New analogies between xQCD and cold atoms

Yusuke Nishida (TITech)

YITP workshop on "thermal quantum field theories and their applications"

August 28 (2013)

Definition

Ultracold atoms (~ 10^{-9} K)

= nonrelativistic
point-like particles
with short-range interactions

↕

Extreme QCD (~ 10^{12} K)

= relativistic quarks
with gauge interactions

Plan of this talk

1. “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]

2. “Quark-hadron continuity” in cold atoms

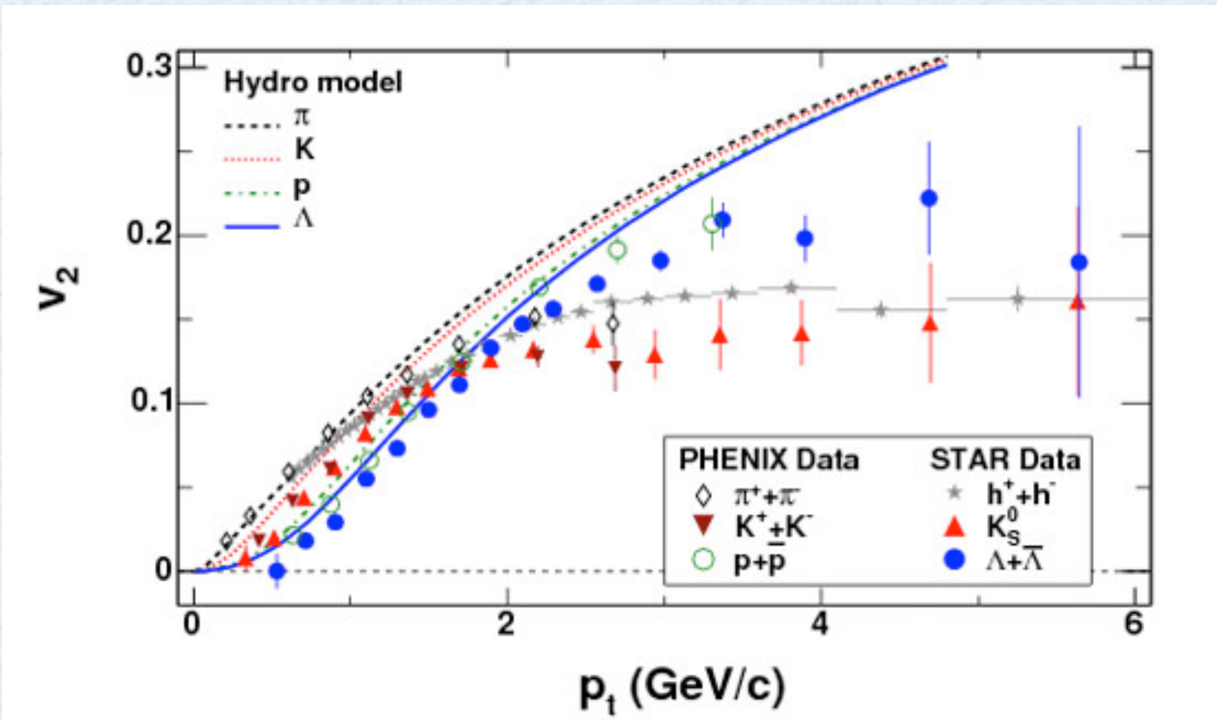
- Smooth crossover from atoms to trimers in 3-component Fermi gases

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

“Hard probes” in cold atoms

xQCD vs. cold atoms

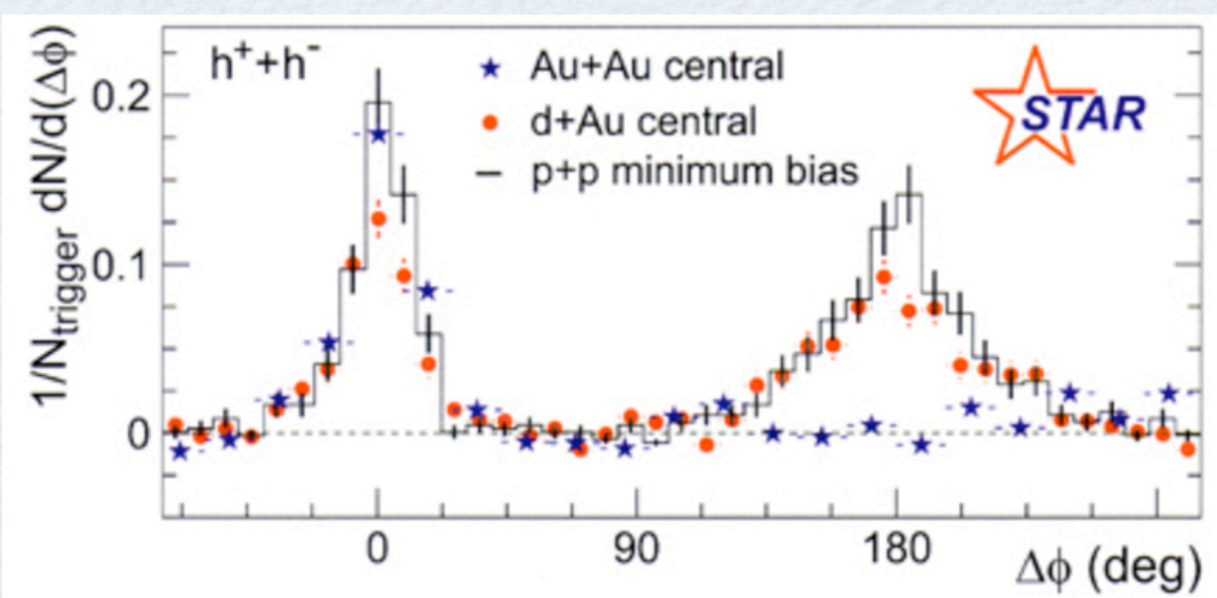
- Elliptic flow



- Small shear viscosity

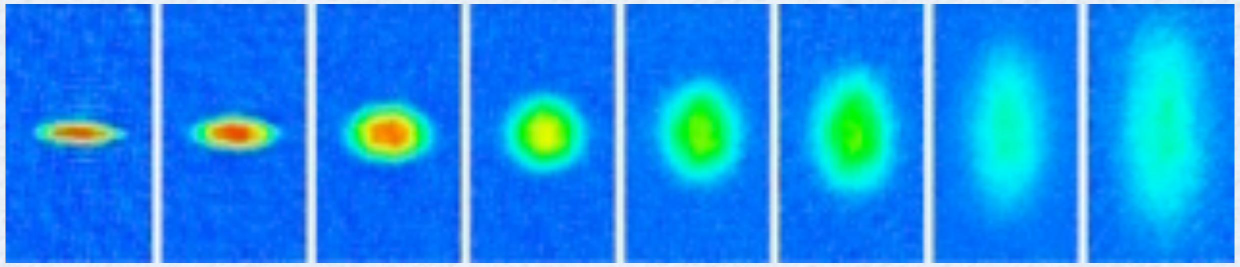
$$\frac{\eta}{s} \gtrsim \frac{1}{4\pi}$$

- Jet quenching



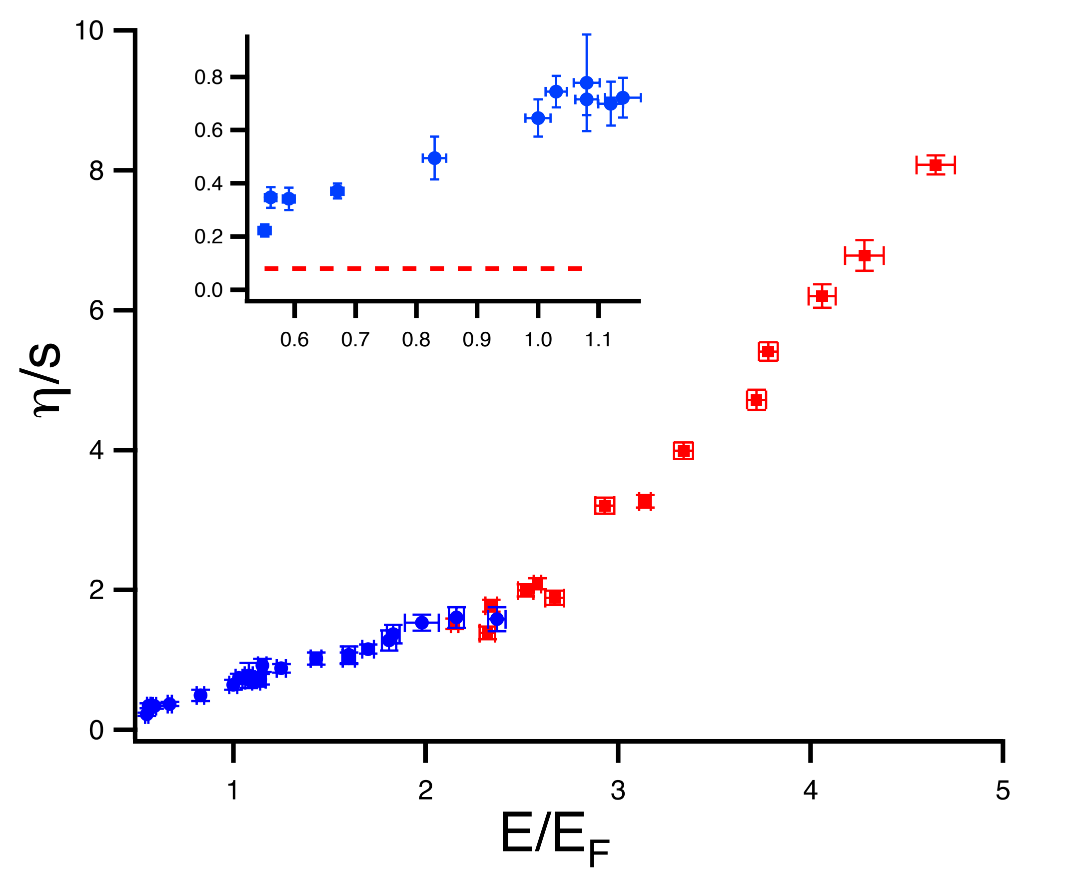
xQCD vs. cold atoms

- Elliptic flow



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

- Small shear viscosity



C. Cao et al., Science (2011)

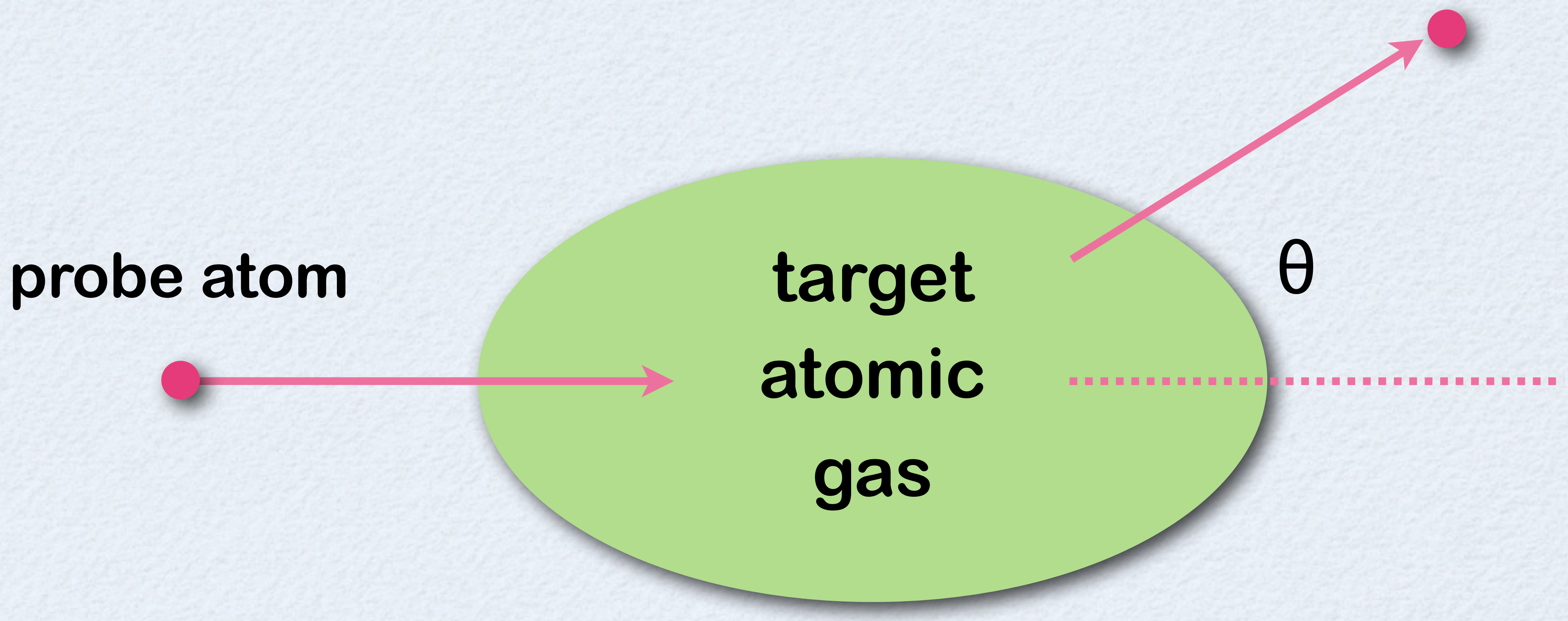
- Jet quenching

???

→ What is its analogue in cold atoms ?

Probe atomic gas with atoms

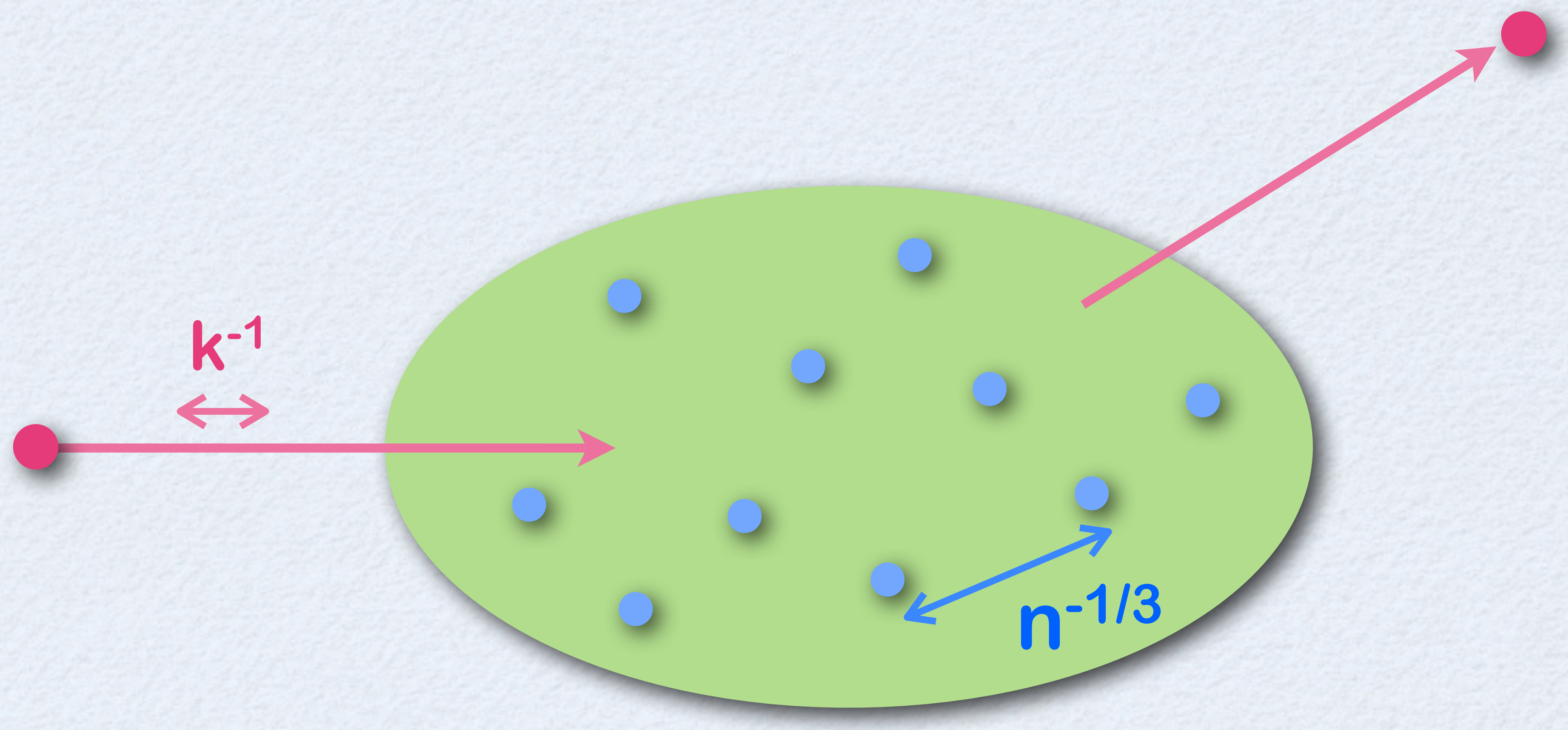
Shoot a probe atom into the target atomic gas
and measure its differential scattering rate



