A fermionic gauge theory for bosonic deconfined criticality

— quantum critical behavior of the QED_3-Gross-Neveu model —

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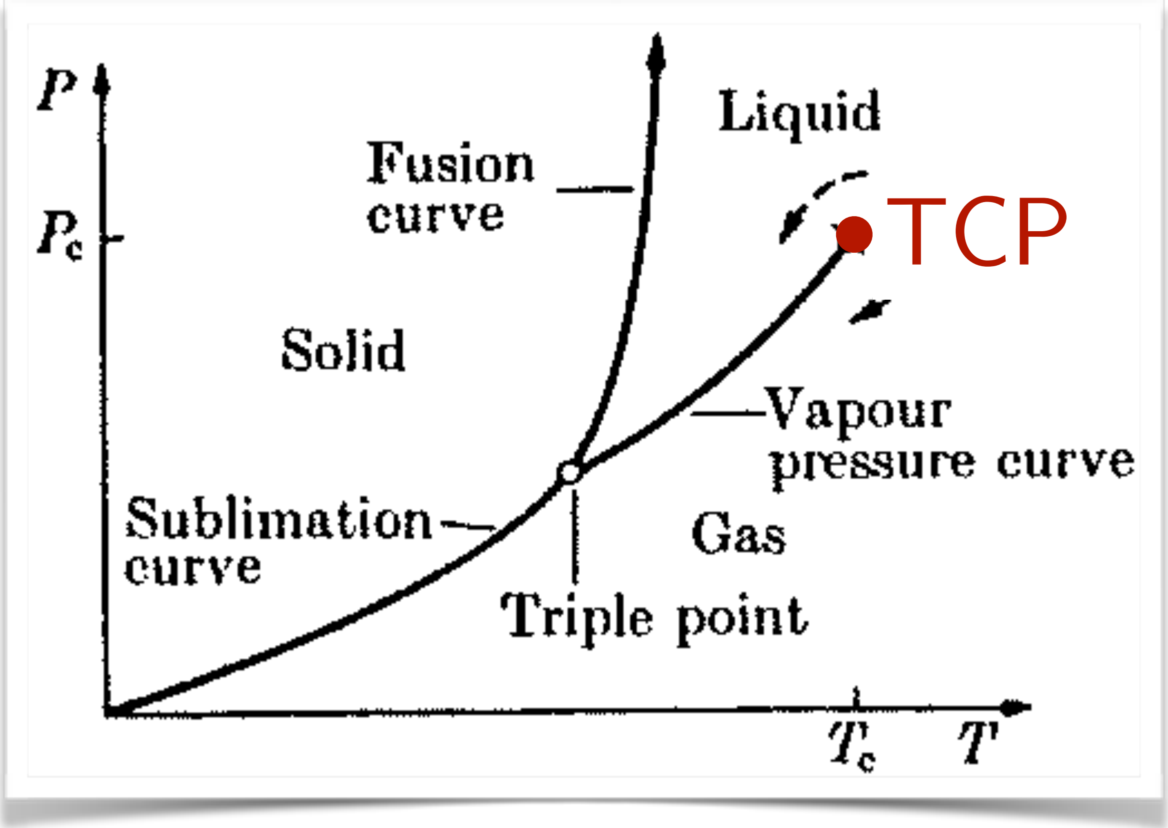
TECHNISCHE UNIVERSITÄT DRESDEN

SFB 1143

Thermal critical point (TCP) vs. quantum critical point (QCP)

