Strongly interacting cold atoms

Subir Sachdev

Talks online at http://sachdev.physics.harvard.edu

Outline

Strongly interacting cold atoms

1. Quantum liquids near unitarity:
   from few-body to many-body physics
   (a) Tonks gas in one dimension
   (b) Paired fermions across a Feshbach resonance

2. Optical lattices
   (a) Superfluid-insulator transition
   (b) Quantum-critical hydrodynamics via mapping to
   quantum theory of black holes.
   (c) Entanglement of valence bonds

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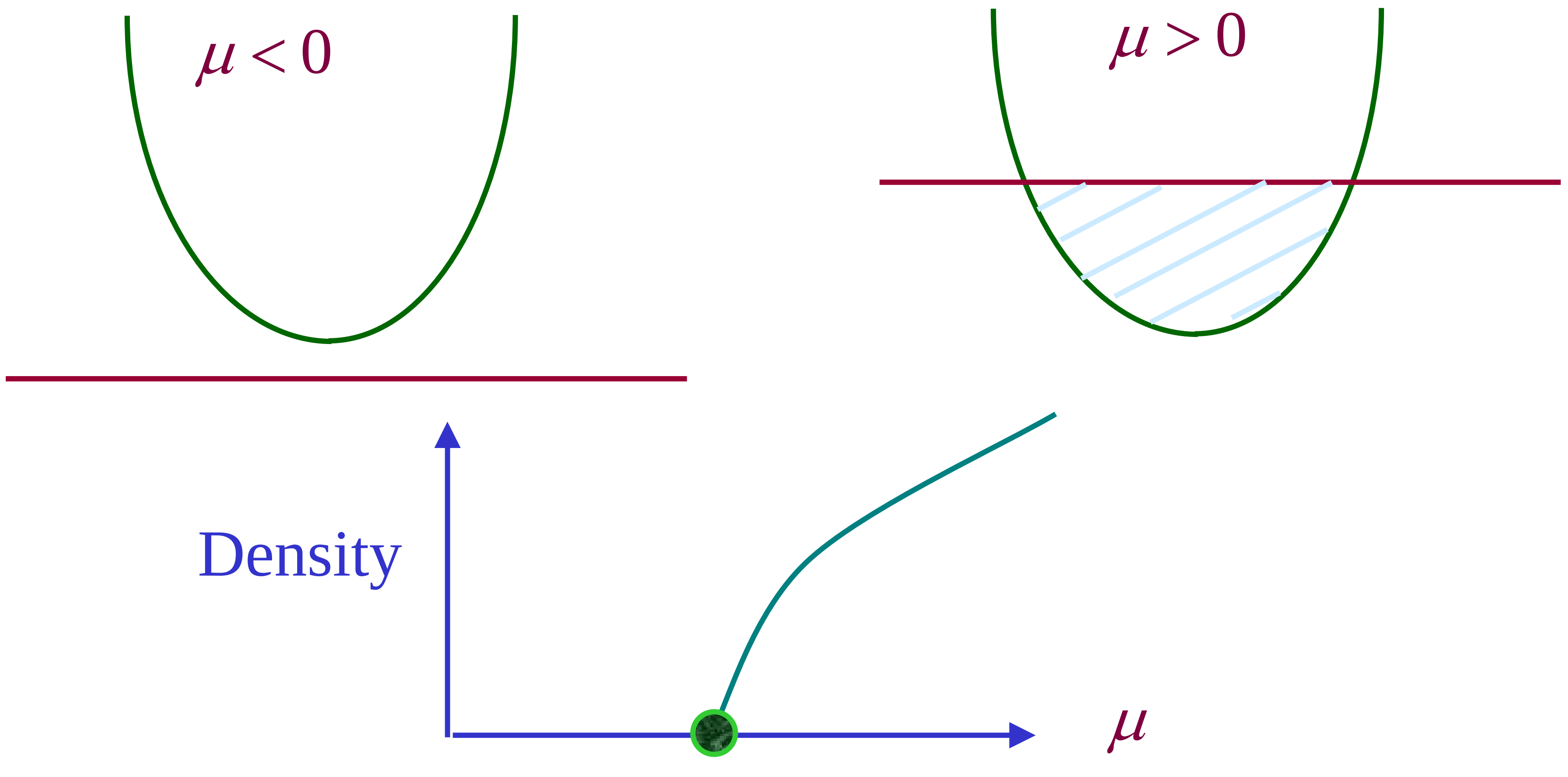
Fermions with repulsive interactions

$$H = \sum_k \left(\varepsilon_k - \mu\right) c_{k\sigma}^\dagger c_{k\sigma}$$

$+$ short-range repulsive interactions of strength u



Fermions with repulsive interactions

Characteristics of this ‘trivial’ quantum critical point:

• Zero density critical point allows an elegant connection between few body and many body physics.

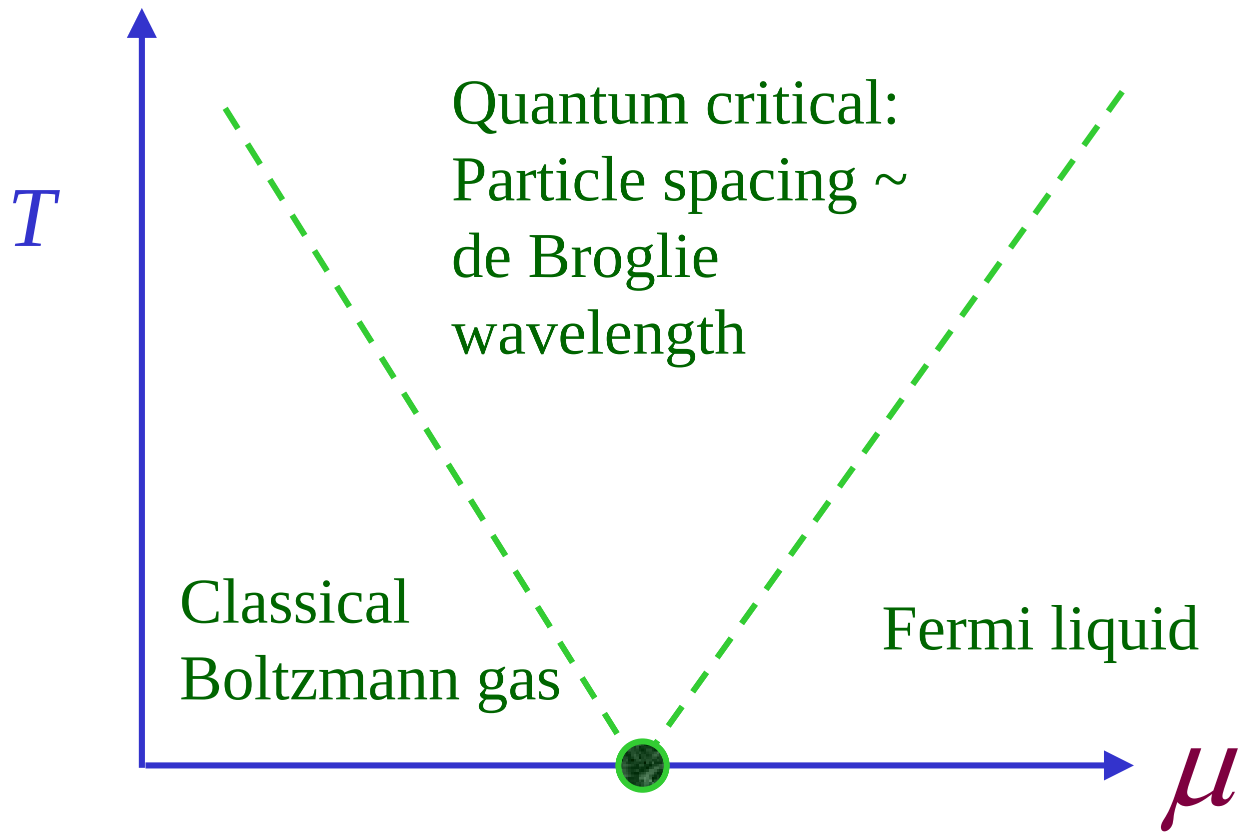
• No “order parameter”. “Topological” characterization in the existence of the Fermi surface in one state.

• No transition at $T > 0$.

• Characteristic crossovers at $T > 0$, between quantum criticality, and low T regimes.

Fermions with repulsive interactions

Characteristics of this ‘trivial’ quantum critical point:

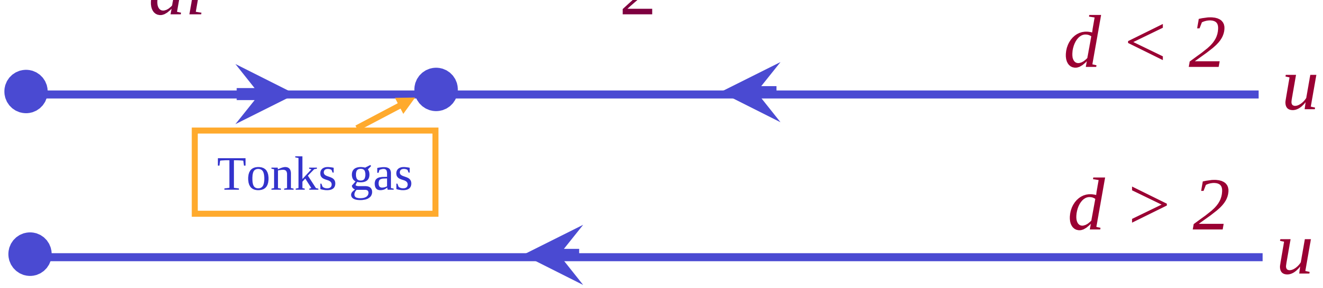


Fermions with repulsive interactions

Characteristics of this 'trivial' quantum critical point:

RG flow characterizing quantum critical point:

$$\frac{du}{dl} = (2-d)u - \frac{u^2}{2}$$

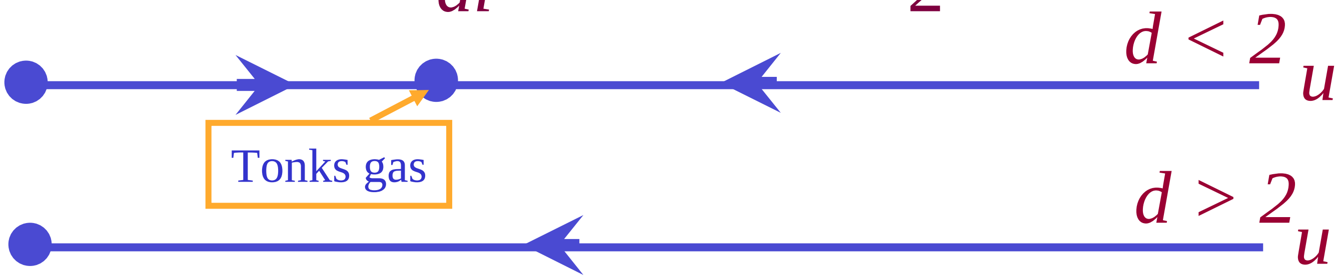


• *d* > *2* – interactions are irrelevant. Critical theory is the *spinful* free Fermi gas.

• *d* < *2* – universal fixed point interactions. In *d=1* critical theory is the *spinless* free Fermi gas (Tonks gas).

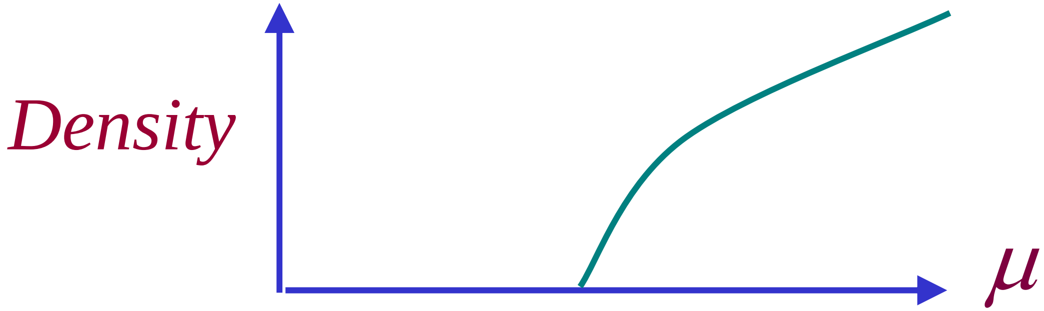
Bosons with repulsive interactions

$$\frac{du}{dl} = (2-d)u - \frac{u^2}{2}$$



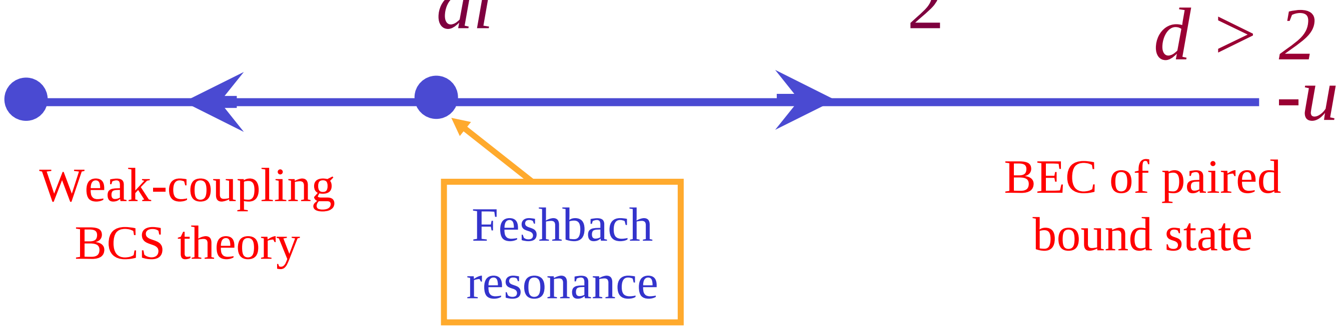
• Critical theory in *d =1* is also the *spinless* free *Fermi* gas (Tonks gas).

• The dilute Bose gas in *d >2* is controlled by the zero-coupling fixed point. Interactions are "dangerously irrelevant" and the density above onset depends upon bare interaction strength (Yang-Lee theory).



Fermions with attractive interactions

$$\frac{du}{dl} = (2-d)u - \frac{u^2}{2}$$

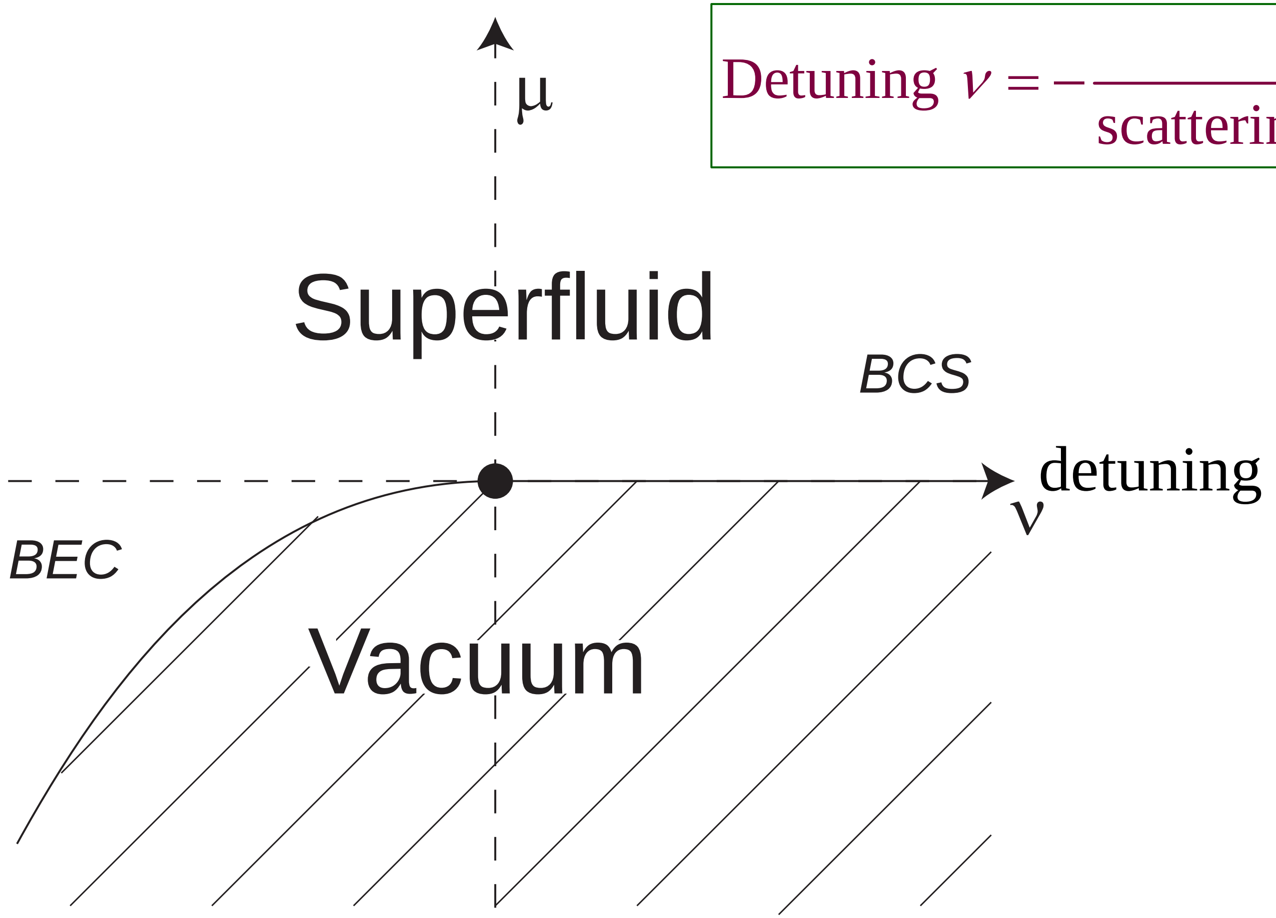


• Universal fixed-point is accessed by *fine-tuning* to a Feshbach resonance.

• Density onset transition is described by free fermions for weak-coupling, and by (nearly) free bosons for strong coupling. The quantum-critical point between these behaviors is the Feshbach resonance.

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007).

Fermions with attractive interactions



Detuning $\nu = -\dfrac{1}{\text{scattering length}}$

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007).

Fermions with attractive interactions

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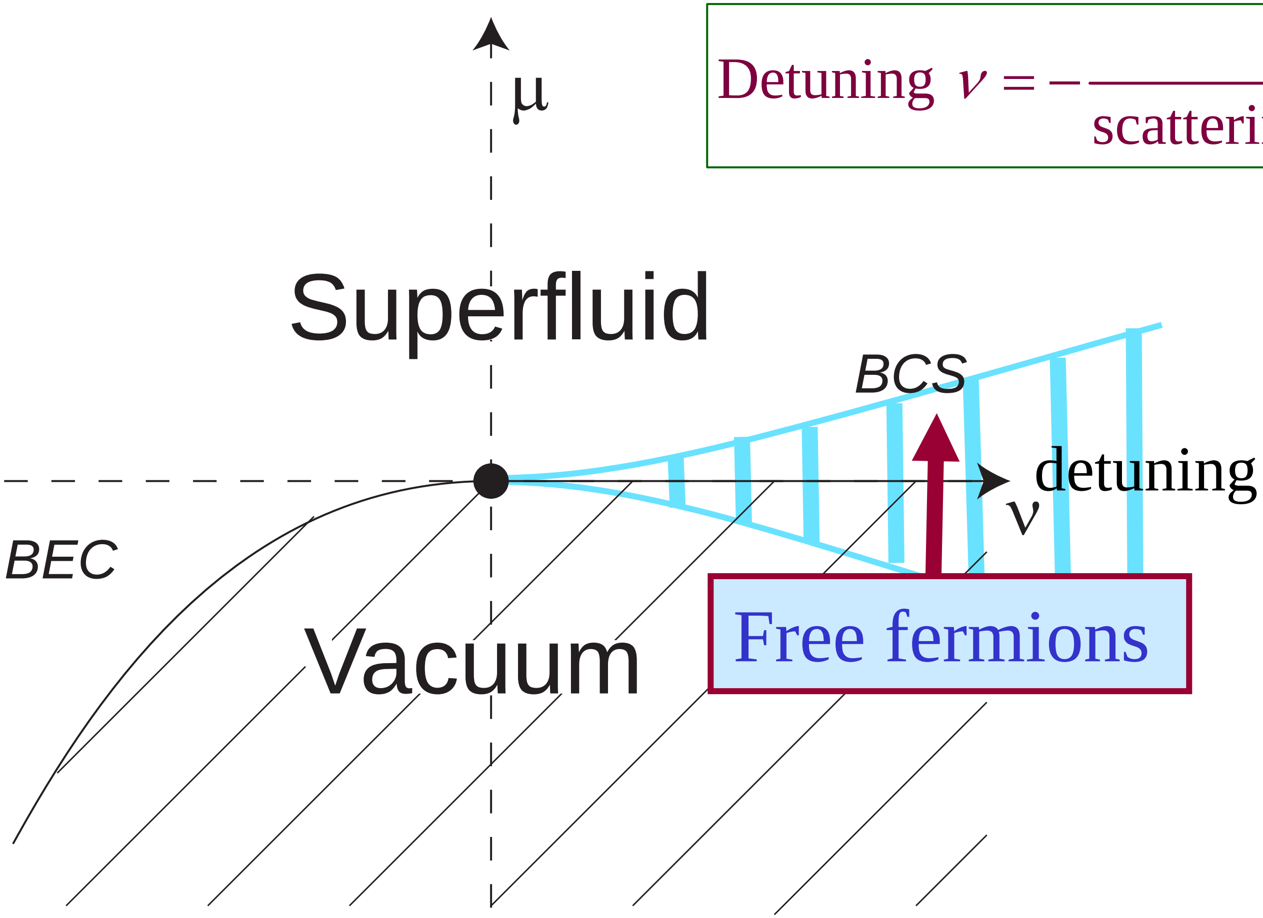

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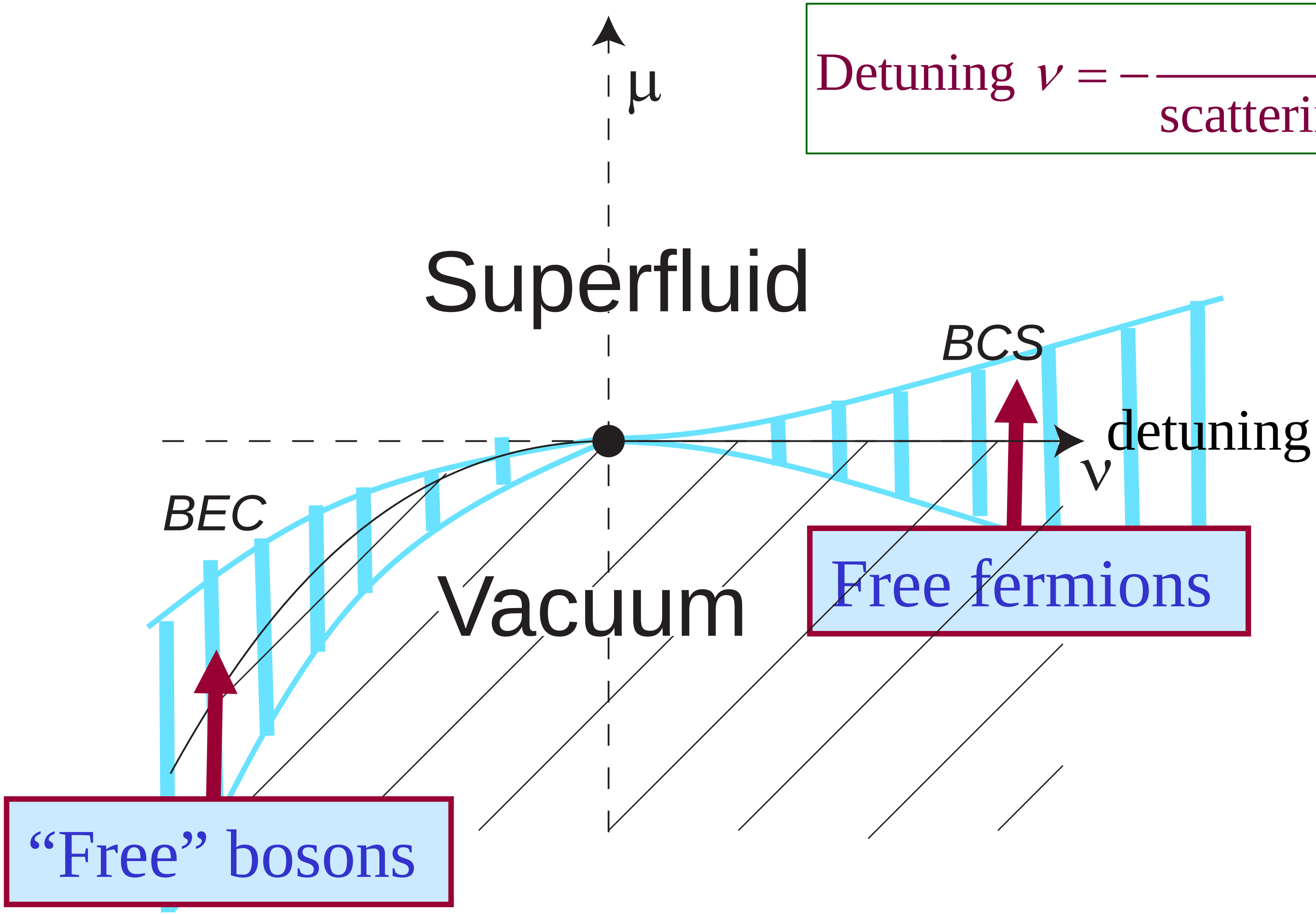

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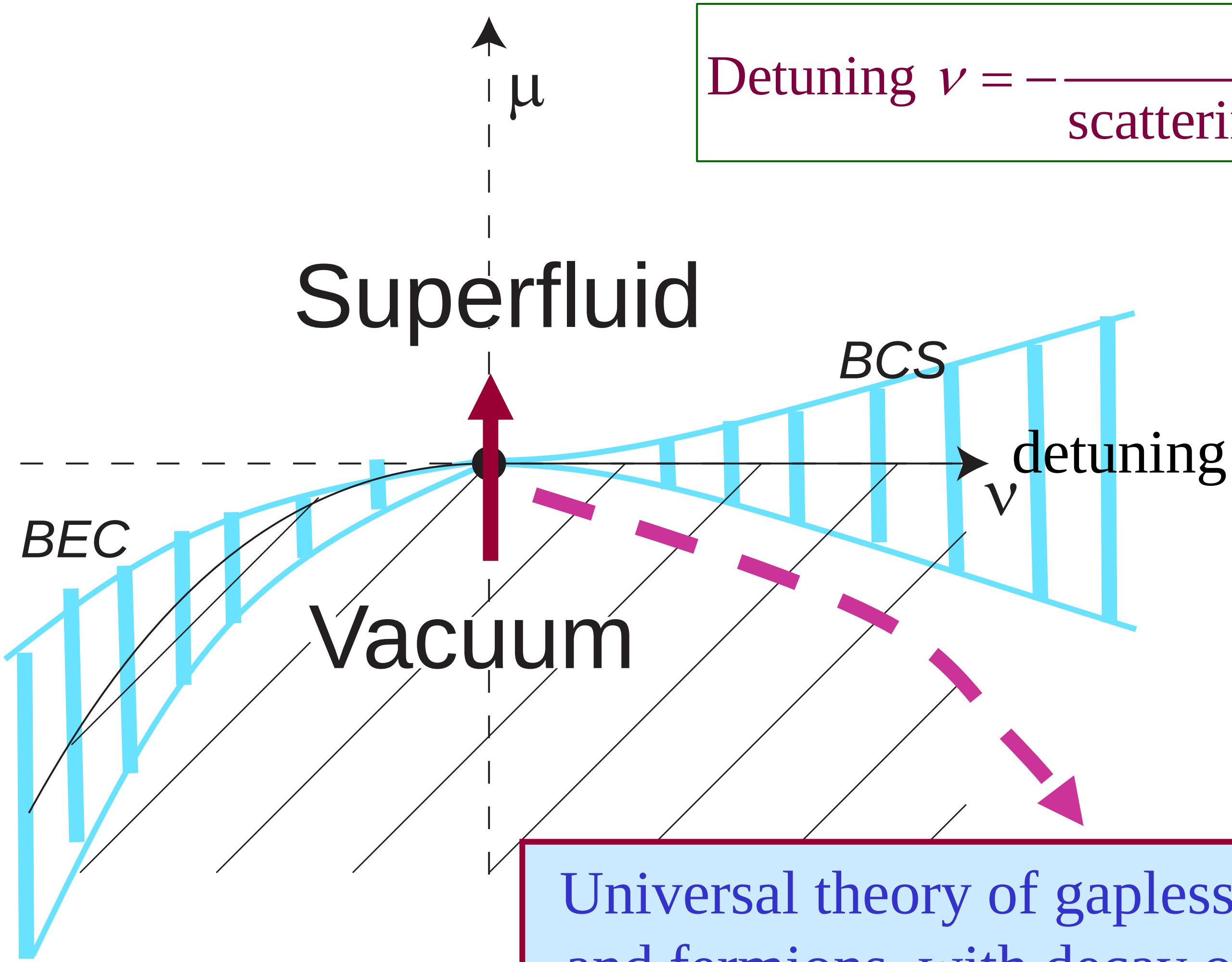
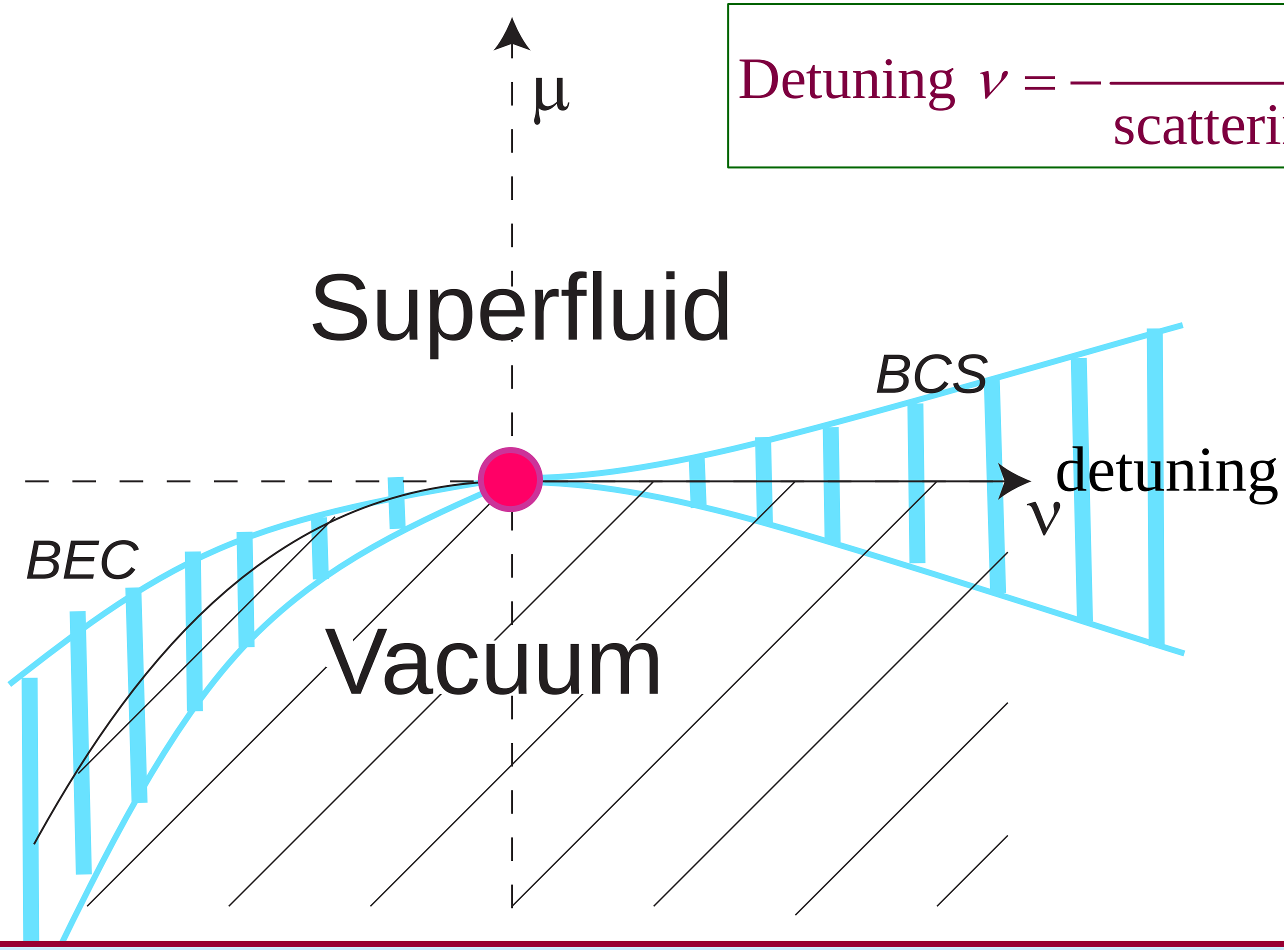


Universal theory of gapless bosons and fermions, with decay of boson into 2 fermions relevant for $d < 4$

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007).

