Ultracold Fermi mixtures with resonant interactions

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Since Nov.'12 at LENS, INO-CNR, University of Florence

Plan

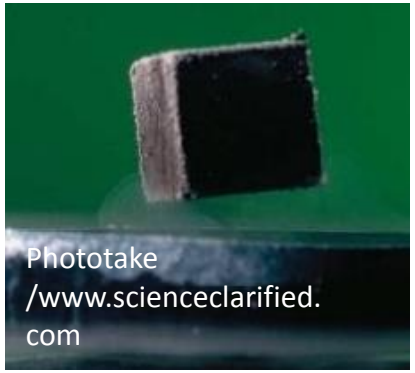
- **Motivation**
- **K-Li systems: some details**
- **Strong atom-dimer attraction in a mass-imbalanced Fermi mixture**

M. Jag *et al*, PRL **112**, 075302 (2014)

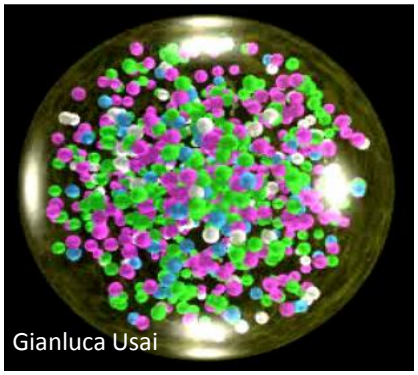
- **Outlook, perspectives**

General idea: Ultracold Fermi gases

systems with many interesting analogies…



high-T_c sc



quark gluon plasma

neutron stars

… & with unprecedented control


Temperature


Geometry


2D-1D-0D


Interaction

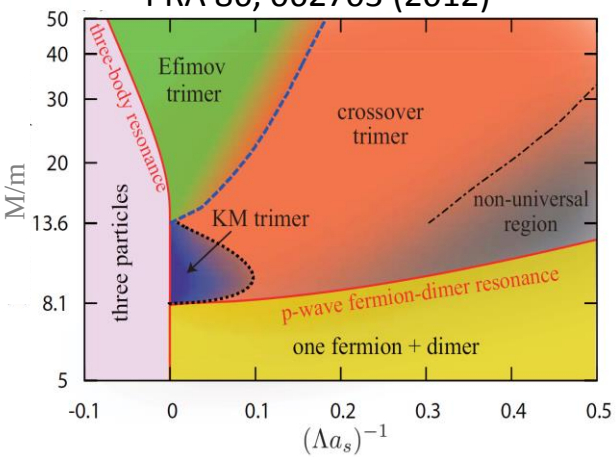

Pop. imbalance

General idea: Ultracold Fermi mix.

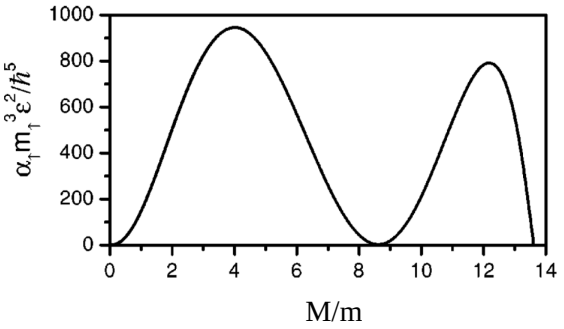
M/m

3B sector

PRA 86, 062703 (2012)

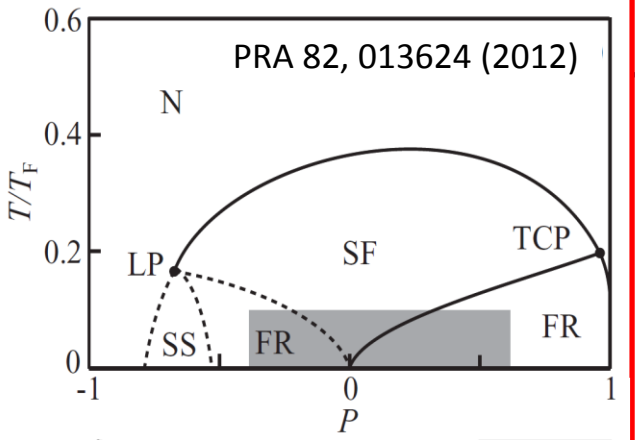


PRA 67, 010703(R) (2003)

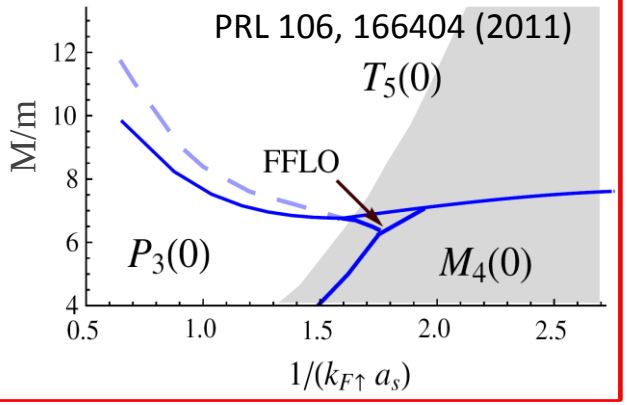


Attractive branch

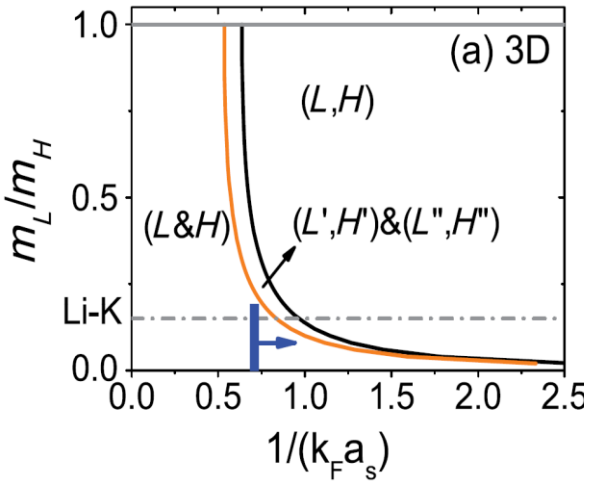
PRA 82, 013624 (2012)



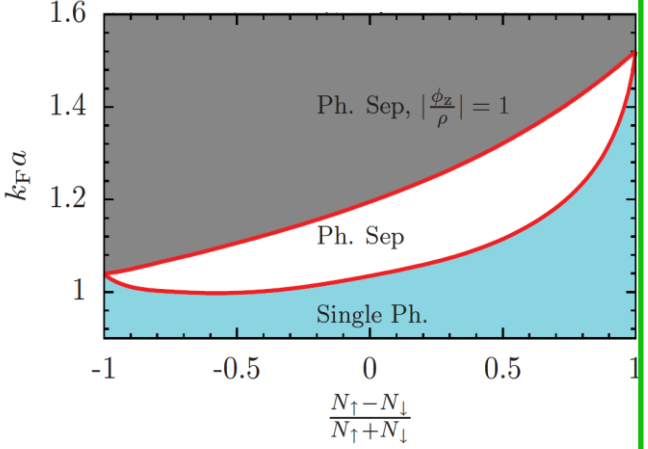
PRL 106, 166404 (2011)



Repulsive branch



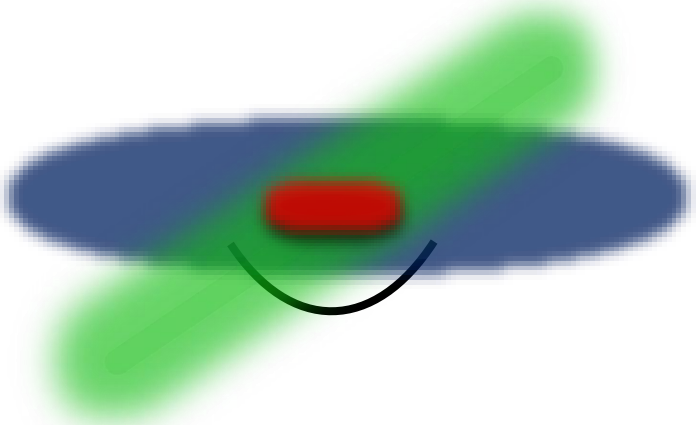
PRL 110, 165302 (2013)



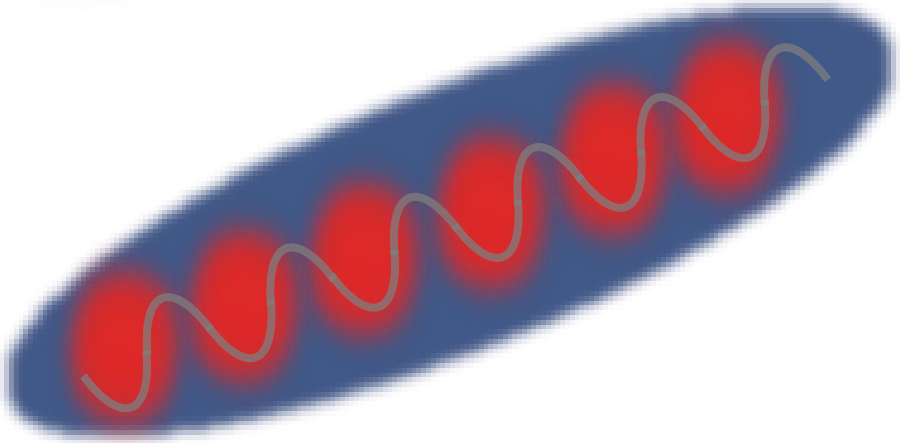
PRA 83, 053625 (2011)

General idea: Ultracold Fermi mix.

