Introductory Course, Innsbruck, 11 July 2023

Rudolf Grimm

Ultracold fermions:

experimental basics

Austrian Acad. of Sciences

IQOQI

universität innsbruck

Inst. of Experimental Physics

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why are fermions interesting?

(even more interesting than bosons,
but this is a matter of taste)

three strong arguments

fermion + fermion = boson

boson physics appears as a special case of fermion physics

fermions are the basic constituents of matter

electrons (solid-state systems)

neutrons, protons and quarks (hadronic matter)

universality

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universality

	neutron star	white dwarf	metal (Cu)	**ultracold gas**
particles	neutrons	electrons	electrons	**^{6}Li atoms**
m in u	1	5.5×10^{-4}	5.5×10^{-4}	**6**
n in m^{-3}	$\sim 10^{44}$	$\sim 5 \times 10^{35}$	4.2×10^{28}	**$\sim 10^{18}$**
E_F	~ 70 MeV	~ 350 keV	~ 7 eV	**~ 300 peV**
T_F	~ 90 GK	~ 4 GK	~ 80 000 K	**~ 3 µK**

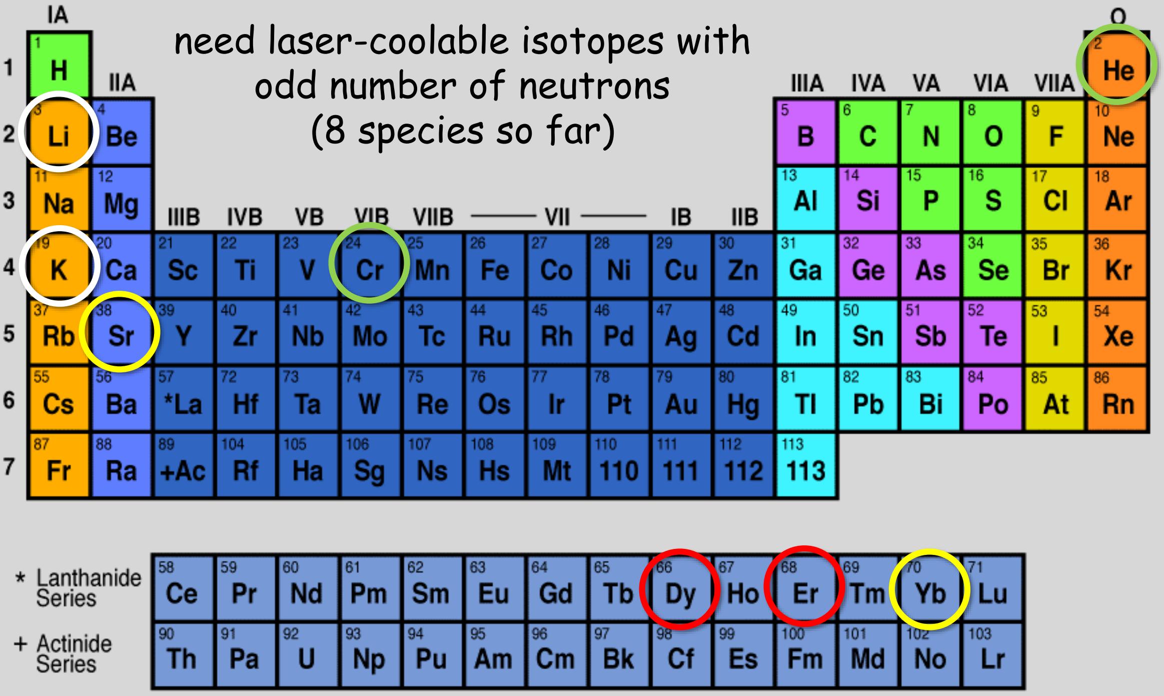
MeV


http://www.nasa.gov/mission_pages/GLAST/science/neutron_stars.html

⟷

peV

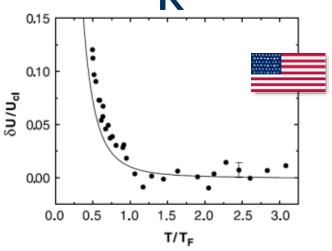
which atoms to use in the ultracold world?



need laser-coolable isotopes with
odd number of neutrons
(8 species so far)

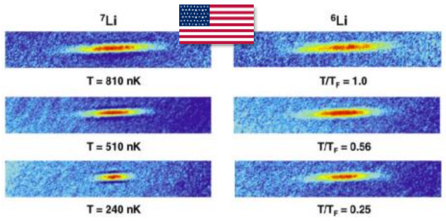
ultracold fermions: a bit of early history

^{40}K

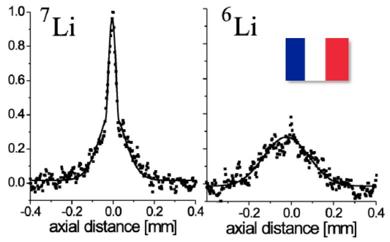


DeMarco and Jin,
Science 285, 1703 (1999)

^{6}Li

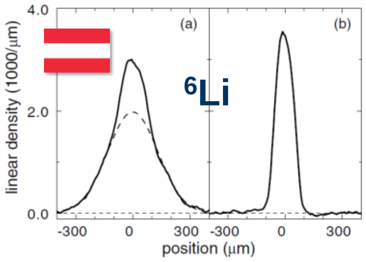


Truscott et al.,
Science 291, 257 (2001)



Schreck et al.,
Phys. Rev. Lett. 87, 080403 (2001)

- ^{40}K in Florence (2002)
- ^{6}Li at Duke Univ. (2002)
- ^{6}Li at MIT (2003)



^{6}Li

Innsbruck joined
in 2003 with
first molecular BEC

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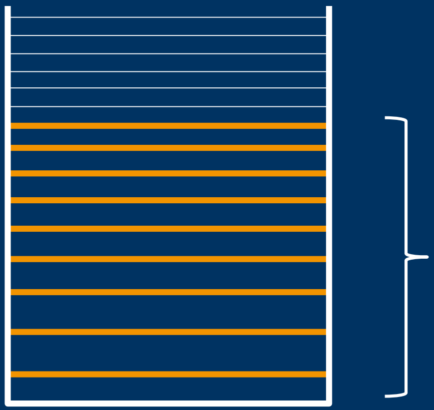
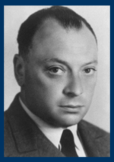
trapped Fermi gas basics

fermions in a (large) 3D box

@ T=0





principle

occupied quantum states

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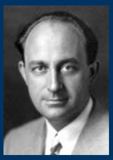
fermions in a (large) 3D box

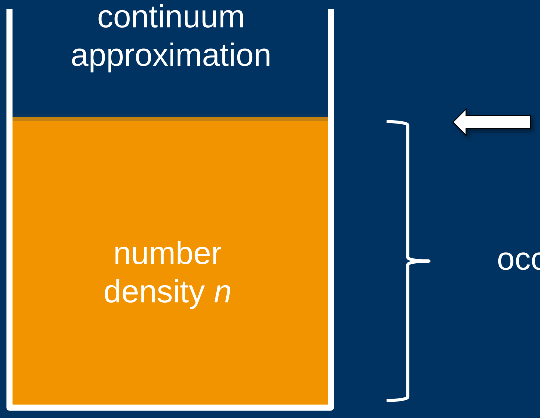
@ T=0

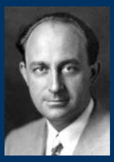


energy E_F

occupied quantum states

fermions in a (large) 3D box

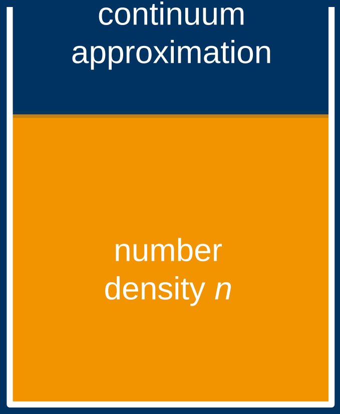




energy E_F

occupied quantum states (unresolved)

fermions in a (large) 3D box



Fermi energy: the relevant energy scale

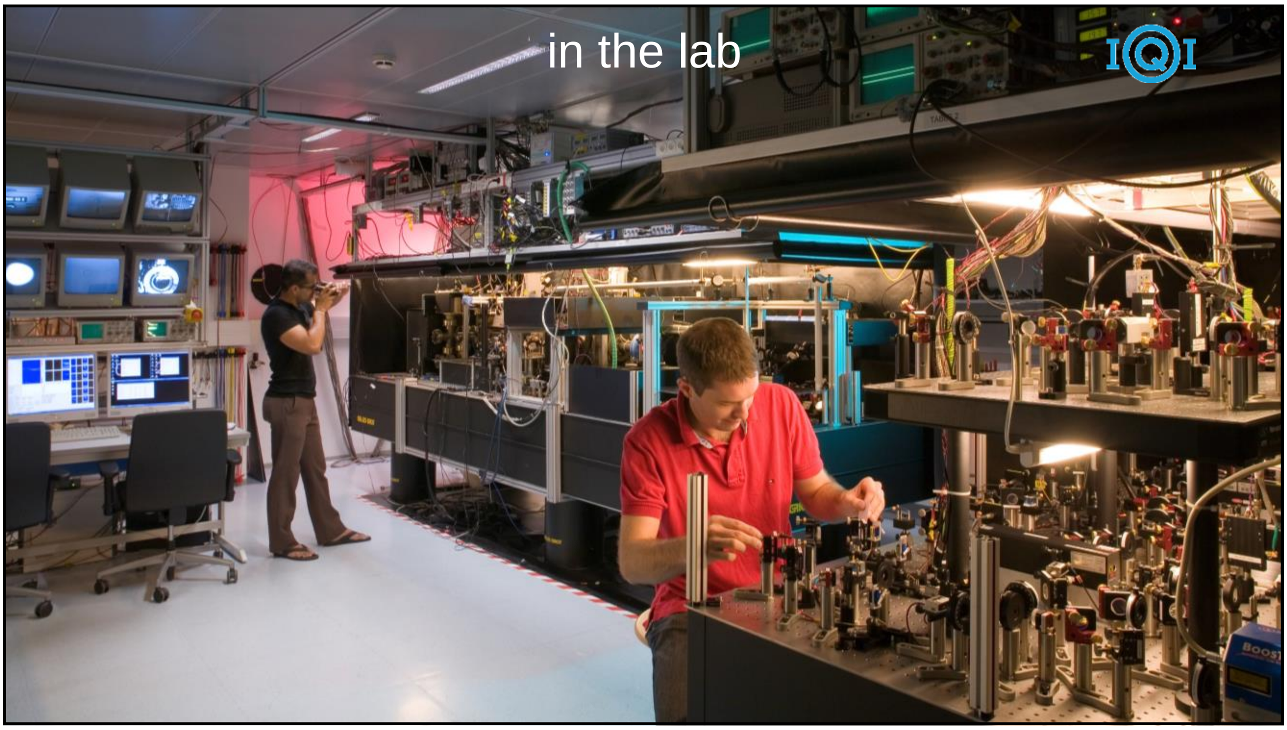
$$E_F = (6\pi^2)^{2/3}\frac{\hbar^2}{2m}n^{2/3} = \frac{\hbar^2 k_F^2}{2m}$$

