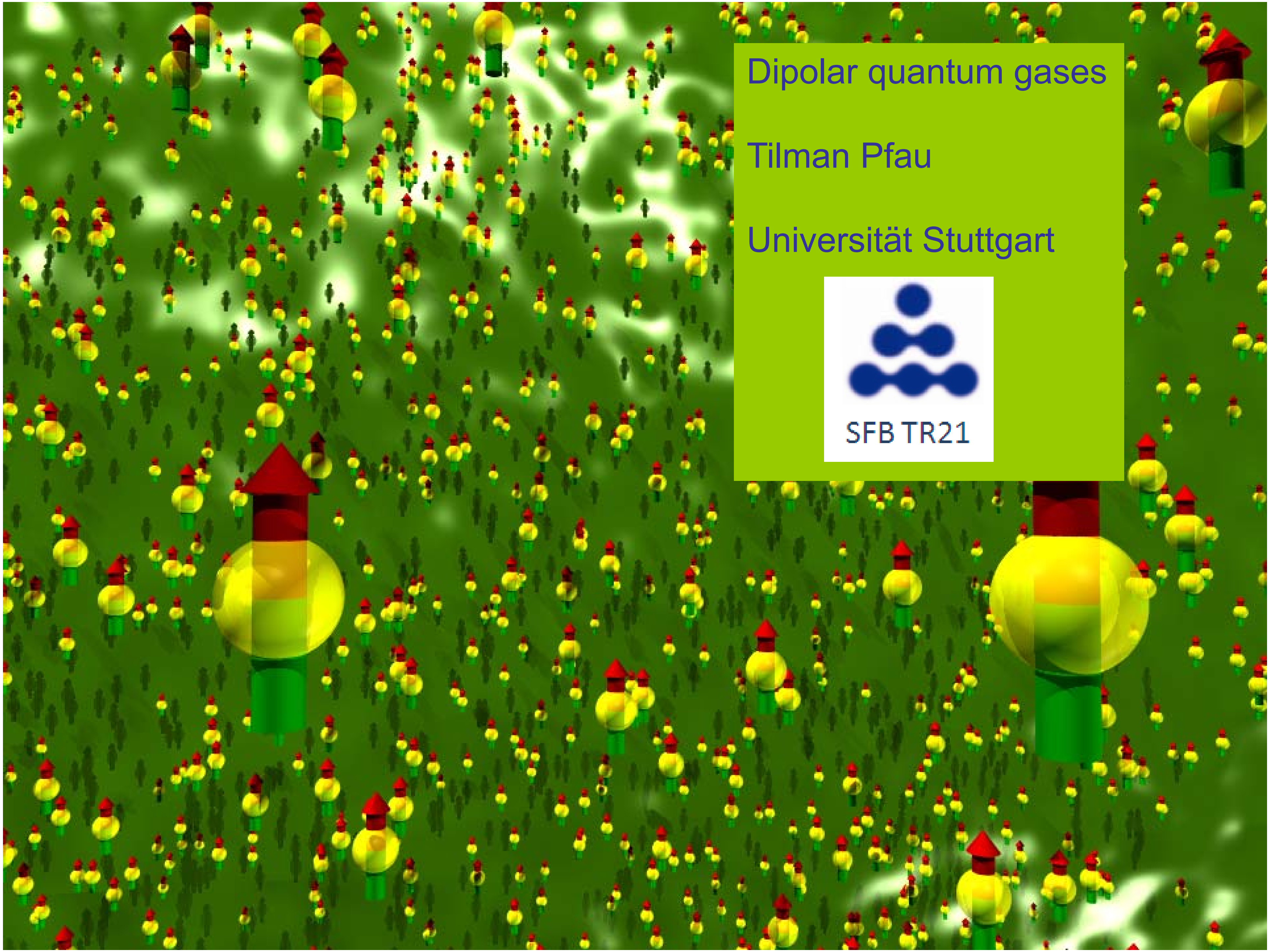


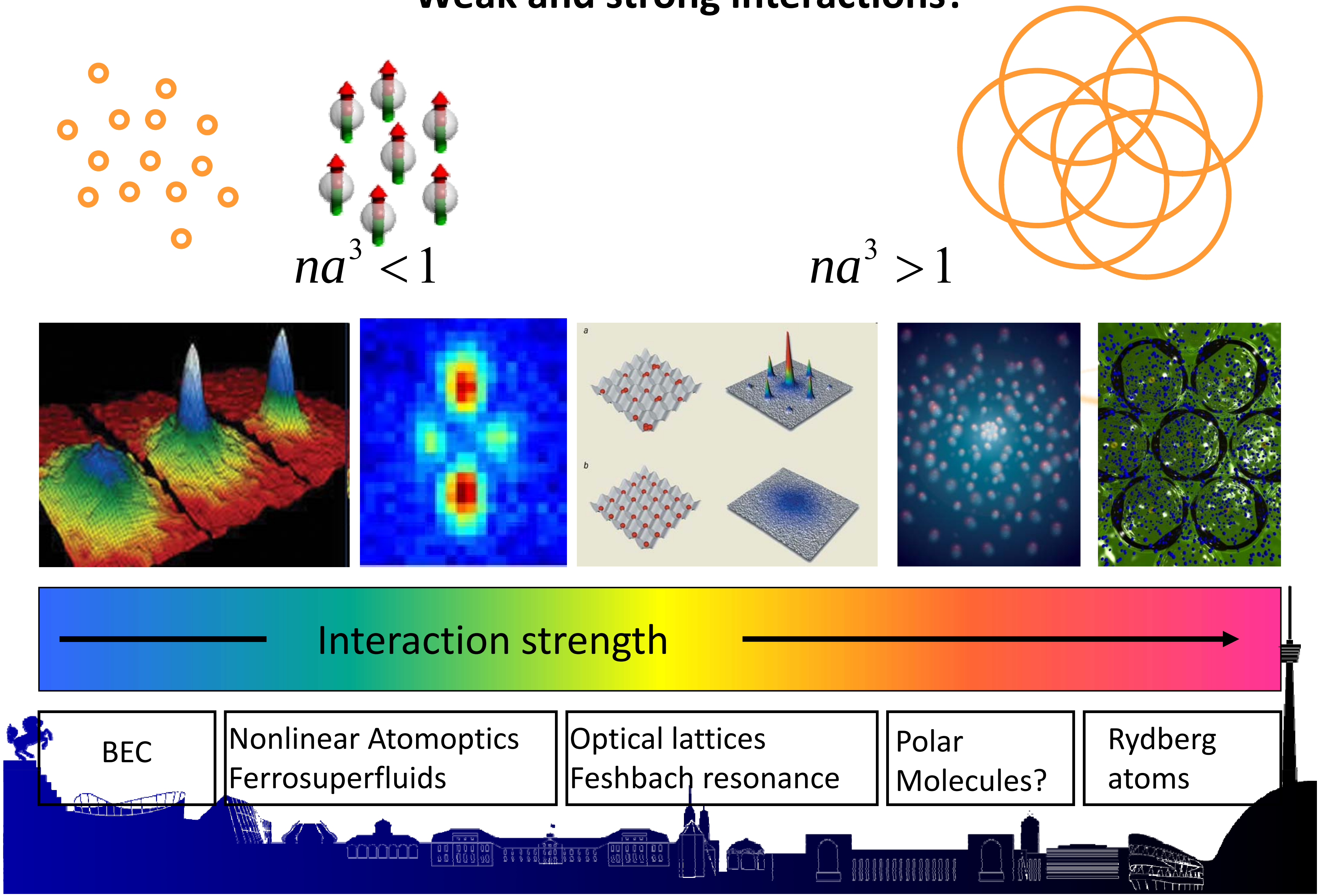
Dipolar quantum gases

Tilman Pfau

Universität Stuttgart

SFB TR21

Weak and strong interactions?



Early interest in dipoles

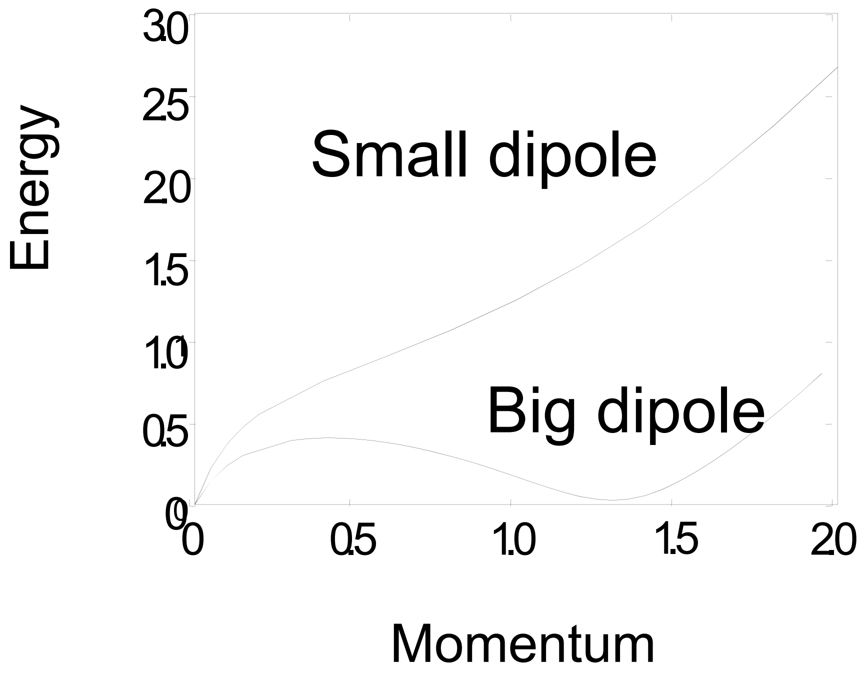
- Compass needles
- 1970 DeGennes:

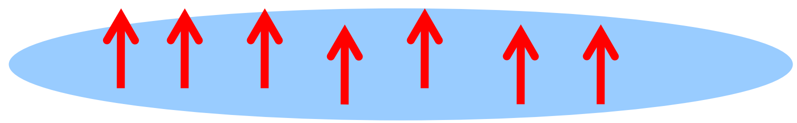
  anisotropic gas; chains
- 1980's ferrofluids

Rosensweig instability
M. D. Cowley and R. E. Rosensweig, J. Fluid Mech. **30**, 671 (1967)

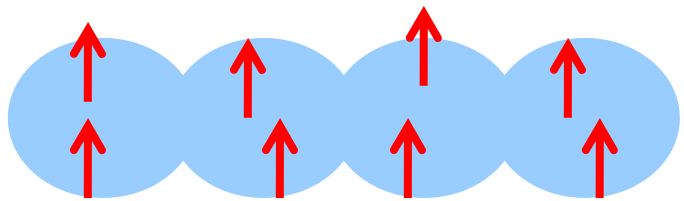
- 21^{st} century : add quantum mechanics

Anisotropy: the roton in dipolar BEC





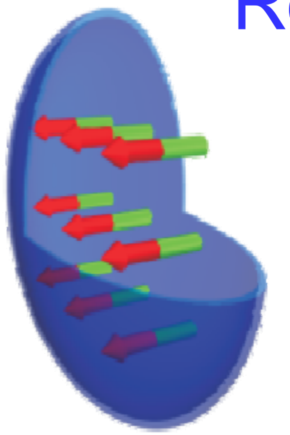
Stable at long wavelengths

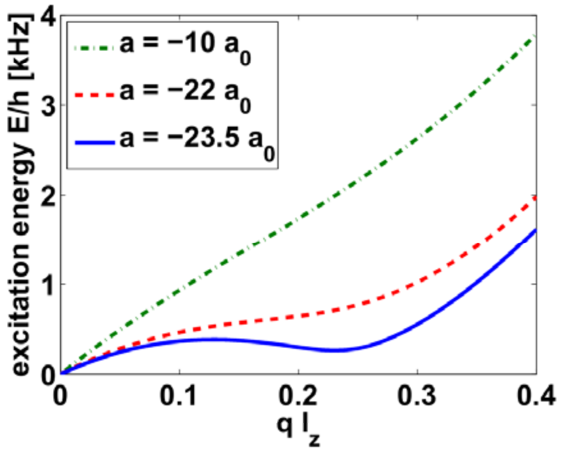


Roton instability at shorter wavelengths

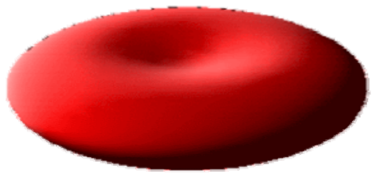
Santos, Shlyapnikov, and Lewenstein PRL 90, 250403 (2003)

Roton – Maxon type excitation spectrum





Structured groundstates



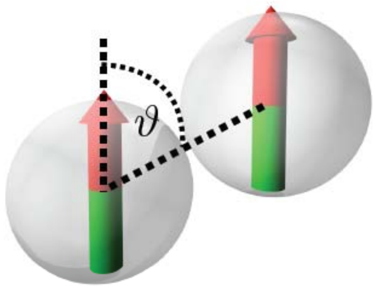
checkerboard
supersolid

R. Richter et al.,
*PRL **94**, 184503 (2005)*

S. Ronen et al.,
*PRL **98**, 030406 (2007)*

K. Góral et al.,
*PRL **88**, 170406 (2002)*

Dipolar gases

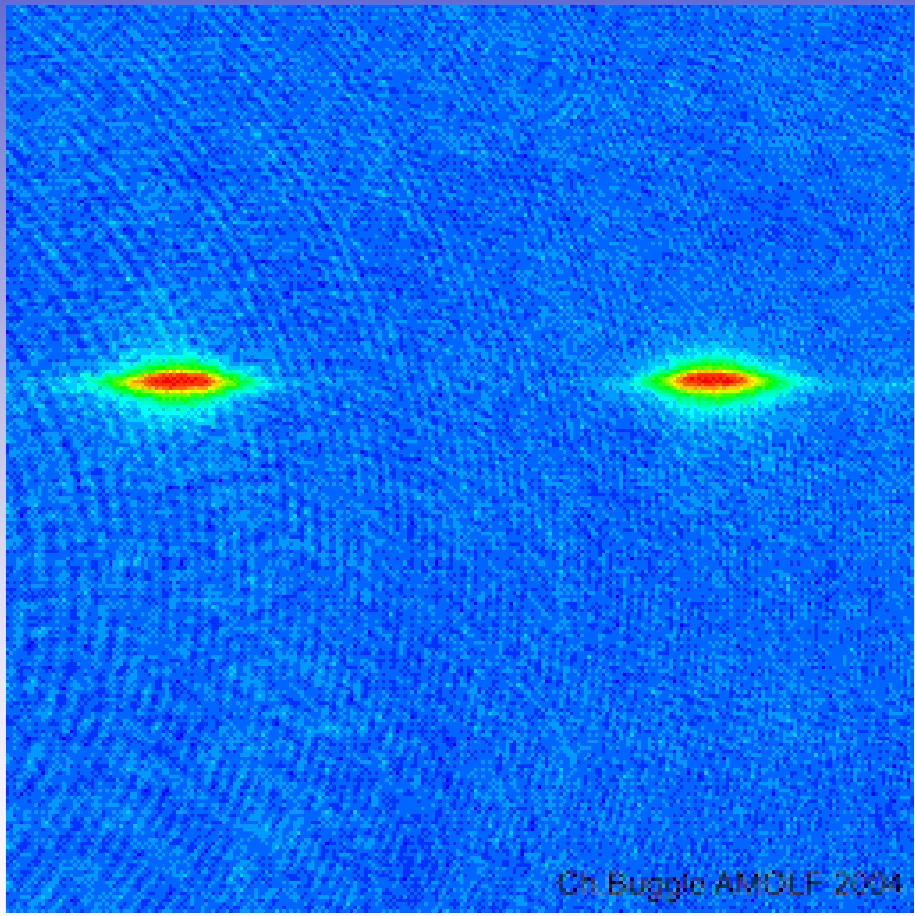


$$\varepsilon_{dd} \propto \frac{m\mu^2}{a}$$

dipolar interaction

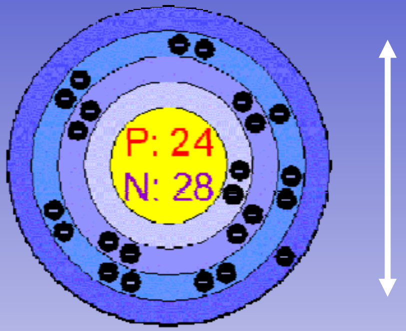
contact interaction

Isotropic „hard sphere“ interaction



AMOLF

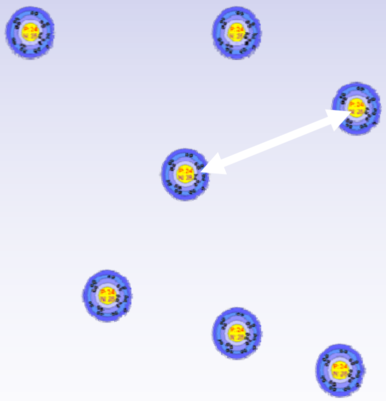
Length scales



size
0.1 nm

de Broglie wavelength
> 100 nm

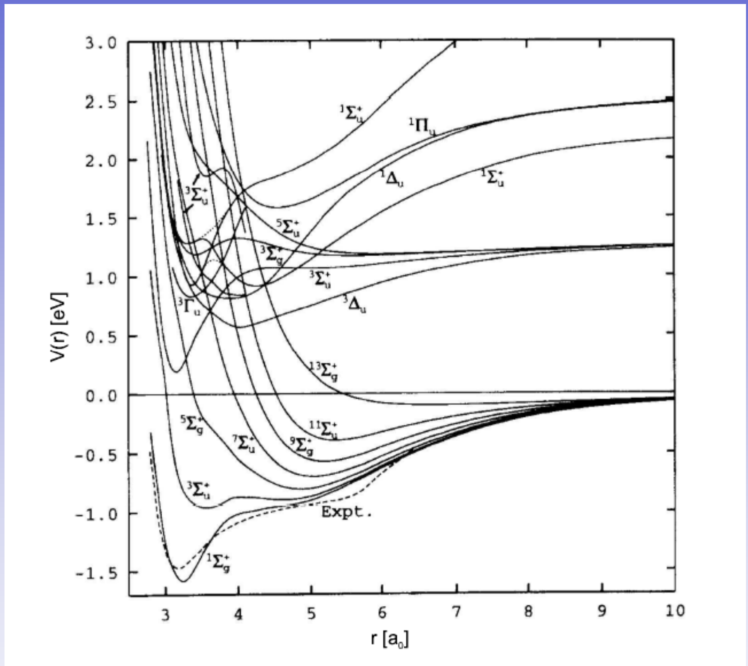
$$\Lambda = \sqrt{\frac{h^2}{2\pi m k T}}$$



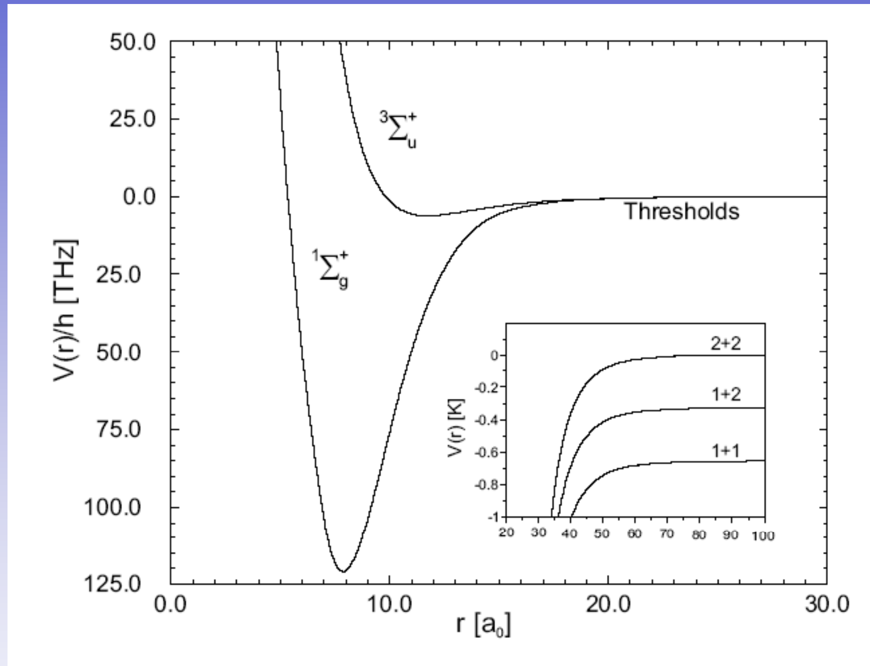
mean distance
>100 nm

Two body is dominant
Quantum treatment required

Real two-body potentials?



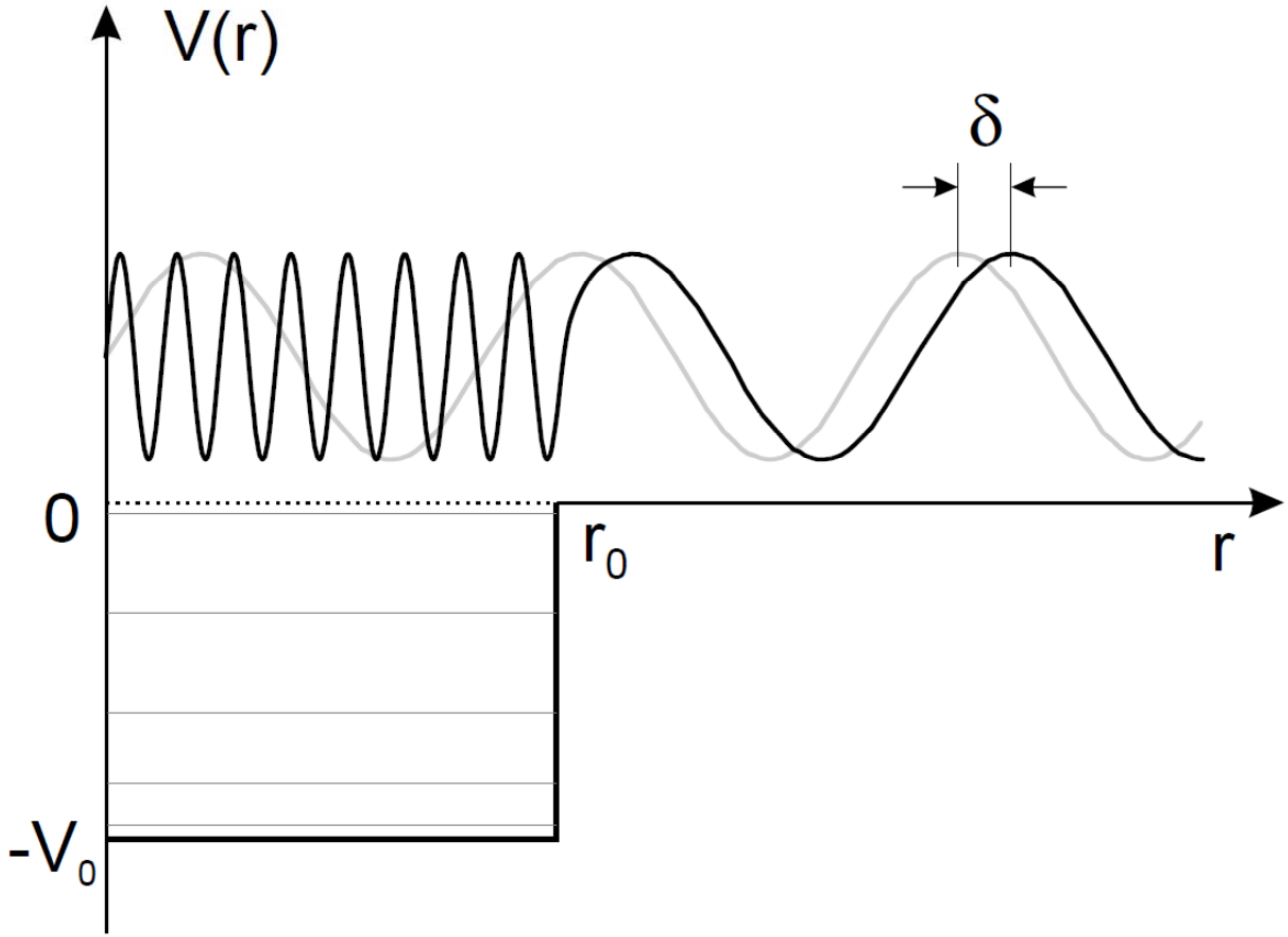
Cr_2



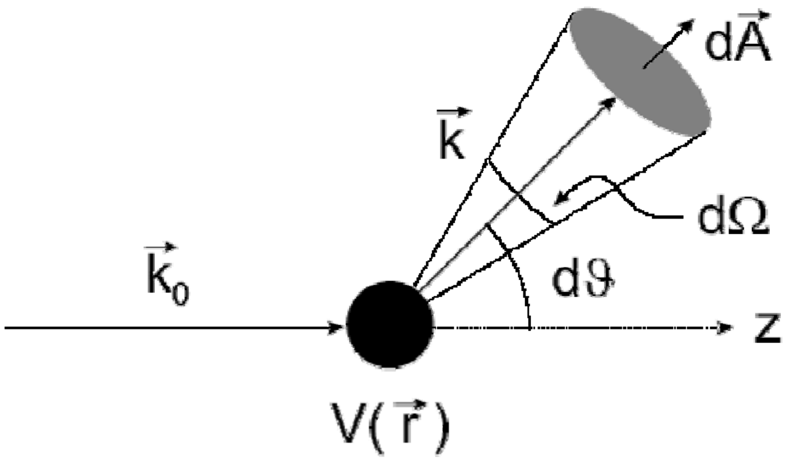
Rb_2

K. Anderson
Chem Phys. Lett. **237**, 212 (1995)

Scattering from box potential



Scattering problem



3D Schödinger Eq.

$$\left[\frac{\hat{\vec{p}}^2}{2m_\mu} + V(\vec{r})\right]\phi(\vec{r}) = E\phi(\vec{r}),$$

$$\phi(\vec{r}) = \phi_0(\vec{r}) + \phi_s(\vec{r}).$$

Scattered wave

Ingoing plane wave

Stationary solution

Partial waves

Central potential (isotropic):

angular momentum conservation
reduce 3D SG to 1 D SG by

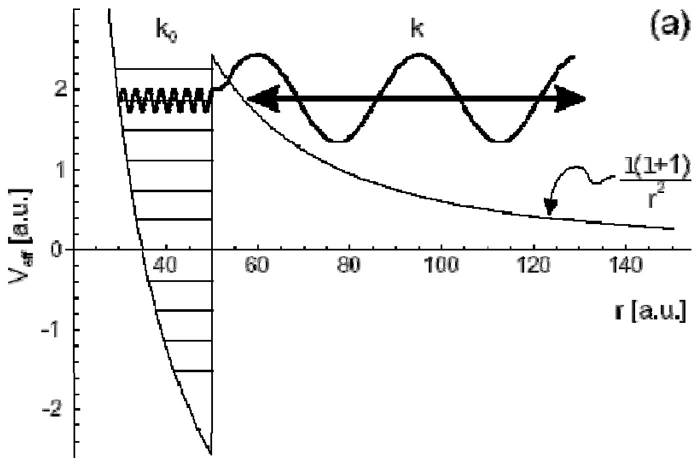
$$\phi(\vec{r}) = \sum_{\ell=0}^{\infty} \frac{u_\ell(r)}{r} P_\ell(\cos\vartheta)$$

Legendre polynomials

$$\frac{\hbar^2}{2m_\mu} u_\ell''(r) + [E - V_{\text{eff}}(r)]\, u_\ell''(r) = 0,$$

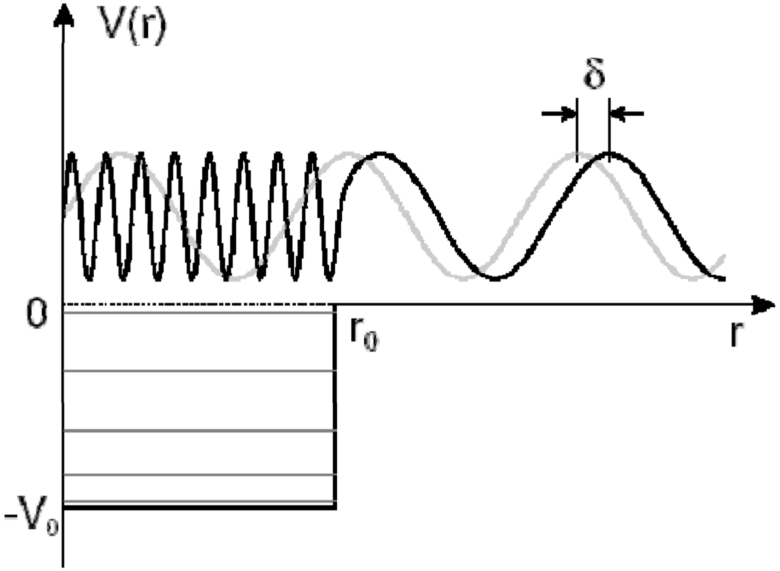
$$V_{\text{eff}}(r) = \left[V(r) + \frac{\hbar^2 \ell(\ell+1)}{2m_\mu r^2} \right]$$

