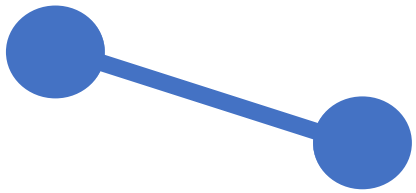
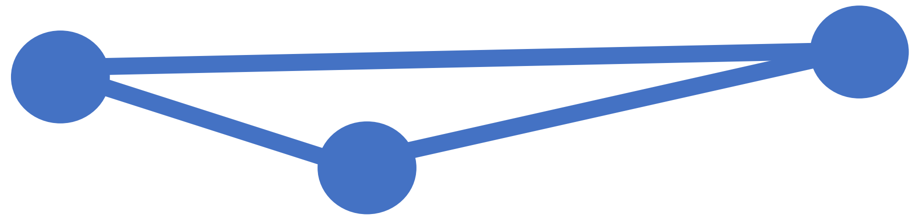



Probing the helium dimer and trimer with fast, intense lasers

Doerte Blume and Qingze Guan
Center for Quantum Research and Technology (CQRT)
Department of Physics and Astronomy
The University of Oklahoma

Supported by the NSF.

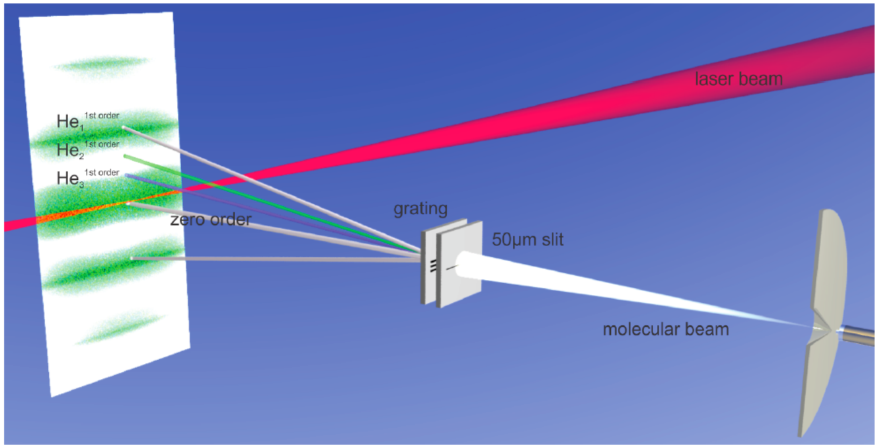
In collaboration with Reinhard Doerner's group at Frankfurt U. (lead Maksim Kunitski)

Two-body (real-time dynamics)

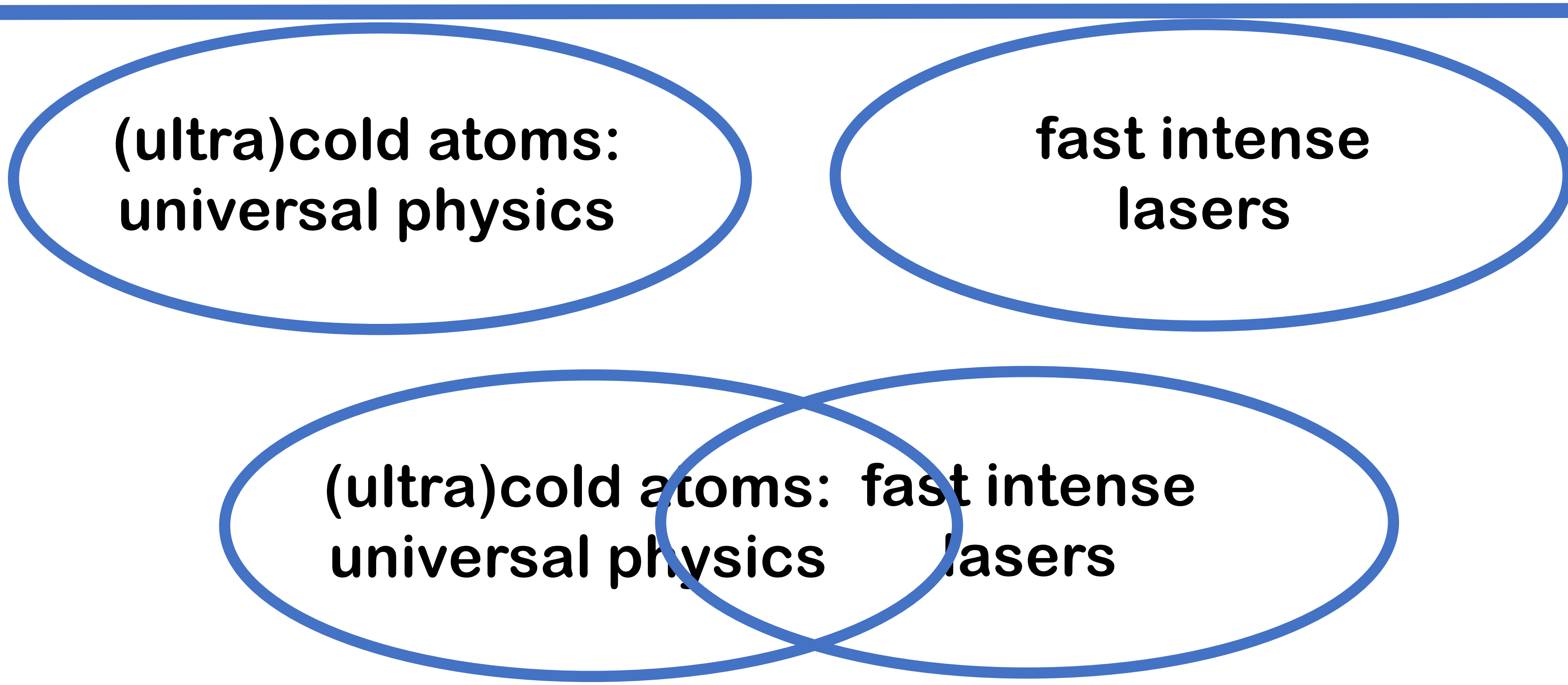
Three-body (three-body Efimov state; no real-time dynamics)

In collaboration with Reinhard Doerner's group at Frankfurt University (lead Maksim Kunitski)

Size-selected nozzle beam expansion experiments and theory



Two Exciting Fields



One may hope: Two good things combined should be better than two good things separated…

But you may object: Aren’t we just gonna blow everything up?