Fermi wavenumber

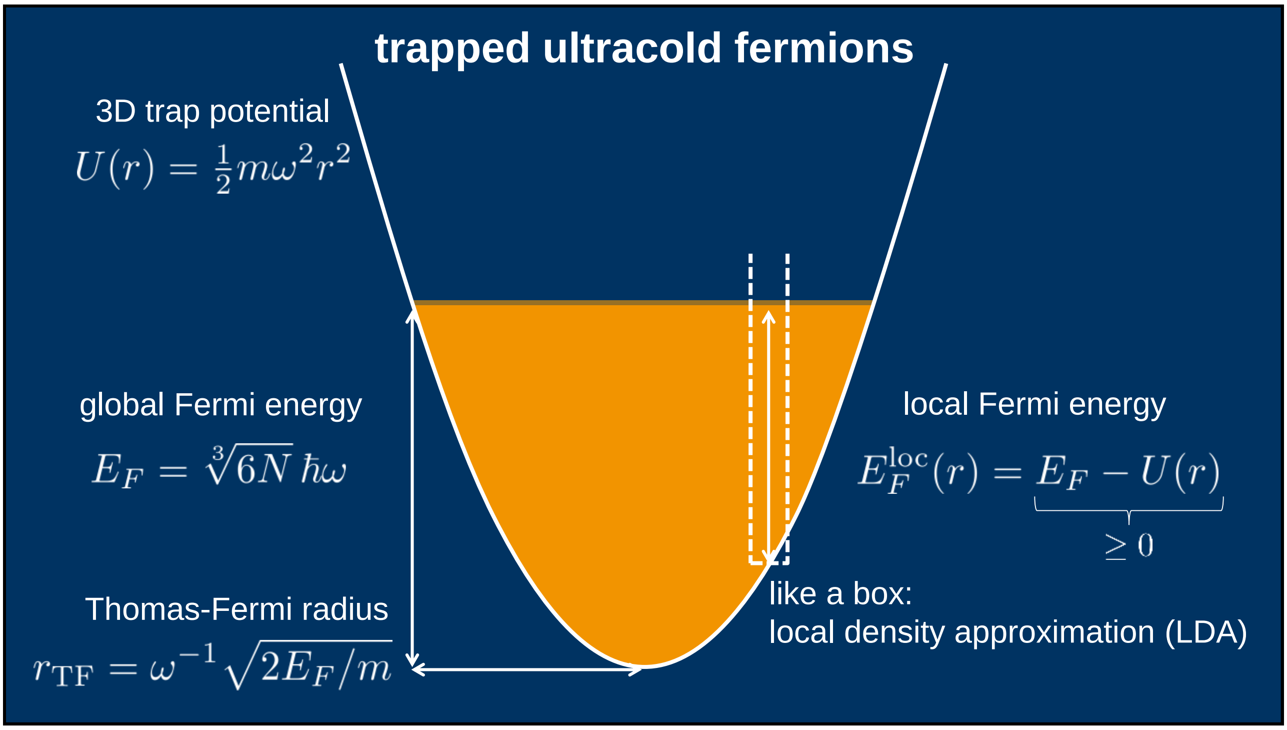
$$\frac{1}{k_F} = \left(6\pi^2 n\right)^{-1/3}$$

the relevant length scale

in the lab



trapped ultracold fermions



3D trap potential

$$U(r) = \tfrac{1}{2} m\omega^2 r^2$$

global Fermi energy

$$E_F = \sqrt[3]{6N}\,\hbar\omega$$

Thomas-Fermi radius

$$r_{\mathrm{TF}} = \omega^{-1}\sqrt{2E_F/m}$$

local Fermi energy

$$E_F^{\mathrm{loc}}(r) = \underbrace{E_F - U(r)}_{\geq 0}$$

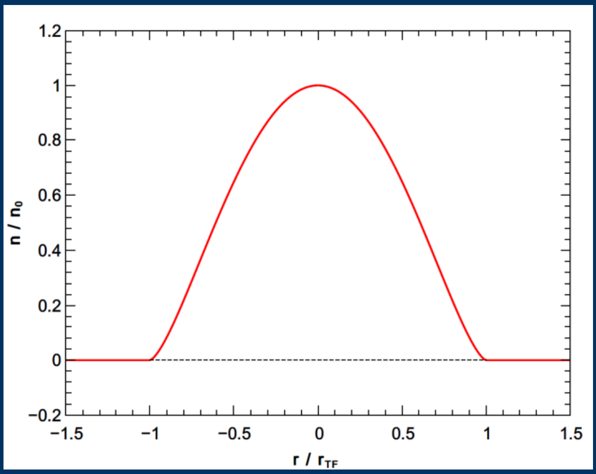
like a box:
local density approximation (LDA)

spatial profile in LDA

Thomas-Fermi profile @ *T*=0

$$n(r) \propto [E_F - U(r)]^{3/2}$$

large-sized, non-interacting
Fermi gas at zero temperature



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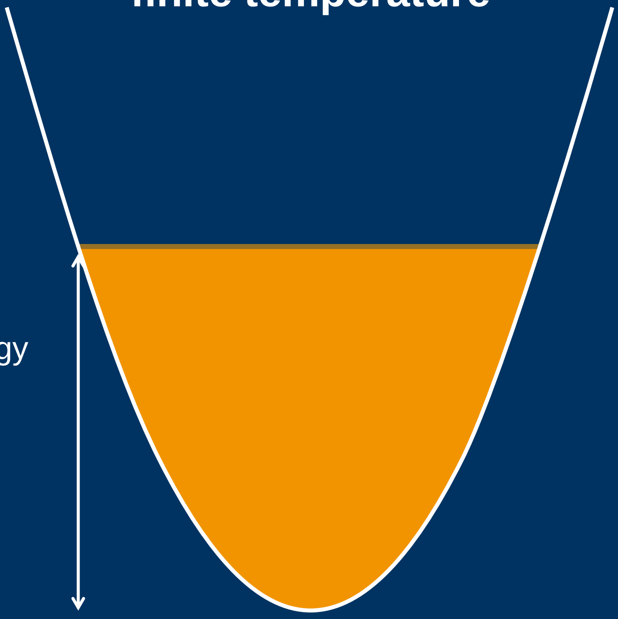
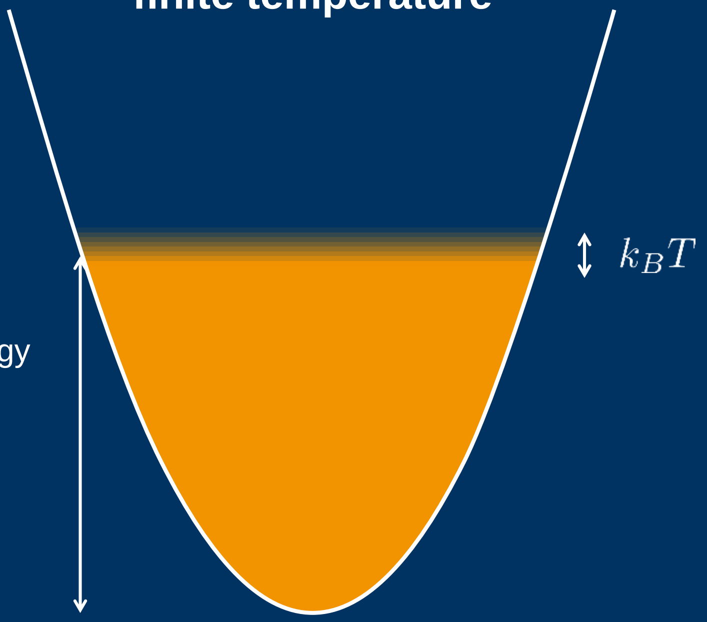
finite temperature



