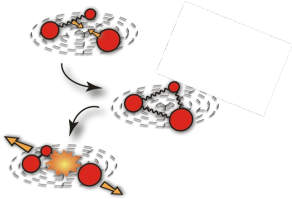
Few-Body Physics with ultracold atoms



Francesca Ferlaino

Universität Innsbruck, Austria

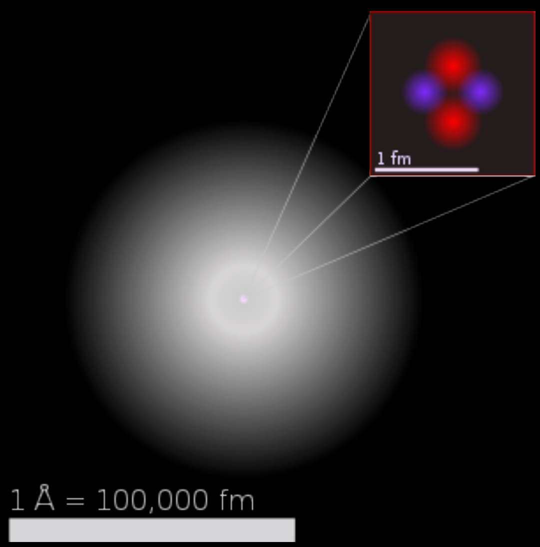
www.ultracold.at

ELECTRON-NUCLEUS SCATTERING XII

Marciana Marina, Isola d'Elba

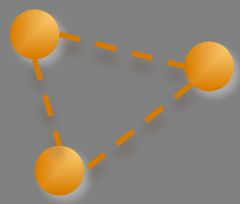
ELECTRON-NUCLEUS SCATTERING XII

ATOM

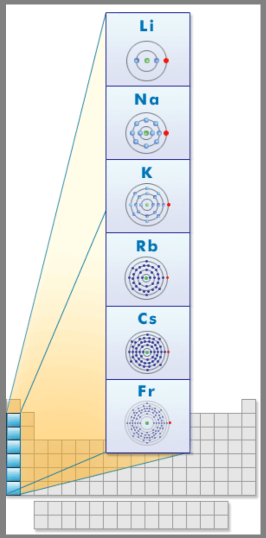


Marciana Marina, Isola d'Elba

FEW-BODY PHYSICS
setting a common dictionary

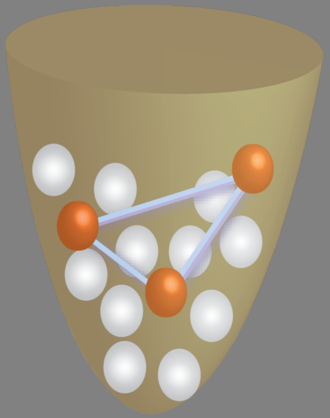


- *Neutral bosonic atoms (Alkali: Li, Na, K, Rb, Cs)*
- *Massive particles* $M = Isotope * M_{proton}$



Ultracold

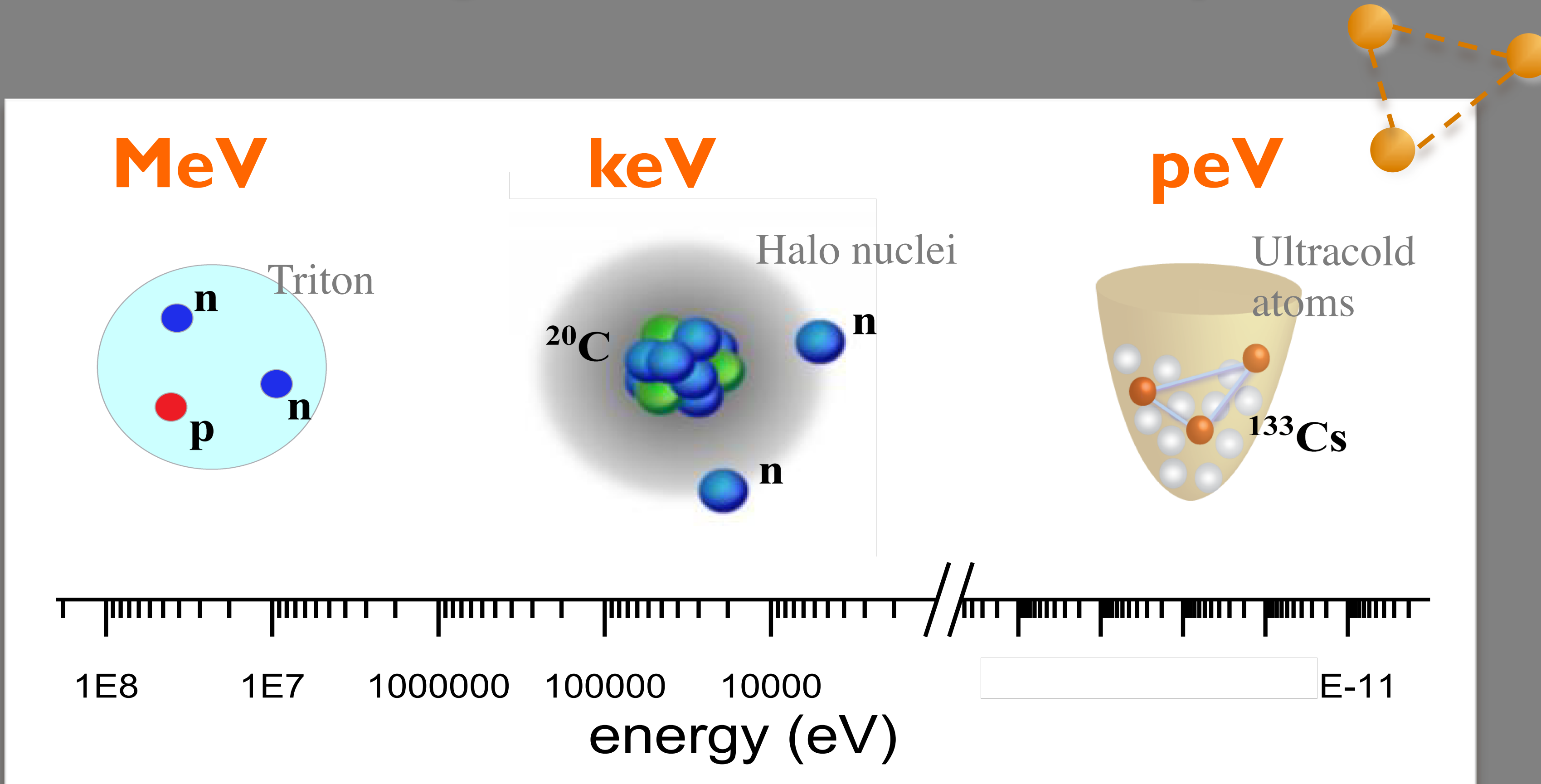
T~ 100 nK → E_{kin} ~ 10 peV



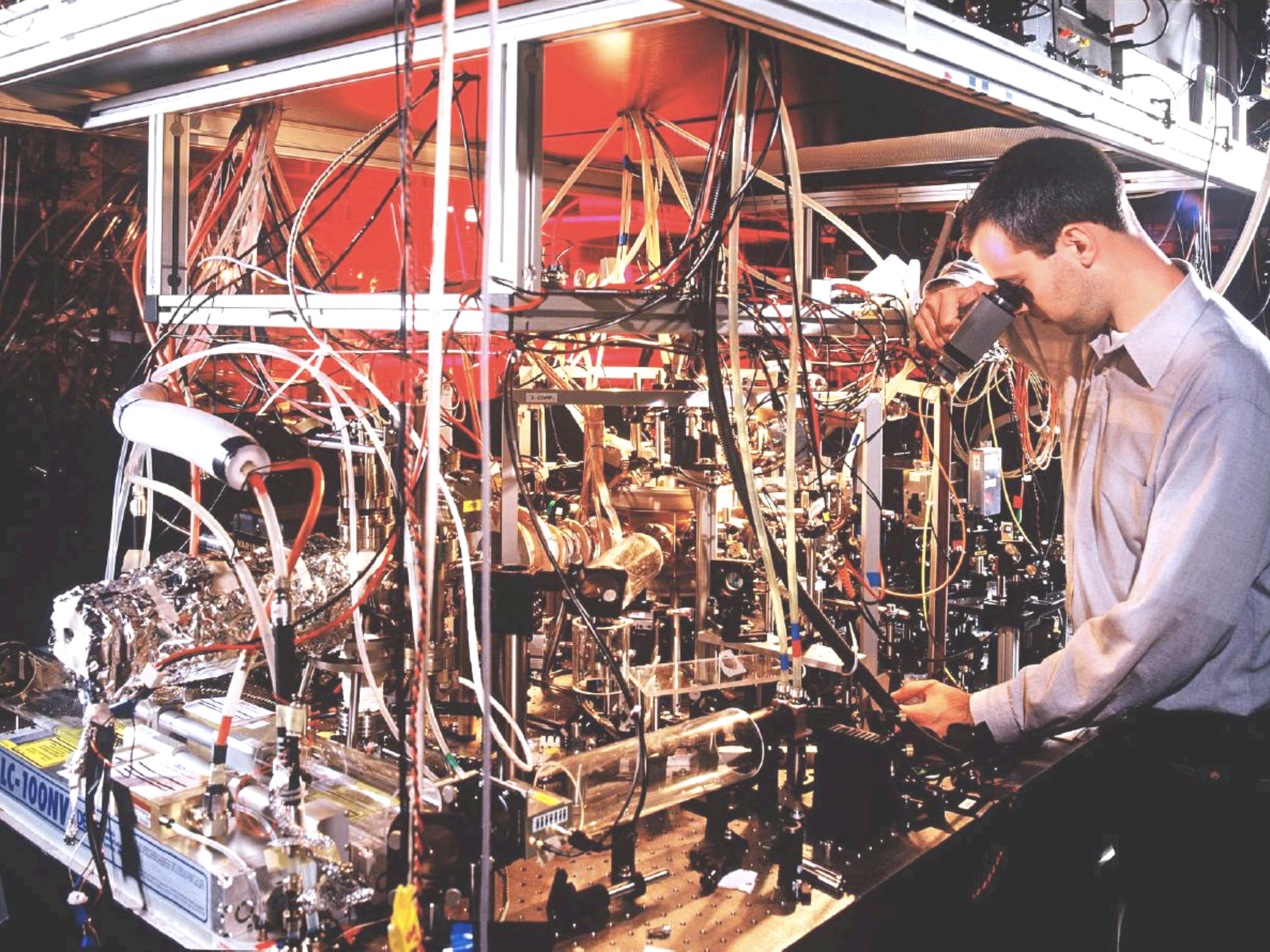
- *Ultracold – dilute* ($n \sim 10^{13}$ cm^{-3})
- *Macroscopic ensemble* (10^5 *atom) – Confined into a trap*

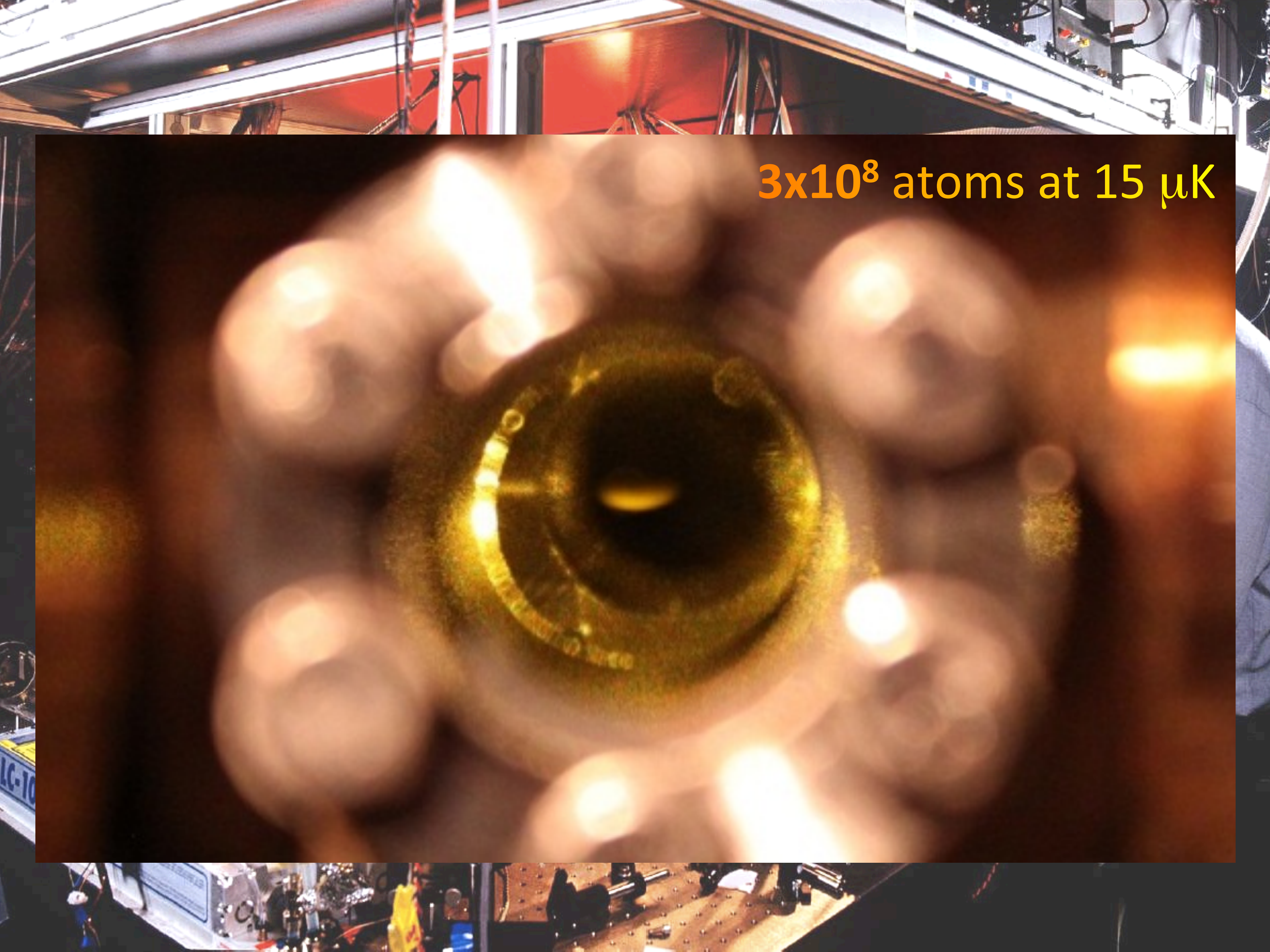
FEW-BODY PHYSICS

setting a common dictionary



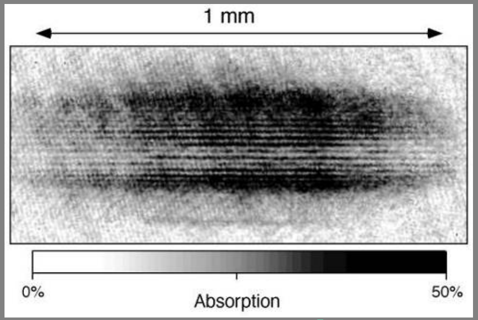
Very different systems – different experimental techniques – common effects


LC-100NV

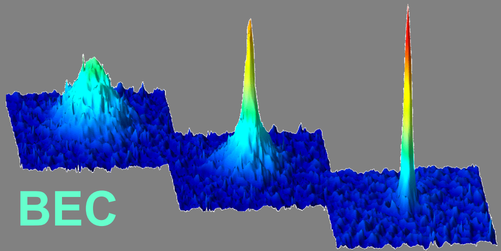

3×10^8 atoms at 15 μK

UltraCold Atoms: Why ?

