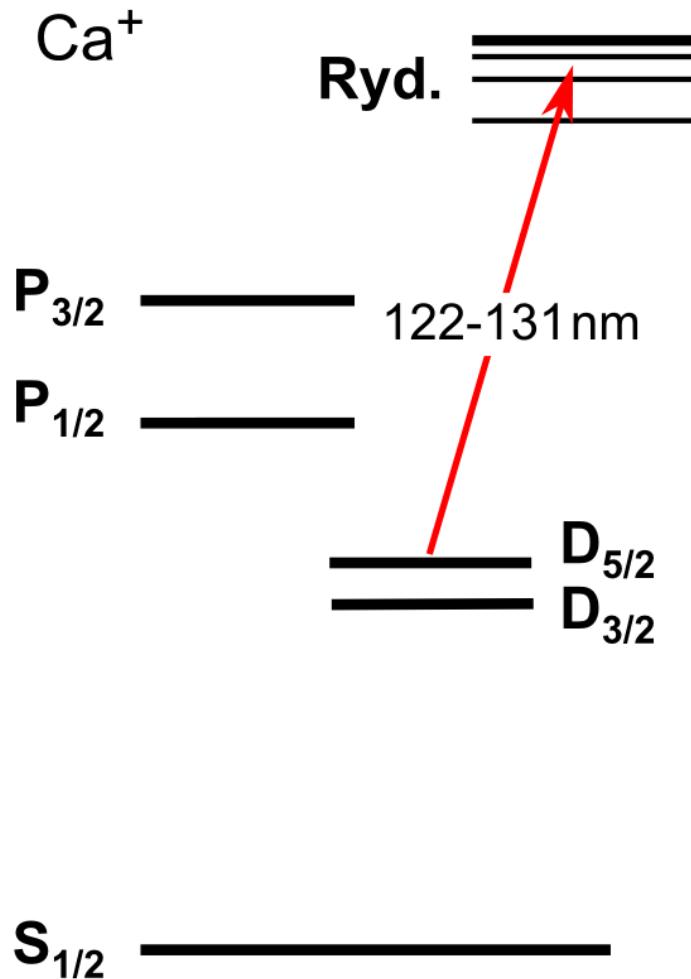


- Doppler cooling
  - Laserdiodes at 397nm, 866nm and 854nm
- Optical Pumping
- Rydberg excitation
- Detection
  - Time < 10ms
  - Only excited ions bright

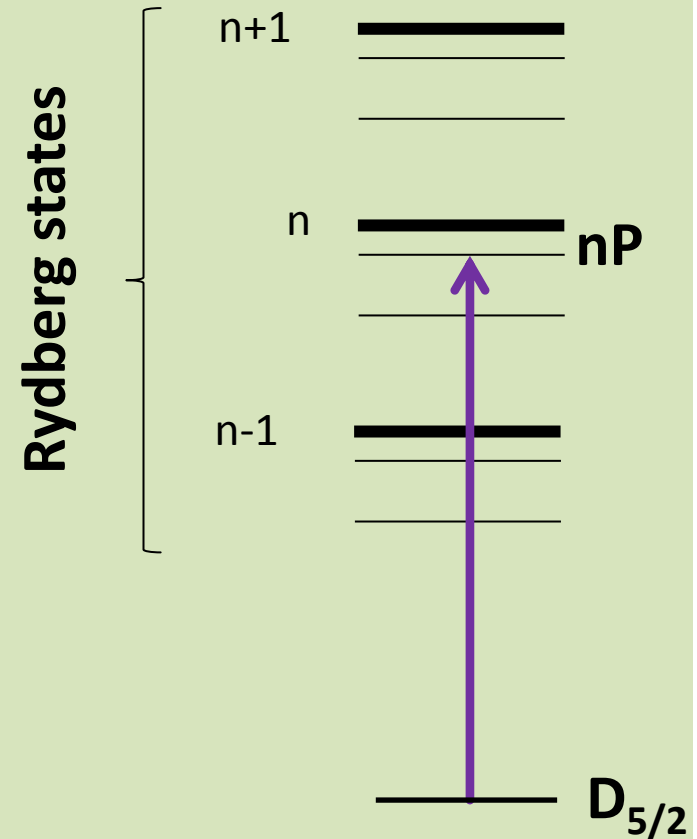


# VUV wavelength for Rydberg excitation

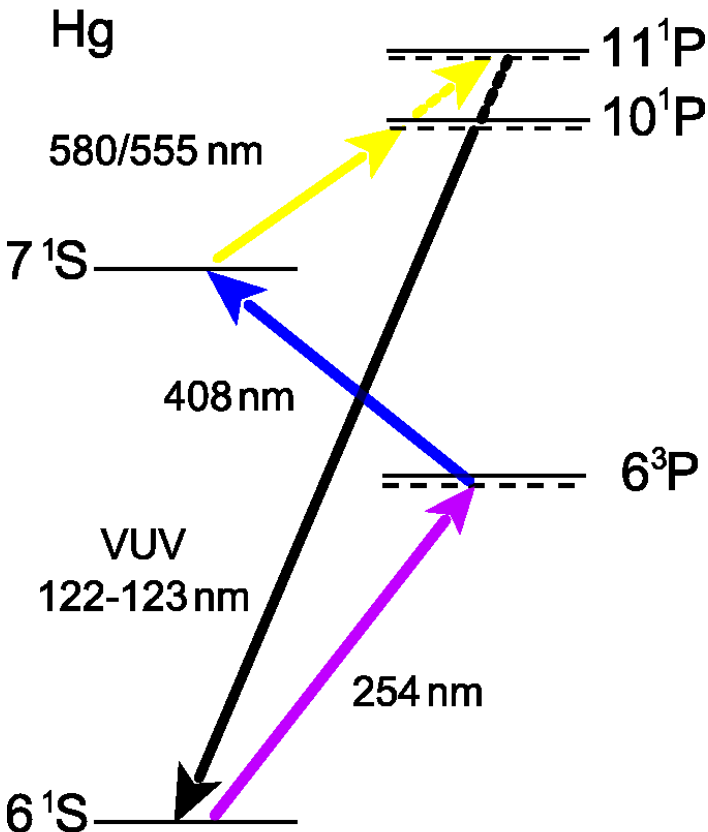
Energy of Rydberg states ( $n=10-100$ )  
determines VUV wavelength



## Rydberg spectrum



# Generation of VUV radiation



- **Four-wave mixing** (nonlinear effect)  
in mercury to generate VUV radiation

$$- P_{\text{VUV}} / P_{254\text{nm}} P_{408\text{nm}} P_{580/555\text{nm}} |\chi^{(3)}|^2$$

- increase  $|\chi^{(3)}|^2$  (third order optical nonlinearity):