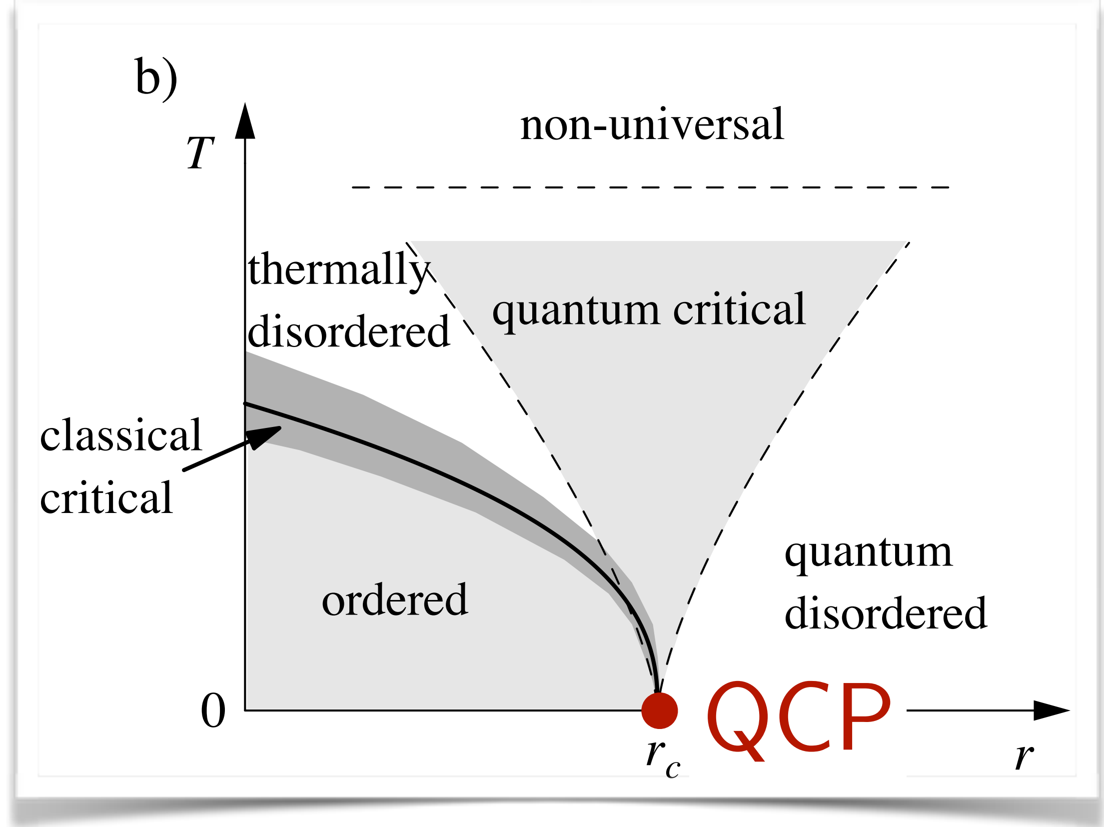
Thermal:



... driven by thermal fluctuations

... tuned by temperature

Quantum:



[M Vojta, Rep. Progr. Phys. '03]

... driven by quantum fluctuations

... tuned by pressure, field, ...

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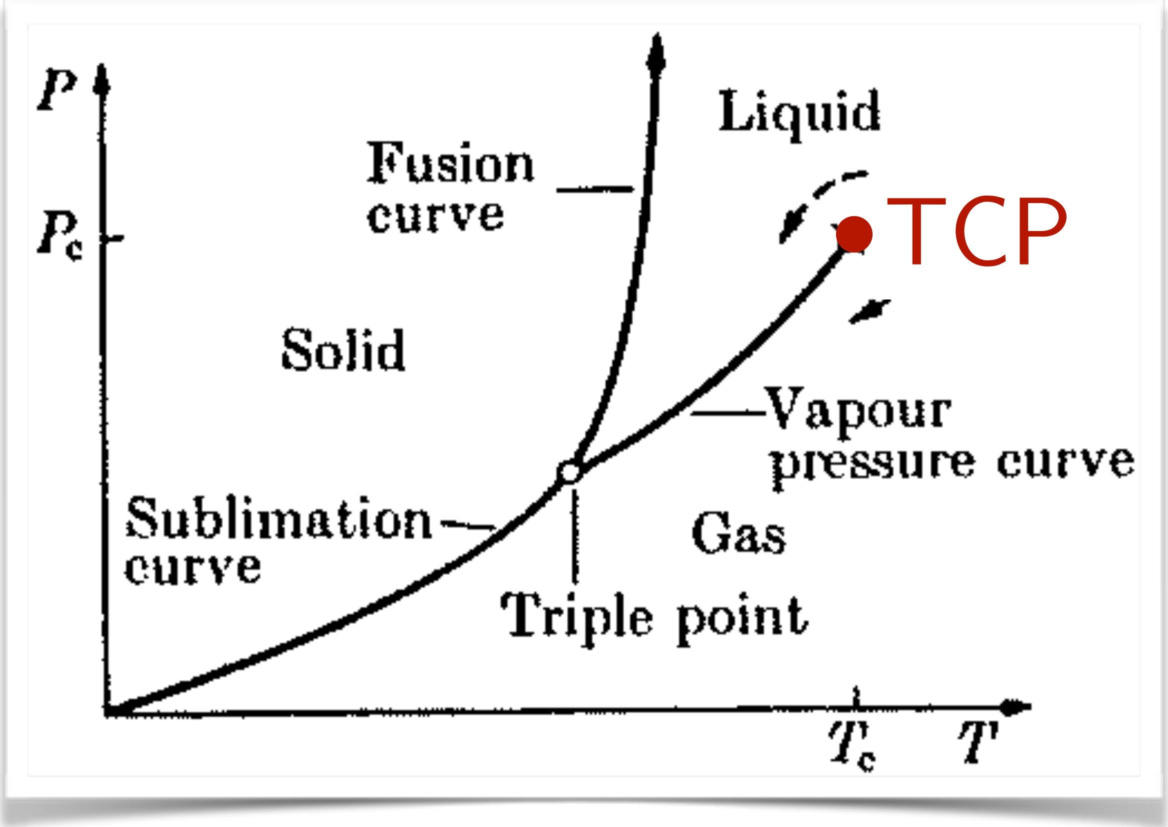

