Soluble fermionic quantum critical point in 2D

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Quantum Critical Matter
JA 2306/4-1
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

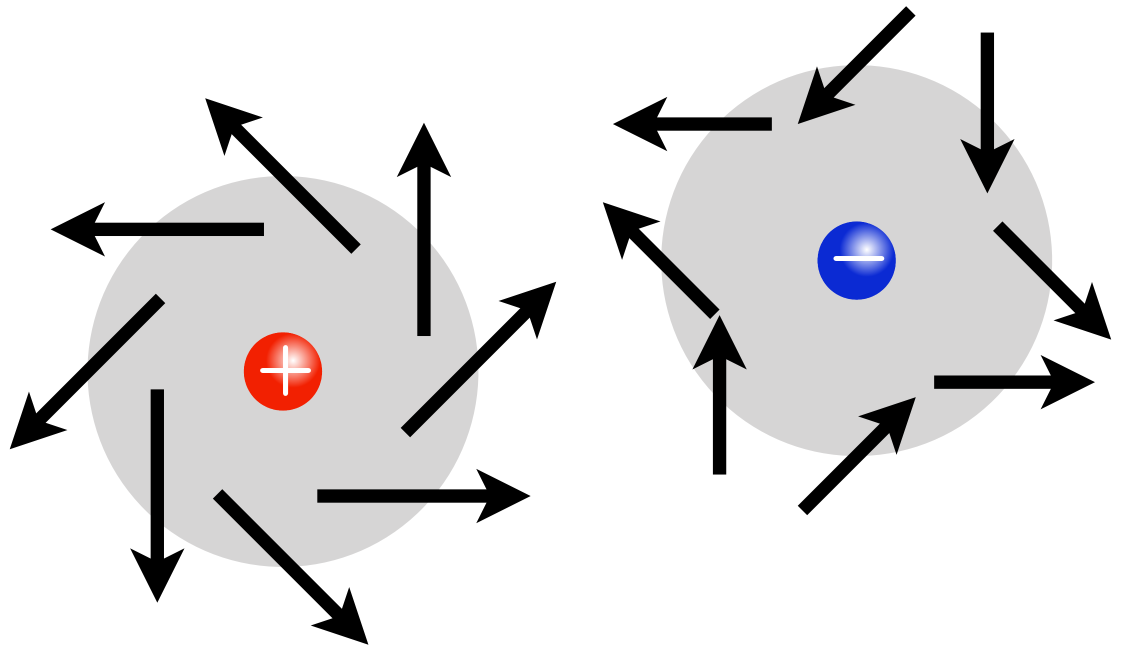
ct.qmat
Complexity and Topology in Quantum Matter
Würzburg-Dresden Cluster of Excellence

SFB 1143

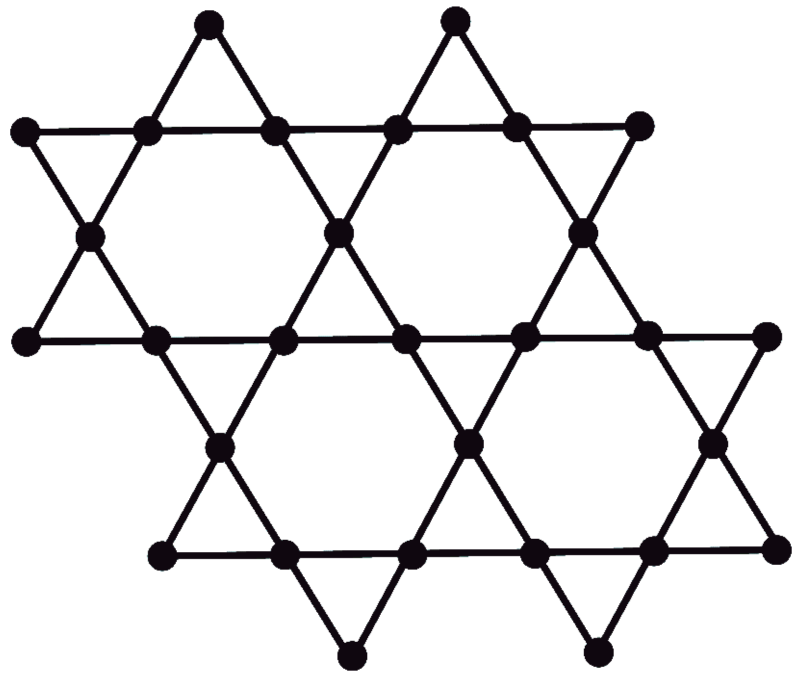
Outline

$\varepsilon_{\mathbf{p}} \propto \pm \mathbf{p}^2$

1) Introduction

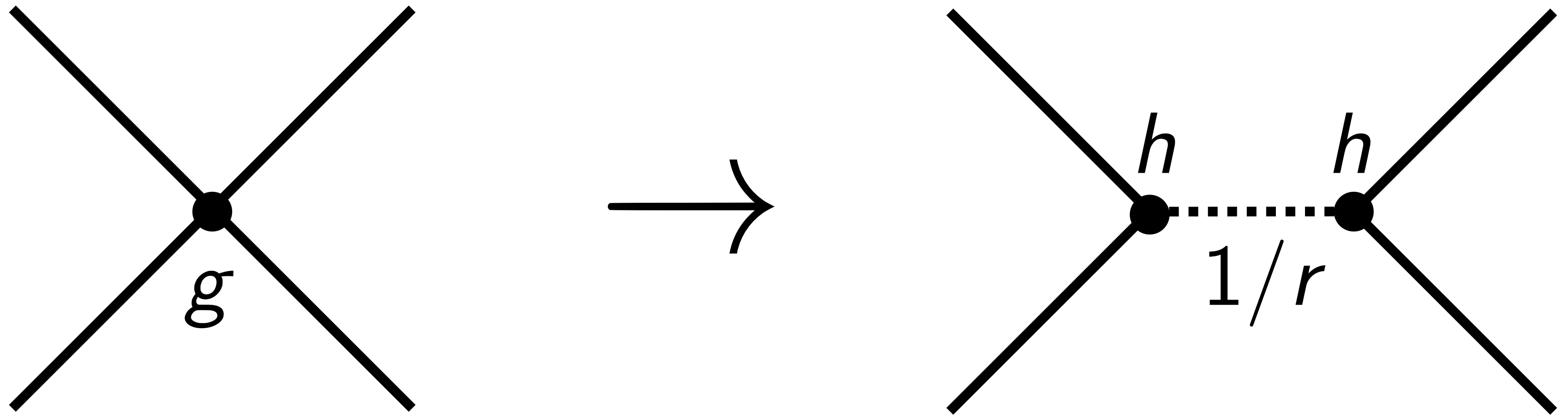


2) Review: BKT transition



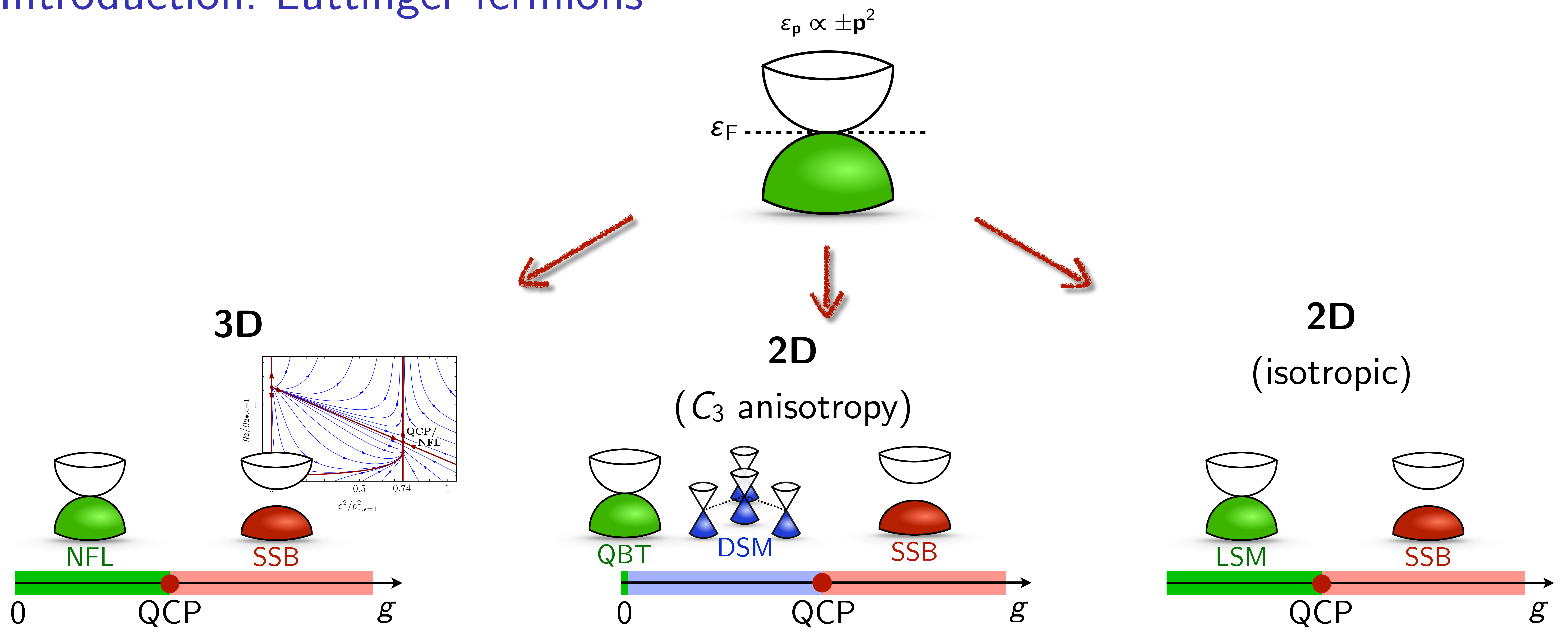
3) "Luttinger" fermions on kagome lattice

4) Critical behavior: "Luttinger-Yukawa" theory



5) Conclusions

Introduction: Luttinger fermions



... non-Fermi liquids (large-N)
... quantum critical points
... fixed-point collisions

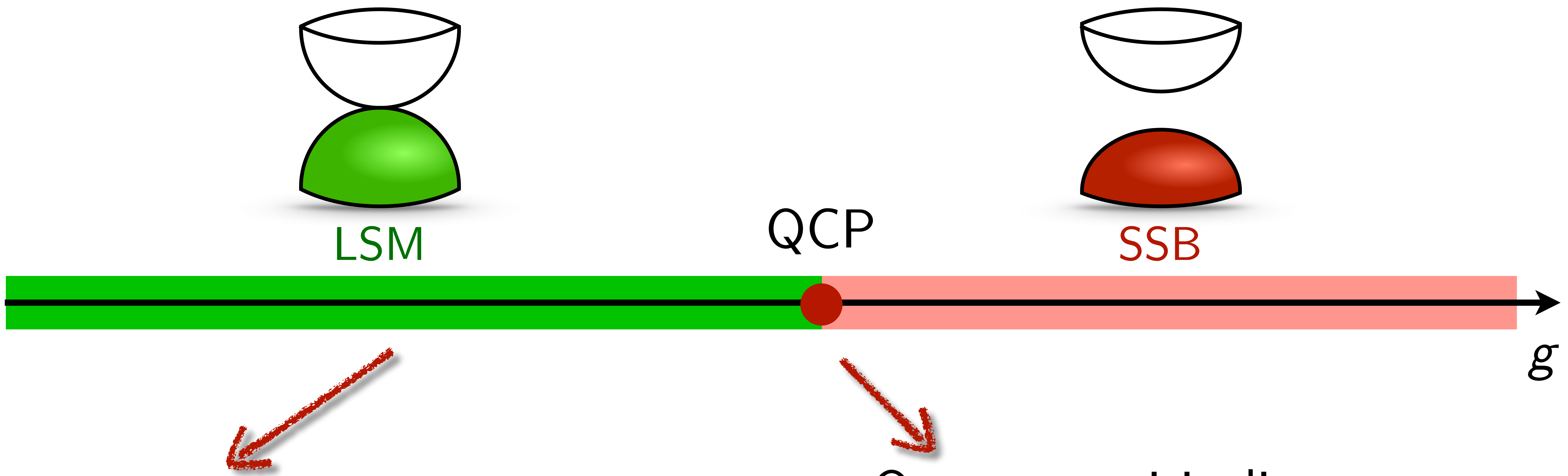
→ talk by I. Herbut

... dynamical generation of Dirac cones
... emergent Lorentz invariance
... Gross-Neveu criticality

→ talk by S. Ray

... solvable and nontrivial

Isotropic QBT in 2D



Disordered phase:

- Stable semimetal ... despite finite DOS
- Emergent scale invariance

$$\langle \phi(0,\mathbf{r})\phi(0,0)\rangle \propto \frac{1}{|\mathbf{r}|^{z+\eta_\phi}}$$

... with $z = 2$
... and $\eta_\phi = 2$

Quantum criticality:

- Essential singularities close to QCP

$$\xi \propto \mathrm{e}^{4\pi/\delta g} \qquad (\delta g \equiv g - g_c > 0)$$

- Power laws right at QCP

$$\langle \phi \rangle \propto h^{1/\delta} \qquad (\delta g = 0)$$

... with $\delta = 1$ exactly

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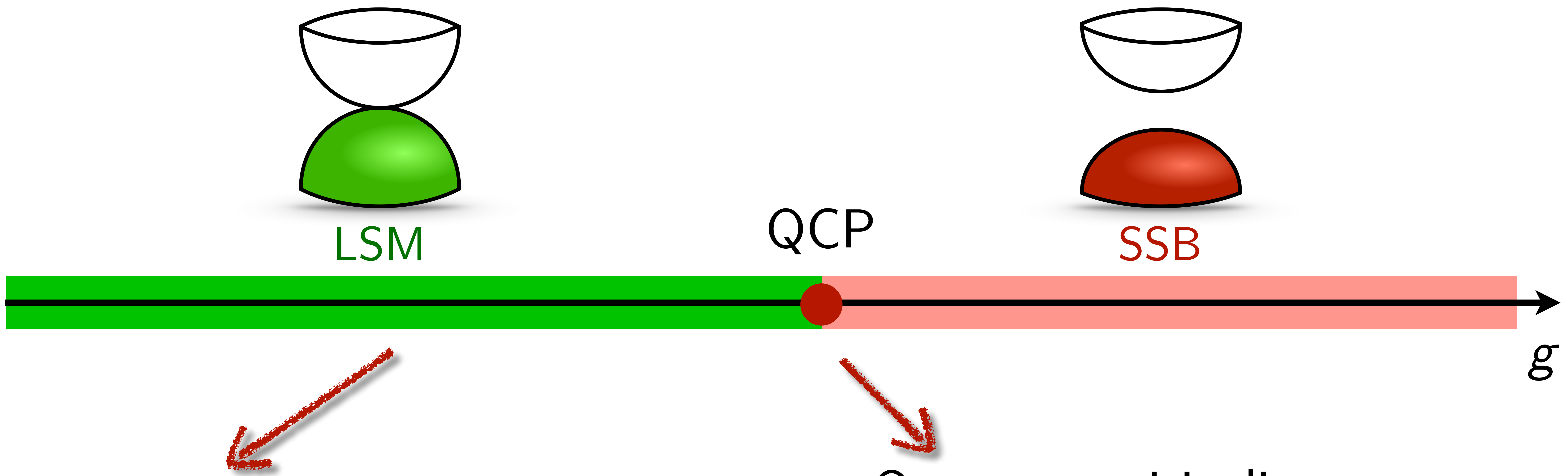

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Phenomenology: Quantum version of BKT transition

Review: BKT transition

[Herbut, CUP '07]

Classical 2D XY model:

$$\mathcal{H}_{\mathrm{XY}} = -\sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \qquad \text{with } \mathbf{S}_i \equiv \mathbf{S}(\mathbf{r}_i) \equiv \begin{pmatrix} \cos\theta(\mathbf{r}_i) \\ \sin\theta(\mathbf{r}_i) \end{pmatrix} : \mathbb{R}^2 \mapsto S^1$$

$$\simeq \frac{1}{2} \int \mathrm{d}^2\mathbf{r} \, (\nabla\theta(\mathbf{r}))^2$$

... in continuum limit

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... in continuum limit

Closed contour $\mathcal{C} \in \mathbb{R}^2$:

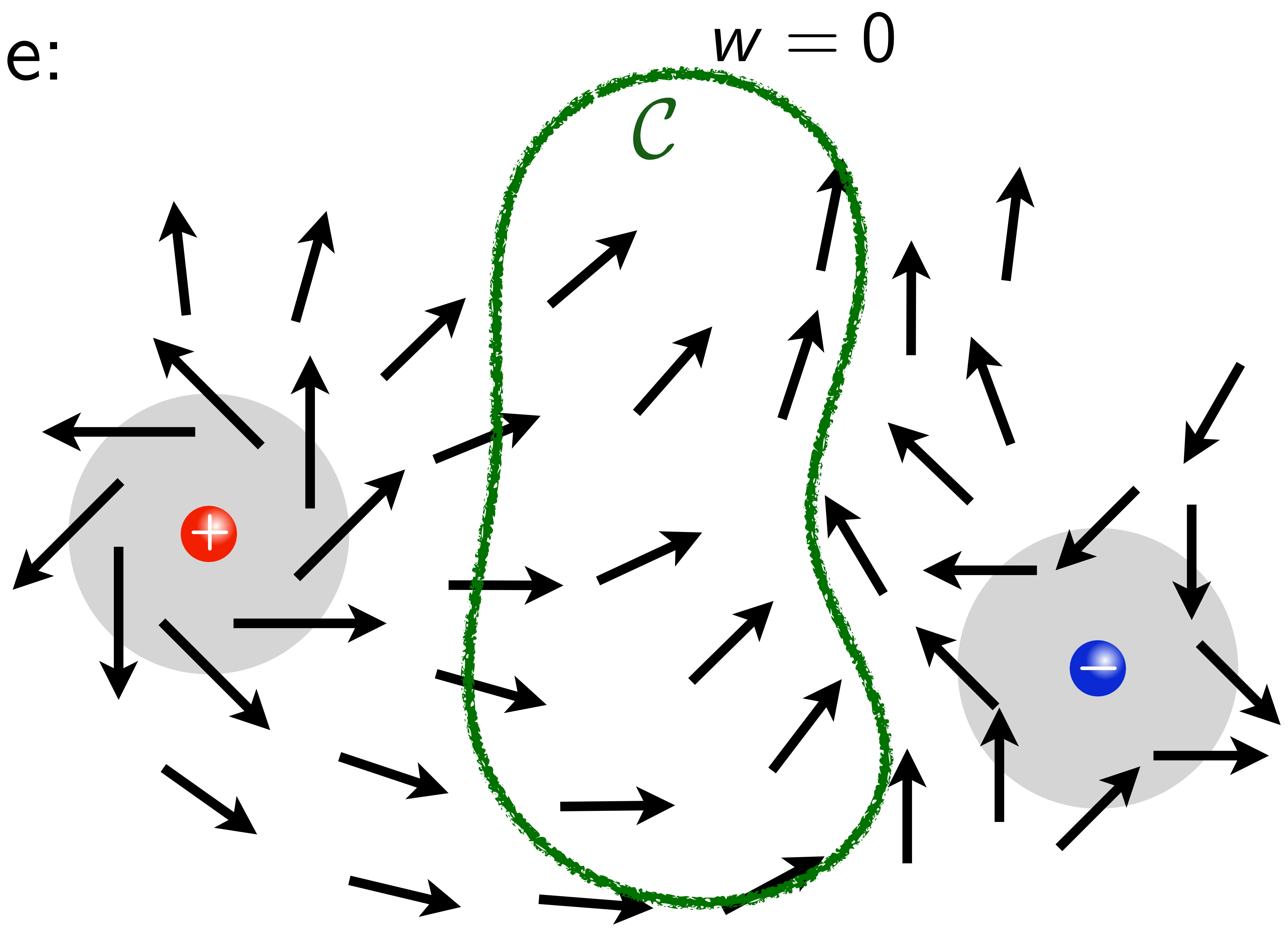
$$w = \frac{1}{2\pi} \oint d\mathbf{r} \cdot \nabla\theta(\mathbf{r}) \in \mathbb{Z}$$

... winding number

$$= \sum_{\substack{\text{vortices} \\ \text{in } \mathcal{C}}} q_i$$

... q_i: vortex charges

Example:



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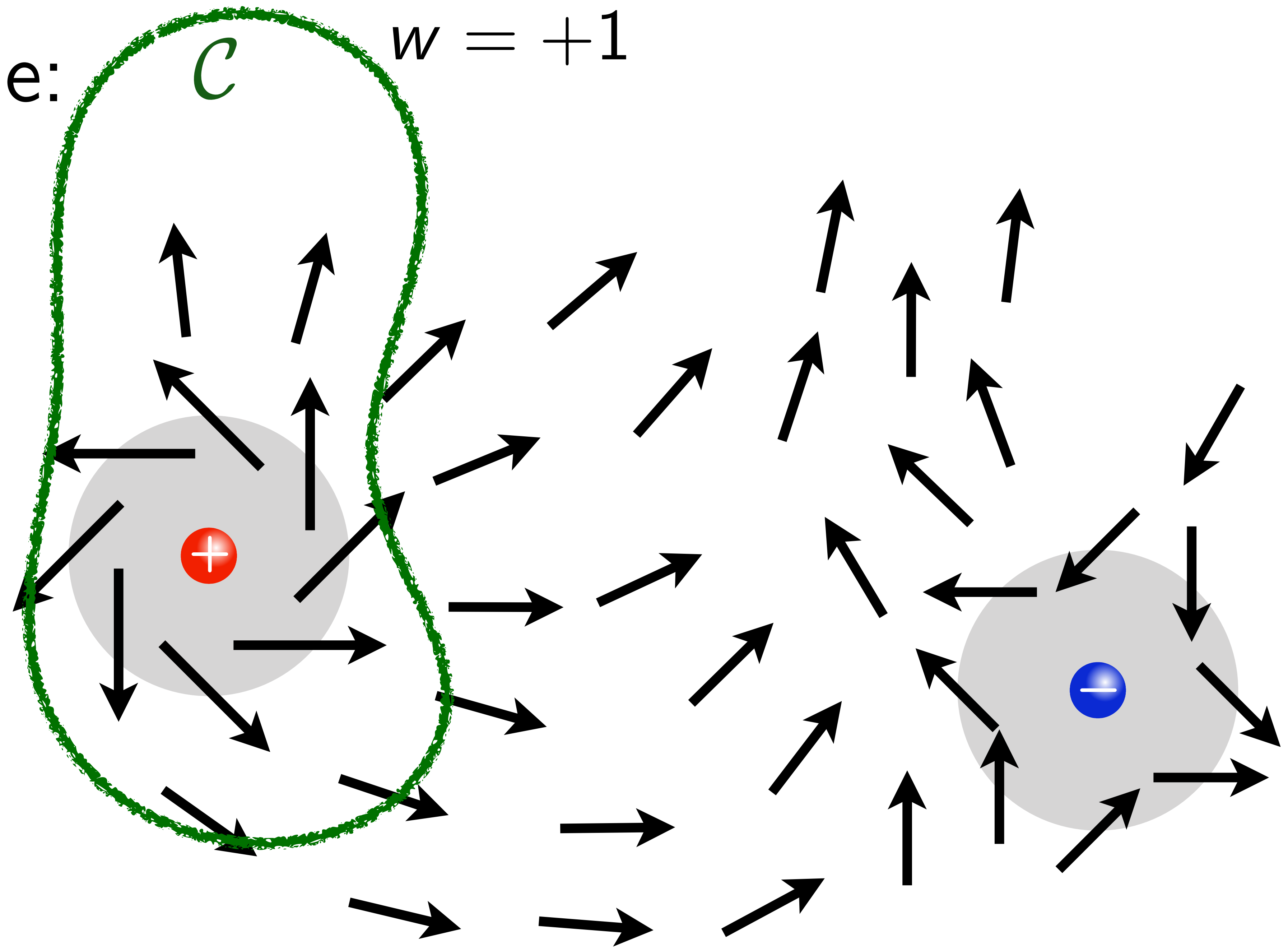

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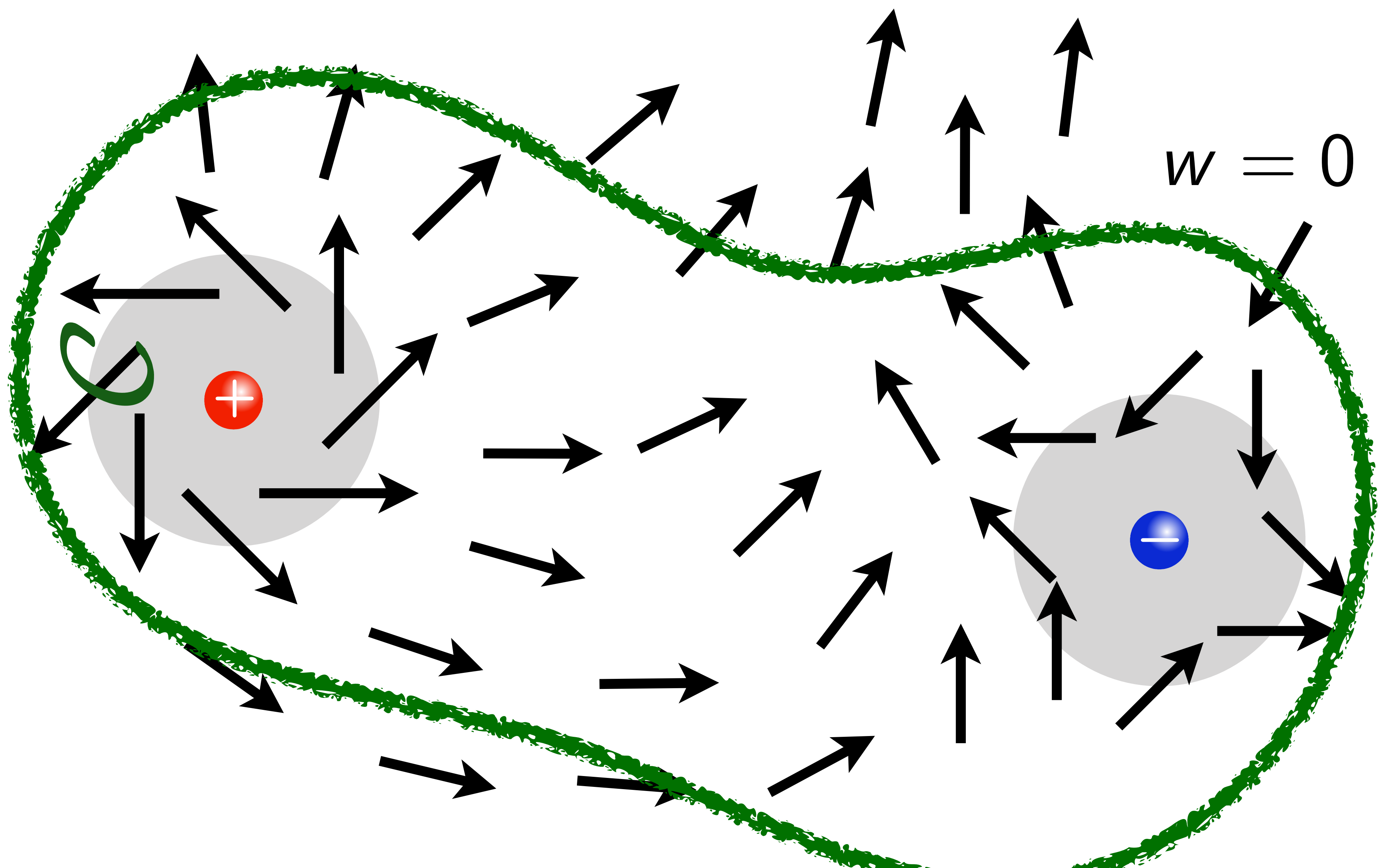
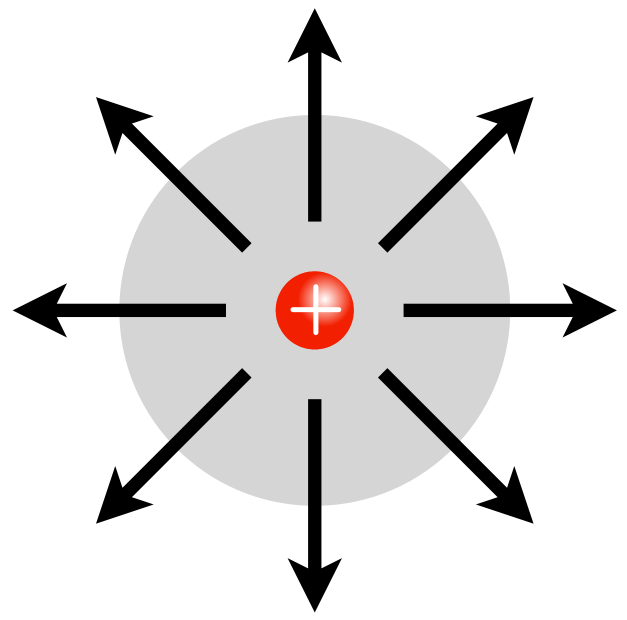


Vortex excitations

Isolated vortex:

$$\theta(\mathbf{r}) = q\alpha \qquad \text{where} \quad \mathbf{r} = r\begin{pmatrix}\cos\alpha \\ \sin\alpha\end{pmatrix}$$



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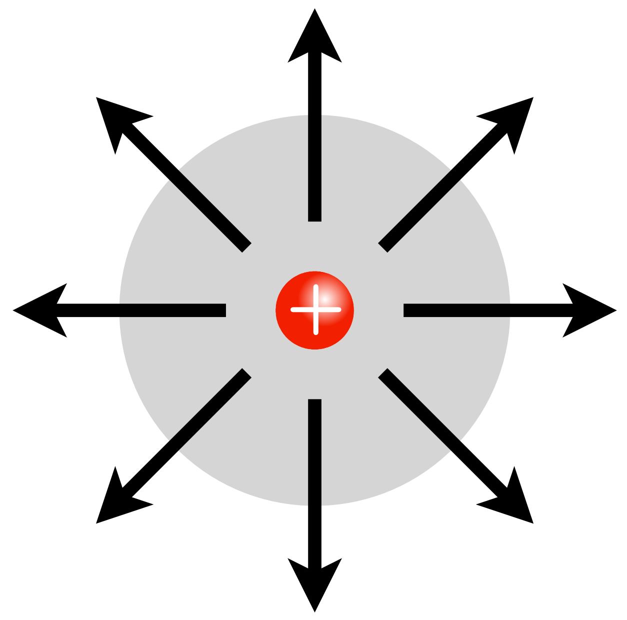

Energy:

system size

$$E_V = \frac{1}{2}\int d^2\mathbf{r}\,(\nabla\theta(\mathbf{r}))^2 = \pi q^2 \ln\frac{R}{r_0} \quad \xrightarrow{R\to\infty} \quad \infty$$

... vortices suppressed at low T

"vortex size" ... short-distance cutoff $r_0 \gtrsim a$

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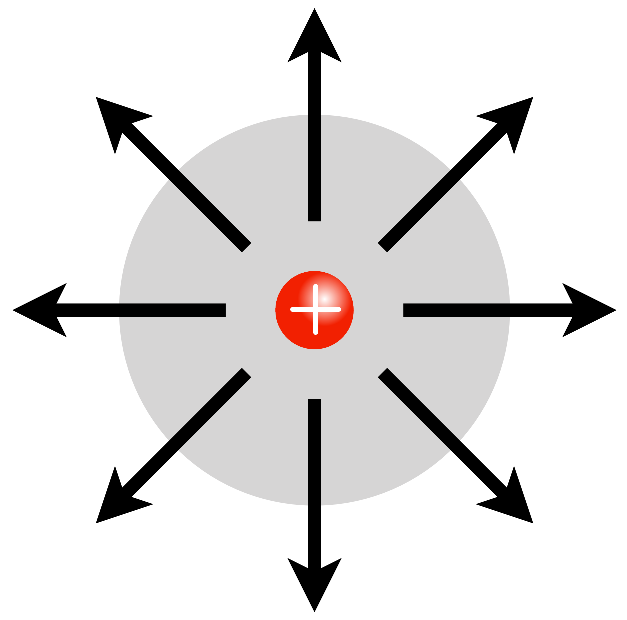

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"vortex size" ... short-distance cutoff $r_0 \gtrsim a$

Entropy:

$$S_V = \ln \Omega \simeq \ln \left(\frac{R}{r_0}\right)^2 \quad \xrightarrow{R\to\infty} \quad \infty$$

... (same) logarithmic divergence
... vortices proliferate at high T

Vortex proliferation

Free energy (isolated vortex):

