Lecture 14: Feshbach Resonances

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Lectures 14 and 15

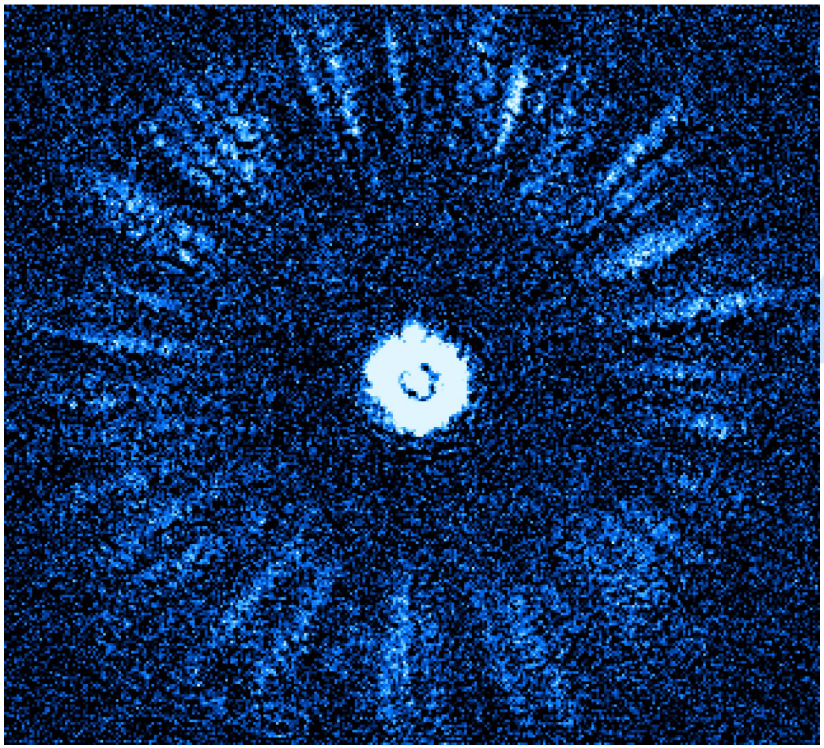
Lecture 1: Feshbach Resonances

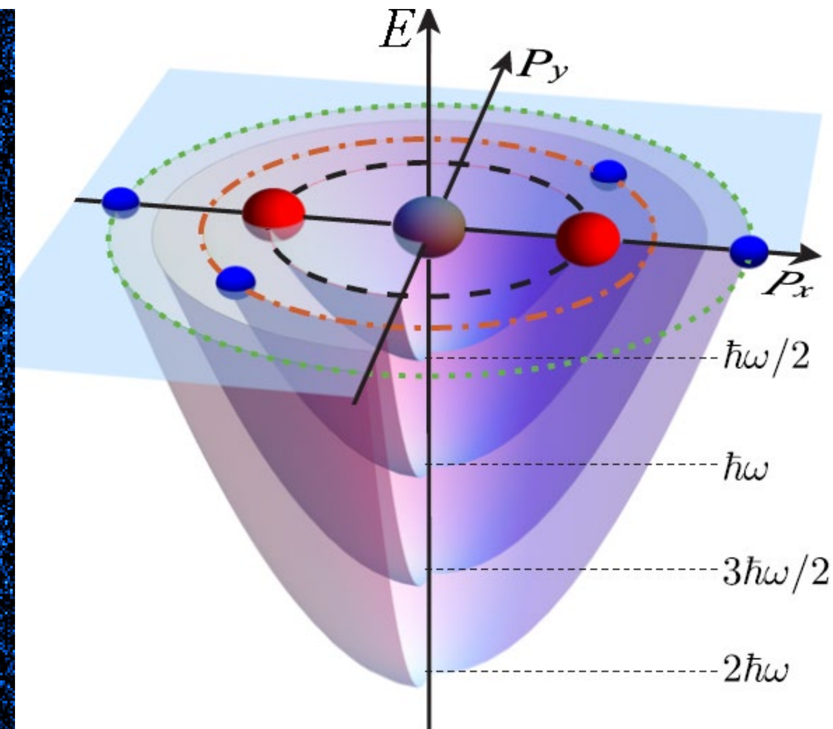
Feshbach resonance has emerged as a common tool to control atomic interactions. In typical experiments, one tunes the atomic scattering length with a magnetic Feshbach resonance to study the cross over from weak- to strong-interaction regimes. New applications have been uncovered in recent years to associate molecules, optically induce a resonance as well as to fast modulate atomic interactions. The fundamentals, applications and future of Feshbach resonances will be surveyed.

Lecture 2: Floquet Quantum Systems: Inflation and Unruh Radiation

What is the shortest cut to new quantum phenomena starting from a run-of-the-mill Bose-Einstein condensate? Beyond optical lattices and Feshbach resonances, a new tool has been developed to temporally modulate the quantum gas, which can immediately lead to exotic behavior even in the perturbation regime. I will discuss two examples by modulating the lattice potential and the atomic interactions. In both cases, surprising results connect cold gases to intriguing cosmological phenomena.

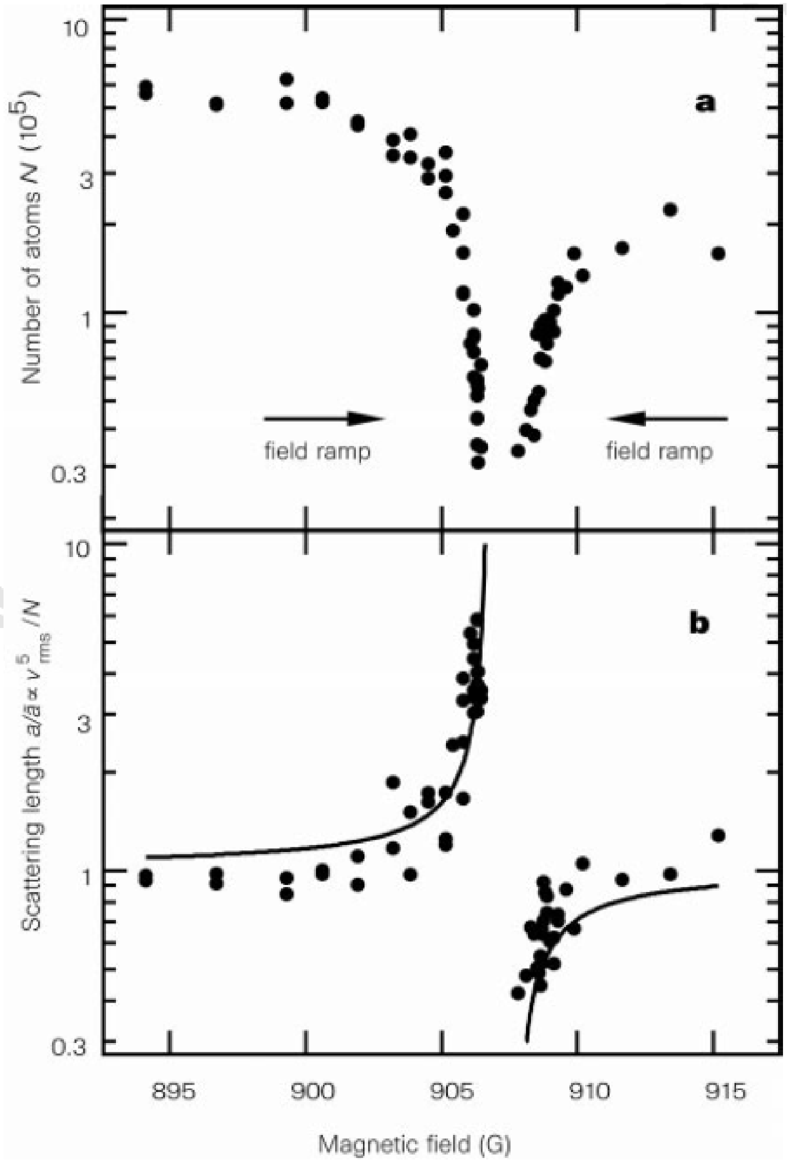
Bose fireworks





Collective emission of matter-wave jets from driven Bose-Einstein condensates, Nature 551 (2017)

