Universität
Stuttgart

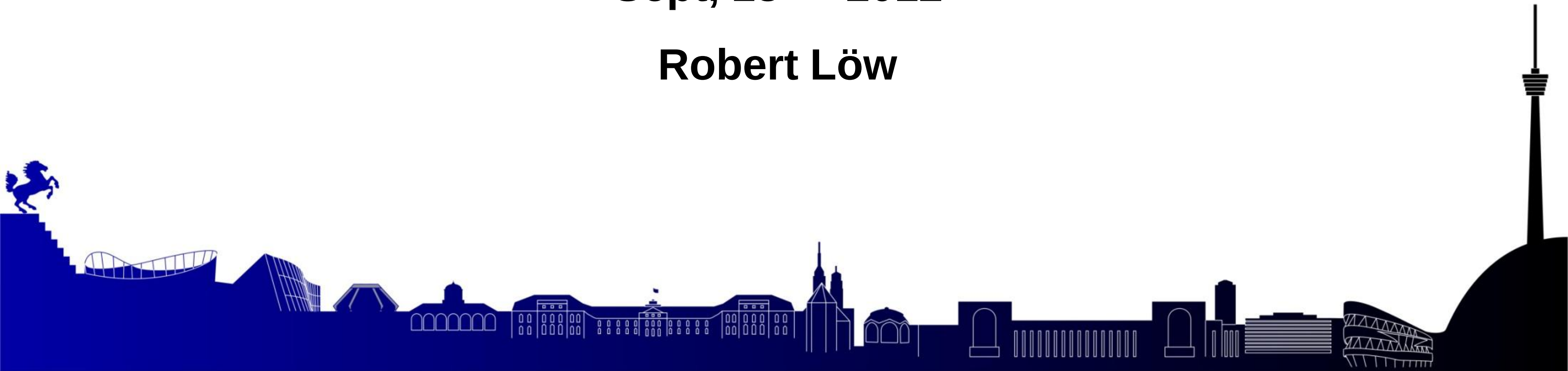
COHERENCE

Rydberg excitation in thermal vapor cells

Pisa

Sept, 18th - 2012

Robert Löw



Outline

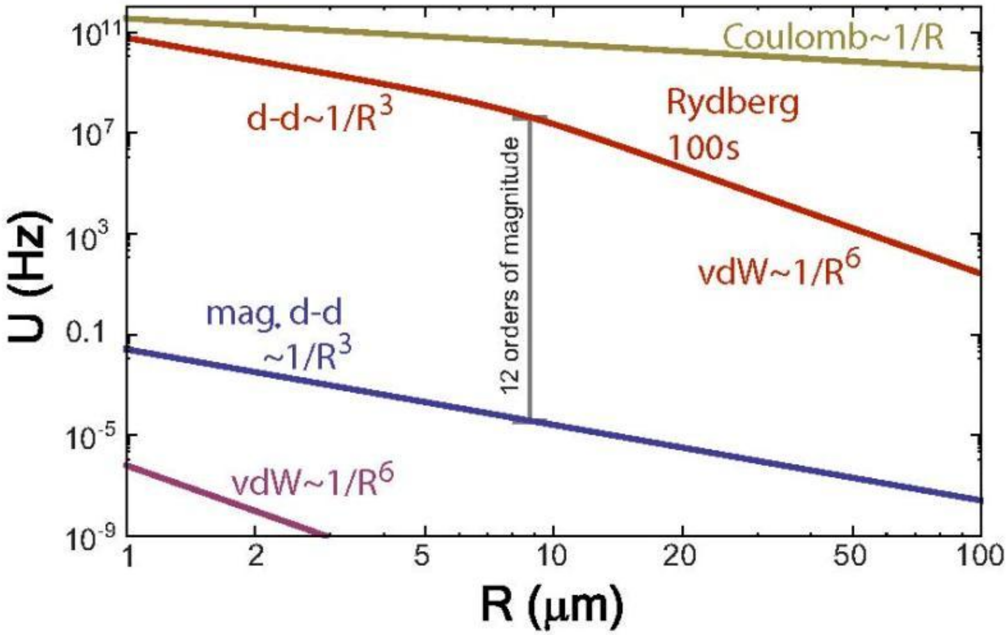
Strongly interacting Rydberg gases – ultracold

Rydberg atoms in thermal vapors

- **Spectroscopy cells**
- **Rydberg – wall interactions**
- **Pulsed Rydberg excitation**
- **Rydberg-Rydberg interaction at room temperature**
- **4 wave mixing**
- **Direct measurment of Rydberg states**
- **RF- sensing**

The interactions between Rydberg states are …

… strong
… long-range
… tunable
… switchable
… anisotropic

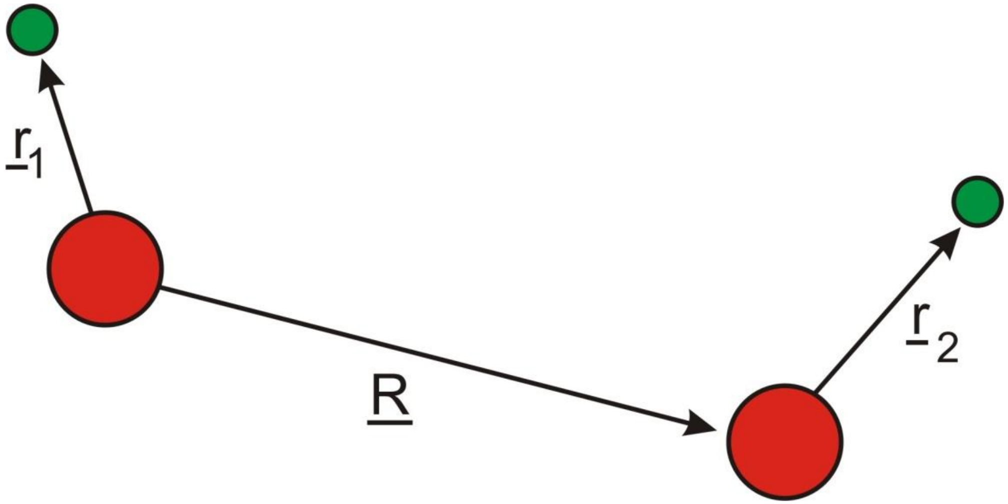


M. Saffman et al., Rev. Mod. Phys. **82**, 2313 (2010)

and can be used

… for neutral atom quantum computing and quantum simulation
… as long range and anisotropic interaction potentials for quantum degenerate gases
… as an optical non-linearity on the single photon level

Interaction between Rydberg atoms



$$V = e^2 \left| \frac{1}{R} + \frac{1}{\left|\underline{R} + \underline{r}_2 - \underline{r}_1\right|} - \frac{1}{\left|\underline{R} + \underline{r}_2\right|} - \frac{1}{\left|\underline{R} - \underline{r}_1\right|} \right|$$

$$\approx e^2 \left| \frac{\underline{r}_1 \cdot \underline{r}_2}{R^3} - \frac{3\left(\underline{r}_1 \cdot \underline{R}\right)\left(\underline{r}_2 \cdot \underline{R}\right)}{R^5} \right|$$

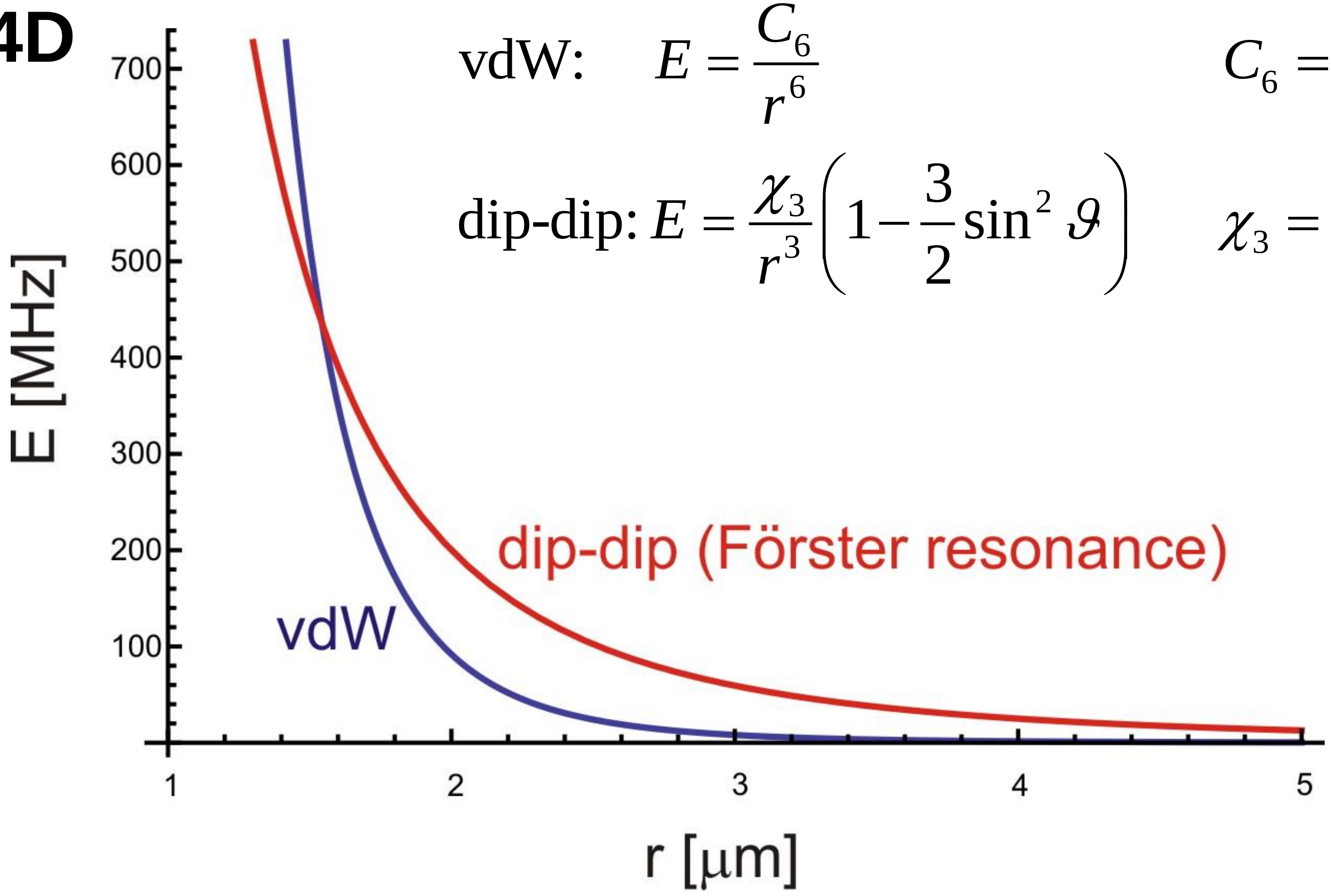
Dipole-dipole interaction

„New“ interactions!

44D

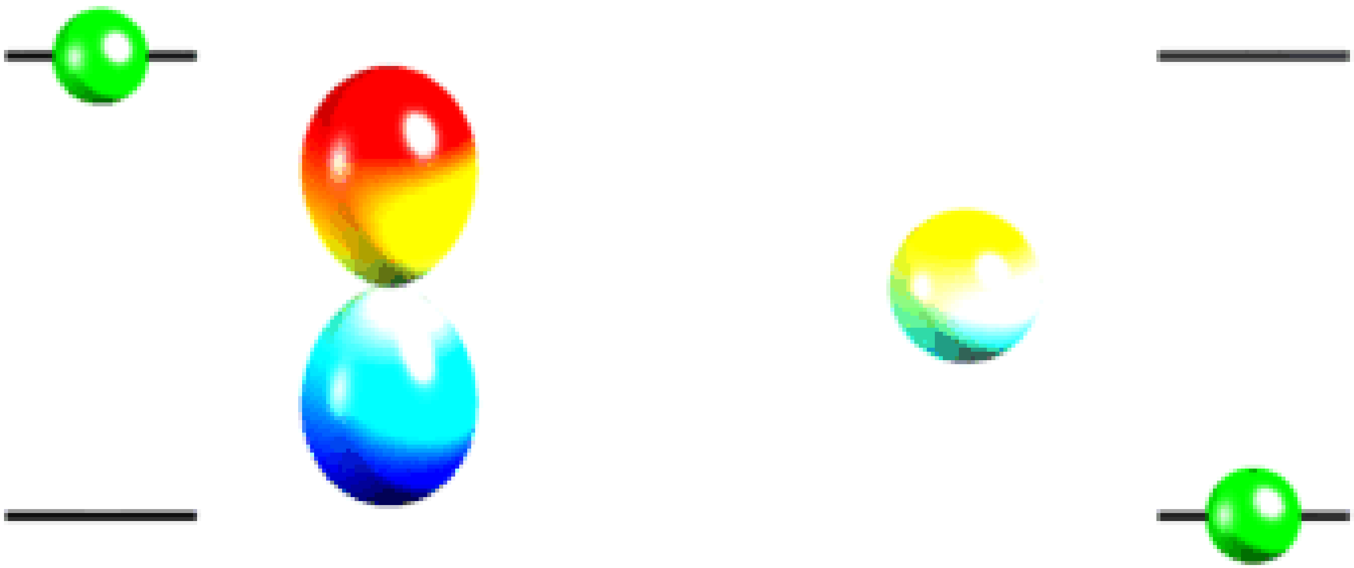
vdW: $$E = \frac{C_6}{r^6}$$ $$C_6 = 5880\ \mathrm{MHz} \cdot \mu\mathrm{m}^6$$

dip-dip: $$E = \frac{\chi_3}{r^3}\left(1 - \frac{3}{2}\sin^2\vartheta\right)$$ $$\chi_3 = 1600\ \mathrm{MHz} \cdot \mu\mathrm{m}^3$$



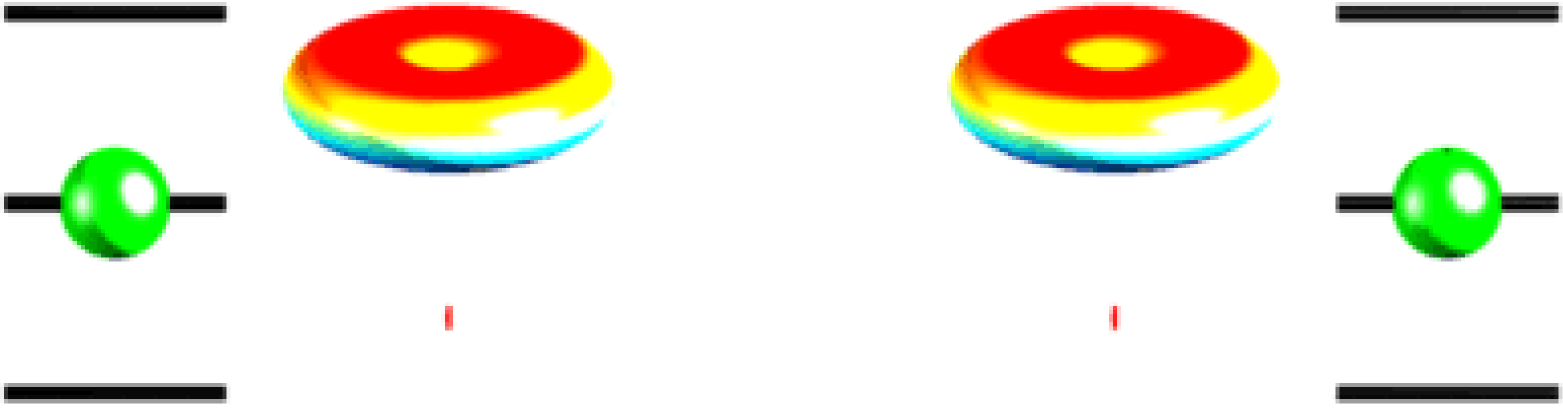
T. Förster, Z. Naturforsch 4a, 321 (1949)

Förster energy transfer



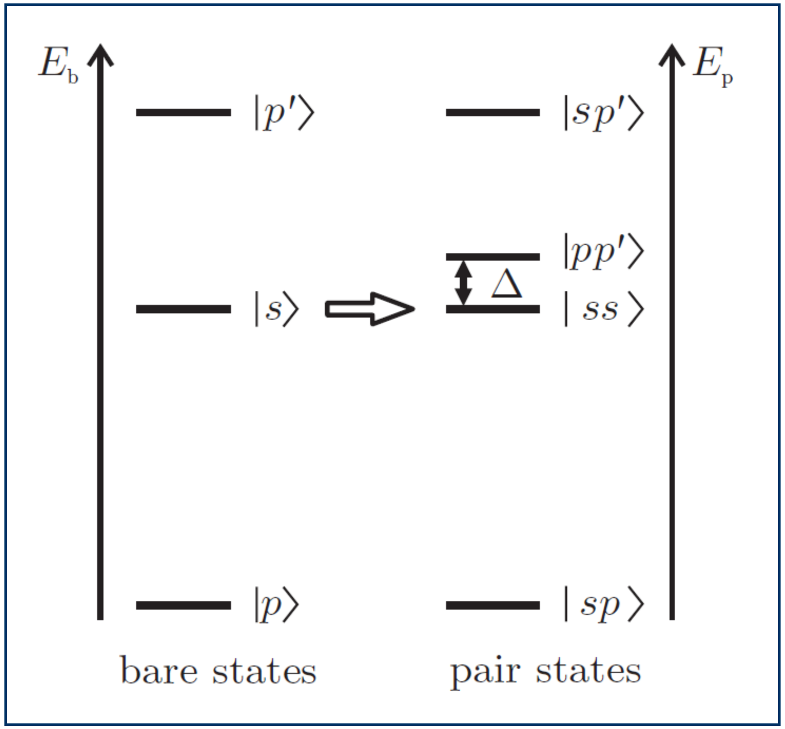
T. Förster, Z. Naturforsch 4a, 321 (1949)

Förster Resonance



See work by Gallagher, Pillet, Raithel, Ryabtsev, Martin, Weidemüller etc.

Interaction between Rydberg atoms



Förster resonance: tune Δ to zero

$$\mathcal{H}_{\mathrm{dd}} = \begin{pmatrix} 0 & \frac{d_1 d_2}{R^3} \\ \frac{d_1 d_2}{R^3} & \boxed{\Delta} \end{pmatrix}$$

$$E_\pm = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \left(\frac{d_1 d_2}{R^3}\right)^2}$$

$$E_{\mathrm{vdW}} = E_- \overset{\Delta \gg d_1 d_2/R^3}{=} -\frac{1}{\Delta}\frac{(d_1 d_2)^2}{R^6} \equiv \frac{C_6}{R^6}$$

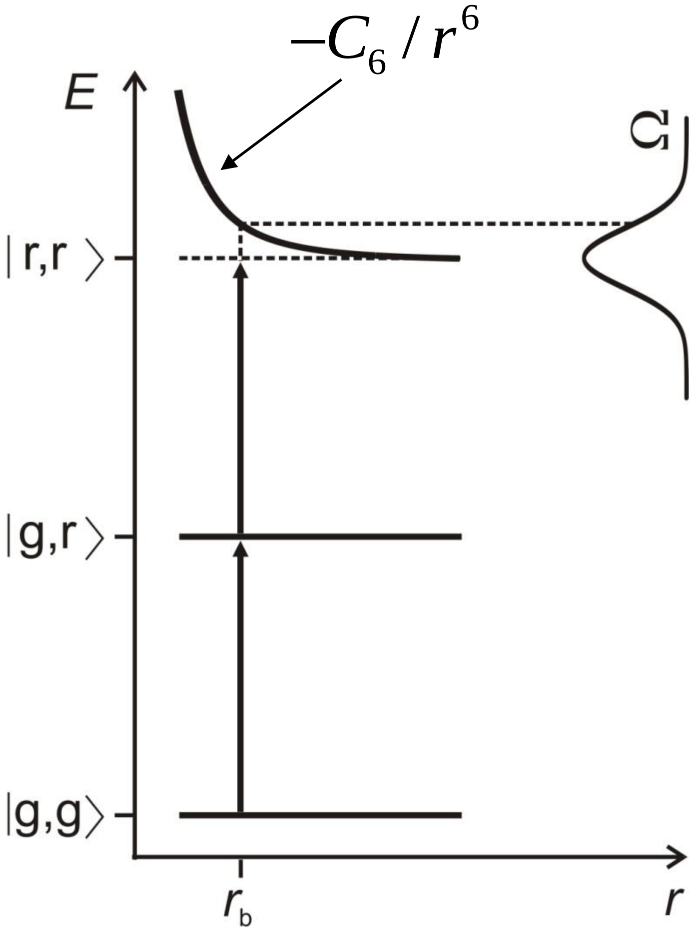
sign depends on Δ !

Dipolar interaction for $R << \sqrt[3]{\frac{d_1 d_2}{\Delta}}$

Excitation blockade by van der Waals interaction

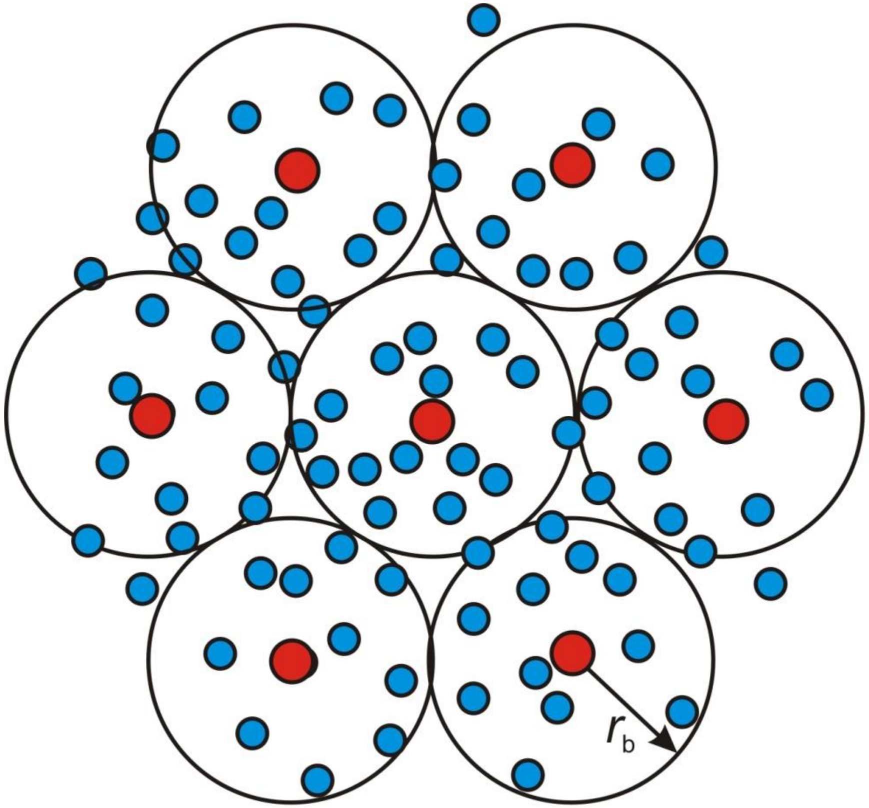
Length scale of the Rydberg-Rydberg interaction:

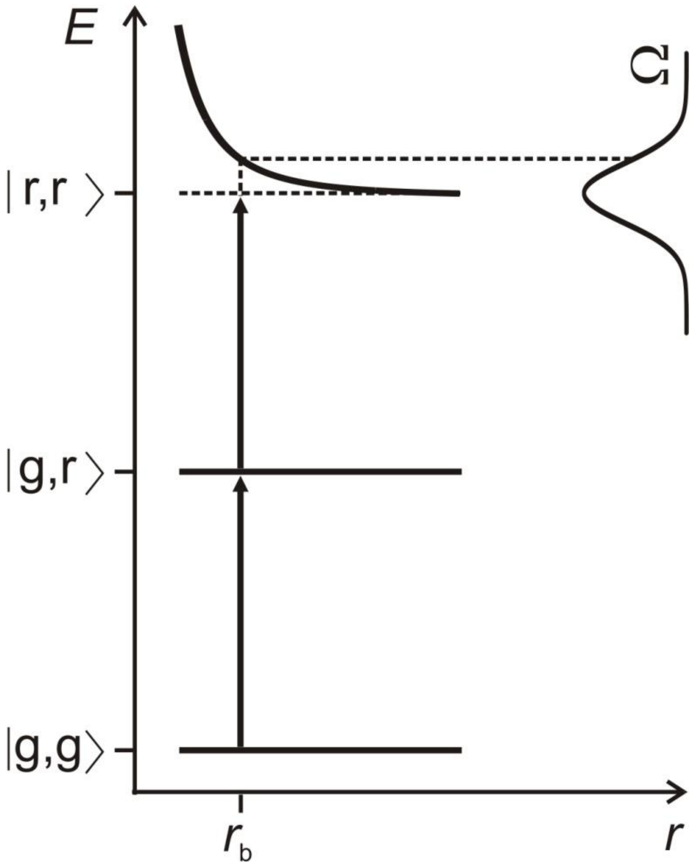
$$r_b = \sqrt[6]{\frac{C_6}{\hbar\Omega}} \approx 5\mu m$$



Distance between two atoms

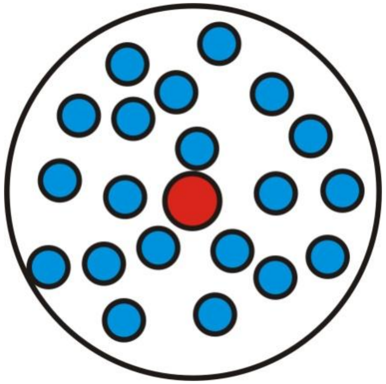
Excitation blockade by van der Waals interaction

