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Few-body physics with Ultracold Magnetic Erbium

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2010

erc

2016

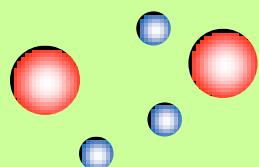
erc

FWF START
Der Wissenschaftsfonds.

IQI



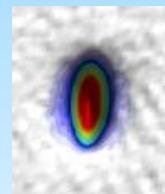
temperatur



atomic mixtures

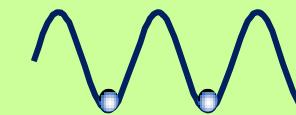
internal energy

Ultracold
atoms



bosons &
fermions

interactions



crystal of atoms

BOSE-EINSTEIN CONDENSATES



1 1 H hydrogen [1.007; 1.009]	2 Li lithium [6.938; 6.997]	3 Be beryllium 9.012	4 Mg magnesium 24.31	5 Cr chromium 52.00	6 Mn manganese 54.94	7 Fe iron 55.85	8 Co cobalt 58.93	9 Ni nickel 58.69	10 Cu copper 63.55	11 Zn zinc 65.38(2)	12 Ga gallium 69.72	13 Al aluminum 26.98	14 Si silicon [28.08; 28.09]	15 P phosphorus 30.97	16 S sulfur [32.05; 32.08]	17 Cl chlorine [35.44; 35.46]	18 Ne neon 20.18	
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.87	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.38(2)	31 Ga gallium 69.72	32 Ge germanium 72.63	33 As arsenic 74.92	34 Se selenium 78.96(3)	35 Br bromine 79.90	36 Kr krypton 83.80	
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96(2)	43 Tc technetium	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3	
55 Cs caesium 132.9	56 Ba barium 137.3	57-71 lanthanoids	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.8	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.6	81 Tl thallium [204.3; 204.4]	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium	85 At astatine	86 Rn radon	
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium		114 Fl flerovium		116 Lv livermorium			
I		I		I		I		I		I		I		I		I		
57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.1	71 Lu lutetium 175.0				
89 Ac actinium	90 Th thorium 232.0	91 Pa protactinium 231.0	92 U uranium 238.0	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium				

BOSE-EINSTEIN CONDENSATES

1	H	hydrogen	[1.007; 1.009]
3	Li	lithium	[6.938; 6.997]
11	Na	sodium	22.99
19	K	potassium	39.10
20	Ca	calcium	40.08
37	Rb	rubidium	85.47
38	Sr	strontium	87.62
55	Cs	caesium	132.9

One-electron atom
“simple” electronic structure ($L=0$),
tunable contact interaction!

$$U_c = \frac{4\pi\hbar^2 a}{m} \delta(r)$$

24	Cr	chromium	52.00
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strong dipolar character

Two-electron atoms
“simple” electronic and
nuclear structure ($L=0$, $S=0$ and
 $I=0$),
clock transitions, ...

$$V_{dd} = \frac{\mu_0 \mu^2}{4\pi} \frac{1 - 3 \cos^2 \theta}{r^3}$$

Multi-electron atom
“complex” electronic structure
(L very large), tunable contact
interaction and dipole-dipole
interaction

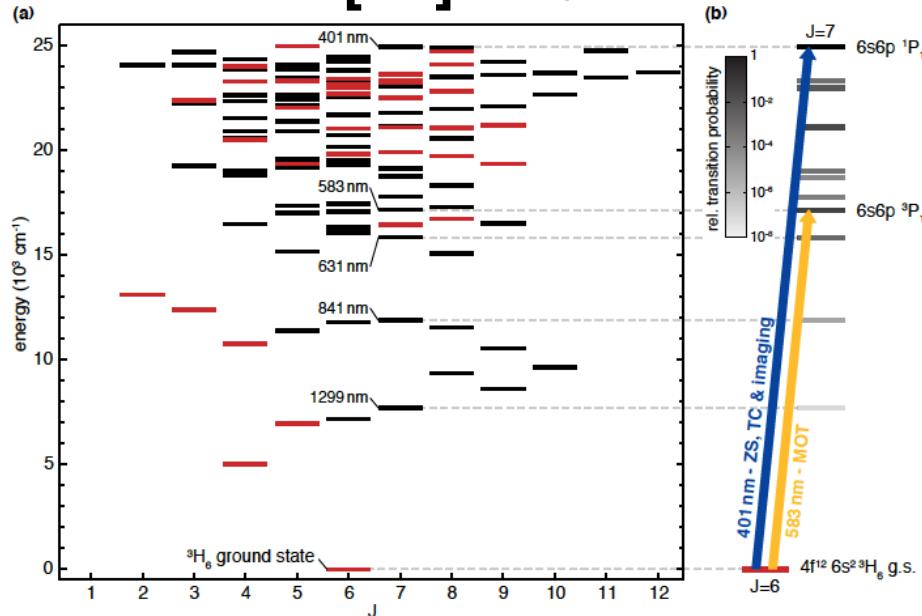
66	Dy	dysprosium	162.5
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68	Er	erbium	167.3
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70	Yb	ytterbium	173.1
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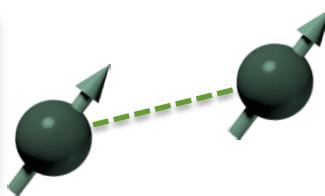
More laser cooled species: Ho and Tm

f-block : [Xe]4f¹²6s²



- ◆ partially filled 4f electron shell, submerged below a filled 6s shell.
- ◆ large magnetic moment and mass
- ◆ Anisotropic van-der-Waals interaction ΔC_6

Large magnetic moment μ !

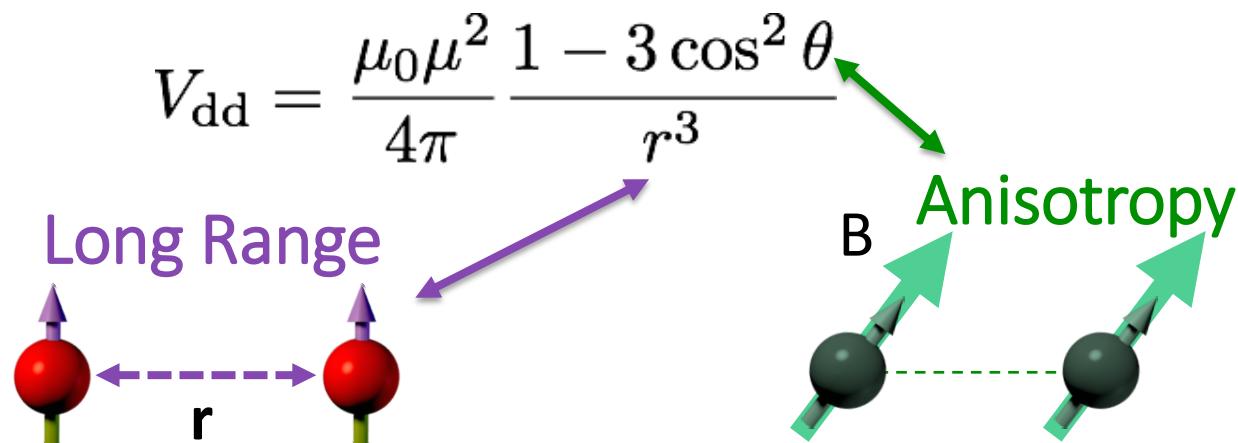


Magnetic Anisotropy
(long range)
 $\mu \approx 7 \mu_B$

Large total angular momentum j !



Orbital Anisotropy
(short range)
 $j=6$



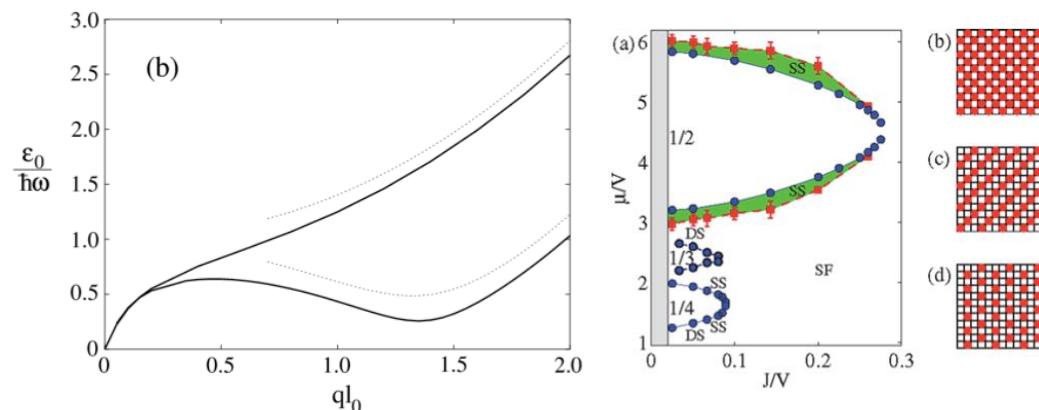
Few-body physics

and scattering behavior (different Wigner threshold law)

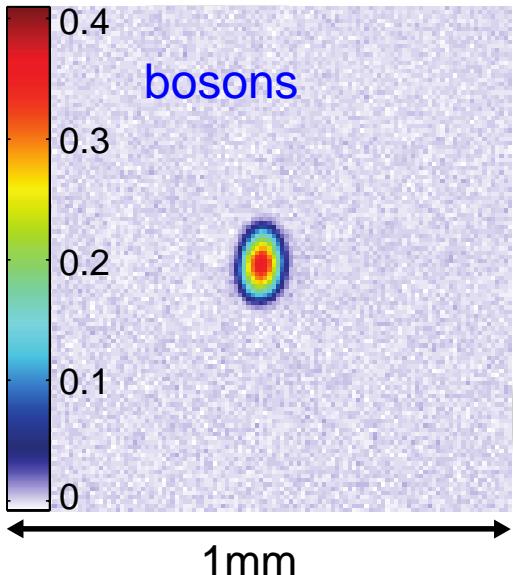
$$\sigma_l \propto \frac{\delta_l^2}{k^2}$$

Many-body physics

e.g. ground state properties, spectrum of excitations, novel quantum phases

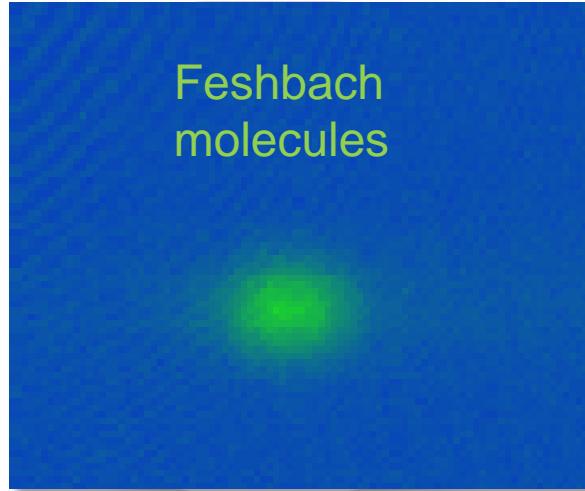


OUR TOOLBOX IN THE LAB



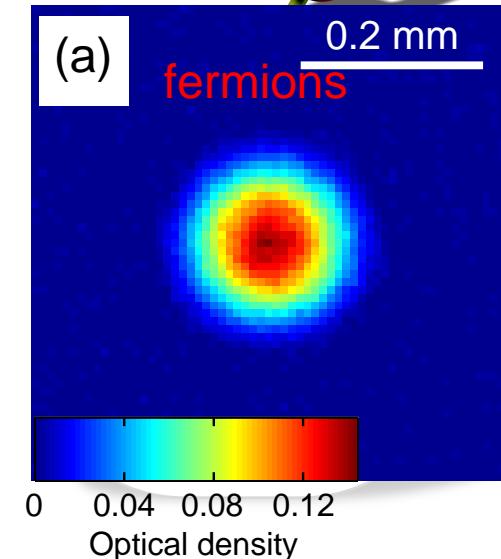
$N = 2 \times 10^5$
Almost pure

Peak density:
 $2 \times 10^{14} \text{ cm}^{-3}$



$N = 3 \times 10^4$
 $T = 250 \text{ nK}$

Er_2 : A. Frisch *et al.* PRL **115** (2015)



$N = 3 \times 10^4$
 $T/T_F = 0.11(2)$

Peak density:
 $4 \times 10^{14} \text{ cm}^{-3}$

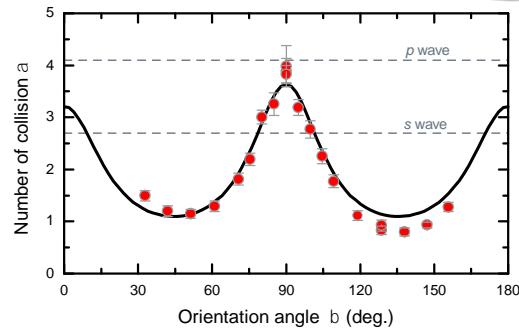
$^{168}\text{Er BEC}$: K. Aikawa, *et al.* PRL **108** (2012)

$^{167}\text{Er dFg}$:

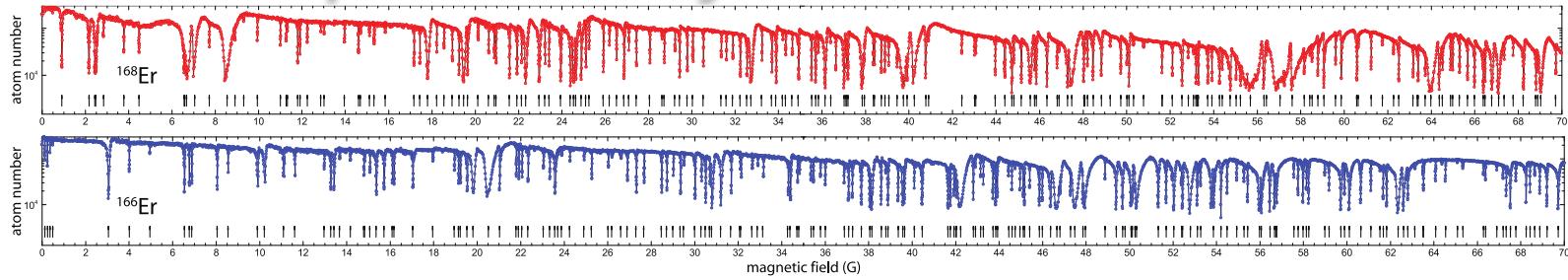
K. Aikawa, *et al.* PRL **112** (2014)

$^{166}\text{Er BEC}$: S. Baier, *et al.* *in prep.* (2016)

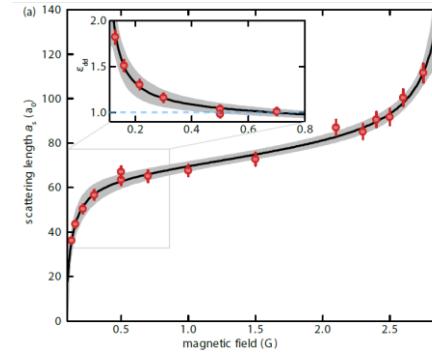
Universal dipolar scattering



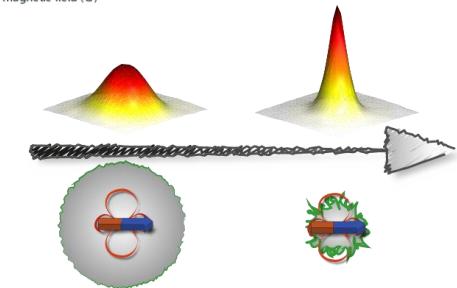
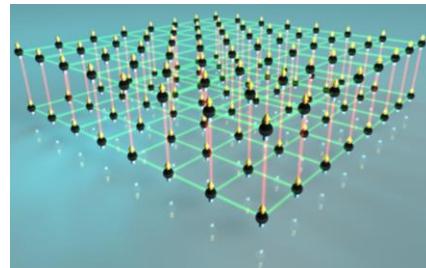
Feshbach spectrum of Ln



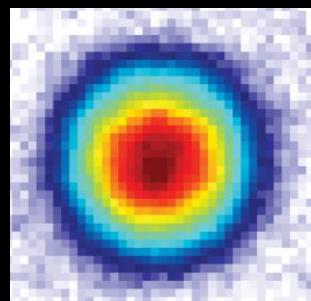
Short range interactions



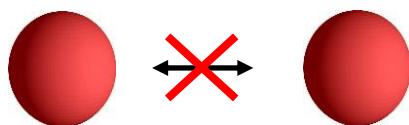
Experiments on many-body level



Universal dipolar scattering



Identical fermions cannot collide at ultralow temperature



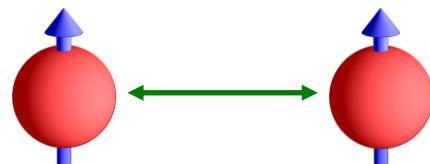
Fermions collide in odd l

$$\sigma_{\ell \neq 0} \propto k^{4\ell} \rightarrow 0$$

Previous solutions: mixing distinguishable particles

- Spin mixture
- Isotopic mixture
- Mixture of different atomic species

$$\sigma_{\ell=0} \rightarrow 4\pi a^2$$



¹⁶⁷Er
Can identical dipolar fermions collide at ultralow T?

