"Hard probes" of strongly-interacting atomic gases

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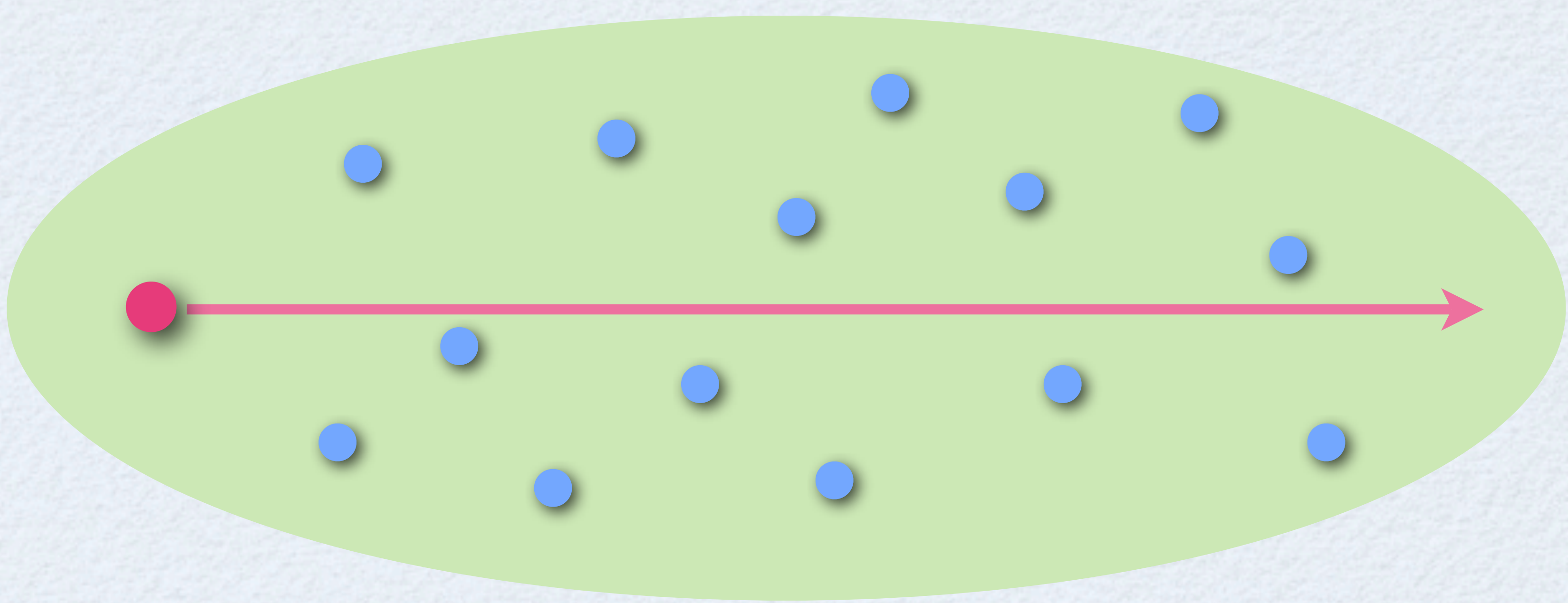
"Electron-Nucleus Scattering"
June 25 - 29 (2012)

LA-UR-12-22245

This talk is about ...

Energetic atom propagating through strongly-interacting atomic gases



✓ energetic atom ⇒ many-body system

✓ energetic atom ⇐ many-body system

This talk is about ...

Energetic atom propagating through strongly-interacting atomic gases

1. Motivations

- ✓ close connection to nuclear physics
- ✓ useful to locally probe many-body physics

2. Ideas & methods

- ✓ large-momentum expansion à la OPE

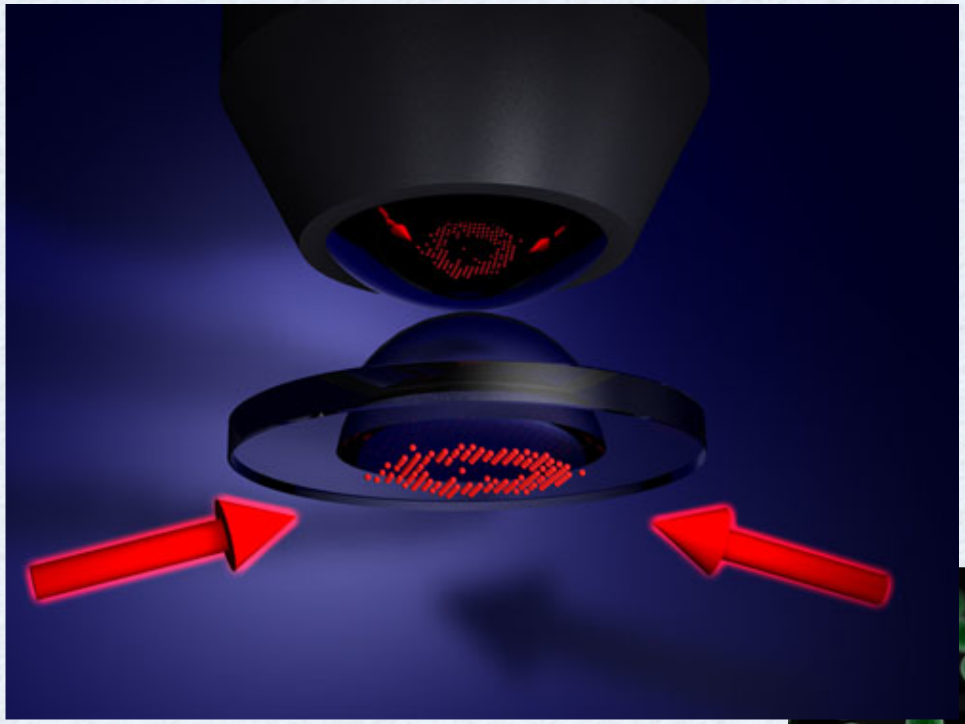
3. Results and discussions

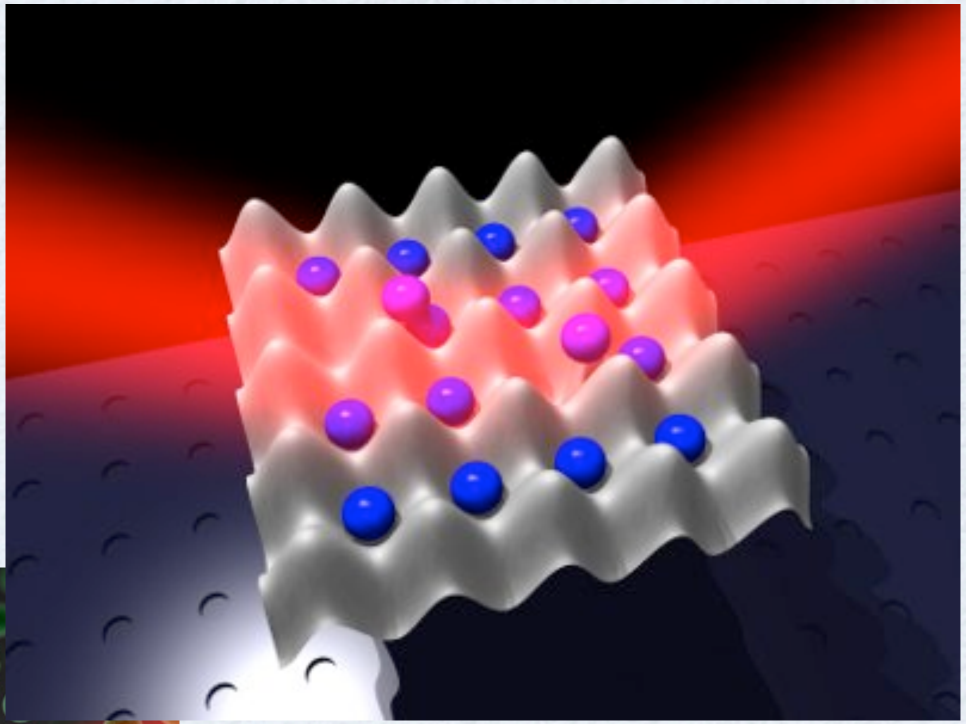
- ✓ energetic atom ⇒ many-body system
- ✓ energetic atom ⇐ many-body system

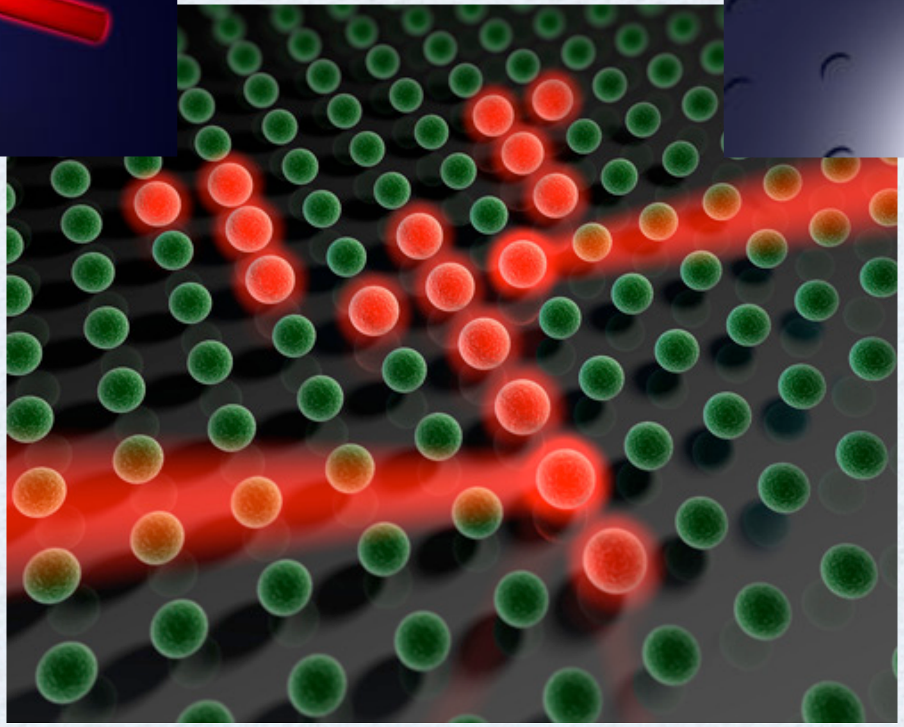
Motivations

How to probe target systems ?