Species selective control

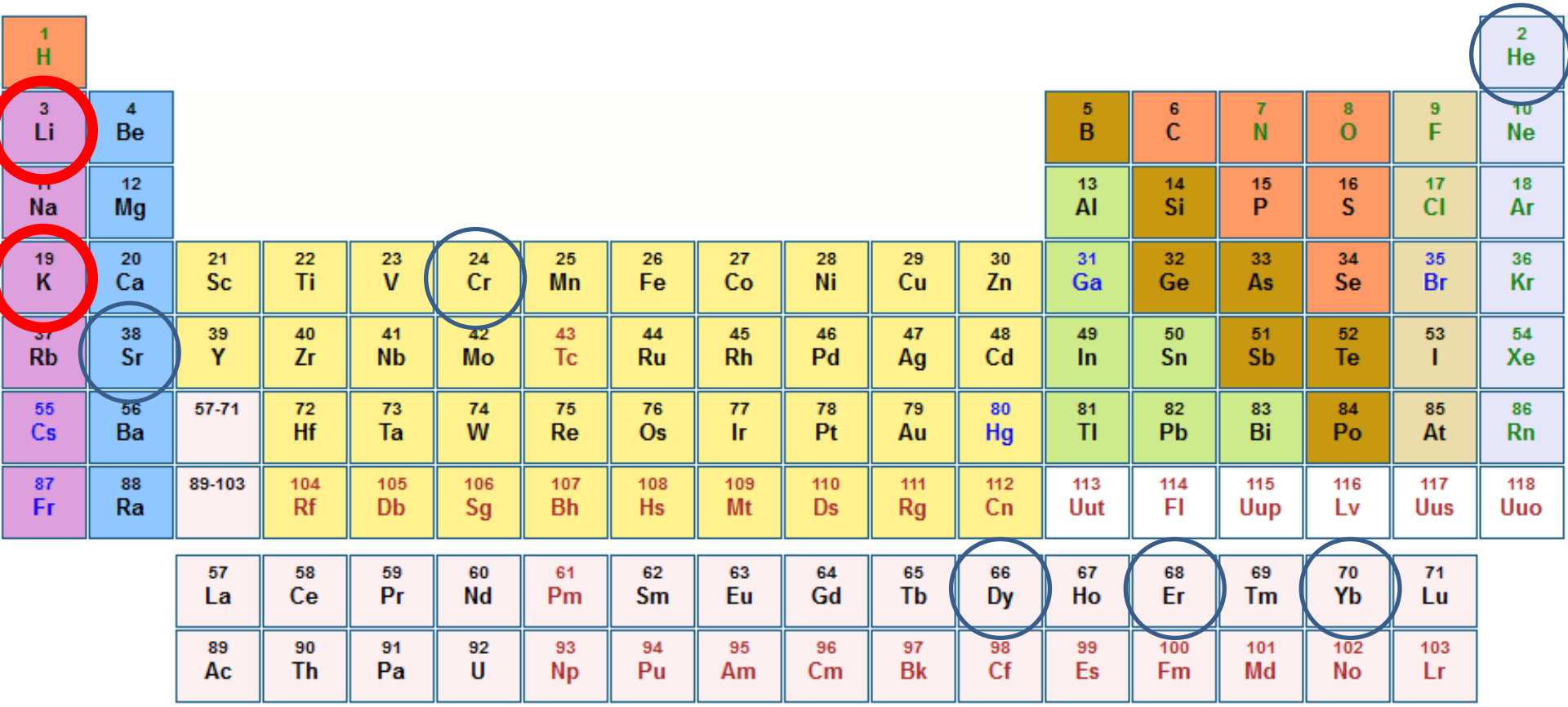


Individual trapping
Individual motion



Mixed dimensions: novel quantum phases
(see e.g. Yusuke's works)

General idea: Ultracold Fermi mix.



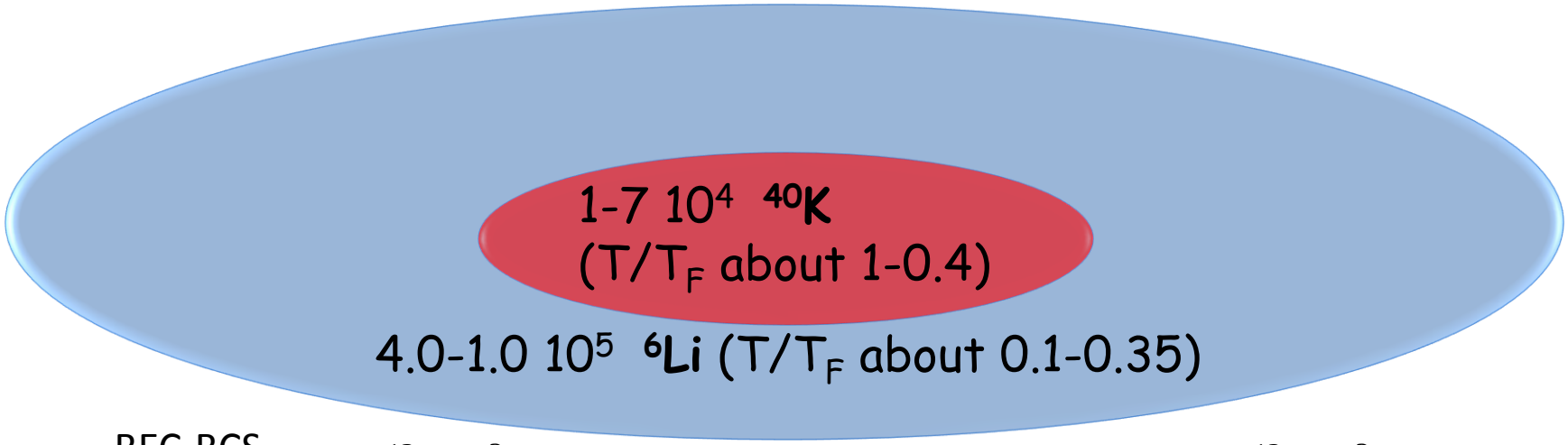
^{40}K-^{6}Li ($M/m \simeq 6.6$): «easy», each component well known, many FRs expected

PRL **100**, 053201 (2008); EPJD **65**, 55 (2011)

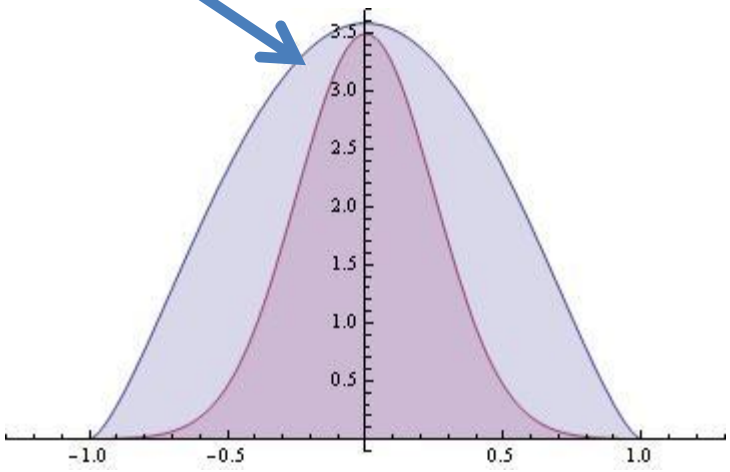
^{40}K- ^{6}Li Fermi mix: weak interaction

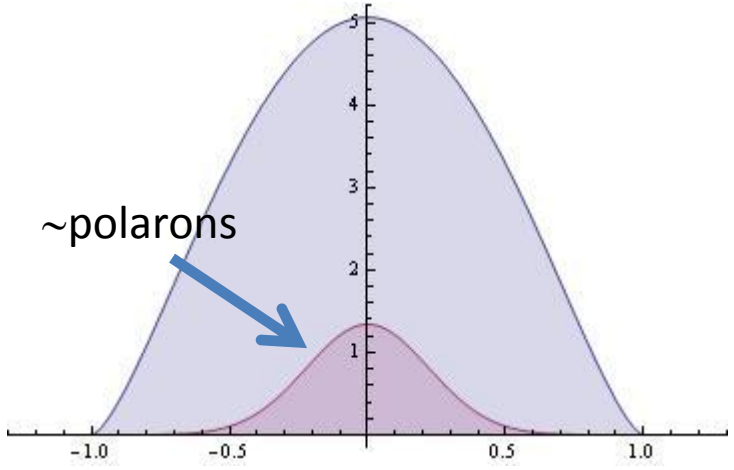
Our starting point (all optical)

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



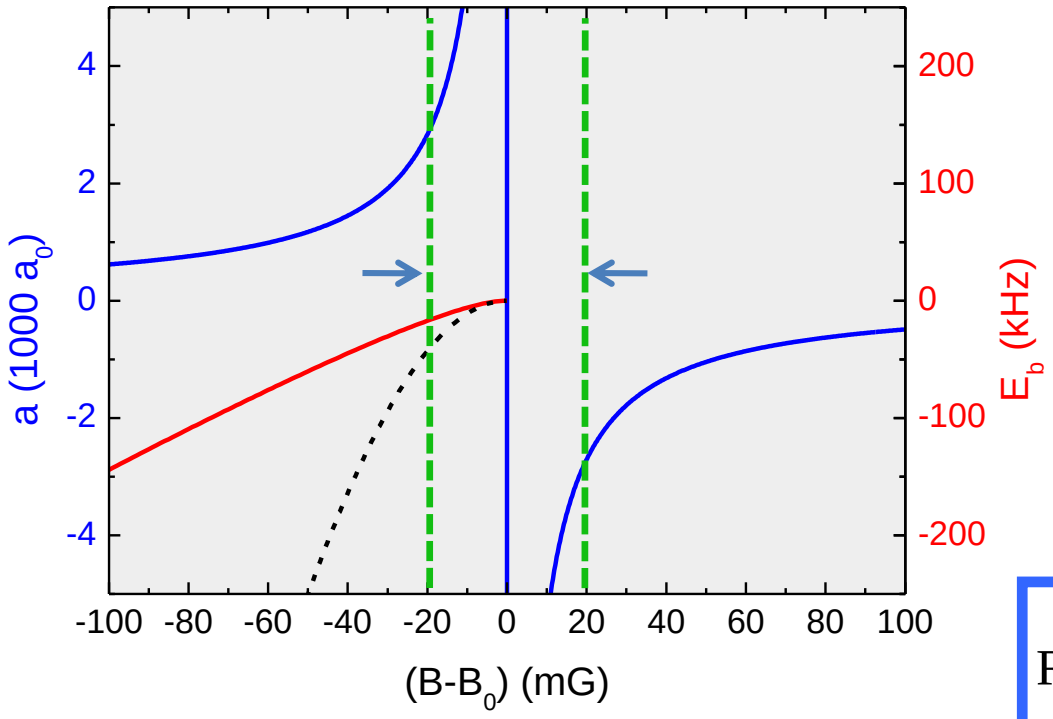
~BEC-BCS





^{40}K- ^{6}Li Fermi mix: interaction tuning

Control of the interaction via Li|1⟩-K|3⟩ FR (*)