Pauli exclusion principle: Fermions collide in *odd* partial wave ($l=1$, p-wave)

Wigner threshold law for $1/r^n$ potentials

For small phase shift

$$\sigma_l \propto \frac{\delta_l^2}{k^2} \left\{ \begin{array}{ll} \text{"short-range" fermions} & \\ V_{\text{vdW}} \propto 1/r^6 & \delta_l = k^{2l+1} \quad \sigma_{l=1} \propto k^4 \rightarrow 0 \\ \text{"long-range" fermions} & \\ V_{\text{DDI}} \propto 1/r^3 & \delta_l = k^{n-2} \end{array} \right.$$

$\sigma_{l=1} = \text{const.}$

Intensive theoretical work, e.g.: L.D. Landau, E.M. Lifshitz, Quantum Mechanics (1999); B. Deb and L. You, PRA (2001);

C. Ticknor, PRL 100, 133202 (2008) , J. L. Bohn, M. Cavagnero, and C. Ticknor, New J. Phys. 11, 055039 (2009), Paul S. Julienne et al., Phys. Chem. Chem. Phys. 13, 19114 (2011), and many more

DDI: finite elastic cross section (energy-independent and universal)

universal dipolar scattering
elastic cross section

$$\sigma_{\ell}^{\text{el}} \xrightarrow{k \rightarrow 0} \frac{16\pi}{30} a_d^2 \propto m^2 \mu^4$$

Typical s-wave cross section for alkali species: $7 \times 10^{-12} \text{ cm}^2$

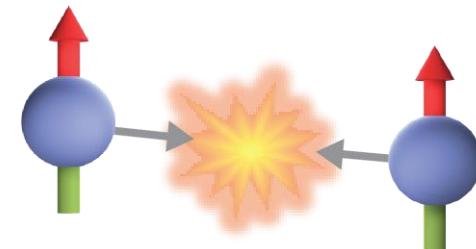
$$a_d = \frac{m\mu_0\mu^2}{4\pi\hbar^2}$$

Calculations:

$${}^{40}\text{K}: 4.4 \times 10^{-17} \text{ cm}^2$$

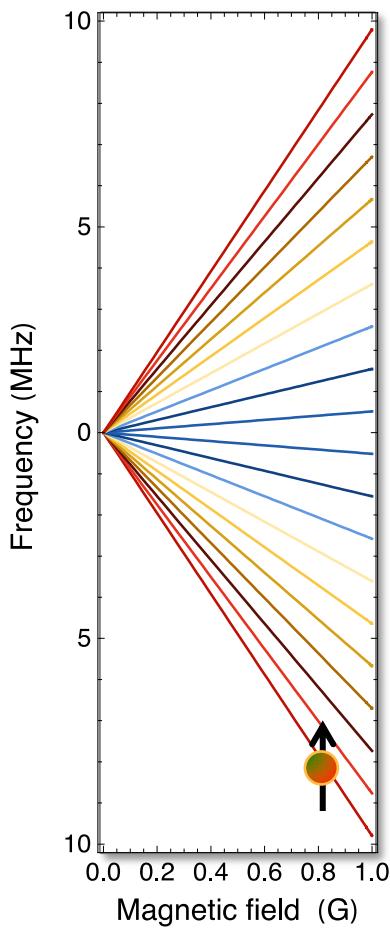
$${}^{40}\text{K} {}^{87}\text{Rb}: 6.4 \times 10^{-9} \text{ cm}^2$$

$${}^{167}\text{Er} : 1.8 \times 10^{-12} \text{ cm}^2$$



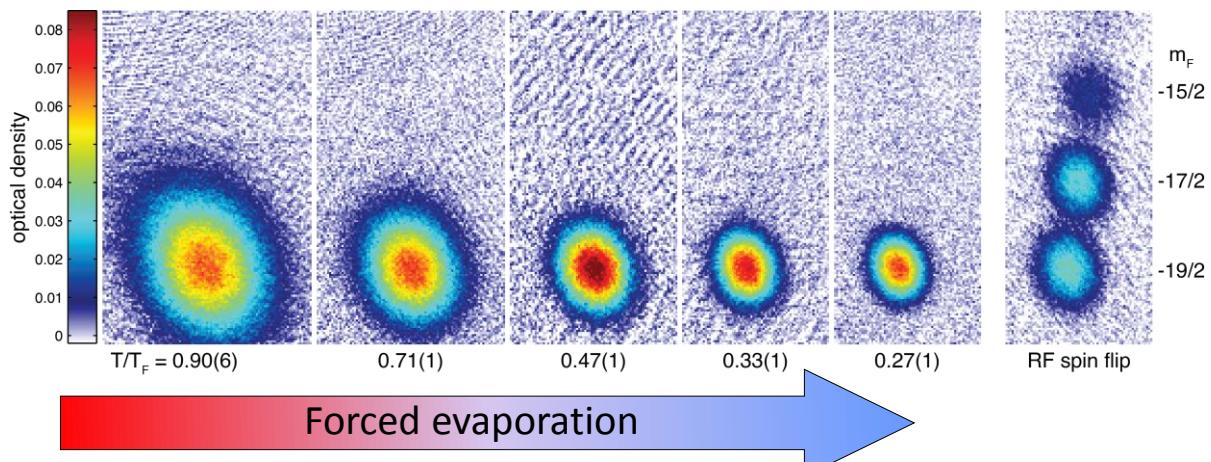
Prospect for evaporative cooling of identical fermions

SPIN-POLARIZED FERMIONS

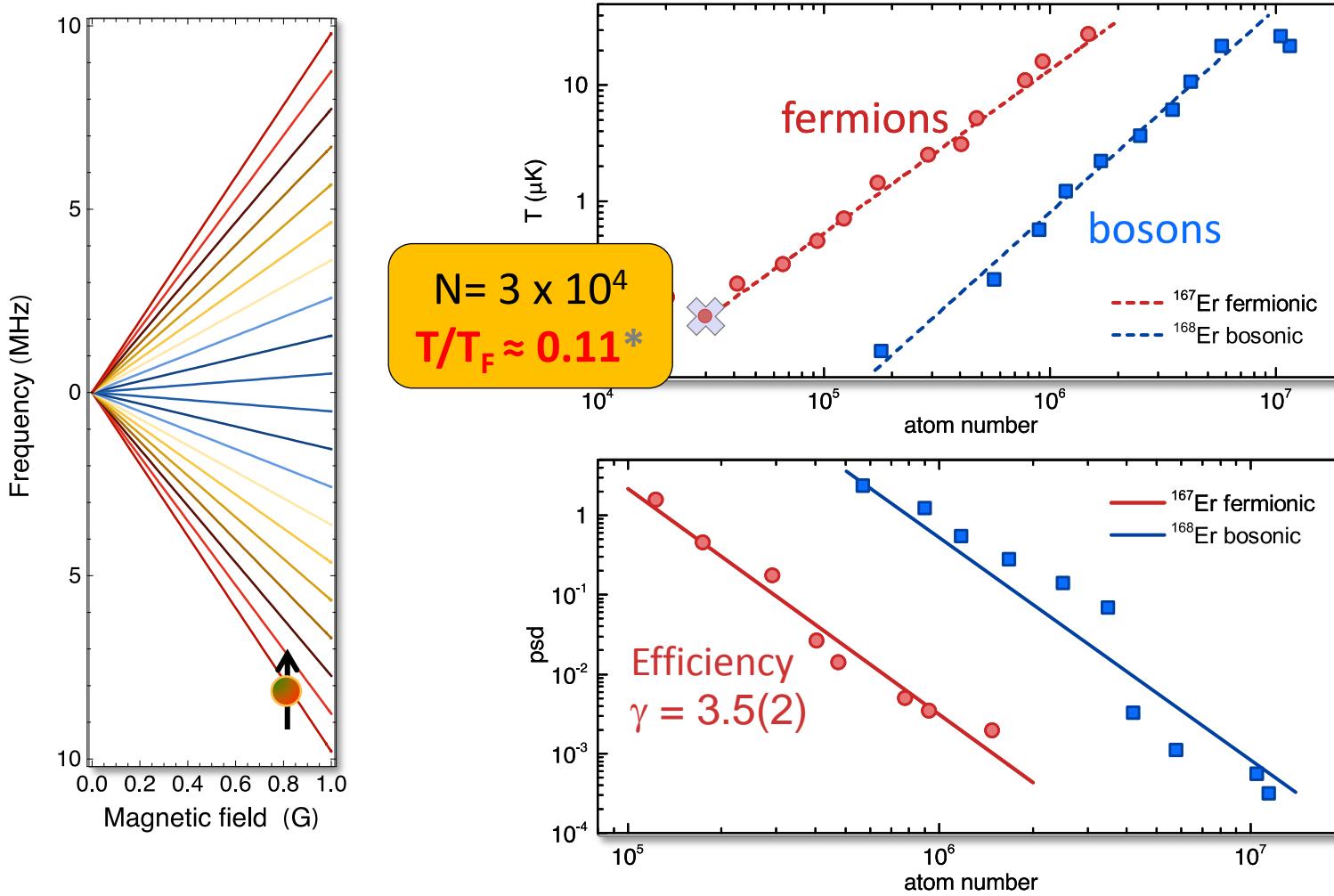


Fermions are **SPIN POLARIZED** in the ODT

Spin-polarization under control using Stern-Gerlach technique



DIPOLAR COOLING of indistinguishable fermions

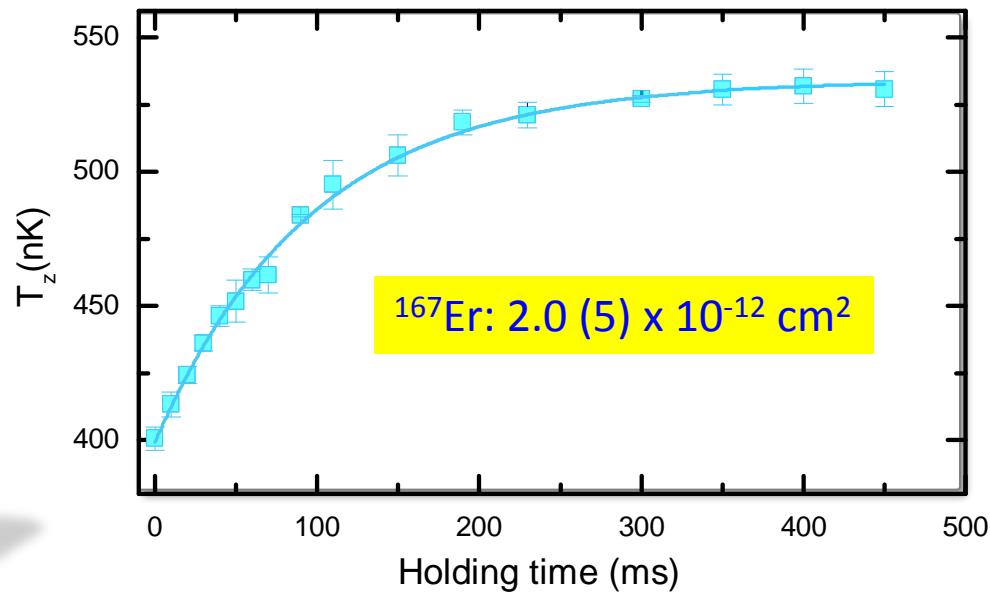
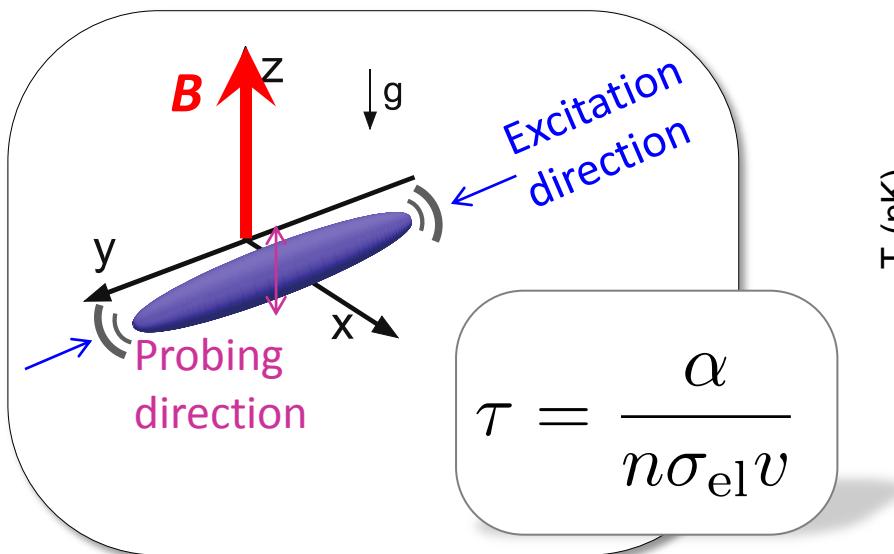


Er dFg: K. Aikawa, et al. PRL **112** (2014)

*Among the (coldest) deepest degenerate Fermi gas

Cross-dimensional thermalization:

bring the system **out of equilibrium** and look at how it relaxes



Mean number of collision/atoms

For “*short-range*” particles

$\alpha = 2.7$ s-wave (bosons)

$\alpha = 4.1$ p-wave (fermions)

(*Monte Carlo cal. + Exps.* *)