Typically in ultracold atoms,
light is used to probe atoms

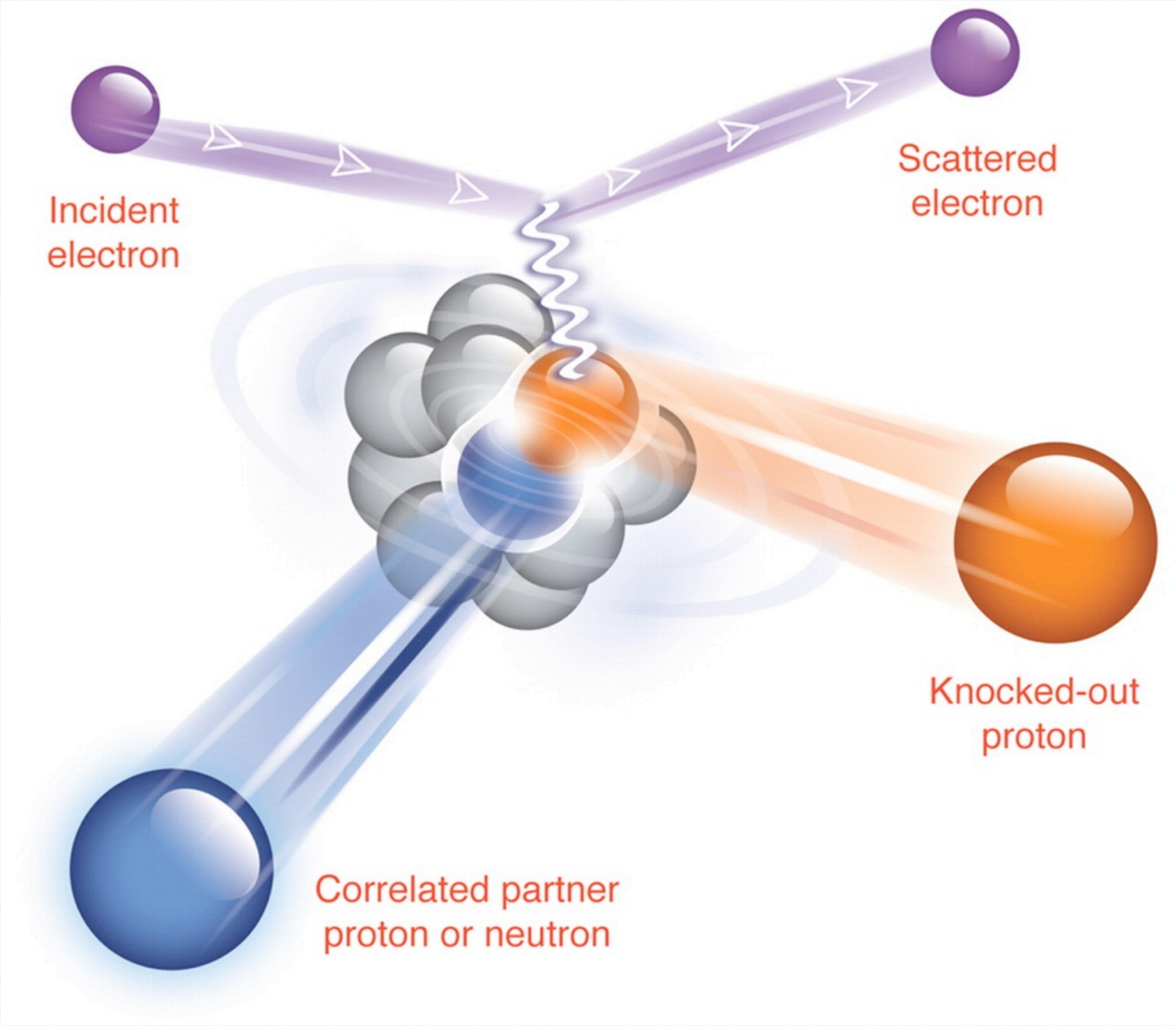


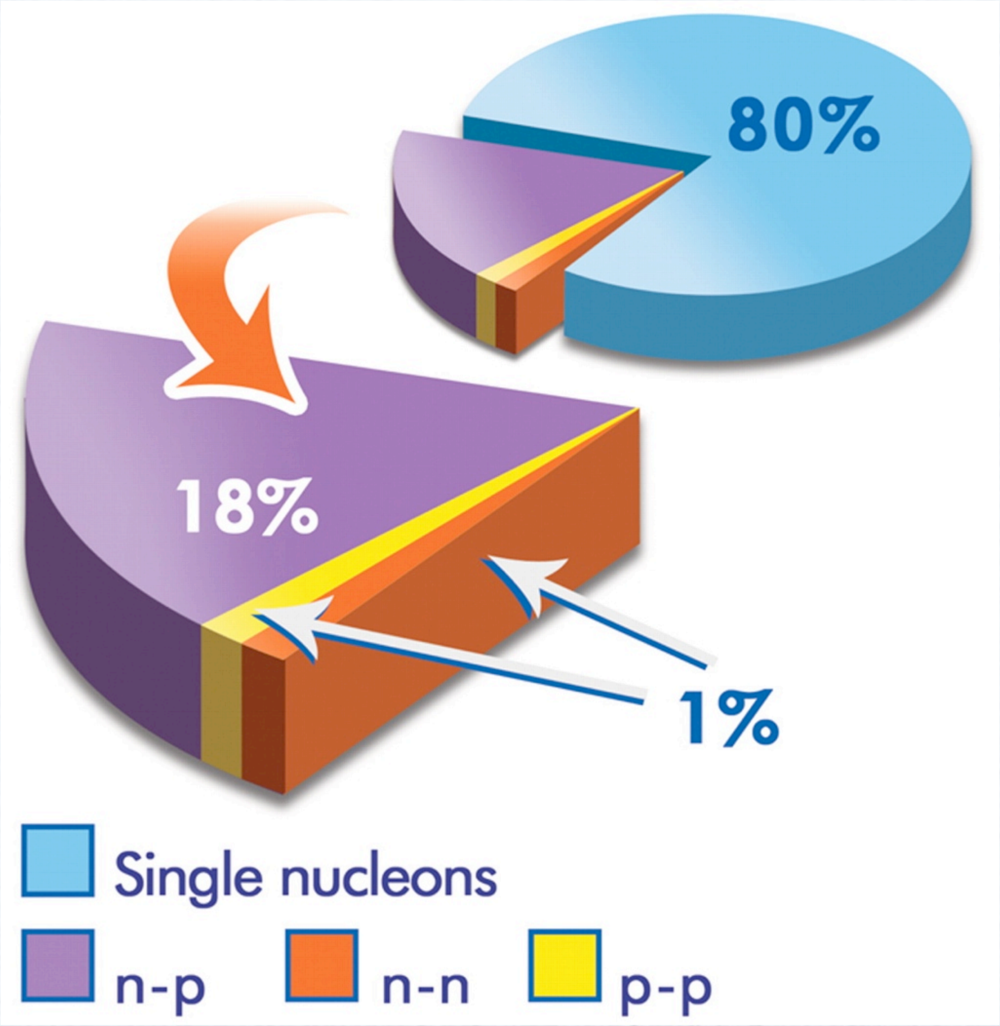




How to probe target systems ?

Often in nuclear and particle physics, "hard probes" (= high-energy particles) are used to probe target systems





JLab, Science 320, 1476 (2008)

How to probe target systems ?

"Hard probes" (= enegetic atoms) may be useful to probe target atomic gases

→ What can be probed ?   And how ?

- Microscopic Hamiltonian is simple

$$H = -\int dx \sum_{\sigma=\uparrow,\downarrow} \psi_\sigma^\dagger \frac{\nabla^2}{2m} \psi_\sigma + g \int dx dy\, \psi_\uparrow^\dagger \psi_\uparrow(x) \delta(x-y) \psi_\downarrow^\dagger \psi_\downarrow(y)$$

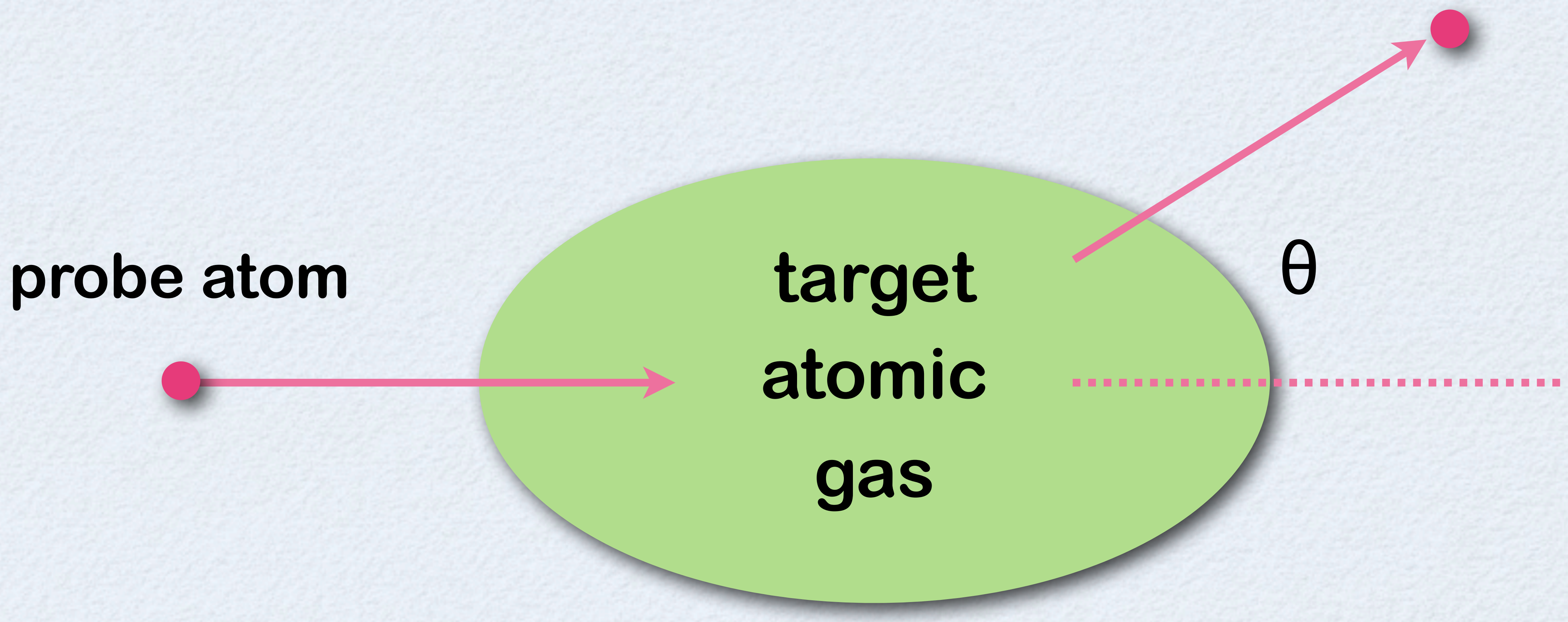
- Systematic approach is possible to develop strict results (without relying on phenomenology)

- Seen as an idealization of nuclear physics (by neglecting relativistic effects, isospins, finite range of interactions, 3-body forces, ...)

