Connections between cold atoms & nuclear/quark physics: Universality and Similarity

冷却原子と原子核・クォーク物理の接点：
普遍性と類似性

Yusuke Nishida (Tokyo Tech)

School for “Clustering as a window on the hierarchical structure of quantum systems”

March 22-24 (2021) @ zoom

Plan of this talk

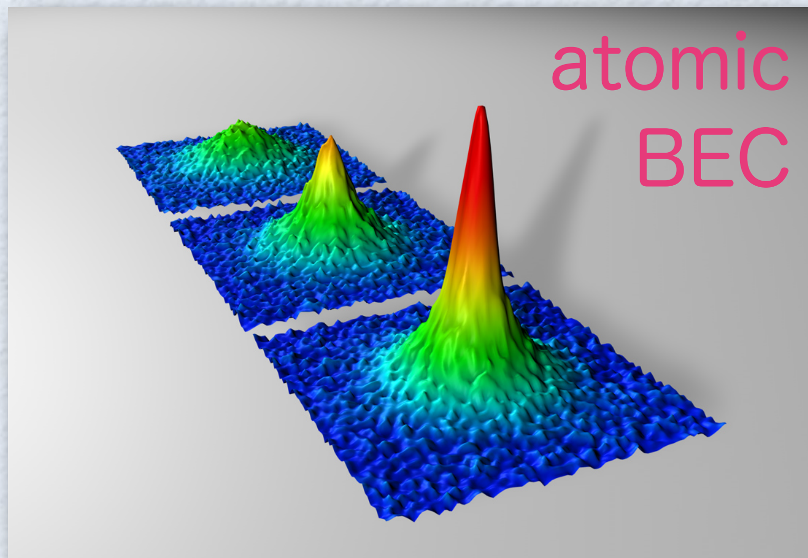
1. Universality in few-body physics
   - Efimov effect
   - Beyond cold atoms
   - Universality class of quantum halos

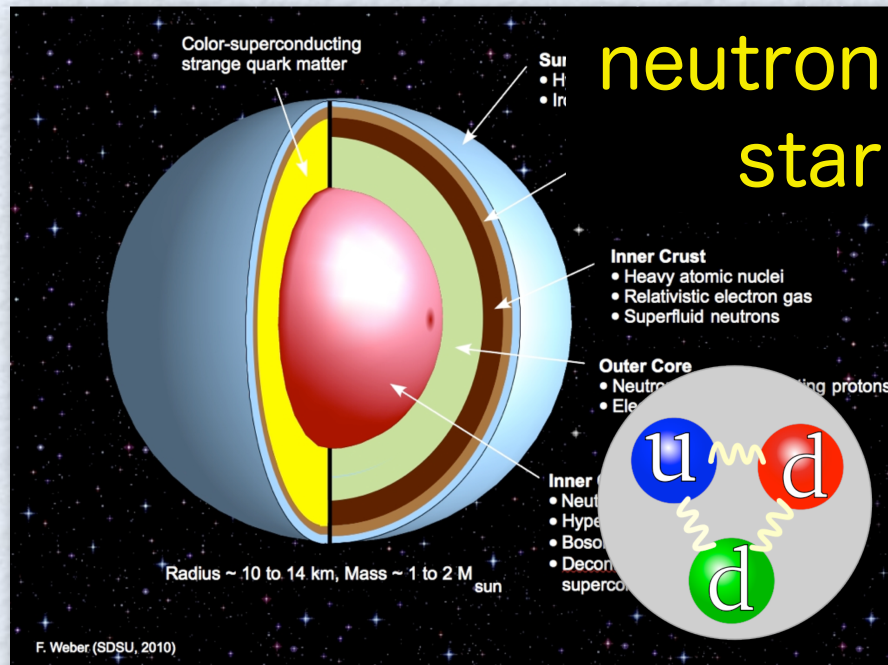
2. Similarity in many-body physics
   - “Hard probes” in cold atoms
   - “Quark-hadron continuity” in cold atoms

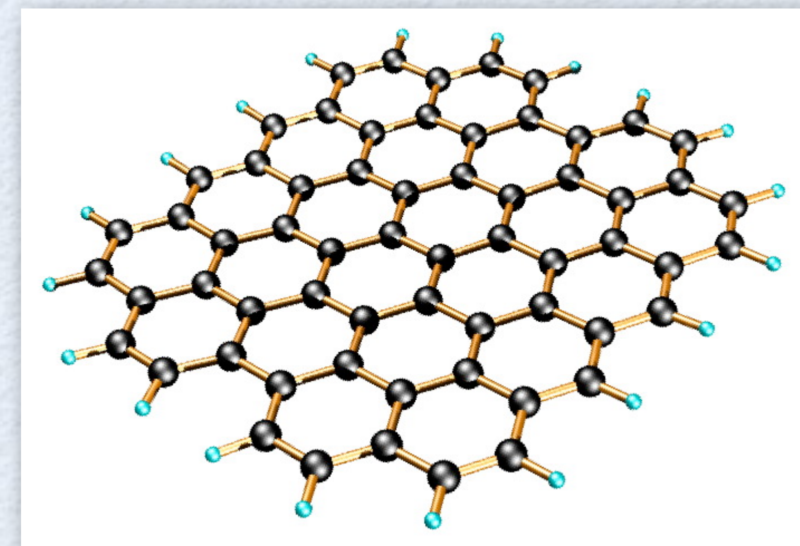
1. Universality in few-body physics

(ultimate) Goal of research

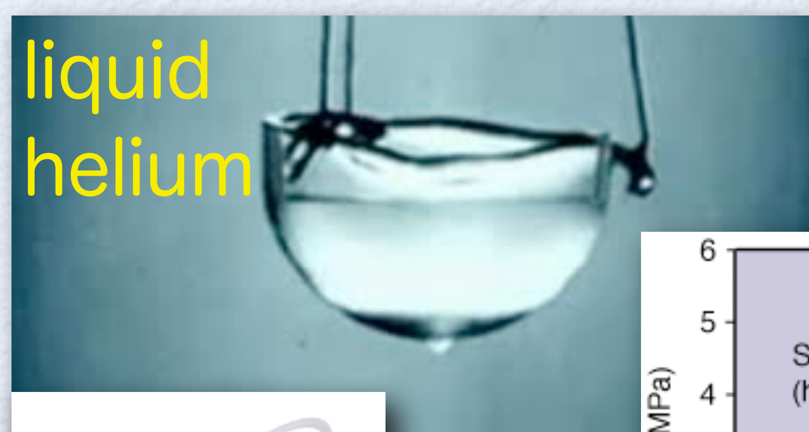
Understand physics of few and many particles governed by quantum mechanics

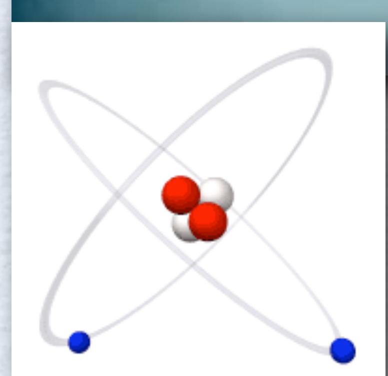


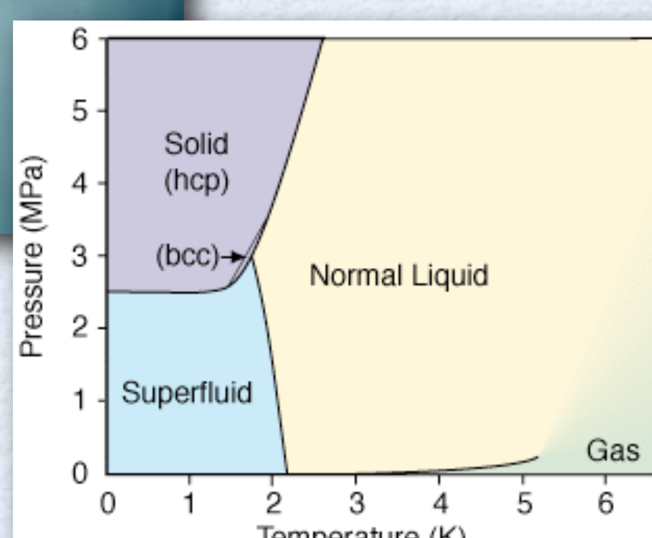




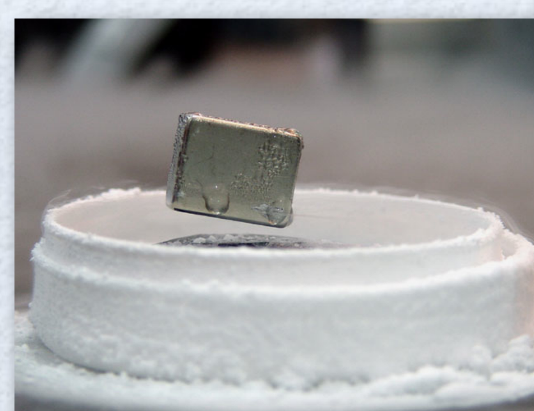
graphene

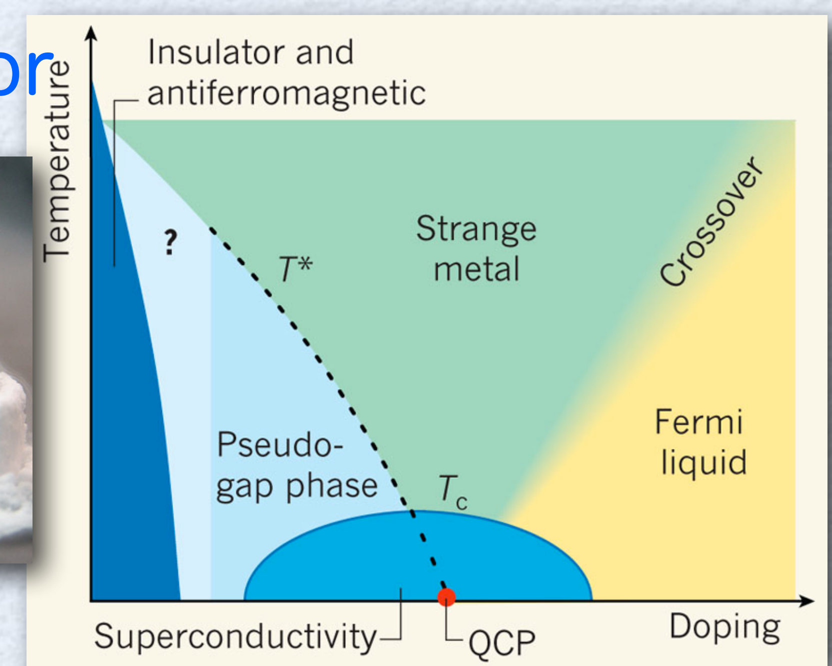






superconductor

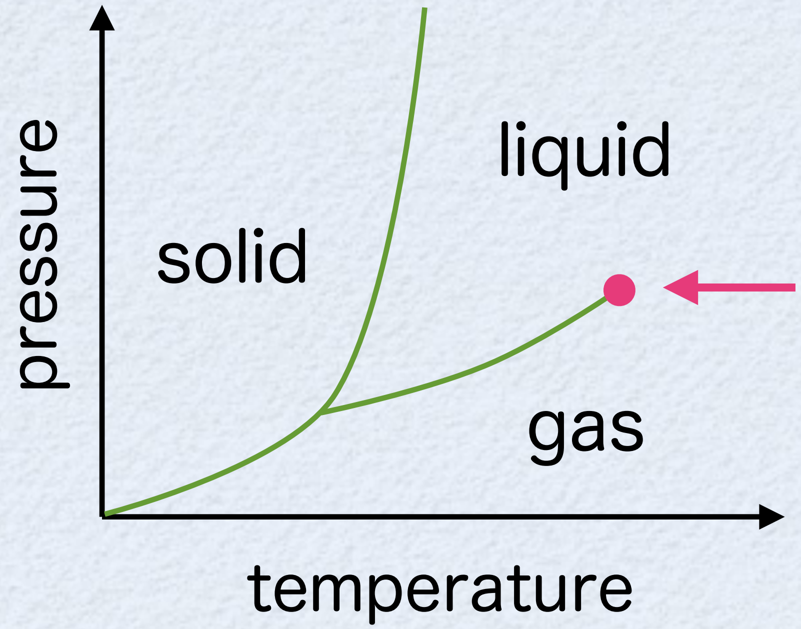


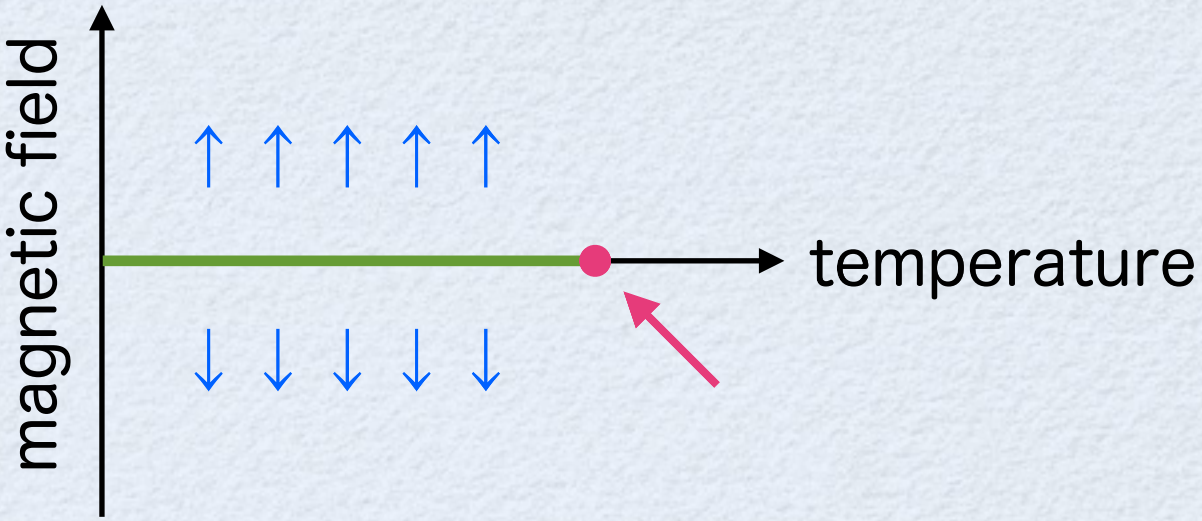


When physics is universal ?

A1. Continuous phase transitions $\Leftrightarrow$ $\xi / r_0 \to \infty$

E.g. Water  vs. Magnet 



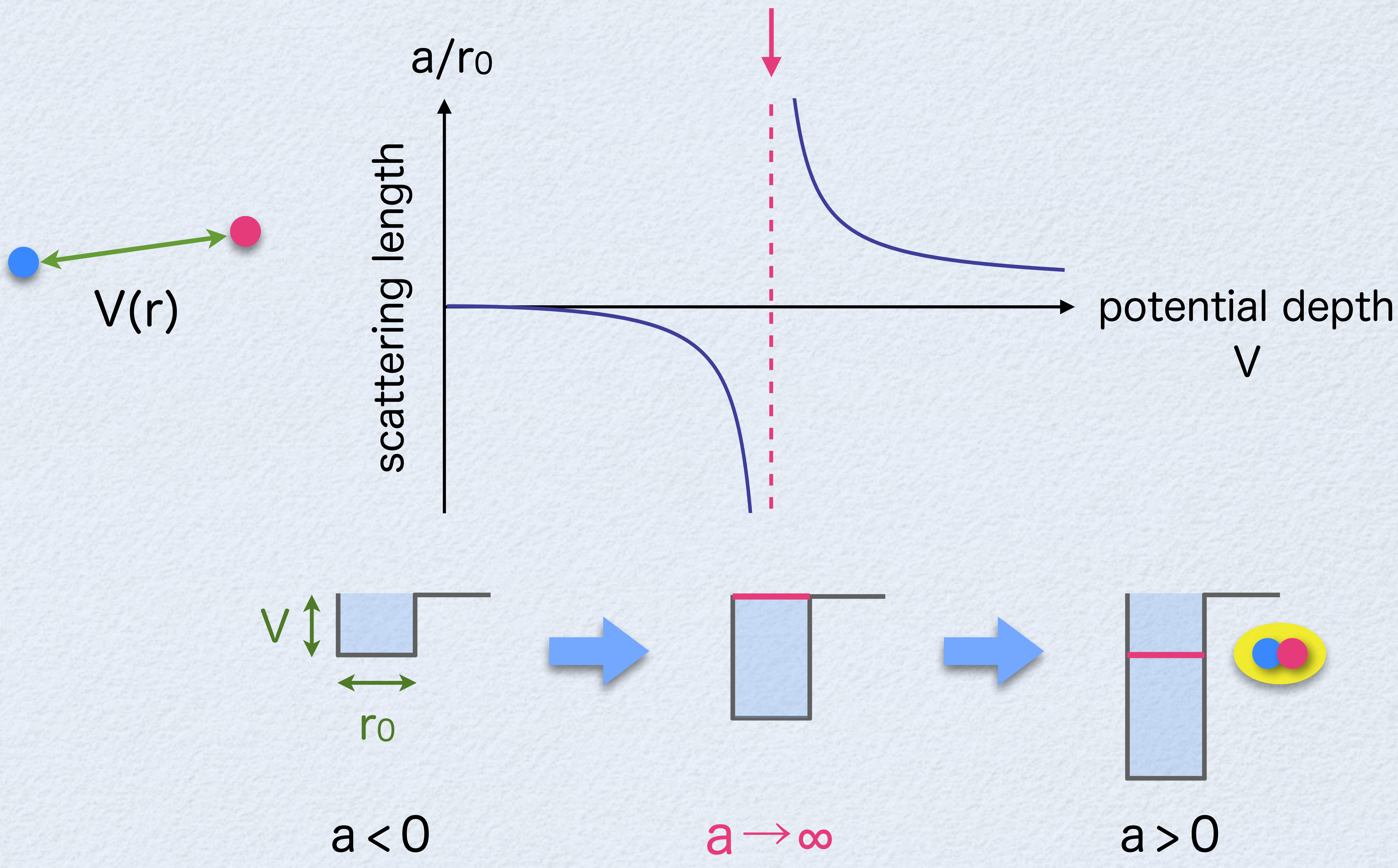


Water and magnet have the same exponent $\beta \approx 0.325$

$$\rho_{\mathrm{liq}} - \rho_{\mathrm{gas}} \sim (T_{\mathrm{c}} - T)^{\beta} \qquad M_{\uparrow} - M_{\downarrow} \sim (T_{\mathrm{c}} - T)^{\beta}$$

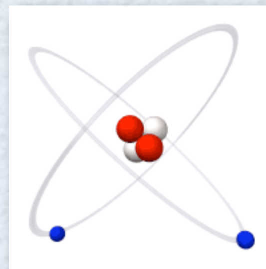
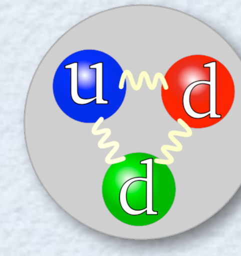
When physics is universal ?

A2. Scattering resonances $\Leftrightarrow$ $a/r_0 \to \infty$



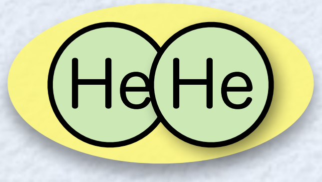
When physics is universal ?

A2. Scattering resonances $\Leftrightarrow$ $a/r_0 \to \infty$

E.g. ^{4}He atoms  vs. proton/neutron 

van der Waals force:

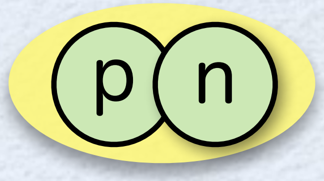
$a \approx 1\times10^{-8}$ m $\approx 20\ r_0$



$E_{\text{binding}} \approx 1.3\times10^{-3}$ K

nuclear force:

$a \approx 5\times10^{-15}$ m $\approx 4\ r_0$



$E_{\text{binding}} \approx 2.6\times10^{10}$ K

Atoms and nucleons have the same form of binding energy

$$E_{\text{binding}} \to -\frac{\hbar^2}{m\,a^2} \qquad (a/r_0 \to \infty)$$

Physics only depends on the scattering length "a"

Efimov effect

Efimov effect

Efimov (1970)

Volume 33B, number 8 PHYSICS LETTERS 21 Decembe

ENERGY LEVELS ARISING FROM RESONANT TWO-BODY FORCES IN A THREE-BODY SYSTEM

V. EFIMOV
A.F.Ioffe Physico-Technical Institute, Leningrad, USSR

Received 20 October 1970

Resonant two-body forces are shown to give rise to a series of levels in three-particle systems. The number of such levels may be very large. Possibility of the existence of such levels in systems of three α-particles (^{12}C nucleus) and three nucleons (^{3}H) is discussed.

The range of nucleon-nucleon forces r_0 is known to be considerably smaller than the scattering lengts a. This fact is a consequence of the resonant character of nucleon-nucleon forces. Apart from this, many other forces in nuclear physics are resonant. The aim of this letter is to expose an interesting effect of resonant forces in a three-body system. Namely, for $a \gg r_0$ a series of bound levels appears. In a certain case, the number of levels may become infinite.

Let us explicitly formulate this result in the simplest case. Consider three spinless neutral

ticle bound states emerge one after the other. At $g = g_0$ (infinite scattering length) their number is infinite. As g grows on beyond g_0, levels leave into continuum one after the other (see fig. 1).

The number of levels is given by the equation

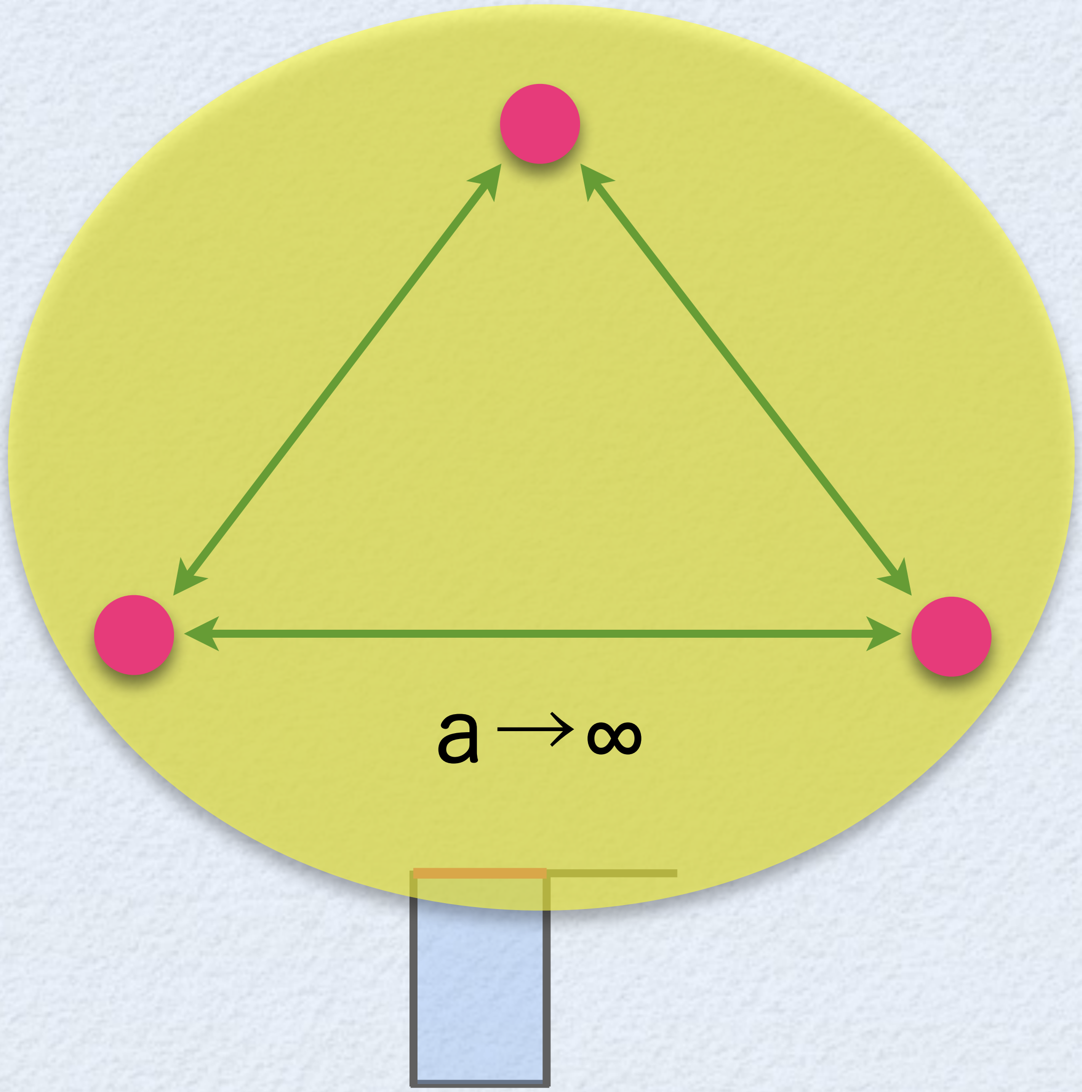
$$N \approx \frac{1}{\pi} \ln(|a|/r_0) \qquad (1)$$

All the levels are of the 0^+ kind; corresponding wave functions are symmetric; the energies $E_N \ll 1/r_0^2$ (we use $\hbar = m = 1$); the range of these bound states is much larger than r_0.

Efimov effect

When 2 bosons interact with infinite “a”,
3 bosons always form a series of bound states

Efimov (1970)



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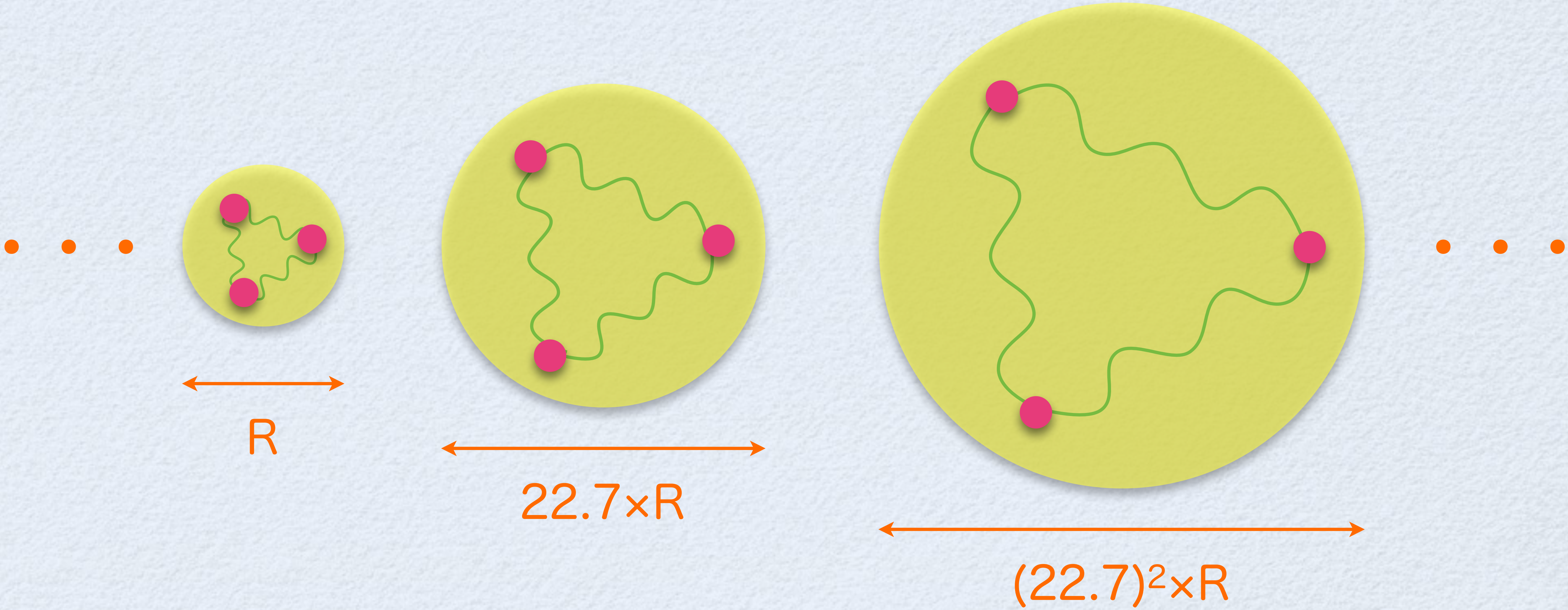


Discrete scaling symmetry

Why Efimov effect happens ?

Keywords

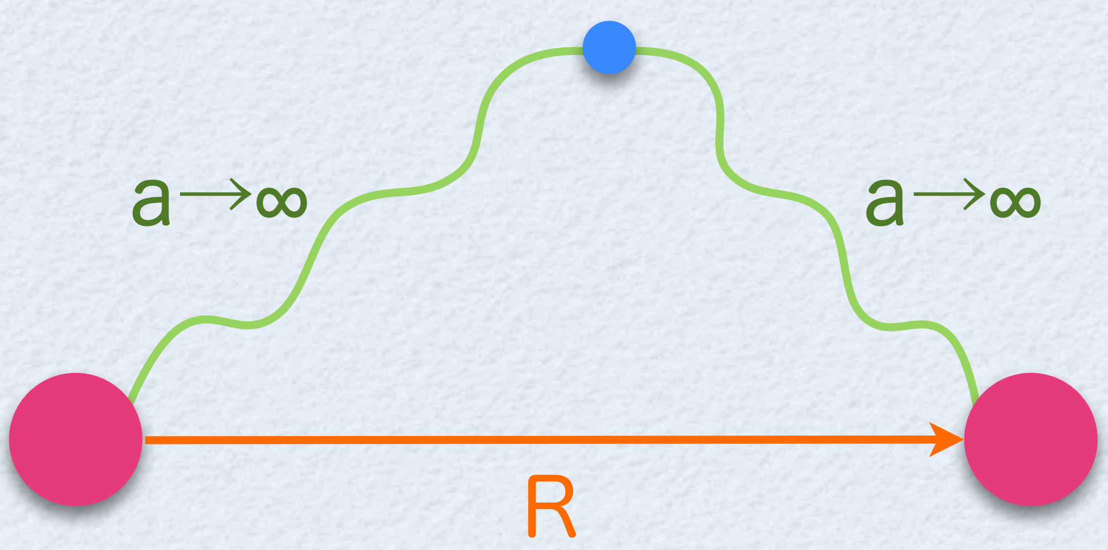
✓ Universality

- Scale invariance
- Quantum anomaly
- RG limit cycle

Why Efimov effect happens ?

Two heavy (M) and one light (m) particles

➡ Born-Oppenheimer approximation



Binding energy of a light particle

$$E_b(R) = -\boxed{\frac{\hbar^2}{2mR^2}} \times (0.5671\ldots)^2$$

Scale invariance at a→∞

Schrödinger equation of two heavy particles :

$$\left[-\frac{\hbar^2}{M}\frac{\partial^2}{\partial \boldsymbol{R}^2} + V(R)\right]\psi(\boldsymbol{R}) = -\frac{\hbar^2\kappa^2}{M}\psi(\boldsymbol{R}) \qquad V(R) \equiv E_b(R)$$

Why Efimov effect happens ?

