24[th] European Conference on Few-Body Problems in Physics, University of Surrey, 9/2/2019

Observation of Efimov States in Ultracold Atoms

Cheng Chin

The University of Chicago

Synopsis

Prediction Vitaly Efimov (1970)

$\alpha+\alpha+\alpha \to C$

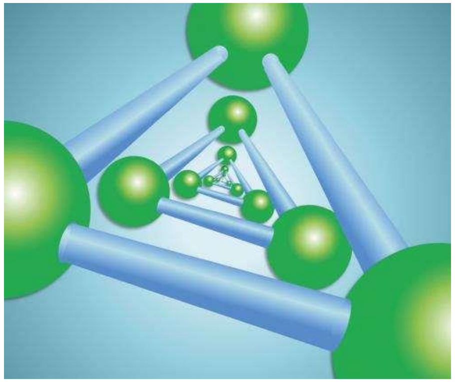
$H+H+H \to T$

Appearance Cs, Li, K, Rb, LiCs, LiRb, He 2006…

Properties Geometric scaling, universality…

Molecular size:

$1, \lambda, \lambda^2$ …



Molecular size ~

Scattering length $a \propto$

van der Waals length

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 = ½. 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.

Hyperspherical equation:

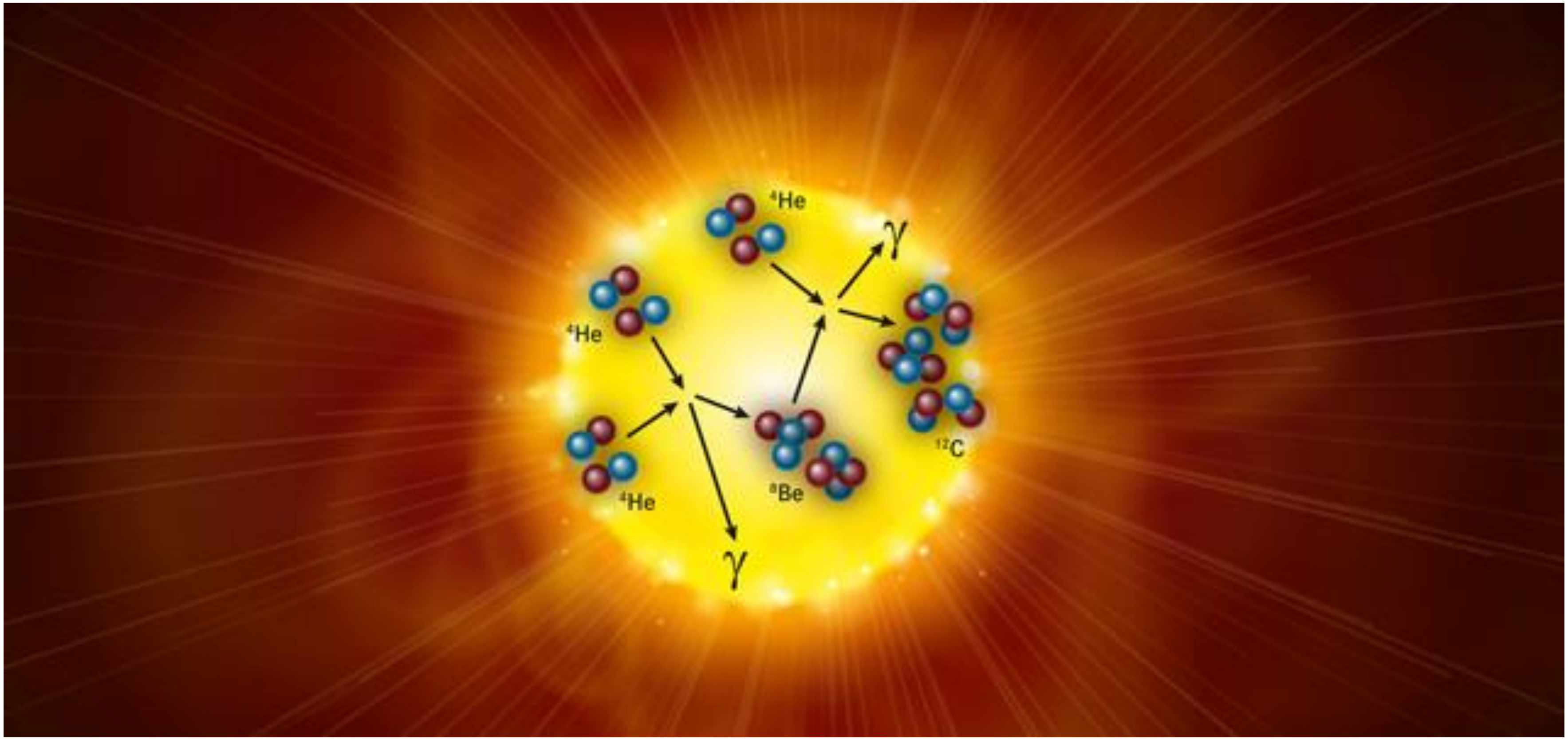
$$i\hbar\frac{\partial\phi}{\partial t} = -\frac{\hbar^2}{m}\frac{\partial^2\phi}{\partial R^2} - \frac{\hbar^2}{m}\frac{s_0^2+1/4}{R^2}\phi$$

$\Rightarrow$ Invariant under dilation transformation $R\rightarrow\lambda R$ and $E\rightarrow\lambda^{-2}E$

Scaling factor $\lambda=\exp(\pi/s_0)$

Vitaly Efimov

Holye state of carbon in nucleosynthesis



Epelbaum, et al. Scientific American (2012)

From Nuclear Physics to Ultracold Atoms

Chris Greene (Purdue)

Brett Esry (Kansas State)

VOLUME 83, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1999

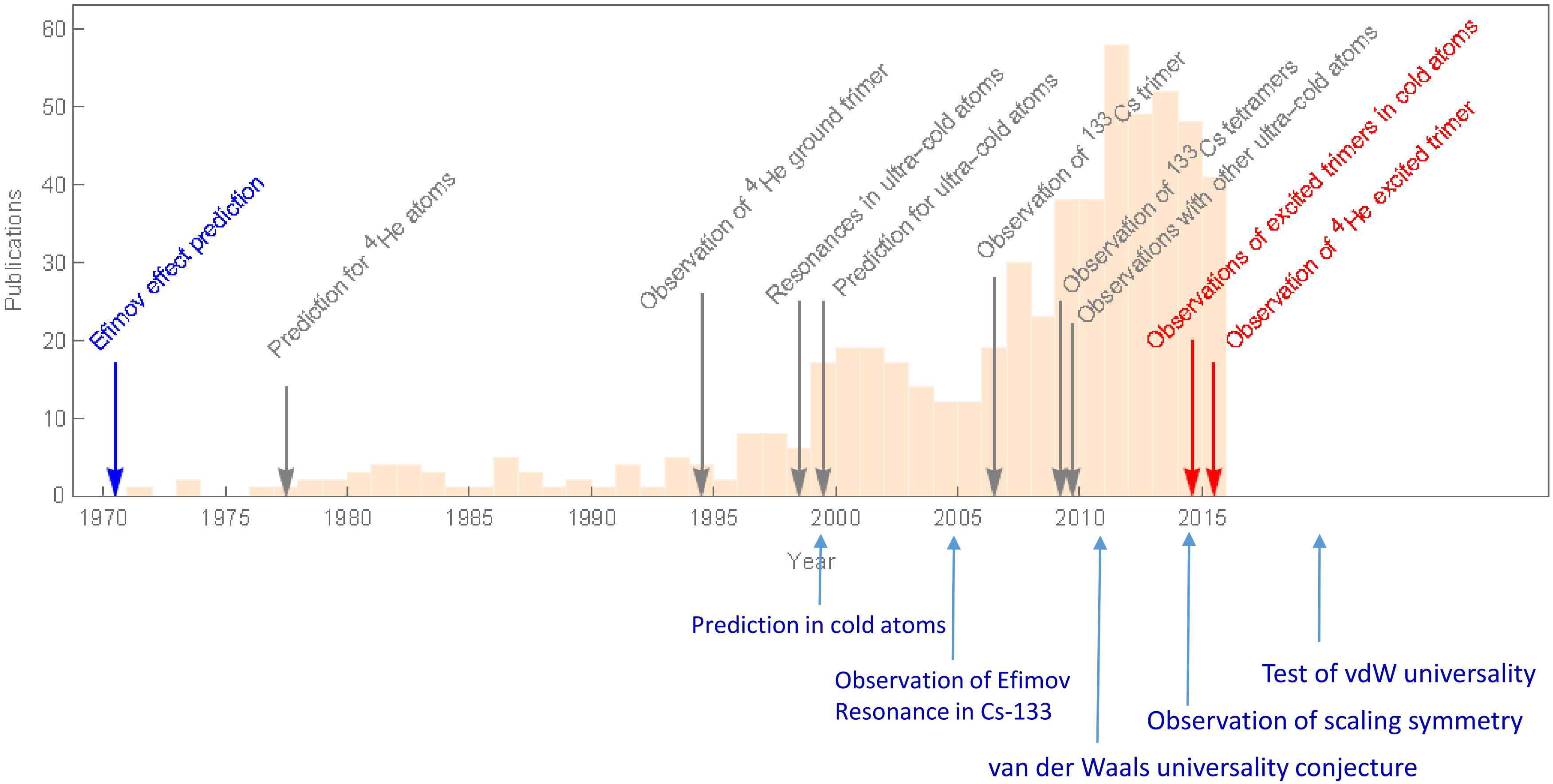
Recombination of Three Atoms in the Ultracold Limit

B. D. Esry
Institute for Theoretical Atomic and Molecular Physics, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

Chris H. Greene and James P. Burke, Jr.
Department of Physics and JILA, University of Colorado, Boulder, Colorado 80309-0440
(Received 19 May 1999)

$$K_3(a<0) = 4590 \sinh 2\eta \frac{\hbar a^4}{m}\left[\sin^2(s_0 \ln a + \phi_-) + \sinh^2 \eta\right]^{-1}$$

Efimov effect in nuclear physics, helium and ultracold atoms

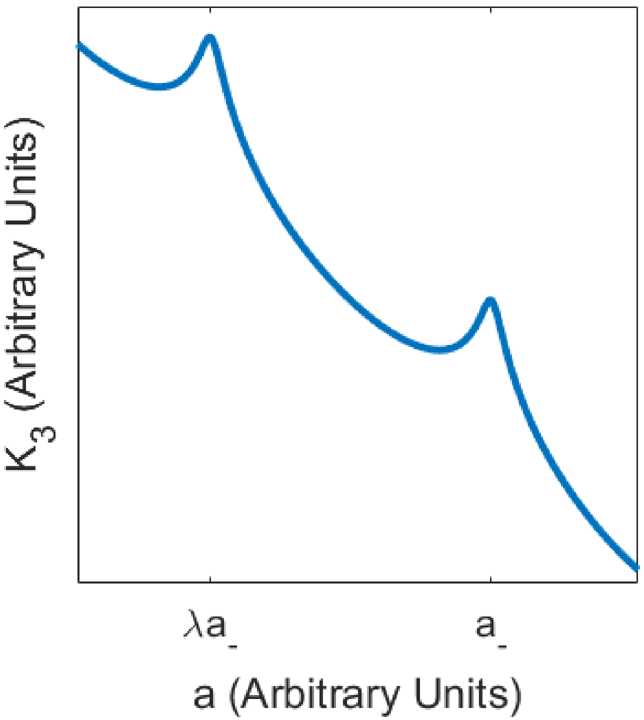


Pascal Naidon, Shimpei Endo, Rep. Prog. Phys. 80 056001 (2017)