Energetic atom ⇒ many-body system

Probe atomic gas with atoms

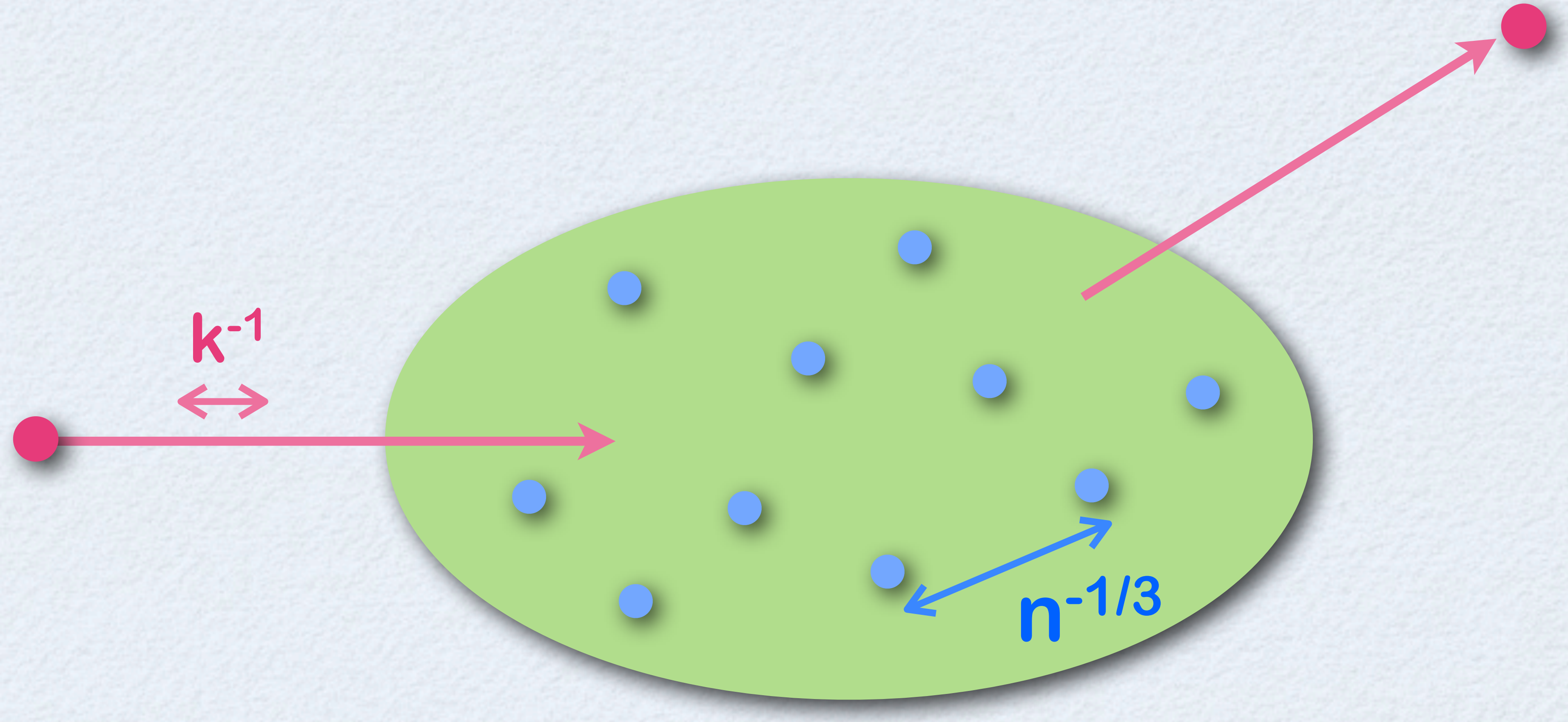
Shoot a probe atom into the target atomic gas and measure its differential scattering rate



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

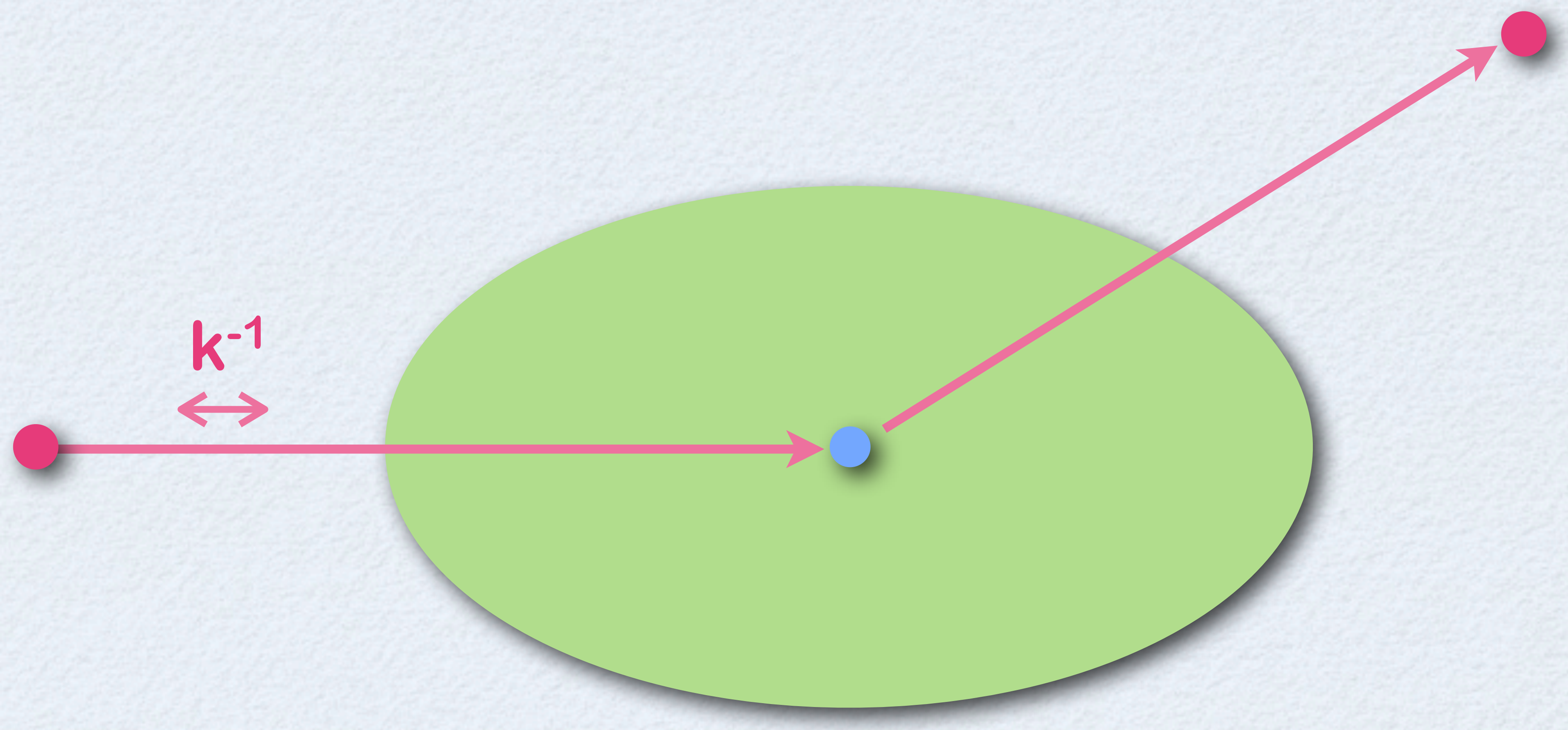


Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

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

Leading contribution

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

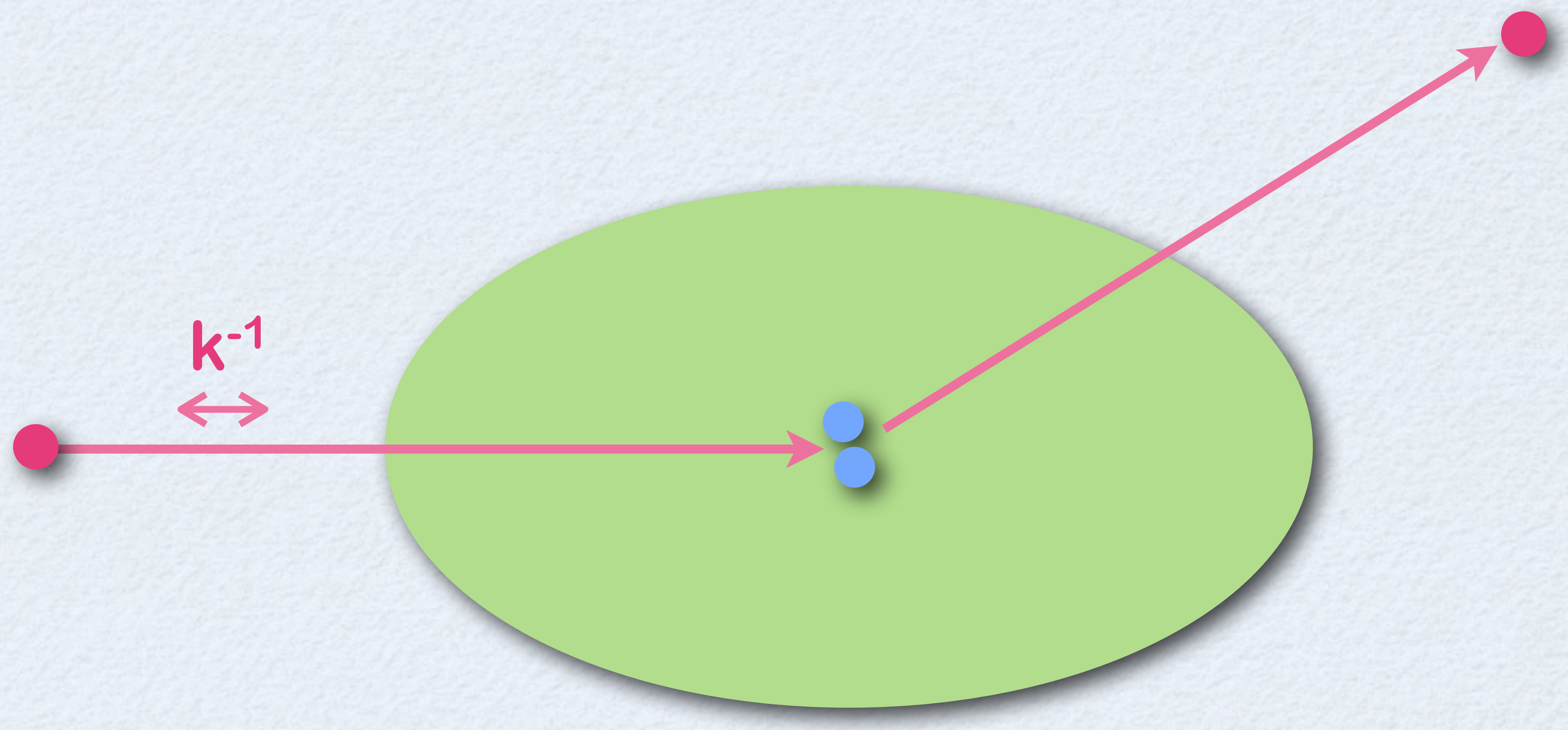


Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

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

Sub-leading contribution

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



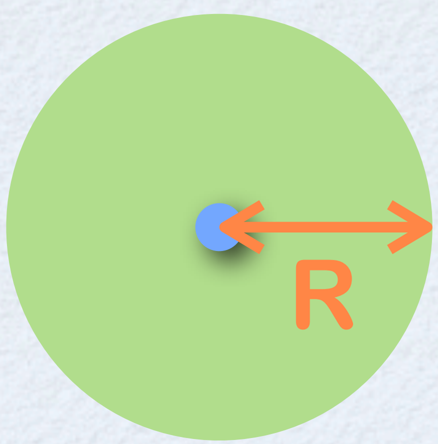
Large k ≫ n$^{1/3}$ ⇒ Few-body scattering problems