Fermions with attractive interactions

Detuning $\nu = -\frac{1}{\text{scattering length}}$

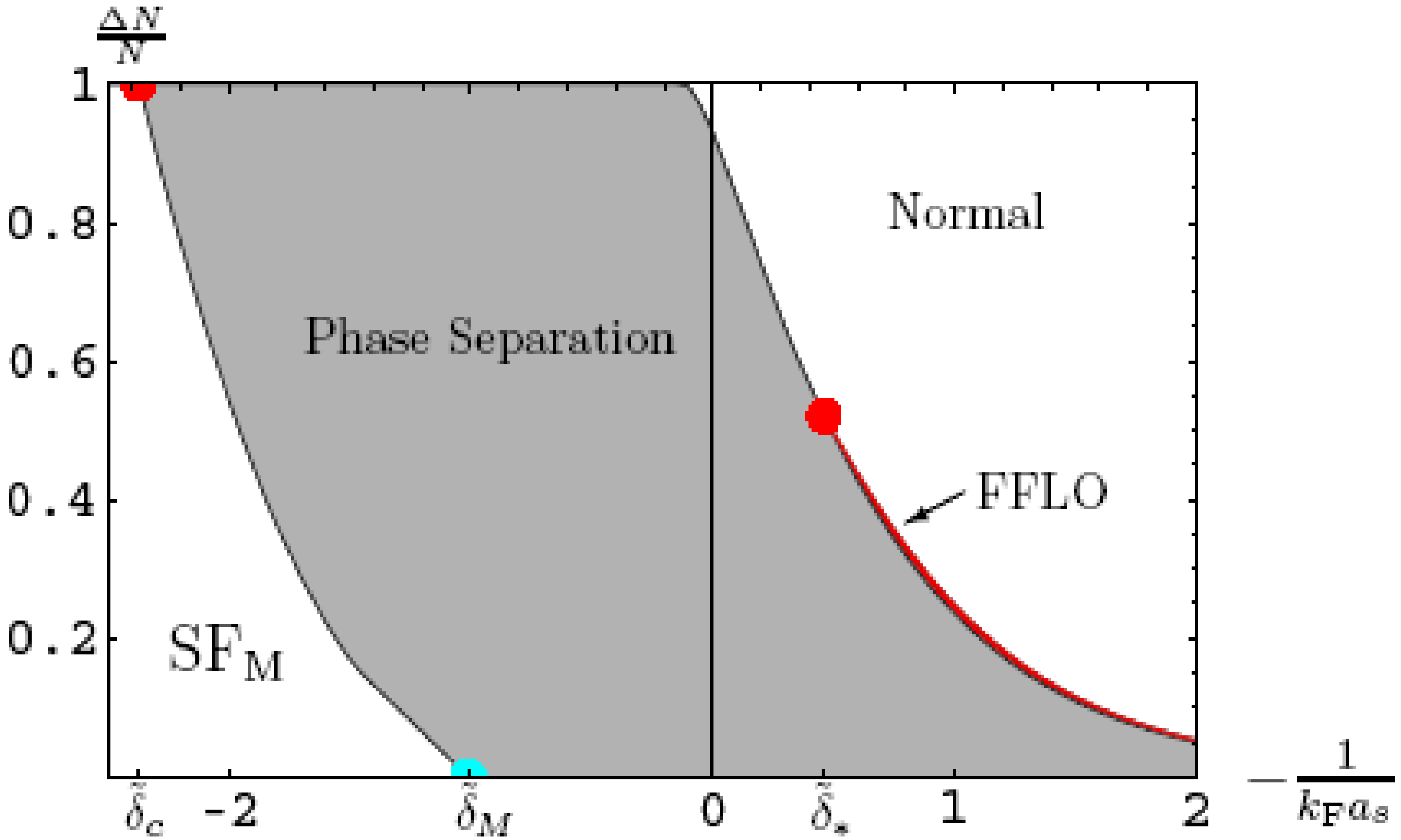


Quantum critical point at μ=0, ν=0, forms the basis of the theory of the BEC-BCS crossover, including the transitions to FFLO and normal states with unbalanced densities

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007).

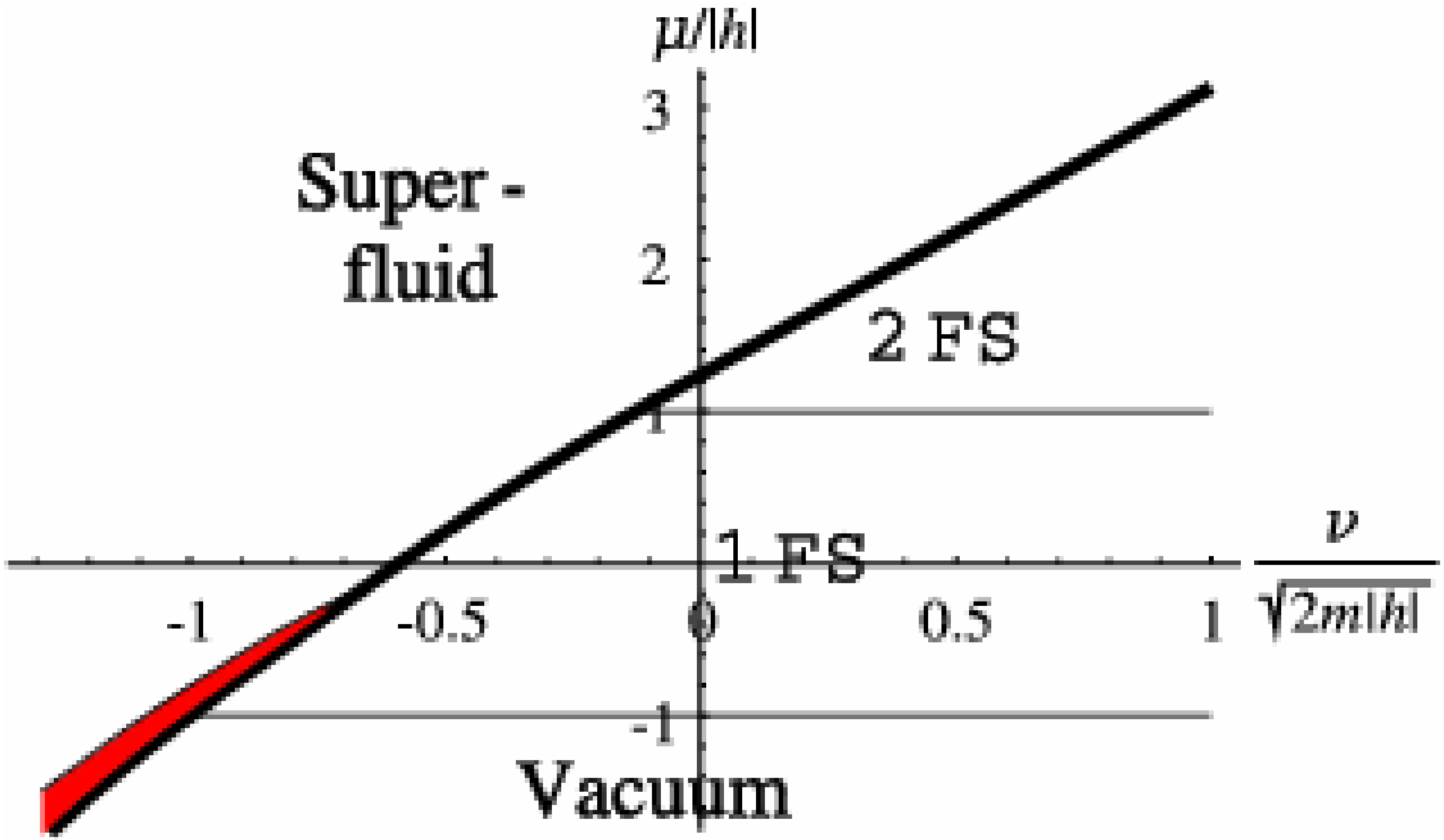
Fermions with attractive interactions

Universal phase diagram



D. E. Sheehy and L. Radzihovsky, *Phys. Rev. Lett.* **95**, 130401 (2005)

Universal phase diagram



h – Zeeman field

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007).

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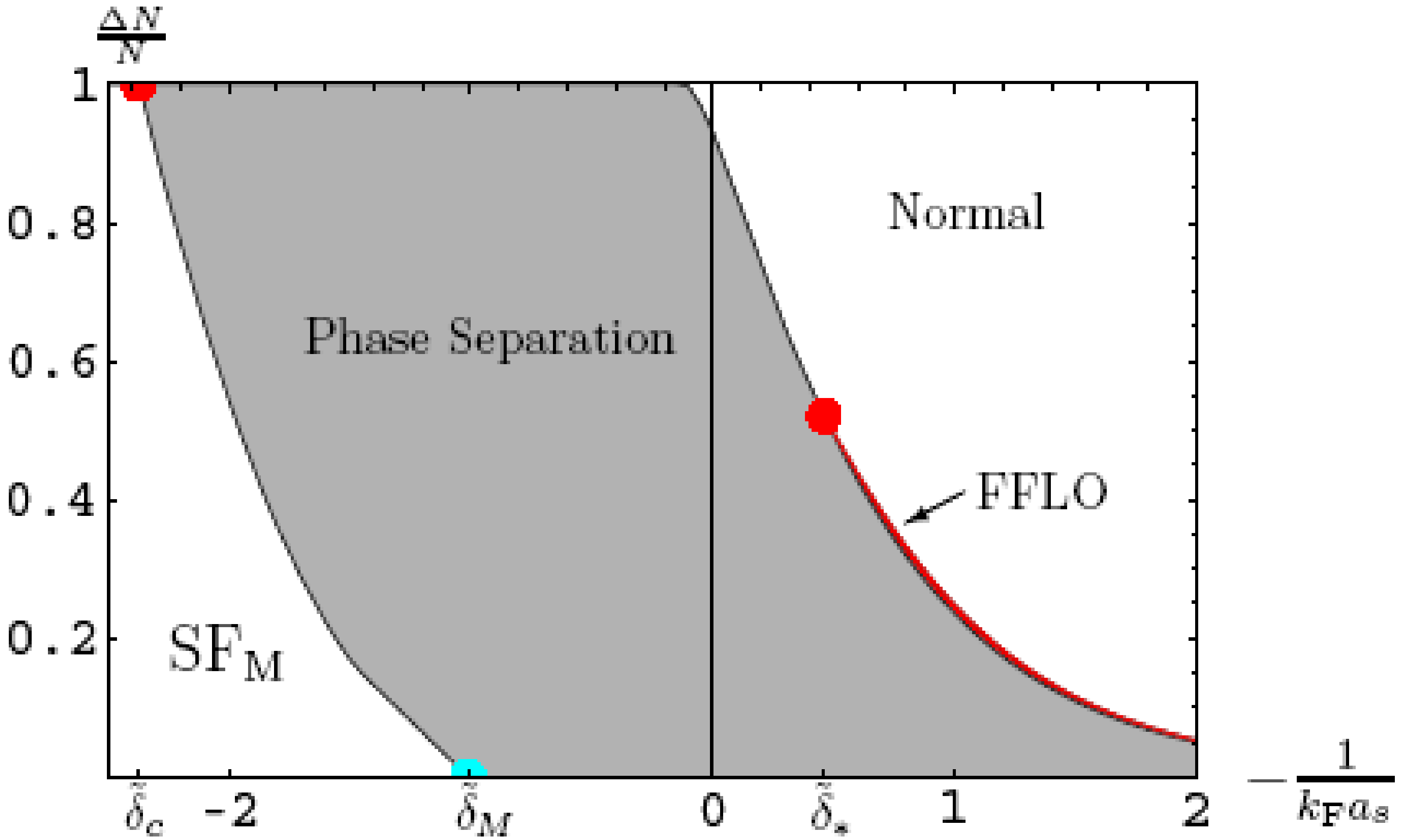

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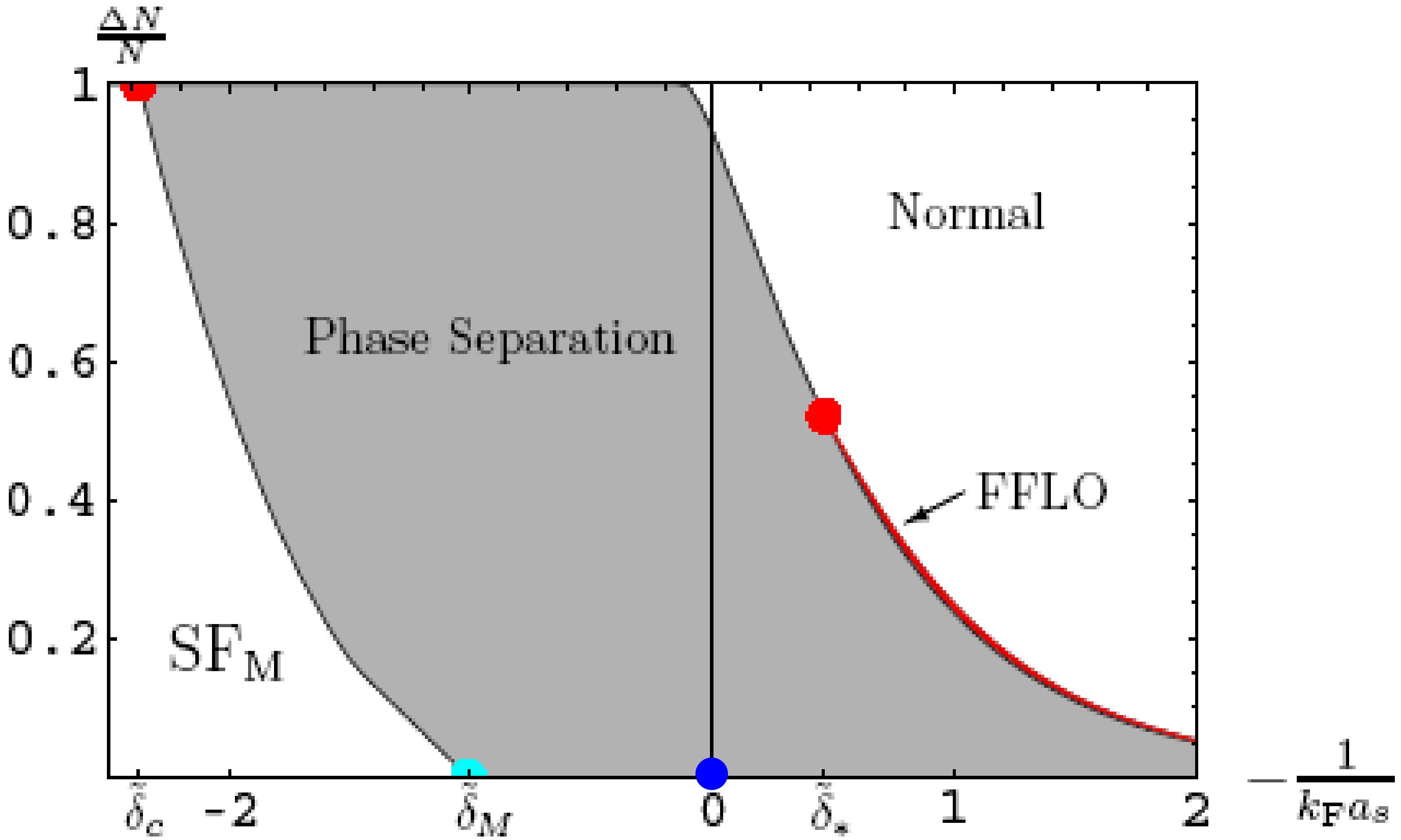


D. E. Sheehy and L. Radzihovsky, *Phys. Rev. Lett.* **95**, 130401 (2005)

Fermions with attractive interactions

Ground state properties at unitarity and balanced density

$$\frac{\Delta}{\varepsilon_F} = \sqrt{\varepsilon} + \frac{\varepsilon^{3/2}}{8}\ln(\varepsilon) - 0.3947\varepsilon^{3/2}$$

$$\frac{\mu}{\varepsilon_F} = \frac{\varepsilon^{3/2}}{2} + \frac{\varepsilon^{5/2}}{16}\ln(\varepsilon) - 0.0246\varepsilon^{5/2}$$

Expansion in ε=4-d

Y. Nishida and D.T. Son,
Phys. Rev. Lett. **97**, 050403 (2006)

$$\frac{\Delta}{\varepsilon_F} = 0.6864 - \frac{0.163}{N}$$

$$\frac{\mu}{\varepsilon_F} = 0.5906 - \frac{0.312}{N}$$

Expansion in 1/*N* with Sp(2*N*) symmetry

M. Y. Veillette, D. E. Sheehy, and L. Radzihovsky
Phys. Rev. A **75**, 043614 (2007)

$$\frac{\Delta}{\varepsilon_F} = 0.54$$

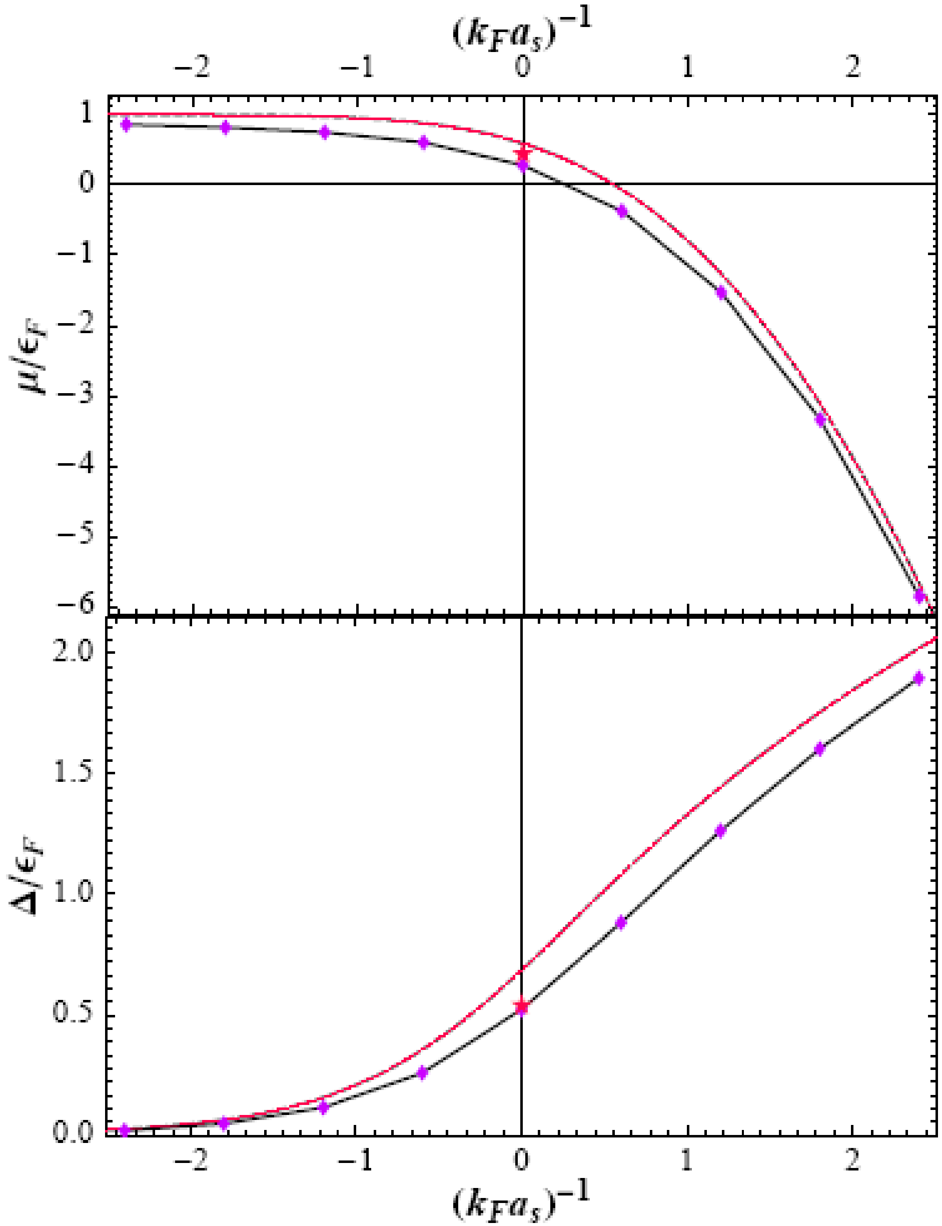
$$\frac{\mu}{\varepsilon_F} = 0.44$$

Quantum Monte Carlo

J. Carlon, S.-Y. Chang, V.R. Pandharipande, and K.E. Schmidt, *Phys. Rev. Lett.* **91**, 050401 (2003).

Fermions with attractive interactions

Ground state properties near unitarity and balanced density



Expansion in $1/N$ with $Sp(2N)$ symmetry

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Quantum Monte Carlo

J. Carlon, S.-Y. Chang,
V.R. Pandharipande, and
K.E. Schmidt, *Phys. Rev. Lett.* **91**, 050401 (2003).

Fermions with attractive interactions

Finite temperature properties at unitarity and balanced density

$$\frac{\varepsilon_F}{T_c} = 2.104 + \frac{5.317}{N}$$

$$\frac{\mu}{T_c} = 1.504 + \frac{2.785}{N}$$

$$\frac{P/N}{(2m)^{3/2} T_c^{5/2}} = 0.132 + \frac{0.405}{N}$$

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M. Y. Veillette, D. E. Sheehy, and L. Radzihovsky
Phys. Rev. A **75**, 043614 (2007)
P. Nikolic and S. Sachdev,
Phys. Rev. A **75**, 033608 (2007).

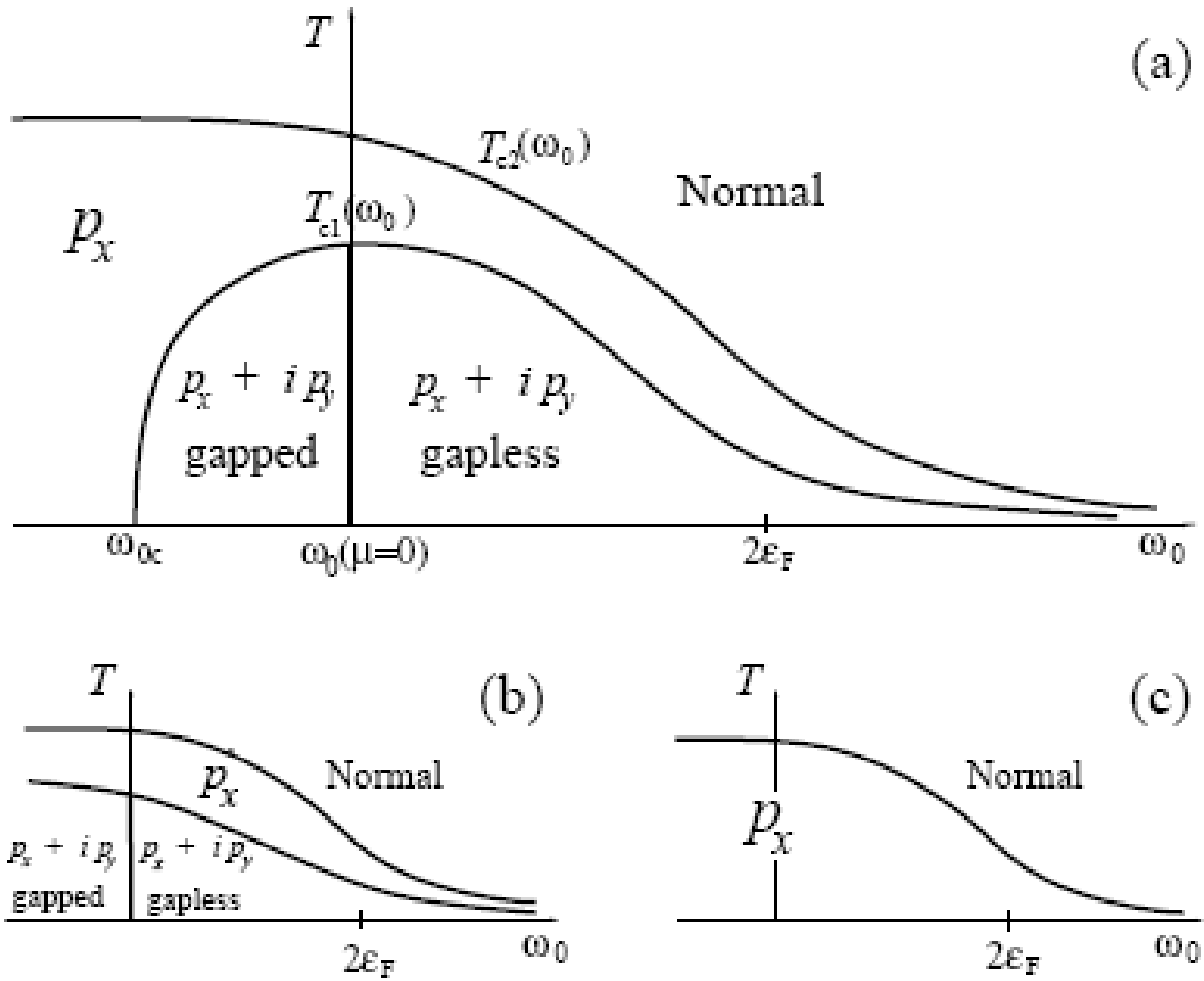
$$\frac{\varepsilon_F}{T_c} = 6.579$$

$$\frac{\mu}{T_c} = 3.247$$

$$\frac{P/N}{(2m)^{3/2} T_c^{5/2}} = 0.776$$

E. Burovski, N. Prokof'ev, B. Svistunov, and
M. Troyer, *New J. Phys.* **8**, 153 (2006)

Fermions with attractive interactions in p-wave channel



V. Gurarie, L. Radzihovsky, and A.V. Andreev, *Phys. Rev. Lett.* **94**, 230403 (2005)
C.-H. Cheng and S.-K. Yip, *Phys. Rev. Lett.* **95**, 070404 (2005)