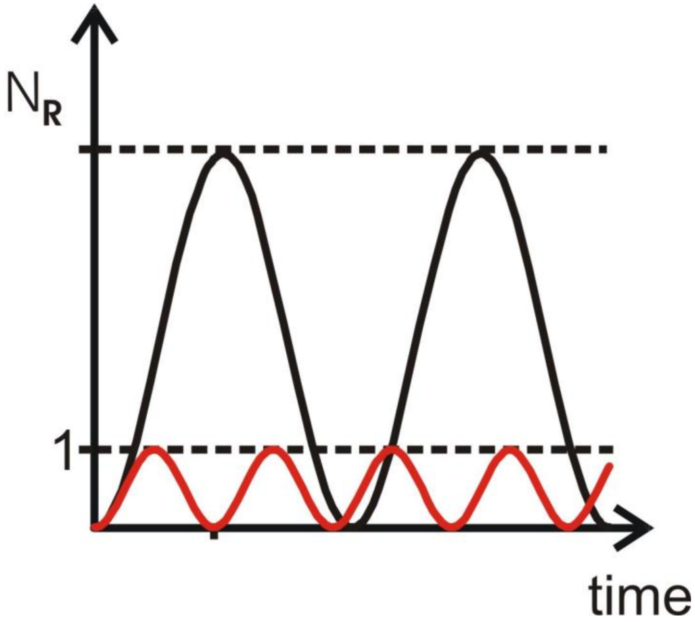




Distance between to atoms

Collective state

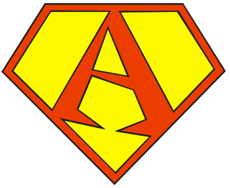




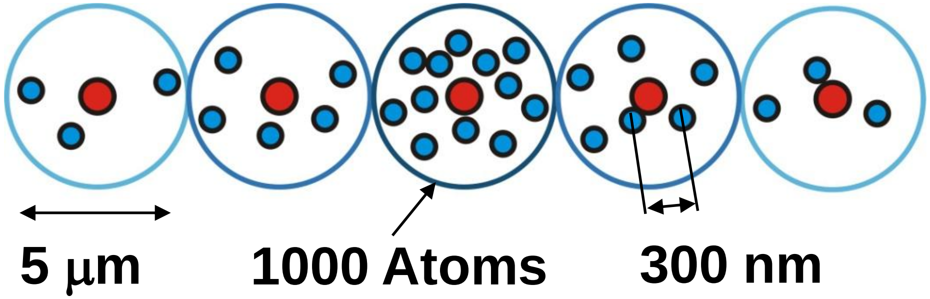
$$|E\rangle = \frac{1}{\sqrt{N}}\{|\,ryd, g, g, ..., g\rangle + |\,g, ryd, g, ..., g\rangle + ... + |\,g, g, ..., g, ryd\rangle\}$$

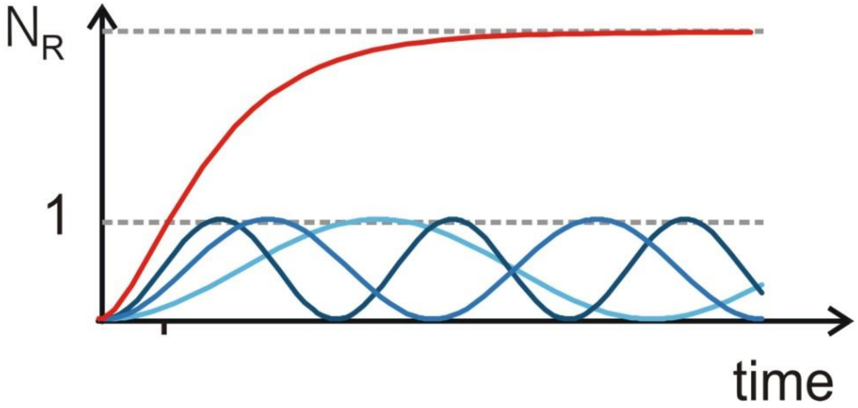
$$\updownarrow \quad \Omega = \sqrt{N}\Omega_0$$

$$|G\rangle = |\,g, g, g, ..., g\rangle$$

Super  **tom**

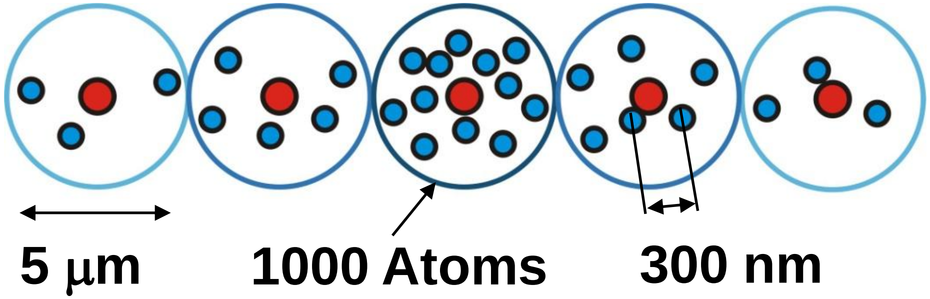
Excitation dynamics in an inhomogeneous Rydberg gas

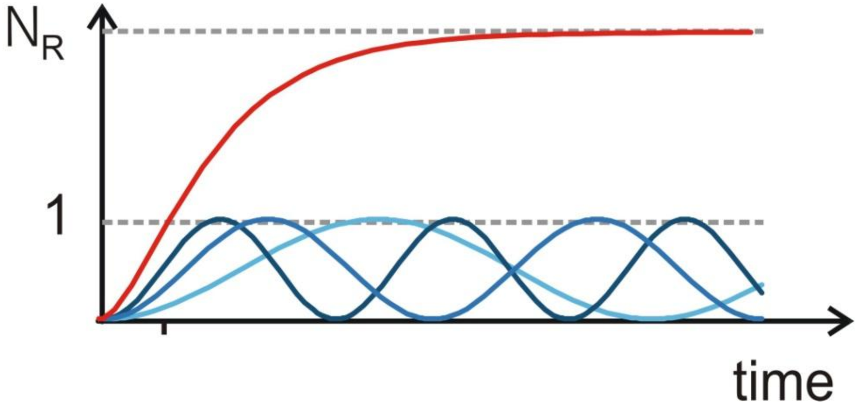


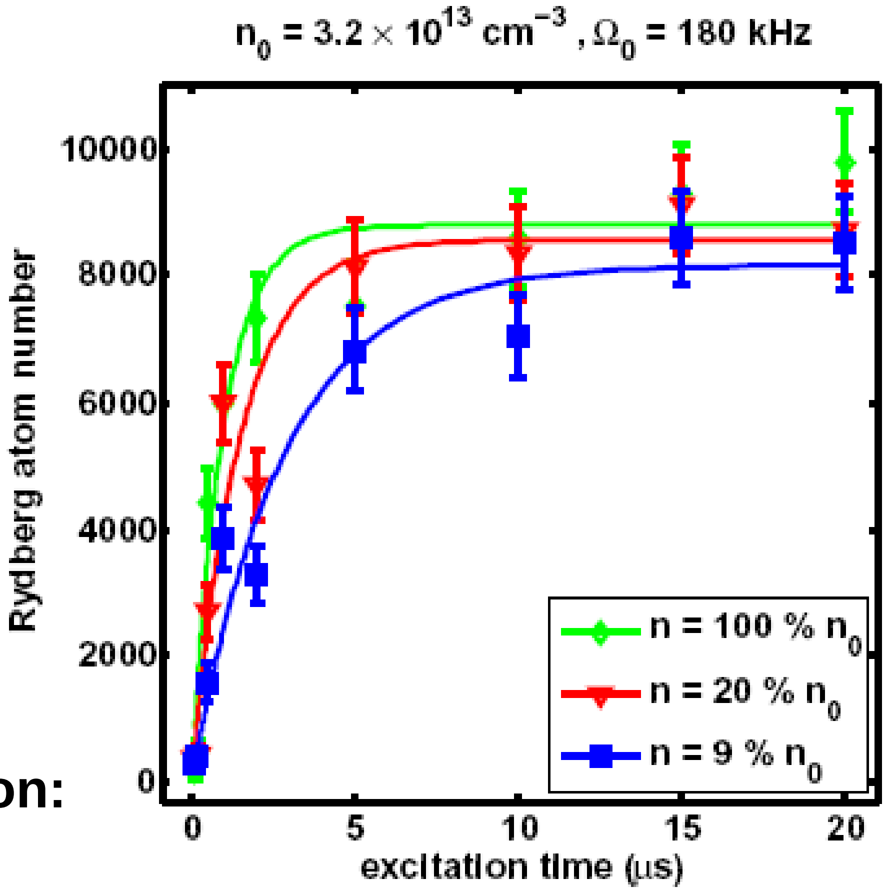


No atomic motion during excitation:
Frozen Rydberg gas!

Excitation dynamics in an inhomogeneous Rydberg gas



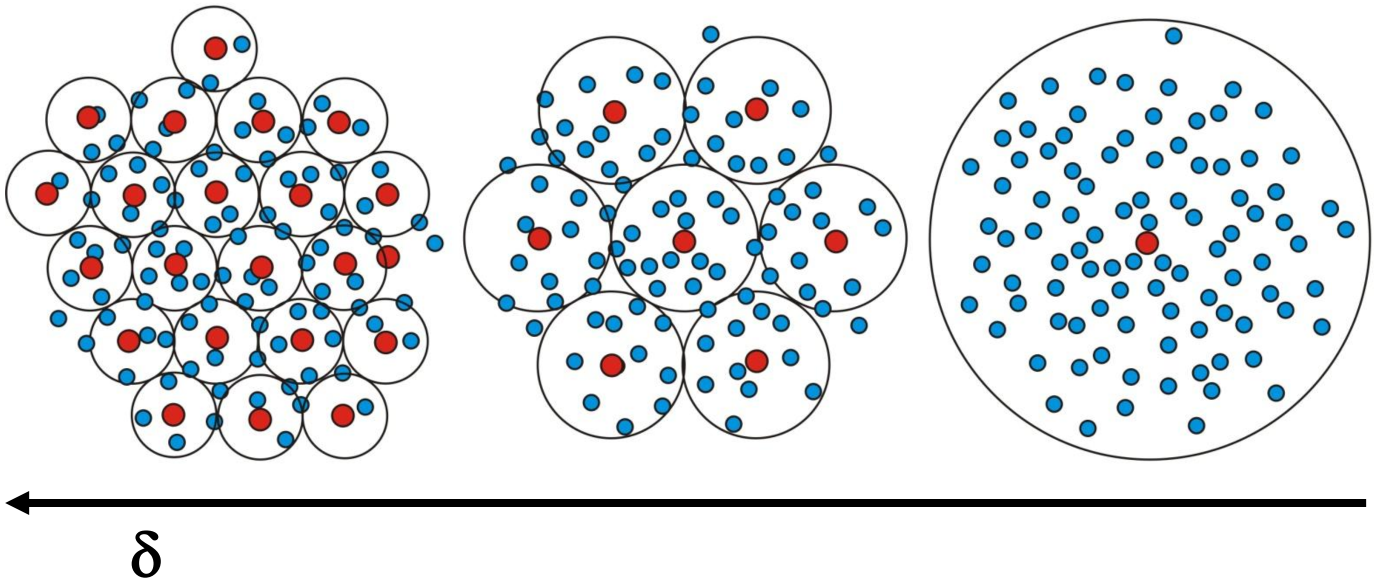


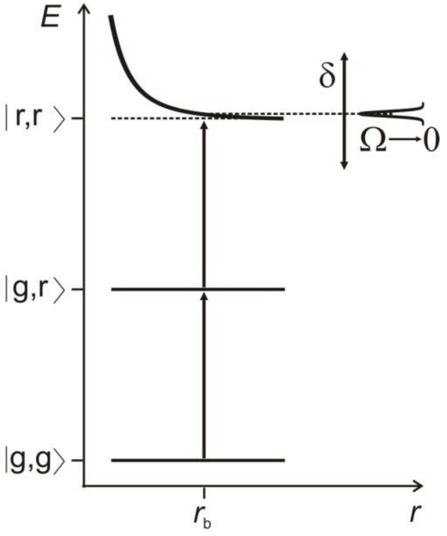


No atomic motion during excitation:
Frozen Rydberg gas!

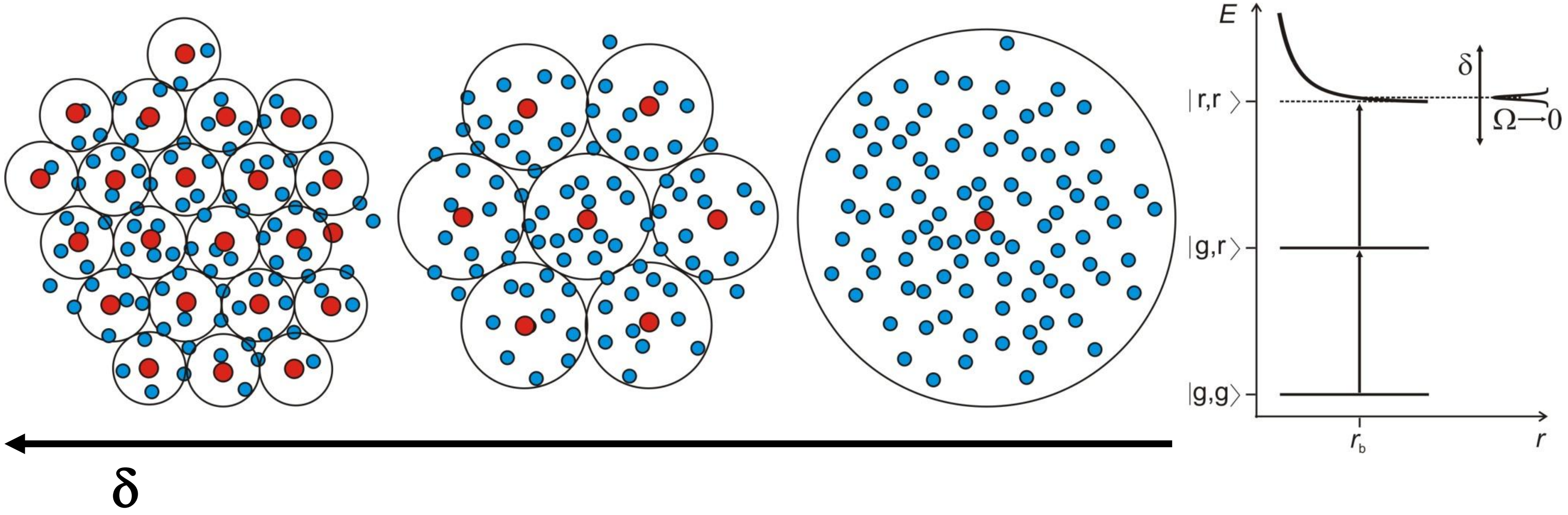
PRL 99, 163601 (2007)

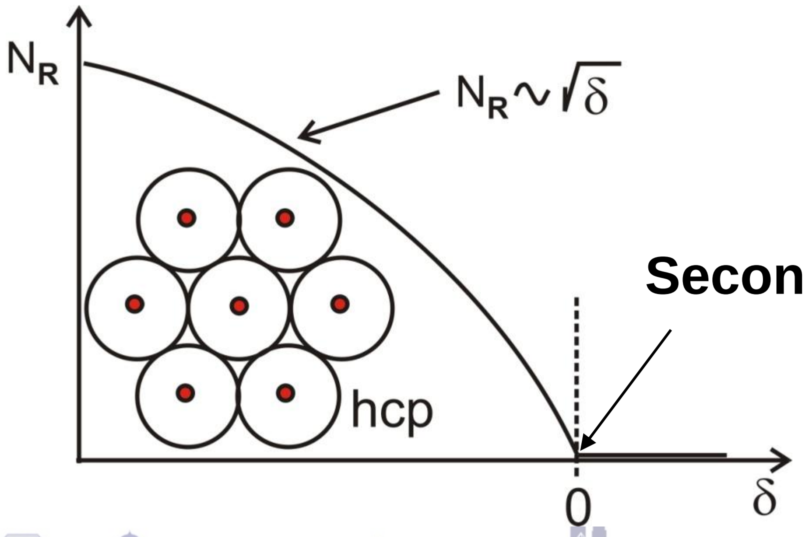
Is it Crystaline?





Is it Crystaline?

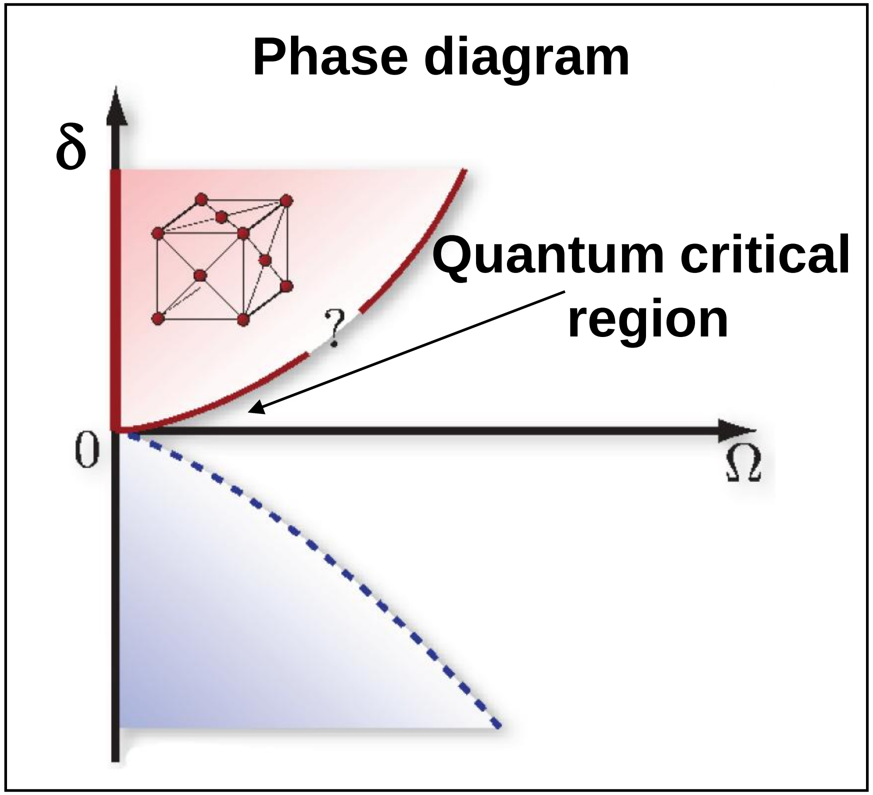




Second order phase transition

Effective Spin Hamiltonian

$$H = -\frac{\hbar\delta}{2}\sum_i \sigma_z^{(i)} + \frac{\hbar\Omega}{2}\sum_i \sigma_x^{(i)} + C_6 \sum_{j<i} \frac{P_{ee}^{(i)} P_{ee}^{(j)}}{\left|r_i - r_j\right|^6}$$



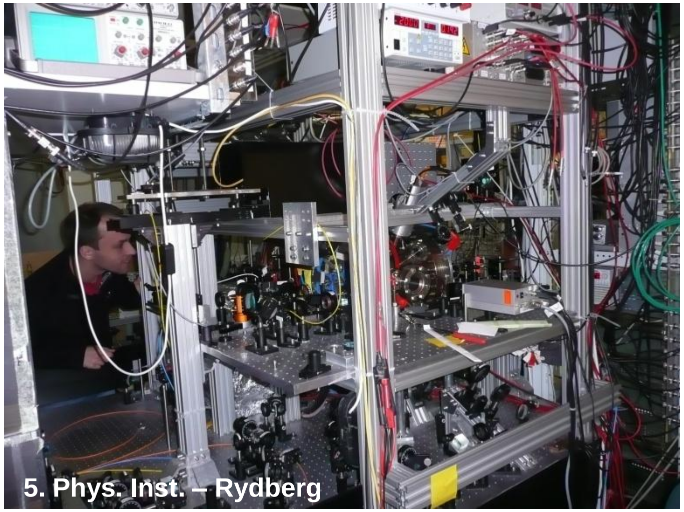
Phase diagram

Quantum critical region

Projector: $P_{ee}^{(i)} = (1+\sigma_z^{(i)})/2$

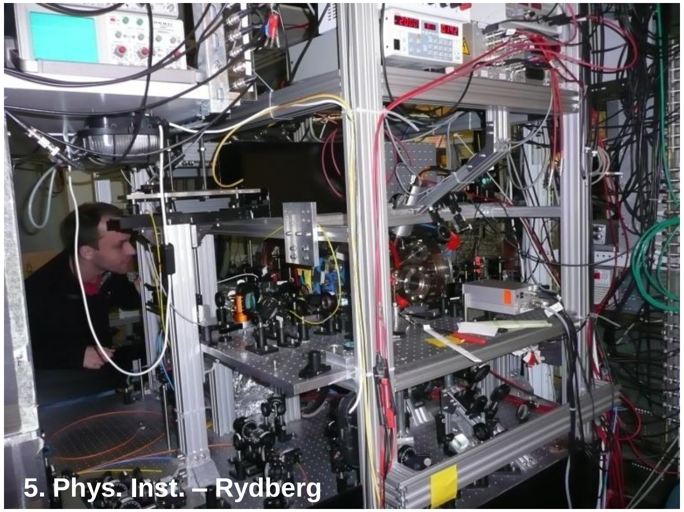
PRL **101** 250601 (2008)
J Phys B, **45** 113001 (2012)

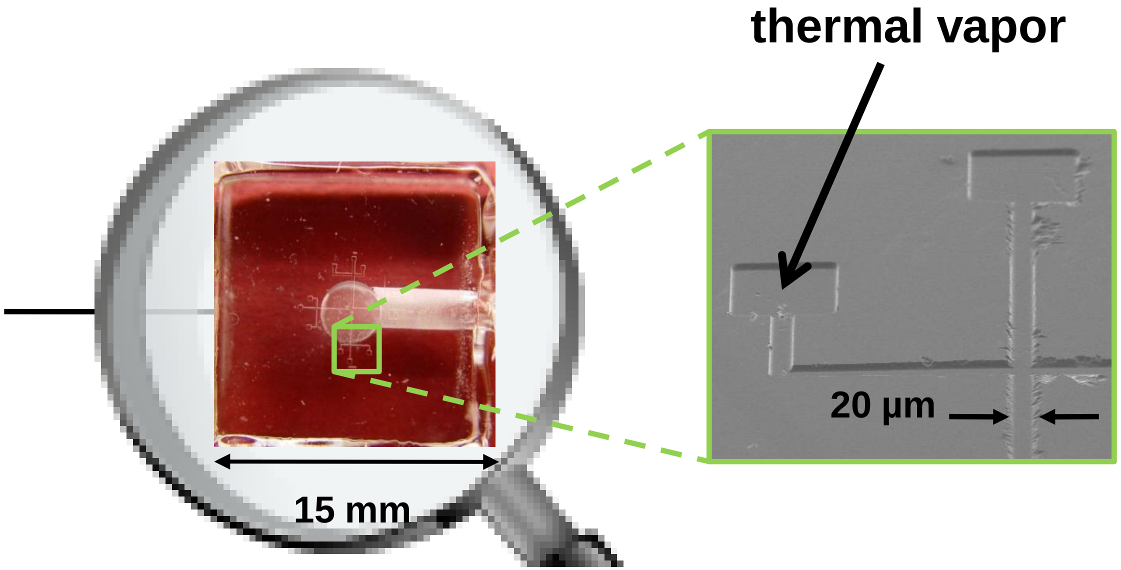
Miniaturization



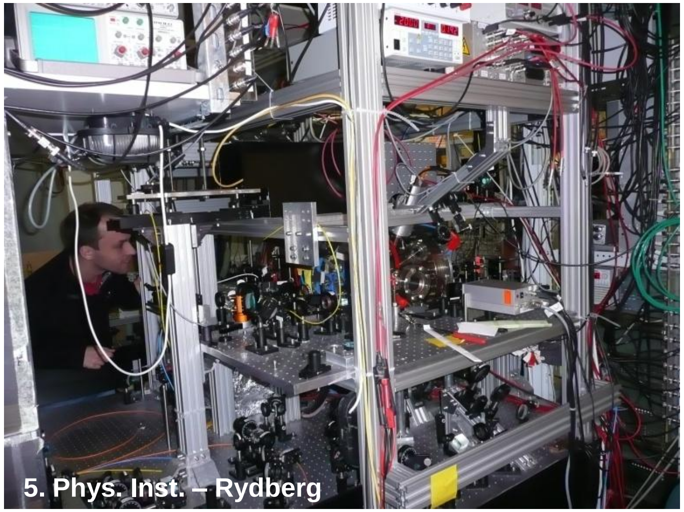
5. Phys. Inst. – Rydberg

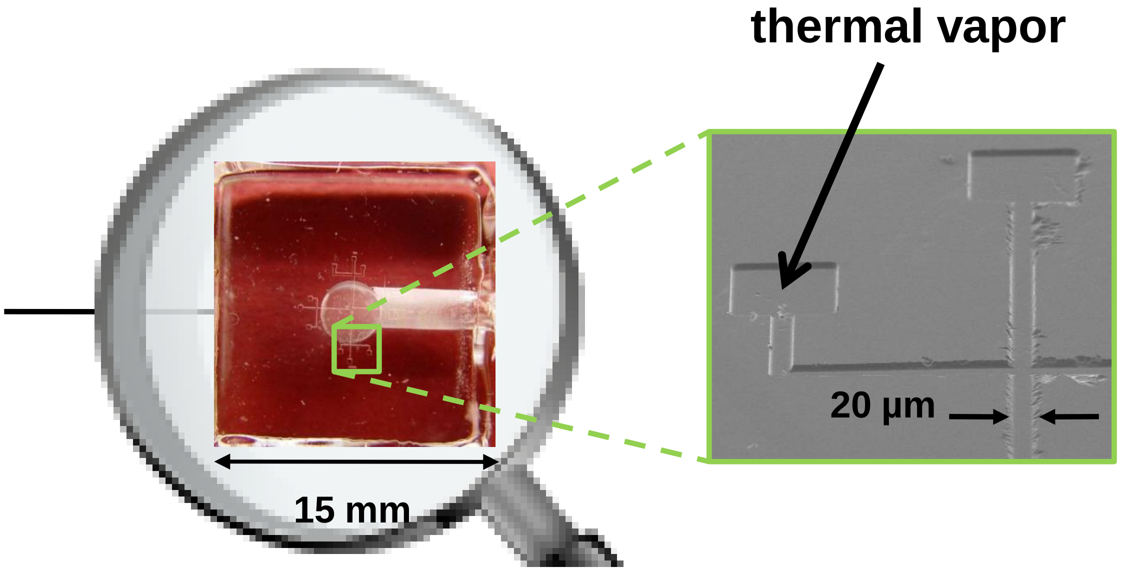
Miniaturization



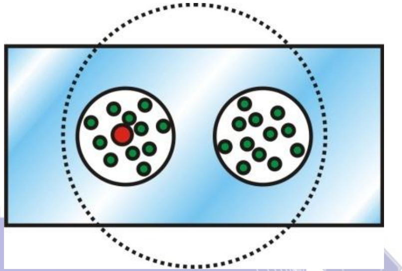


Miniaturization

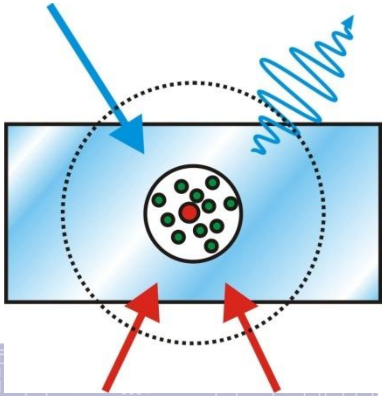




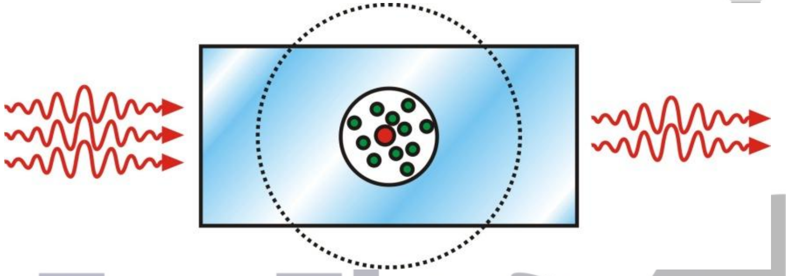
Entangle cells



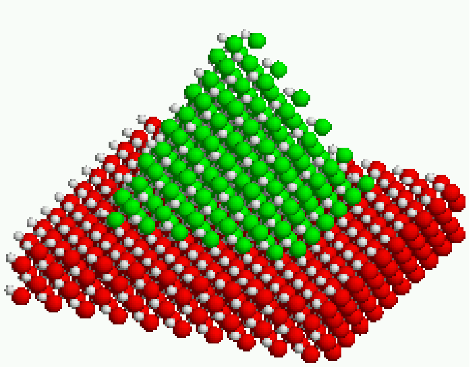
Create a photon



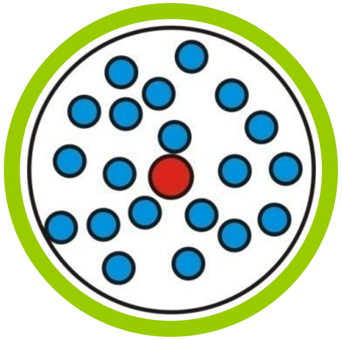
Destroy a photon



Perspectives for QIP with hot Rydberg atoms



Artificial Atoms



Artificial Quantum Dots

Quantum dot	**Micro cell (size < a_{block})**
Single exciton	**Single Rydberg excitation**
Size ~10-20 nm	**Size > λ_{opt}**
Low temperature	**Room temperature**
Hard to control nuclear spins	**Pure nuclear spin states**
Shorter spin coherence times	**Long spin coherence times**
Epitaxial growth	**Photolithography**
Positioning is tricky	**Easy positioning**

What do we need?

