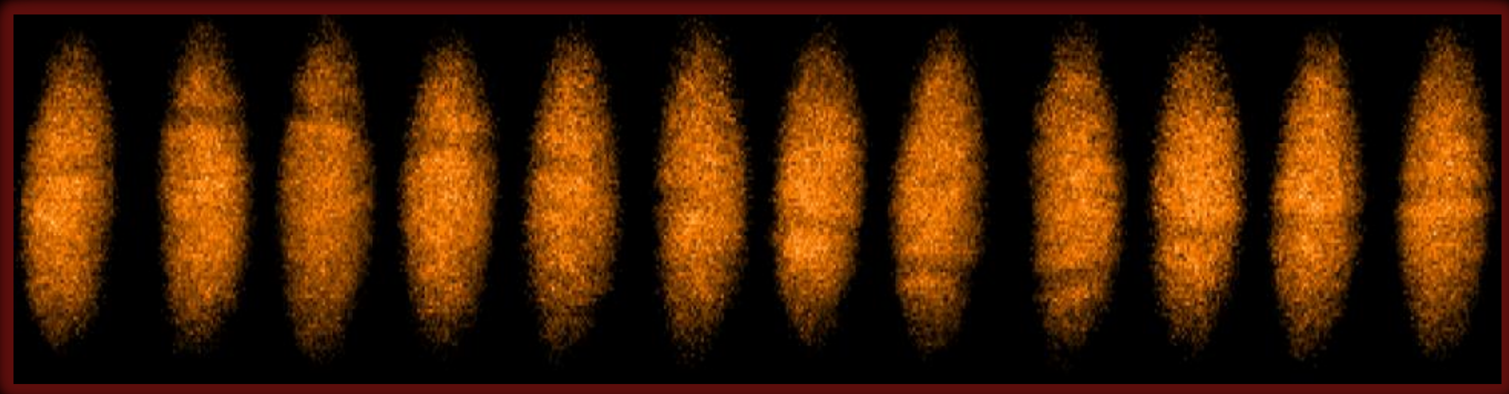
Spin-orbit coupling and Heavy solitons in atomic Fermi Gases

Tarik Yefsah, MIT



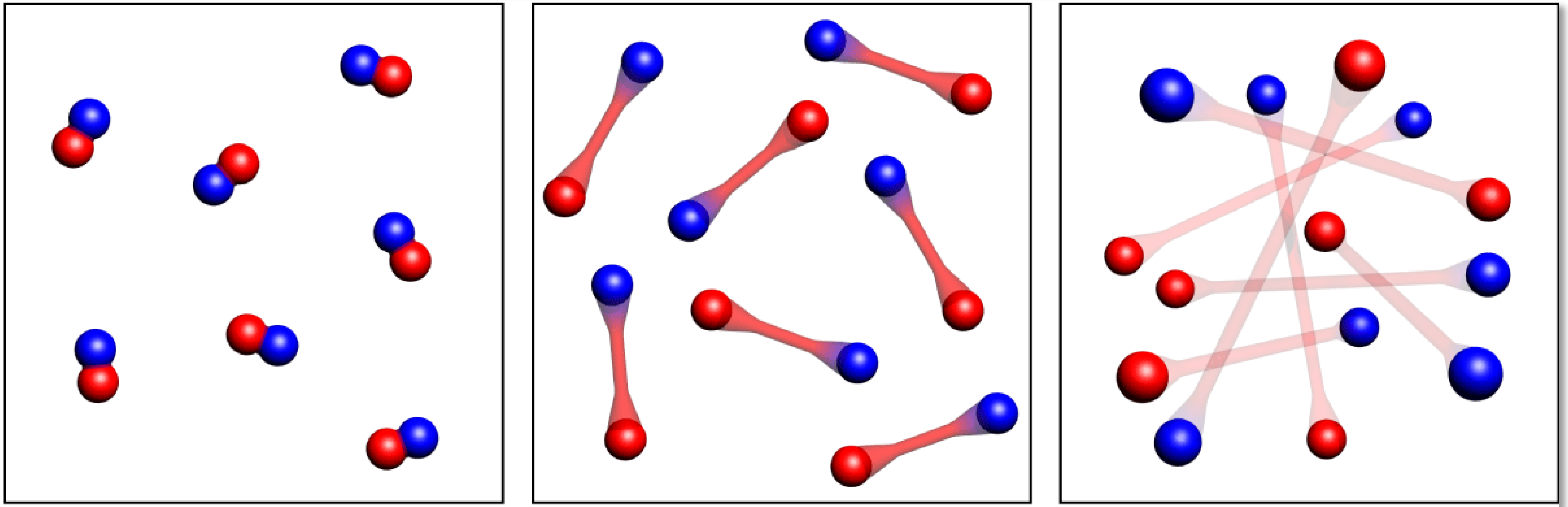
From BEC to BCS

Atomic gas of spin ½ with tunable interactions

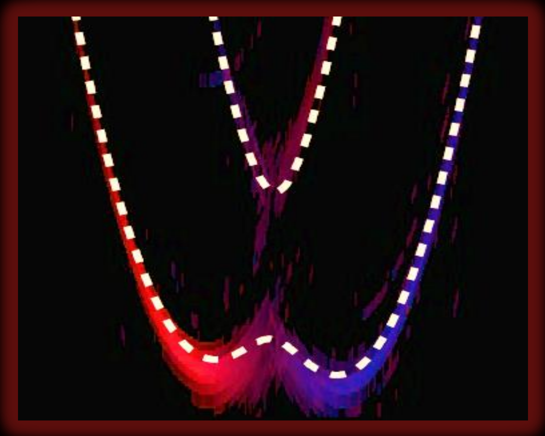
(**50% spin ↑** – **50% spin ↓**)

interactions

Feshbach resonances



BEC of Molecules | Crossover Superfluid | BCS state



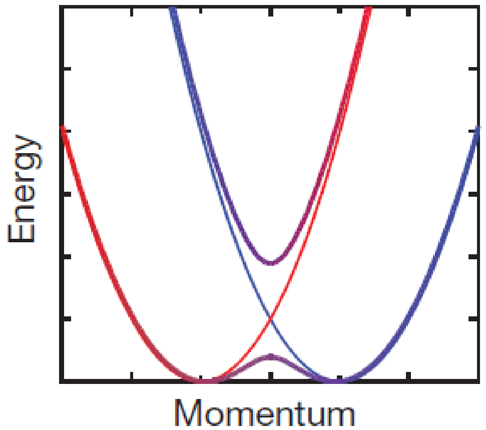
Spin-Injection Spectroscopy of a Spin-Orbit coupled Fermi Gas

Spin-orbit Hamiltonian

- Electron moving in an electric field feels a momentum-dependent magnetic fields in the moving frame

- In materials : electric field can arises from structure

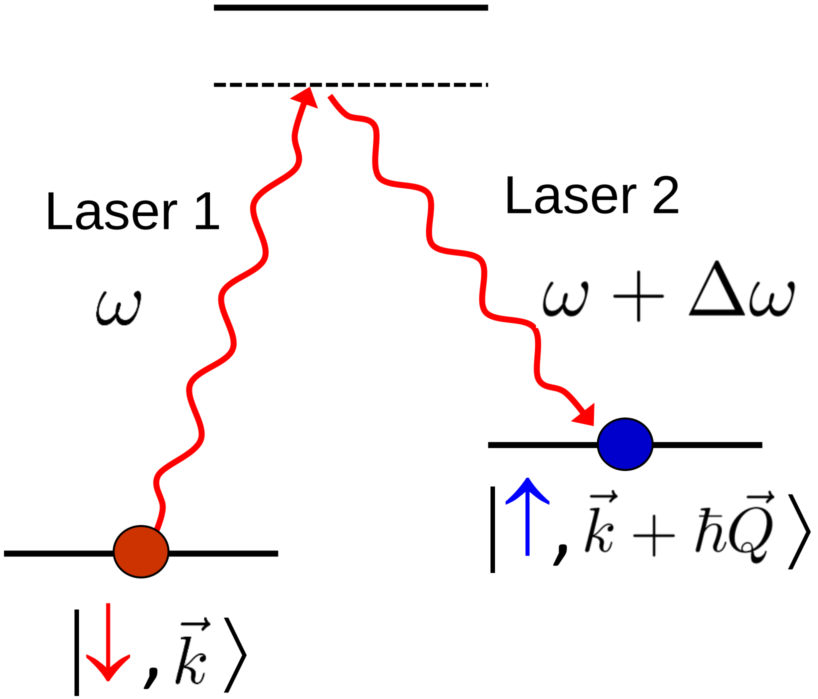
$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} - \mu \cdot [\mathbf{B} + \mathbf{B}_{\rm SO}(\mathbf{k})]$$



$$-\mu \cdot \mathbf{B}_{\rm SO}(\mathbf{k}) \propto = \begin{cases} \sigma_x k_y - \sigma_y k_x & \text{Rashba} \\ -\sigma_x k_y - \sigma_y k_x & \text{Dresselhaus} \end{cases}$$

Provides a good description of 2D SOC in solids

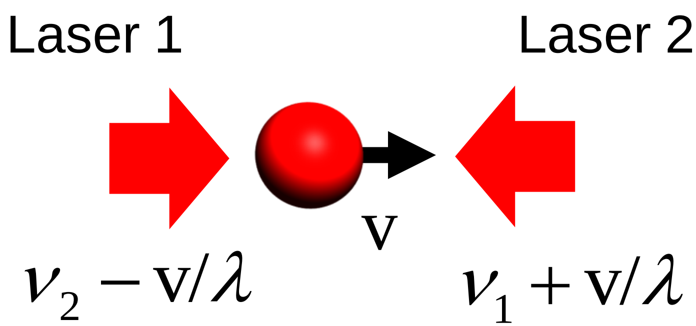
Engineering SO coupling



Raman Beams

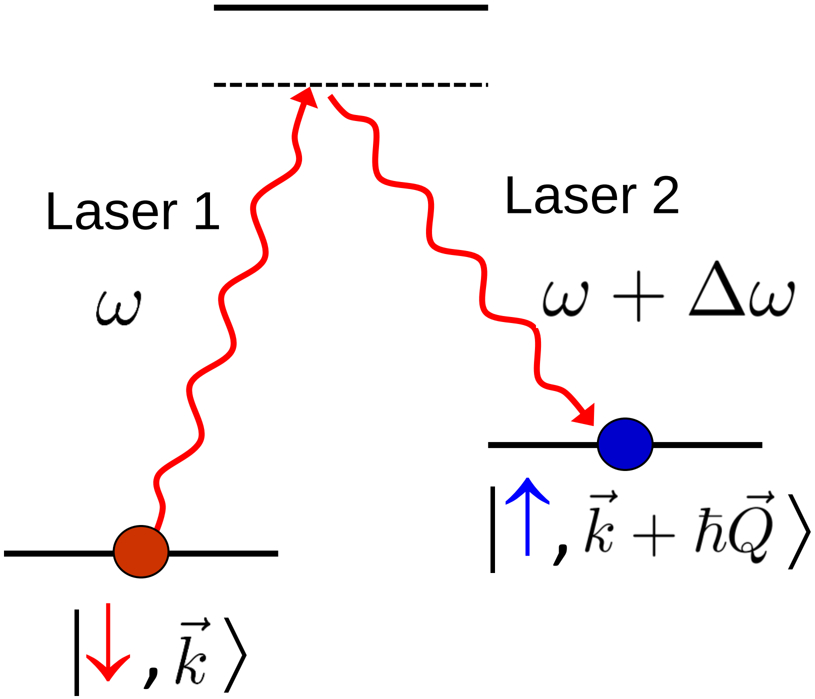
↓

Flip spin + imparts momentum



momentum selective process

Engineering SO coupling



How does the Hamiltonian look like ?

Reminder

2-level system + electric field

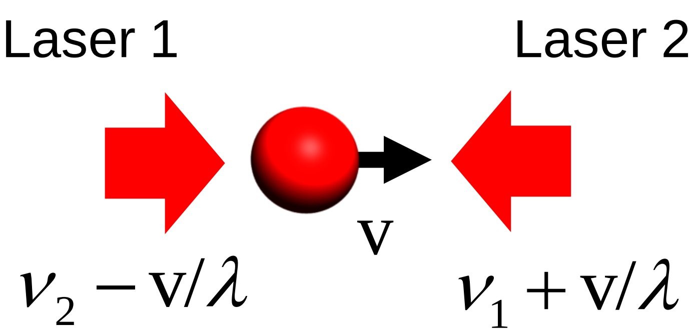
e

g

$$\vec{E} = E_0 \vec{\epsilon} \cos(\omega t + \phi)$$

RWA approx. :

$$-\vec{d} \cdot \vec{E} = \frac{\hbar\Omega}{2}(\sigma_x \cos\phi - \sigma_y \sin\phi)$$



Adiabatic elimination of the excited state

2-level system + $E_0 \vec{\epsilon} \cos(\Delta\omega t + Qx)$

$$-\vec{d} \cdot \vec{E} = \frac{\hbar\Omega_R}{2}(\sigma_x \cos Qx - \sigma_y \sin Qx)$$

Engineering SO coupling

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar\Omega_R}{2}(\sigma_x \cos Qx - \sigma_y \sin Qx) + \frac{\delta}{2}\sigma_z$$

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar^2 Q}{2m}\sigma_y k_x + \frac{\hbar\Omega_R}{2}\sigma_z + \frac{\delta}{2}\sigma_y + \frac{E_R}{4}\mathbb{I}$$

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)

Engineering SO coupling

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar\Omega_R}{2}(\sigma_x \cos Qx - \sigma_y \sin Qx) + \frac{\delta}{2}\sigma_z$$

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} - \mu \cdot [\mathbf{B} + \mathbf{B}_{\mathrm{SO}}(\mathbf{k})]$$

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar^2 Q}{2m}\sigma_y k_x + \frac{\hbar\Omega_R}{2}\sigma_z + \frac{\delta}{2}\sigma_y + \frac{E_R}{4}\mathbb{I}$$

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)

Engineering SO coupling

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar\Omega_R}{2}(\sigma_x \cos Qx - \sigma_y \sin Qx) + \frac{\delta}{2}\sigma_z$$

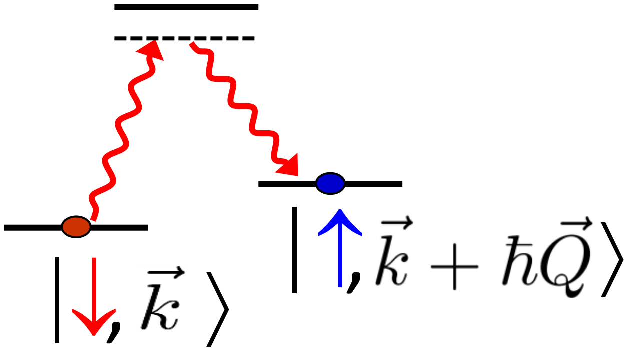
$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} - \mu\cdot[\mathbf{B} + \mathbf{B}_{\mathrm{SO}}(\mathbf{k})]$$

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \underbrace{\frac{\hbar^2 Q}{2m}\sigma_y k_x}_{-\mu\cdot\mathbf{B}_{\mathrm{SO}}(\mathbf{k})} + \underbrace{\frac{\hbar\Omega_R}{2}\sigma_z + \frac{\delta}{2}\sigma_y}_{-\mu\cdot\mathbf{B}} + \frac{E_R}{4}\mathbb{I}$$

Momentum dependent Zeeman field
"equal Rashba and Dresselhaus contributions"

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)

Engineering SO coupling



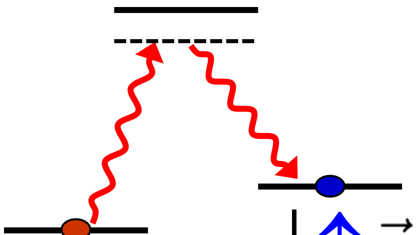
Define quasi-momentum q

$|\downarrow\rangle \quad q = k + Q/2$

$|\uparrow\rangle \quad q = k - Q/2$

real momentum space

Engineering SO coupling



$|\downarrow, \vec{k}\,\rangle$ $\quad |\uparrow, \vec{k} + \hbar\vec{Q}\rangle$

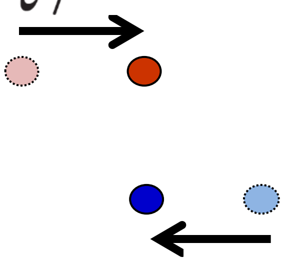
$$\mathcal{H}_{SO} = \begin{pmatrix} \frac{\hbar^2(q-Q/2)^2}{2m} + \frac{d}{2} & \frac{\hbar\Omega_R}{2} \\ \frac{\hbar\Omega_R}{2} & \frac{\hbar^2(q+Q/2)^2}{2m} - \frac{d}{2} \end{pmatrix}$$

Define quasi-momentum q

$|\downarrow\rangle \quad q = k + Q/2$

$|\uparrow\rangle \quad q = k - Q/2$

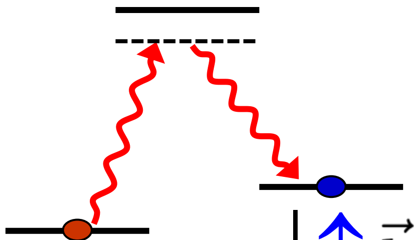
$+Q/2$



$-Q/2$

quasi-momentum space

Engineering SO coupling



$|\downarrow, \vec{k}\,\rangle$ $\quad|\uparrow, \vec{k} + \hbar\vec{Q}\rangle$

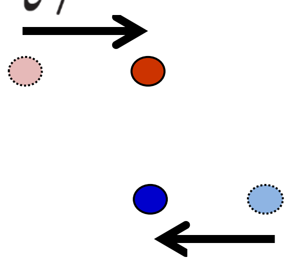
$$\mathcal{H}_{SO} = \begin{pmatrix} \frac{\hbar^2(q - Q/2)^2}{2m} + \frac{d}{2} & \\ & \frac{\hbar^2(q+Q/2)^2}{2m} - \frac{d}{2} \end{pmatrix}$$