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

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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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

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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

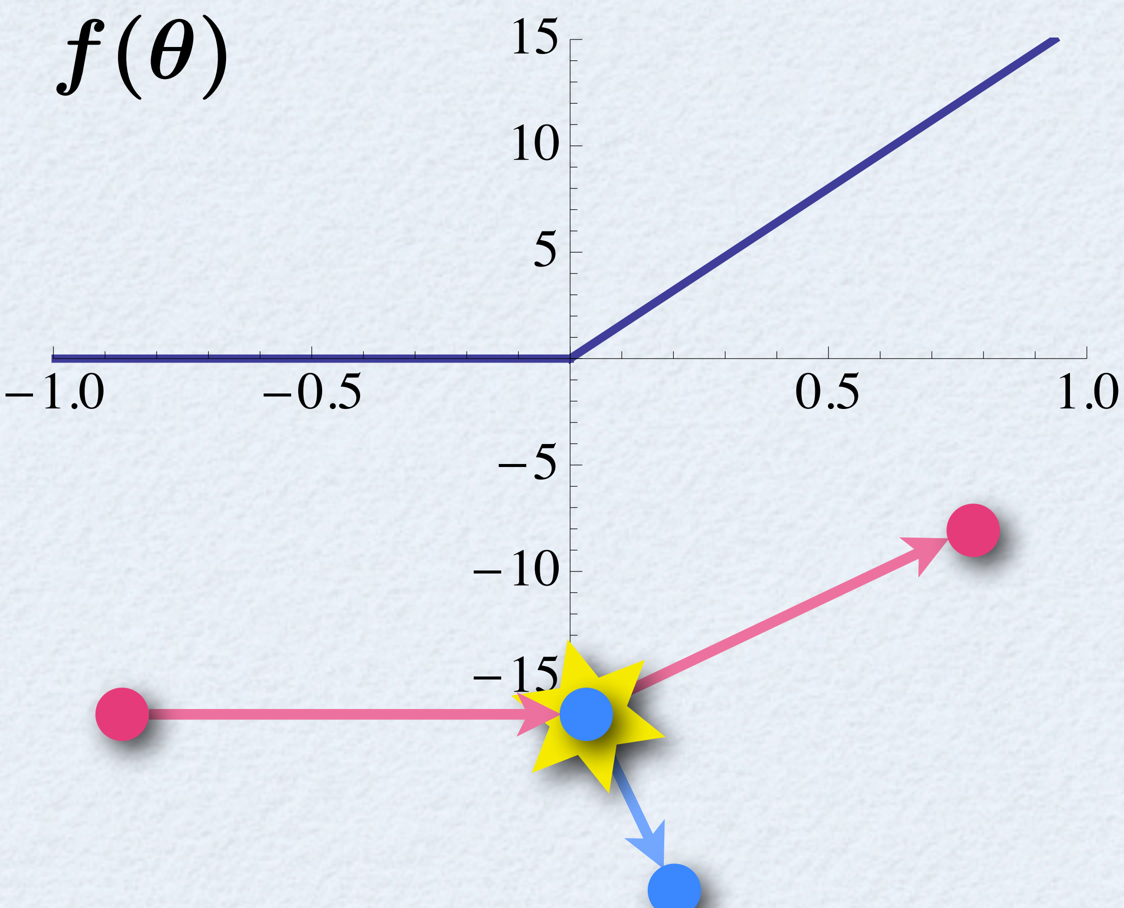
Few-body physics plays an important role to probe many-body physics !

Differential scattering rate

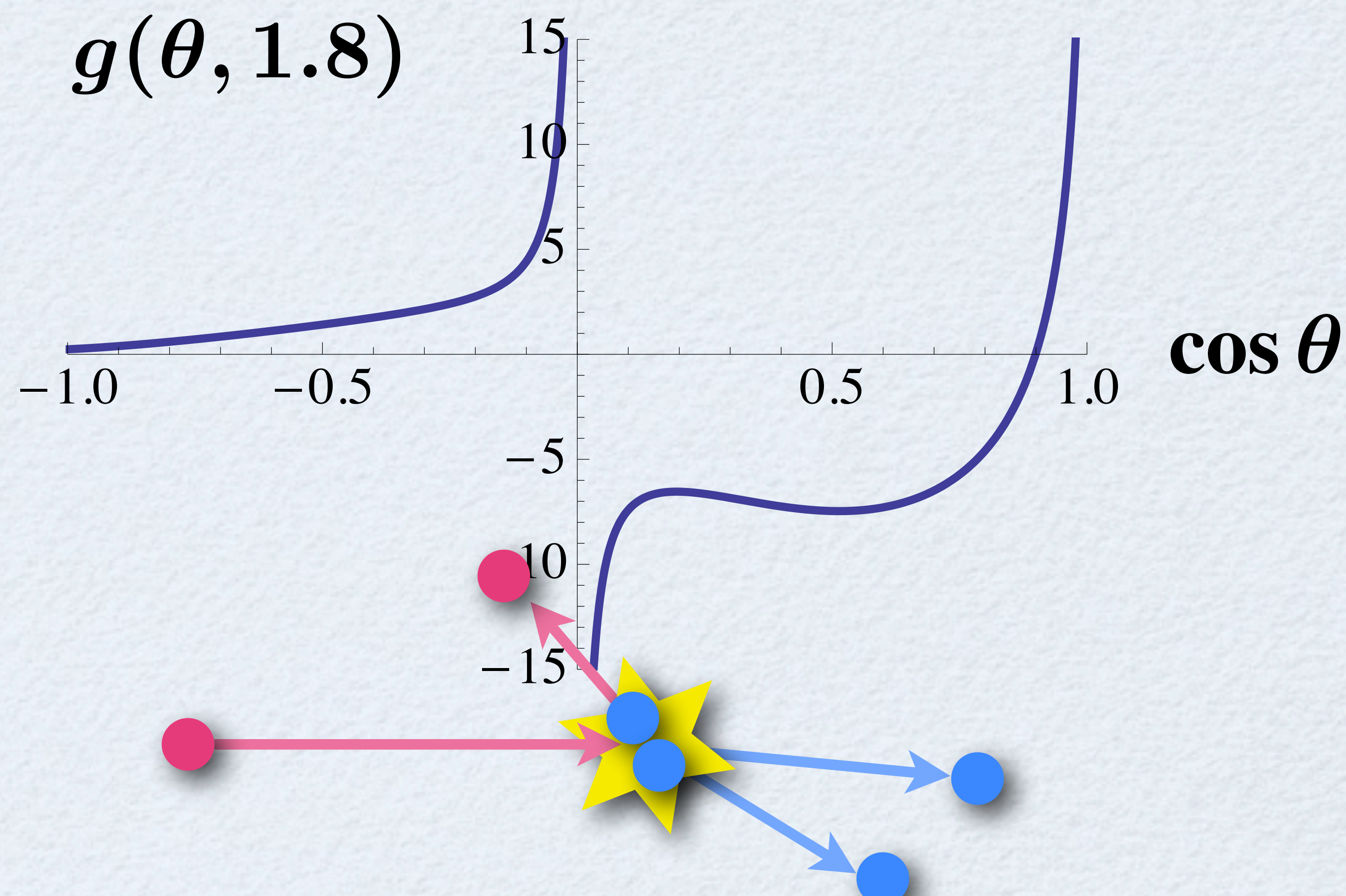
$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta, k/\kappa_*)\,\frac{C}{k^2} + \cdots$$

