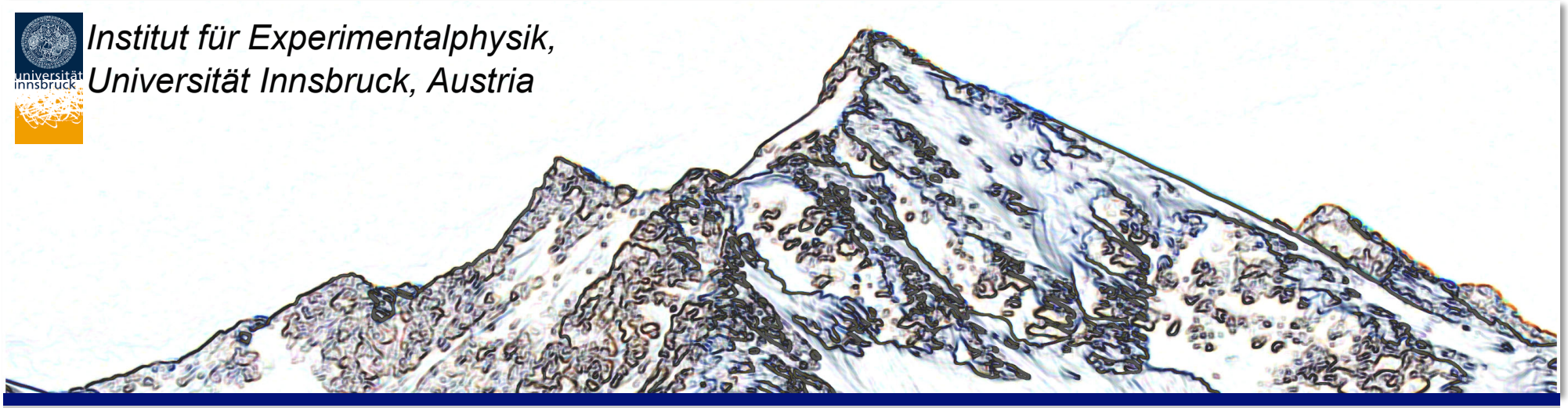
Institut für Experimentalphysik,
Universität Innsbruck, Austria



Few-body physics with ultracold Cs atoms and molecules

Francesca Ferlaino, Steven Knoop, Micheal Mark, Martin Berninger, Walter Harm, H. Christophe Naegerl, Rudi Grimm

Institut für Experimentalphysik, Universität Innsbruck, Austria

Few-body physics with Feshbach molecules (all ultracold)

Motivation:

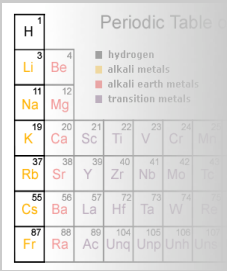
- **New energy regime**
  (VERY LOW COLLISIONAL ENERGY)
- **External control of collisions**
  (T, B, E, a ….)
- **Extremely state-selective**
  (POPULATION OF A SPECIFIC STATE)
- **Complex scattering: reactive collisions**
  (PRODUCTS ARE CHEMICALLY DISTINCT FROM REACTANS)
- **Universal few-body states**
  (HALO DIMERS, EFIMOV TRIMERS,…)

Can we ??

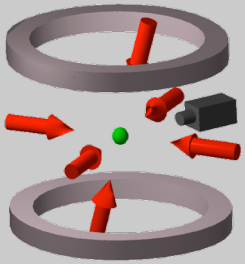
- **The starting system**
  (TRAPPED ULTRACOLD ATOMS)
- **The control knobs**
  (T, B, E, a ….)
- **molecule formation**
  (halo dimers, highly rotating dimers)
- **The observables**
  (INELASTIC LOSSES)

Welcome to the ultracold-atom world

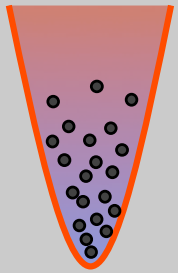
(I.) Ultracold atoms: (bosonic/fermionic)



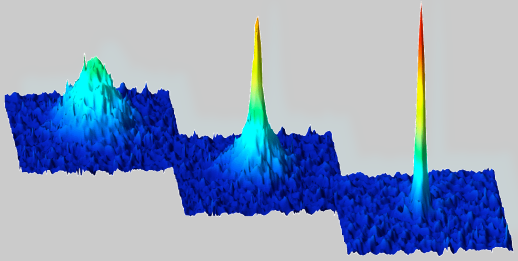
NEUTRAL ATOMS
(alkali)



COOLING
(laser c. and evaporative c.)



TRAPPING
(optical or magnetic)



PROBING
(density distribution)

Typical numbers

collision energies: few peV

relative velocities: few mm/s

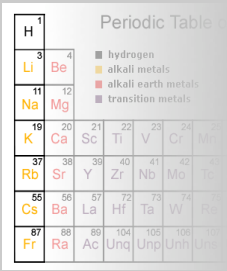
Scattering completely s-wave dominated:

s-wave scattering length a !!

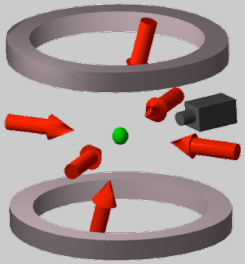
$$\sigma_{el} = \frac{8\pi}{k^2}\sum(2l+1)\sin^2\delta_l(k) \underset{(l=0)}{\overset{k\to 0}{\longrightarrow}} 8\pi a^2$$

WELCOME TO THE ULTRACOLD-ATOM WORLD

(I.) ULTRACOLD ATOMS: (bosonic/fermionic)



NEUTRAL ATOMS
(alkali)



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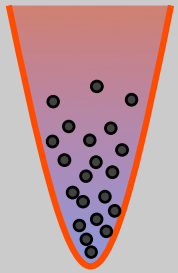
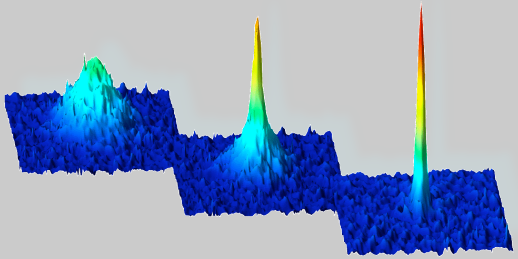
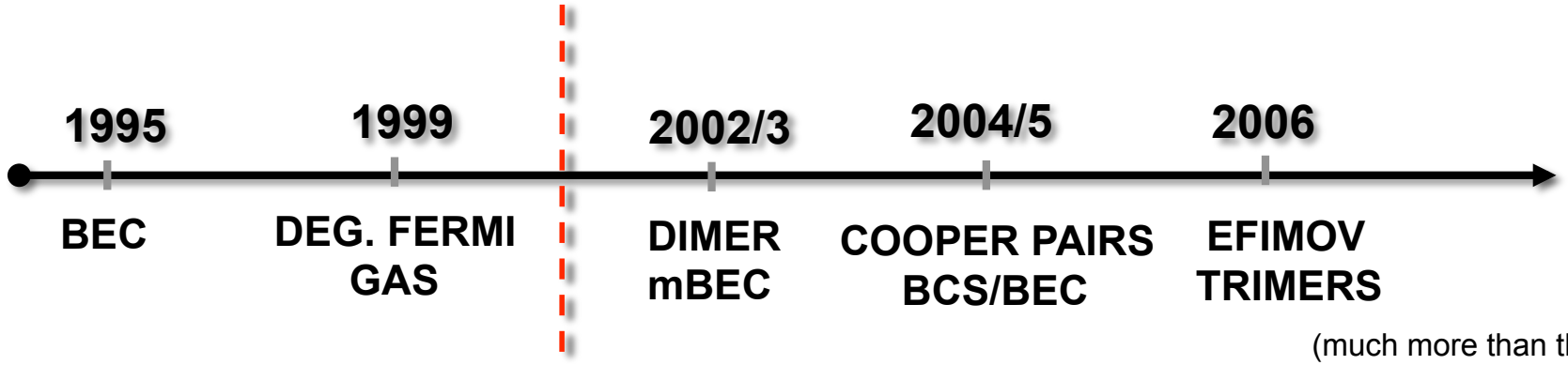


TRAPPING
(optical or magnetic)



PROBING
(density distribution)

MILESTONES IN THE FIELD (ultracold gases)



(much more than this..)

Welcome to the ultracold-atom world

(II.) Control knobs:

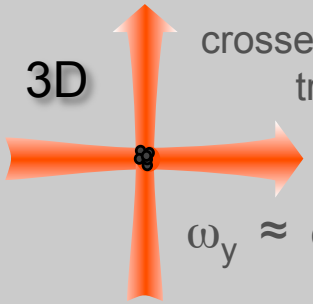
TEMPERATURE

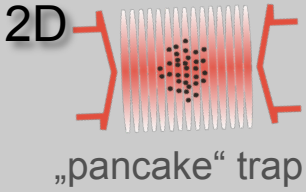
$T \approx 1\ \mu K\text{-}20\ nK$

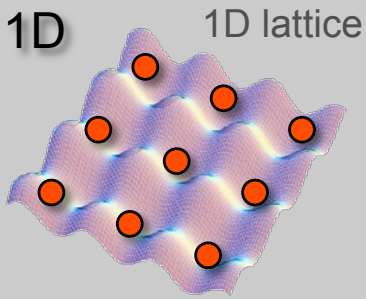
$$n\lambda_T^3 \begin{cases} >>1 & \text{Classical gas} \\ <<1 & \text{Quantum gas} \end{cases}$$

$$\left(\lambda_T = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}\right)$$

