

# Ultracold ${}^6\text{Li}$ - ${}^{40}\text{K}$ mixtures with resonant interactions

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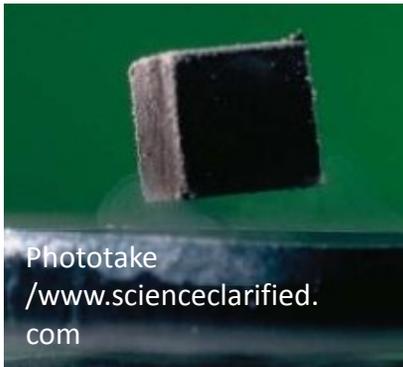


# Plan

- **Motivation, experimental details**
- **$^{40}\text{K}$  impurities in a  $^6\text{Li}$  Fermi sea**  
(C. Kohstall et al, *Nature*, 458, 615 (2012))
- **Repulsive branch of a Fermi-Fermi mix**  
(ongoing)
- ~~• **Attractive branch of a Fermi-Fermi mix**  
(ongoing)~~

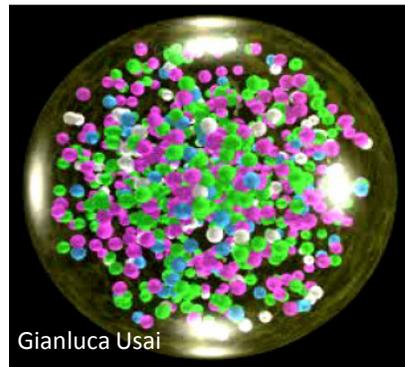
# General idea

**Ultracold Fermi gases:**  
systems with many interesting analogies...



Phototake  
/www.scienceclarified.  
com

high- $T_c$  sc



Gianluca Usai

quark gluon plasma



NASA/ESA

neutron stars

... & with unprecedented control



Temperature



Geometry



2D-1D-0D



Interaction



Pop. imbalance

# General idea

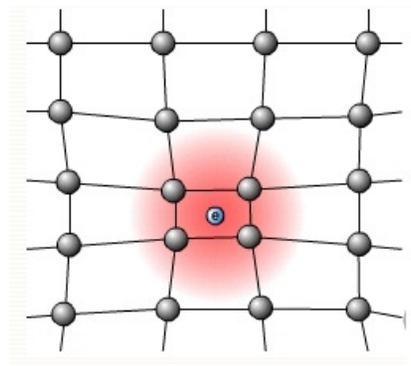
## Ultracold Fermi-Fermi mix:



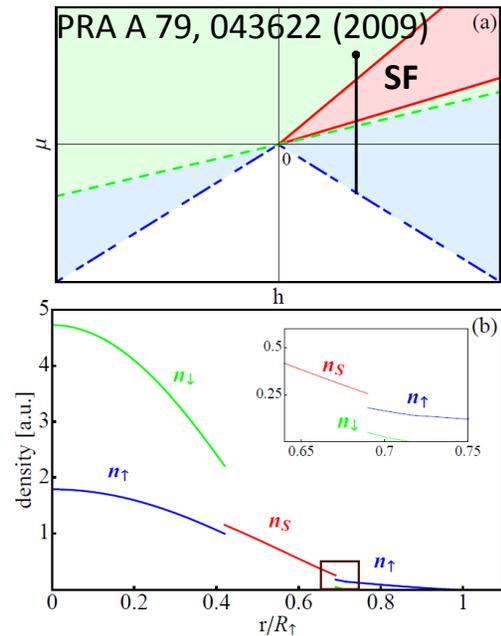
Mass imbalance



Few-body physics



Polaron physics



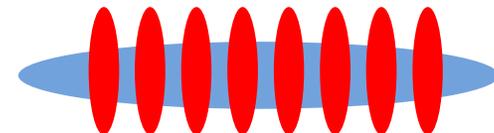
Rich phase diagrams



Species selective control



Individual trapping  
Individual motion

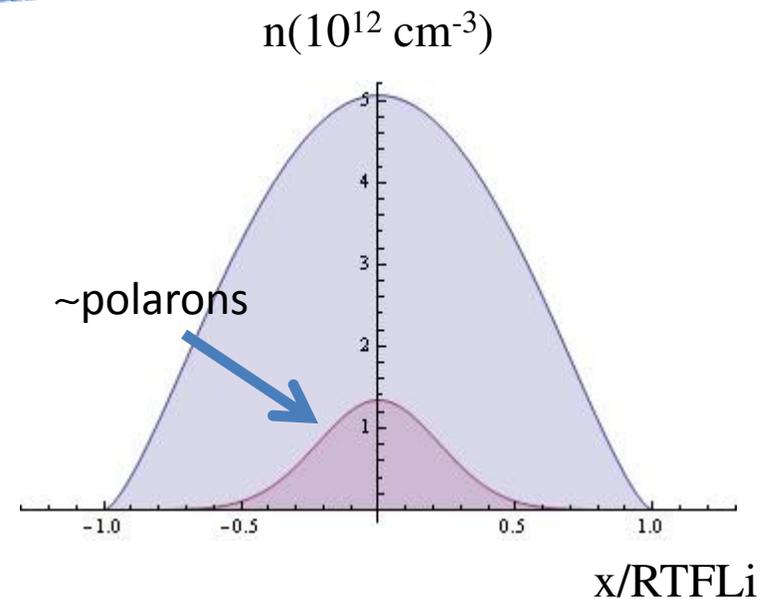
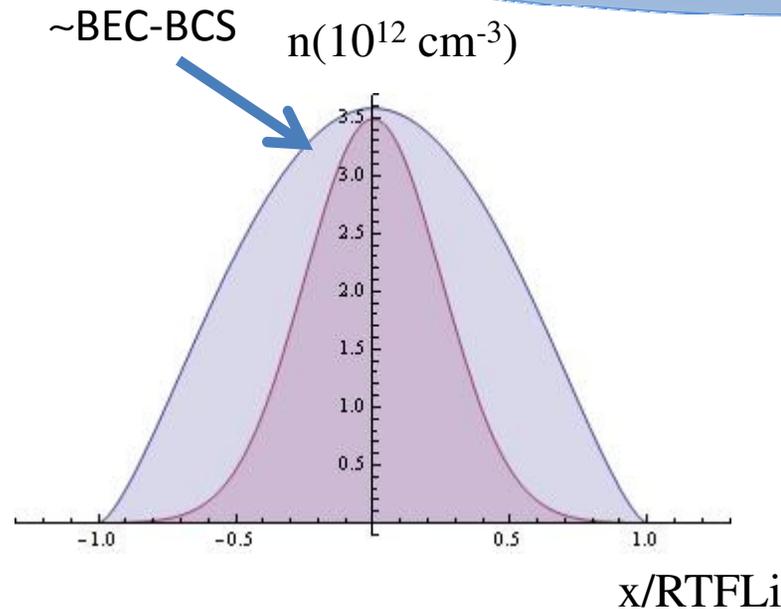
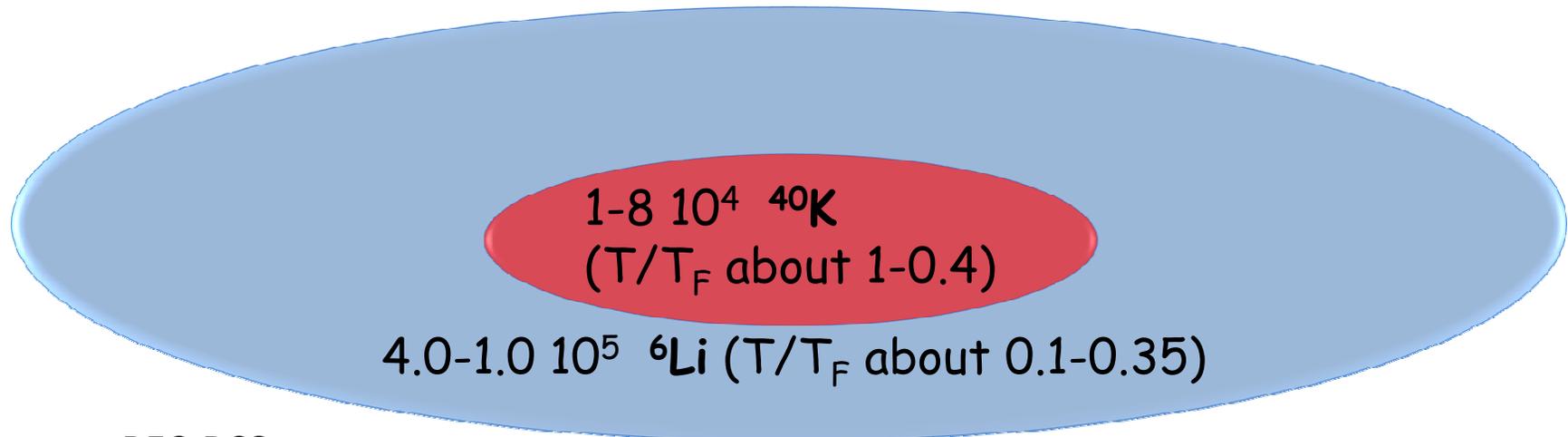


Mixed dimensions: novel quantum phases (e.g. Y. Nishida's works)

# $^{40}\text{K}$ - $^6\text{Li}$ Fermi mix: weak interaction

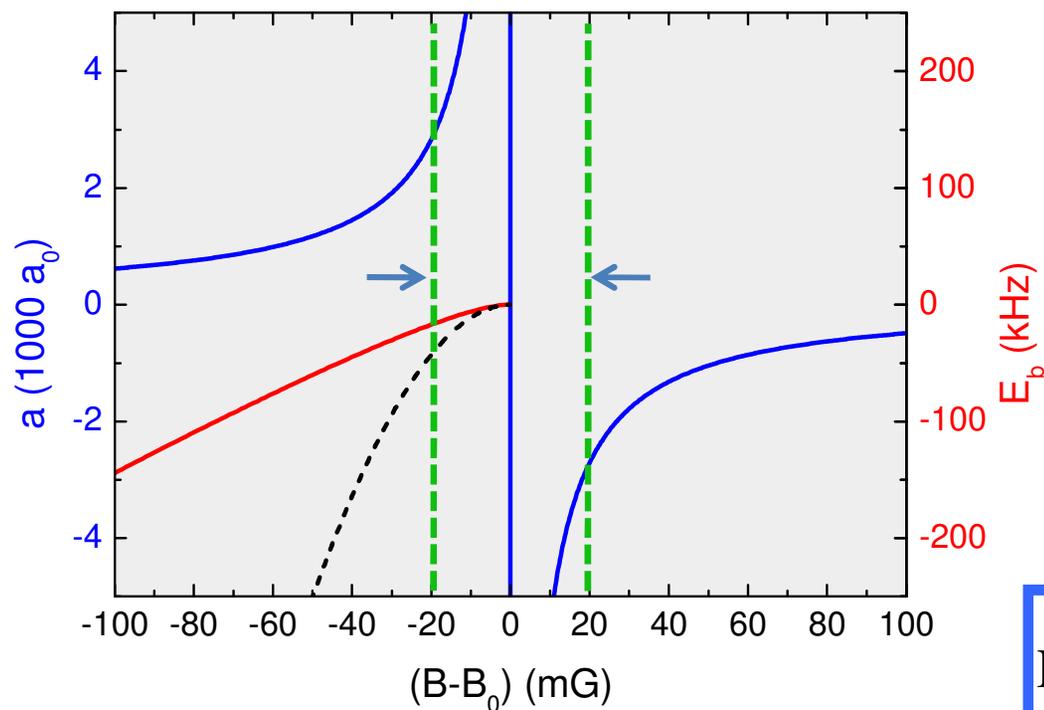
## Our starting point (all optical)

F. Spiegelhalder et al, PRA **81**, 043637 (2010)



# $^{40}\text{K}$ - $^6\text{Li}$ Fermi mix: interaction tuning

Control of the interaction via  $\text{Li}|1\rangle$ - $\text{K}|3\rangle$  Feshbach resonance (\*)



$$a(B) = 63 a_0 \left( 1 - \frac{0.88}{B - 154.719} \right)$$

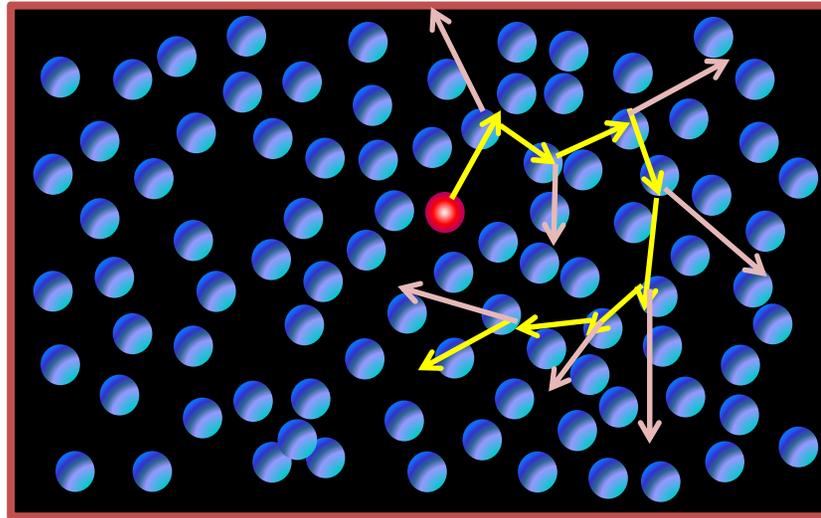
Excited state of mix:  
 $\tau_{2B} < 20 \text{ ms}$

$$R^* = \frac{\hbar^2}{2 m_r a_{bg} \Delta \delta \mu} = 2710 a_0 \approx 1 / \kappa_F^{Li}$$

(\*) Naik et al, EJPD **65**, 55 (2011); A. Trenkwalder et al. PRL **106** 115304 (2011)

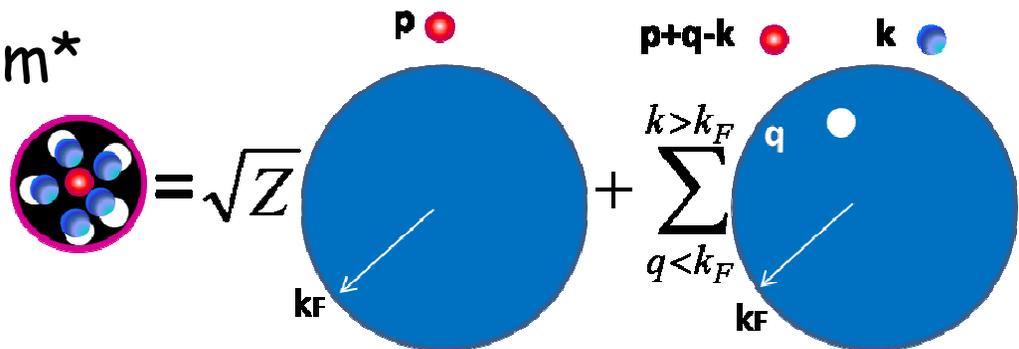
# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

Polaron scenario: strong interactions with the Fermi sea modify the impurity properties...