- **Micro cells** ✓

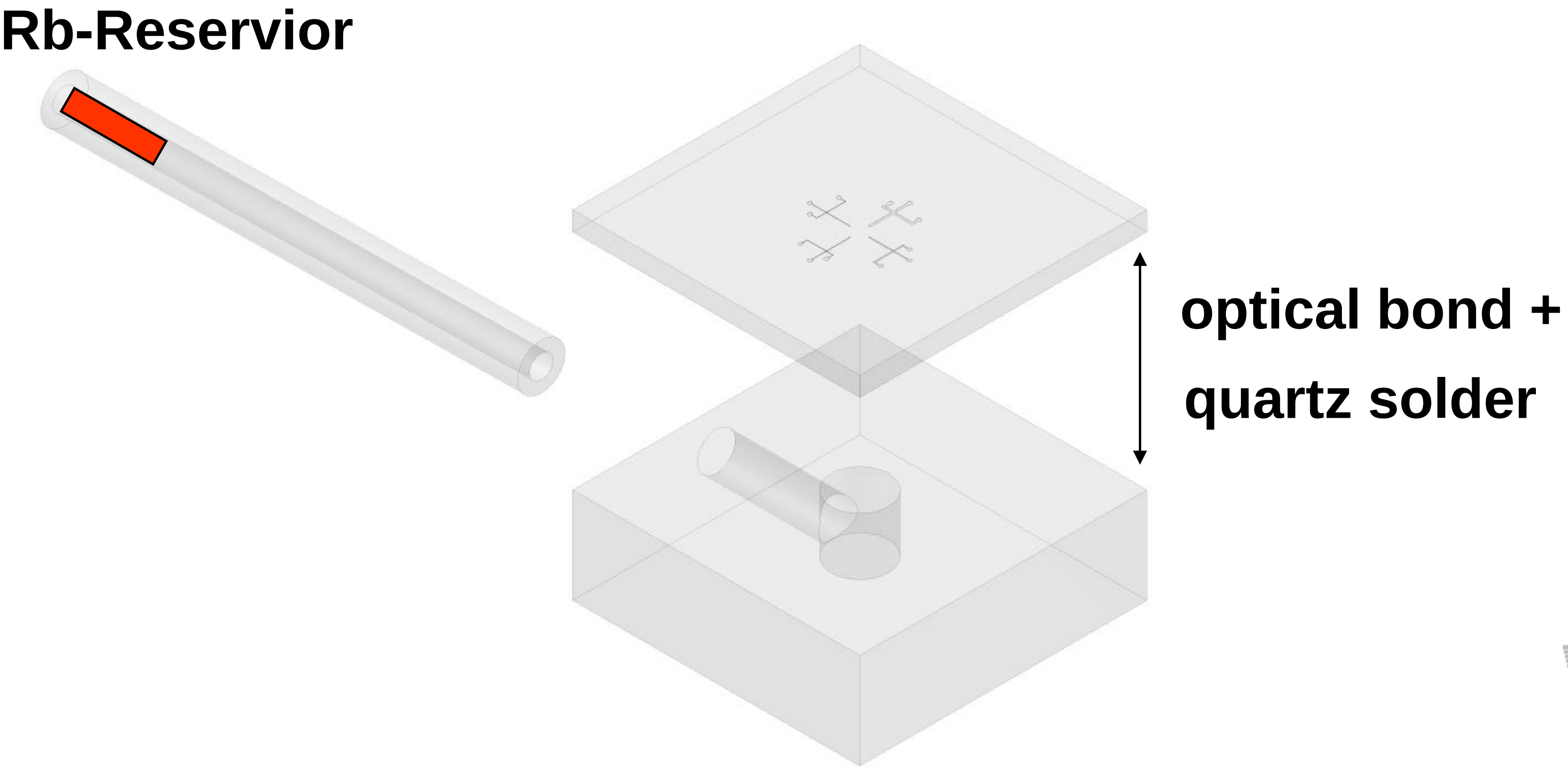
  Fabrication method for microscopic vapor cells for alkali atoms
  T. Baluktsian, et al., Opt. Lett. 35, 1950 (2010)
  - **confinement of the atoms < a_{block}**
- **Narrow lines** ✓

  Coherent excitation of Rydberg atoms in micrometre-sized atomic vapor cells
  H. Kübler, et al., Nature Photonics 4, 112 (2010)
  - **width << hyperfine splitting**
- **Coherent dynamics** ✓

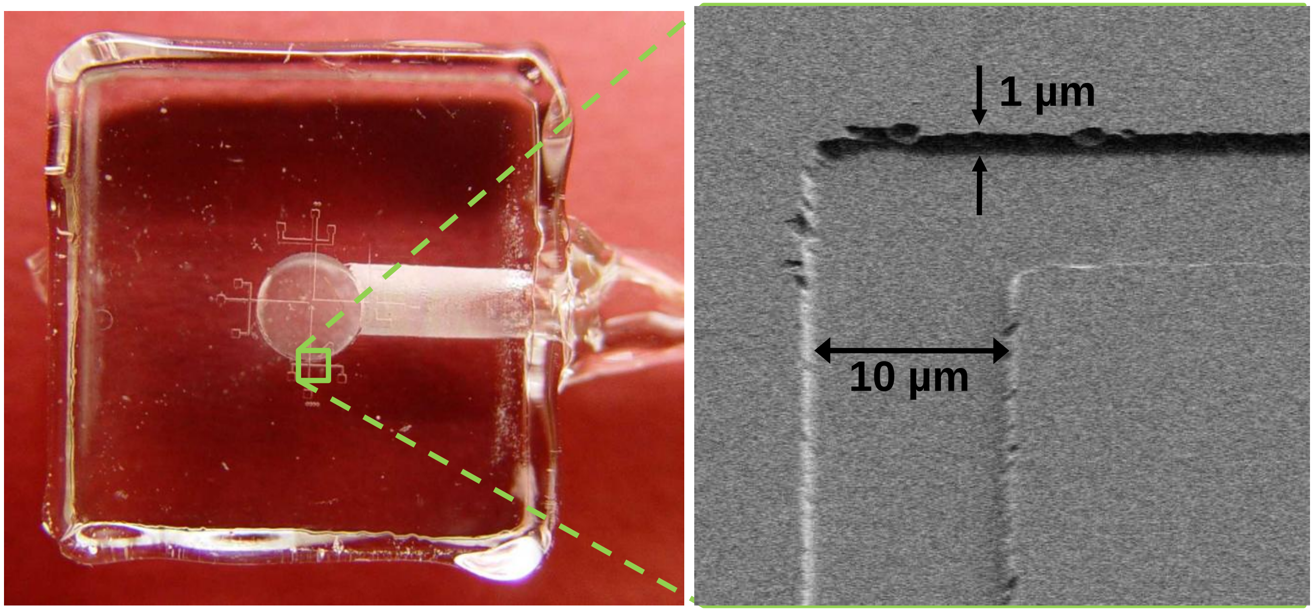
  GHz Rabi flopping to Rydberg states in hot atomic vapor cells
  B. Huber, et. al., PRL 107, 243001 (2011)
  - **thermal vapor → excitation on the ns timescale**
- **Interaction** ✓

  Evidence for strong van der Waals-type Rydberg-Rydberg interaction in thermal vapor, submitted
  - **Rydberg blockade**

Cover method



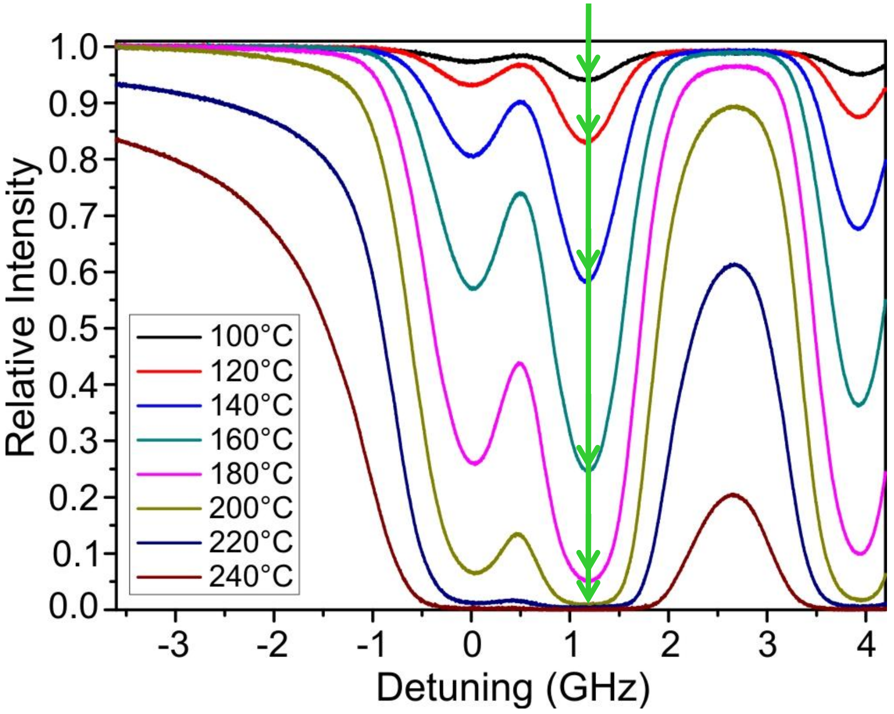
Micro - cells



T. Baluktsian, C. Urban, T. Bublat, H. Giessen, R. Löw, and T. Pfau
"Fabrication method for micro vapor cells for alkali atoms"
Opt. Lett. ***35****, 1950 (2010)*

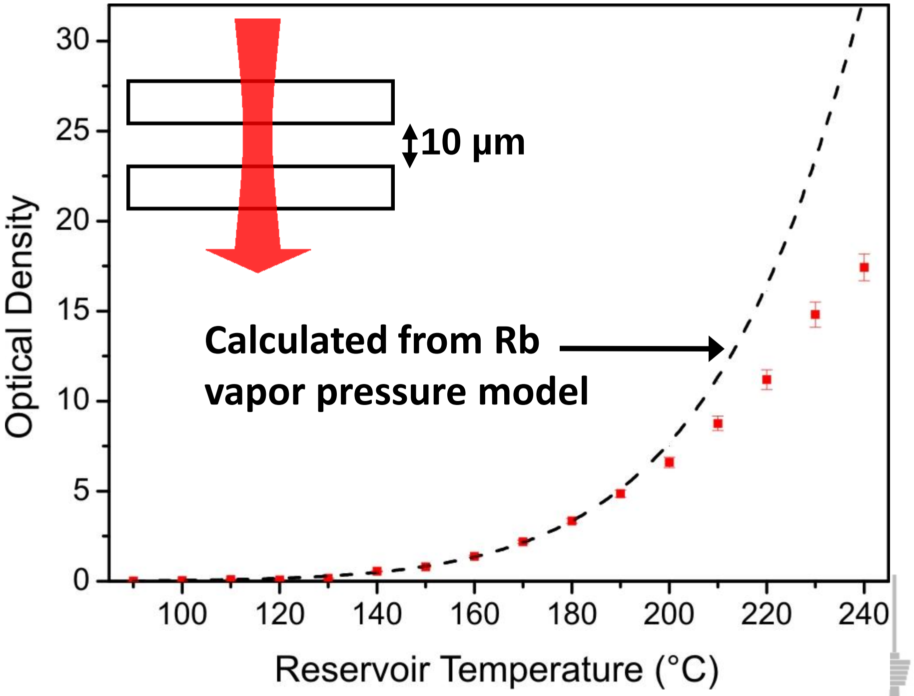
Absorption spectroscopy in a 10 µm vapor layer

Absorption spectra



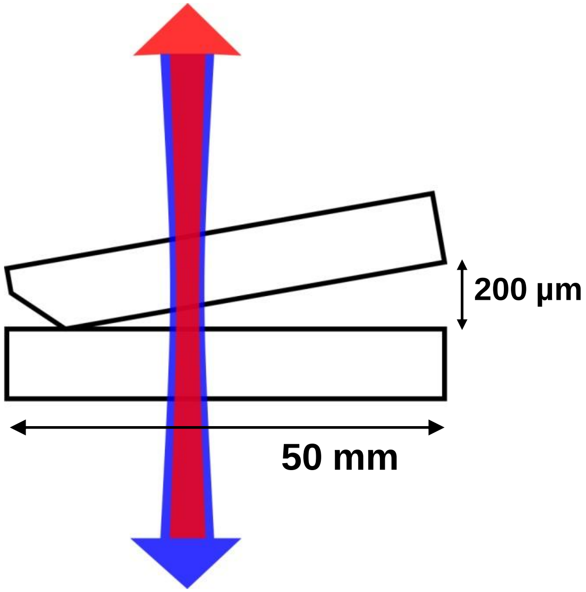
^{85}**Rb 5S$_{1/2}$ F=3 → 5P$_{3/2}$ F=4**

Optical density

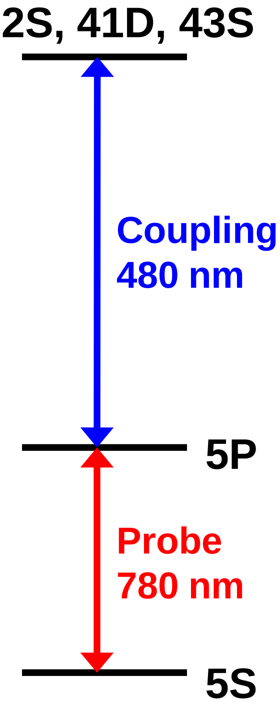


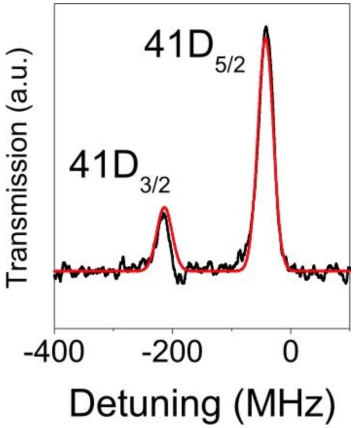
Opt. Lett. **35**, 1950 (2010)

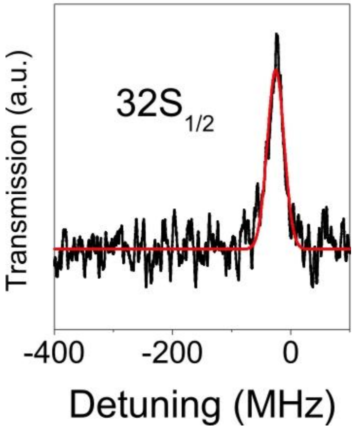
Coherent Rydberg excitation



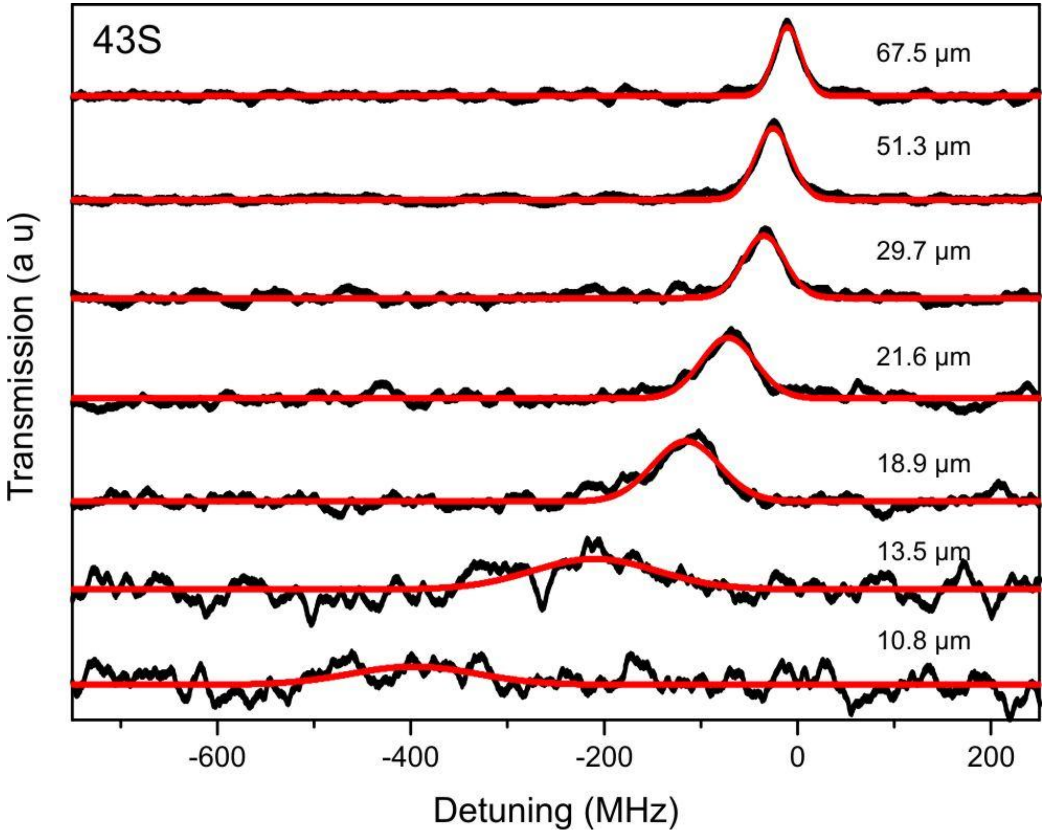
EIT Scheme



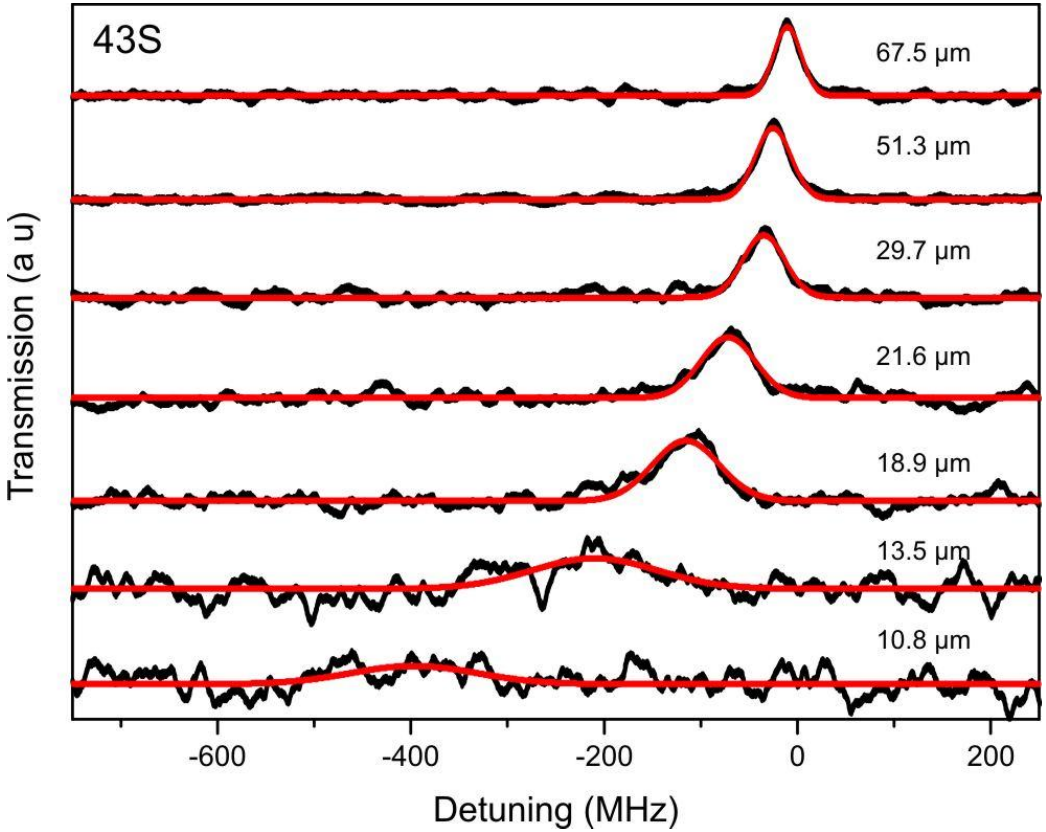


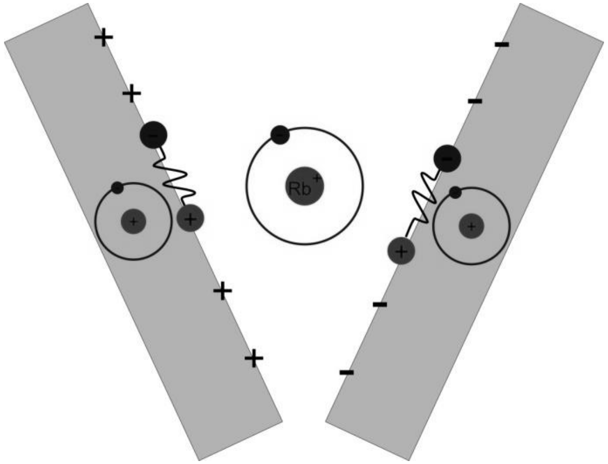


Coherent Rydberg excitation



Wall interactions !!!