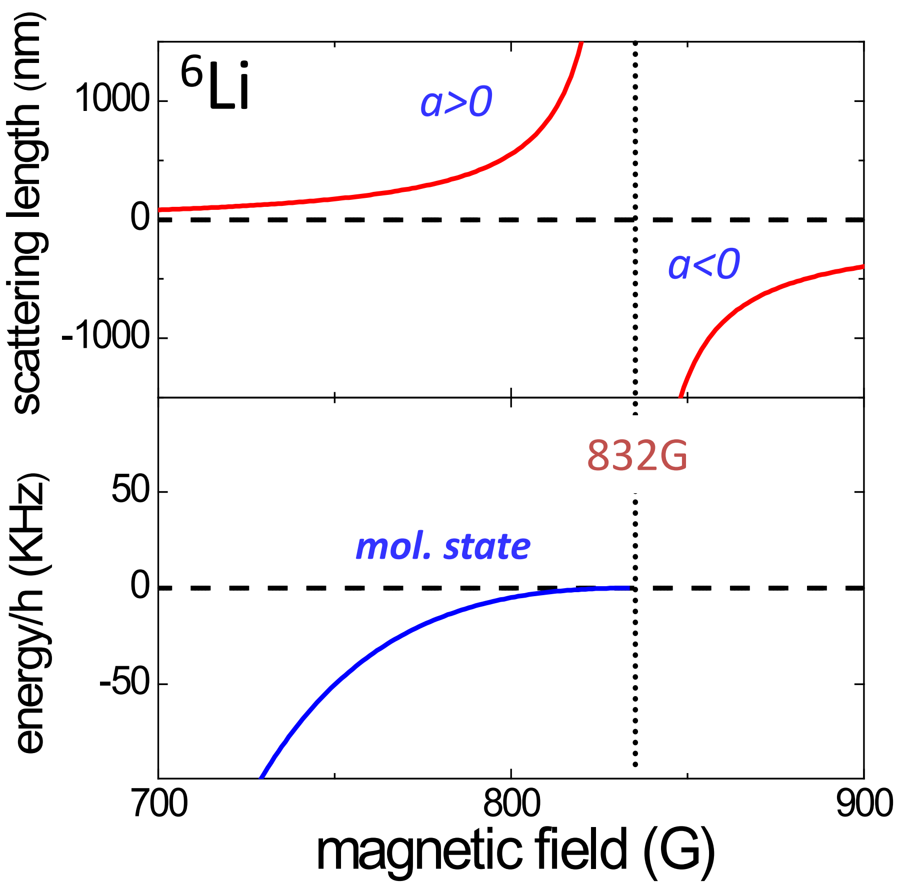
Feshbach resonance in sodium Bose-Einstein condensate (1998 MIT)



Strong inelastic loss

$$a = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$$

Universal behavior in the threshold regime



$$a = a_{bg}\left(1 - \frac{\Delta B}{B - B_0}\right)$$

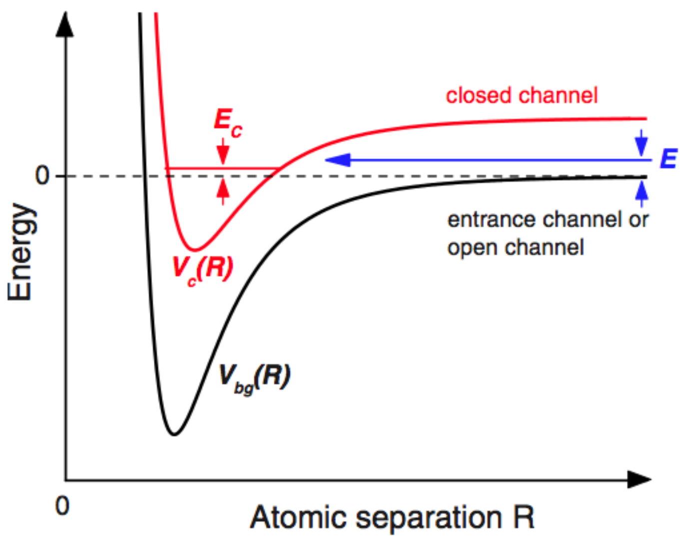
$$E_b = \frac{\hbar^2}{m(a - r_0)^2}$$

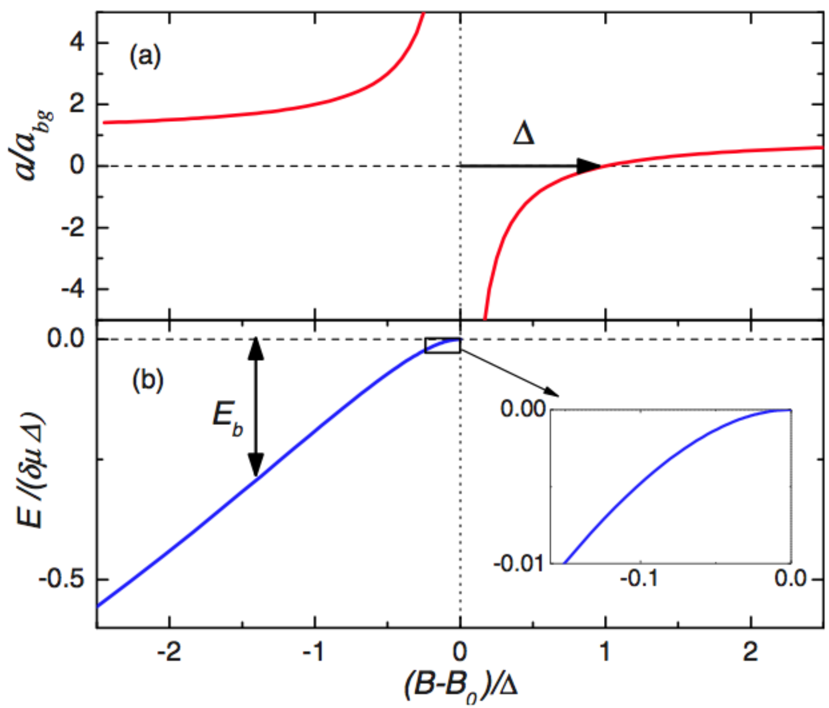
What is scattering length?

Why does molecular state approach continuum non-linearly?

Many more questions…

Physics picture of Feshbach resonance



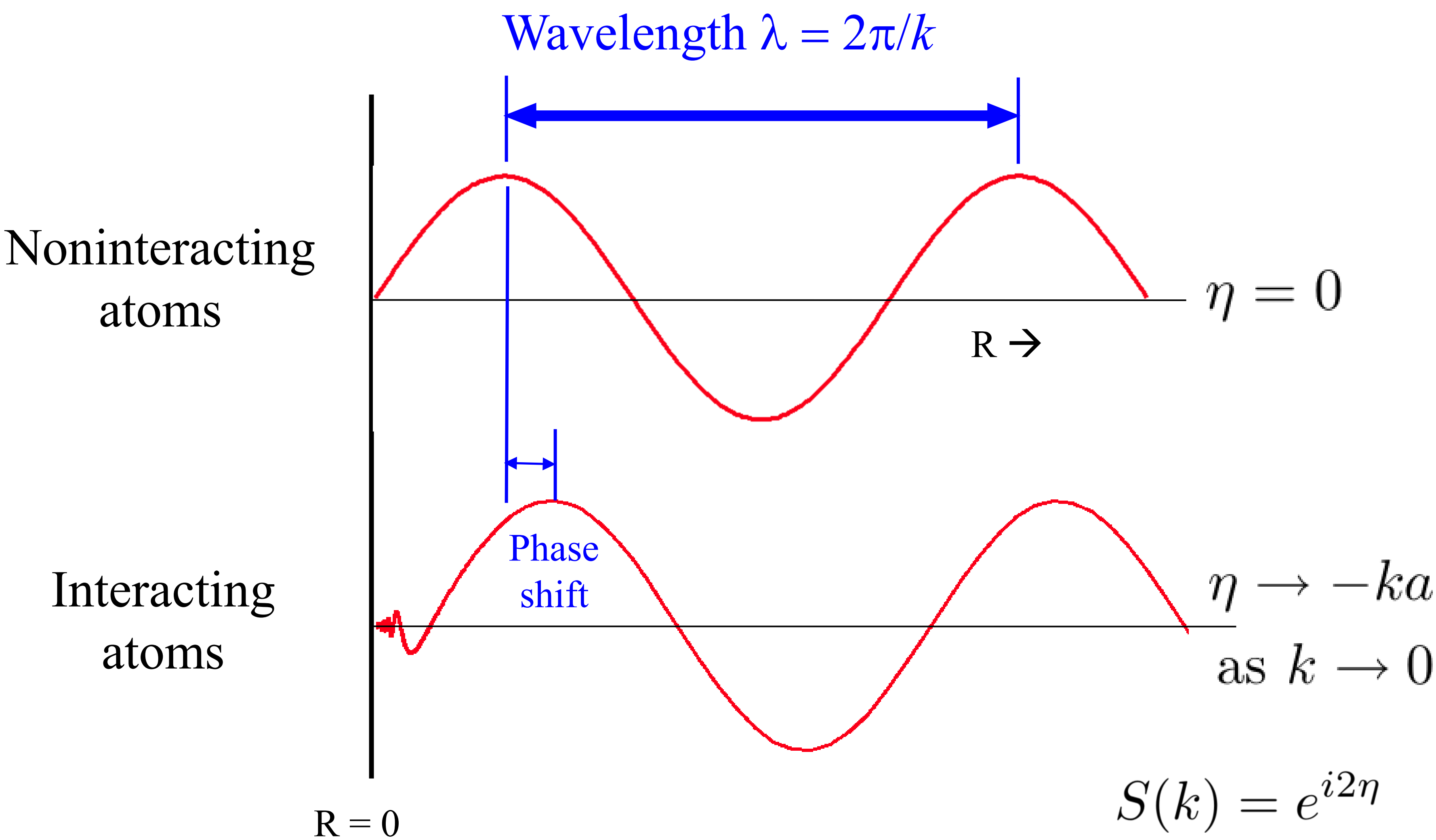


CC, Grimm, Tiesinga, Julienne, RMP (2010)

Simple picture: Feshbach resonance occurs when a bound state in the closed channel matches the scattering state.