global Fermi energy

$$E_F = k_B T_F$$

finite temperature



$k_B T$

global Fermi energy

$E_F = k_B T_F$

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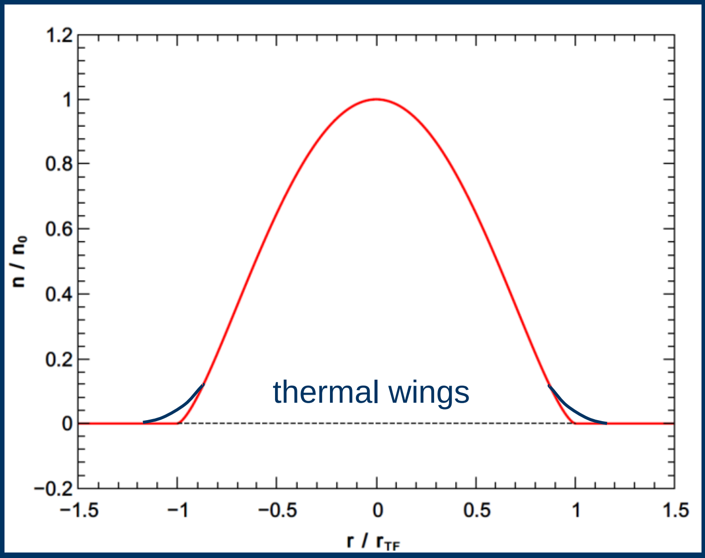
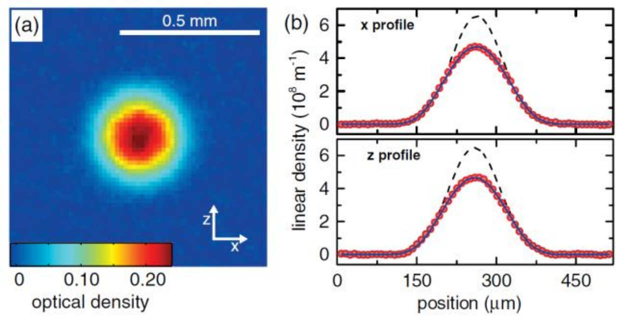
cloud shape at finite temperature



thermometry
at low T/T_F
challenging

two examples from Innsbruck

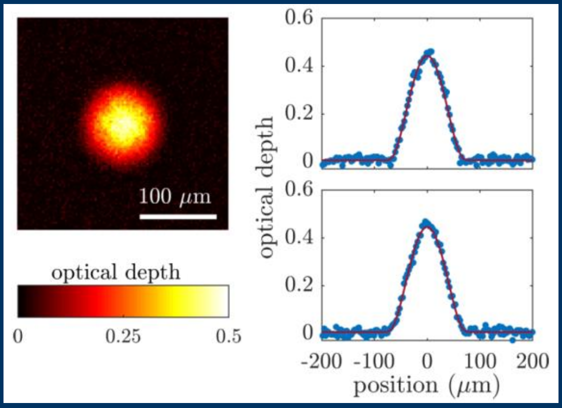
^{167}Er



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

$T/T_F \approx 0.2$

^{161}Dy



Ravensbergen et al., PRA 98, 063624 (2018)

$T/T_F \approx 0.1$

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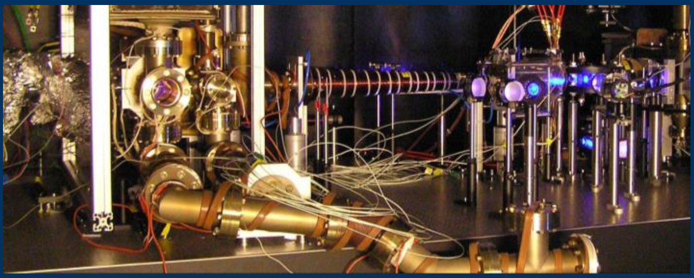
but how do we get there?

cooling fermions

laser cooling and trapping:
Zeeman slowing, MOTs,
optical dipole traps ...

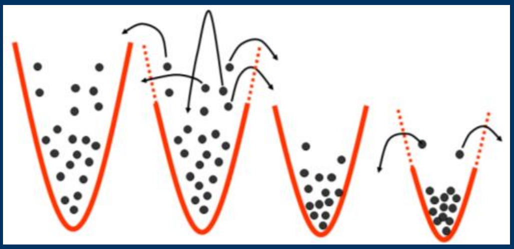
some species (Sr, Yb, Dy, Er)
narrow-line Doppler cooling

our Li-K machine



evaporative cooling

need elastic collisions!



video lecture on
evaporative cooling
MSc course

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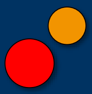
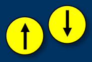
elastic collisions: three options

s-wave collisions between unlike atoms

- sympathetic cooling, i.e. cooling by another species
  mixtures of ^{7}Li-^{6}Li, ^{23}Na-^{6}Li, or ^{87}Rb-^{40}K, ...

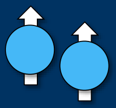


- single species, but two different spin states
  spin mixtures of ^{6}Li, ^{40}K, ^{87}Sr, ^{171}Yb



dipolar collisions (higher partial waves) for identical fermions

- strongly magnetic atoms
  ^{161}Dy, ^{167}Er



what makes fermions so interesting?

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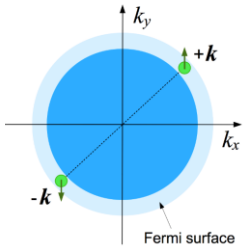
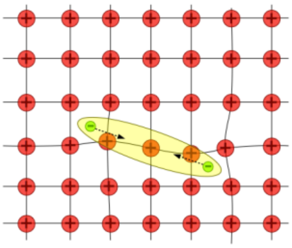
famous example





Cooper pairs

(BCS theory, 1957)

http://inspirehep.net/
record/1181776/plots

but,

$T_c/T_F < 10^{-4}$ for conventional superconductors
$T_c/T_F \sim 10^{-3}$ for high-Tc superconductors

and we typically reach $T/T_F \sim 0.1$

but, we can introduce ***very strong interactions***!

strong interactions in a Fermi gas

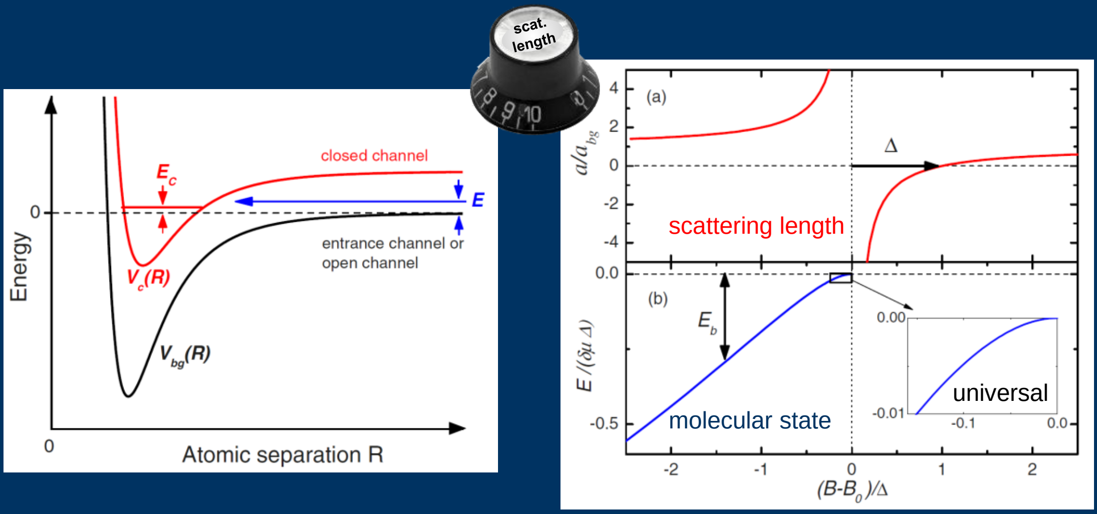
which parameter characterizes the interaction in a quantum gas?

s-wave scattering length *a*

$|a| \ll 1/k_F$	weak interaction: elastic collisions, mean field *straightforward theory, easy description*
$|a| \gtrsim 1/k_F$	strong interaction: exciting many-body physics *challenges our theoretical understanding*

how can we control this?

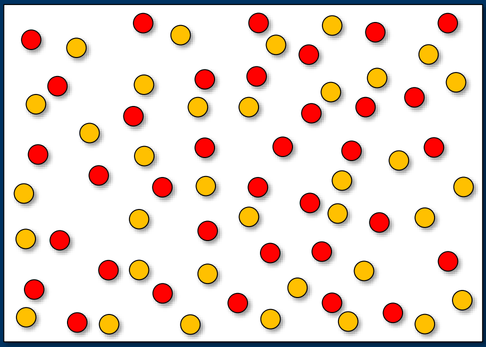
Feshbach resonance: interaction control



review article
Chin et al., RMP 82, 1225 (2010)

width can vary over very wide range!

fermionic spin mixture with Feshbach resonance



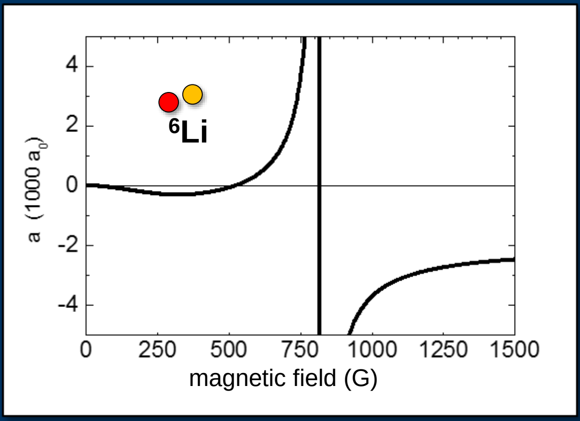
spin mixtures of

^{6}Li or **^{40}K**

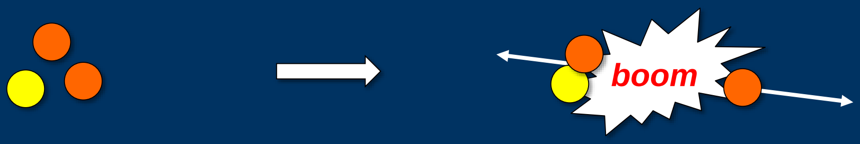
two systems widely used

Feshbach resonance

(broad, with large universal range)