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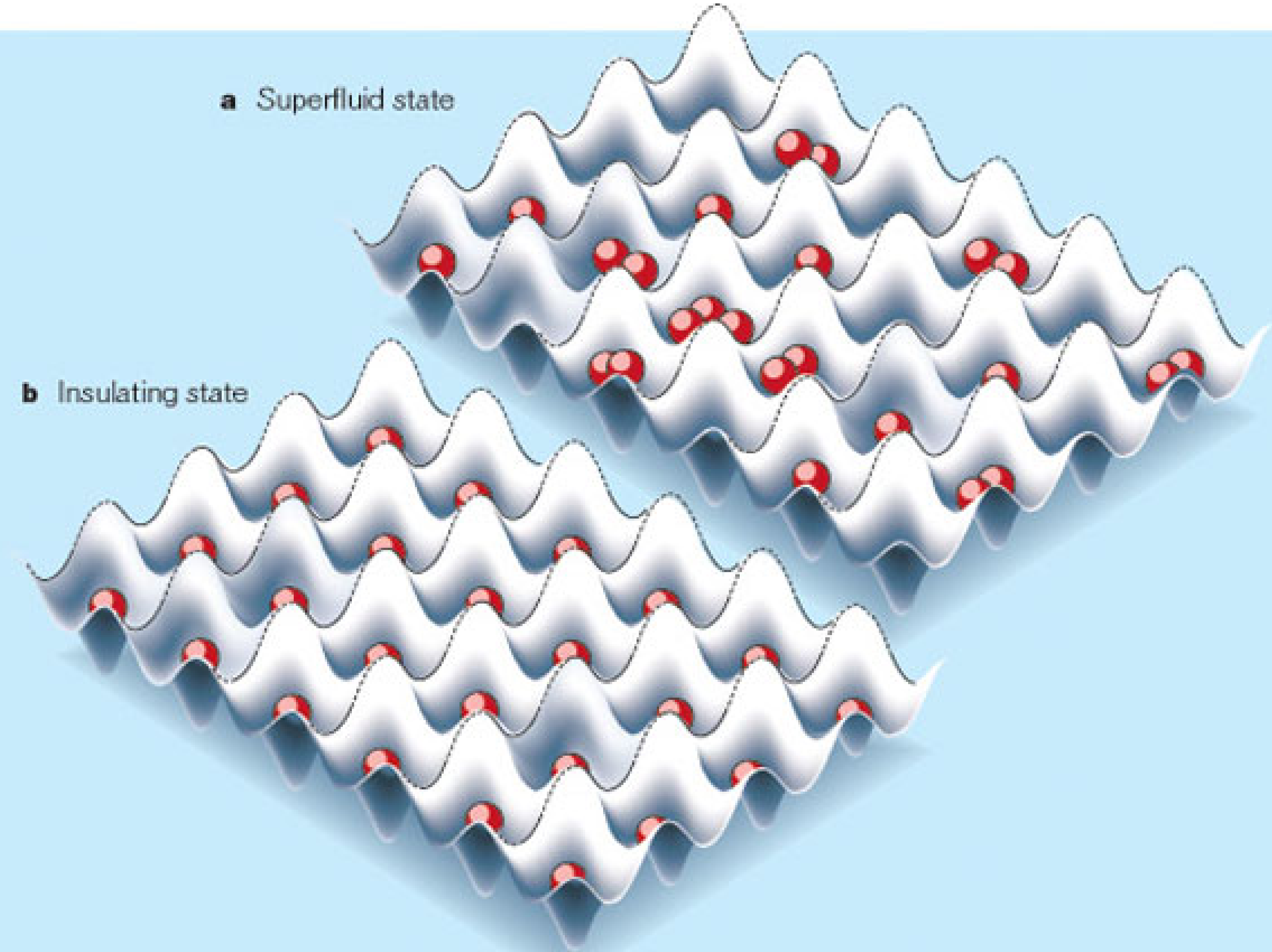
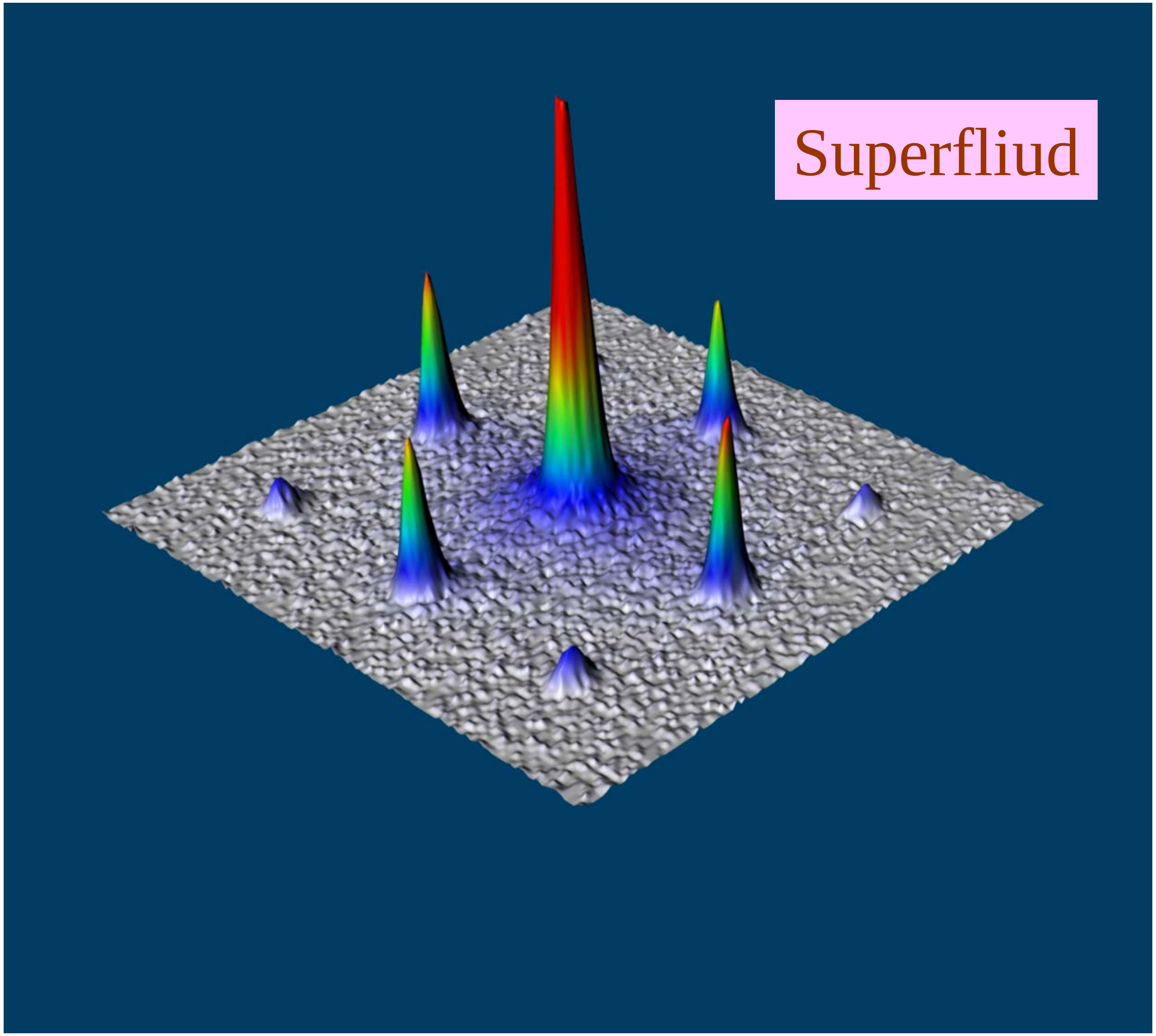


M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

Velocity distribution of ^{87}Rb atoms



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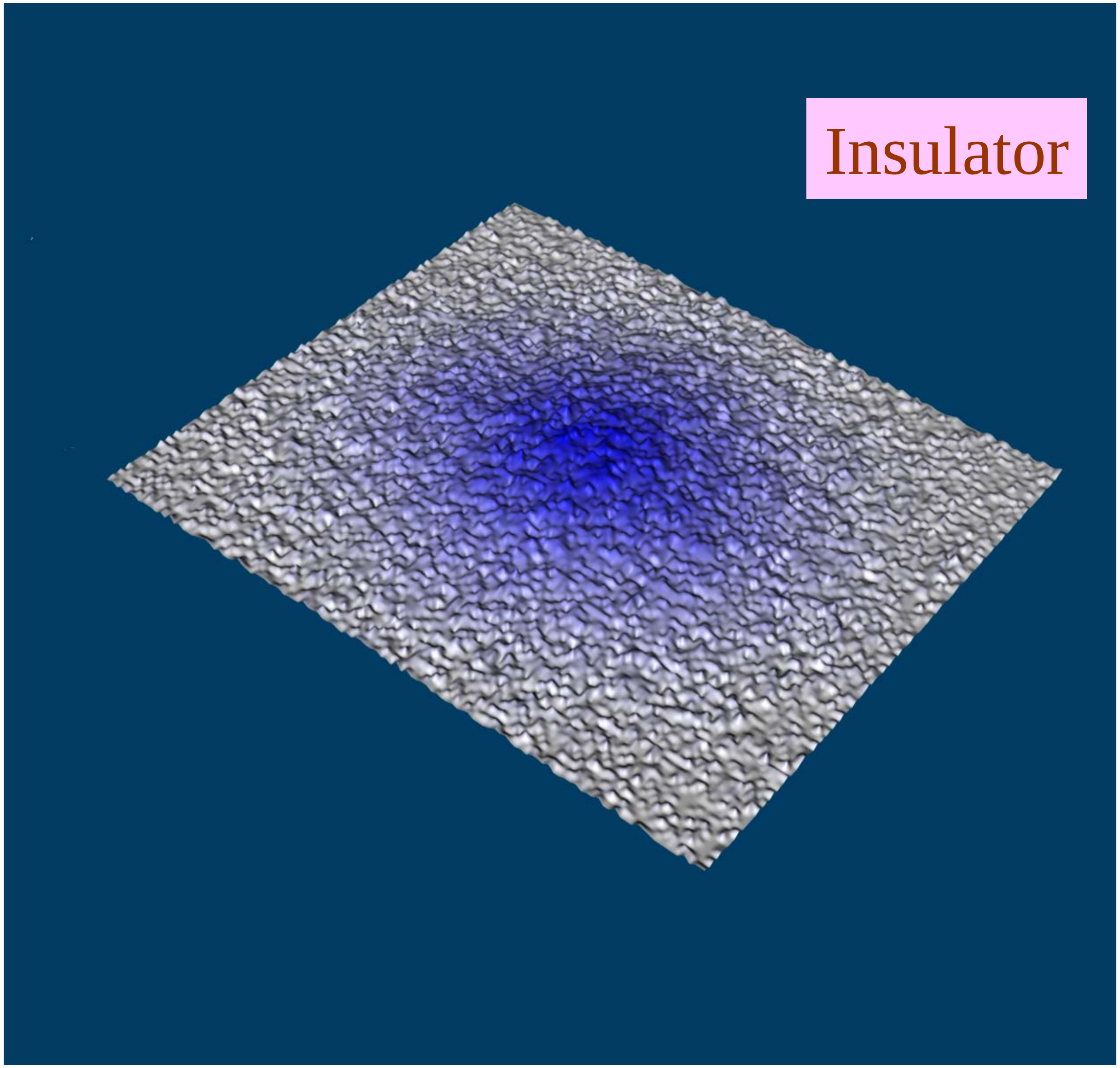

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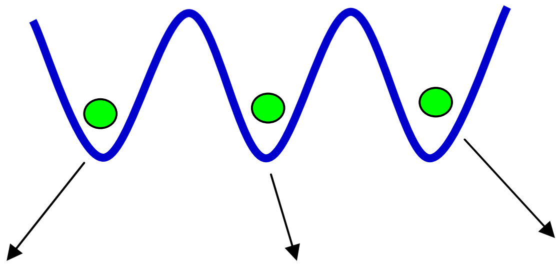
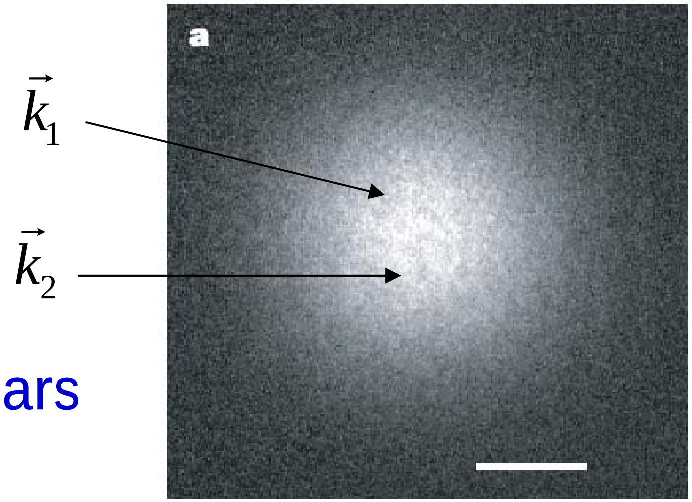
Noise correlation (time of flight) in Mott-insulators

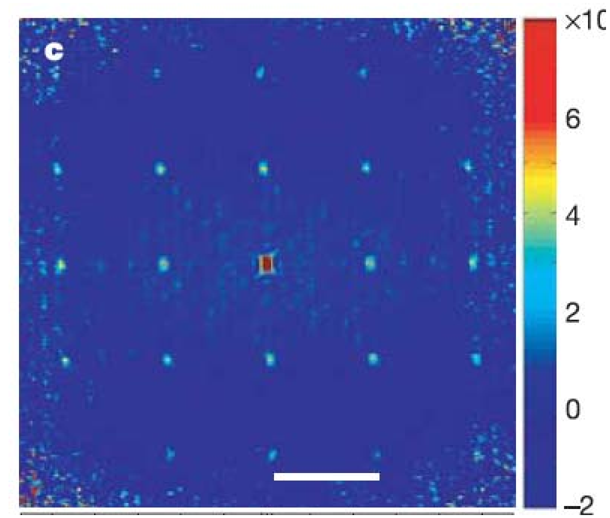




• 1st order coherence $\langle n(\vec{k}) \rangle$ disappears in the Mott-insulating state.

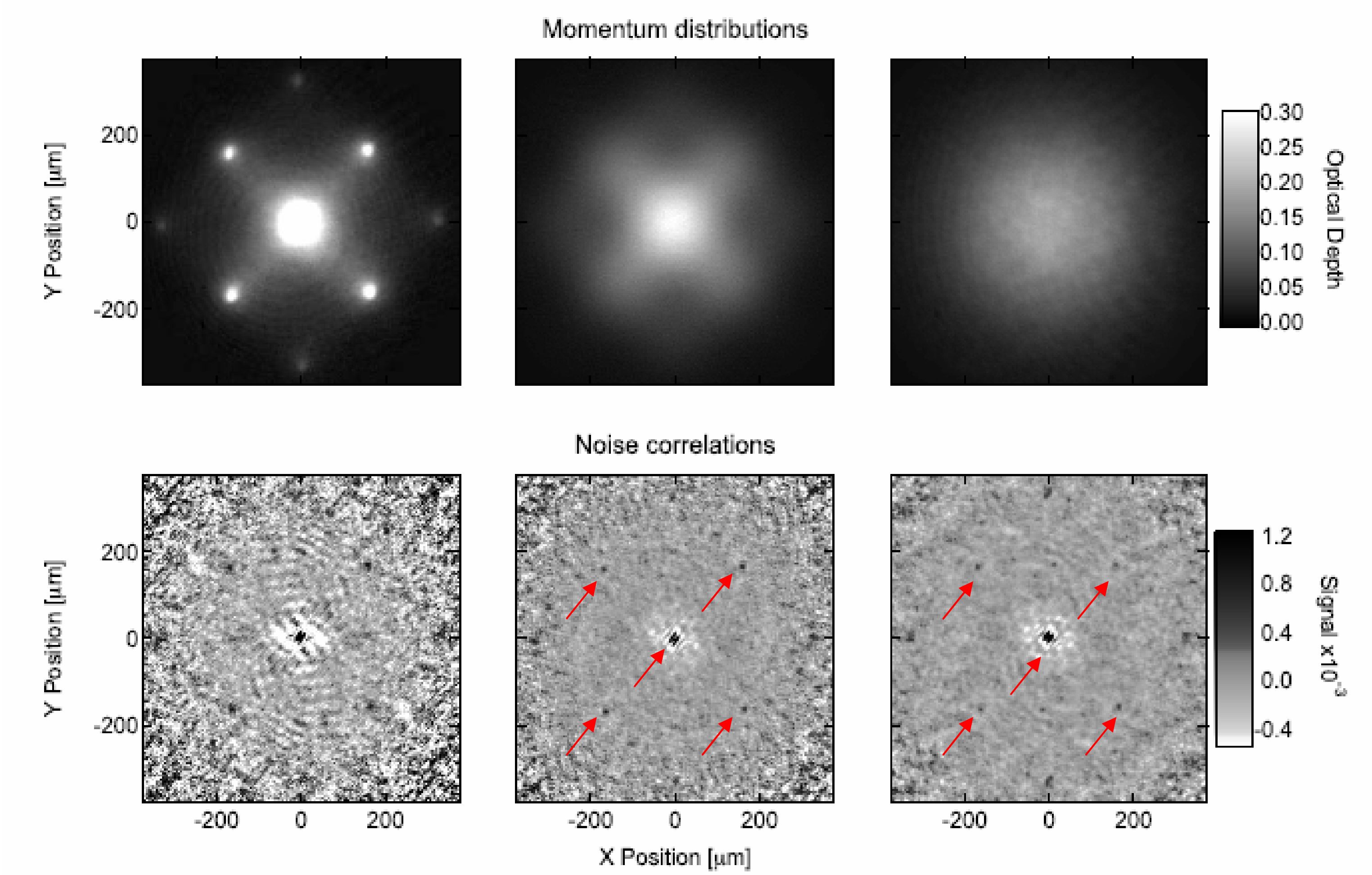
• Noise correlation function oscillates at reciprocal lattice vectors; bunching effect of bosons.

$$\langle n(\vec{k}_1) n(\vec{k}_2) \rangle - \langle n(\vec{k}_1) \rangle \langle n(\vec{k}_2) \rangle \propto \sum_G \delta(\vec{k}_1 - \vec{k}_2 - \vec{G})$$



Folling et al., Nature 434, 481 (2005); Altman et al., PRA 70, 13603 (2004).

Two dimensional superfluid-Mott insulator transition

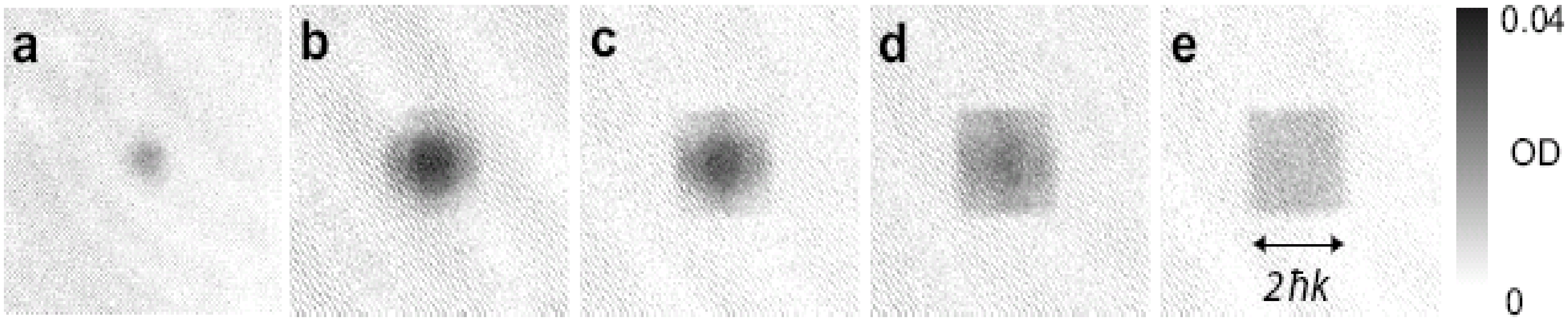


$V/E_R = 12$ $V/E_R = 20$ $V/E_R = 21$

I. B. Spielman et al., cond-mat/0606216.

Fermionic atoms in optical lattices

- Observation of Fermi surface. $^{40}K: \ |Fm\rangle = \left|\frac{9}{2}\frac{9}{2}\right\rangle, \left|\frac{9}{2}\frac{7}{2}\right\rangle$



Low density: metal

high density: band insulator

Esslinger et al., PRL 94:80403 (2005)

Fermions with near-unitary interactions in the presence of a periodic potential

Fermions with near-unitary interactions in the presence of a periodic potential

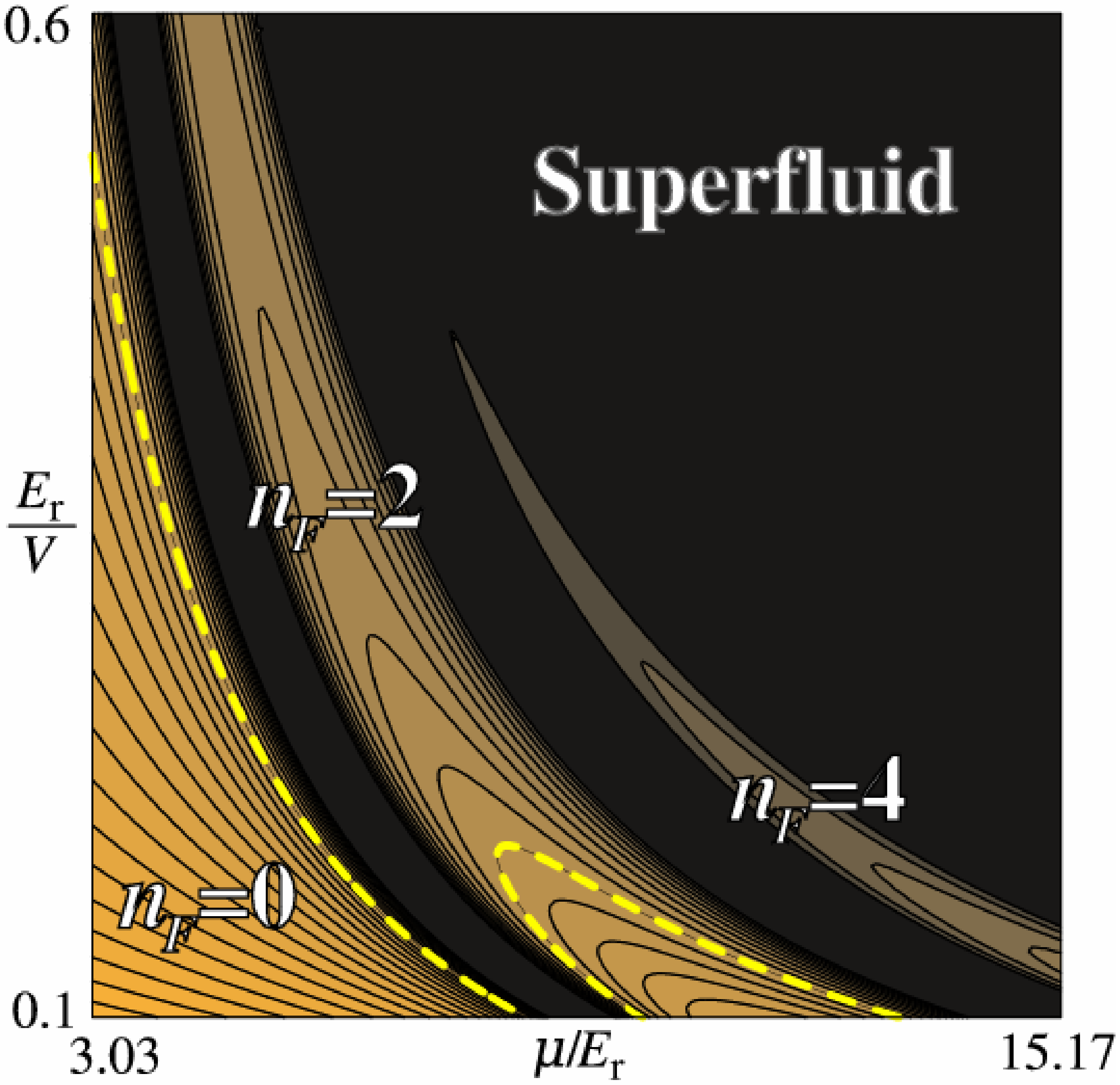
In the presence of a potential

$$V(r) = V\left[\cos\left(\frac{2\pi x}{a_L}\right) + \cos\left(\frac{2\pi y}{a_L}\right) + \cos\left(\frac{2\pi z}{a_L}\right)\right]$$

there is a universal phase diagram determined by the ratio of 3 energy scales: V, the chemical potential μ, and the recoil energy $E_r = \frac{\hbar^2}{4ma_L^2}$

E.G. Moon, P. Nikolic, and S. Sachdev, to appear

Universal phase diagram of fermions with near-unitary interactions in the presence of a periodic potential



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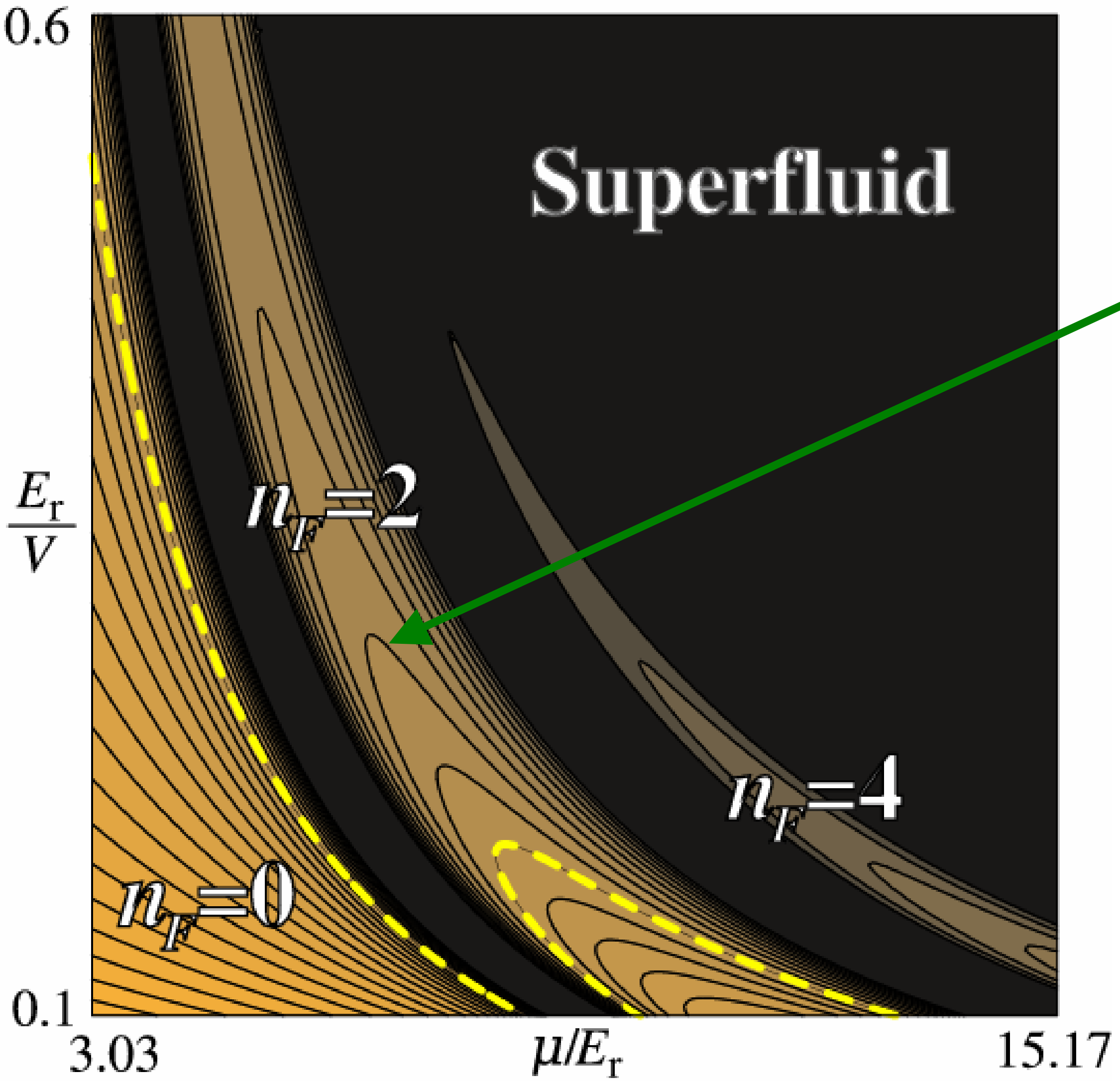

Boundaries to insulating phases for different values of νa_L where ν is the detuning from the resonance

E.G. Moon, P. Nikolic, and S. Sachdev, to appear

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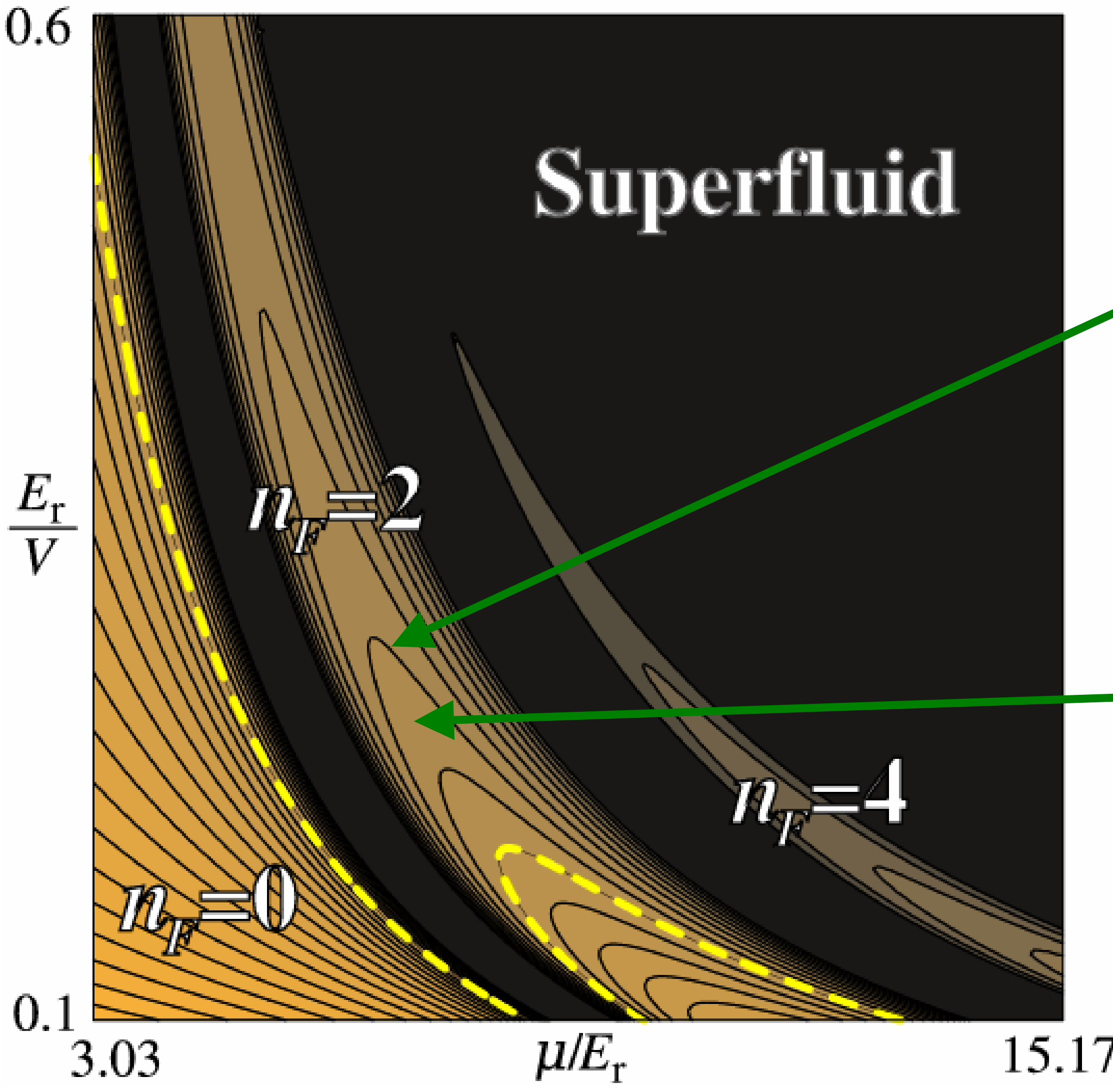