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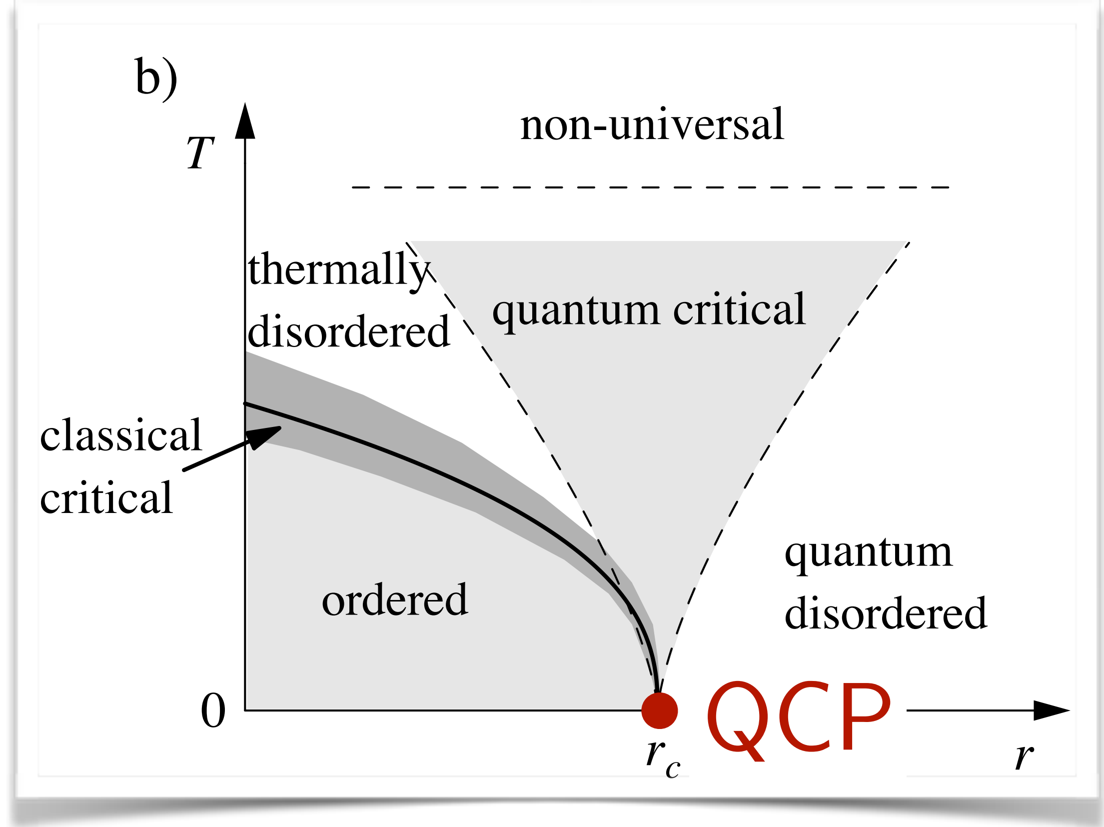