...mb system describable as QUASI PARTICLES

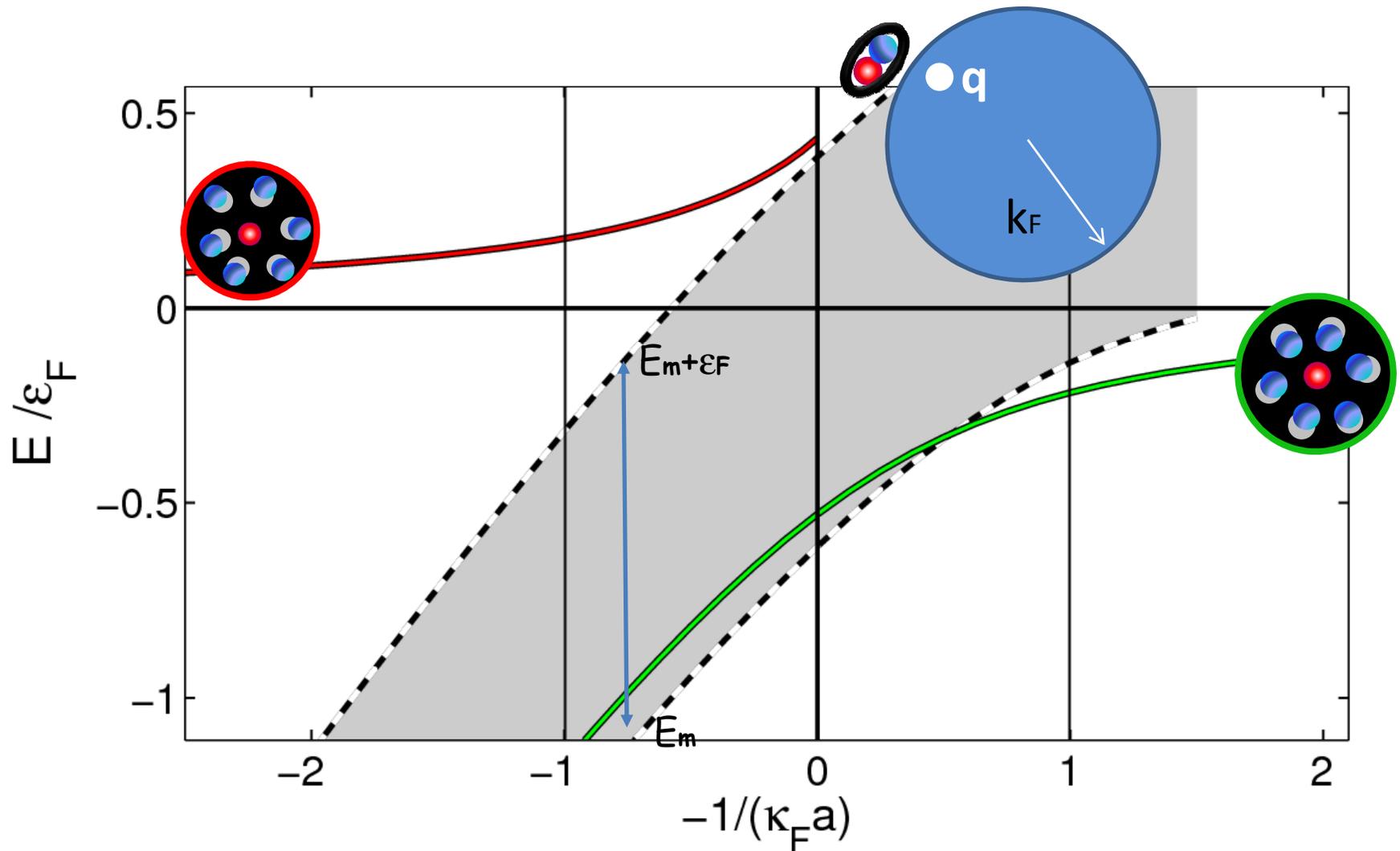
- ✓ Renormalized energy &  $m^*$
- ✓ Lifetime
- ✓ QP Residue  $Z$



F. Chevy, PRA 74, 063628 (2006)

# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

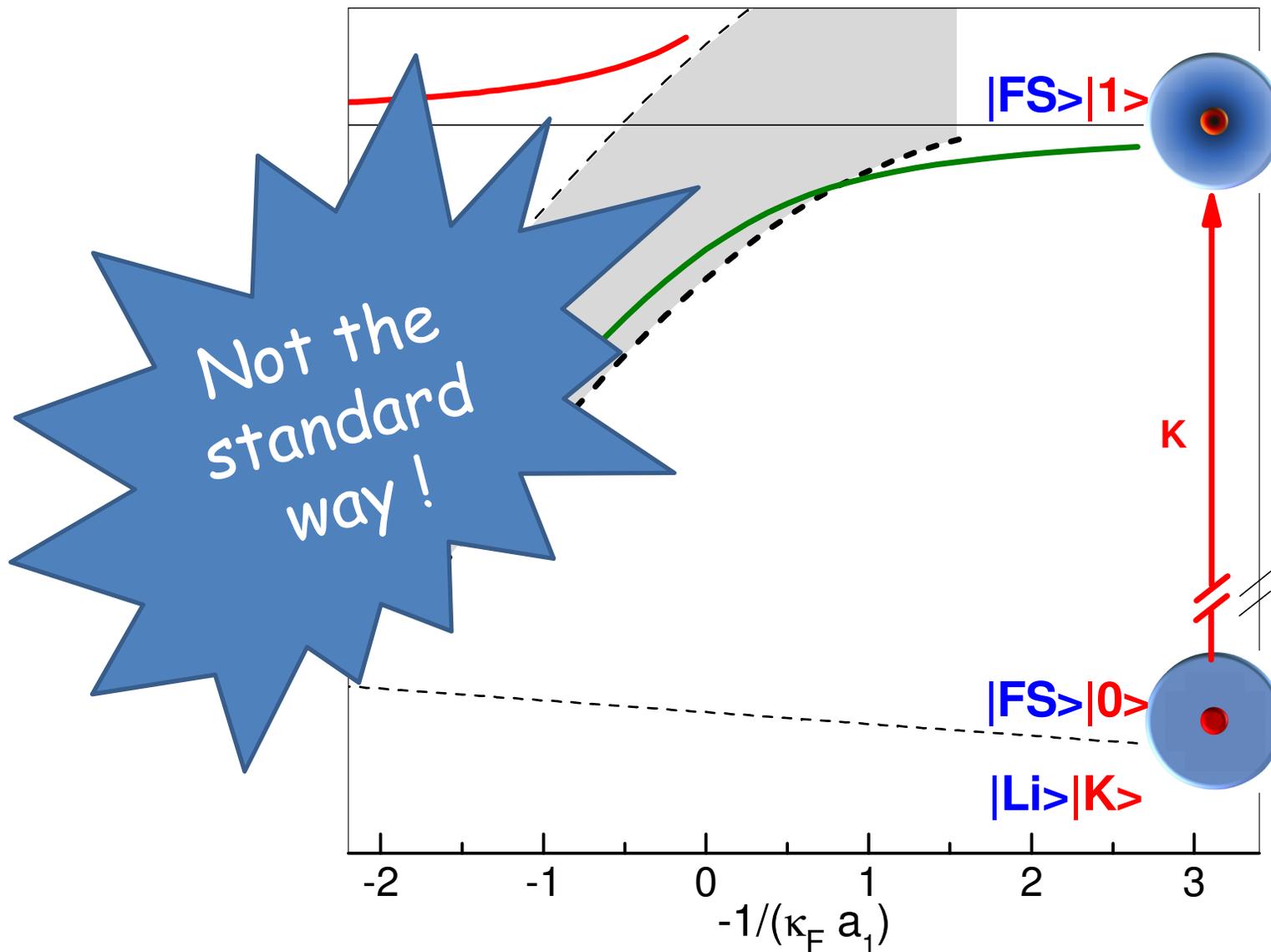
## Energy landscape: spectral function



Theory for  $\varepsilon_F = 37$  kHz,  $\kappa_F \times R^* = 0.95$  (P. Massignan, EPL, **98**, 10012 (2012))

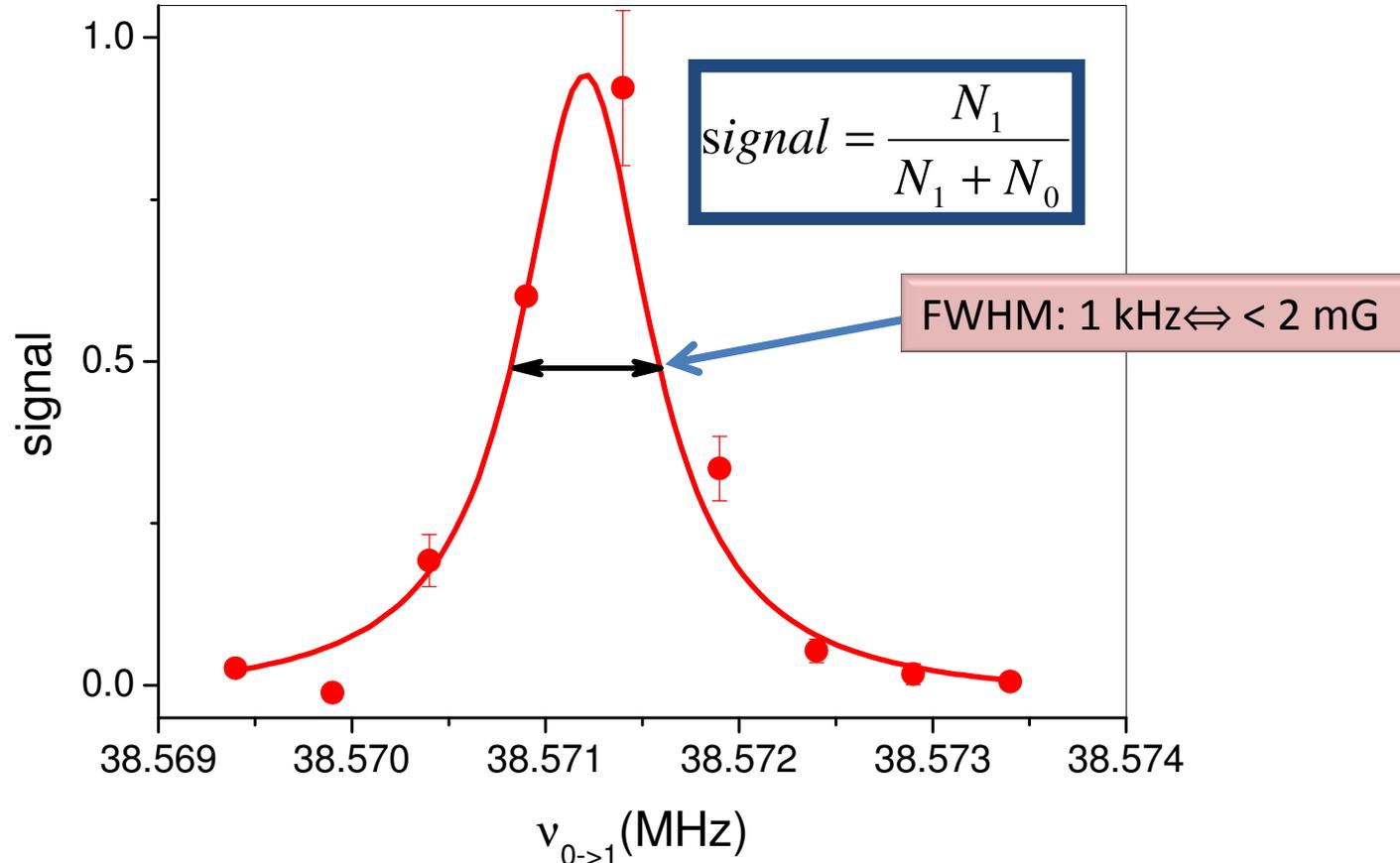
# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