Define quasi-momentum q

$|\downarrow\rangle \quad q = k + Q/2$

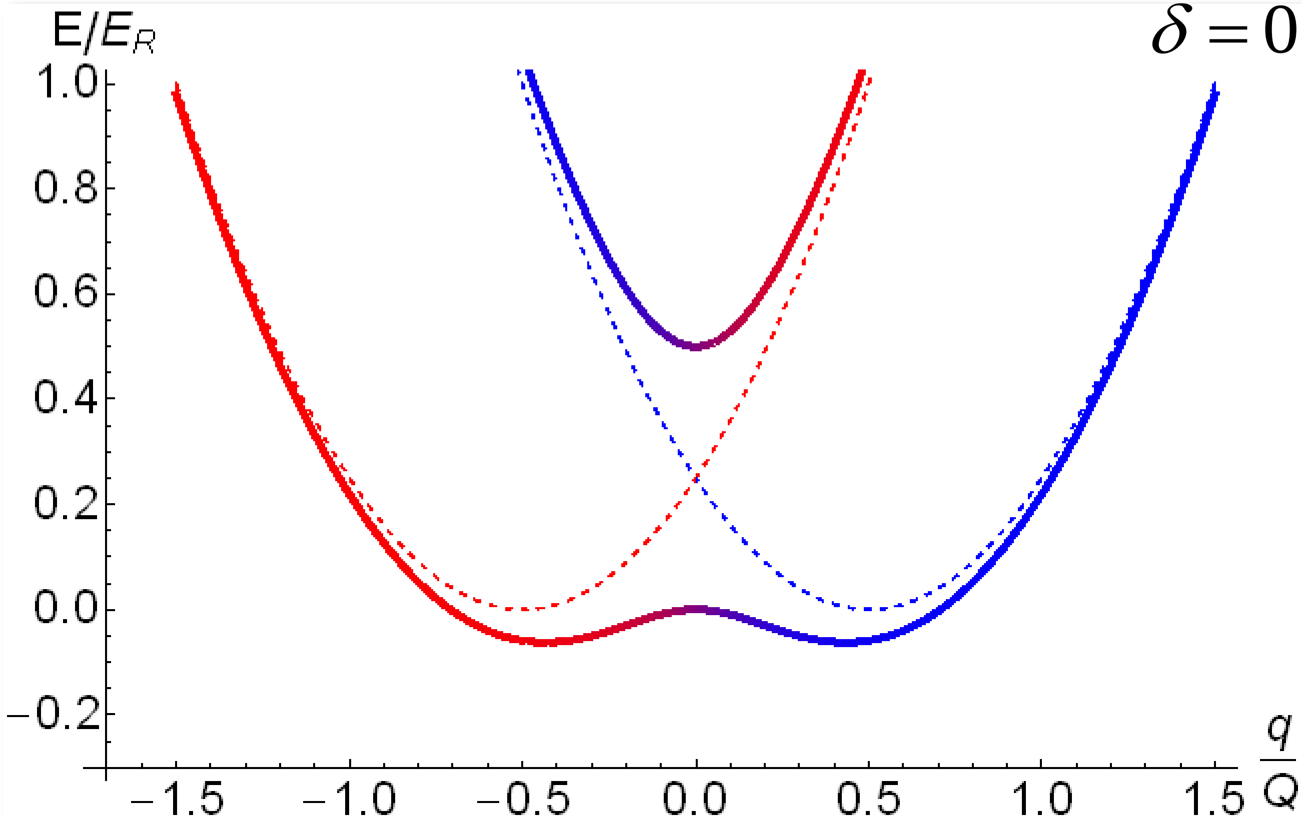
$|\uparrow\rangle \quad q = k - Q/2$

$+\,Q/2$



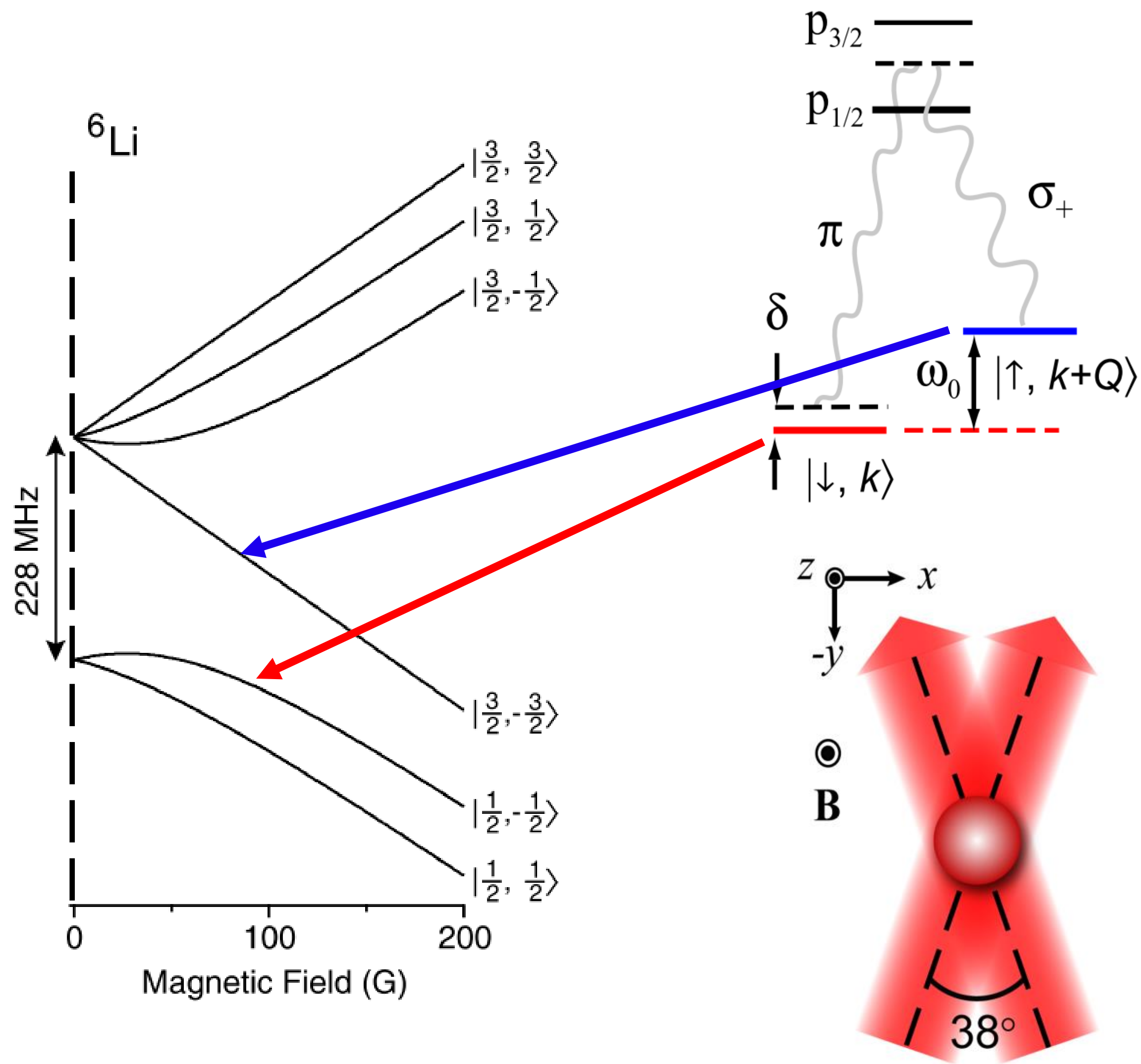
$-\,Q/2$

quasi-momentum space

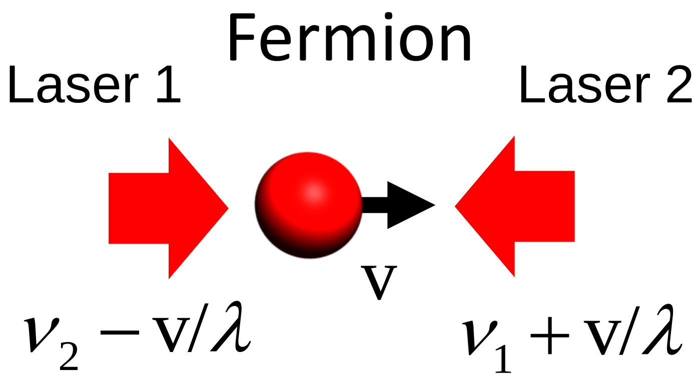


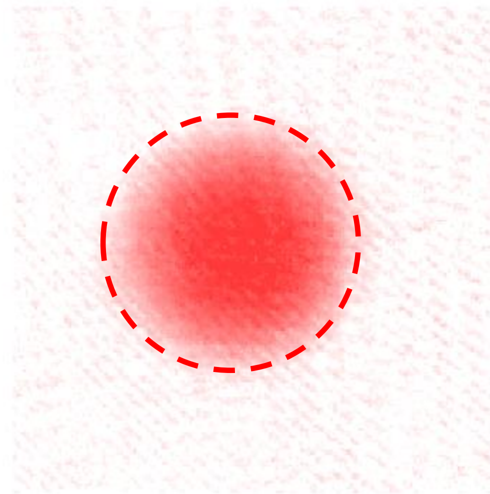
Experimental Setup

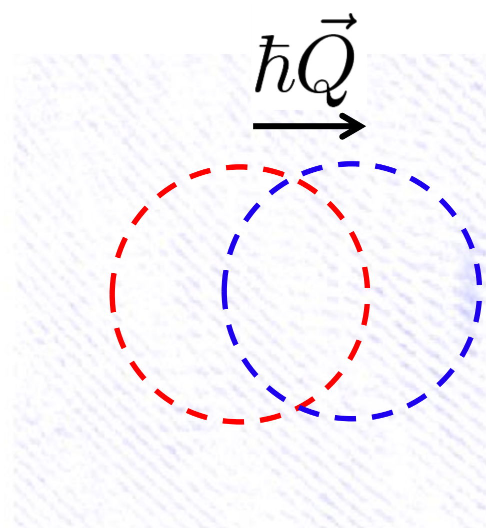
- Fermionic ^{6}Li atoms sympathetically cooled by ^{23}Na
- Relevant states are 2nd and 3rd lowest states at 11G
- Interactions are negligible ($20a_0$)



Coupling spin and momentum via Raman







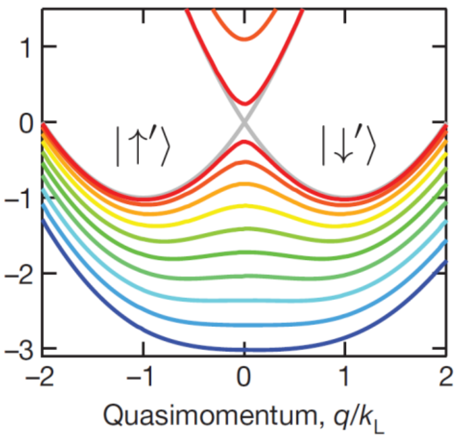
Vary detuning

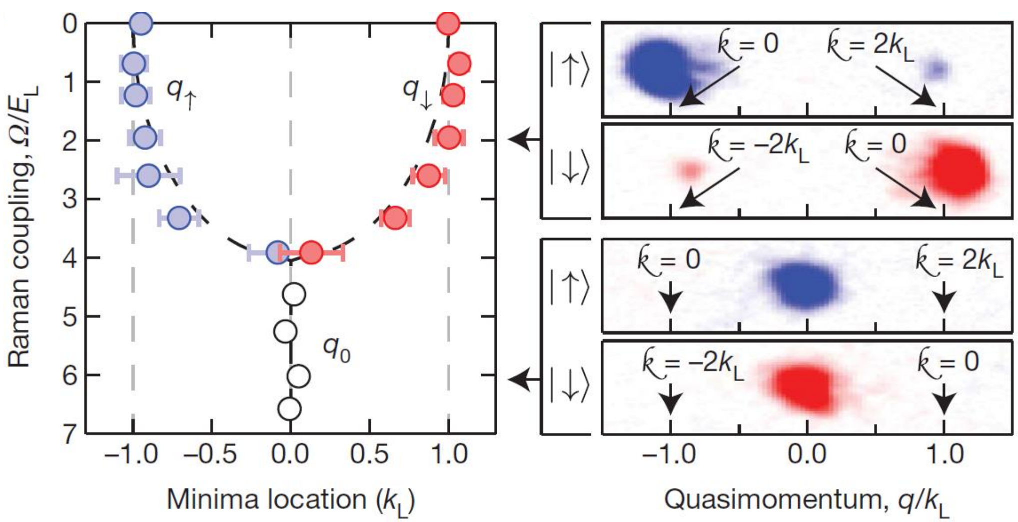
Short pulse

State-selective imaging after TOF provides
<u>spin</u> and <u>momentum</u> information

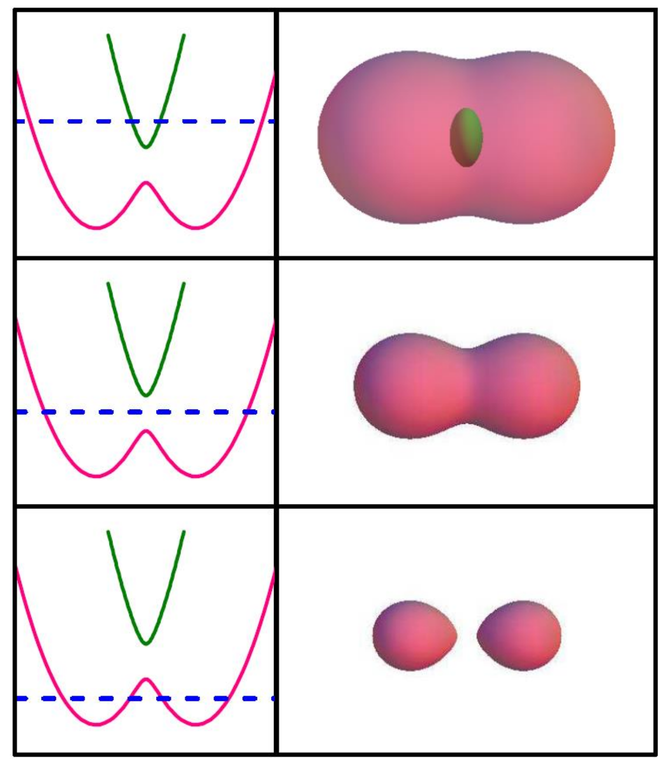
Probing the spin-orbit coupling in atomic gases

Y. J. Lin *et al.* *Nature* **471**, 83-86 (2011)
Ian Spielman's group





P. Wang *et al.* *PRL* **109**, 095301 (2012)
Jing Zhang's group



Tarik Yefsah, Trieste, May 2013

Spin-injection spectroscopy

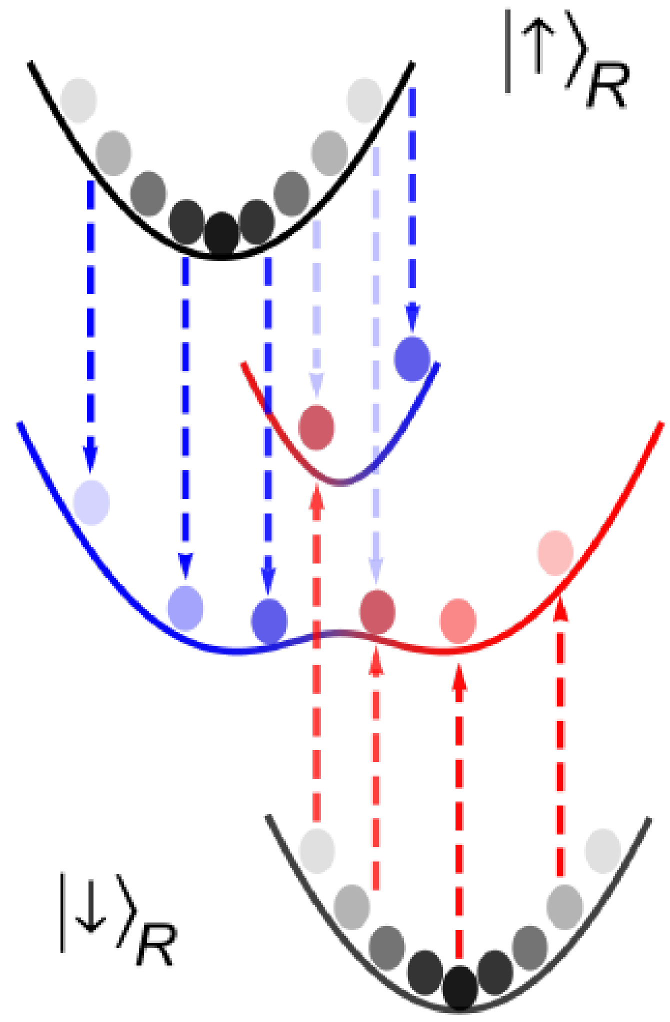
Can the hamiltonian be directly characterized?

Spin-injection spectroscopy:

Measures spin, energy, momentum

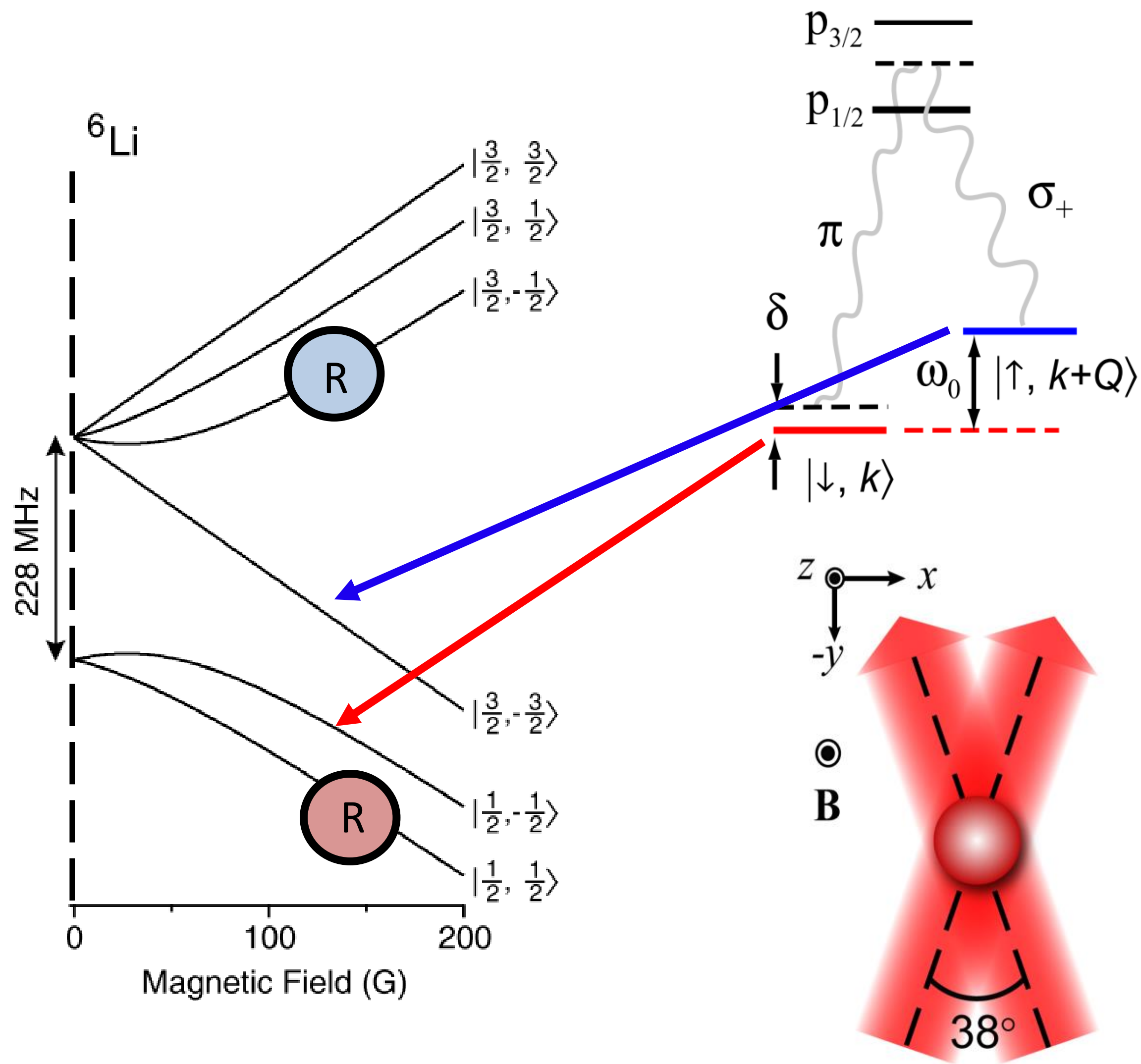
1. Inject atoms from “reservoir”
2. Project into free space
3. Spin-selective imaging