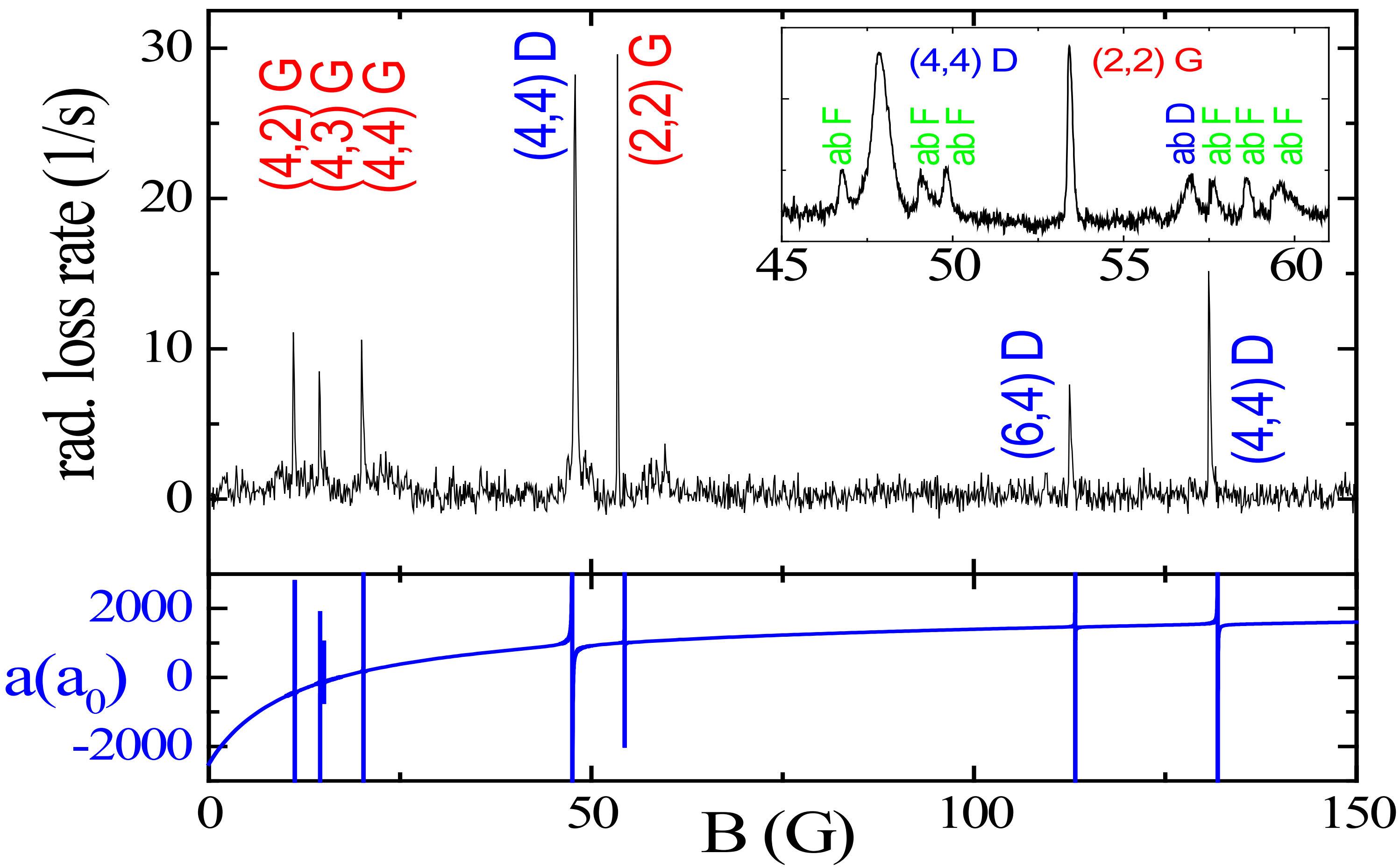
s-wave scattering phase shift

$$\Psi(R) \rightarrow \sin(kR + \eta)$$



$$S(k) = e^{i2\eta}$$

Radiative Feshbach resonances in Cesium



Stanford (exp.) and NIST (theo.), 1999-01

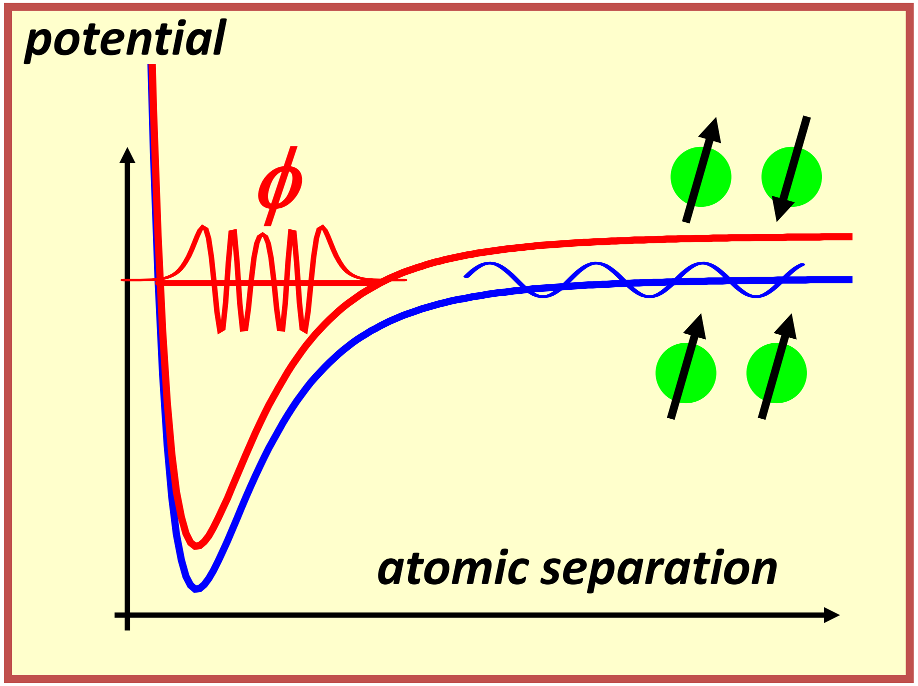
Feshbach resonances in cold atom collisions

TABLE IV. Properties of selected Feshbach resonances. The first column describes the atomic species and isotope. The next three columns characterize the scattering and resonance states, which include the incoming scattering channel (ch.), partial wave ℓ, and the angular momentum of the resonance state ℓ_c. This is followed by the resonance location B_0, the width Δ, the background scattering length a_{bg}, the differential magnetic moment $\delta\mu$, the dimensionless resonance strength s_{res}, the background scattering length in van der Waals units $r_{bg}=a_{bg}/\bar{a}$, and the bound state parameter ζ from Eq. (52). Here a_0 is the Bohr radius and μ_B is the Bohr magneton. Definitions are given in Sec. II. The last column gives the source. A string "na" indicates that the corresponding property is not defined. For example a_{bg} is not defined for p-wave scattering.

Atom	ch.	ℓ	ℓ_c	B_0 (G)	Δ (G)	a_{bg}/a_0	$\delta\mu/\mu_B$	s_{res}	r_{bg}	ζ	Reference
^{6}Li	*ab*	*s*	*s*	834.1	−300	−1405	2.0	59	−47	1400	Bartenstein *et al.*, 2005
	ac	*s*	*s*	690.4	−122.3	−1727	2.0	29	−58	850	Bartenstein *et al.*, 2005
	bc	*s*	*s*	811.2	−222.3	−1490	2.0	46	−50	1200	Bartenstein *et al.*, 2005
	ab	*s*	*s*	543.25	0.1	60	2.0	0.001	2.0	0.001	Strecker *et al.*, 2003
	aa	*p*	*p*	159.14	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
	ab	*p*	*p*	185.09	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
	bb	*p*	*p*	214.94	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
^{7}Li	*aa*	*s*	*s*	736.8	−192.3	−25	1.93	0.80	−0.79	0.31	Strecker *et al.*, 2002; Pollack *et al.*, 2009[a]
^{23}Na	*cc*	*s*	*s*	1195	−1.4	62	−0.15	0.0050	1.4	0.004	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]
	aa	*s*	*s*	907	1	63	3.8	0.09	1.5	0.07	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]
	aa	*s*	*s*	853	0.0025	63	3.8	0.0002	1.5	0.0002	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]

Reference: Cheng Chin, Rudolf Grimm, Paul Julienne, Eite Tiesinga, RMP (2012)

Scattering channels and Feshbach resonance



Open channel

(typically) Triplet potential

Closed channel

(typically) Singlet potential

Feshbach tuning

External magnetic field

Transition matrix

$$T_{fi} = T_{fi}^{0} + \frac{\langle \chi_f^- | V | \phi \rangle \langle \phi | V | \chi_i^+ \rangle}{E - E_\phi + i\Gamma/2}$$