For zero-range interactions

Efimov effect



forward scattering (θ<90°) only



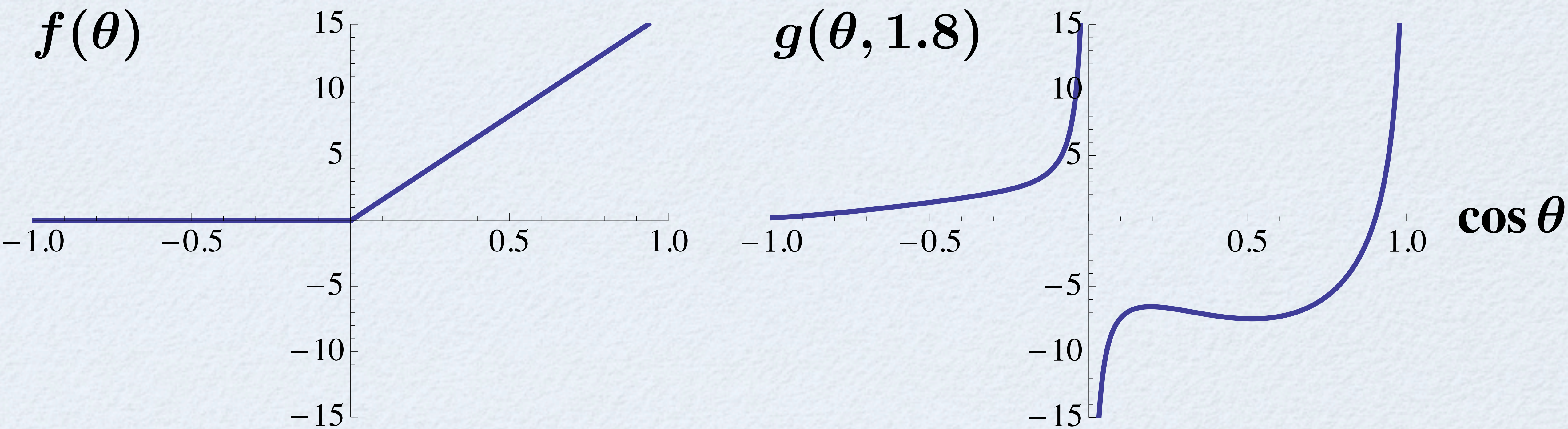
backward scattering (θ>90°) possible

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



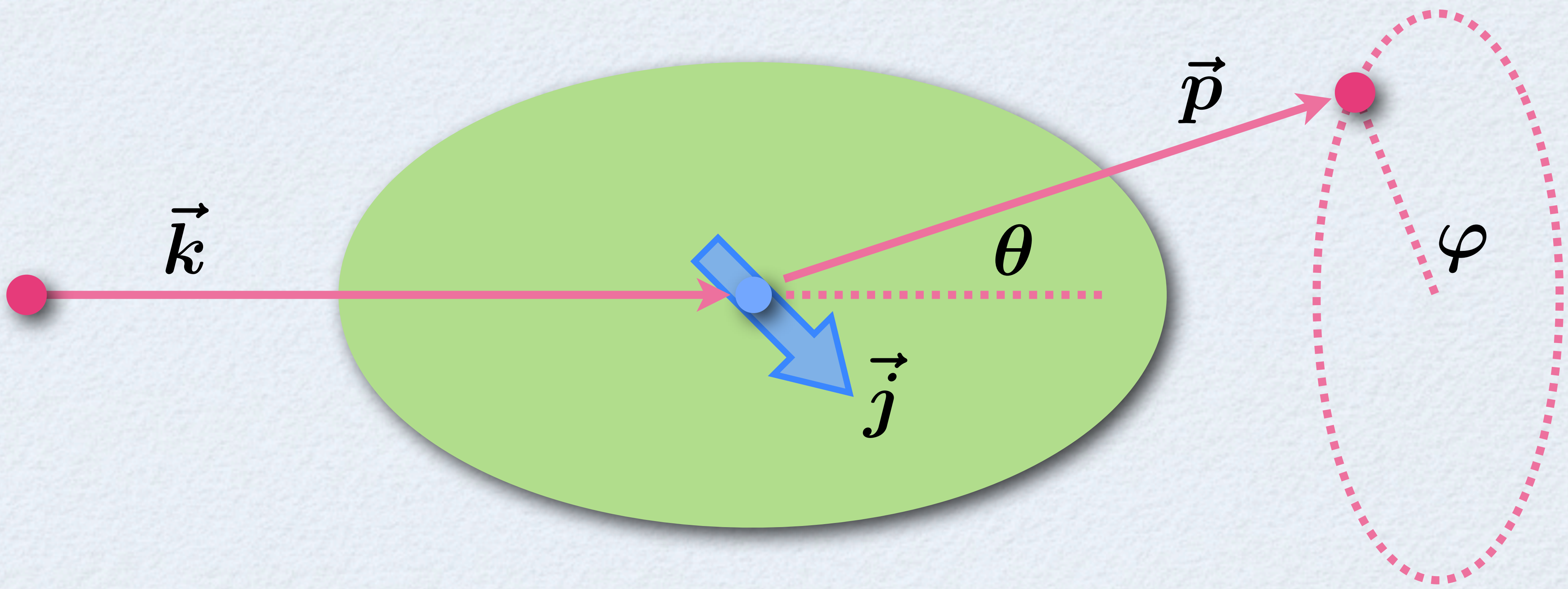
Backward scattering rate measures contact density

→ New local probe of strongly-int atomic gases

Differential scattering rate

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

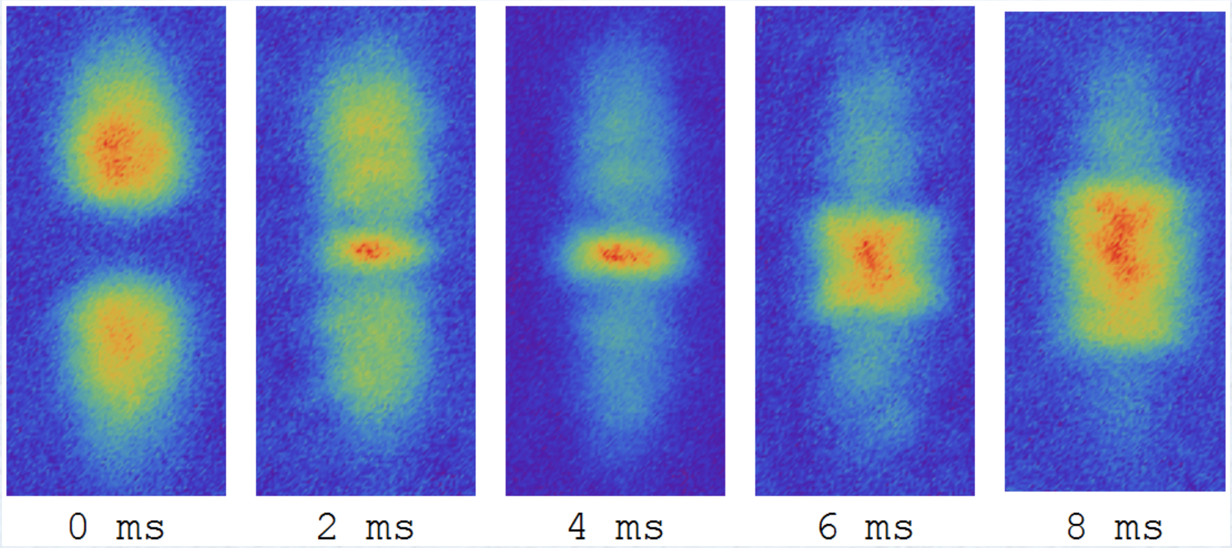
$$+\,16\,\Theta(\cos\theta)\,(2\cos\theta\,\hat{k} + \hat{p})\cdot\frac{\vec{j}}{k^2} + \cdots$$



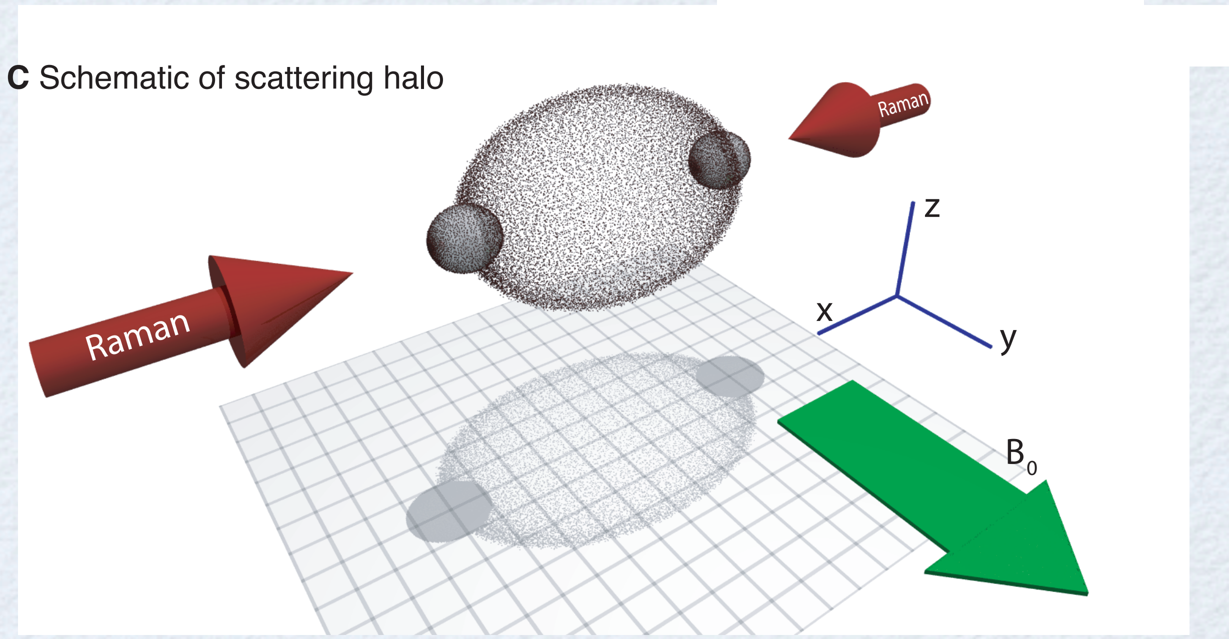
Azimuthal (φ) anisotropy reveals currents in many-body states

Ultracold atom “colliders”

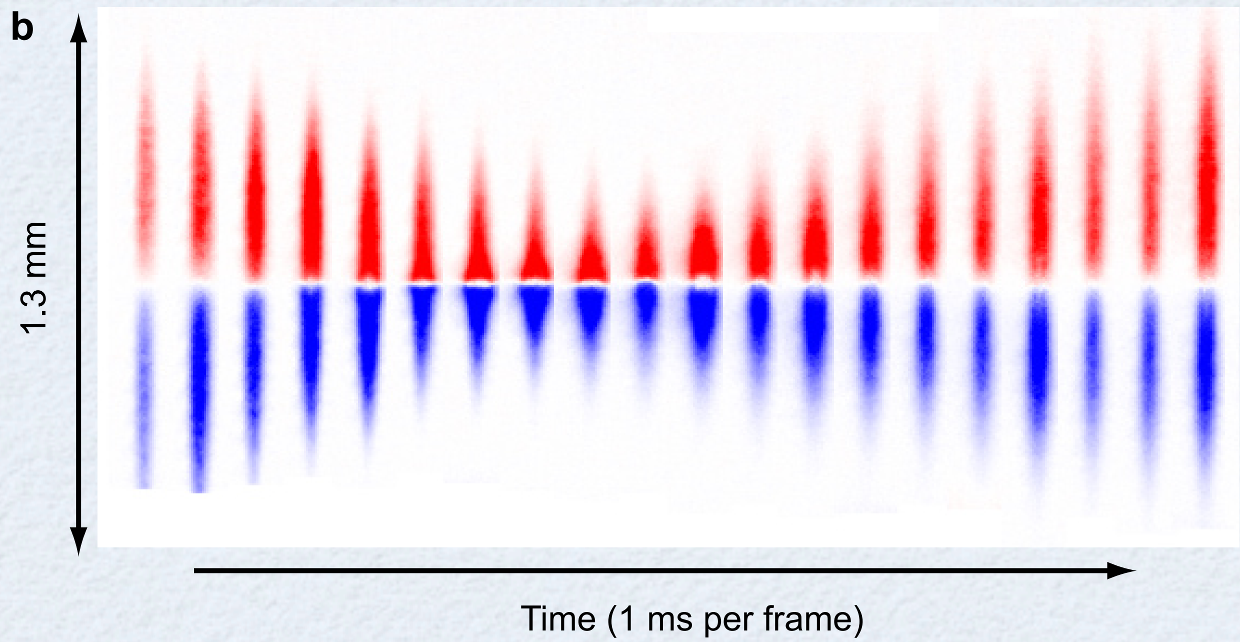
Duke (2011)



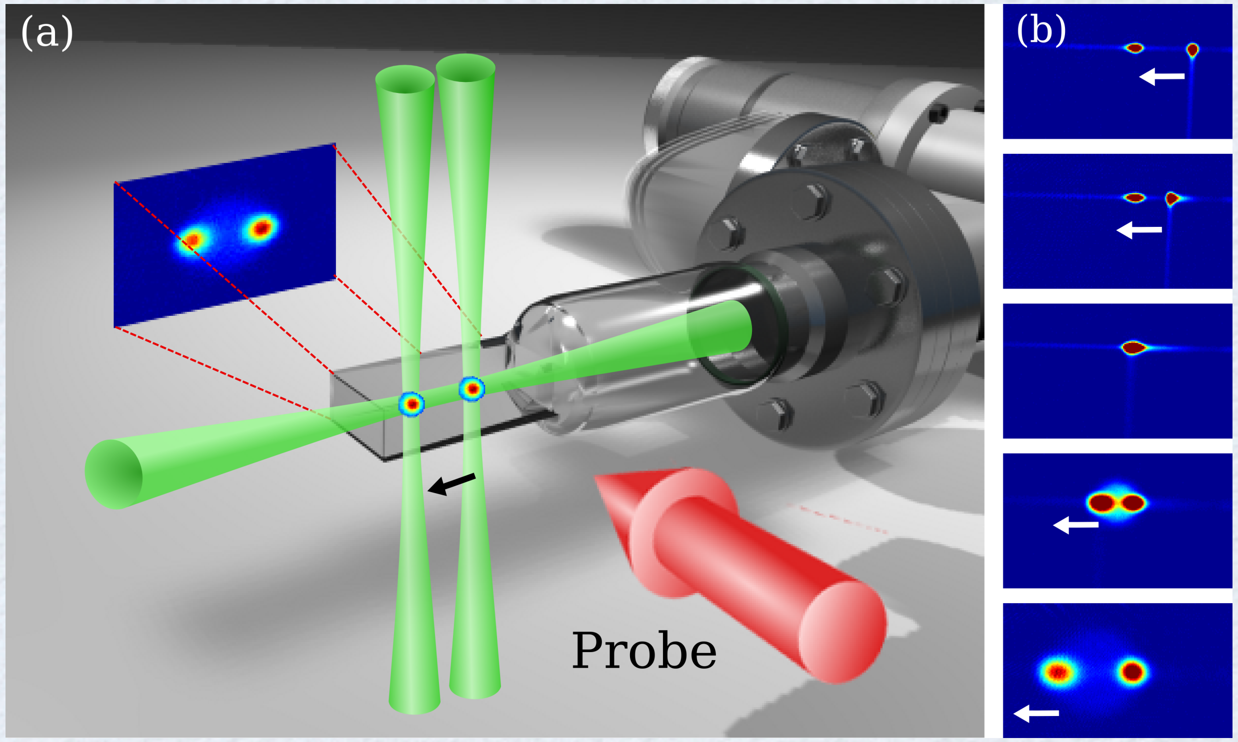
NIST (2012)



