Emergent Dirac fermions and broken symmetries in confined and deconfined phases of Ising gauge theories

Snir Gazit, Mohit Randeria and Ashvin Vishwanath

Intertwined Order and Fluctuations in Quantum Materials
KITP 2017

Nature Physics **13**, 484-490 (2017)

see also - Assaad, Grover, Phys. Rev. X **6**, 041049

The Ohio State University

Berkeley
University of California

Motivation - Conventional quantum criticality

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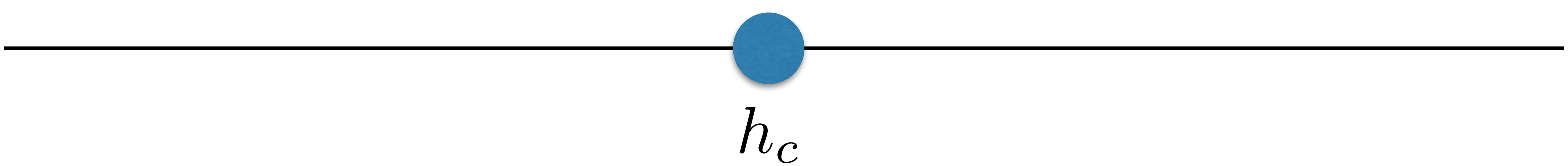

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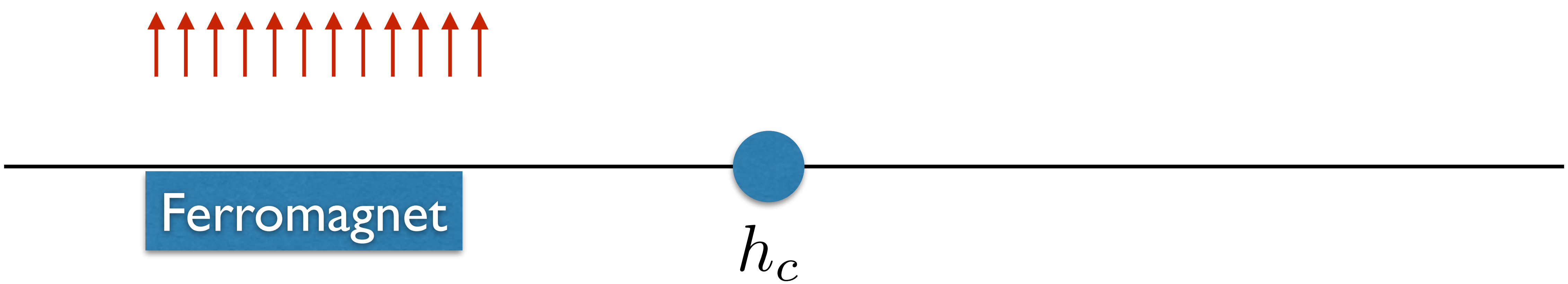

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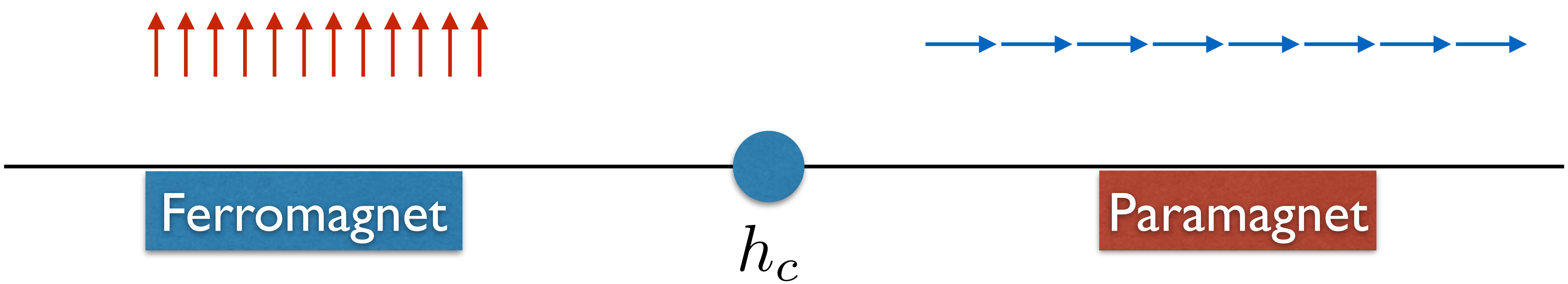

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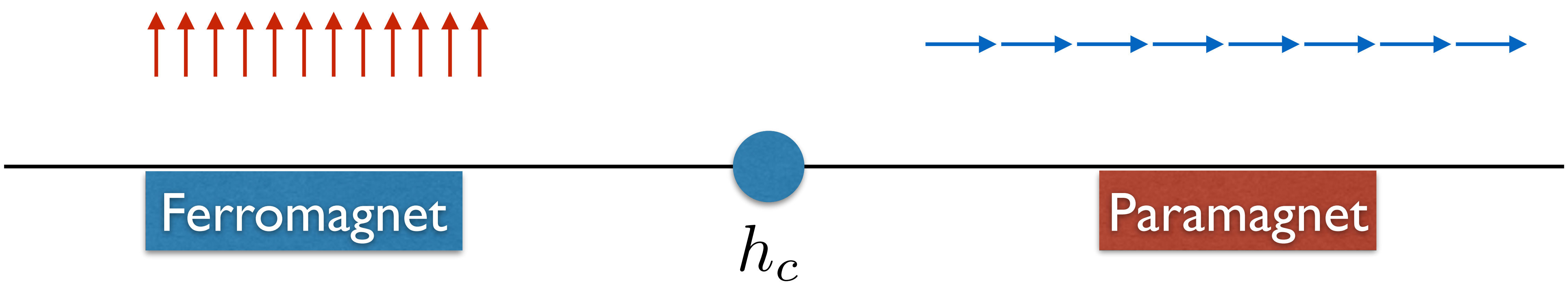

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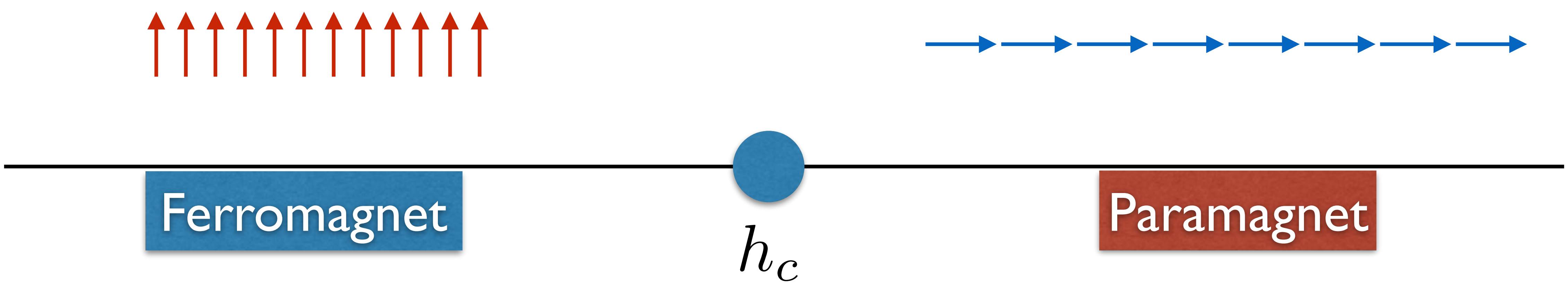

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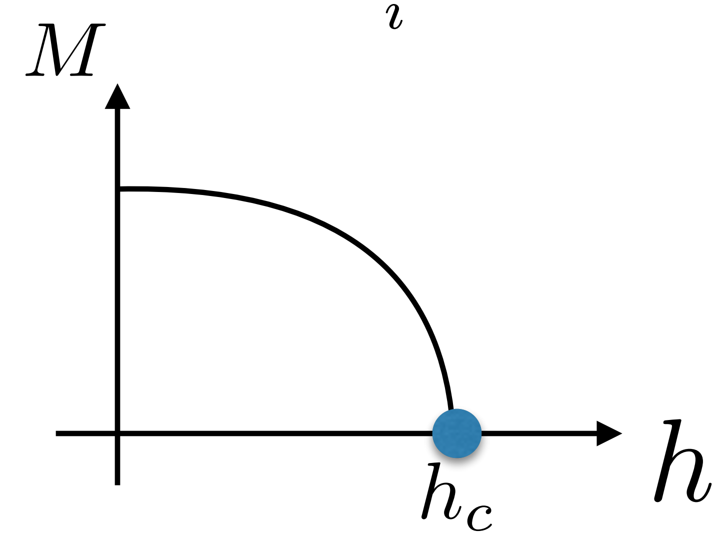

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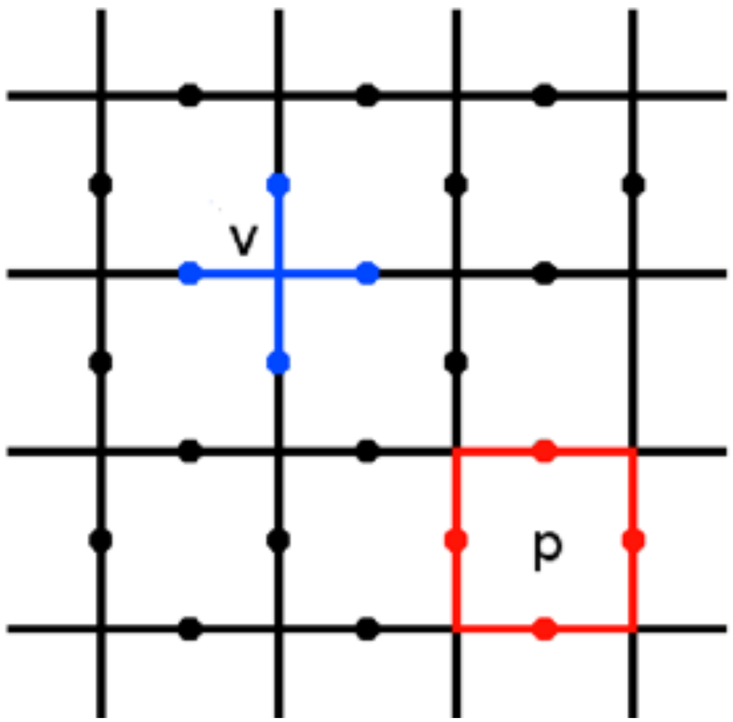

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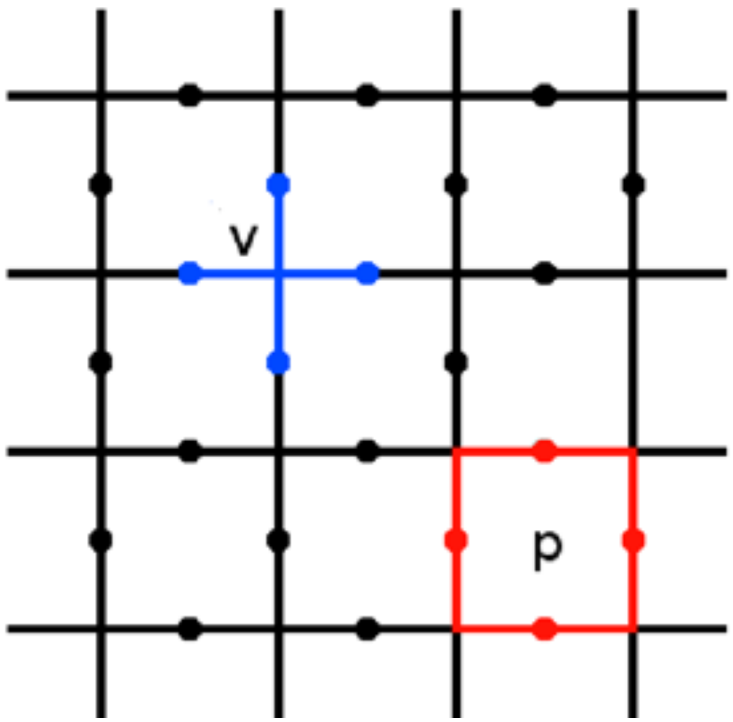

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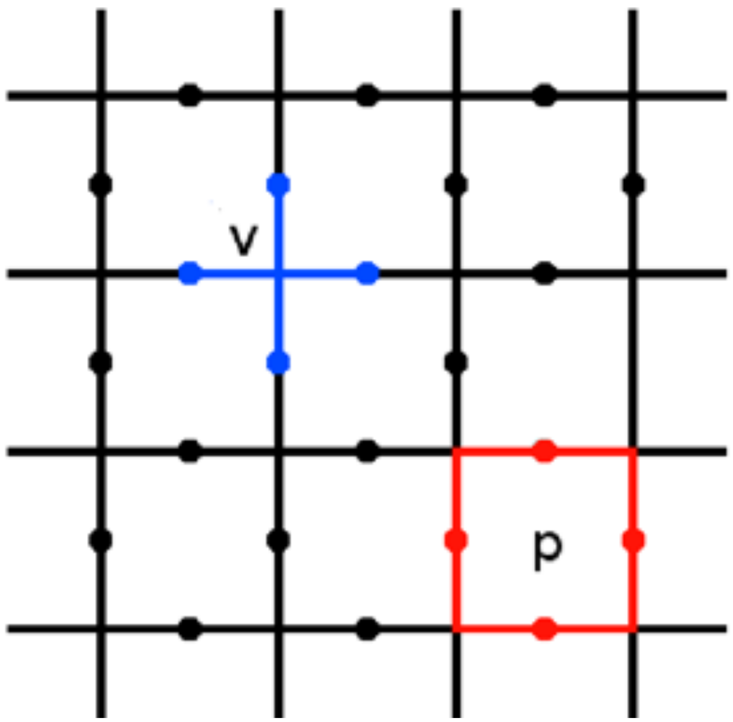

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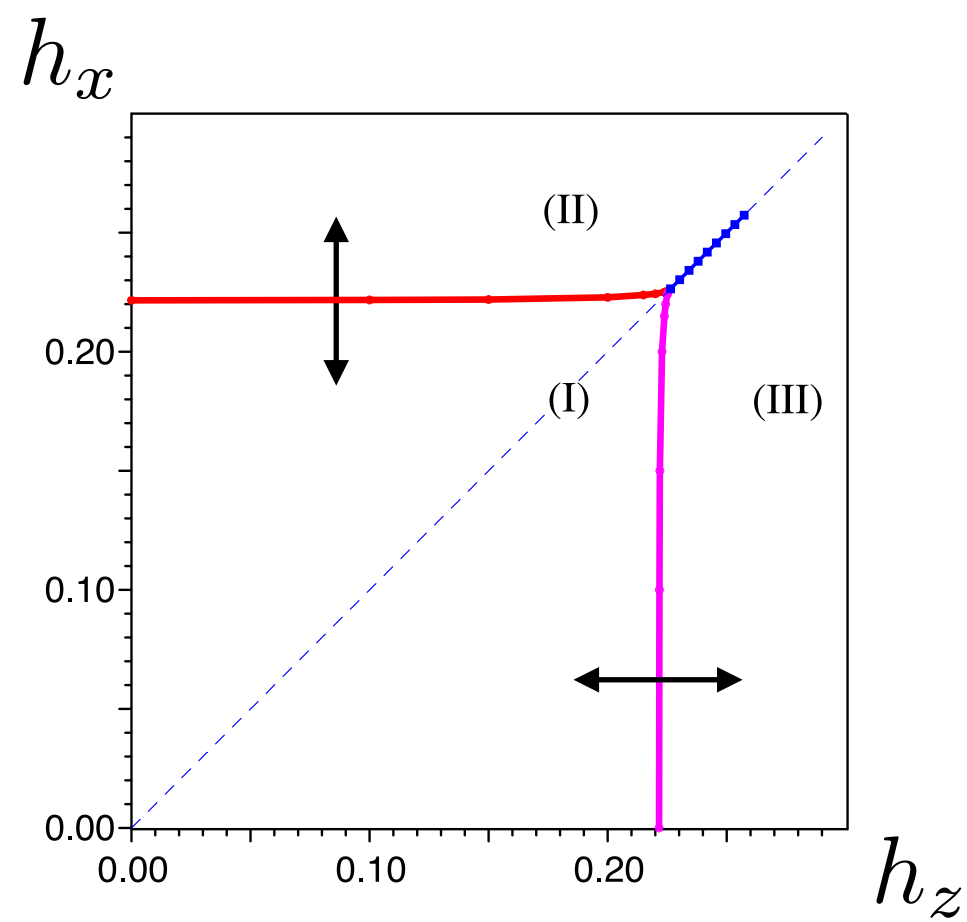

Tupitsyn (2010)

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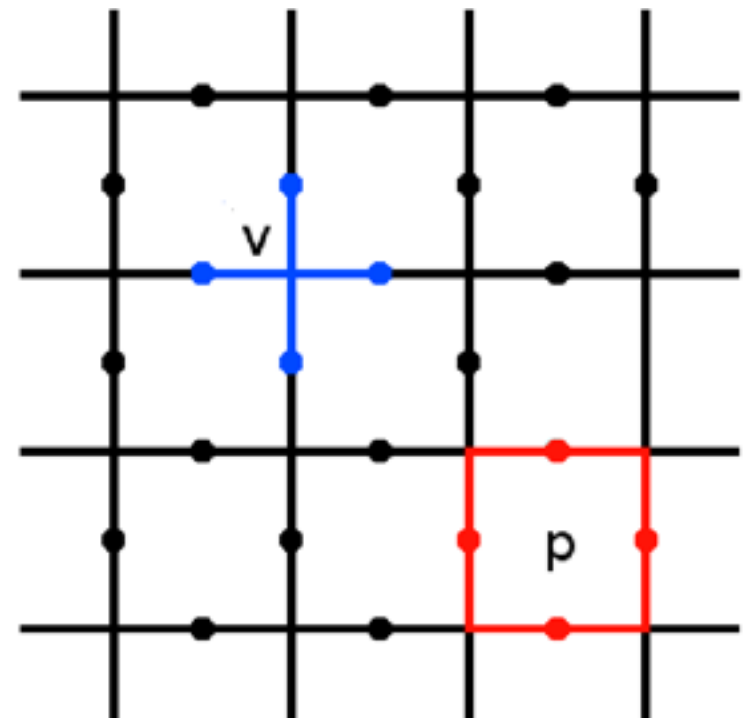

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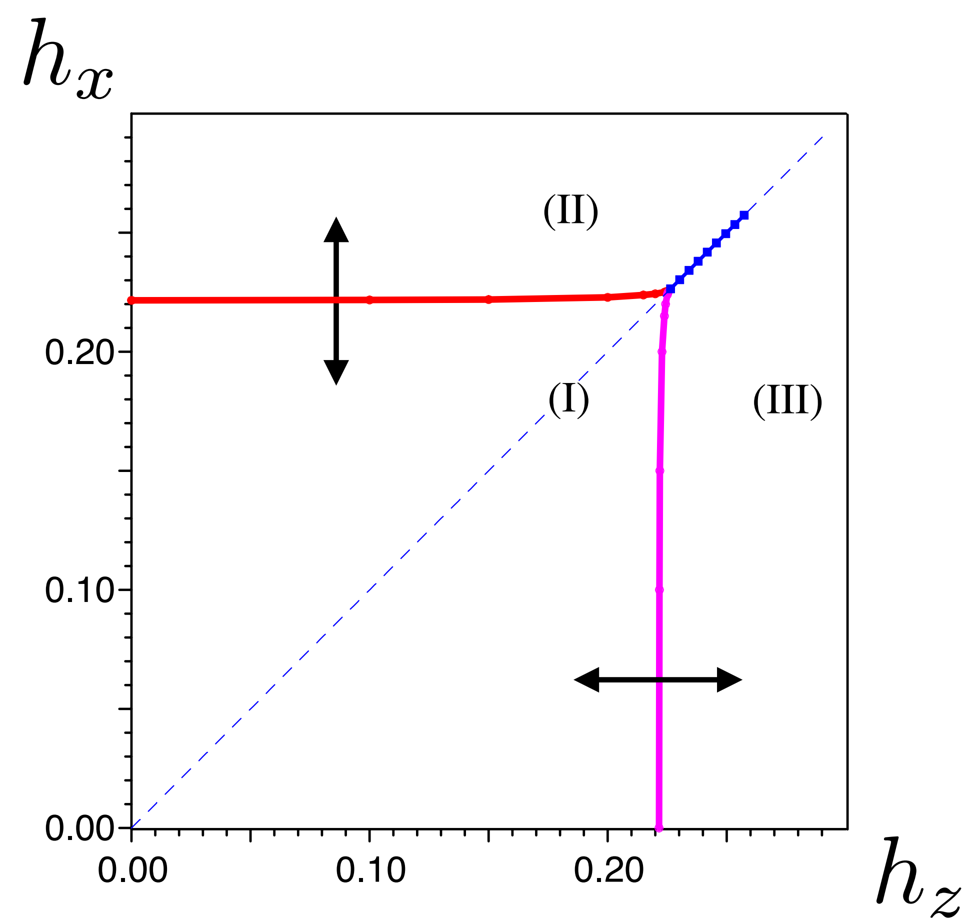

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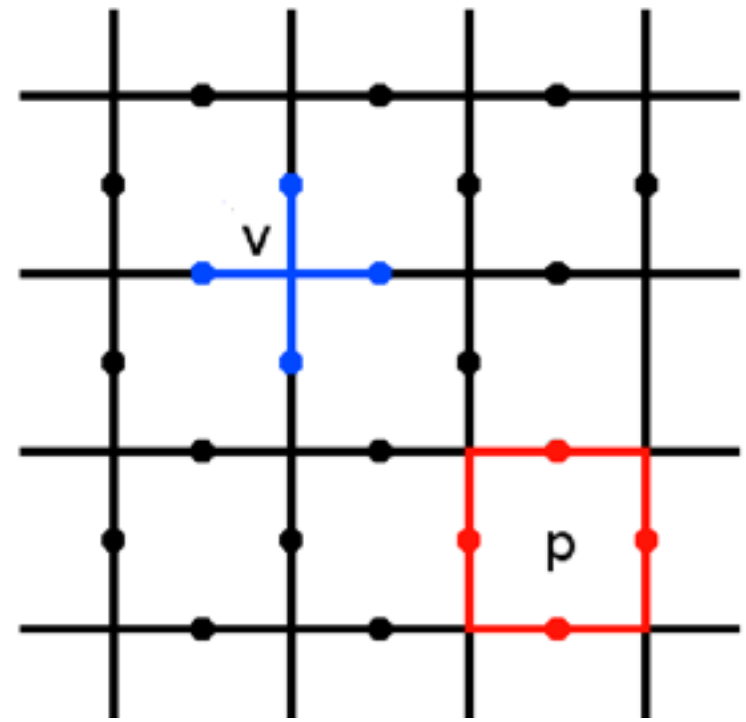