$\rightarrow$

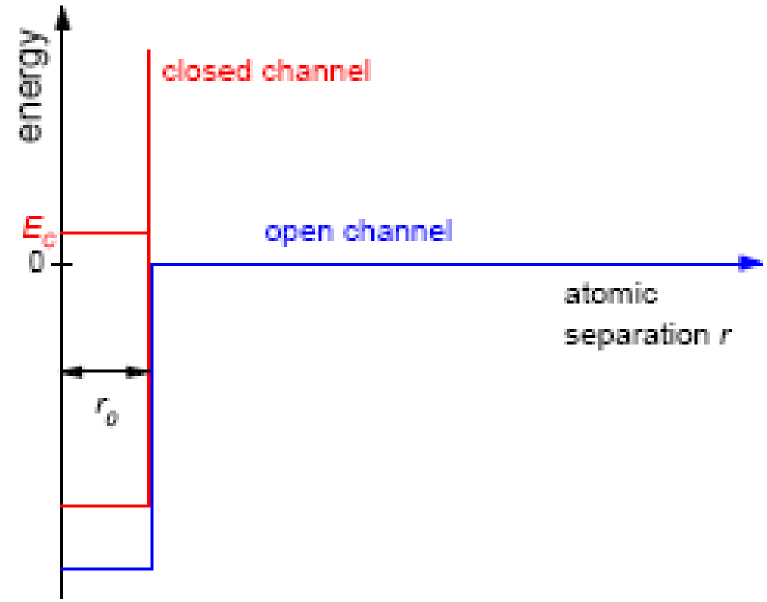
Scattering length:

$$a = a_{bg}\left(1 - \frac{\Delta B}{B - B_0}\right)$$

Simple two-channel model for Feshbach resonance

1. Box model with $r_0 \sim r_{vdw}$ simulates molecular potential

2. Closed channel supports a bound state at E_c near the continuum.



Parameterization
Open channel depth V_o determines a_{bg}
Closed channel depth V_c determines E_c
Feshbach Coupling is Γ.

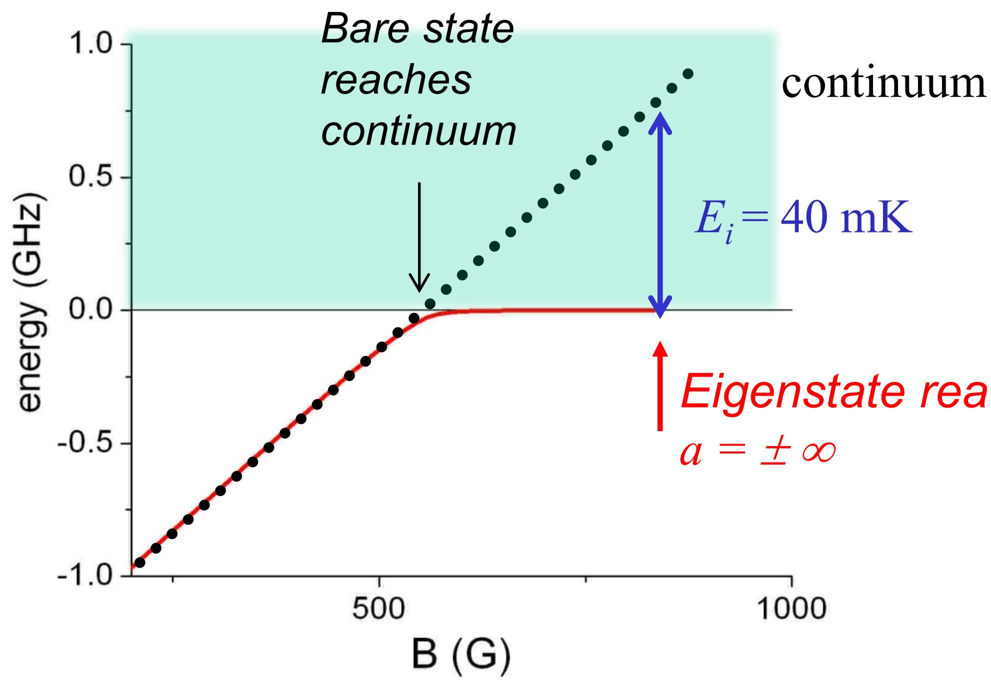
$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + \hat{V}\right)|\psi\rangle = E|\psi\rangle$$

$$\hat{V} = \begin{pmatrix} -V_c & \hbar\Omega \\ \hbar\Omega & -V_o \end{pmatrix} \text{ for } R < \bar{a}$$

$$= \begin{pmatrix} \infty & 0 \\ 0 & 0 \end{pmatrix} \text{ for } R > \bar{a}.$$

Result: $$\frac{1}{a - r_0} = \frac{1}{a_{bg} - r_0} + \frac{\Gamma / 2r_0}{E_i}$$

An extreme case: ^{6}Li with a_{bg} =-1700 Bohr

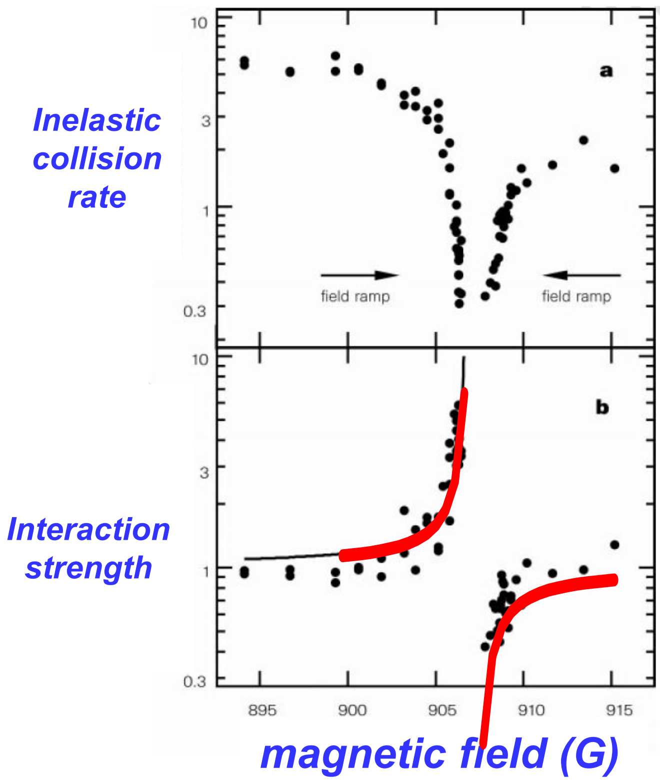


$$\frac{1}{a - r_0} = \frac{1}{a_{bg} - r_0} + \frac{\Gamma / 2r_0}{E_i}$$

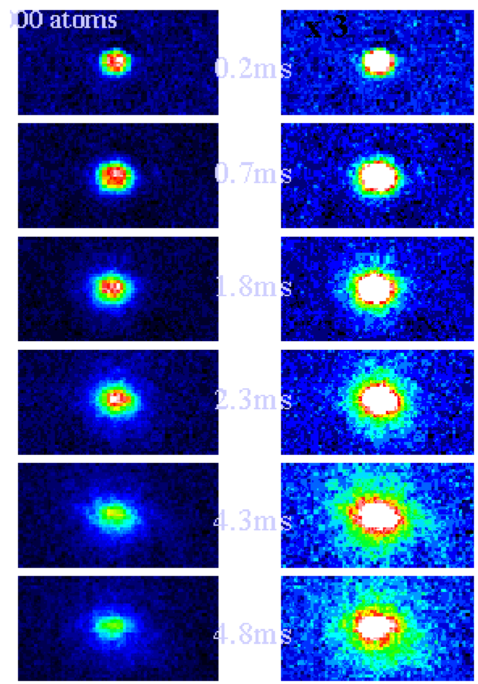
r_0=30 a_0
E_i=bare state energy
Γ=Feshbach coupling

A tunable Bose gas (98~01)

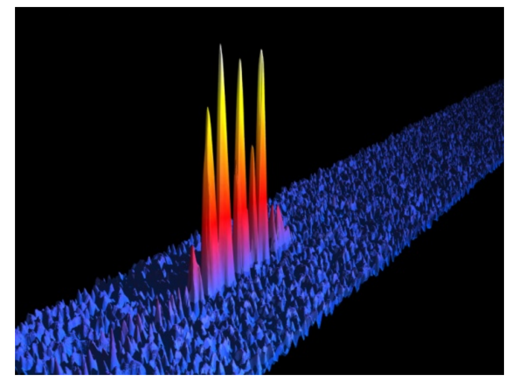
Feshbach resonance in Na
Ketterle group, 1997



BEC implosion and explosion (bosenova)
Wieman group, 2001



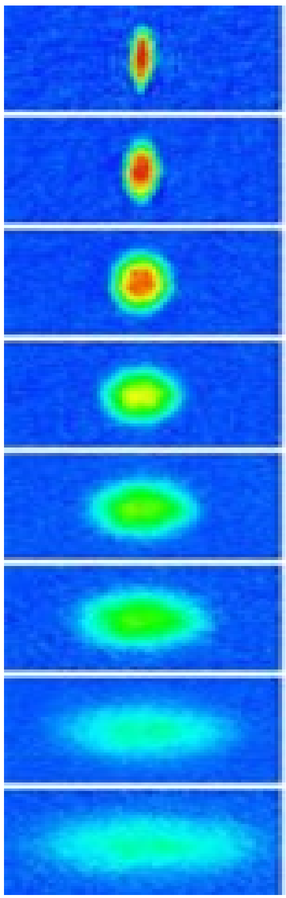
Bright Soliton
Hulet group, 2001
Salomon group, 2001



