INT Seattle, 16 May 2011

Strongly interacting Fermi-Fermi mixture of ^{6}Li and ^{40}K

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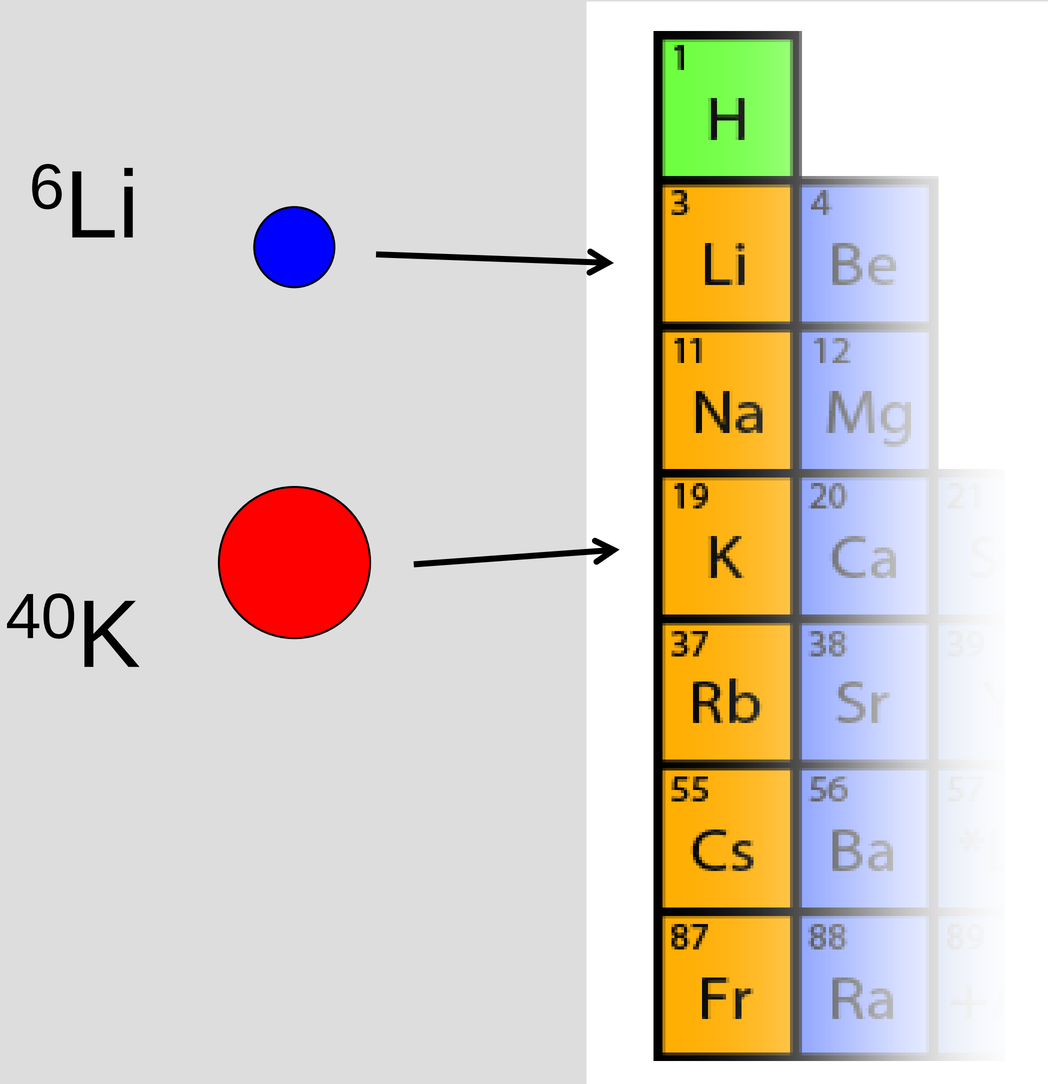
University of Innsbruck

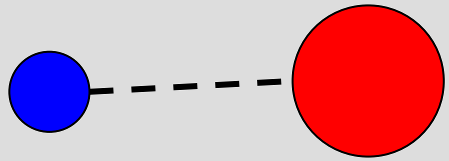
Austrian Academy of Sciences

the ^{6}Li-^{40}K mixture



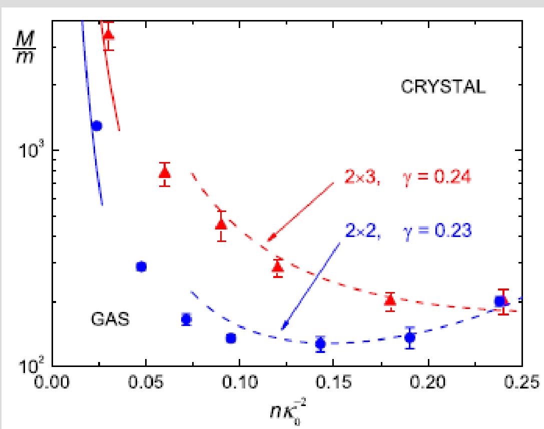
more candidates:
non-alkali species

$^{3}He^{*}$, ^{87}Sr, ^{171}Yb, ^{173}Yb, ^{53}Cr, ^{161}Dy, ^{163}Dy, ^{167}Er



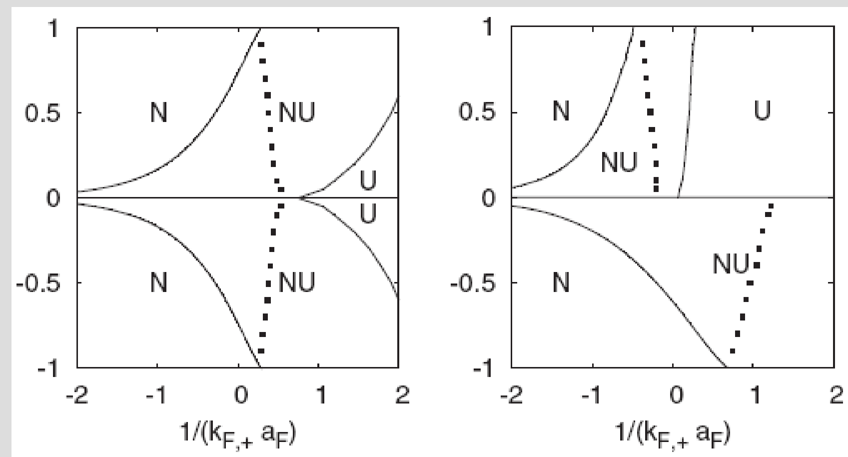
I. mass imbalance

very rich phases



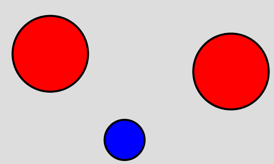
Petrov et al., PRL **99**, 130407 (2007)

crystalline phase



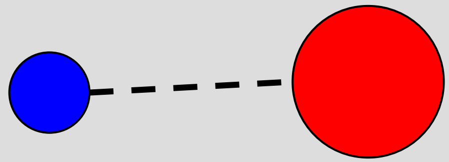
Iskin & Sá de Melo, PRL **97**, 100404 (2006)

novel few-body phenomena



mediated interactions

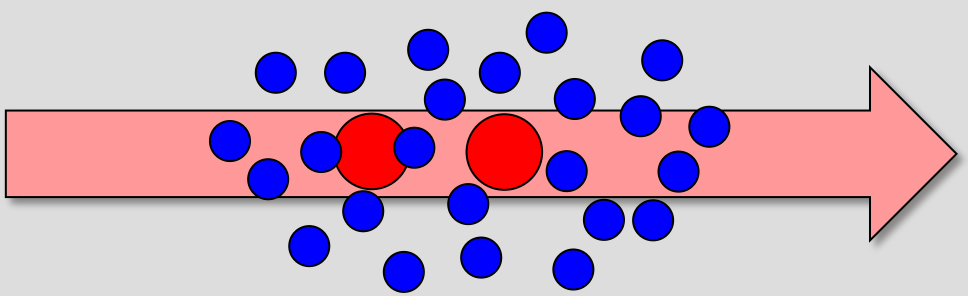
three-body states



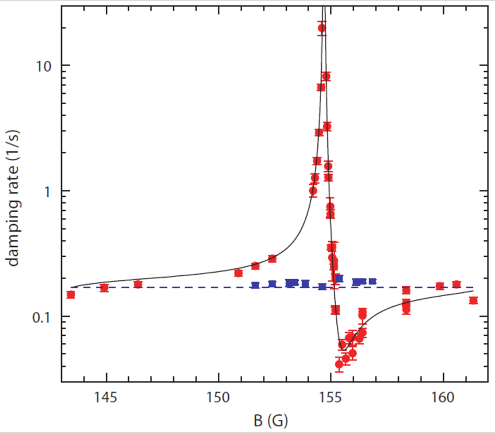
II. trap imbalance

different resonance lines:

species-specific optical potentials



selective manipulation of one component !



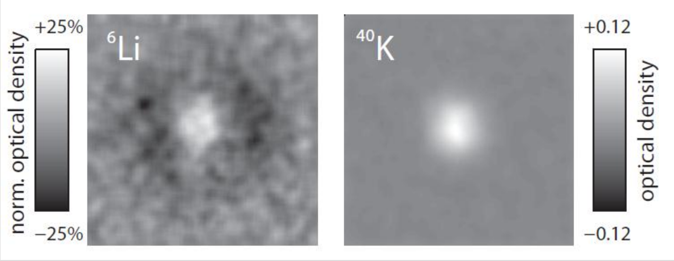
the FFF story: tunability in the mixture

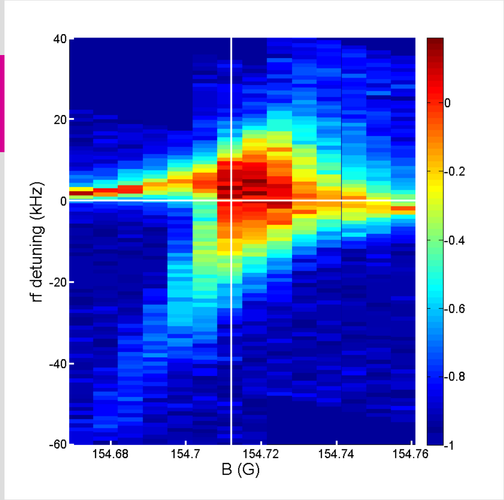
Naik et al., EPJD (2011)

a first step: hydrodynamic expansion

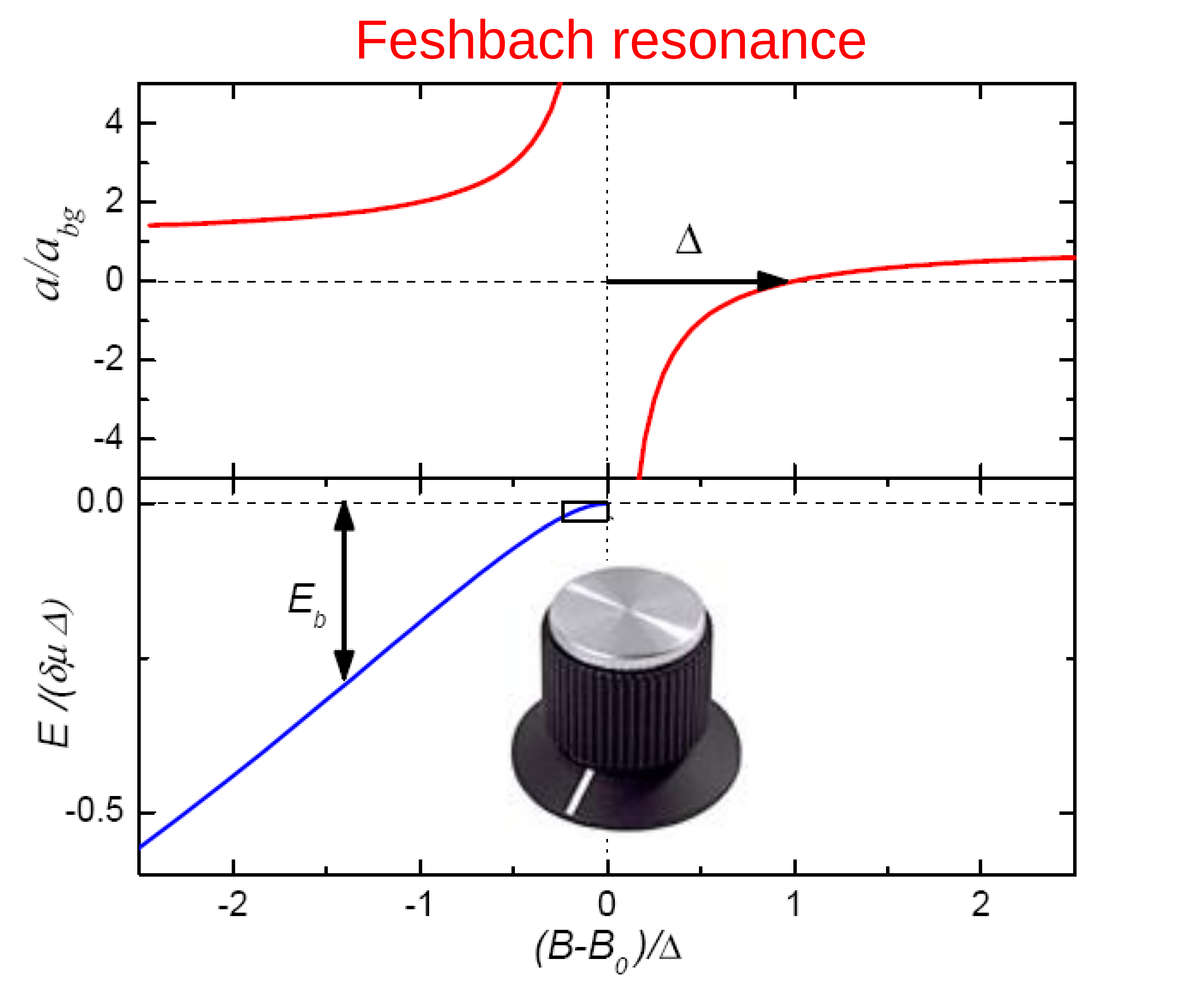
Trenkwalder et al., PRL **106**, 115304 (2011)

more insight: rf spectroscopy





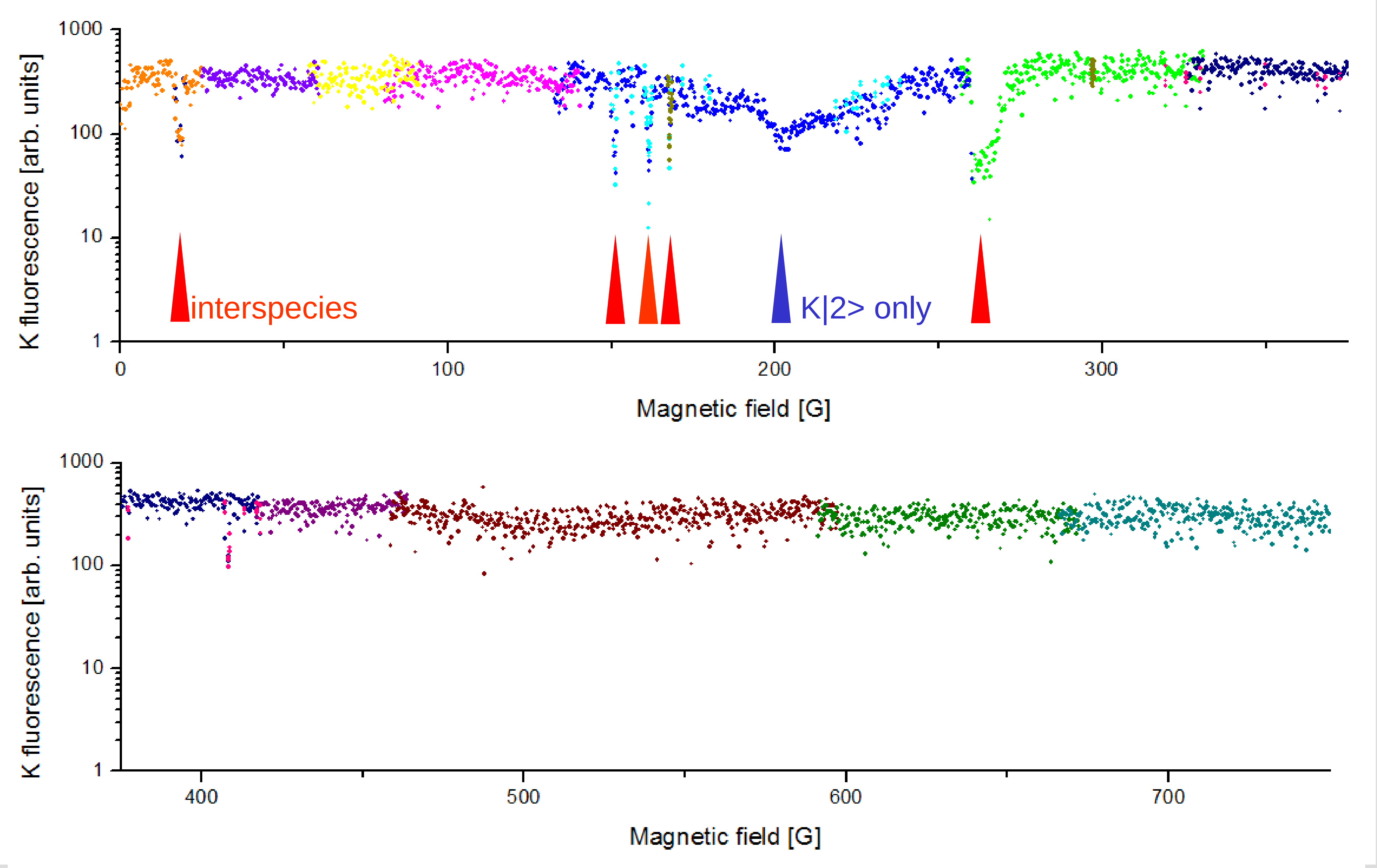
how about tunability?



review: Chin, Grimm, Julienne, Tiesinga, RMP 74, 1205 (2009)

Feshbach spectroscopy: a long story

Wille et al., PRL **100**, 053201 (2008)



the end of a long story

Naik et al., EPJD (2010)

ultracold.atoms

			Experiment			Coupled channels						
Channel	M_{tot}	Group	B_0 (G)	Δ (G)	Ref.	B_0 (G)	Δ (G)	a_{bg}/a_0	$\delta\mu/h$ (MHz/G)	a_{res} (10^6 a_0)	s_{res}	γ_B (μG)
ba	-5	△	215.6		[4]	215.52	0.27	64.3	2.4	160	0.0048	0.11
aa	-4	○	157.6		[4]	157.50	0.14	65.0	2.3		0.0023	0
		◇	168.170(10)		[8]	168.04	0.13	63.4	2.5		0.0023	0
ab	-3	○	149.2		[4]	149.18	0.23	67.0	2.1	14	0.0037	1.1
		□	159.5		[4]	159.60	0.51	62.5	2.4	5.3	0.0086	6.1
		◇	165.9		[4]	165.928	2×10^{-4}	58	2.5	0.3	3.3×10^{-6}	0.04
ac	-2	○	141.7		[4]	141.46	0.25	67.6	2.1	7.5	0.0040	2.3
		□	154.707(5)	0.92(5)	this work	154.75	0.88	63.0	2.3	4.0	0.014	14
		◇	162.7		[4]	162.89	0.09	56.4	2.5	0.89	0.0014	5.7
ad	-1	○				[illegible]	0.24	62.7	2.0	4.5	0.0038	3.7
		□				149.40	1.06	63.8	2.2	3.2	0.017	20
		◇				159.20	0.33	55.8	2.45	1.4	0.0051	13
ae	0	○				127.01	0.22	68.5	2.05	2.8	0.0035	5.4
		□				143.55	1.20	65.7	2.2	2.8	0.020	29
		◇				154.81	0.69	55.1	2.4	1.6	0.010	24
af	1	○				120.33	0.20	66.8	2.1	1.7	0.0031	7.9
		□				137.23	1.19	65.3	2.2	2.2	0.019	35
		◇				149.59	1.14	53.6	2.4	1.6	0.016	37
ag	2	○				114.18	0.14	67.4	2.1	0.97	0.0023	9.7
		□				130.49	1.07	66.4	2.2	1.8	0.018	40
		◇				143.39	1.57	54.4	2.4	1.6	0.023	53
ah	3	○				108.67	0.098	66.6	2.2	0.48	0.0016	14
		□				123.45	0.86	68.4	2.3	1.3	0.015	44
		◇				135.90	1.87	55.9	2.45	1.5	0.029	72
ai	4	○				104.08	0.06	65.9	2.25	0.19	0.0010	21
		□				116.38	0.54	68.6	2.4	0.98	0.010	38
		◇				126.62	1.97	54.7	2.6	1.3	0.032	83
aj	5	○				100.90	0.02	64.3	2.3	0.03	3.2×10^{-4}	43
		◇	114.47(5)	1.5(5)	[7]	114.78	1.81	57.3	2.3	1.08	0.027	96

