Quantum Mixtures with Ultracold Atoms, Varenna, 18-23 July 2022

Rudolf Grimm

Experiments with quantum mixtures III: Dy meets K – new mixture

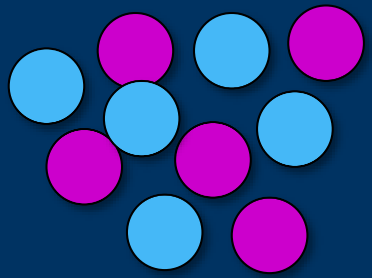
Austrian Acad. of Sciences

IQOQI

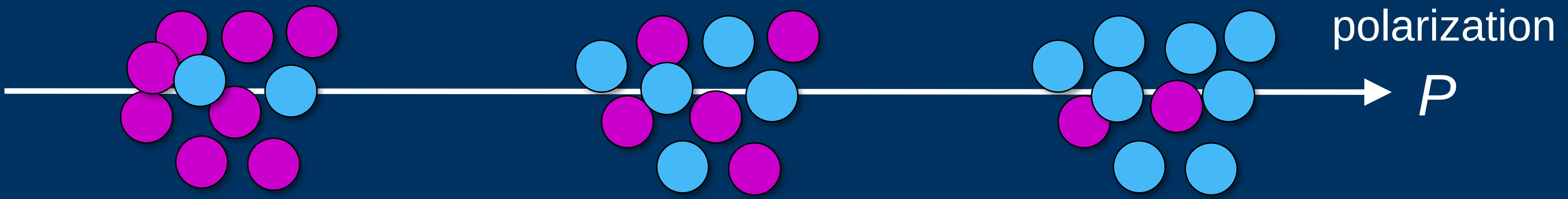
universität innsbruck

Inst. of Experimental Physics

50/50
spin mixture



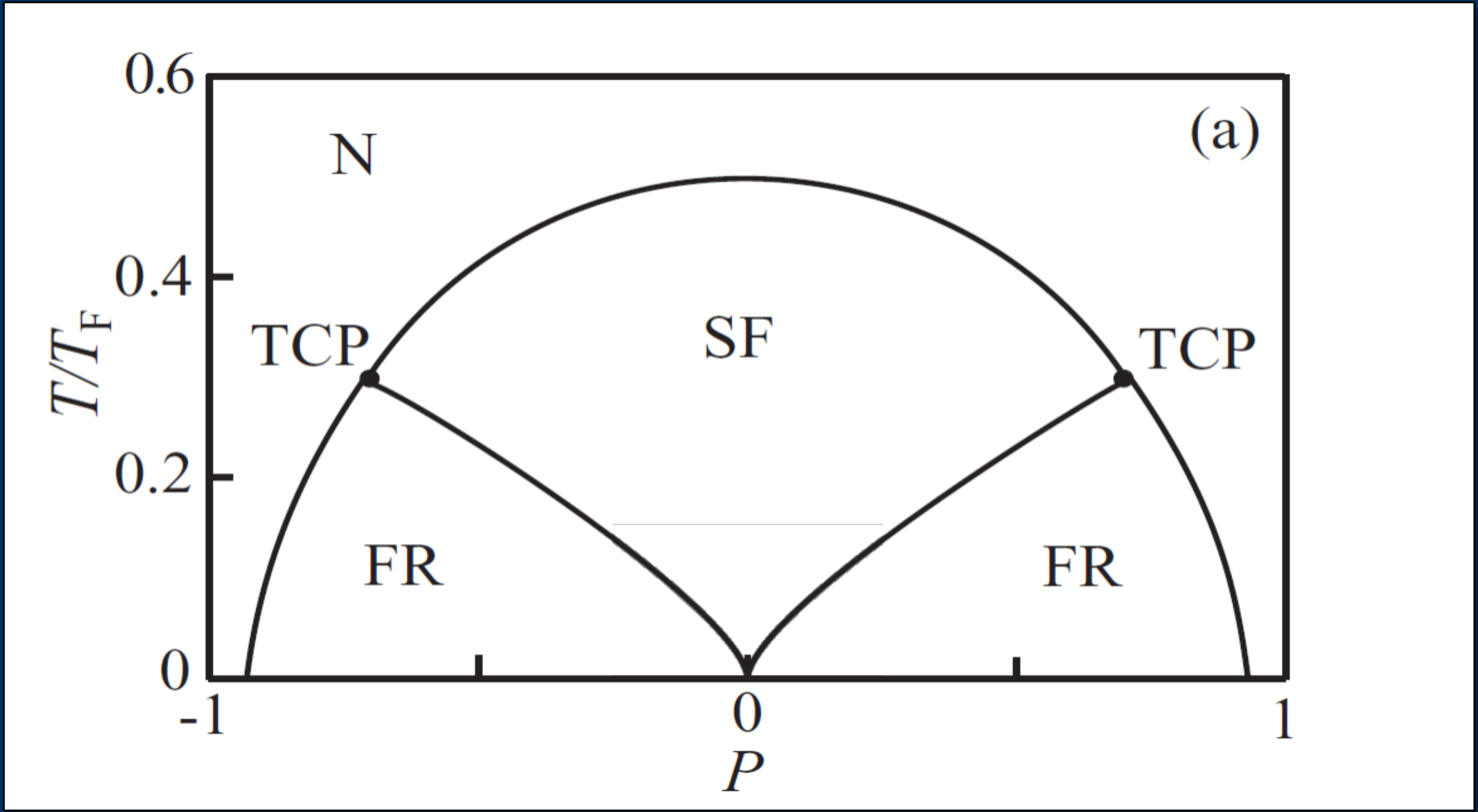
population imbalance



theoretical phase diagram

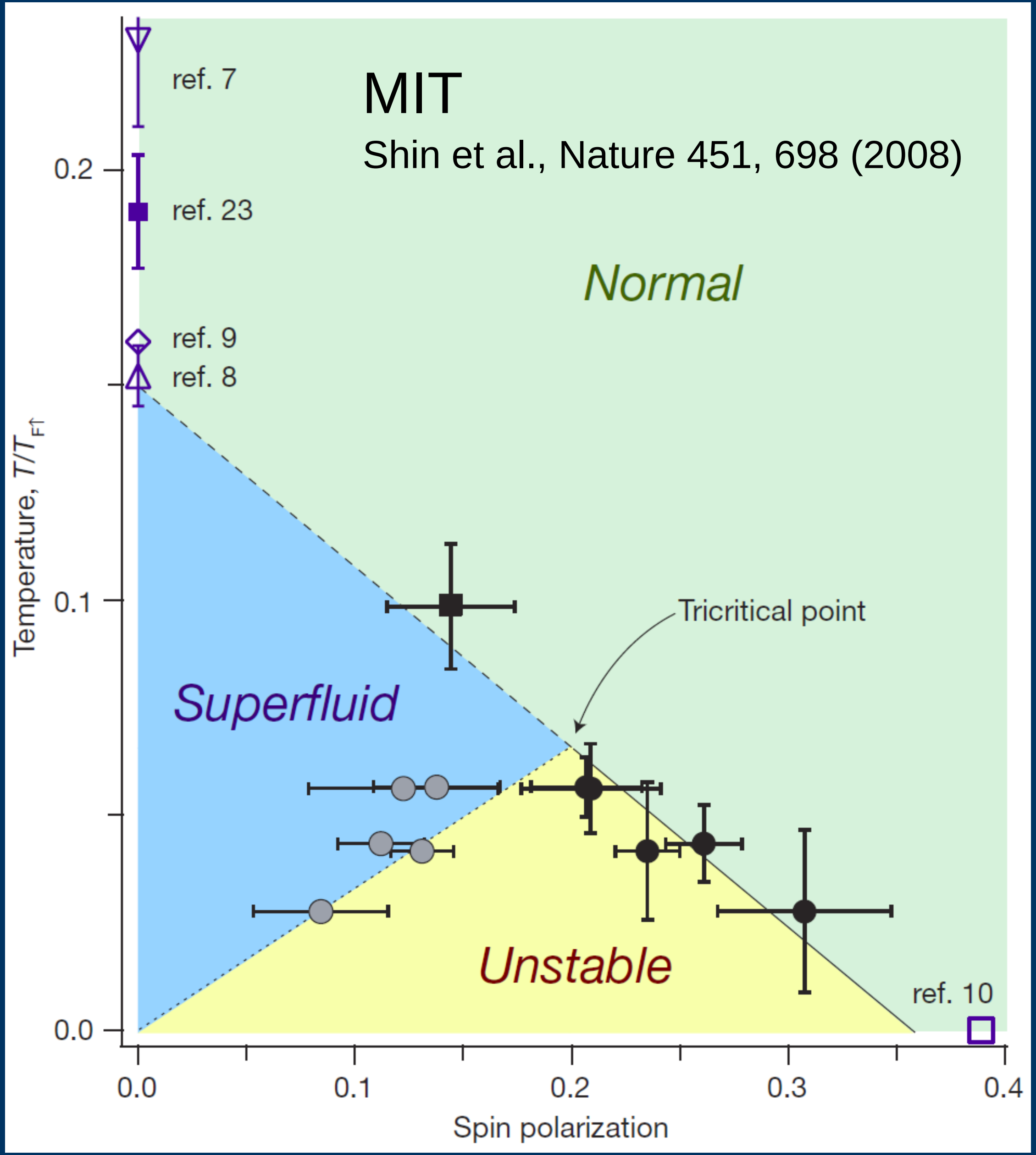
Baarsma, Gubbels, Stoof, PRA 82, 013624 (2010)

homogeneous case on resonance, mean-field approach



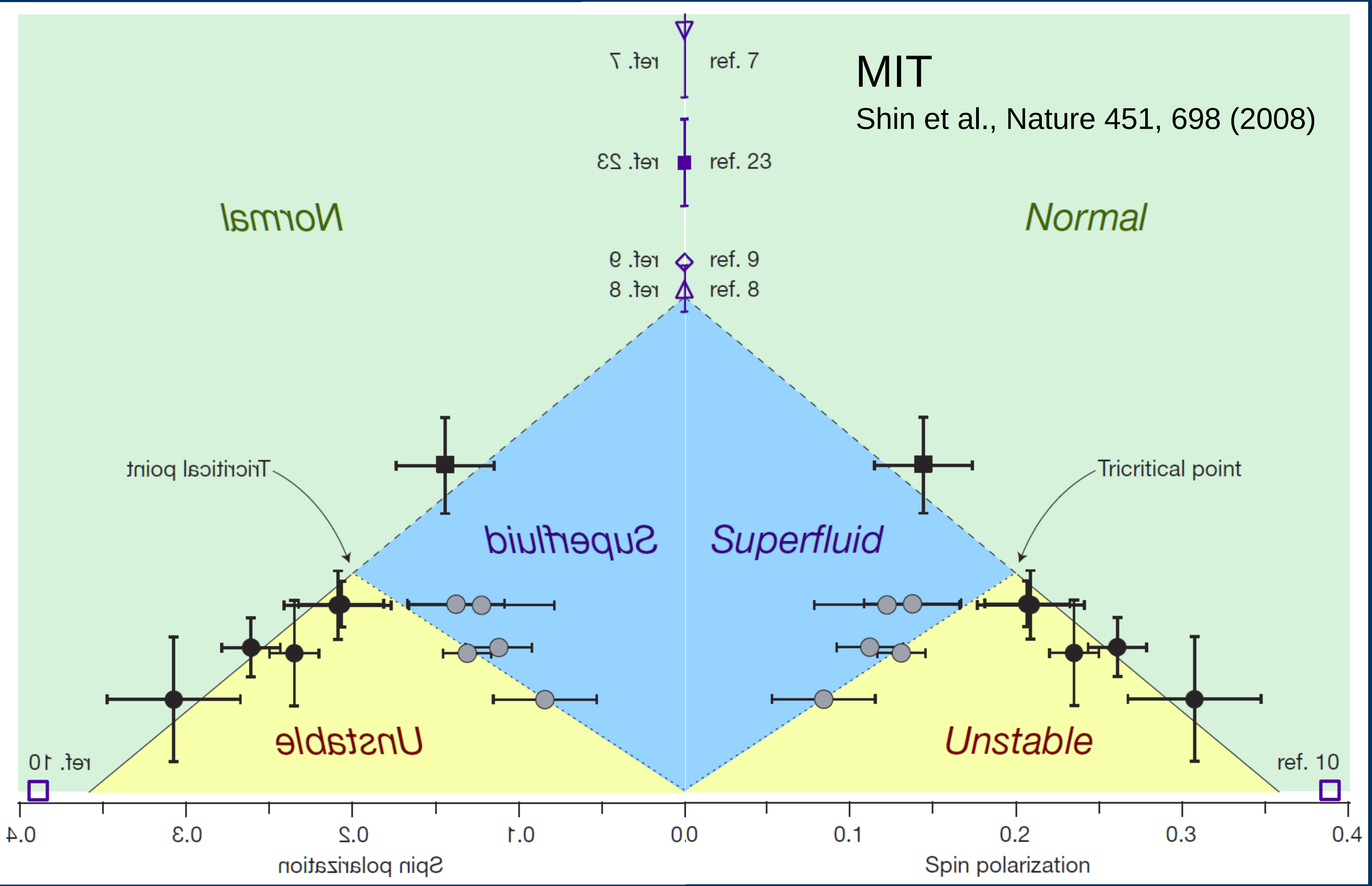
phase diagram of a resonant "unitary" Fermi gas

analyzing in-trap density profiles
→
phase diagram
for homogeneous system



early expt. work on polarized
Fermi gases, see also:
Hulet group at Rice (2006)
Salomon group at ENS (2009)

phase diagram of a resonant “unitary” Fermi gas



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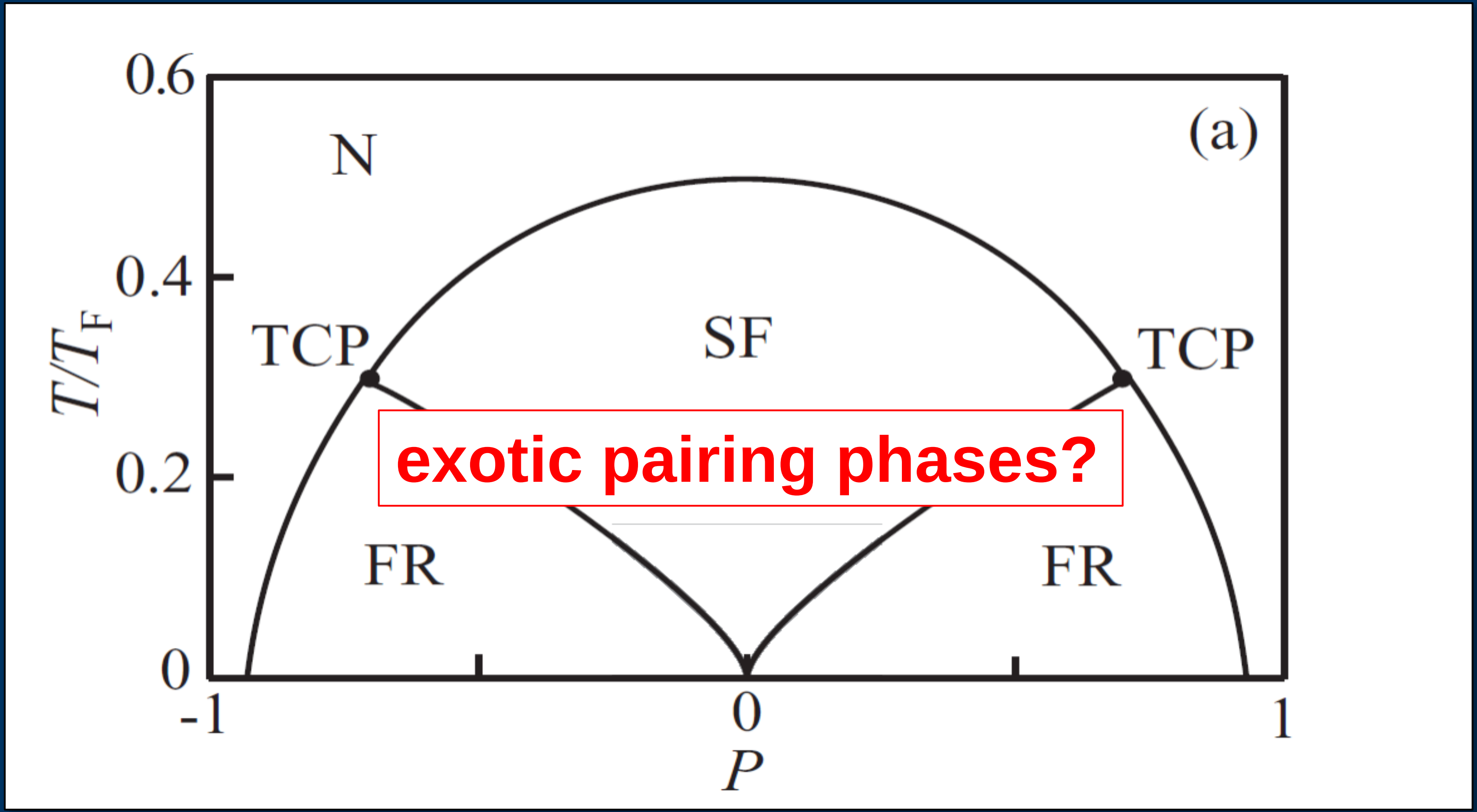
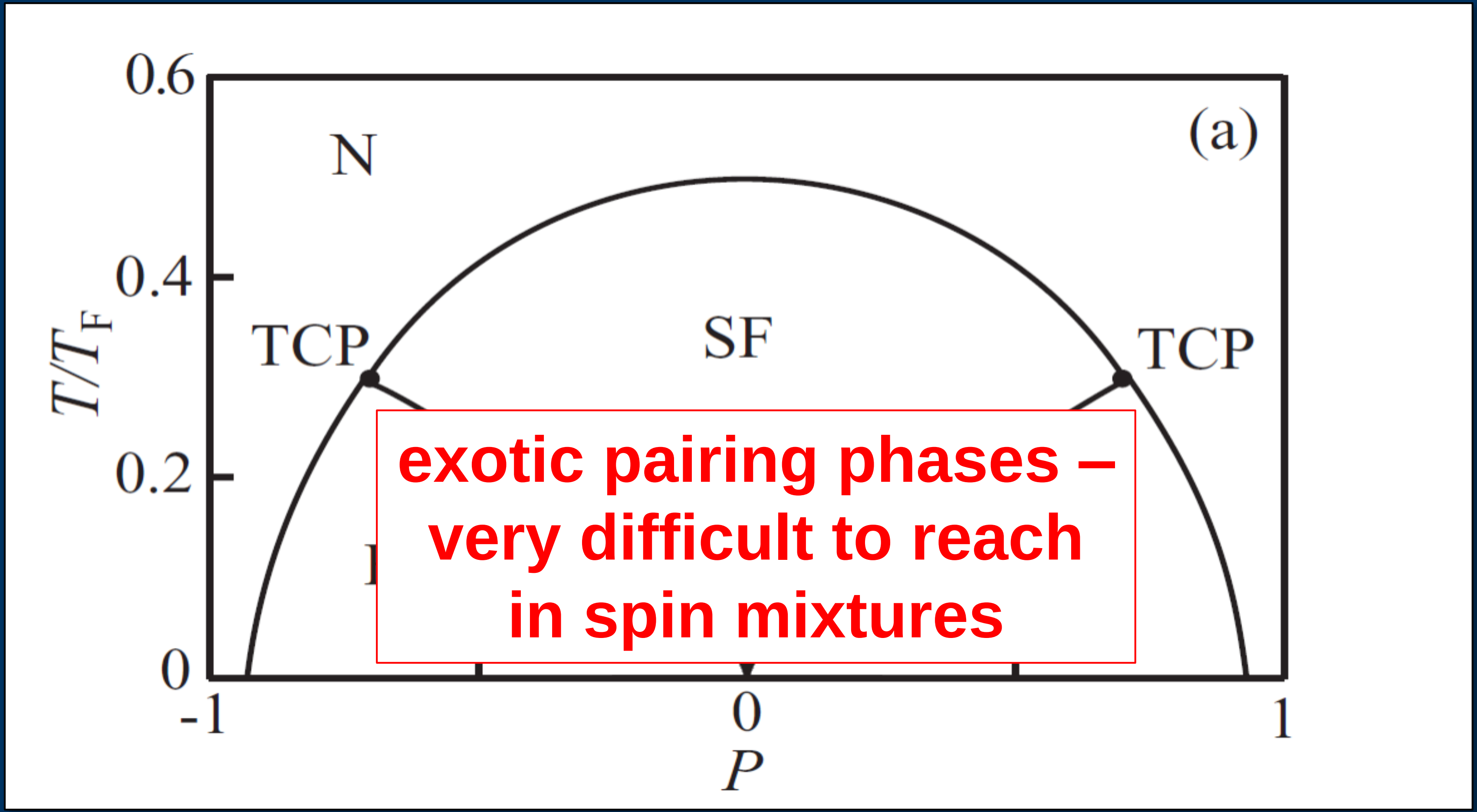


