TAMIONS online discussion meeting, 20 May 2021

Rudolf Grimm

Ultracold fermion mixtures: Interactions make them strong

Austrian Acad. of Sciences

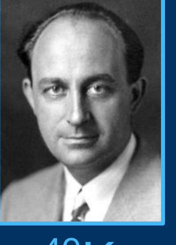
IQI

universität innsbruck

Inst. of Experimental Physics

key players

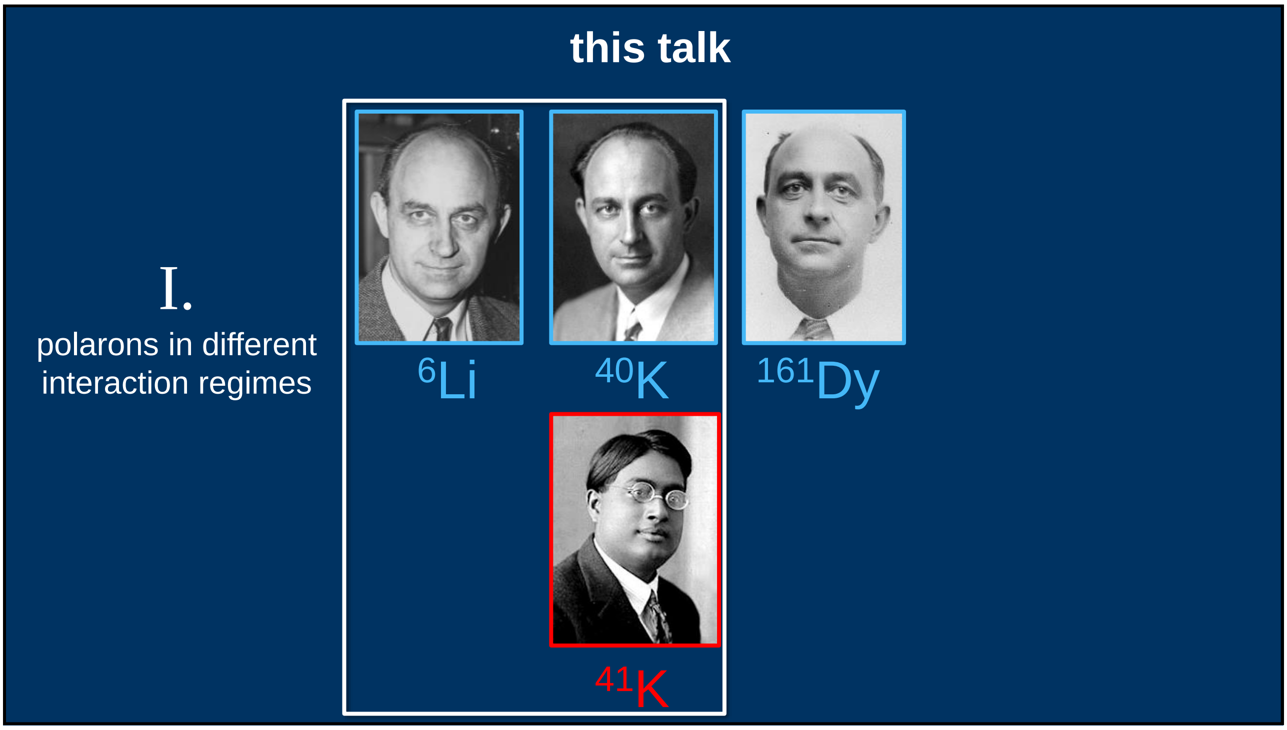
^{6}Li

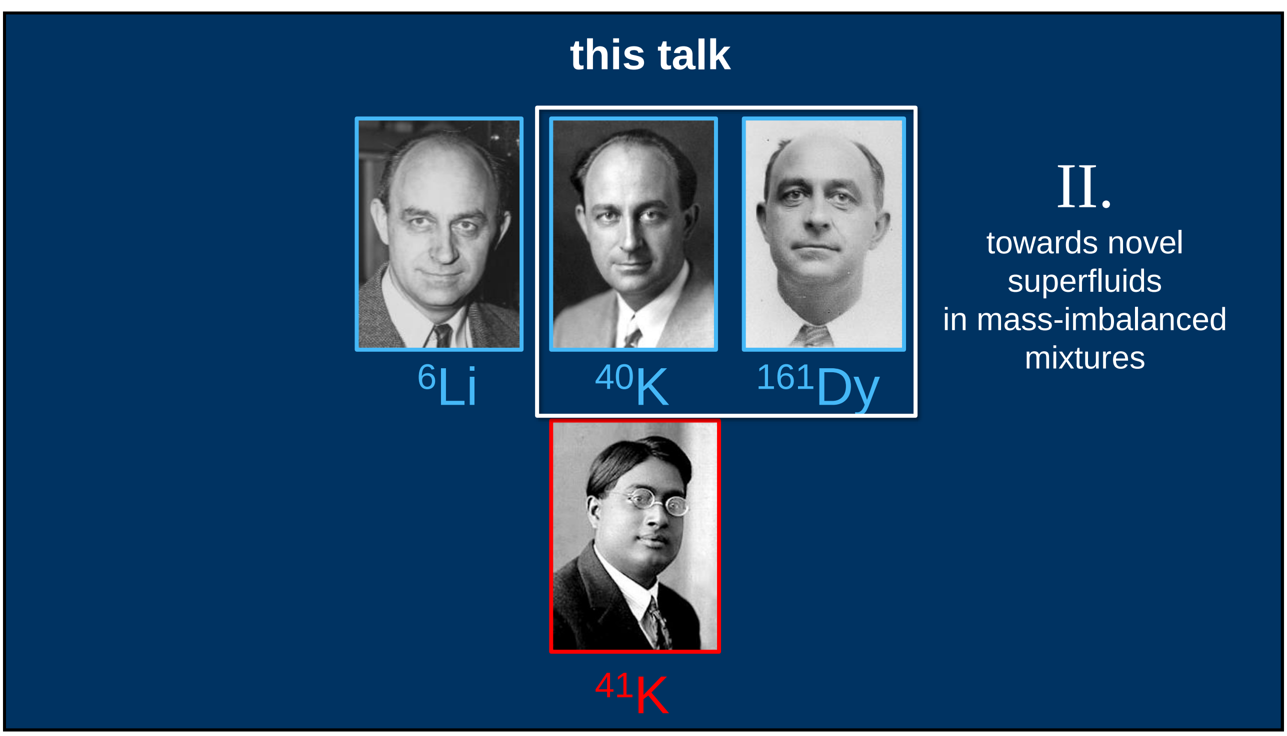


^{40}K

^{161}Dy

^{41}K

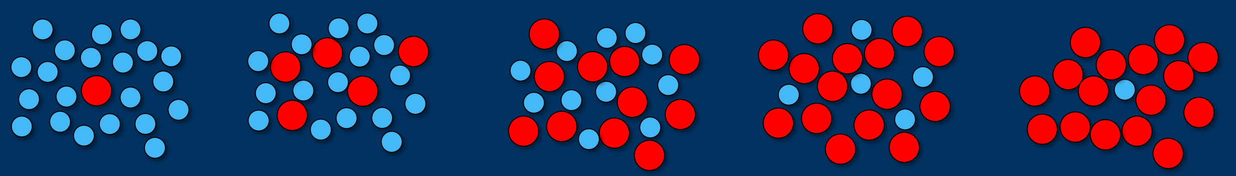

this talk
I.
polarons in different
interaction regimes
6Li
40K
161Dy
41K


this talk
6Li
40K
161Dy
41K
II.
towards novel
superfluids
in mass-imbalanced
mixtures