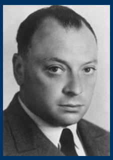


suppression of three-body losses



three atoms

dimer + atom

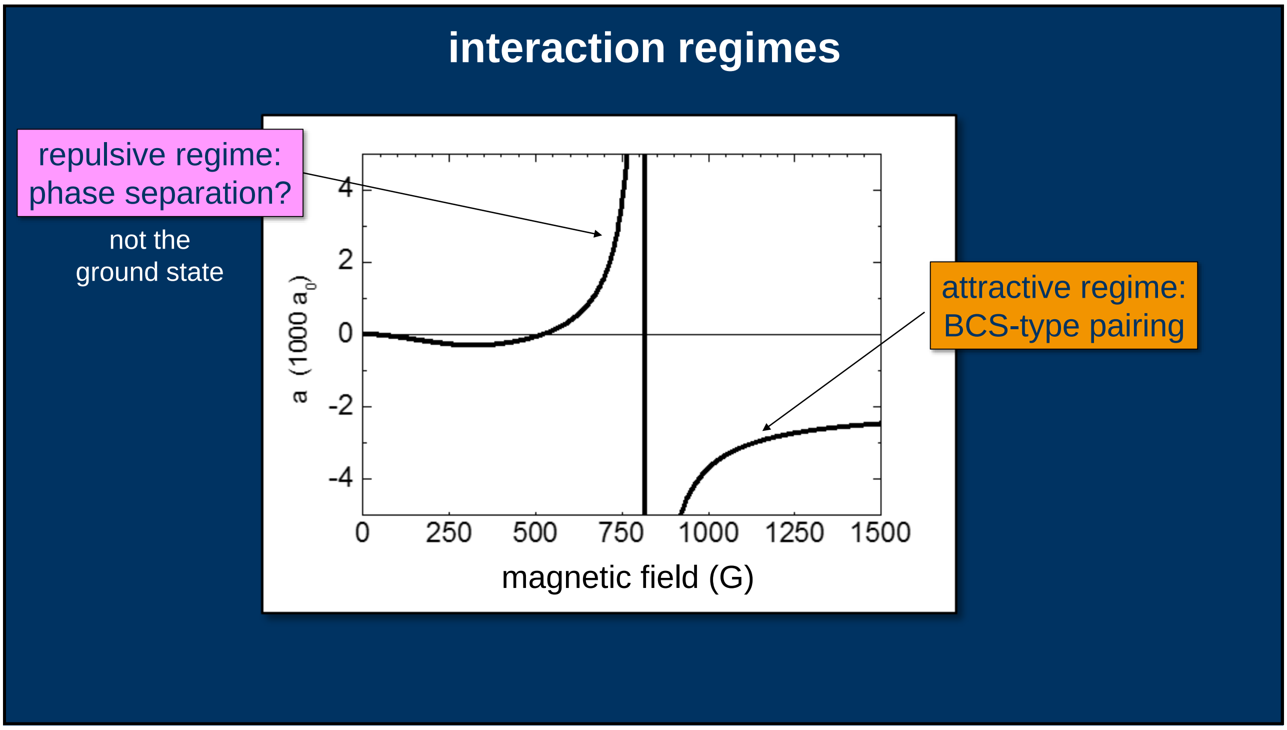


this guy can suppress it,
but needs broad Feshbach resonance

^{40}K

^{6}Li

Petrov, Salomon, Shlyapnikov, PRL 93, 090404 (2004)

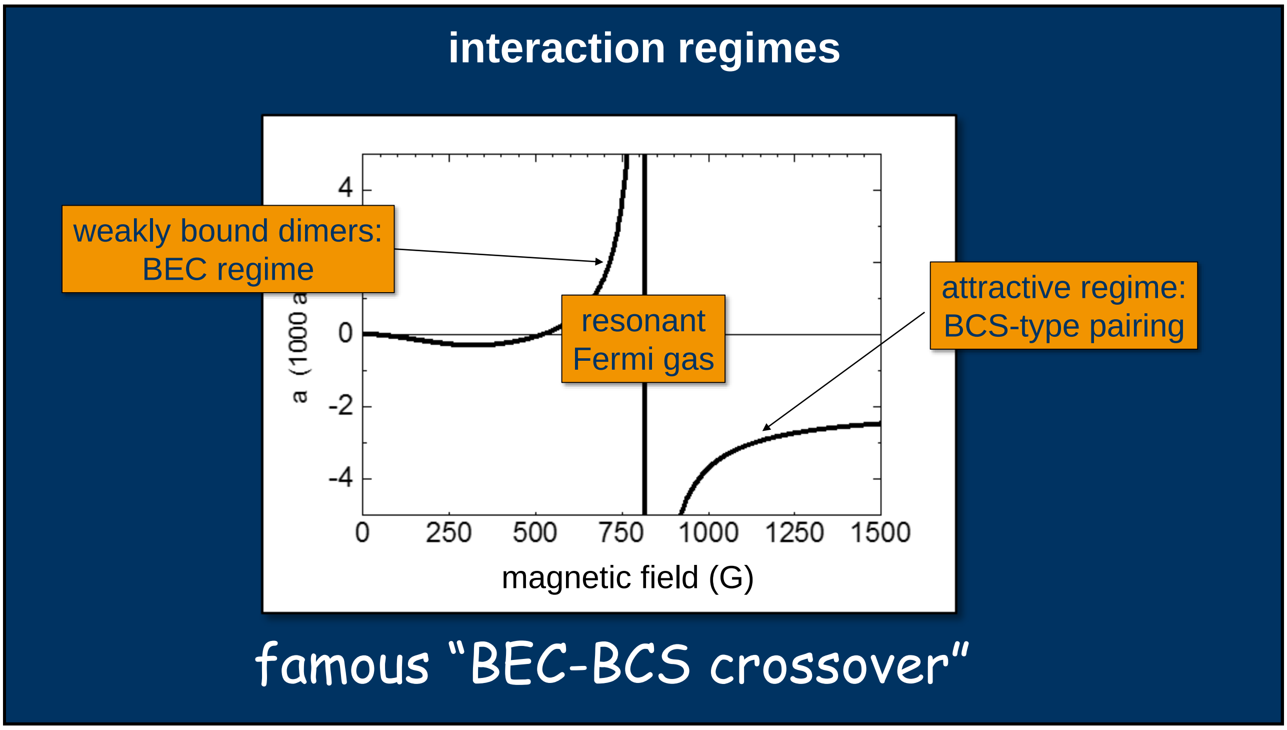


interaction regimes

repulsive regime:
phase separation?

not the
ground state

attractive regime:
BCS-type pairing



interaction regimes

weakly bound dimers:
BEC regime

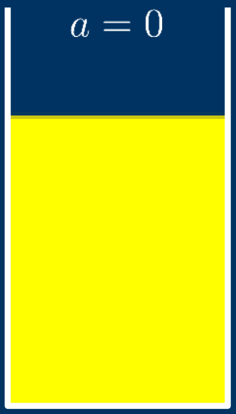
resonant
Fermi gas

attractive regime:
BCS-type pairing

famous "BEC-BCS crossover"

resonant (unitary) Fermi gas

what happens in case of the strongest interaction that quantum mechanics allows?



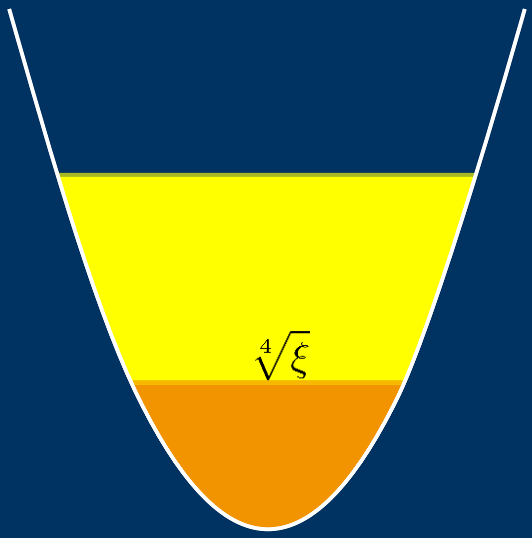
$\mu_0 = E_F$: chemical potential
of non-interacting gas

μ_{res}: chemical potential
of resonant gas

$$\mu_{res} = \xi\, \mu_0$$

“Bertsch parameter”

resonant Fermi gas in harmonic trap



“universality”

parameter ξ is <u>universal</u>,
because $1/k_F$ is the only length scale
in the problem

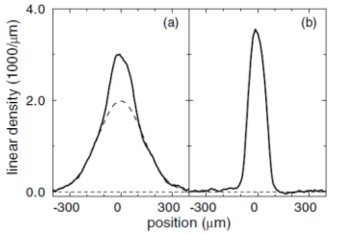
harmonically trapped just rescaled,
shrinks in size, but keeps its shape!