Efimov Resonances in recombination

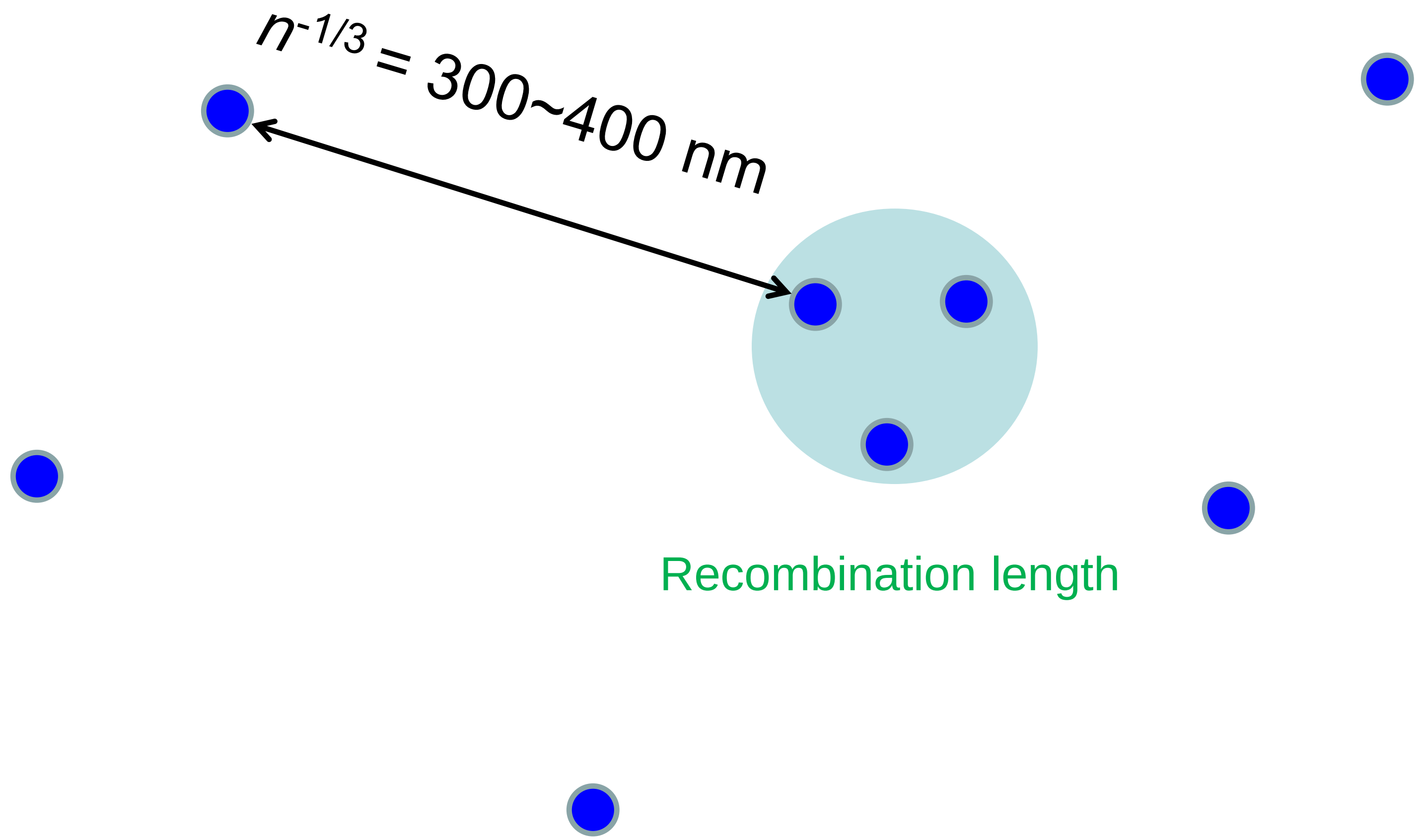
$$K_3 = \frac{4590\hbar a^4}{m} \frac{\sinh(2\eta_-)}{\sin^2[\pi \log_\lambda(a/a_-)] + \sinh^2 \eta_-}$$

- K_3: 3-bdy Recombination rate
- a_-: Efimov resonance position
- λ: scaling constant
- η_-: Efimov resonance width parameter (Lorentzian)

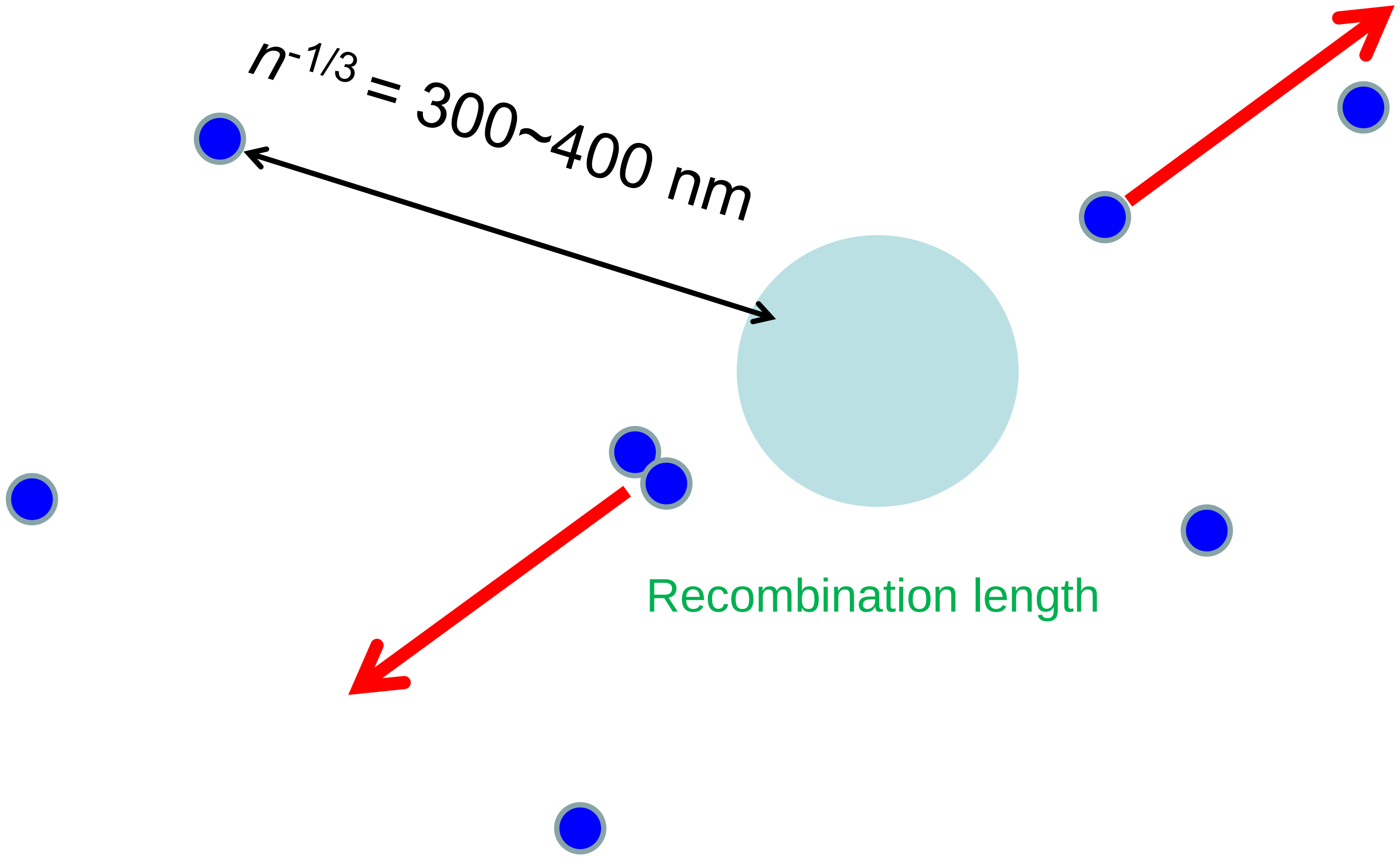


Esry, Greene and Burke, PRL (1999)

Recombination in cold atoms

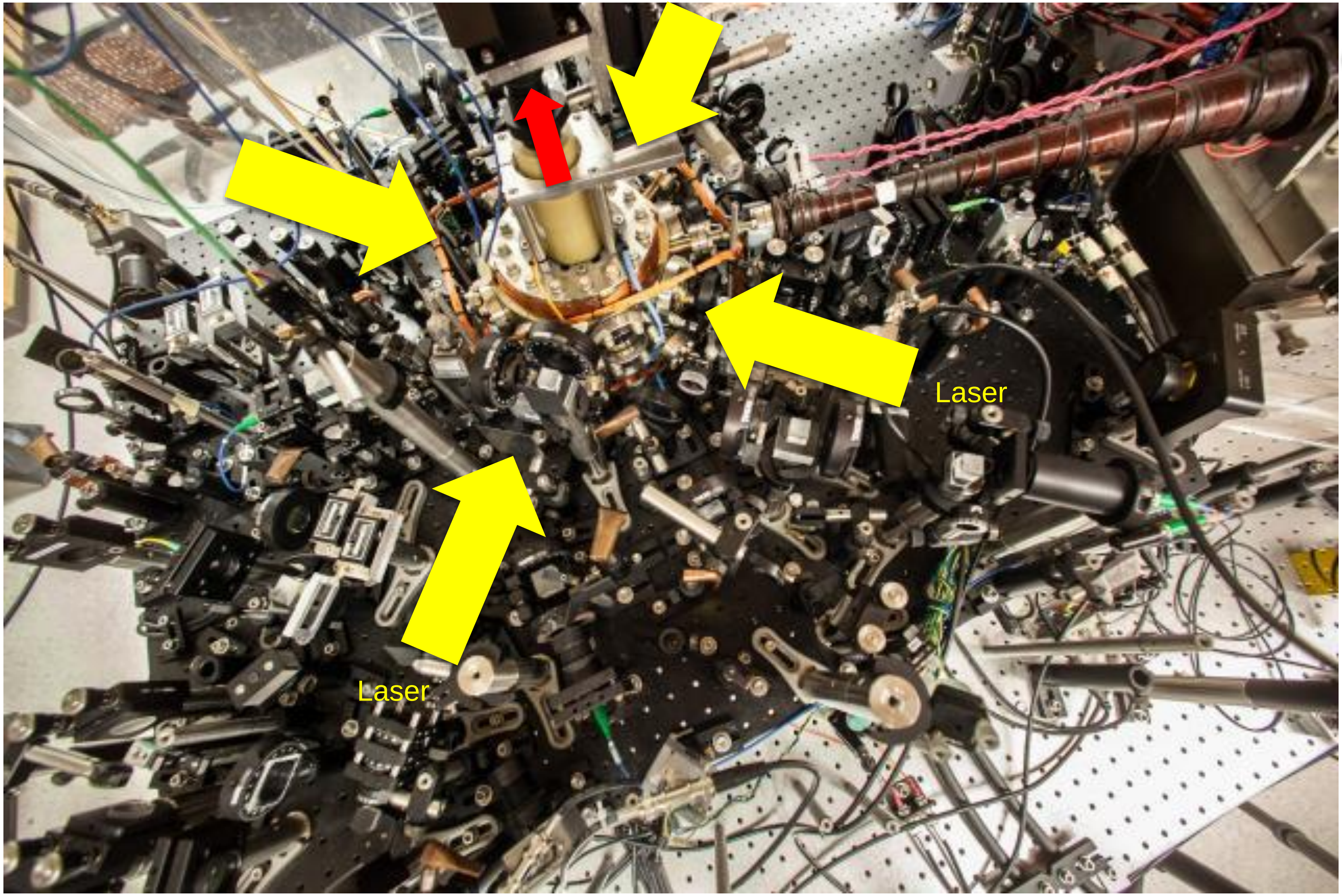


Recombination in cold atoms



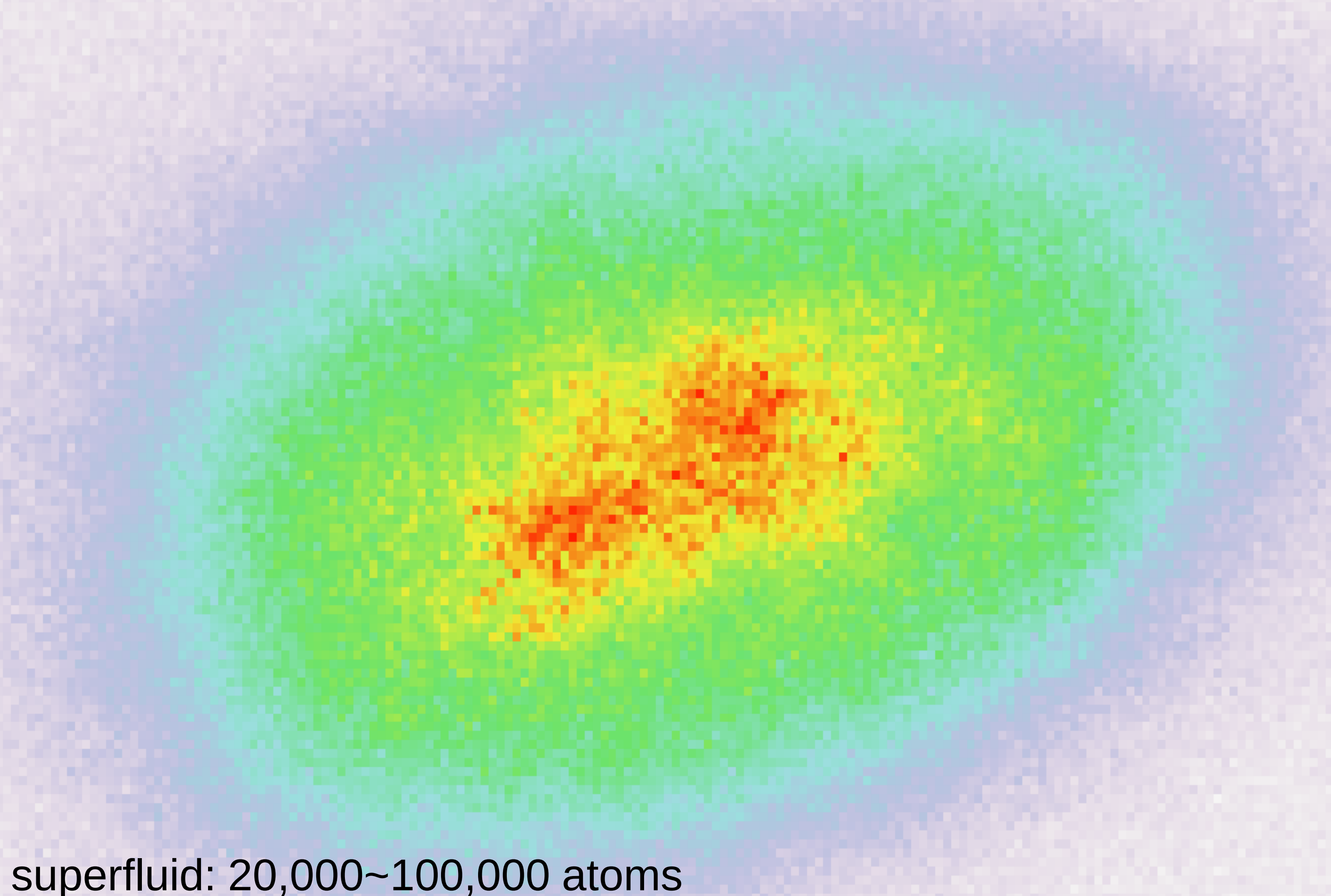
Ultracold atom lab at the Univ. of Chicago