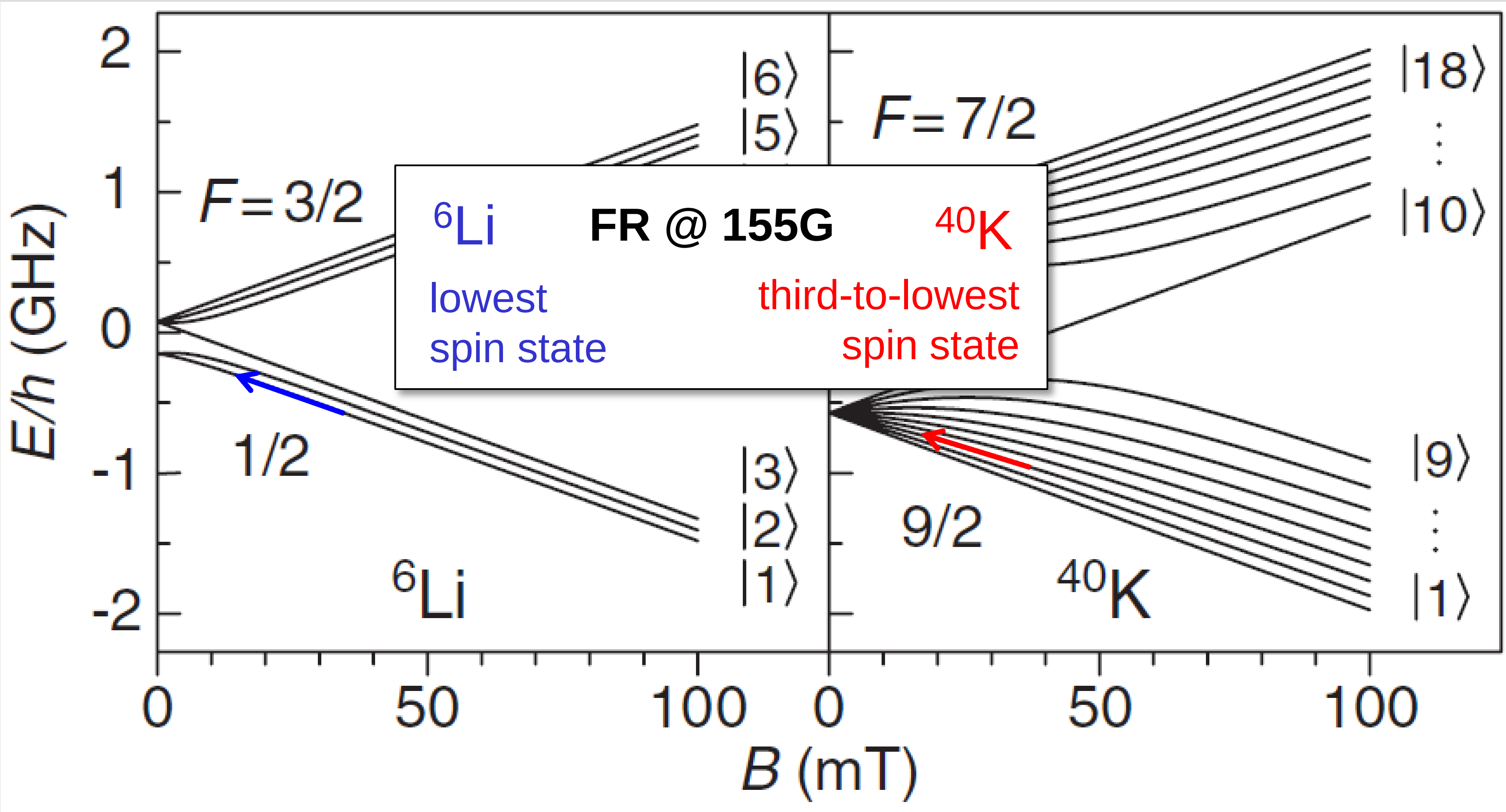
the “optimum” resonance (for us)

theory

Tom Hanna

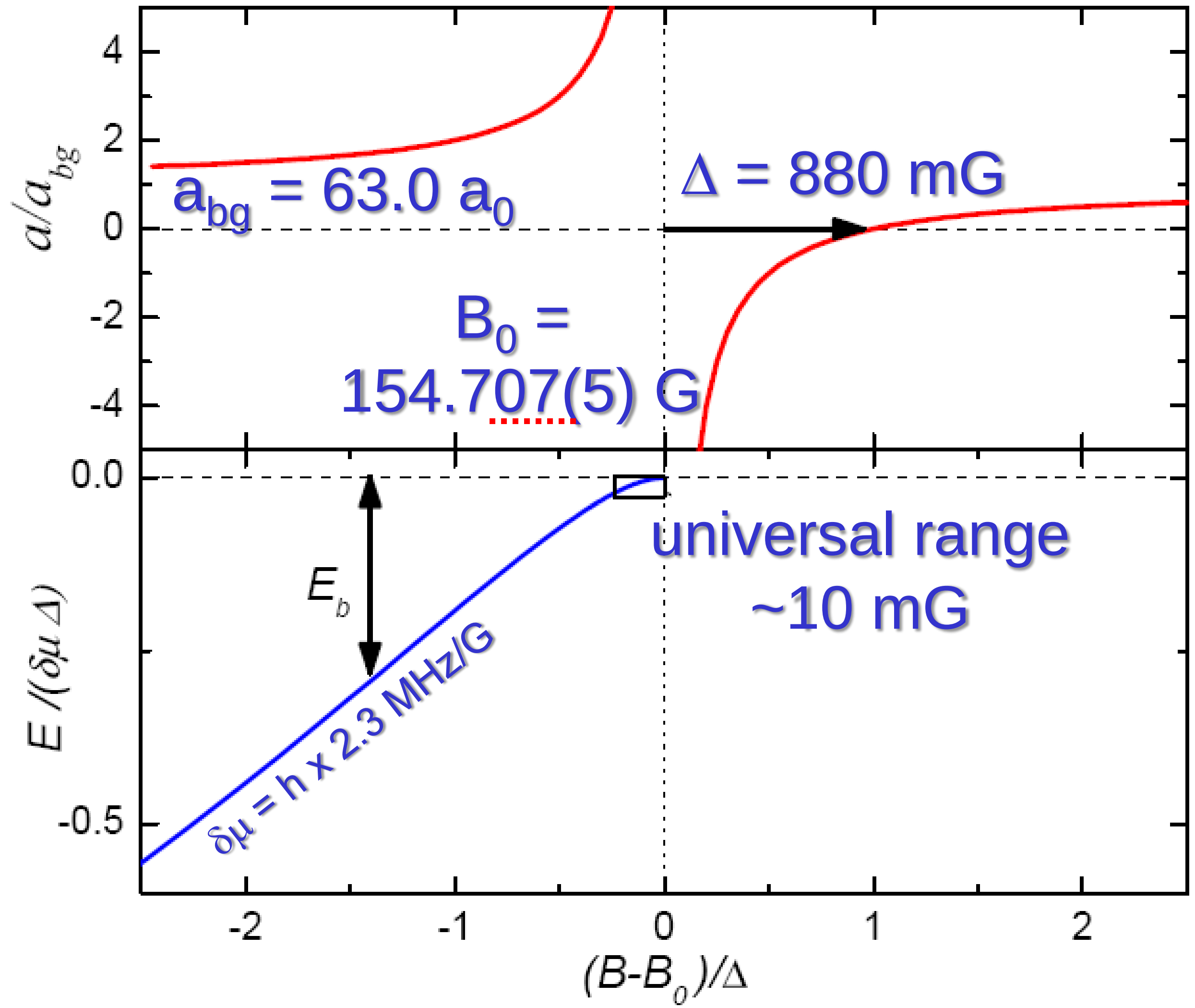
Paul Julienne

related work by Amsterdam-Eindhoven group

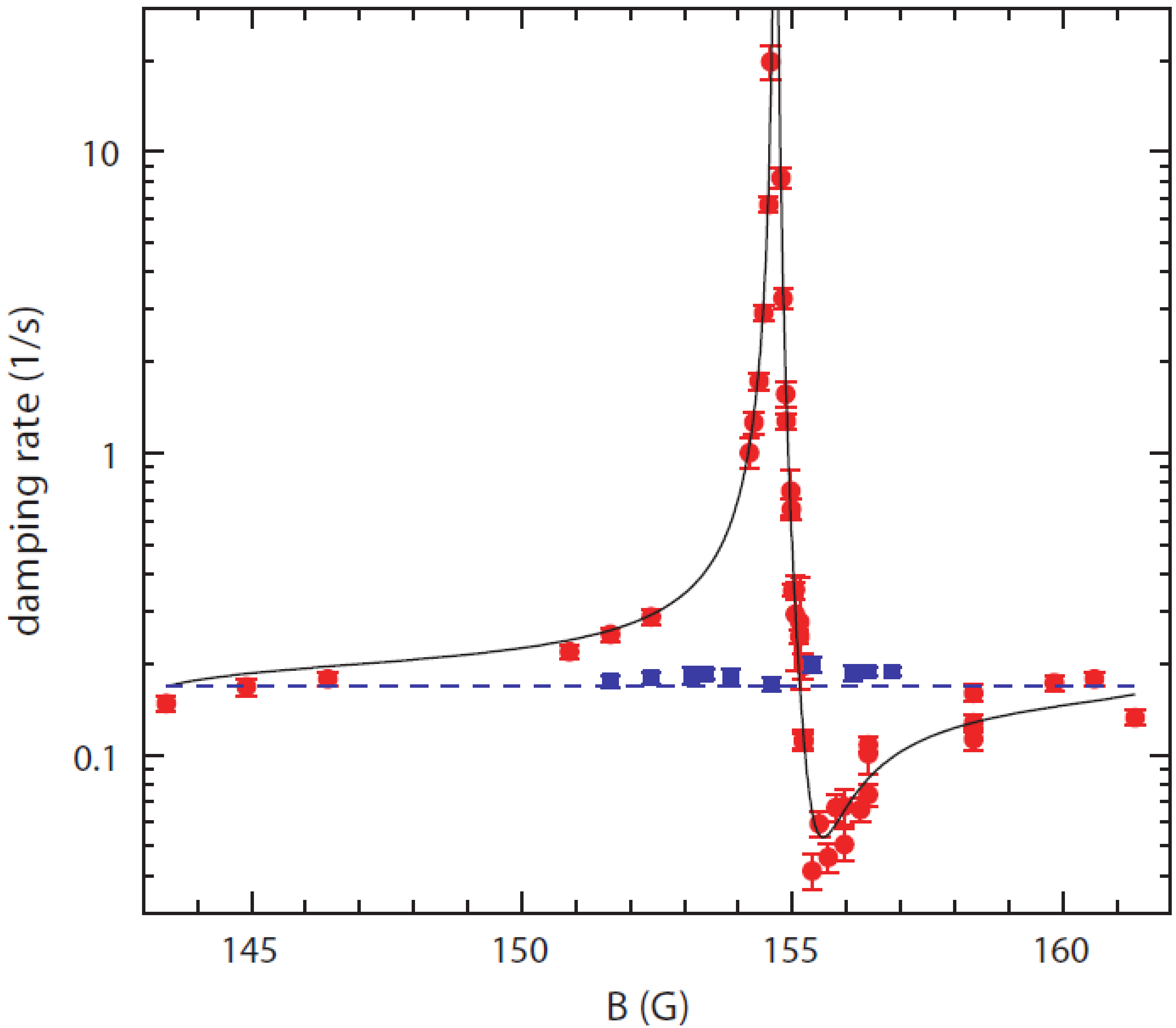


powerful tool-box of radio-frequency transitions

Li-K resonance @ 155 G



elastic scattering



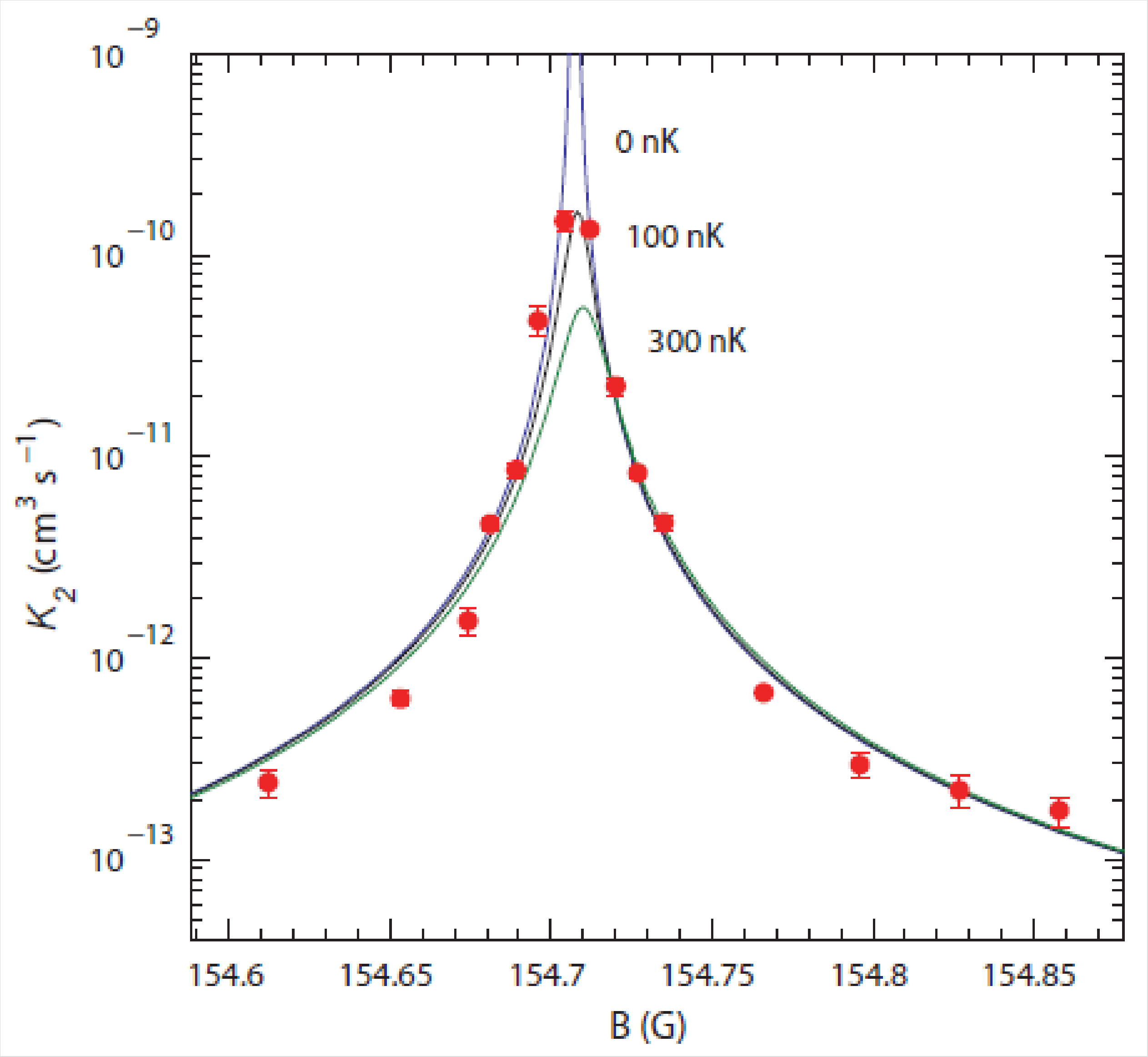
Li – K spin channels

1 – 3

1 – 2

inelastic *two-body* scattering

ultracold.atoms



^{6}Li-^{40}K Feshbach conclusion

- only narrow (i.e. closed-channel dominated) resonances
- best choice (for us):
  155G resonance in 1-3 spin channel
- reasonable universal range: ~10mG

for typical experimental conditions:

- lifetime on resonance: ~10ms
- strongly interacting regime ±15mG

OK for experiments in strongly interacting regime

Observation of a Strongly Interacting Degenerate Fermi Gas of Atoms

K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, J. E. Thomas*

Science **298**, 2179 (2002)

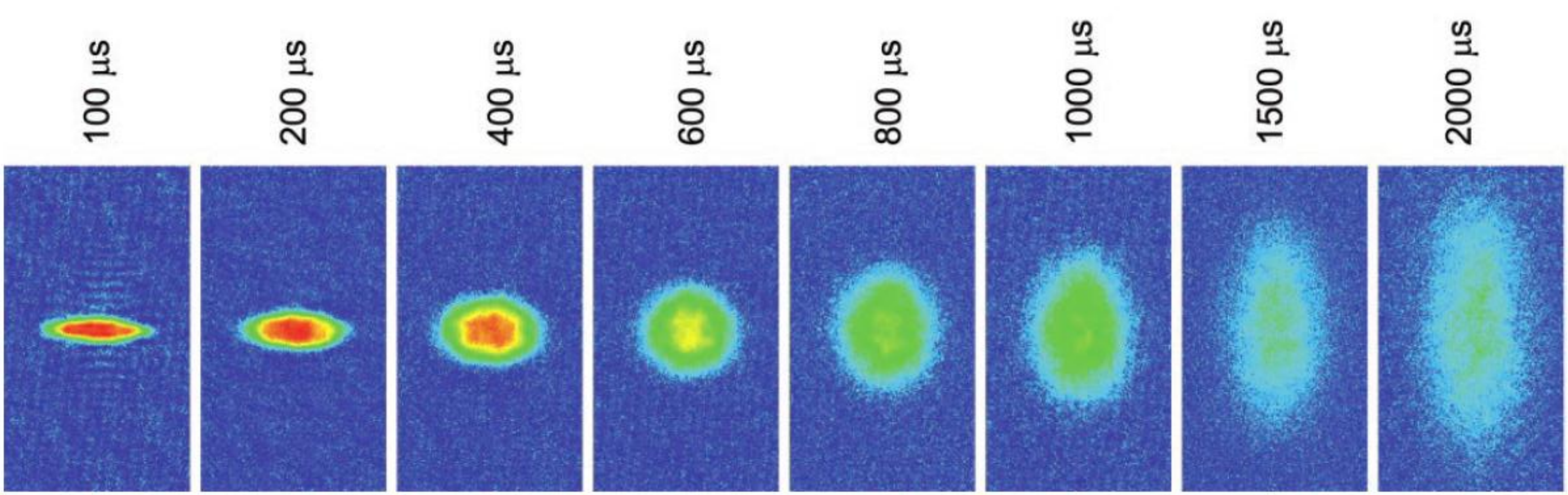


Fig. 1. False-color absorption images of a strongly interacting, degenerate Fermi gas as a function of time t after release from full trap depth for $t = 0.1$ to 2.0 ms, top to bottom. The axial width of the gas remains nearly stationary as the transverse width expands rapidly.

hydrodynamic expansion

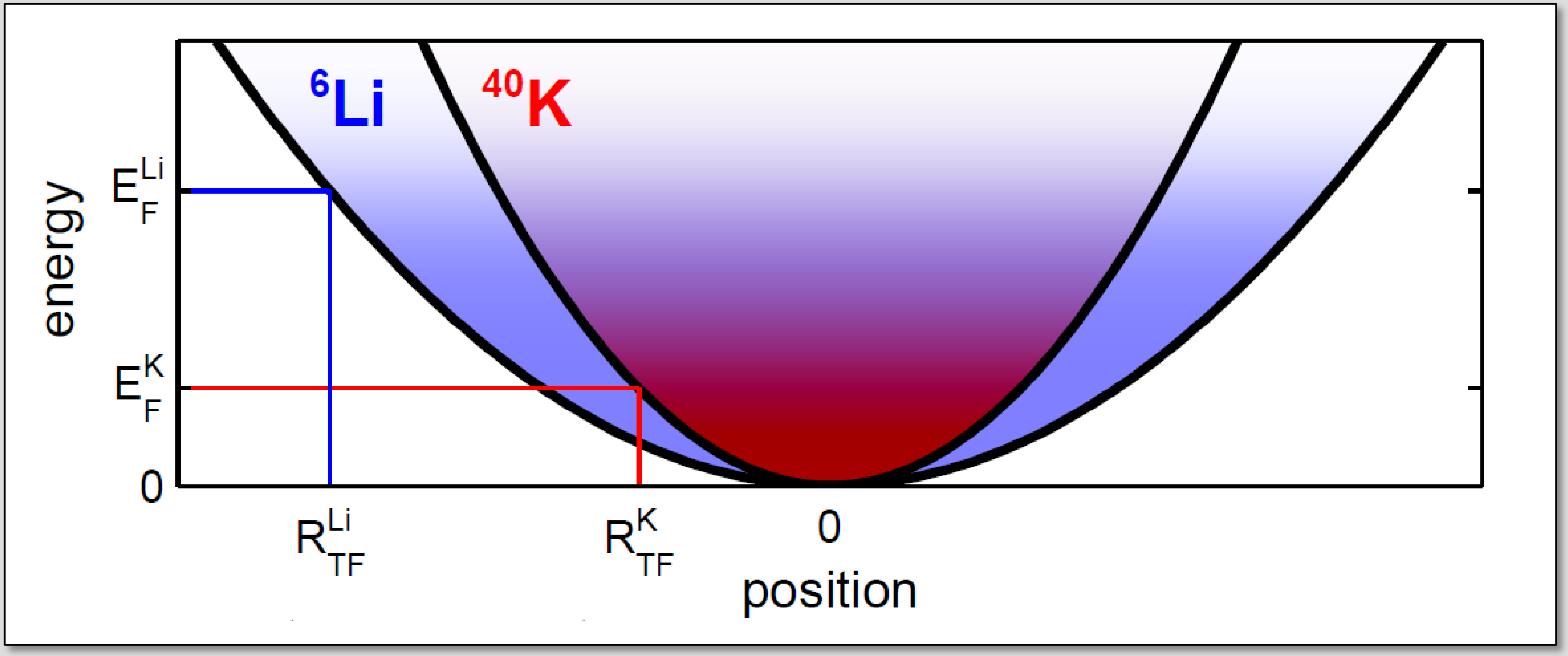
first signature of strongly interacting regime

our experimental situation

^{6}Li: N = 7.5 x 10^4
E_F = 1.1 µK

^{40}K: N = 1.5 x 10^4
E_F = 500 nK

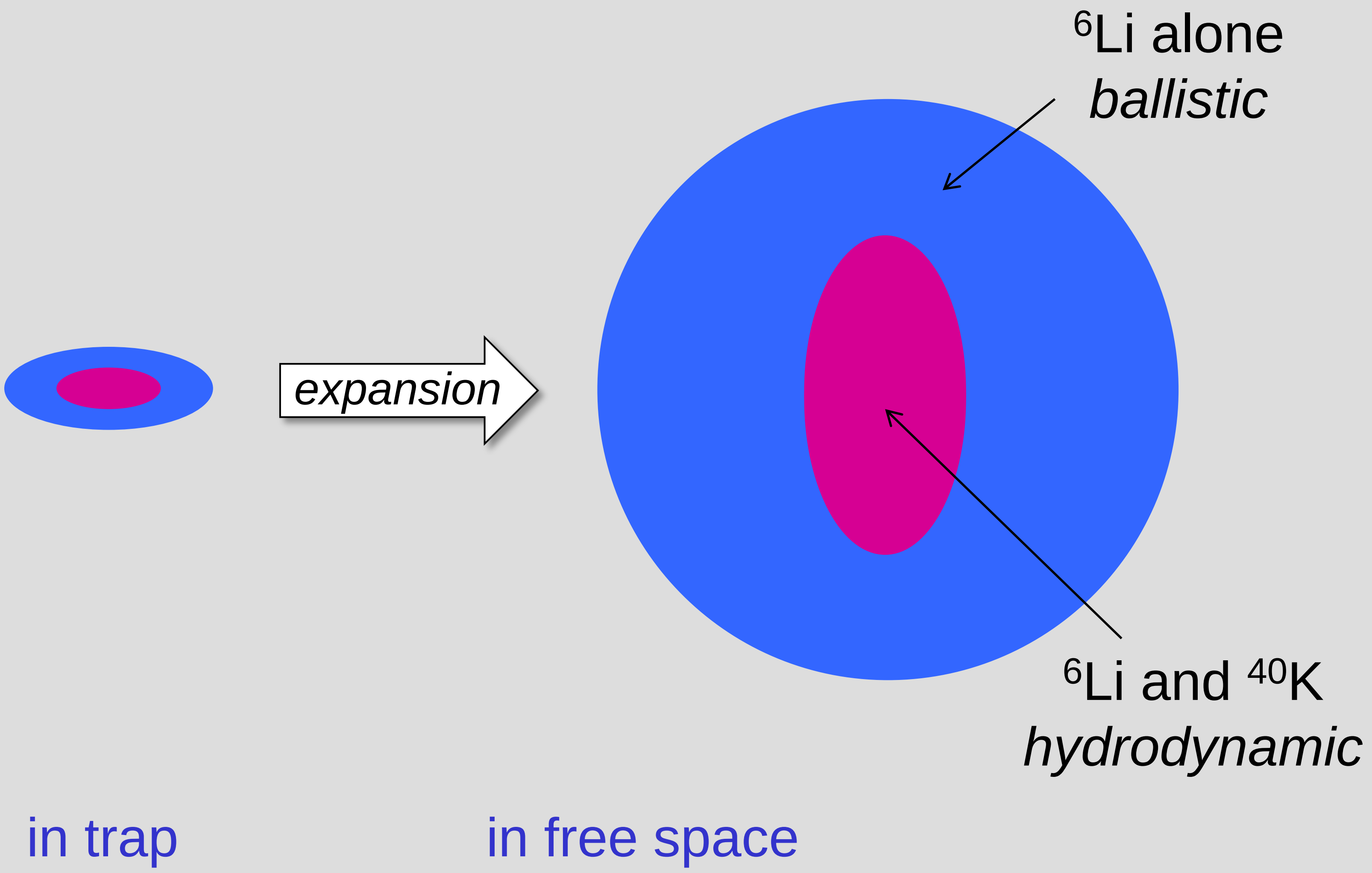
T = 300 nK



Li Fermi energy
our leading energy scale!