Ibk 2004
$\xi = 0.32(13)$

MIT 2013
$\xi = 0.376(4)$

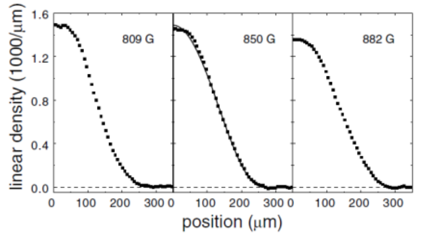
in agreement
with advanced
many-body theory

early experiments in Innsbruck (^{6}Li)

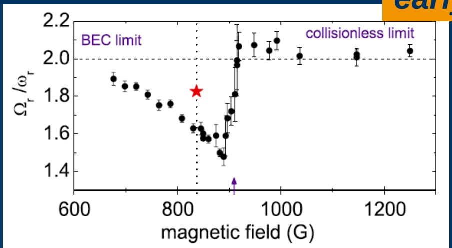


molecular BEC
(2003/04)

BEC-BCS
crossover
(2004)

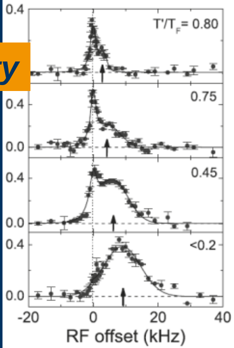


collective modes (2004)

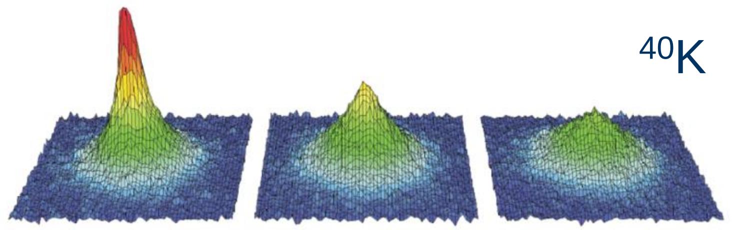


early hints on superfluidity

radio-freq.
spectrosc.
pairing gap
(2004)



superfluidity in Fermi gases: two breakthroughs



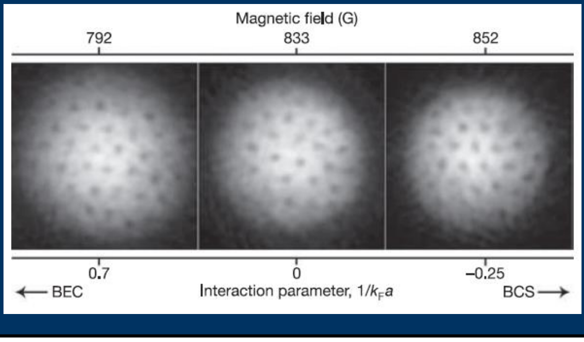
fermionic condensate @ JILA

Regal, Greiner, Jin,
PRL 92, 040403 (2004)

vortices @ MIT

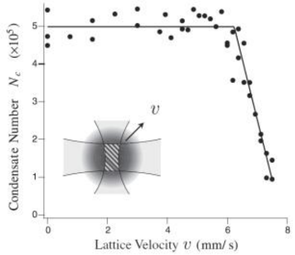
Zwierlein, Abo-Shaeer,
Schirotzek, Schunck, Ketterle
Nature 435, 1047 (2005)

^{6}Li

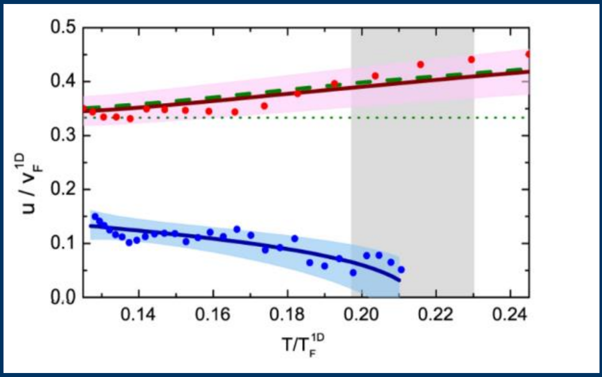


superfluidity in Fermi gases

critical velocity
(MIT, 2007)

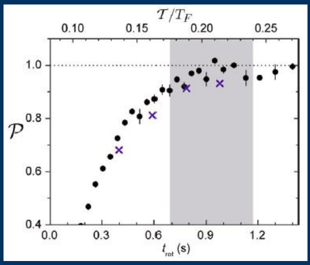


second sound (Innsbruck-Trento, 2013)



quenching of moment
of inertia (Ibk, 2011)

^{6}Li



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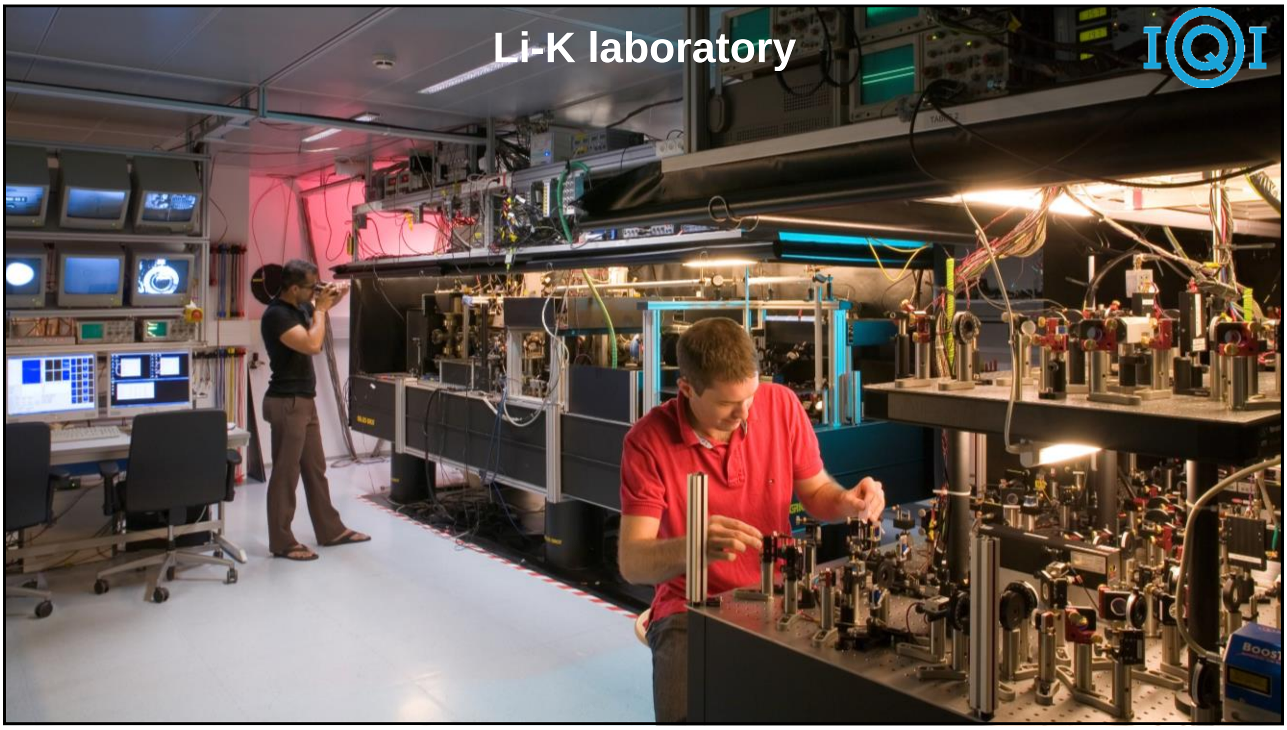
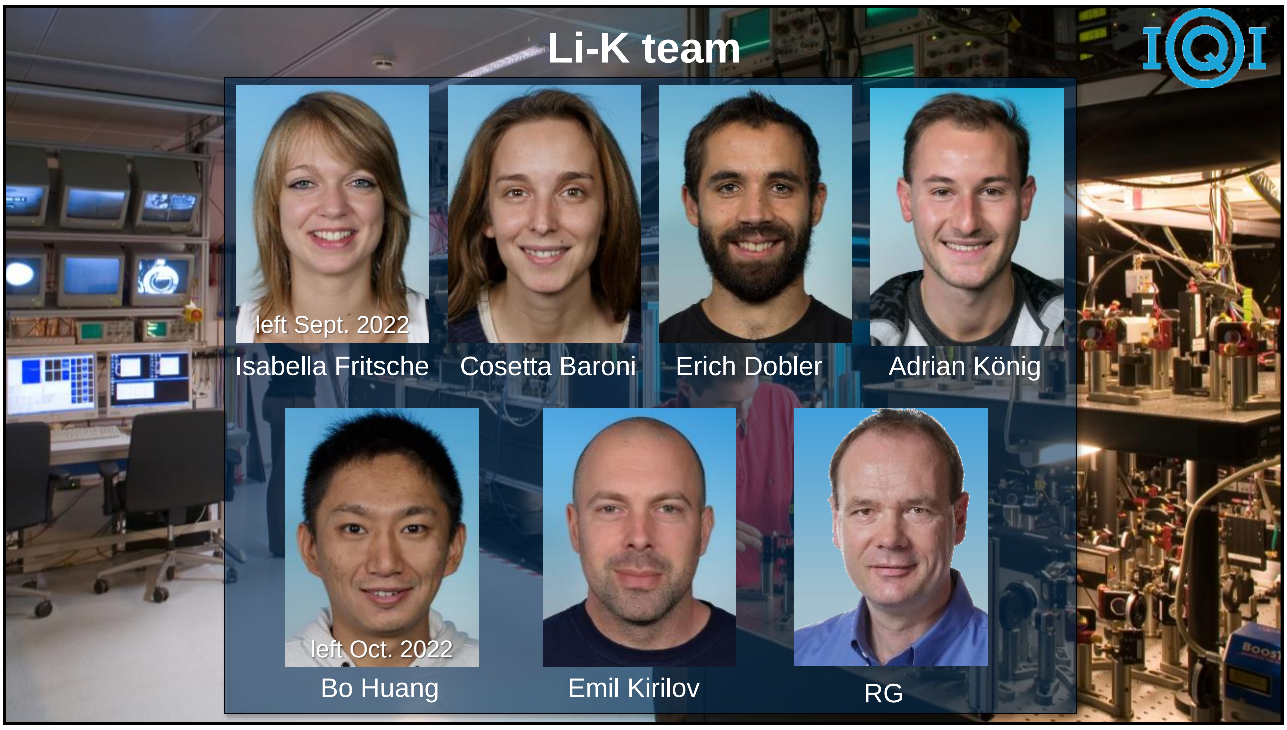
current research in Innsbruck:
Mixtures with fermions



Li-K laboratory



Li-K team

left Sept. 2022
Isabella Fritsche

Cosetta Baroni

Erich Dobler

Adrian König

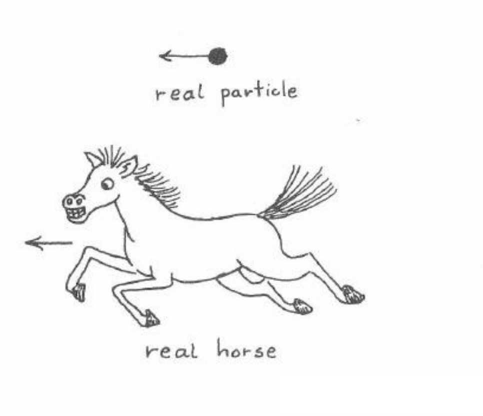
left Oct. 2022
Bo Huang

Emil Kirilov

RG

quasiparticle and quasihorse

Richard D. Mattuck: *A guide to Feynman diagrams in the many-body problem* (McGraw-Hill, 1976)