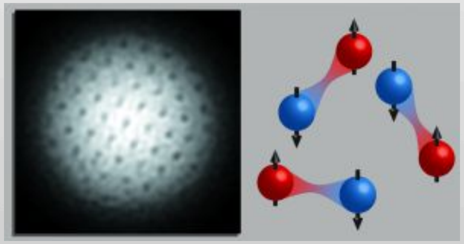
Main Motivation: Many-Body Quantum States



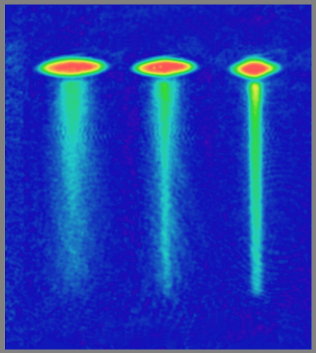
matter-wave coherence



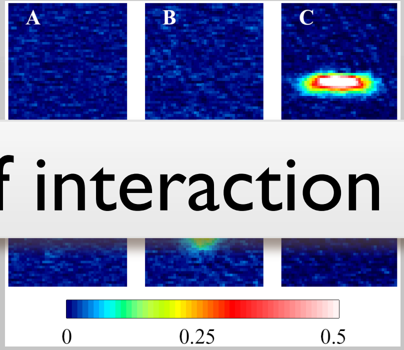
BEC



fermions

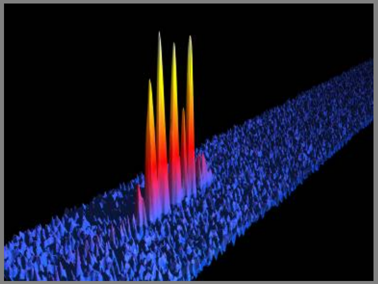


laser



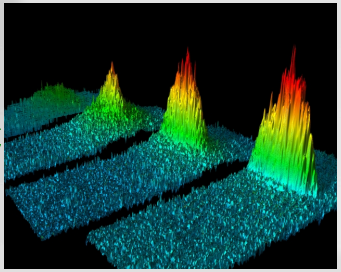
Tuning of interaction

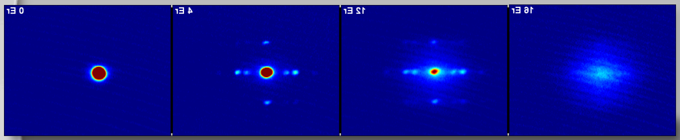
ultracold molecules



solitons

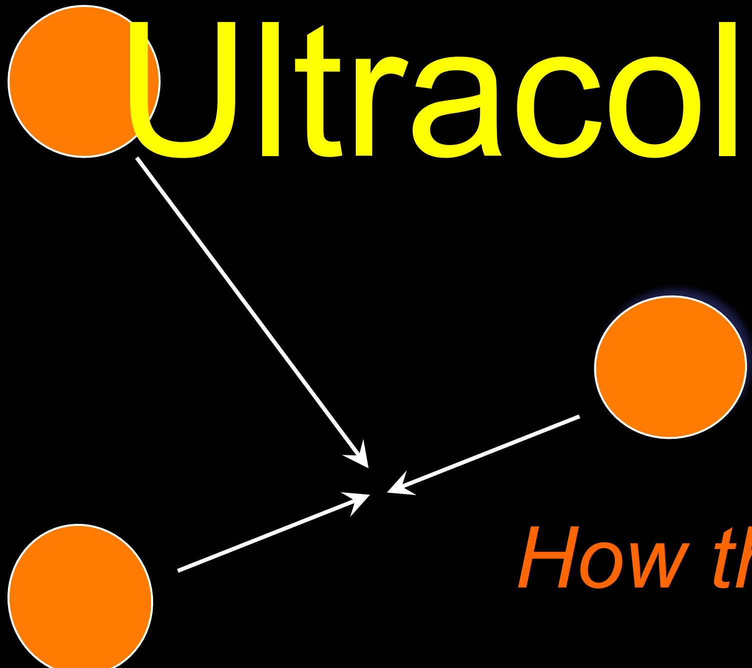
mBEC





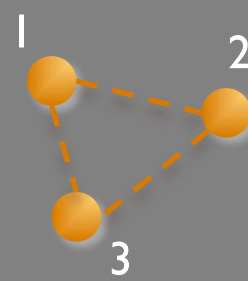
Mott insulator

Few-Body Physics and … Ultracold Atoms



How three particles interact ?

FEW-BODY PHYSICS
setting a common dictionary

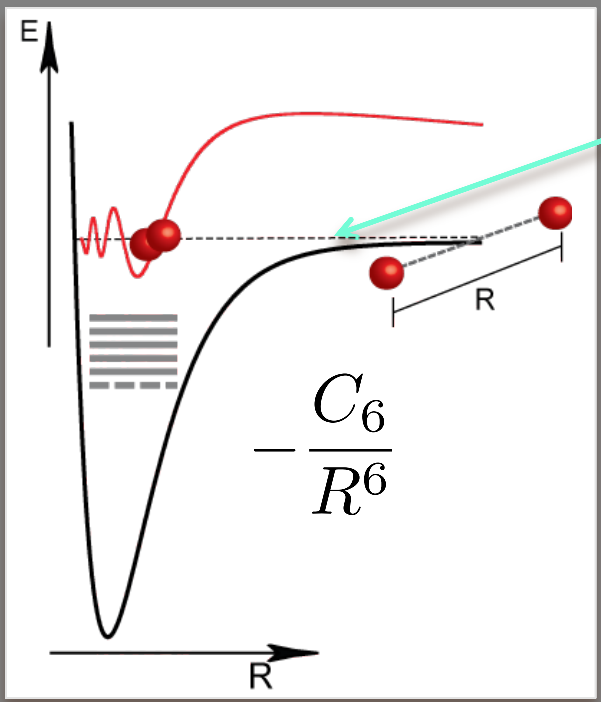


A very important concept: INTERACTION

$$V_{123} = \underbrace{V_{12} + V_{23} + V_{31}}_{\text{pair-wise potentials}} + V_{3B}$$

"True" 3B potential

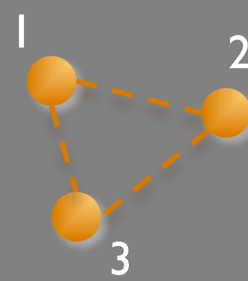
pair-wise potentials



In ultracold gases, the 2B interaction is governed by a single parameter:

The s-wave scattering length a

FEW-BODY PHYSICS
setting a common dictionary

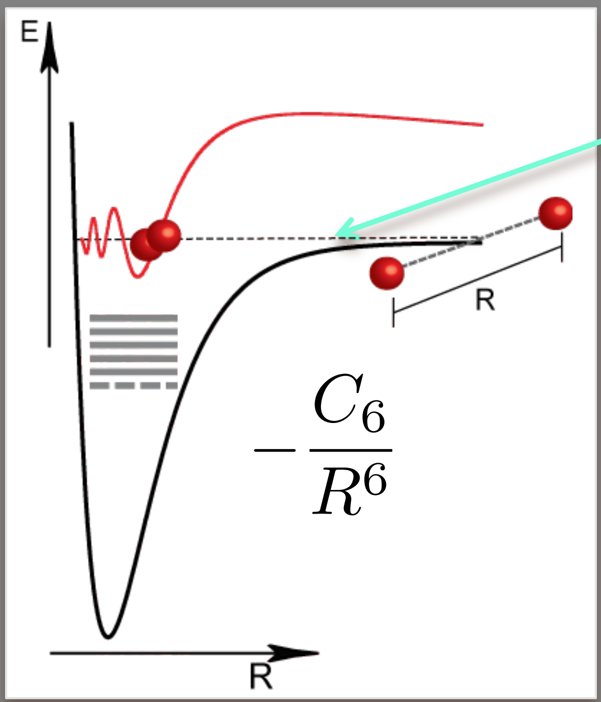


A very important concept: INTERACTION

$$V_{123} = V_{12} + V_{23} + V_{31} + V_{3\mathrm{B}}$$

"True"3B potential

pair-wise potentials



$$-\frac{C_6}{R^6}$$

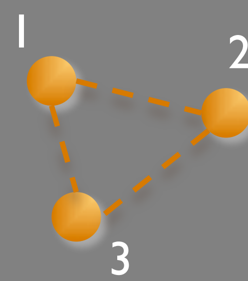
Sensitivity to short-range physics is included into a

$$a = -\lim_{k \to 0} \frac{\delta_{2B}}{k}$$

δ_{2B} phase shift

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

FEW-BODY PHYSICS
setting a common dictionary



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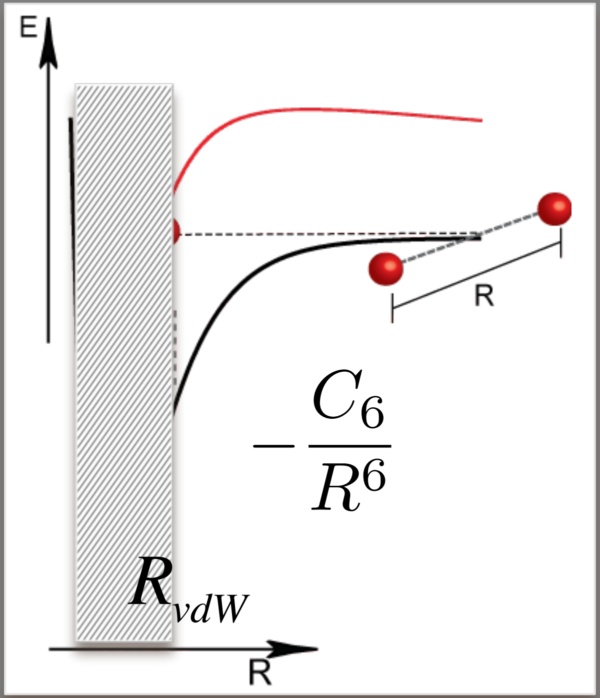
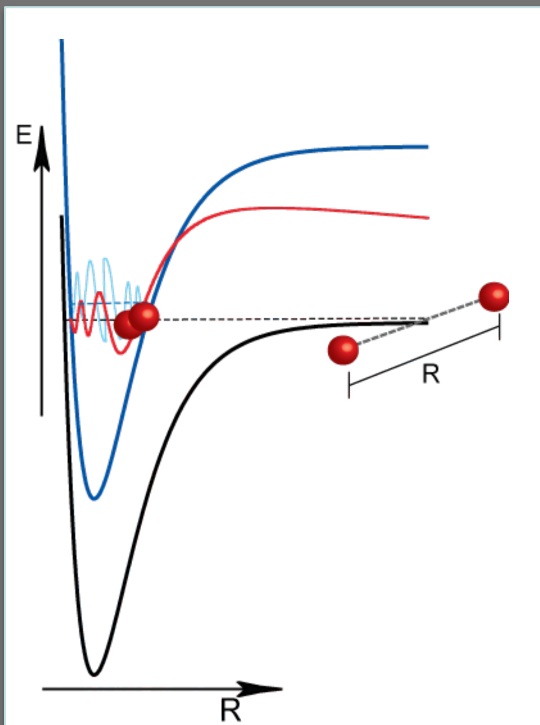


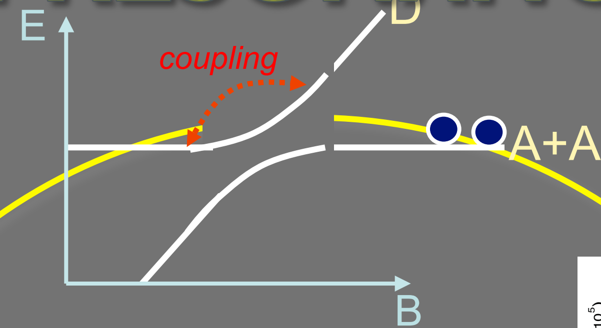
UNIVERSAL REGIME

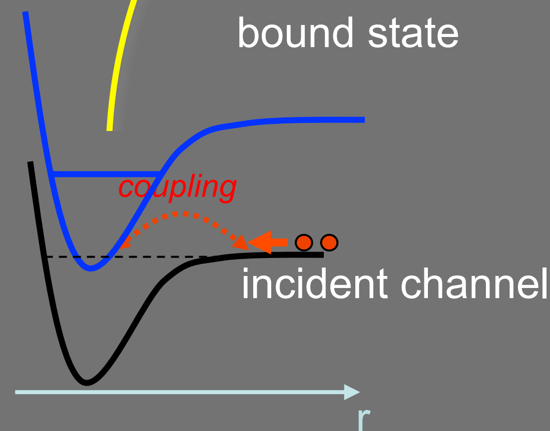
$$a >> R_{vdW}$$

RESONANT PAIRWISE INTERAC.

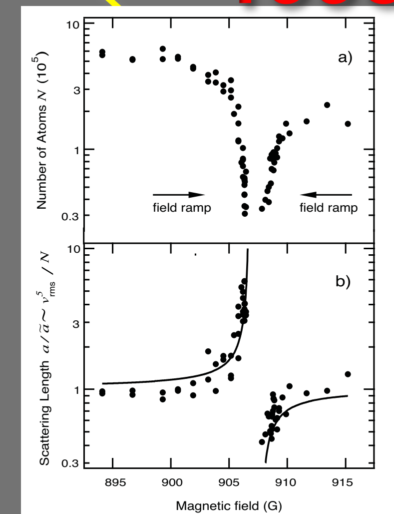
FESCHBACH RESONANCE



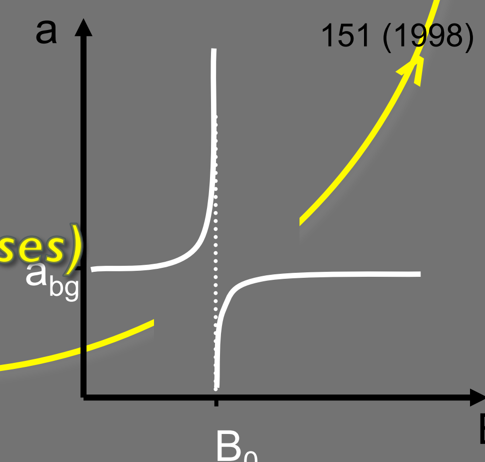




1998



Inouye, et al. Nature 392, 151 (1998)

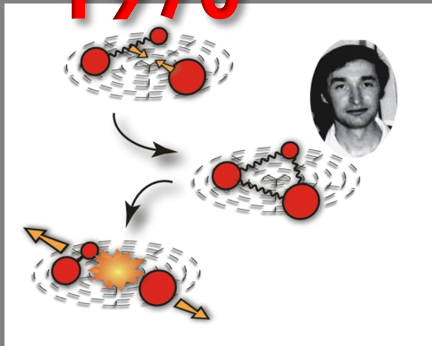


Magnetic TUNING !!