$1/k_F^{Li} \approx 3600\ a_0$

what we may expect



preparation of the strongly interacting mixture

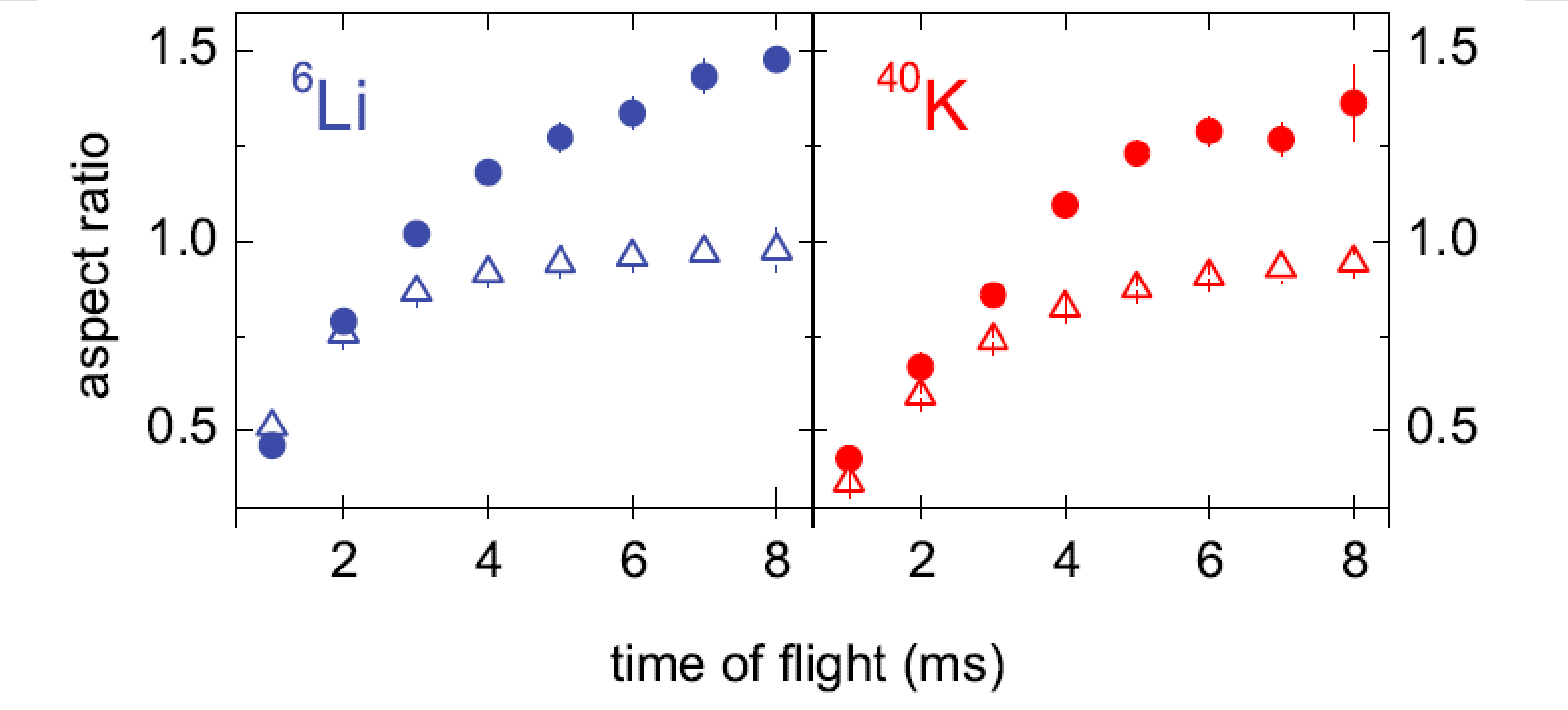
need precise tuning with minimum losses

- start in weakly interacting spin channel (Li 1 - K 2)
- precisely set magnetic field
- immediate rf-transfer (K 2 -> K 3)

> strongly interacting mixture
> with density distributions defined by non-interacting case

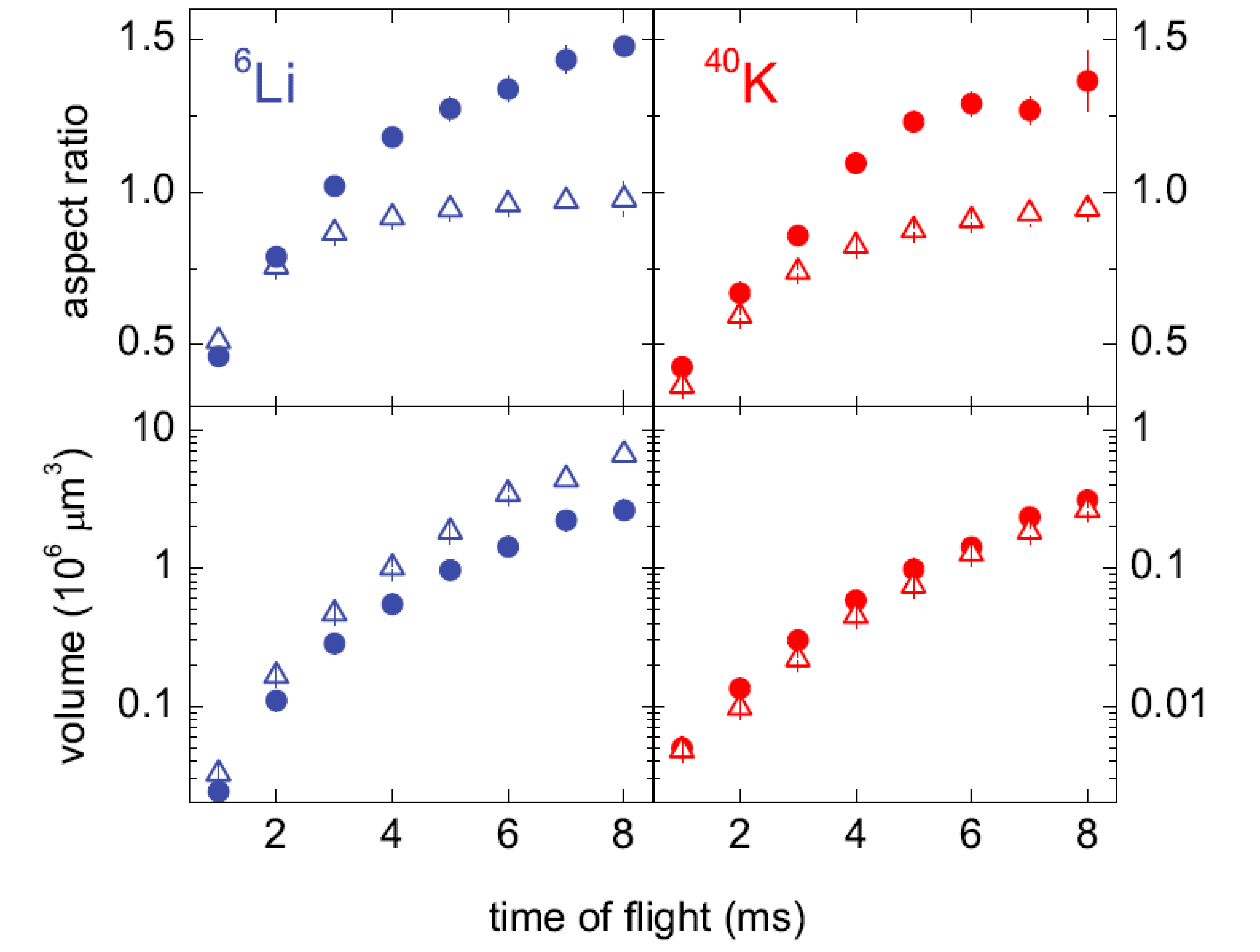
- do experiments without any further delay
  (e.g. immediate release frome trap)

results



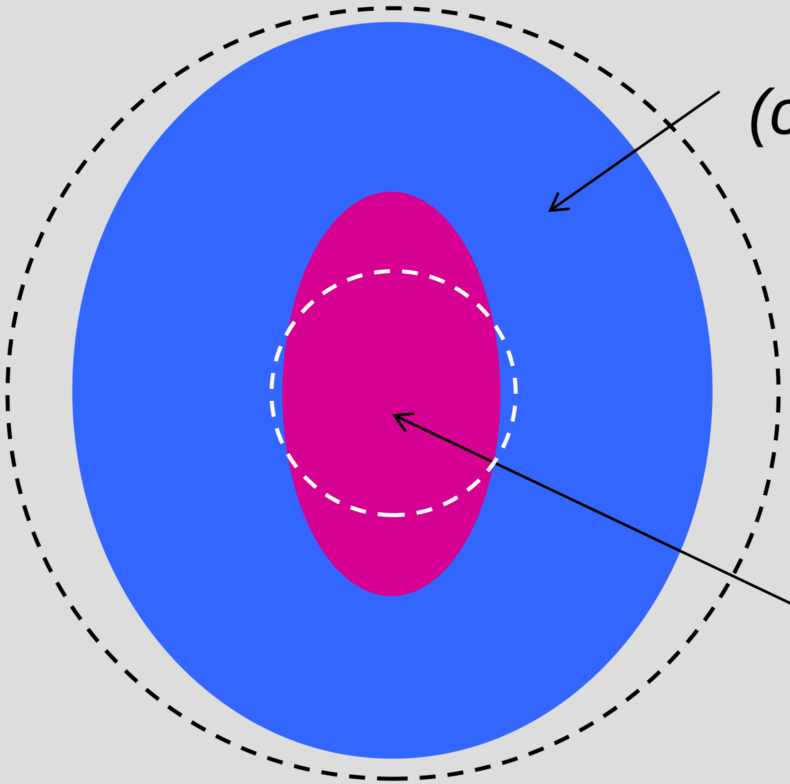
inversion of aspect ratio!

results



aspect ratio
volume (10^6 µm^3)
^{6}Li
^{40}K
1.5
1.0
0.5
10
1
0.1
0.01
2
4
6
8
time of flight (ms)

hydrodynamic interactions



volume occupied by ^{6}Li (^{40}K) decreases (increases):
"hydrodynamic drag"

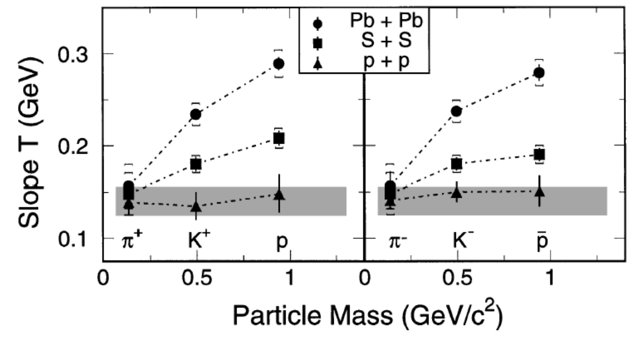
intriguing analogies

ultracold quantum gases (Fermi-Fermi mixtures) | high-energy physics (quark-gluon plasma)

"anisotropic expansion" | *"elliptic flow"*

new analogy

"hydrodynamic drag" | *"collective flow"*

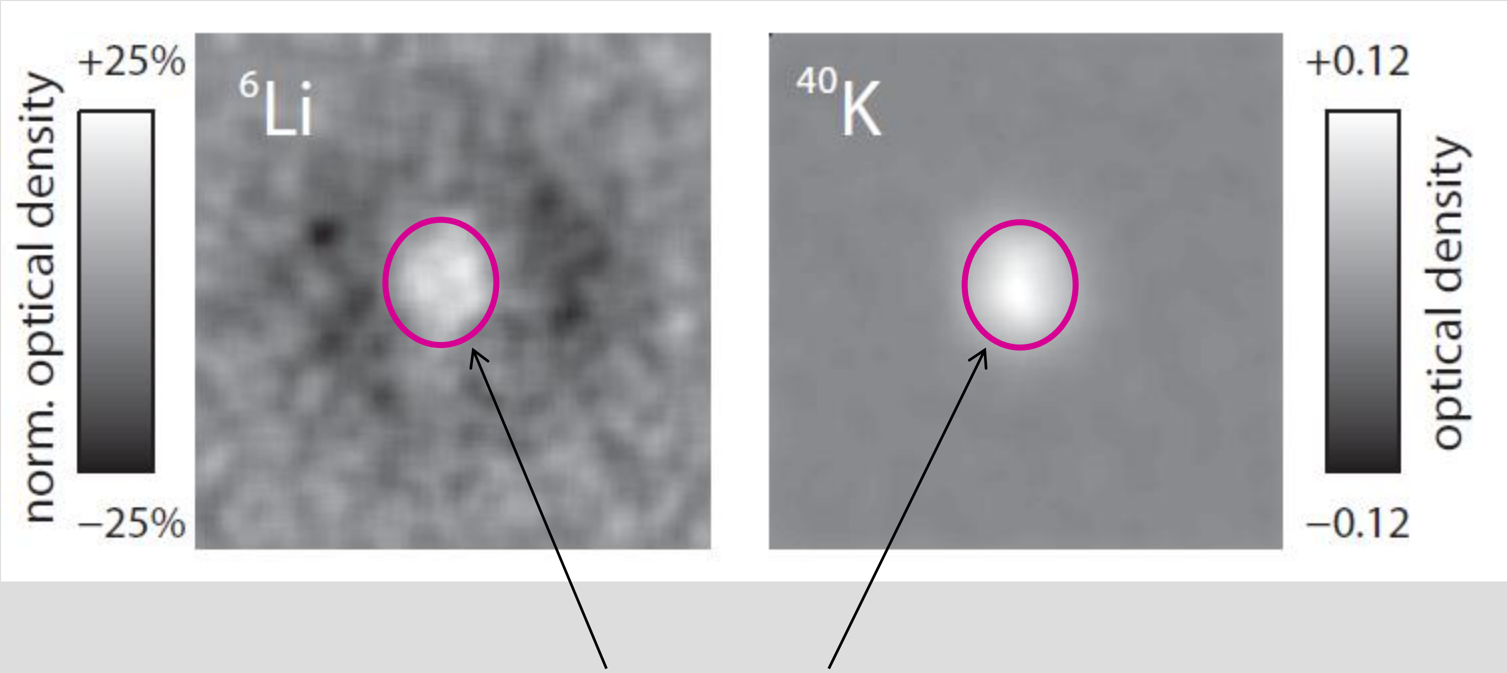


NA44 collaboration, PRL 78, 2080 (1997)

can we image the hydrodynamic core?

differential
^{6}Li image

normal
^{40}K image

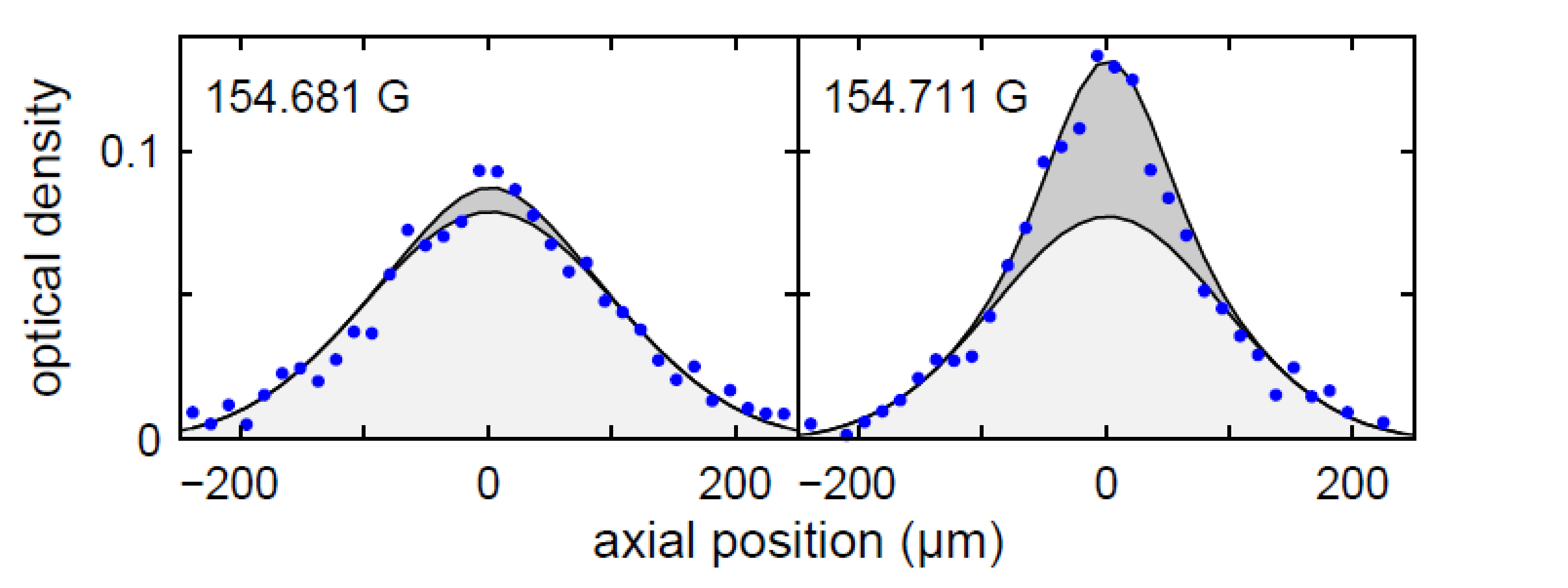


hydrodynamic core

bimodal distributions of ^{6}Li

~25 mG away

on resonance



how does all this
depend on the interaction strength?

$1/(k_F^{Li}\,|a|) > 1 \Rightarrow$

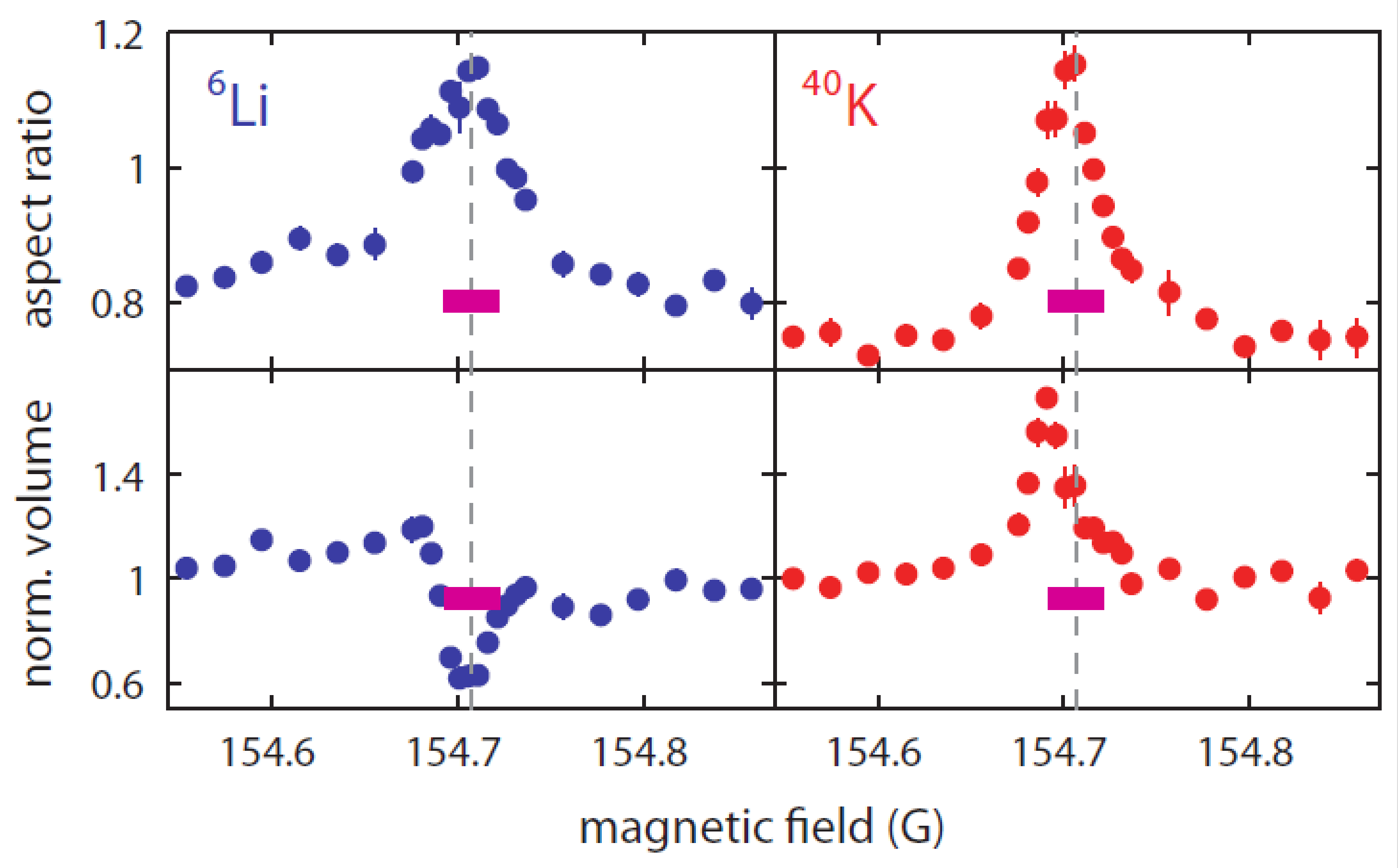
$|a| > 3500\ a_0$

$|B-B_0| < 15\ \text{mG}$

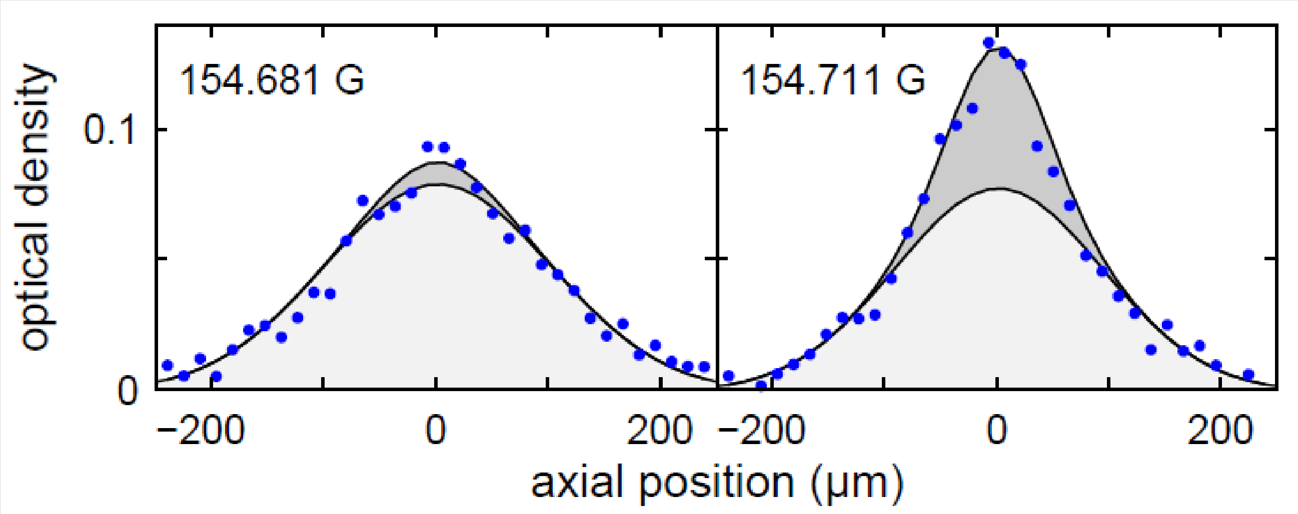
condition for strong interaction

expansion vs. interaction strength

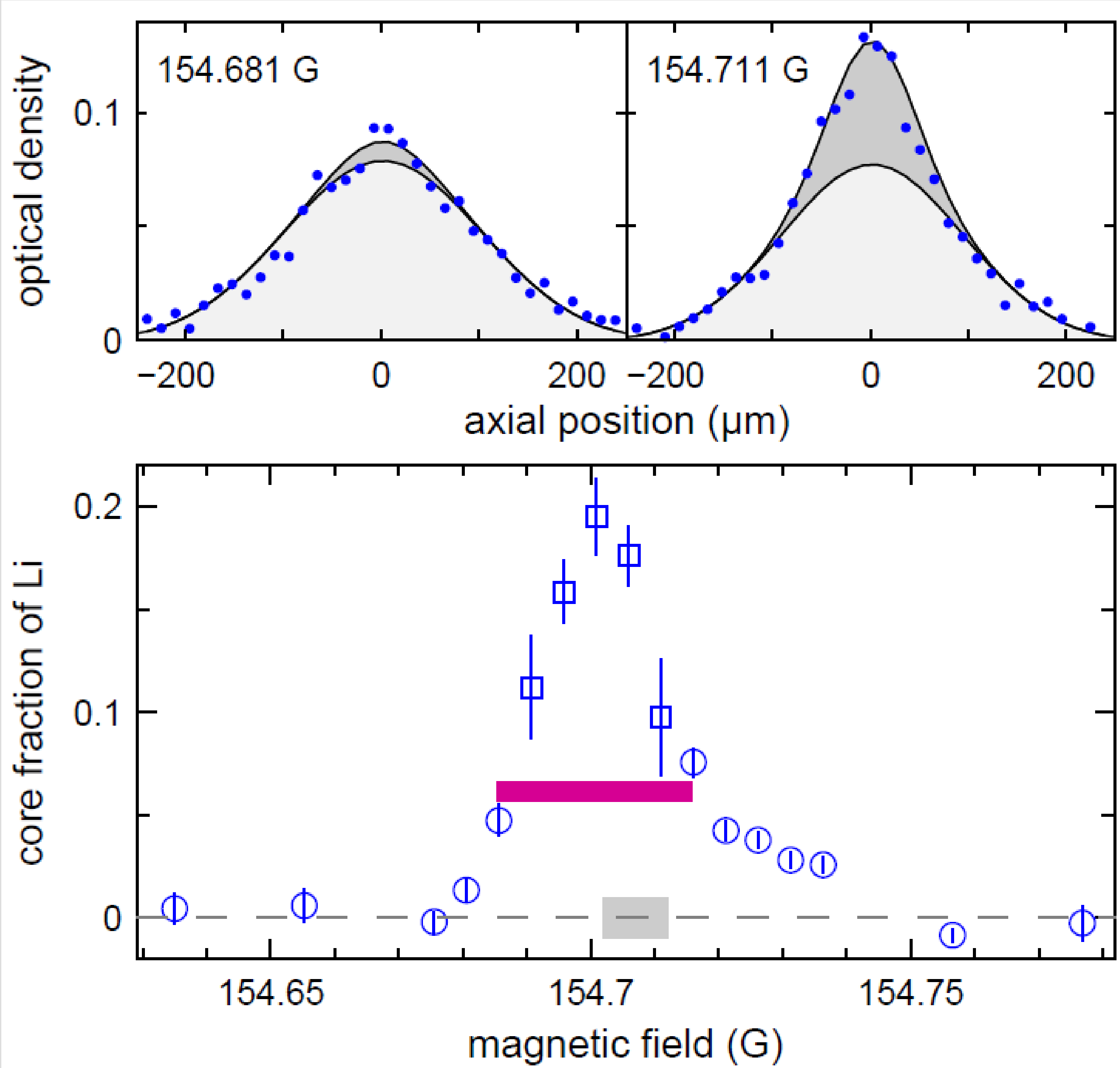
fixed TOF 4ms, variable B



bimodal distributions



bimodal distributions



interim conclusion (March 2011)