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

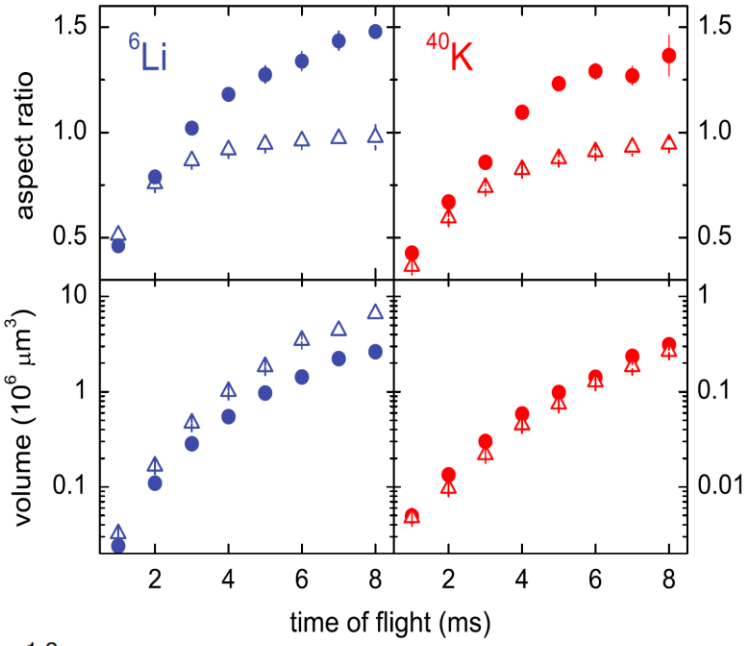
Excited state of mix:
$\tau_{2B} <$ 20 ms

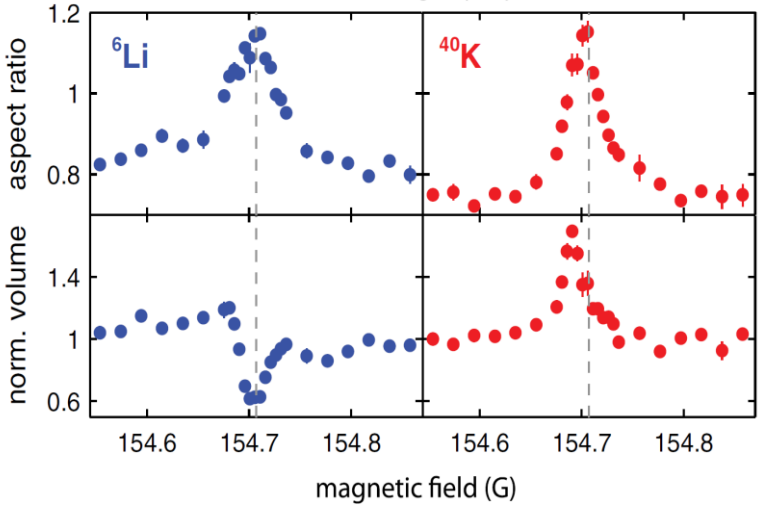
$$R^* = \frac{\hbar^2}{2\, m_r\, a_{bg}\, \Delta\, \delta\mu} = 2710\, a_0 \approx 1/\kappa_F^{Li}$$

(*) EJPD **65**, 55 (2011); PRL **106** 115304 (2011)

^{40}K- ^{6}Li Fermi mix: so far…

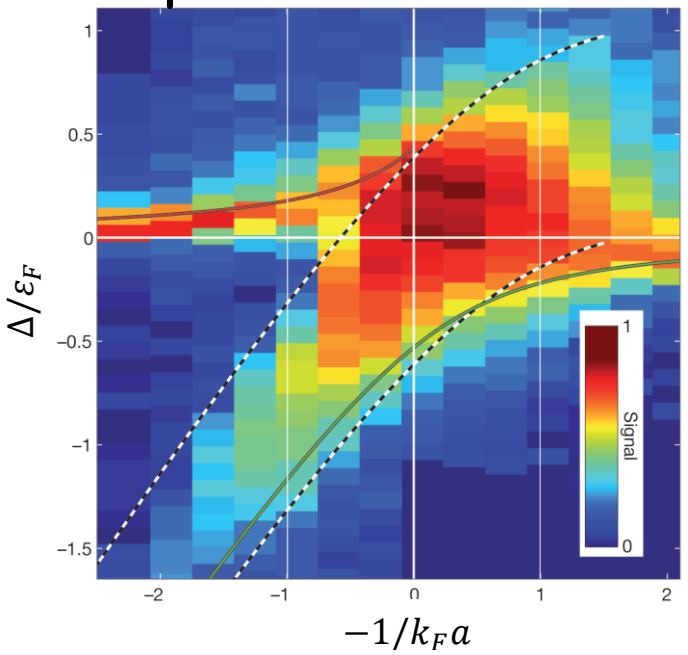
Accessing strong interaction…

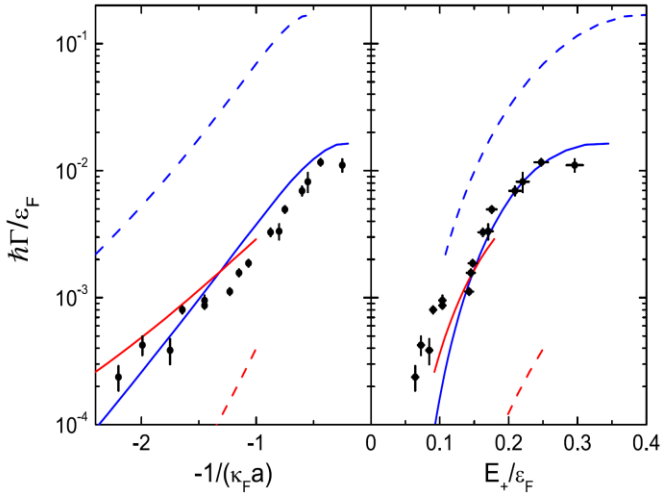




PRL **106**, 115304 (2011)

…K polarons in a Li FG





Nature **485**, 615 (2012)

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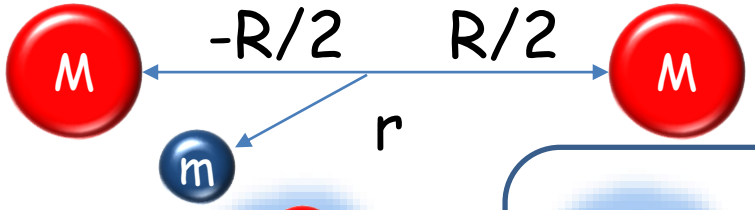
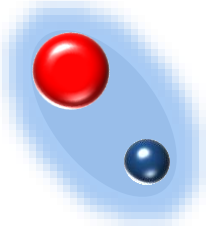
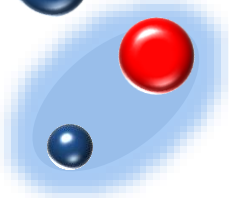
  M. Jag *et al*, PRL **112**, 075302 (2014)

- Outlook, perspectives

M-M-m Fermi systems: B.O. approx.