MIT (2011)

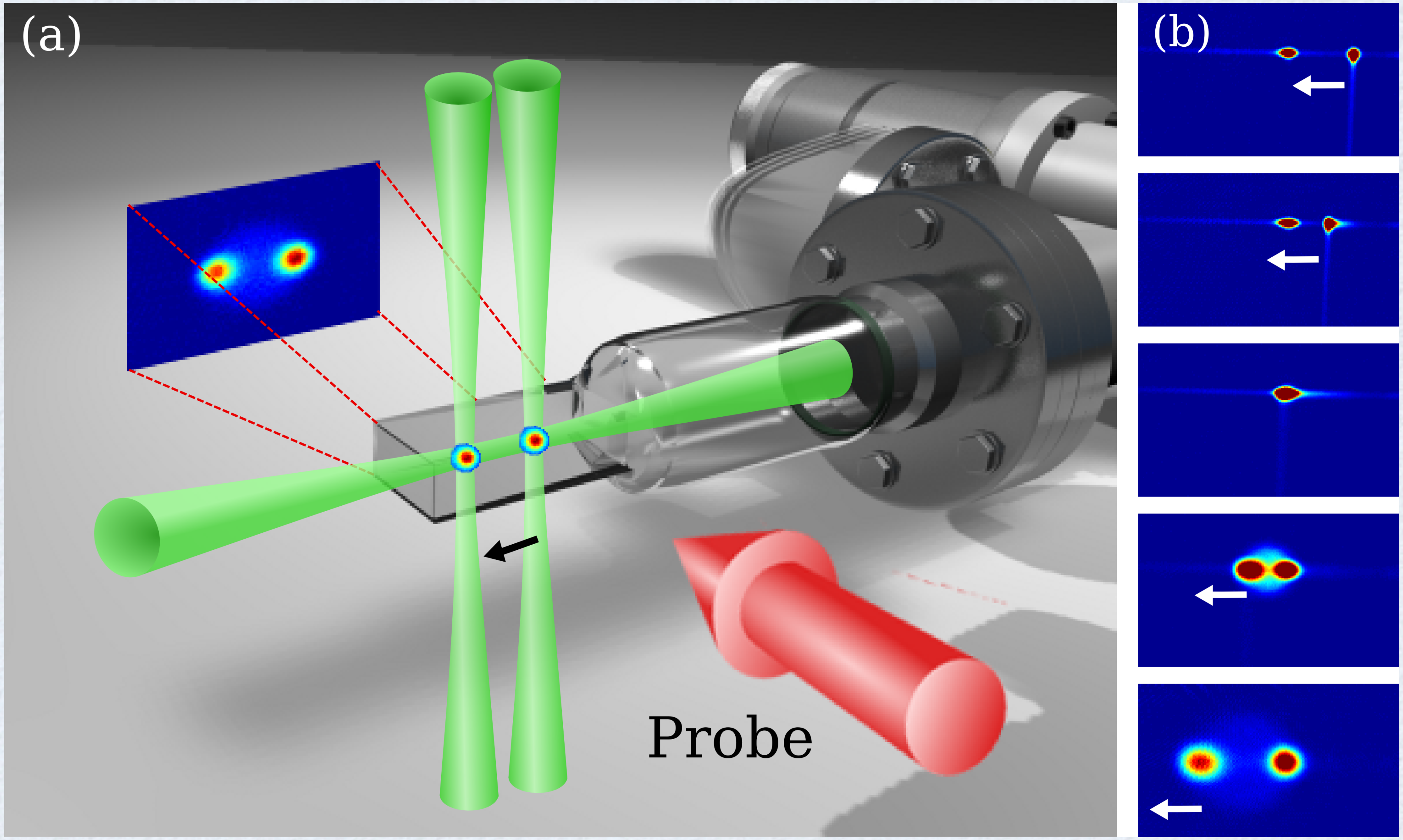


Otago (2012)



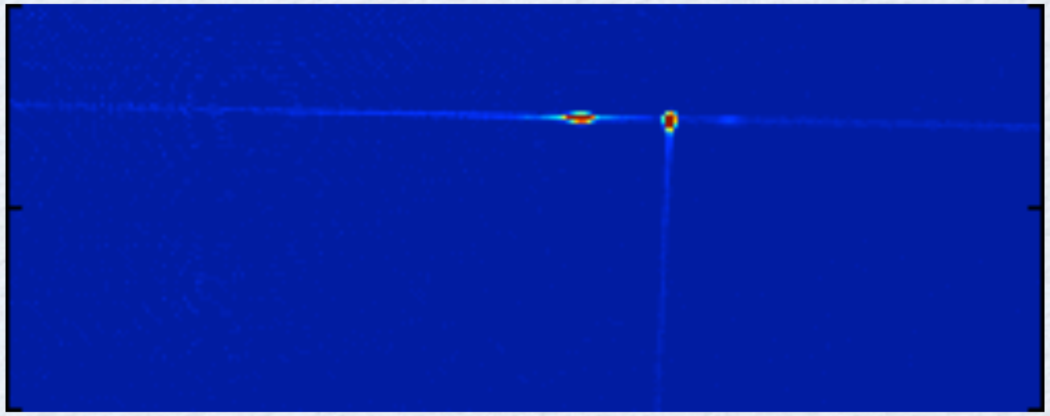
Ultracold atom "colliders"

"A laser based accelerator for ultracold atoms"



University of Otago
(New Zeeland)

Optics Letters (2012)



Energetic atom ⇒ many-body system

Energetic atom $\Leftarrow$

many-body system

Energy in a Fermi gas

$$E_{\uparrow}(k) = \frac{k^2}{2m}$$

$$\Gamma_{\uparrow}(k) = 0$$

Energetic spin-↑ fermion

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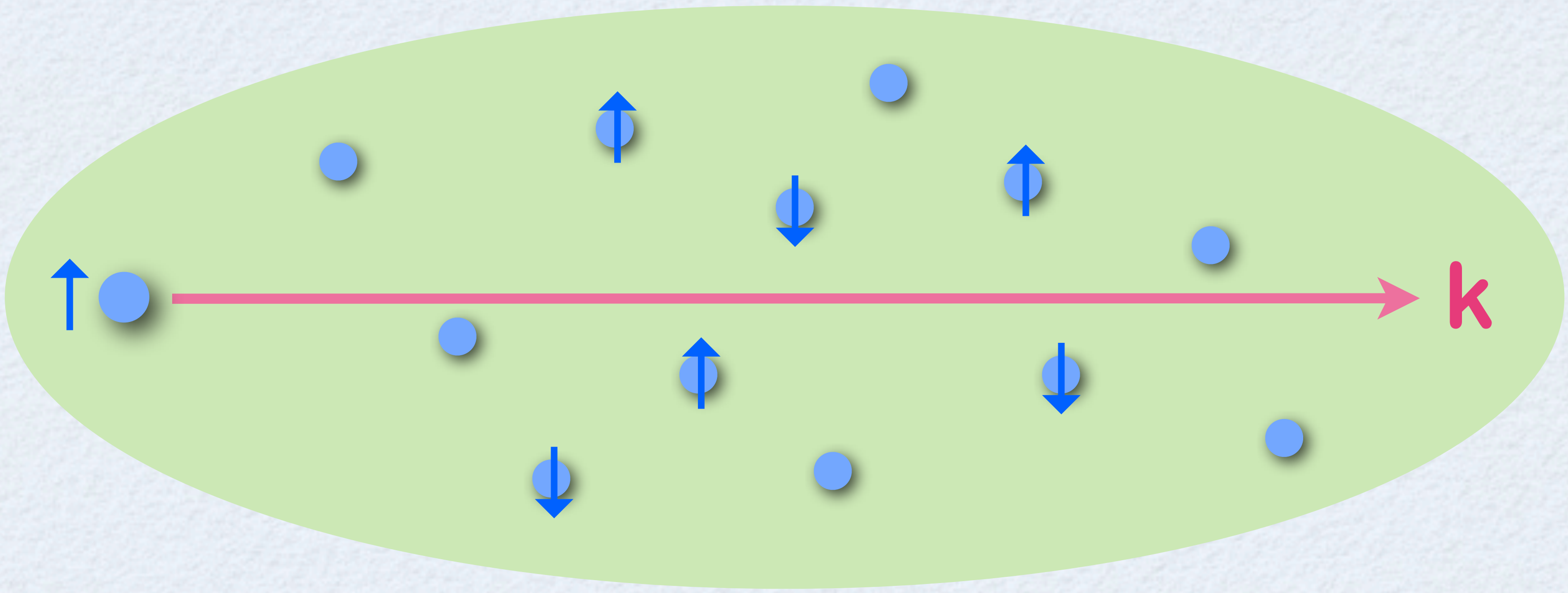