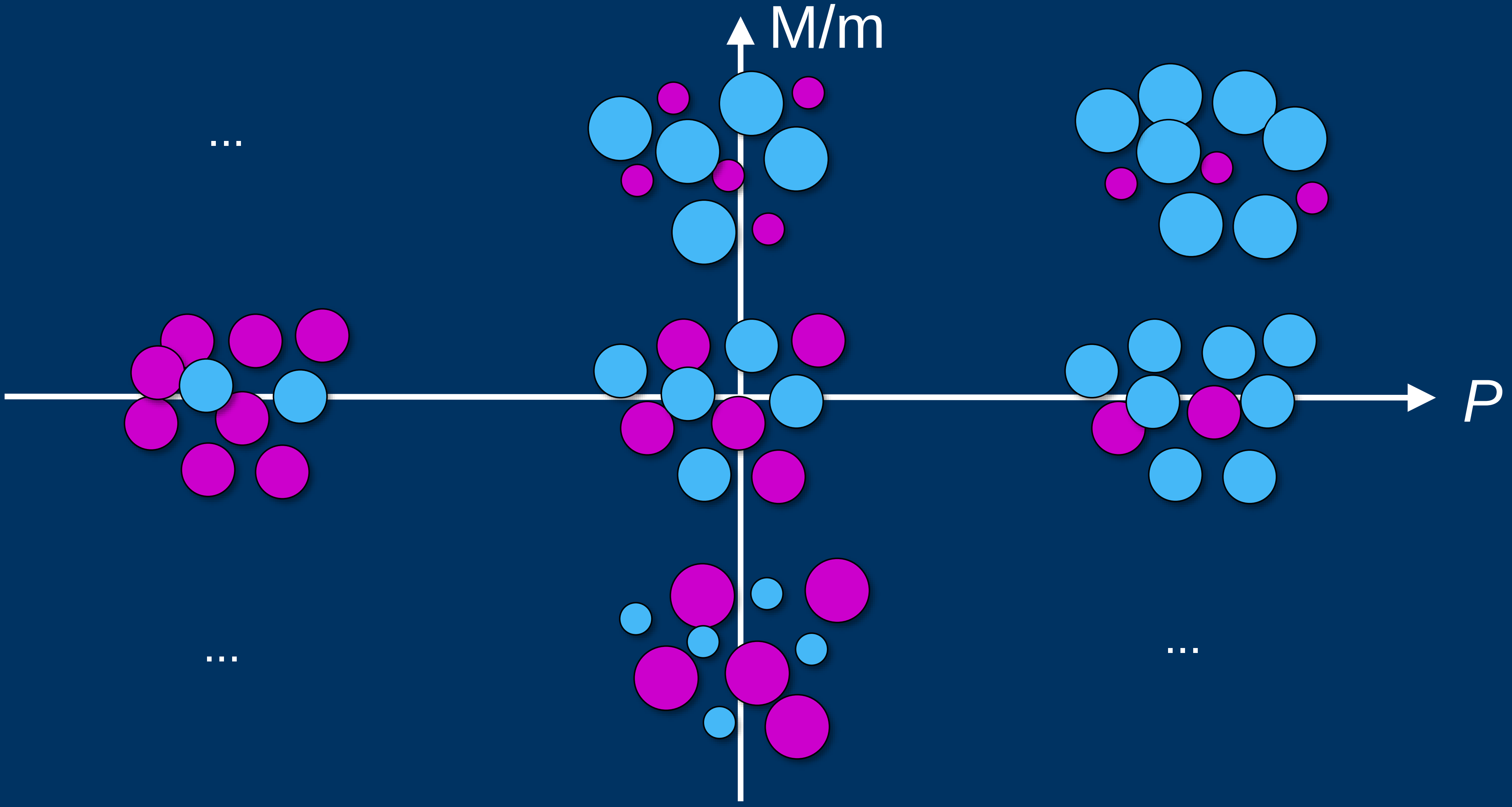
theoretical phase diagram

Baarsma, Gubbels, Stoof, PRA 82, 013624 (2010)

homogeneous case on resonance, mean-field approach



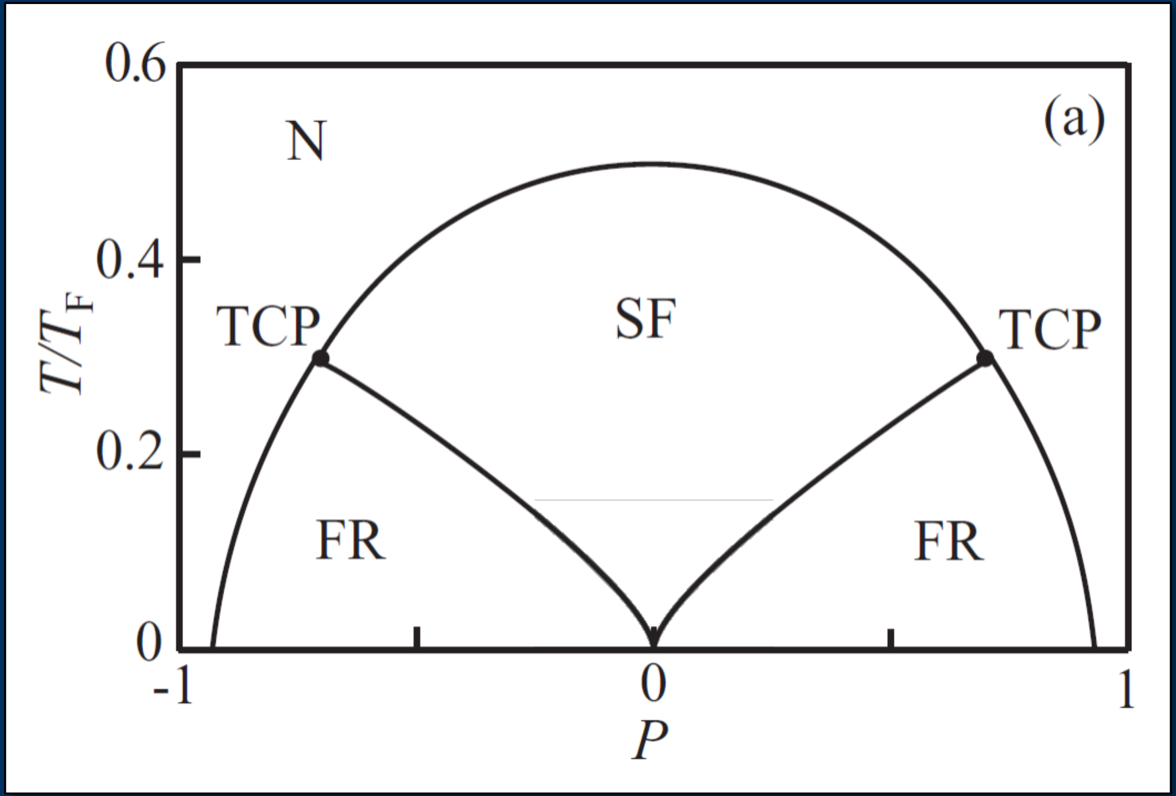
both mass and population imbalance



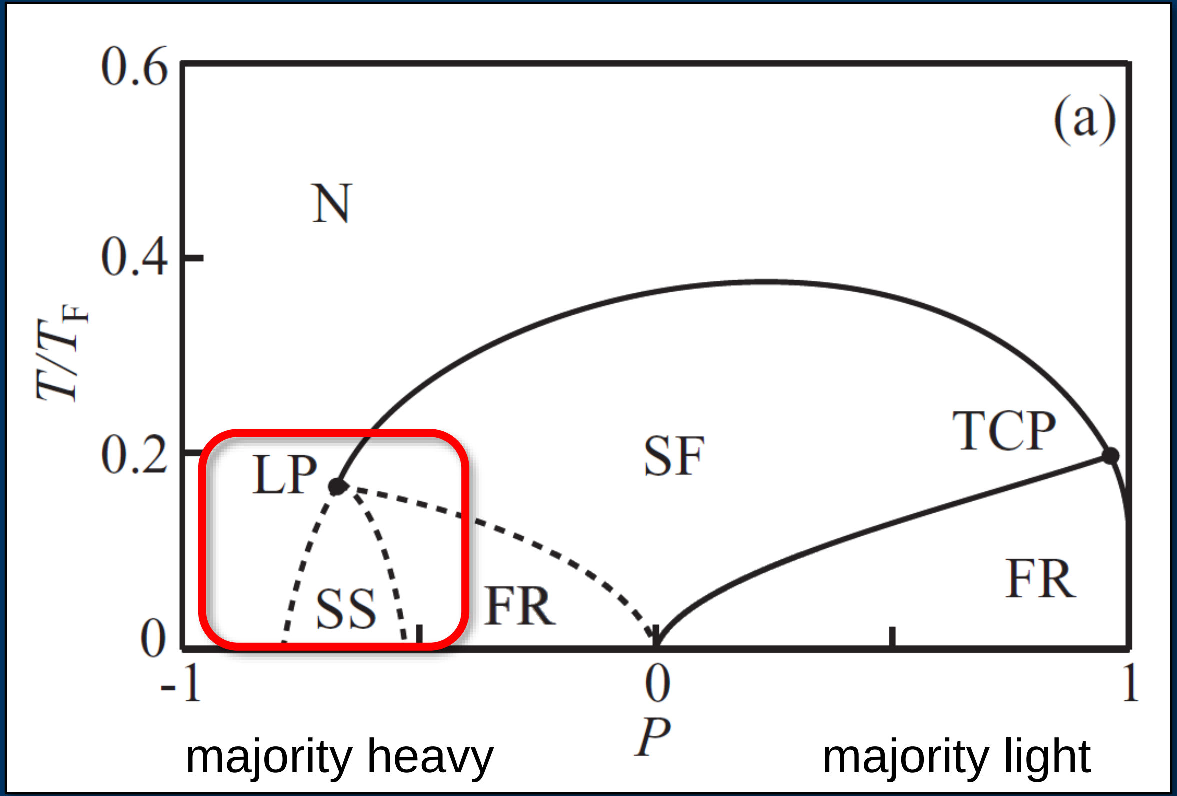
effect of mass imbalance on phase diagram

unitarity $1/k_F a = 0$, homogeneous system

M/m = 1 (mass balanced)



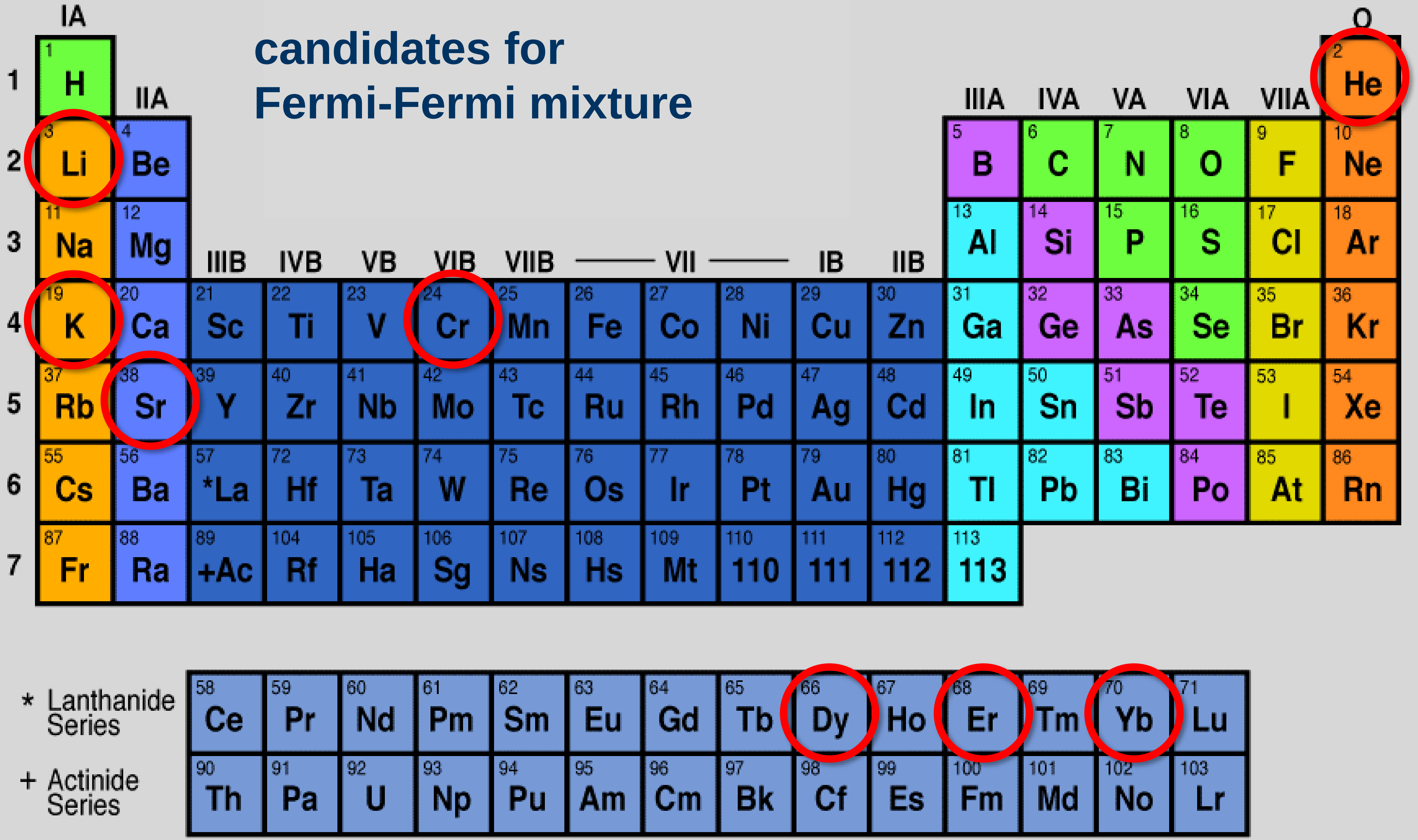
M/m = 40/6 (mass imbalanced)



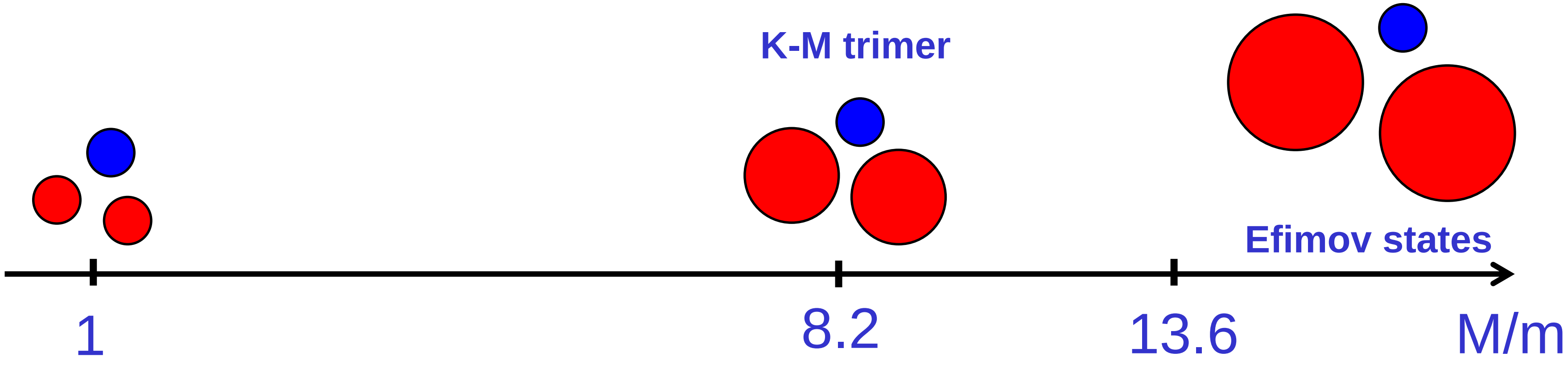
Baarsma, Gubbels, Stoof, PRA 82, 013624 (2010)

exciting things happen in expt. accessible range

candidates for Fermi-Fermi mixture



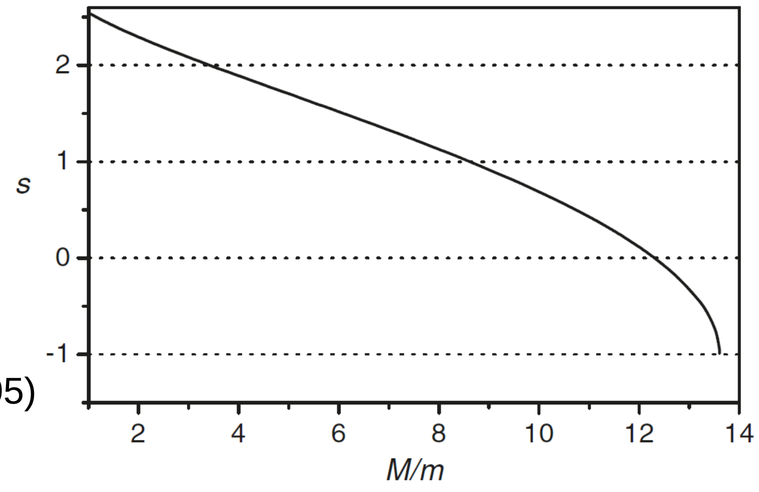
few-body physics of fermionic mixtures



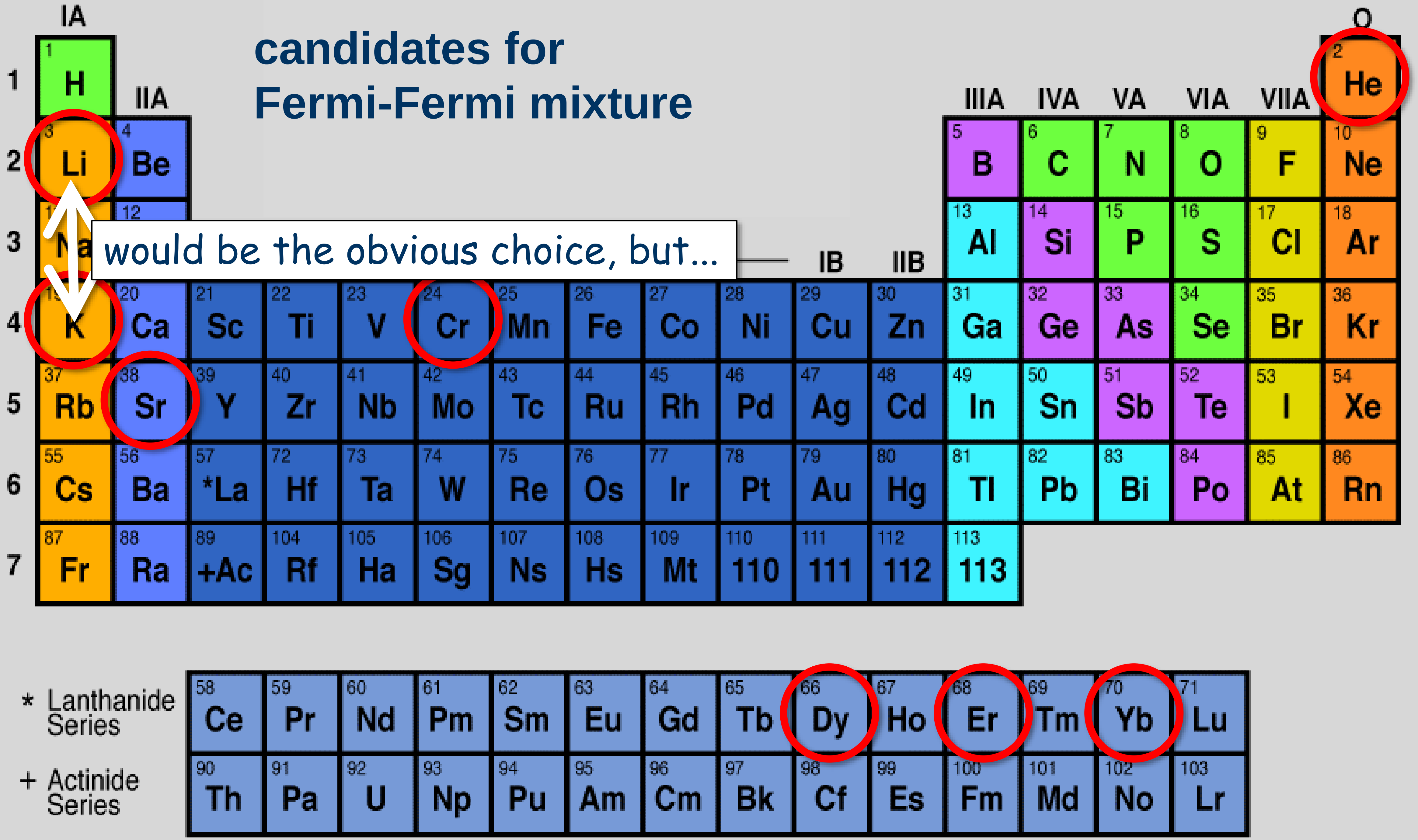
substantial mass imbalance,
but (hopefully) stable enough

at large scattering length
loss scales as a^{-s}

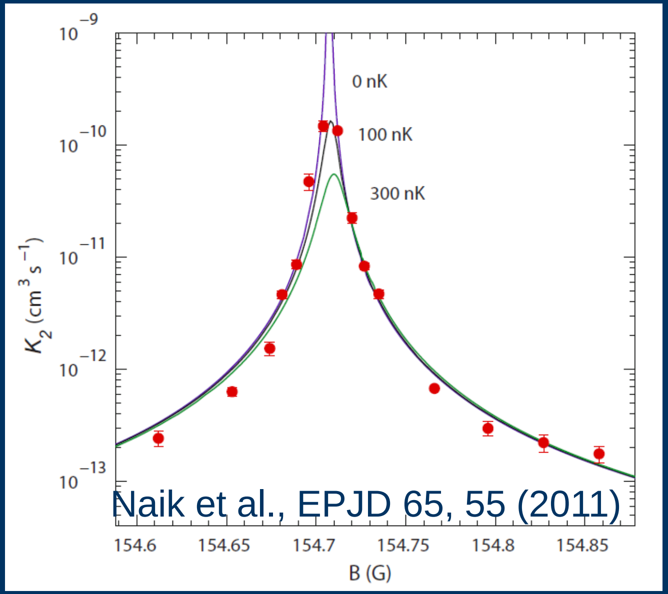
Petrov et al., J. Phys. B 38, S645 (2005)