GEOMETRY







INTERACTIONS

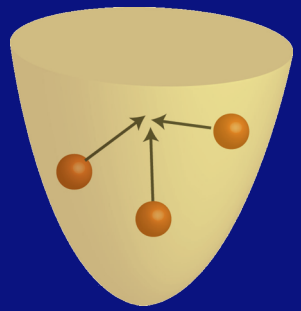
Interaction strength a

$$(\sigma_{el} = 8\pi a^2)$$

Ultracold atoms a model system for few- and many-body physics

Ultracold few-body physics: a simple introduction

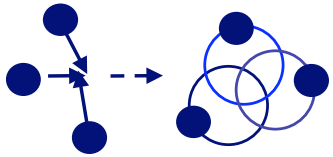
Atom

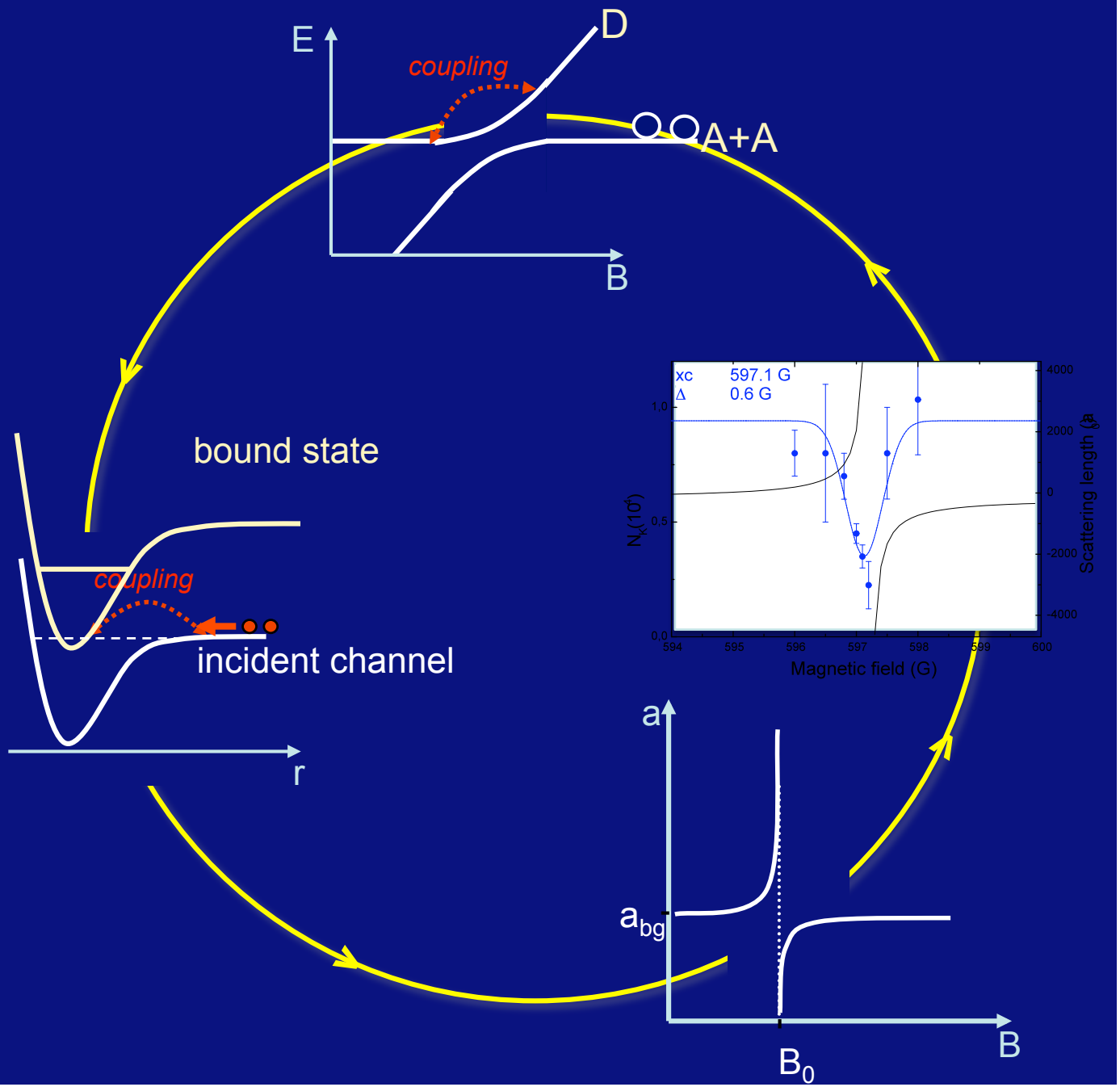


- spin dynamics
- recombination

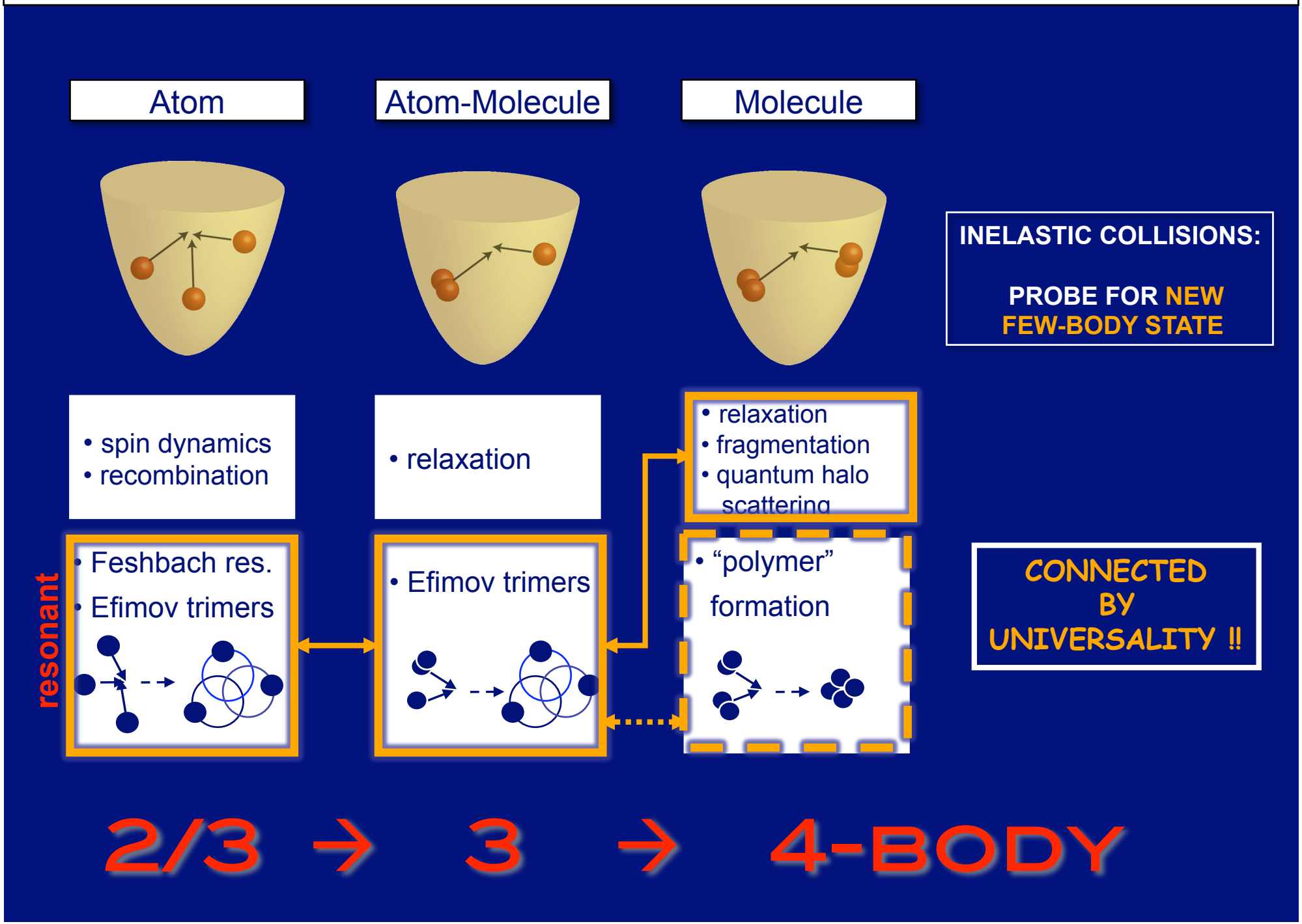
resonant

- Feshbach res.
- Efimov trimers

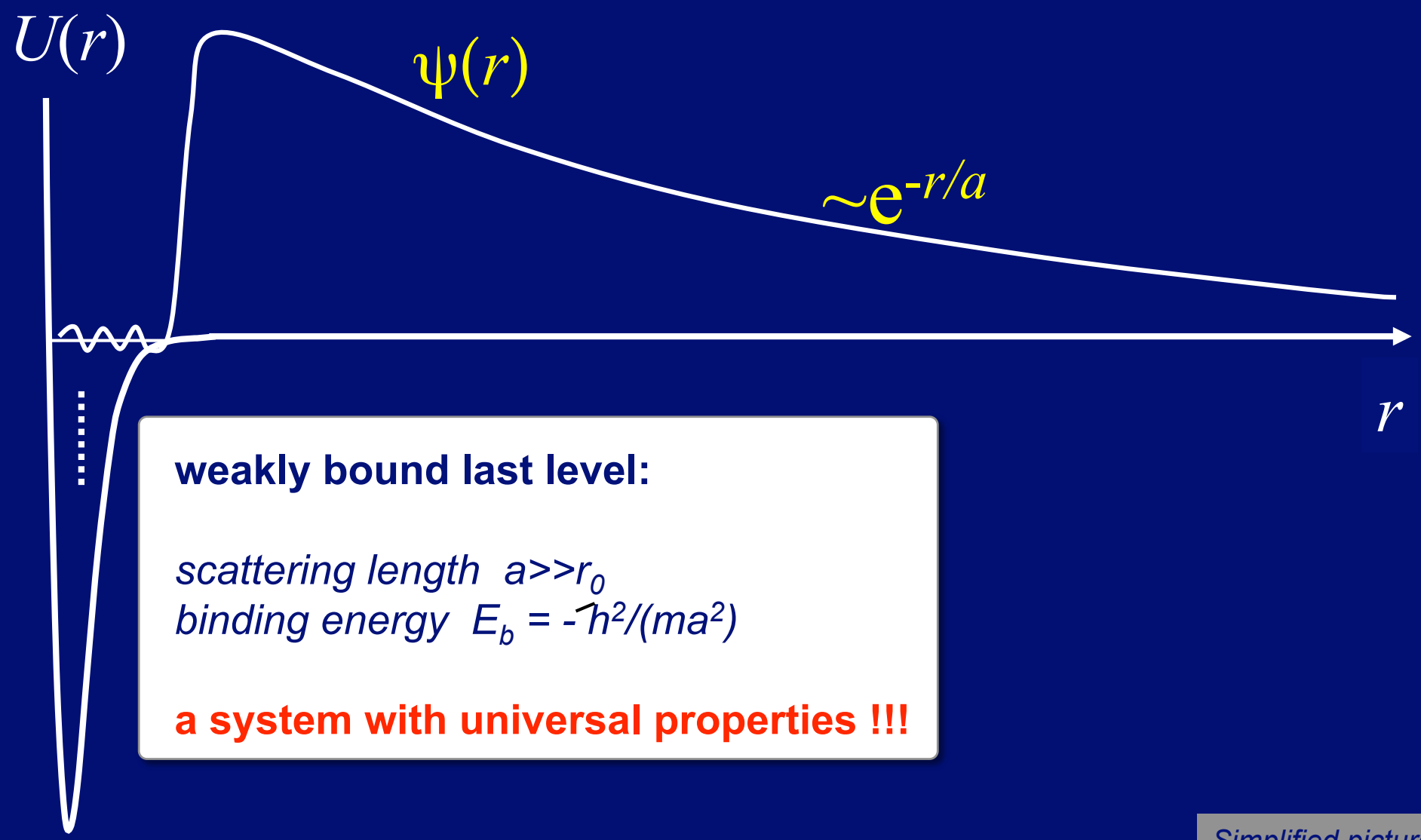




Ultracold few-body physics: a simple introduction



2-BODY UNIVERSAL STATE: QUANTUM HALO DIMER



weakly bound last level:

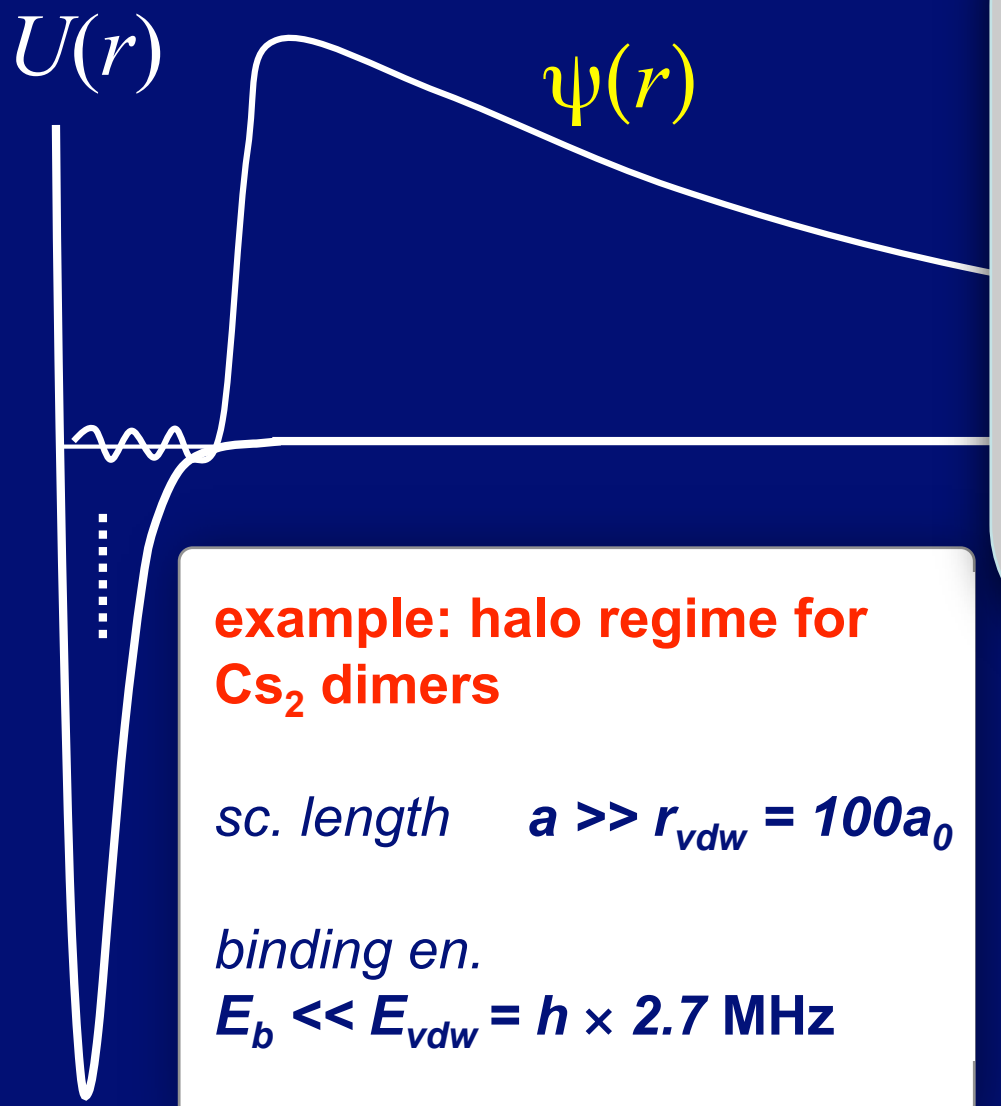
scattering length $a >> r_0$

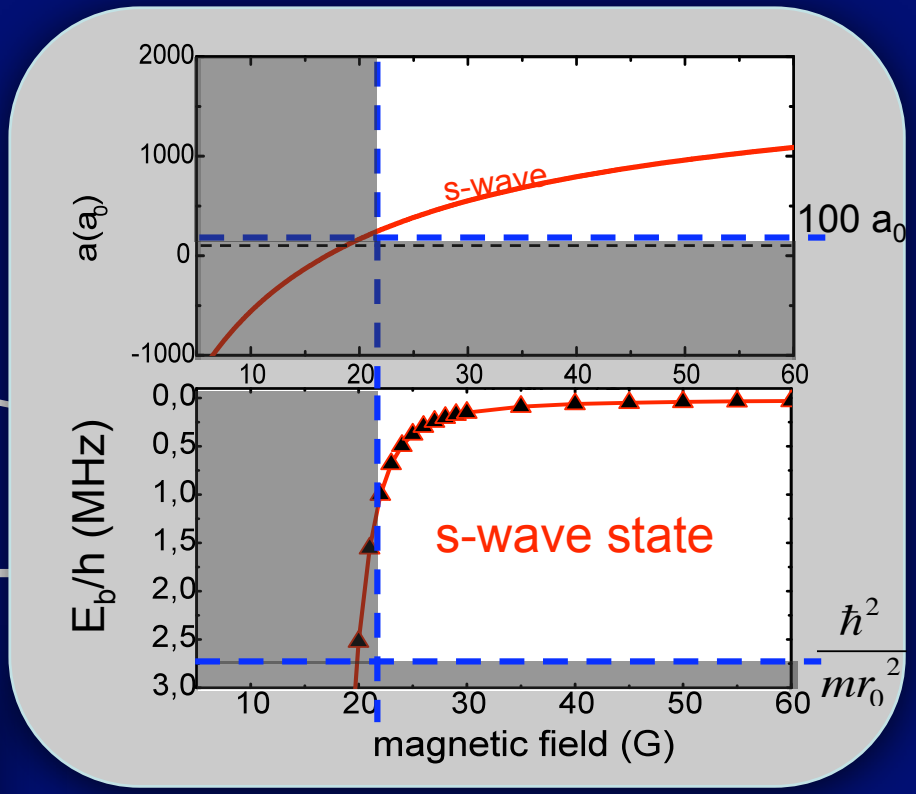
binding energy $E_b = -\hbar^2/(ma^2)$

a system with universal properties !!!

Simplified picture

2-BODY UNIVERSAL STATE: TUNABLE HALO DIMER





example: halo regime for Cs_2 dimers

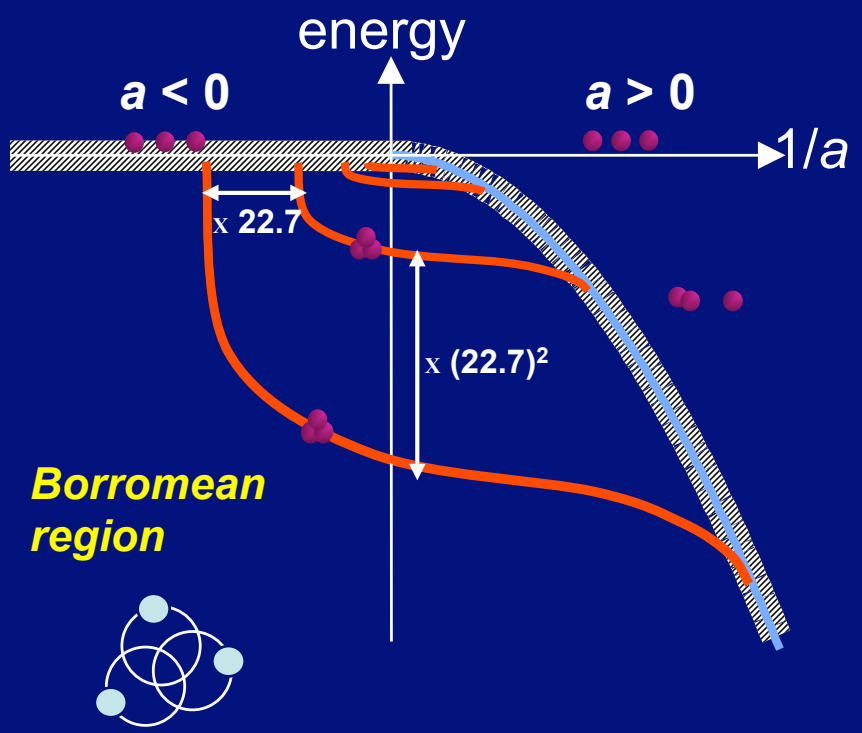
sc. length $a >> r_{vdw} = 100a_0$

binding en.
$E_b << E_{vdw} = h \times 2.7$ MHz

Simplified picture

3-BODY UNIVERSAL STATE: EFIMOV TRIMERS

Universal regime $|a| >> r_0$



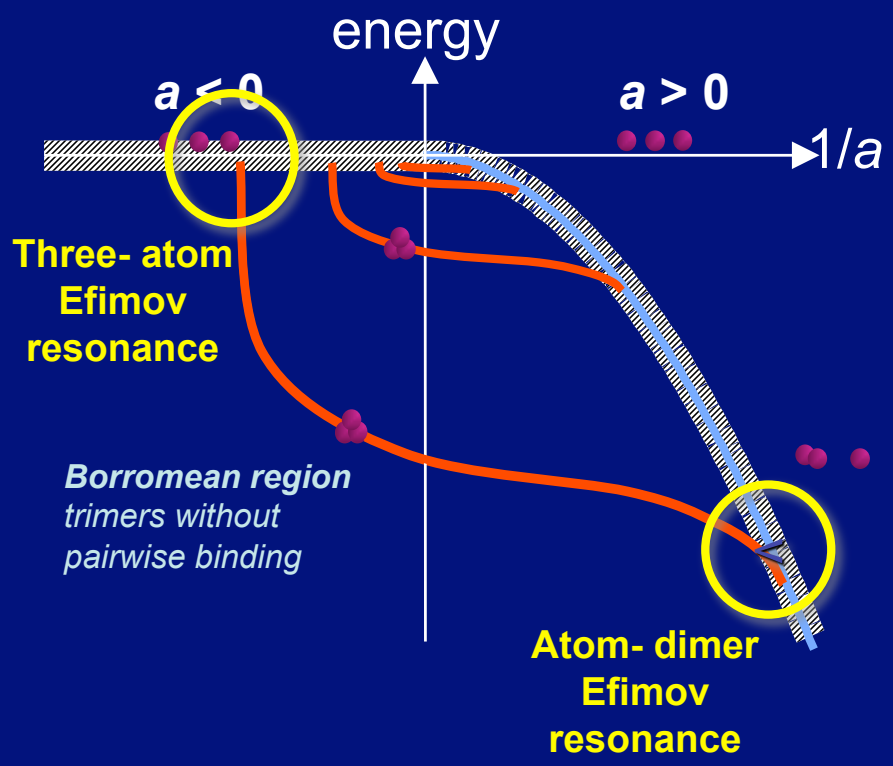
⇛ **Weakly bound trimers**

a<0 without pairwise binding

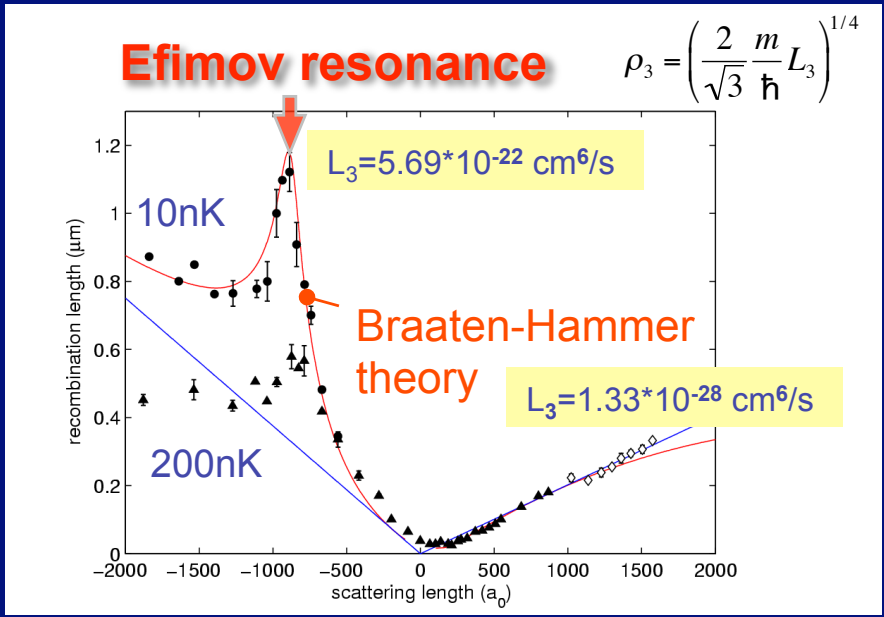
See Jose D'Incao talk

3-BODY UNIVERSAL STATE: EFIMOV TRIMERS

CAN WE OBSERVE EFIMOV PHYSICS ?