- **Image charges**
- **Charges**
- **Surface polaritons**

Resonant energy transfer to Quartz walls by surface polaritons

INFRARED LATTICE BANDS OF QUARTZ 1331

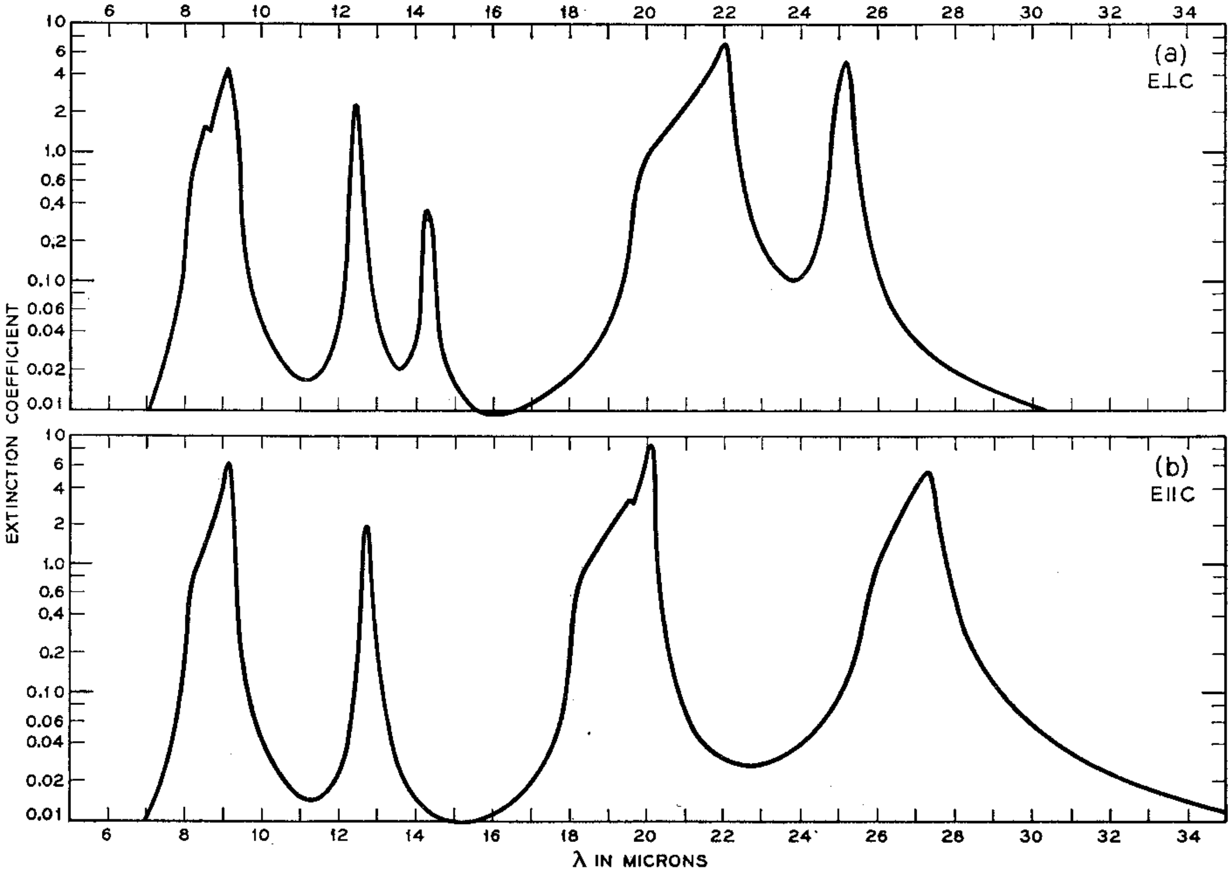
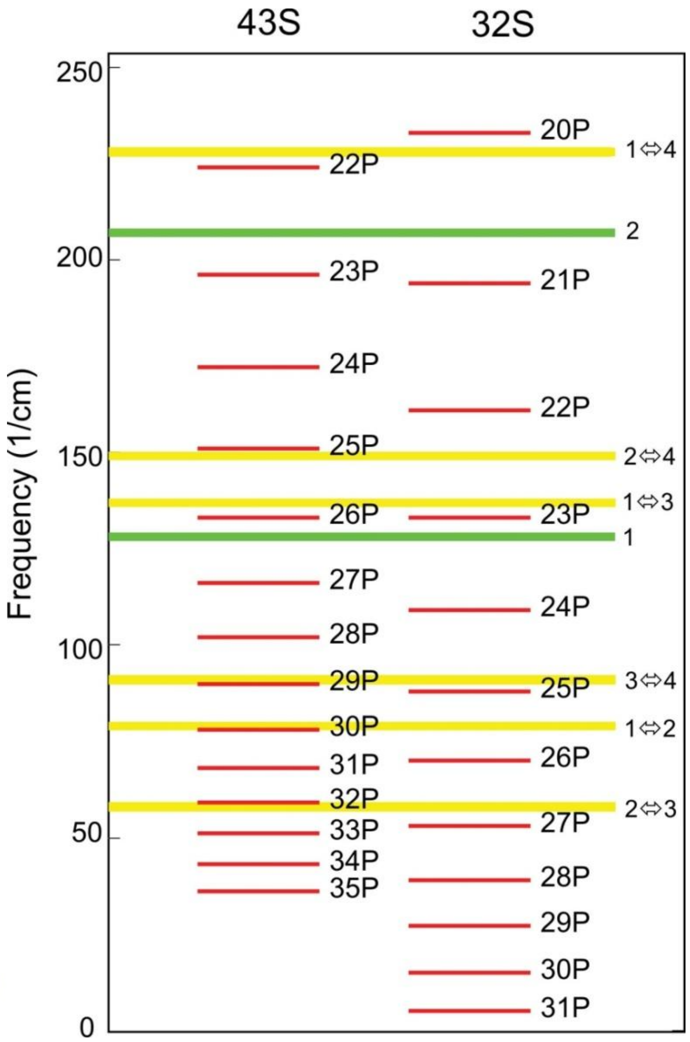
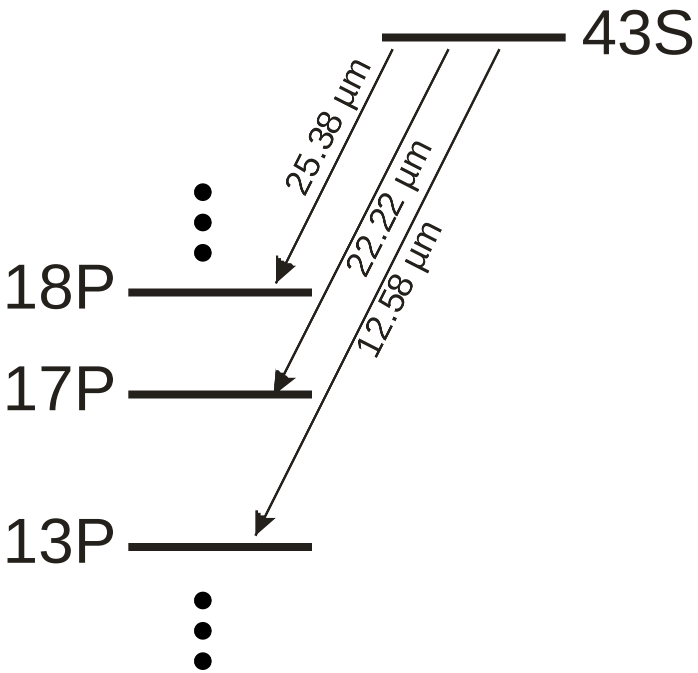


FIG. 6. The extinction coefficient of quartz for the ordinary ray (a) and the extraordinary ray (b) as obtained from the dispersion analysis of the reflectivity.

Spitzer and Kleinman, *Infrared Lattice Bands in Quartz*, Phys. Rev., **121** 1324 (1961)

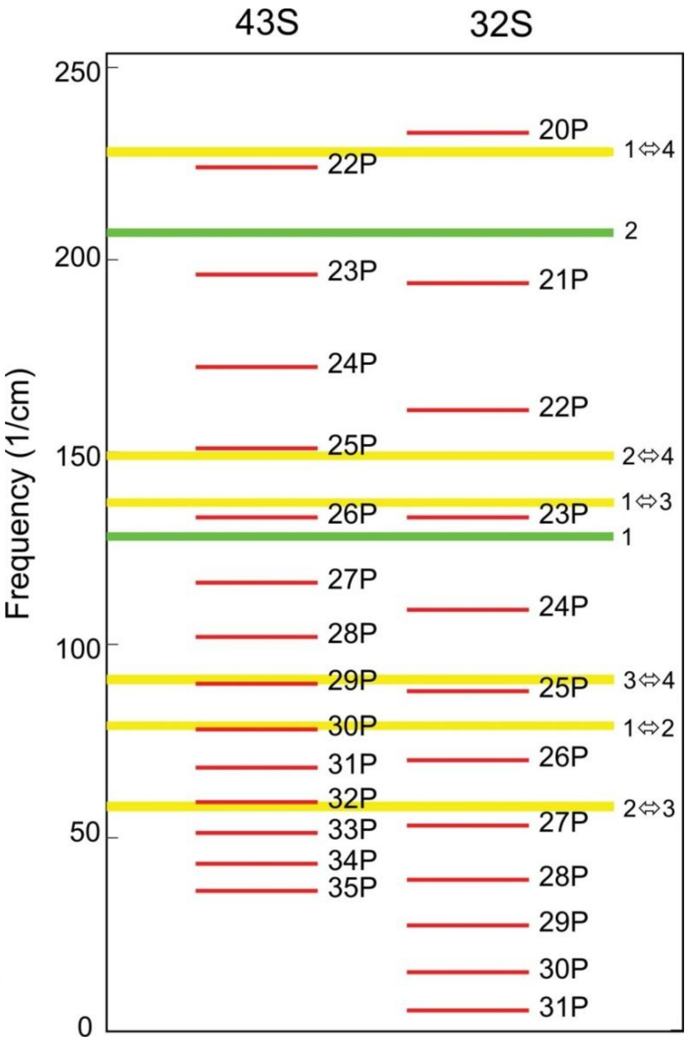
Resonant coupling to infrared surface polaritons

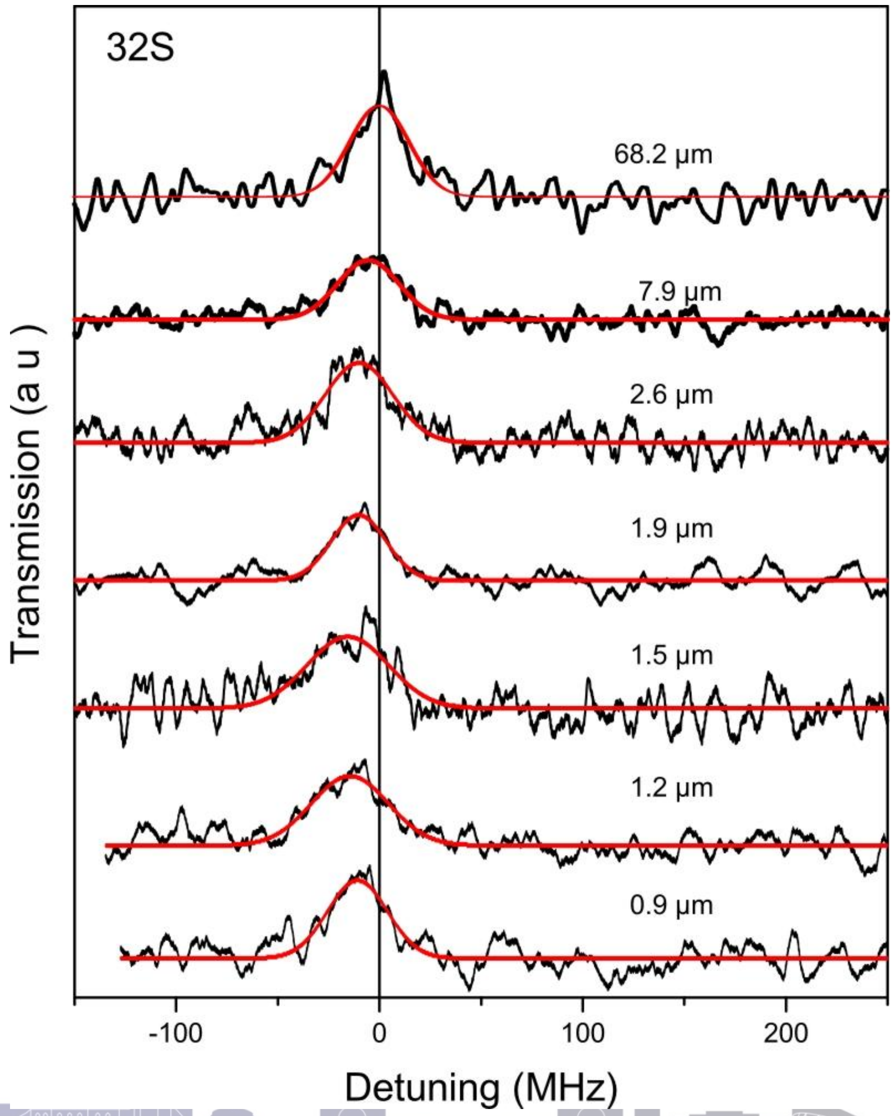




Infrared Lattice Bands in Quartz
Spitzer and Kleinman
Phys. Rev. 121, 1324 (1961)

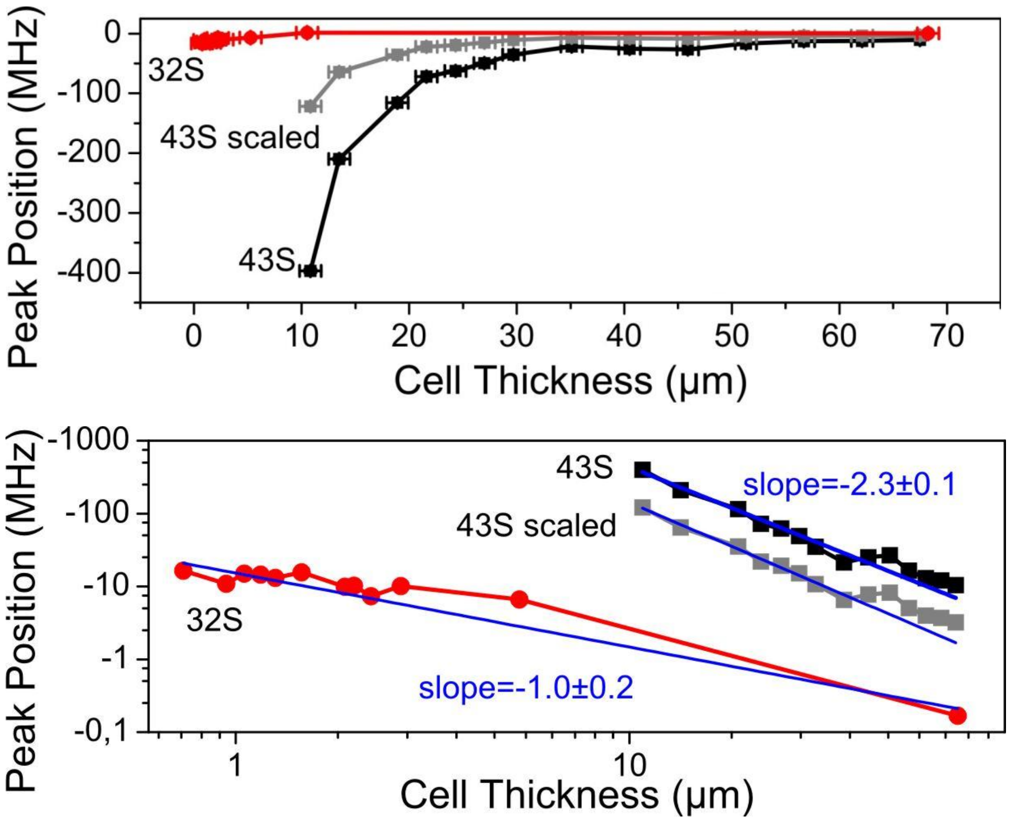
Avoid resonant coupling to infrared surface polaritons





Nature Photonics **4**, 112 (2010)

Rydberg EIT in 1 µm vapor layer



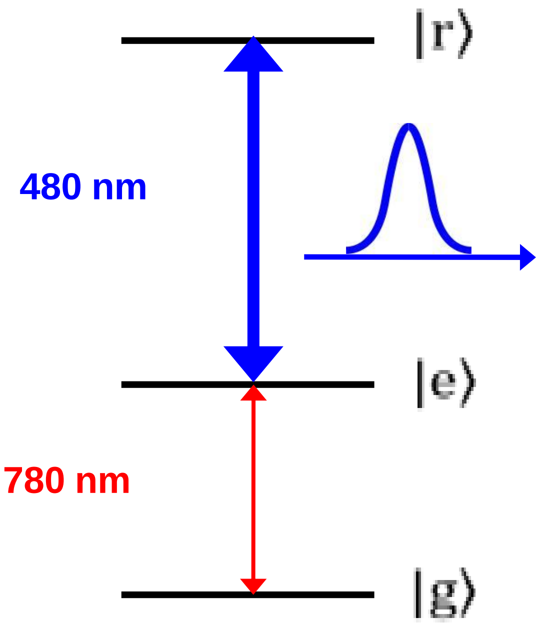
Nature Photonics **4**, 112 (2010)

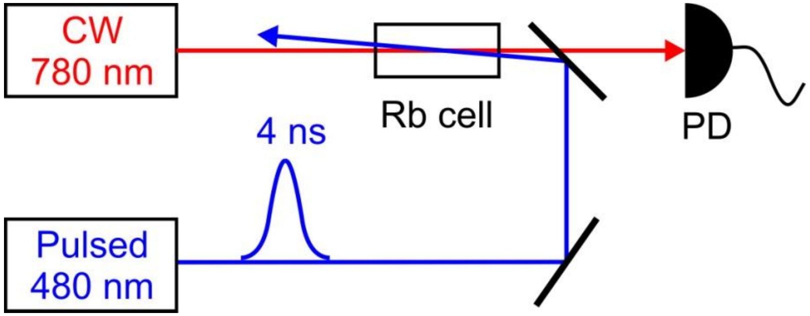
Freezing hot atoms

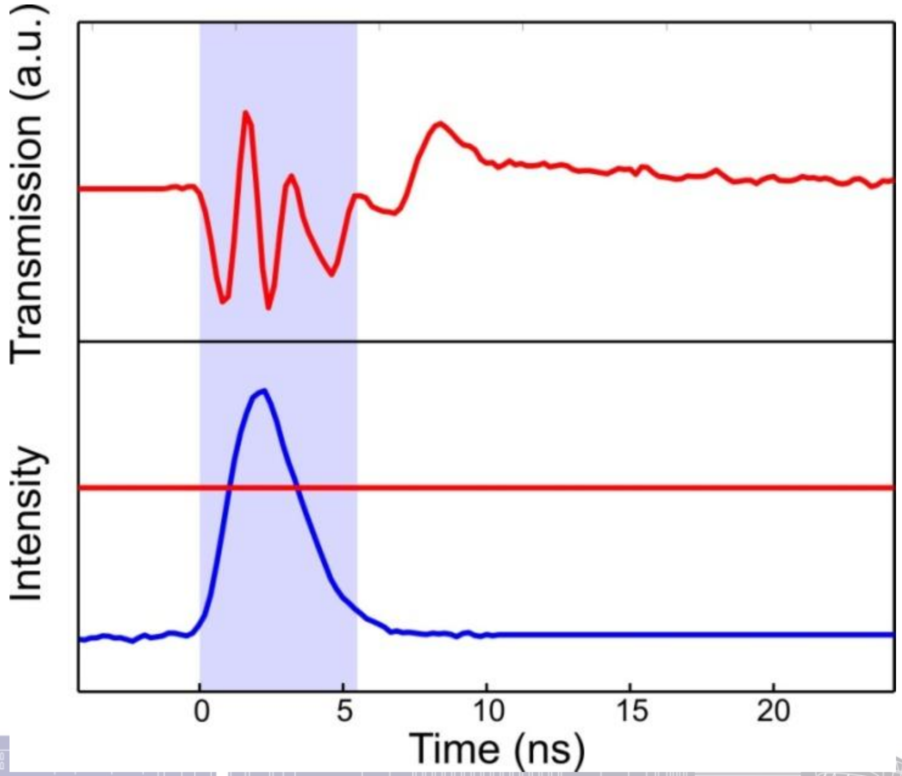
cold: $1\,\frac{\mathrm{cm}}{\mathrm{s}} \cdot 10\ \mu\mathrm{s} = 100\ \mathrm{nm}$

hot: $100\,\frac{\mathrm{m}}{\mathrm{s}} \cdot 1\ \mathrm{ns} = 100\ \mathrm{nm}$

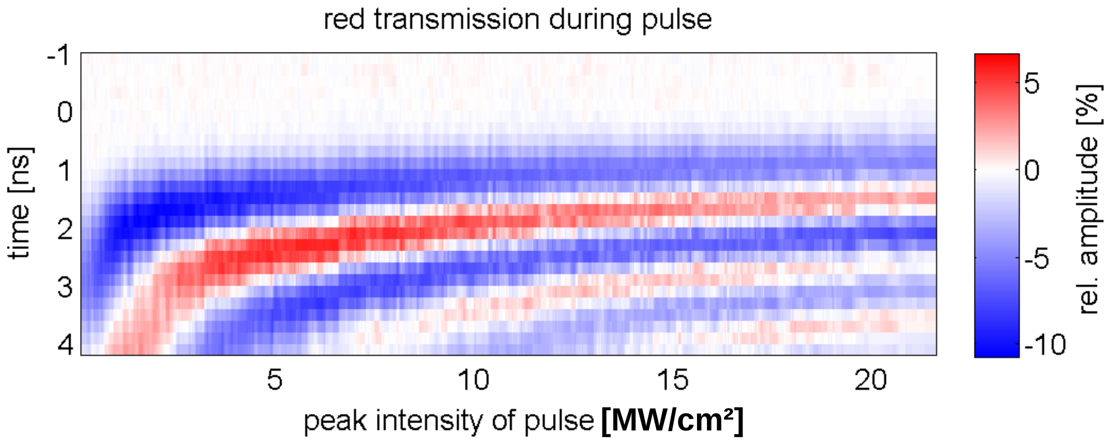
Pulsed excitation of Rydberg states





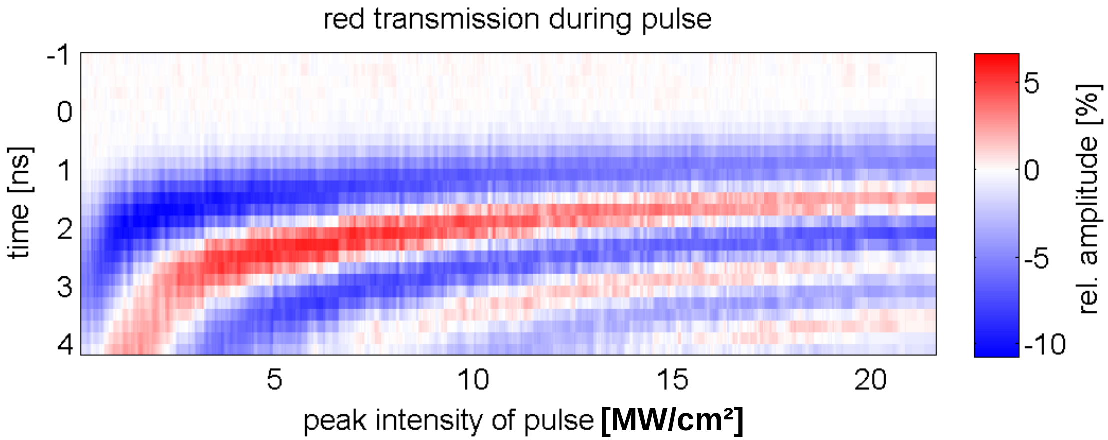


Power dependence of oscillations



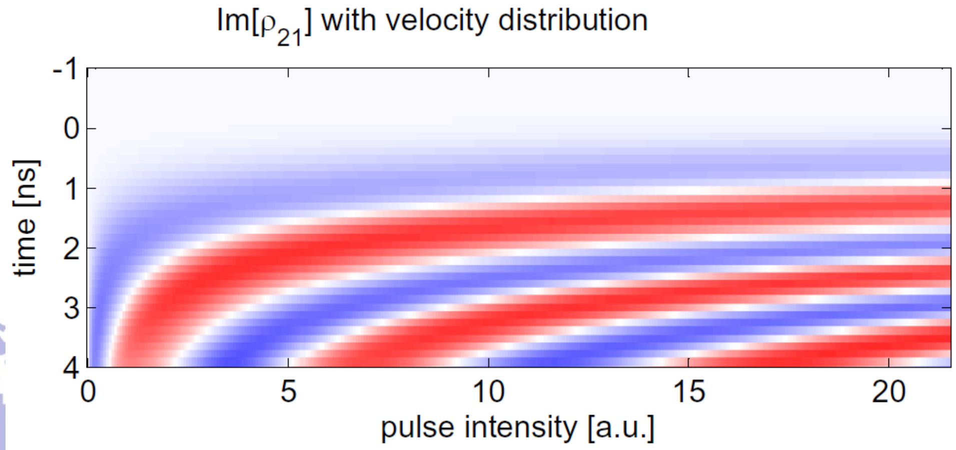
$$\Omega_{\text{eff}} \propto \sqrt{\Omega_{780}^2 + \Omega_{480}^2}$$

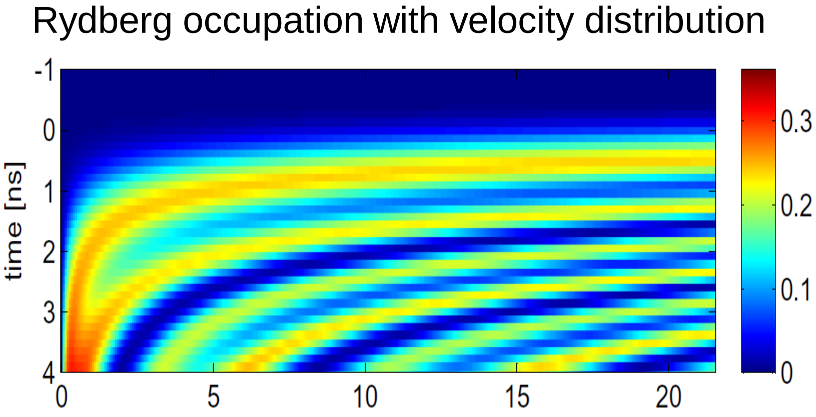
Power dependence of oscillations


red transmission during pulse

$$\Omega_{\text{eff}} \propto \sqrt{\Omega_{780}^2 + \Omega_{480}^2}$$

Simulations


$\text{Im}[\rho_{21}]$ with velocity distribution


Rydberg occupation with velocity distribution

- 12 π-pulse in 4 ns
- only limited by pulse length!