→ Reconstruct *E(k)* along with “color” of band

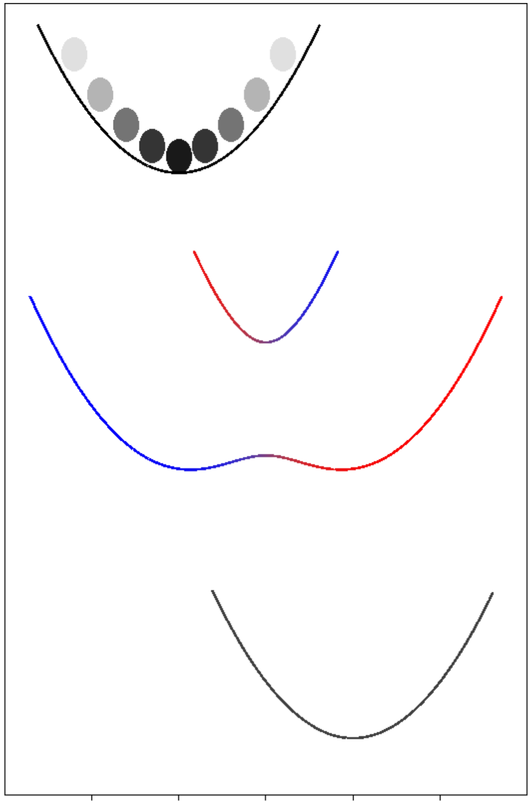


Experimental Setup

- 1st and 4th states used as reservoir states

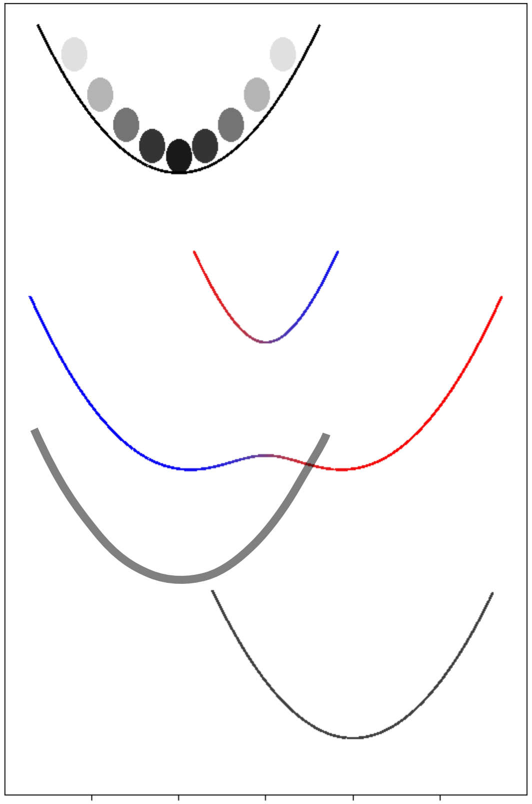


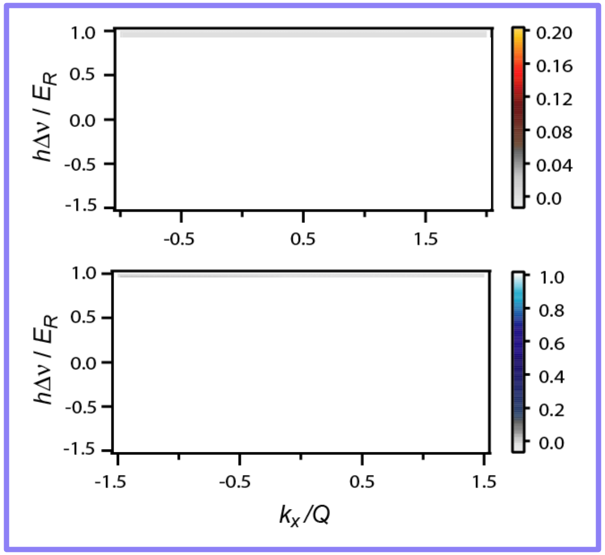
Spin-injection spectroscopy



L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

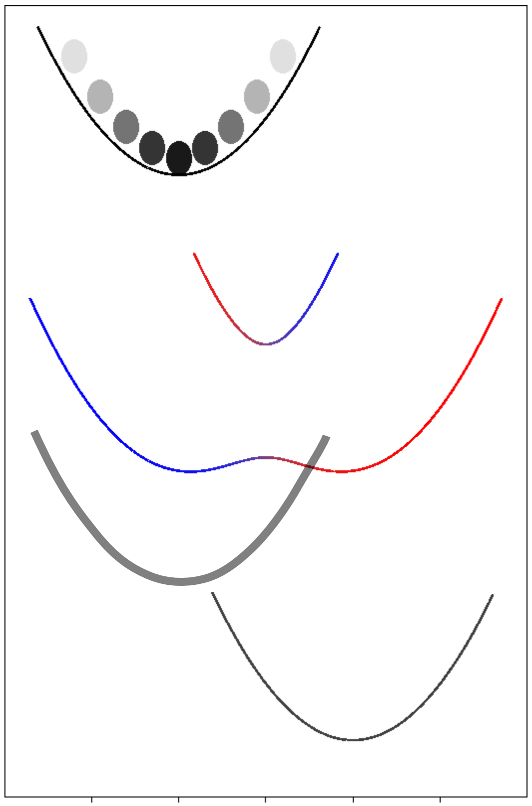
Spin-injection spectroscopy

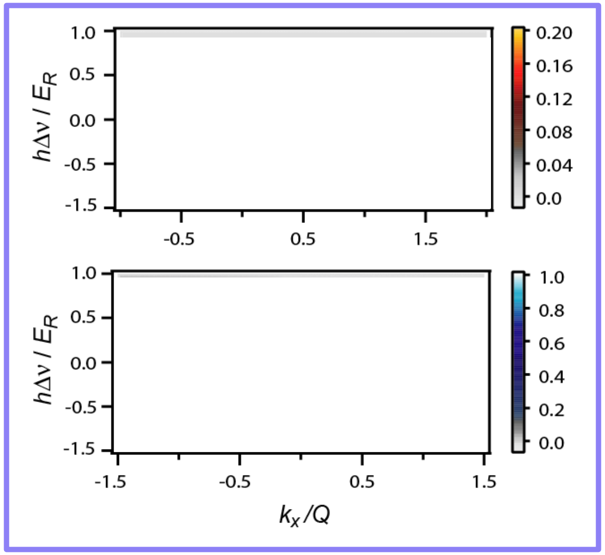


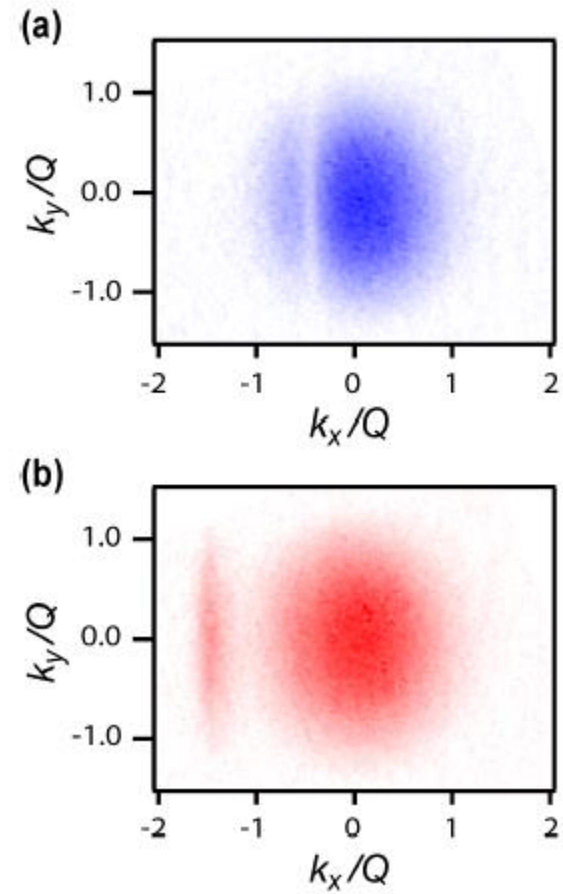


L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

Spin-injection spectroscopy

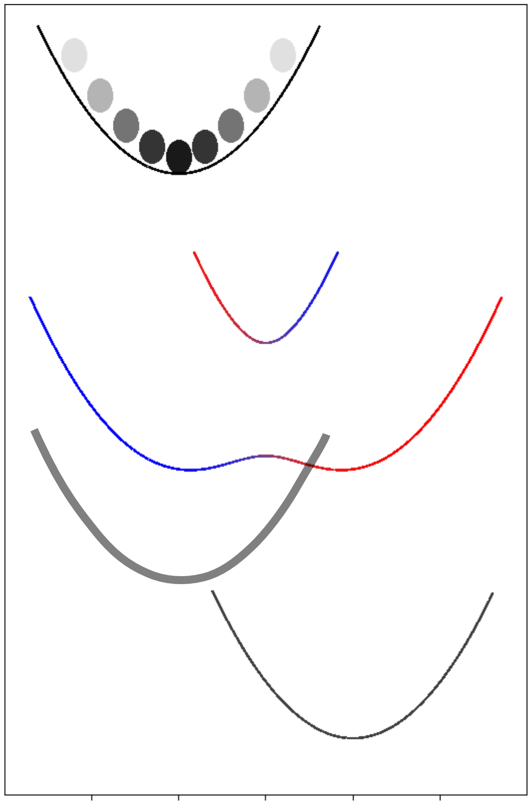


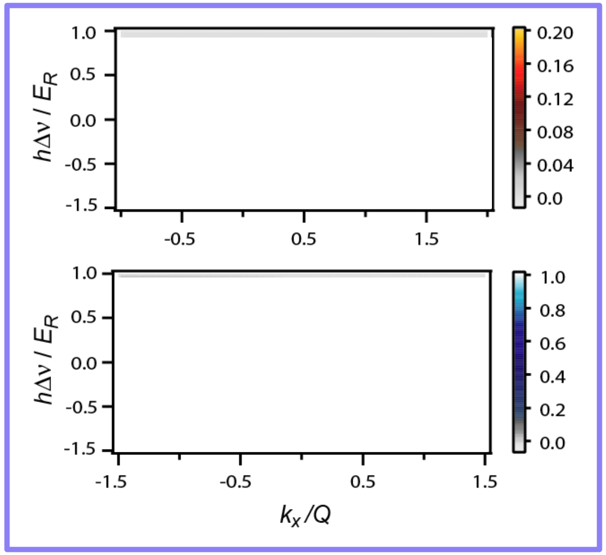




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

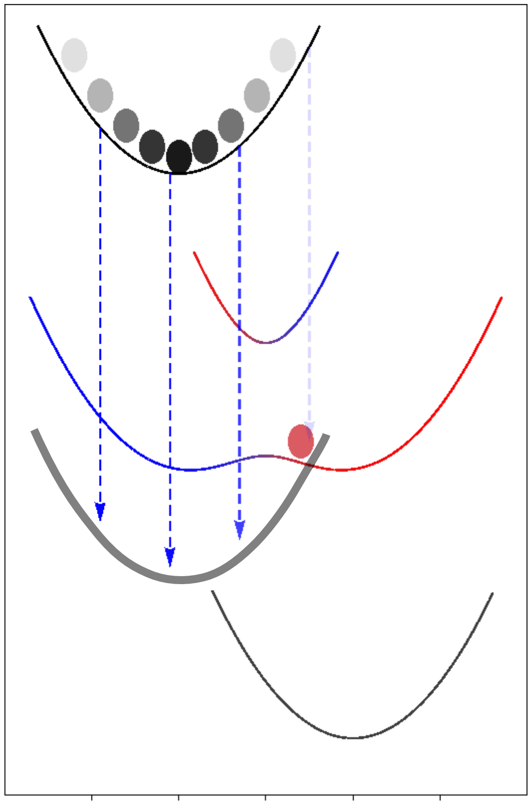
Spin-injection spectroscopy

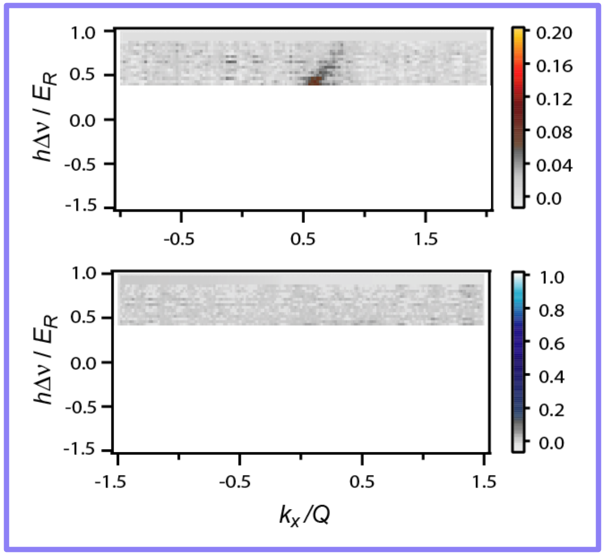




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

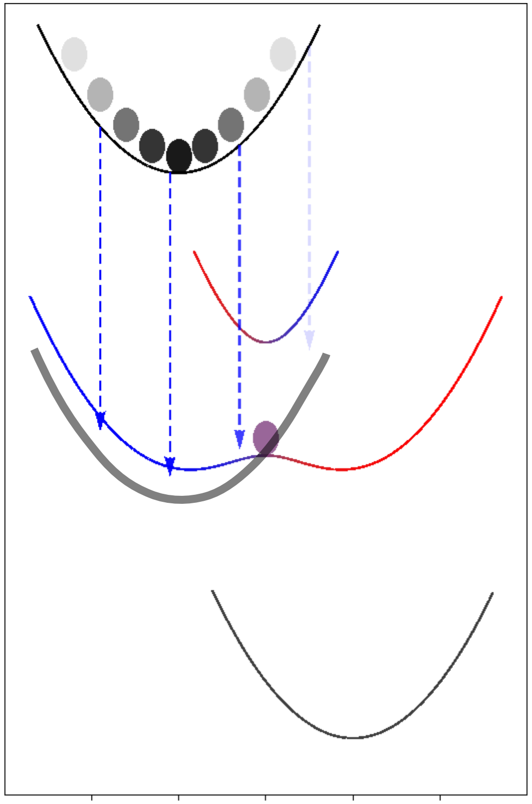
Spin-injection spectroscopy

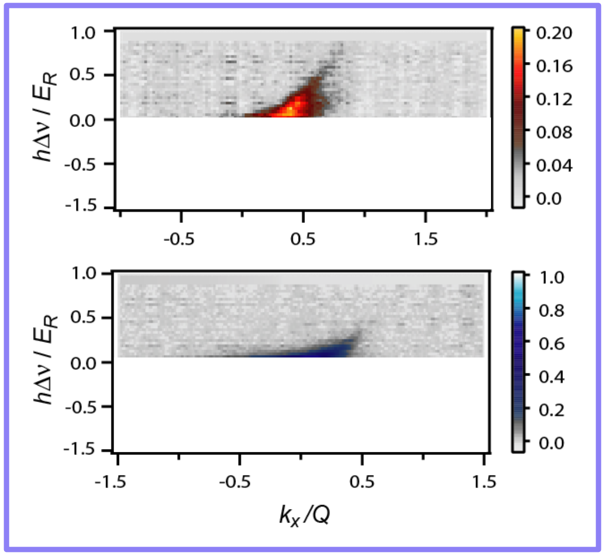




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

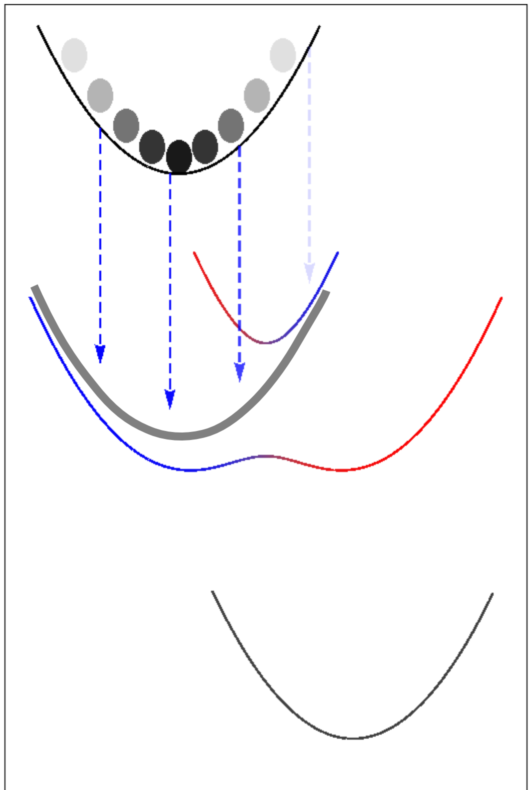
Spin-injection spectroscopy

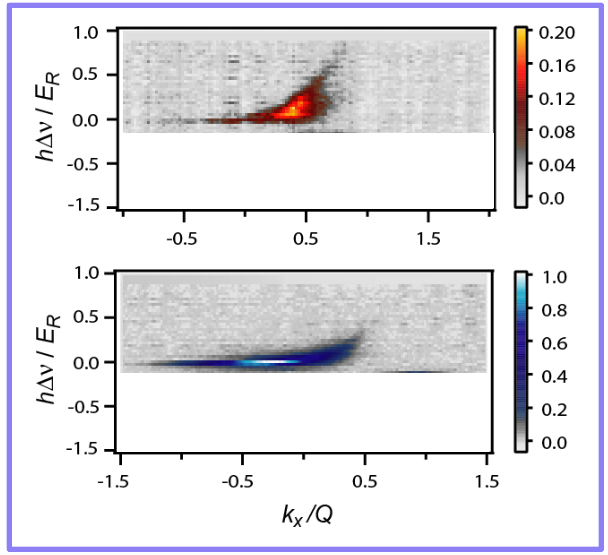




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

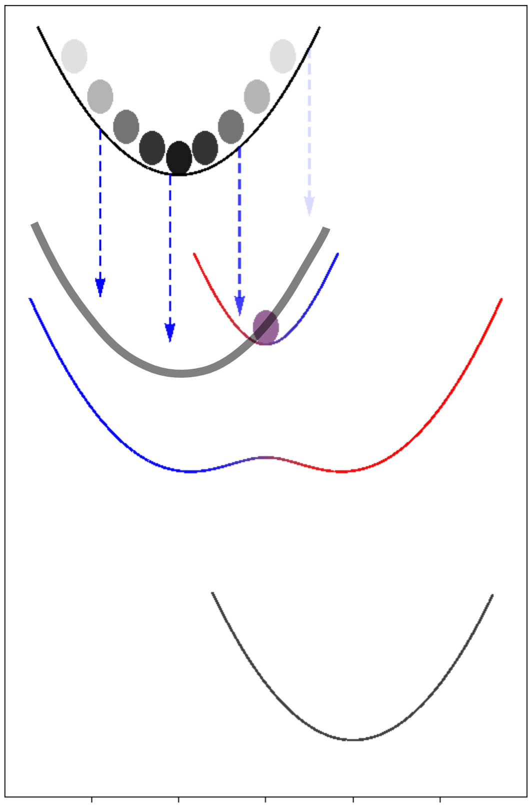
Spin-injection spectroscopy

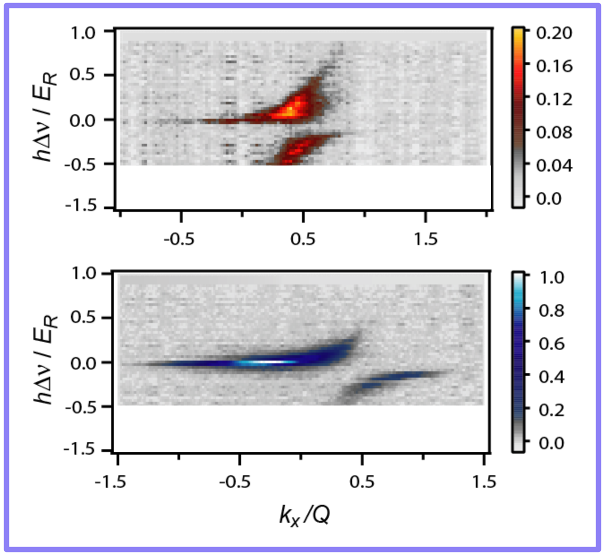




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

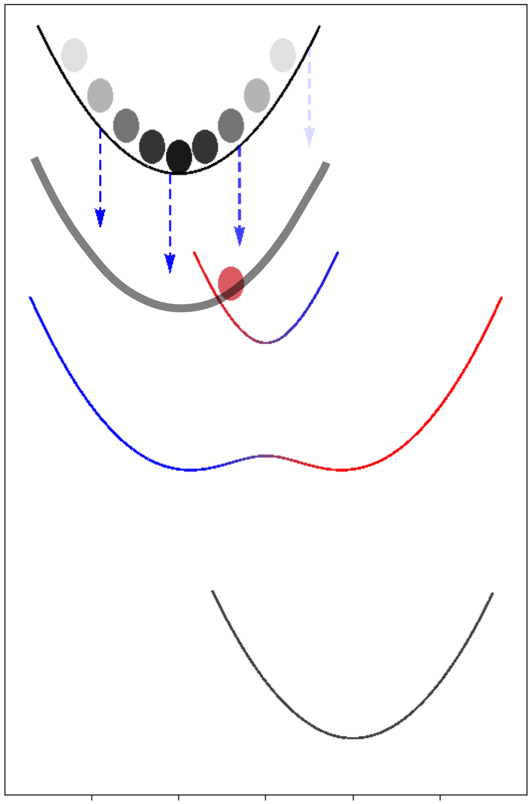
Spin-injection spectroscopy

