Strong atom-dimer attraction in a Fermi-Fermi mixture

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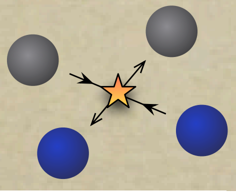
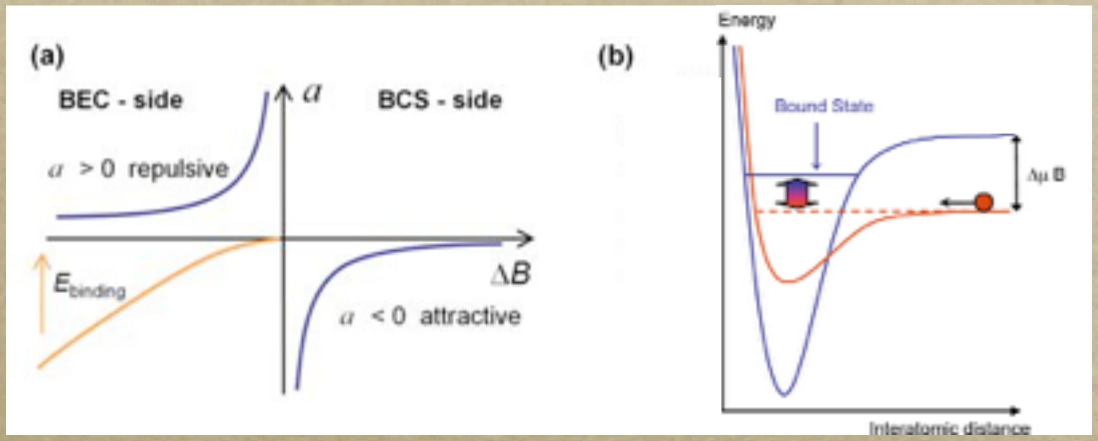
AARHUS UNIVERSITY

Tunability of a cold atomic gas

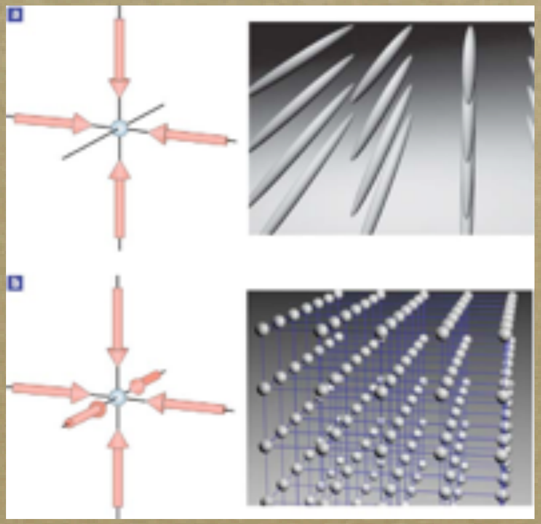
- Two-body interaction



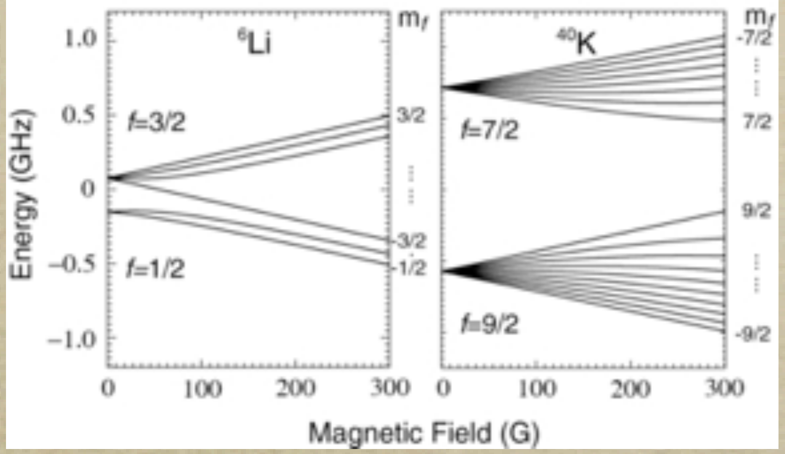


$$a(B) = a_{\rm bg}[1 - \Delta B/(B - B_0)]$$

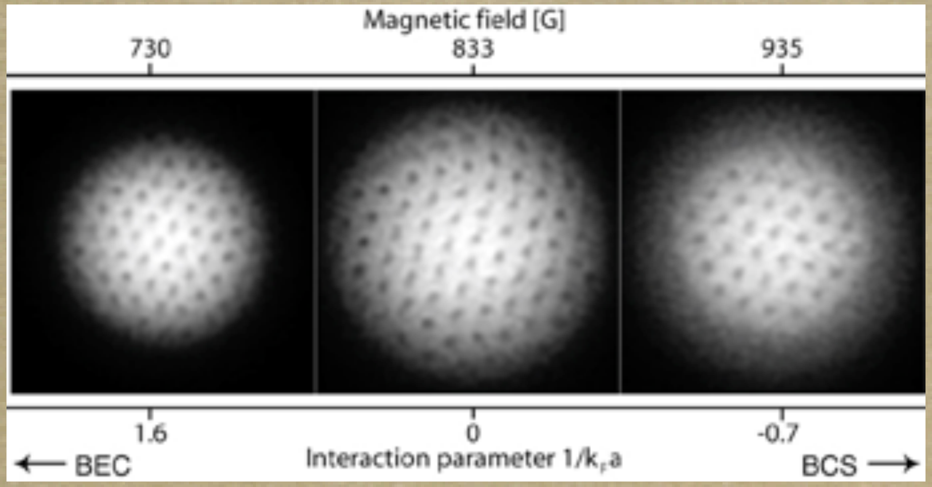
- Dimensionality



- Population

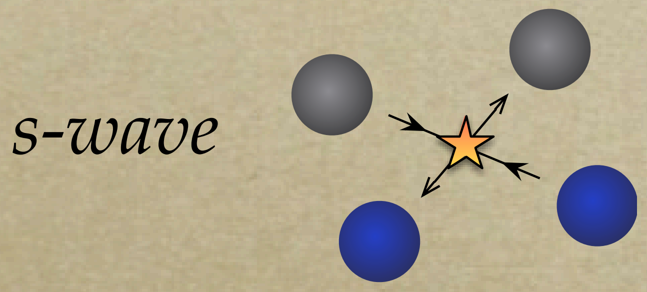


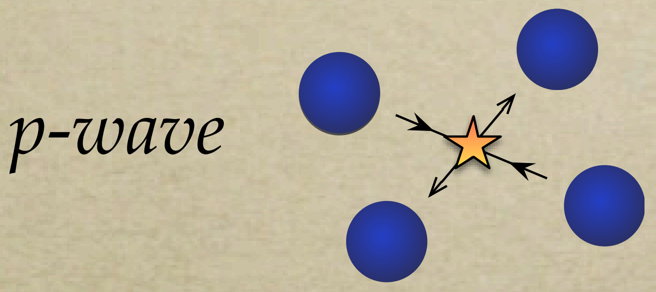
Goal: Interesting phases with applications to the solid state



p-wave pairing in a Fermi gas

- Whereas *s*-wave interactions usually dominate low temperature physics, *p*-wave pairing appears naturally for *identical* fermions





- *p*-wave superfluids are highly sought because of their unusual properties
    - The p_x+ip_y phase is predicted to be topological in 2D
        - Supports gapless Majorana mode on boundary to vacuum
        - Vortices obey non-Abelian statistics
        - Applications in topologically protected quantum computing

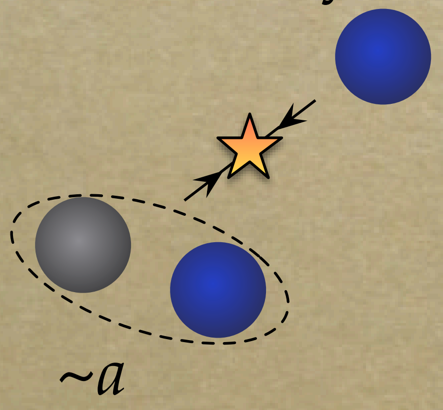
p-wave pairing in a Fermi gas

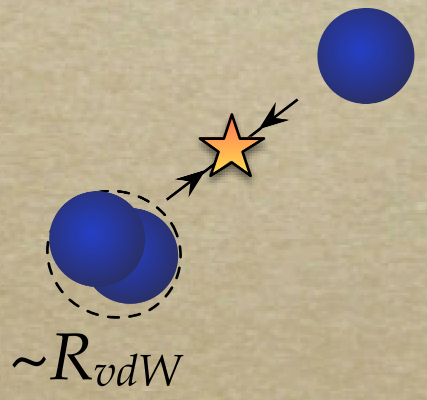
Gaebler et al, PRL 2007

- Early attempts to study the BCS-BEC crossover with identical fermions failed
    - Contact interaction is inherently unstable for *p*-waves, equilibration not possible
        - *This is due to wavefunction in short-distance region*