(almost unique to ultracold atomic gases)

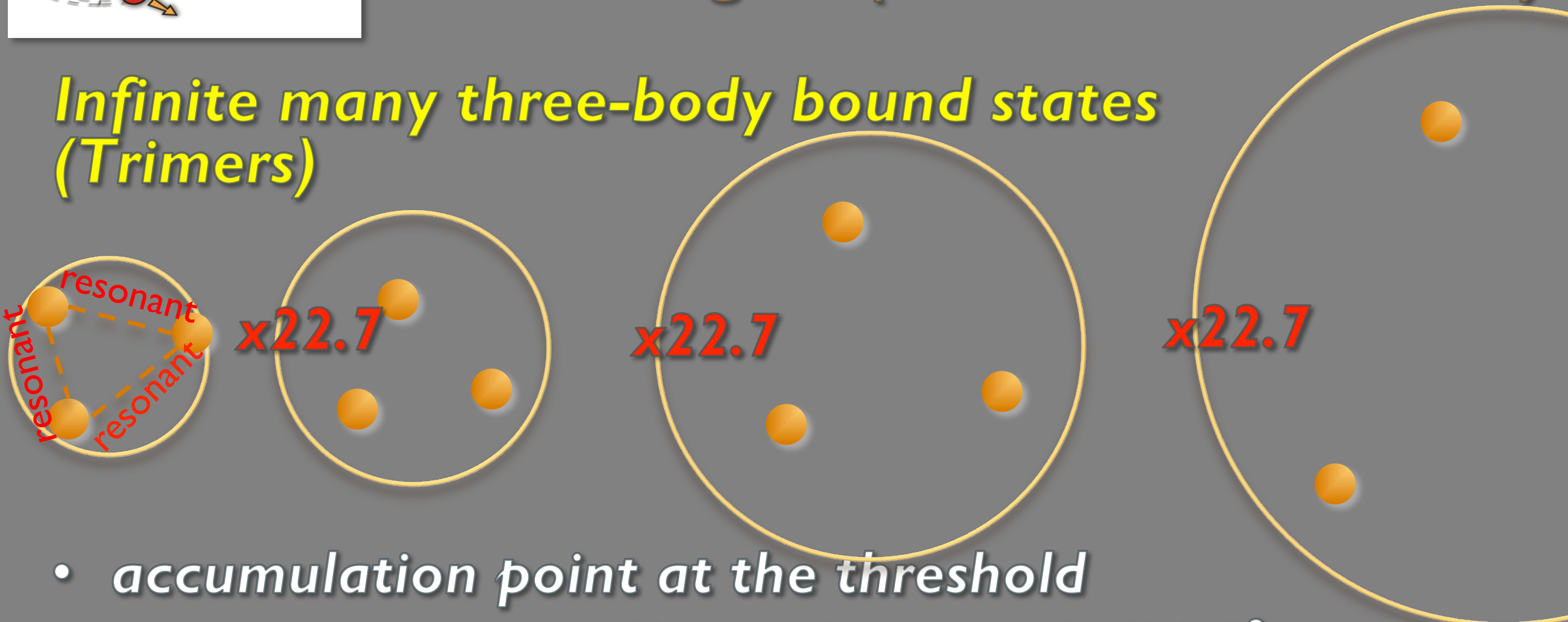
EFIMOV EFFECT

1970



How three particles interact in the universal regime (three identical bosons)

Infinite many three-body bound states (Trimers)



- *accumulation point at the threshold*
- *binding energies differ by factors of $1/22.7^2$*
- *sizes differ by factors of 22.7*

ENERGY SPECTRUM

SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 12, NUMBER 5 MAY, 1971

WEAKLY-BOUND STATES OF THREE RESONANTLY-INTERACTING PARTICLES

V. N. EFIMOV

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted February 16, 1970

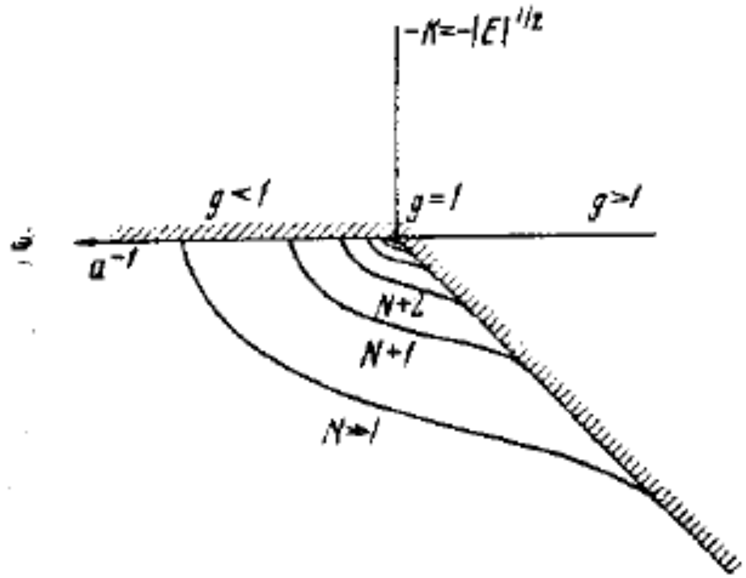
Yad. Fiz. 12, 1080–1091 (November, 1970)

It is shown that if the pair forces of three identical particles are sufficiently resonant, a family of bound states of low energy is produced. The quantum numbers of all the states are the same: for spinless bosons 0^+ and for nucleons $\frac{1}{2}^+$, T = $\frac{1}{2}$. The dimension of the states is larger than the radius of the pair forces. The most favorable conditions for the appearance of a family of levels occur for three spinless neutral bosons: the conditions are less favorable for charged particles and particles with spin and isospin. The possibility of existence of such levels in a system of three particles (in the C^{12} nucleus) and of three nucleons (H^3) is considered.

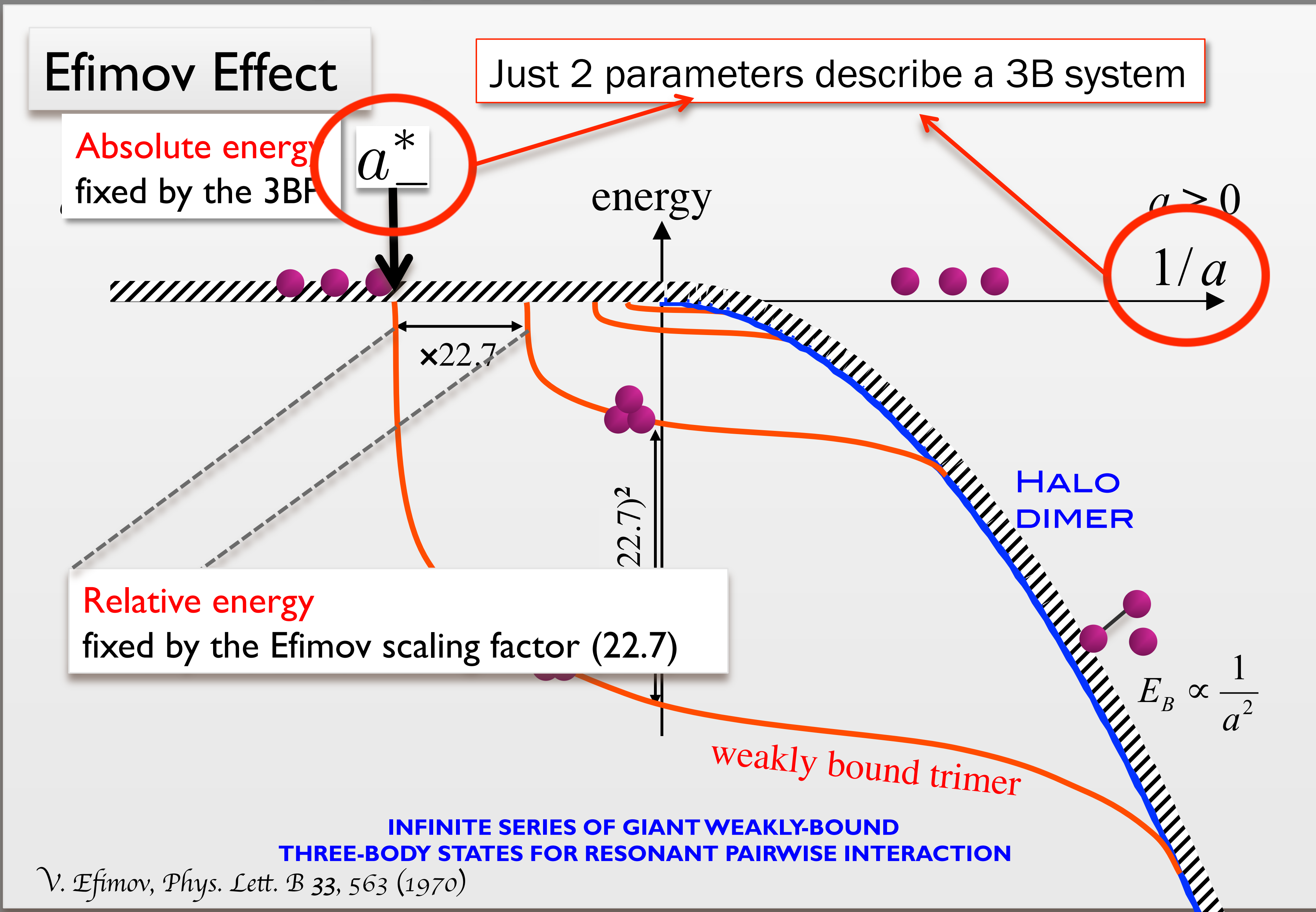
ENERGY SPECTRUM

SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 12, NUMBER 5 MAY, 1971

FIG. 1. Level spectrum of three spinless neutral particles. The cross hatching denotes the boundary of the continuous spectrum of the three particles. Neighboring level trajectories differ only in a scale transformation by an approximate factor of 22. For clarity, this ratio is not maintained in the figure.

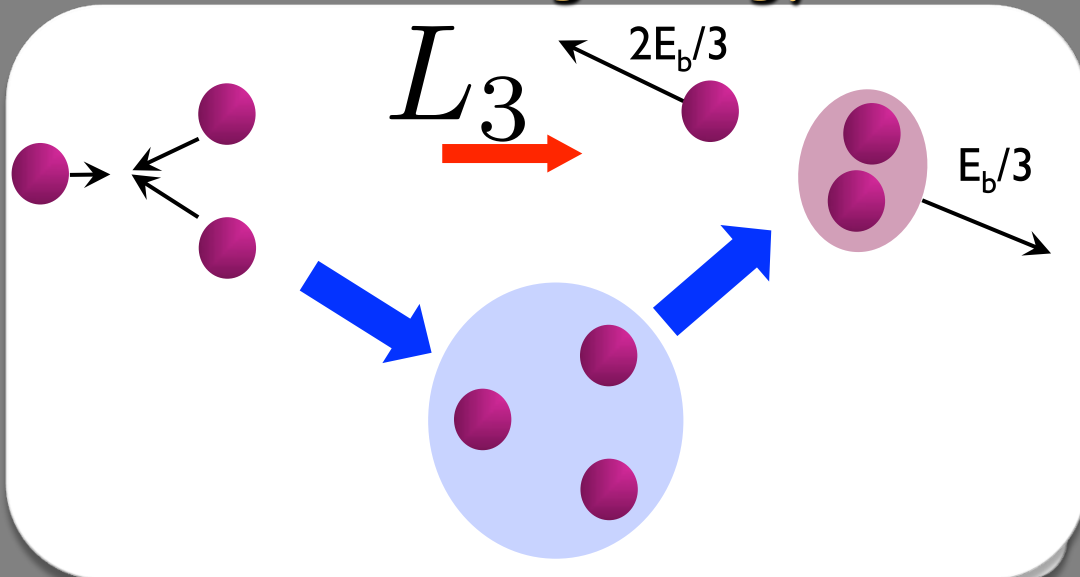


Energy Spectrum of the Efimov Trimers



OUR OBSERVABLES: LOSS

release of binding energy -> loss



Impact of Efimov trimers on L_3

$$\dot{n} = -L_3\, n^3$$

L_3: three-body loss coefficient [cm^6/s]

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

Fedichev *et al.*, PRL **77**, 2921 (1996)

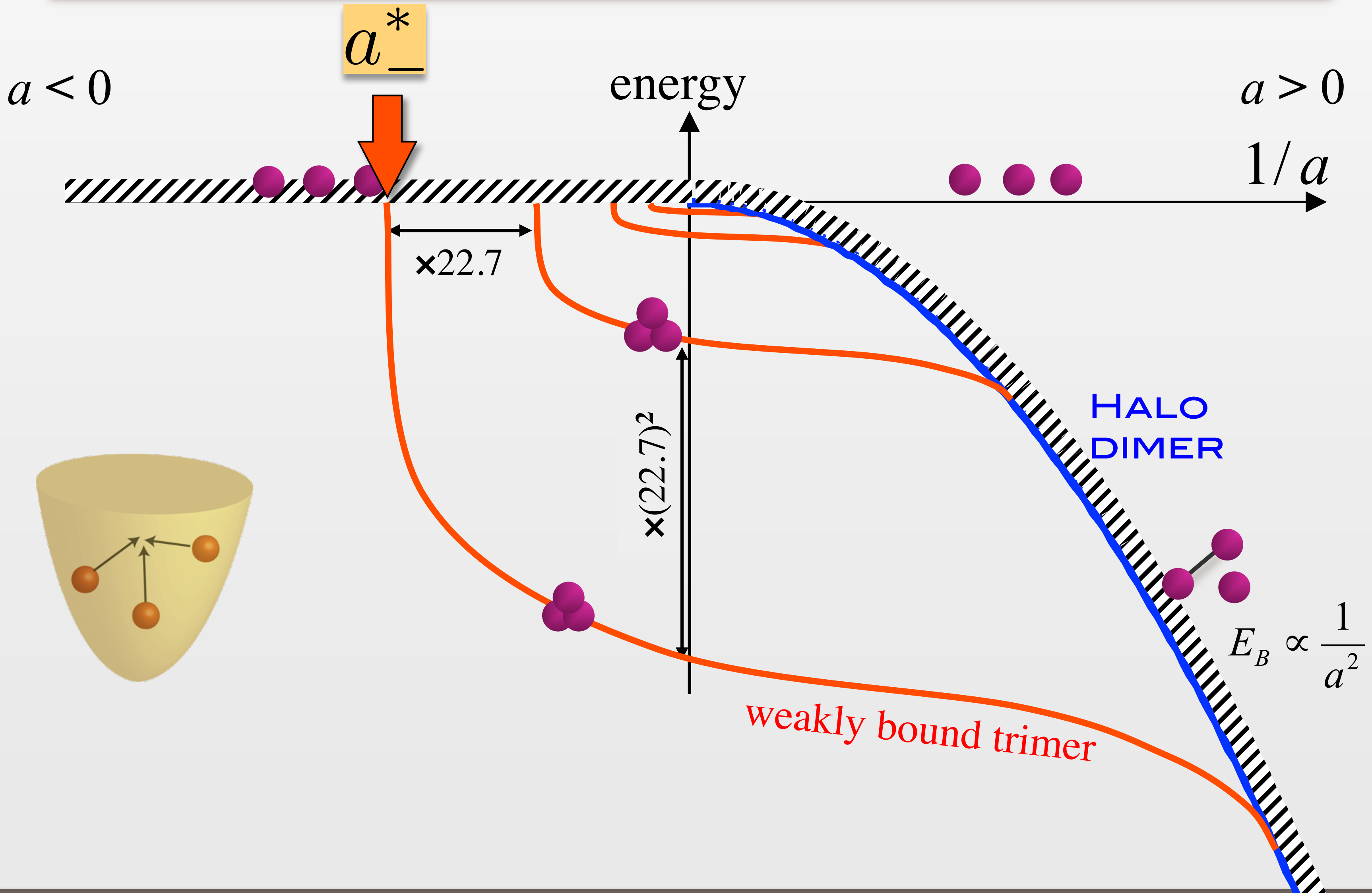
Prediction of a^4 scaling
$C = 3.9$

$$C(a) = \frac{4590\ \sinh(2\eta_-)}{\sin^2[s_0 \ln(|a|/a_-^*)] + \sinh^2 \eta_-}$$

E. Nielsen et al., PRL. 83, 1751 (1999)
B. D. Esry, et al., PRL 83, 1751 (1999)
E. Braaten et al., Phys. Rep. 428, 259 (2006)

