

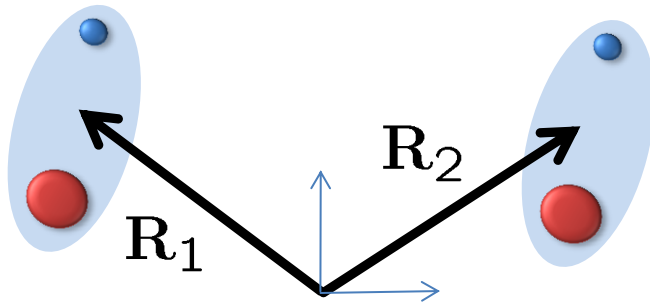
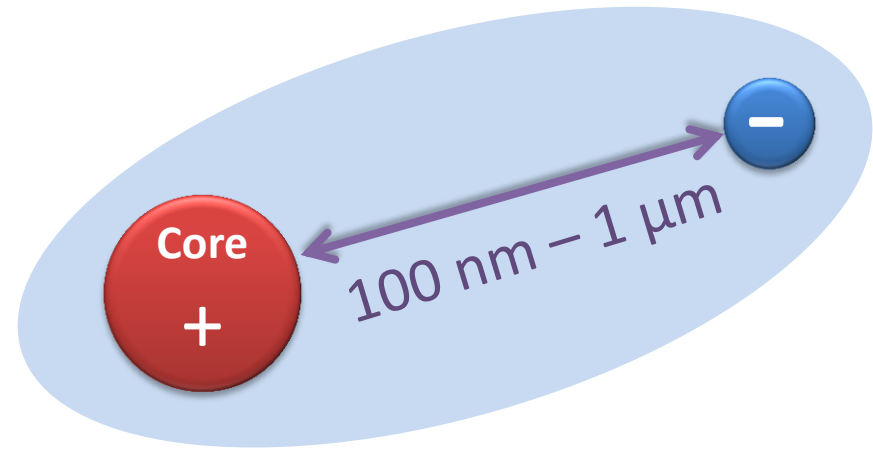
Rydberg excited Calcium Ions for quantum interactions

Innsbruck – Mainz – Nottingham



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



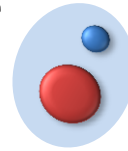
- charge distributions between two atoms interact with each other