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

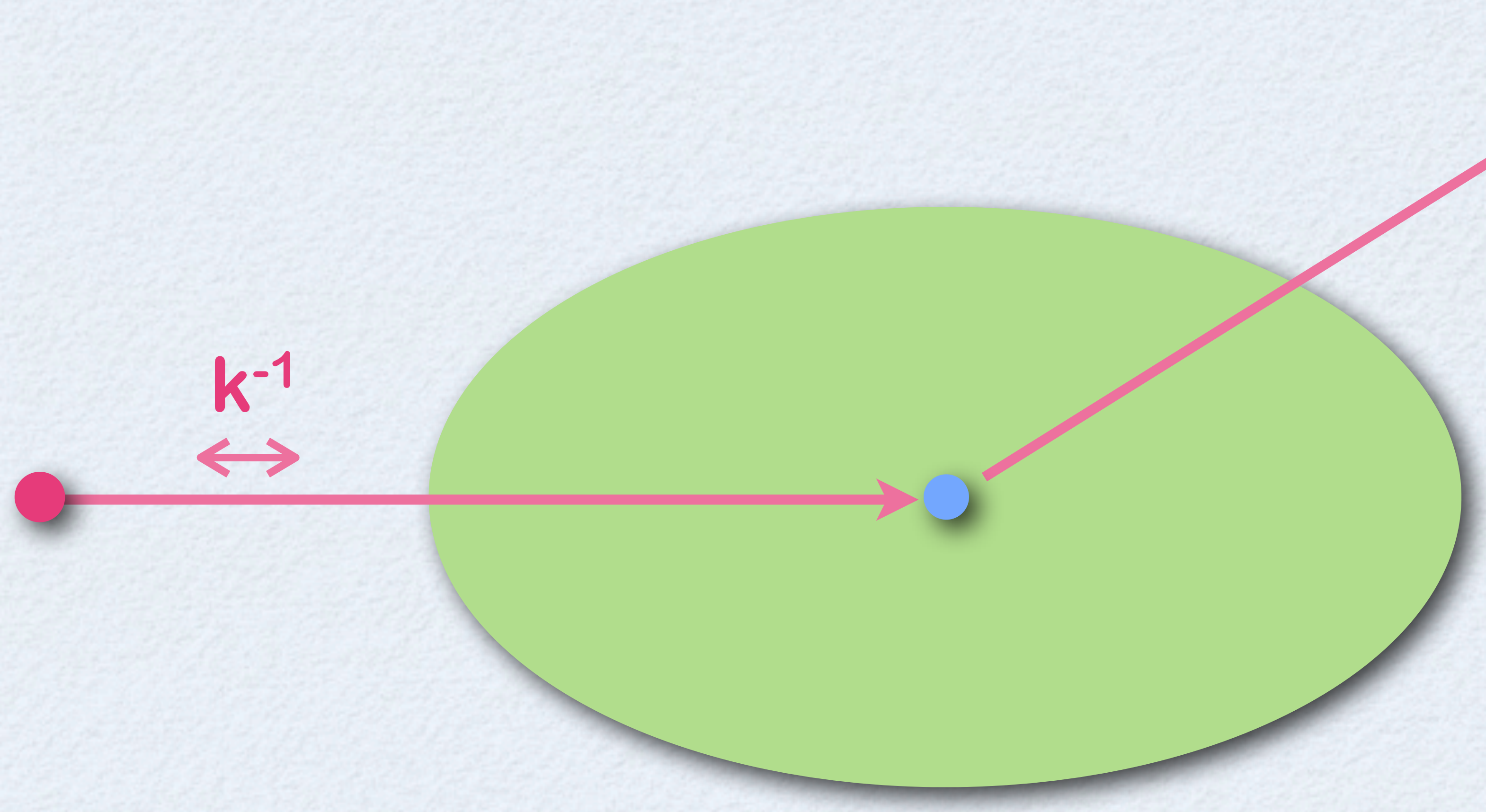


Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

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

Leading contribution

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

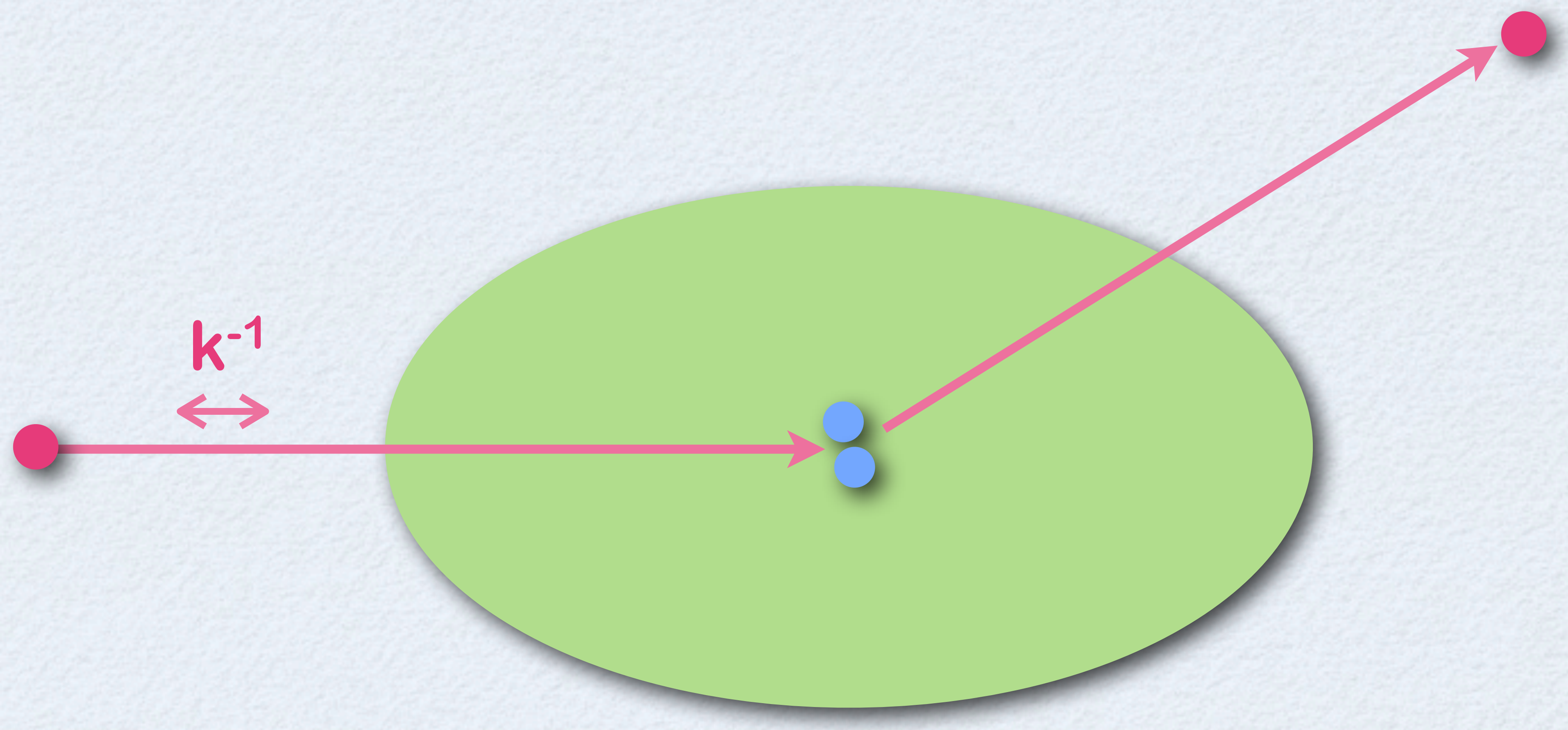


Large k ≫ n^{1/3} ⇒ Few-body scattering problems

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

Sub-leading contribution

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



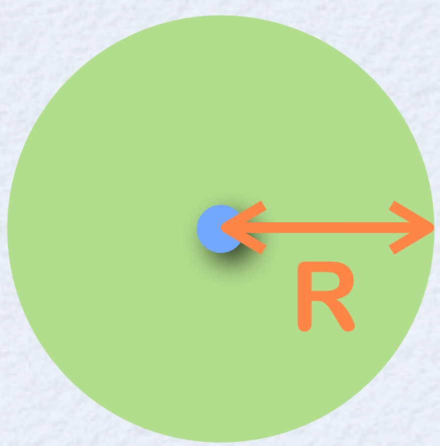
Large k ≫ $n^{1/3}$ ⇒ Few-body scattering problems

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

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 : $\langle \hat{n}(r)\hat{n}(0)\rangle \to \dfrac{C}{(4\pi|r|)^2}$



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

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)

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Viewpoint: How the tail wags the dog in ultracold atomic gases

Eric Braaten, *Department of Physics, Ohio State University, Columbus, OH 43210 USA and and Bethe Center for Theoretical Physics, University of Bonn, Bonn, Germany*

Published February 2, 2009 | *Physics* **2**, 9 (2009) | DOI: 10.1103/Physics.2.9

Recent calculations of the properties of ultracold atoms have revealed how two-body interactions at very short distances determine essential properties of many-body systems.

The development of the field of ultracold atoms has opened up new frontiers in both few-body and many-body physics. Of particular interest ... only to various

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Universal properties of the ultracold Fermi gas
Shizhong Zhang and Anthony J. Leggett
Phys. Rev. A **79**, 023601 (2009)

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Subject Areas

- Atomic and Molecu

Viewpoint: Fermi gases as a test bed for strongly interacting systems

Daniel E. Sheehy, *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA*

Published June 7, 2010 | *Physics* **3**, 48 (2010) | DOI: 10.1103/Physics.3.48

A new perspective on strongly interacting fermions emerges from the experimental confirmation of a universal formula.

Some of the most vexing present-day problems in physics center on understanding the many-body properties and phases of strongly interacting fermions. Part of the difficulty arises from the fact that while

Verification of Universal Relations in a Strongly Interacting Fermi Gas
J. T. Stewart, J. P. Gaebler, T. E. Drake, and

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Subject Areas

In ... s

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Formulations à la OPE

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

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

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

Lowest few O_i are needed at large k

Systematic large-k expansion !

Differential scattering rate

Many-body physics

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

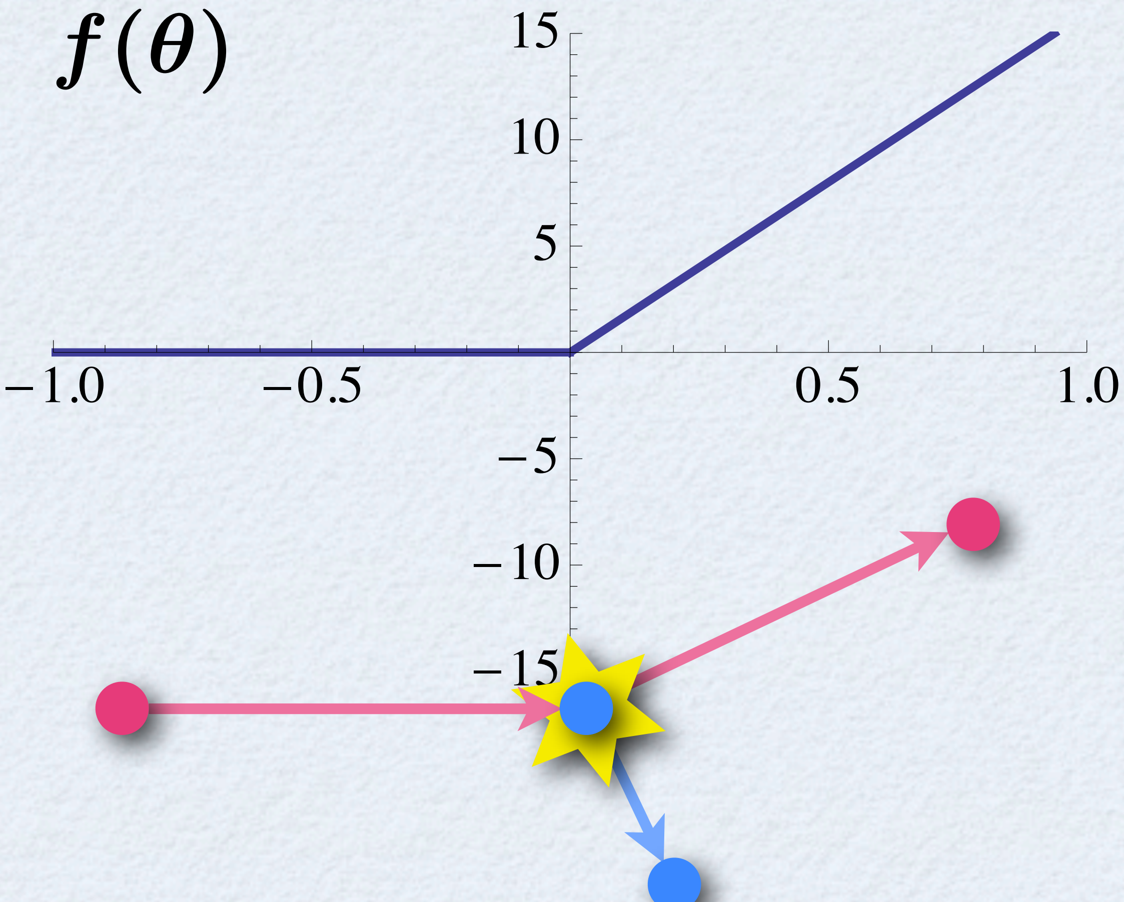
Few-body physics

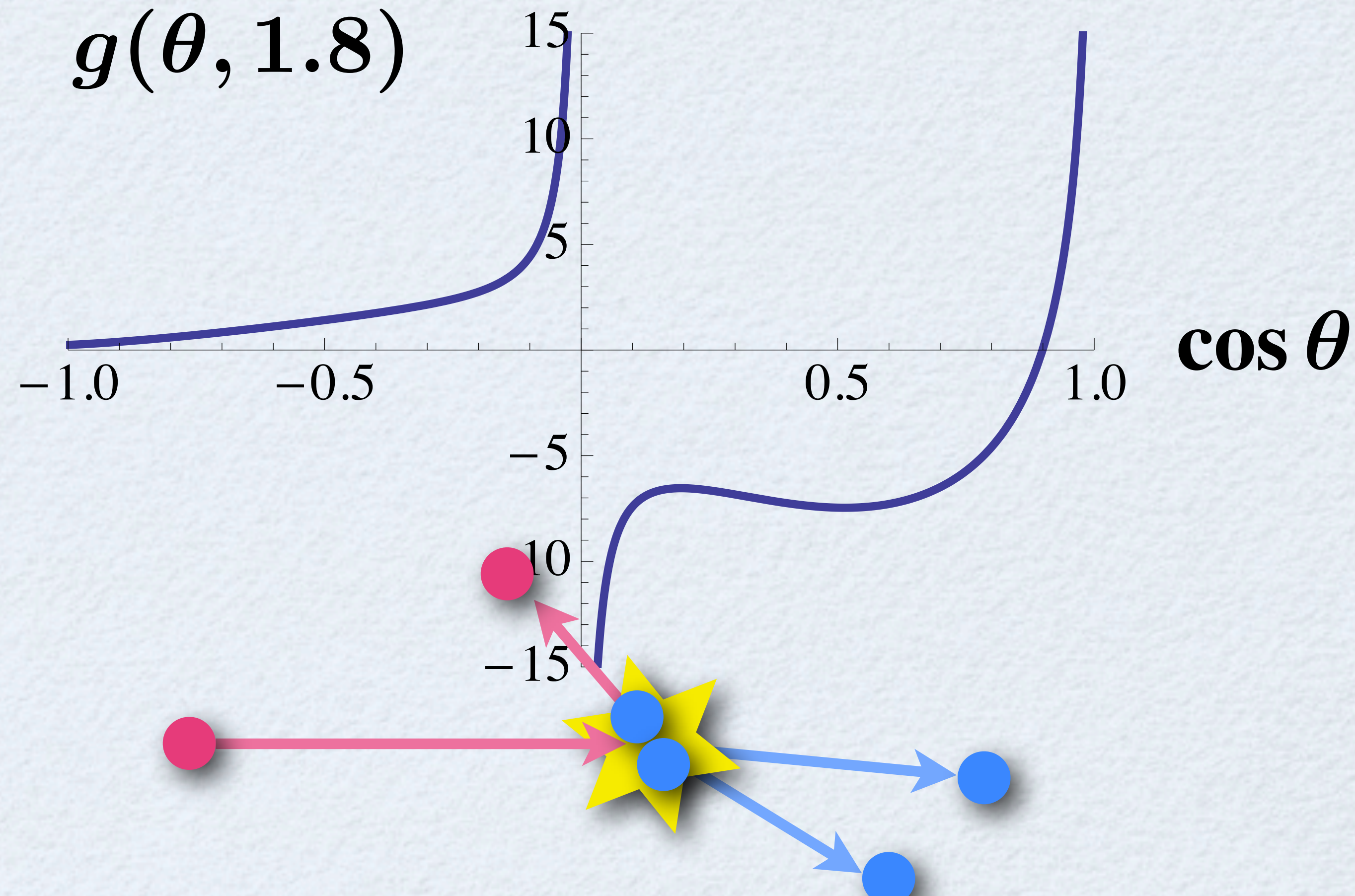
Few-body physics plays an important role to probe many-body physics !

