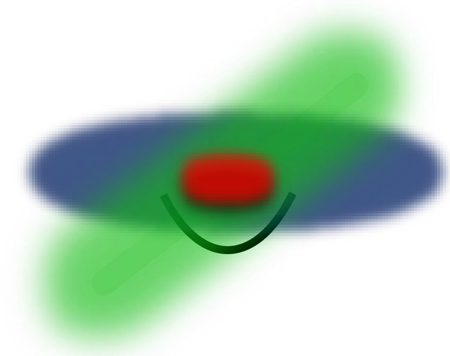
Mass imbalanced Fermi mixtures with resonant interactions

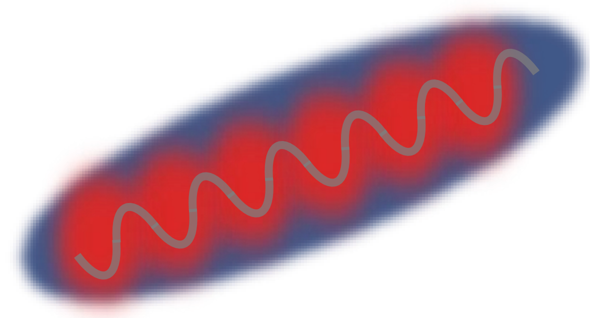
Matteo Zaccanti
CNR-INO & LENS
zaccanti@lens.unifi.it

Mass-imbalanced Fermi mixtures: why?

Different optical properties

Species selective control





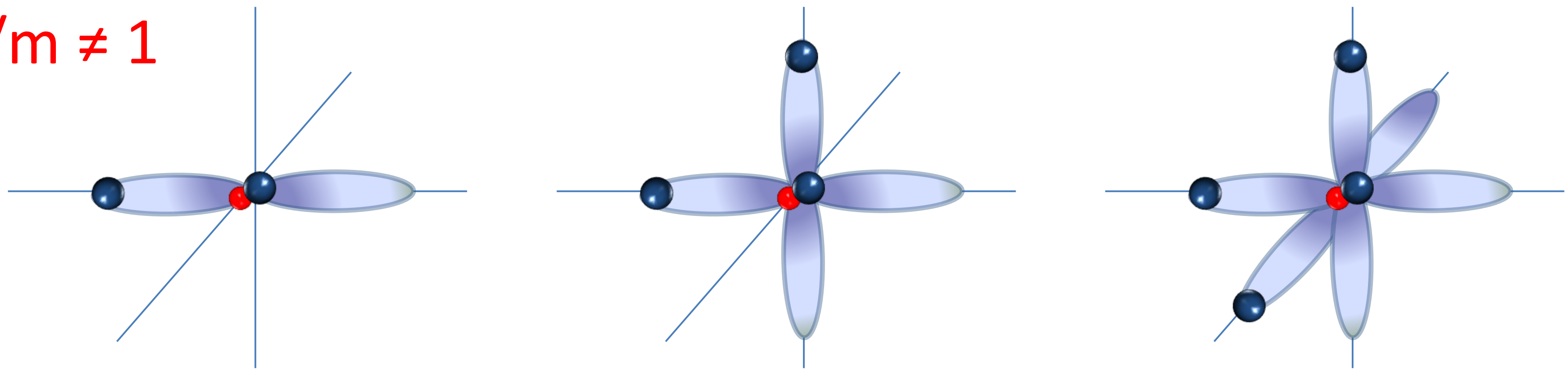
Individual trapping
motion
tunneling
…

Mixed-D: novel quantum phases (see e.g. Y. Nishida and F. Minardi/G. Lamporesi‘s works)

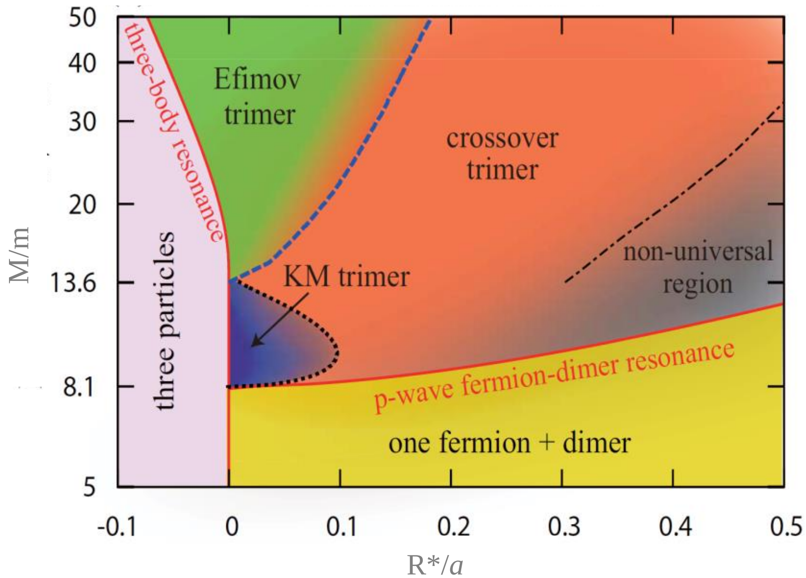
Mass-imbalanced Fermi mixtures: why?

Rich few-body physics

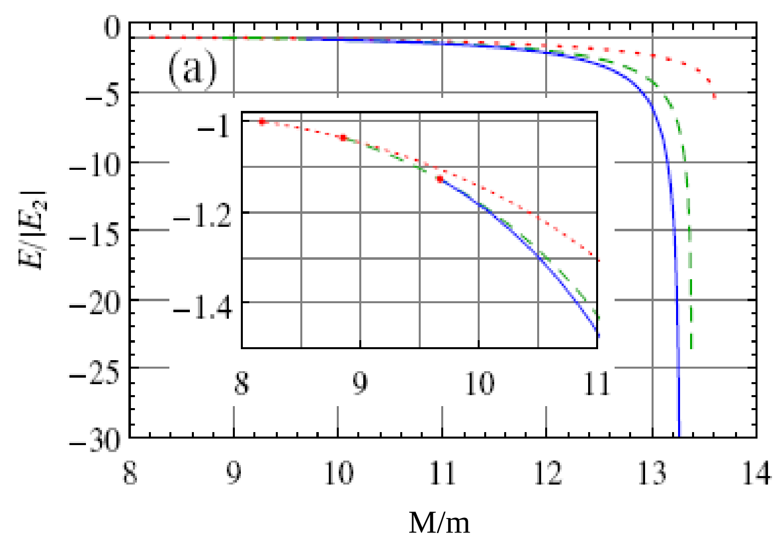
M/m ≠ 1



PRA 86, 062703 (2012)



PRL 118, 083002 (2017)

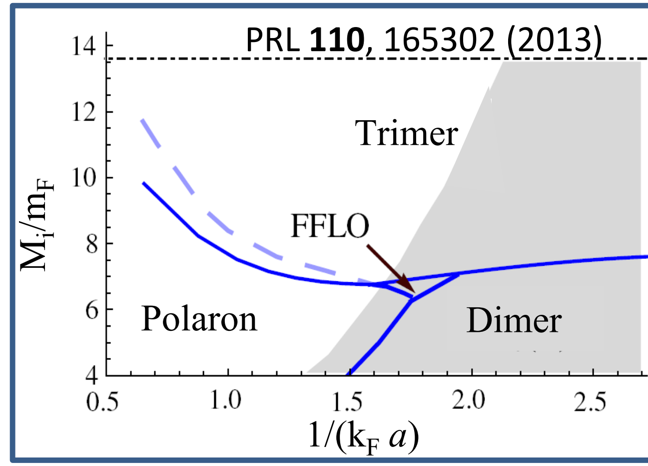


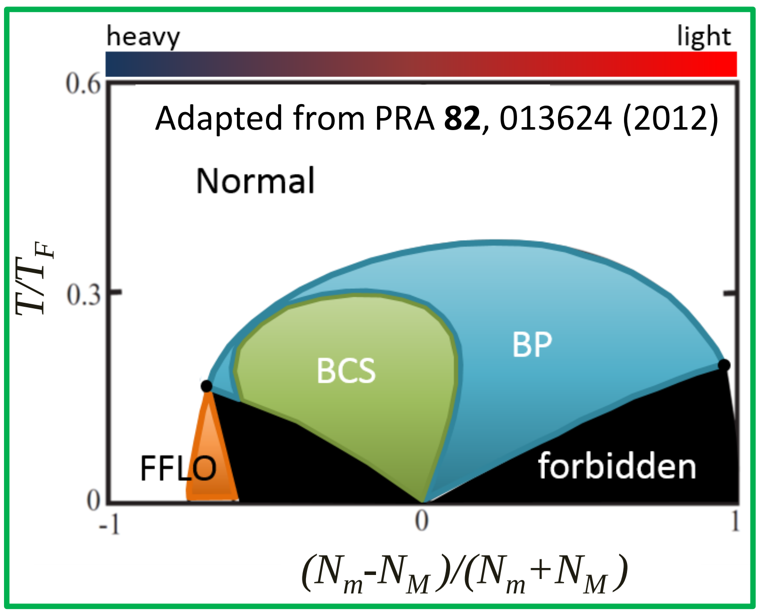
Mass-imbalanced Fermi mixtures: why?

M/m ≠ 1

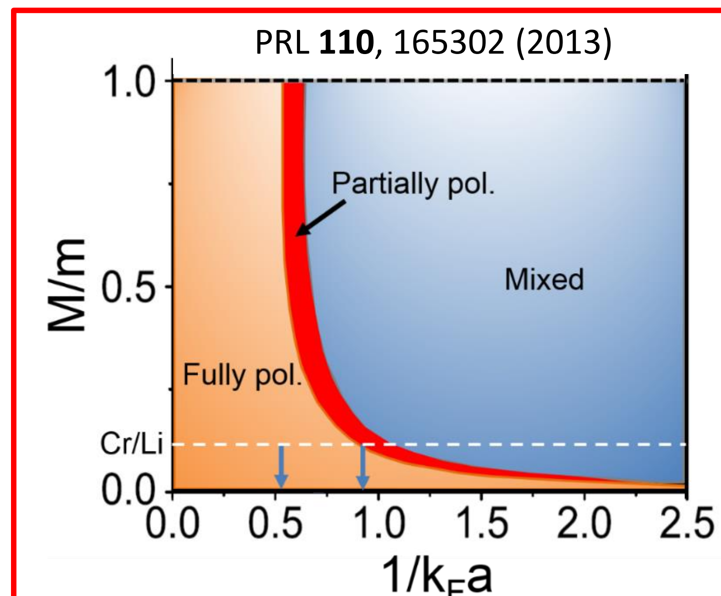
Rich many-body physics

Novel impurity problems





High-T_c exotic superfluid states



(Ferro-)magnetic states at low repulsion

Plan

- 2-body scattering: recall of some results

Landau&Lifshitz, Quantum Mechanics: Non-Relativistic Theory (Chapters 17-18)
Castin Lectures in Ultracold Fermi Gases (2007)
Chin et al, Rev. Mod. Phys. **82**, 1225 (2010)
Petrov, The few atom problem, arxiv:1206.5752v2

Courtesy: The Scientific Secretary

Plan

- 2-body scattering: recall of some results

  Landau&Lifshitz, Quantum Mechanics: Non-Relativistic Theory (Chapters 17-18)
  Castin Lectures in Ultracold Fermi Gases (2007)
  Chin et al, Rev. Mod. Phys. **82**, 1225 (2010)
  Petrov, The few atom problem, arxiv:1206.5752v2

- From 2 to 3 fermion systems

  Petrov, The few atom problem, arxiv:1206.5752v2
  Levinsen&Petrov, EPJD **65**, 67 (2011)
  M. Jag *et al*, Phys. Rev. Lett. **112**, 075302 (2014)

Courtesy: The Scientific Secretary

Plan

- 2-body scattering: recall of some results

  Landau&Lifshitz, Quantum Mechanics: Non-Relativistic Theory (Chapters 17-18)
  Castin Lectures in Ultracold Fermi Gases (2007)
  Chin et al, Rev. Mod. Phys. **82**, 1225 (2010)
  Petrov, The few atom problem, arxiv:1206.5752v2

- From 2 to 3 fermion systems

  Petrov, The few atom problem, arxiv:1206.5752v2
  Levinsen&Petrov, EPJD **65**, 67 (2011)
  M. Jag *et al*, Phys. Rev. Lett. **112**, 075302 (2014)

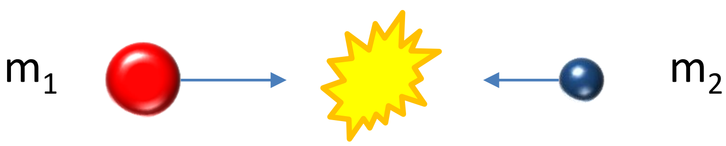
- The special case of ^{6}Li-^{53}Cr

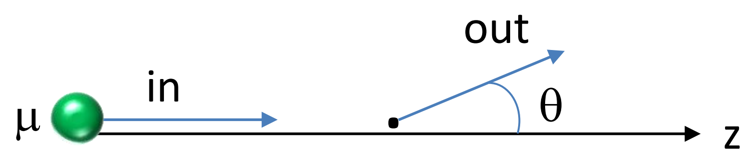
  Neri et al, PRA 101, 063602 (2020)
  Ciamei et al, arXiv:2203.12965 (Accepted in Phys. Rev. Lett.)
  Ciamei et al, arXiv:2207.07579

Courtesy: The Scientific Secretary

Basic facts on scattering theory

General problem: 2-body collision

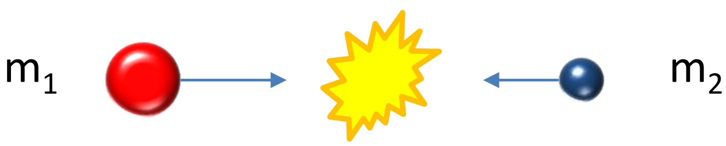


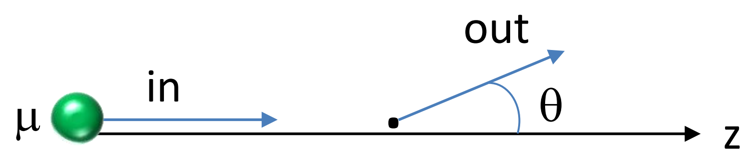


$$\mathcal{H} = \frac{p^2}{2\mu} + V(\vec{r}_1 - \vec{r}_2)$$

Basic facts on scattering theory

General problem: 2-body collision





$$\mathcal{H} = \frac{p^2}{2\mu} + V(\vec{r}_1 - \vec{r}_2)$$

All infos encoded in the scattering amplitude:

$$\psi \sim e^{ikz} + f(\vartheta, k)\,\frac{e^{ikr}}{r}$$

scattering amplitude

Basic facts on scattering theory

If V(**r**)=V(r), ψ has axial symmetry, and can be expanded in partial waves

After some algebra... the scattering amplitude reads:

$$f(\vartheta) = \frac{1}{2ik} \cdot \sum_{\ell} P_{\ell}(\cos\vartheta) \cdot (2l+1) \cdot (e^{2i\delta_{\ell}} - 1)$$

Legendre polynomials

Phase shift

Basic facts on scattering theory

If V(**r**)=V(r), ψ has axial symmetry, and can be expanded in partial waves

After some algebra... the scattering amplitude reads:

$$f(\vartheta) = \frac{1}{2ik} \cdot \sum_{l} P_l(\cos\vartheta) \cdot (2l+1) \cdot \left(e^{2i\delta_l} - 1\right)$$

Legendre polynomials

Phase shift

✓ From phase shifts get the scattering cross section

$$\sigma = 2\pi \int |f(\vartheta)|^2 \sin\vartheta \, d\vartheta = \ldots = \frac{4\pi}{k^2} \cdot \sum_{l=0}^{\infty} (2l+1) \sin^2\delta_l$$

Basic facts on scattering theory

If V(**r**)=V(r), ψ has axial symmetry, and can be expanded in partial waves

After some algebra... the scattering amplitude reads:

$$f(\vartheta) = \frac{1}{2ik} \cdot \sum_{\ell} P_{\ell}(\cos\vartheta) \cdot (2l+1) \cdot (e^{2i\delta_\ell} - 1)$$

Legendre polynomials

Phase shift

- ✓ From phase shifts get the scattering cross section

$$\sigma = 2\pi \int |f(\vartheta)|^2 \sin\vartheta \, d\vartheta = \ldots = \frac{4\pi}{k^2} \cdot \sum_{l=0}^{\infty} (2l+1) \sin^2\delta_\ell$$

- ✓ For each partial wave channel the maximum cross section is:

$$\sigma_{\ell\,MAX} = \frac{4\pi}{k^2} \cdot (2l+1) \quad \text{for} \quad \delta_\ell = \frac{\pi}{2}$$

Basic facts on scattering theory

Useful to take in mind (details on L&L Ch. 49 and 123):

✓ (In 3D) if V(r) faster than $1/r^3$:

$$\delta_\ell \sim k^{2\ell+1} \qquad f_\ell \sim (2\ell+1) \cdot k^{2\ell}$$

for $k \to 0$ and all l values

V(r) short/long range if decays faster/slower than $1/r^3$

- Long range: all l-waves contribute as $k \to 0$
- Short range: only $f_0 \neq 0$ as $k \to 0$

Basic facts on scattering theory

Useful to take in mind (details on L&L Ch. 49 and 123):

✓ (In 3D) if V(r) faster than $1/r^3$:

$$\delta_\ell \sim k^{2\ell+1} \qquad f_\ell \sim (2\ell+1)\cdot k^{2\ell}$$

for $k \to 0$ and all l values

V(r) short/long range if decays faster/slower than $1/r^3$

- Long range: all l-waves contribute as $k \to 0$
- Short range: only $f_0 \neq 0$ as $k \to 0$

✓ For short-ranged V(r), only need s-wave as $k \to 0$

$$f = f_0 = \frac{1}{2ik}\cdot\left(e^{2i\delta_0} - 1\right) = \frac{1}{k\cot\delta - ik}$$

Basic facts on scattering theory

✓ For k→0 one can further approximate $f_0(k)$ as:

$$f_s(k \to 0) \sim \frac{1}{k \cot \delta_0(k) - ik} \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

a= scattering length

R^*= effective range parameter

Basic facts on scattering theory

✓ For k→0 one can further approximate $f_0(k)$ as:

$$f_s(k\to 0) \sim \frac{1}{k\cot\delta_0(k) - ik} \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

a= scattering length
R^*= effective range parameter

- The problem reduces to the knowledge of two constants

Basic facts on scattering theory

✓ For k→0 one can further approximate $f_0(k)$ as:

$$f_s(k\to 0) \sim \frac{1}{k\cot\delta_0(k) - ik} \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

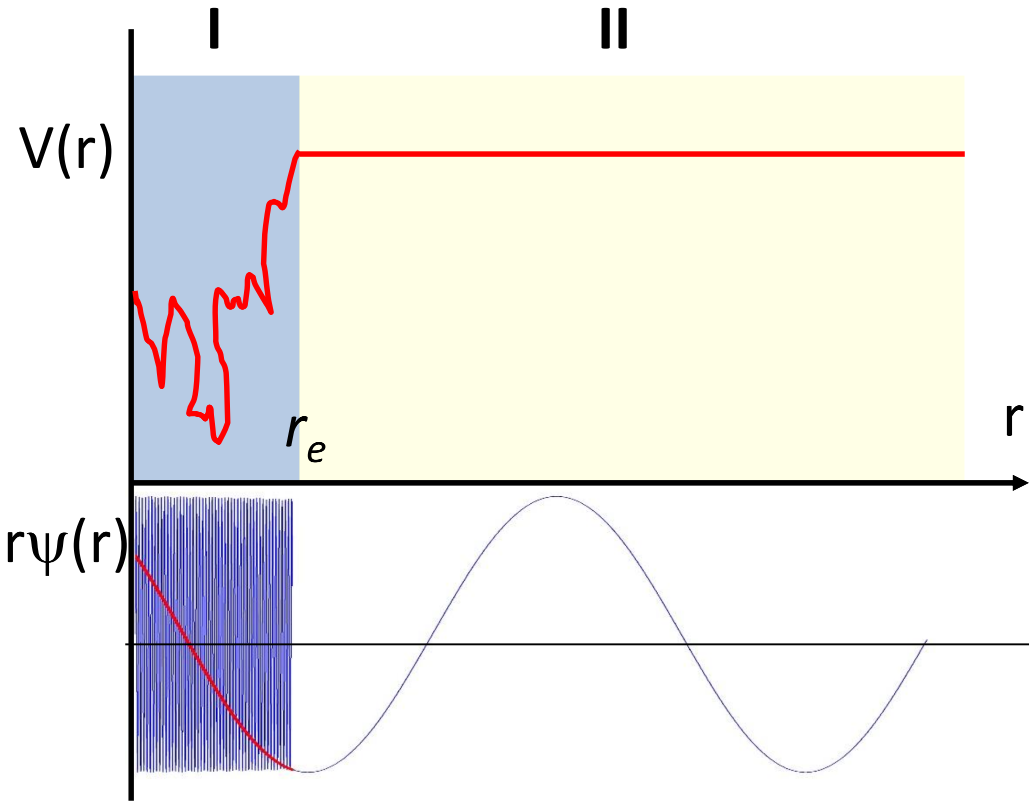
a= scattering length

R^*= effective range parameter

- The problem reduces to the knowledge of two constants
- Any potential yielding the same *a* and R^* can be employed to describe the low-*k* scattering from the real V(r)