part I: general research question

Fermi-Bose mixture

with strong (tunable) interspecies interaction
and population imbalance



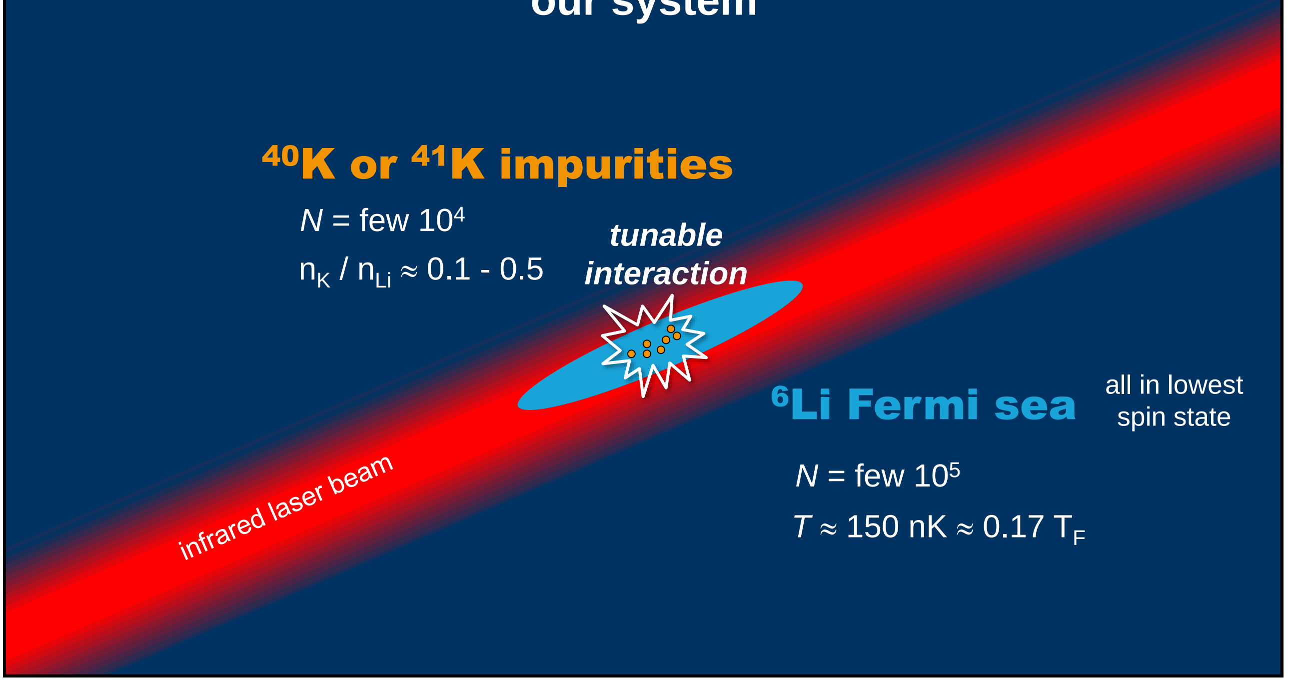
Fermi polaron
very well investigated

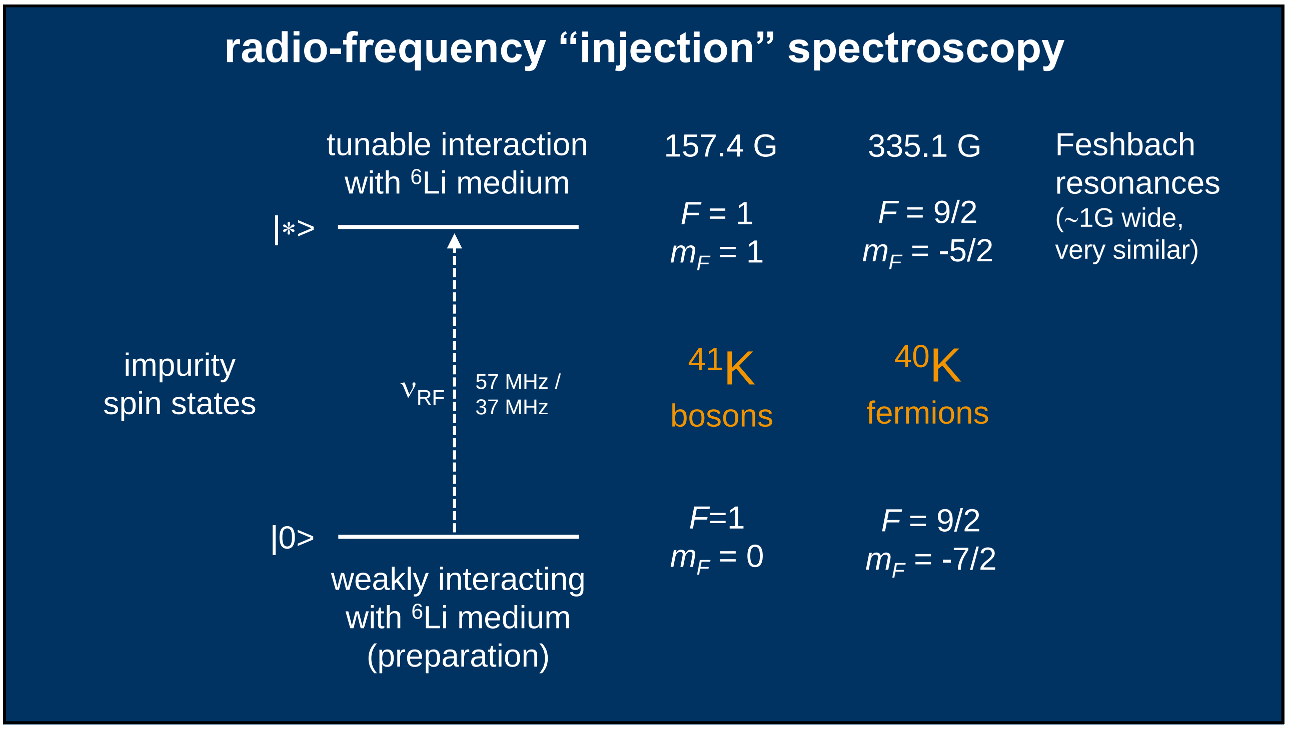
Bose polaron
well investigated

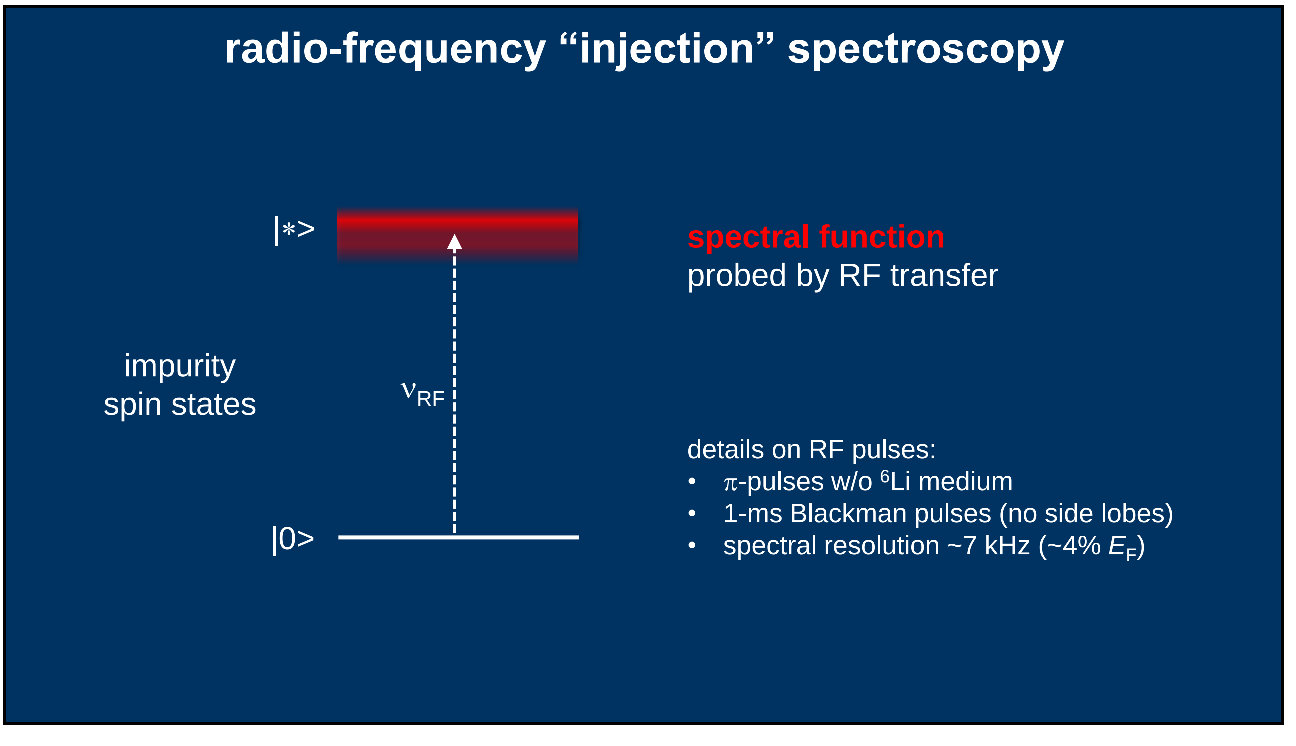
how are these worlds connected?

our approach: study finite-concentration effects
impurity-impurity interactions / mediated interactions

our system



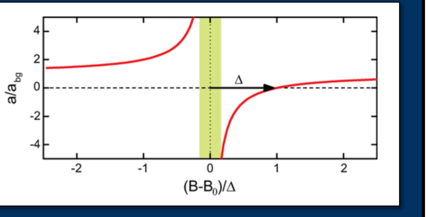

radio-frequency “injection” spectroscopy
tunable interaction with ^{6}Li medium
|*>
impurity spin states
ν_{RF}
57 MHz / 37 MHz
|0>
weakly interacting with ^{6}Li medium (preparation)
157.4 G
$F = 1$
$m_F = 1$
^{41}K
bosons
$F=1$
$m_F = 0$
335.1 G
$F = 9/2$
$m_F = -5/2$
^{40}K
fermions
$F = 9/2$
$m_F = -7/2$
Feshbach resonances
(~1G wide, very similar)


radio-frequency “injection” spectroscopy
|*>
impurity spin states
ν_{RF}
|0>
spectral function
probed by RF transfer
details on RF pulses:
• π-pulses w/o ^{6}Li medium
• 1-ms Blackman pulses (no side lobes)
• spectral resolution ~7 kHz (~4% E_F)

interaction parameter

dimensionless

$$X \equiv -\frac{1}{k_F a}$$



Fermi wave number
(interparticle distance)$^{-1}$

$$E_F = \frac{(\hbar k_F)^2}{2m}$$

s-wave
scattering length

tunable via
Feshbach resonance

typically $1/k_F \approx 4000\, a_0$

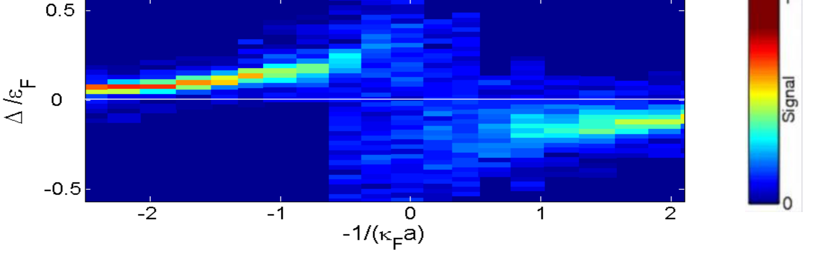
strongly interacting regime (|*X*| ≤ 1)
just ±13mG wide,
experimentally very challenging

spectral response

^{40}K

1 ms rf pulse (π w/o interaction)

population
transfer
|0> → |∗>



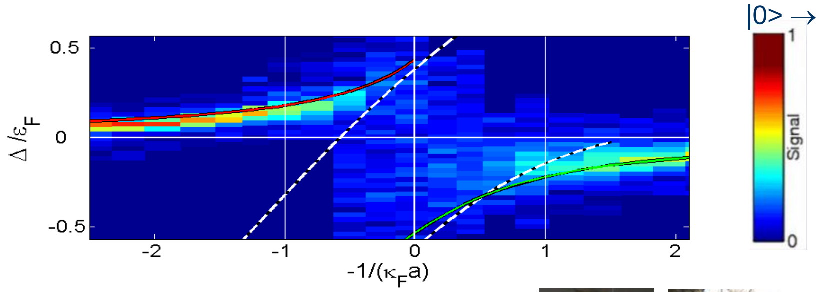
C. Kohstall et al., Nature **485**, 615 (2012)