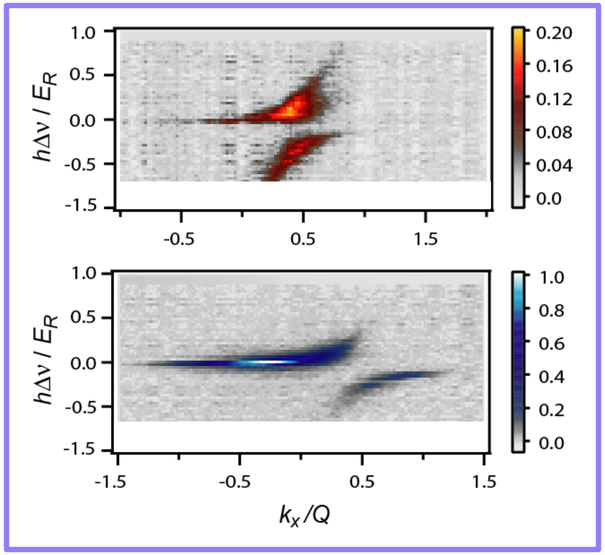




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

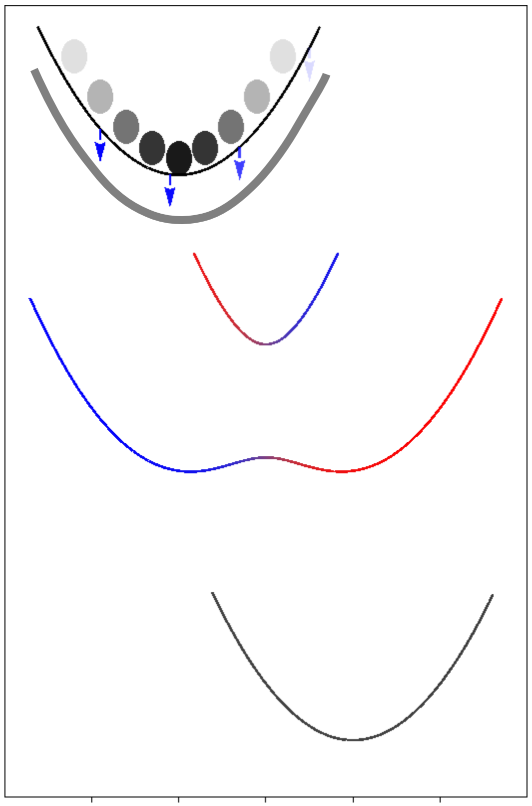
Spin-injection spectroscopy

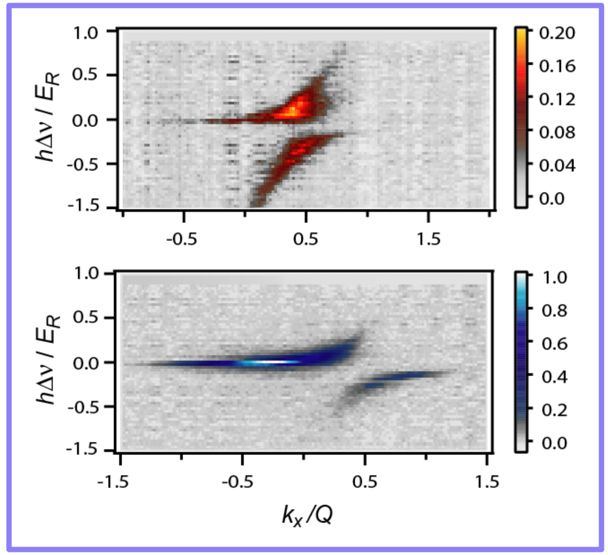




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

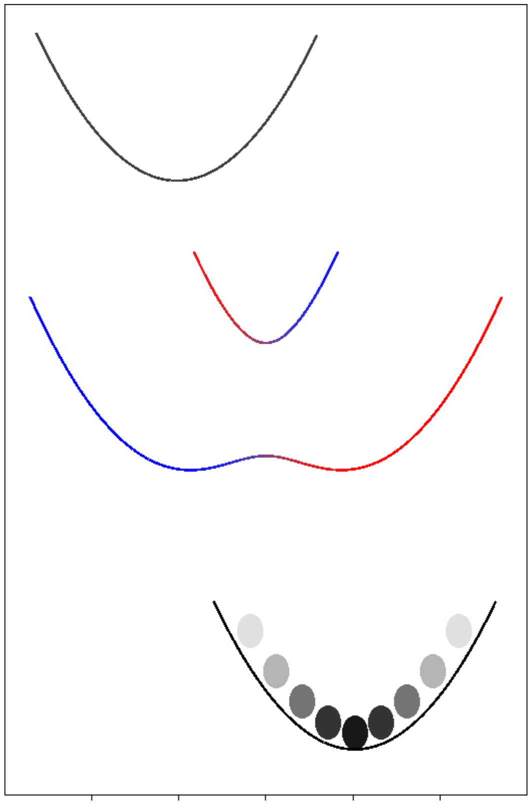
Spin-injection spectroscopy

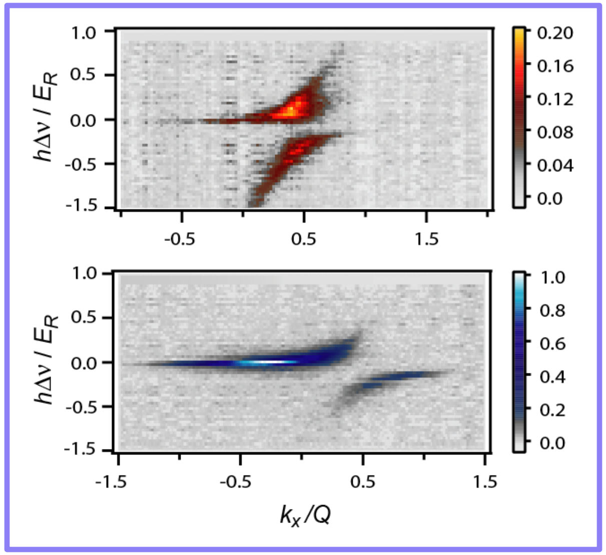




L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

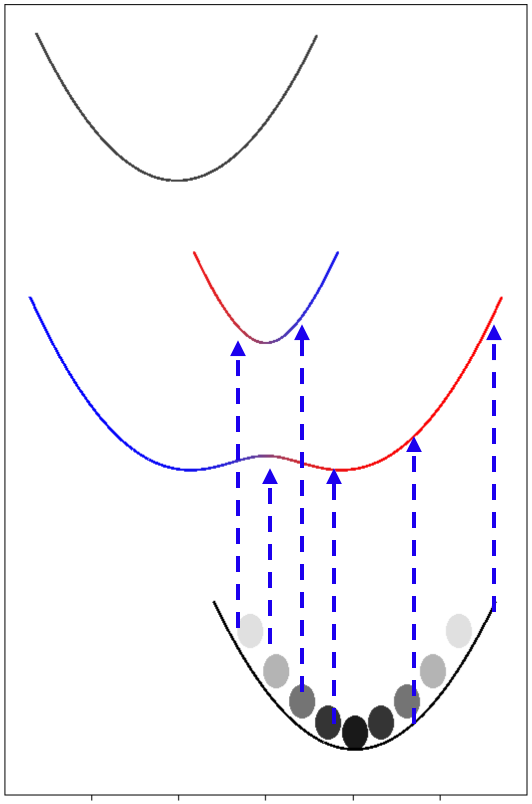
Spin-injection spectroscopy

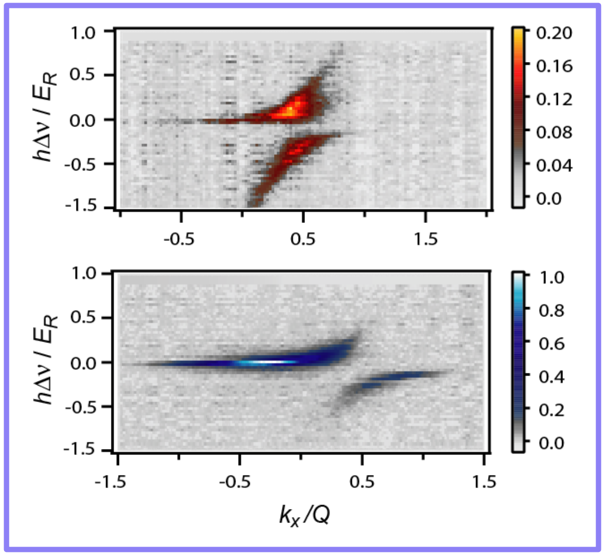


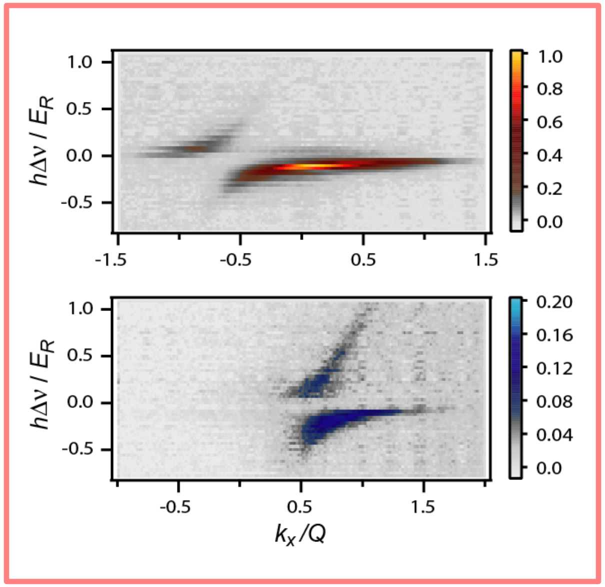


L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

Spin-injection spectroscopy

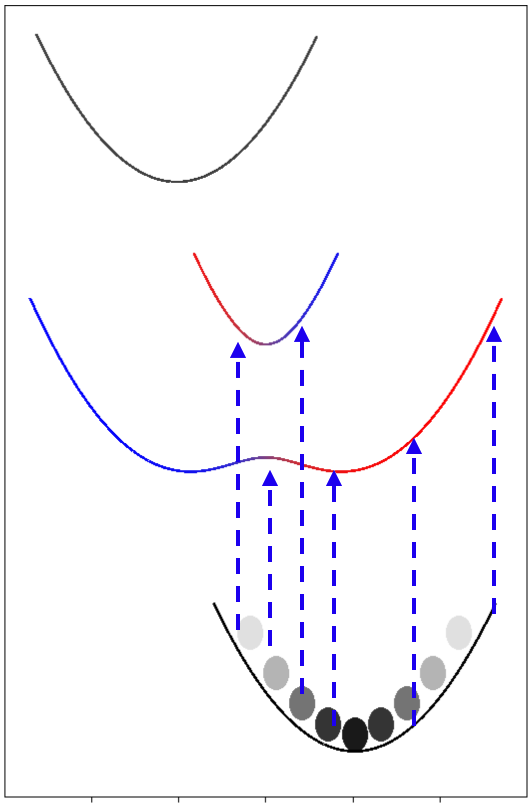


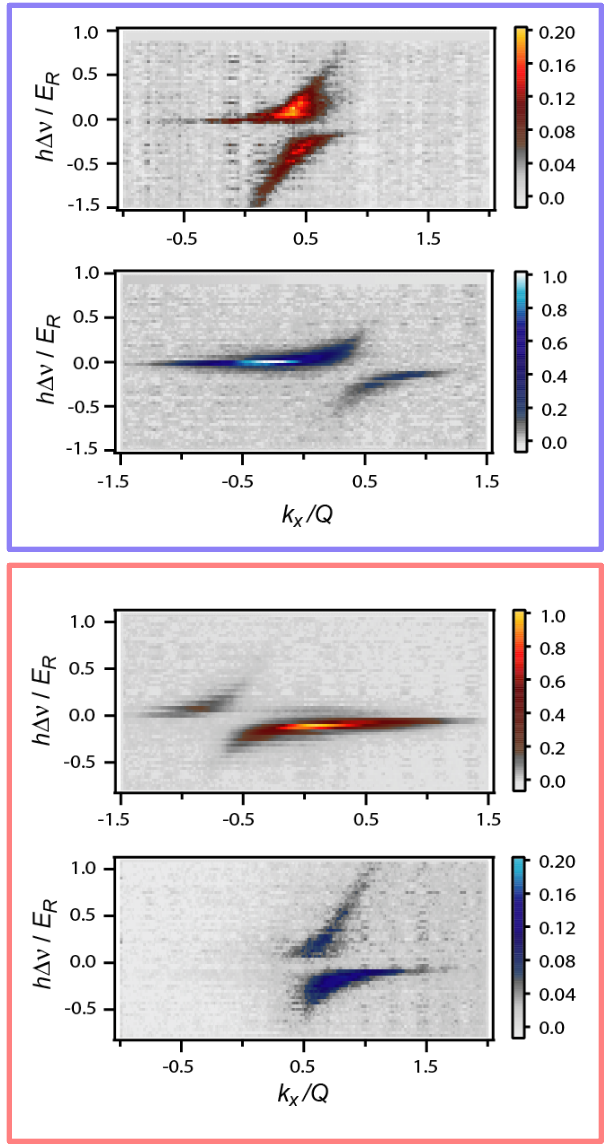


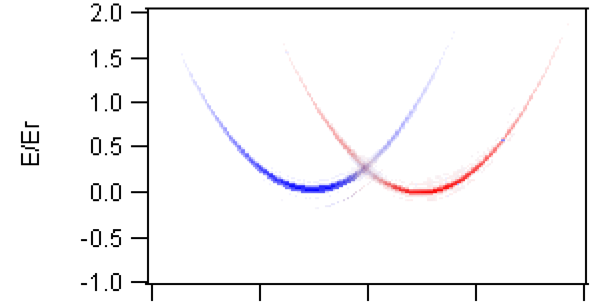


L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

Spin-injection spectroscopy

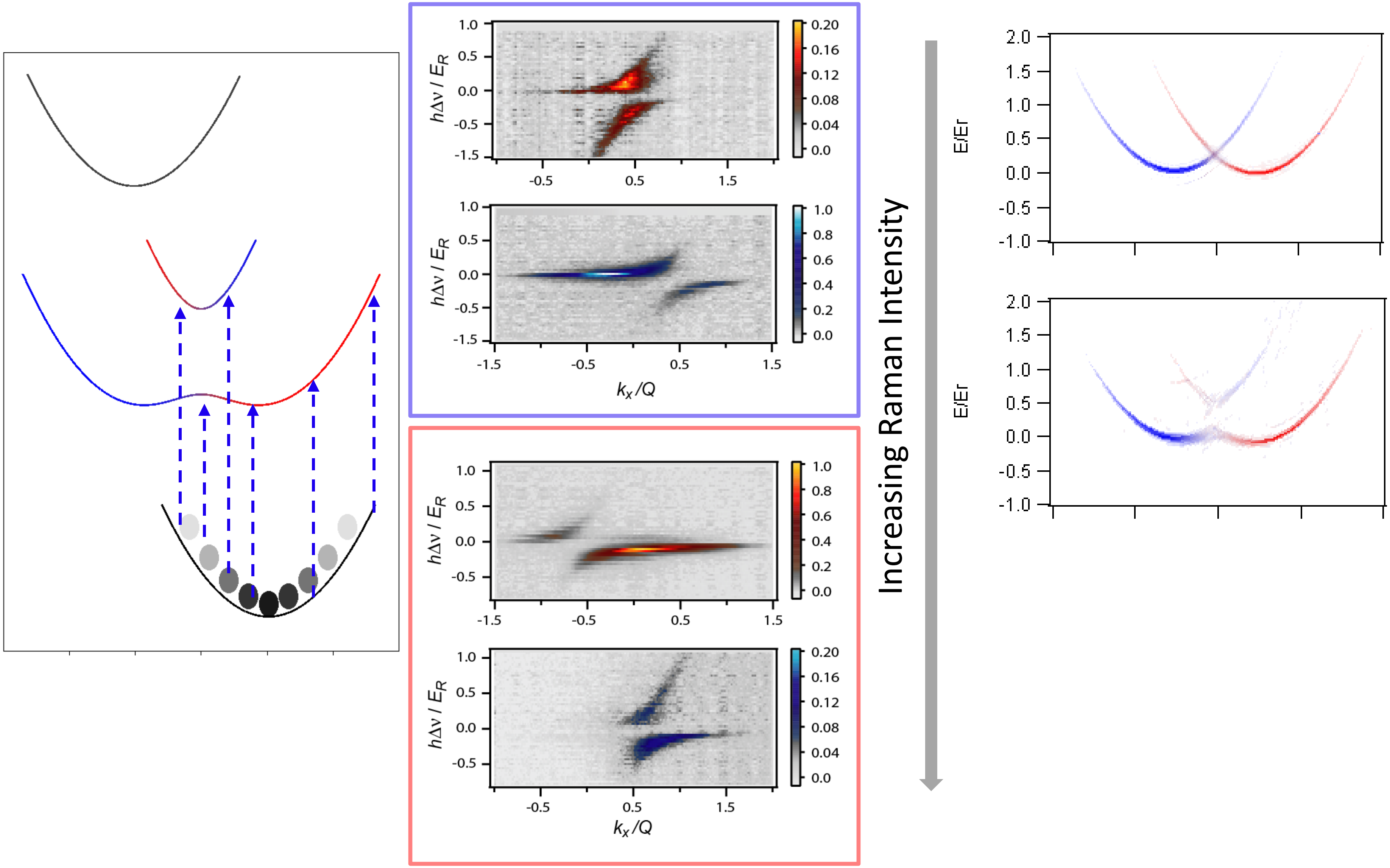






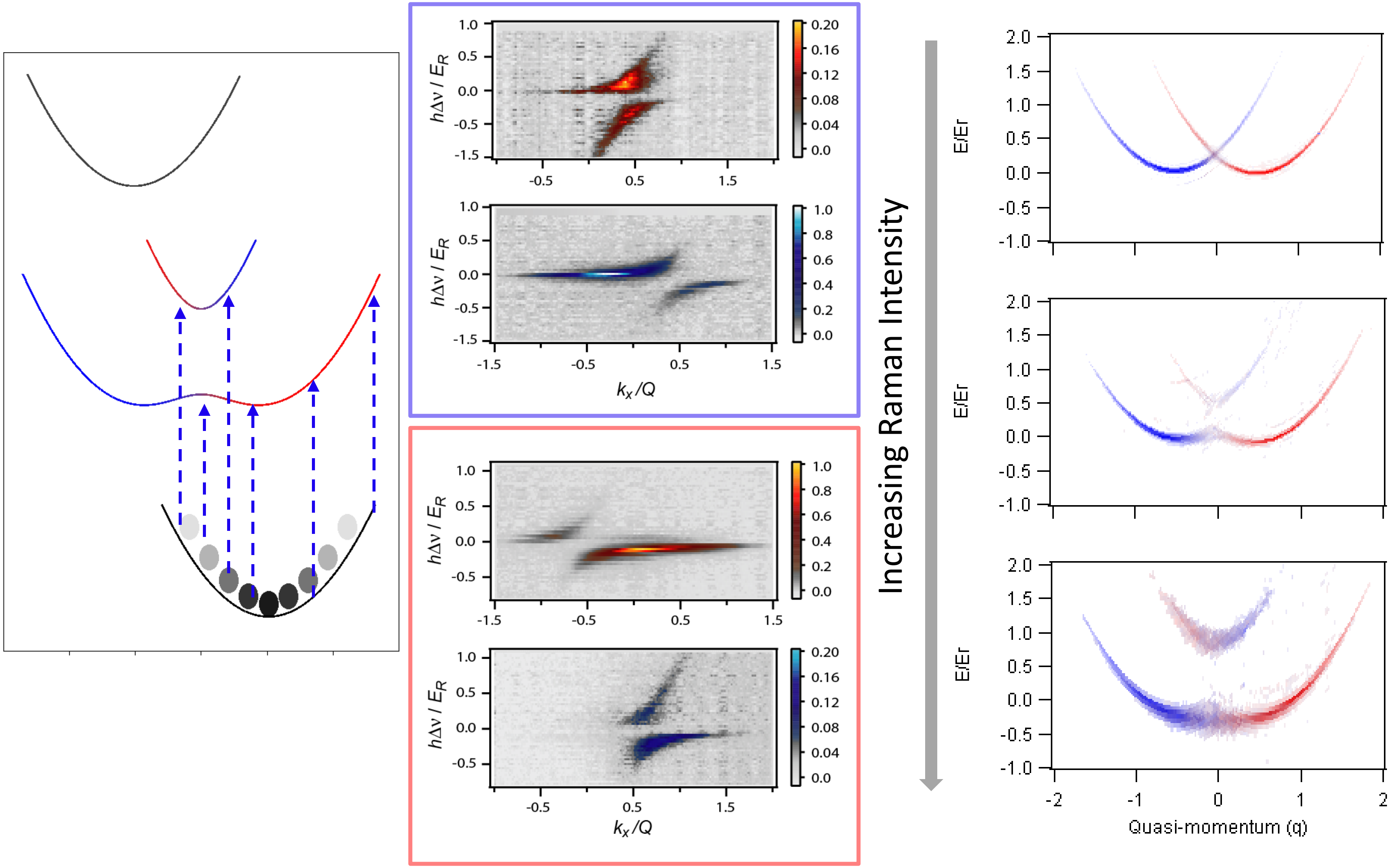
L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

Spin-injection spectroscopy



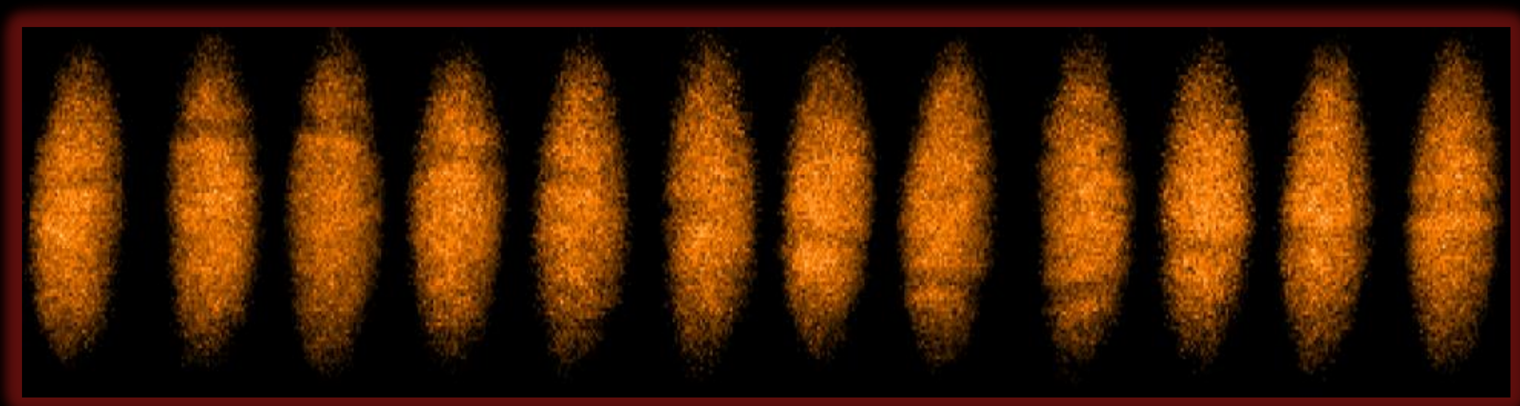
L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

Spin-injection spectroscopy



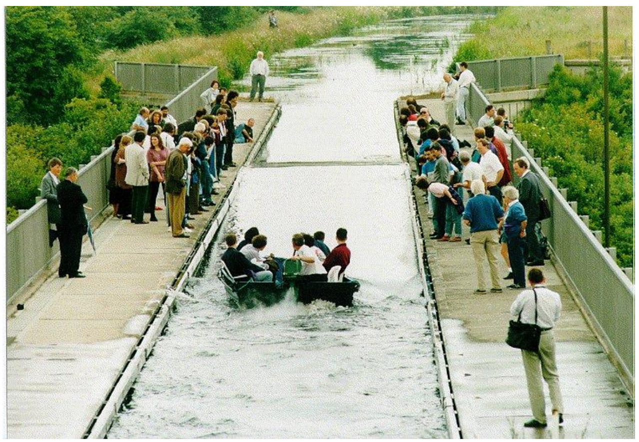
L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, M. W. Zwierlein
Phys. Rev. Lett. **109**, 095302 (2012)

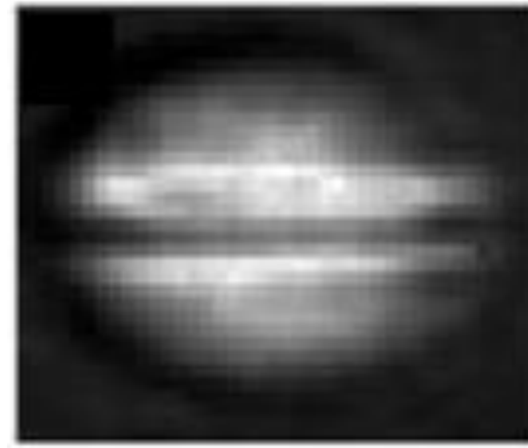
Heavy Solitons in a Fermionic Superfluid



What is a soliton ?