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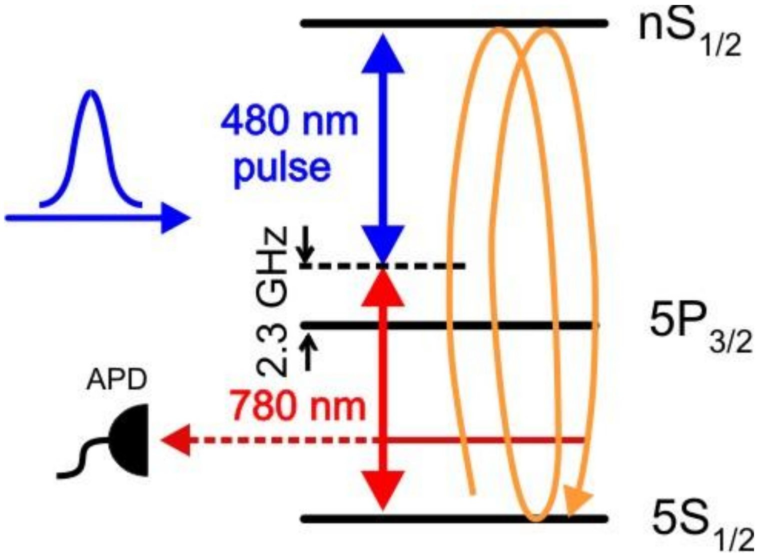
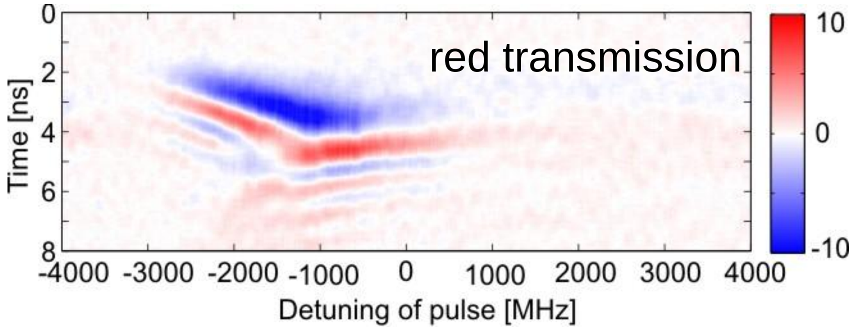
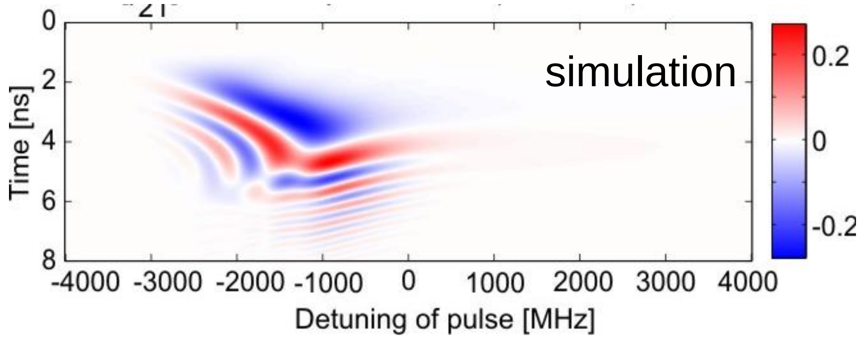
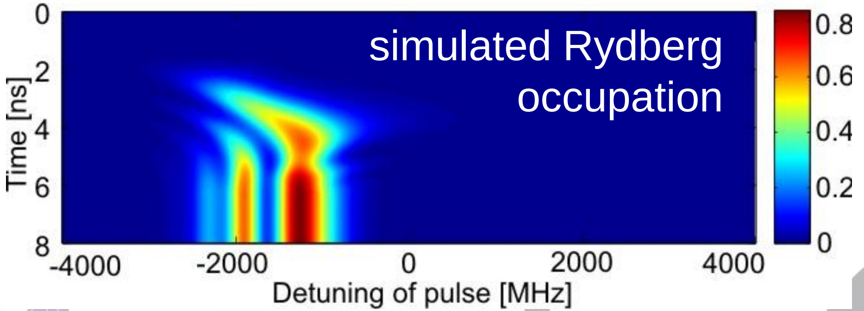
Ground - Rydberg Rabi oscillations

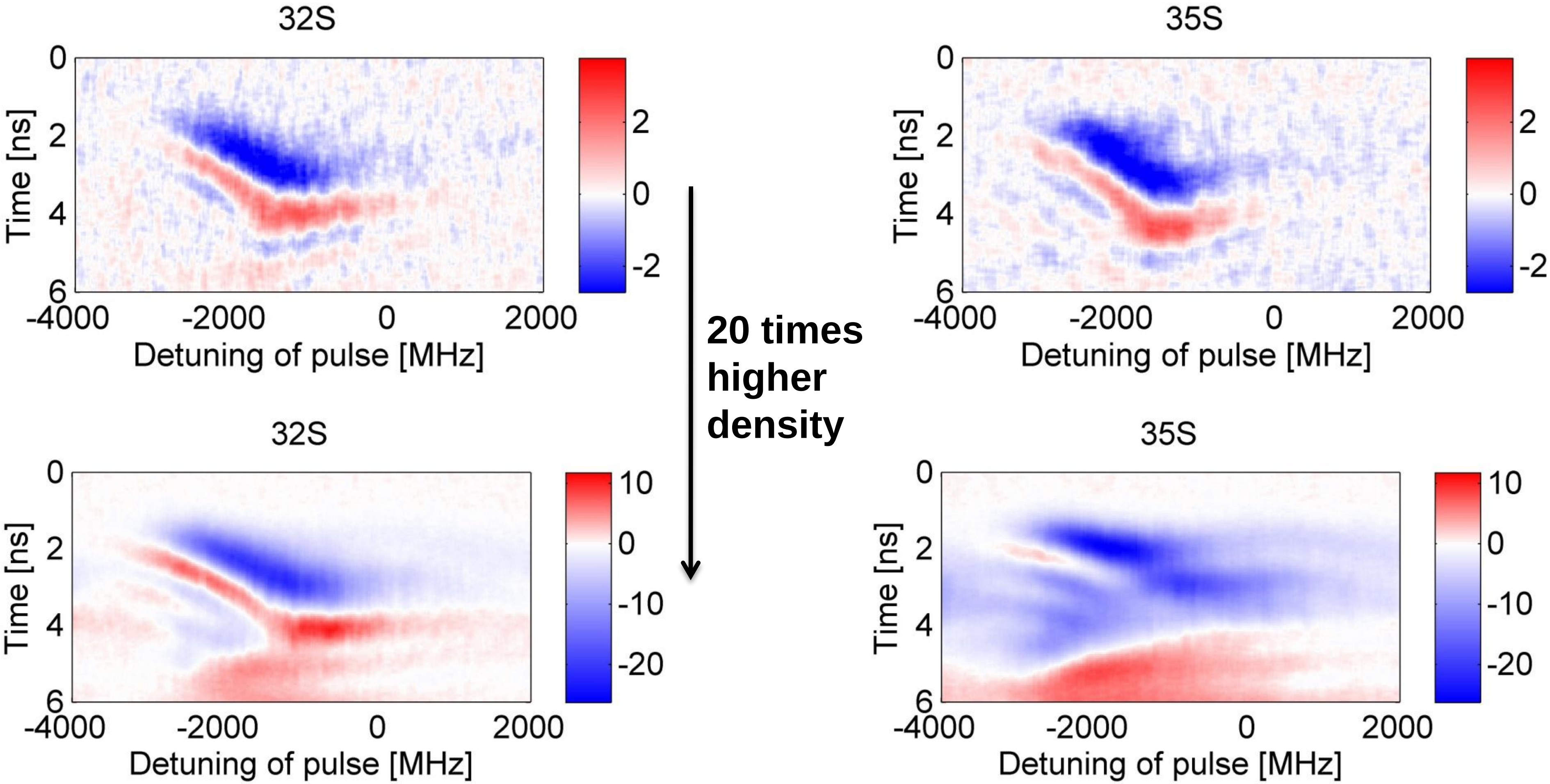








Dephasing due to interactions



20 times higher density

Dephasing due to interactions

Systematic measurements

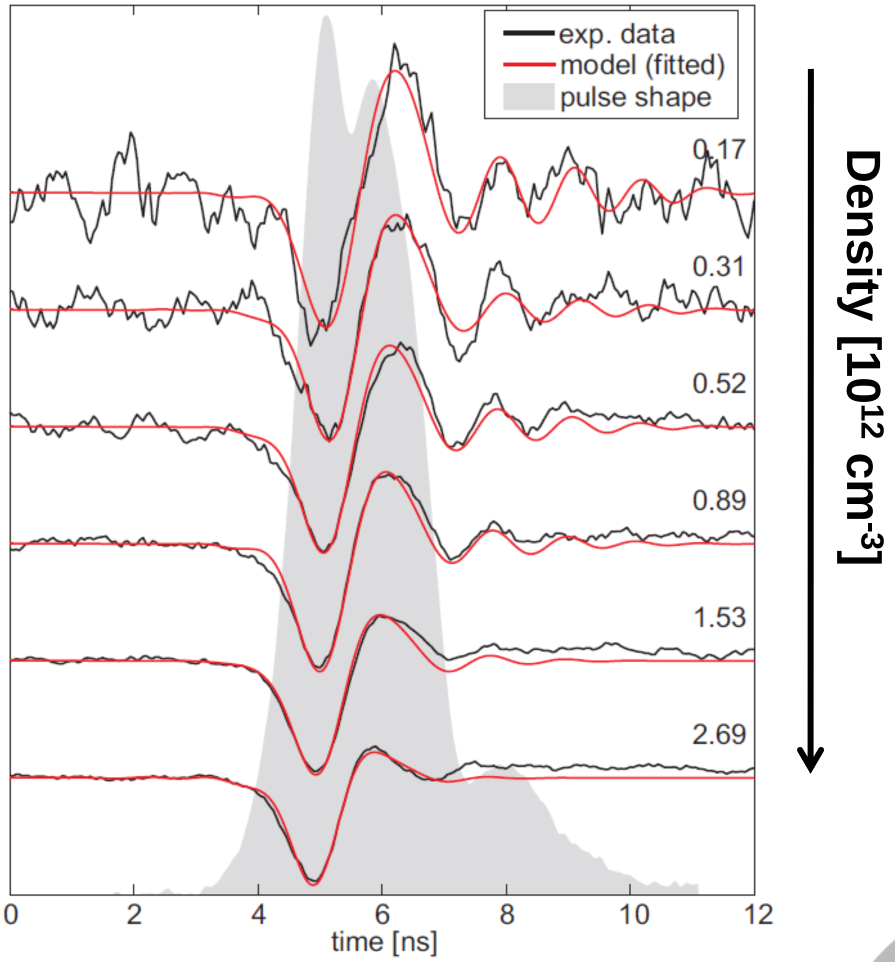
→ densities in the range of

$$N_g \sim (10^{11} - 10^{13})\,\mathrm{cm}^{-3}$$

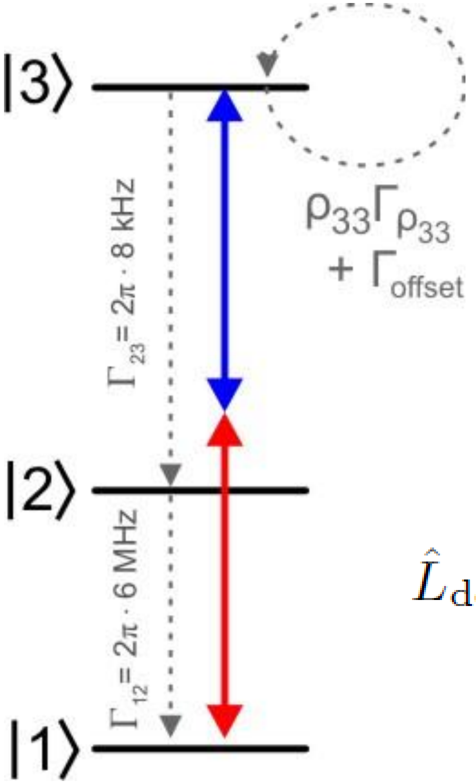
→ Rydberg states:

22S, 29S, 32S, 35S, 37S, 40S

n = 37



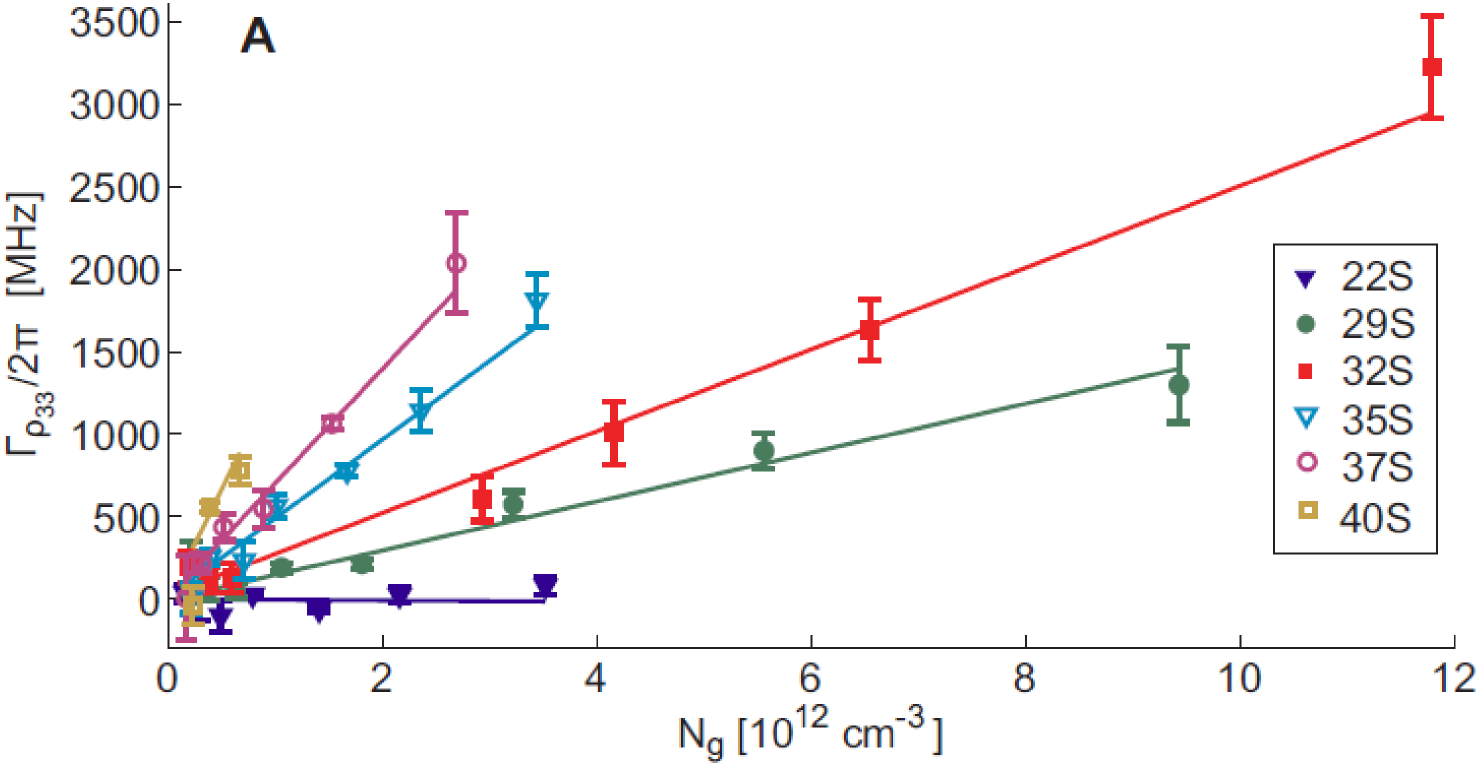
Dephasing model for data fitting



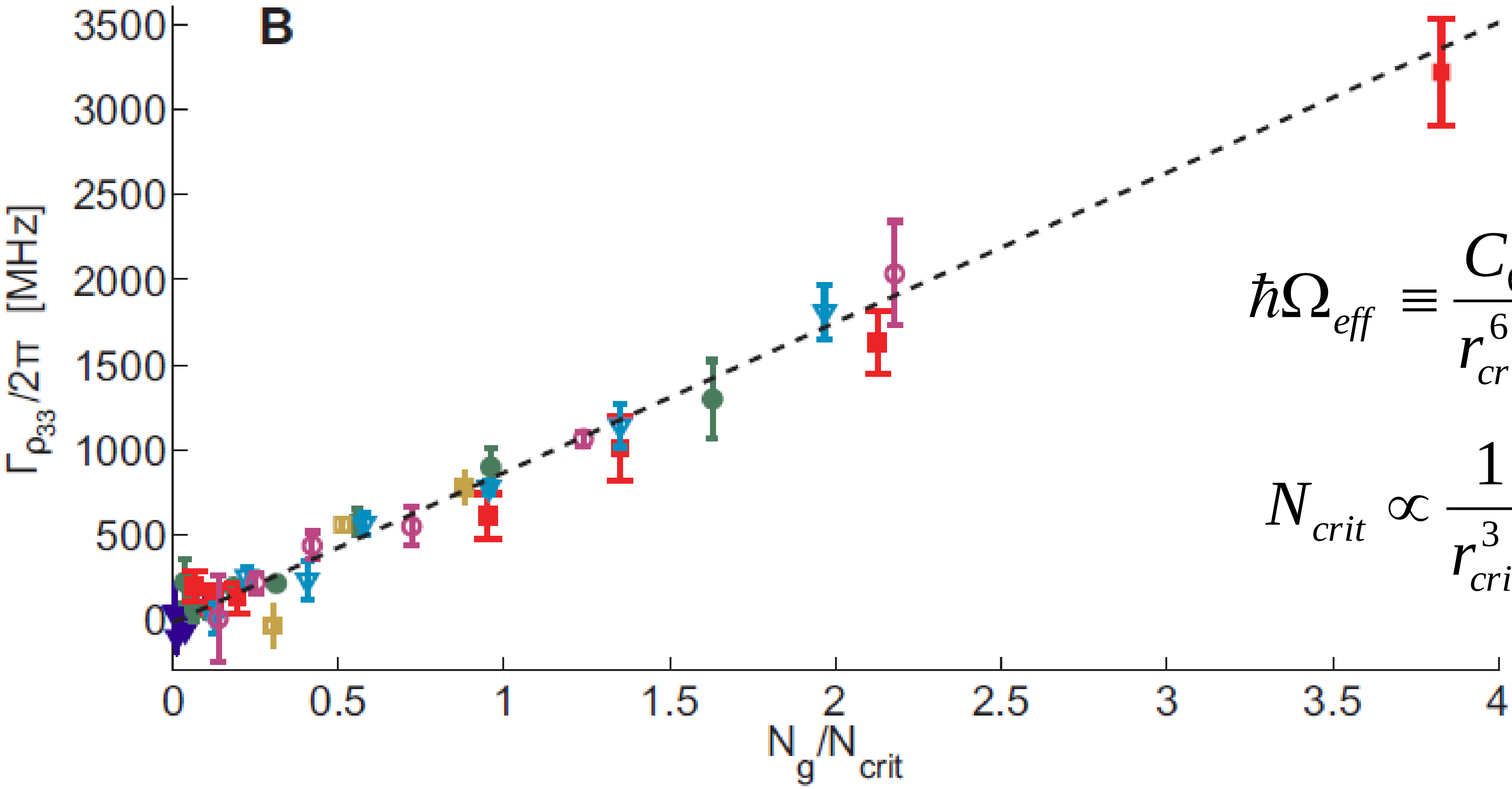
$$\frac{\partial\hat{\rho}}{\partial t} = -\frac{i}{\hbar}\left[\hat{H},\hat{\rho}\right] + \hat{L}\left(\hat{\rho}\right) + \hat{L}_{deph}\left(\hat{\rho}\right)$$

$$\hat{L}_{\mathrm{deph}}\left(\hat{\rho}\right) = \left(\Gamma_{\rho33}\,\rho33 + \Gamma_{\mathrm{offset}}\right)\begin{pmatrix} 0 & 0 & -\frac{1}{2}\rho13 \\ 0 & 0 & -\frac{1}{2}\rho23 \\ -\frac{1}{2}\rho31 & -\frac{1}{2}\rho32 & 0 \end{pmatrix}$$

Dephasing rates linear with density



Data collapse

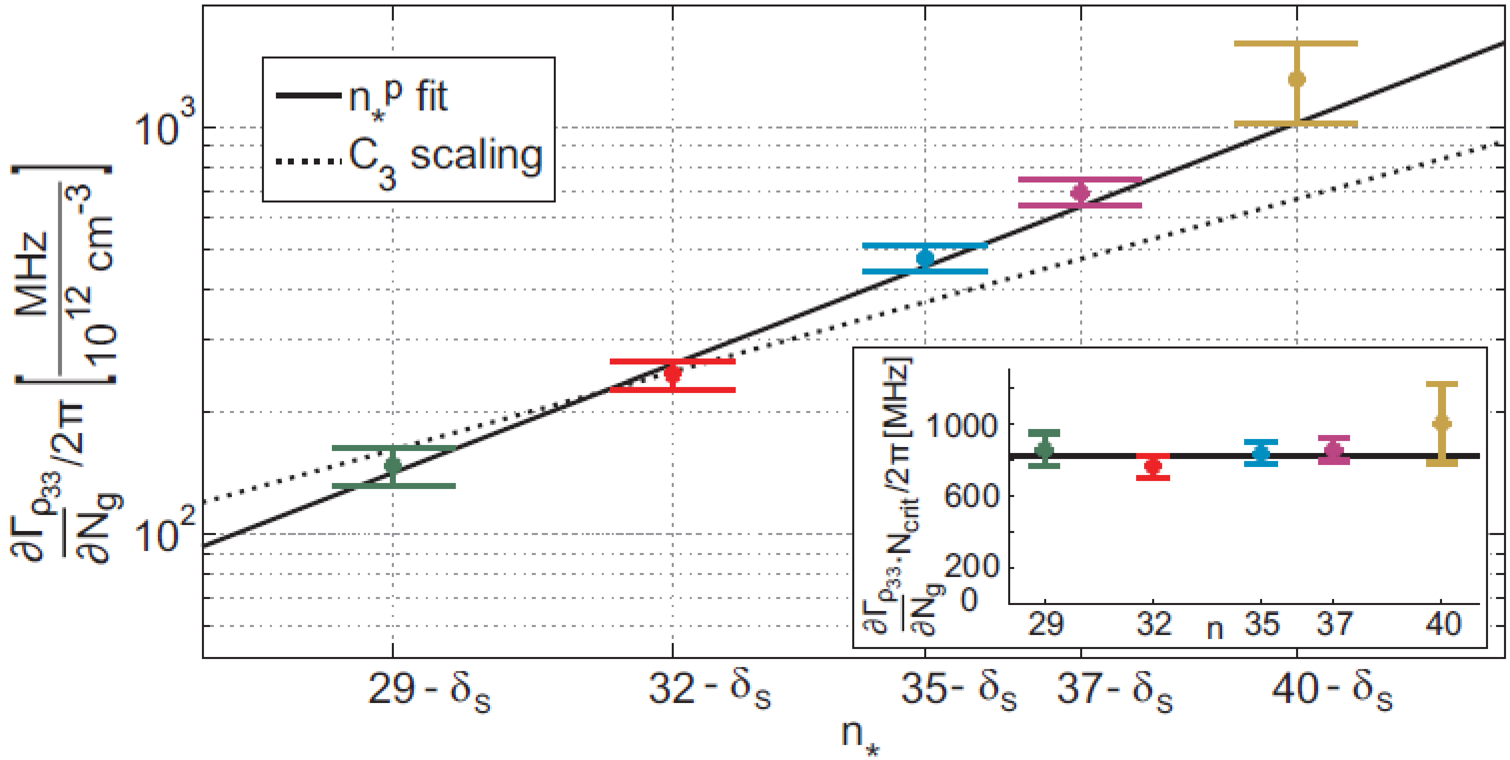


$$\hbar\Omega_{eff} \equiv \frac{C_6}{r_{crit}^6}$$

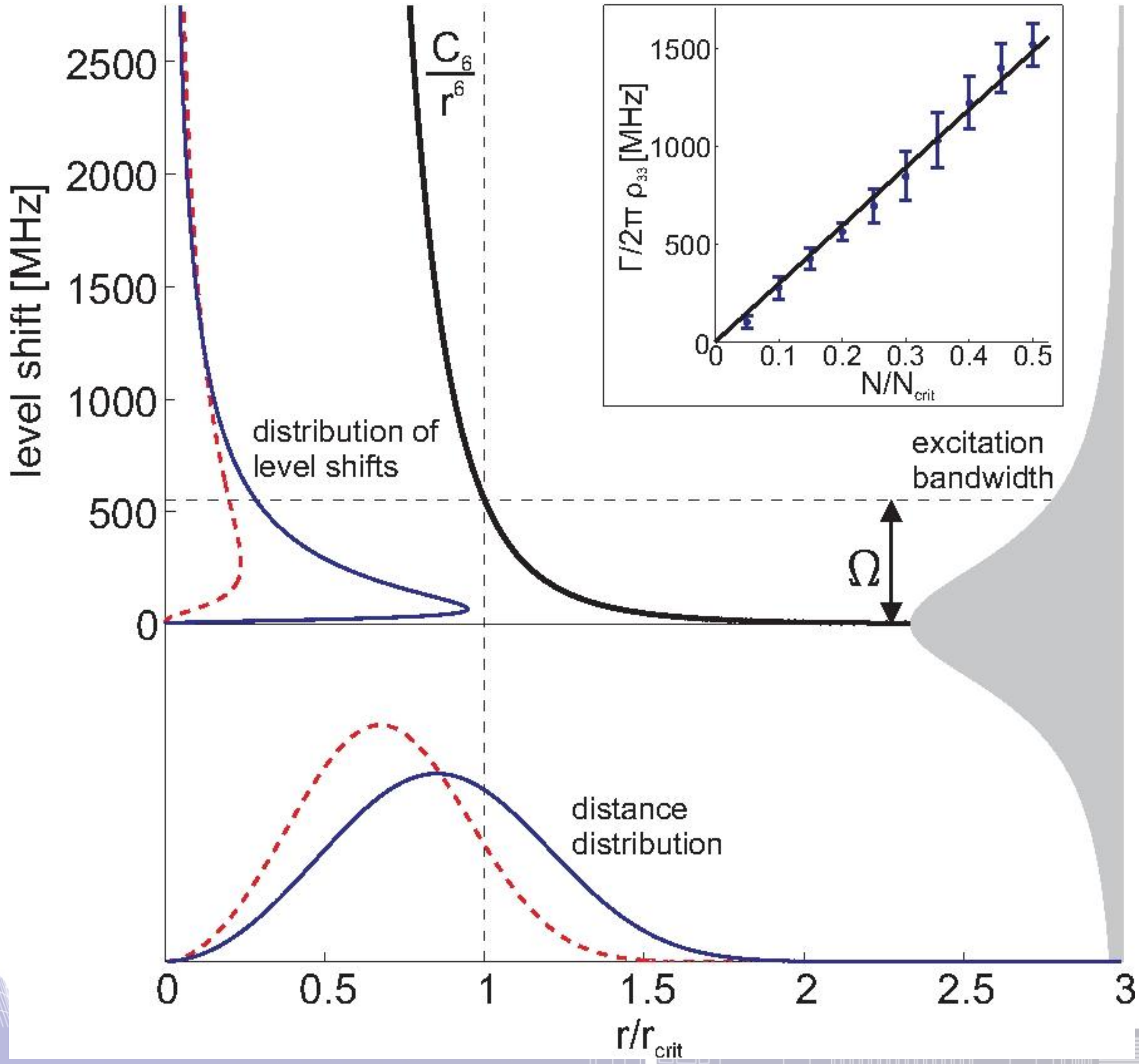
$$N_{crit} \propto \frac{1}{r_{crit}^3}$$