Dipolar threshold law

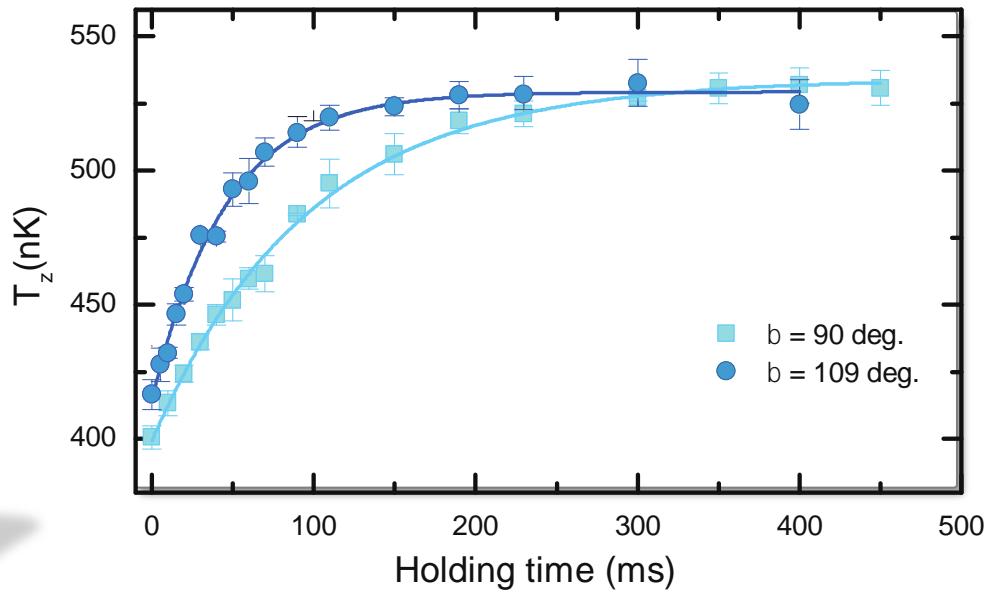
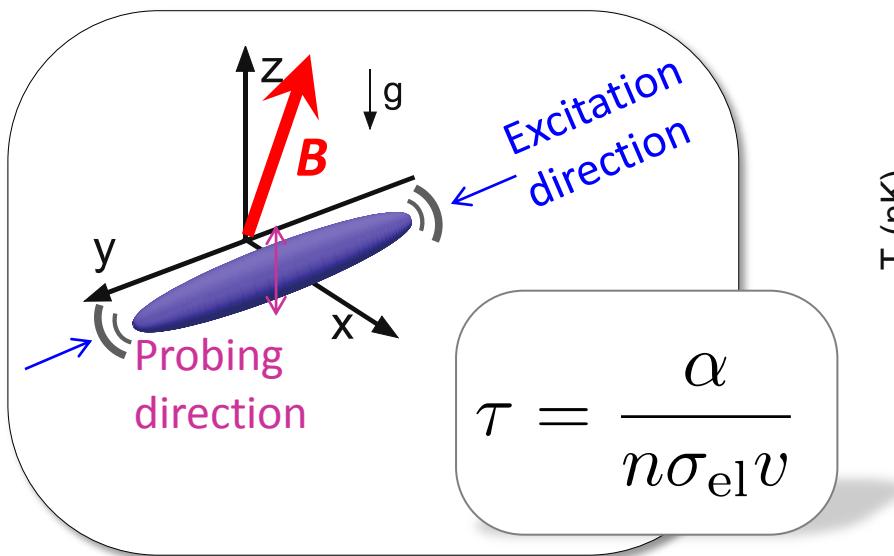
$$\frac{16\pi}{30} a_{dd}^2 \approx 1.8 \times 10^{-12} \text{cm}^2$$

(*): Introduced with Rb in C. R. Monroe et al., PRL (1993) and successfully applied in many experiments

Short-range fermions: B. DeMarco et al., PRL 82 (1999)

RbK dipolar molecules: K.-K. Ni et al., Nature 464 (2010) (inelastic dipolar scattering)

UNIVERSAL DIPOLAR SCATTERING



Mean number of collision/atoms

For “*short-range*” particles

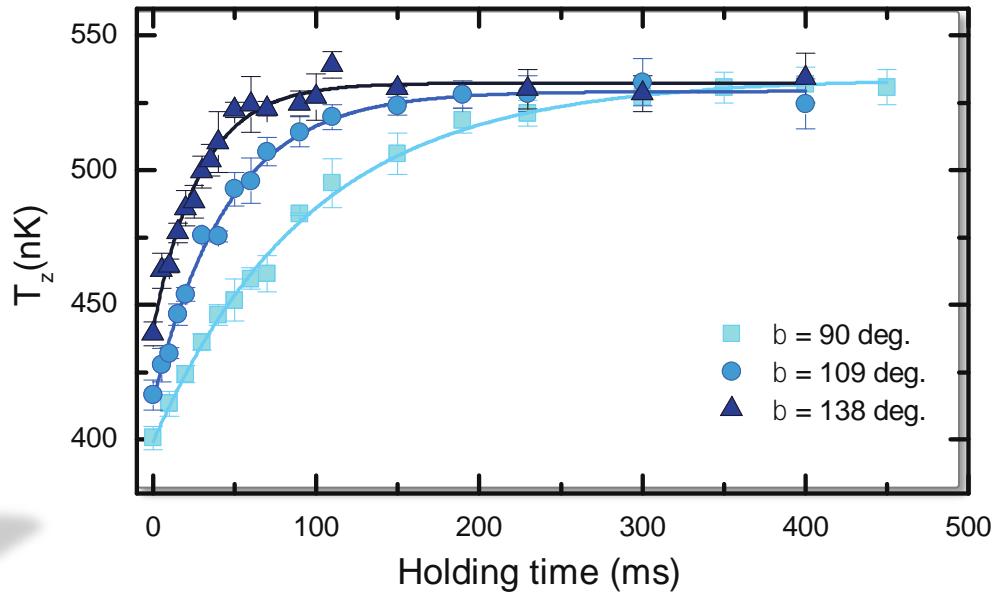
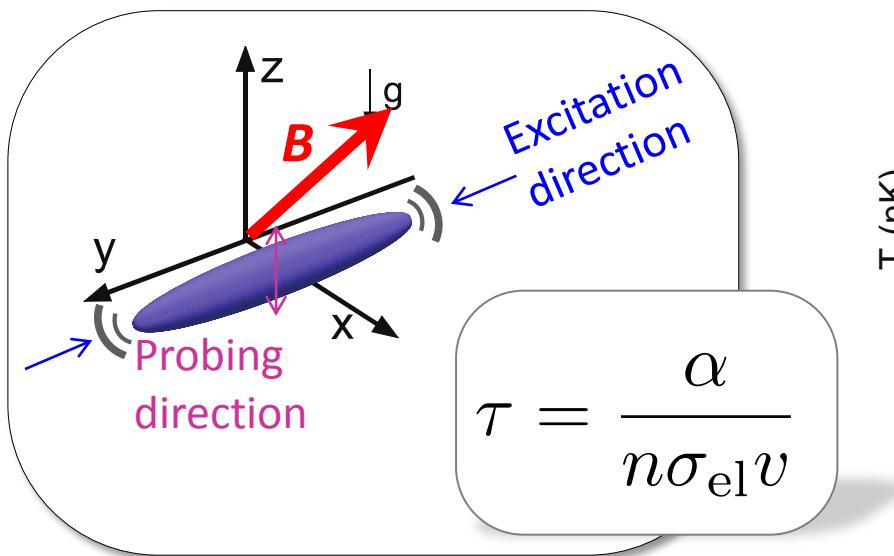
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UNIVERSAL DIPOLAR SCATTERING



Mean number of collision/atoms

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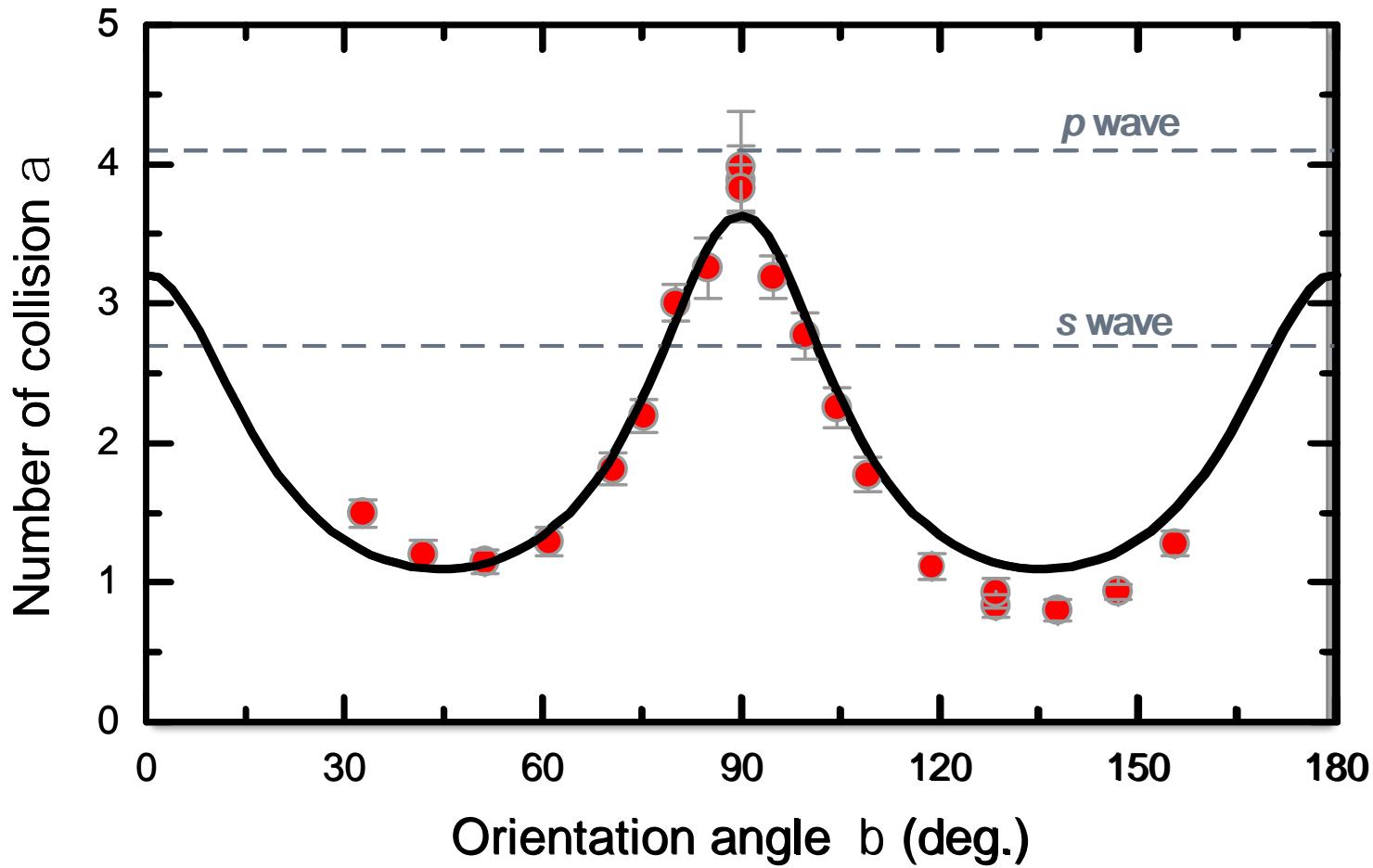
Dipolar threshold law

$$\frac{16\pi}{30} a_{dd}^2 \approx 1.8 \times 10^{-12} \text{ cm}^2$$

Collaboration D. Jin, J. Bohn

J. Bohn and D. Jin, PRA 89, 022702 (2014)

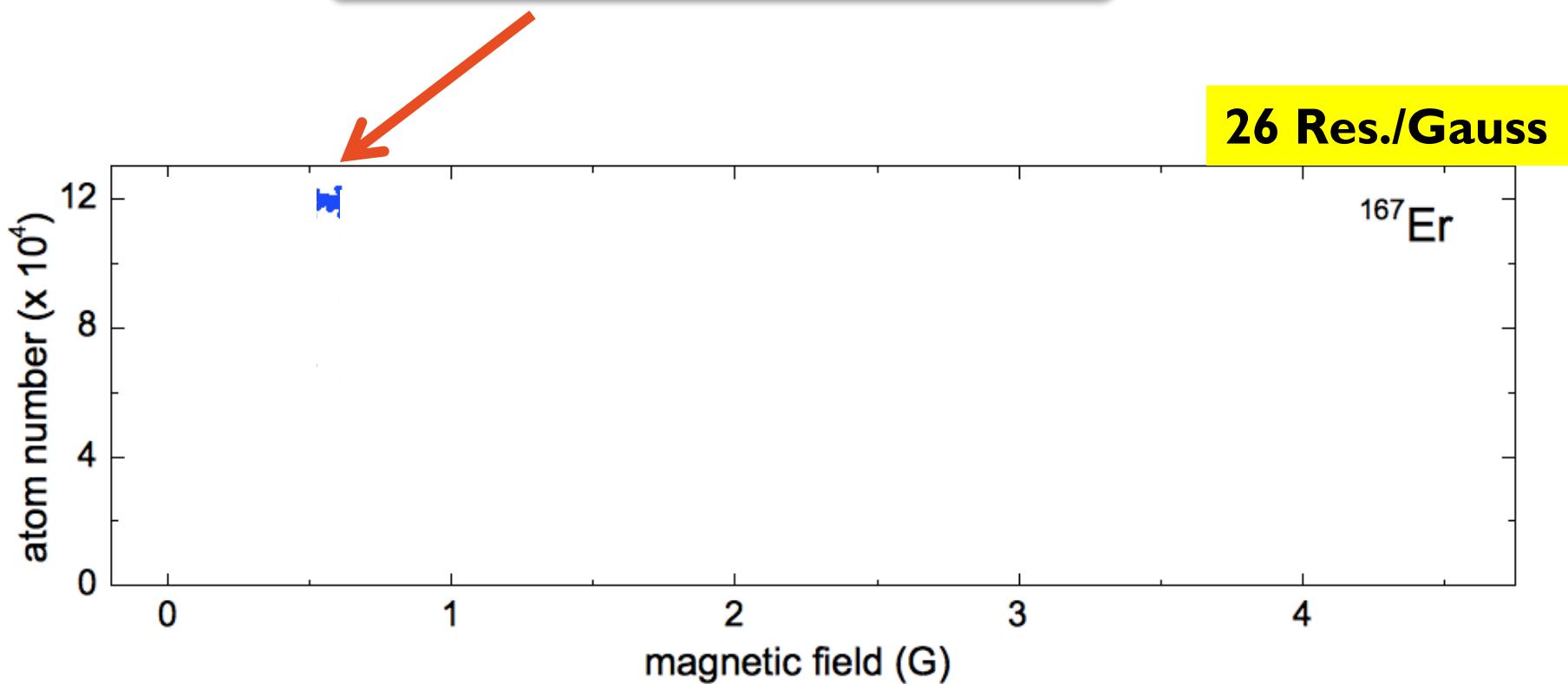
ANISOTROPY IN THE DIPOLAR SCATTERING



Theory (J. Bohn & D. Jin): **NO** free parameters

Feshbach spectroscopy

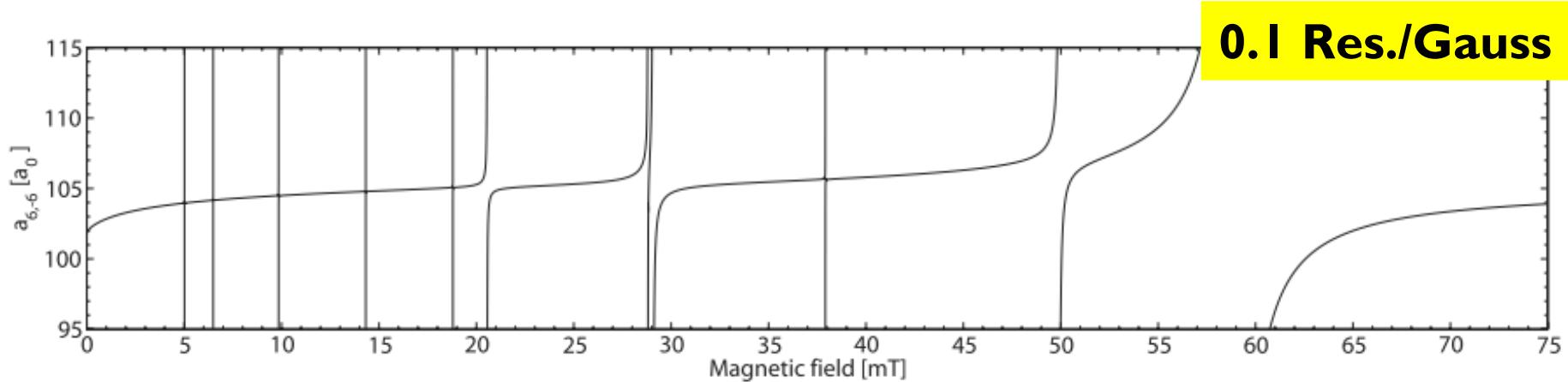
all this work performed at 0.58G



what is the origin?