CCD



atoms

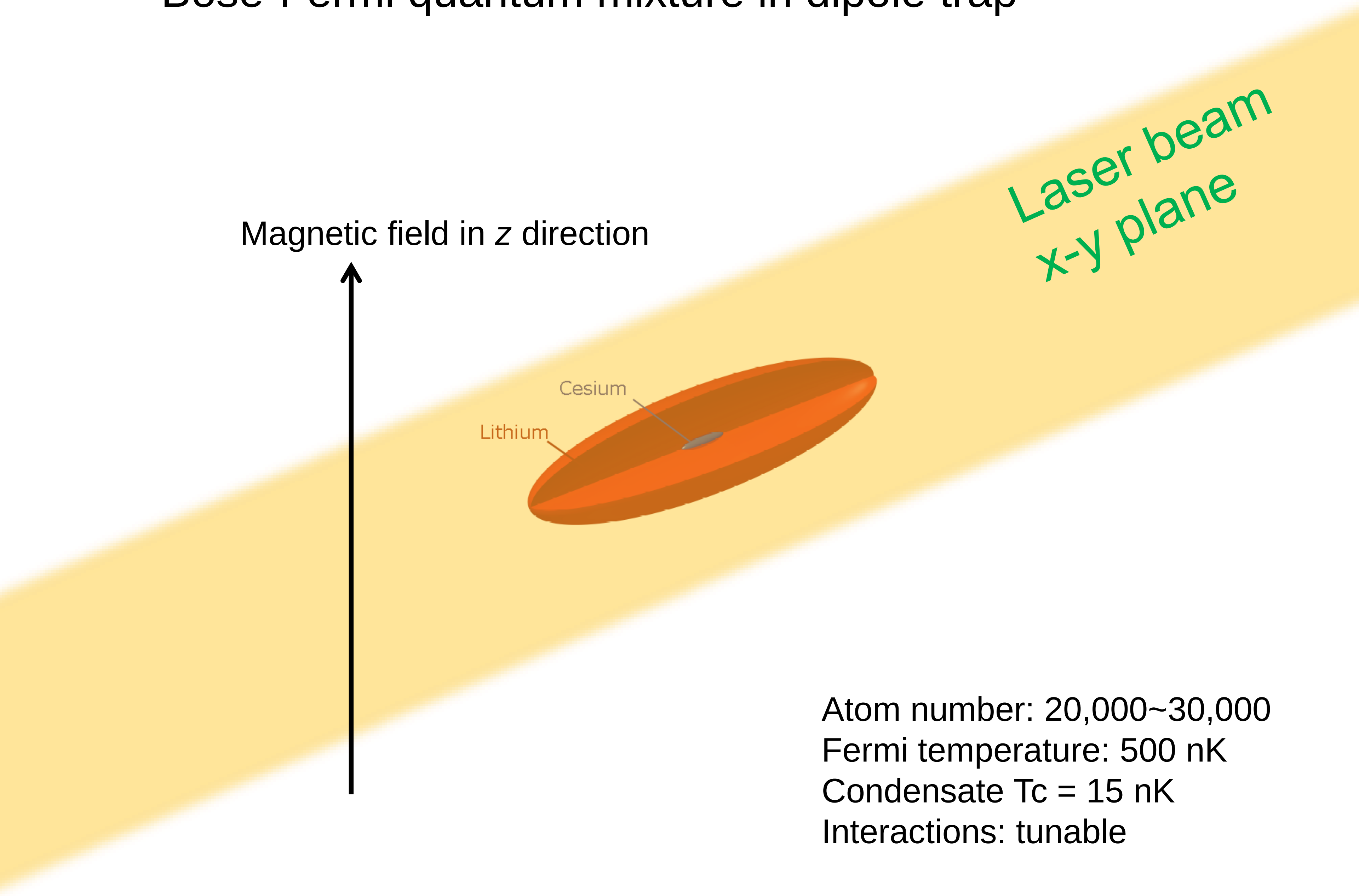
Imaging of ultracold atoms



Cs superfluid: 20,000~100,000 atoms
Imaging resolution: 1.0 µm
Sample size: 25 µm
20~100 atoms/μm^3

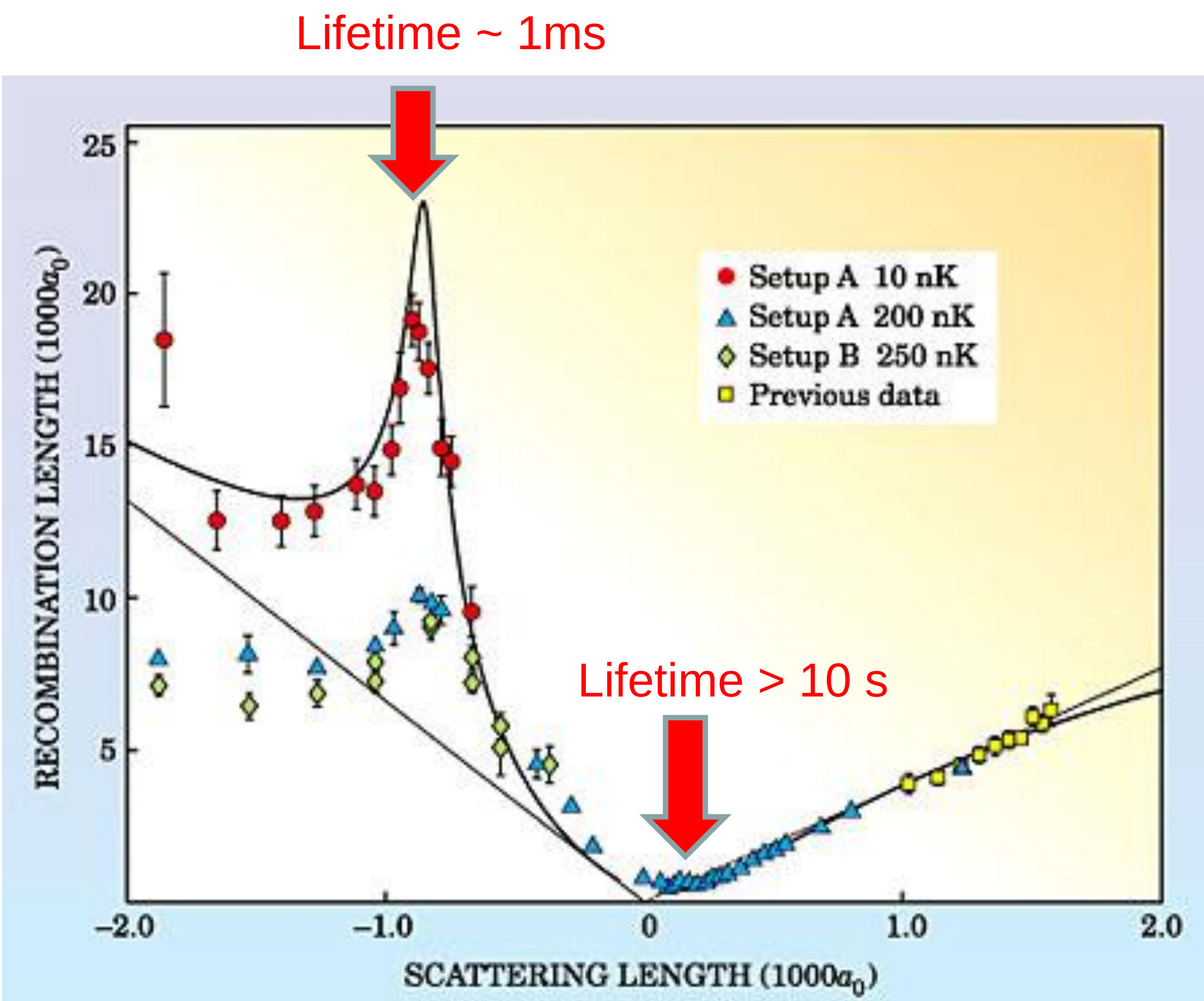
Nature 2009, Nature 2011

Bose-Fermi quantum mixture in dipole trap



Atom number: 20,000~30,000
Fermi temperature: 500 nK
Condensate Tc = 15 nK
Interactions: tunable

Observation of Efimov Resonance in ultracold atoms



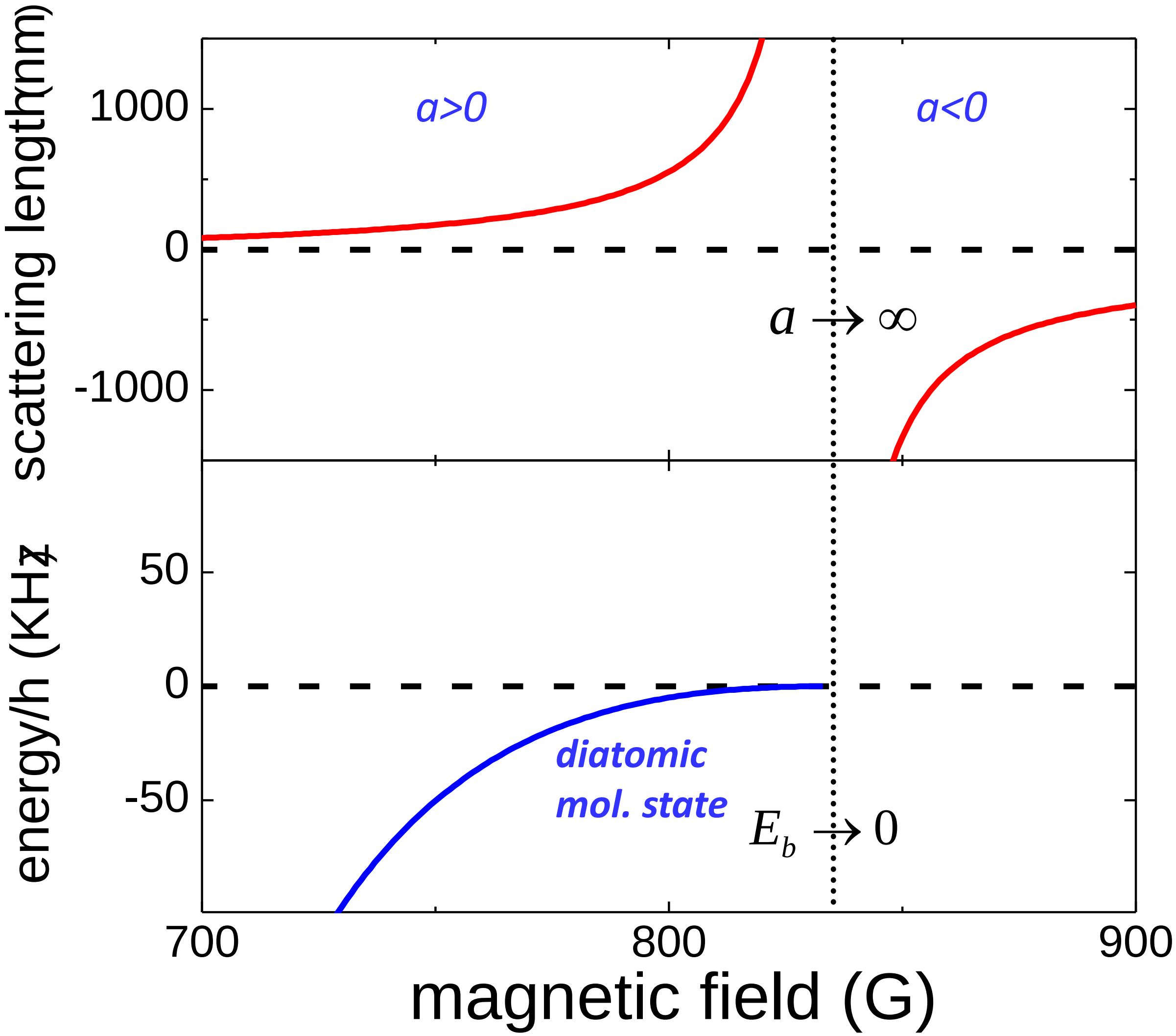
Other species:
Li6 (Penn State, Heidelberg),
Li7 (Rice, Bar-Ilan)
K39 (LENS),
Rb85 (JILA),
KRb (LENS),
LiCs (Chicago, Heidelberg)