Schrödinger equation of two heavy particles :

$$\left[-\frac{\hbar^2}{M}\left(\frac{\partial^2}{\partial R^2}+\frac{2}{R}\frac{\partial}{\partial R}\right)-\frac{\hbar^2}{2mR^2}(0.5671\ldots)^2\right]\psi(R)=-\frac{\hbar^2\kappa^2}{M}\psi(R)$$

$$\psi(R)=R^{-1/2}K_{i\alpha}(\kappa R) \qquad \alpha^2\equiv\frac{M}{2m}(0.5671\ldots)^2-\frac{1}{4}$$

$$\to R^{-1/2}\sin[\alpha\ln(\kappa R)+\delta] \qquad (R\to 0)$$

ψ'/ψ has to be fixed by short-range physics

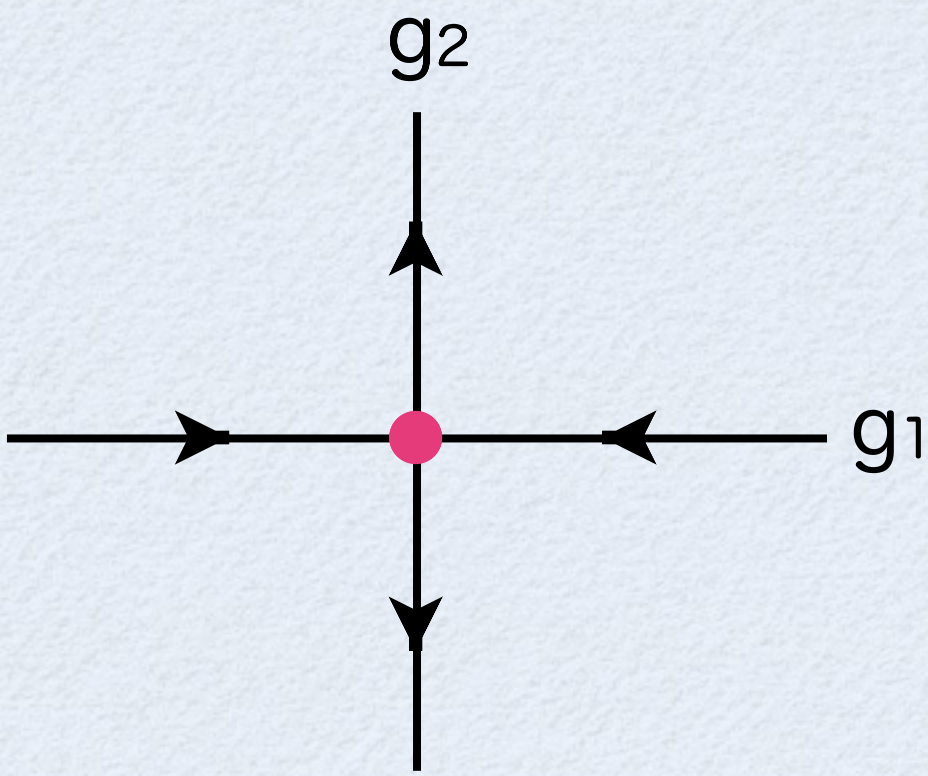
➡ If $\kappa=\kappa_*$ is a solution, $\kappa=(e^{\pi/\alpha})^n\kappa_*$ are solutions!

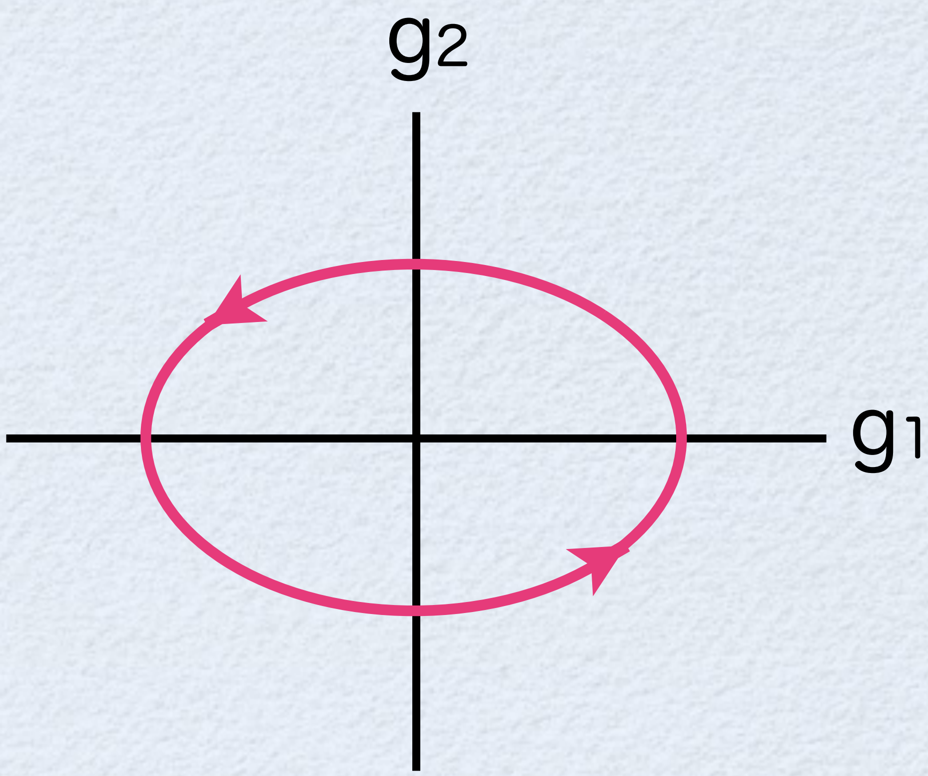
Classical scale invariance is broken by κ_*

= Quantum anomaly

Renormalization group limit cycle

Renormalization group flow diagram in coupling space





RG fixed point

⇒ Scale invariance

E.g. critical phenomena

RG limit cycle

⇒ Discrete scale invariance

E.g. E????v effect

Renormalization group limit cycle

K. Wilson (1971) considered for strong interactions

L REVIEW D VOLUME 3, NUMBER 8 15 APRIL 1971

Renormalization Group and Strong Interactions*

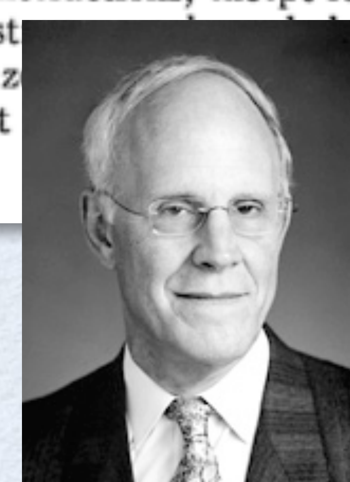
KENNETH G. WILSON
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850†

(Received 30 November 1970)

The renormalization-group method of Gell-Mann and Low is applied to field theories of strong interactions. It is assumed that renormalization-group equations exist for strong interactions which involve one or several momentum-dependent coupling constants. The further assumption that these coupling constants approach fixed values as the momentum goes to infinity is discussed in detail. However, an alternative is suggested, namely, that these coupling constants approach a limit cycle in the limit of large momenta. Some results of this paper are: (1) The e^+-e^- annihilation experiments above 1-GeV energy may distinguish a fixed point from a limit cycle or other asymptotic behavior. (2) If electrodynamics or weak interactions become strong above some large momentum Λ, then the renormalization group can be used (in principle) to determine the renormalized coupling constants of strong interactions, except for $U(3)\times U(3)$ symmetry-breaking parameters. (3) Mass terms in the Lagrangian of st… must break a symmetry of the combined interactions with z… weak interactions can be understood assuming only that … interactions.

QCD is asymptotic free

(2004 Nobel prize)



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Efimov effect (1970) is its rare manifestation!

PHYSICAL REVIEW LETTERS

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Renormalization of the Three-Body System with Short-Range Interactions

P.F. Bedaque,[1,*] H.-W. Hammer,[2,†] and U. van Kolck[3,4,‡]
[1]Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195
[2]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3
[3]Kellogg Radiation Laboratory, 106-38, California Institute of Technology, Pasadena, California 91125
[4]Department of Physics, University of Washington, Seattle, Washington 98195
(Received 9 September 1998)

We discuss renormalization of the nonrelativistic three-body problem with short-range forces. The problem becomes nonperturbative at momenta of the order of the inverse of the two-body scattering length, and an infinite number of graphs must be summed. This summation leads to a cutoff dependence that does not appear in any order in perturbation theory. We argue that this cutoff dependence can be absorbed in a single three-body counterterm and compute the running of the three-body force with the cutoff. We comment on the relevance of this result for the effective field theory program in nuclear and molecular physics. [S0031-9007(98)08276-3]

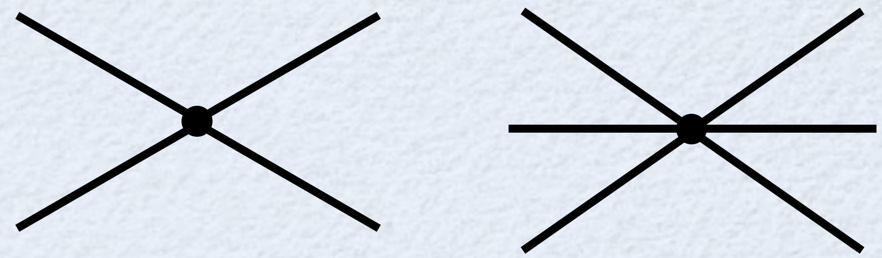
PACS numbers: 03.65.Nk, 11.80.Jy, 21.45.+v, 34.20.Gj

Systems composed of particles with momenta k much

dence can be absorbed in the coefficients of the leading-

Effective field theory

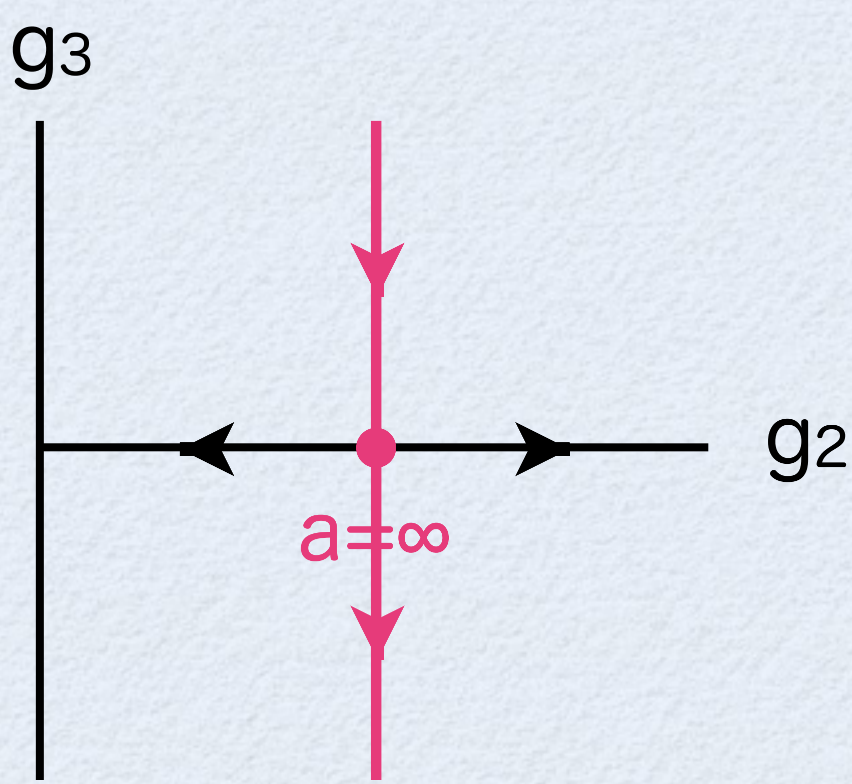
$$\mathcal{L} = \psi^\dagger \left(i\partial_t + \frac{\boldsymbol{\nabla}^2}{2m} \right) \psi + g_2(\psi^\dagger\psi)^2 + g_3(\psi^\dagger\psi)^3$$



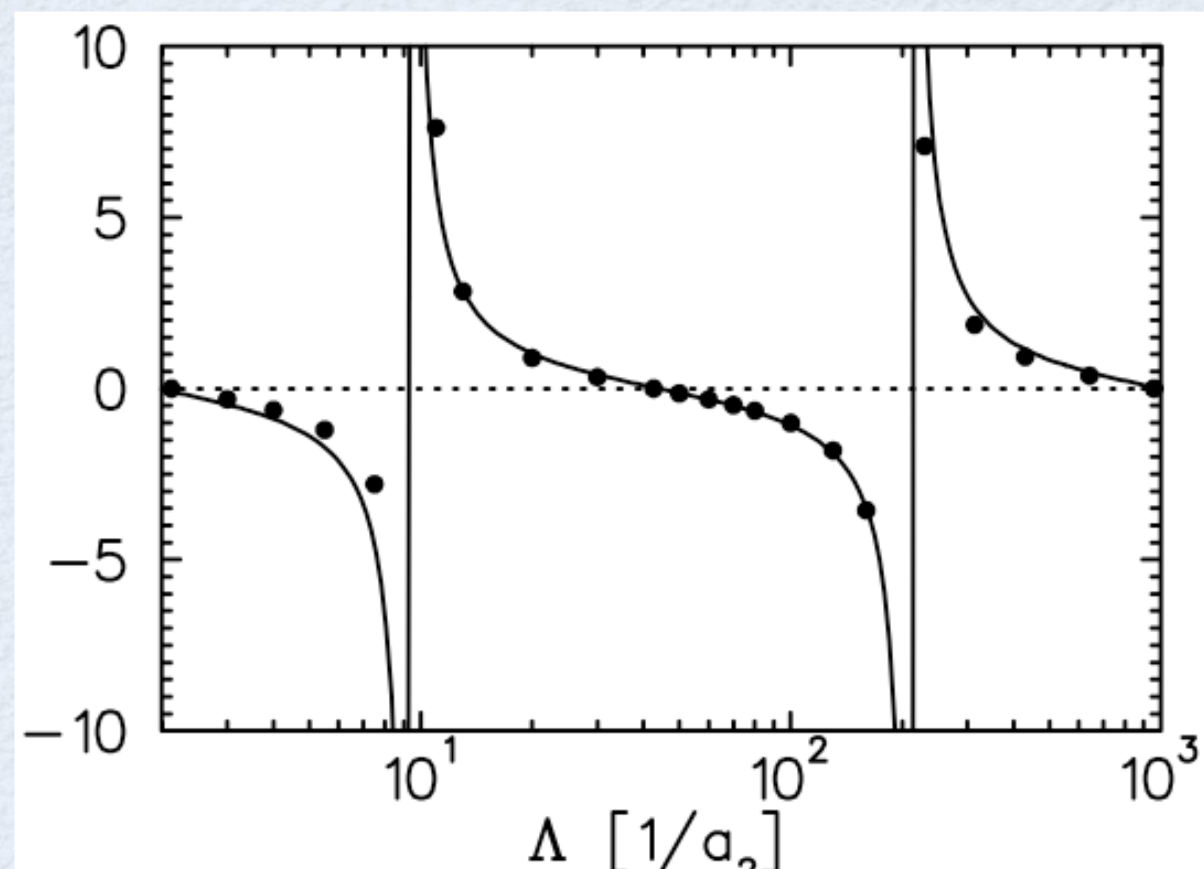
g_2 has a fixed point corresponding to a=∞

What is flow of g_3 ?

$$g_3(\Lambda) = -\frac{\sin[s_0 \ln(\Lambda/\Lambda_*) - \arctan(1/s_0)]}{\sin[s_0 \ln(\Lambda/\Lambda_*) + \arctan(1/s_0)]}$$



RG limit cycle



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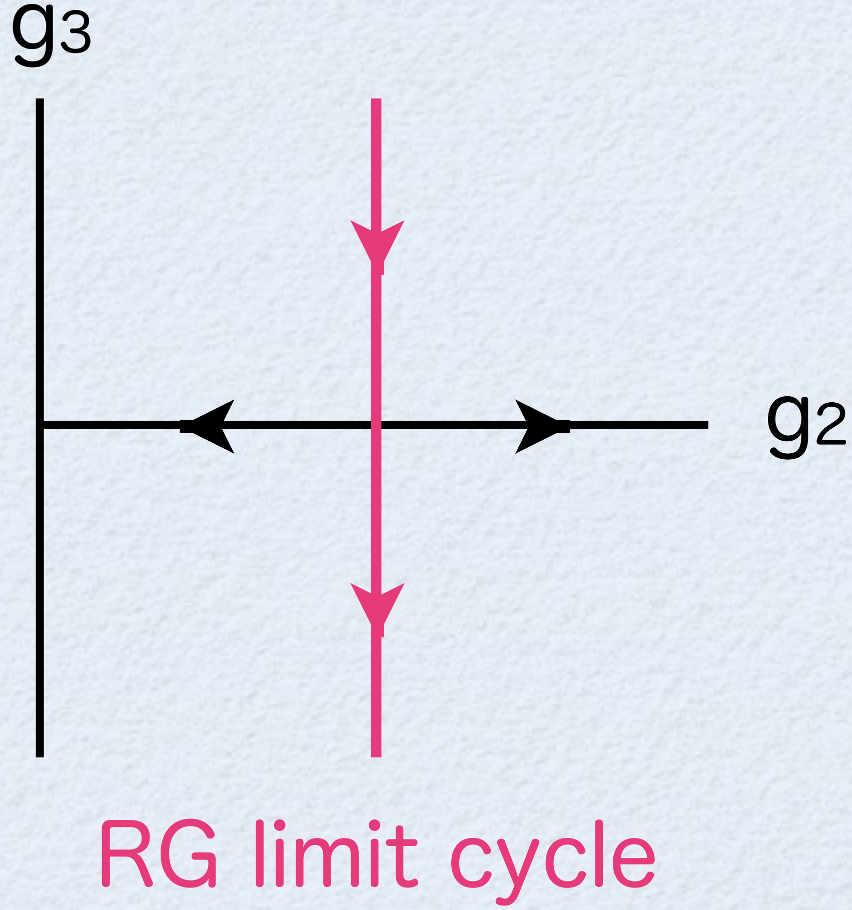
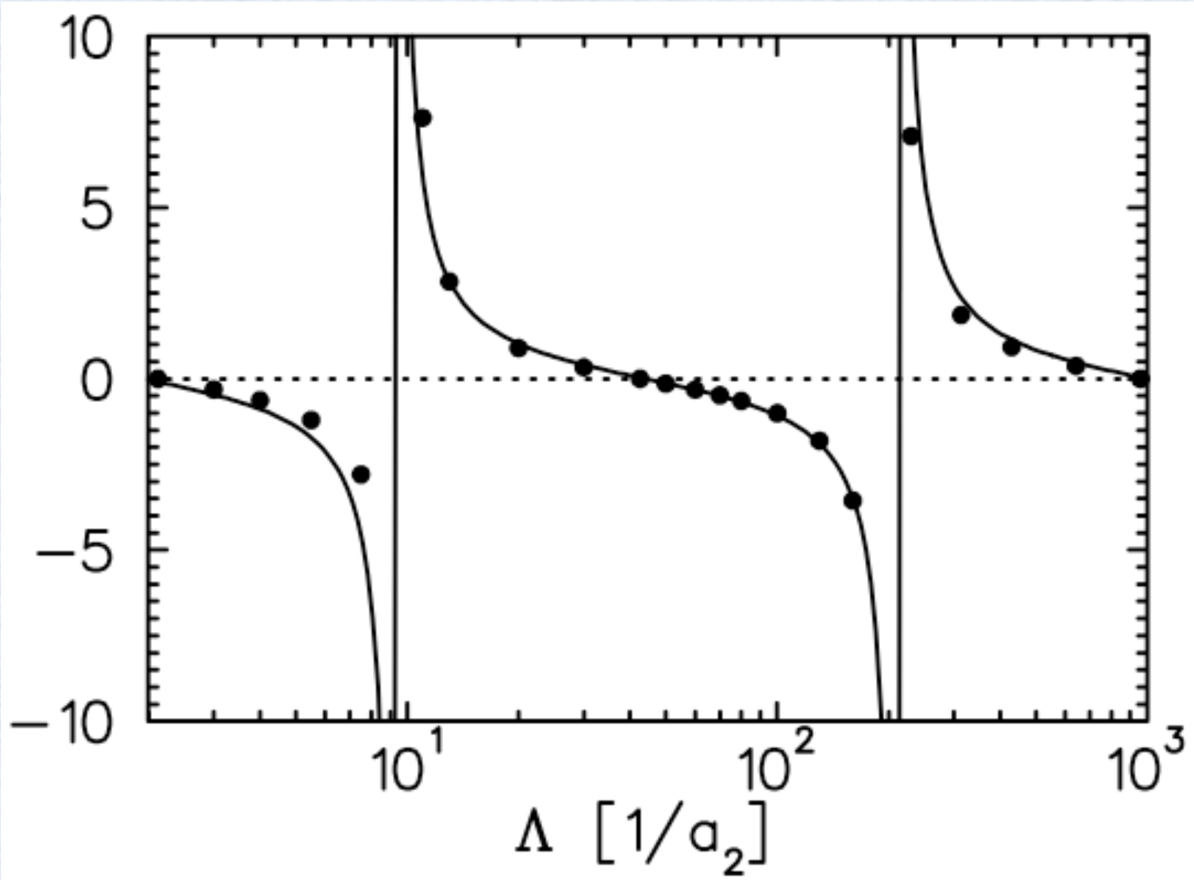
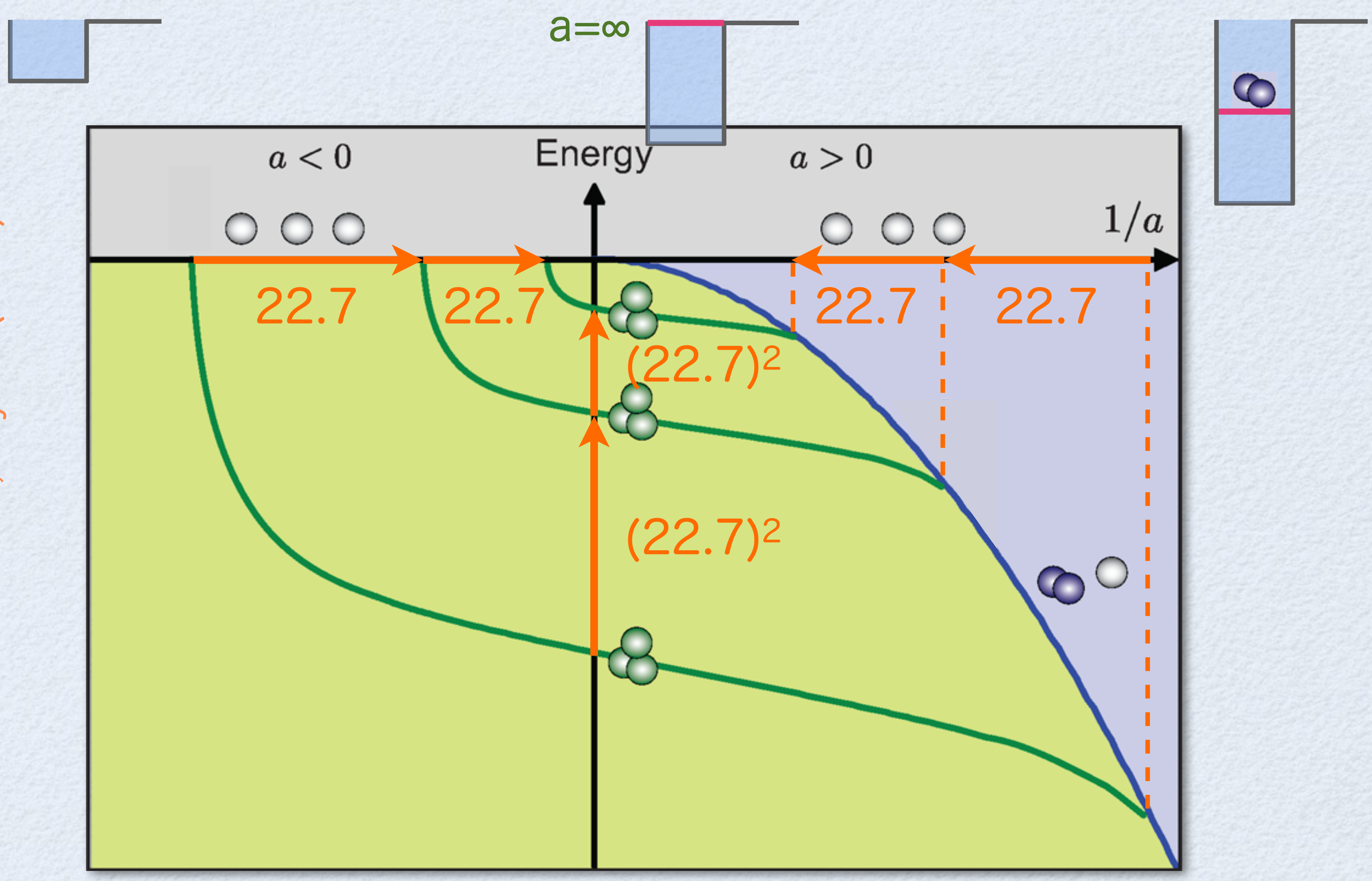




Efimov effect at a≠∞



Ferlaino & Grimm, Physics (2010)

Discrete scaling symmetry

Where Efimov effect appears ?

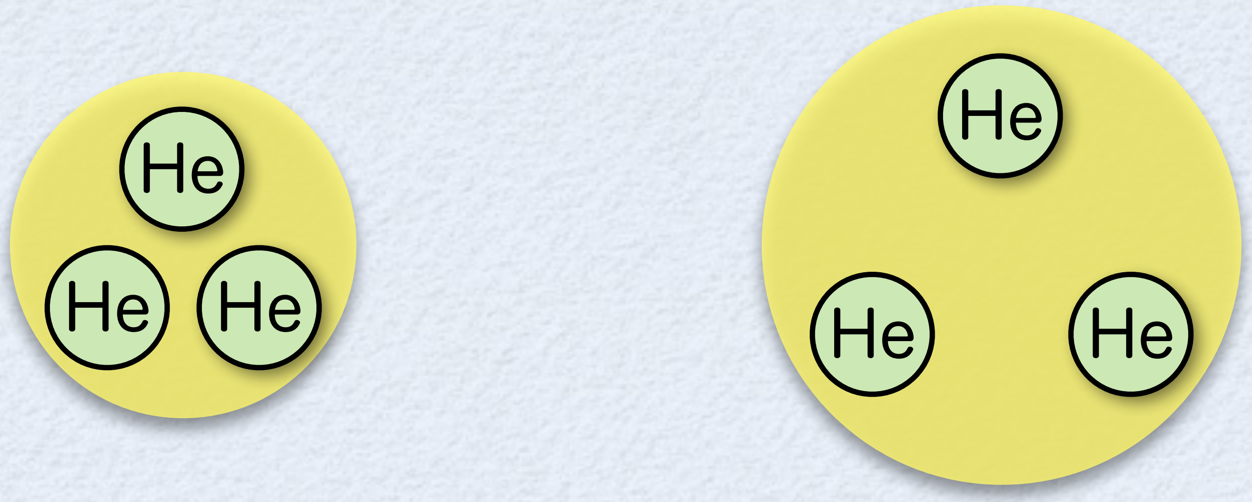
× Originally, Efimov considered

^{3}H nucleus (≈3n) and ^{12}C nucleus (≈3α)

△ ^{4}He atoms ($a \approx 1\times10^{-8}$ m $\approx 20 r_0$) ?

2 trimer states were predicted

and observed in 1994 and 2015

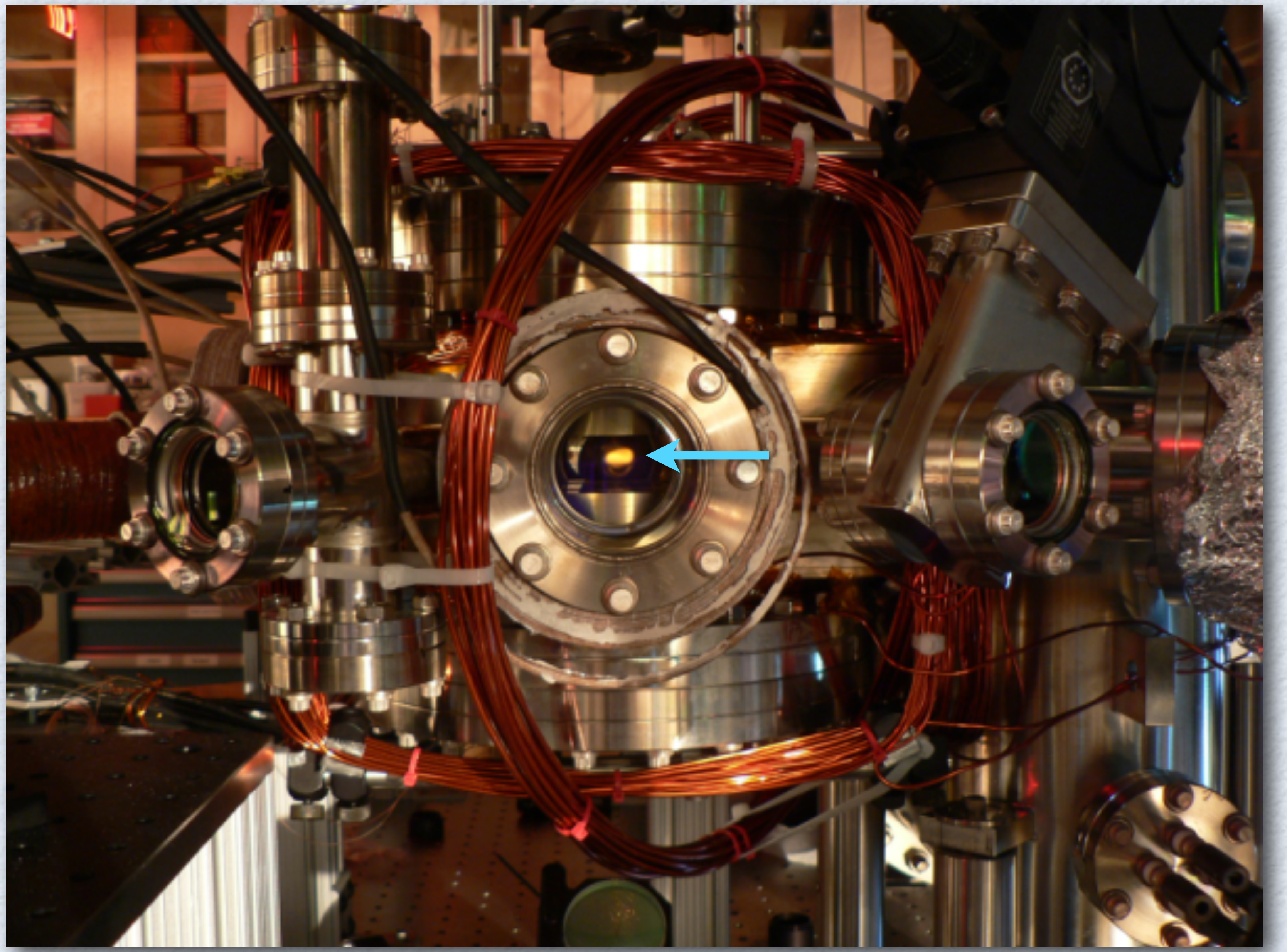


E_b = 125.8 mK　　　E_b = 2.28 mK

but no discrete scaling → Ultracold atoms !