Yes, we will… and it’s fun and useful…

Works in This Direction

PHYSICAL REVIEW LETTERS **124,** 253201 (2020)

Ultrafast Creation of Overlapping Rydberg Electrons in an Atomic BEC and Mott-Insulator Lattice

M. Mizoguchi,[1,2] Y. Zhang,[1,3] M. Kunimi,[1] A. Tanaka,[1] S. Takeda,[1,2,†] N. Takei,[1,2,‡] V. Bharti,[1] K. Koyasu,[1,2] T. Kishimoto,[4] D. Jaksch,[5,6] A. Glaetzle,[5,6] M. Kiffner,[5,6] G. Masella,[7] G. Pupillo,[7] M. Weidemüller,[8,9] and K. Ohmori[1,2,*]

ARTICLE

DOI: 10.1038/s41467-018-04556-3 OPEN

Quantum simulation of ultrafast (
trapped ultracold atoms

Ruwan Senaratne[1], Shankari V. Rajagopal[1], Toshihiko Shimasaki[1], ... Kurt M. Fujiwara[1], Kevin ...[1]
Zachary A. Geiger[1] & David M. Weld[1]

(ultra)cold atoms: universal physics

fast intense lasers

Found Phys (2014) 44:813–818
DOI 10.1007/s10701-014-9773-5

Optically Engineered Quantum States in Ultrafast and Ultracold Systems

Kenji Ohmori

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **95**, 011403(R) (2017)

Ultracold-atom quantum simulator for attosecond science

Simon Sala, Johann Förster, and Alejandro Saenz
AG Moderne Optik, Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany

(Received 23 November 2016; published 25 January 2017)

PRL **103,** 260401 (2009) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2009

Pump-Probe Spectroscopy of Two-Body Correlations in Ultracold Gases

Christiane P. Koch[1,*] and Ronnie Kosloff[2]

Works in This Direction

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(ultra)cold atoms: universal physics

fast intense lasers

NICATIONS

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DOI 10.1007/s10701-014-977

**Optically Enginee
and Ultracold Sys**

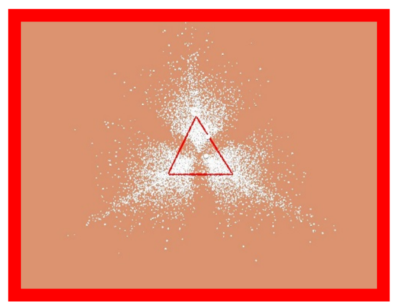
Kenji Ohmori

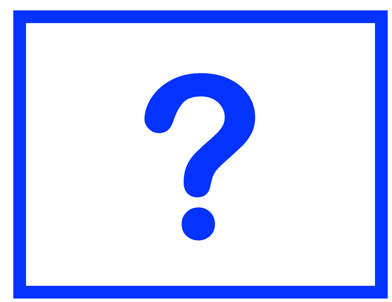
Hopefully, will be able to transfer ideas and insights to nuclear physics and condensed matter physics…!
Has been fruitful approach for Efimov physics --- can knowledge transfer be extended to dynamic sector???

Some Background on the Helium System

1 K = 8.6 x 10^{-5} eV

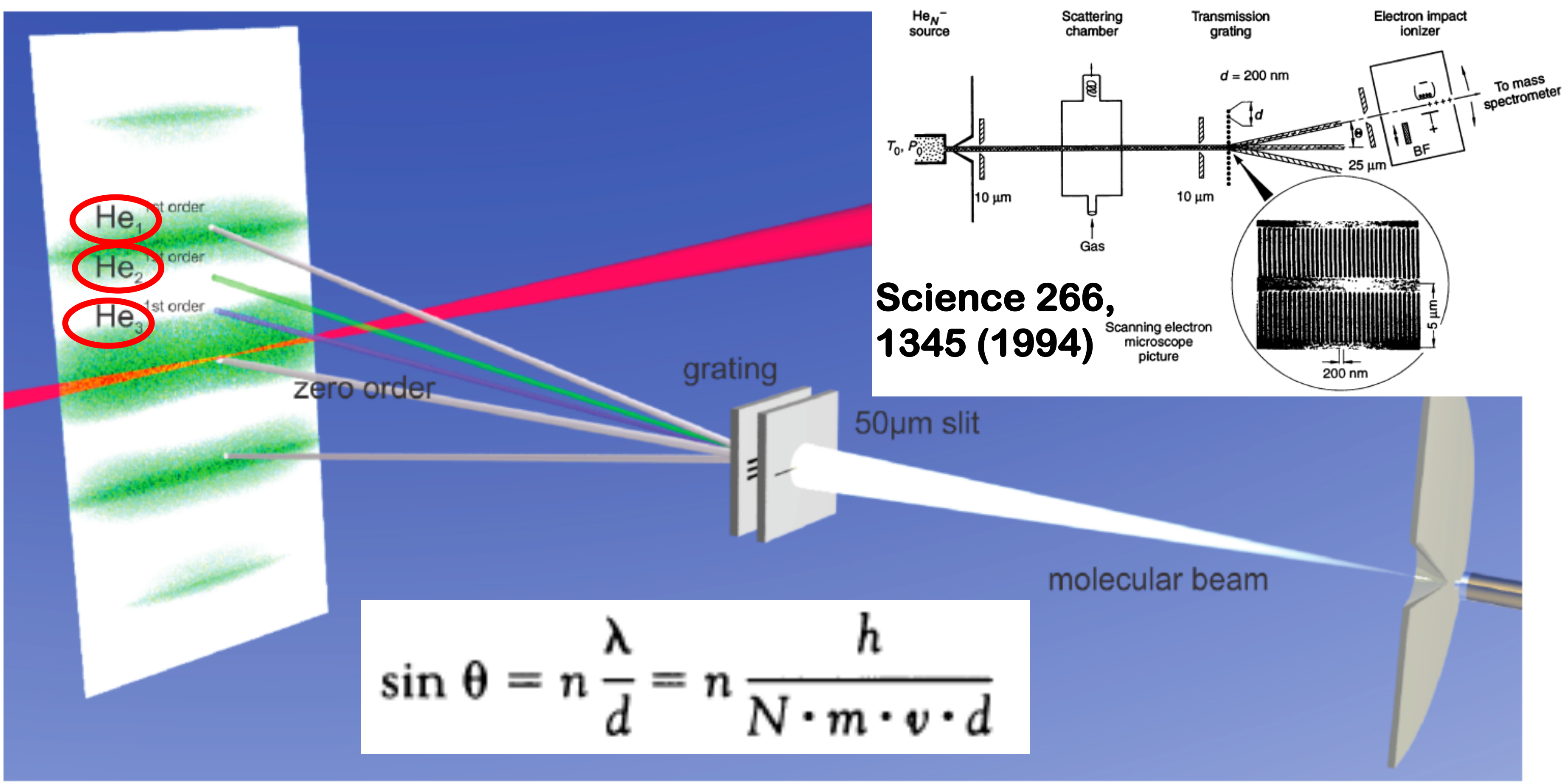
- Dimer:
  - ^{4}He-^{4}He bound state energy $E_{dimer} = -1.7$mK.
  - No J > 0 bound states.
  - Two-body s-wave scattering length $a_s = 171a_0$.
  - Two-body effective range $r_{eff} = 15.2a_0$ (alternatively, two-body van der Waals length $r_{vdW} = 5.1a_0$).
- Trimer:
  - Two J = 0 bound states with $E_{trimer} =$ −131.8mK and −2.65mK.
  - No J > 0 bound states.