^{40}K

spectral response

1 ms rf pulse (π w/o interaction)

population transfer
|0> → |∗>



theory: T-matrix approach
single particle-hole excitations

Pietro Massignan
ICFO, Spain

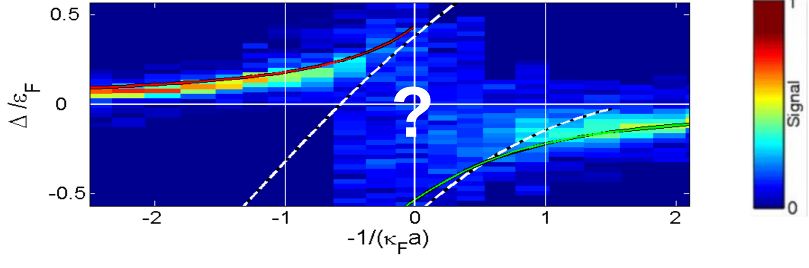
Georg Bruun
U Aarhus, Denmark

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

^{40}K

spectral response

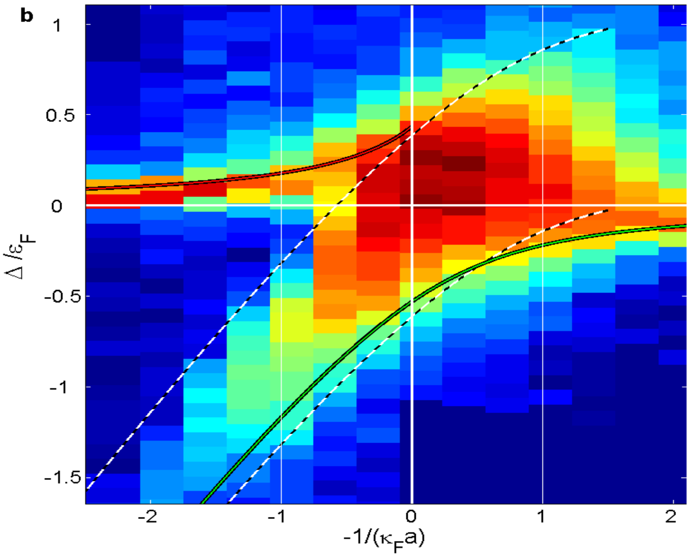
population transfer
|0> → |∗>



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

^{40}K

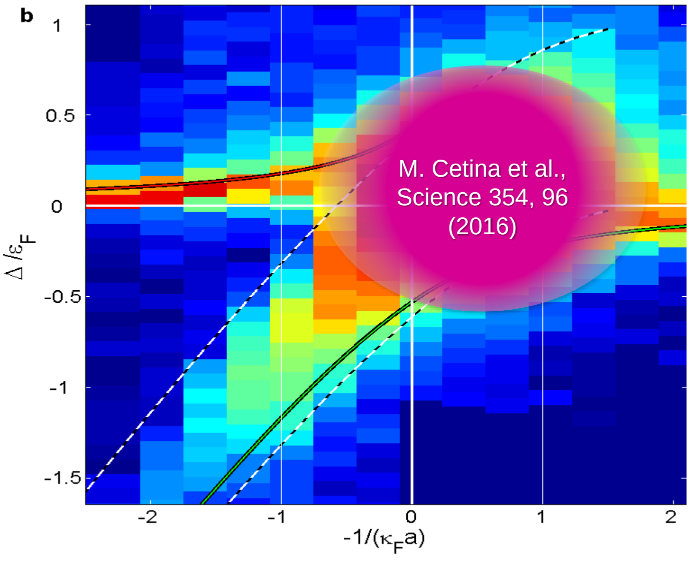
spectral response
(strong rf)



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

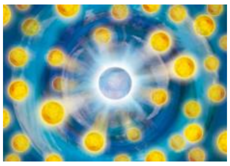
^{40}K

spectral response
(strong rf)



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

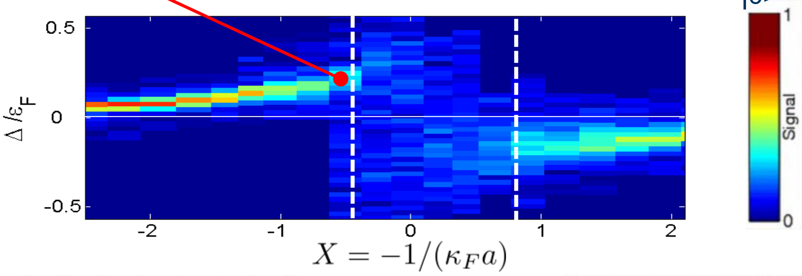
spectral response

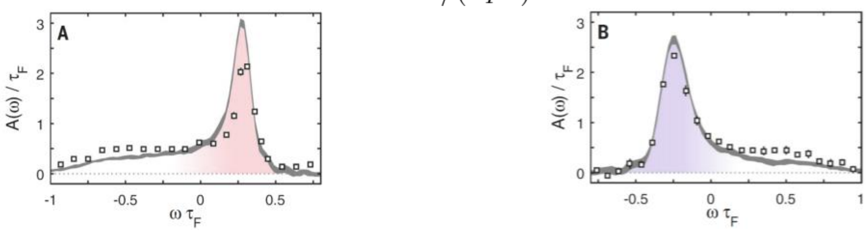


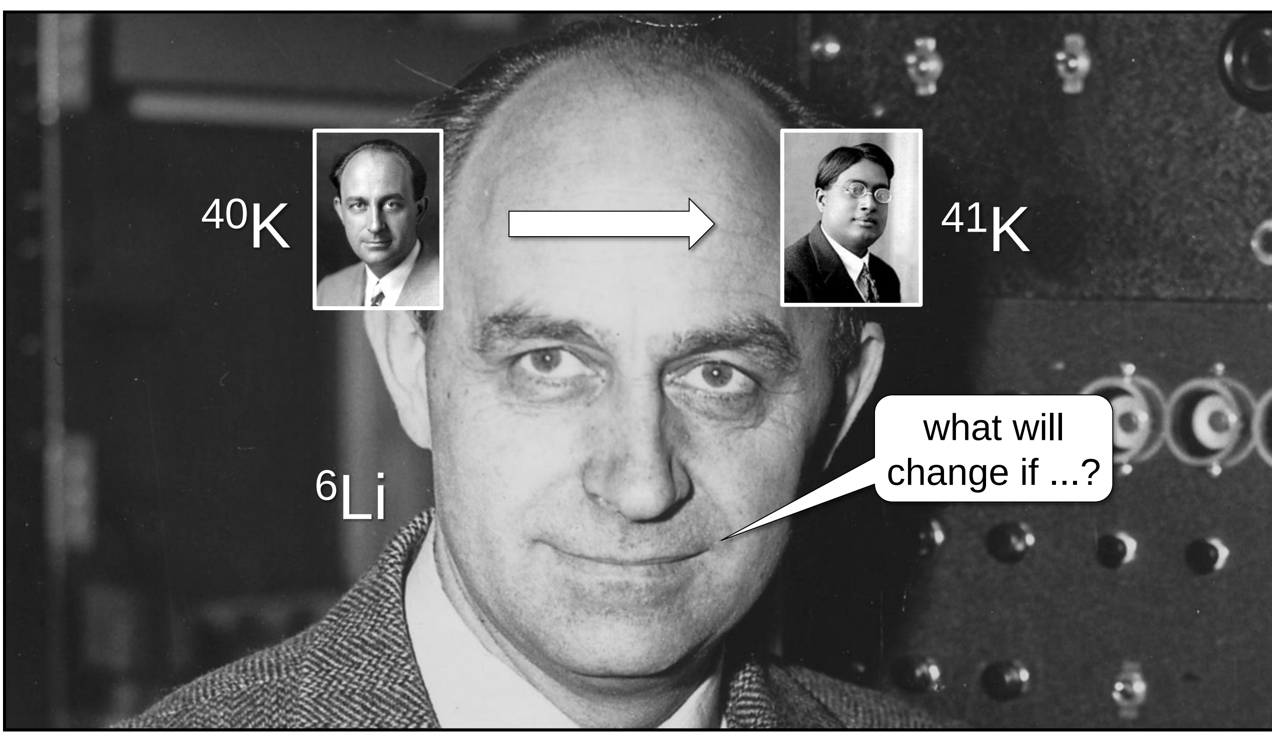
"repulsive polaron" lifetime ms

1 ms rf pulse (π w/o interaction)