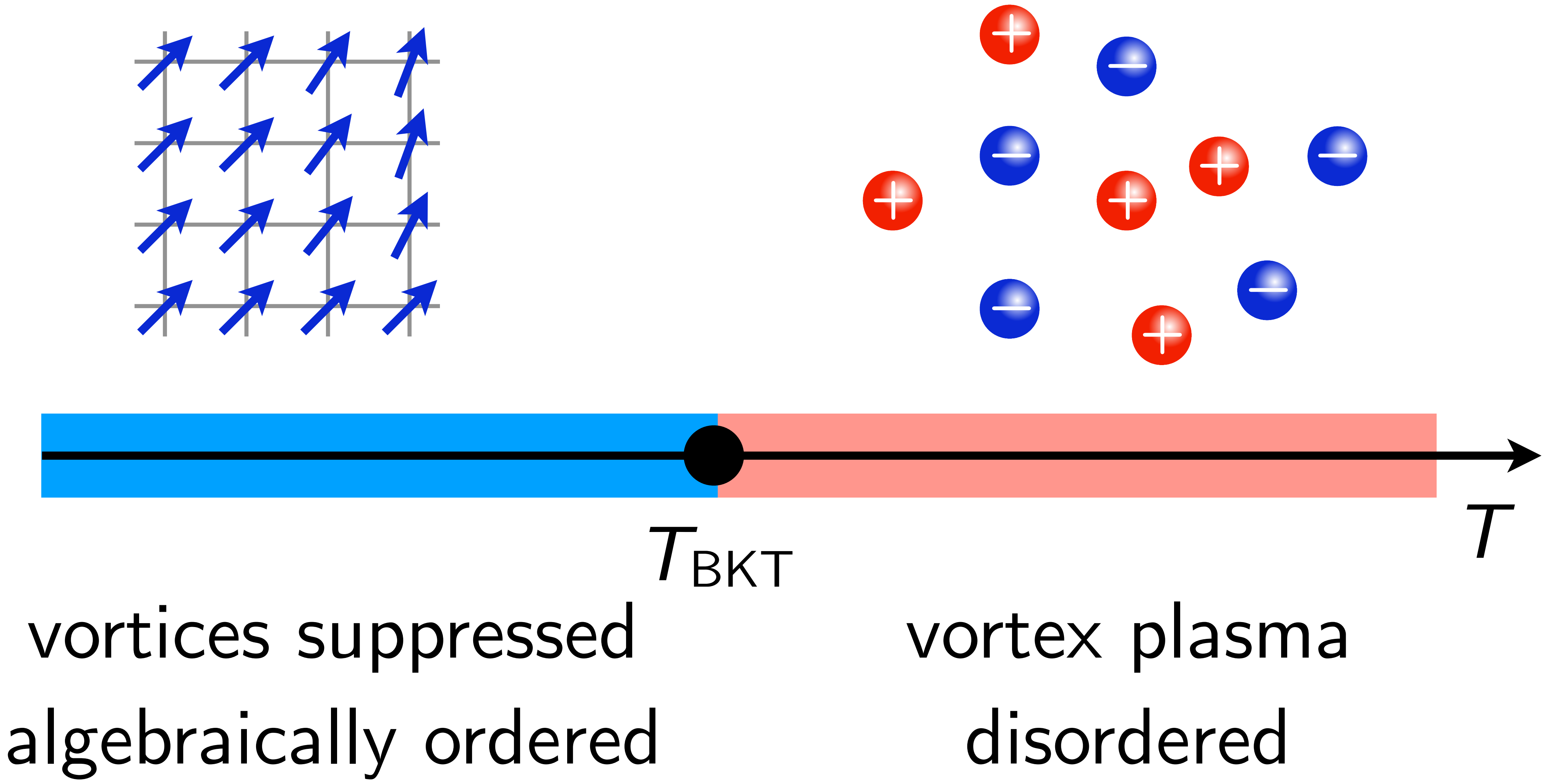
$$\Delta F = E_\mathrm{V} - T S_\mathrm{V}$$
$$= \pi q^2 \ln \frac{R}{r_0} - 2T \ln \frac{R}{r_0}$$
$$\begin{cases} > 0 & \text{for } T < \frac{\pi}{2} q^2 \\ < 0 & \text{for } T > \frac{\pi}{2} q^2 \end{cases}$$

Transition temperature:

$$T_\mathrm{BKT} = \frac{\pi}{2}$$

... above which $q = \pm 1$ vortices proliferate

Phase diagram:

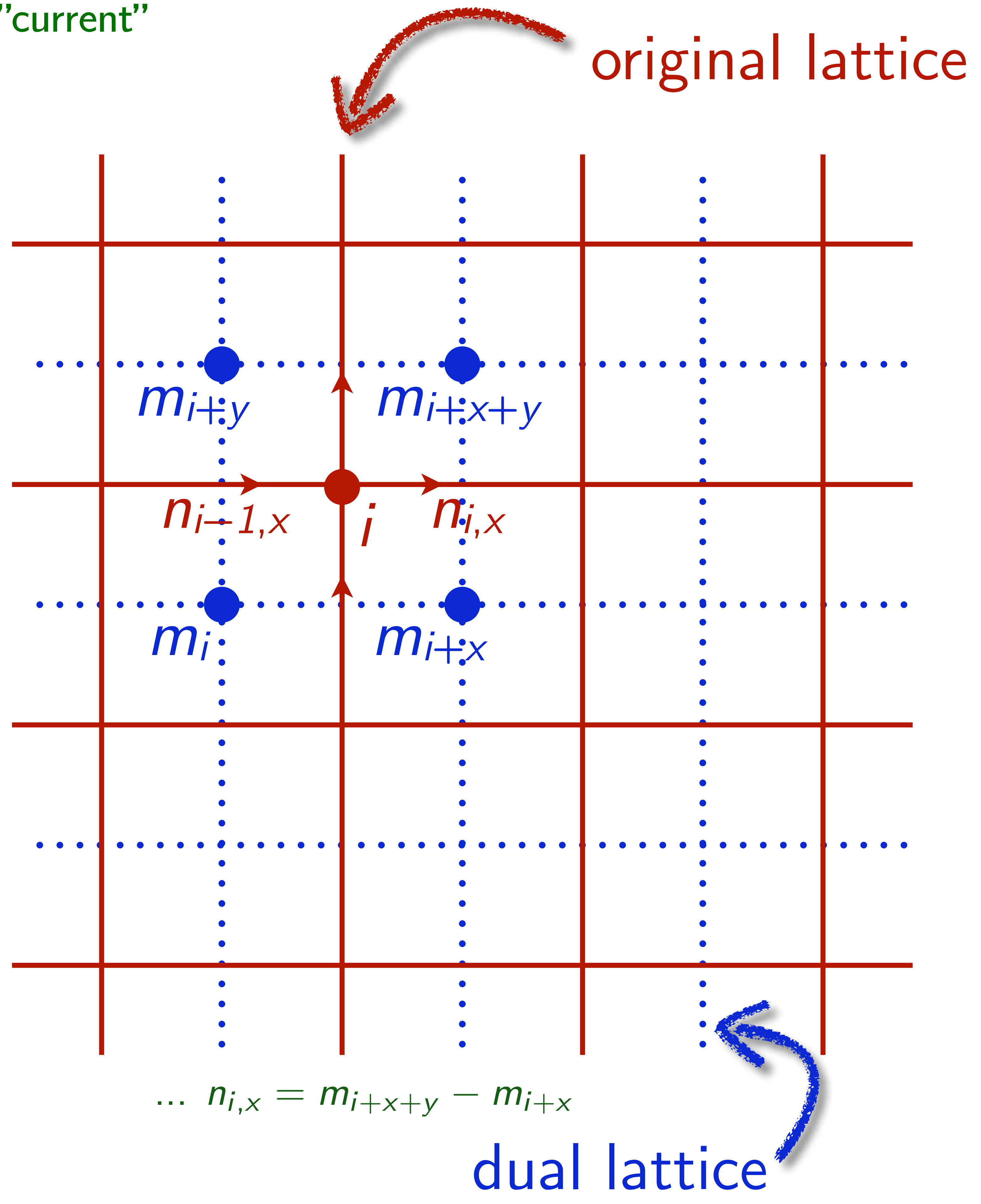


Duality transformation: Sine-Gordon model

XY model:

$$Z_{\rm XY} = \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} e^{-\mathcal{H}_{\rm XY}/T} = \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} e^{\frac{1}{T}\sum_{i,\hat\mu} \underbrace{\cos(\theta_i - \theta_{i+\hat\mu})}_{\sim n_{i,\mu}}}$$

...”current”



... $n_{i,x} = m_{i+x+y} - m_{i+x}$

Duality transformation: Sine-Gordon model

XY model:

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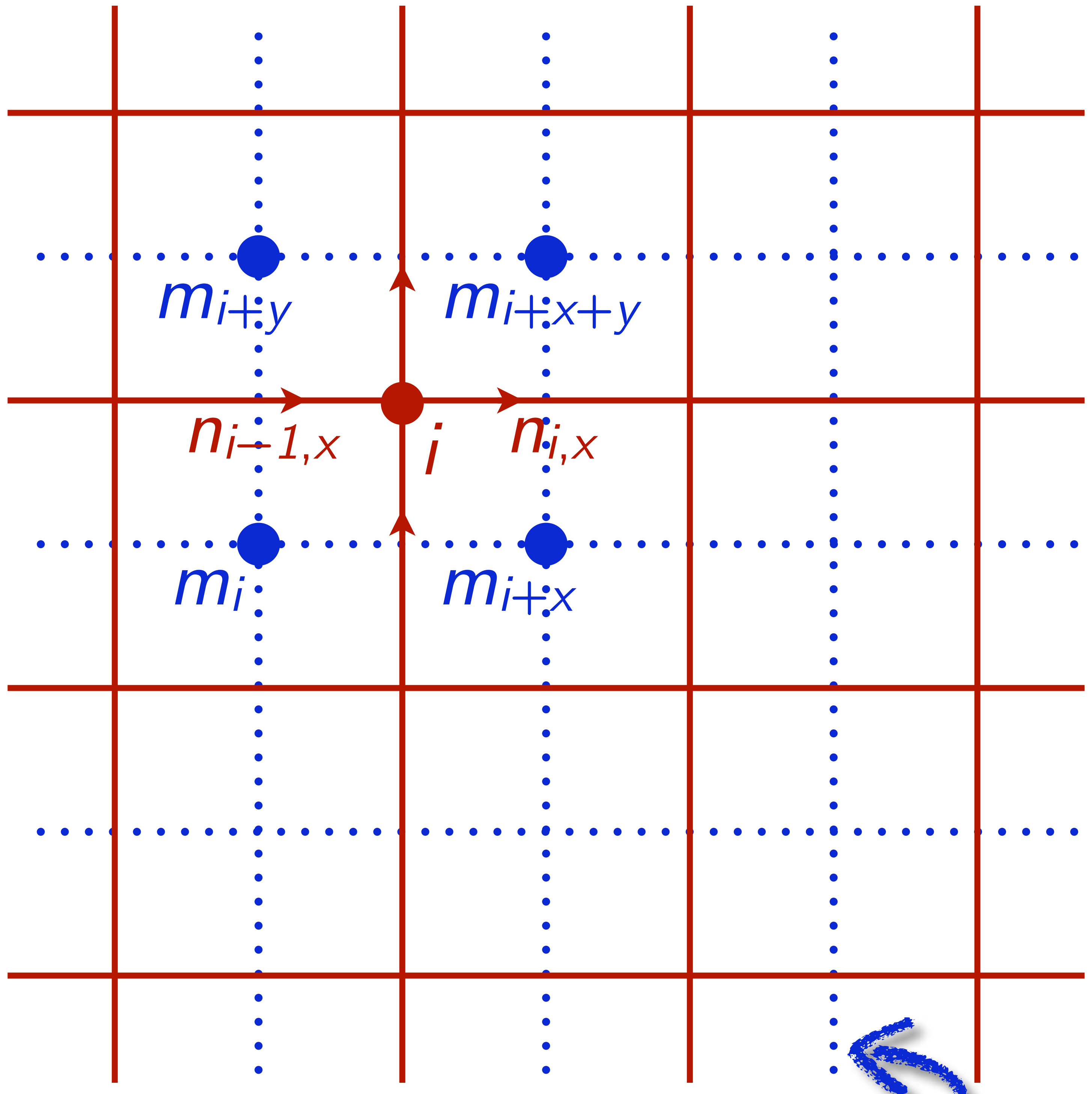
..."current"

original lattice



... $n_{i,x} = m_{i+x+y} - m_{i+x}$

dual lattice

Dual model:

role of T inversed!

$$Z_{\mathrm{dual}} = \sum_{\{m_i\}} \mathrm{e}^{-\frac{T}{2} \sum_{i,\hat{\mu}} (m_{i+\hat{\mu}} - m_i)^2}$$

... using Villain approximation $\theta \approx 2\pi\mathbb{Z} + \delta\theta$

... and Hubbard-Stratonovich $n_{i,\mu} \sim \theta_i - \theta_{i+\hat{\mu}}$

$$\simeq \int \mathcal{D}\varphi \mathrm{e}^{-\int \mathrm{d}^2\mathbf{r} \mathcal{L}_{\mathrm{sG}}(\varphi)}$$

with $\mathcal{L}_{\mathrm{sG}} = \frac{T}{2} \left(\nabla\varphi(\mathbf{r})\right)^2 - 2y \cos\left(2\pi\varphi(\mathbf{r})\right)$

..."sine-Gordon model"

... assuming low "fugacity" $y \ll 1$

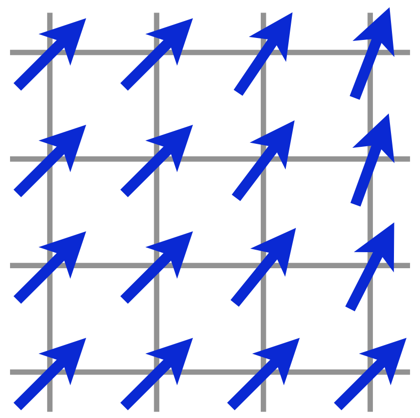
XY—Sine-Gordon duality

XY model

$$\mathcal{L}_{\rm XY} = \frac{1}{2T}(\nabla\theta)^2$$

... with $\theta \equiv \theta + 2\pi$

spin angles



spin picture

... vortices gapped

Sine-Gordon model

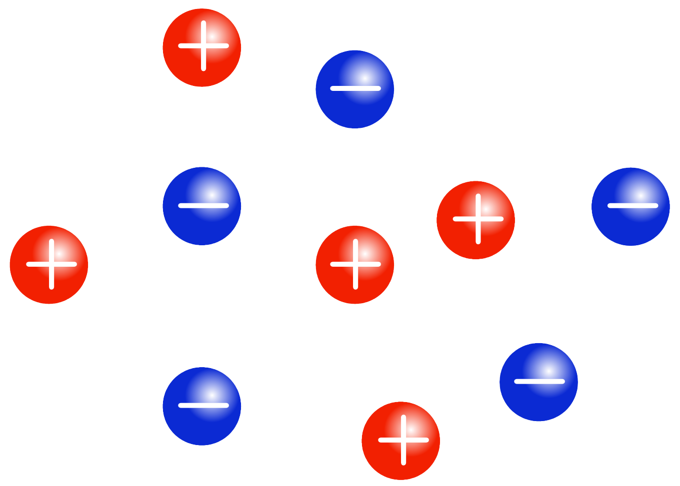
$$\mathcal{L}_{\rm sG} = \frac{T}{2}(\nabla\varphi)^2 - 2y\cos(2\pi\varphi)$$

... without any constraint on φ

vortex density

vortex fugacity

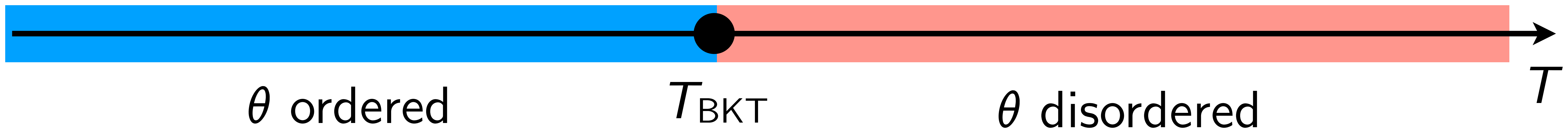
... $e^{\mu/T}$



vortex picture

... "Coulomb plasma"

Phase diagram:



θ ordered
φ disordered
"dielectric phase"

$T_{\rm BKT}$

θ disordered
φ ordered ... "disorder variables"
"metallic phase"

Renormalization group

[Herbut, CUP '07]

Flow equations:

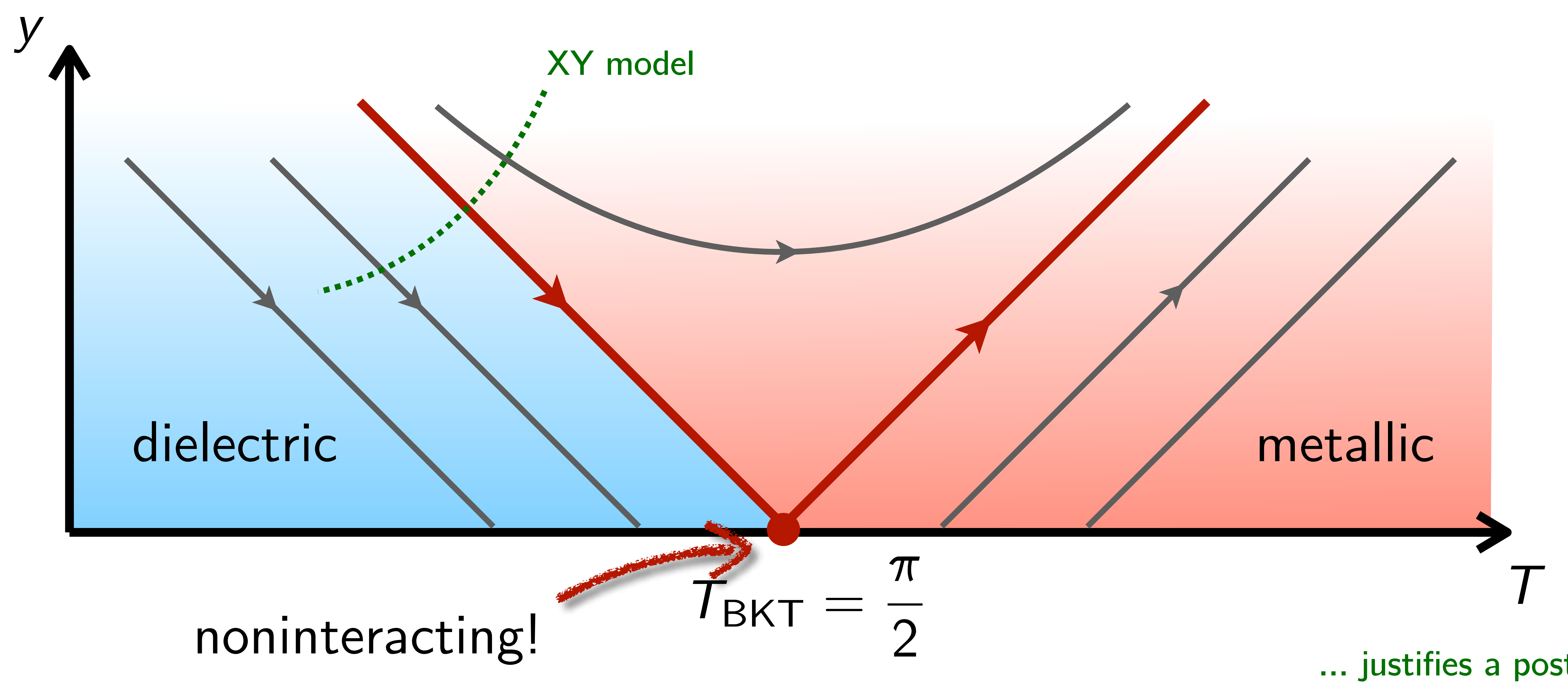
$$\frac{dy}{d\ln b} = \left(2 - \frac{\pi}{T}\right) y + \mathcal{O}(y^3)$$