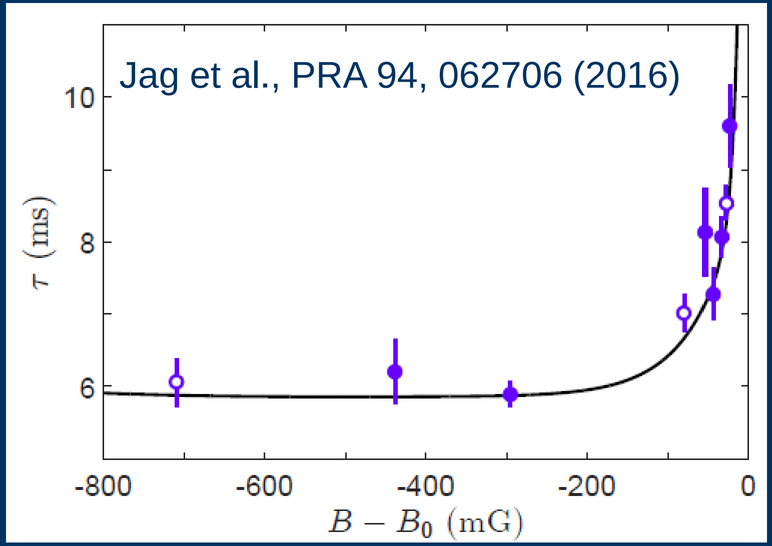
candidates for Fermi-Fermi mixture



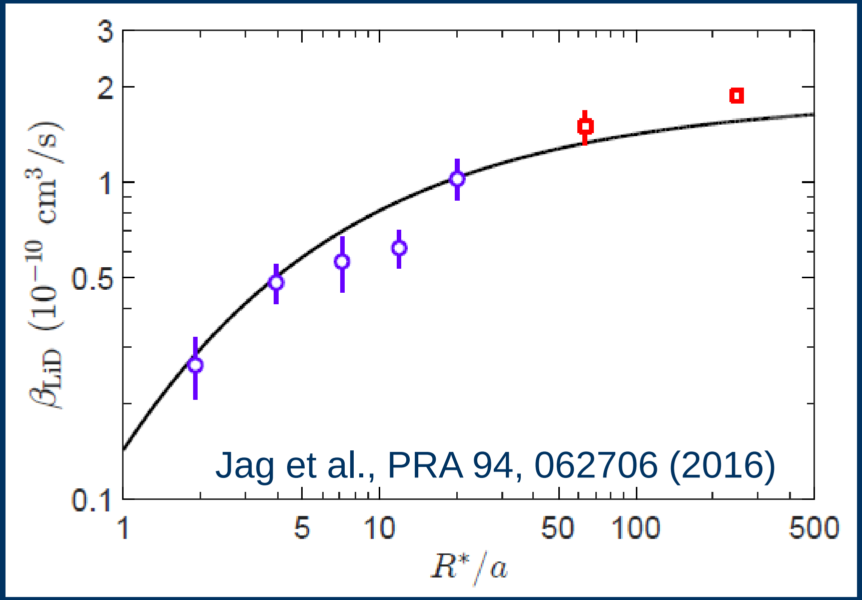
“secrets” of ^{6}Li - ^{40}K Feshbach resonances



two-body losses
in atomic mixture



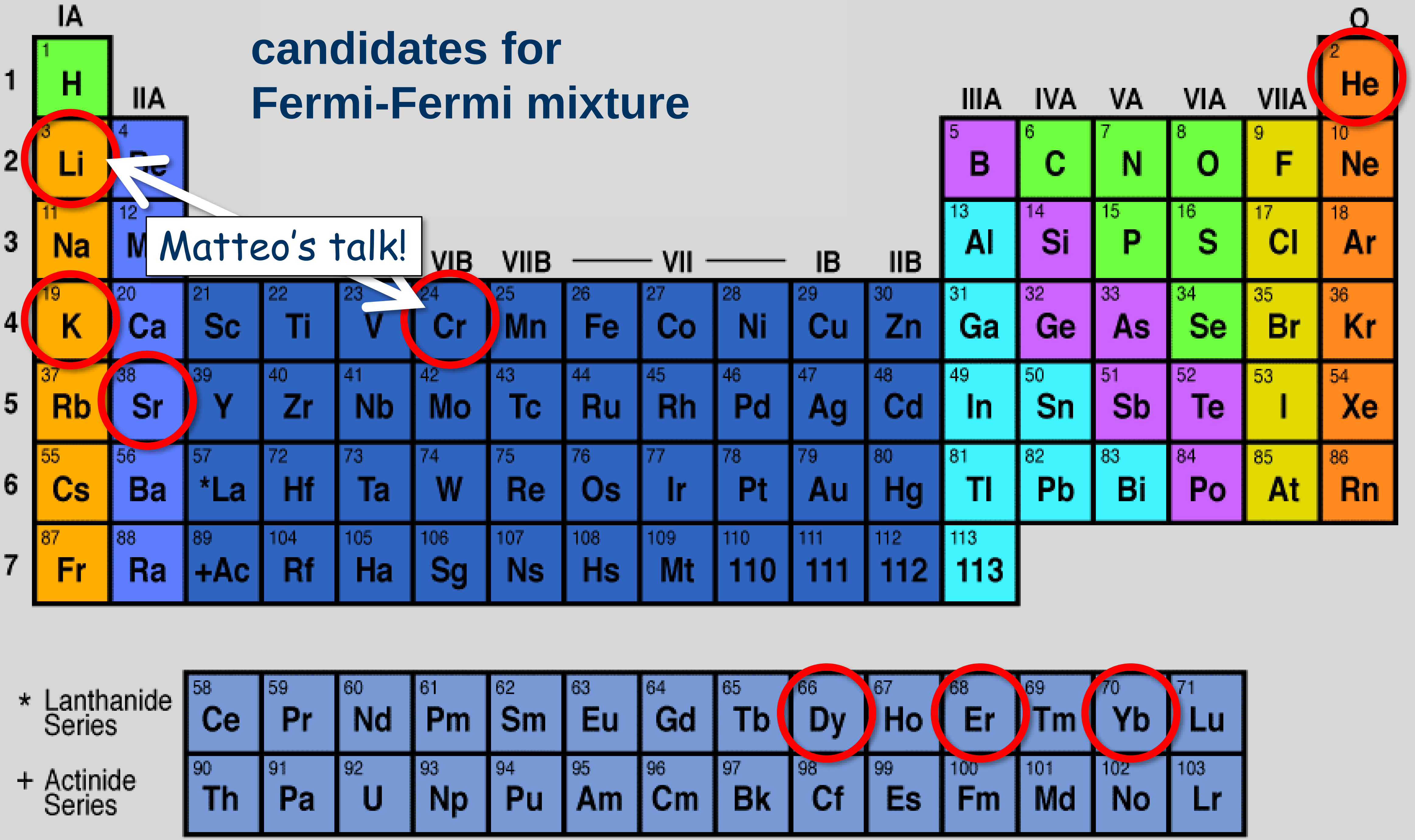
spontaneous dissociation
of Feshbach molecules



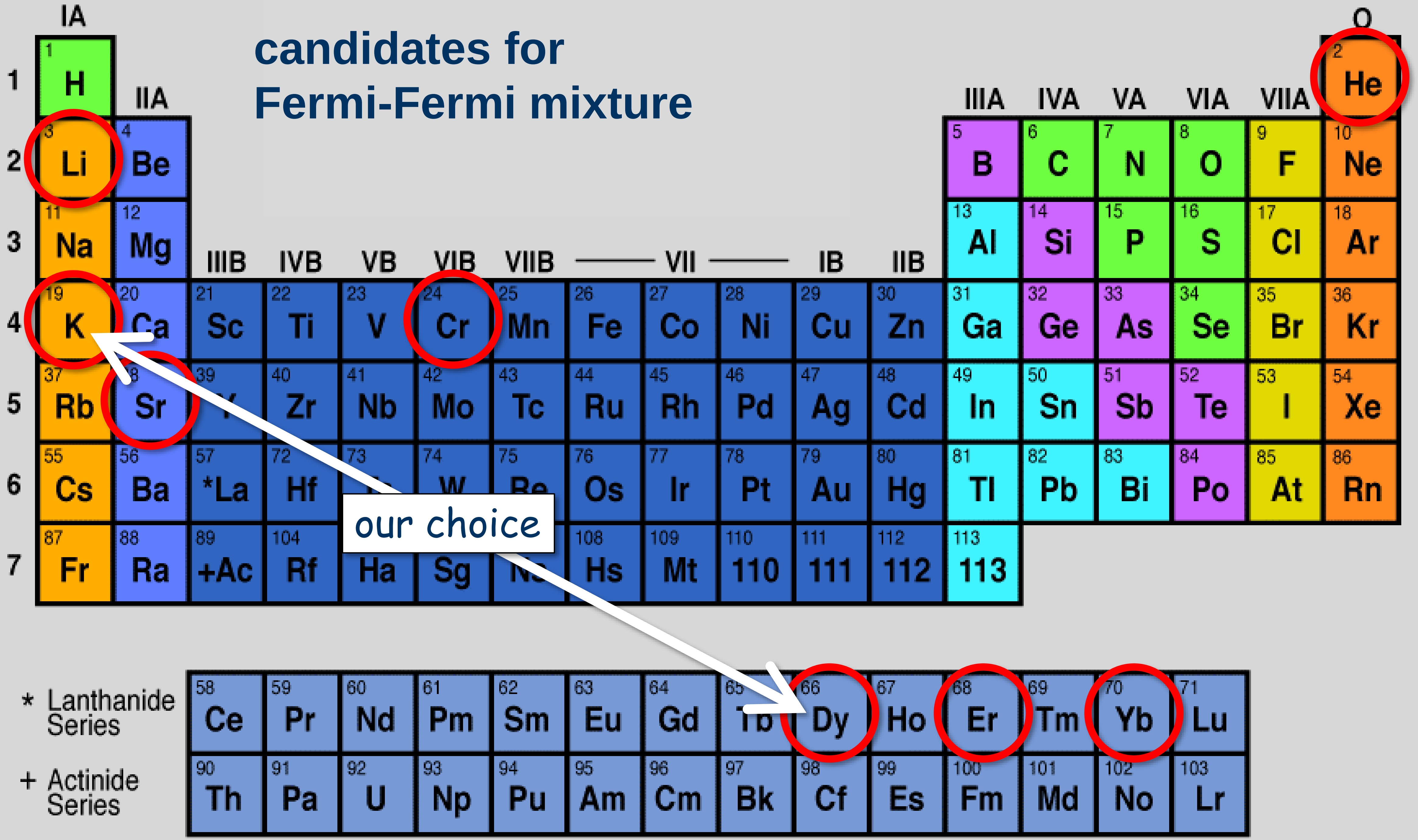
weak Pauli suppression
of few-body decay

Nature not kind to us:
unfavorable character of Feshbach resonances
-> short lifetimes of few ms only!

candidates for Fermi-Fermi mixture



candidates for Fermi-Fermi mixture



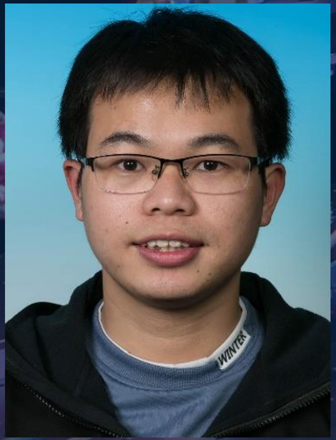
Dy-K team

present

Elisa
Soave

Marian
Kreyer

Alberto
Canali



Zhuxiong
Ye

Emil
Kirilov

RG

past

Cornee
Ravensbergen

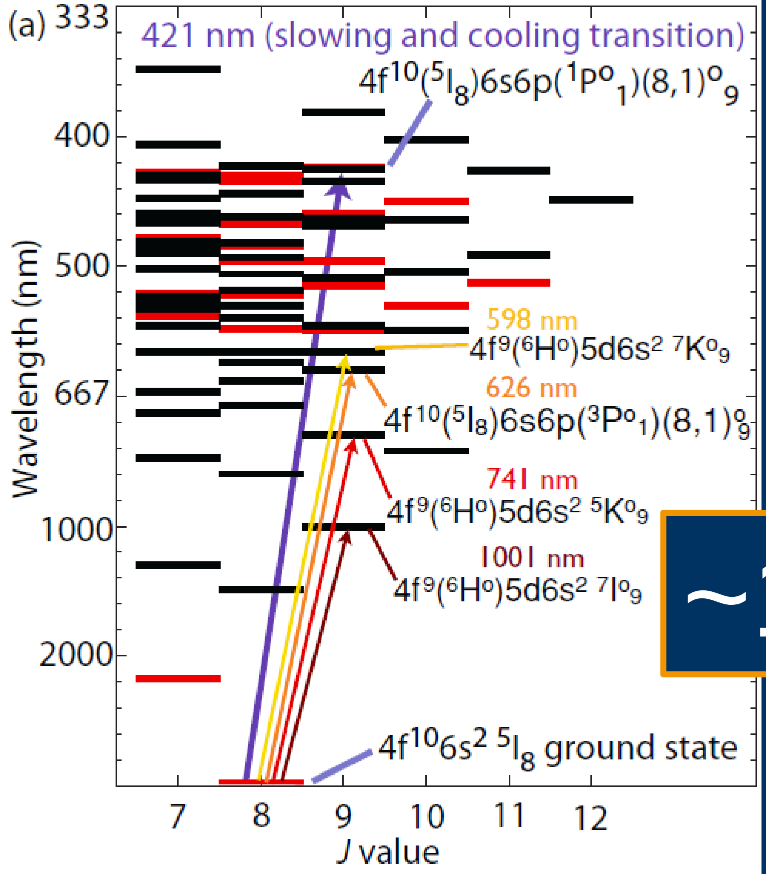
Slava
Tzanova

Jeong Ho
Han

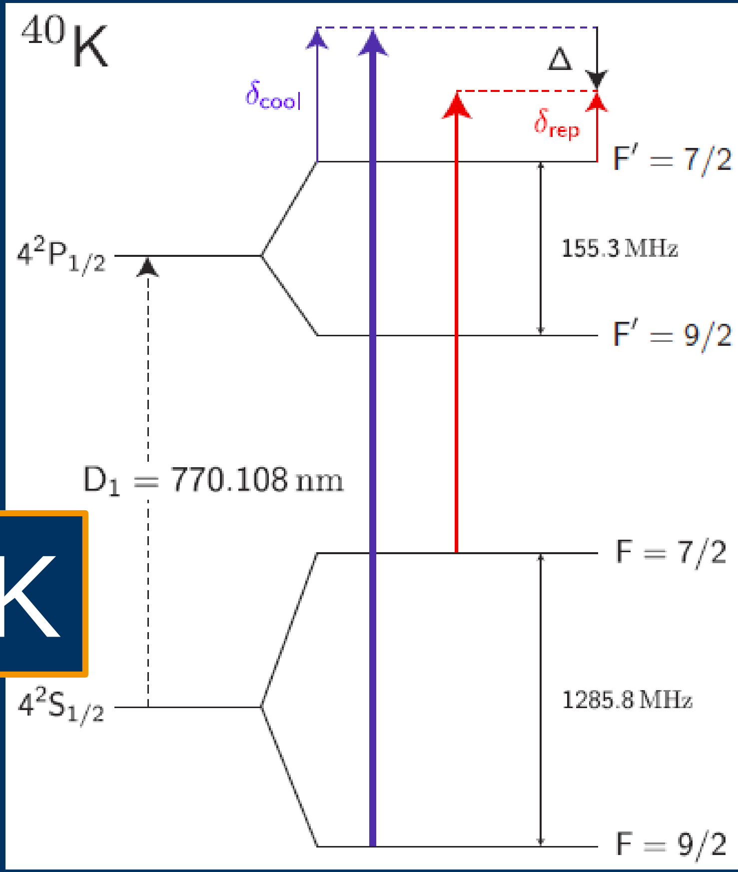
Vincent
Corre

laser cooling properties of Dy and K

Figure from Lu et al., PRA 83, 012110 (2011)



~10μK

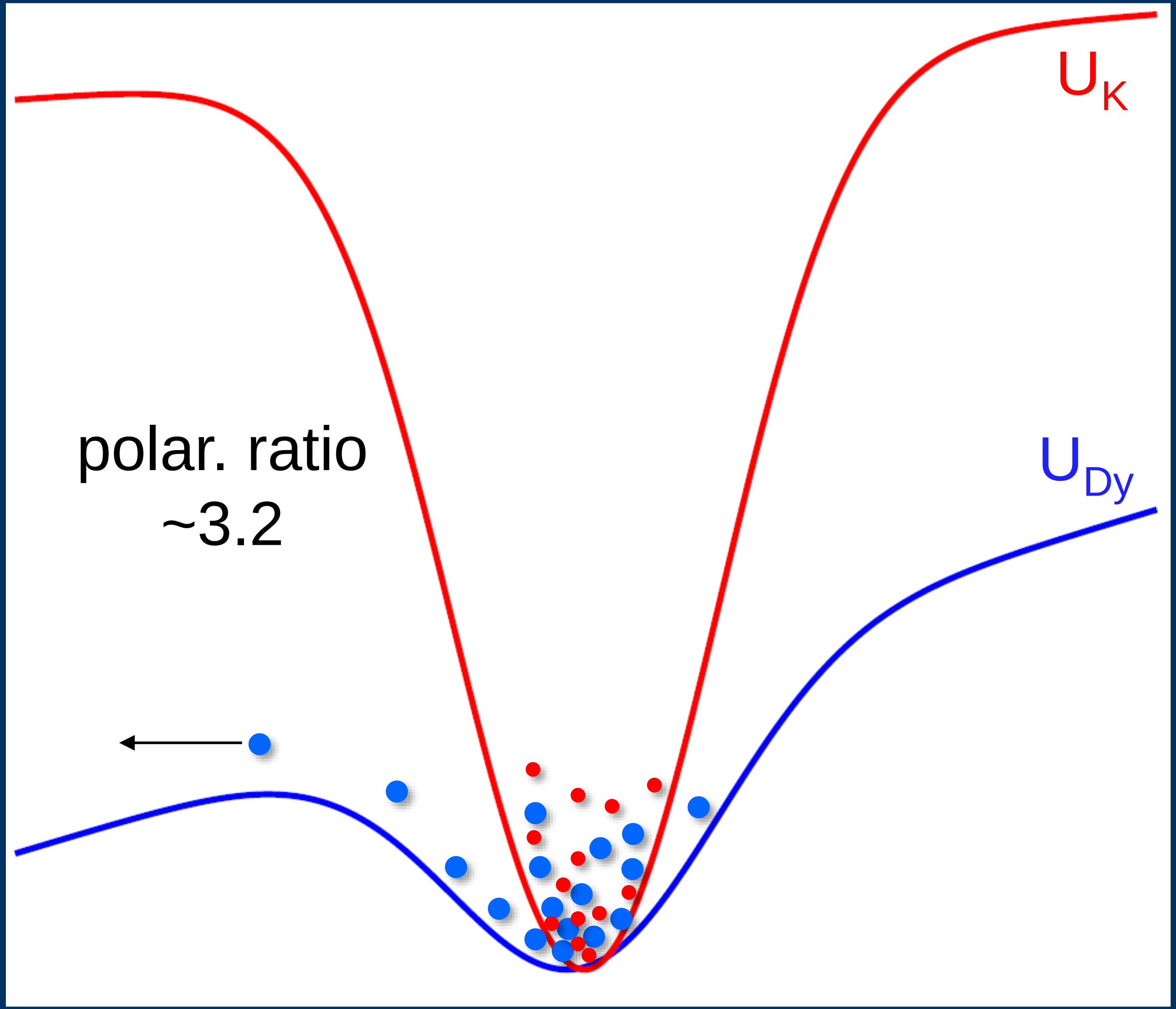


421nm - Zeeman slowing
626nm – MOT
Maier et al., Opt. Lett. 39, 3138 (2014)