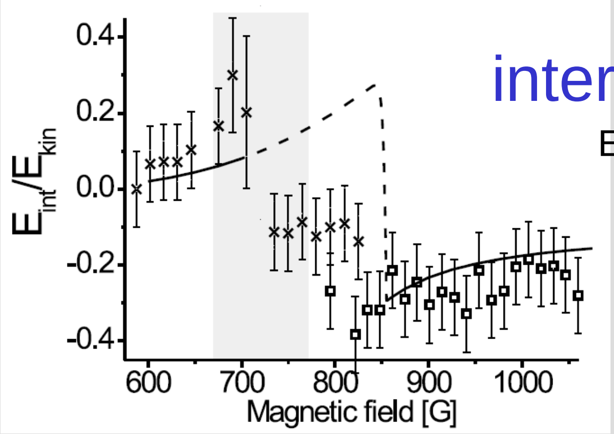
Trenkwalder et al., PRL **106**, 115304 (2011)

first observation of a strongly interacting Fermi-Fermi mixture

high level of interaction control demonstrated

experiments on short timescale (few ms) possible without suffering from losses

... from single-species fermion experiments

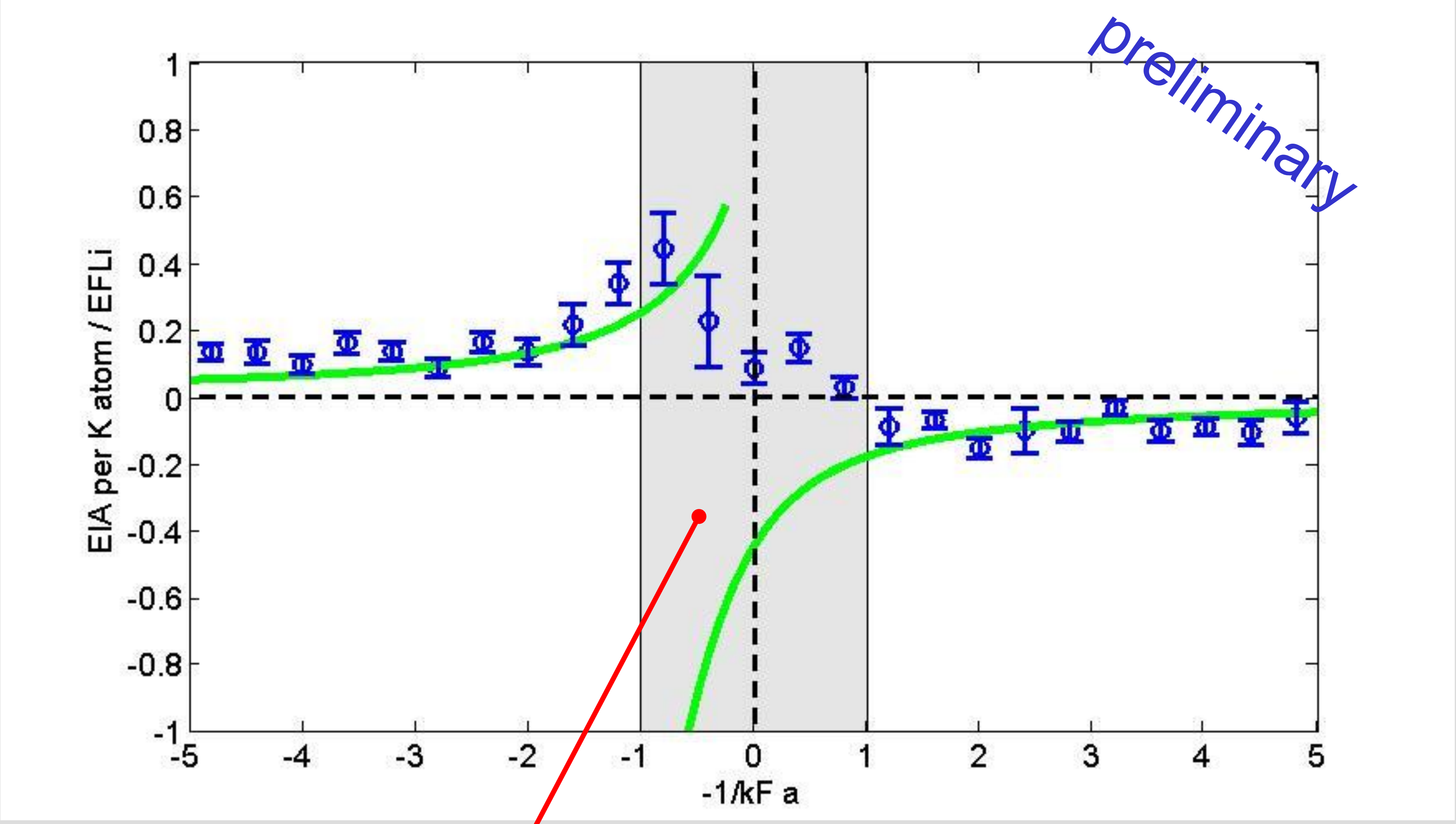


interaction energy

ENS Paris (2003)

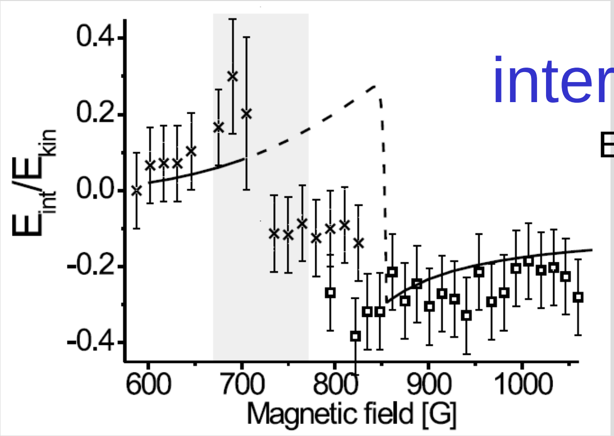
interaction energy measurement

analyzing the expanding clouds (quite involved...)



what kind of state is produced by the rapid rf quench?

... from single-species fermion experiments

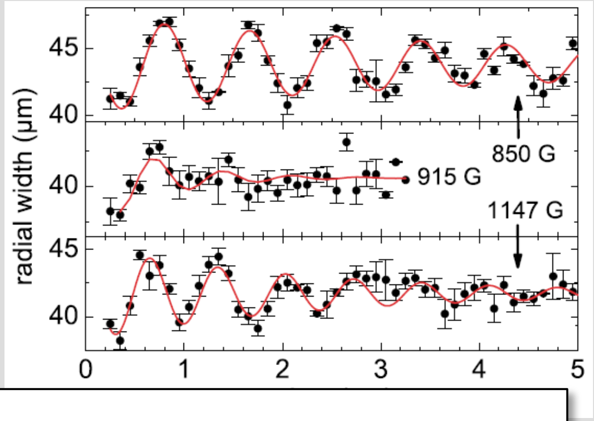


interaction energy

ENS Paris (2003)

collective modes

Duke, Innsbruck (2004)

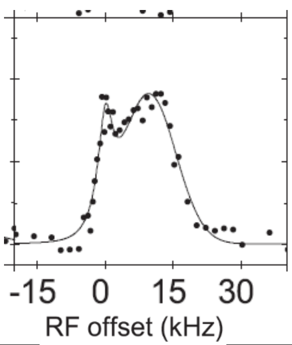


mBEC

Innsbruck, Boulder, MIT (2003)

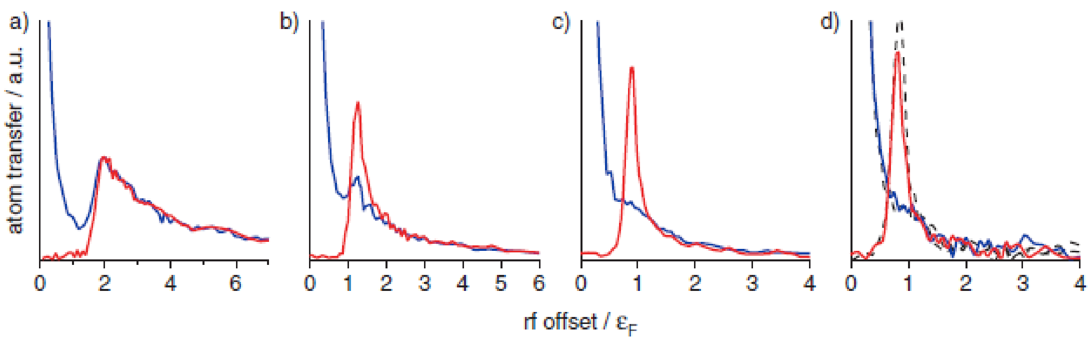
rf spectroscopy

Innsbruck (2004), Boulder, MIT



Fermi polarons

MIT (2009)

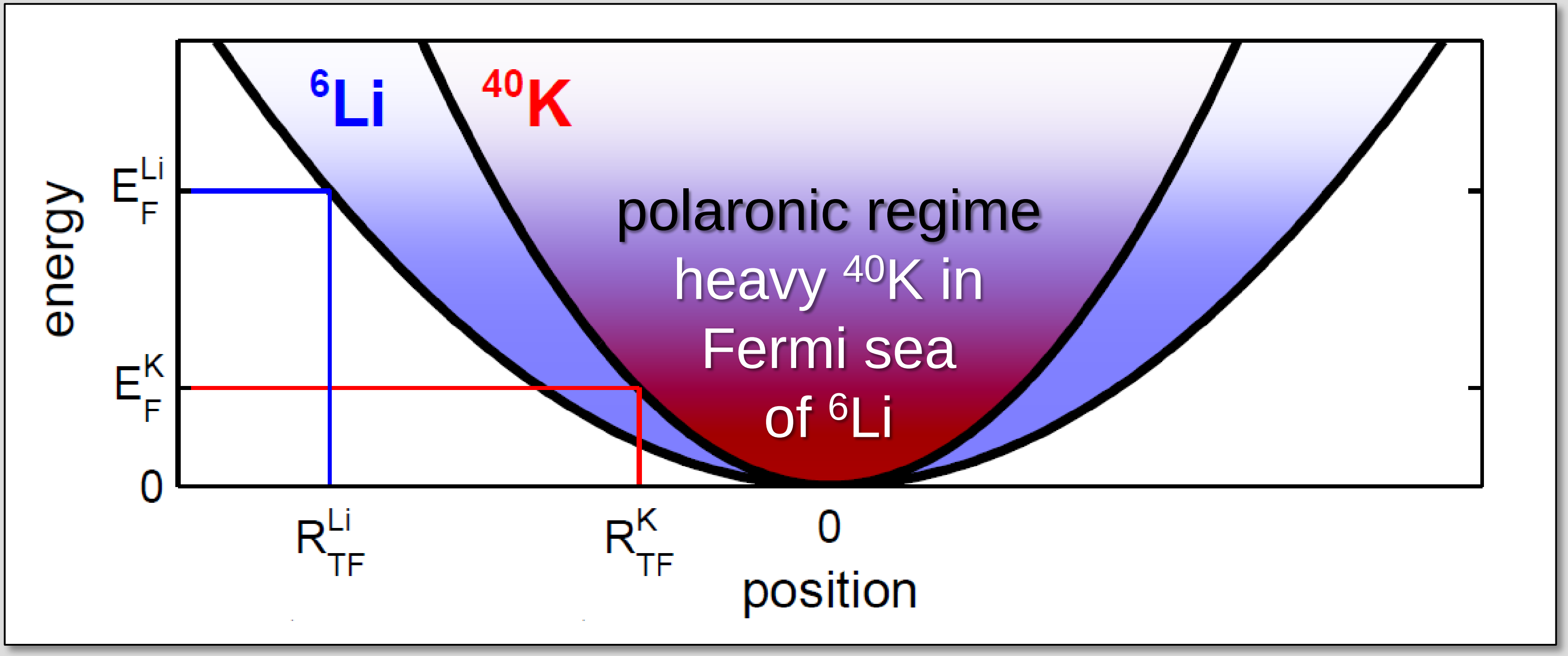


our experimental situation (rf spectroscopy)

^{6}Li: N = 1.9 x 10^5
E_F = 1.6 μK

^{40}K: N = 1.2 x 10^4
E_F = 400 nK

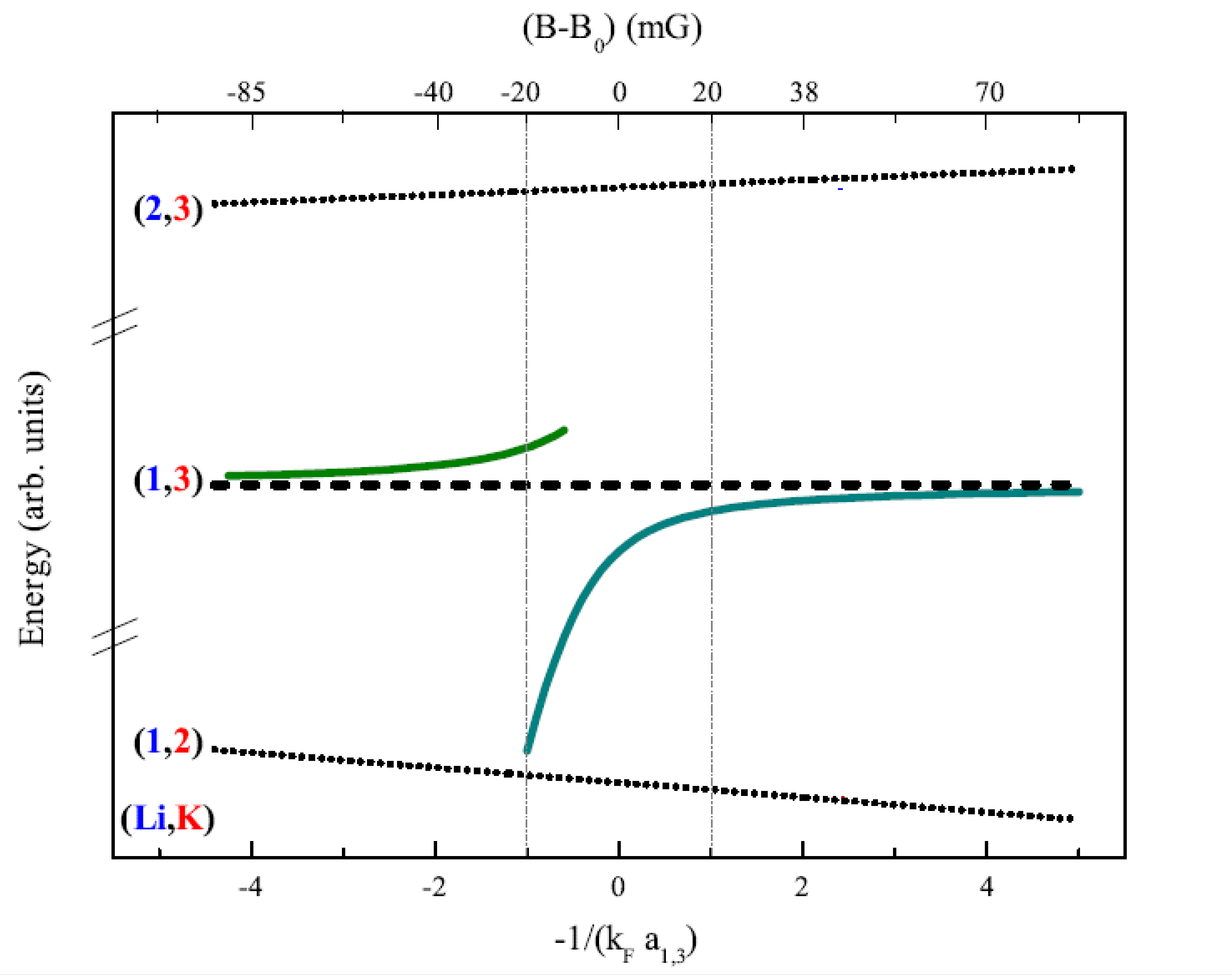
T = 330 nK



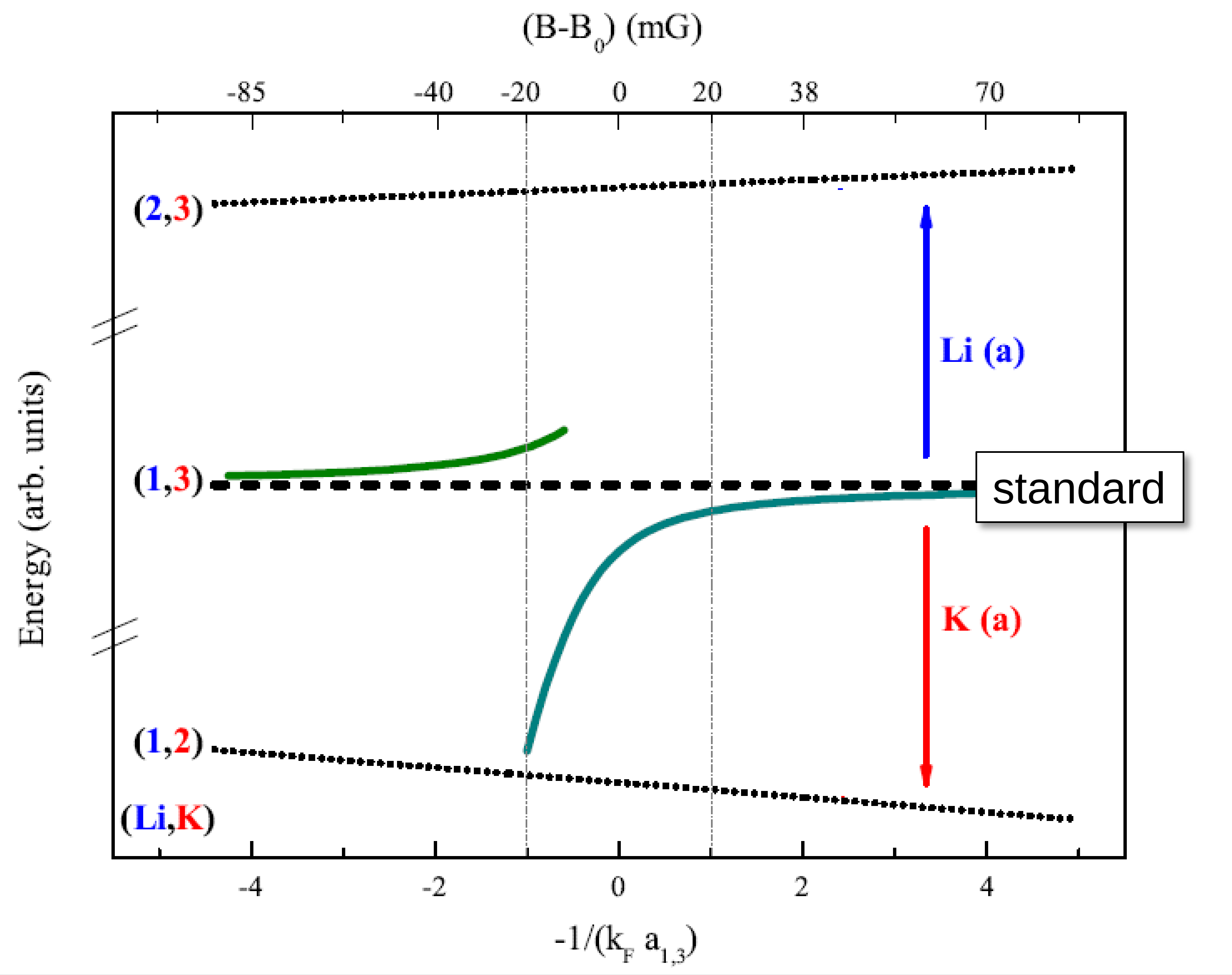
Li Fermi energy
our leading energy scale!