$$\frac{dT}{d\ln b} = \frac{y^2}{2T} + \mathcal{O}(y^4)$$

... irrelevant for $T < \frac{\pi}{2}$
... relevant for $T > \frac{\pi}{2}$

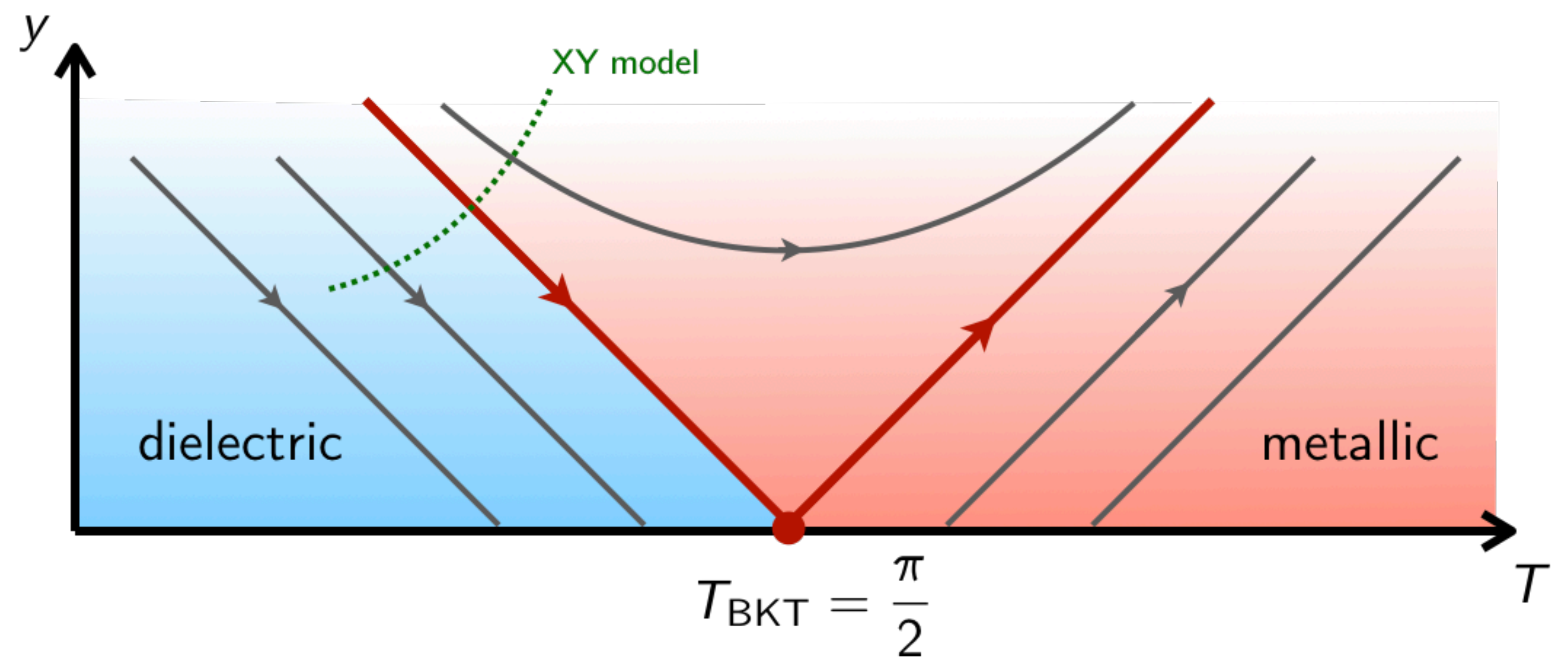
... marginal for $y = 0$
... relevant for $y > 0$

Flow diagram:



... justifies a posteriori simple energy-entropy argument

Critical behavior and algebraic order



For $T < T_c$:

$y \to 0$
$T \to T_\infty < \frac{\pi}{2}$

$$\left\langle e^{i\theta(\mathbf{r})} e^{-i\theta(0)} \right\rangle \propto \frac{1}{|\mathbf{r}|^{T_\infty/(2\pi)}}$$

"algebraic order"

... on line of fixed points

For $T = T_c$:

$y \to 0$
$T \to \frac{\pi}{2}$

$$\left\langle e^{i\theta(\mathbf{r})} e^{-i\theta(0)} \right\rangle \propto \frac{1}{|\mathbf{r}|^{1/4}}$$

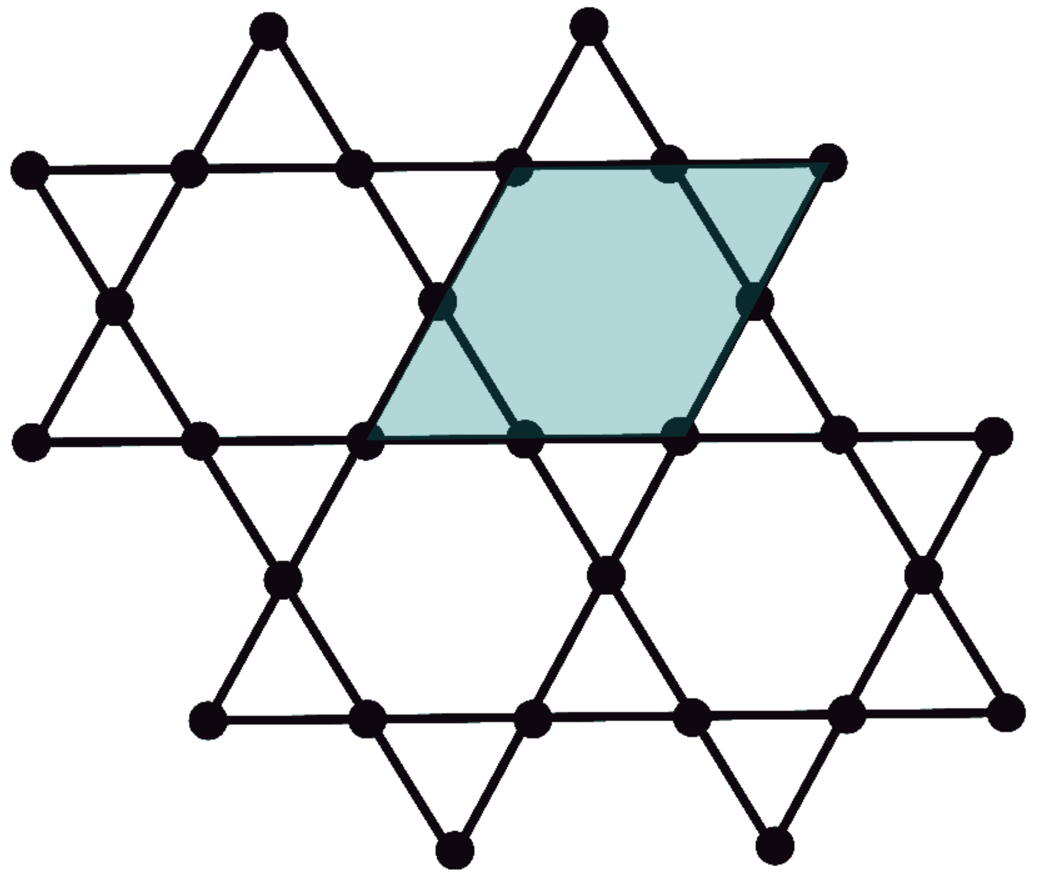
... i.e., $\eta = 1/4$

For $T > T_c$:

$$\left\langle e^{i\theta(\mathbf{r})} e^{-i\theta(0)} \right\rangle \propto e^{-|\mathbf{r}|/\xi}$$ with correlation length $$\xi \propto e^{C\sqrt{T_c/(T-T_c)}}$$

... essential singularity
... since T marginal at $y = 0$

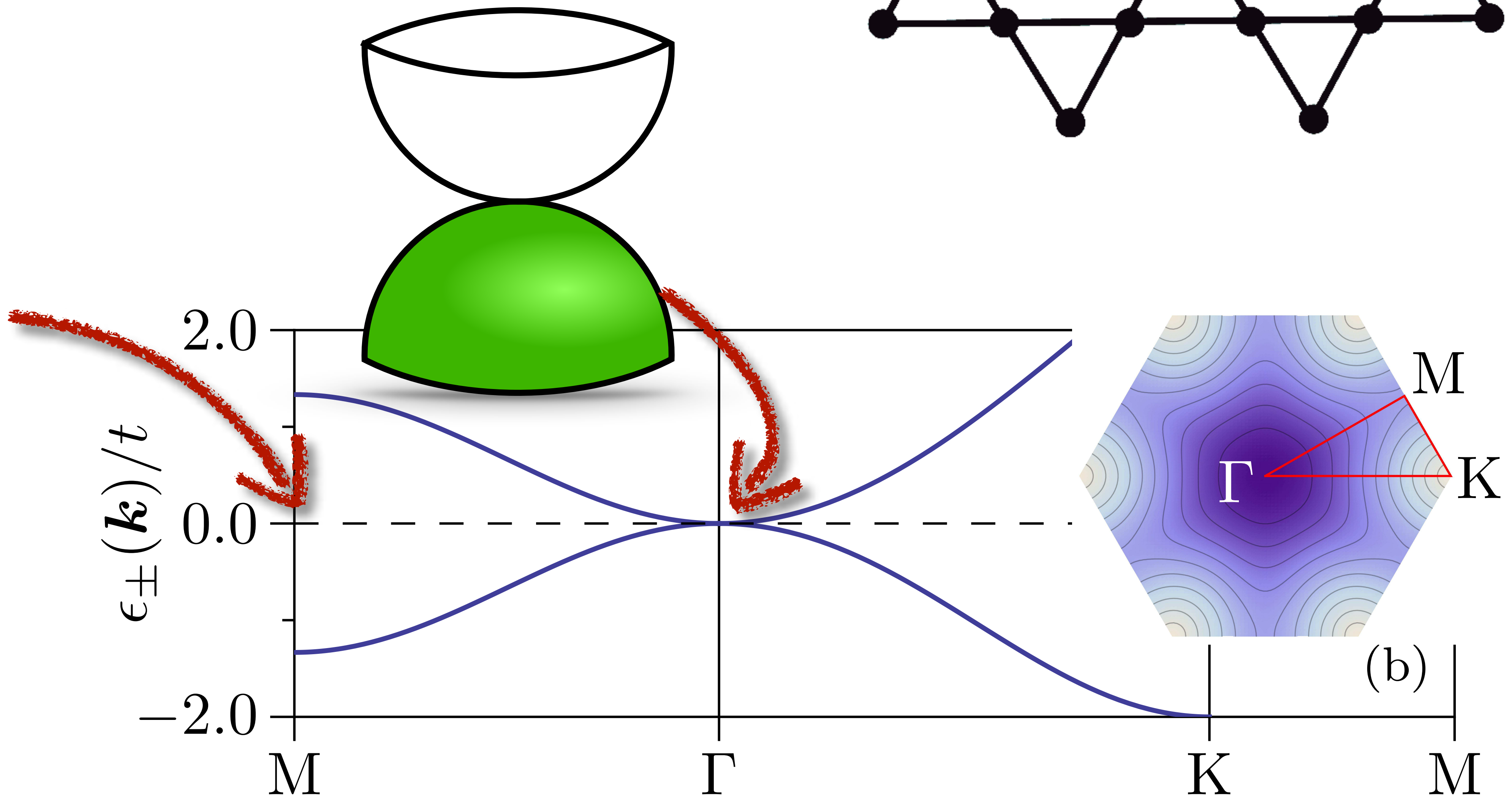
"Luttinger" fermions on kagome lattice



Hopping Hamiltonian (spinless fermions):

$$\mathcal{H}_0 = -t \sum_{\langle ij \rangle} c_i^\dagger c_j - t' \sum_{\langle\langle ij \rangle\rangle} c_i^\dagger c_j + \text{H.c.}$$

1/3 filling



Spectrum:

$$\varepsilon_\pm(\mathbf{q}) = \frac{1}{2}\left[-(t+3t') \pm (t-3t')\right]\mathbf{q}^2 + \mathcal{O}(\mathbf{q}^4)$$

... choose t' = $-t/3$ for simplicity

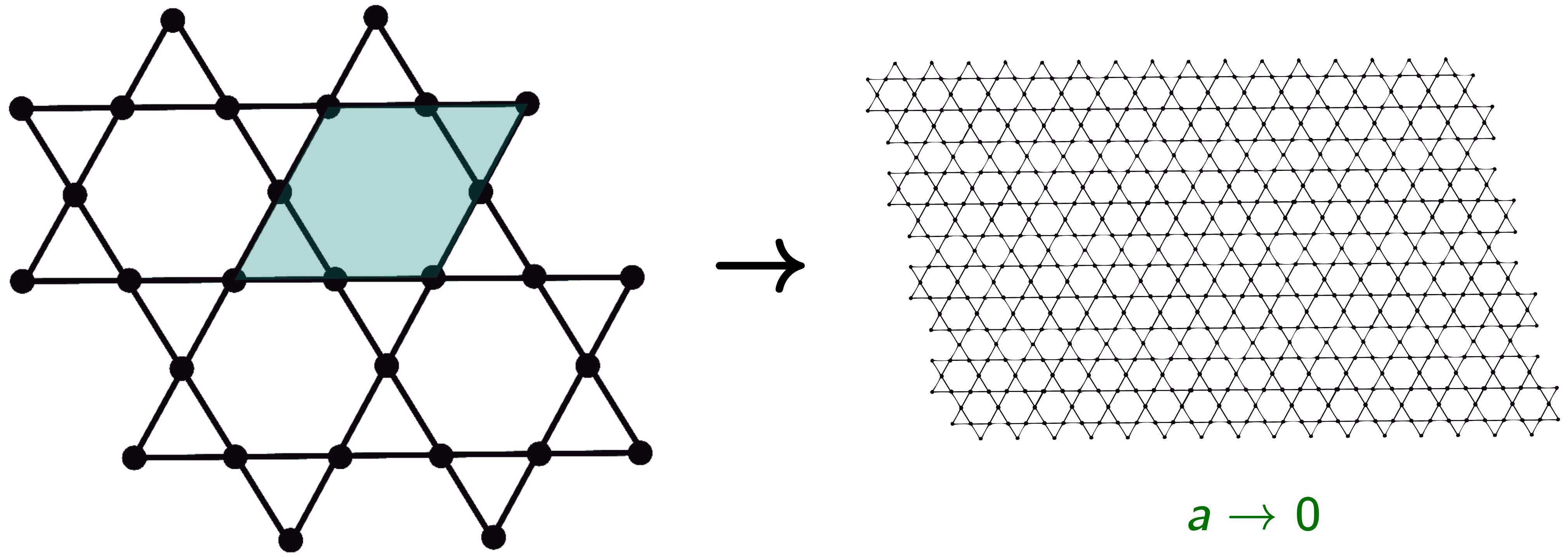
Interactions:

$$\mathcal{H}_{\text{int}} = V_1 \sum_{\langle ij \rangle} c_i^\dagger c_i c_j^\dagger c_j + V_2 \sum_{\langle\langle ij \rangle\rangle} c_i^\dagger c_i c_j^\dagger c_j$$

... $V_{1,2} > 0$ repulsive

... $V_{1,2} < 0$ repulsive

Low-energy field theory



Effective Lagrangian:

... $g > 0$ repulsive
... $g < 0$ attractive

$$\mathcal{L}_\psi = \psi^\dagger \left[\partial_\tau + (\partial_x^2 - \partial_y^2)\sigma_1 + 2\partial_x\partial_y\sigma_3\right] \psi - \frac{g}{2}(\psi^\dagger\sigma_2\psi)^2 + \ldots$$

$\psi = \begin{pmatrix}\psi_1 \\ \psi_2\end{pmatrix}$ two-component

... higher-order terms, such as $g'(\psi^\dagger\sigma_\alpha\psi)\partial_i\partial_j(\psi^\dagger\sigma_\beta\psi)$
... irrelevant

Fierz completeness:

$$(\psi^\dagger\sigma_2\psi)^2 = -2\psi_1^*\psi_1\psi_2^*\psi_2 = -(\psi^\dagger\psi)^2 \propto (\psi\mathcal{O}\psi)^2$$

... single interaction channel

Comparison with microscopic model:

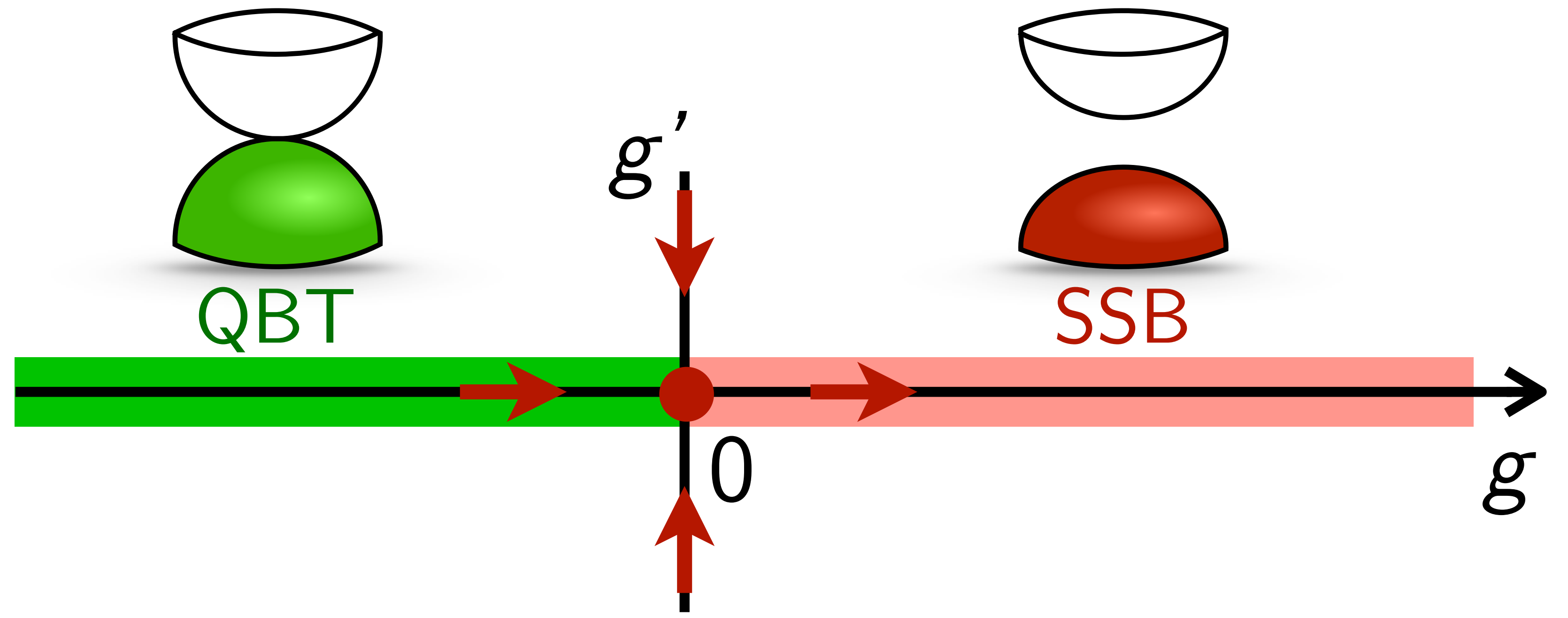
$$g \equiv \frac{2(V_1 + V_2)}{t}$$

... $g \sim V_1 + V_2$ marginal
... $g' \sim V_1 - V_2$ irrelevant

Phase diagram

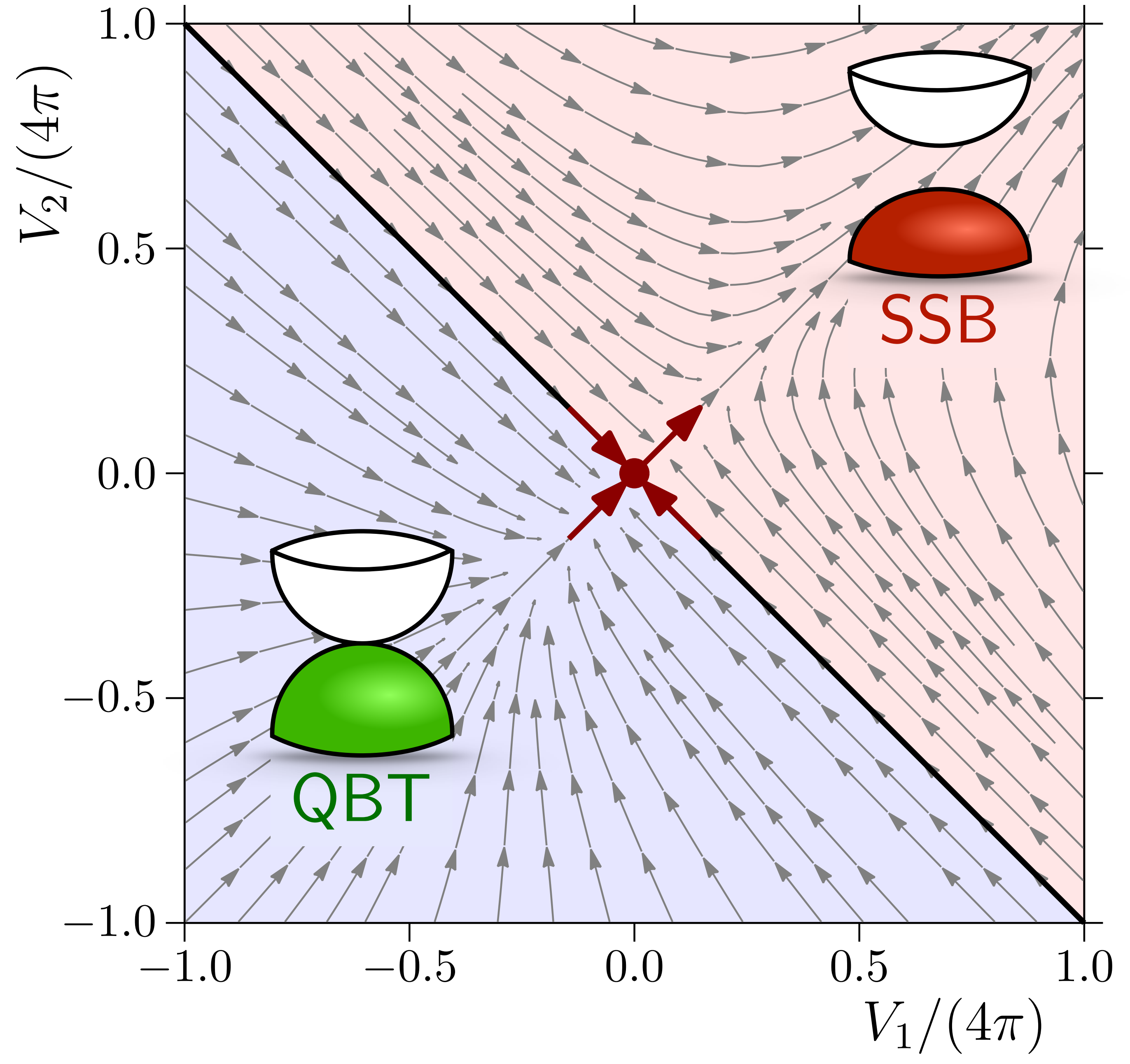
RG flow:

$$\frac{dg}{d\ln b} = \frac{g^2}{4\pi} + \dots$$
$$\frac{dg'}{d\ln b} = -2g' + \dots$$



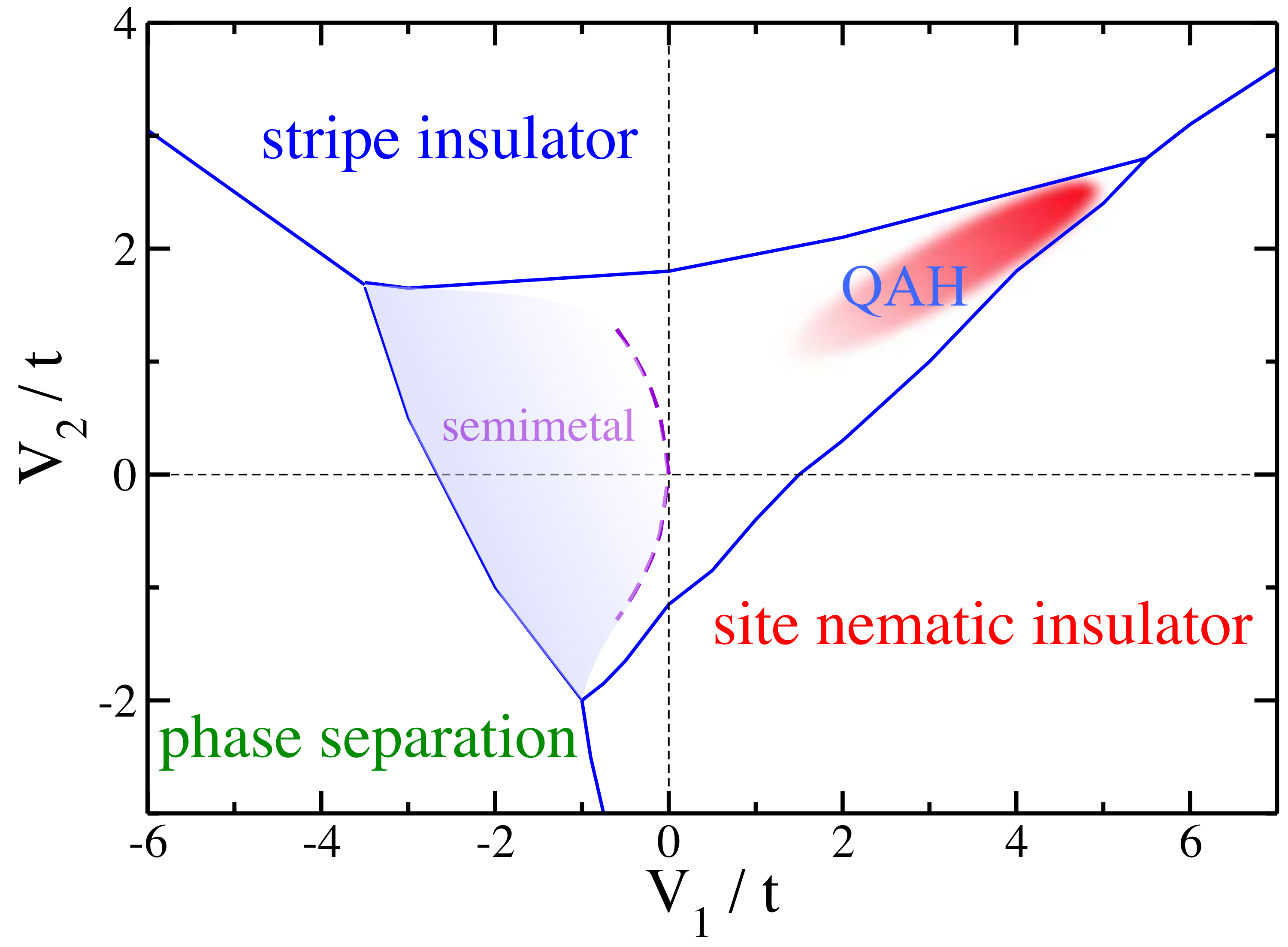
[Sun *et al.*, PRL ’09]
[Zhu *et al.*, PRL ’16]

Phase diagram:



... $g \sim V_1 + V_2$
... $g' \sim V_1 - V_2$

DMRG (checkerboard):



[Sur *et al.*, PRB 18]

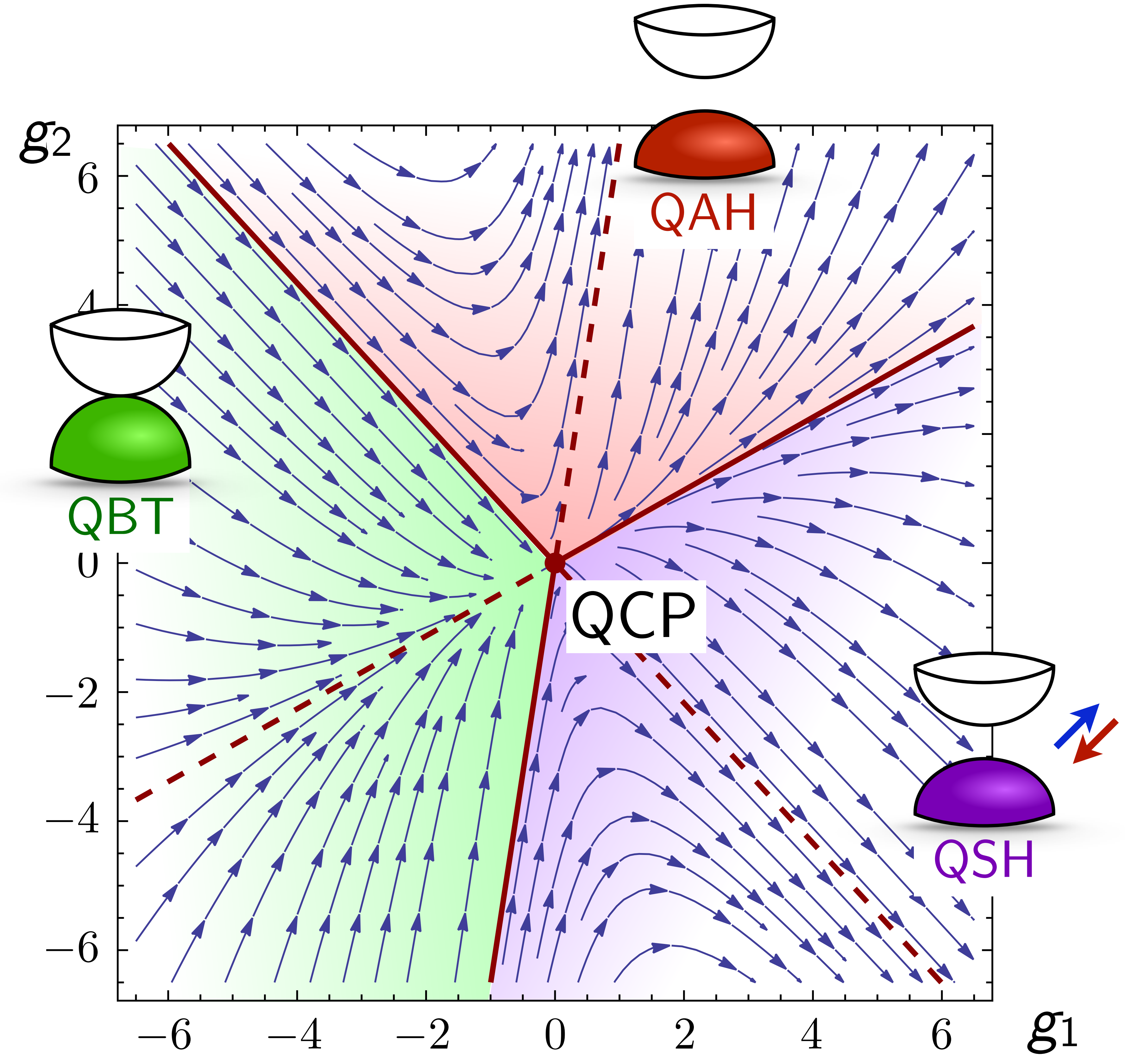
Spin-1/2 fermions ($N = 2$)

Interactions:

$$\mathcal{L}_{\text{int}} = g_0(\psi^\dagger\psi)^2 + g_1\left[(\psi^\dagger\sigma_1\psi)^2 + (\psi\sigma_3\psi)^2\right] + g_2(\psi^\dagger\sigma_2\psi)^2$$

four-component

Phase diagram:



... for $g_0 = 0$

... or nematic

[Murray & Vafek, PRB '14]