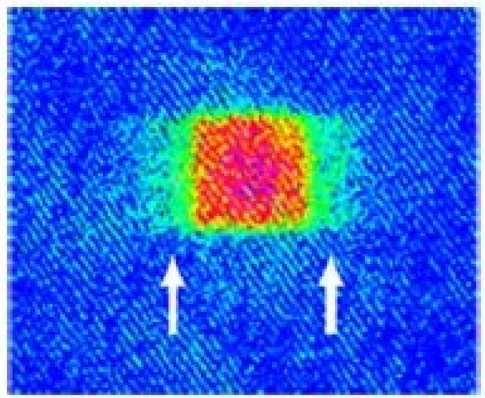
Feshbach resonances are found in all alkali species

Experiments on Fermionic condensates near a Feshbach resonance (02~05)

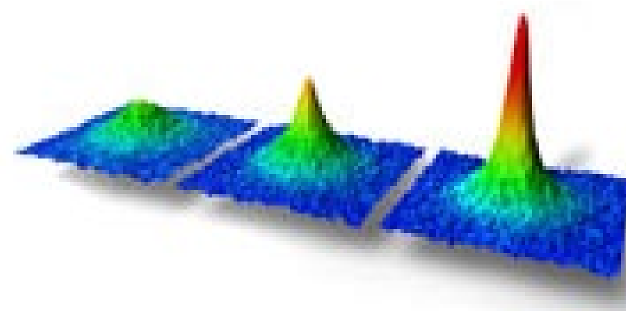
Hydrohynamic expansion
(Duke, ENS)

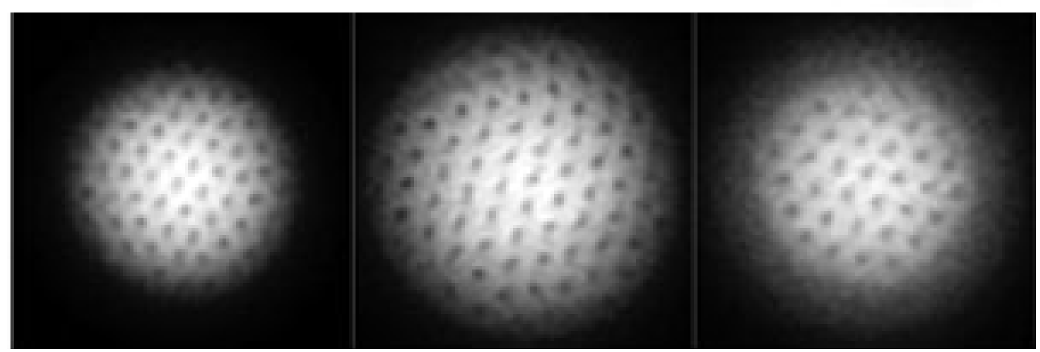


Band insulator
(ETH, Florence)

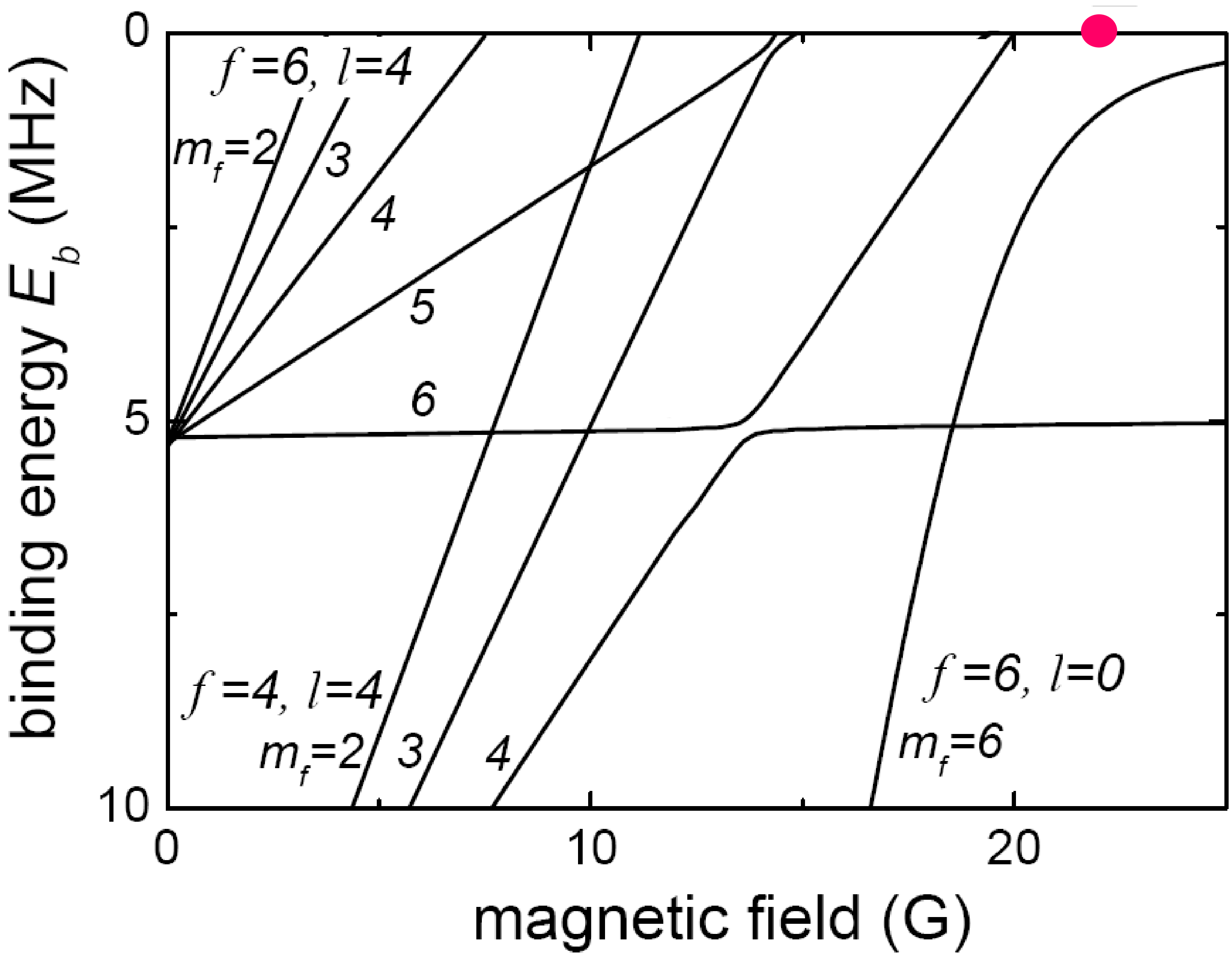


(BEC of Fermion pairs)
(Innsbruck, JILA, Rice, MIT, ENS)





Feshbach resonance: gateway to cold molecules (2003)

