Spin caloritronics with cold atoms

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Netherlands Organisation for Scientific Research
European Research Council

Spin caloritronics with (ferromagnetic) metals

- Understanding of: (NB: $\sigma = (\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow})/2$)

$$\begin{pmatrix} j_\uparrow \\ j_\downarrow \\ j_{Q\uparrow} \\ j_{Q\downarrow} \end{pmatrix} = \begin{pmatrix} \sigma_{\uparrow\uparrow} & \sigma_{\uparrow\downarrow} & \sigma TS_{\uparrow\uparrow} & \sigma TS_{\uparrow\downarrow} \\ \sigma_{\downarrow\uparrow} & \sigma_{\downarrow\downarrow} & \sigma TS_{\downarrow\uparrow} & \sigma TS_{\downarrow\downarrow} \\ \sigma P_{\uparrow\uparrow} & \sigma P_{\uparrow\downarrow} & \kappa_{\uparrow\uparrow} & \kappa_{\uparrow\downarrow} \\ \sigma P_{\downarrow\uparrow} & \sigma P_{\downarrow\downarrow} & \kappa_{\downarrow\uparrow} & \kappa_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} -\nabla \mu_\uparrow \\ -\nabla \mu_\downarrow \\ -\nabla T_\uparrow \\ -\nabla T_\downarrow \end{pmatrix}$$

+ magnetization dynamics

+applications

(Spin) drag effects due to interactions

Spin caloritronics with cold atoms

- Does it exist?
- What can we learn from it?
- What is it good for?

Collaborators

Ph. D. Students: Ties Lucassen, Aaron Swaving, Hedwig van Driel, Erik van der Bijl, Martijn Mink,
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Alvaro Núñez *(Valparaiso, Chile)*
Jairo Sinova *(Texas A&M)*
Achim Rosch's group *(Cologne)*
Christian Pfleiderers group *(TU Munich)*
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Giovanni Vignale (Missouri)
Marco Polini (SNS Pisa)

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Gerrit Bauer (*Delft*)
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Maxim Mostovoy (*Groningen*)

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First: introducting cold atoms

Introducing cold atoms (I)

Electrons in metals

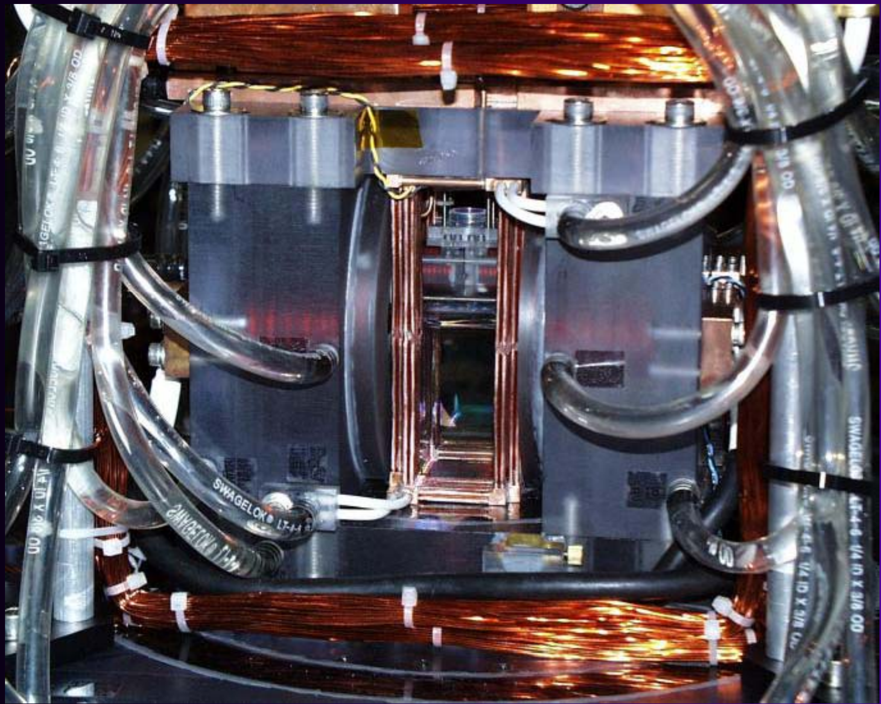
- charge $-e$
- Spin $S=1/2$
- fermion
- ionic lattice
- disorder
- phonons
- spin-orbit coupling
- long range *e*-*e* interactions
- magnons (in ferromagnet)

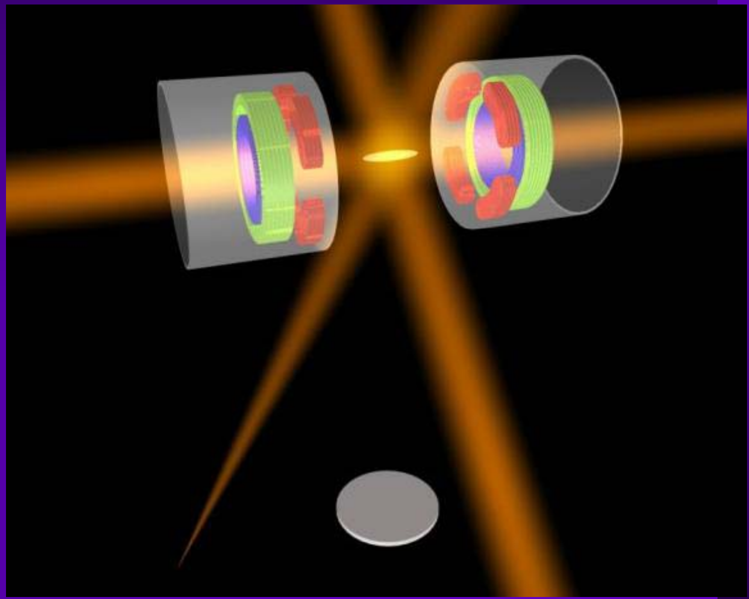
Trapped cold atoms

- neutral, e.g., Rb-87, Li-6/7, ...
- (hyperfine) spin $F=$...
- Bosons and/or fermions
- magnetic and/or optical trap
- disorder
- phonons
- spin-orbit coupling
- short-range atomic interactions
- magnons (in ferromagnet)

can be engineered

Introducing cold atoms (II)