CHROMIUM

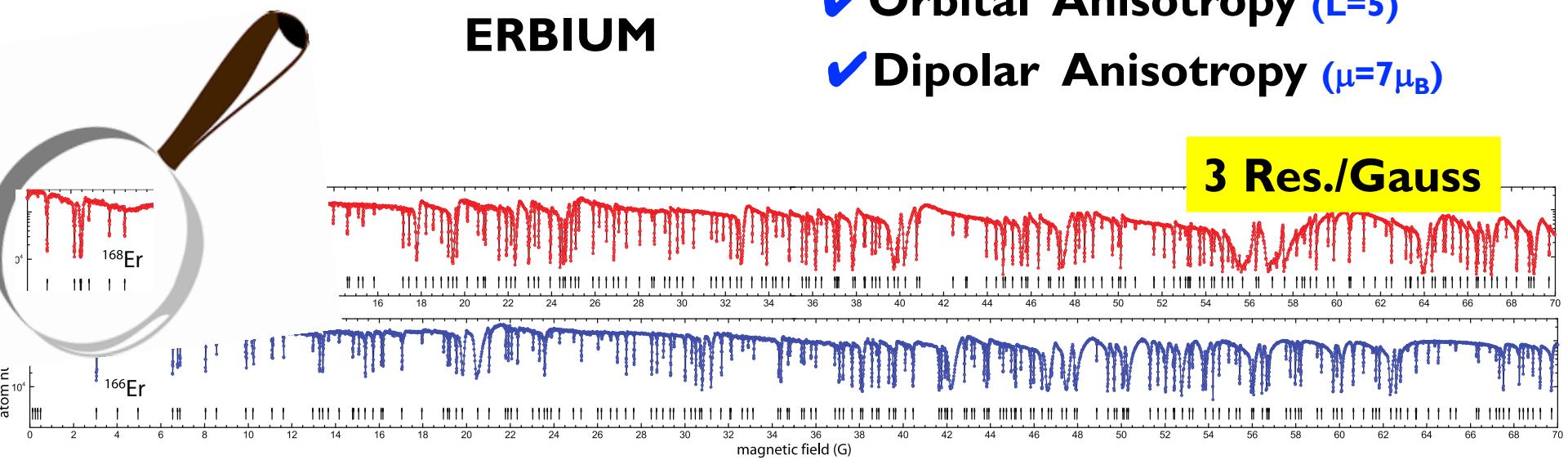
- Orbital Anisotropy ($L=0$)
- Dipolar Anisotropy ($\mu=5\mu_B$)



From Werner et al. PRL (2015)

ERBIUM

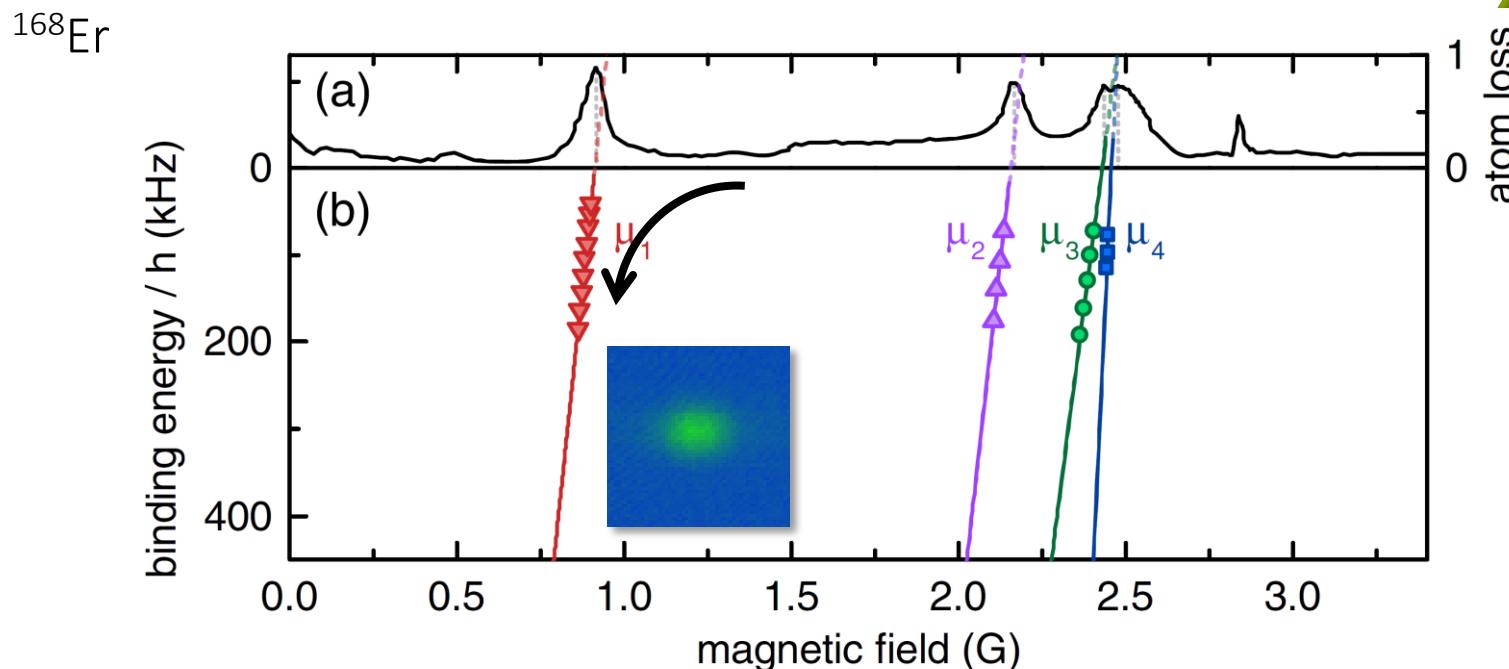
- ✓ Orbital Anisotropy ($L=5$)
- ✓ Dipolar Anisotropy ($\mu=7\mu_B$)



Er FR: A. Frisch et al. Nature (2014)

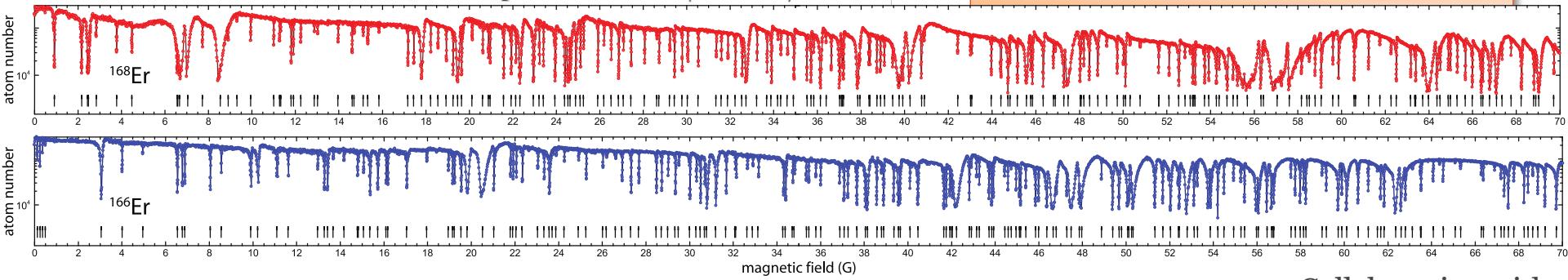
Er and Dy Collaboration: T. Maier et al. PRX (2015)

ASSIGNMENT OF MOLECULAR STATES

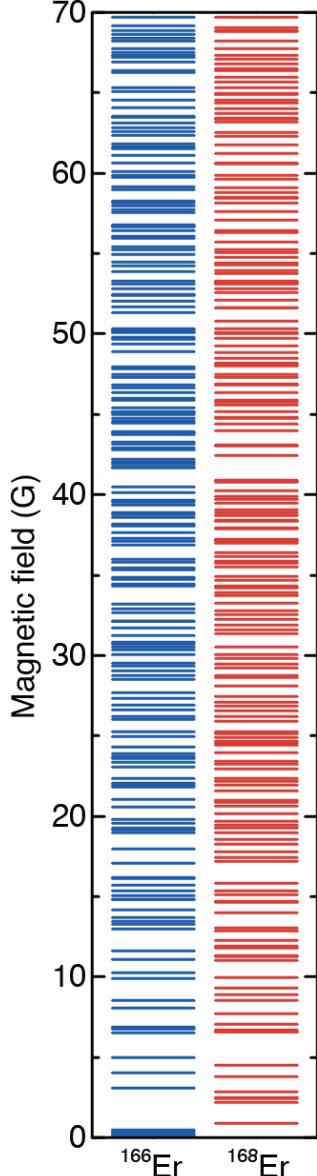


B_{FR} (G)	μ/μ_B	$ \ell, J, M\rangle$
Expt.		

Assignment is possible!

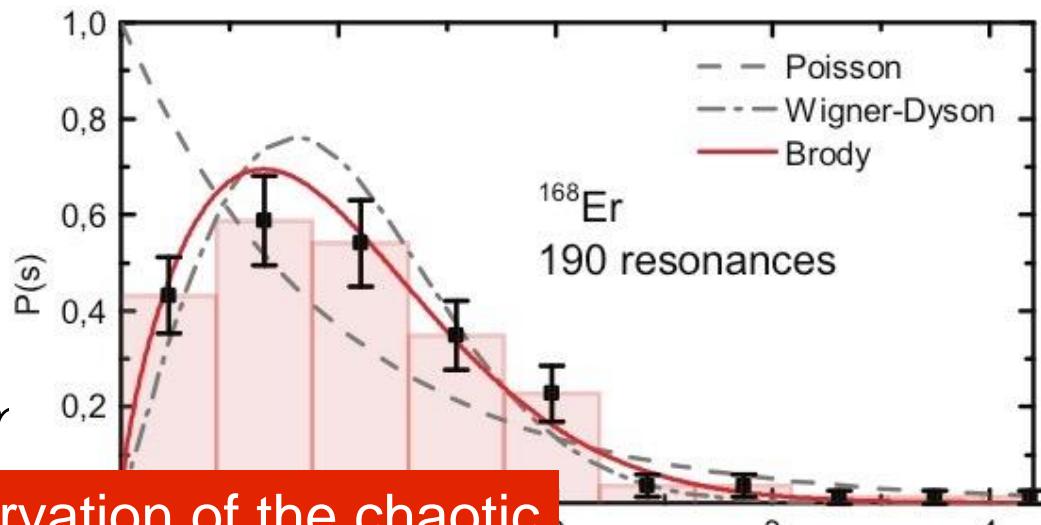


HOW TO TREAT THIS DENSE SPECTRUM IN GENERAL?

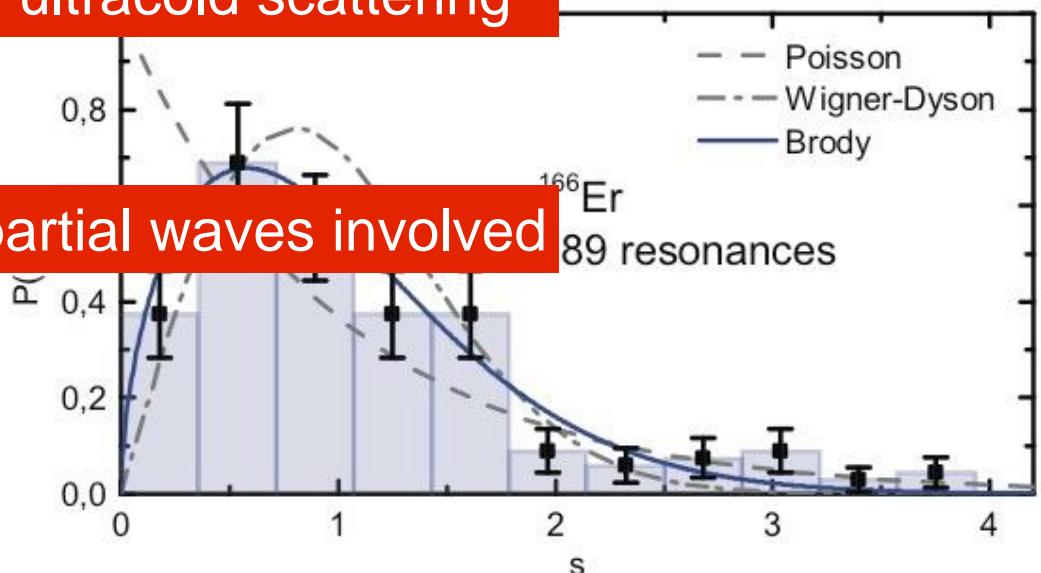


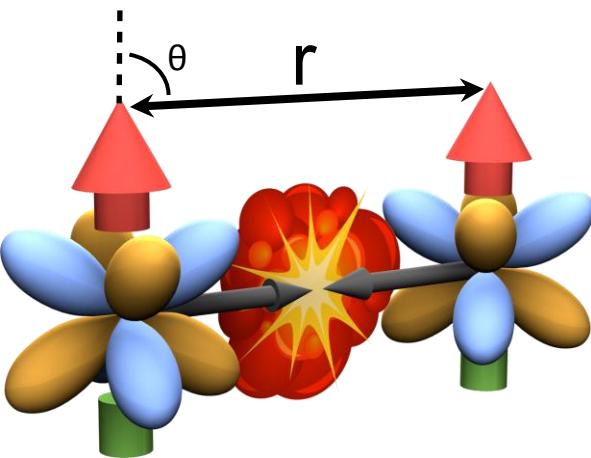
Applying Random

Matrix First observation of the chaotic
Er FR nature of ultracold scattering
resonances



Up to 50 partial waves involved





$$\hat{H}_{\text{rel}} = -\frac{\hbar^2}{2\mu_r} \frac{d^2}{d^2\vec{r}} + \hat{V}(\vec{r}) \left(+ \hat{H}_Z(B) \right)$$

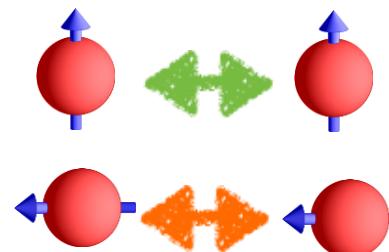
μ_r : reduced mass

Zeeman energy

Which specific interaction potential $\hat{V}(\vec{r})$ for lanthanide atoms?