D1 sub-Doppler cooling

Fernandes et al., EPL 100, 63001 (2012)
Sievers et al., PRA 91, 023426 (2015)

two-species evaporation scheme



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

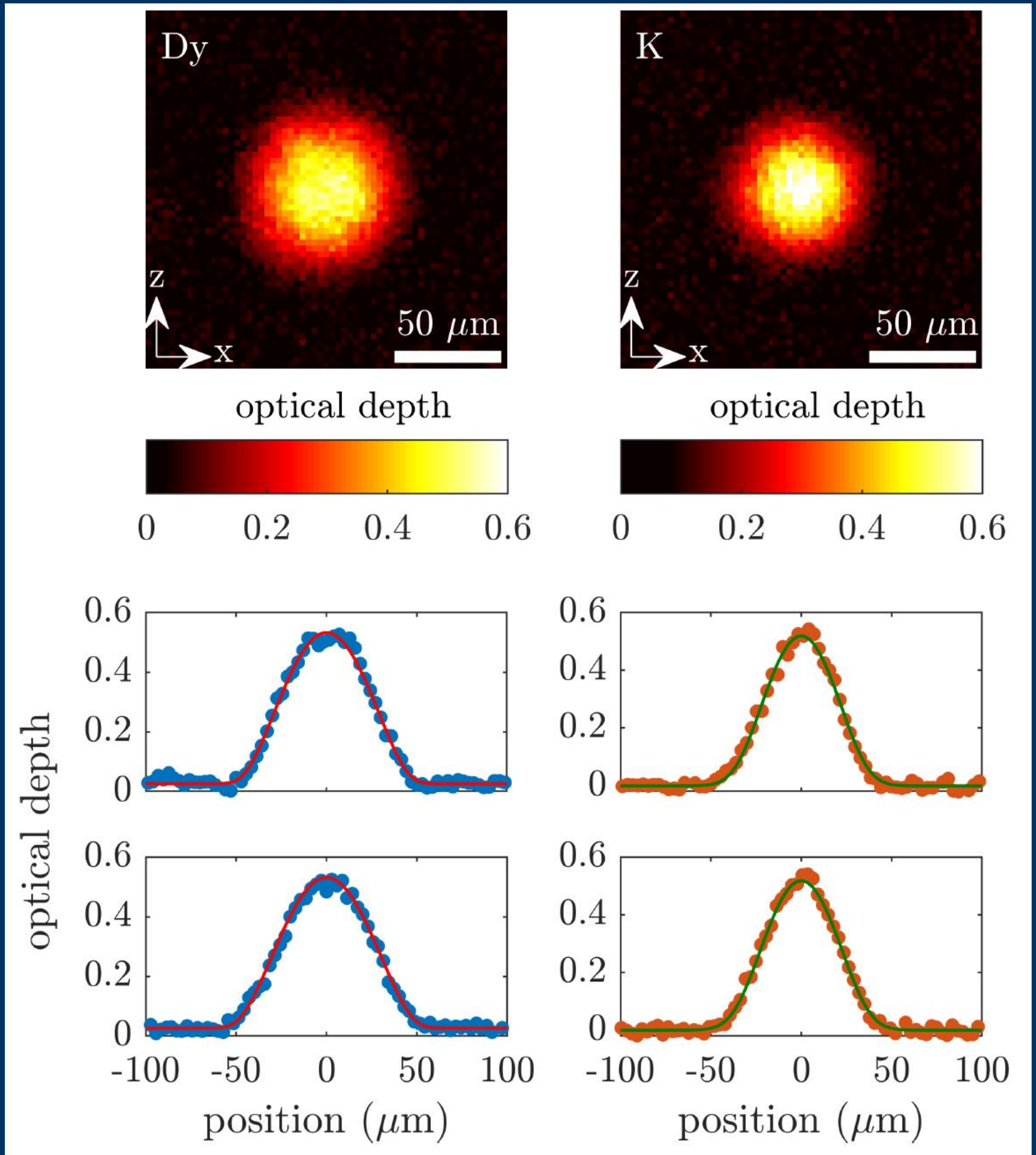
^{161}Dy – cooling agent

universal dipolar collisions

^{40}K – sympathetically cooled

low magnetic field of few 100 mG
avoid any resonances
$|a| \approx 60\ a_0$

optimum evaporative cooling result



Ravensbergen et al., PRA 98, 063624 (2018)
E. Soave, PhD thesis (2022)

^{161}Dy

7.5×10^4 atoms @ $T/T_F \approx 0.13$

^{40}K

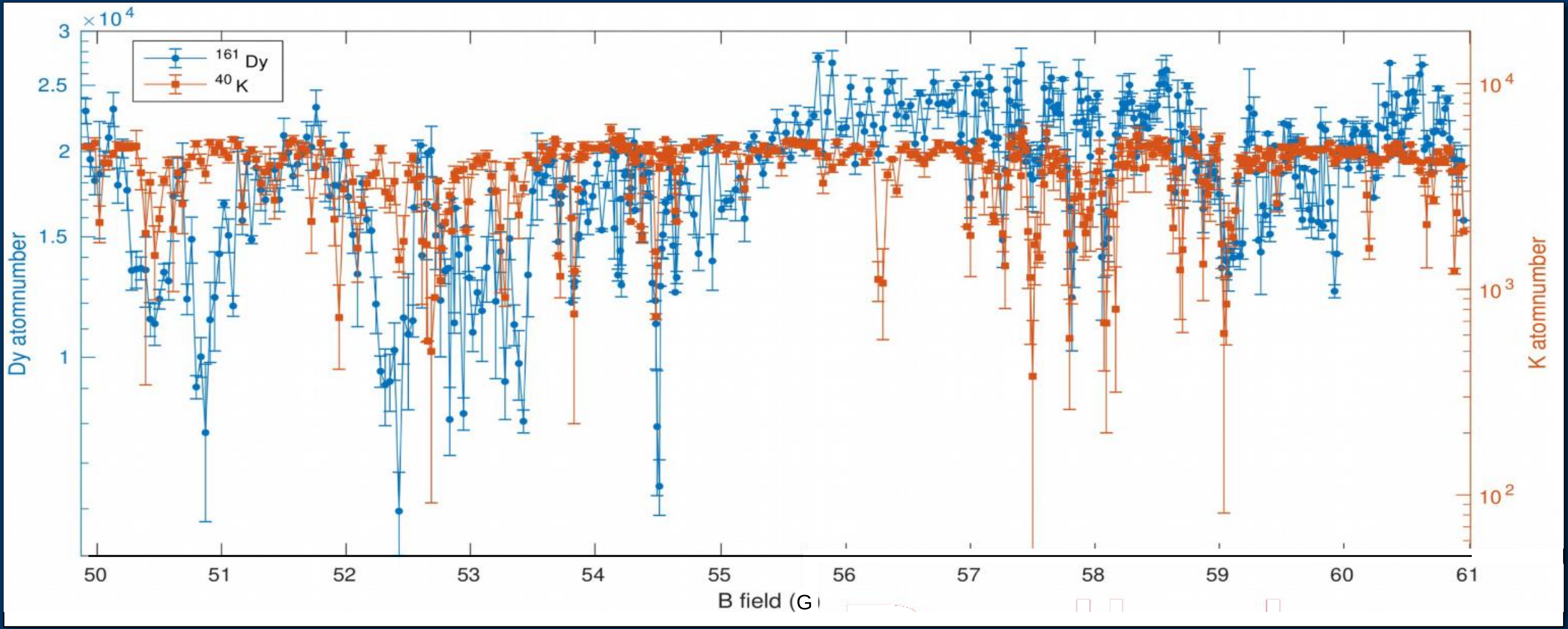
~ 10^4 atoms @ $T/T_F \approx 0.08$

number ratio can be controlled
by MOT loading times

does a good
interaction control knob
exist for ^{161}Dy-^{40}K ?

many narrow resonances (as expected)

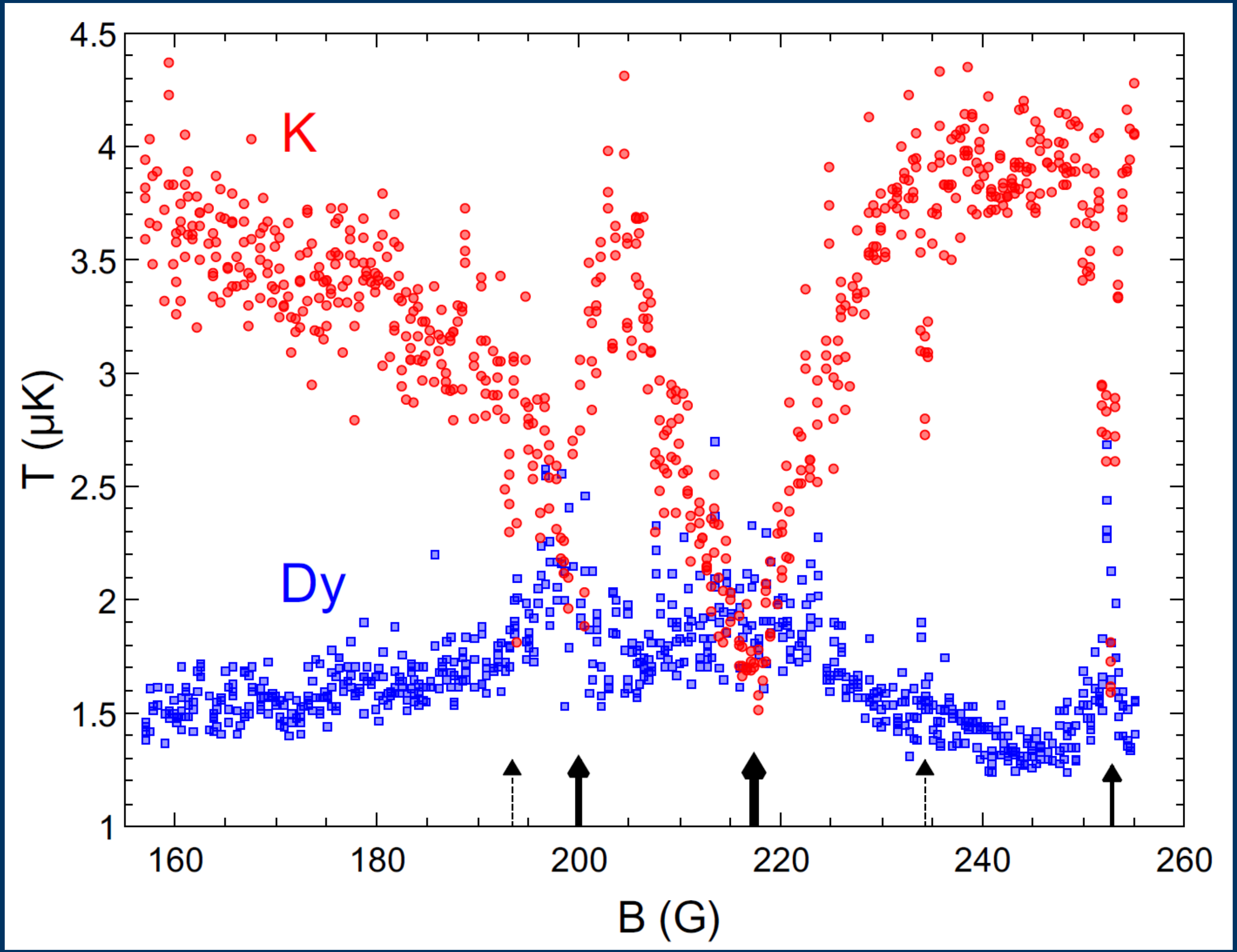
early B scan (2018)



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

search for broad Feshbach resonances

elastic scattering: cross-species thermalization



scenario of broad overlapping FRs

Ravensbergen et al., PRL 123, 203402 (2020)

overlapping FRs: recipe to extract scattering length

use product formula

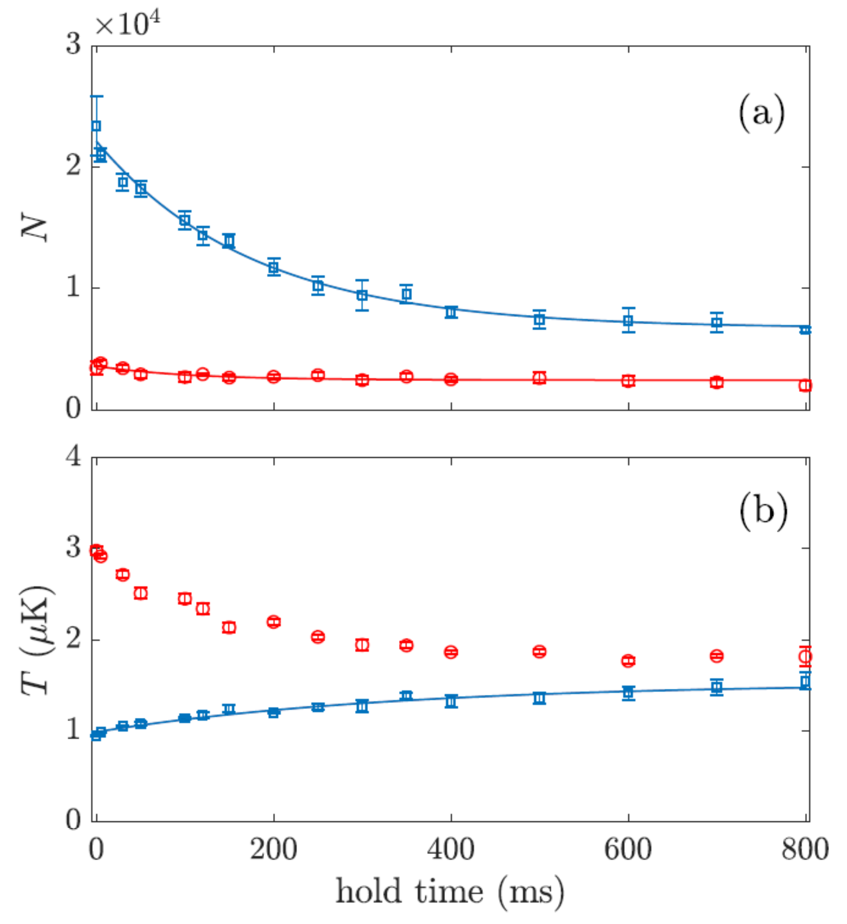
$$a(B) = a_{\mathrm{bg}} \prod_{i=1}^{n} \frac{B - c_i}{B - p_i}$$

zero crossings:
slowest interspecies thermalization

resonance poles:
fastest interspecies thermalization

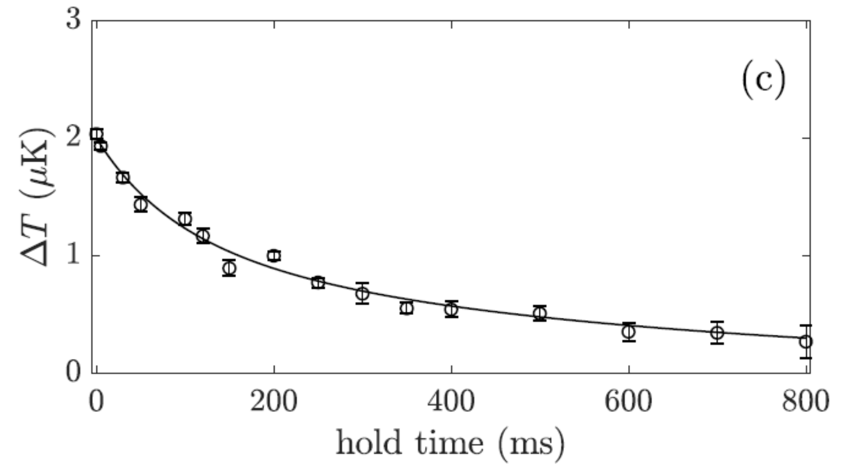
background scattering length:
from interspecies thermalization
at selected values of *B*
Mosk et al., Appl. Phys. B **73**, 791 (2001)

interspecies thermalization

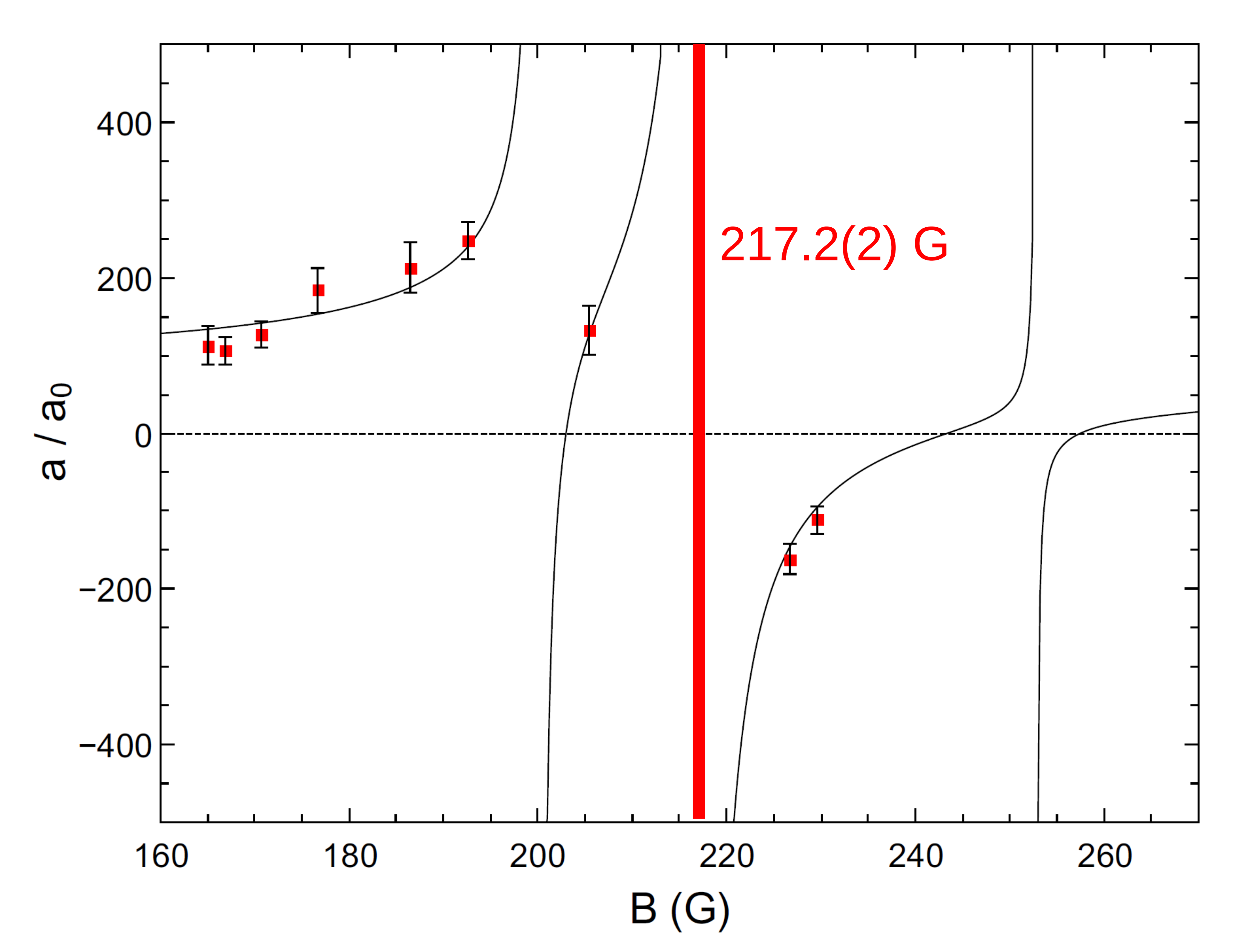


$$\frac{d}{dt}\Delta T = -\sigma_{\mathrm{el}} \frac{\xi q}{3\pi^2} \frac{m_{\mathrm{Dy}} \bar{\omega}_{\mathrm{Dy}}^3}{k_{\mathrm{B}} T_{\mathrm{Dy}}} (N_{\mathrm{Dy}} + N_{\mathrm{K}}) \Delta T$$