Efimov effect adapted to our world

Efimov physics ←→ three-body recombination



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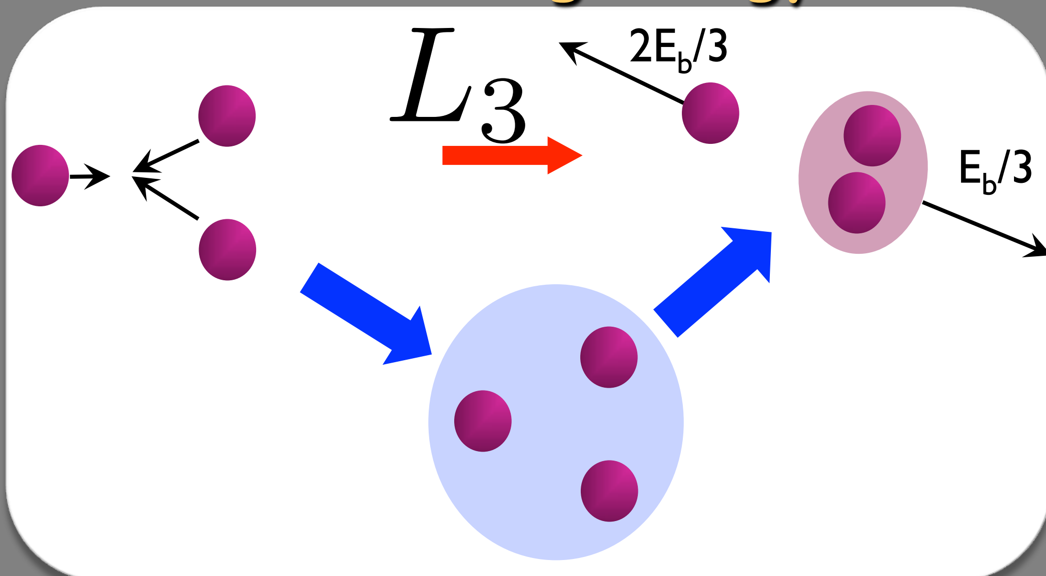
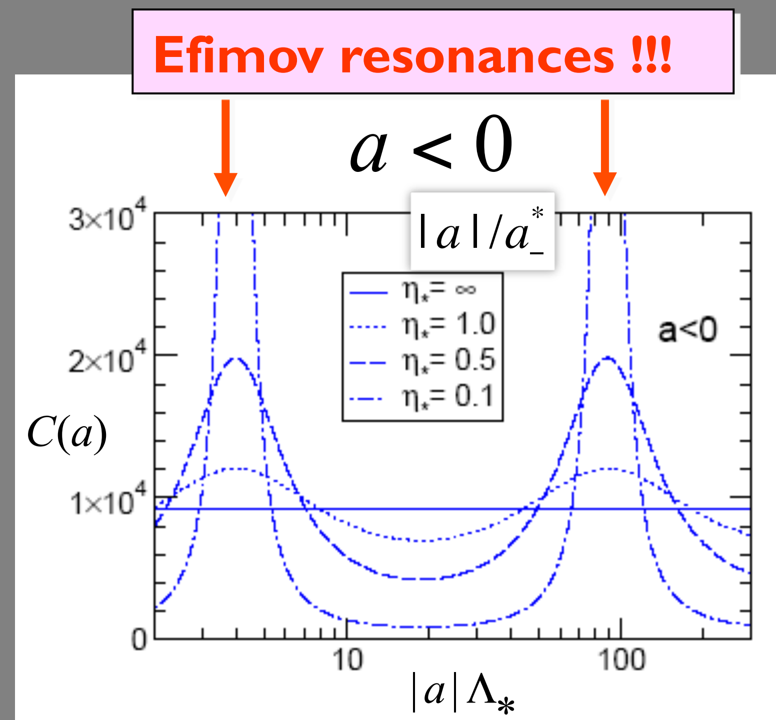


Impact of Efimov trimers on L_3

$$C(a) = \frac{4590\ \sinh(2\eta_-)}{\sin^2[s_0 \ln(|a|/a_-^*)] + \sinh^2 \eta_-}$$



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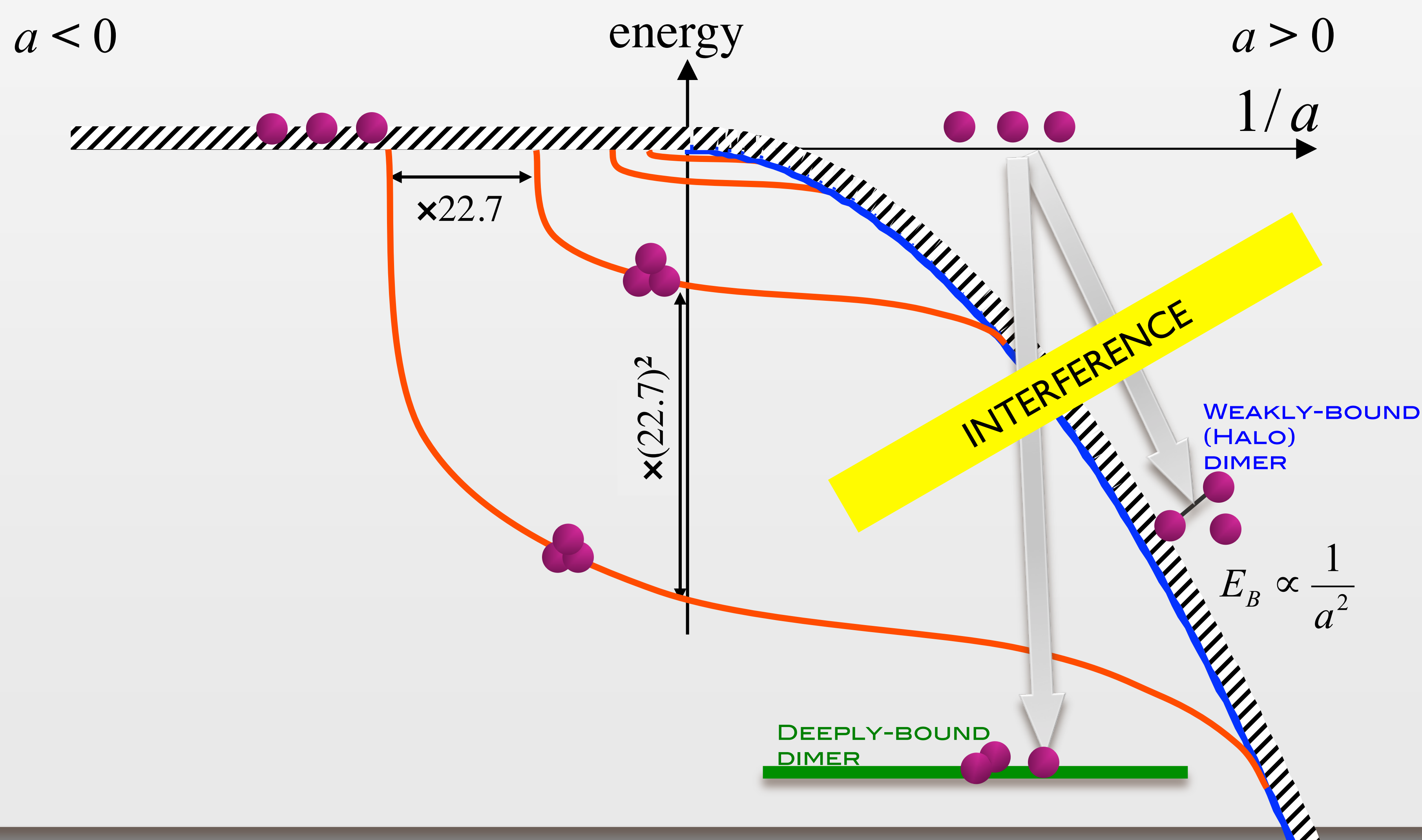
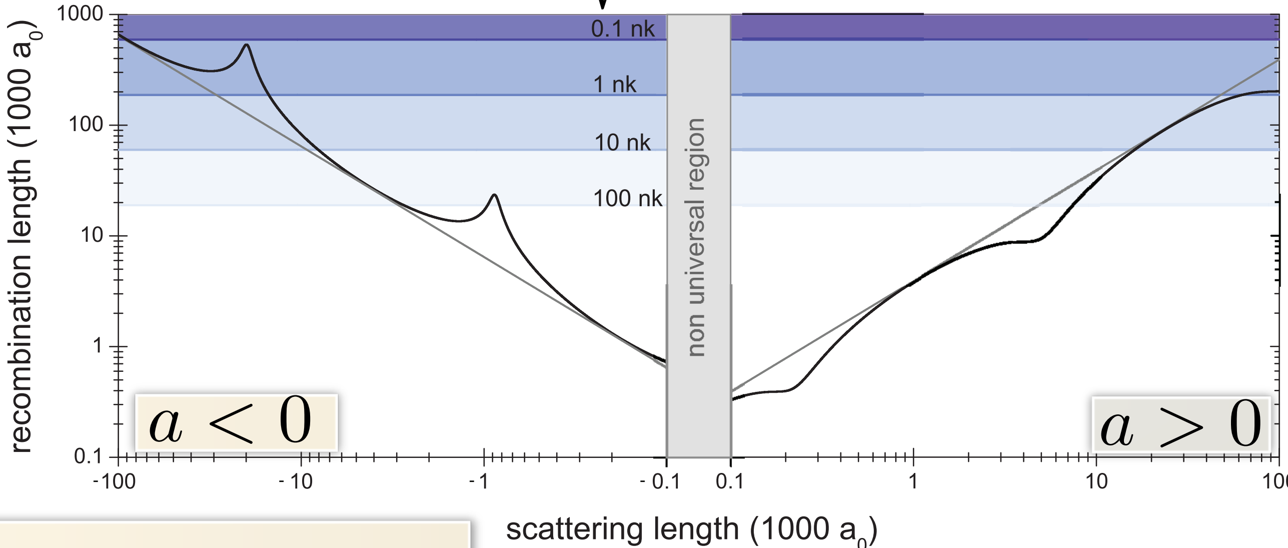


RECOMBINATION LENGTH

$$\rho_3^{\max} = 5.2 \frac{\hbar}{\sqrt{m k_B T}}$$

Effect of temperature:
Unitarity limit prevents the observation of two consecutive Efimov resonances (maxima) !!

$$\rho_3 = \sqrt[4]{2m/(\sqrt{3}\hbar) L_3}$$



$$L_3 = 3\frac{\hbar}{m}\frac{4590\sinh(2\eta_-)}{\sin^2[s_0\ln(|a|/a_-^*)] + \sinh^2\eta_-}a^4$$

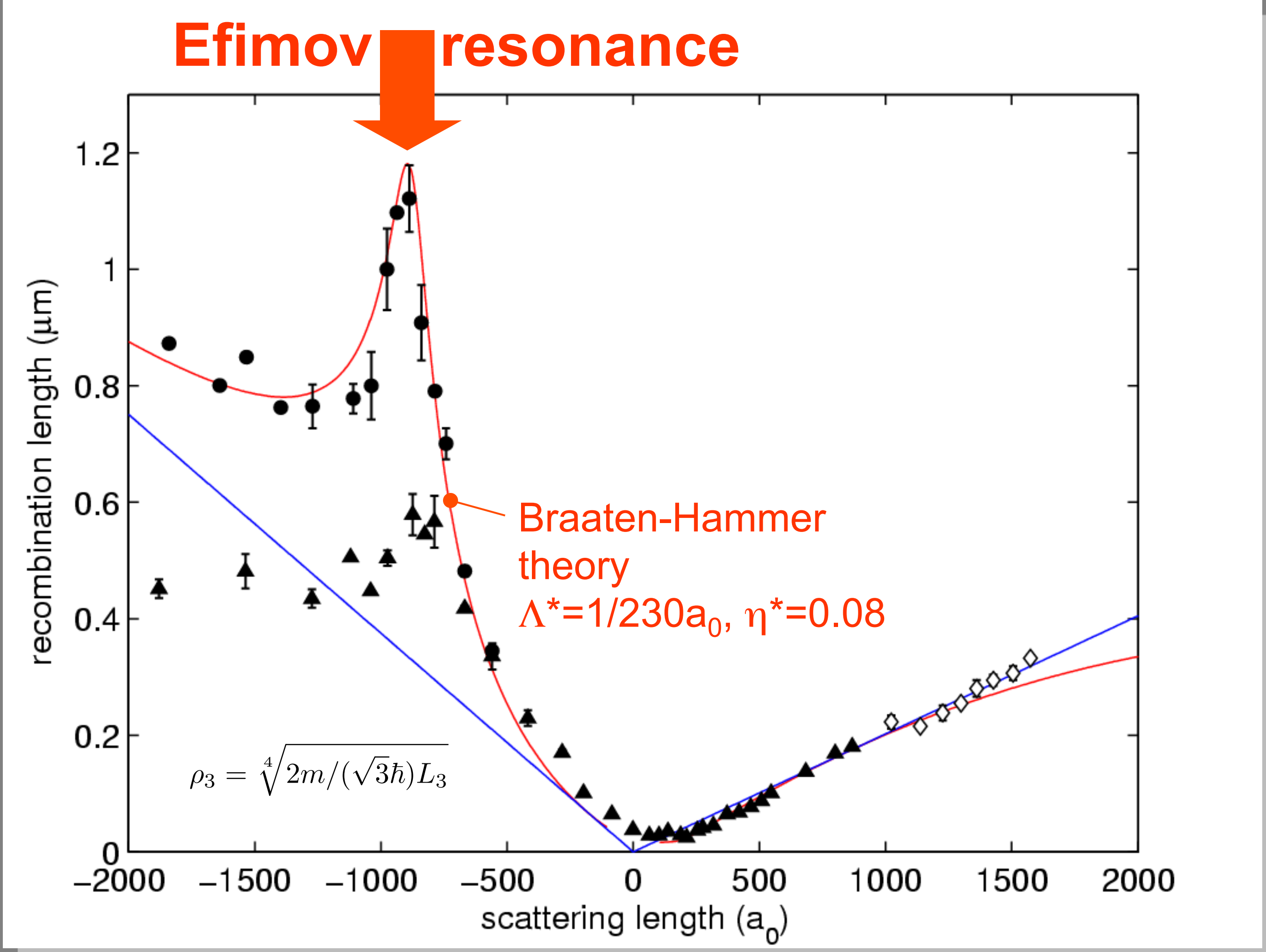
$$L_3 \approx 3\frac{\hbar}{m}[67.1\, e^{-2\eta_+}(\sin^2[s_0\ln(a/a_+)] + \sin^2\eta_+)]a^4$$

E. Braaten and H.-W. Hammer, Phys. Rep., vol. 428, pp. 259–390, 2006.

FIRST EXP. RESULTS (2005)

T = 10nK

200nK



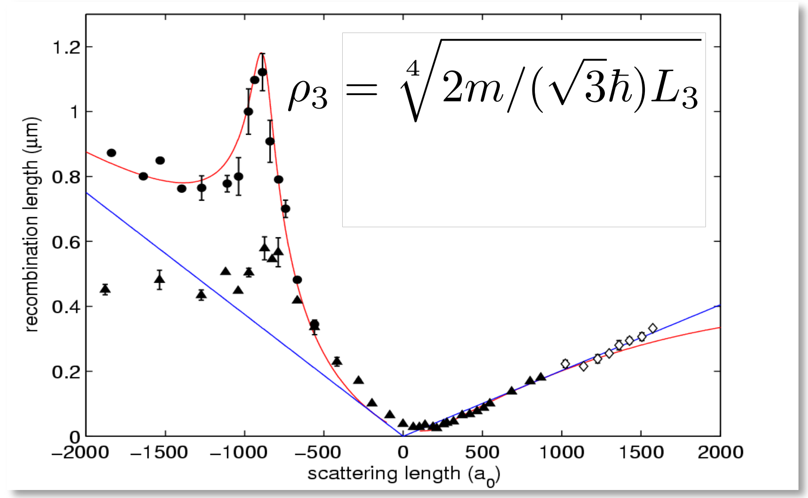
Kraemer et al., Nature 440, 315 (2006)

EXPERIMENTAL OBSERVATIONS

Efimov physics ←→ three-body recombination

Many important experimental steps forwards

First Experimental observation (Cs, 2005)