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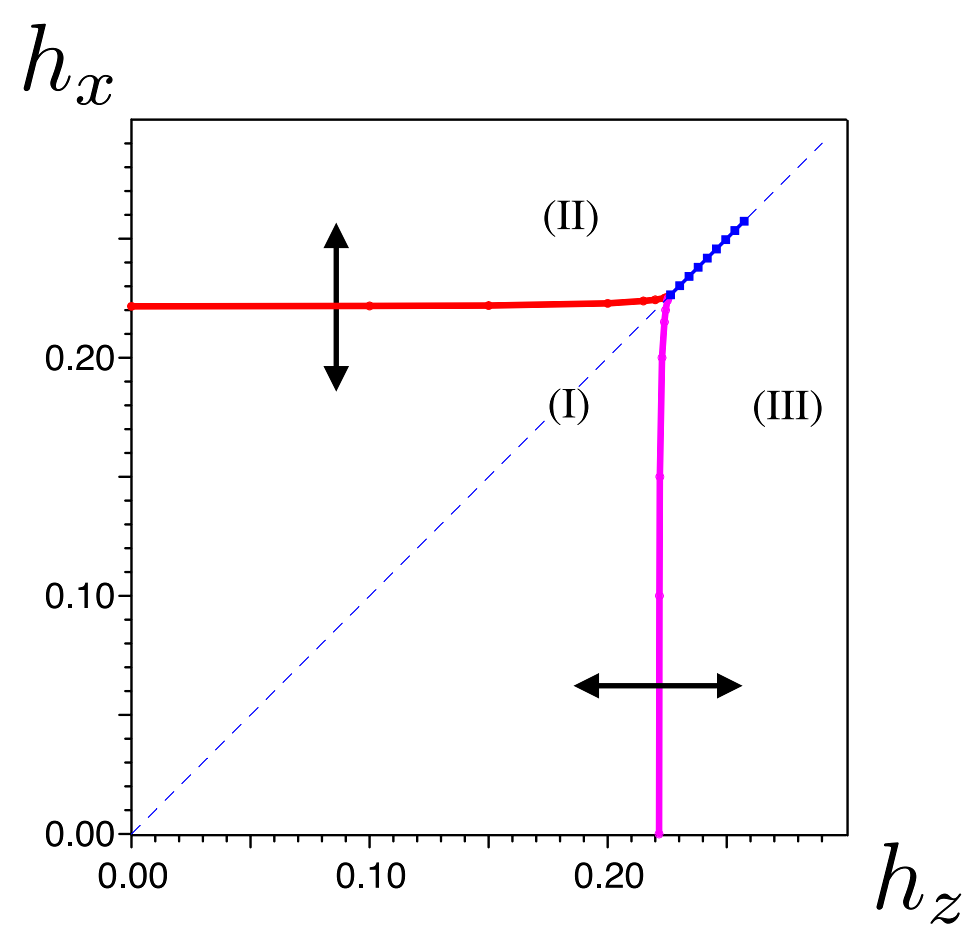
Higgs (confinement) transition



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Motivation - emergent gauge theory in CMT

Baskaran, Zou, Anderson, Fradkin, Kivelson, Sachdev

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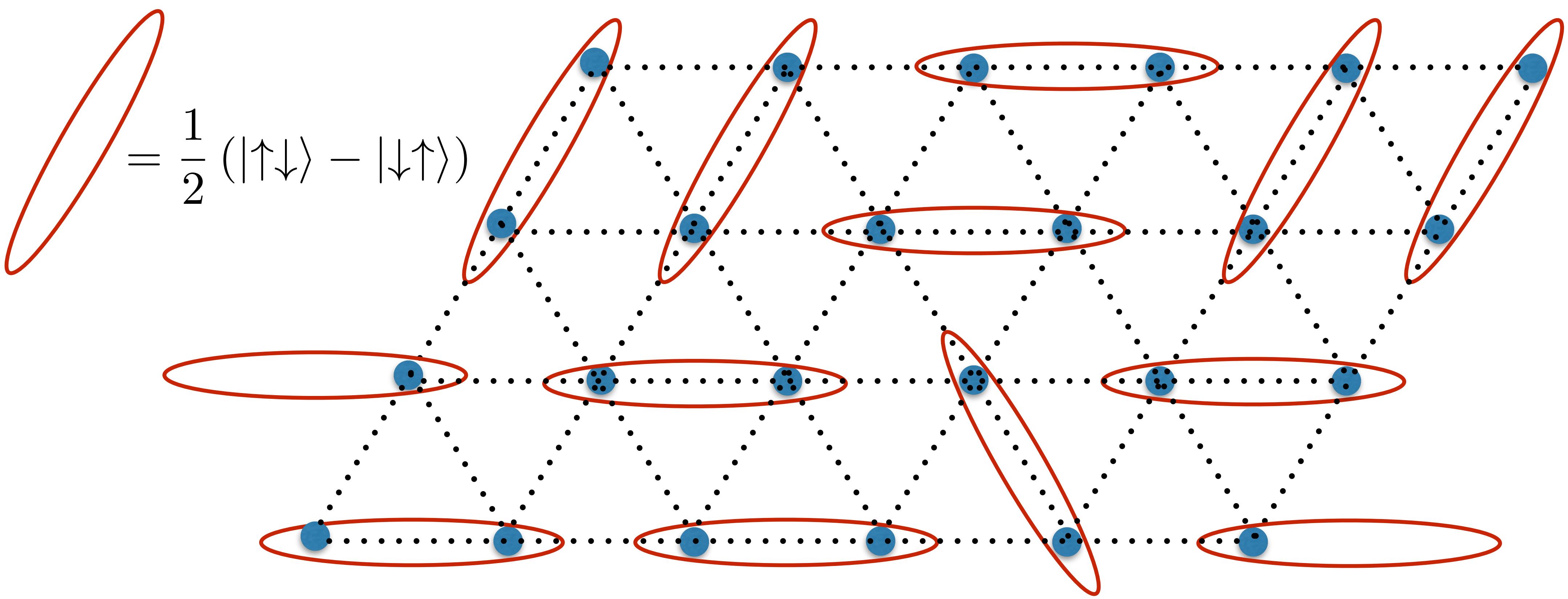
Dimer covering on a triangular lattice



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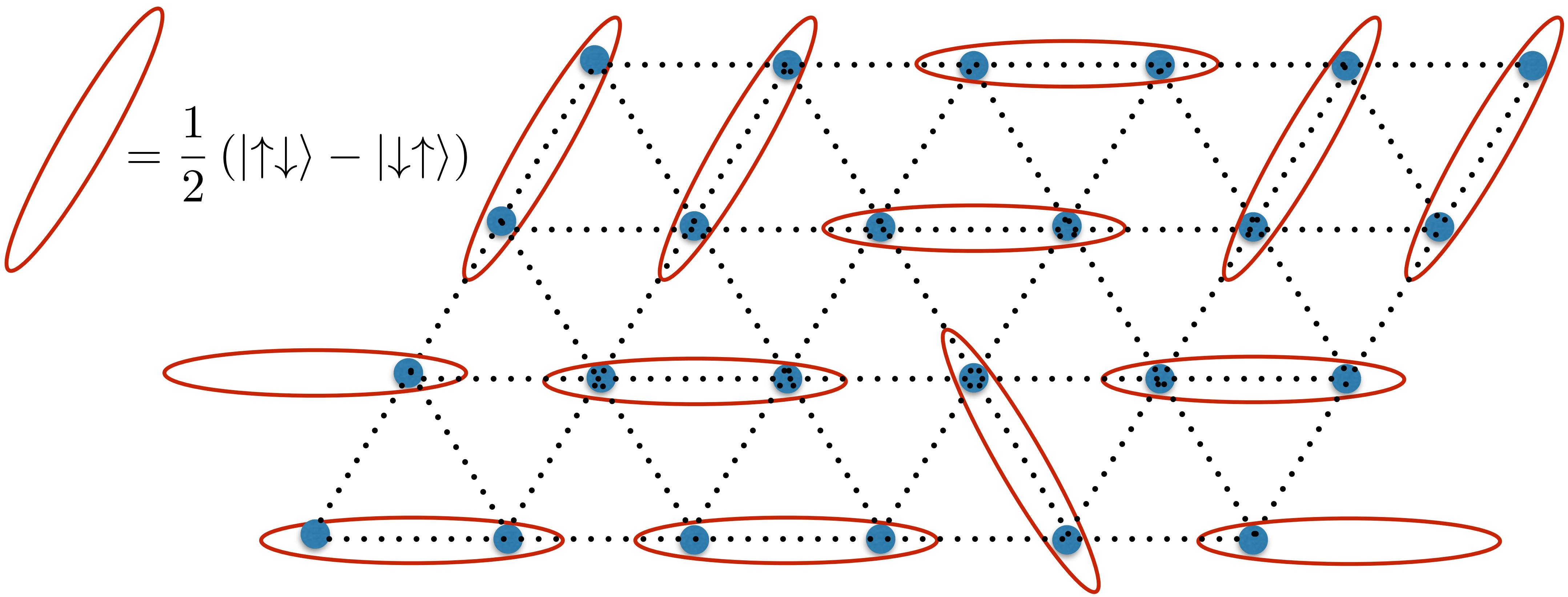

$$= \frac{1}{2}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Assign a quantum number $\sigma_b^x = \pm 1$

-1 dimer on a bond

1 no dimer on a bond

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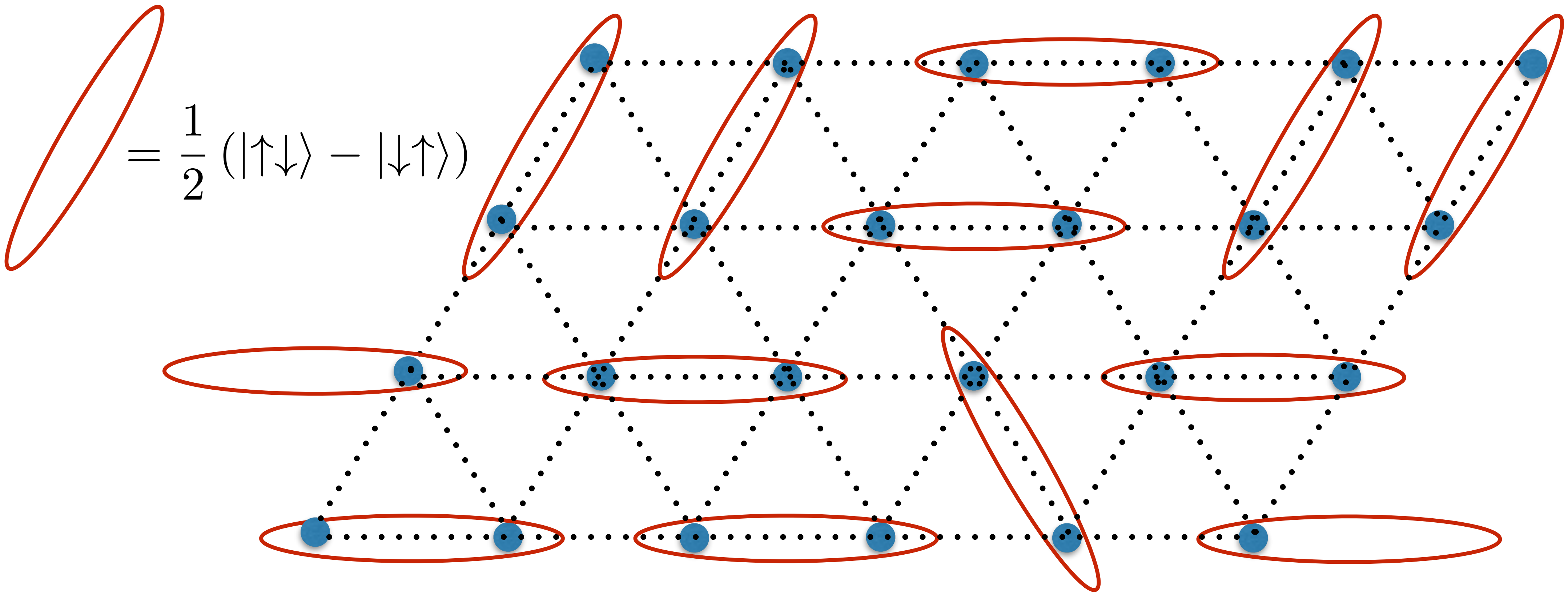

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The dimer hardcore constraint translates into an Ising "Gauss law"

$$\prod_{b \in r} \sigma_b^x = -1$$

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- Symmetry breaking and confinement coincide.

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Ising Lattice Gauge Theory

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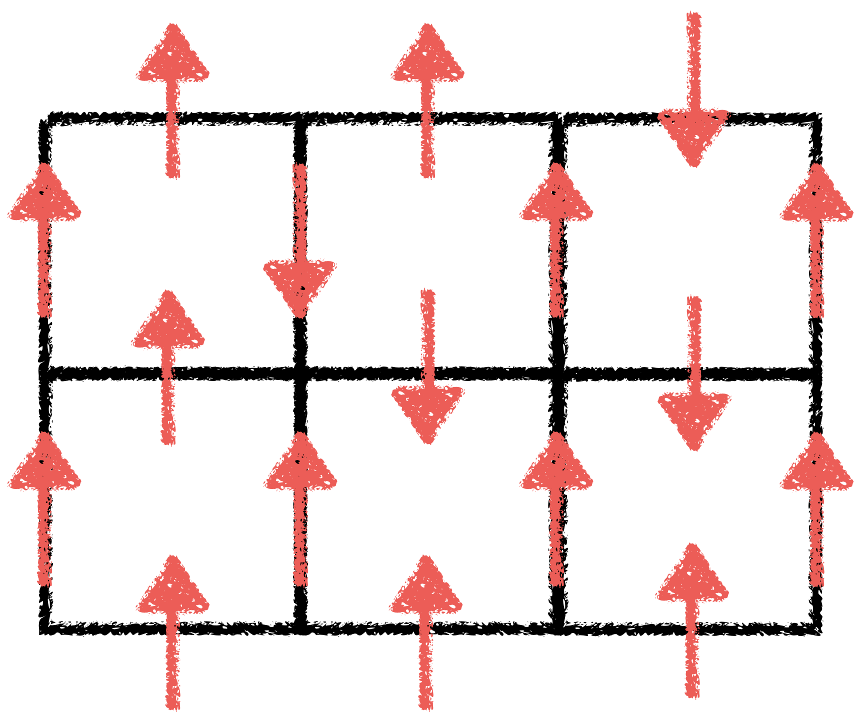

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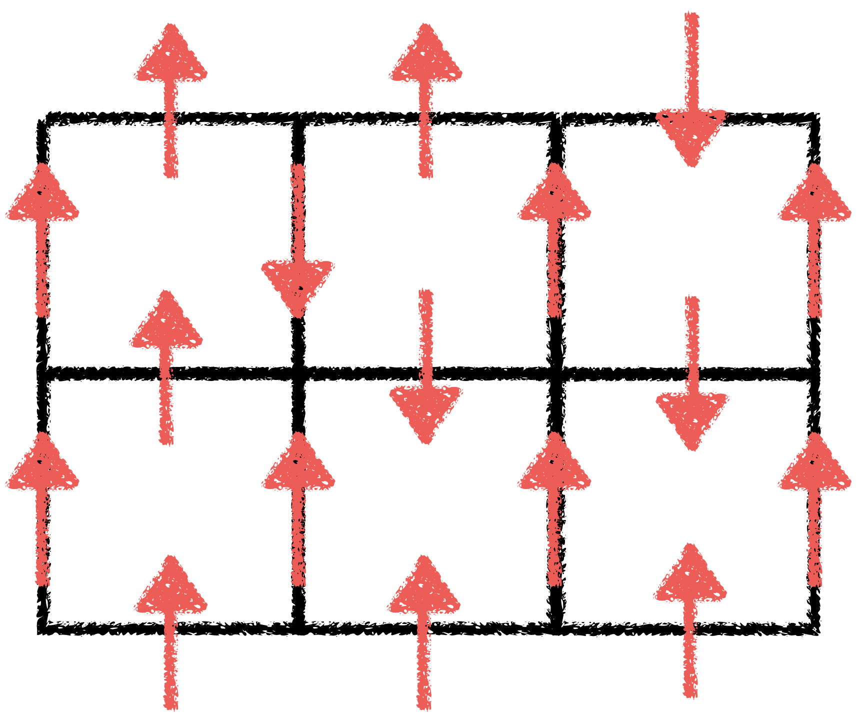

EM "dictionary"

$$\sigma_b^z = e^{iA_b} \qquad A_b = 0/\pi$$

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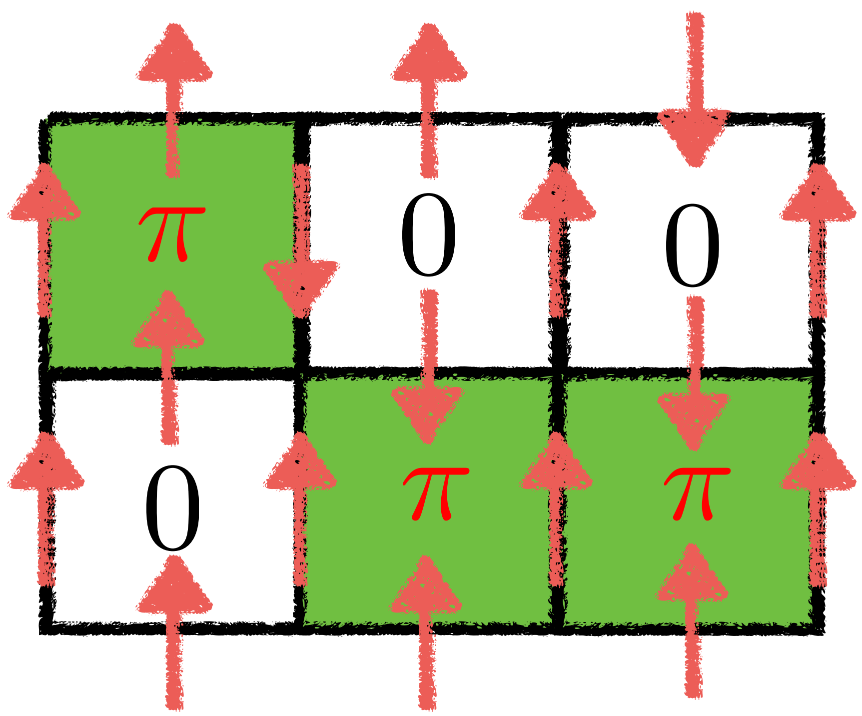

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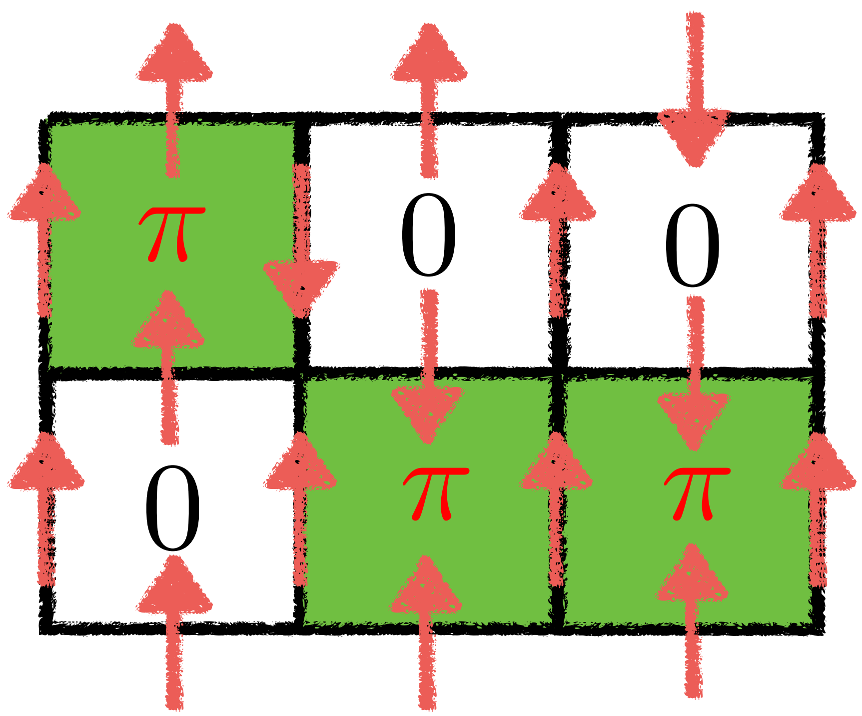

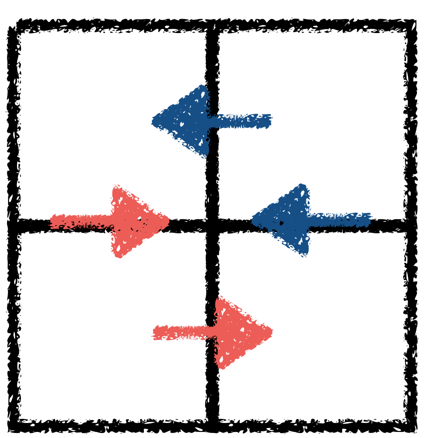

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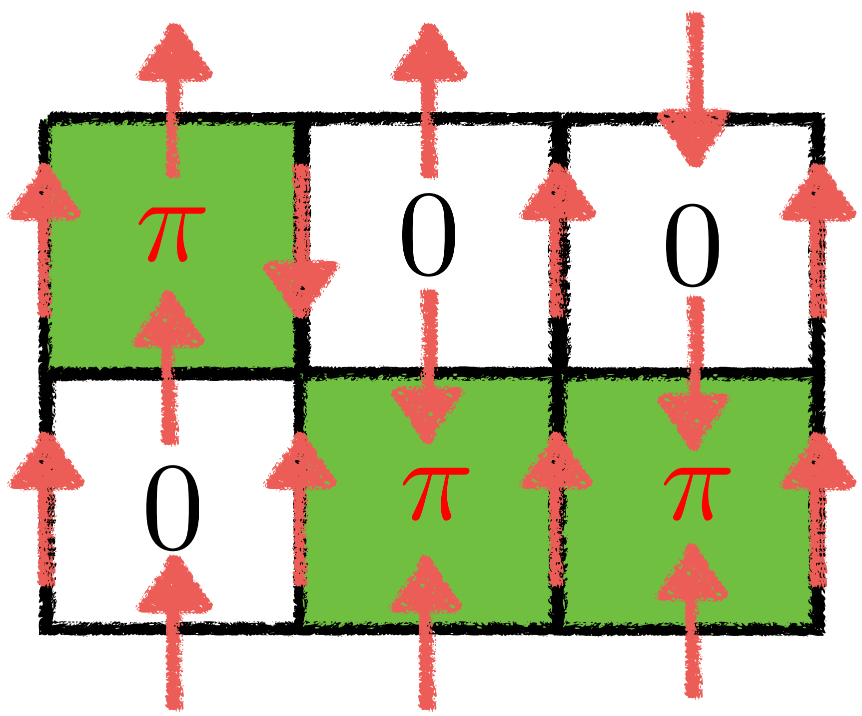

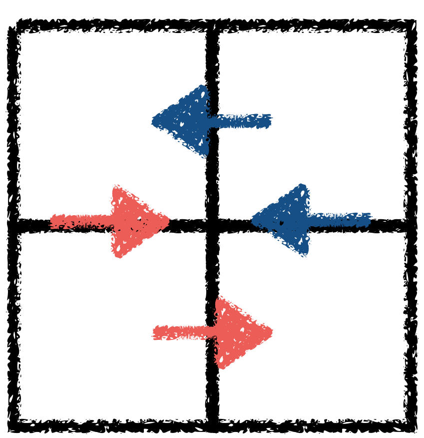

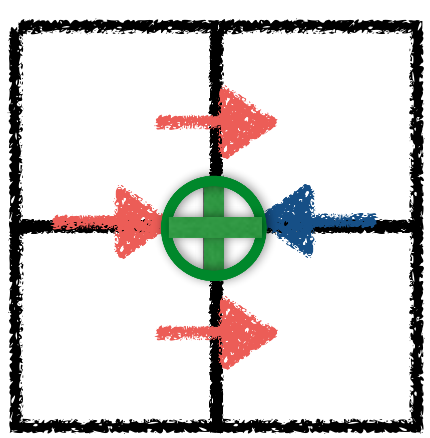

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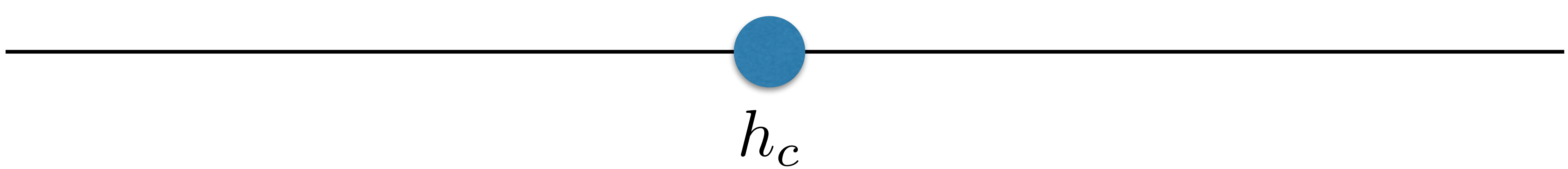