→ATOMIC SAMPLE: 3-BODY RECOMBINATION



T. Kraemer *et al.* , Nature 440, 315-318 (2006)

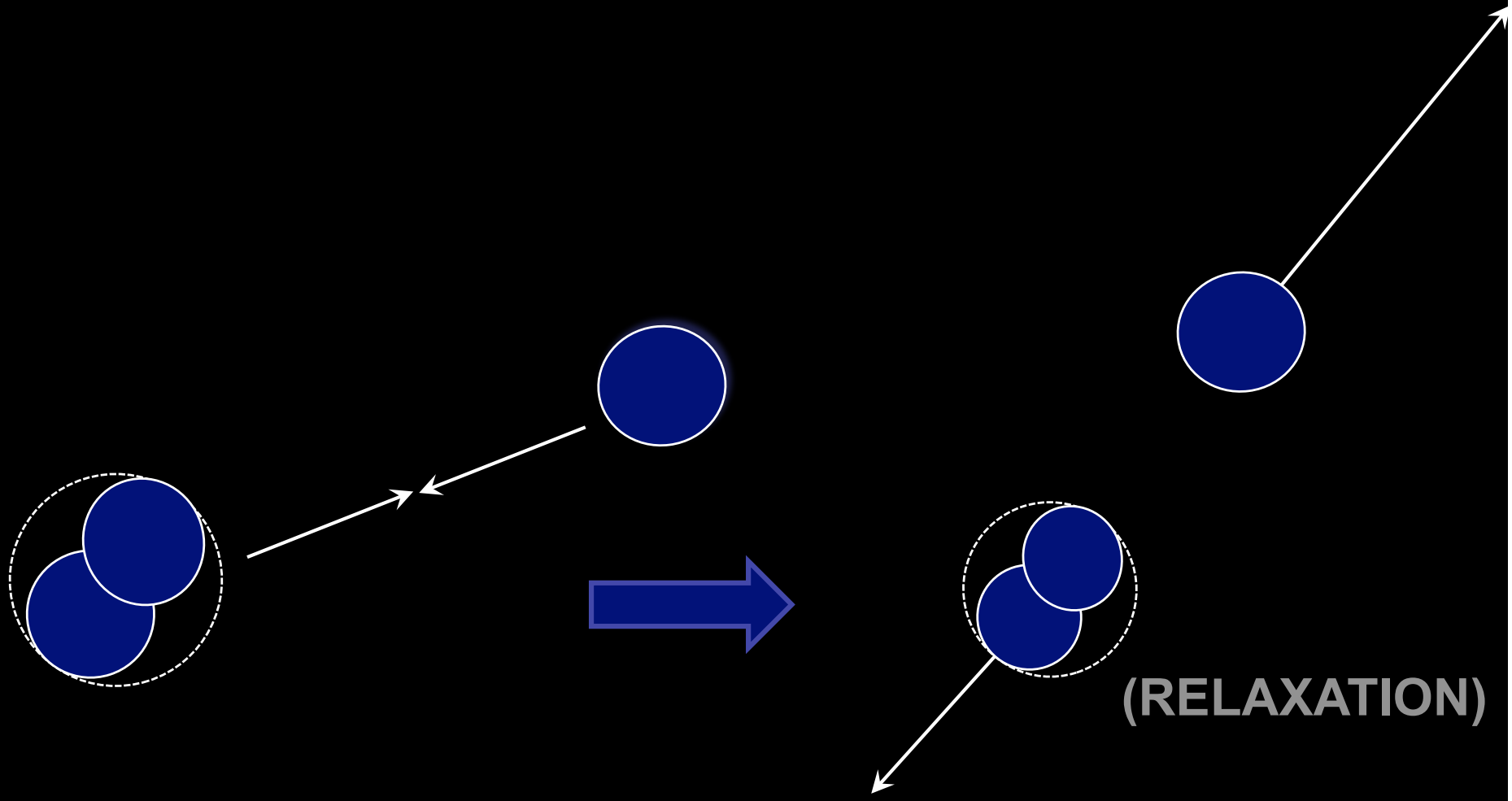
⇛ **Can we go further ?**

→ **atom-dimer mixture: losses**

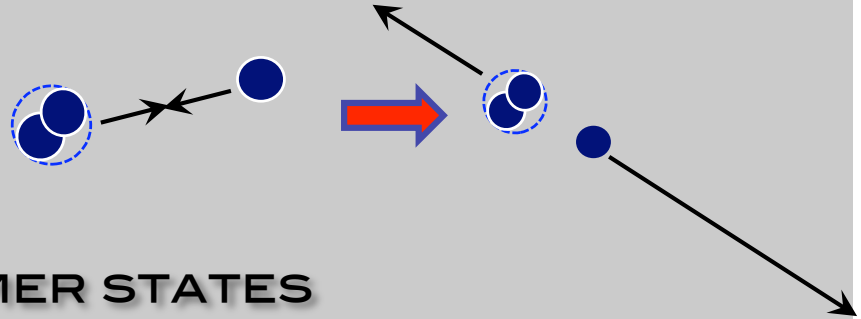
$$L_3 = 3C(a)\frac{\hbar}{m}a^4$$

See Jose D'Incao talk

3 - body



3–body collisions



ATOM-DIMER COLLISIONS

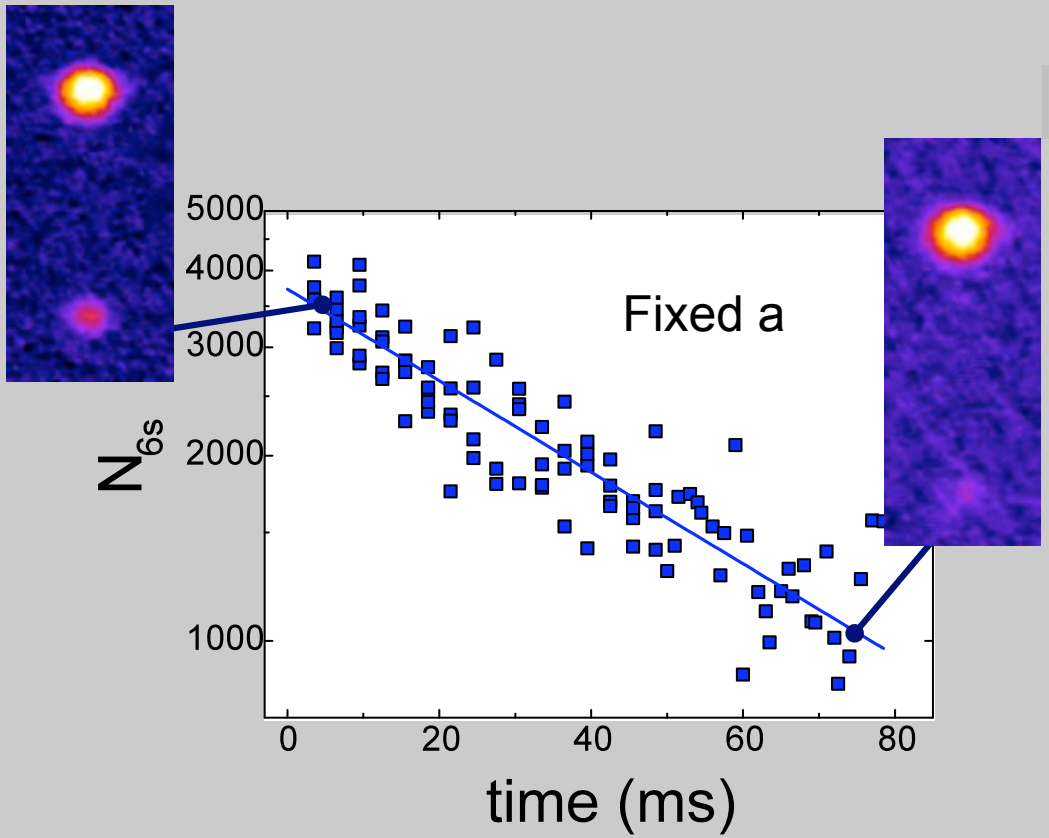
→ RELAXATION INTO DEEPLY BOUND DIMER STATES

→TRAP LOSS

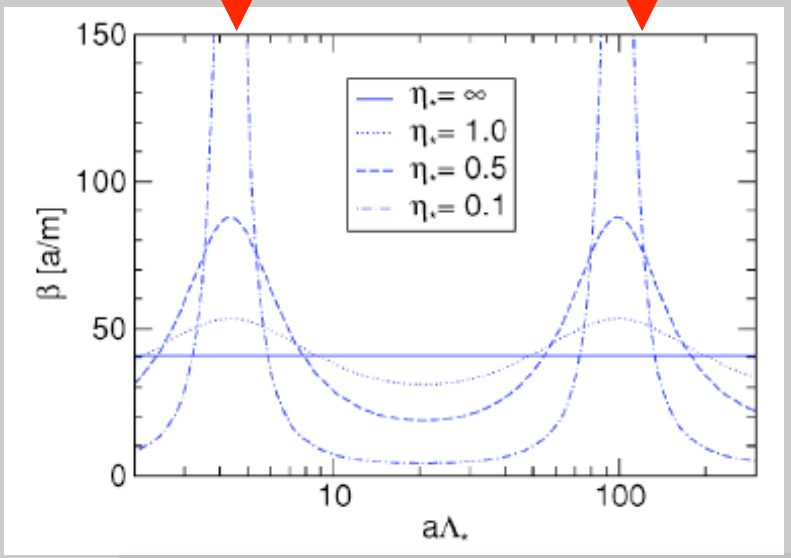
→ LIFETIME MEASUREMENT $\dot{n}_D = -\beta n_A n_D$

$$\beta = C'(a)\frac{\hbar}{m}a$$

Efimov — universality



Enhancement when coupled to Efimov trimer



Nielsen, Suno, Esry, PRA 66, 012705 (2002)
Braaten & Hammer, PRA 70, 042706 (2004)
D'Incao & Esry, PRL 94, 213201 (2005)
Braaten & Hammer, PRA 75, 052710 (2007)

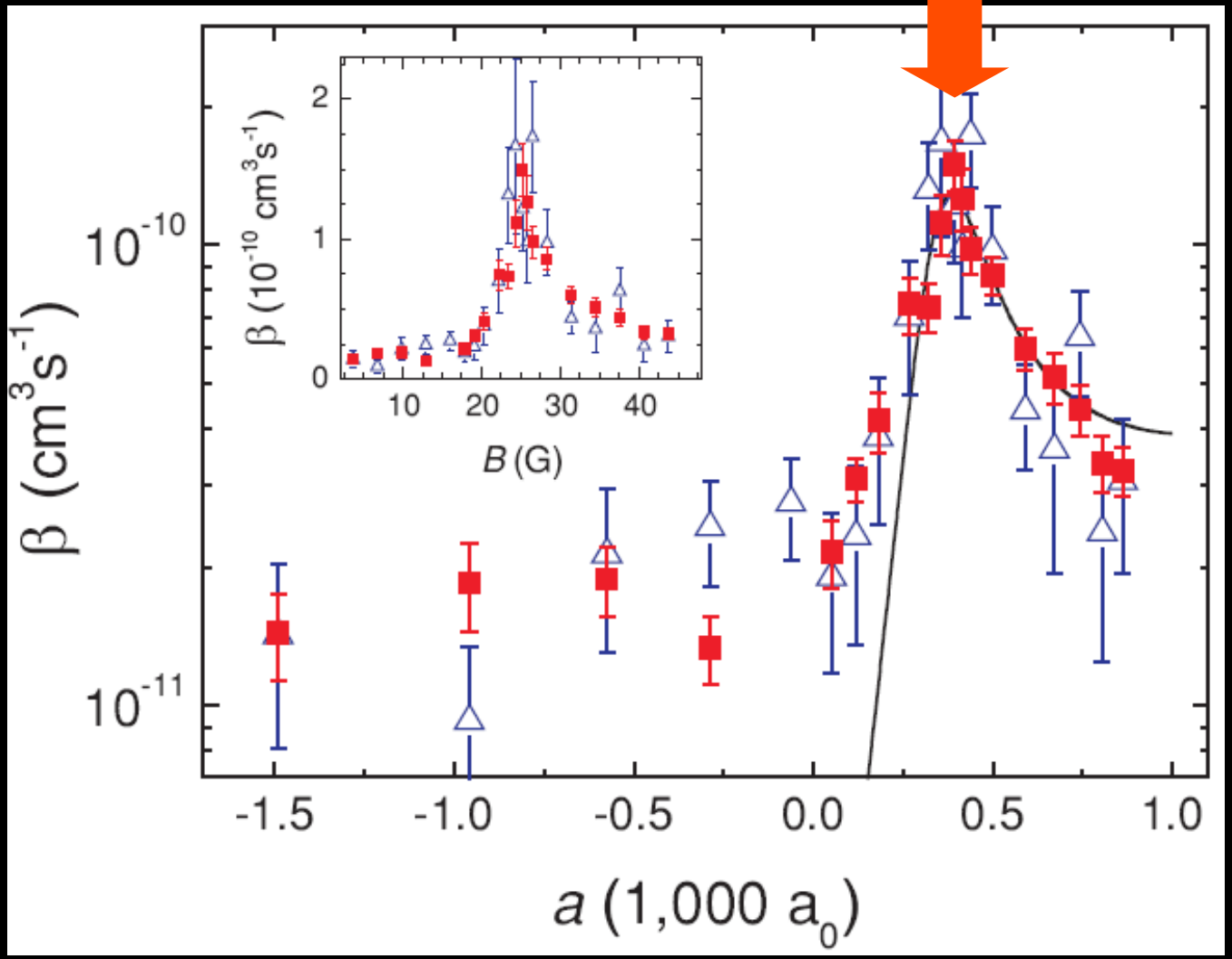
EXP. RESULTS !

ATOM-DIMER RESONANCE !!

