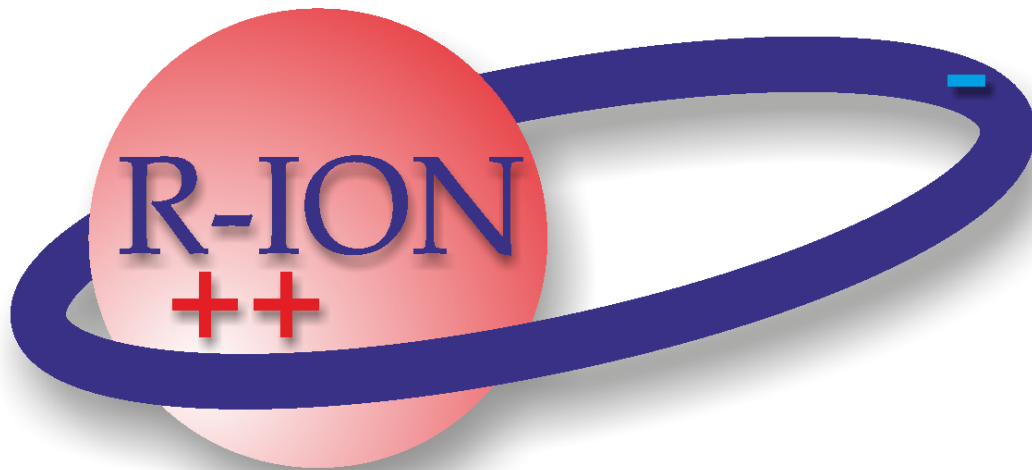


Rydberg excited Calcium Ions for quantum interactions

Innsbruck – Mainz – Nottingham



The R-ION Consortium

Experiment

Ferdinand Schmidt-Kaler
University of Mainz/Germany

Trapped ions

Jochen Walz
University of Mainz/Germany

Laser system

Theory

Peter Zoller
University of Innsbruck/Austria

Igor Lesanovsky
University of Nottingham/UK

<http://www.chistera.eu/projects/r-ion>



3rd R-ION Meeting
Innsbruck, Oct 2012

The R-ION Consortium

Funding period

August 2011

today

July 2014



Requested funds

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

General aim (Research programme with 3 WPs)

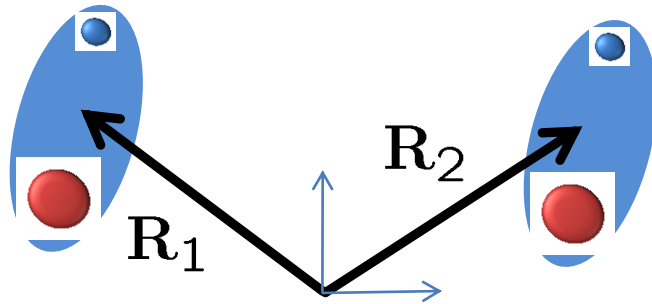
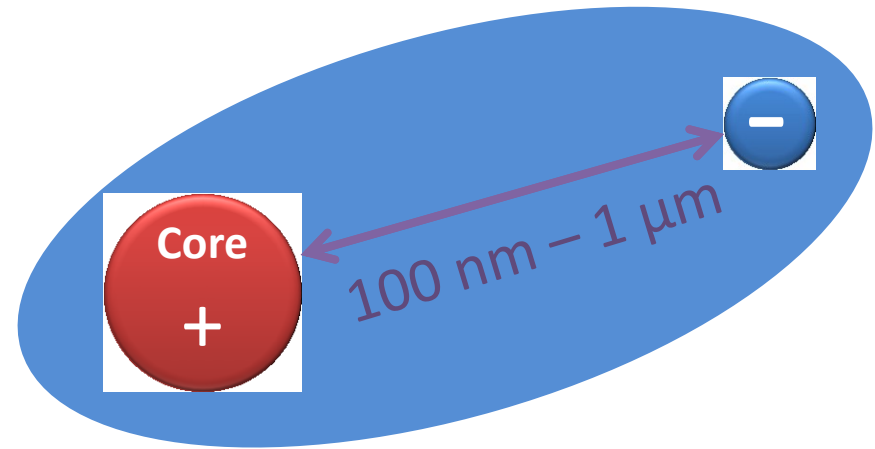
- explore and understand fundamental properties of a new platform for quantum information processing and for quantum simulations

Outline

1. **Background - Rydberg states and trapped ions**
2. **Aim of the project and challenges**
3. **Experimental developments**
 - Laser system
 - Ion trap setup
4. **Theoretical progress**
 - Many body effects in Rydberg ion laser excitation
 - Rydberg mode shaping and parallel quantum gates
 - Many-body spin systems
5. **Summary, Problems and Outlook**

Atoms in Rydberg states

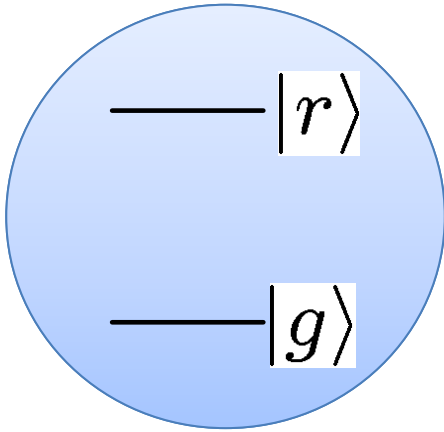
- hydrogen-like atoms
- simple level structure
- **long lifetime** $\tau / n^{3...5}$ ($\tau \frac{1}{4} 100 \mu\text{s}$)
- large displacement between charges



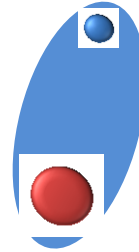
- charge distributions between two atoms interact with each other

Rydberg atoms interact strongly and over large distances, e.g. via permanent or induced dipole interaction (interaction strengths of several MHz achievable)