Basic facts on scattering theory

✓ In particular, can employ a zero-range pseudo-potential



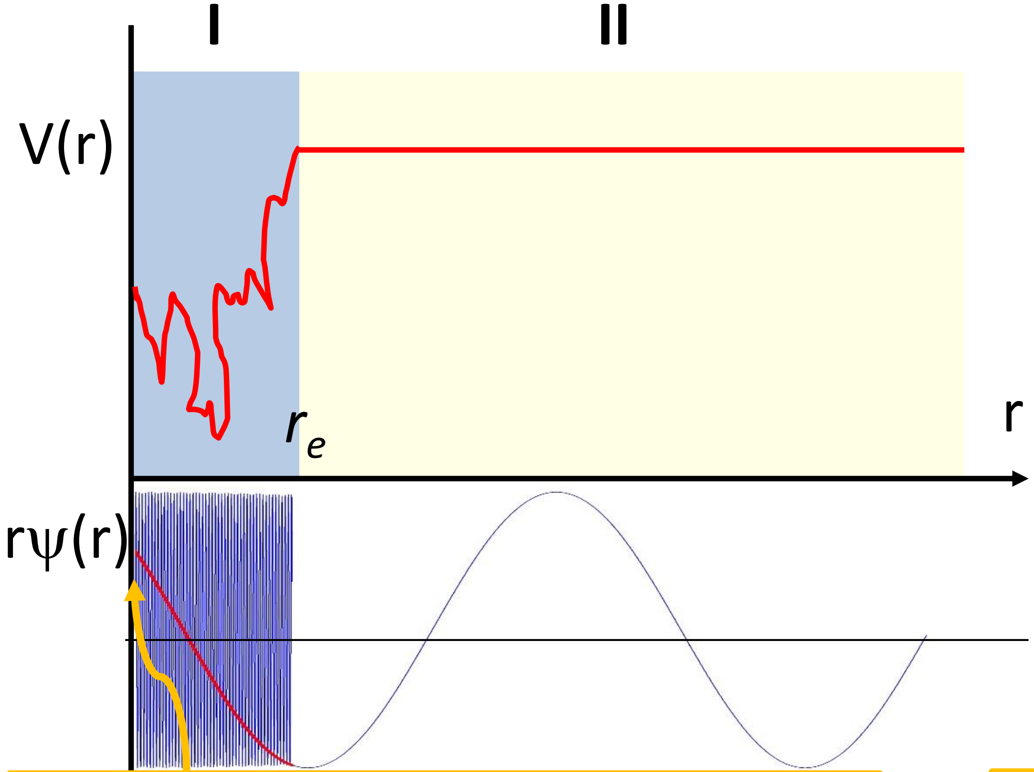
I: inner (short-range) region

II: outer (free) region

Excellent approximation as long as $kr_e \ll 1$

Basic facts on scattering theory

✓ In particular, can employ a zero-range pseudo-potential



I: inner (short-range) region

II: outer (free) region

Excellent approximation as long as $\boldsymbol{kr_e \ll 1}$

$$\frac{\chi'(0)}{\chi(0)} = k \cot \delta_0(k)$$

$$\left.\frac{\chi'(r)}{\chi(r)}\right|_{r \to 0} = -\left(\frac{1}{a} + R^* k^2\right).$$

Bethe-Peierls boundary conditions *(see Y. Castin in Ultracold Fermi Gases 2007)*

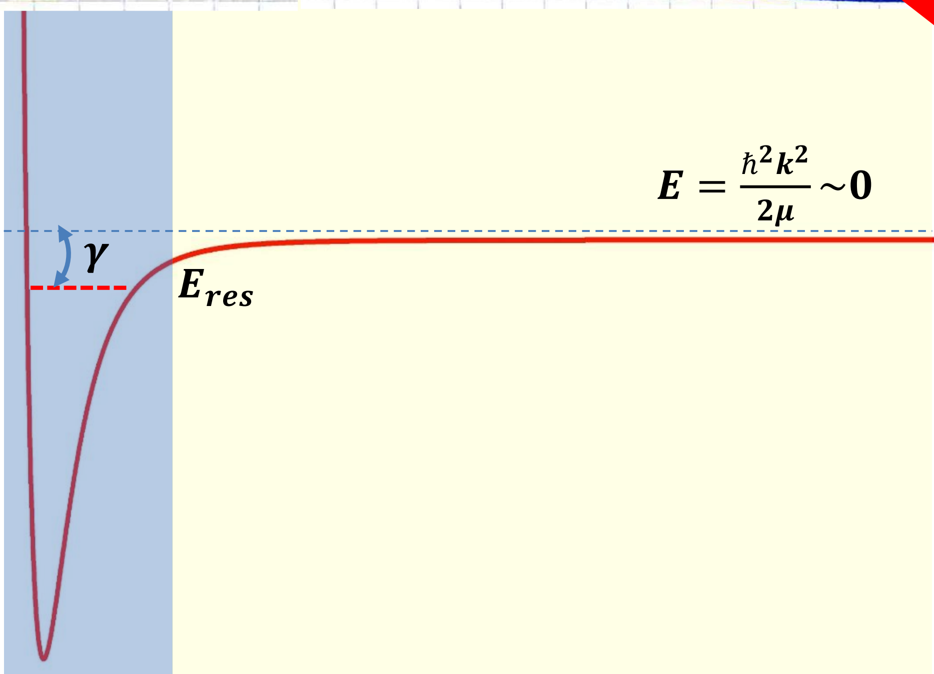
Basic facts on scattering theory

✓ Low-k scattering amplitude and Breit-Wigner resonance

$$f_s(k\to 0) \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

G. Breit & E. Wigner, *Capture of Slow Neutrons*
Phys. Rev. **49**, 519 (1936)

$$f_{BW}(E) = -\frac{\hbar\gamma/\sqrt{2\mu}}{E - E_{res} + i\gamma\sqrt{E}}$$

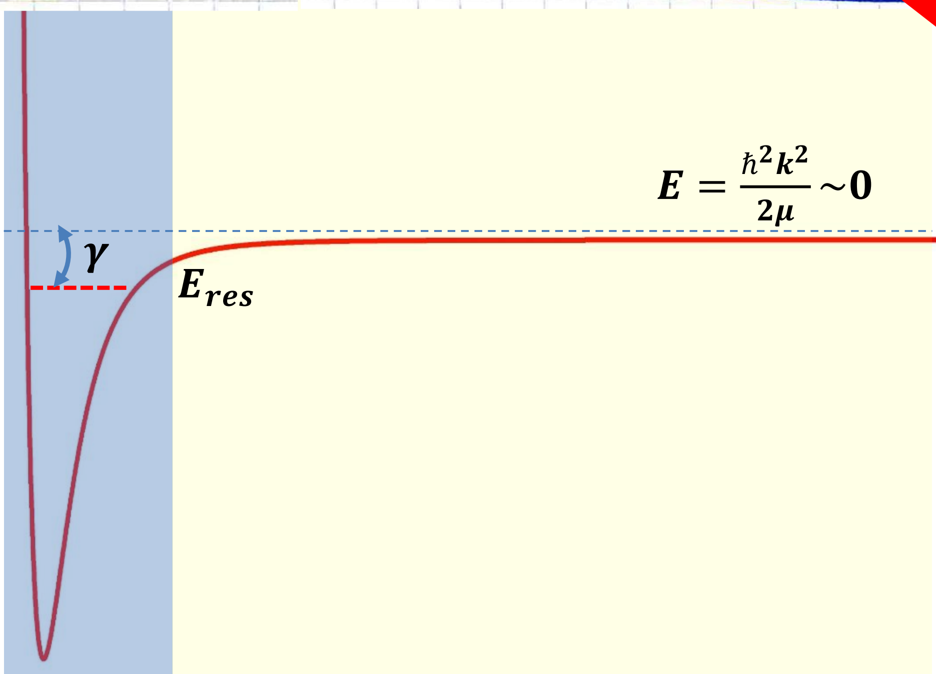


Basic facts on scattering theory

✓ Low-k scattering amplitude and Breit-Wigner resonance

$$f_s(k \to 0) \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

G. Breit & E. Wigner, *Capture of Slow Neutrons*
Phys. Rev. **49**, 519 (1936)



$$f_{BW}(E) = -\frac{\hbar\gamma/\sqrt{2\mu}}{E - E_{res} + i\gamma\sqrt{E}}$$

$$a = -\frac{\hbar\gamma}{\sqrt{2\mu}\, E_{res}}$$

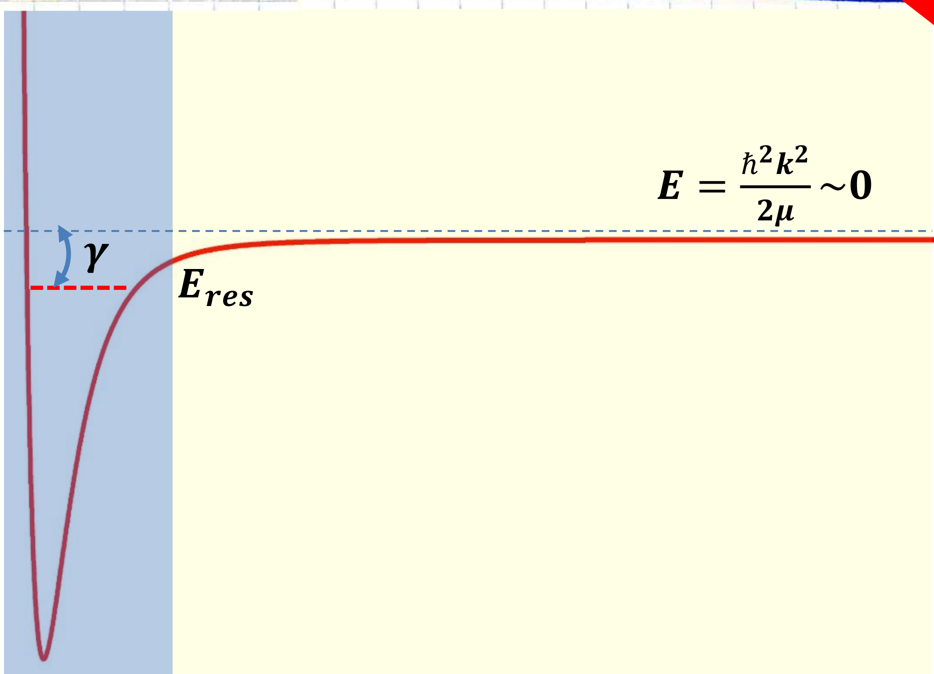
$$R^* = \frac{\hbar}{\sqrt{2\mu}\cdot\gamma}$$

Basic facts on scattering theory

✓ Low-k scattering amplitude and Breit-Wigner resonance

$$f_s(k \to 0) \simeq -\frac{1}{\left(\frac{1}{a} + R^* k^2\right) + ik}$$

G. Breit & E. Wigner, *Capture of Slow Neutrons* Phys. Rev. **49**, 519 (1936)



$$f_{BW}(E) = -\frac{\hbar\gamma/\sqrt{2\mu}}{E - E_{res} + i\gamma\sqrt{E}}$$

$$a = -\frac{\hbar\gamma}{\sqrt{2\mu}\,E_{res}}$$

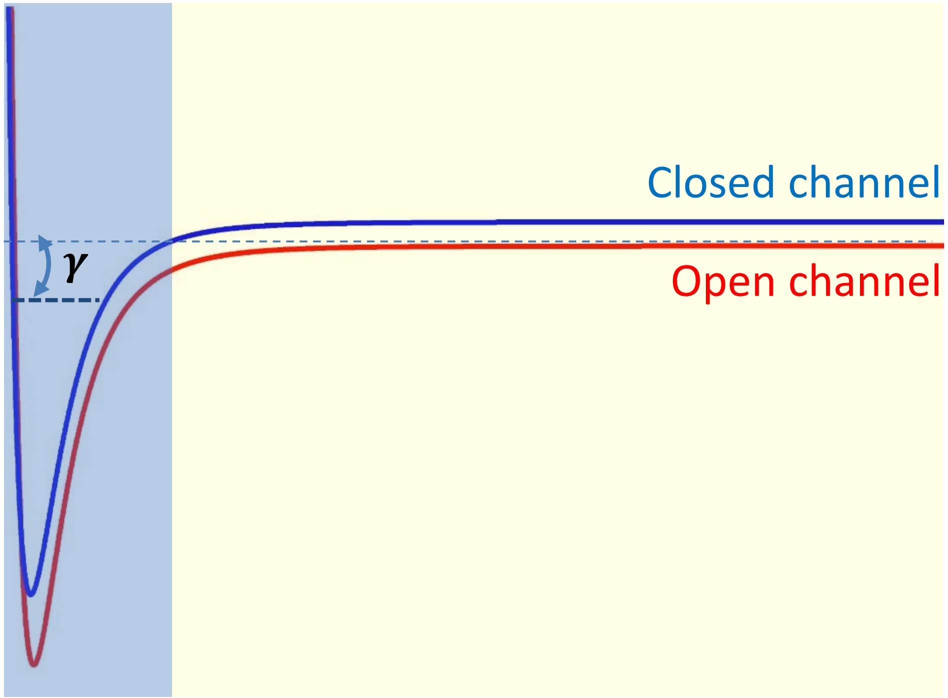
$$R^* = \frac{\hbar}{\sqrt{2\mu}\cdot\gamma}$$

a linked to the energy of a real (or virtual) bound state $E_{res} \sim 0$. $R^*>0$ depends only on coupling amplitude γ

Basic facts on scattering theory

✓ Our case: the Feshbach resonance

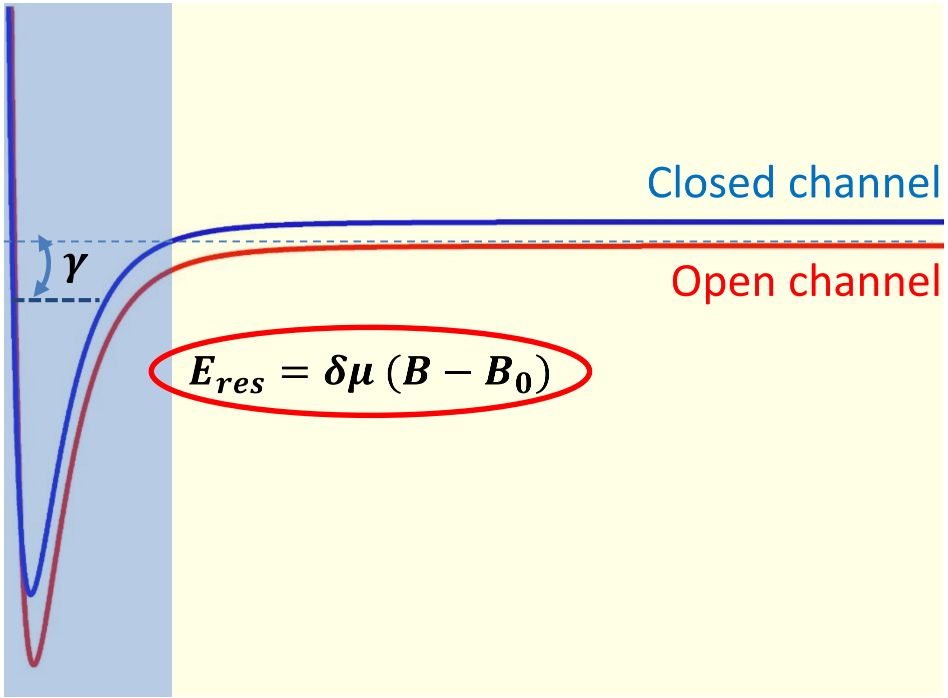
Chin *et al*, Rev. Mod. Phys. **82**, 1225 (2010)



Basic facts on scattering theory

✓ Our case: the Feshbach resonance

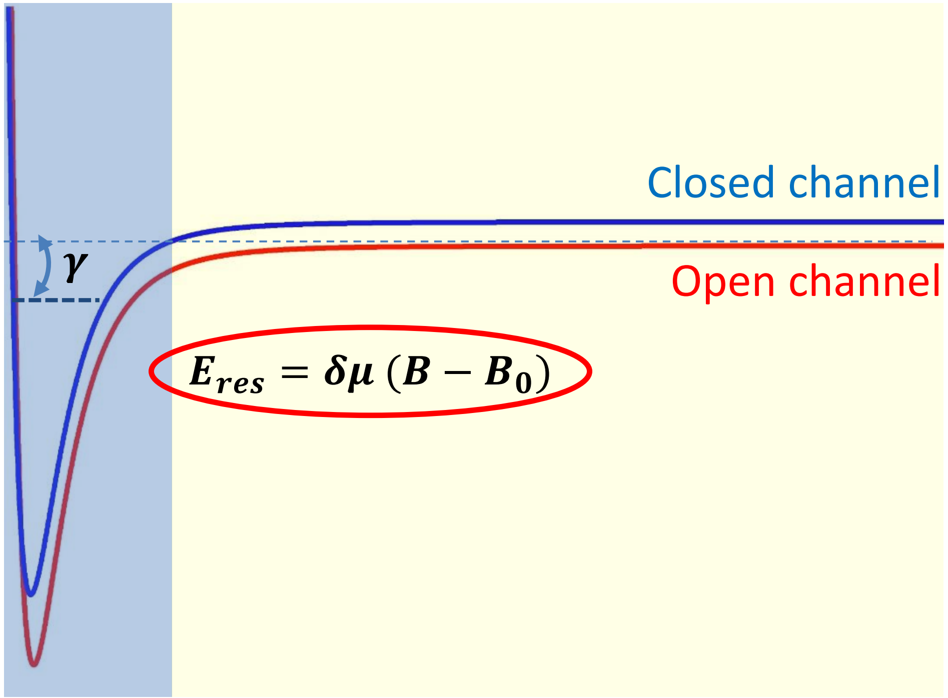
Chin *et al*, Rev. Mod. Phys. **82**, 1225 (2010)



Basic facts on scattering theory

✓ Our case: the Feshbach resonance

Chin *et al*, Rev. Mod. Phys. **82**, 1225 (2010)

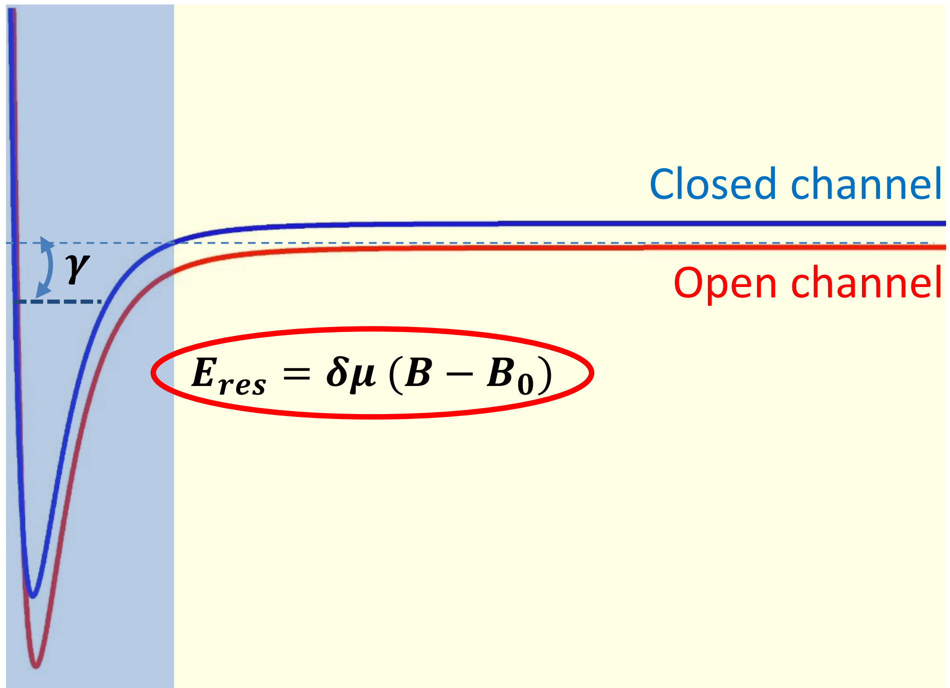


$$a(B) = -\frac{\hbar\gamma}{\sqrt{2\mu}\cdot\delta\mu\,(B-B_0)} \sim -a_{bg}\frac{\Delta B}{B-B_0}$$

Basic facts on scattering theory

✓ Our case: the Feshbach resonance

Chin *et al*, Rev. Mod. Phys. **82**, 1225 (2010)



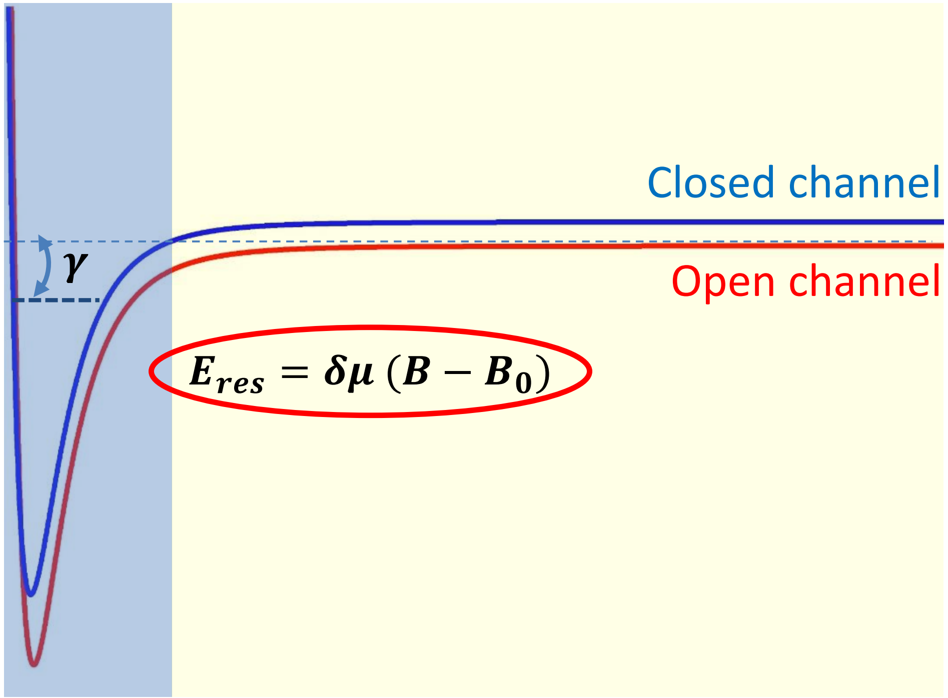
$$a(B) = -\frac{\hbar\gamma}{\sqrt{2\mu}\cdot\delta\mu\,(B - B_0)} \sim -a_{bg}\,\frac{\Delta B}{B - B_0}$$

$$R^* = \frac{\hbar^2}{2\mu}\cdot\frac{1}{a_{bg}\cdot\Delta B\,\delta\mu}$$

Basic facts on scattering theory

✓ Our case: the Feshbach resonance

Chin *et al*, Rev. Mod. Phys. **82**, 1225 (2010)



$$a(B) = -\frac{\hbar\gamma}{\sqrt{2\mu}\cdot\delta\mu\,(B-B_0)} \sim -a_{bg}\frac{\Delta B}{B-B_0}$$

$$R^* = \frac{\hbar^2}{2\mu}\cdot\frac{1}{a_{bg}\cdot\Delta B\,\delta\mu}$$

$$\gamma = \frac{\sqrt{2\mu}}{\hbar}\cdot a_{bg}\cdot\Delta B\,\delta\mu$$

Strong coupling=Broad resonance=small *R**

Basic facts on scattering theory

✓ Bound state: the Feshbach dimer

set $\begin{cases} k \to i\kappa \\ \mathcal{E} = -\dfrac{\hbar \kappa^2}{2\mu} < 0 \end{cases}$ and search the pole of the scattering amplitude

$$\kappa = \frac{1}{a^*} = \frac{\sqrt{4R^*/a + 1} - 1}{2R^*}$$

$$\psi_d(r) \sim \frac{e^{-\kappa r}}{r}$$

Basic facts on scattering theory

✓ Bound state: the Feshbach dimer

set $\begin{cases} k \to i\kappa \\ \mathcal{E} = -\frac{\hbar \kappa^2}{2\mu} < 0 \end{cases}$ and search the pole of the scattering amplitude

$$\kappa = \frac{1}{a^*} = \frac{\sqrt{4R^*/a + 1} - 1}{2R^*}$$

$$\psi_d(r) \sim \frac{e^{-\kappa r}}{r}$$

- Broad resonance

$$R^*/a \ll 1 \Rightarrow \frac{1}{a^*} \simeq \frac{1}{a} \Rightarrow \mathcal{E}_b = -\frac{\hbar^2}{2\mu a^2}$$