Ultracold atom experiments

Ultracold atoms are ideal to study universal quantum physics because of the ability to design and control systems at will



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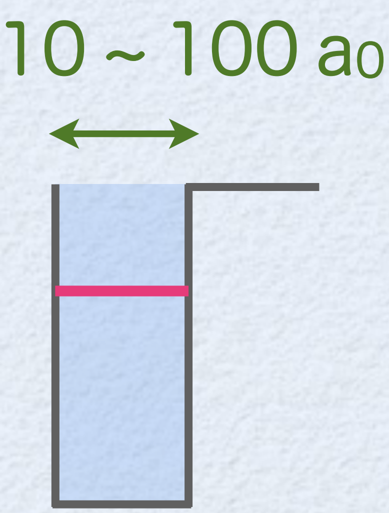
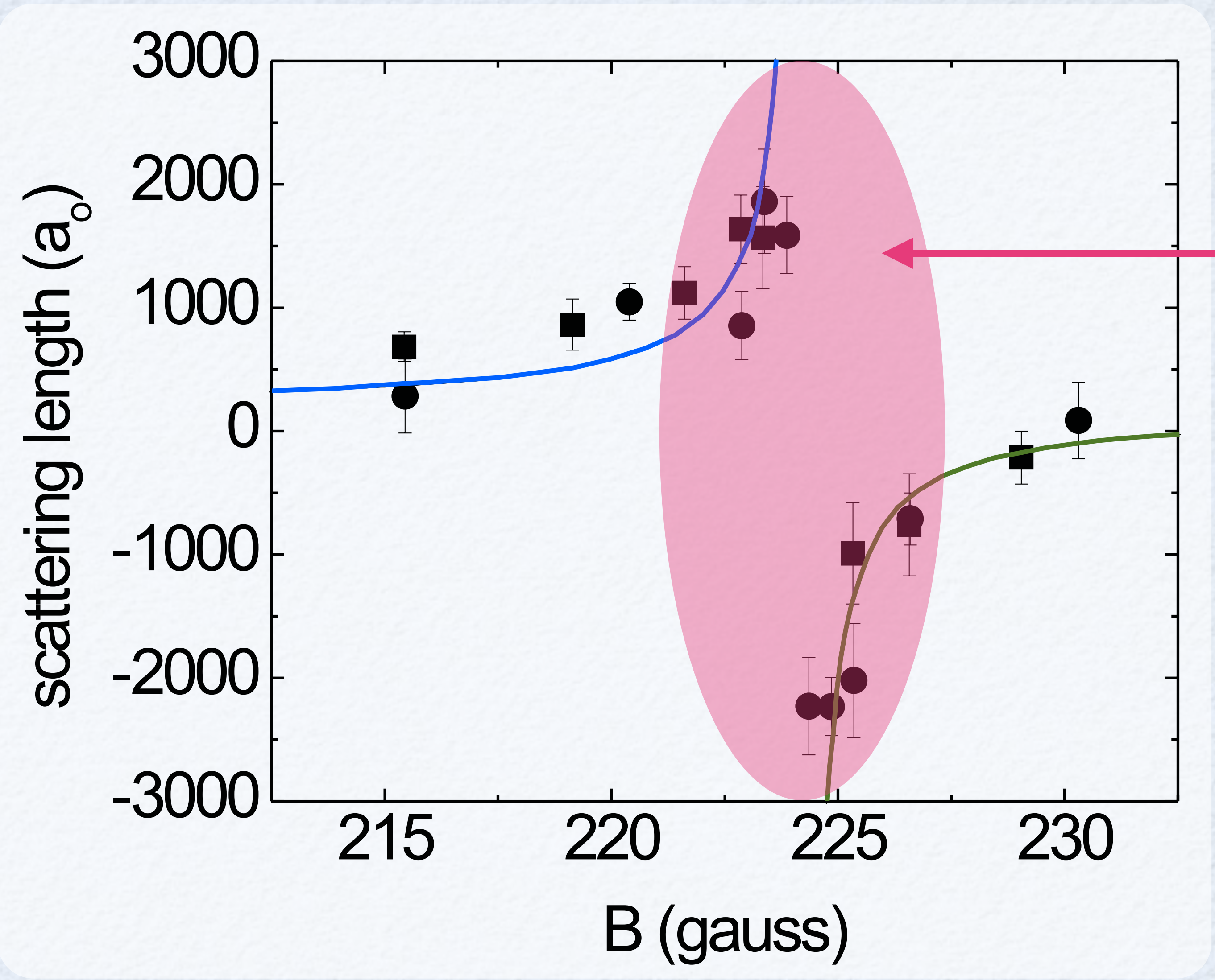
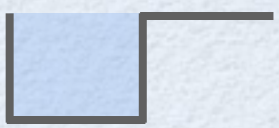
✓ Interaction strength by Feshbach resonances





Universal regime



C.A. Regal & D.S. Jin
PRL90 (2003)

Ultracold atom experiments

Ultracold atoms are ideal to study universal quantum physics because of the ability to design and control systems at will

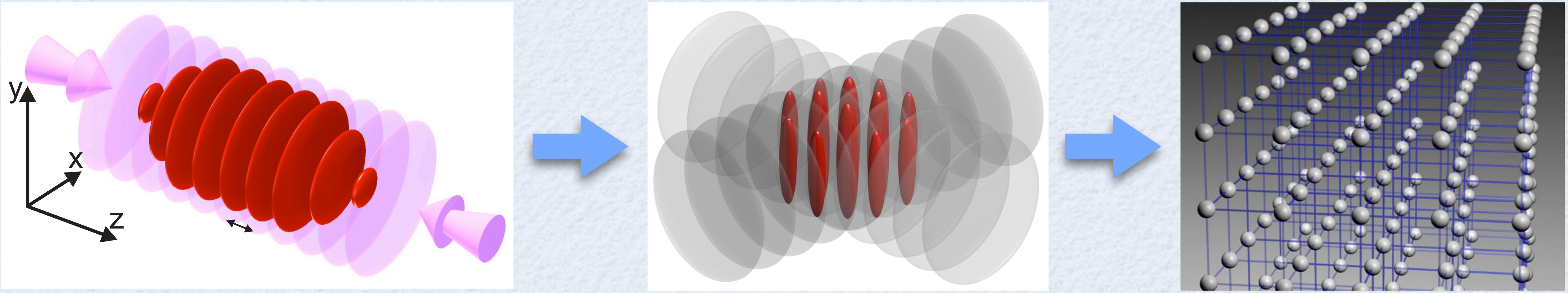
✓ Interaction strength by Feshbach resonances

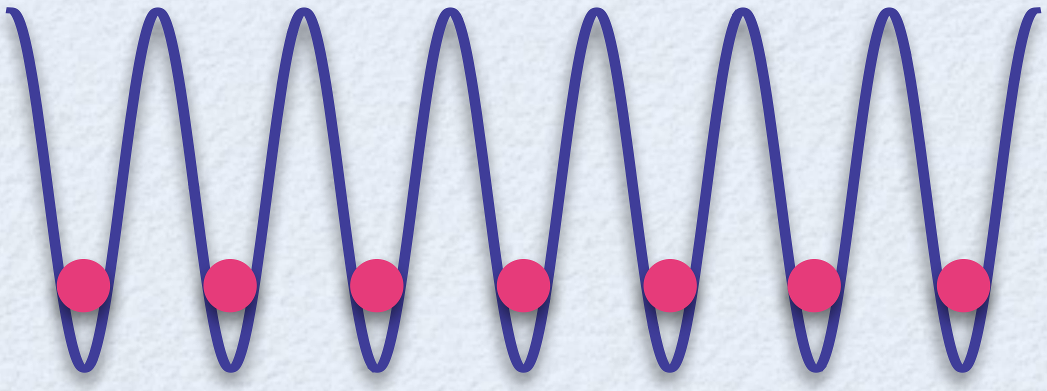
✓ Spatial dimensions by strong optical lattices

2D

1D

0D





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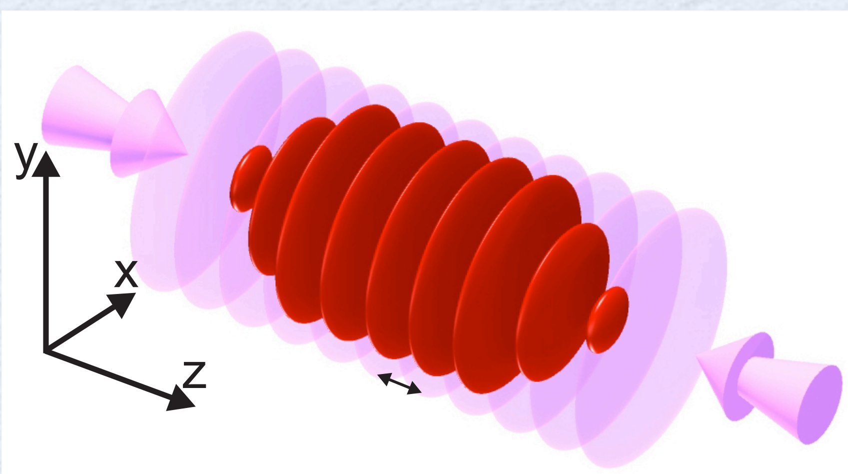
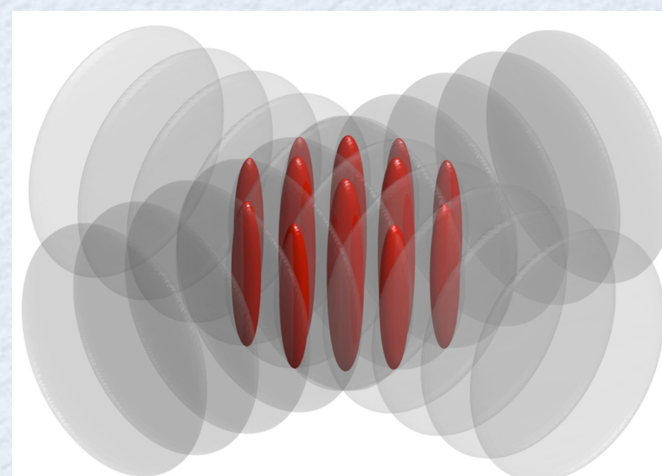
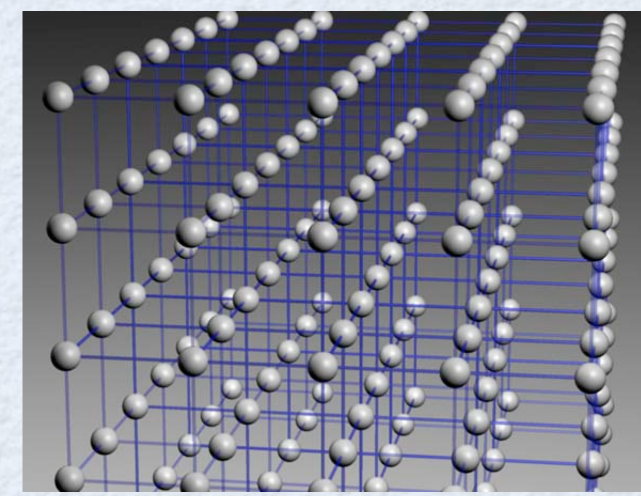


1D



0D

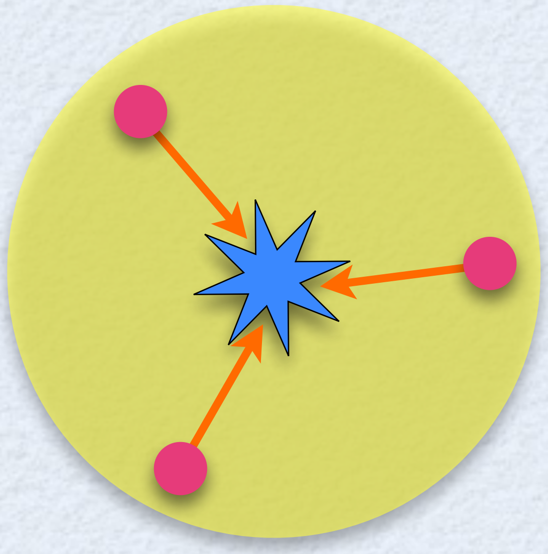


✓ Quantum statistics of particles

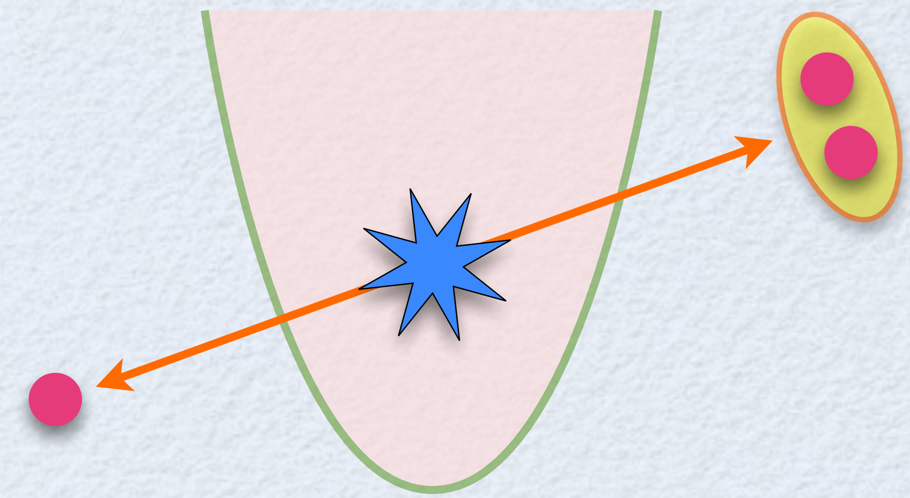
- Bosonic atoms (^{7}Li, ^{23}Na, ^{39}K, ^{41}K, ^{87}Rb, ^{133}Cs, ...)
- Fermionic atoms (^{6}Li, ^{40}K, ...)

Ultracold atom experiments

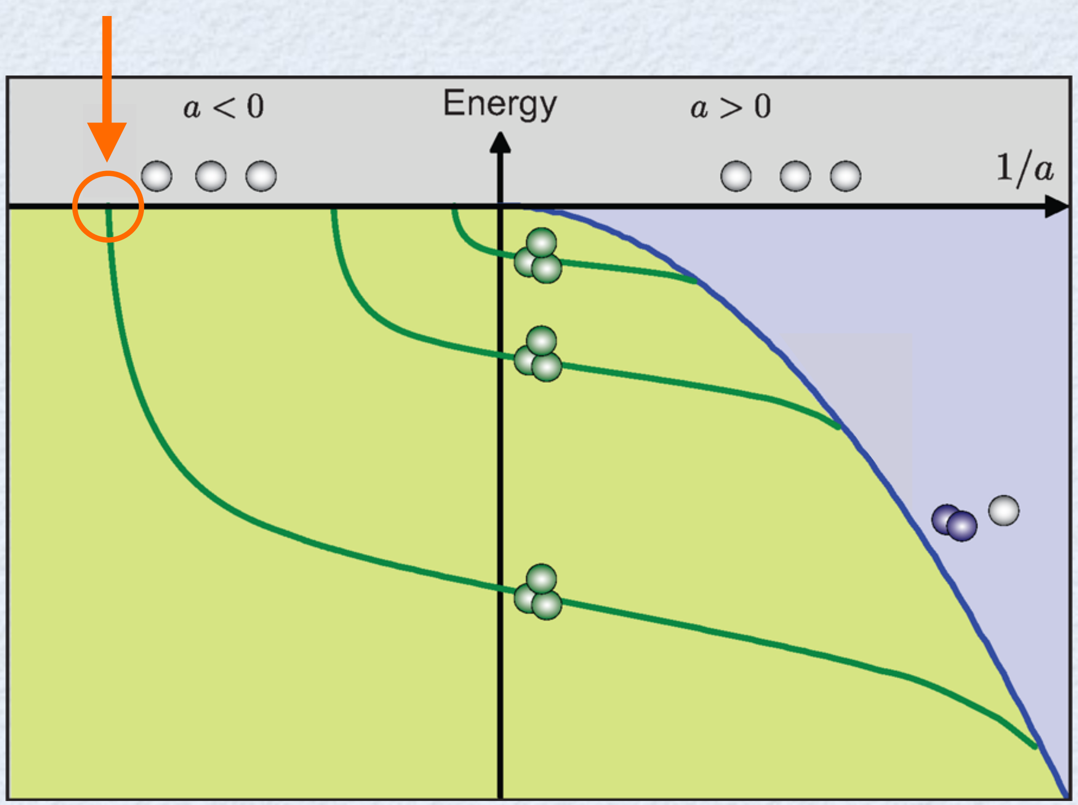
First experiment by Innsbruck group for ^{133}Cs (2006)

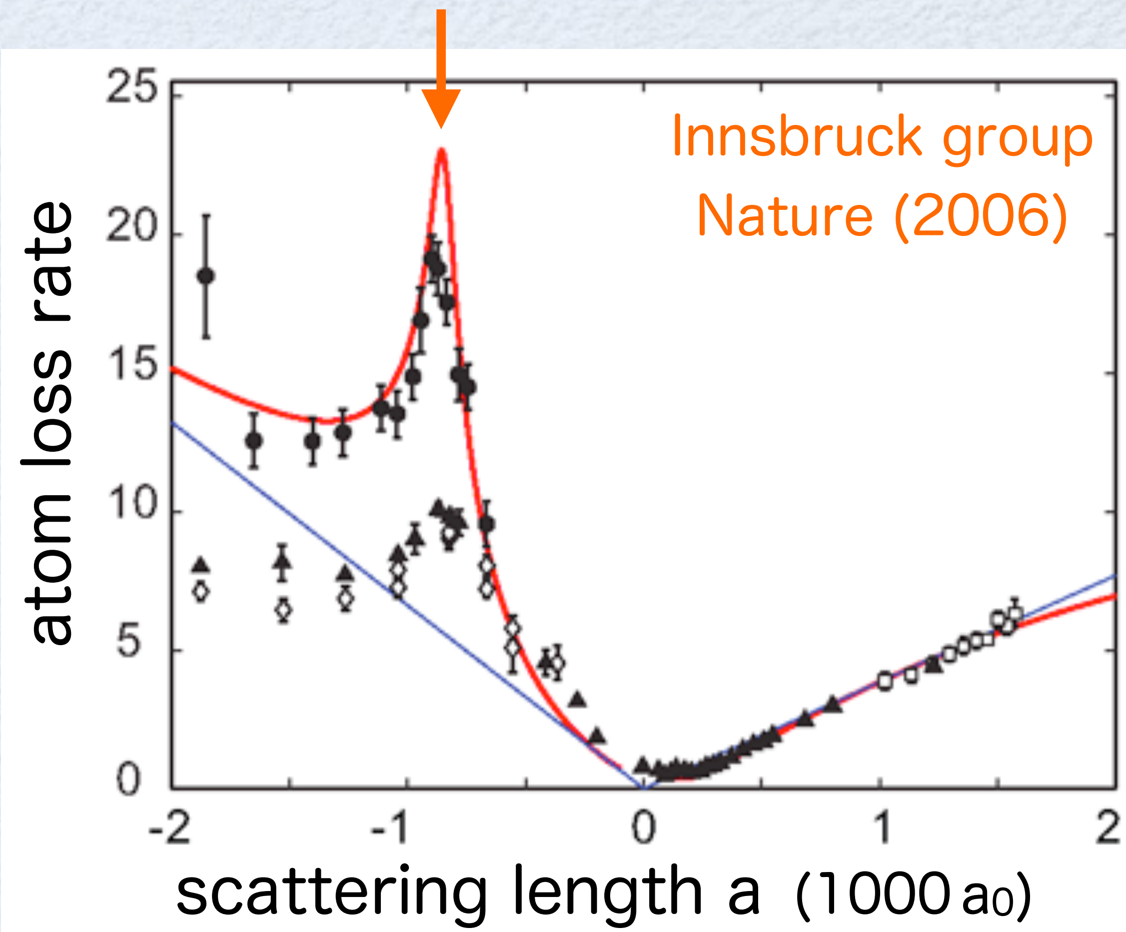


Trimer is unstable → atom loss



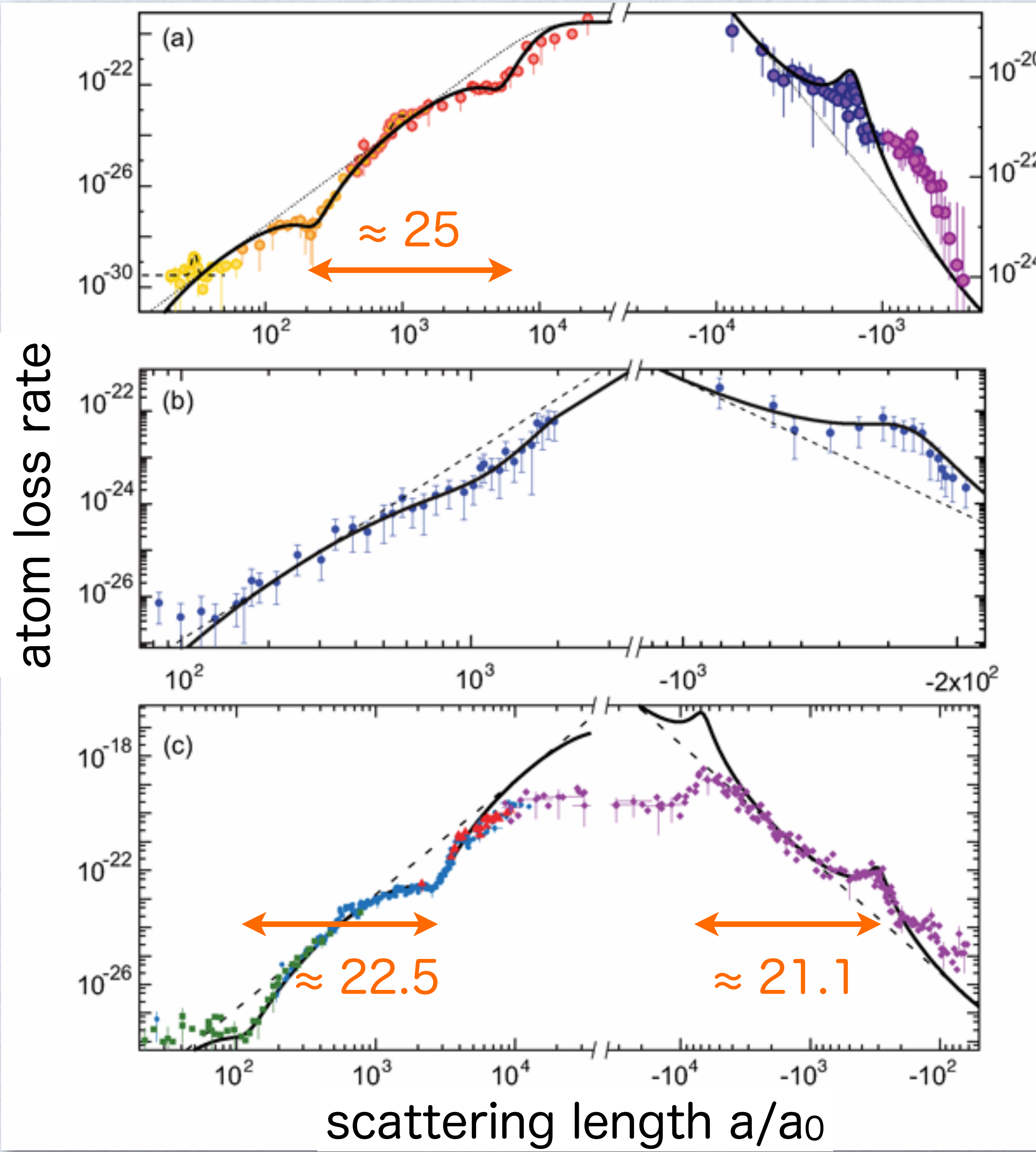
signature of trimer formation





Ultracold atom experiments

Ferlaino & Grimm, Physics (2010)



Florence group for ^{39}K (2009)

Bar-Ilan University for ^{7}Li (2009)

Rice University for ^{7}Li (2009)

Discrete scaling & Universality !

Beyond cold atoms

Nucleons

VOLUME 91, NUMBER 10 PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2003

An Infrared Renormalization Group Limit Cycle in QCD

Eric Braaten

Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

H.-W. Hammer

Helmholtz-Institut für Strahlen-und Kernphysik (Abteilung Theorie), Universität Bonn, 53115 Bonn, Germany

(Received 19 March 2003; published 4 September 2003)

We use effective field theories to show that small increases in the up and down quark masses would move QCD very close to the critical renormalization group trajectory for an infrared limit cycle in the three-nucleon system. We conjecture that QCD can be tuned to the critical trajectory by adjusting the quark masses independently. At the critical values of the quark masses, the binding energies of the deuteron and its spin-singlet partner would be tuned to zero and the triton would have infinitely many excited states with an accumulation point at the 3-nucleon threshold. The ratio of the binding energies of successive states would approach a universal constant that is close to 515.

DOI: 10.1103/PhysRevLett.91.102002 PACS numbers: 12.38.Aw, 11.10.Hi, 21.45.+v

The development of the renormalization group (RG) has had a profound effect on many branches of physics. Its successes range from explaining the universality of critical phenomena in condensed matter physics to the nonperturbative formulation of quantum field theories that describe elementary particles [1]. The RG can be reduced to a set of differential equations that define a flow in the space of coupling constants. Scale-invariant behavior at long distances, as in critical phenomena, can be explained by RG flow to an infrared fixed point. Scale-invariant behavior at short distances, as in asymptotically free field theories, can be explained by RG flow to an ultraviolet fixed point. However, a fixed point is only the simplest topological feature that can be exhibited by a RG flow. dom while leaving the long-distance physics invariant define a *RG flow* on the multidimensional space of coupling constants $\mathbf{g}$ for operators in the Hamiltonian:

$$\Lambda \frac{d}{d\Lambda} \mathbf{g} = \boldsymbol{\beta}(\mathbf{g}), \qquad (1)$$

where Λ is an ultraviolet momentum cutoff. Standard critical phenomena are associated with *infrared fixed points* $\mathbf{g}_*$ of the RG flow, which satisfy $\boldsymbol{\beta}(\mathbf{g}_*) = 0$. The tuning of macroscopic variables to reach a critical point corresponds to the tuning of the coupling constants $\mathbf{g}$ to a *critical trajectory* that flows to the fixed point $\mathbf{g}_*$ in the infrared limit $\Lambda \to 0$. One of the signatures of an RG fixed point is *scale invariance:* symmetry with respect to

Pions

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **89**, 032201(R) (2014)

Universal physics of three bosons with isospin

Tetsuo Hyodo,[1,2,*] Tetsuo Hatsuda,[3,4] and Yusuke Nishida[1]

[1]*Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo 152-8551, Japan*

[2]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

[3]*Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan*

[4]*Kavli IPMU (WPI), University of Tokyo, Chiba 277-8583, Japan*

(Received 25 November 2013; revised manuscript received 14 January 2014; published 7 March 2014)

We show that there exist two types of universal phenomena for three-boson systems with isospin degrees of freedom. In the isospin symmetric limit, there is only one universal three-boson bound state with the total isospin one, whose binding energy is proportional to that of the two-boson bound state. With large isospin symmetry breaking, the standard Efimov states of three identical bosons appear at low energies. Both phenomena can be realized by three pions with the pion mass appropriately tuned in lattice QCD simulations, or by spin-one bosons in cold atom experiments. Implication to the in-medium softening of multi-pion states is also discussed.

DOI: 10.1103/PhysRevC.89.032201 PACS number(s): 03.65.Ge, 11.30.Rd, 21.65.Jk, 67.85.Fg

Introduction. The properties of particles interacting with a large scattering length are universal, i.e., they are determined irrespective of the short range behavior of the interaction. In particular, three-particle systems with a large two-body scattering length lead to the emergence of the Efimov states [1], which have been extensively studied in cold atom physics [2]. Moreover, in condensed matter physics, collective excitations in quantum magnets are shown to exhibit the Efimov effect [3].

Since the intrinsic energy scale of the system is not relevant for such universal phenomena, they could be also realized in strong interaction governed by quantum chromodynamics which can be tested by simulating the three pions on the lattice by changing the quark mass. From the point of view of the statistical noise, three pions with heavy quark mass are much less costly than the three nucleons with light quark mass [10]. In this sense, the three-pion system is an ideal testing ground for the universal physics in QCD.

Universal physics with the isospin symmetry. Let us first consider the three-pion system with exact isospin symmetry. We assume that by an appropriate tuning of the quark mass, only the s-wave $\pi\pi$ scattering length in the $I = 0$ channel, $|a_{I=0}|$, becomes much larger than the typical length scale R characterized by the interaction range. In addition, we

Halo nuclei

PRL **111,** 132501 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Efimov Physics Around the Neutron-Rich ^{60}Ca Isotope

G. Hagen,[1,2] P. Hagen,[3] H.-W. Hammer,[3] and L. Platter[4,5]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, Universität Bonn, 53115 Bonn, Germany*
[4]*Argonne National Laboratory, Physics Division, Argonne, Illinois 60439, USA*
[5]*Department of Fundamental Physics, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*

(Received 18 June 2013; published 23 September 2013)

We calculate the neutron-^{60}Ca S-wave scattering phase shifts using state of the art coupled-cluster theory combined with modern *ab initio* interactions derived from chiral effective theory. Effects of three-nucleon forces are included schematically as density dependent nucleon-nucleon interactions. This information is combined with halo effective field theory in order to investigate the ^{60}Ca-neutron-neutron system. We predict correlations between different three-body observables and the two-neutron separation energy of ^{62}Ca. This provides evidence of Efimov physics along the calcium isotope chain. Experimental key observables that facilitate a test of our findings are discussed.

DOI: 10.1103/PhysRevLett.111.132501 PACS numbers: 21.10.Gv, 21.60.−n, 27.50.+e

Introduction.– ... dom is one of t... along the neutro... characterized by... valence nucleon... effective degree... an extremely lar... one- or two-nucleon separation energy along an isotope chain. The features of these halos are universal if the small separation energy of the valence nucleons is associated with

...st is still an open ...h interest, both ...rmining precise ...olution and the ...alcium isotopes ...eutron rich cal- ... the scattering continuum and schematic three-nucleon forces, suggested that there is an inversion of the *gds* shell-model orbitals in ^{53,55,61}Ca. In particular it was suggested that a large S-wave

Other possible systems :

^{11}Li = ^{9}Li+n+n ^{20}C = ^{18}C+n+n

DNA chains

PRL **110,** 028105 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Renormalization Group Limit Cycle for Three-Stranded DNA

Tanmoy Pal,* Poulomi Sadhukhan,† and Somendra M. Bhattacharjee‡

Institute of Physics, Bhubaneswar 751005, India

(Received 23 August 2012; published 11 January 2013)

We show that there exists an Efimov-like three strand DNA bound state at the duplex melting point and it is described by a renormalization group limit cycle. A nonperturbative renormalization group is used to obtain this result in a model involving short range pairing only. Our results suggest that Efimov physics can be tested in polymeric systems.

DOI: 10.1103/PhysRevLett.110.028105 PACS numbers: 87.14.gk, 64.60.ae, 87.15.Zg

Consider a three-particle quantum system with a pairwise short-range potential. Apart from the occurrence of the usual three-body bound state, a very special phenomenon occurs at the critical two-body zero-energy state. An infinite number of three-body bound states appear though the corresponding potential is not appropriate to bind any two of them; the removal of any one of them destroys the bound state. This phenomenon, valid for any short-range interaction, is known as the Efimov effect. The size of the three-body bound states, or Efimov trimers, is large compared to the potential range, and so it is a purely quantum effect [1]. Although it was predicted in the context of nuclear physics [2,3], it has now been detected in cold atoms [4].

An ideal DNA consisting of two Gaussian polymers interacting with native base pairing undergoes a critical melting transition where the two strands get detached. Maji *et al.* recently showed that if, to a double-stranded DNA at point is of a different type. This "few-chain problem" is actually described by a renormalization group "limit cycle"[2,8]. The appearance of a limit cycle invokes log periodicity in the corresponding three-body coupling in the polymer problem. So they break the continuous scale invariance around the two-body fixed point imposing a discrete scaling symmetry, the hallmark of the Efimov states.

Another motivation of this Letter is to emphasize that a three-chain polymer model, a three-stranded DNA in particular, by virtue of mathematical similarities, provides an alternative system for Efimov physics. Triplex DNA is known to occur in nature. The possibility of recognizing the bound base pairs of a duplex without opening it, by forming Hoogsteen pairs, has the potentiality of designing new types of antibiotics. In addition, H-DNA is a common motif formed during many DNA activities where there is a stretch of triplex DNA via a strand exchange mechanism

Quantum magnet

nature physics

ARTICLES

PUBLISHED ONLINE: 13 JANUARY 2013 | DOI: 10.1038/NPHYS2523

Cristian Batista

Efimov effect in quantum magnets

Yusuke Nishida*, Yasuyuki Kato and Cristian D. Batista

Physics is said to be universal when it emerges regardless of the underlying microscopic details. A prominent example is the Efimov effect, which predicts the emergence of an infinite tower of three-body bound states obeying discrete scale invariance when the particles interact resonantly. Because of its universality and peculiarity, the Efimov effect has been the subject of extensive research in chemical, atomic, nuclear and particle physics for decades. Here we employ an anisotropic Heisenberg model to show that collective excitations in quantum magnets (magnons) also exhibit the Efimov effect. We locate anisotropy-induced two-magnon resonances, compute binding energies of three magnons and find that they fit into the universal scaling law. We propose several approaches to experimentally realize the Efimov effect in quantum magnets, where the emergent Efimov states of magnons can be observed with commonly used spectroscopic measurements. Our study thus opens up new avenues for universal few-body physics in condensed matter systems.