✓ $\psi(\boldsymbol{r}) \sim C_1$  $+ C_2$ 

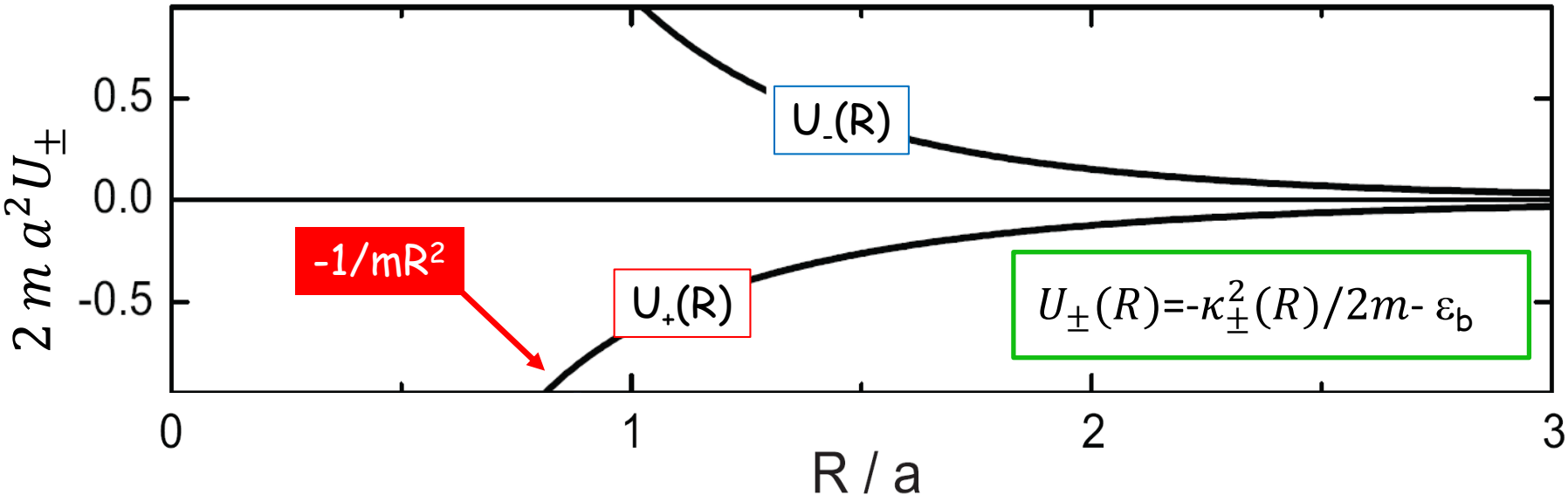
$$\sim \frac{e^{-\kappa(R)|\boldsymbol{r}\pm\boldsymbol{R}/2|}}{|\boldsymbol{r} \pm \frac{\boldsymbol{R}}{2}|}$$

$$\varepsilon(R) = -\kappa^2(R)/2m$$

✓ Bethe Peierls b.c. @ $\mathbf{r} = \pm \mathbf{R}/2$

$$\{C_1, C_2\}_\pm = \{1, \pm 1\}$$

$$\kappa_\pm(R) \mp \frac{e^{-\kappa_\pm(R)R}}{R} = \frac{1}{a} - \mathrm{R}^* \kappa_\pm(R)^2$$



J. Levinsen & D. Petrov, EPJD **65**, 67 (2011); D. Petrov, arXiv:1206.5752

M-M-m Fermi systems: B.O. approx.

M = identical fermions:

$$\phi(\boldsymbol{R})\psi_{\pm}(\boldsymbol{r})$$

antisymmetric with resp. to permutation of atoms M

$\psi_+(\boldsymbol{r})$ symmetric

$\phi(\boldsymbol{R})$ a.-symmetric

$U_+(R)$ = attraction in odd l-channels

$\psi_-(\boldsymbol{r})$ a. symmetric

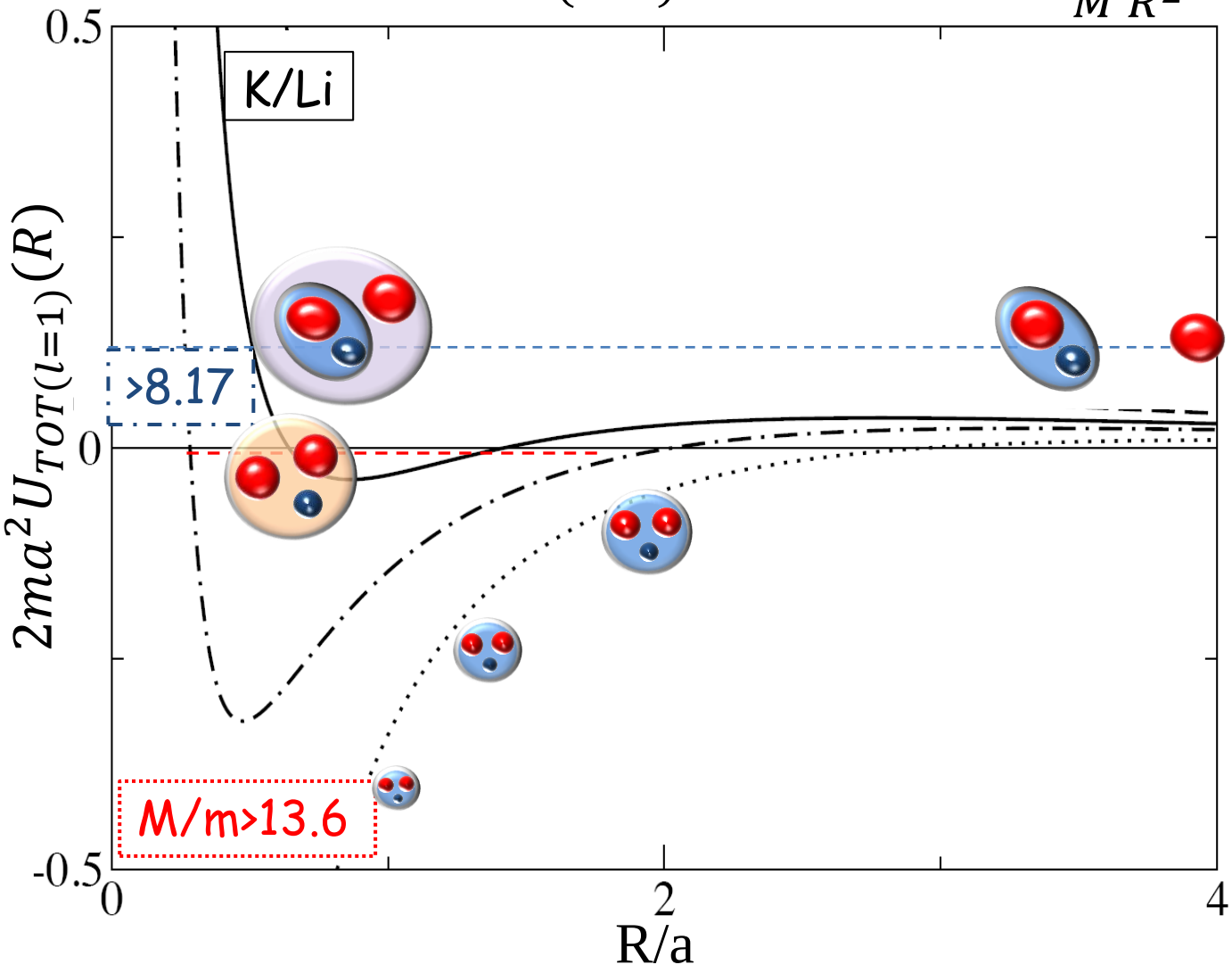
$\phi(\boldsymbol{R})$ symmetric

$U_-(R)$ = repulsion in even l-channels

M-M-m Fermi systems: B.O. approx.