Dipole blockade



Rydberg state

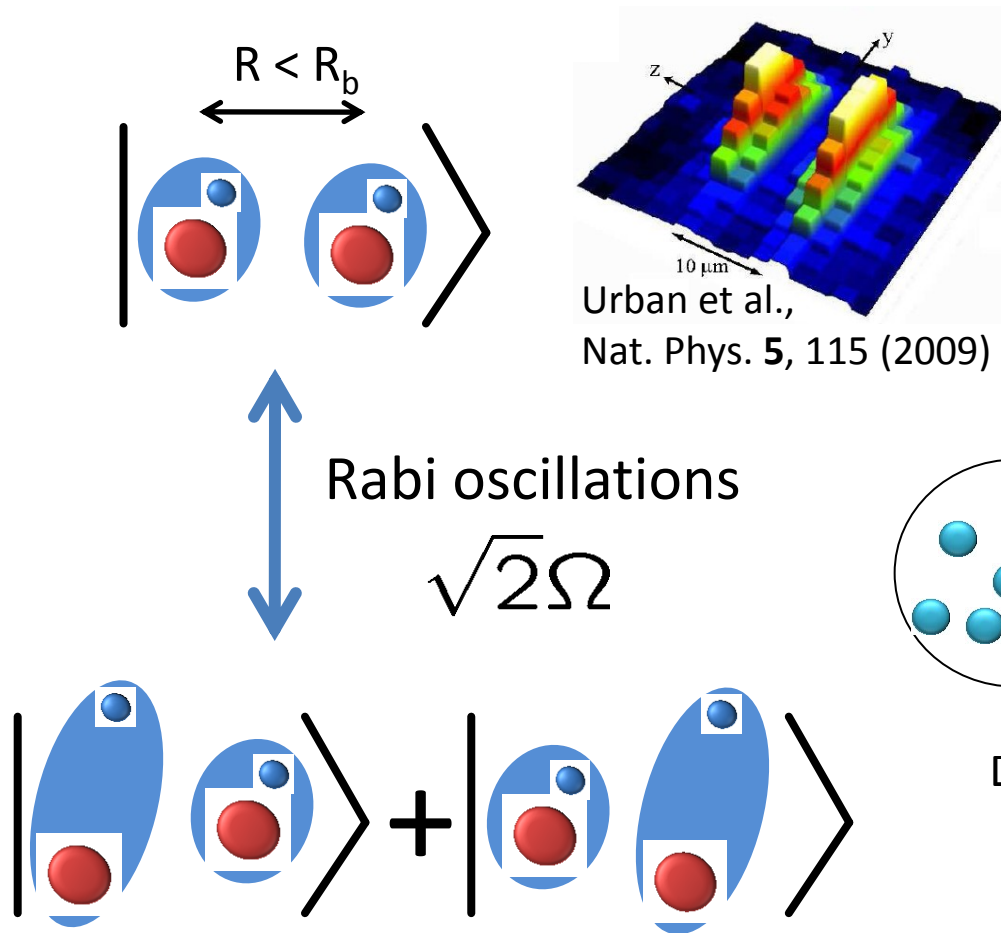


ground state



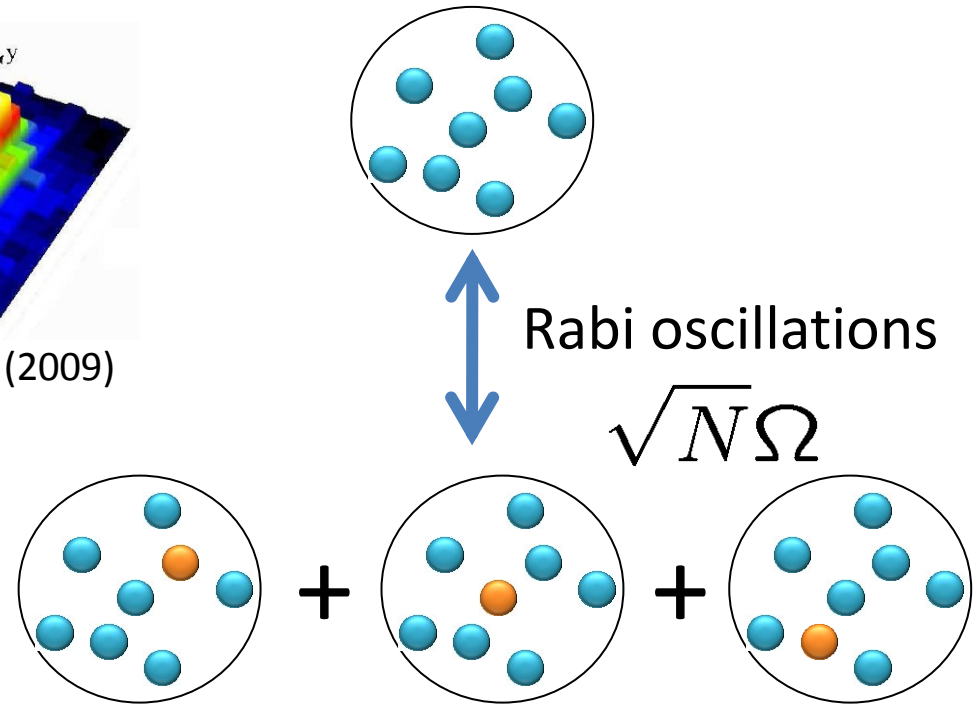
Interacting Rydberg Atoms

Two blockaded atoms



**Entangled state is
created „for free“**

Atomic ensembles



Dudin et al., Nature Physics 8, 790 (2012)

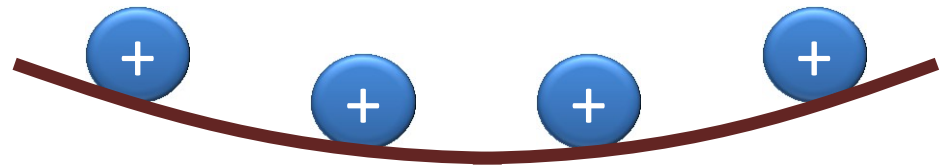
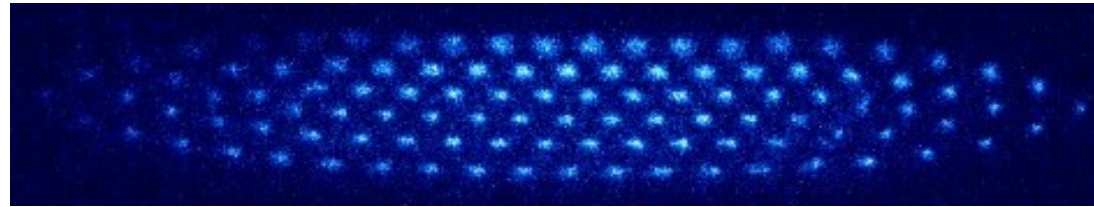
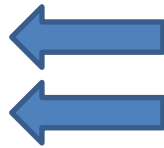
Trapped ions