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

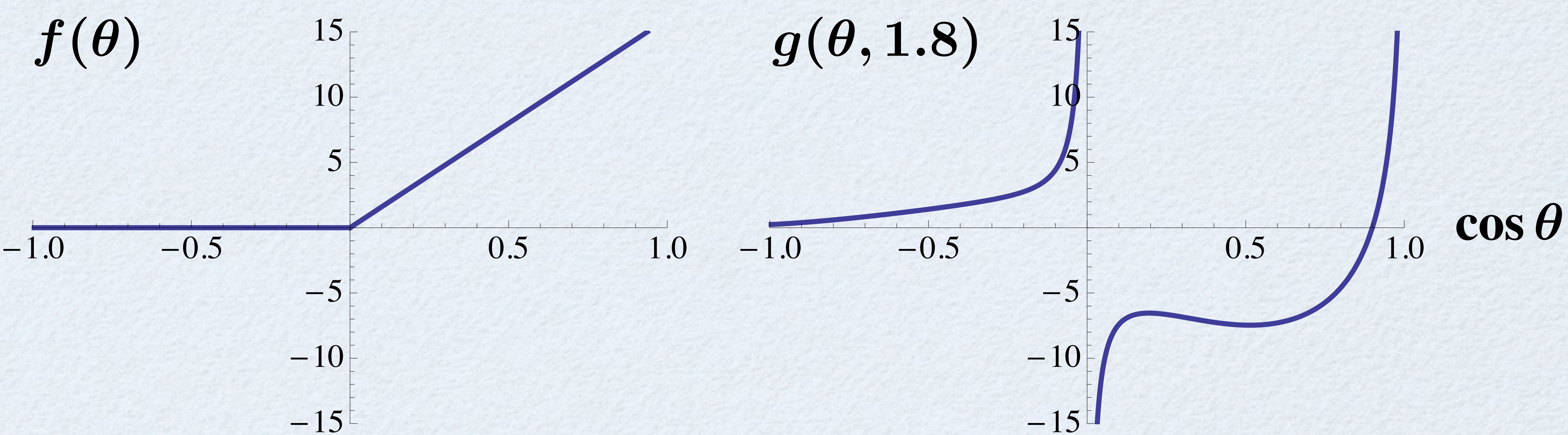
backward scattering
(θ>90°) possible

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



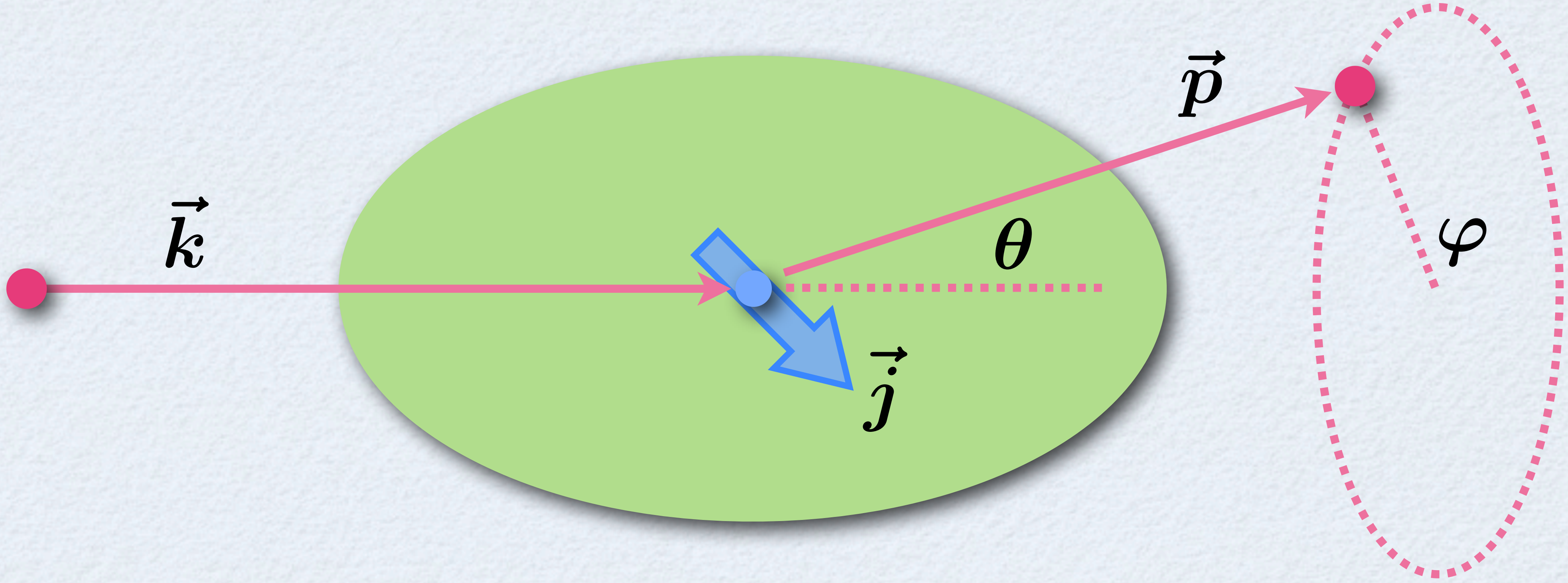
Backward scattering rate measures contact density

New local probe of strongly-int atomic gases

Differential scattering rate

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

$$+\,16\,\Theta(\cos\theta)\,(2\cos\theta\,\hat{k} + \hat{p})\cdot\frac{\vec{j}}{k^2} + \cdots$$

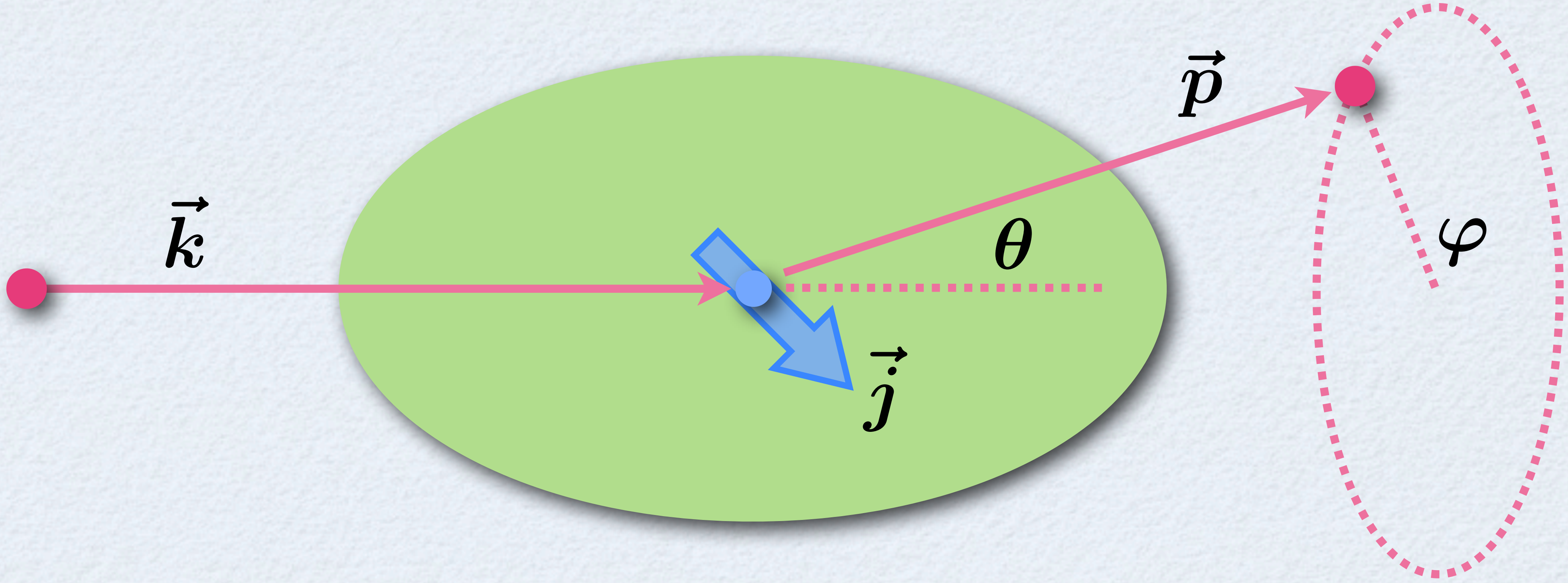


Azimuthal (φ) anisotropy reveals currents in many-body states

Differential scattering rate

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

$$+ 16\,\Theta(\cos\theta)\,(2\cos\theta\,\hat{k} + \hat{p})\cdot\frac{\vec{j}}{k^2} + \cdots$$

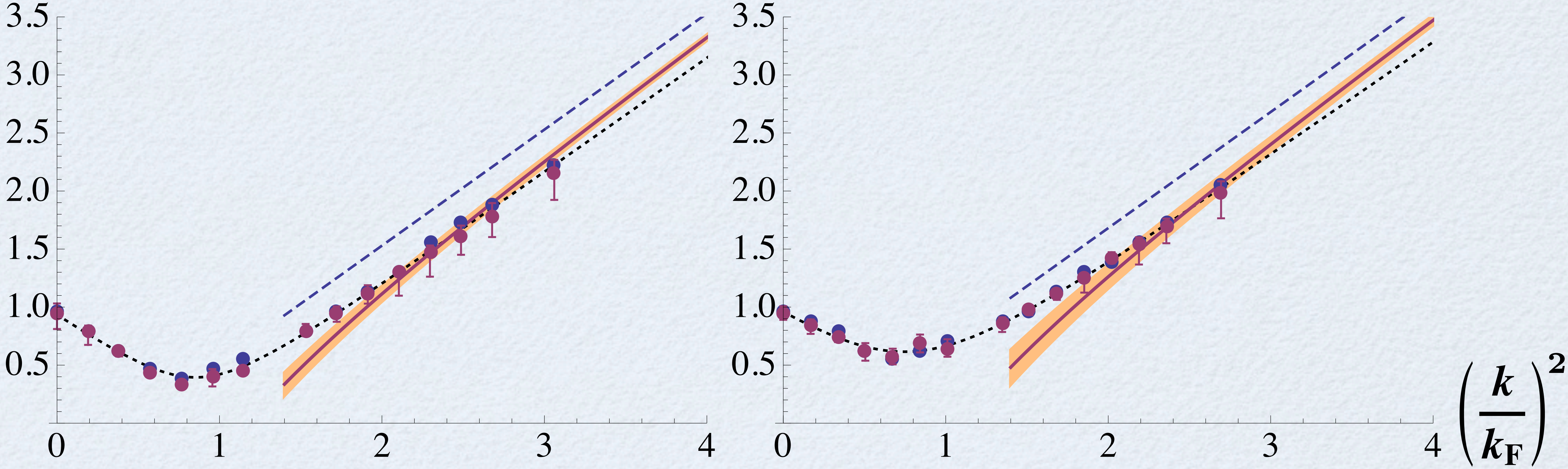


$$N_{\text{measured}}(\theta, \varphi) = \frac{1}{k}\int dl\,\frac{d\Gamma(k)}{d\Omega} \times N_{\text{shot}}$$

How large is large ?

$$E_\uparrow(k) = \left[1 + 32\pi\frac{n_\downarrow}{ak^4} - 7.54\frac{C}{k^4} + O(k^{-6})\right]\frac{k^2}{2m}$$

Comparison of $E(k)/\epsilon_F$ with QMC P. Magierski et al., PRL (2011)



$(a_f k_F)^{-1} = 0 \quad T/\epsilon_F = 0.15$

$C/k_F^4 = 0.110$ Goulko et al, Lattice2010

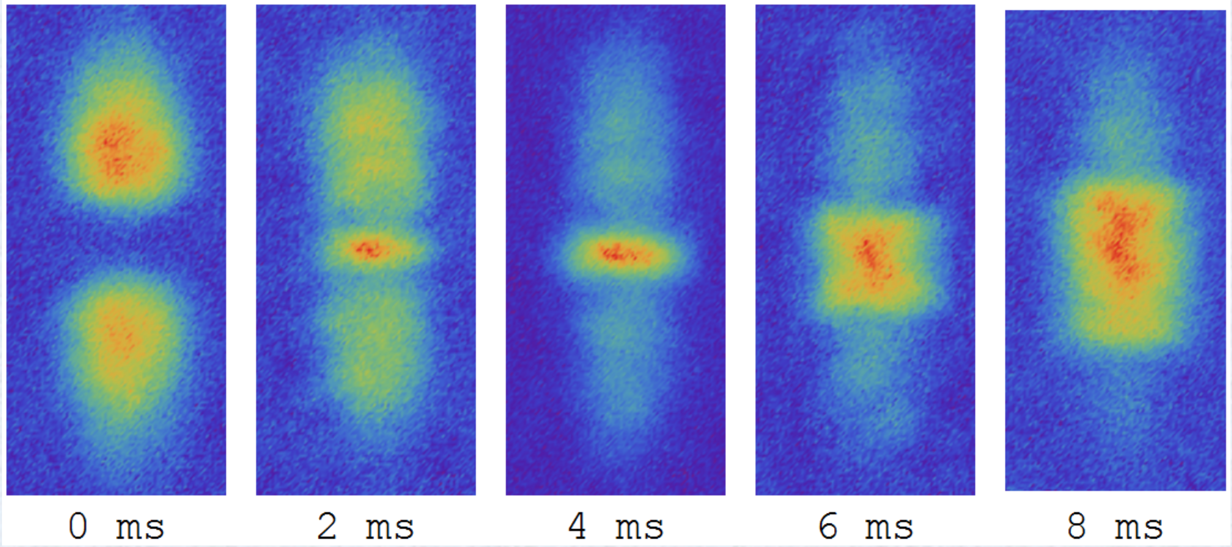
$(a_f k_F)^{-1} = 0.2 \quad T/\epsilon_F = 0.19$

$C/k_F^4 = 0.156$ Gandolfi et al, PRA (2011)

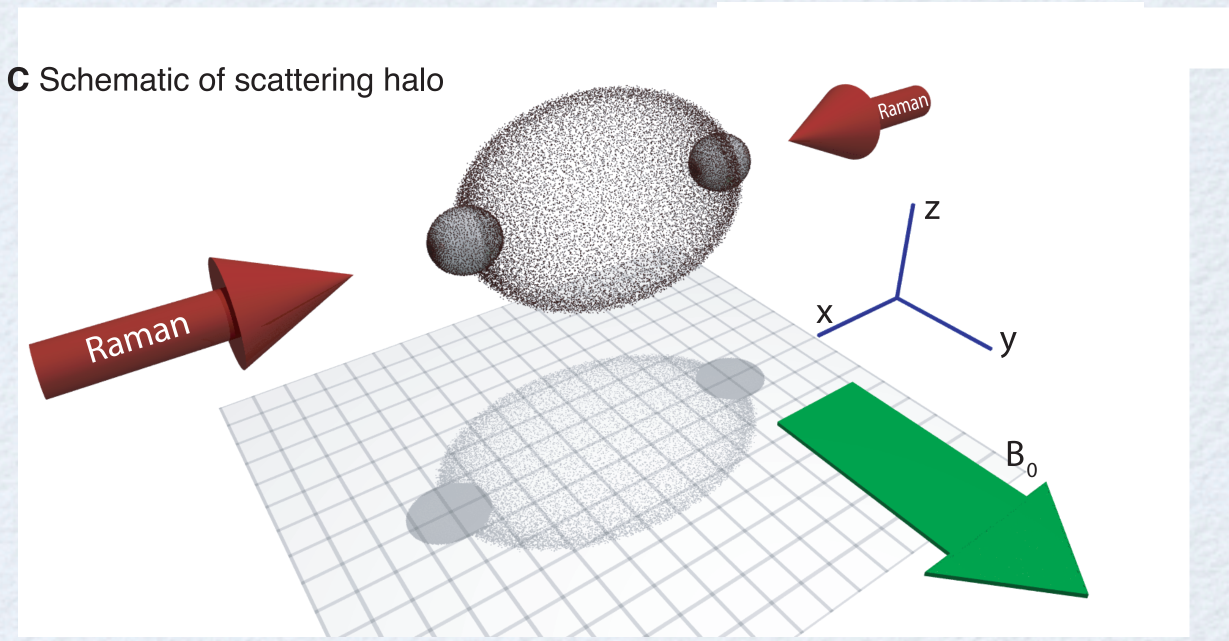
Reasonable agreement even at $k/k_F > 1.5$!