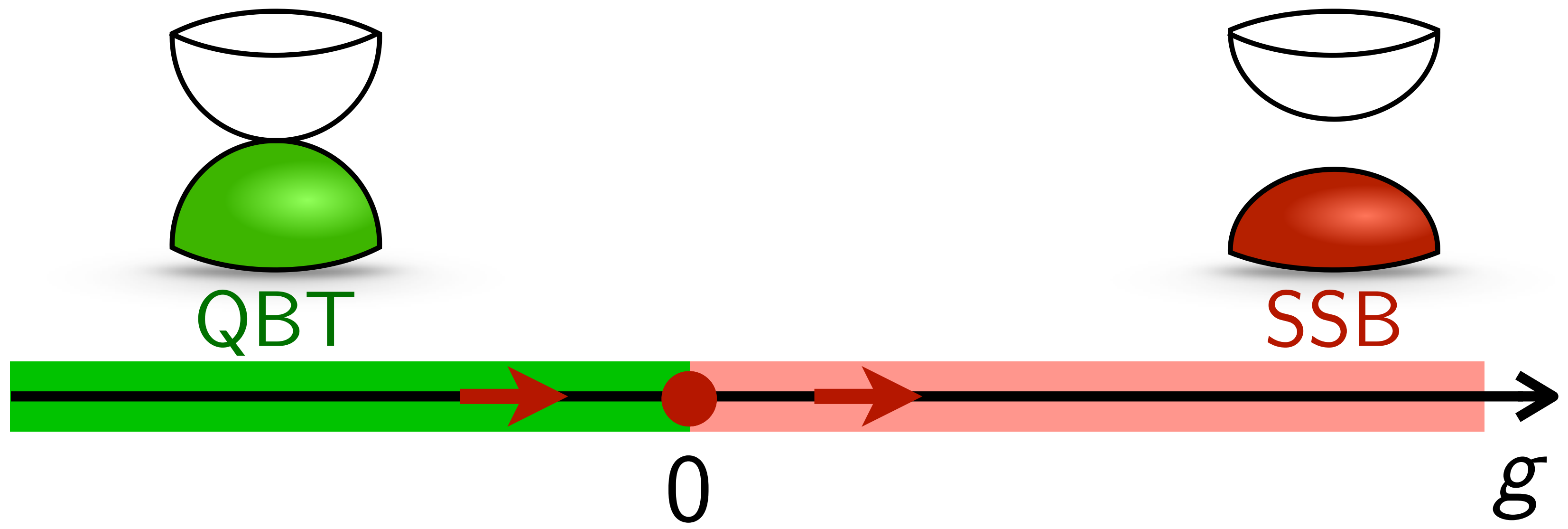
Critical behavior: Partial bosonization

Technical trick:

$$d = 2 \qquad \mapsto \qquad d = 2 + \epsilon$$

RG flow:

$$\frac{dg}{d \ln b} = -\epsilon g + \frac{g^2}{4\pi} + \dots$$



Fixed point: $g_\star = 4\pi\epsilon$

... for $0 < \epsilon \ll 1$

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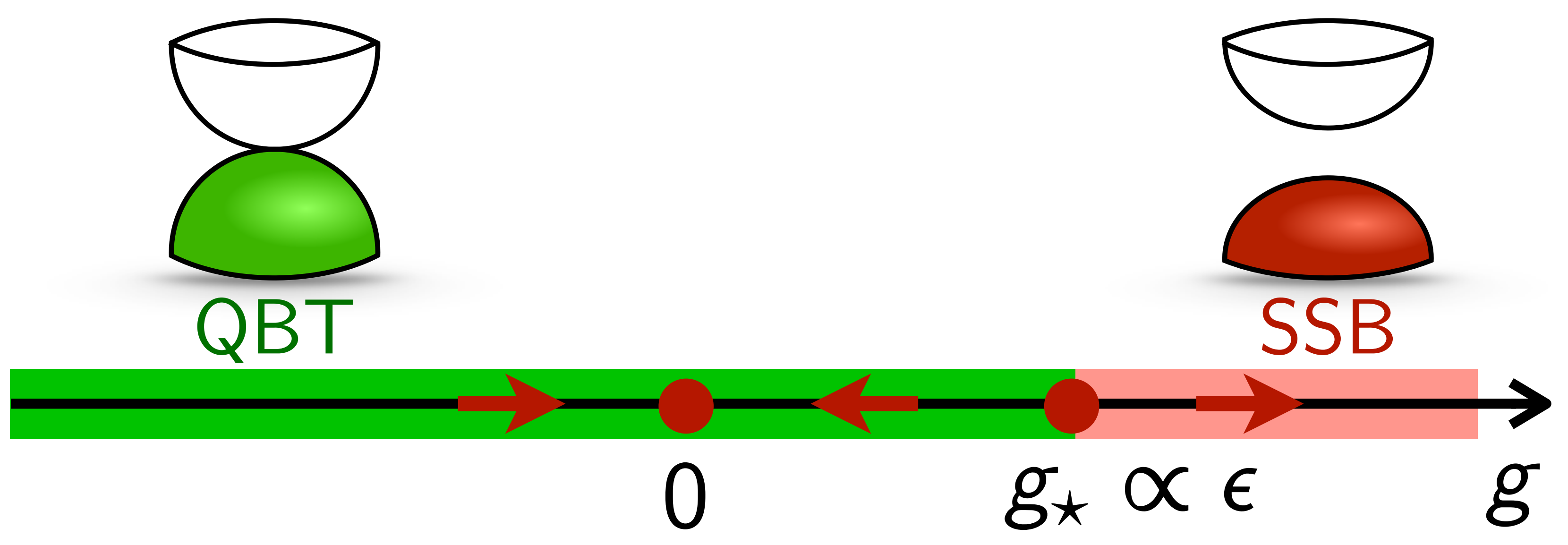

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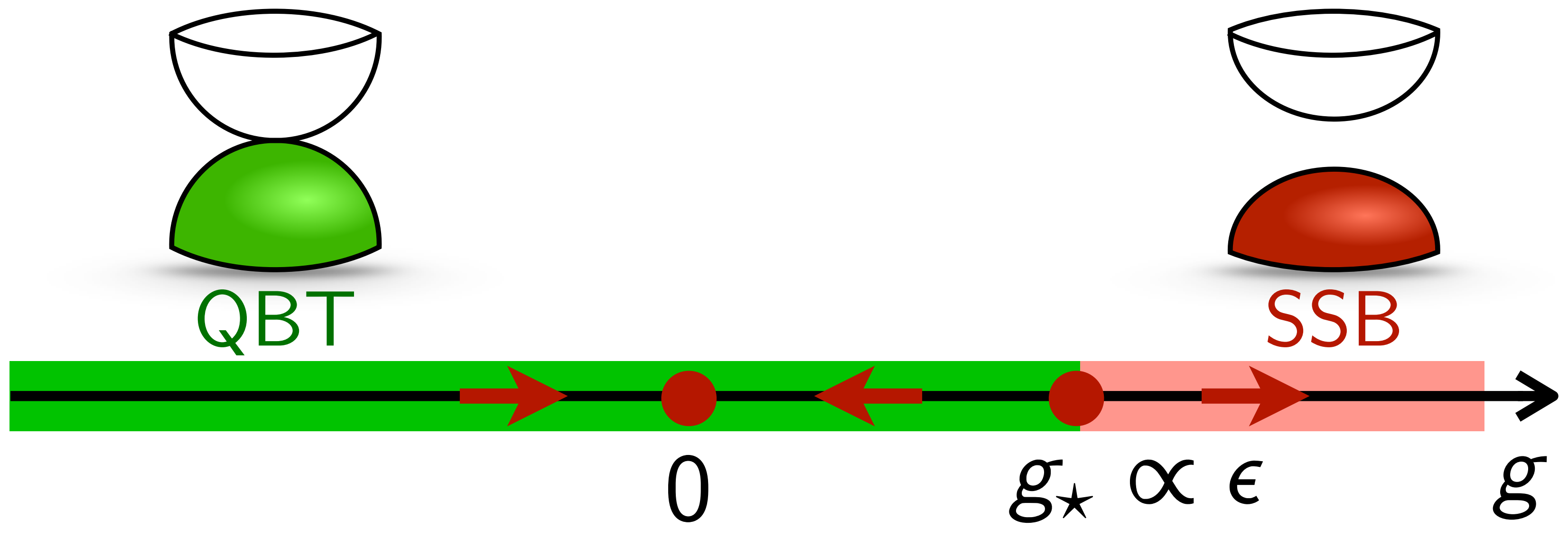

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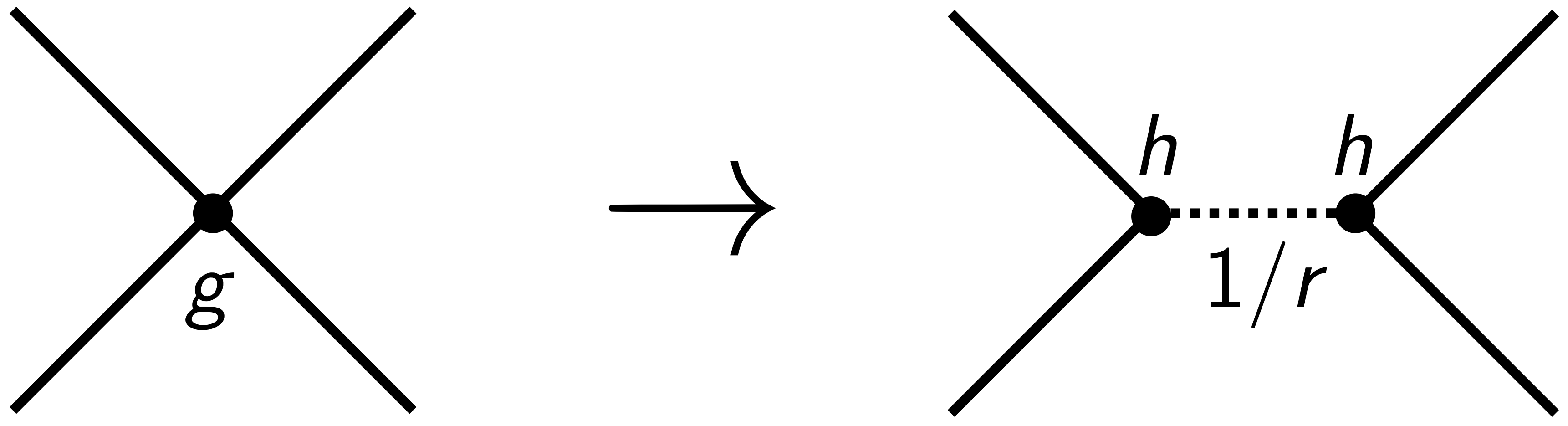
Hubbard-Stratonovich transformation:



"Luttinger-Yukawa" theory

tuning parameter

parametrizes $z = 1$ (ϕ) vs. $z = 2$ (ψ)

Lagrangian:

$$\mathcal{L}_\psi = \psi^\dagger \left[\partial_\tau + (\partial_x^2 - \partial_y^2)\sigma_1 + 2\partial_x\partial_y\sigma_3\right]\psi + \frac{1}{2}\phi(r - c\partial_\tau^2 - \partial_x^2 - \partial_y^2)\phi - h\phi\psi^\dagger\sigma_2\psi$$

"meson"

"Yukawa" coupling

... ϕ^4 coupling irrelevant for $\epsilon > 0$

Equivalence to $\mathcal{L}_\psi$:

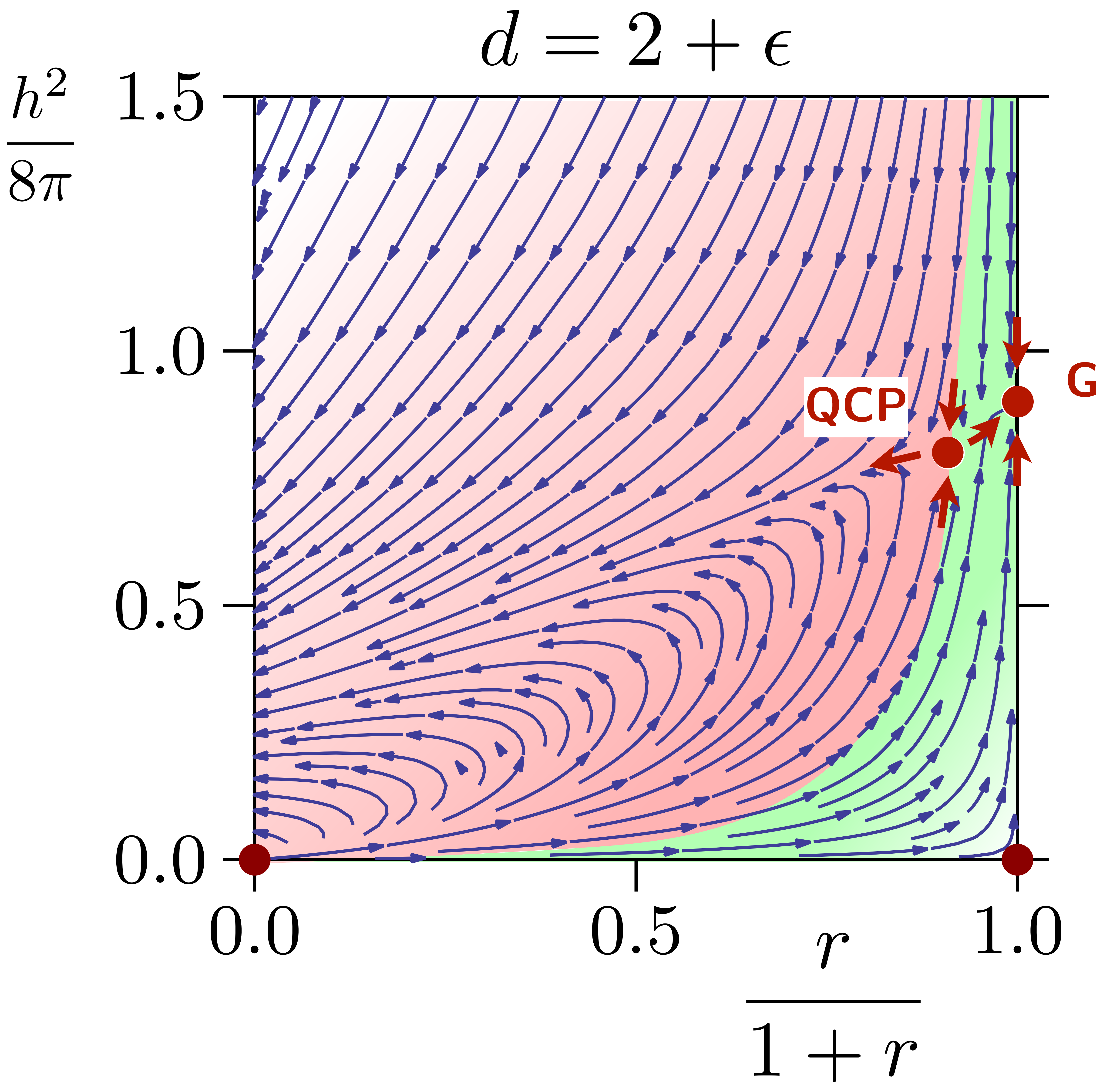
$$g \equiv \frac{h^2}{r}$$

... assume $g > 0$

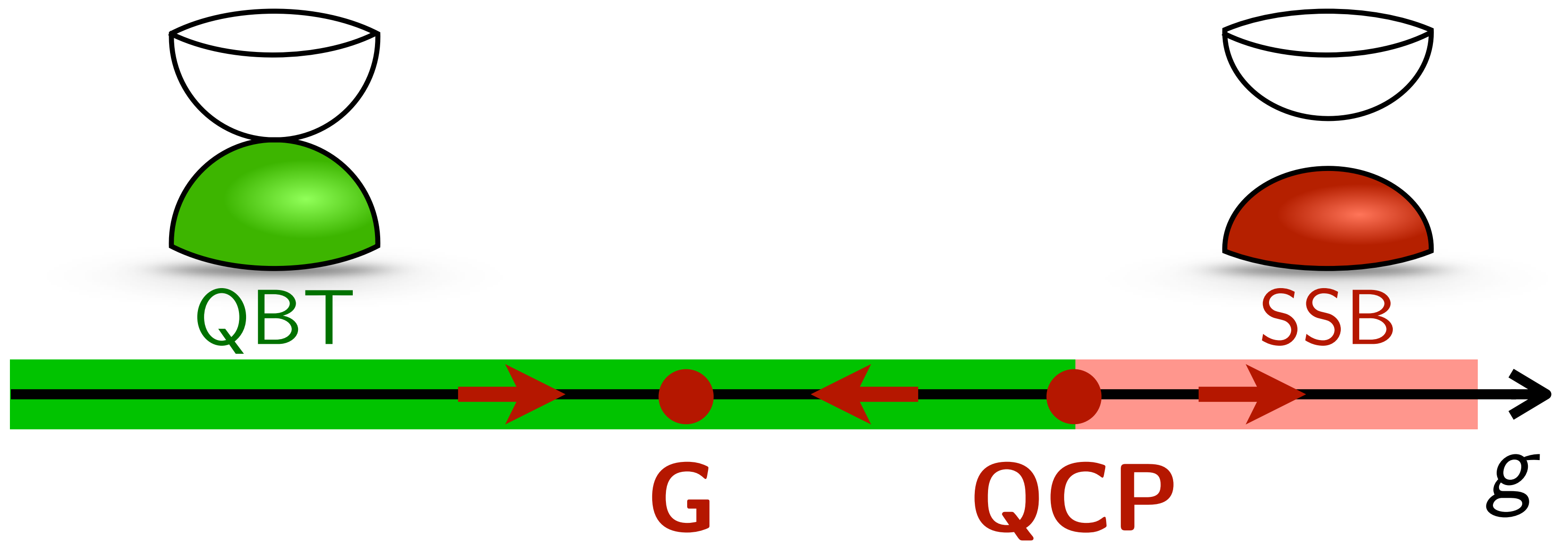
Order parameter:

$$\langle\phi\rangle = \frac{h}{r}\langle\psi^\dagger\sigma_2\psi\rangle$$

RG flow

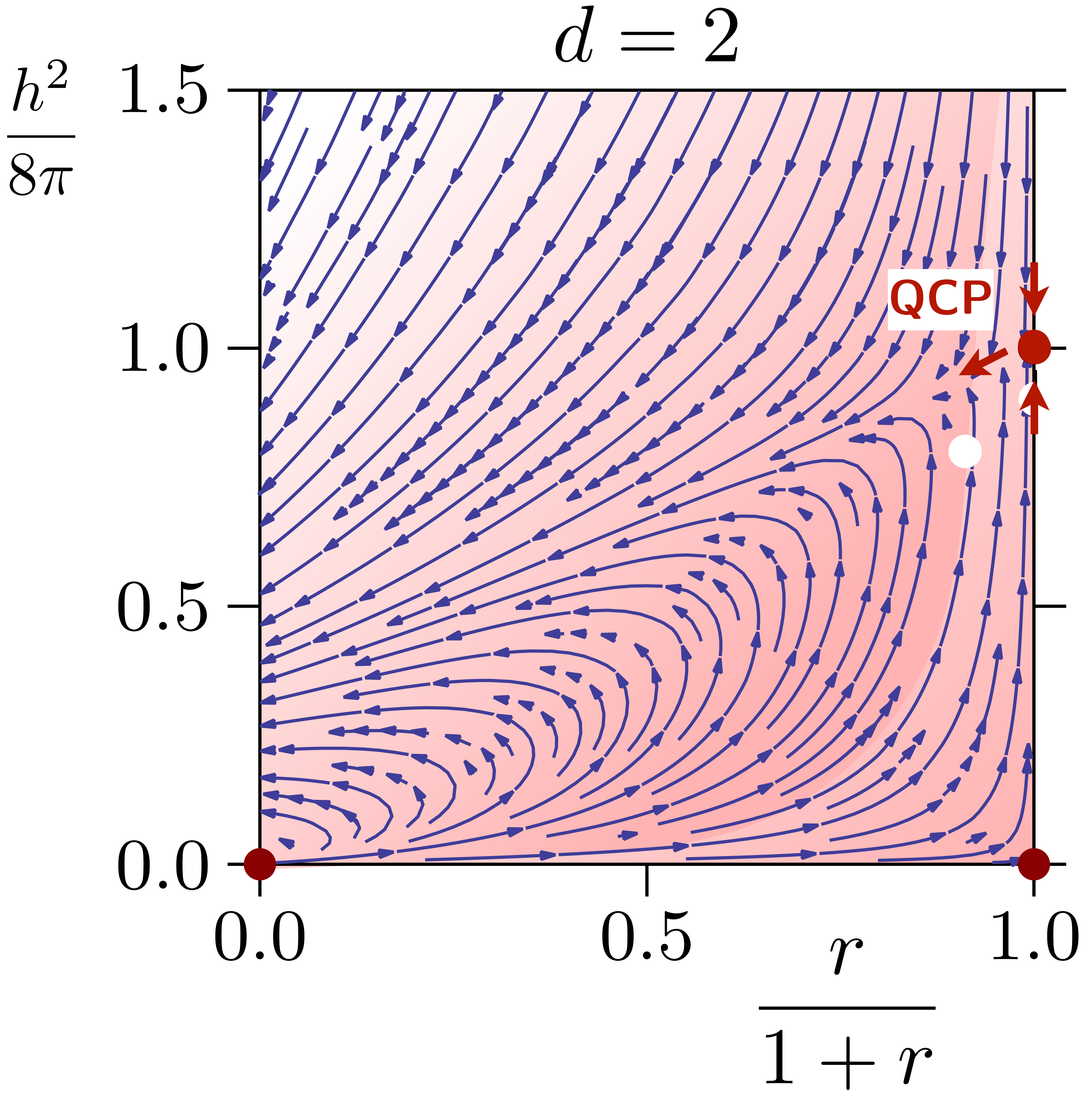


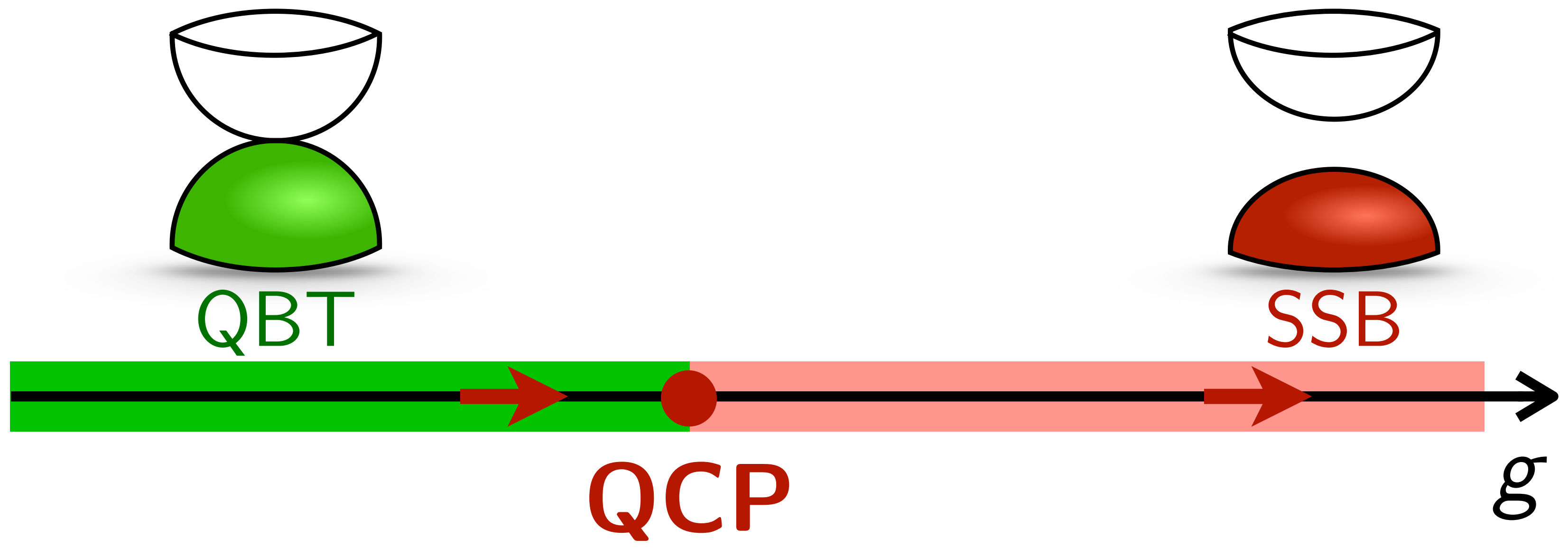
$d = 2 + \epsilon$
$\frac{h^2}{8\pi}$
1.5
1.0
0.5
0.0
0.0
0.5
1.0
$\frac{r}{1+r}$
QCP
G



QBT
SSB
G
QCP
g

RG flow





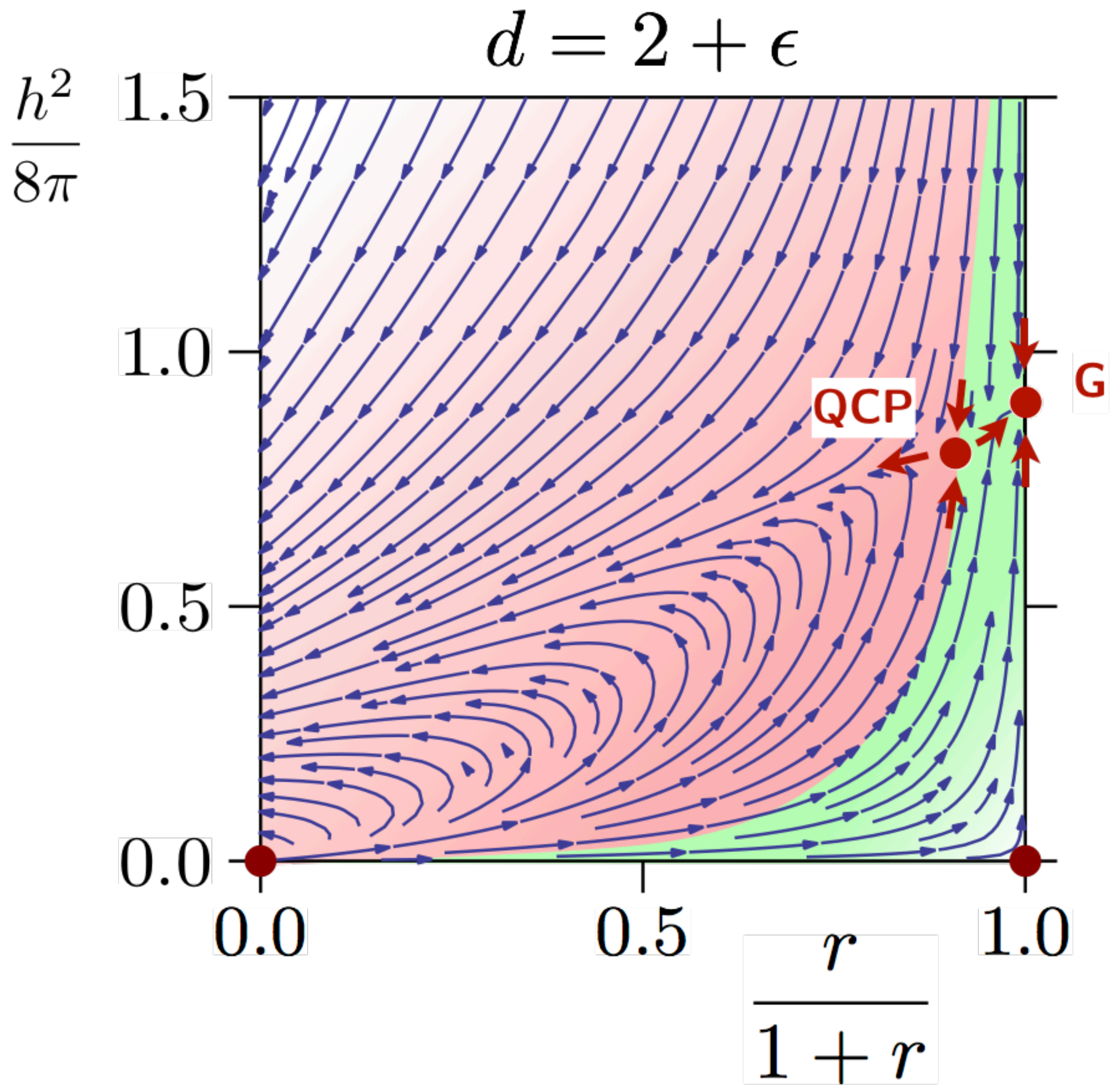
Quantum critical fixed point ($\varepsilon > 0$)

Couplings:

$$r_\star = \frac{2}{\epsilon}$$

$$c_\star = \frac{1}{4} - \frac{\epsilon}{8} \qquad \rightarrow \text{ equivalent to } g_\star = \frac{h_\star^2}{r} = 4\pi\epsilon$$

$$h_\star^2 = 8\pi(1-\epsilon)$$



Critical exponents:

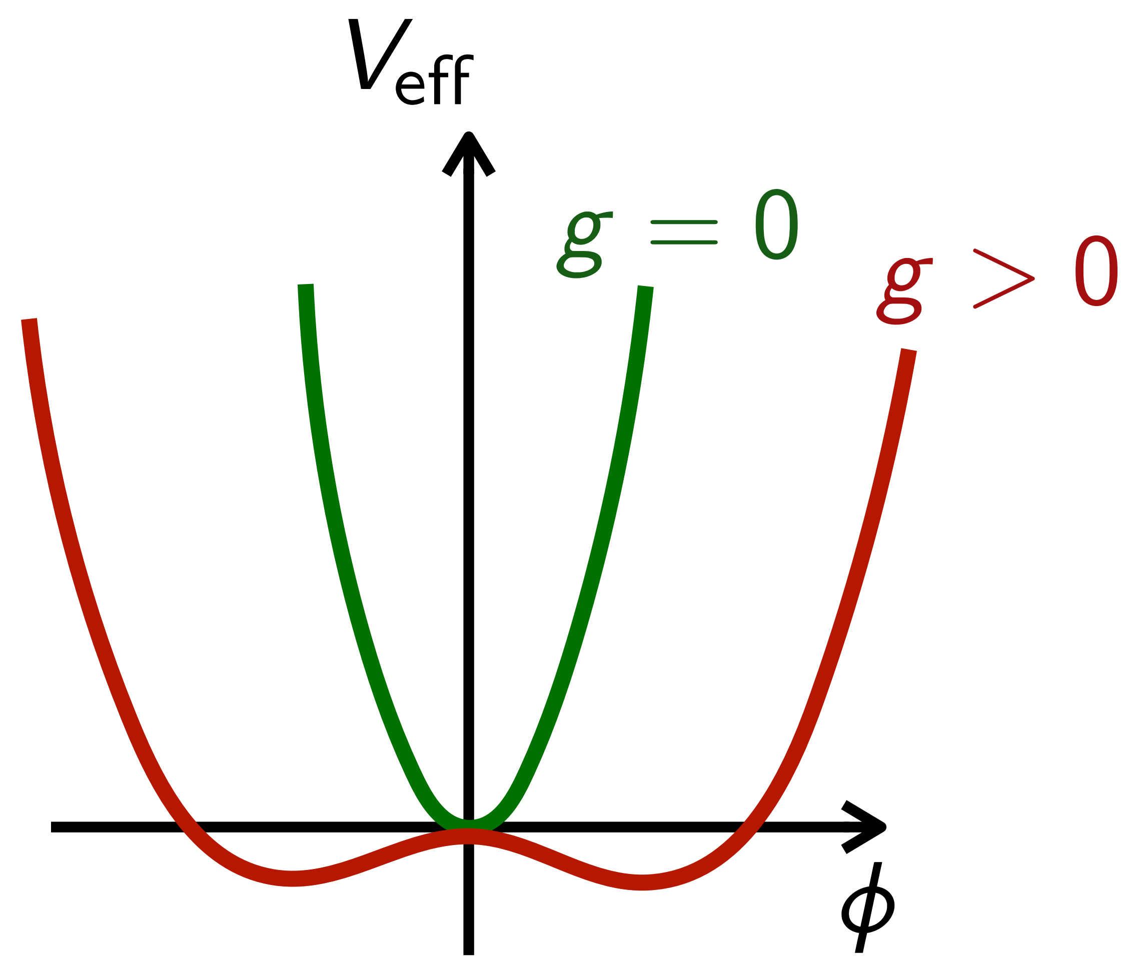
$$\eta_\phi = 2 - 2\epsilon \qquad \xrightarrow{\epsilon\to 0} 2$$

$$\eta_\psi = 0$$

$$z = 2$$

$$\nu = 1/\epsilon \qquad \xrightarrow{\epsilon\to 0} \infty$$

(Careful) 2D limit $\varepsilon \to 0$



Effective potential in $d = 2$:

... from fully integrating out ψ

$$V_{\text{eff}}(\phi) = \frac{1}{2g}\phi^2 - \frac{1}{16\pi}\phi^2\left(1 - \ln\frac{\phi^2}{4}\right) + \frac{1}{(16\pi)^2}\frac{g}{2}\phi^2\left(\ln\frac{\phi^2}{4}\right)^2$$

Order parameter:

$$\langle\phi\rangle \propto \mathrm{e}^{-8\pi/g}$$

... essential singularity

... c.f. $\langle\phi\rangle \propto (\delta g)^{2/(d-2)}$ for $d > 2$

Critical "isotherm":

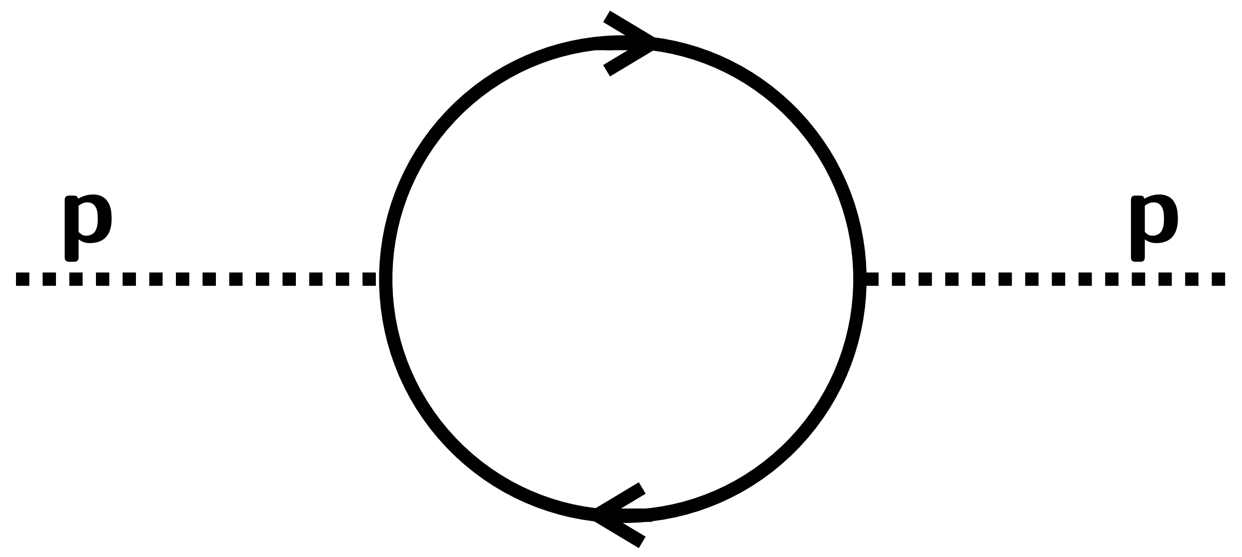
$$h \propto \langle\phi\rangle^{\delta} \qquad \text{with} \quad \delta = 1$$

... in agreement with hyperscaling $\delta = \frac{d+z+2-\eta_\phi}{d+z-2+\eta_\phi} = 1$ for $\eta_\phi = 2$, $z = 2$

Correlation length and hyperscaling

Correlator near criticality:

$$\langle \phi(0, \mathbf{p}) \phi(0, 0) \rangle^{-1} \quad \sim$$



Correlation length:

$$\xi \propto \mathrm{e}^{4\pi/g} \qquad (\text{“}\nu = \infty\text{”})$$

... for $g > 0$

... as expected from marginal g

Hyperscaling:

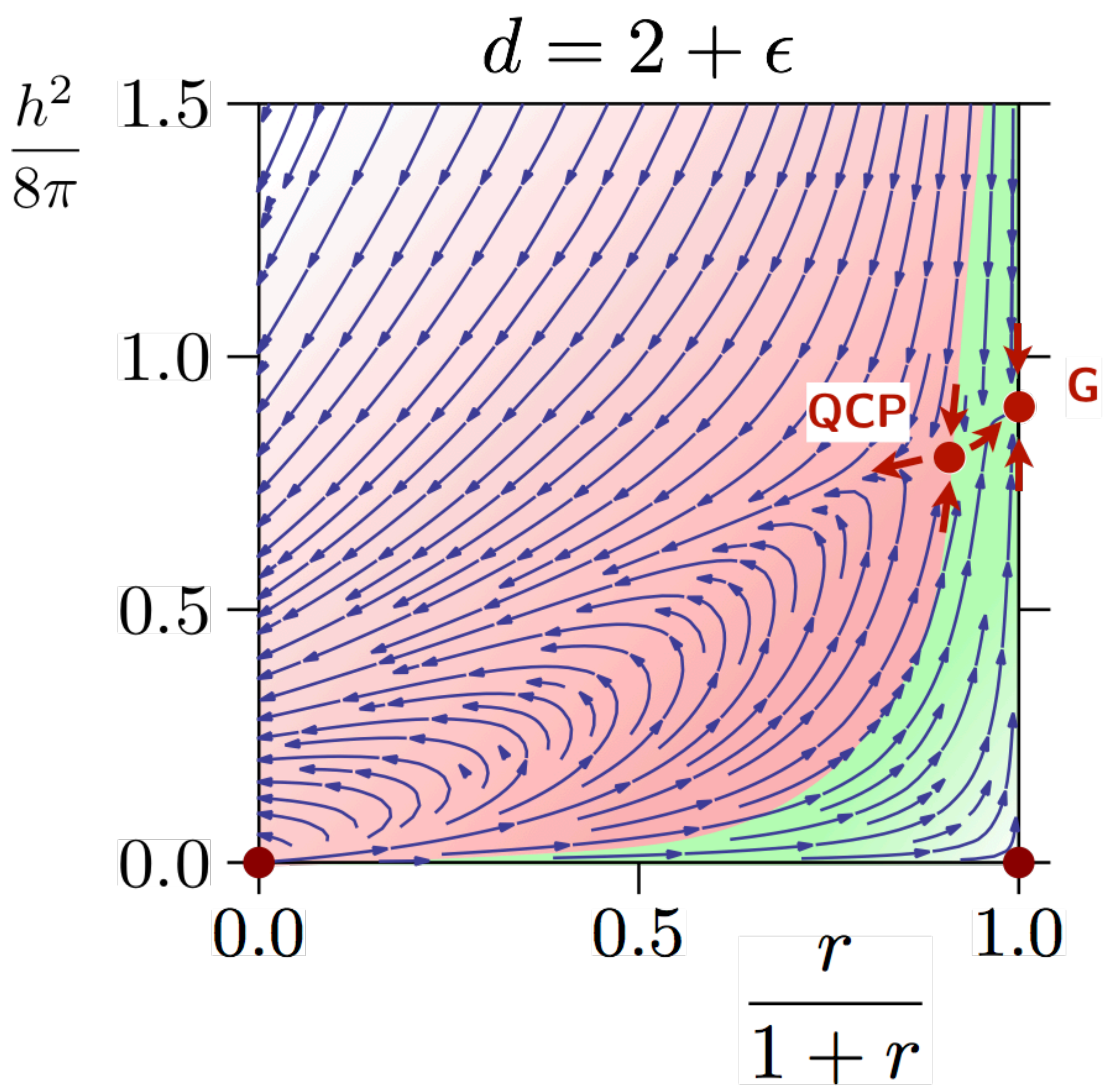
$$V_{\text{eff}}(\langle \phi \rangle) \propto \xi^{-(d+z)} \qquad \text{with } z = 2 \text{ and } d = 2$$

... fulfilled despite marginally irrelevant ϕ^4 coupling

Semimetallic fixed point: Luttinger semimetal

Couplings:

$$r_\star = \infty$$
$$c_\star = \frac{1}{4} - \frac{\epsilon}{16} \qquad \to \text{equivalent to } g_\star = 0$$
$$h_\star^2 = 4\pi(2-\epsilon)$$



Critical exponents:

$$\eta_\phi = 2 - \epsilon \quad \xrightarrow{\epsilon \to 0} 2$$
$$\eta_\psi = 0$$
$$z = 2$$

$\to$ scale-invariant phase: “LSM”

... à la 3D QBT @ large N
[LJ & Herbut, PRB ’17]

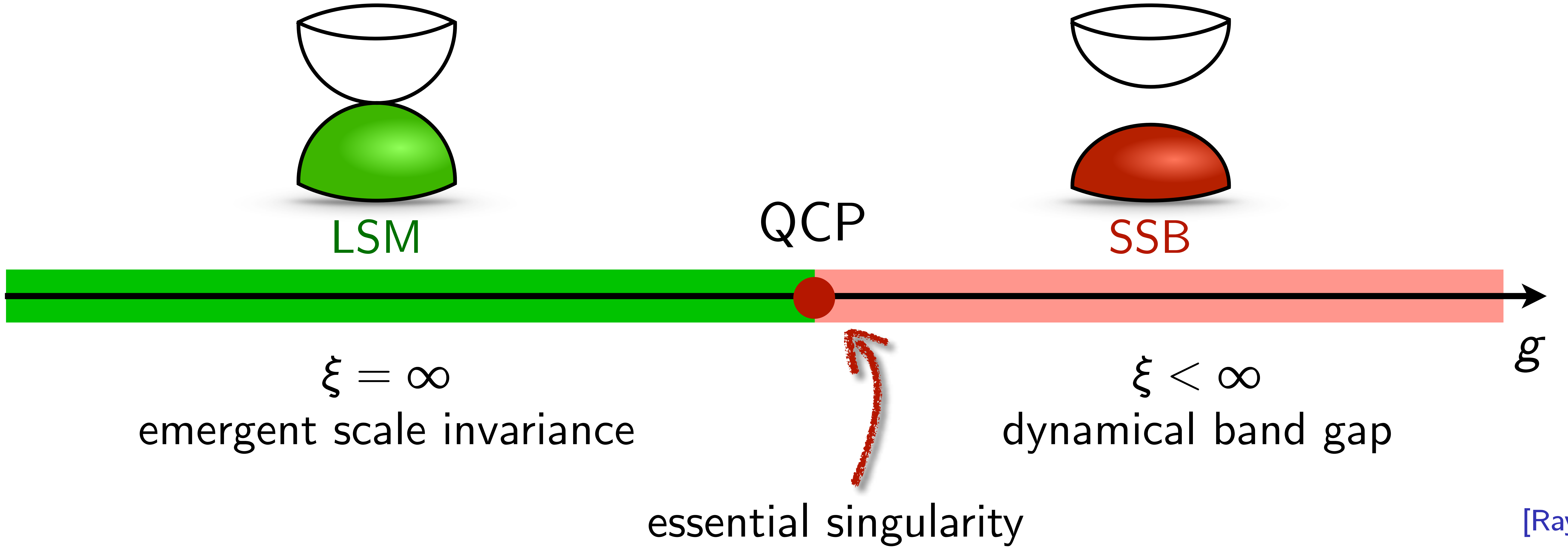
Algebraic “order”

Correlator in semimetallic phase:

$$\langle \phi(0,\mathbf{r})\phi(0,0)\rangle \propto \frac{1}{|\mathbf{r}|^4} \qquad \text{for all } g \leq 0$$

... i.e., $\eta_\phi = 2$

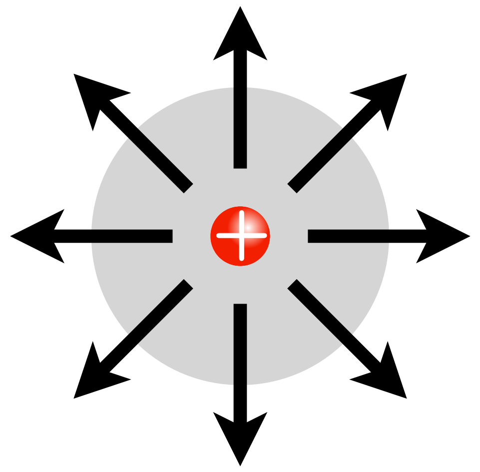
Phase diagram:



[Ray, Vojta, LJ, arXiv:1910.XXXX]

Phenomenological analogy: 2D QBT vs. BKT

2D QBT



BKT

Semimetallic phase ($g < 0$):

$$\langle \phi(0,\mathbf{r})\phi(0,0)\rangle \propto \frac{1}{|\mathbf{r}|^{z+\eta_\phi}}$$

... with $z = 2$ and $\eta_\phi = 2$

Ordered phase ($g > 0$):

$$\langle \phi(0,\mathbf{r})\phi(0,0)\rangle \propto e^{-|\mathbf{r}|/\xi}$$

Critical behavior:

$$\xi \propto e^{4\pi/g} \quad (g > 0)$$

$$h \propto \langle \phi \rangle^{\delta} \quad \text{with } \delta = 1 \quad (g = 0)$$

Dielectric phase ($t \equiv \frac{T - T_c}{T_c} < 0$):

$$\langle e^{i\theta(\mathbf{r})} e^{-i\theta(0)}\rangle \propto \frac{1}{|\mathbf{r}|^{\eta}}$$

... with $\eta = \frac{T_\infty}{2\pi} \leq \frac{1}{4}$

... emergent scale invariance

Metallic phase ($t > 0$):

$$\langle e^{i\theta(\mathbf{r})} e^{-i\theta(0)}\rangle \propto e^{-|\mathbf{r}|/\xi}$$

... gapped

Critical behavior:

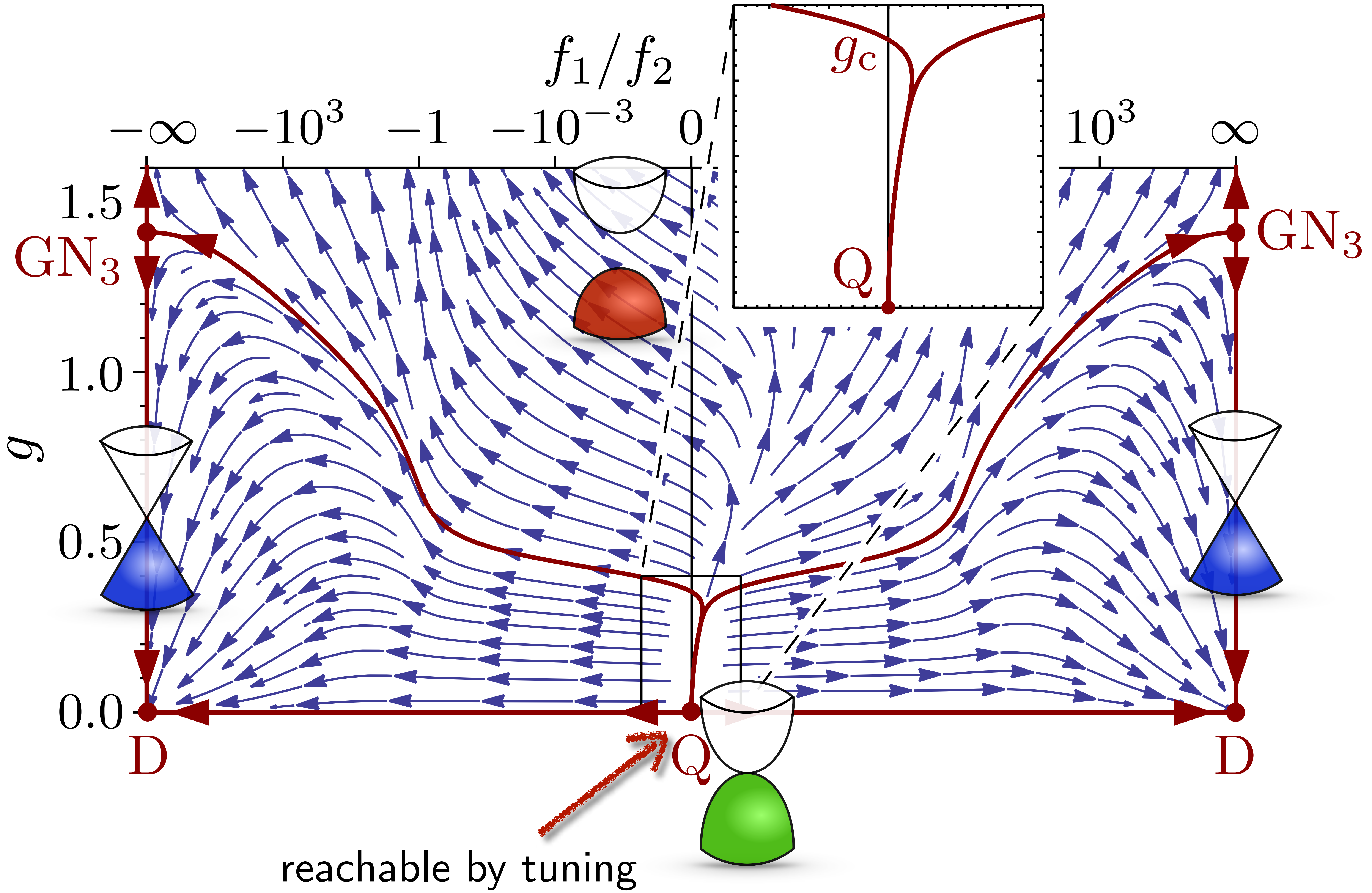
$$\xi \propto e^{C/\sqrt{t}} \quad (t > 0)$$

... essential singularity

$$h \propto \langle e^{i\theta(\mathbf{r})} \rangle^{\delta} \quad \text{with } \delta = 15 \quad (t = 0)$$

... power law

$z = 2$ QCP in bilayer honeycomb model



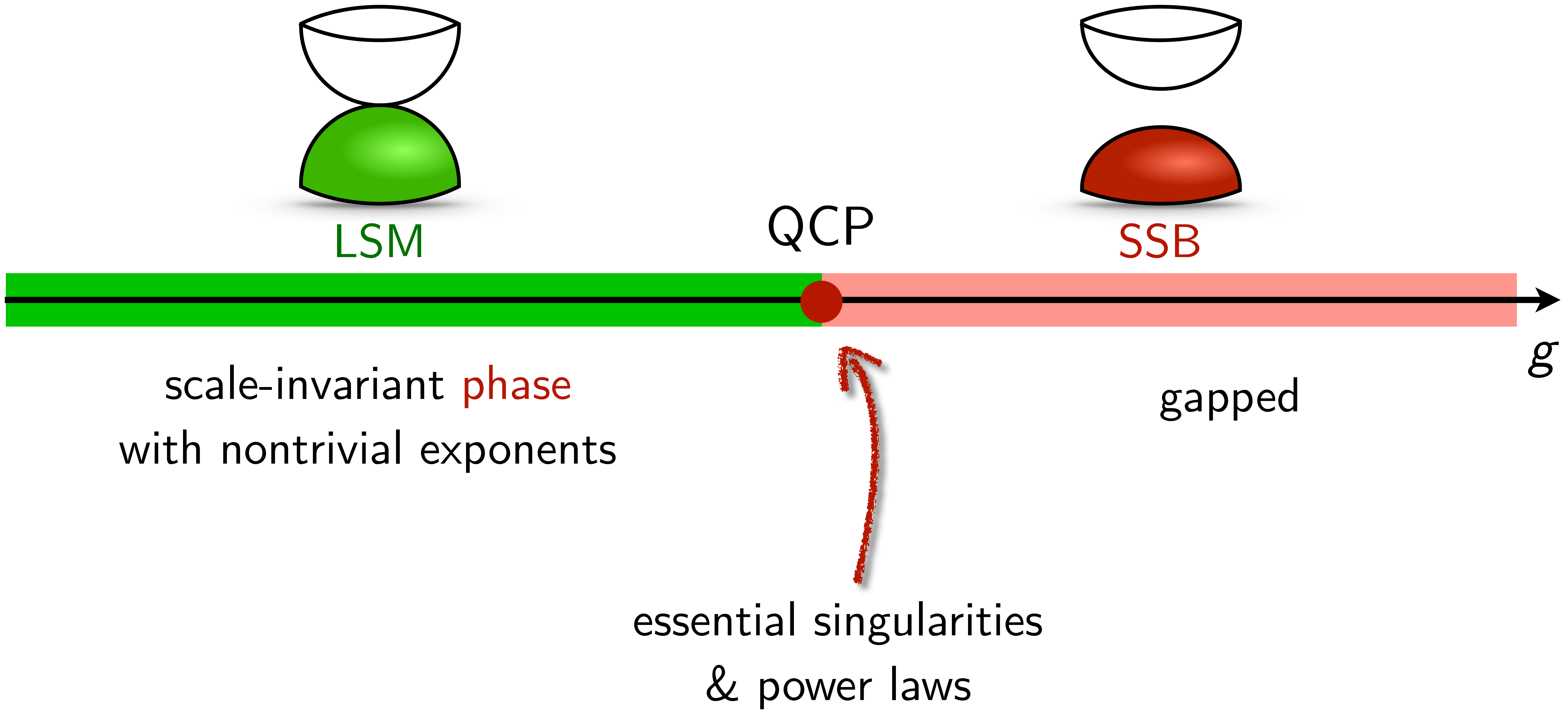
reachable by tuning
both g and t_w!

... accessible to QMC

[Ray, Vojta, LJ, PRB '18]

→ talk by S. Ray

Summary


LSM
QCP
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g
scale-invariant phase
with nontrivial exponents
gapped
essential singularities
& power laws