$1/k_F^{Li} \approx 3000\ a_0$

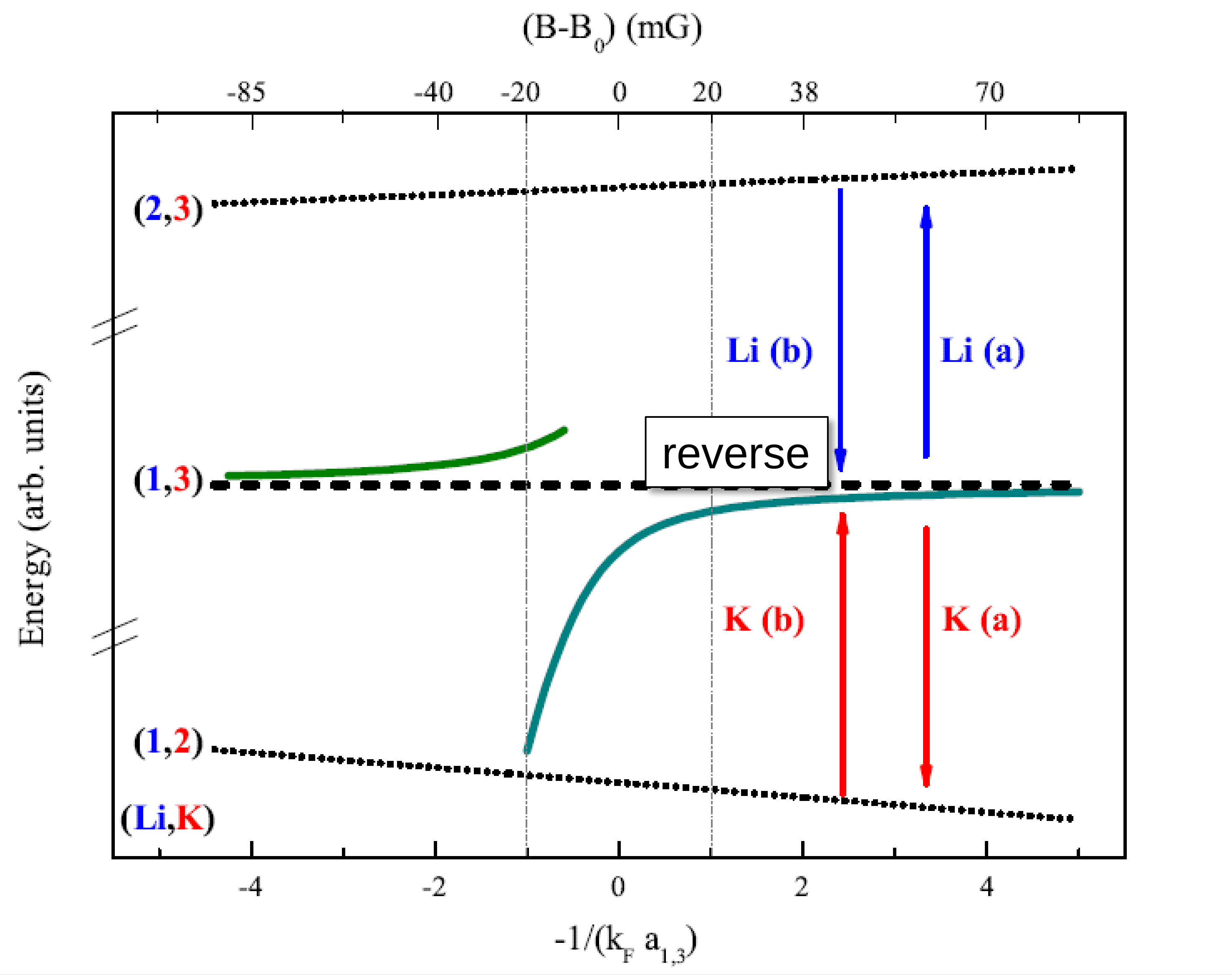
probing the system by rf spectroscopy



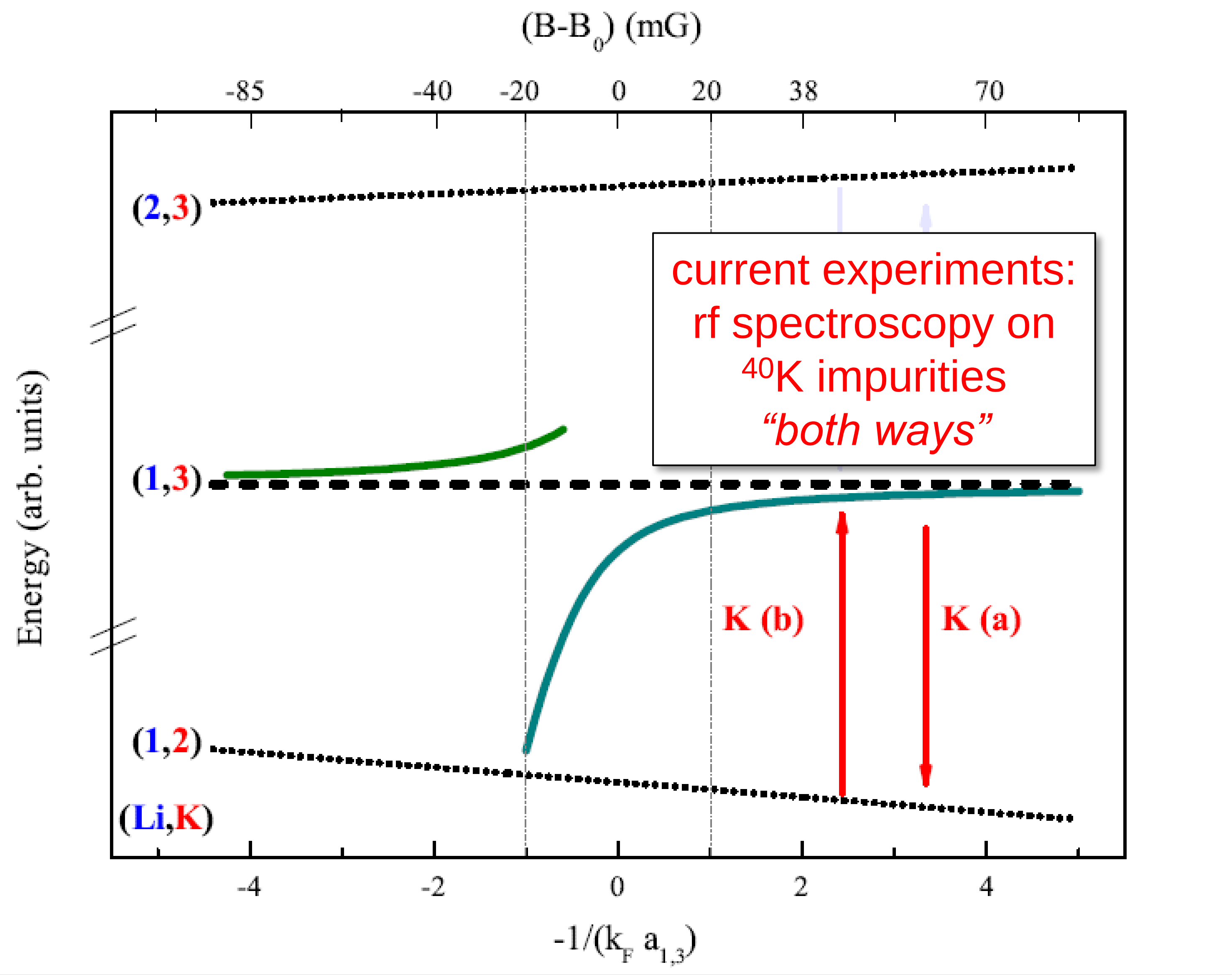
four ways of doing rf spectroscopy



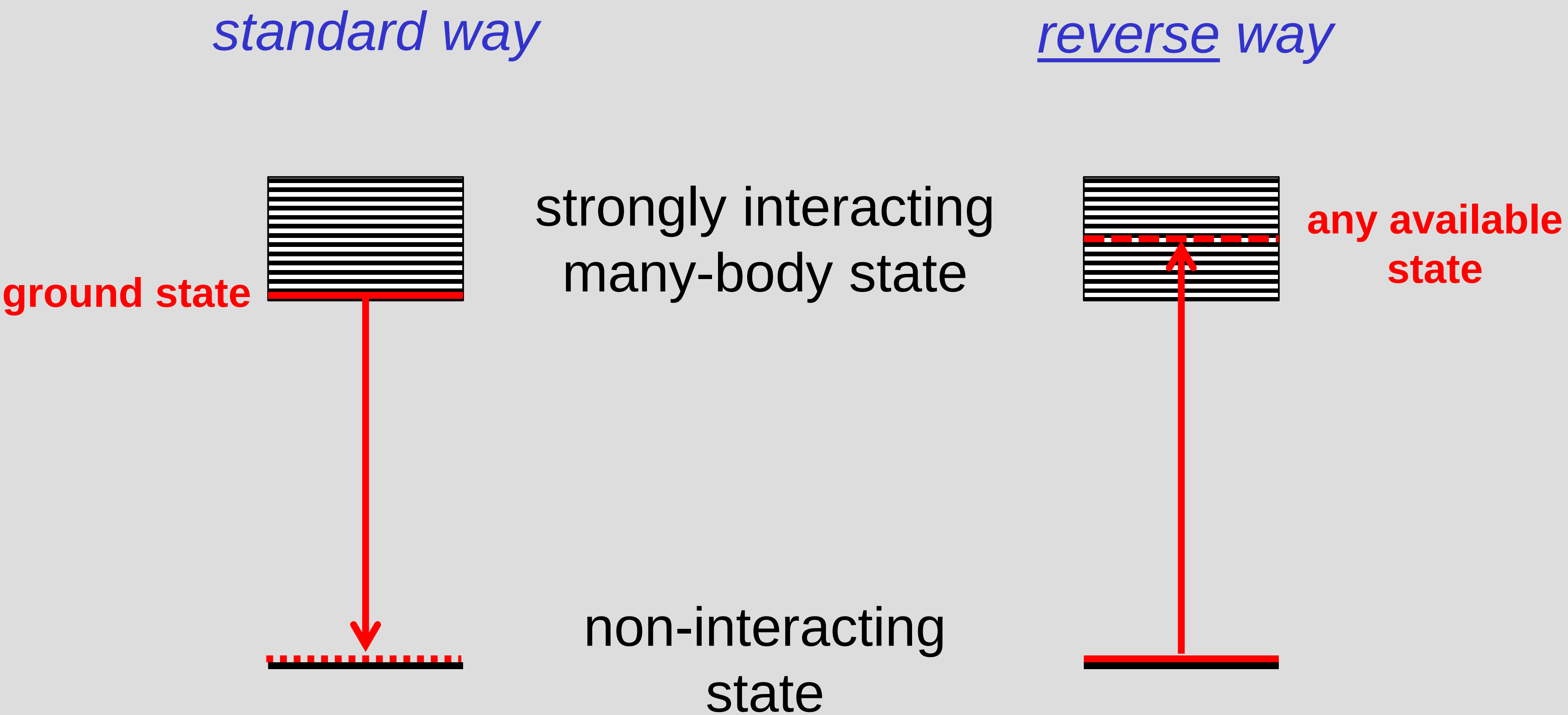
four ways of doing rf spectroscopy



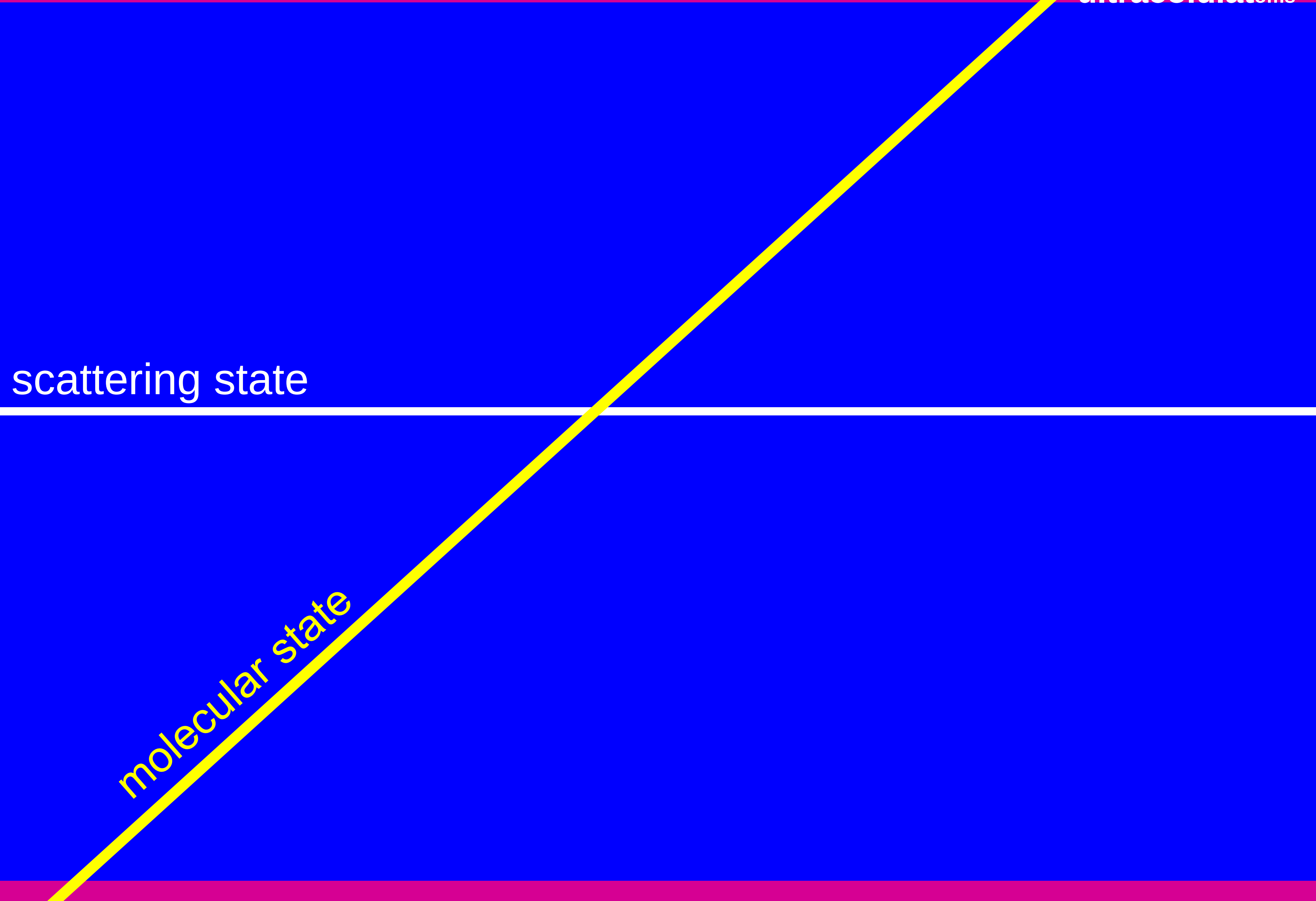
how we do rf spectroscopy



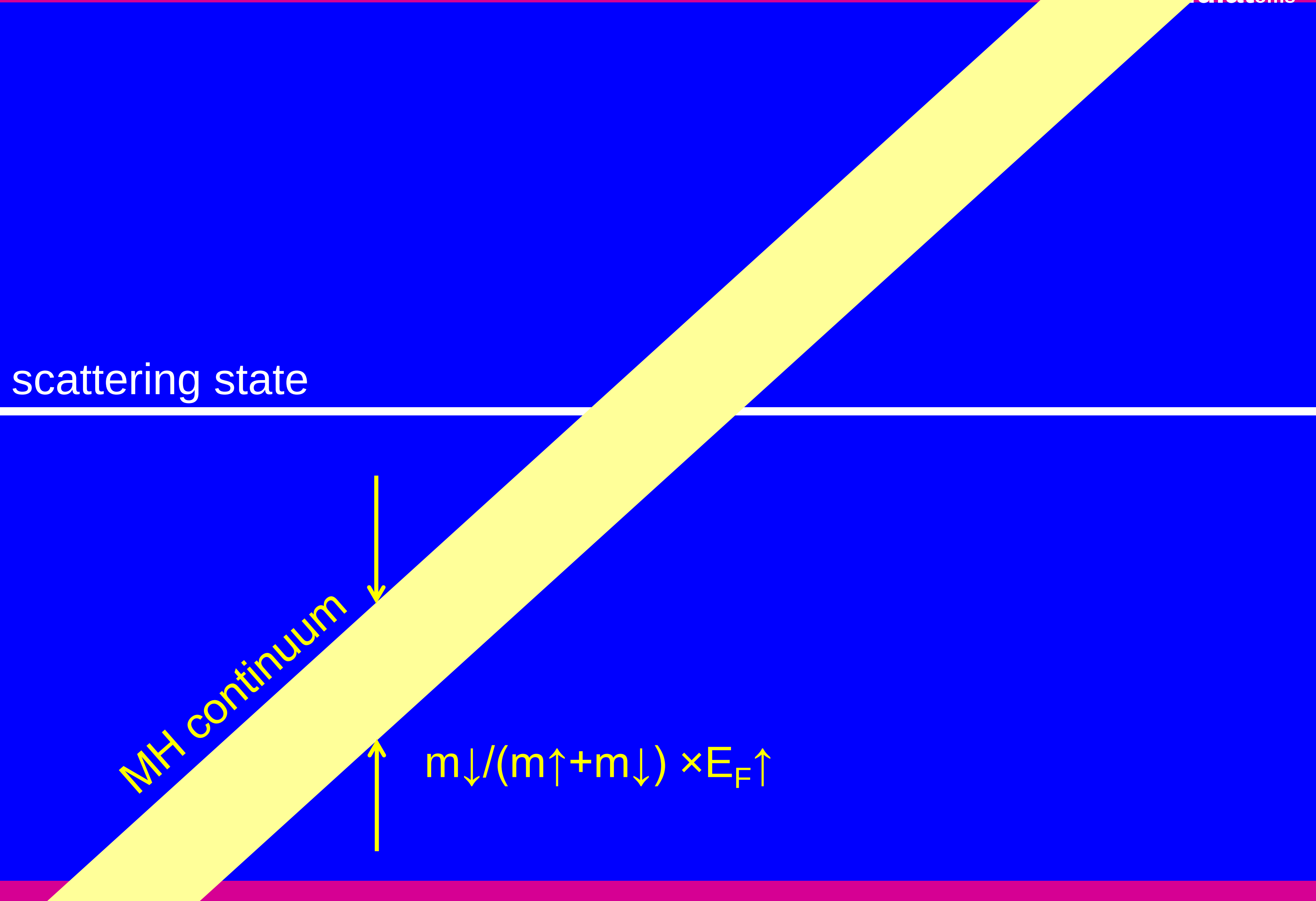
rf spectroscopy: standard vs. reverse



extended Feshbach picture

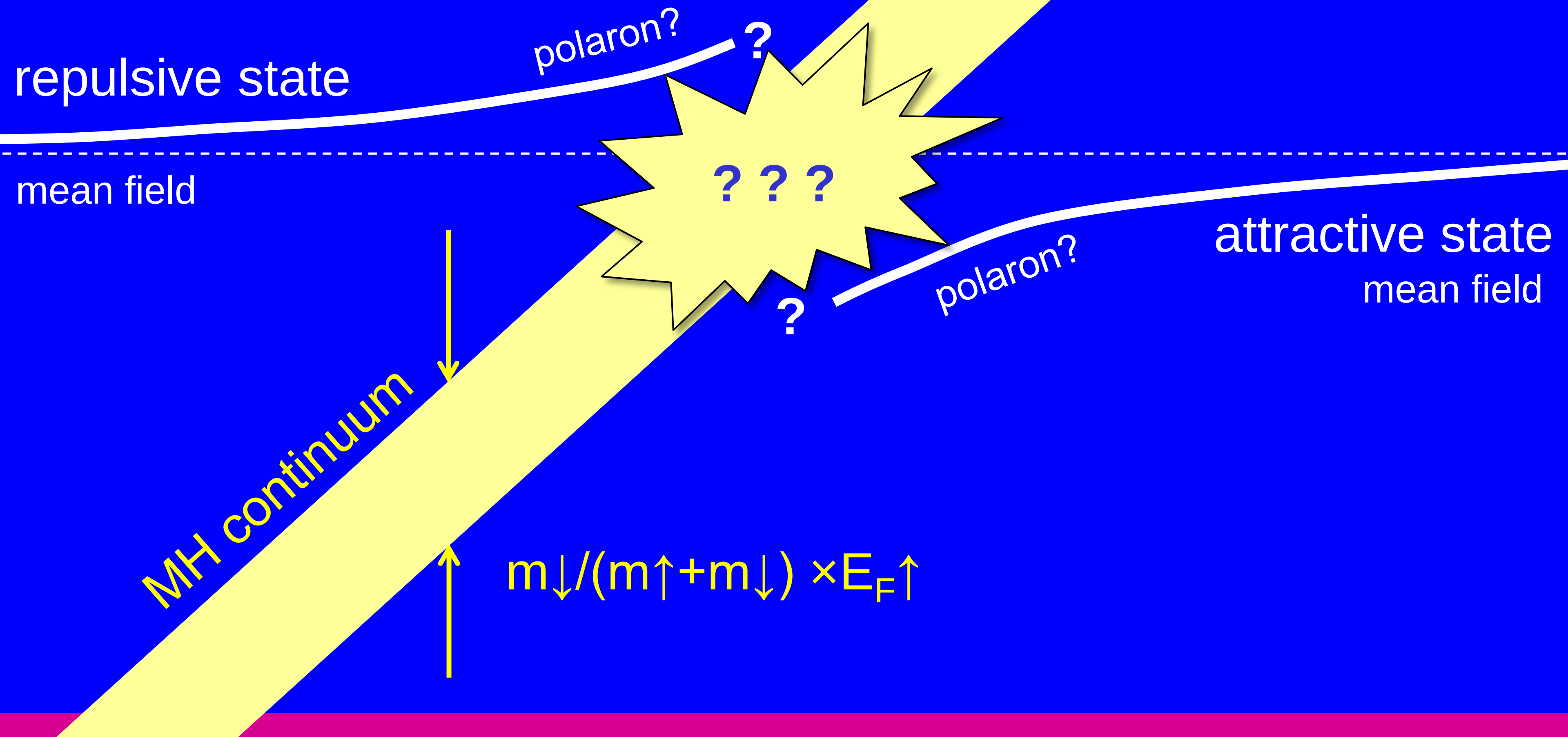


extended Feshbach picture

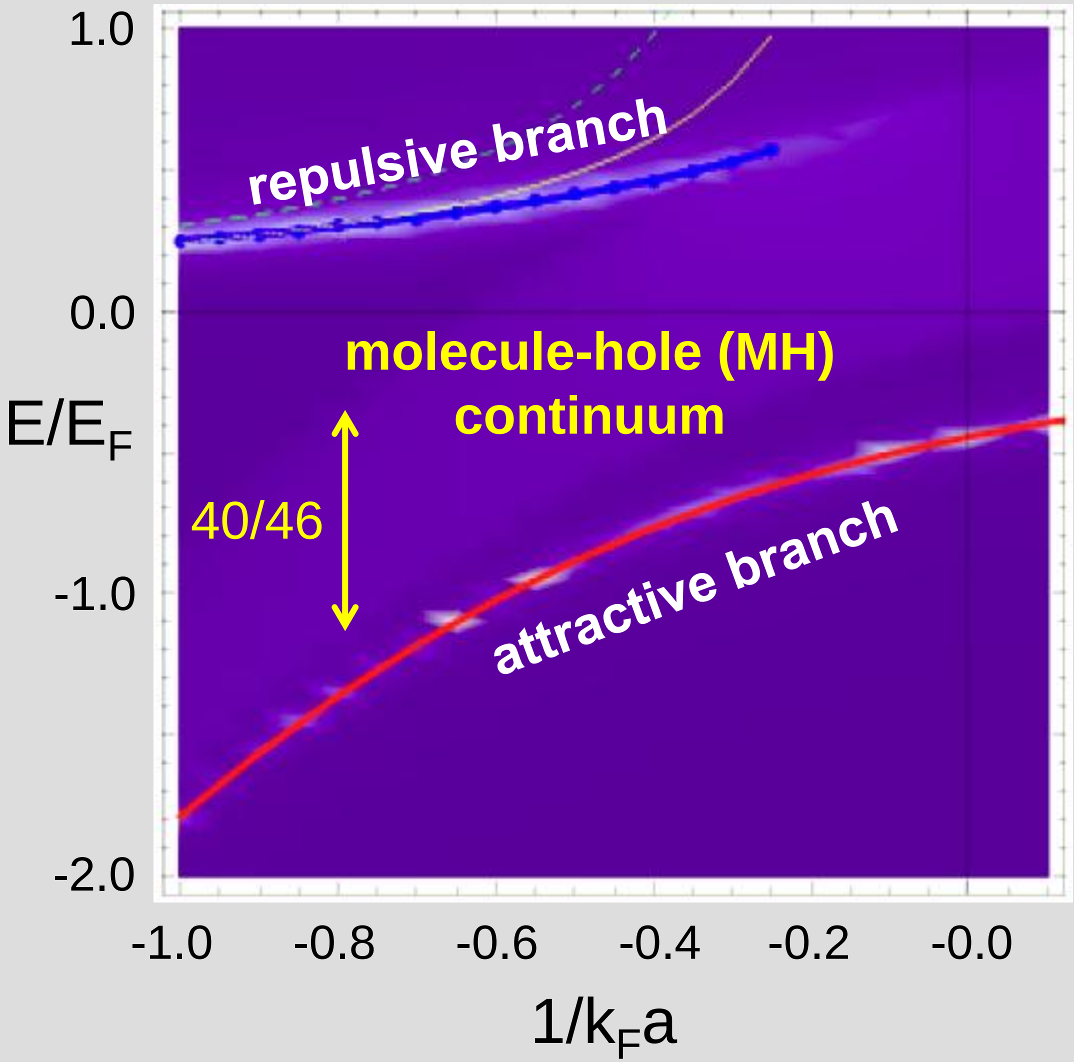


extended Feshbach picture

role of the FR character?
broad vs. narrow



what we may expect for reverse rf spectroscopy



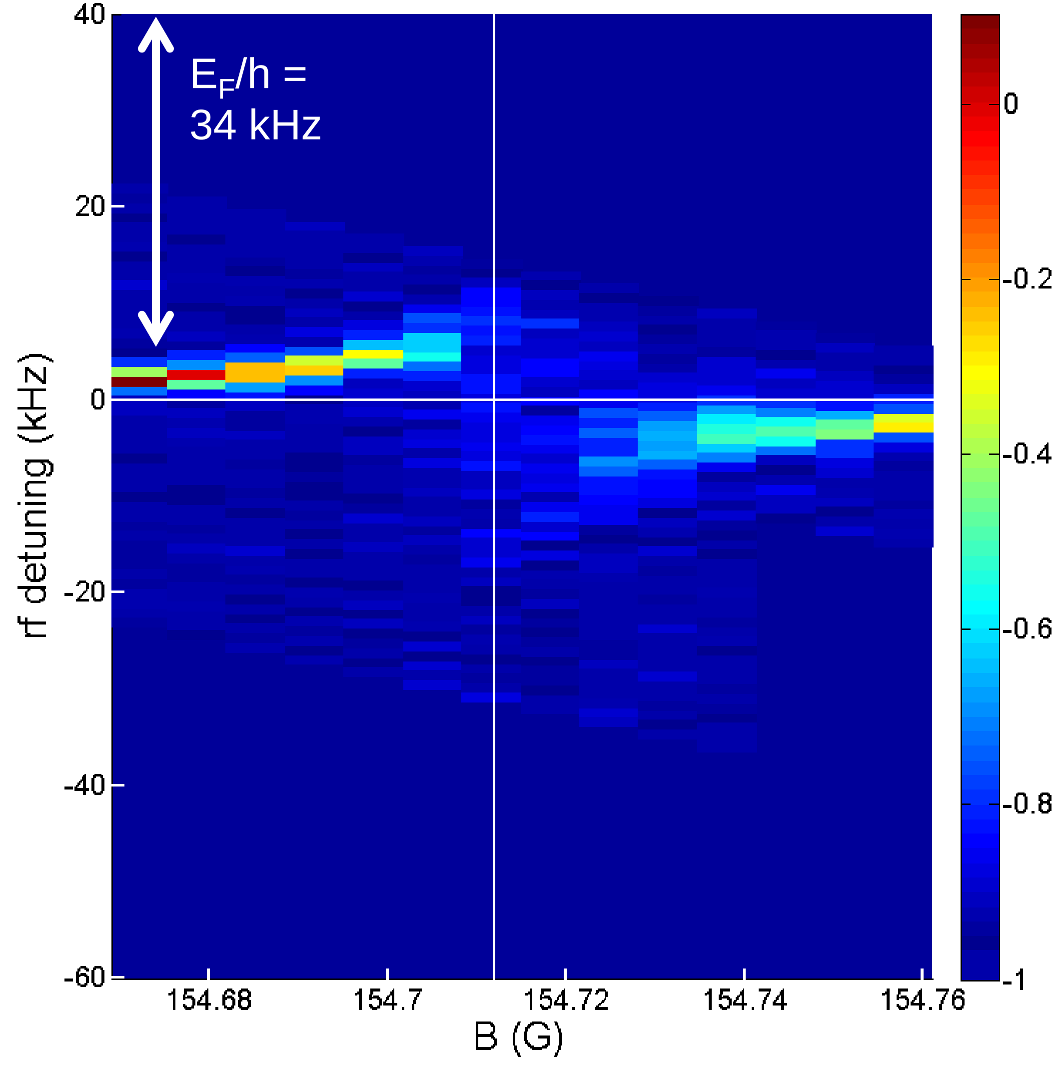
Pietro Massignan
ICFO, Spain

Georg Bruun
U Aarhus, Denmark

and what does the experiment tell us?

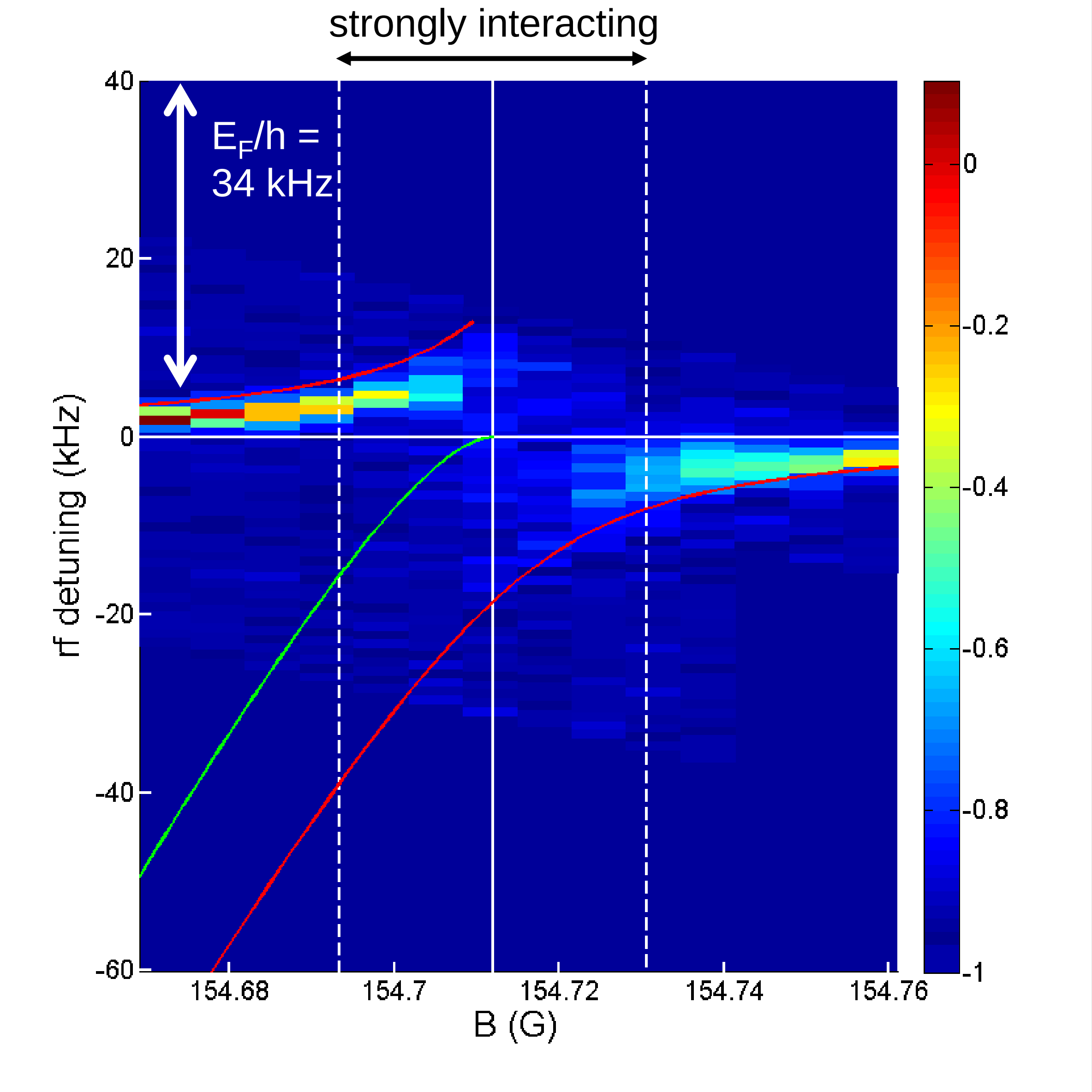
probing the spectral function