→ one photon resonance  $6^1S$ - $6^3P$

→ two photon resonance  $6^1S$ - $7^1S$

→ one photon resonance  $6^1S$ - $10^1P/11^1P$

triple resonant scheme: **enhancement of  $10^4$**

**original purpose of laser system: (anti-)hydrogen spectroscopy**

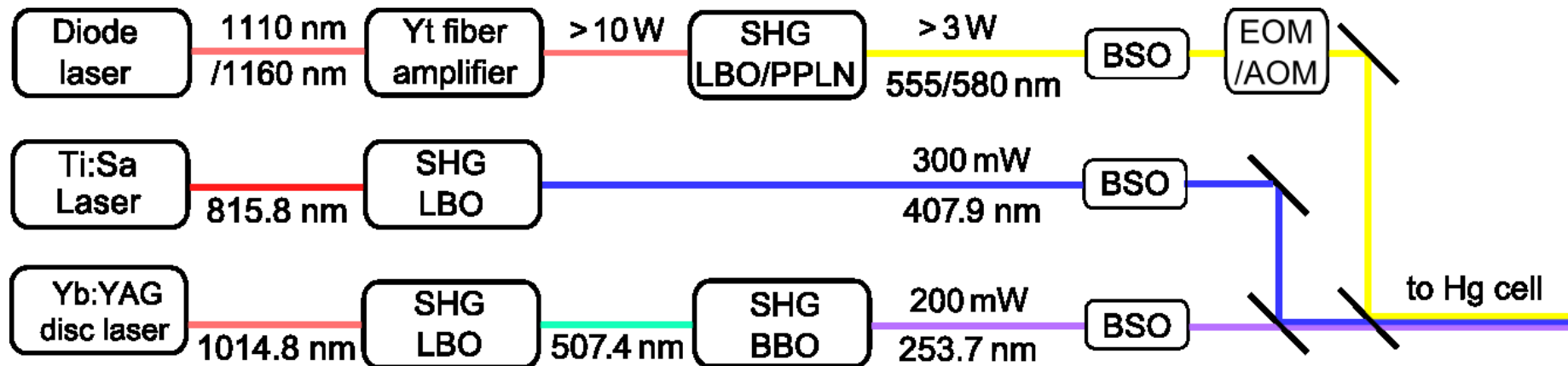
# Setup fundamental lasers

SHG: second-harmonic generation

BSO: beam shaping optics

LBO/BBO/PPLN: nonlinear crystals

EOM/AOM: electro-/acousto-optic modulator

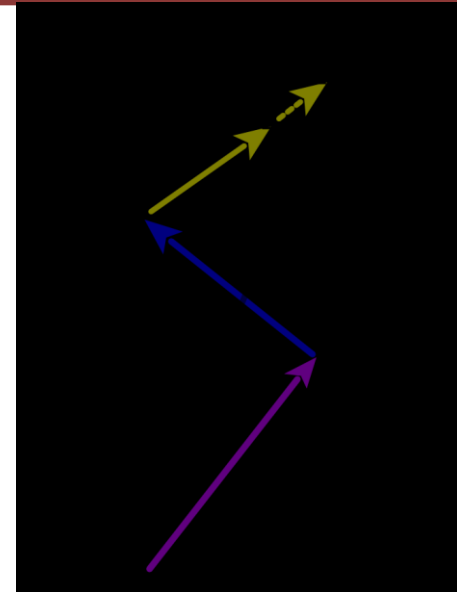
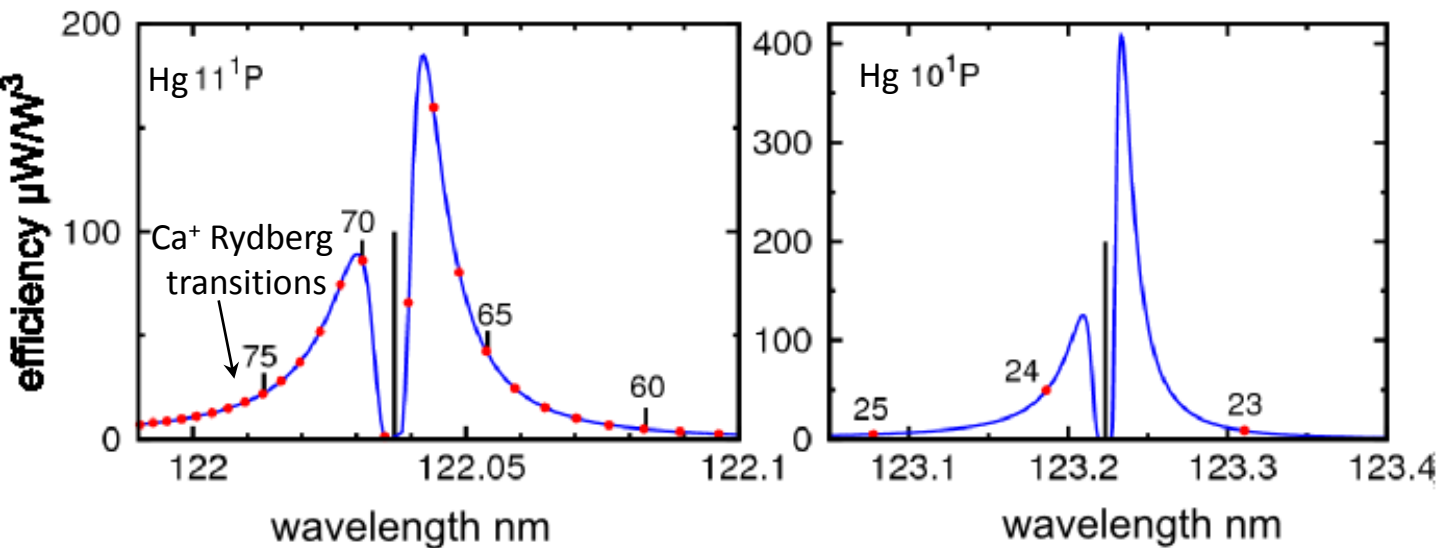