Eg: p-wave channel

$$U_{TOT(l=1)}(R)=U_{+}(R)+\frac{2}{M\,R^2}$$

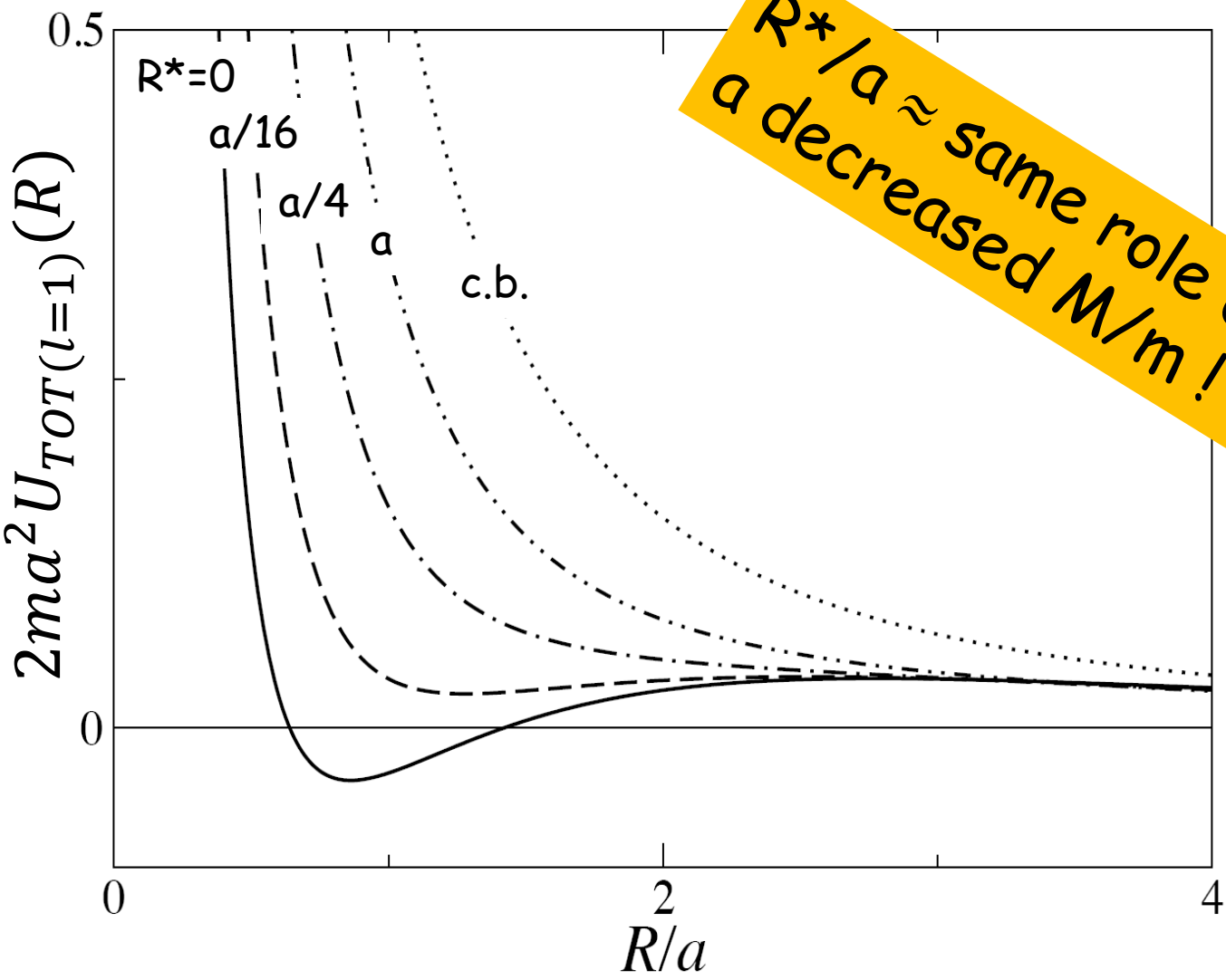


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

K-K-Li system: effect of R*

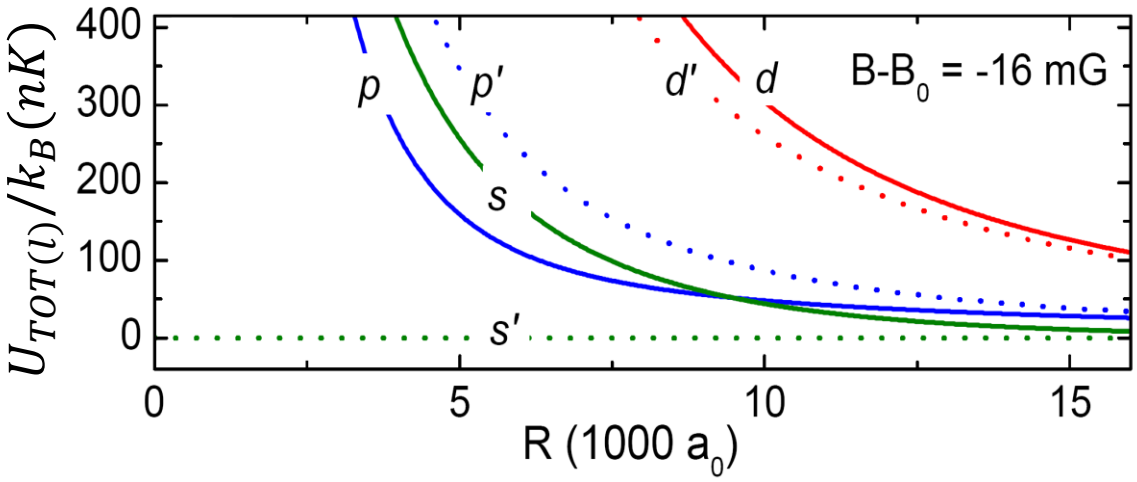
Eg: p-wave channel

$$U_{TOT(l=1)}(R) = U_{+}(R) + \frac{2}{M\,R^2}$$



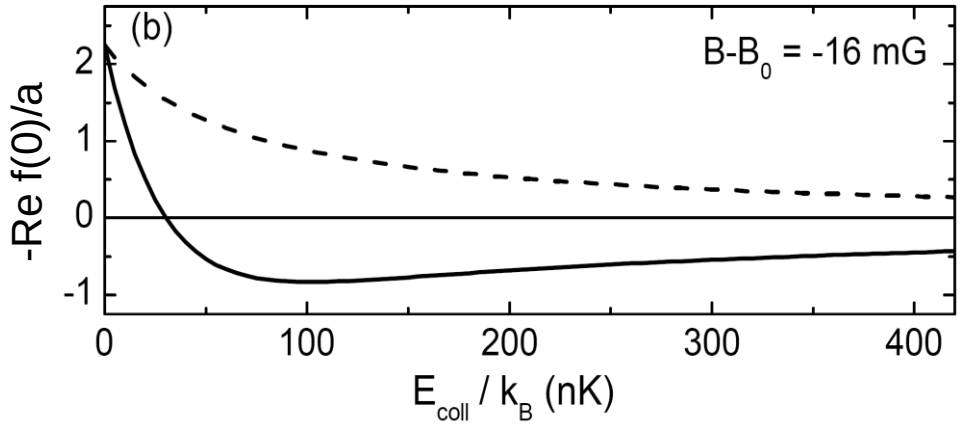
R*/a ≈ same role of a decreased M/m !

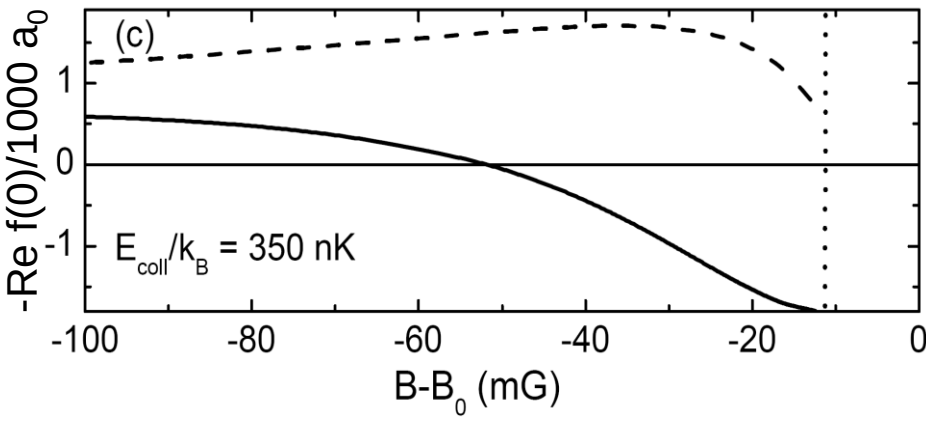
K-KLi: multichannel interactions



Net effect of all l:

$$f(0) = \sum_{l=0}^{\infty} (2l+1) \left[\frac{\sin 2\delta_l(k_{\text{coll}})}{2k_{\text{coll}}} + i \frac{\sin^2 \delta_l(k_{\text{coll}})}{k_{\text{coll}}} \right]$$





Ecoll/Eb < 0.1: s-wave repulsion dominated
Ecoll/Eb > 0.1: sign reversal and attractive interactions!

K-KLi interactions: RF spectroscopy

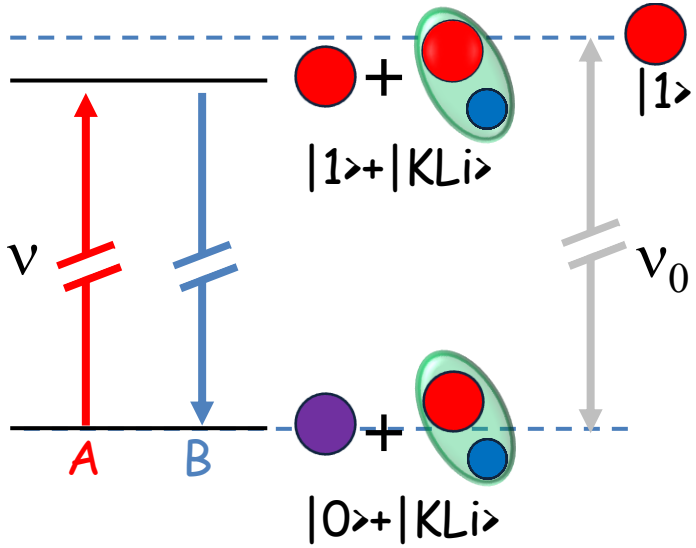
Thermal Mix @ T= 165, 232, 370 nK

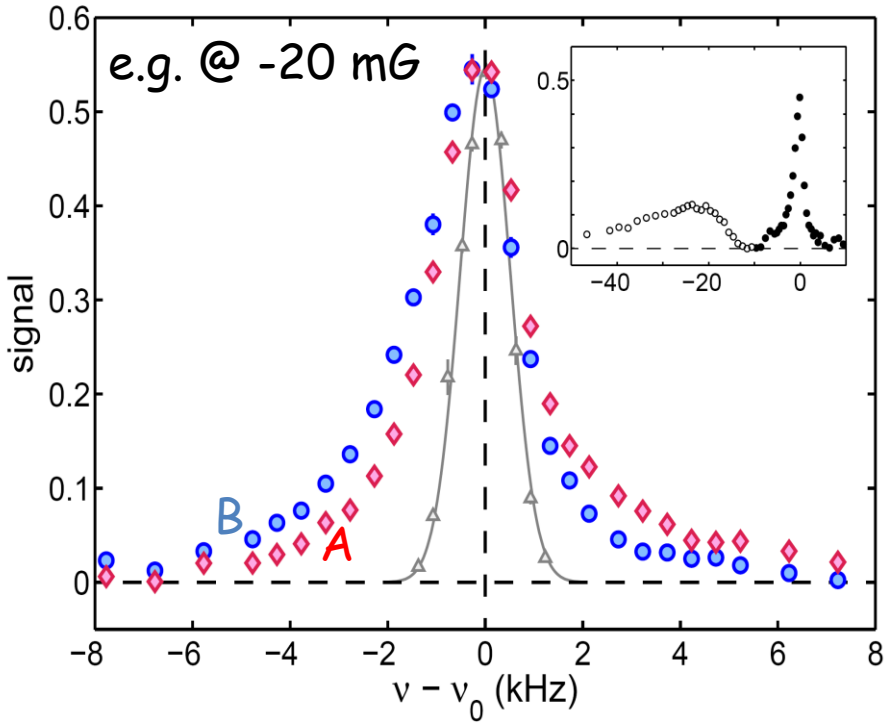
7000 K

15000 KLi

$\langle n_{KLi} \rangle = 5.2, 8.2, 14 \times 10^{12}\ cm^{-3}$

Initially: KLi in resonant state, K in $|0\rangle$ (or in $|1\rangle$)