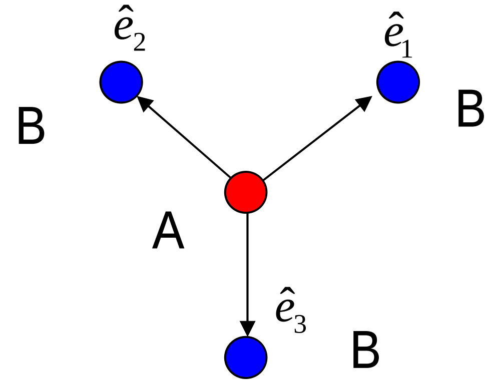
Boundaries to insulating phases for different values of νa_L where ν is the detuning from the resonance

Insulators have multiple band-occupancy, and are intermediate between band insulators of fermions and Mott insulators of bosonic fermion pairs

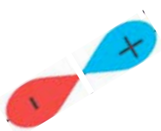
E.G. Moon, P. Nikolic, and S. Sachdev, to appear

Artificial graphene in optical lattices

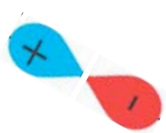
- Band Hamiltonian (σ-bonding) for spin-polarized fermions.



$$H_t = t_{//}\Big\{ \sum_{\vec{r}\in A} [p_1^+(\vec{r})p_1(\vec{r}+\hat{e}_1)+h.c.]$$
$$+[p_2^+(\vec{r})p_1(\vec{r}+\hat{e}_2)+h.c]$$
$$+[p_3^+(\vec{r})p_3(\vec{r}+\hat{e}_3)+h.c]\ \Big\}$$

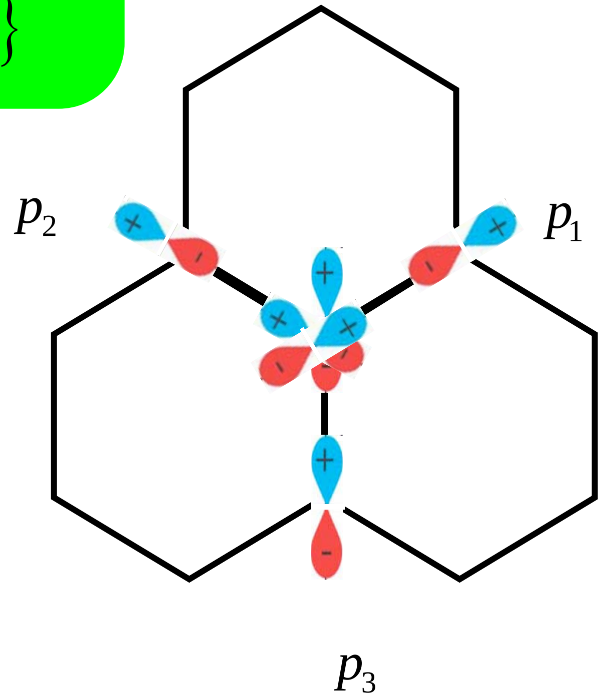


$$p_1 = \frac{\sqrt{3}}{2}p_x + \frac{1}{2}p_y$$



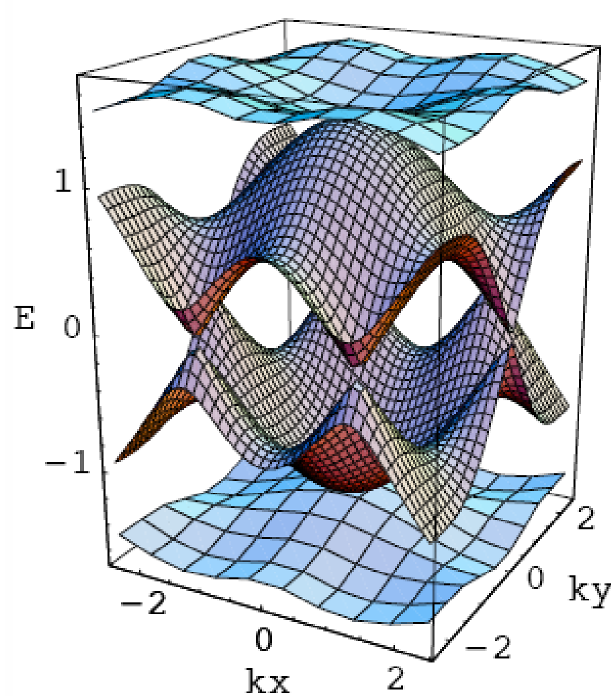
$$p_2 = \frac{\sqrt{3}}{2}p_x - \frac{1}{2}p_y$$

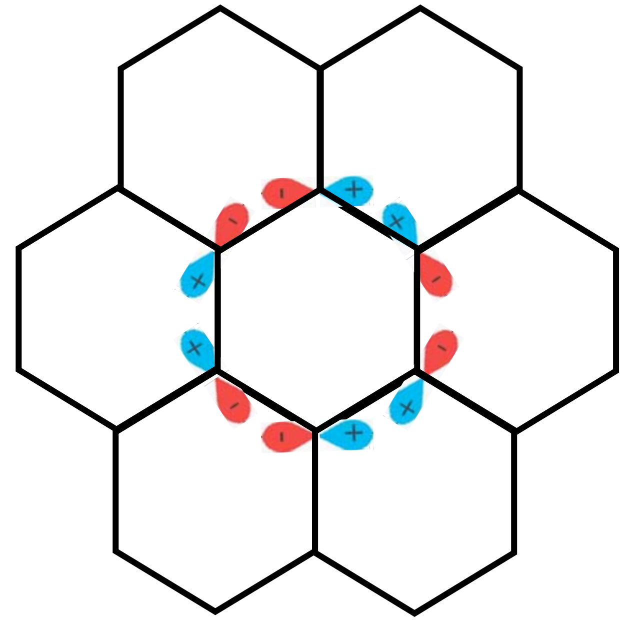
$$p_3 = -p_y$$



Congjun Wu et al

Flat bands in the entire Brillouin zone





- Flat band + Dirac cone.
- localized eigenstates.

Many correlated phases possible

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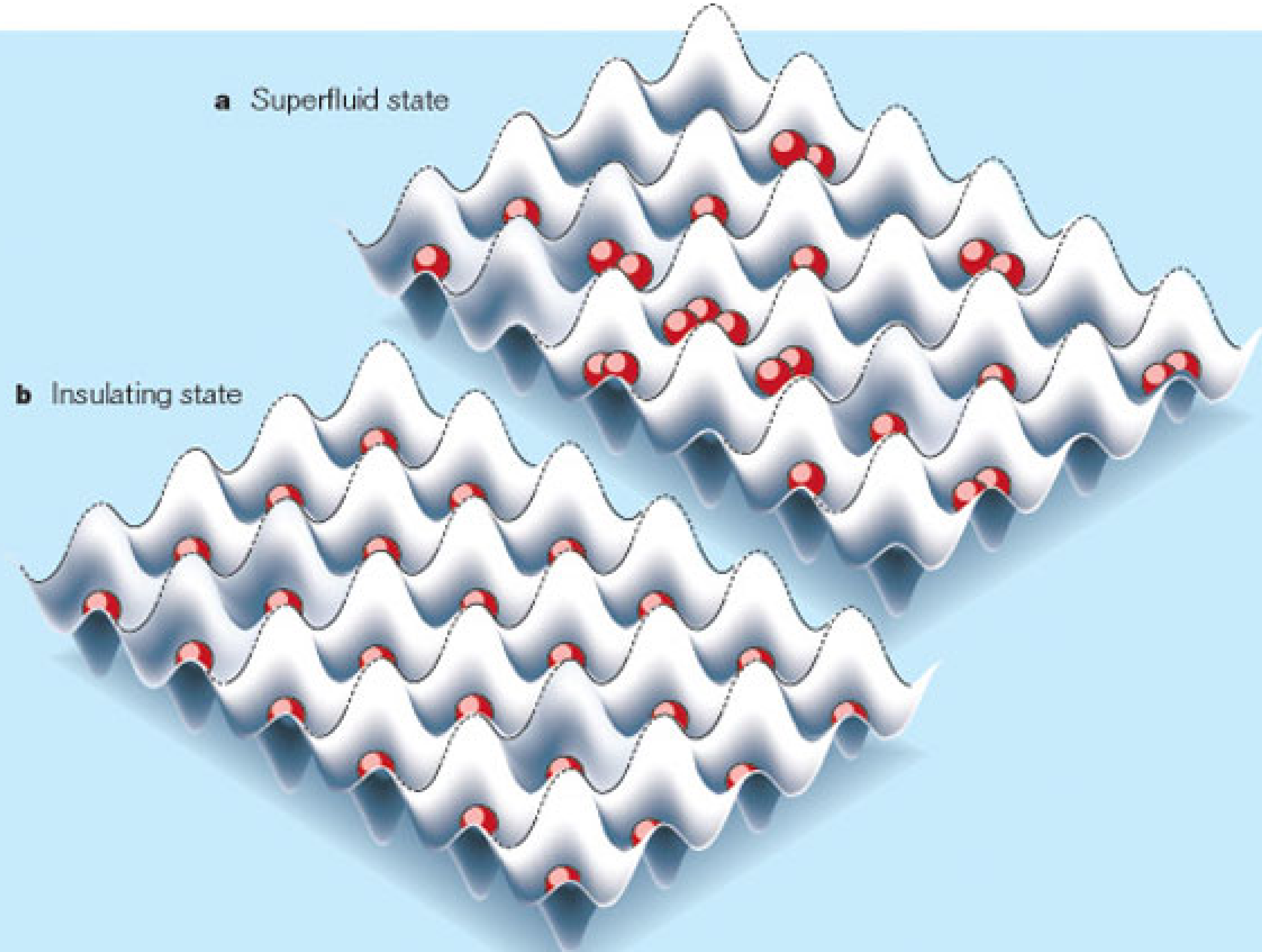
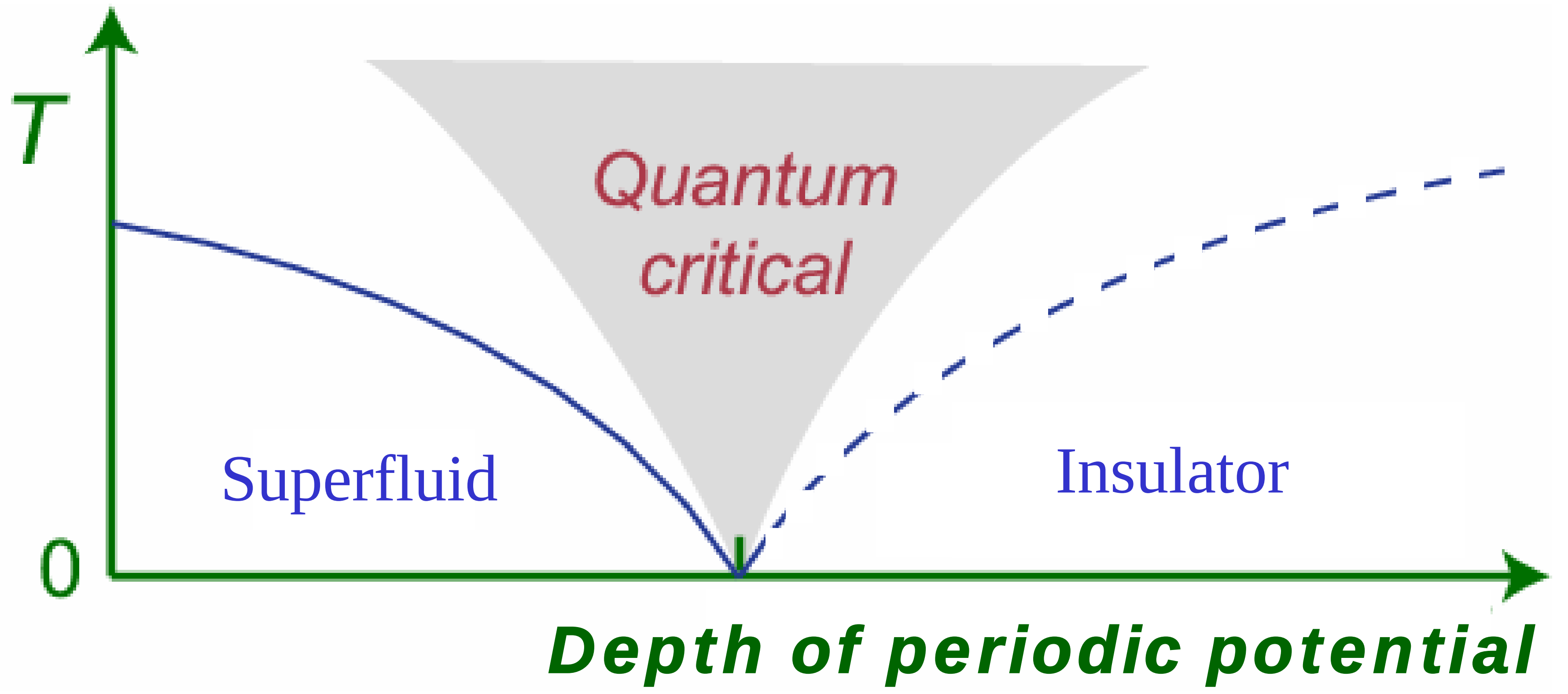


M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

Non-zero temperature phase diagram



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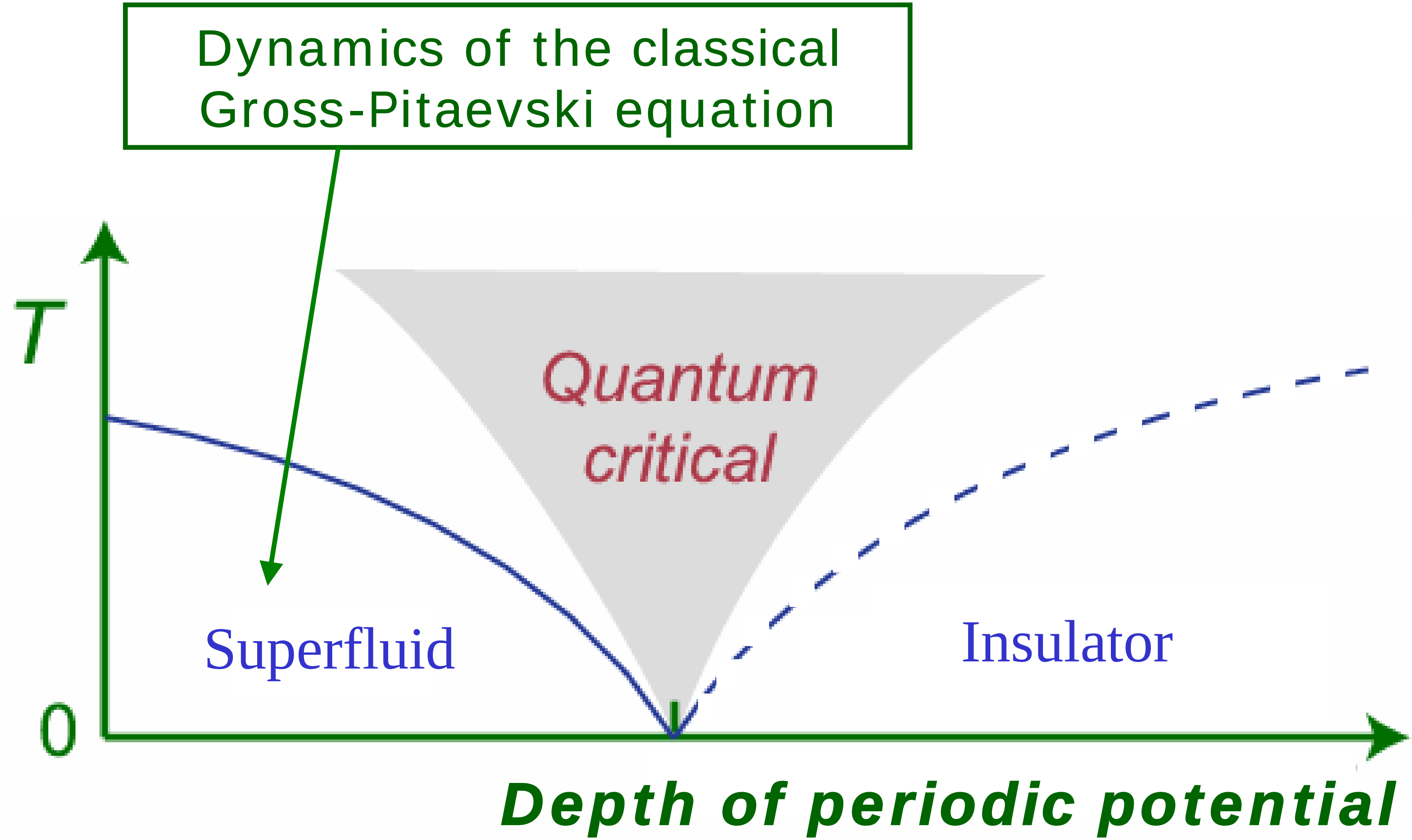

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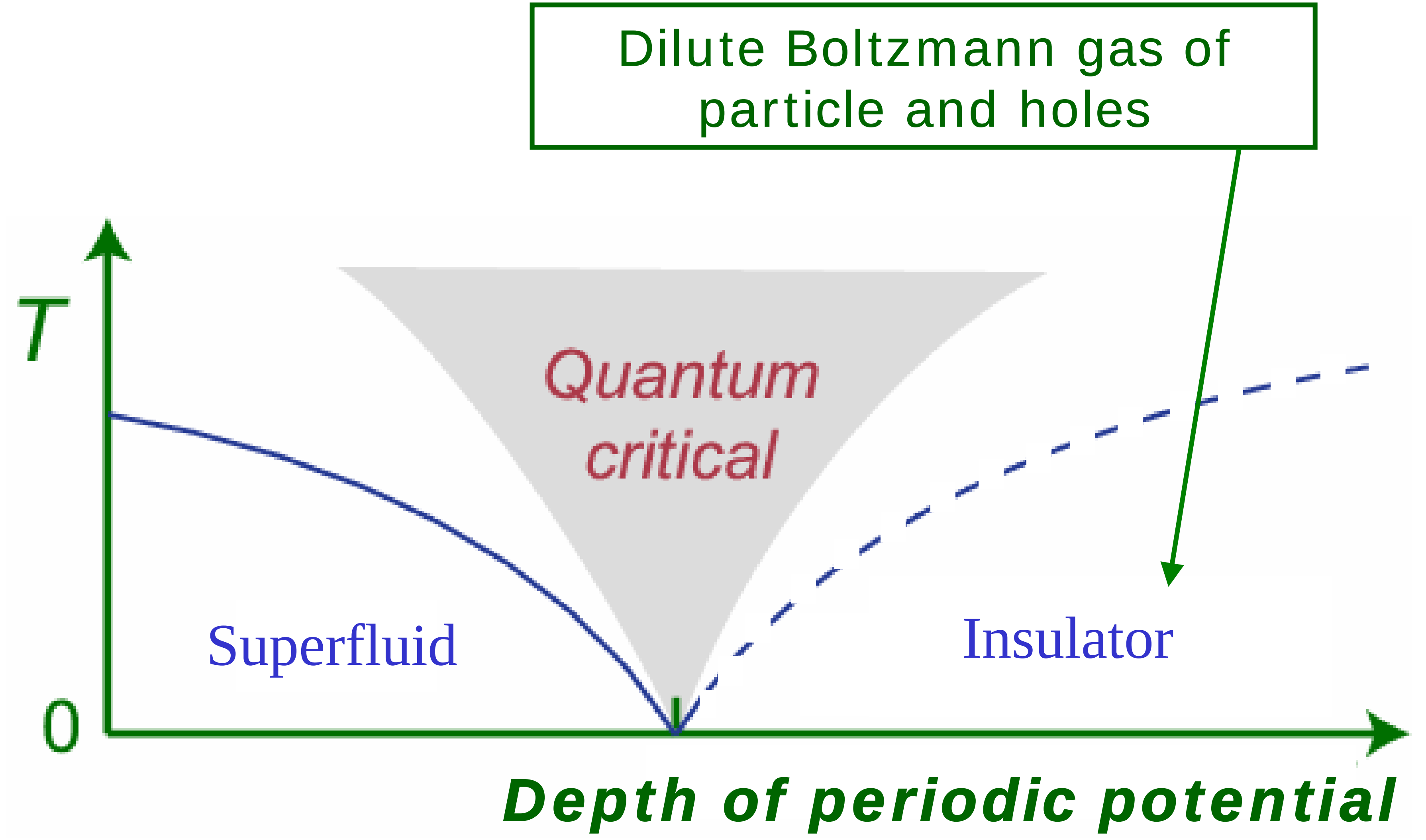

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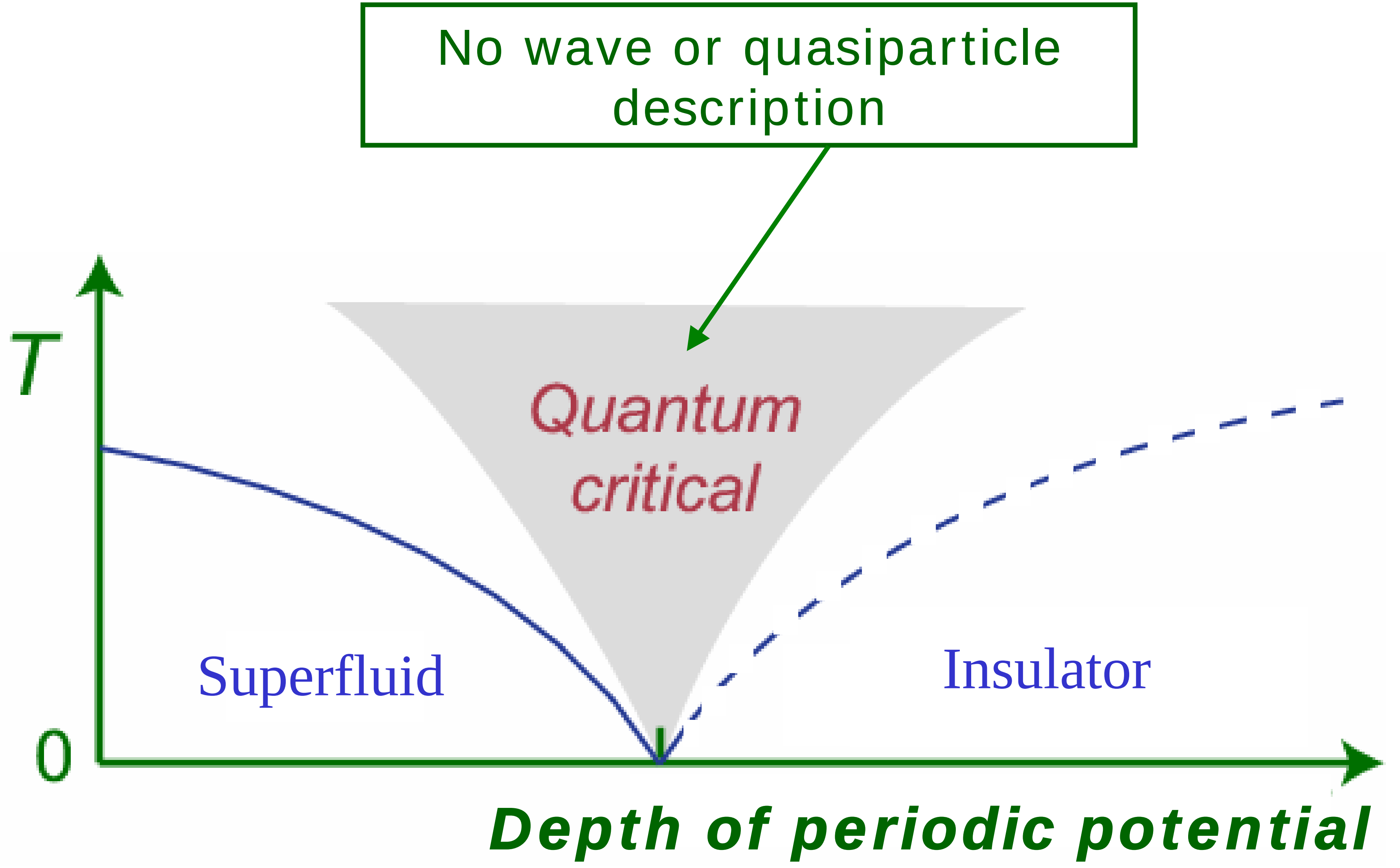


Resistivity of Bi films

Conductivity σ

$$\sigma_{\text{Superconductor}}\left(T \rightarrow 0\right) = \infty$$

$$\sigma_{\text{Insulator}}\left(T \rightarrow 0\right) = 0$$

$$\sigma_{\text{Quantum critical point}}\left(T \rightarrow 0\right) \approx \frac{4e^2}{h}$$