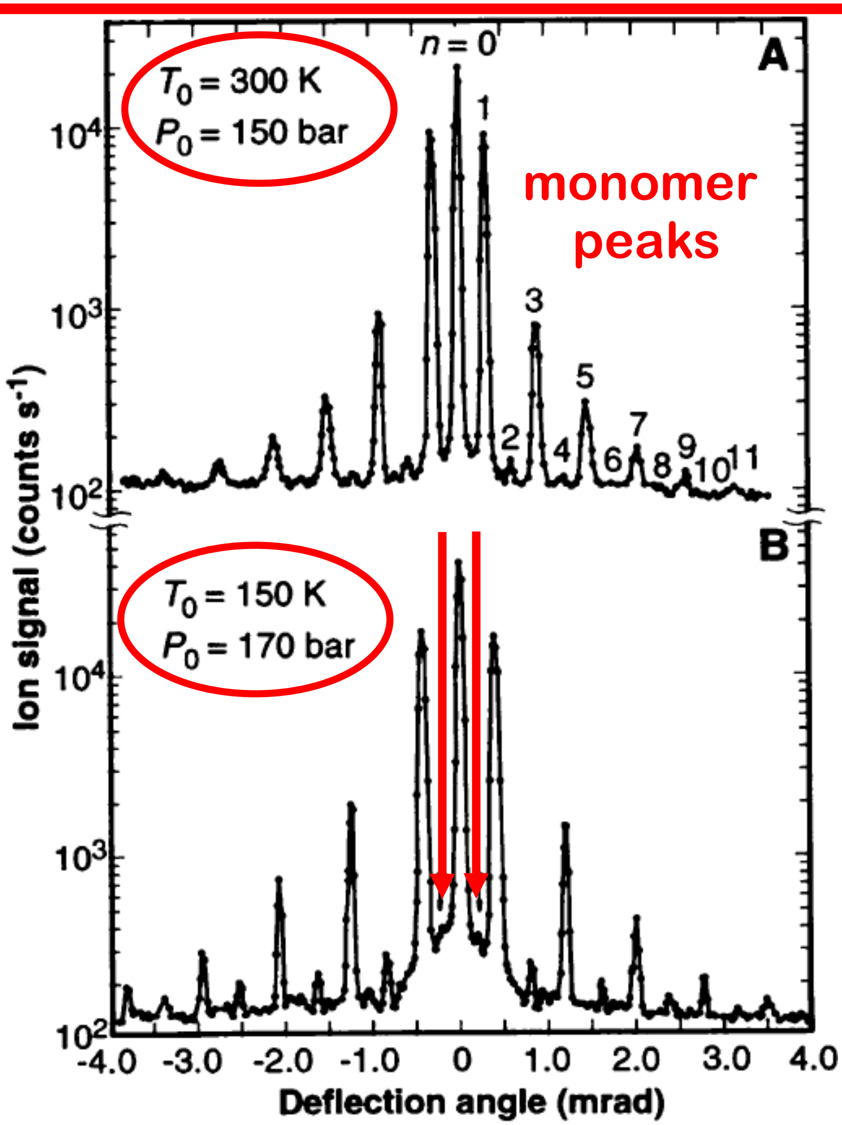
- Binding energy of liquid helium is E/N = −7K.

How to Prepare Helium Dimers and Trimers?



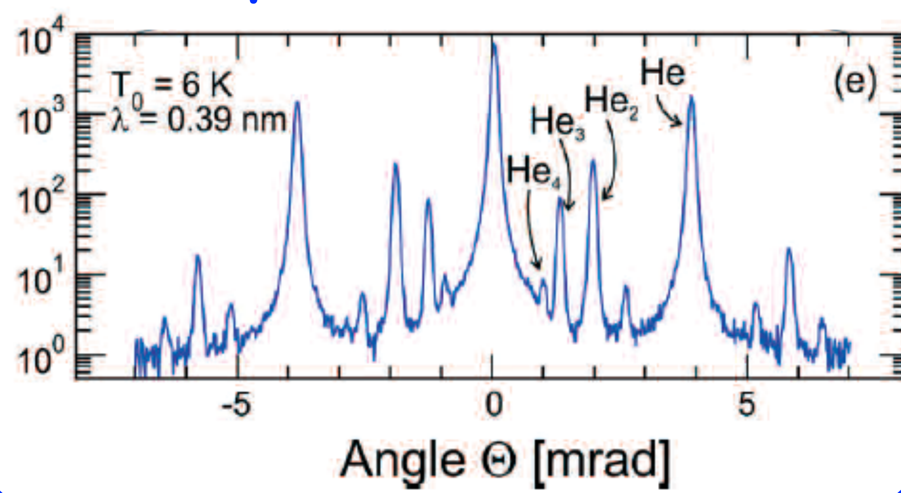
Grating serves as mass selector (N times atom mass m).
For fixed order n, larger N yields smaller angle θ.