Nobel Prize 2012

- robust trapping
- storage and manipulation quantum information
- single and two-qubit gates with fidelity $> 99\%$ possible
- unity state detection efficiency

Applications

- ultra precise clocks
- precision measurements
- quantum computer
- quantum simulator



trapped ions

Problems

- scalability is a problem
- not because the lack of large ion crystals
- because interactions rely on structure of vibrational modes
(**vibrational mode structure becomes too complex** for large crystals)

Aim of this project

Join advantages of **trapped ions**

- trapped, localized qubits
- near unity detection efficiency
- quantum gate operations with >99% fidelity
- reliable state 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

The Challenges

hydrogen 1 H 1.0079			
lithium 3 Li 6.941	beryllium 4 Be 9.0122		
sodium 11 Na 22.990	magnesium 12 Mg 24.305		
potassium 19 K 39.098			
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 ✱	scandium 21 Sc 44.956
francium 87 Fr [223]	radium 88 Ra [226]	89-102 ✱ ✱	titanium 22 Ti 47.867
			yttrium 39 Y 88.906
			zirconium 40 Zr 91.224
			lutetium 71 Lu 174.97
			hafnium 72 Hf 178.49
			lawrencium 103 Lr [262]
			rutherfordium 104 Rf [261]

Experimental challenges

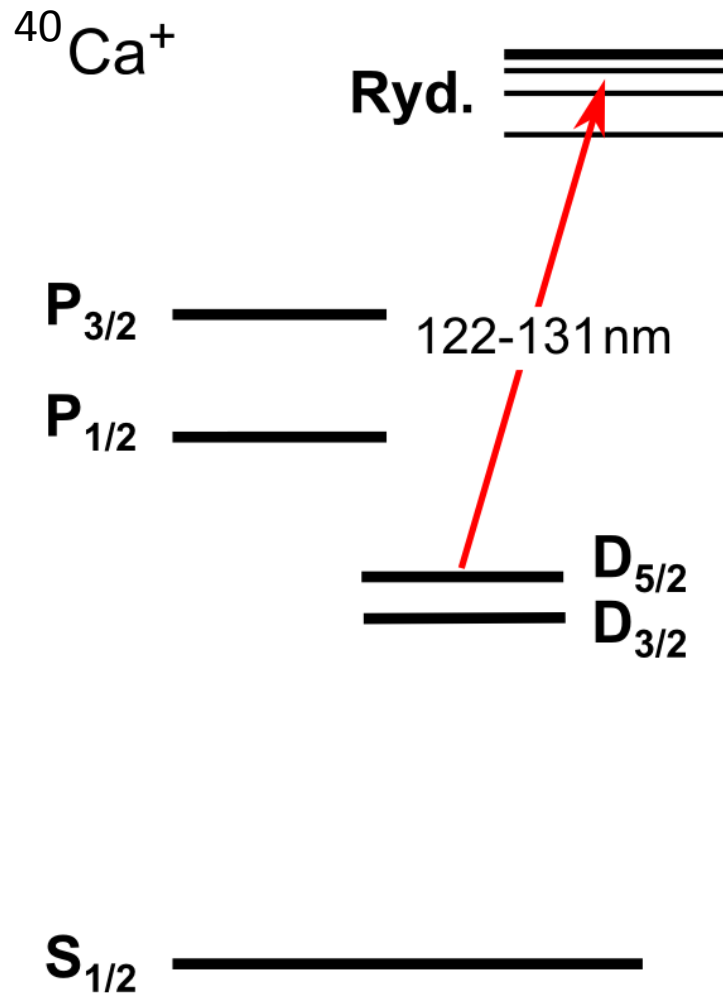
- need **coherent laser source** with 122 nm wave length (vacuum ultra violet VUV)
- need to combine this with ion trap

Theoretical challenges

- need to understand the physics of ionic Rydberg states in a trap
- need to identify physical protocols for the implementation of QIP and many-body spin models