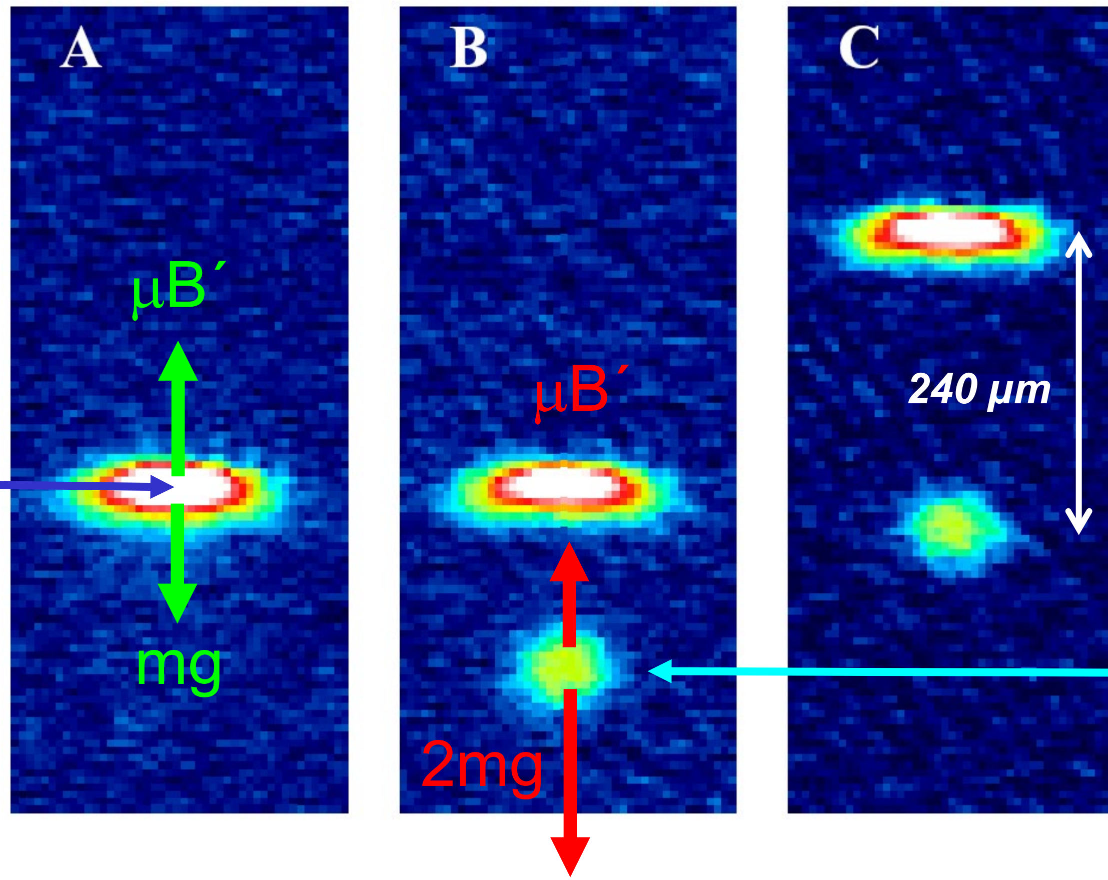


data from NIST group

Observation of ultracold Feshbach molecules

dB/dz=31.3 G/cm   31.3 G/cm   50.3 G/cm

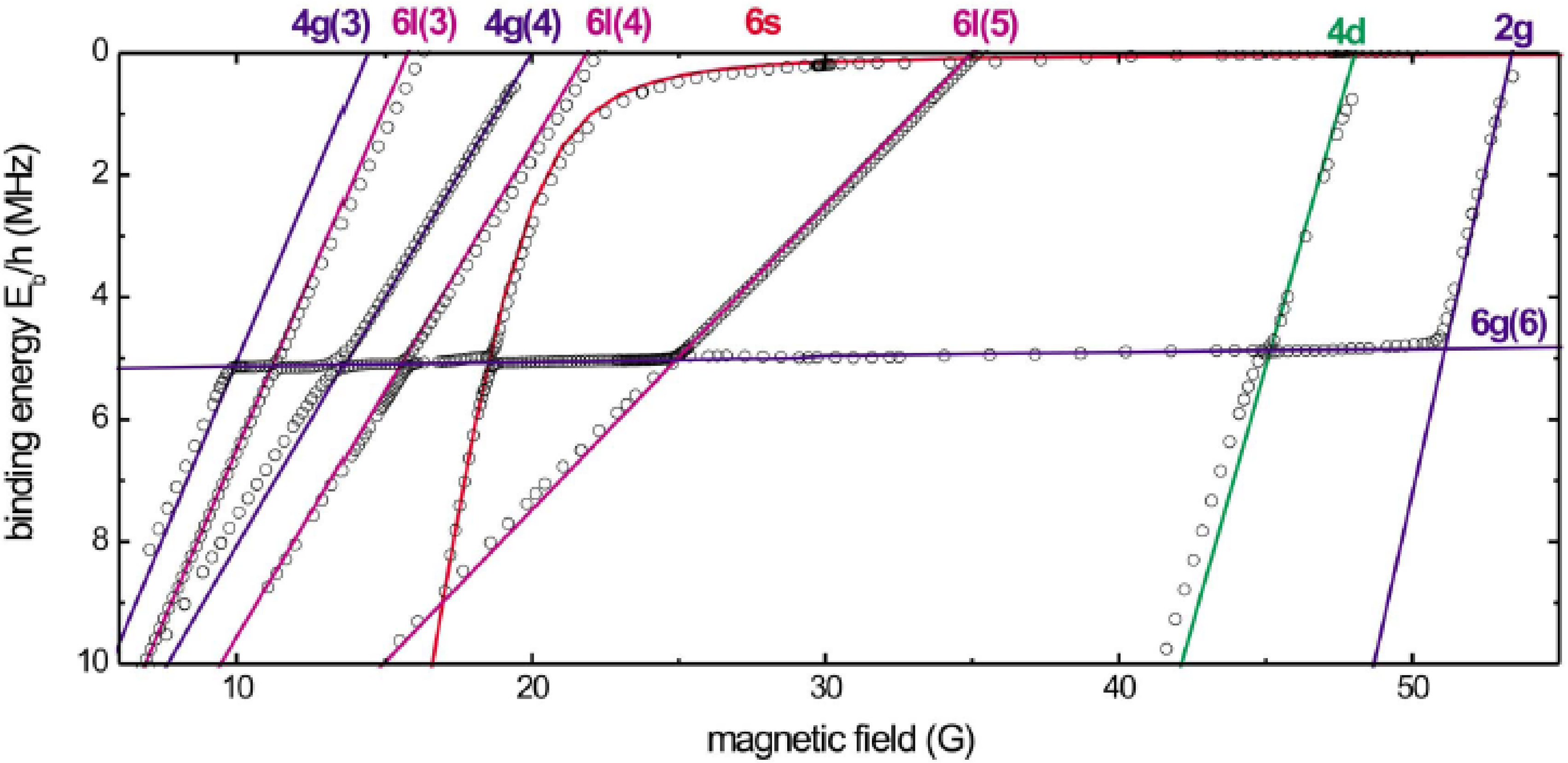
Atomic Cs BEC
60,000 atoms
$\mu=0.755\ \mu_B$



3,000 (10%)
Cs_2 molecules
$\mu=0.95\ \mu B$
1.8 nK

J. Herbig et al., Science '03. Also see C. Regal et al., Nature '03 on K_2
S. Durr et al., PRL '03 on Rb_2, K. Xu et al., PRL '03 on Na_2, S. Jochim et al., PRL '03 on Li_2