Reverse spectroscopy: probing all excitations



# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

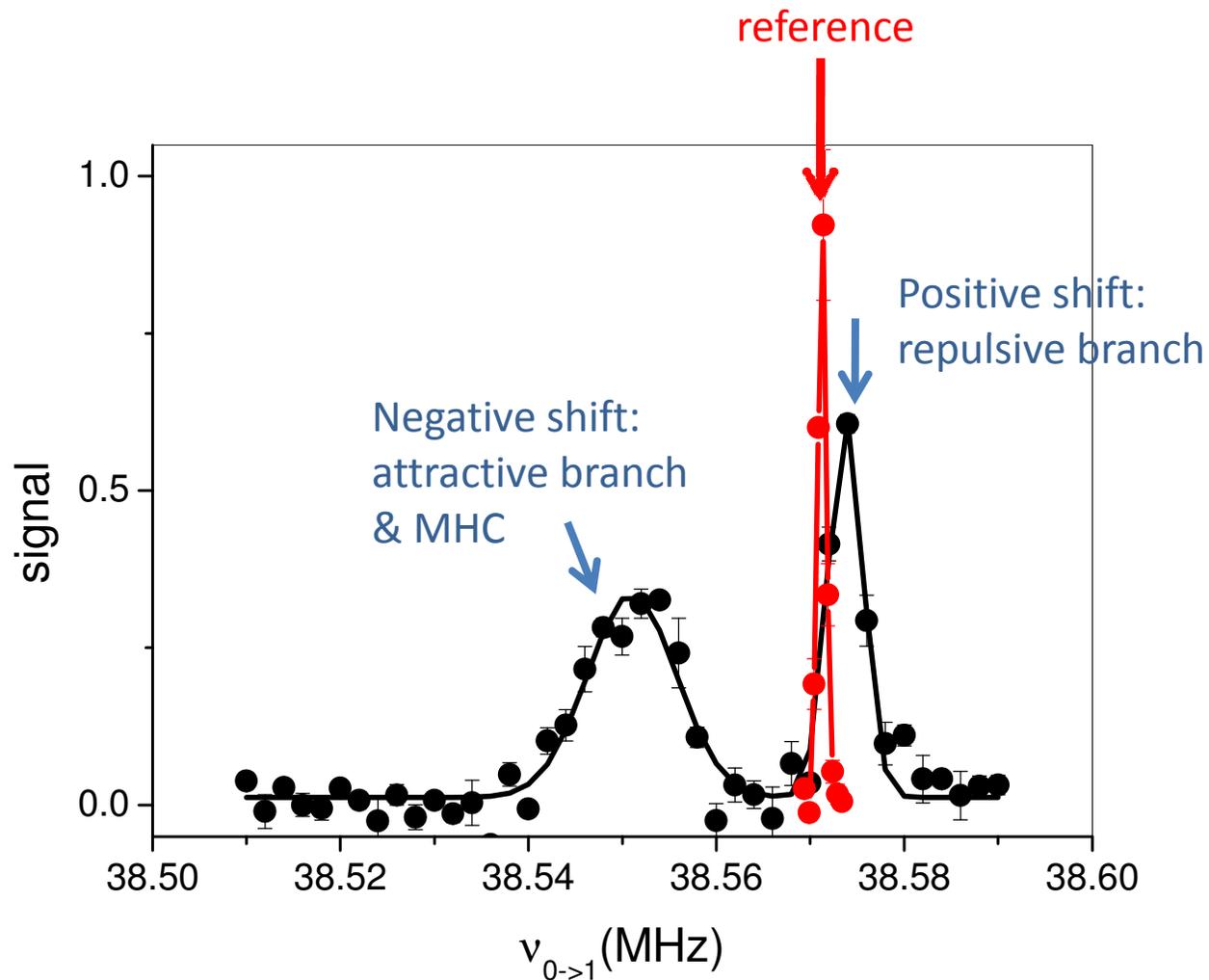
interaction OFF (Li in non resonant state): field calibration with  $\text{K}0 \rightarrow \text{K}1$   
e.g. @  $B=154.685(2)$  G, i.e. BEC side @ -34 mG



# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

interaction ON (Li in resonant state): spectroscopy with  $\text{K}0 \rightarrow \text{K}1$

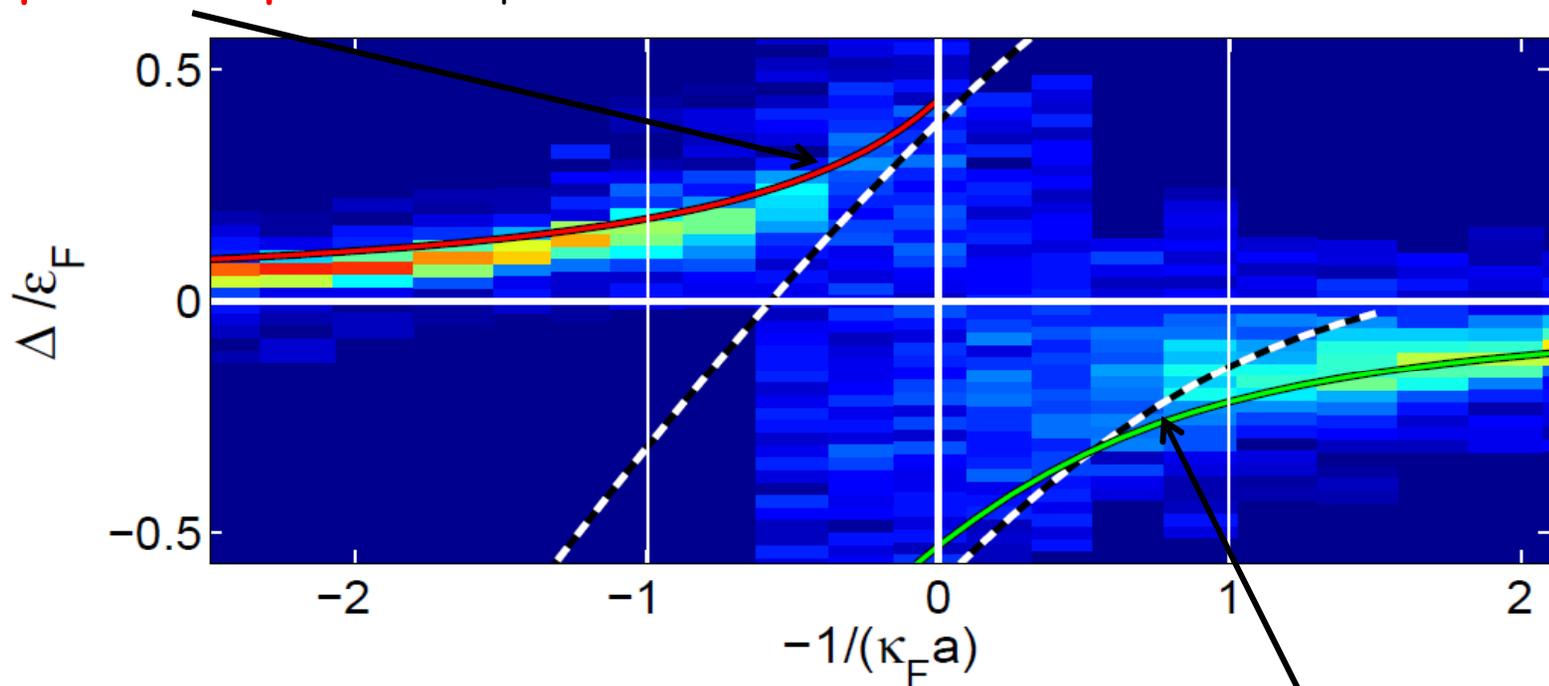
e.g. @  $B=154.685(2)$  G, i.e. BEC side @  $-34$  mG



# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

Low power: unveiling the polaronic branches

Rep. polaron up to  $-1/\kappa_F a \sim -0.25$  !



$$\Delta = (v_{rf} - v_0)$$

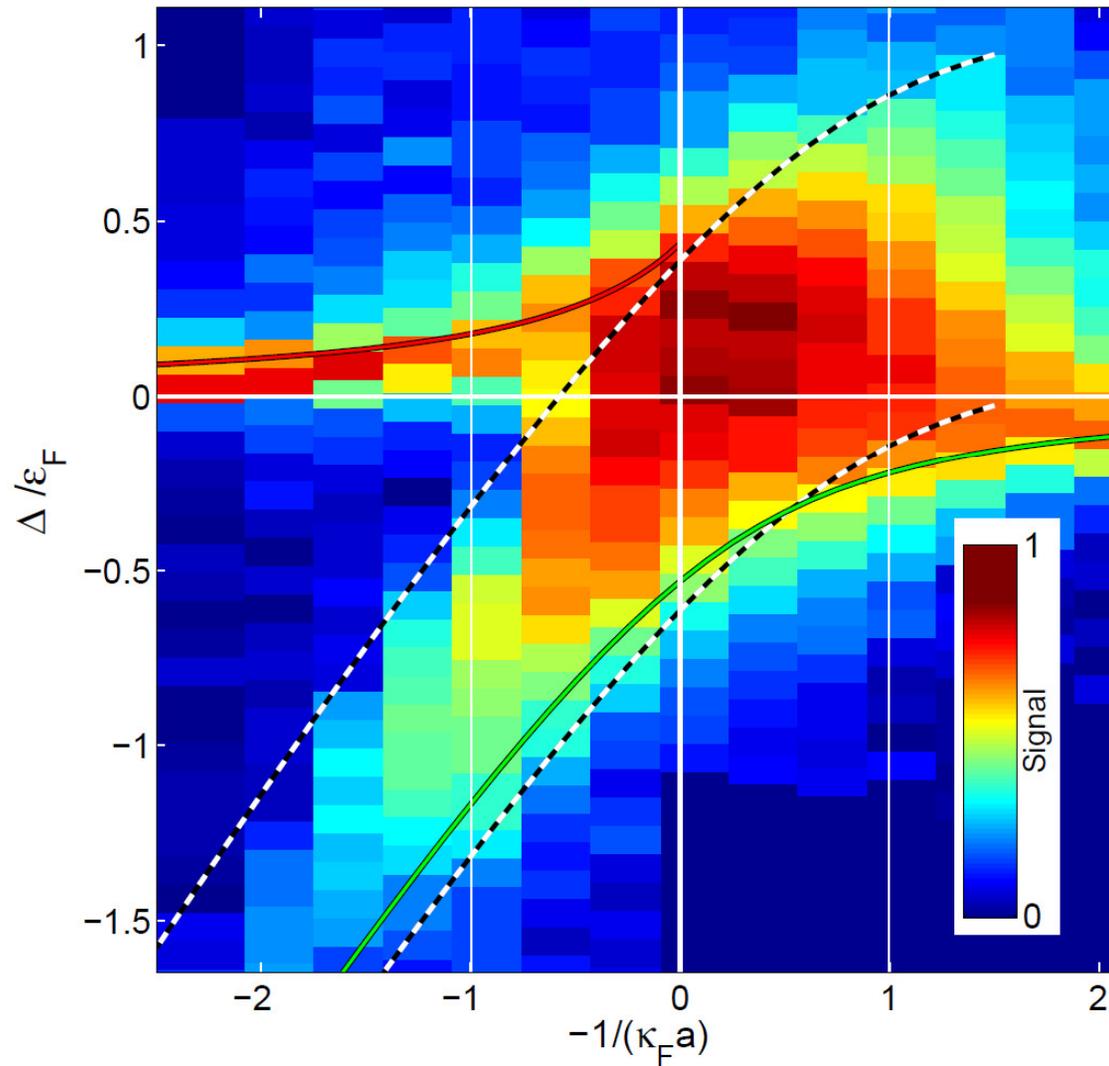
Attr. Polaron down to  $-1/\kappa_F a \sim 0.8$   
(theory says:  $-1/\kappa_F a \sim 0.6$ )

$$(\kappa_F a)^{-1} \sim (B - B_0)/20\text{mG}$$

1 ms  $\pi$  pulse (w/o interactions)

# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

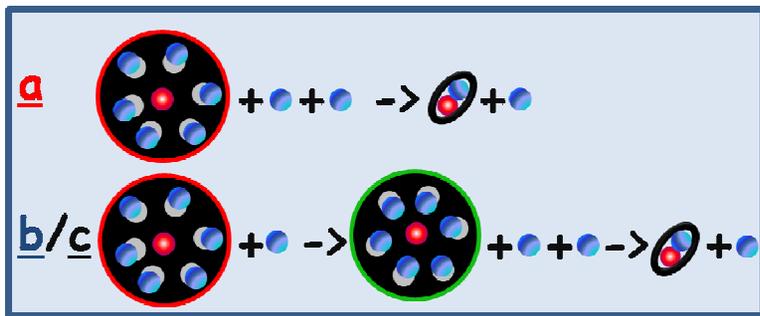
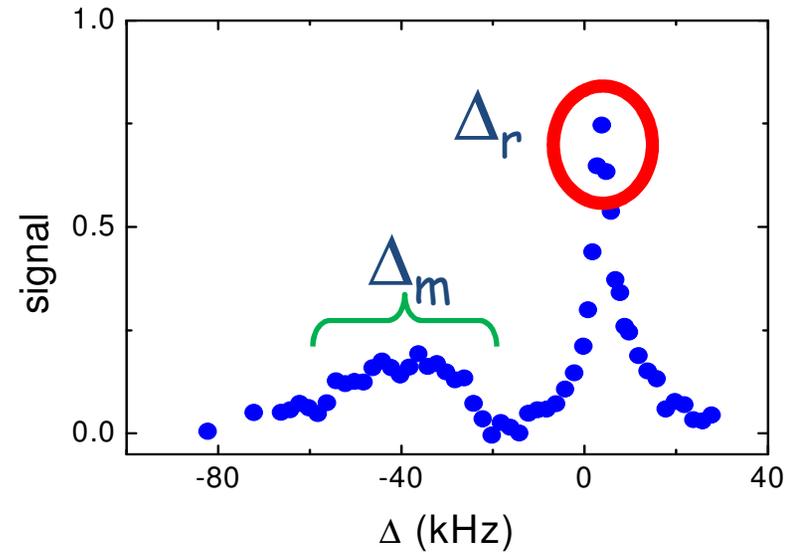
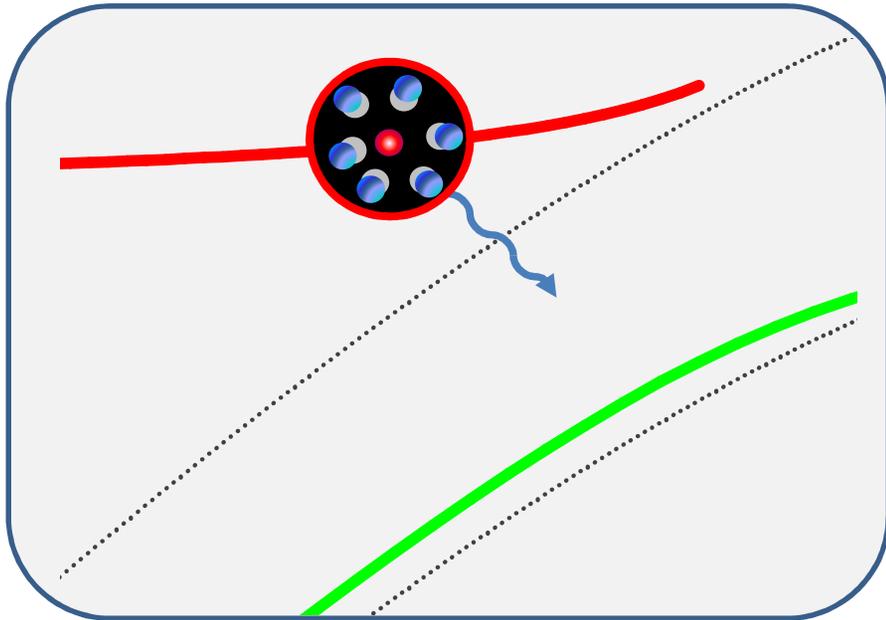
High power: unveiling the Molecule Hole Continuum



5  $\pi$  pulses (100X increased Rf power)

# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

## Decay of repulsive polarons



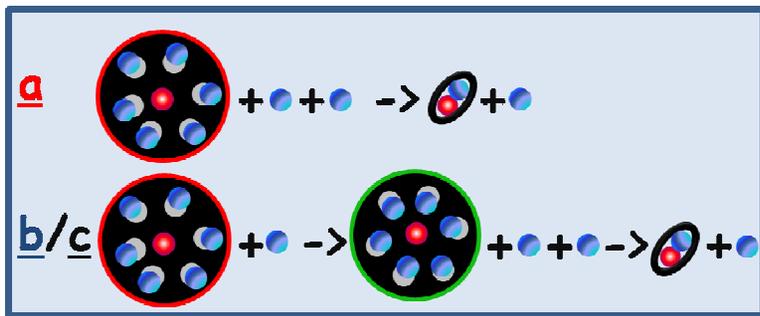
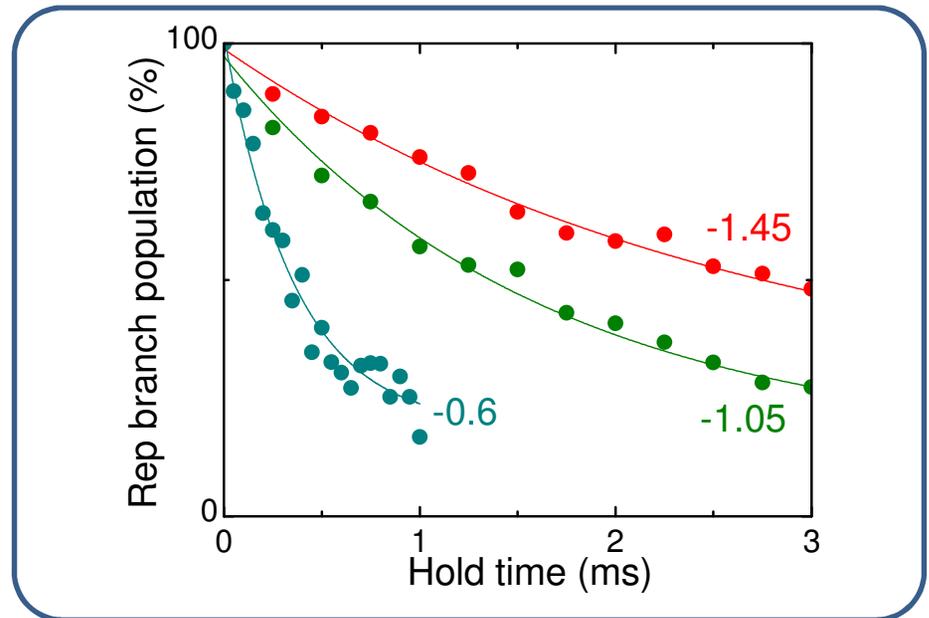
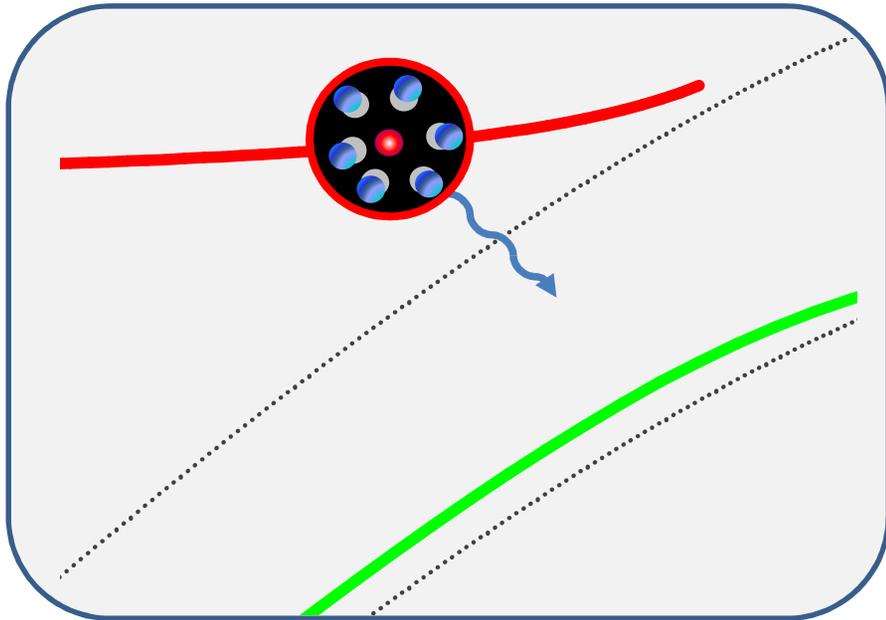
- 1<sup>st</sup> : 0→1 transfer @  $\Delta_r$
- 2<sup>nd</sup>: cleaning of remnant 0

..... variable hold time: allow decay .....

- 3<sup>rd</sup>: 1→0 back @  $\Delta_r$

# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

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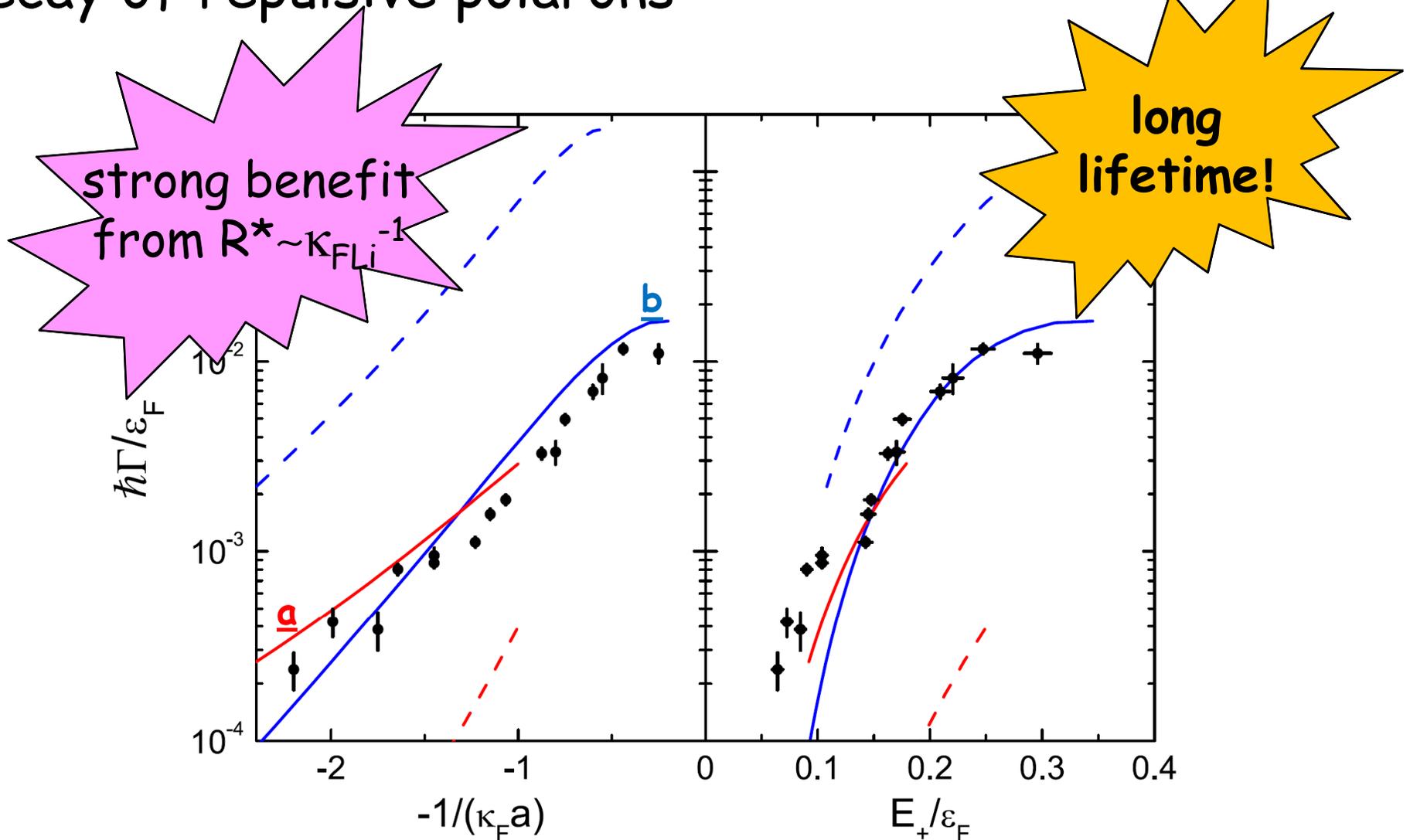
..... variable hold time: allow decay .....