J.L., Cooper, Gurarie PRL 2007

    - Stark contrast with longevity of *s*-waves due to separation of scales and fermionic antisymmetry





- Instead consider long-range interactions

Outline

- Long range *p*-wave interactions in a heteronuclear Fermi gas
  - Resonant atomic exchange illustrated within the Born-Oppenheimer approximation
  - Theoretical predictions
  - Experimental observation of strong atom-dimer attraction
- Three-body problem in 2D: Hydrogen-like spectrum of trimers
- Polarized heteronuclear Fermi gases in 2D

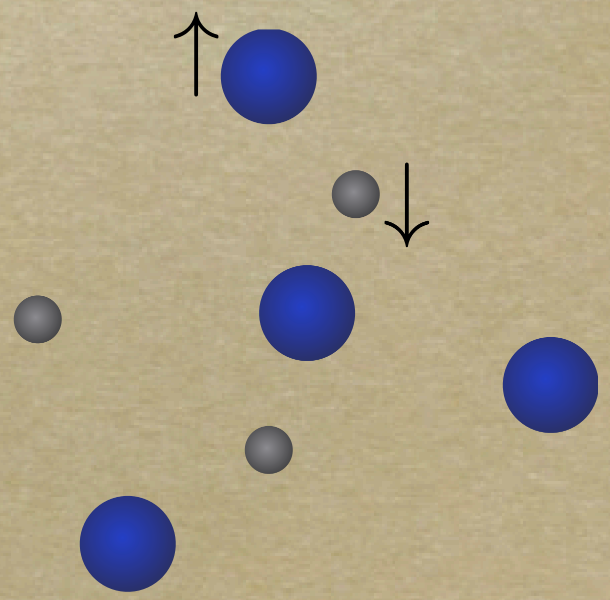
Long-range *p*-wave interactions through resonant atomic exchange

Heteronuclear Fermi mixtures

- Long-range interactions through resonant atomic exchange
  - Mixture of heavy and light fermionic atoms
    - *Short range interactions, characterized by scattering length a*
  - Long range interactions generated between heavy atoms

J.L., Tiecke, Walraven,
Petrov PRL 2009

  - Consider $a>0$ (i.e. two-body bound state exists)



Born-Oppenheimer approximation

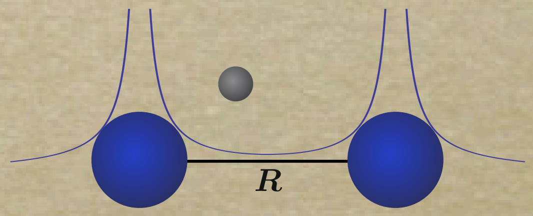
Ultracold identical fermionic atoms do not interact directly

- Effective interaction between (slow) heavy atoms is mediated by light atom

Understood intuitively in Born-Oppenheimer approximation:

- *Assume light atom adiabatically adjusts its wave function to positions of heavy atoms:*

$$\psi_{\boldsymbol{R}} \propto \frac{\bar{e}^{\kappa(R)|\boldsymbol{r}-\boldsymbol{R}/2|}}{|\boldsymbol{r}-\boldsymbol{R}/2|} \pm \frac{\bar{e}^{\kappa(R)|\boldsymbol{r}+\boldsymbol{R}/2|}}{|\boldsymbol{r}+\boldsymbol{R}/2|}$$



-/+ for even/odd partial waves

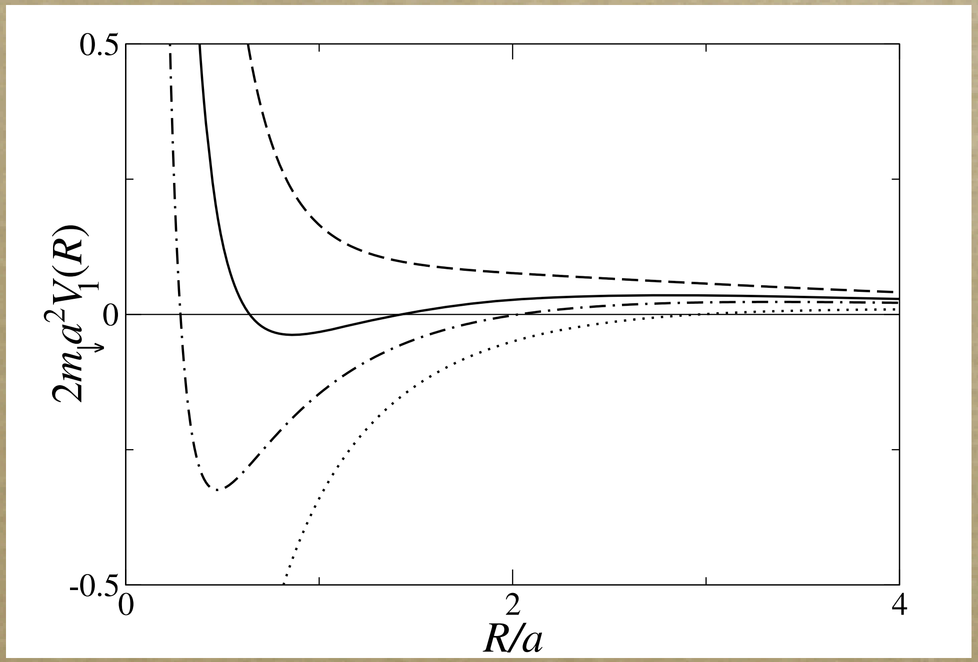
Analogy: H_2^+

J.L. & Petrov, EPJD 2011

Born-Oppenheimer approximation

- Energy of the light atom = effective potential for the motion of heavy atoms
  - *Repulsive (attractive) for even (odd) partial waves*
- For partial waves higher than *s*-wave, consider also the centrifugal barrier. Total potential in the *p*-wave scattering:

Bottom to top: $m_\uparrow/m_\downarrow = 13.6,\ 8.2,\ 6.64,\ 5$



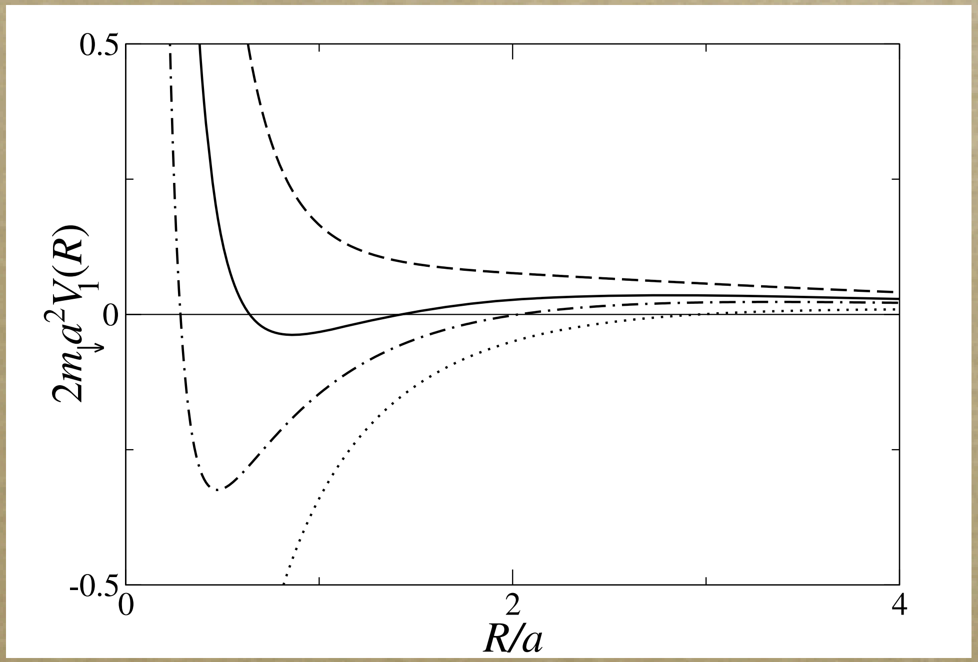
J.L. & Petrov, EPJD 2011

- *At mass ratio 5, the p-wave potential is purely repulsive*
- *Potassium 40-Lithium 6 mixture: potential develops an attractive well and enhanced p-wave scattering [J.L., Tiecke, Walraven, Petrov, PRL 2009]*
- *Above 8.2 the well supports a bound state (trimer) [Kartavtsev & Malykh, J. Phys. B 2007]*
- *Above 13.6 the short-distance potential is attractive leading to Efimov physics*

Born-Oppenheimer approximation

The induced interaction between the two heavy fermionic atoms is inherently of a long range, of the order of the scattering length (which diverges at resonance).