Observation of Helium Dimer: $^4He_2$

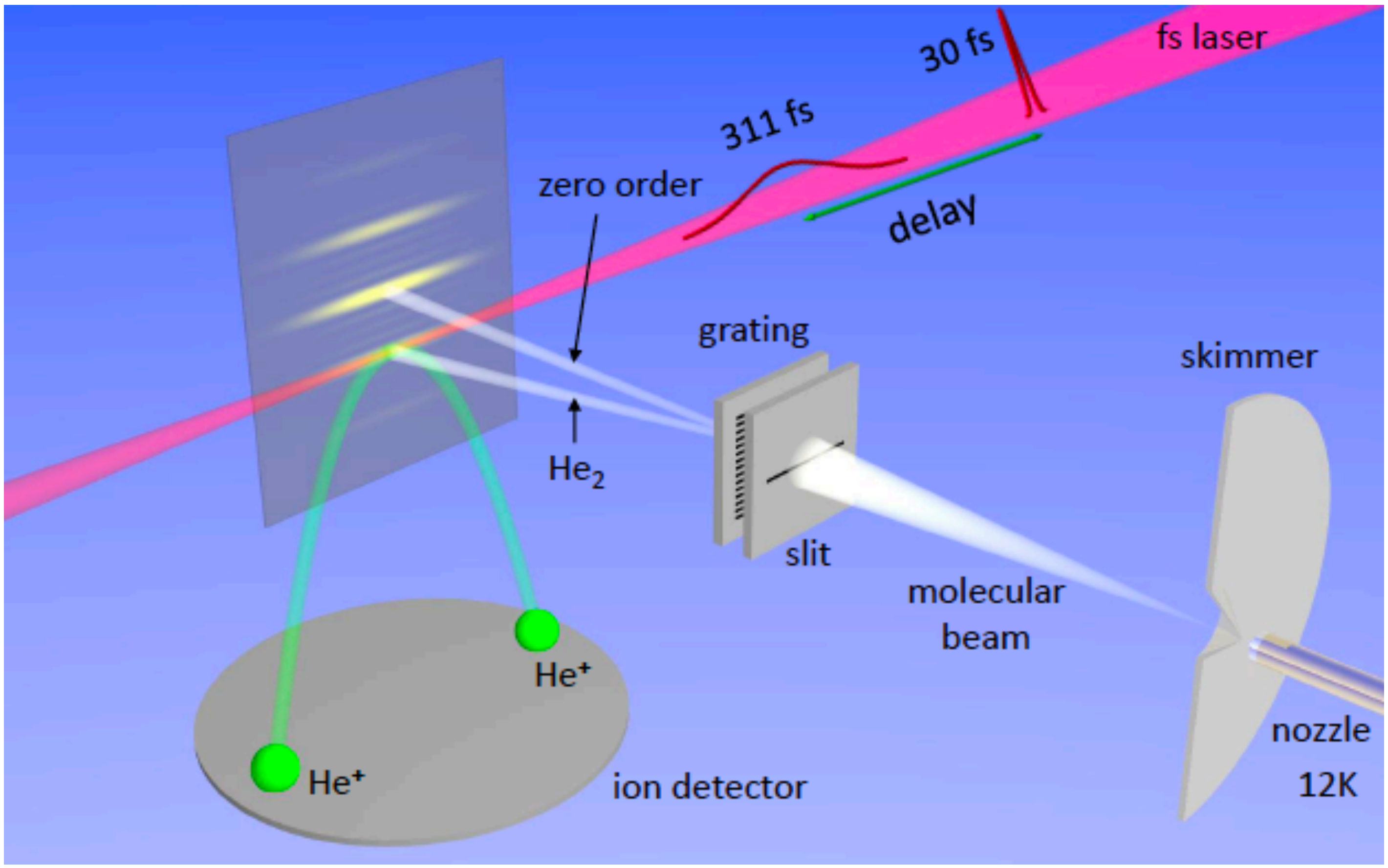


Fragile helium dimer forms in beam and can be isolated.
Schoellkopf and Toennies, Science 266, 1345 (1994)

Nozzle temperature and pressure can be adjusted. Kornilov, Toennies, 10.1051/epn:2007003

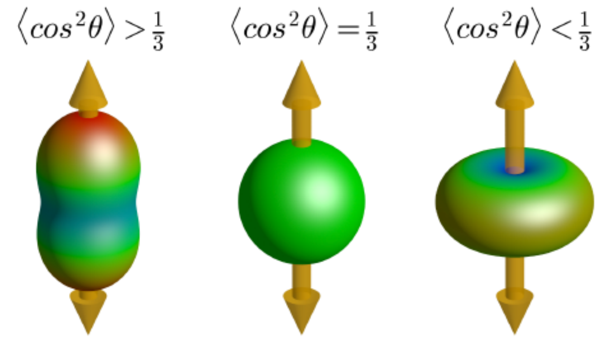


Pump-Probe Spectroscopy of Isolated Helium Dimers



Pump pulse: pulse length of 311 fs and intensity of 1.3×10^{14} W/cm^2.
Probe pulse rips off two electrons (Coulomb explosion).
What do we expect to happen as a function of the delay time???

Alignment $\langle cos^2\theta \rangle$ for N_2



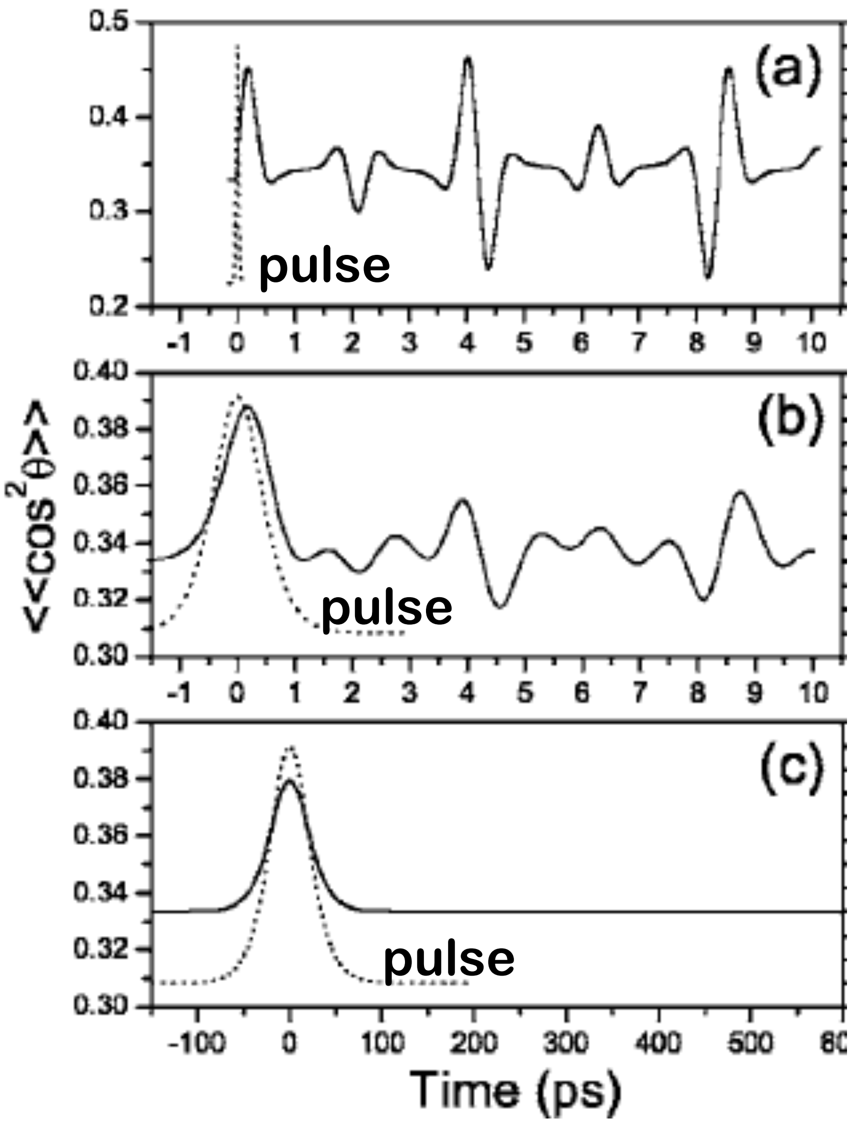


Figure from Torres et al., PRA 72, 023420 (2005)

Pulse length 50 fs

Intensity $2.5 \times 10^{13} \frac{W}{cm^2}$

Impulse regime.