Other observables:
Binding energy
4- and 5-body states
Coherent coupling

Kraemer et al., Nature 2006

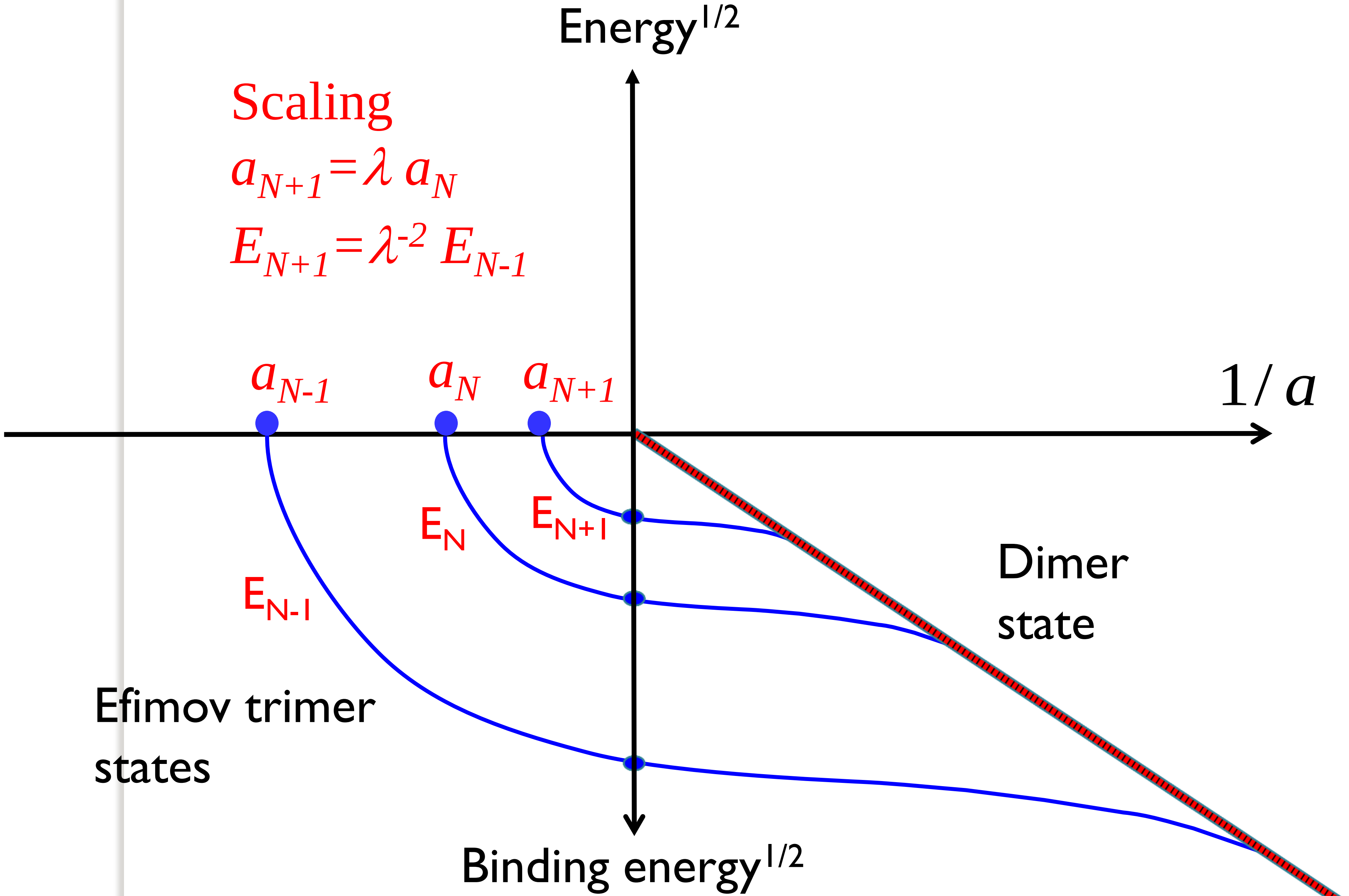
Physics Today 2006

Tuning scattering length with Feshbach resonances

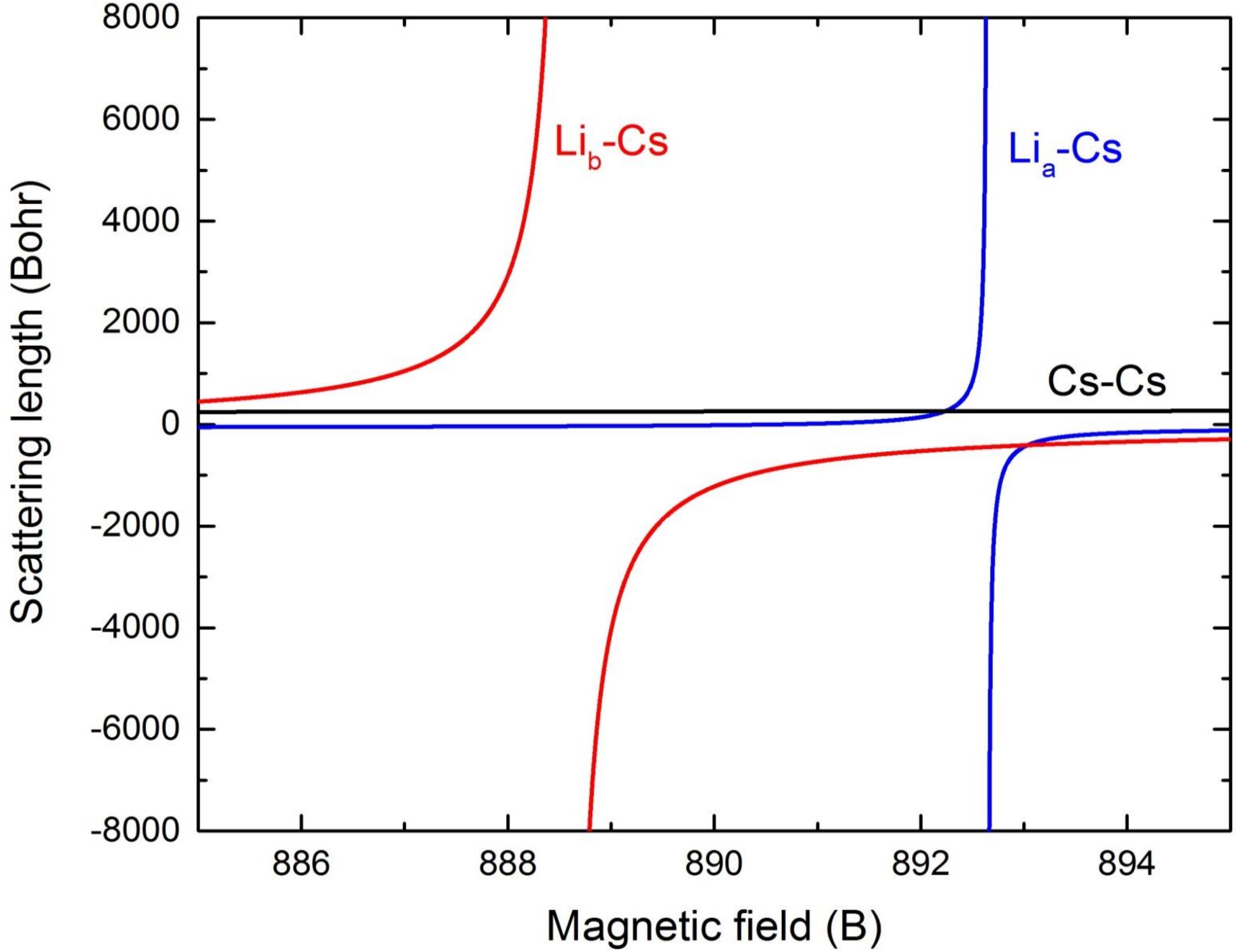


CC, R. Grimm, P. Julienne and E. Tiesinga, RMP (2010)