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

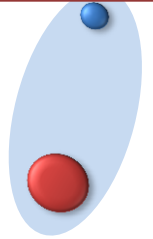
Dipole blockade

Two atoms

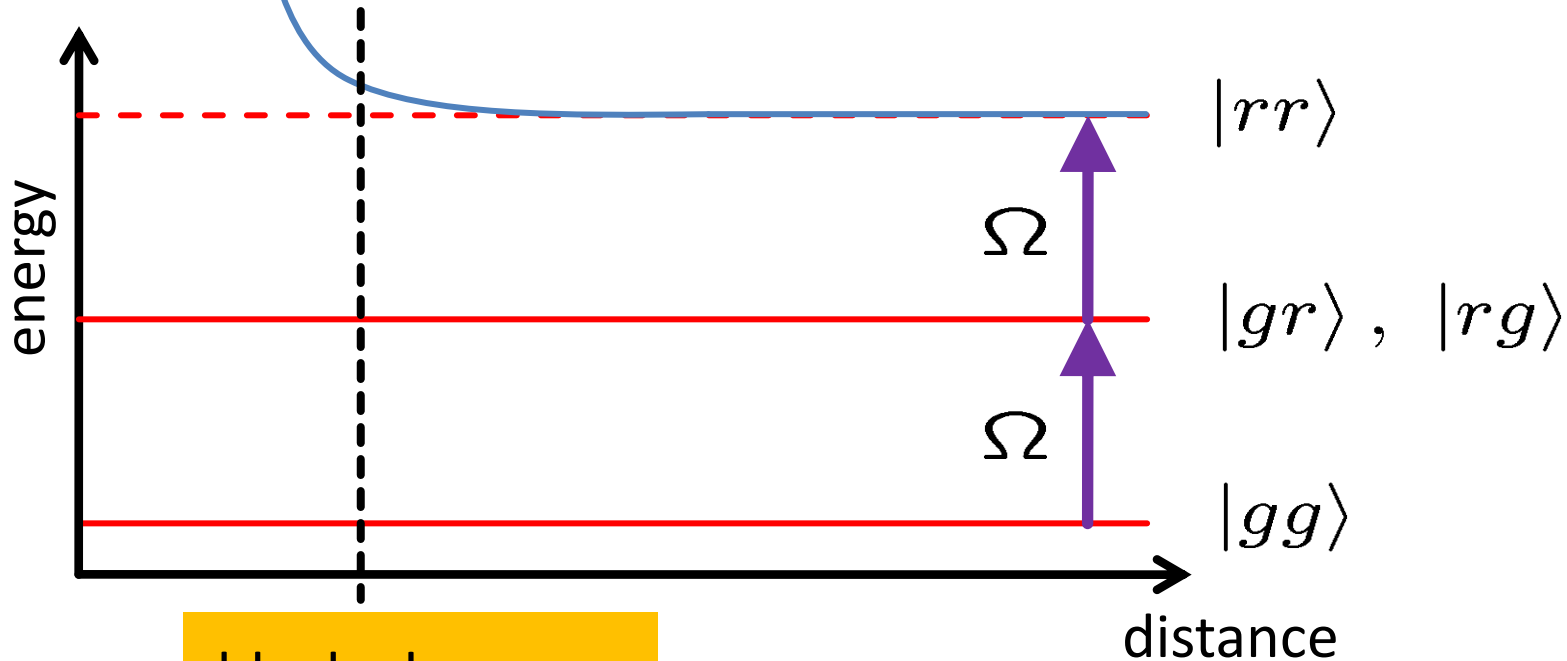
ground state
 $|g\rangle$



Rydberg state
 $|r\rangle$



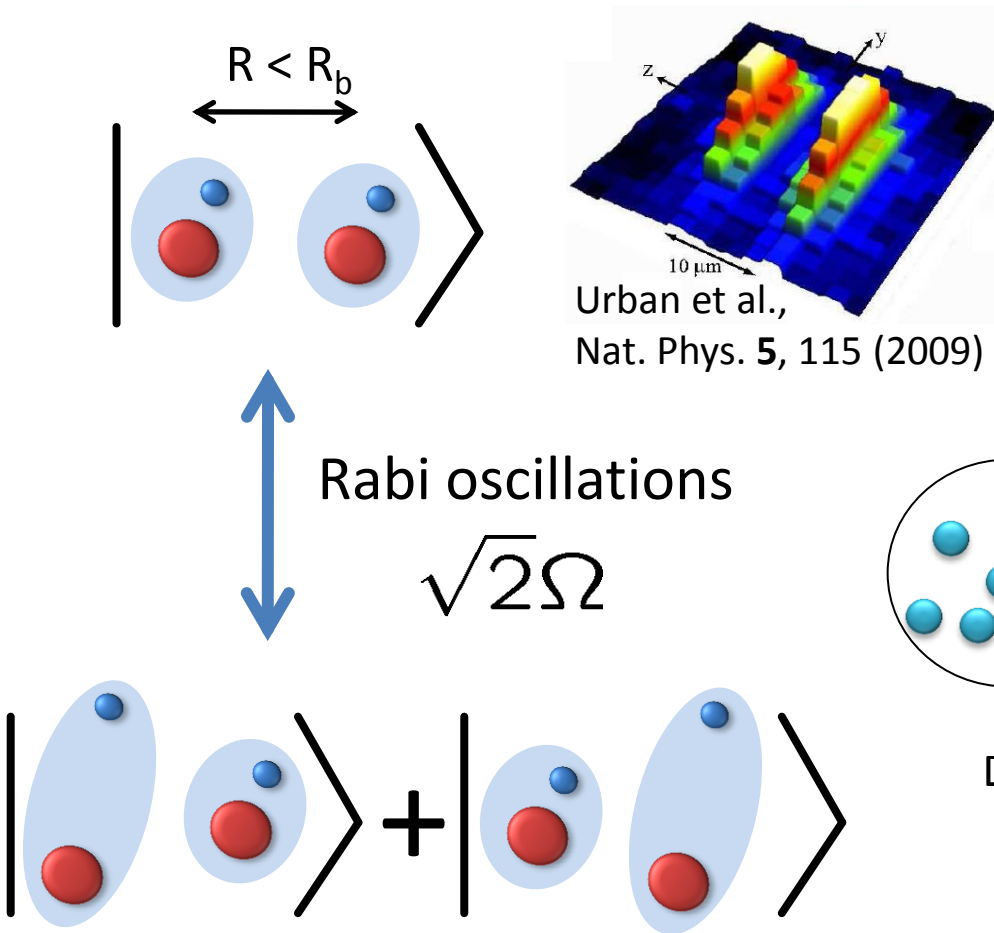
Rydberg-Rydberg interaction



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

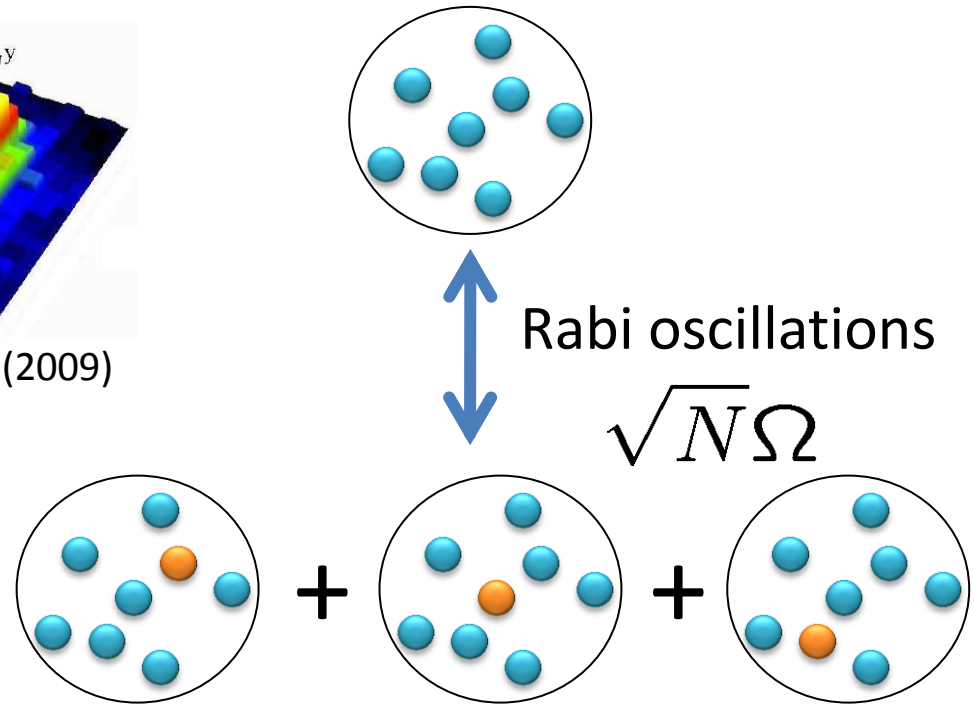
Interacting Rydberg Atoms

Two blockaded atoms



Entangled state is created „for free“

Atomic ensembles



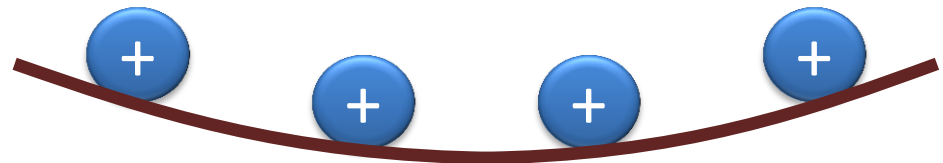
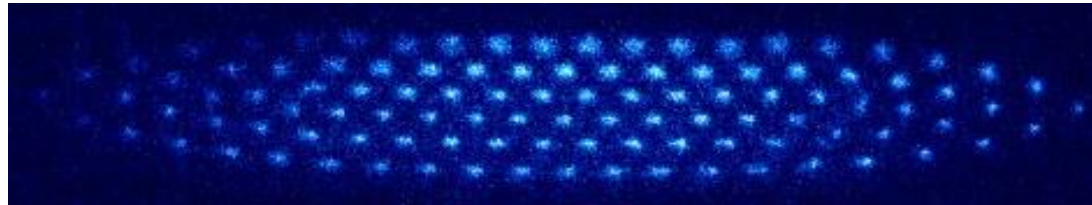
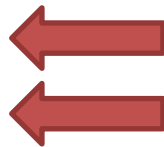
Dudin et al., Nature Physics 8, 790 (2012)

Trapped ions

- 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**

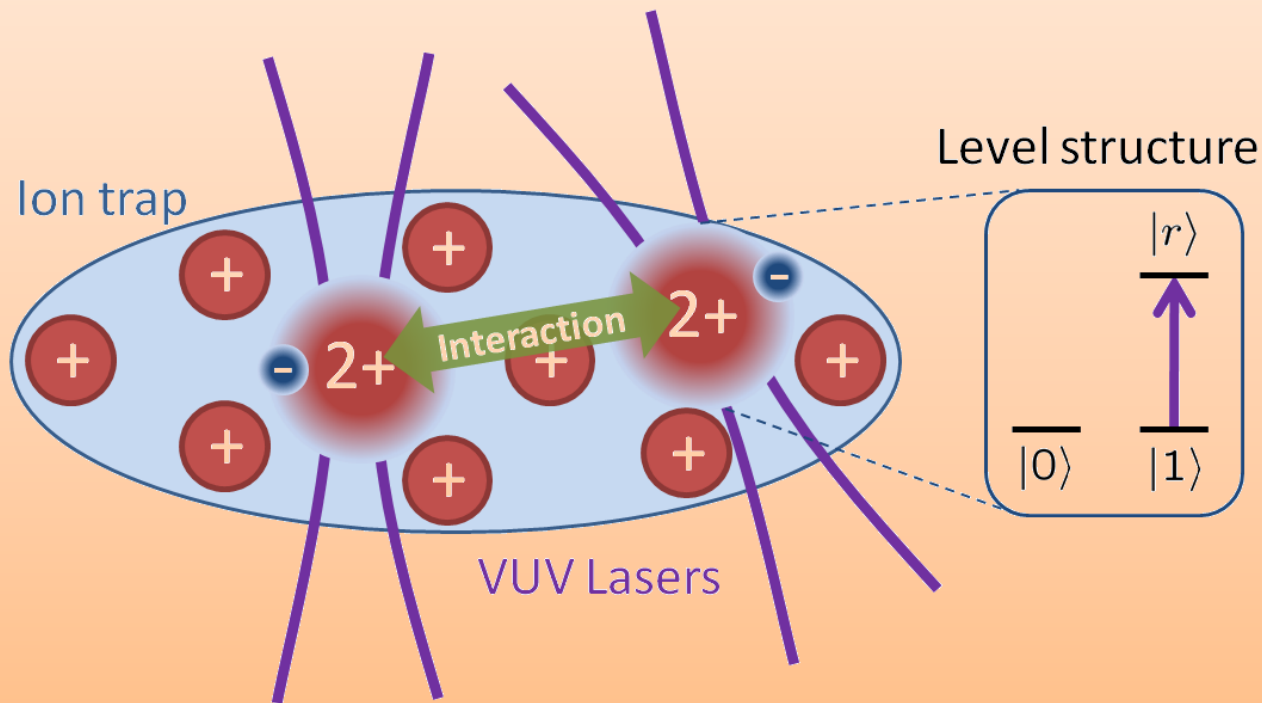
- trapped, localized qubits
- near unity detection efficiency
- quantum gate operations with $>99\%$ fidelity
- reliable state tomography

with **Rydberg excitations and interactions**

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

Aim of this project

Lets us use Rydberg states of trapped ions



... 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	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867		
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224		
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 ✱	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	
francium 87 Fr [223]	radium 88 Ra [226]	89-102 ✱ ✱	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