Ultracold atom "colliders"

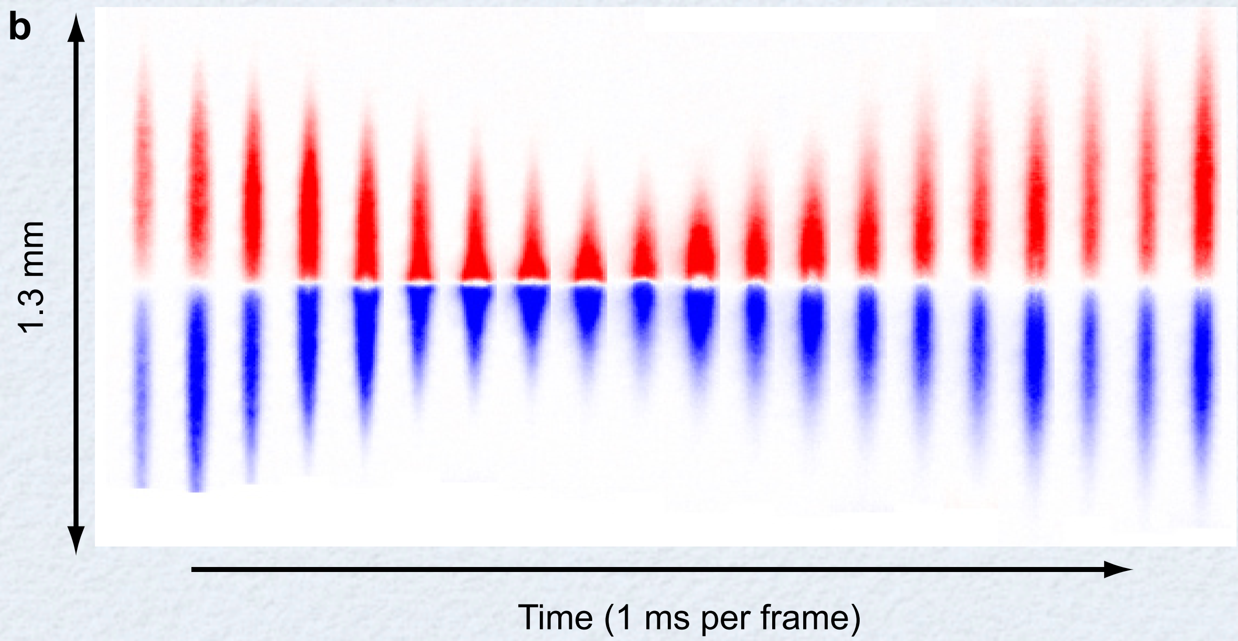
Duke (2011)



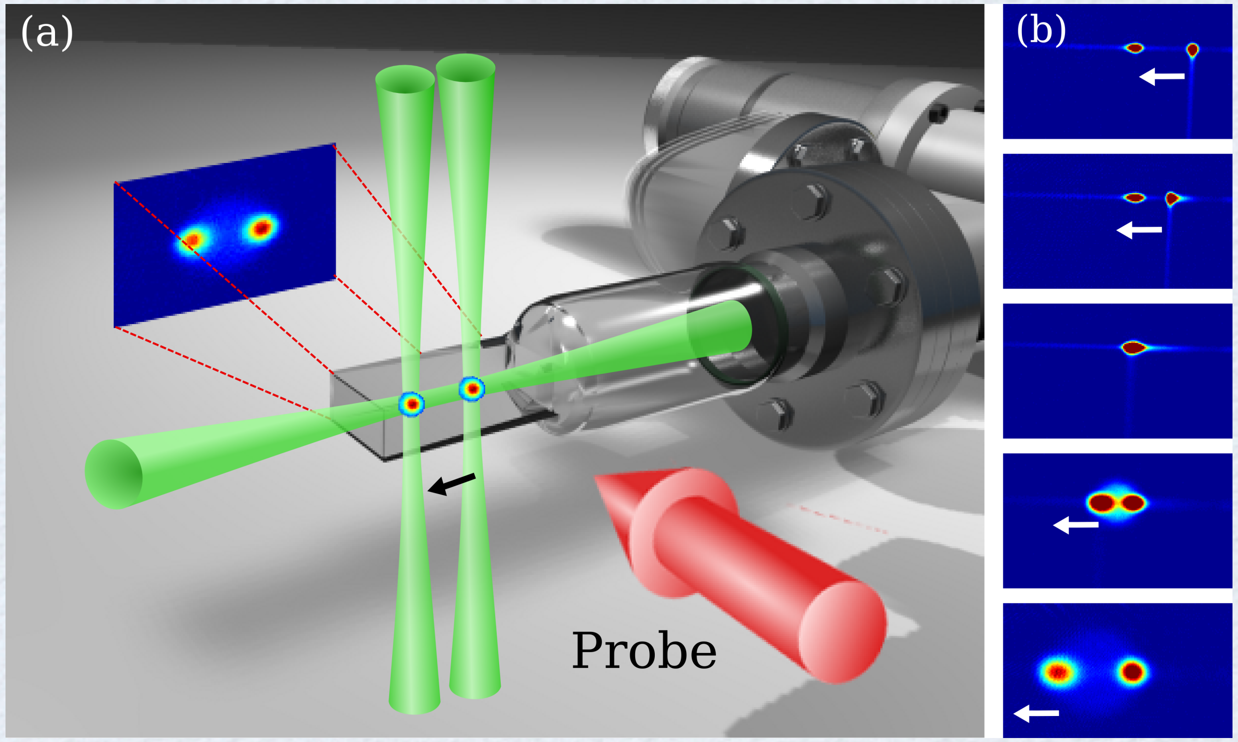
NIST (2012)



MIT (2011)

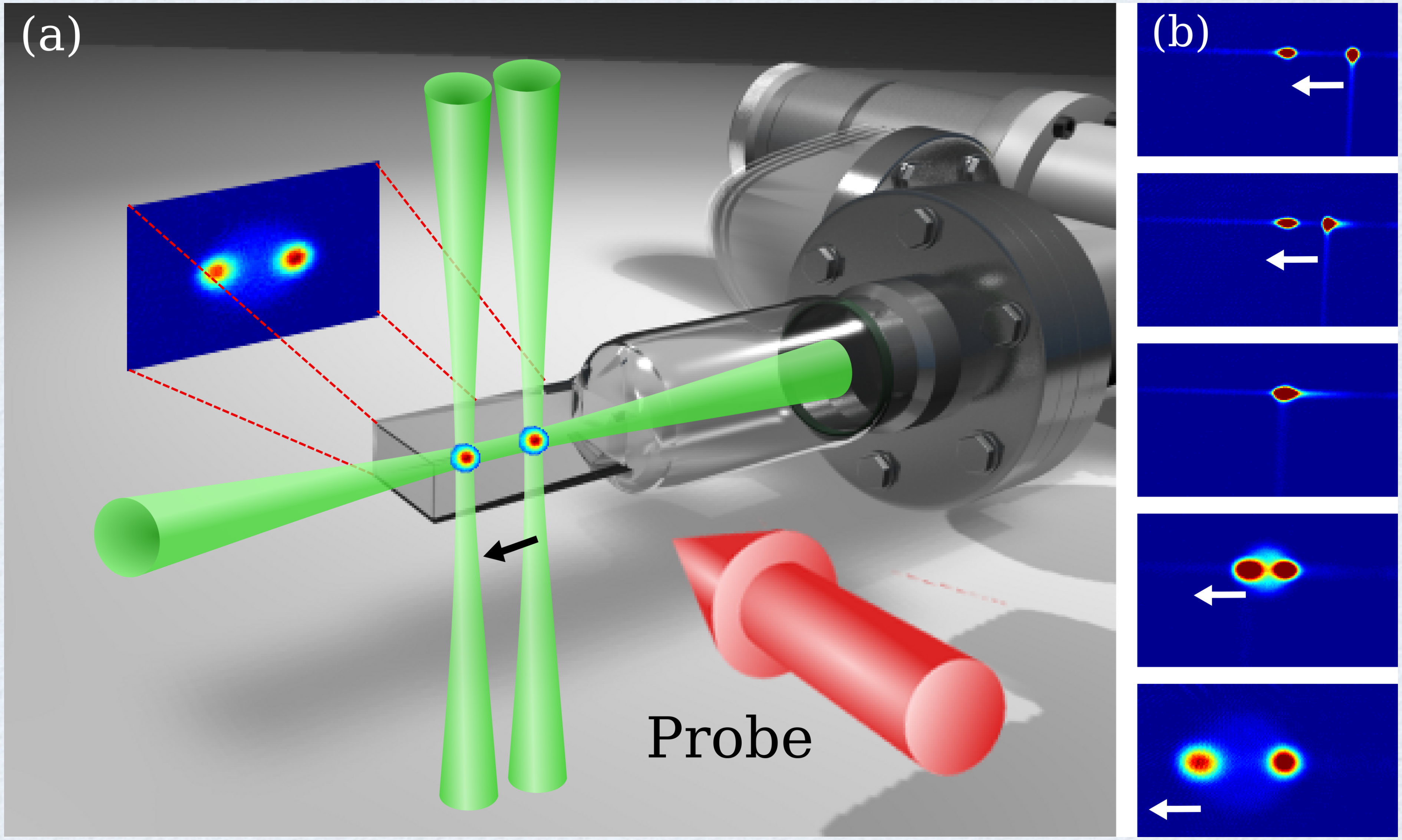


Otago (2012)



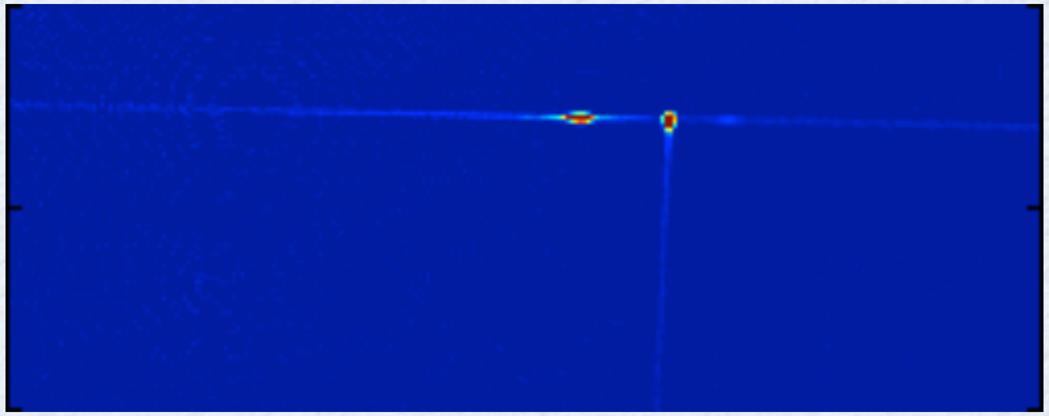
Ultracold atom “colliders”

“A laser based accelerator for ultracold atoms”



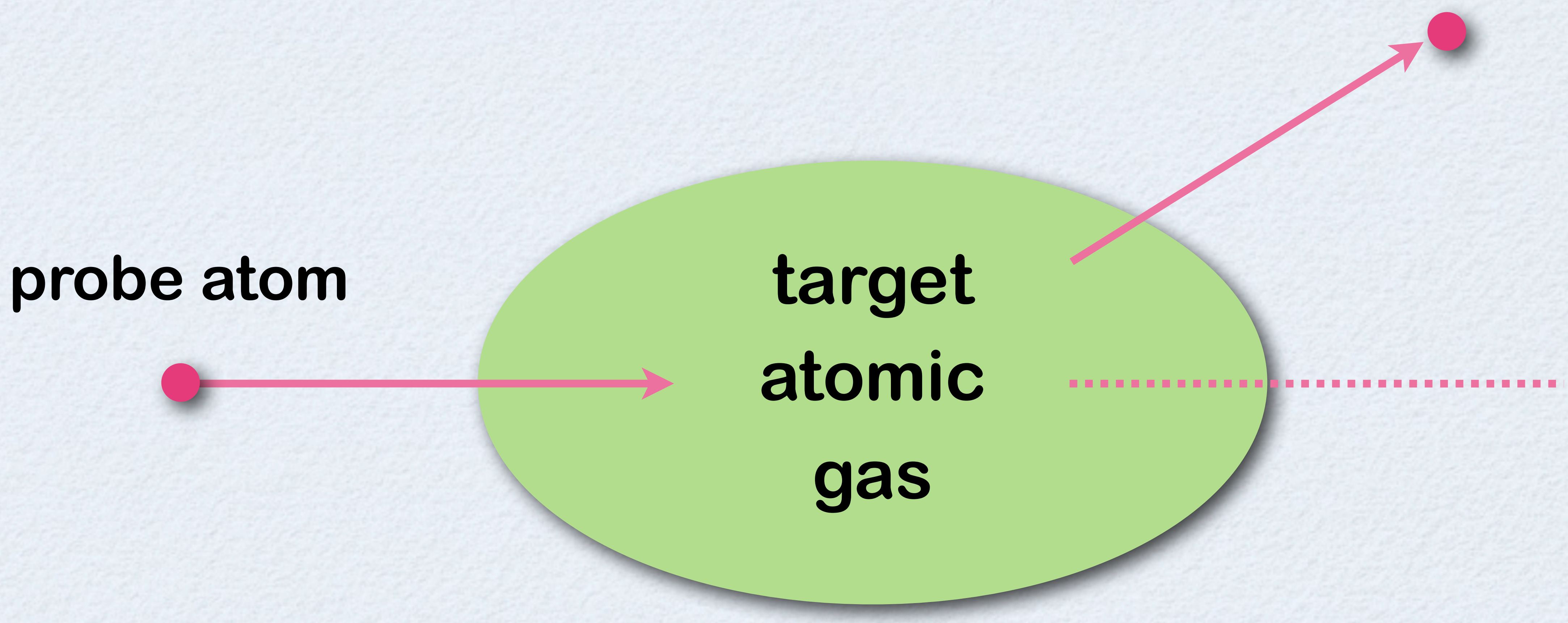
University of Otago (New Zeeland)

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



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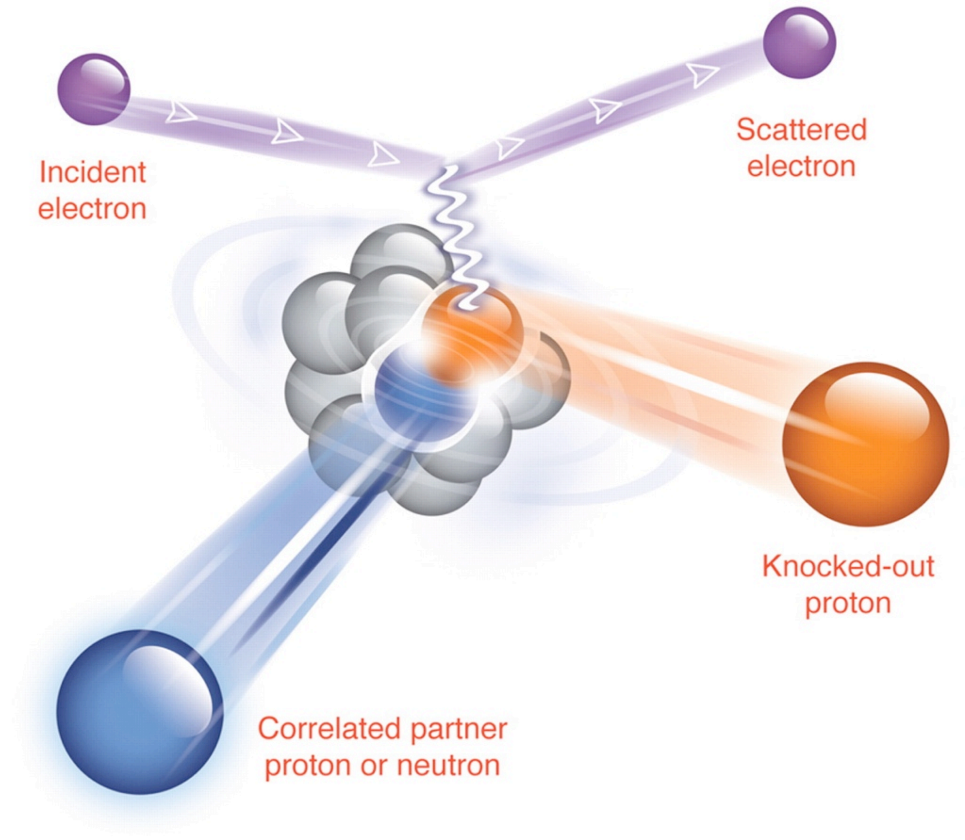
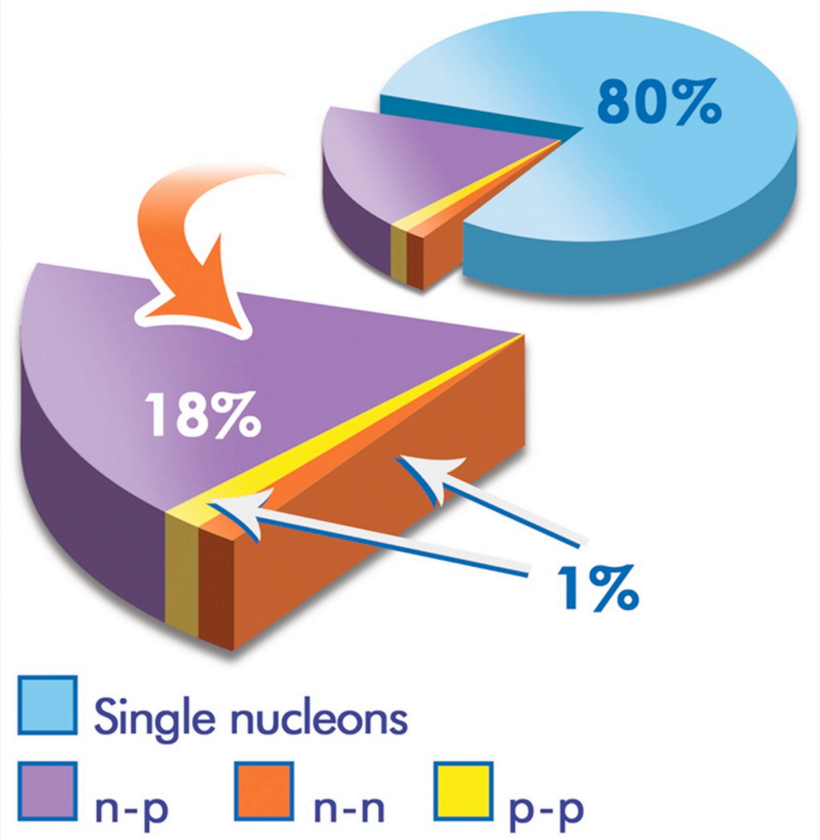
- Close connection to nuclear/particle physics

JLab, Science 320, 1476 (2008)





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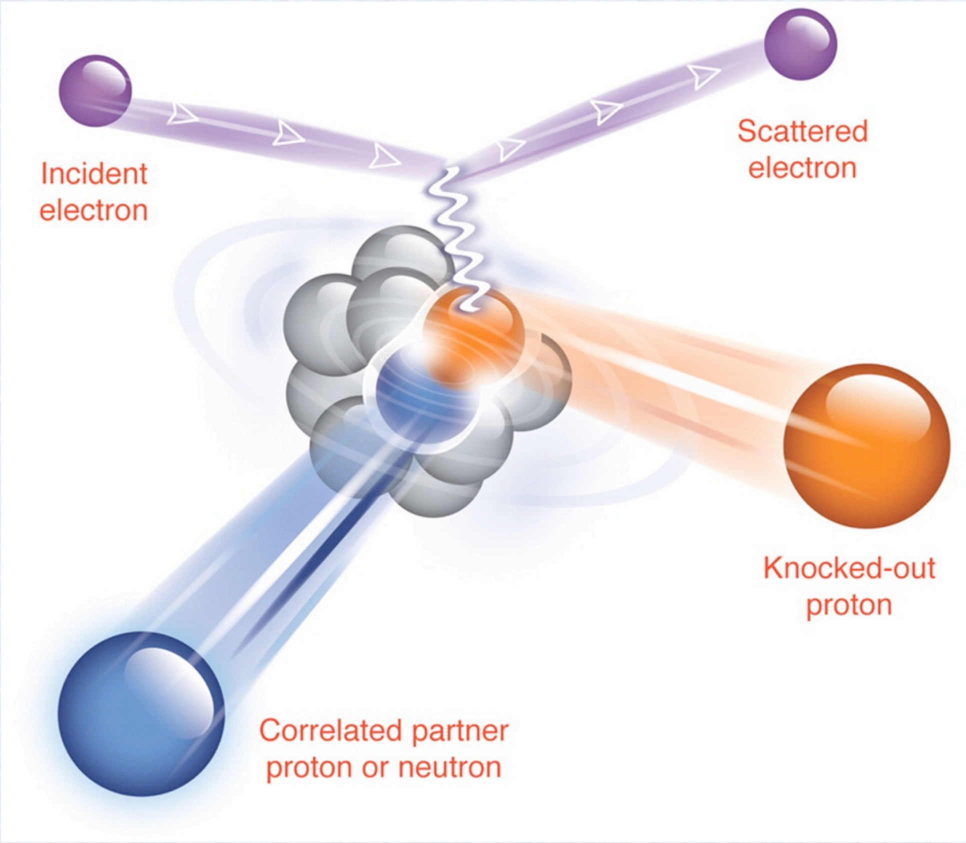


"Hard probes" are useful to reveal short-range pair correlations both in atomic gases and nuclei (QGP?)