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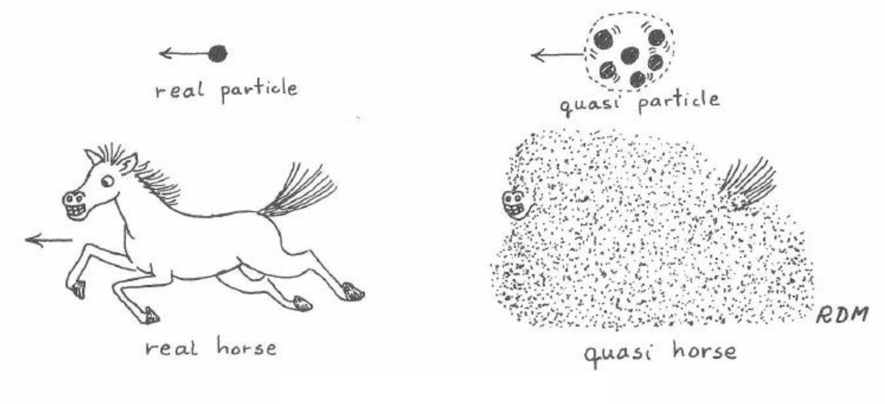
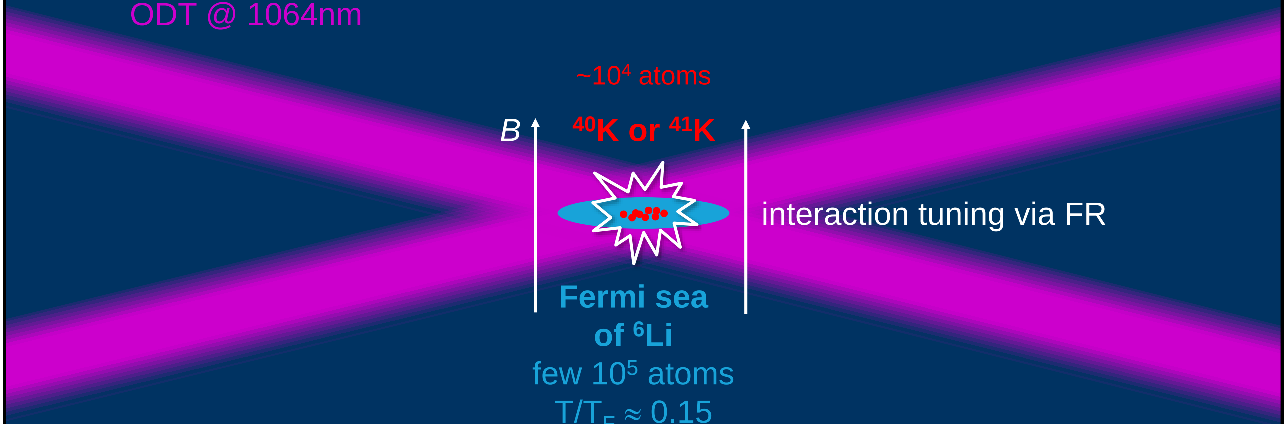
quasiparticle and quasihorse

Richard D. Mattuck: *A guide to Feynman diagrams in the many-body problem* (McGraw-Hill, 1976)



shielded, different mass,
different energy, finite lifetime

typical experimental situation



ODT @ 1064nm

~10^4 atoms

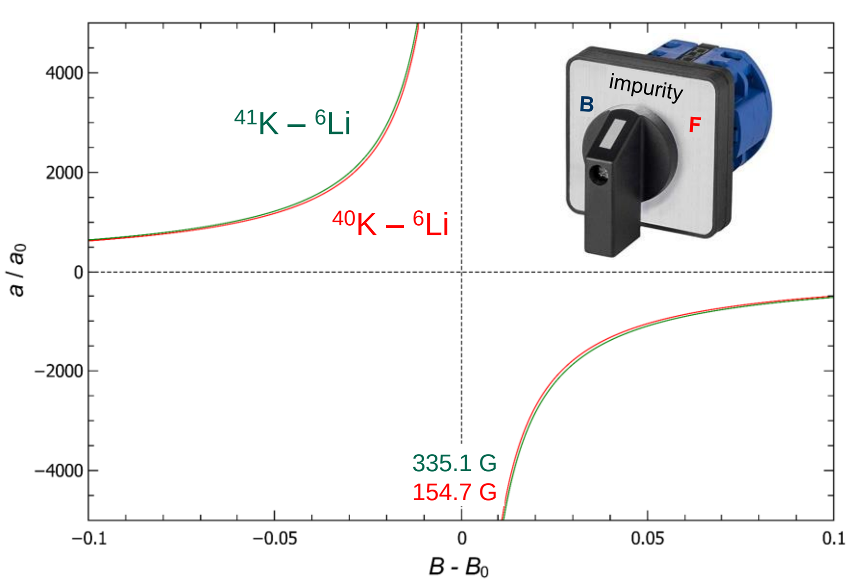
^{40}K or ^{41}K

B

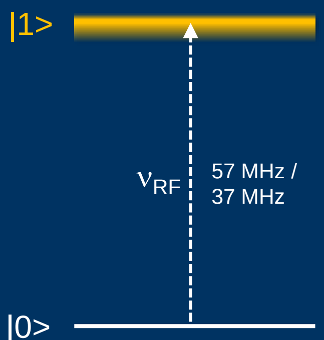
interaction tuning via FR

Fermi sea
of ^{6}Li
few 10^5 atoms
$T/T_F \approx 0.15$
strongly interacting spin mixture
or single spin state

gift of nature



radio-frequency “injection” spectroscopy



tunable interaction
with ^{6}Li medium

impurity
spin states

weakly interacting
with ^{6}Li medium
(preparation)

^{41}K bosons	^{40}K fermions
335.1 G	154.7 G
$F = 1$ $m_F = 1$	$F = 9/2$ $m_F = -5/2$
$F = 1$ $m_F = 0$	$F = 9/2$ $m_F = -7/2$

Feshbach
resonances
(~1G wide,
very similar) !

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universality: dimensionless quantities

all energies normalized
to Fermi energy $E(X)/E_F$

dimensionles
interaction strength $X \equiv -\dfrac{1}{k_F a}$

$$E_F = \frac{(\hbar k_F)^2}{2m} \approx k_B \times 1\mu K$$

$$1/k_F \approx 4000 a_0 \approx 200\text{nm}$$

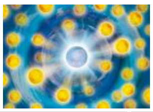
typical expt. conditions

note: for narrow Feshbach resonances
another parameter (*R*/a*) enters the problem

^{40}K

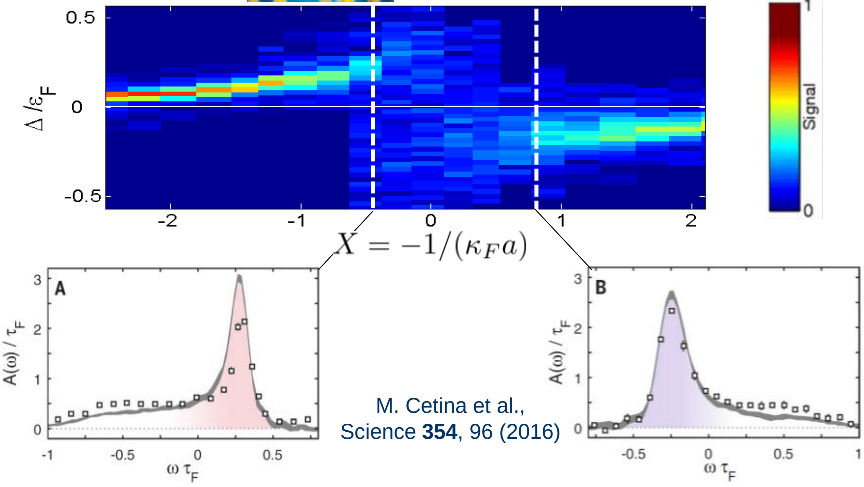
spectral response

C. Kohstall, M. Zaccanti et al., Nature **485**, 615 (2012)



"repulsive polaron"
lifetime ms

population
transfer
|0> → |∗>



M. Cetina et al., Science **354**, 96 (2016)

single-impurity physics well understood
thanks to a lot of theoretical and experimental work
in the last 10 years

Fermi liquid: first part of the story

what's new?