D. B. Haviland, Y. Liu, and A. M. Goldman, *Phys. Rev. Lett.* **62**, 2180 (1989)

M. P. A. Fisher, *Phys. Rev. Lett.* **65**, 923 (1990)

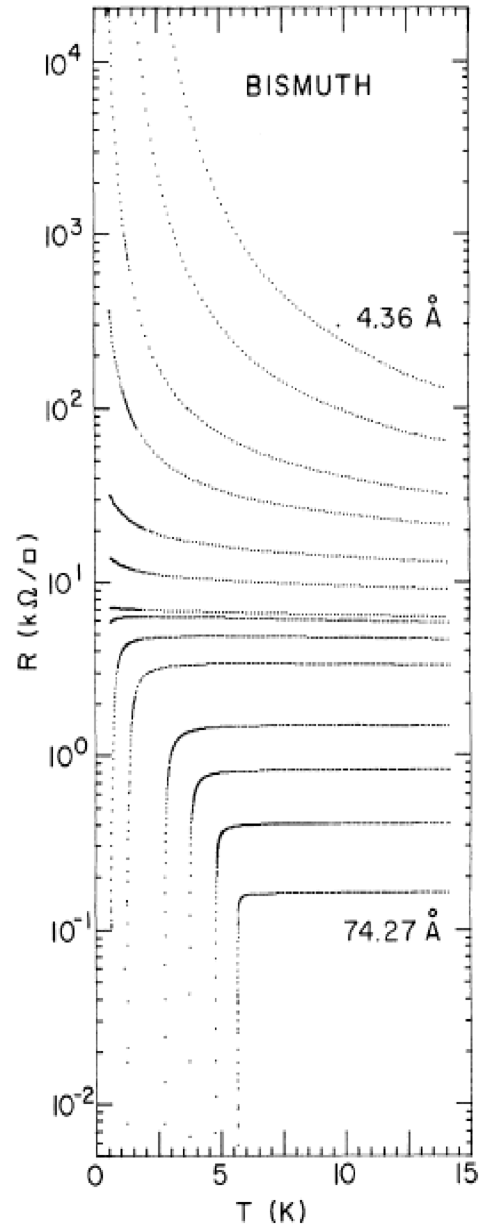
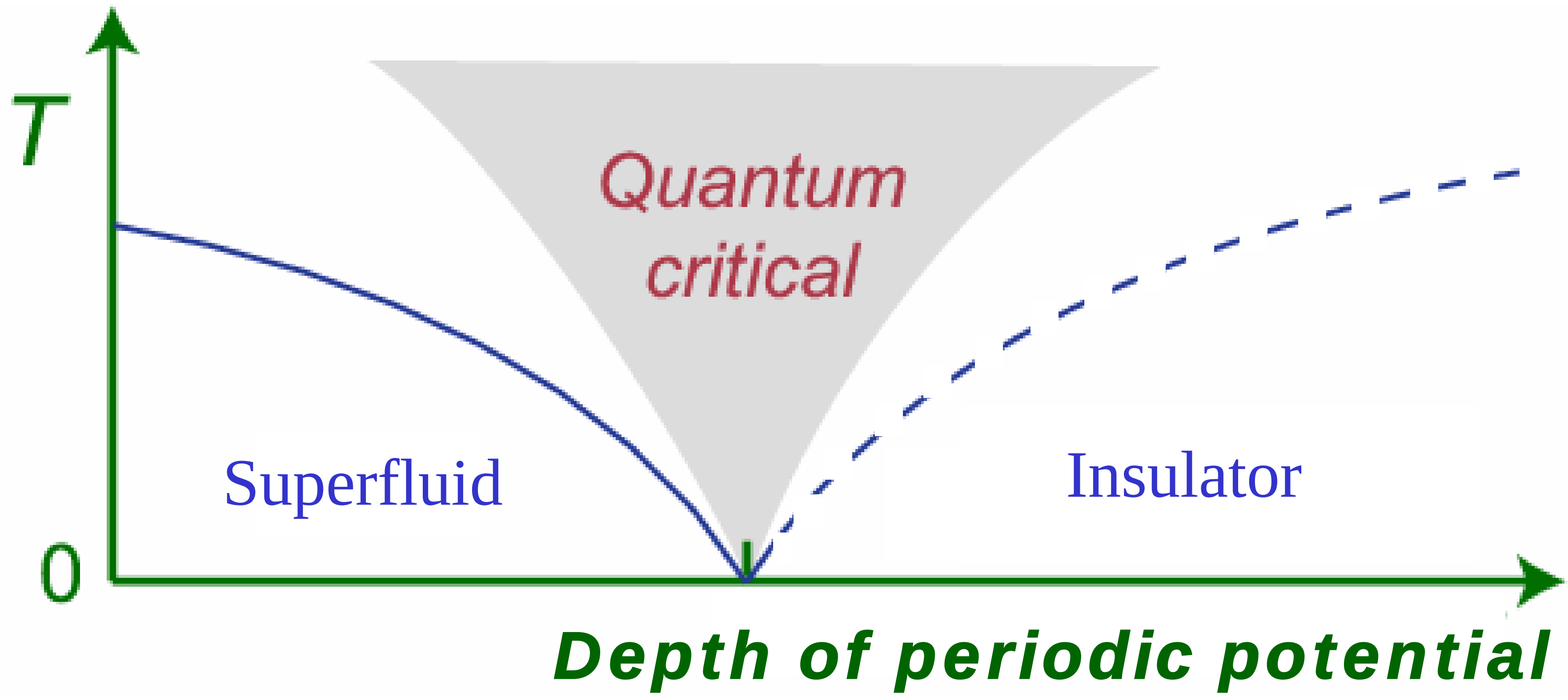
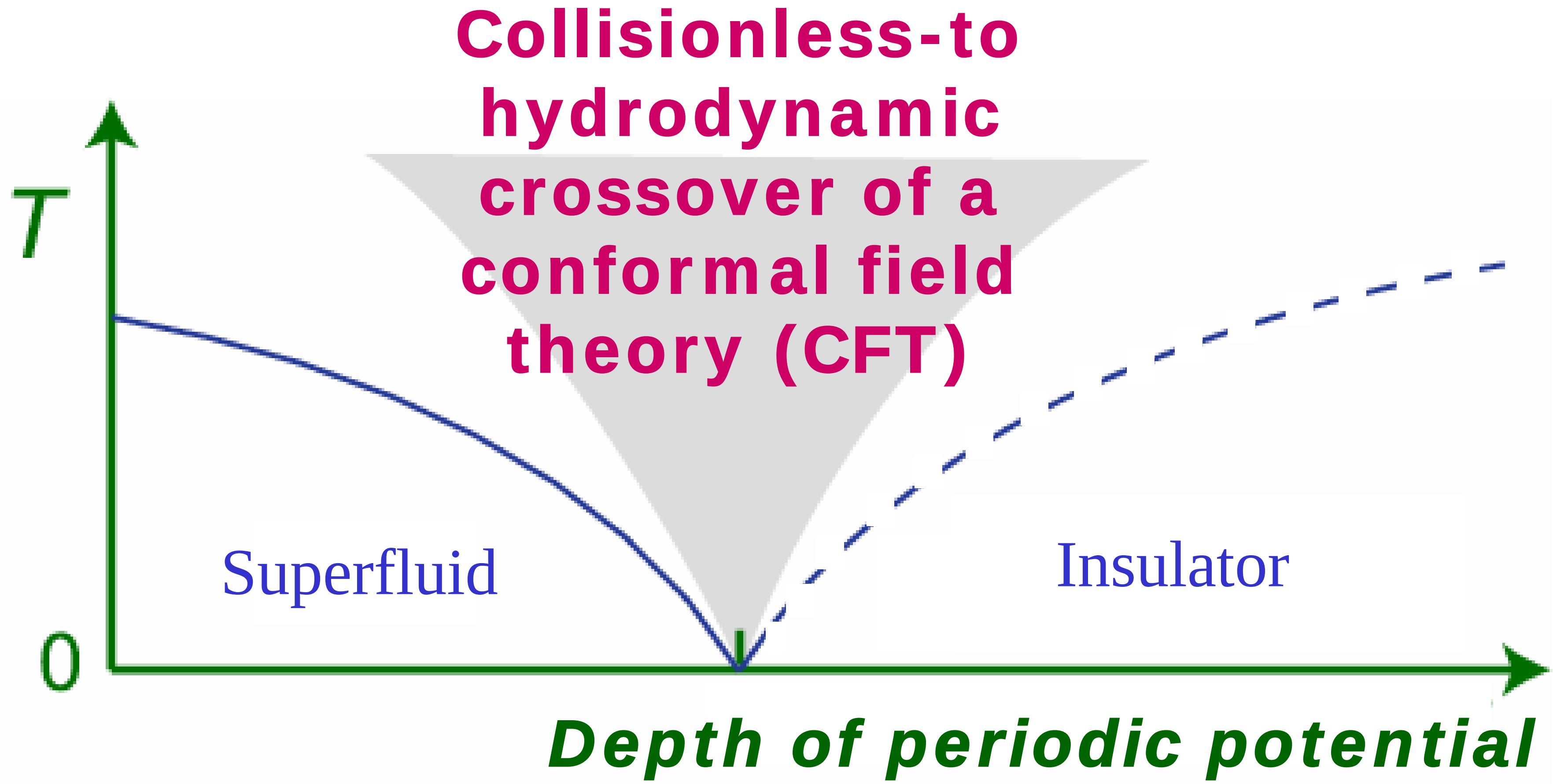


FIG. 1. Evolution of the temperature dependence of the sheet resistance $R(T)$ with thickness for a Bi film deposited onto Ge. Fewer than half of the traces actually acquired are shown. Film thicknesses shown range from 4.36 to 74.27 Å.

Non-zero temperature phase diagram



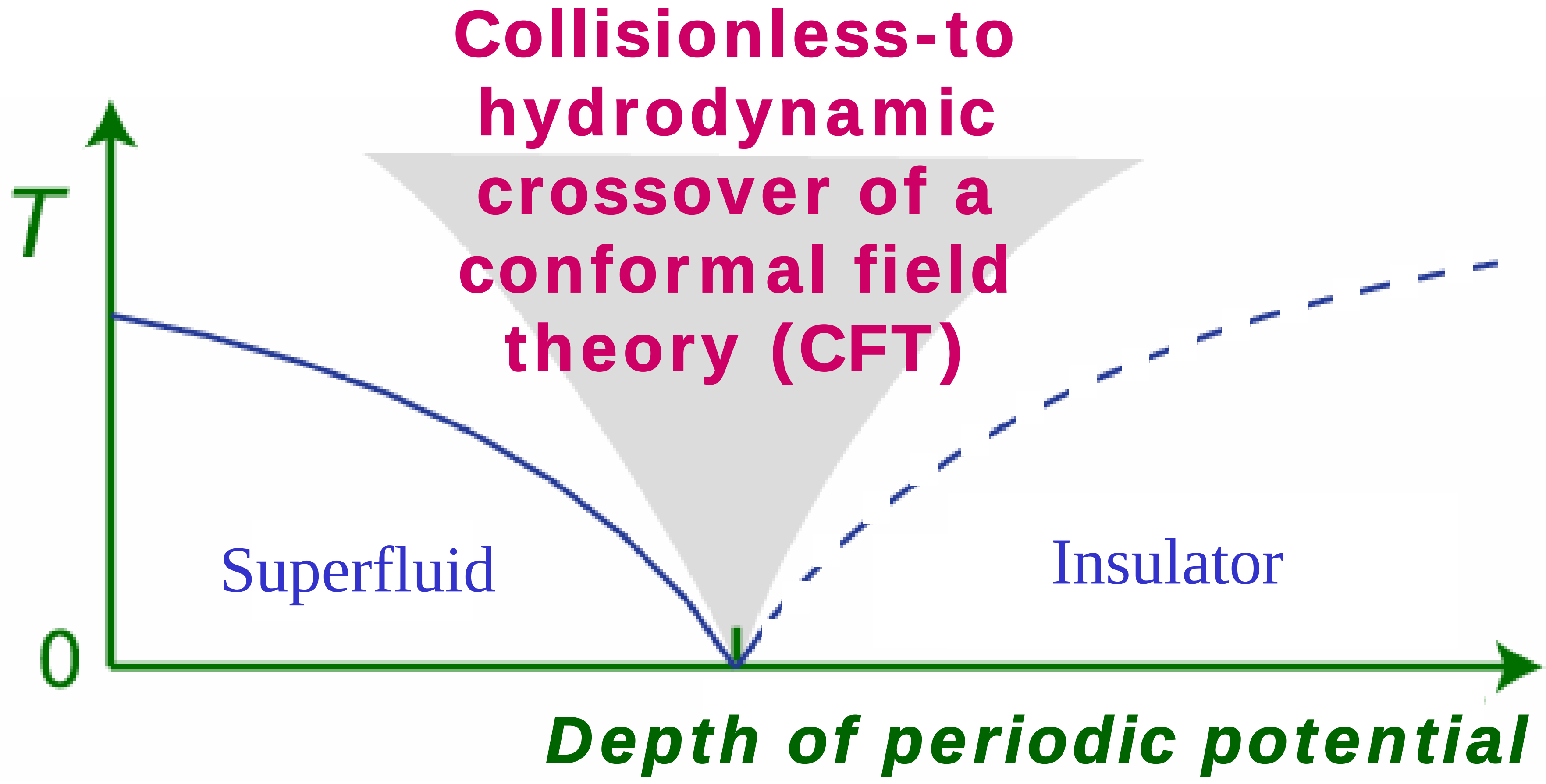
Non-zero temperature phase diagram



K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Non-zero temperature phase diagram

Needed: Cold atom experiments in this regime



K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Hydrodynamics of a conformal field theory (CFT)

Maldacena’s AdS/CFT correspondence relates the hydrodynamics of CFTs to the quantum gravity theory of the horizon of a black hole in Anti-de Sitter space.

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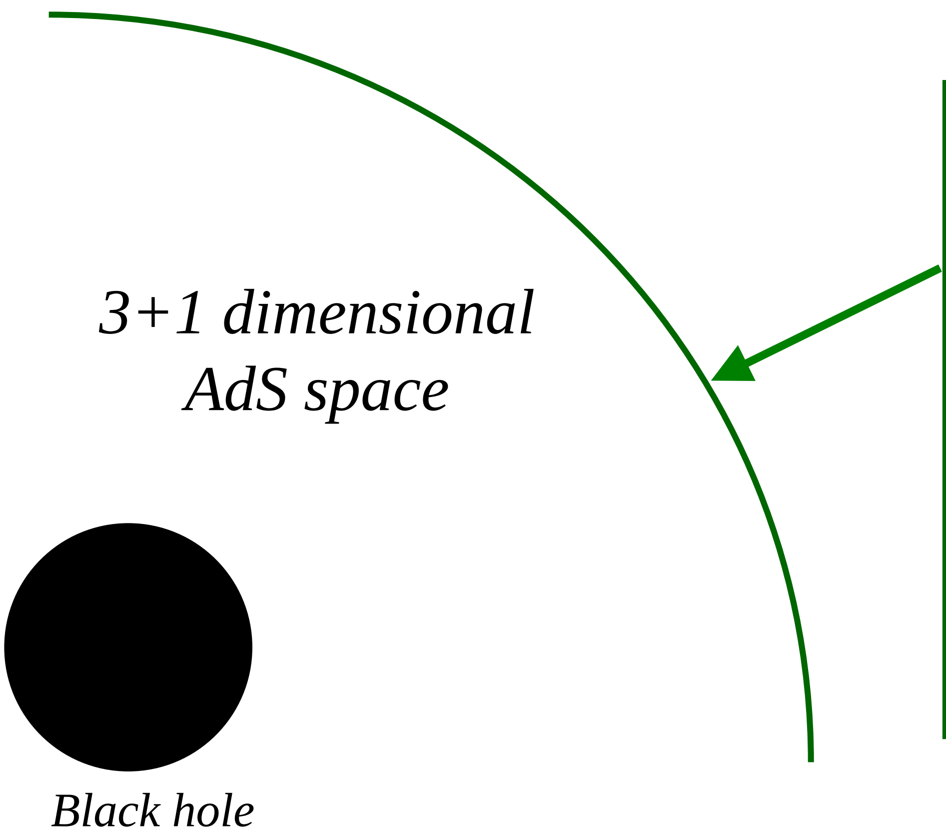
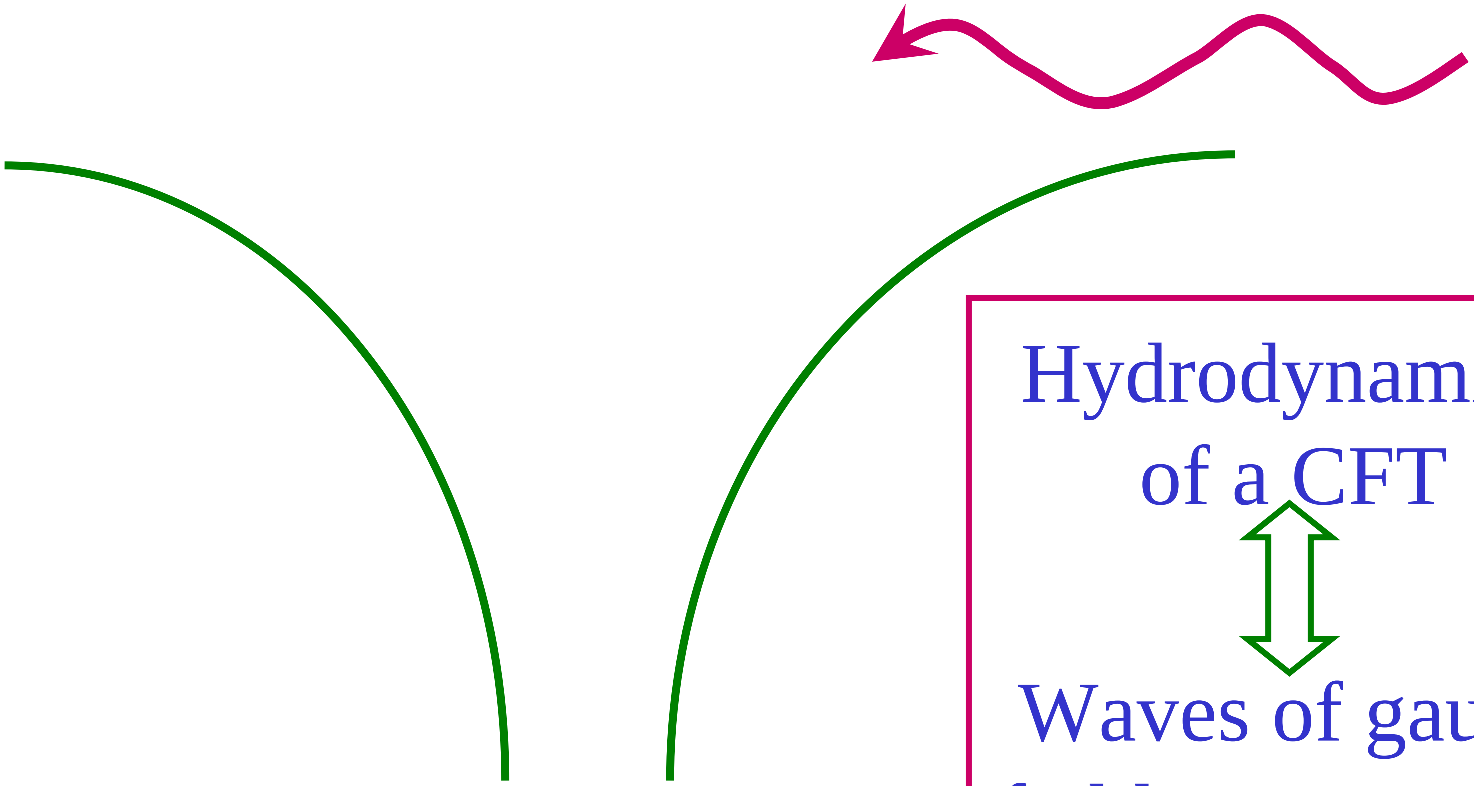


Holographic representation of black hole physics in a 2+1 dimensional CFT at a temperature equal to the Hawking temperature of the black hole.

Hydrodynamics of a conformal field theory (CFT)



Hydrodynamics of a CFT

⇕

Waves of gauge fields in a curved background

Hydrodynamics of a conformal field theory (CFT)

The scattering cross-section of the thermal excitations is universal and so transport co-efficients are universally determined by $k_B T$

Charge diffusion constant $$D_c = \Theta \frac{c^2}{k_B T}$$

Conductivity $$\sigma = \bar{\Theta} \frac{4e^2}{h}$$

K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Hydrodynamics of a conformal field theory (CFT)

For the (unique) CFT with a SU(N) gauge field and 16 supercharges, we know the exact diffusion constant associated with a global SO(8) symmetry:

Spin diffusion constant $$D_s = \frac{3}{4\pi}\frac{c^2}{k_B T}$$

Spin conductivity $$\sigma = \frac{N^{3/2}}{3\sqrt{2}\pi}$$

P. Kovtun, C. Herzog, S. Sachdev, and D.T. Son, hep-th/0701036

Outline

Strongly interacting cold atoms

1. Quantum liquids near unitarity:
   from few-body to many-body physics
   (a) Tonks gas in one dimension
   (b) Paired fermions across a Feshbach resonance

2. Optical lattices
   (a) Superfluid-insulator transition
   (b) Quantum-critical hydrodynamics via mapping to
   quantum theory of black holes.
   (c) Entanglement of valence bonds

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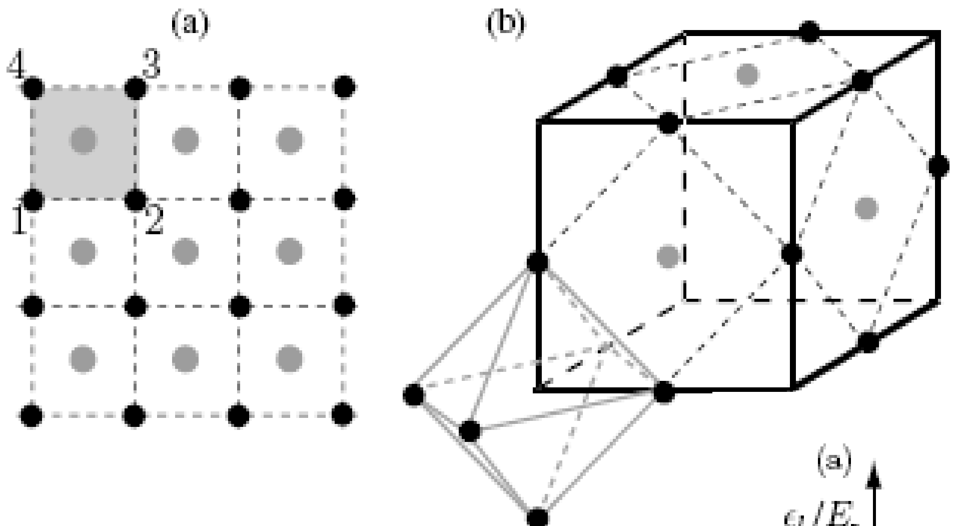
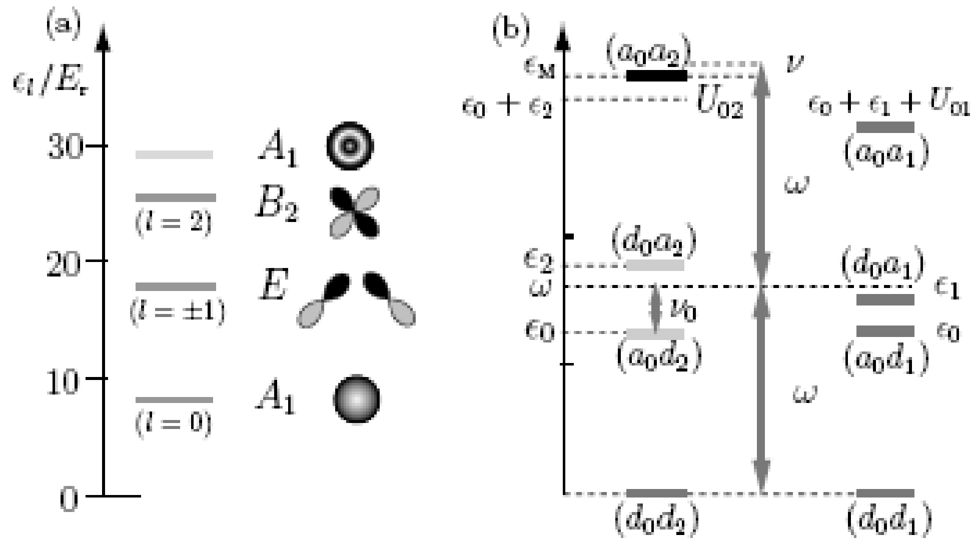
Ring-exchange interactions in an optical lattice using a Raman transition





H.P. Büchler, M. Hermele, S.D. Huber, M.P.A. Fisher, and P. Zoller, *Phys. Rev. Lett.* **95**, 040402 (2005)

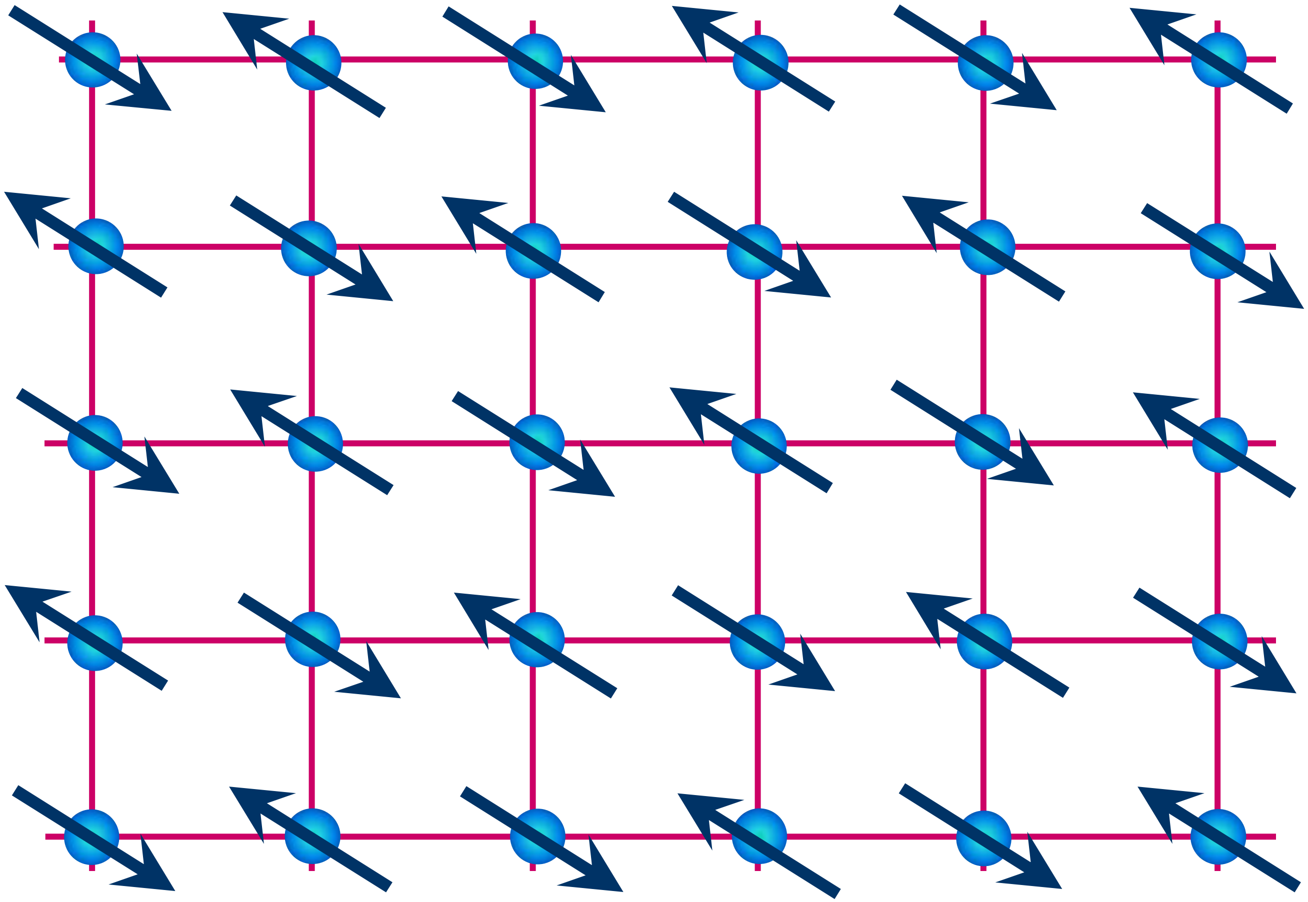
At each site, identify the states $|\uparrow\rangle$, $|\downarrow\rangle$, with the occupation number of a hard-core boson:

$$\begin{aligned} |\downarrow\rangle &= |0\rangle \\ |\uparrow\rangle &= b^\dagger|0\rangle \end{aligned}$$

Then the spin operators map as follows

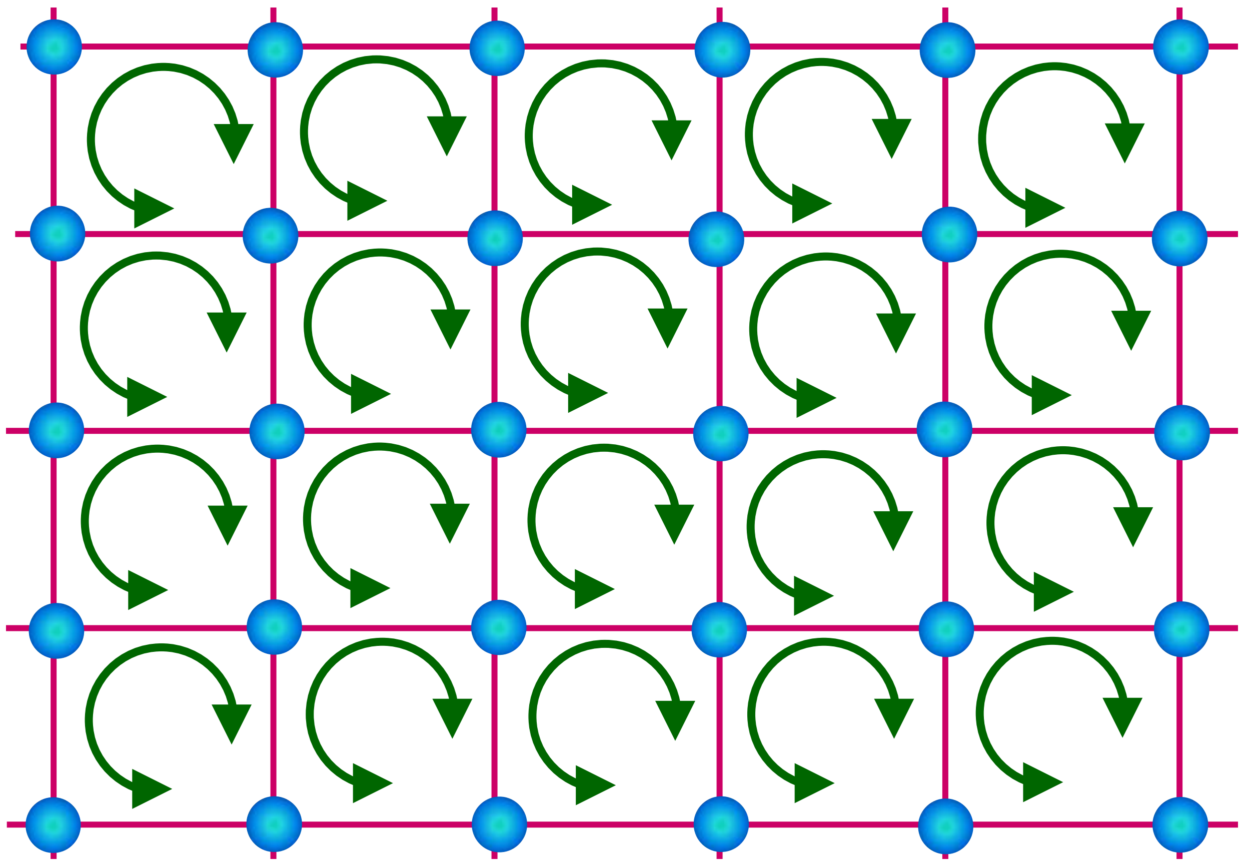
$$\begin{aligned} S_z &= b^\dagger b - 1/2 \\ S_+ &= b^\dagger \\ S_- &= b \end{aligned}$$