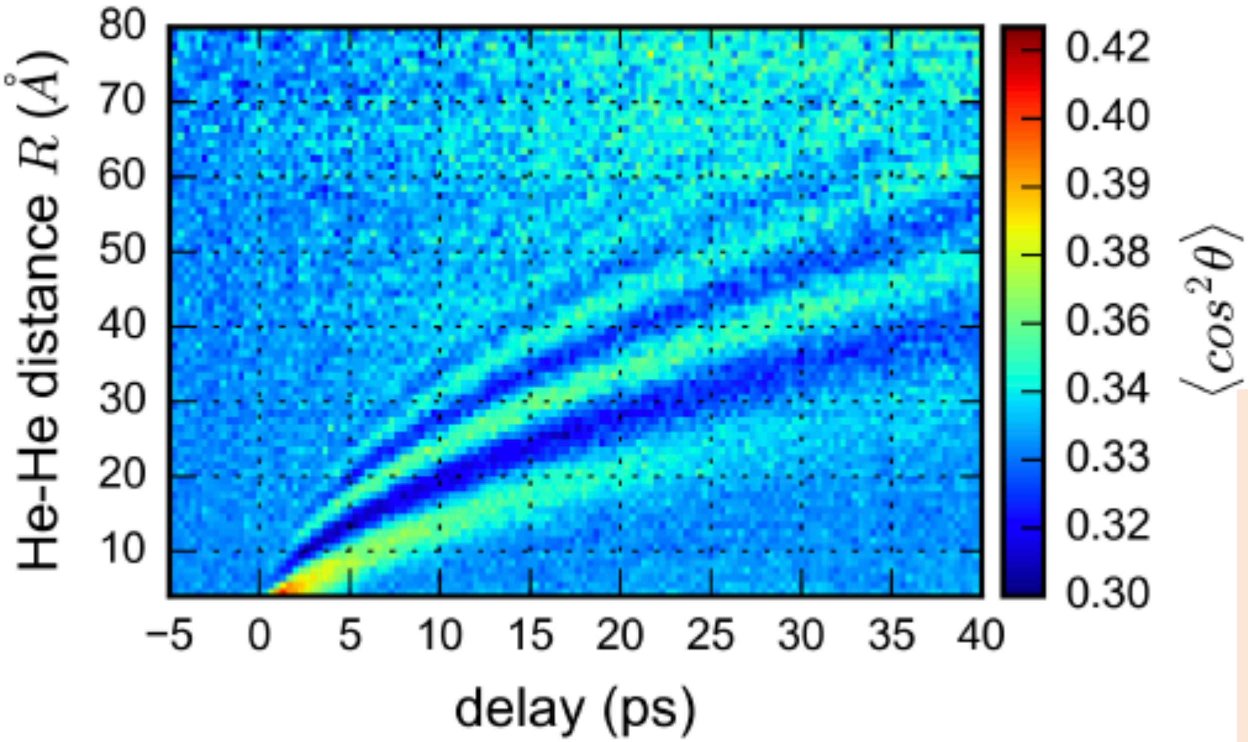
Alignment signal of 1/3 = spherically symmetric. "Rotational revivals" require particular phase relation: $E_J = B_0 J(J+1) - D_0 J^2 (J+1)^2$.

Pulse length 50 ps

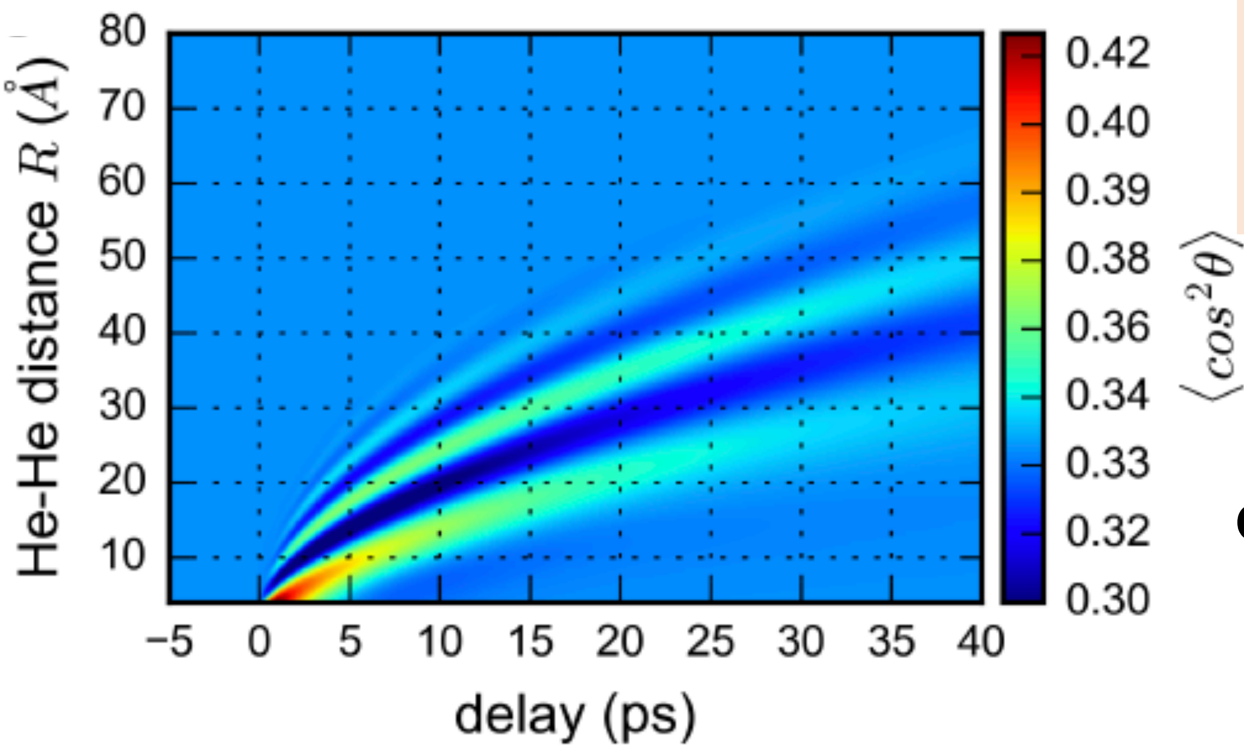
Intensity $2.5 \times 10^{12}\ W/cm^2$

Adiabatic regime.

Experiment (data by Maksim Kunitski, Reinhard Doerner et al.; Frankfurt University)



Parameter-free theory (using measured pulse length, intensity, spatial resolution)



Interference between J=0 and J=2 partial waves.
J=2 portion "travels" on structureless background.

Kunitski, Guan,…,Blume, Doerner, Nature Physics 17, 174 (2021).

“Kicking” the ^{4}He Dimer

For the first time: Intense laser used to probe dynamics at single-atom level using universal, scattering length dominated initial state.

“Rotationless” ^{4}He dimer can be aligned! It’s the continuum portion of the wave packet…

Pattern due to interference between J=0 and J=2 channels: Measurement of spatially and time dependent relative phase between these two partial wave channels. State tomography!

Many outstanding challenges:
Resonances as in ultracold atoms? Need longer pulses…
Time-dependent modulation of interaction strength?
Dynamics of (Efimov) trimers and larger excited states? Need to populate them first…

Pioneering theory predictions for $^4He_2$: Friedrich et al., Collect. Czech. Chem. Commun. 63, 1089 (1998); Nielsen et al., PRL 82, 2844 (1999); Bruch, JCP 112, 9773 (2000).