Bottom to top: $m_\uparrow / m_\downarrow = 13.6,\ 8.2,\ 6.64,\ 5$



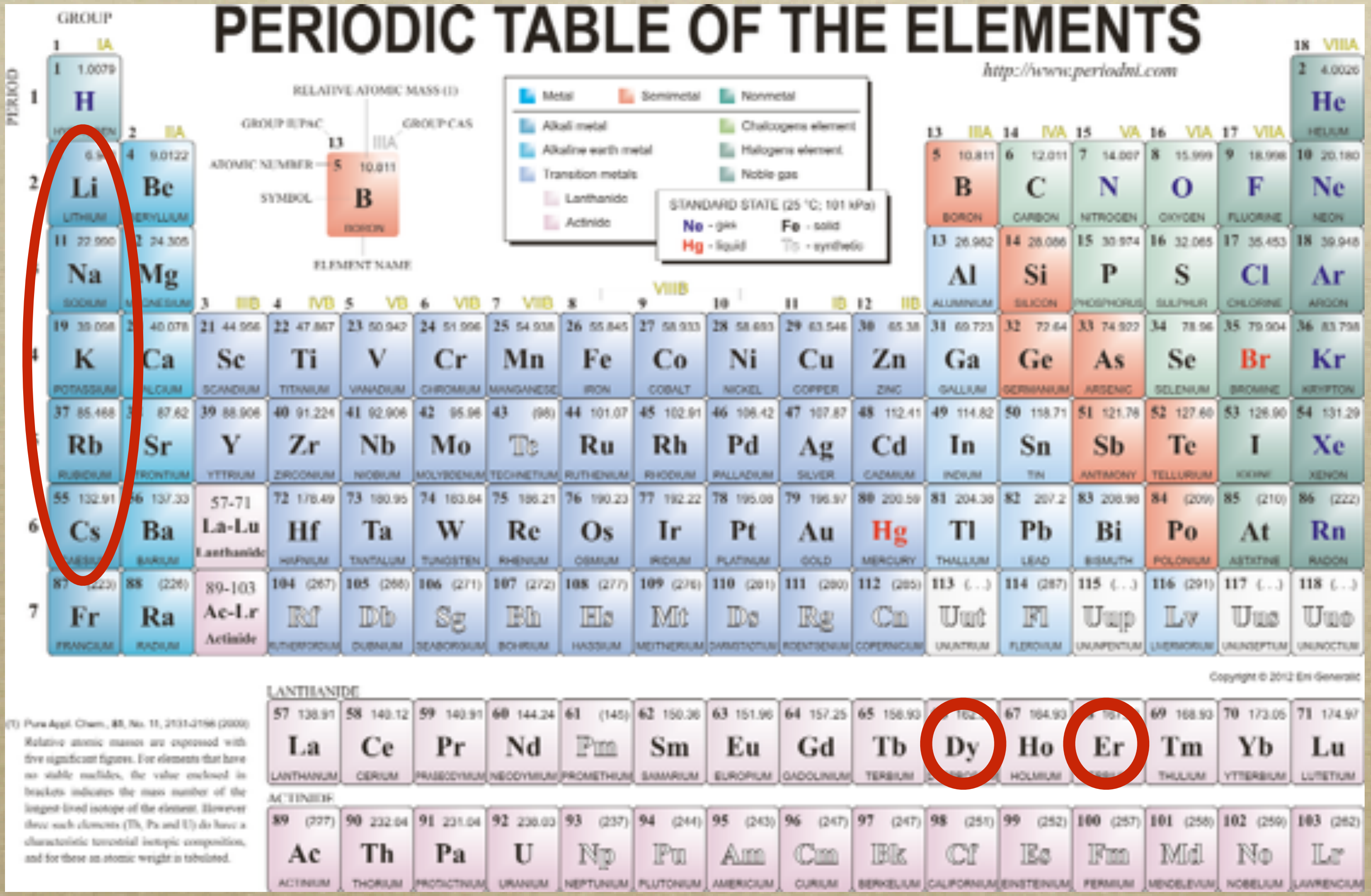
J.L. & Petrov, EPJD 2011

- The centrifugal barrier prevents the two identical fermions from approaching to short distances, suppressing three-body losses
- This scenario is fundamentally different from the bosonic case, where losses are enhanced close to the formation of (Efimov) trimers

=> a (relatively) **stable** mixture of atoms and dimers with **strong *p*-wave** interactions. This is a new paradigm for few-body physics

Heteronuclear mixtures

- ^{6}Li-^{40}K (Innsbruck, Paris, Singapore)
- ^{6}Li-^{7}Li-^{133}Cs (Chicago, Heidelberg)
- ^{40}K-^{87}Rb (JILA, Aarhus)
- ^{23}Na-^{40}K (MIT)
- ^{41}K-^{40}K-^{6}Li (MIT)
- ^{87}Rb-Sr (Innsbruck/Amsterdam)
- many more…



PERIODIC TABLE OF THE ELEMENTS

http://www.periodni.com

Metal, Semimetal, Nonmetal; Alkali metal, Alkaline earth metal, Transition metals, Lanthanide, Actinide; Chalcogens element, Halogens element, Noble gas

STANDARD STATE (25 °C; 101 kPa): Ne - gas, Fe - solid, Hg - liquid, Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 La-Lu Lanthanide	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 Ac-Lr Actinide	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

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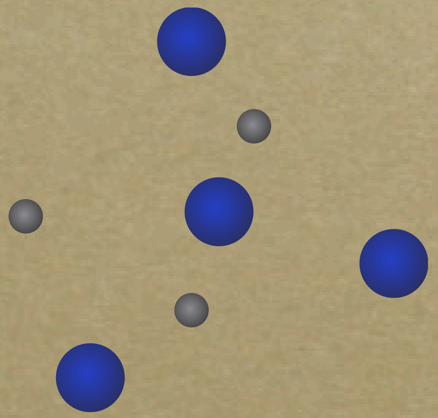
LANTHANIDE

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

ACTINIDE

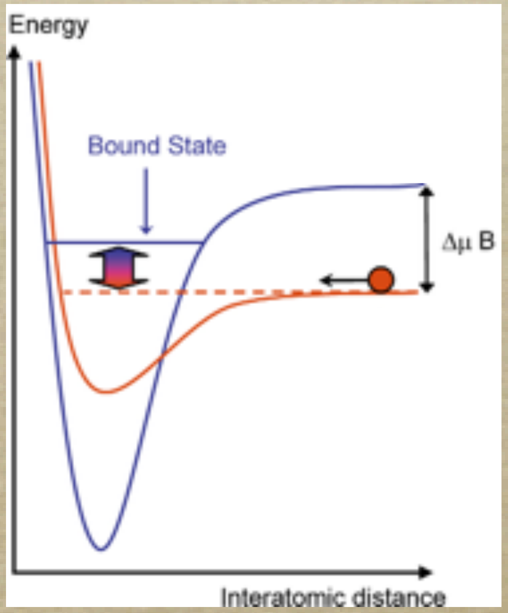
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



Theorists may consider mass ratio a free parameter…

Narrow Feshbach resonance

- Typically, Feshbach resonances in heteronuclear mixtures are narrow in magnetic field width
  - *This translates into an effective range much larger than the van der Waals range of the atomic interactions*



Petrov, PRL 2004

$$R^* = -r_0/2 = \frac{1}{2\mu a_{\text{bg}}\mu_{\text{rel}}\Delta B}$$

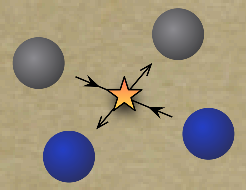
- *In ^{40}K-^{6}Li mixture:*

$$R^* \gtrsim 2000a_0$$

$$R_{\text{vdW}} \simeq 50a_0$$

- Assume no other terms in scattering amplitude are anomalously large and neglect higher partial waves:

$$f(\mathbf{k}) = -\frac{1}{1/a + R^* k^2 + ik}$$



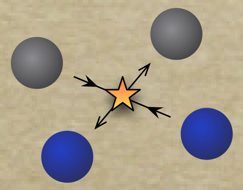
Narrow Feshbach resonance: Two-channel model

The coupling to a closed channel may be modelled by a two-channel model (Timmermanns et al., Phys. Rep. 1999):

$$\hat{H} = \sum_{\mathbf{k},\sigma=\uparrow,\downarrow} \frac{k^2}{2m_\sigma} \hat{a}^\dagger_{\mathbf{k},\sigma} \hat{a}_{\mathbf{k},\sigma} + \sum_{\mathbf{p}} \left(\omega_0 + \frac{p^2}{2M} \right) \hat{b}^\dagger_{\mathbf{p}} \hat{b}_{\mathbf{p}} + \sum_{\mathbf{k},\mathbf{p}} \frac{g}{\sqrt{V}} \left(\hat{b}^\dagger_{\mathbf{p}} \hat{a}_{\frac{\mathbf{p}}{2}+\mathbf{k},\uparrow} \hat{a}_{\frac{\mathbf{p}}{2}-\mathbf{k},\downarrow} + \hat{b}_{\mathbf{p}} \hat{a}^\dagger_{\frac{\mathbf{p}}{2}-\mathbf{k},\downarrow} \hat{a}^\dagger_{\frac{\mathbf{p}}{2}+\mathbf{k},\uparrow} \right)$$