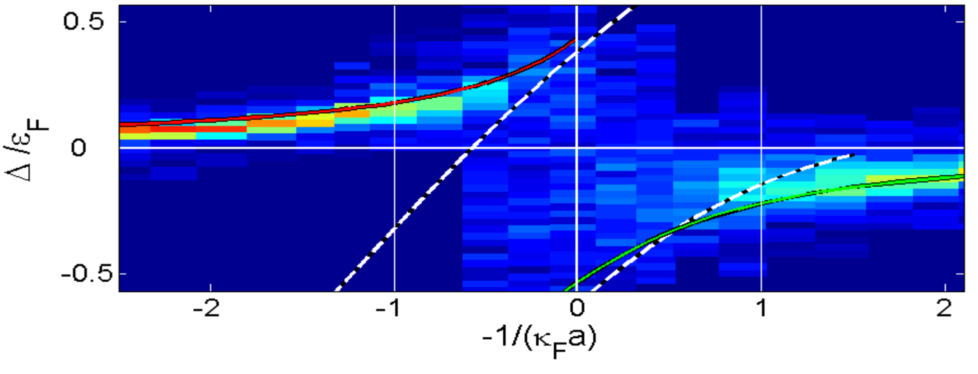
population transfer
|0> → |*>





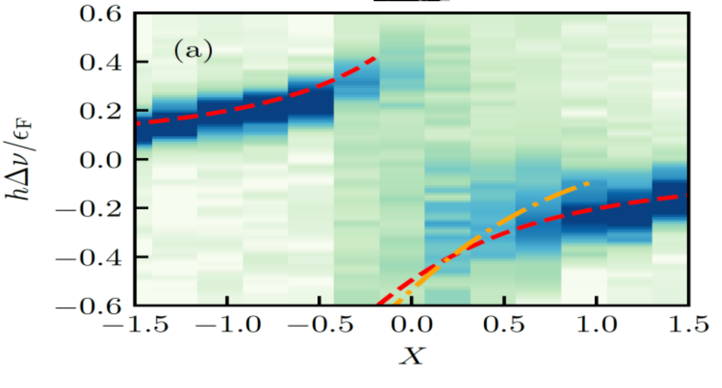


direct comparison

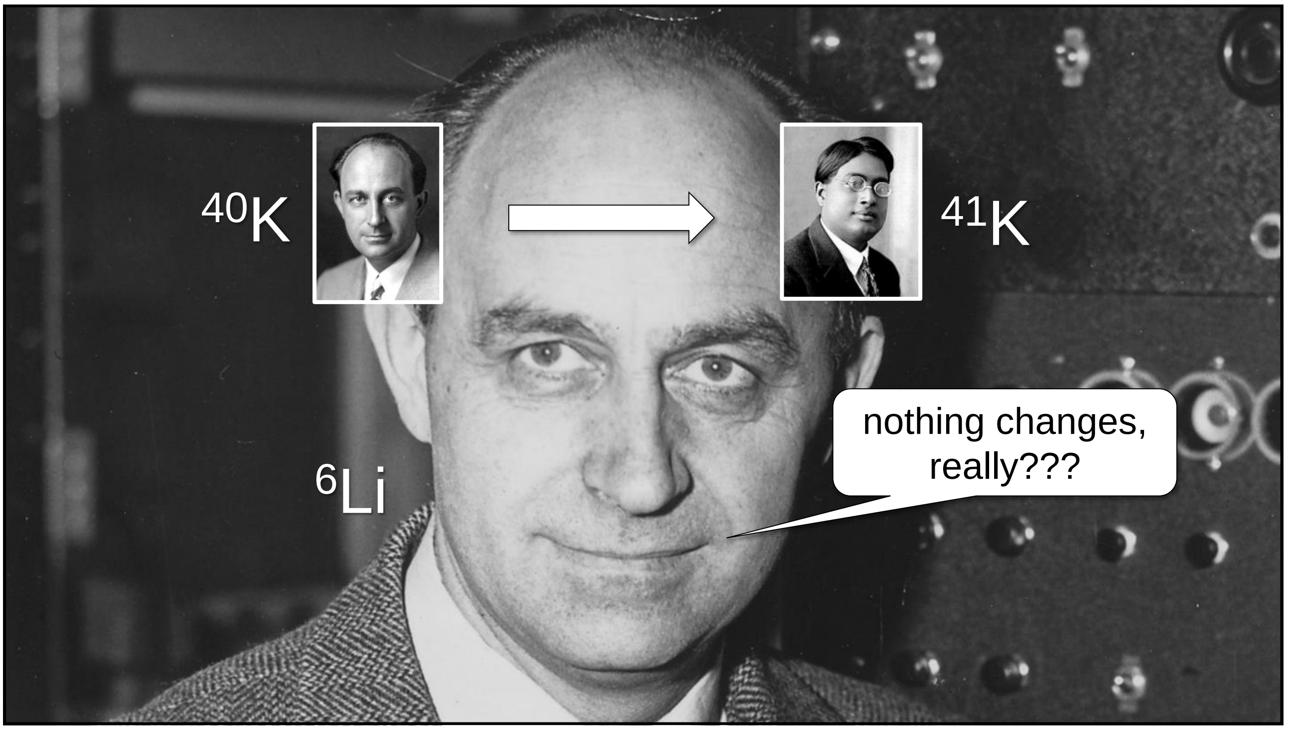


C. Kohstall et al., Nature **485**, 615 (2012)

direct comparison



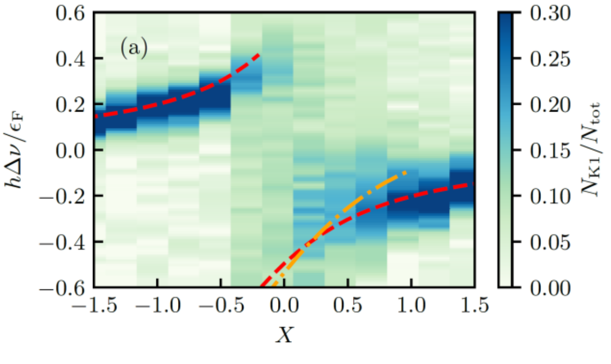
I. Fritsche et al., Phys. Rev. A **103**, 053314 (2021)



spectral response of bosonic ^{41}K impurities

thermal impurity cloud
T/T_F=0.19

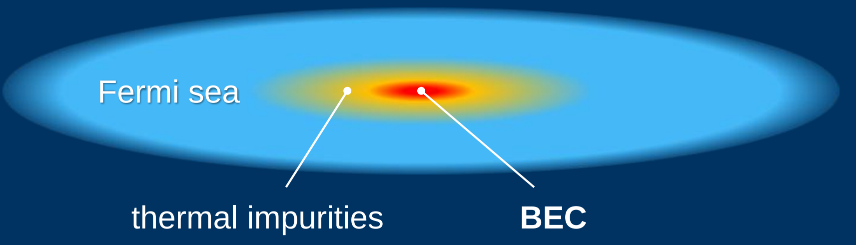
partially condensed impurity cloud
T/T_F=0.14



Fritsche et al., PRA **103**, 053314 (2021)

new branch emerges in the spectrum:
BEC with much less energy shift

regions in the trap

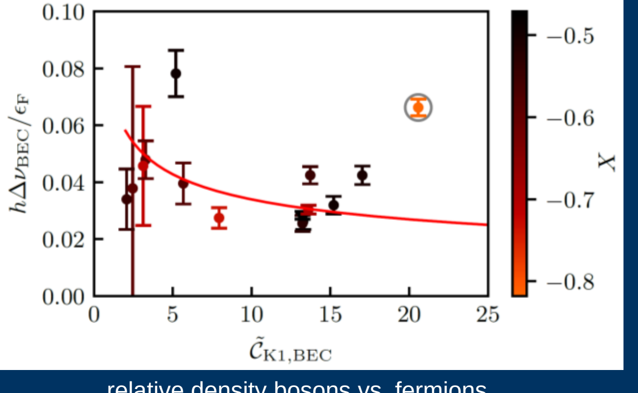


what we studied before:
phase separation of BEC in Fermi gas at repulsive interaction

- static behavior (reduced overlap), Lous et al., PRL **120**, 243403 (2018)
- dynamics (collective oscillations), Huang et al., PRA **99**, 041602(R) (2019)

current experiments: *no time to phase separate!*

energy shift of BEC: glimpse of the Bose polaron?



relative density bosons vs. fermions

$X \approx -0.6$

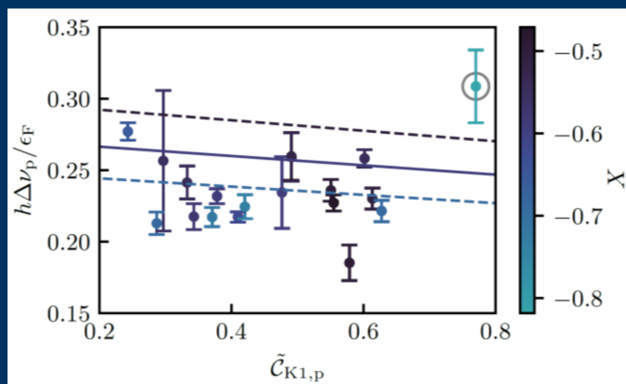
simple backaction model
based on universal Bose polaron ($\xi \approx 0.5$)

$$\Delta E_{\mathrm{tot}}/N_{\mathrm{K1,BEC}} = (6/41)(\tilde{C}_{\mathrm{K1,BEC}})^{-1/3}\xi\epsilon_{\mathrm{F}}.$$

technical issues:
large fluctuations of X (and T)

thermal impurities: polaron peak shift?

Fermi-liquid theory (perturbative approach): Yu and Pethick, PRA 85, 063616 (2012)



relative density bosons vs. fermions

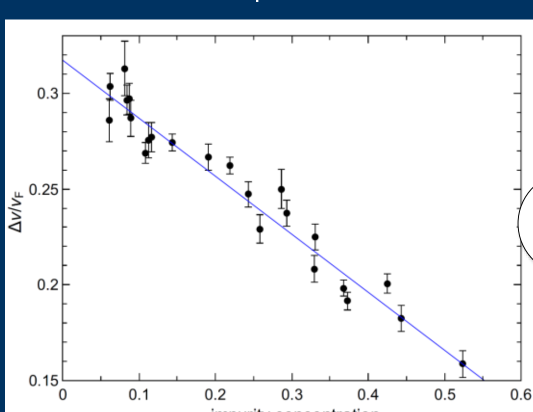
$X \approx -0.6$

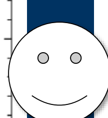
there may be a little down shift, but...

technical issues:
large fluctuations of *X* (and *T*)

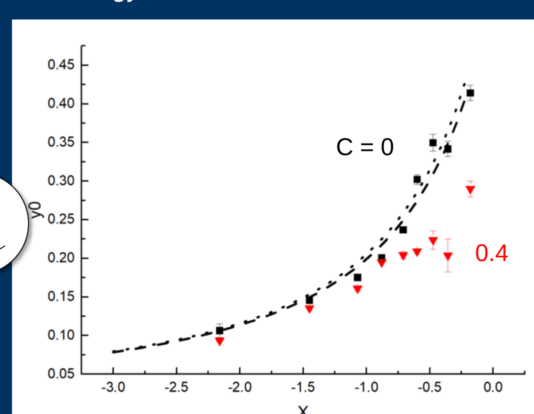
new measurements (from last two weeks)

concentration dependence at X = -0.6





energy shift vs. X at two concentrations



C. Baroni et al, in progress

first clear observation of an energy shift induced by mediated interactions

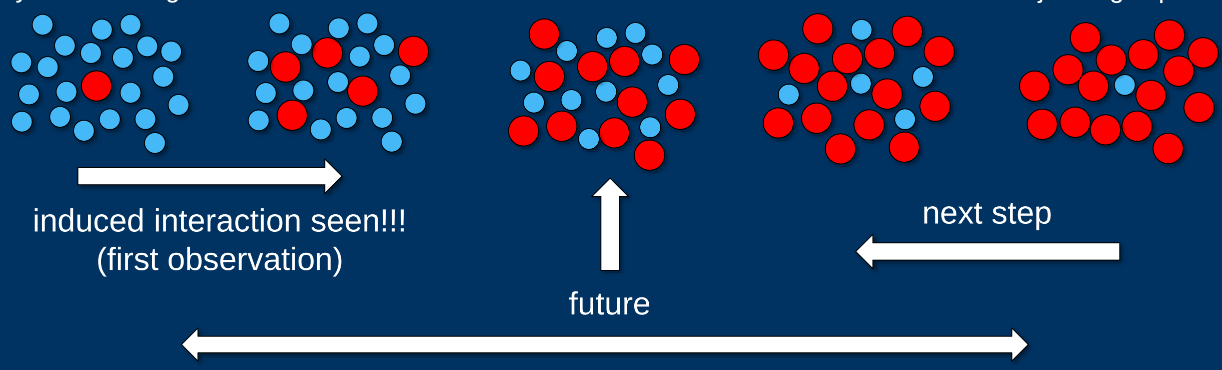
(data analysis still preliminary)

where do we stand?