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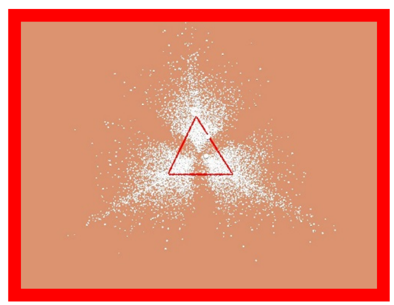
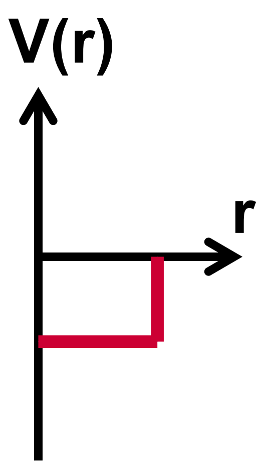
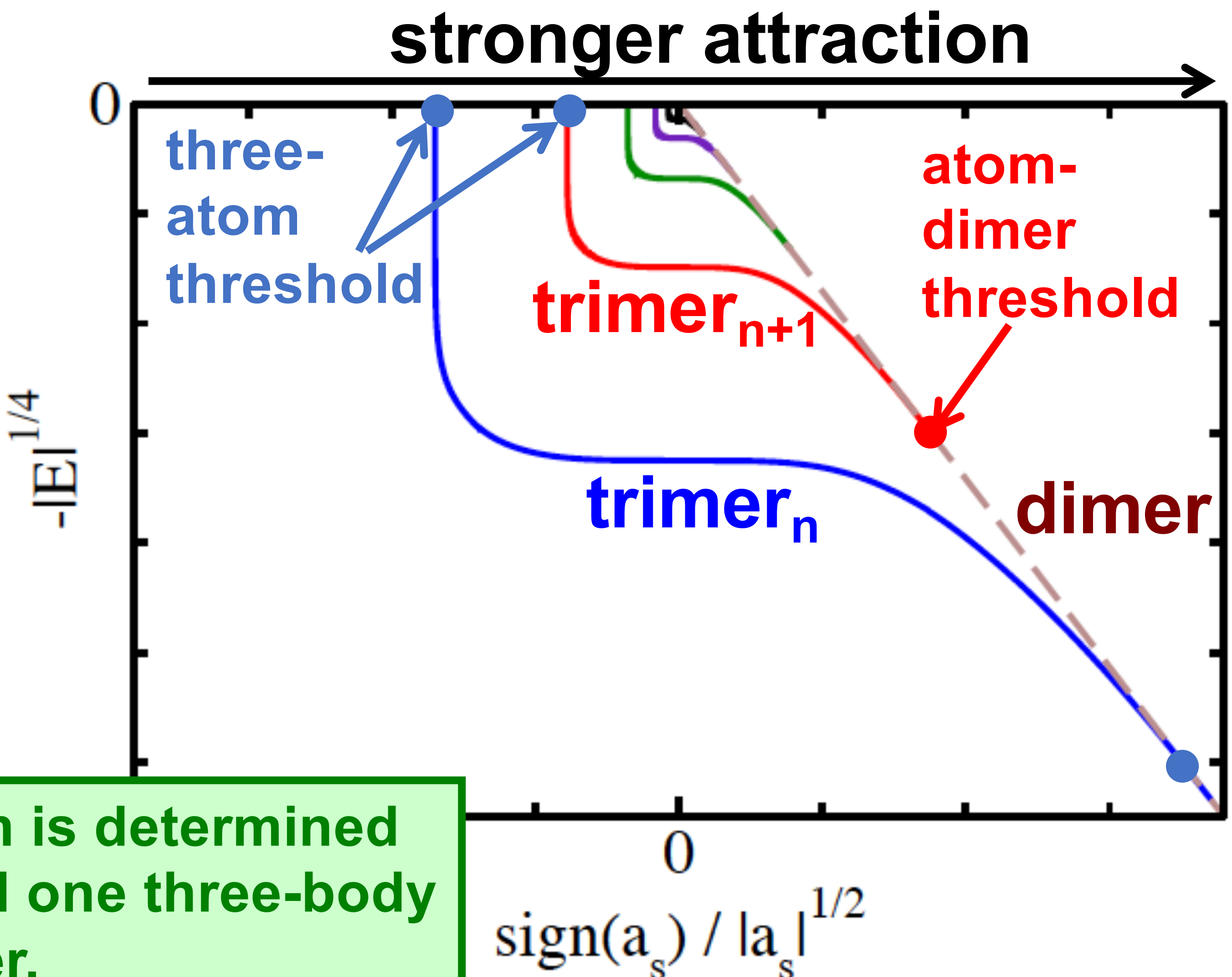
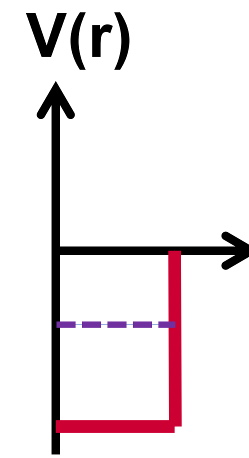


- Binding energy of liquid helium is $E/N = -7K$.

Finite s-wave Scattering Length: Universally Linked States







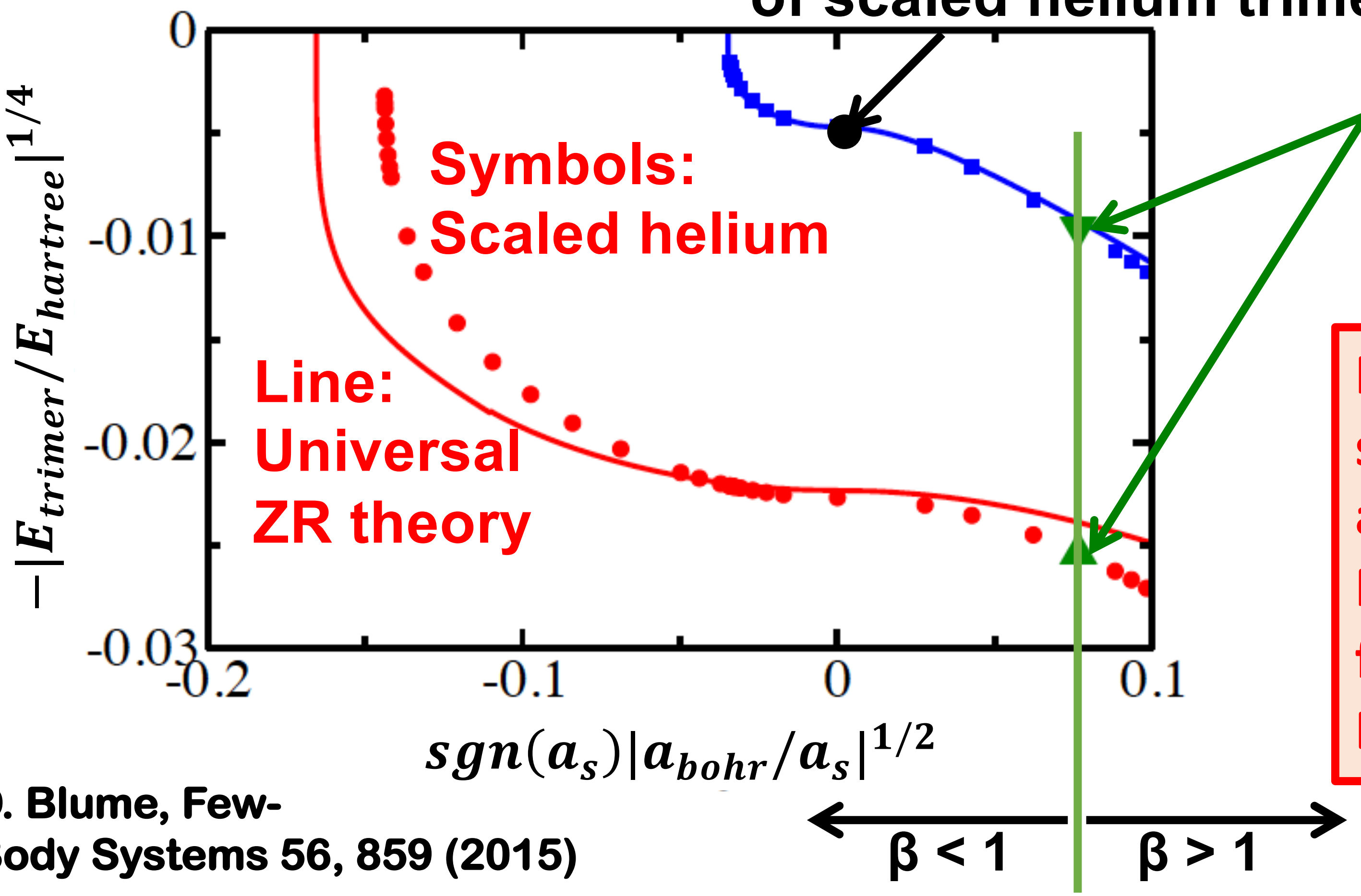
Spectrum is determined by a_s and one three-body parameter.