Taking the coupling to be constant up to a cutoff relates the parameters of the model to the coefficients of the 2-body scattering amplitude:

$$a = \frac{\mu g^2}{2\pi} \frac{1}{\frac{g^2 \mu \Lambda}{\pi^2} - \omega_0}, \qquad R^* = \frac{\pi}{\mu^2 g^2}$$

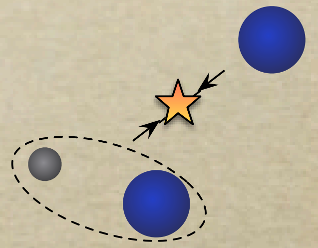


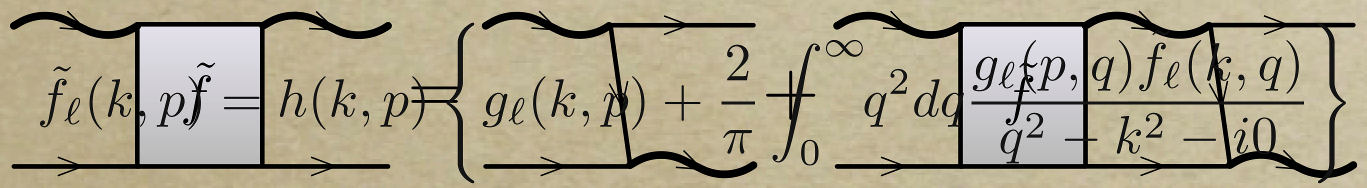
Weakly bound state with binding energy (*a*>0)

$$\epsilon_0 = -\left(\sqrt{1 + 4R^*/a} - 1 \right)^2 / 8\mu {R^*}^2$$

Three-body problem: Skorniakov — Ter-Martirosian equation

- The interaction between an atom and a dimer may be treated exactly in the limit $a \gg R_{vdW}$ by applying the Skorniakov—Ter-Martirosian integral equation
  - *Sums an infinite number of three-body diagrams*





$$\tilde{f}_\ell(k,p) = h(k,p)\left\{ g_\ell(k,p) + \frac{2}{\pi} \fint_0^\infty q^2 dq \frac{g_\ell(p,q)\tilde{f}_\ell(k,q)}{q^2 - k^2 - i0} \right\}$$

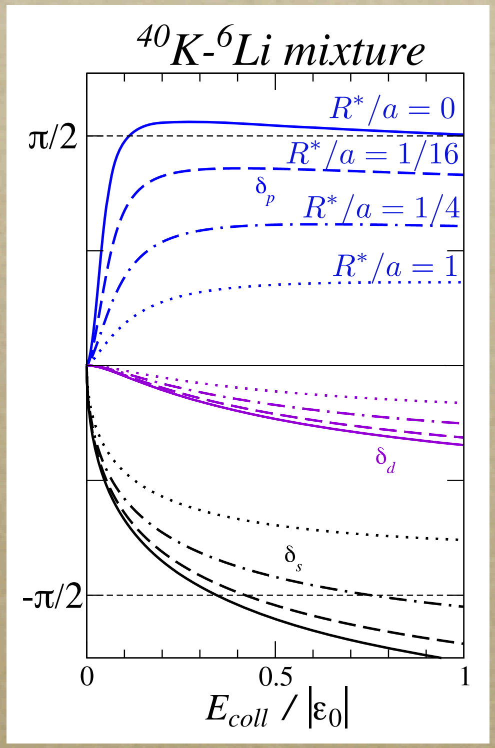
- The atom-dimer interaction may be separated in its partial wave components:

$$f(\mathbf{k}, \mathbf{k}') = \sum_{\ell=0}^{\infty} (2\ell + 1) P_\ell(\cos\theta) f_\ell(k)$$

$$f_\ell(k) = \frac{1}{k \cot \delta_\ell(k) - ik} = \tilde{f}_\ell(k,k)$$

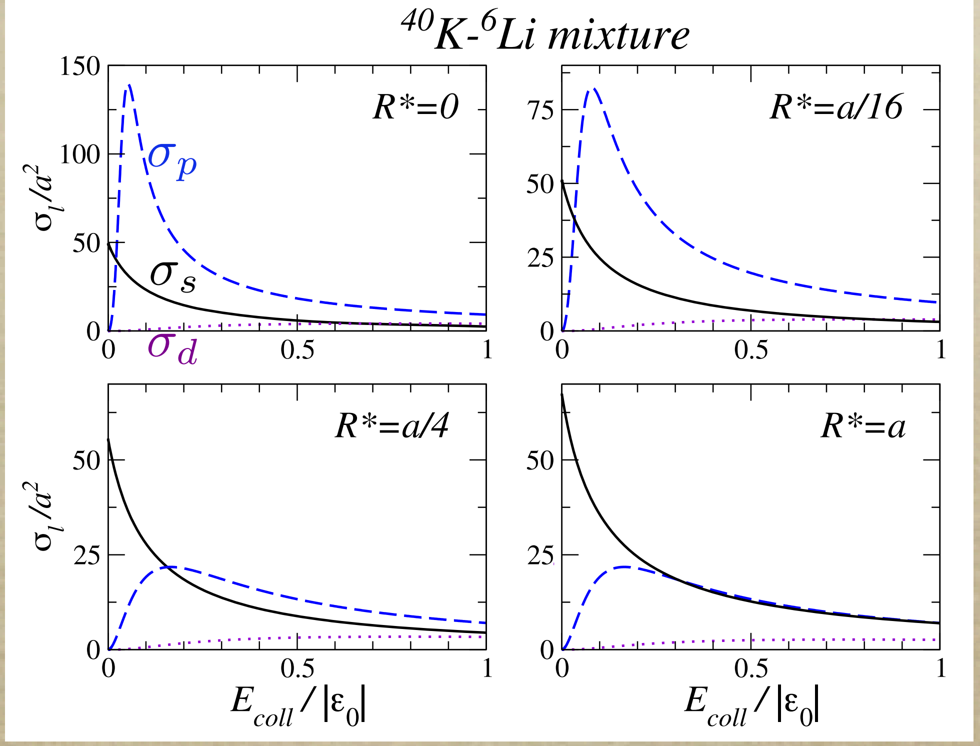
$$\sigma_\ell(k) = 4\pi(2\ell + 1)k^{-2} \sin^2 \delta_\ell(k)$$

Atom-dimer scattering in Li-K mixture

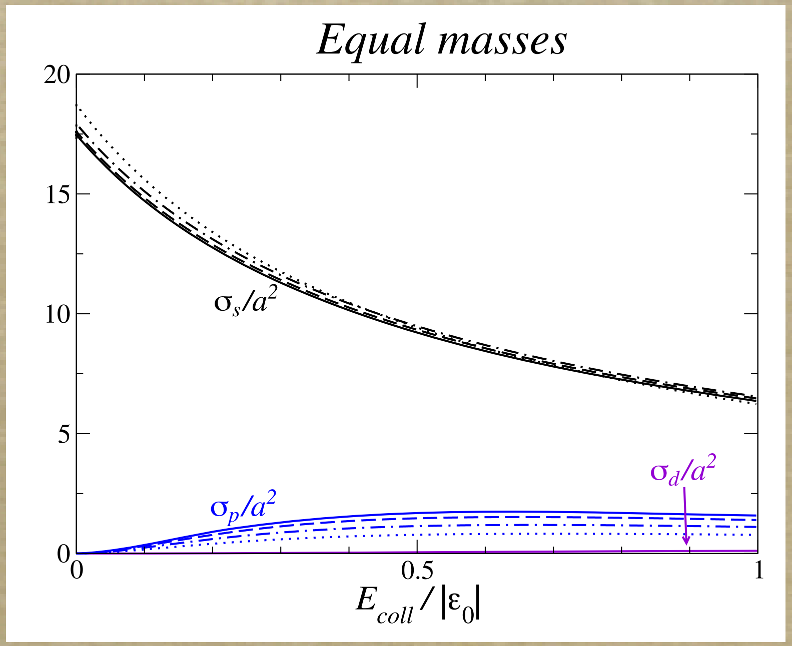


$R^* = -\frac{1}{2} r_0$

Close to resonance, phase shift crosses $\pi/2$ at collision energy of 10% of binding energy — p-wave resonance