Sometimes we observe that completely different systems exhibit the same physics. Such physics is said to be universal and its most famous example is the critical phenomena[1]. In the vicinity of second-order phase transitions where the correlation length diverges, microscopic details become unimportant and the critical phenomena are characterized by only a few ingredients; dimensionality, interaction range and symmetry of the order parameter. Accordingly, fluids and magnets exhibit the same critical exponents. The universality in critical phenomena has been one of the central themes in condensed matter physics.

Similarly, we can also observe universal physics in the vicinity of scattering resonances where the s-wave scattering length diverges. Here low-energy physics is characterized solely by the s-wave scattering length and does not depend on other microscopic details.

emergent Efimov states of magnons. Our study thus opens up new avenues for universal few-body physics in condensed matter systems. Also, in addition to the Bose–Einstein condensation of magnons[24], the Efimov effect provides a novel connection between atomic and magnetic systems.

Anisotropic Heisenberg model

To demonstrate the Efimov effect in quantum magnets, we consider an anisotropic Heisenberg model on a simple cubic lattice:

$$H = -\frac{1}{2}\sum_{\mathbf{r}}\sum_{\hat{\mathbf{e}}}(J\, S^+_{\mathbf{r}} S^-_{\mathbf{r}+\hat{\mathbf{e}}} + J_z\, S^z_{\mathbf{r}} S^z_{\mathbf{r}+\hat{\mathbf{e}}}) - D\sum_{\mathbf{r}}(S^z_{\mathbf{r}})^2 - B\sum_{\mathbf{r}} S^z_{\mathbf{r}} \quad (2)$$

where $\sum_{\hat{\mathbf{e}}}$ is a sum over six unit vectors; $\sum_{\hat{\mathbf{e}}=\pm\hat{\mathbf{x}},\pm\hat{\mathbf{y}},\pm\hat{\mathbf{z}}}$. Two types

Quantum magnet

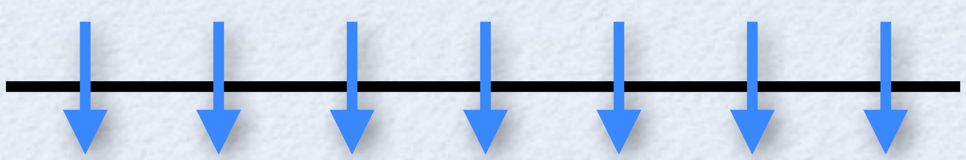
Anisotropic Heisenberg model on a 3D lattice

$$H = -\sum_{r}\left[\sum_{\hat{e}}\left(J S_r^+ S_{r+\hat{e}}^- + J_z S_r^z S_{r+\hat{e}}^z\right) + D(S_r^z)^2 - B S_r^z\right]$$

exchange anisotropy

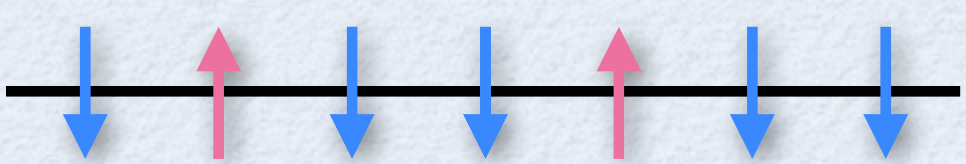
single-ion anisotropy

Spin-boson correspondence

 ⇔

fully polarized state (B→∞)

No boson = vacuum

 ⇔ 

N spin-flips

N bosons = magnons

Quantum magnet

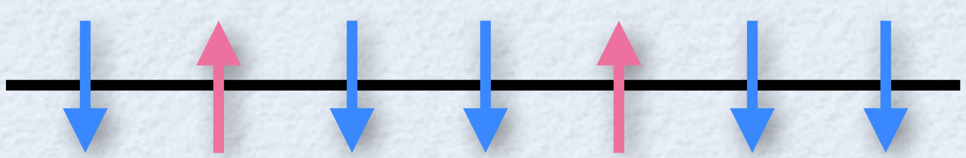
Anisotropic Heisenberg model on a 3D lattice

$$H = -\sum_{r} \left[\sum_{\hat{e}} \left(J S_{r}^{+} S_{r+\hat{e}}^{-} + J_z S_{r}^{z} S_{r+\hat{e}}^{z} \right) + D (S_{r}^{z})^2 - B S_{r}^{z} \right]$$

xy-exchange coupling
⇔ hopping

single-ion anisotropy
⇔ on-site attraction

z-exchange coupling
⇔ neighbor attraction



⇔

N spin-flips

N bosons = magnons

Quantum magnet

Anisotropic Heisenberg model on a 3D lattice

$$H = -\sum_{r}\left[\sum_{\hat{e}}(J S_r^+ S_{r+\hat{e}}^- + J_z S_r^z S_{r+\hat{e}}^z) + D(S_r^z)^2 - B S_r^z\right]$$

xy-exchange coupling
⇔ hopping

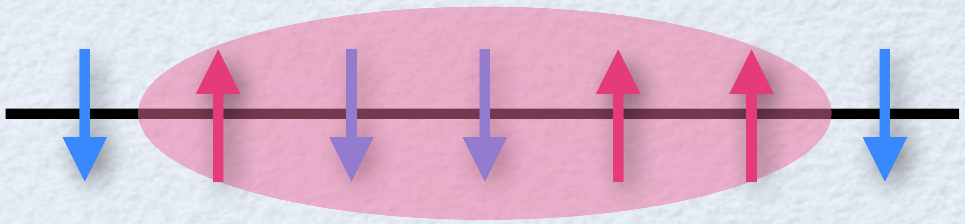
single-ion anisotropy
⇔ on-site attraction

z-exchange coupling
⇔ neighbor attraction

Tune these couplings to induce scattering resonance between two magnons
⇒ Three magnons show the Efimov effect

Three-magnon spectrum

At the resonance, three magnons form bound states with binding energies E_n



- **Spin-1/2**

n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-2.09×10^{-1}	—
1	-4.15×10^{-4}	22.4
2	-8.08×10^{-7}	22.7

- **Spin-1, D=0**

n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-5.16×10^{-1}	—
1	-1.02×10^{-3}	22.4
2	-2.00×10^{-6}	22.7

- **Spin-1, J_z=J>0**

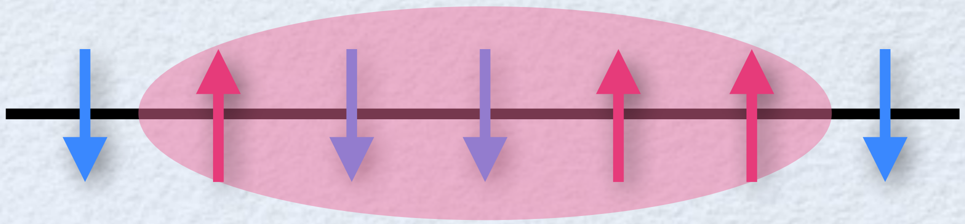
n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-5.50×10^{-2}	—
1	-1.16×10^{-4}	21.8

- **Spin-1, J_z=J<0**

n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-4.36×10^{-3}	—
1	-8.88×10^{-6}	22.2

Three-magnon spectrum

At the resonance, three magnons form bound states with binding energies E_n



- **Spin-1/2**

n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-2.09×10^{-1}	—
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- **Spin-1, D=0**

n	E_n/J	$\sqrt{E_{n-1}/E_n}$
0	-5.16×10^{-1}	—
1	-1.02×10^{-3}	22.4
2	-2.00×10^{-6}	22.7

Universal scaling law by ~ 22.7 confirms they are Efimov states !

KPZ roughening transition

PHYSICAL REVIEW E **103**, 012117 (2021)

Efimov effect at the Kardar-Parisi-Zhang roughening transition

Yu Nakayama[1] and Yusuke Nishida[2]
[1]*Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan*
[2]*Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo 152-8551, Japan*

(Received 30 October 2020; accepted 23 December 2020; published 19 January 2021)

Surface growth governed by the Kardar-Parisi-Zhang (KPZ) equation in dimensions higher than two undergoes a roughening transition from smooth to rough phases with increasing the nonlinearity. It is also known that the KPZ equation can be mapped onto quantum mechanics of attractive bosons with a contact interaction, where the roughening transition corresponds to a binding transition of two bosons with increasing the attraction. Such critical bosons in three dimensions actually exhibit the Efimov effect, where a three-boson coupling turns out to be relevant under the renormalization group so as to break the scale invariance down to a discrete one. On the basis of these facts linking the two distinct subjects in physics, we predict that the KPZ roughening transition in three dimensions shows either the discrete scale invariance or no intrinsic scale invariance.

DOI: 10.1103/PhysRevE.103.012117

I. INTRODUCTION

The Kardar-Parisi-Zhang (KPZ) equation for surface growth [1],

$$\frac{\partial h}{\partial t} = \nu \nabla^2 h + \frac{\lambda}{2}(\nabla h)^2 + \sqrt{D}\,\eta, \tag{1}$$

has been a paradigmatic model in nonequilibrium statistical physics [2–6]. Here, $h = h(t, \boldsymbol{r})$ represents a height of d-

with $z = 2 - \chi$ imposed by the "Galilean" invariance [13]. On the other hand, there have been a number of claims that $d = 4$ is an upper critical dimension beyond which the surface is only marginally rough with $\chi = 0$ [14–26], although it contradicts numerical simulations of models belonging to the KPZ universality class [27–40]. The very existence of the upper critical dimension has been one of the most controversial issues regarding the KPZ equation.

PhysRevABCDE completed !

My first PRA (2006)

PHYSICAL REVIEW A **74**, 013615 (2006)

Effective field theory of boson-fermion mixtures and bound fermion states on a vortex of boson superfluid

Yusuke Nishida[1,2] and Dam Thanh Son[2]

My first PRB (2010)

PHYSICAL REVIEW B **81**, 224515 (2010)

Quantizing Majorana fermions in a superconductor

C. Chamon,[1] R. Jackiw,[2] Y. Nishida,[2] S.-Y. Pi,[1] and L. Santos[3]

My first PRC (2014)

PHYSICAL REVIEW C **89**, 032201(R) (2014)

Universal physics of three bosons with isospin

Tetsuo Hyodo,[1,2,*] Tetsuo Hatsuda,[3,4] and Yusuke Nishida[1]

My first PRD (2004)

PHYSICAL REVIEW D **69**, 094501 (2004)

Phase structures of strong coupling lattice QCD with finite baryon and isospin density

Yusuke Nishida

My first PRE (2021)

PHYSICAL REVIEW E **103**, 012117 (2021)

Efimov effect at the Kardar-Parisi-Zhang roughening transition

Yu Nakayama[1] and Yusuke Nishida[2]

Universality class of quantum halos

Quantum halos

REVIEWS OF MODERN PHYSICS, VOLUME 76, JANUARY 2004

Structure and reactions of quantum halos

A. S. Jensen, K. Riisager, and D. V. Fedorov

Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

E. Garrido

Instituto de Estructura de la Materia, CSIC, Serrano 123, E-28006 Madrid, Spain

(Published 5 February 2004)

This article provides an overview of the basic principles of the physics of quantum halo systems, defined as bound states of clusters of particles with a radius extending well into classically forbidden regions. Exploiting the consequences of this definition, the authors derive the conditions for occurrence in terms of the number of clusters, binding energy, angular momentum, cluster charges, and excitation energy. All these quantities must be small. The article discusses the transitions between different cluster divisions and the importance of thresholds for cluster or particle decay, with particular attention to the Efimov effect and the related exotic states. The pertinent properties can be described by the use of dim[illegible] properties can be distinguished, as shown in a series of examples selected from nuclear, atomic, and molecular systems. The neutron dripline is especia[illegible] for atoms. For molecules, in which the cluster division comes naturally, a wider range of possibilities exists. Halos in two dimensions have very different properties, and their states are easily spatially extended, whereas Borromean systems are unlikely and spatially confined. The Efimov effect and the Thomas collapse occur only for dimensions between 2.3 and 3.8 and thus not for 2. High-energy reactions directly probe

size >> potential range ~ r_0

⇒ no classical counterparts

⇒ universal properties

Quantum halos

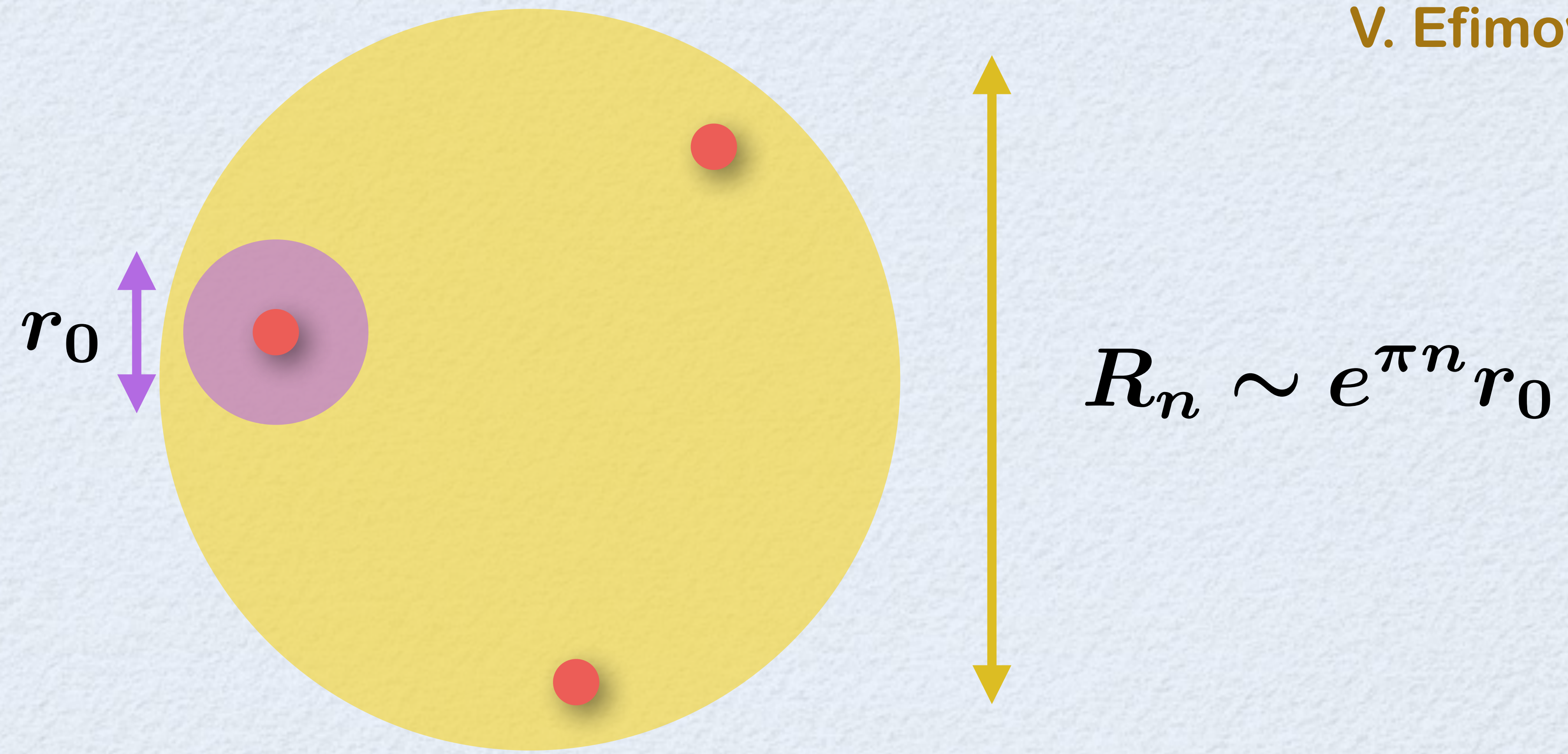
Efimov effect

- ✓ 3 bosons
- ✓ 3 dimensions
- ✓ s-wave resonance

Infinite bound states with universal scaling

$$E_n \sim e^{-2\pi n}$$

V. Efimov, PLB (1970)



Quantum halos can be arbitrarily large for n>>1 !

Quantum halos

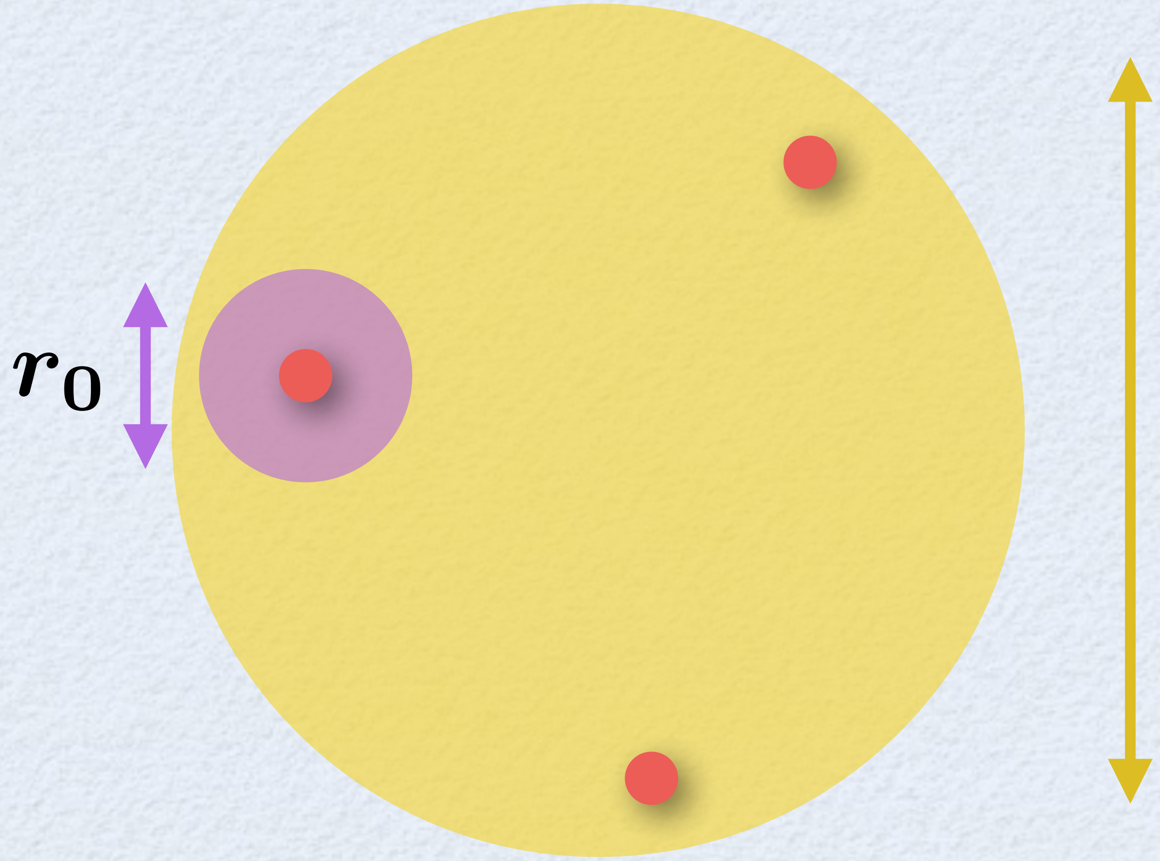
Super Efimov effect

- ✓ 3 fermions
- ✓ 2 dimensions
- ✓ p-wave resonance

→ Infinite bound states with universal scaling

$$E_n \sim e^{-2e^{3\pi n/4}}$$

Y. Nishida, S. Moroz, D. T. Son, PRL (2013)



$$R_n \sim e^{e^{3\pi n/4}} r_0$$

Quantum halos can be arbitrarily large for n>>1 !

Quantum halos

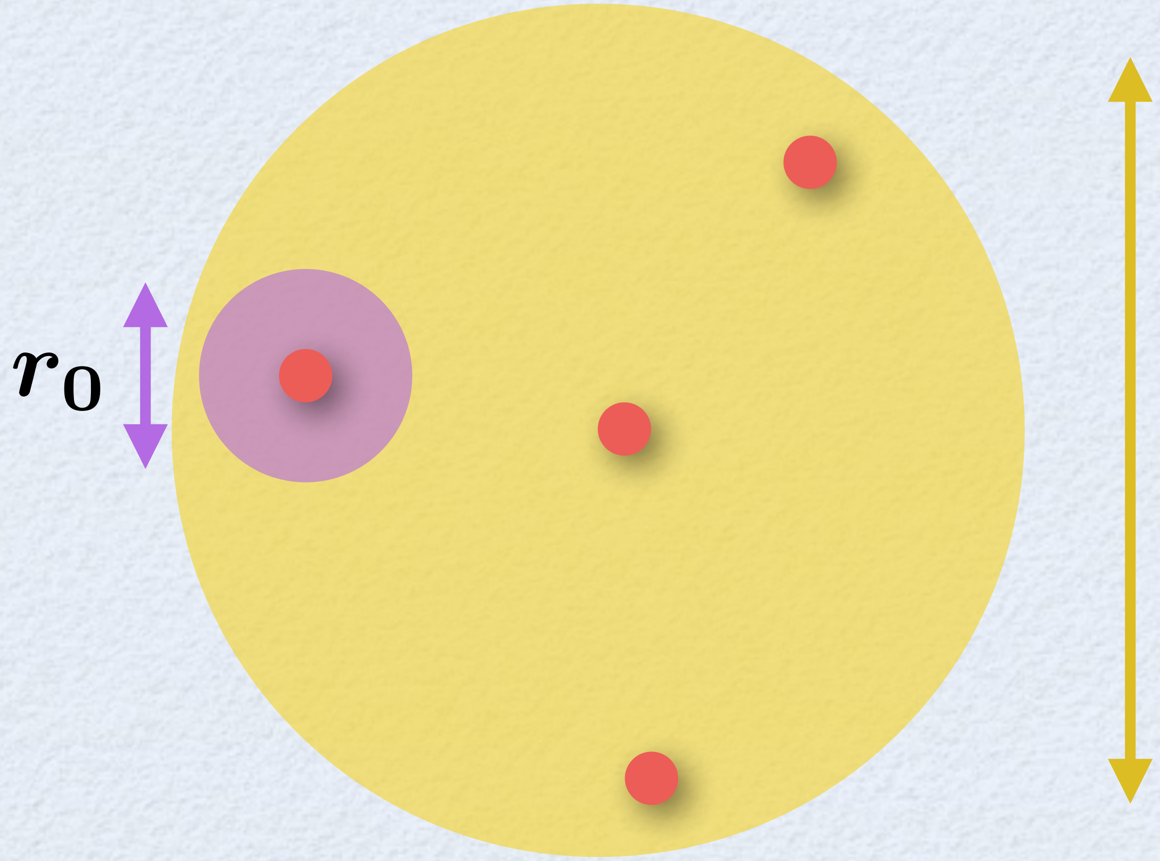
Semi-super Efimov effect

✓ 4 bosons
✓ 2 dimensions
✓ 3-body resonance

→ Infinite bound states with universal scaling

$$E_n \sim e^{-2(\pi n)^2/27}$$

Y. Nishida, PRL (2017)



$$R_n \sim e^{(\pi n)^2/27} r_0$$

Quantum halos can be arbitrarily large for n>>1 !

Universal scaling laws

Spinless bosons

- 3D + 2-body res. ⇒ $\kappa_n \sim e^{-\pi n/1.006}$ V.Efimov, PLB (1970)
- 2D + 3-body res. ⇒ $\kappa_n \sim e^{-(\pi n)^2/27}$ Y.Nishida, PRL (2017)
- 1D + 4-body res. ⇒ $\kappa_n \sim e^{-\pi n/1.247}$ Y.Nishida & D.T.Son, PRA (2010)

Spinless fermions

- 2D + 2-body res. ⇒ $\kappa_n \sim e^{-e^{3\pi n/4}}$ Y.Nishida, S.Moroz, D.T.Son, PRL (2013)
- unknown in 3D & 1D

Interesting hierarchy & interplay among statistics, dimensionality, required interaction, and emergent universal scaling laws

Universal scaling laws

Spinless bosons

- 3D + 2-body res. ⇒ Efimov effect
- 2D + 3-body res. ⇒ Semi-super Efimov effect
- 1D + 4-body res. ⇒ Efimov effect

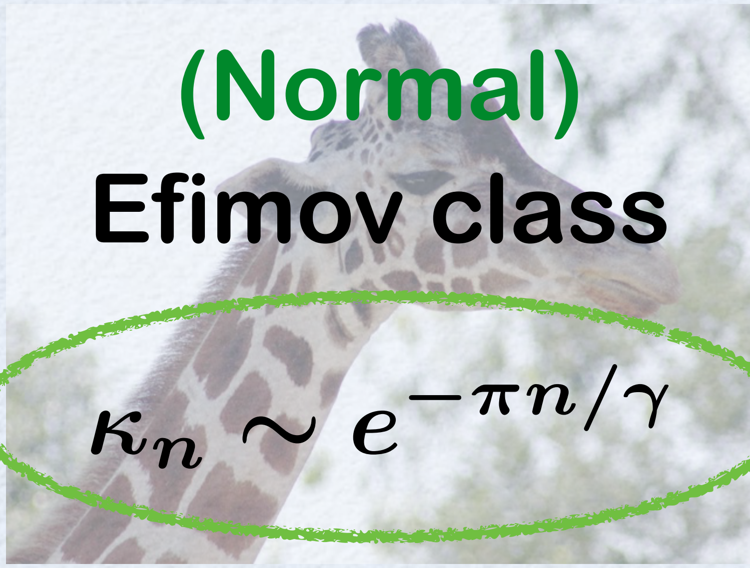
Spinless fermions

- 2D + 2-body res. ⇒ Super Efimov effect
- unknown in 3D & 1D

Interesting hierarchy & interplay among statistics, dimensionality, required interaction, and emergent universal scaling laws

Classification

Known universal scaling laws are classified into



(Normal) Efimov class

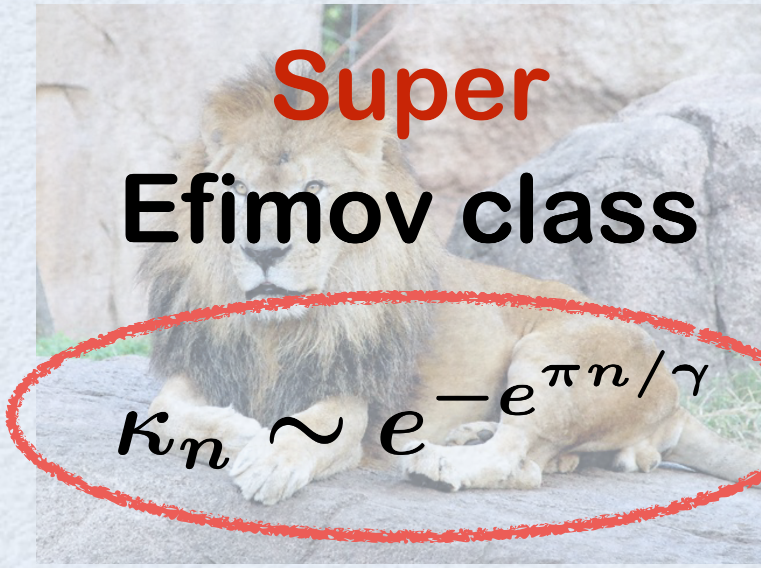
$$\kappa_n \sim e^{-\pi n/\gamma}$$

- ✓ 3 bosons in 3D (Efimov, 1970)
- 4 anyons in 2D (Nishida, 2008)
- ✓ 5 bosons in 1D (Nishida & Son, 2010)
- mass-imbalanced 3, 4, 5 fermions in 3D (Efimov, 1973; Castin et al., 2010 Bazak & Petrov, 2017)
- mixed dimensions (Nishida & Tan, 2008; 2011)

Semi-super Efimov class

$$\kappa_n \sim e^{-(\pi n/\gamma)^2}$$

- ✓ 4 bosons in 2D (Nishida, 2017)
- mixed dimensions (Zhang & Yu, 2017)
- …



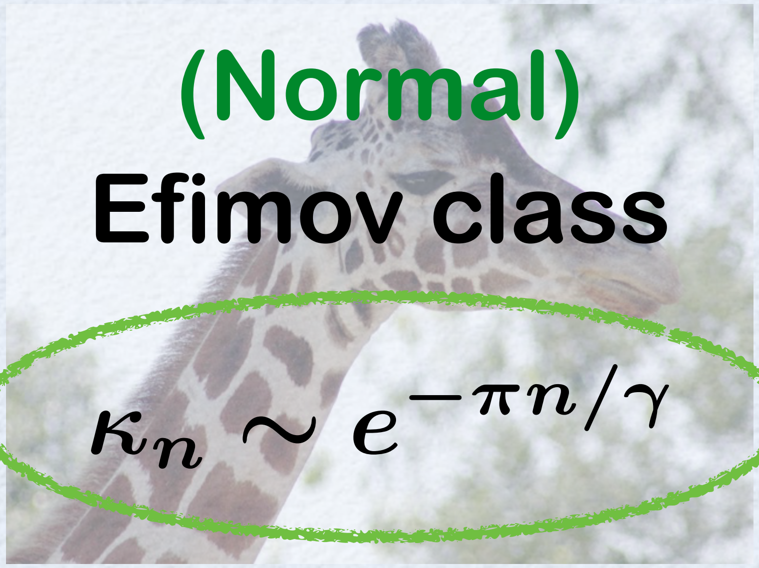
Super Efimov class

$$\kappa_n \sim e^{-e^{\pi n/\gamma}}$$

- ✓ 3 fermions in 2D (Nishida et al., 2013)
- mass-imbalanced bosons / fermions in 2D (Moroz & Nishida, 2014)
- mixed dimensions (Zhang & Yu, 2017)
- …

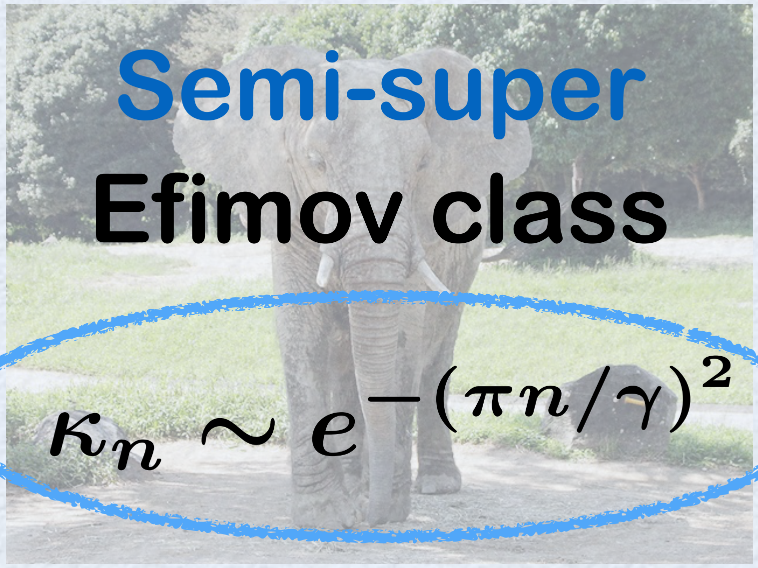
Classification

Known universal scaling laws are classified into



(Normal)
Efimov class

$$\kappa_n \sim e^{-\pi n/\gamma}$$



Semi-super
Efimov class

$$\kappa_n \sim e^{-(\pi n/\gamma)^2}$$

Super
Efimov class

$$\kappa_n \sim e^{-e^{\pi n/\gamma}}$$

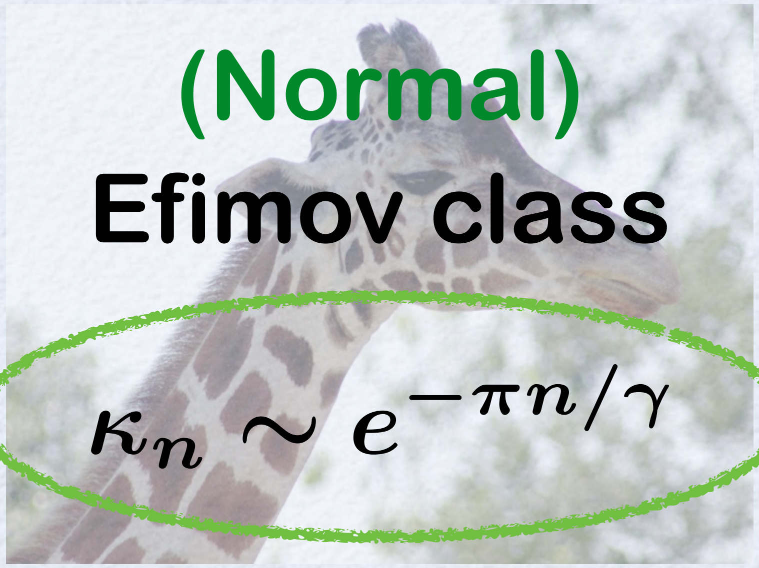
TRiO of few-body universality classes

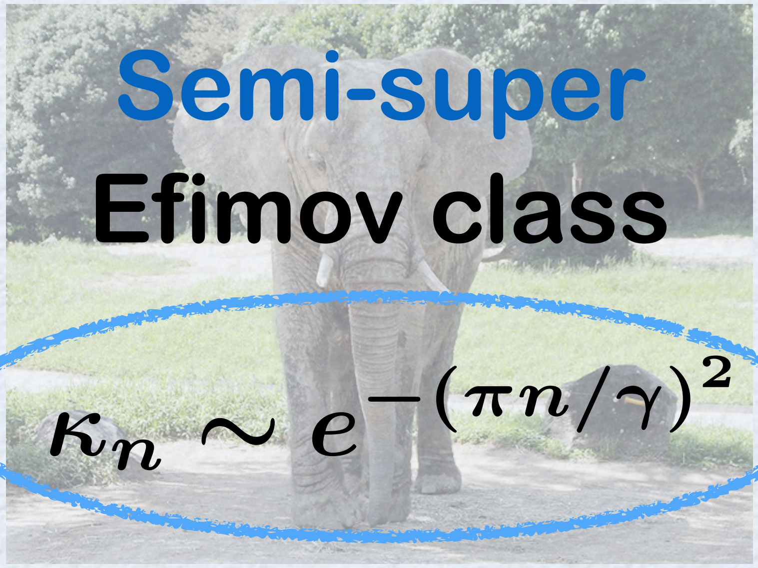
Q3. Even more universality classes ?