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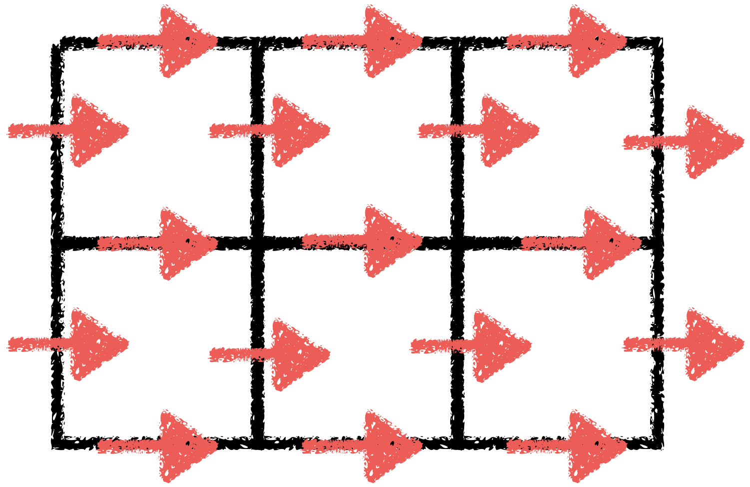

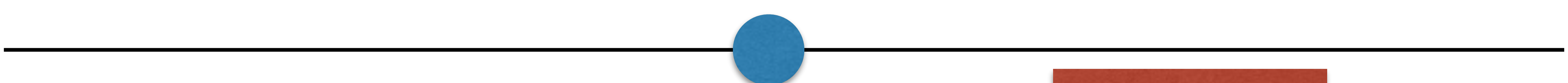

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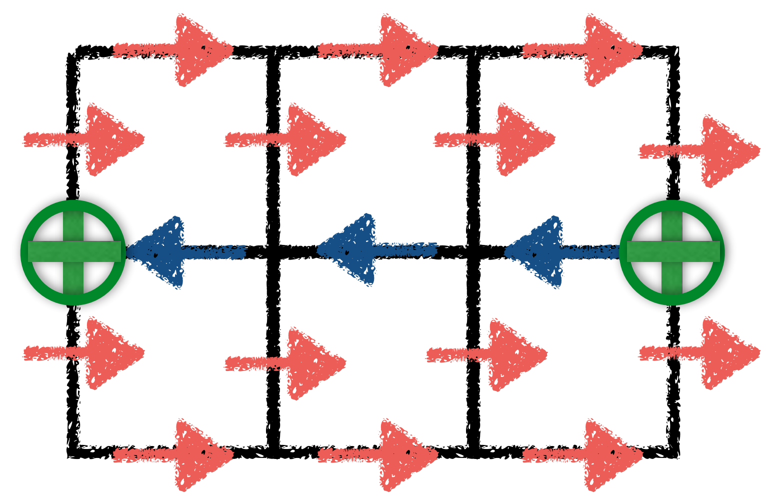

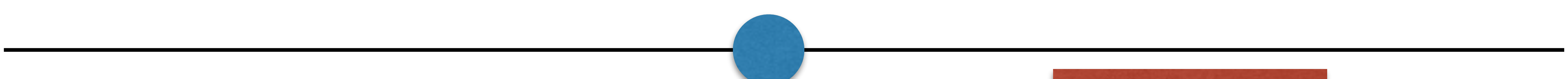

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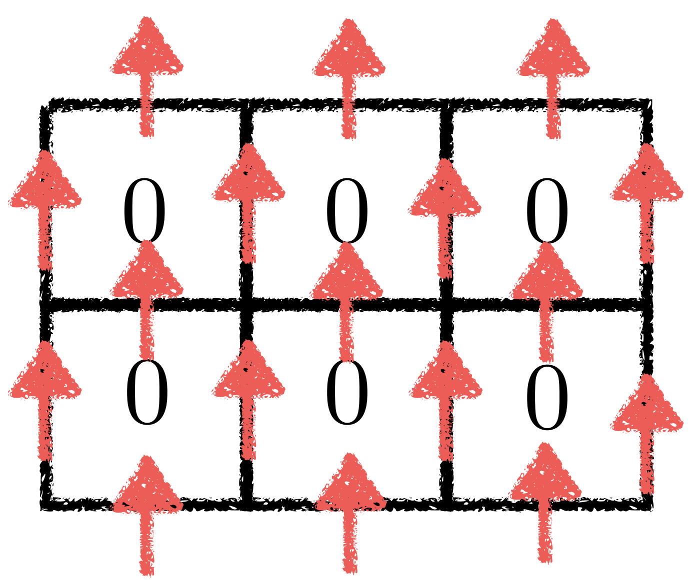

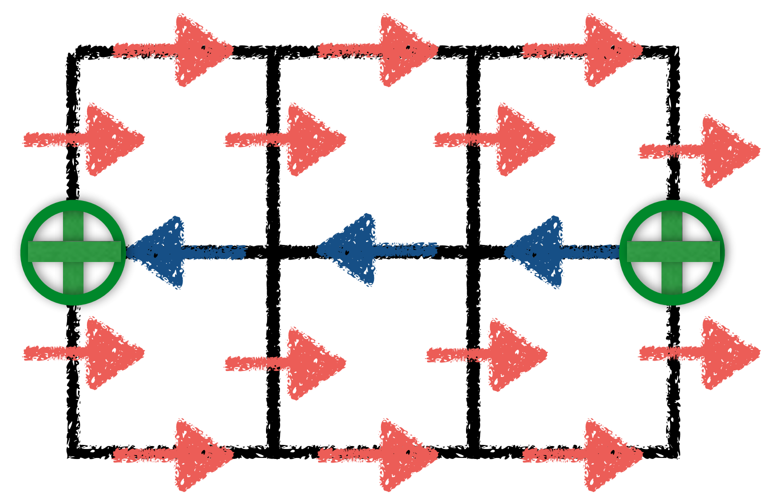

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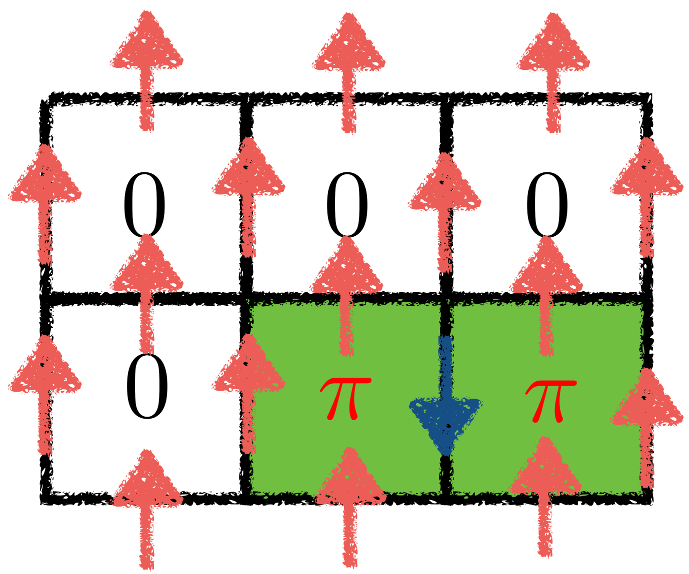

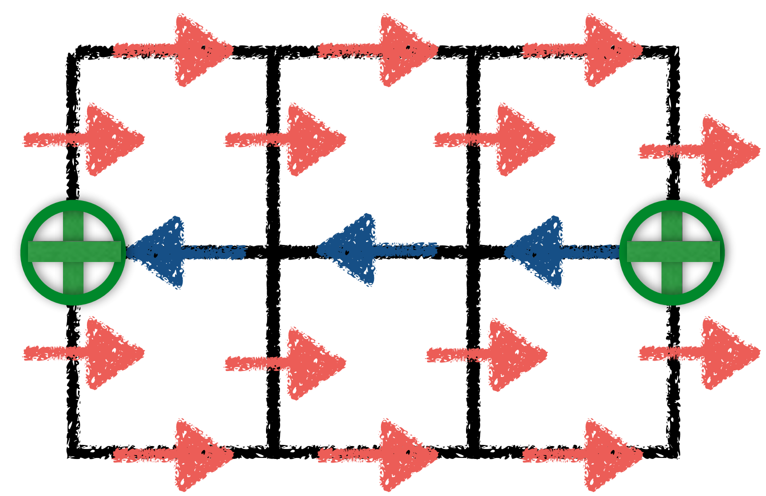

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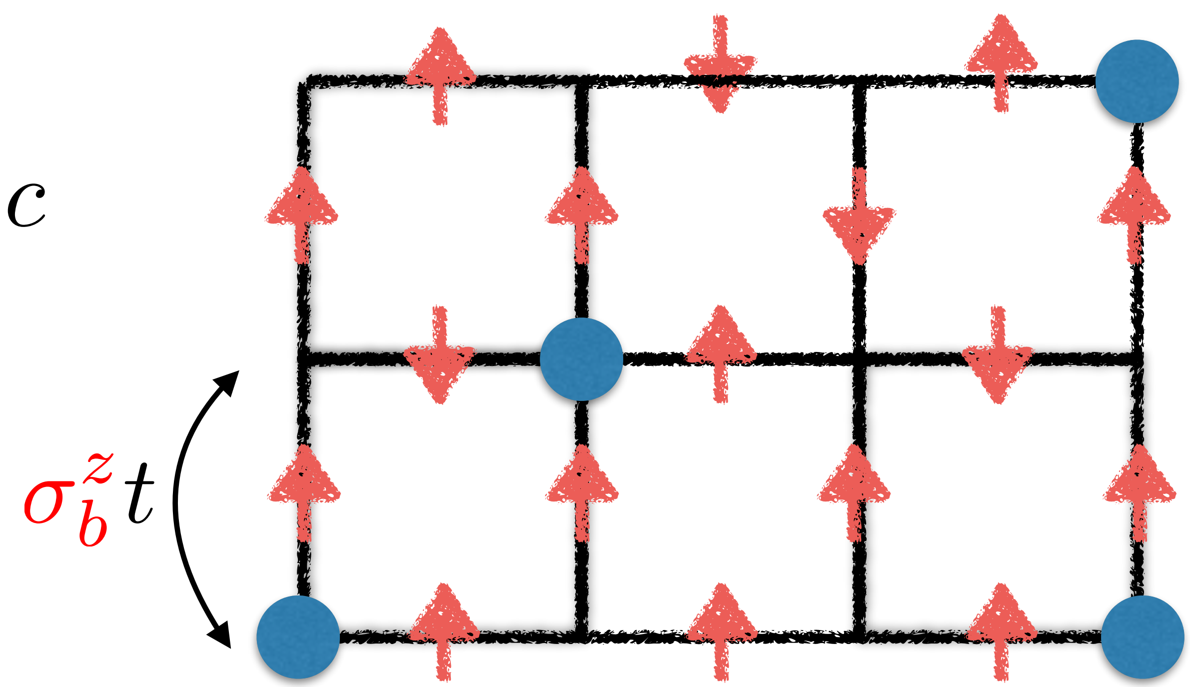
Ising gauge theory with matter fields

Senthil, Fisher (2000)
Moessner, Sondhi, Fradkin (2002)

Ising gauge theory with matter fields

$$\mathcal{H}_f = -t \sum_{b=\langle i,j \rangle} \sigma_b^z c_{i,\alpha}^\dagger c_{j,\alpha} + h.c$$

$$- \mu \sum_{i,\alpha} c_{i,\alpha}^\dagger c_{i,\alpha}$$



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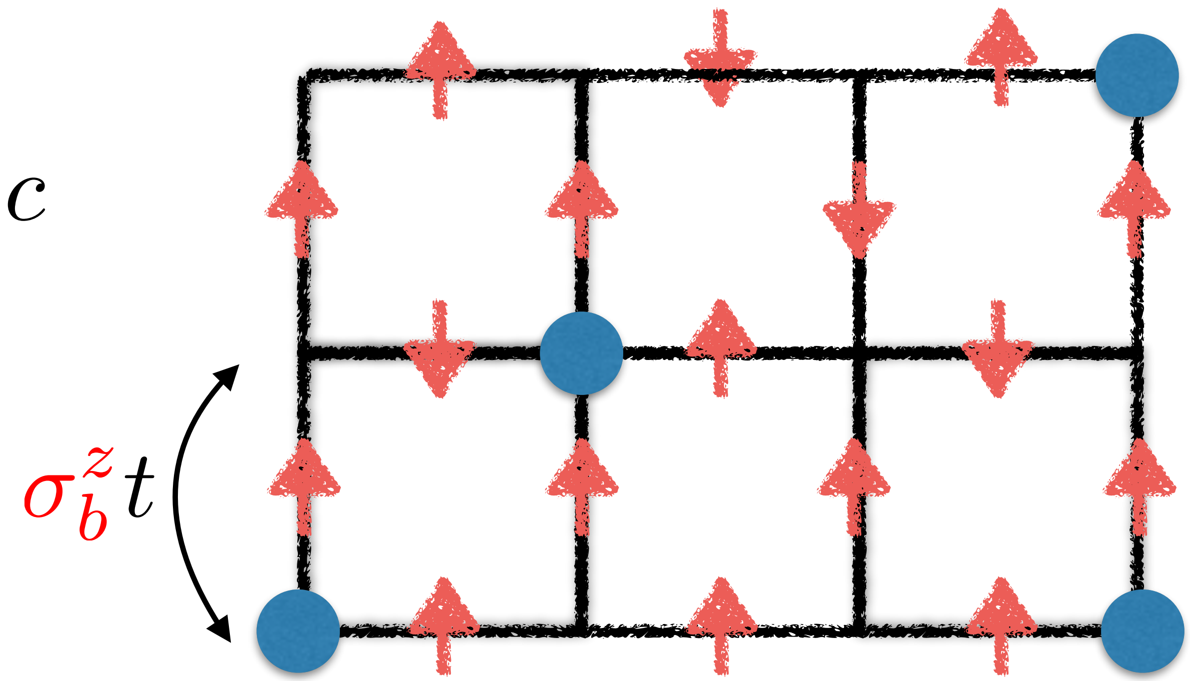

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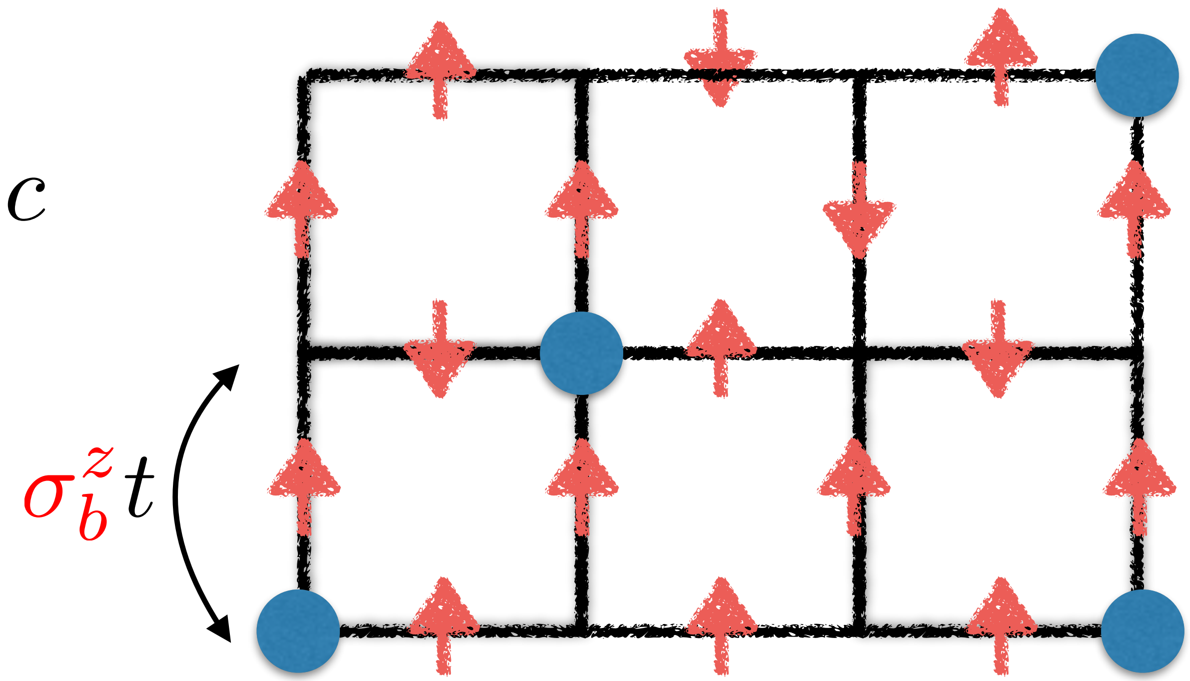

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Key observation - for real gauge theories the fermion determinant is also real

$$\det(\uparrow)\det(\downarrow) = \det(\uparrow)^2 > 0$$

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Confinement transition with fermions (generic filling)

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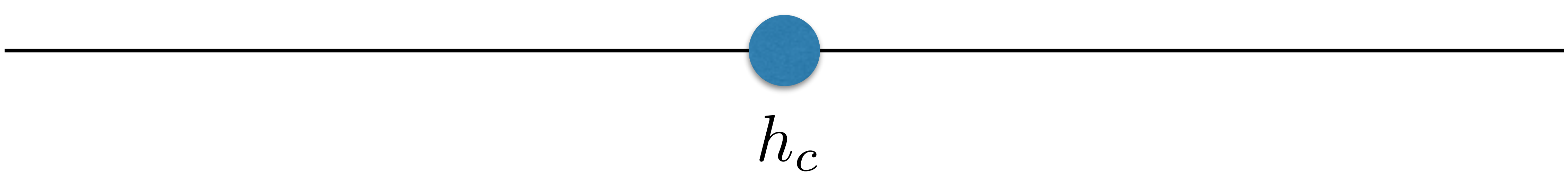

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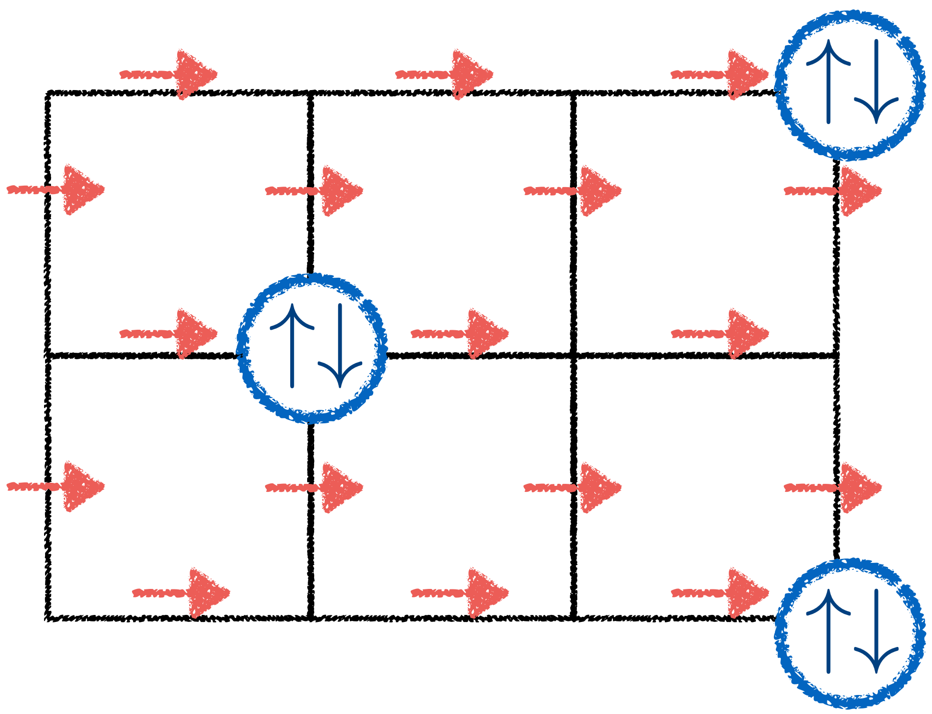

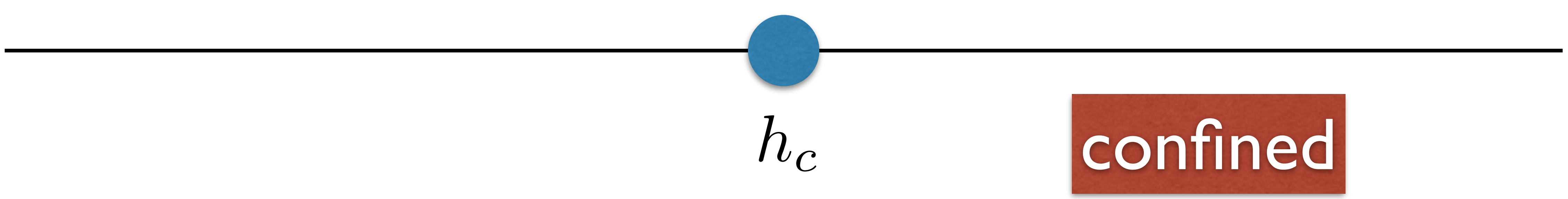

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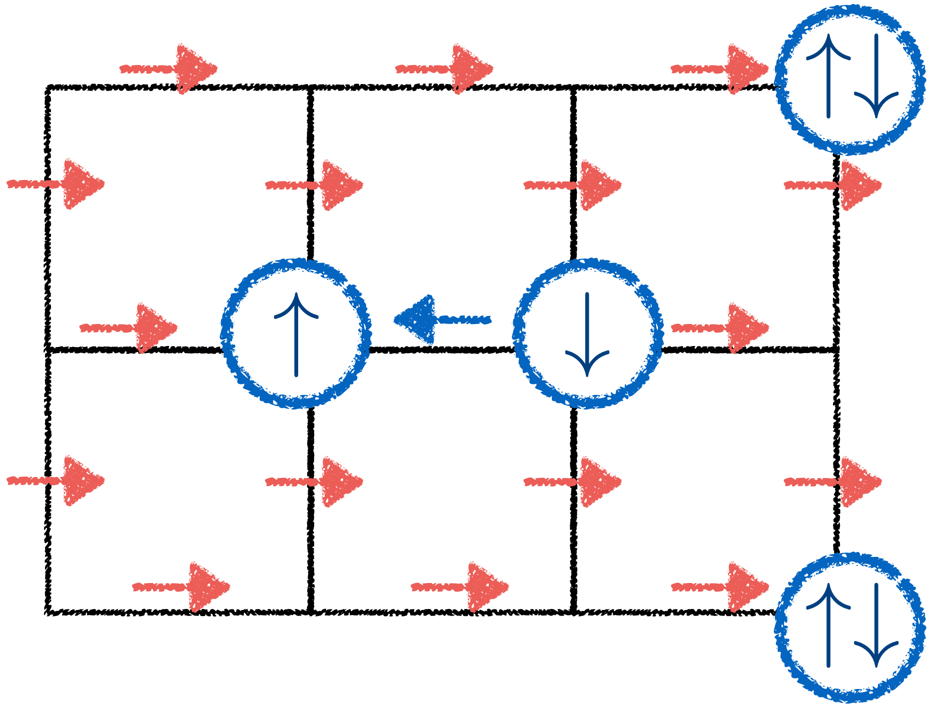