Efimov states near a Feshbach resonance

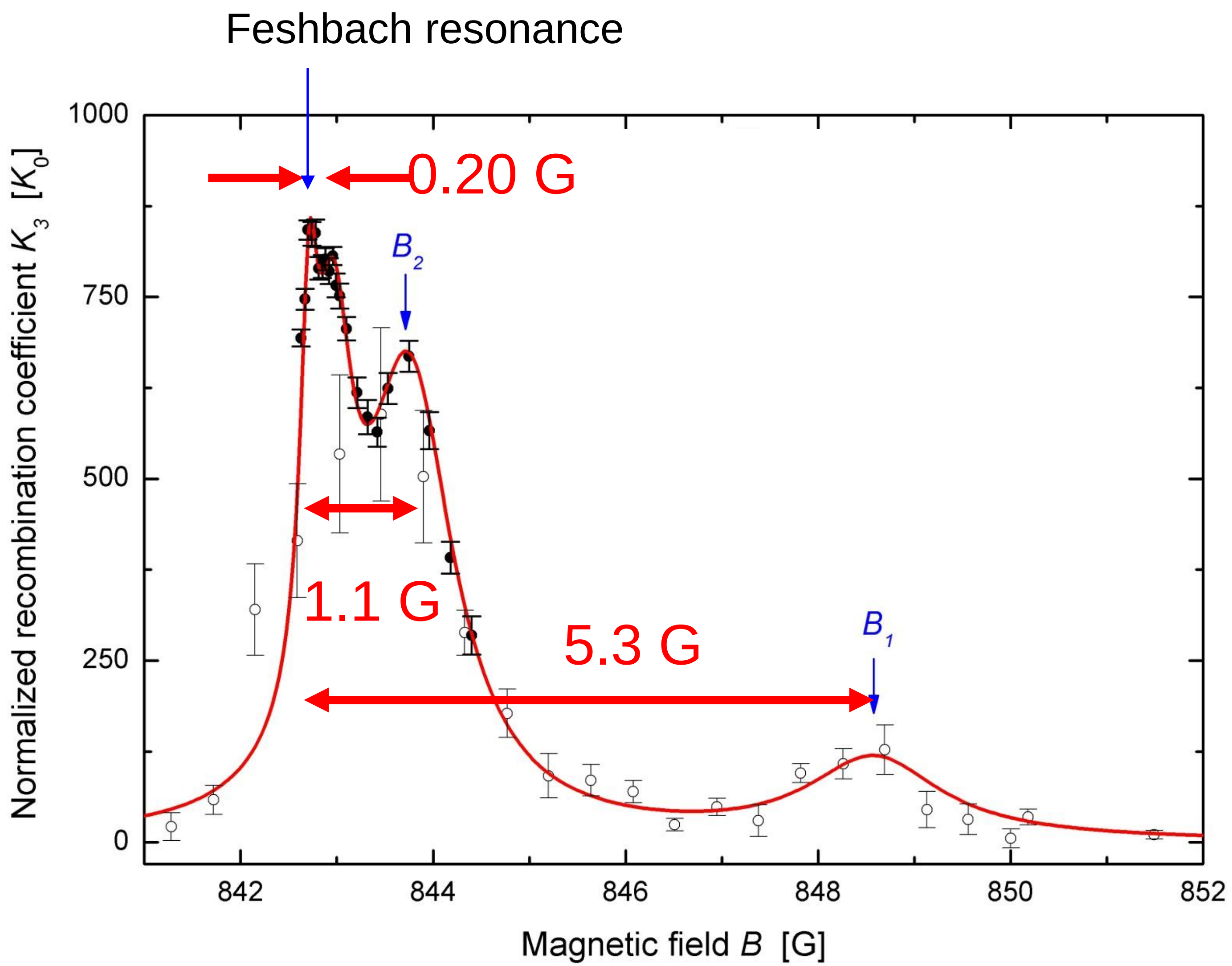


LiCs Feshbach resonances



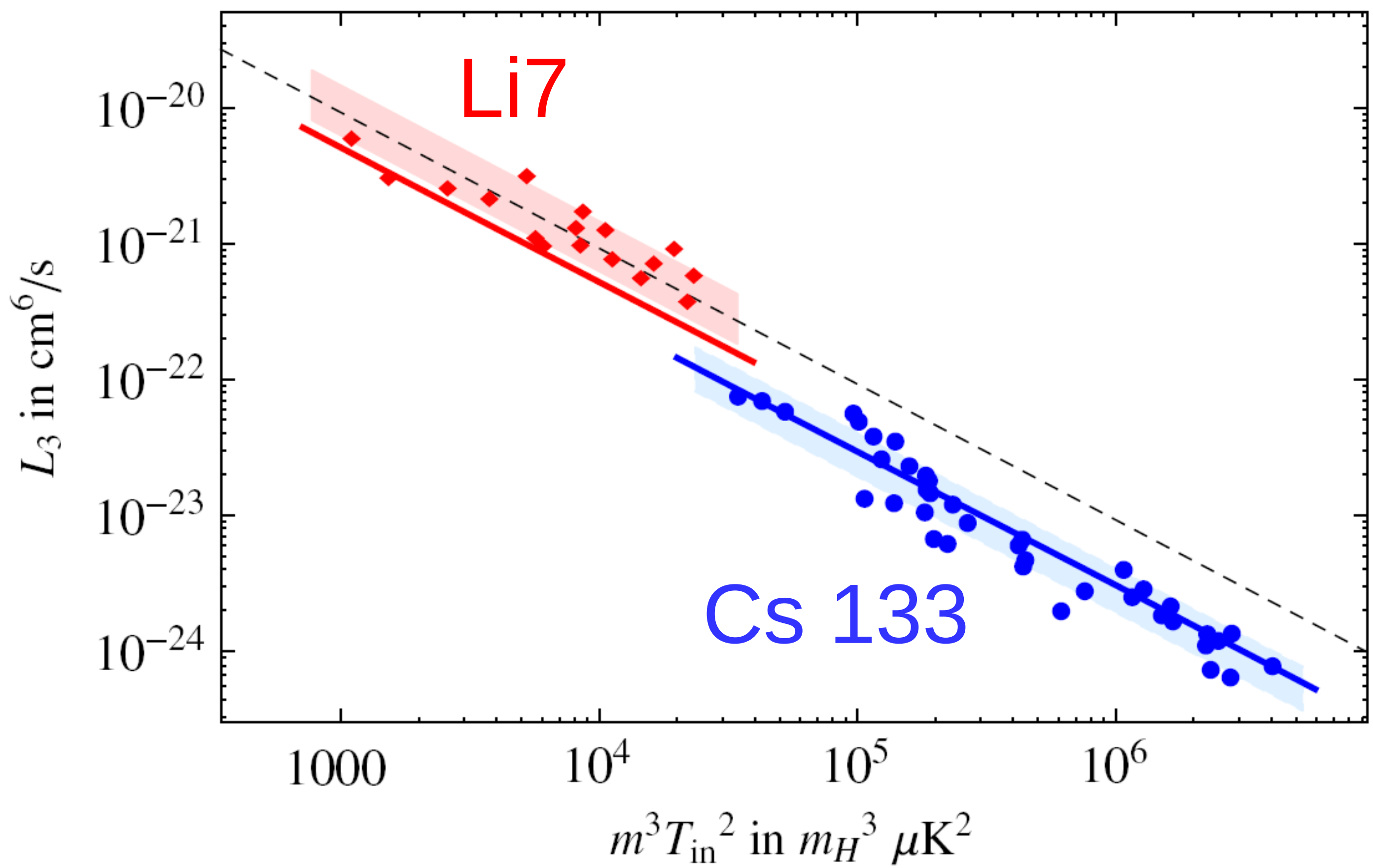
S.K. Tung et al., PRA (2013)   See also (Heidelberg group) M. Repp et al., PRA(2013)
Ulmanis et al., PRL(2016)

Geometric scaling of Efimov resonances in Li-Cs system (λ=4.9)



Tung et al., PRL (2014), see also Heidelberg and Innsbruck groups PRL (2014)

Universal scaling of resonant Bose gas



(ENS-Chicago Collaboration) U. Eismann et al, PRX (2016)

Related works: ENS, PRL (2013), Cambridge, PRL (2013), JILA: Nature Physics (2014)

Short summary: Efimov states in cold atoms

Prediction — Vitaly Efimov (1970)

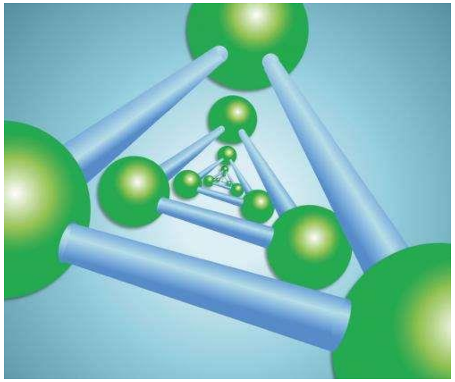
$\alpha+\alpha+\alpha \rightarrow C$

$H+H+H \rightarrow T$

Appearance — Cs, Li, K, Rb, LiCs, LiRb, He — 2006…

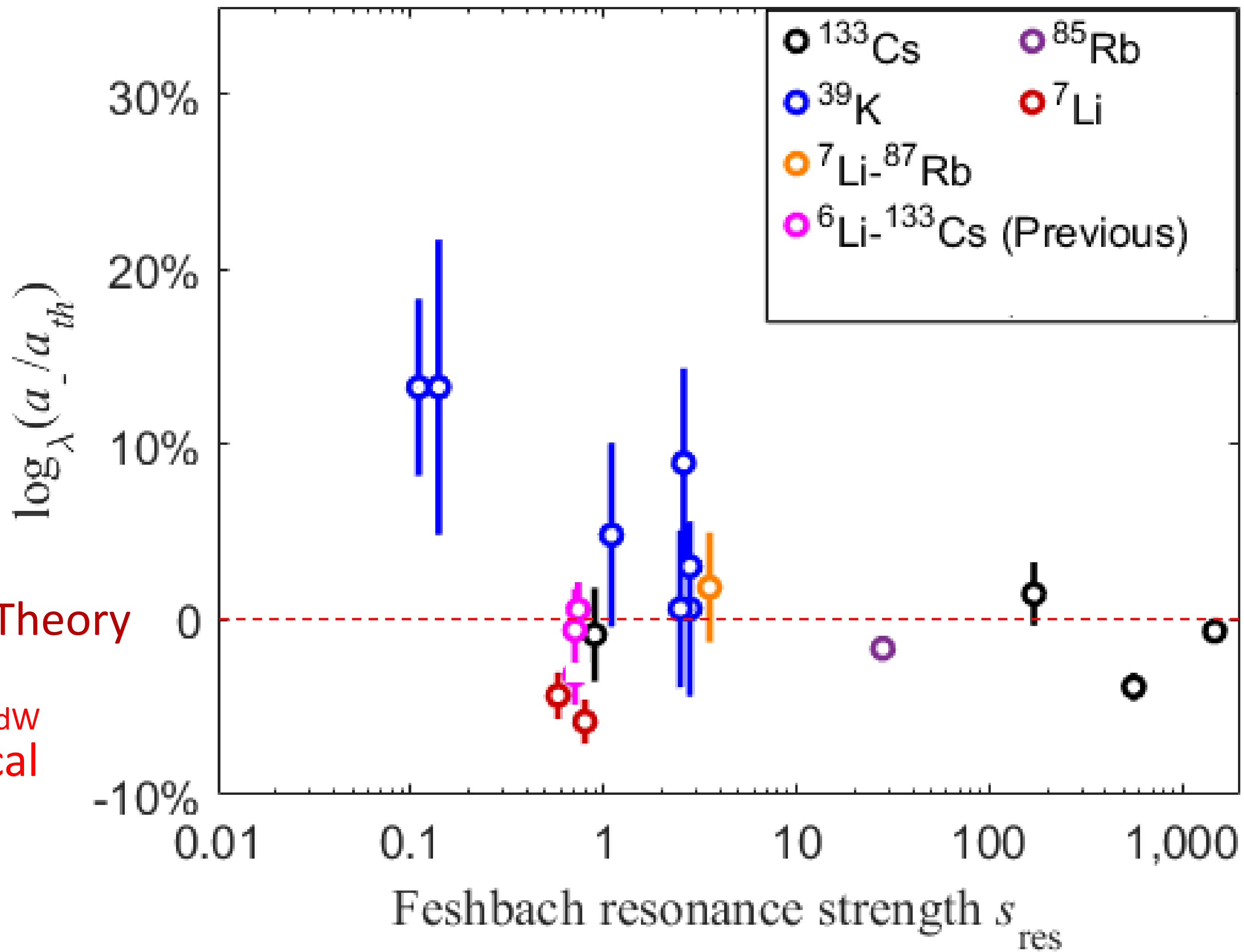
Properties — Geometric scaling, universality…

Molecular size:
1, λ, λ² …



Molecular size ~
Scattering length $a \propto$
van der Waals length

van der Waals Universality? (Grimm, *2011)*



Universal Theory

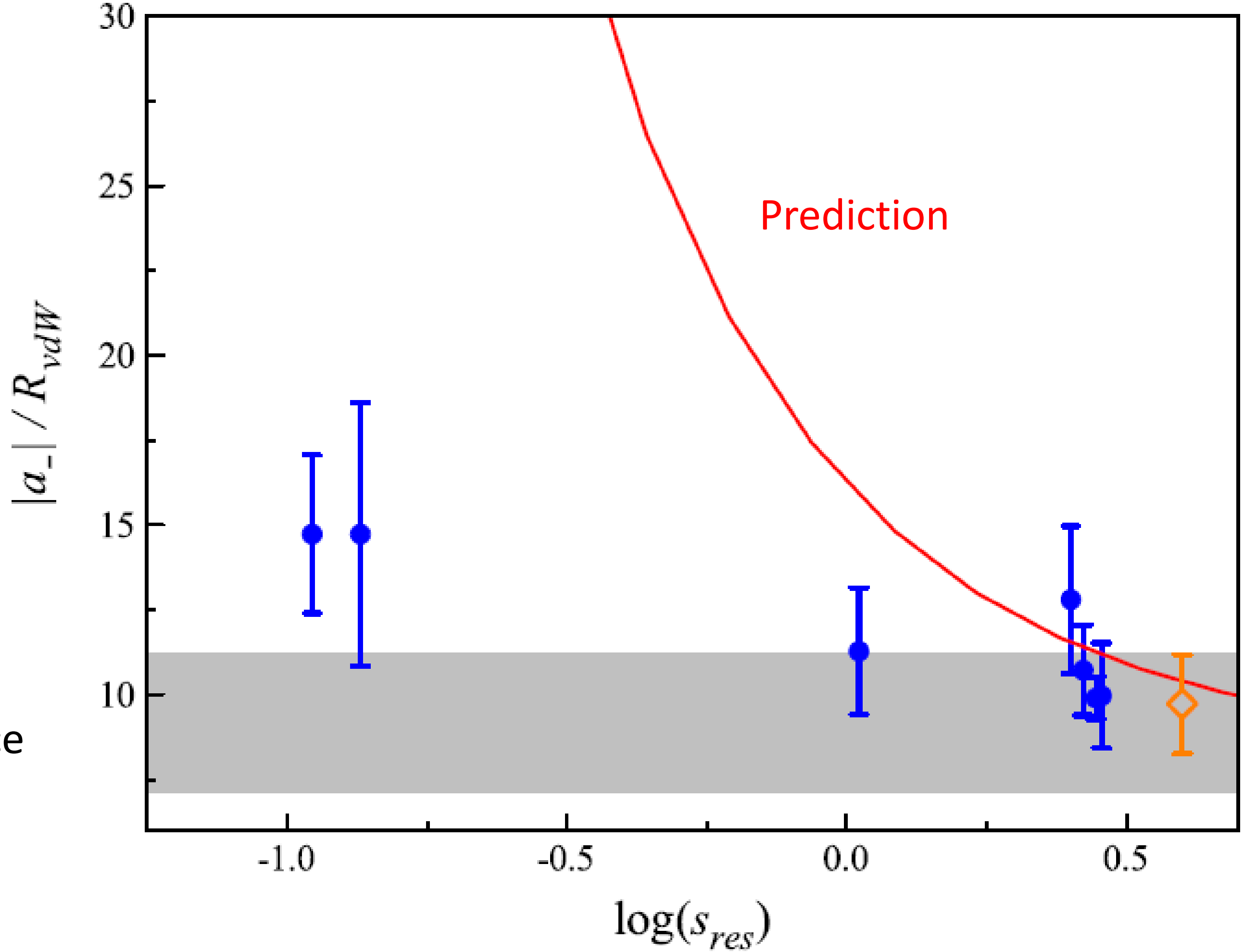
$a_{-} \approx 9.5\ r_{vdW}$ for identical bosons

Model for identical bosons: Chin C. arXive: 1111.1484, Wang J. et al., PRL (2012)

Review: CC, Y. Wang, Nature Physics (2016)