⇒ My speculation is ...

Classification

Known universal scaling laws are classified into





$$V(R) \sim \frac{\#}{R^2}$$

$$V(R) \sim \frac{\#}{R^2(\ln R)}$$

$$V(R) \sim \frac{\#}{R^2(\ln R)^2}$$

hyperspherical potential

no (arbitrarily large) quantum halos if power > 2

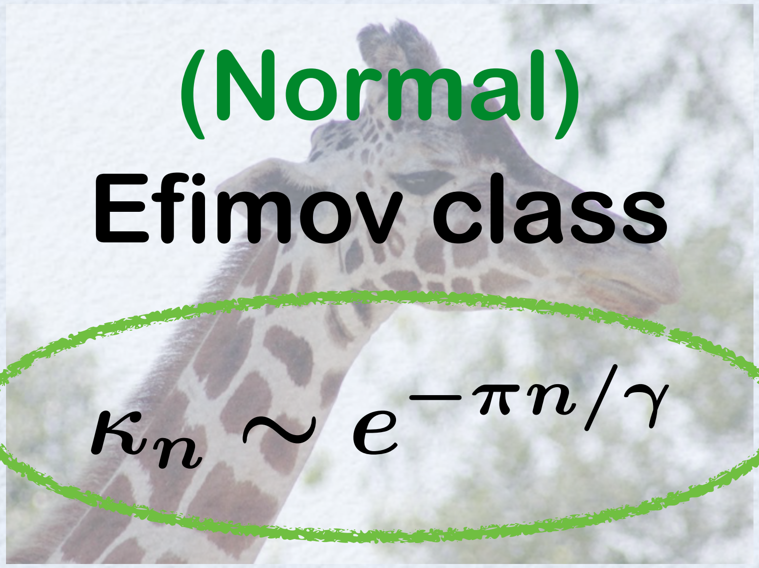
V.Efimov, PLB (1970)

M.A.Efemov & W.P.Schleich, arXiv:1407; arXiv:1511

Volosniev et al., JPB (2014); C.Gao et al., PRA (2015)

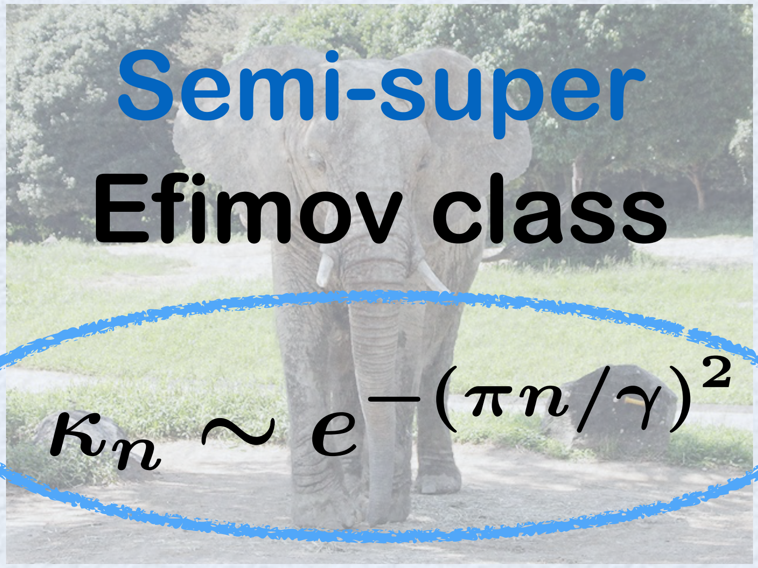
Classification

Known universal scaling laws are classified into



(Normal) Efimov class

$$\kappa_n \sim e^{-\pi n/\gamma}$$



Semi-super Efimov class

$$\kappa_n \sim e^{-(\pi n/\gamma)^2}$$

Super Efimov class

$$\kappa_n \sim e^{-e^{\pi n/\gamma}}$$

$$V(R) \sim \frac{\#}{R^2} \qquad V(R) \sim \frac{\#}{R^2(\ln R)} \qquad V(R) \sim \frac{\#}{R^2(\ln R)^2}$$

If $V(R) \sim \dfrac{\#}{R^2(\ln R)^2(\ln \ln R)}$ $\qquad V(R) \sim \dfrac{\#}{R^2(\ln R)^2(\ln \ln R)^2}$

$$\Rightarrow \kappa_n \sim e^{-e^{(\pi n/\gamma)^2}} \qquad \Rightarrow \kappa_n \sim e^{-e^{e^{\pi n/\gamma}}}$$

Semi-hyper Efimov class

Hyper Efimov class

Classification

Q4. Do semi-hyper and hyper Efimov effects emerge in quantum few-body systems with short-range interactions ?

⇒ I don't know (at this moment).

Cf. Dynamical "realization" is possible

S.Deng et al., Science (2016); PRL (2018)

If $V(R) \sim \dfrac{\#}{R^2(\ln R)^2(\ln\ln R)}$

$\Rightarrow \kappa_n \sim e^{-e^{(\pi n/\gamma)^2}}$

Semi-hyper Efimov class

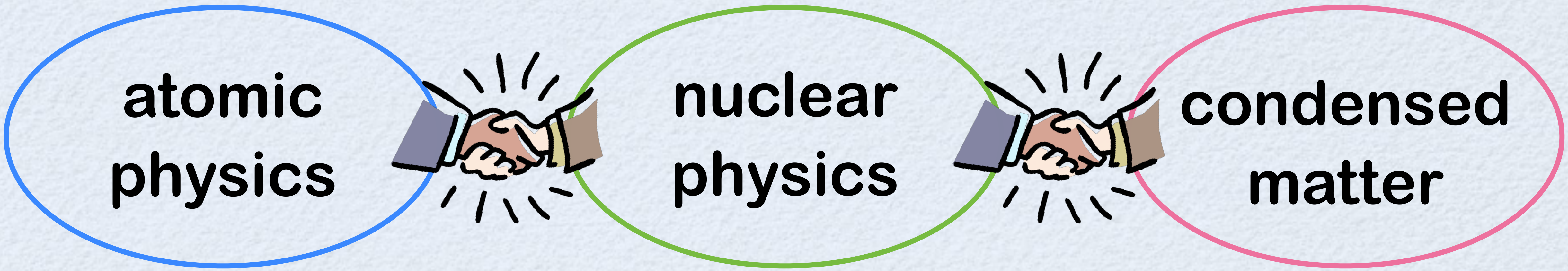
$V(R) \sim \dfrac{\#}{R^2(\ln R)^2(\ln\ln R)^2}$

$\Rightarrow \kappa_n \sim e^{-e^{e^{\pi n/\gamma}}}$

Hyper Efimov class

Summary

Efimov effect: universality, discrete scale inv,
quantum anomaly, RG limit cycle



cold atoms, ^{4}He atoms, nucleons, pions, halo nuclei,
DNA chains, magnons, KPZ roughening transition, ...

✓ Few-body universality classes

Efimov, semi-super, super & semi-hyper, hyper, … ?

2. Similarity in many-body physics

Plan of this talk

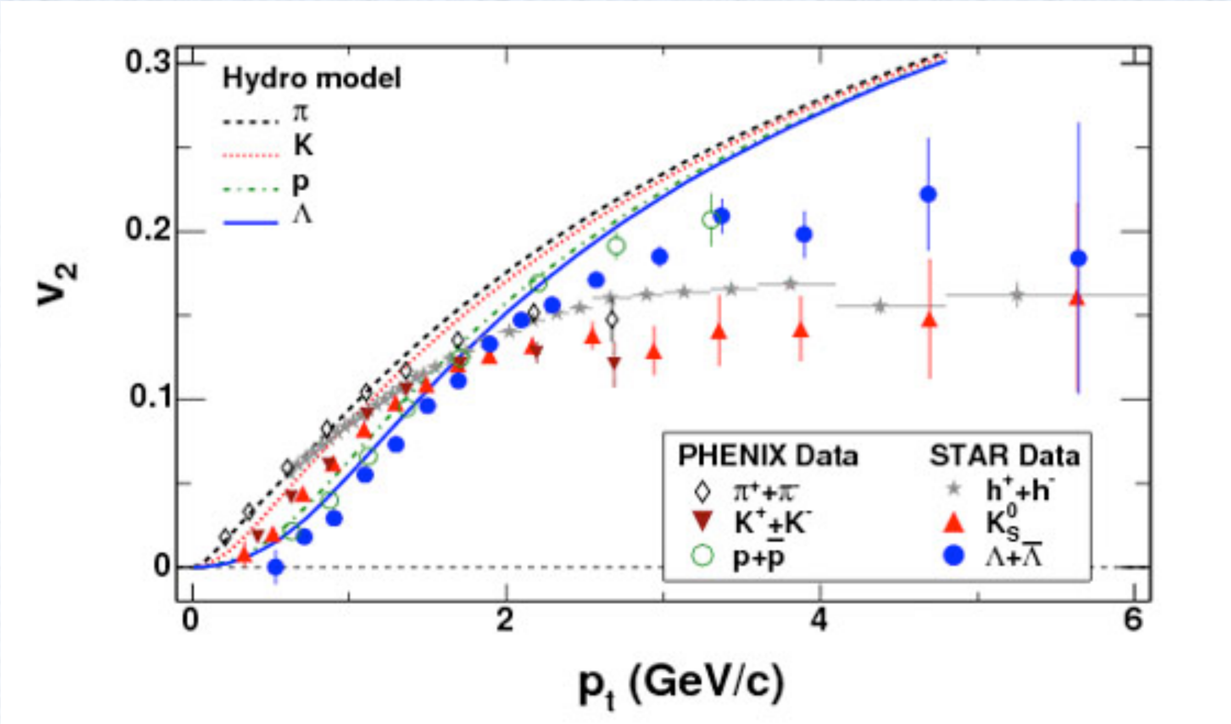
1. Universality in few-body physics
   - Efimov effect
   - Beyond cold atoms
   - Universality class of quantum halos

2. Similarity in many-body physics
   - “Hard probes” in cold atoms
   - “Quark-hadron continuity” in cold atoms

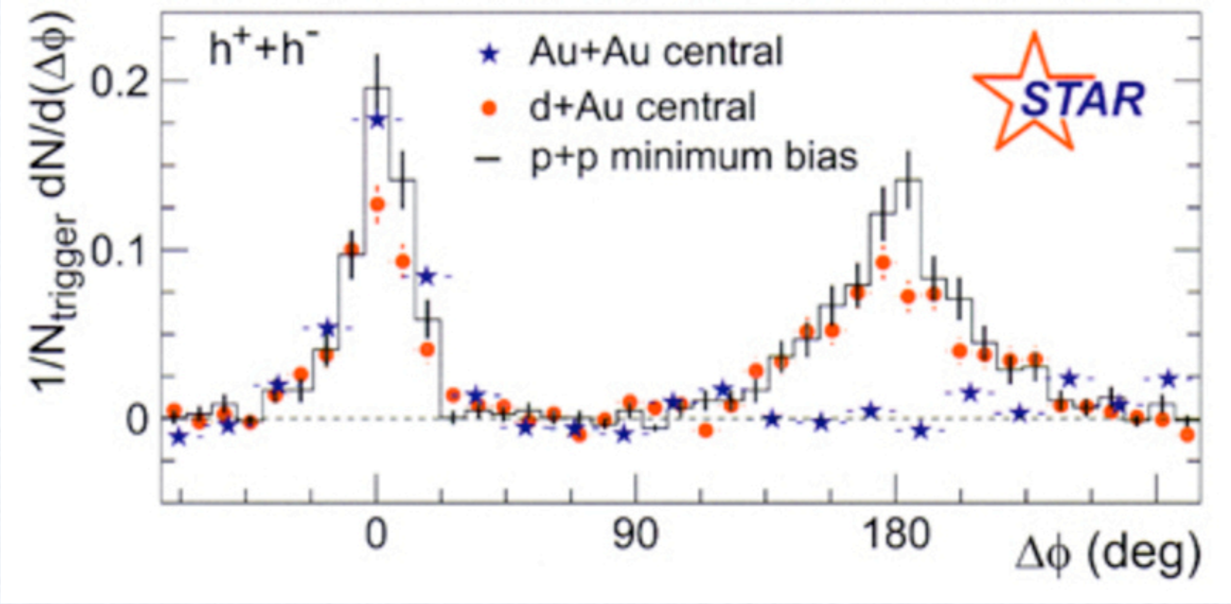
“Hard probes” in cold atoms

xQCD vs. cold atoms

- Elliptic flow



- Jet quenching

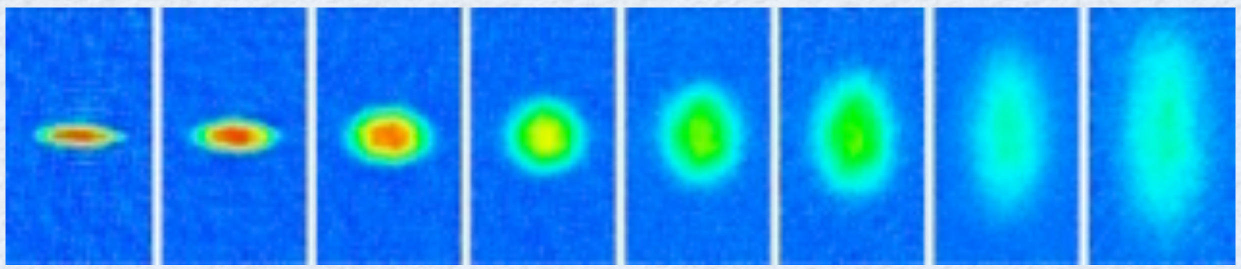


- Small shear viscosity

$$\frac{\eta}{s} \gtrsim \frac{1}{4\pi}$$

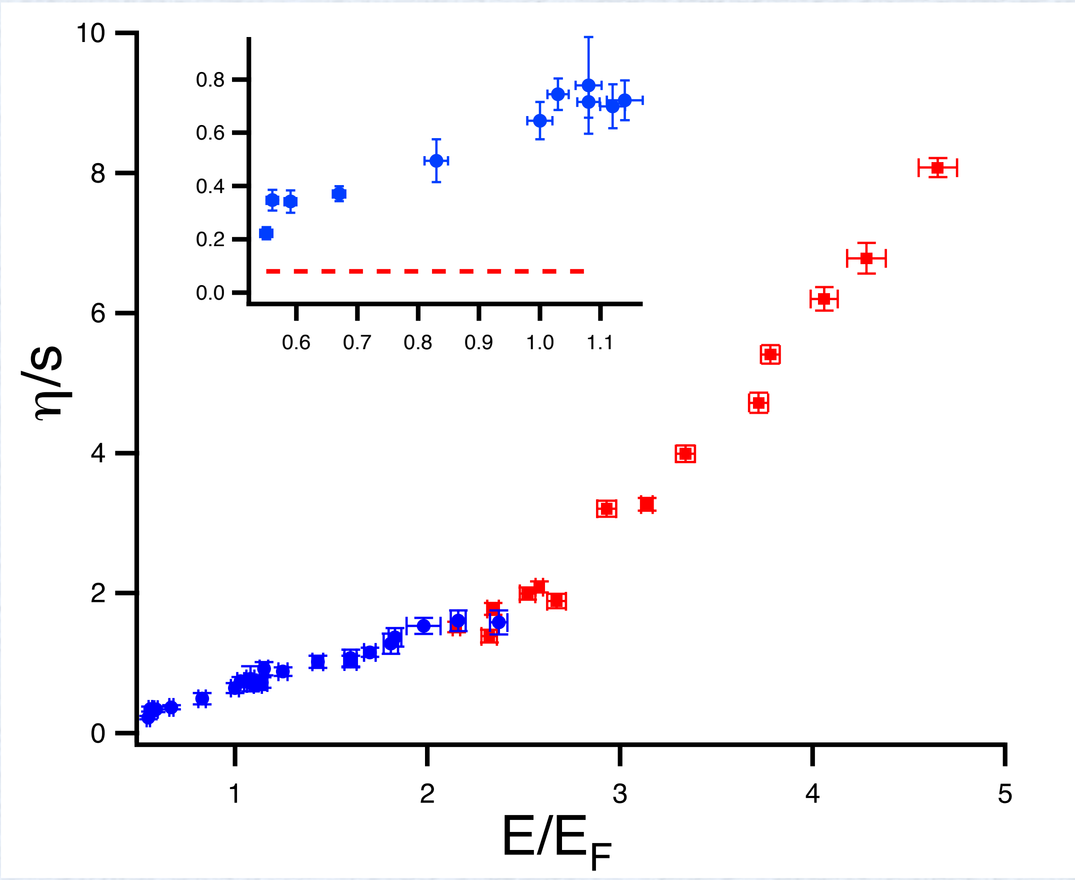
xQCD vs. cold atoms

- Elliptic flow



K. M. O'Hara et al., Science (2002)

- Small shear viscosity



C. Cao et al., Science (2011)

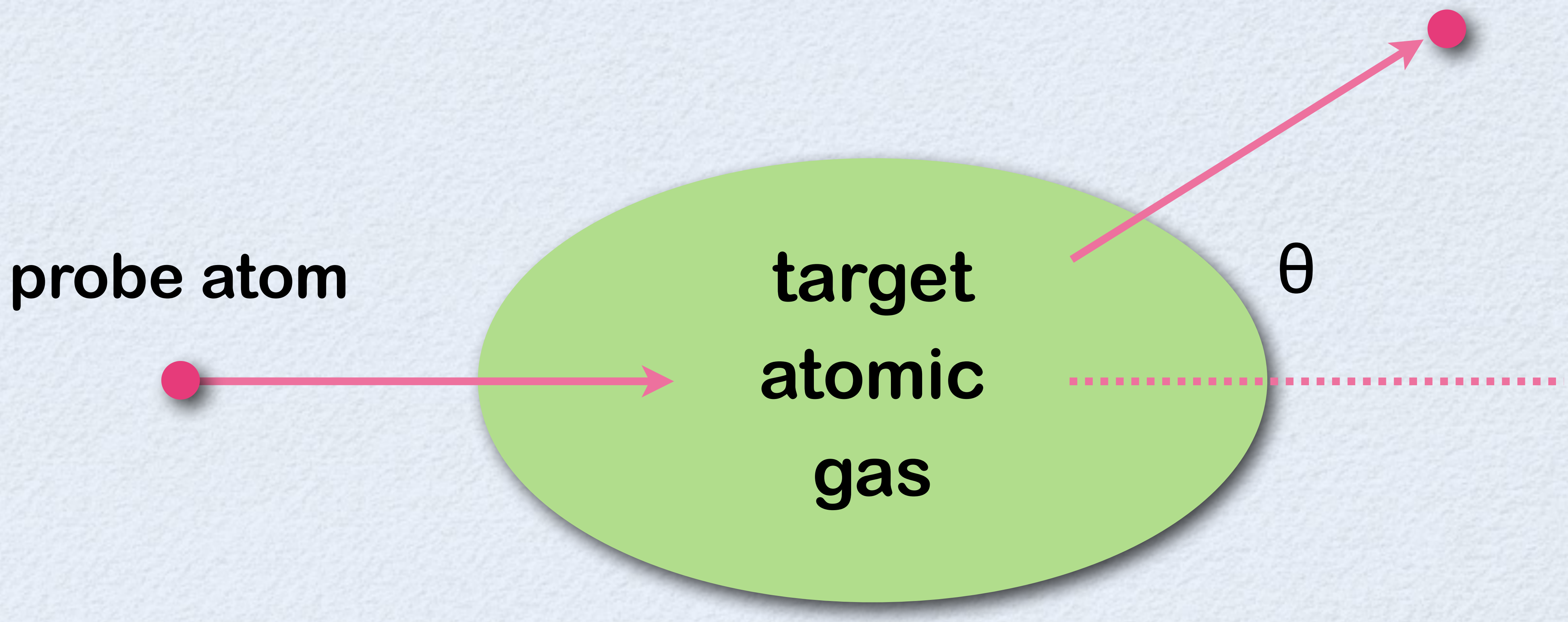
- Jet quenching

???

What is its analogue in cold atoms ?

Probe atomic gas with atoms

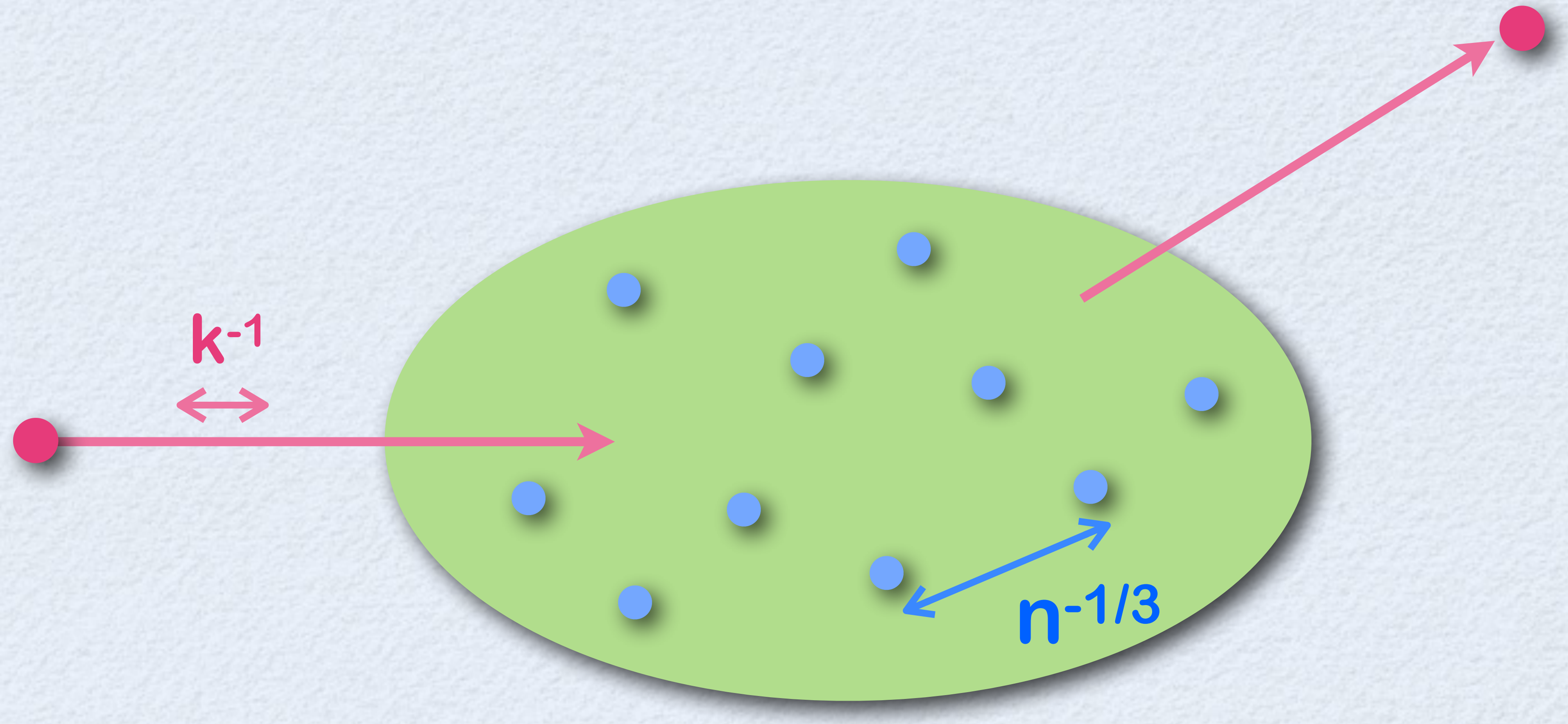
Shoot a probe atom into the target atomic gas and measure its differential scattering rate



What can we learn from the scattering data on the (strongly-interacting) target atomic gas ?

Probe atomic gas with atoms

Shoot a probe atom into the target atomic gas and measure its differential scattering rate

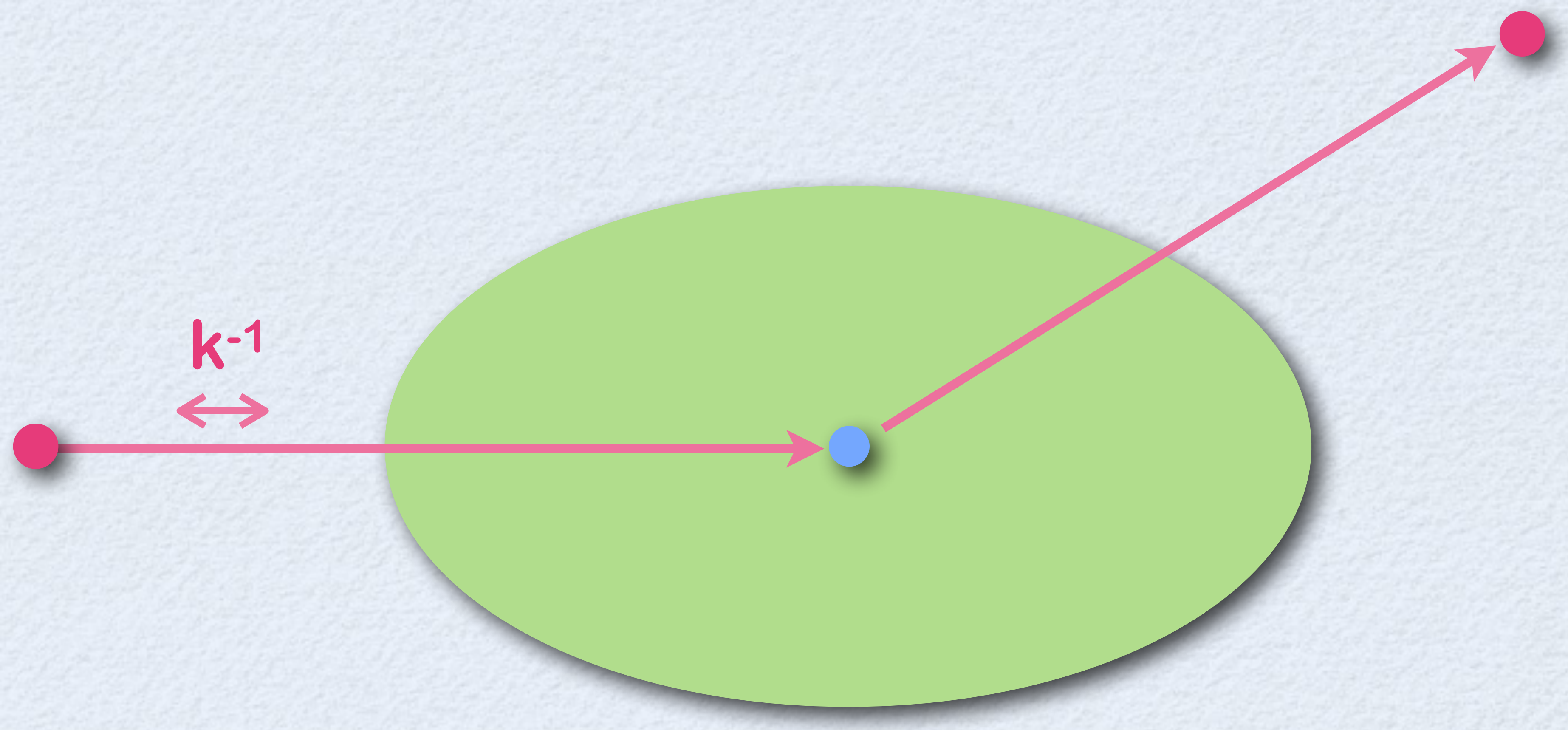


Large k ≫ $n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = \cdots$$

Leading contribution

Shoot a probe atom into the target atomic gas and measure its differential scattering rate

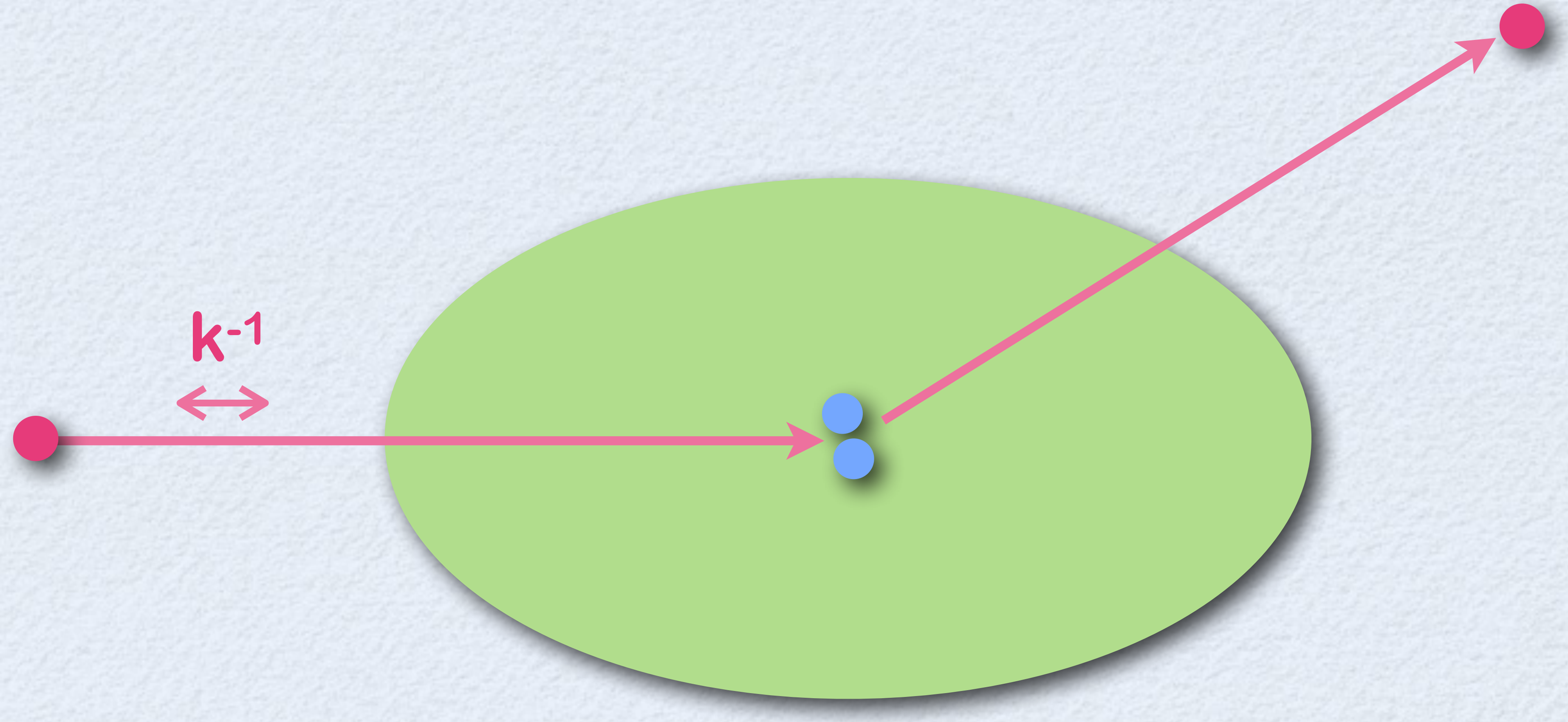


Large k ≫ $n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + \cdots$$

Sub-leading contribution

Shoot a probe atom into the target atomic gas and measure its differential scattering rate



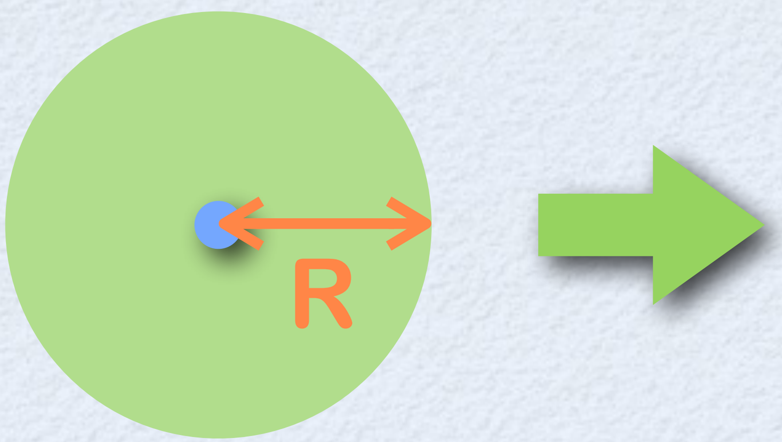
Large k ≫ n$^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta)\,\frac{C}{k^2} + \cdots$$

What is "C" ?