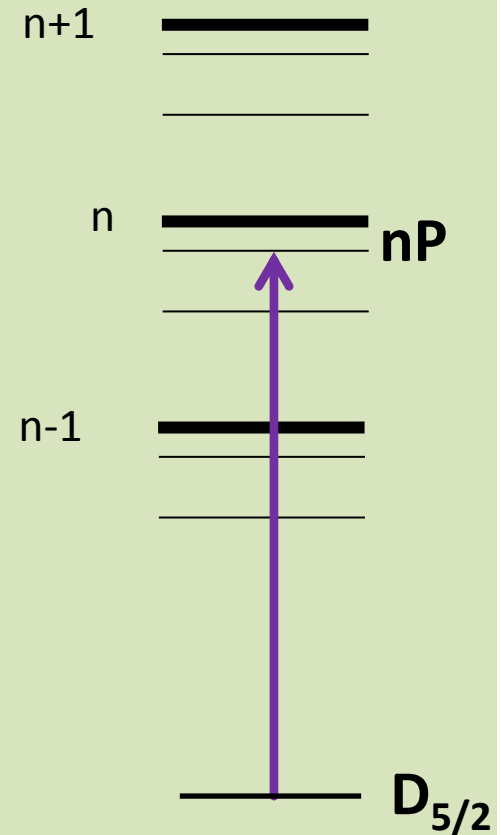
VUV – Rydberg excitation

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



Rydberg spectrum

Rydberg states



Generation of VUV radiation

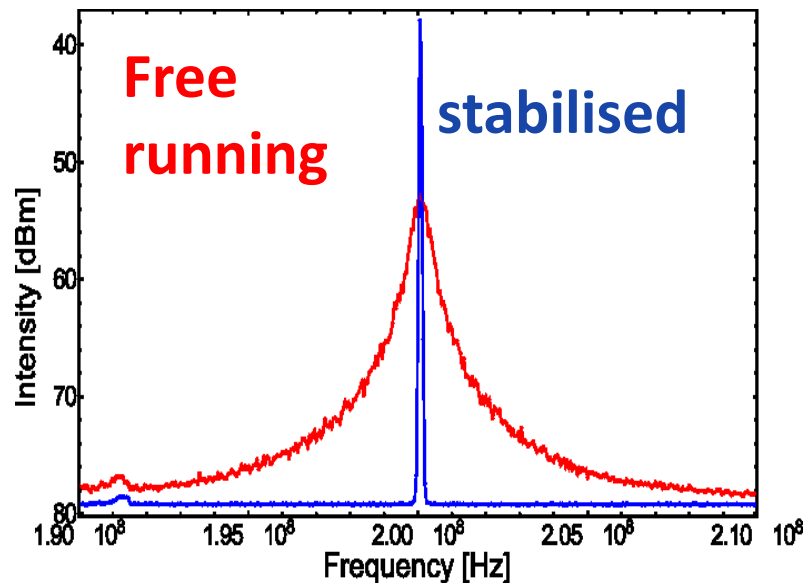


- original purpose of laser system: (anti-)hydrogen spectroscopy
- first time that laser is not „experiment“ but tool

Achievements (WP2, WP3)

Frequency stabilisation

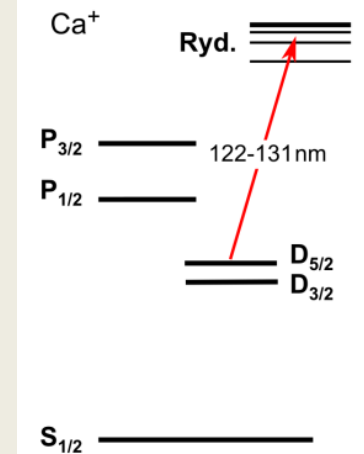
all infrared Lasers actively stabilized to < 100 kHz



Optimization of output power

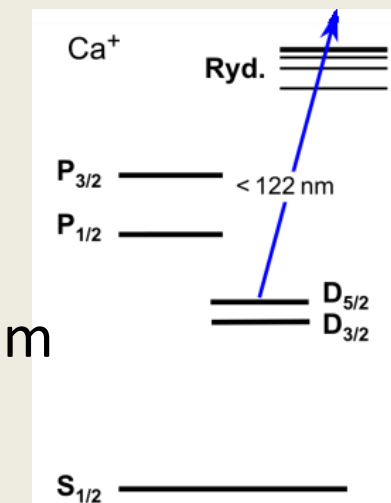
**Rydberg
excitation
wavelength**

$\sim 1 \mu\text{W}$ @ 122 nm

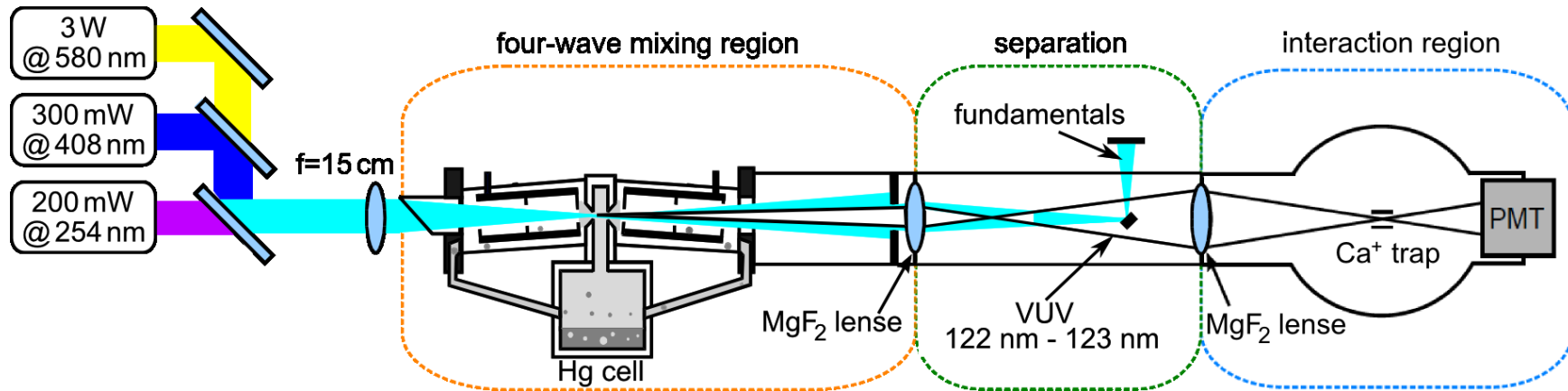


**ionization
wavelength**

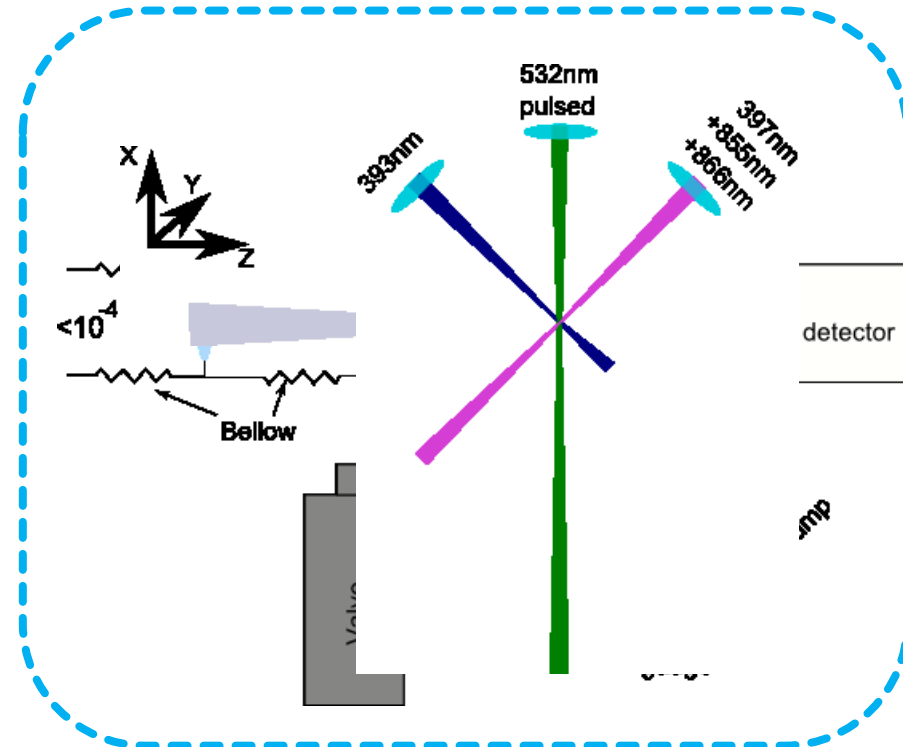
$6 \mu\text{W}$ @ 121.26 nm



Laser and ion trap



- MgF₂ – lens separates laser vacuum and ion trap vacuum
- flexible connection between laser vacuum and ion trap (laser focus can hardly be moved, **need to move trap**)