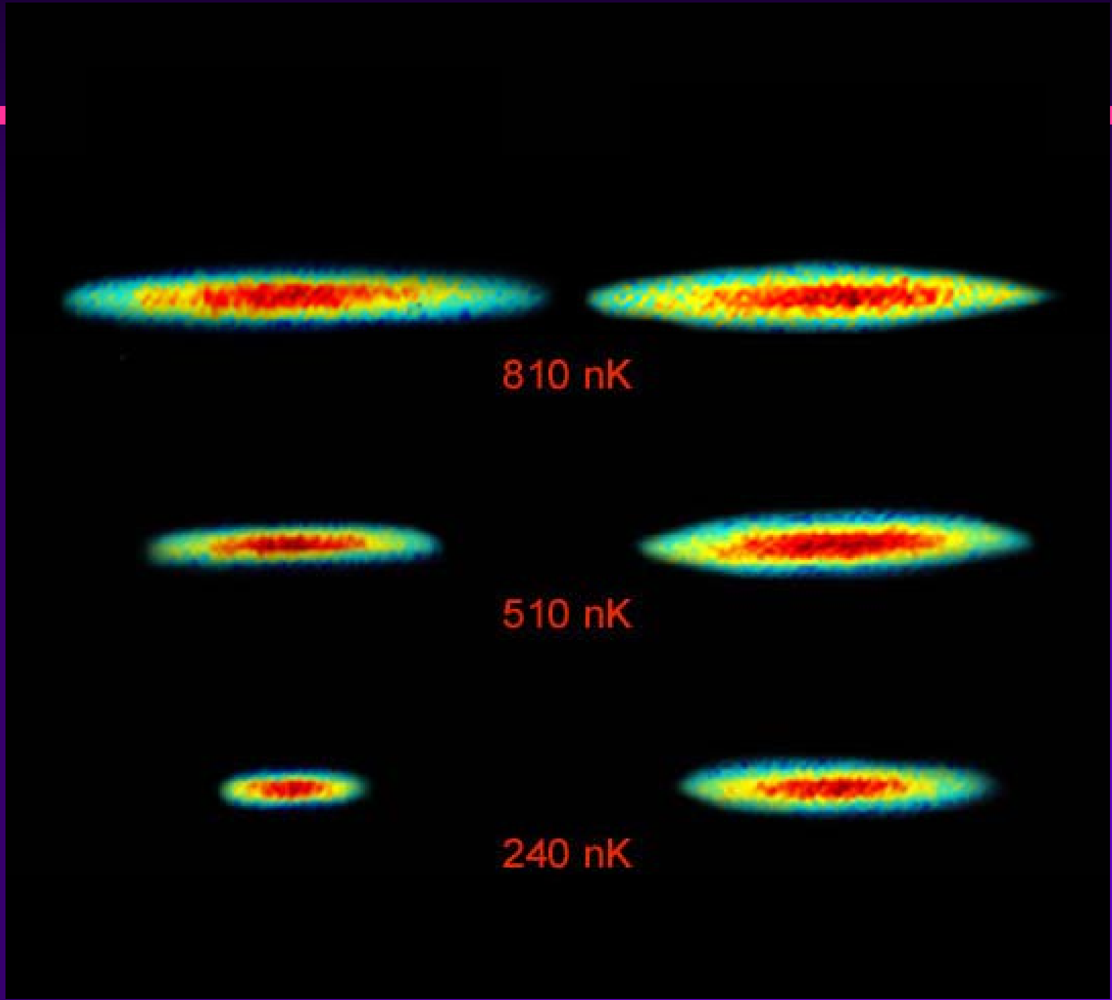


Laser cooling, harmonic confining potential, evaporative cooling,absorption imaging

Introducing cold atoms (III)

This experiment: few million atoms

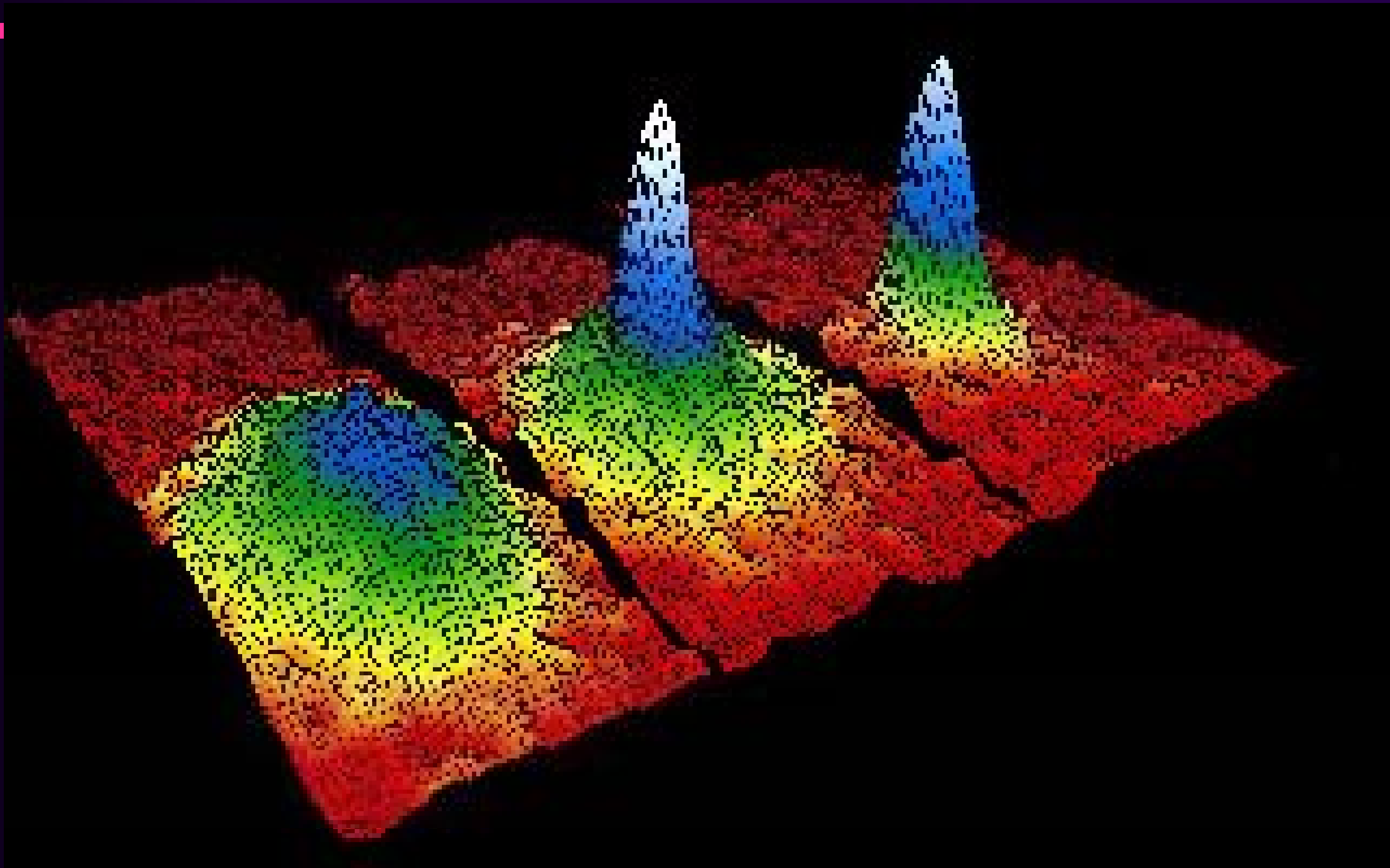
(Generally ranges from 10^4-10^9)