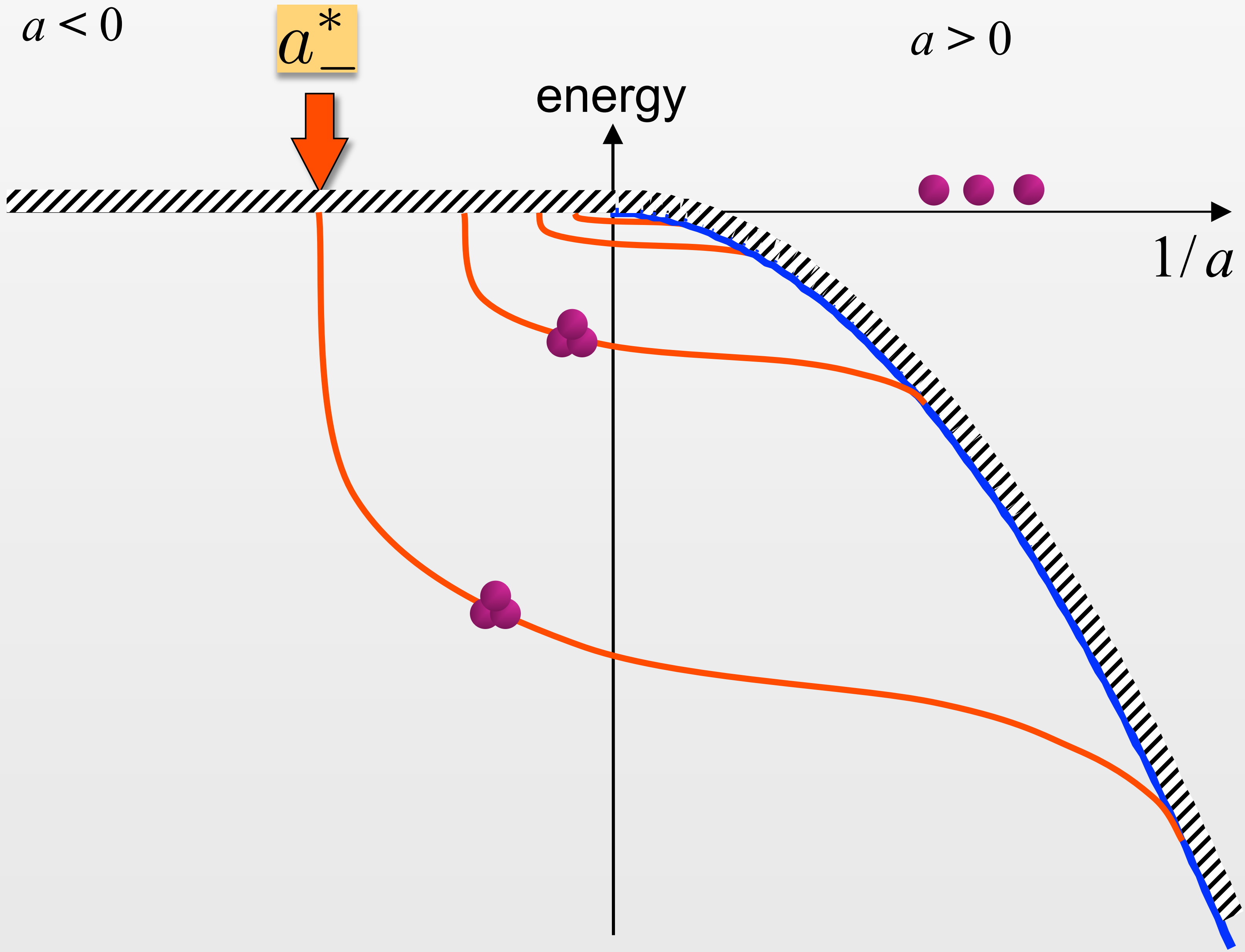
T. Kraemer et al. , Nature 440, 315-318 (2006)

^{6}Li	Heidelberg (2008,...), Penn State (2009,...), Tokyo (2010, ...)	Three-component spin mixture of fermions
^{7}Li	Rice (2009), Bar-Ilan (2009,...)	three identical bosons
^{39}K	LENS (2009)	three identical bosons
^{85}Rb	JILA (2012)	three identical bosons
^{133}Cs	Innsbruck (2005,...)	three identical bosons
RbK	LENS (2009), JILA (2012)	Heteronuclear mixture

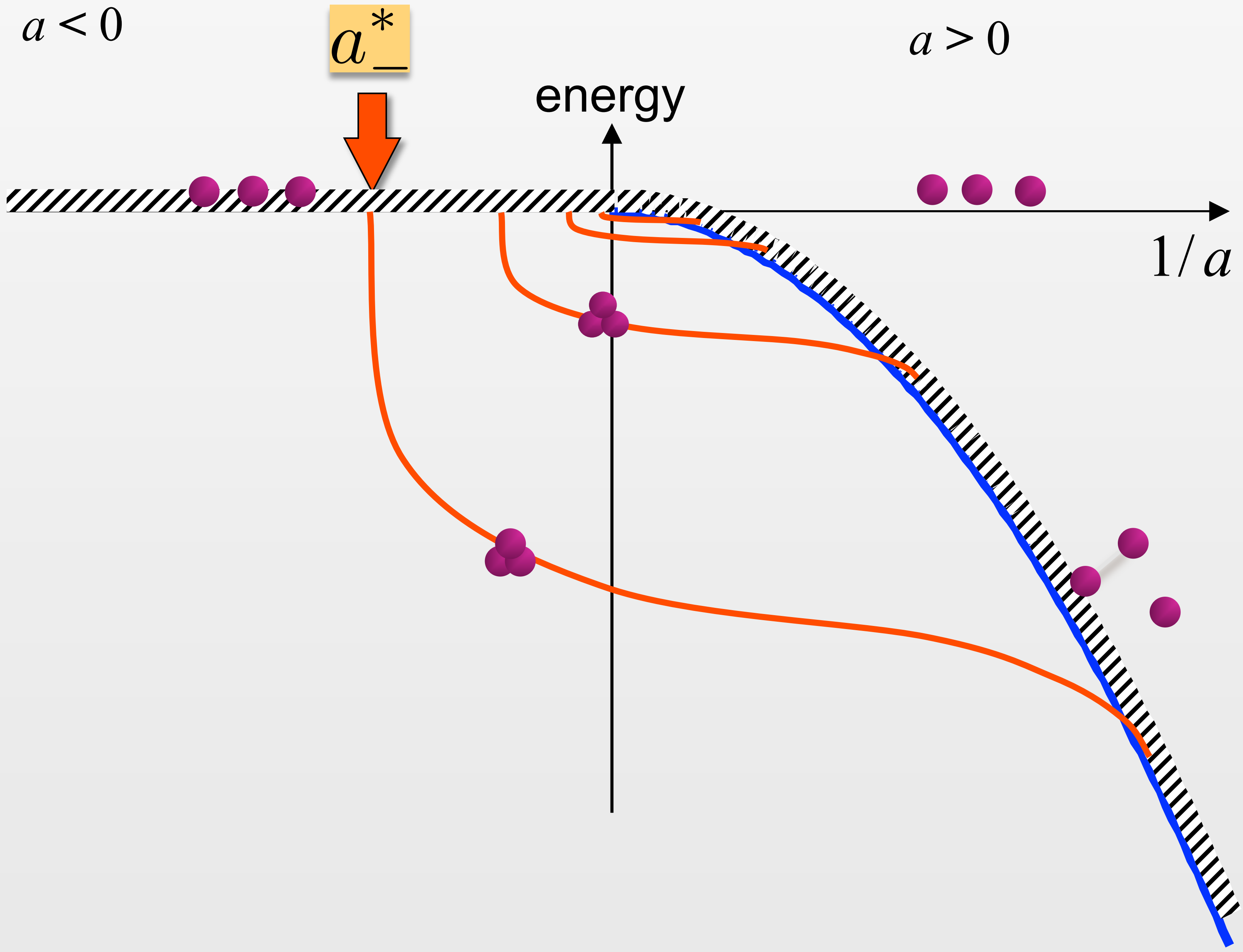
Reviews:

F. Ferlaino and R. Grimm, Physics 3, 9 (2010)

C. H. Greene, Phys. Today 63(3), 40 (2010)



$a < 0$
a^*_-
$a > 0$
energy
$1/a$



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$a > 0$
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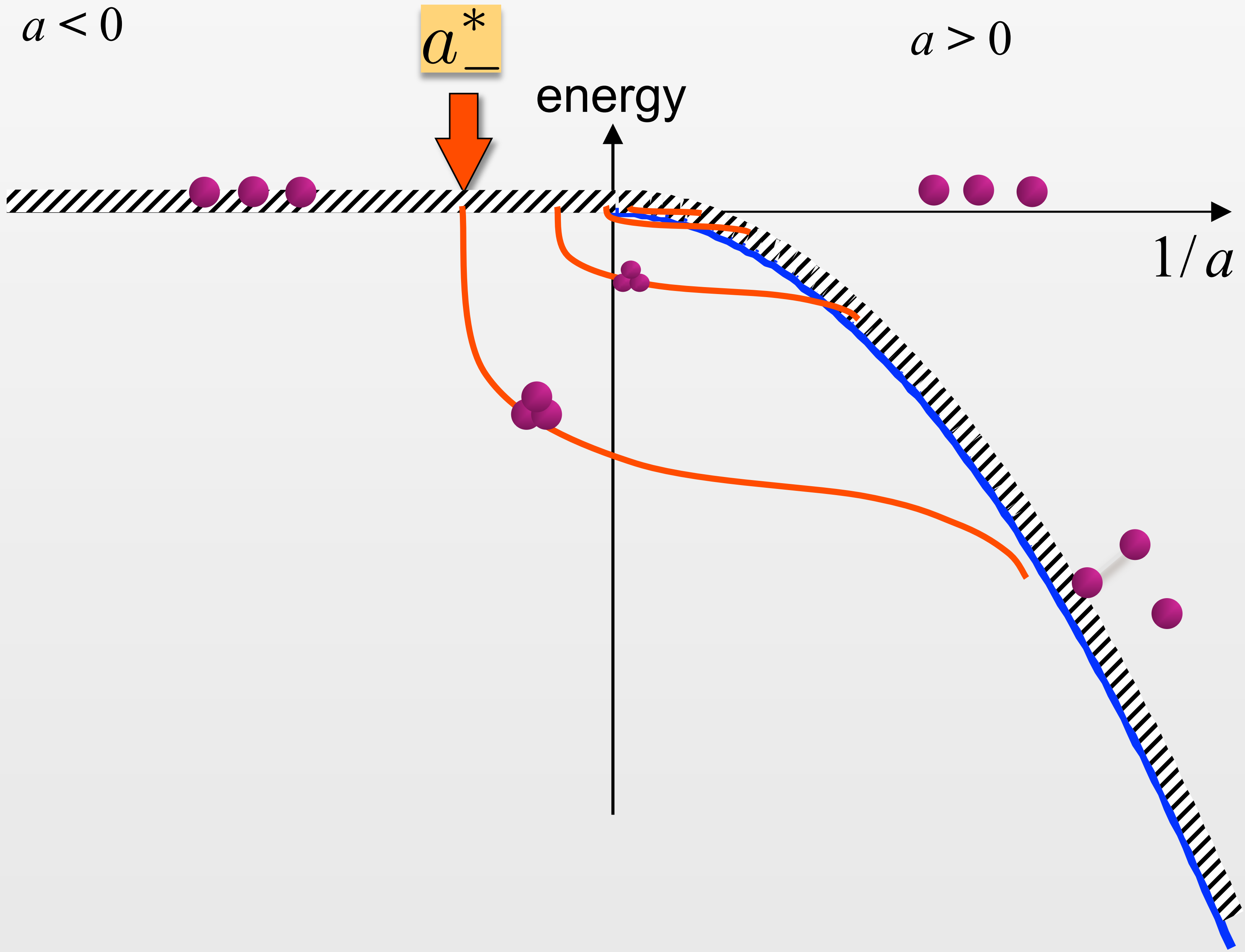


$a < 0$
a^*_-
energy
$a > 0$
$1/a$

A very intriguing issue

Our general understanding till mid 2011:

a^*_- is a fully system-dependent parameter (short-ranged, non-universal, uncorrelated)

$$a^*_-(2\mathrm{B}, 3\mathrm{B})$$

??