π pulse (1 ms)



probing the spectral function

π pulse (1 ms)



theory by Massignan and Bruun:

attractive/ repulsive branch

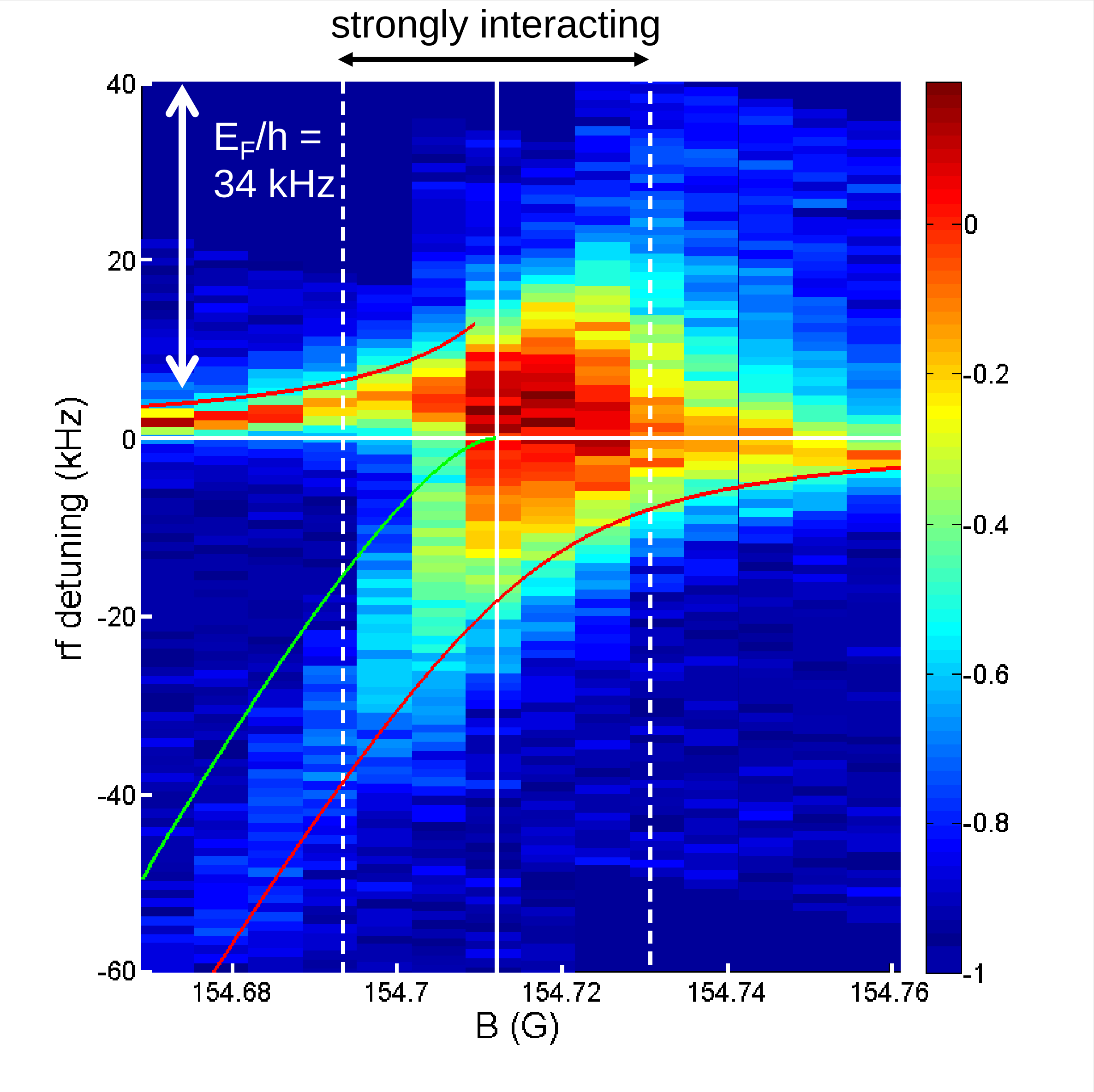
molecular state

probing the spectral function

pulse 25x power (1 ms)

theory by Massignan and Bruun:
attractive/ repulsive branch

molecular state

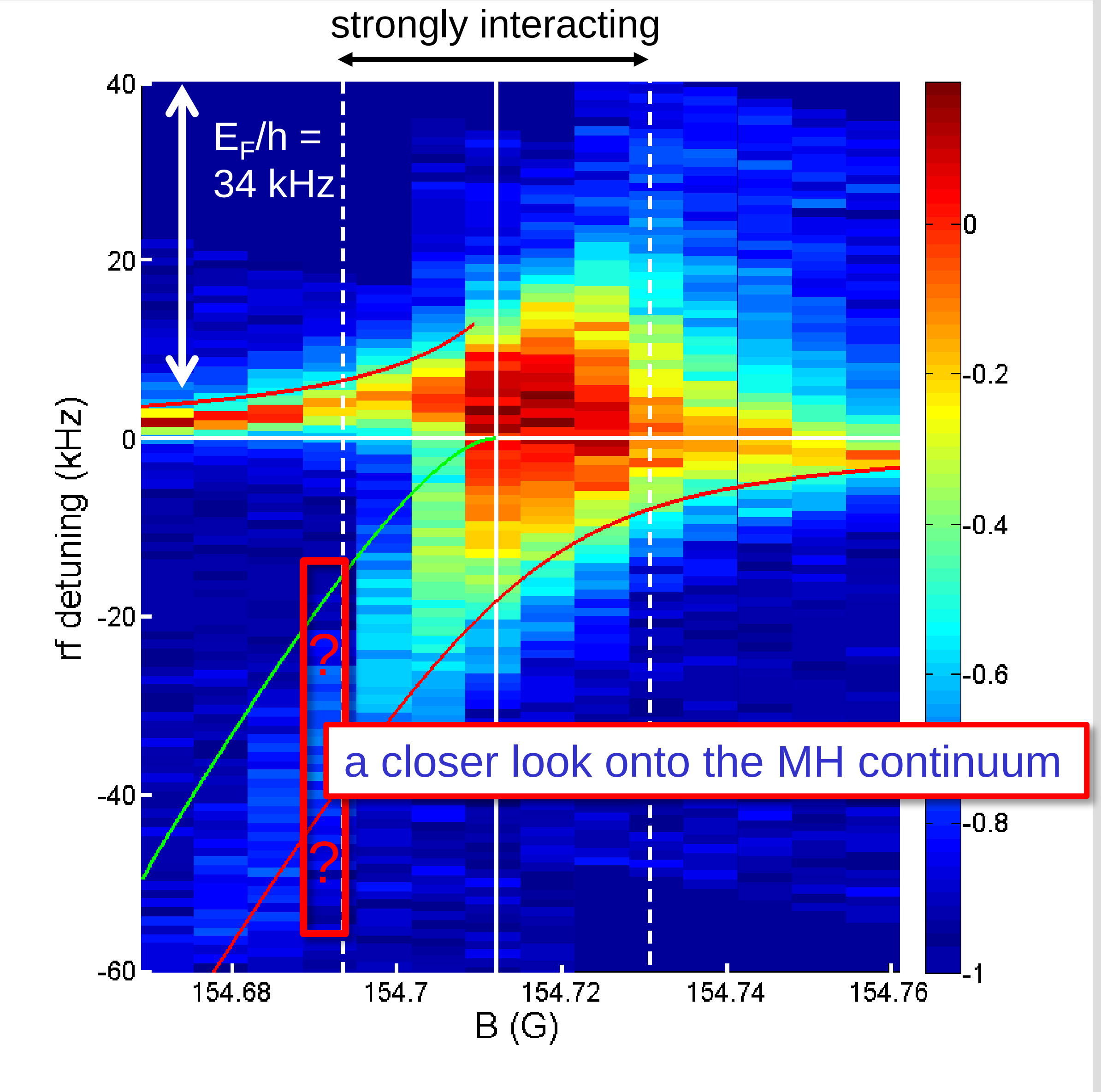


probing the spectral function

pulse 25x power (1 ms)

theory by Massignan and Bruun:
attractive/ repulsive branch

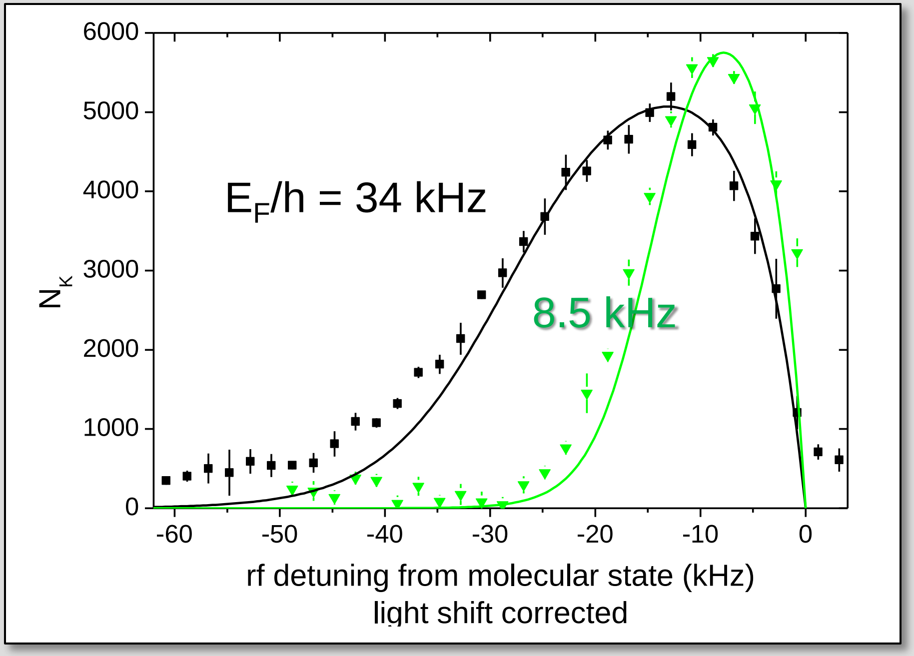
molecular state



a closer look onto the MH continuum

probing the MH continuum

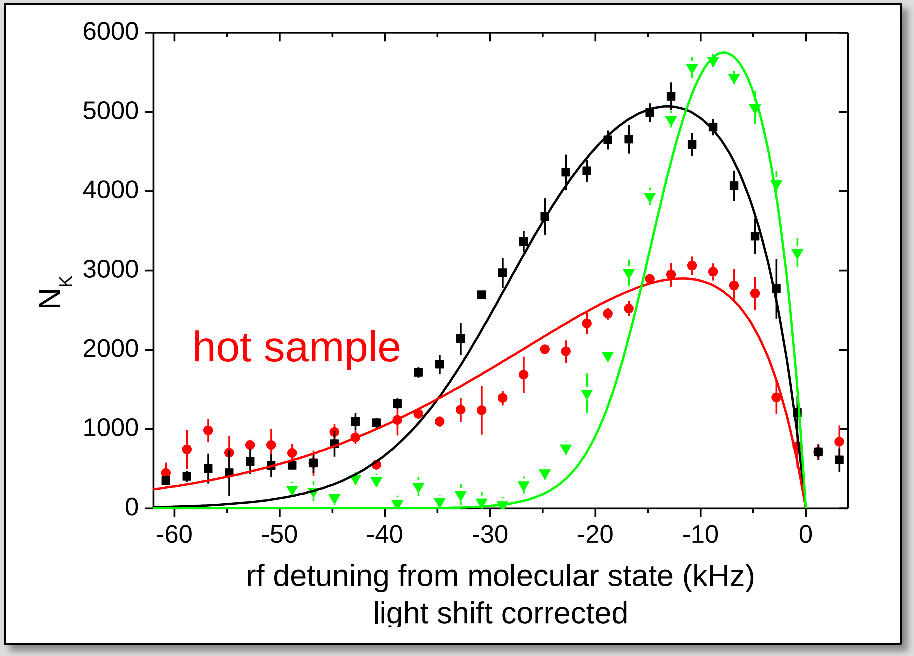
magnetic detuning -20mG, $1/k_F a = 1.1$



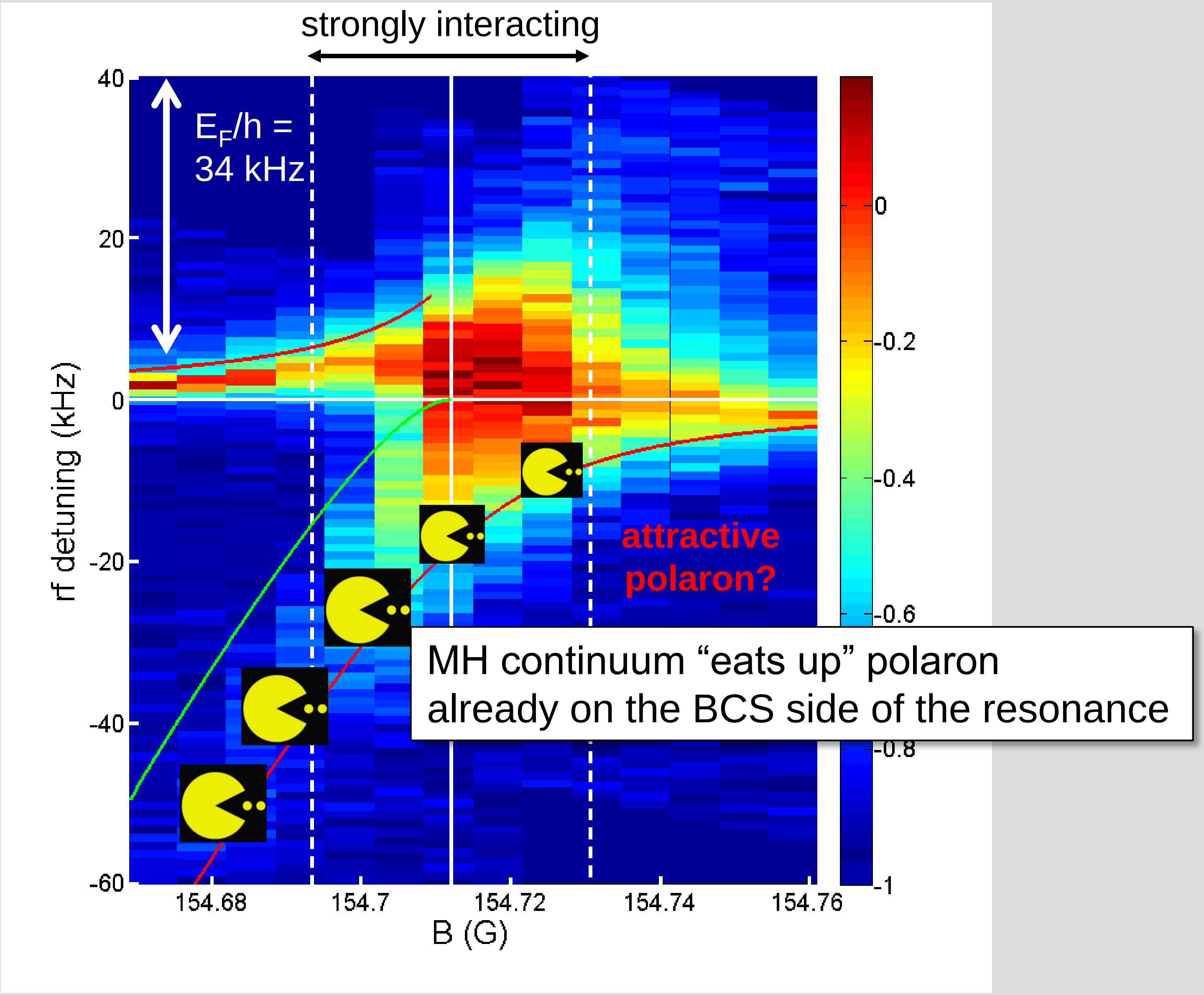
probing the MH continuum

ultracold.atoms

magnetic detuning -20mG, $1/k_F a = 1.1$

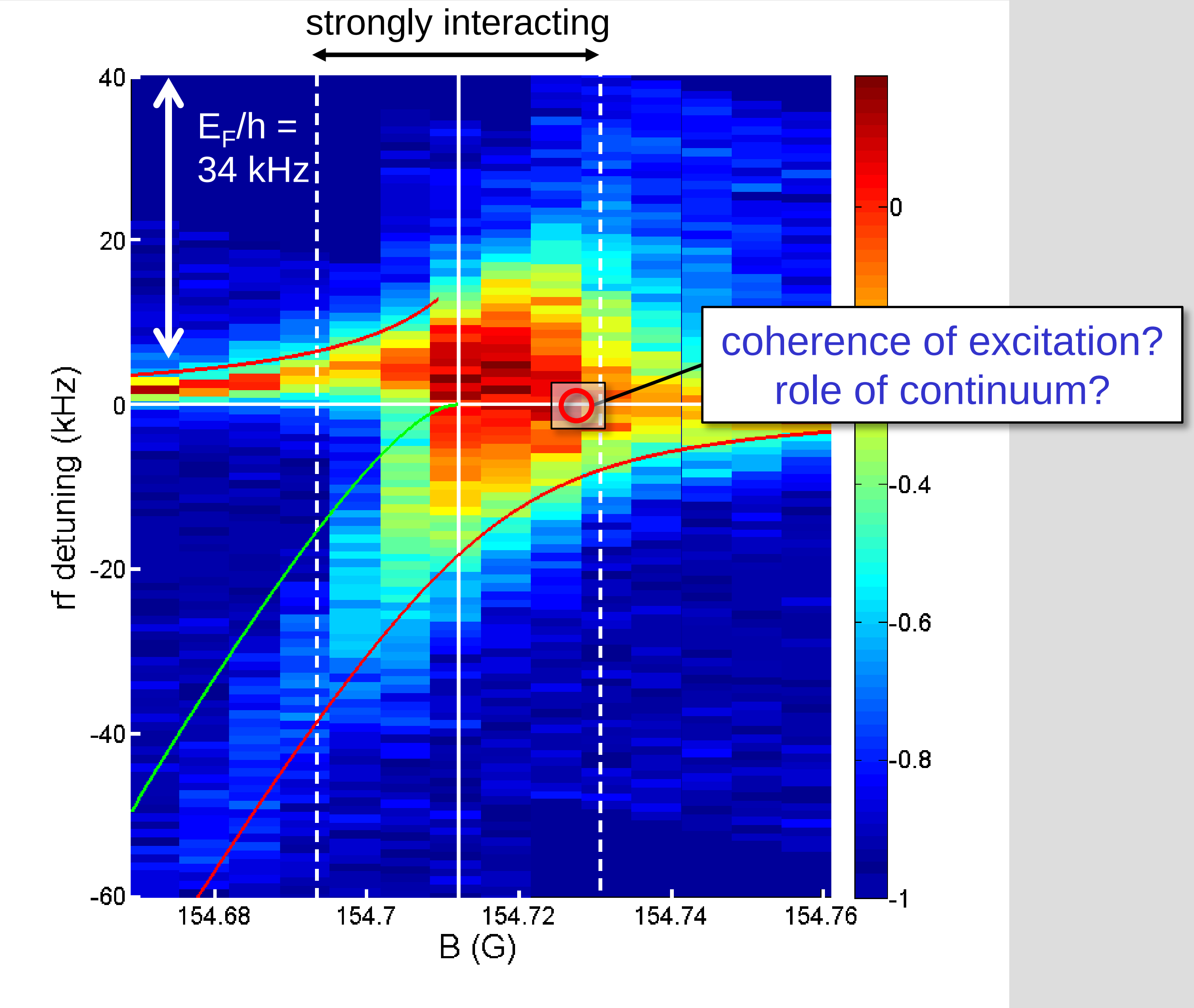


survival of the attractive polaron?