Lithium-7
(Boson -> Bose Condensation!)

Lithium-6
(Fermion, T/T_F~0.1)

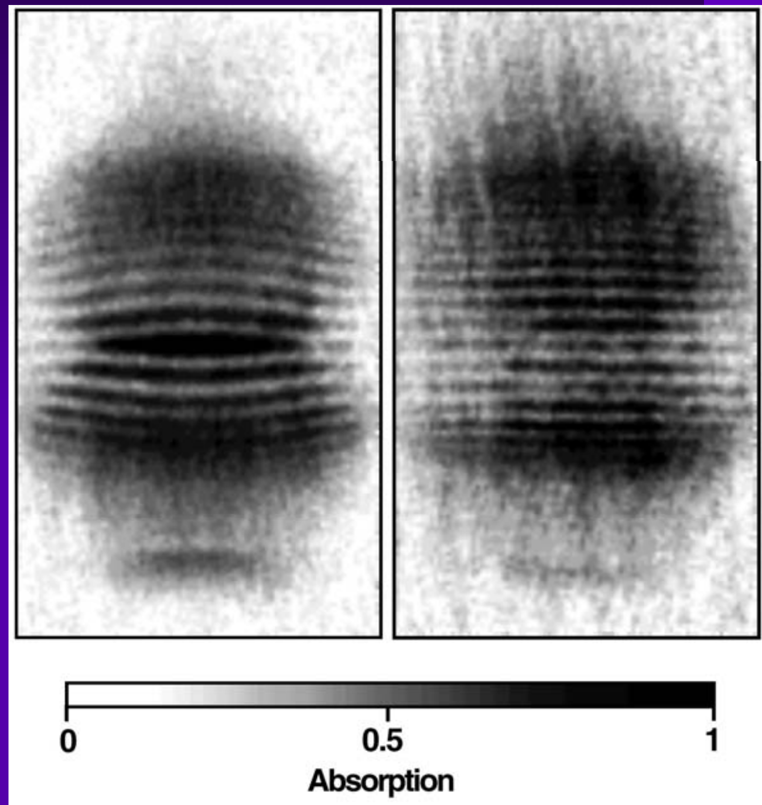
First Bose condensate (1995)