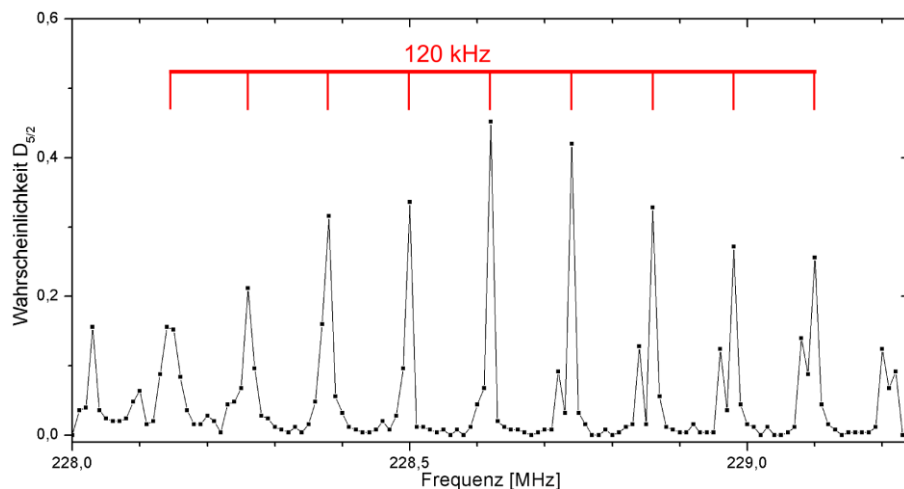
Achievements (WP2, WP3)

Linear Paul trap in place

- trap frequencies
 $\omega_{\text{rad}} \approx 2\pi \times 1 \text{ MHz}$,
 $\omega_{\text{ax}} \approx 2\pi \times 120 \text{ kHz}$
- 1D and 2D ion crystals

Spectroscopy of low-lying levels

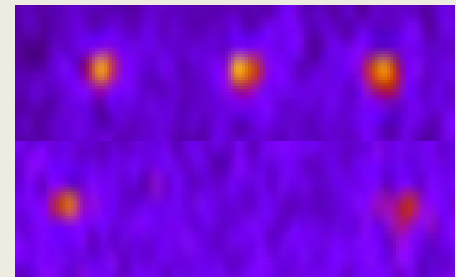
- axial side bands



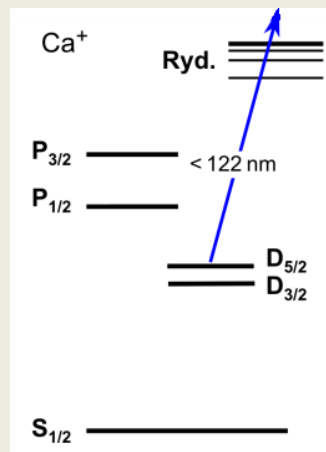
First observations of Ca^+ - VUV interaction

3 Ca^+

2 Ca^+ + 1 Ca^{2+}

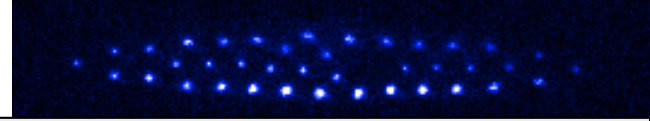


Ionisation rate
 $\sim 1/\text{min}$ @ $0.5 \mu\text{W}$



Achievements (WP2, WP3)