Antiferromagnetic (Neel) order in the insulator



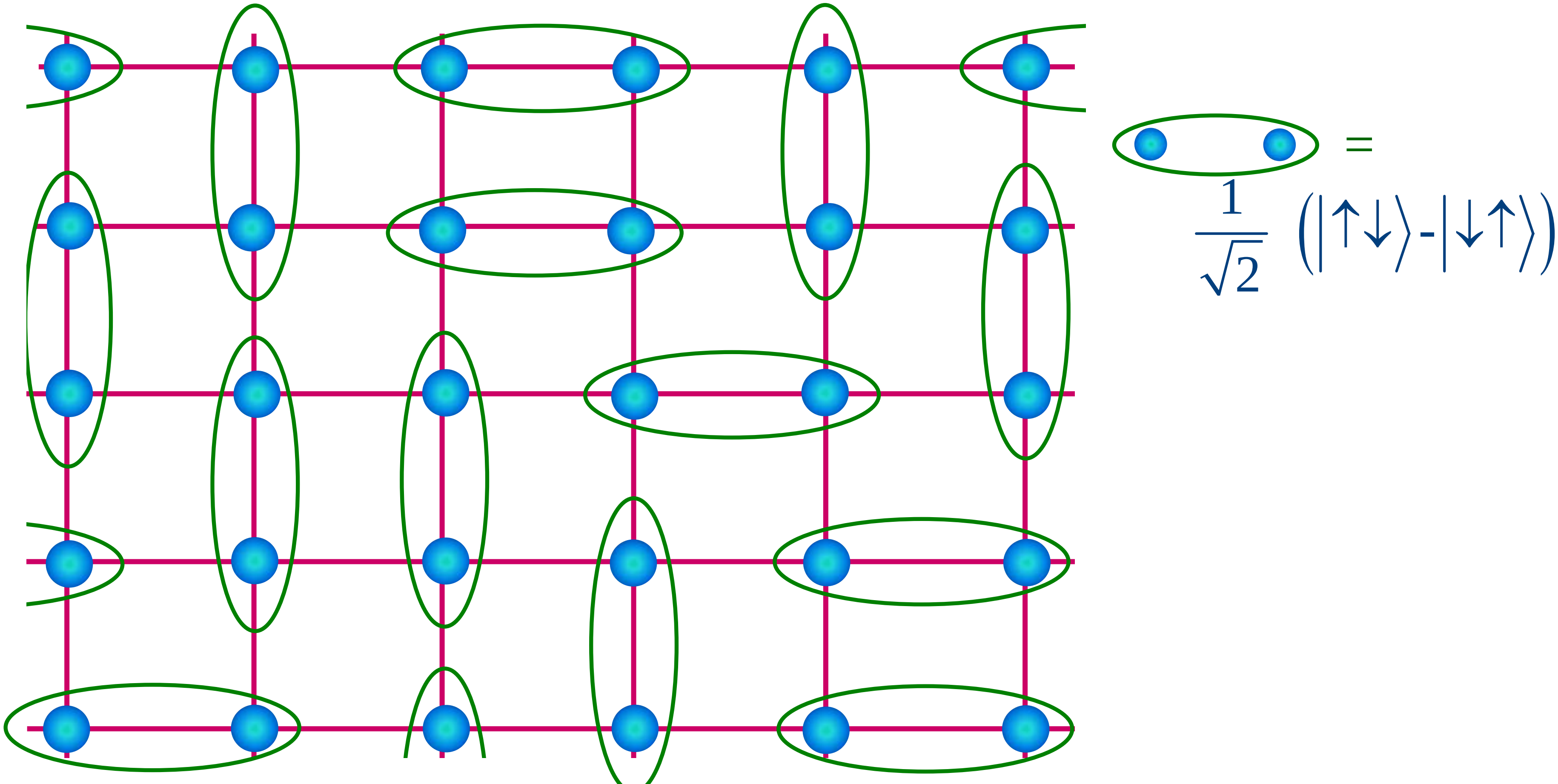
$$H = J\sum_{\langle ij\rangle}\vec{S}_i\bullet\vec{S}_j \quad ; \quad \vec{S}_i \Rightarrow \text{ spin operator with } S=1/2$$

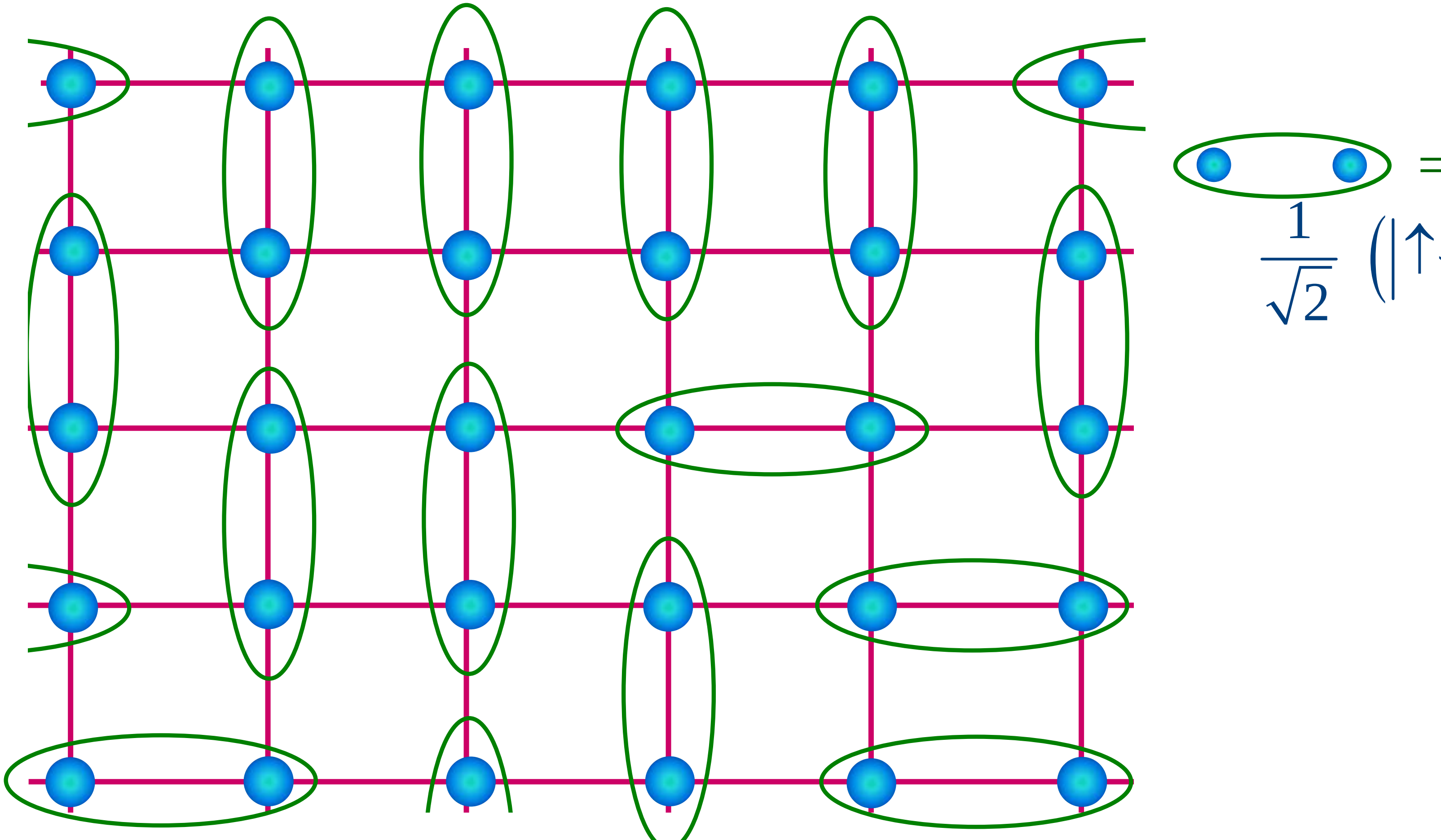
Induce formation of valence bonds by *e.g.* ring-exchange interactions



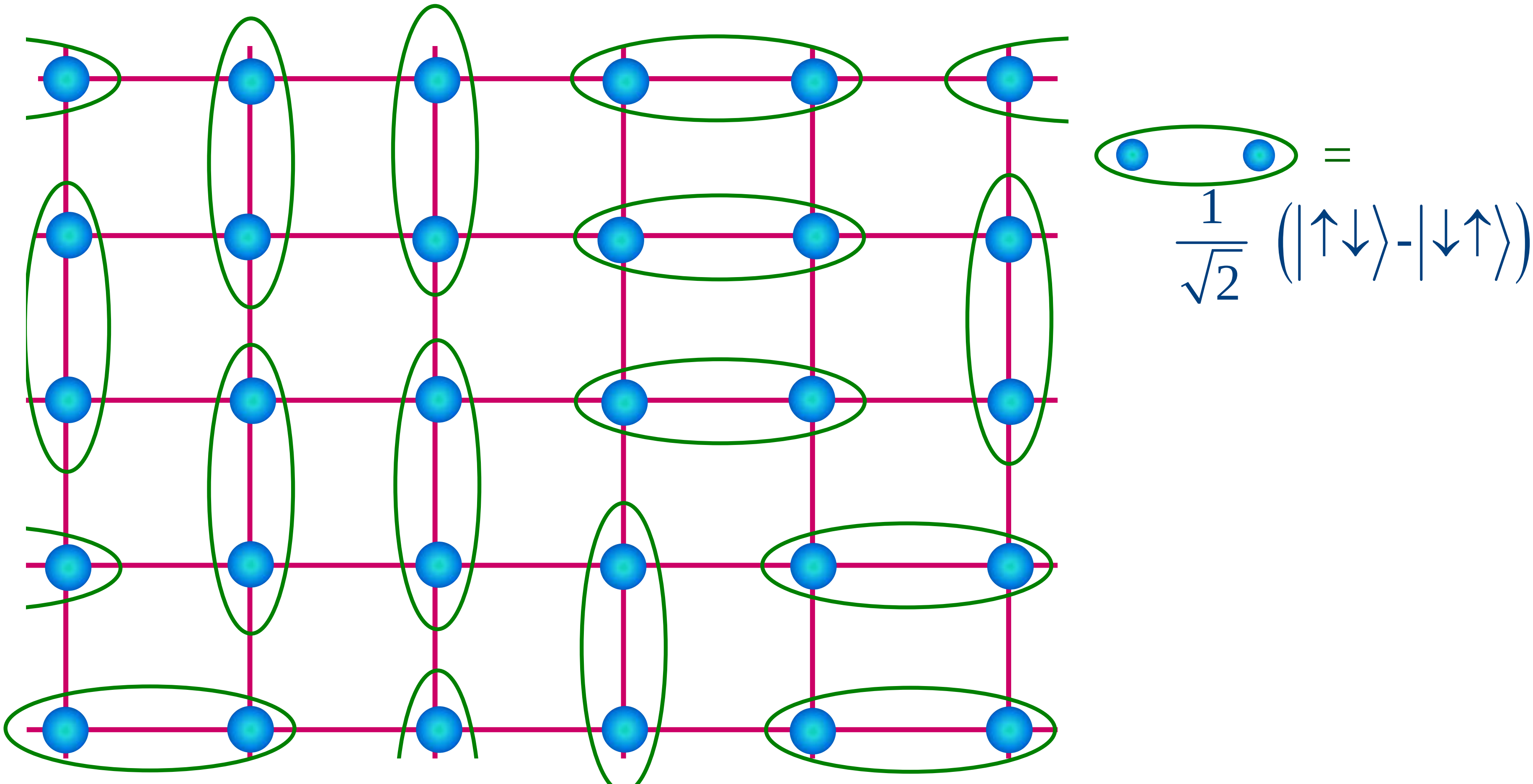
$$H = J\sum_{\langle ij\rangle} \vec{S}_i \cdot \vec{S}_j \;+\; K\sum_{\square} \text{4-spin exchange}$$

A. W. Sandvik, cond-mat/0611343


=
$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$



$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$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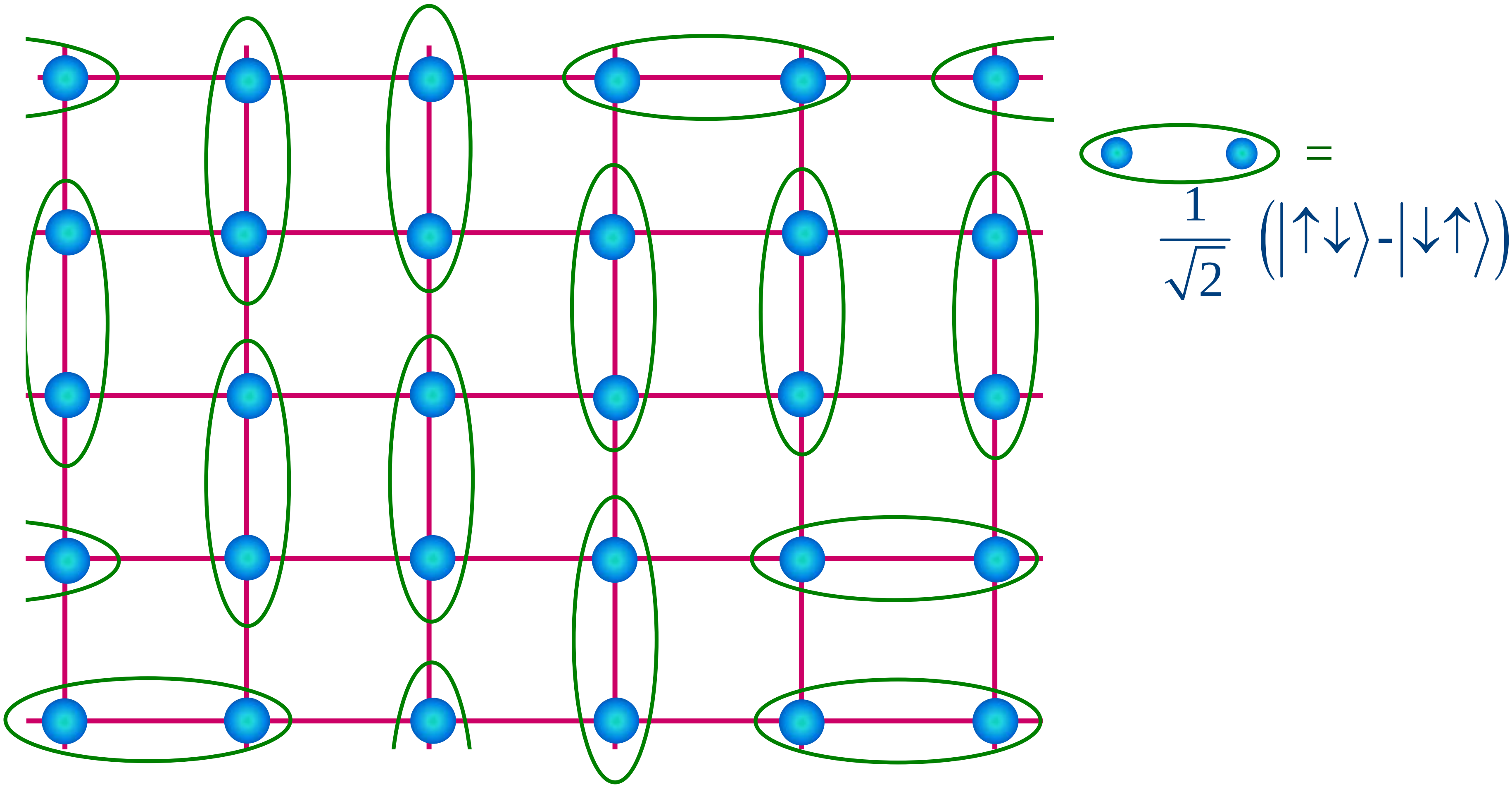
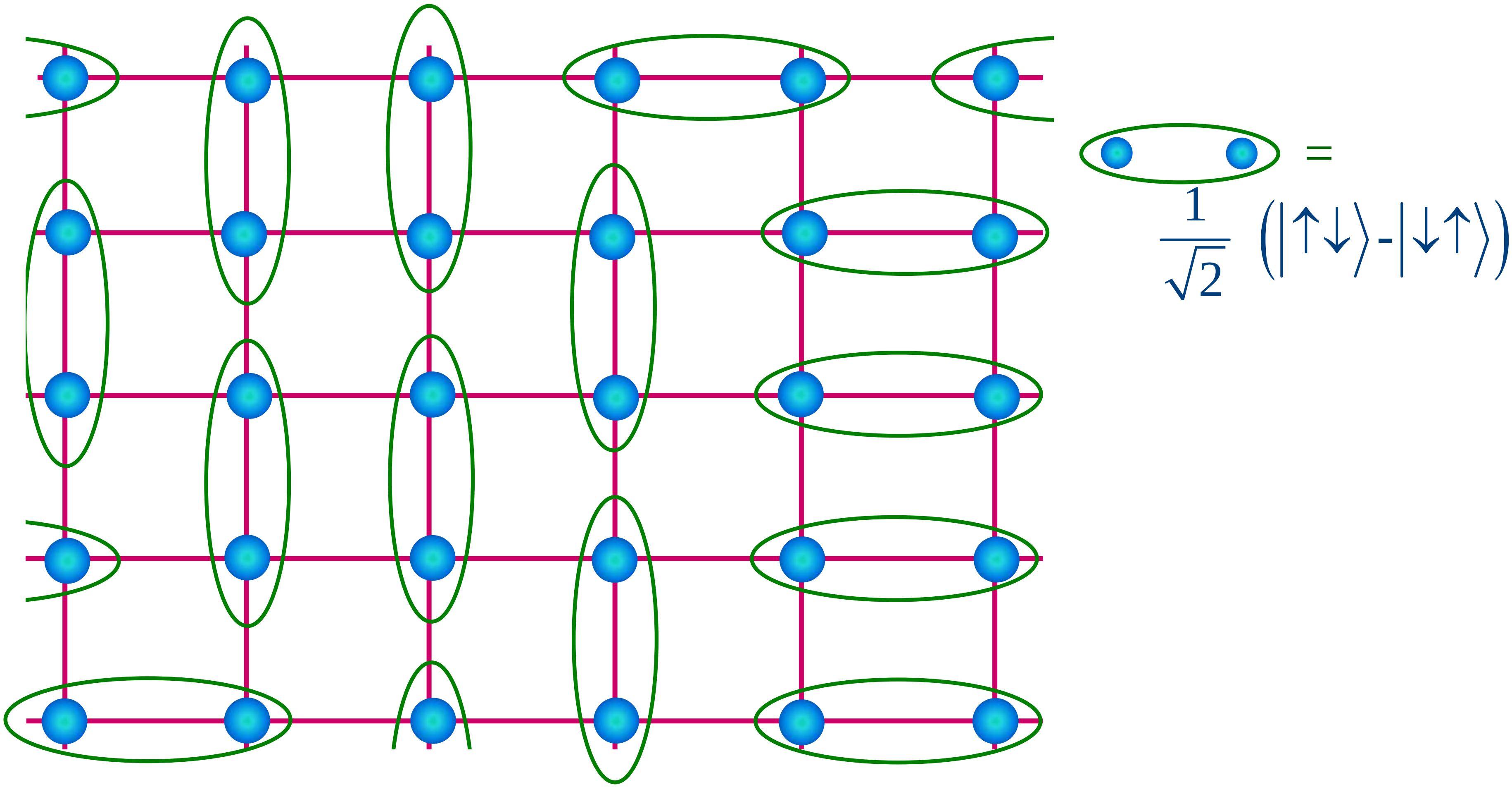
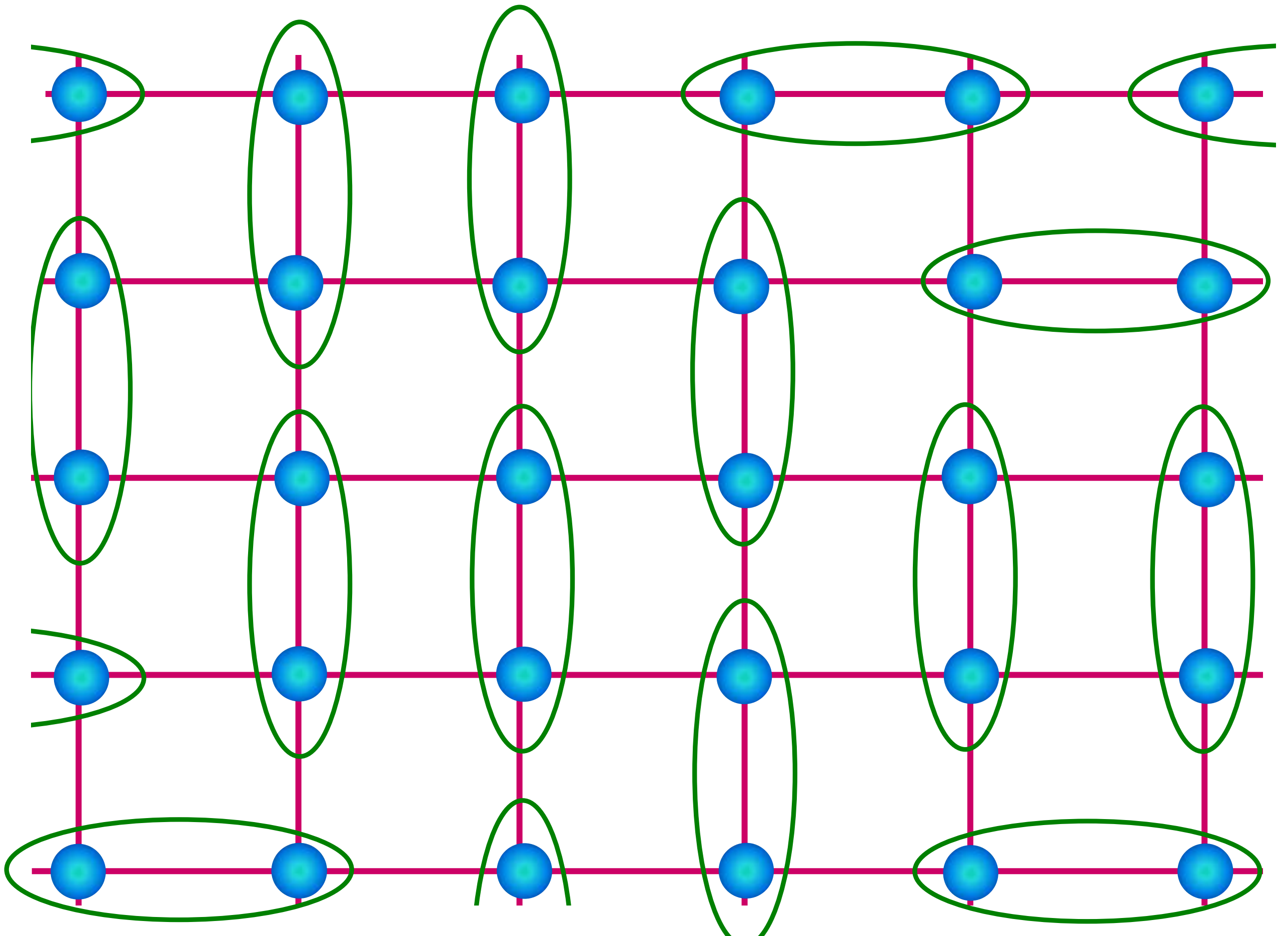
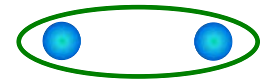


$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$


=
$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

Entangled liquid of valence bonds (Resonating valence bonds – RVB)

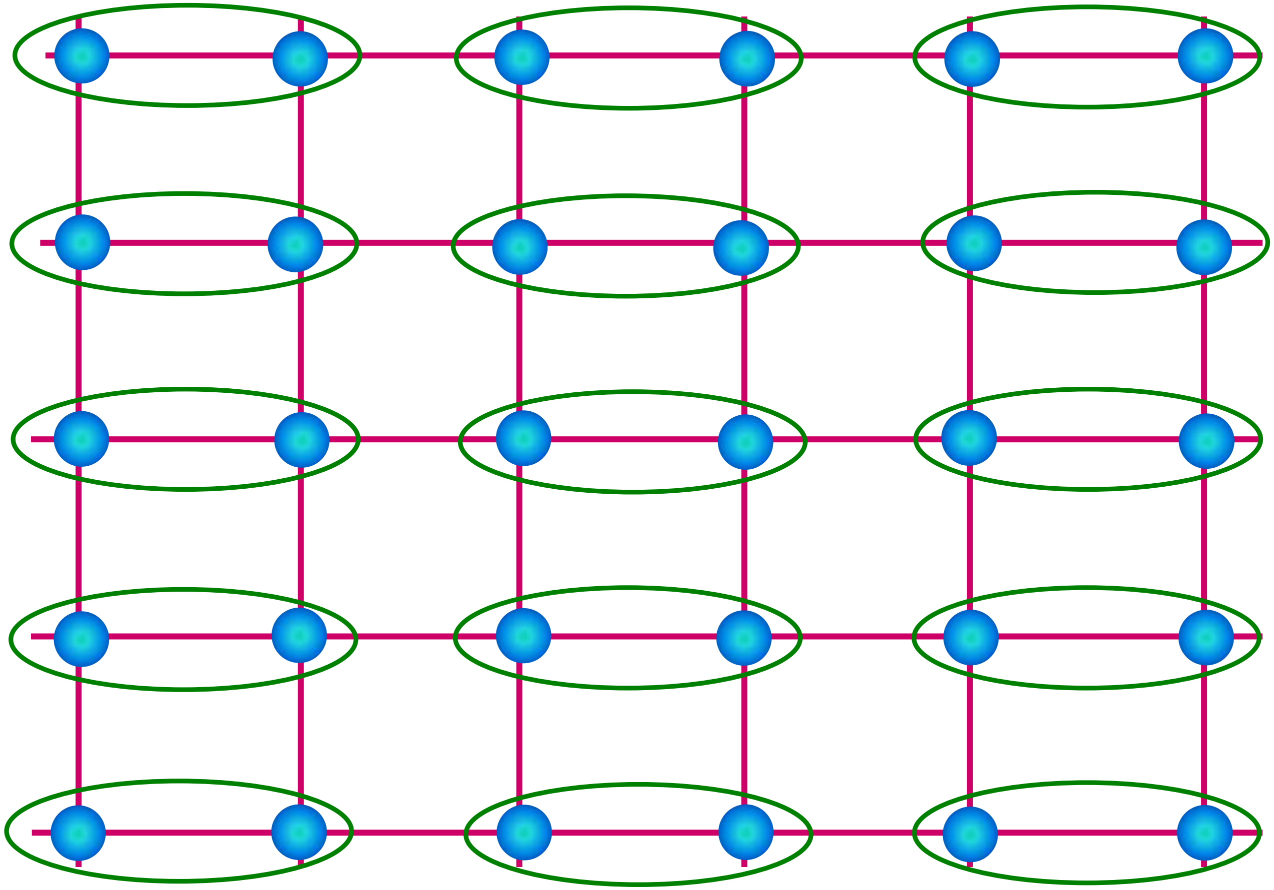


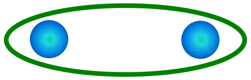


$$= \frac{1}{\sqrt{2}}\Big(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\Big)$$

P. Fazekas and P.W. Anderson, *Phil Mag* **30**, 23 (1974).

Valence bond solid (VBS)



 =

$$\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).
R. Moessner and S. L. Sondhi, *Phys. Rev.* B **63**, 224401 (2001).

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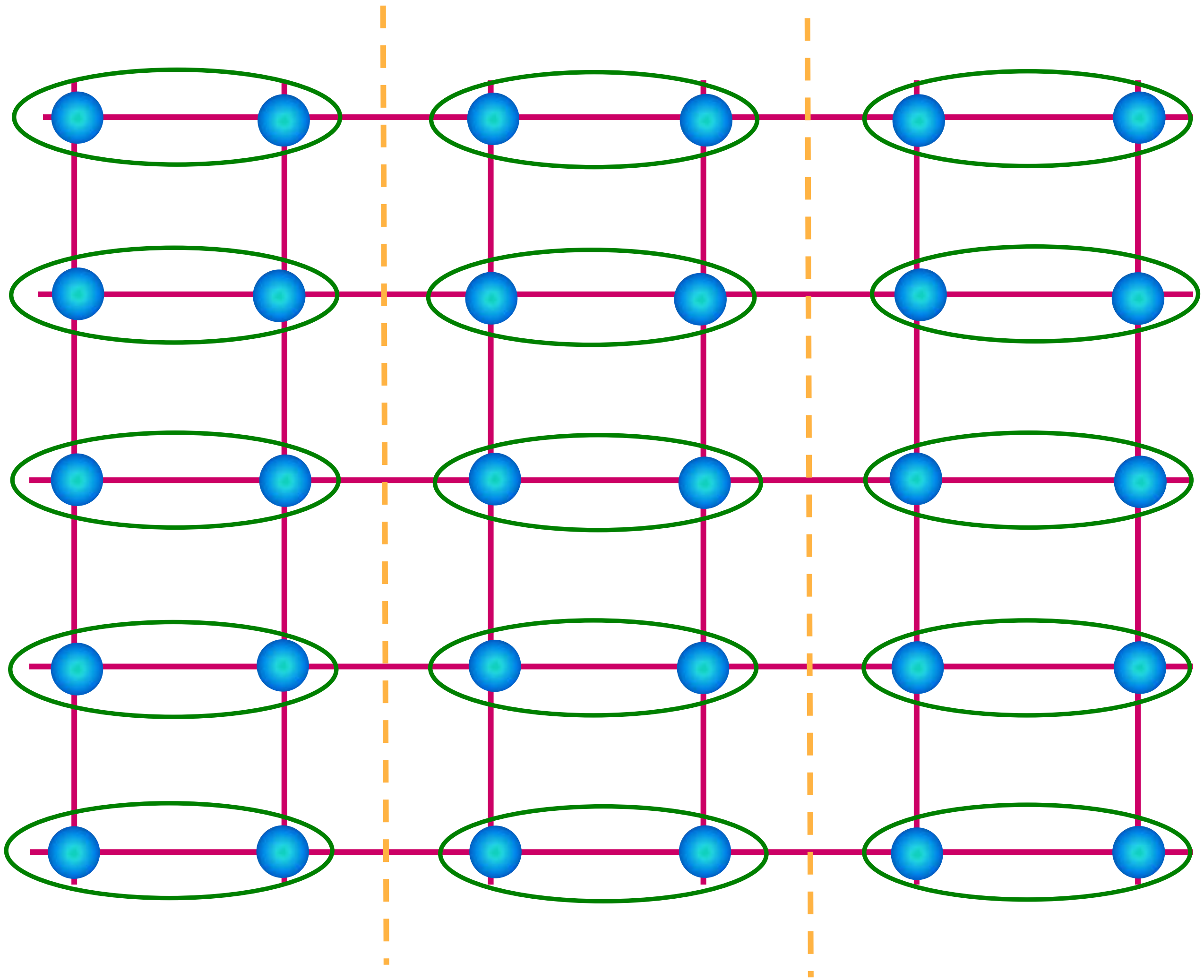