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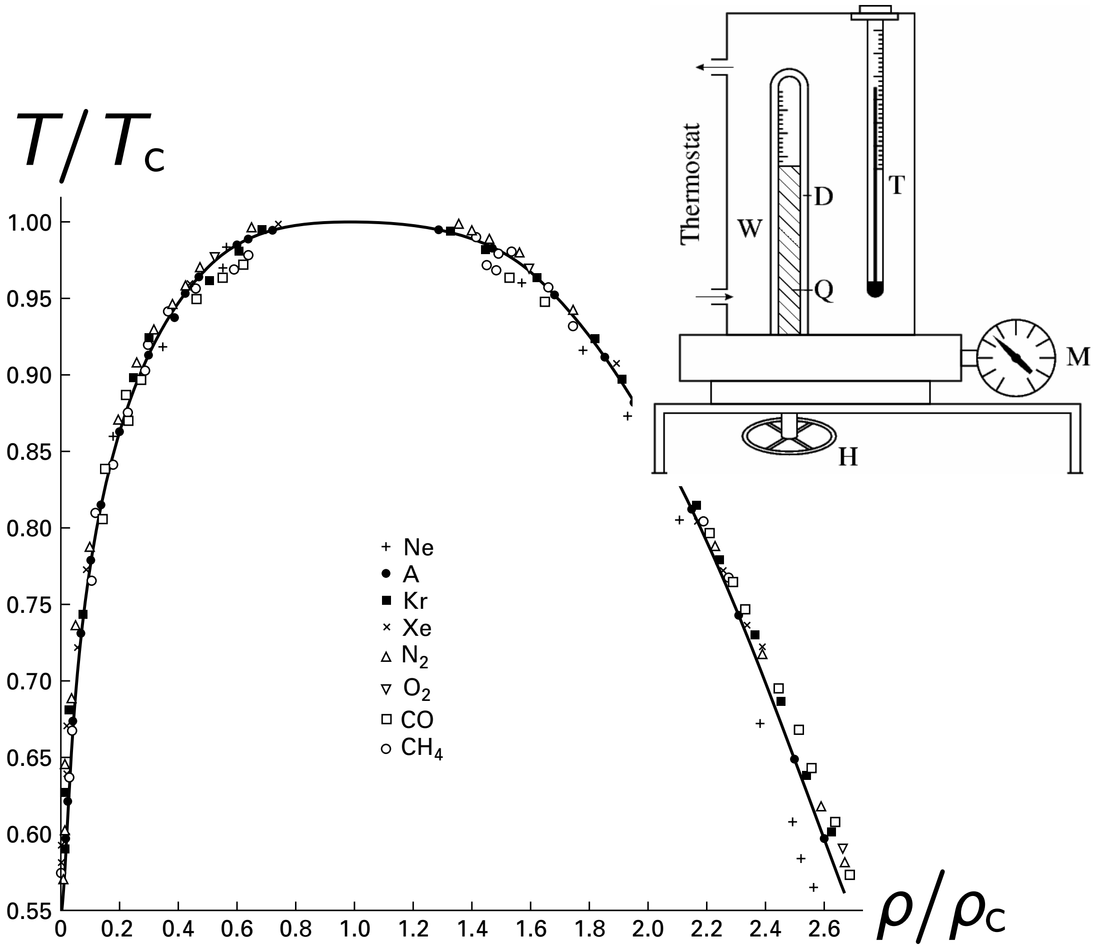
... driven by quantum fluctuations

... tuned by pressure, field, ...

Any significant differences?