- 3<sup>rd</sup>: 1→0 back @  $\Delta_r$

Measure ONLY population back in 0 vs holding time

# $^{40}\text{K}$ impurities in a $^6\text{Li}$ Fermi sea

## Decay of repulsive polarons



More about this: C. Kohstall et al, *Nature*, **458**, 615 (2012)

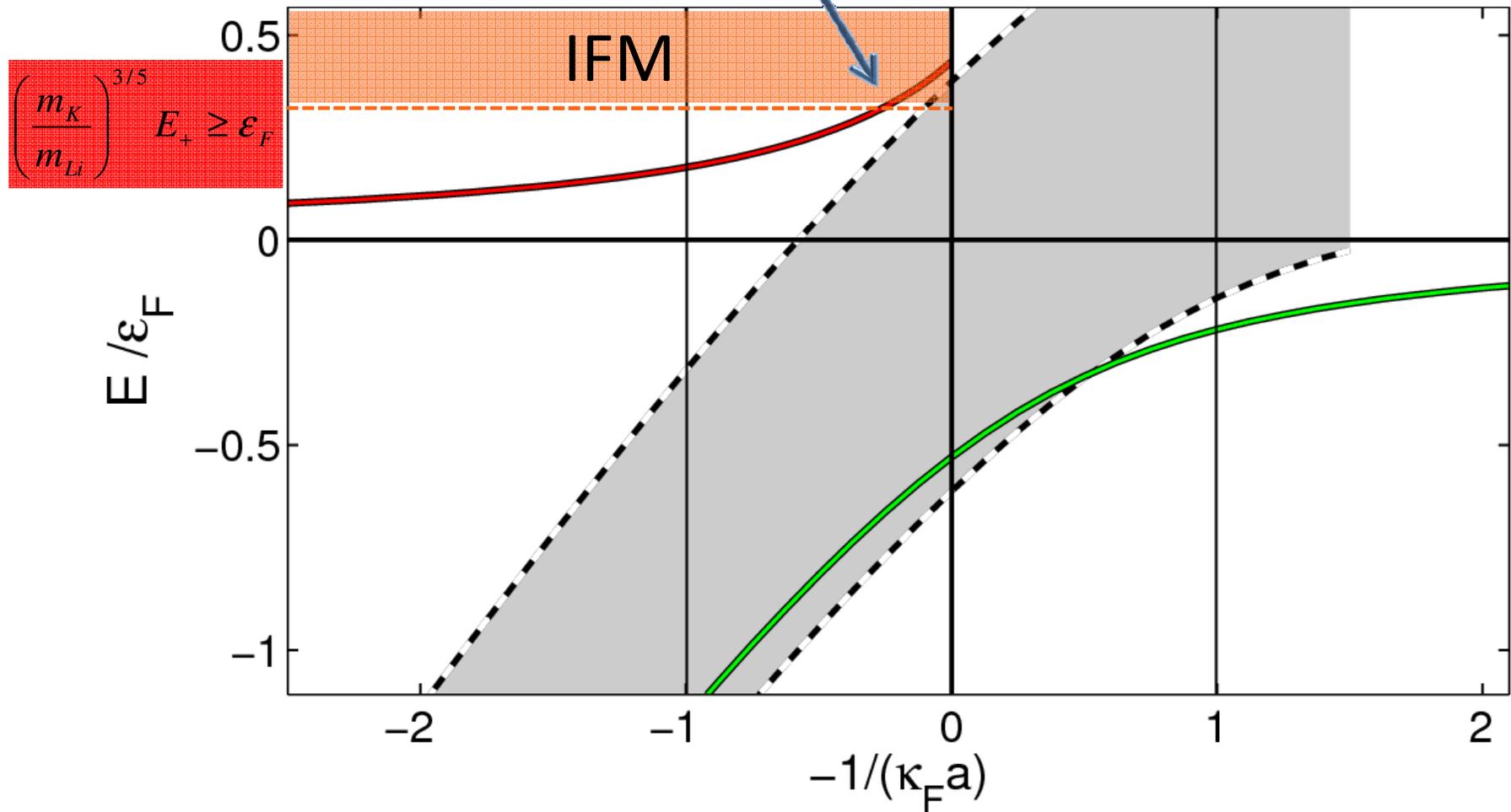
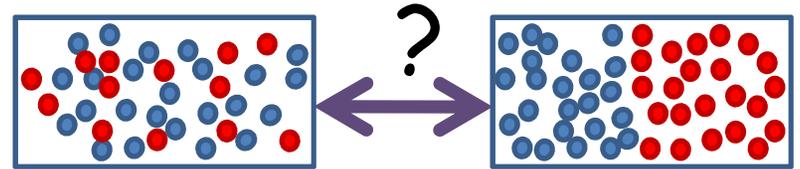
# Repulsive branch: why interesting?

$E_+$  sets stability of a fully ferromagnetic phase

Pilati et al., Phys. Rev. Lett. **105**, 030405 (2010)

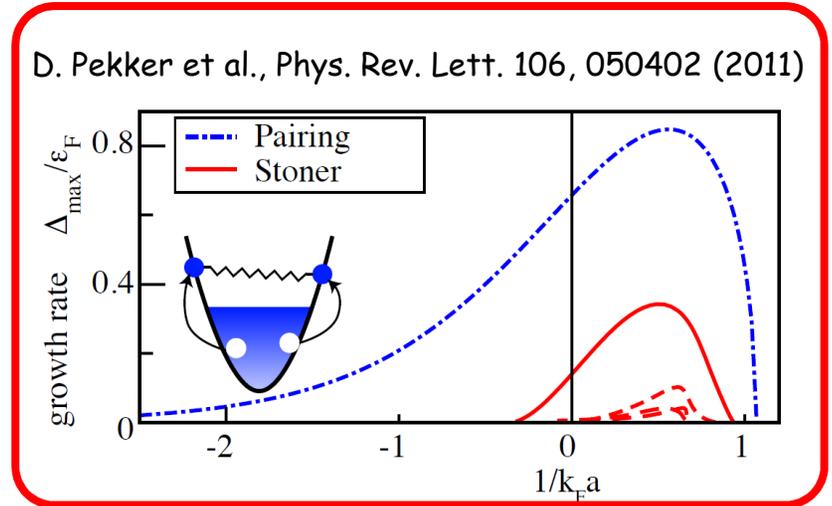
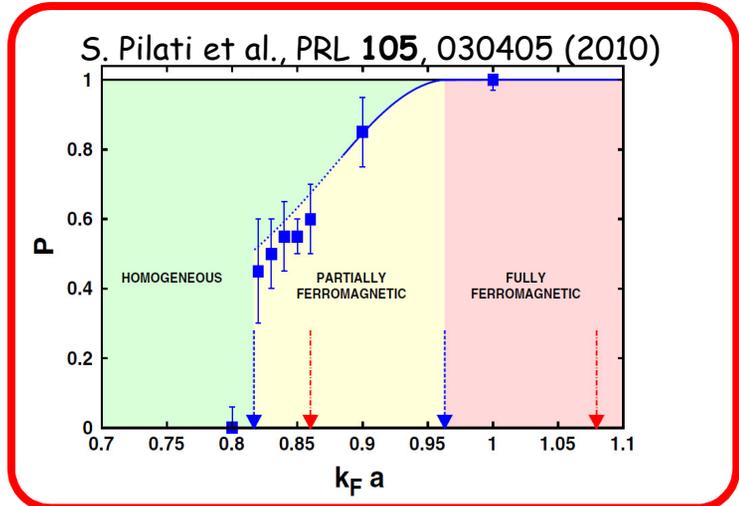
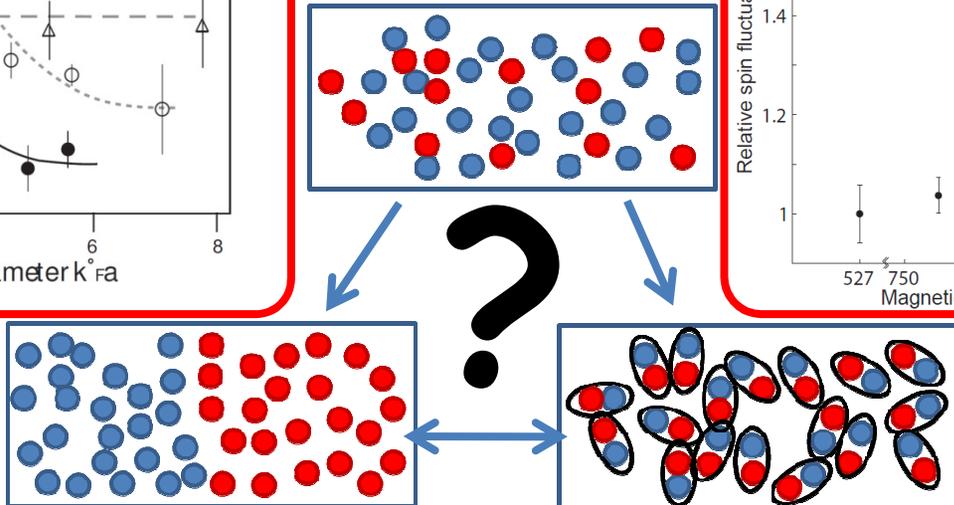
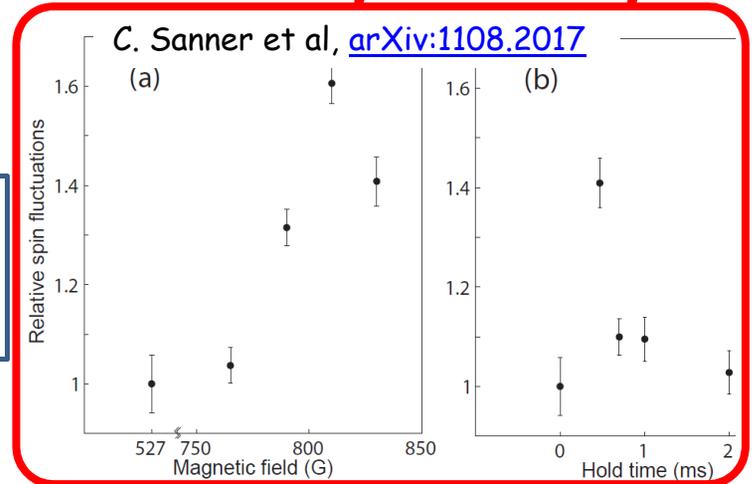
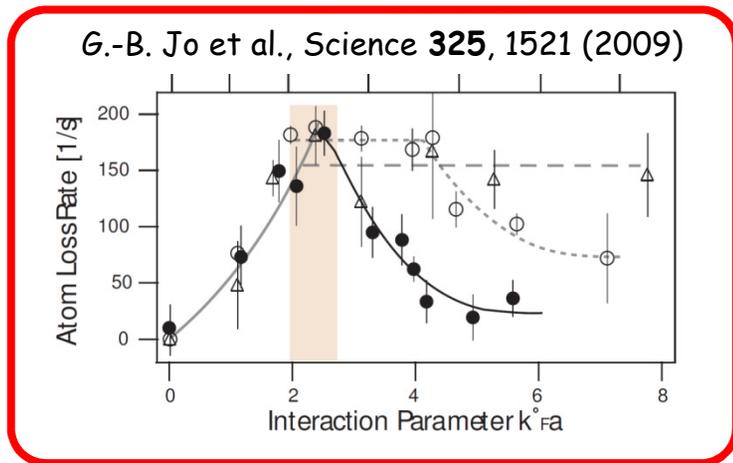
Chang et al., PNAS **108**, 51 (2011)

Massignan et al., EPJD **65**, 83 (2011)



# Repulsive branch: why interesting?

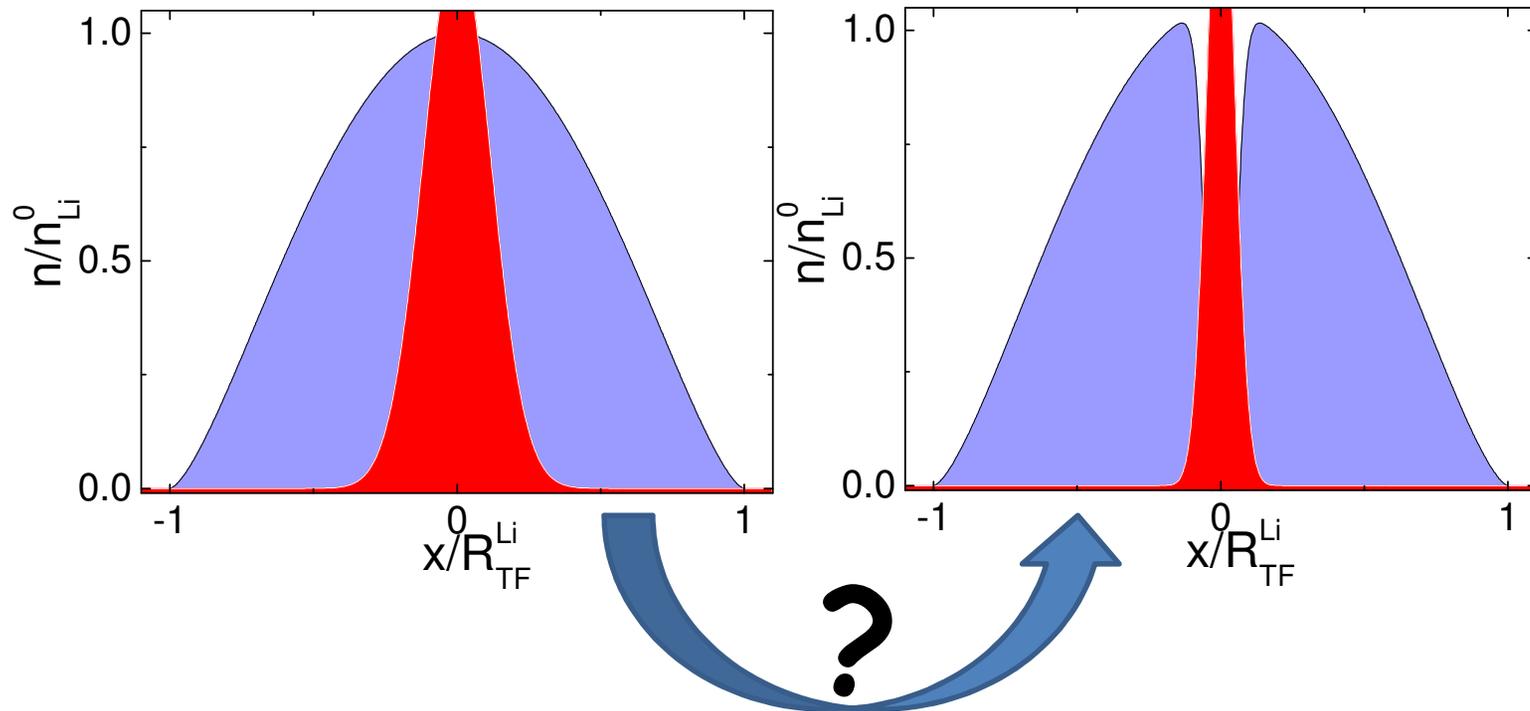
... challenging at a FR: unstable against decay, set by  $\Gamma$



# Repulsive branch of a F-F mixture

What happens to our system (more balanced)?