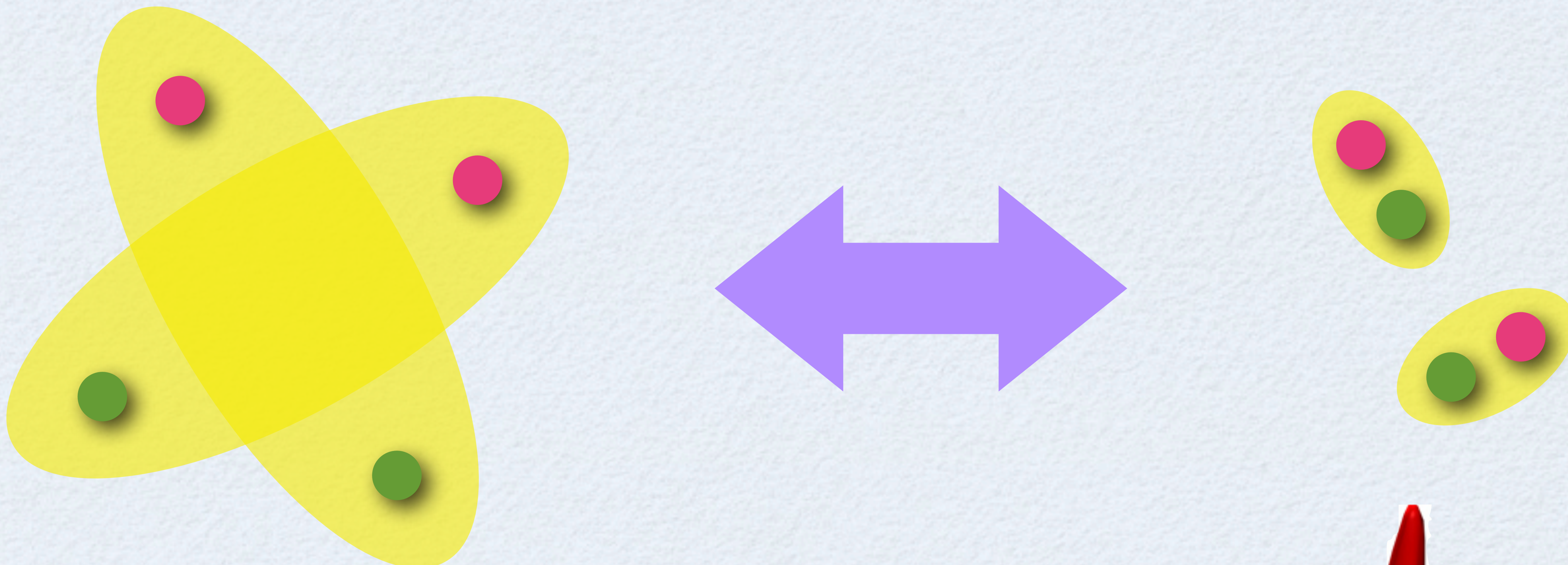
“Quark-hadron continuity” in cold atoms

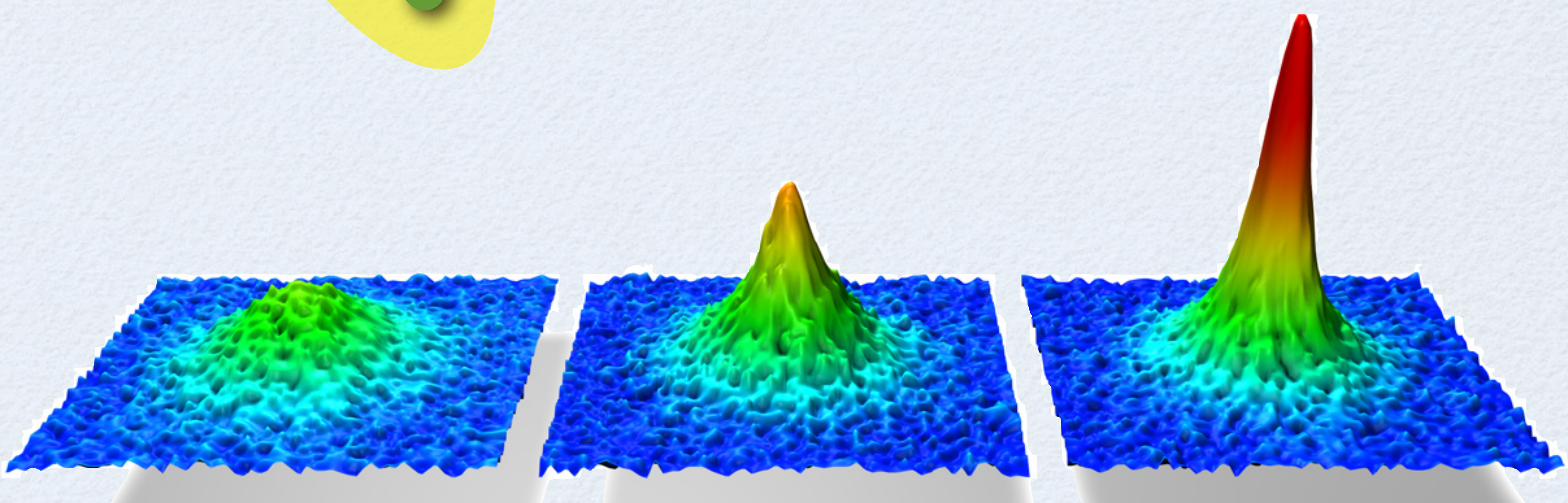
BCS-BEC crossover

- 2-component Fermi gas

loosely bound Cooper pairs

tightly bound dimers



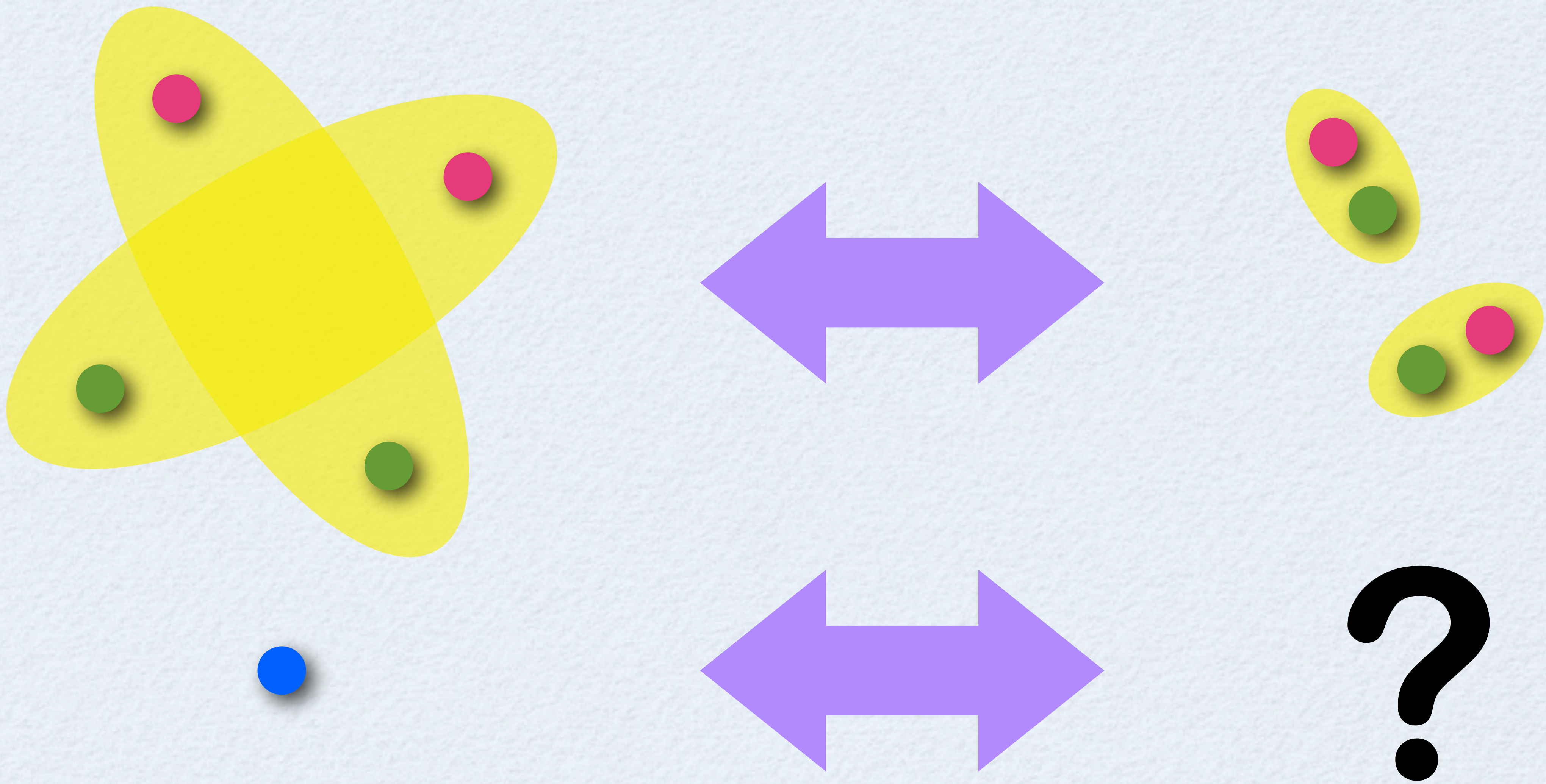


Jin Group at JILA

BCS-BEC crossover

- 3-component Fermi gas

loosely bound Cooper pairs tightly bound dimers

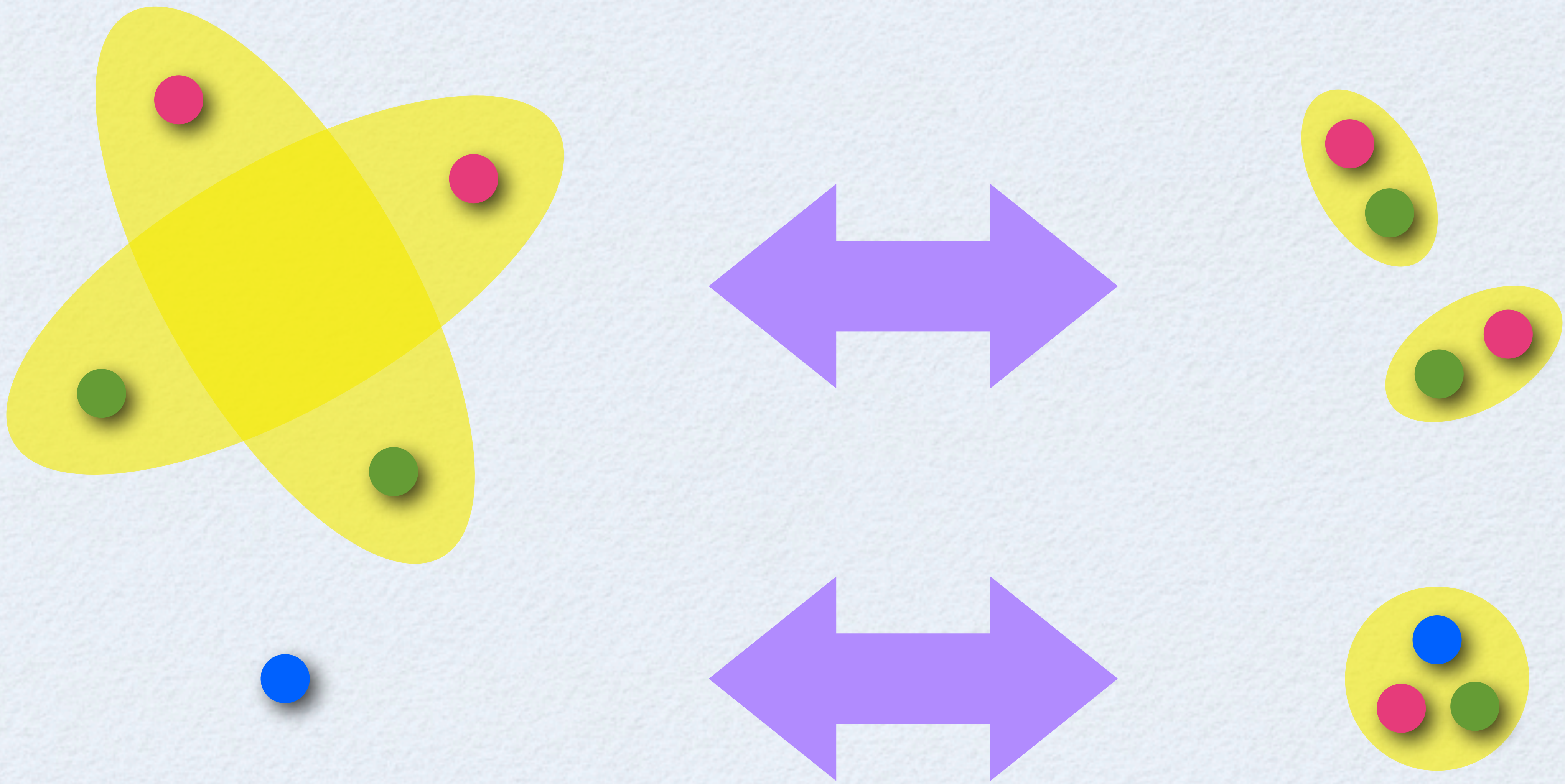


unpaired atoms

BCS-BEC crossover

- 3-component Fermi gas

loosely bound Cooper pairs — tightly bound dimers



unpaired atoms — unpaired timers

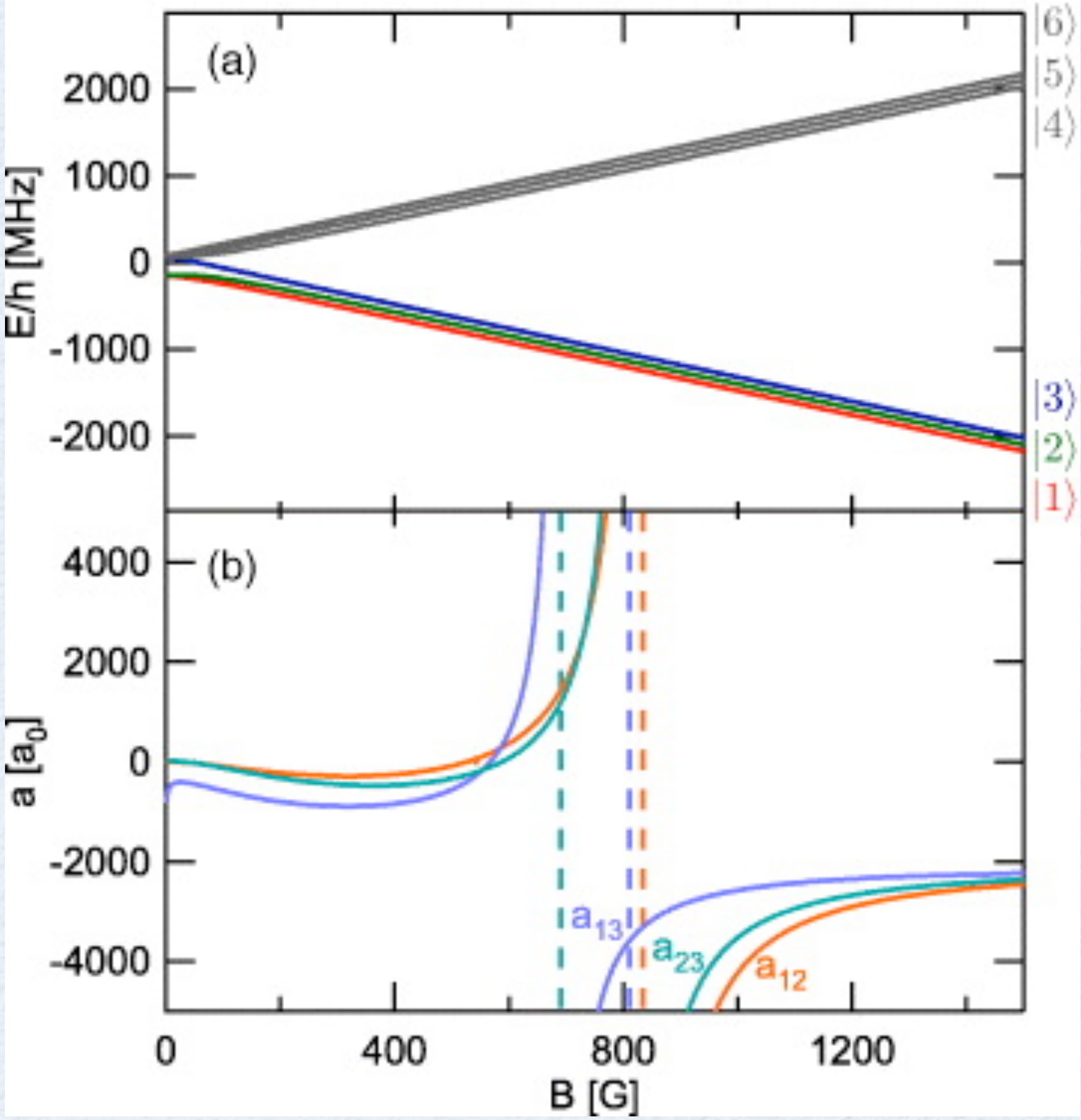
"Atom-trimer continuity" = New crossover physics !