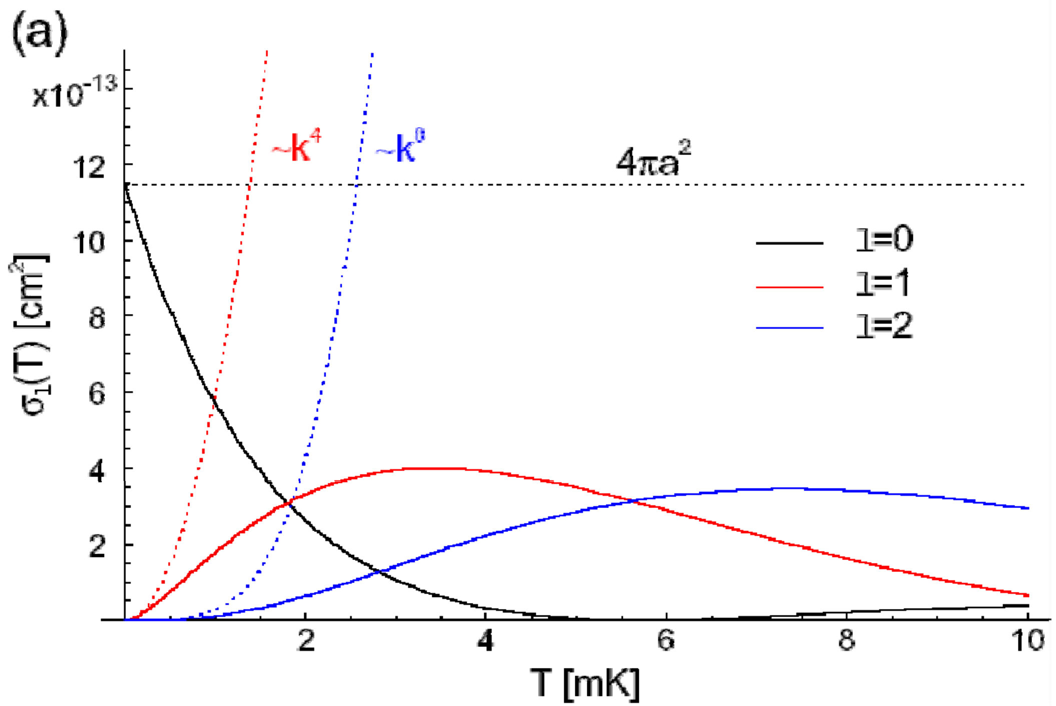
Centrifugal barrier



box plus centrifugal

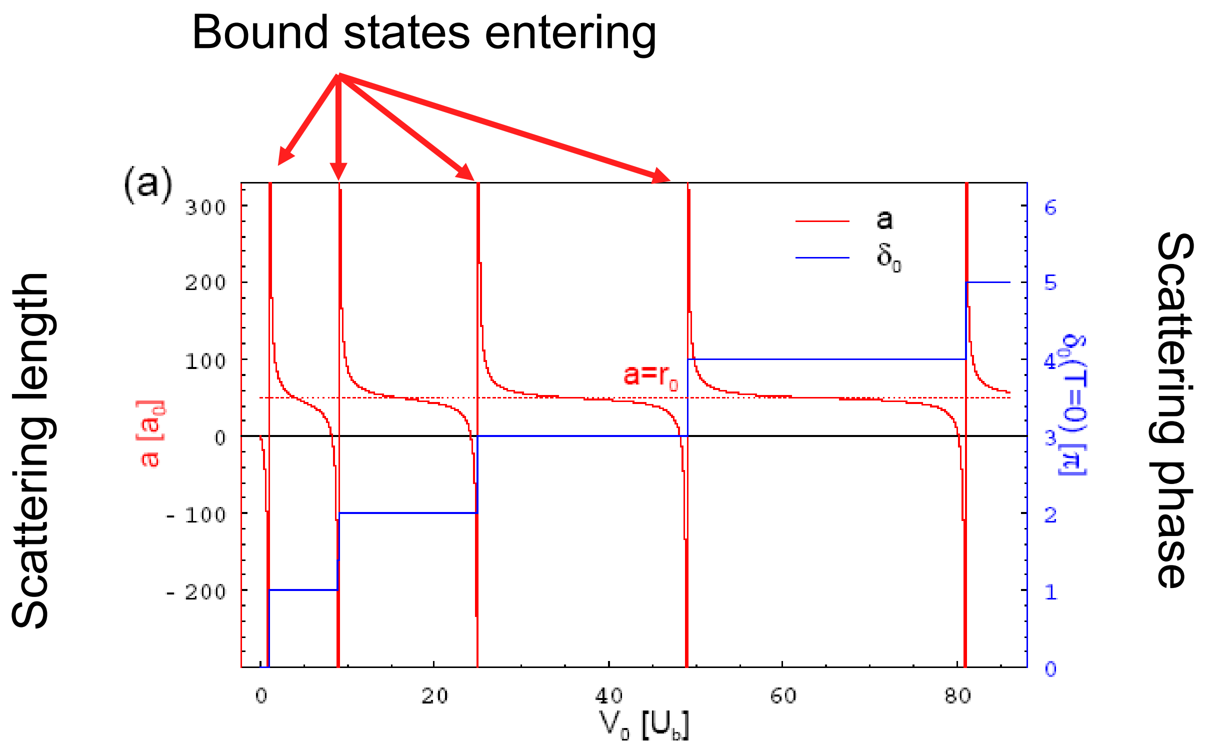
Basic scattering theory

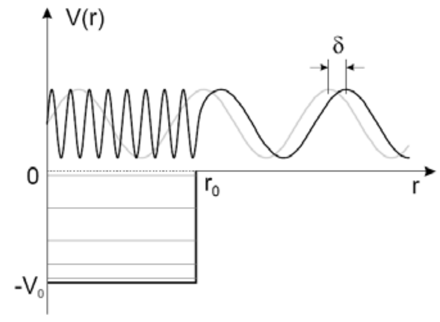




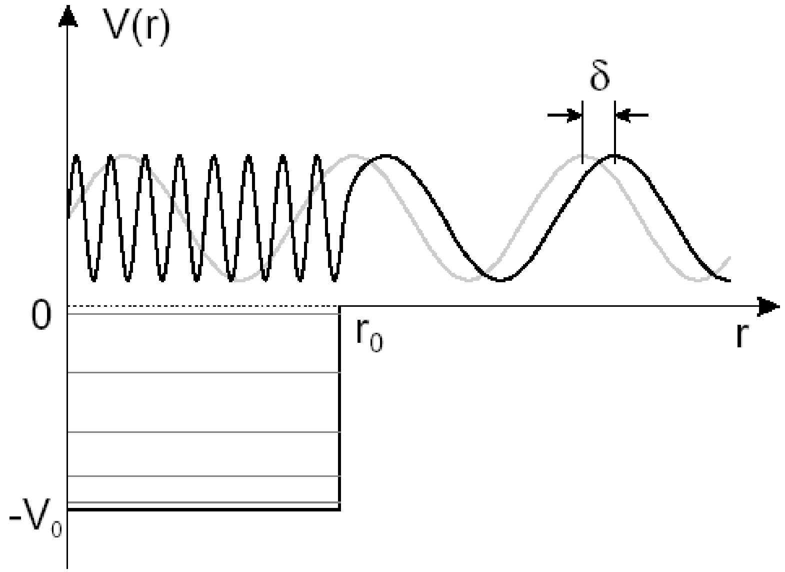
Wigner threashold law $\sigma \sim k^{-4l}$

Square well case





Basic scattering theory – for neutrons



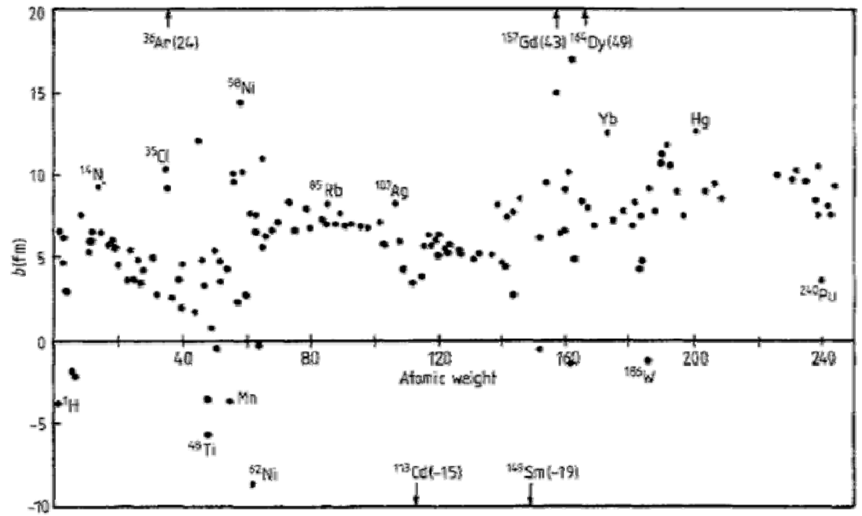


Figure 7. This diagram shows the distribution of scattering lengths as a function of atomic weight. Note that 1 fm = 10^{-13} cm. Data taken from the compilation of Koester and Rauch (1981).

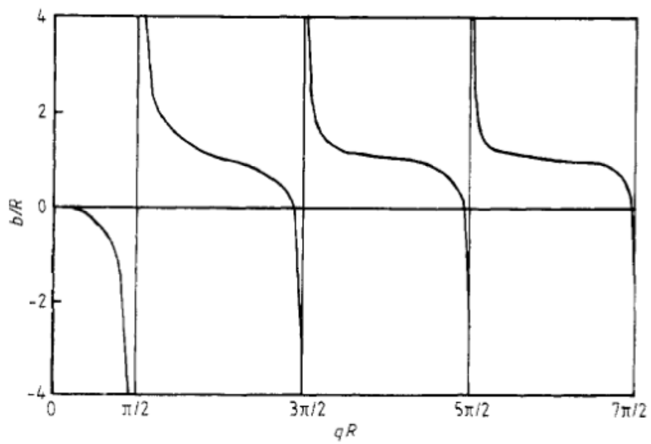


Figure 6. A plot of the ratio of the scattering length b to the nuclear radius R as a function of qR, where q is proportional to the square root of the depth of the nuclear potential well.

the s wave scattering length

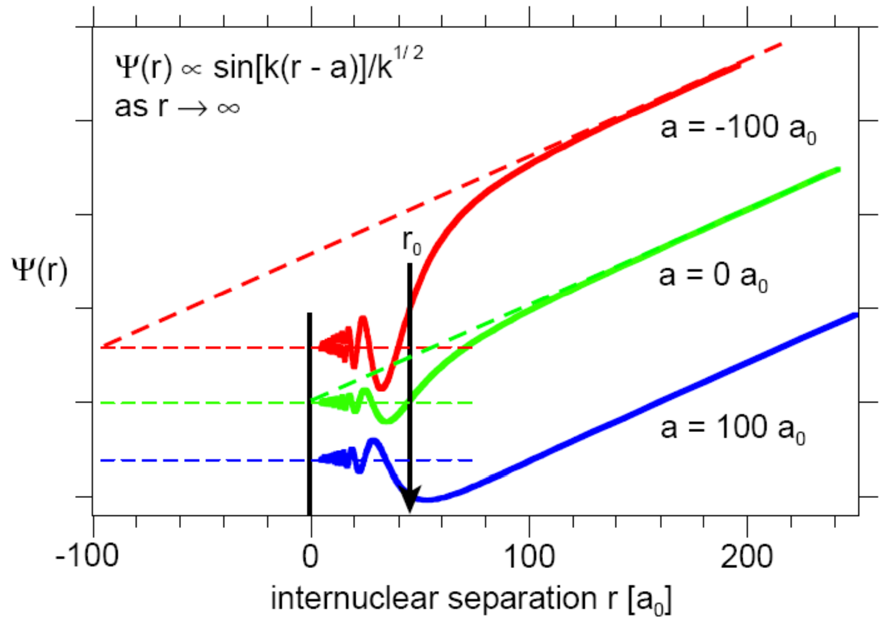
low energy scattering

$$\sigma_0(k) = \frac{4\pi}{k^2} \sin^2 \delta_0(k).$$

Definition

$$a = -\lim_{k\to 0} \frac{\tan \delta_0(k)}{k}$$

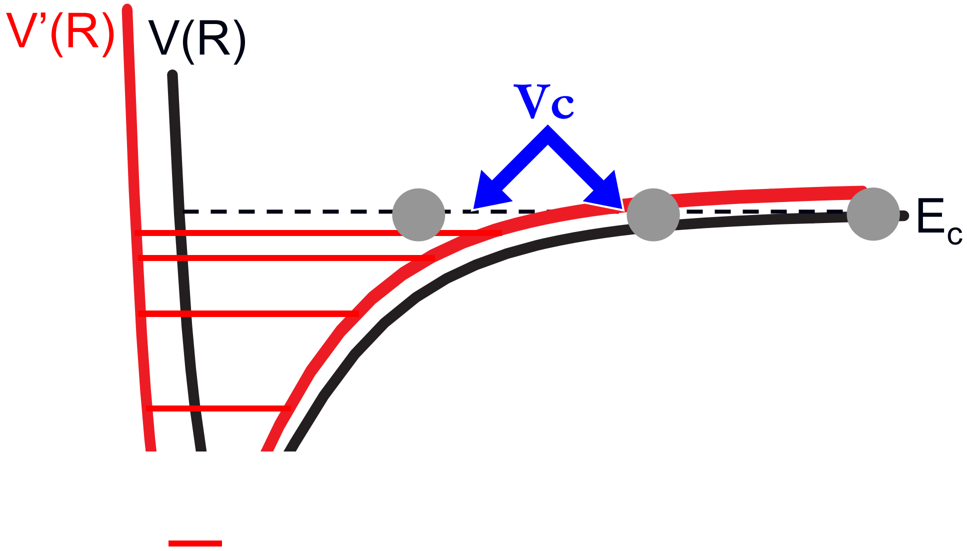
$$\underset{\text{square well}}{=} \left[1 - \frac{\tan \lambda_0 r_0}{\lambda_0 r_0}\right] r_0,$$



Feshbach resonances

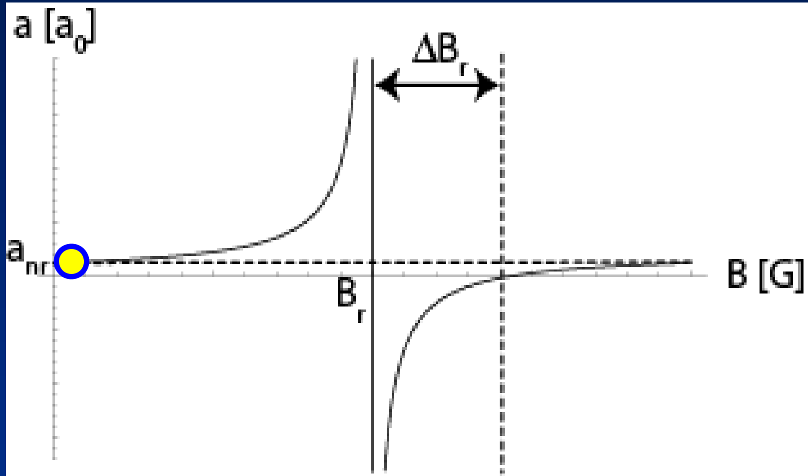
collision with molecular potential V(R):

V'(R) with $M_{s'} \neq M_s$ + B-field + coupling:



⇒ a ! describes scattering @ low T

⇒ a is modified !

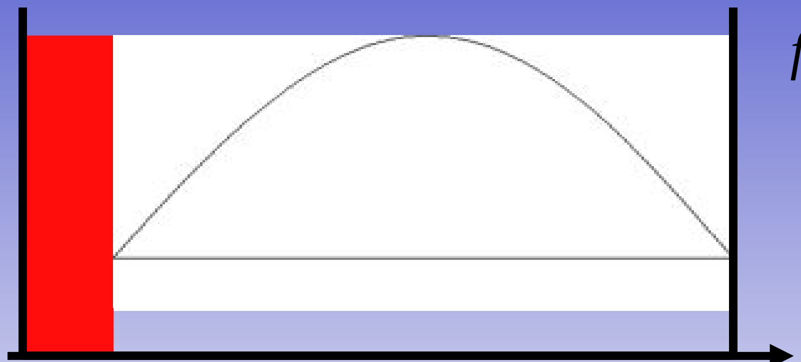


$$a_{FB}(B) = a_{nr}\left(1 - \frac{\Delta B_r}{B - B_r}\right)$$

scattering length a can be tuned with B-field !

Effect of contact interaction

Two particles in a box potential (s-wave)



$$for \quad a << b$$

$$E_{n=1} = \frac{\hbar^2 k^2}{2m_\mu} = \frac{\hbar^2}{2m_\mu}\frac{\pi^2}{(b-a)^2} = \frac{\hbar^2}{2m_\mu}\frac{\pi^2}{b^2}(1-\frac{a}{b})^{-2}$$

$$\approx E(a=0) + \frac{\hbar^2}{2m_\mu}\frac{\pi^2}{b^3}a$$

$$\Rightarrow \quad \boxed{E_{contact} = \frac{4\pi\hbar^2}{m}|\psi|^2 a}$$

Periodic table

of magnetic moments

					2004												
H 1																	He 0
Li 1	Be 0											B 0.3	C 0	N 3	O 3	F 2	Ne 0
Na 1	Mg 0											Al 0.3	Si 0	P 3	S 3	Cl 2	Ar 0
K 1	Ca 0	Sc 1.2	Ti 1.3	V 0.6	Cr 6	Mn 5	Fe 6	Co 6	Ni 5	Cu 1	Zn 0	Ga 0.3	Ge 0	As 3	Se 3	Br 2	Kr 0
Rb 1	Sr 0	Y 1.2	Zr 1.3	Nb 1.7	Mo 6	Tc 5	Ru 7	Rh 6	Pd 0	Ag 1	Cd 0	In 0.3	Sn 0	Sb 3	Te 3	I 2	Xe 0
Cs 1	Ba 0		Hf 1.3	Ta 0.6	W 0	Re 5	Os 6	Ir 6	Pt 4	Au 1	Hg 0	Tl 0.3	Pb 0	Bi 3	Po 3	At 2	Rn 0
Fr 1	Ra 0		Rf 1.3	Db 0.6	Sg 0	Bh 5	Hs 6	Mt 6	Ds 4	Rg 1	Cn 0	Uut 0.3	Uuq 0	Uup 3	Uuh 3	Uus 2	Uuo 0

									2011		2012			
La 1.2	Ce 4	Pr 3.3	Nd 2.4	Pm 0.7	Sm 0	Eu 7	Gd 5.3	Tb 10	Dy 10	Ho 9	Er 7	Tm 4	Yb 0	Lu 1.2
Ac 1.2	Th 1.3	Pa 4.2	U 4.3	Np 3.4	Pu 0	Am 7	Cm 5.3	Bk 10	Cf 10	Es 9.1	Fm 7	Md 4	No 0	Lr 0.3

Periodic table
of magnetic moments

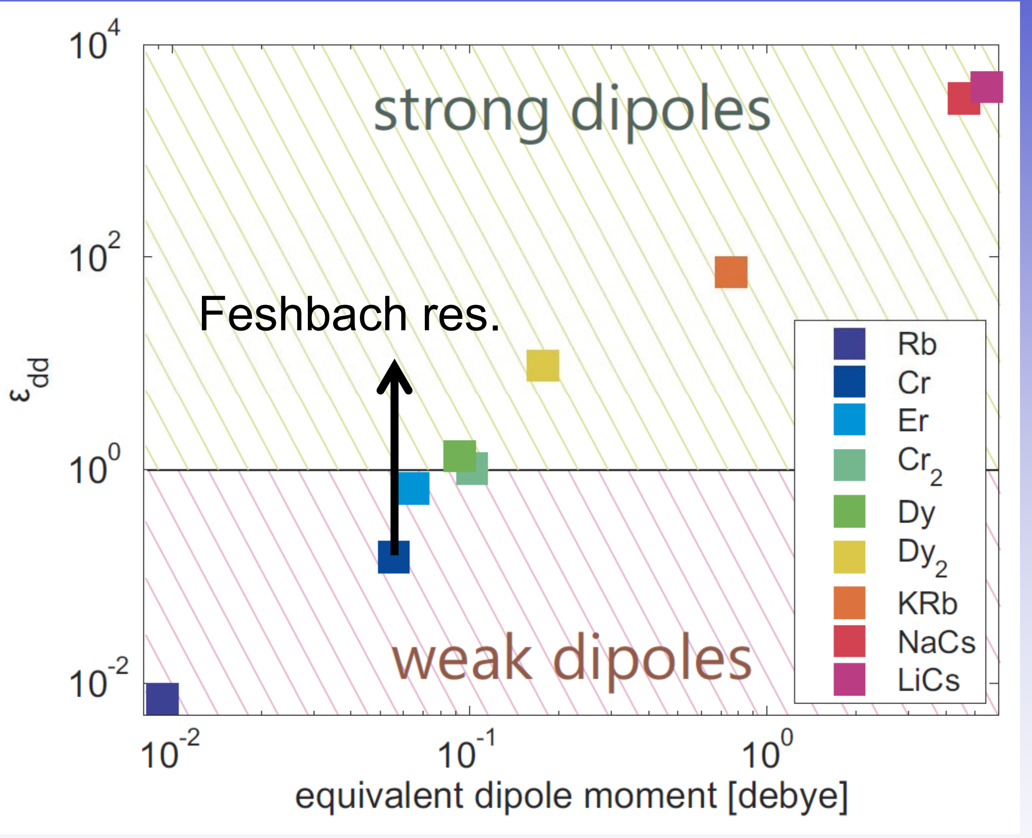
$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 m}{12\pi\hbar^2 a_{bg}}$$

2004

H 1																	He 0
Li 7	Be 0											B 1	C 0	N 126	O 144	F 76	Ne 0
Na 23	Mg 0											Al 3	Si 0	P 279	S 289	Cl 142	Ar 0
K 39	Ca 0	Sc 65	Ti 85	V 18	Cr 1872	Mn 1373	Fe 2010	Co 2122	Ni 1467	Cu 64	Zn 0	Ga 8	Ge 0	As 674	Se 711	Br 320	Kr 0
Rb 85	Sr 0	Y 128	Zr 162	Nb 258	Mo 3455	Tc 2450	Ru 4952	Rh 3705	Pd 0	Ag 108	Cd 0	In 13	Sn 0	Sb 1096	Te 1148	I 508	Xe 0
Cs 133	Ba 0		Hf 317	Ta 65	W 0	Re 4655	Os 6848	Ir 6920	Pt 3121	Au 197	Hg 0	Tl 23	Pb 0	Bi 1881	Po 1881	At 840	Rn 0
Fr 223	Ra 0		Rf 471	Db 96	Sg 0	Bh 6800	Hs 9720	Mt 9936	Ds 4496	Rg 280	Cn 0	Uut 32	Uuq 0	Uup 2592	Uuh 2637	Uus 1176	Uuo 0

2011 2012

La 200	Ce 2242	Pr 1509	Nd 831	Pm 74	Sm 0	Eu 7446	Gd 4473	Tb 15893	Dy 16250	Ho 13359	Er 8196	Tm 2703	Yb 0	Lu 252
Ac 327	Th 413	Pa 4135	U 4372	Np 2715	Pu 0	Am 11907	Cm 7026	Bk 24700	Cf 25100	Es 21017	Fm 12593	Md 4128	No 0	Lr 29



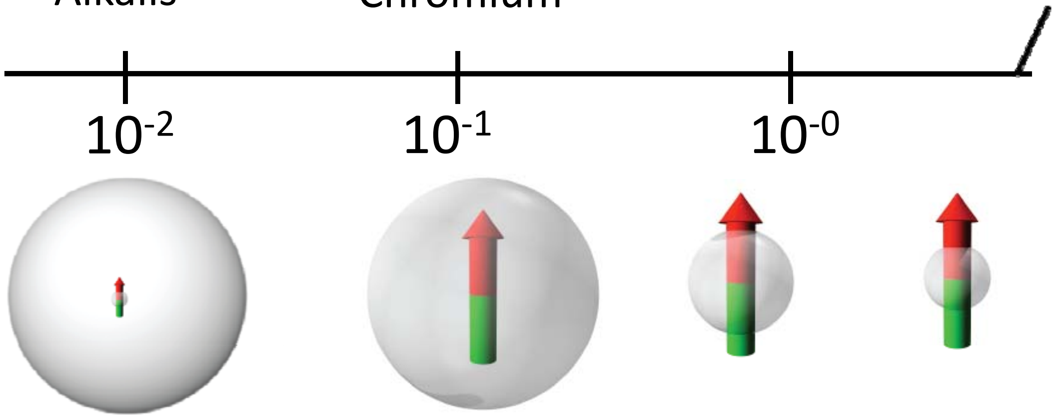
strong dipoles
weak dipoles
Feshbach res.
10^4
10^2
10^0
10^{-2}
ε_{dd}
10^{-2}
10^{-1}
10^0
equivalent dipole moment [debye]
Rb
Cr
Er
Cr_2
Dy
Dy_2
KRb
NaCs
LiCs

dipolar interaction

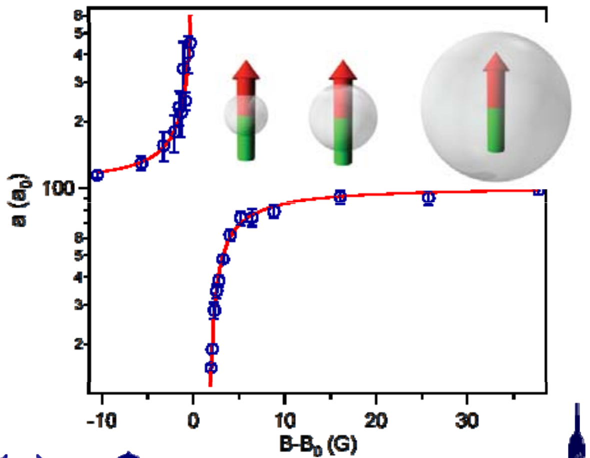
$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 m}{12\pi\hbar^2 a_{bg}}$$

BEC 2004
first mechanical dipolar effects 2005

Alkalis   Chromium



Feshbach resonance →



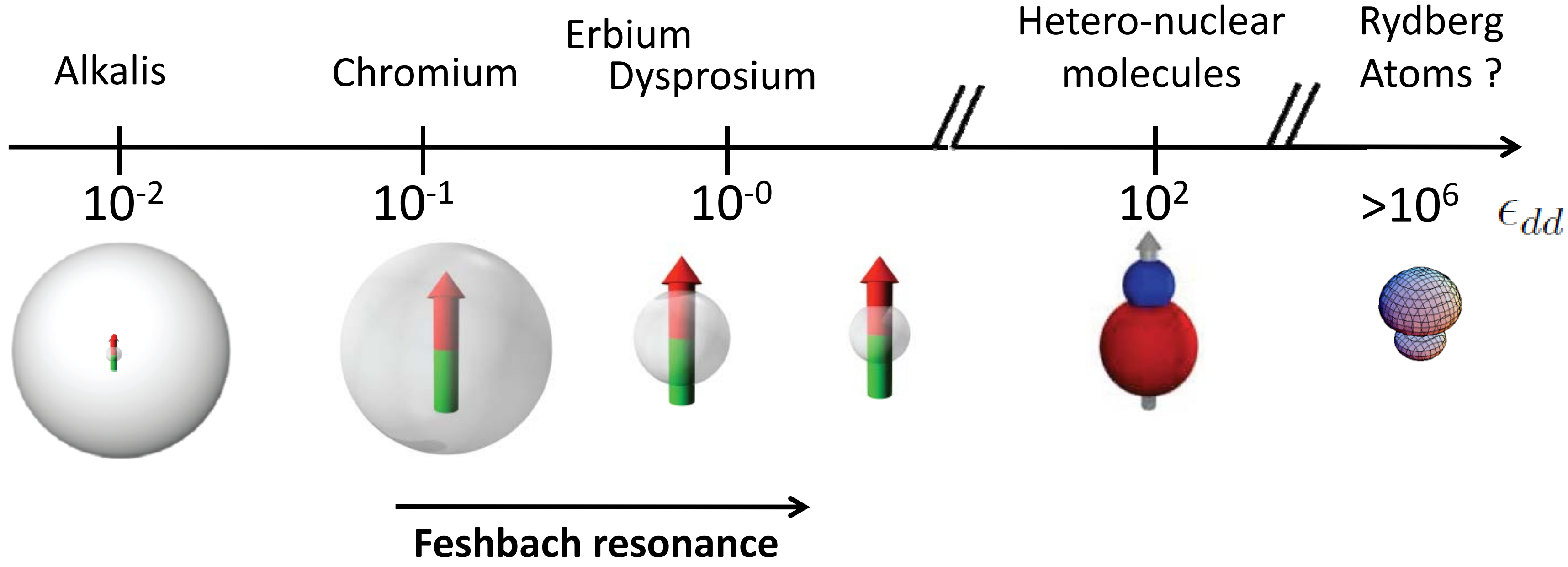
→ *Realization of a purely dipolar condensate*

T. Lahaye *et al.*, Nature **448**, 672 (2007)

T. Koch, *et al.*, Nature Physics **4**, 218 (2008)

dipolar interaction

$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 m}{12\pi\hbar^2 a_{bg}}$$



→ *Realization of a purely dipolar condensate*

T. Lahaye *et al.*, Nature **448**, 672 (2007)

T. Koch, *et al.*, Nature Physics **4**, 218 (2008)

How to describe an interacting quantum gas

5. Physikalisches Institut

Gross-Pitaevskii equation for the order parameter:

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\triangle\psi + \left(V_{\text{ext}} + g|\psi|^2 + \Phi_{\text{dd}}(\boldsymbol{r},t)\right)\psi$$

$$g \equiv \frac{4\pi\hbar^2 a}{m}$$

Contact interaction

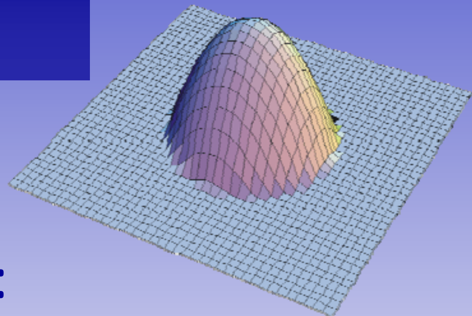
$$\Phi_{\text{dd}}(\boldsymbol{r},t) = \int |\psi(\boldsymbol{r}',t)|^2\, U_{\text{dd}}(\boldsymbol{r}-\boldsymbol{r}')\,\mathrm{d}^3r'$$

Dipolar interaction
NON-LOCAL term

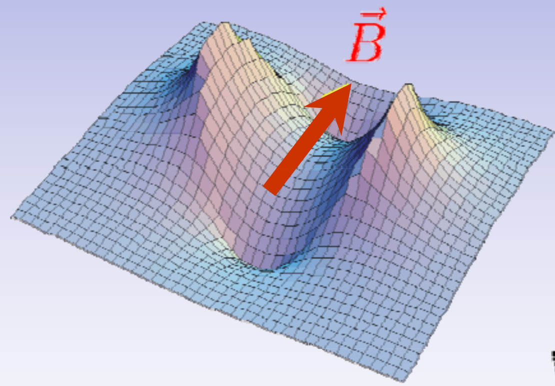
$$U_{\text{dd}}(\boldsymbol{r}) = \frac{\mu_0\mu^2}{4\pi}\frac{1-3\cos^2\theta}{r^3}$$

Elongation of the condensate along *B*

$\varepsilon_{dd} << 1$, spherical trap:



Mean-field potential due to the dipolar interaction:



Saddle potential.