- For $R^* \leq a$, *p*-wave scattering dominates for most collision energies



Compare with mass-balanced case

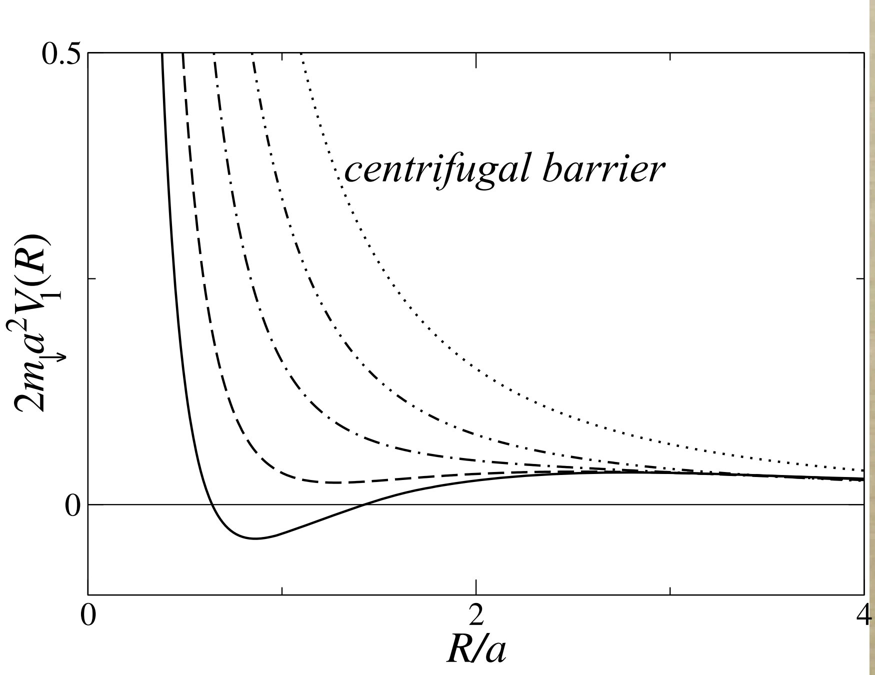
- ***p-wave resonance a unique consequence of mass-imbalance***

J.L., Tiecke, Walraven, Petrov PRL 2009

J.L. & Petrov, EPJD 2011

Born-Oppenheimer picture: Narrow resonance

Effect of resonance width:



Bottom to top: $R^*/a = 0,\ 1/16,\ 1/4,\ 1$

When the light atom spends more time in the closed channel molecular state, the strength of the exchange potential is decreased

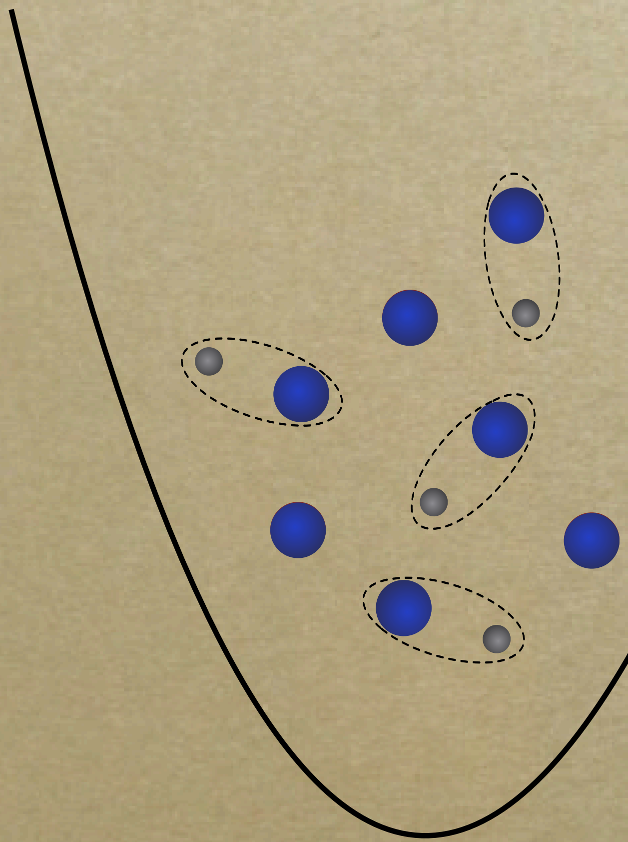
Experimental observation of strong atom-dimer attraction

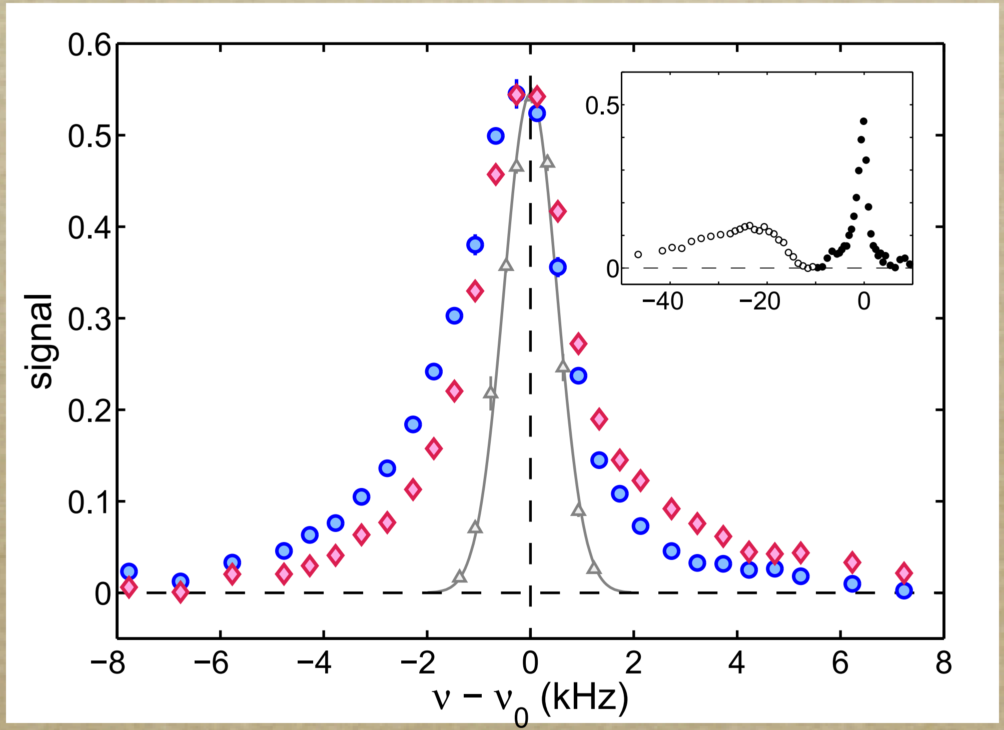
Jag, Zaccanti, Cetina, Lous,
Schreck, Grimm, Petrov, J.L.,
PRL 2014

Experimental observation

Experiment in the group of Rudi Grimm (IQOQI, Innsbruck)

Thermal mixture of K atoms and KLi dimers, perform RF spectroscopy





- Signal: fraction of atoms transferred as a function of the RF detuning from the bare transition

Jag, Zaccanti, Cetina, Lous,
Schreck, Grimm, Petrov, J.L.,
PRL 2014

Theory-experiment comparison

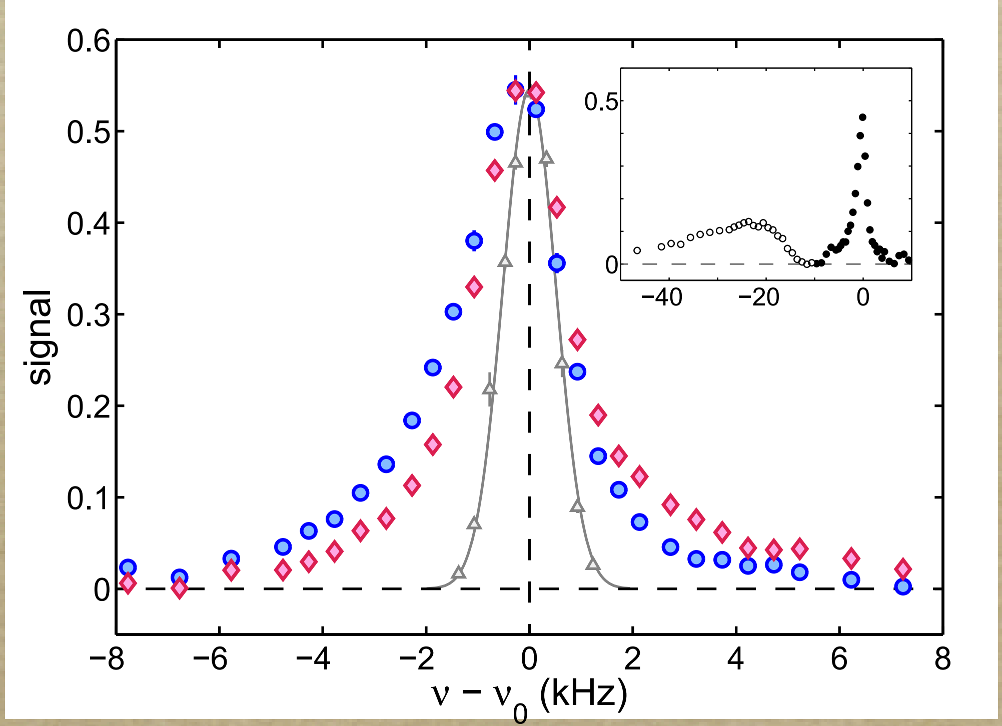
Main theory assumption: Interaction energy shift is dominated by three-body correlations

Mean field shift of K atom in bath of LiK dimers: $\Delta E = \frac{2\pi\hbar^2 n_D a_{ad}}{m_{ad}} > 0$