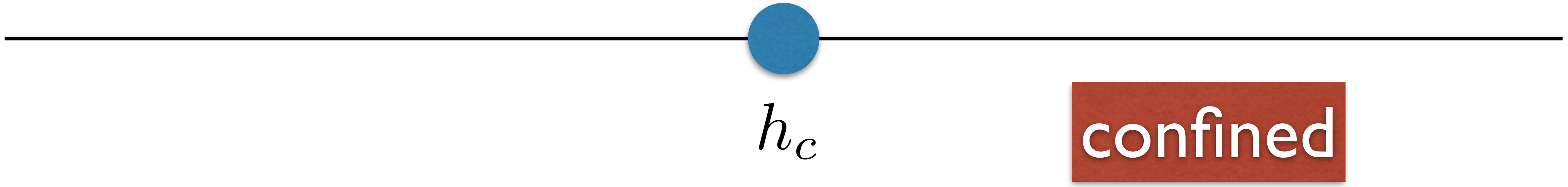

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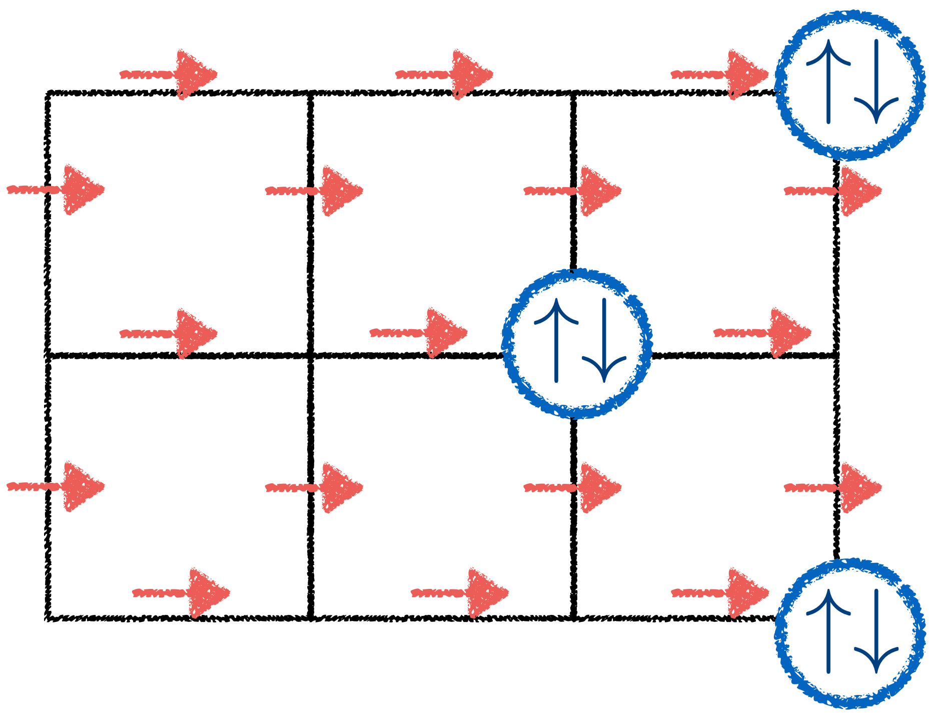

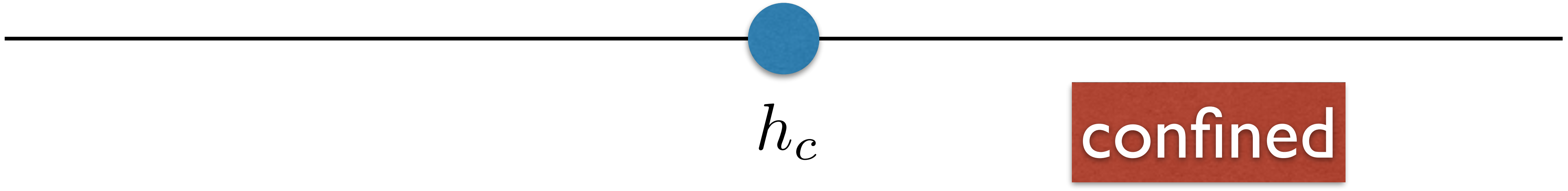

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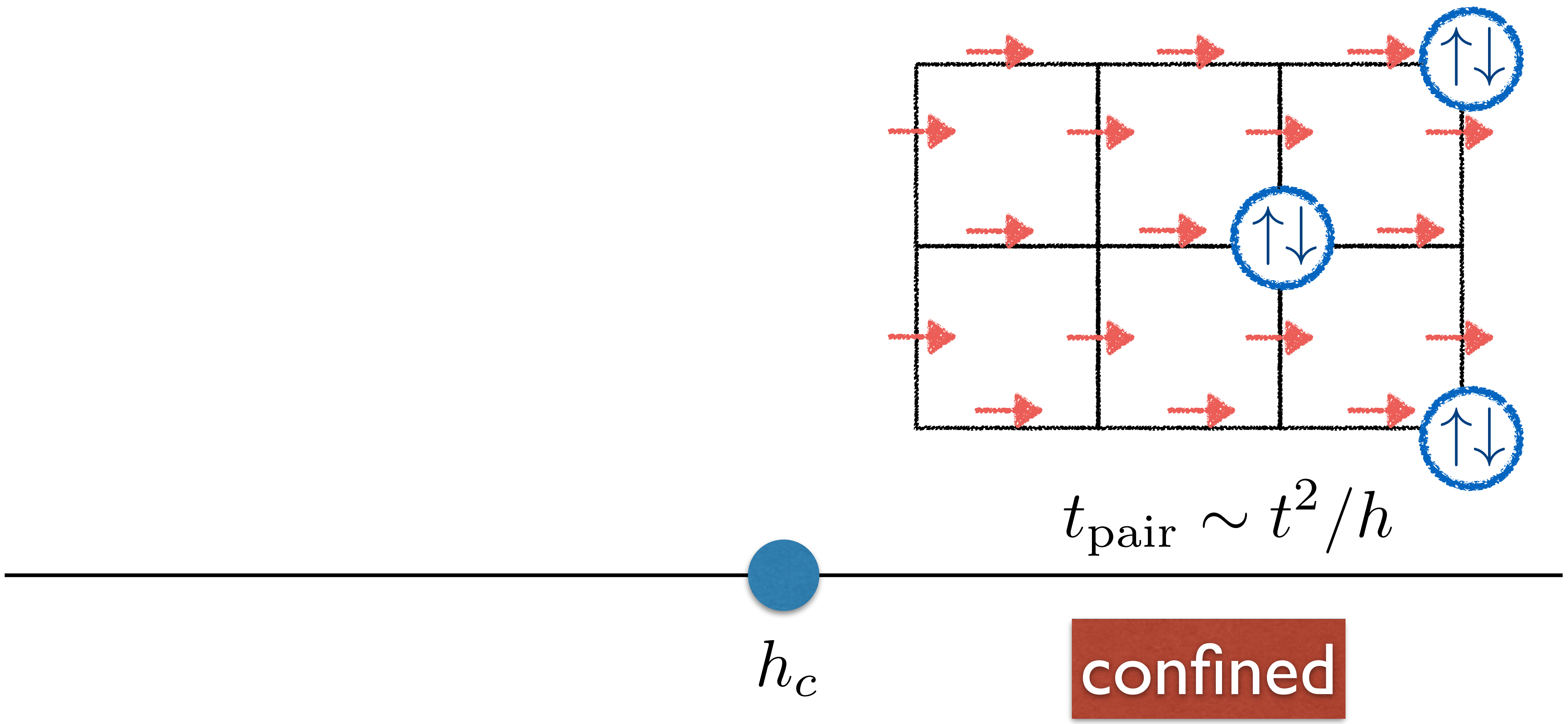

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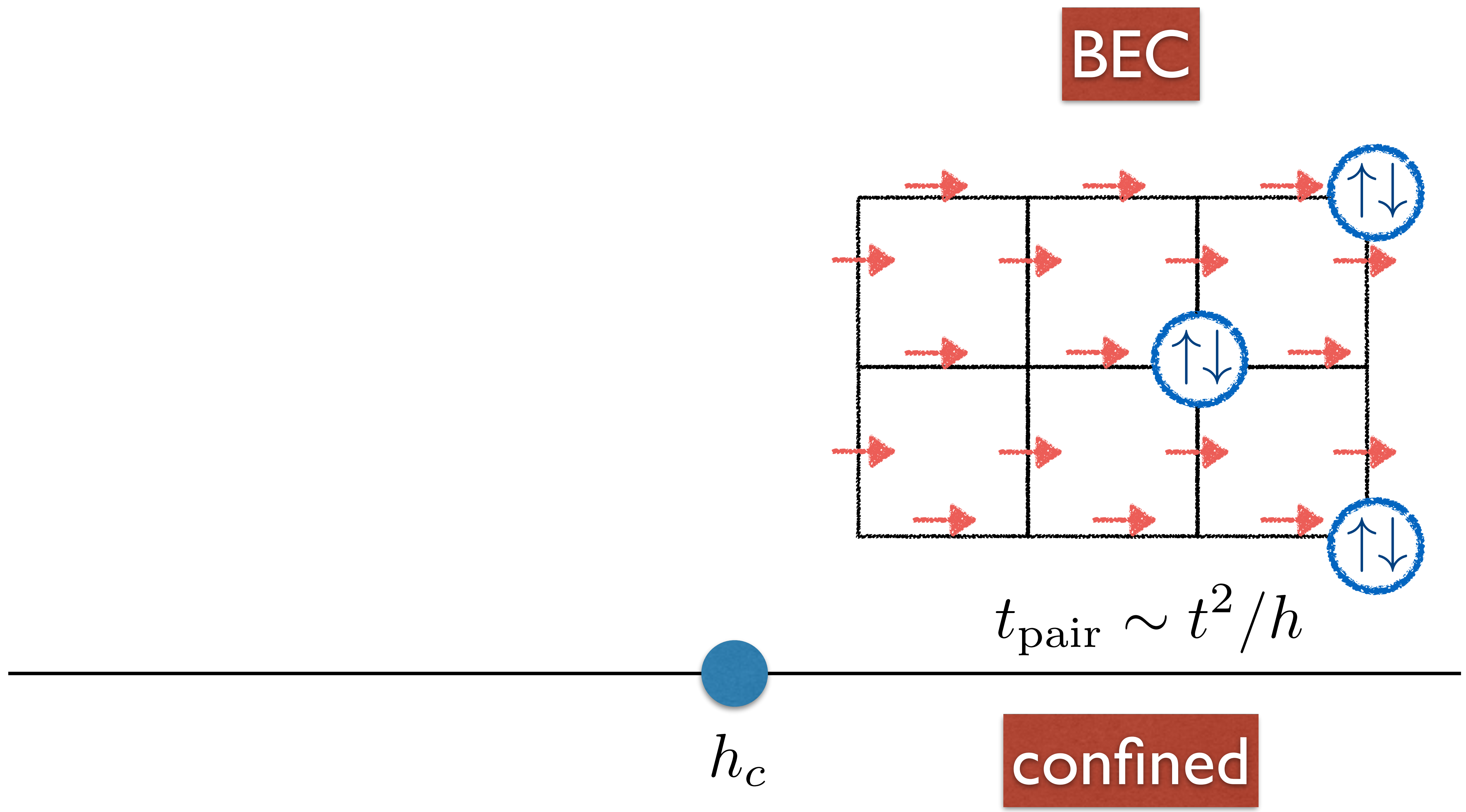

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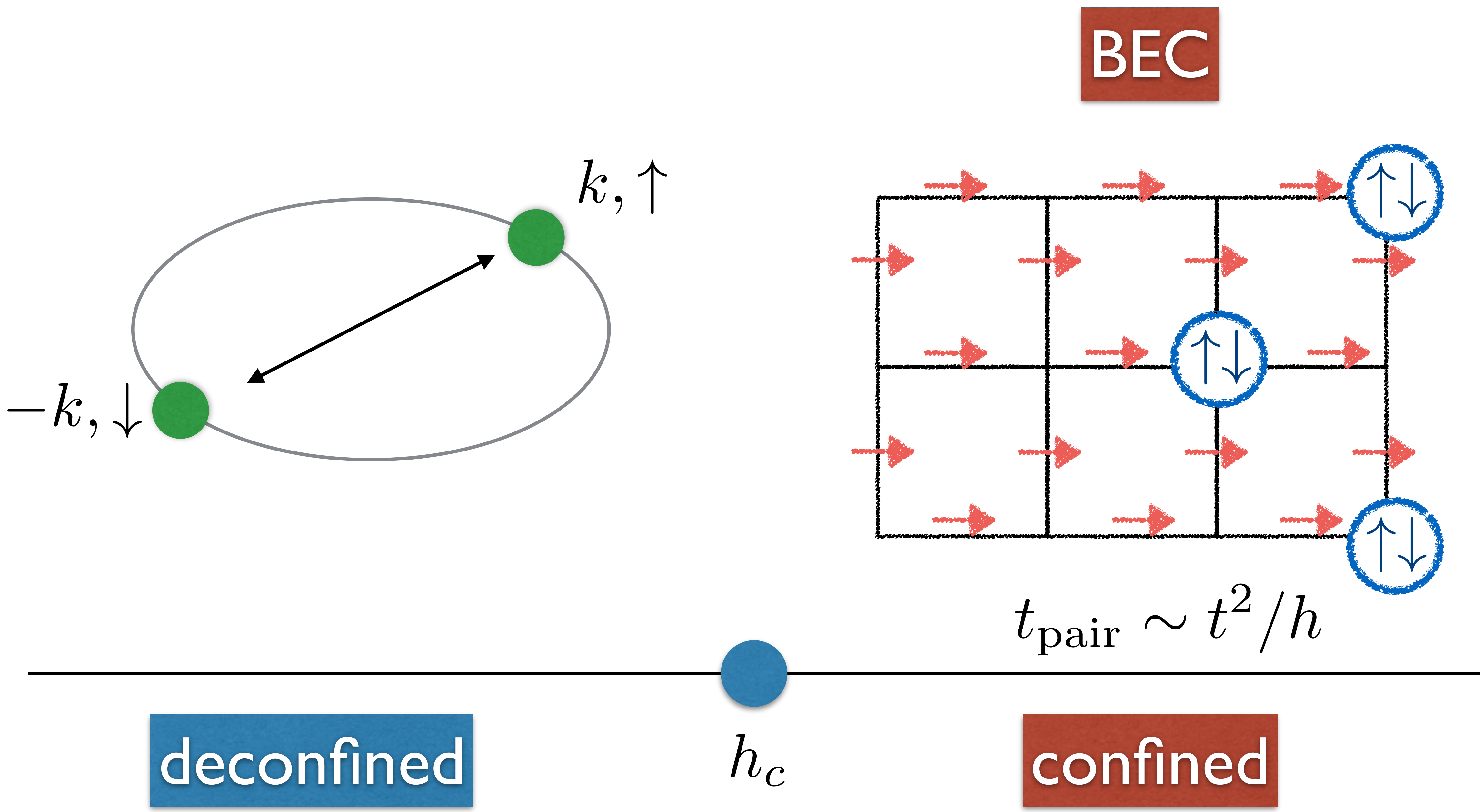

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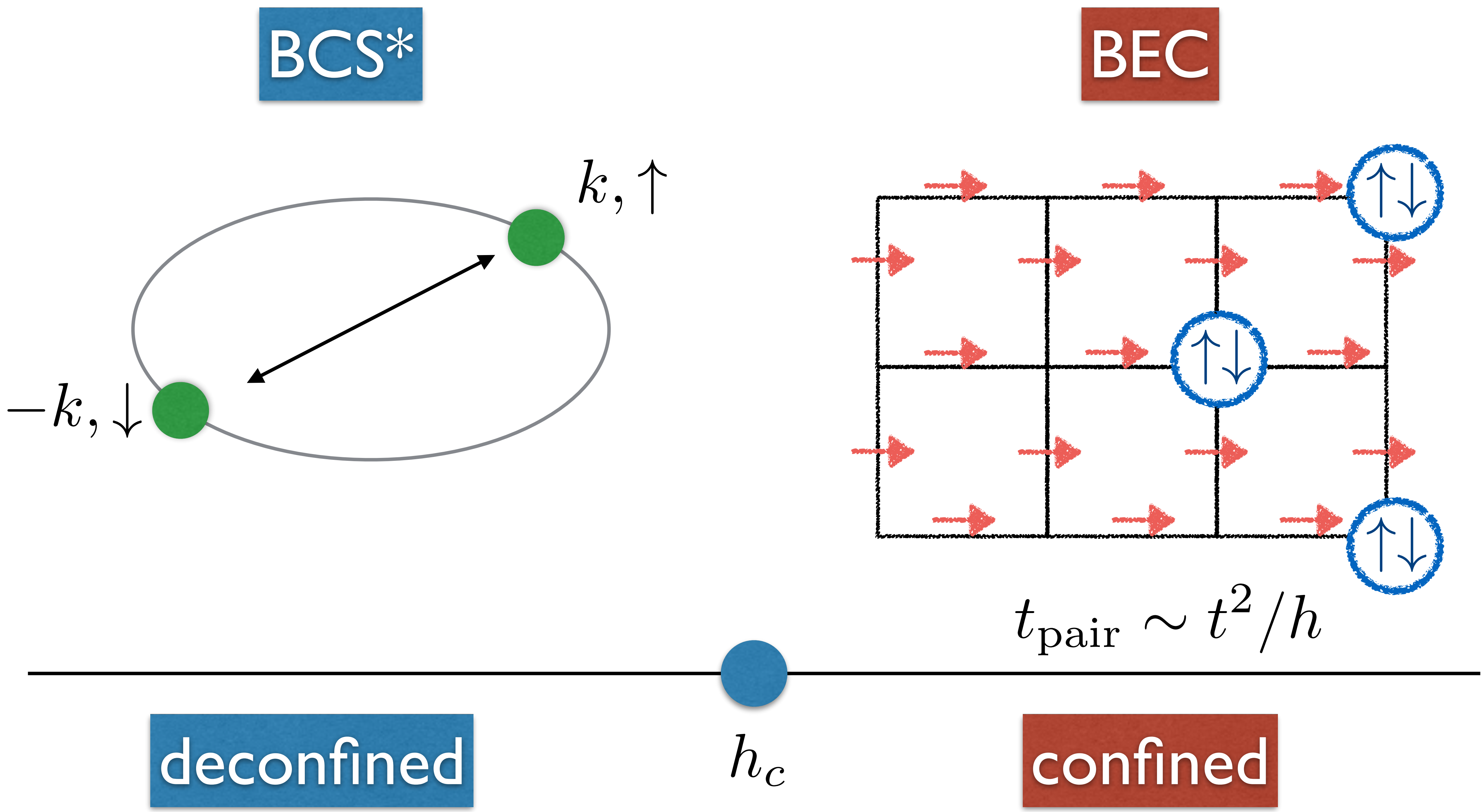

Large "t" limit $\mu = 0$

Affleck, Marston (1988)
Arovas, Auerbach (1988)
Leib (1994)

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What happens at large hopping amplitude t?

Find $\{\sigma_b^z\}$ that minimizes $\mathcal{H}_f = -t \sum_{b=\langle i,j \rangle} \sigma_b^z c_{i,\alpha}^\dagger c_{j,\alpha} + h.c$

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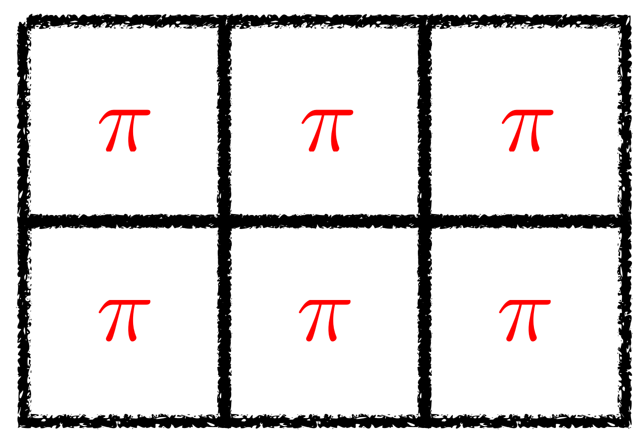
π-flux phase!



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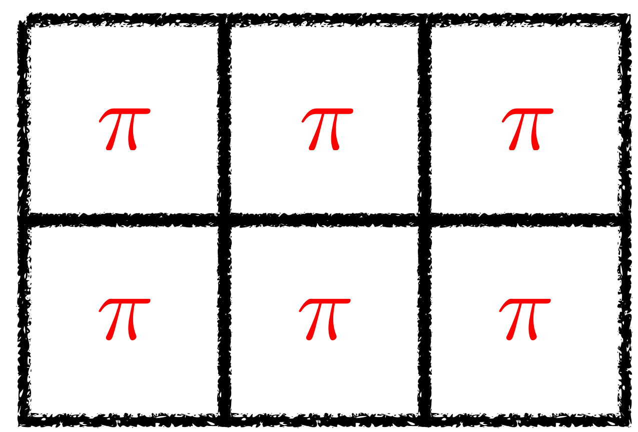
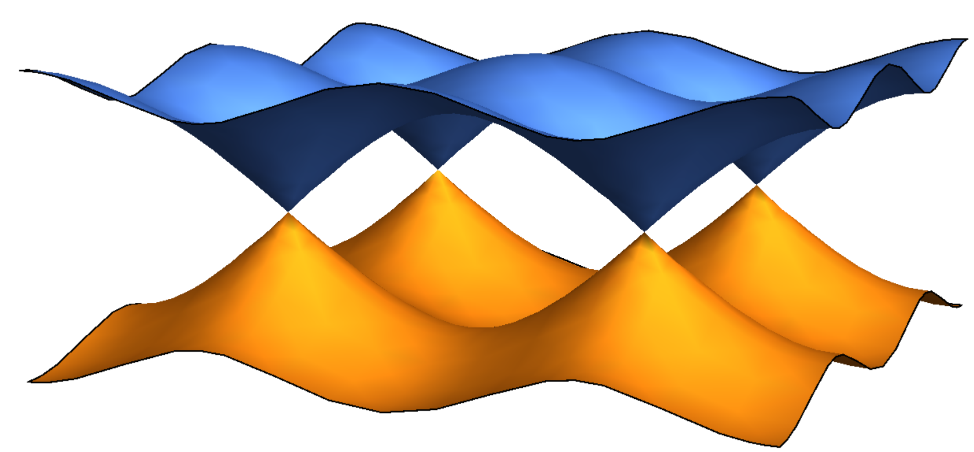
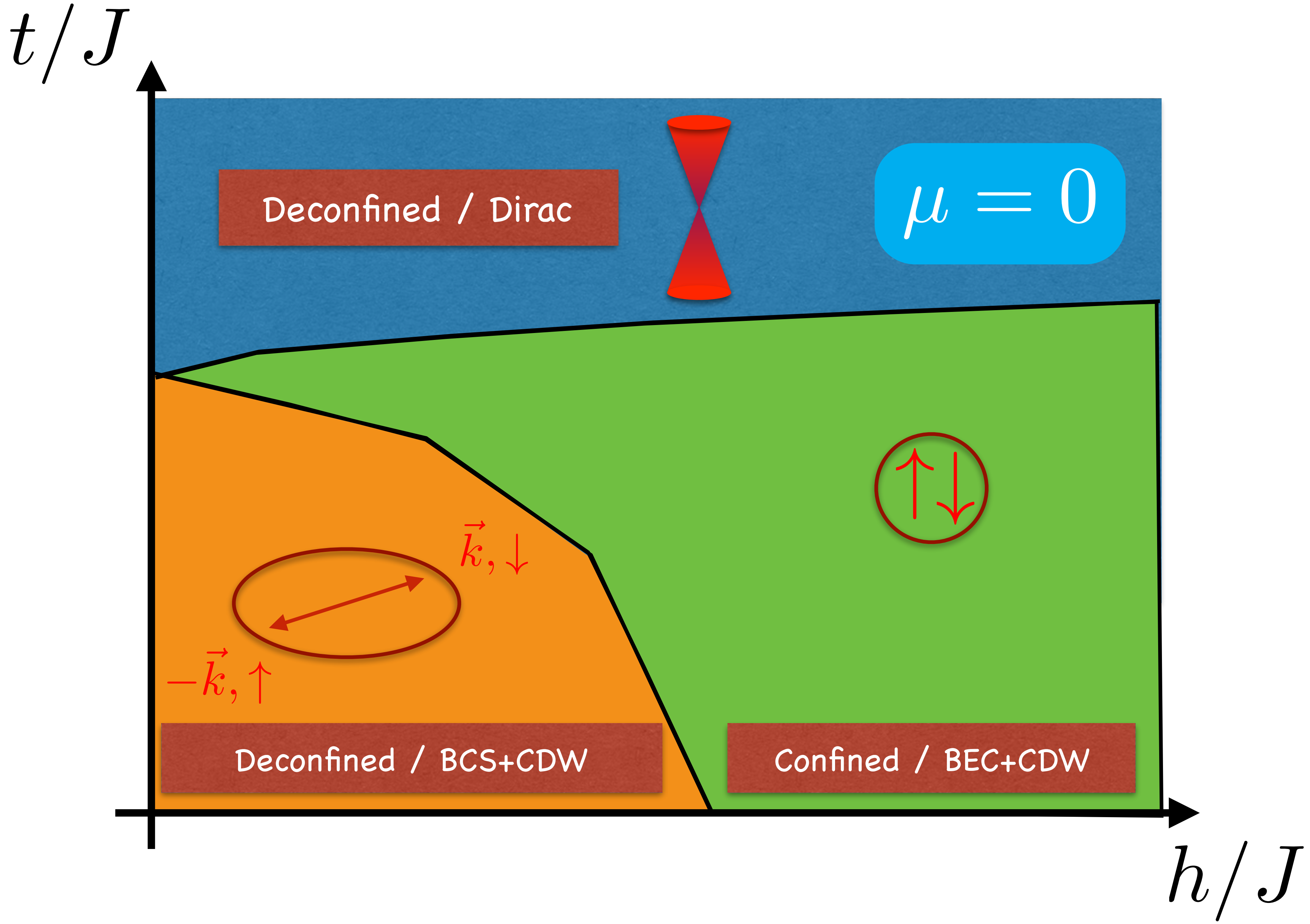