**Experimental value:** 6  $\mu$ W @ 121.26nm <sup>[1]</sup>

[1] Kolbe D., Koglbauer A., Scheid M. and Walz J., to be published

# Calculated four-wave mixing efficiency

- not all wavelengths can be generated efficiently



## Highest calculated efficiencies:

$50\mu\text{W}/\text{W}^3$  for  $24\text{P}_{3/2}$

$150\mu\text{W}/\text{W}^3$  for  $67\text{P}_{3/2}$

## Estimated VUV-power:

$9\mu\text{W}$  for  $24\text{P}_{3/2}$

$27\mu\text{W}$  for  $67\text{P}_{3/2}$

## Calculated Rabi frequencies:

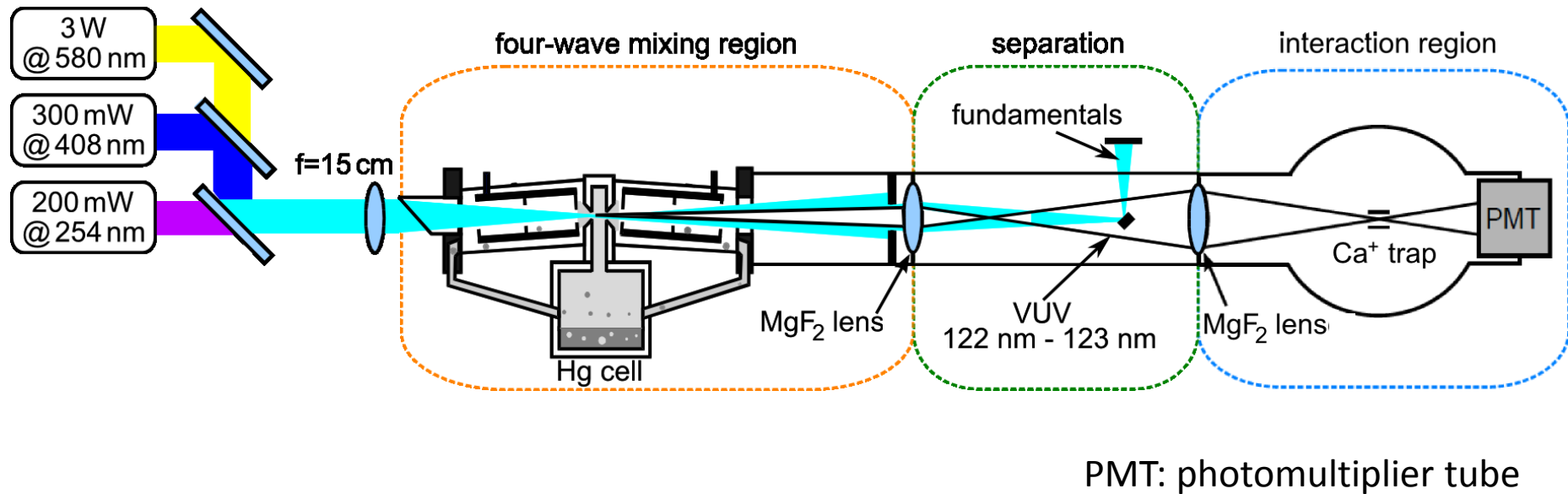
$5.2\text{ MHz}$  for  $24\text{P}_{3/2}$

$1.8\text{ MHz}$  for  $67\text{P}_{3/2}$

# Our (colourful) laser lab

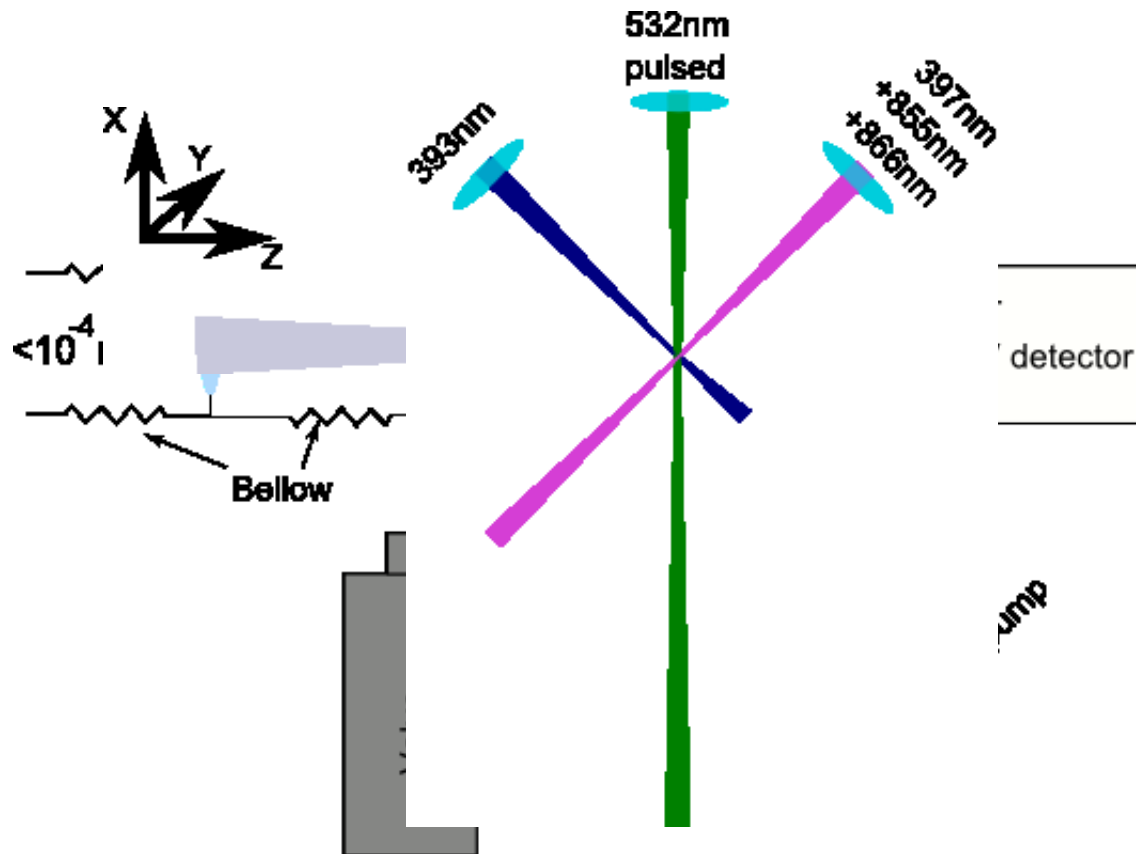


# Experimental setup of four-wave mixing in mercury



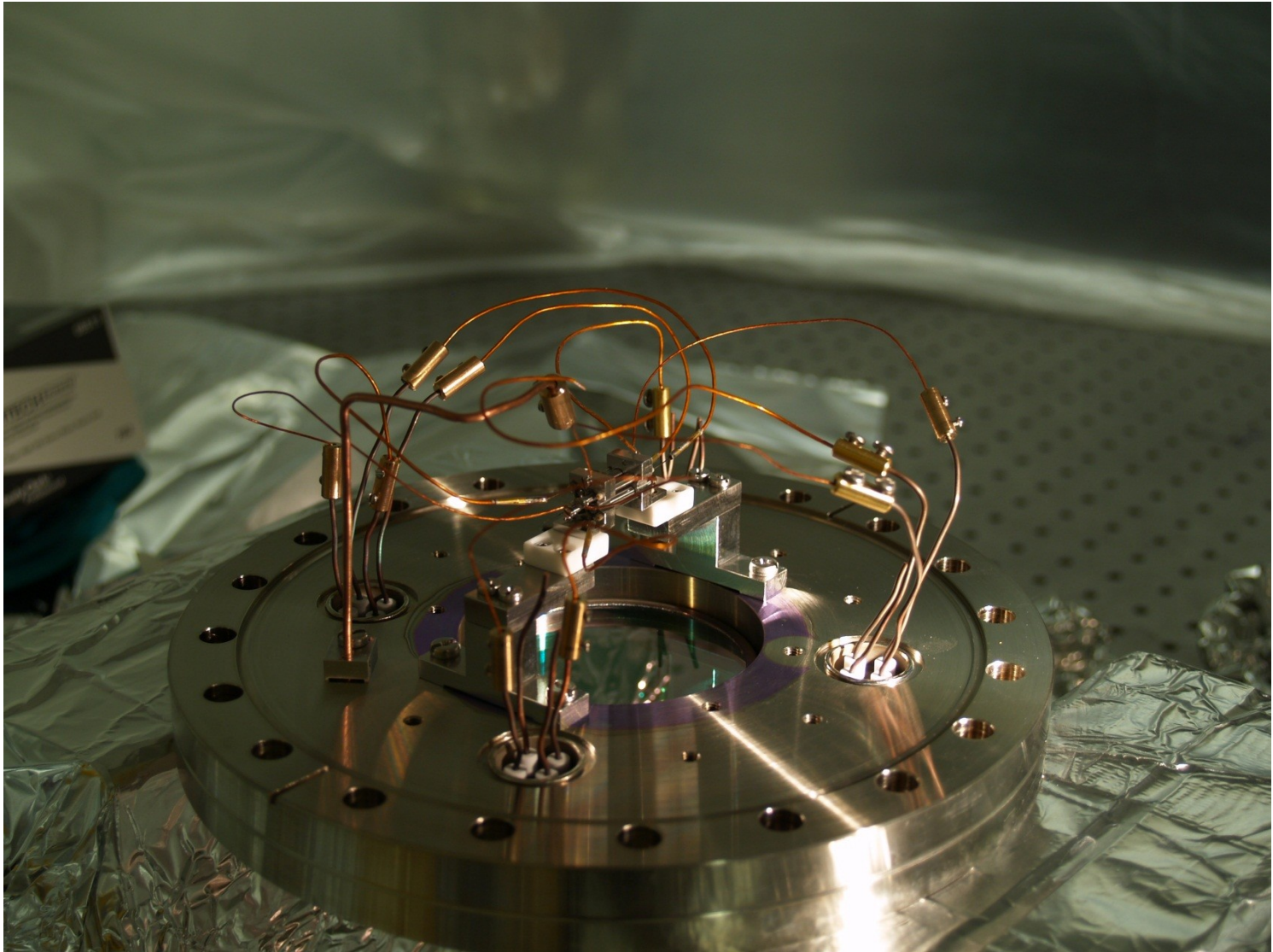
**This combined setup exists since last week.**