- Localized wave-packet
- Maintained shape during propagation



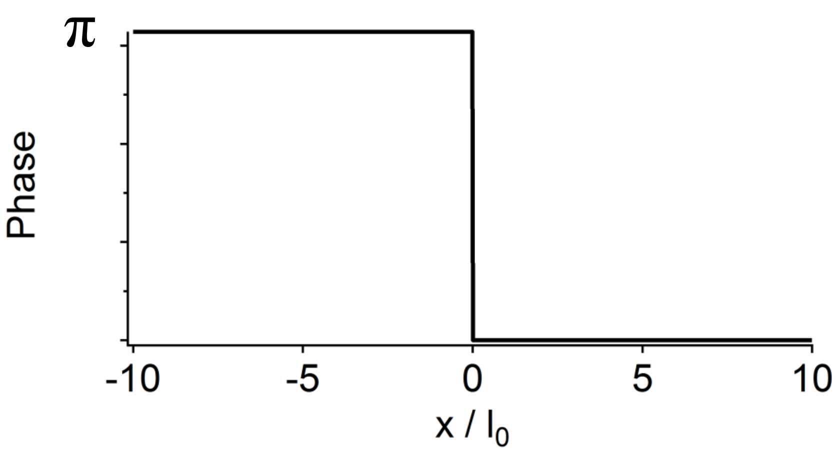


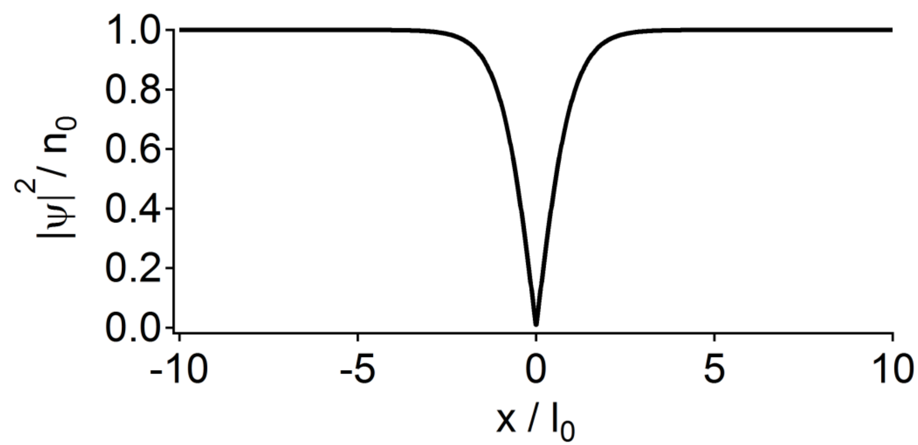
Dispersion
(broadening)

Non-linearity
(localization)

Dark soliton in a BEC

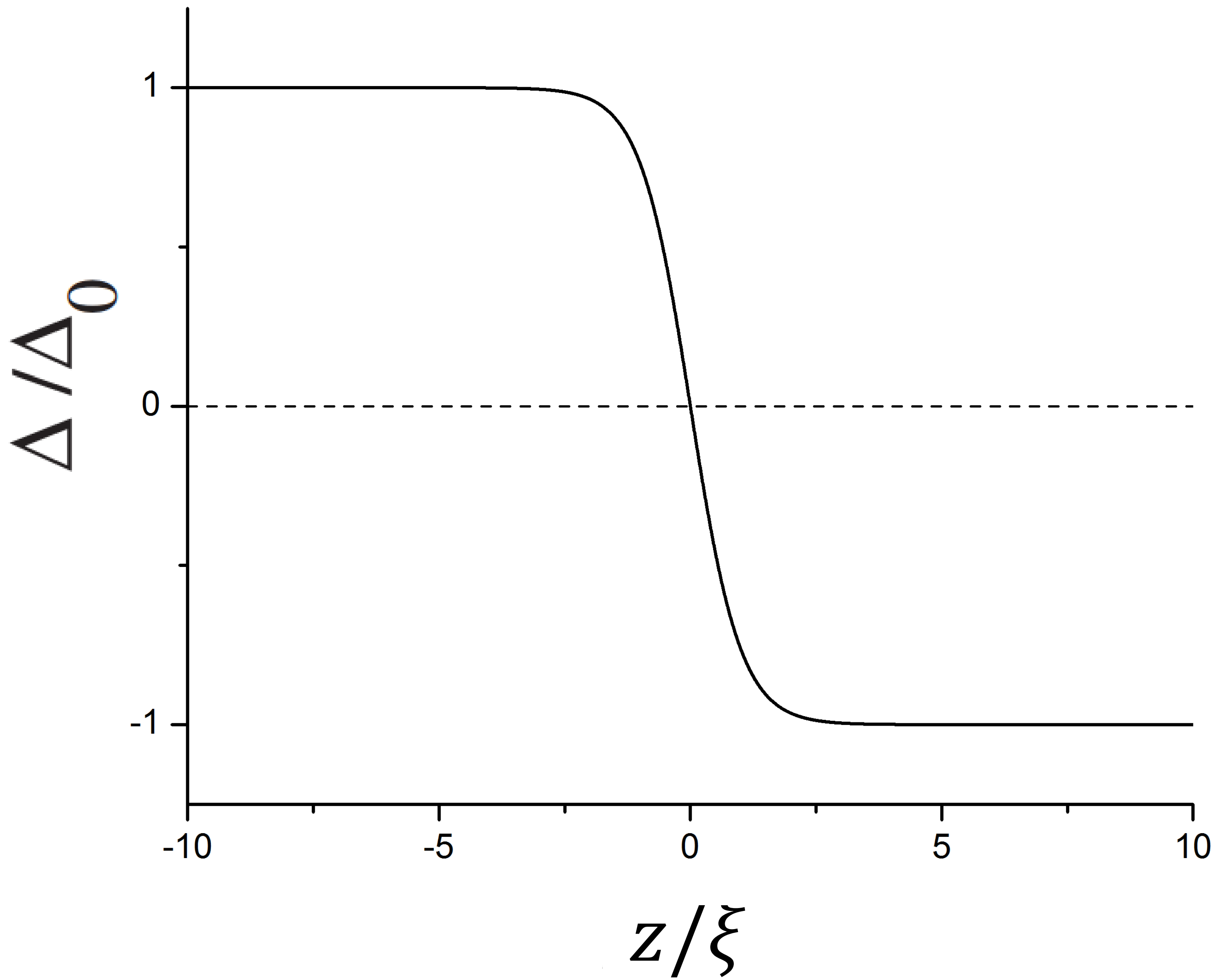
Dark soliton in a BEC = phase jump + density depletion



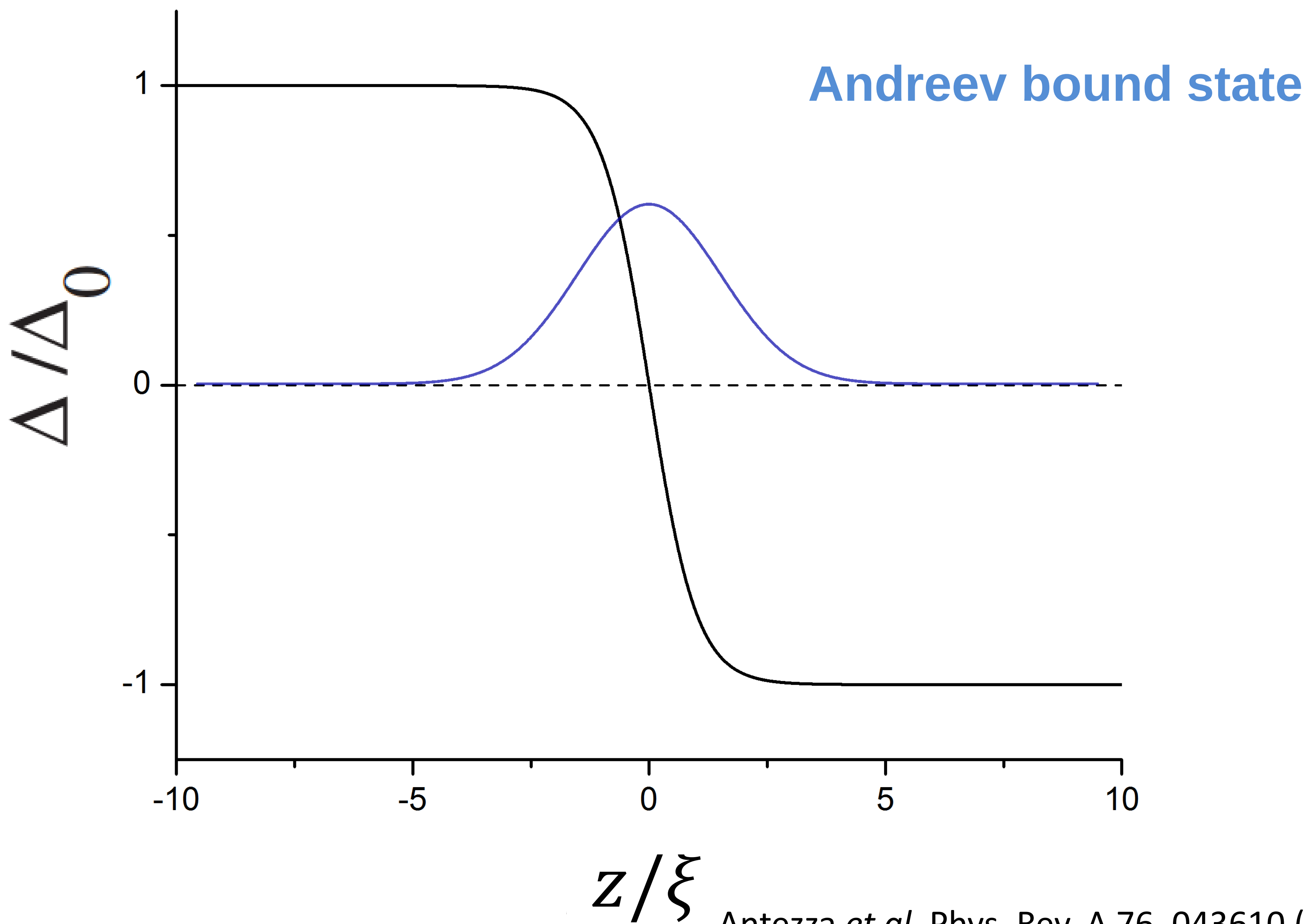


Many experiments : Sengstock, Philips, Oberthaler
Also bright solitons : Salomon, Hulet

Dark soliton in a Fermi Superfluid



Dark soliton in a Fermi Superfluid



Antezza *et al.* Phys. Rev. A 76, 043610 (2007)

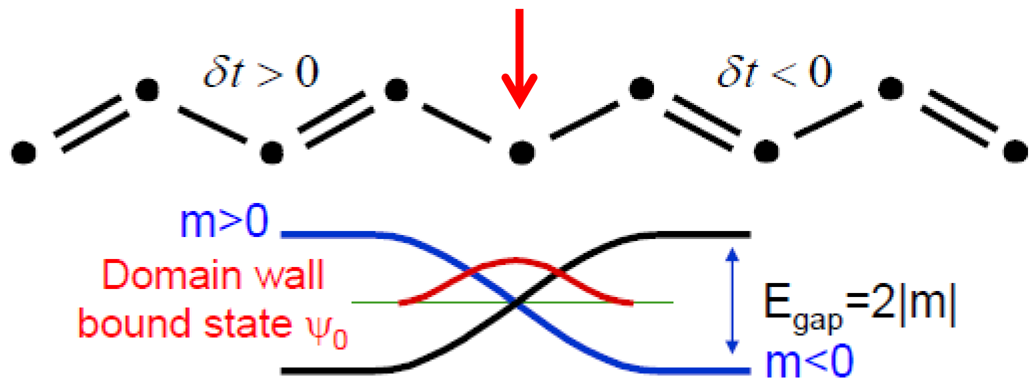
Connection with edge states physics

In the BCS limit with vanishing gap

$$\left(-i\hbar v_F \sigma_z \frac{\partial}{\partial z} + \Delta(z)\sigma_x\right)\begin{pmatrix} u_n \\ v_n \end{pmatrix} = E_n \begin{pmatrix} u_n \\ v_n \end{pmatrix}$$

Dirac equation with a varying mass

Also describes the **Su-Schrieffer-Heeger** (SSH) Model (1979)



Soliton in polyacetylene

topologically protected
bound state
at the soliton

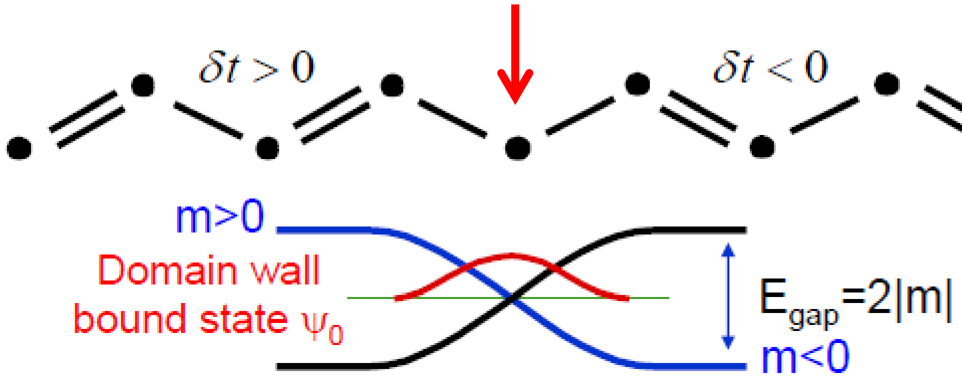
Connection with edge states physics

In the BCS limit with vanishing gap

$$\left(-i\hbar v_F \sigma_z \frac{\partial}{\partial z} + \Delta(z)\sigma_x\right)\begin{pmatrix} u_n \\ v_n \end{pmatrix} = E_n \begin{pmatrix} u_n \\ v_n \end{pmatrix}$$

Dirac equation with a varying mass

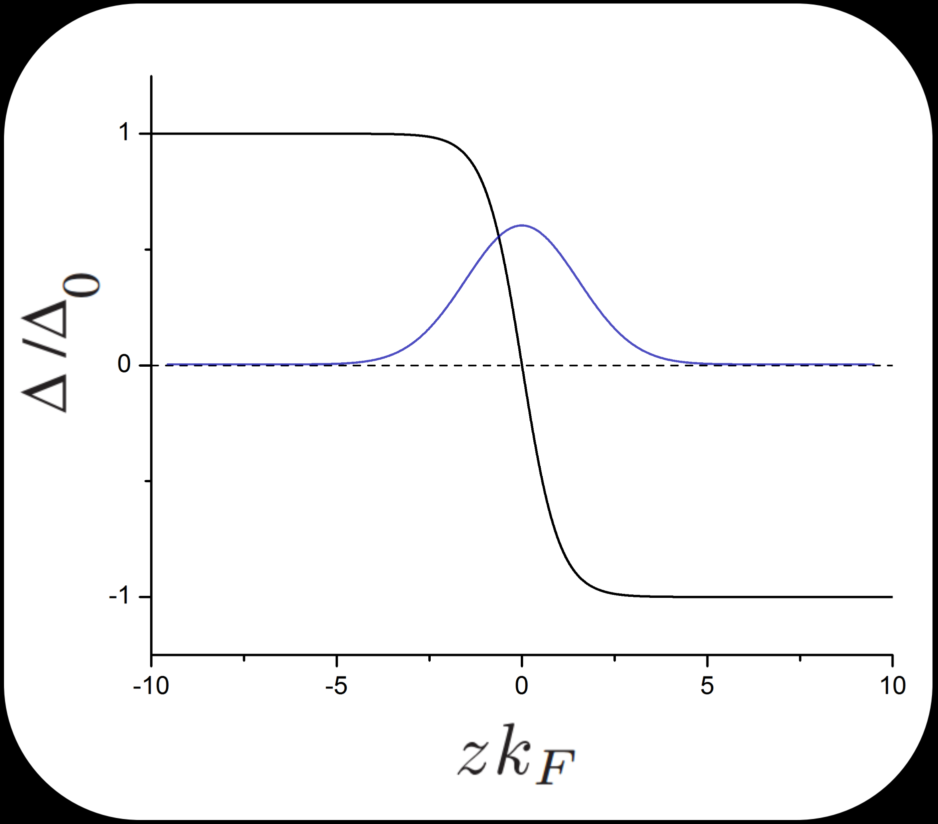
Also describes the **Su-Schrieffer-Heeger** (SSH) Model (1979)



Soliton in polyacetylene

topologically protected
bound state
at the soliton

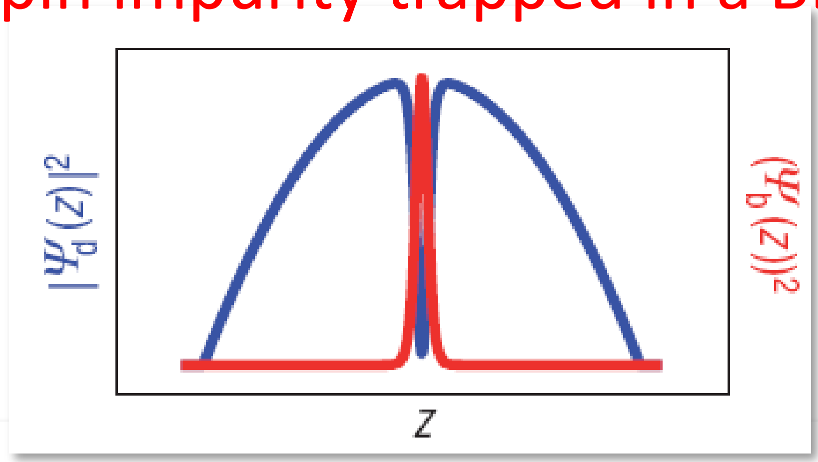
What kind of measurement ?