Dipole-Dipole interaction (DDI):

$$V_{\text{dd}}(\vec{r}) = -\frac{C_3}{|\vec{r}|^3} (3 \cos^2 \theta - 1)$$

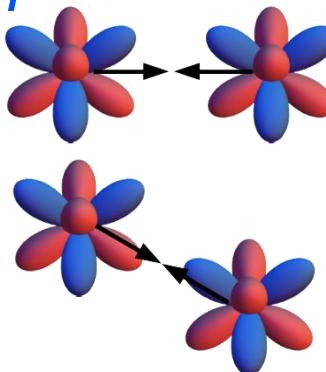


$$C_3 = \frac{\mu_0 \mu^2}{4\pi}$$

Anisotropic van der Waals dispersion:

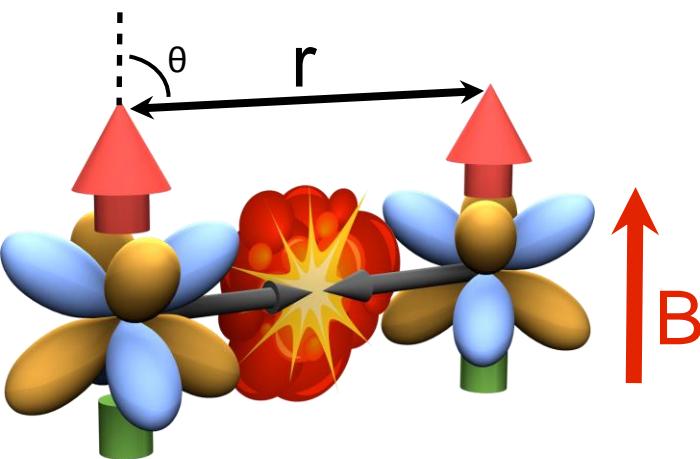
$$V_{\text{vdW}}(\vec{r}) = -\frac{C_6}{|\vec{r}|^6}$$

$$-\frac{C_6^{\text{ani}}}{|\vec{r}|^6} (3 \cos^2 \theta - 1)$$



	C ₆ (a.u)	ΔC ₆ (a.u)
Er	1703	174
Dy	2003	188

RANDOM MATRIX THEORY MODEL



$$\hat{H}_{\text{rel}} = -\frac{\hbar^2}{2\mu_r} \frac{d^2}{d^2\vec{r}} + \hat{V}(\vec{r}) + \hat{H}_Z(B)$$

Zeeman energy

Anisotropic
interaction potential:
Coupling of Zeem
sublevel

Difficult
to simulate

large j : Large number
of Zeeman sublevel in
the ground state.

Toy
model based on
RMT idea

→
replace by

$$\hat{H}_{\text{RMT}} = \hat{H}_0 + \hat{H}_Z(B)$$

\hat{H}_0 B=0 Hamiltonian $\hat{H}_Z(B)$ Zeeman energy

- ◆ Set of random matrices, extract global properties of spectra

Toy
model based on
RMT idea

$$\hat{H}_0 = \begin{pmatrix} E_1^{(0)} & & 0 \\ & \ddots & \\ 0 & & E_n^{(0)} \end{pmatrix} + \begin{pmatrix} 0 & & H_{ij} \\ & \ddots & \\ H_{ji} & & 0 \end{pmatrix}$$

Diagonal «sublevels Energies»
distributed with Brody η_d .

$$\hat{H}_{\text{RMT}} = \hat{H}_0 + \hat{H}_{\text{Z}}(B)$$

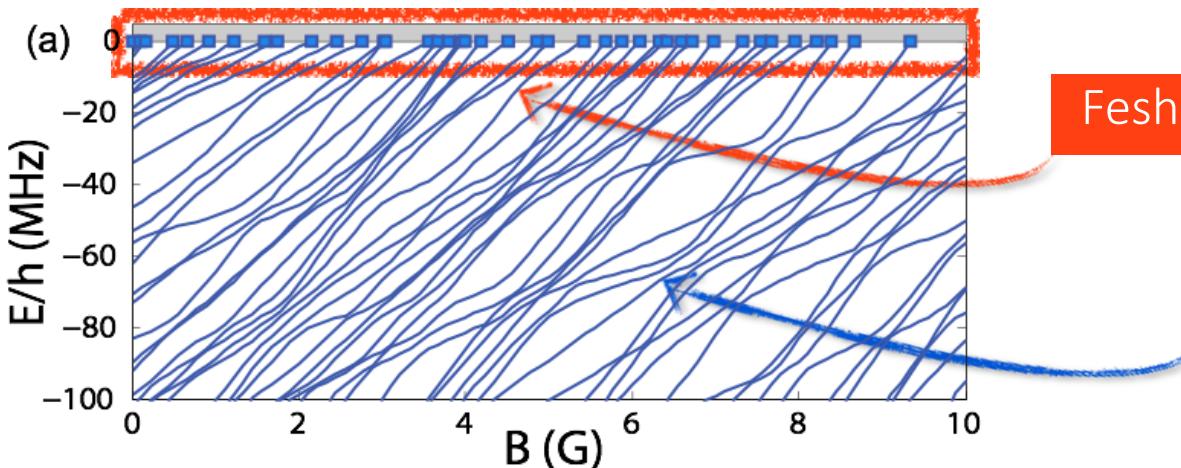
B=0 Hamiltonian Zeeman energy

$$\hat{H}_{\text{Z}}(B) = g\mu_B B \begin{pmatrix} m_1 & & 0 \\ & \ddots & \\ 0 & & m_n \end{pmatrix}$$

Zeeman
sublevels
 $m_i \in \{-12, 12\}$

Coupling between the
sublevels from $V_{\text{ani}}(r)$,
Gaussian-distributed,
strength v_{cpl}

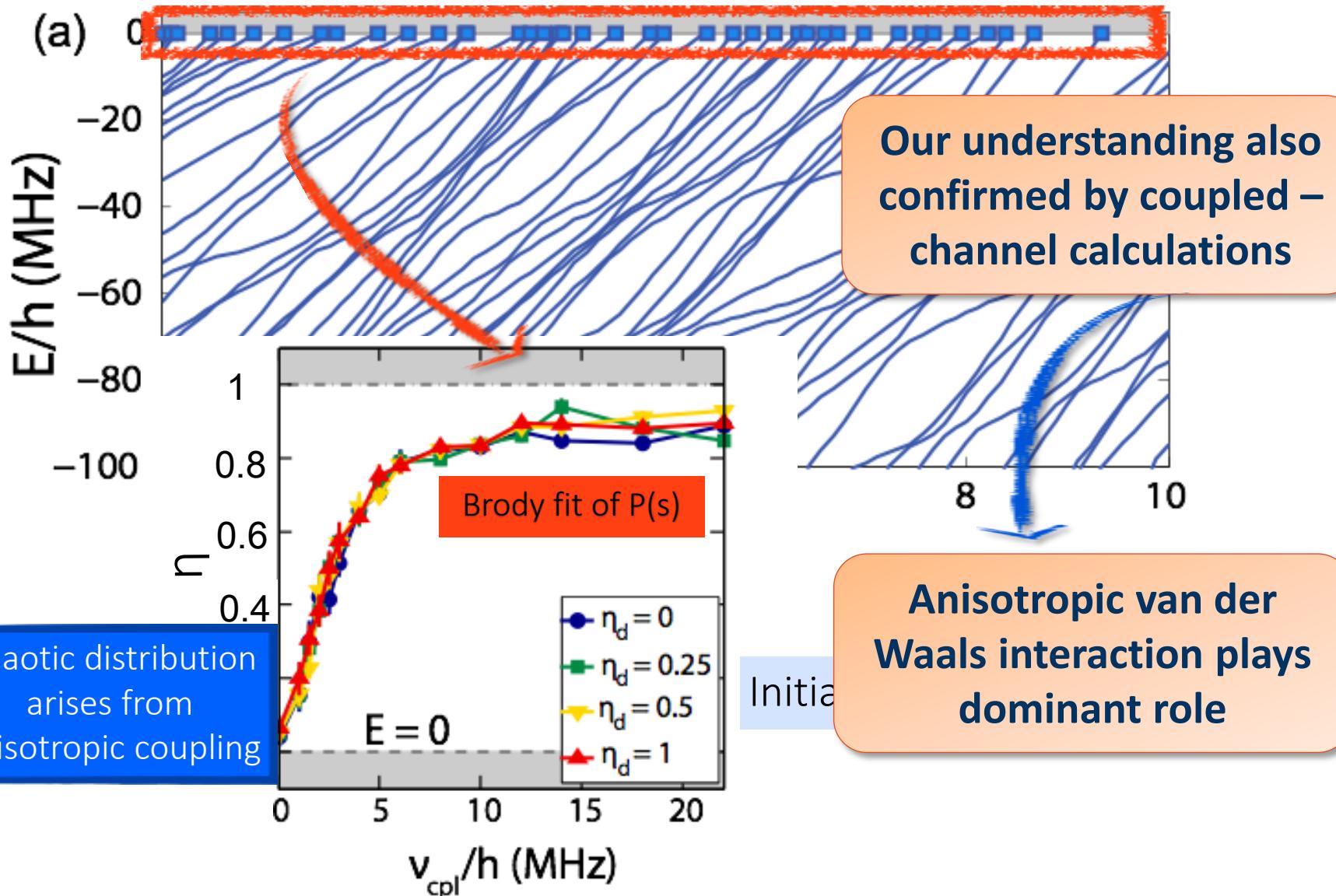
Eigenvalues of H_{RMT} :



Feshbach resonances spectrum.

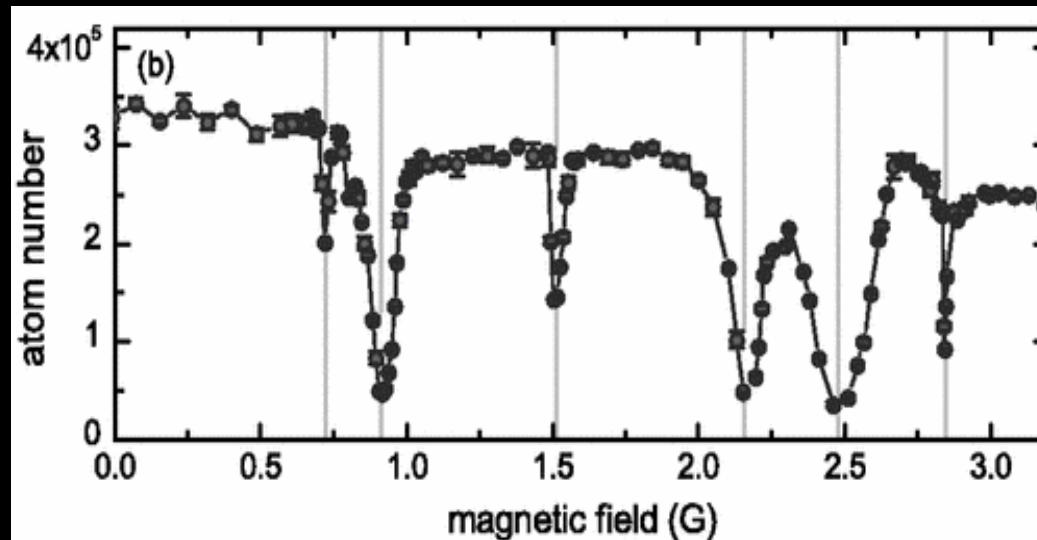
Very dense spectra
=> multiple
(avoided) crossings

RANDOM MATRIX THEORY MODEL

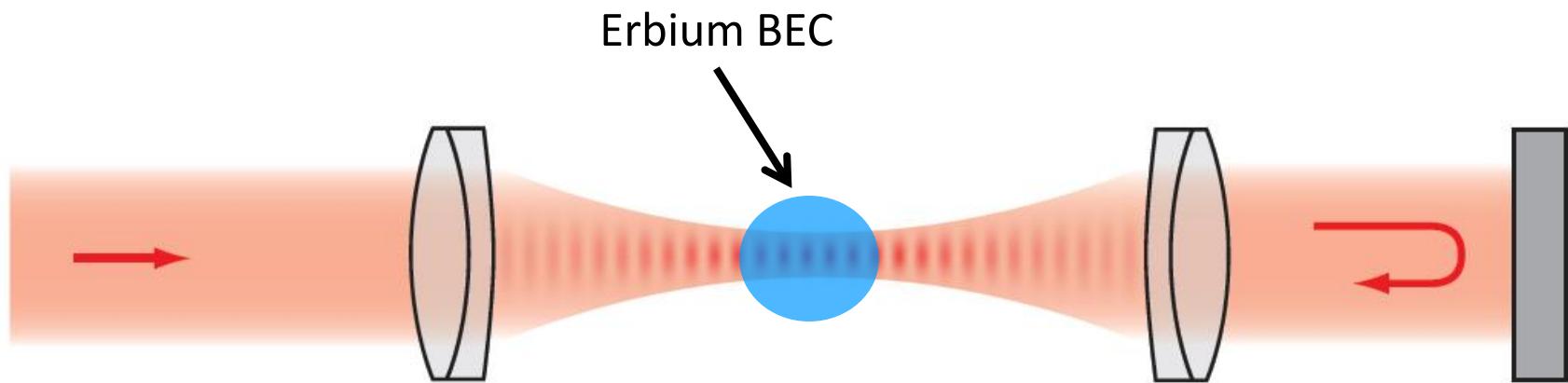


Short range interaction

precise measurements



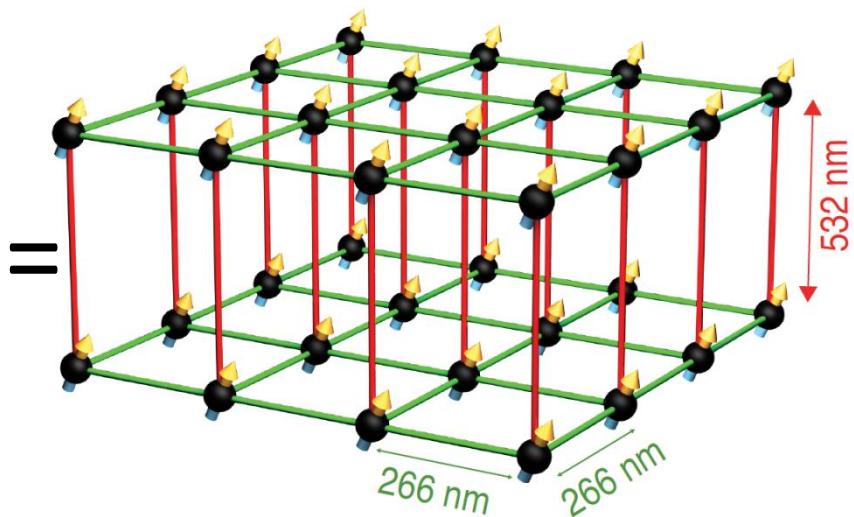
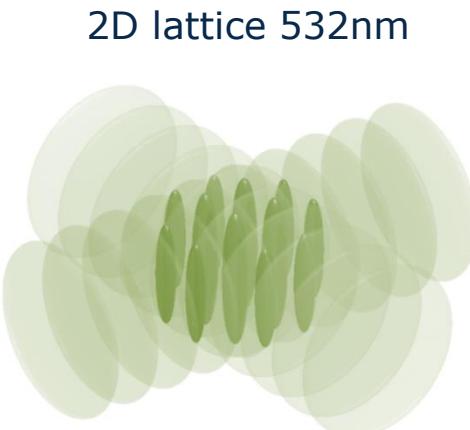
PRODUCING A CRYSTAL BY LIGHT