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>

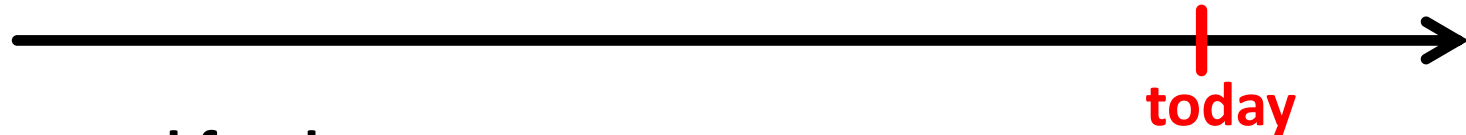


The R-ION Consortium

Funding period

August 2011

July 2014



Requested funds

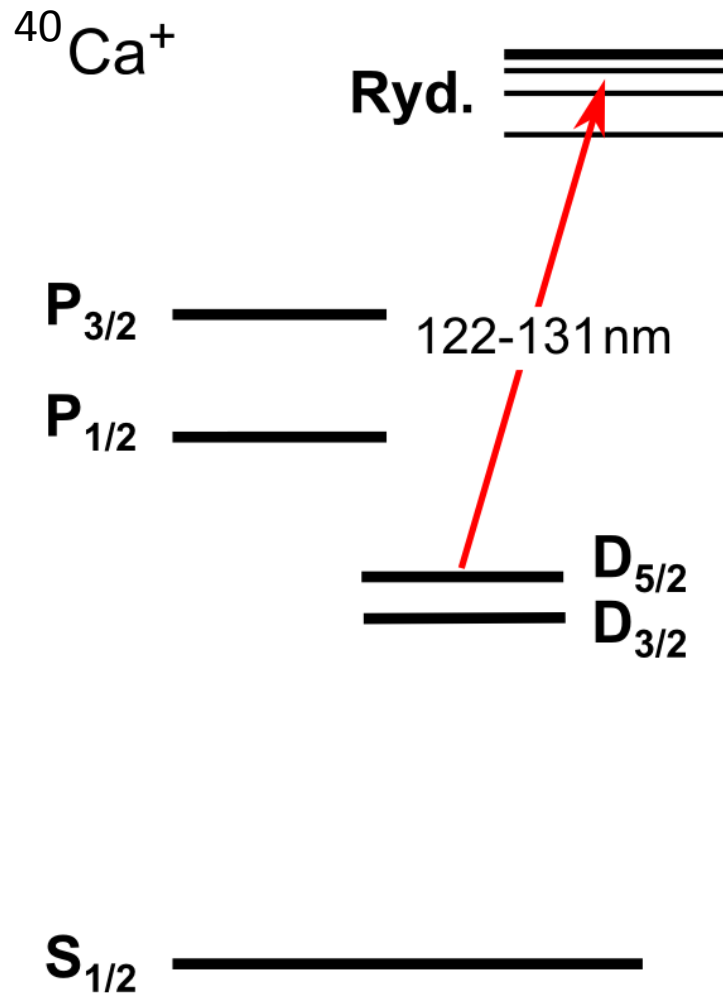
- six postdoc years for theory
- six postdoc years for experiment
- 200 kEUR for consumables
- 70 kEUR travel and subsistence

General aim (Research programme with 3 WPs)