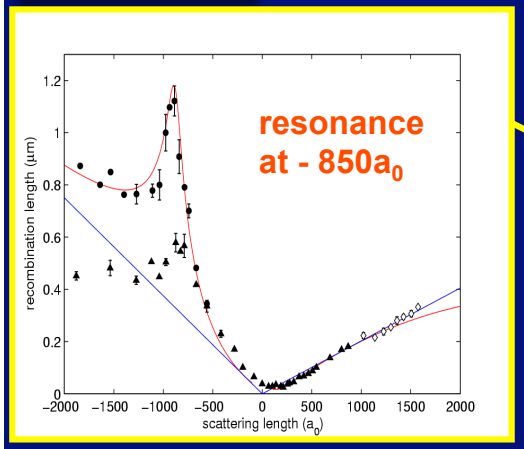
KNOOP ET AL., ARXIV0807.3306

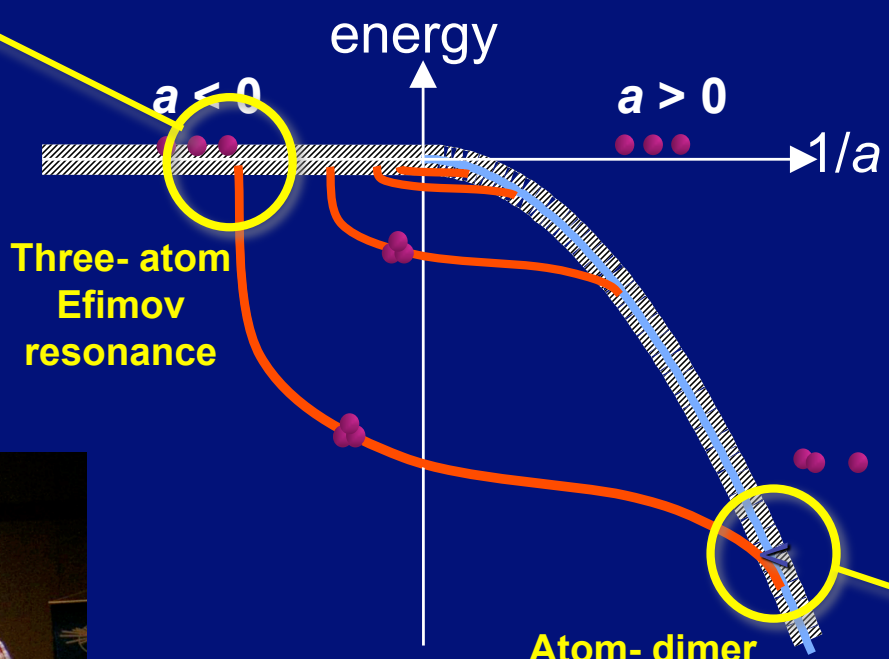
Trimer resonance

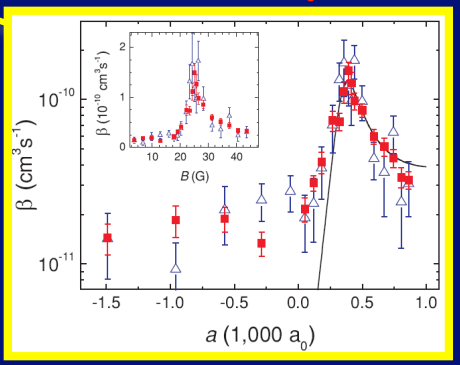
T = 40nK
T=200nK



Universal and Efimov physics: conclusions



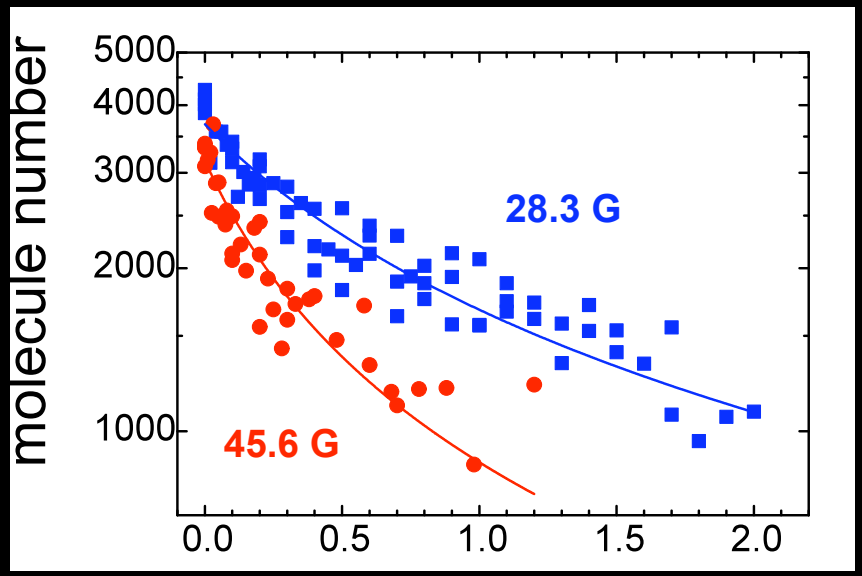




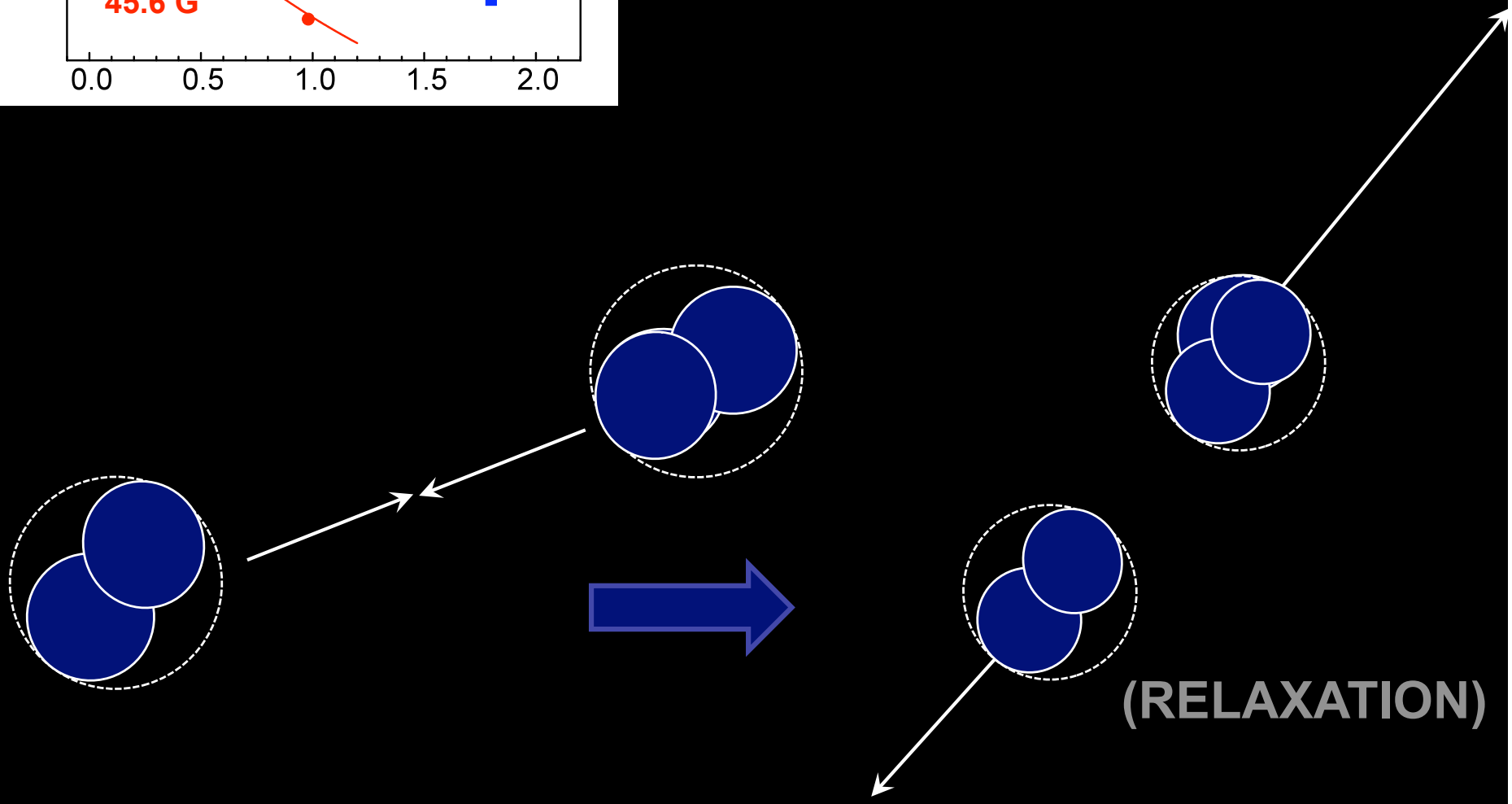
Vitaly Efimov Rudi Grimm
FB18, July 2006

open issues:

- universal regime ? a>>r0, r0 ~100 a0
- connection with the triatomic Efimov state ?
- theoretical model: decay channels
- transition universal to non-universal regime



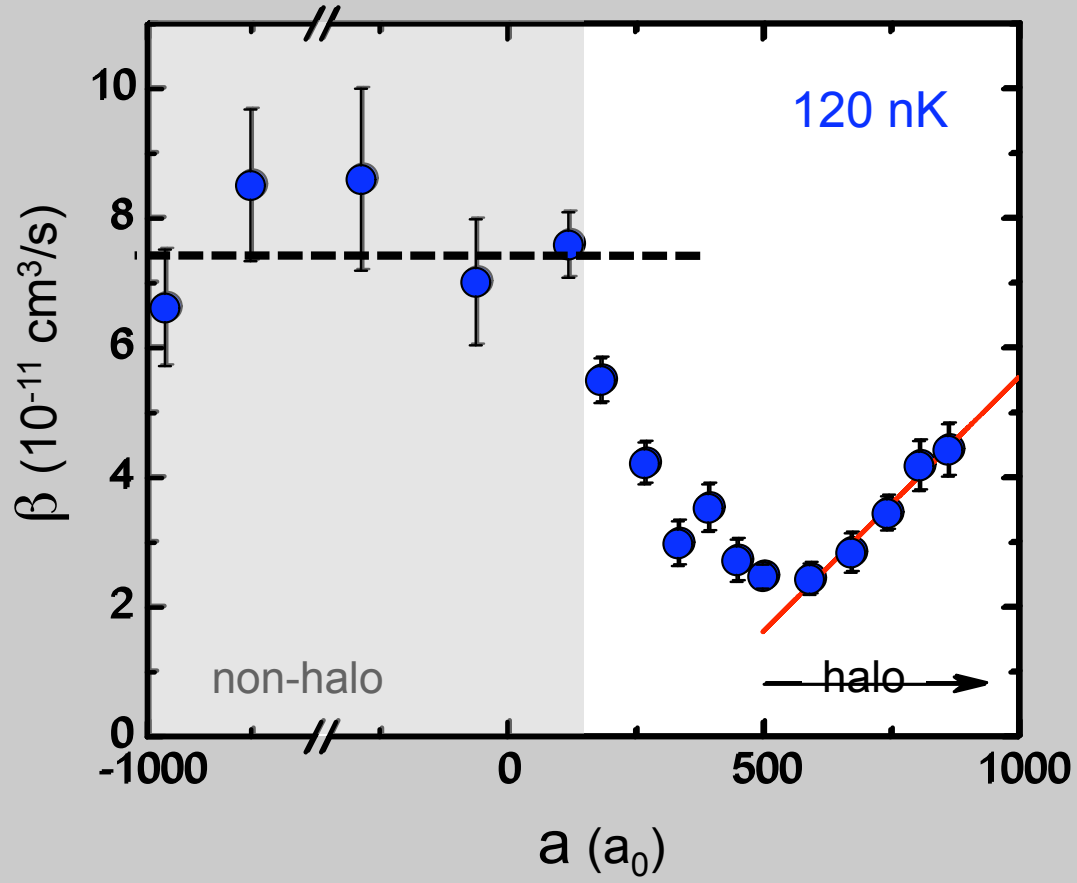
4- body



(RELAXATION)

Dimer-Dimer collisional rate

B-dependence, a-dependence



Quantum halo dimers for $a >> r_0$:

$$\beta = C(a)\frac{\hbar a}{m}$$

universality

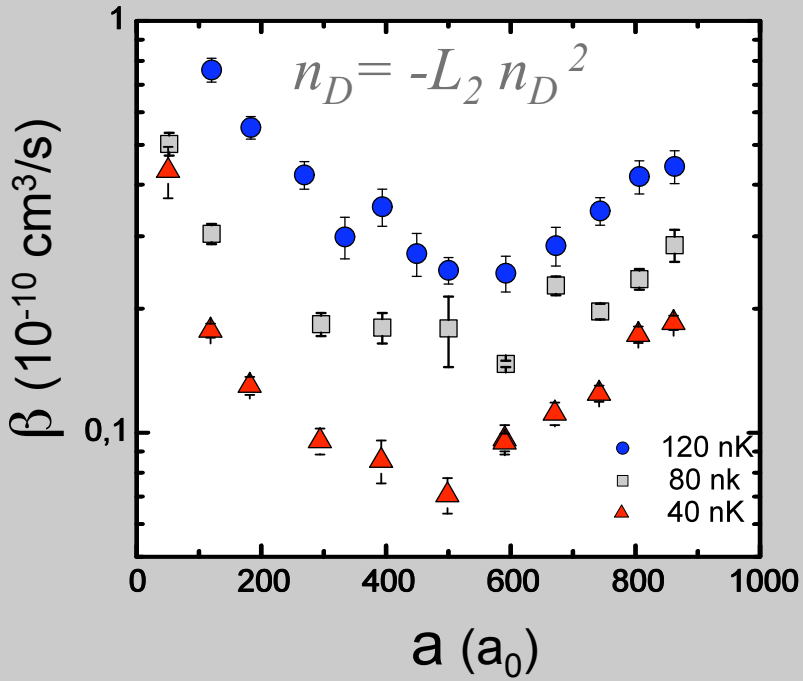
- a-dependence
- existence of a minimum

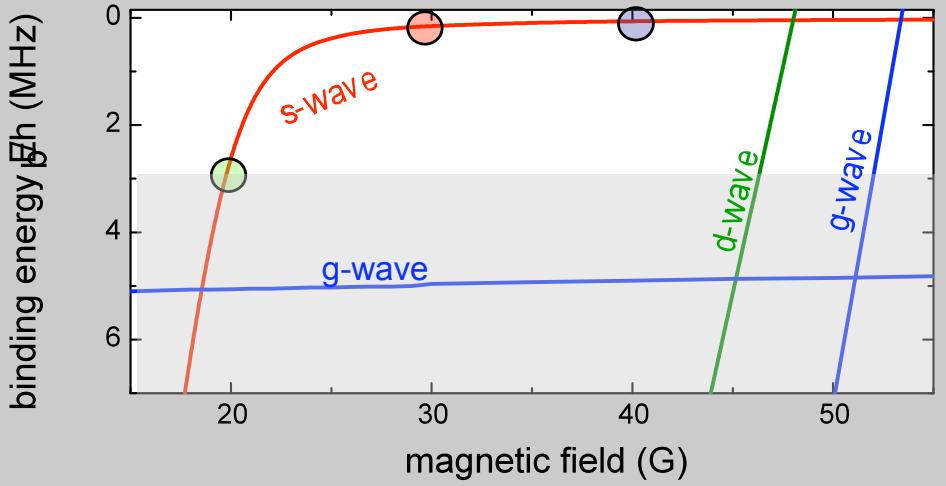
→ **Controlled reactions at ultracold temperatures** (magnetic field)

Ferlaino et al., PRL 101, 023201 (2008)

Private comm. D. Petrov, et al.

T-DEPENDENCE ?