C. Wieman, E. Cornell (Nobel prize, 2001)

Two interfering Bose condensates

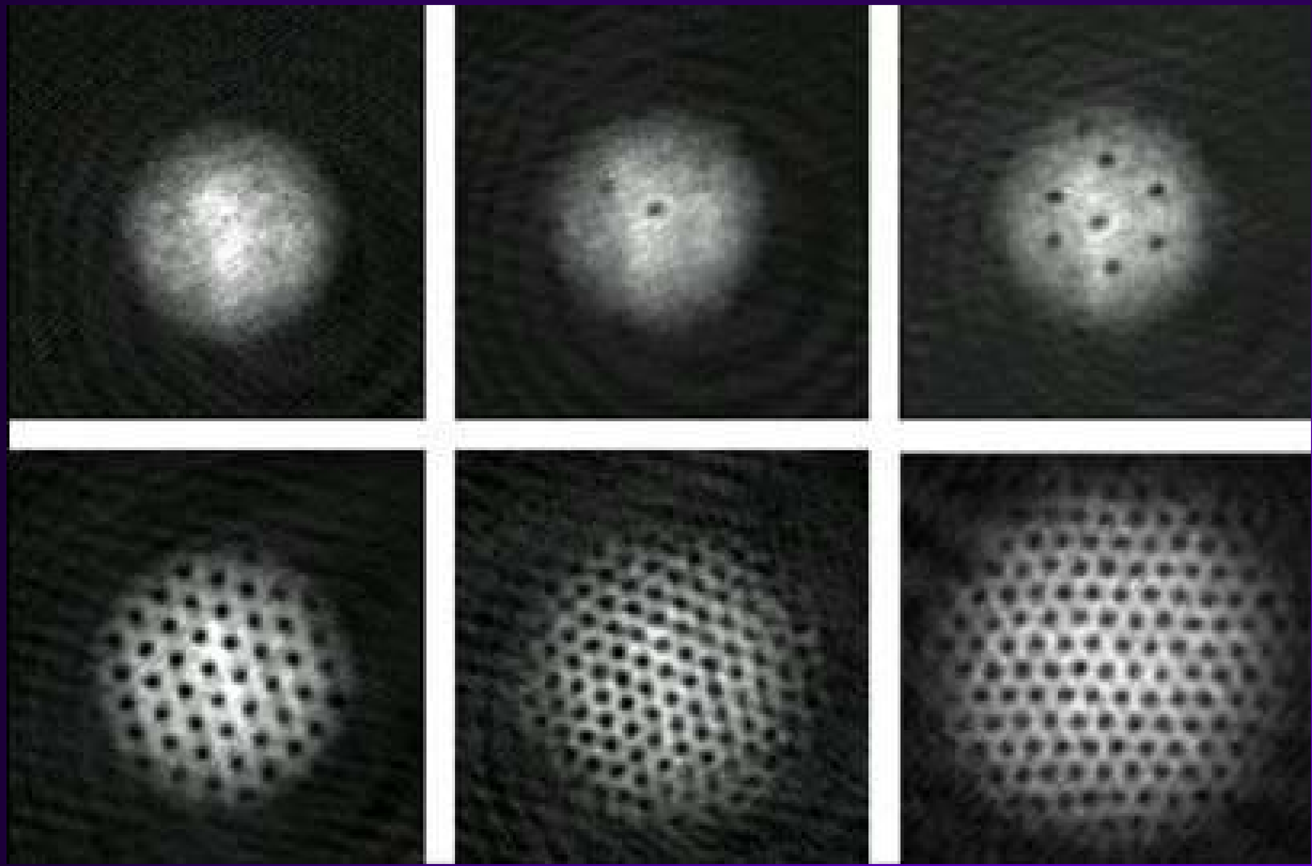
Classical waves



"matter waves"

W. Ketterle (Nobel prize, 2001)

Rotation: quantum vortices

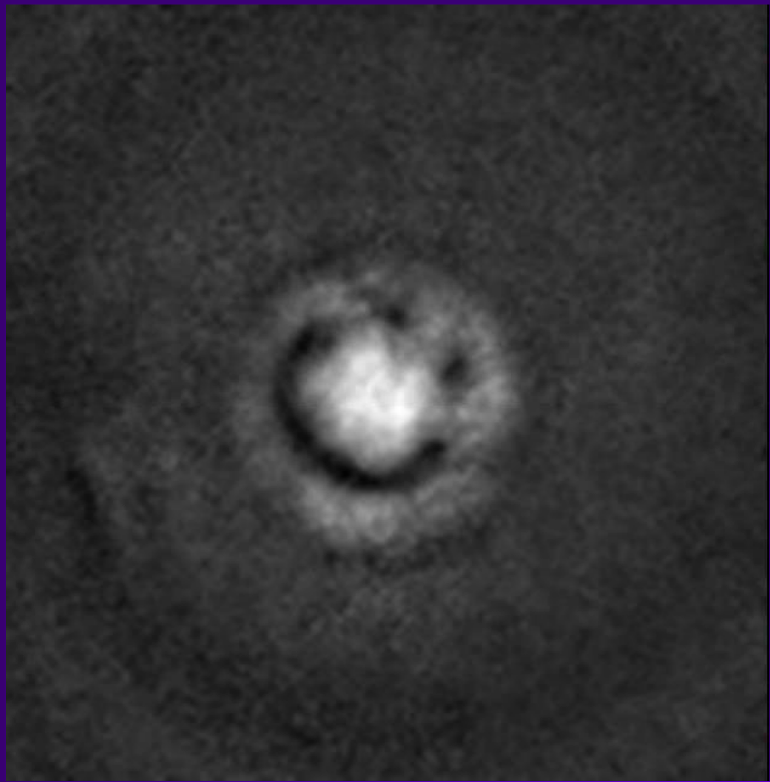


NB: rotation acts like magnetic field!!

http://jilawww.colorado.edu/bec

Introducing cold atoms (IV)

- + many more (mostly equilibrium) results...e.g:



happy Bose condensate

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Spin caloritronics with cold atoms? (I)

- Cold atoms have spin (take for now *F=1/2*)
  - Coupled mass (*not charge*), spin, and heat:

$$\begin{pmatrix} j_\uparrow \\ j_\downarrow \\ j_{Q\uparrow} \\ j_{Q\downarrow} \end{pmatrix} = \begin{pmatrix} \sigma_{\uparrow\uparrow} & \sigma_{\uparrow\downarrow} & \sigma TS_{\uparrow\uparrow} & \sigma TS_{\uparrow\downarrow} \\ \sigma_{\downarrow\uparrow} & \sigma_{\downarrow\downarrow} & \sigma TS_{\downarrow\uparrow} & \sigma TS_{\downarrow\downarrow} \\ \sigma P_{\uparrow\uparrow} & \sigma P_{\uparrow\downarrow} & \kappa_{\uparrow\uparrow} & \kappa_{\uparrow\downarrow} \\ \sigma P_{\downarrow\uparrow} & \sigma P_{\downarrow\downarrow} & \kappa_{\downarrow\uparrow} & \kappa_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} -\nabla \mu_\uparrow \\ -\nabla \mu_\downarrow \\ -\nabla T_\uparrow \\ -\nabla T_\downarrow \end{pmatrix}$$

- No disorder, phonons, no relaxation of center-of-mass

$\sigma_{\uparrow\uparrow}, \sigma_{\downarrow\downarrow}, \sigma \to \infty$ but $\sigma_{\uparrow\downarrow} = \sigma_{\downarrow\uparrow}$ affected by interactions

Spin caloritronics with cold atoms? (II)

- System only reaches transport-steady-state if: $F_\uparrow = -F_\downarrow \equiv F_s$ and $\nabla T_\uparrow = -\nabla T_\downarrow \equiv \nabla T_s$
- ✓ Coupled spin and spin-dependent heat transport:

$$\begin{pmatrix} j_\uparrow - j_\downarrow \\ j_{Q\uparrow} - j_{Q\downarrow} \end{pmatrix} = \begin{pmatrix} j_s \\ j_{Qs} \end{pmatrix} = \begin{pmatrix} \sigma_s & \sigma_s T S_s \\ \sigma_s P_s & \kappa_s \end{pmatrix} \begin{pmatrix} F_s \\ -\nabla T_s \end{pmatrix}$$

- ✗ Can bulk transport regime be reached? electrons: τ~ps, $l<<L$ (typically), cold atoms, τ~ms, $l>L$, or $l<L$

Spin caloritronics with cold atoms? (III)

- Study of:

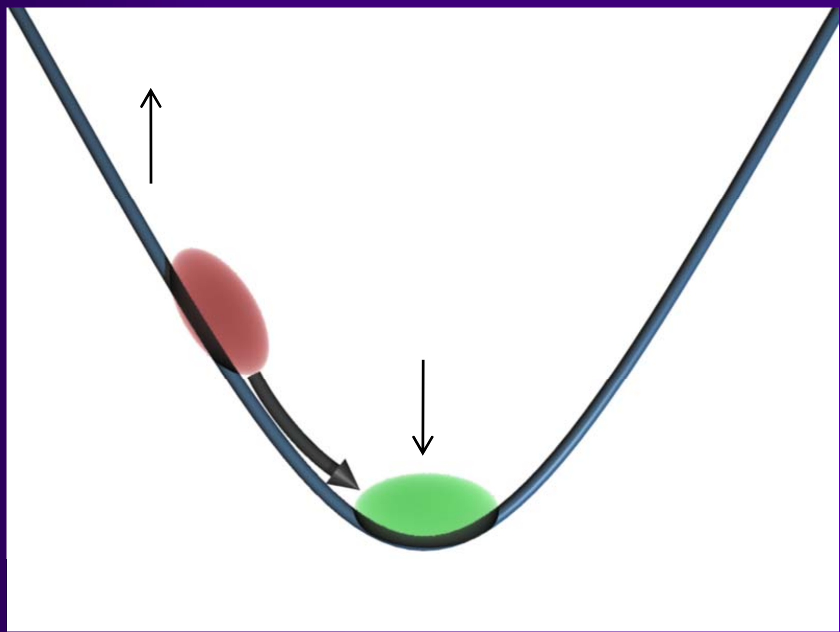
$$\begin{pmatrix} j_\uparrow - j_\downarrow \\ j_{Q\uparrow} - j_{Q\downarrow} \end{pmatrix} = \begin{pmatrix} j_s \\ j_{Qs} \end{pmatrix} = \begin{pmatrix} \sigma_s & \sigma_s T S_s \\ \sigma_s P_s & \kappa_s \end{pmatrix} \begin{pmatrix} F_s \\ -\nabla T_s \end{pmatrix}$$

- ✓ (Theory of)...spin caloritronics w/ cold atoms!
- ✗ Experiment? (no leads, V/I meters, ...)

Example: measuring spin conductivity

$$j_s = \sigma_s F_s; \text{ define: } \sigma_s = \frac{n\tau_{sd}}{m}$$

"Spin drag"



Damping rate of spin-dipole model=1/τ_{sd}

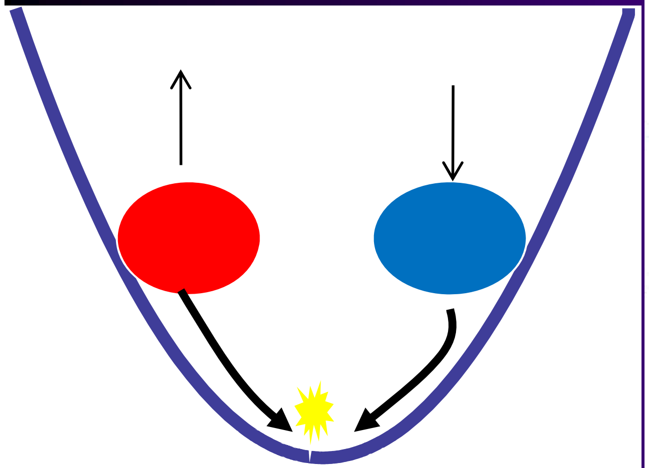
Experiments on cold fermions

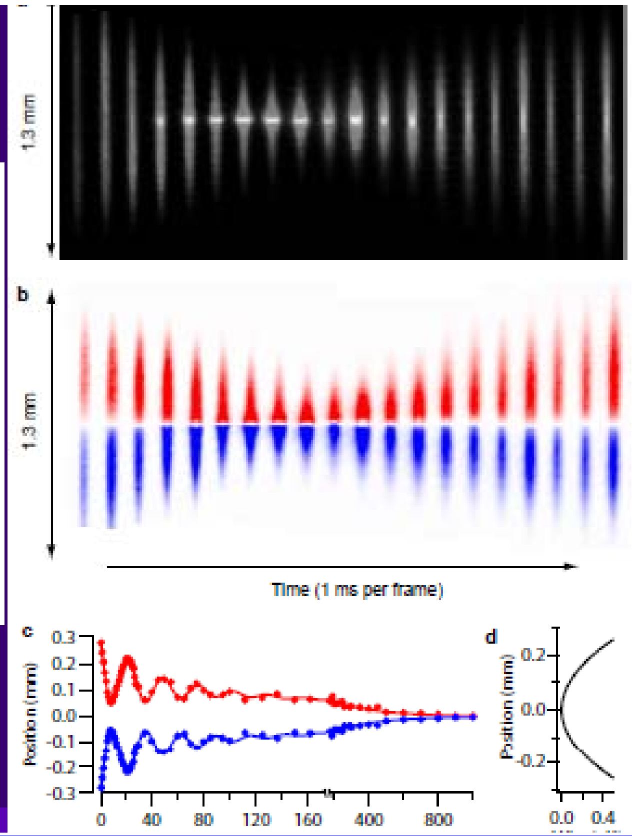
LETTER

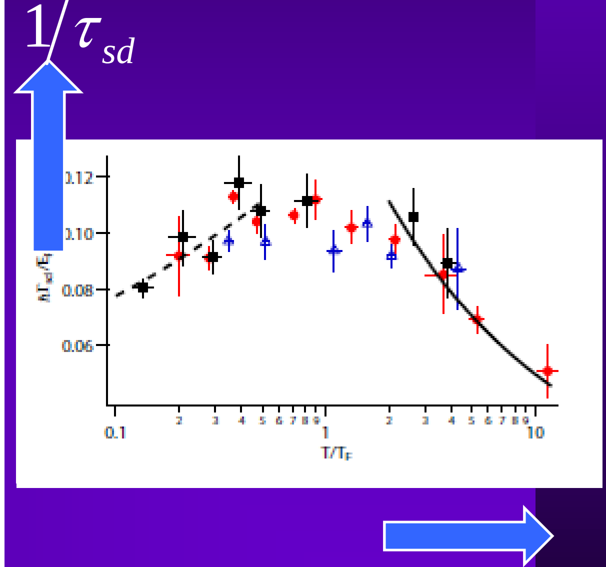
doi:10.1038/nature09989

Universal spin transport in a strongly interacting Fermi gas

Ariel Sommer[1,2,3], Mark Ku[1,2,3], Giacomo Roati[4,5] & Martin W. Zwierlein[1,2,3]







temperature

Ongoing experiments with bosons: P. van der Straten (Utrecht)