Fermi (^{6}Li) – Bose (^{41}K) mixture

Fermi polaron
very well investigated

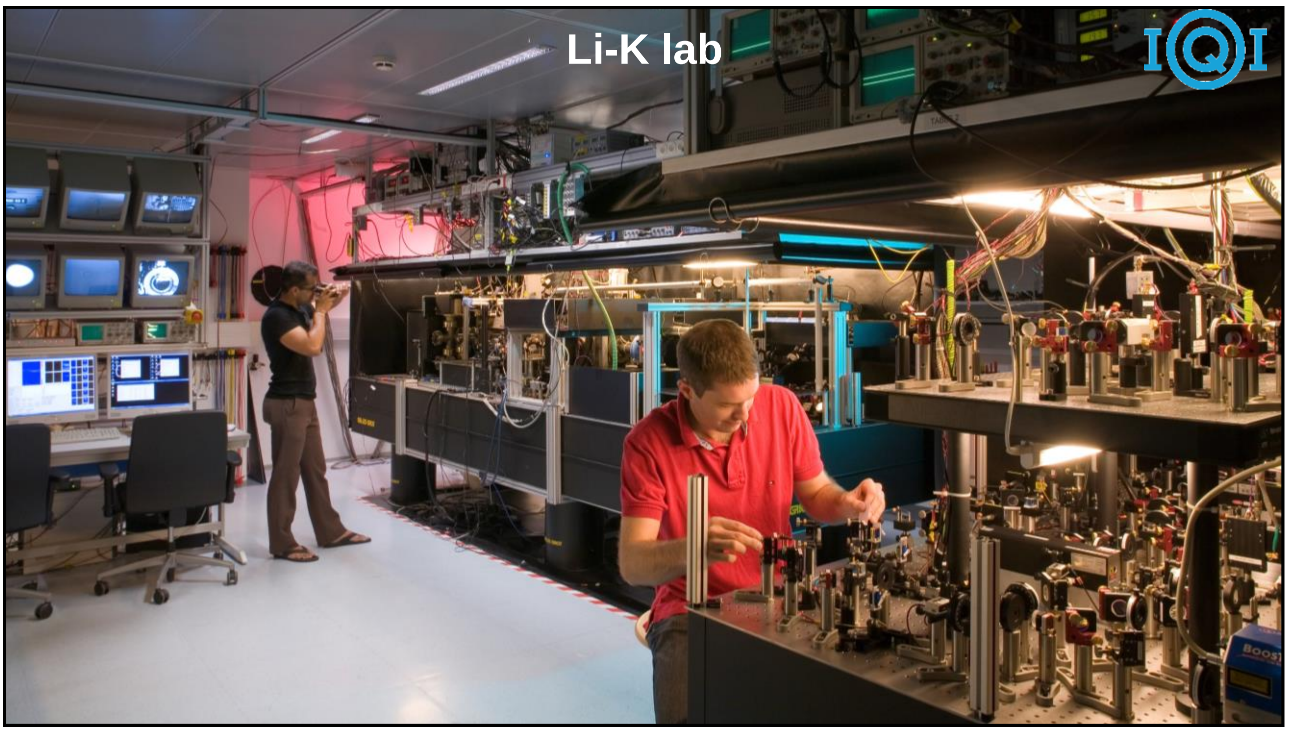
Bose polaron
just a glimpse

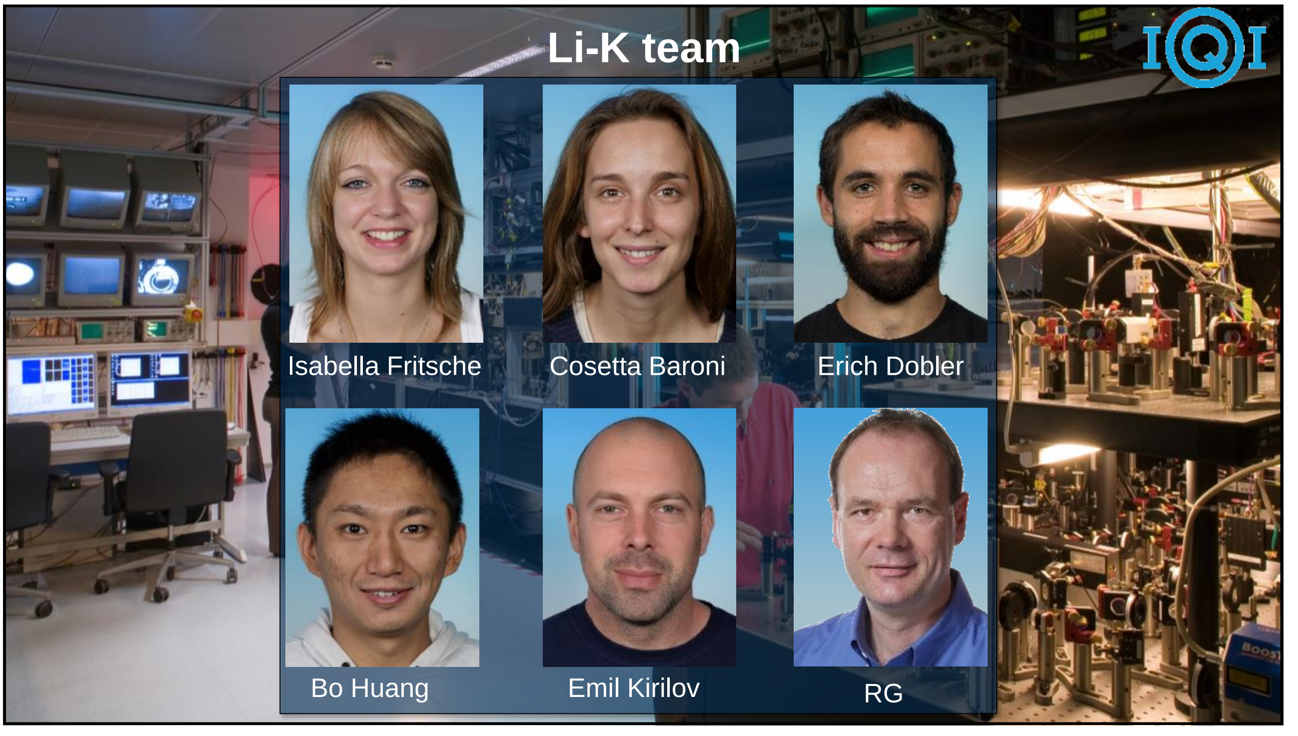


induced interaction seen!!!
(first observation)

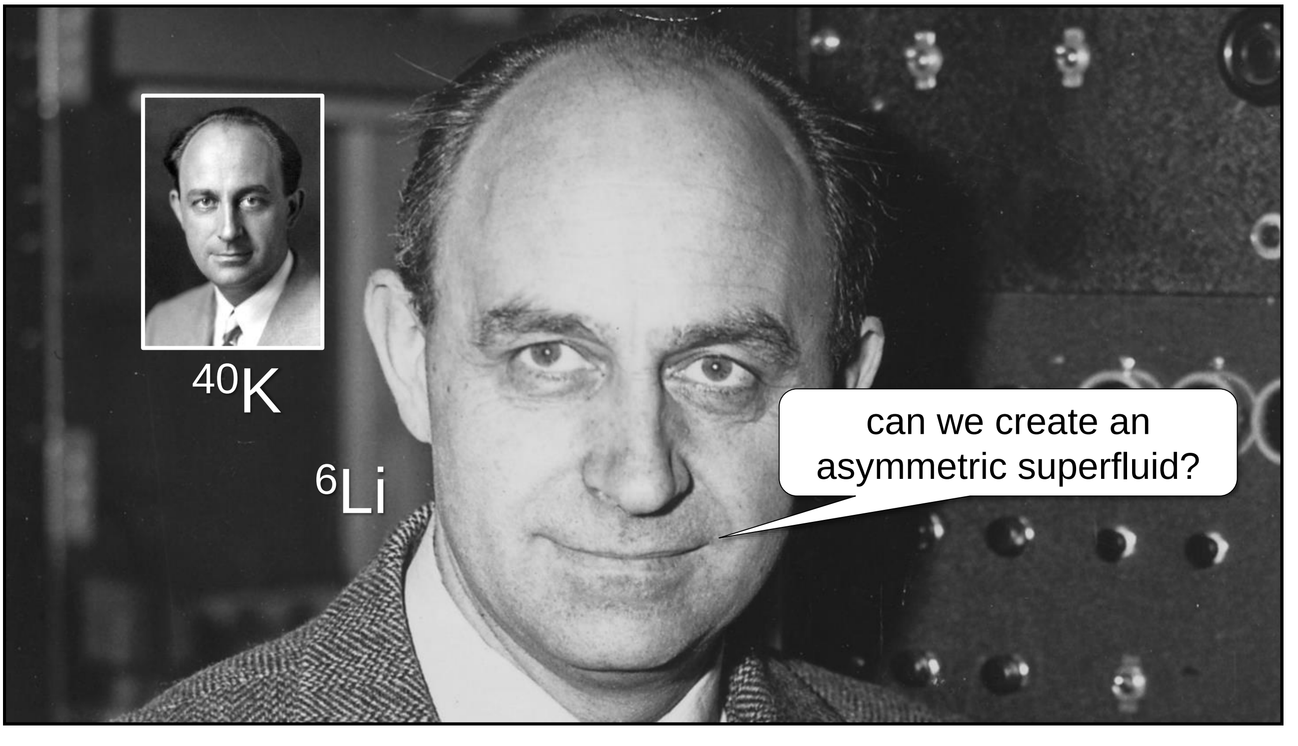
future

next step





Li-K team
IQI
Isabella Fritsche
Cosetta Baroni
Erich Dobler
Bo Huang
Emil Kirilov
RG