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

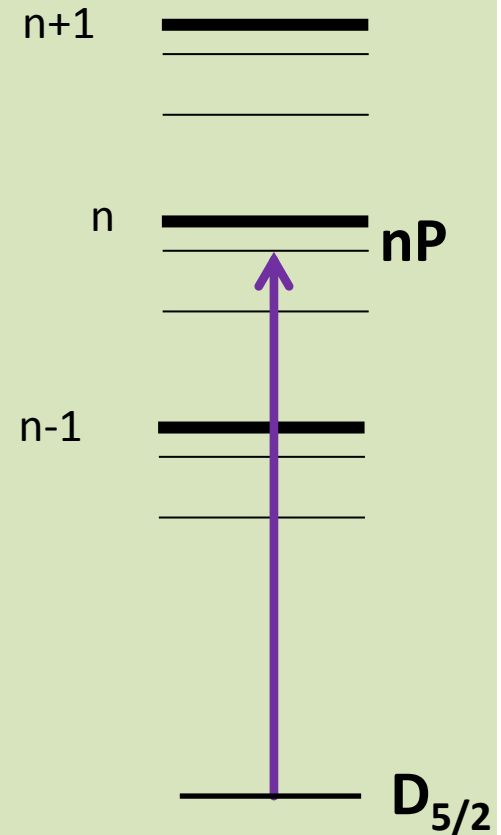
VUV – Rydberg excitation

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



Rydberg spectrum

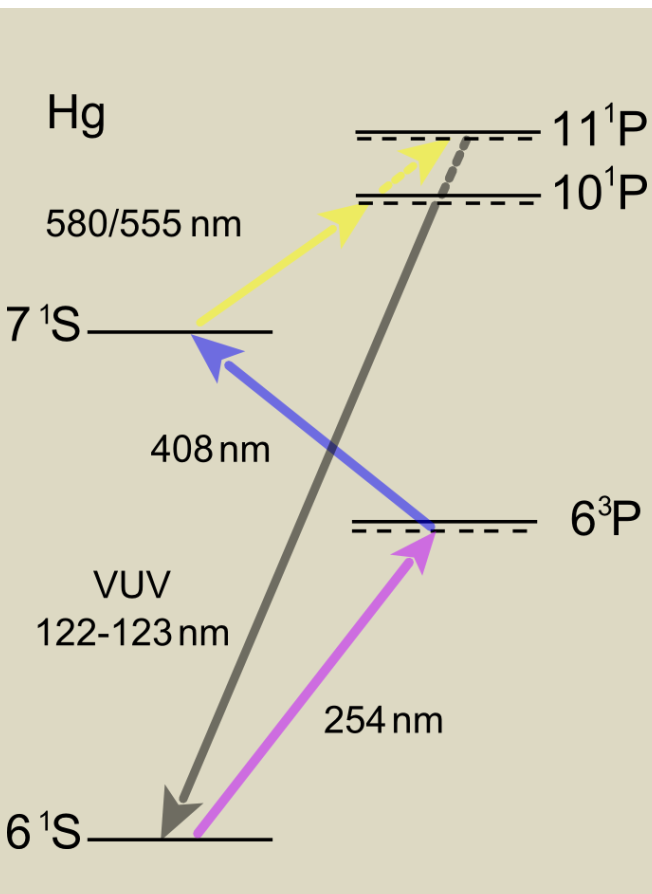
Rydberg states



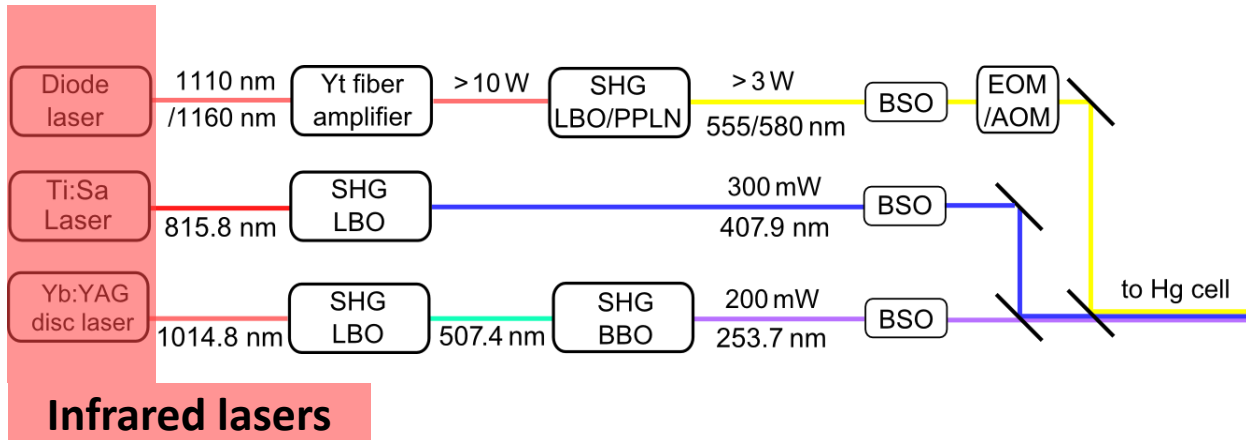
Generation of VUV radiation

Four-wave mixing

in mercury vapour to generate coherent VUV radiation



Laser system



Power

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

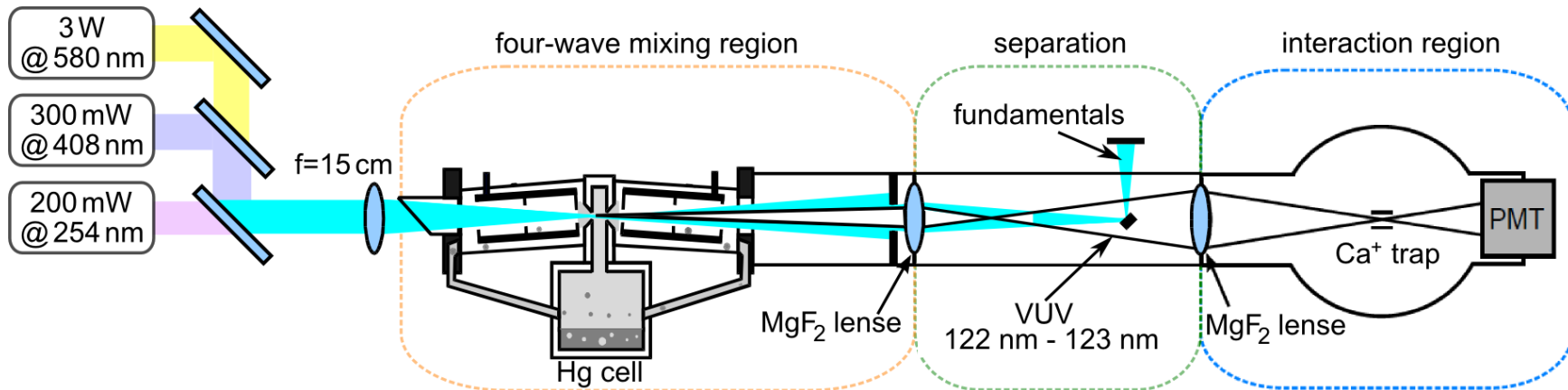
$|\chi^{(3)}|^2$ = third order optical nonlinearity

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

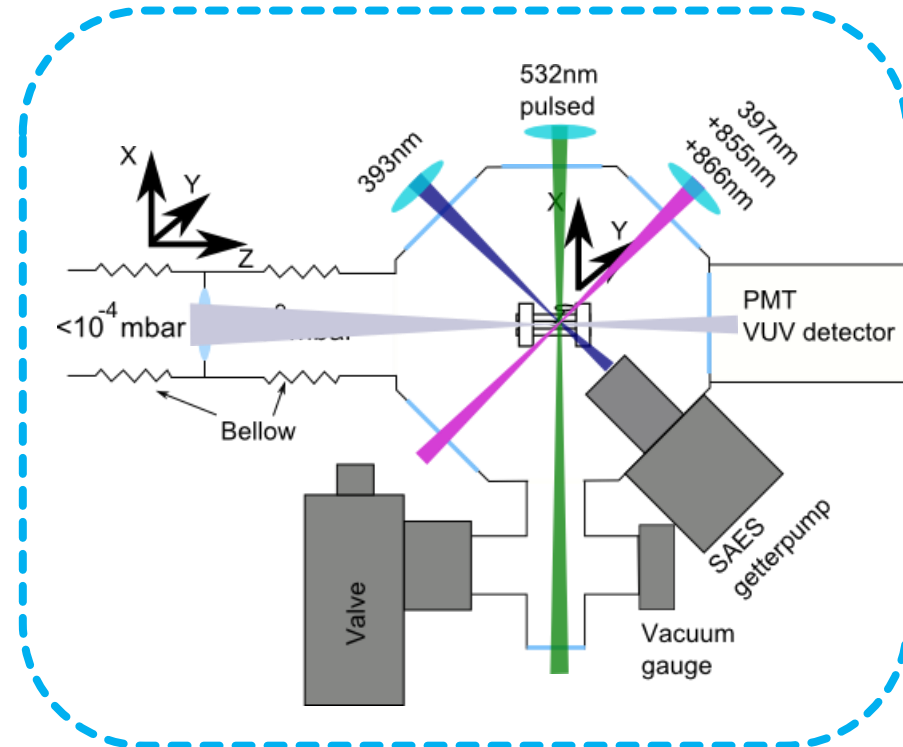
Generation of VUV radiation



Laser and ion trap



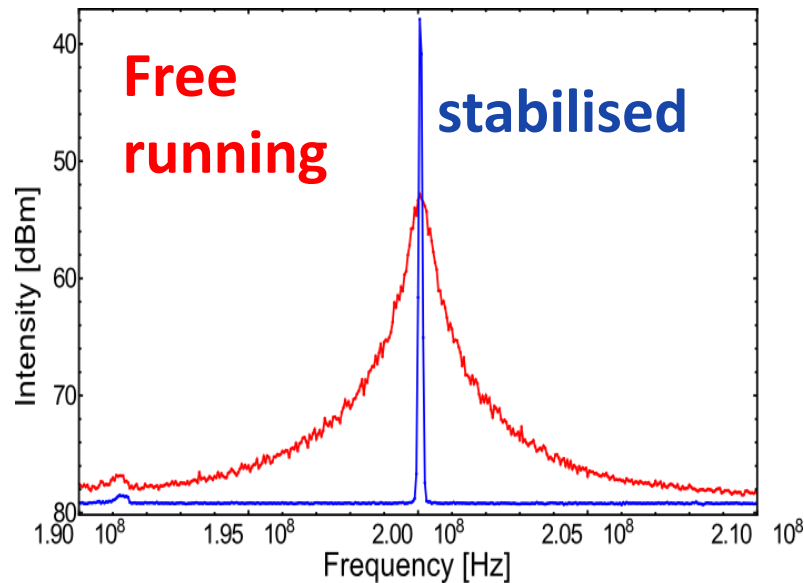
- MgF_2 – lens separates laser vacuum and ion trap vacuum
- flexible connection between laser vacuum and ion trap (laser focus can hardly be moved, **need to move trap**)



Achievements (WP2, WP3)

Frequency stabilisation

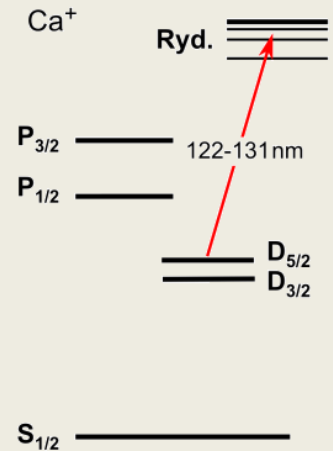
all infrared Lasers actively stabilized to < 100 kHz