# The vacuum chamber

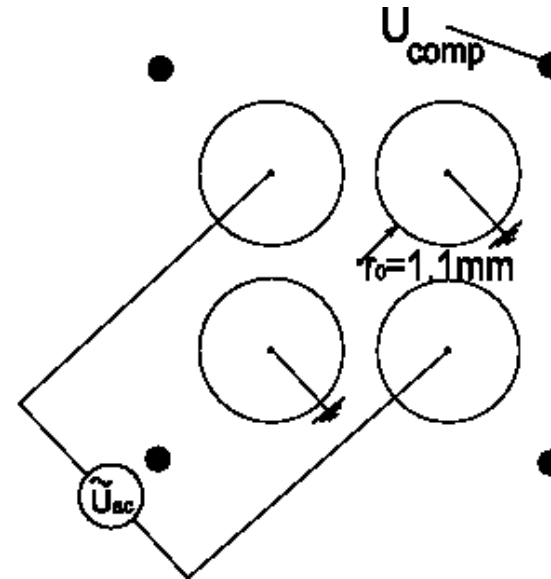
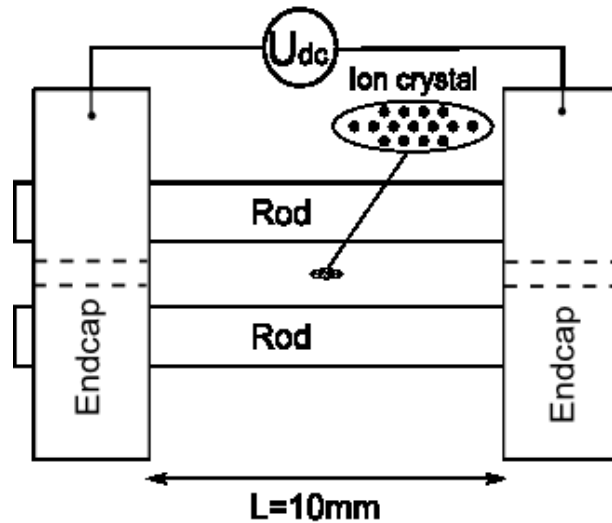


- $\text{MgF}_2$  – lens separates laser vacuum and ion trap vacuum
- flexible connection between laser vacuum and ion trap (laser focus can hardly be moved)

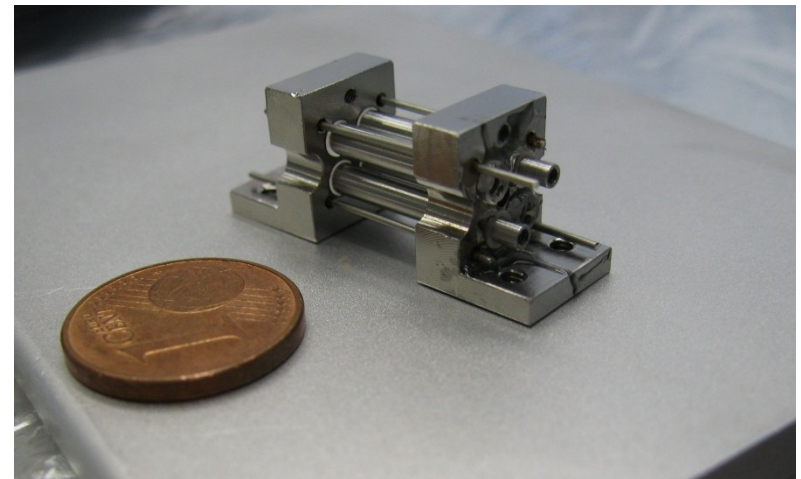
# The Rydberg Trap



# The Trap

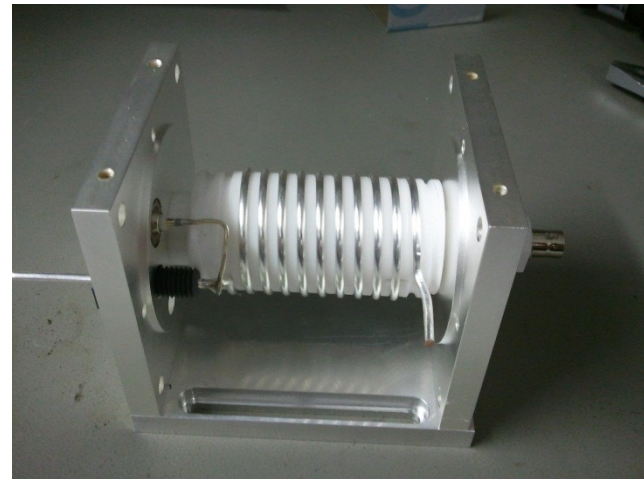
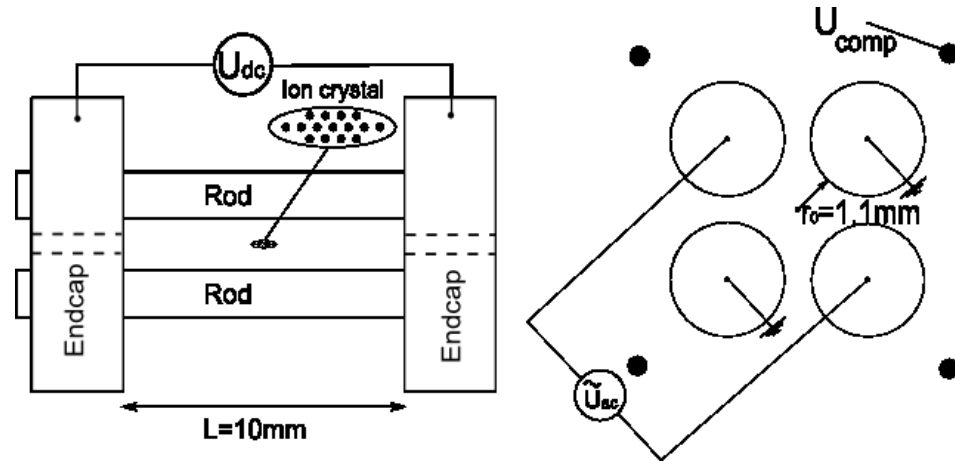