Dpehasing vs. principal quantum number n

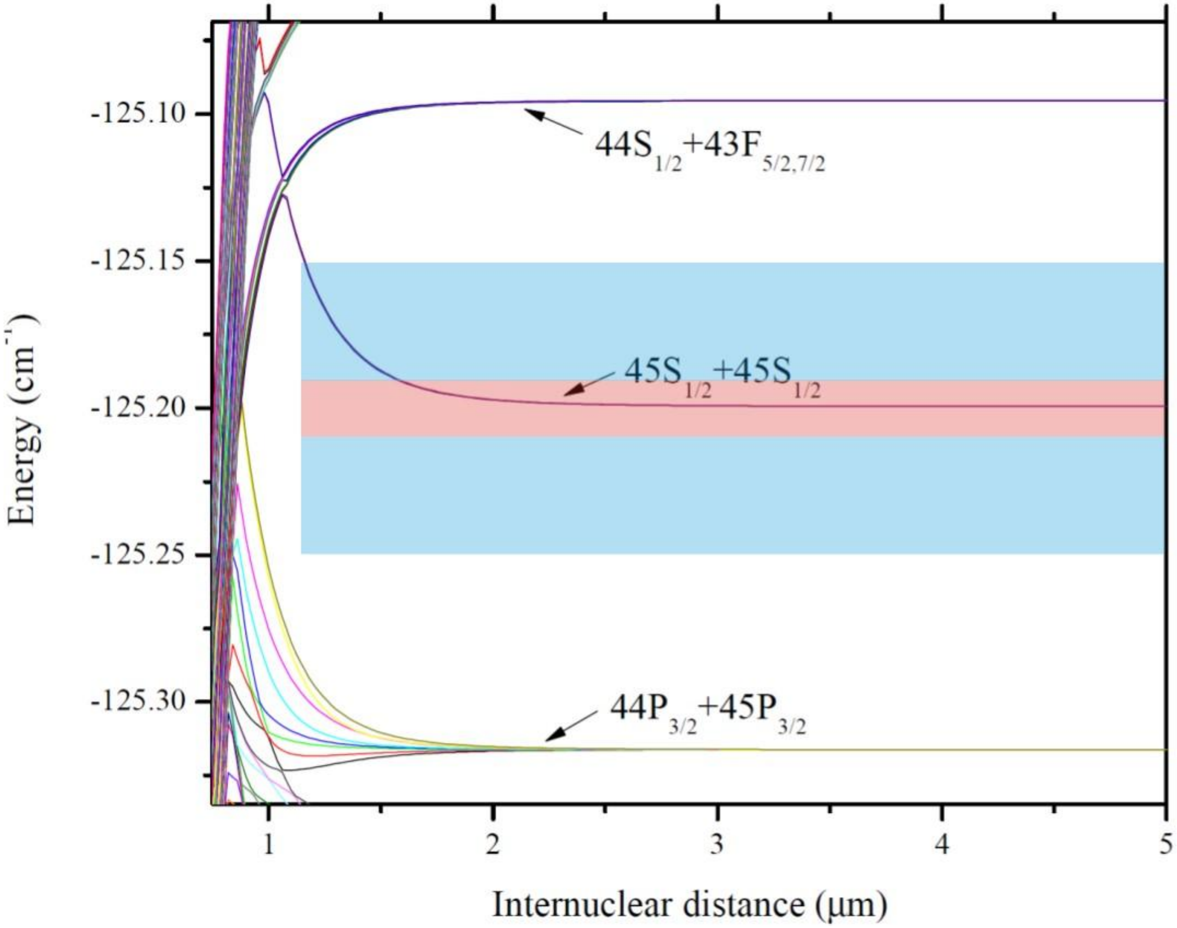
$$\frac{C_6}{r^6} \propto n^{11} \cdot {N_g}^2 \qquad N_{crit} \propto n^{-11/2} \qquad \frac{\partial \Gamma_{\rho_{33}}}{\partial N_g} \propto n^{11/2}$$



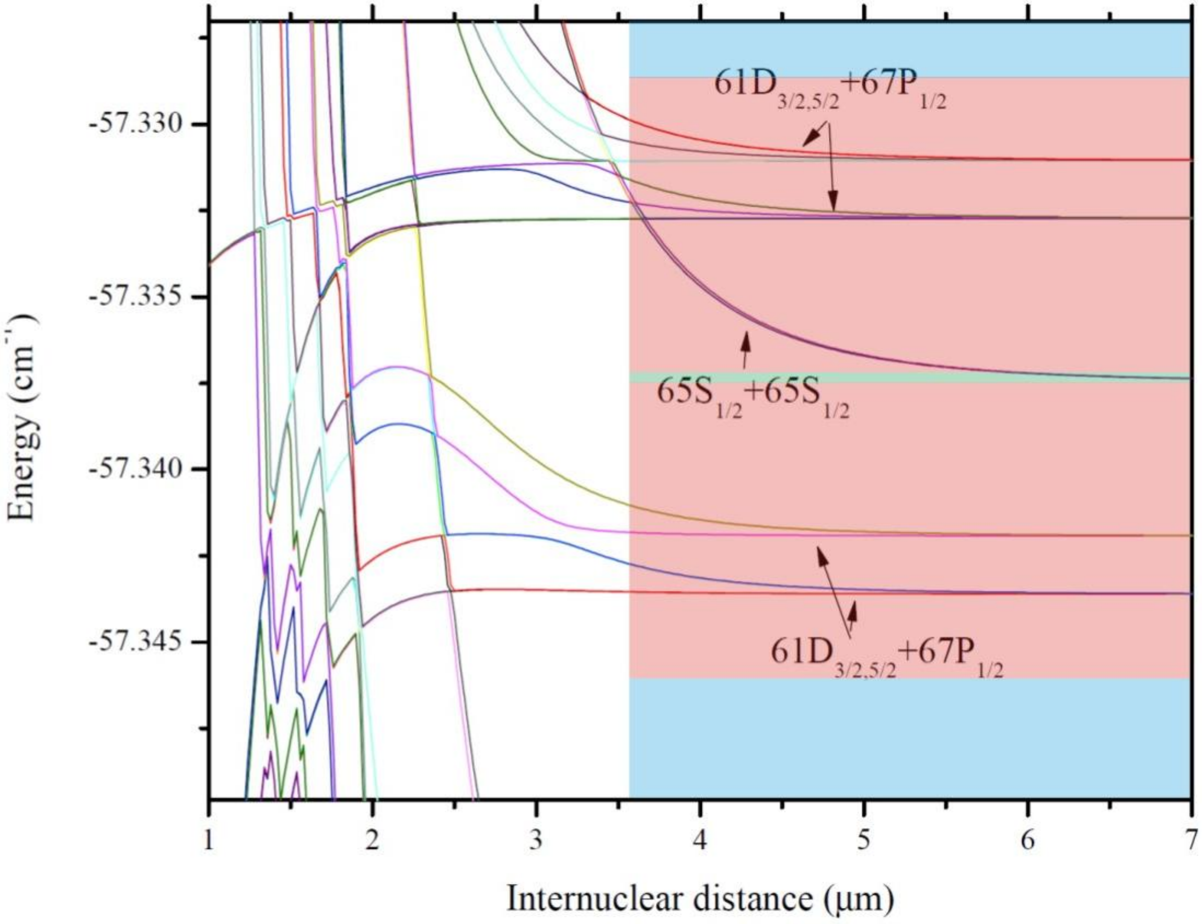
A microscopic model



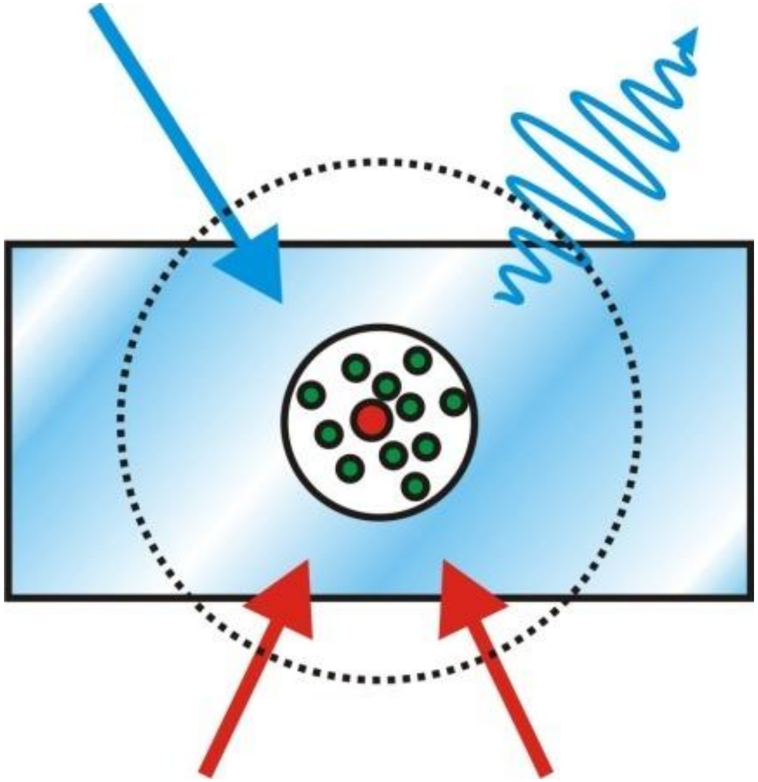
Van-der-Waals is effecitve at large bandwidth



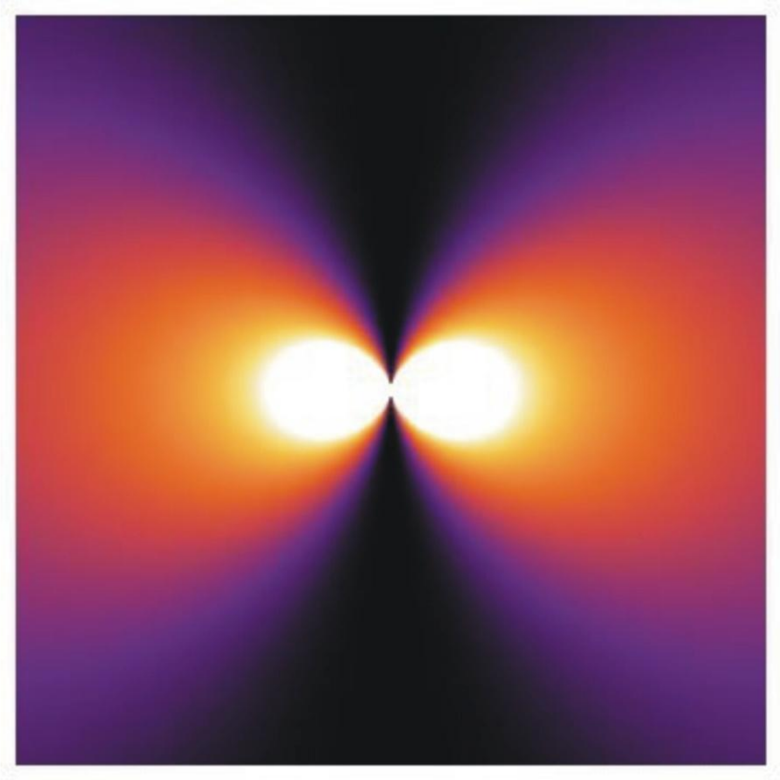
Van-der-Waals is effecitve at large bandwidth?