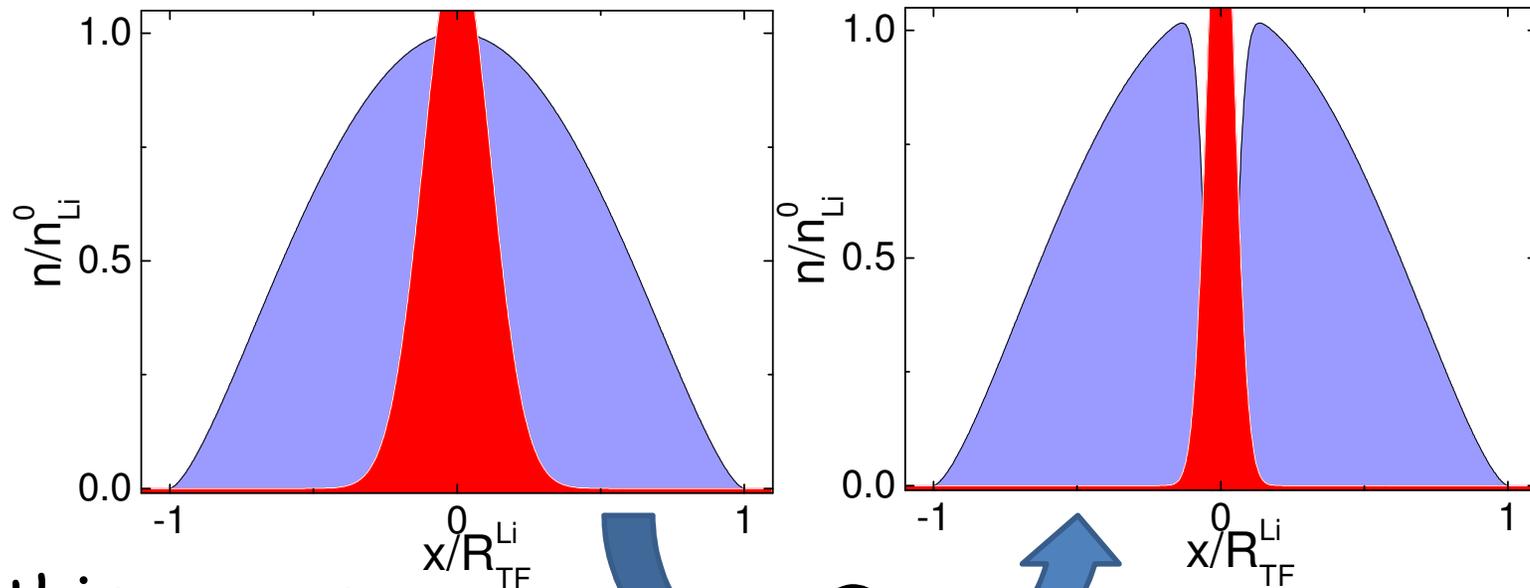
$N_K \sim 5.5 \cdot 10^4$ ;  $N_{Li} \sim 2.2 \cdot 10^5$ ;  $T \sim 420$  nK;  $k_{FLi} a \geq 1$  at  $-17$  mG ( $k_{FLi} \sim 0.6 k_{FK}$ )



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• If this occurs...

Atom losses will stop

K size will squeeze

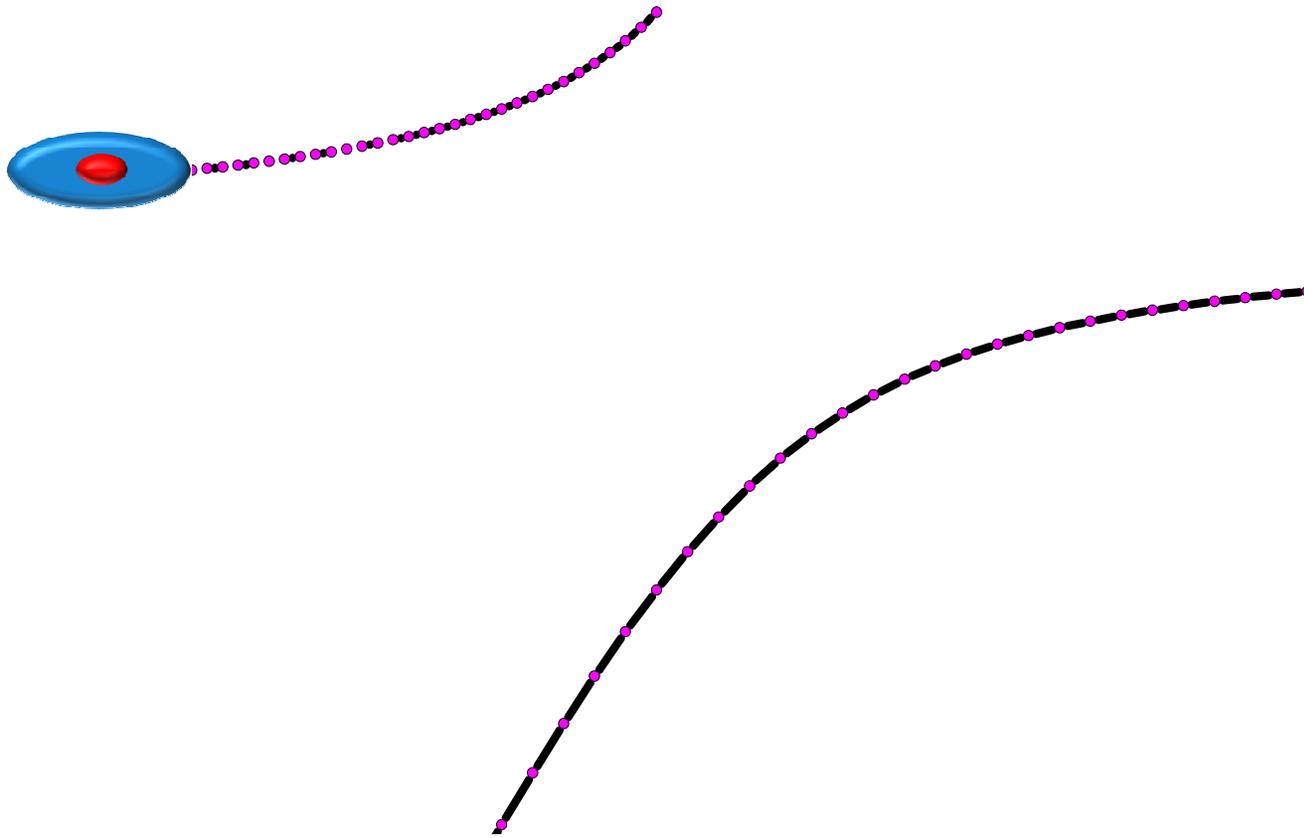
K kinetic energy will increase

Rf shift will decrease

Li will have a hole in the center

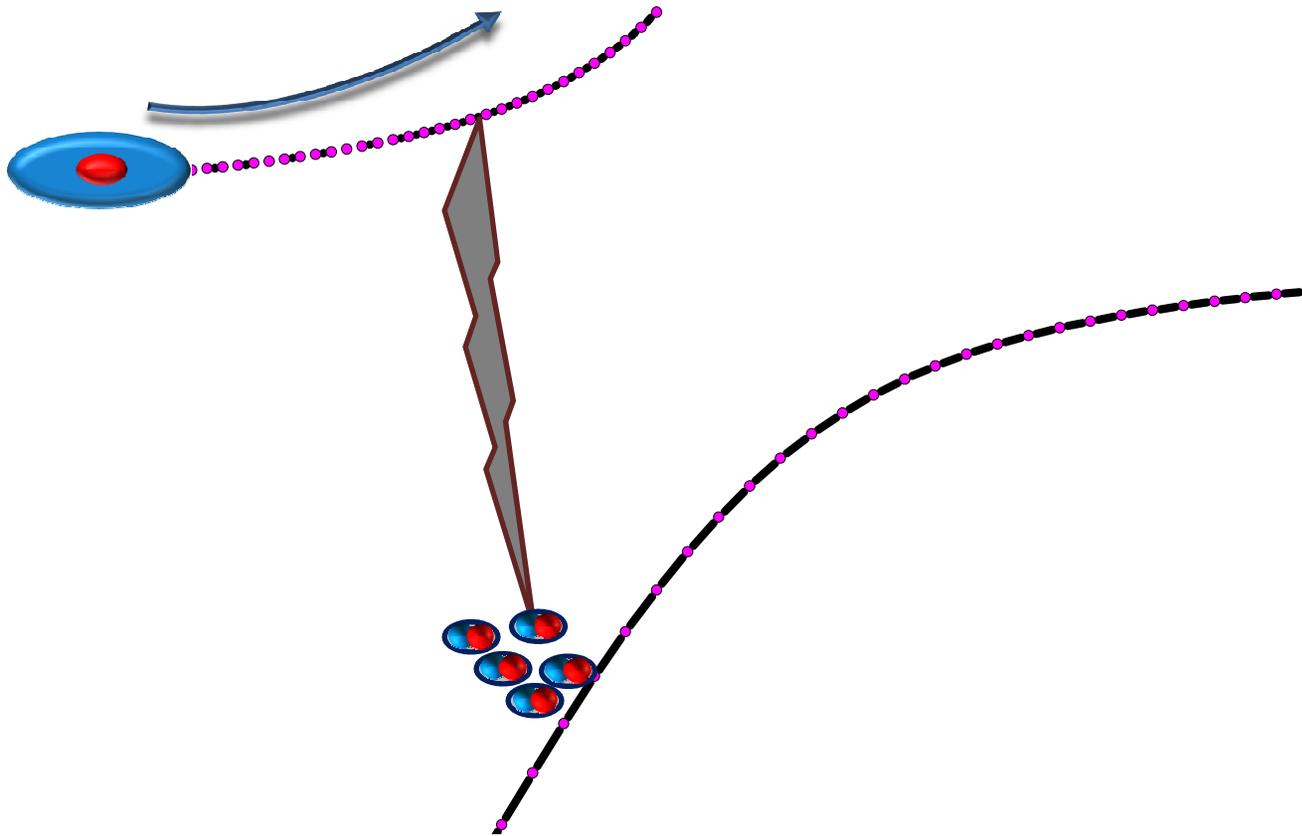
# Repulsive branch of a F-F mixture

IDEA: ramp to  $B_f$  along rep branch & let system evolve...