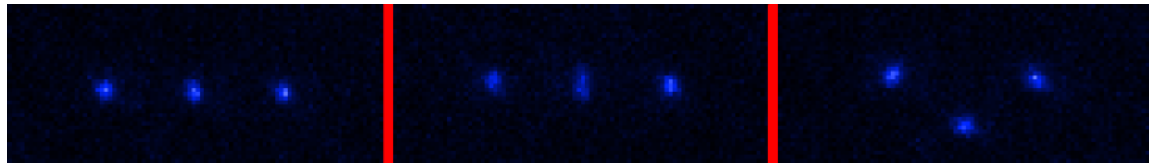
Mixed Ca^+ - Ca^{2+} ion crystals



Experiment: changing ratio $\omega_{\text{rad}} / \omega_{\text{ax}}$

$\omega_{\text{rad}} / 2\pi =$ 212kHz 187kHz 175kHz

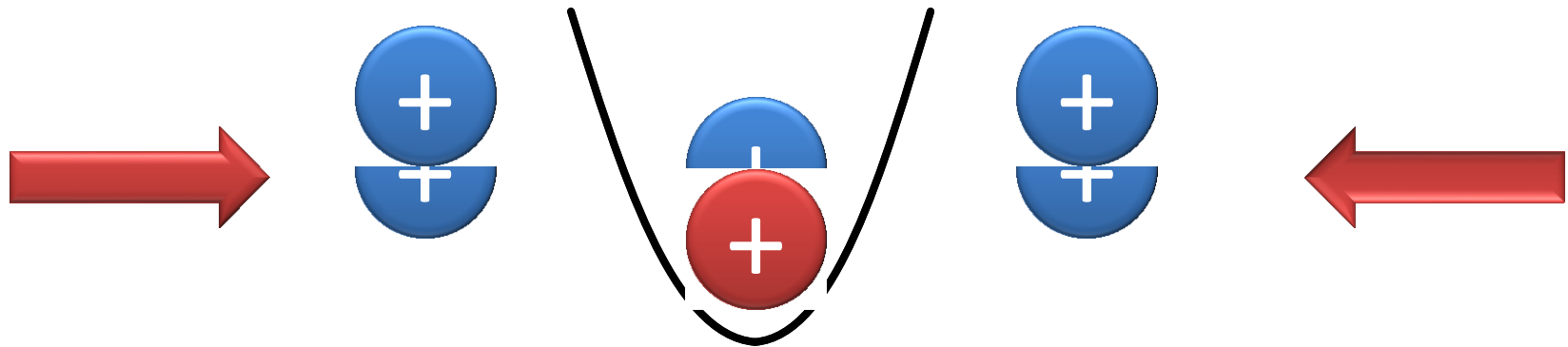
3 x Ca^+



- direct link to theoretical proposal made within R-ION consortium

Many-body effects in laser excitation

Consider crystal of three ions



- transition takes place at critical gradient $\beta_0 = \frac{5}{29} \frac{\alpha^2}{M\Omega^2}$
- Rydberg atom experiences additional confinement