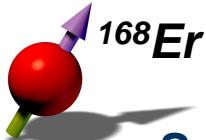
1D lattice 1064nm



+



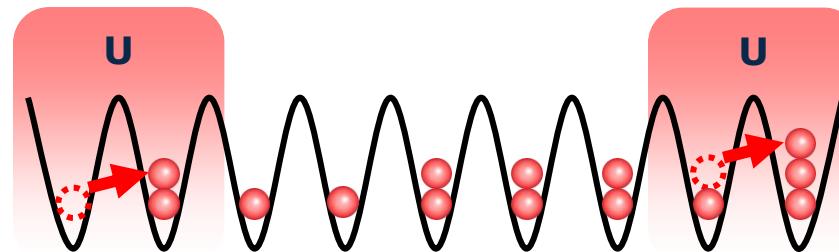
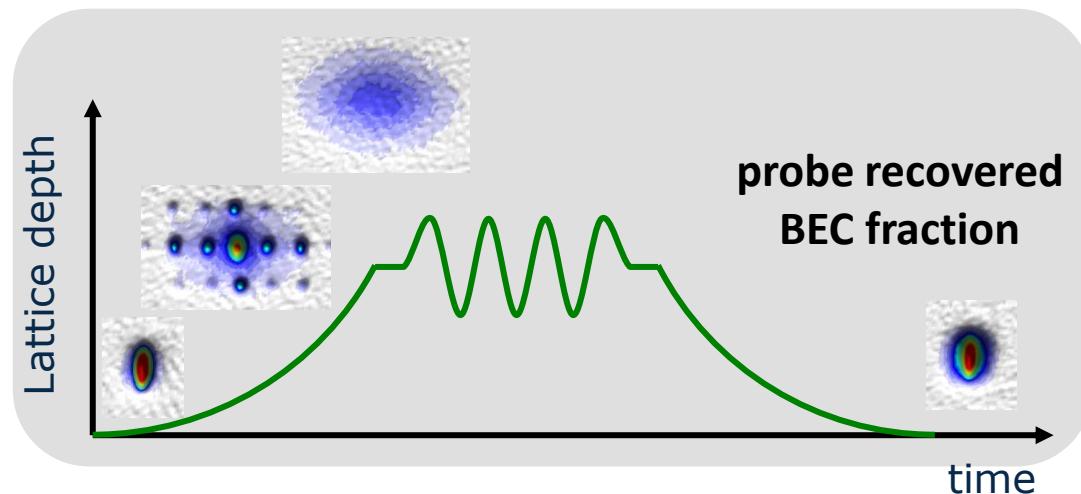
MODULATION SPECTROSCOPY



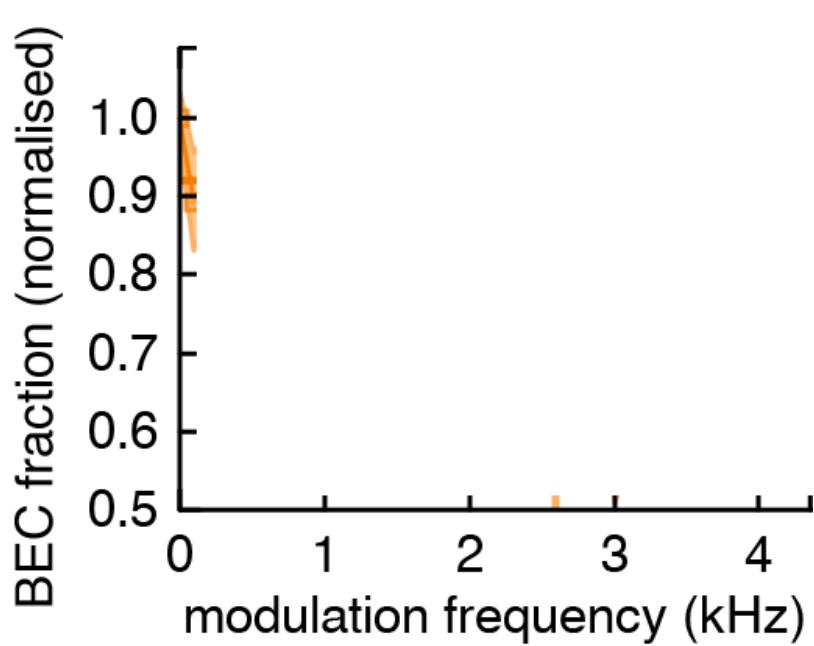
STARTING
POINT

1.5×10^5
atoms in BEC

MODULATION SPECTROSCOPY

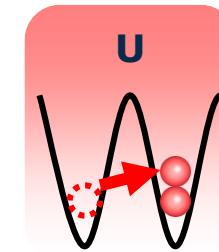


$$\mathcal{H} = U_{\text{onsite}} n_i(n_i - 1)$$



Energy of particle hole excitation
(on-site interaction)

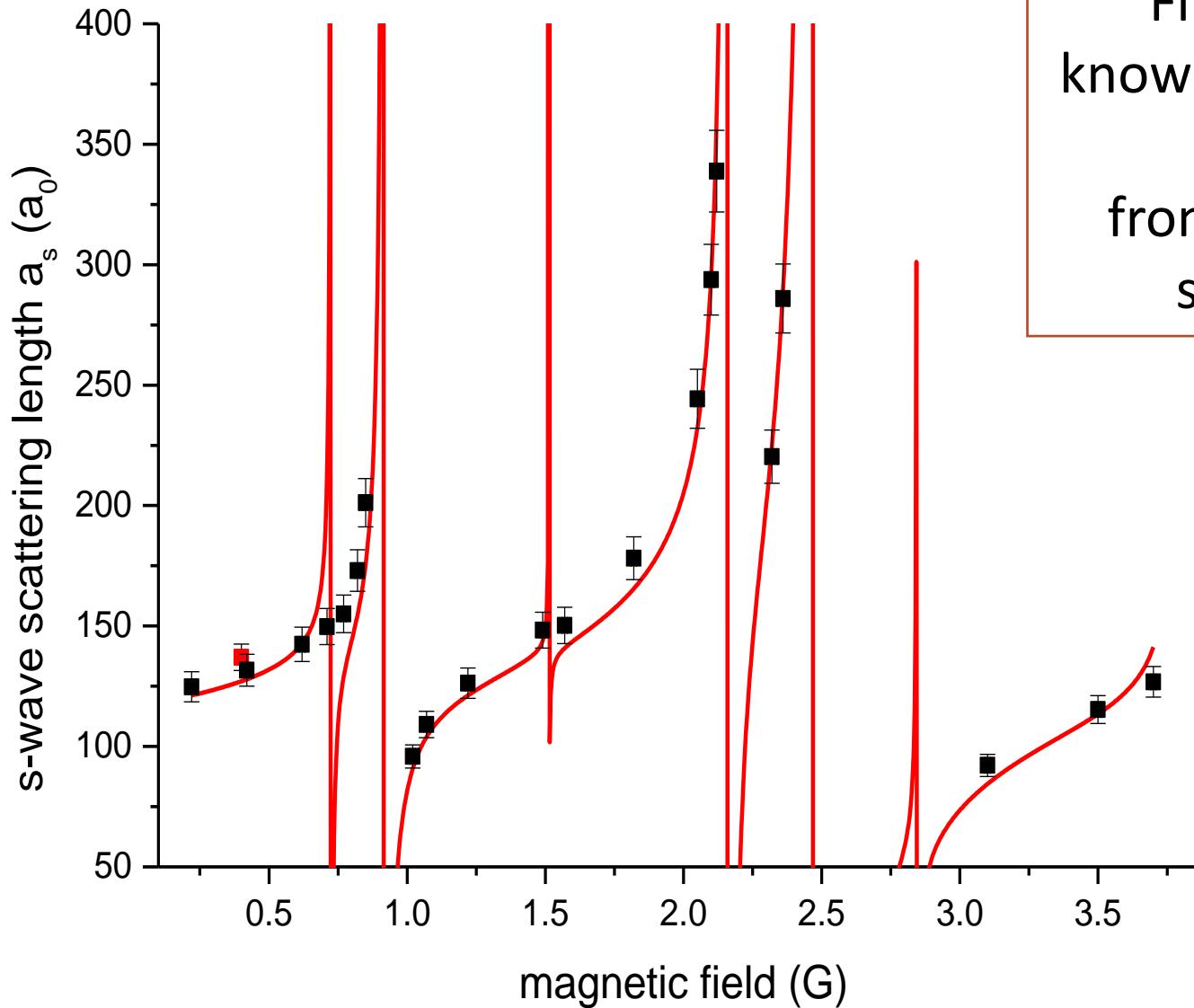
**direct proportional to
s-wave scattering length**



SCATTERING LENGTH 168ER ISOTOPE



$$a_{\text{bg}} = [97(9) + 8(7) \cdot B/1G] a_0$$

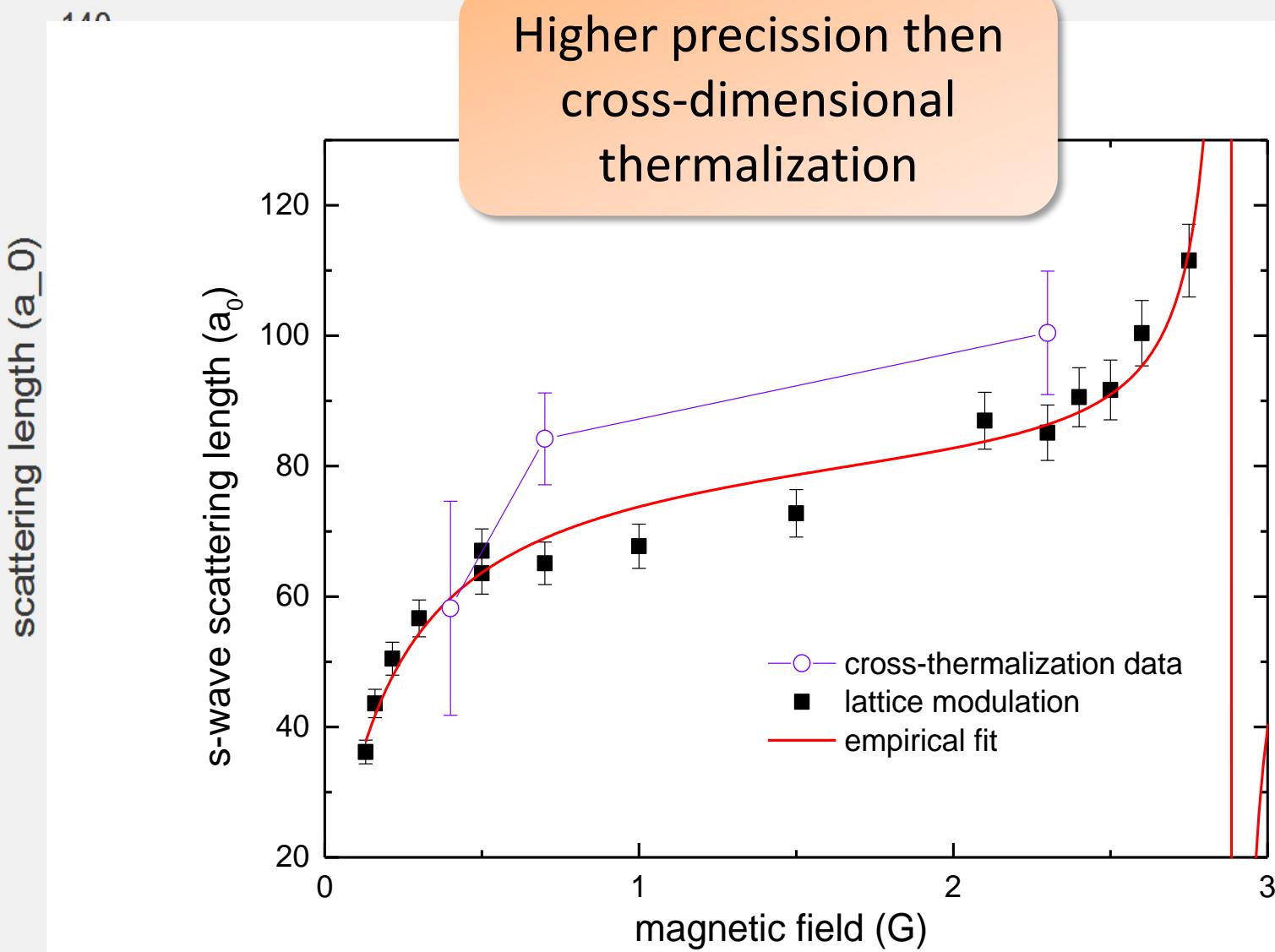


Fit includes our
knowledge on position
and width
from our Feshbach
spectroscopy

SCATTERING LENGTH ^{166}ER ISOTOPE



Higher precision than
cross-dimensional
thermalization



tical
or
cw
10

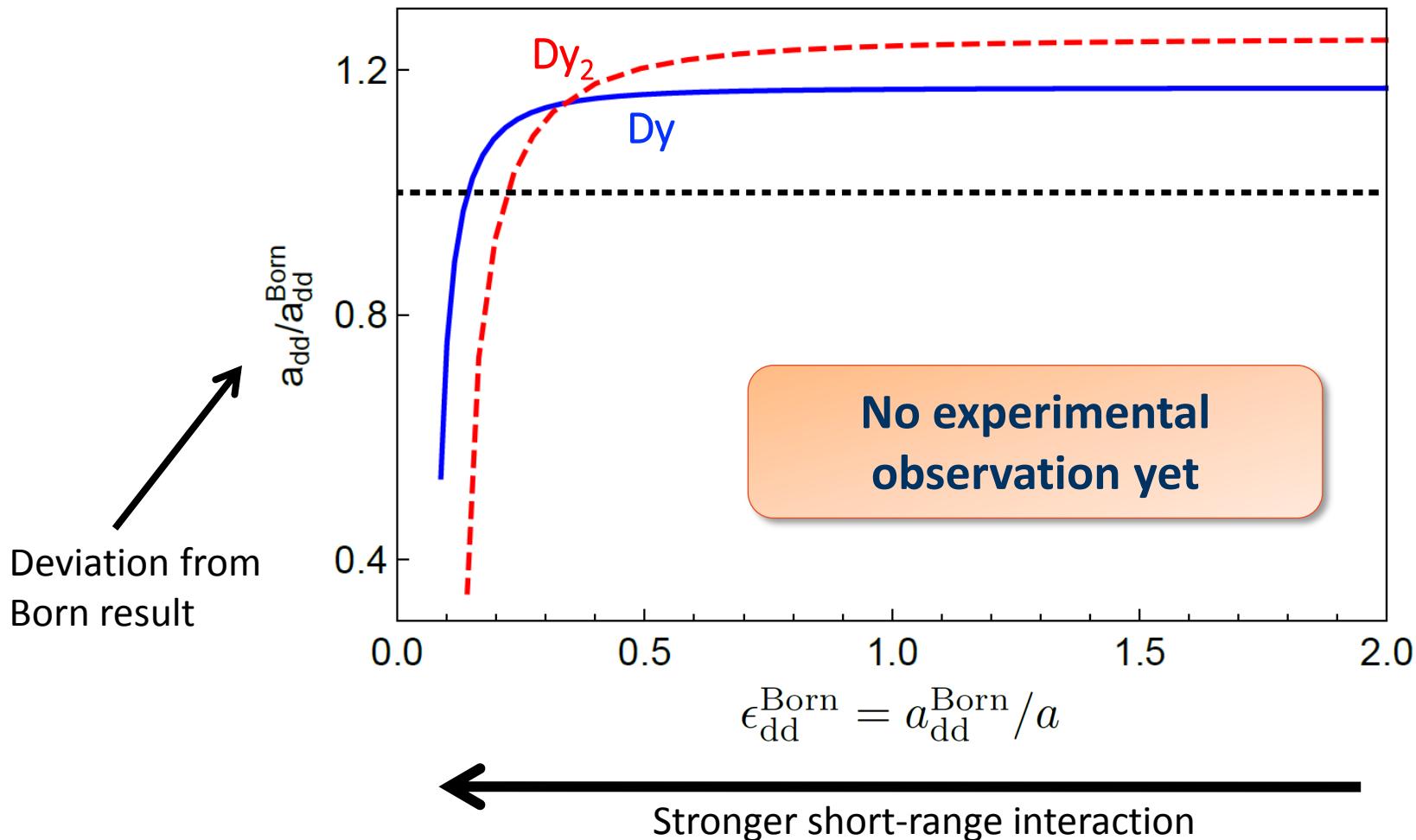
Dipolar scattering and short range interacton is decoupled!