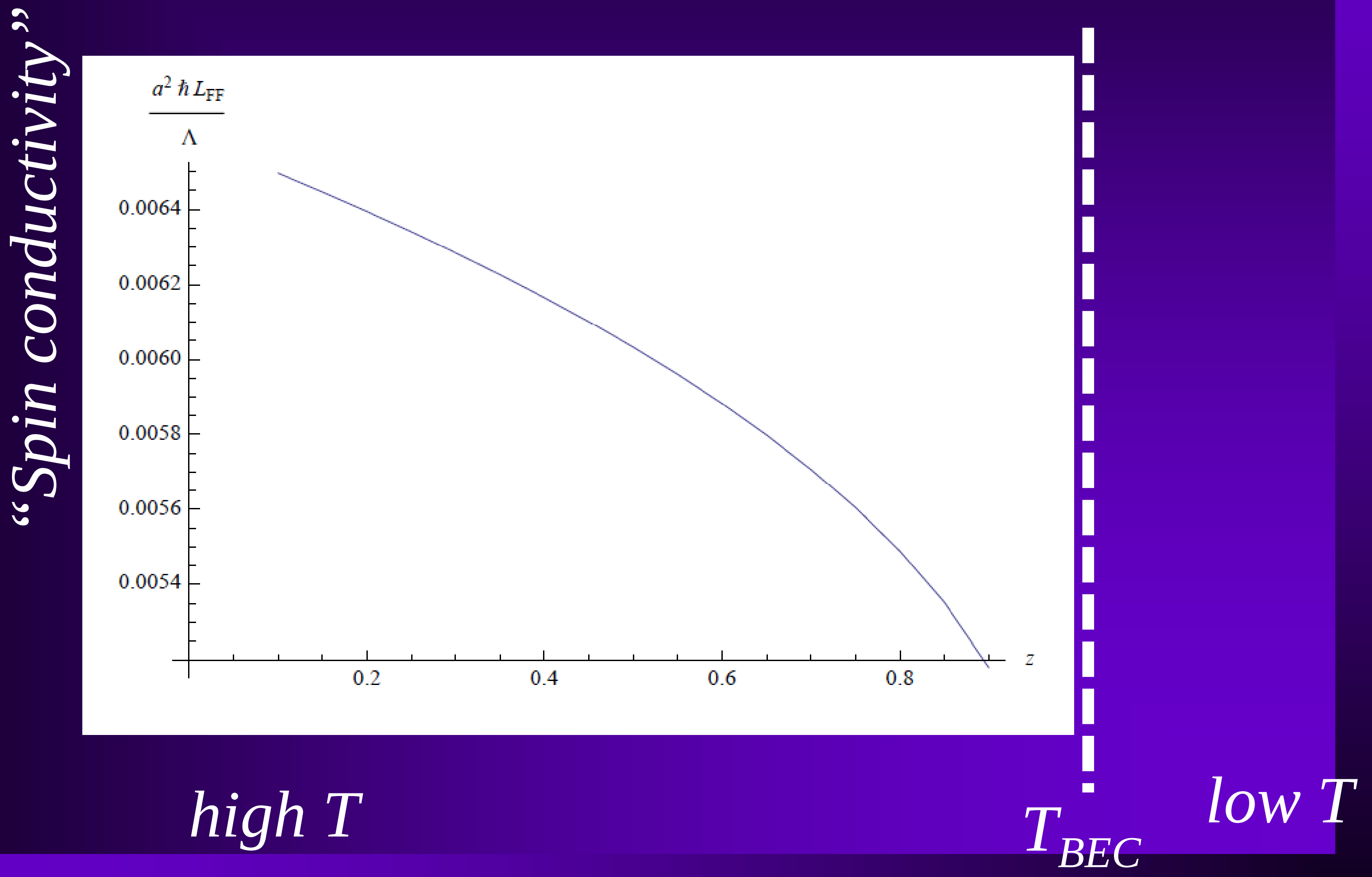
Theory of spin resistivity of cold gases:

$\rho_s \sim 1/\tau_{sd} \sim T^2$ (fermions "blocking" in 3D) $10^{-9}\ \Omega$m

$\rho_s \sim 1/\tau_{sd} \sim T^{-2}$ (bosons "lasing" in quasi-1D) $10^{-5}\ \Omega$m (use charge=e)