TCP vs. QCP: Example

Liquid-gas transition: ... in 3D



[Grundpraktikum @ FSU Jena]

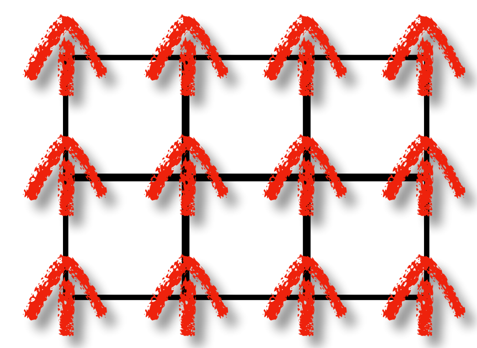
Order parameter:

$$|\rho_L - \rho_G| \propto |T - T_c|^\beta, \quad \beta \approx 1/3$$

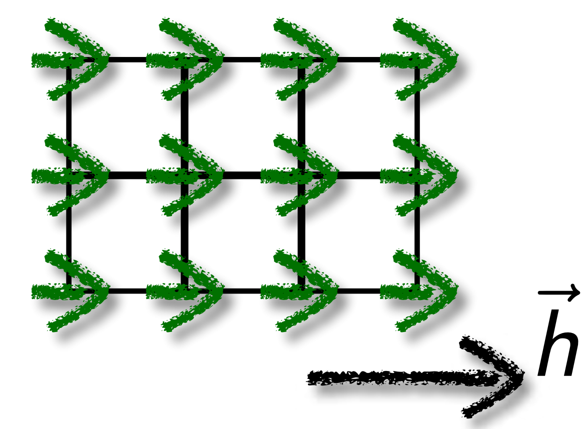
[Guggenheim, J. Chem. Phys. '45]

Transverse-field Ising model: ... in 2D

$$\mathcal{H} = -J \sum_{\langle ij \rangle} S_i^z S_j^z - \vec{h} \cdot \sum_i \vec{S}_i$$



$h/J < (h/J)_c$



$h/J > (h/J)_c$

Order parameter:

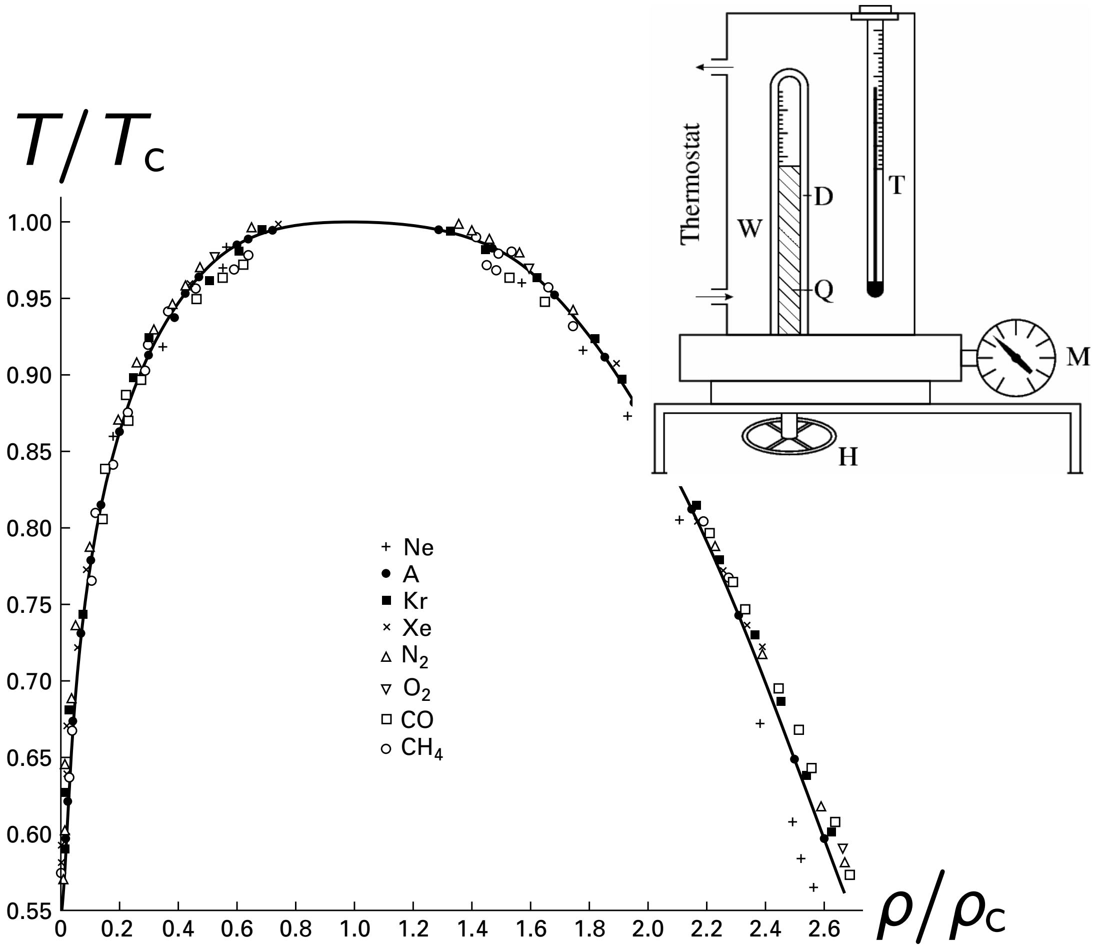
$$|m_z| \propto |J - J_c|^\beta, \quad \beta \approx 0.33$$