- Linear Paul trap
- Simple, symmetric design
  - Trapping of big ion crystals
- Pinhole in endcaps
- No isolators facing the ions



# RF and DC electronics

- $V_{ac}$  Amplitude up to 1000V with 5W amplifier and quarter-wave-resonator
- 17MHz RF-Frequency
- Up to 2000V Endcap Voltage
- Compensation with DC electrodes and special compensation electrodes



Theory

# Stability of Rydberg states

- electron is loosely bound by the ionic core  
strong electric fields that form the trap might lead to ionization

**classical potential for electron**

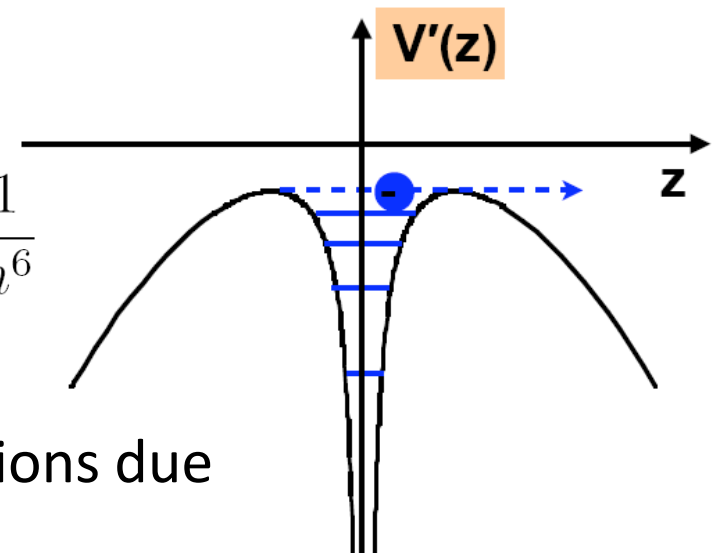
saddle points at

$$V' = -\frac{2e^2}{4\pi\epsilon_0 r} + e\beta [x^2 + y^2 - 2z^2]$$

$$z_{\text{sad}} = \pm \left[ \frac{e}{4\pi\epsilon_0\beta} \right]^{1/3}$$

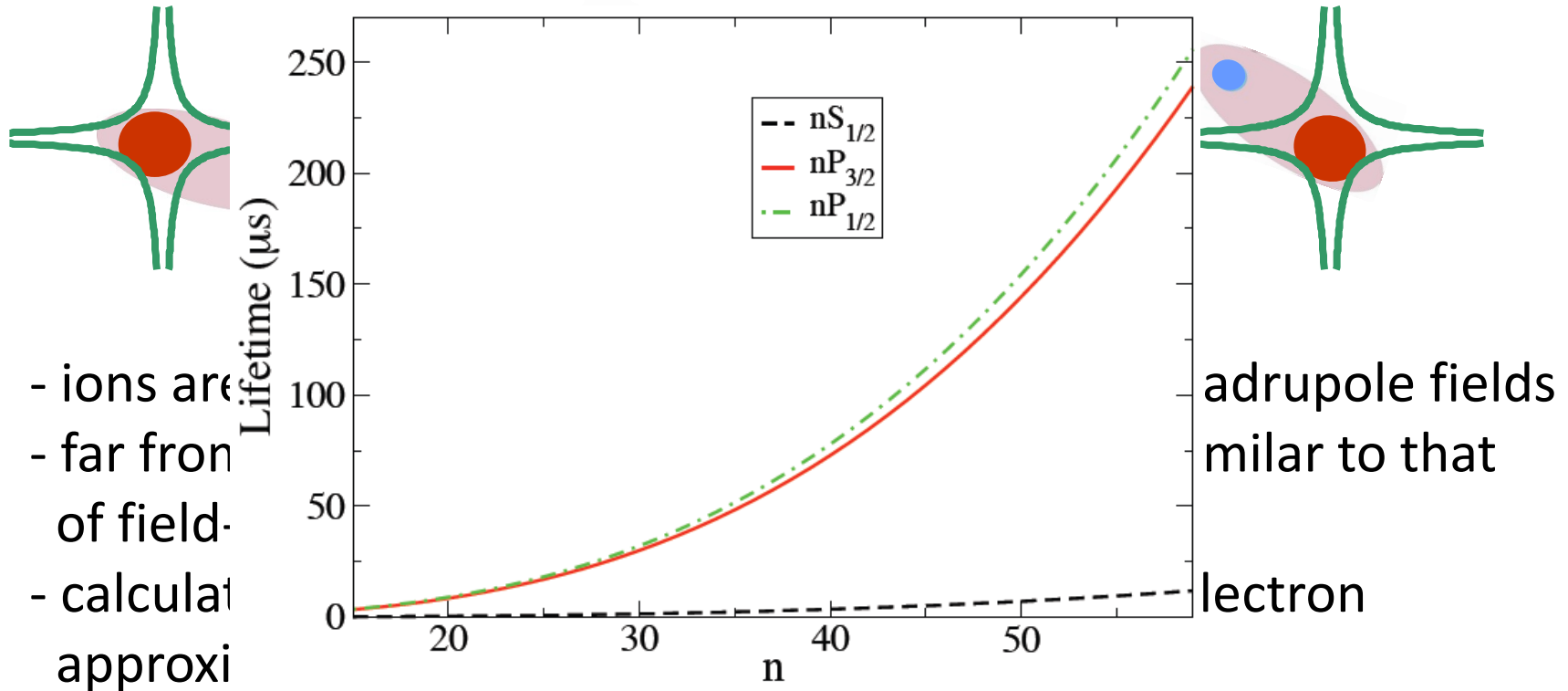
**gradient that would lead to ionization**

$$\beta_{\text{ion}} = \frac{4}{27} \frac{e^7 m^3}{(4\pi\epsilon_0)^4 \hbar^6 n^6} = 1.44 \times 10^{21} \frac{\text{V}}{\text{m}^2} \times \frac{1}{n^6}$$



multi-phonon and Landau-Zehner transitions due to oscillating field are negligible in a typical experimental environment one is safe up to  **$n^{1/4} 50 \dots 70$**

# Spectral properties



$$\tau_{nP_{1/2}} = 1.534 \times (n - 1.436)^{2.967} \text{ ns}$$

- $n=24 \rightarrow 16 \mu\text{s}$
- $n=67 \rightarrow 350 \mu\text{s}$  (most certainly overestimated)