coherence effects in the excitation

pi pulses
and
beyond



coherence effects in the excitation

pi pulses
and
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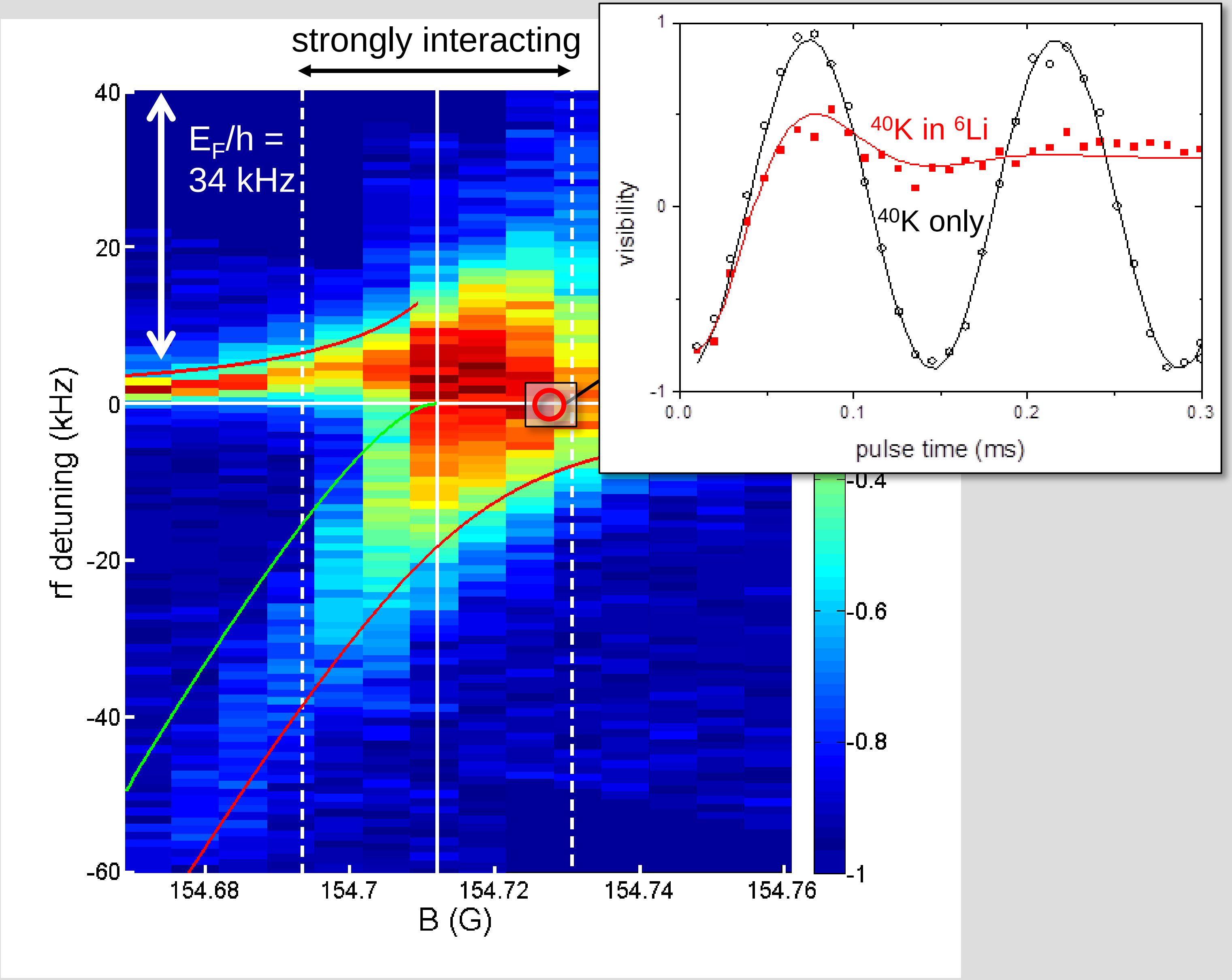
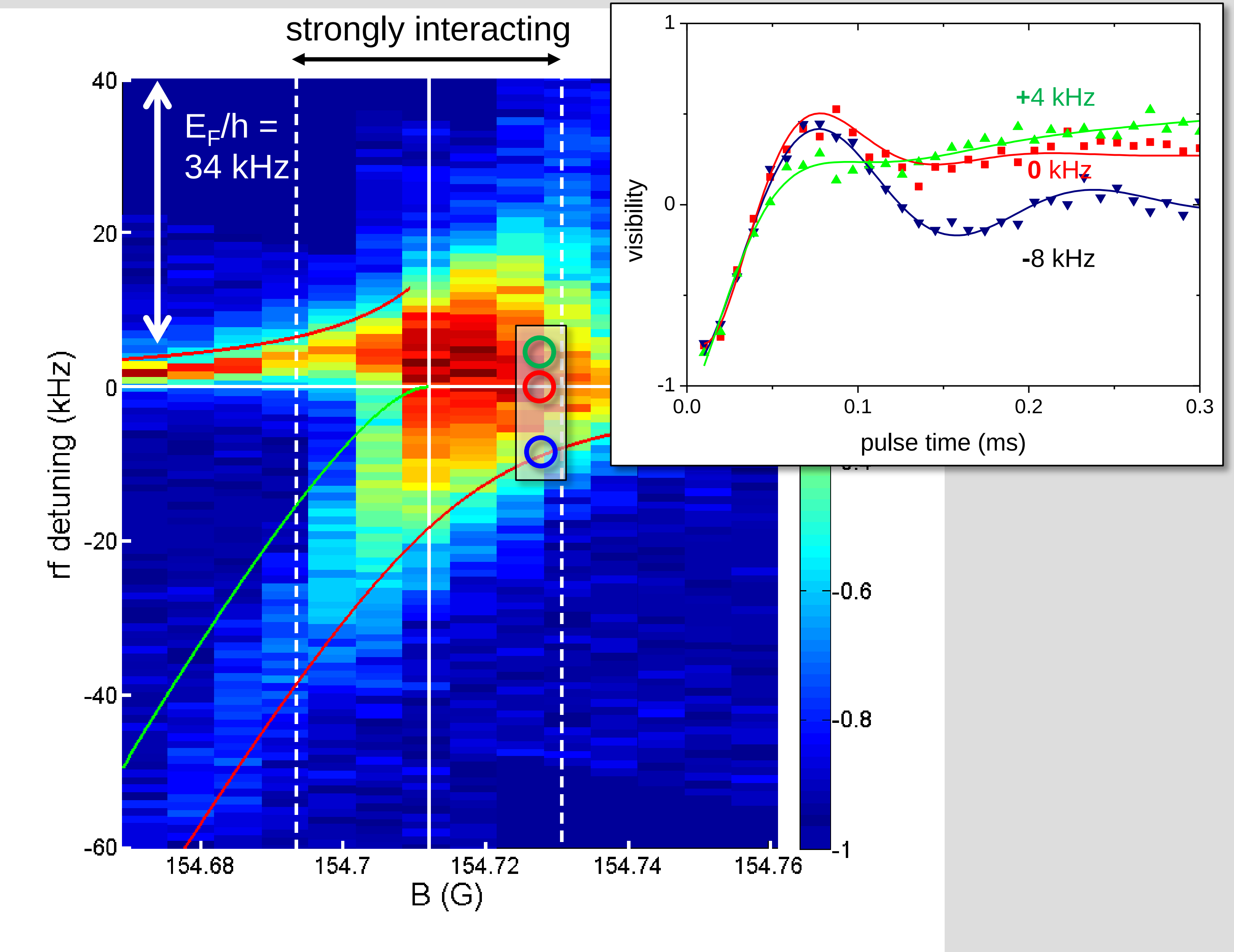


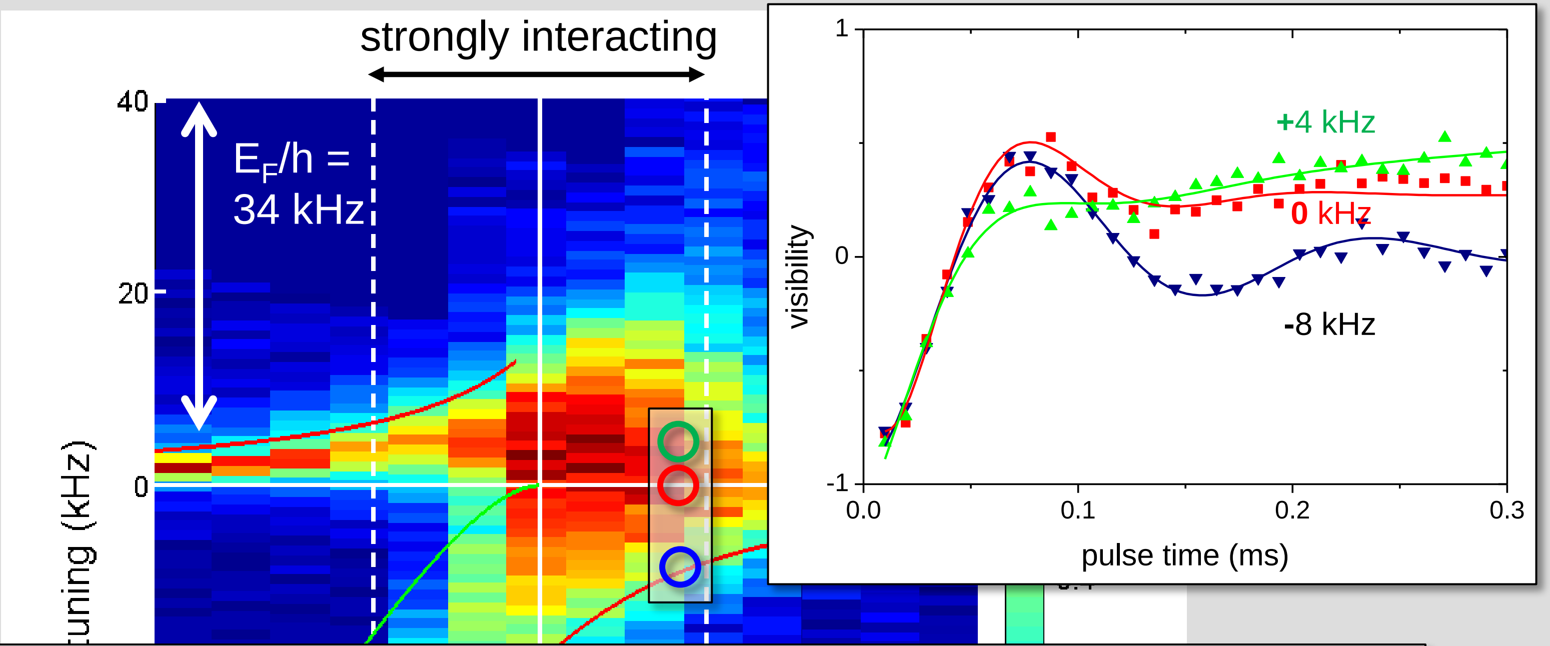
coherence effects in the excitation

pi pulses and beyond



coherence effects in the excitation

pi pulses
and
beyond



coherent rf spectrocopy on many-body state

mapping out Rabi frequency and damping rate vs. B and δf

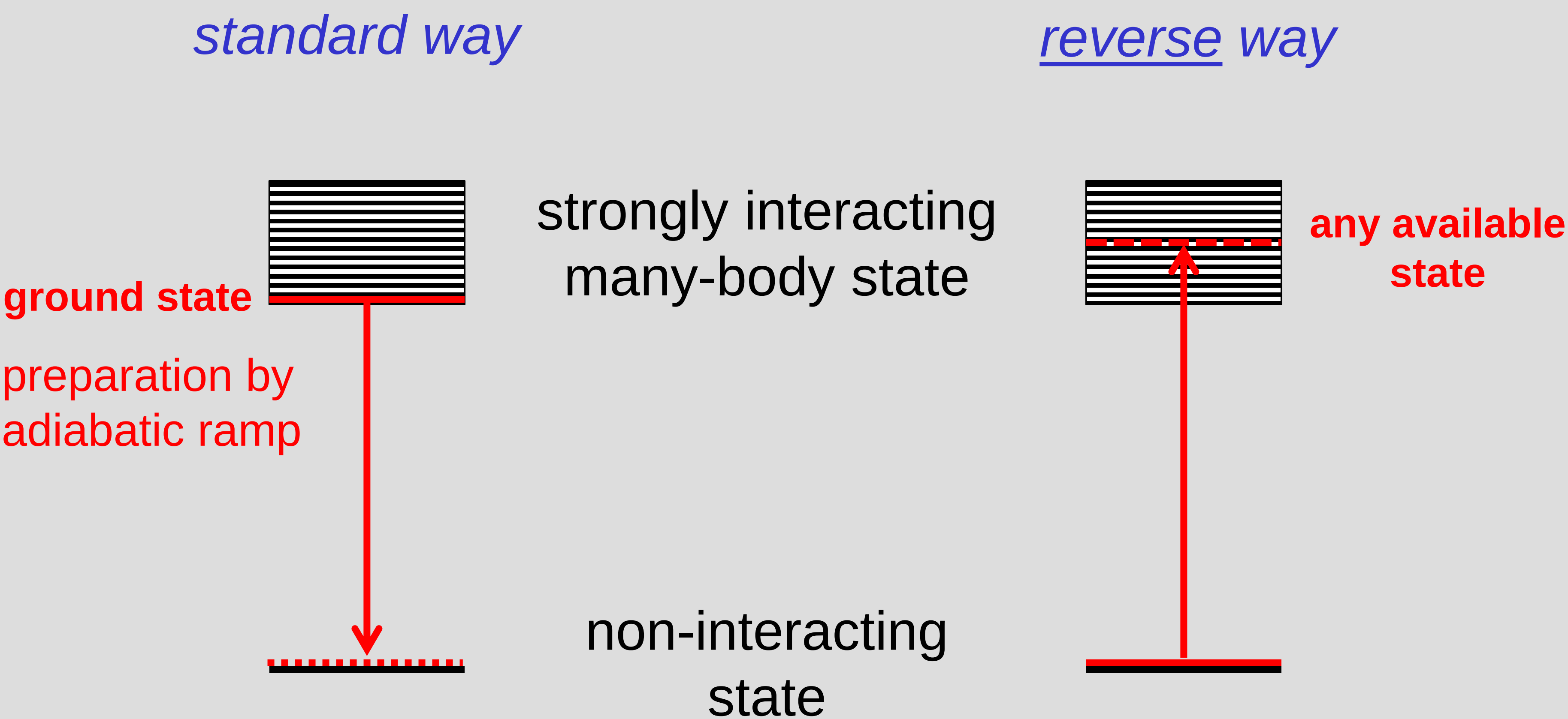
what can we learn from that?

polaron: sharp peak in spectrum -> Rabi oscillation
continuum: no Rabi oscillation

coherence times? relaxation effects ?

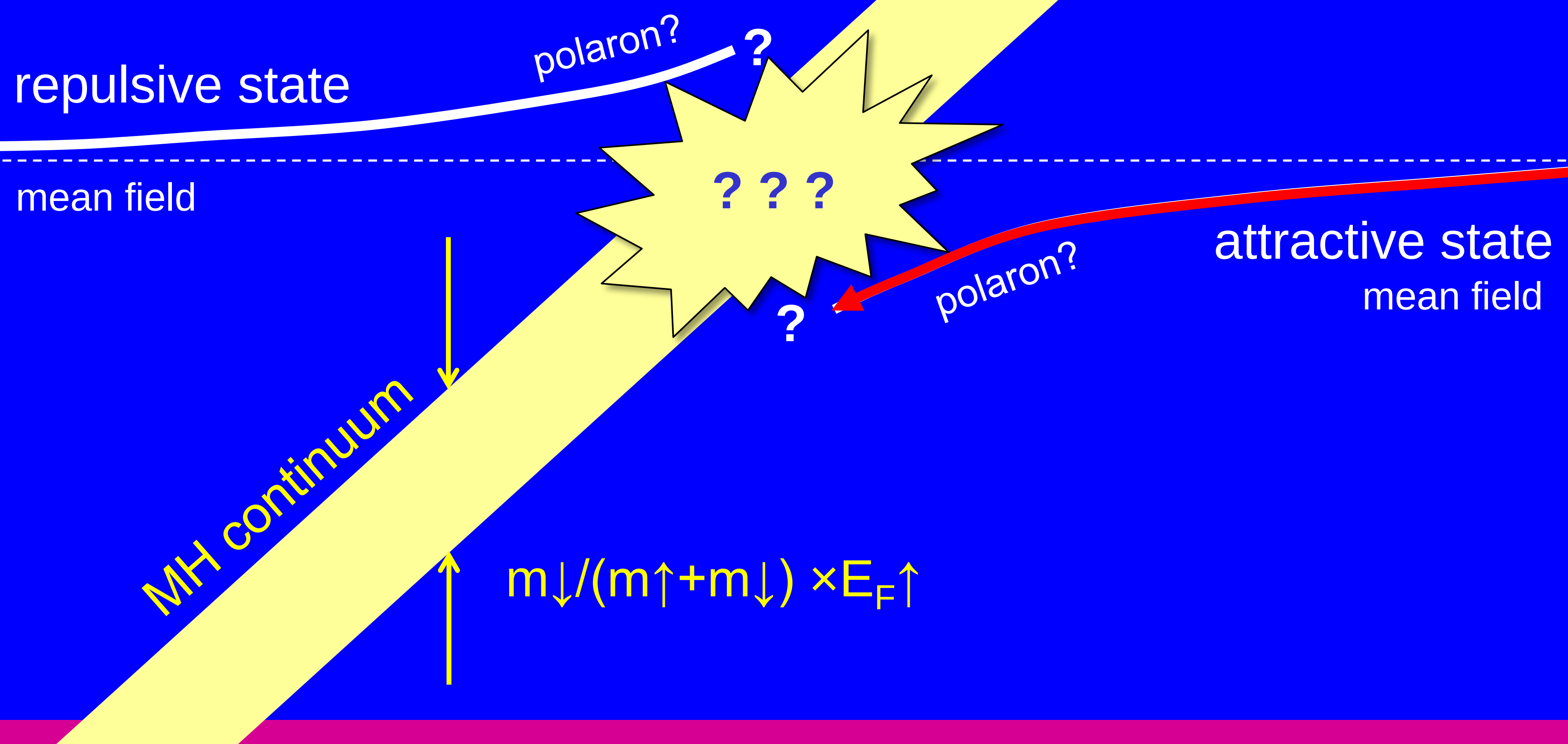
rf spectroscopy: standard vs. reverse

ultracold.atoms

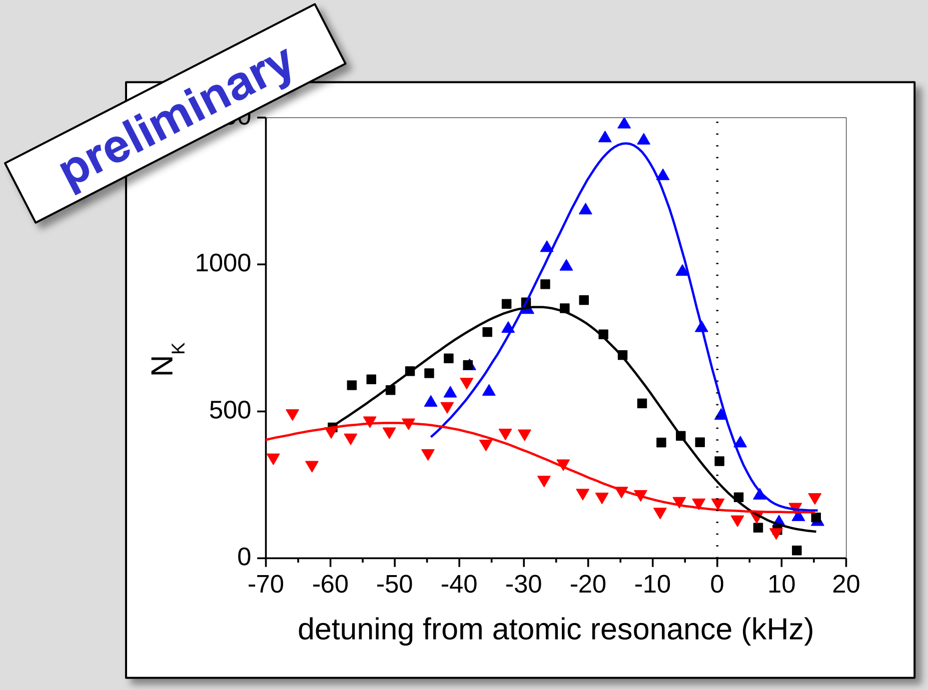


extended Feshbach picture

role of the FR character?
broad vs. narrow



"standard" rf spectroscopy on attractive branch



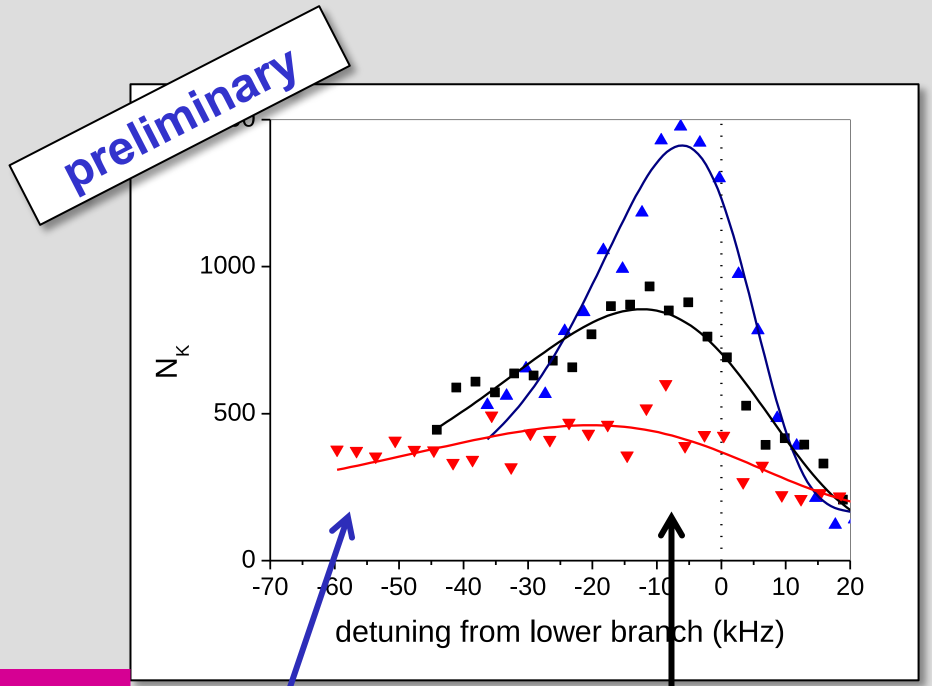
+15mG ($1/k_Fa \approx -0.8$)

on resonance

-15mG ($1/k_Fa \approx -0.8$)

“standard” rf spectroscopy on attractive branch

same data,
... but now <u>relative to polaronic ground state</u> (Massignan-Bruun theory)



+15mG ($1/k_F a \approx -0.8$)

on resonance

-15mG ($1/k_F a \approx -0.8$)

contact *C* ?