Multichannel two-body interaction

$U^{2\mathrm{B}}, E^D_\mathrm{B}$

Genuine three-body force

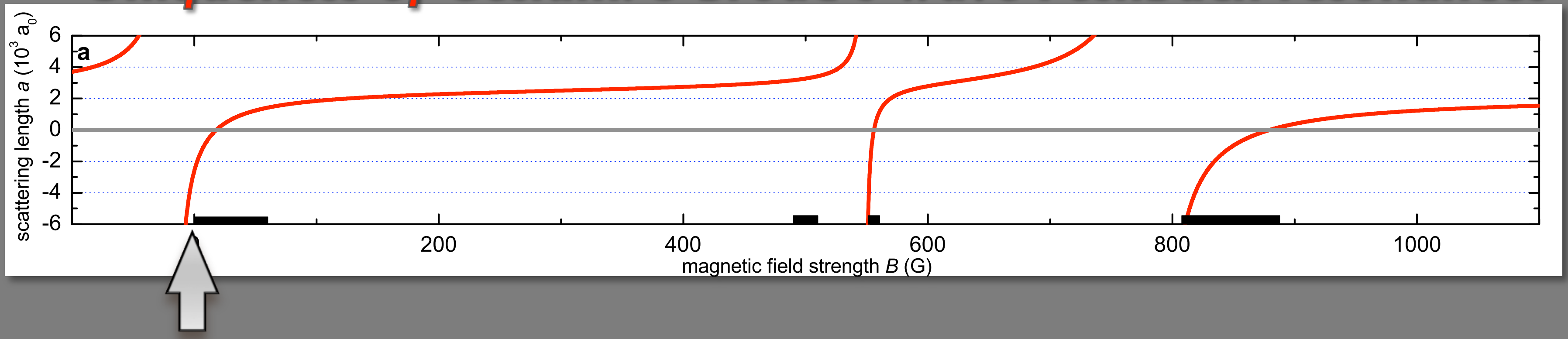
$U^{3\mathrm{B}}, E^T_\mathrm{B}$

M. D. Lee, T. Köhler, and P. S. Julienne PRA 76 (2007)

J. P. D'Incao, C. H Greene and B. D. Esry J. Phys. B (2009)

Tuning the scattering length

Uniqueness of Cesium: 3 broad s-wave Feshbach resonances



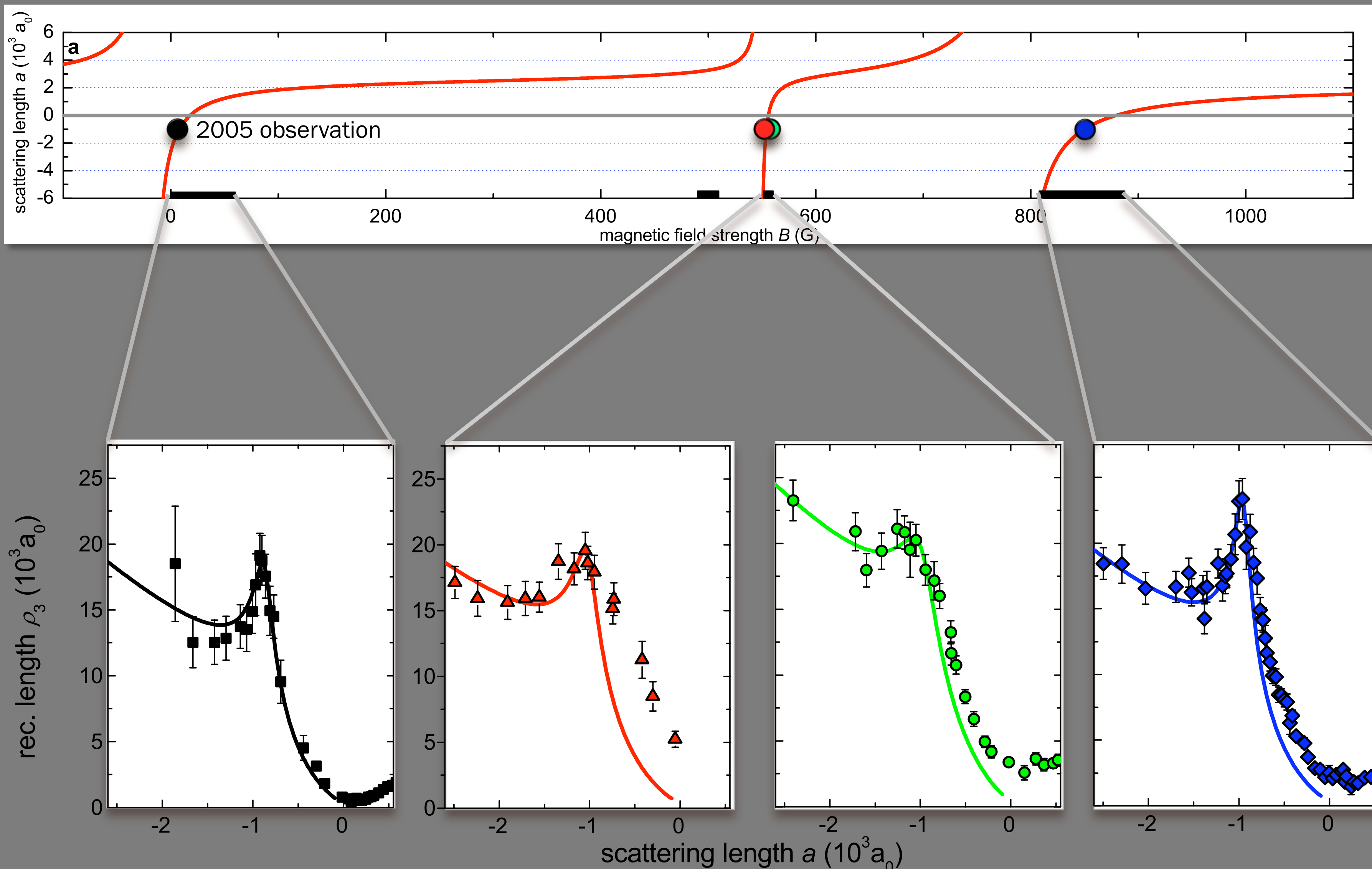
Change short-range (2B, 3B) physics while keeping the universal character at long range

$$a^*_-(2\mathrm{B}, 3\mathrm{B}), a$$

Cs as test bed for the 3BP

Efimov resonances in Cs

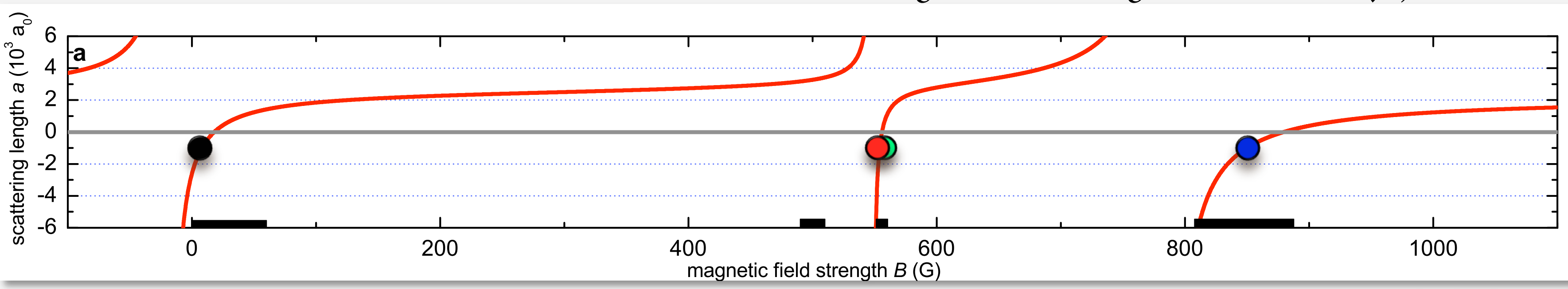
In collaboration with P. Julienne and J. Hutson



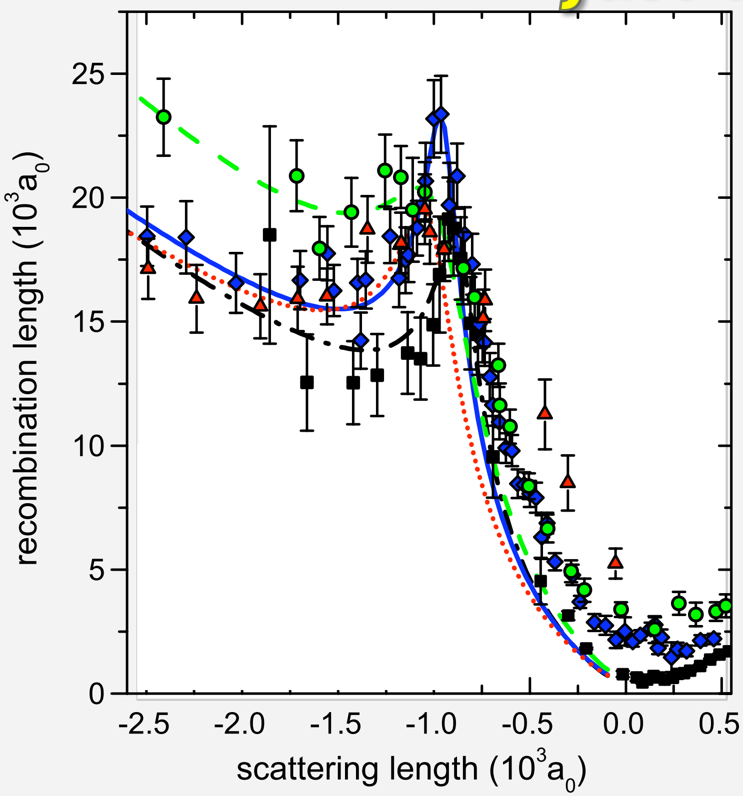
M. Berninger, et al. PRL 107, 120401 (2011)

Efimov resonance over 1000G

Intensive collaboration with P. Julienne and J. Hutson on a(B) conversion

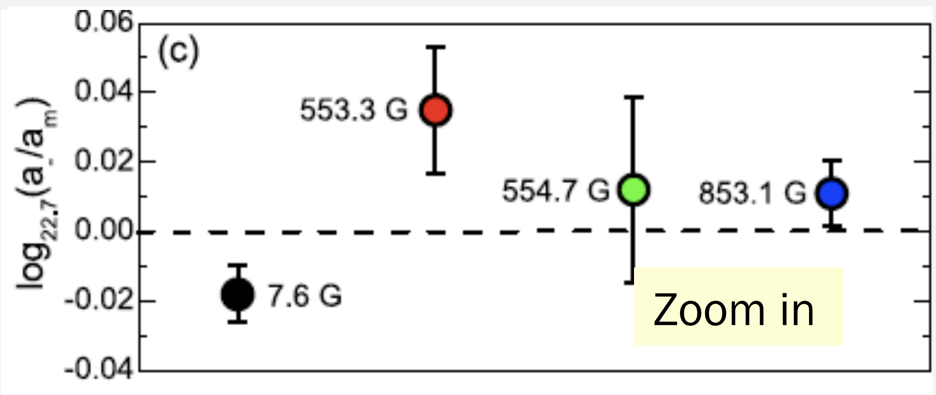


Just a copy and paste over 1000 G ?



the y-scale covers 1/10 of the Efimov period

Changes over an Efimov period (22.7)



M. Berninger, et al. PRL **107**, 120401 (2011)

Universal three-body parameter

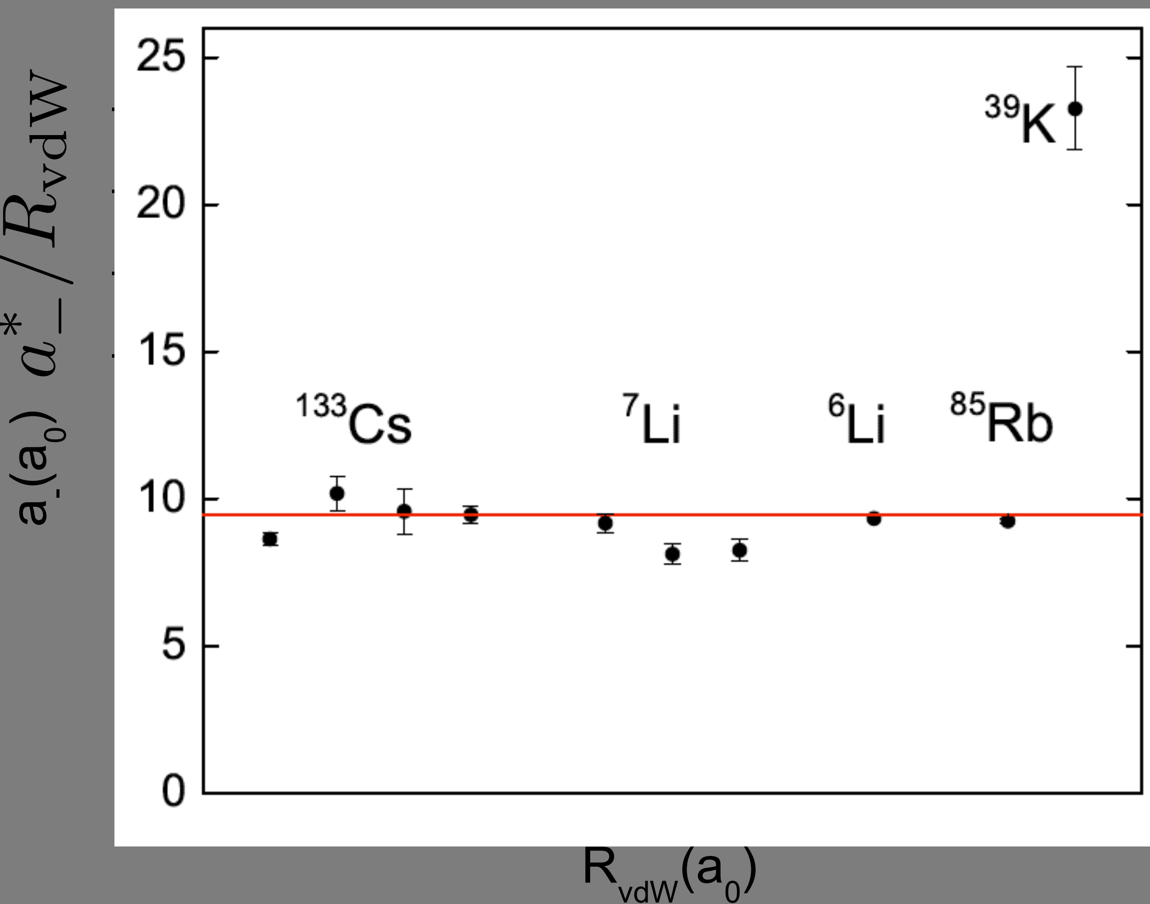
... 3BP fairly insensitive to short-range physics

(3BP for other systems?)

New theories based on the concept of quantum reflection

arXiv:1111.1484: Chin
arXiv:1201.1176; Wang et al.
arXiv:1201.4310: Schmidth et al.

$$a_-^* \approx -9R_{\mathrm{vdW}}$$



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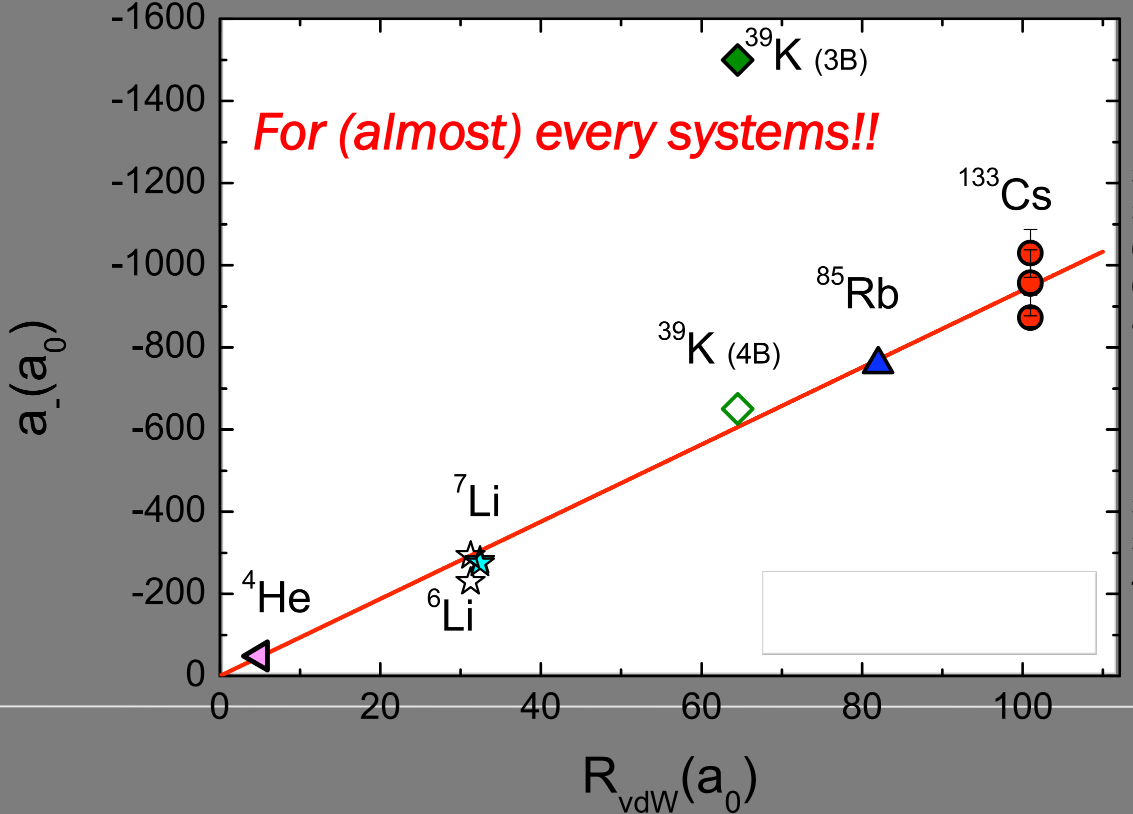


$$a_-^* \approx -9R_{\rm vdW}$$

FROM.....