Optimization of output power

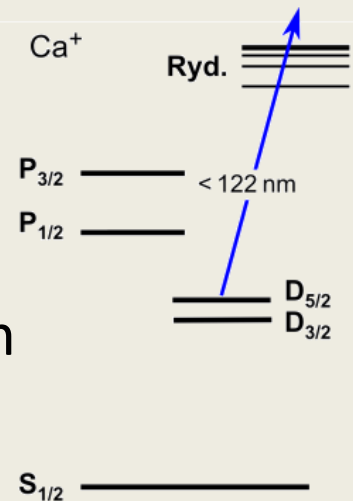
**Rydberg
excitation
wavelength**

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



**ionization
wavelength**

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



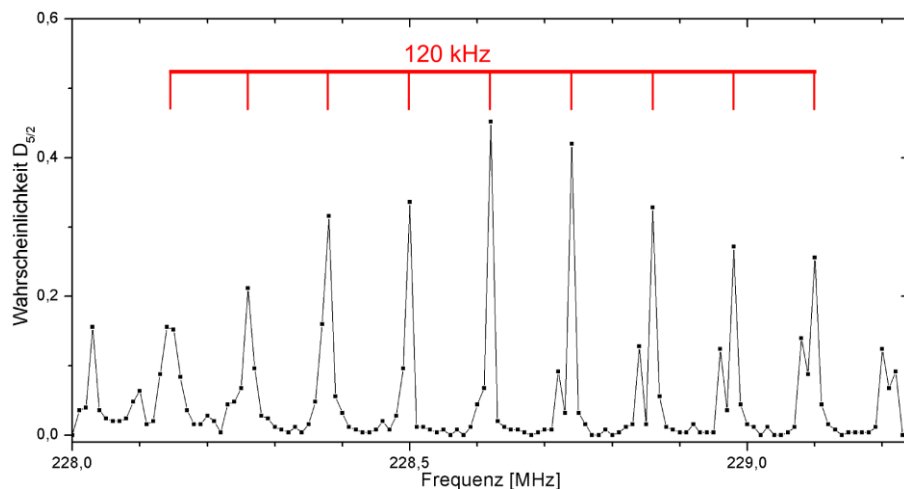
Achievements (WP2, WP3)

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

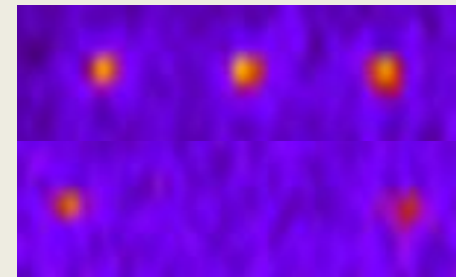
- axial side bands



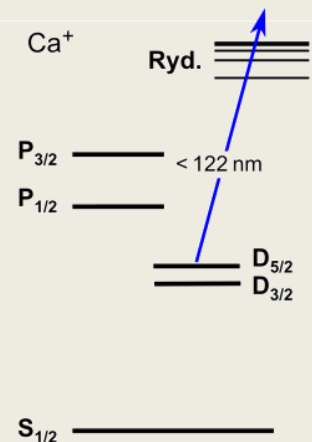
First observations of Ca^+ - VUV interaction

3 Ca^+

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

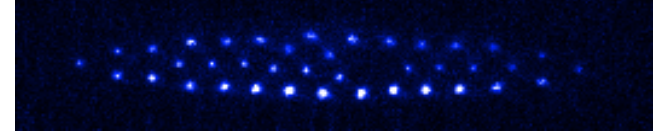


Ionisation rate
 $\sim 1/\text{min}$ @ $0.5 \mu\text{W}$



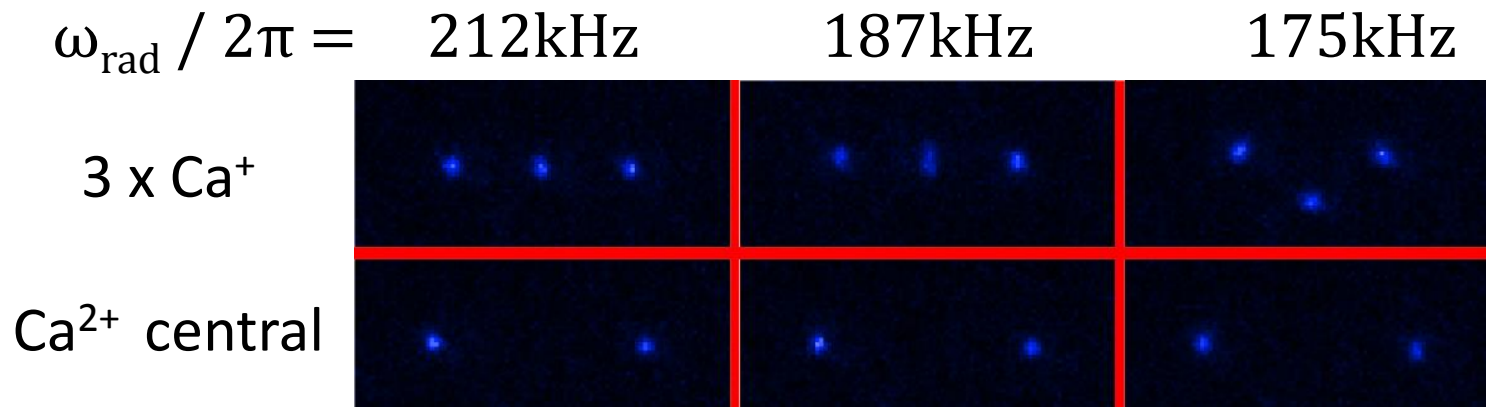
Achievements (WP2, WP3)

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



- production of doubly charged ions @ 121.6nm
- detection through increased displacement (21% for 3 ions) and gaps in large crystals

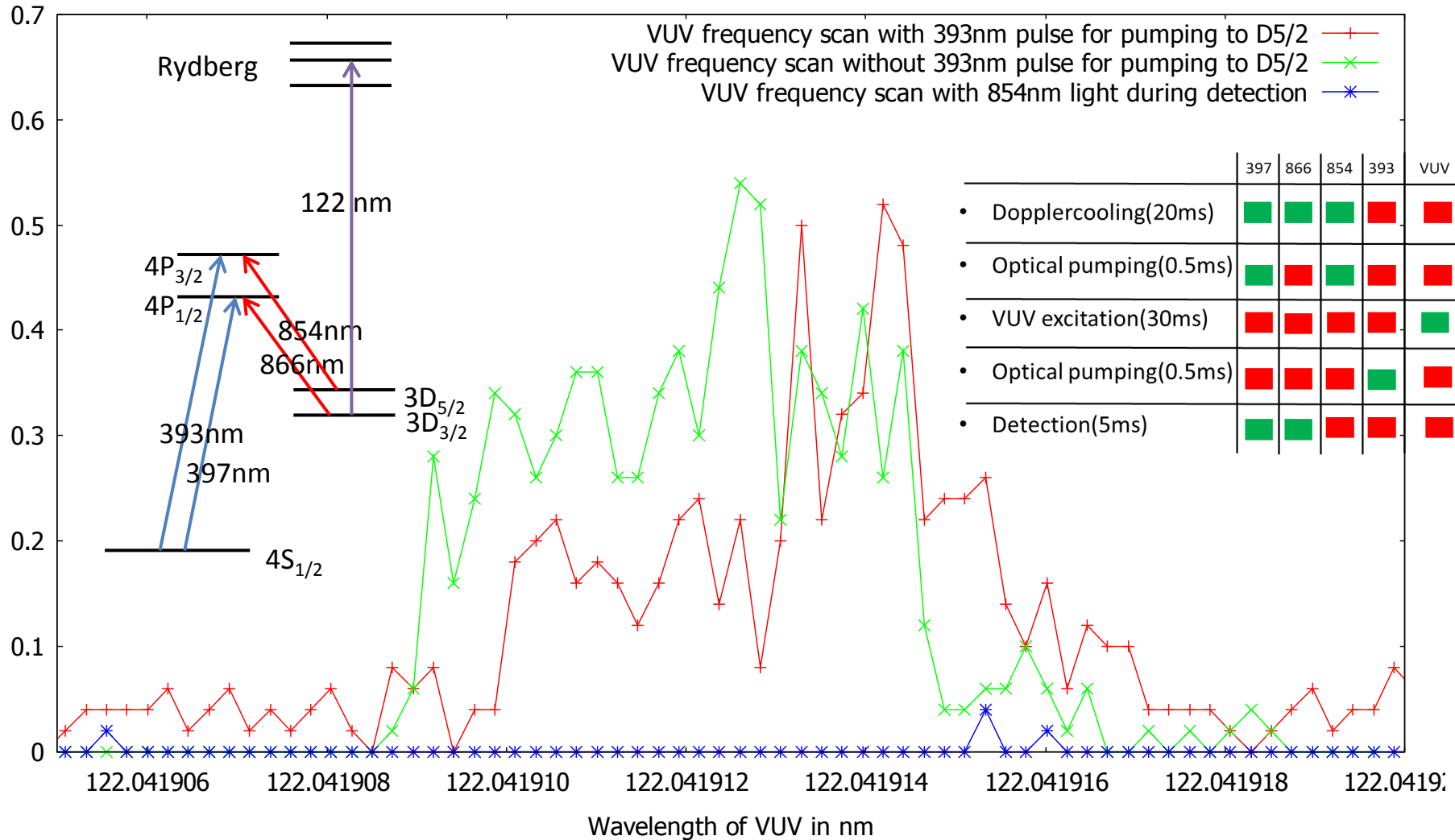
Experiment: changing ratio $\omega_{\text{rad}} / \omega_{\text{ax}}$