Mosk et al., Appl. Phys. B 73, 791 (2001)



Broad FRs in Dy-K



time-of-flight expansion

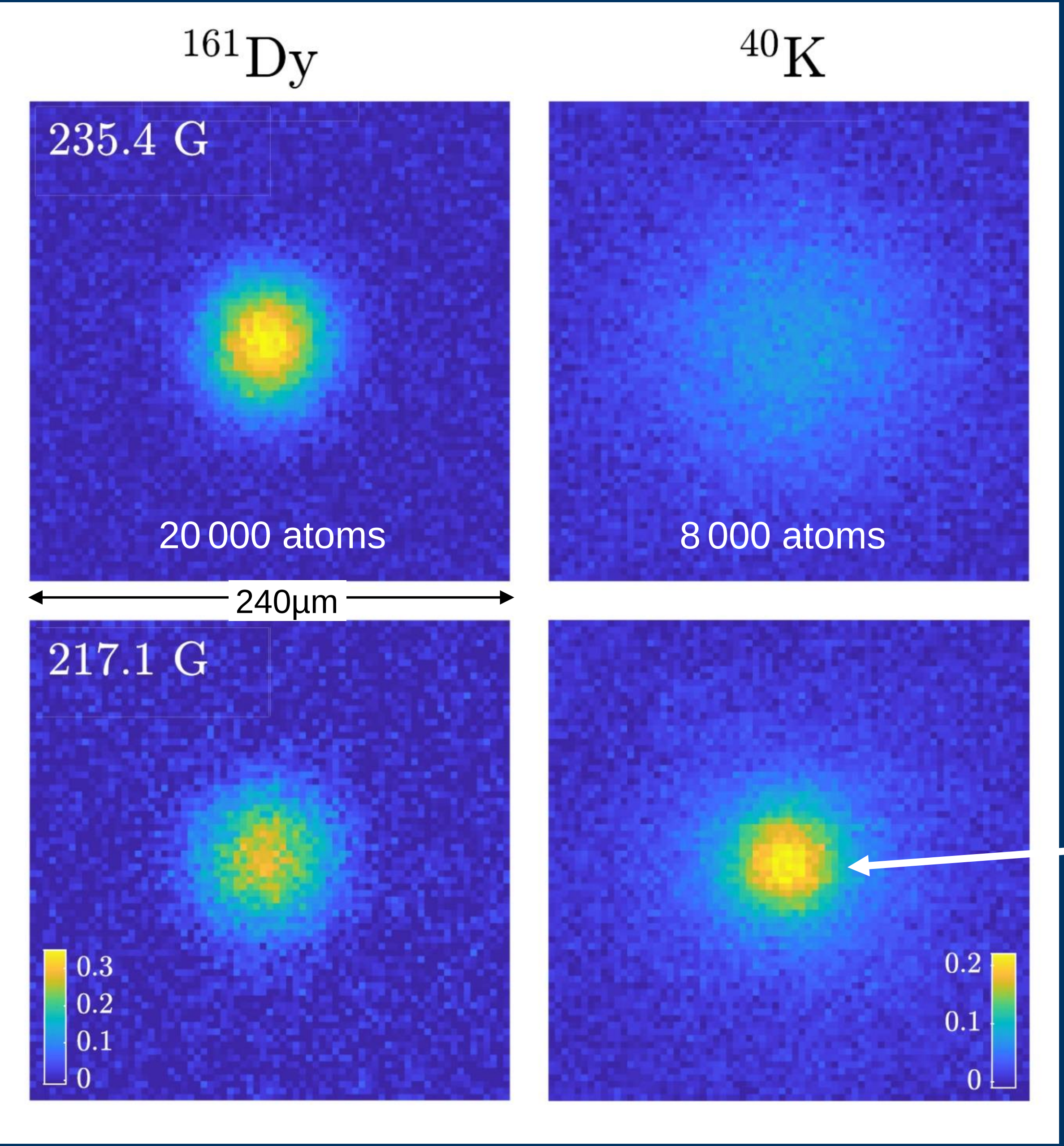
thermalized mixt.
$(T/T_F)_{Dy} = 1.7$
$(T/T_F)_K = 0.65$

4.5 ms TOF

Ravensbergen et al.,
PRL 124, 203402 (2020)

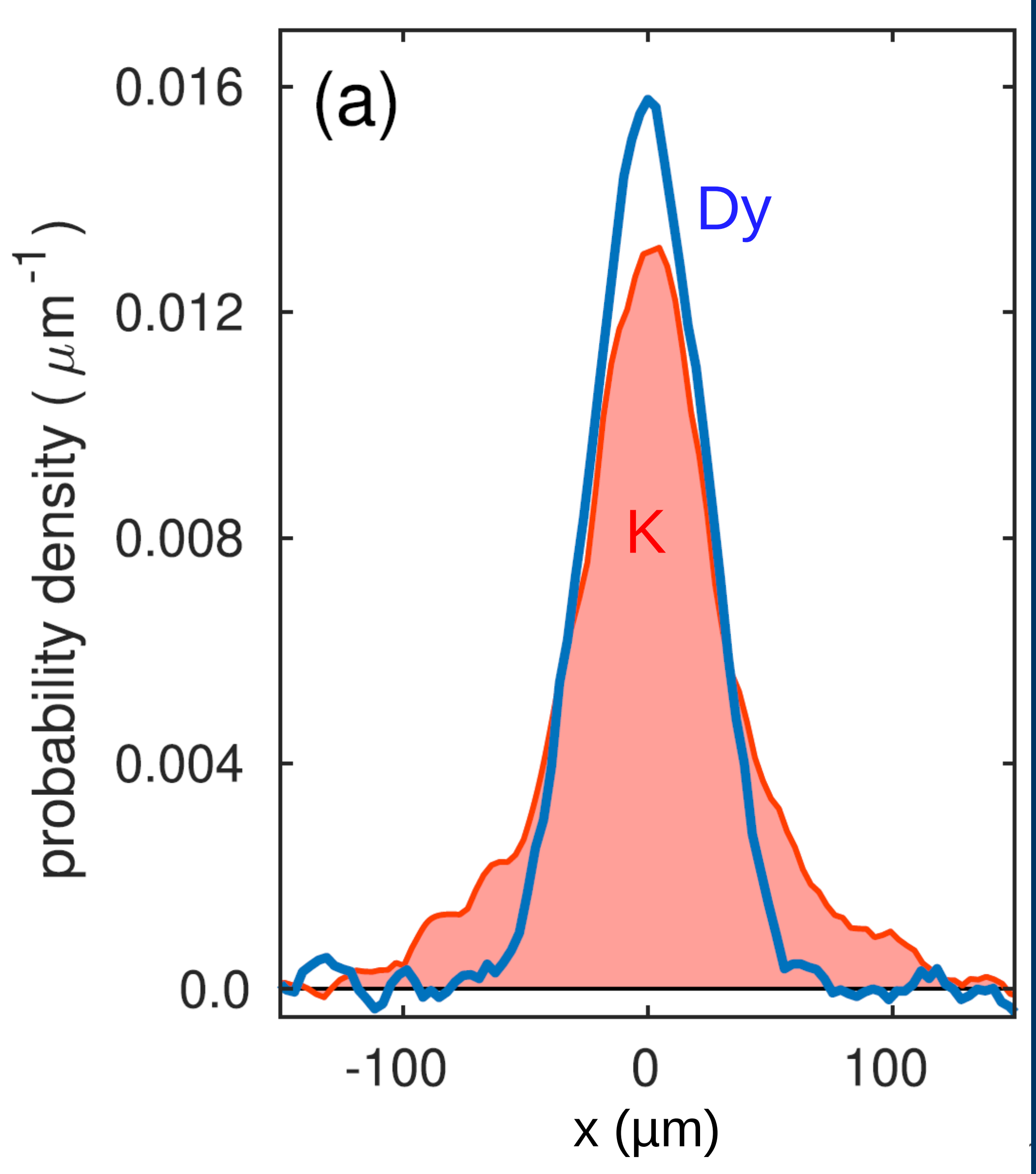
no interaction

resonant
interaction



!!!
locked hydrodynamic
expansion

density profiles: a surprise

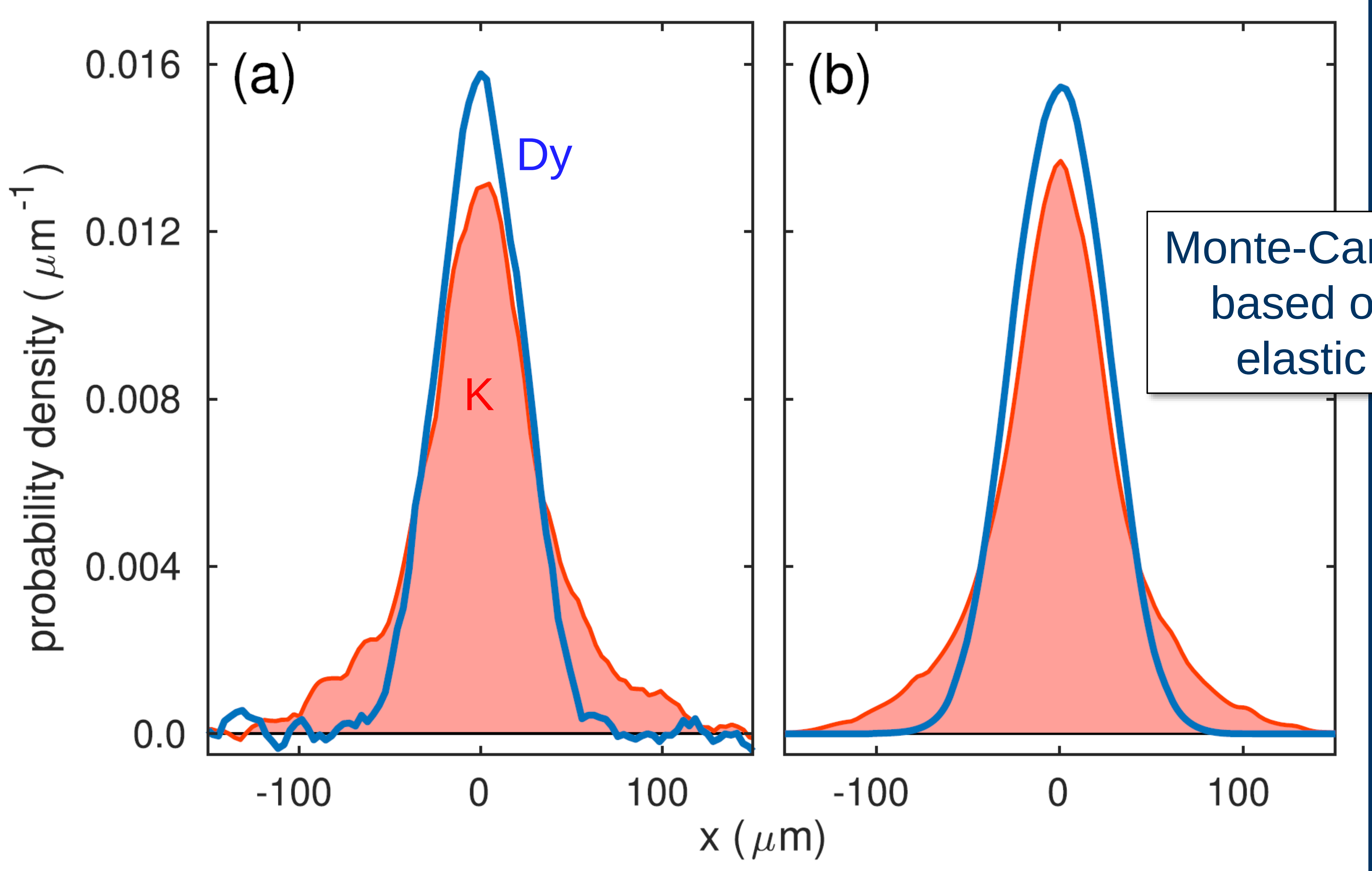


bimodality in K profile?

superfluidity???

no, a generic effect of
collisional hydrodynamics
in a mass-imbalanced mixture

density profiles: a surprise



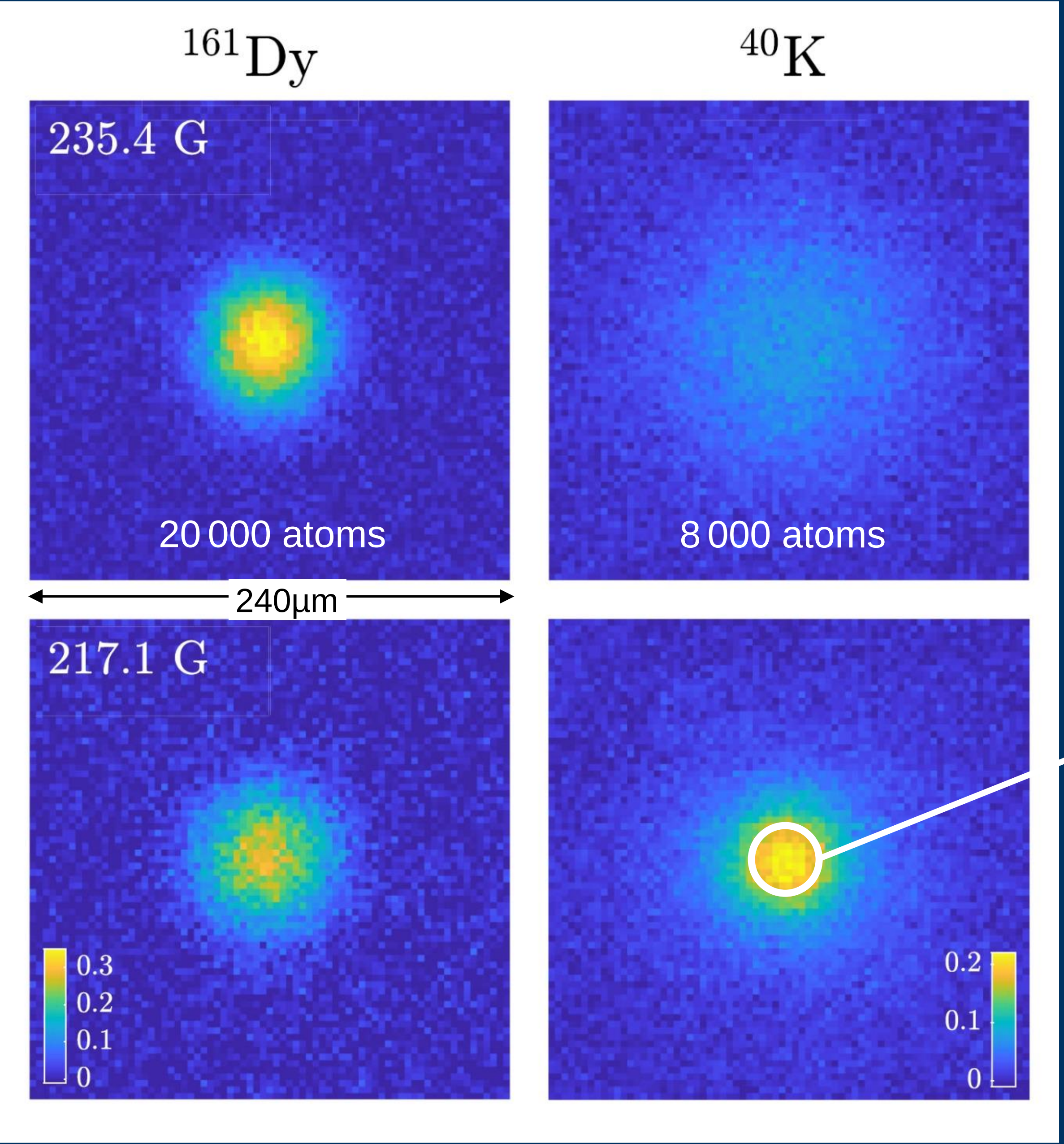
Monte-Carlo simulation based on resonant elastic collisions

time-of-flight expansion

thermalized mixt.
$(T/T_F)_{Dy} = 1.7$
$(T/T_F)_K = 0.65$

no interaction

resonant interaction

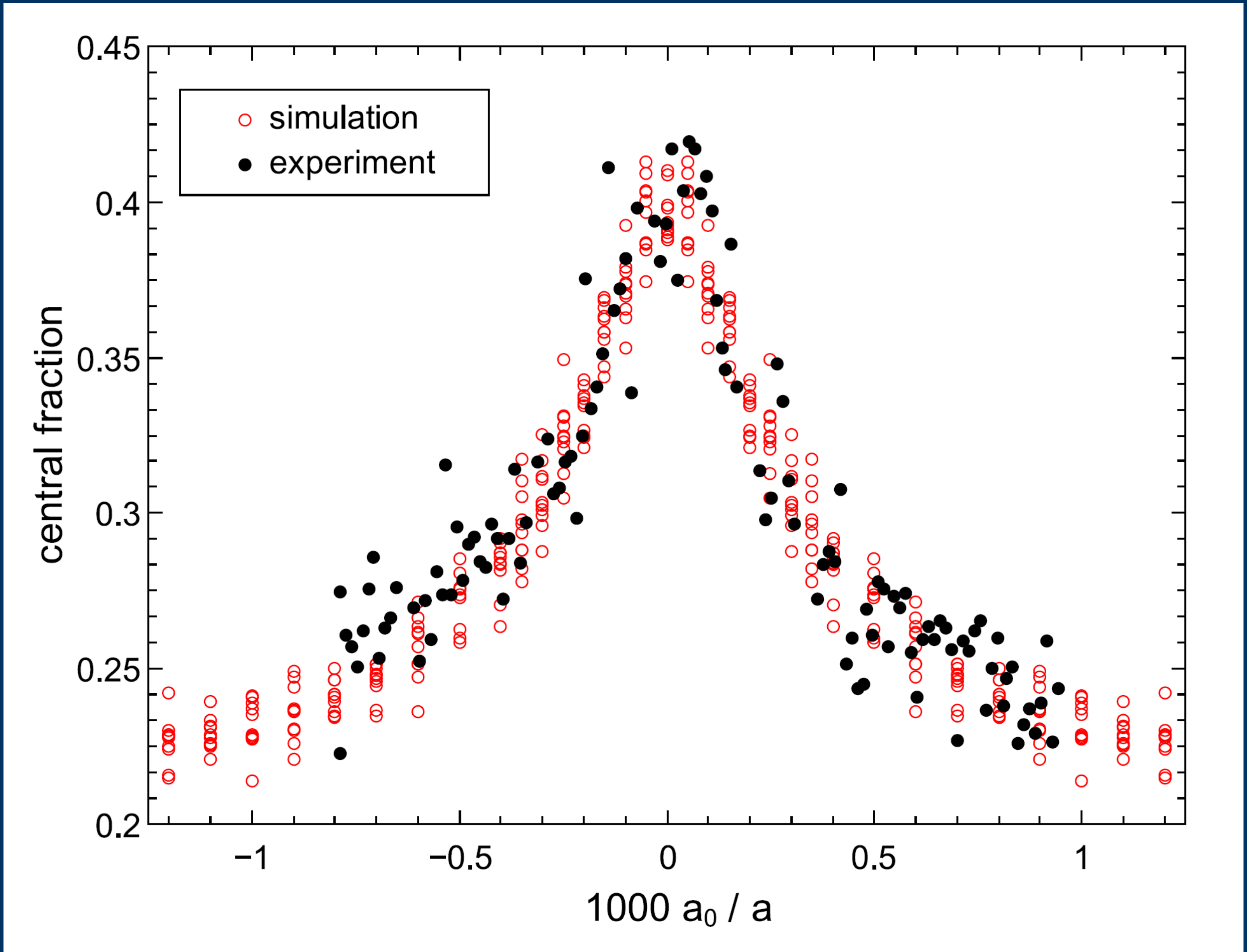


4.5 ms TOF

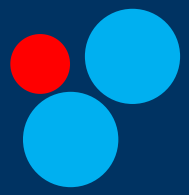
Ravensbergen et al., PRL 124, 203402 (2020)