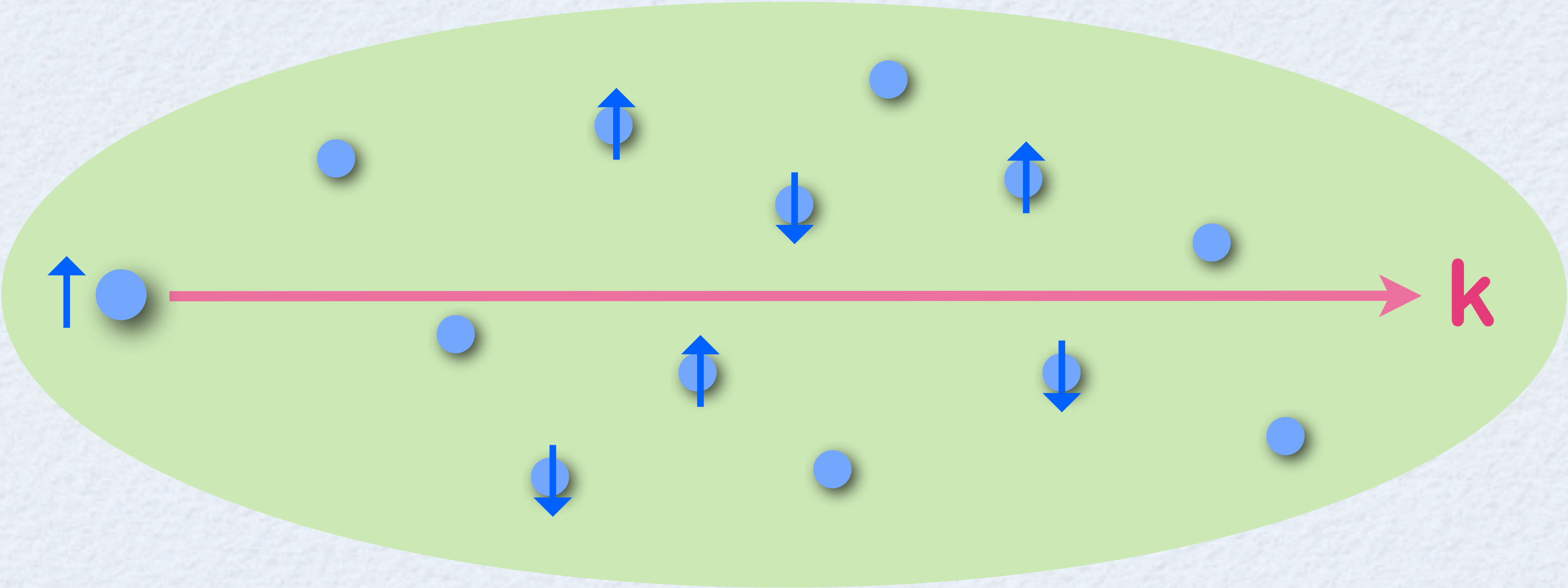
Energetic spin-↑ fermion

in a Fermi gas with scattering length a

Energy in a Fermi gas

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

$$\Gamma_\uparrow(k) = \left[32\pi \left(1 - \frac{4}{a^2k^2}\right) \frac{n_\downarrow}{k^3} + 44.2 \frac{C}{ak^5} + O(k^{-6})\right] \frac{k^2}{2m}$$



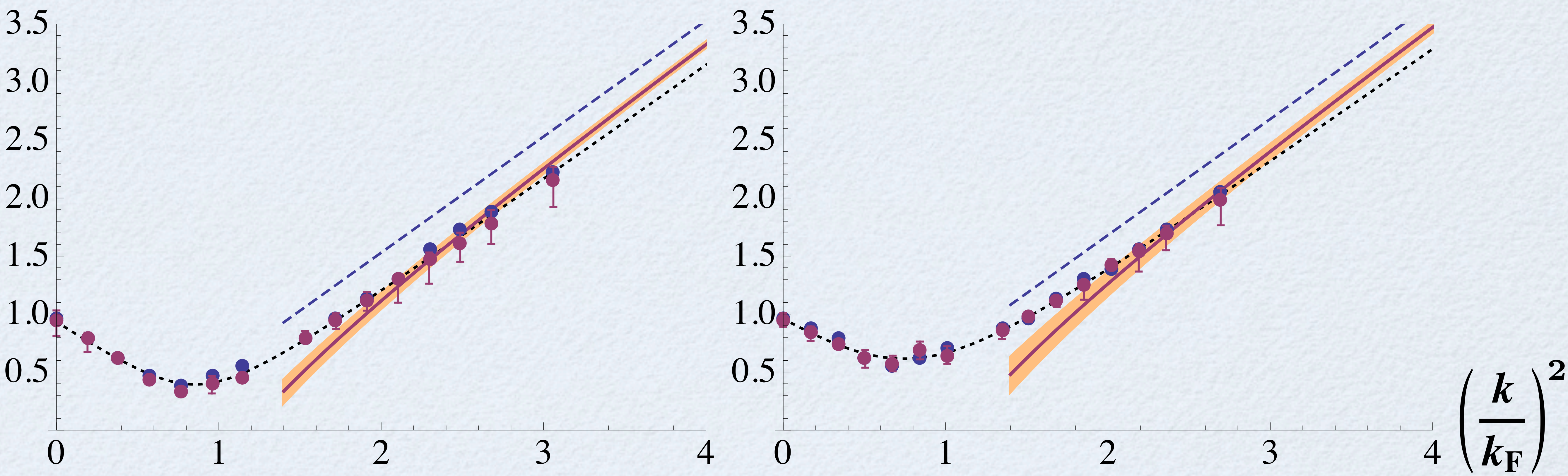
Energetic spin-↑ fermion

in a Fermi gas with scattering length a

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

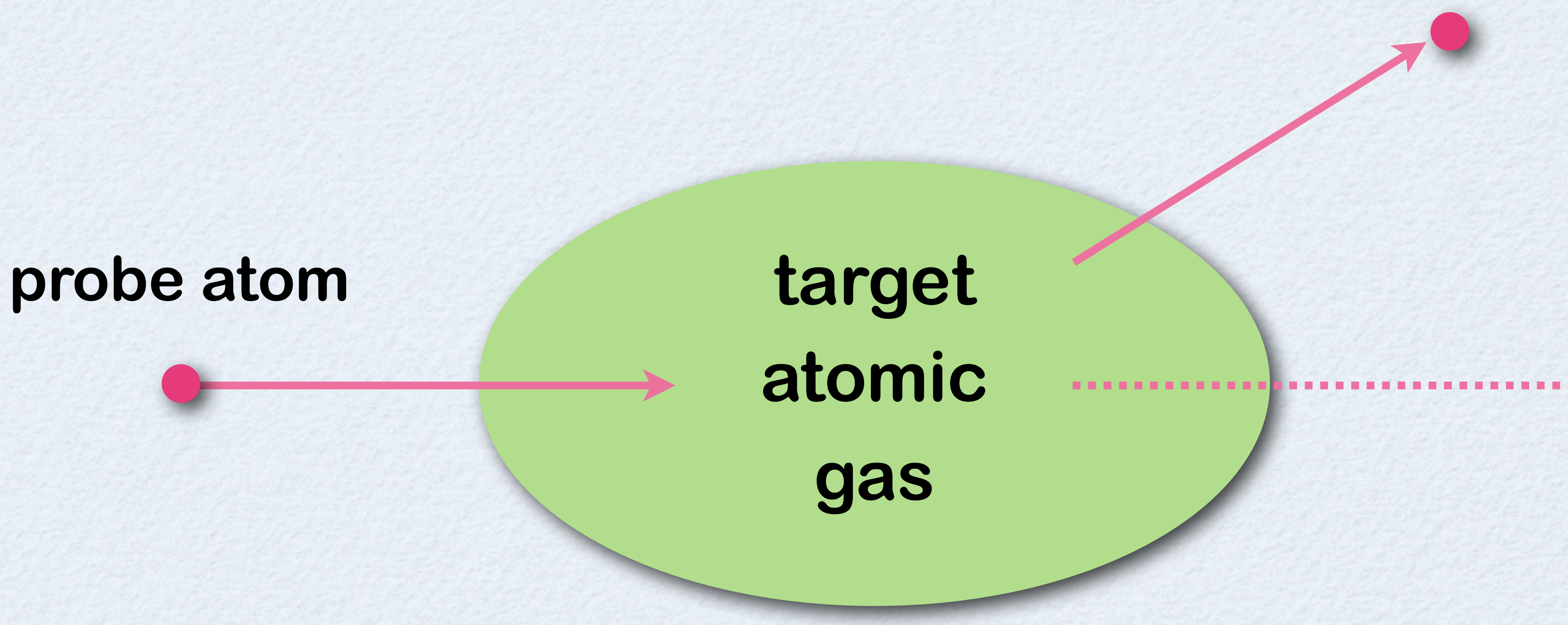
$(a_f k_F)^{-1} = 0.2 \quad T/\epsilon_F = 0.19$

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

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

Summary of this talk

- 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

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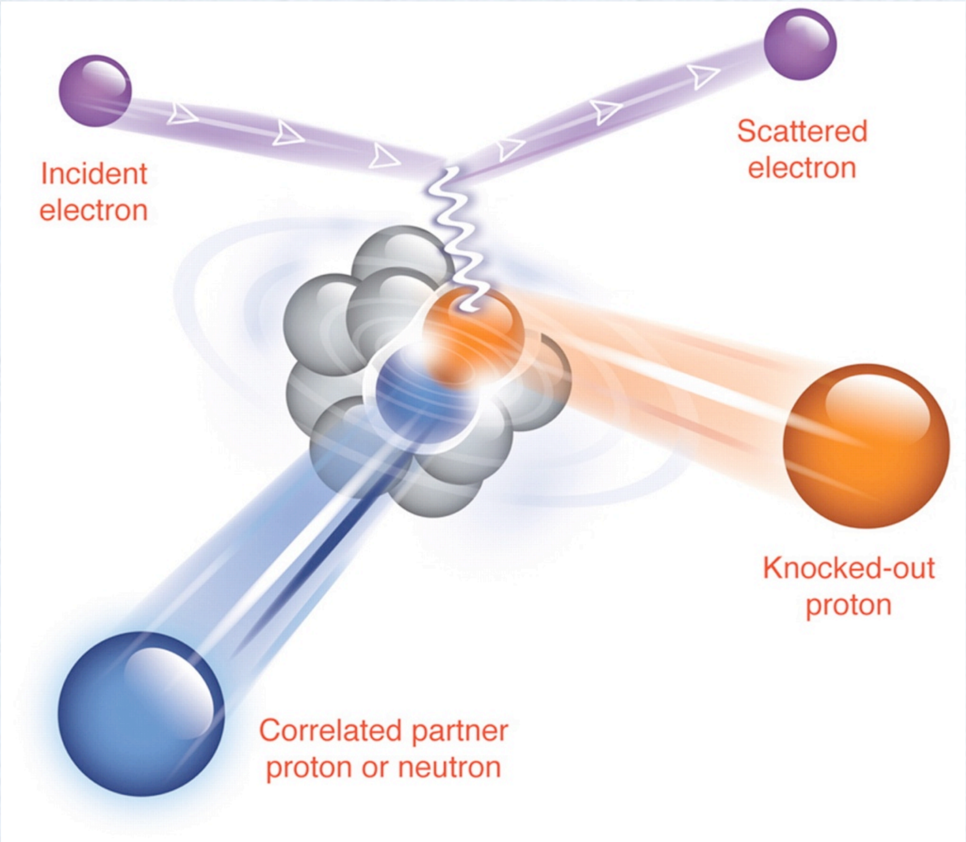