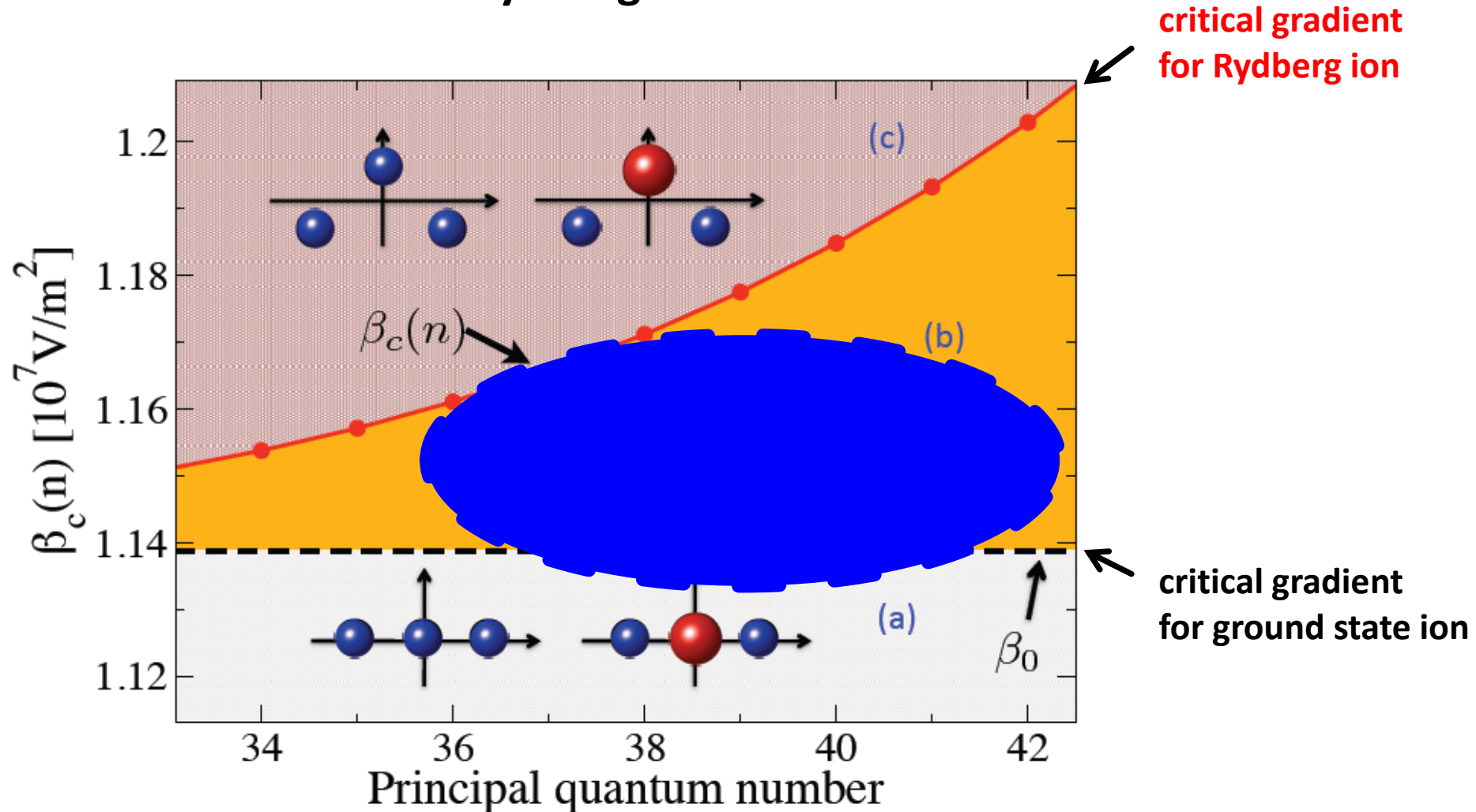


$P(n)$... polarizability, n ... principal quantum number

→ n -dependent critical gradient $\beta_c(n)$

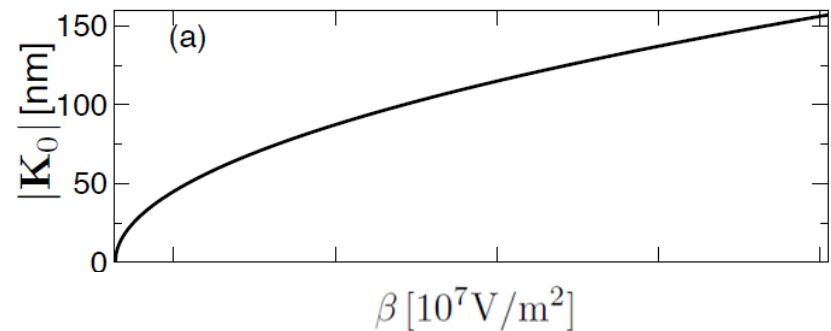
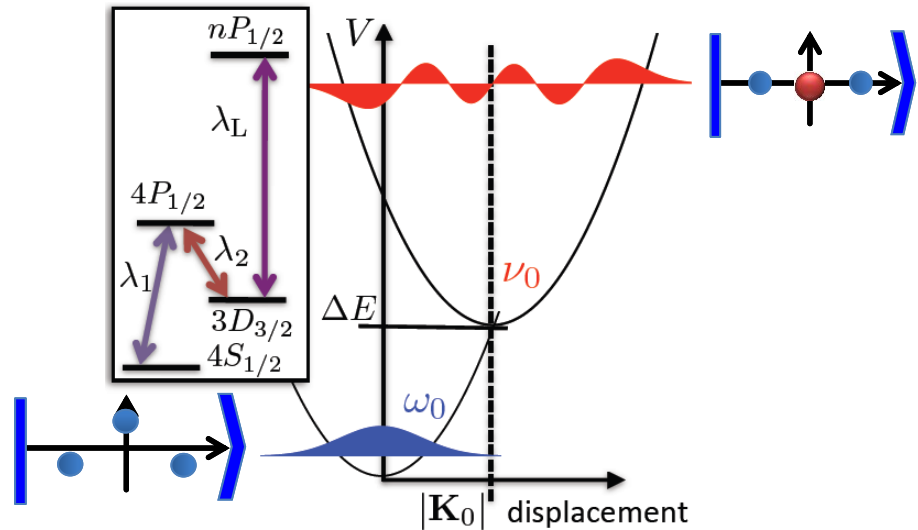
State-dependent crystal (WP2)

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

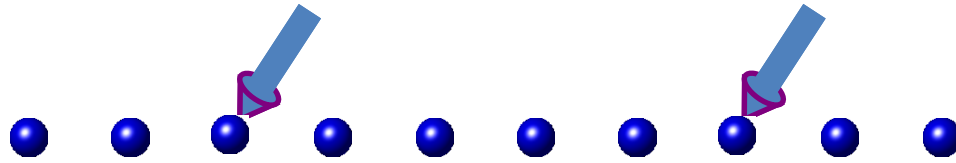


Rydberg excitation of ion crystal

- even the excitation of a single ion to a Rydberg state is a many-body phenomenon as the entire crystal has to rearrange
- consequence for laser excitation visible in the Franck-Condon factors
- mechanism allows to exert large forces on trapped ions



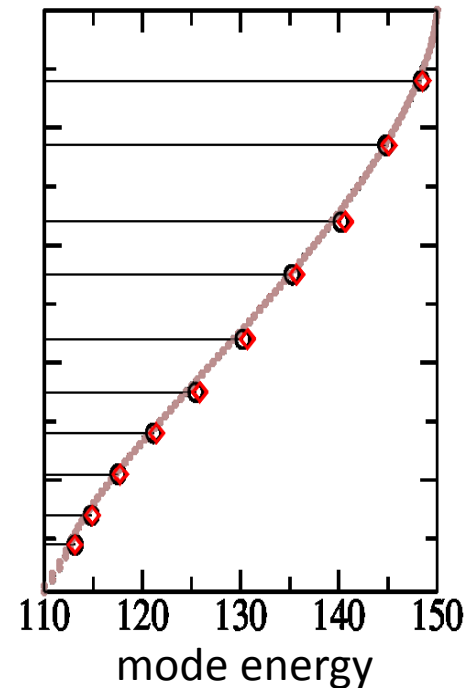
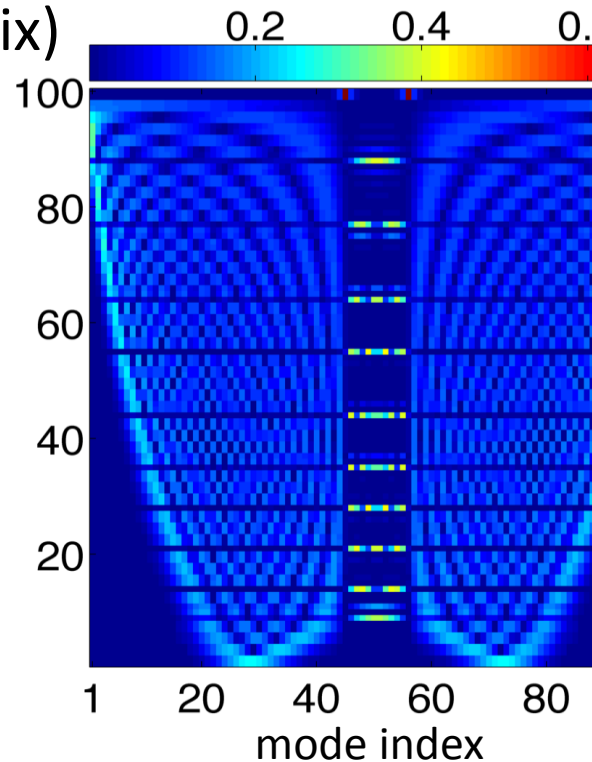
Vibrational mode shaping (WP4)



- Rydberg excitation of few ions within **long ion chain** (100 ions)

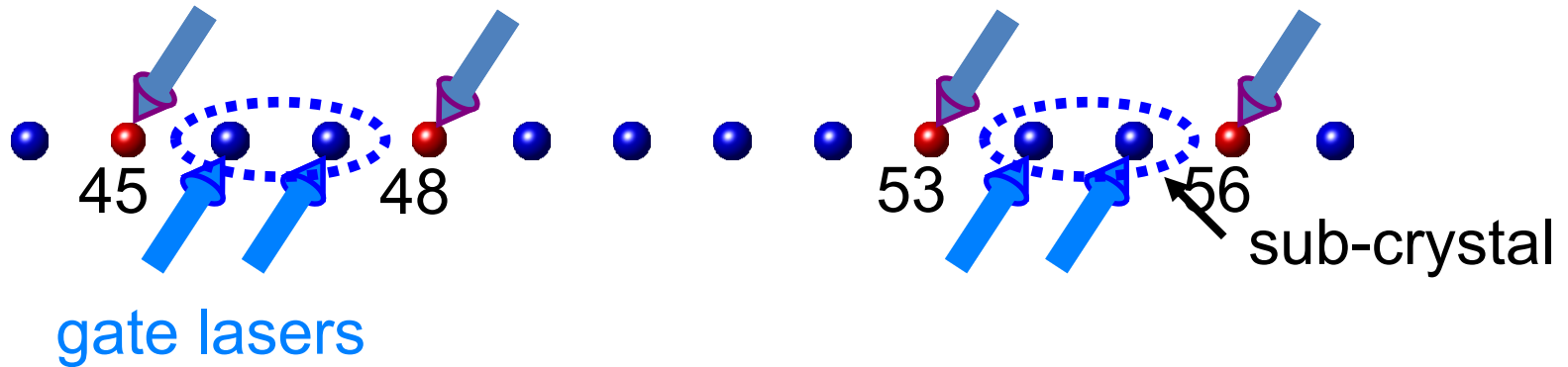
Transverse vibrational modes

(entries of normal mode matrix)