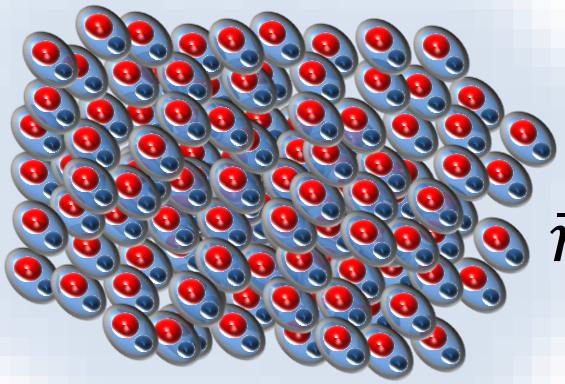




K-KLi interactions: RF spectroscopy

Analysis: Impact theory of pressure broadening(*)

$\hbar k_{coll} = \sqrt{2\,\mu_3 E_{coll}}$



$\bar{n}_{KLi}$

$$Signal(\nu) \sim \frac{1}{(\nu - \nu_0 \ - \delta\nu)^2 + (1/2\pi\tau)^2/4}$$

- ✓ **Shift:** $\delta\nu = -\hbar\bar{n}_{KLi}\mathrm{Re}\langle f(0)\rangle/\mu_3$
- ✓ **Broadening:** $\tau^{-1} = 4\pi\hbar\bar{n}_{KLi}\mathrm{Im}\langle f(0)\rangle/\mu_3$

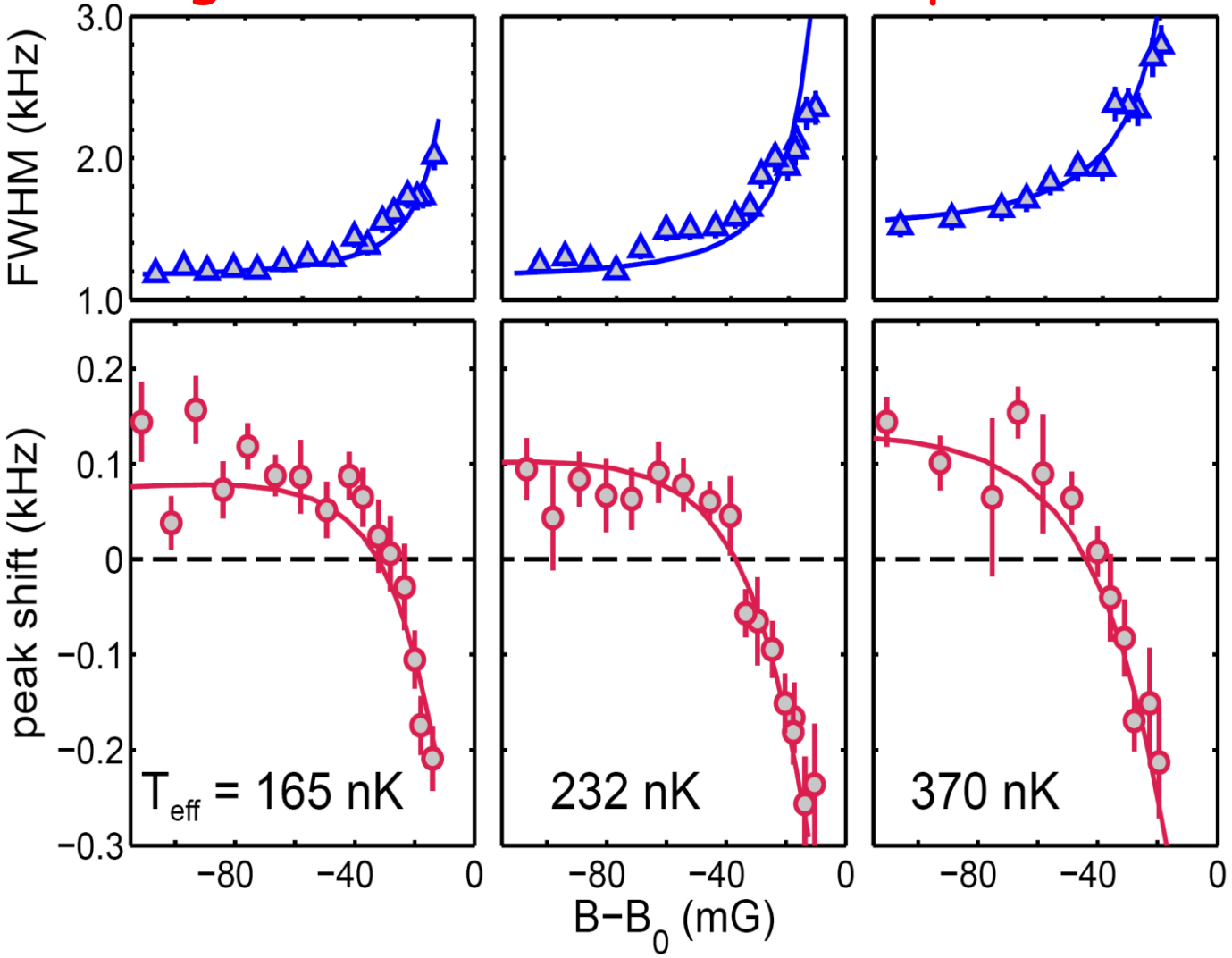
From double Gauss fit: FWHM and peak shift $\delta\nu$

Dima & Jesper calculated f(0) up to 16-th partial wave

(*) M. Baranger, Phys. Rev. **111**, 481 (1958); Phys. Rev. **112**, 855 (1958)

K-KLi interactions: RF spectroscopy

Remarkable agreement over the whole parameter range!



Typical scattering rates (-20 mG): τ^{-1}= 1/100 μs >50 times larger than molecule inelastic decay!!!

K-KLi interactions: RF spectroscopy

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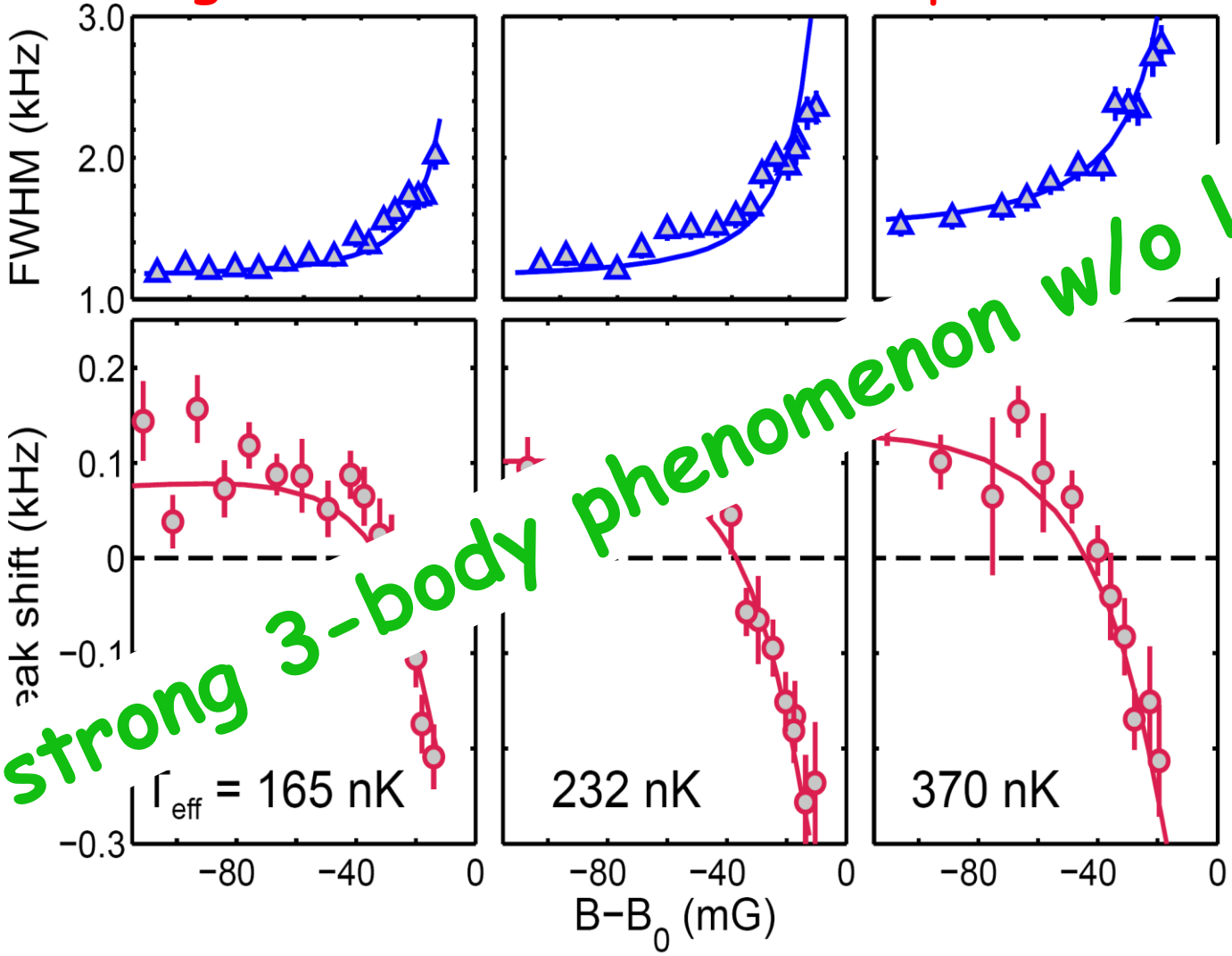
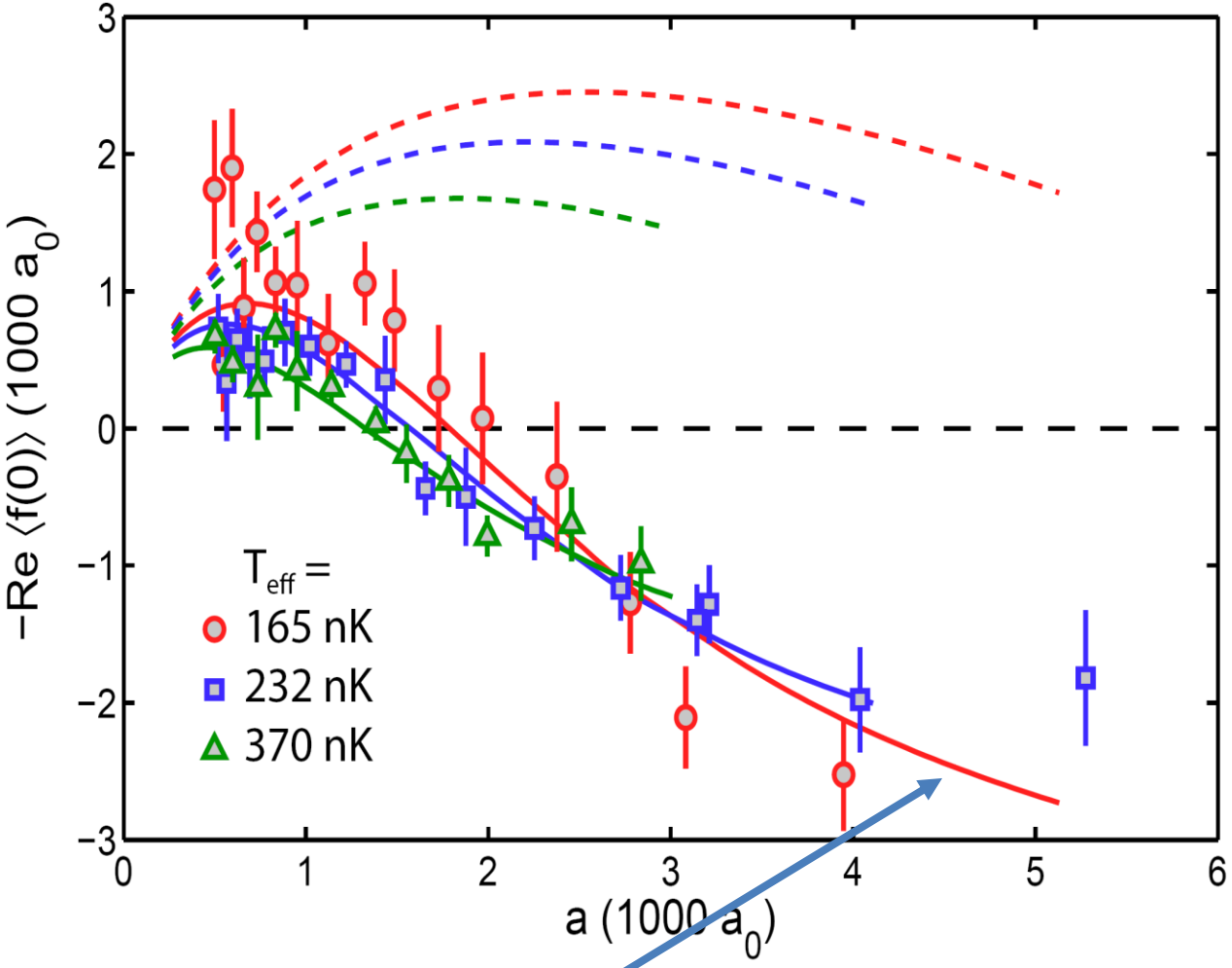