Review by Braaten and Hammer, Physics Reports 428, 259 (2006).

Helium Trimer Excited State is an Efimov State

$\beta V_{He\text{-}He}(r_{12}) + \beta V_{He\text{-}He}(r_{23}) + \beta V_{He\text{-}He}(r_{31})$.

Three-body parameter is chosen such that ZR energy agrees with energy of scaled helium trimer excited state.

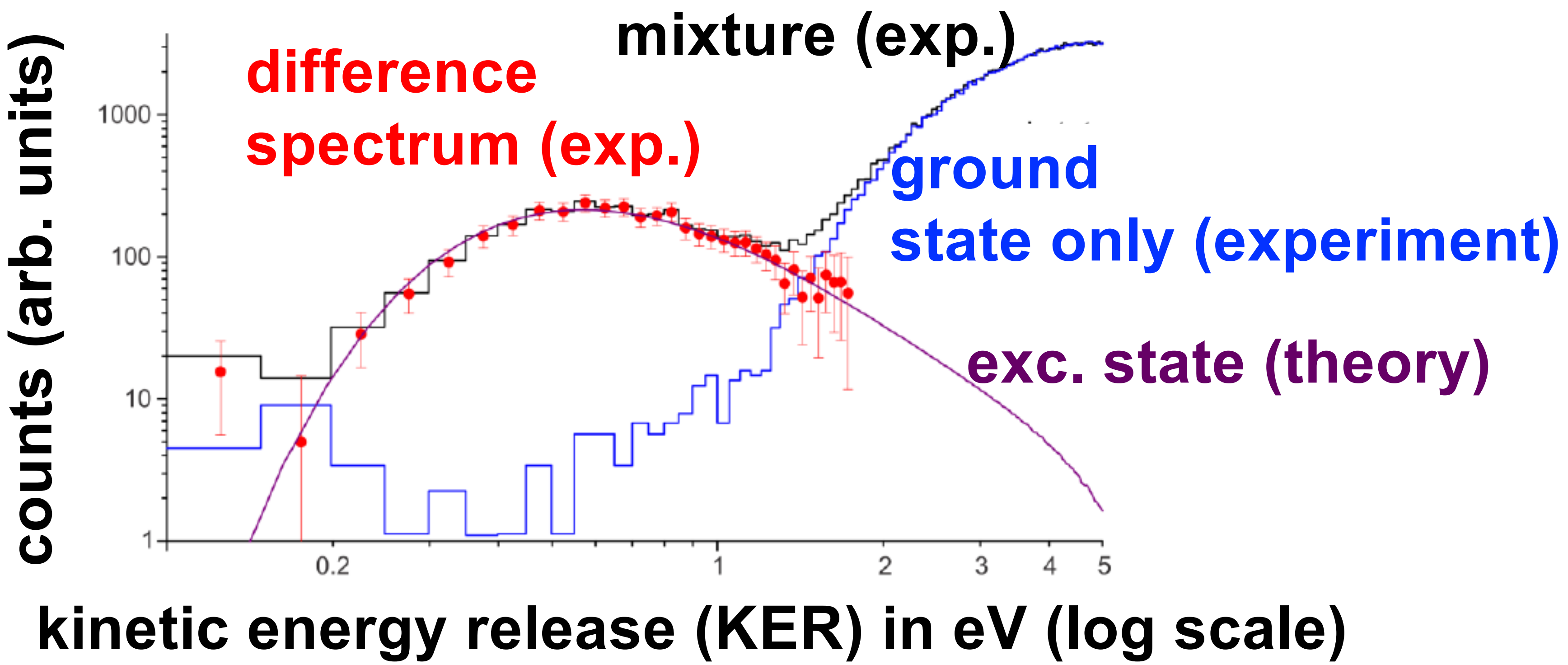


True helium (ground and excited states)

For the excited state, symbols agree with line! Molecular system follows predicted Efimov behavior.

D. Blume, Few-Body Systems 56, 859 (2015)

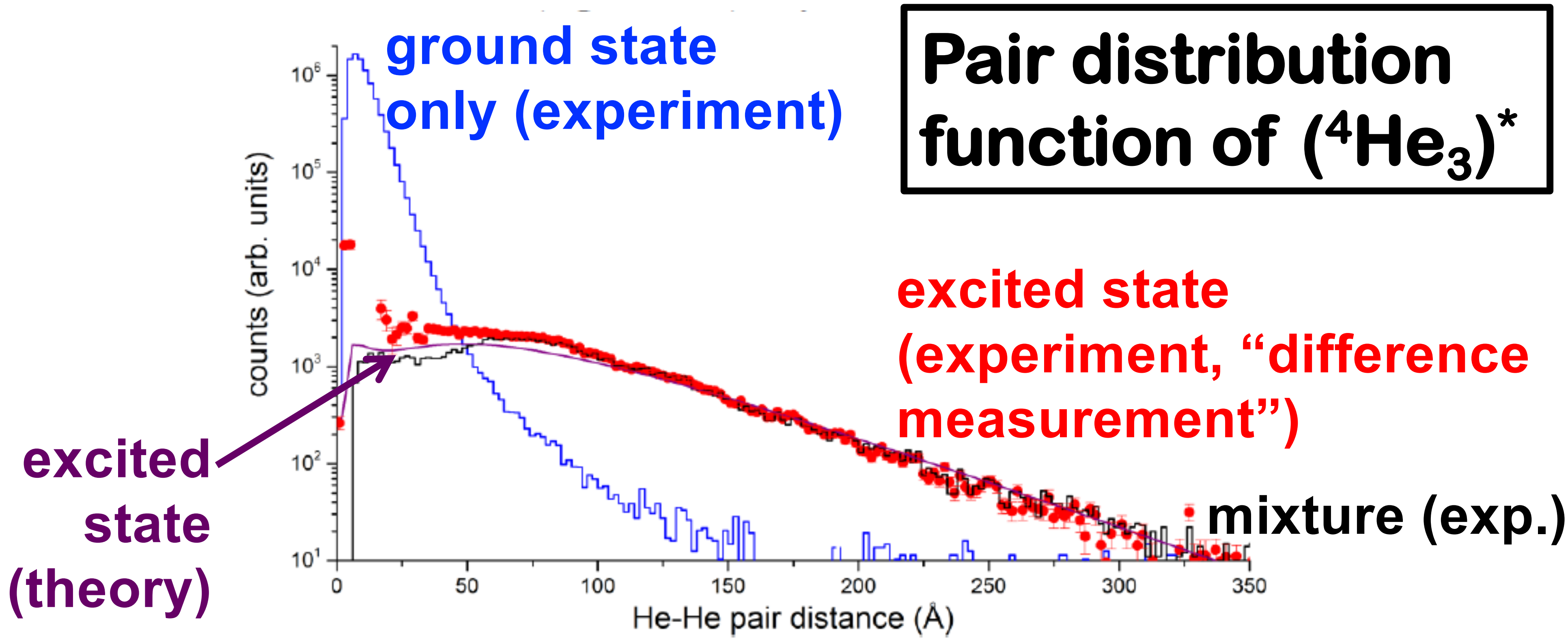
Kinetic Energy Release Measurement: Observing $(^4He_3)^*$