... and other exponents also agree

[Elliot *et al.*, PRL '70]

TCP vs. QCP: Example

Liquid-gas transition: ... in 3D



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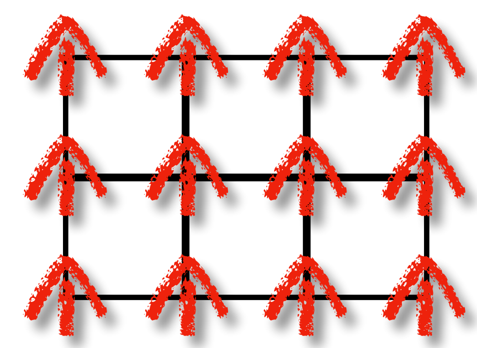

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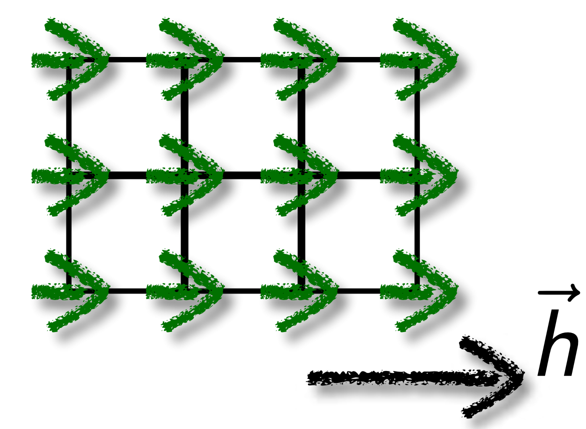


$h/J > (h/J)_c$

Quantum-to-classical mapping:

$$\mathrm{TCP}(d+z) \iff \mathrm{QCP}(d)$$

z ... dynamical critical exponent

Landau-Ginzburg-Wilson theory

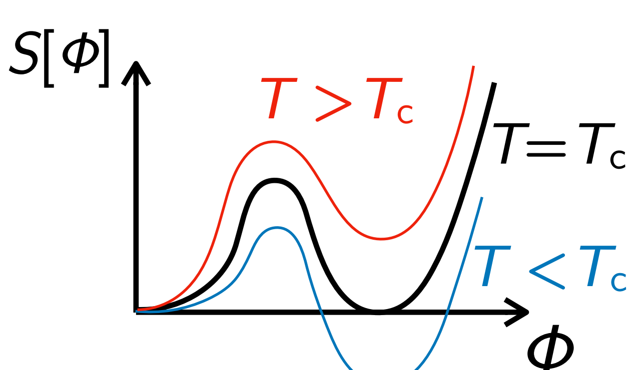
Assumption:

$$\boxed{\text{Transition uniquely characterized by order-parameter fluctuations}}$$

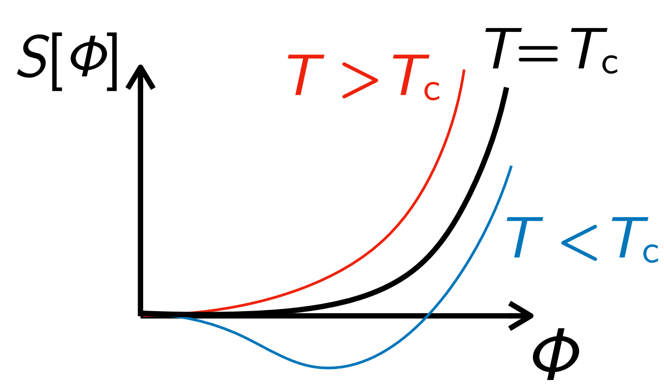
Continuum field theory: $S[\phi] = \int d^d\vec{r}\left[\frac{1}{2}(\nabla\phi)^2 + \frac{r}{2}\phi^2 + \lambda\phi^4 + \ldots\right]$