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

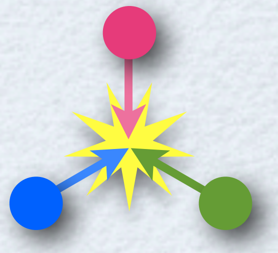
- 3 spin states (i=1,2,3) of ^{6}Li atoms near a Feshbach resonance:

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

- $a_{12} = a_{23} = a_{31}$ ⇒ 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:

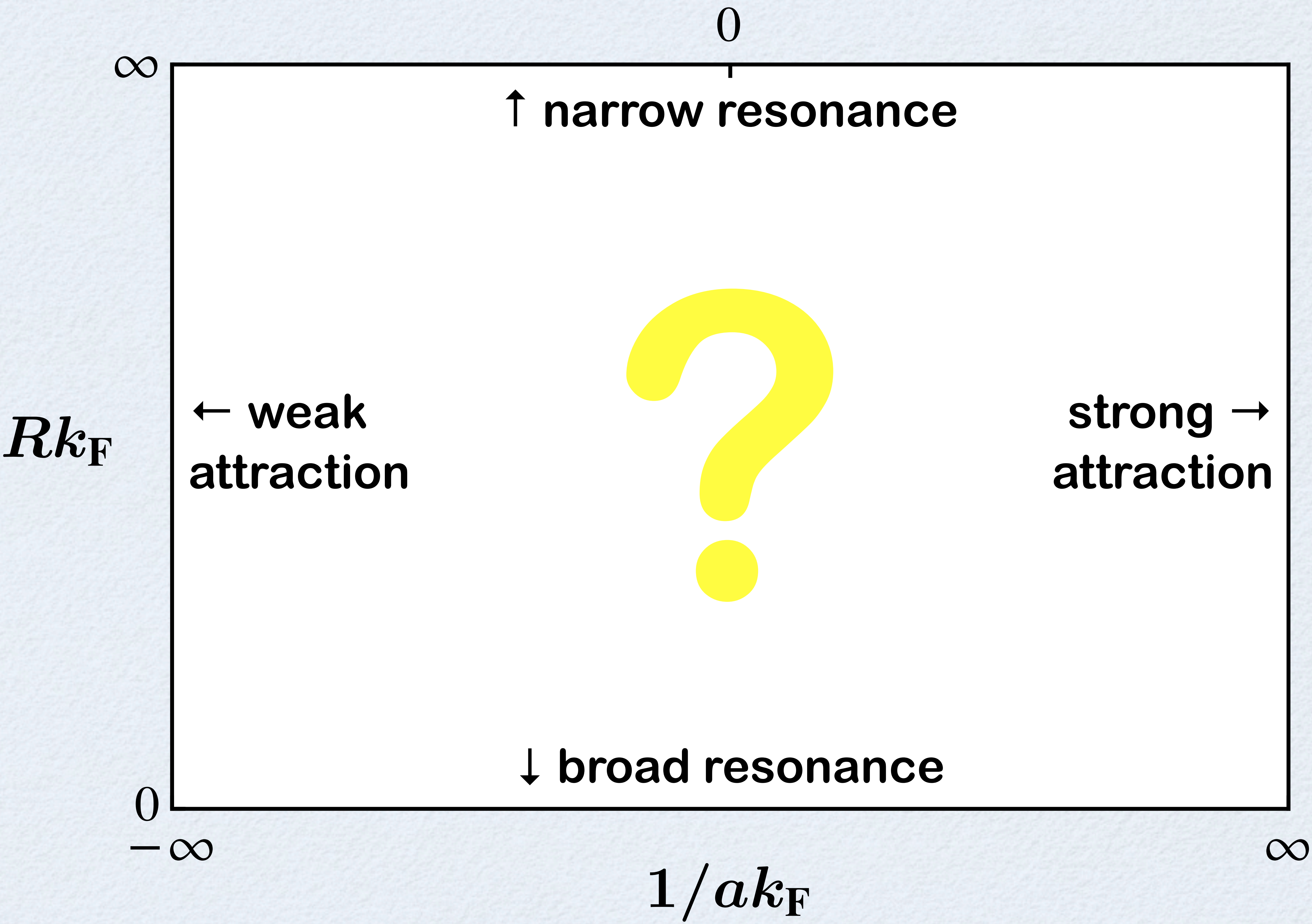
$$f(k) = \frac{-1}{ik + \frac{1}{a}} \;\Rightarrow\; f(k) = \frac{-1}{ik + \frac{1}{a} + Rk^2}$$

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

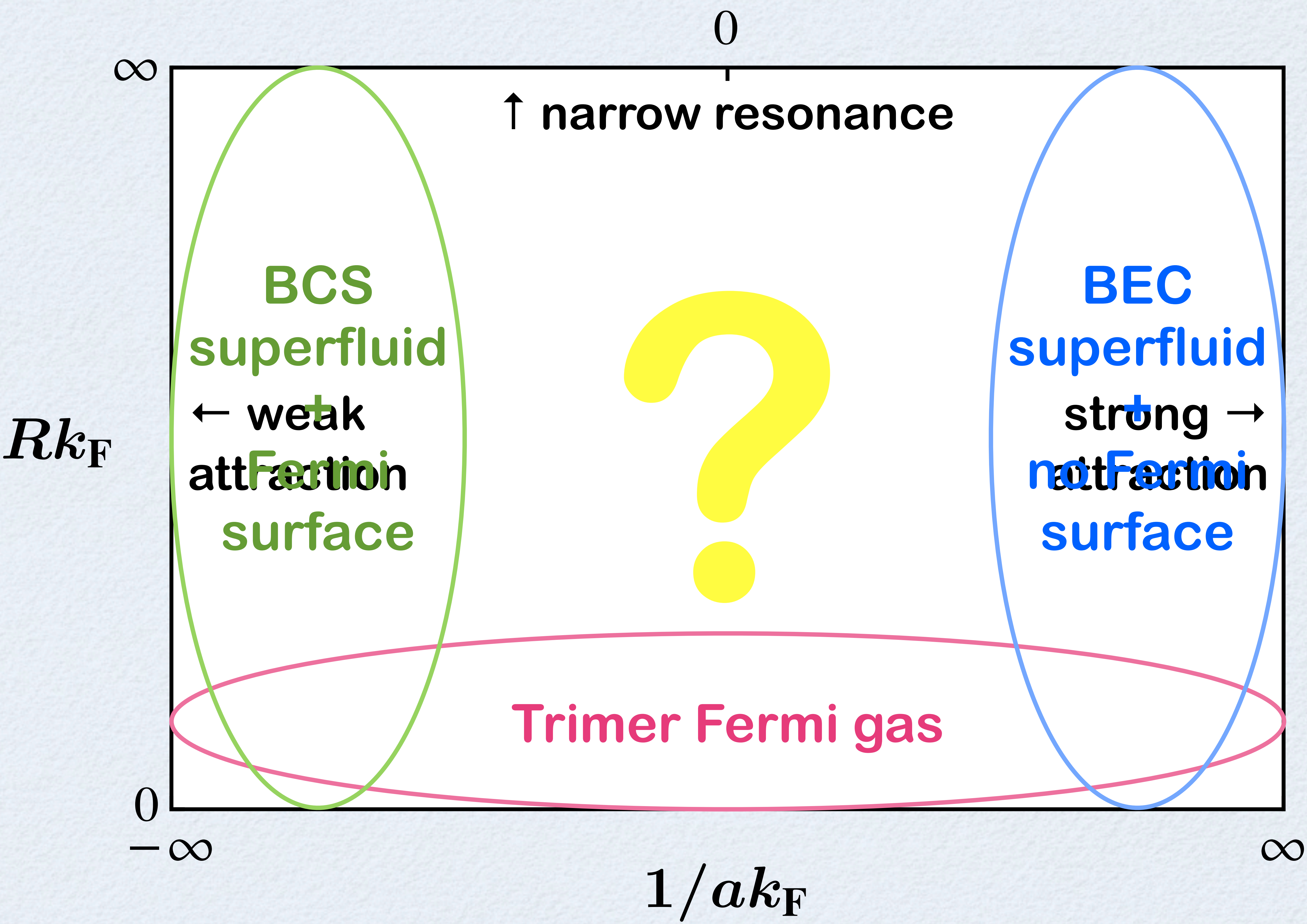
- R regularizes short-distance behaviors (⇒ no Thomas collapse)