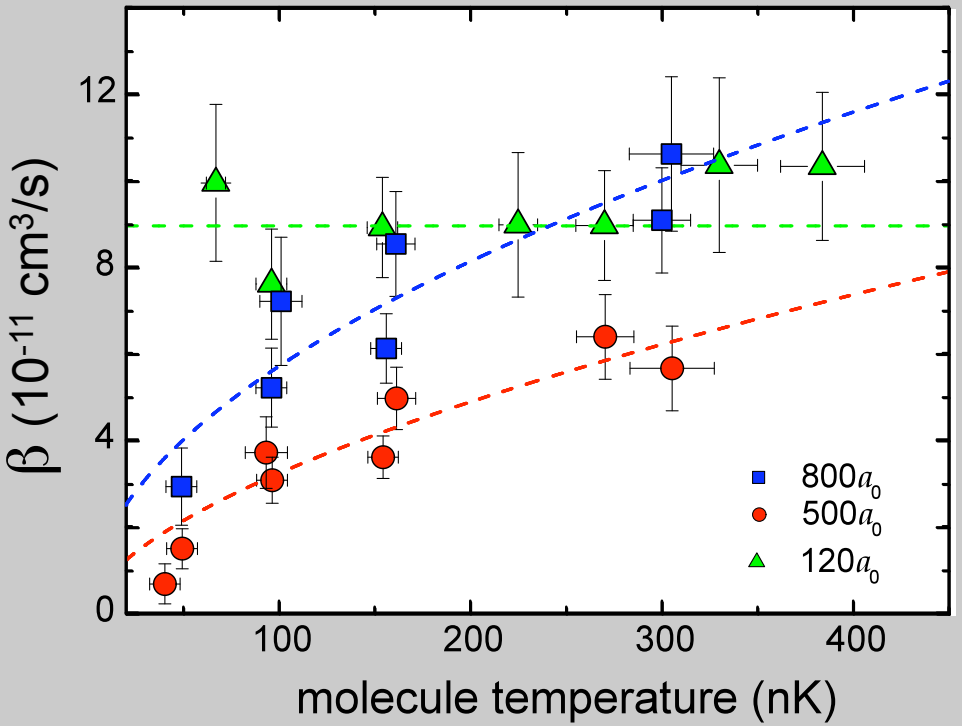


2-body reaction cross section **(Wigner 1948)**

$$\sigma_{in} \sim \frac{1}{v} \sim \frac{1}{T^{1/2}} \qquad L_2 \sim v\sigma_{in} \rightarrow const$$

Collision energy: lowest energy scale ??

$k_B T << E_B$



FERLAINO ET AL., PRL 101, 023201 (2008)

Hammer and Platter, Eur. Phys. J. A **32**, 113 (2007)

D'Incao, Stecher, and Greene, talk at DAMOP 2008

Yamashita et al., Europhys. Lett. **75**, 555 (2006)

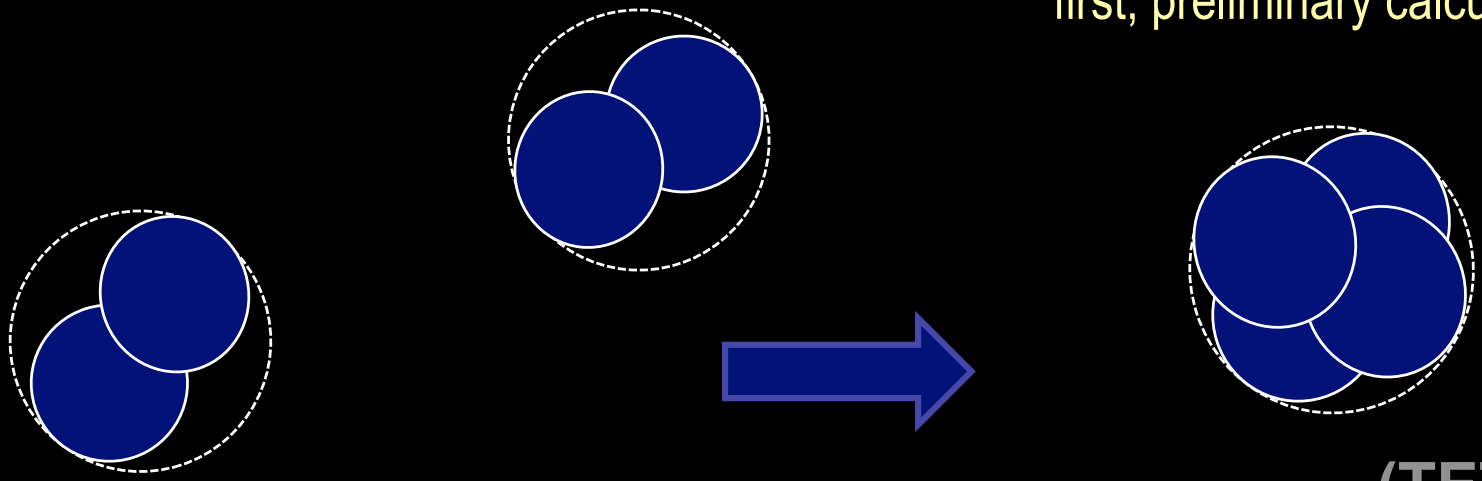
4 - body

what do we understand ?

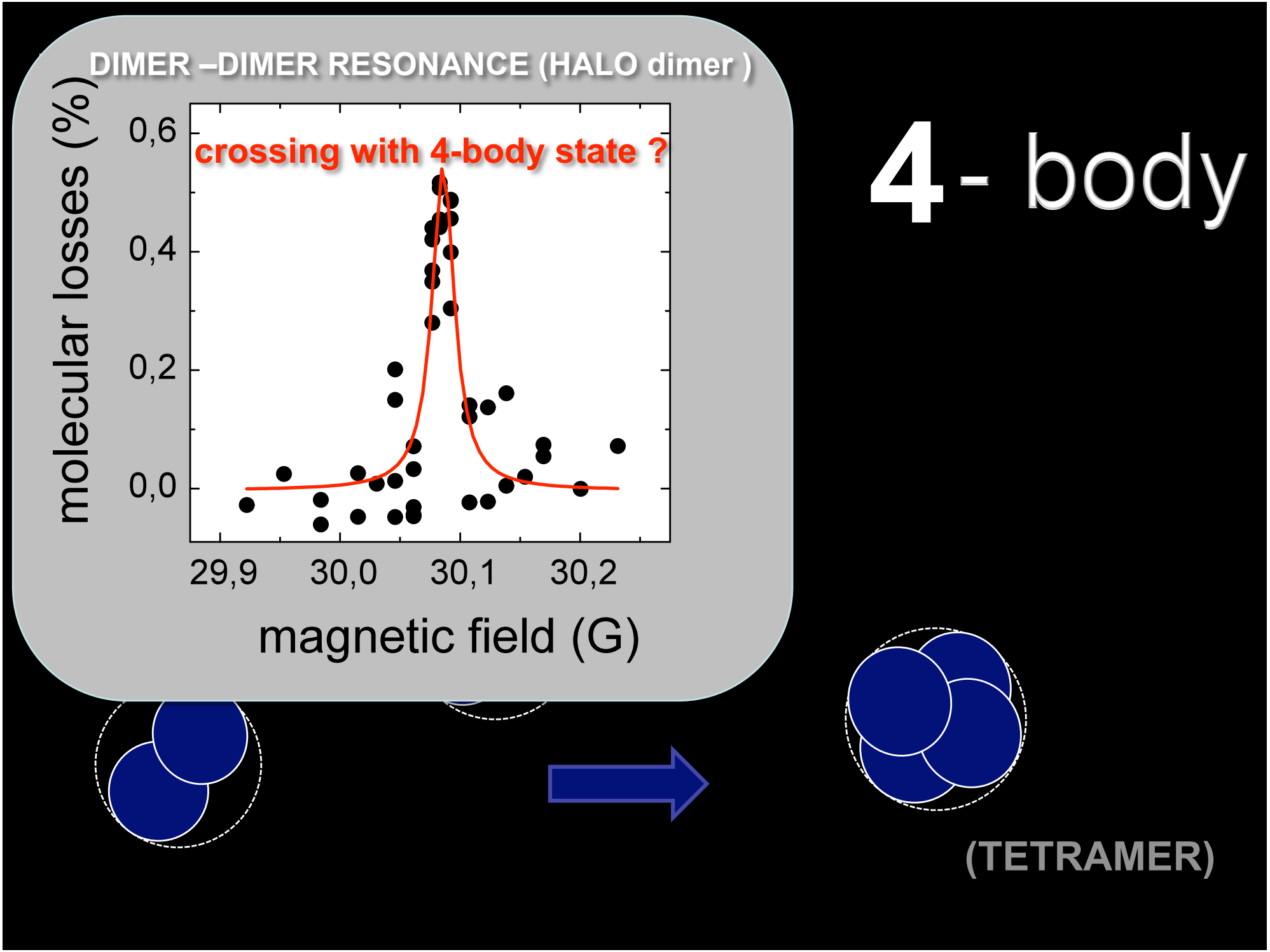
universal 4-body states should exist !

is a 4-body parameter needed ?
question under debate

energy spectrum of these states ?
first, preliminary calculations available

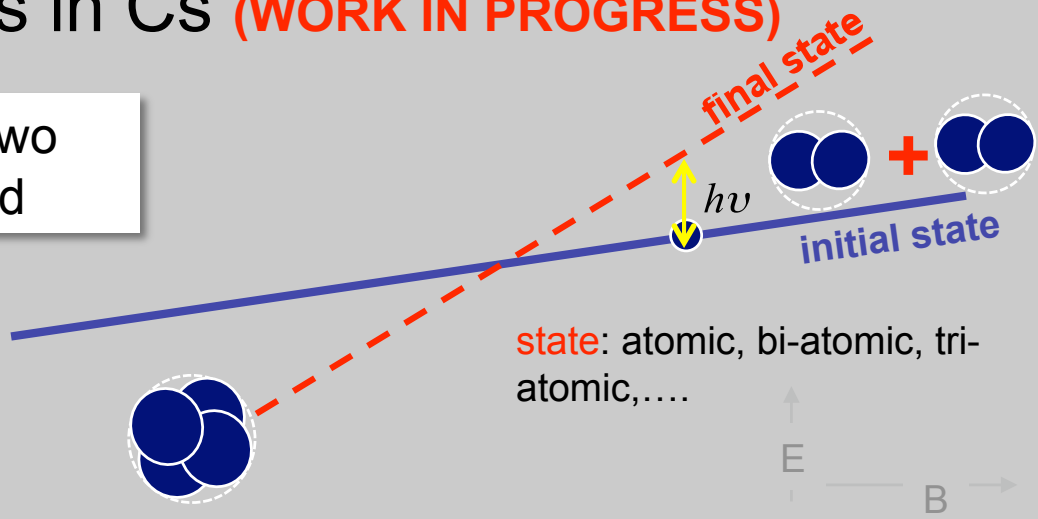


(TETRAMER)

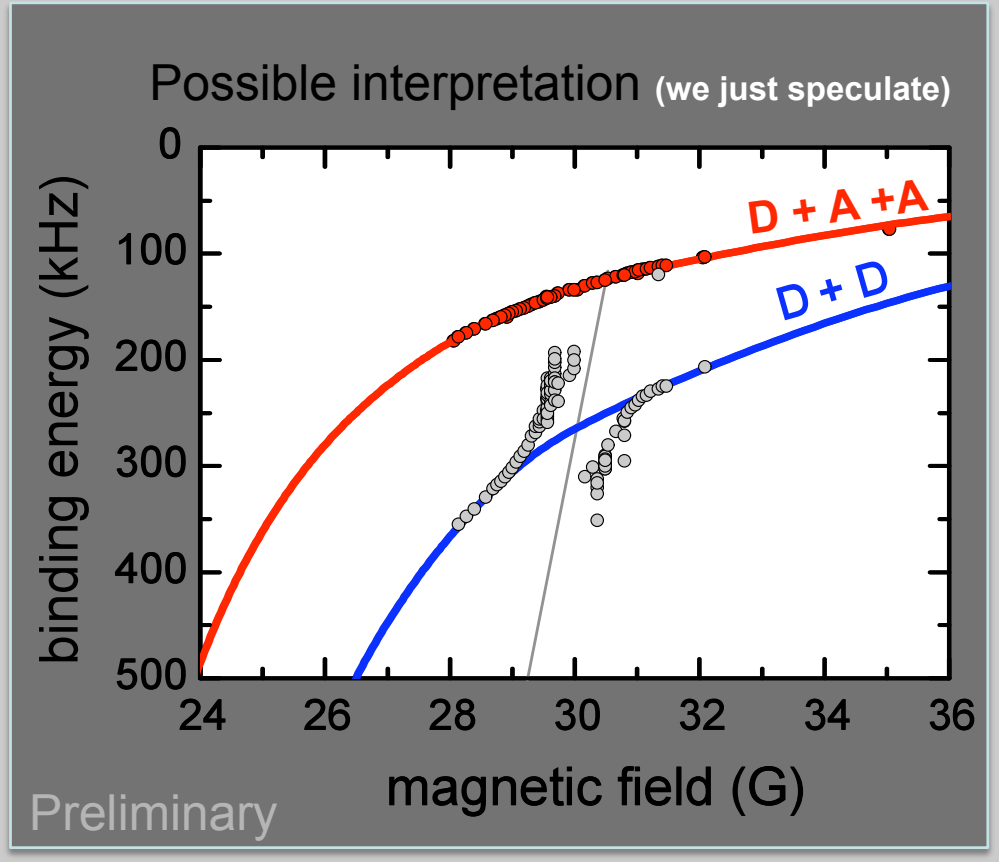

DIMER –DIMER RESONANCE (HALO dimer)
crossing with 4-body state ?
molecular losses (%)
0,6
0,4
0,2
0,0
29,9
30,0
30,1
30,2
magnetic field (G)
4- body
(TETRAMER)

puzzling 4-body observations in Cs (WORK IN PROGRESS)