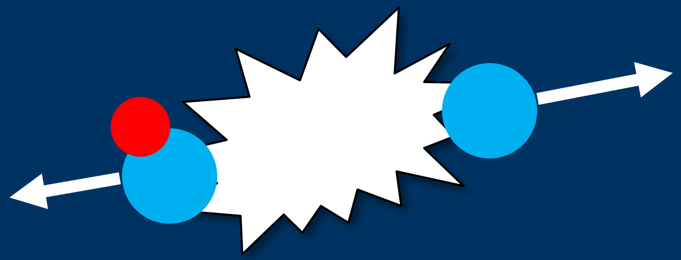
further analysis: fraction of atoms in the center

hydrodynamic expansion: central fraction of K atoms

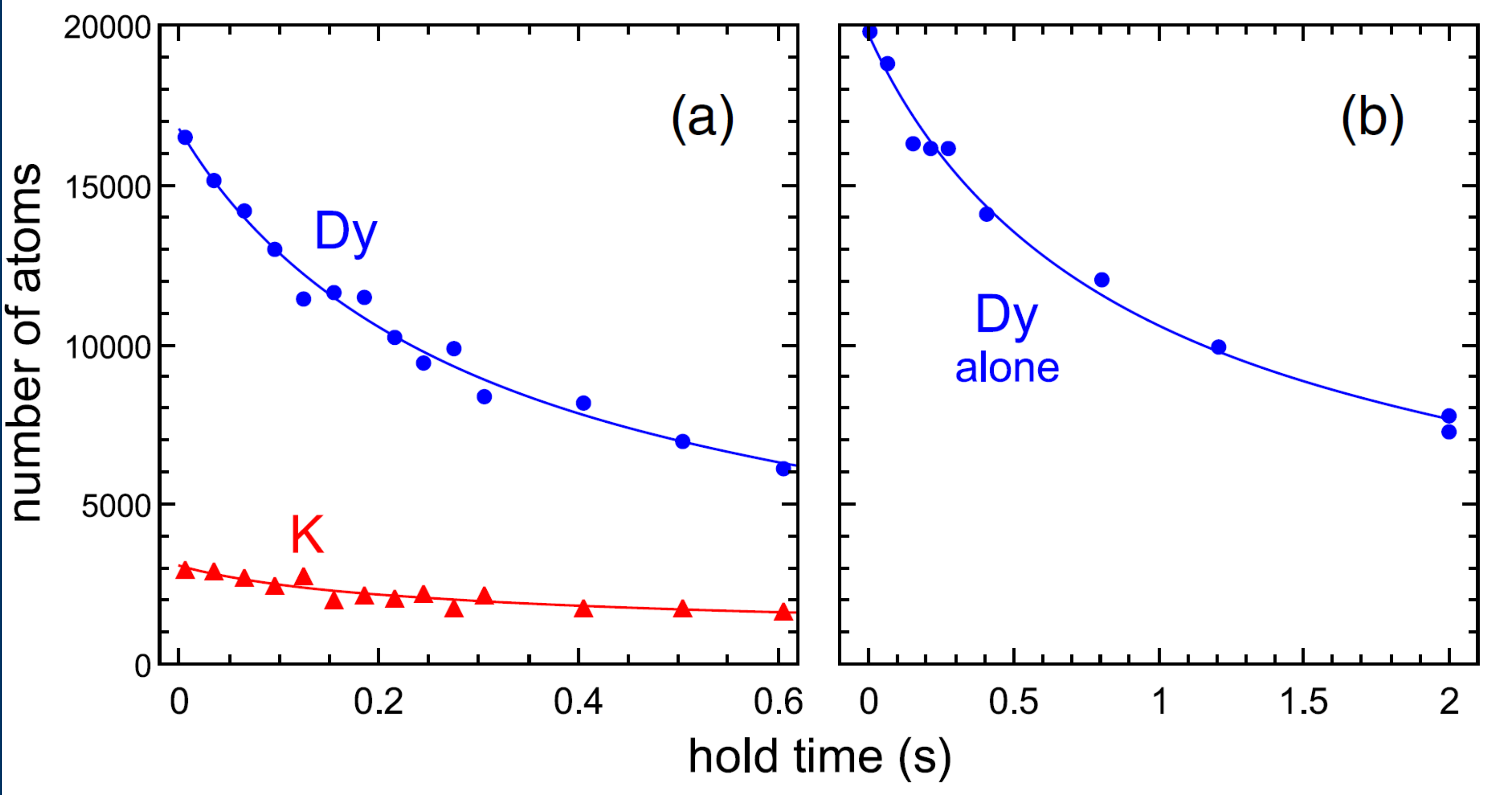


collisional stability:
will few-body processes kill us?





analyzing decay curves



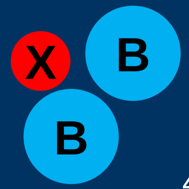
217.5 G

event rate coefficients for all three-body processes
(K-Dy-Dy, K-K-Dy, Dy-Dy-Dy)
below 10^{-25} cm^6/s

three-body event rate coefficient

Bose-Fermi and Bose-Bose systems
(Efimov physics)

our Fermi-Fermi mixture



^{40}K-^{87}Rb (JILA)

^{6}K-^{41}K (Innsbruck)

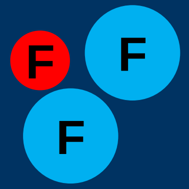
^{6}K-^{133}Cs (Heidelb., Chicago)

^{40}K-^{162}Dy (Innsbruck)

^{39}K-^{87}Rb (Aarhus)

^{41}K-^{87}Rb (Aarhus, LENS)

^{7}Li-^{87}Rb (Tübingen)



^{40}K-^{161}Dy (Innsbruck)

10^{-23} ... 10^{-21} cm^6/s

10^{-25} cm^6/s

2...4 orders of magnitude suppression !!!!

Superfluidity in reach?

G. Strinati

PHYSICAL REVIEW A **103**, 023314 (2021)

Beyond-mean-field description of a trapped unitary Fermi gas with mass and population imbalance

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[2]Dipartimento di Fisica e Astronomia, Università di Bologna, I-40127 Bologna (BO), Italy
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(Received 30 November 2020; accepted 22 January 2021; published 15 February 2021)

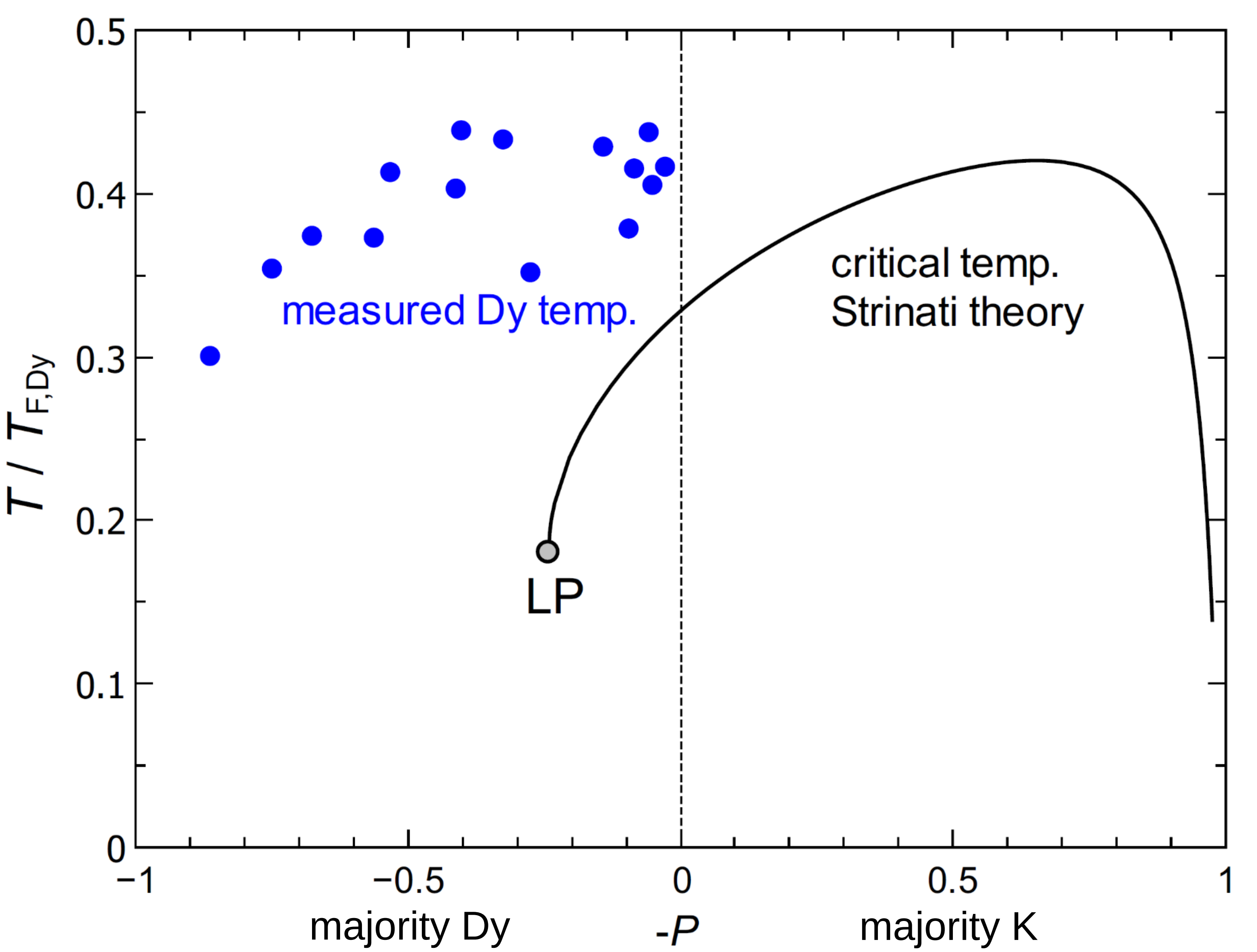
A detailed description is given of the phase diagram for a two-component unitary Fermi gas with mass and population imbalance, for both homogeneous and trapped systems. This aims at providing quantitative benchmarks for the normal-to-superfluid phase transition of a mass-imbalanced Fermi gas in the temperature-polarization parameter space. A self-consistent t-matrix approach is adopted, which has already proven to accurately describe the thermodynamic properties of the mass- and population-balanced unitary Fermi gas. Our results provide a guideline for the ongoing experiments on heteronuclear Fermi mixtures.

DOI: 10.1103/PhysRevA.103.023314

Superfluidity in reach?

critical temperature for Dy-K under our trapping conditions

Soave et al., PhD thesis (2022)



$$P \equiv \frac{N_{Dy} - N_K}{N_{Dy} + N_K}$$

intermediate conclusion

key ingredients for experiments on fermionic superfluids demonstrated!

- cooling into deeply degenerate regime achieved **@ few 100mG**
- interaction tuning via broad Feshbach resonance demonstrated **~217 G**
- Pauli suppression of losses for resonant mixture observed

good reasons to be very optimistic!

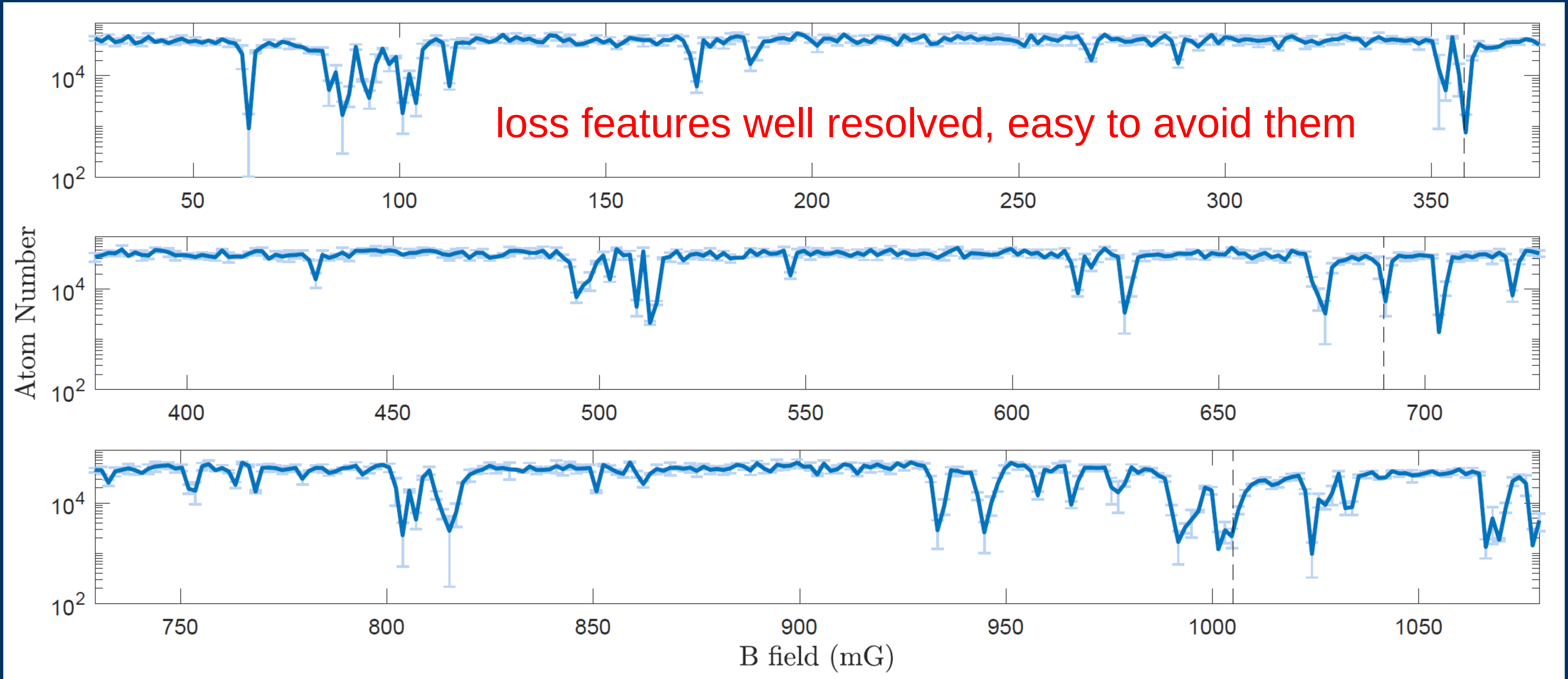
but…

transfer from low field to high field without losses and heating technically very challenging (very sensitive to eddy currents)