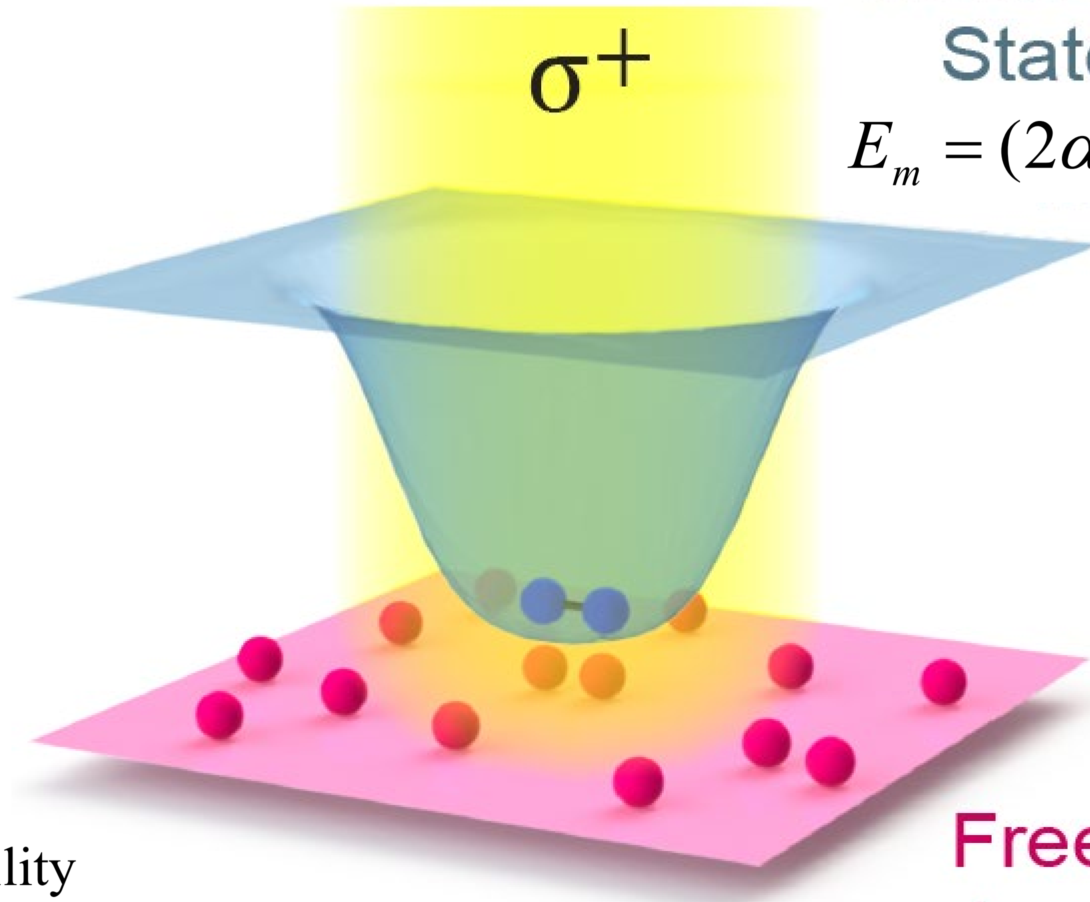
Map of Cs_2 molecular city



M. Mark et al., PRA 2007

Optical control of Feshbach resonances

Logan Clark



$$E_m = (2\alpha + \beta\ \mu_m) I$$

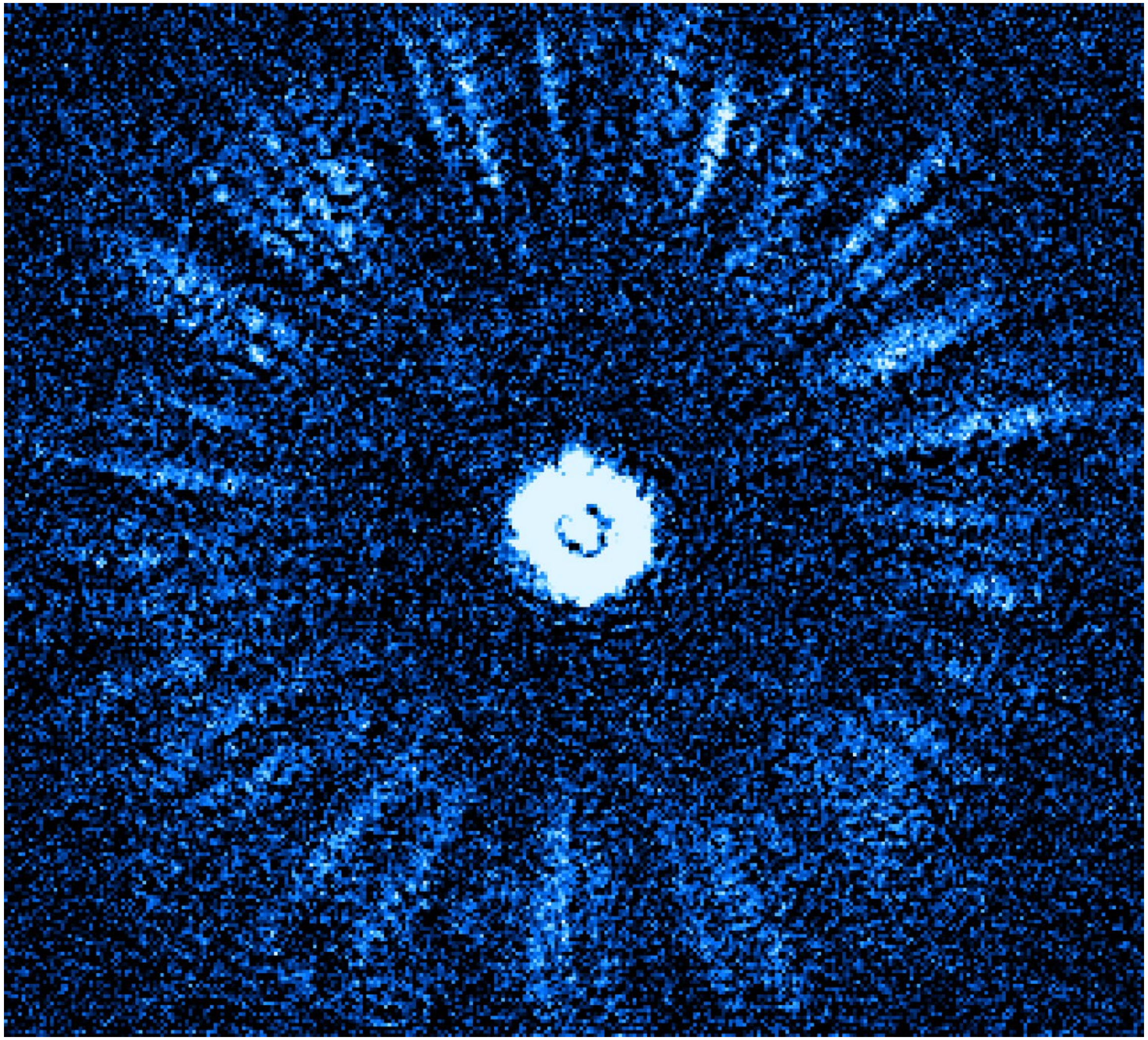
$$E_a = (\alpha + \beta\ \mu_a) I = 0$$

α : scalar polarizability

$\beta\mu$: vector polarizability

μ : magnetic moment

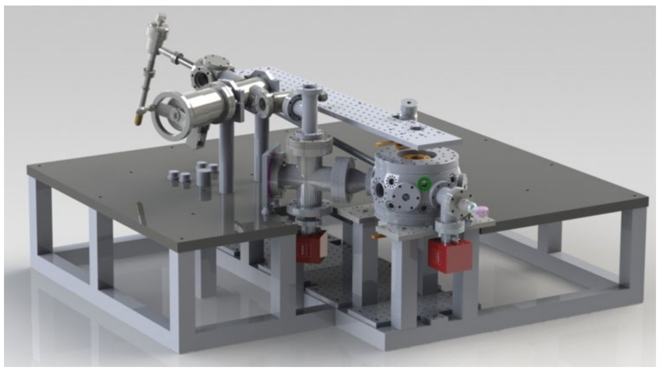
Bose fireworks



Logan Clark

Nature 551, 356 (2017)