Broad vs. narrow resonances

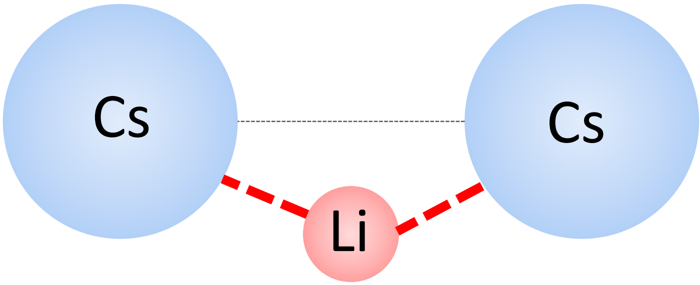
Narrow resonance



Broad resonance

S. Roy et al., Phys. Rev. Lett. **111**, 053282 (2013)
Prediction: (Red curve) R. Schmidt et al., The European Physical Journal B **85**, 1 (2012)
Other predictions: Petrov (2004), J. Wang et al., PRL (2012), Ueda, (2014), W. Zwerger, 1709.00749

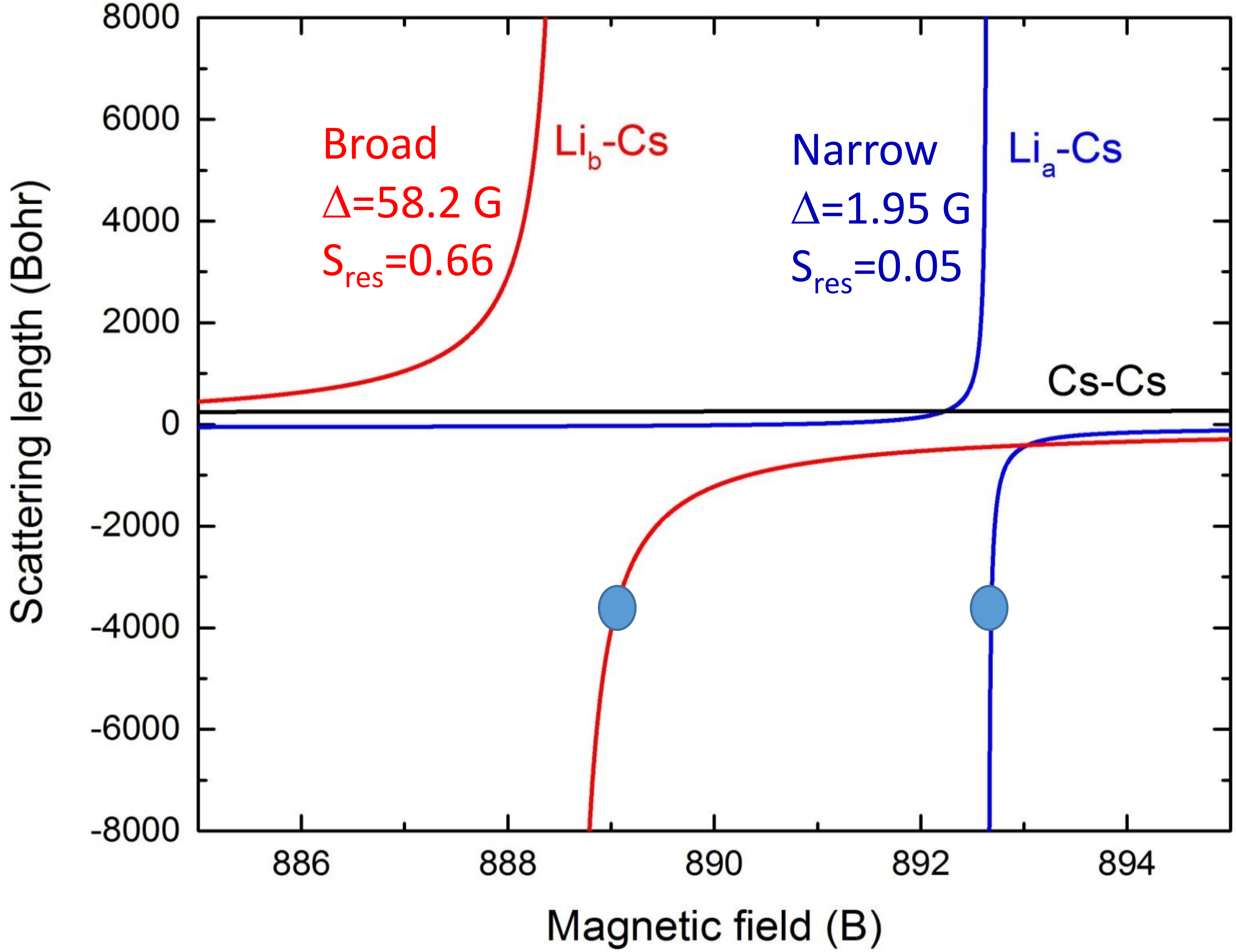
vdW Universality Hypothesis



$|a_{\mathrm{LiCs}}| >> |a_{\mathrm{CsCs}}|$

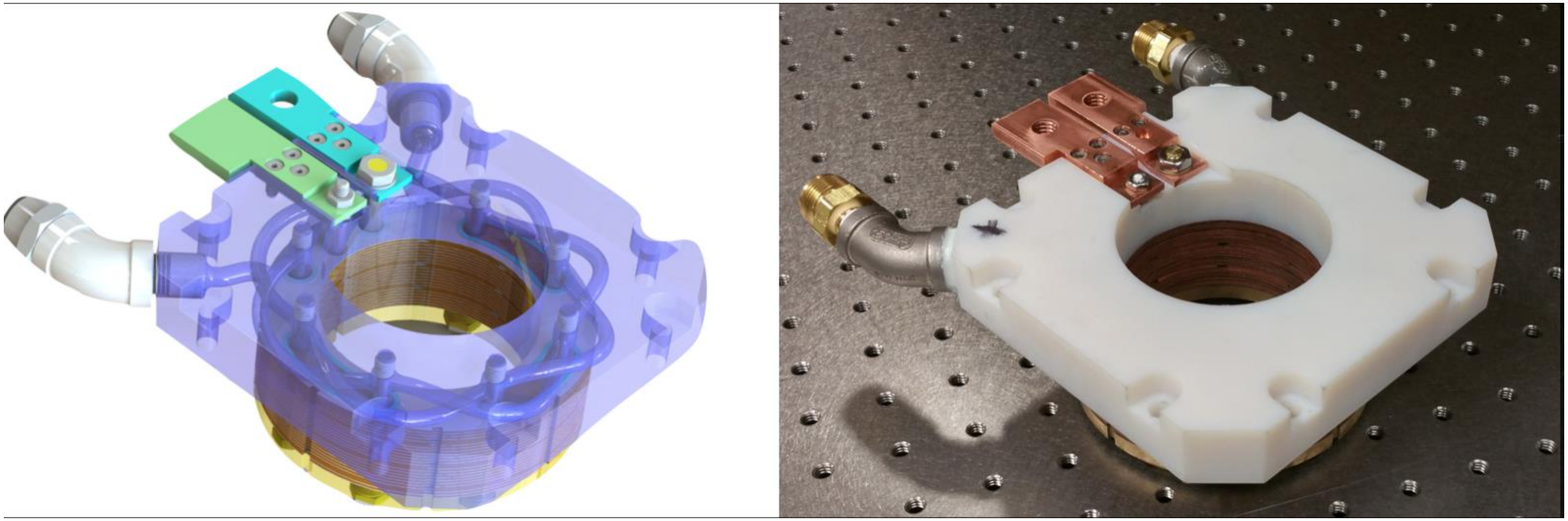
Does Efimov resonance position only depend on the van der Waals length(s)?

LiCs Feshbach resonances



S.K. Tung et al., PRA (2013) See also (Heidelberg group) M. Repp et al., PRA(2013)
Ulmanis et al., PRL(2016)