Two Dirac nodes

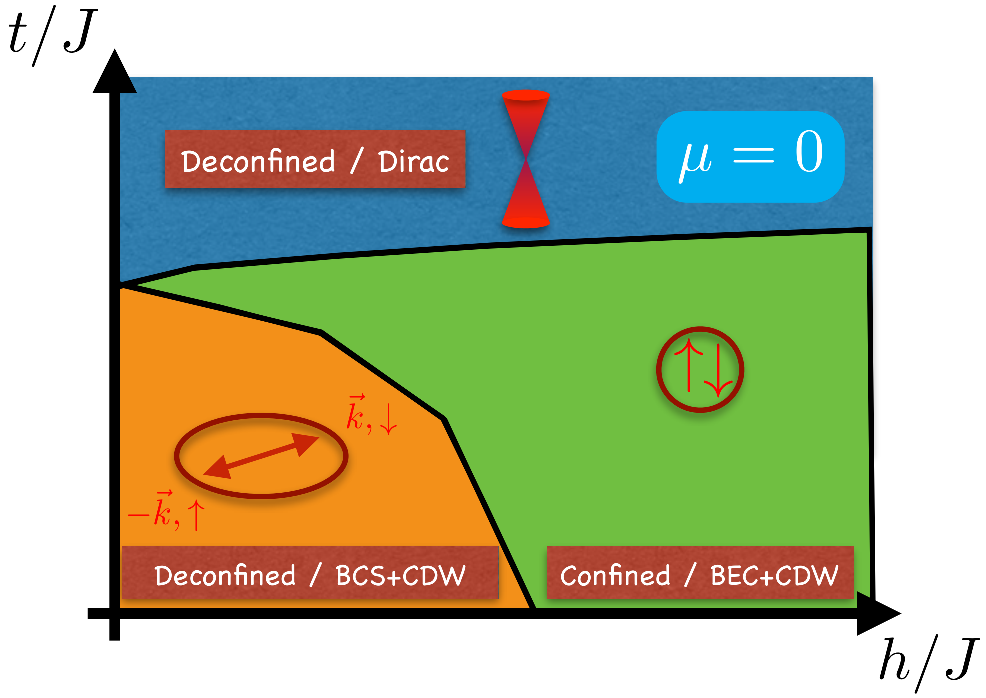
$$E_k = \pm 2t\sqrt{\cos(k_x)^2 + \cos(k_y)^2}$$



Phase Diagram at $\mu = 0$

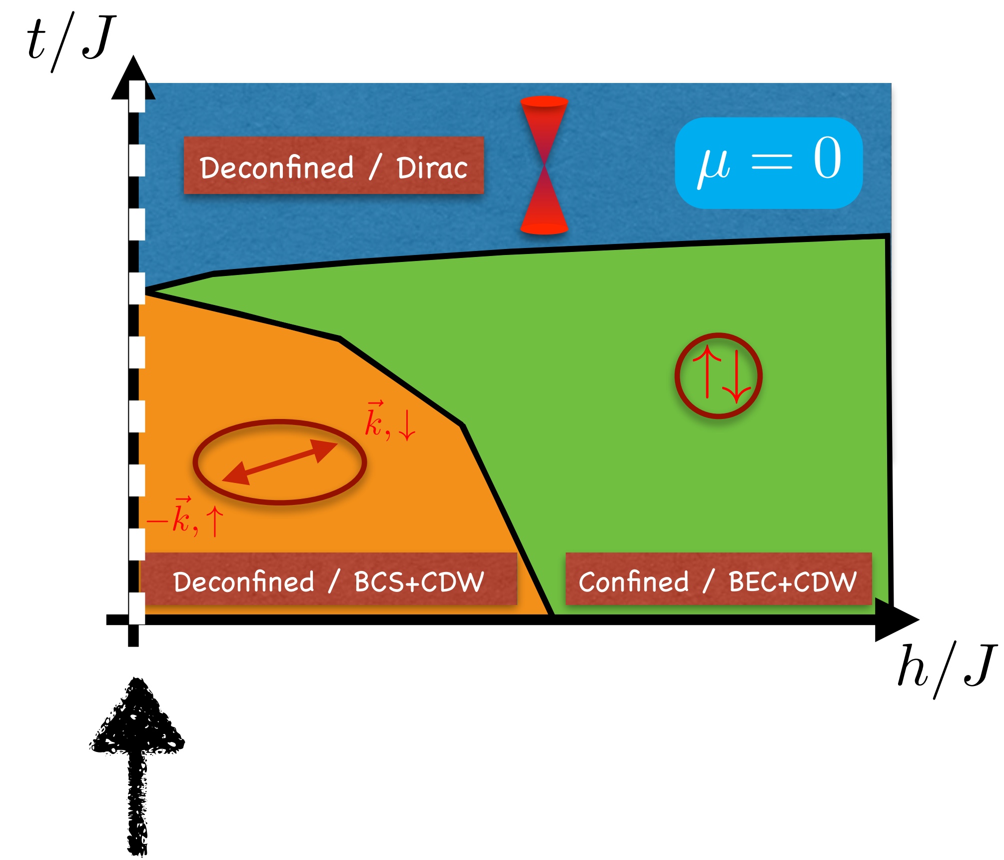


Frozen gauge field limit $h \to 0$



Frozen gauge field limit $h \to 0$

$$\mathcal{H} = -t \sum_{b=\langle i,j \rangle} \sigma_b^z c_{i,\alpha}^\dagger c_{j,\alpha} - J \sum_{\square} \prod_{b \in \square} \sigma_b^z$$



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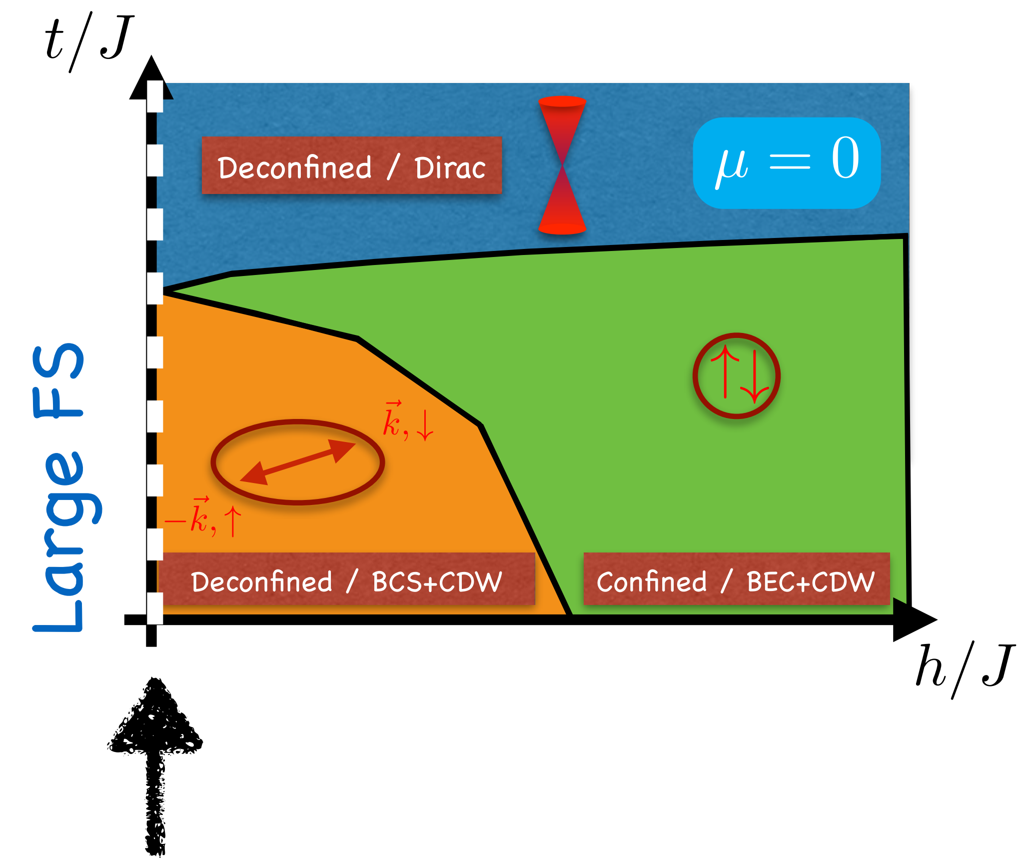
$t \ll J$ Zero flux phase

$\sigma_b^z = 1$ Large FS



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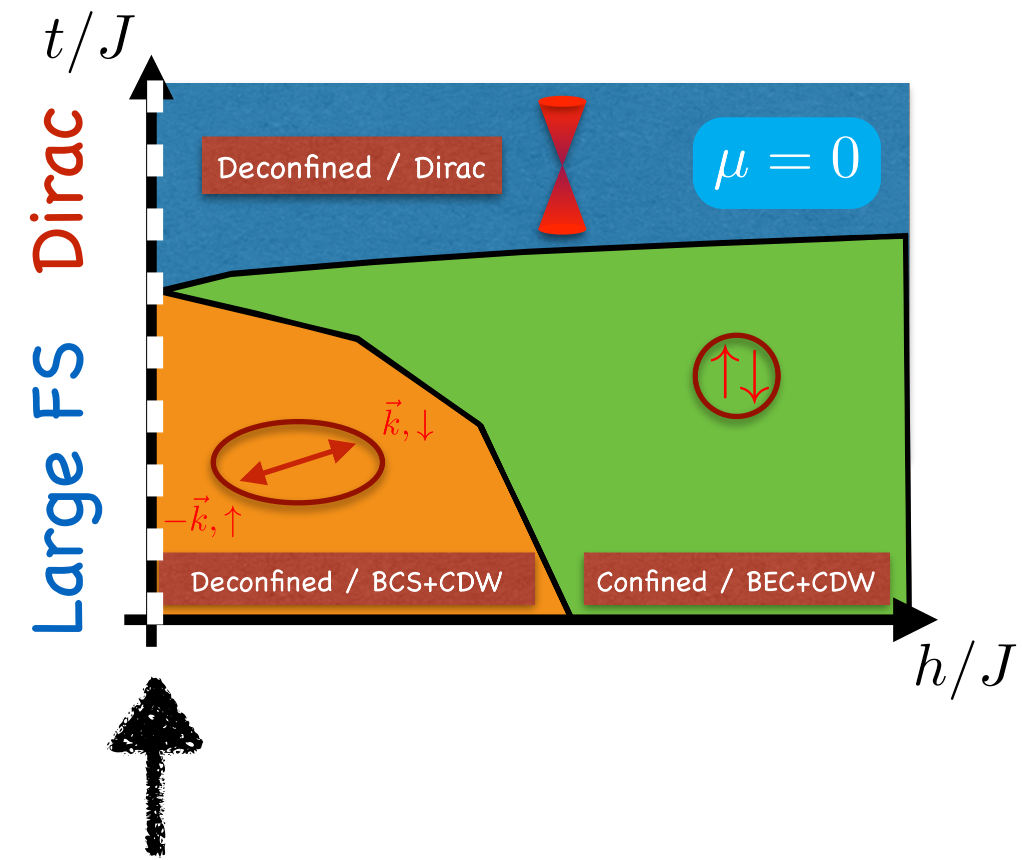

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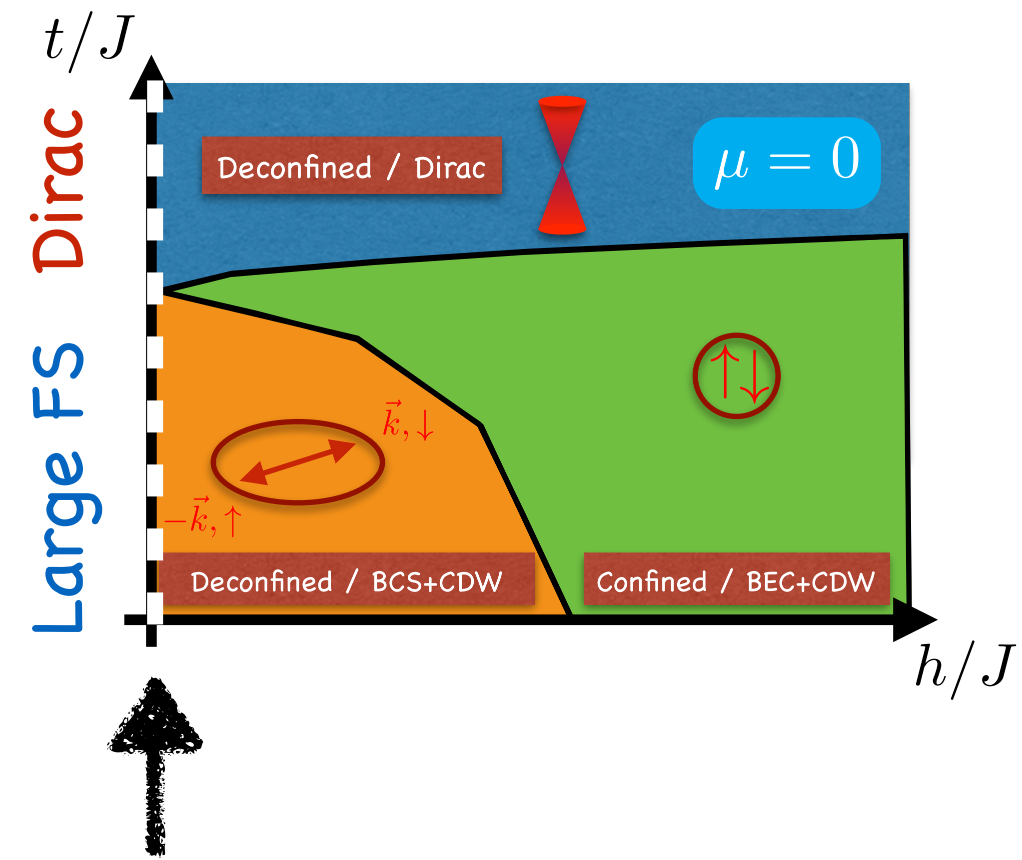
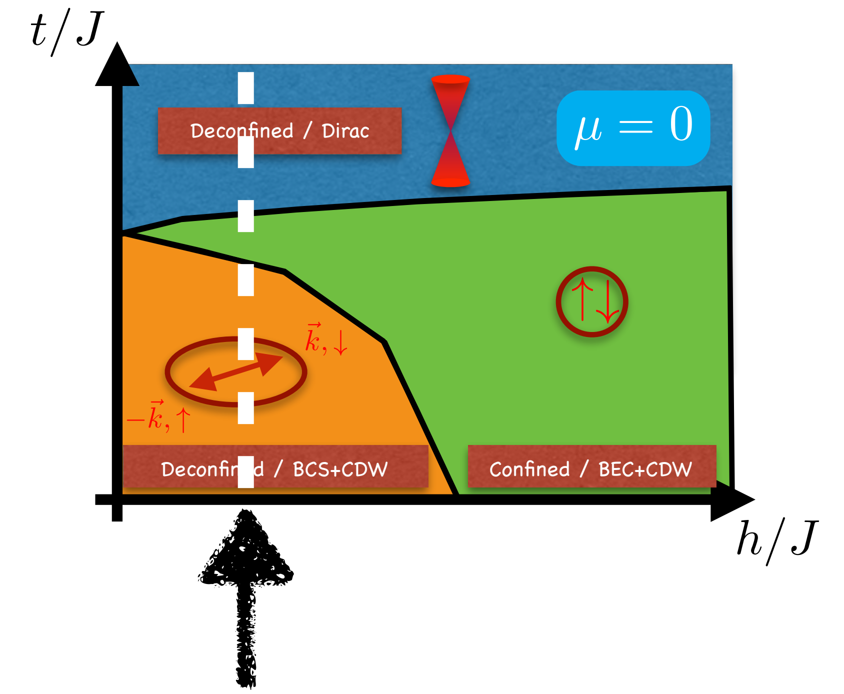


Phase transition at $t/J = 6.77$

Weak coupling $h \ll J$



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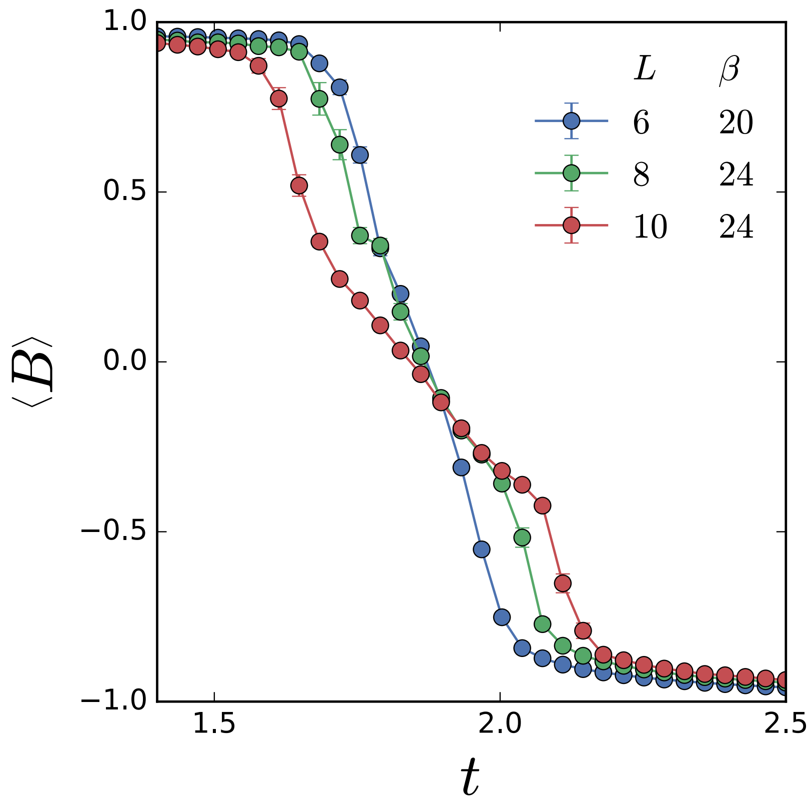
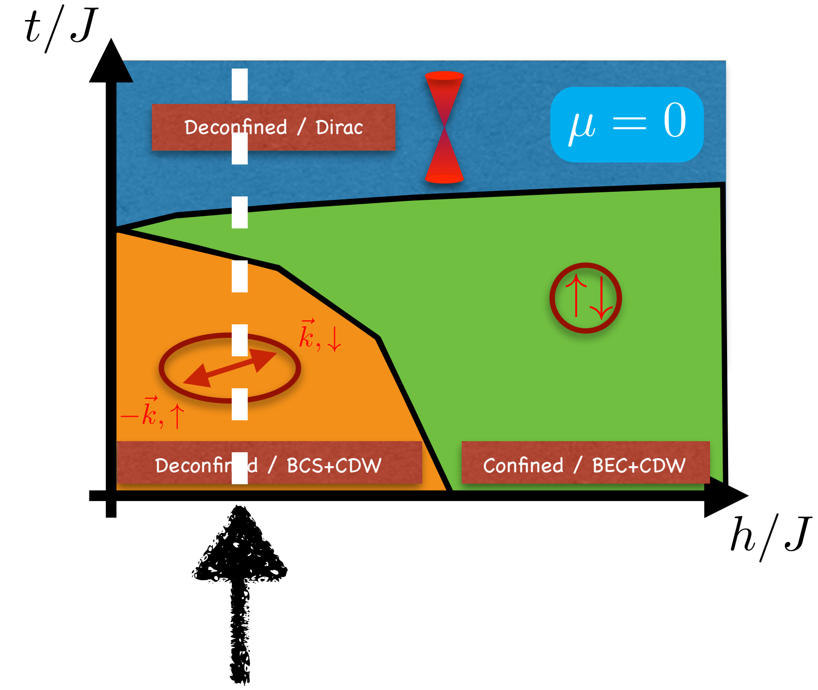
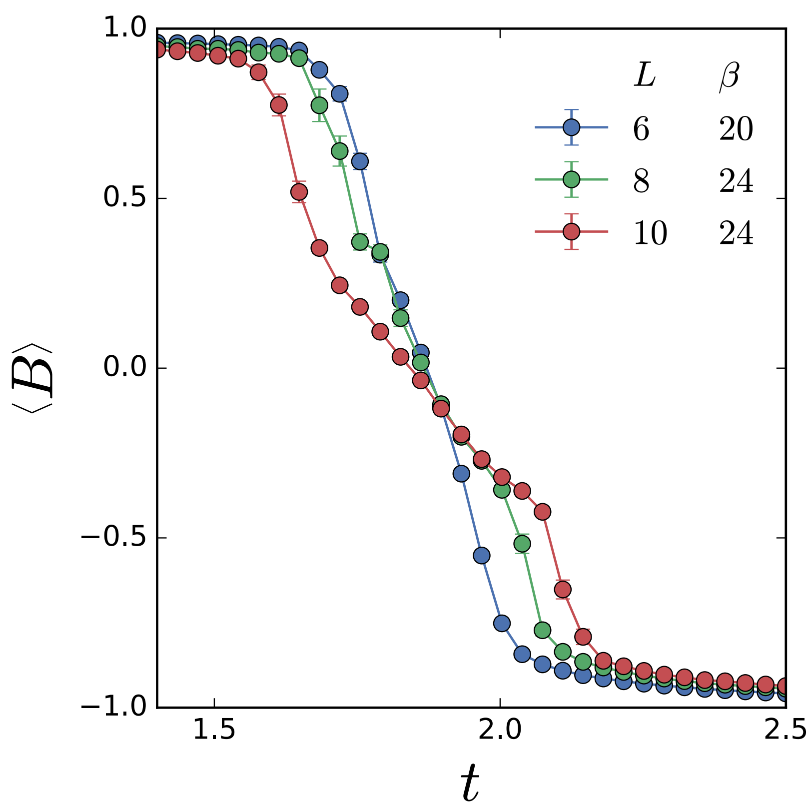