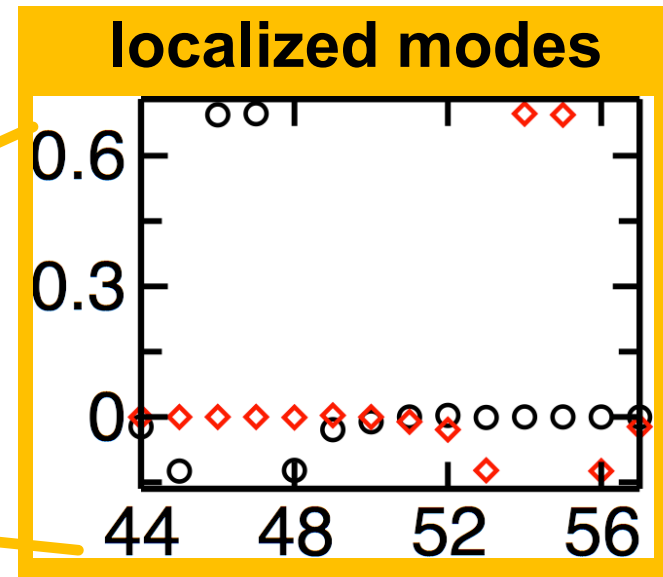
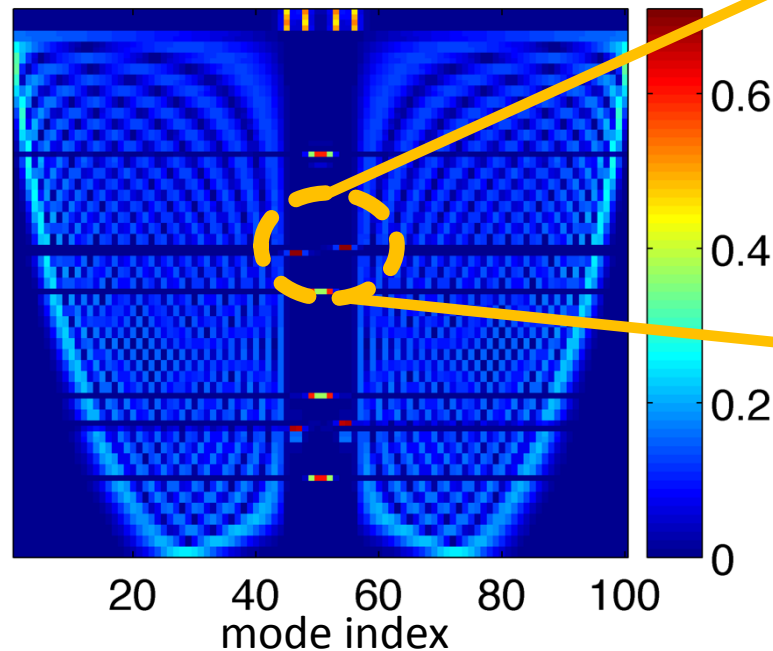


- Rydberg ions chop long crystal into sub-crystals (F
[W. Li, R. Nath, A. Glätzle and I. Lesanovsky, arXiv:1208.2005 (2012)]

Parallelization of quantum gates (WP4)



- Rydberg ion
- ion in electronically low lying state



- quantum gates can be executed in parallel on the sub-crystals with high fidelity

Summary

Experiment

- combined laser and trap setup exists
- evolution to second generation (optimized laser and trap)
- first evidence of VUV-laser ion interaction
- first experiments geared towards R-ION theory proposal

Theory

- even Rydberg excitation of a single ion in a crystal is non-trivial
- Rydberg ions can dynamically split large ion crystals
- dynamical mode shaping permits parallel execution of gates

Problems

Experiment

- experiments are difficult (laser itself is an experiment)
- two experiments = at least twice the number of problems
- 6 months down-time due to broken laser source

Theory

- for the moment only blue sky physics
- needs experimental input since there is a number of loose ends (incomplete spectral data, Rydberg ion modelling sufficient?)

Big problem !

- UK is not in Schengen zone + Border Agency is acting unreasonably
- severely hinders exchange of scientist
(R-ION employs indian and chinese researchers)

Outlook

Experiment

- increase laser-power for coherent excitation wavelength
- investigate many-body effects in ionisation
- demonstrate coherent excitation of ionic Rydberg states
- implement quantum gate protocol(s)

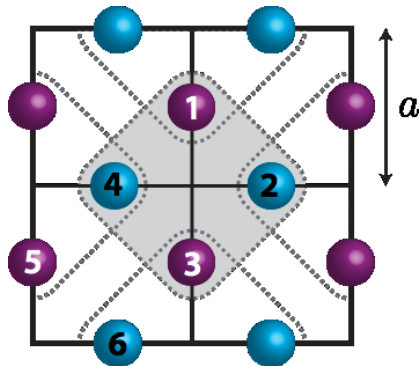
Theory

- calculate long-range interactions among ions
- devise and characterize quantum gate based on long-range interactions
- engineer and investigate many-body quantum systems

Outlook (WP4)

led by Innsbruck group

Spin ice in two dimensional ion crystal



Classical spin ice

$$H_0 = J_z (\sigma_z^1 + \sigma_z^2 + \sigma_z^3 + \sigma_z^4)^2$$

Quantum fluctuations

$$H_1 = \sum_{i < j} J_{\perp} (\sigma_+^i \sigma_-^j + \sigma_-^i \sigma_+^j)$$

Realization with Rydberg atoms/ions

- challenge: all ions on a plaquette must interact equally
- exploiting long-range interactions, MW tuning and magic angles