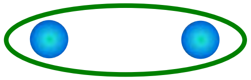

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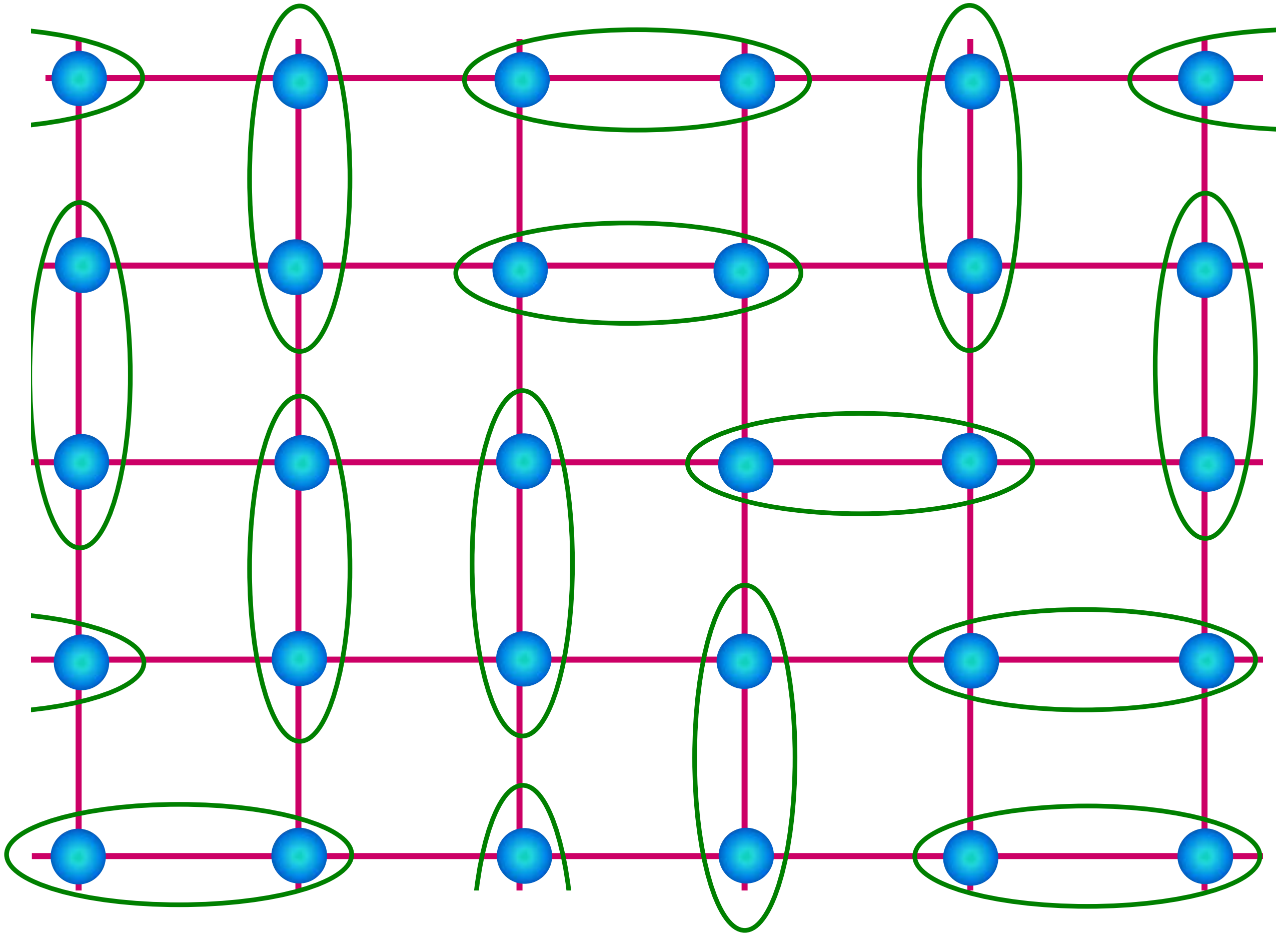
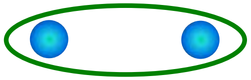
Excitations of the RVB liquid





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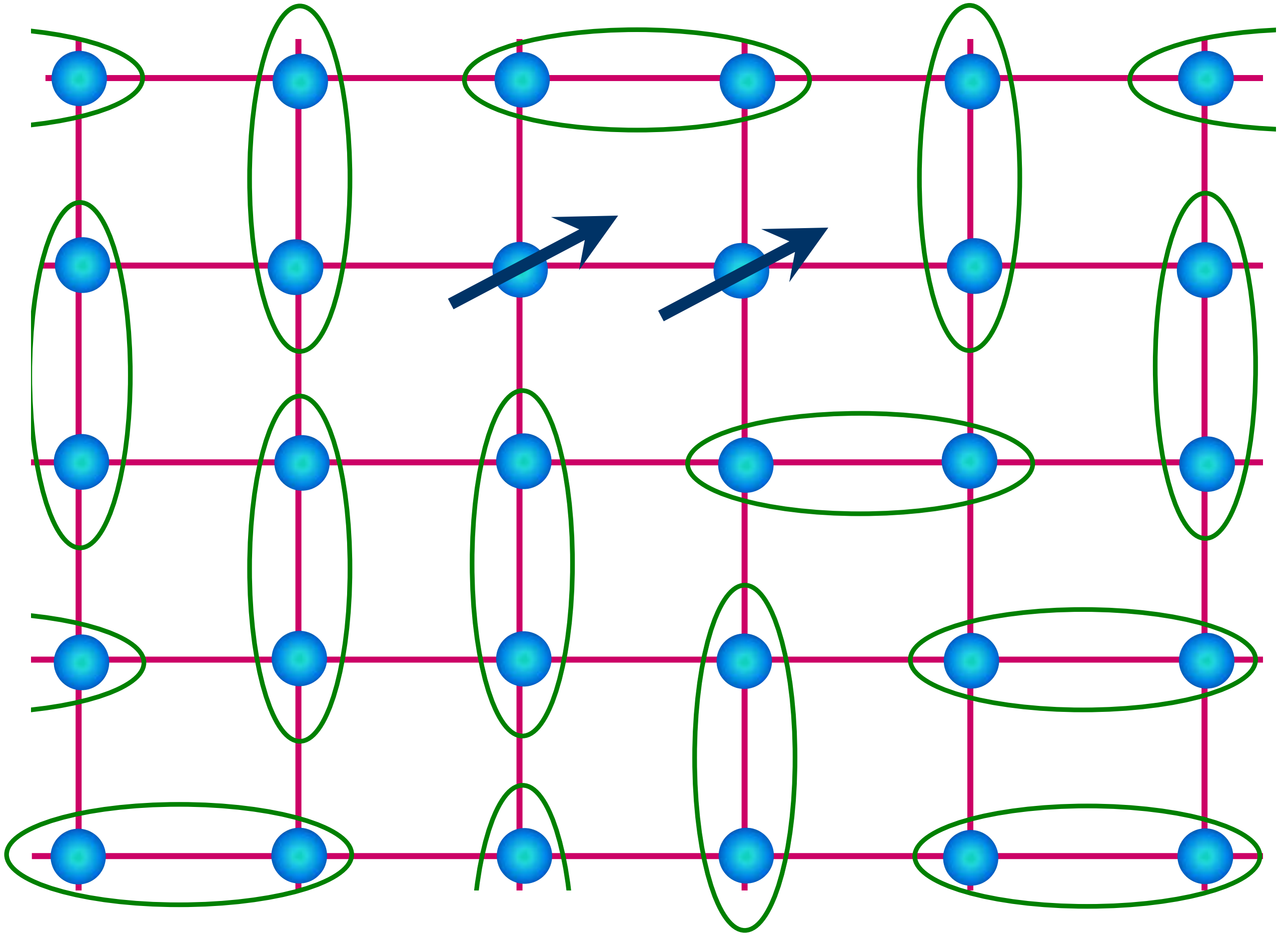
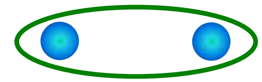
Excitations of the RVB liquid



 =

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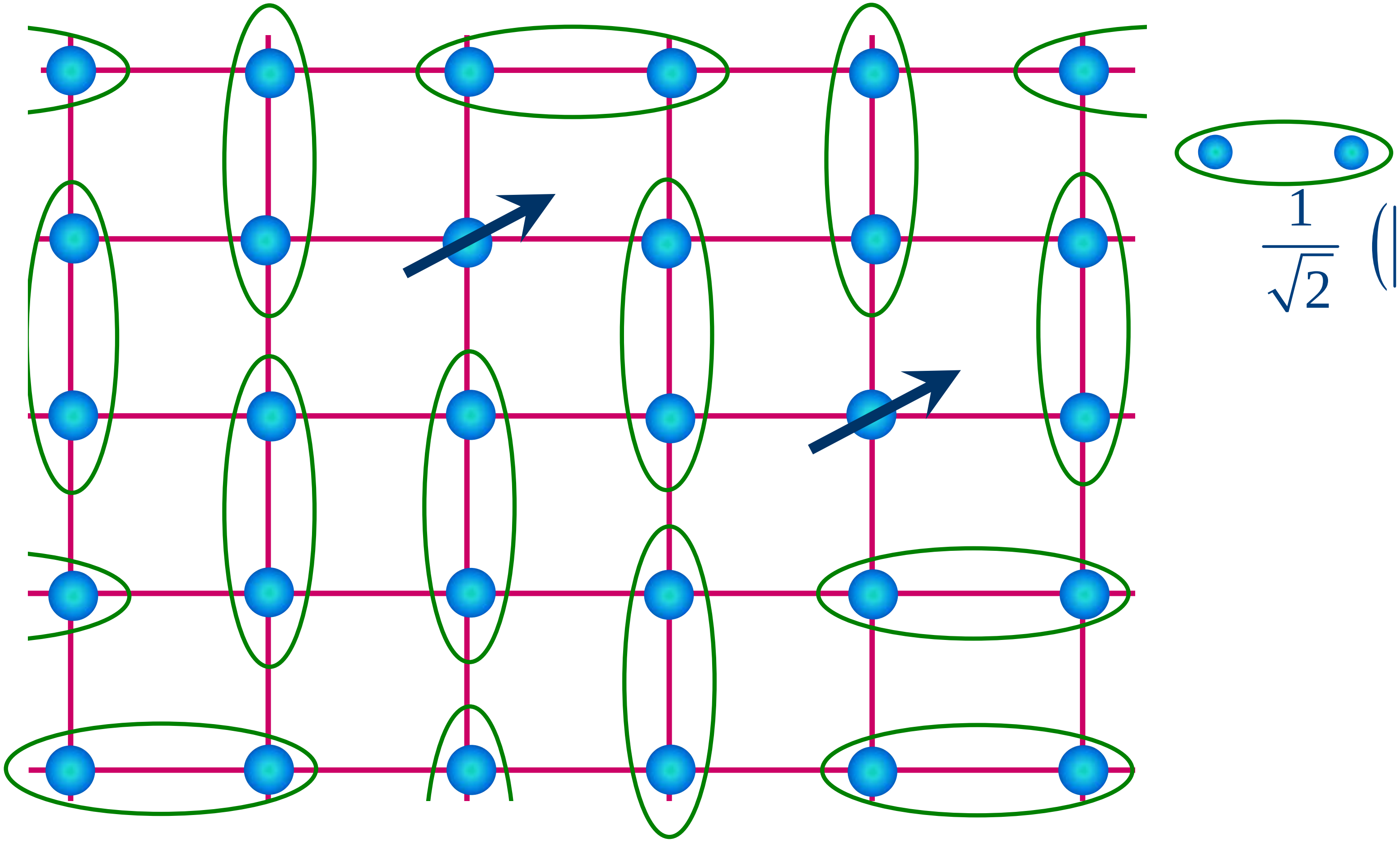
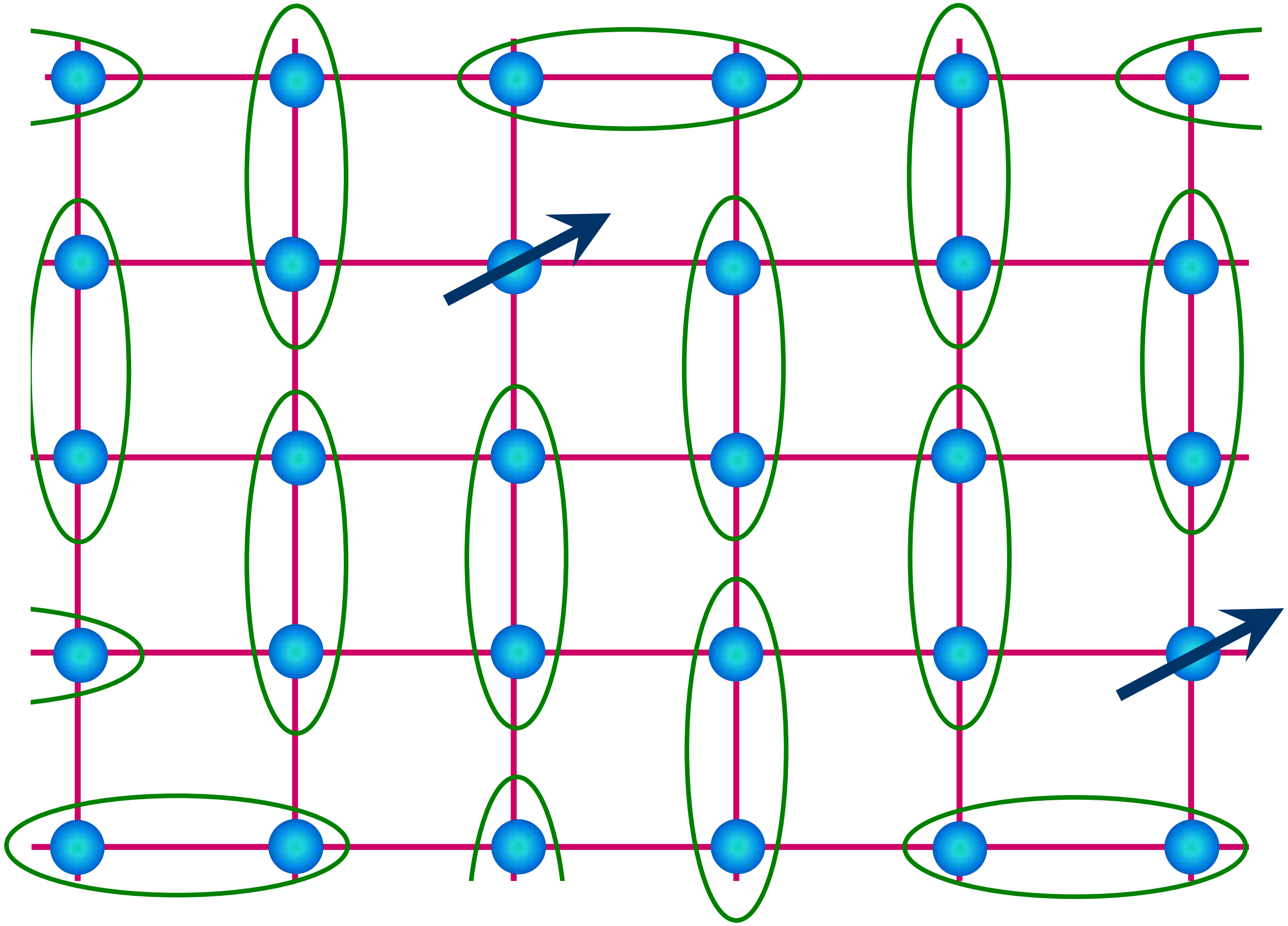
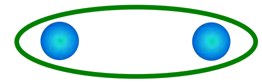
Excitations of the RVB liquid



$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$

Excitations of the RVB liquid





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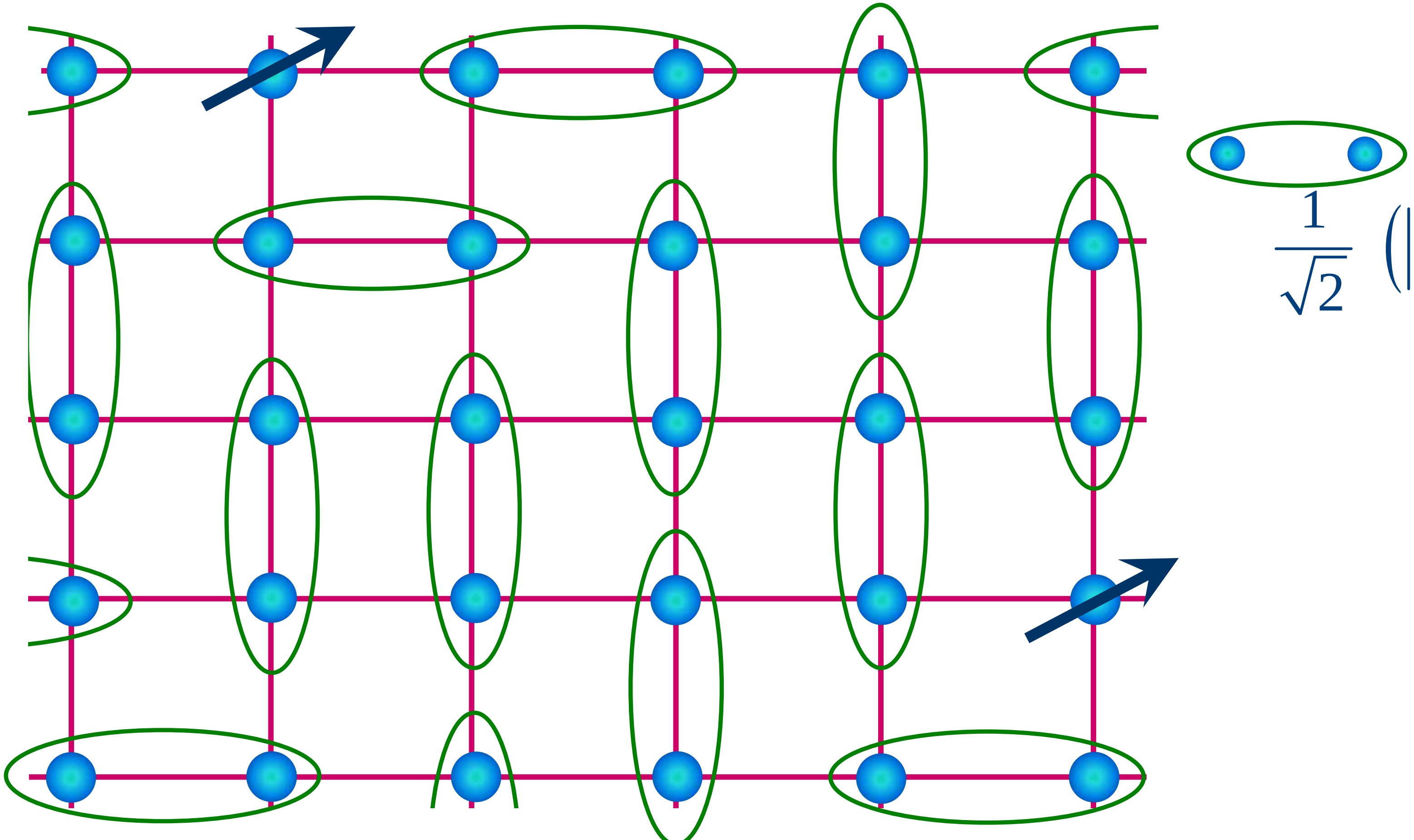
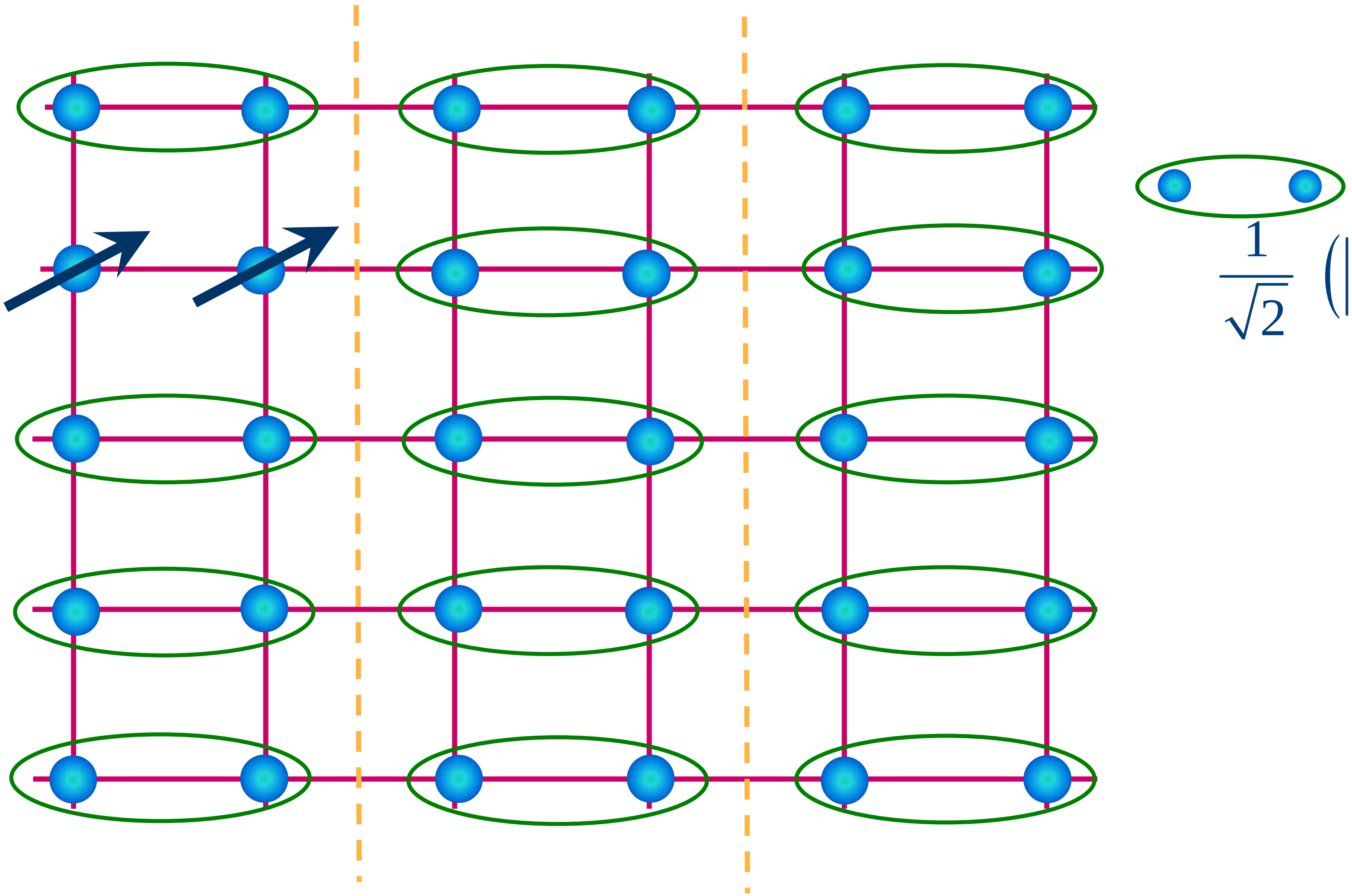


$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Electron ***fractionalization***:

Excitations carry spin $S=1/2$ but no charge

Excitations of the VBS



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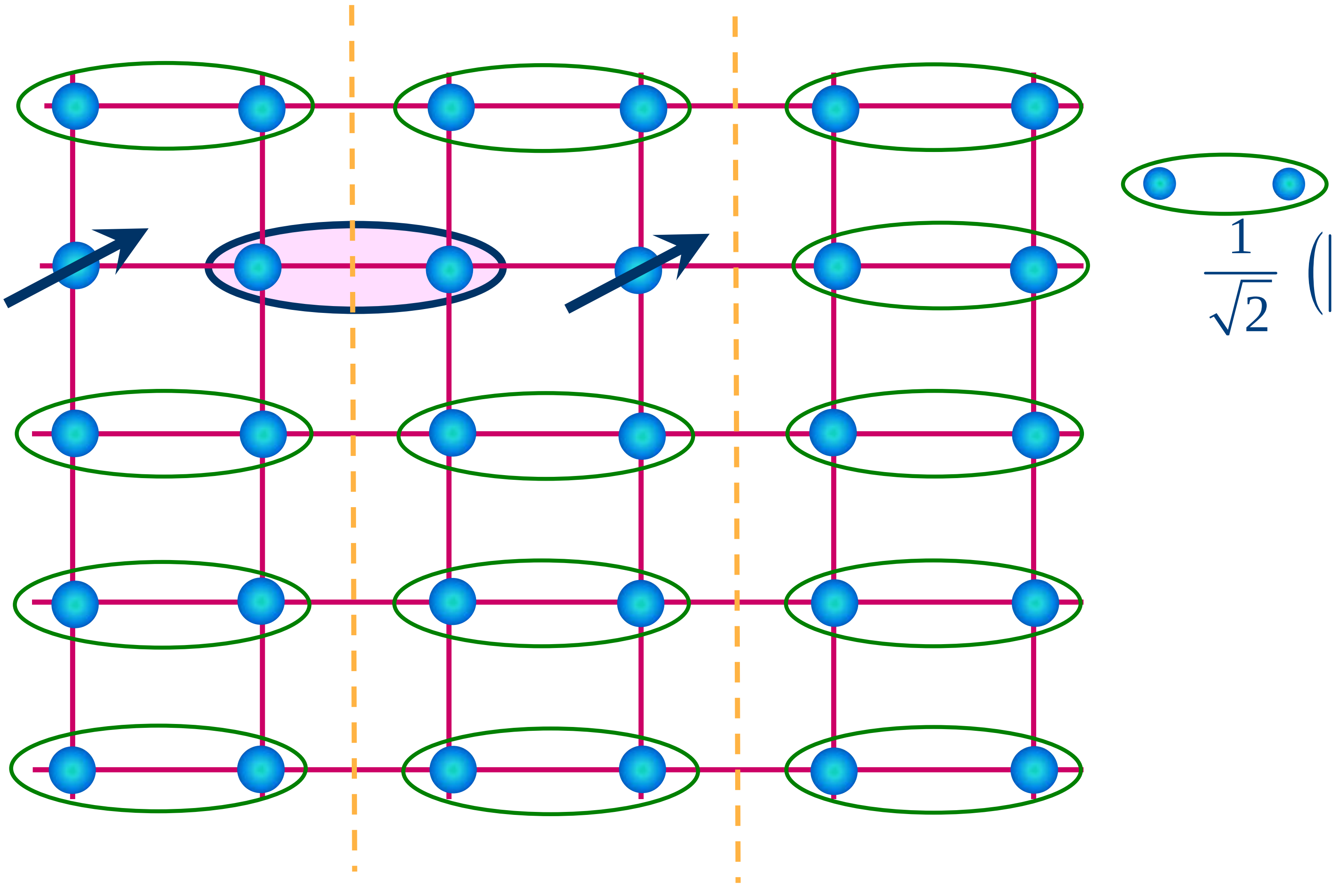

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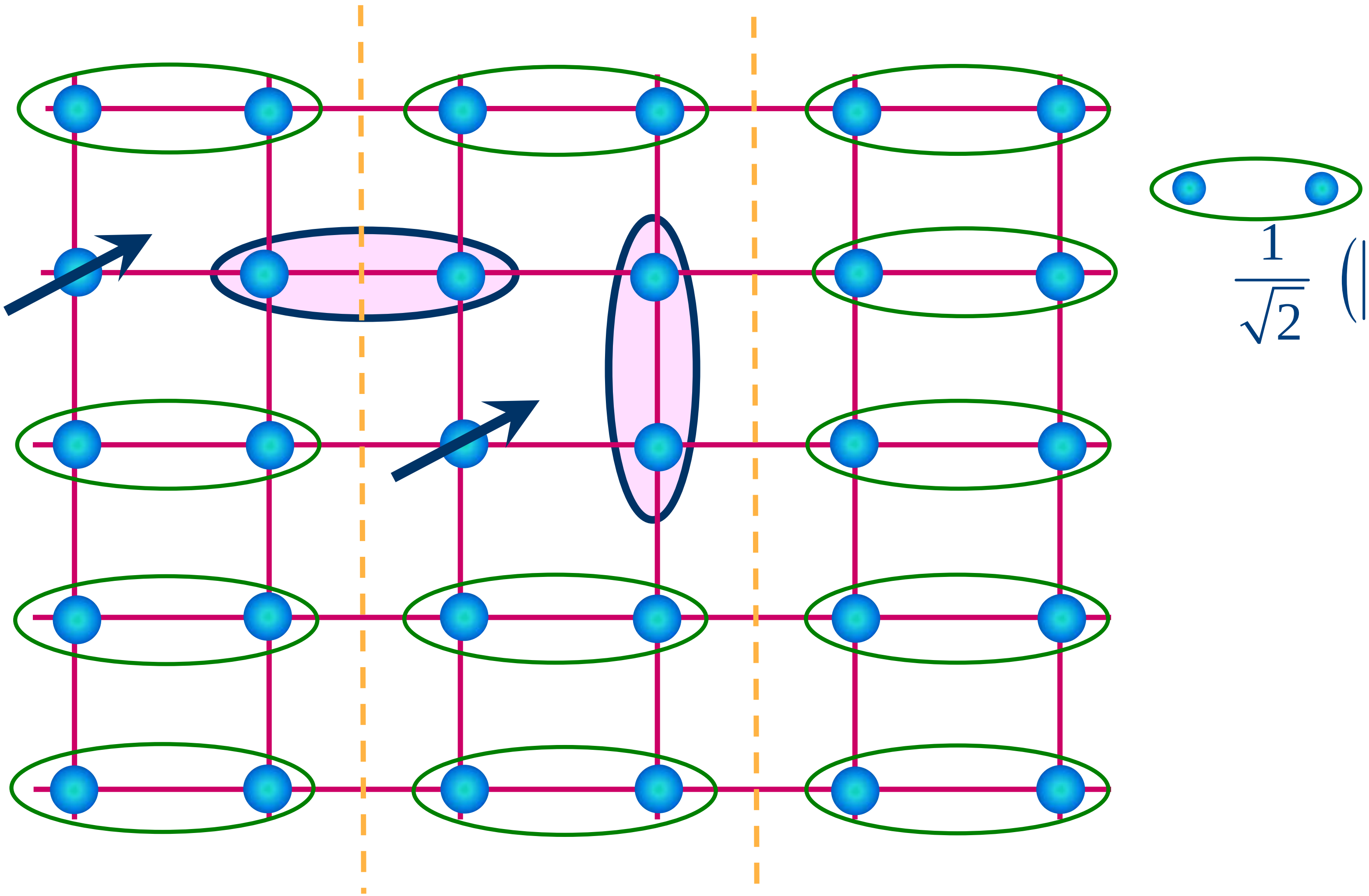