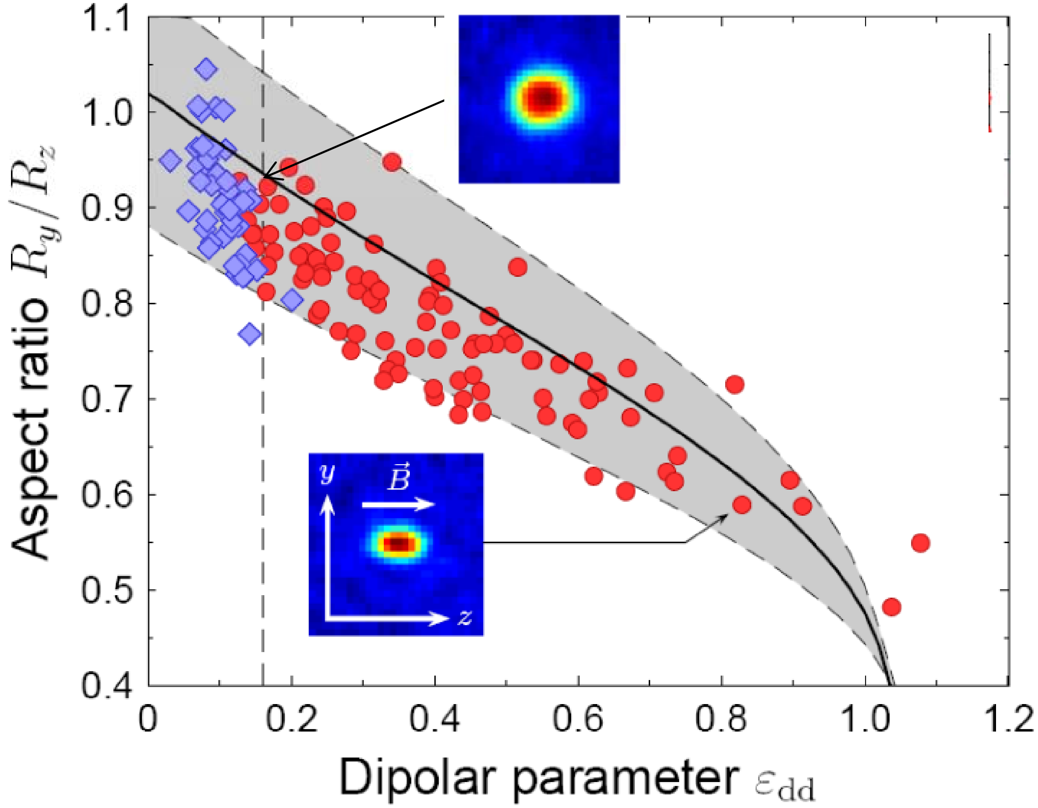
→ The atoms are accommodated **close to the *z* axis**.

These conclusions remain valid:

- for anisotropic traps,
- for arbitrary ε_{dd},
- during the time of flight.

S. Giovanazzi
D. O'Dell
C. Eberlein

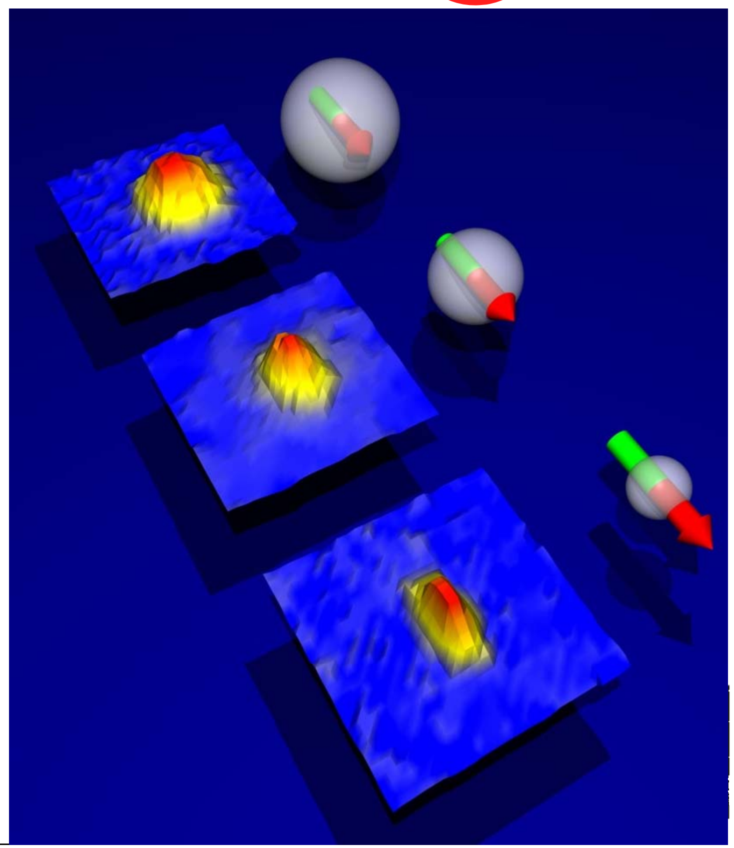
A quantum ferrofluid



dipolar

$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

contac



T. Lahaye, T. Koch, B. Fröhlich,
M. Fattori, J. Metz, A. Griesmaier,
S. Giovanazzi, T. Pfau;
Nature **448**, 672 (2007)

RAPID COMMUNICA

PHYSICAL REVIEW A, VOLUME 61, 051601(R)

Bose-Einstein condensation with magnetic dipole-dipole forces

Krzysztof Góral,[1] Kazimierz Rzążewski,[1] and Tilman Pfau,[2,*]
[1]Center for Theoretical Physics and College of Science, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland
[2]Faculty of Physics, University of Konstanz, 78457 Konstanz, Germany
(Received 20 July 1999; revised manuscript received 1 October 1999; published 24 March 2000)

Ground-state solutions in a dilute gas interacting via contact and magnetic dipole-dipole forces are investigated. To the best of our knowledge, it is the first example of studies of Bose-Einstein condensation in a system with realistic long-range interactions. We find that for the magnetic moment of, e.g., chromium ($6\mu_B$), and a typical value of the scattering length, all solutions are stable and only differ in size from condensates without long-range interactions. By lowering the value of the scattering length we find a region of unstable solutions. In the neighborhood of this region, the ground-state wave functions show internal structures that we believe have not been seen before in condensates. Finally, we find an analytic estimate for the characteristic length appearing in these solutions.

PACS number(s): 03.75.Fi, 05.30.Jp

L. Santos, G. Shlyapnikov, P. Zoller, M. Lewenstein, PRL **85**, 1791 (2000).

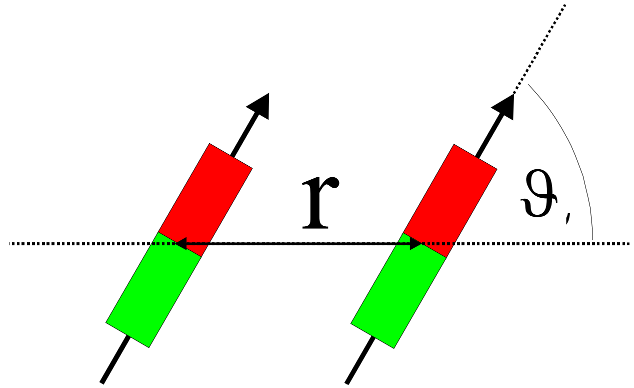
Stabilization of a dipolar gas

polarized sample

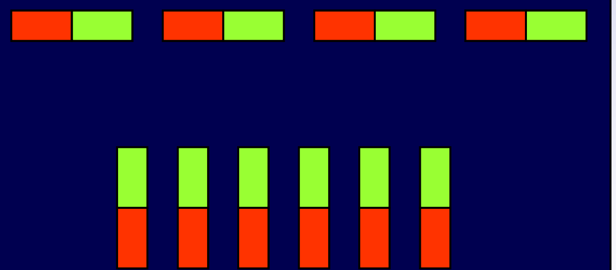
$$V_{dd}(r) \propto \frac{d^2}{r^3}(1-3\cos^2\vartheta)$$

long range

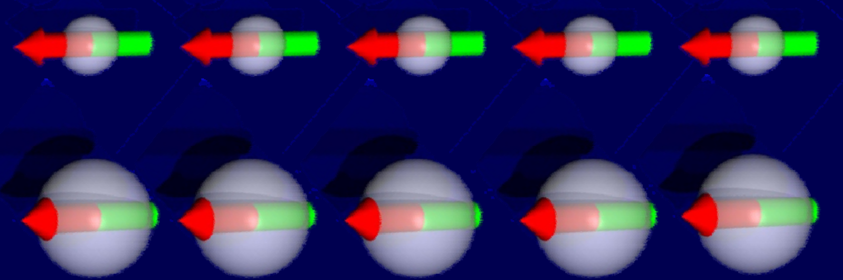
anisotropic



by geometry



by contact interaction



The stability of a dipolar condensate…

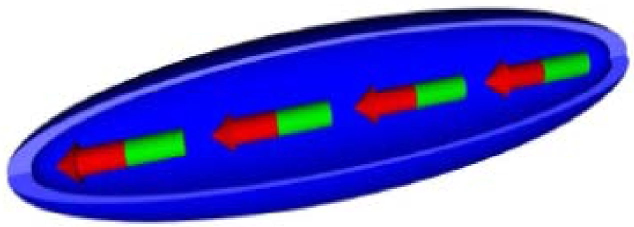
…depends *strongly* on the trap geometry:

$$V(x,y,z) = \frac{m}{2}\left[\omega_\rho^2(x^2+y^2)+\omega_z^2 z^2\right]$$

Aspect ratio: $\lambda \equiv \frac{\omega_z}{\omega_\rho}$

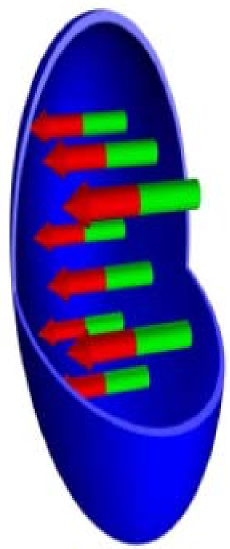
Cigar-shaped

$\lambda < 1$



Pancake

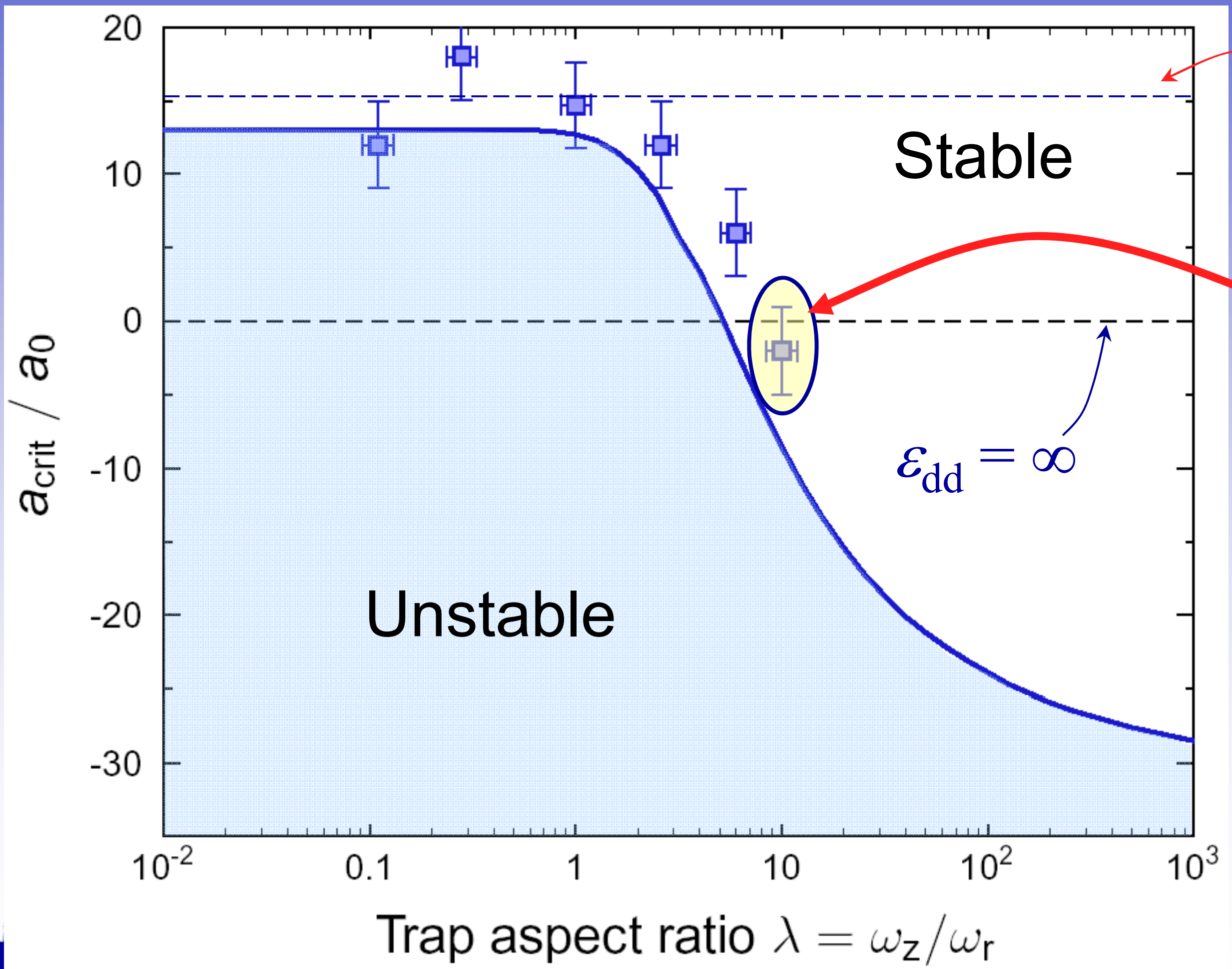
$\lambda > 1$



Attractive: unstable

Repulsive: stable

Stability diagram



$\varepsilon_{dd} = 1$

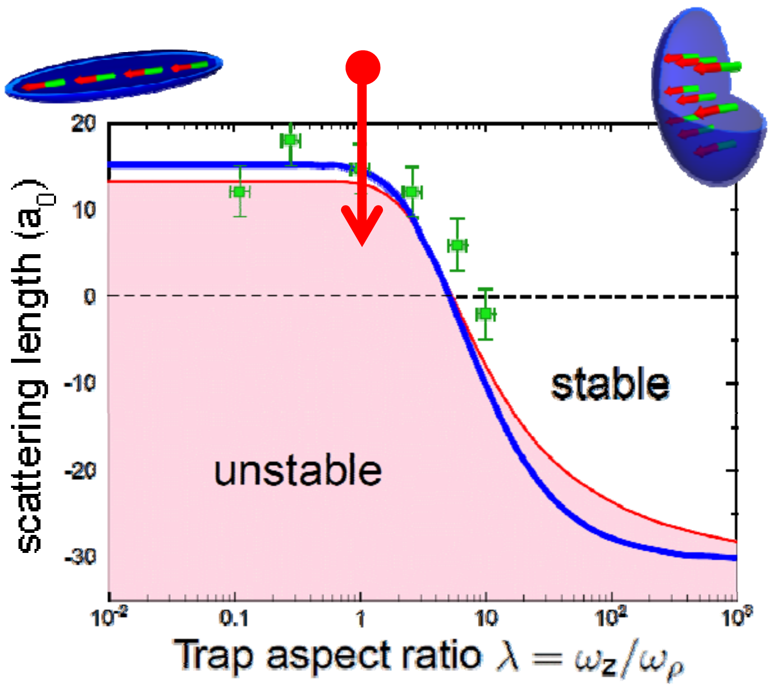
Stabilization of a purely dipolar condensate!

T. Koch *et al.*, arXiv:0710

Stability & collapse of a dipolar BEC

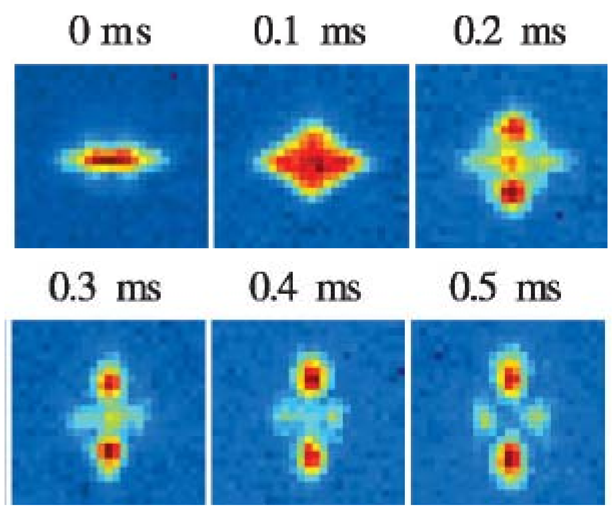
dipole-dipole interaction:
long-range and anisotropic

$\rightarrow$ *geometry-dependent stability / collapse*



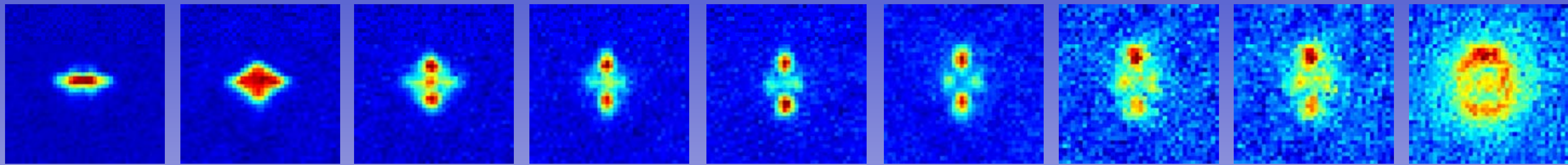
T. Koch *et al., Nat. Phys.* **4** (2008)

d-wave collapse

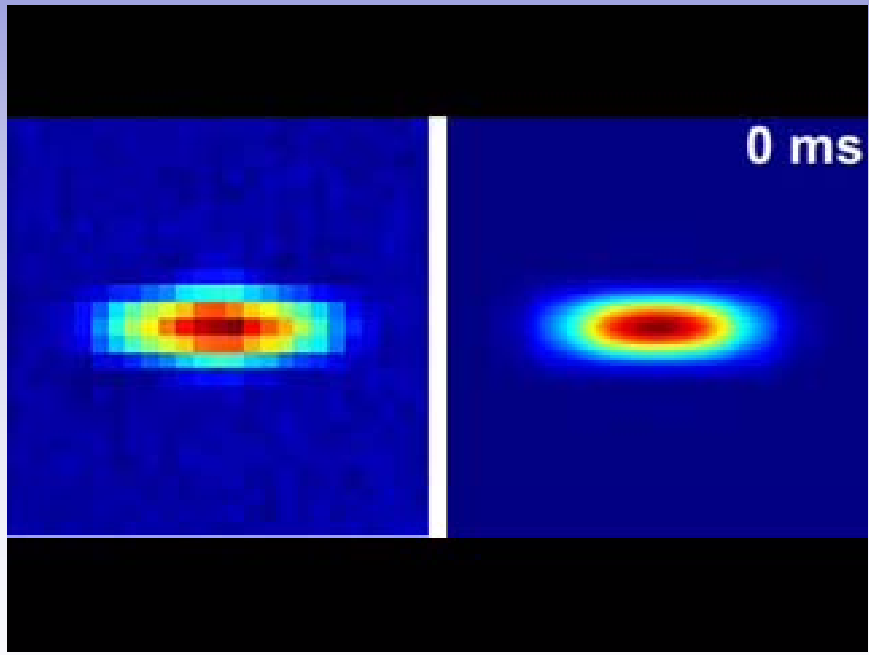


T. Lahaye et al., PRL ***101*** *(2008)*
J. Metz et al., New J. Phys. ***11*** *(2009)*

Collapse dynamics



0 ms 0.1 ms 0.2 ms 0.3 ms 0.4 ms 0.5 ms 0.6 ms 0.7 ms 0.8 ms



*T. Lahaye, M. Ueda et al., PRL **101** (2008)*

Atomwolken wie Kleeblätter geformt

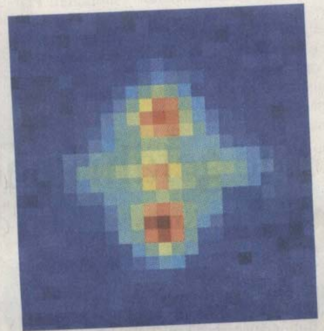
FAZ 27.8.08

Der Tanz nach dem großen Kollaps: Bei der Explosion von Bose-Einstein-Kondensaten aus magnetischen Teilchen prägen die magnetischen Kräfte das Bild.

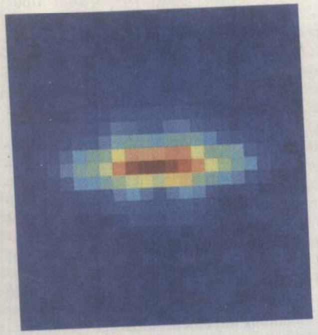
Atomare Gase verhalten sich eigenartig, wenn sie auf extrem tiefe Temperaturen gekühlt werden. In der Nähe des absoluten Nullpunkts geben die Atome plötzlich ihre Individualität auf und stimmen ihr Verhalten perfekt aufeinander ab. Es entstehen Bose-Einstein-Kondensate, an denen sich viele physikalische Phänomene studieren lassen – bei nahezu perfekter Kontrolle aller wichtigen Parameter. Beispiele sind das reibungslose Fließen von Supraflüssigkeiten oder der widerstandslose elektrische Stromfluss in Supraleitern. Von den Experimenten erhoffen sich die Wissenschaftler neue Einblicke in die noch immer rätselhafte Hochtemperatur-Supraleitung. Ein mitunter überraschendes Verhalten legen Bose-Einstein-Kondensate aus magnetischen Atomen – Atomen mit magnetischem Moment – an den Tag, die sich seit kurzem herstellen lassen. Das haben jetzt Wissenschaftler der Universität Stuttgart beobachtet. Die Kondensate kollabieren, und gleich darauf fliegen sie wieder in Form eines Kleeblatts auseinander.

Explosionen von extrem kalten Quantengasen hatten die späteren Nobelpreisträger Eric Cornell und Carl Wieman an der University of Colorado in Boulder erstmals vor sieben Jahren beobachtet. Die Kondensate, die aus Atomen des Isotops Rubidium-85 bestanden, kollabierten, wenn die Atome sich stark anzogen. Die beiden Forscher verstärkten dazu die zwischen den Atomen wirkenden elektrischen Kräfte mit einem äußeren Magnetfeld. Nach dem Kollaps dehnte sich die Atomwolke explosionsartig in alle Richtungen aus. Wieman hatte den Explosionen deshalb den scherzhaften Namen „Bose-Nova" verliehen.

Für den Ablauf einer Bose-Nova haben die Forscher folgende Erklärung: Kollabiert das Bose-Einstein-Kondensat, wird es verdichtet. Das schränkt zum einen die Bewegungsfreiheit der Atome ein, wodurch nach der Heisenbergschen Unschärfebeziehung die Geschwindigkeit der Atome so groß wird, dass viele Teilchen aus der Wolke entweichen können. Zum anderen kollidieren die Atome häufiger, und es treten mehr Kollisionen von drei Atomen auf. Aus kinematischen Gründen kann nur dann, wenn mindestens drei Atome aufeinandertreffen, eines davon entfliehen.



Nach 0,2 Millisekunden Fotos Phys. Rev. Lett.



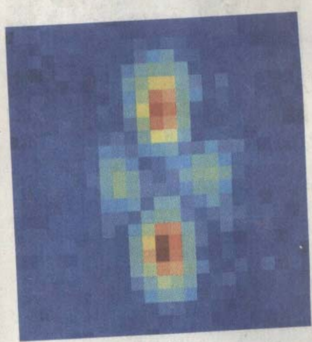
der Explosion

Eine kleeblattförmige Wolke, wie sie die Stuttgarter Forscher um Tilman Pfau jetzt bei der Explosion von Bose-Einstein-Kondensaten aus magnetischen Atomen beobachtet haben, hatte man mit unmagnetischen Atomen nicht feststellen können. Das liegt daran, dass sich die beiden Atomarten bei Kollisionen unterschiedlich verhalten. Stoßen zwei unmagnetische Atome zusammen, gleichen sie perfekten Kugeln, deren räumliche Orientierung auf den Verlauf der Kollision keinen Einfluss hat. Magnetische Atome üben zusätzlich zu der bei Kollisionen wirkenden elektrischen Kraft auch noch eine richtungsabhängige magnetische Kraft aufeinander aus. Setzt man eine Wolke aus magnetischen Atomen einem starken äußeren Magnetfeld aus, dann zeigen die magnetischen Momente der Atome alle in ein und dieselbe Richtung. Wenn zwei Momente nebeneinanderliegen, so stoßen sie sich ab. Sind sie hingegen hintereinander aufgereiht, dann ziehen sie sich an. Wie eine Kollision zwischen magnetischen Atomen verläuft, hängt deshalb vor allem von ihrer räumlichen Anordnung ab.

Für ihre Experimente haben Tilman Pfau und seine Kollegen ein Bose-Einstein-Kondensat aus etwa 20 000 magnetischen Chrom-52-Atomen hergestellt und in einer Magnetfalle festgehalten. Dabei konnten sie der Atomwolke die Gestalt einer Zigarre oder eines Pfannkuchens aufprägen. In einer pfannkuchenförmigen Wolke lagen die magnetischen Momente zumeist nebeneinander, wodurch sich die Atome abstießen und es somit zu keiner Explosion kam. Das änderte sich, wenn die Atomwolke die Form einer Zigarre annahm. Nun waren die Atome und deren magnetische Momente überwiegend hintereinander angeordnet und zogen sich an. Die Wolke kollabierte.