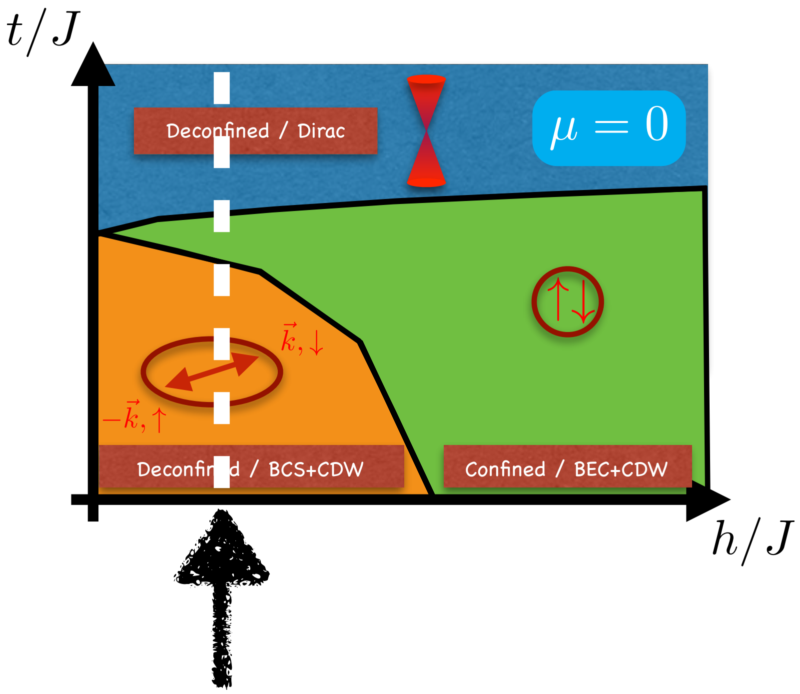


Weak coupling $h \ll J$

$\langle B \rangle \to 1$

Deconfined





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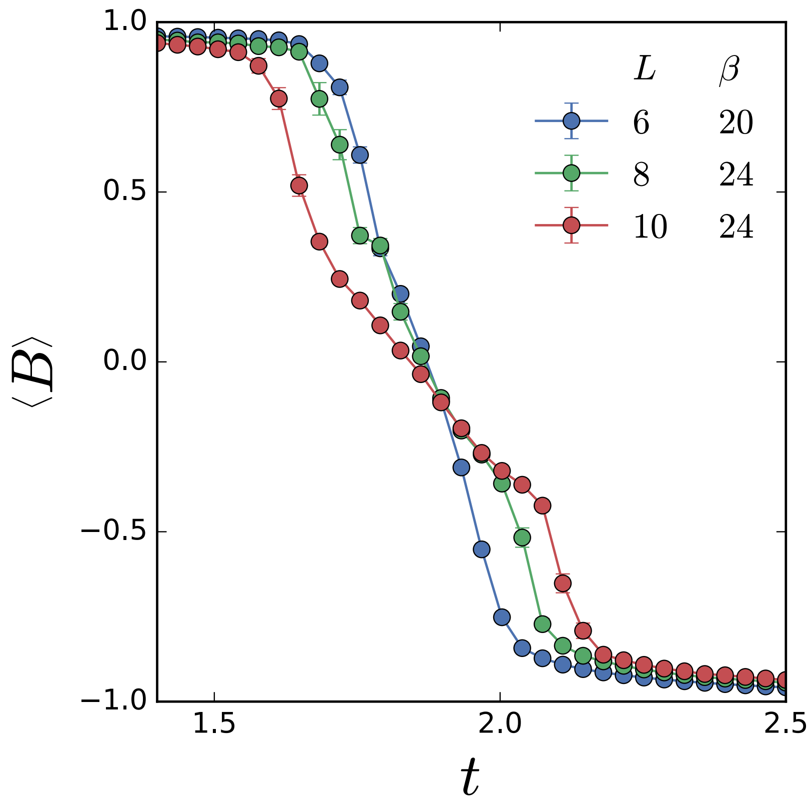
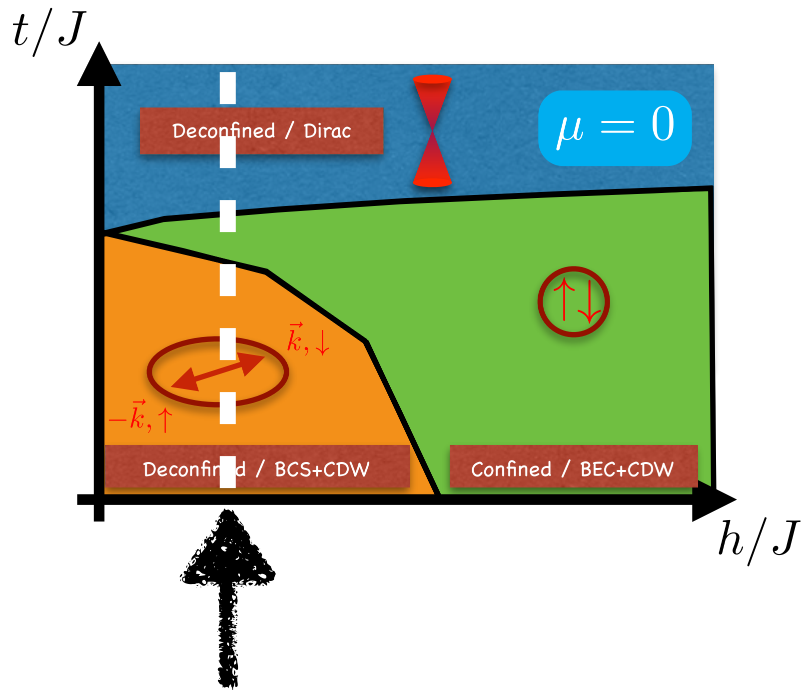


Deconfined

Dirac

$\langle B \rangle \to -1$



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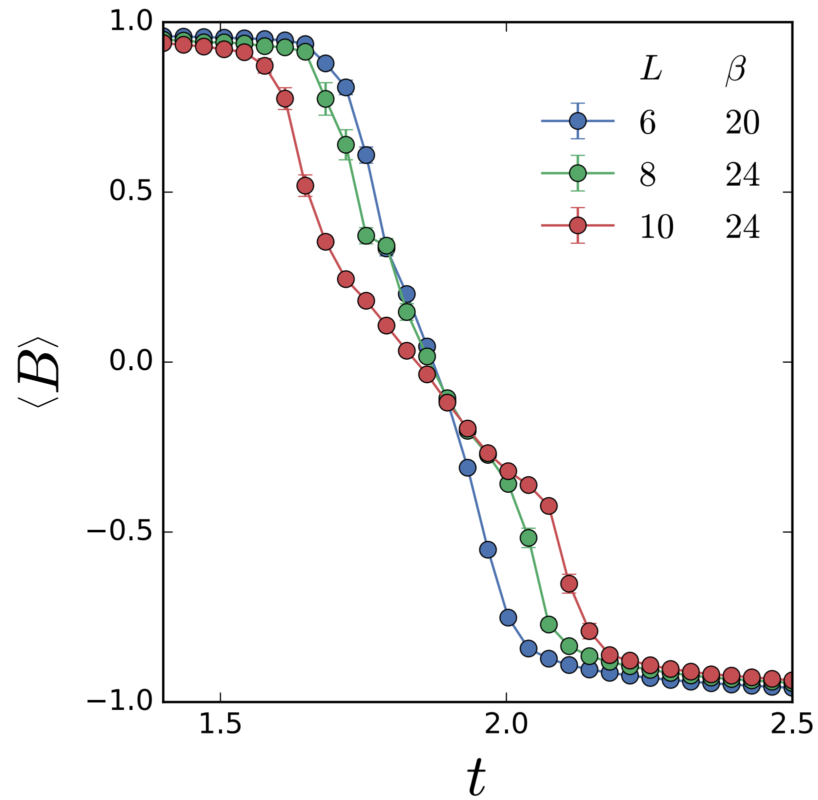

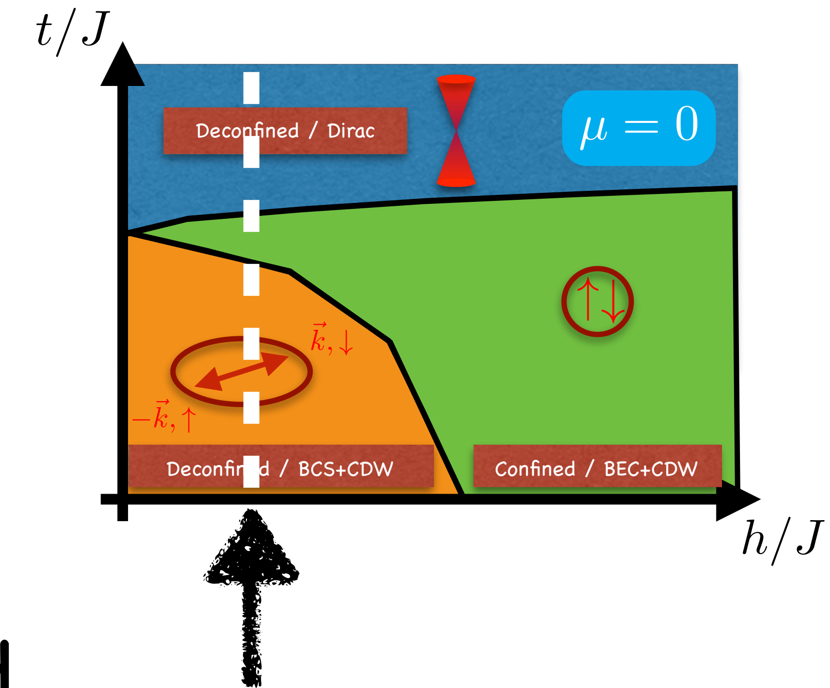

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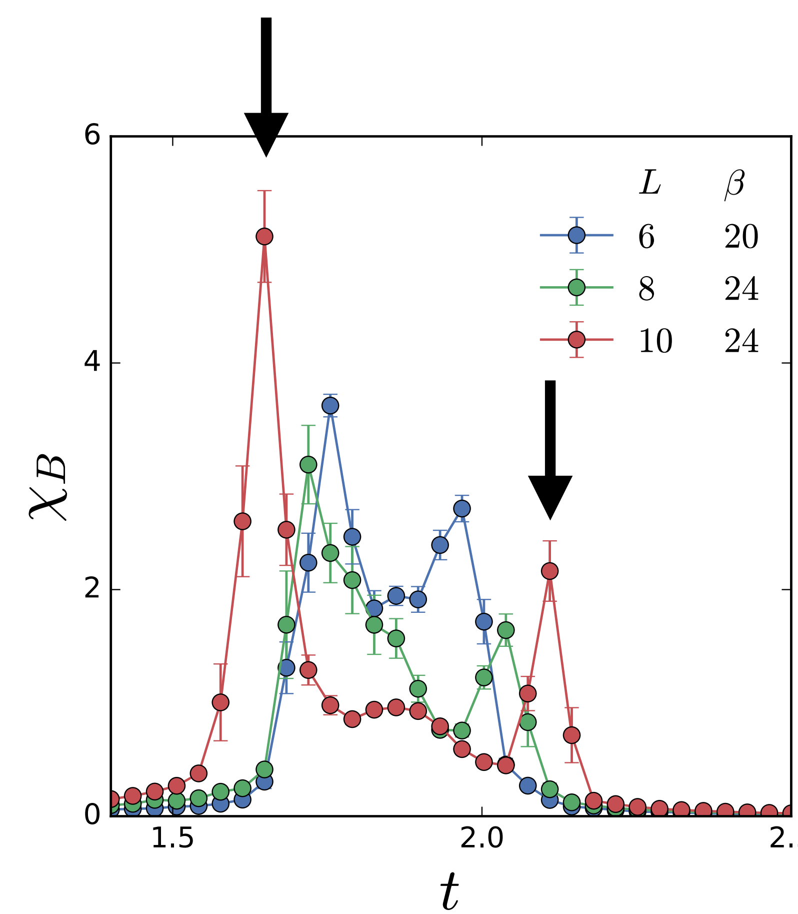
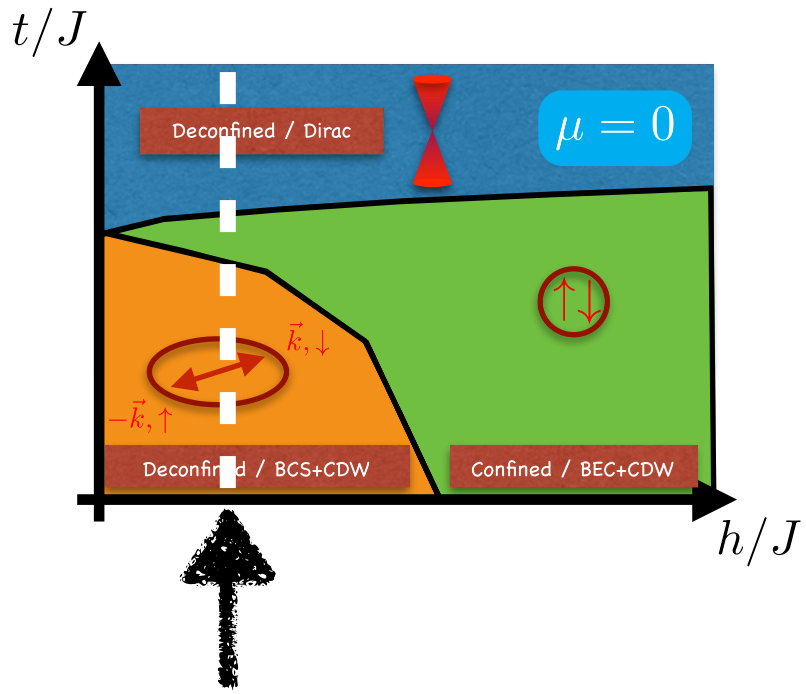


Two phase transition:

Intervening confined phase

$$J_{eff} \to J - c \times t$$

Weak coupling $h \ll J$



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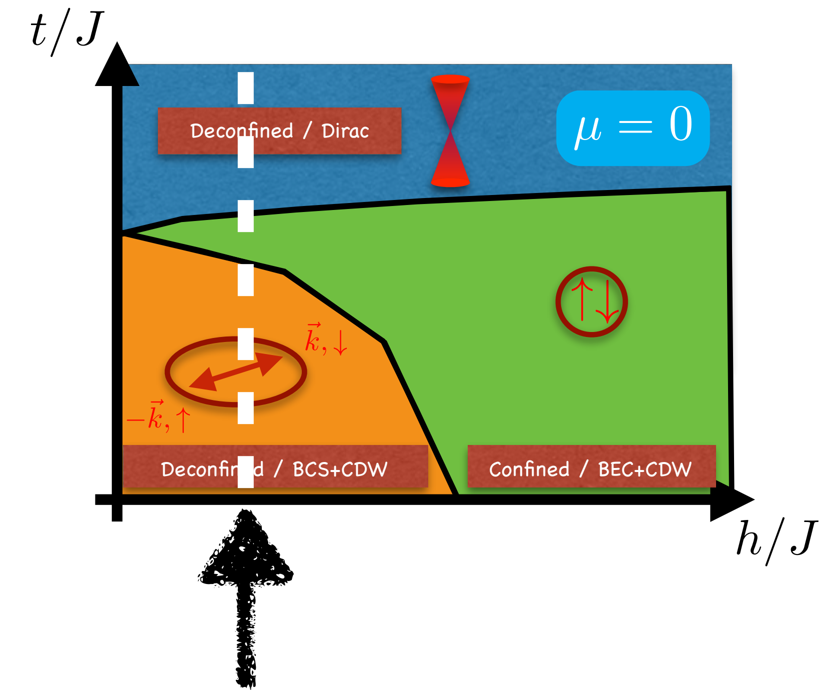

How to detect a Dirac fermion?

The single particle Green's function is not gauge invariant $G(q, i\omega_m)$

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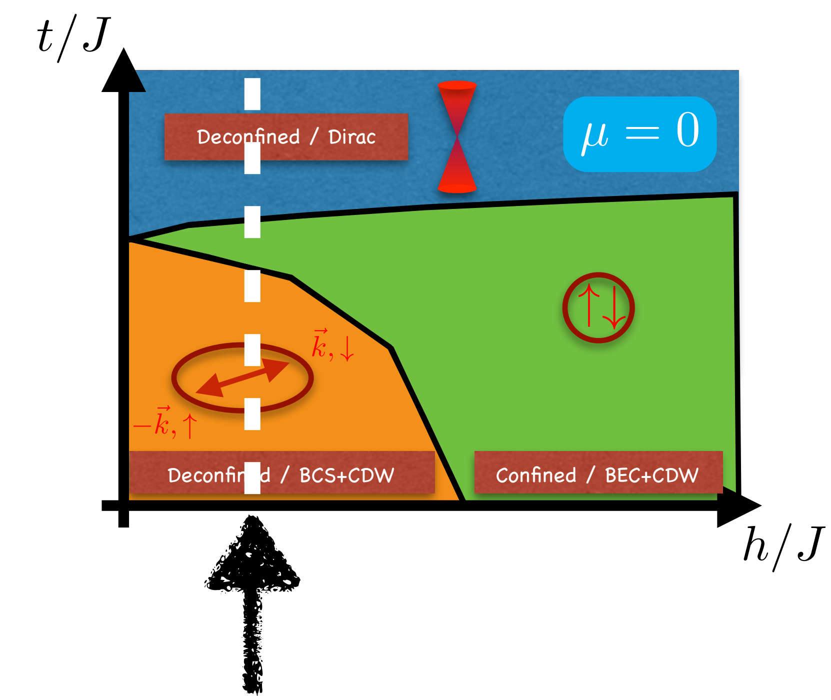

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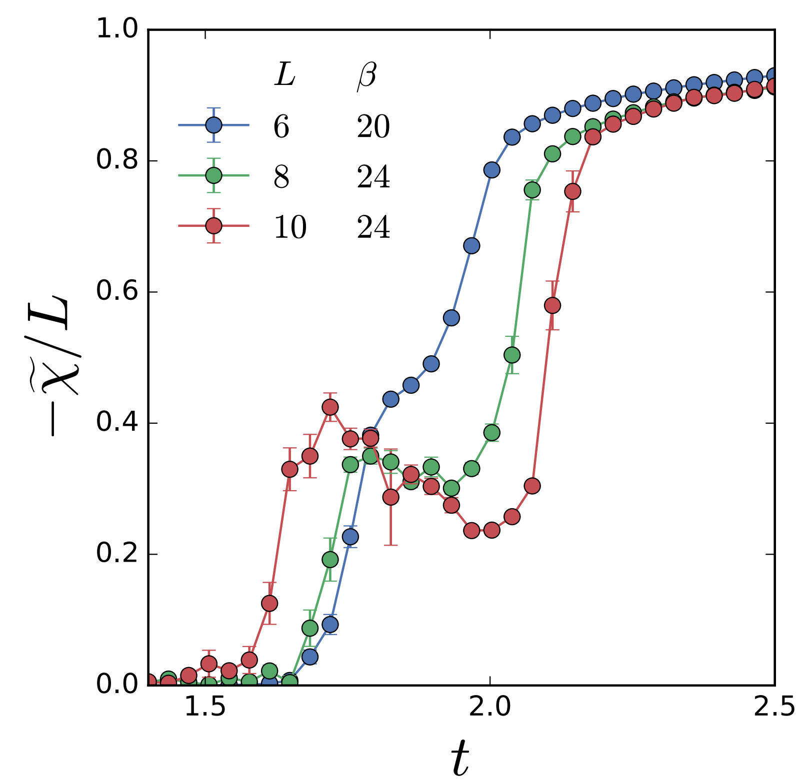
$$\chi(q) = \frac{\partial M(q)}{\partial B(q)} = -\frac{v_F}{4q}$$



Koshino, Arimura, Ando (2009)

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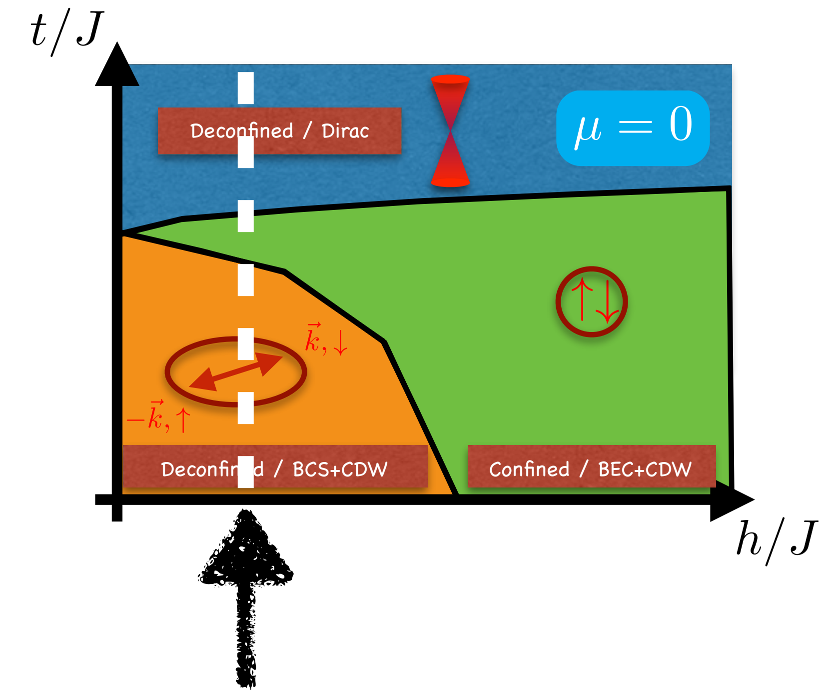

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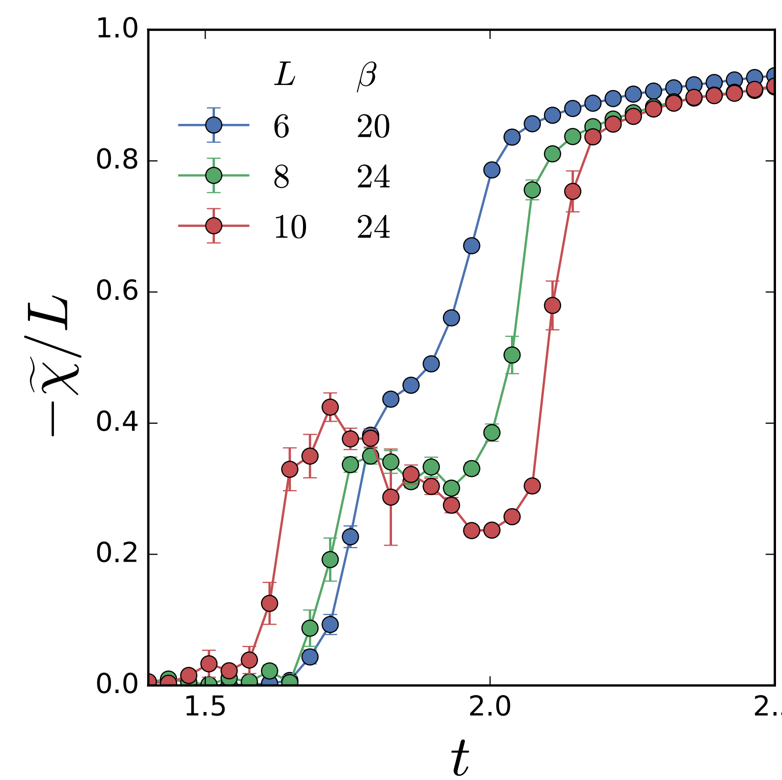
$$\frac{\tilde{\chi}}{L} = -\frac{4\pi}{Lt}\chi(q = 2\pi/L) \rightarrow \frac{v_F}{2t} \rightarrow 1$$

Non-interacting Dirac limit



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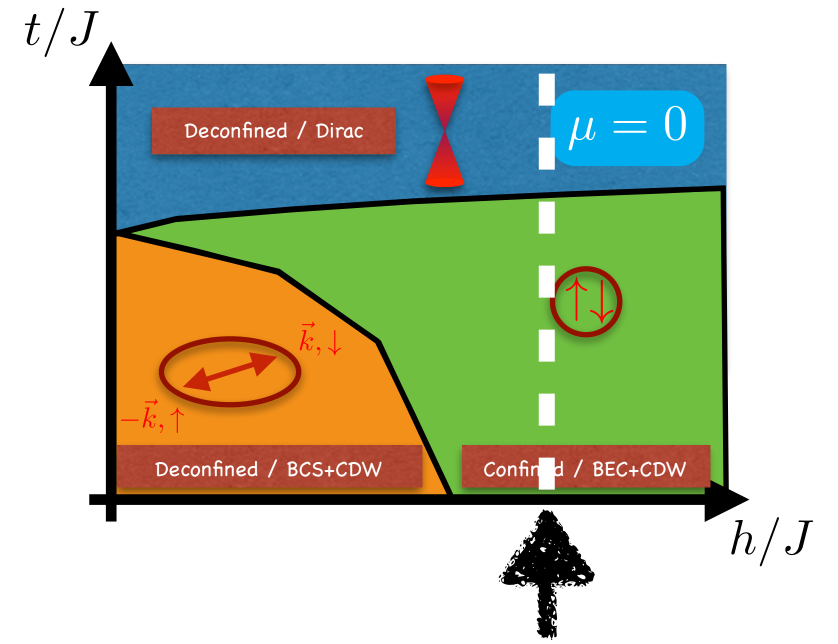