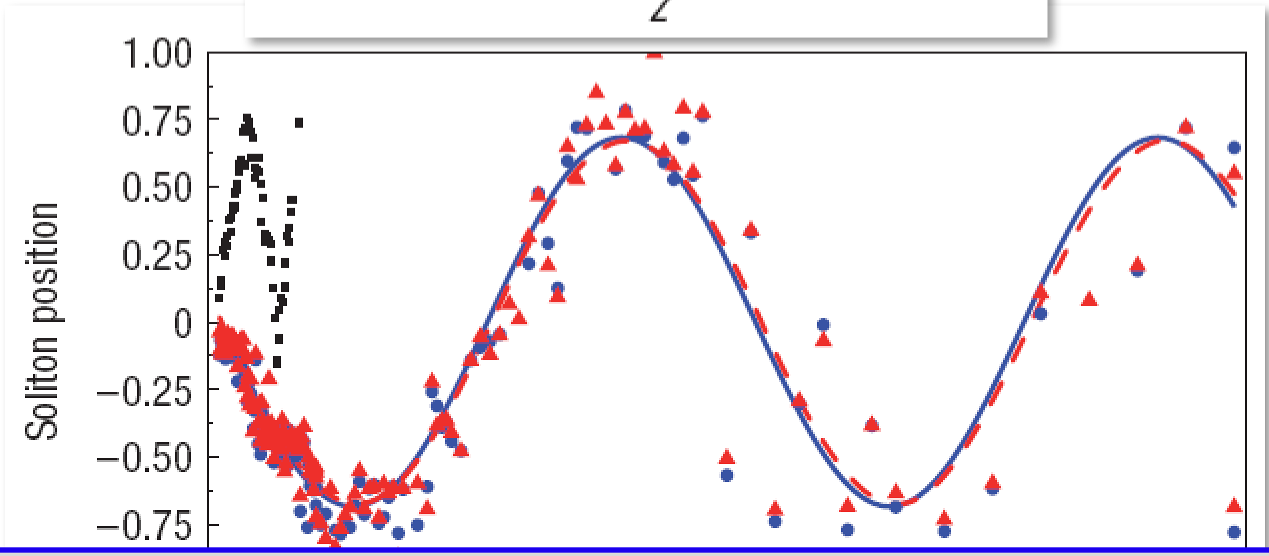


The Dark-Bright soliton experiment

Spin impurity trapped in a BEC

Sengstock group
Becker et al.,
Nature Physics 2008





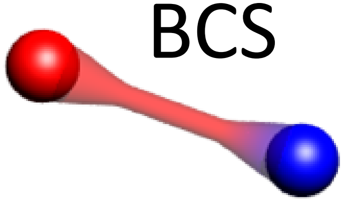
Large increase in the period for a filled soliton

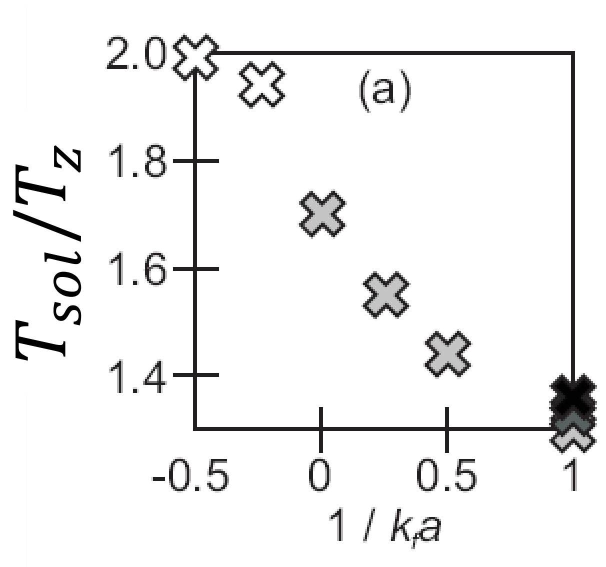
Dynamics of a soliton in a trapped Superfluid

Mean-Field Bogoliubov – de Gennes prediction:
Solitons should get heavier for stronger interactions

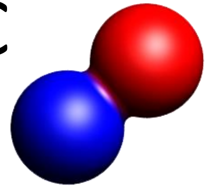
$T_{sol} = \sqrt{3}T_z$ at unitarity

BCS





BEC



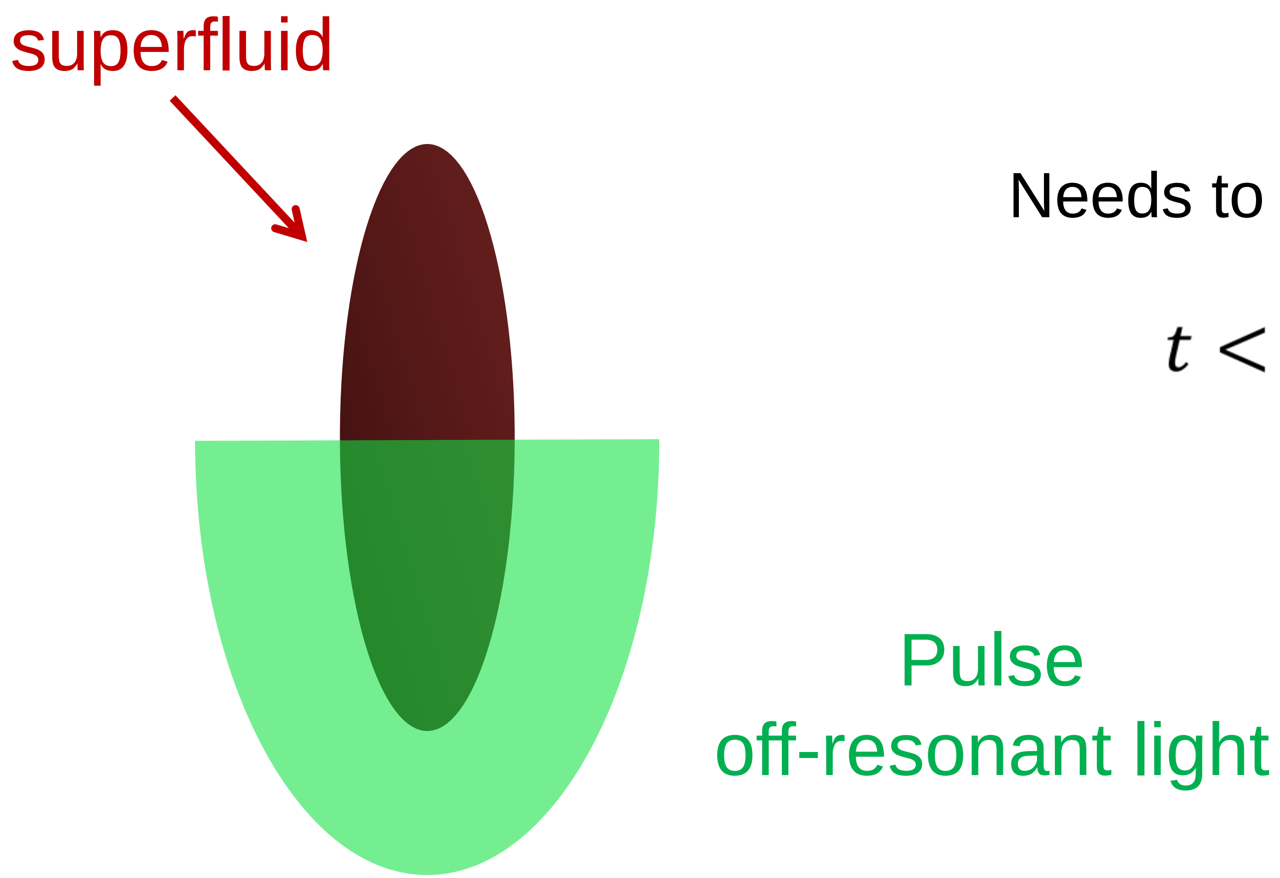
$$T_{sol} = \sqrt{2}T_z$$

G-P prediction
(confirmed in exp.)

Scott, Dalfovo, Pitaevskii & Stringari
Phys. Rev. Lett. **106**, 185301 (2011)

See also:
Liao and Brand , Phys. Rev. A **83**, 041604(R) (2011)
Antezza *et al.* Phys. Rev. A 76, 043610 (2007)

Making a soliton by phase imprinting

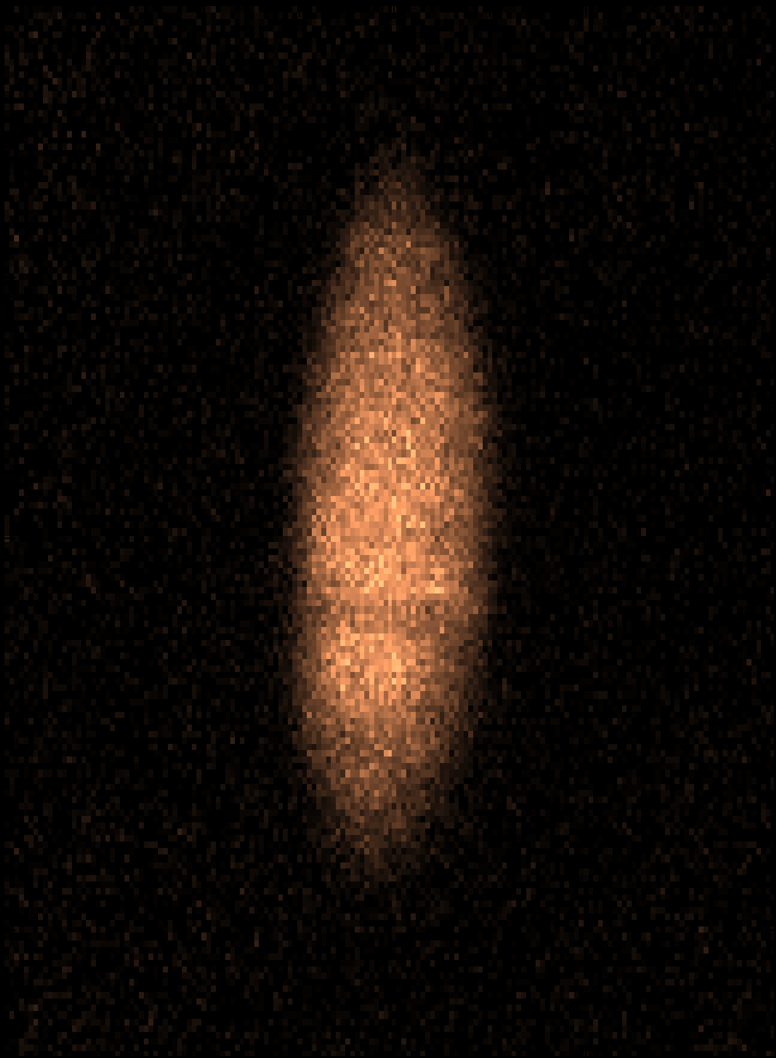


Needs to be fast enough:

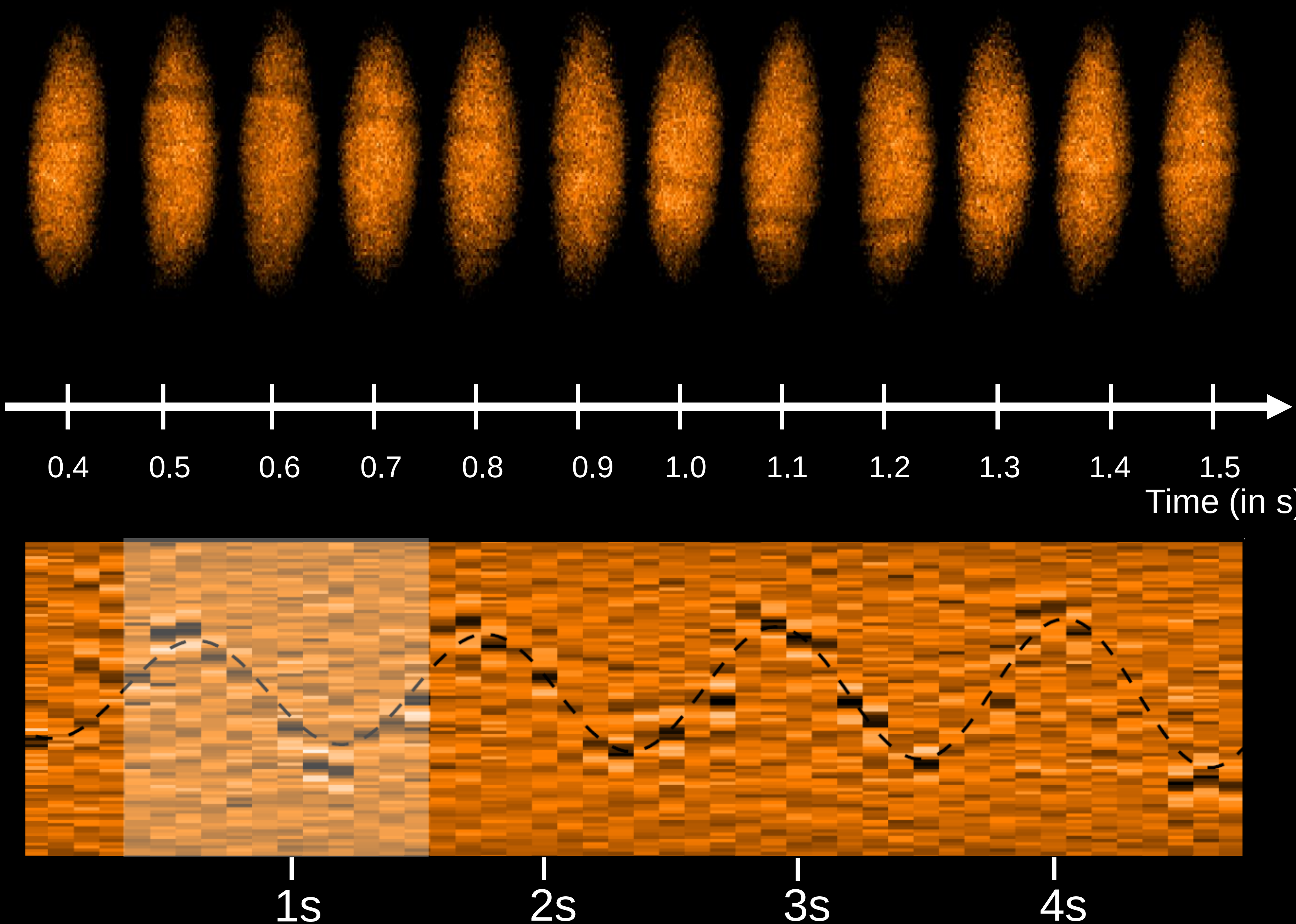
$$t < \frac{\hbar}{\mu} \sim 100\ \mu s$$

After the pulse $\Delta\phi = -2U\ t\ /\hbar$

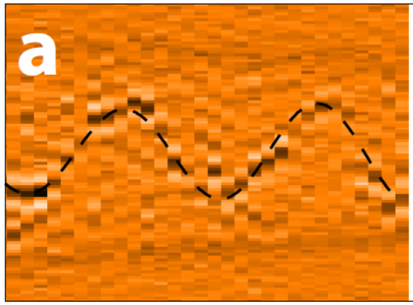
Solitons in BECs by phase imprinting: Hamburg, NIST