Basic facts on scattering theory

✓ Bound state: the Feshbach dimer

set $\begin{cases} k \to ik \\ \mathcal{E} = -\frac{\hbar k^2}{2\mu} < 0 \end{cases}$ and search the pole of the scattering amplitude

$$\kappa = \frac{1}{a^*} = \frac{\sqrt{4R^*/a + 1} - 1}{2R^*}$$

$$\psi_d(r) \sim \frac{e^{-\kappa r}}{r}$$

- Broad resonance

$$R^*/a \ll 1 \Rightarrow \frac{1}{a^*} \simeq \frac{1}{a} \Rightarrow \mathcal{E}_b = -\frac{\hbar^2}{2\mu a^2}$$

- Narrow resonance

$$\frac{R^*}{a} \gg 1 \Rightarrow \frac{1}{a^*} = \frac{1}{\sqrt{a R^*}} \Rightarrow \mathcal{E}_b(R^*/a \gg 1) = -\frac{\hbar^2}{2\mu a R^*}$$

Basic facts on scattering theory

✓ Bound state: the Feshbach dimer

set $\begin{cases} k \to i\kappa \\ E = -\dfrac{\hbar \kappa^2}{2\mu} < 0 \end{cases}$ and search the pole of the scattering amplitude

$$\kappa = \frac{1}{a^*} = \frac{\sqrt{4R^*/a + 1} - 1}{2R^*}$$

$$\psi_d(r) \sim \frac{e^{-\kappa r}}{r}$$

- Broad resonance

$$R^*/a \ll 1 \;\Rightarrow\; \frac{1}{a^*} \simeq \frac{1}{a} \;\Rightarrow\; E_b = -\frac{\hbar^2}{2\mu a^2}$$

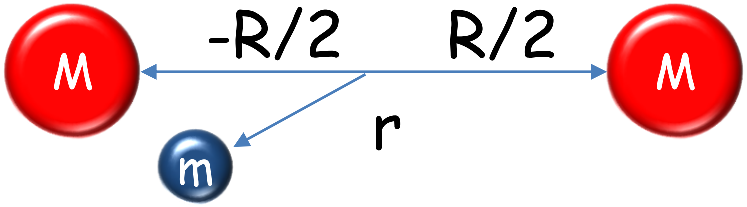
- Narrow resonance

$$\frac{R^*}{a} \gg 1 \;\Rightarrow\; \frac{1}{a^*} = \frac{1}{\sqrt{a\,R^*}} \;\Rightarrow\; E_b\left(R^*/a \gg 1\right) = -\frac{\hbar^2}{2\mu\, a\, R^*}$$

Plug in R^* and *a(B)* and get that… $E_b\left(R^*/a \gg 1\right) = \delta\mu \cdot (B - B_0)$

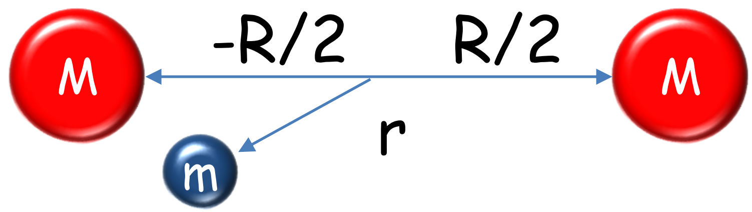
From 2- to 3-body systems

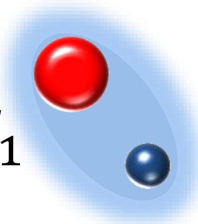
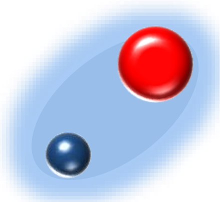
Born Oppenheimer approximation

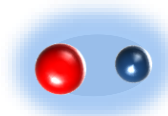


J. Levinsen & D. Petrov, EPJD **65**, 67 (2011); D. Petrov, arXiv:1206.5752

Born Oppenheimer approximation



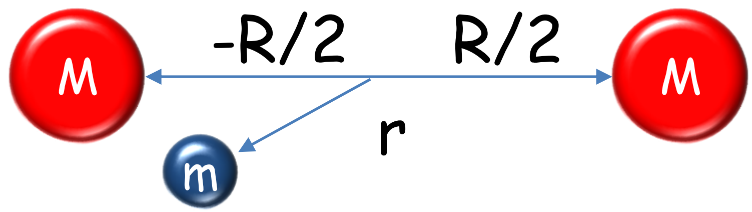
✓ $\psi_{\boldsymbol{R}}(\boldsymbol{r}) \sim C_1$  $+\, C_2$ 

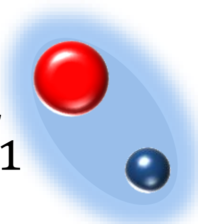
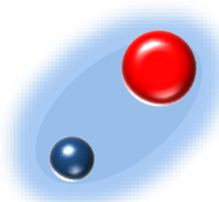
 $\sim \dfrac{e^{-\kappa(R)|\boldsymbol{r}\pm\boldsymbol{R}/2|}}{|\boldsymbol{r}\pm\frac{\boldsymbol{R}}{2}|}$

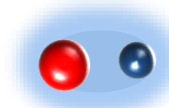
$\varepsilon(R) = -\hbar^2\kappa^2(R)/2m$

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

Born Oppenheimer approximation



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

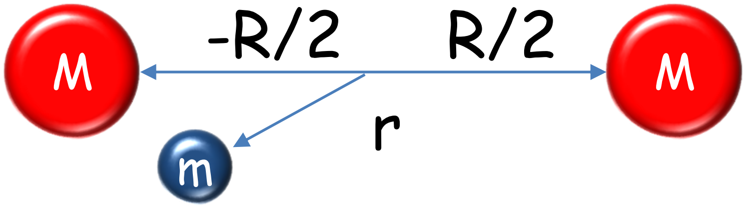
 $\sim \dfrac{e^{-\kappa(R)|\boldsymbol{r} \pm \boldsymbol{R}/2|}}{|\boldsymbol{r} \pm \frac{\boldsymbol{R}}{2}|}$

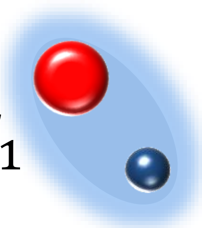
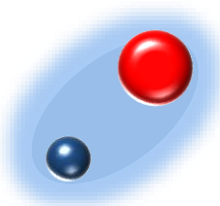
$\varepsilon(R) = -\hbar^2\kappa^2(R)/2m$

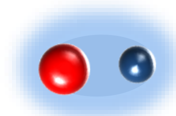
✓ only 2 eigenstates : $\psi_{\boldsymbol{R}\pm}(\boldsymbol{r})$ $\{C_1, C_2\} = \{\mathbf{1}, \pm\mathbf{1}\}$

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

Born Oppenheimer approximation



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

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

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

✓ only 2 eigenstates : $\psi_{\boldsymbol{R}\pm}(\boldsymbol{r})$ $\{C_1, C_2\} = \{\mathbf{1}, \pm\mathbf{1}\}$

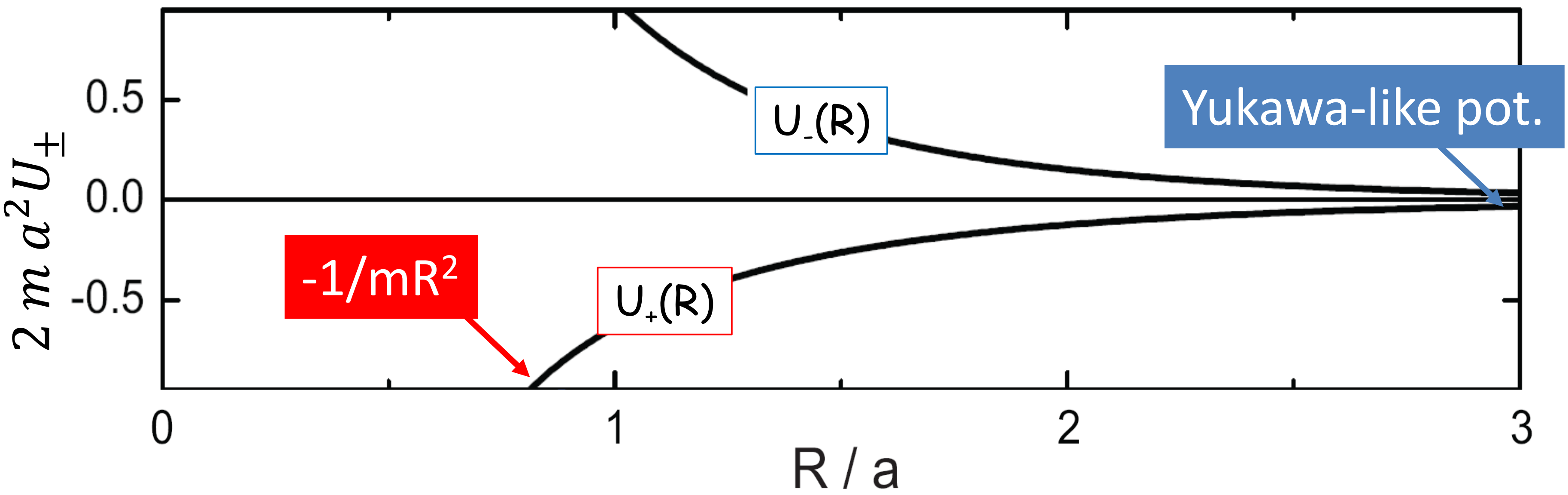
✓ eigenenergies given by: $\kappa_{\pm}(R) \mp \frac{e^{-\kappa_{\pm}(R)R}}{R} = \frac{1}{a} - \mathrm{R}^*\kappa_{\pm}(R)^2$

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

Born Oppenheimer approximation

✓ effective potentials for heavy particles (e.g. R^*=0)

$$U_\pm(R) = -\frac{\hbar^2\kappa_\pm^2(R)}{2m} - |\varepsilon_b|$$



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

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

M = identical fermions:

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

antisymmetric with resp. to permutation of atoms M

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

M = identical fermions:

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

antisymmetric with resp. to permutation of atoms M

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

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

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

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

M = identical fermions:

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

antisymmetric with resp. to permutation of atoms M

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

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

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

$\psi_{\boldsymbol{R}-}(\boldsymbol{r})$ anti-symmetric

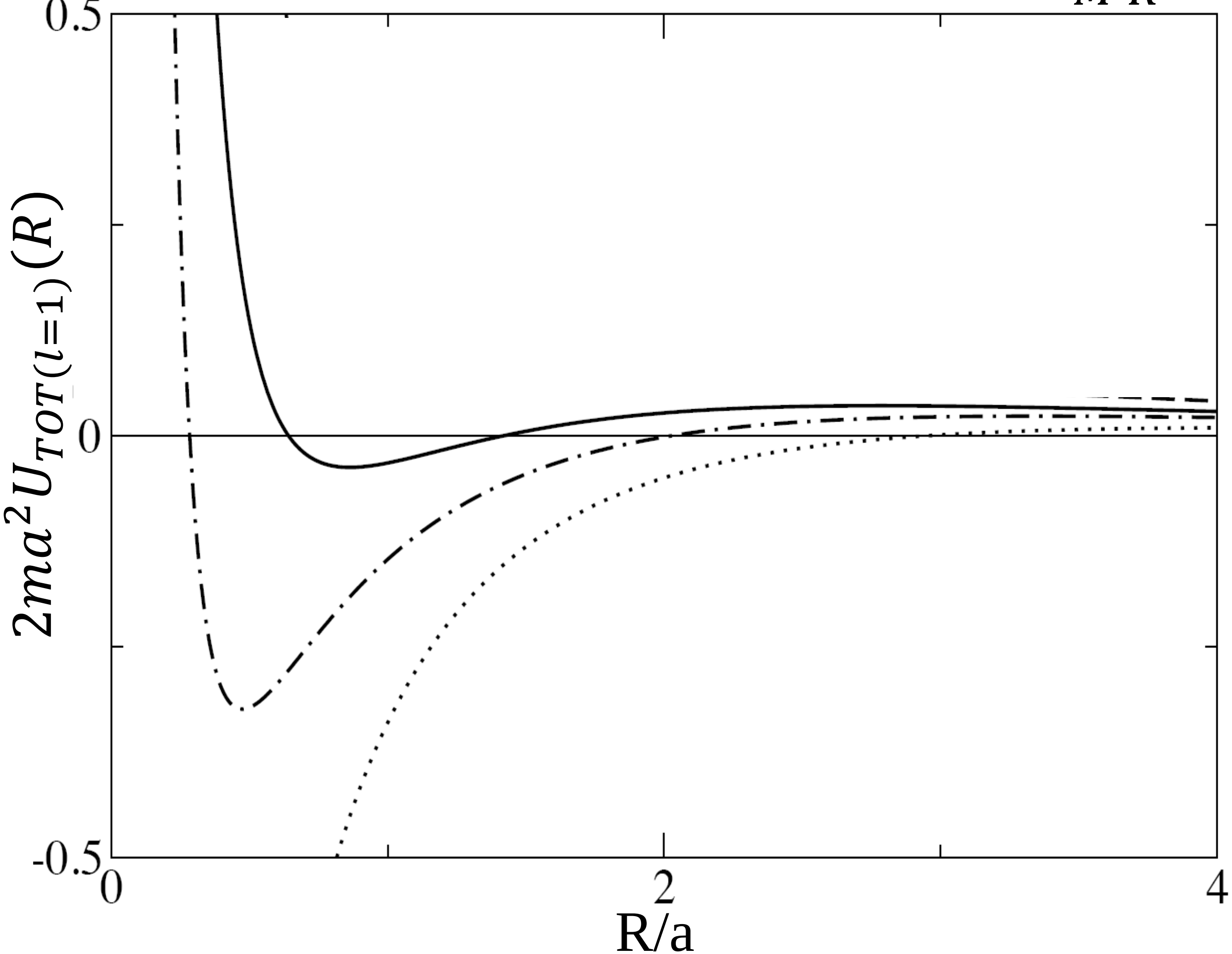
$\phi(\boldsymbol{R})$ symmetric

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

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

p-wave channel

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

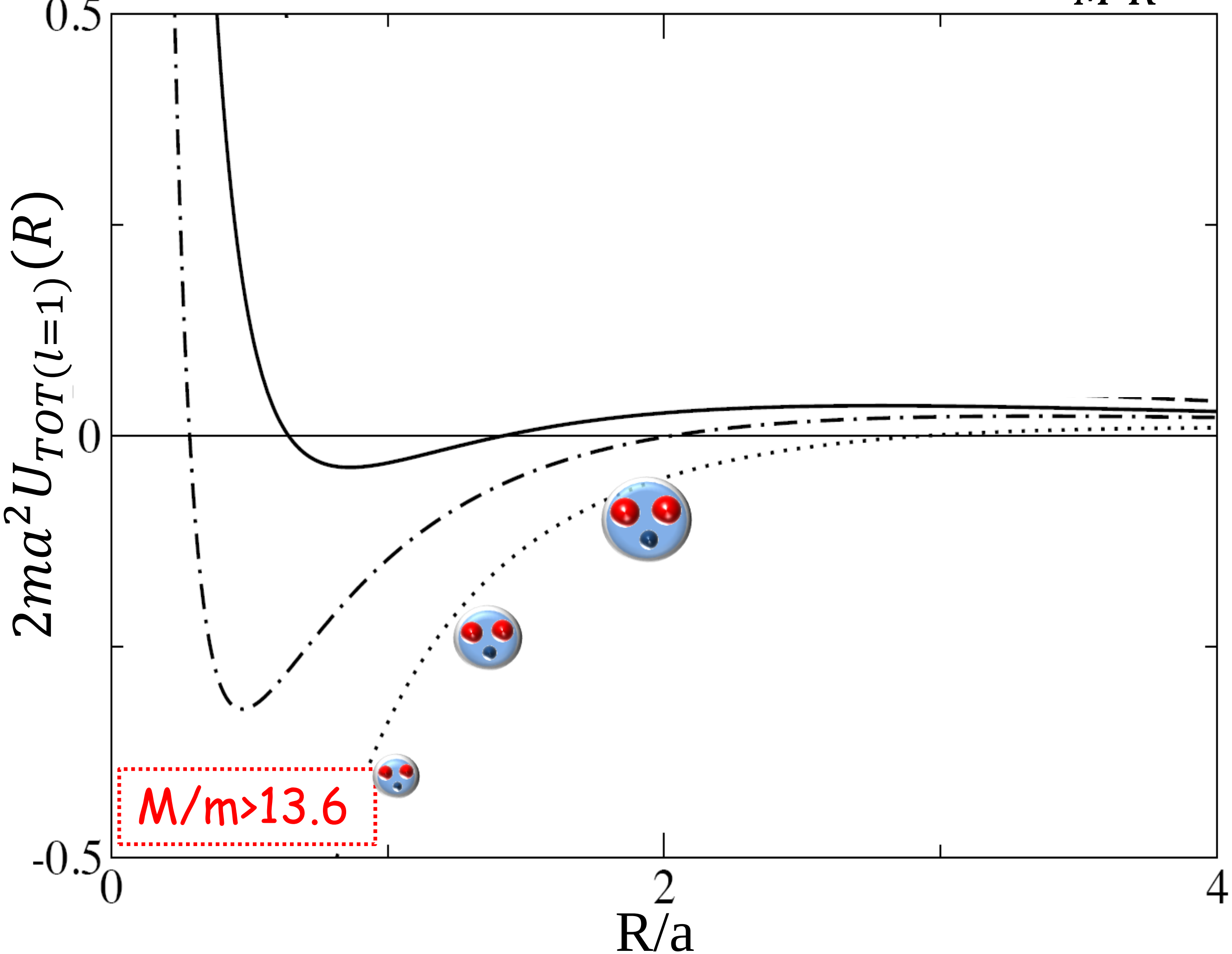


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

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

p-wave channel

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

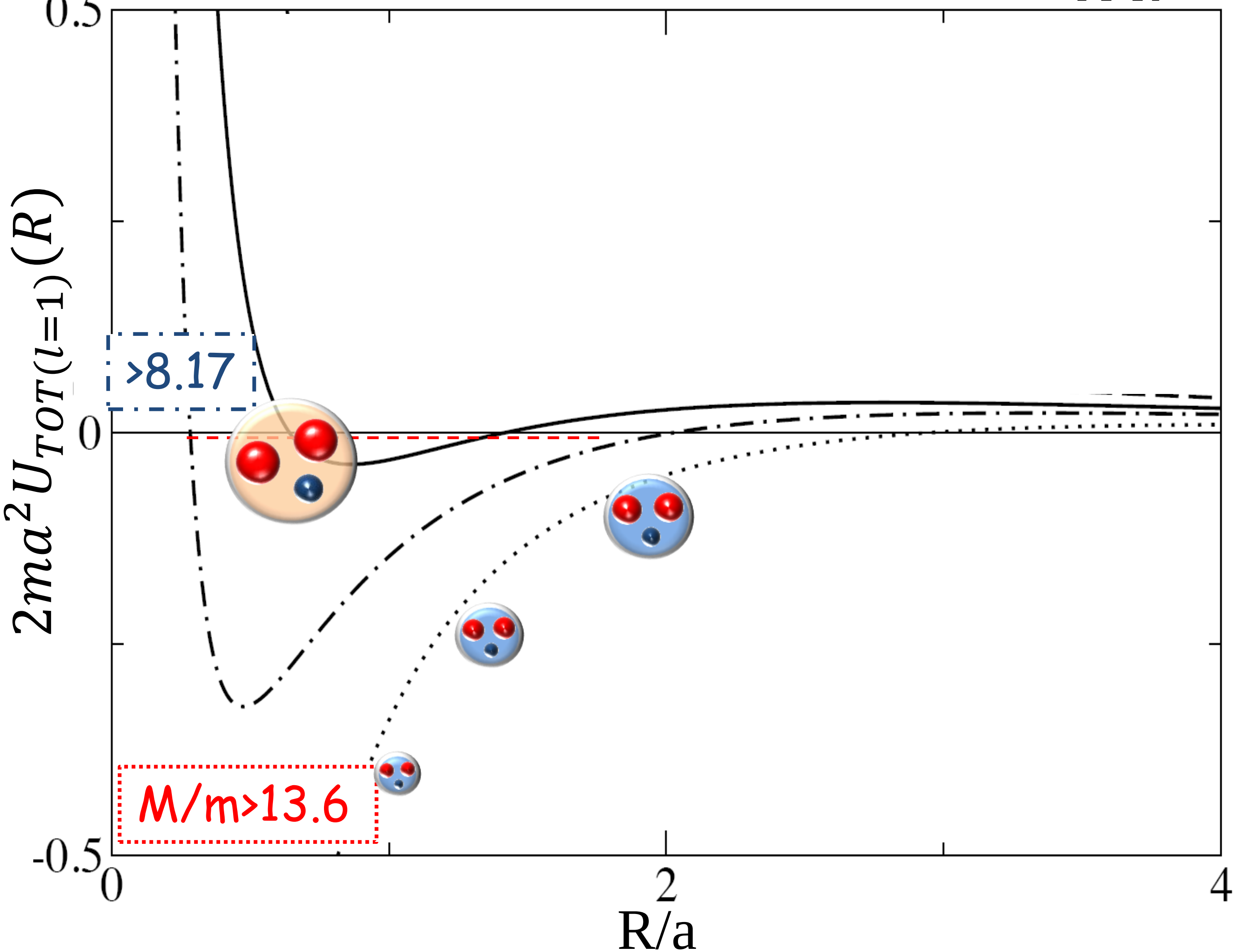


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

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

p-wave channel

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

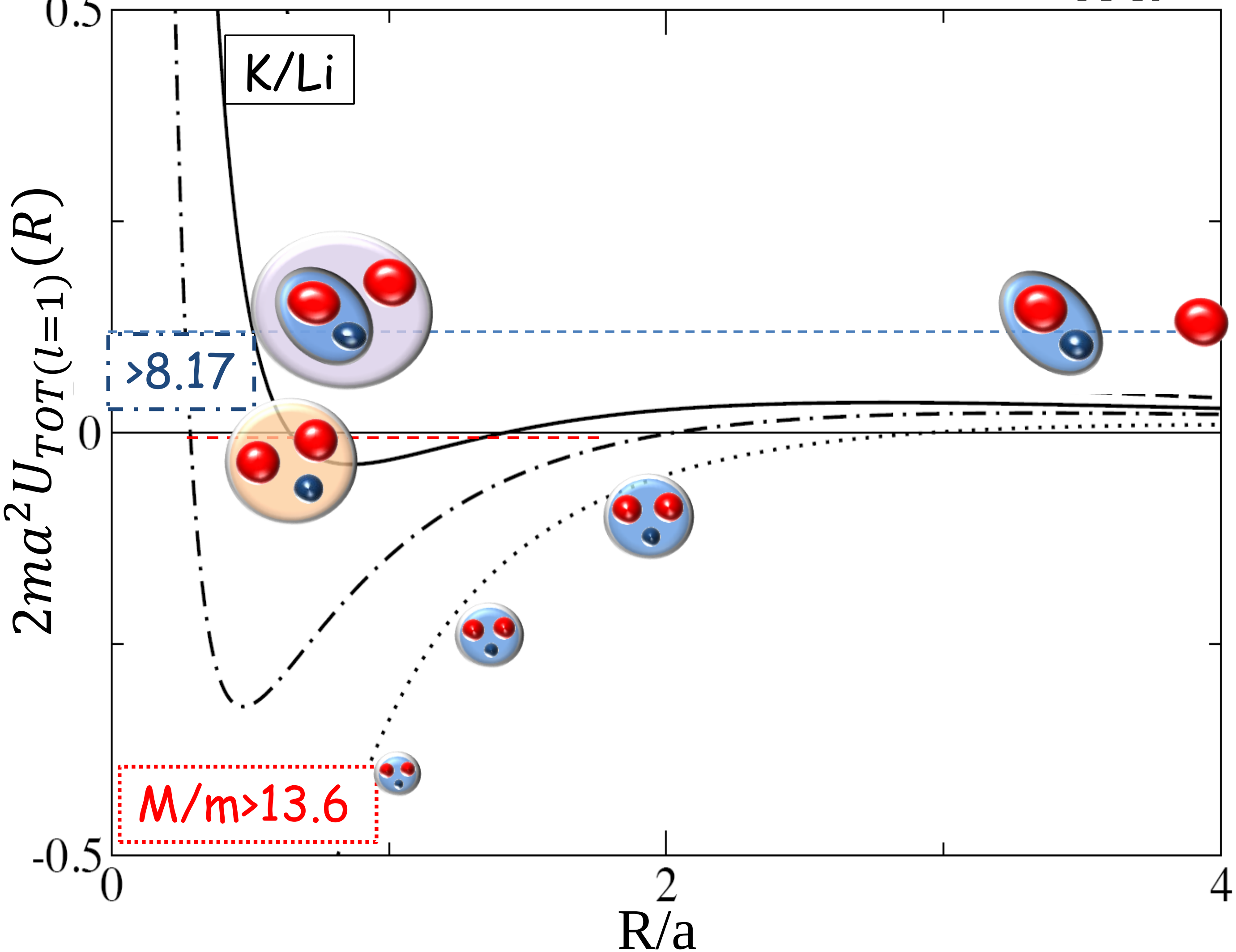


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

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

p-wave channel

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

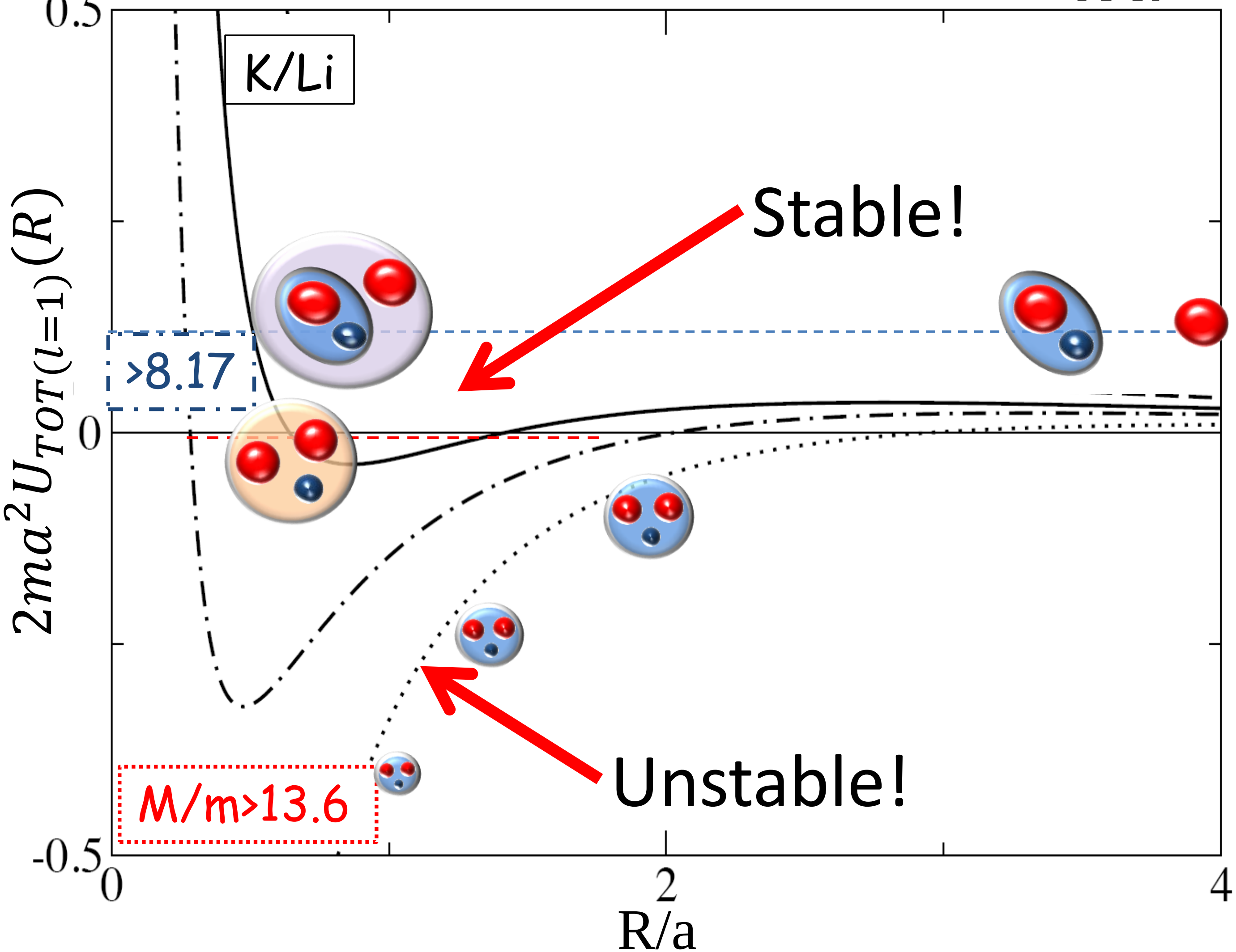


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

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

p-wave channel

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

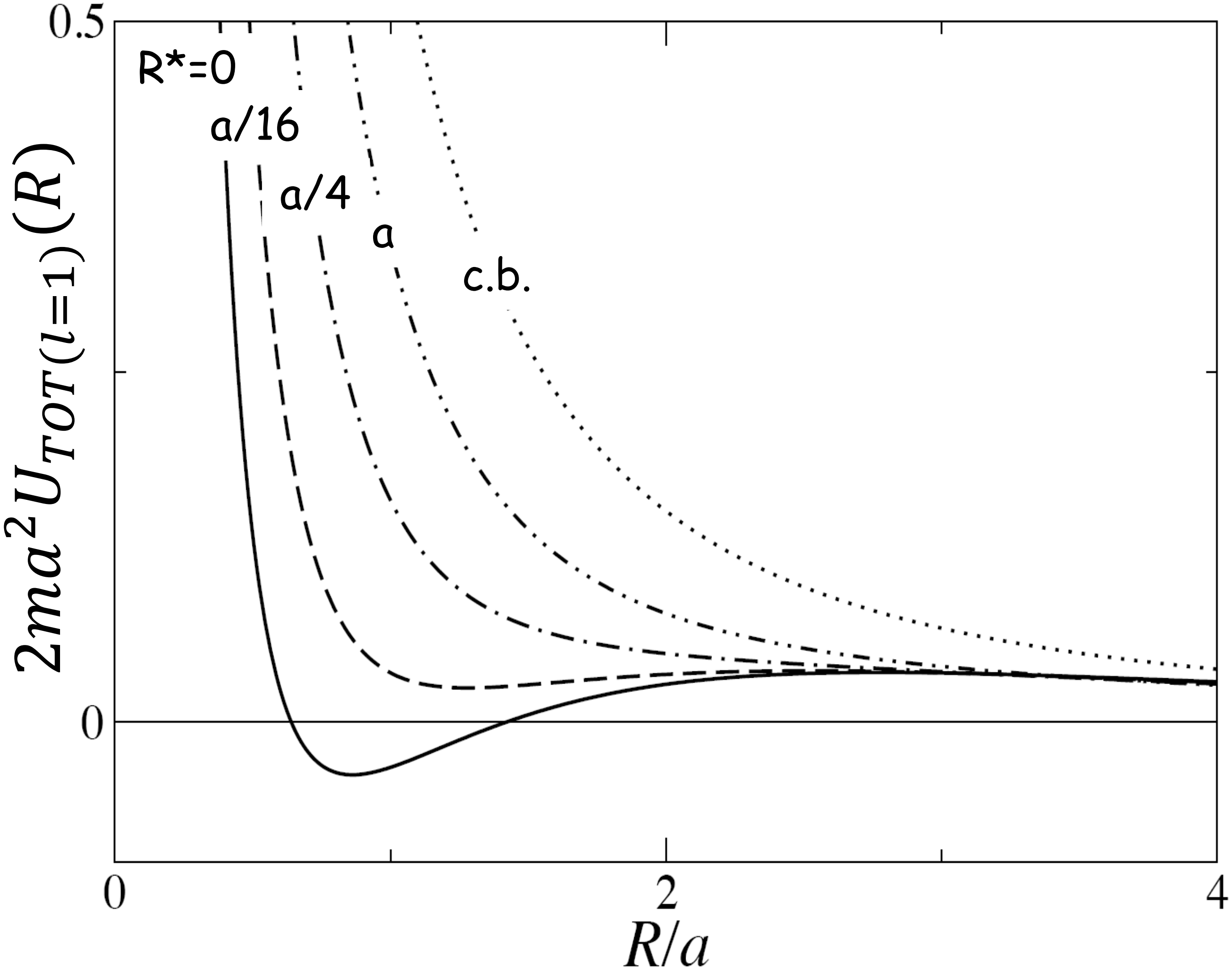


Kartavstsev&Malykh, J. Phys. B **40**, 1429 (2007); Levinsen&Petrov, EPJD **65**, 67 (2011)

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

p-wave channel

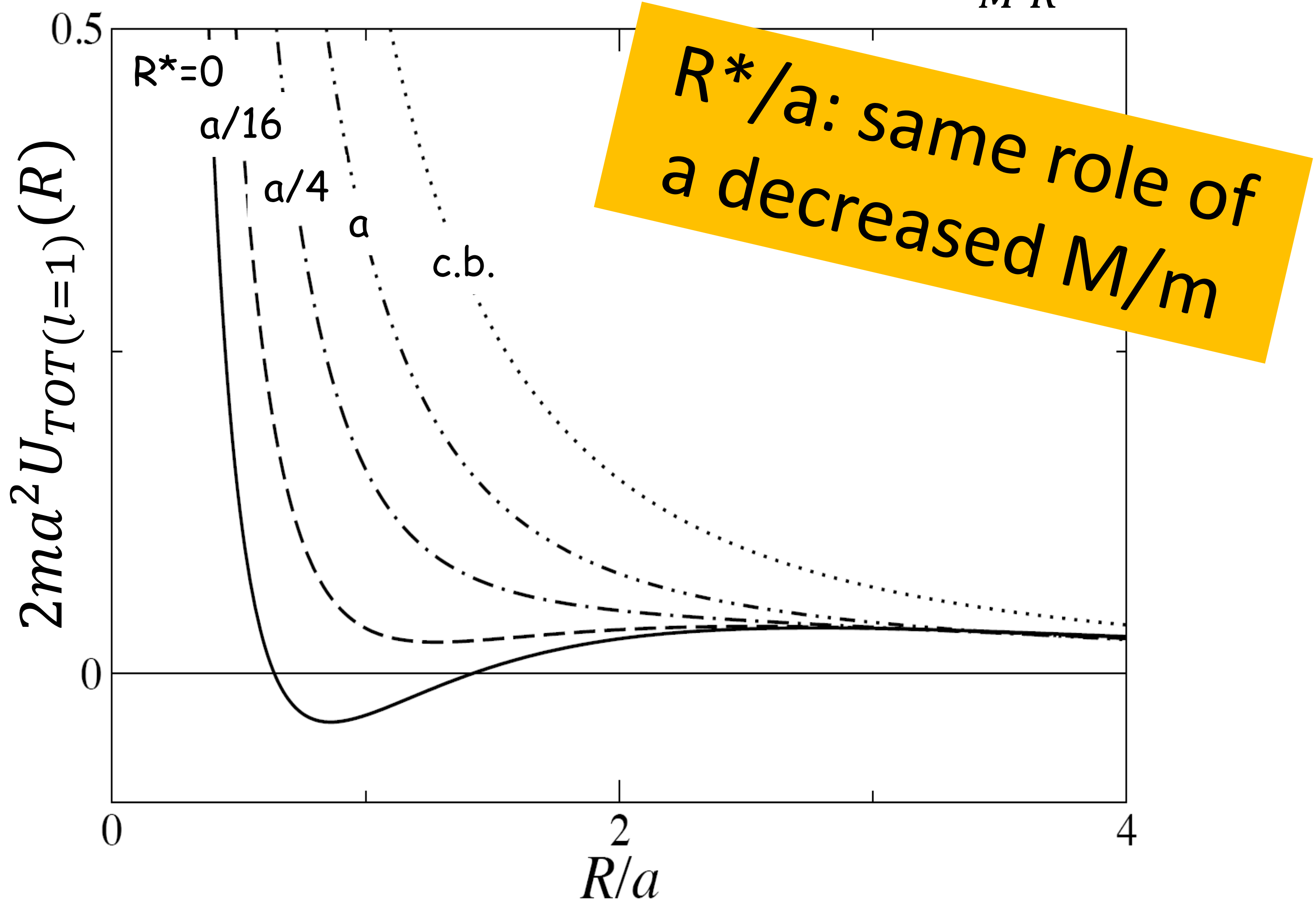
$$U_{TOT(l=1)}(R) = U_{+}(R) + \frac{2}{M\,R^2}$$



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

p-wave channel

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



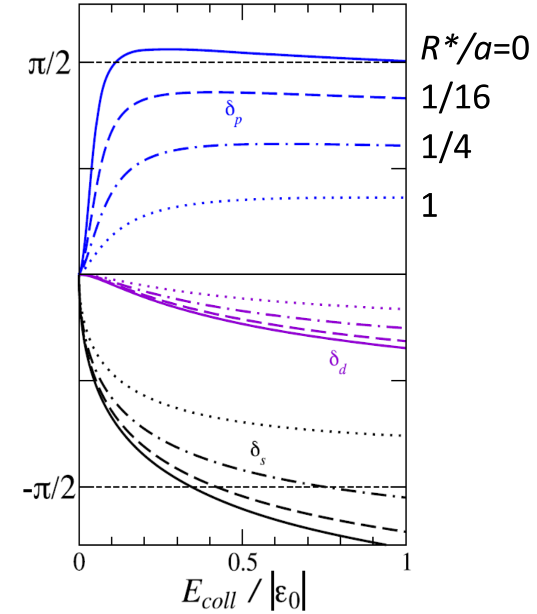
For K-Li case: see M. Jag *et al*, Phys. Rev. Lett. **112**, 075302 (2014).

M-M-m Fermi systems: the K-K-Li example

M_K/m_{Li}=6.64 (no real trimer!)

✓ Atom-dimer potential is long ranged: all δ_l contribute at ultralow temperatures !

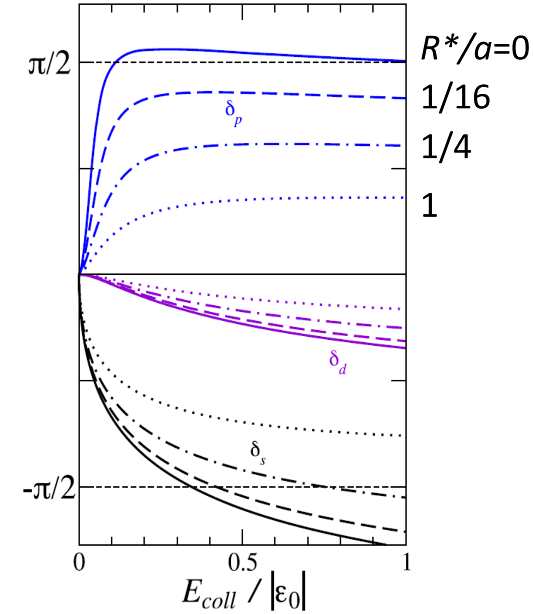
$$f(0) = \sum_{l=0}^{\infty}(2l+1)\left[\frac{\sin 2\delta_l(k_{\rm coll})}{2k_{\rm coll}} + i\frac{\sin^2\delta_l(k_{\rm coll})}{k_{\rm coll}}\right]$$



Levinsen&Petrov, EPJD **65**, 67 (2011)

M-M-m Fermi systems: the K-K-Li example

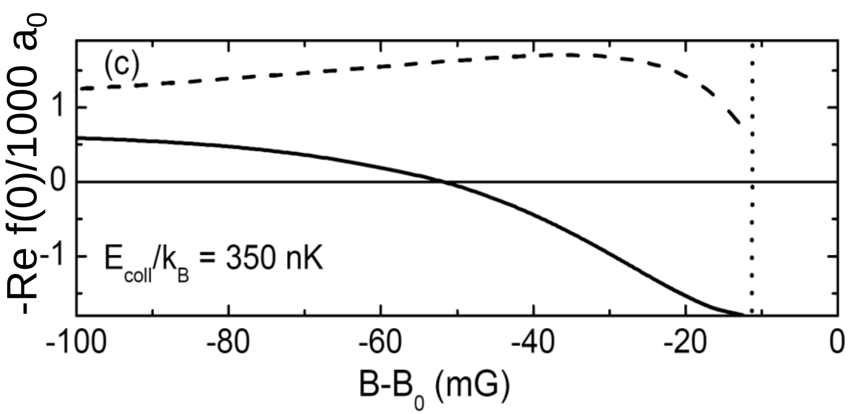
M_K/m_{Li}=6.64 (no real trimer!)



- ✓ Atom-dimer potential is long ranged: all δ_l contribute at ultralow temperatures !

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

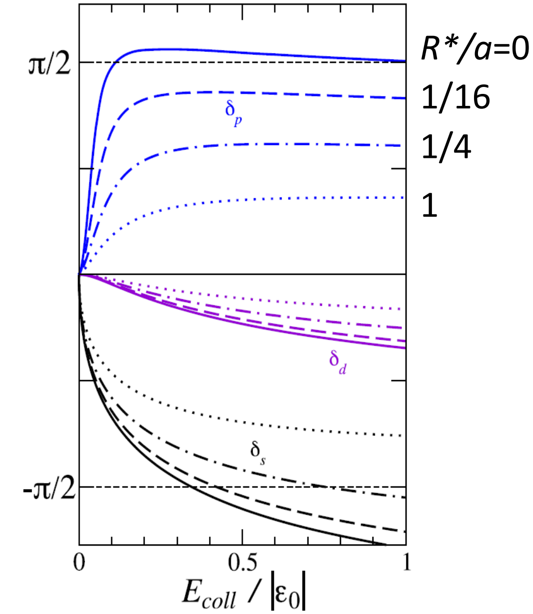
- ✓ Strong dependence of K-KLi interaction on E_{coll} and R^*/a



Levinsen&Petrov, EPJD **65**, 67 (2011)

M-M-m Fermi systems: the K-K-Li example

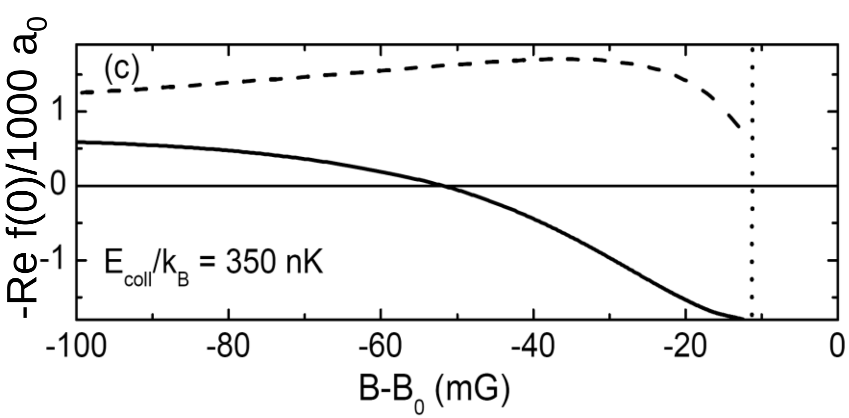
M_K/m_{Li}=6.64 (no real trimer!)