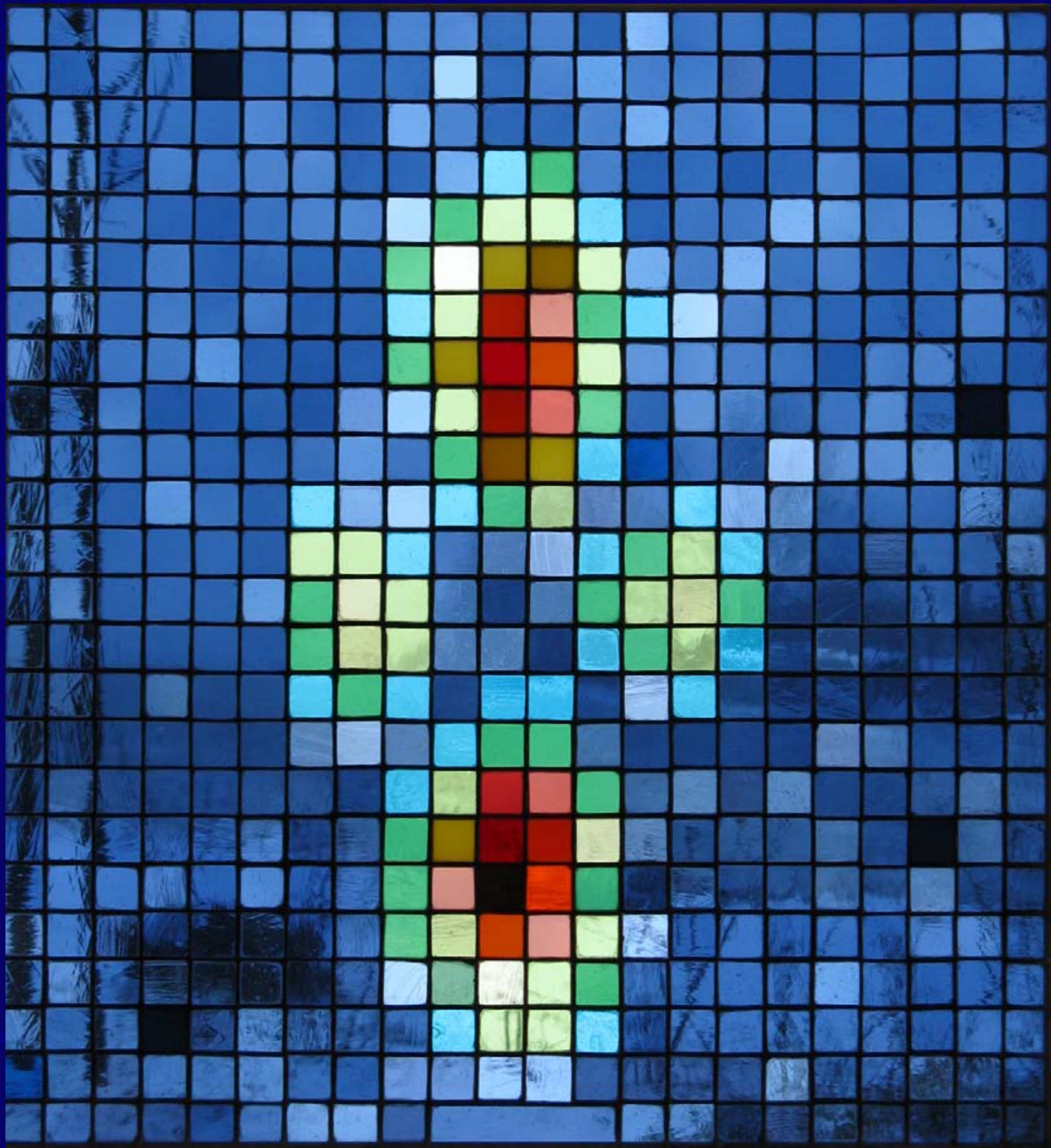
Das zigarrenförmige Kondensat stürzte in weniger als einer Millisekunde in sich zusammen, wobei es zunächst einem etwa drei Mikrometer langen, hauchdünnen Faden glich. Die darauf folgende Explosion führte dazu, dass die Wolke bevorzugt in bestimmte Richtungen expandierte. Dabei nahm sie schließlich die Form eines vierblättrigen Kleeblatts an, berichten die Forscher in den „Physical Review Letters" (Bd. 101, Nr. 080401).

Mit Computersimulationen, die die zwischen den Atomen wirkenden Kräfte berücksichtigen, konnten die Wissenschaftler die Kleeblattform der explodierenden Atomwolken reproduzieren. Die



Nach 0,5 Millisekunden

Rechnungen zeigten zudem, dass sich die Atome in den einzelnen Blättern in unter- schiedlichen Richtungen bewegen soll- ten. Dabei kann es zur Bildung von Wir- belringen kommen, wie man sie vom Zi- garrenrauch her kennt. Diese Wirbel wol- len die Forscher künftig auch experimen- tell nachweisen. RAINER SCHAR



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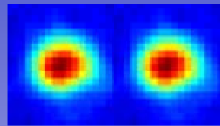
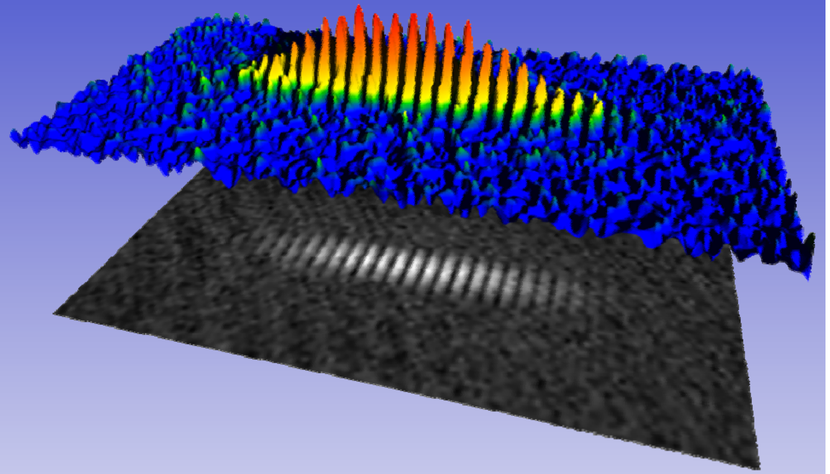
zwischen den Atomen wirkenden Kräfte berücksichtigen, konnten die Wissenschaftler die Kleeblattform der explodierenden Atomwolken reproduzieren. Die

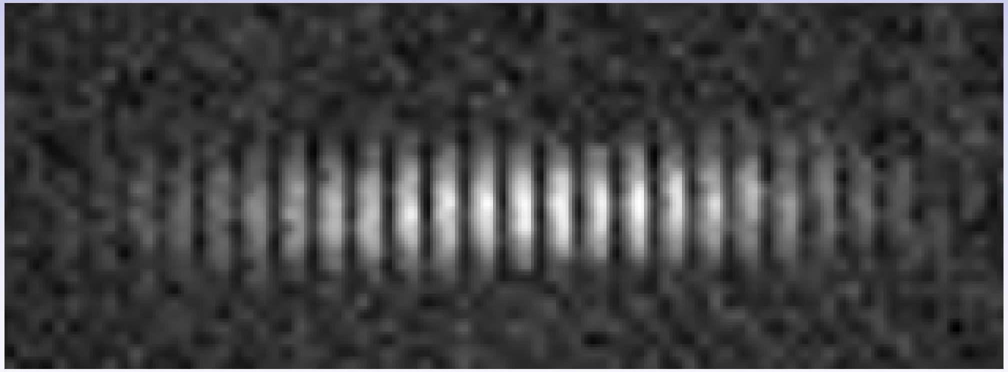
Nach 0,5 Millisekunden

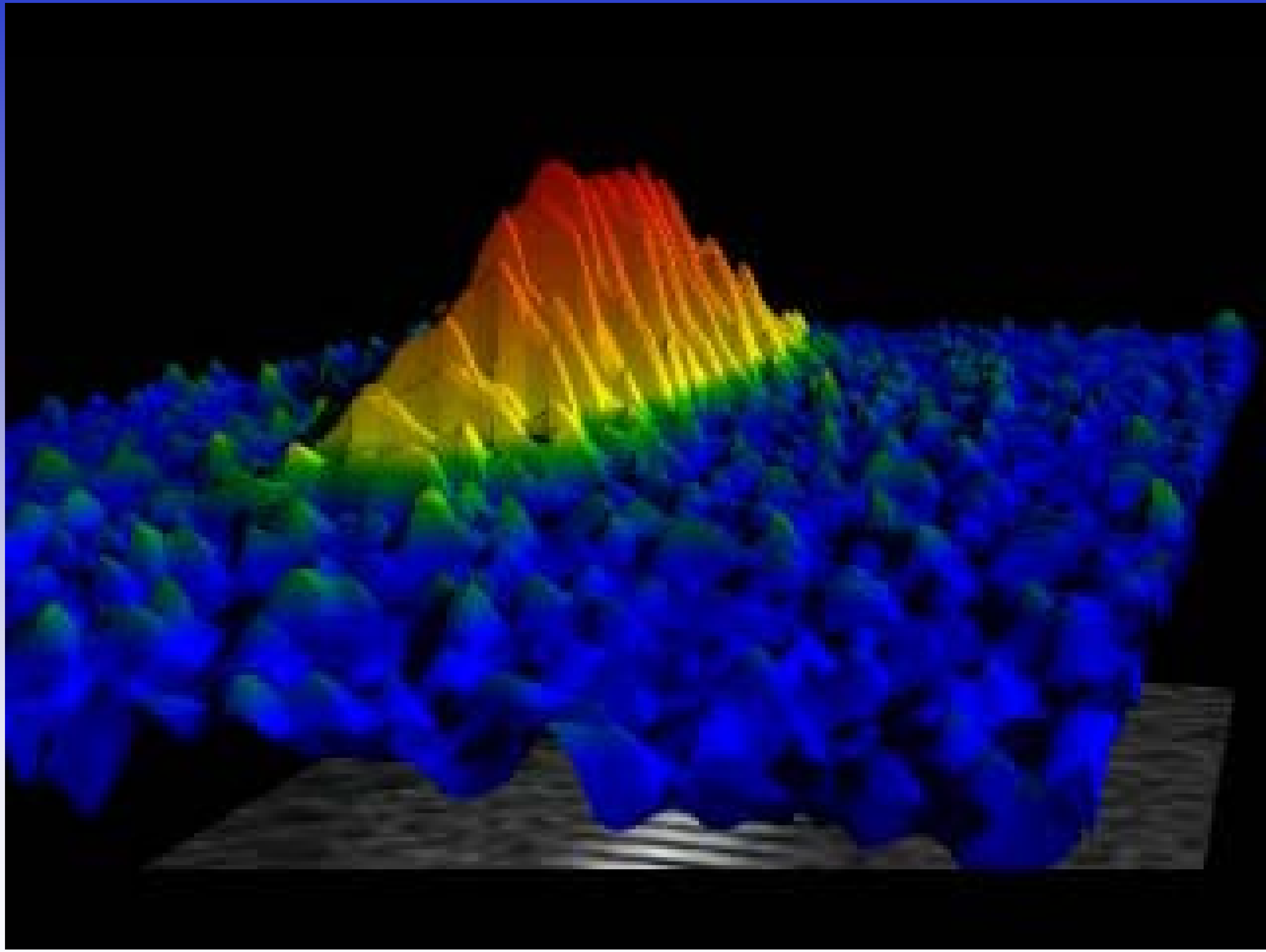
Brigitte Simon, Lohmar

Is the collapse coherent?

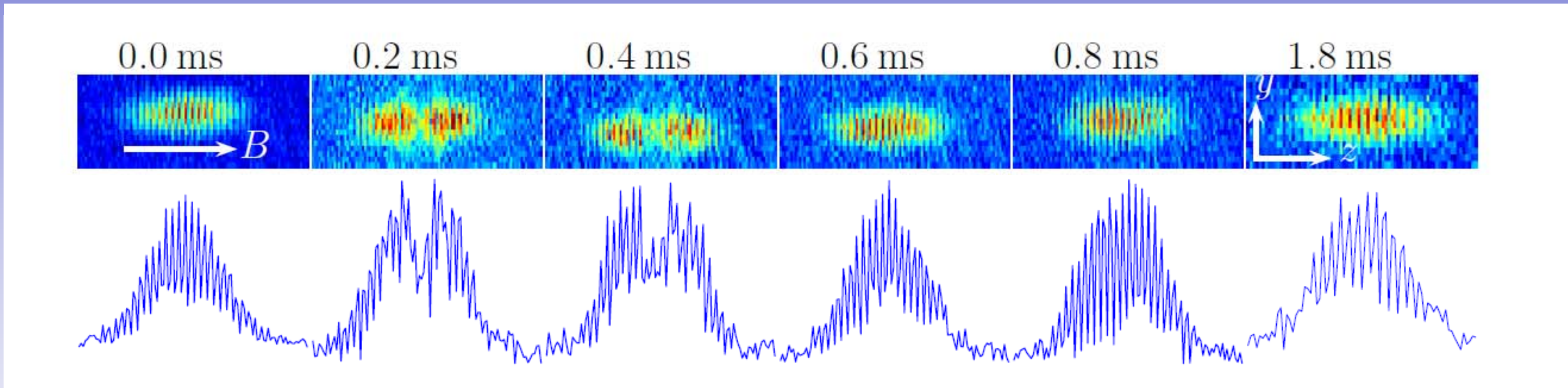






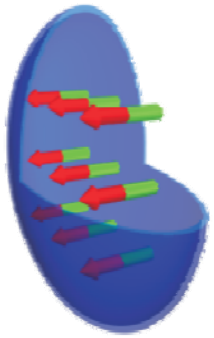


Coherent collapse dynamics



J. Metz, T. Lahaye, B. Fröhlich, A. Griesmaier, T. Pfau, H. Saito, Y. Kawaguchi, and M. Ueda
New J. Phys. ***11***, *055032 (2009)*

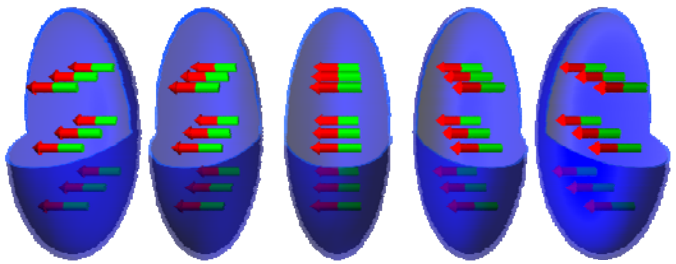
Stability of a dipolar BEC



Interactions:

- contact interaction (scattering length *a):*
  tuned via Feshbach resonance
  isotropic and short-range

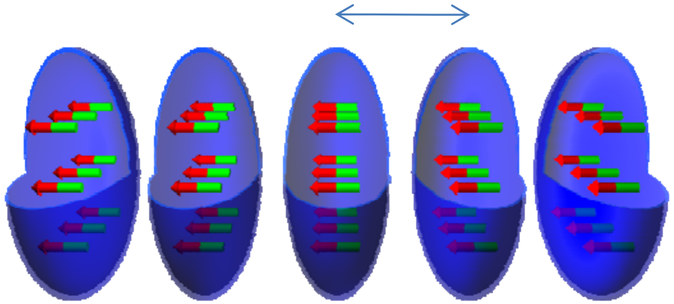
- dipole-dipole interaction (DDI):
  anisotropic and long-range



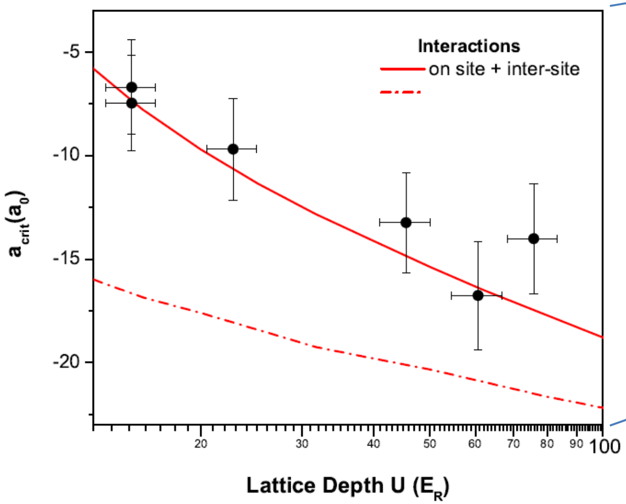
Multi-well potentials:
inter-site interaction mediated by DDI

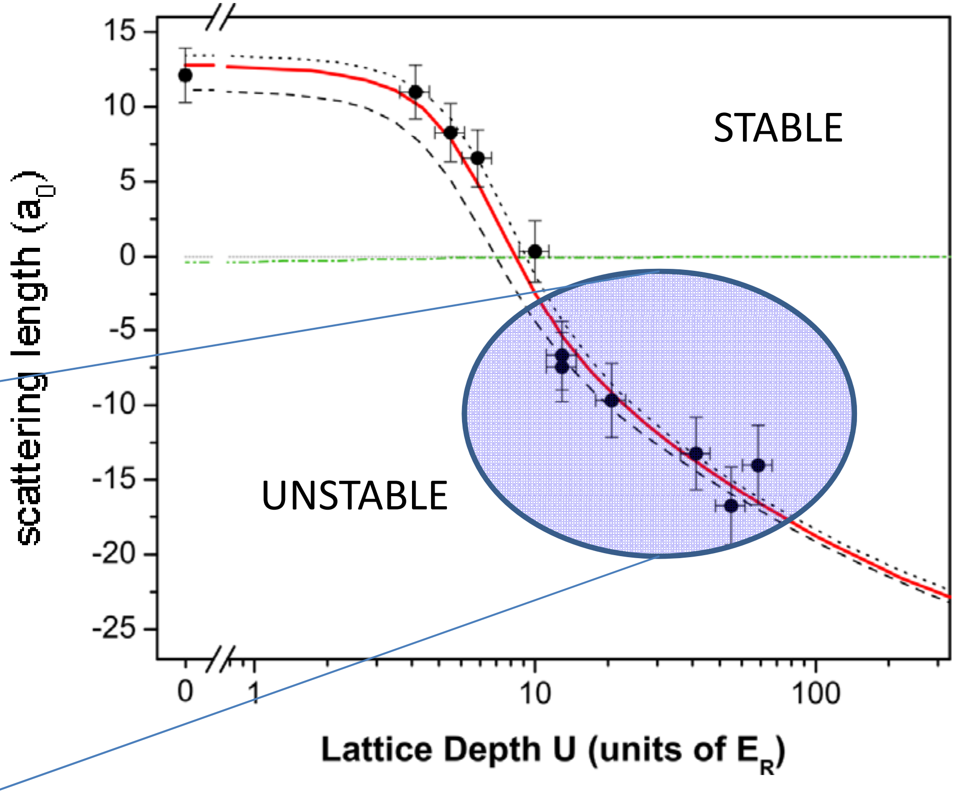
Stability given by energy balance between
- on-site interaction (contact + DDI)
- inter-site interaction (DDI)

A dipolar BEC in a 1D optical lattice



Confinement: lattice + optical trap



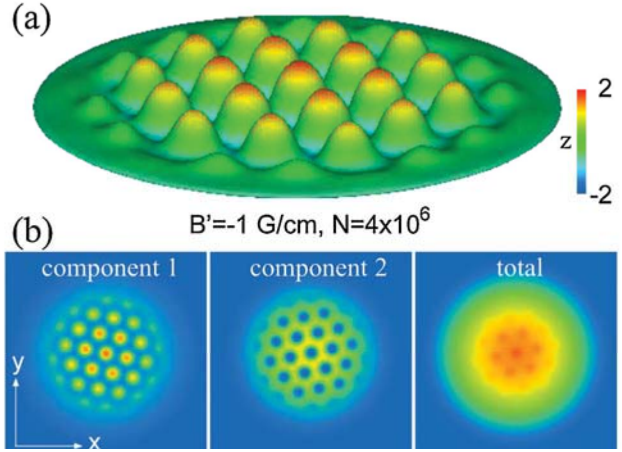


S. Müller et al., PRA 84, 053601 (2011)

Outlook: Stronger dipoles - ferrofluid

Classical

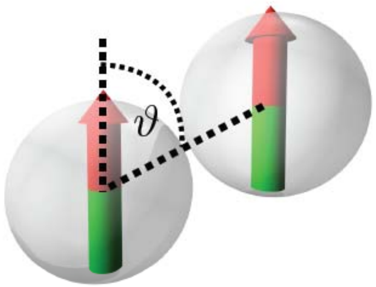
Quantum



H. Saito, Y. Kawaguchi, and M. Ueda
Phys. Rev. Lett. **102**, 230403 (2009)

Interactions in ultracold gases

Dipolar gases



$$\varepsilon_{dd} \propto \frac{m\boxed{\mu^2}}{\boxed{a}}$$

dipolar interaction

contact interaction

	Chromium	Erbium	Dysprosium
Magnetic moment μ	6 μ_B	7 μ_B	10 μ_B
$\varepsilon_{dd} = \dfrac{\mu_0 \mu^2 m}{12\pi\hbar^2 a_{bg}}$	0.16	0.33-0.45	≈ 1

Degenerate Erbium

K. Aikawa et al., PRL **108**, 210401 (2012)

K. Aikawa et al., PRL **112**, 010404 (2014)

Degenerate Dysprosium

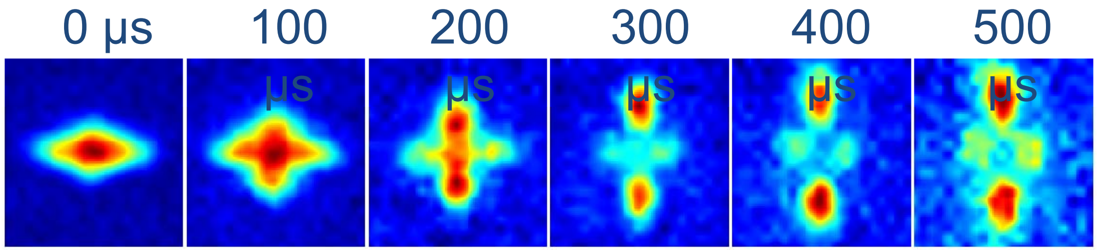
M. Lu et al., PRL **107**, 190401 (2011)

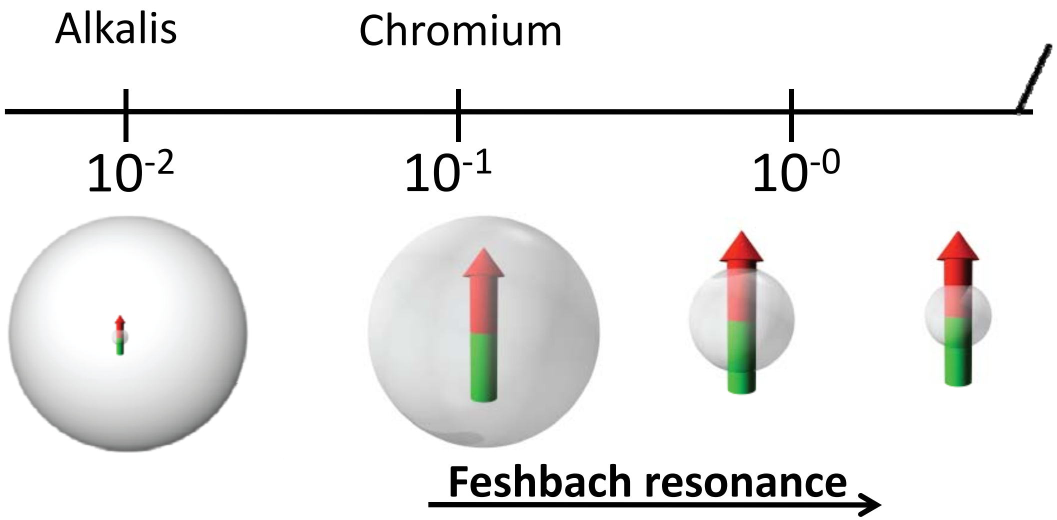
M. Lu et al., PRL **108**, 215301 (2012)

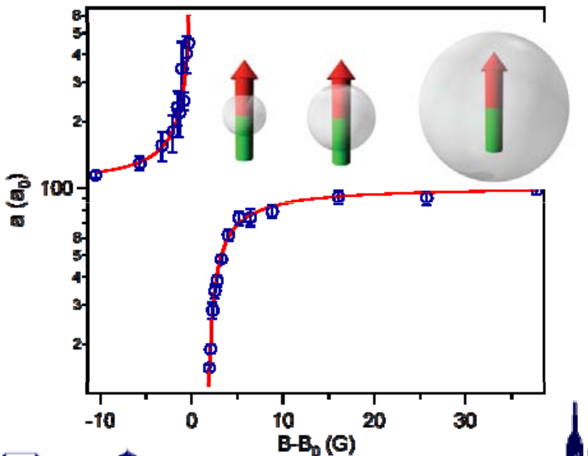
The Team

Matthias Wenzel

dipolar interaction





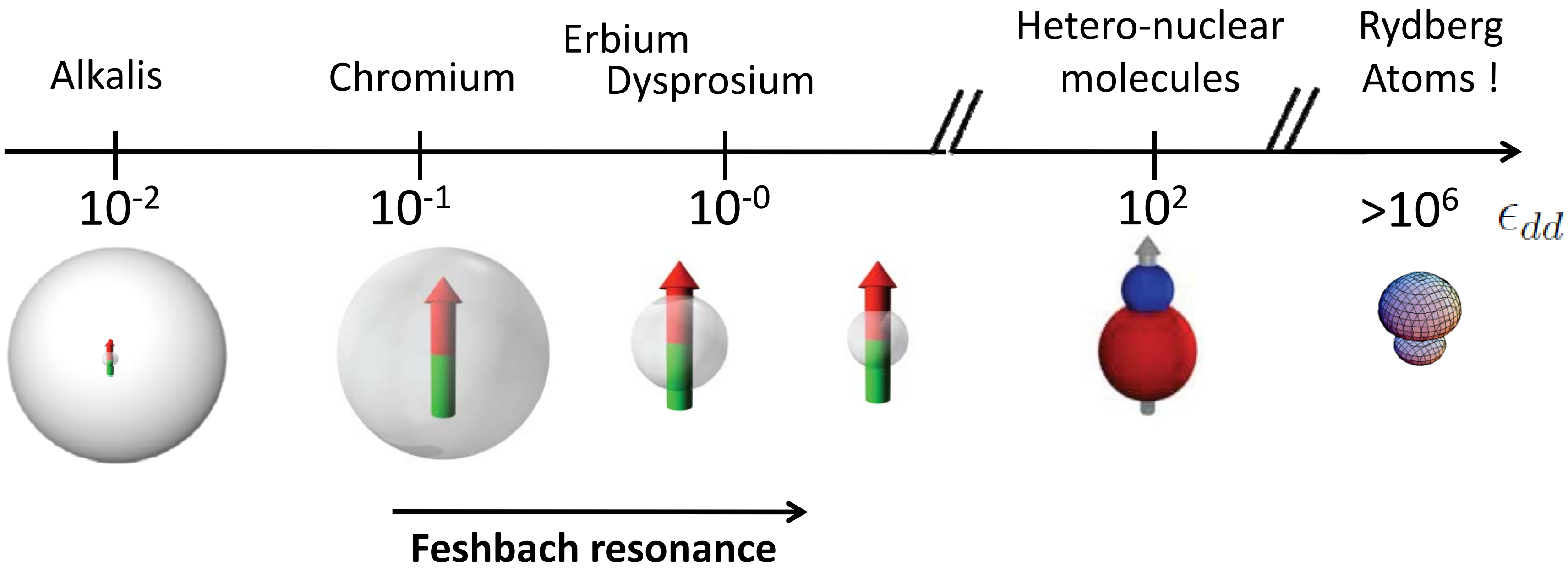


→ *Realization of a purely dipolar condensate*

T. Lahaye *et al.*, Nature **448**, 672 (2007)

T. Koch, *et al.*, Nature Physics **4**, 218 (2008)

dipolar interaction

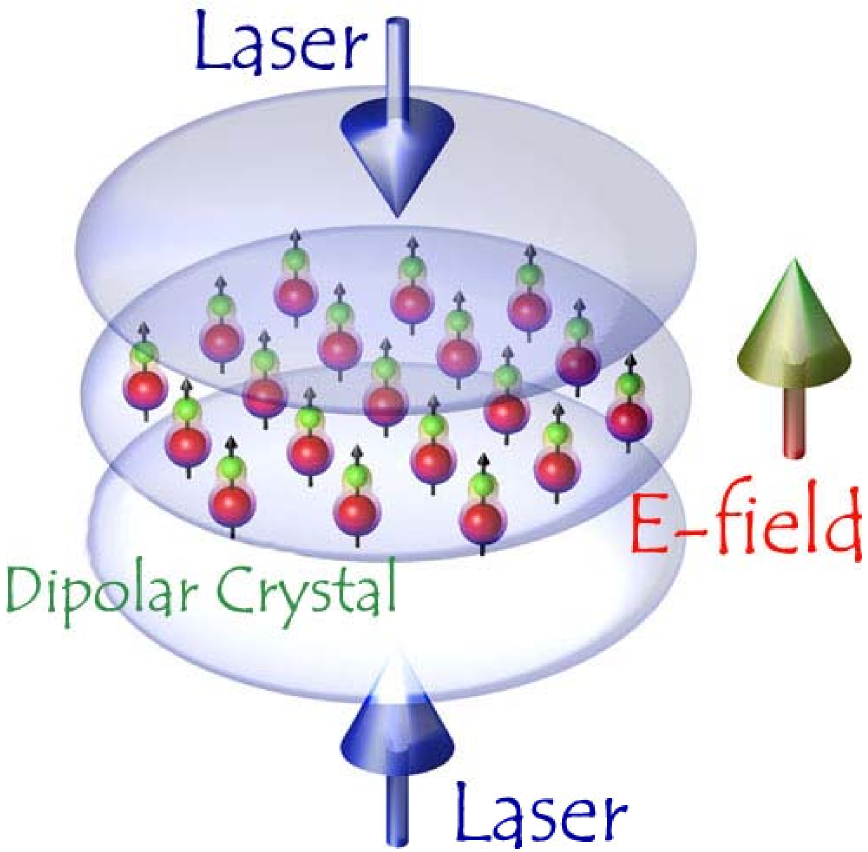


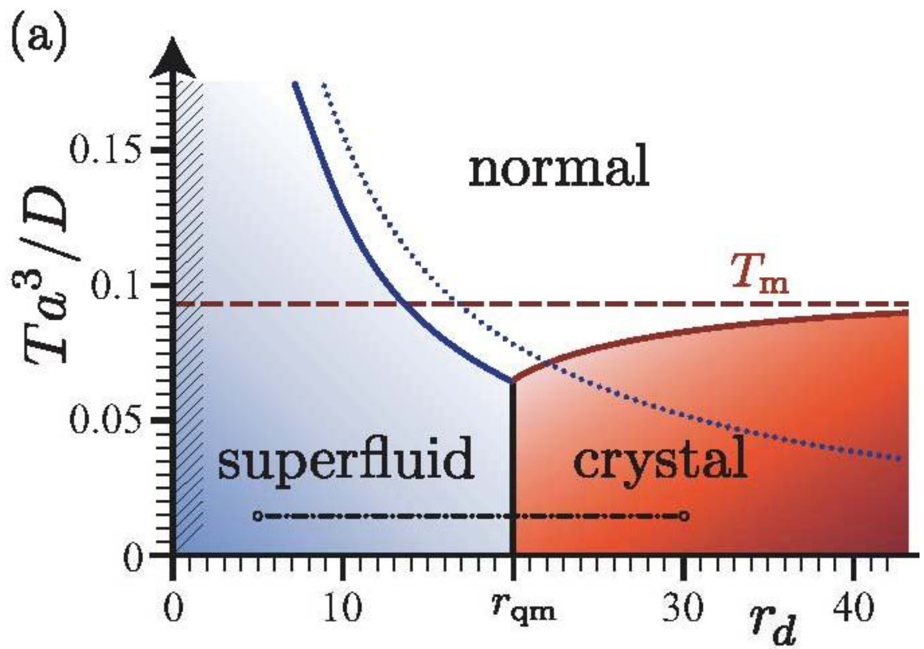
$\rightarrow$ *Realization of a purely dipolar condensate*