815 Gauss

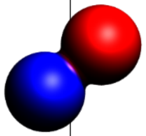

0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Time (in s)
1s
2s
3s
4s

700 G

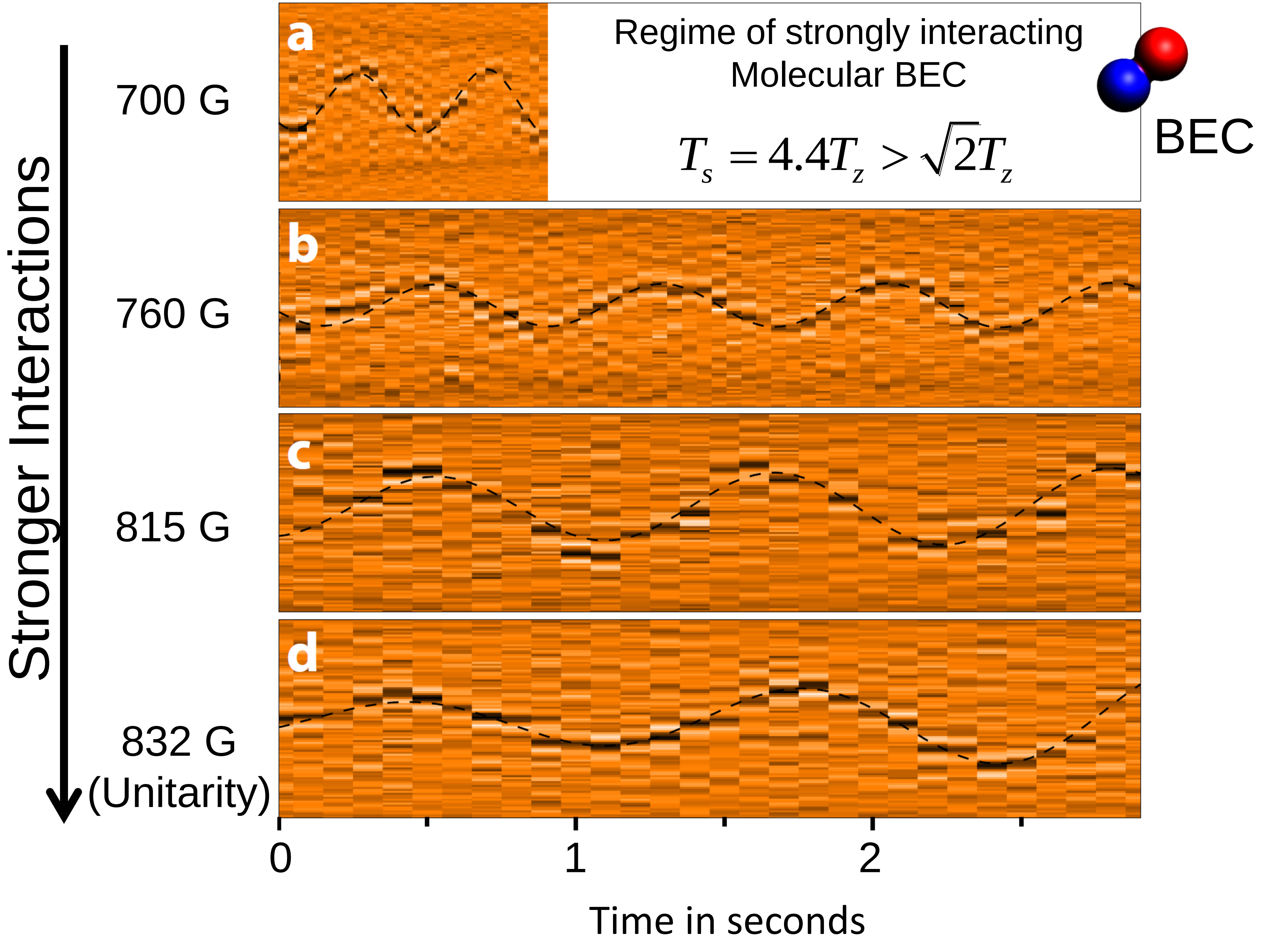


Regime of strongly interacting
Molecular BEC

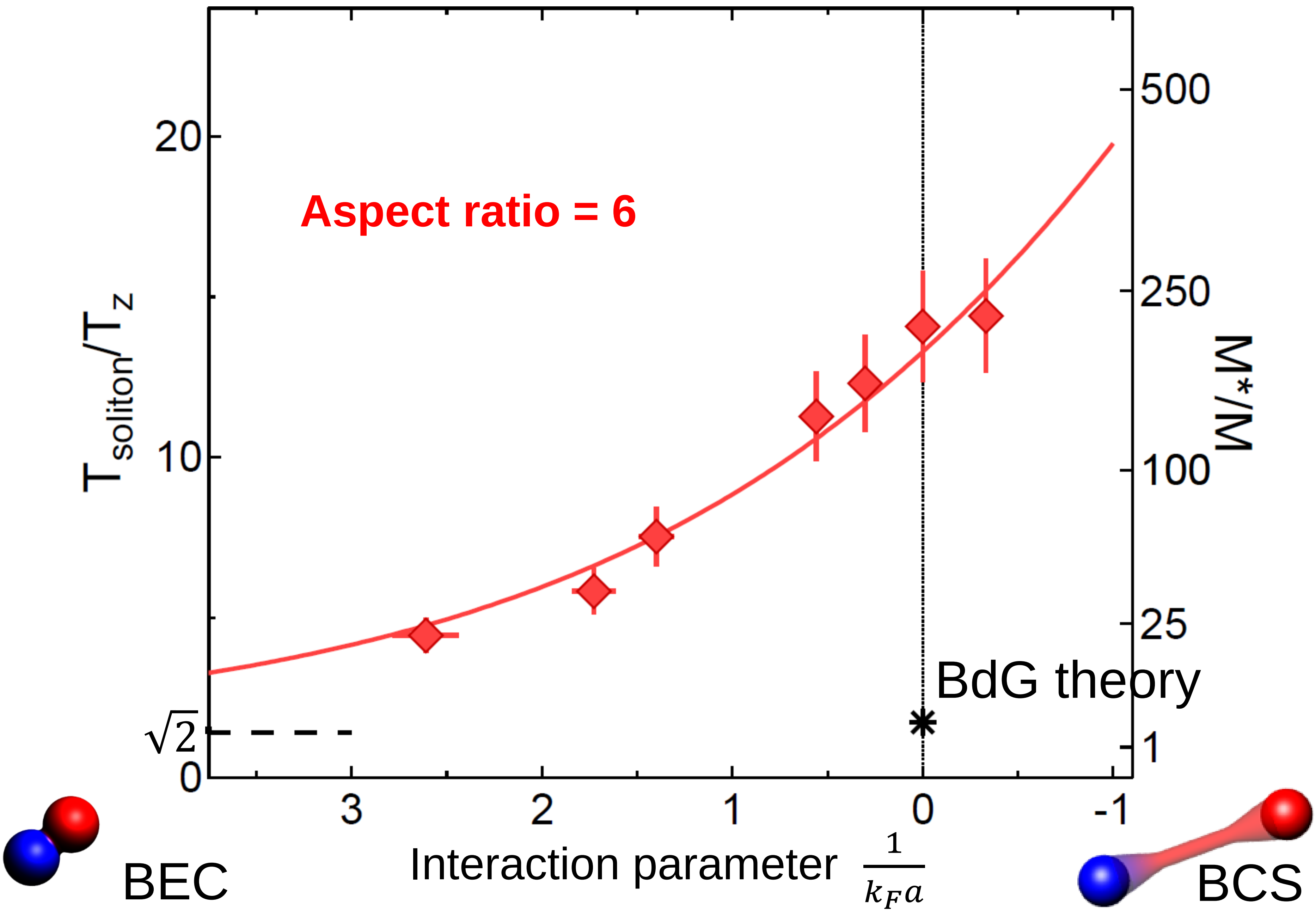
$$T_s = 4.4T_z > \sqrt{2}T_z$$



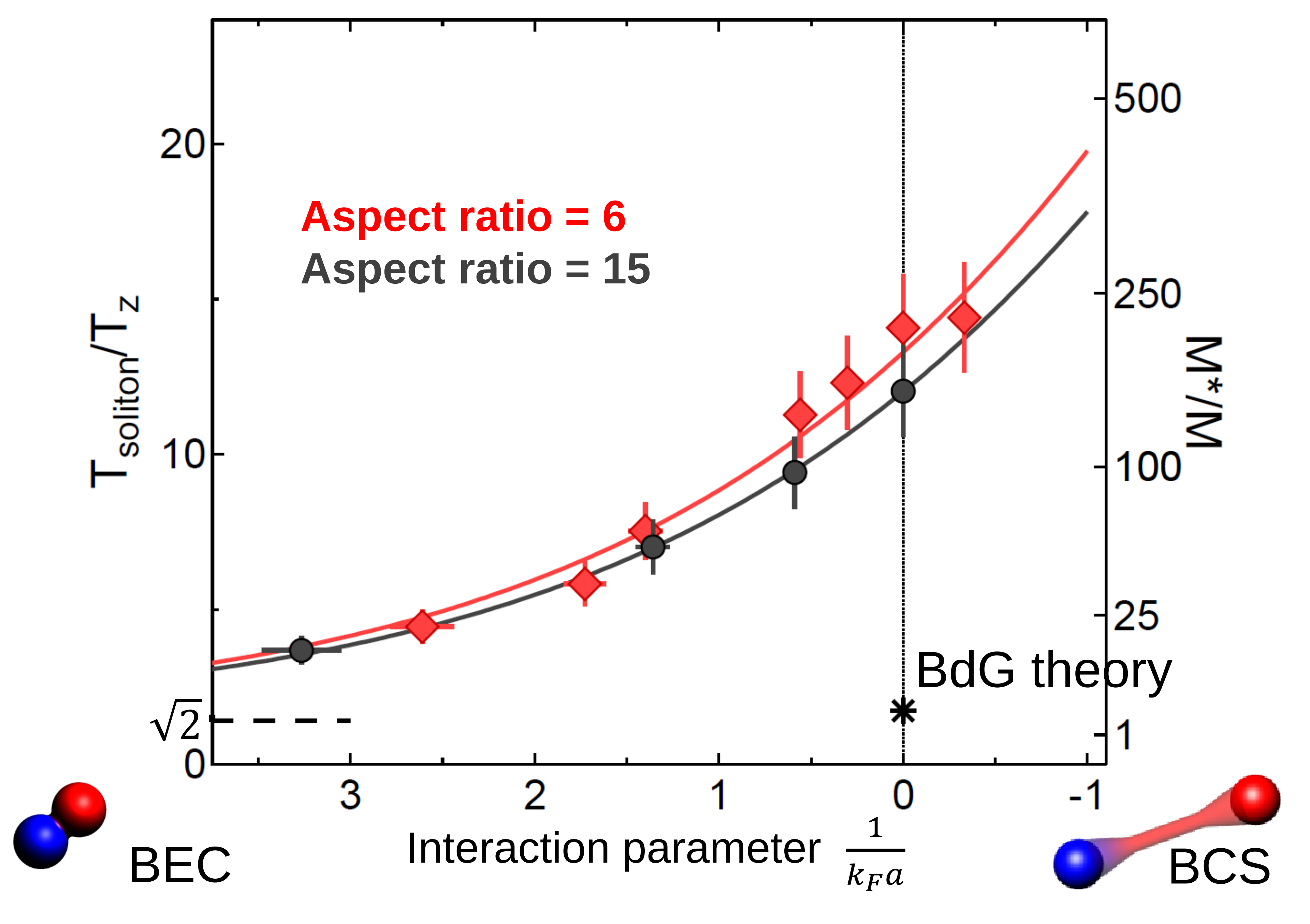
BEC



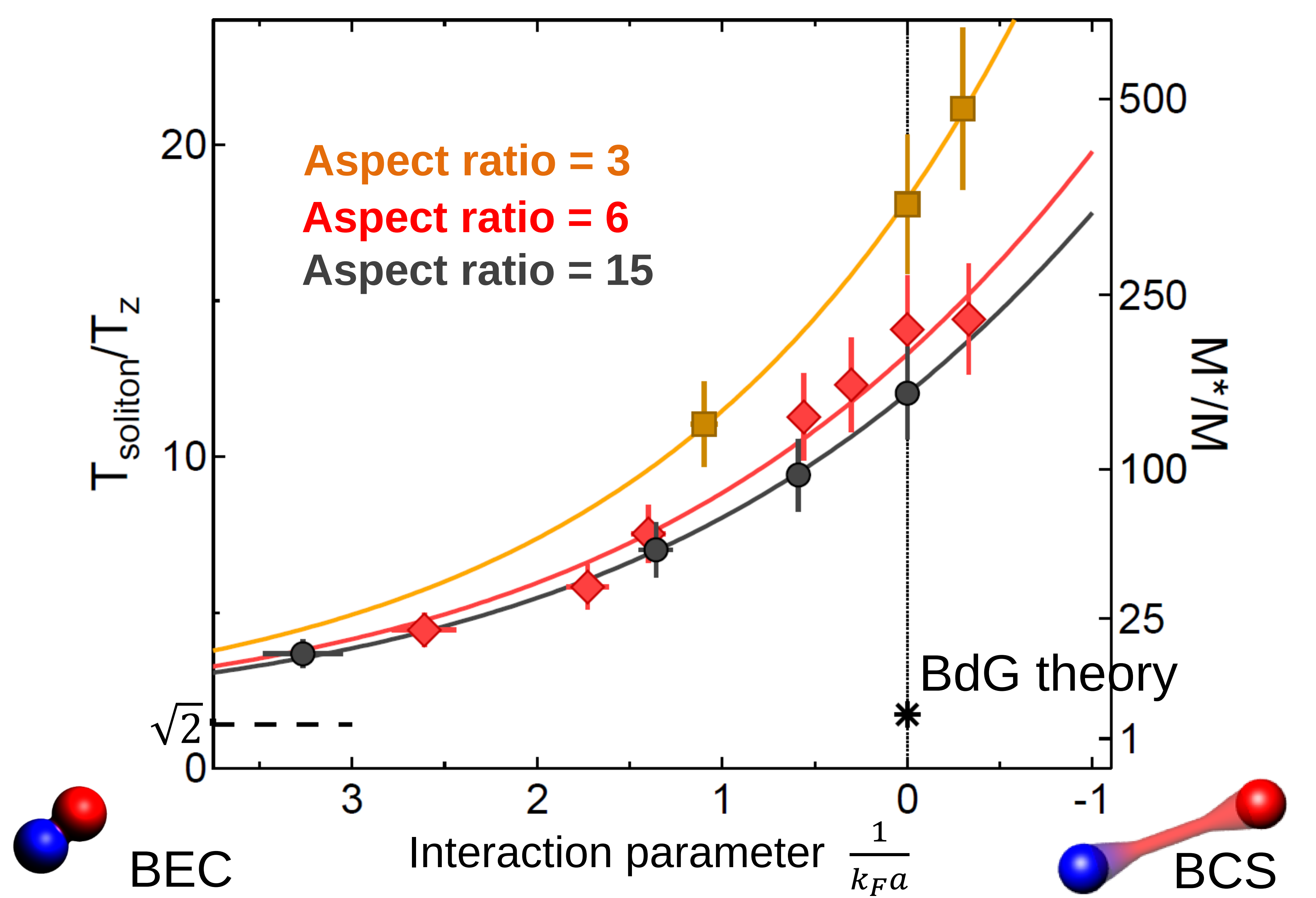
Regime of strongly interacting
Molecular BEC
$T_s = 4.4 T_z > \sqrt{2} T_z$
BEC
Stronger Interactions
700 G
760 G
815 G
832 G
(Unitarity)
a
b
c
d
0
1
2
Time in seconds



Aspect ratio = 6
$T_{soliton}/T_z$
M^*/M
20
10
$\sqrt{2}$
0
500
250
100
25
1
3
2
1
0
-1
BdG theory
BEC
BCS
Interaction parameter $\frac{1}{k_F a}$

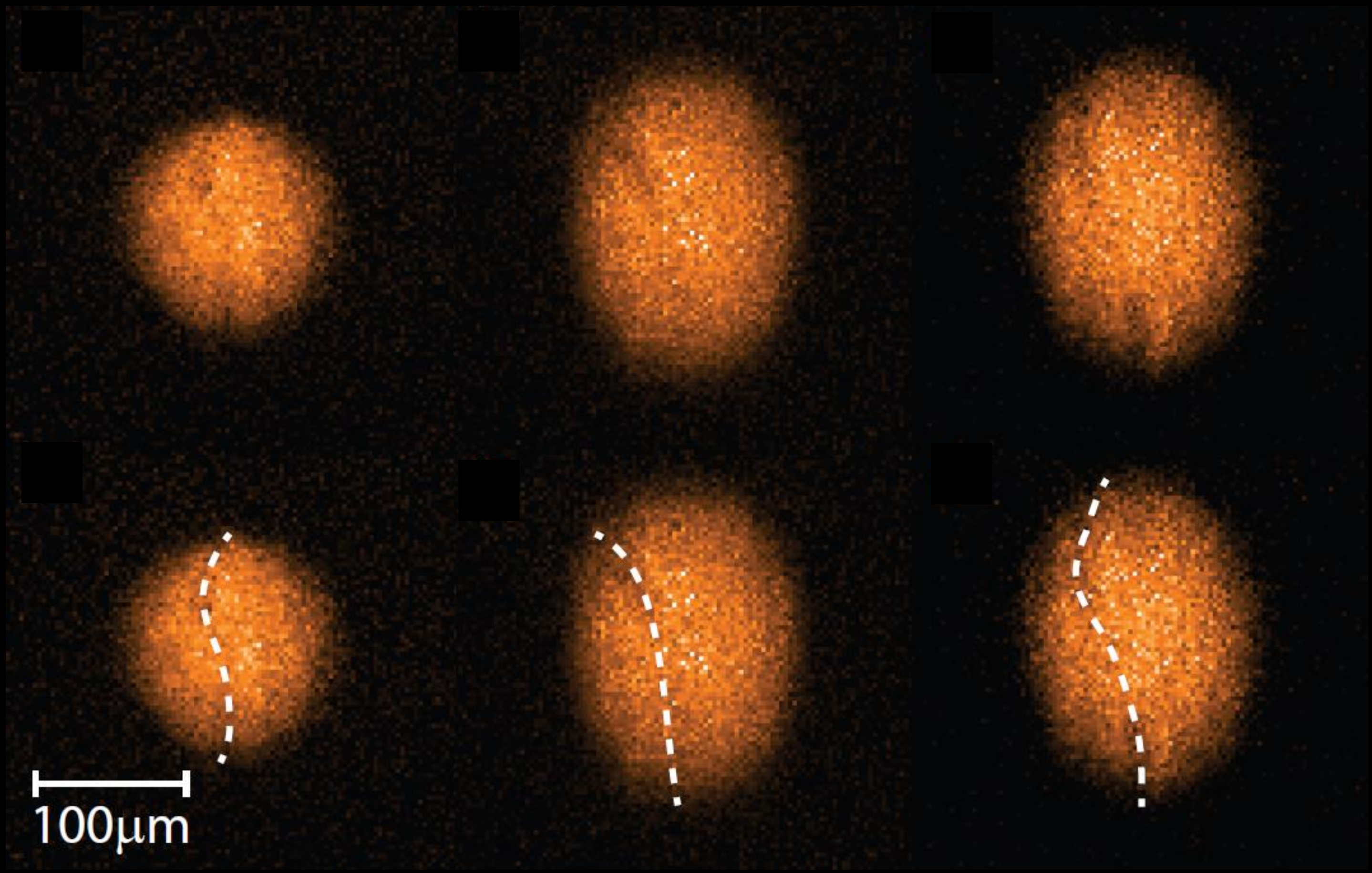


Aspect ratio = 6
Aspect ratio = 15
$T_{soliton}/T_z$
20
10
$\sqrt{2}$
0
3
2
1
0
-1
500
250
100
25
1
M^*/M
BdG theory
BEC
BCS
Interaction parameter $\frac{1}{k_F a}$

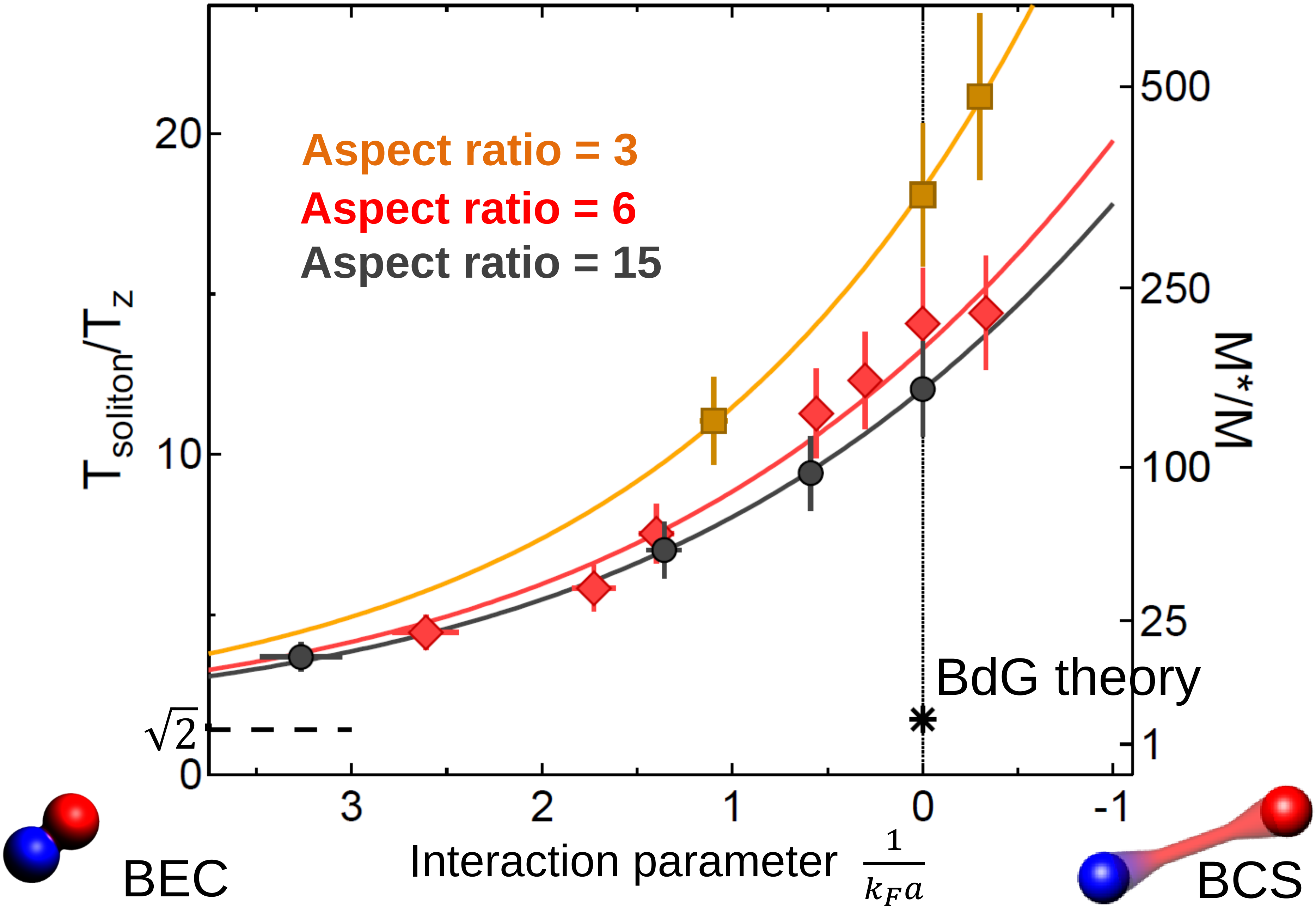


Aspect ratio = 3
Aspect ratio = 6
Aspect ratio = 15
$T_{soliton}/T_z$
M^*/M
BdG theory
Interaction parameter $\frac{1}{k_F a}$
BEC
BCS
20
10
$\sqrt{2}$
0
500
250
100
25
1
3
2
1
0
-1

Snake instability for rounder clouds

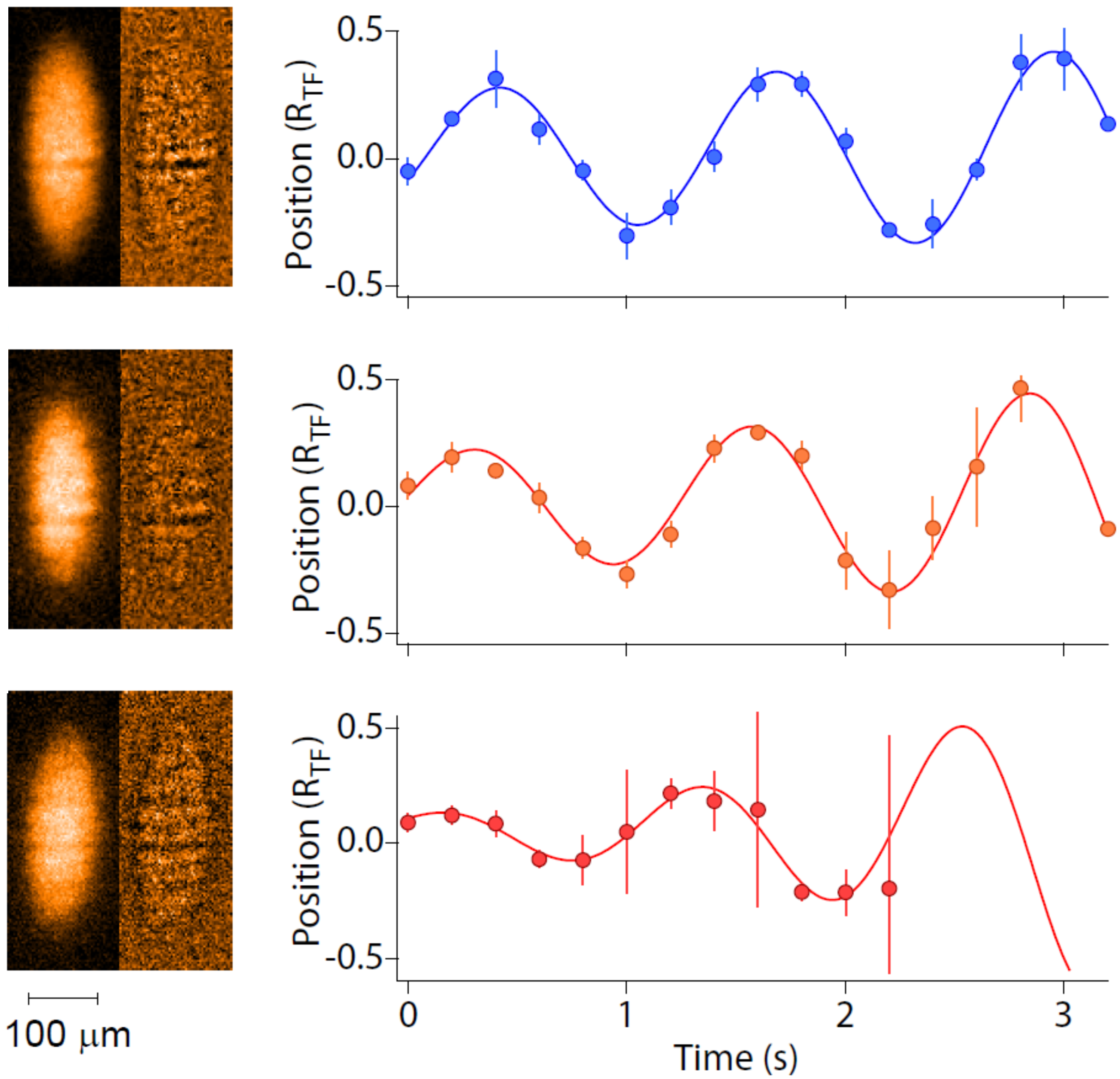


arXiv : 1302.4736



Quantum or thermal effect?