# Spectral properties

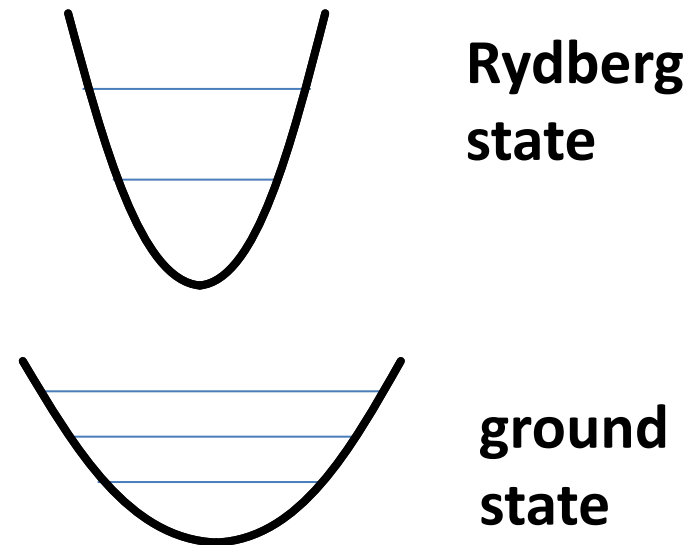
- **time-dependent inhomogeneous field** of Paul trap

$$V_{\text{Paul}}(r, t) = e\alpha \cos(\omega t)[x^2 - y^2] + e\beta[x^2 + y^2 - 2z^2]$$

- **coupling** between **internal** and **external** dynamics
- internal and external motion are not separable

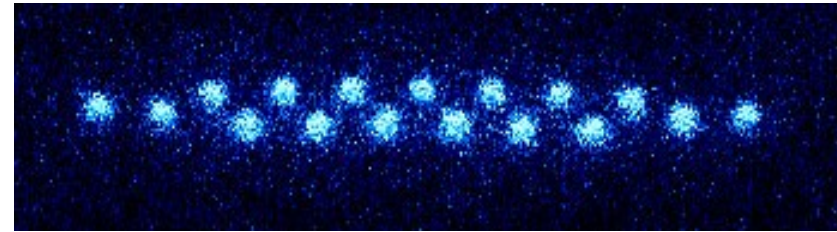
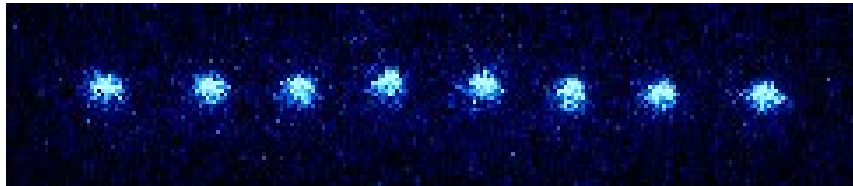
$$H_{\text{int-ext}} = -2e [\alpha \cos(\omega t) (Xx - Yy) - \beta(Xx + Yy - 2Zz)]$$

- electronic levels are shifted
- confinement is altered

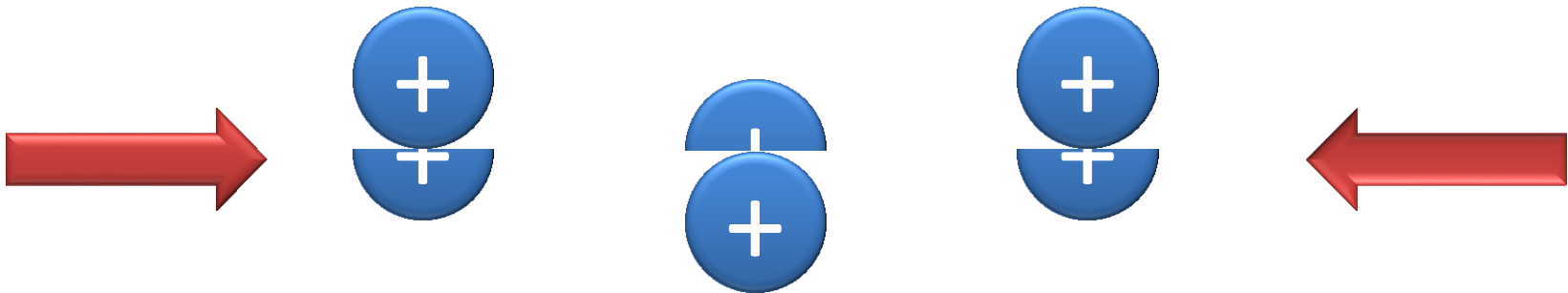


# Linear to zig-zag transition

## Linear to zig-zag transition



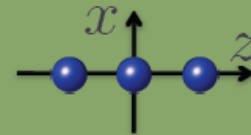
- linear configuration
- increase longitudinal confinement



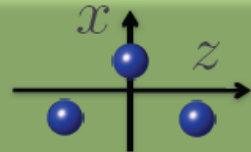
# State-dependent crystals

- transition is controlled by static field gradient  $\beta$
- critical gradient for three ions:  
$$\beta_0 = \frac{5}{29 + 5\epsilon} \frac{e\alpha^2}{M\Omega^2}.$$

$\beta < \beta_0$  , linear string along z-axis:



$\beta > \beta_0$  , zigzag in the x-z plane:

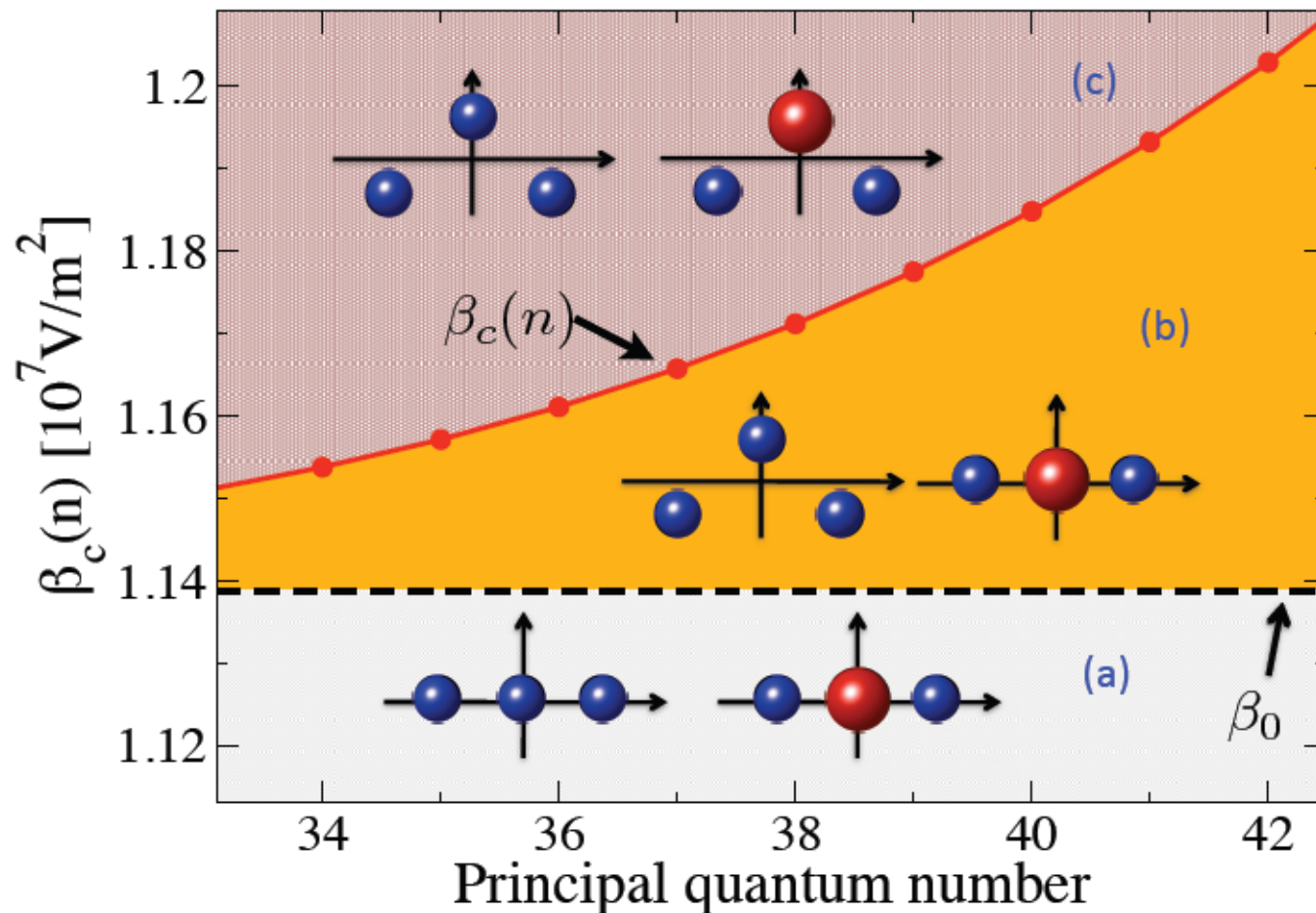


Additional potential due to polarizability of Rydberg state

**Rydberg excitation**

# State-dependent crystal

- Configuration of the crystal depends on field gradient and on whether a Rydberg state is excited or not



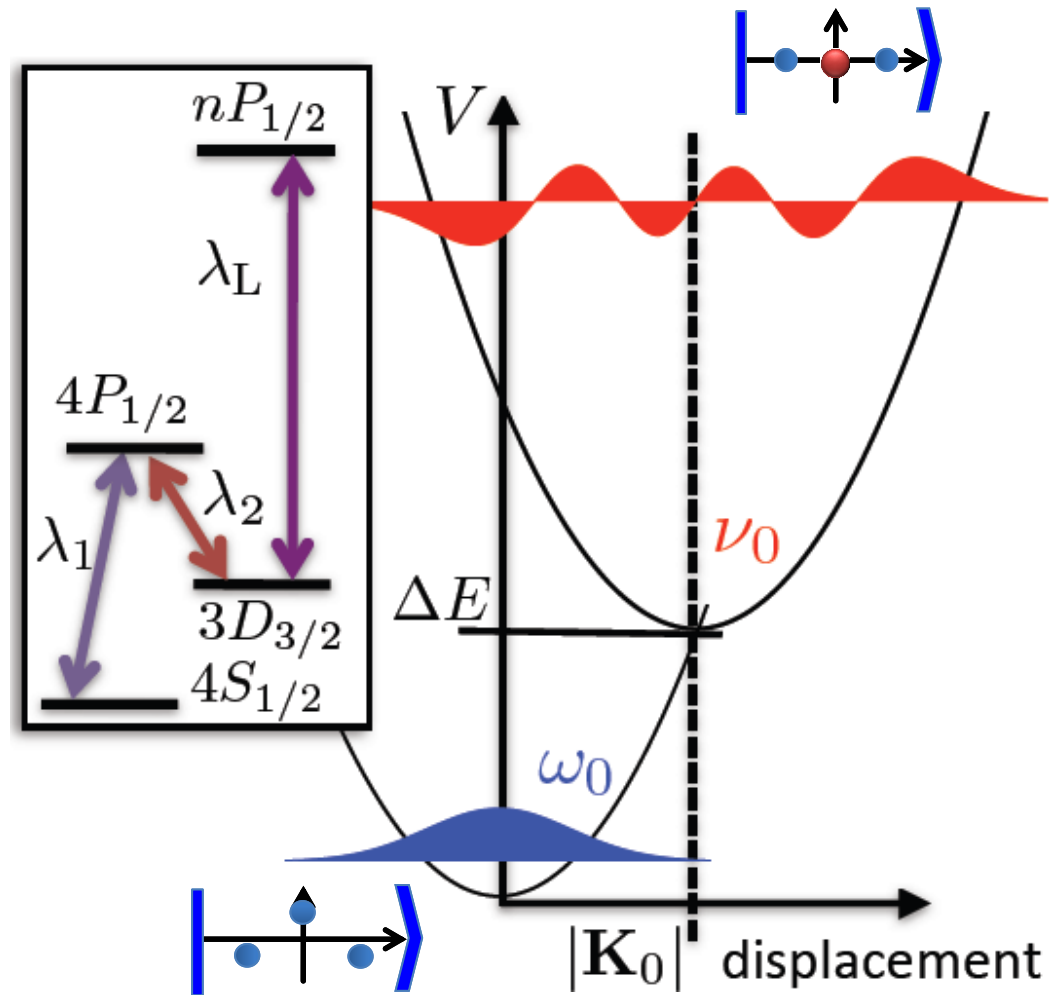
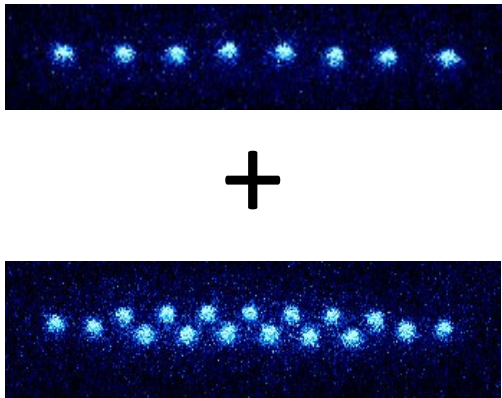
$$\Omega = 2\pi \times 30 \text{ MHz}$$

$$\alpha = 10^9 \text{ V/m}^2$$

$$\varepsilon = 0.15$$

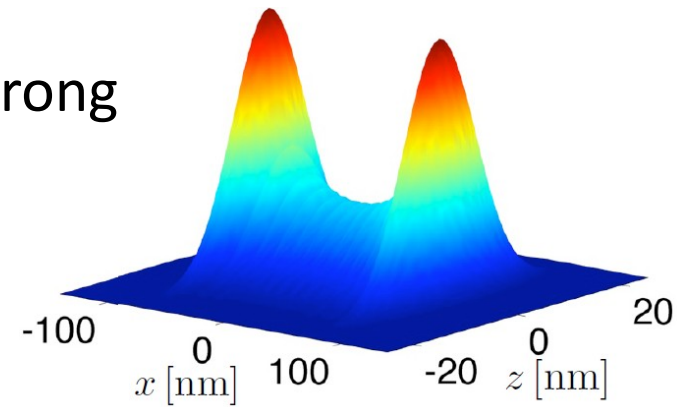
# Rydberg excitation of ion crystal

- even the excitation of a single ion to a Rydberg state is a many-body phenomenon as the entire crystal has to rearrange



# Possible applications

- creation of large coherent forces
- creation of non-classical motional states
- spin systems on dynamical lattices with strong electron-photon interaction