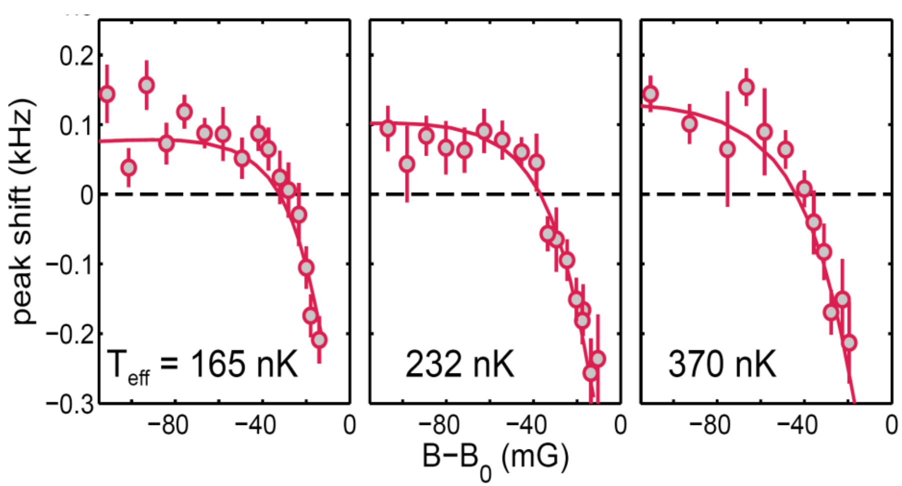


- ✓ Atom-dimer potential is long ranged: all δ_l contribute at ultralow temperatures !

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

- ✓ Strong dependence of K-KLi interaction on E_{coll} and R^*/a





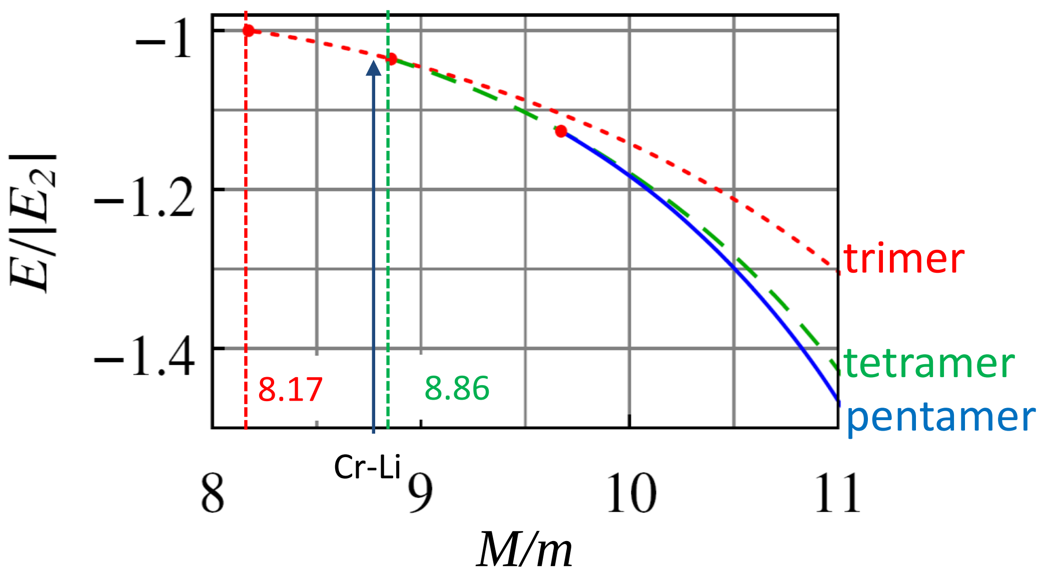
Levinsen&Petrov, EPJD **65**, 67 (2011)   M. Jag *et al*, Phys. Rev. Lett. **112**, 075302 (2014).

The special case of ^{6}Li-^{53}Cr

Cr-Cr-Li Fermi system

M_{Cr}/m_{Li}=8.8

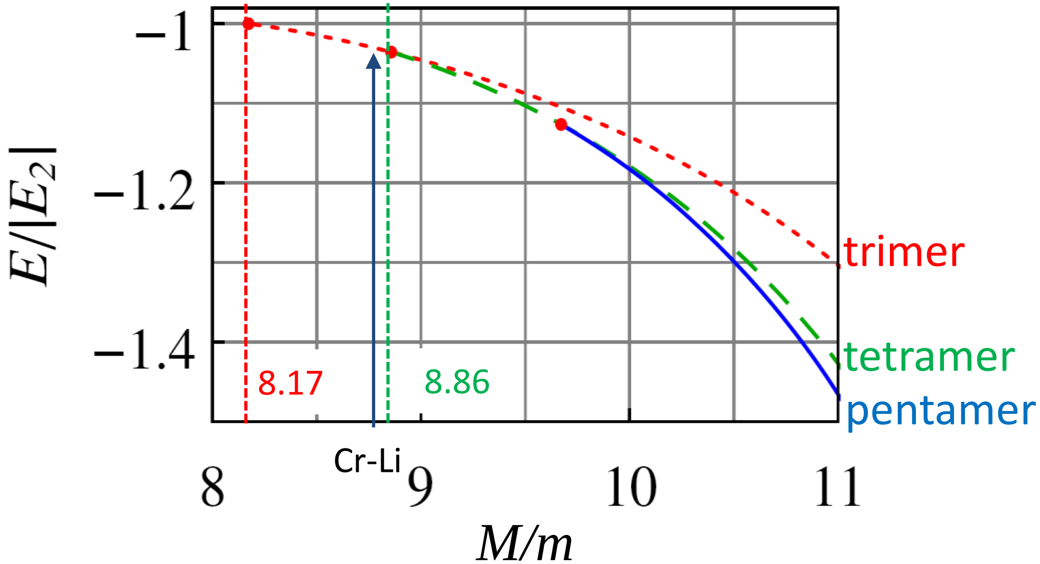
Bazak & Petrov, PRL 118, 083002 (2017)



Cr-Cr-Li Fermi system

$M_{Cr}/m_{Li}=8.8$

Bazak & Petrov, PRL 118, 083002 (2017)

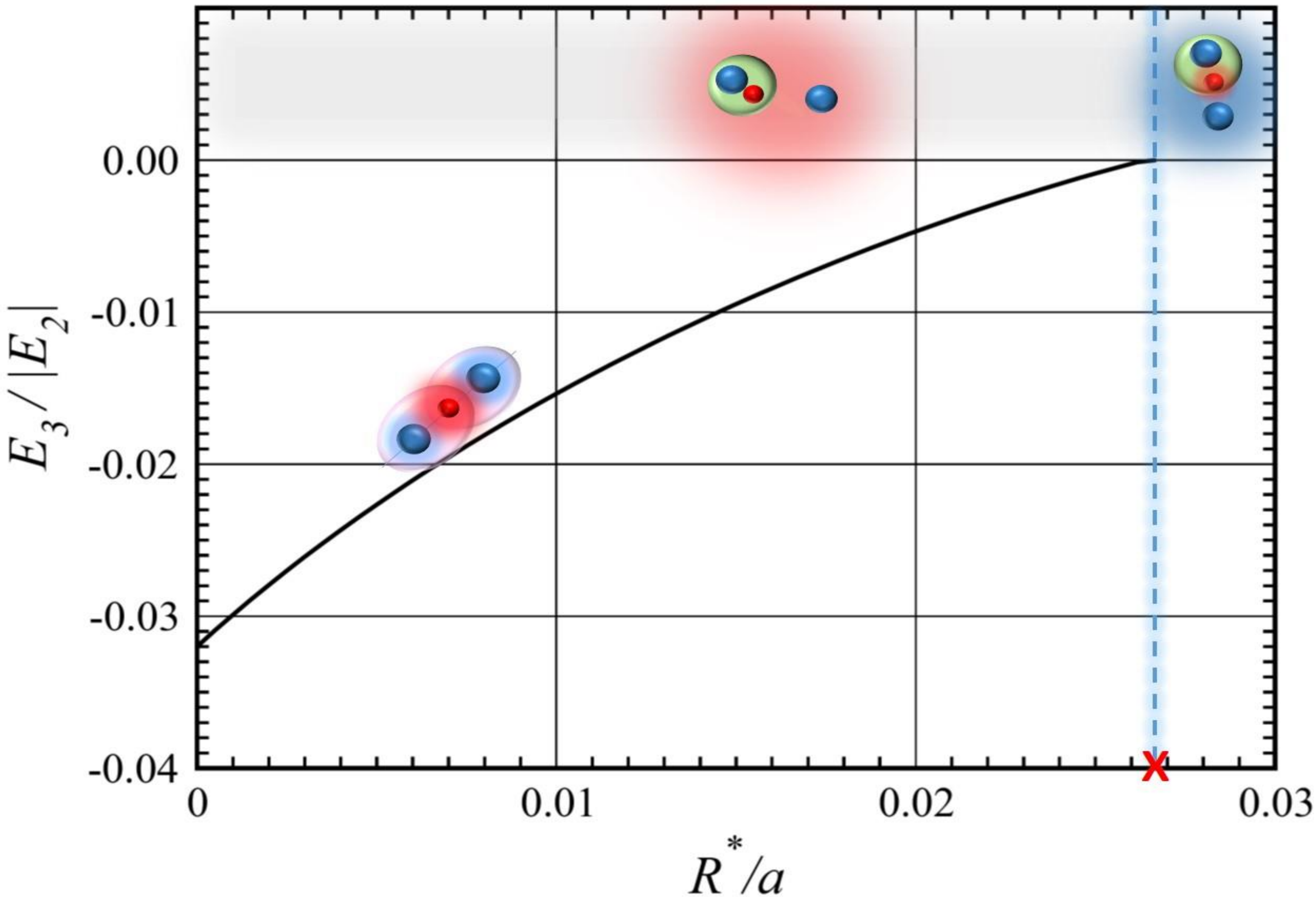


<u>For *R**=0:</u>

- ✓ M_{Cr}/m_{Li} about 7% higher than the critical value for a real (fermionic) trimer to exist
- ✓ M_{Cr}/m_{Li} <1% away from critical value for the emergence of a (bosonic) tetramer

Cr-Cr-Li Fermi system

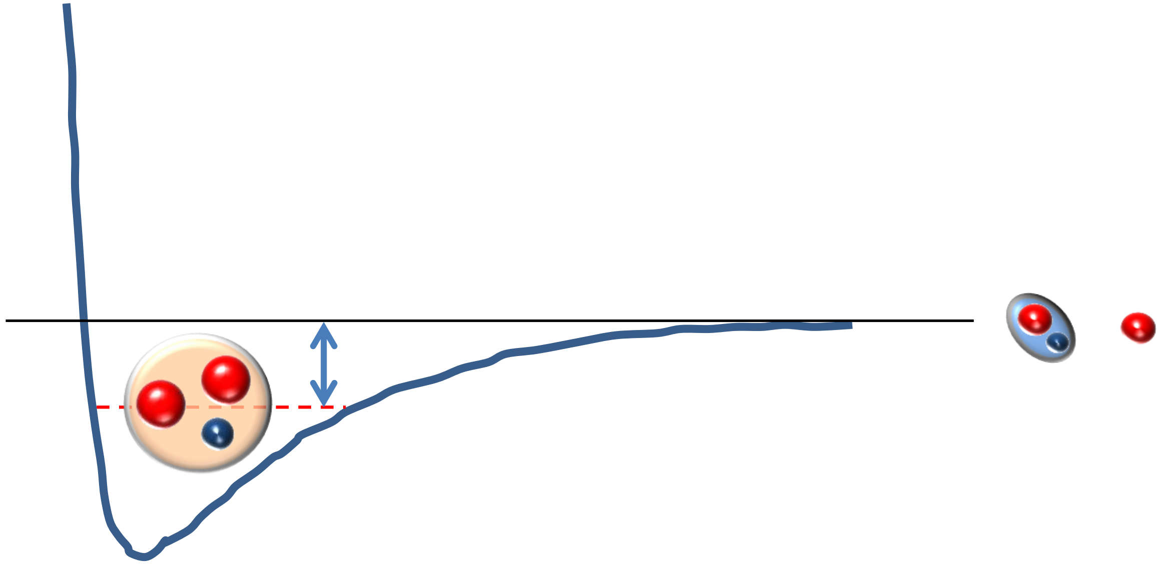
R*/a: same role of a decreased M/m !



D. Petrov, Private Communication (2014).

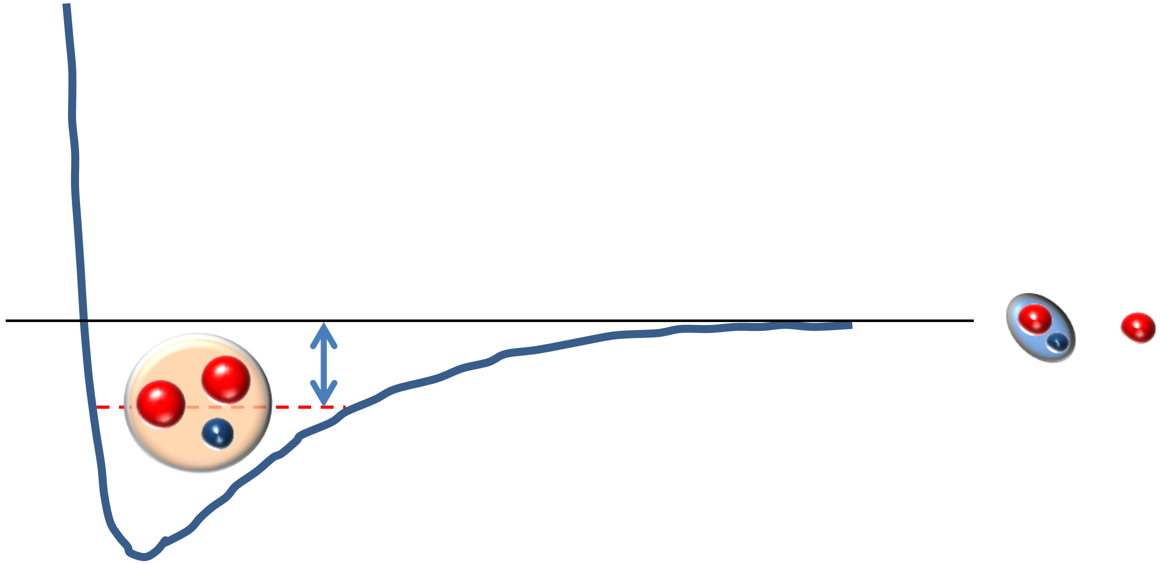
Cr-Cr-Li Fermi system

R/a* sets trimer energy detuning from A-D threshold



Cr-Cr-Li Fermi system

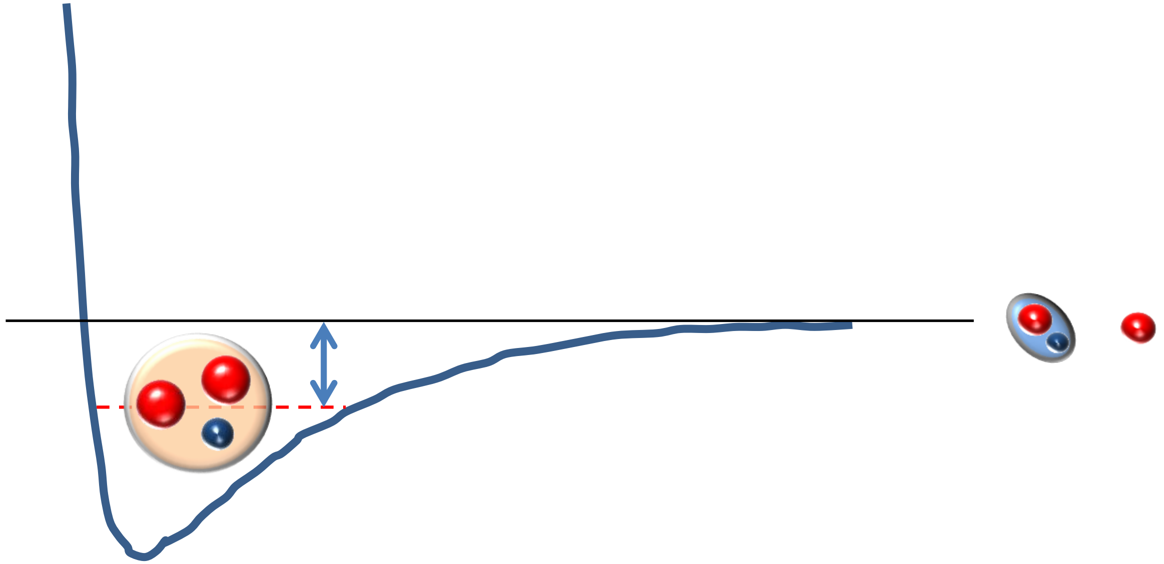
R^*/a sets trimer energy detuning from A-D threshold



Since $a=a(B)$, also $R^*/a=R^*/a(B)$ ➡ magnetic tuning of 3-body interactions on top of 2-body ones!

Cr-Cr-Li Fermi system

R/a* sets trimer energy detuning from A-D threshold

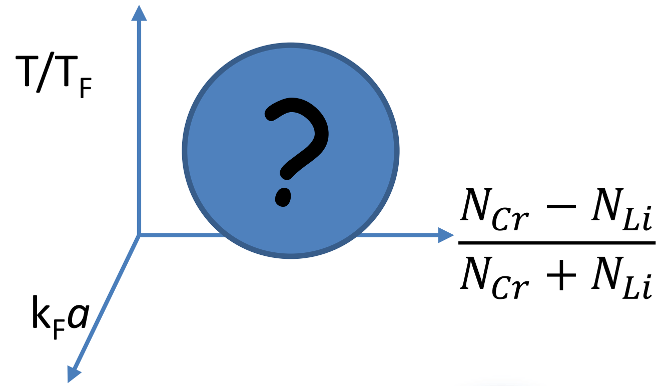


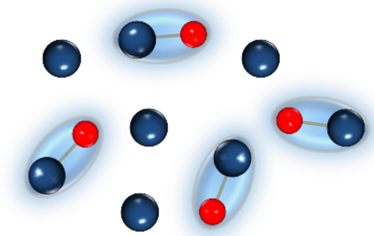
Since $a=a(B)$, also $R^*/a=R^*/a(B)$ ⇨ magnetic tuning of 3-body interactions on top of 2-body ones!

Potential barrier at small distances: **elastic** *p*-wave Cr-CrLi resonant interaction!

3-body interaction for exotic superfluids

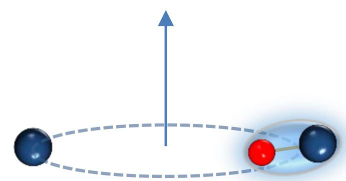
few-body interaction





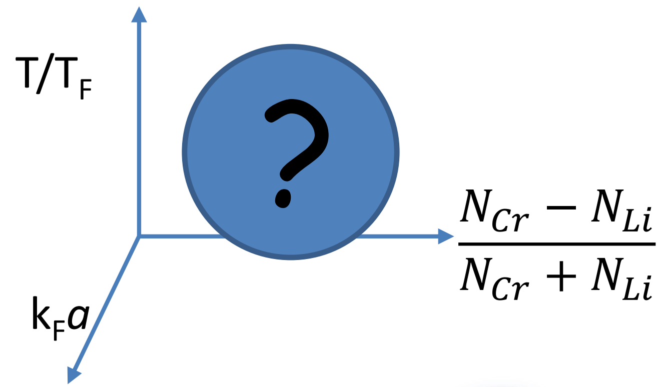
✓ Atom-pair attraction: **polarized SF!**

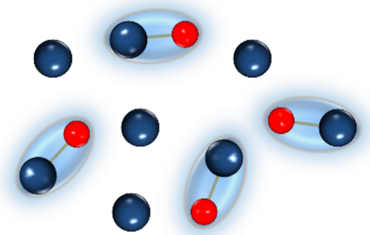
✓ *p*-wave character: **FFLO!?**



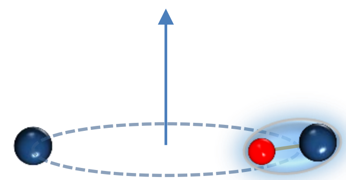
3-body interaction for exotic superfluids

few-body interaction

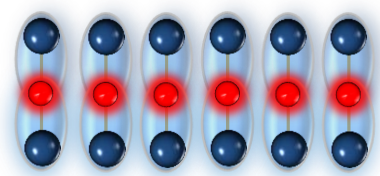




✓ Atom-pair attraction: **polarized SF!**



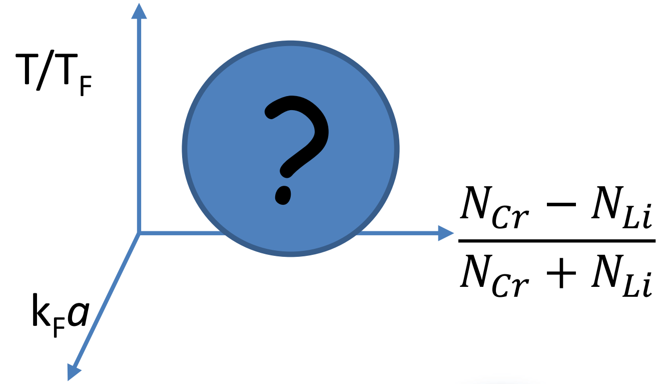
✓ *p*-wave character: **FFLO!?**



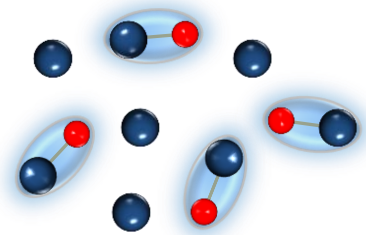
✓ Novel normal phase: **trimer Fermi gas!**

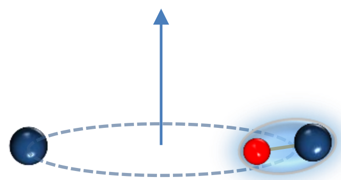
3-body interaction for exotic superfluids

few-body interaction



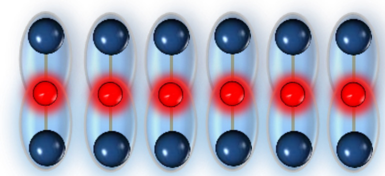
✓ Atom-pair attraction: **polarized SF!**



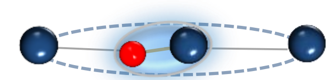


✓ *p*-wave character: **FFLO!?**

✓ Novel normal phase: **trimer Fermi gas!**



✓ New SF states: **tetramer BEC, induced *p*-wave pairing** …



The special case of ^{53}Cr-^{6}Li

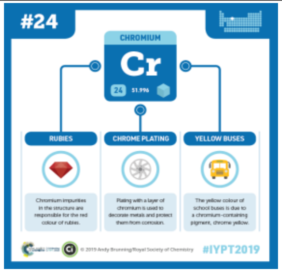
Not a bi-alkali mixture!