Probability of finding 2 particles at small separation

- noninteracting gas : $\langle \hat{n}(r)\hat{n}(0)\rangle = n^2$
- interacting gas : $\langle \hat{n}(r)\hat{n}(0)\rangle \rightarrow \dfrac{C}{(4\pi|r|)^2}$



$$\int_{|r|<R} \langle \hat{n}(r)\hat{n}(0)\rangle \sim \begin{cases} n^2 R^3 \\ C\,R \end{cases}$$

Anomalously enhanced probability is quantified by the "contact density" C

Important characteristic of strongly-int atomic gases

S. Tan, Ann. Phys. (2009); E. Braaten & L. Platter PRL (2008)

Formulations à la OPE

- scattering rate : $\Gamma(k) = -2\,\mathrm{Im}\,\Sigma(k)$
- optical theorem : $\Gamma(k) = \int d\Omega \, \frac{d\Gamma(k)}{d\Omega}$

$$
\begin{aligned}
\Rightarrow \quad iG(k) &= \int dx\, e^{ikx} \langle T\, \psi(x)\psi^\dagger(0)\rangle \\
&= \sum_i A_i(k) \langle O_i \rangle
\end{aligned}
$$

$$n = \langle \psi^\dagger \psi \rangle, \;\; C = \langle (\psi^\dagger \psi)^2 \rangle, \;\; \ldots$$

Lowest few O_i are needed at large k

⇒ **Systematic large-k expansion !**

Differential scattering rate

Many-body physics

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta)\,\frac{C}{k^2} + \cdots$$

Few-body physics

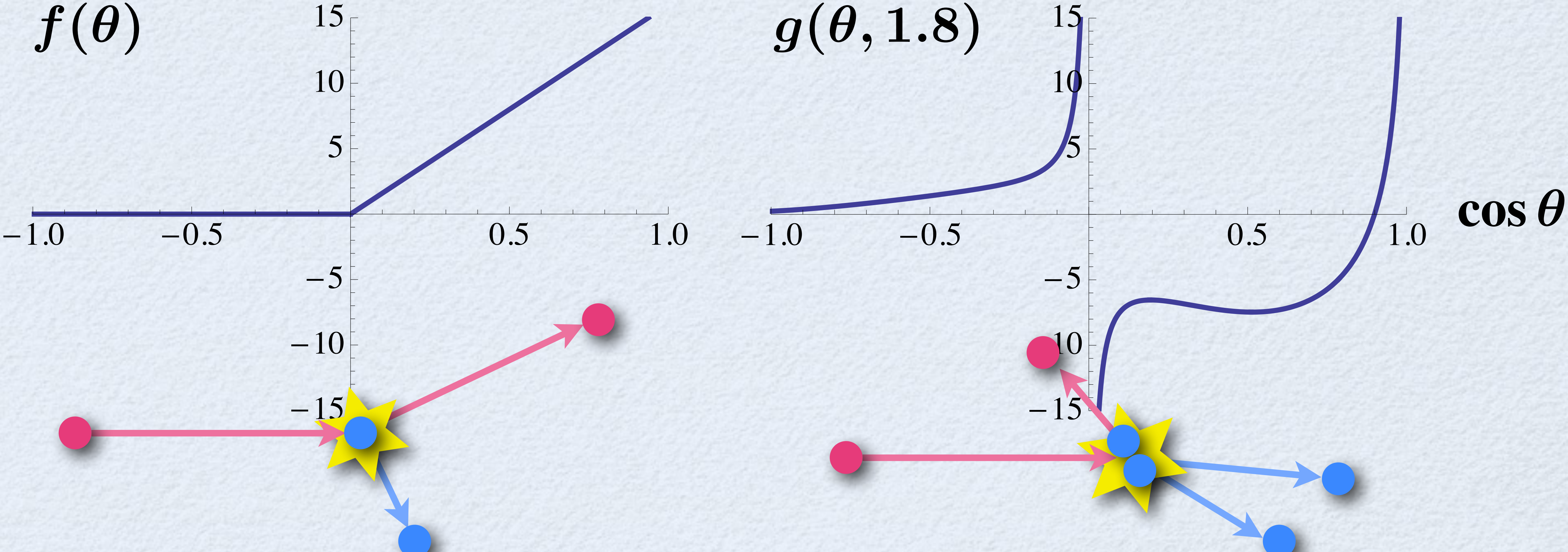
Few-body physics plays an important role to probe many-body physics !

Differential scattering rate

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta, k/\kappa_*)\,\frac{C}{k^2} + \cdots$$

For zero-range interactions

Efimov effect



forward scattering (θ<90°) only

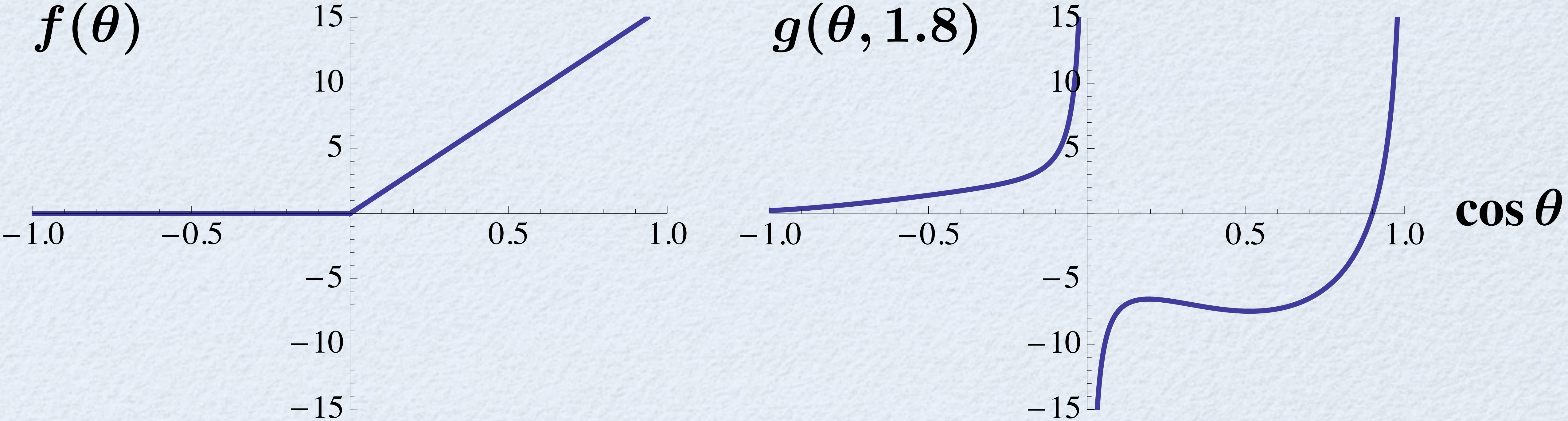
backward scattering (θ>90°) possible

Differential scattering rate

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta, k/\kappa_*)\,\frac{C}{k^2} + \cdots$$

For zero-range interactions

Efimov effect

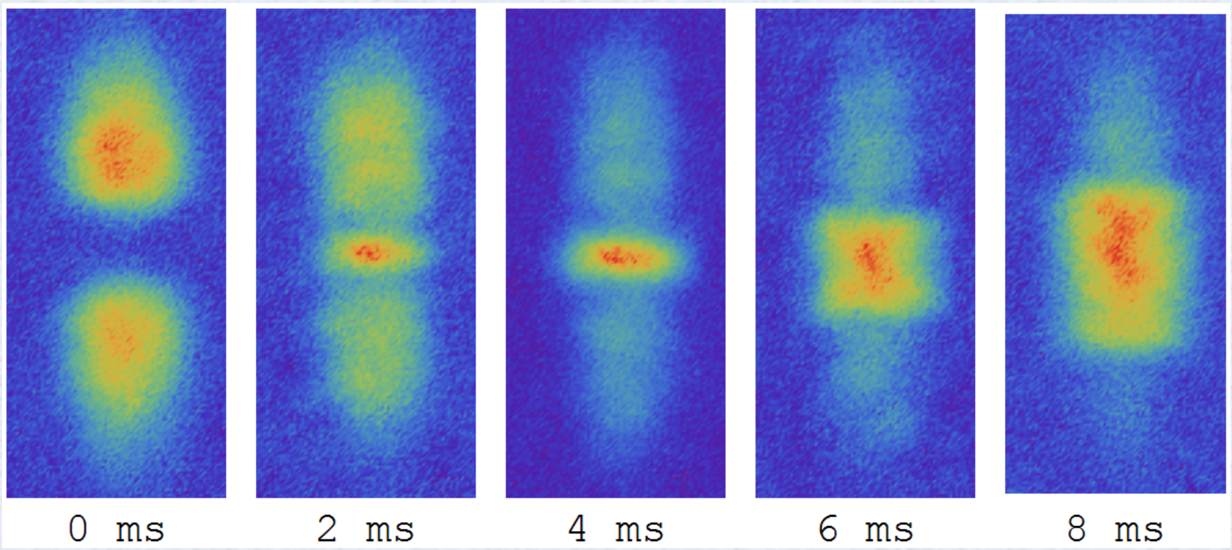


Backward scattering rate measures contact density

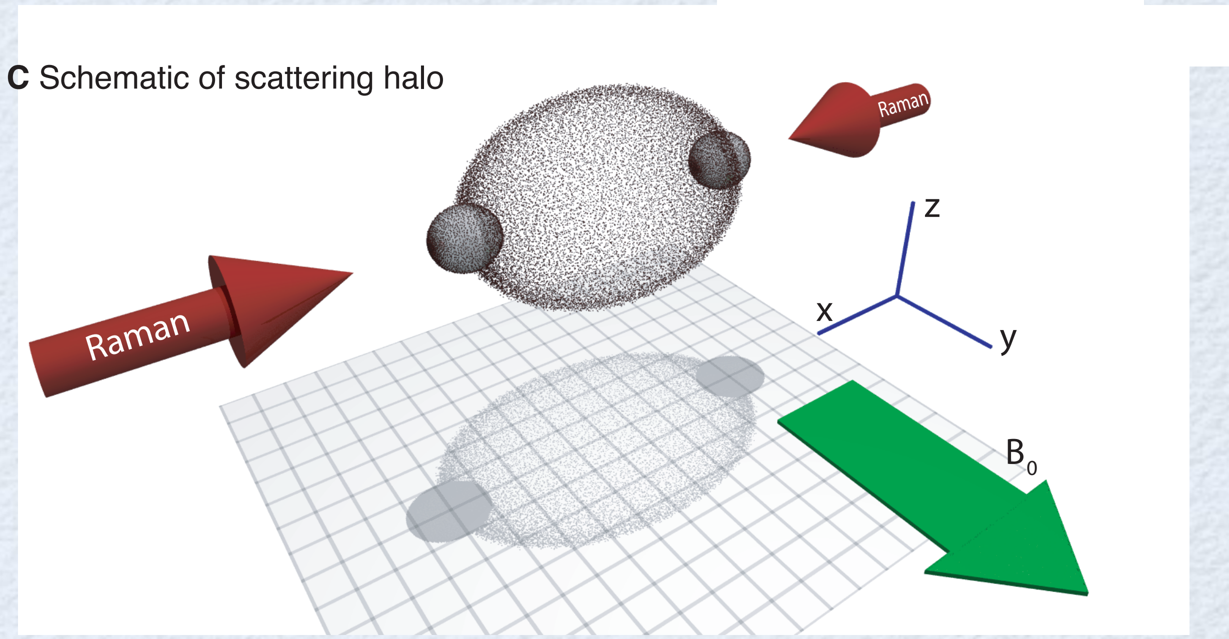
New local probe of strongly-int atomic gases

Ultracold atom “colliders”

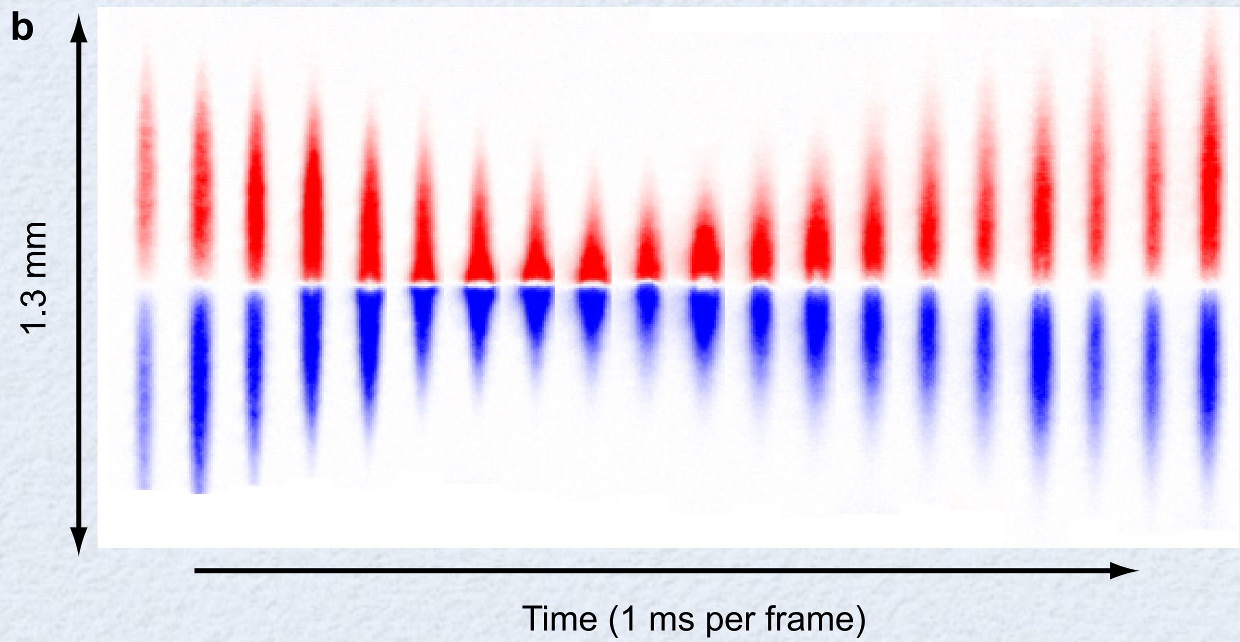
Duke (2011)



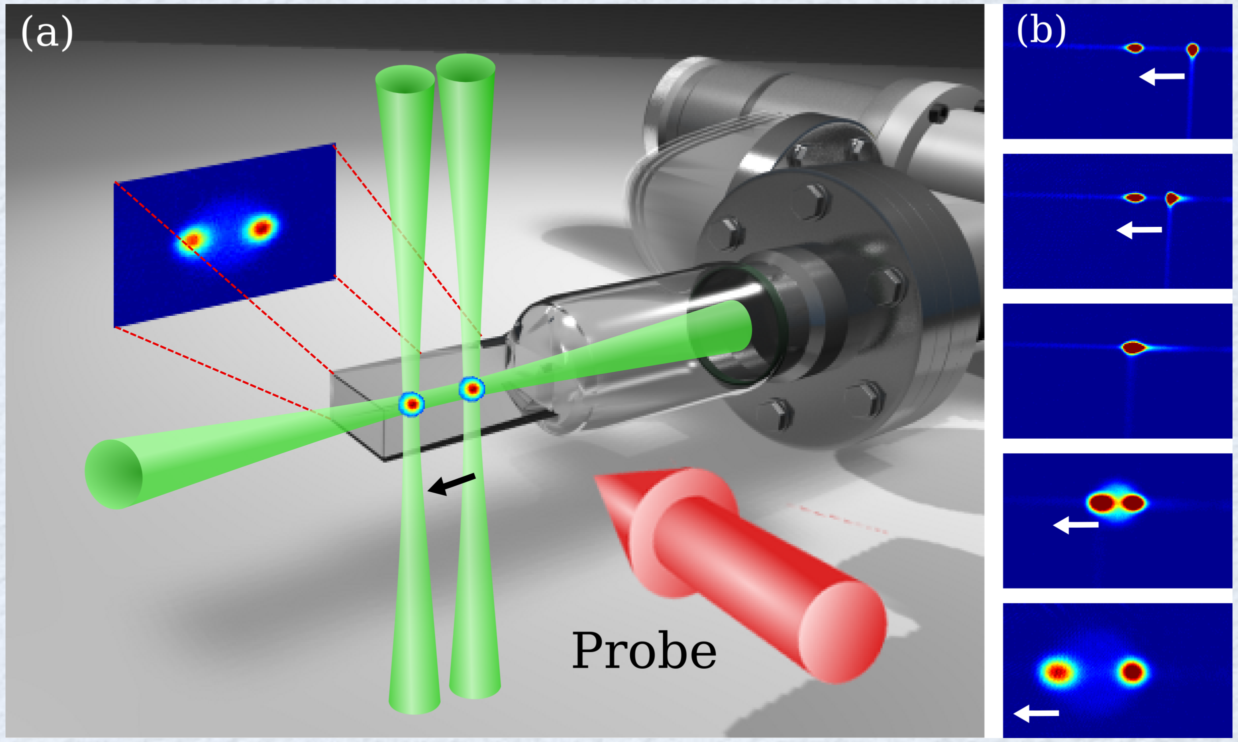
NIST (2012)



MIT (2011)

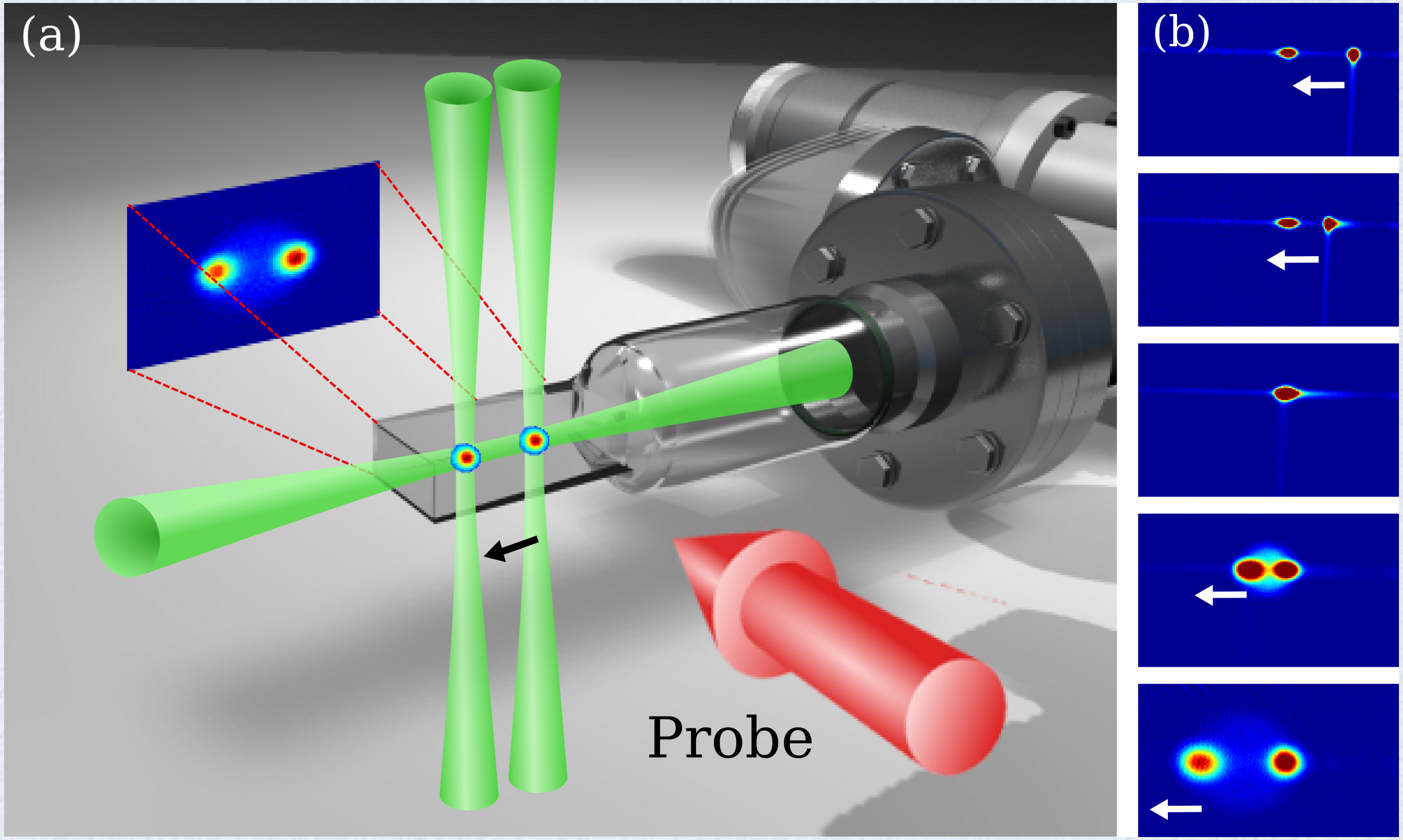


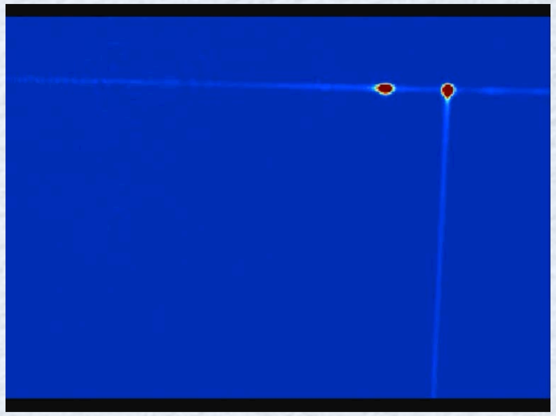
Otago (2012)



Ultracold atom "colliders"

"A laser based accelerator for ultracold atoms"



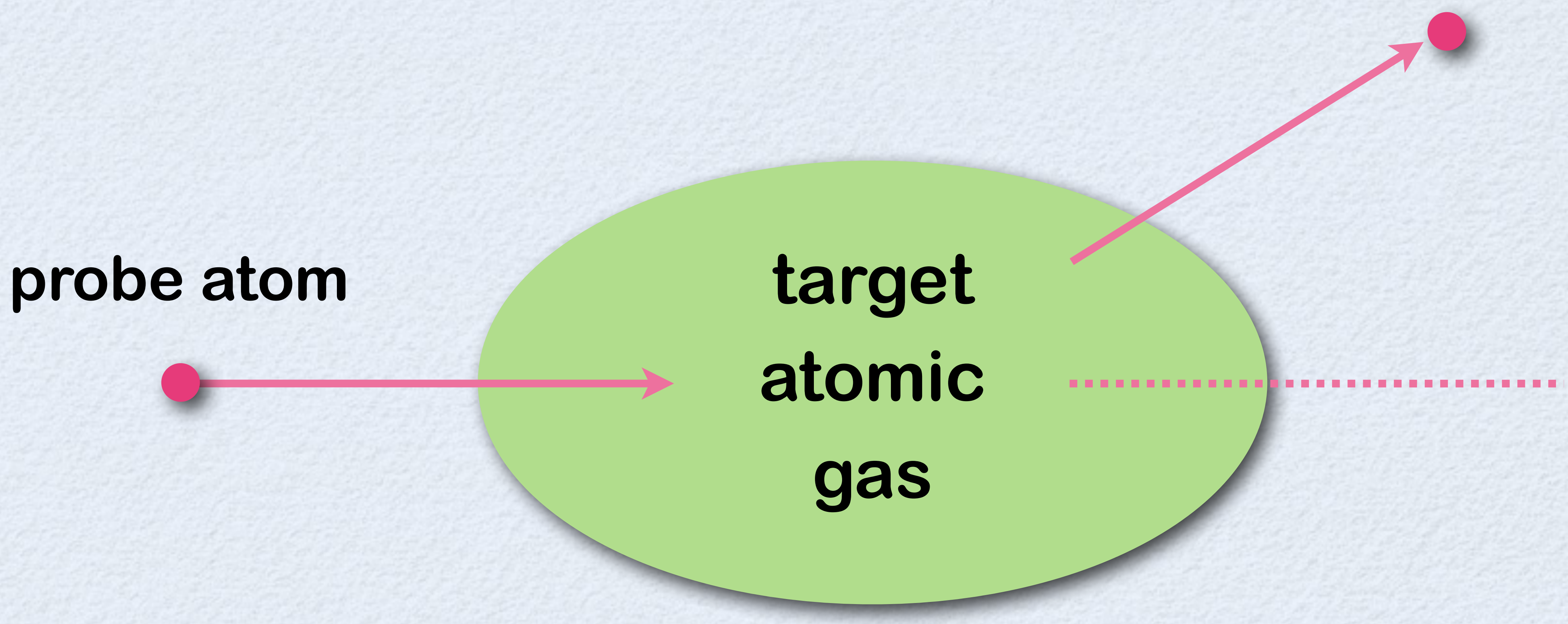


University of Otago
(New Zeeland)

Optics Letters (2012)

Short summary

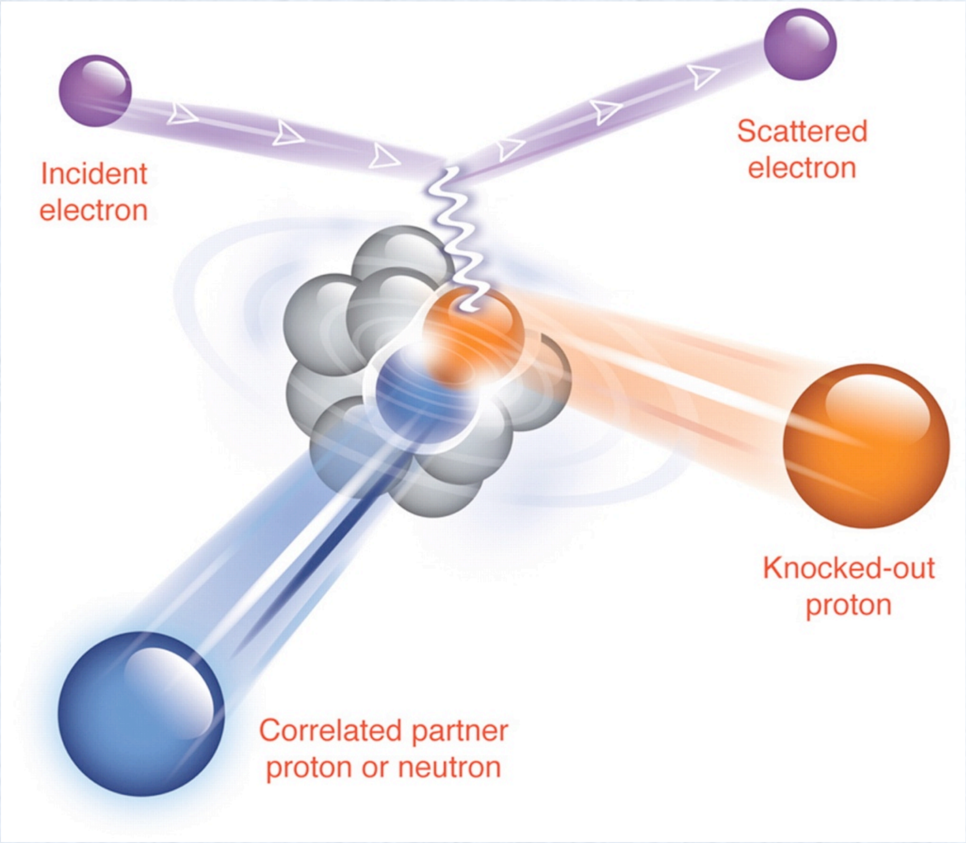
- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
- Systematic large-k expansions are possible
  - ✓ backward scattering ⇒ contact density
  - ✓ azimuthal anisotropy ⇒ current density

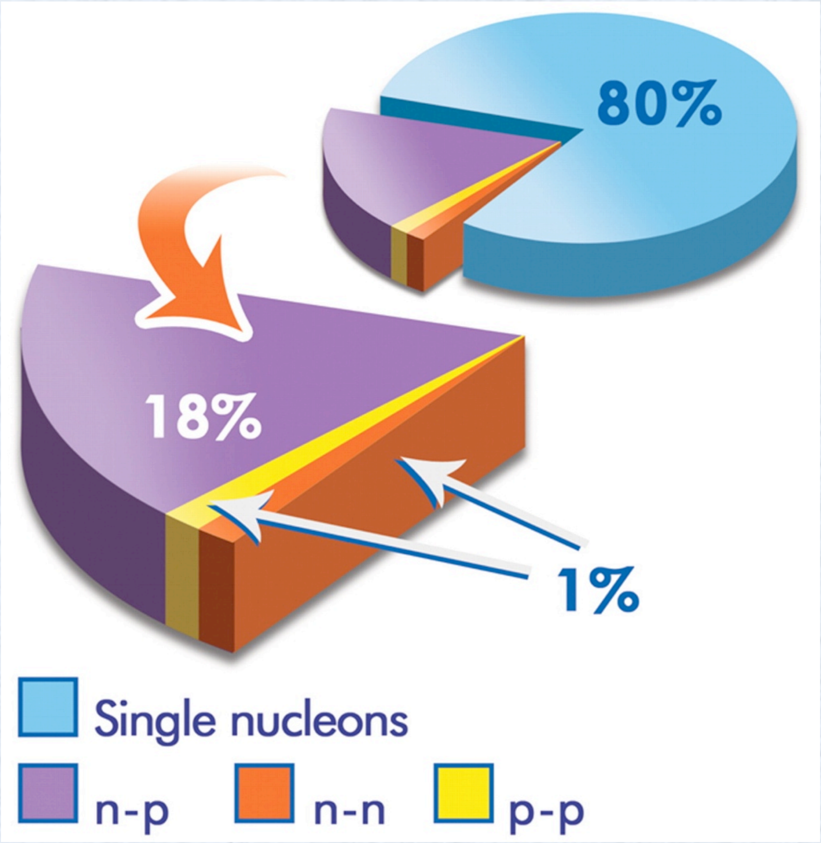


Short summary

- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
- Systematic large-k expansions are possible
  - ✓ backward scattering ⇒ contact density
  - ✓ azimuthal anisotropy ⇒ current density
- Close connection to nuclear/particle physics