complex behavior of Dy-Dy-Dy background losses

narrow Dy FRs resolved at low field

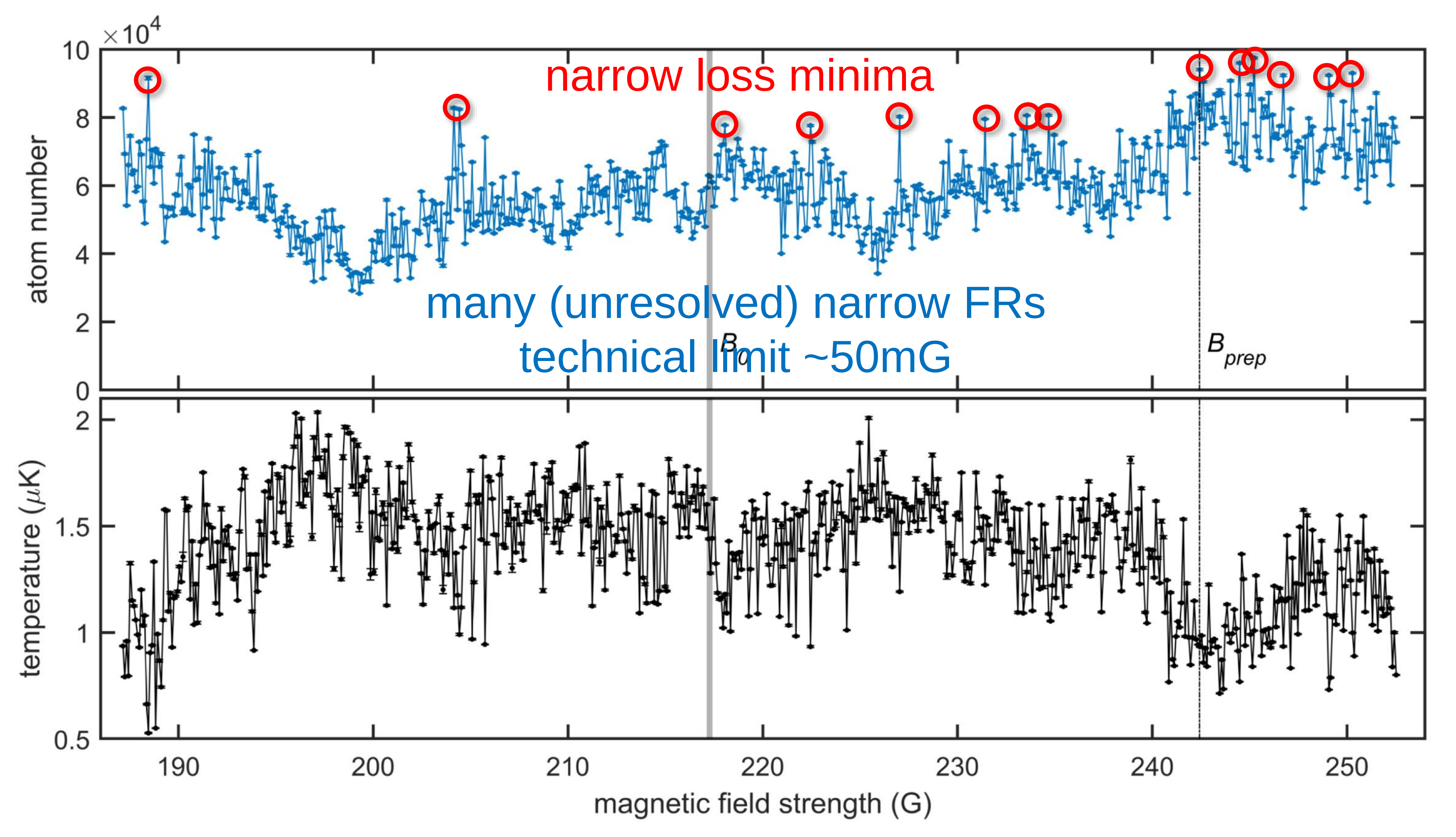
full range ~1G



Soave et al., Ukr. J. Phys., in press

Dy background losses

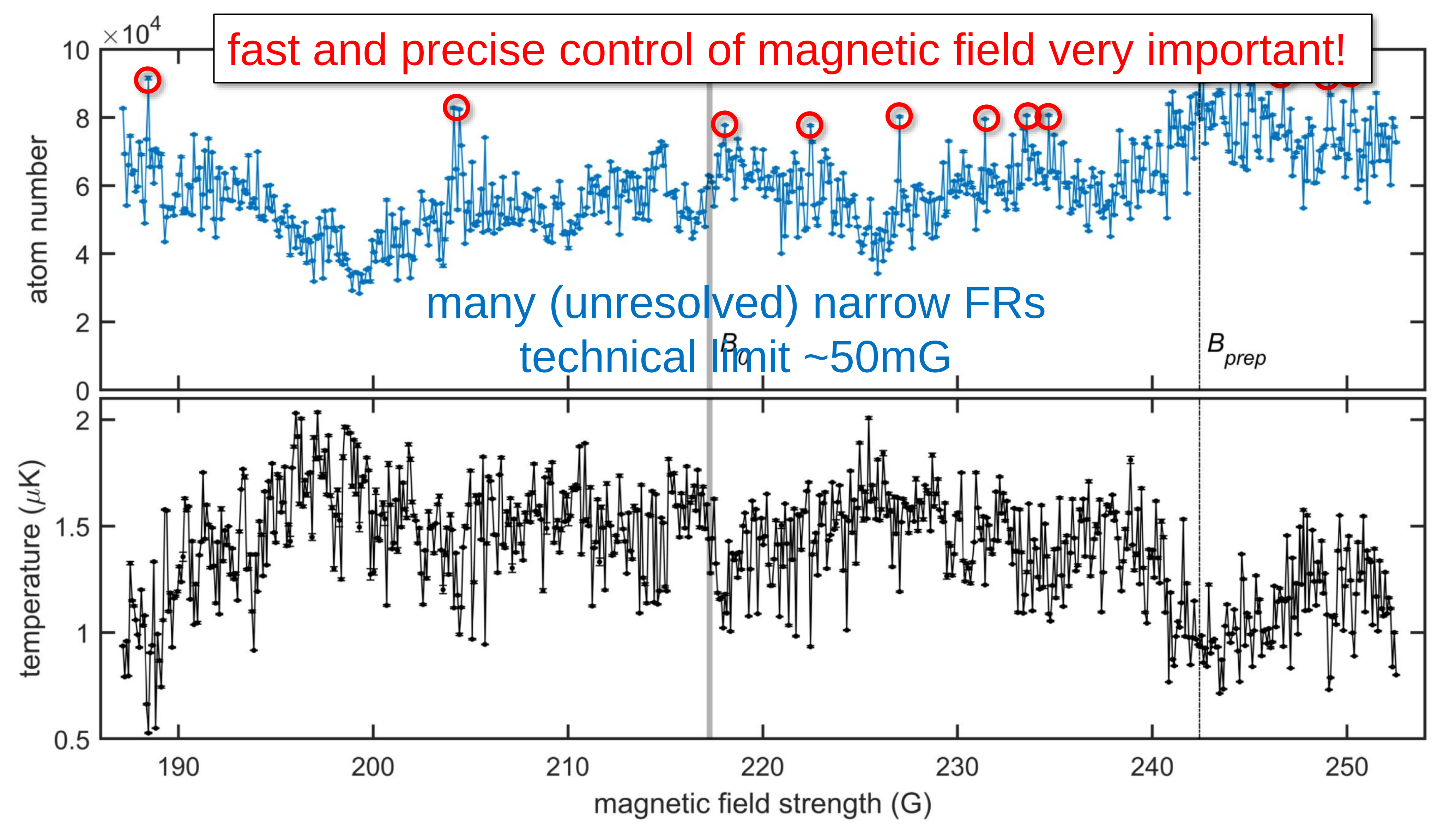
hold time 600ms



E. Soave, PhD thesis

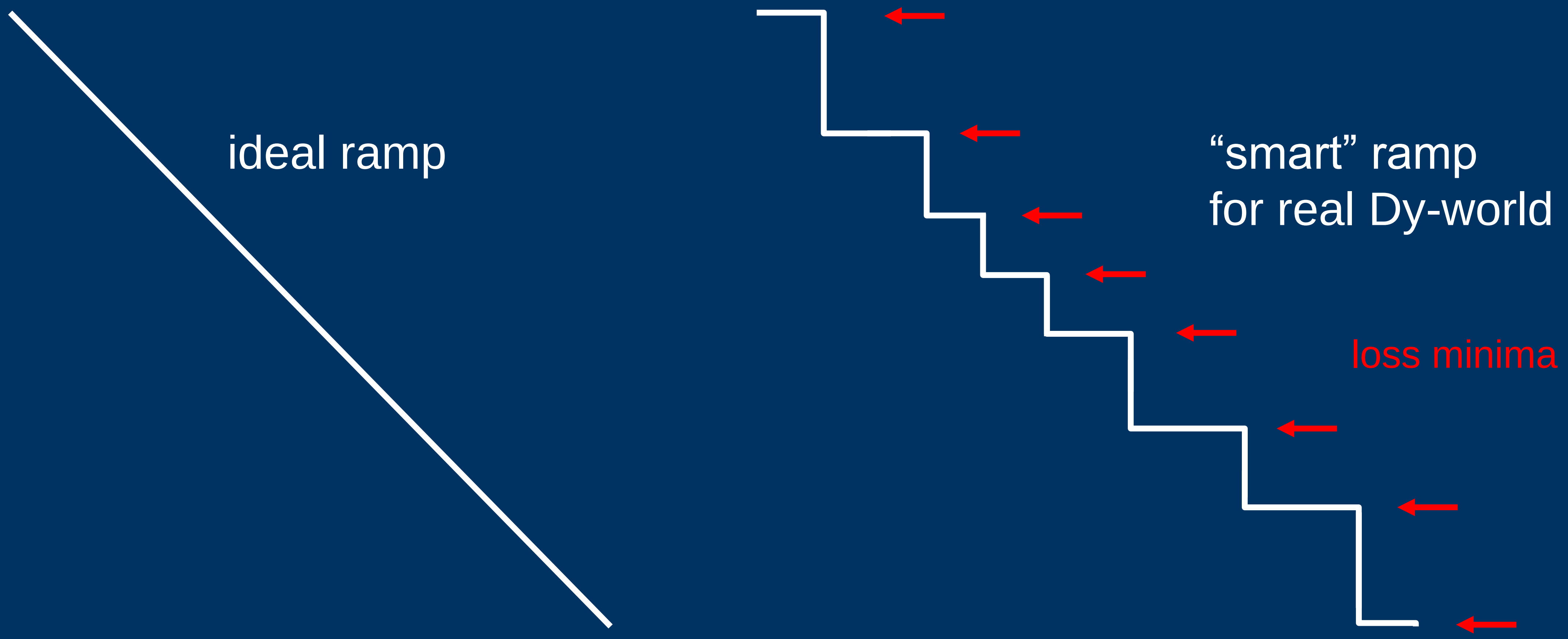
Dy background losses

hold time 600ms



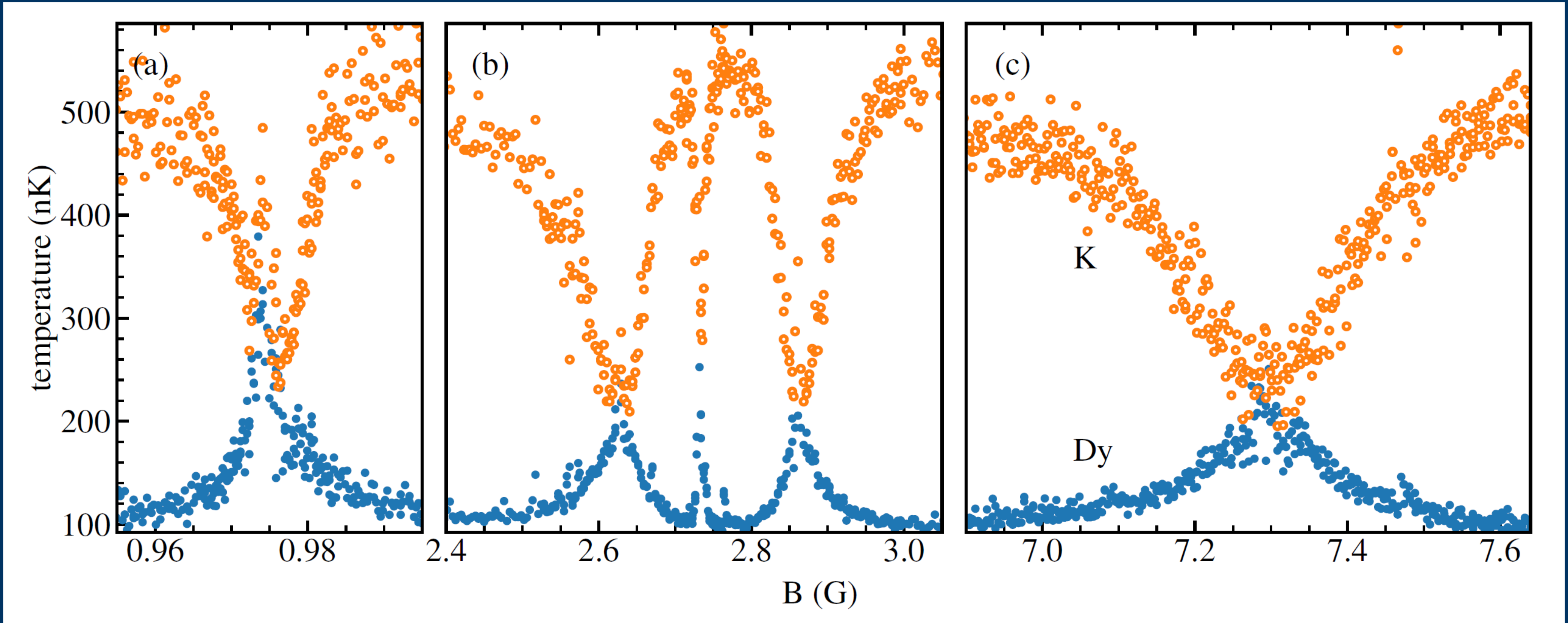
E. Soave, PhD thesis

B-field ramping



surprise: FRs below 10G

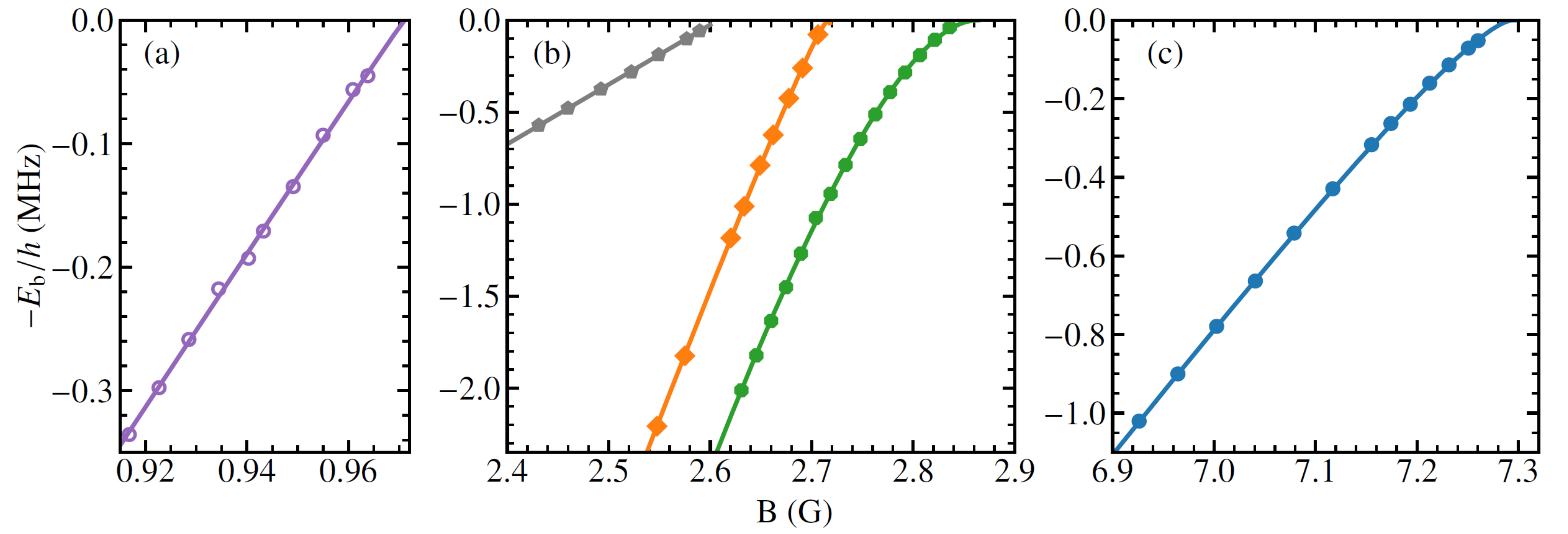
interspecies thermalization



Ye et al., arXiv:2007.03407

surprise: FRs below 10G

binding energy measurements
by wiggle spectroscopy



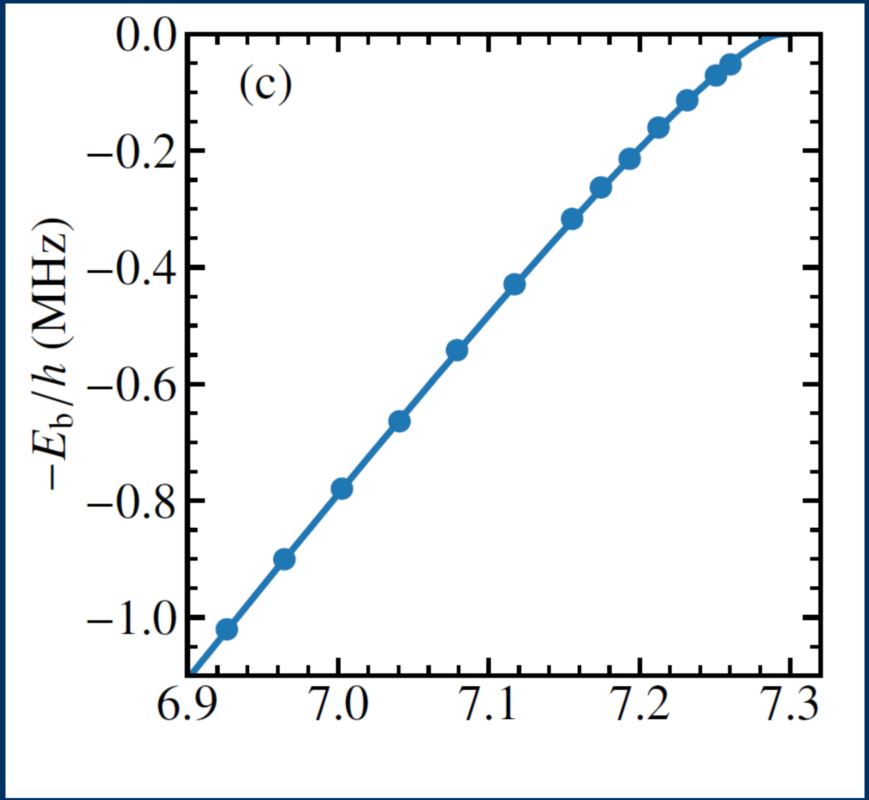
Ye et al., arXiv:2007.03407

surprise: FRs below 10G

binding energy measurements
by wiggle spectroscopy

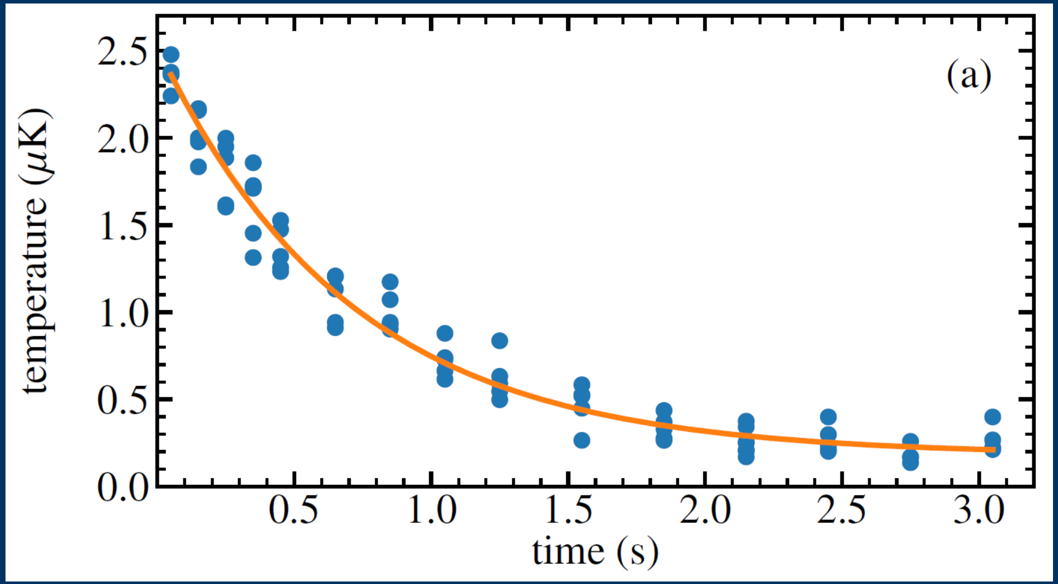
$$E_{\rm b} = \frac{\hbar^2}{8\,(R^*)^2\,m_{\rm r}}\left(\sqrt{1-\frac{4R^*(B-B_0)}{a_0 A}}-1\right)^2$$

Petrov, PRL 93, 143201 (2004)

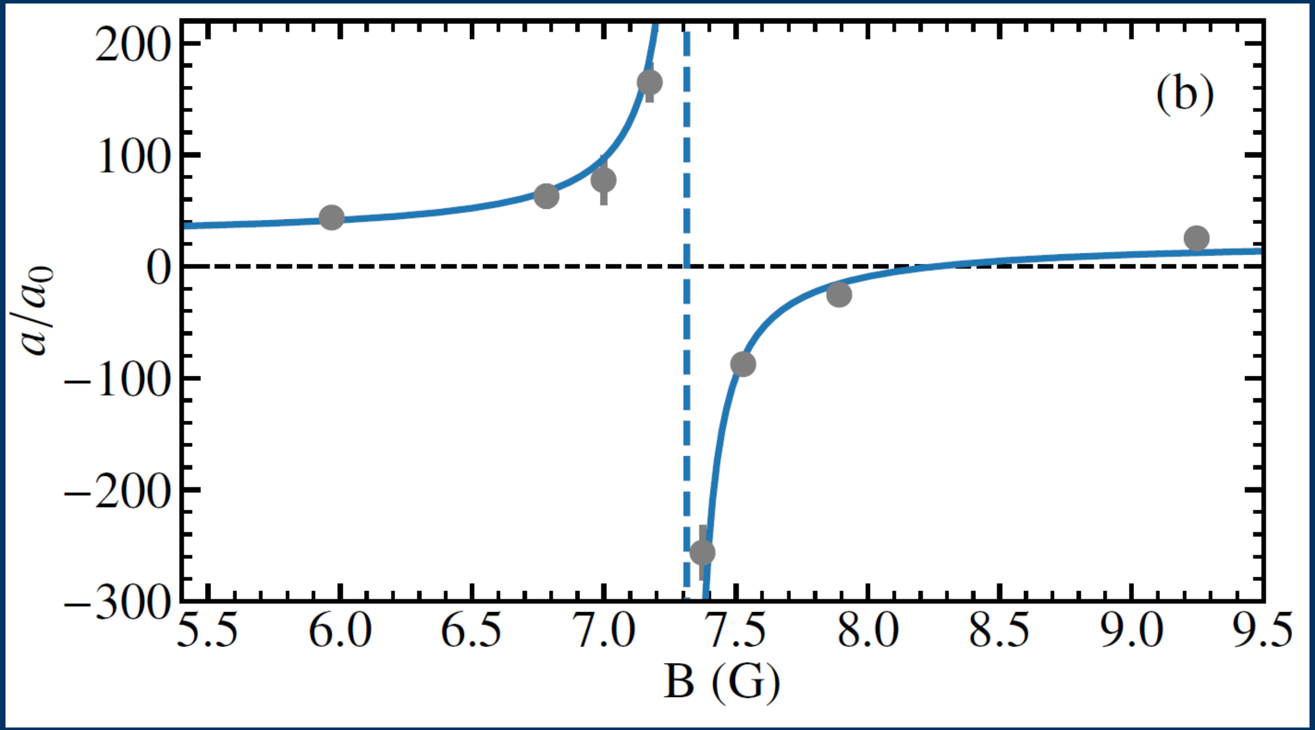


well-isolated FR near 7G

binding energy (B wiggle)



scatt. length (thermal. meas.)



properties of 7G resoance

$$a(B) = a_{\mathrm{bg}} - \frac{A}{B - B_0}\, a_0$$

TABLE II. Comparison of fit parameter values related to the 7.29-G Feshbach resonance extracted from different observations (see text).

Method	B_0 (G)	A (G)	R^*/a_0	a_{bg}/a_0
Binding energy III C	7.295(1)	23.2(9)	643(30)	-
Thermalization IV A	7.314(20)	22.8(2.6)	-	24.2(4.7)
	7.295[a]	23.4(2.4)	-	22.8(4.5)
Hydrodynamics IV C	7.290(2)	23.2[b]	-	-

[a] The pole position B_0 is fixed to the value of the binding energy measurements.