Impact theory of pressure-induced effects on spectral lines:

$$\delta\nu = -\hbar\bar{n}_{\mathrm{D}}\mathrm{Re}\,\langle f(0)\rangle/\mu_3$$

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



Optical theorem:

$$\tau^{-1} = 4\pi\hbar\bar{n}_{\mathrm{D}}\mathrm{Im}\,\langle f(0)\rangle/\mu_3$$

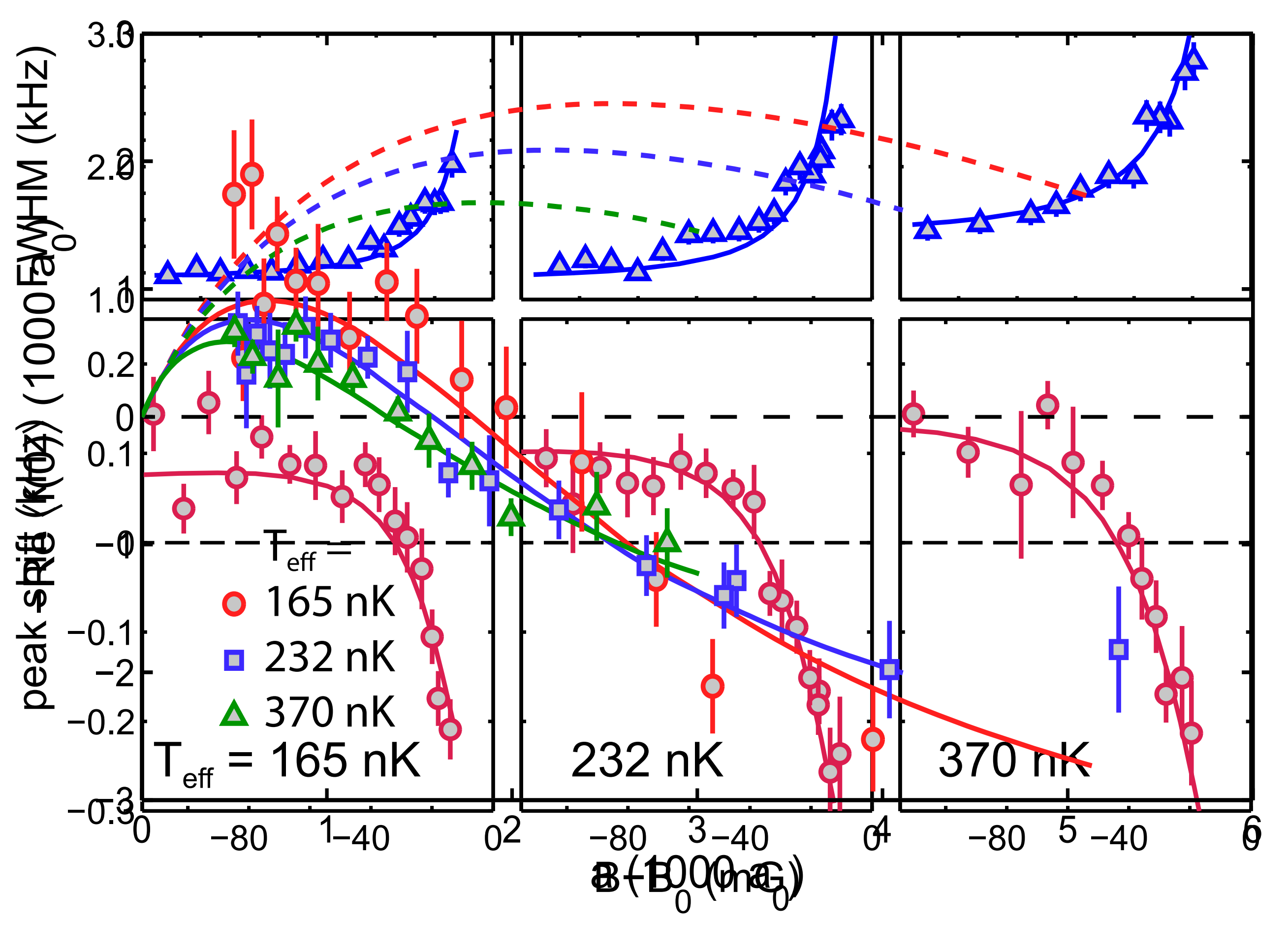
Lorentzian broadening with FWHM $1/(2\pi\tau)$

(additional broadening due to finite duration of RF pulse)

Jag, Zaccanti, Cetina, Lous,
Schreck, Grimm, Petrov, J.L.,
PRL 2014

Theory-experiment comparison

$$\tau^{-1} = 4\pi\hbar\bar{n}_{\mathrm{D}}\mathrm{Im}\,\langle f(0)\rangle/\mu_3 \quad 1/(2\pi\tau)$$



$$\delta\nu = -\hbar\bar{n}_{\mathrm{D}}\mathrm{Re}\,\langle f(0)\rangle/\mu_3$$

Theory: No adjustable parameters

- The normally repulsive atom-dimer interaction is turned into strong attraction

p-wave dominant, but theory curves contain lowest 16 partial waves

Trimers in (quasi) 2D

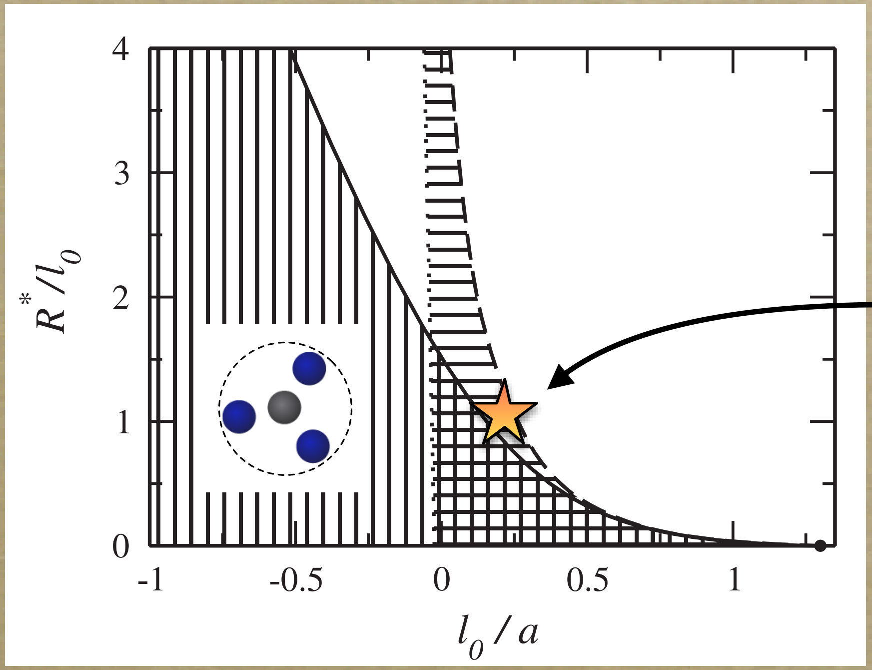
Confinement induced trimers

Now that we've seen enhanced scattering in higher partial waves, observing stable trimers is the next goal

Kartavtsev & Malykh, J. Phys. B 2007

- *Critical mass ratio in 3D is 8.2 while in 2D it is 3.3*

Pricoupenko and Pedri, PRA 2009

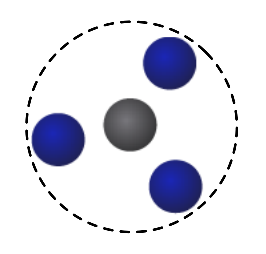


$\omega_z \simeq 2\pi \times 25\text{kHz}$ *(well within experimental reach)*

J.L., Tiecke, Walraven, Petrov PRL 2009

3 fermions with large mass ratio in 2D

Pricoupenko and Pedri, PRA 2010:

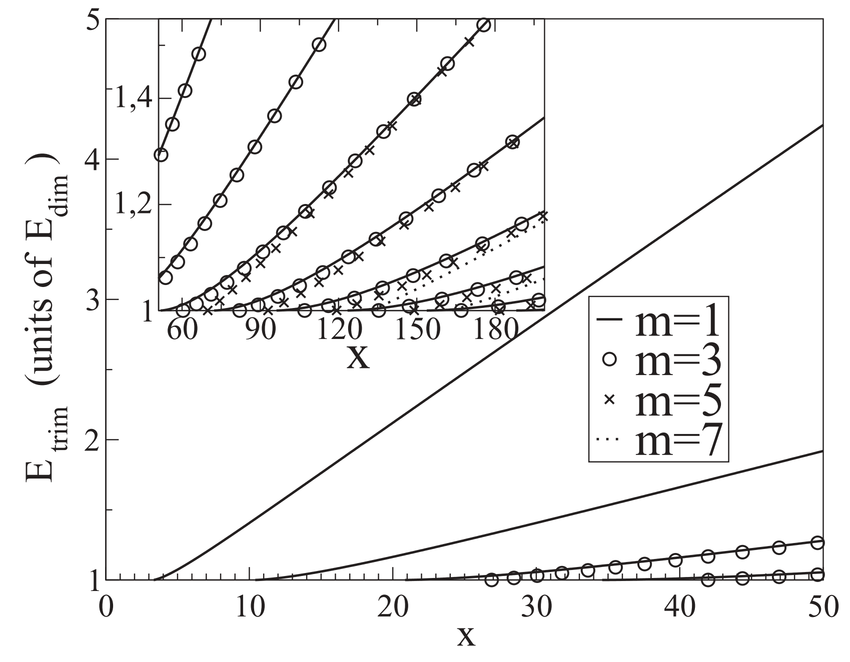


- No trimers for equal masses
- 1st trimer appears at mass ratio 3.3
- 2nd trimer appears at 10.4
- As mass ratio is increased, an ever increasing number of trimers appear in the spectrum
- Trimers are degenerate among different partial waves