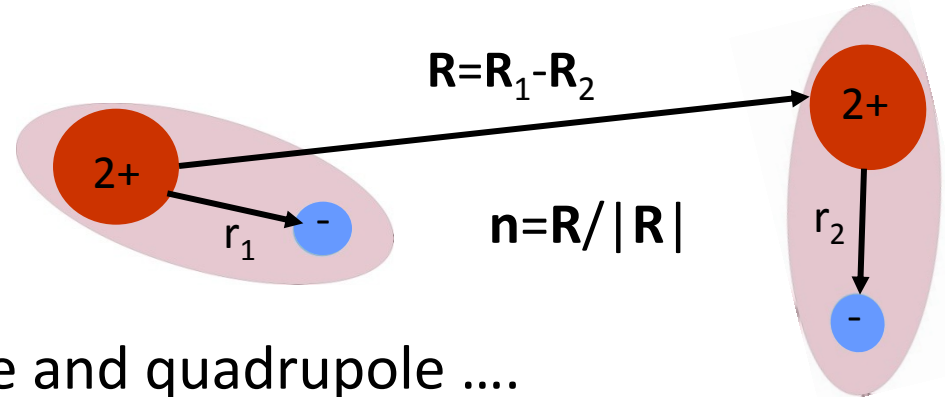


- so far no interactions between Rydberg ions have been taken into account

# Interactions between Rydberg ions

internal atomic structure  
becomes important if  
electrons are excited to  
Rydberg states

ions exhibit a charge, a dipole and quadrupole ....



## Multipole expansion

$$\begin{aligned}
 \frac{V(\mathbf{R}, \mathbf{r}_1, \mathbf{r}_2)}{e^2 (4\pi\epsilon_0)^{-1}} = & \underbrace{\frac{1}{|\mathbf{R}|}}_{\text{Coulomb repulsion}} + \underbrace{\frac{r_1^2 - 3(\mathbf{n} \cdot \mathbf{r}_1)^2 + r_2^2 - 3(\mathbf{n} \cdot \mathbf{r}_2)^2}{2|\mathbf{R}|^3}}_{\text{Charge quadrupole interaction}} \\
 & + \underbrace{\frac{(\mathbf{r}_1 - \mathbf{r}_2) \cdot \mathbf{R}}{|\mathbf{R}|^3}}_{\text{charge-dipole interaction}} + \underbrace{\frac{\mathbf{r}_1 \cdot \mathbf{r}_2 - 3(\mathbf{n} \cdot \mathbf{r}_1)(\mathbf{n} \cdot \mathbf{r}_2)}{|\mathbf{R}|^3}}_{\text{dipole-dipole interaction}}
 \end{aligned}$$

# To do – Outlook

- Calculate interactions between excited ions
- tune interaction strength and shape with microwave fields
- implement quantum simulator for spin models
- implement quantum gate protocols based on Rydberg excited ions
- find ways to create wavelengths for transitions different to  $n=24, 67$

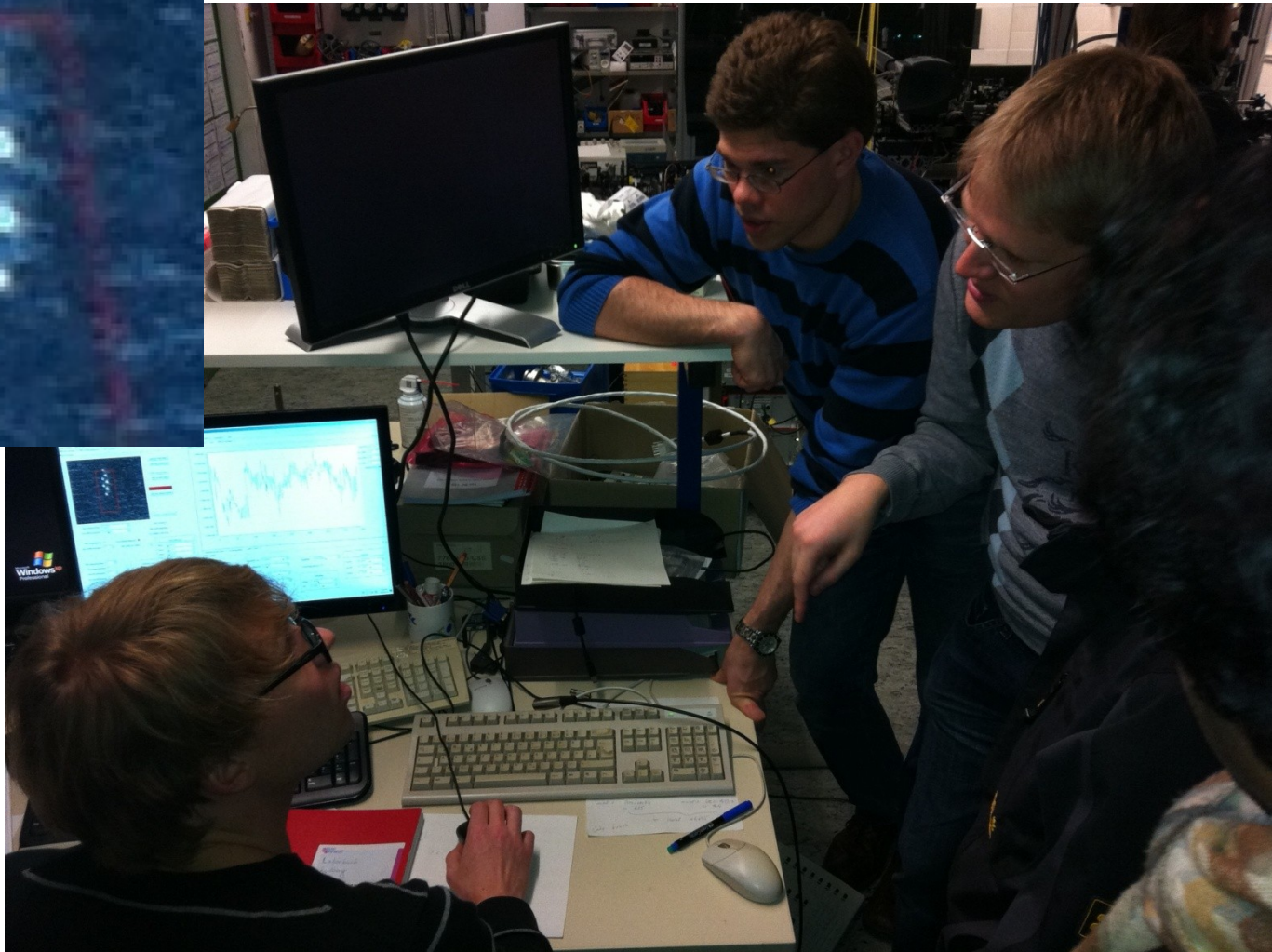
## Emerging collaborations

- M. Hennrich (University of Innsbruck)  
Rydberg excitations of Strontium ions
- M. Müller (Universidad Complutense de Madrid)  
Simulation of spin systems with trapped ions

F. Schmidt-Kaler *et al.*, New Journal of Physics **13**, 075014 (2011)

W. Li and I. Lesanovsky, Physical Review Letters **108**, 023003 (2012)

# 2<sup>nd</sup> meeting of R-ION consortium



Mainz/Germany 05.03.-06.03.2012