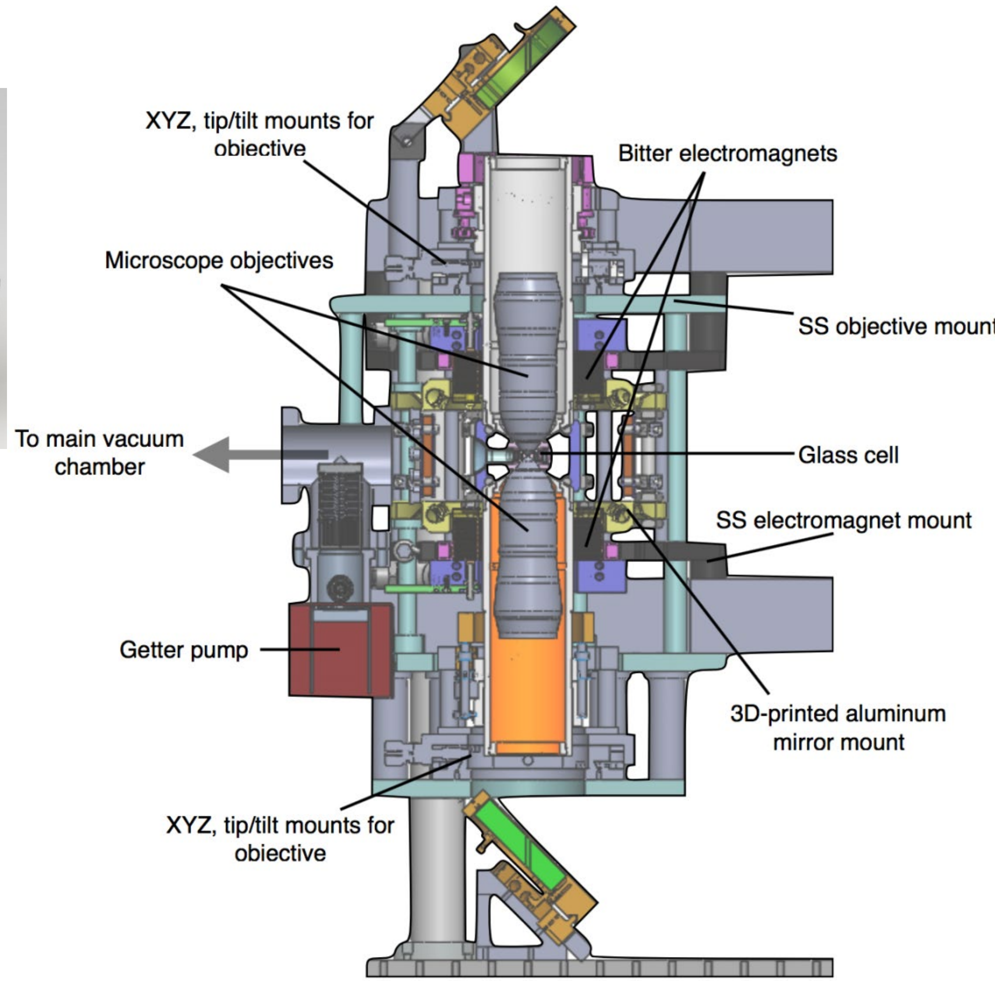
Quantum Matter Synthesizer



Modular mechanical design

Single reference frame

Decoupled from magnetic coils and vacuum system



A High Phase-Space-Density Gas of Polar Molecules

SCIENCE VOL 322 10 OCTOBER 2008

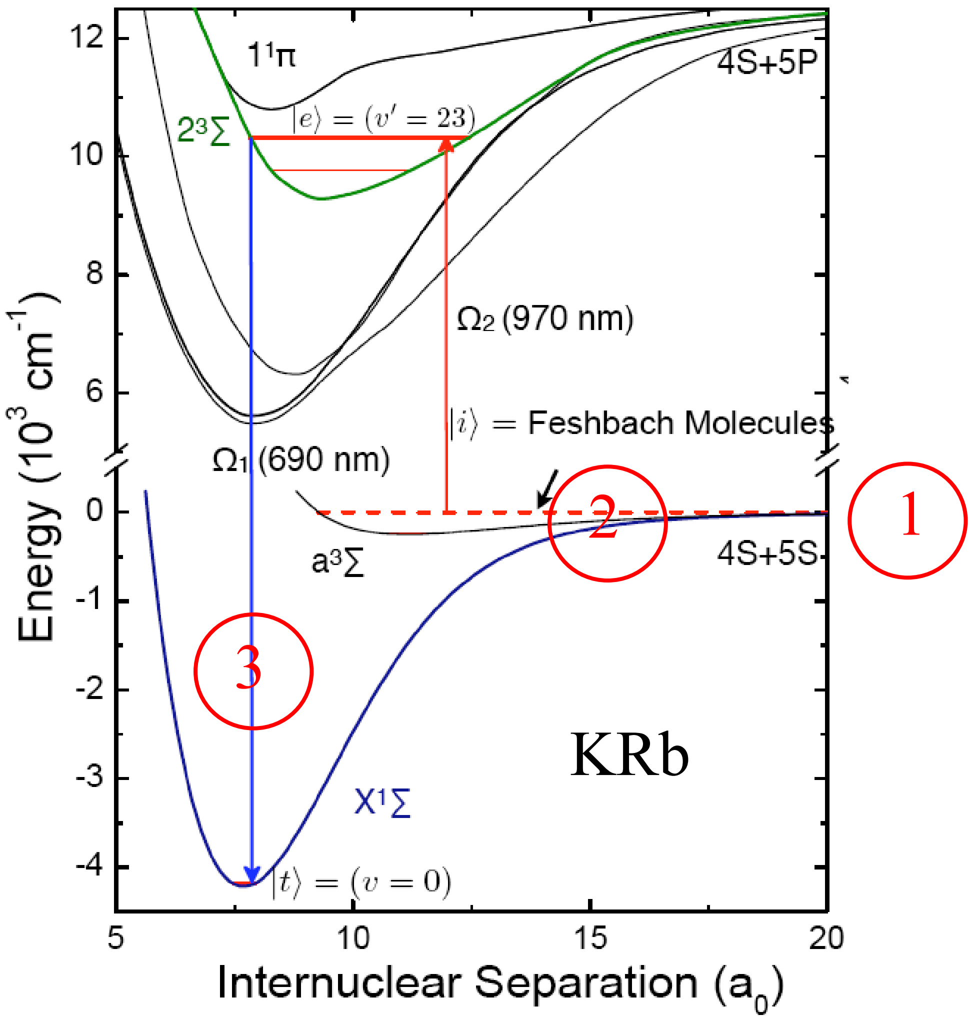
K.-K. Ni,[1*] S. Ospelkaus,[1*] M. H. G. de Miranda,[1] A. Pe'er,[1] B. Neyenhuis,[1] J. J. Zirbel,[1] S. Kotochigova,[2] P. S. Julienne,[3] D. S. Jin,[1†] J. Ye[1†]

40000 ^{40}K^{87}Rb molecules
v=0, J=0, single spin level
200 to 800 nK
Density ≈ 10^{12} cm^{-3}

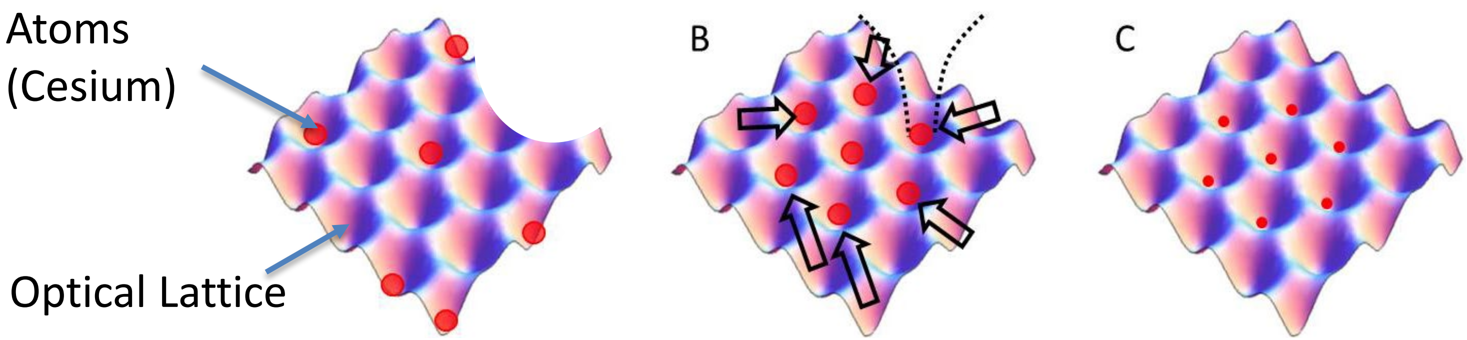
1. Prepare mixed atomic gas

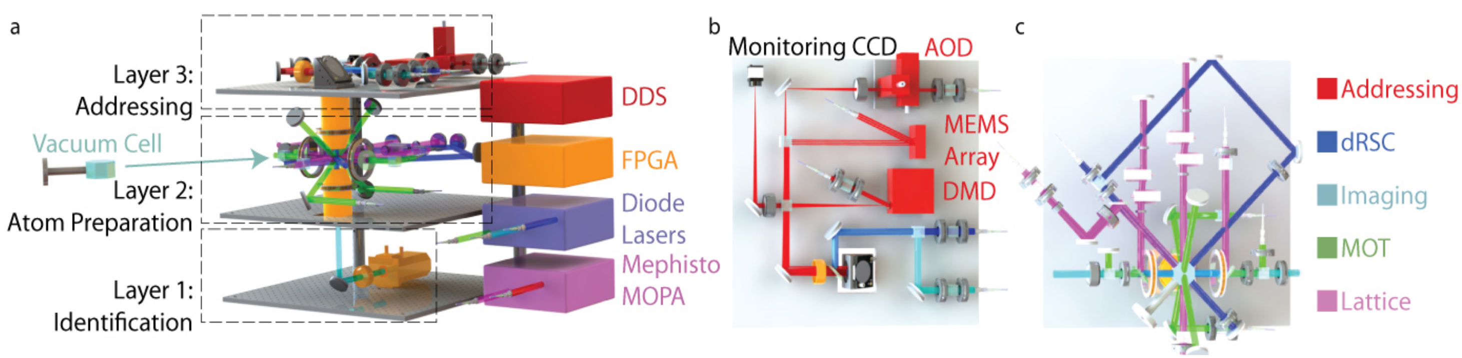
2. Magneto-association to
   Feshbach molecule

3. Optically switch to
   v=0 ground state



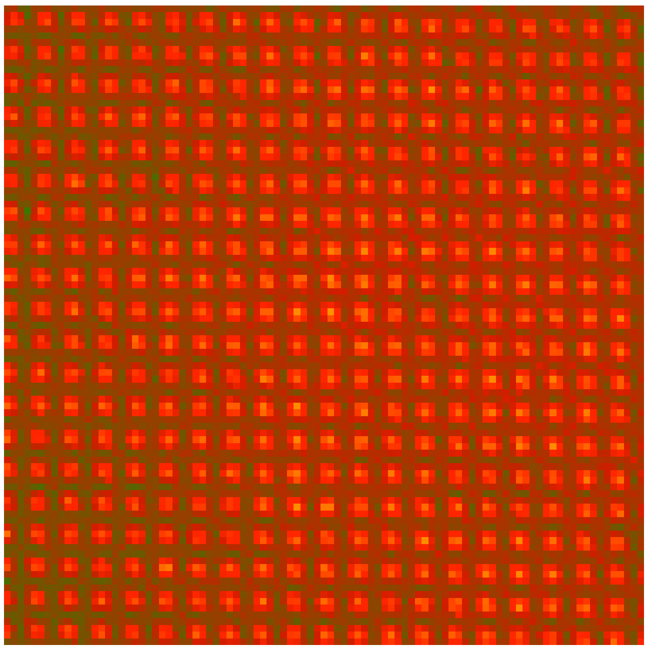
Quantum Matter Synthesizer





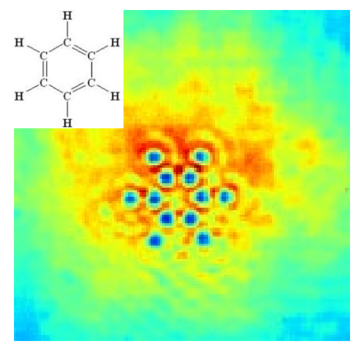
Quantum control, quantum chemistry

DMD-based optical lattices
700nm spacing

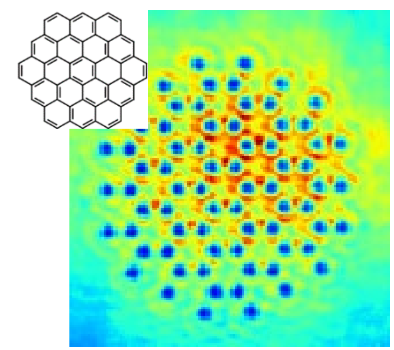


Simulation of quantum molecules

Benzene



Circumcoronene



Summary of Feshbach resonances

Tools to control atomic interactions

B field tunability: simulating condensed matter, nuclear physics,

Many-body applications: Solitons, BEC-BCS crossover, Hubbard model…

Pairing atoms into molecules: Feshbach molecules, Efimov trimers

Toward quantum manipulation: Coherent control of entangelment

New ideas

Test of fundamental constant variation

Bose fireworks, synthetic gauge field, quantum entanglement…

Thank you.