Alkali

S=1/2

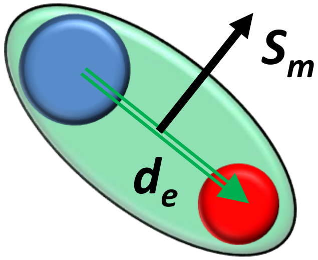
+

Transition metal



S=3

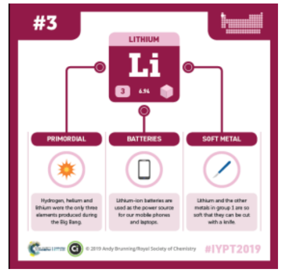
=



The special case of ^{53}Cr-^{6}Li

Not a bi-alkali mixture!

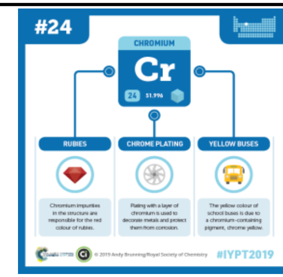
Alkali



S=1/2

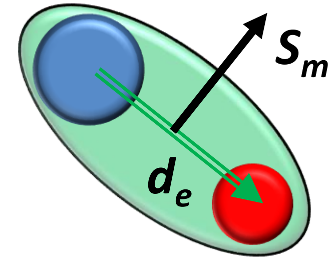
+

Transition metal



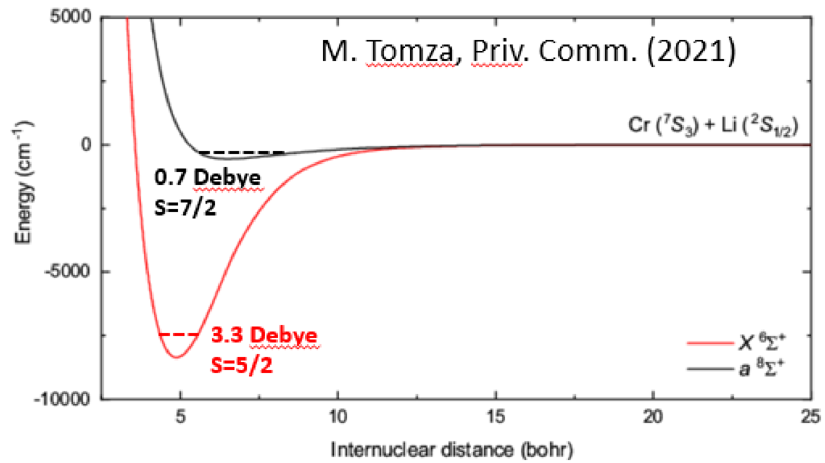
S=3

=



CrLi ground state dimers

Both electric and magnetic dipole moment

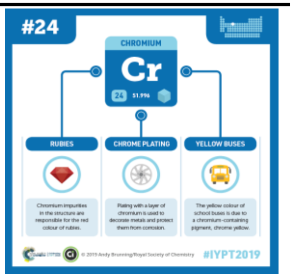


The special case of ^{53}Cr-^{6}Li

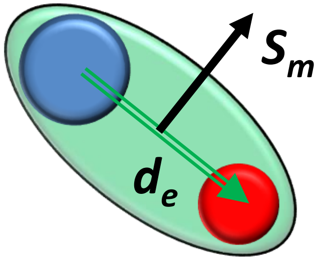
Not a bi-alkali mixture!

Alkali | **Transition metal**

+



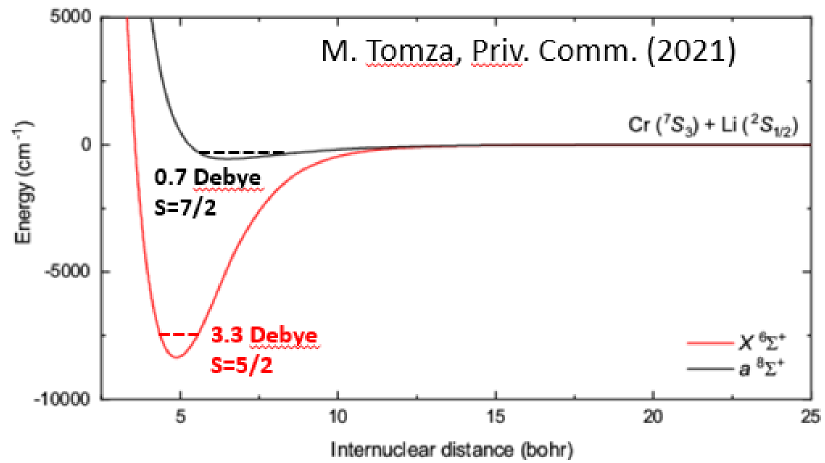
=



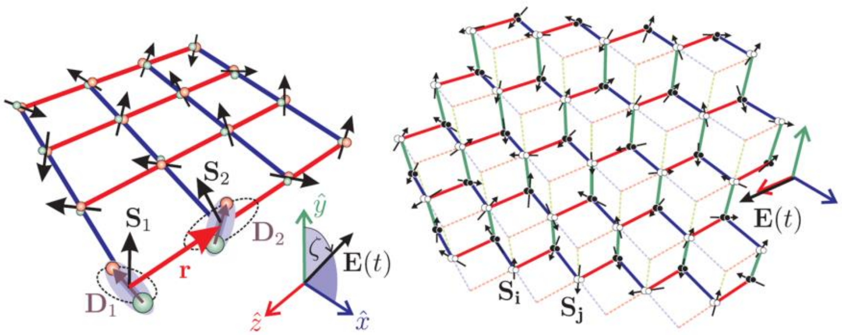
S=1/2 **S=3**

CrLi ground state dimers

Both electric and magnetic dipole moment



Nature Physics **2**,341 (2006)



Ultracold paramagnetic polar molecules

Quantum info/computation

quantum simulation

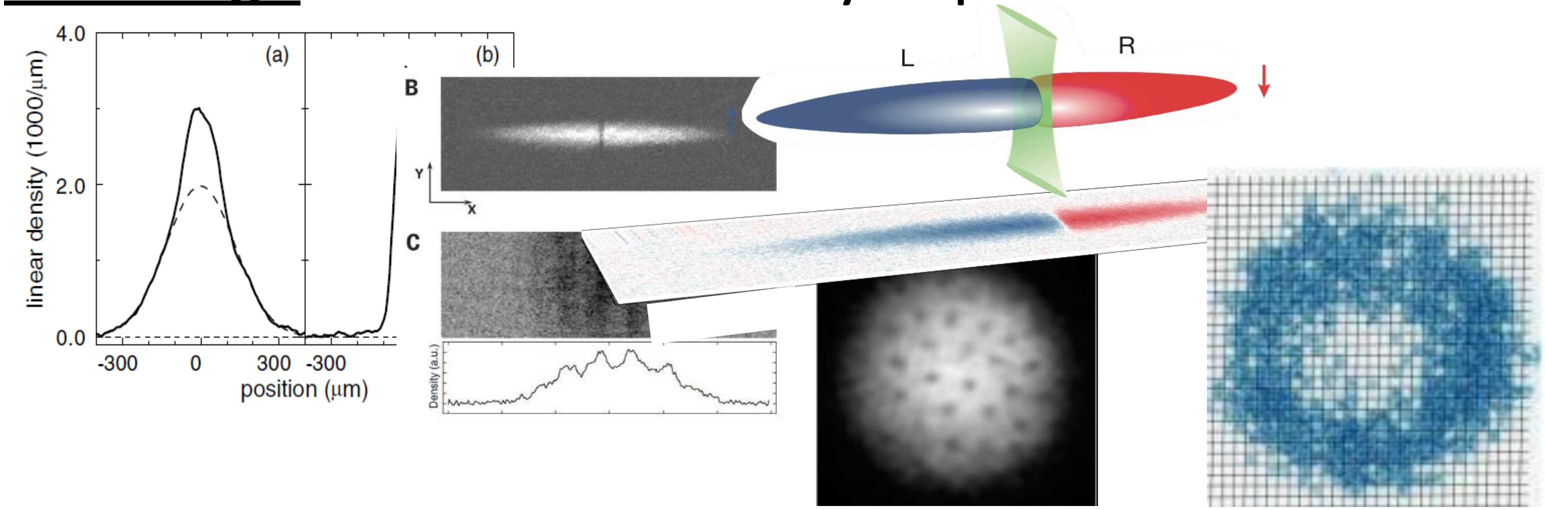
quantum chemistry

precision measurements

PRL 88, 067901 (2002); Chem. Rev. 112, 5012 (2012); Nat. Phys. 13, 13 (2017); PRX 10, 041005 (2020) ….

Cr-Li in practice: the PoLiChroM lab

<u>Challenge</u>: combine a widely explored alkali atom…

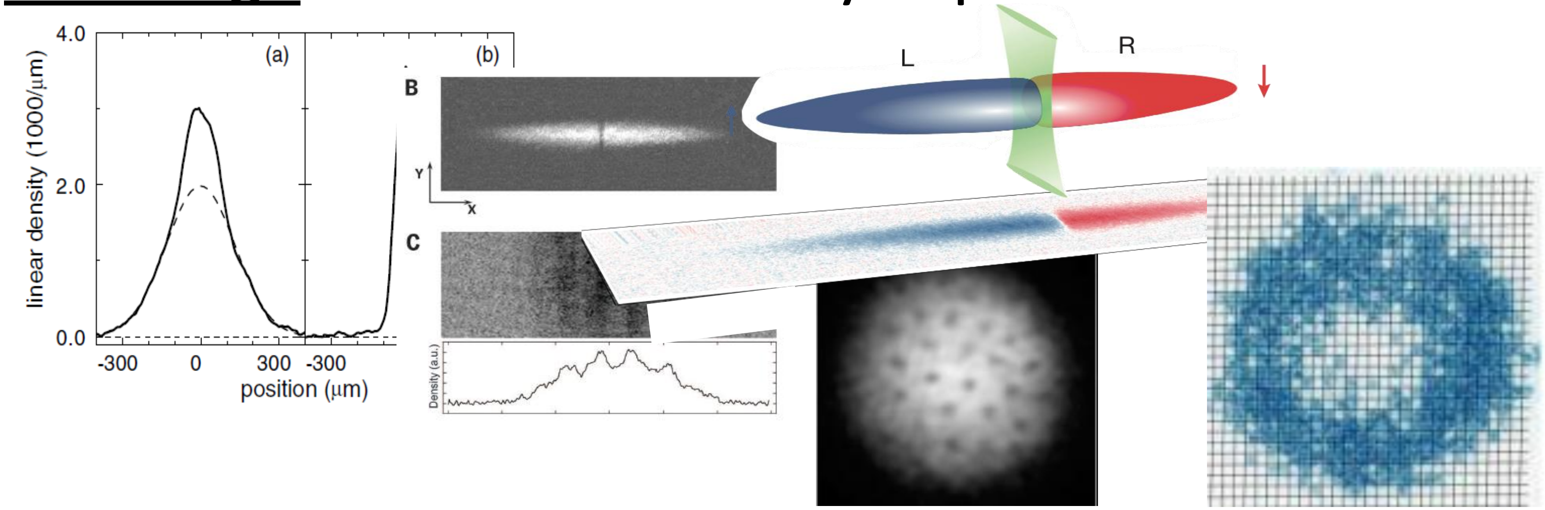


^{6}Li

MIT, Paris, Innsbruck, Zurich, Swinburne, Florence, Harvard, Hamburg, …

Cr-Li in practice: the PoLiChroM lab

<u>Challenge</u>: combine a widely explored alkali atom…



^{6}Li

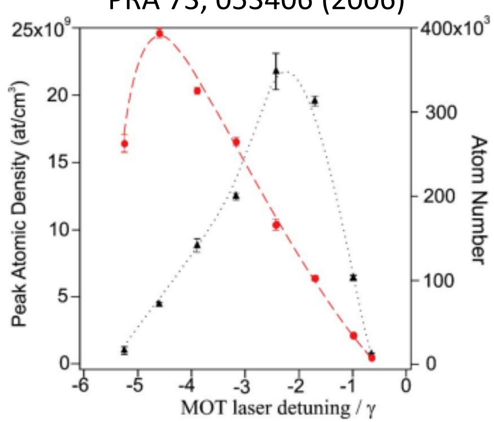
MIT, Paris, Innsbruck, Zurich, Swinburne, Florence, Harvard, Hamburg, …

… with an almost unexplored transition metal element

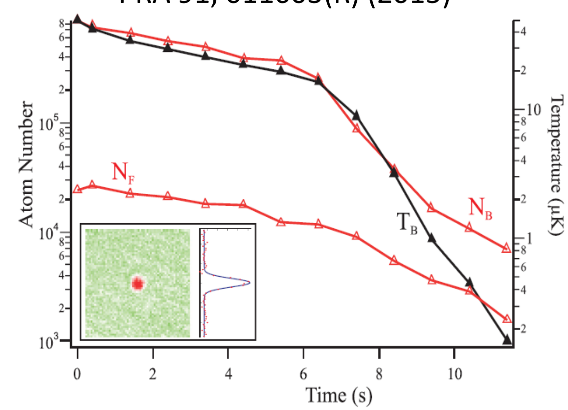
^{53}Cr

Paris Nord

PRA 73, 053406 (2006)

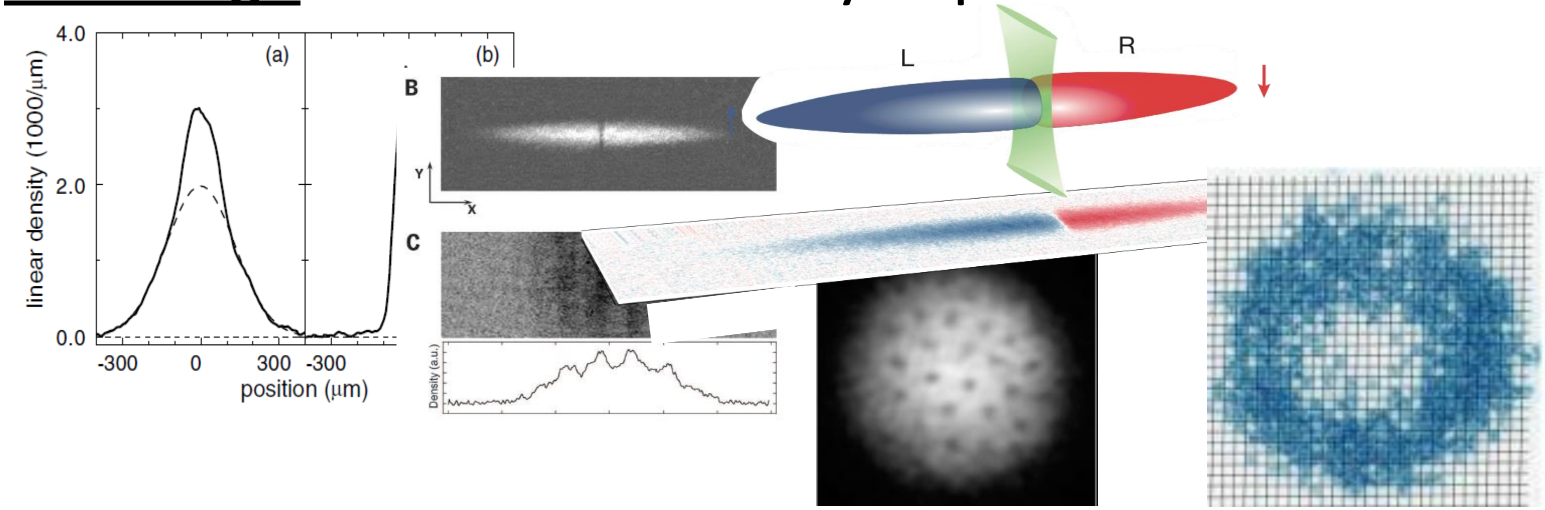


PRA 91, 011603(R) (2015)



Cr-Li in practice: the PoLiChroM lab

Challenge: combine a widely explored alkali atom…



^{6}Li

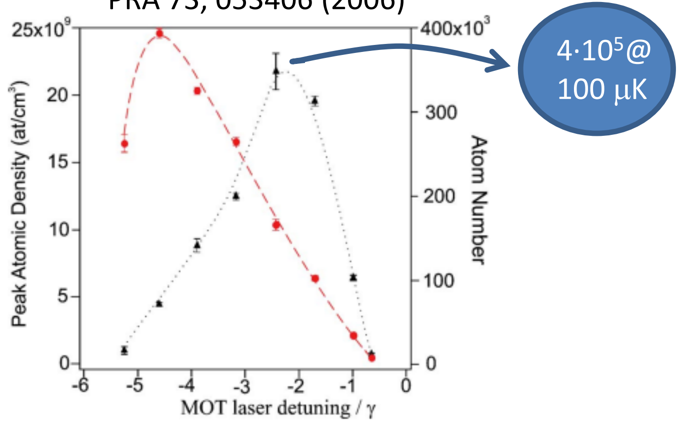
MIT, Paris, Innsbruck, Zurich, Swinburne, Florence, Harvard, Hamburg, …

… with an almost unexplored transition metal element

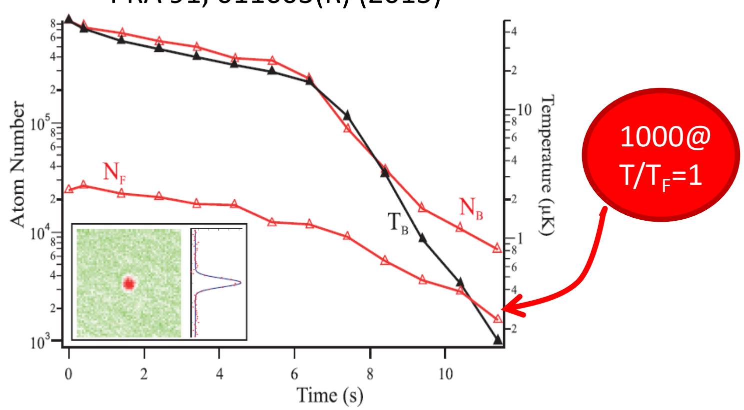
^{53}Cr

Paris Nord

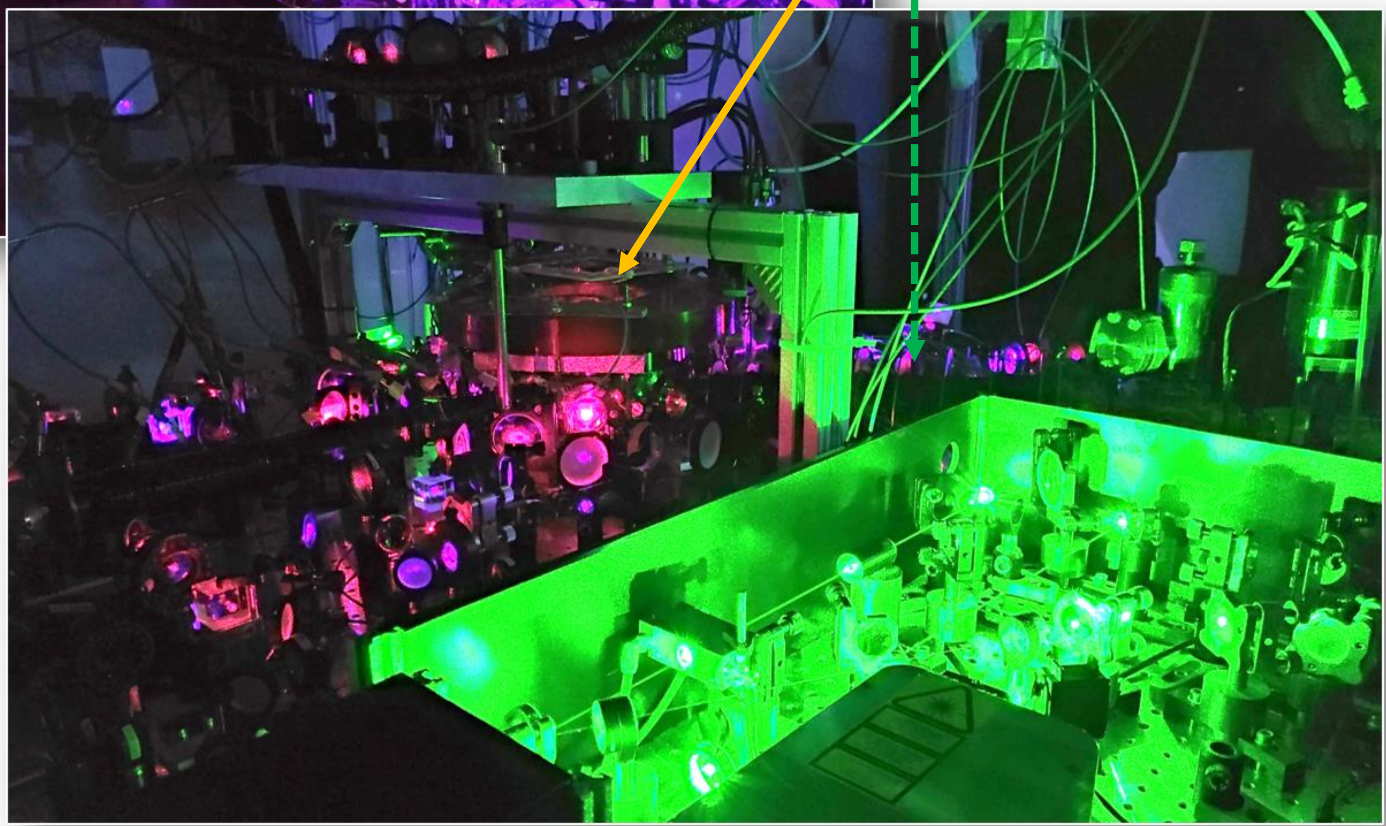
PRA 73, 053406 (2006)