4

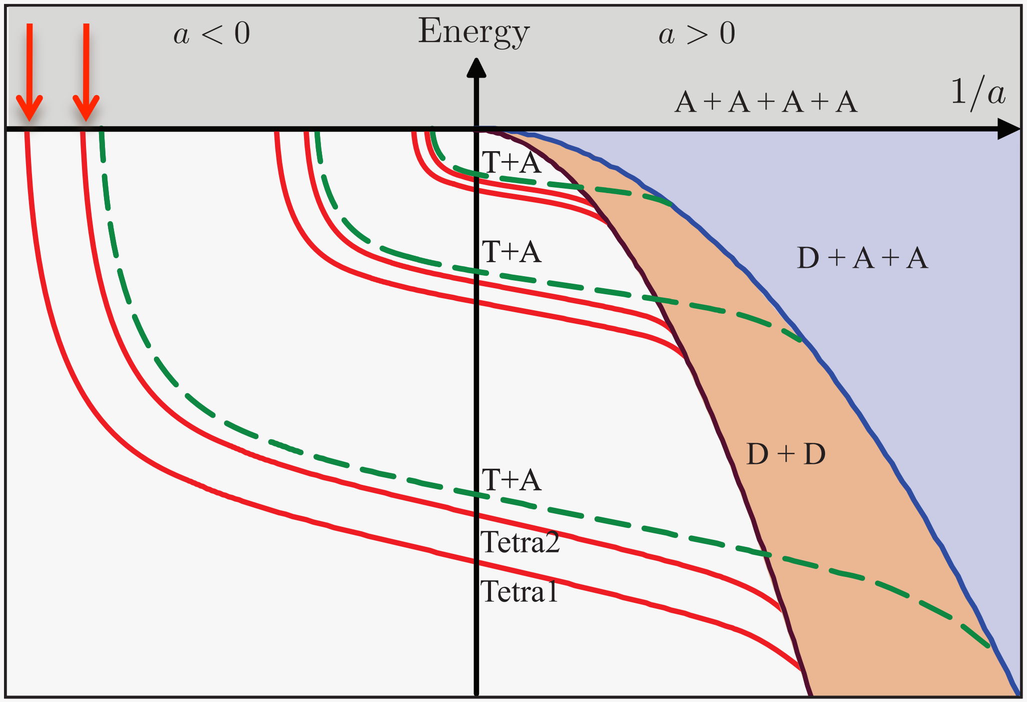
Four-body states tied to an Efimov trimer

Tetramer states ←→ four-body recombination

THEORY

$a^*_{Tetra1} \approx 0.43 a^*_T$

$a^*_{Tetra2} \approx 0.9 a^*_T$



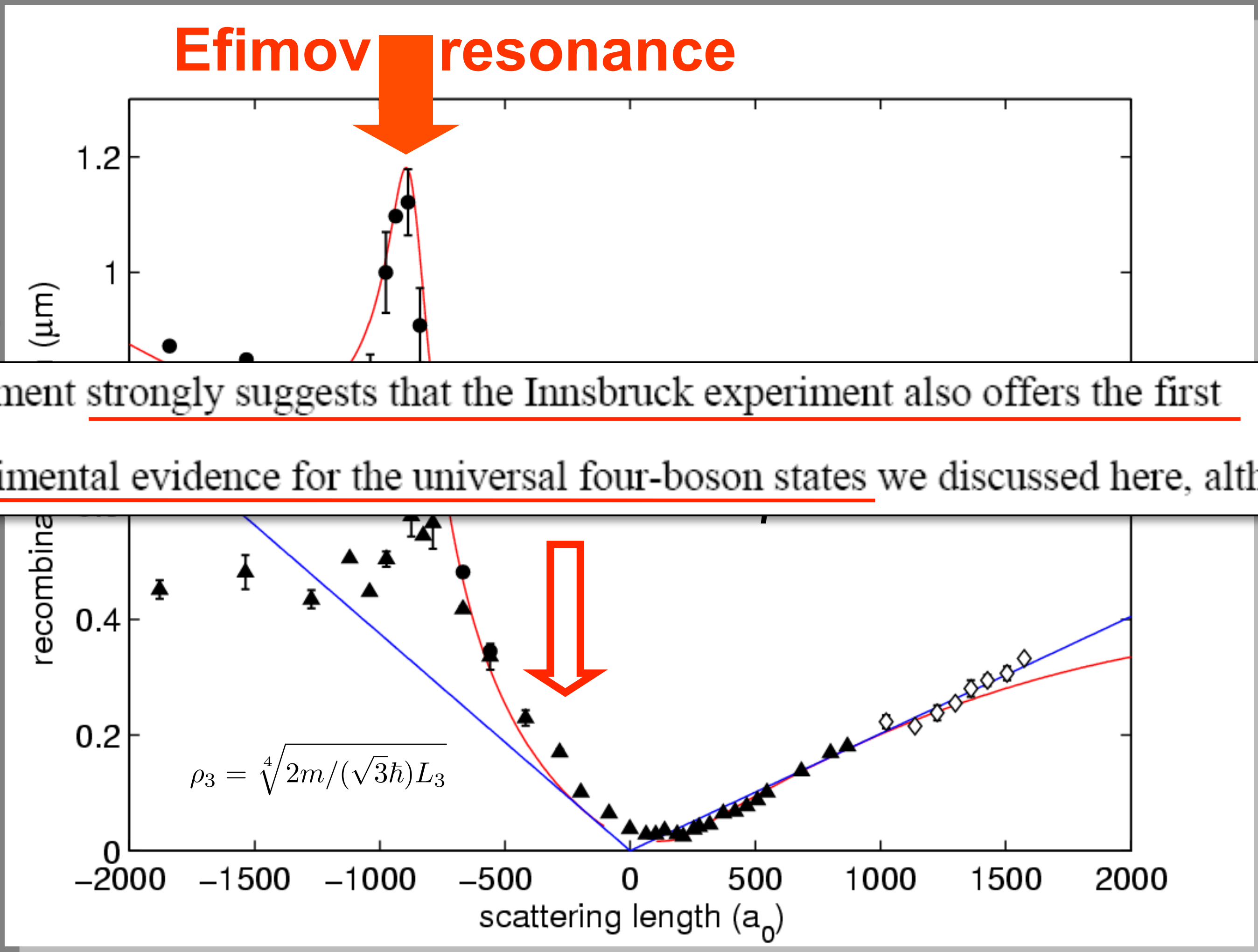
J. von Stecher, J. P. D'Incao, and C. H. Greene, Nature Physics 5, 417 (2009)

EXP. RESULTS REVISITED BY C. GREENE ET AL. (2008)

J. von Stecher, J. P. D'Incao, and C. H. Greene, Nature Physics 5, 417 - 421 (2009)

T = 10nK

200nK



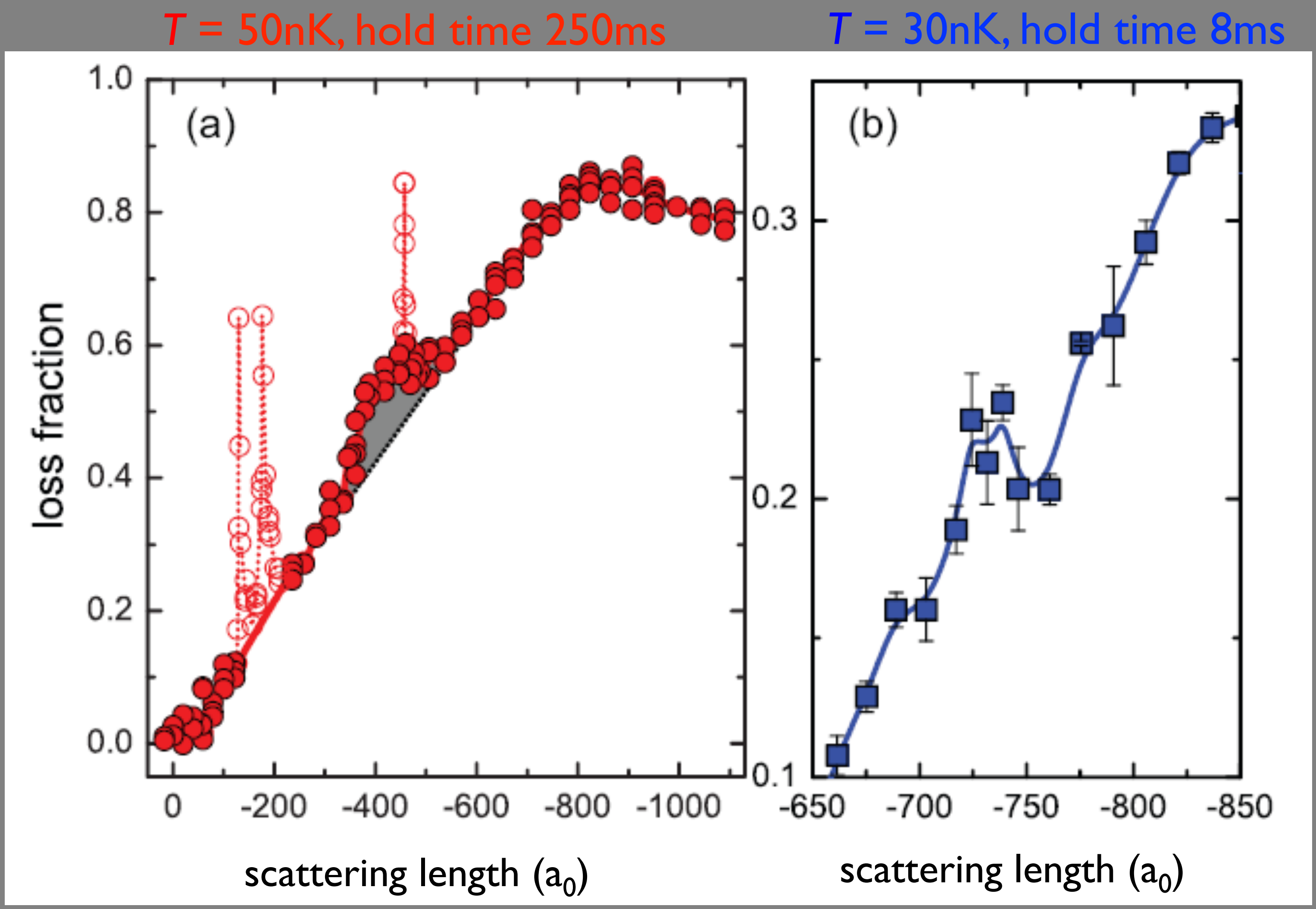
agreement strongly suggests that the Innsbruck experiment also offers the first experimental evidence for the universal four-boson states we discussed here, although

Kraemer et al., Nature 440, 315 (2006)

NEW SET OF EXPERIMENTS

prepare sample very close to BEC

Ferlaino et al., PRL **102**, 140401 (2009)



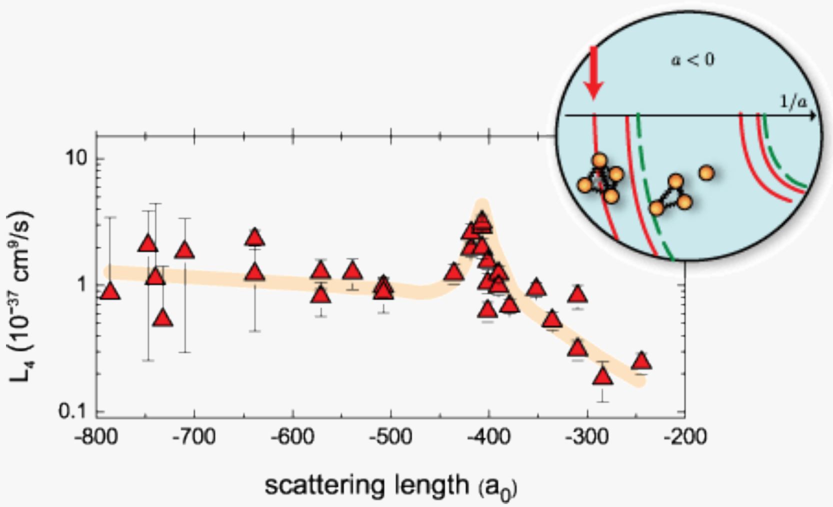
Four-body states tied to an Efimov trimer

Tetramer states ←→ four-body recombination

Theory

$a^*_{Tetra1} \approx 0.43 a^*_T$

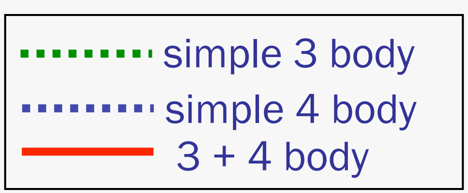
$a^*_{Tetra2} \approx 0.9 a^*_T$

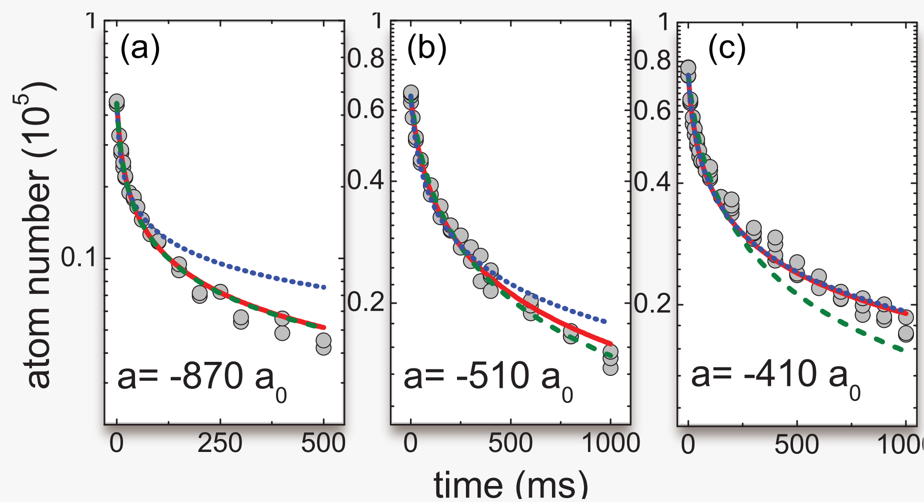


Experiment

$a^*_{Tetra1} \approx 0.47 a^*_T$

$a^*_{Tetra2} \approx 0.84 a^*_T$





Ferlaino et al., PRL 102, 140401 (2009)

Universal cluster states tied to Efimov trimer

Family of universally connected N-body states

IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. **43** (2010) 101002 (5pp) — doi:10.1088/0953-4075/43/10/101002

FAST TRACK COMMUNICATION

Weakly bound cluster states of Efimov character

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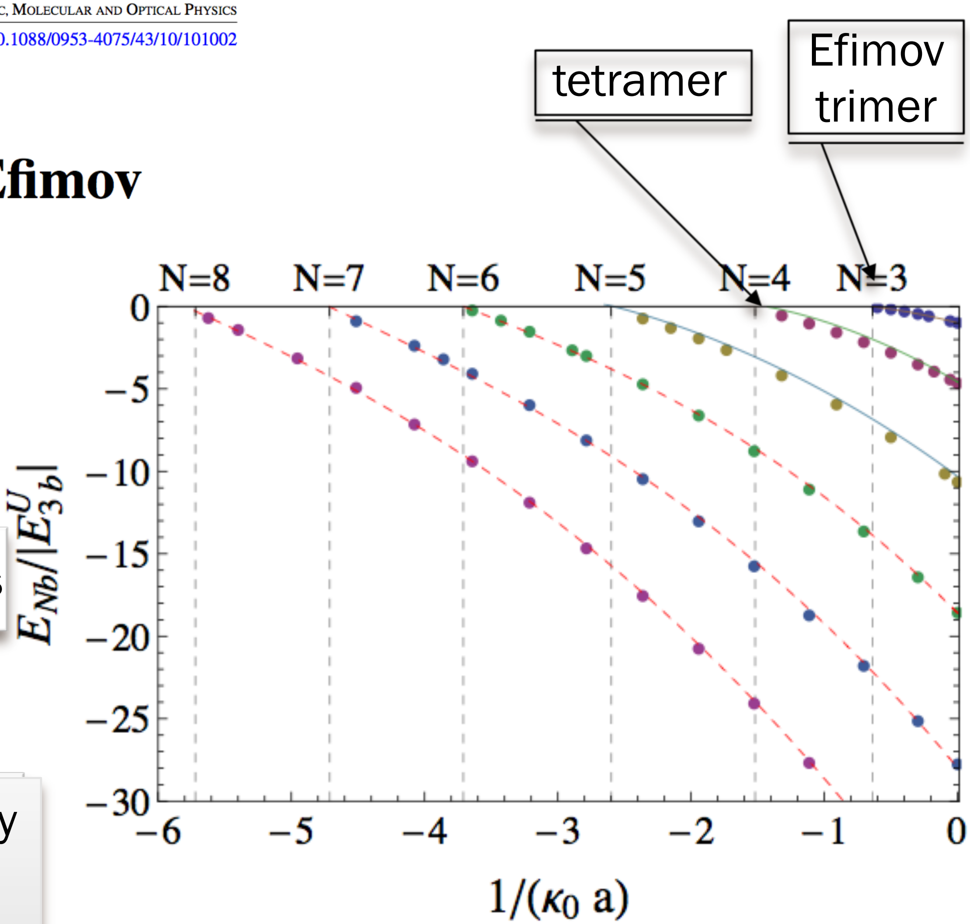
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440, USA