[b] The strength parameter A is fixed to the value of binding energy measurements.

universal range:

$|B-B_0| \ll A\, a_0 / R^* \approx 36$ mG

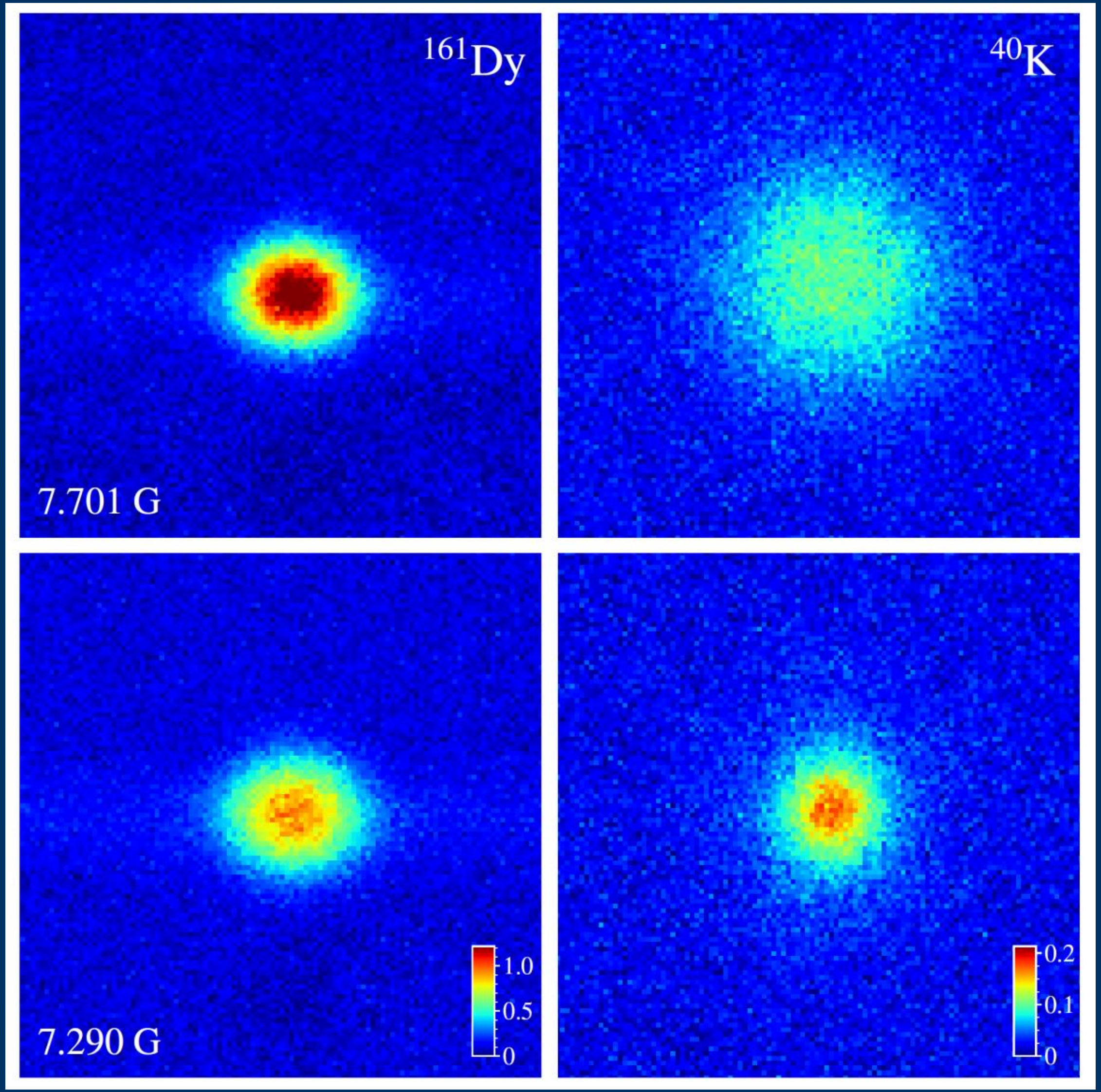
mG control of B-field at 7.3G

rather convenient for experimentalists

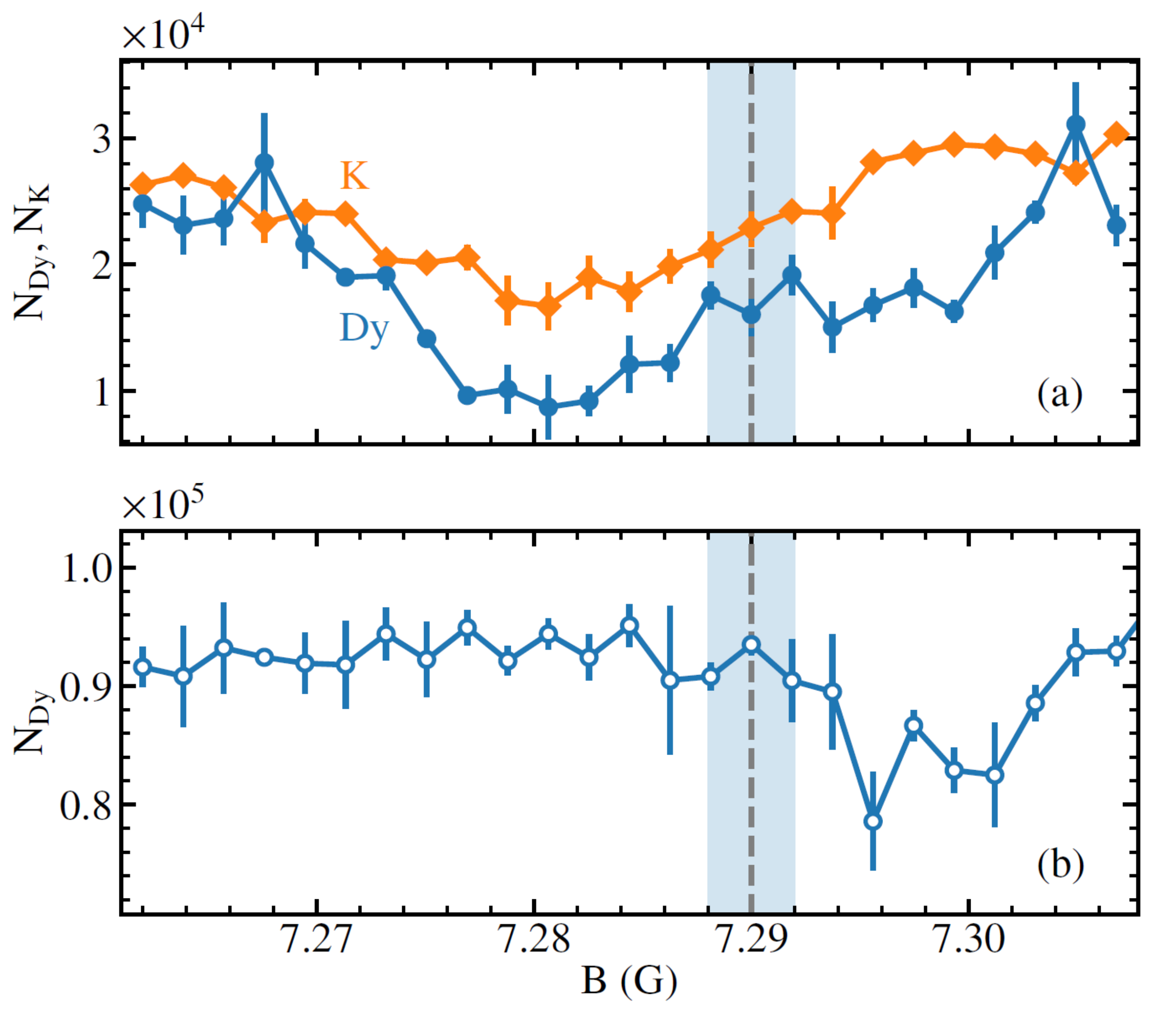
hydrodynamic expansion on 7.3G resonance

$a \approx -40\ a_0$

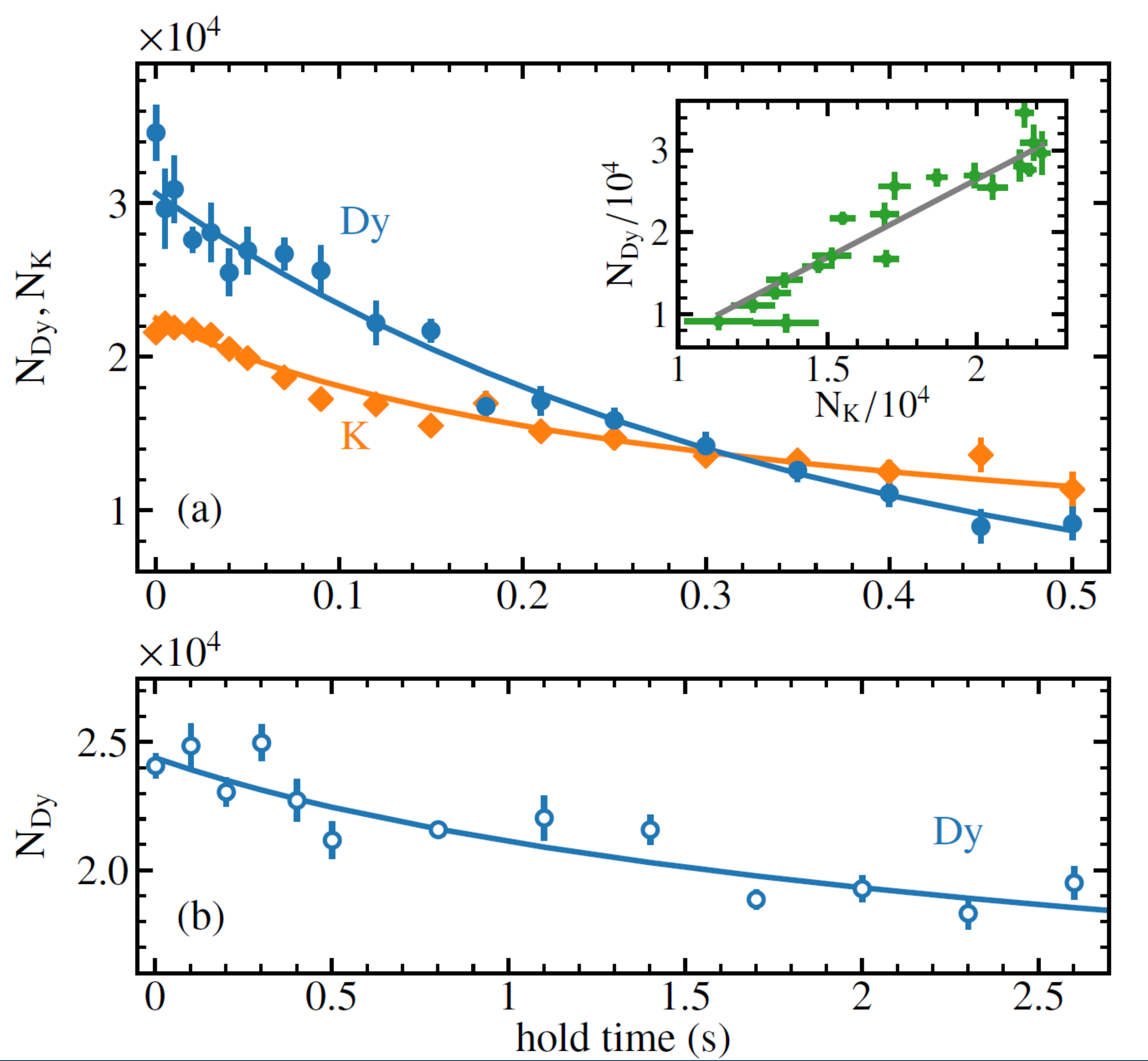
on resonance



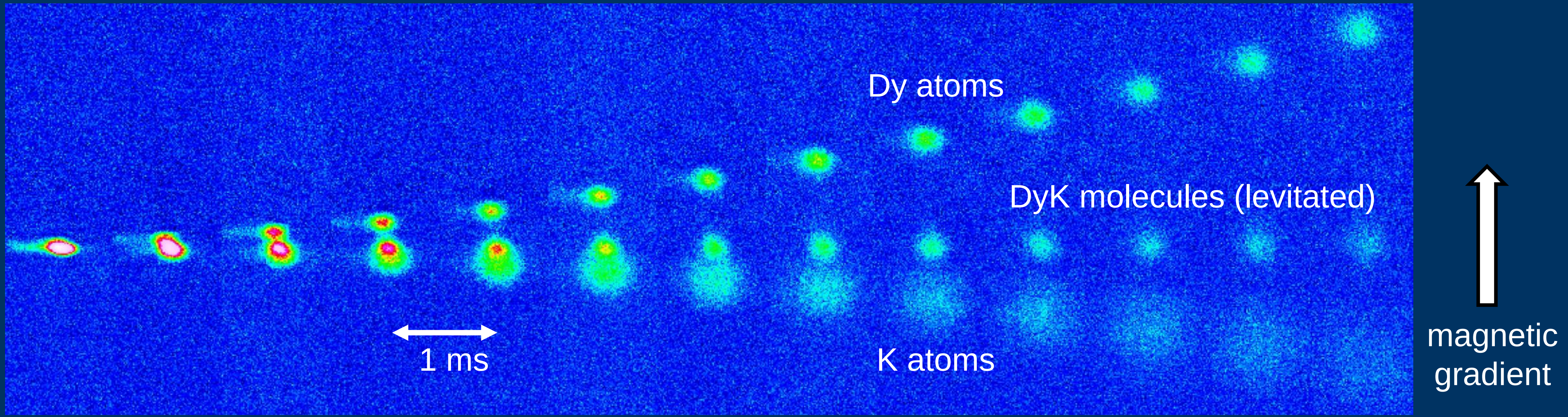
loss scan



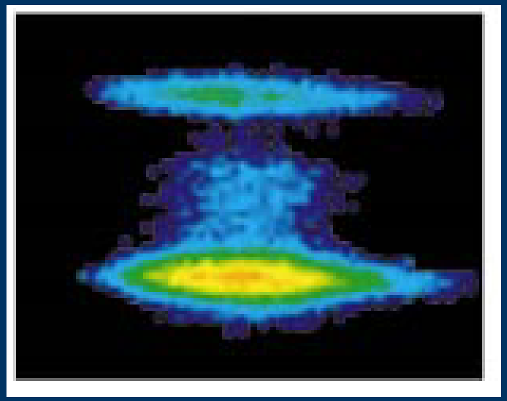
lifetime on resonance



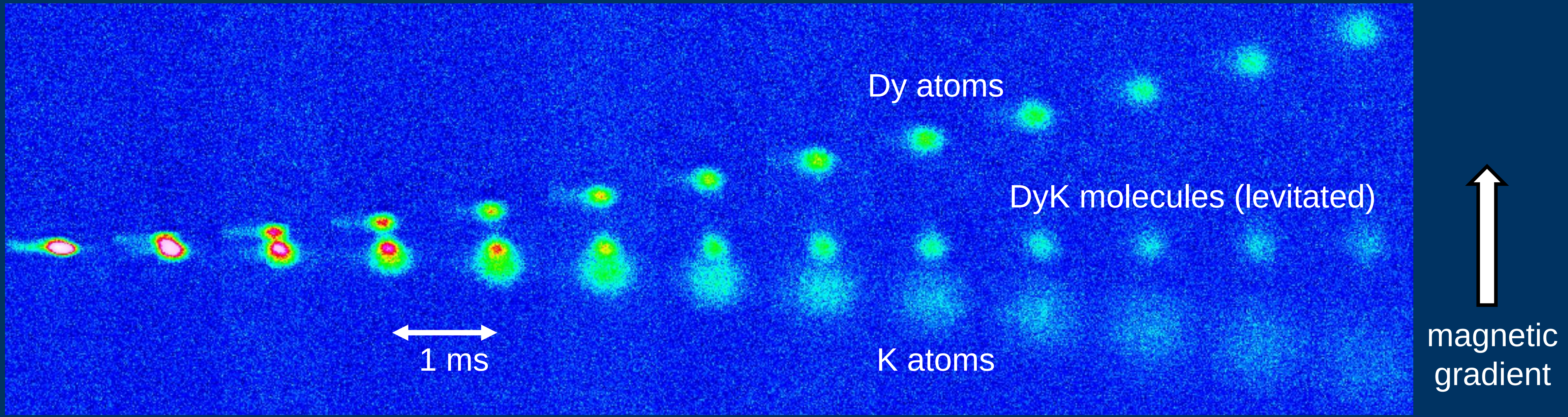
formation of molecules on low-field resonance



JILA 2003
experiment on ^{40}K dimers



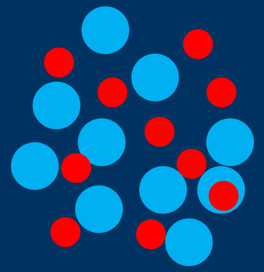
formation of molecules on low-field resonance



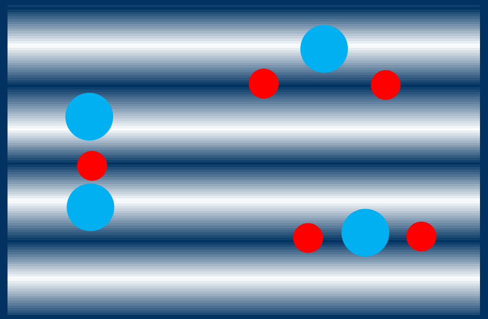
let‘s go for the next step:

BEC of heteronuclear Feshbach molecules

great potential in few- and many-body physics



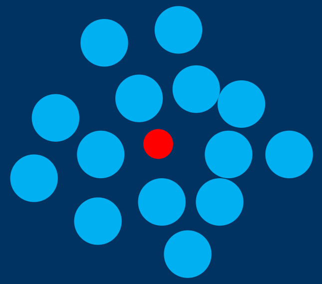
novel superfluids with
both mass- and population imbalance



few-body states in low-D and mixed-D

Nishida and Tan, PRL 101, 170401 (2008)

Levinsen et al., PRL 103, 153202 (2009)



Fermi polarons in medium of heavy particles

general conclusion

Ultracold fermion mixtures:

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

many opportunities and challenges
for experiment and theory

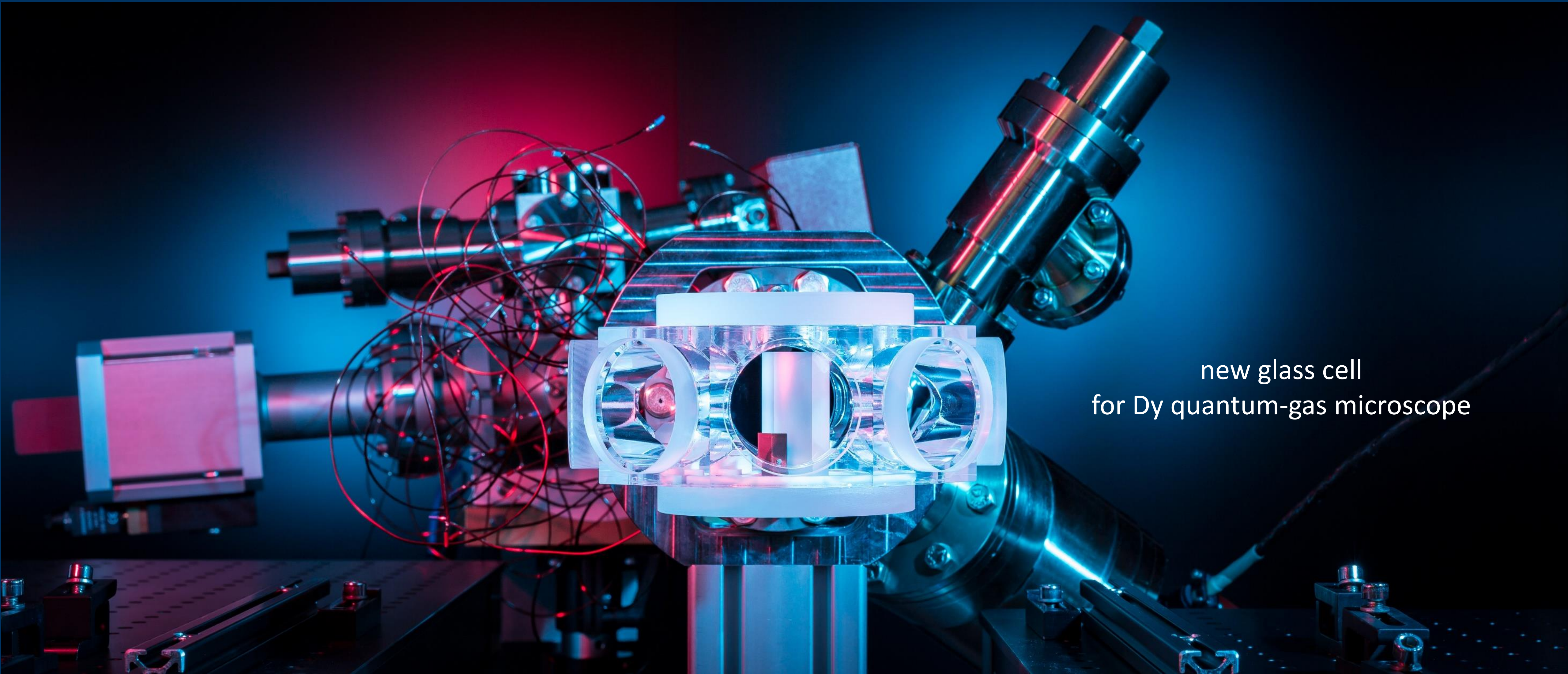
SuperCoolMix
started Jan 2022

MARIE CURIE ACTIONS

FWF
Der Wissenschaftsfonds.

Doktoratskolleg
ALM

positions for ambitious PhD students and postdocs available
www.ultracold.at/grimm/



new glass cell
for Dy quantum-gas microscope