PRA 91, 011603(R) (2015)



Cr-Li in practice: the PoLiChroM lab



Lithium lights

Chromium lights

Science chamber/coils setup

Bichromatic optical trap
(1070nm/300W + 532nm/10W)

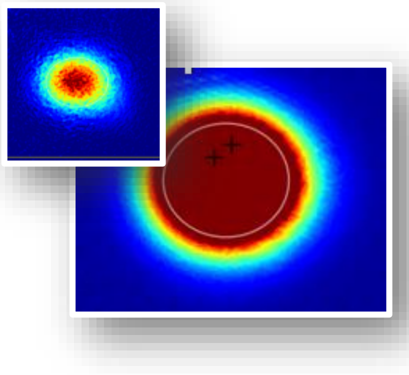
<u>For details:</u>

E. Neri et al, PRA 101, 063602 (2020); A. Ciamei et al, arXiv:2207.07579

Cr-Li in practice: the PoLiChroM lab

Surprise #1

Large Cr & Li samples in a 2-species MOT



After 5 + 2 seconds loading: ~10^9 Li + 10^8 Cr @300 μK

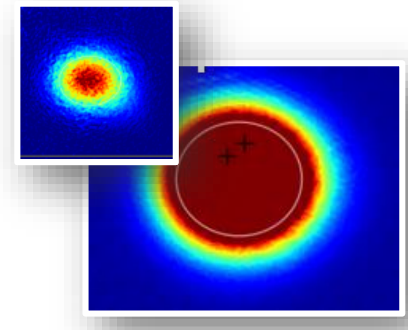
(all six repumpers employed, MOT beams with very low I/I_{sat})

X400 gain compared to previous studies of the Paris group

No bad effect of Li on Cr MOT, and vice-versa

Cr-Li in practice: the PoLiChroM lab

Surprise #1



Large Cr & Li samples in a 2-species MOT

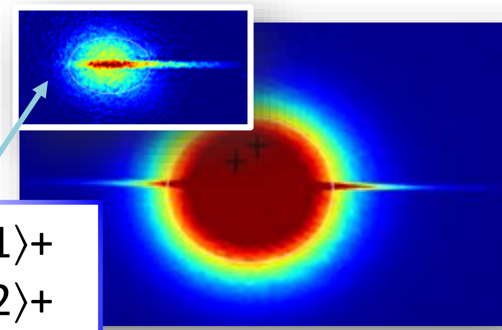
After 5 + 2 seconds loading: ~10^9 Li + 10^8 Cr @300 μK

(all six repumpers employed, MOT beams with very low I/I_{sat})

X400 gain compared to previous studies of the Paris group

No bad effect of Li on Cr MOT, and vice-versa

Surprise #2



Efficient loading in bichromatic trap possible

ODT loading: ~10^7 Li + 3×10^6 Cr @250 μK

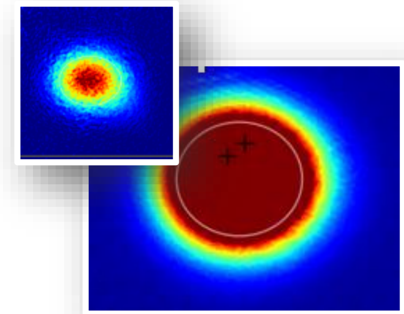
IR light bad for loading (light shift).

Exploit 532nm light as dark-spot!

X100 gain compared to previous studies

50% in Cr|1⟩+
35% in Cr|2⟩+
15% in Cr|3⟩

Cr-Li in practice: the PoLiChroM lab



Surprise #1

Large Cr & Li samples in a 2-species MOT

After 5 + 2 seconds loading: ~10^9 Li + 10^8 Cr @300 μK

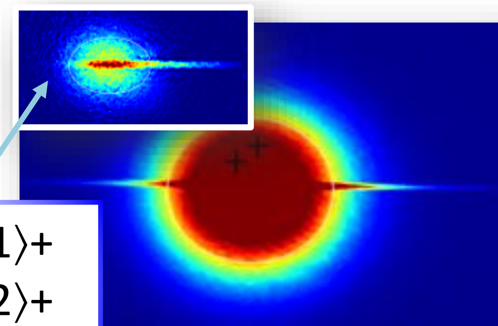
(all six repumpers employed, MOT beams with very low I/I_{sat})

X400 gain compared to previous studies of the Paris group

No bad effect of Li on Cr MOT, and vice-versa

Surprise #2

Efficient loading in bichromatic trap possible



ODT loading: ~10^7 Li + $3x10^6$ Cr @250 μK

IR light bad for loading (light shift).

Exploit 532nm light as dark-spot!

X100 gain compared to previous studies

50% in Cr|1⟩+
35% in Cr|2⟩+
15% in Cr|3⟩

→ Cr-Li works even better than K-Li !!!

Cr-Li in practice: the PoLiChroM lab

Same strategy of Li-K Innsbruck experiment*: All-optical route

Evaporative cooling of a Li$|1\rangle$-Li$|2\rangle$ mixture near a broad Feshbach resonance @830G
Sympathetic cooling of Chromium in its ground state via interspecies collisions

*Phys. Rev. A **81**, 043637 (2010)

Cr-Li in practice: the PoLiChroM lab

Same strategy of Li-K Innsbruck experiment*: All-optical route

Evaporative cooling of a Li|1⟩-Li|2⟩ mixture near a broad Feshbach resonance @830G
Sympathetic cooling of Chromium in its ground state via interspecies collisions ???

*Phys. Rev. A **81**, 043637 (2010)

Cr-Li in practice: the PoLiChroM lab

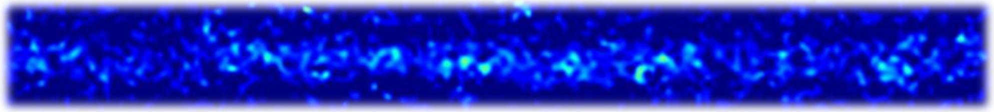
Same strategy of Li-K Innsbruck experiment*: All-optical route

Evaporative cooling of a Li|1⟩-Li|2⟩ mixture near a broad Feshbach resonance @830G
Sympathetic cooling of Chromium in its ground state via interspecies collisions ???

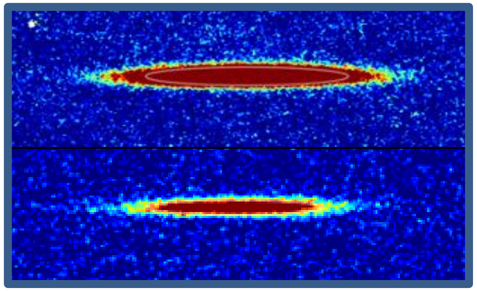
Surprise #3

Symp. cooling works! Quantum degeneracy reached!

Within 5 seconds evaporation: ~$3.5\ 10^5$ Li + 10^5 Cr @ <200 nK!
($T/T_{F,Li}=0.2$ & $T/T_{F,Cr}=0.5$)



Without Li



With Li

*Phys. Rev. A **81**, 043637 (2010)

Cr-Li in practice: the PoLiChroM lab

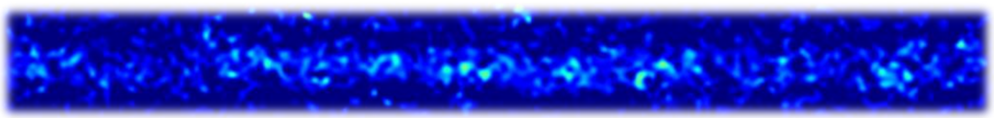
Same strategy of Li-K Innsbruck experiment*: All-optical route

Evaporative cooling of a Li|1⟩-Li|2⟩ mixture near a broad Feshbach resonance @830G
Sympathetic cooling of Chromium in its ground state via interspecies collisions ???

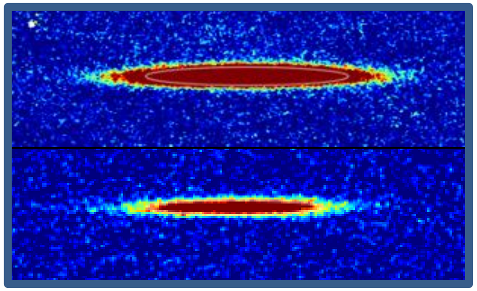
Surprise #3

Symp. cooling works! Quantum degeneracy reached!

Within 5 seconds evaporation: ~3.5 10^5 Li + 10^5 Cr @ <200 nK!
($T/T_{F,Li}$ =0.2 & $T/T_{F,Cr}$ =0.5)



Without Li



With Li

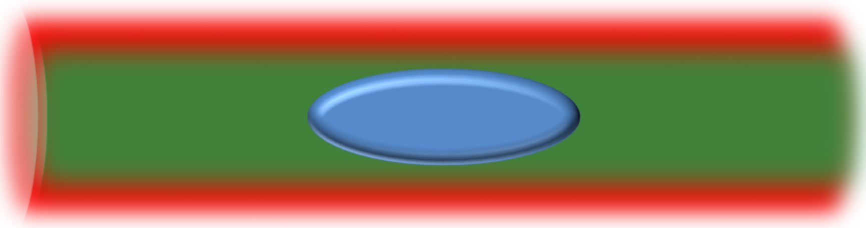
Favorable Cr-Li scattering properties!!!

Thermalization measurements yield estimate $|a_{CrLi}|$=55(15) a_0

*Phys. Rev. A **81**, 043637 (2010)

Cr-Li in practice: the PoLiChroM lab

Latest tool: a bichromatic crossed trap



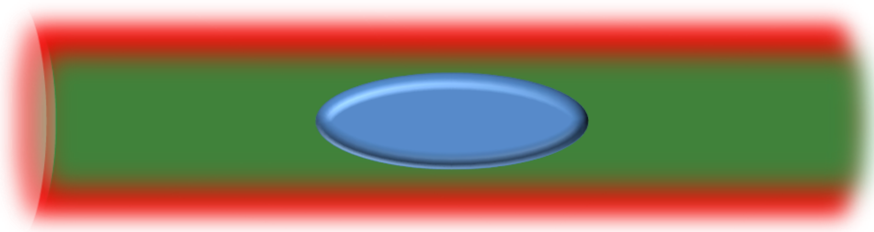
~3.5 10^5 Li @ $T/T_{F,Li}$ =0.2

~ 10^5 Cr @ $T/T_{F,Cr}$ =0.5

Ciamei et al, arXiv:2207.07579

Cr-Li in practice: the PoLiChroM lab

Latest tool: a bichromatic crossed trap



~3.5 10^5 Li @ $T/T_{F,Li}$ =0.2

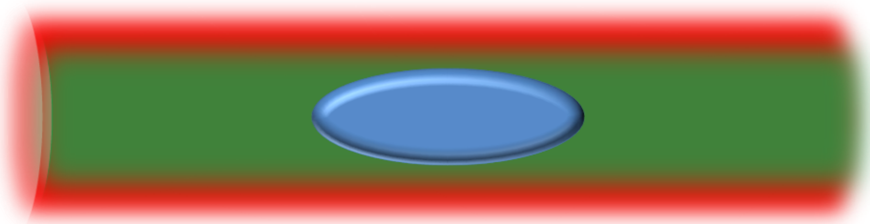
~ 10^5 Cr @ $T/T_{F,Cr}$ =0.5

- ✓ No change in trap depth
- ✓ Individual compression/decompression
- ✓ Density matching of the two clouds

Ciamei et al, arXiv:2207.07579

Cr-Li in practice: the PoLiChroM lab

Latest tool: a bichromatic crossed trap



~3.5 10^5 Li @ $T/T_{F,Li}$ =0.2
~ 10^5 Cr @ $T/T_{F,Cr}$ =0.5

- ✓ No change in trap depth
- ✓ Individual compression/decompression
- ✓ Density matching of the two clouds
- ✓ Substantially enhance Cr density (and thus $T_{F,Cr}$)

~1.5 10^5 Li @ $T/T_{F,Li}$ =0.2
~ 10^5 Cr @ $T/T_{F,Cr}$ =0.25 !

Ciamei et al, arXiv:2207.07579

Cr-Li in practice: the PoLiChroM lab

Are there Feshbach resonances in lithium-chromium ?

➡ <u>Loss spectroscopy!</u>   Ciamei et al, arXiv:2203.12965

Cr-Li in practice: the PoLiChroM lab

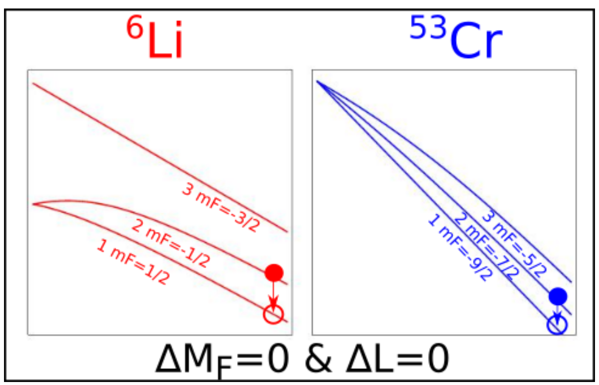
Are there Feshbach resonances in lithium-chromium ?

➡ Loss spectroscopy! Ciamei et al, arXiv:2203.12965

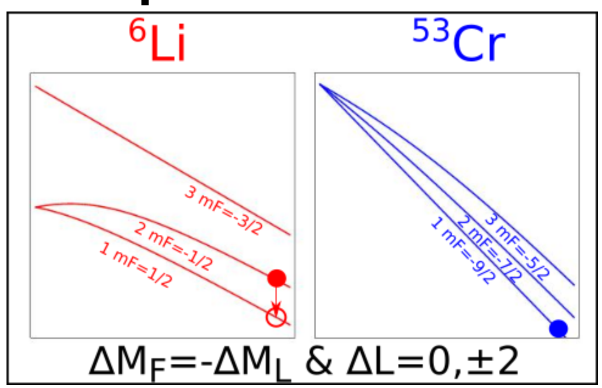
Enhanced loss mechanisms near a FR

Two-body

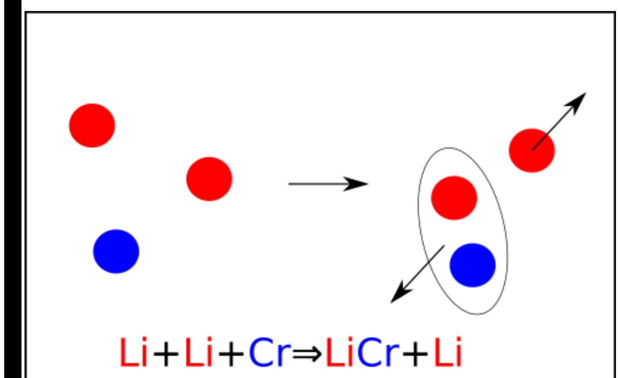
Spin-exchange



Dipolar relaxation



Three-body



Spin state:
Li1,2
Cr1,2,3

Peak densities:
Li: 2×10^{12} cm^{-3}
Cr: 3×10^{11} cm^{-3}

Temperature:
3...10uK

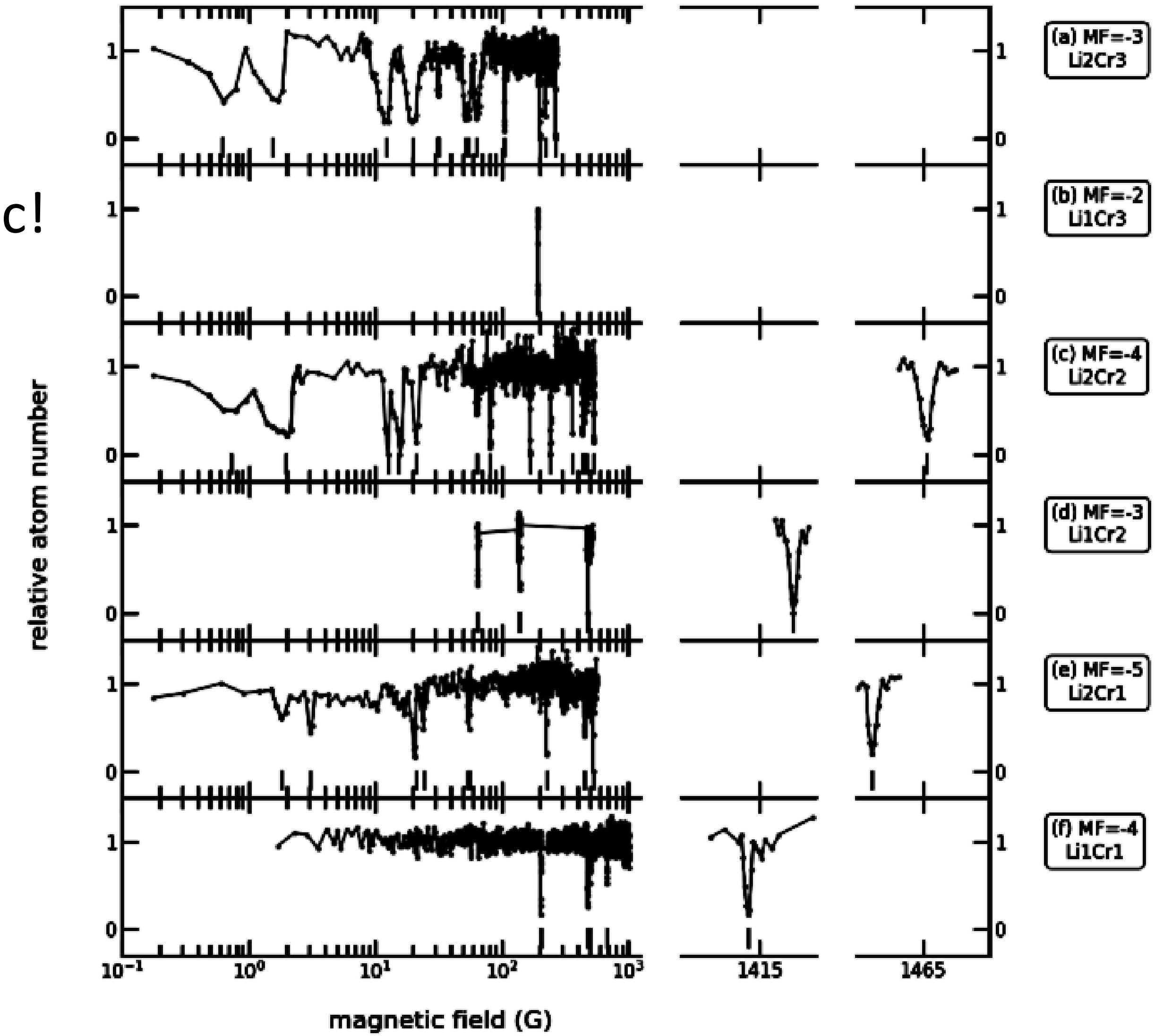
Magnetic Field:
0...1500G

Hold time:
1...5s

Cr-Li in practice: the PoLiChroM lab

Loss spectroscopy results

- ✓ >50 resonances found
- ✓ Spectrum is not chaotic!