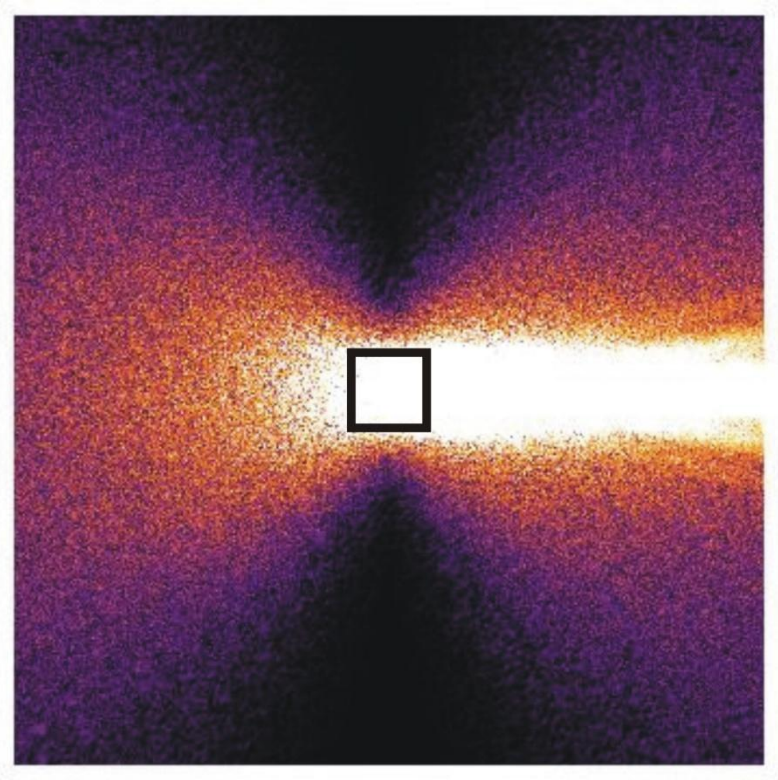
How to create a photon



Superatom - 4 wave mixing

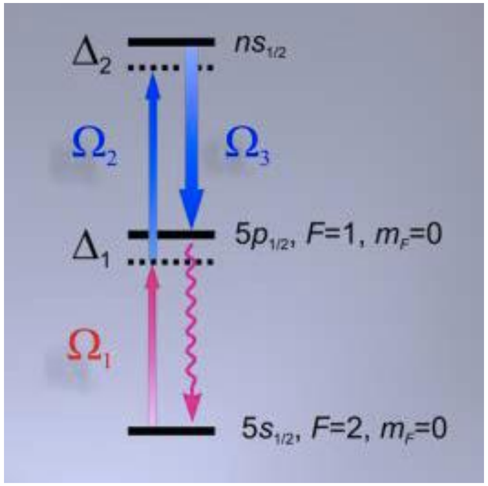


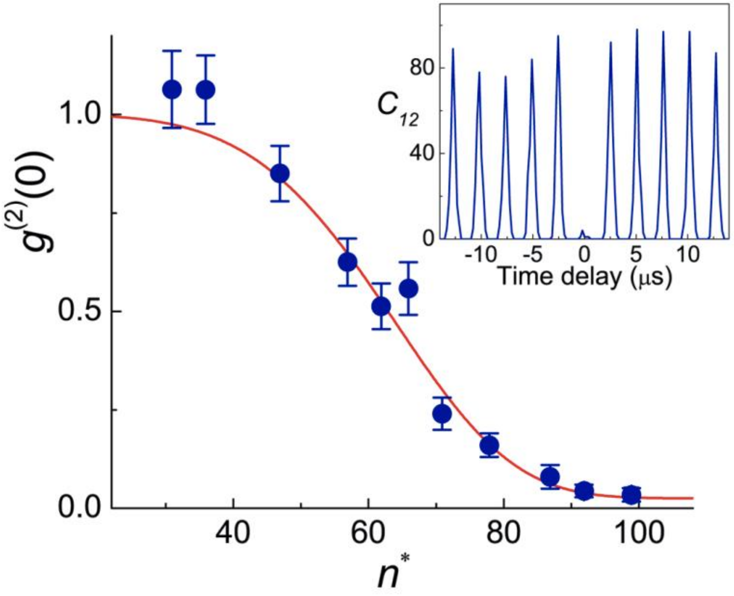
Dipole pattern of 1 atom

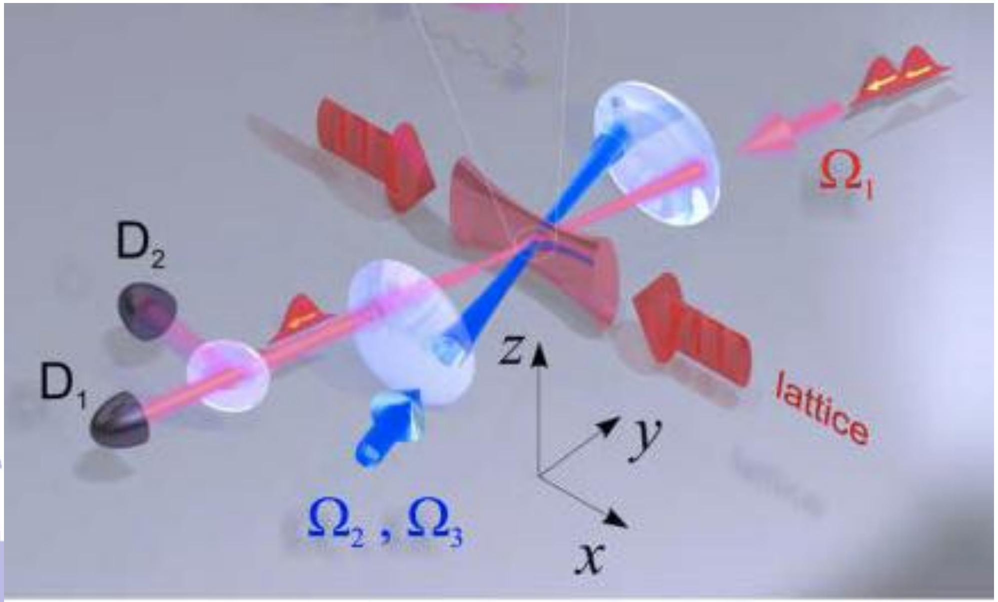


Dipole pattern of 100 phase matched atoms confined within 5 μm

Single photons with ultracold atoms

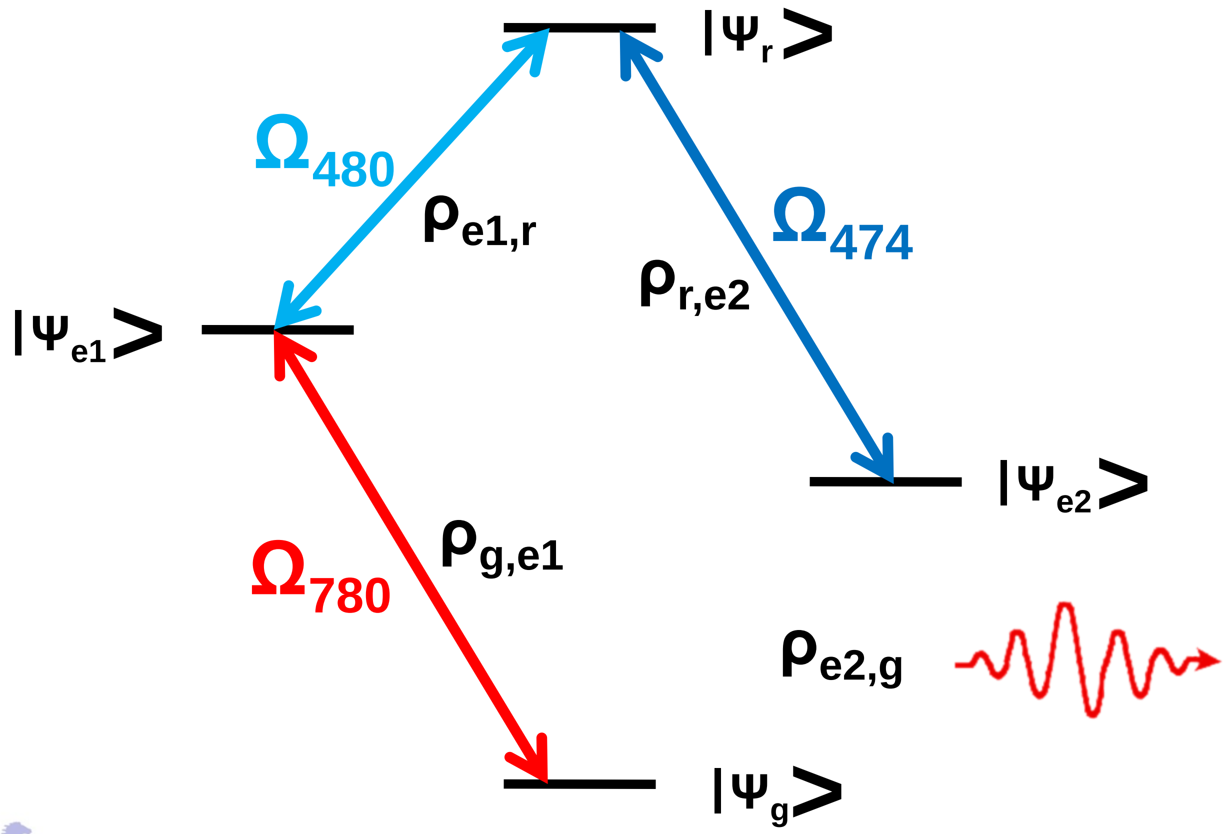


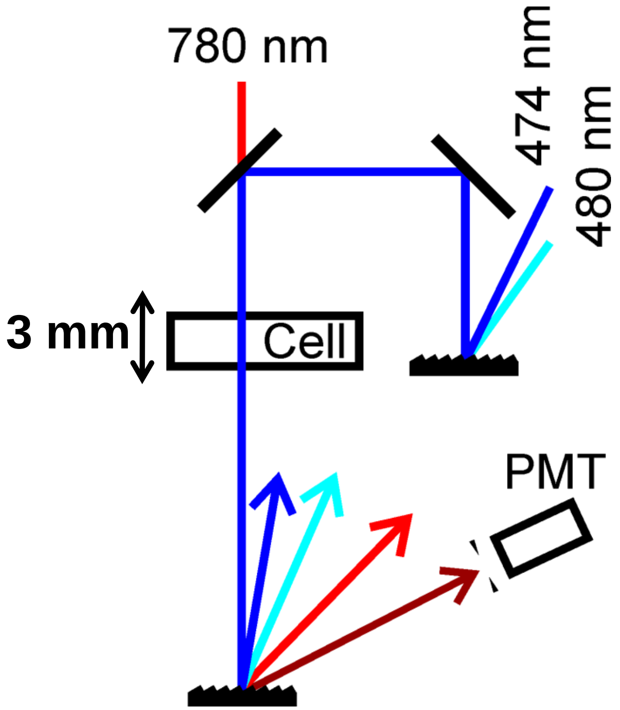




Y. O. Dudin and A. Kuzmich
Science 2012
Also Vuletic, Adams

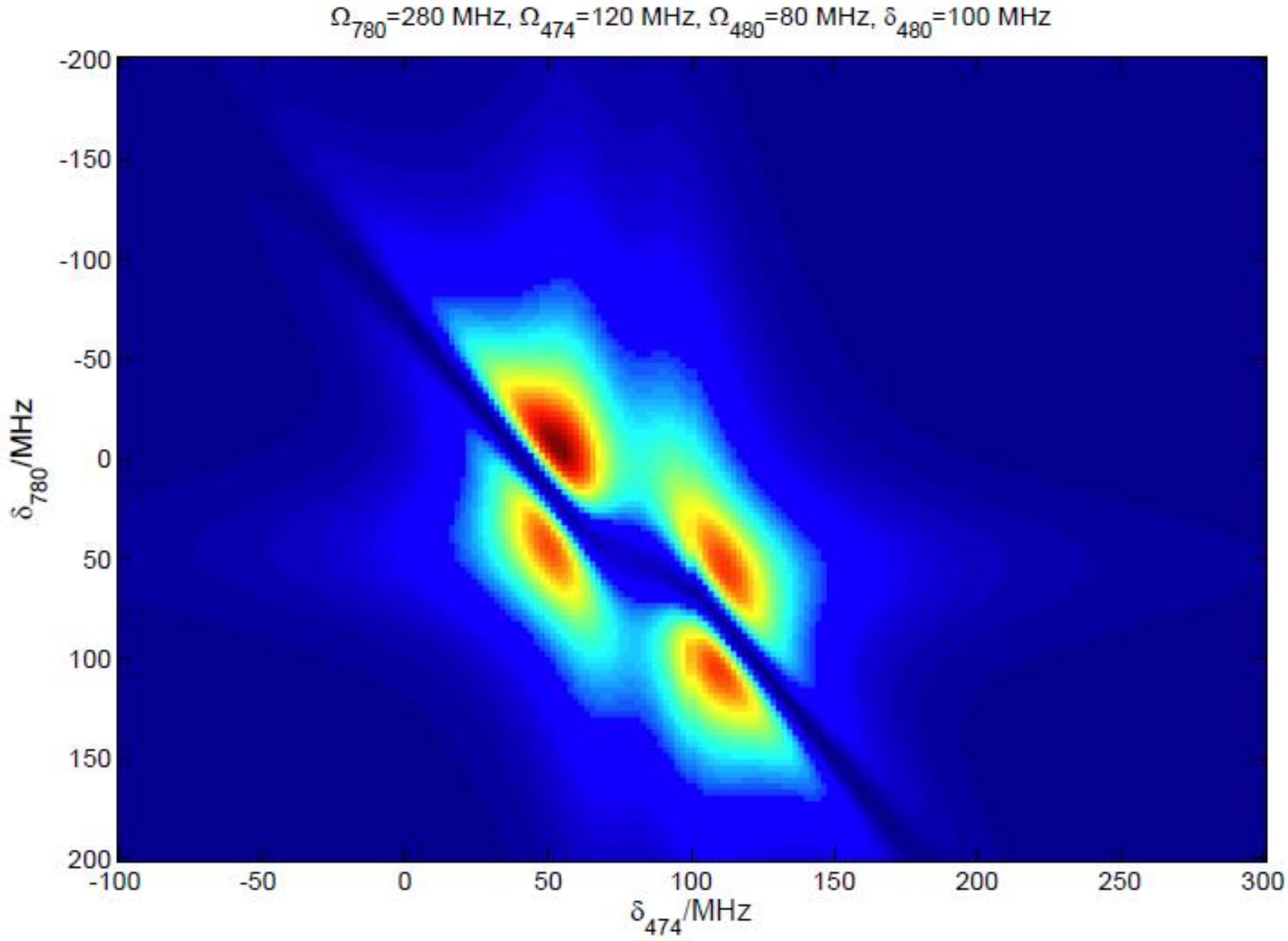
4 wave mixing



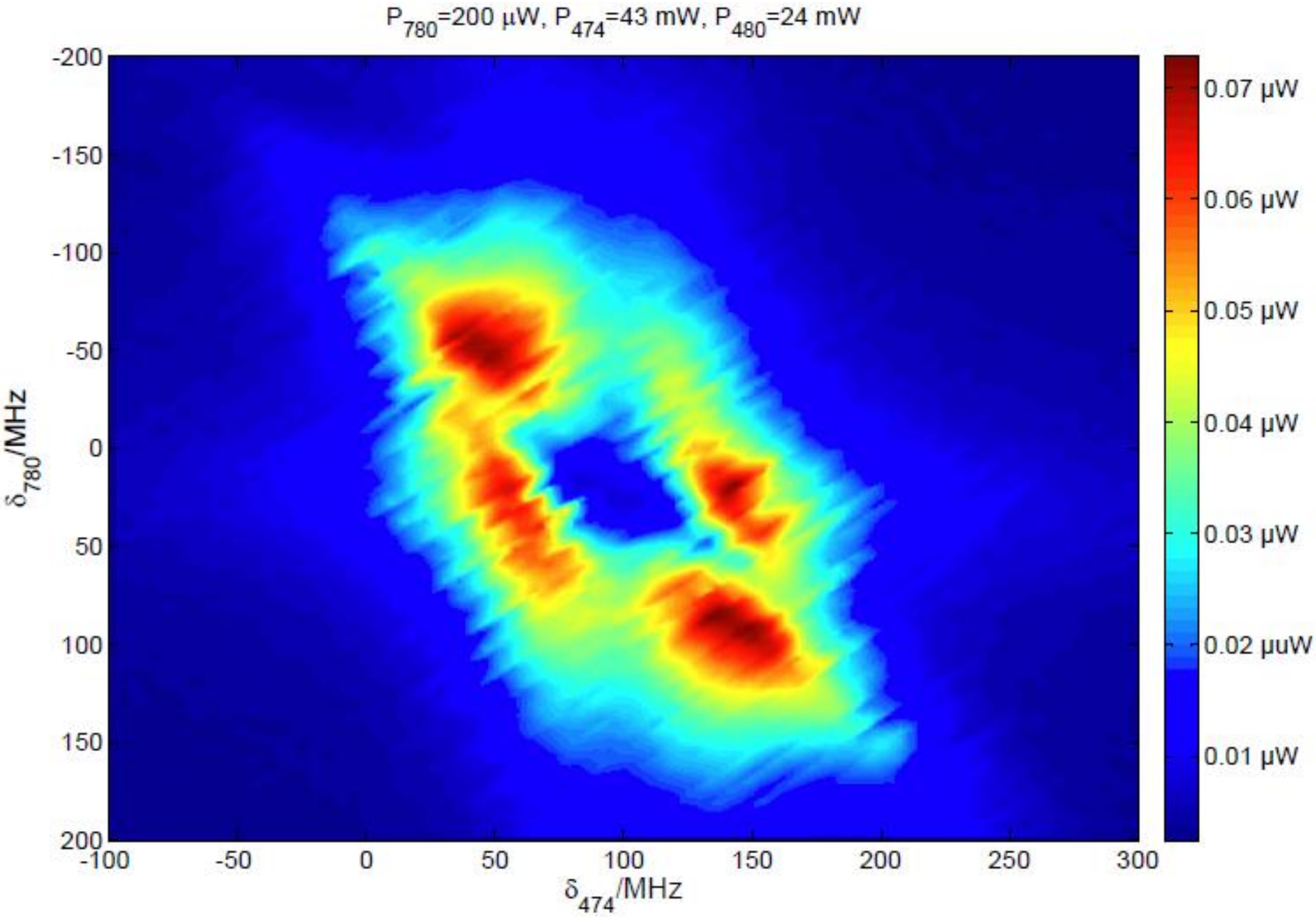


$$\vec{k}_{780} + \vec{k}_{480} = \vec{k}_{474} + \vec{k}_{795}$$

Simulation incl. Doppler broadening

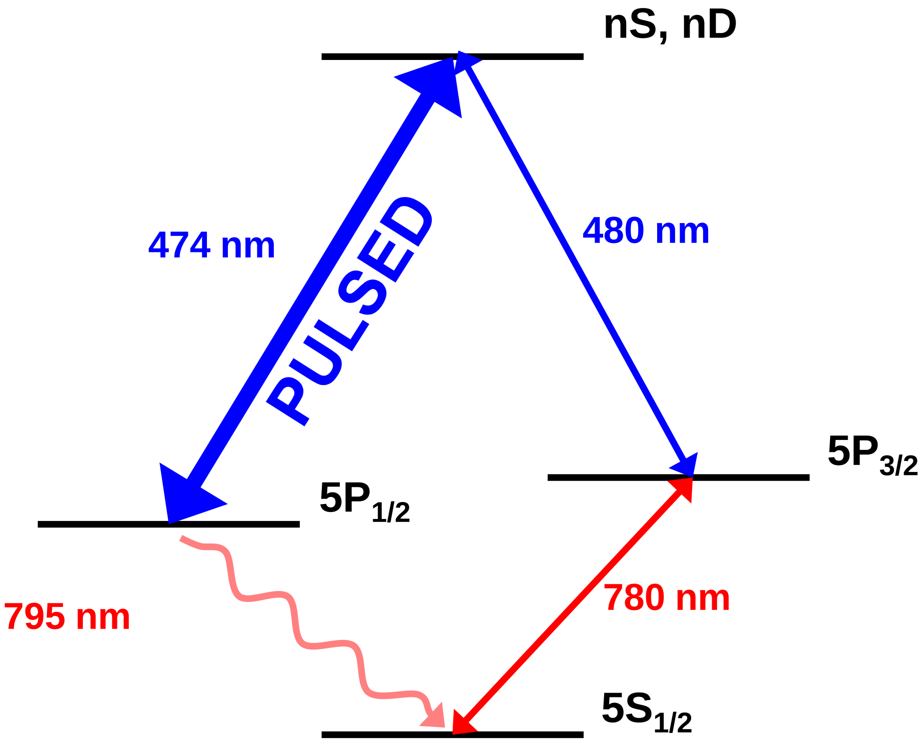


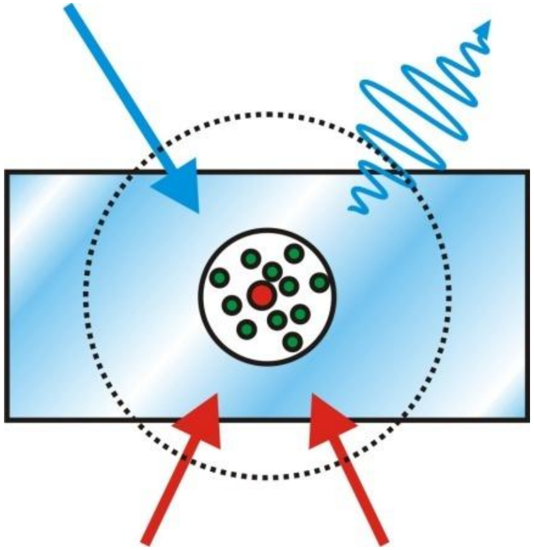
Experiment



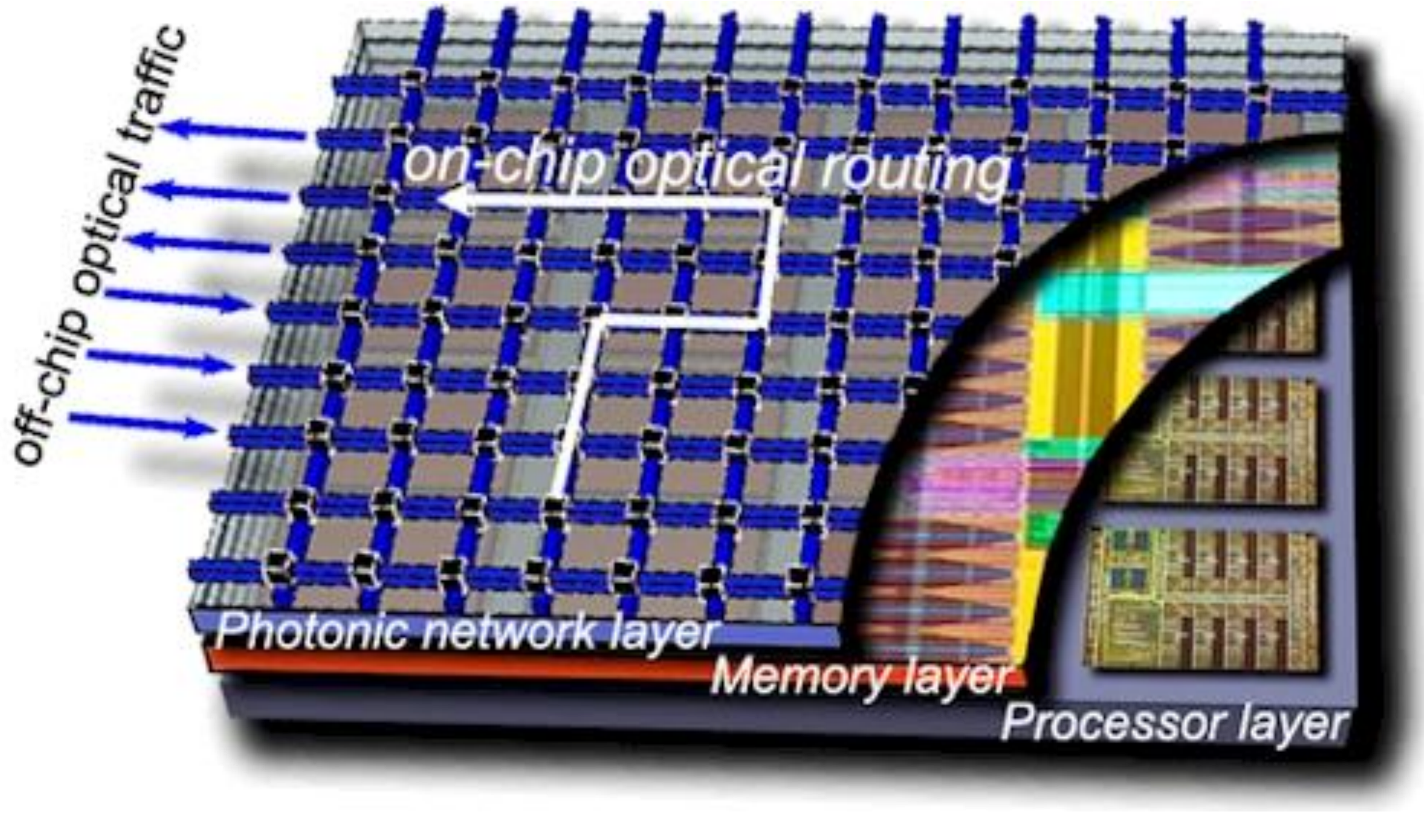
PRA **85** 063821 (2012)

Superatom - 4 wave mixing





Perspectives for integration



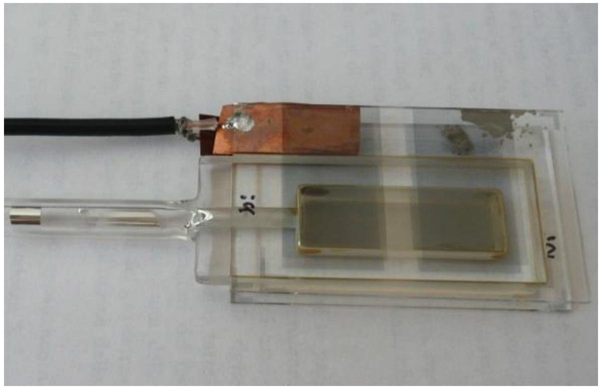
New cells – Electrically contacted

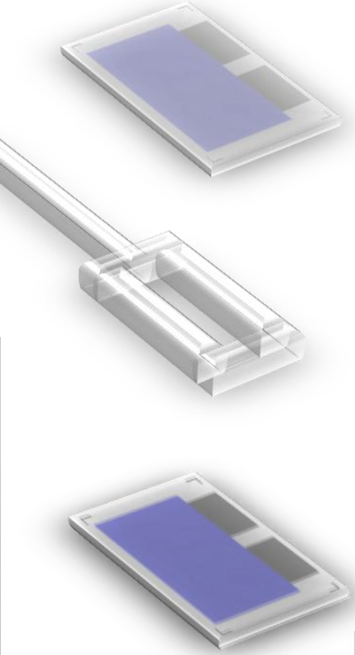
Electrically conductive coatings
(ITO + SiN, ITO + SiOx, Al, Ni, Cr+Au)

Production Process:

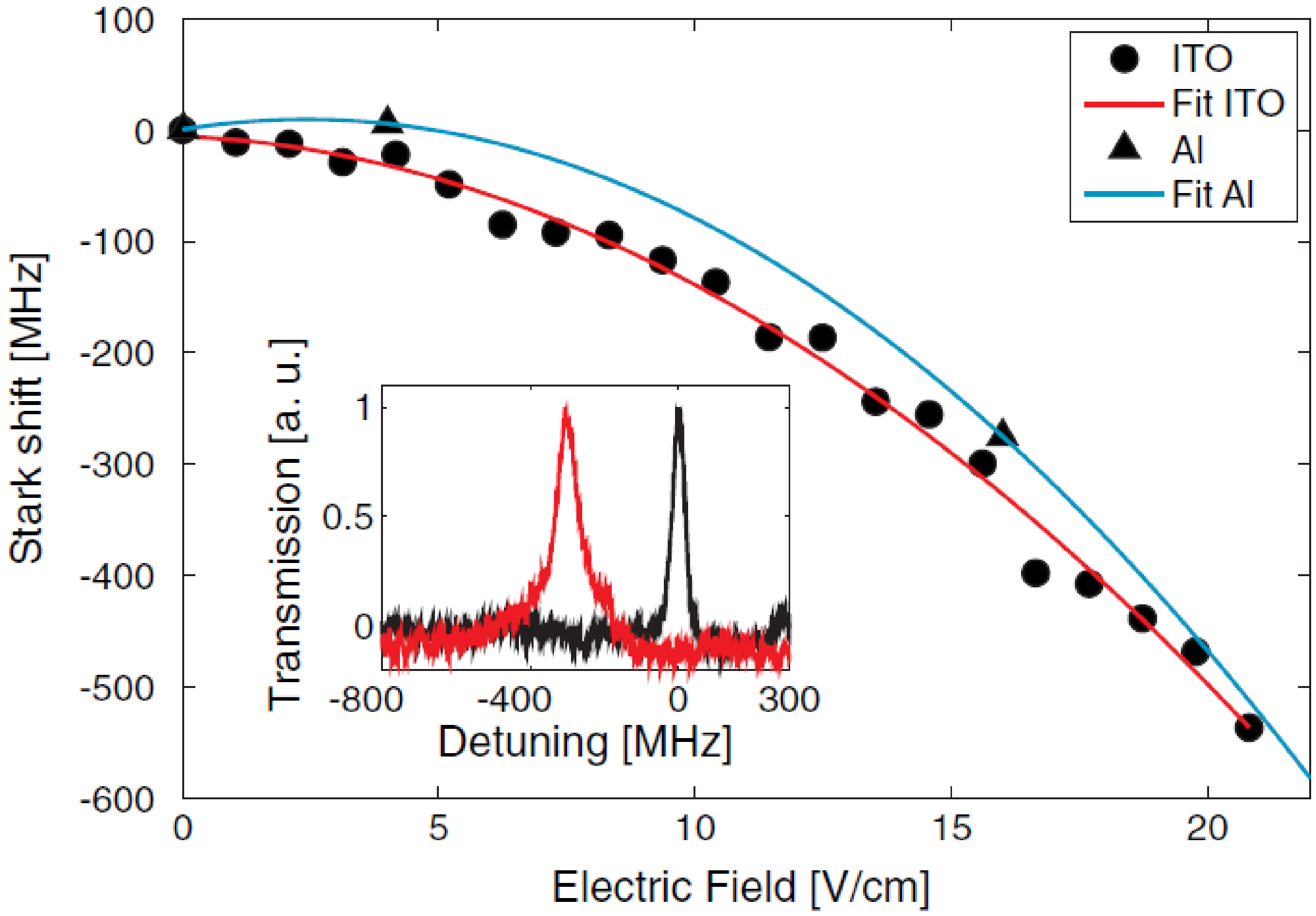
- Sputtering
- Photolithography
- Plasma Etching

- Gluing of the cell



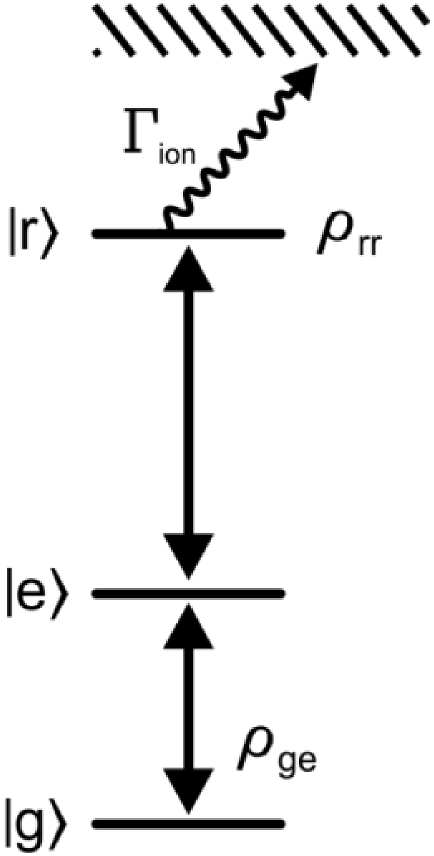


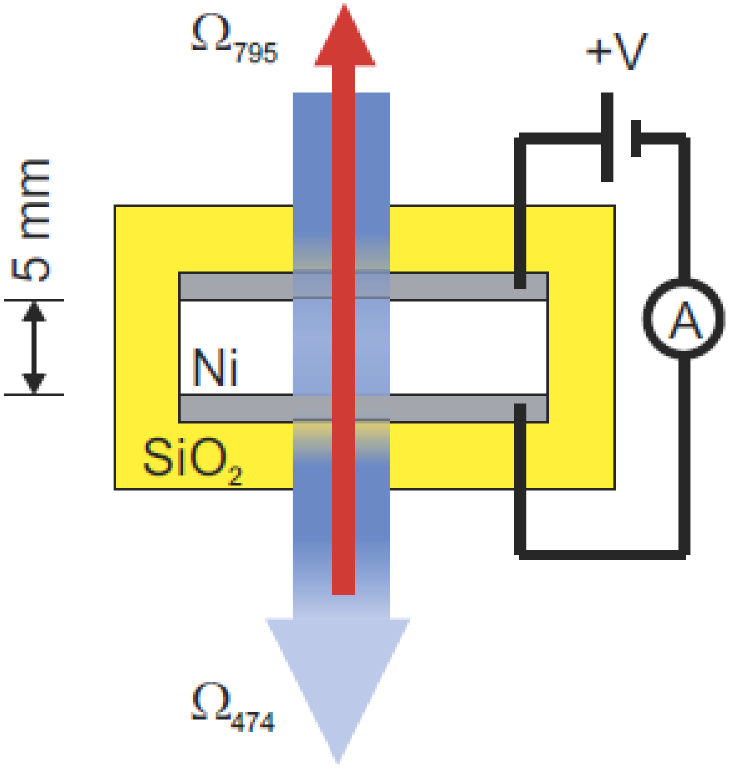
Stark maps



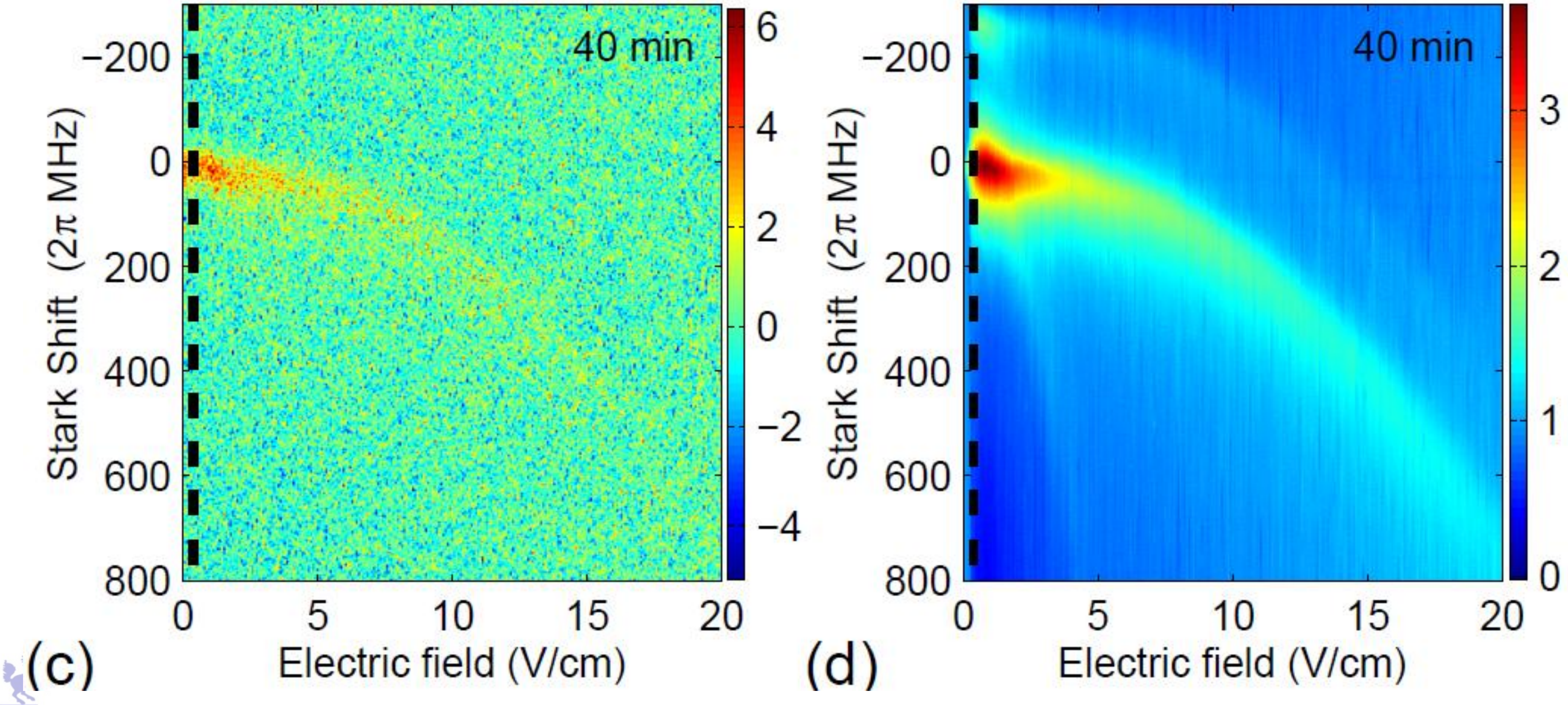
Stark shift [MHz]
100
0
-100
-200
-300
-400
-500
-600
Electric Field [V/cm]
0
5
10
15
20
● ITO
Fit ITO
▲ Al
Fit Al
Transmission [a. u.]
1
0.5
0
-800
-400
0
300
Detuning [MHz]