The ionization is instantaneous and the He-ions are distributed according to the quantum mechanical eigen states of the ground and excited helium trimers.

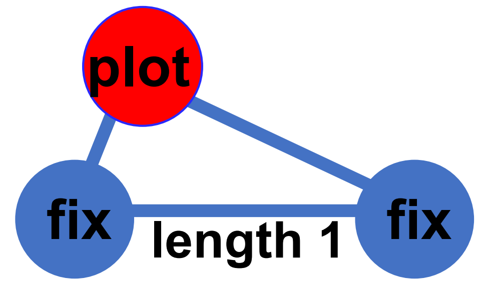
Large r_{12}, r_{23} and r_{31} correspond to small $KER=1/r_{12}+1/r_{23}+1/r_{31}$.

Reconstructing Real Space Properties

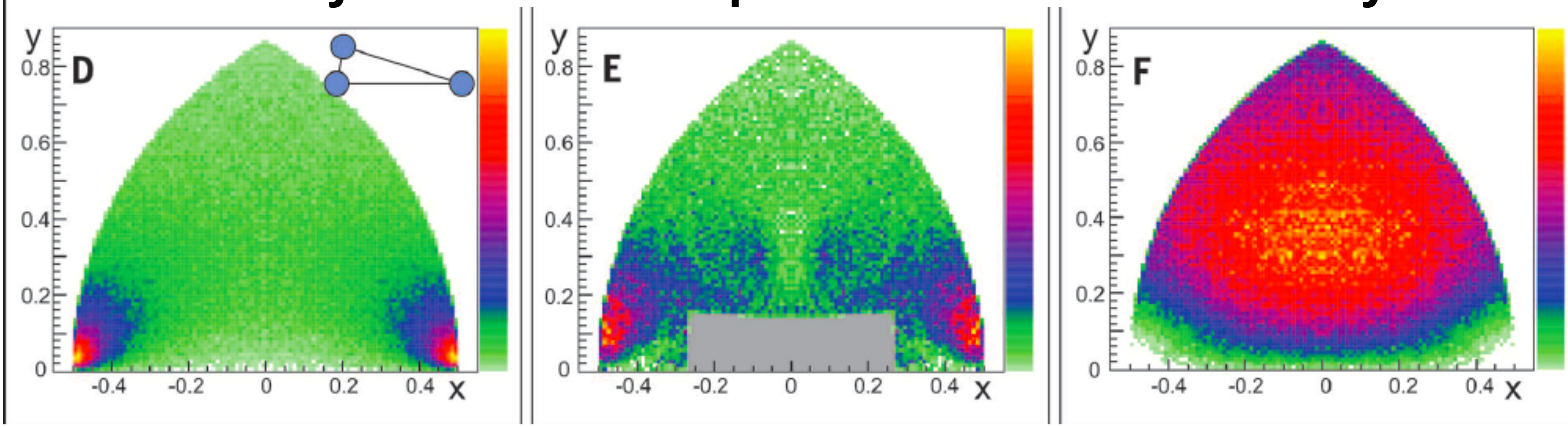


The excited state is eight times larger than the ground state. Assuming an "atom-dimer geometry", the tail can be fit to extract the binding energy of the excited helium trimer. Fit to experimental data yields 2.6(2)mK. Theory 2.65mK.

Normalized Structural Properties of $^{4}He_{3}$



excited state: theory | **excited state: experiment** | **ground state: theory**



Divide all three interparticle distances by largest r_{ij} and plot k^{th} atom (positive y): Corresponds to placing atoms i and j at $(-1/2,0)$ and $(1/2,0)$.

Ground state and excited states have distinct characteristics!!!

Message: Reconstruction of quantum mechanical trimer density.

Summary and Next Steps

Experimental technique: Coulomb explosion induced by instantaneous ionization via femtosecond laser.

$^4He_2$ ("test case"): "Kicking" extremely weakly-bound non-rigid rotor molecule.

$^4He_3$: Obtained quantum mechanical (stationary) density of excited helium Efimov trimer.

Next natural step: N=4 ground and excited states…

Long-term goal: Watch (and eventually control) real time dynamics of weakly-bound complexes with single-atom resolution.

PHYSICAL REVIEW LETTERS **122,** 200402 (2019)

Coherent Superposition of Feshbach Dimers and Efimov Trimers

Yaakov Yudkin,[1] Roy Elbaz,[1] P. Giannakeas,[2] Chris H. Greene,[3] and Lev Khaykovich[1]
[1]*Department of Physics, QUEST Center and Institute of Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 5290002, Israel*
[2]*Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, 01187 Dresden, Germany*
[3]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*

Thank you!

Many thanks to collaborators Qingze Guan, Maksim Kunitski, Reinhard Doerner, and the entire Doerner group.

Ultrafast manipulation of the weakly bound helium dimer

Maksim Kunitski[1], Qingze Guan[2,3], Holger Maschkiwitz[1], Jörg Hahnenbruch[1], Sebastian Eckart[1], Stefan Zeller[1,4], Anton Kalinin[4], Markus Schöffler[1], Lothar Ph. H. Schmidt[1], Till Jahnke[1], Dörte Blume[2,3] and Reinhard Dörner[1]

Observation of the Efimov state of the helium trimer

Maksim Kunitski[1,*], Stefan Zeller[1], Jörg Voigtsberger[1], Anton Kalinin[1], Lothar Ph. H. Schmidt[1], Markus Schöffler[1], Achim Czasch[1], Wieland Schöllkopf[2], Robert E. Grisenti[1,3], Till Jahnke[1], Dörte Blume[4], Reinhard Dörner[1,*]

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