Ciamei et al, arXiv:2203.12965

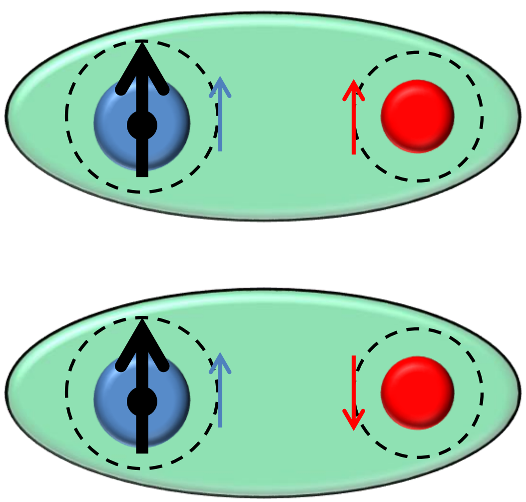
Cr-Li in practice: the PoLiChroM lab

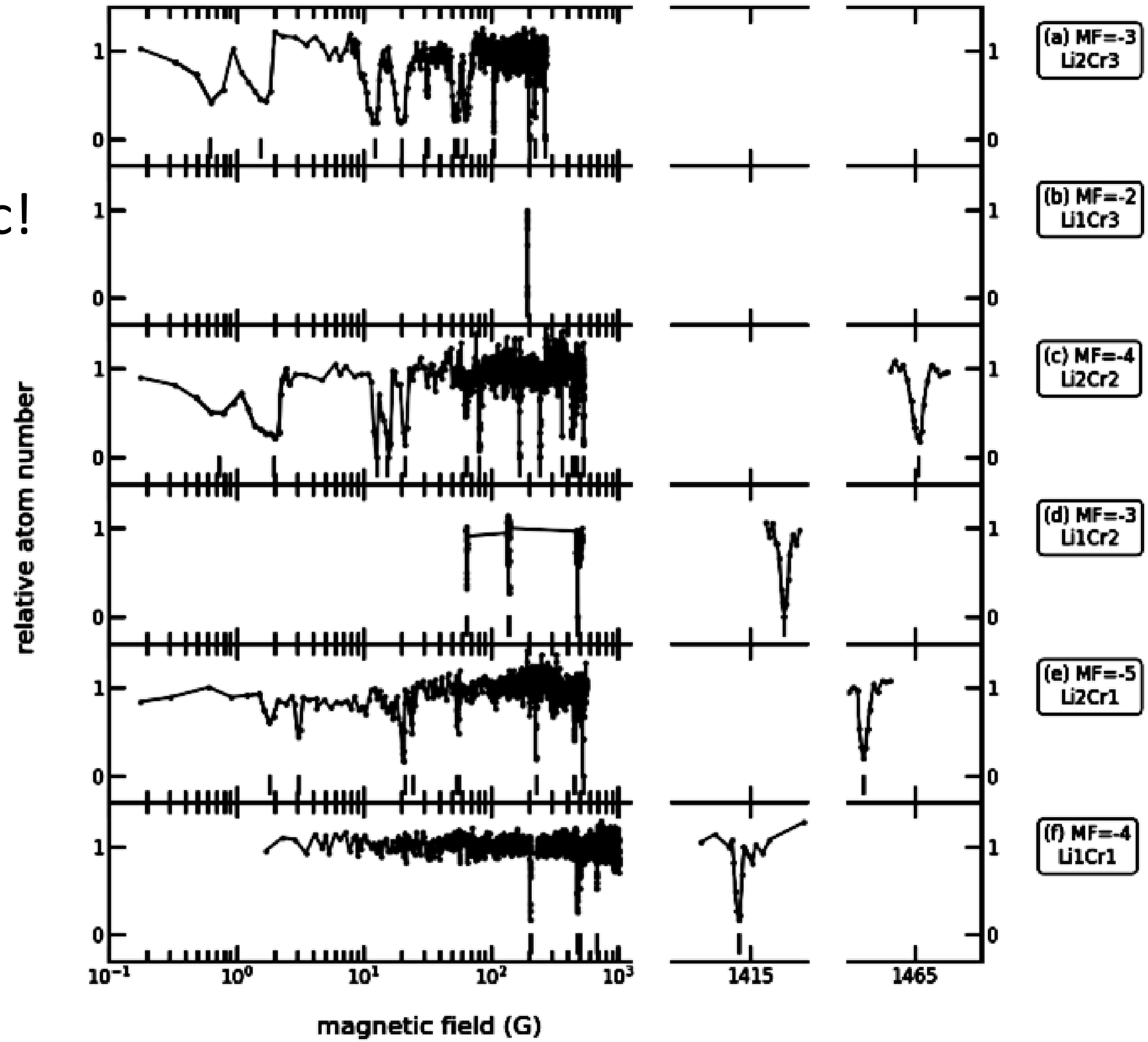
Loss spectroscopy results

- ✓ >50 resonances found
- ✓ Spectrum is not chaotic!
- ✓ Despite Cr complex structure: 2 channels only, as for alkalis

S=7/2

S=5/2

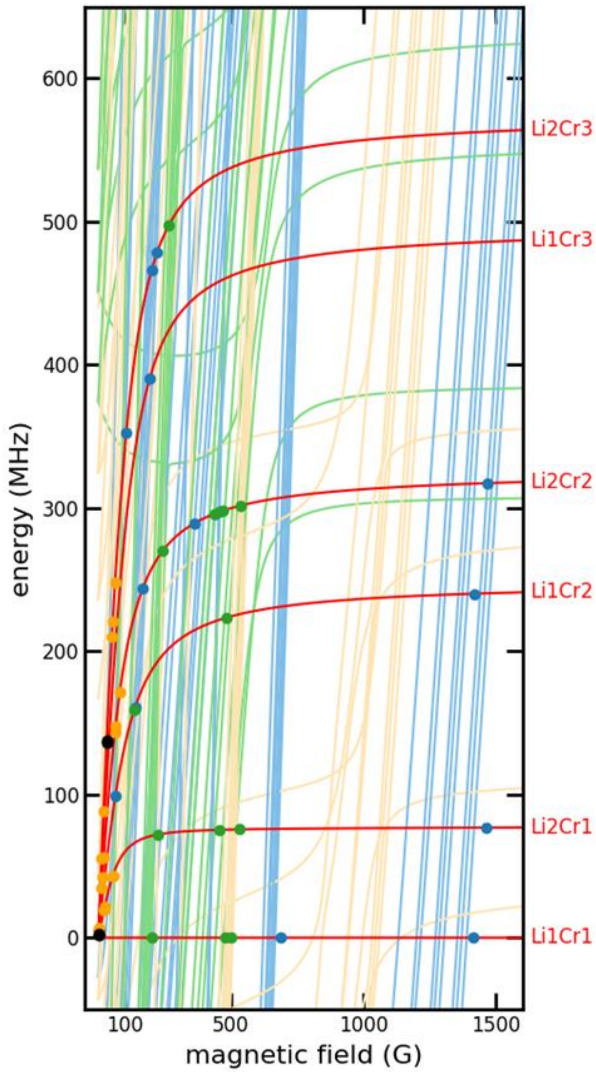


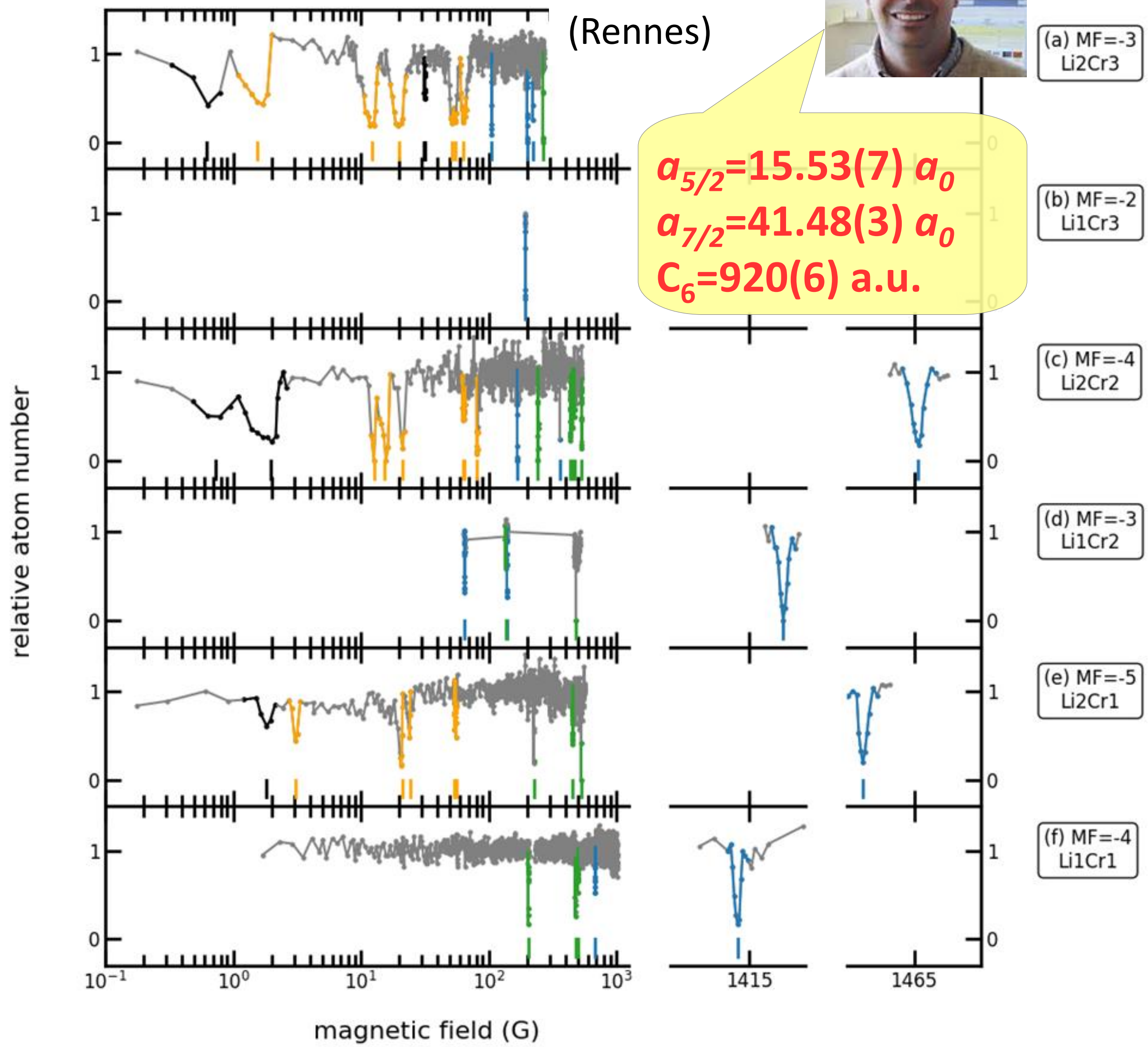


Ciamei et al, arXiv:2203.12965

Cr-Li in practice: the PoLiChroM lab

Loss spectroscopy results: theory





Theory by
Andrea Simoni
(Rennes)

$a_{5/2}$=15.53(7) a_0
$a_{7/2}$=41.48(3) a_0
C_6=920(6) a.u.

Ciamei et al, arXiv:2203.12965

Cr-Li in practice: the PoLiChroM lab

Among other infos…

✓ Several Gauss wide p-wave resonances at low field (0…50 G)

✓ High-field (>1.4kG) resonances are *s*-wave. Two w/o 2-body losses

P-wave resonant Fermi mixtures possible with Cr-Li !
S-wave good for few-body physics discussed previously!
Perfect for molecule formation !

Cr-Li in practice: the PoLiChroM lab

Among other infos…

✓ Several Gauss wide p-wave resonances at low field (0…50 G)

✓ High-field (>1.4kG) resonances are *s*-wave. Two w/o 2-body losses

P-wave resonant Fermi mixtures possible with Cr-Li !
S-wave good for few-body physics discussed previously!
Perfect for molecule formation !

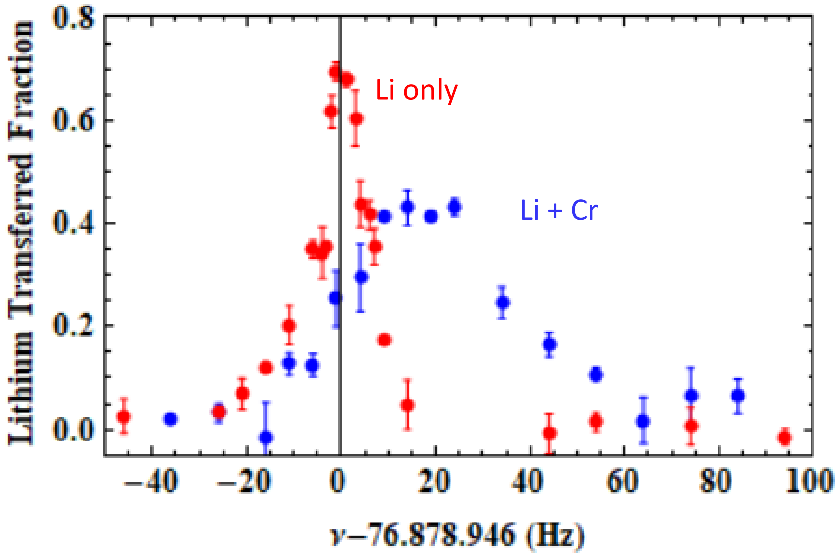
✓ But broadest *s*-wave resonances are narrow (ΔB ~0.5 G, R*~5000a_0): similar to K-Li mixtures, but at much higher fields

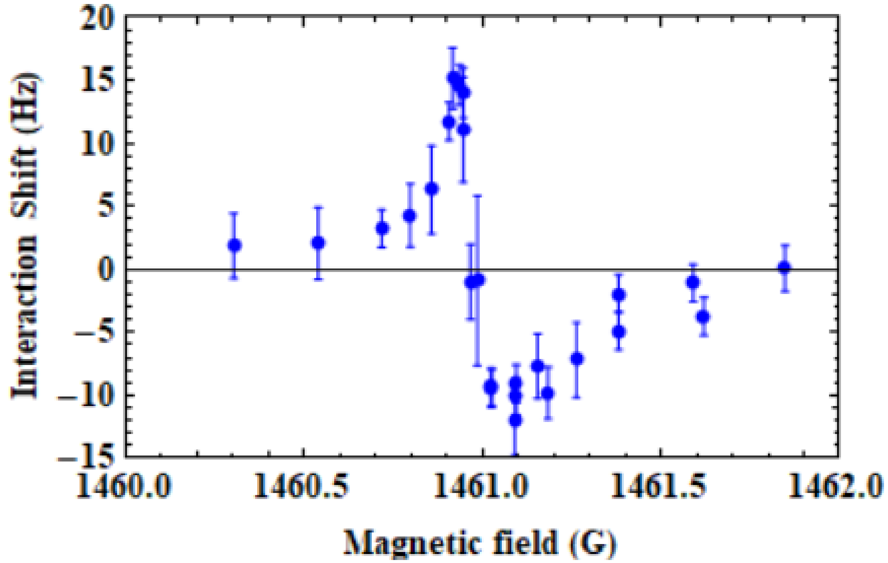
Can we exploit them really??

Cr-Li in practice: the PoLiChroM lab

Can we exploit them really ??

1. RF spectroscopy on thermal samples (7 μK)





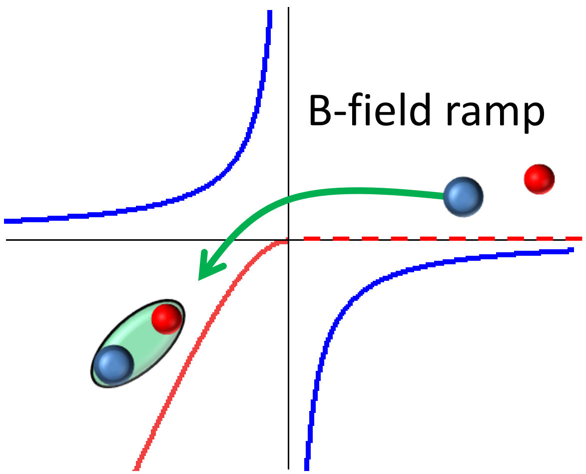
Magnetic-field stability: < 5 mG over 500 ms ✓

Extreme (<1 Hz) sensitivity to interaction shifts ✓

Cr-Li in practice: the PoLiChroM lab

Can we exploit them really ??

2. Association of CrLi dimers on degenerate mix. (ONGOING)

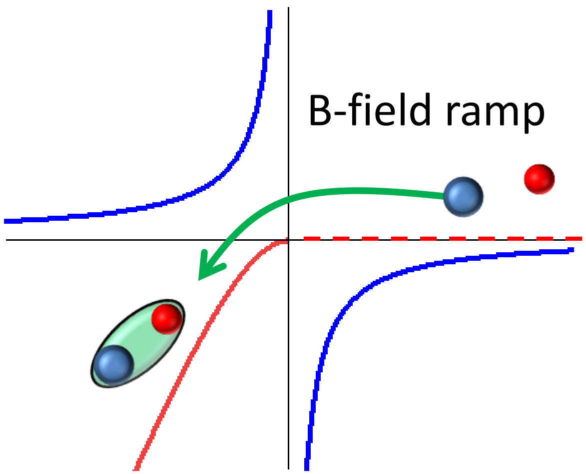


+ Stern-Gerlach ($B=B_0+b'z$)

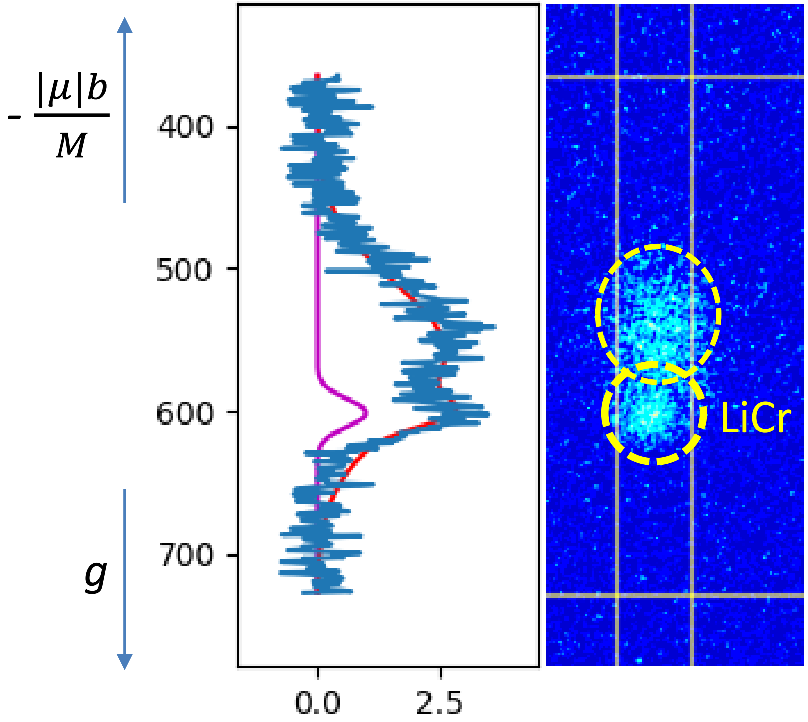
Cr-Li in practice: the PoLiChroM lab

Can we exploit them really ??

2. Association of CrLi dimers on degenerate mix. (ONGOING)



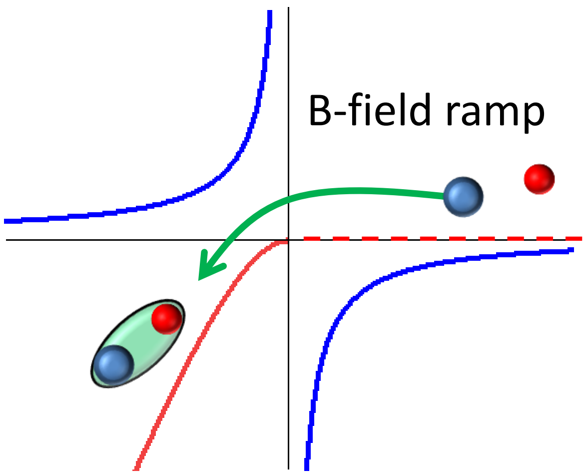
+ Stern-Gerlach ($B=B_0+b'z$)



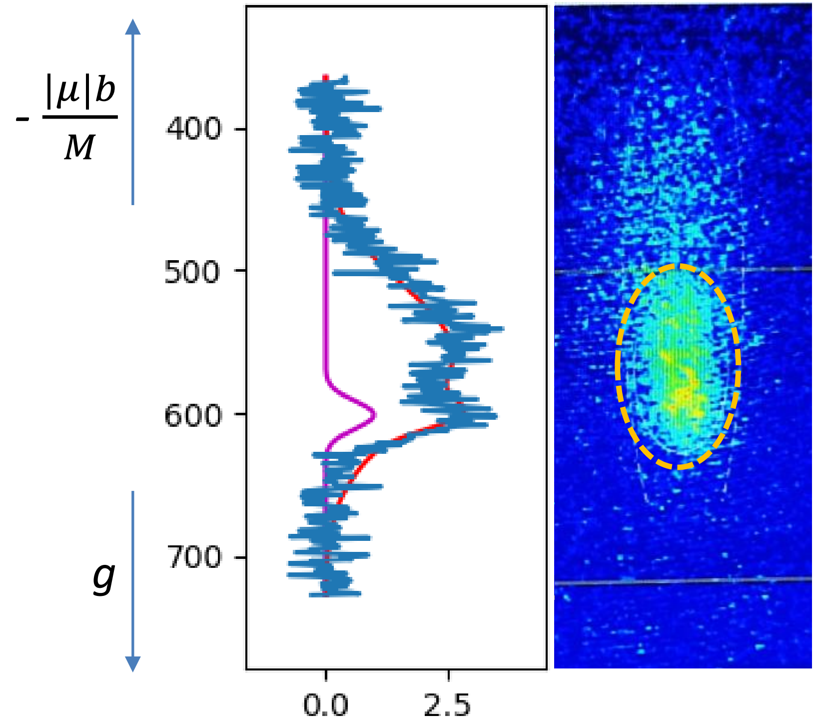
Cr-Li in practice: the PoLiChroM lab

Can we exploit them really ??

2. Association of CrLi dimers on degenerate mix. (ONGOING)



+ Stern-Gerlach ($B=B_0+b'z$)



>60k molecules formed, still room for improvement ! ✓

Already now: **PSD~1**, close to/below T_c for condensation ! ✓

Outlook

- ✓ Maximize molecule number in crossed BODT (ONGOING)

Outlook

- ✓ Maximize molecule number in crossed BODT (ONGOING)
- ✓ Collisional stability of dimers (with Li, Cr & LiCr) (ONGOING)
- ✓ Condensation of LiCr Feshbach molecules (ONGOING)

Outlook

- ✓ Maximize molecule number in crossed BODT (ONGOING)
- ✓ Collisional stability of dimers (with Li, Cr & LiCr) (ONGOING)
- ✓ Condensation of LiCr Feshbach molecules (ONGOING)
- ✓ Cr-dimer interactions & few-body physics (3D, but also 2D)
- ✓ Light vs heavy impurity problems
- ✓ Optical spectroscopy on Feshbach dimers

NEAR FUTURE

Outlook

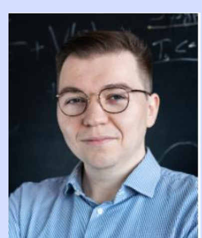
- ✓ Maximize molecule number in crossed BODT (ONGOING)
- ✓ Collisional stability of dimers (with Li, Cr & LiCr) (ONGOING)
- ✓ Condensation of LiCr Feshbach molecules (ONGOING)
- ✓ Cr-dimer interactions & few-body physics (3D, but also 2D)
- ✓ Light vs heavy impurity problems
- ✓ Optical spectroscopy on Feshbach dimers
- ✓ Similar studies near p-wave resonances

NEAR FUTURE

Thanks !

Andrea
Simoni

Dmitry
Petrov



Michal
Tomza

€€€

erc

FARE
RICERCA IN ITALIA
FRAMEWORK PER L'ATTRAZIONE E IL RAFFORZAMENTO DELLE ECCELLENZE PER LA RICERCA IN ITALIA

MARIE CURIE ACTIONS