First strong 3-body phenomenon w/o losses!

Typical scattering rates (-20 mG): τ^{-1}= 1/100 μs >50 times larger than molecule inelastic decay!!!

K-KLi interactions: RF spectroscopy

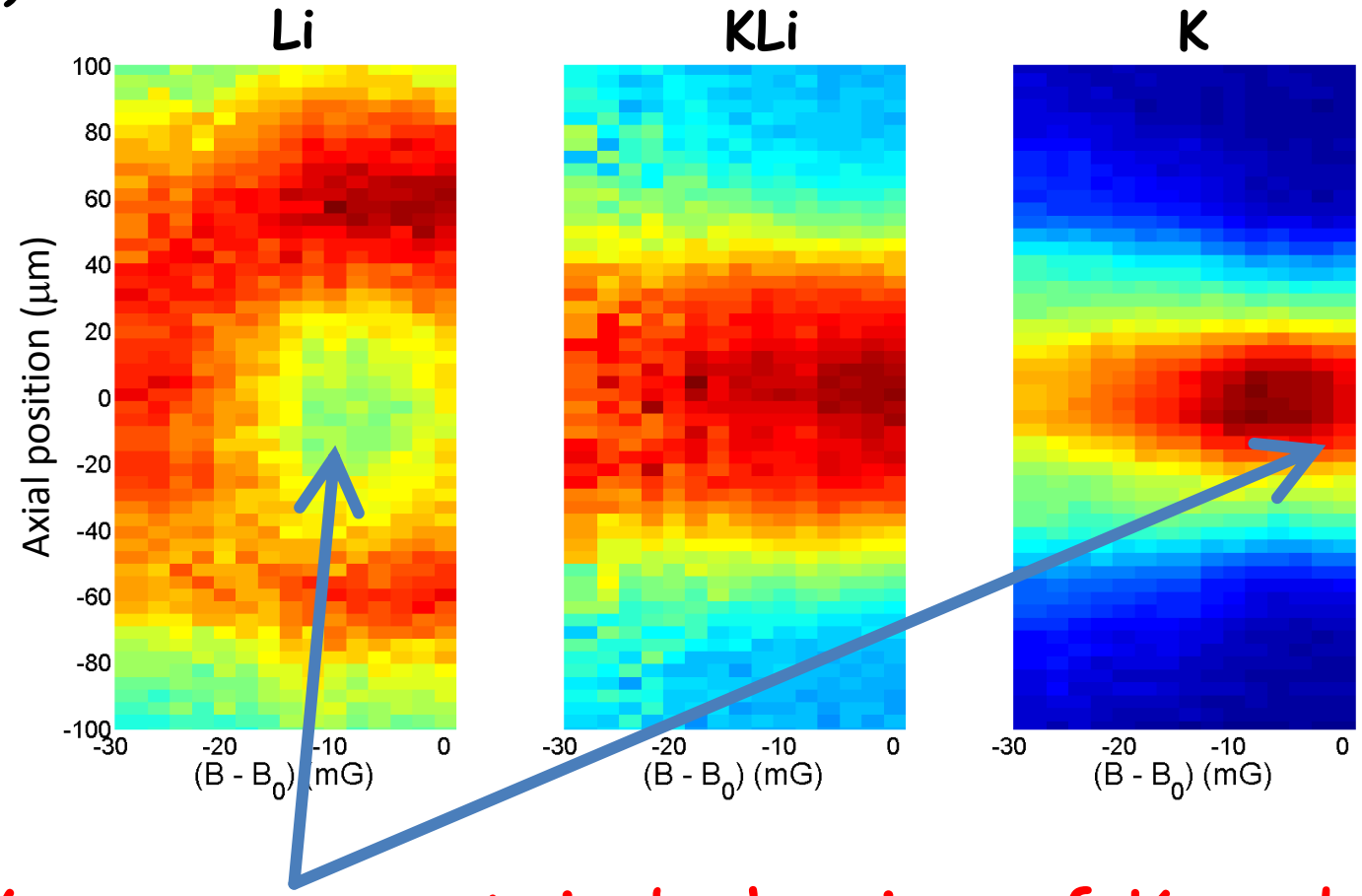
Interaction strength in terms of -Re⟨f(0)⟩



Strong int. start: Theory stops but more and more attraction!

K-KLi interactions: density profiles

At lowest T, after «adiabatic» preparation & sel. imaging… (Aug '13)



Very asymmetric behavior of K and Li !!!

Take-home messages

- ✓ First case of an elastic 3B strong interaction !
- ✓ Stable trimers in 2D/mixed dimensions

ONGOING

- ✓ Density profiles: qualitatively new low-T states (?)

-inhomogeneous SF (Sarma/Breached Paired)
-trimers stabilized by a K FS
-p-wave A-D interaction: FFLO, p-wave SF… (?)

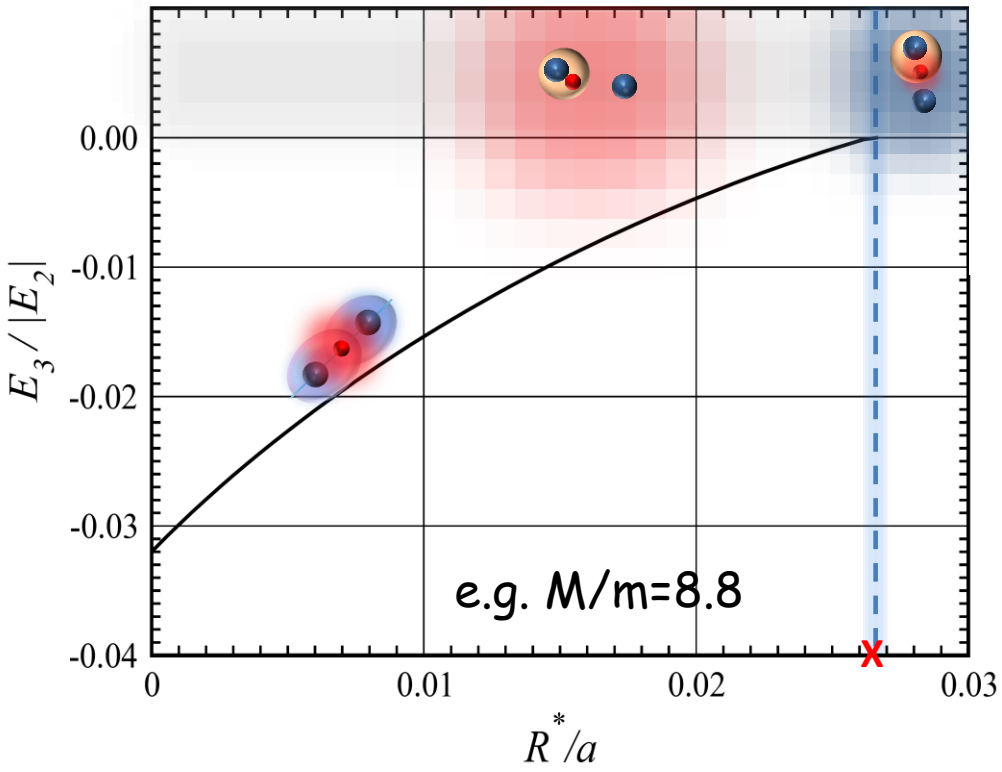
- ✓ Hard exp in K-Li mix! 2B losses, narrow FR,…

Take-home messages

✓ Strong and elastic 3B forces @ M/m>8.17 !!!