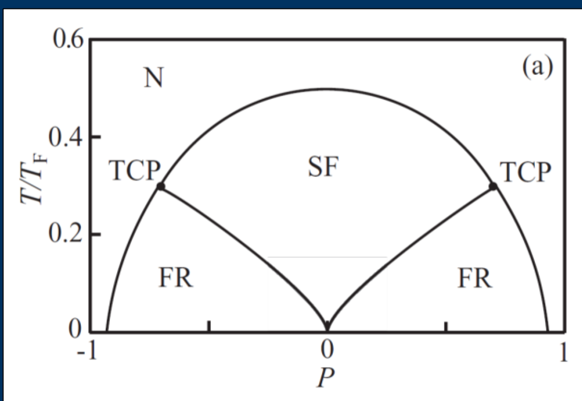


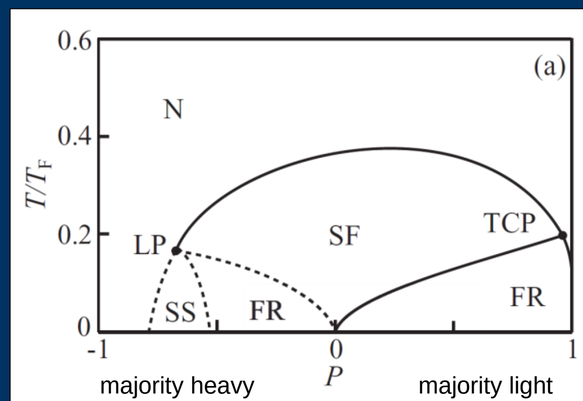
^{40}K
^{6}Li
can we create an asymmetric superfluid?

effect of mass imbalance on phase diagram

unitarity $1/k_F a = 0$

M/m = 1 (mass balanced) | M/m = 40/6 (mass imbalanced)



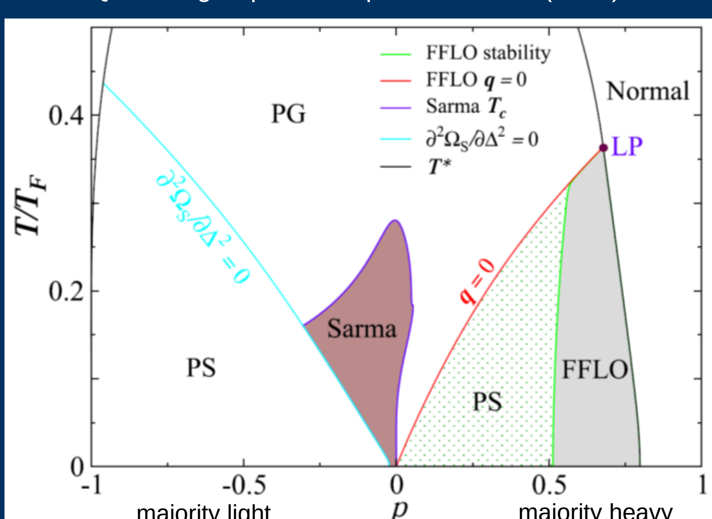


Baarsma, Gubbels, Stoof, PRA 82, 013624 (2010)
homogeneous case

exciting things happen in expt. accessible range

phase diagram for M/m = 6.7

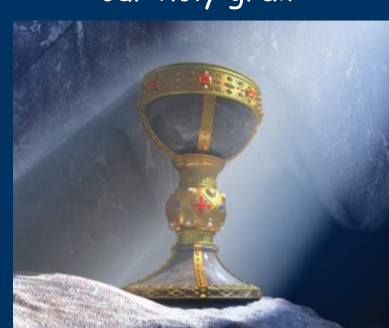
Q. Chen group, Sci. Reports 7, 39783 (2017)



population imbalance

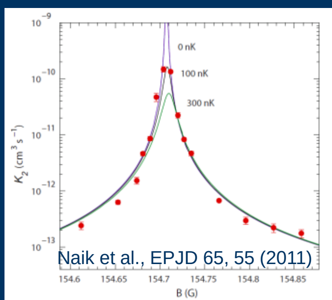
mass imbalance favors exotic superfluid phases !

our holy grail

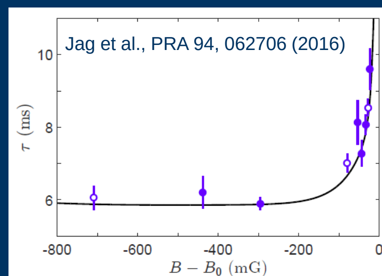


http://medicalrepublic.com.au/universal-flu-vaccine-quest-holy-grail/14430

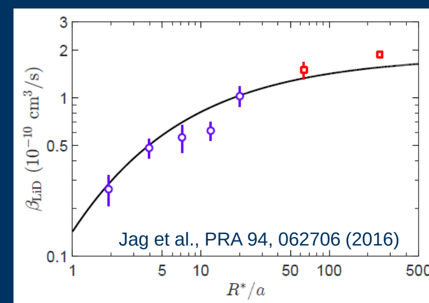
"secrets" of ^{6}Li - ^{40}K Feshbach resonances



two-body losses
in atomic mixture

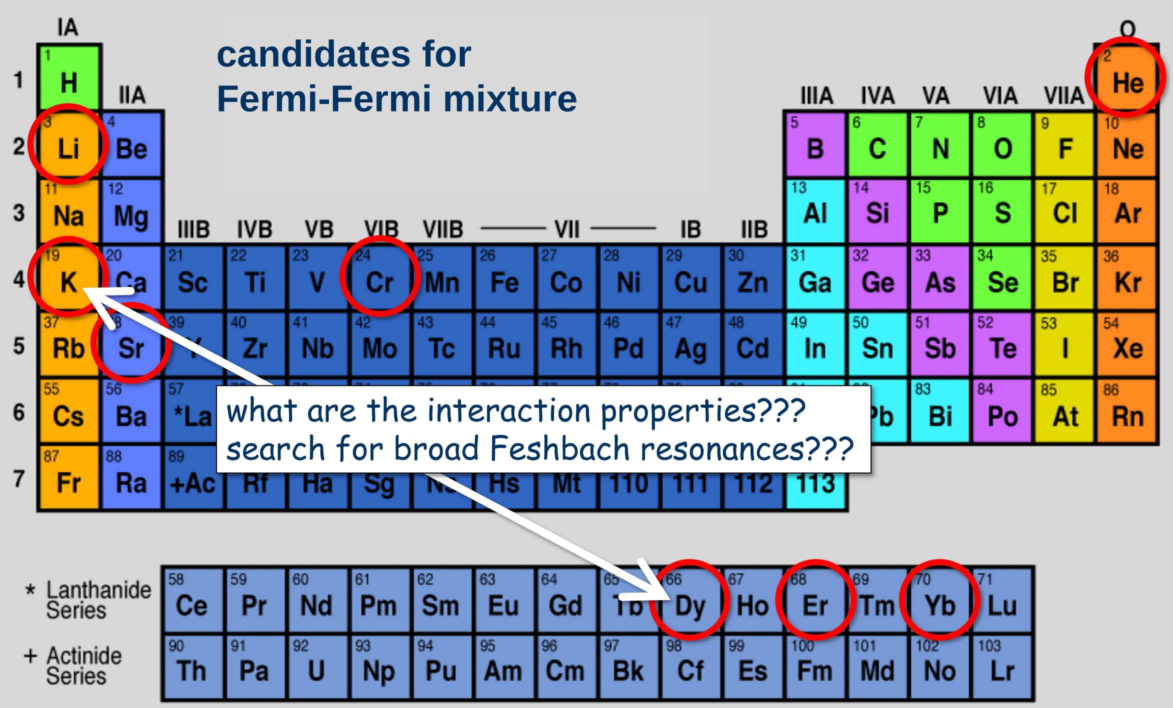


spontaneous dissociation
of Feshbach molecules

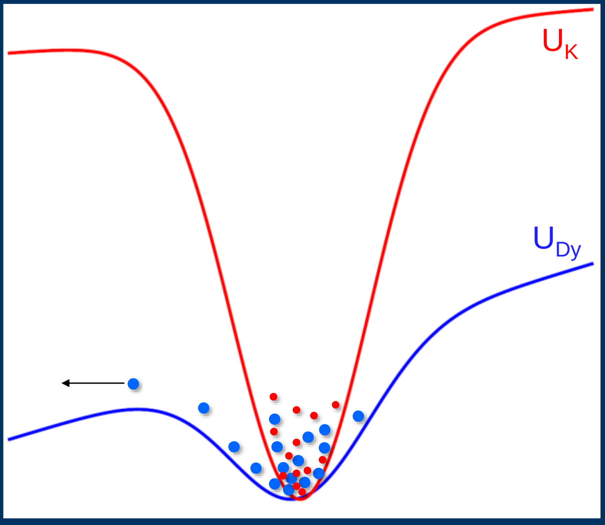


weak Pauli suppression
of few-body decay

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



two-species cooling scheme



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

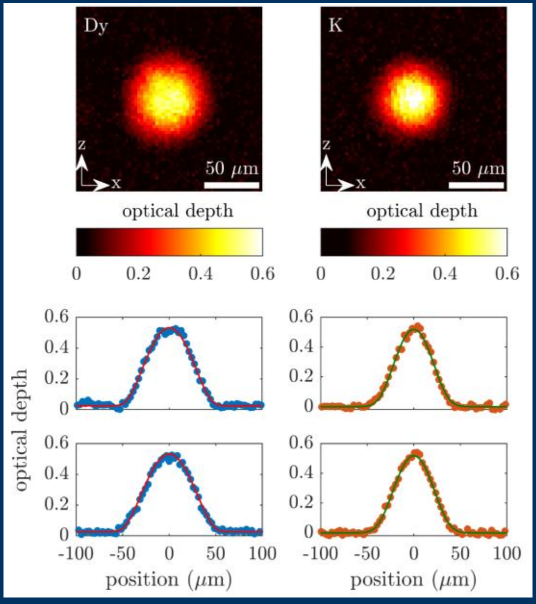
^{161}Dy – cooling agent

universal dipolar collisions

^{40}K – sympathetically cooled

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

optimum cooling result



^{161}Dy

2×10^4 atoms @ $T/T_F \approx 0.1$

^{40}K

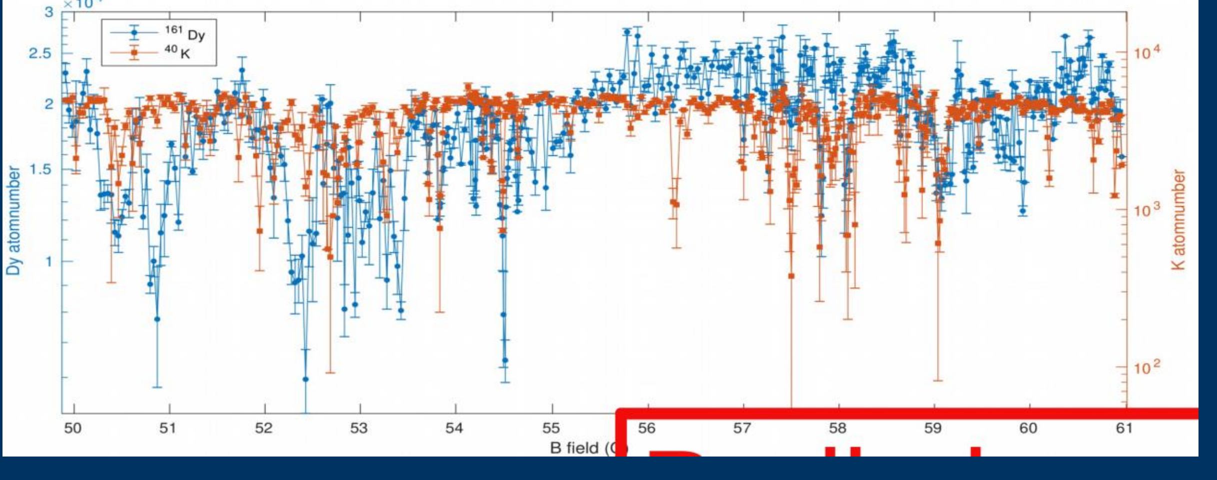
4×10^3 atoms @ $T/T_F \approx 0.2$

equal numbers can be reached
by initially loading more K atoms

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

many narrow resonances (as expected)