T. Lahaye *et al.*, Nature **448**, 672 (2007)

T. Koch, *et al.*, Nature Physics **4**, 218 (2008)

Polar molecules: Wigner crystal

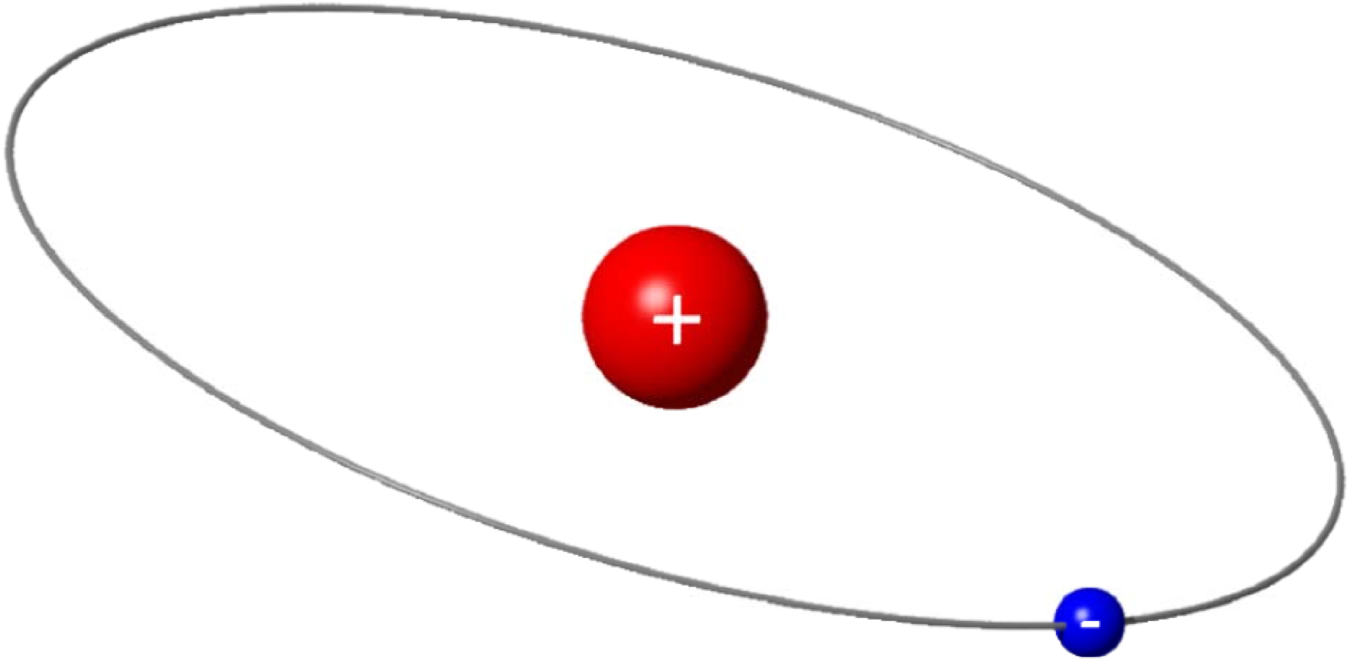




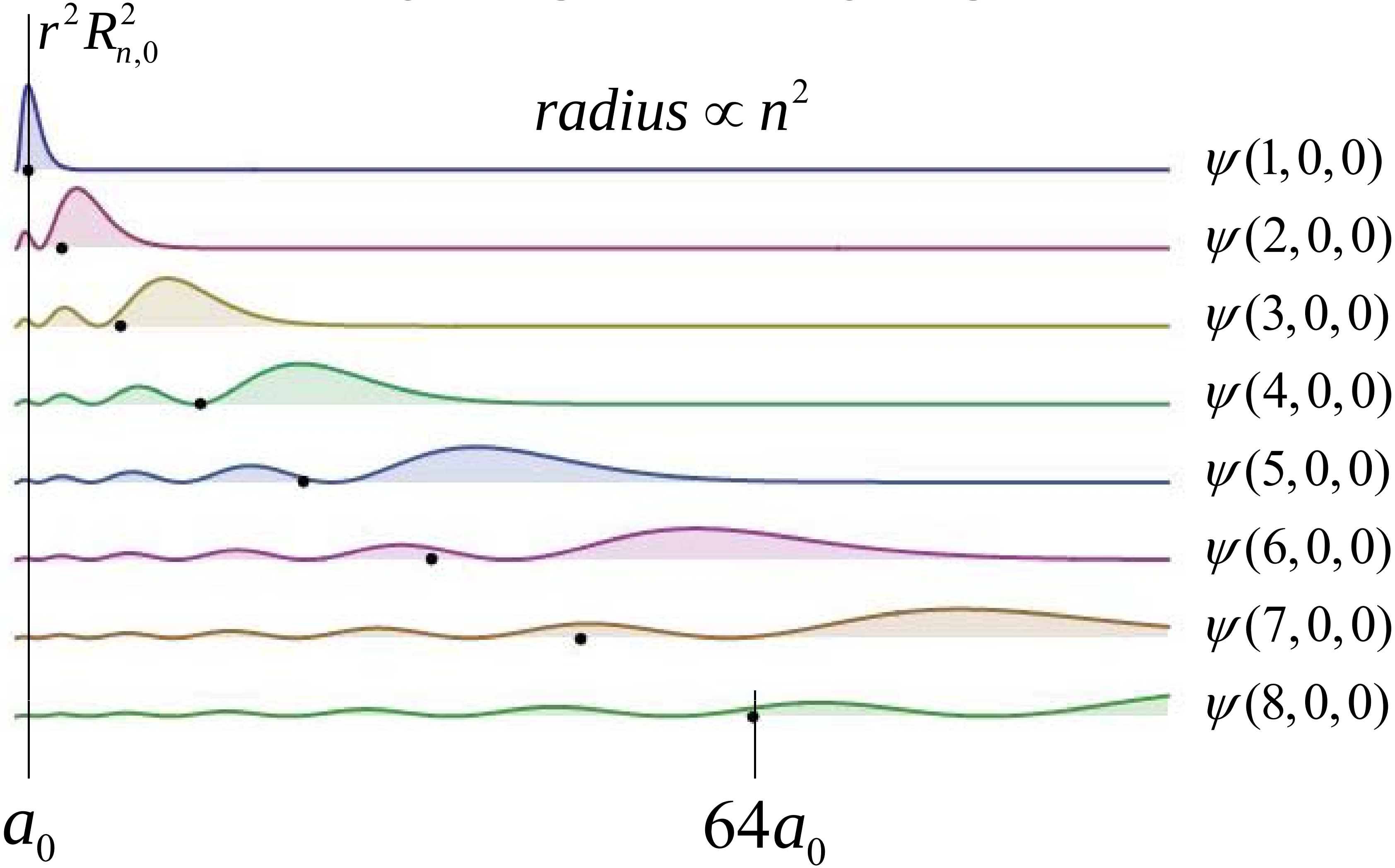
Pupillo, Büchler, Zoller

Bose gas
Bose liquid
Bose crystal

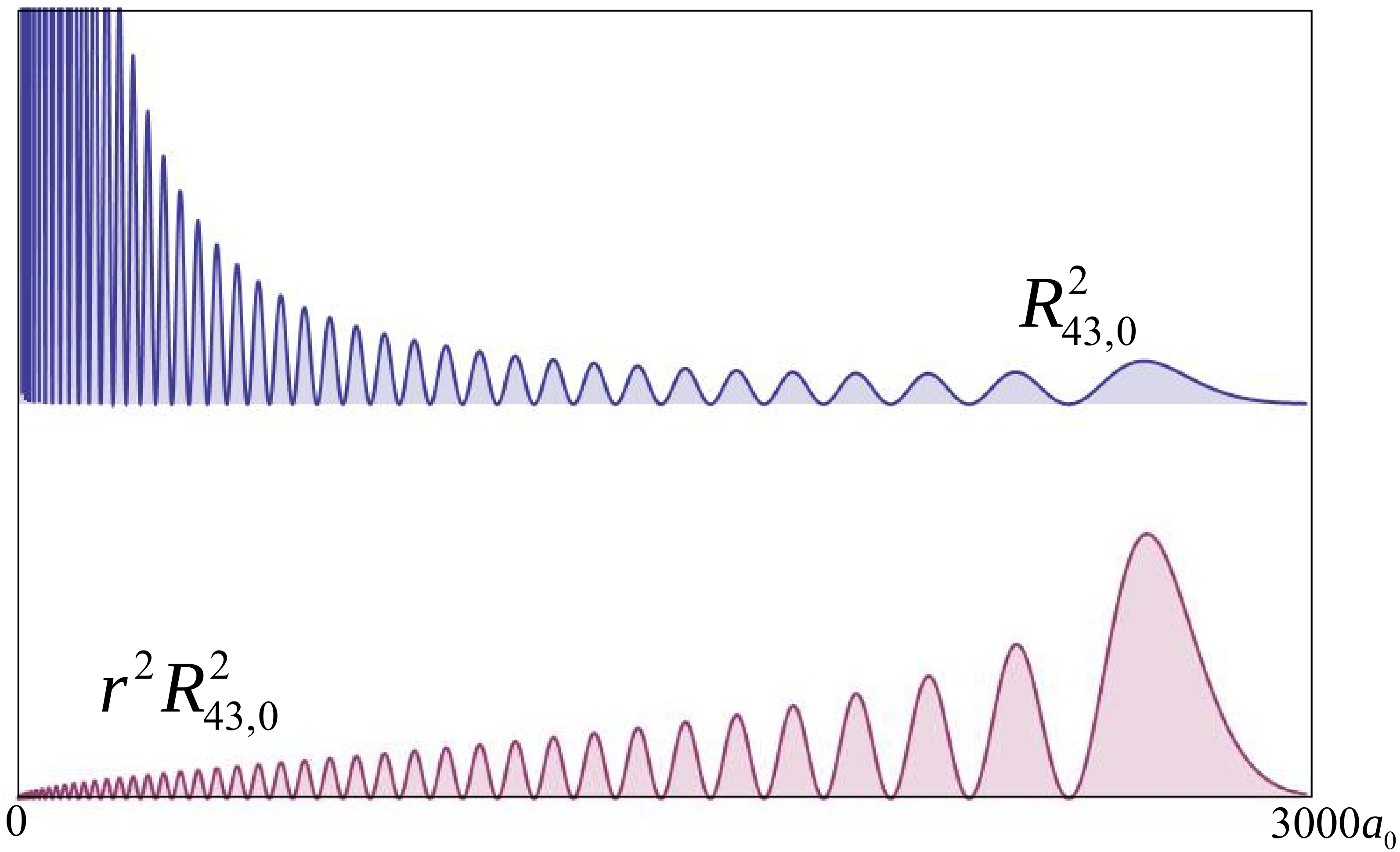
Rydberg atoms



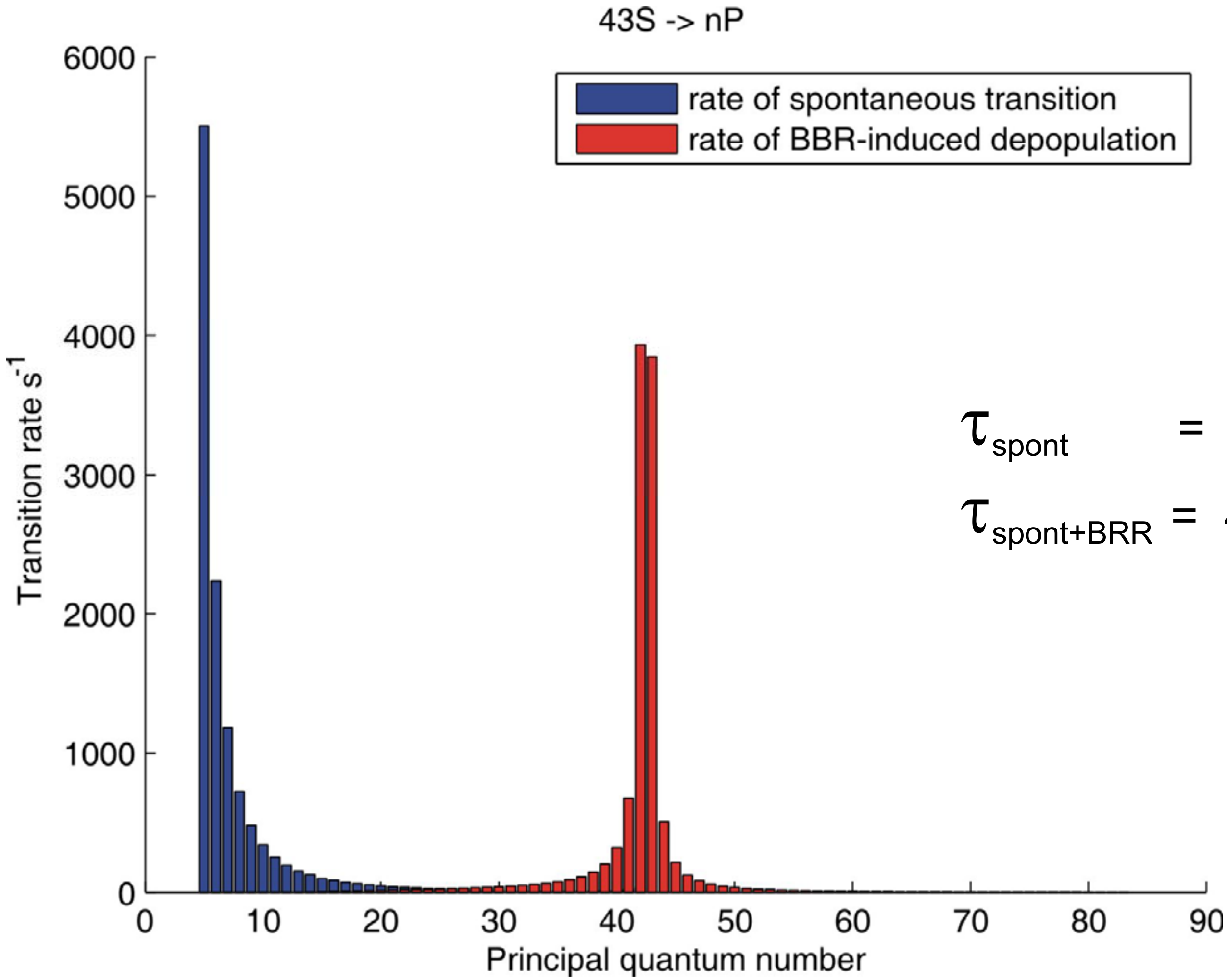
Rydberg basics - Hydrogen



One typical example: 43S



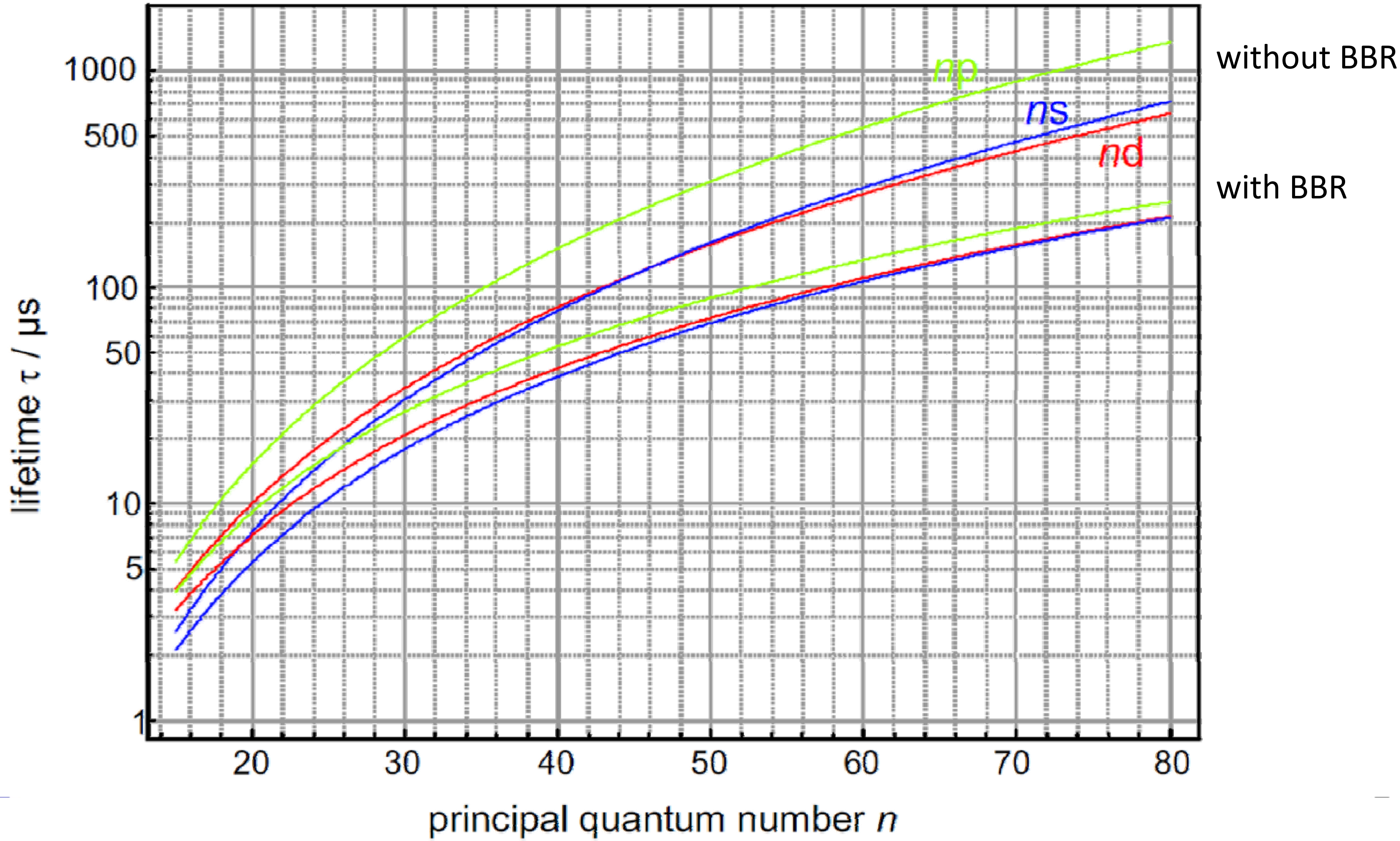
Lifetime of the 43s state with Blackbody Radiation

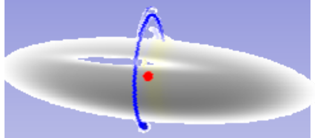


$$\tau_{spont} = 99\mu s$$

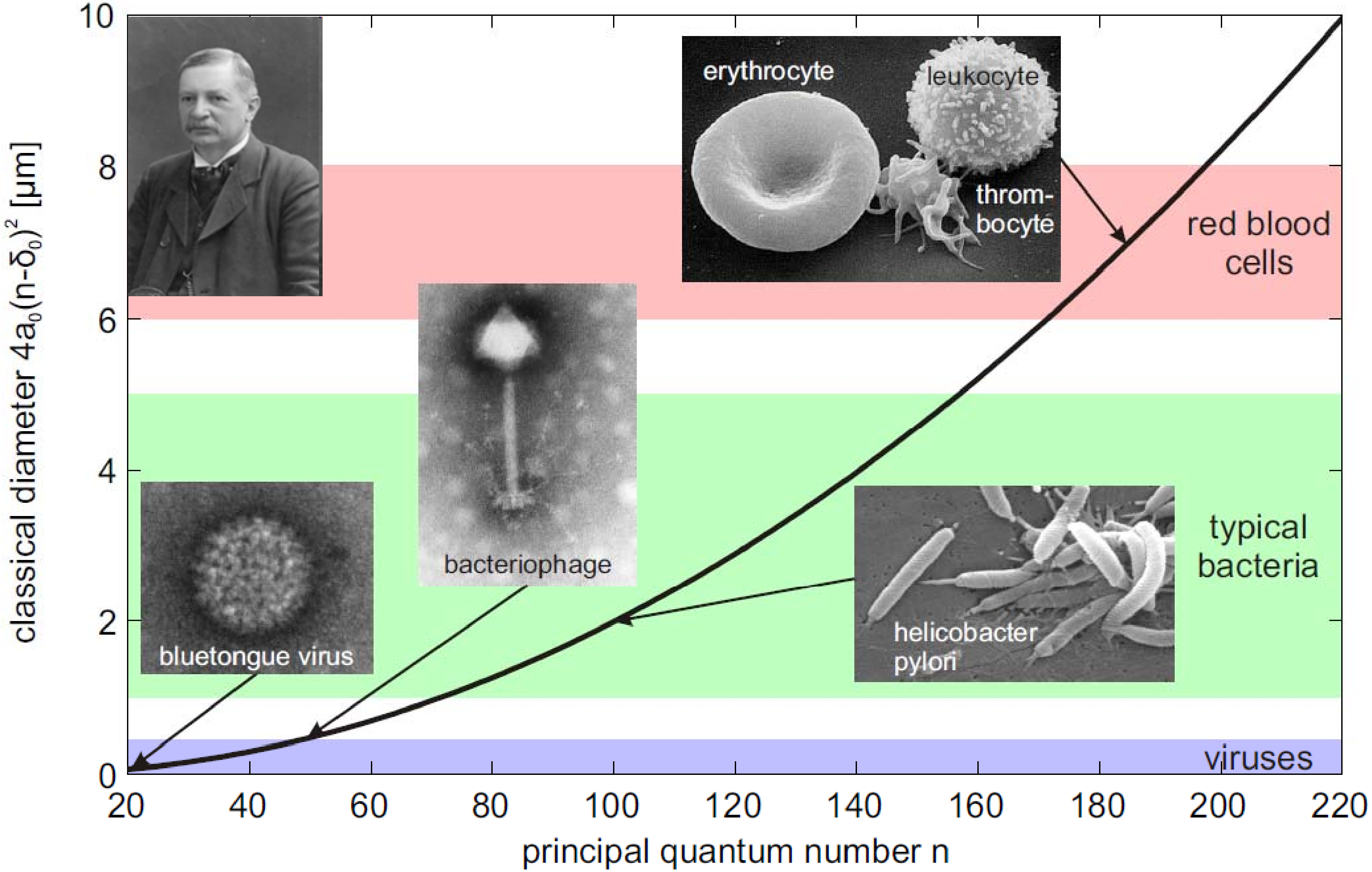
$$\tau_{spont+BRR} = 46\mu s$$

Rb lifetimes



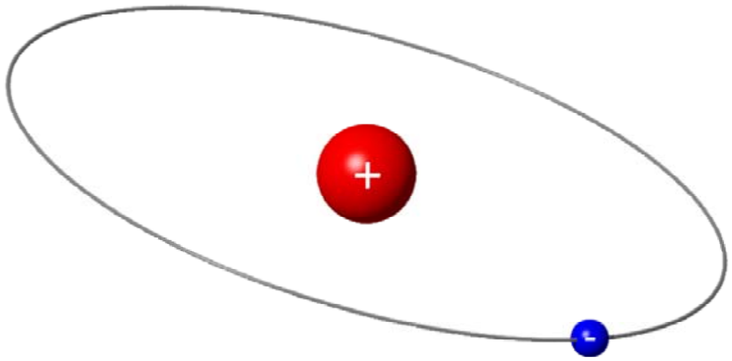


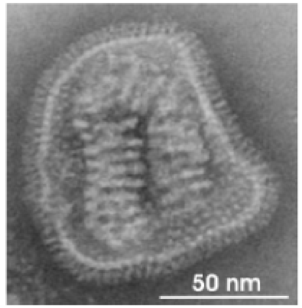
BEC



classical diameter $4a_0(n-\delta_0)^2$ [µm]
principal quantum number n
erythrocyte
leukocyte
throm-
bocyte
red blood
cells
bacteriophage
typical
bacteria
bluetongue virus
helicobacter
pylori
viruses

Properties of Rydberg Atoms

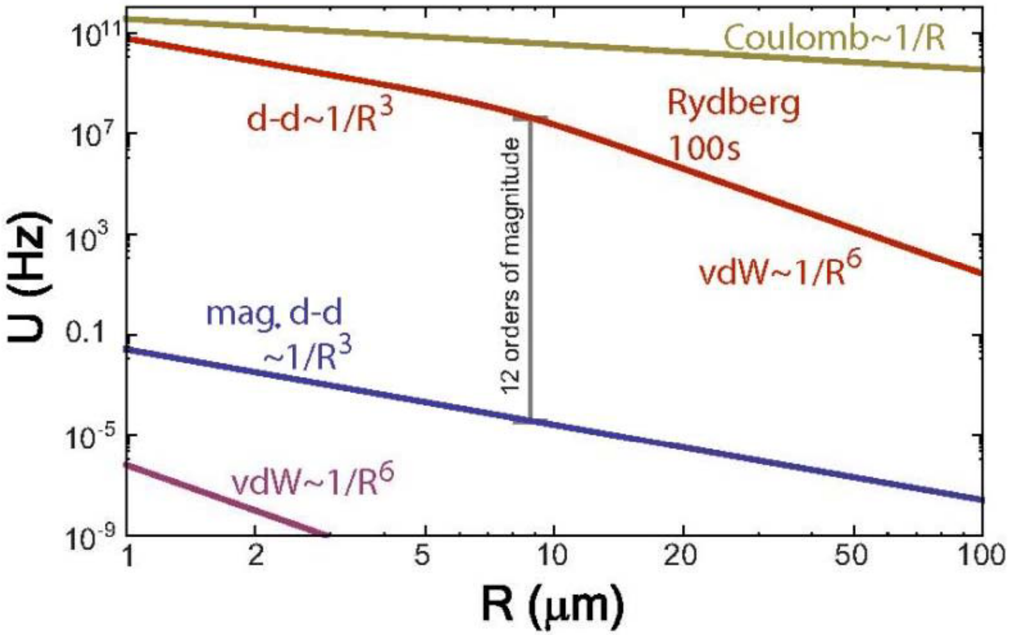




quantity	scaling	43S-state of ^{87}Rb
radius	$\propto n^2$	2384 a_0
lifetime	$\propto n^3$	50µs
Polarizability	$\propto n^7$	8 MHz $(V/cm)^{-2}$
Van der Waals C_6	$\propto n^{11}$	-1.7×10^{19} a.u.