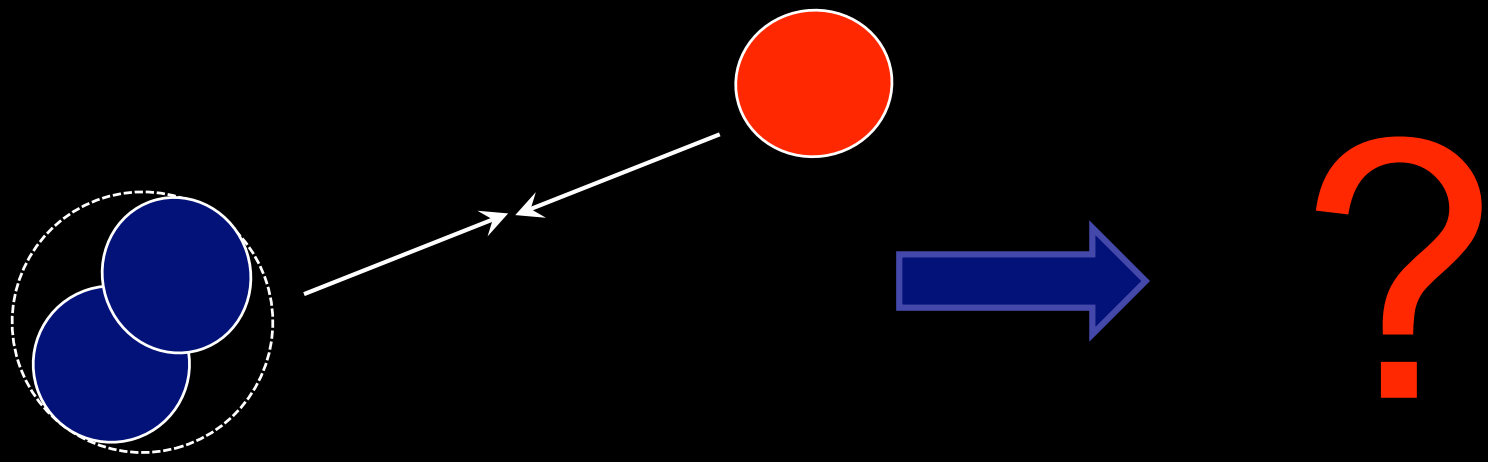
Driving a resonant coupling between two states via an oscillating magnetic field



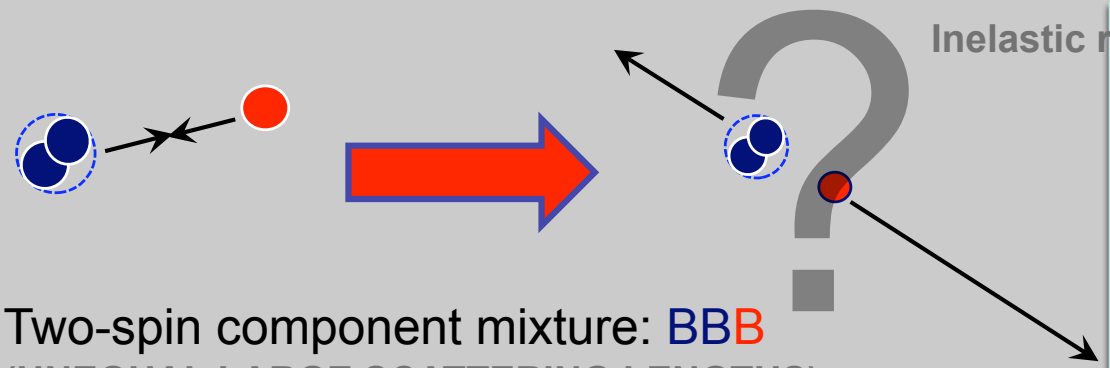
attempt to do "wiggle" spectroscopy: avoided crossing with 4-body state ???



3 - body
(but not identical !)

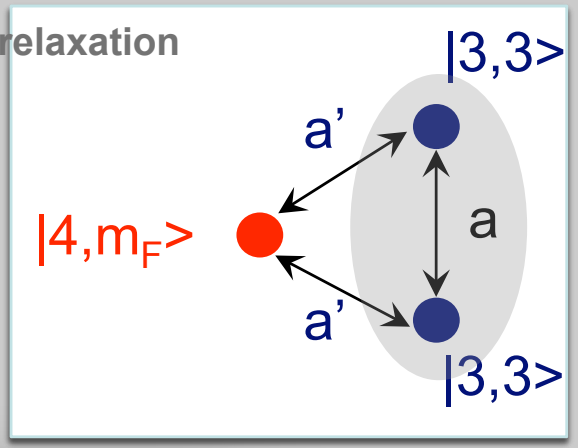


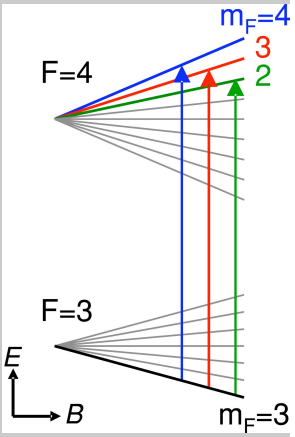
Ultracold Quantum Chemistry with Feshbach Molecules

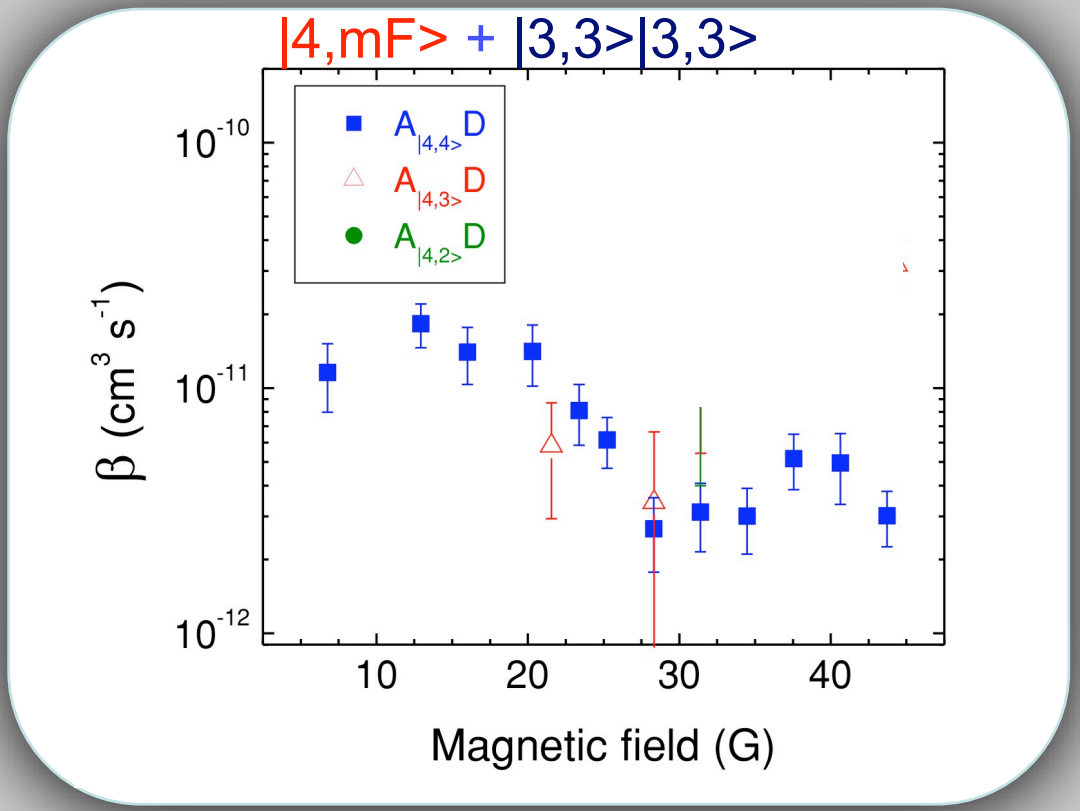


Two-spin component mixture: BBB

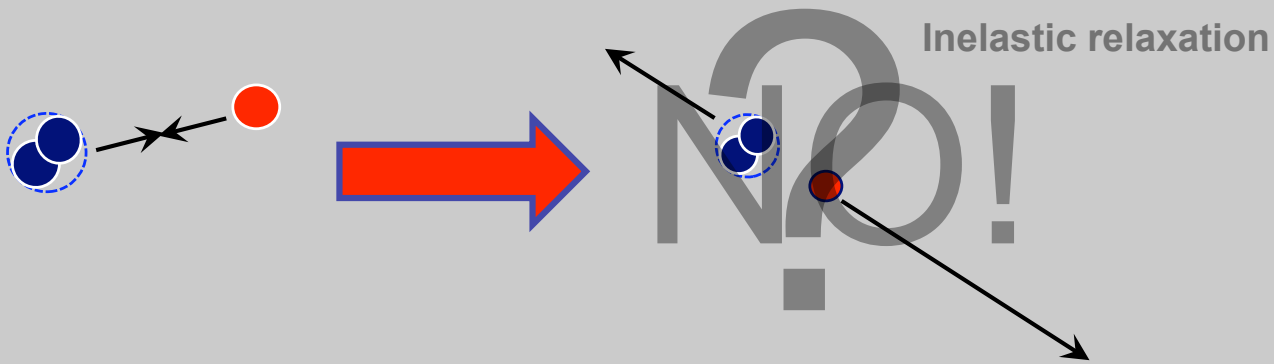
(UNEQUAL LARGE SCATTERING LENGTHS)

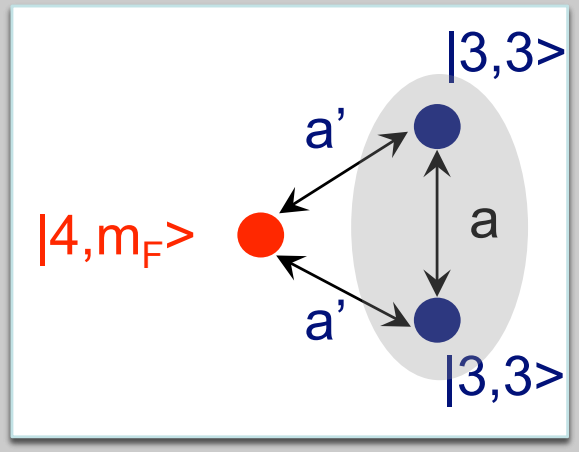


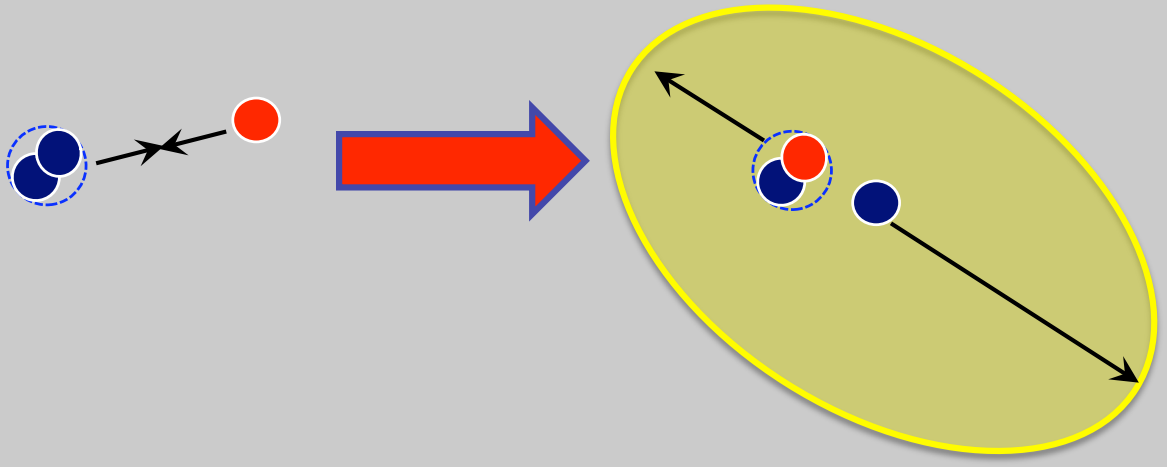




Ultracold Quantum Chemistry with Feshbach Molecules







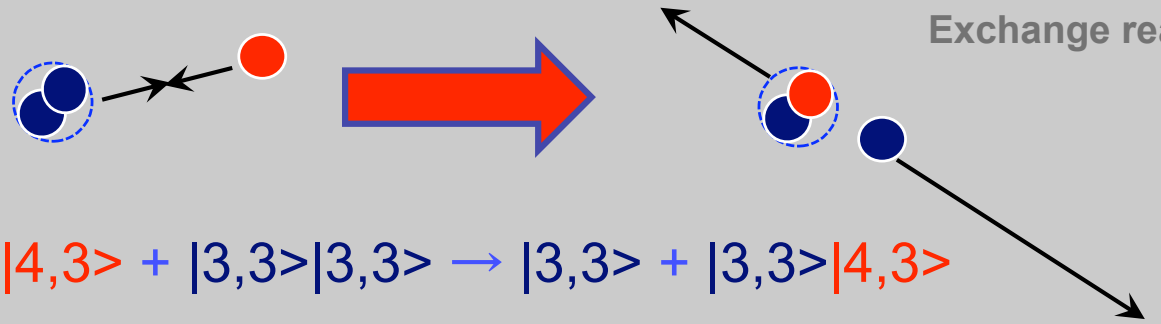
$|4,3\rangle + |3,3\rangle|3,3\rangle \rightarrow |3,3\rangle + |3,3\rangle|4,3\rangle$