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

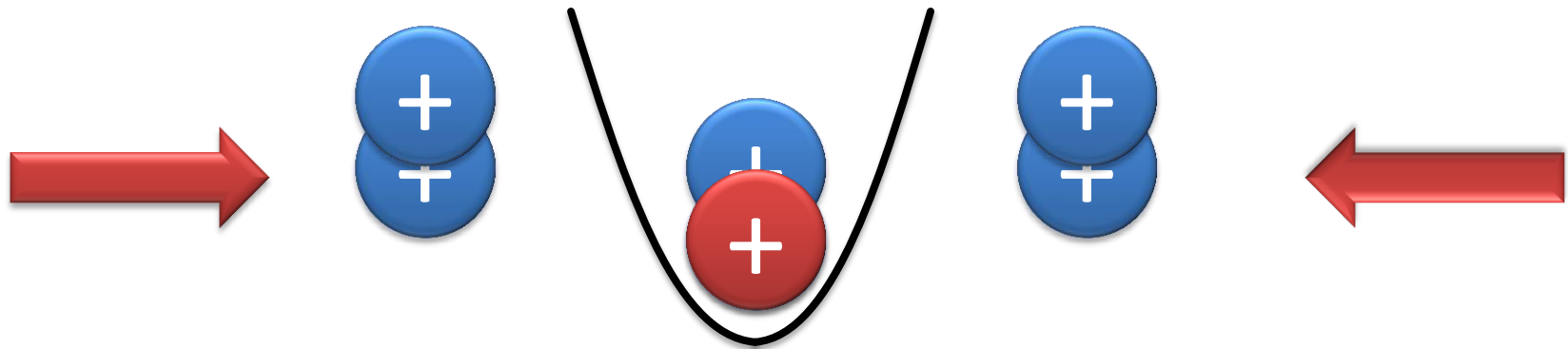
Achievements (WP2, WP3)

First observation of Ca^+ Rydberg excitation using VUV radiation



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

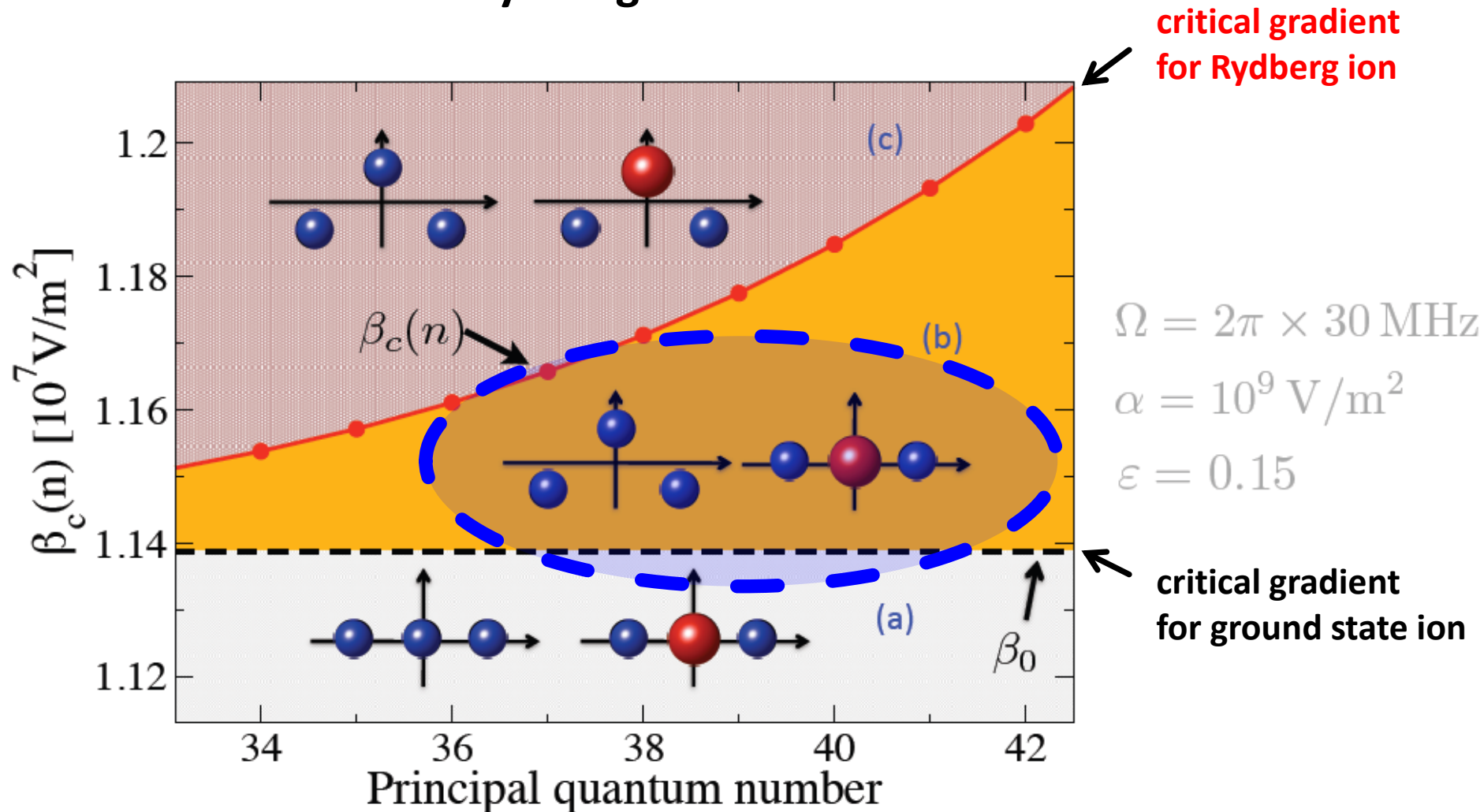
$$V_{\text{add}} = \frac{1}{2} M \bar{\omega}^2 (X^2 + Y^2) \quad \bar{\omega} \sim \alpha \sqrt{\frac{P(n)}{M}} \sim n^{7/2}$$

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

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

State-dependent crystal (WP2)