The interactions between Rydberg states are …

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



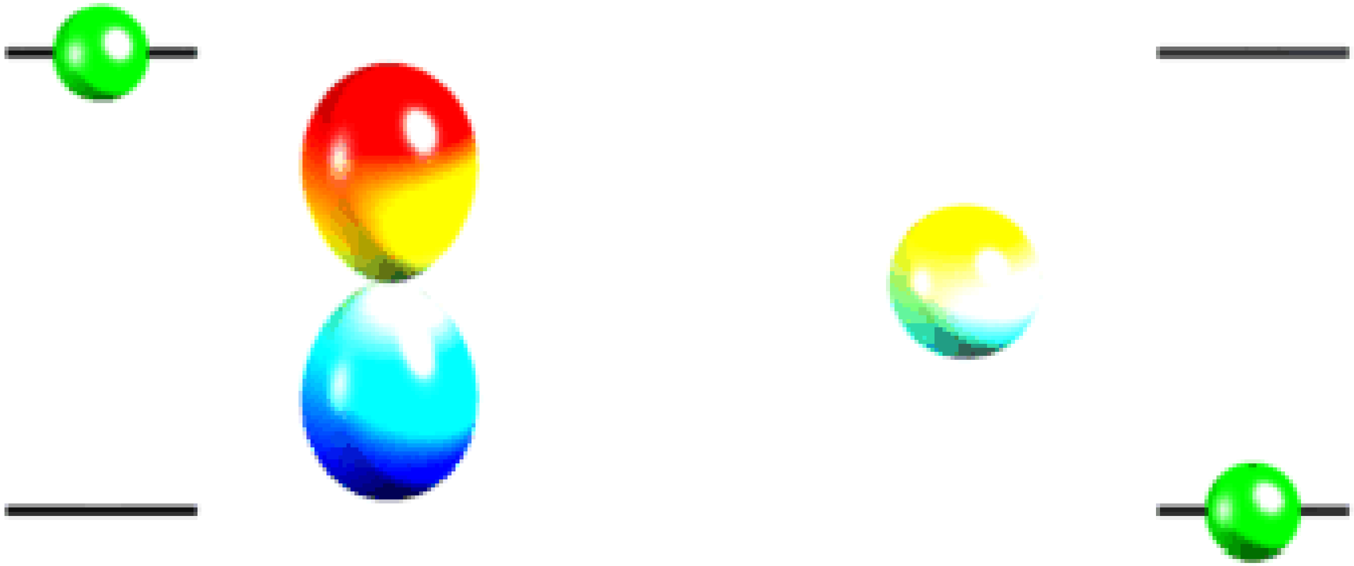
M. Saffman et al., Rev. Mod. Phys. 82, 2313 (2010)

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

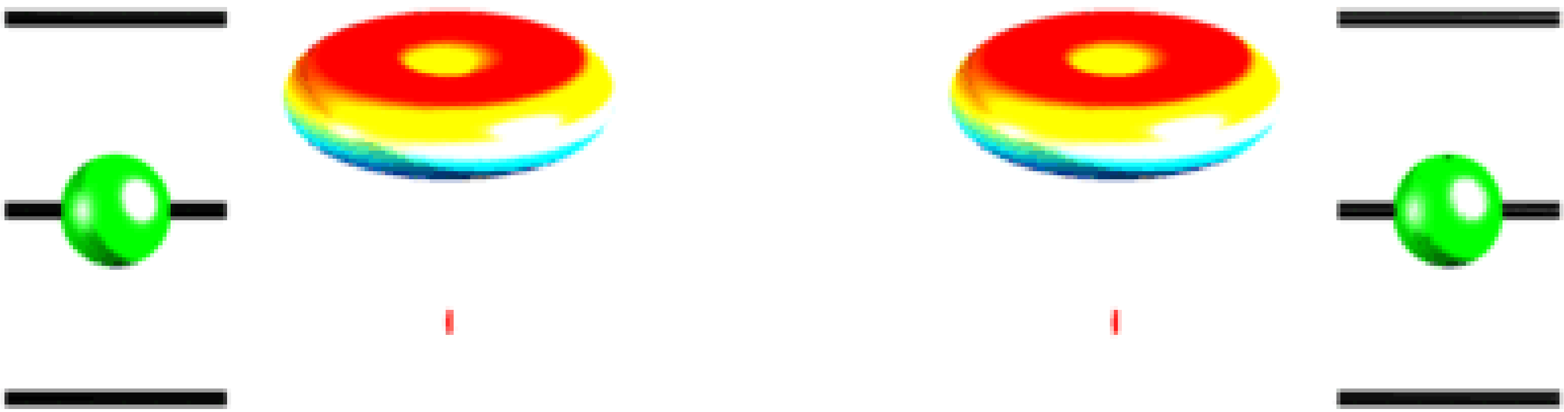
T. Förster, Z. Naturforsch 4a, 321 (1949)

Förster energy transfer



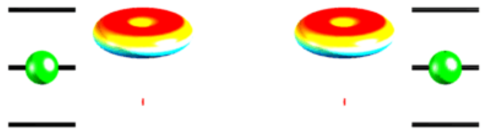
T. Förster, Z. Naturforsch 4a, 321 (1949)

Förster Resonance

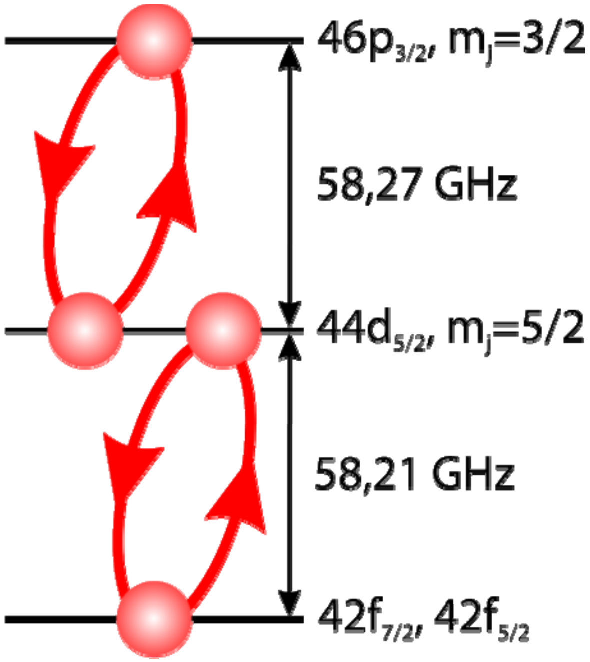


Dipolar interactions: Förster resonances

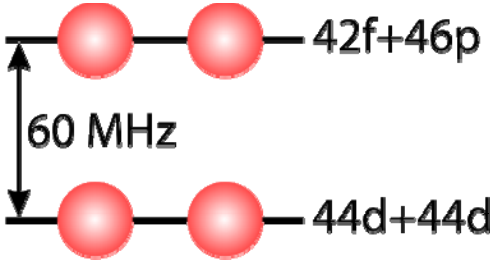
T. Förster, Z. Naturforsch 4a, 321 (1949)



Bare states



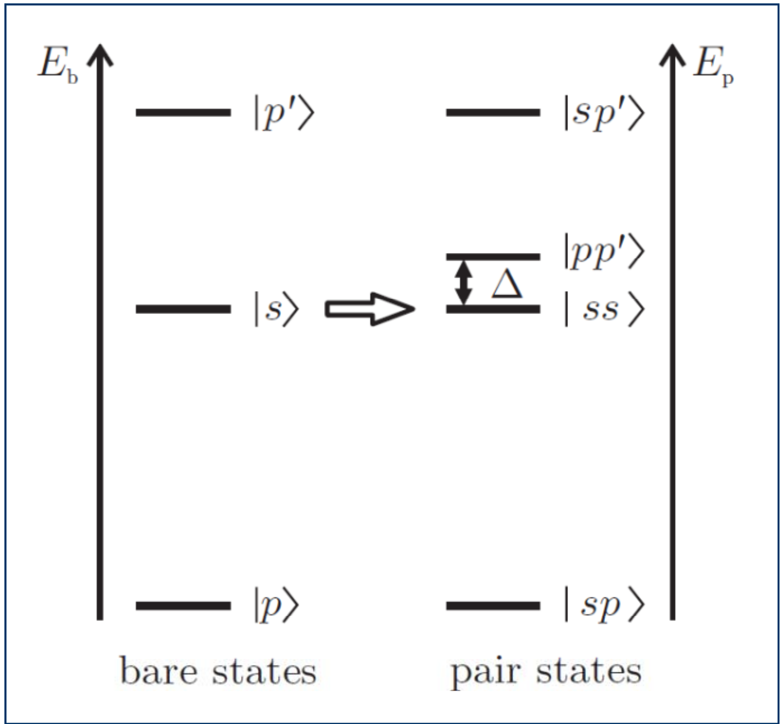
Pair states



finite Förster defect Δ:
van-der-Waals interaction (~ $1/R^6$)

no Förster defect $\Delta = 0$:
resonant dipole-dipole interaction (~ $1/R^3$)

Interaction between Rydberg atoms



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

Förster resonance: tune Δ to zero

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

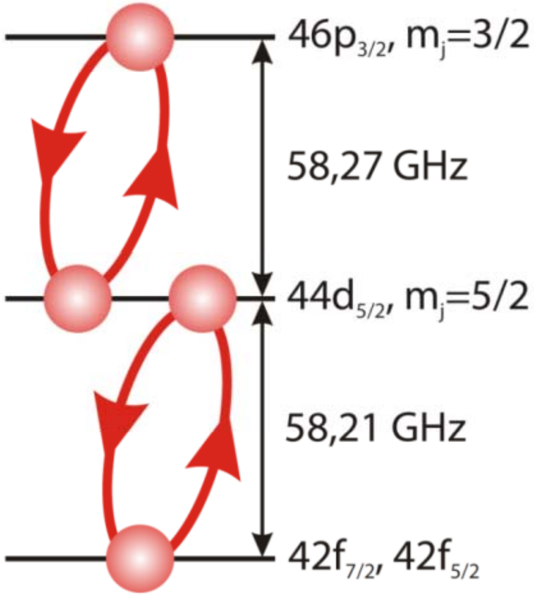
$$E_{\pm} = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \left(\frac{d_1 d_2}{R^3}\right)^2}$$

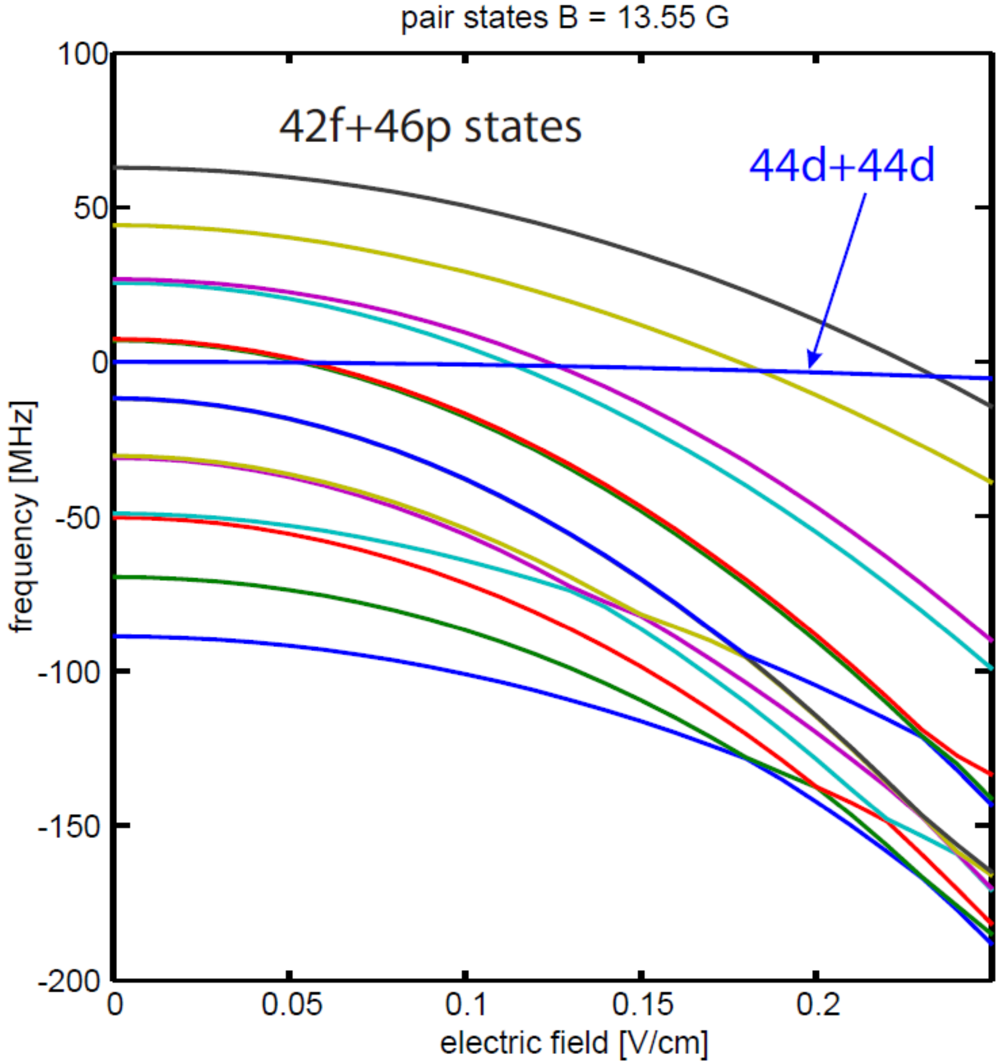
$$\Delta \gg d_1 d_2 / R^3$$

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

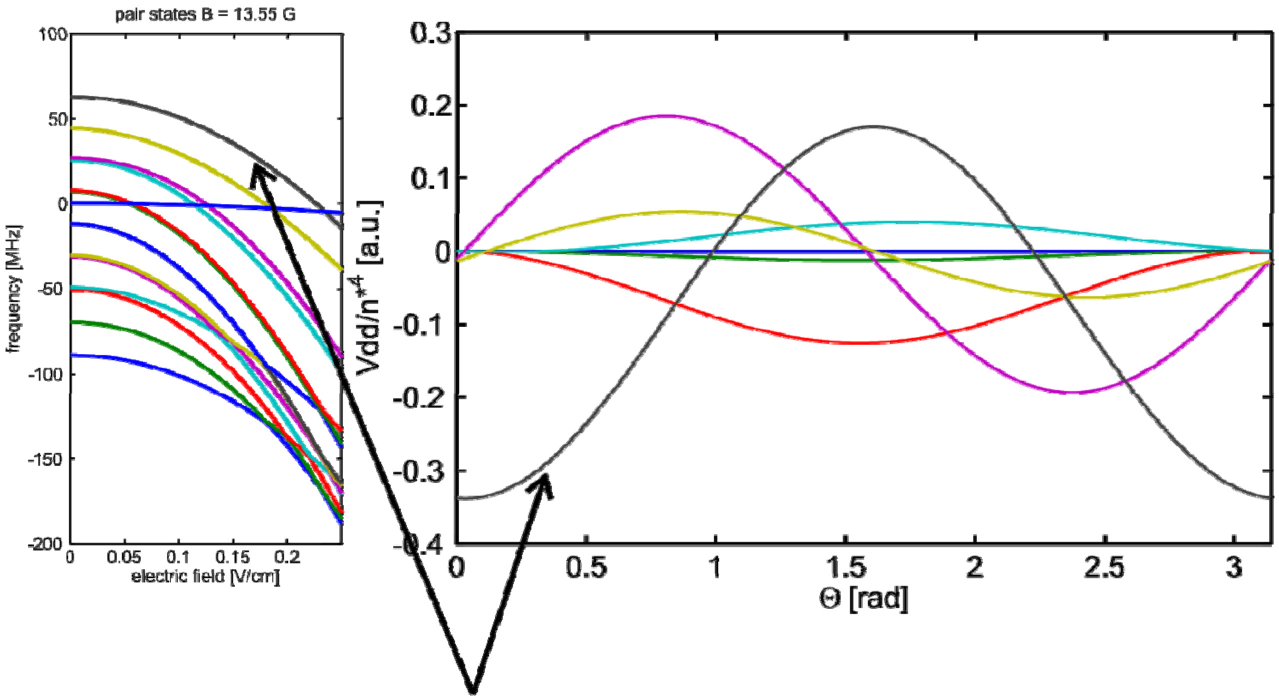
sign depends on Δ !

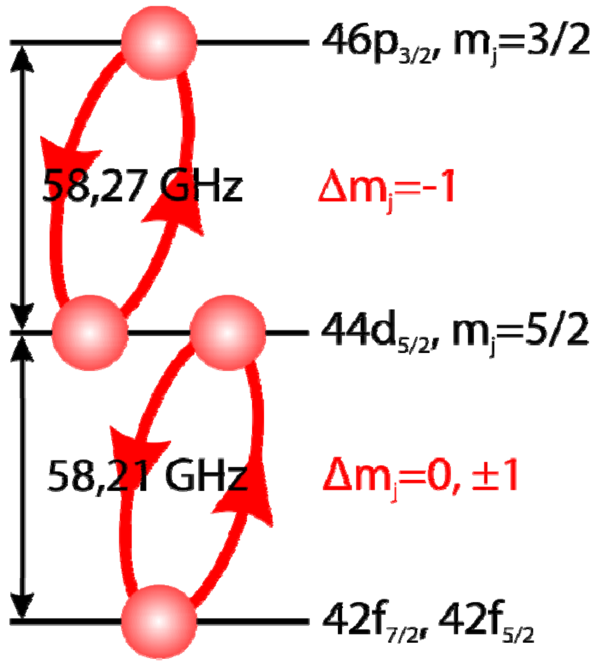
Stark tuned Förster resonances





Förster resonances





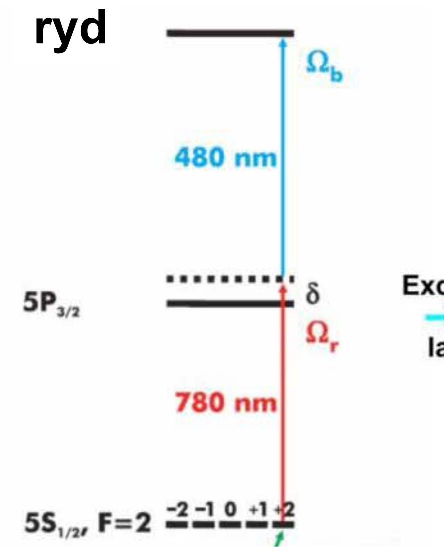
$|46p_{3/2}, m_j=3/2; 42f_{7/2}, m_j=7/2\rangle$

$\leftrightarrow |44d_{5/2}, m_j=5/2; 44d_{5/2}, m_j=5/2\rangle$

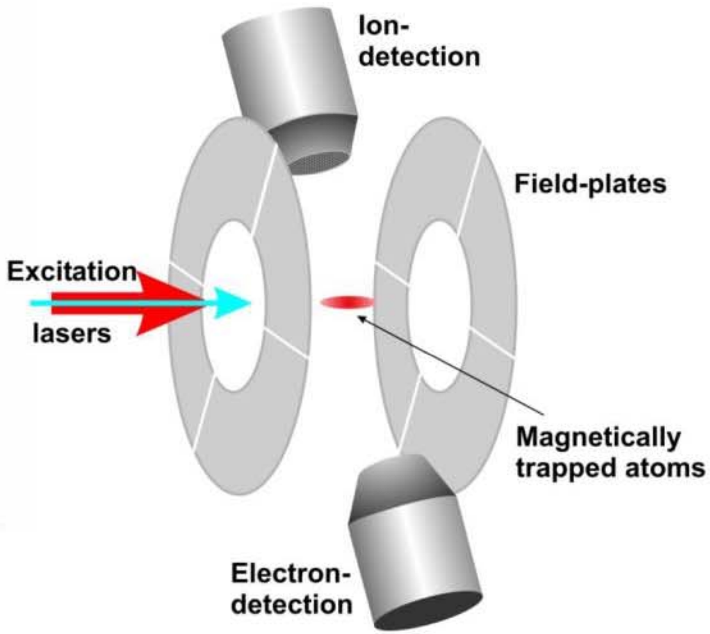
Förster resonances

Is this all coherent
in a dense gas??

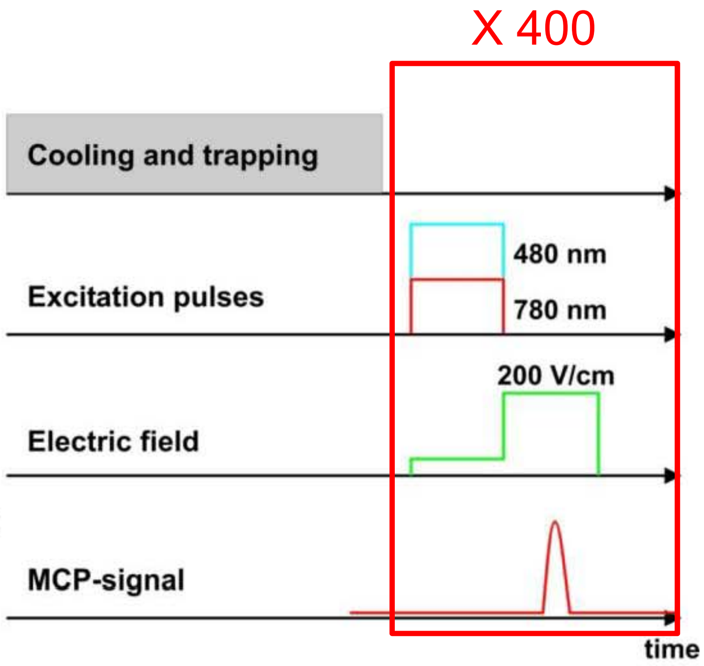
Some experimental details



Excitation scheme

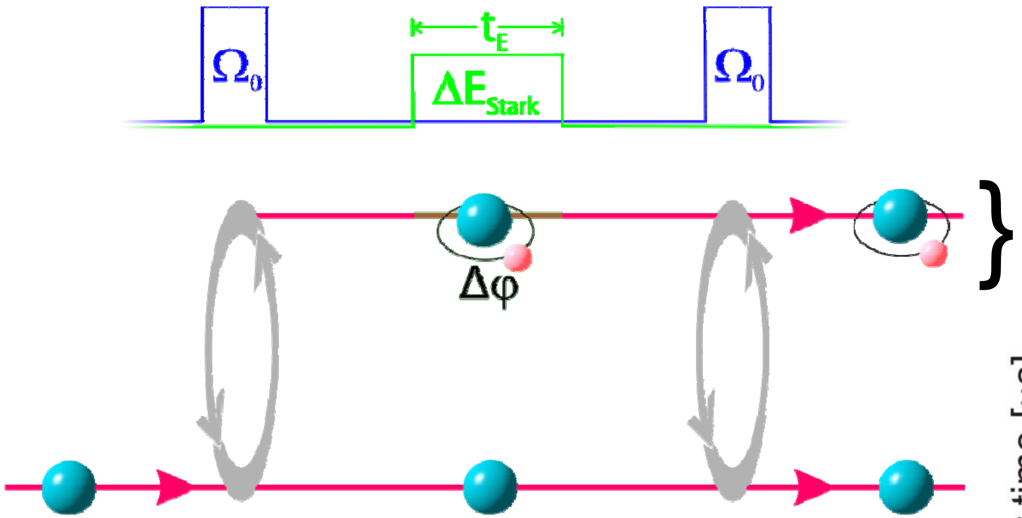


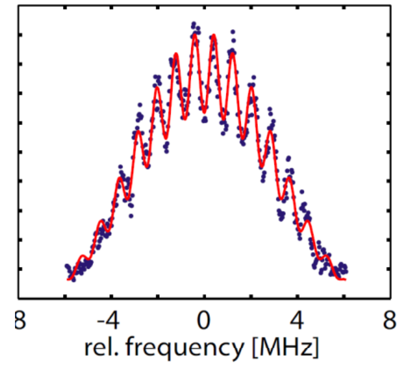
Experimental setup

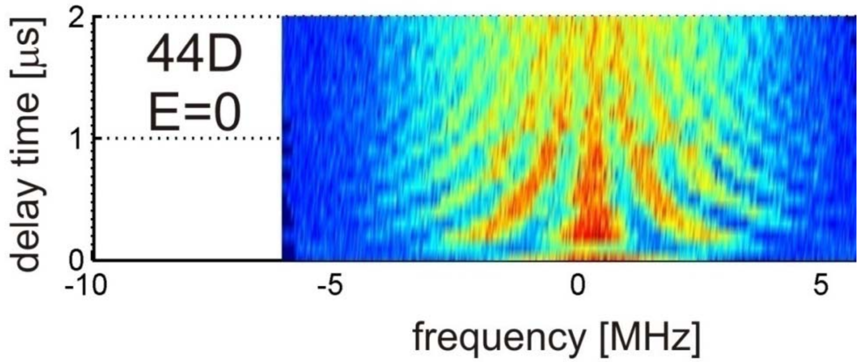


Experimental sequence

Ramsey interferometer



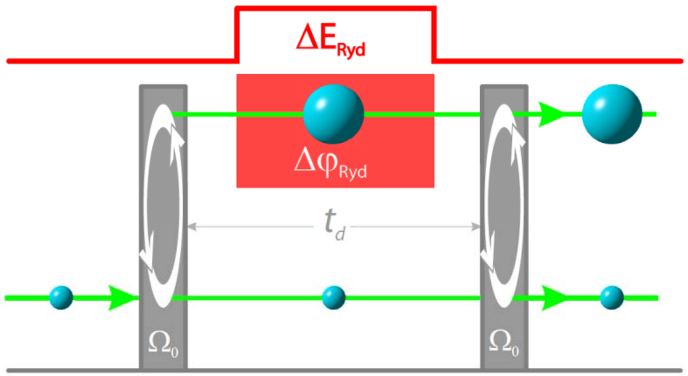


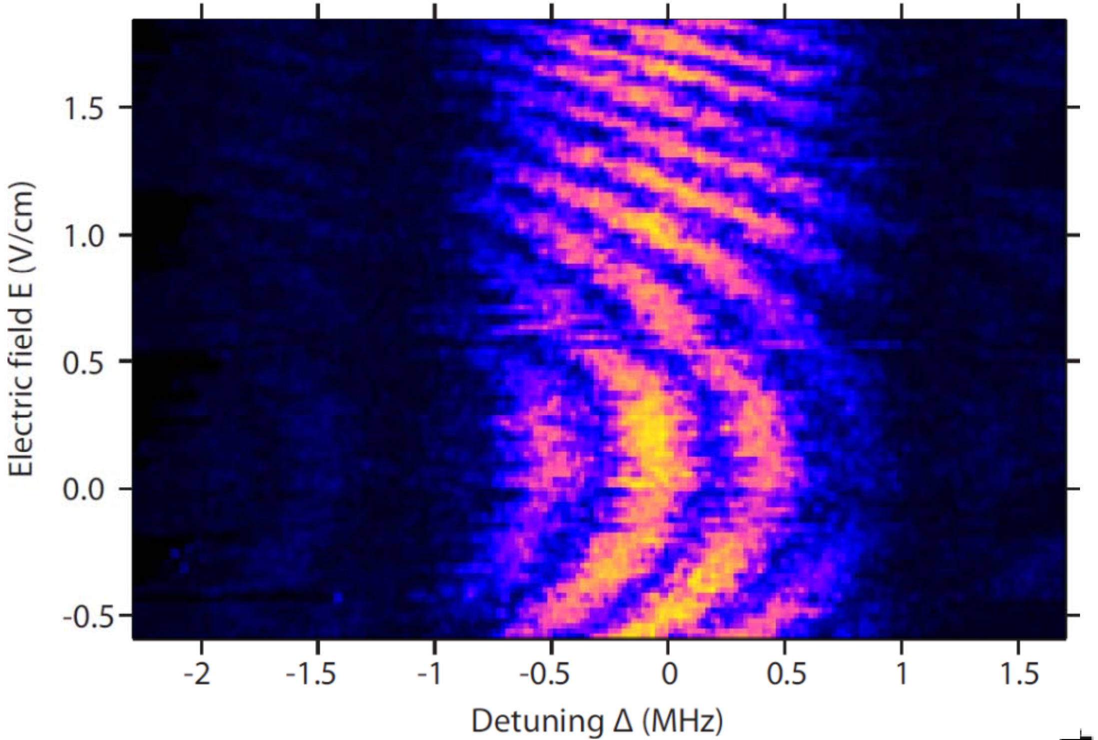


- visibility:
  - ➔ decoherence
  - ➔ population transfer
- phase:
  - ➔ energy shift (e.g. Stark effect $\Delta\ \Phi=1/2\alpha E^2/h\ t$)

Rydberg atom interferometry

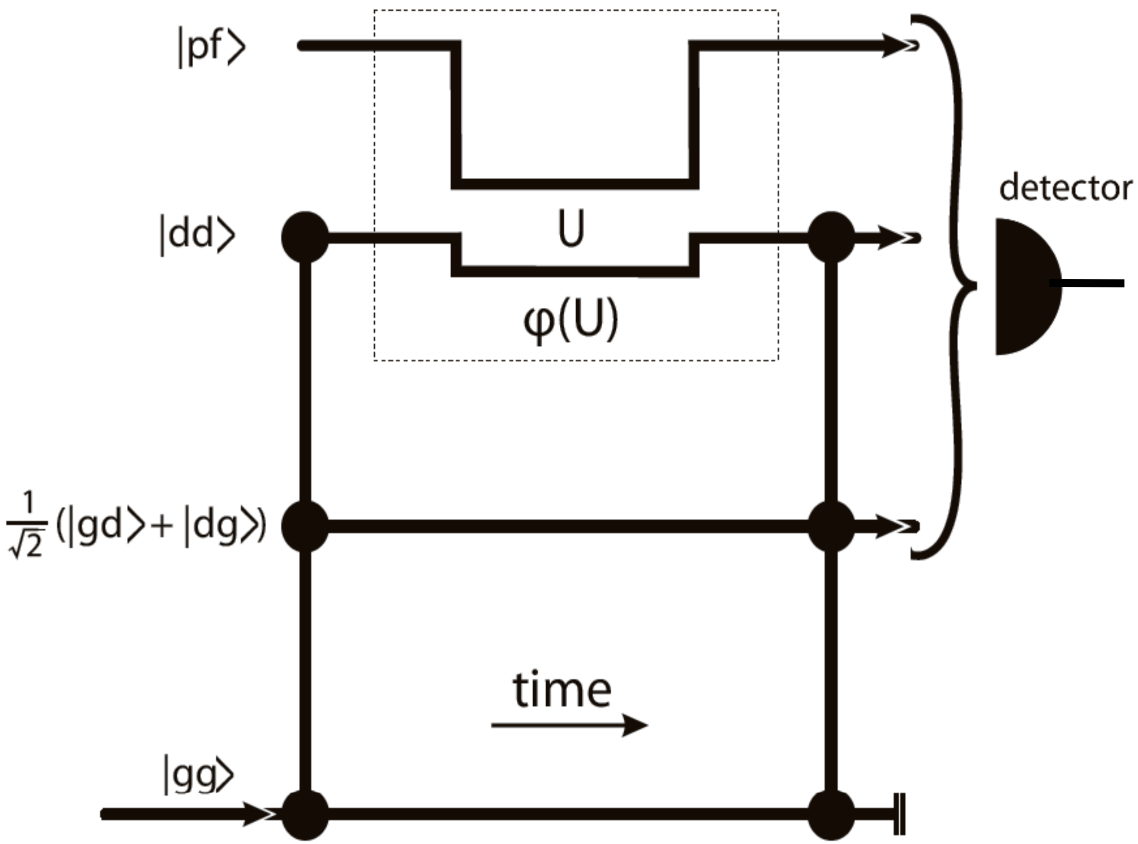
$$\Delta\varphi_{Ryd} = \frac{1}{\hbar}\int \alpha \underline{E}^2(t)dt$$