Is this true?

BEYOND BORN APPROXIMATION

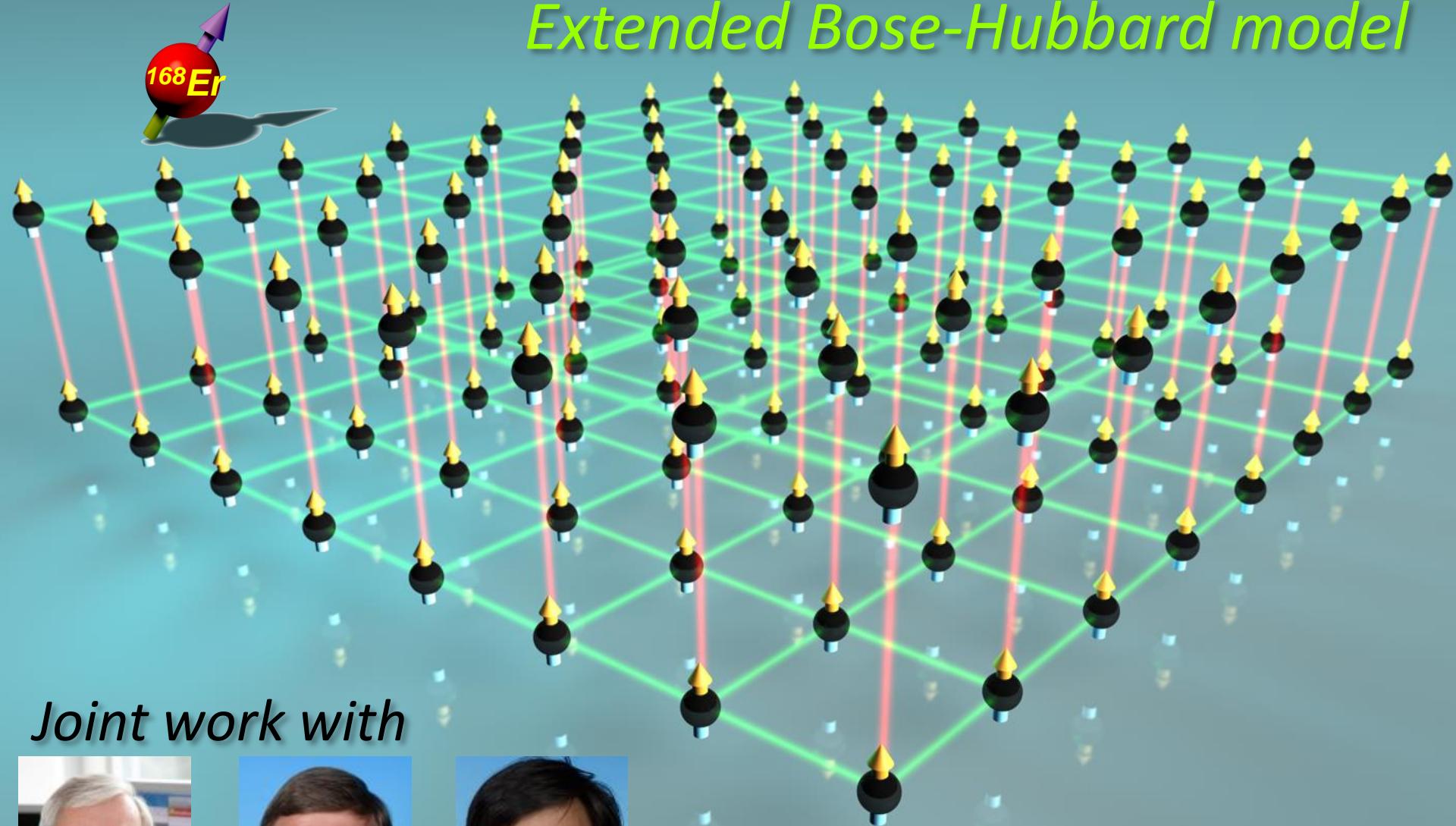


R. Oldziejewski and K. Jachymski, arXiv:1611:07355 (2016)



Experiments on many-body level

Extended Bose-Hubbard model



Joint work with



Peter Zoller

Misha Baranov

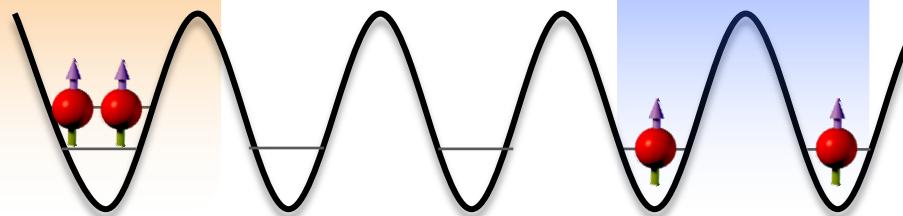
Zi Cai

DIPOLE-DIPOLE INTERACTION

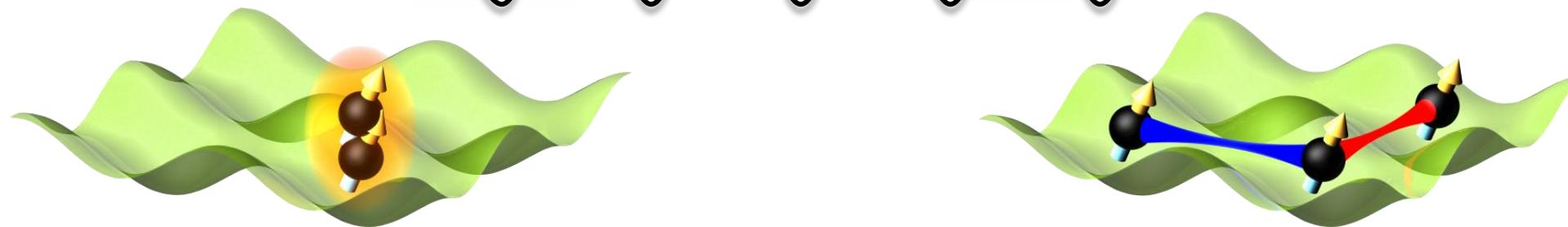
$$V_{dd} = \frac{\mu_0 \mu^2}{4\pi} \frac{1 - 3 \cos^2 \theta}{r^3}$$

**anisotropic
long range**

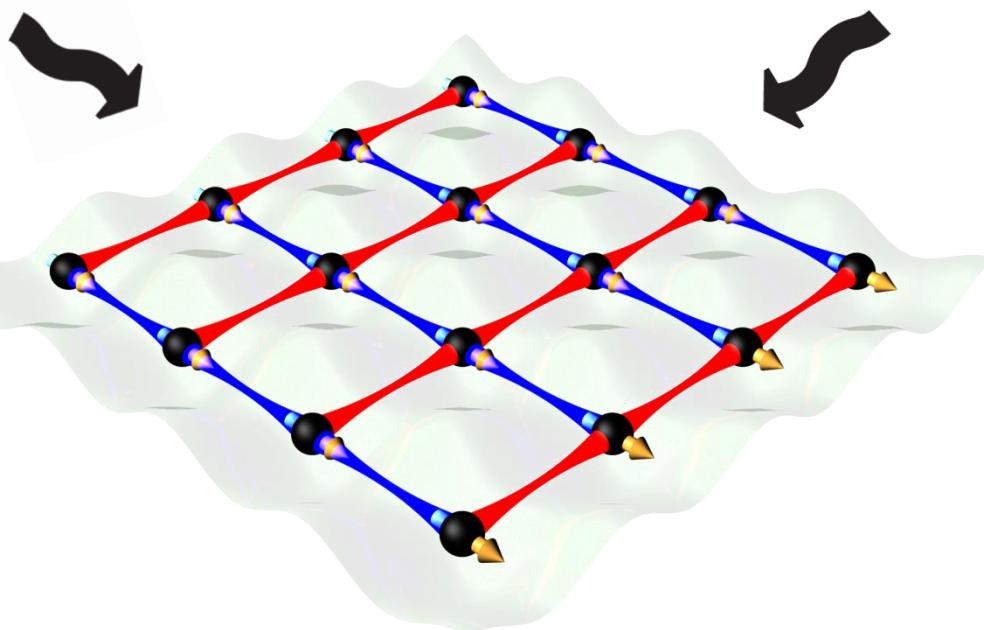
$$\mathcal{H} = U_{\text{onsite}}^{\text{DDI}} n_i(n_i - 1)$$



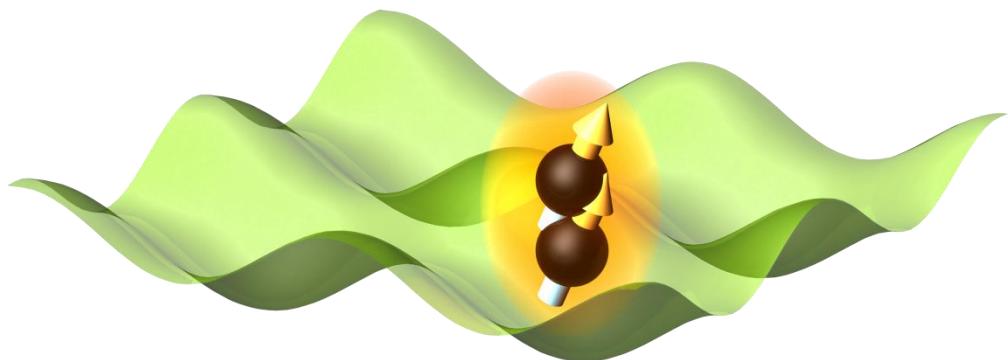
Difficult to observe:
100 times
lower energy



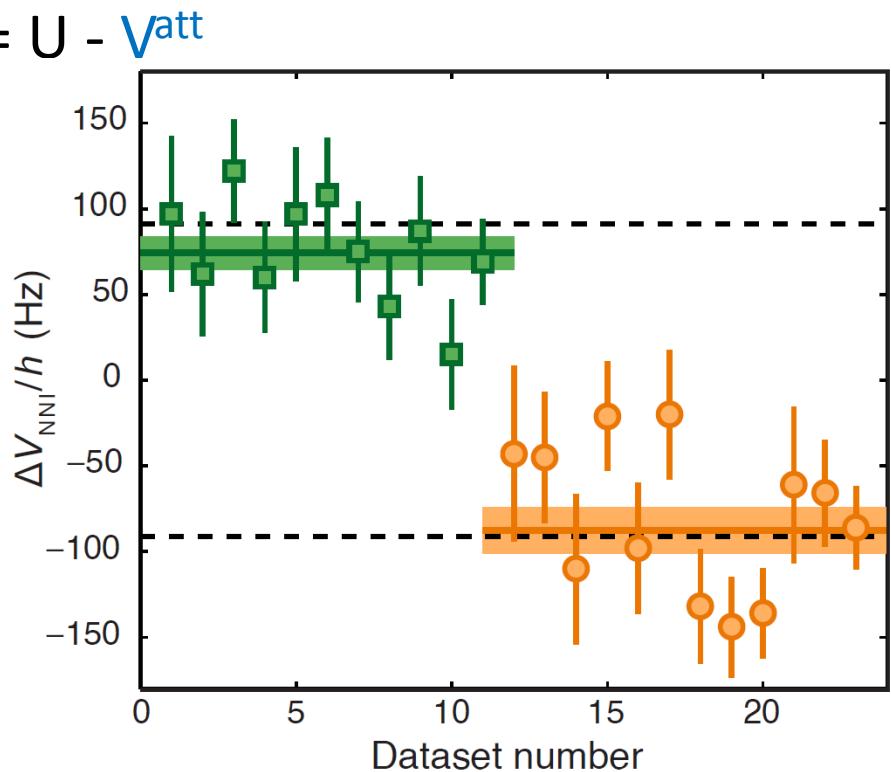
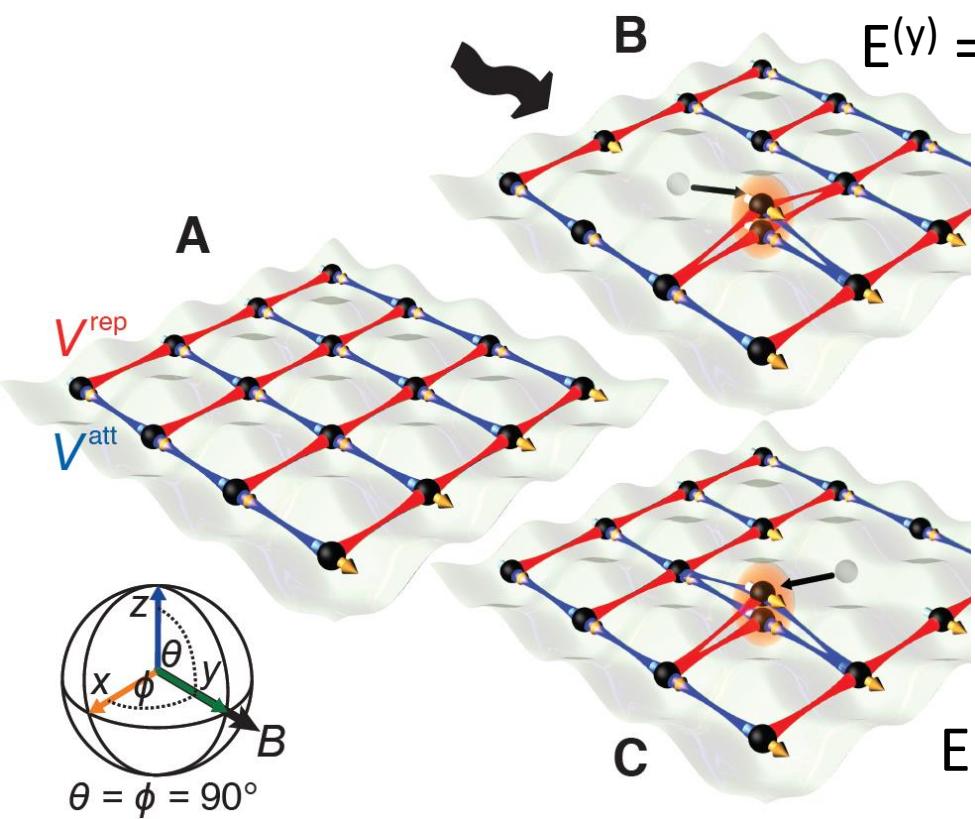
Dipoles along the plane