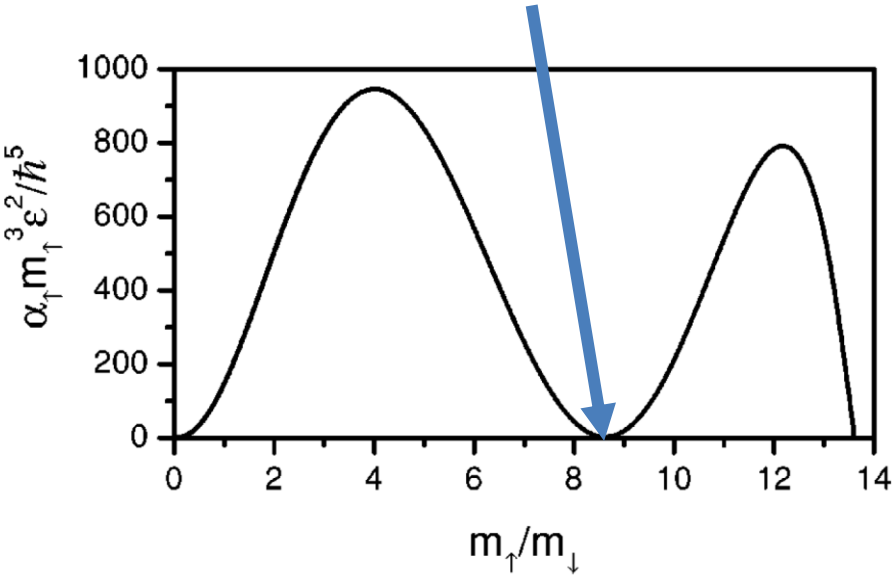
- Existence of stable (p-wave) trimers in vacuum

-R*/a gives an AD resonance!!!



D. Petrov, *Private Comm.* (2014)

-Ideal place for rep branch study (0 @ 8.612…)!!!



D. Petrov, PRA 67, 010703(R) (2003)

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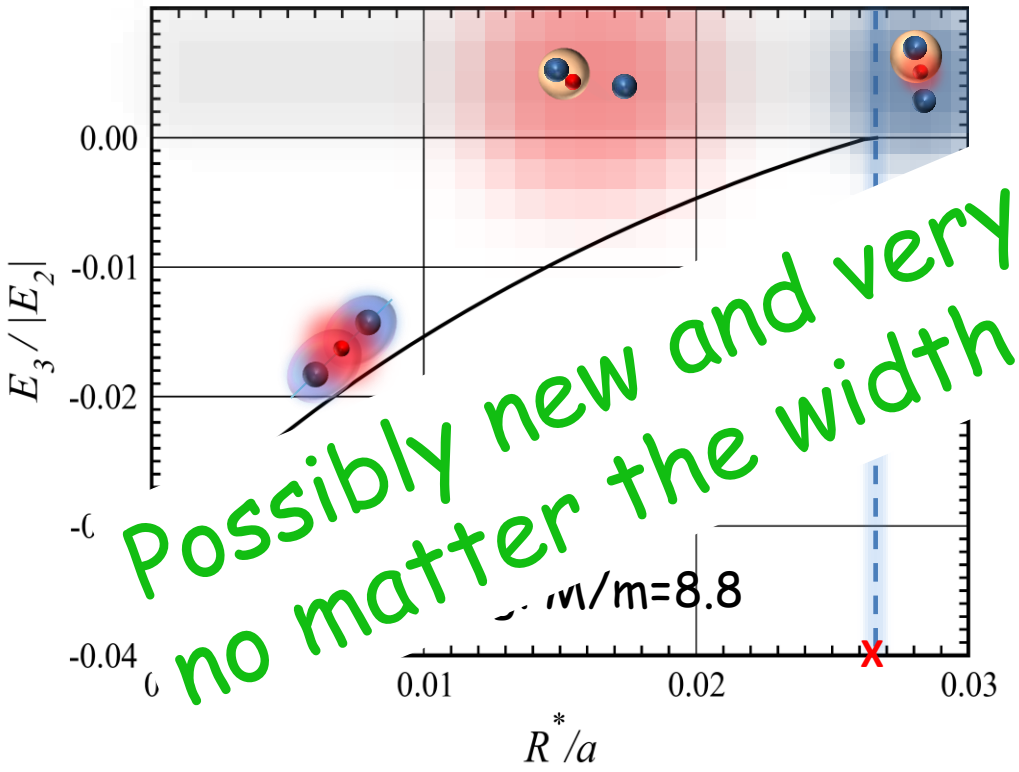
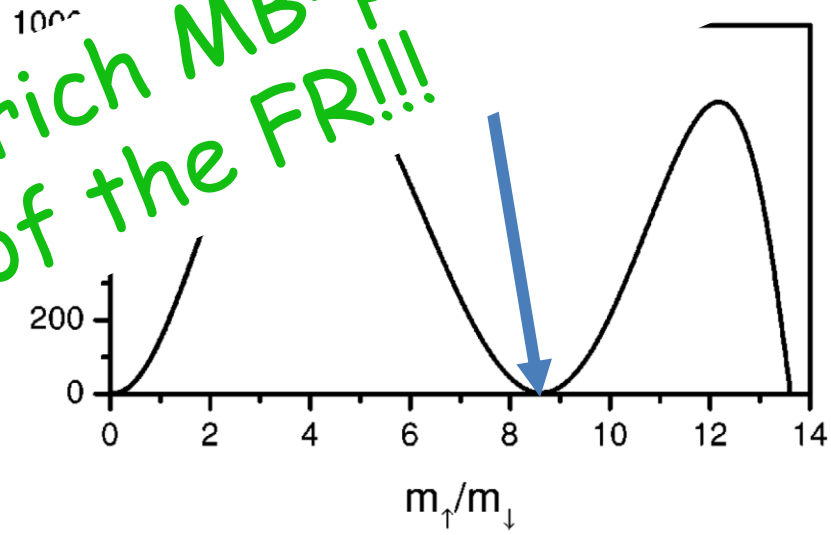
-Ideal place for [illegible] study (0 @ [illegible]



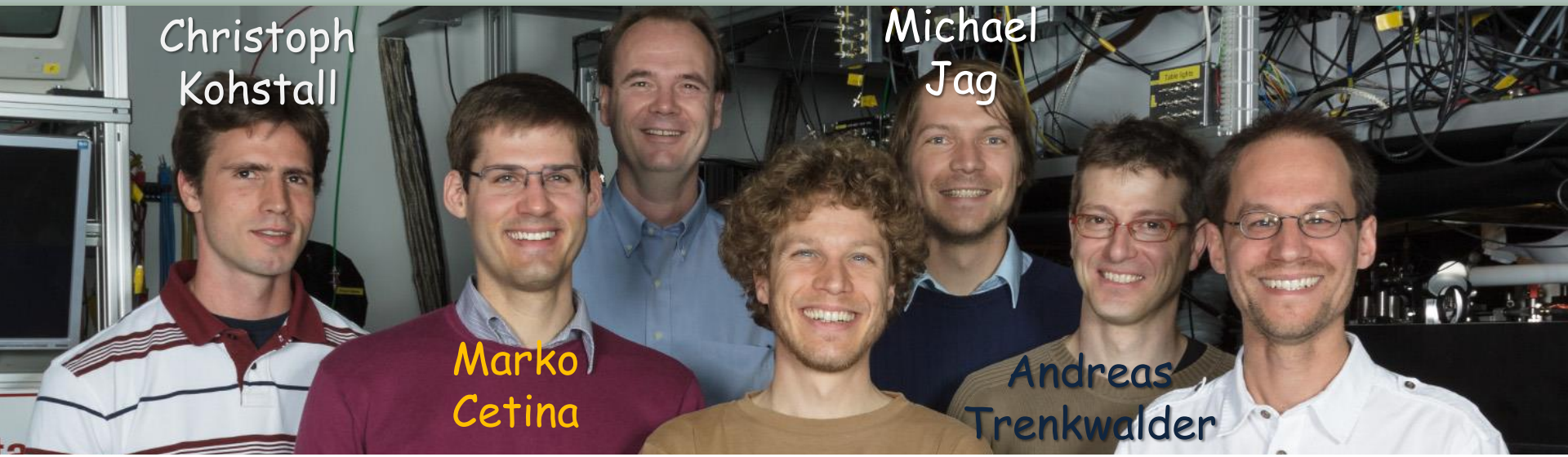
D. Petrov, *Private Comm.* (2014)

Possibly new and very rich MB-physics, no matter the width of the FR!!!



D. Petrov, PRA 67, 010703(R) (2003)

Thank you !



Pietro Massignan

Georg Bruun

Dmitry Petrov

Jesper Levinsen

European Network

EuroQUAM

Collaborative Research Project

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SFB FoQuS

Foundations and Applications of Quantum Science

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