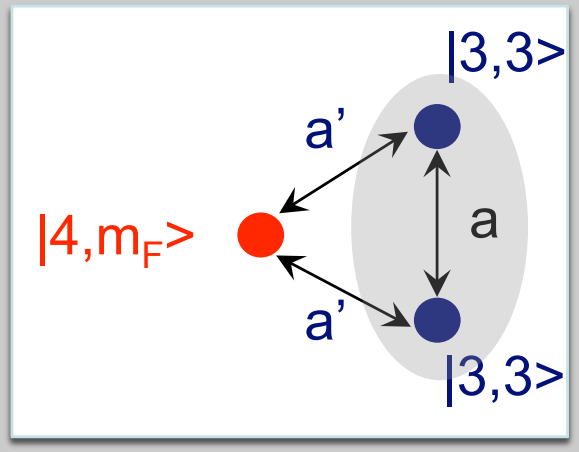
ultracold exchange reaction !

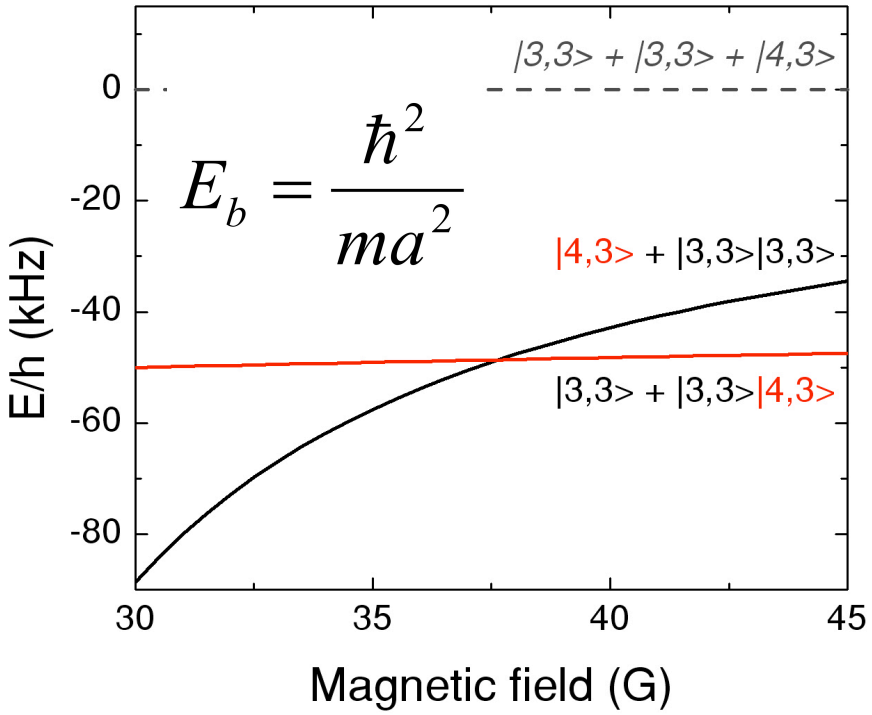
(PRODUCTS ARE CHEMICALLY DISTINCT FROM REACTANS)

with the (BIG) help J. D'Incao & B. Esry

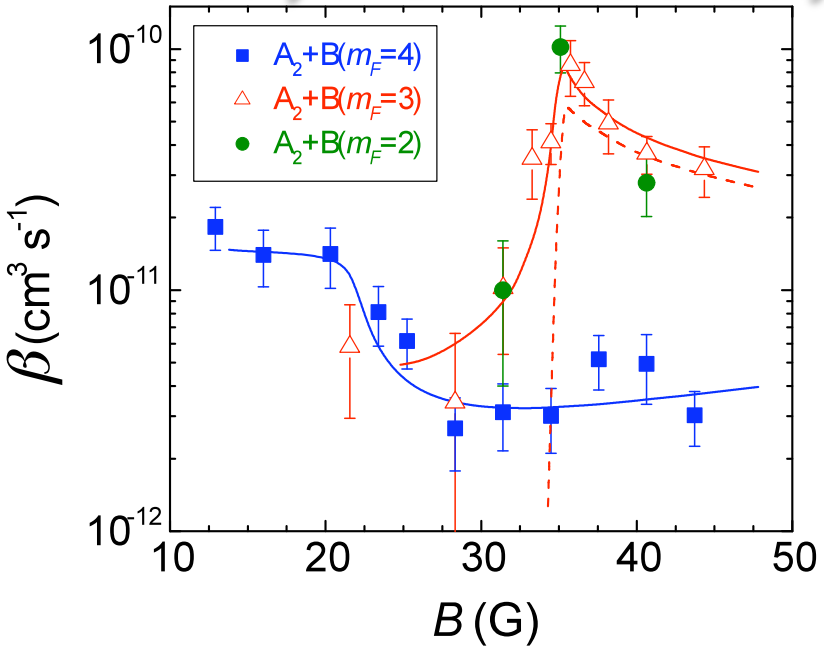
Evidence for Ultracold Exchange Reaction !



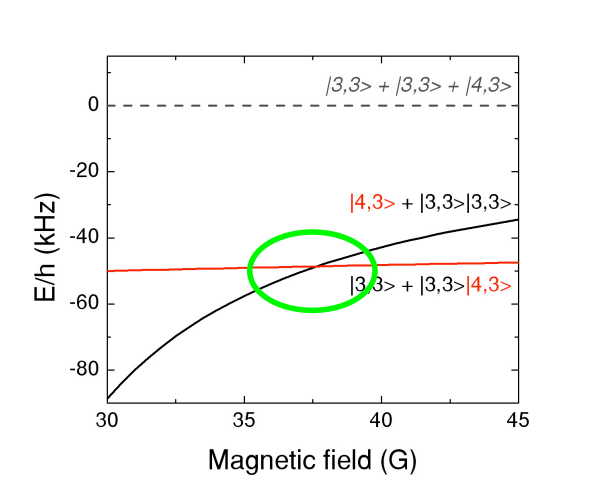




Theory J. D'Incao & B. Esry



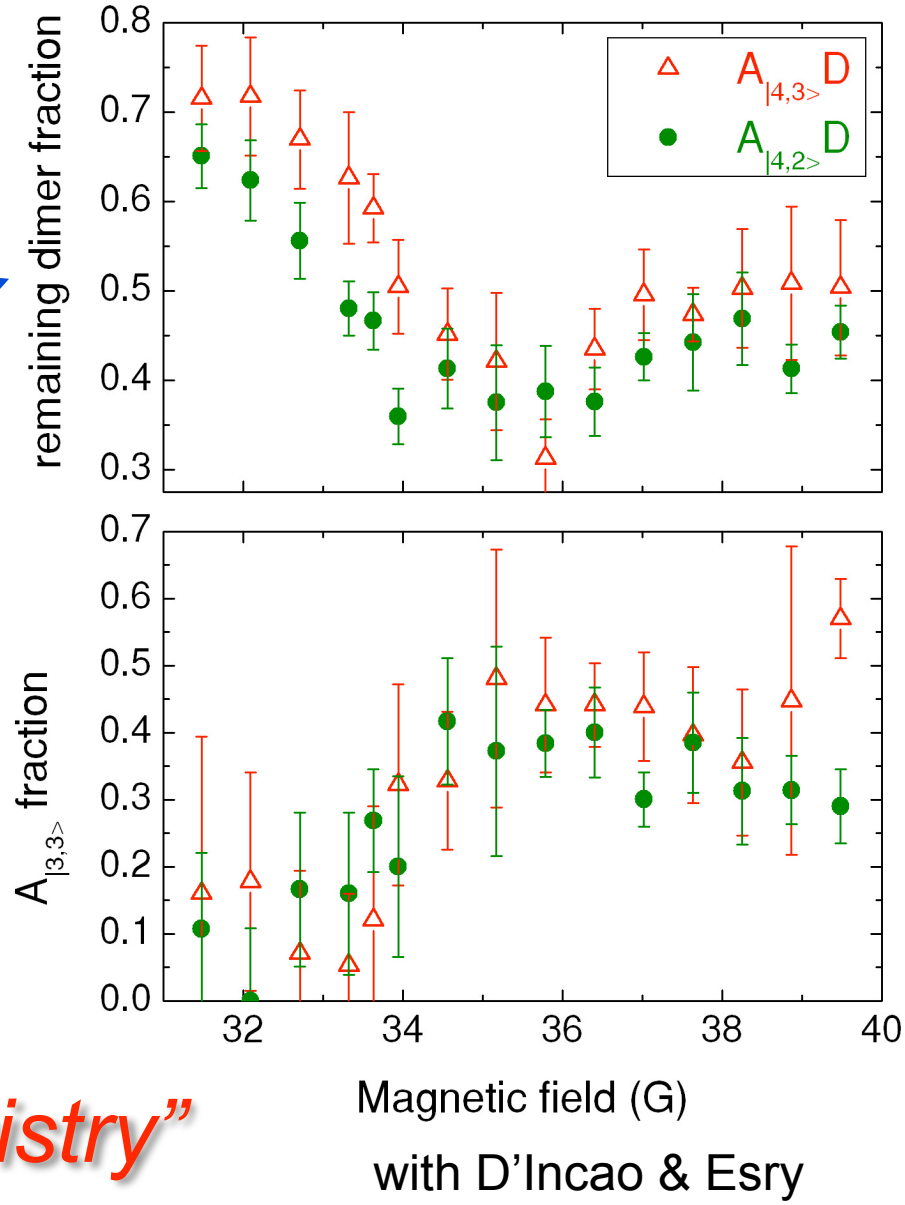
Evidence for Ultracold Exchange Reaction !



$|4,3\rangle + |3,3\rangle|3,3\rangle \rightarrow |3,3\rangle + |3,3\rangle|4,3\rangle$

Same for

$|4,2\rangle + |3,3\rangle|3,3\rangle \rightarrow |3,3\rangle + |3,3\rangle|4,2\rangle$



"Ultracold quantum chemistry"

with D'Incao & Esry

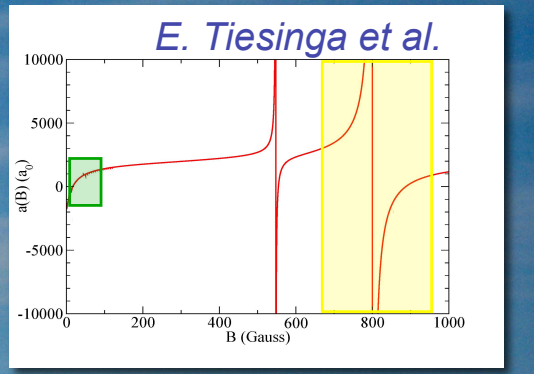
Summary and outlook…

- Feshbach resonance:
  coupling two atoms to bound dimer state
  enormous impact on ultracold physics in last few years

- Few-body physics with ultracold Cs atoms and molecules
  (atom-dimer resonance, dimer-dimer collisional suppression)

- Efimov resonance:
  coupling three atoms to bound trimer state
  connects ultracold world to few-body quantum physics

- 800-G Feshbach resonance
  (deeper into universal regime, second Efimov resonance)



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