Major conceptual advance

Few-body catches up many-body physics

New challenge

Standard observables lessen in visibility with increasing N
→ Call for novel Theo/Exp approaches

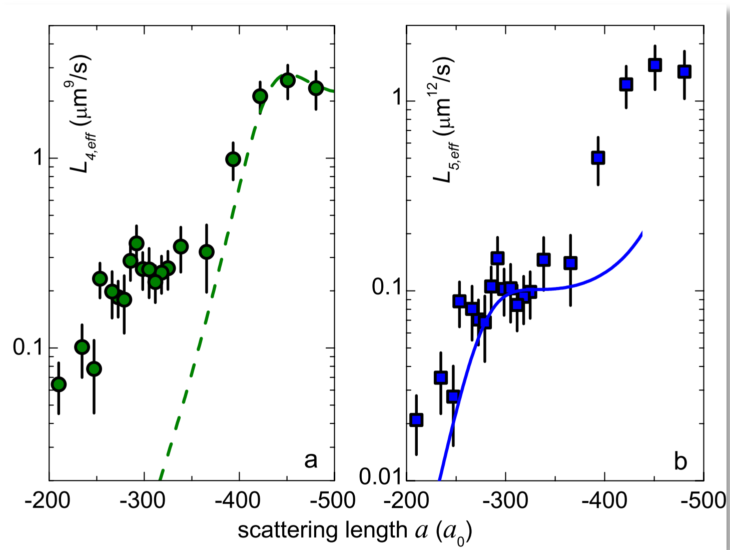
Universal five-body states

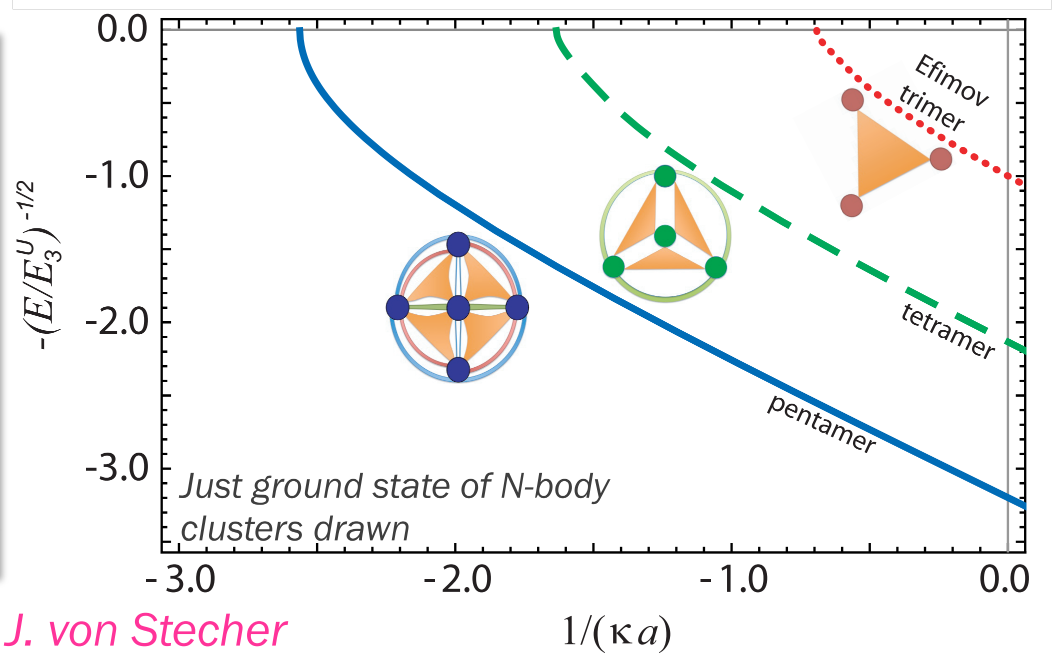
(… and we stop here)

Five-body state ←→ Five-body recombination

Required a combined experimental and theoretical effort and specific tools

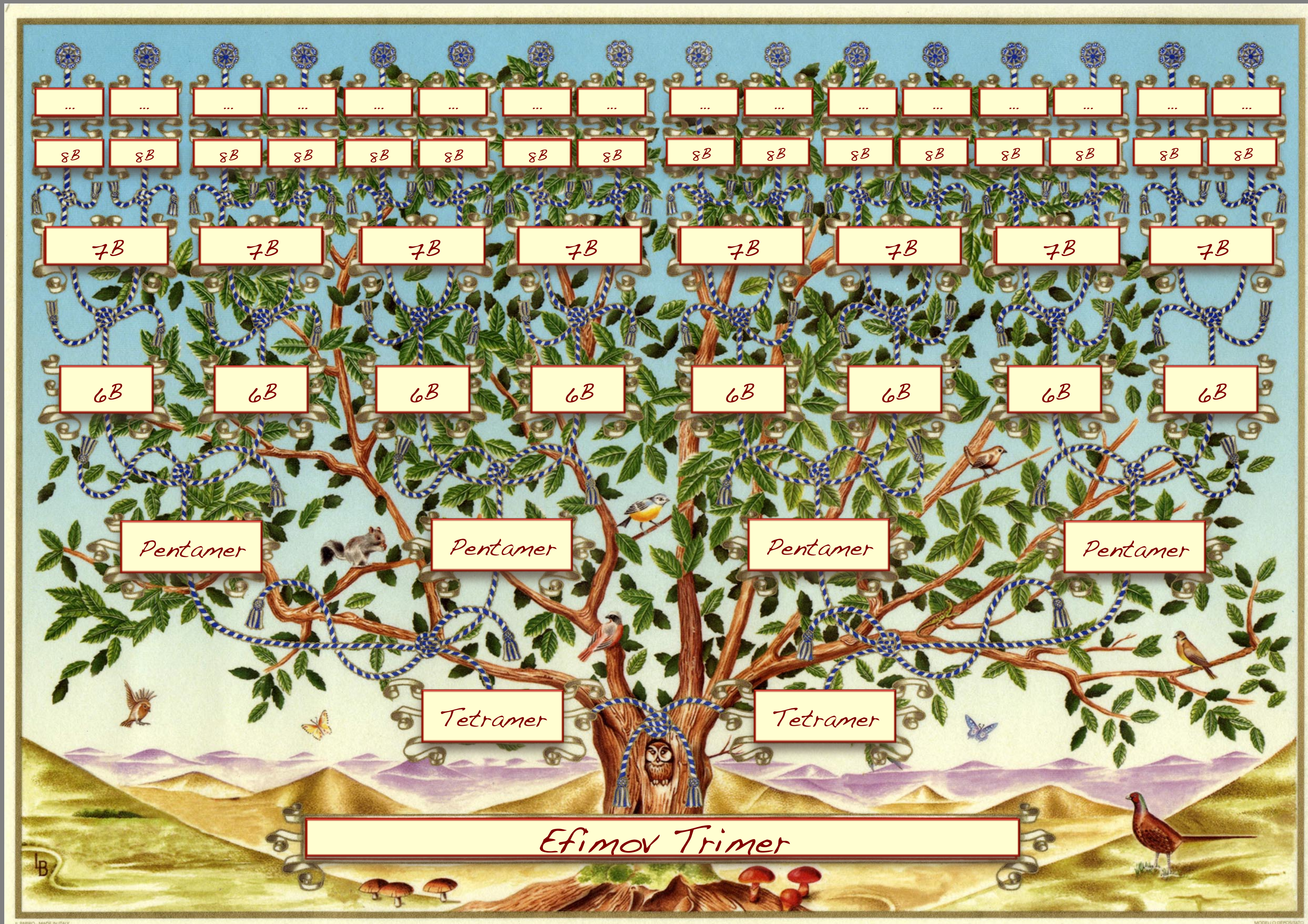
Strong evidence of the existence of a family of Efimov-related universal clusters



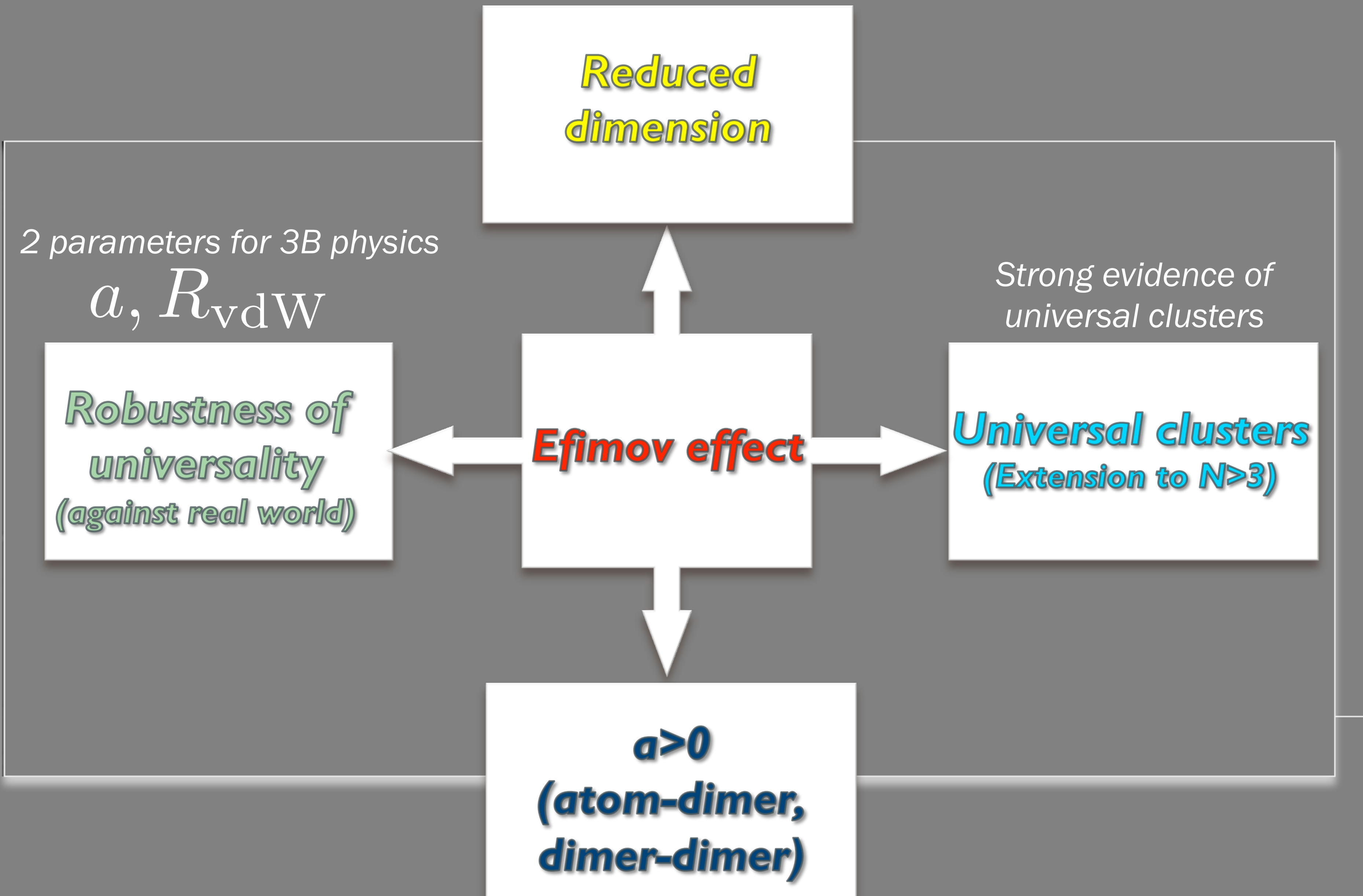


In collaboration with C. Greene and J. von Stecher

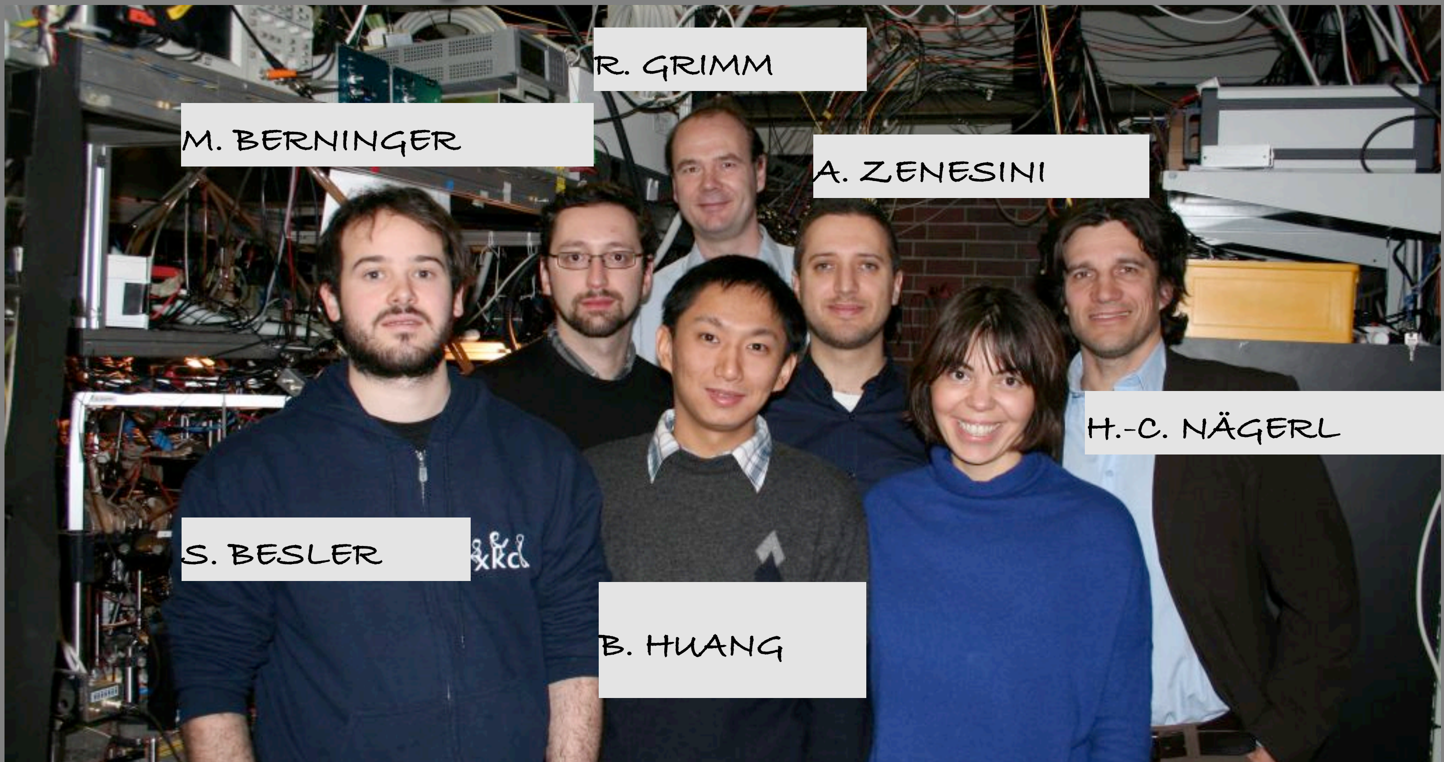
EFIMOV'S FAMILY TREE



Building an universal picture



Few-body Team



FWF Der Wissenschaftsfonds.

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