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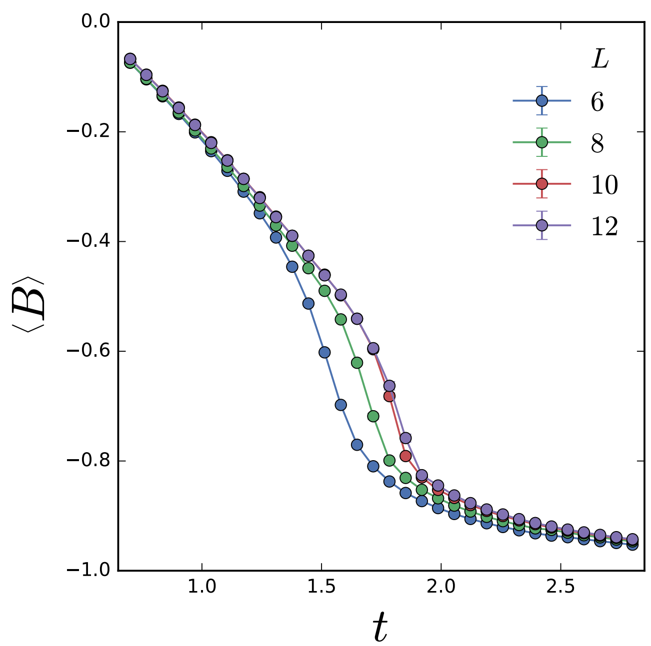

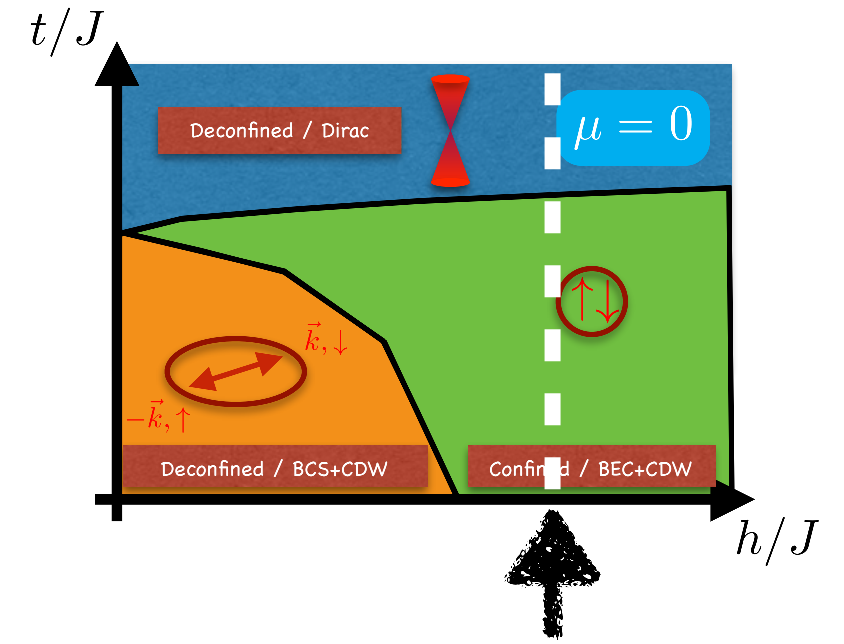

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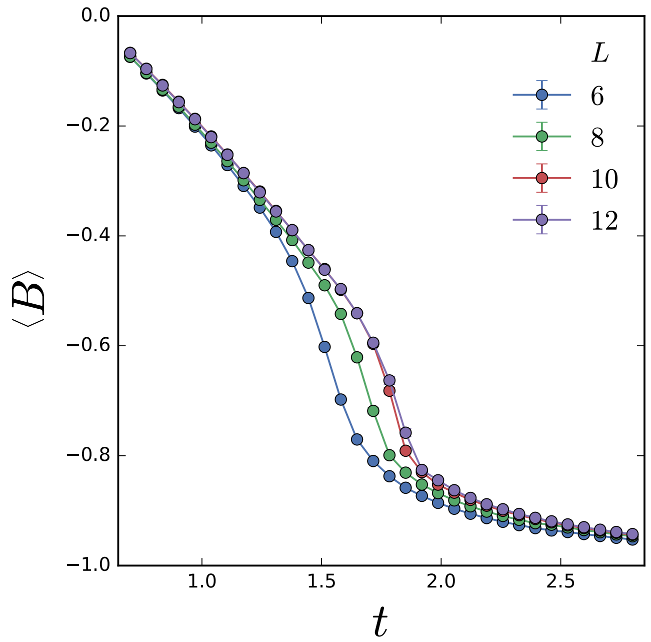
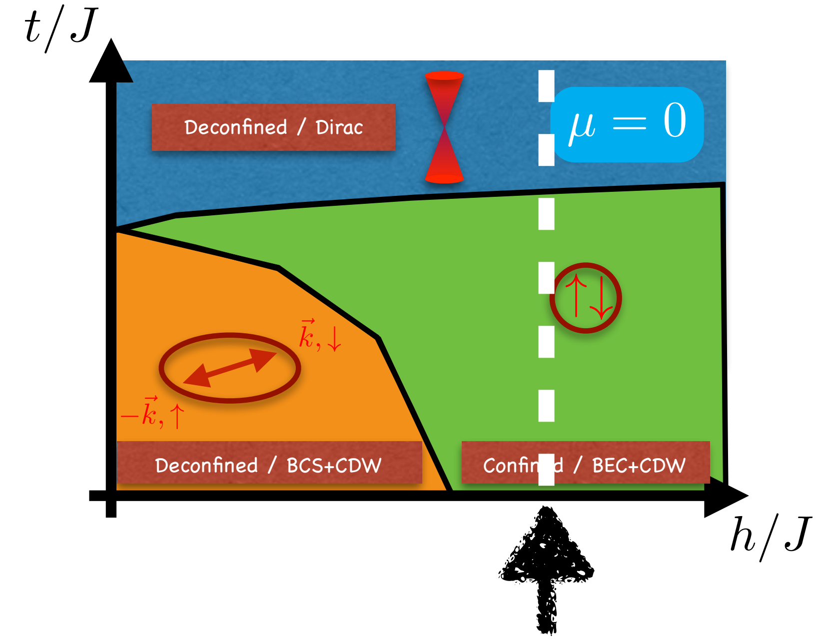
Confined





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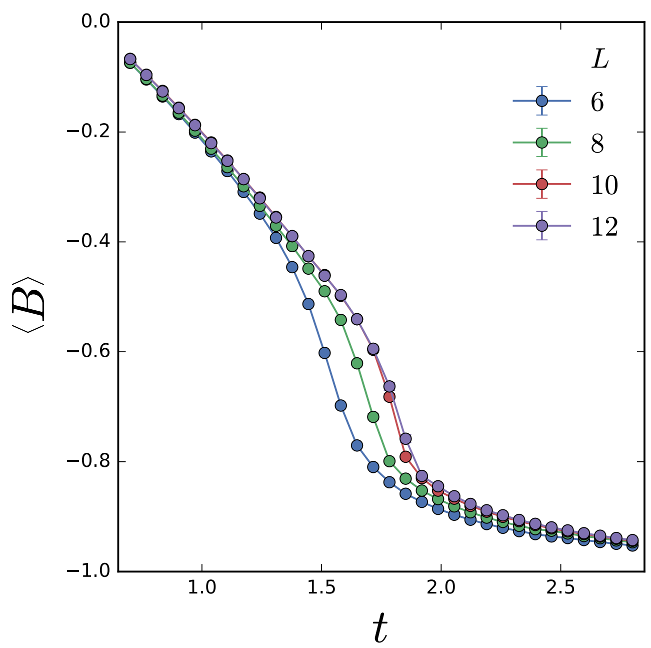

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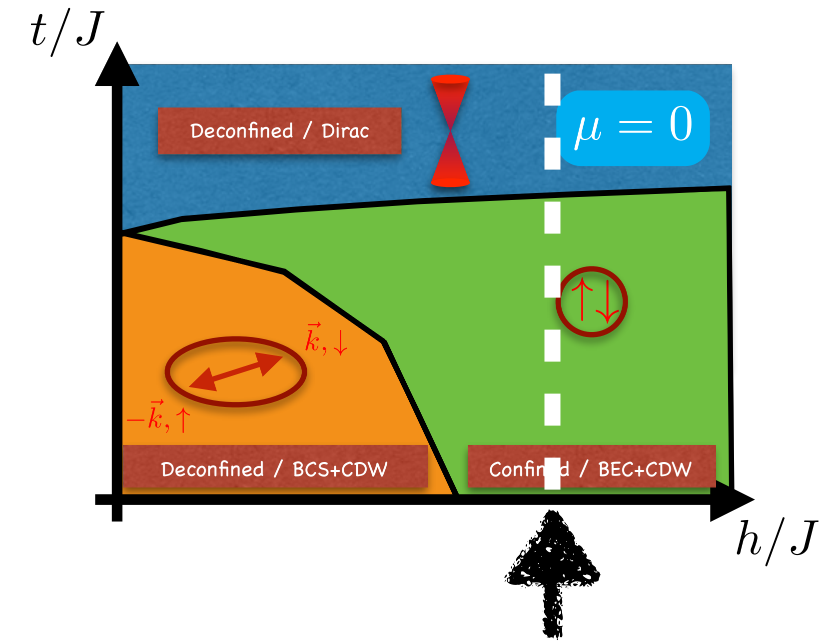

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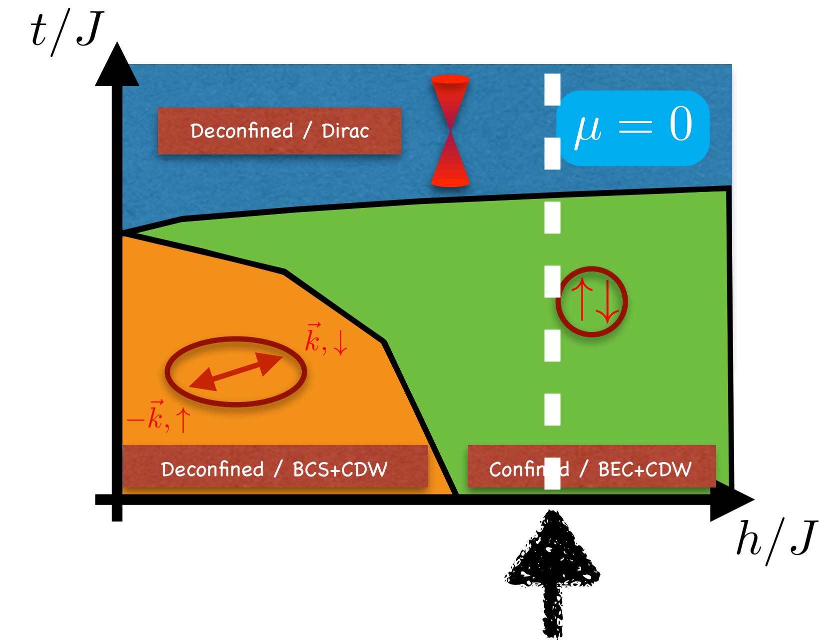

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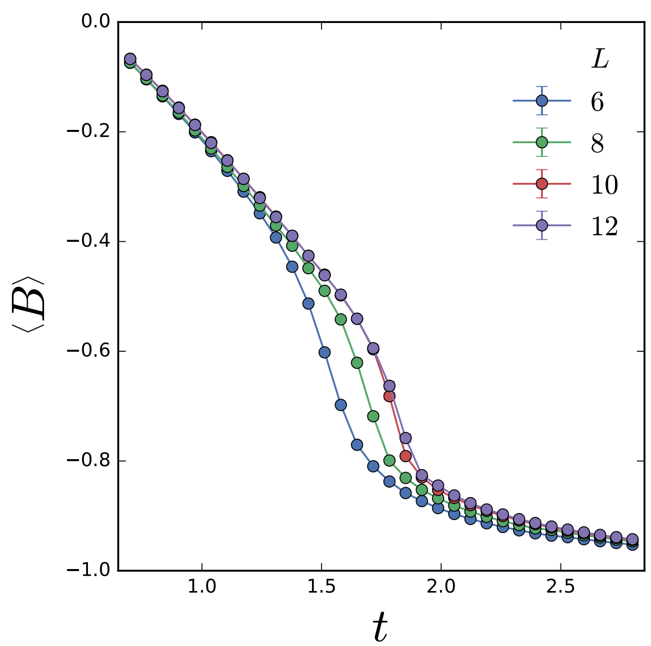

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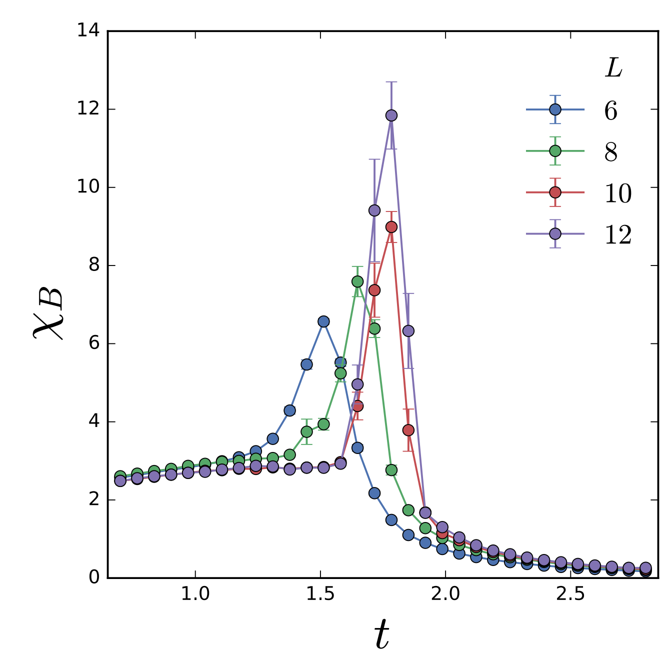

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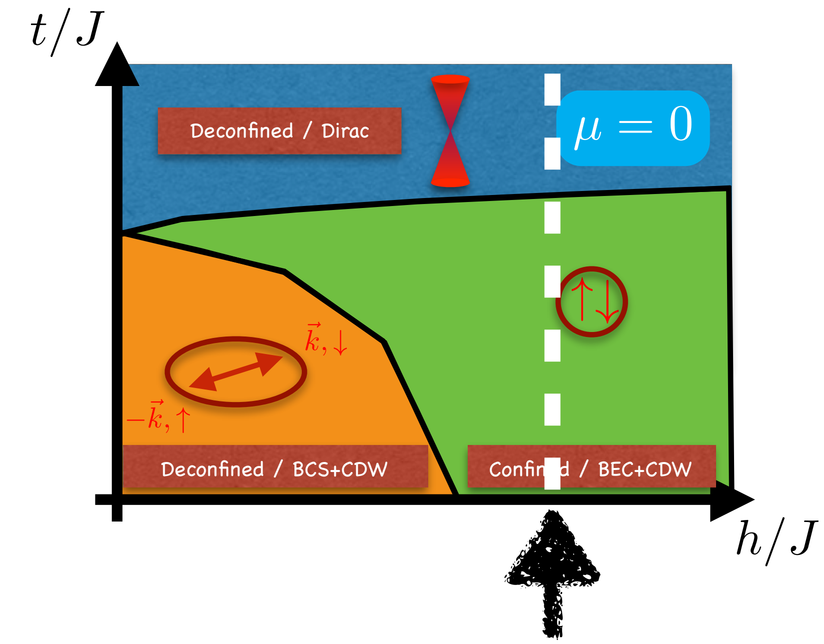

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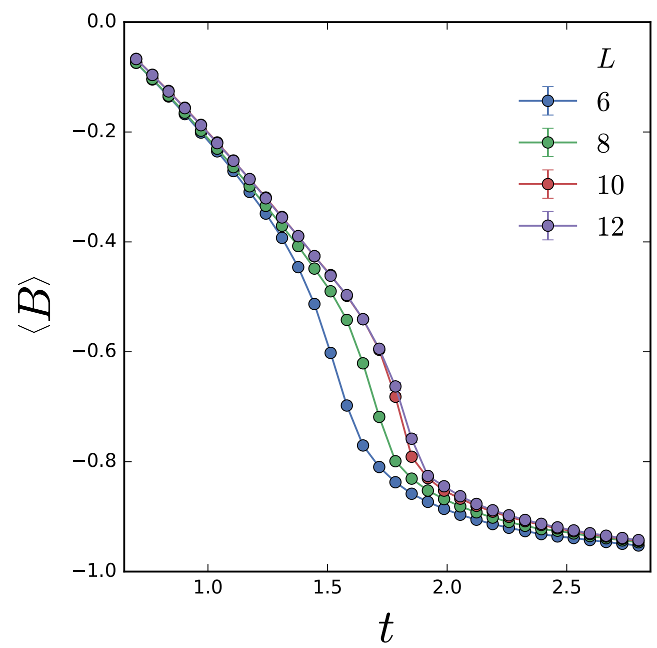

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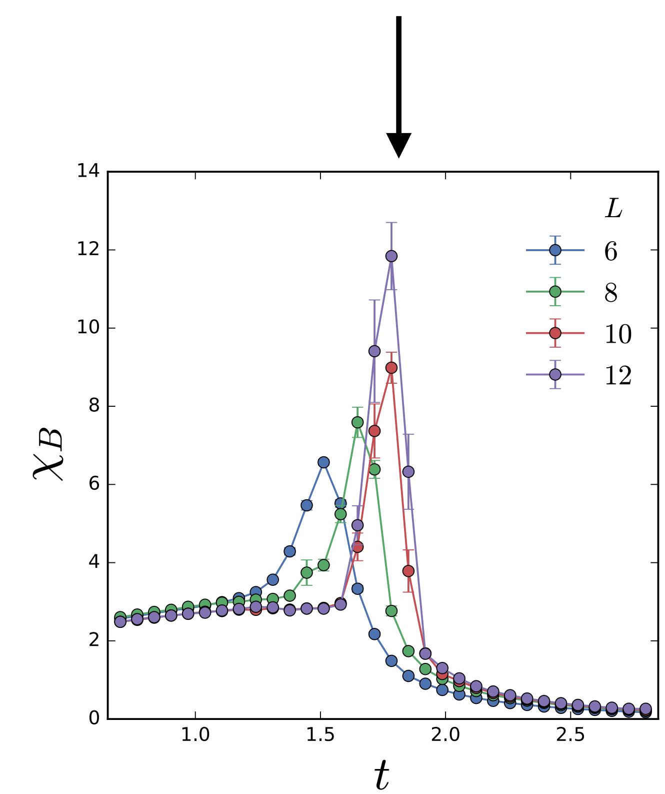
Dirac

Peak at $t_c = 1.8(1)$



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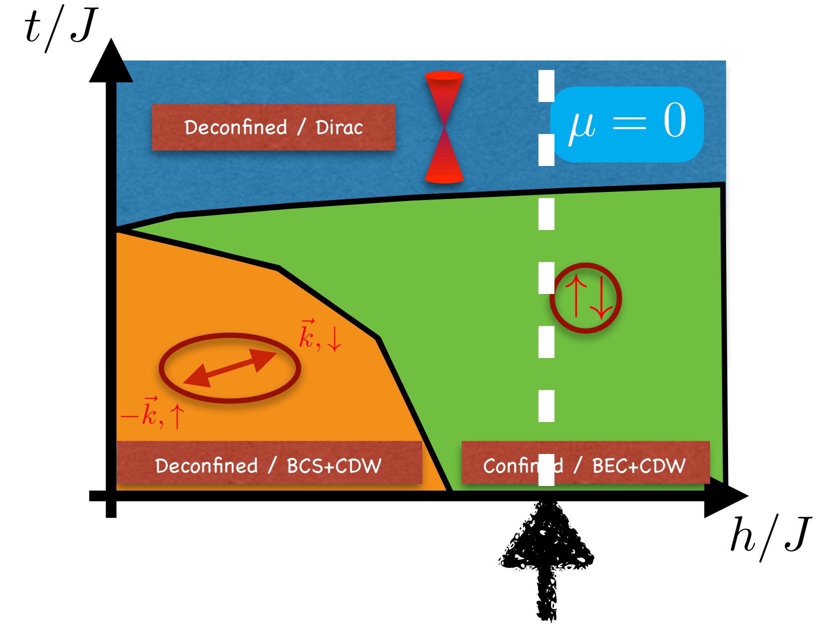

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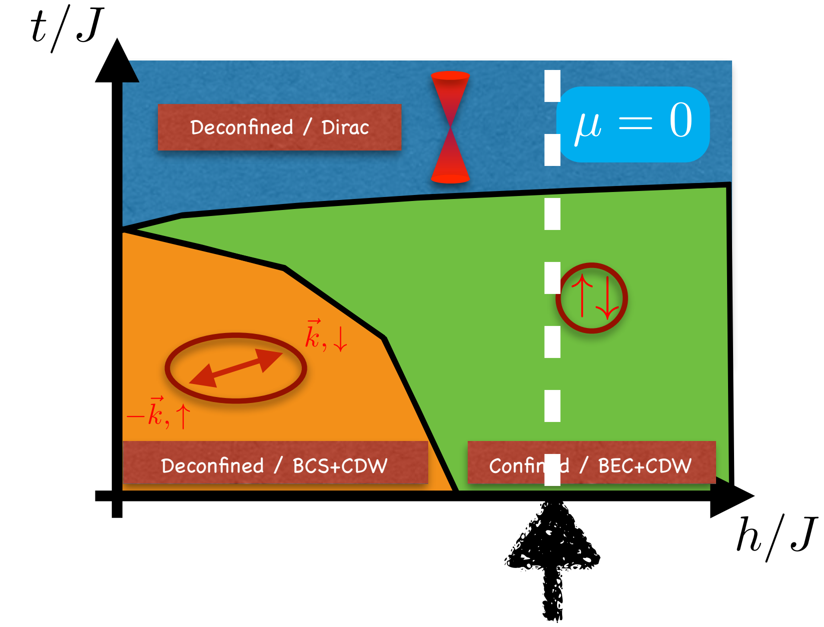
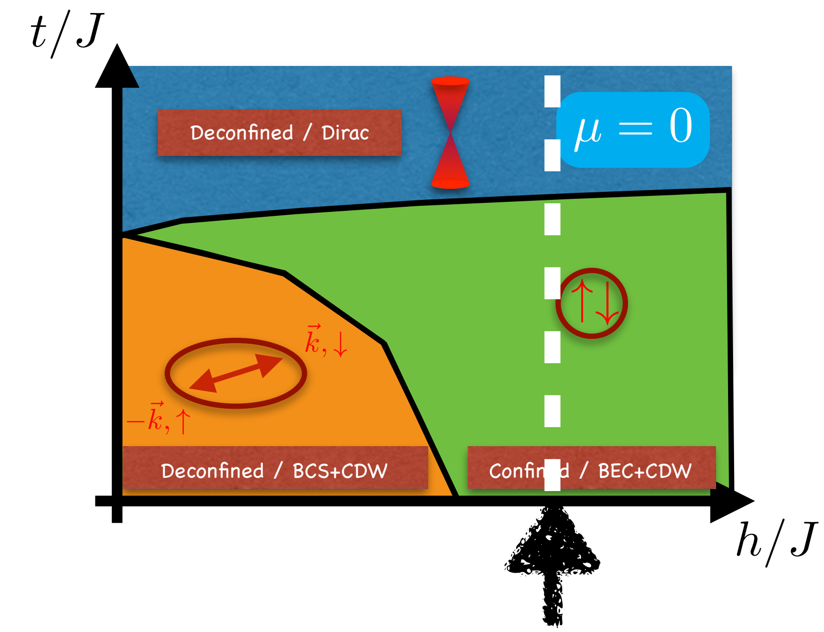