JLab, Science 320, 1476 (2008)





Short summary

“Contact” may be useful both in atoms and nuclei

PRL **114,** 012501 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

Nuclear Neutron-Proton Contact and the Photoabsorption Cross Section

Ronen Weiss, Betzalel Bazak, and Nir Barnea*
The Racah Institute of Physics, The Hebrew University, Jerusalem 9190401, Israel
(Received 12 May 2014; revised manuscript received 21 August 2014; published 7 January 2015)

PHYSICAL REVIEW C **92**, 054311 (2015)

Generalized nuclear contacts and momentum distributions

Ronen Weiss, Betzalel Bazak, and Nir Barnea*
The Racah Institute of Physics, The Hebrew University, Jerusalem 9190401, Israel
(Received 7 April 2015; published 17 November 2015)

PHYSICAL REVIEW C **92**, 045205 (2015)

Correlated fermions in nuclei and ultracold atomic gases

O. Hen,[1,*] L. B. Weinstein,[2] E. Piasetzky,[1] G. A. Miller,[3] M. M. Sargsian,[4] and Y. Sagi[5]
[1]*Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Old Dominion University, Norfolk, Virginia 23529, USA*

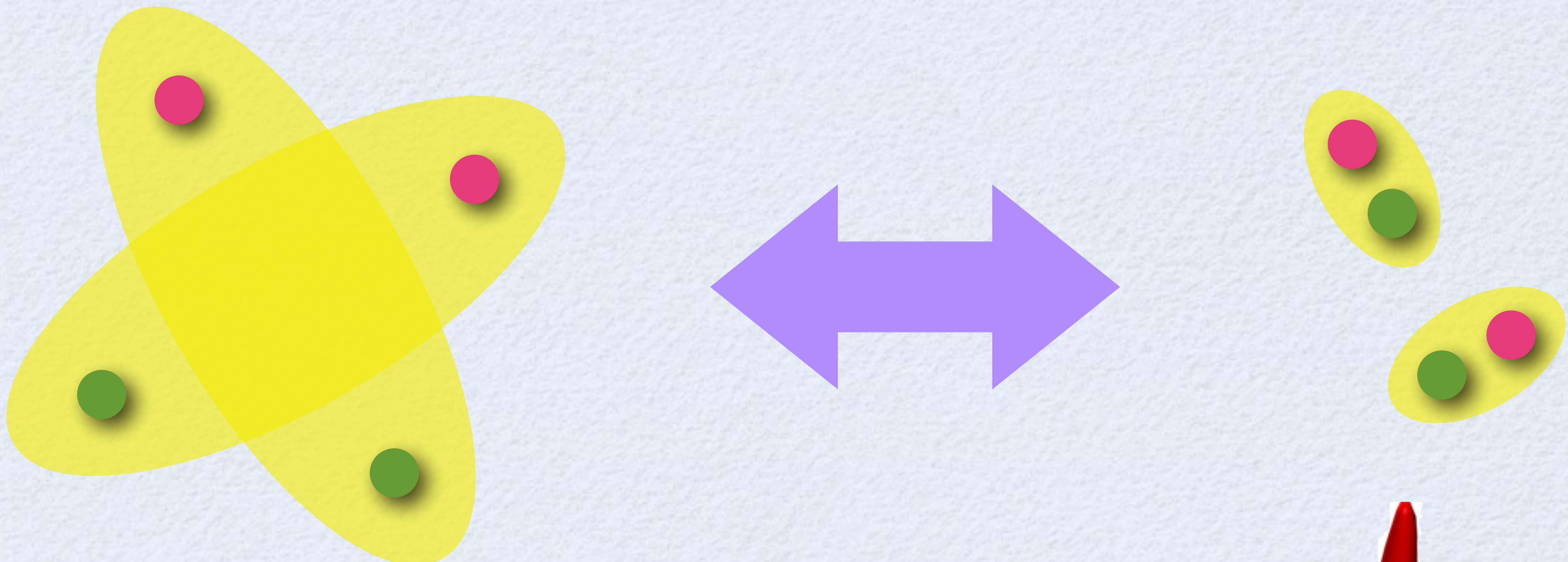
"Quark-hadron continuity" in cold atoms

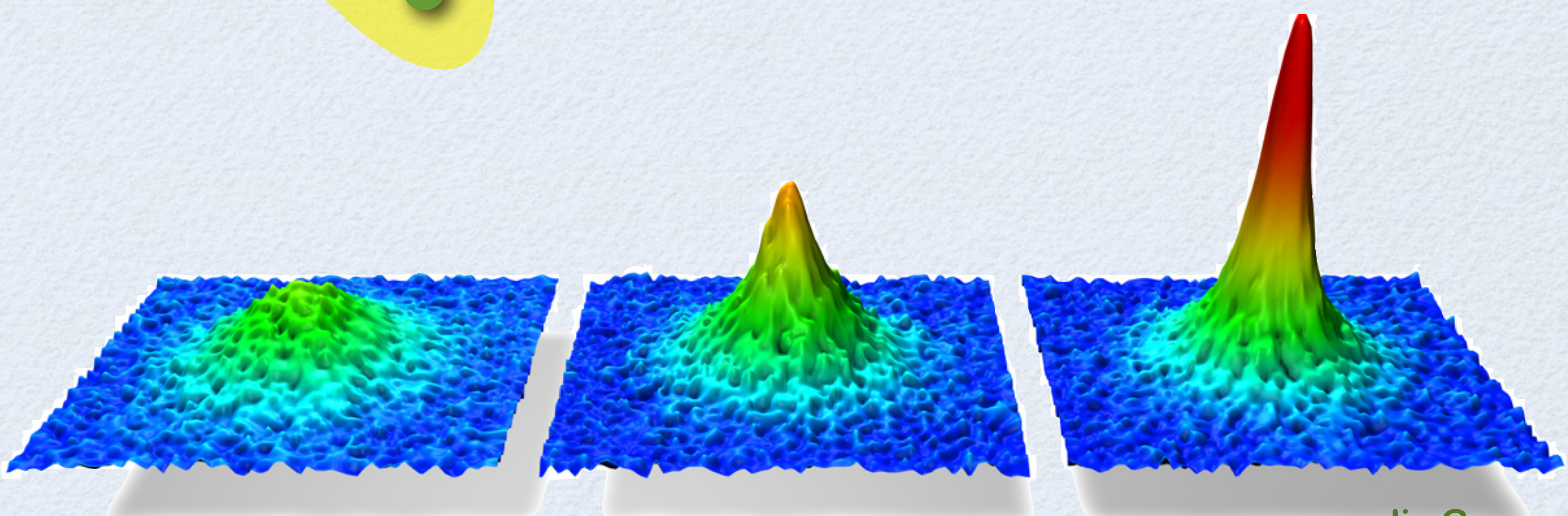
BCS-BEC crossover

- 2-component Fermi gas

loosely bound Cooper pairs

tightly bound dimers





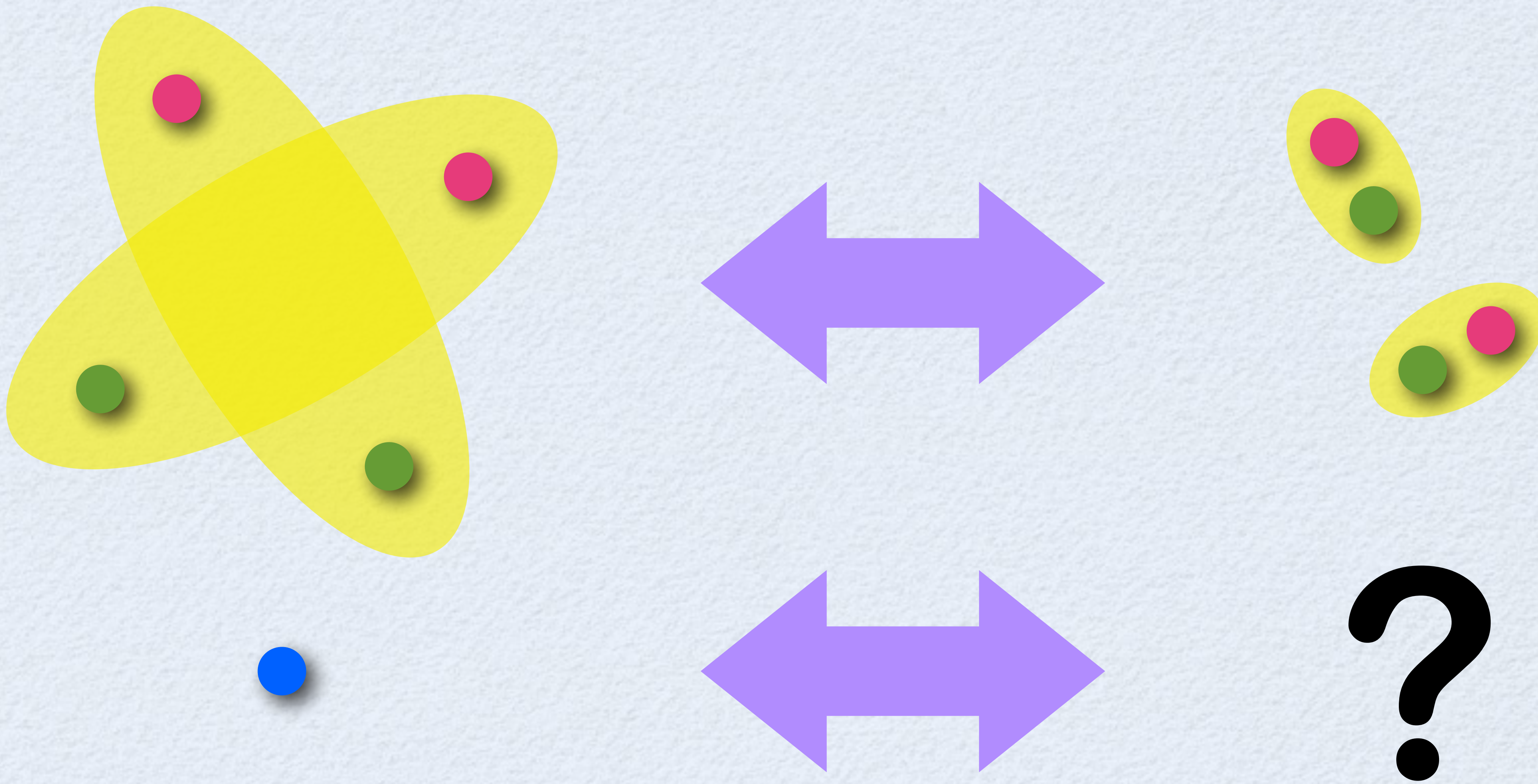
Jin Group at JILA

BCS-BEC crossover

- 3-component Fermi gas

loosely bound Cooper pairs

tightly bound dimers



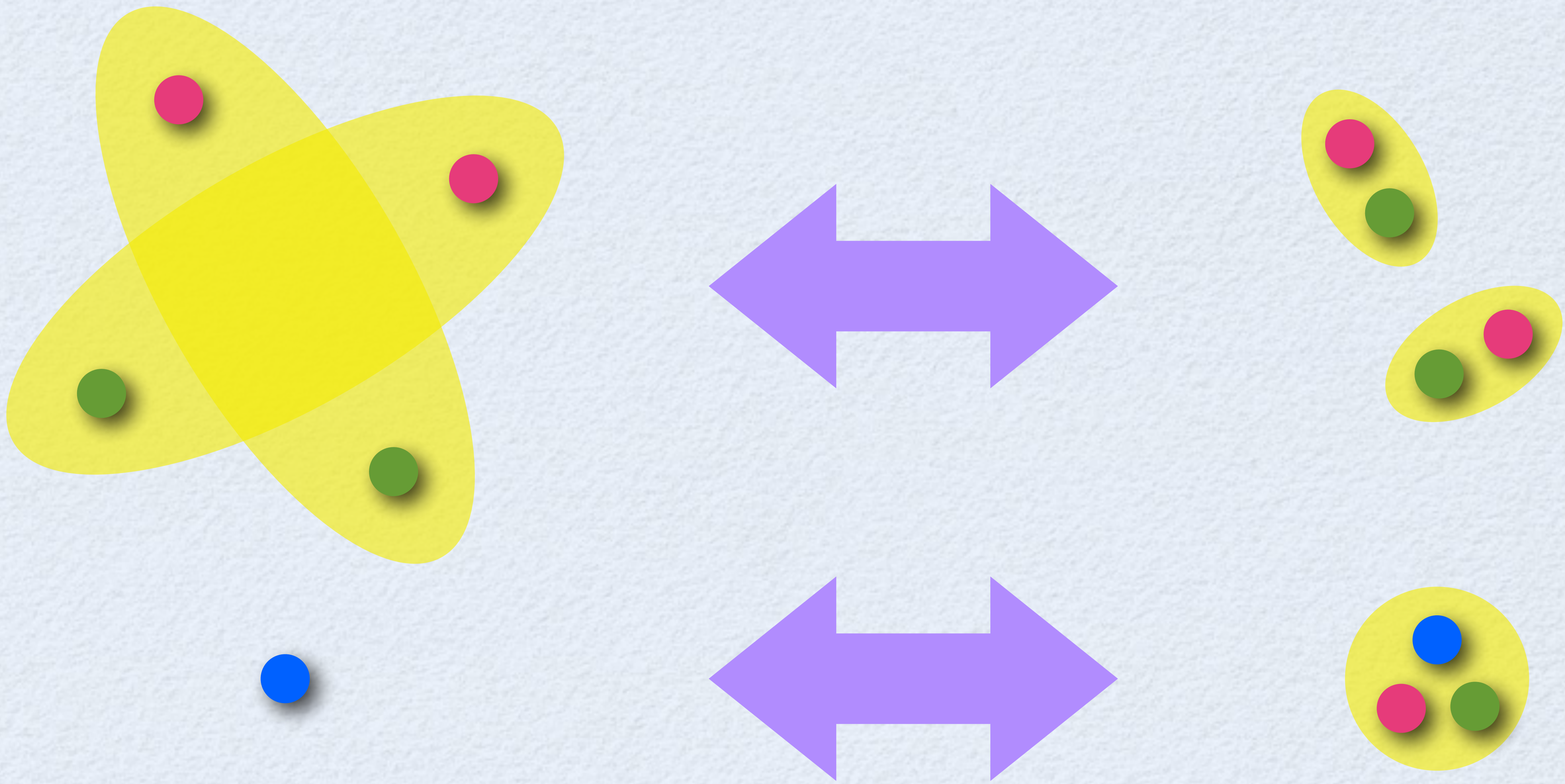
unpaired atoms

BCS-BEC crossover

- 3-component Fermi gas

loosely bound Cooper pairs

tightly bound dimers



unpaired atoms

unpaired timers

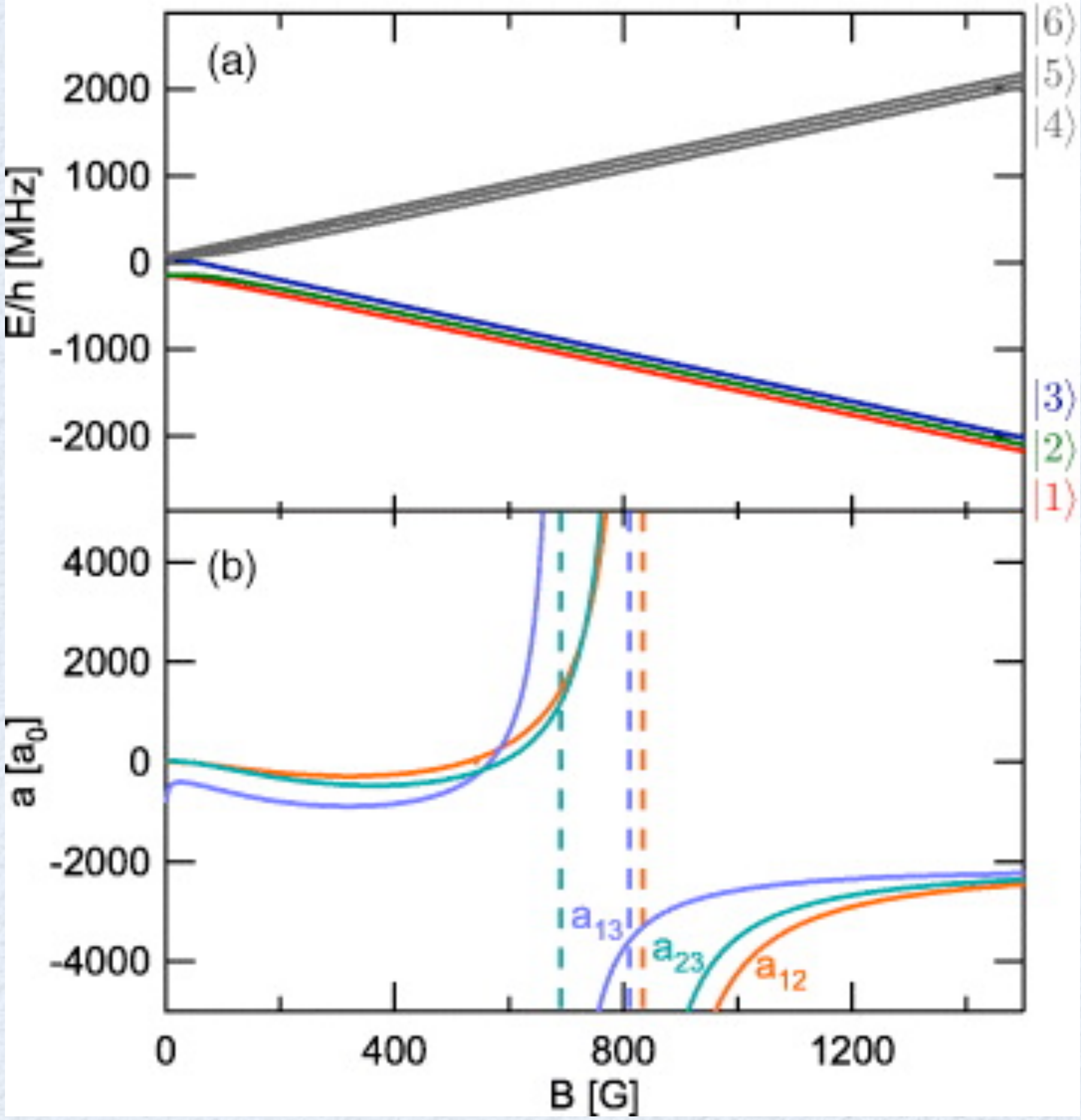
“Atom-trimer continuity” = New crossover physics !

3-component Fermi gas

- 3 spin states (i=1,2,3) of ^{6}Li atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31}$



K. M. O'Hara, New J. Phys. (2011)

3-component Fermi gas

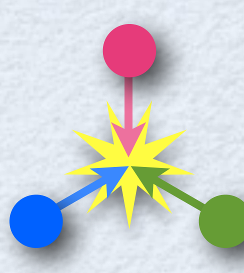
- 3 spin states (i=1,2,3) of ^{6}Li atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31}$ ⇒ SU(3) × U(1) invariance

$$\mathcal{L} = \psi_i^\dagger \left(i\partial_t + \frac{\nabla^2}{2m} \right) \psi_i + \frac{g}{2} \psi_i^\dagger \psi_j^\dagger \psi_j \psi_i$$

- Problem ! 3 fermions form an infinitely deep bound state (Thomas collapse)



⇒ No many-body ground state :-(

3-component Fermi gas

- 3 spin states (i=1,2,3) of ^{6}Li atoms near a "narrow" Feshbach resonance:

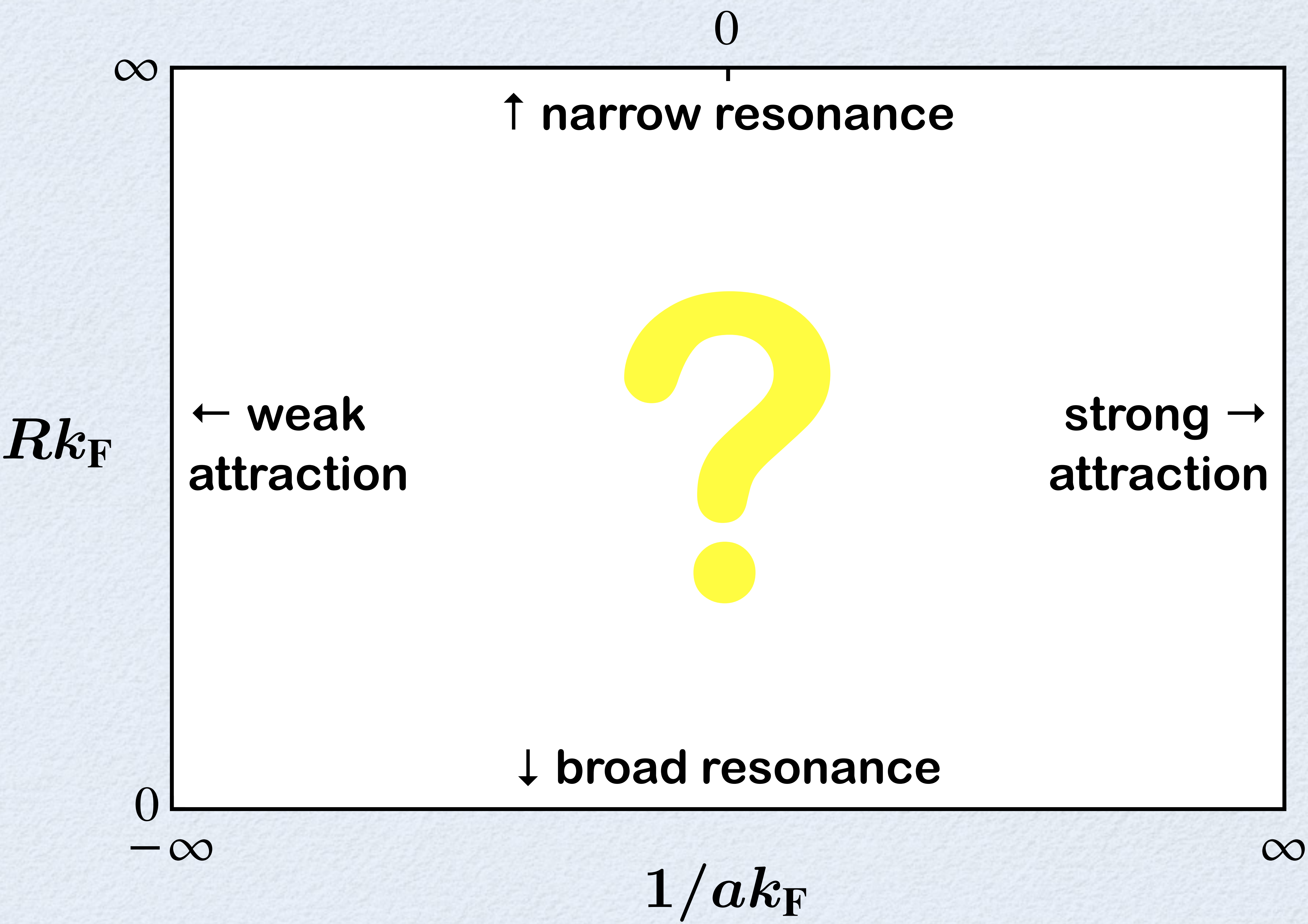
$$f(k) = \frac{-1}{ik + \frac{1}{a}} \quad \Rightarrow \quad f(k) = \frac{-1}{ik + \frac{1}{a} + Rk^2}$$

$r_{\mathrm{eff}} = -2R$ is the effective range

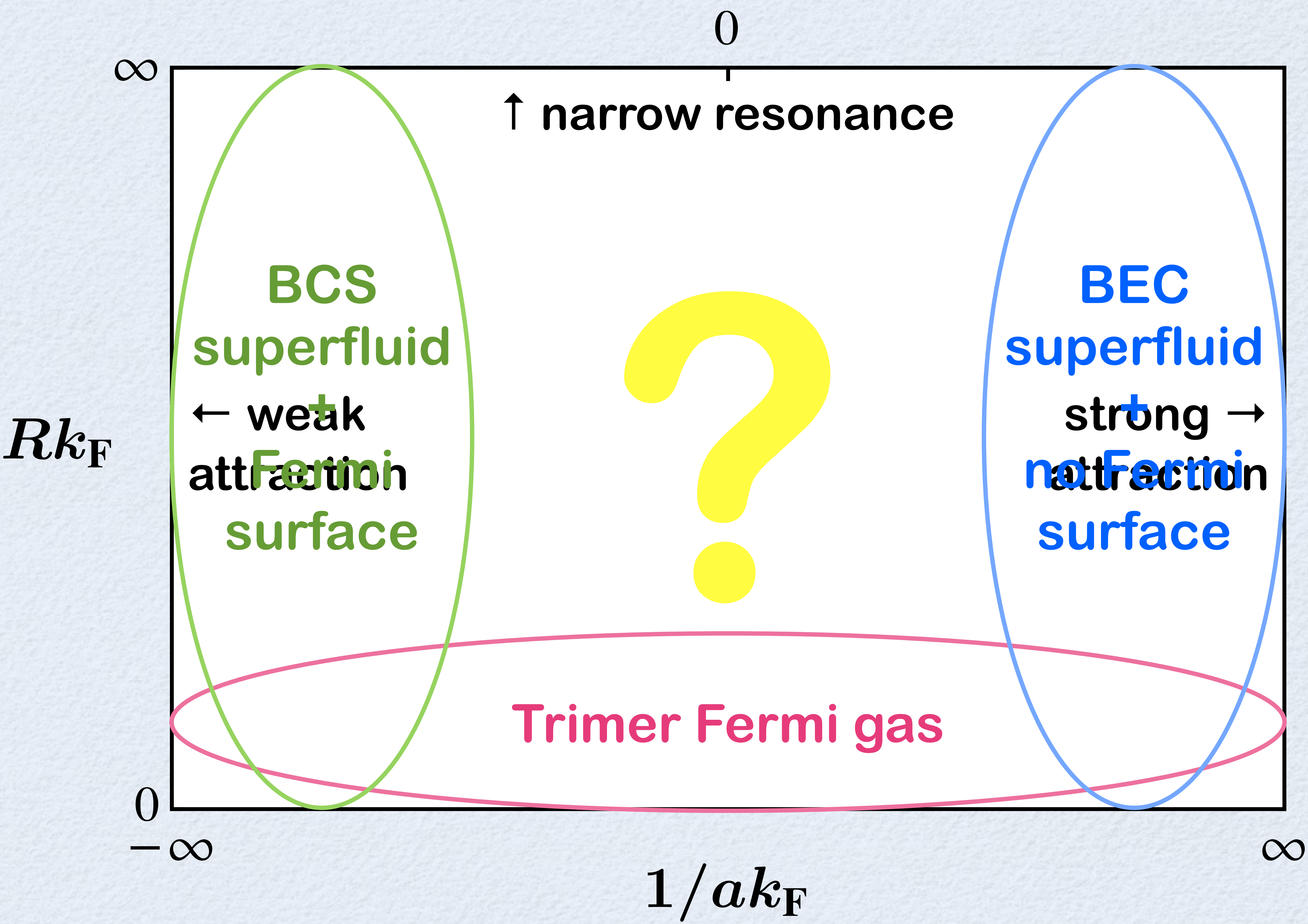
- R regularizes short-distance behaviors (⇒ no Thomas collapse)

⇒ Universal many-body ground state (depends only on a, R, k_F)