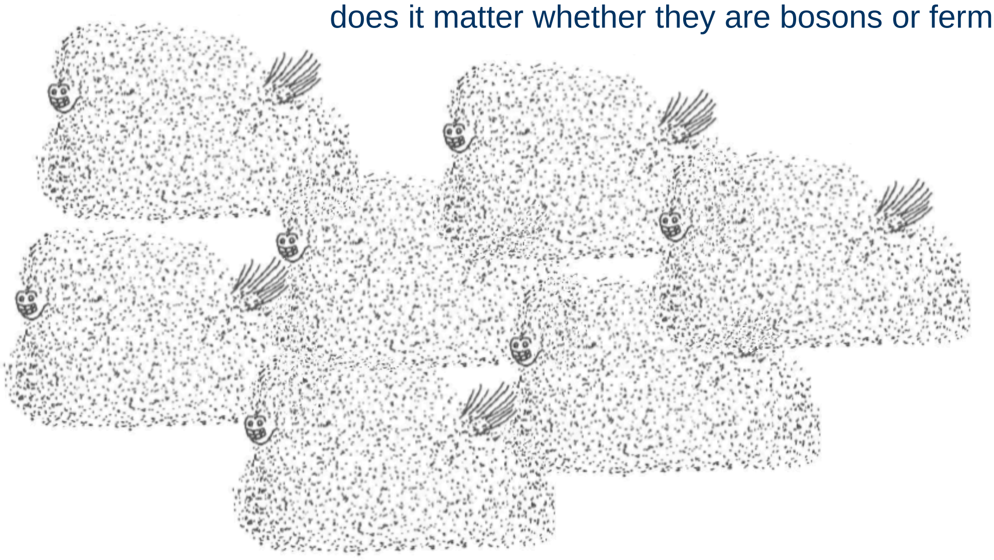
mediated impurity-impurity interaction

second part of the story

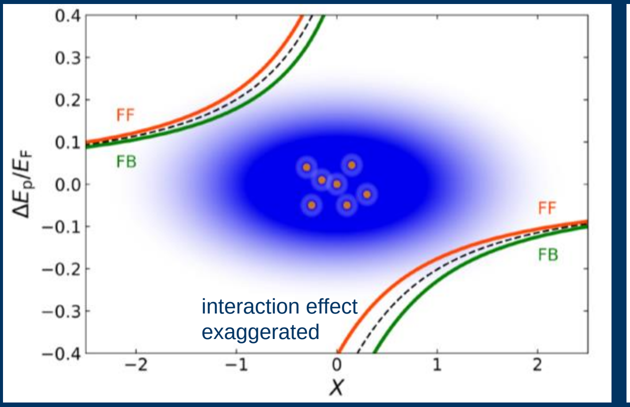
research interest

what happens if they interact?

does it matter whether they are bosons or fermions?



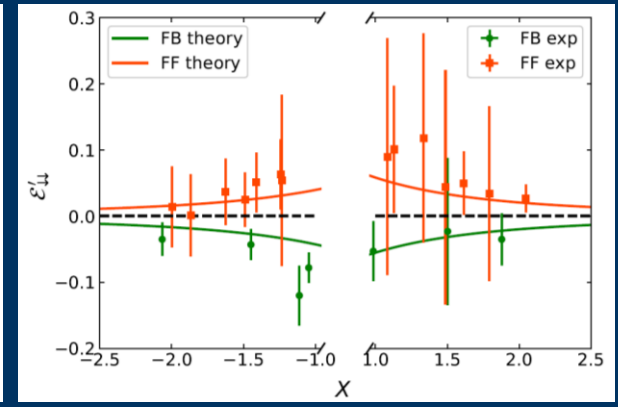
spectacular recent result



interaction effect
exaggerated

expectation from Fermi-liquid theory

Yu and Pethick, Phys. Rev. A **85**, 063616 (2012)

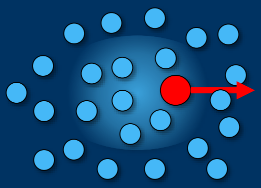


first observation of
mediated pol.-pol. interactions

Baroni et al, arXiv:2305.04915 (2023)

in preparation: polarons in motion

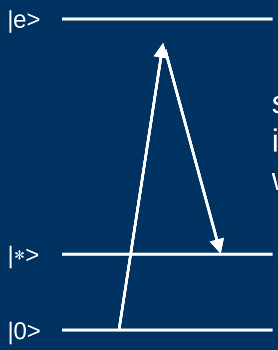
breakdown
of the quasiparticle ?



Fermi speed

$$E_F \approx k_B \times 700\ \mathrm{nK}$$

$$v_F = \sqrt{2E_F/m} \approx \mathbf{44\ mm/s}$$



suggested tool:
injection spectroscopy
with Raman pulses

$$\frac{2\hbar k}{m} \approx \mathbf{26}\,\frac{\mathbf{mm}}{\mathbf{s}} \approx \frac{v_F}{2}$$

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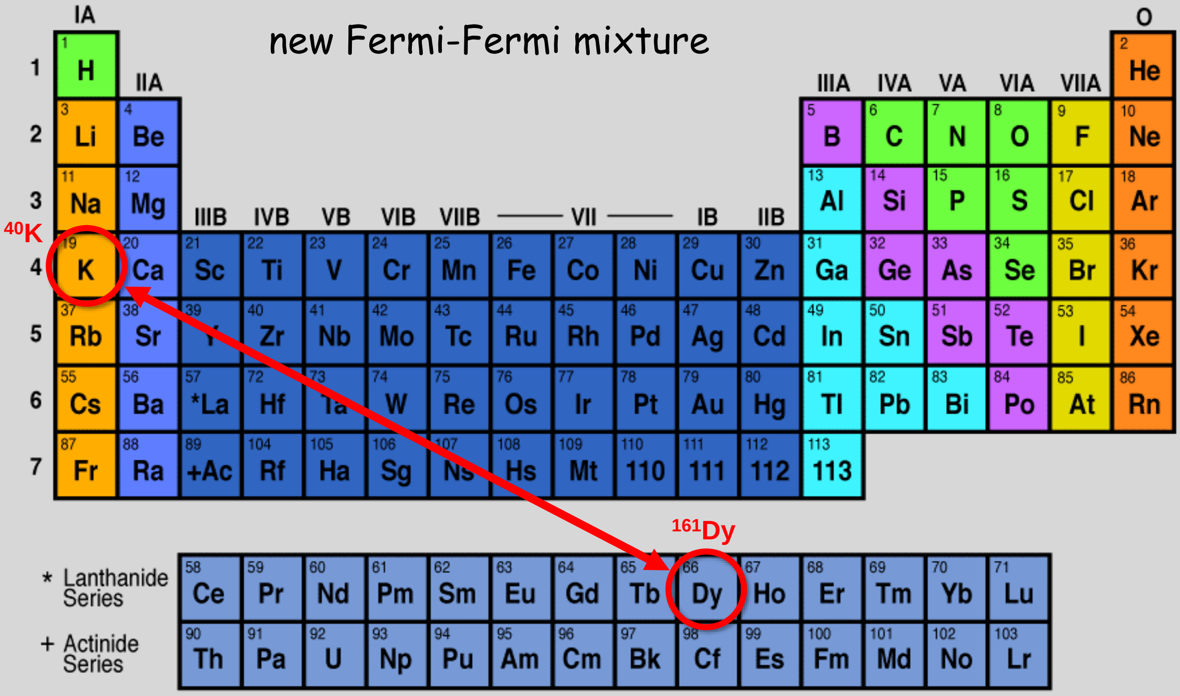
towards novel superfluids with mixtures of Dy and K

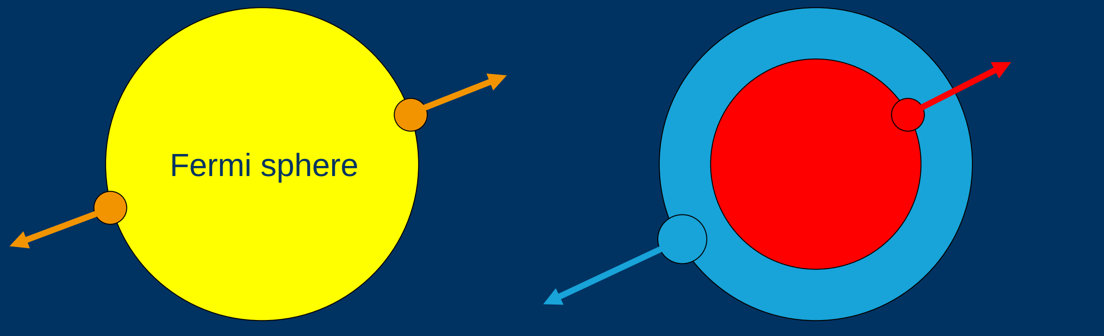
new Fermi-Fermi mixture



	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

pairing in fermion mixtures



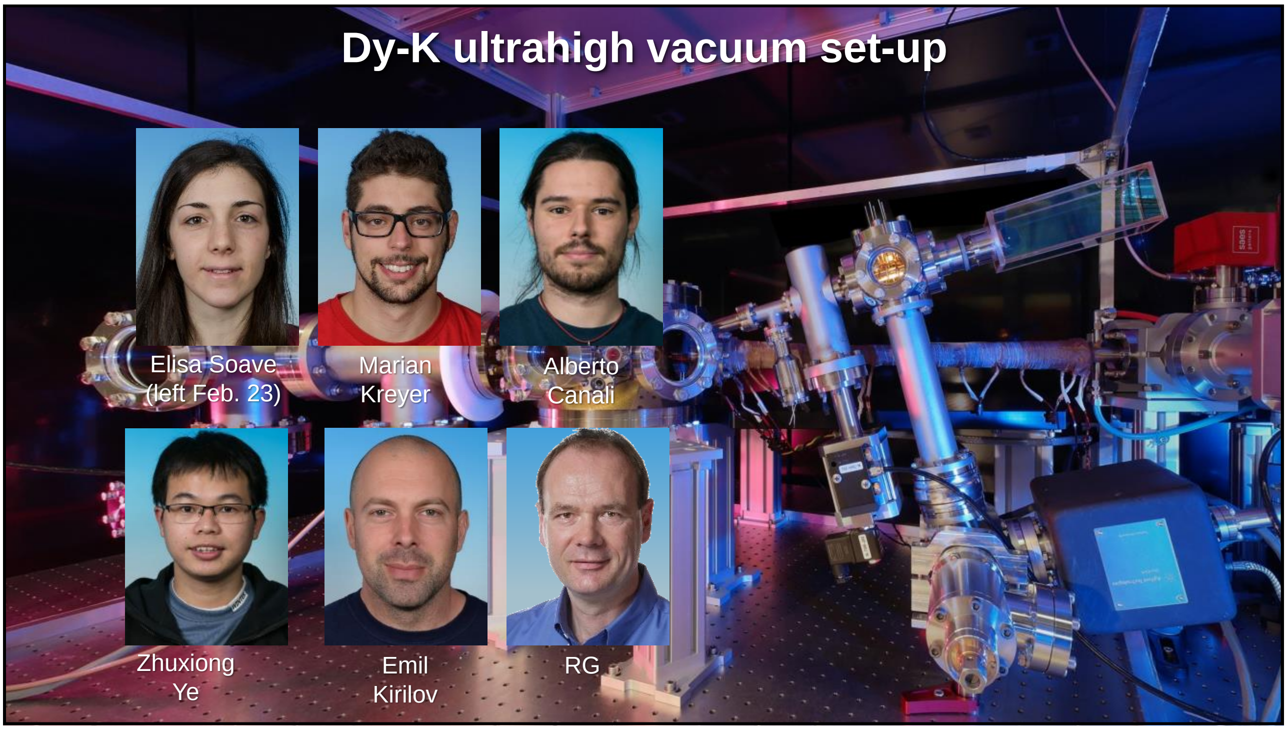
Cooper pair (BCS)

finite momentum pair (beyond BCS)