Tan & Nishida, Few-body Systems 2011:

- *No Efimov effect in 2D, as interaction vanishes at short range*

(caveat: Meera's talk on Friday…)



Pricoupenko & Pedri, PRA 2010

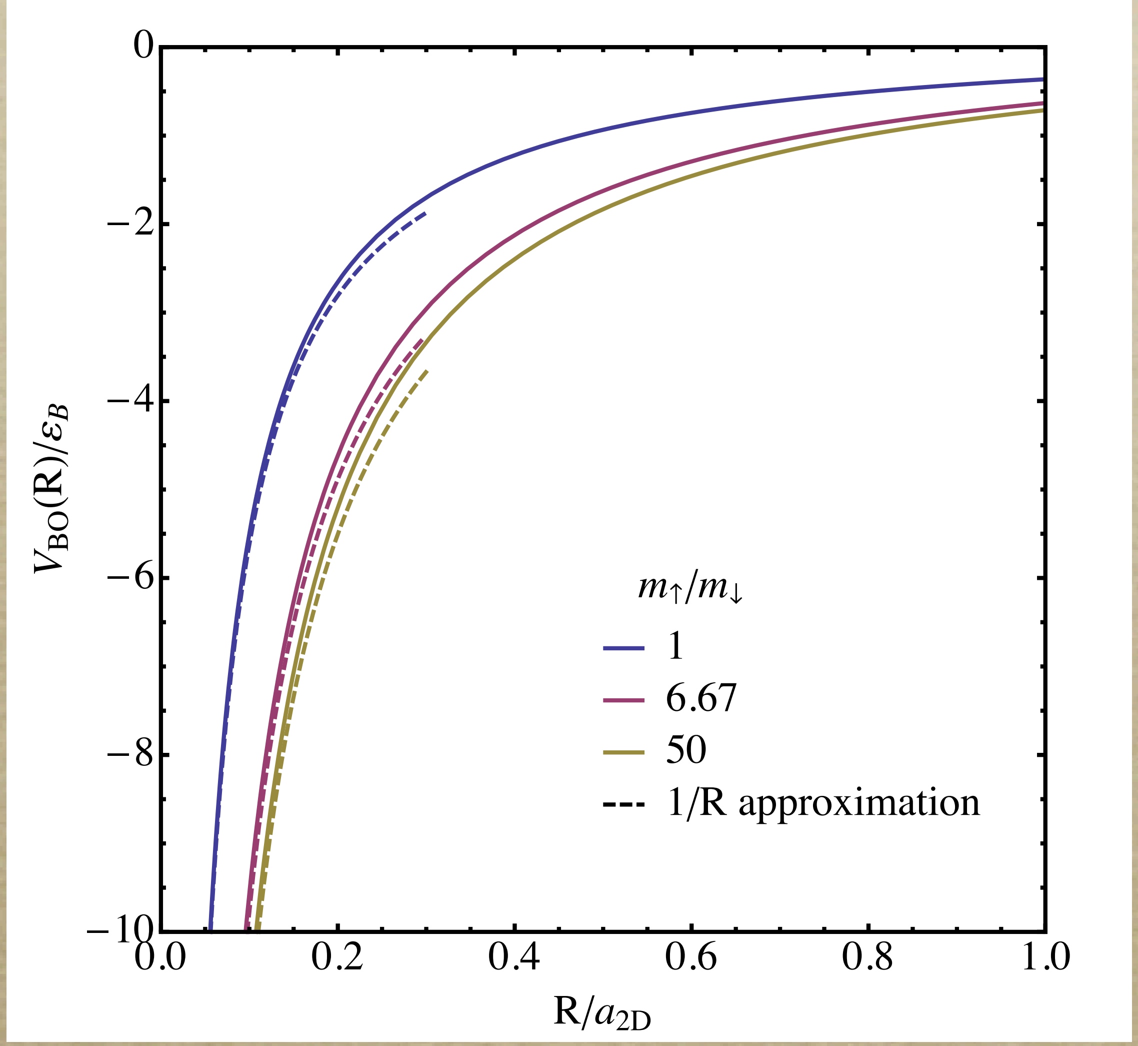
3 fermions with large mass ratio in 2D

Trimers appear in the short range part of the potential, $R \ll a_{2\mathrm{D}}$

Born-Oppenheimer effective potential at short range:

$$\epsilon(R) \approx -\frac{2\varepsilon_B}{e^\gamma}\frac{a_{2\mathrm{D}}}{R}$$

So the spectrum is simply that of a hydrogen atom confined to 2D - different partial waves have the same spectrum

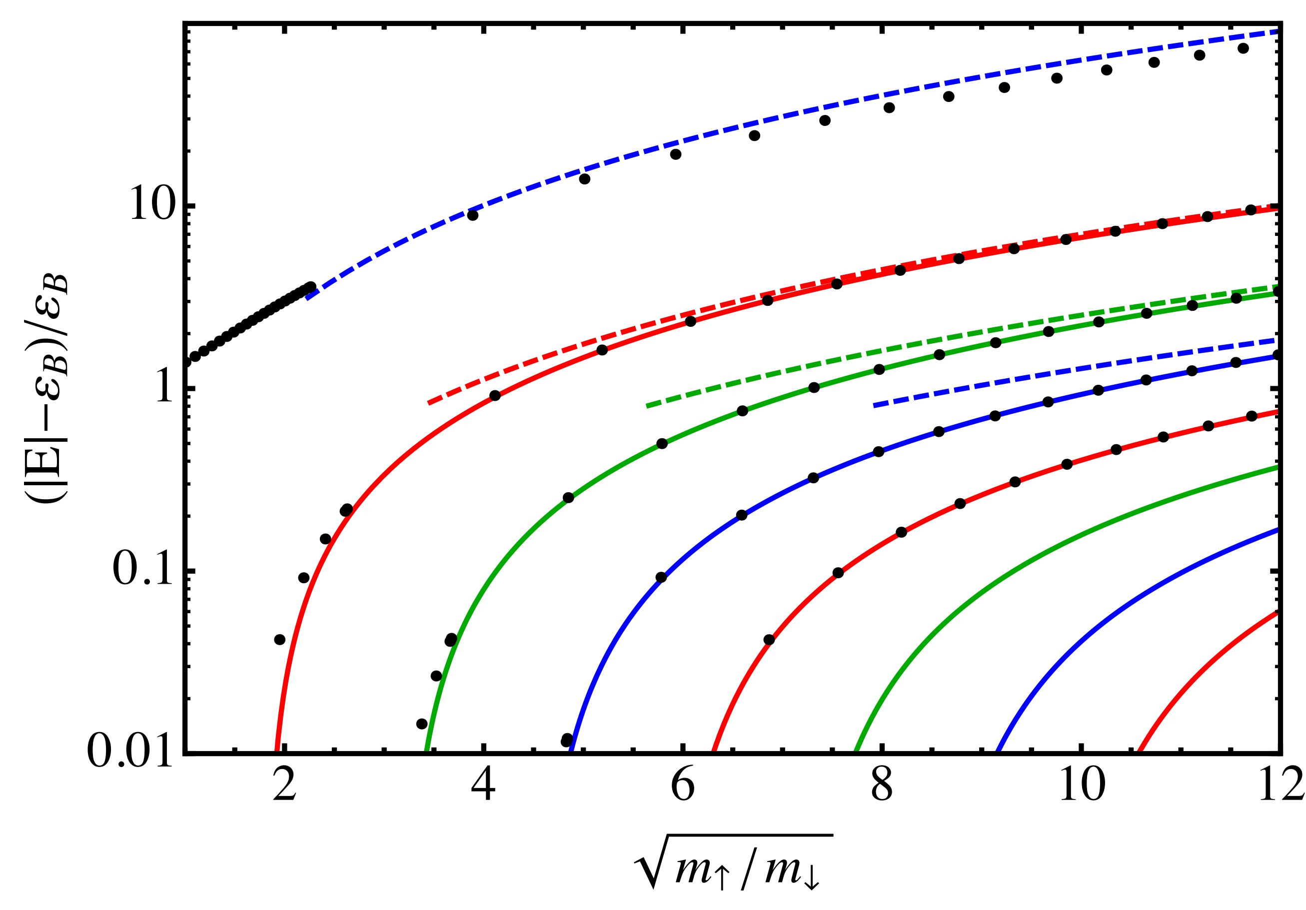


$$\boxed{E_n = -\frac{m_\uparrow}{e^{2\gamma}m_\downarrow}\frac{\varepsilon_B}{2(n+1/2)^2} - \varepsilon_B \qquad n \geq \ell}$$