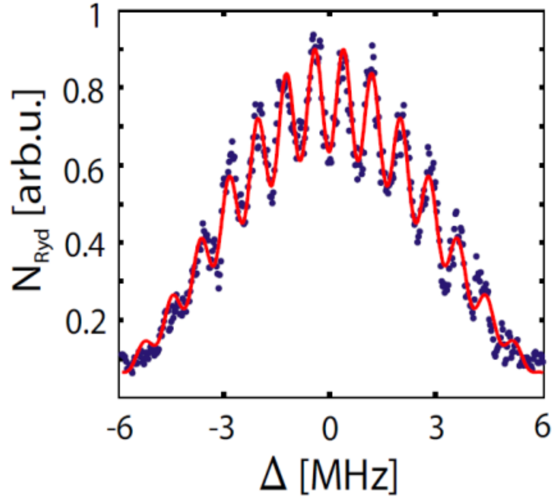


43S high density

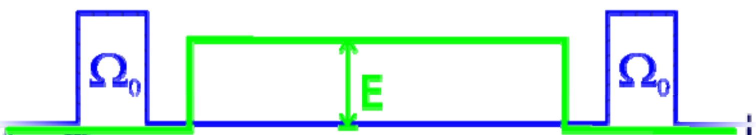
A pair state interferometer



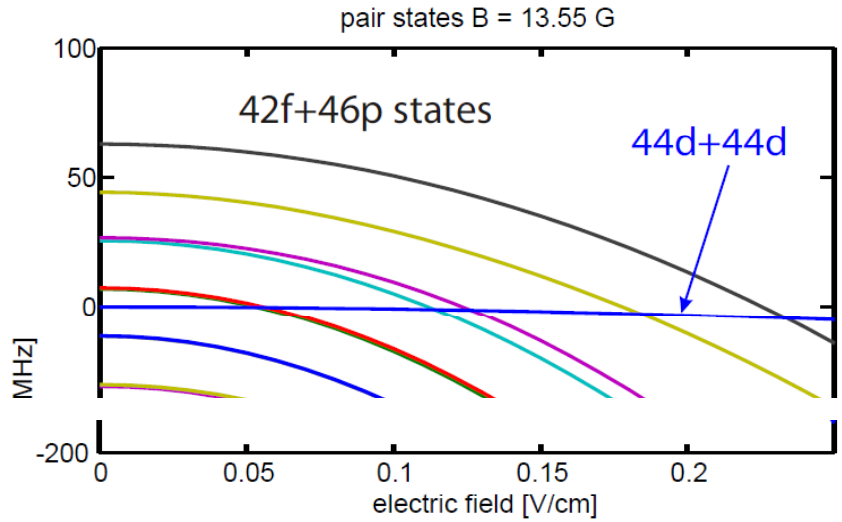
Single shot data

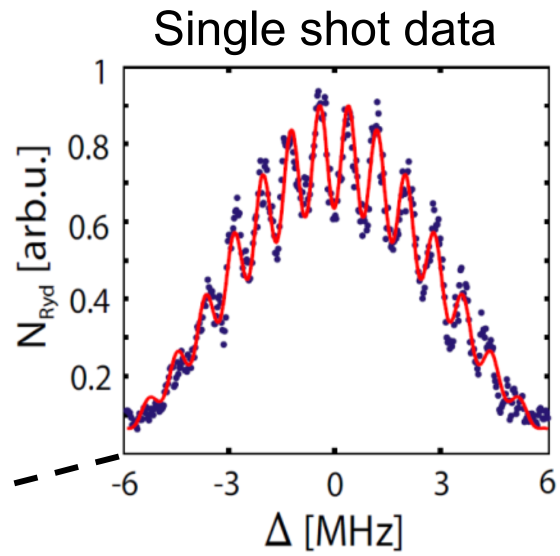


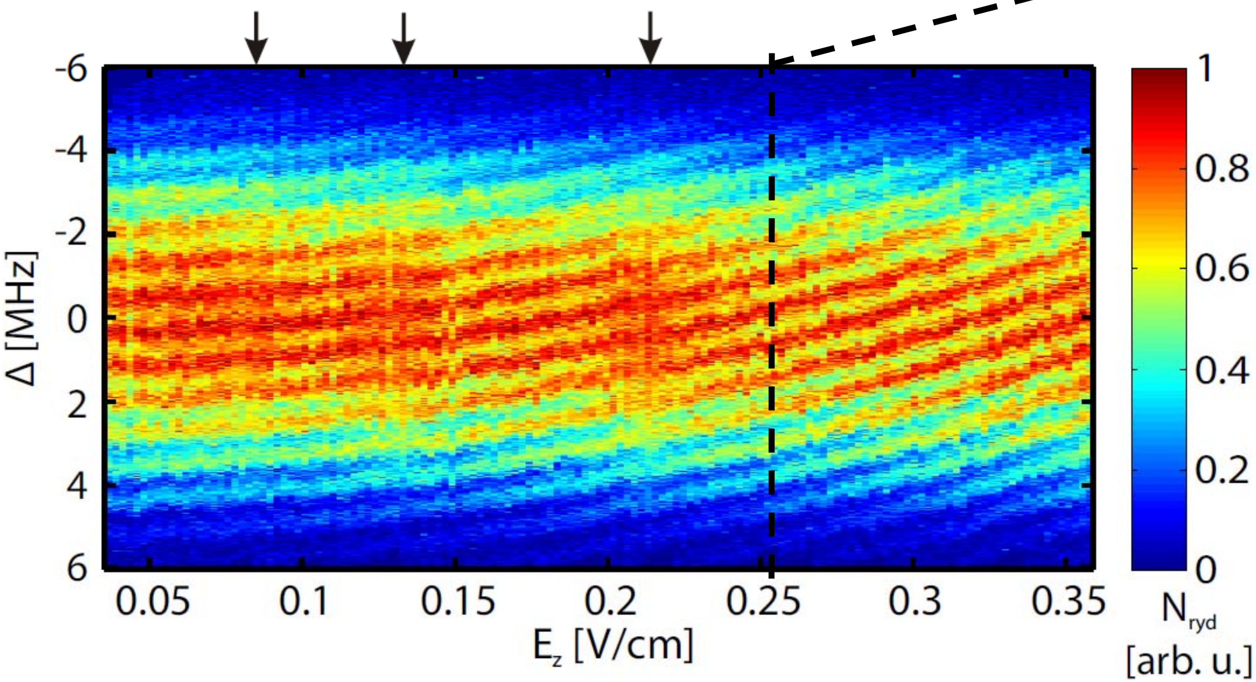
→ see Nipper et al.
PRL 2012
PRX 2012



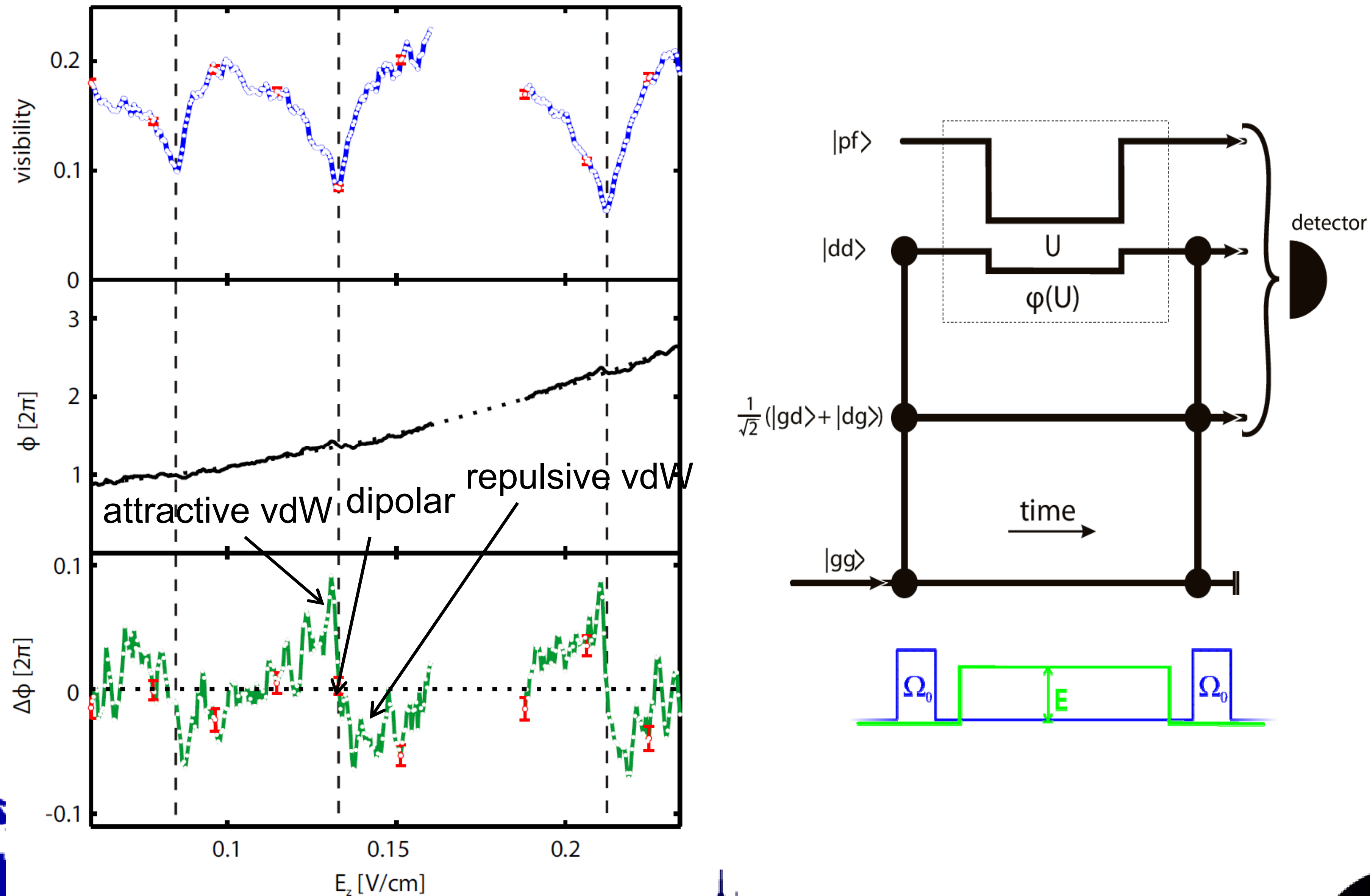
A pair state interferometer



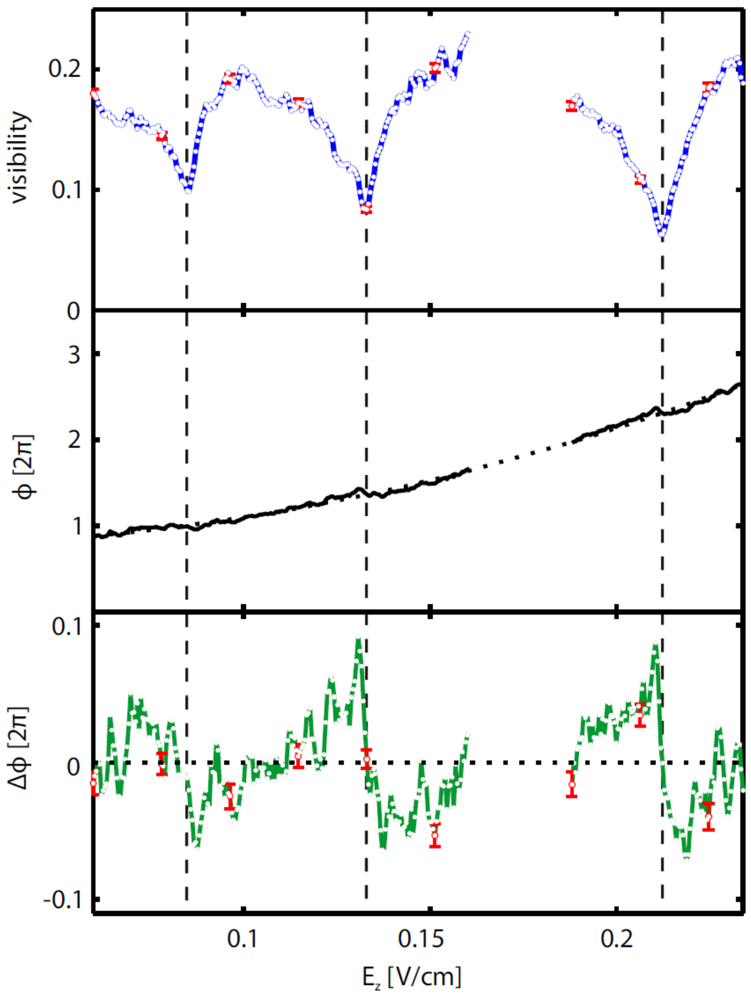


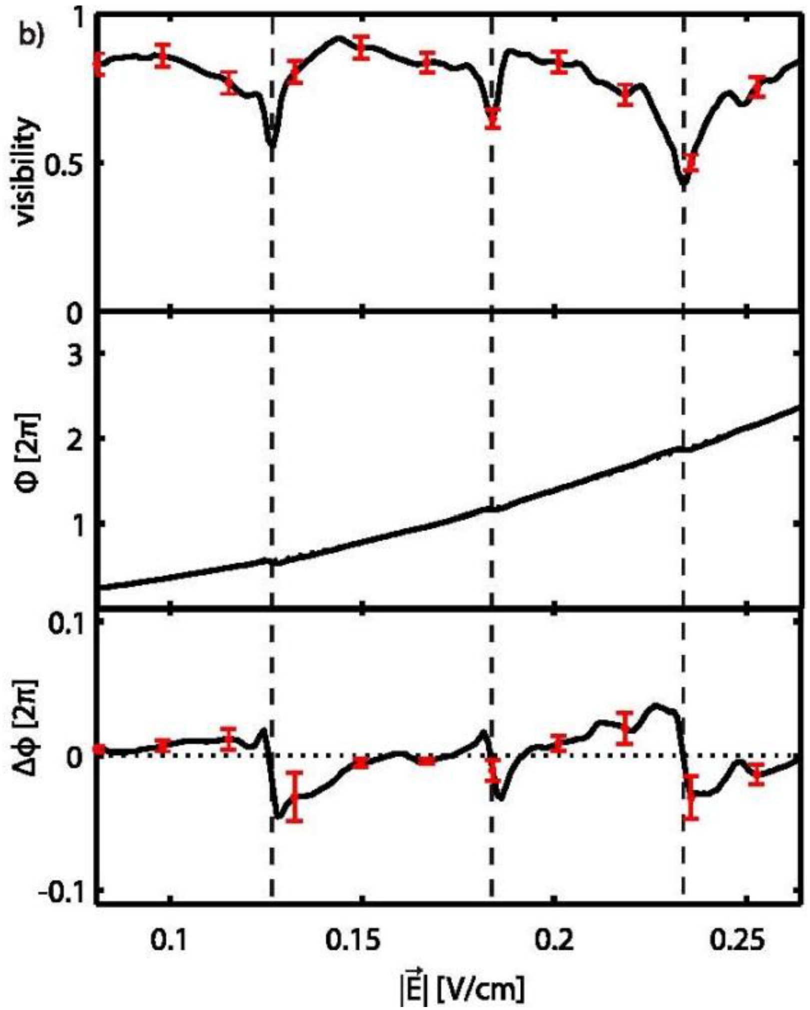


Interaction induced dephasing and phase shift

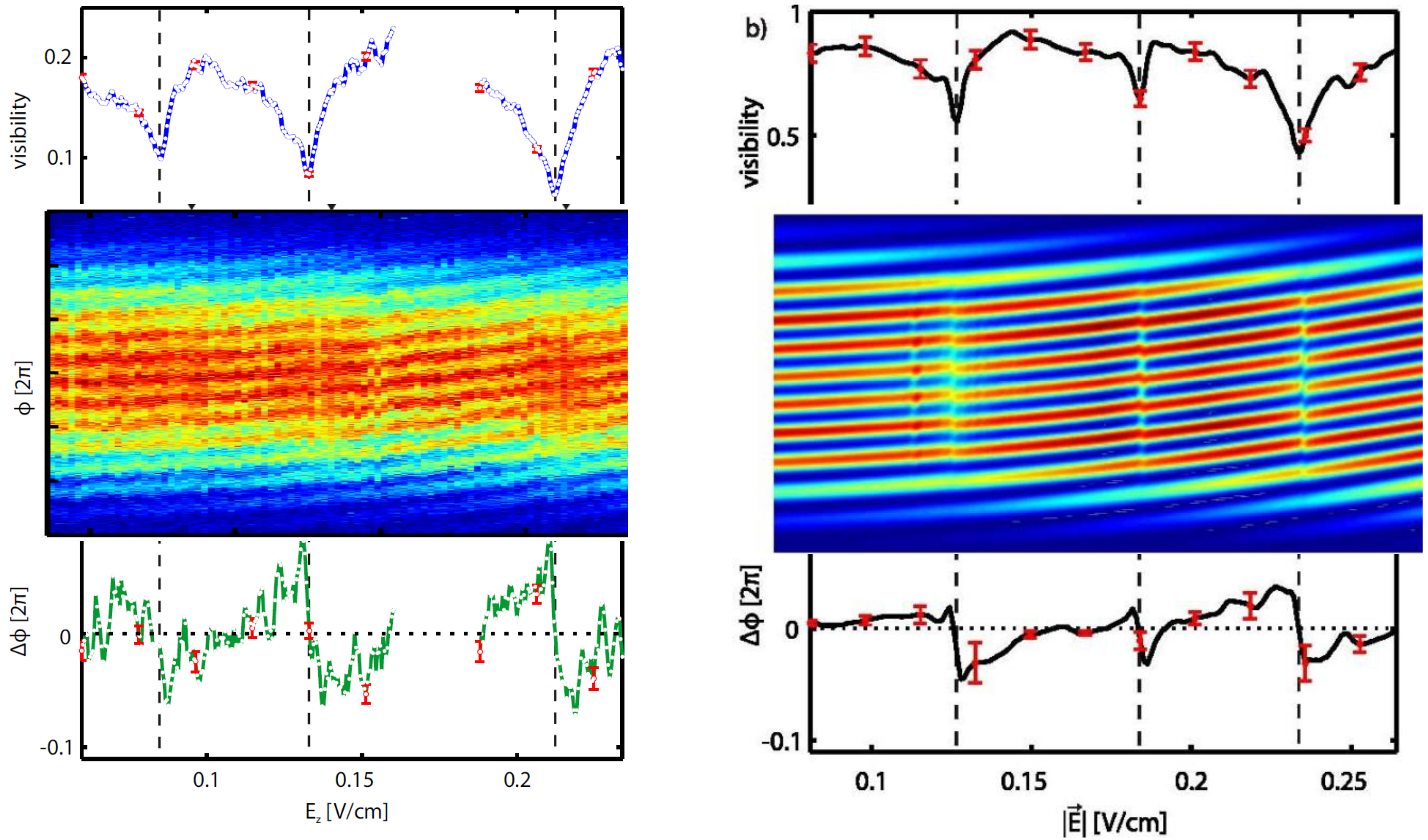


Interaction induced dephasing and phase shift

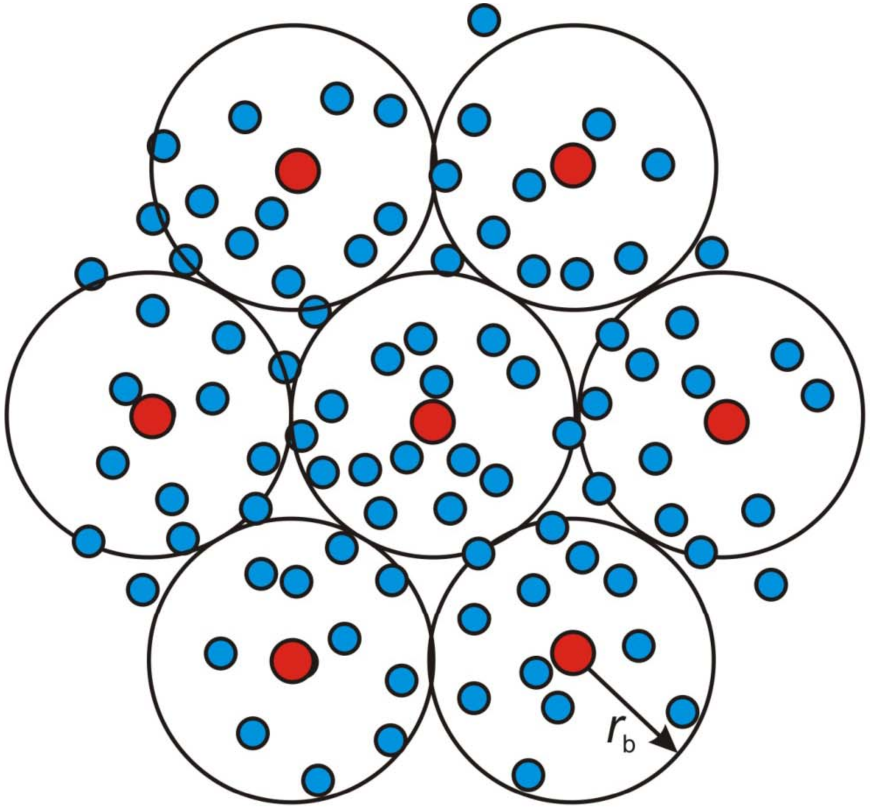


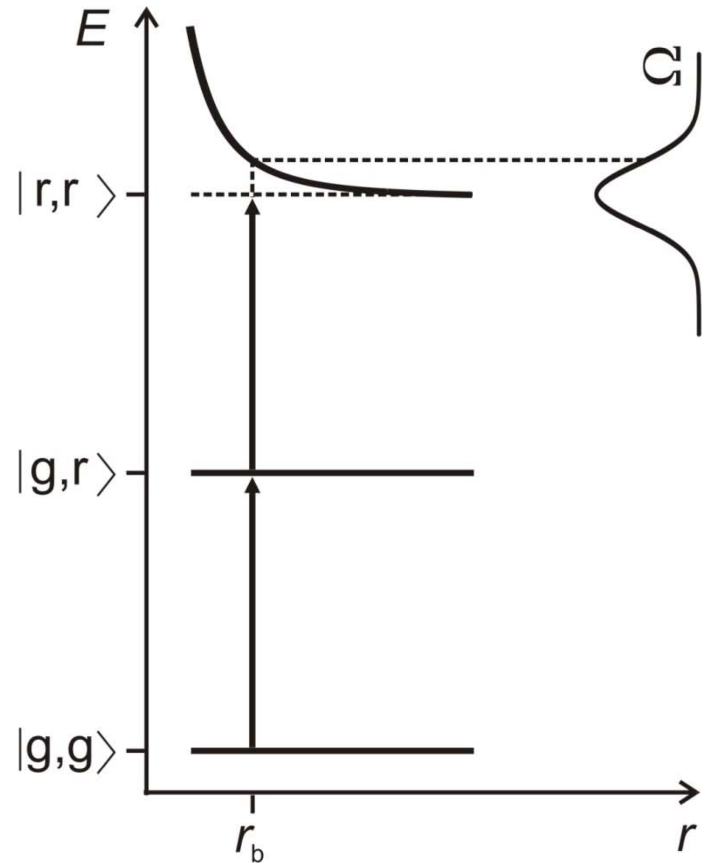


Interaction induced dephasing and phase shift



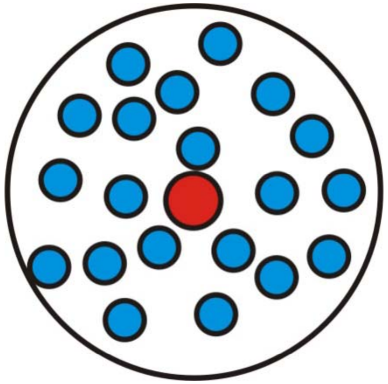
Excitation blockade by van der Waals interaction

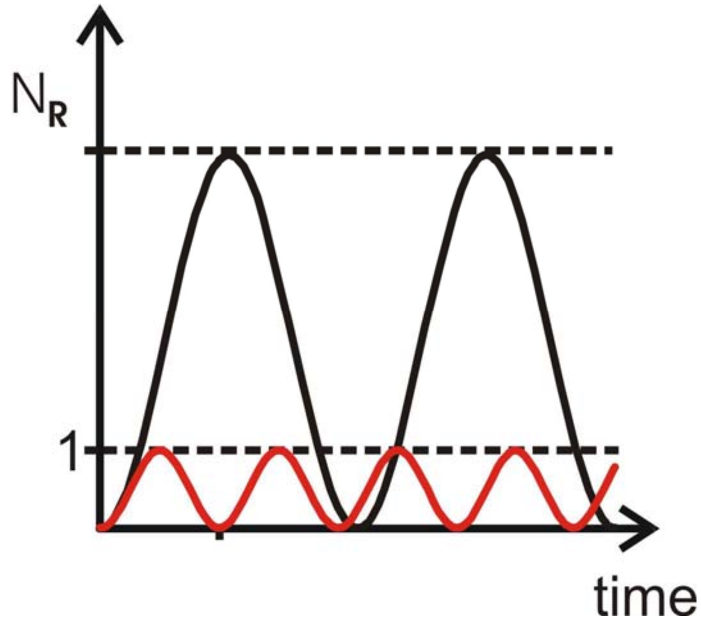




Distance between to atoms

Collective state



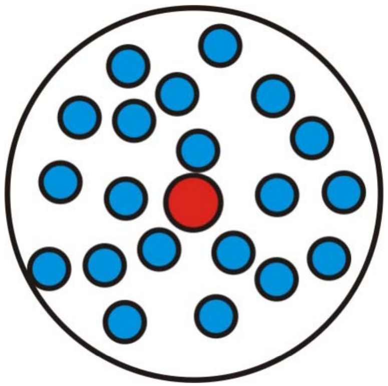


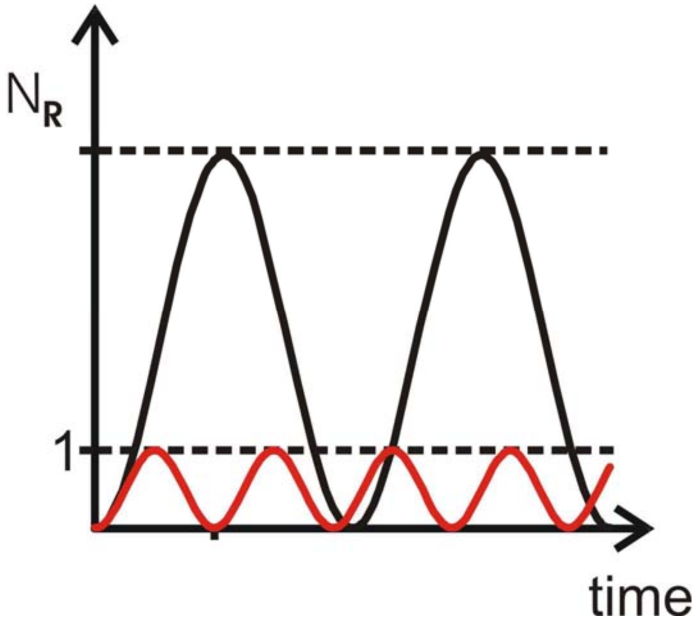
$$|E\rangle = \frac{1}{\sqrt{N}}\left\{|ryd, g, g, \ldots, g\rangle + |g, ryd, g, \ldots, g\rangle + \ldots + |g, g, \ldots, g, ryd\rangle\right\}$$

$$\Omega = \sqrt{N}\,\Omega_0$$

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

Collective state





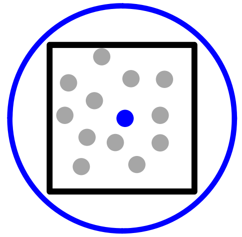
$$|E\rangle = \frac{1}{\sqrt{N}}\{|\,\color{red}{ryd}, g, g, \ldots, g\rangle + |\,g, \color{red}{ryd}, g, \ldots, g\rangle + \ldots + |\,g, g, \ldots, g, \color{red}{ryd}\rangle\}$$