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

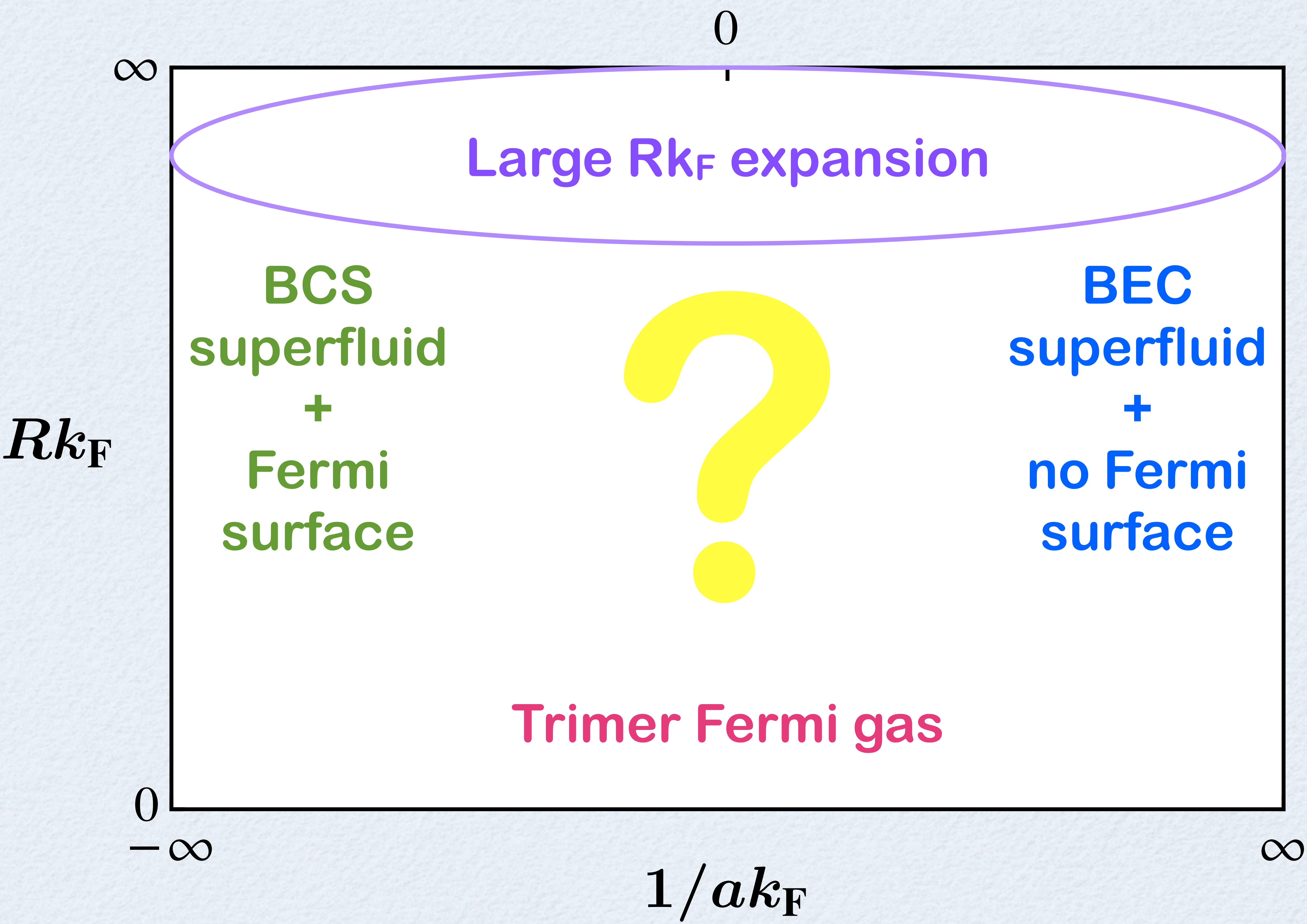
Phase diagram



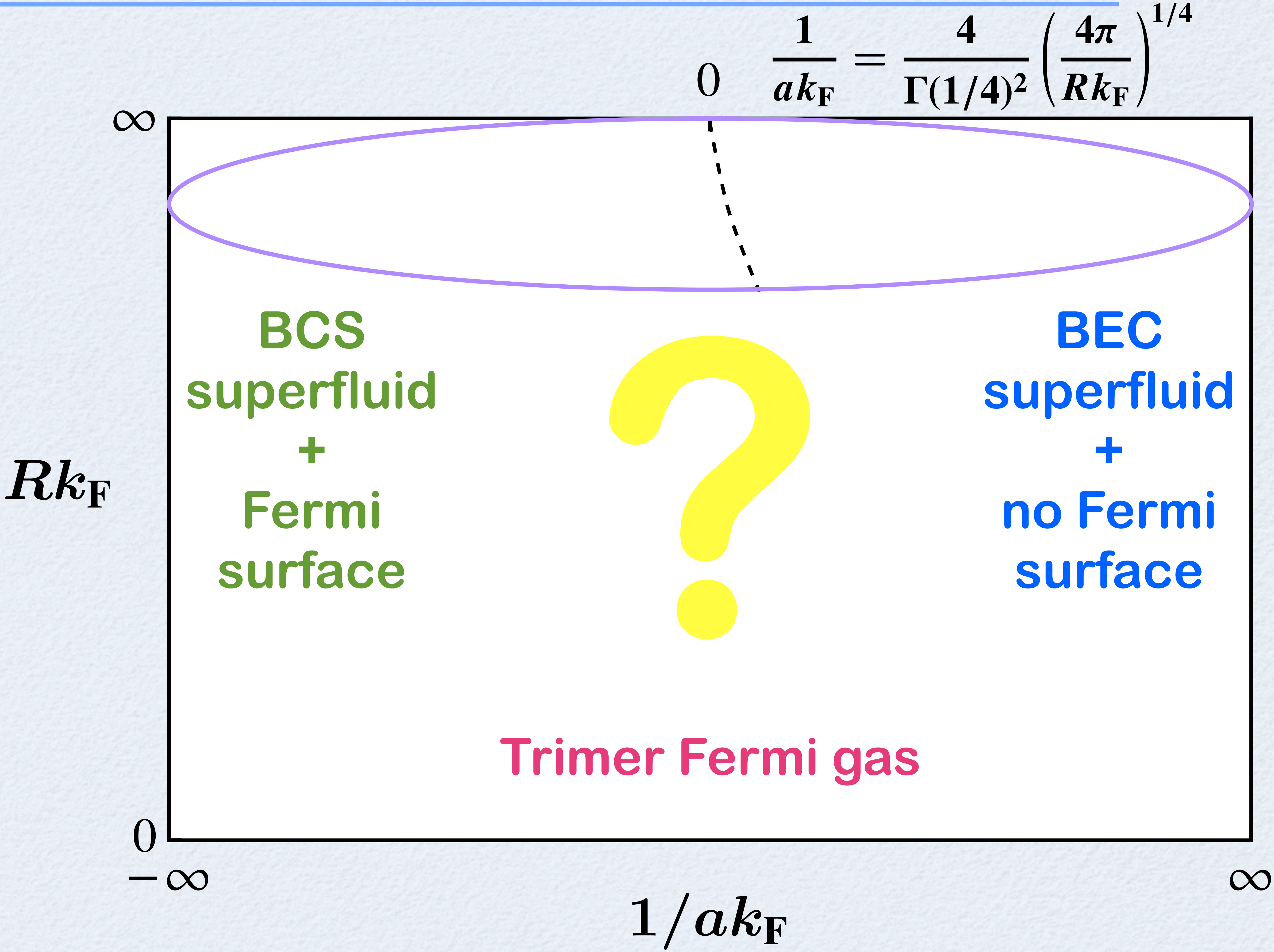
Phase diagram



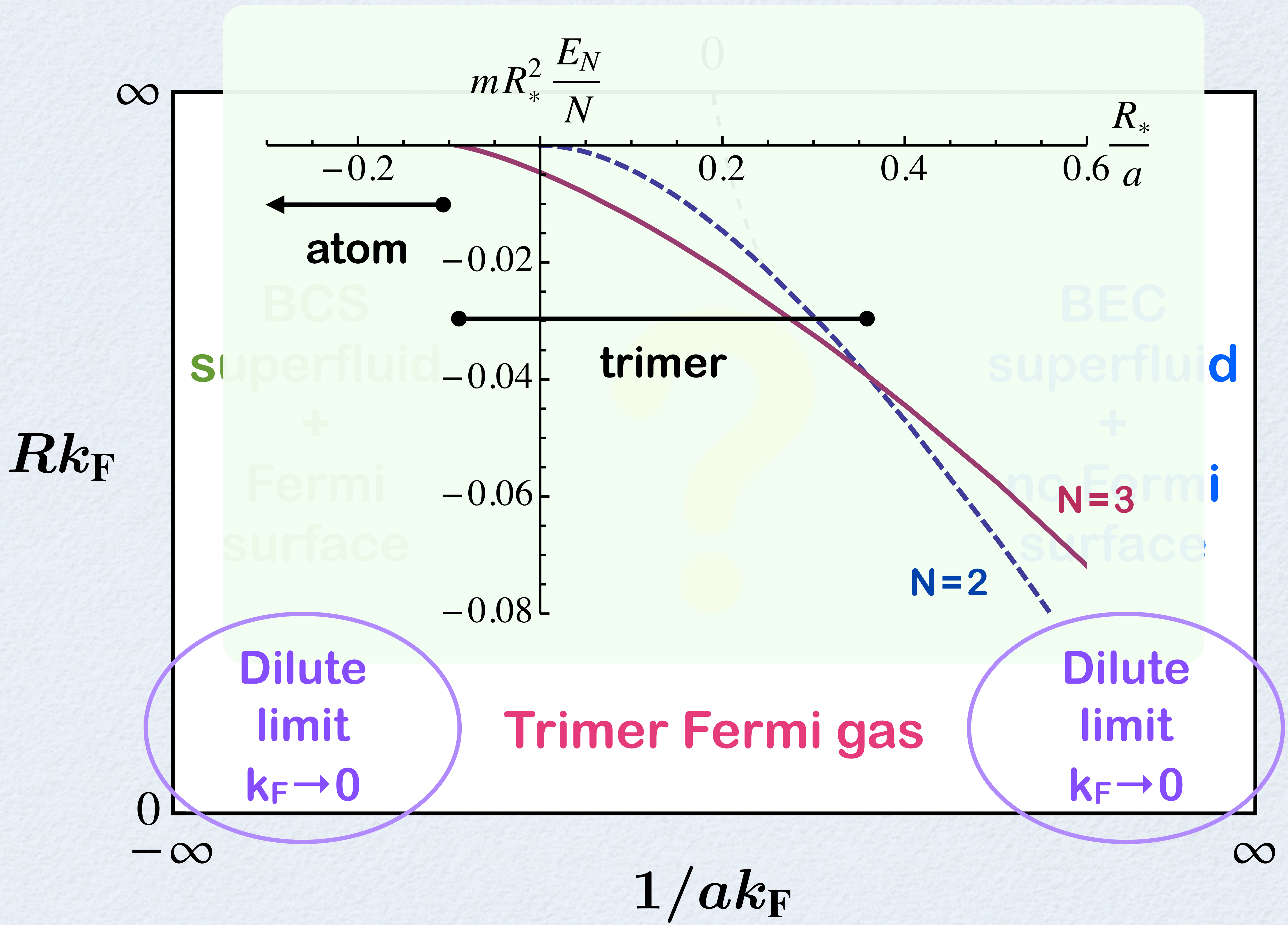
Phase diagram



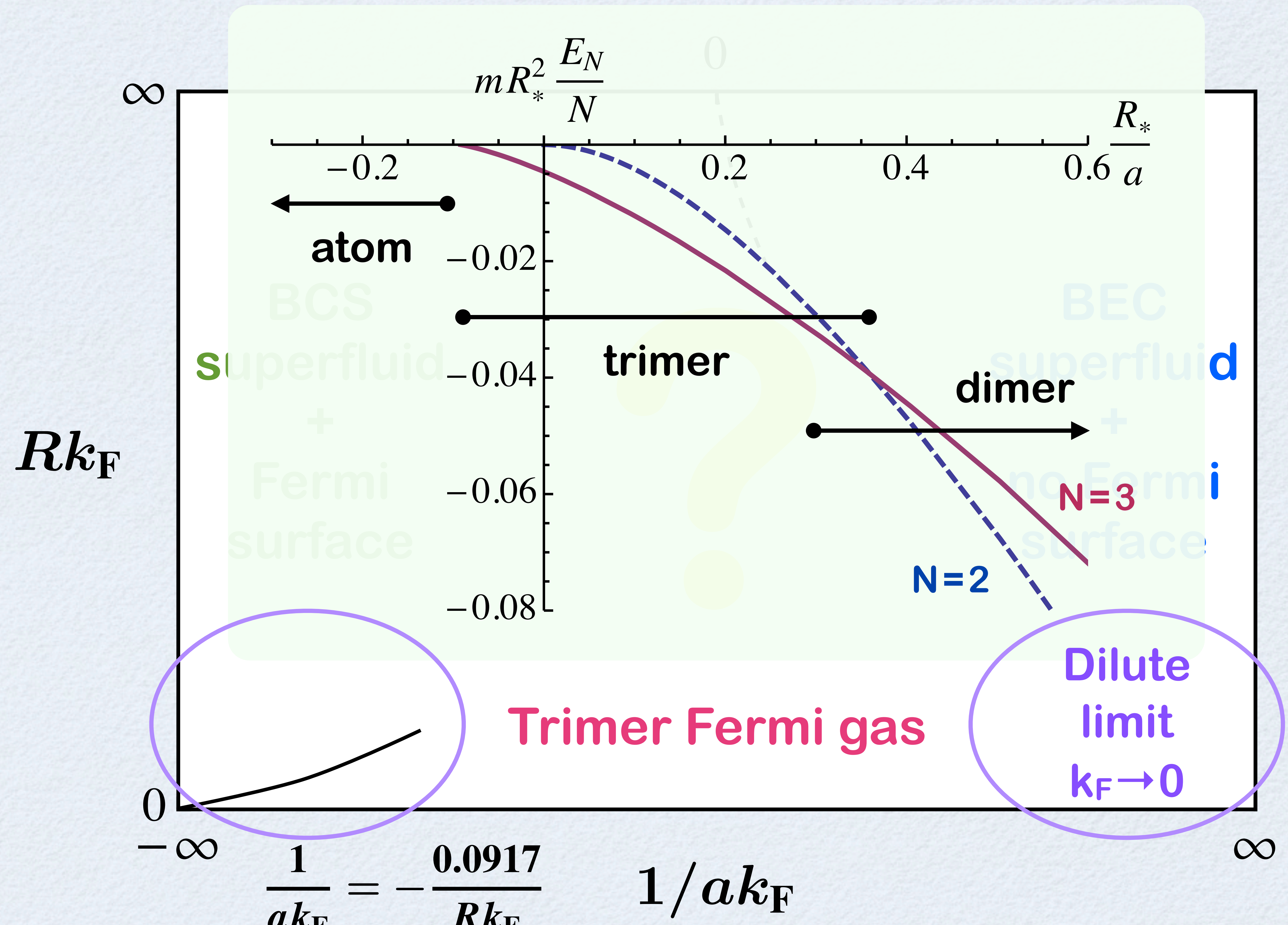
Phase diagram



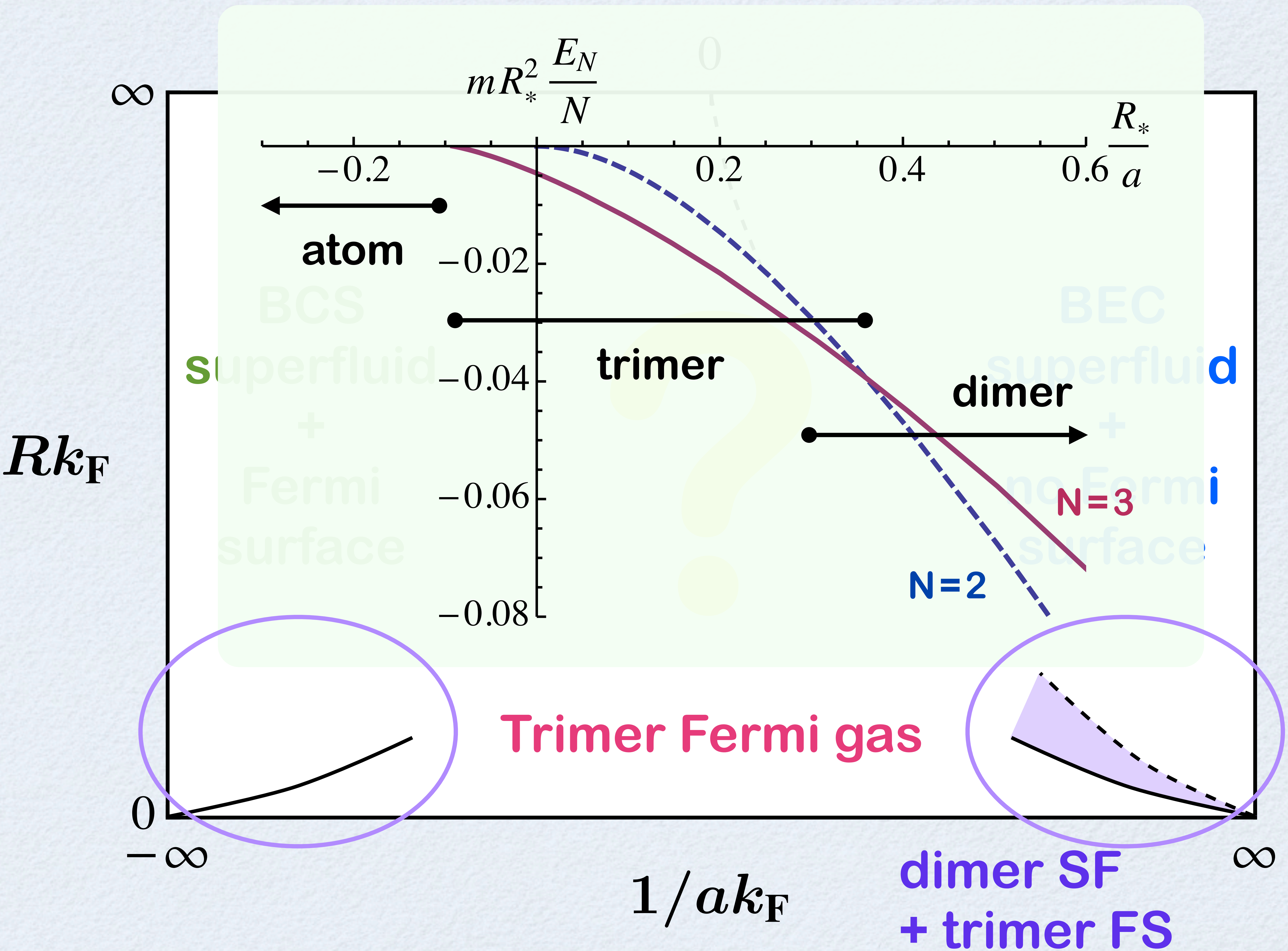
Phase diagram



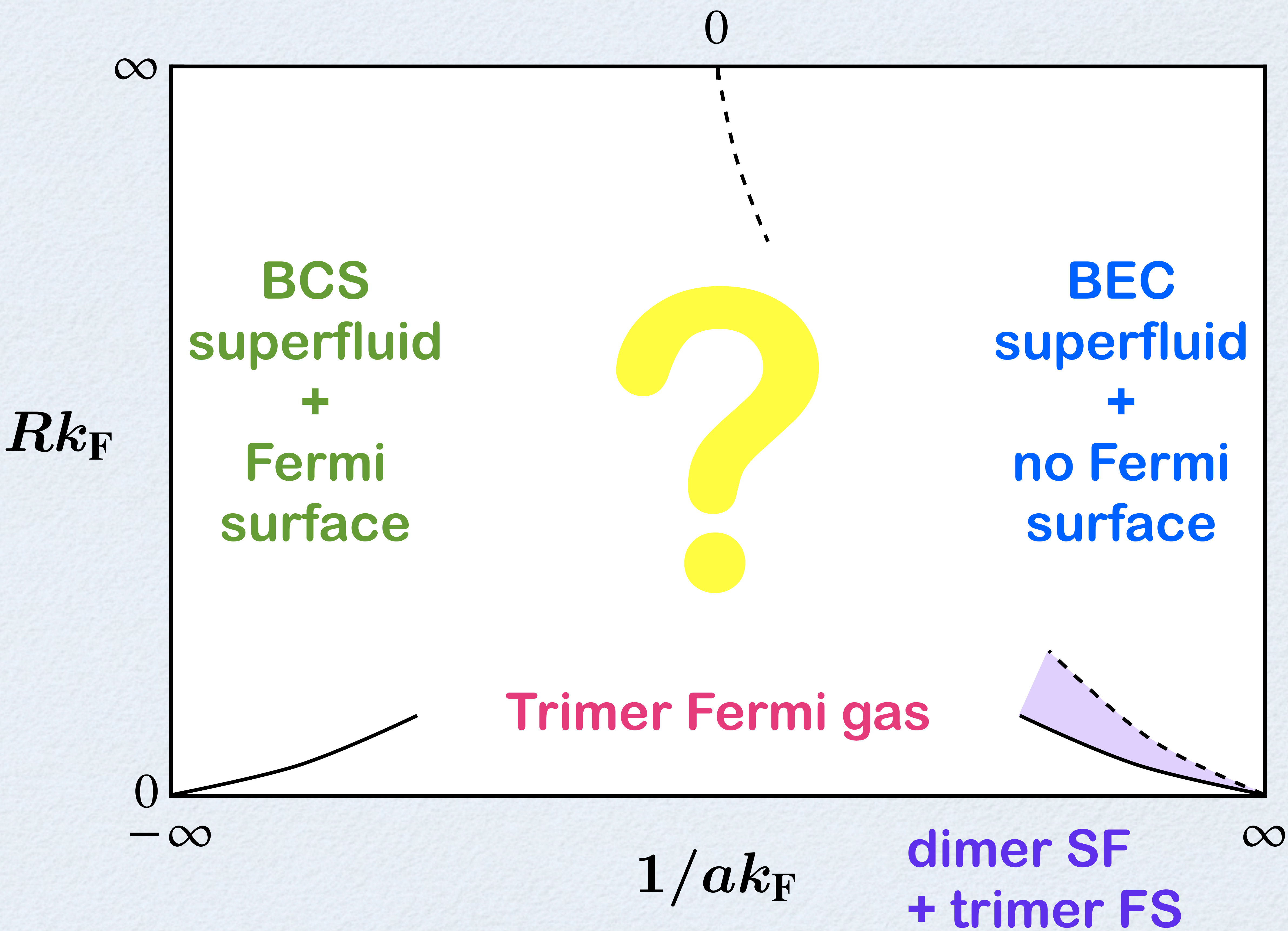
Phase diagram



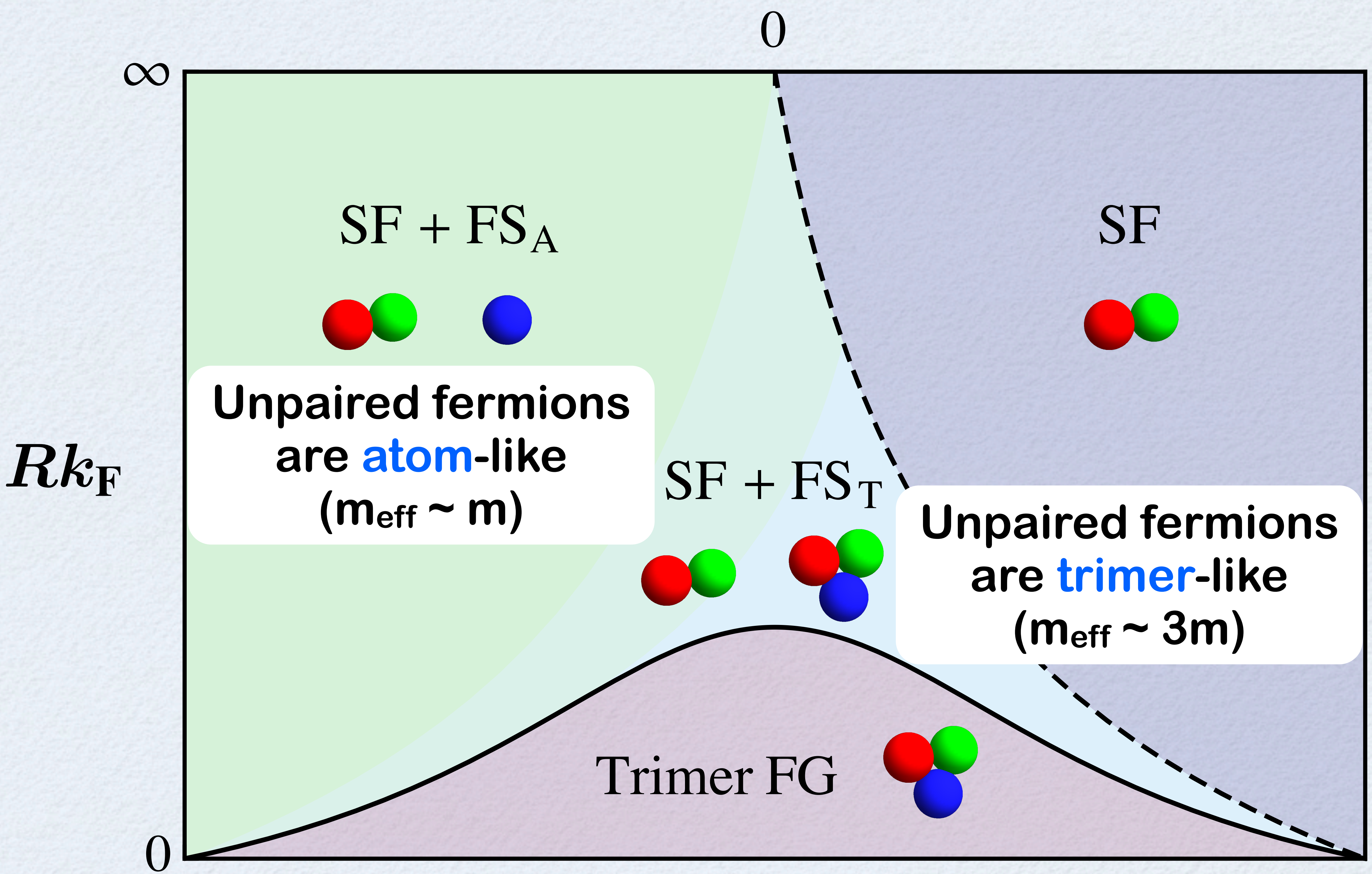
Phase diagram



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-

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

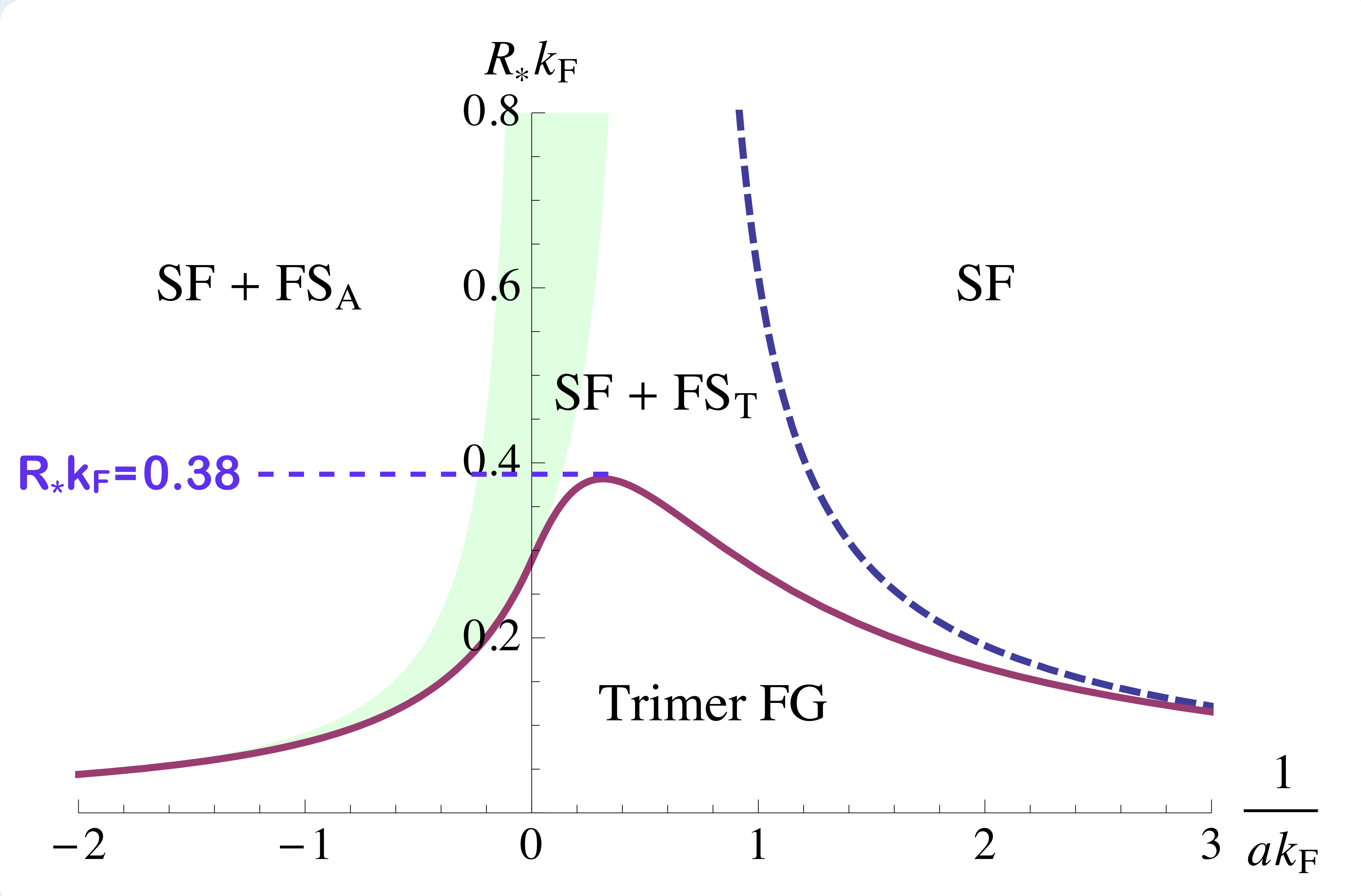
form [1]

New link between atomic and nuclear systems !

Mean-field + trimer model