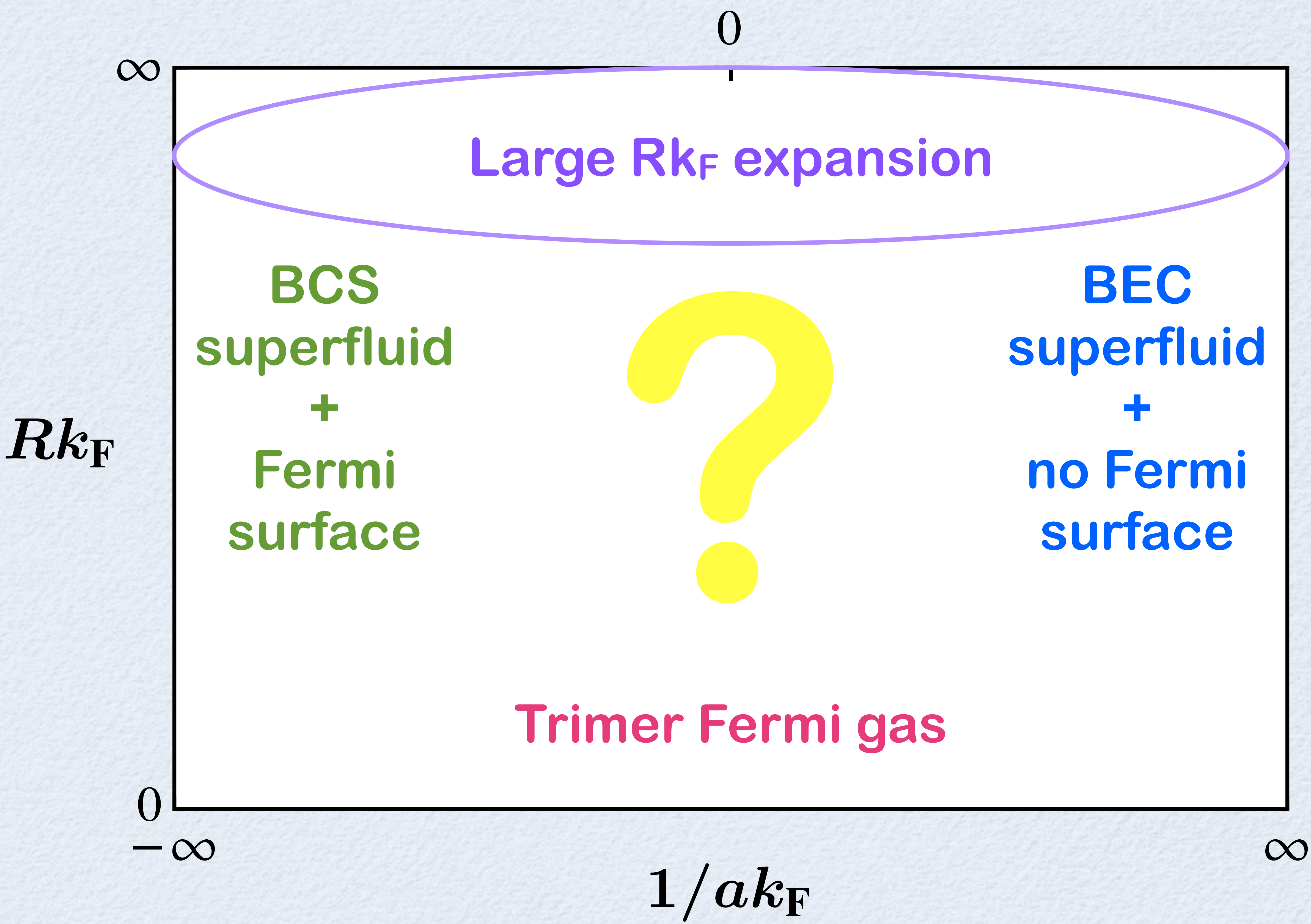
Phase diagram



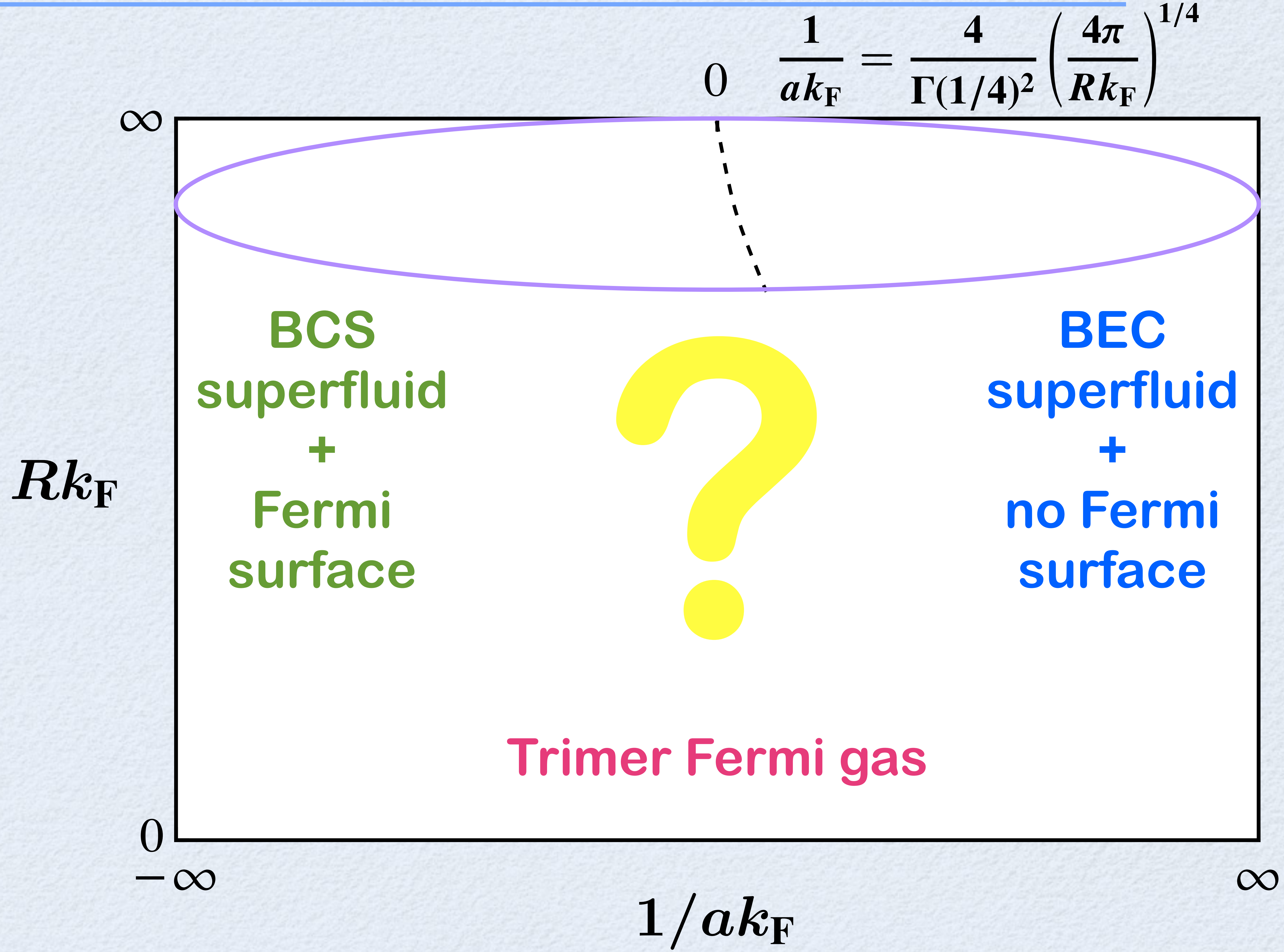
Phase diagram



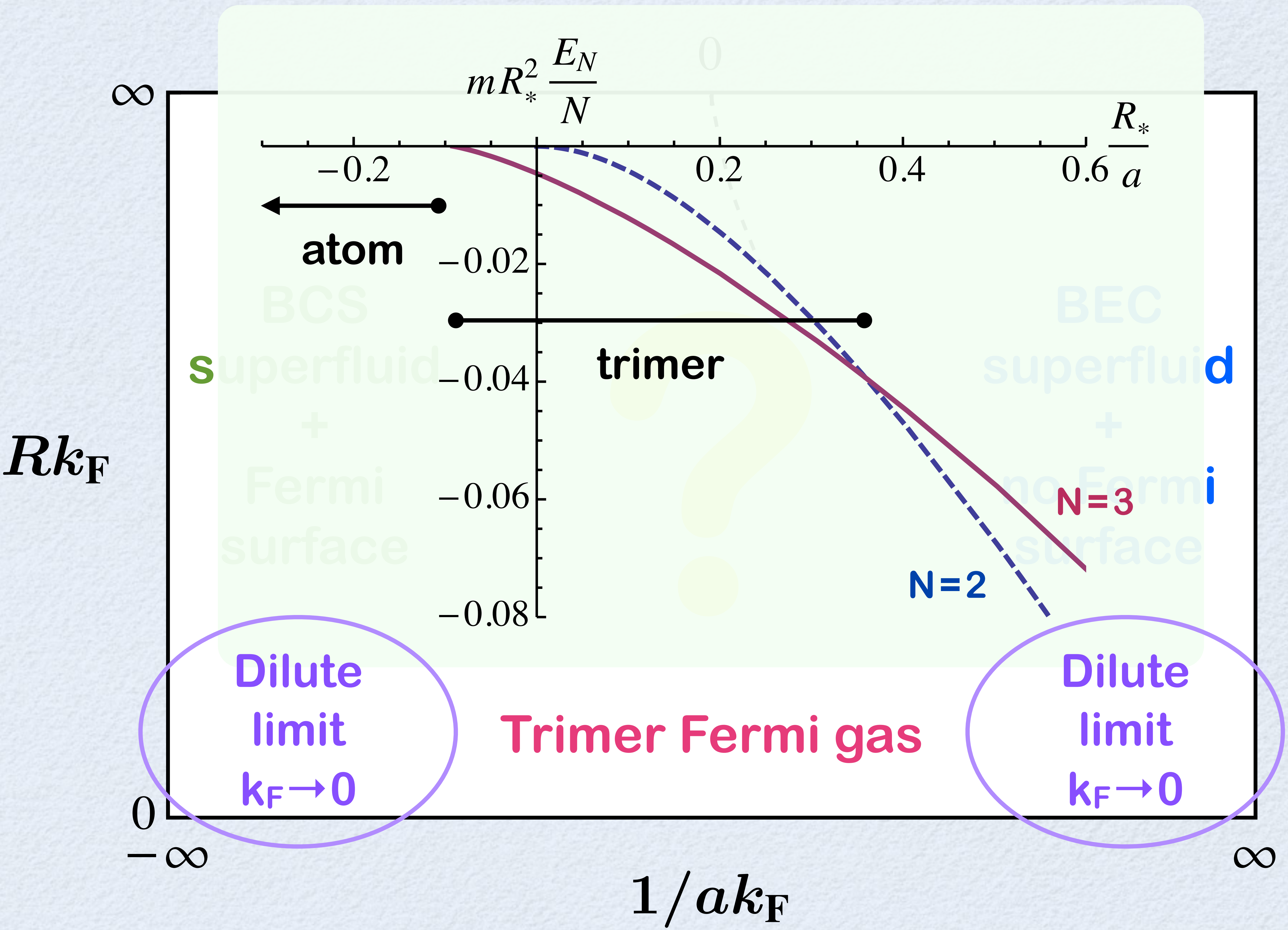
Phase diagram



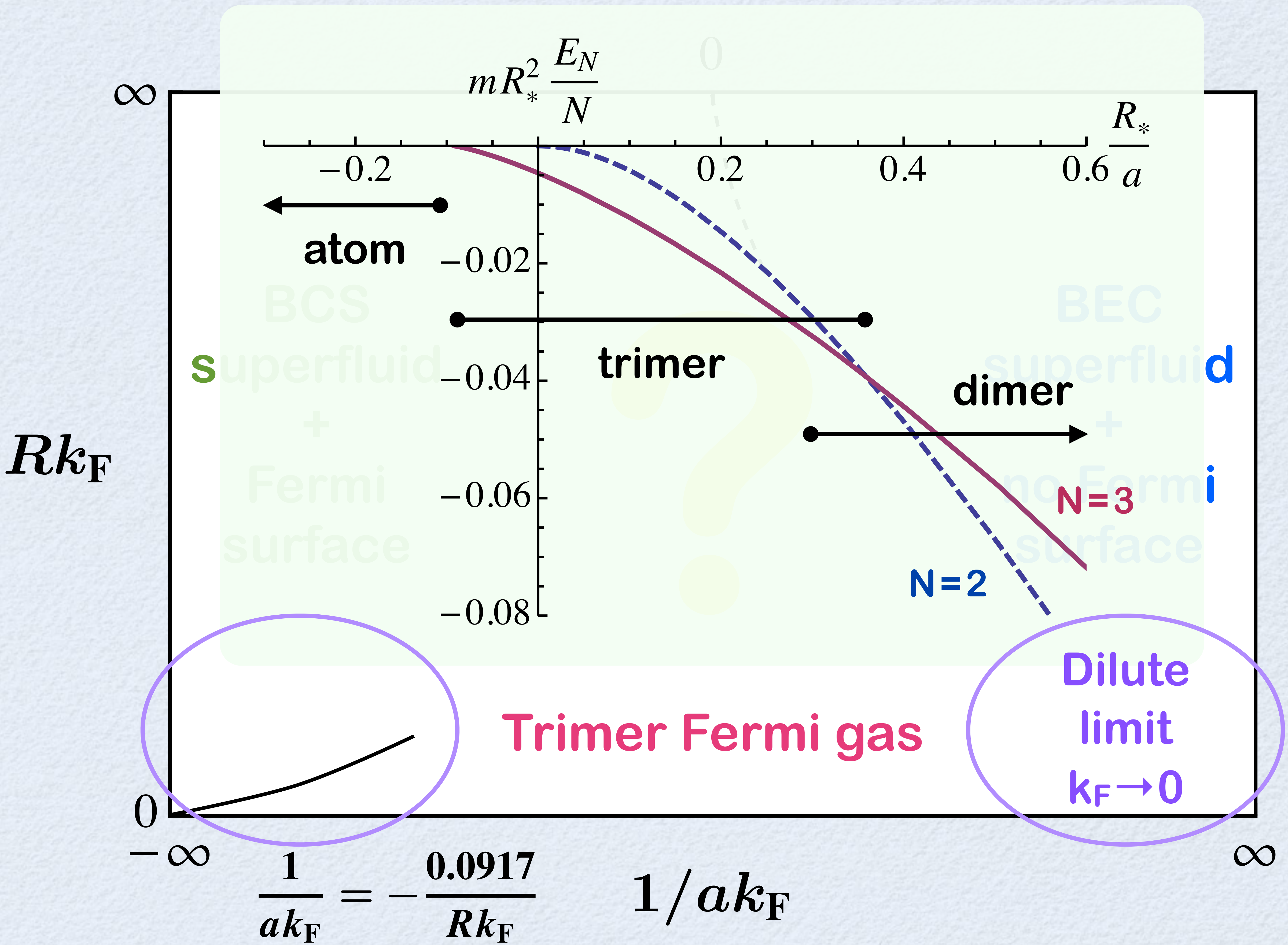
Phase diagram



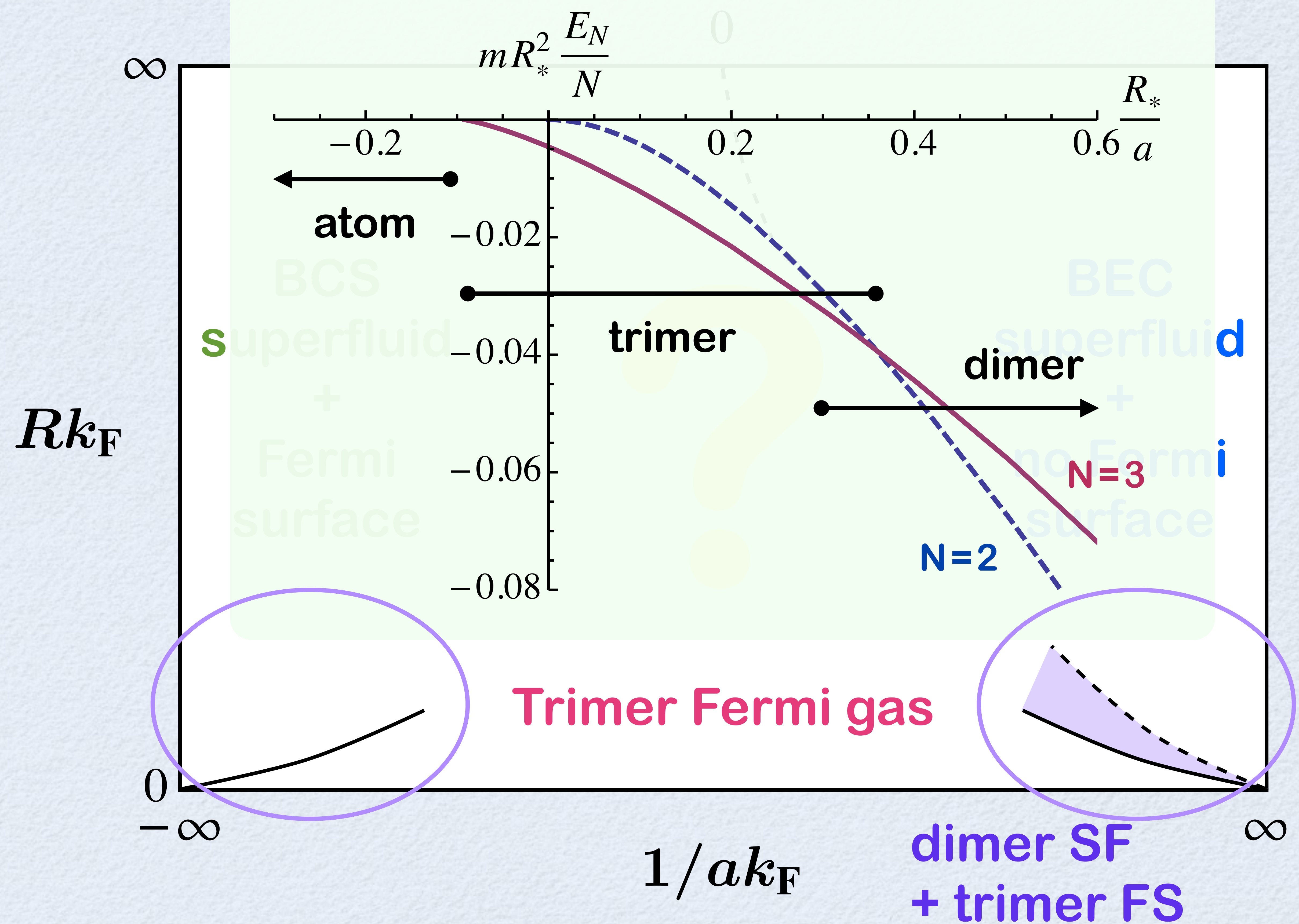
Phase diagram



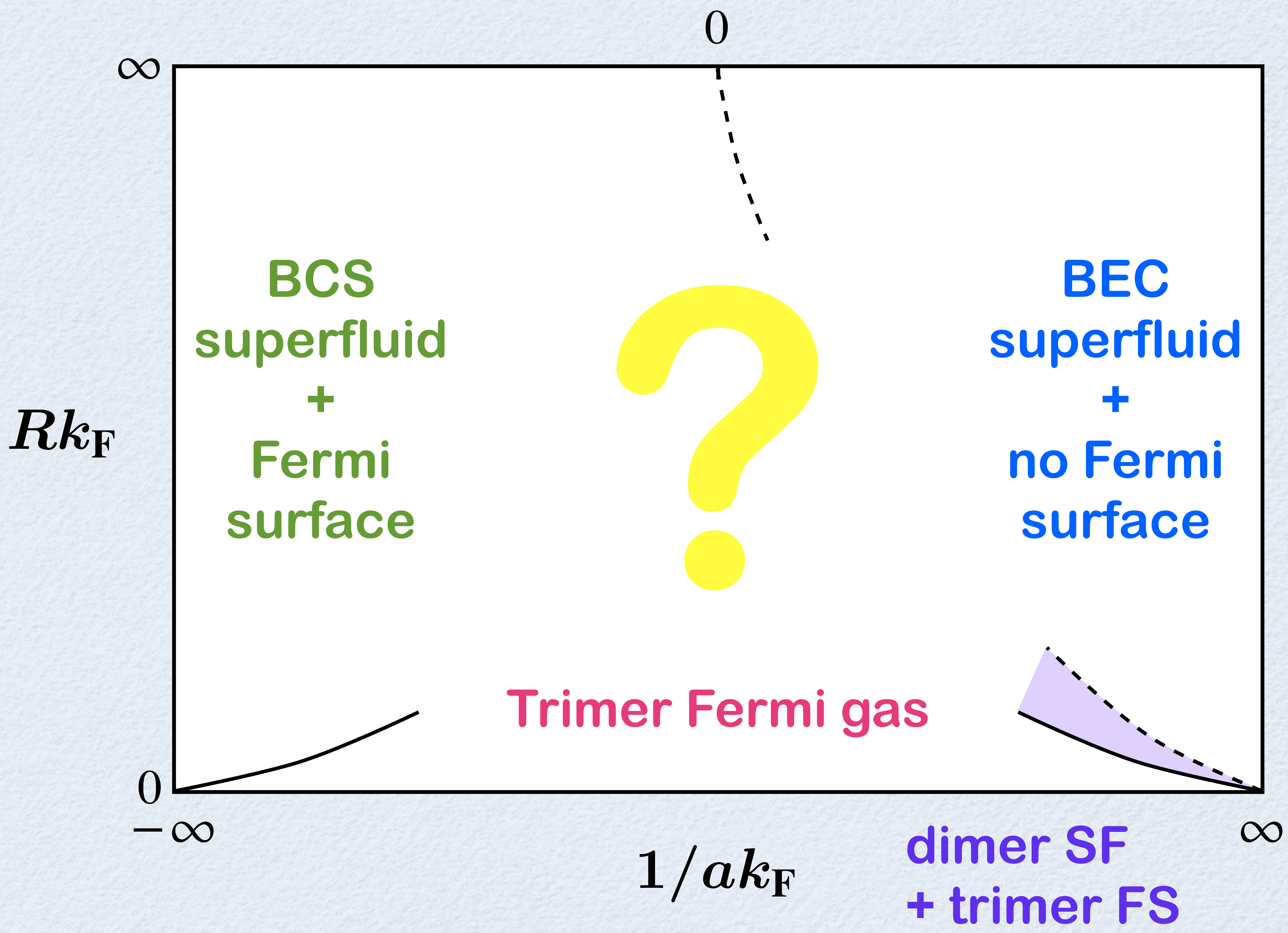
Phase diagram



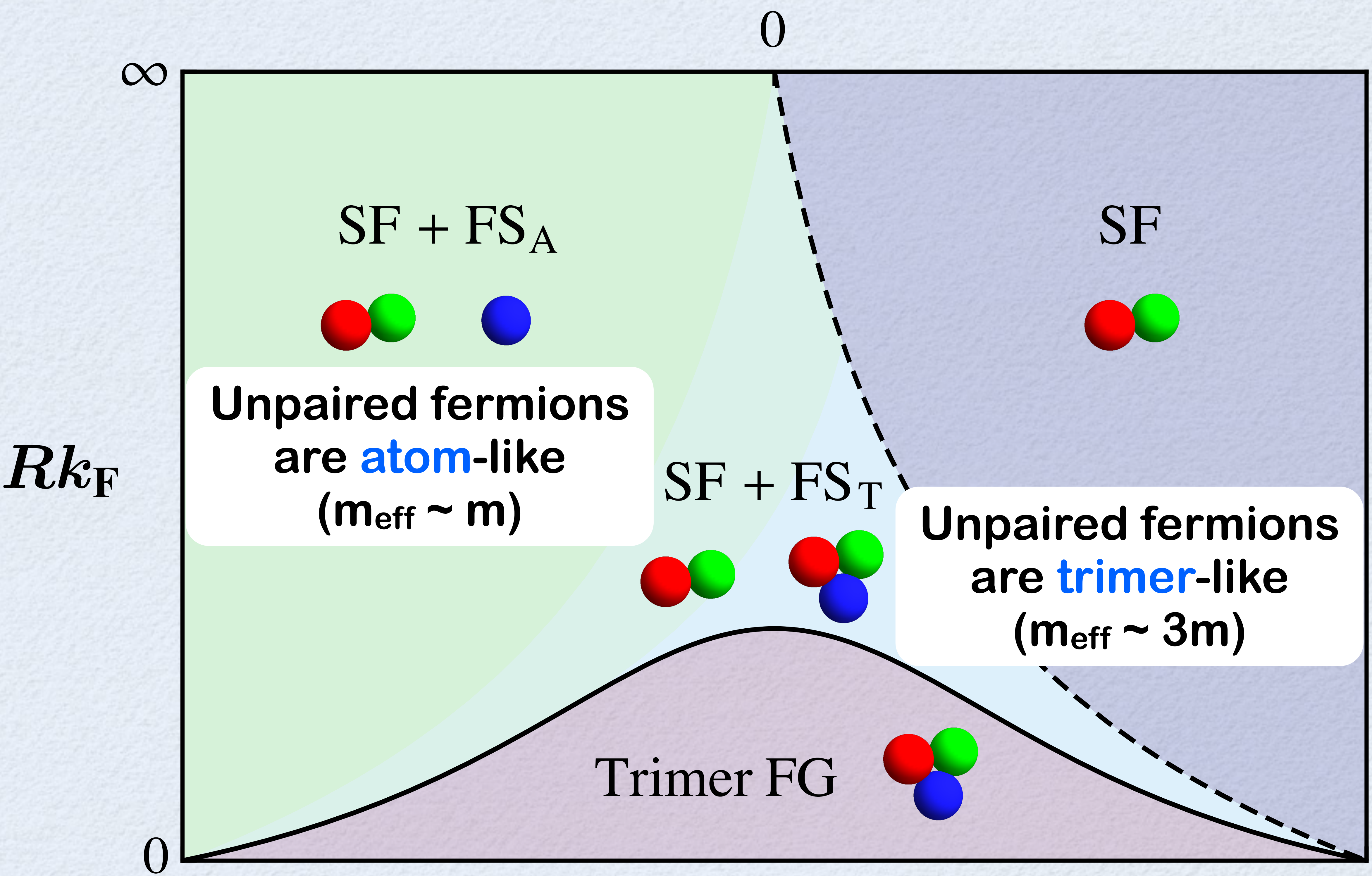
Phase diagram



Phase diagram



Phase diagram



"Atom-trimer continuity" = New crossover physics !

Quark-hadron continuity

VOLUME 82, NUMBER 20 PHYSICAL REVIEW LETTERS 17 MAY 1999

Continuity of Quark and Hadron Matter

Thomas Schäfer and Frank Wilczek
School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540
(Received 30 November 1998)

We review, clarify, and extend the notion of color-flavor locking. We present evidence that for three degenerate flavors the qualitative features of the color-flavor locked state, reliably predicted for high density, match the expected features of hadronic matter at low density. This provides, in particular, a controlled, weak-coupling realization of confinement and chiral symmetry breaking in this (slight) idealization of QCD. [S0031-9007(99)09191-7]

PACS numbers: 12.38.Aw

In a recent study [1] of QCD with three degenerate flavors at high density, a new form of ordering was predicted, wherein the color and flavor degrees of freedom become rigidly correlated in the ground state: color-flavor locking. This prediction is based on a weak-coupling analysis using a four-fermion interaction with quantum numbers abstracted from one gluon exchange. One expects that such a weak-coupling analysis is appropriate at high density, for the following reason [2,3]. Tentatively assuming that the quarks start out in a state close to their free quark state, i.e., with large Fermi surfaces, one finds that the relevant interactions, which are scattering the states near the Fermi surface, for the most part involve large momentum trans-

New link between atomic and nuclear systems !

tivity [4], even weak couplings near the Fermi surface can

vor quantum numbers, including integral electric charge. Thus, the gluons match the octet of vector mesons, the quark octet matches the baryon octet, and an octet of collective modes associated with chiral symmetry breaking matches the pseudoscalar octet. However, there are also a few apparent discrepancies: there is an extra massless singlet scalar, associated with the spontaneous breaking of baryon number (superfluidity); there are eight rather than nine vector mesons (no singlet); and there are nine rather than eight baryons (extra singlet). We will argue that these "discrepancies" are superficial — or rather that they are features, not bugs.

Let us first briefly recall the fundamental concepts of

form [1]

Summary of this talk

- **"Hard probes" in cold atoms**

  Use of energetic atoms to locally probe strongly-interacting atomic gases

  Y.N., Phys. Rev. A (2012) [arXiv:1110.5926]

- **"Quark-hadron continuity" in cold atoms**

  Smooth crossover from atoms to trimers in 3-component Fermi gases

  Y.N., Phys. Rev. Lett. (2012) [arXiv:1207.6971]

Summary of this talk

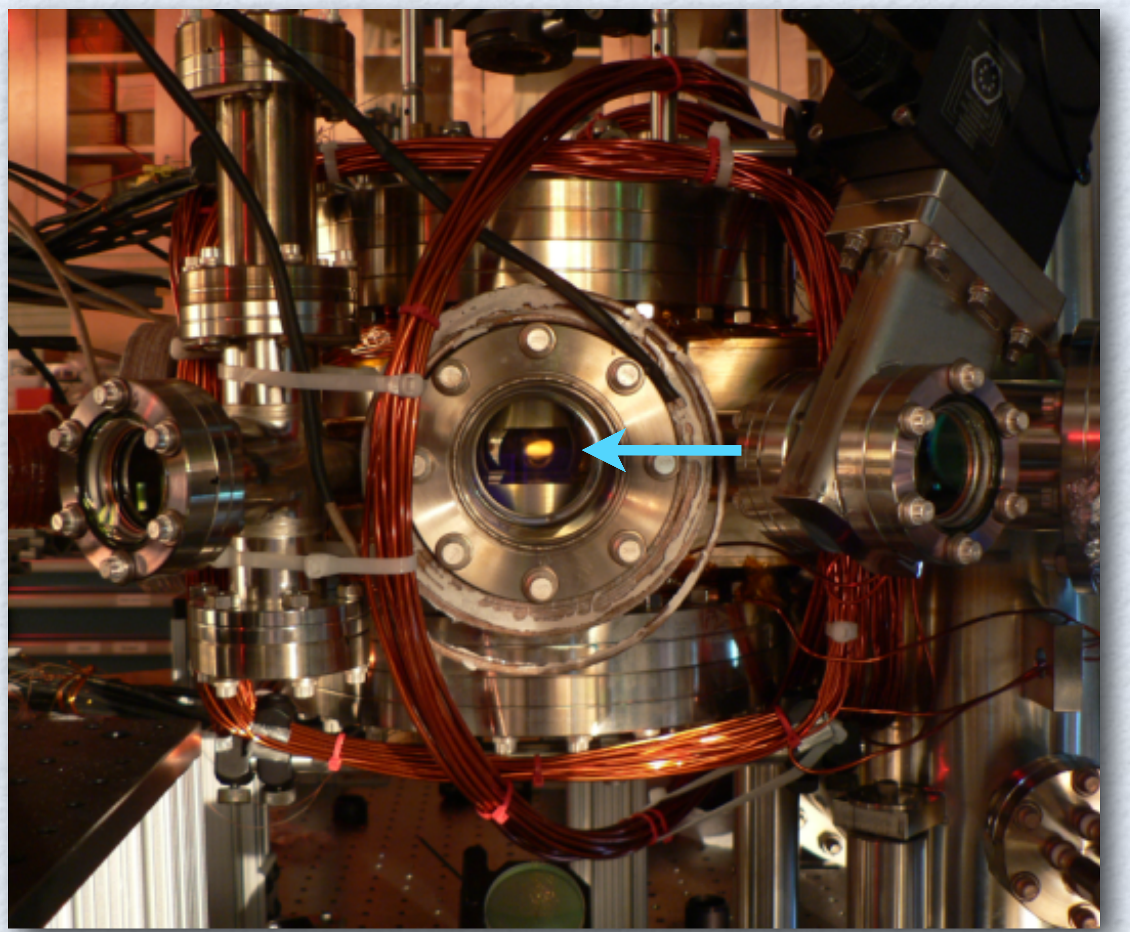
1. Universality in few-body physics
    - Efimov effect
    - Beyond cold atoms
    - Universality class of quantum halos

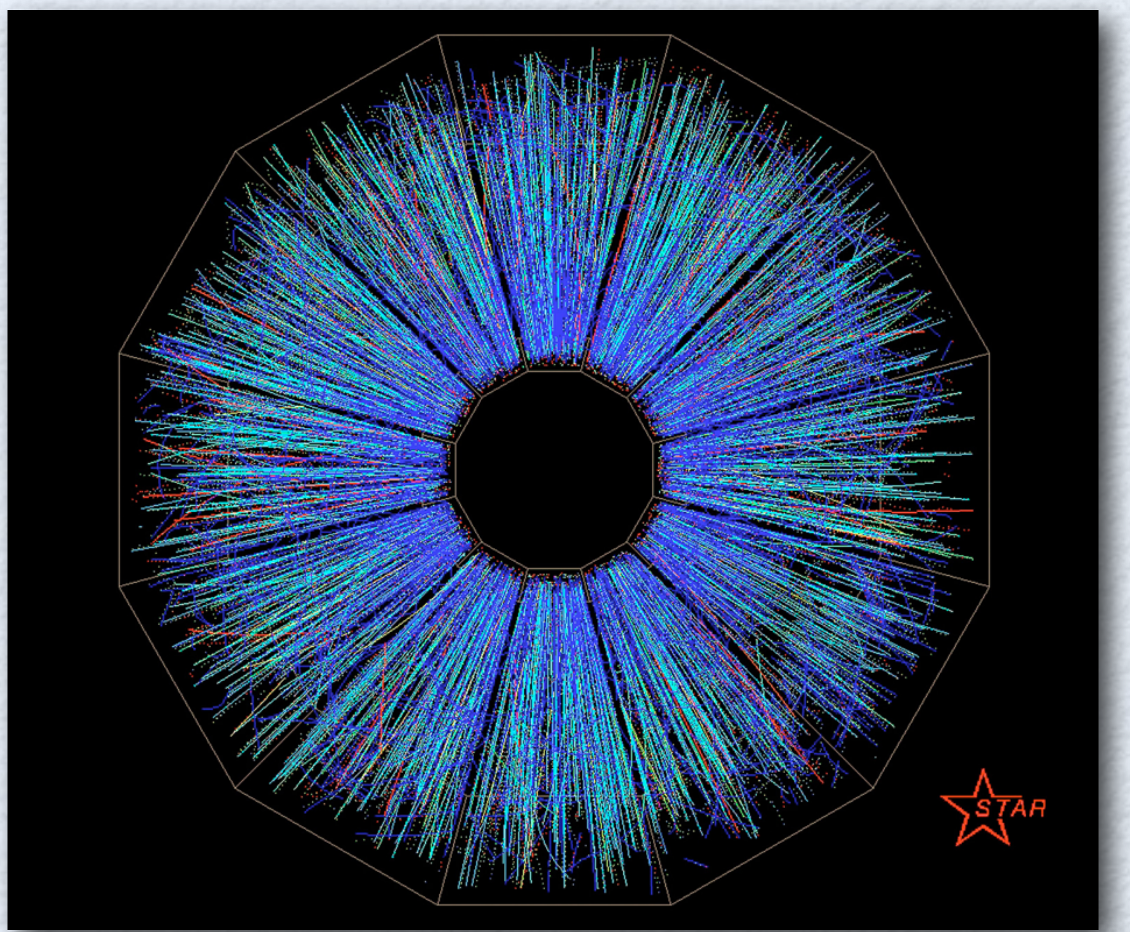
2. Similarity in many-body physics
    - “Hard probes” in cold atoms
    - “Quark-hadron continuity” in cold atoms

Summary of this talk

Ultracold atoms

Nuclear/quark physics





New ideas wanted !