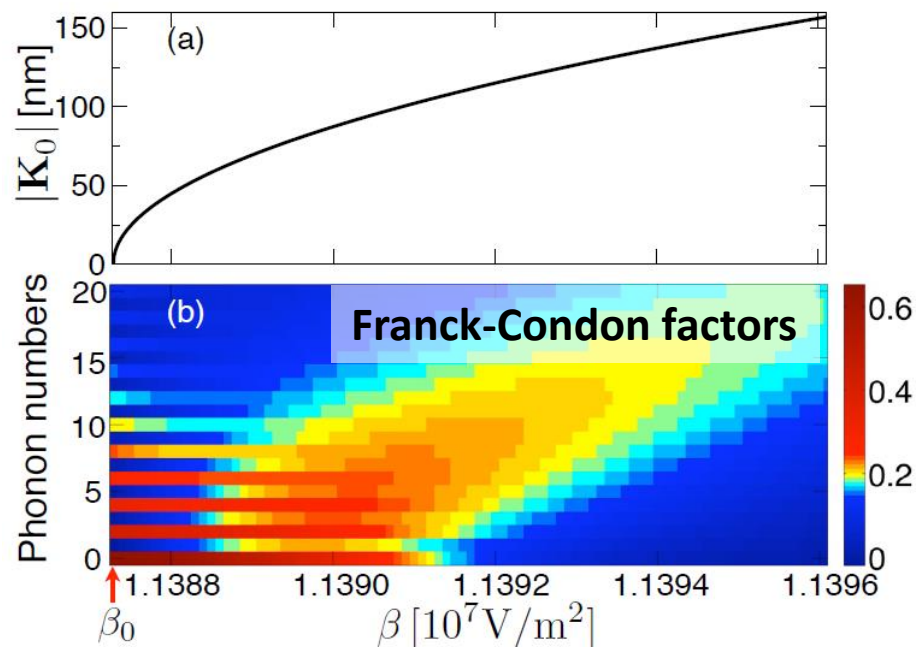
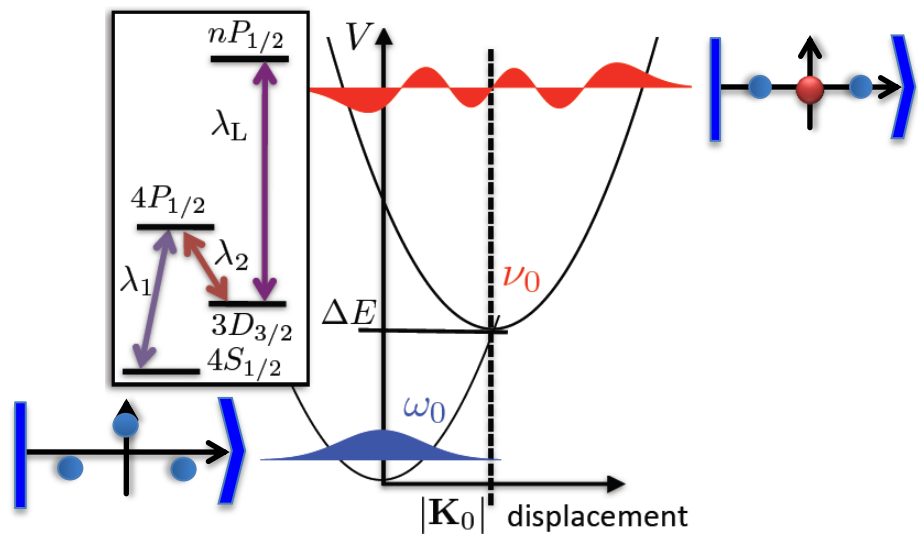
- equilibrium **configuration** of the crystal **depends** on field gradient and on whether a **Rydberg state** is excited or not



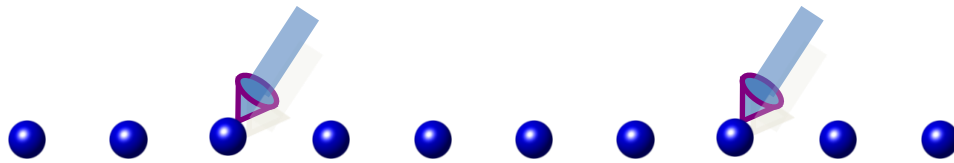
Rydberg excitation of ion crystal

- 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

Weibin Li and Igor Lesanovsky,
PRL **108**, 023003 (2012)

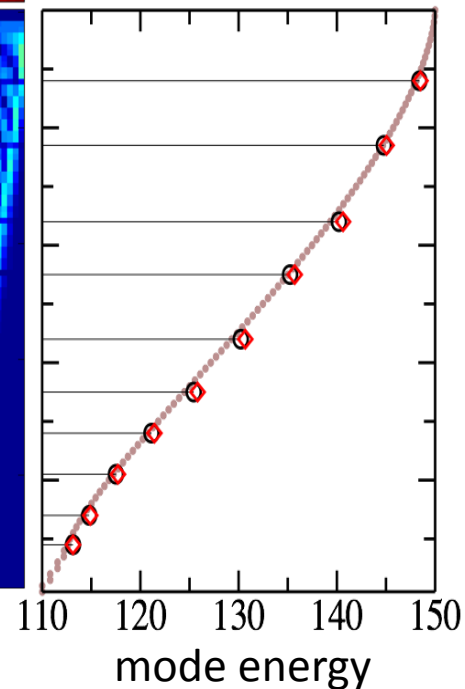
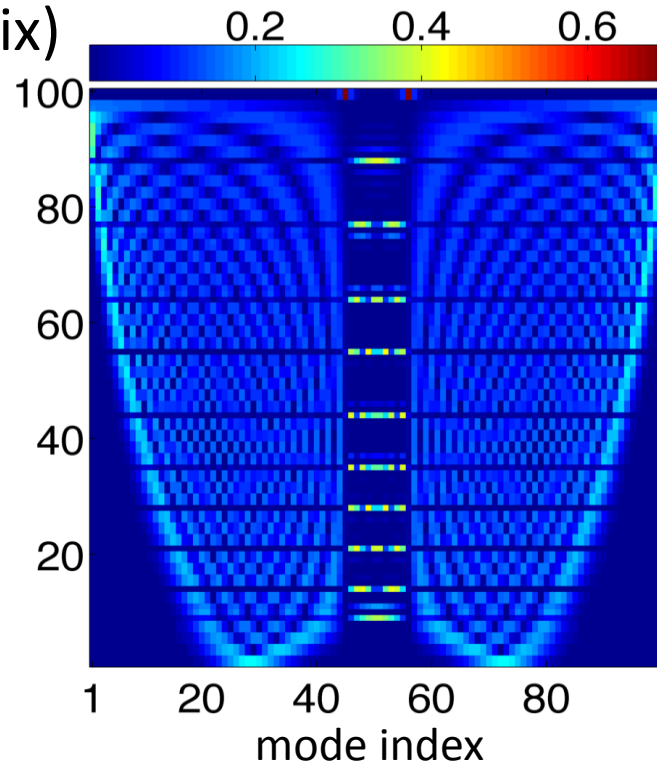
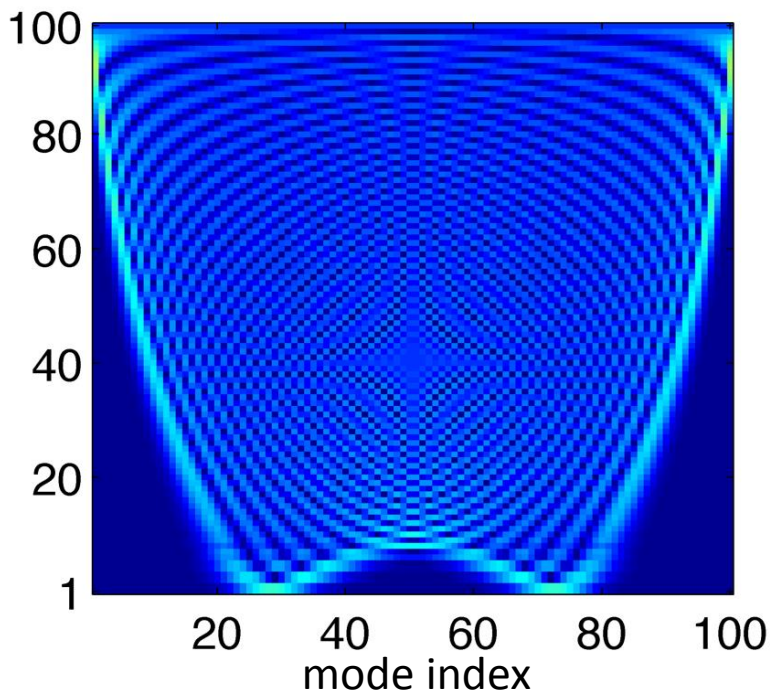


Vibrational mode shaping (WP4)