Fermi sphere

“conventional”
superfluid

“novel” superfluid
our research goal



Dy-K ultrahigh vacuum set-up

Elisa Soave
(left Feb. 23)

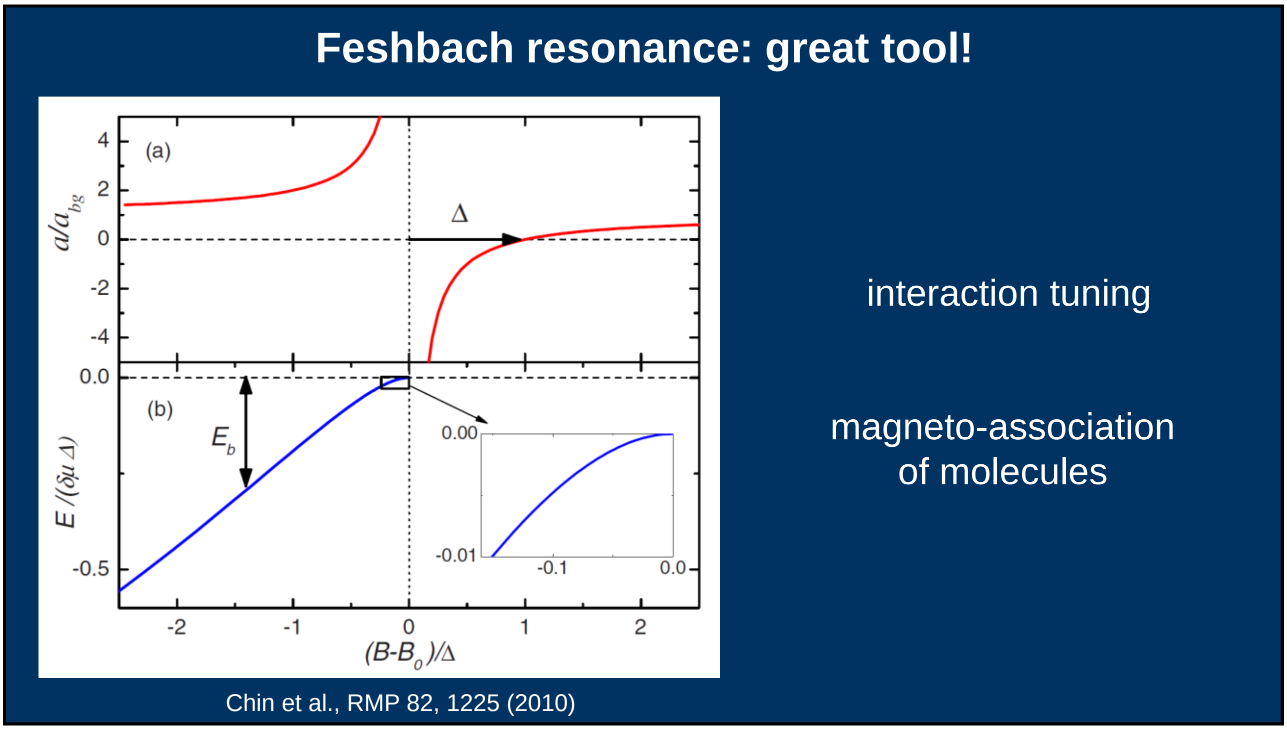
Marian
Kreyer

Alberto
Canali

Zhuxiong
Ye

Emil
Kirilov

RG



Feshbach resonance: great tool!

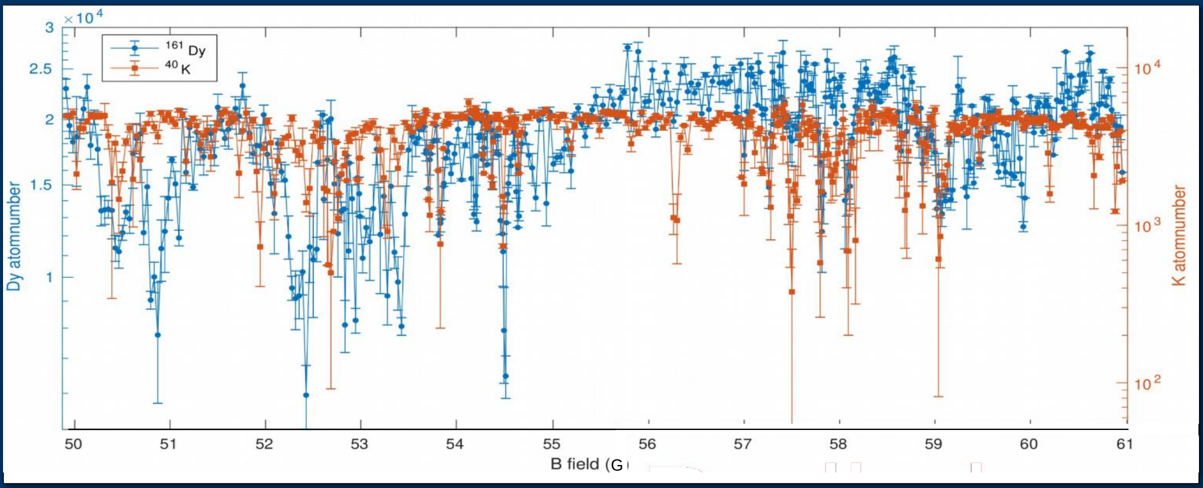
Chin et al., RMP 82, 1225 (2010)

interaction tuning

magneto-association
of molecules

too many resonances!

early B scan (2018)



many narrow intraspecies (Dy) and interspecies (Dy-K) resonances

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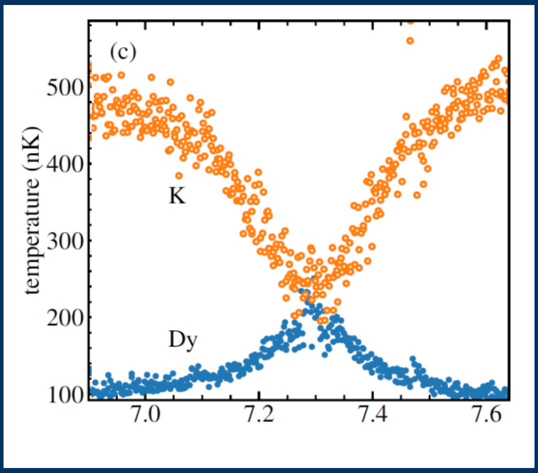
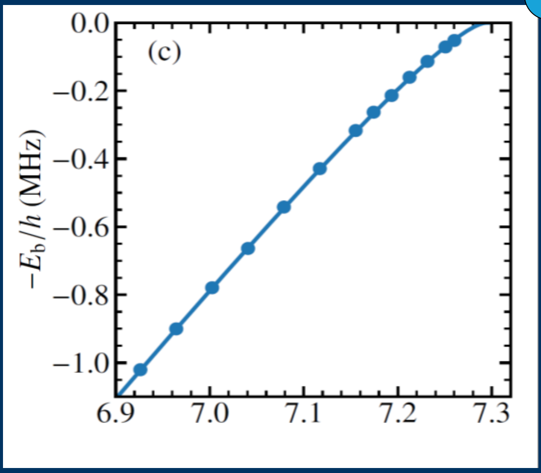
surprise: good FR found near 7.3 G

interspecies thermalization

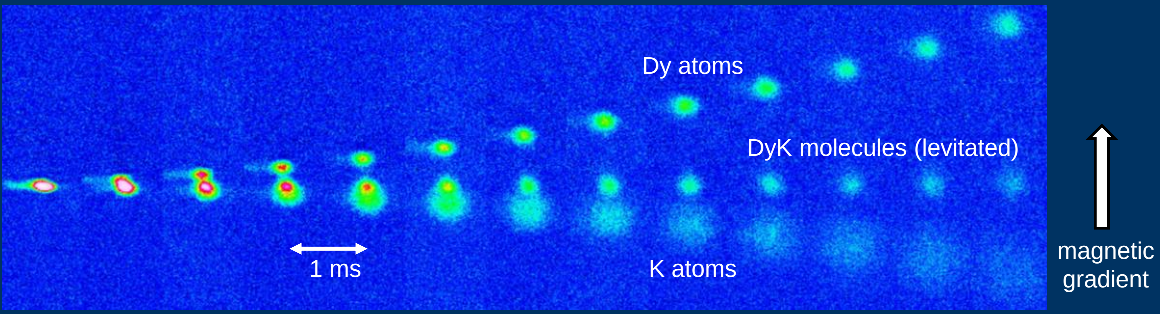


binding energy spectroscopy



Ye et al., PRA 106, 043314 (2022)

formation of molecules on low-field resonance



let‘s go for the next steps:
trap the molecules and go for BEC

Soave et al., arXiv:2204.07921 (2023)

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general conclusion


Enrico Fermi

Ultracold fermions:
a great playground for physics
of strongly interacting many-body systems

many challenges ahead for experiment and theory

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FWF
Der Wissenschaftsfonds.
Doktoratskolleg
ALM
erc