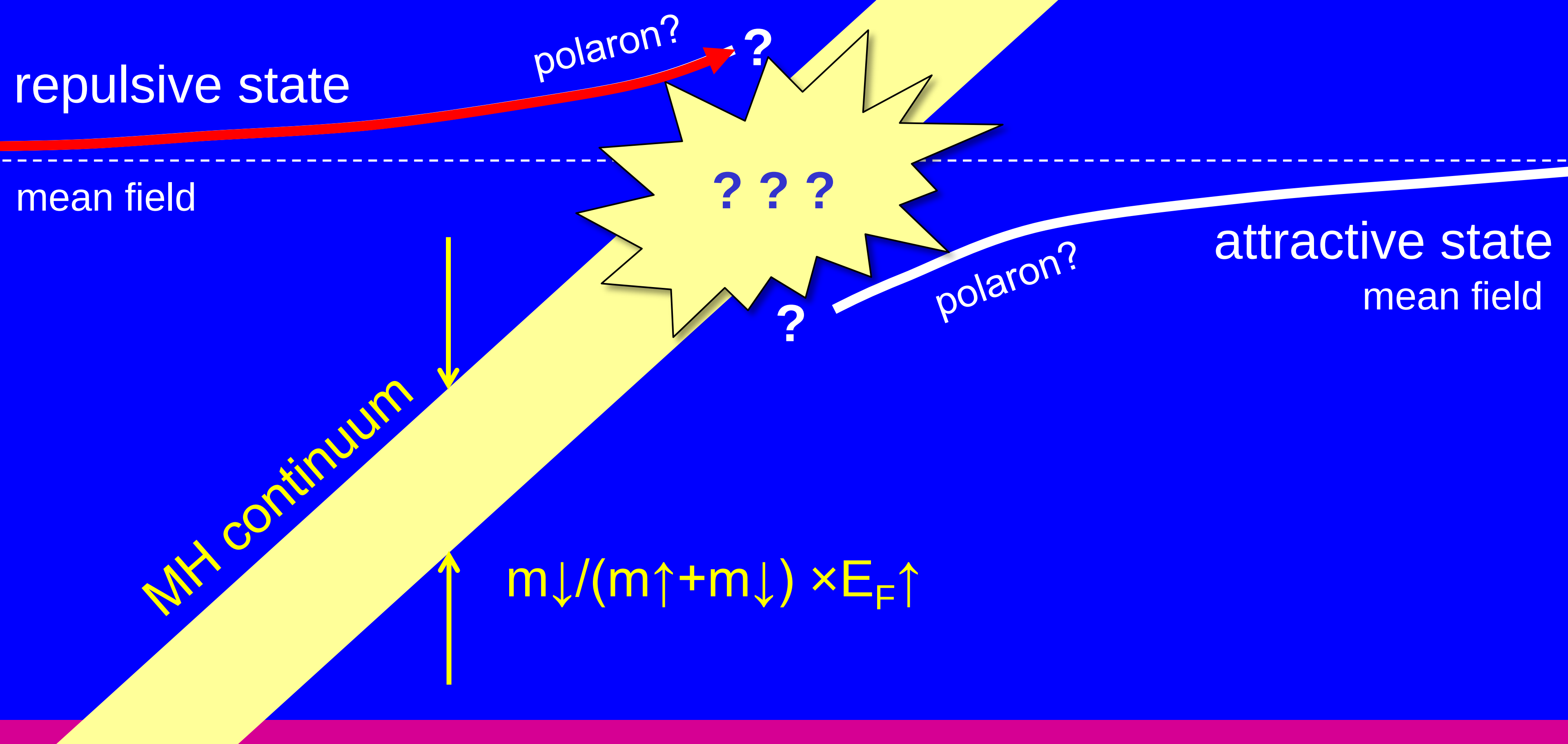
broadening towards
low-frequency side
(shows high-*k* states)

peak stays near
expected ground state

quasi-particle residue ?

extended Feshbach picture

role of the FR character?
broad vs. narrow

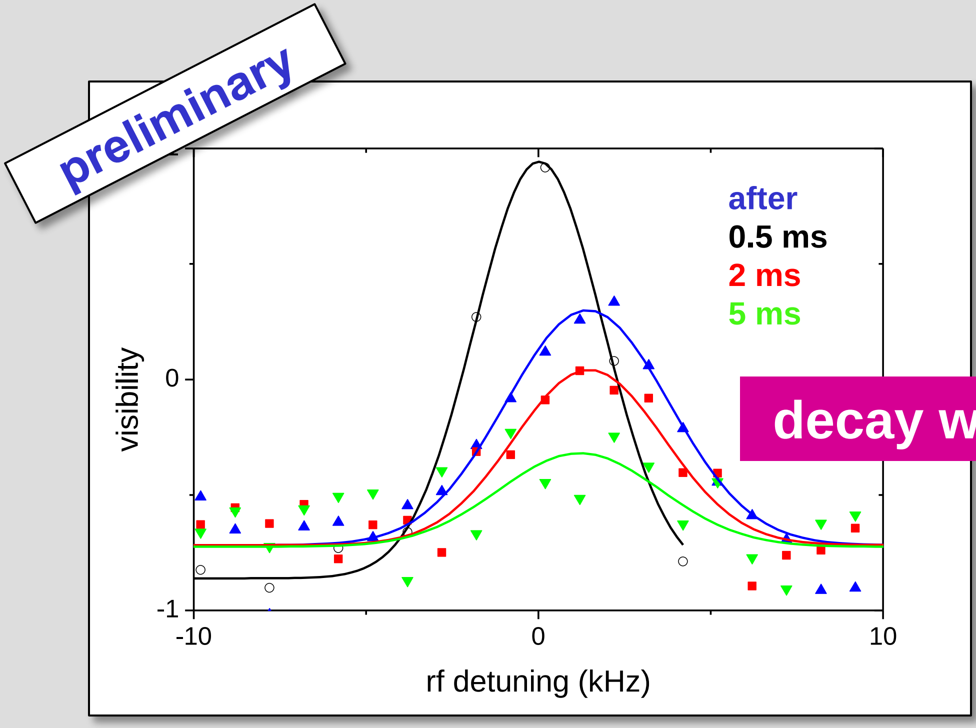


probing the repulsive polaron

ramp: 100mG in 20ms

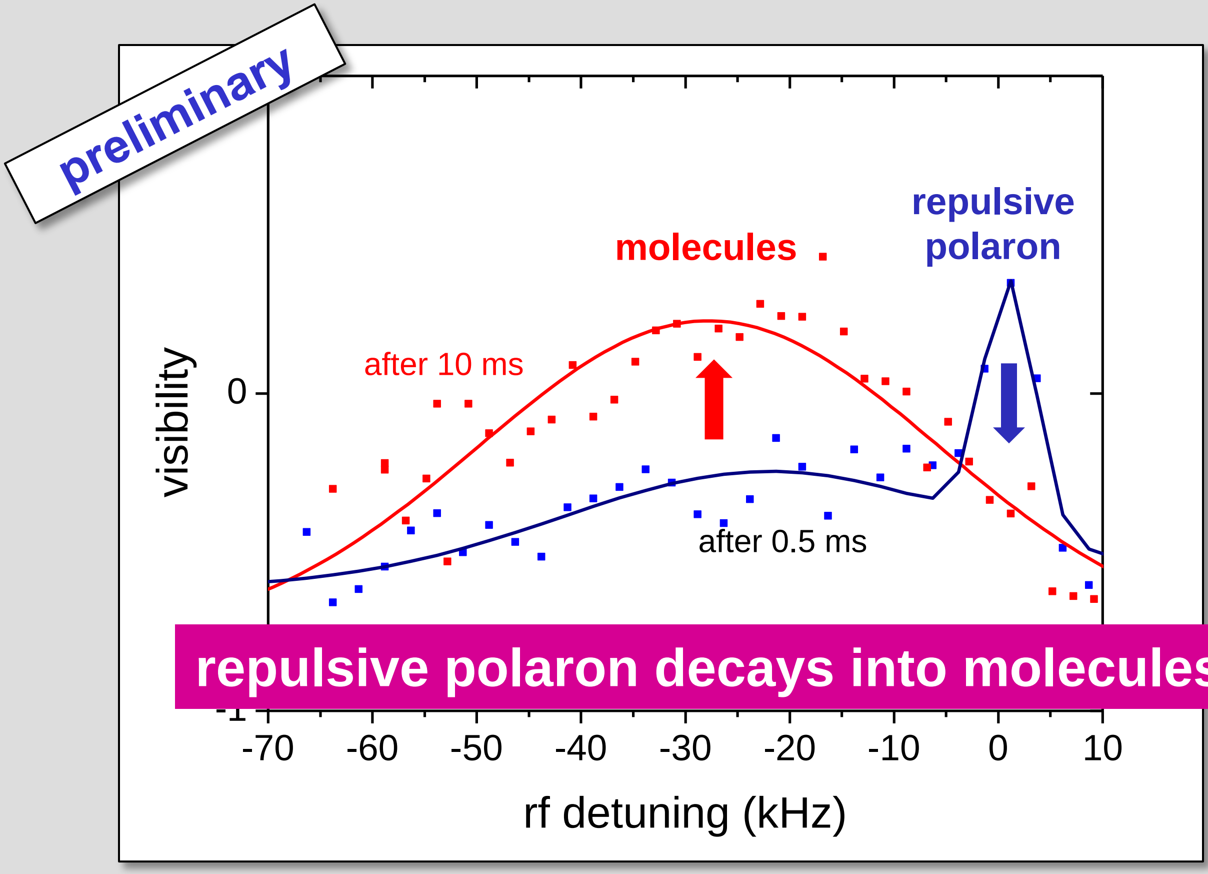
magn. detuning: -12mG ($1/k_F a \approx +0.6$)

rf excitation: 0.3ms pi-pulse

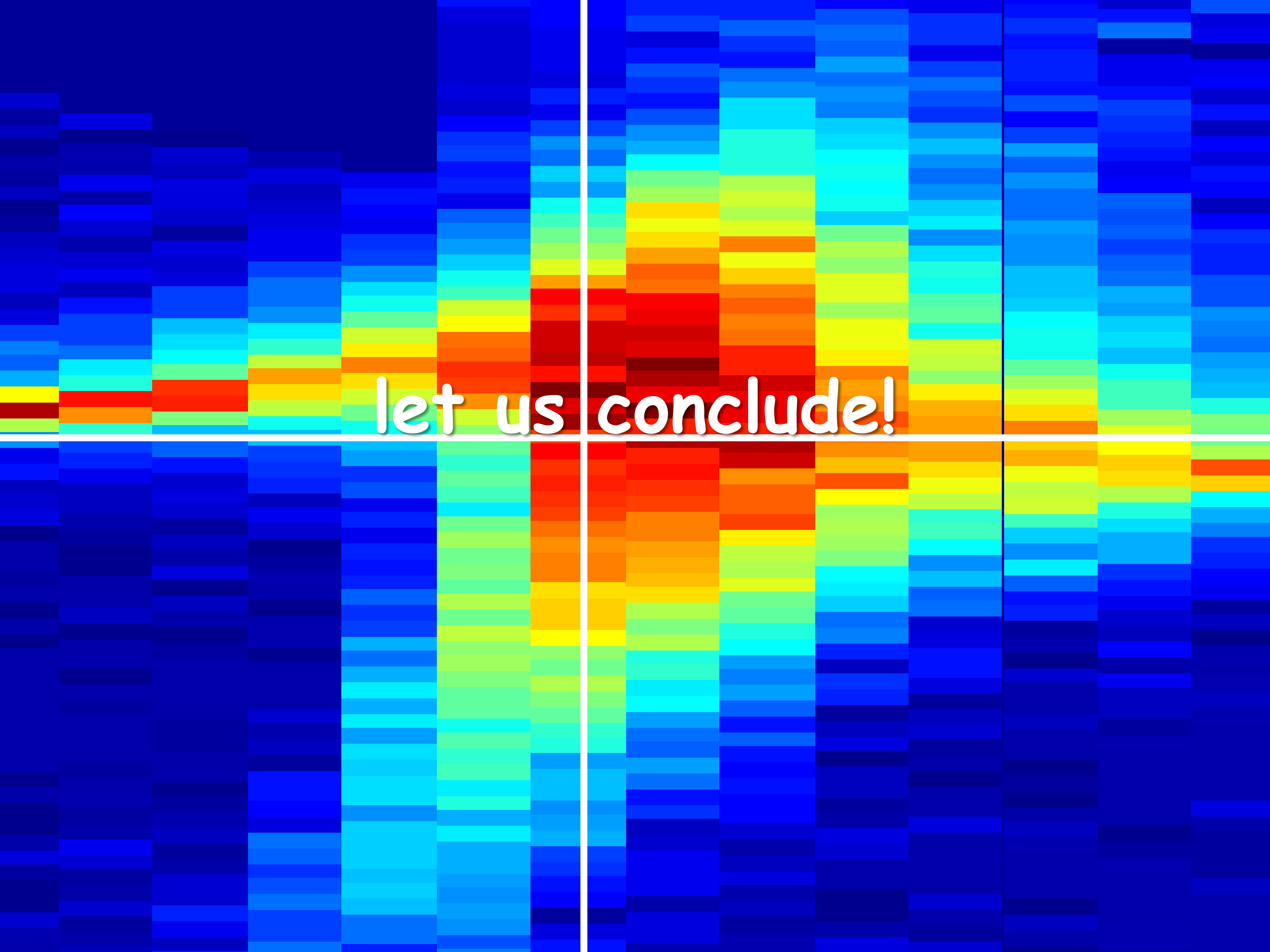


decay with lifetime ~5ms

decay of the repulsive polaron



repulsive polaron decays into molecules


let us conclude!

strongly interacting
Fermi-Fermi mixture
created

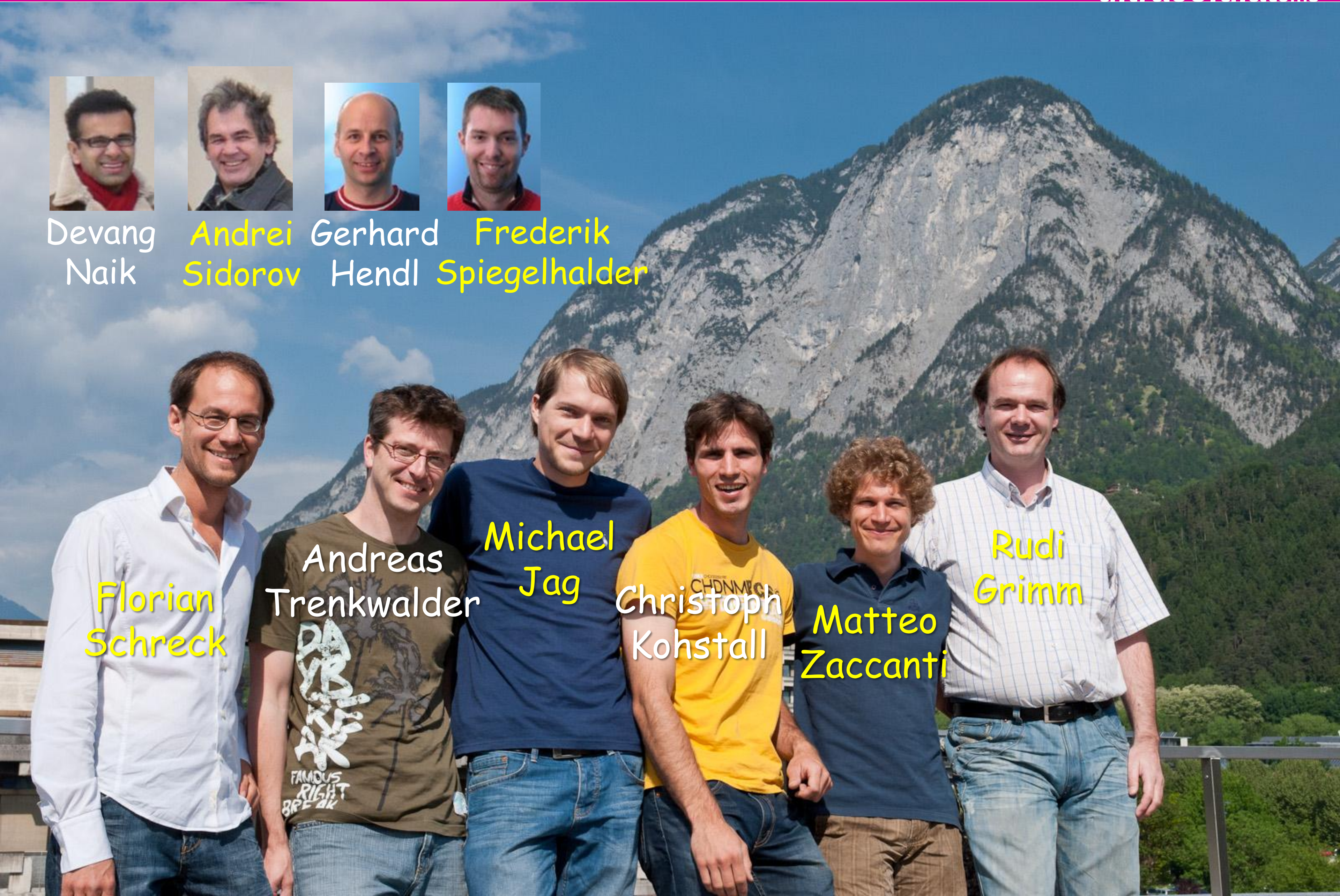
hydrodynamic expansion
observed

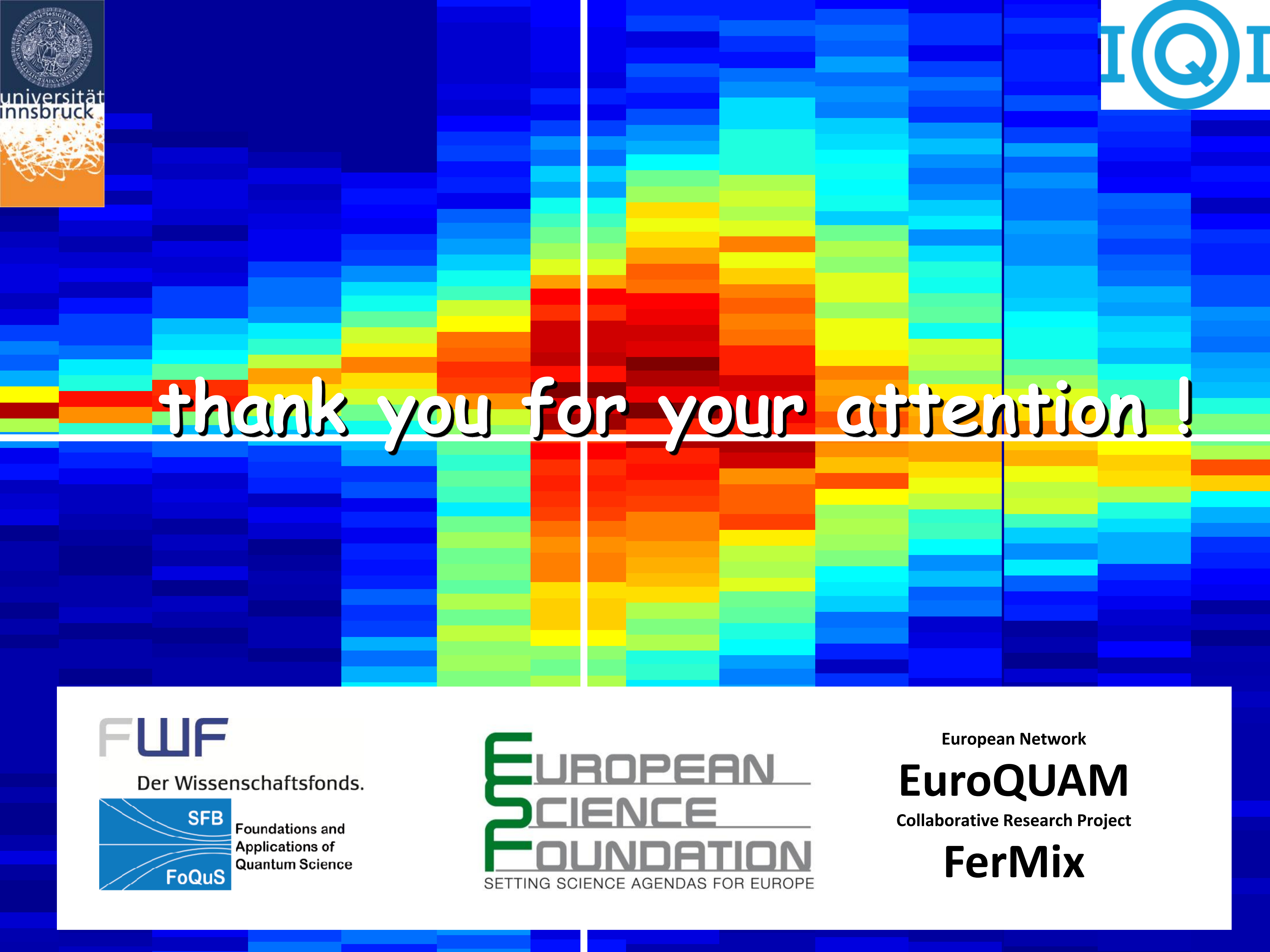
lots of fun...

rf spectroscopy
in polaronic regime
(very rich!)

many more things to come:
rf and Bragg spectroscopy,
lattices, low-D, mixed-D...

Innsbruck Fermi-Fermi team





thank you for your attention !

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