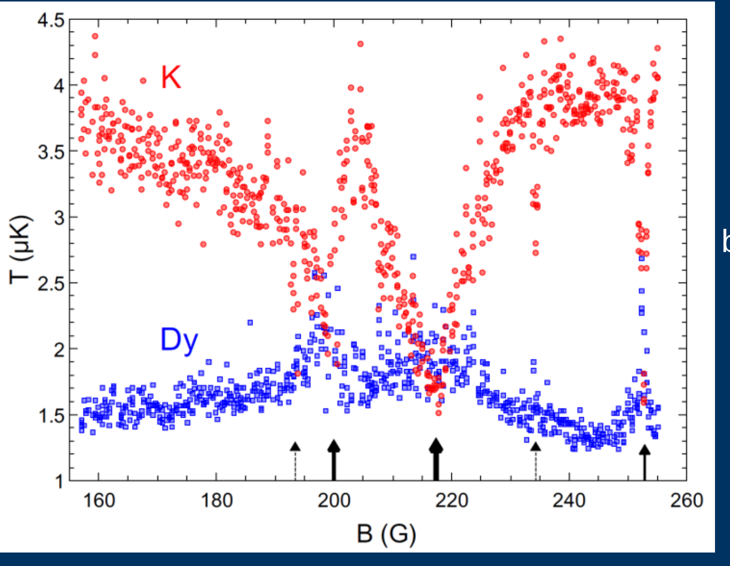
early B scan (2018)



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

search for broad Feshbach resonances

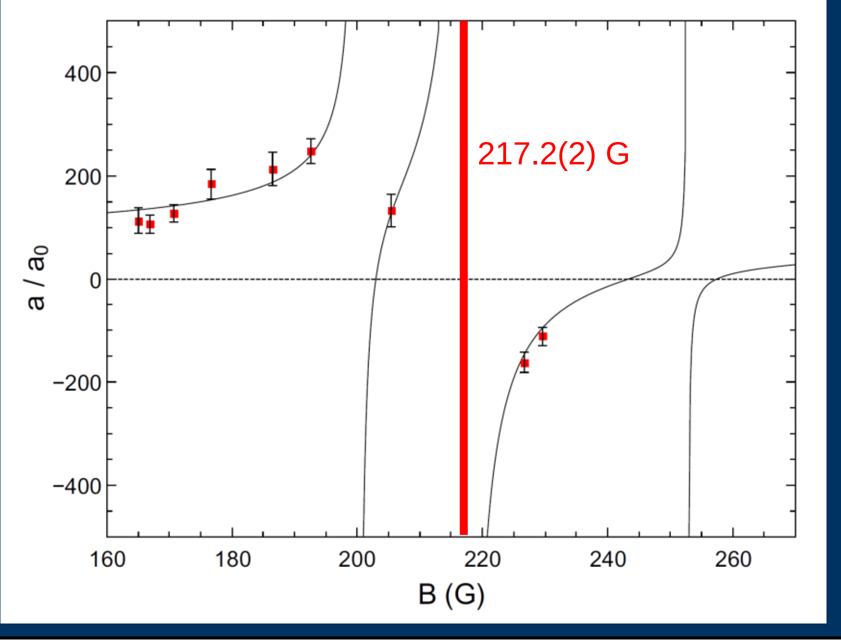
elastic scattering:
cross-species
thermalization



scenario of
broad overlapping
FRs

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

Broad FRs in Dy-K

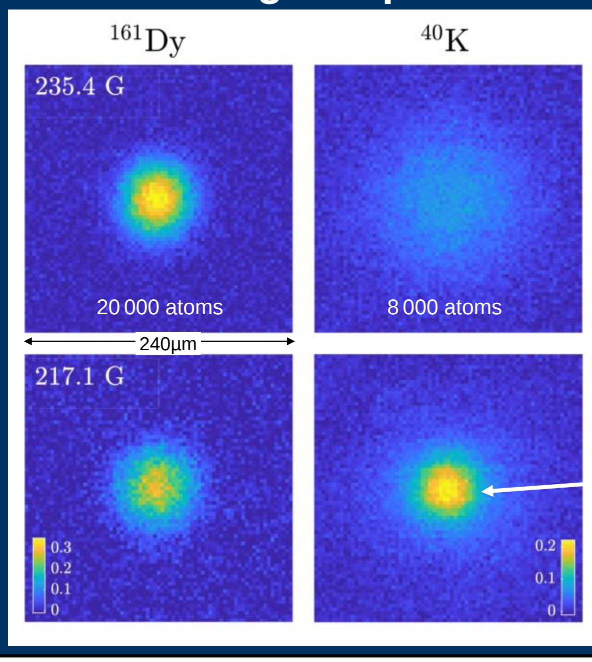


time-of-flight expansion

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

no interaction

resonant interaction

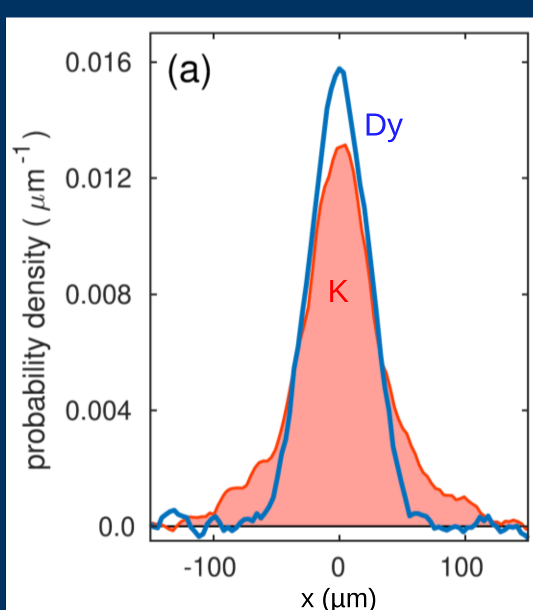


4.5 ms TOF

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

!!!

density profiles: a surprise

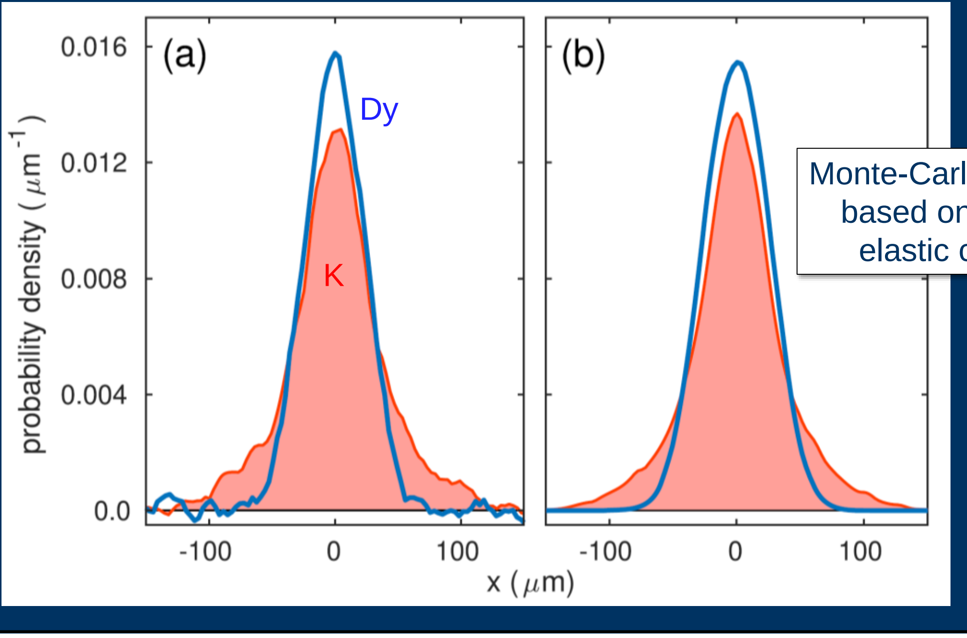


bimodality in K profile?

superfluidity???