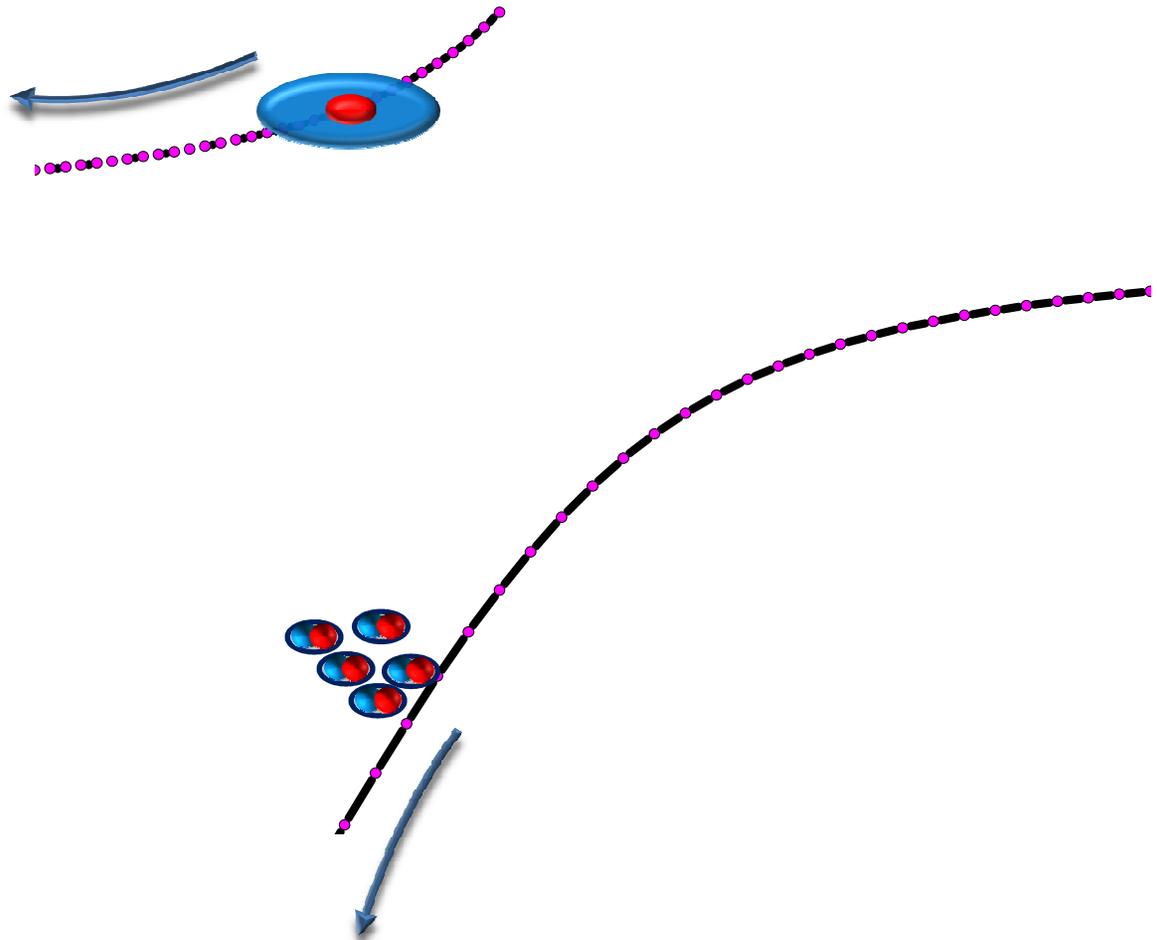
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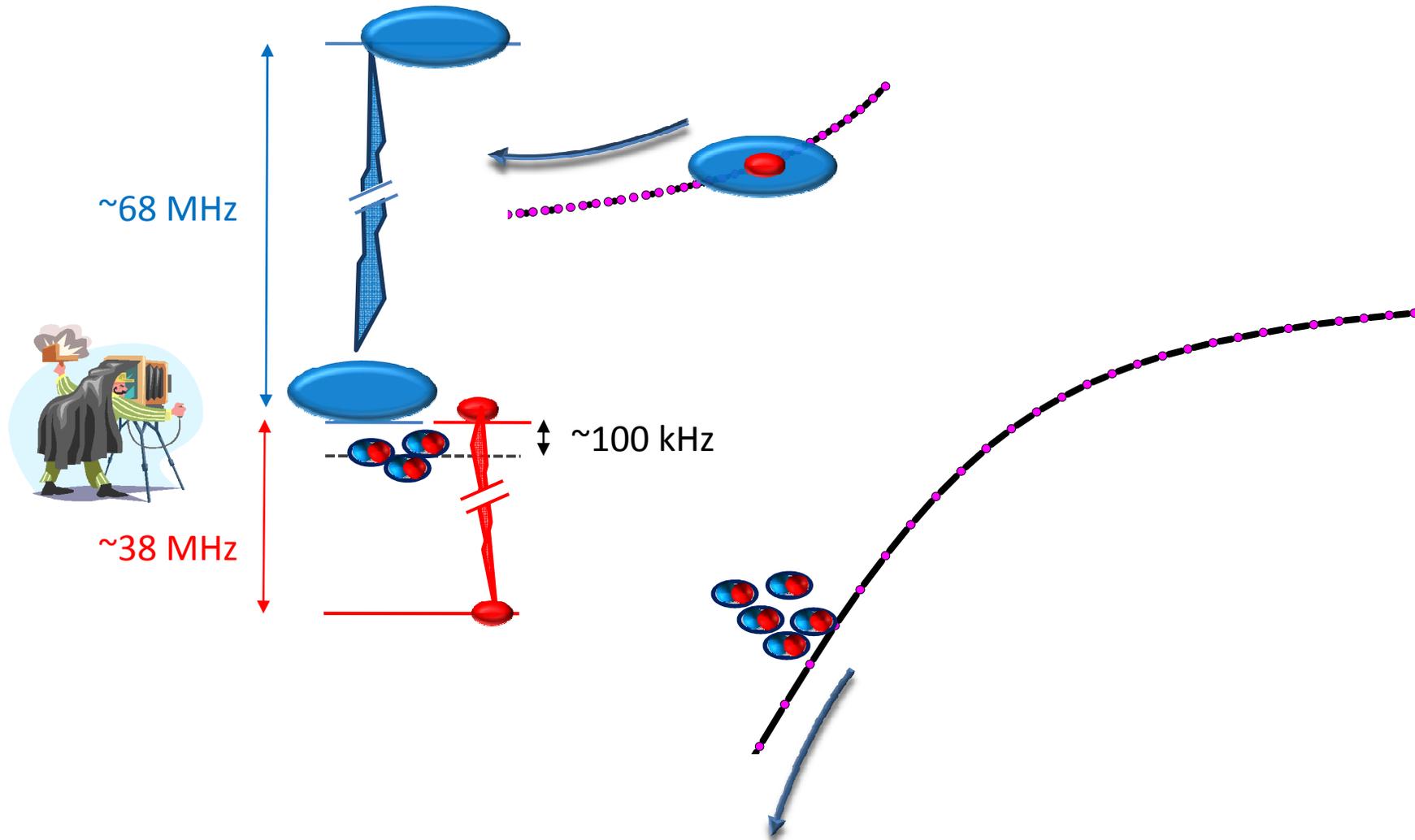
# Repulsive branch of a F-F mixture

... then monitor K (Li and molecules) at -300 mG after 1.5 ms ball. expansion



# Repulsive branch of a F-F mixture

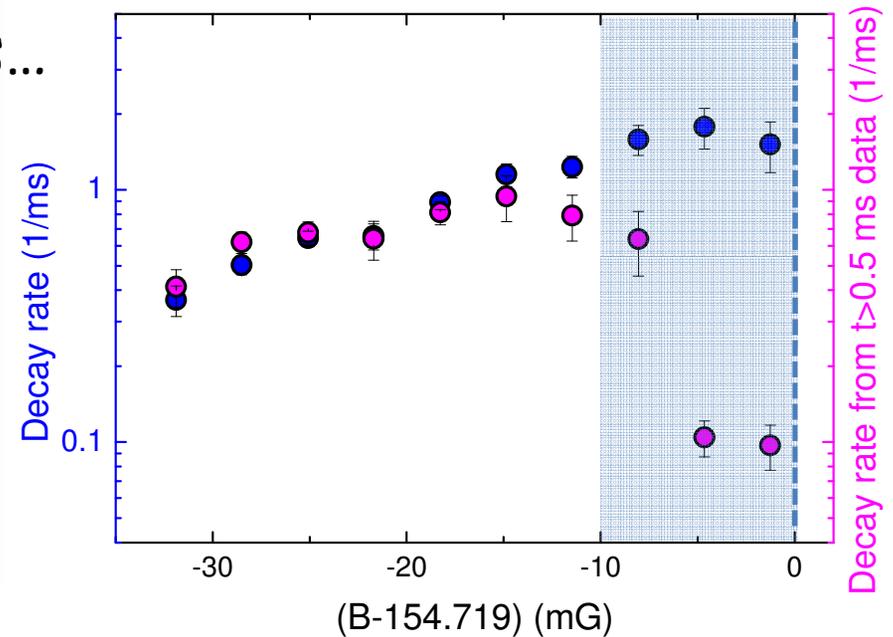
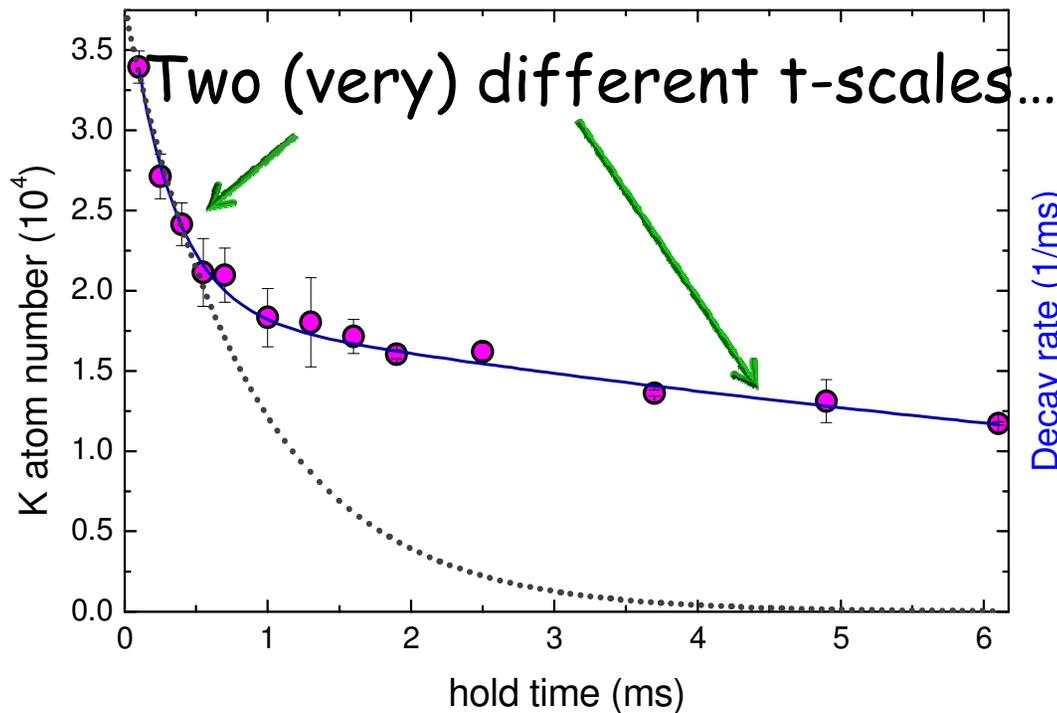
... then monitor K (Li and molecules) at -300 mG after 1.5 ms ball. expansion



# Repulsive branch of a F-F mixture

K Atom loss

$|B-B_0| = 4.5$  mG...



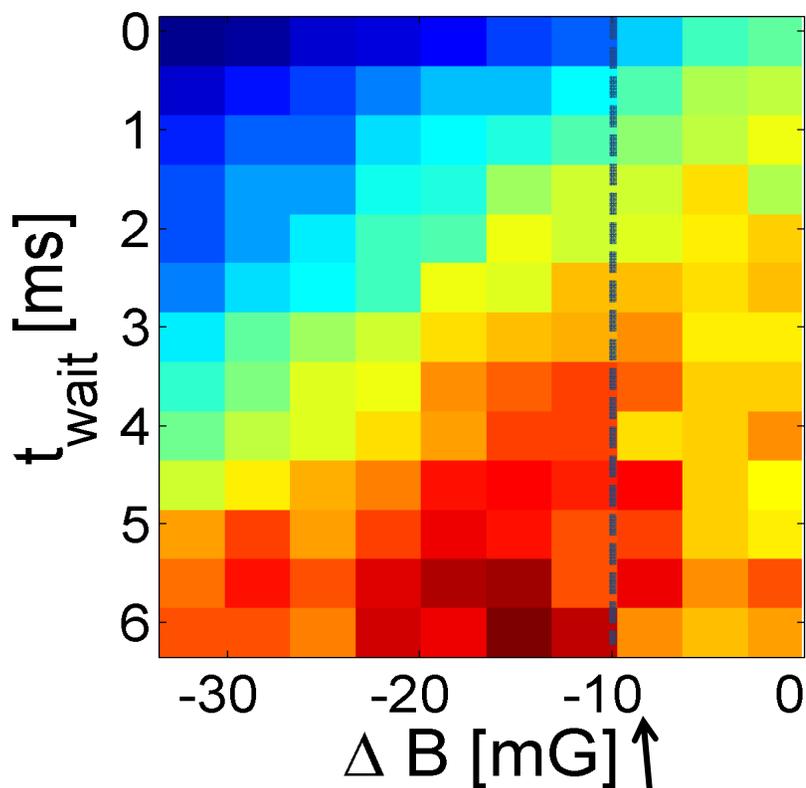
$|B-B_0| < 10$  mG: fast dynamics followed by almost static behavior:  $(\Gamma_{\text{slow}} / \Gamma_{\text{fast}}) \sim 15$

Similar trend in  ${}^6\text{Li}$ , Sanner et al. [arXiv:1108.2017](https://arxiv.org/abs/1108.2017)