High Precision Bitter coil

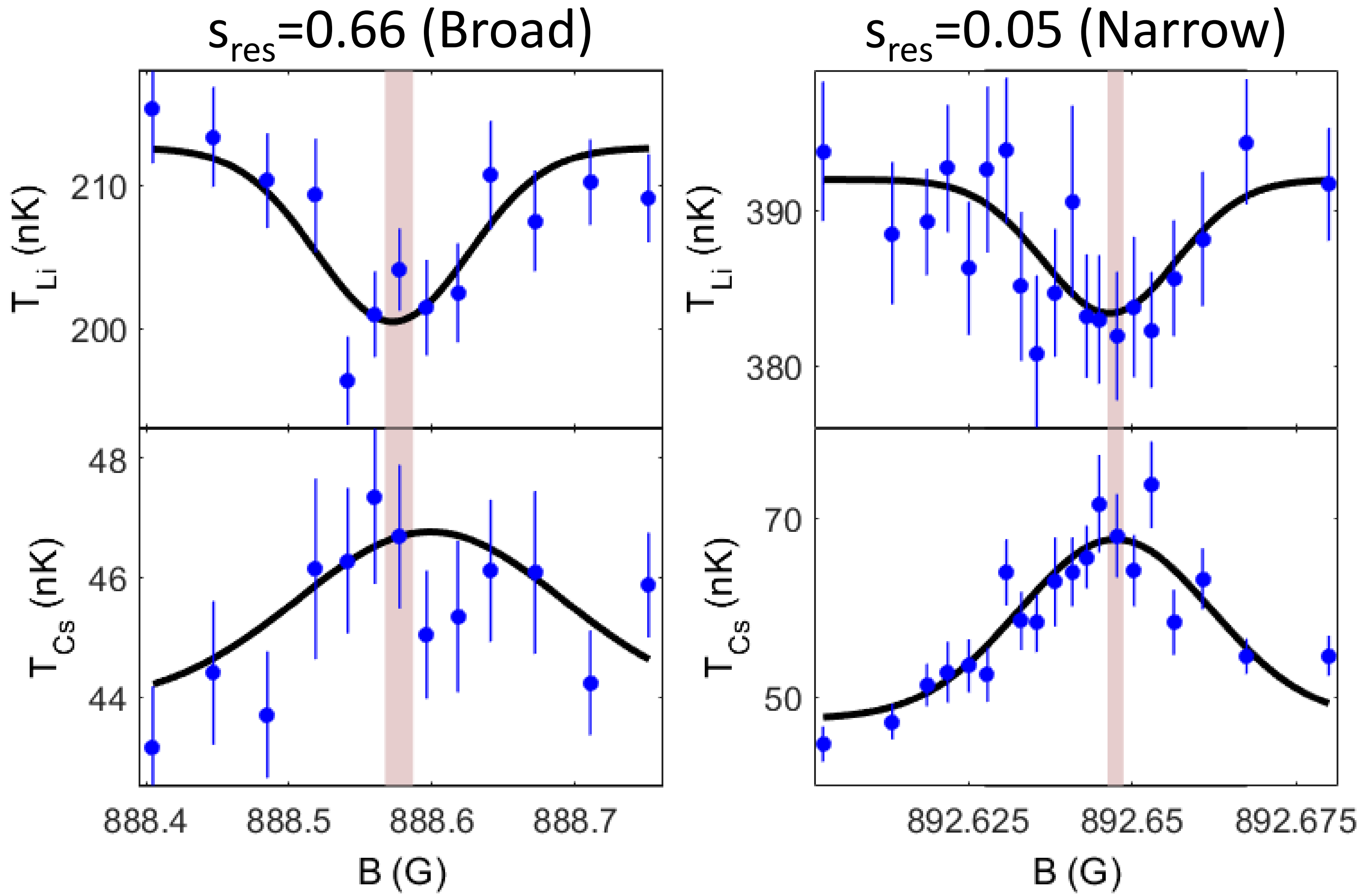


Precision field control at $2x10^{-6}$ at 1000G

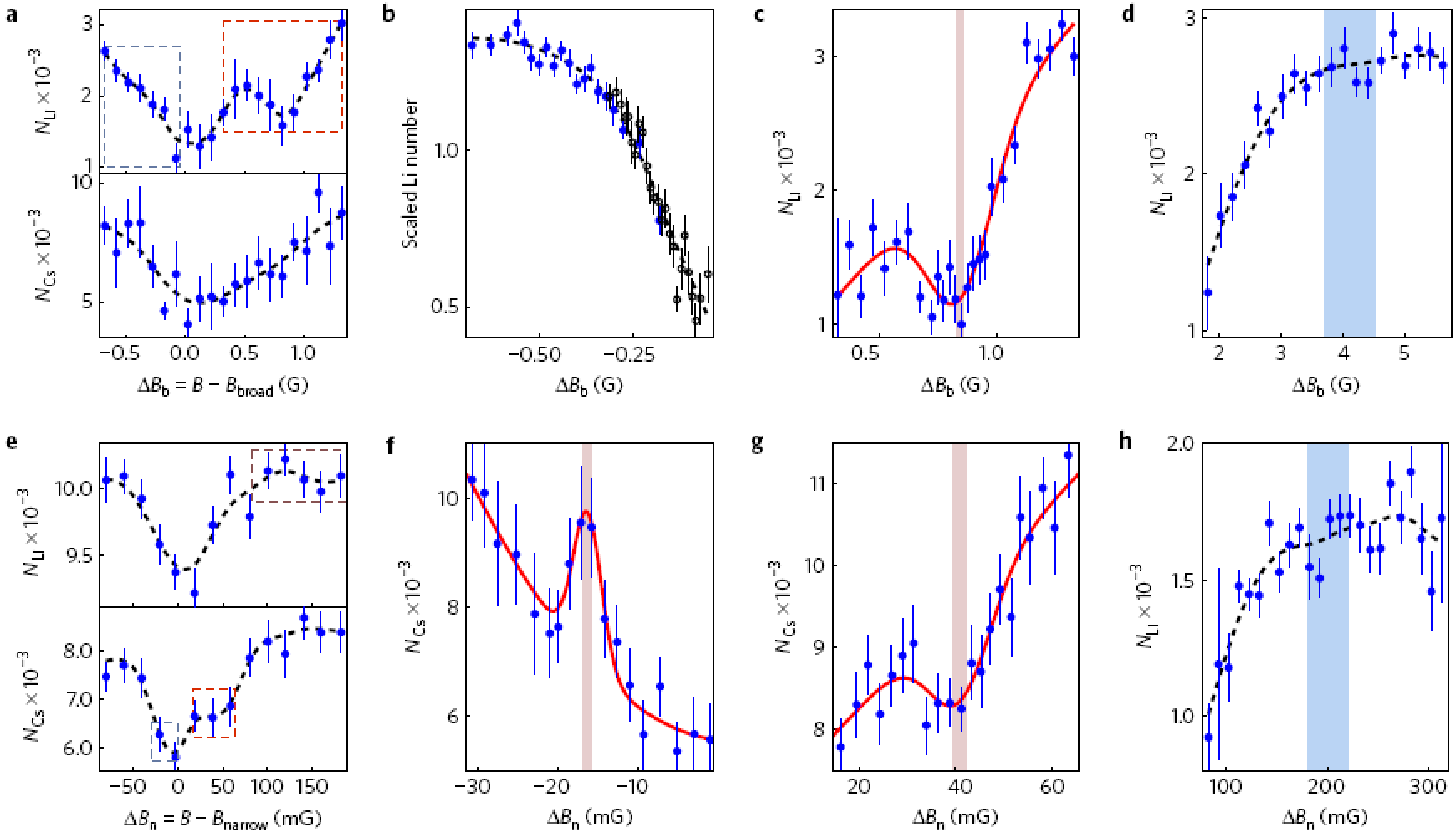
Highe packing ratio, 10x cooling, no epoxy, low thermal drifts

Prototype : Rev. Sci. Instrum. 84, 104706 (2013)

Interspecies Thermalization



Searching for Efimov resonances…



Results

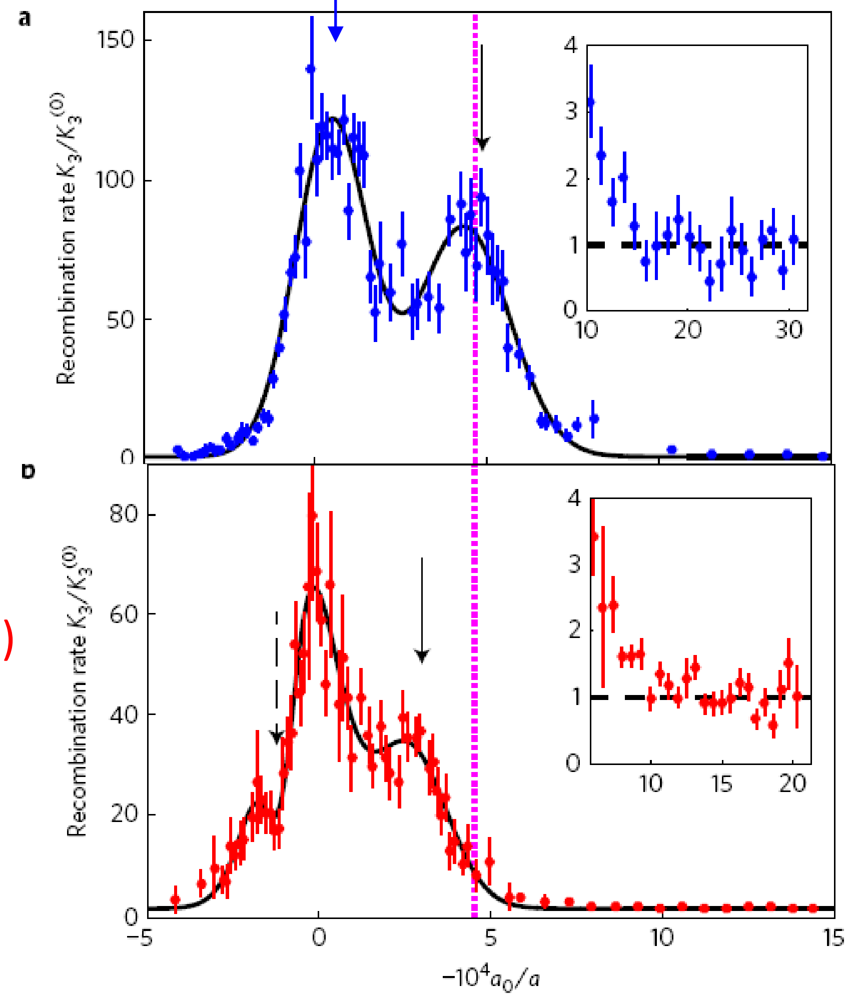
Feshbach resonance

Broad Feshbach (S_{res}=0.66)

$a\_$= **-2050(40)** a_0

Narrow Feshbach (S_{res}=0.05)

$a\_$= **-3330(220)** a_0



Universal Theory: -2150 a_0

Universal Theory: -2200 a_0

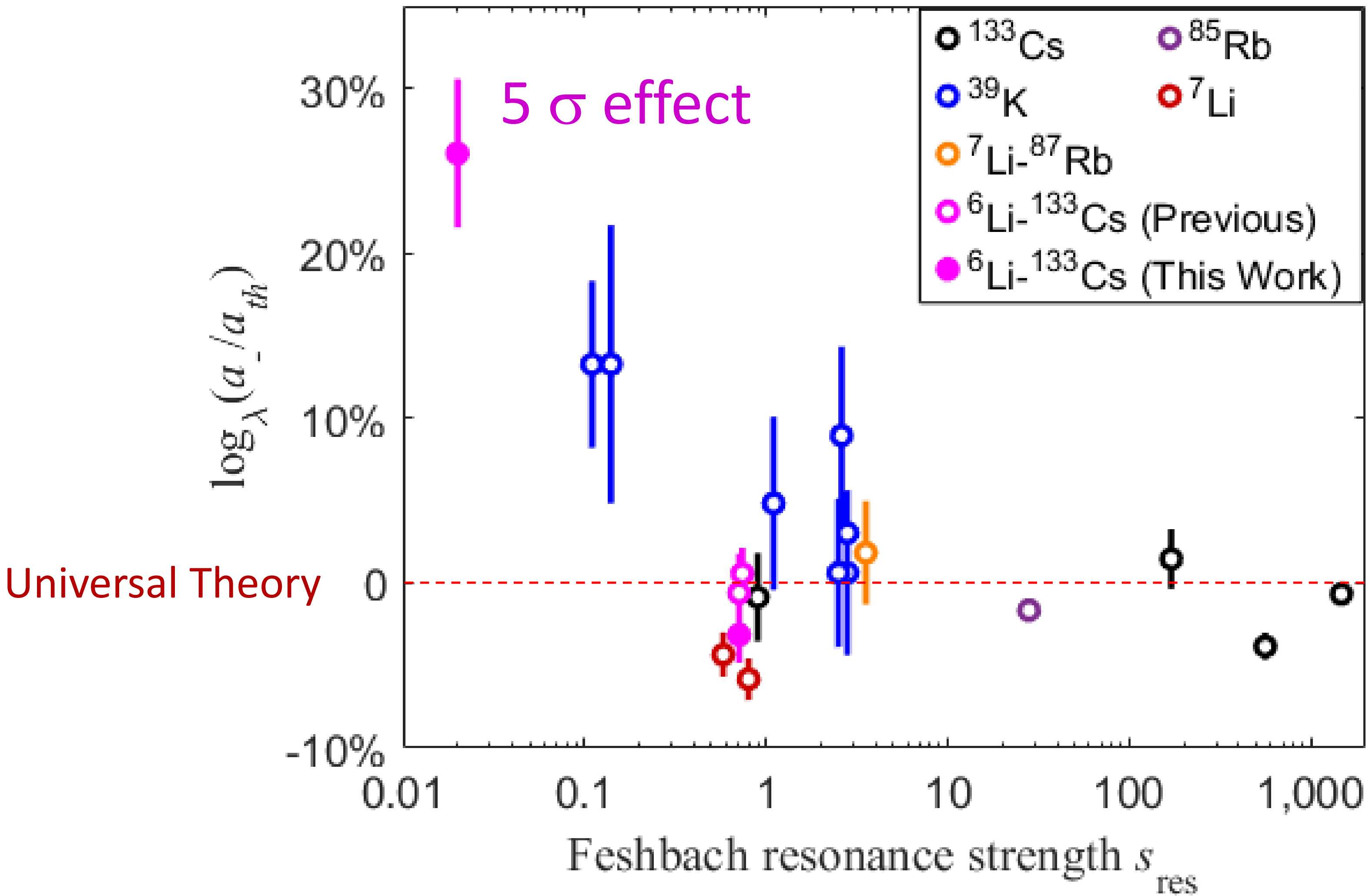
Theory: Yujun Wang, Chris Greene, Paul Julienne

Table 1 | Summary of Efimov resonances for the three Feshbach resonances in Li–Cs at 843 (ref. 12), 889, and 893 G.

B_0 (G)	s_{res}	$a_{CsCs}(a_0)$	$a_-^{(2)}(a_0)$	$a_{th}^{(2)}(a_0)$
888.577(10)(10)	0.66	200	−2,050(60)	−2,150
892.648(1)(10)	0.05	260	−3,330(240)	−2,200
842.750(1)(3)	0.66	−1,400	−1,635(60)	−1,680

J. Johansen, B.J. DeSalvo, K. Patel and C.C., Nature Physics (2017)

Deviation from the van der Waals Universality



J. Johansen, B.J. DeSalvo, K. Patel and C.C., Nature Physics 13, 731 (2017)

Conclusion

- Over a dozen Efimov states seen in recombination
- Geometric scaling symmetry: confirmed
- van der Waals universality…
  - Broad resonance: consistent with universal theory
  - Narrow resonance s_{res}=0.05: +51(10)% deviation

Emergence of new length scale(s).

Future: Efimov trimers in Fermi sea

Efimov experiments at the University of Chicago

Jacob Johansen
Now at NW Univ.