Ngampruetikorn, Parish, J.L., EPL 2013

Trimer energies

Very good agreement between exact trimer energies (from STM equation) and the hydrogen spectrum



Bosons in even partial wave described by same potential as fermions in odd partial wave so the spectrum is the same

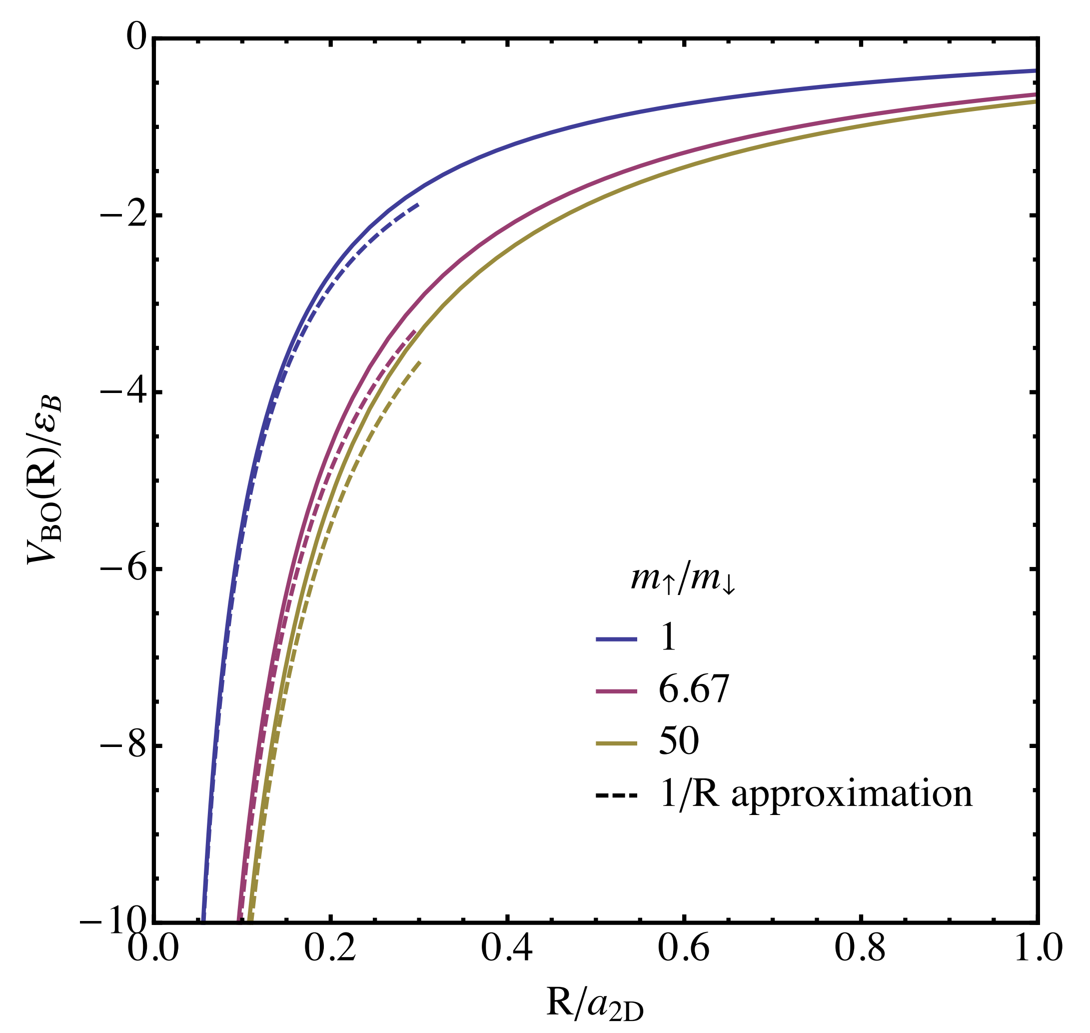
$$\boxed{E_n = -\frac{m_\uparrow}{e^{2\gamma} m_\downarrow} \frac{\varepsilon_B}{2(n+1/2)^2} - \varepsilon_B}$$

Ngampruetikorn, Parish, J.L., EPL 2013

Number of bound trimers

Solution of Schrödinger equation at distances $R \ll a_{2\mathrm{D}}$

$$J_{2\ell}(2\sqrt{e^{-\gamma}(m_\uparrow/m_\downarrow)R/a_{2\mathrm{D}}})$$



Each time the argument increases by π an extra node appears

$$\boxed{\#\ \text{bound states} \sim \sqrt{m_\uparrow/m_\downarrow}}$$

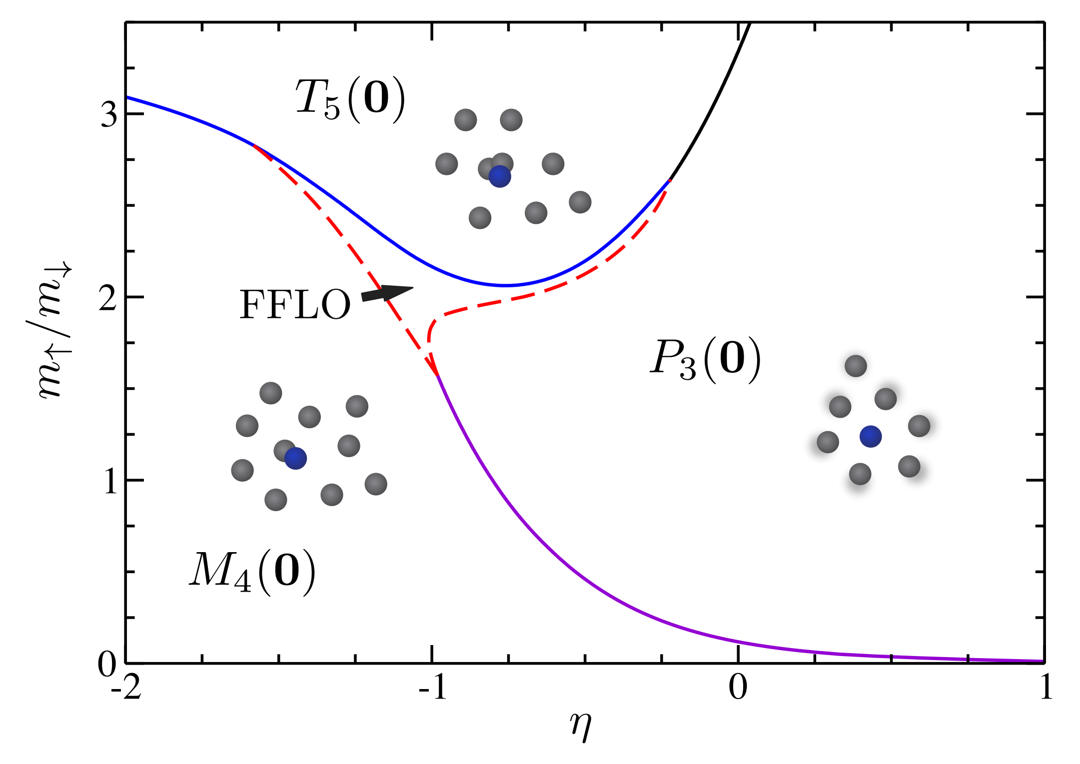
Ngampruetikorn, Parish, J.L., EPL 2013

see also Bellotti et al, J. Phys. B: At. Mol. Opt. Phys. (2013)

Polarized heteronuclear Fermi gas

Consequences: Polarized heteronuclear Fermi gas in 2D

- *Trimer exists at lower mass ratios in the polarized Fermi gas*
- *FFLO phase becomes possible at finite polarization*



Parish & J.L., PRA 2013

See also Mathy et al., PRL 2011 (3D calculation)

Conclusions & outlook

J.L., Tiecke, Walraven, Petrov, PRL 2009

J.L. & Petrov, EPJD 2011

- Strong "stable" long-range p-wave interactions in a quantum gas
  - Heteronuclear mixture with short-range interactions
  - Experimental observation of strong attraction

Jag, Zaccanti, Cetina, Lous, Schreck, Grimm, Petrov, J.L., PRL 2014

- Hydrogenic spectrum of trimers in 2D

Ngampruetikorn, Parish, J.L., EPL 2013

- Outlook:
  - Trimers à la Kartavtsev and Malykh, J. Phys. B 2007, by confining K atoms to quasi-2D
  - FFLO state in a polarised gas

Parish & J.L., PRA 2013

Thank you!