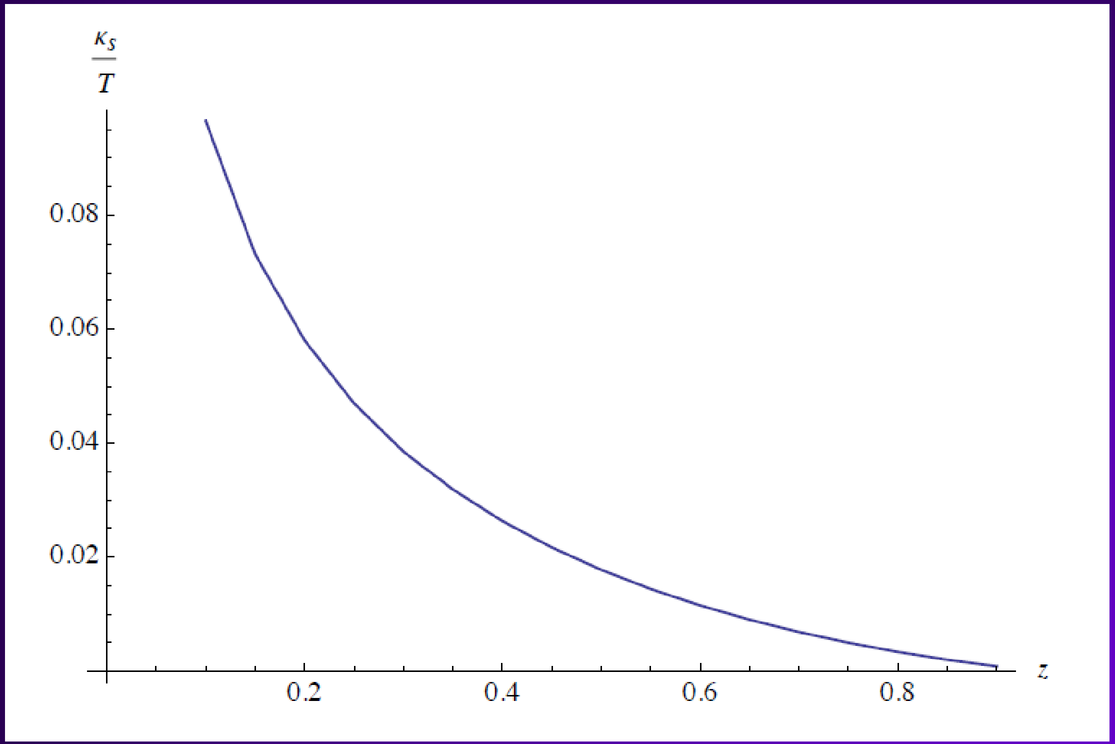
Enhancement of spin resistivity
(reduction of spin conductivity)
upon approaching
critical temperature for Bose condensation!
-> interesting temperature dependence
in all transport coefficients?

Some more (very preliminary theory results) for bosons (I):



Some more (very preliminary theory results) for bosons (II):

"spin-dependent heat conductivity"



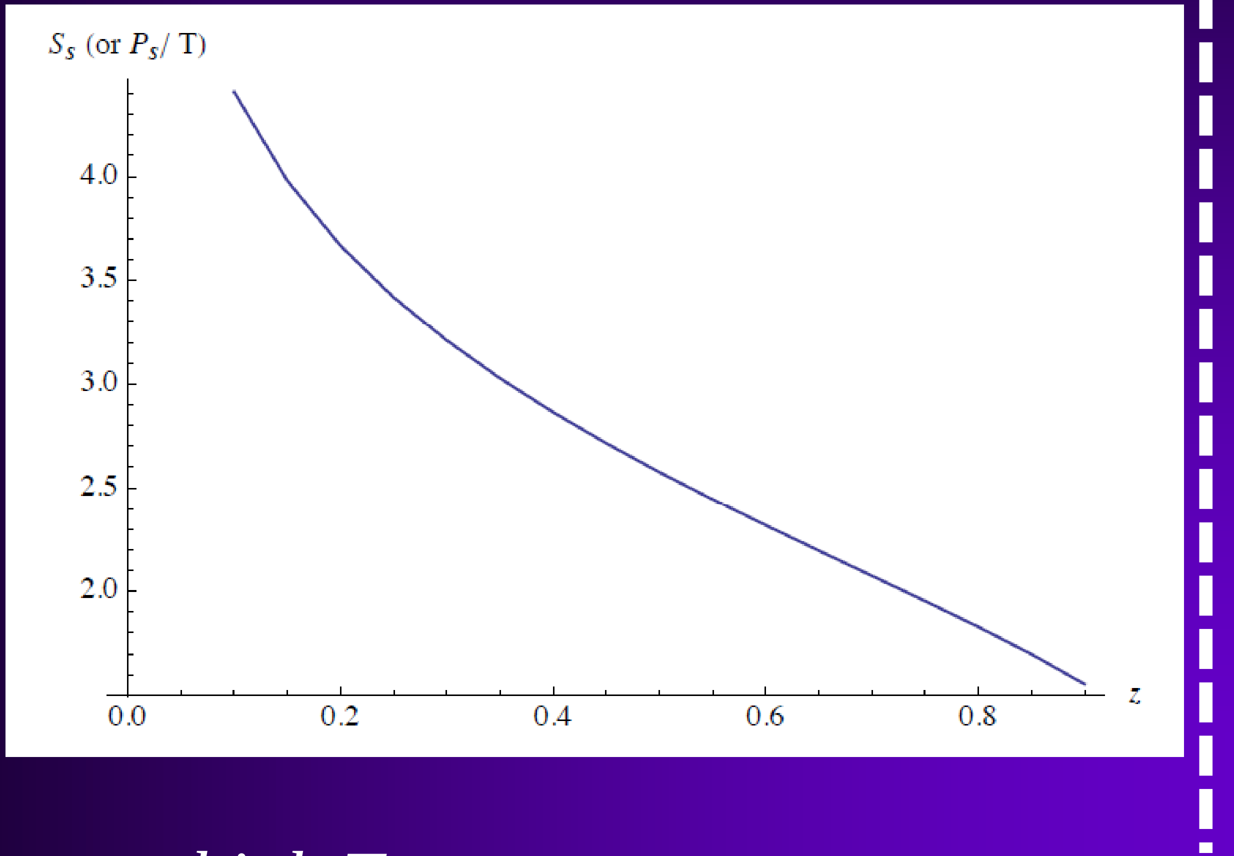
high T

T_{BEC}

low T

Some more (very preliminary theory results) for bosons (III):

"Seebeck/Peltier"