SU(2) Pseudo-spin symmetry breaking

Strong coupling $h \gg J$



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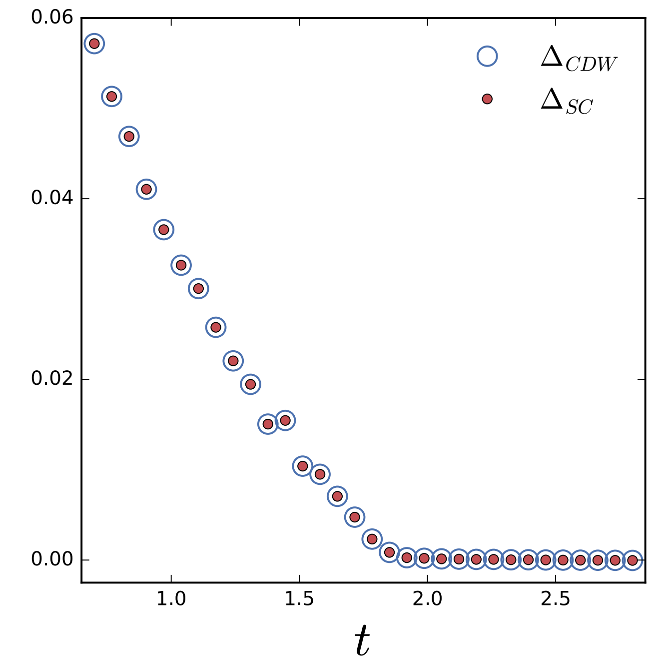
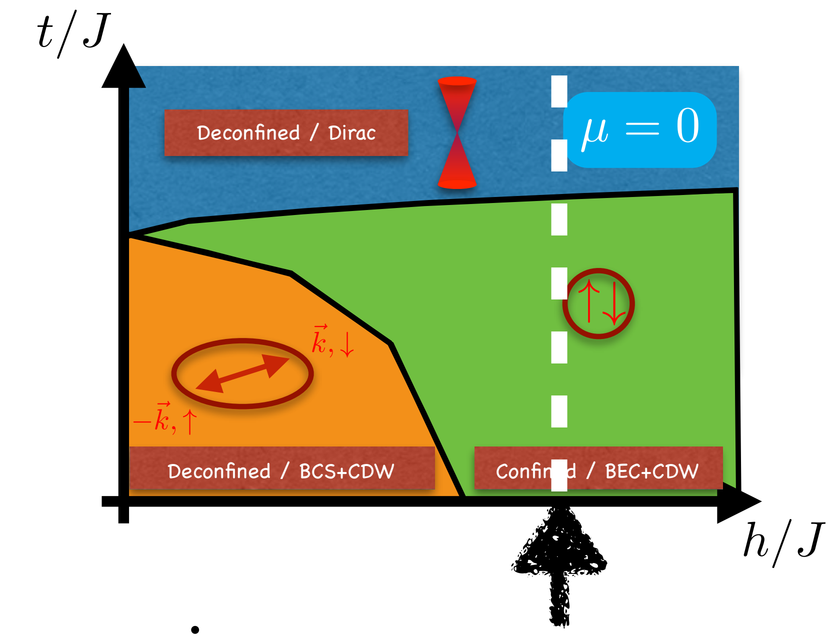


SU(2) order parameter

$$\Delta_{CDW/SC} = \lim_{L\to\infty} \lim_{\beta\to\infty} \sqrt{P_{D/P}(q = 0/G, \tau = 0)}$$

Strong coupling $h \gg J$



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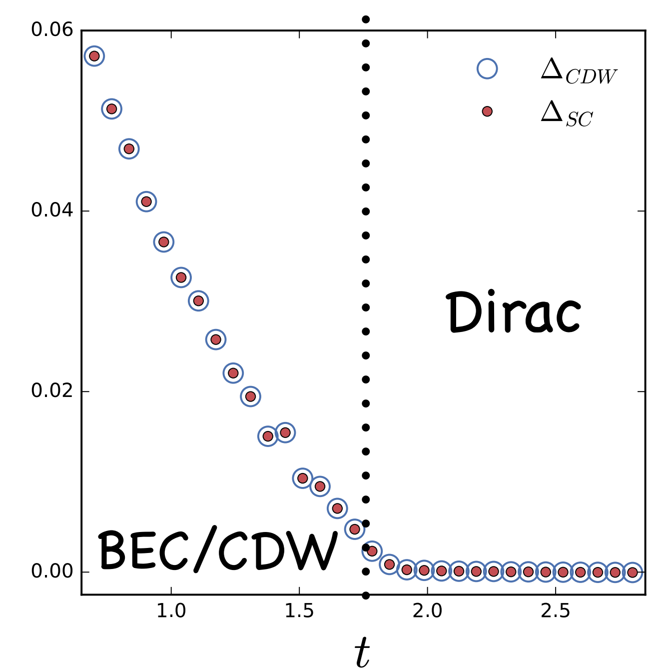

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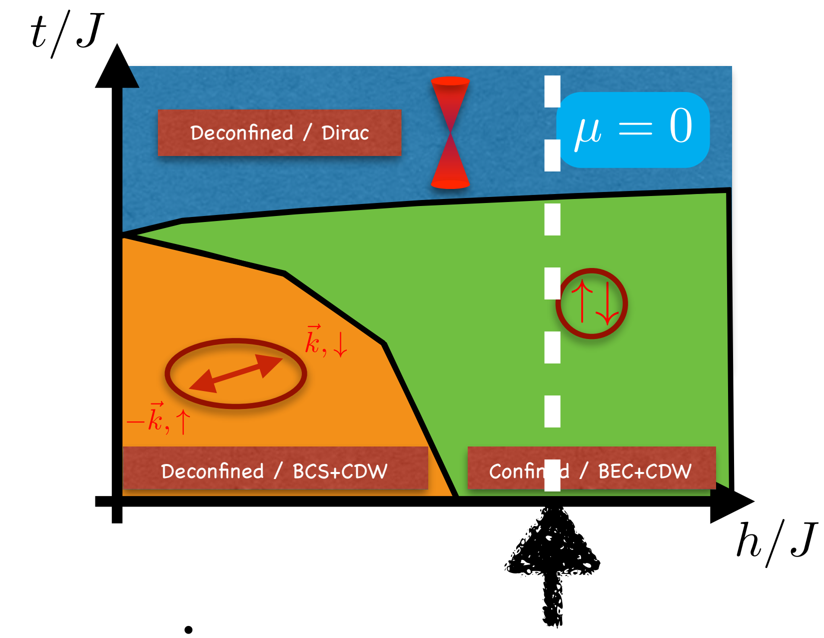

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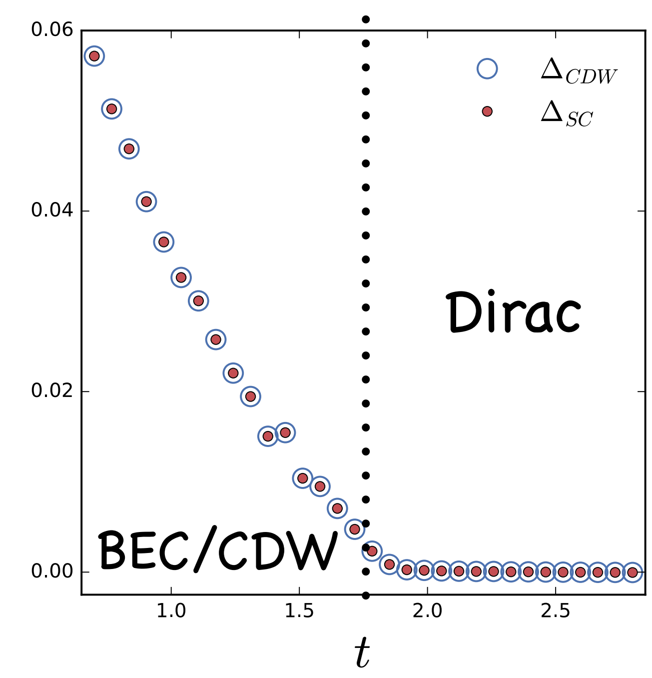

Same critical coupling!

Single continuous transition

SU(2) symmetry breaking and confinement coincide.

Single continuous transition

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Without fine tuning:

1. 1st order phase transition

2. Two split second order transitions

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Numerics suggest a single and continuous transition

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Numerics suggest a single and continuous transition

new universality class?

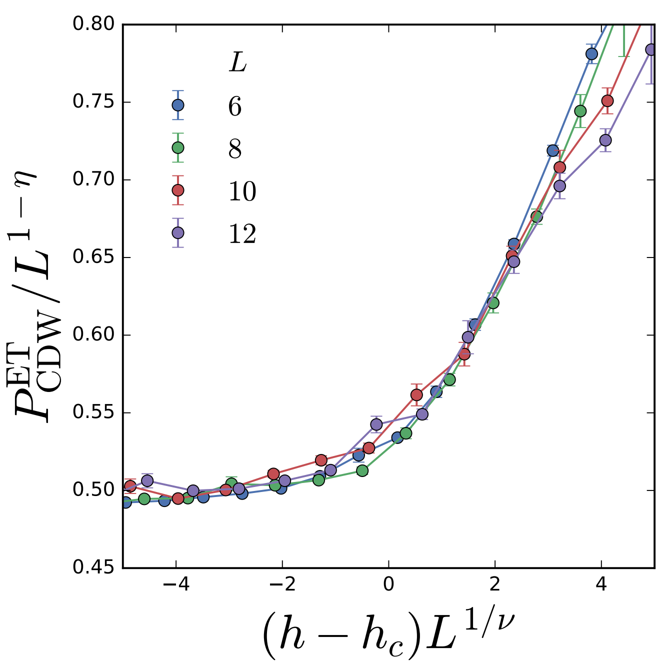
Scaling analysis

Scaling analysis

Pairing susceptibility

$$\tilde{P}_{\rm CDW} = L^{1-\eta} P_{\rm CDW}(\delta h L^{1/\nu})$$

$$h_c = 0.71(2), \nu = 0.58(5), \eta = 1.0(3)$$



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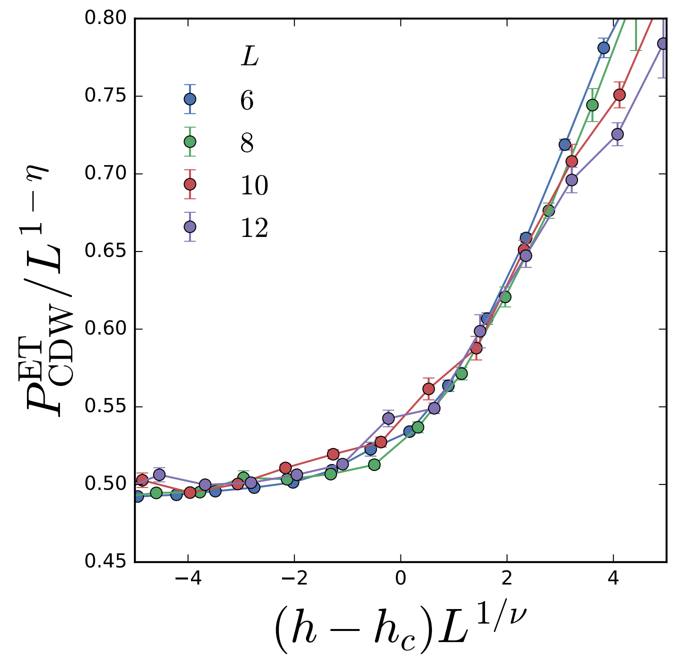
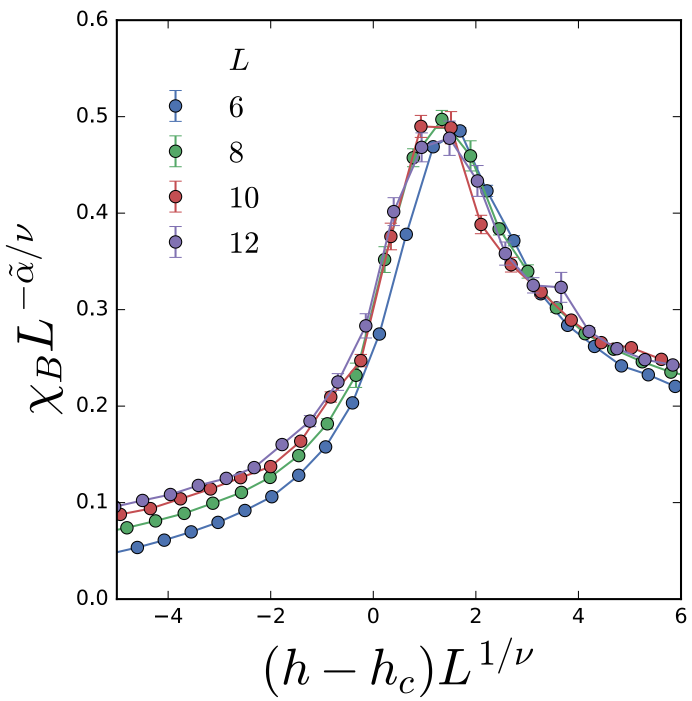


Ising susceptibility $\alpha = 0.25(5)$

$$\tilde{\chi}_B = L^{\alpha/\nu} \chi_B(\delta h L^{1/\nu})$$

Same! h_c and ν

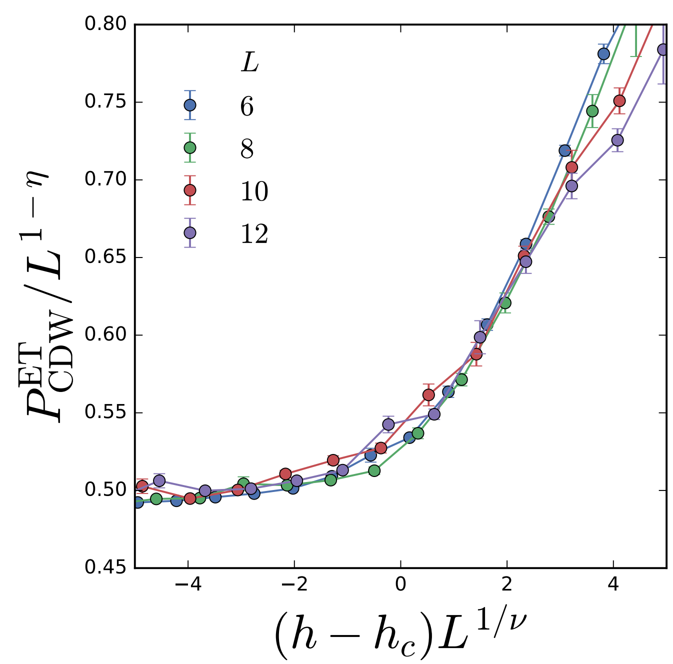


Scaling analysis

Pairing susceptibility

$$\tilde{P}_{\rm CDW} = L^{1-\eta} P_{\rm CDW}(\delta h L^{1/\nu})$$

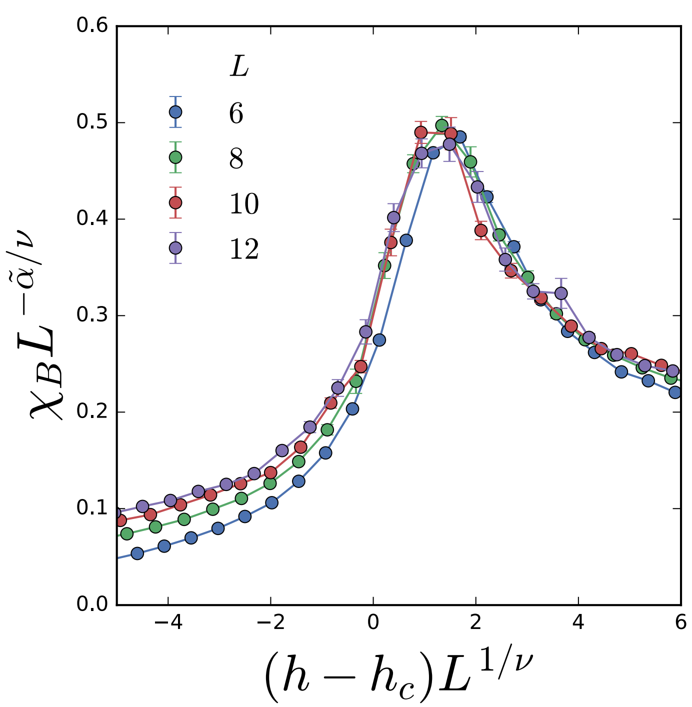
$$h_c = 0.71(2), \nu = 0.58(5), \eta = 1.0(3)$$



Ising susceptibility $\alpha = 0.25(5)$

$$\tilde{\chi}_B = L^{\alpha/\nu} \chi_B(\delta h L^{1/\nu})$$

Same! h_c and ν



Obeys hyper-scaling $2-\alpha = d\nu$

Outlook

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- Field theory description of the confinement transition. How to force confinement and symmetry breaking coincide?

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- Other Gauge groups?

Summary

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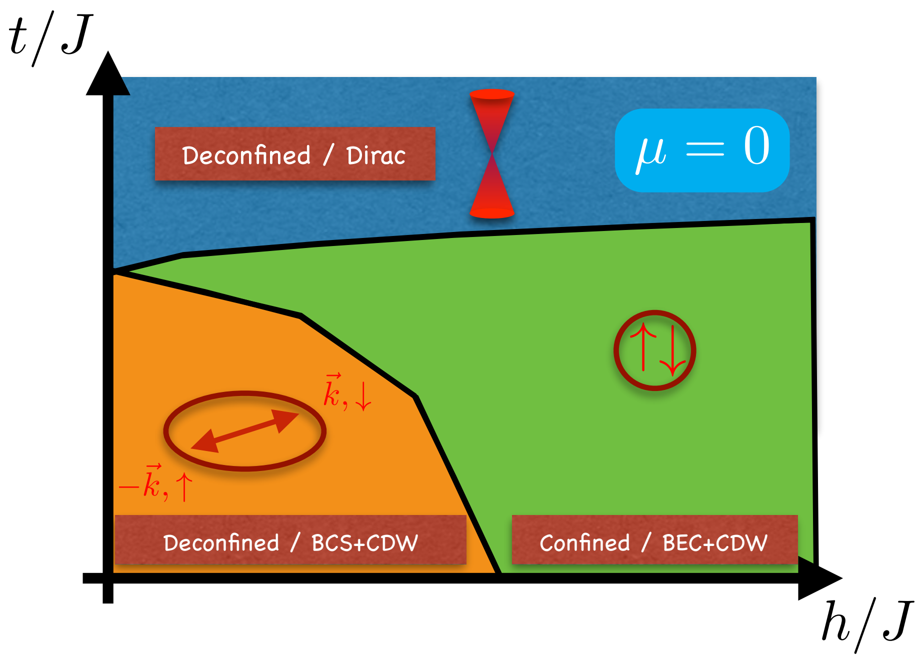
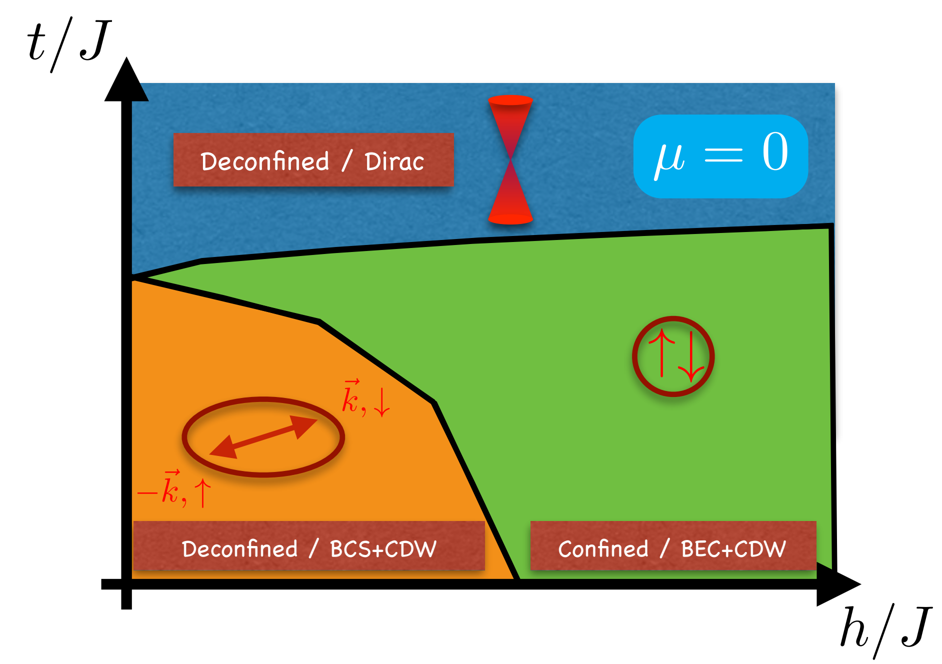
- Sign problem free lattice gauge theory at finite fermion density.



Summary

- Sign problem free lattice gauge theory at finite fermion density.
- BCS* to BEC transition driven by confinement



Summary

- Sign problem free lattice gauge theory at finite fermion density.
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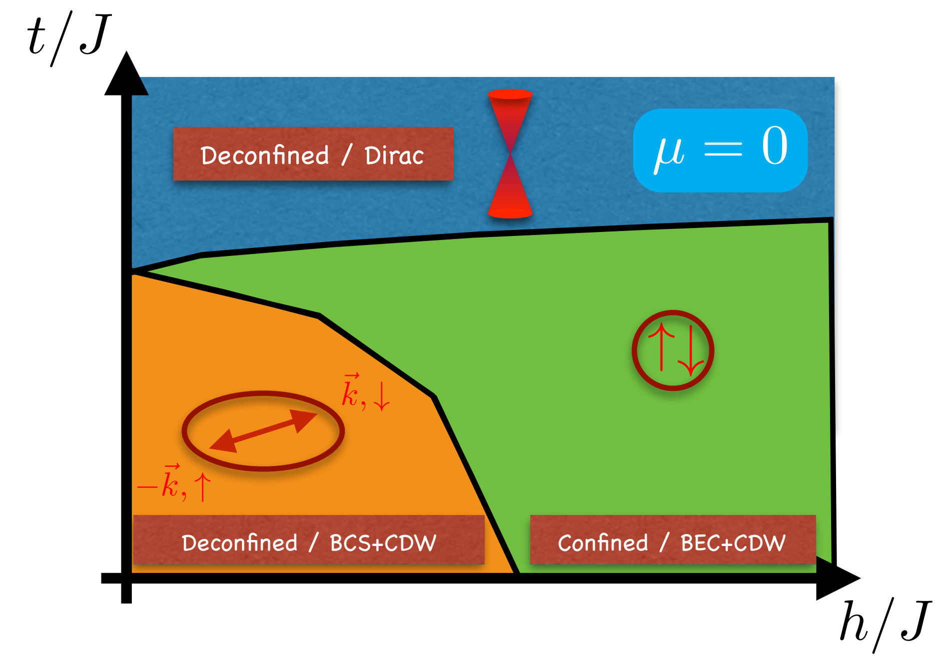

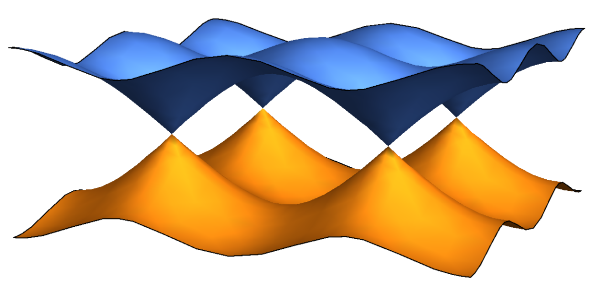

Summary

- Sign problem free lattice gauge theory at finite fermion density.
- BCS* to BEC transition driven by confinement
- Emergent Dirac fermion at zero chemical potential and large hopping amplitude
- New universality class where symmetry breaking and confinement coincide