*For purely on-site interaction U
-> direction of modulation
does not matter*



NEAREST-NEIGHBOR INTERACTION



$$\Delta V_{\text{NNI}} = E^{(y)} - E^{(x)} = V^{\text{rep}} - V^{\text{att}}$$

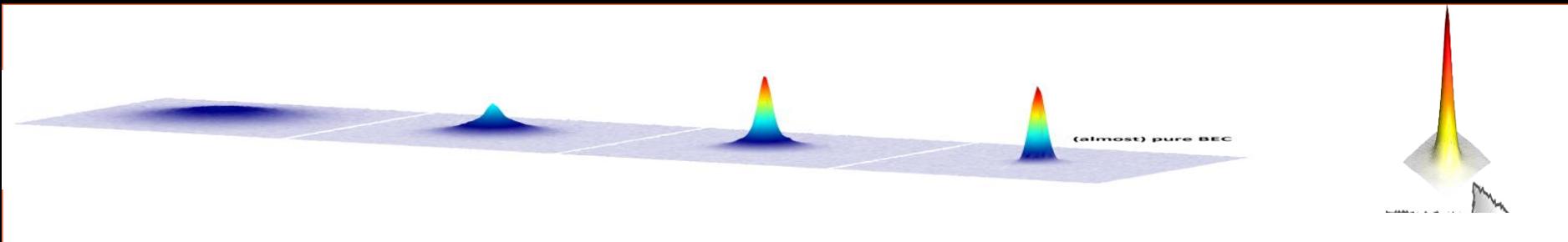
Theory $2\pi \times 91$ Hz

Experiment $2\pi \times 81$ (9) Hz

first observation of nearest-neighbor interaction dynamics

Quantum droplets

Novel of phases in the quantum world



Thermal → BEC → Q-Droplet
Joint work with



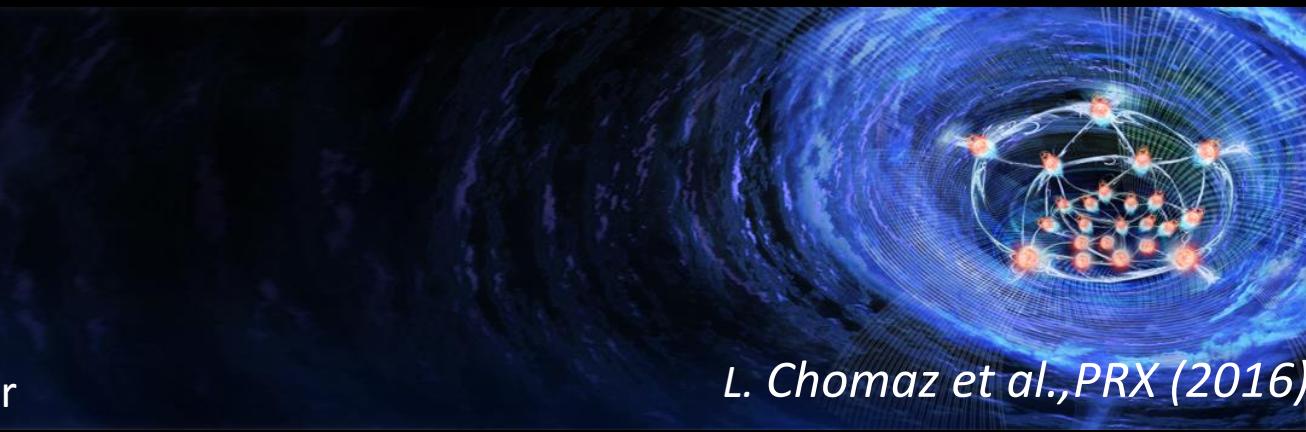
Luis Santos



Falk Wächtler

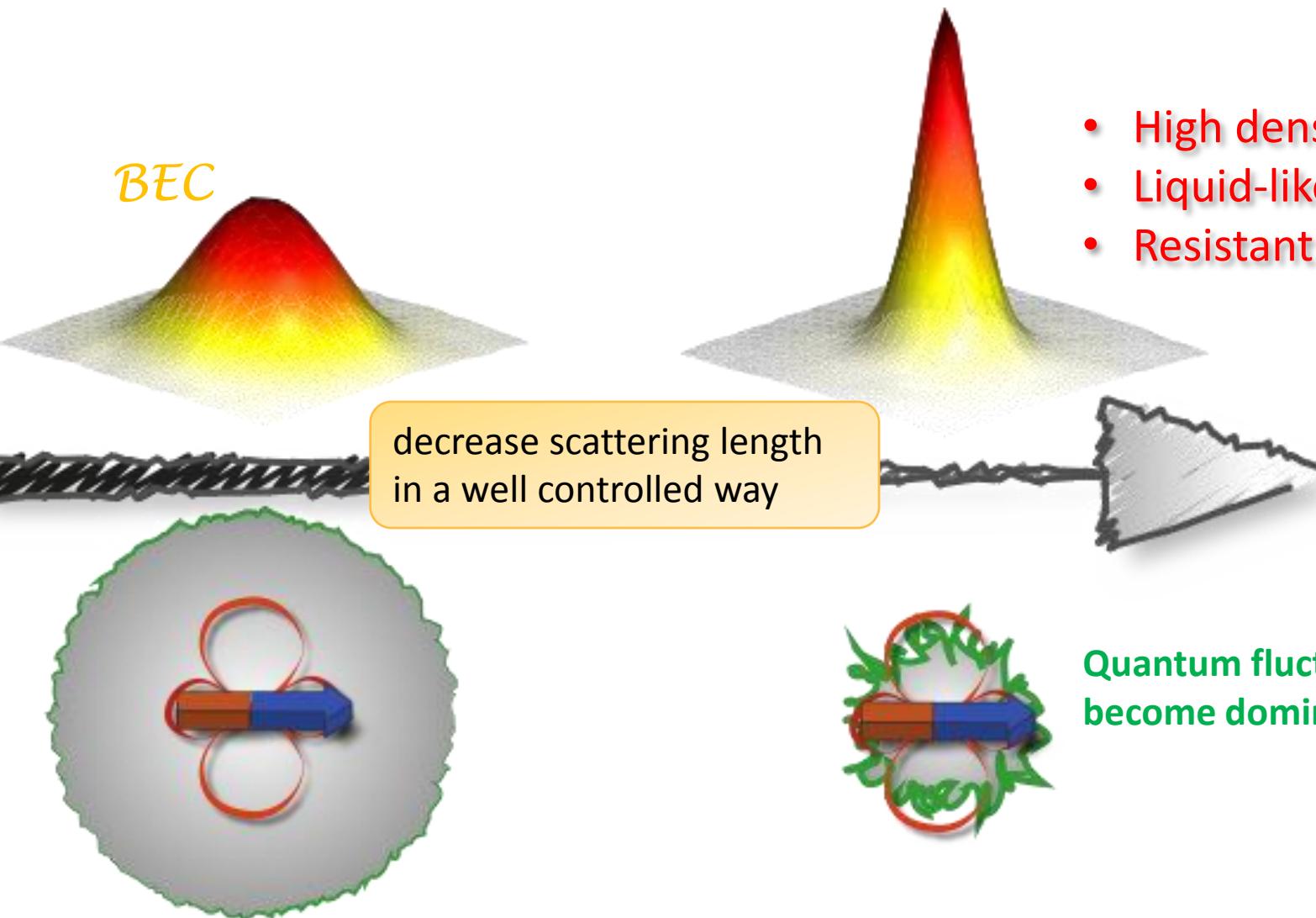
Phase transition
decrease T

Crossover
decreasing a



L. Chomaz et al., PRX (2016)

BEC



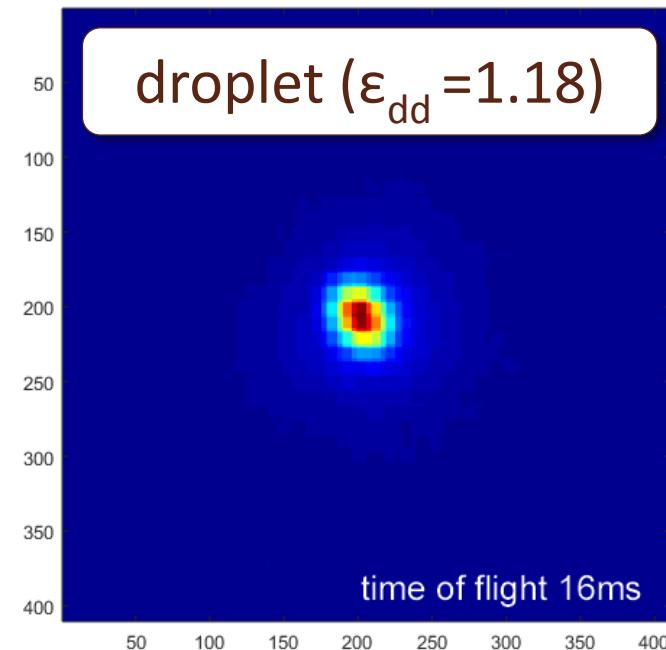
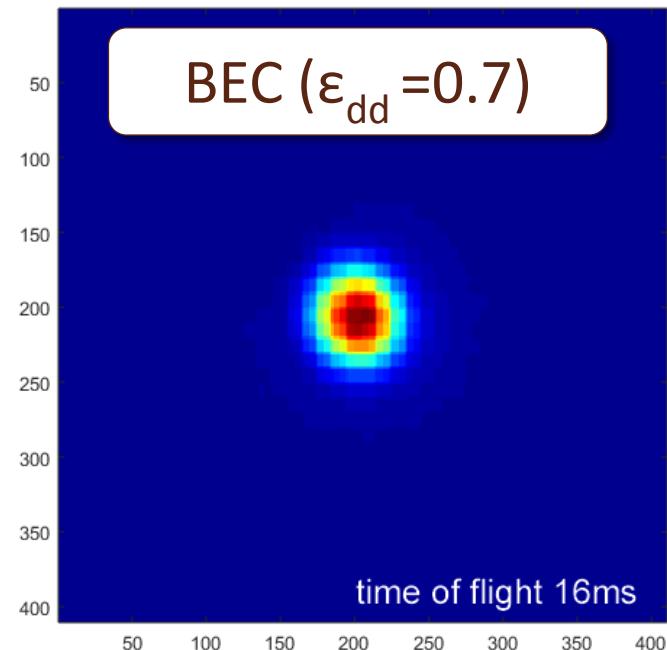


“When released, it falls down as a stone”

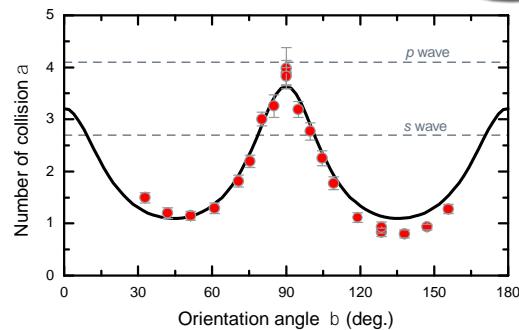
F. Wächtler and L. Santos, PRL (2016)

D. Baillie et al., PRL (2016)

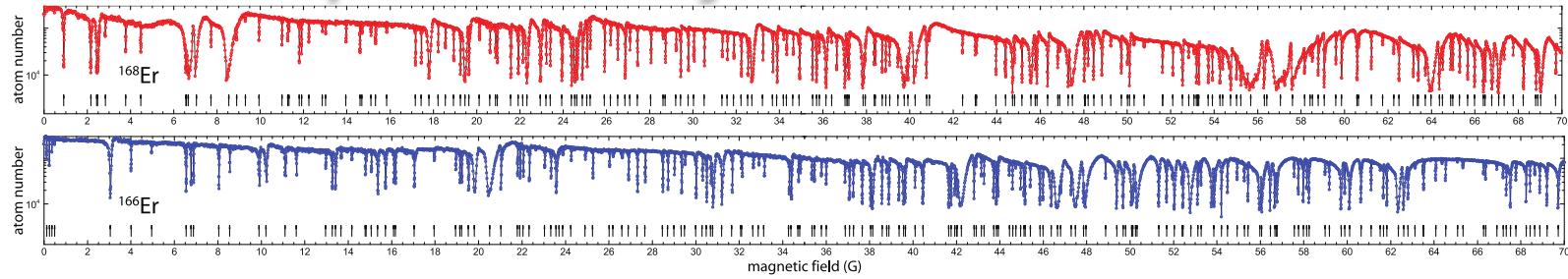
Expansion dynamics



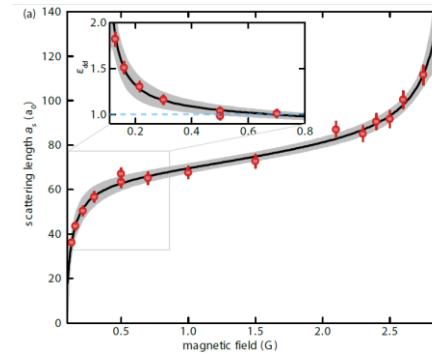
Universal dipolar scattering



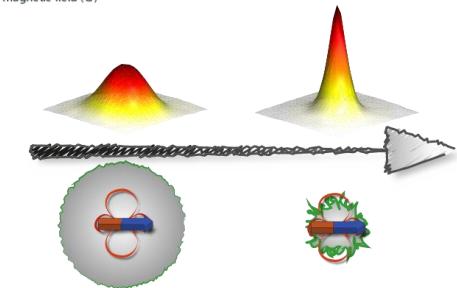
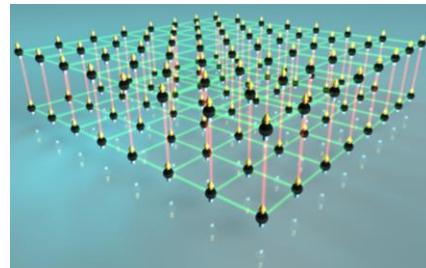
Feshbach spectrum of Ln

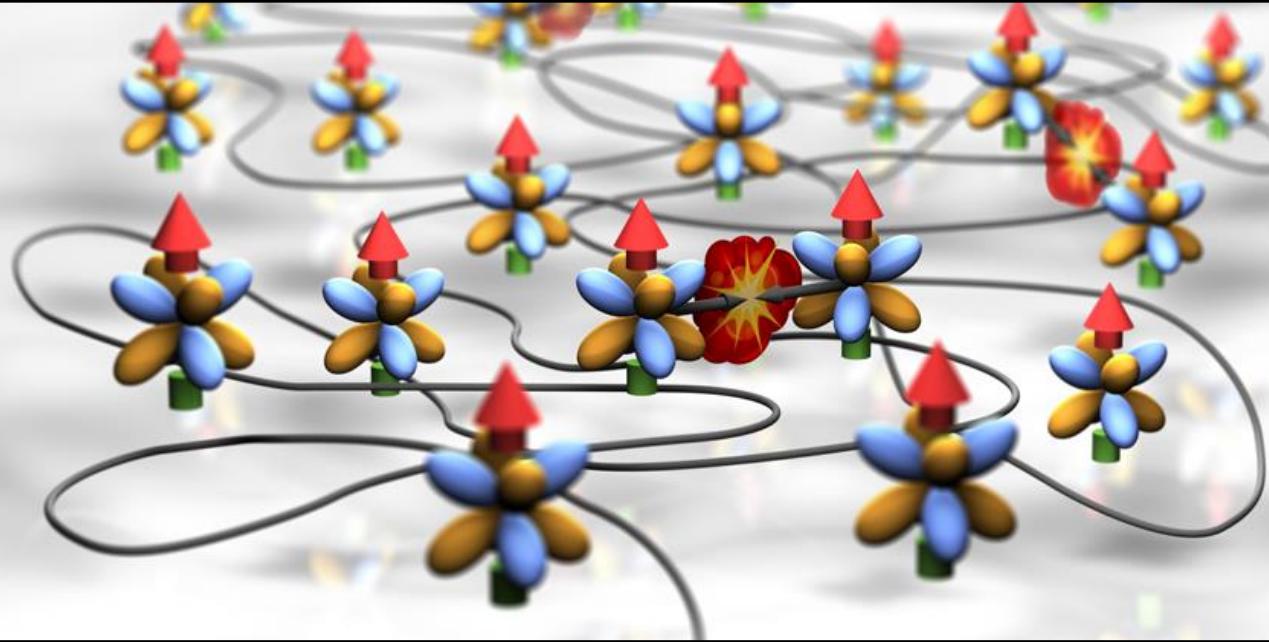


Short range interactions



Experiments on many-body level





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