high T

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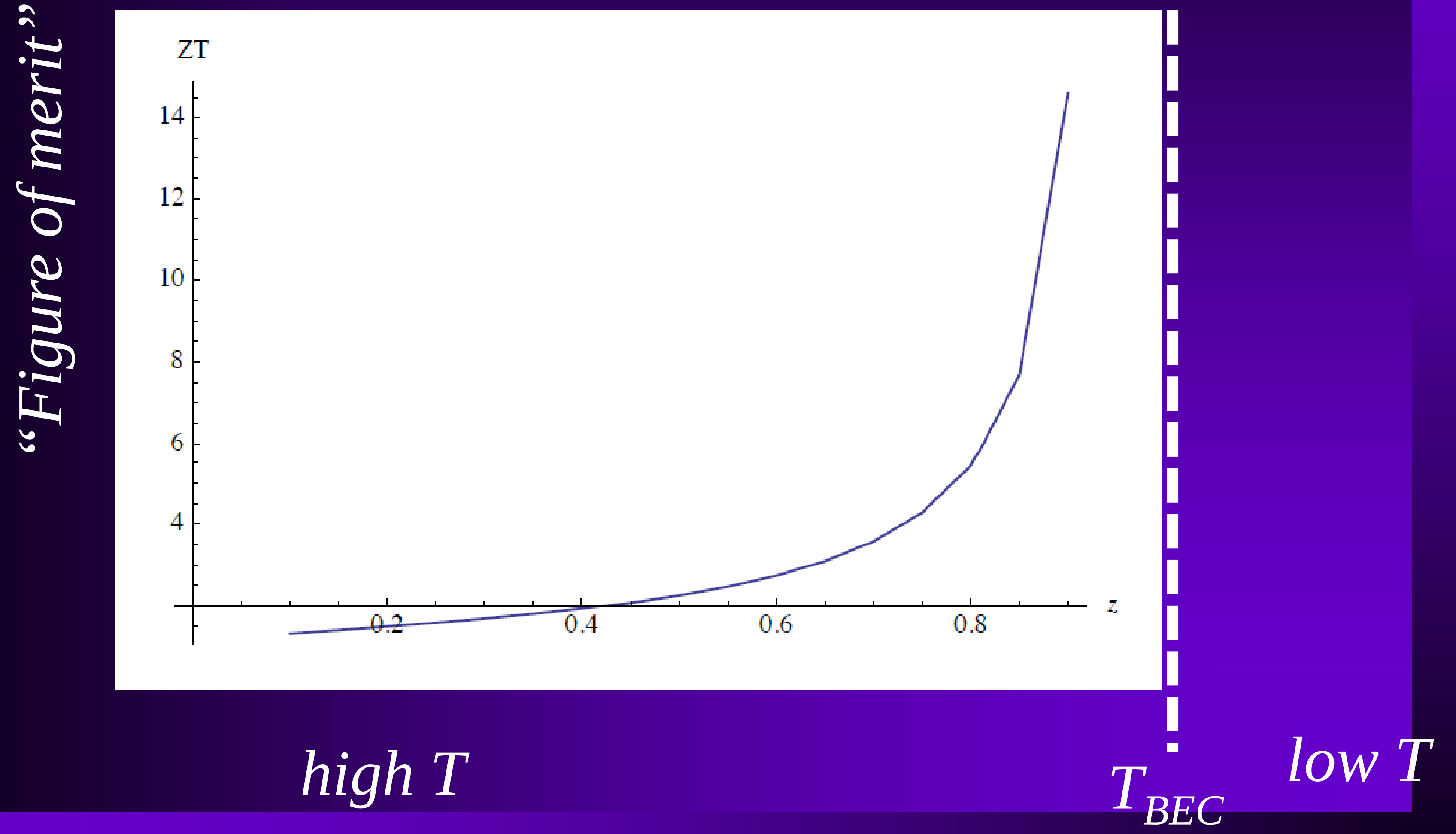
Some more (very preliminary theory results) for bosons (IV):



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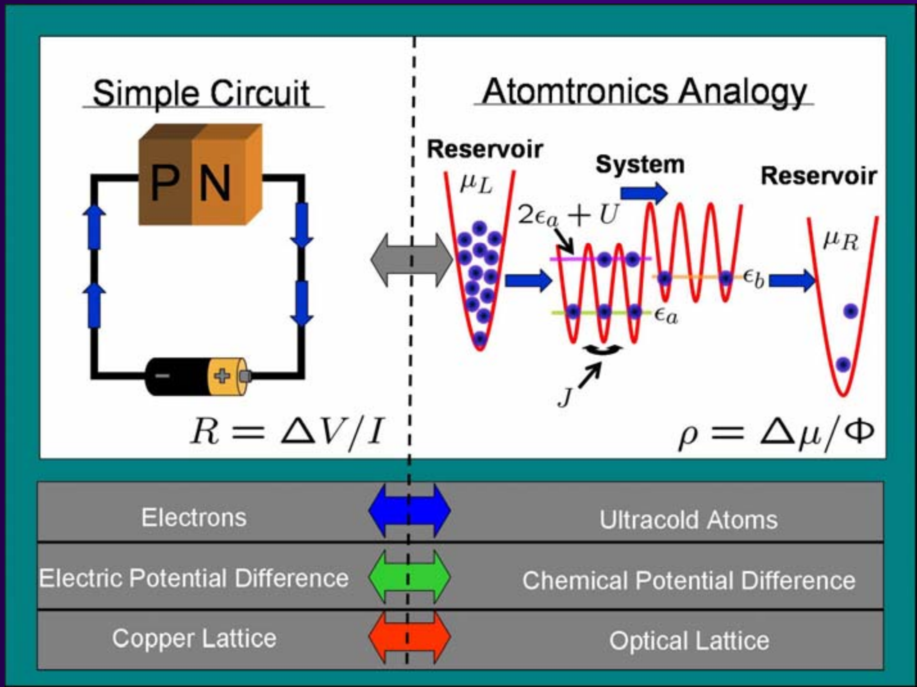
- What is it good for?

What can we learn from it and what is it good for?

- Intrinsically interesting fundamental physics
- Cold atom systems are easy and tunable -> simulate models, solve controversies, etc... (Hubbard model, high T-c)
- New regimes (e.g. spin drag effects)
- Magnonic (bosons) spintronics; Bose condensation of magnons
- Direct applications?

Atomtronics?

- Direct applications of cold-atom systems:



Murray Holland, Dana Anderson

- Probably not consumer electronics, quantum computing?

Spin caloritronics with cold atoms

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NEWSPIN2

Spin physics and topological effects in cold atoms, condensed matter, and beyond

International Winter School and Workshop

December 12th-17th 2011
Mitchell Institute of Fundamental Physics
College Station, Texas

Topics

- Magnetism in cold atoms
- Spin and Anomalous Hall effect
- Spin transfer and spin pumping
- Spin motive forces
- Controlling spins by light
- Spin orbit coupling in cold-atom systems
- Spin-imbalance in cold Fermi gases
- Topological insulators
- Dirac physics in cold atoms and condensed matter
- Pseudospin physics

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