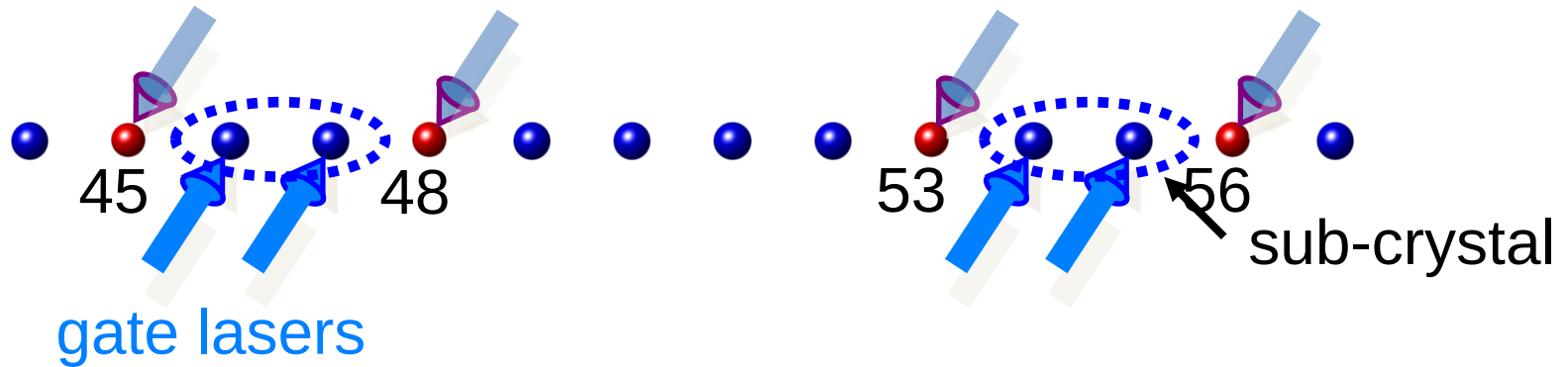
- Rydberg excitation of few ions within **long ion chain** (100 ions)

Transverse vibrational modes
(entries of normal mode matrix)

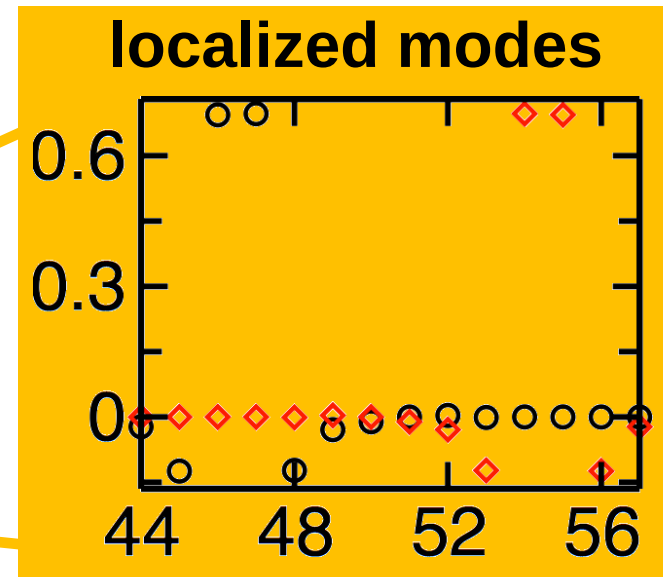
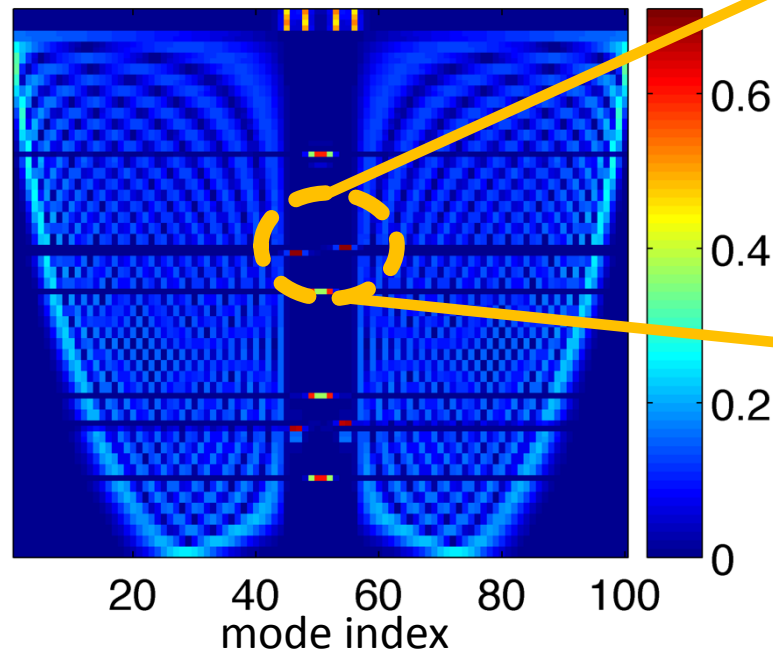


- Rydberg ions chop long crystal into sub-crystals (R-ION collaboration)
[W. Li, R. Nath, A. Glätzle and I. Lesanovsky, arXiv:1208.2863 (2012)]

Parallelization of quantum gates (WP4)



- Rydberg ion
- ion in electronically low lying state

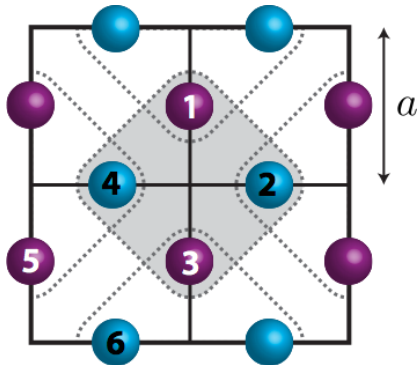


- quantum gates can be executed in parallel on the sub-crystals with high fidelity

Outlook (WP4)

Spin ice in two dimensional ion crystal

led by Innsbruck group



Classical spin ice

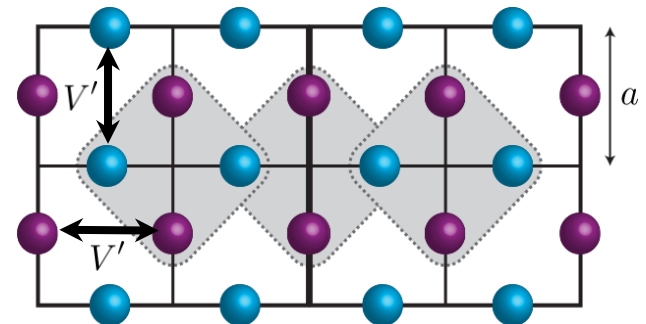
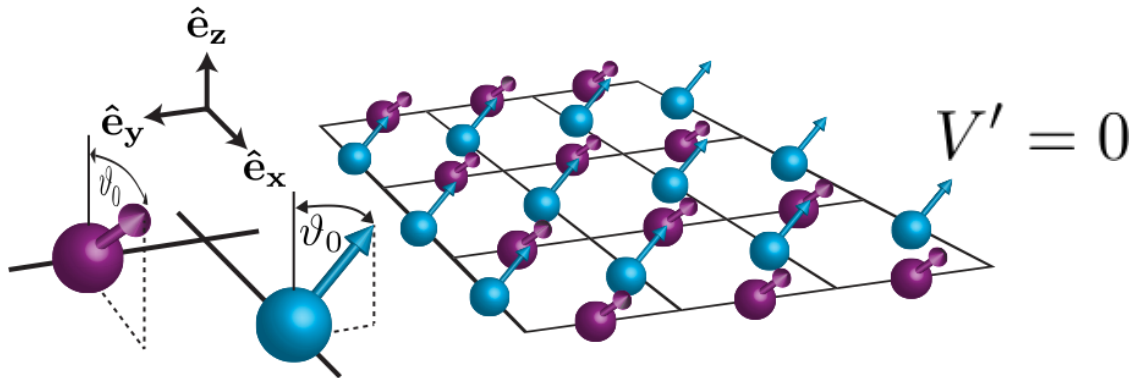
$$H_0 = J_z (\sigma_z^1 + \sigma_z^2 + \sigma_z^3 + \sigma_z^4)^2$$

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



Summary

Experiment

- combined laser and trap setup exists
- has been optimized (second generation setup)
- VUV-laser ion interaction: double ionization
- first Rydberg excitation using VUV radiation

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

Outlook

Experiment

- investigate Rydberg excitation in detail
- investigate Rydberg blockade and many-body effects
- 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