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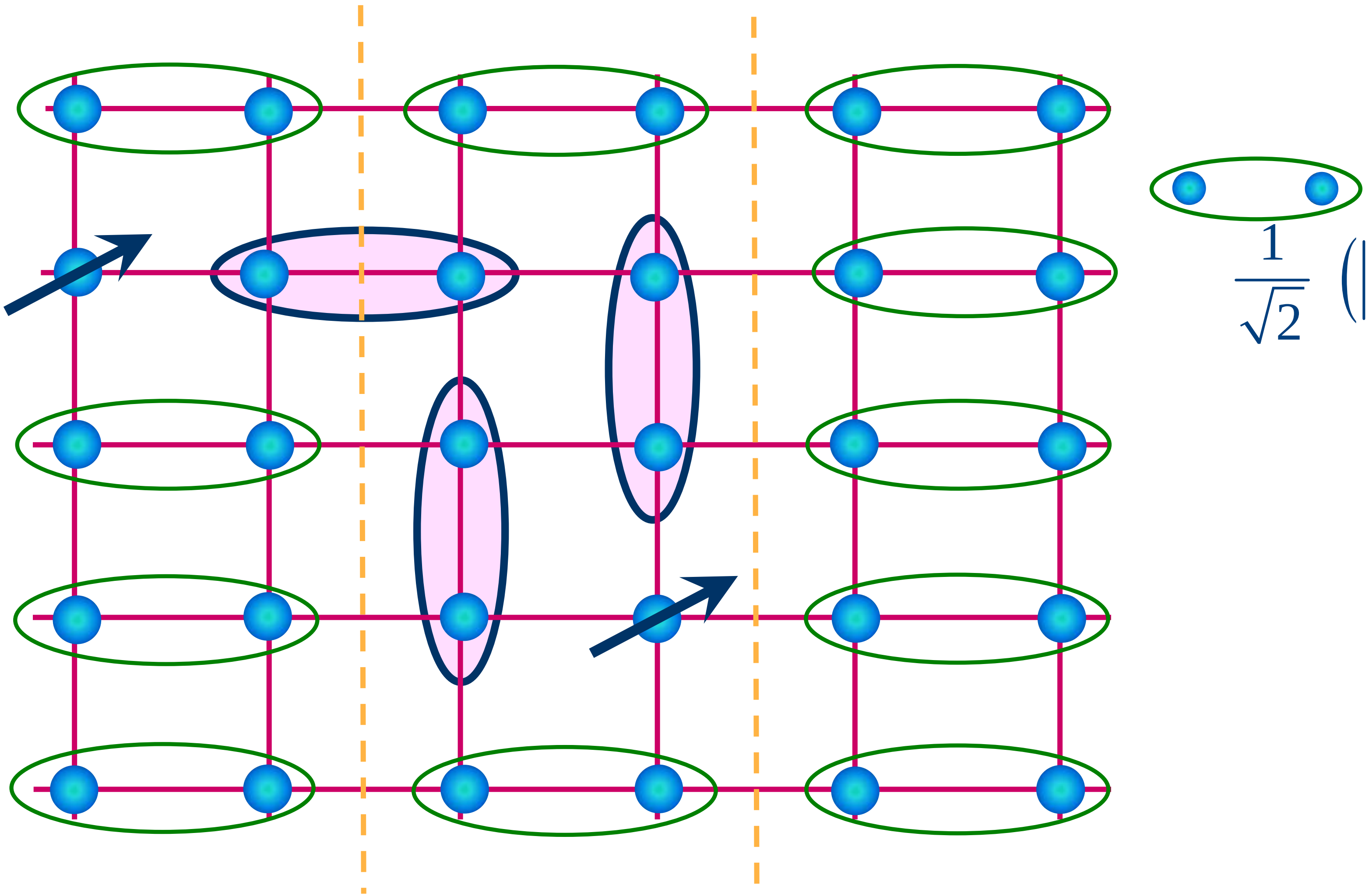

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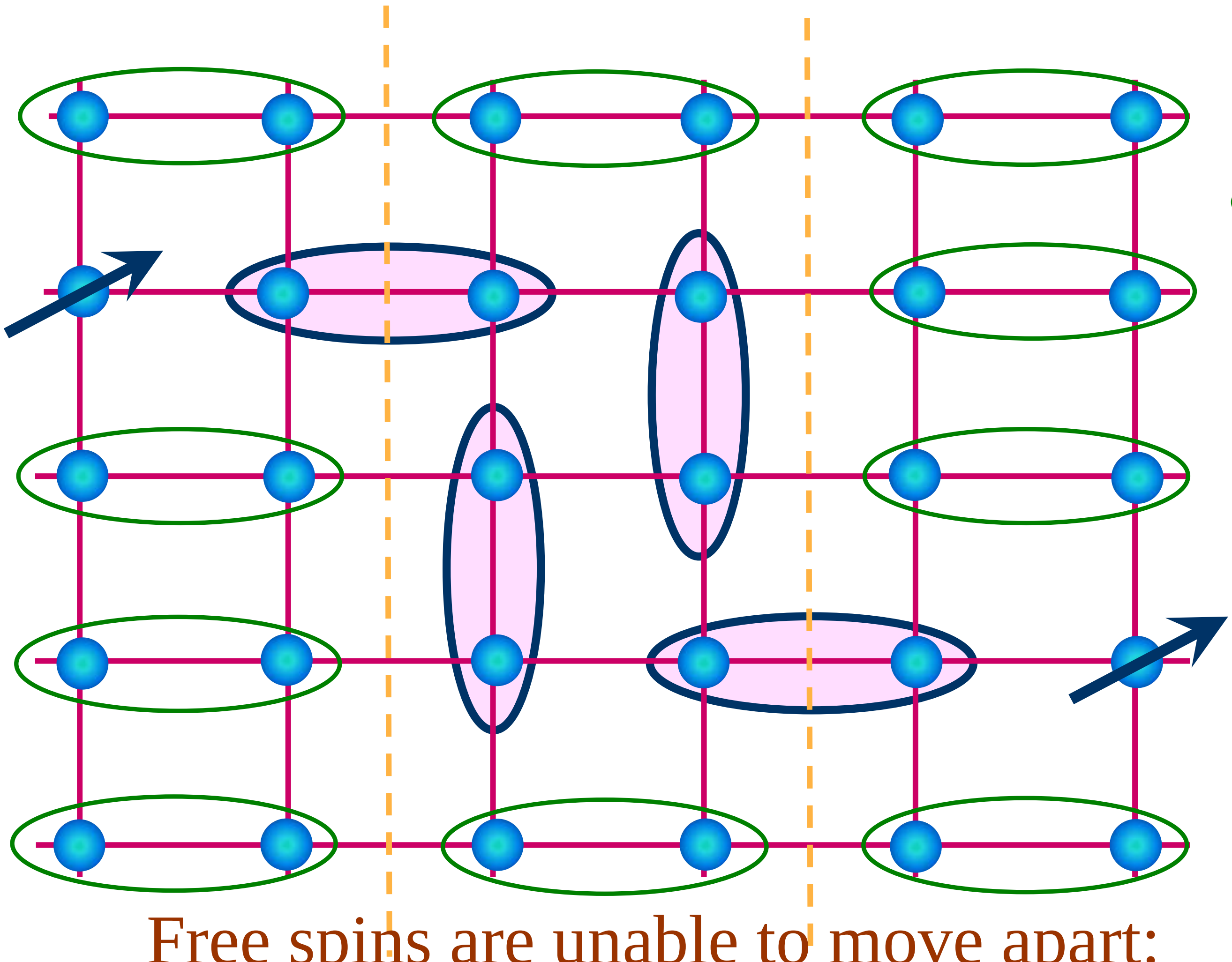
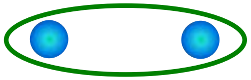
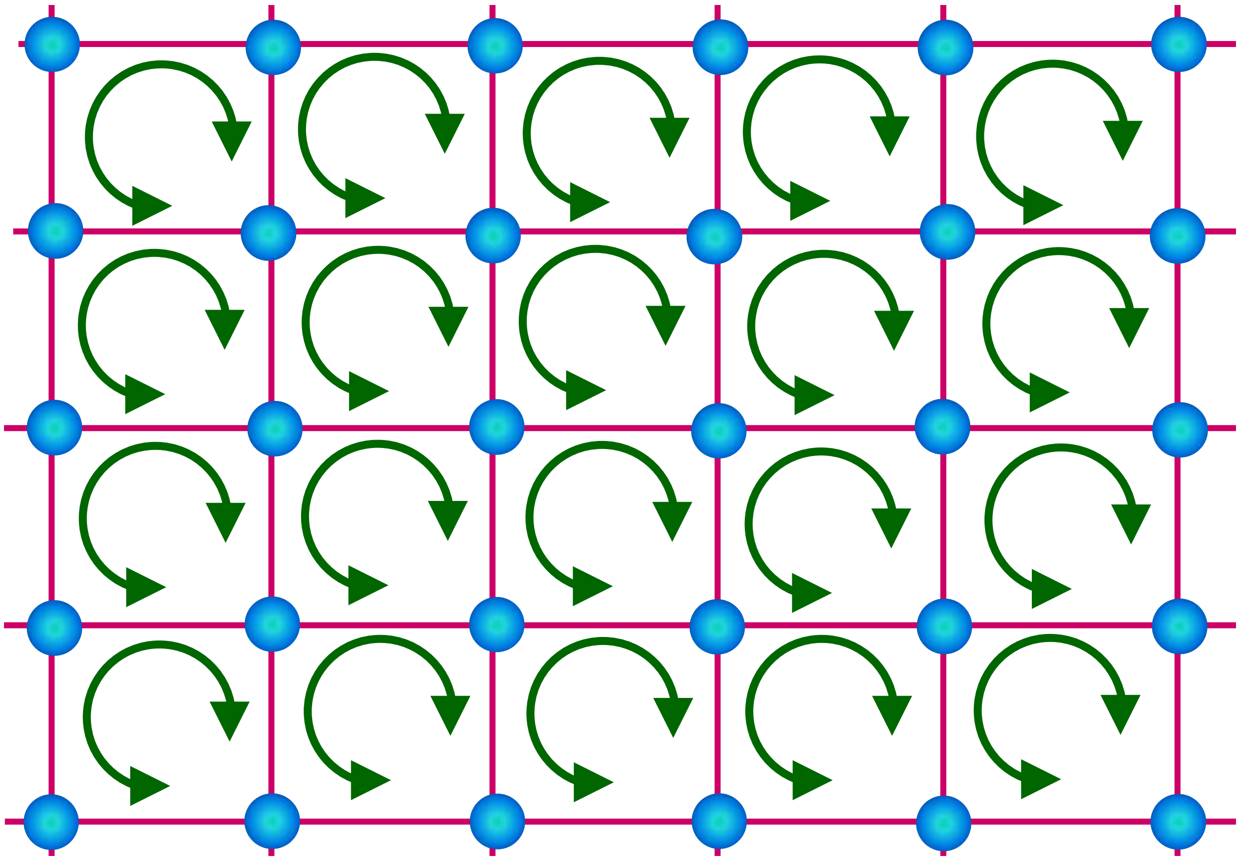


 $= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

Free spins are unable to move apart:
no fractionalization, but ***confinement***

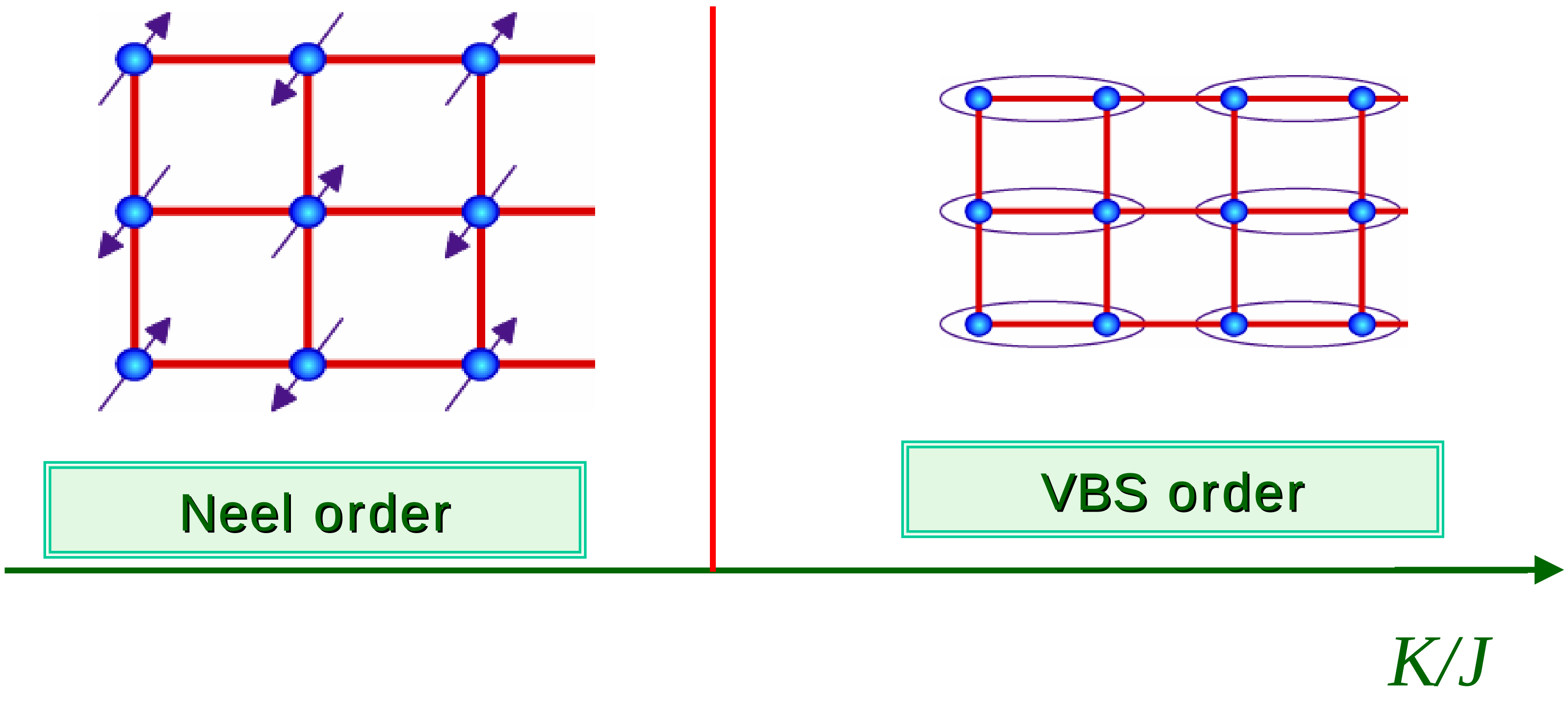
Phase diagram of square lattice antiferromagnet



$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + K \sum_{\square} \text{4-spin exchange}$$

A. W. Sandvik, cond-mat/0611343

Phase diagram of square lattice antiferromagnet



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T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).

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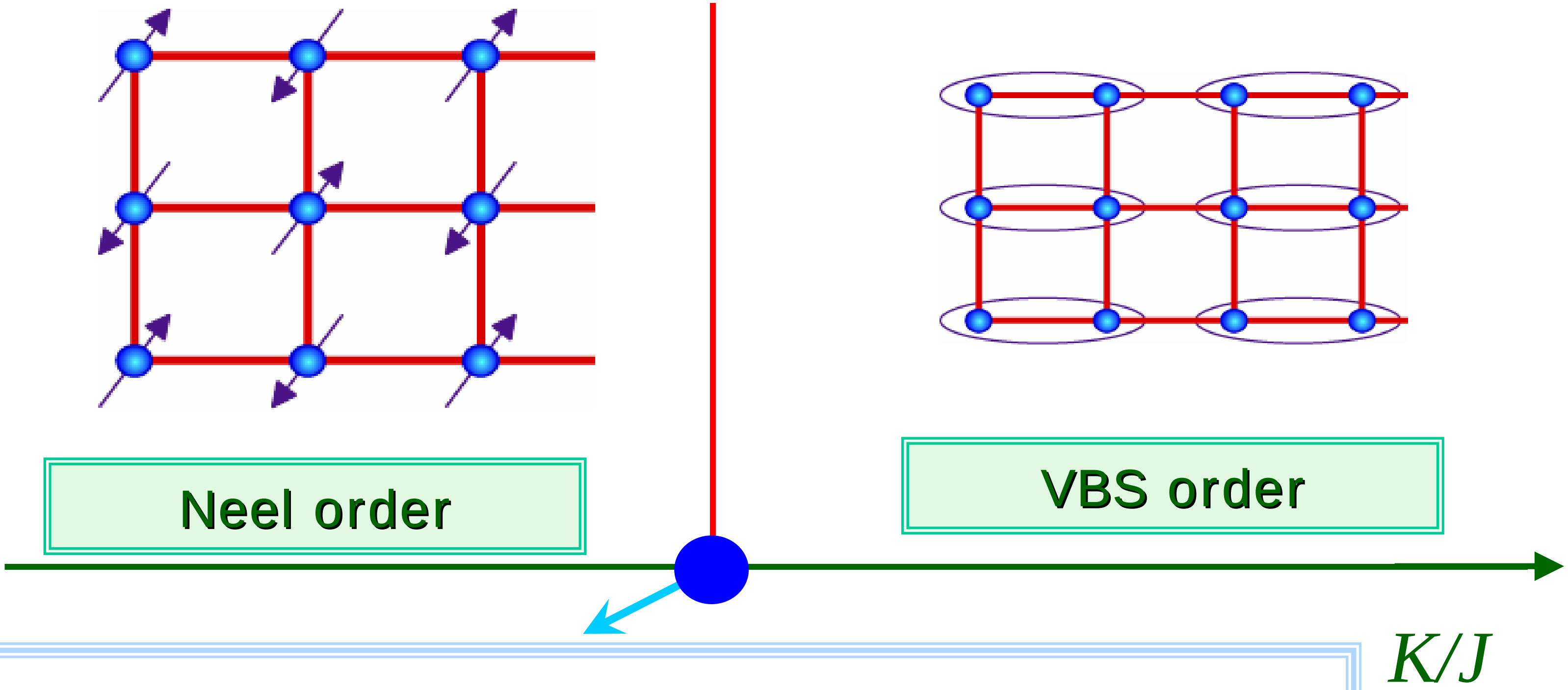
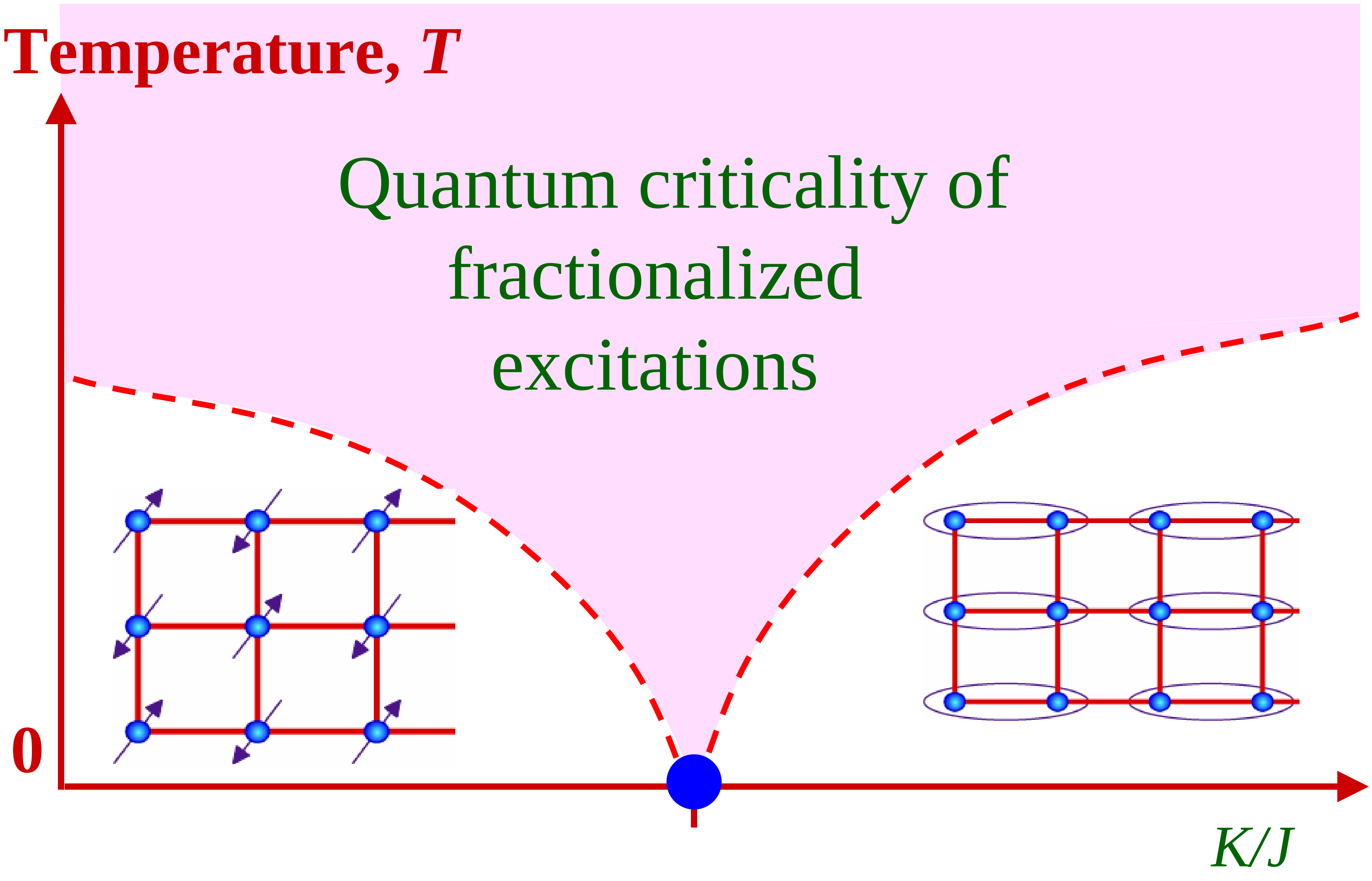


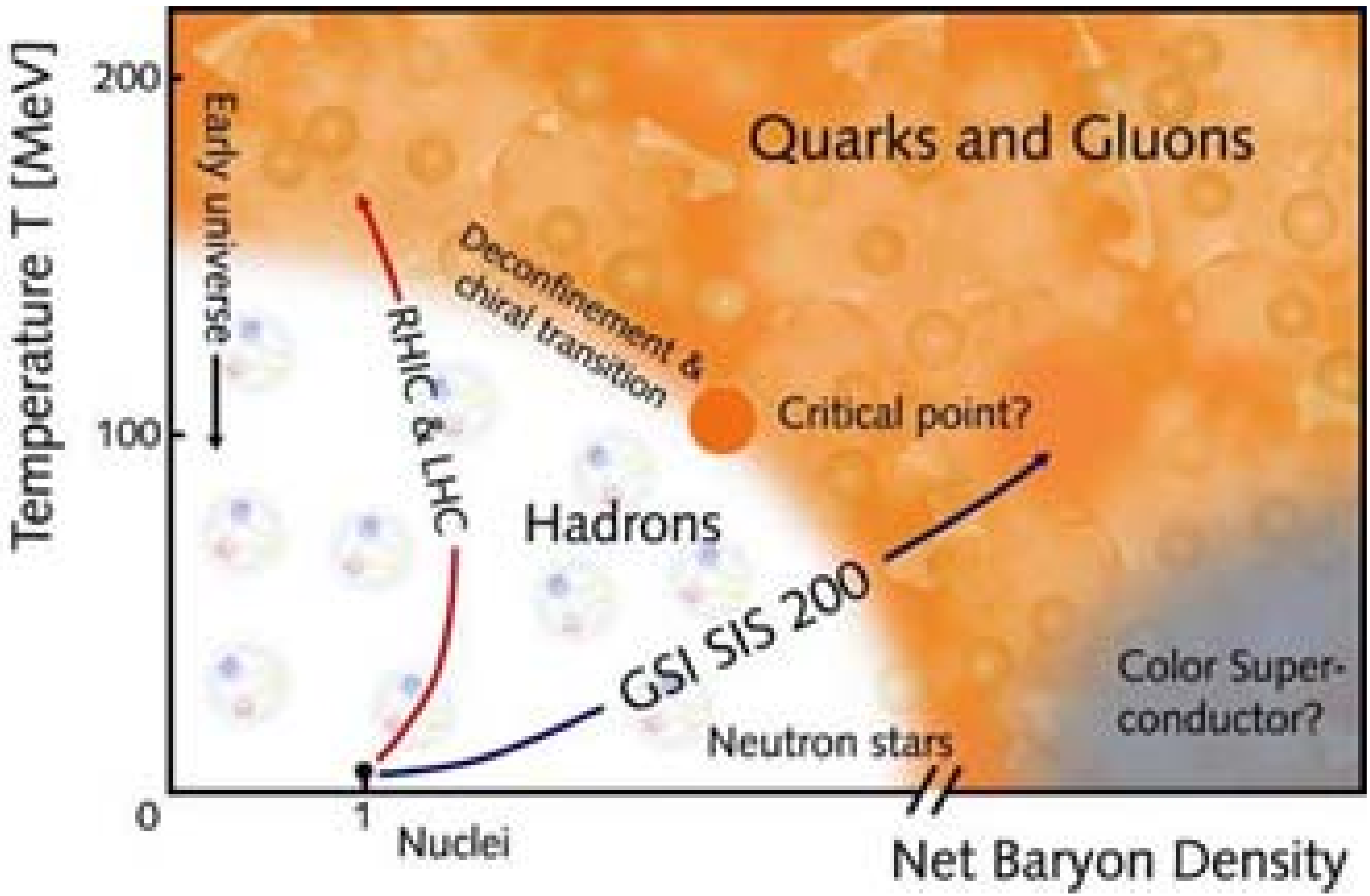
RVB physics appears at the quantum critical point which has fractionalized excitations: "deconfined criticality"

$$H = J\sum_{\langle ij\rangle} \vec{S}_i \cdot \vec{S}_j + K\sum_{\square} \text{4-spin exchange}$$

T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).

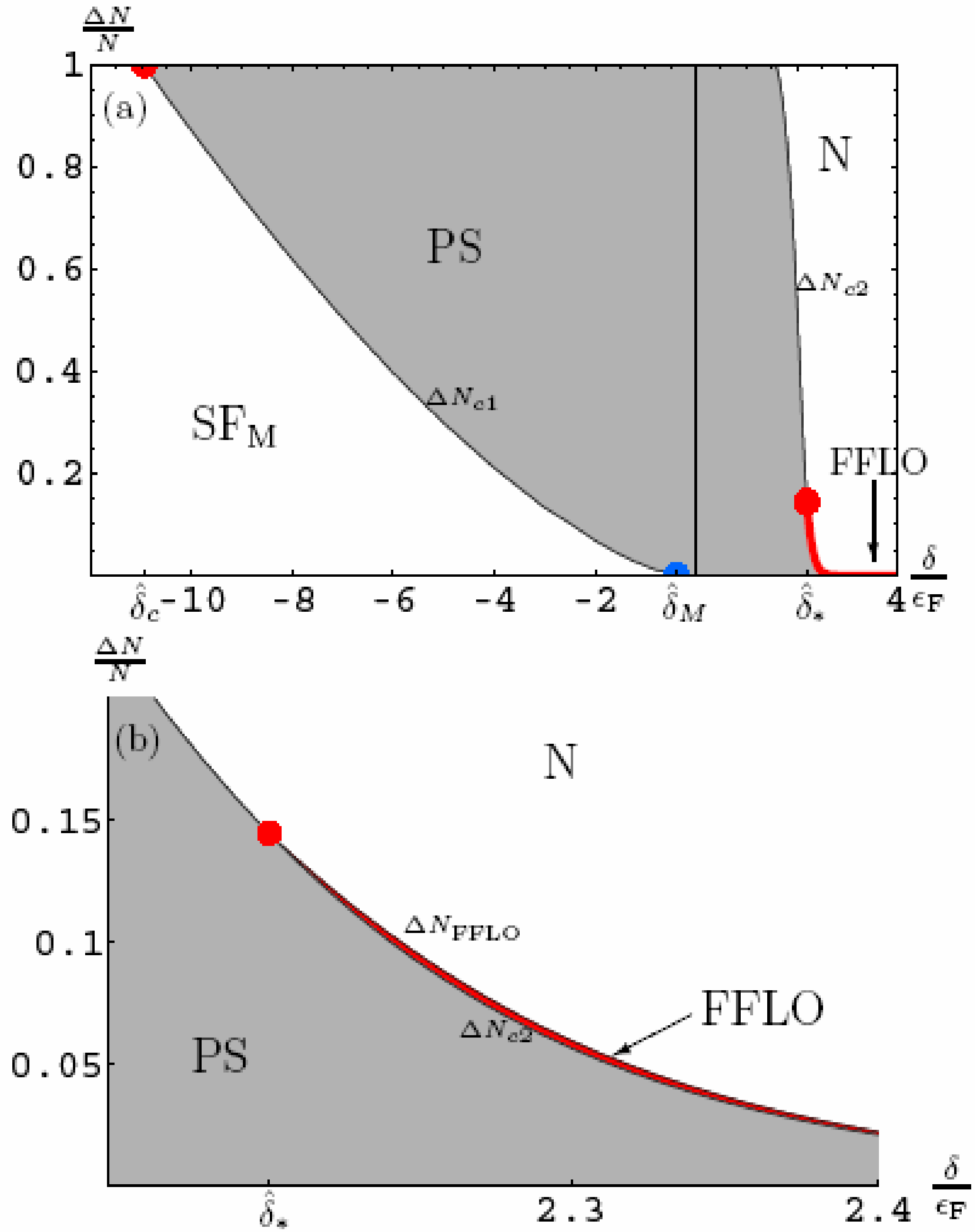

Temperature, T
Quantum criticality of fractionalized excitations
0
K/J

Phases of nuclear matter



Conclusions

- Rapid progress in the understanding of quantum liquids near unitarity
- Rich possibilities of exotic quantum phases in optical lattices
- Cold atom studies of the entanglement of large numbers of qubits: insights may be important for quantum cryptography and quantum computing.
- Tabletop "laboratories for the entire universe": quantum mechanics of black holes, quark-gluon plasma, neutrons stars, and big-bang physics.



(a)
ΔN/N
1
0.8
0.6
0.4
0.2
PS
N
SF_M
ΔN_c1
ΔN_c2
FFLO
δ̂_c -10 -8 -6 -4 -2 δ̂_M δ̂_* 4
δ/ε_F
(b)
ΔN/N
0.15
0.1
0.05
N
PS
ΔN_FFLO
ΔN_c2
FFLO
δ̂_*
2.3
2.4
δ/ε_F