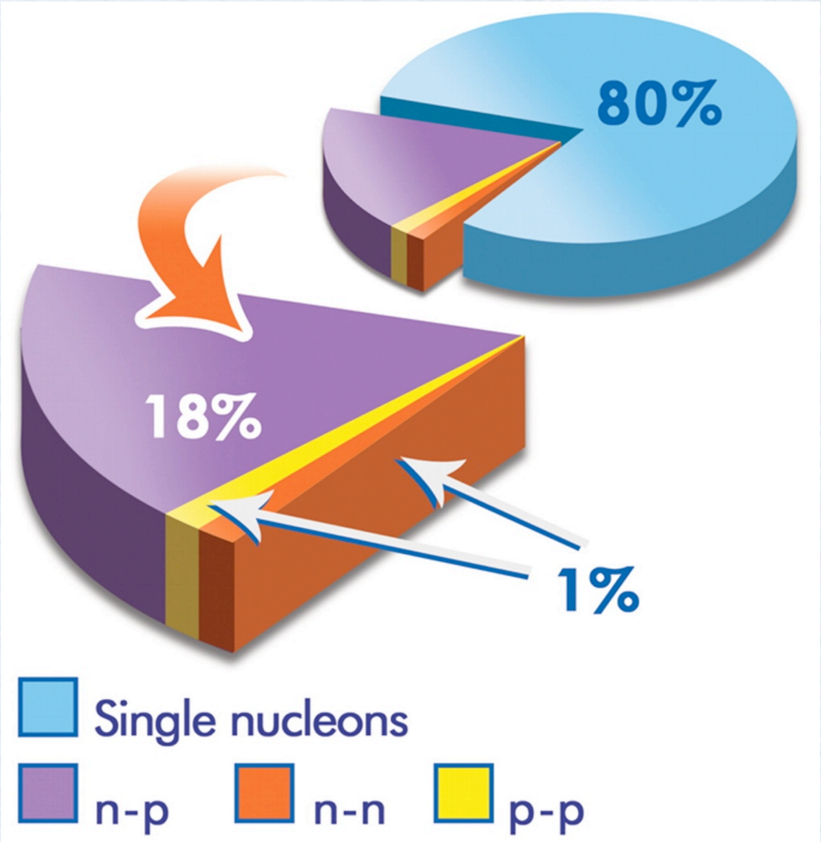

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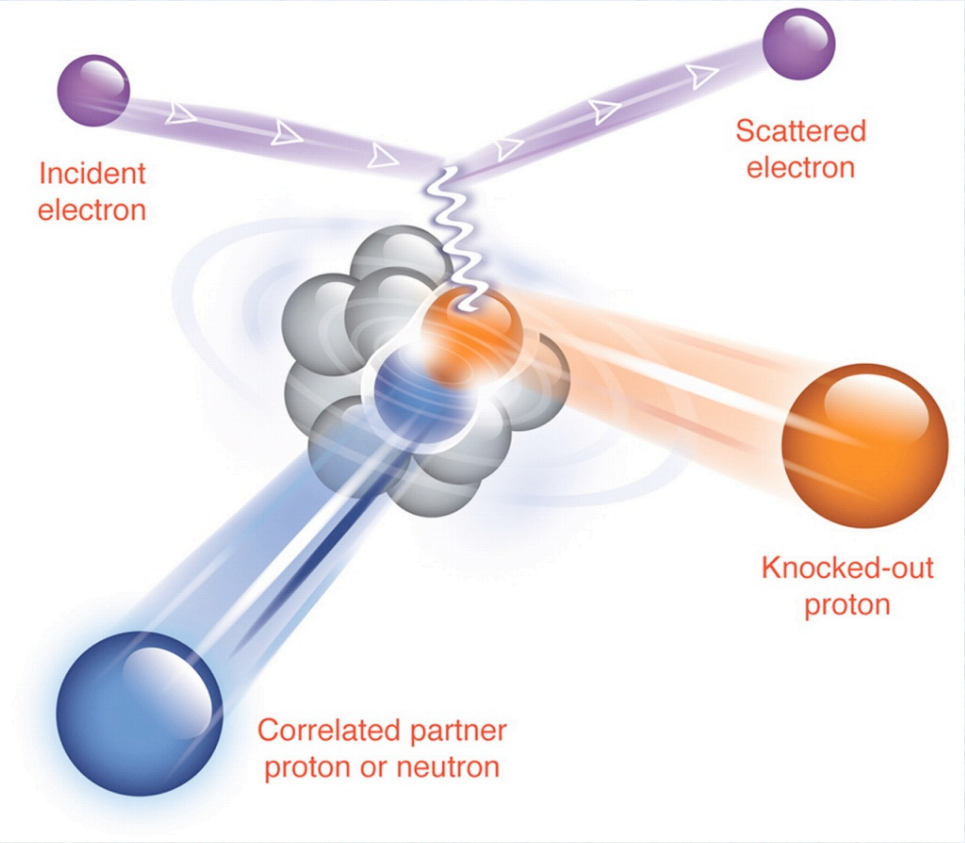
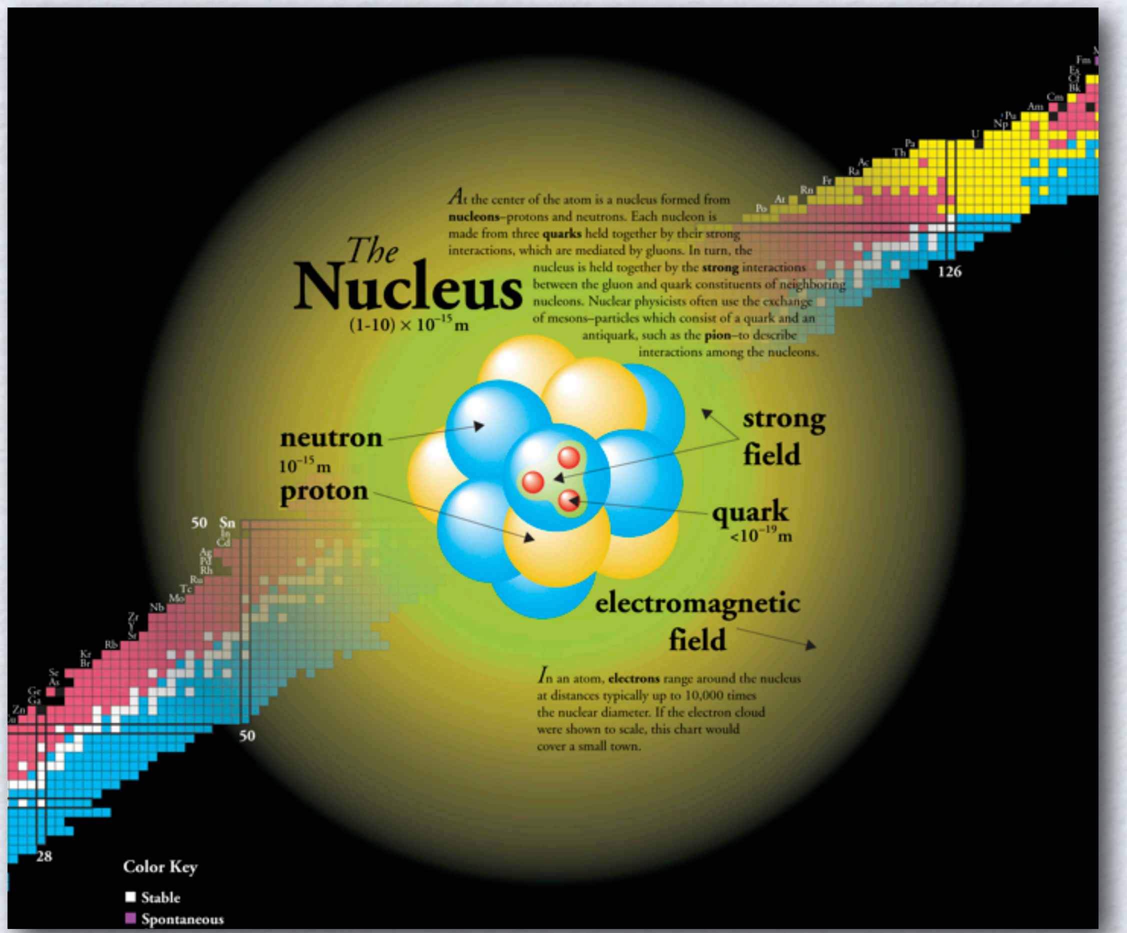


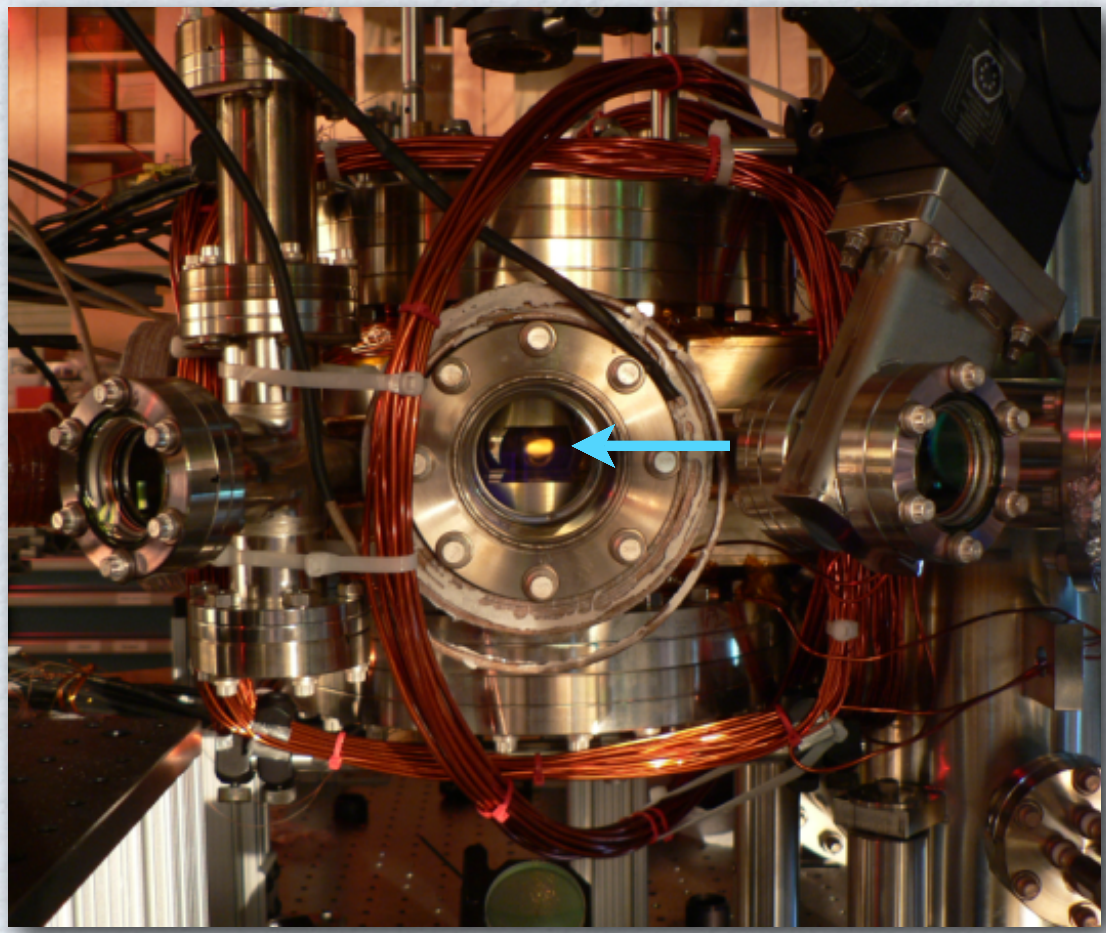
"Hard probes" are useful to reveal short-range pair correlations both in nuclei and atomic gases

Summary of this talk

Nuclear physics

Ultracold atoms





New ideas wanted !