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

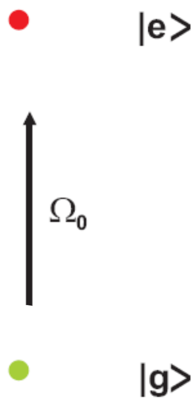
$$|G\rangle = |\,g, g, g, \ldots, g\rangle$$

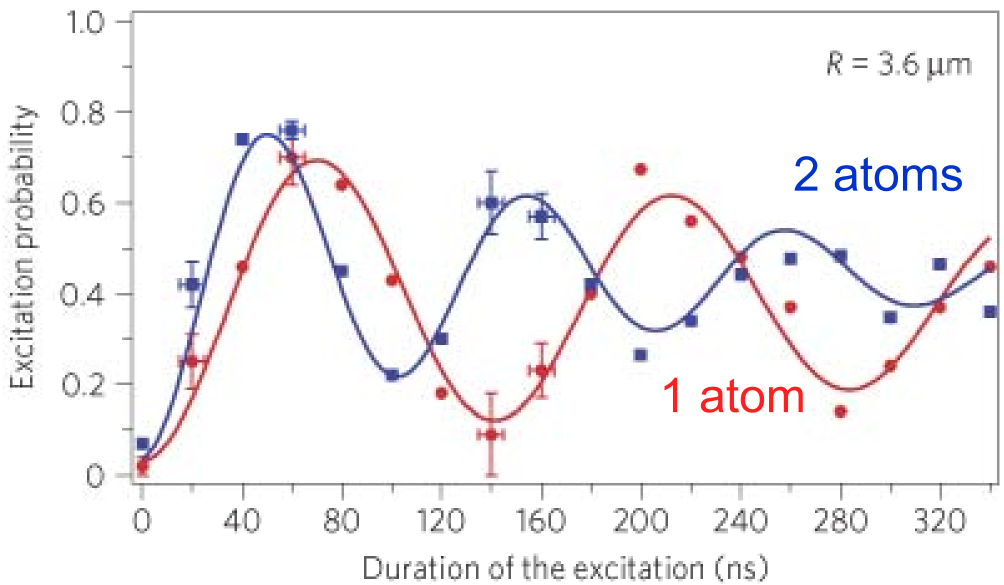
Super A tom

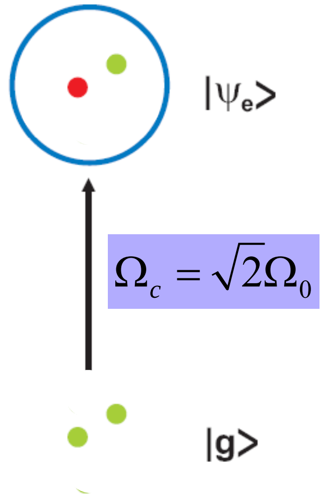
- SuperAtom made of 2-100000 atoms



Ultracold samples:

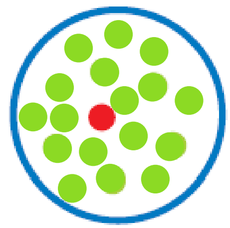






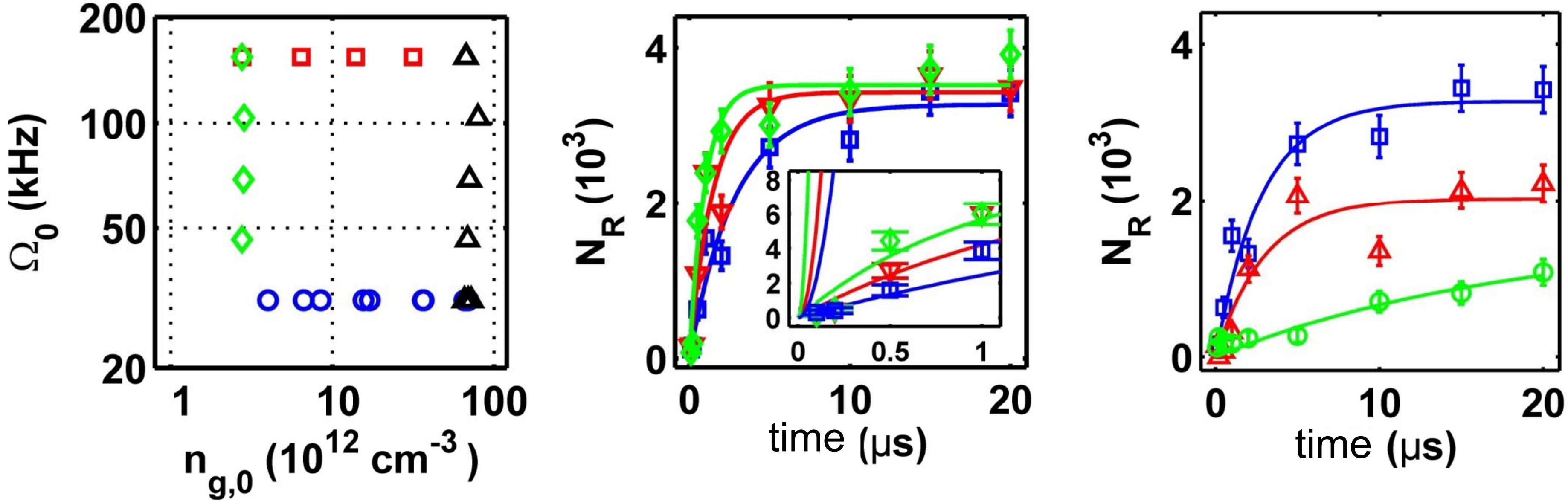
N=2: Gaetan et al., *Nature Phys.* ***5****, 115 (2009)*

N ~ 1000: Heidemann et al., *PRL* ***99****, 163601 (2007)*
see also Kuzmich group 2012
see also Walker/Saffman 2013
see J. Balewski phD thesis 2013 (N>1000



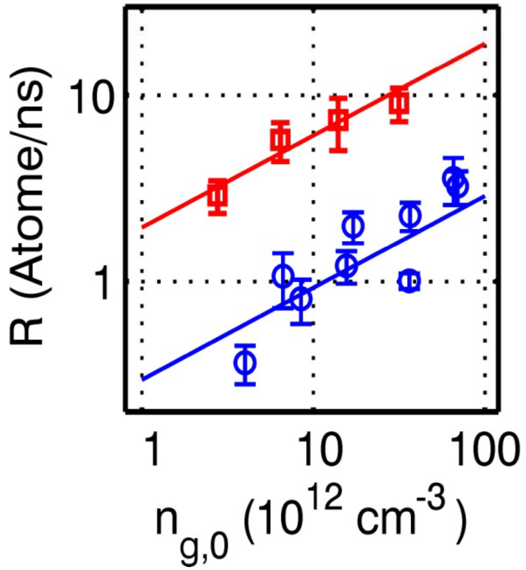
Blockade measurements

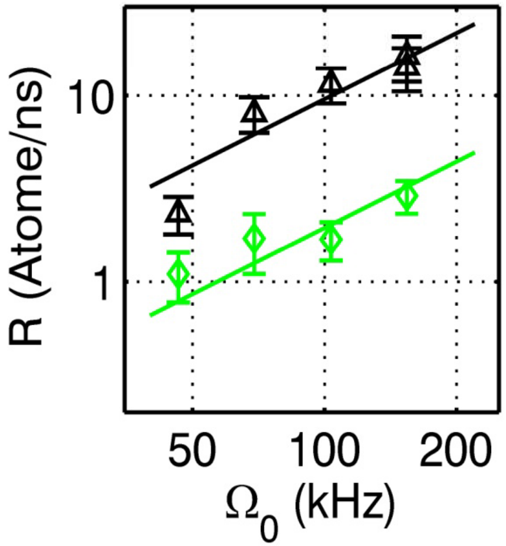
change density by microwave   change Ω_0



Heidemann et al., *PRL **99**, 163601 (2007)*

Scaling of excitation rate R





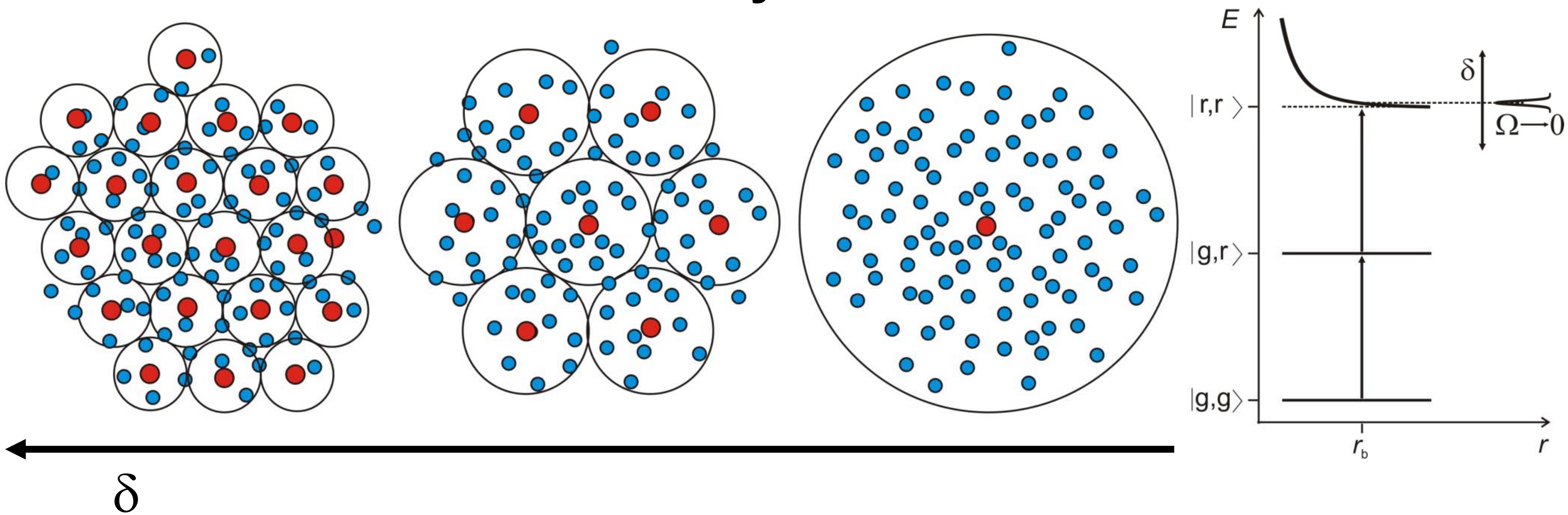
$$\boxed{R \propto \Omega_0^2 \Gamma^{-1}}$$

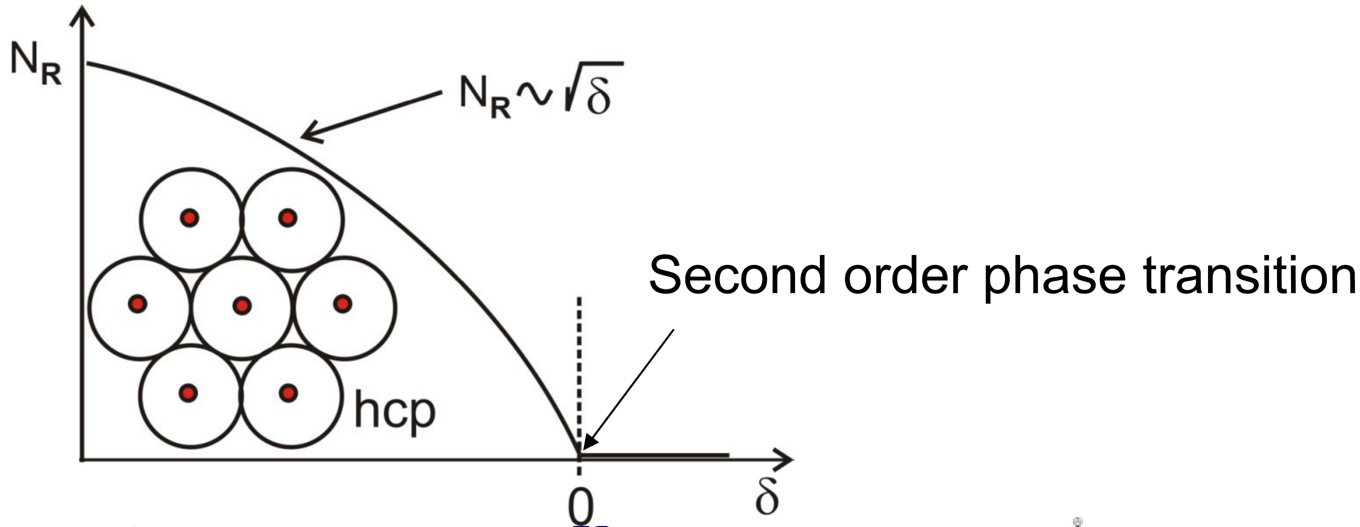
$$\boxed{R \propto n_{g,0}}$$

$$\boxed{R \propto n_{g,0}^{0.49(7)} \Omega_0^{1.2(1)}}$$

Heidemann et al., *PRL **99**, 163601 (2007)*

Is it Crystaline?

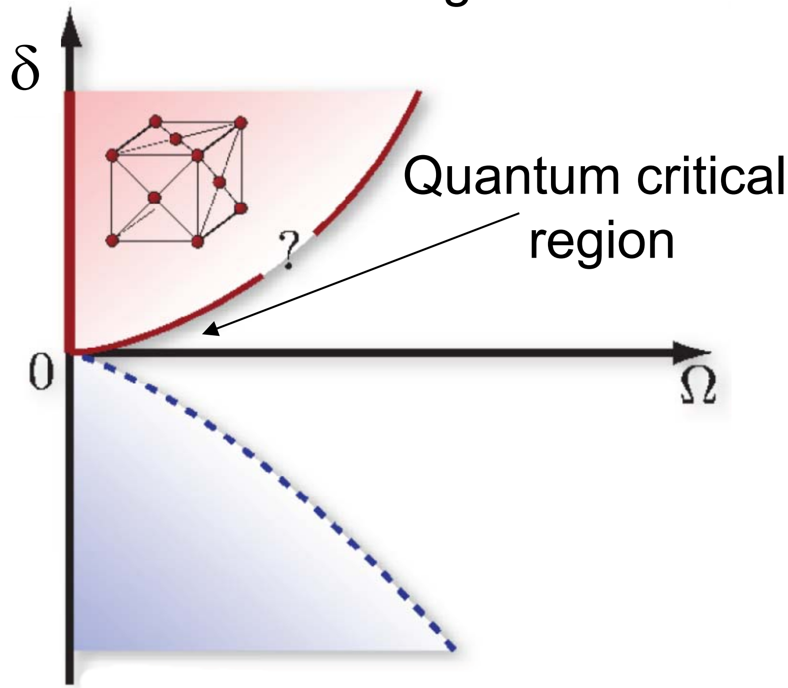




Effective Spin Hamiltonian

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

Phase diagram



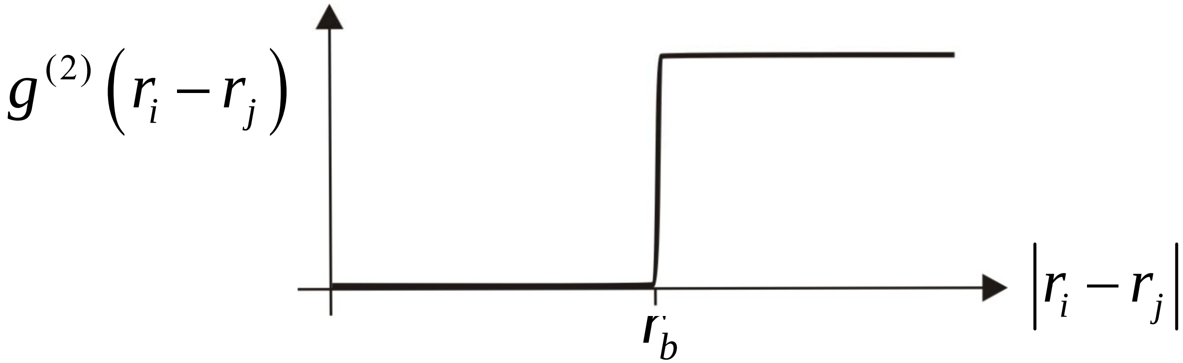
Projector: $P_{ee}^{(i)} = (1+\sigma_z^{(i)})/2$

PRL **101** 250601 (2008)

Effective Spin Hamiltonian – Mean-field description

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

Second order correlation function for the excited state



Equation of state:
(Rydberg fraction)

$$\frac{N_R}{N}=f_R(\Delta,\alpha)$$

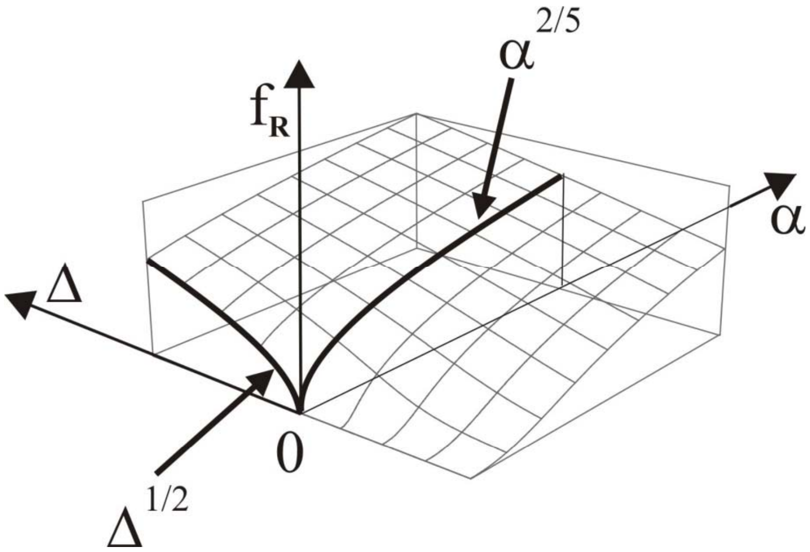
Dimensionless parameters

$$\alpha=\frac{\hbar\Omega}{C_6 n^2}\qquad \Delta=\frac{\hbar\delta}{C_6 n^2}$$

$$\alpha=\left(\frac{\text{Mean atomic distance}}{\text{blockade radius } r_b}\right)^6$$

Universal scaling close to a quantum critical point

Strongly interacting Rydberg gas

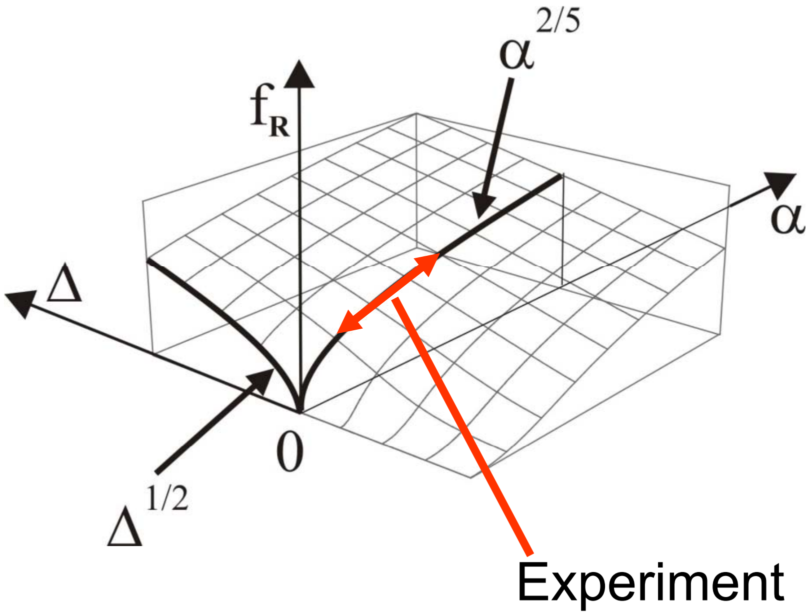


Mean-field result:

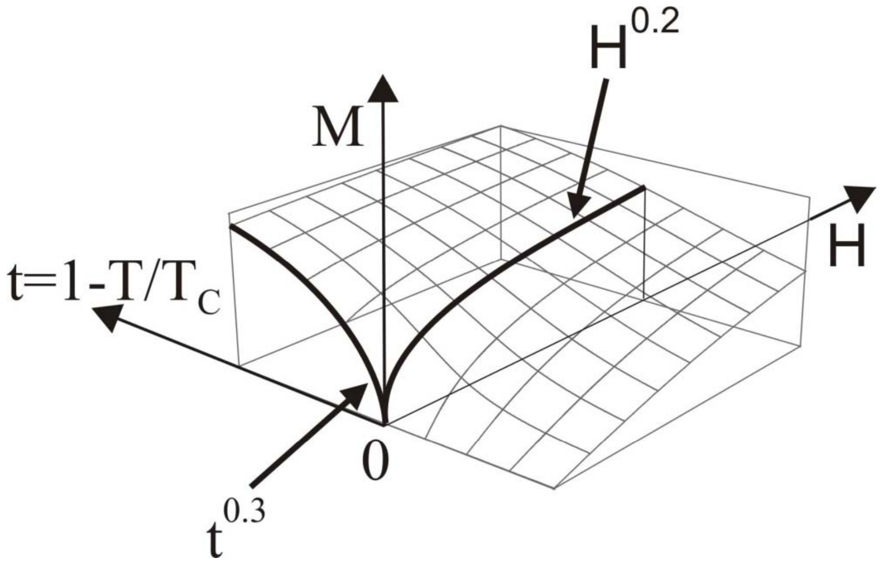
$$\alpha = f_R^{5/2} \left| 1 - \frac{\Delta}{f_R^2} \right|$$

Universal scaling close to a quantum critical point

Strongly interacting Rydberg gas



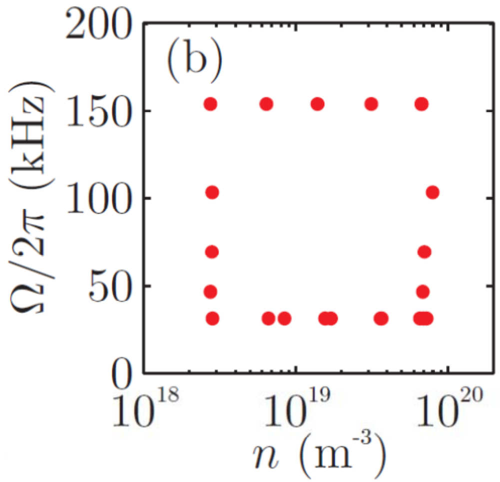
Ferromagnet - Ising model

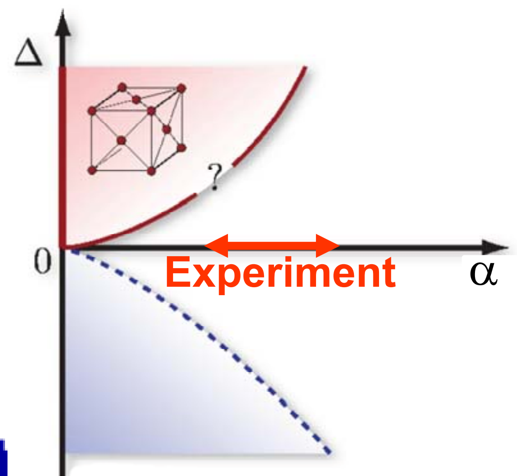


PRA 80, 033422 (200

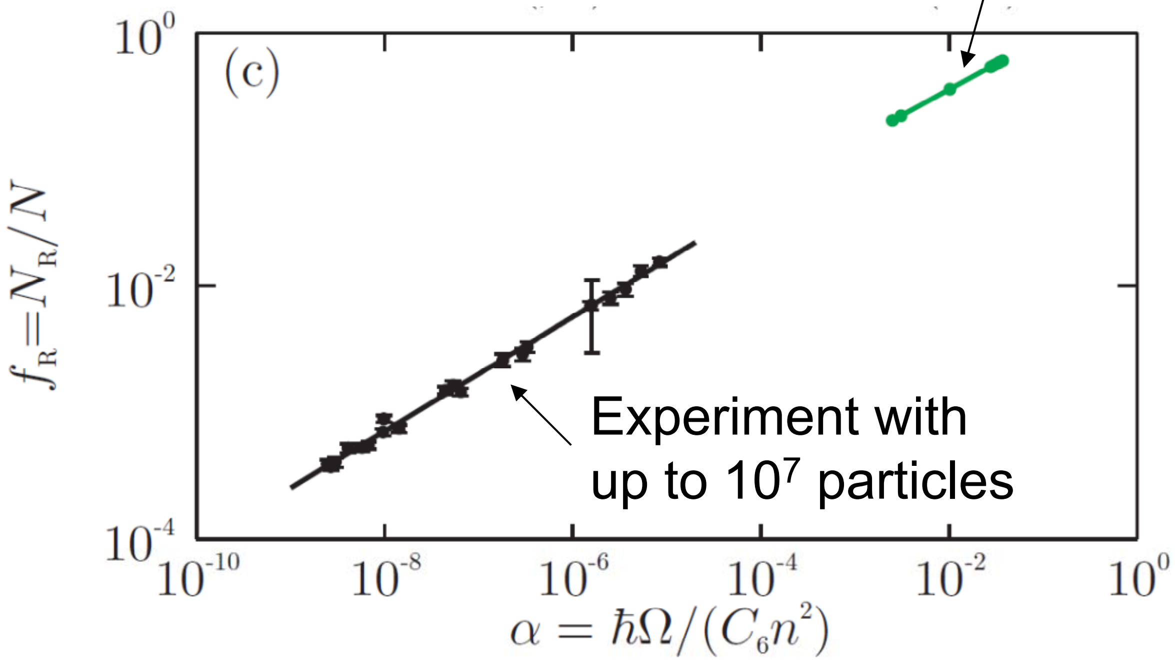
Data collapse on a simple power law – Universal scaling

Scanned parameter space





Numerical simulations with up to 100 particles



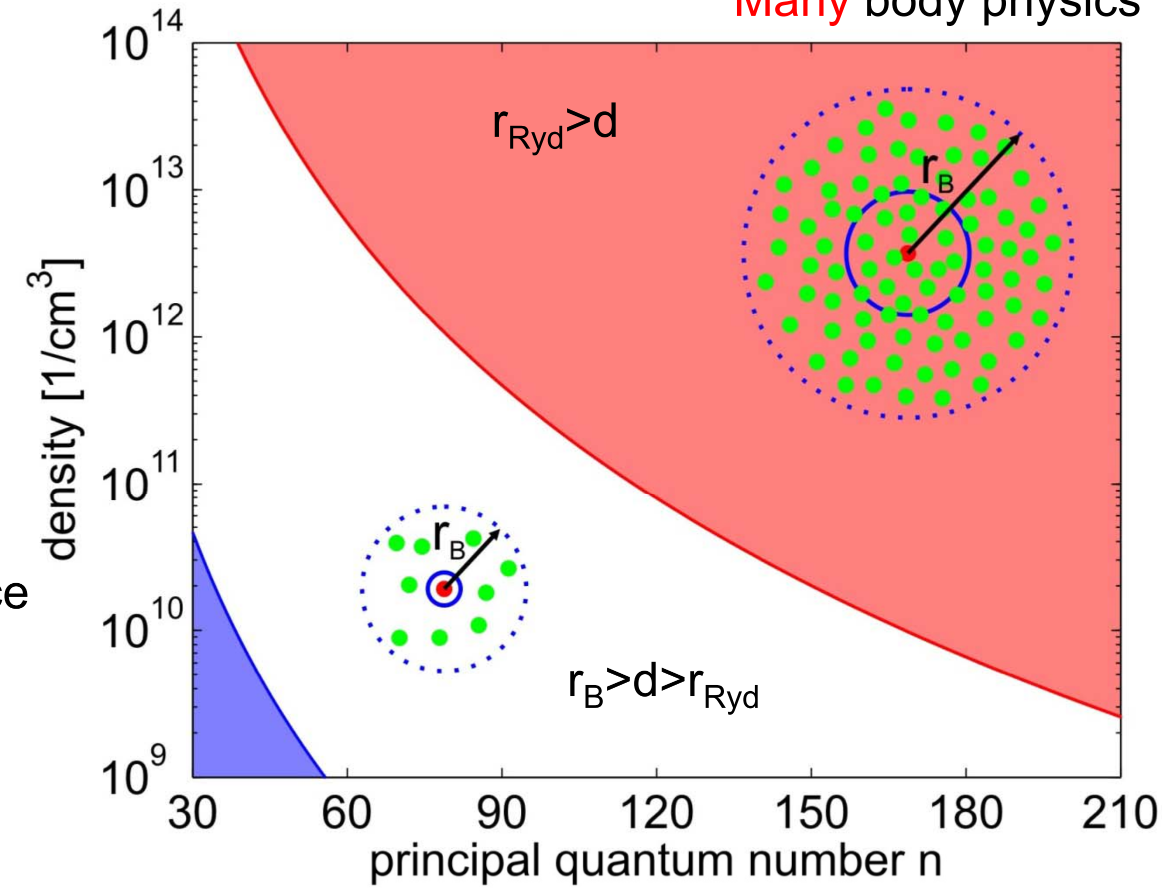
Fit result: $f_R \propto \alpha^{0.45\pm0.01}$

Theory: $f_R \propto \alpha^{2/5} = \alpha^{0.4}$

PRA 80, 03

Rydberg atoms in dense gases

Many body physics



d: mean particle distance

r_B: blockade radius

r_{Ryd}: size of electron orbit