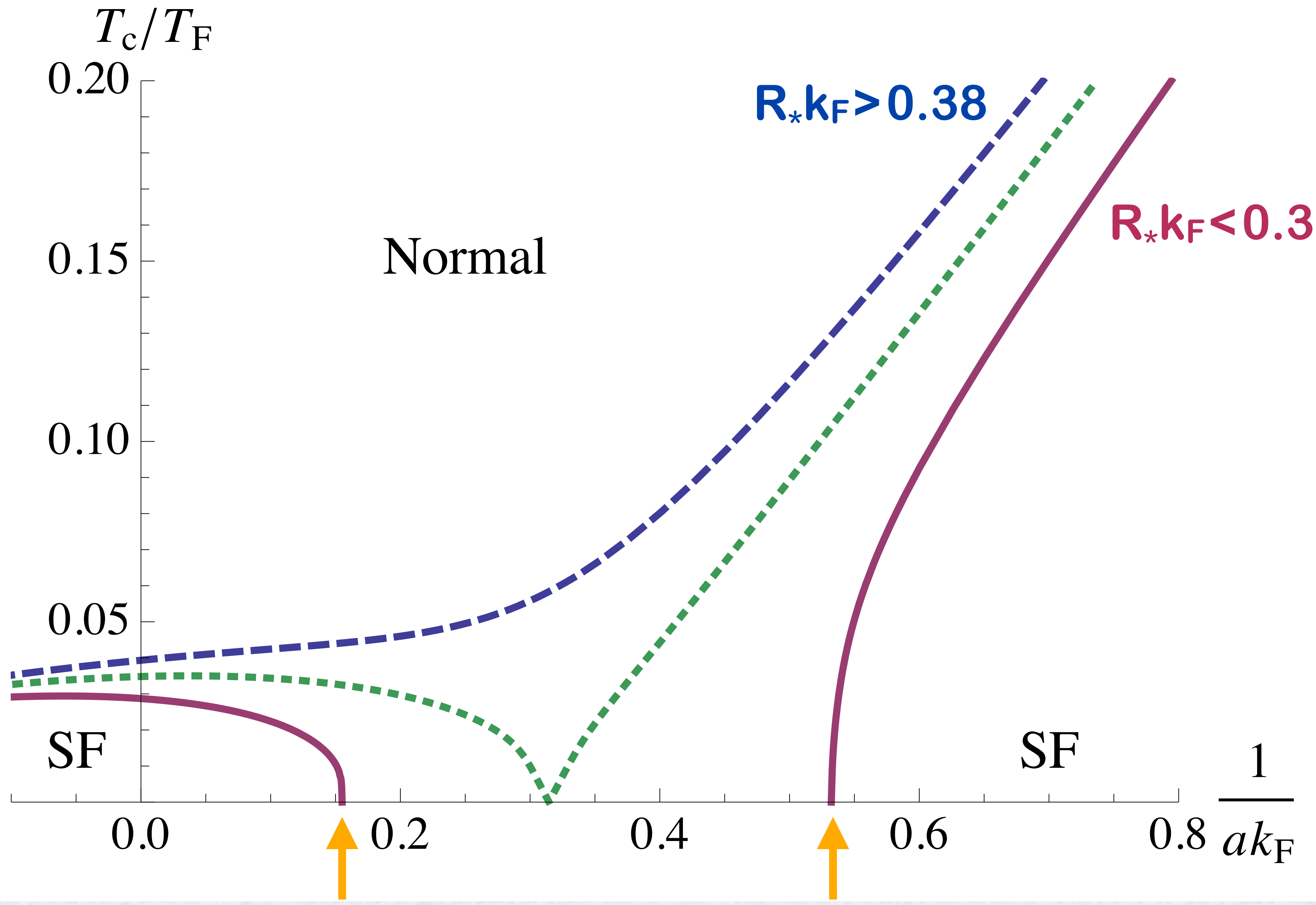
$$\Omega_{\mathrm{MF+T}} = \Omega_{\text{mean field}} + \Omega_{\text{trimer}}$$

knows correct asymptotic behaviors



Critical temperature

A pair of quantum critical points (complete depletion of SF) appear for $R_* k_F < 0.38$



See also, S. Floerchinger et al., PRA (2009)

Summary of this talk

1. "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]

2. "Quark-hadron continuity" in cold atoms

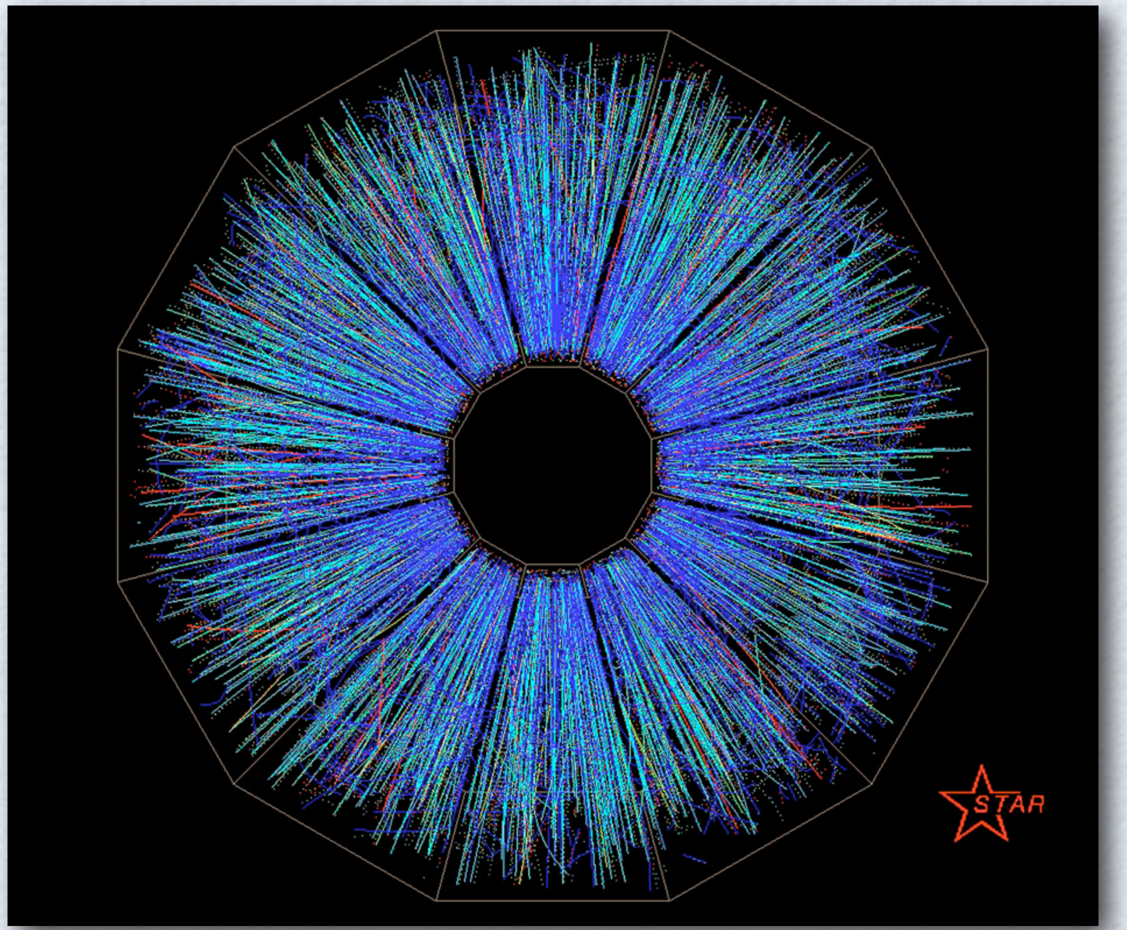
- Smooth crossover from atoms to trimers in 3-component Fermi gases

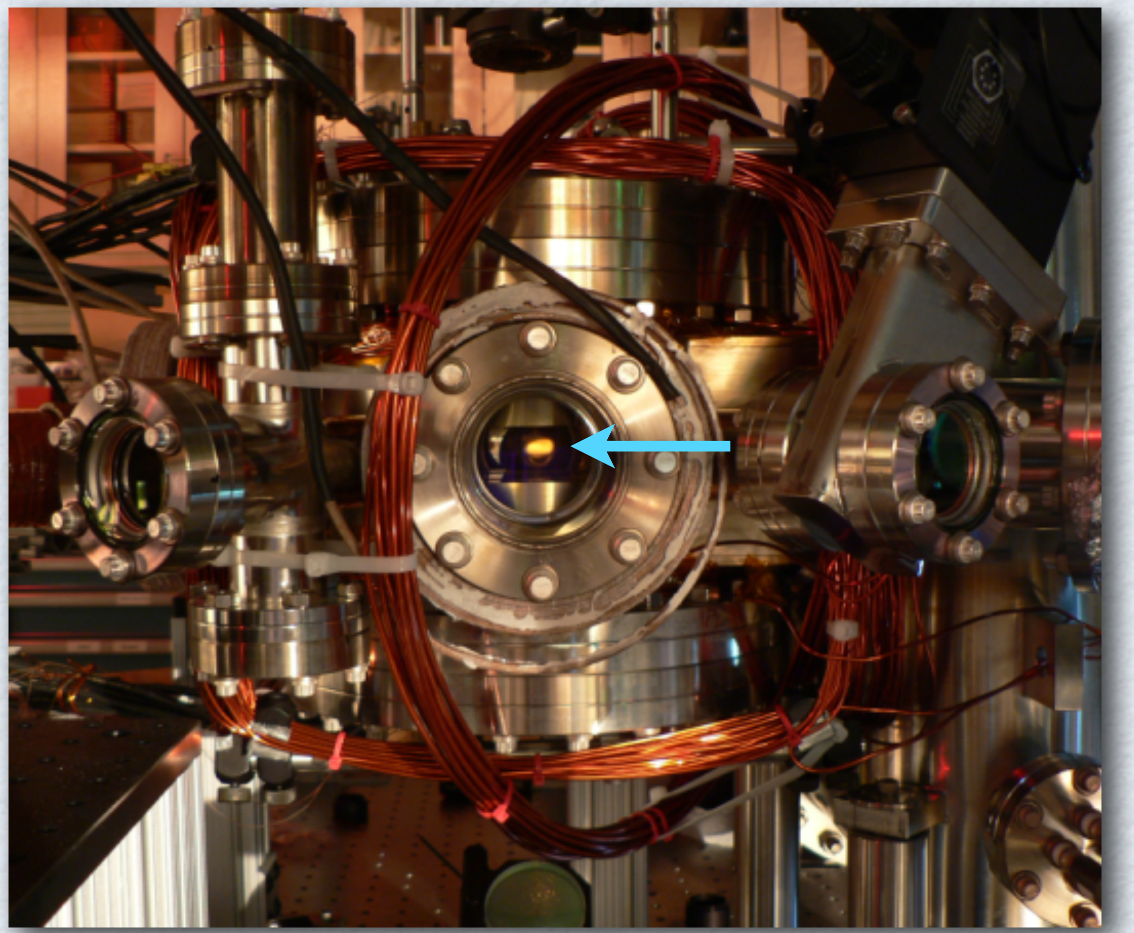
- Y.N., Phys. Rev. Lett. (2012) [arXiv:1207.6971]

Summary of this talk

Extreme QCD

Ultracold atoms





New ideas wanted !