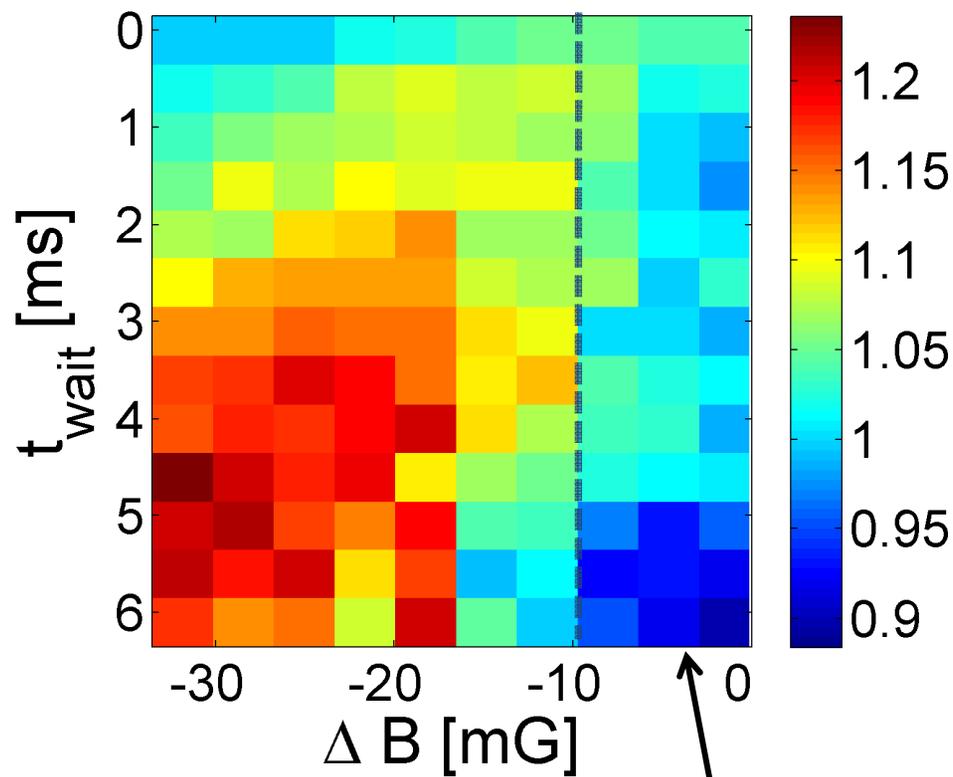
# Repulsive branch of a F-F mixture

$$K E_{\text{Kin}} \sim (\sigma_{\text{rad}})^2$$

$$\text{In trap } K \text{ size} \sim \sigma_{\text{ax}}$$



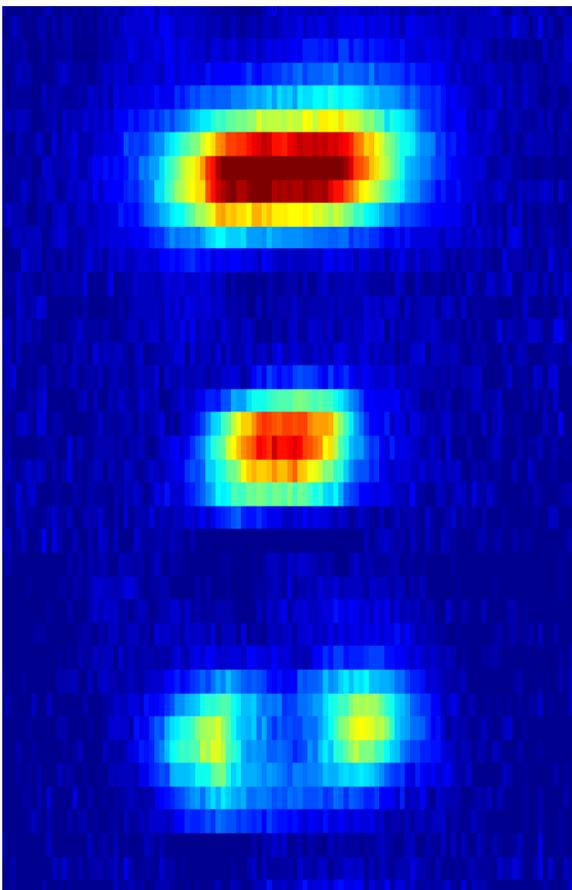
kinetic energy does not change much



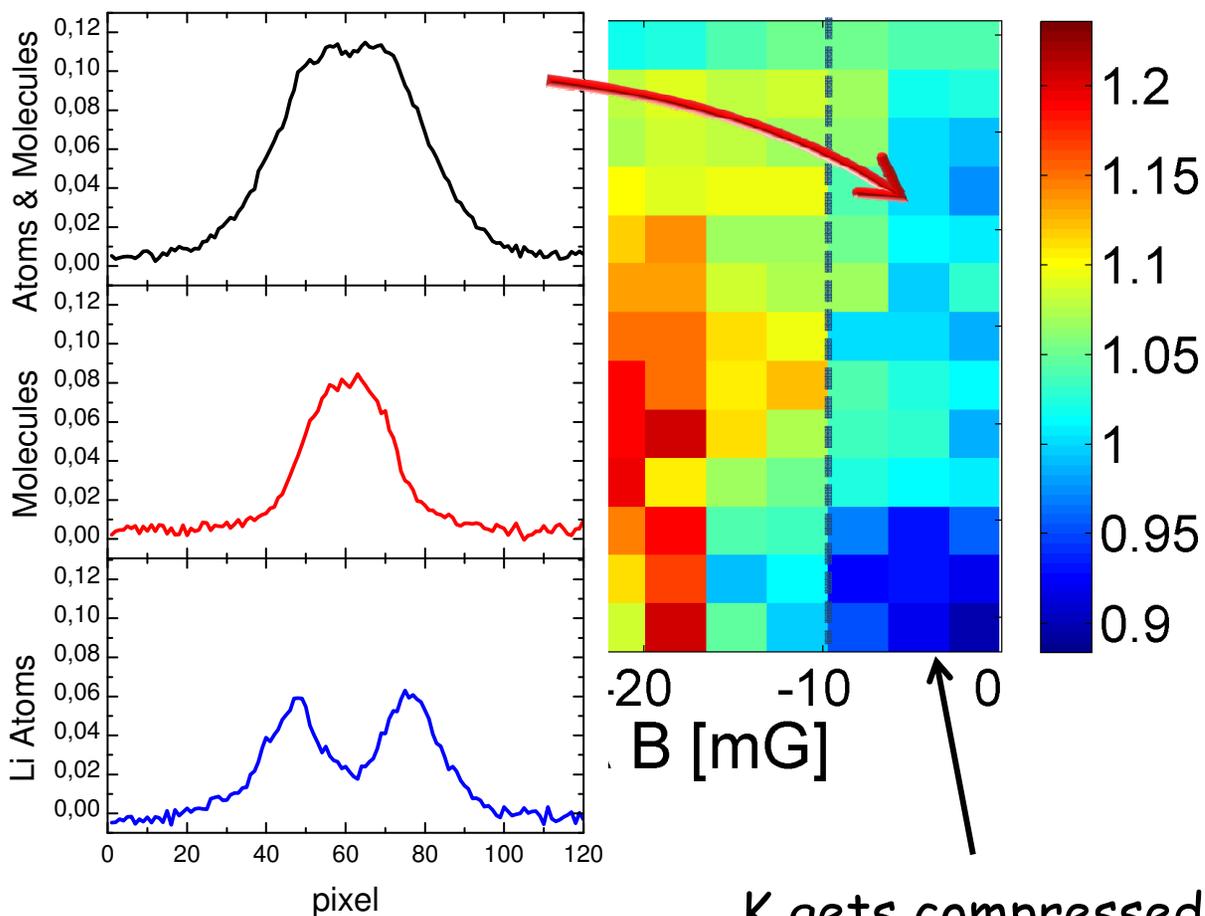
K gets compressed

# Repulsive branch of a F-F mixture

Lithium *in situ*  
image

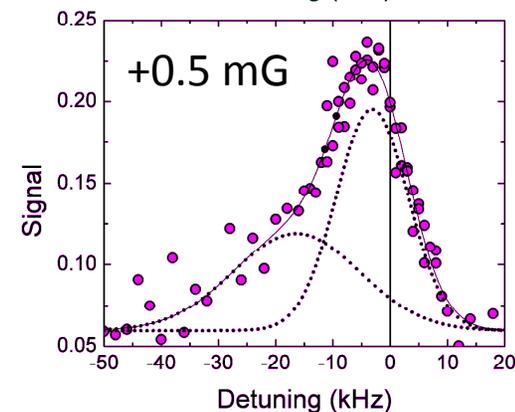
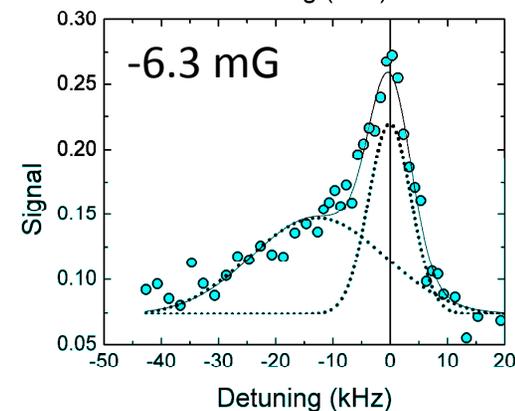
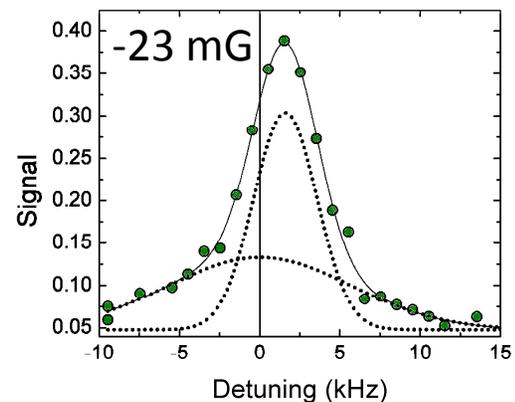
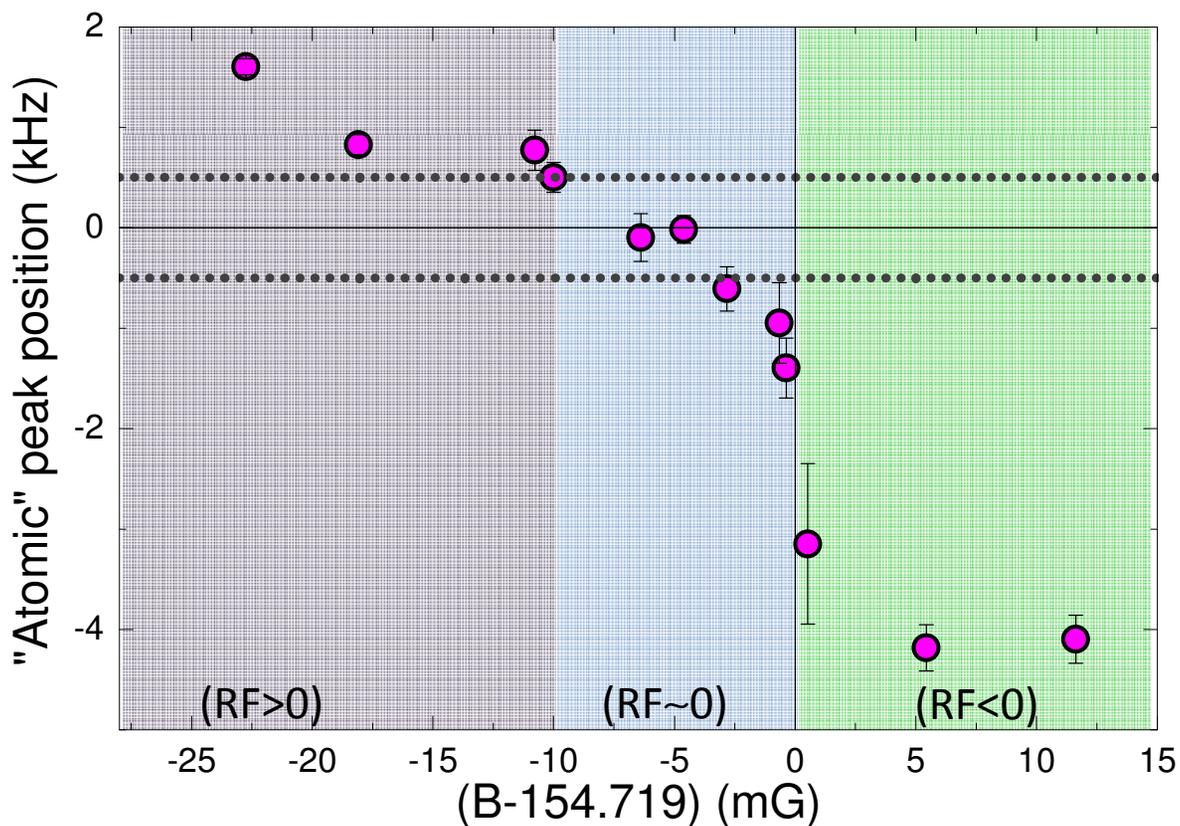
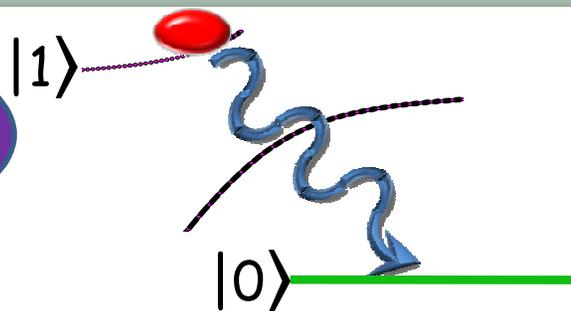


In trap  $K$  size  $\sim \sigma_{ax}$



# Repulsive branch of a F-F mixture

K Rf spectra  
after 4 ms at  $B_f$



# Conclusions

- ✓ K impurities in a Li Fermi sea by RF spectroscopy: long lived repulsive polarons

*C. Kohstall et al, Nature, 458, 615 (2012)*

- ✓ Evolution of the repulsive branch of a Fermi Fermi mixture: loss assisted phase separation of Li and K

*Ongoing*

- ✓ Not discussed: attractive branch, p-wave resonances, ...

# Thank you !



Christoph  
Kohstall

Michael  
Jag

Marko  
Cetina

Andreas  
Trenkwalder

Theory: P. Massignan and G. Bruun



**FWF**

Der Wissenschaftsfonds.



Foundations and  
Applications of  
Quantum Science

European Network

**EuroQUAM**

Collaborative Research Project

**FerMix**

**EUROPEAN  
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