Direct current measurement



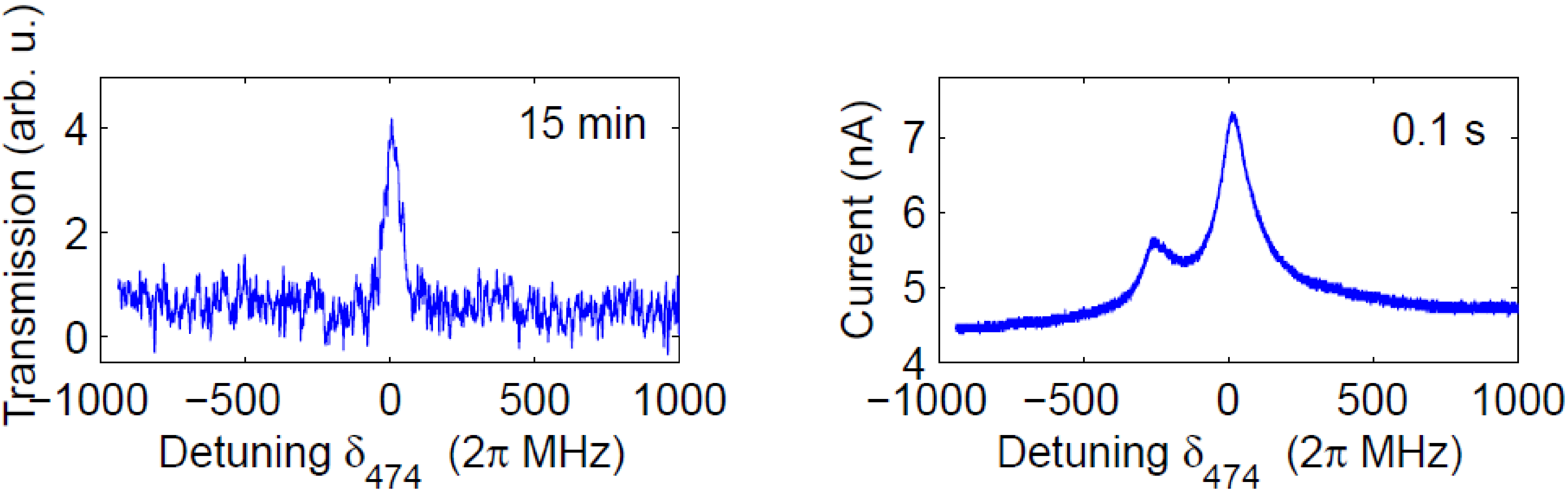


Improved signal to noise

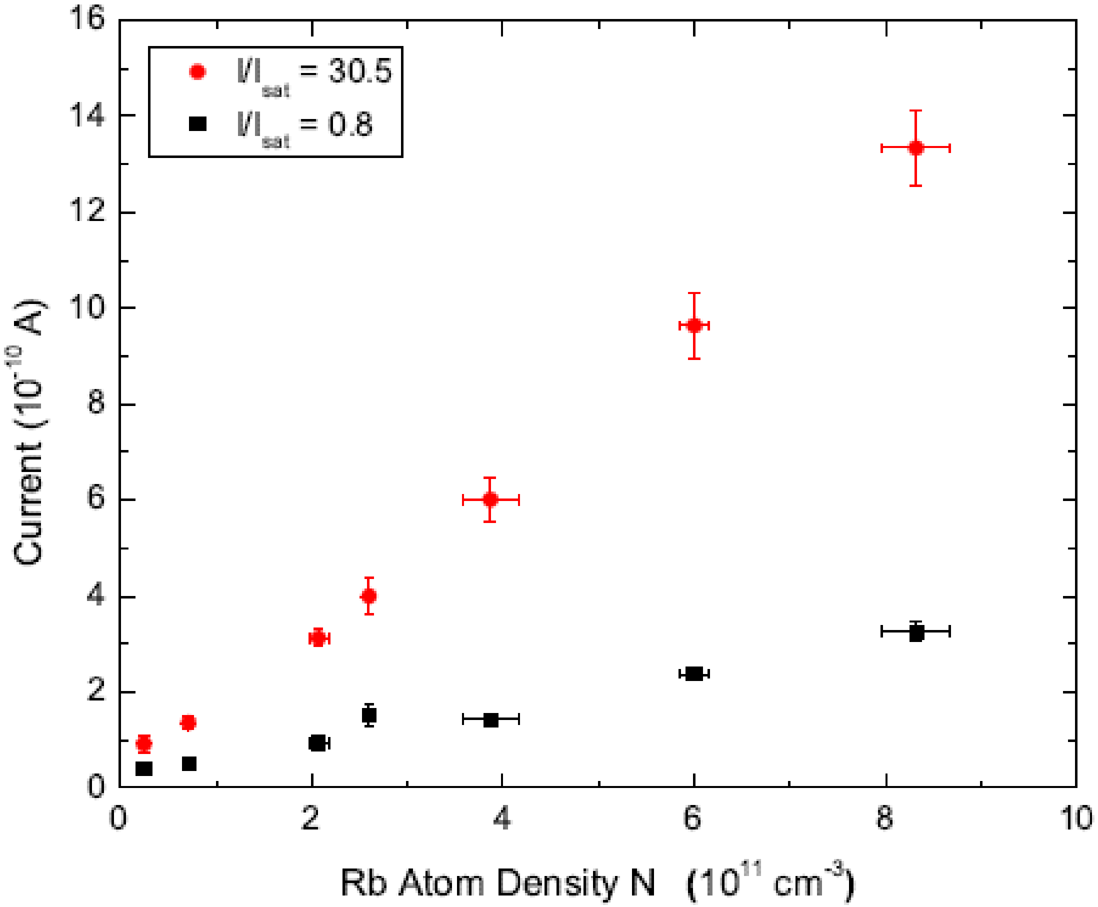


Optical **Current**

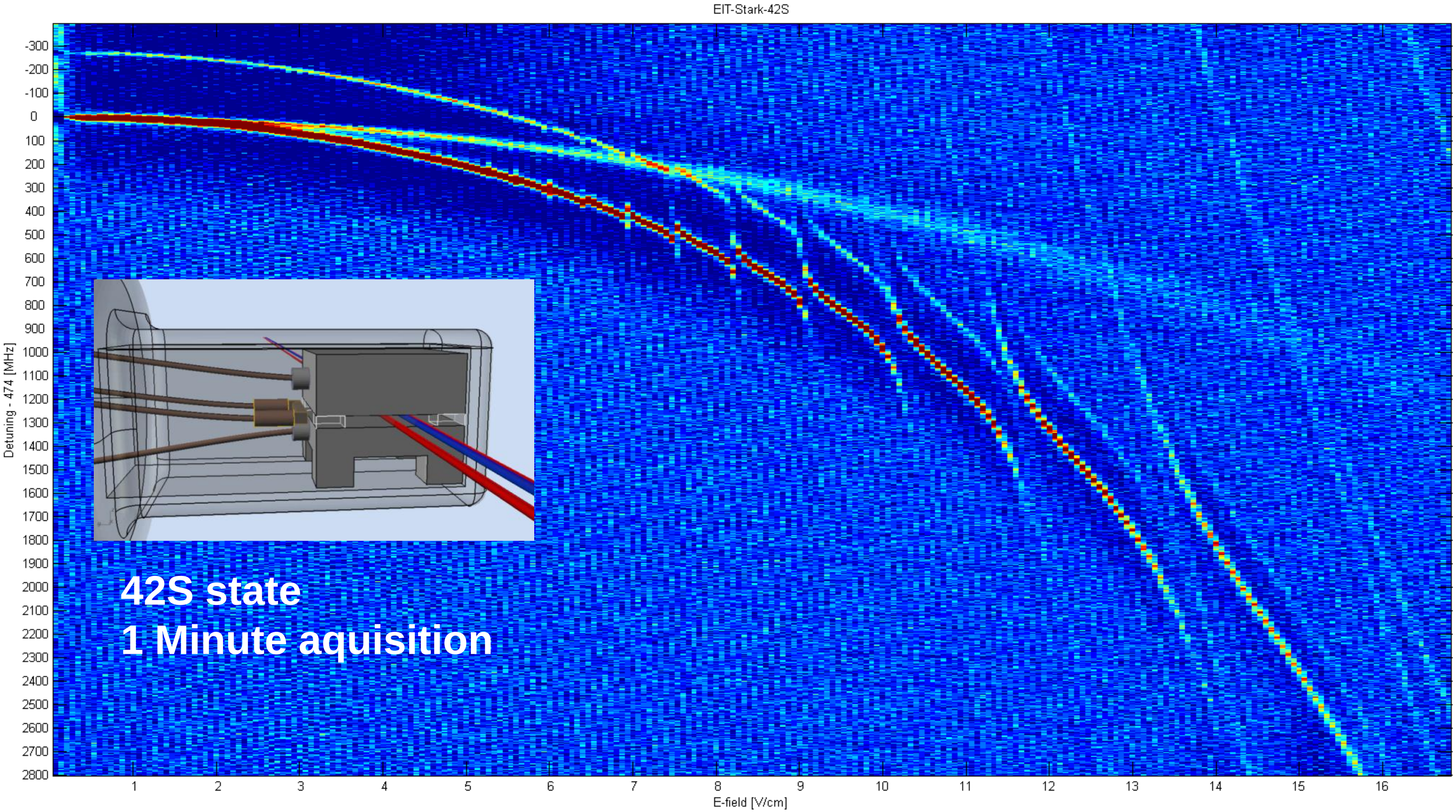
Improved signal to noise



Current is linear with density

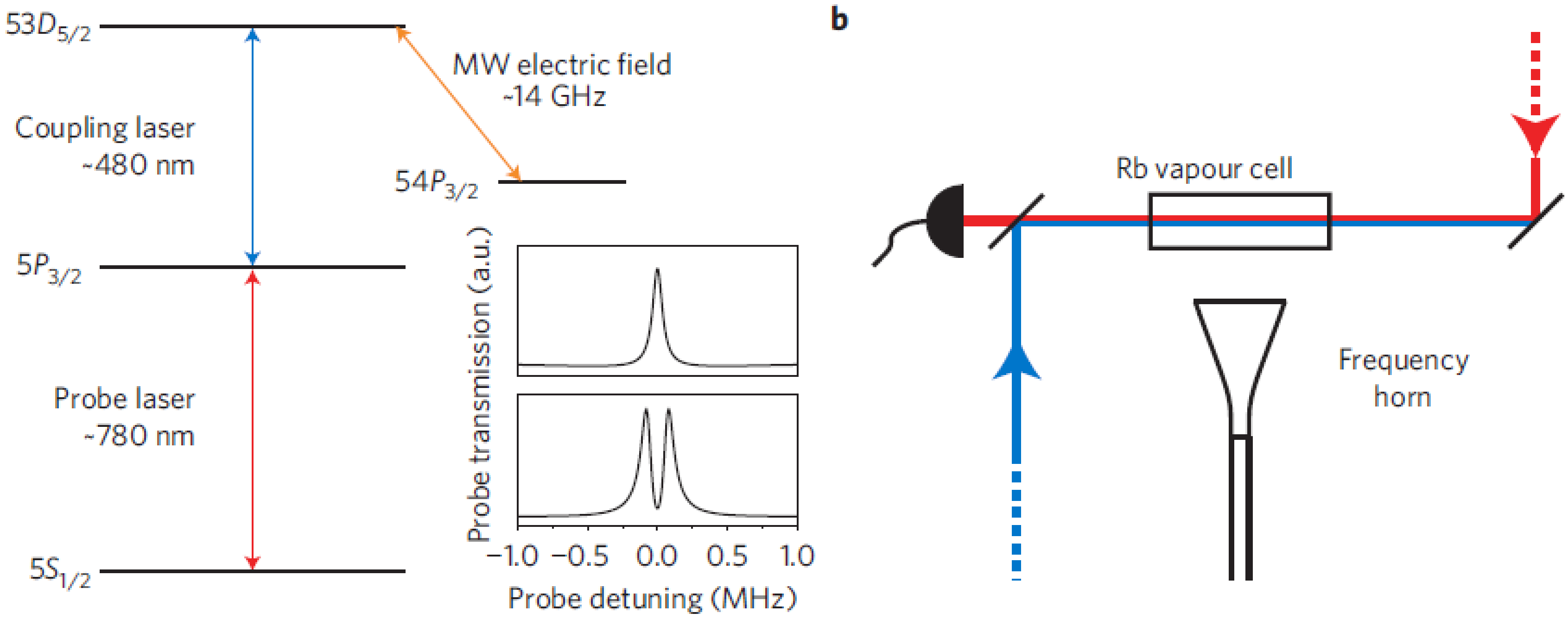


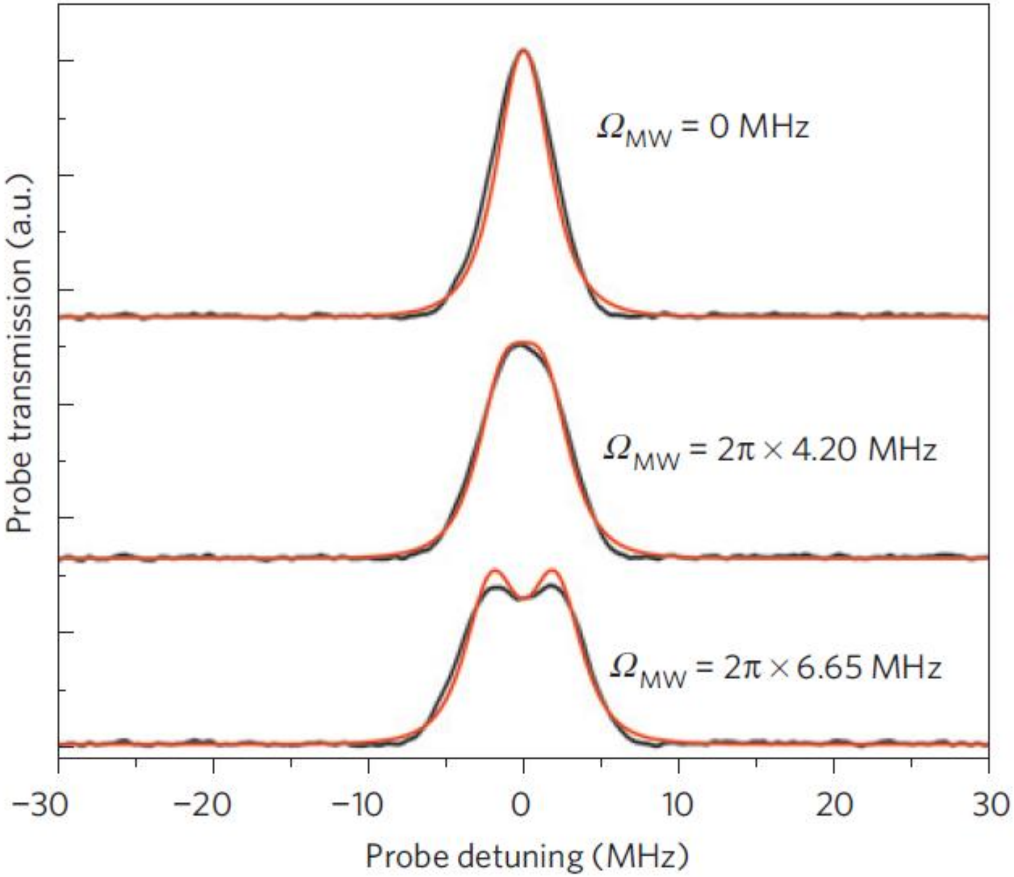
Highly resolved spectroscopy



42S state
1 Minute aquisition

Micro-wave sensing with Rydbergs

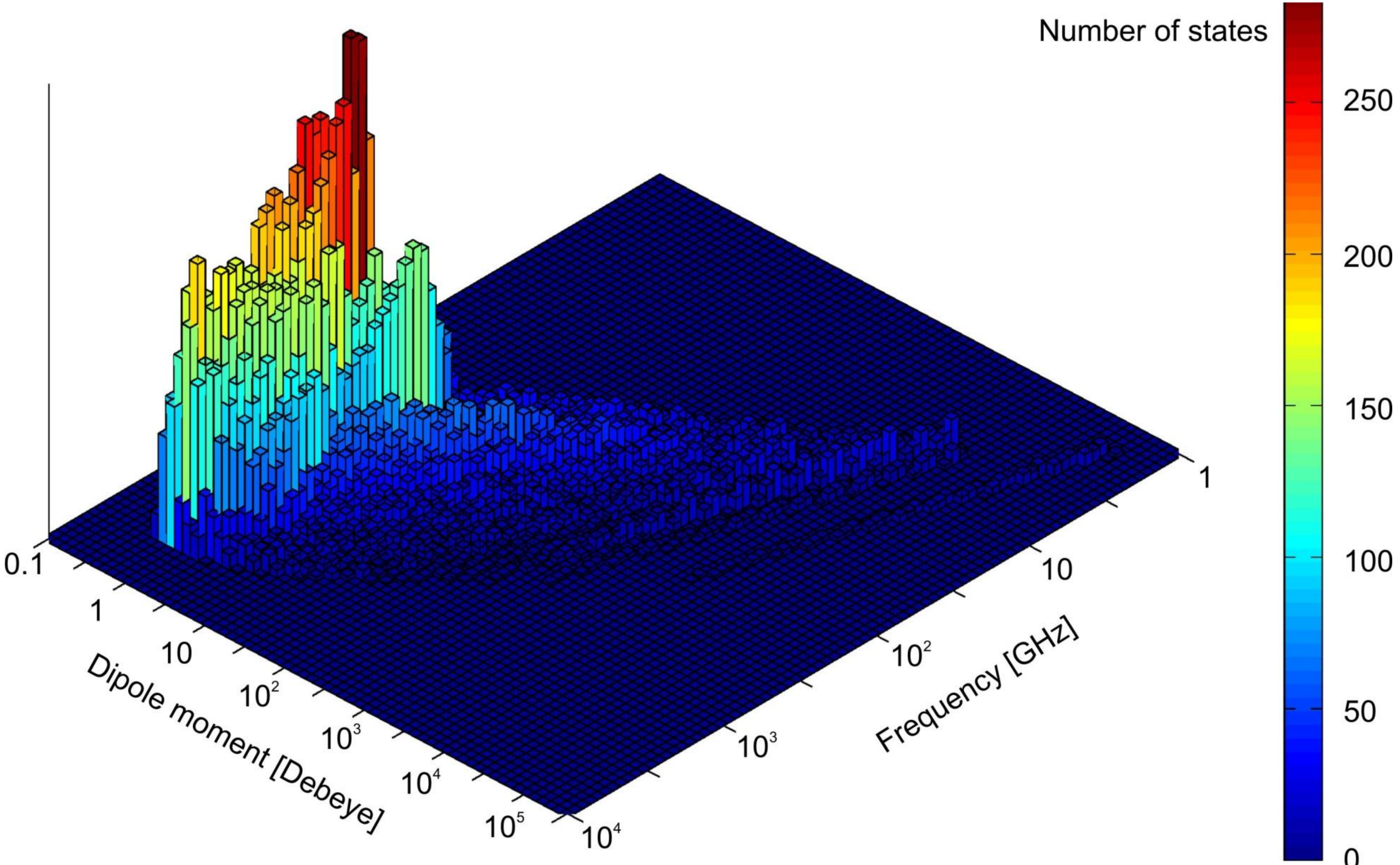




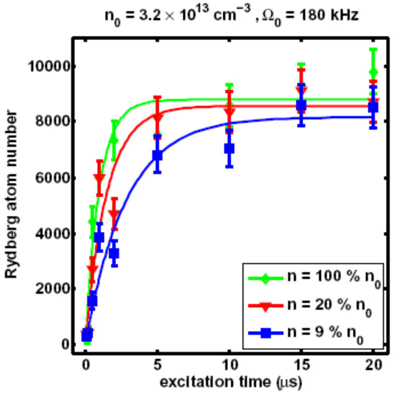
Achieved sensitivity

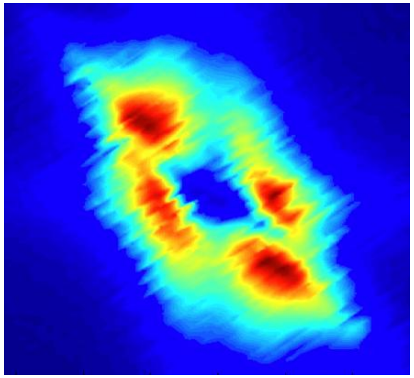
$\sim 30\ \mu\mathrm{V\,cm}^{-1}\,\mathrm{Hz}^{-1/2}$

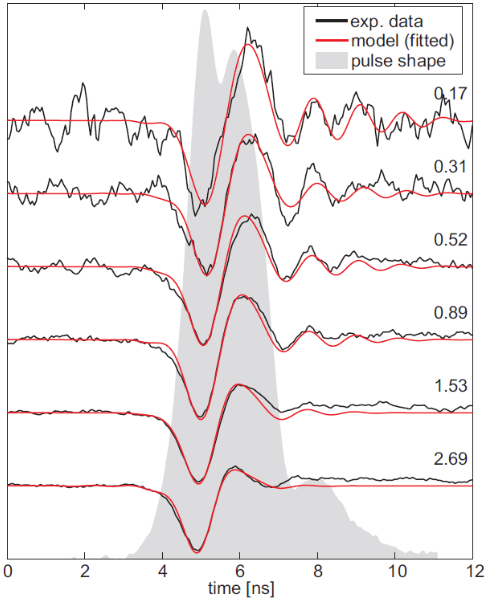
Nature physics, online

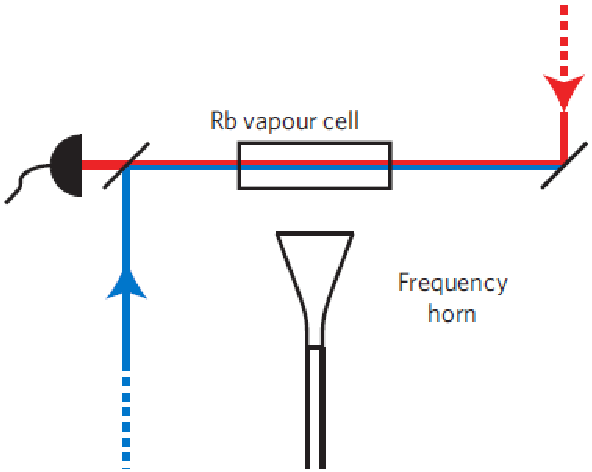

Number of states
250
200
150
100
50
0
0.1
1
10
10^2
10^3
10^4
10^5
Dipole moment [Debeye]
1
10
10^2
10^3
10^4
Frequency [GHz]

Summary


$n_0 = 3.2 \times 10^{13}$ cm^{-3}, $\Omega_0 = 180$ kHz
Rydberg atom number
10000
8000
6000
4000
2000
0
0
5
10
15
20
excitation time (μs)
n = 100 % n_0
n = 20 % n_0
n = 9 % n_0

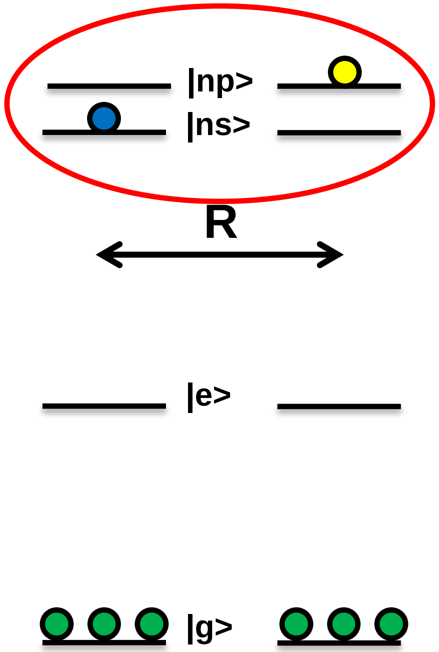


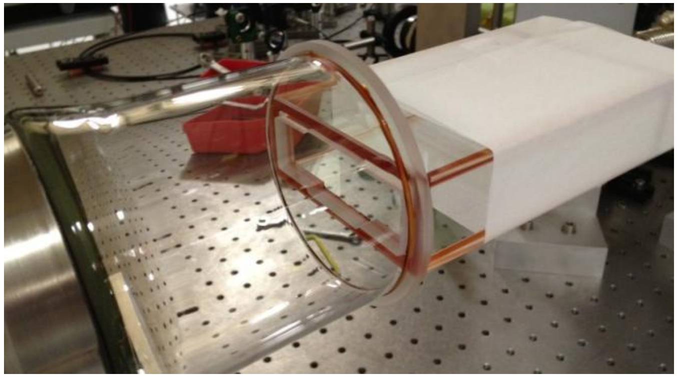

exp. data
model (fitted)
pulse shape
0.17
0.31
0.52
0.89
1.53
2.69
0
2
4
6
8
10
12
time [ns]

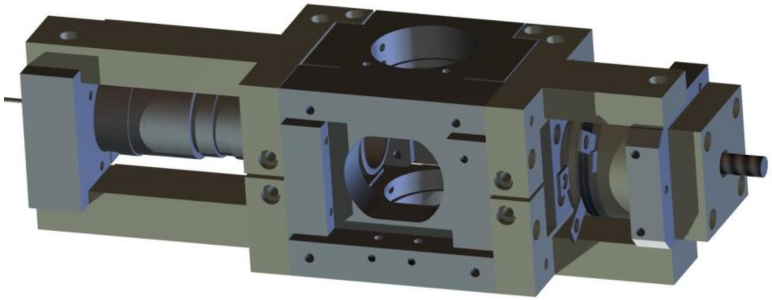

Rb vapour cell
Frequency horn

Back to the cold – outlook

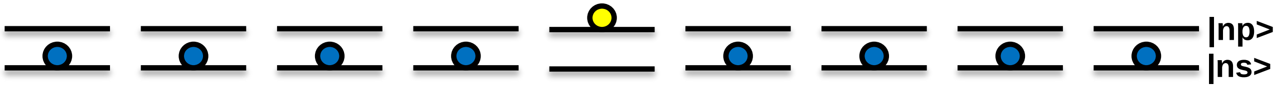
Excitation hopping in Rydberg Networks



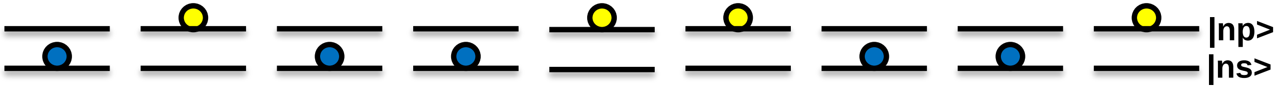




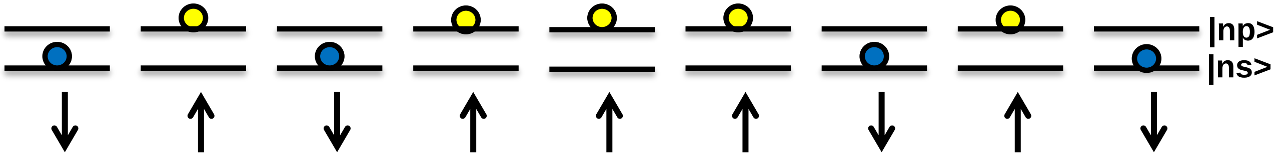
Possible systems



1 excitation + many „network nodes“: quantum random walk



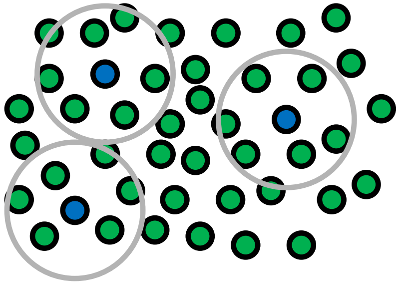
1 < # excitations < # network nodes: 1d Bose gas



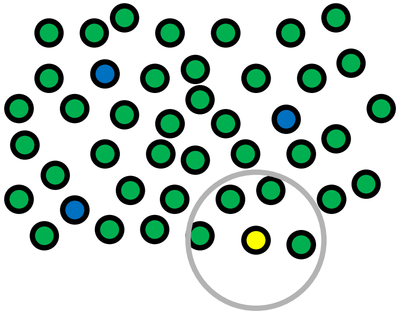
 # excitations ~ ½ # network nodes: spin chains

Hopping toolbox

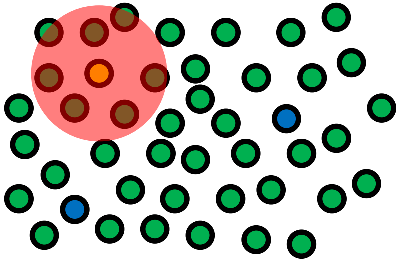
1. Network preparation

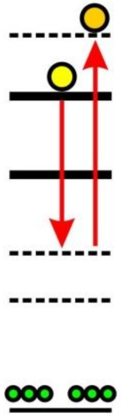


2. excitation „write“

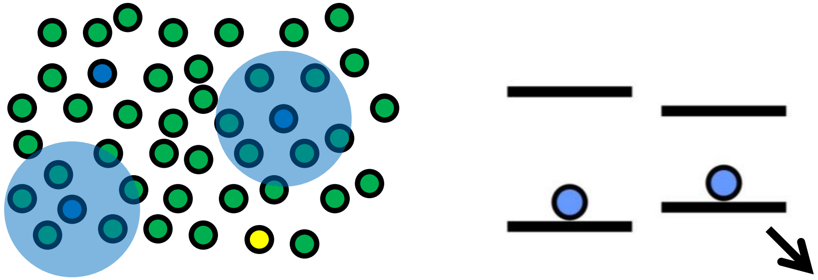


3. excitation „read“





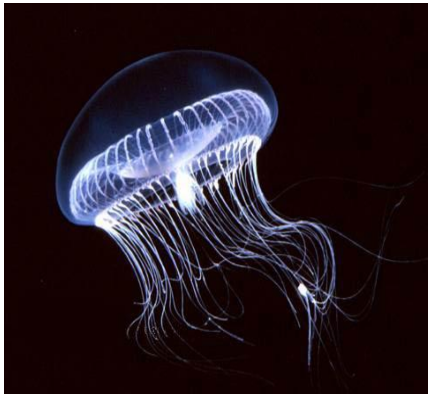
4. controlled disorder



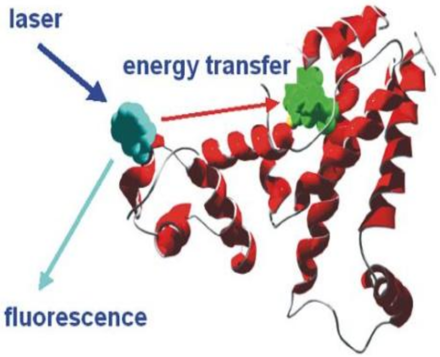
Dissipative many body quantum systems

Coherent quantum dynamics in biological systems

light harvesting complexes



bioluminescence



spectroscopic ruler

Thomas Baluktsian
Daniel Barredo
Renate Daschner
Georg Epple
Anita Gaj
Bernhard Huber
Andreas Kölle
Harald Kübler
Ralf Ritter
Eva Schöll
Alban Urvoy

MARIE CURIE ACTIONS
erc
PROJEKTTRÄGER FÜR DAS
Bundesministerium für Bildung und Forschung
BADEN-WÜRTTEMBERG STIFTUNG
Wir stiften Zukunft
DARPA