Prof. Brian DeSalvo

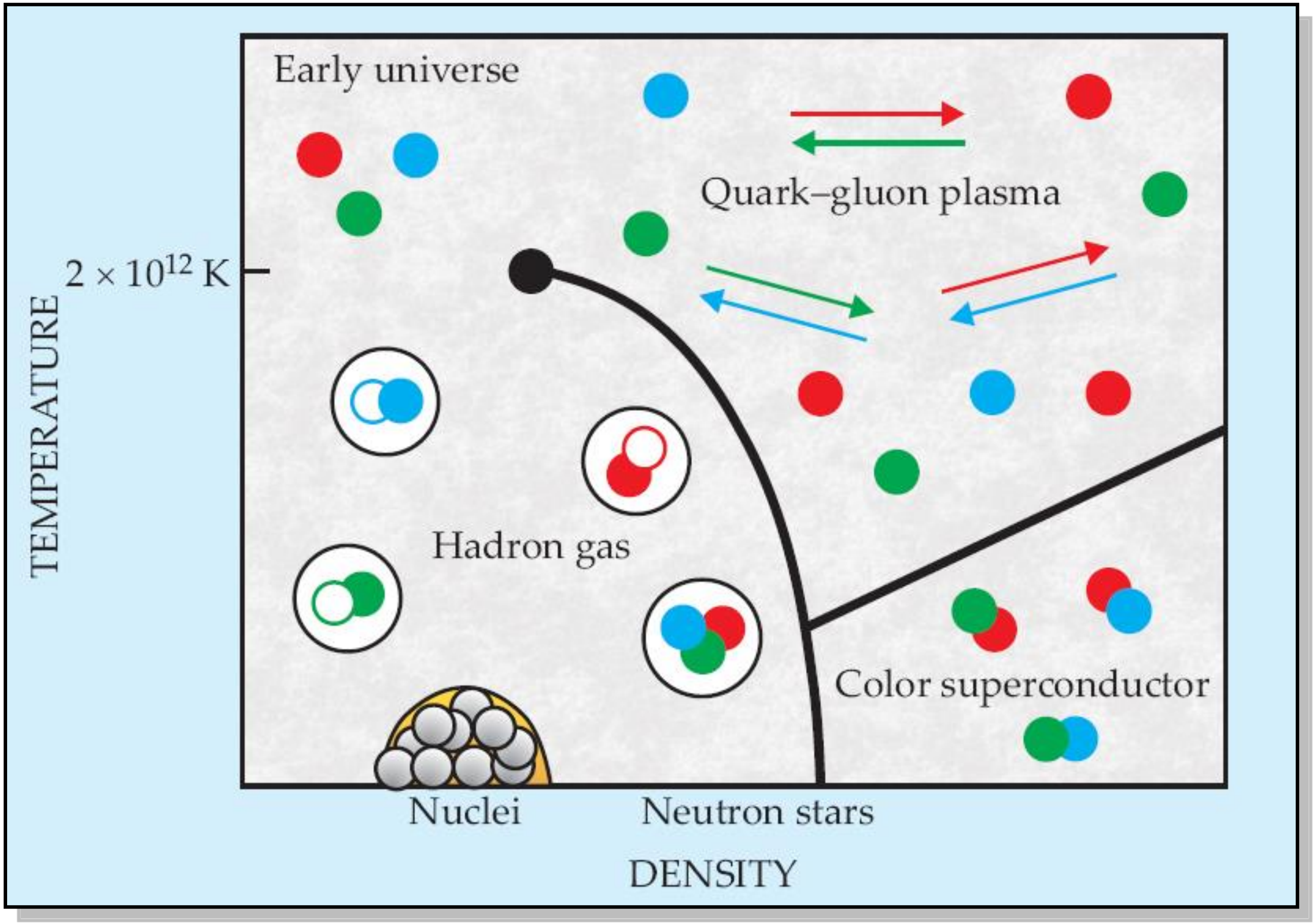
Krutik Patel

Prof. Colin Parker
George Institute of Technology

Prof. S.K. Tung
National Tsinghus University

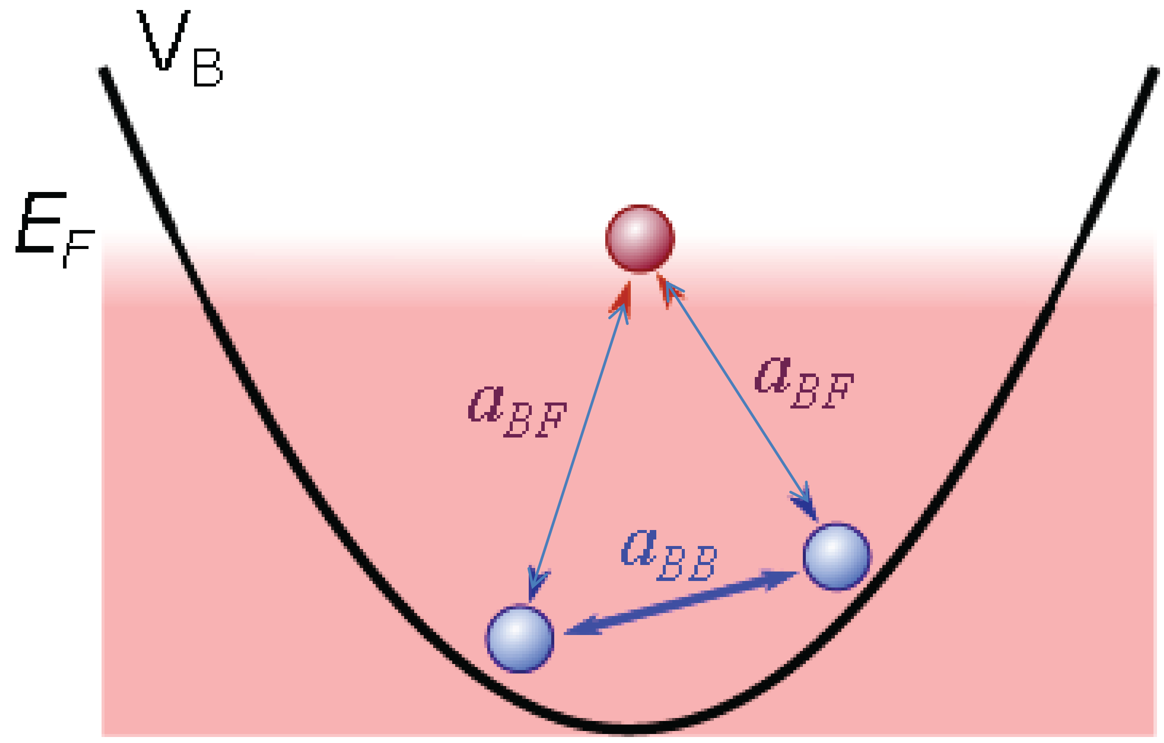
Prof. Karina Garcia
Univ. of Mexico

QCD Phase Diagram



C. Sa de Melo, Physics Today, Oct. 2008

Efimov-RKKY interactions in quantum gas



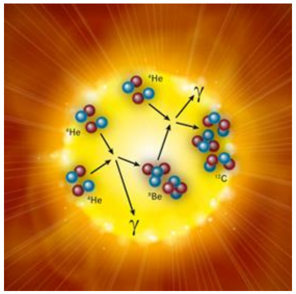
$$E = \frac{\hbar^2}{2m_B}|\nabla\psi_B(r)|^2 + V_{\text{eff}}(r)|\psi_B(r)|^2 + \frac{g_{\text{eff}}}{2}|\psi_B(r)|^4$$

$$g_{\text{eff}} = g_{BB} - \xi\frac{3}{2}\frac{n_F}{E_F}g_{BF}^2$$

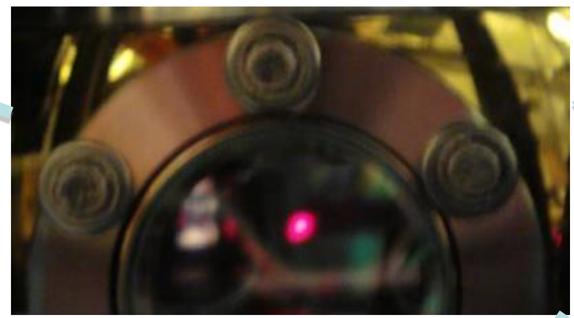
DeSalvo, Patel, Cai, and CC, Nature 568, 61 (2019)

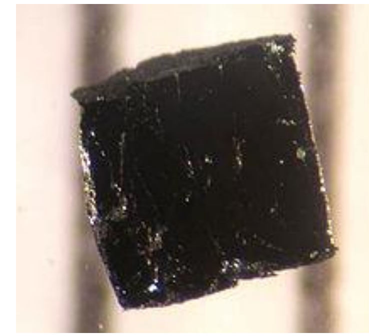
Quantum simulation in our lab

THE UNIVERSITY OF CHICAGO

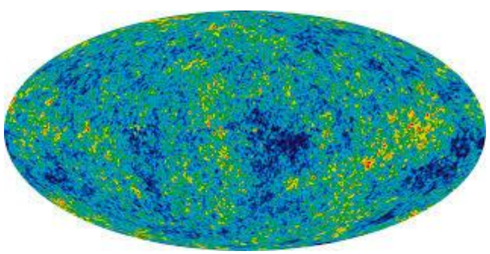


Nuclear Physics:
Feshbach resonances
Efimov physics

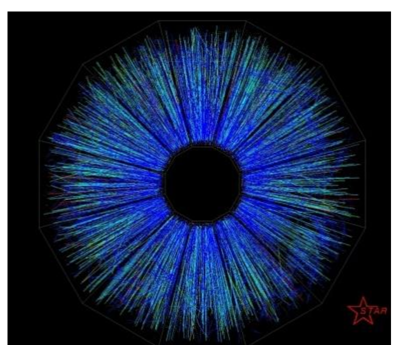




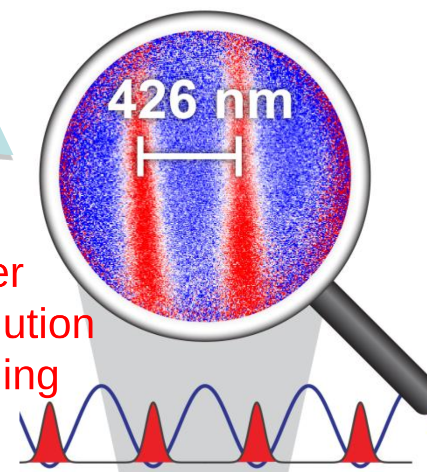
Condensed Matter:
Quantum criticality
RKKY interactions
BEC-BCS crossover



Cosmology
Sakharov oscillations
Kibble mechanism
Inflation, Unruh radiation



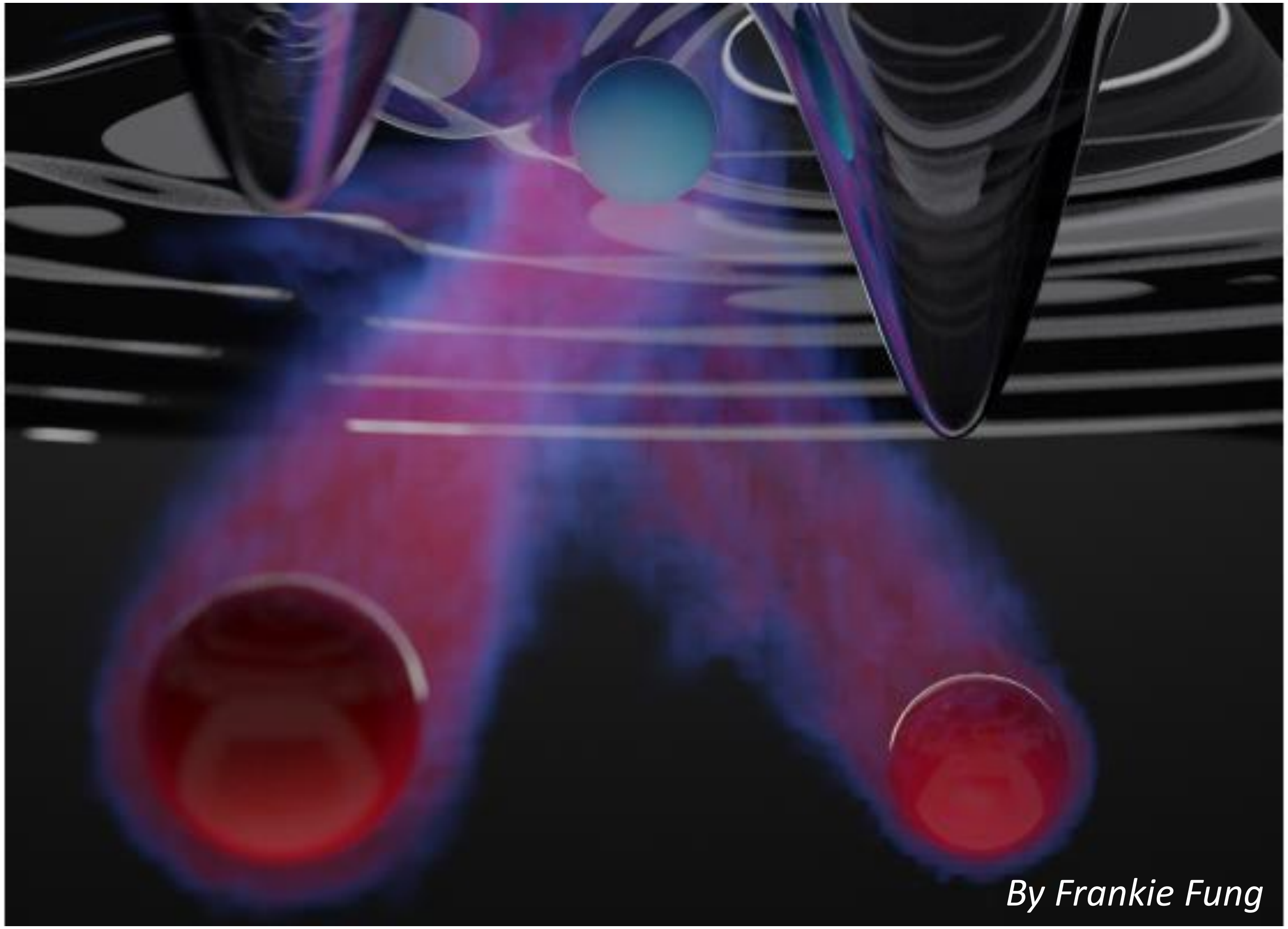
Particle Physics
Jet formation
Pattern formation



Super resolution imaging

Ruderman–Kittel–Kasuya–Yosida mechanism in quantum gas

Li
Fermi sea



Cs
atoms