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

density profiles: a surprise



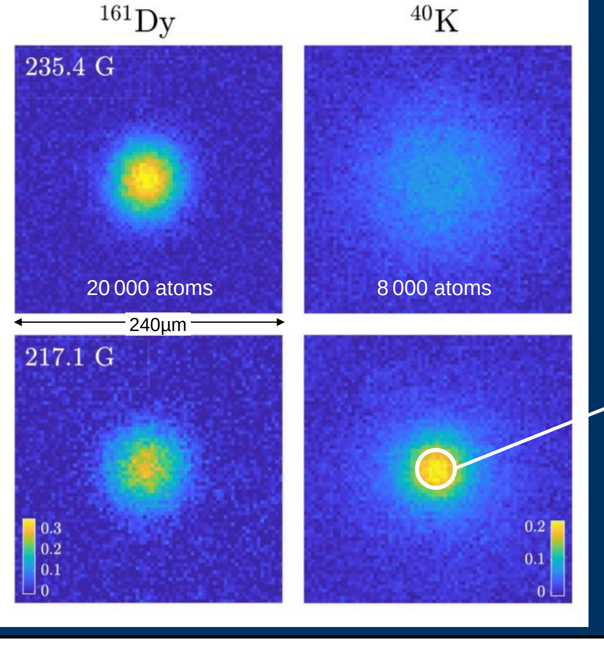
Monte-Carlo simulation based on resonant elastic collisions

time-of-flight expansion

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

no interaction

resonant interaction

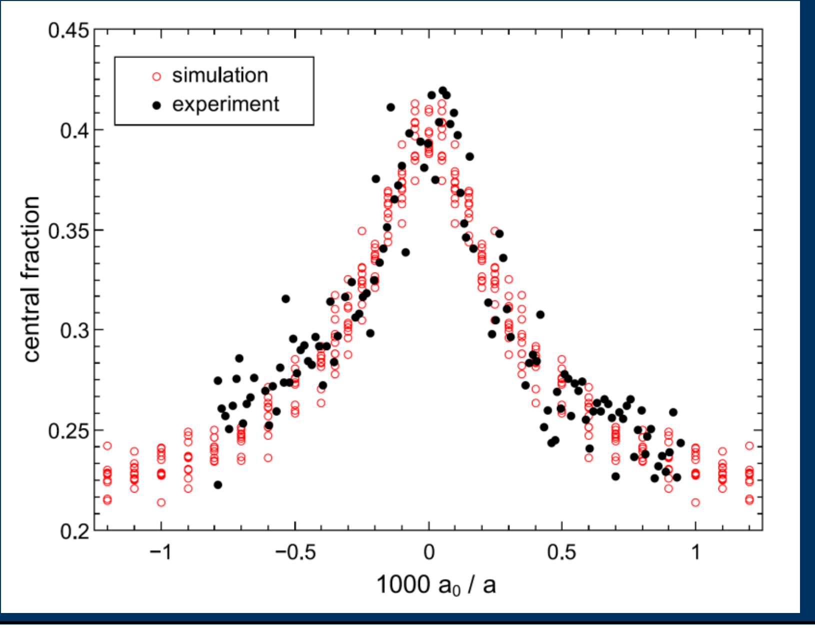


4.5 ms TOF

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

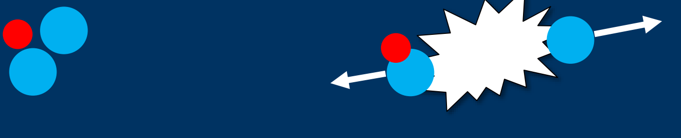
further analysis: fraction of atoms in the center

hydrodynamic expansion: central fraction of K atoms

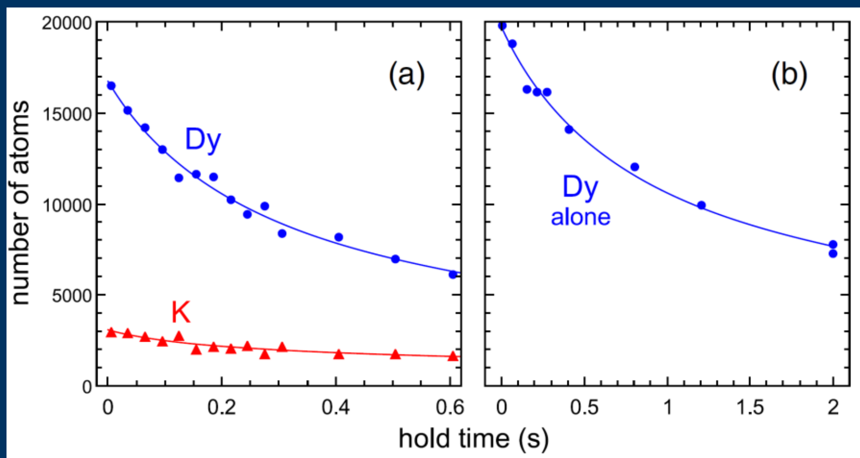


collisional stability:

will few-body processes kill us?



analyzing decay curves

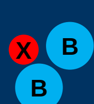


217.5 G

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)

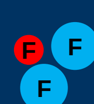


^{40}K-^{87}Rb (JILA)
^{6}K-^{41}K (Innsbruck)
^{6}K-^{133}Cs (Heidelb., Chicago)
^{40}K-^{162}Dy (Innsbruck)

^{39}K-^{87}Rb (Aarhus)
^{41}K-^{87}Rb (Aarhus, LENS)
^{7}Li-^{87}Rb (Tübingen)

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

our Fermi-Fermi mixture



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

10^{-25} cm^6/s

2…4 orders of magnitude suppression !!!!

where do we stand?

key ingredients for experiments on fermionic superfluids demonstrated!

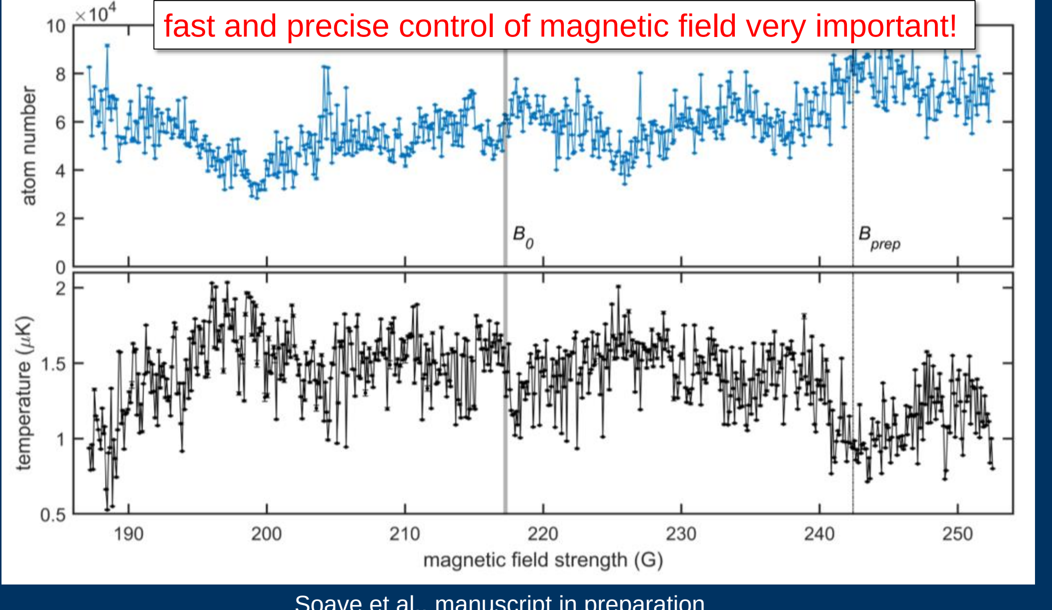
- cooling into deeply degenerate regime achieved **@ few 100mG**
  - interaction tuning via broad Feshbach resonance demonstrated **~217 G**
    - Pauli suppression of losses for resonant mixture observed

but...

transfer from low field to high field without losses and heating technically very challenging

complex behavior of Dy-Dy-Dy background losses

Dy background losses



Soave et al., manuscript in preparation

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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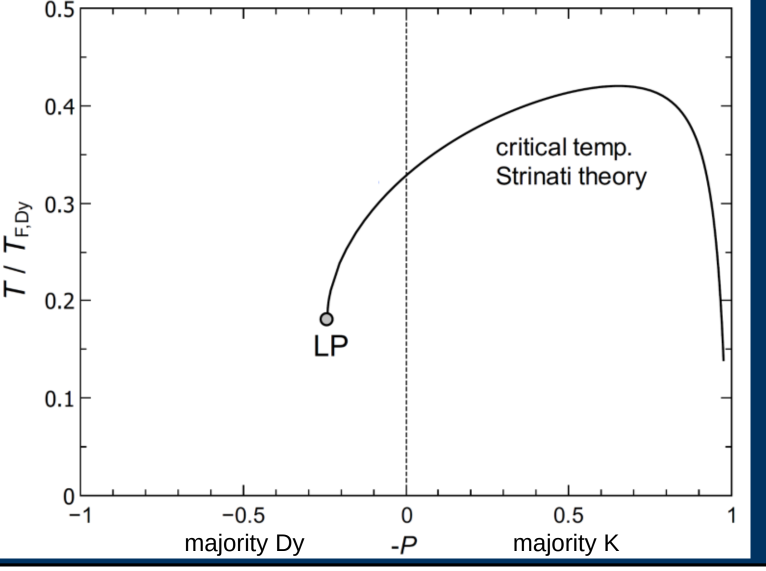
(Received 30 November 2020; accepted 22 January 2021; published 15 February 2021)

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

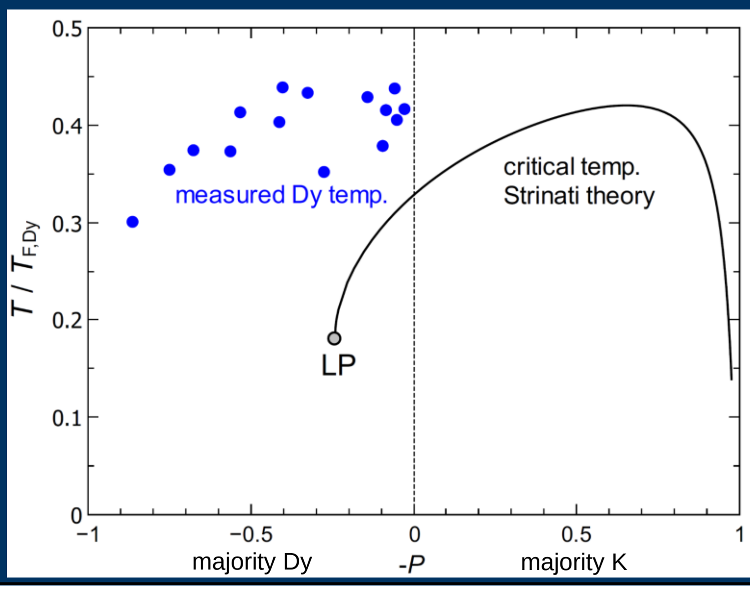


$$P \equiv \frac{N_{\mathrm{Dy}} - N_{\mathrm{K}}}{N_{\mathrm{Dy}} + N_{\mathrm{K}}}$$

Superfluidity in reach?

critical temperature for Dy-K under our trapping conditions

Soave et al., manuscript in preparation



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

Dy-K team

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Elisa Soave

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(2) back to France
(3) now at Korean Res. Inst. of Standards and Science

Vincent Corre (2)

Jeong Ho Han (3)

Emil Kirilov

RG

general conclusion

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

many opportunities and challenges
for experiment and theory

FWF Der Wissenschaftsfonds.
Doktoratskolleg ALM
MARIE CURIE ACTIONS