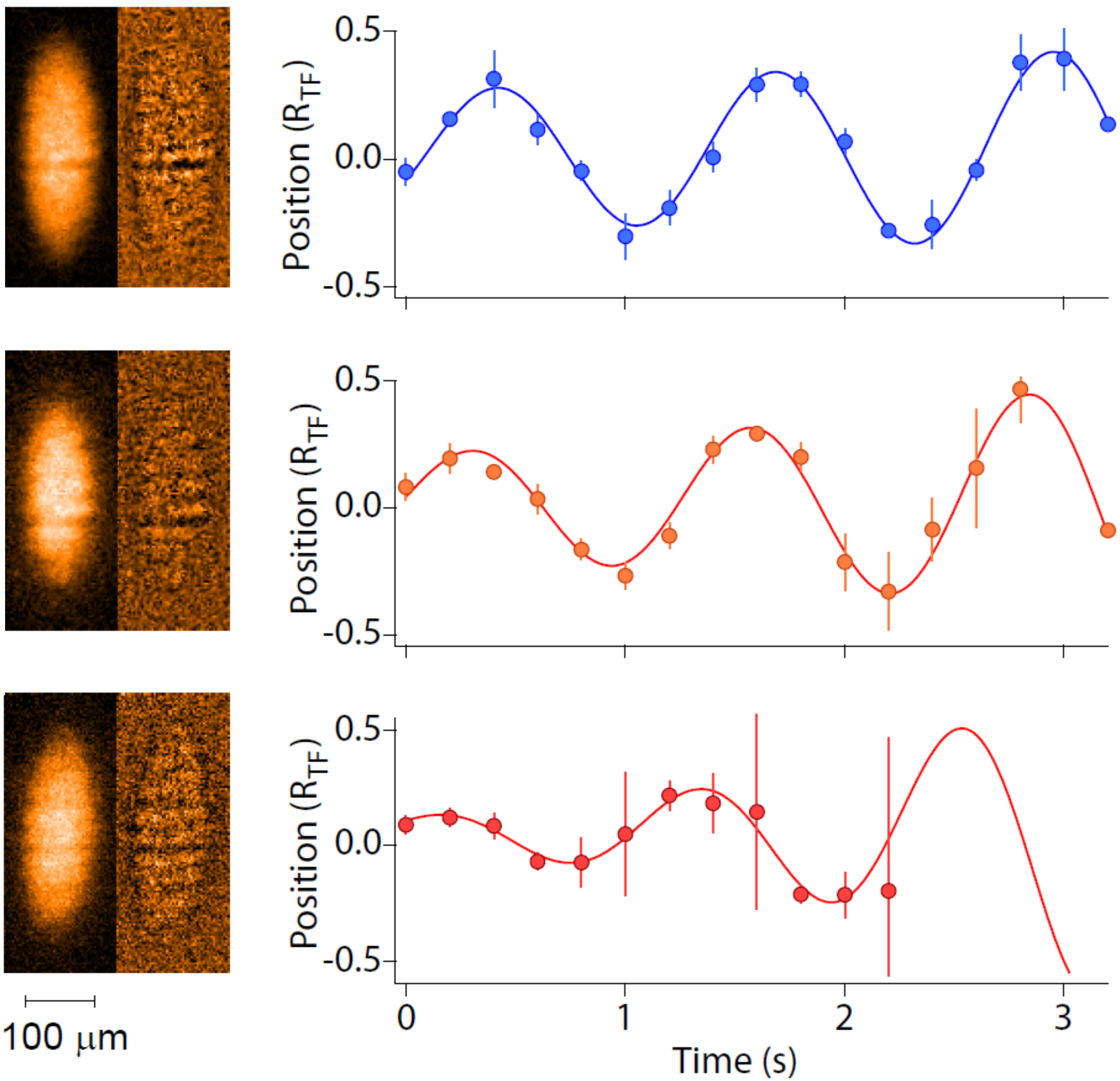
- Temperature below 0.05 T_F



4% thermal fraction

Quantum or thermal effect?

- Temperature below 0.05 T_F



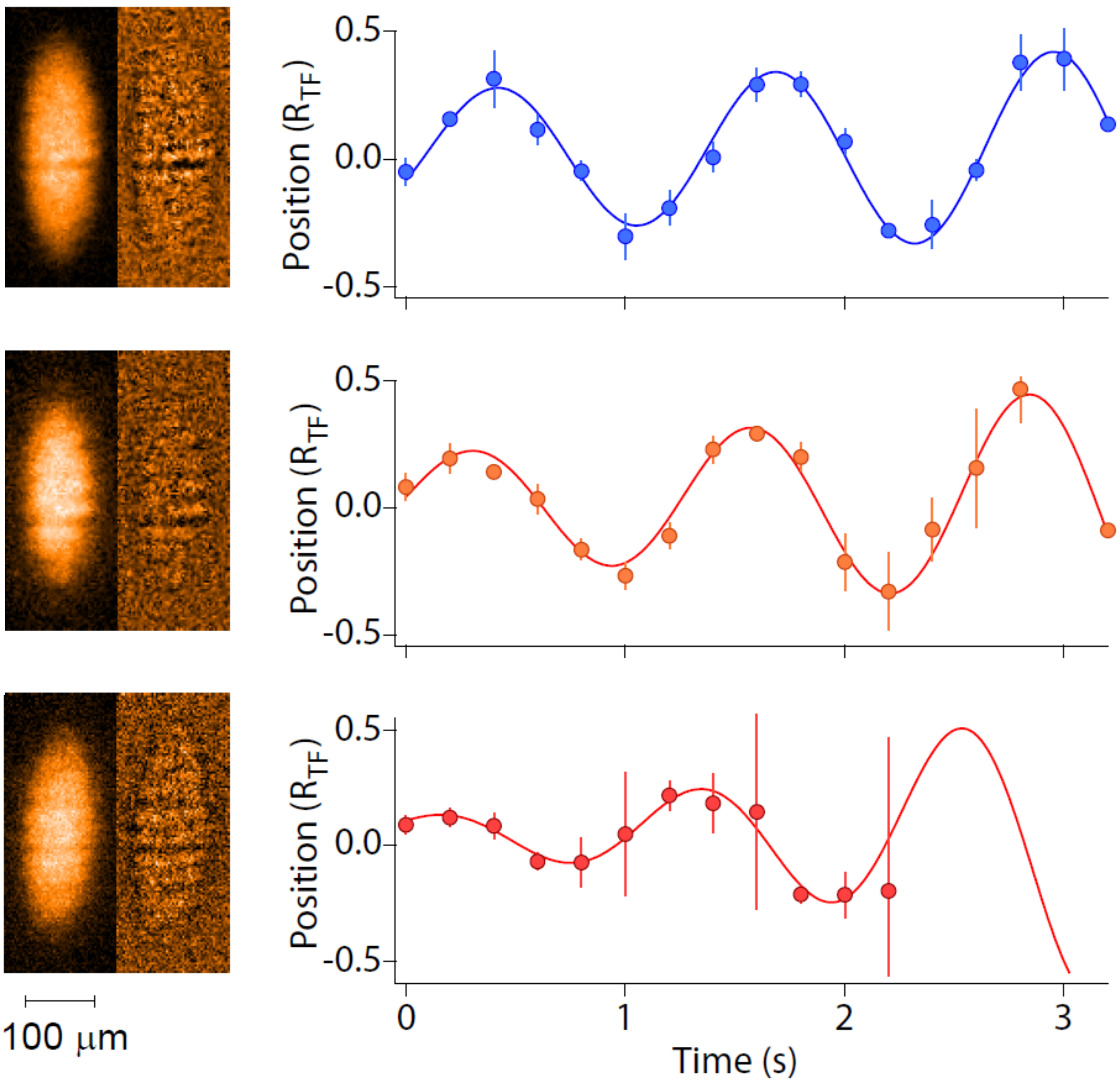
4% thermal fraction

14% thermal fraction

- Anti-damping : the soliton reduces its energy by accelerating

Quantum or thermal effect?

- Temperature below 0.05 T_F



4% thermal fraction

14% thermal fraction

- Anti-damping : the soliton reduces its energy by accelerating

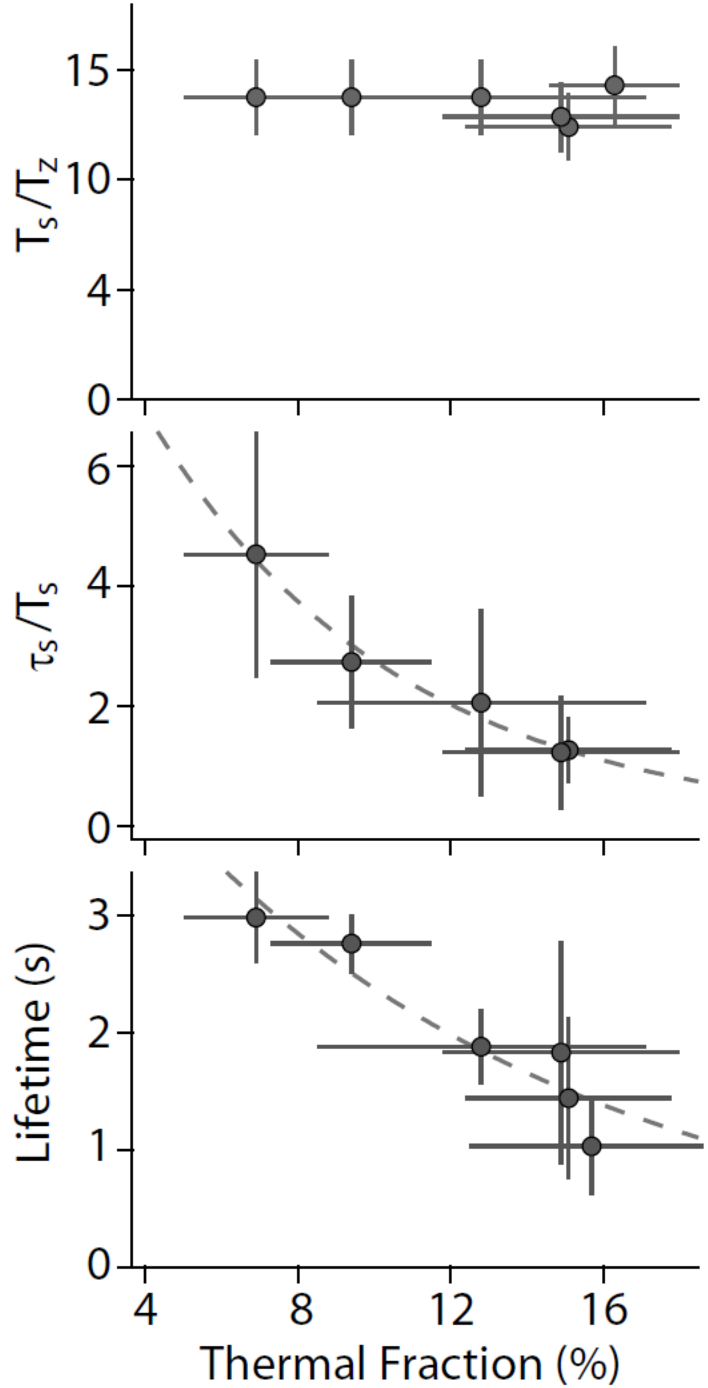
17% thermal fraction

- Stronger anti-damping
- Less deterministic trajectory
- Shorter lifetime

Period

Anti-Damping Time

Lifetime

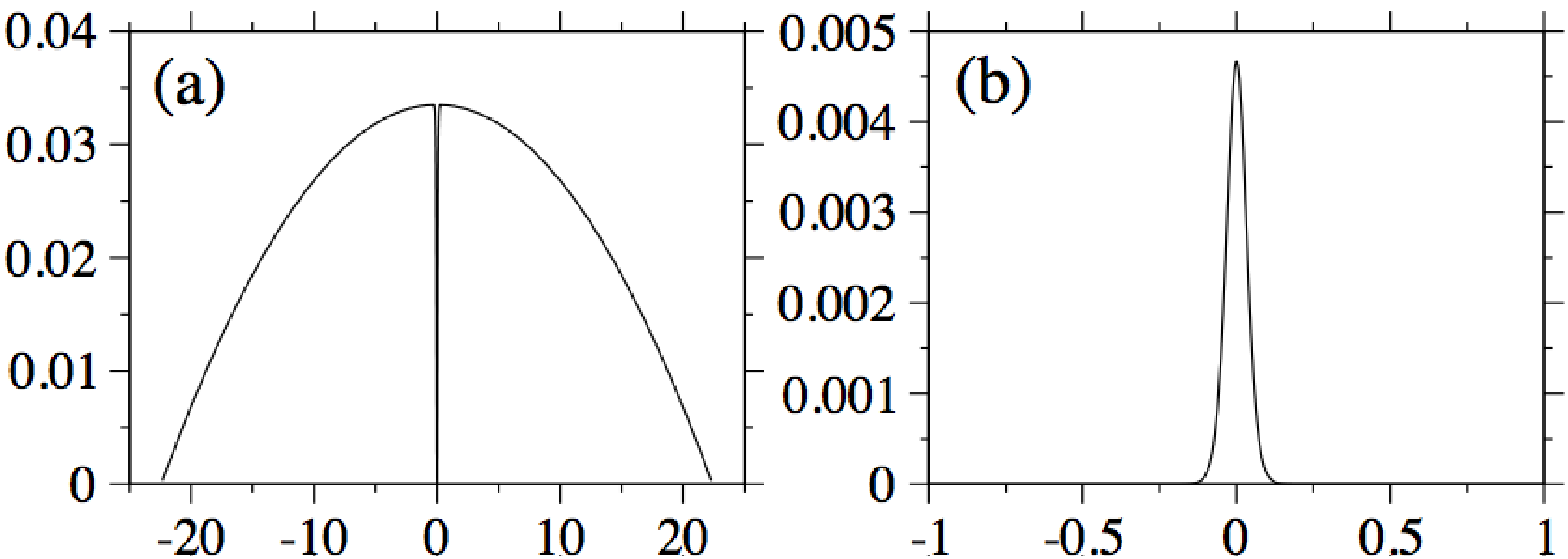


Long period and large M*/M is a Quantum Effect

Quantum fluctuations?

In weakly interacting Bose Gases

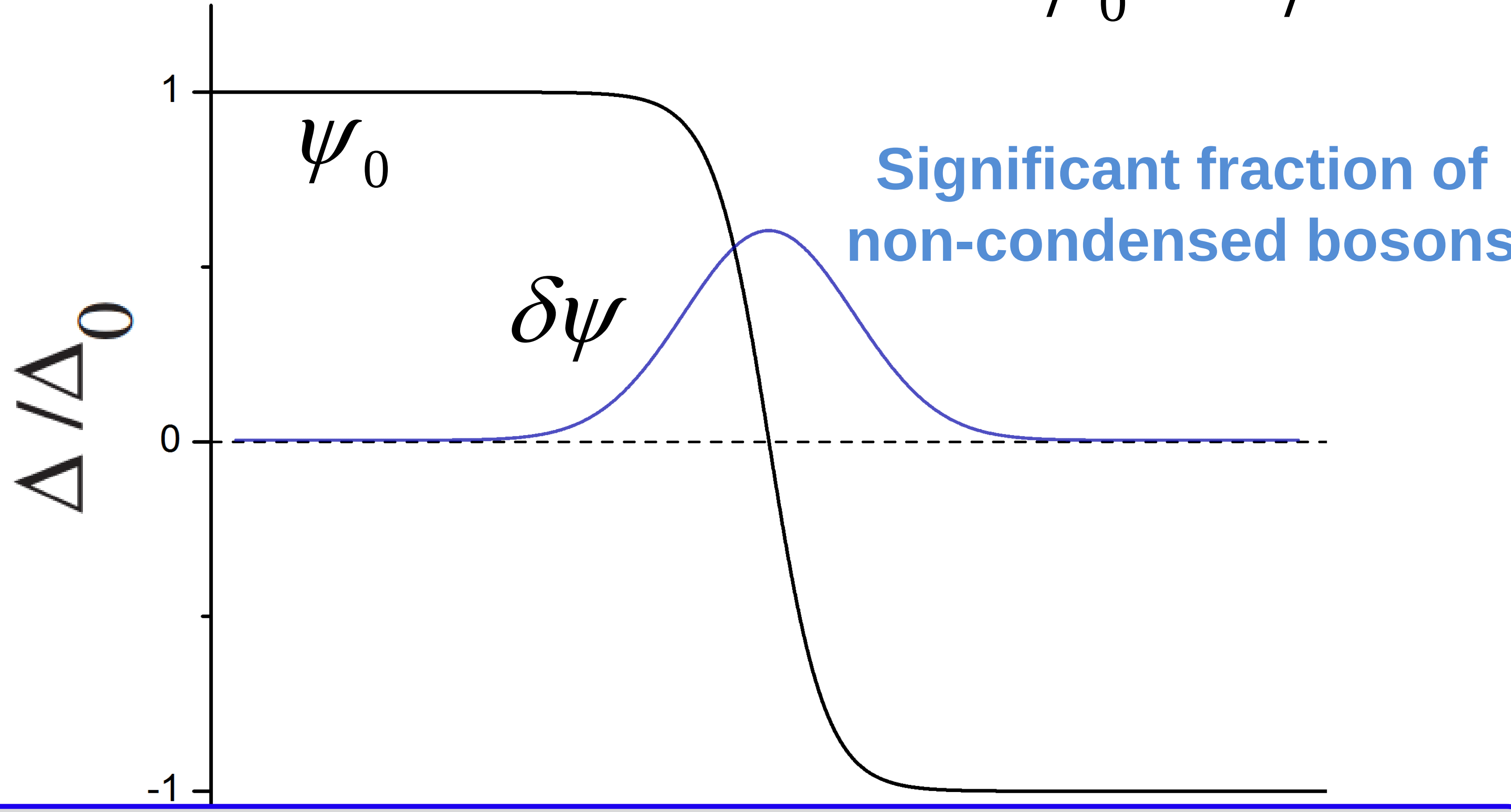
$$\hat{\Psi} = \sqrt{N}\Phi_0 + \hat{\psi}$$



Dziarmaga, Sacha, PRA 66, 043620 (2002)
Law, PRA 68, 015602 (2003)

Quantum fluctuations?

In **strongly** interacting Bose Gases $\Psi = \psi_0 + \delta\psi$



Soliton filled with un–condensed pairs
Contribution to the mass enhancement ?

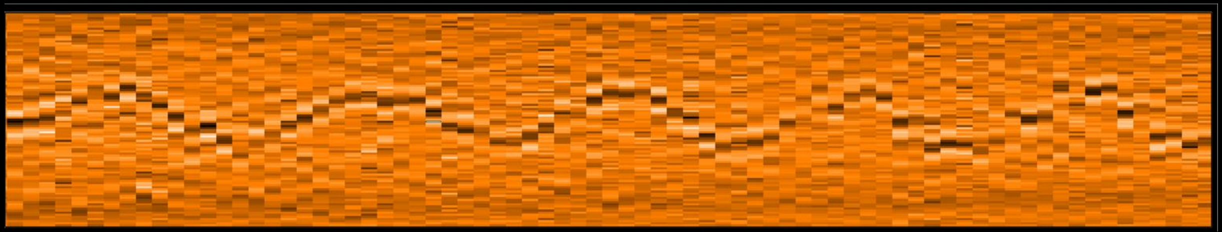
Conclusion

- Spin-Injection Spectroscopy of a spin-orbit coupled Fermi gas
  → access to energy, momentum and spin

  Phys. Rev. Lett. **109**, 095302 (2012)

- Heavy Solitons in a Fermionic Superfluid
  → Effective mass 50 times larger than the current predictions
  → Filling with bosonic and fermionic bound states (?)

T. Yefsah, A. Sommer, M. J.-H. Ku, L. Cheuk, W. Ji, W. Bakr, M. Zwierlein
arXiv:1302.4736 (2013)



Upcoming works on solitons

- Collisions of solitons: elastic in BEC limit, inelastic collisions across crossover might shed light on Andreev bound states.

- Locally resolved RF spectroscopy to directly detect bound states.

Thanks

Lawrence Cheuk

Ariel Sommer

Mark Ku

Wenjie Ji

Zoran Hadzibabic

Waseem Bakr

Martin Zwierlein