ϕ ... order-parameter field

Mean-field theory (Landau):



$S[\phi] \propto \frac{r}{2}\phi^2 + \mu\phi^3 + \lambda\phi^4$



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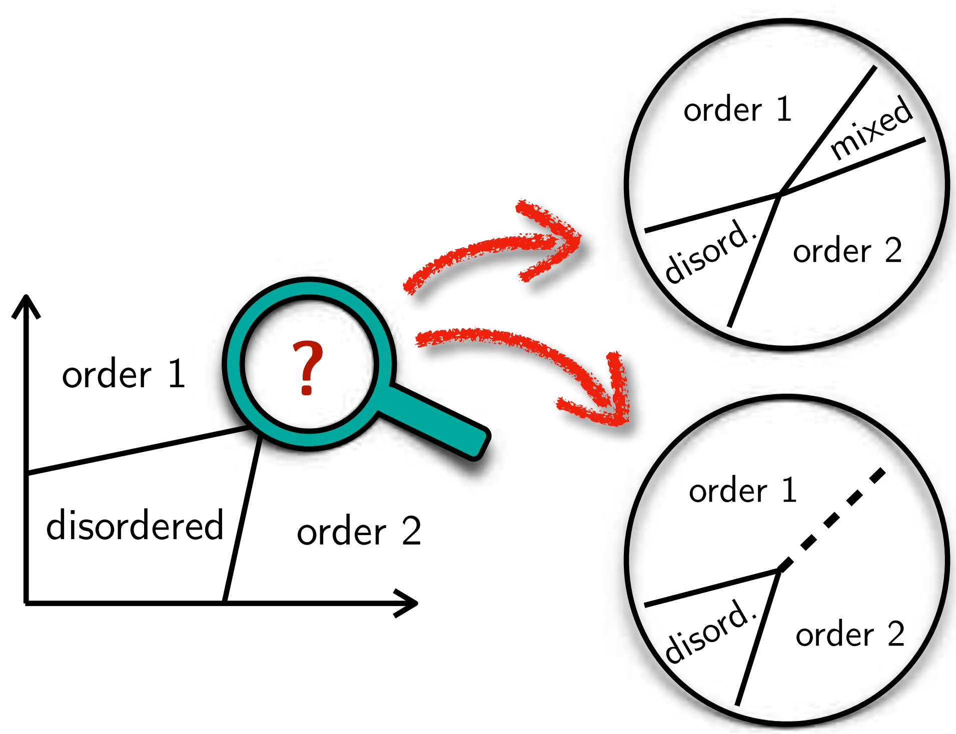
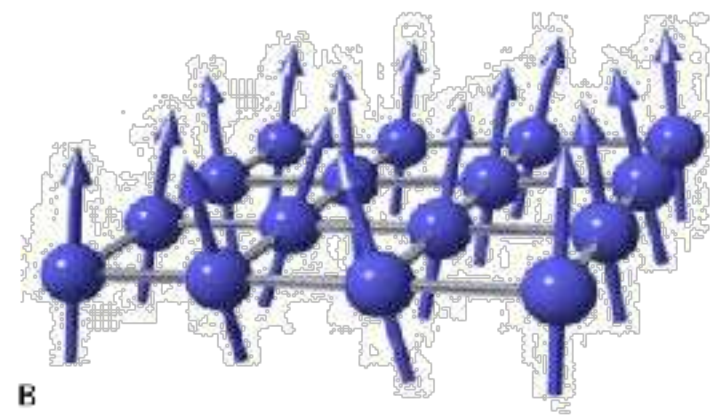


Renormalization group (Wilson):

$$\boxed{\text{Universality} \iff \text{Existence of stable RG fixed point}}$$

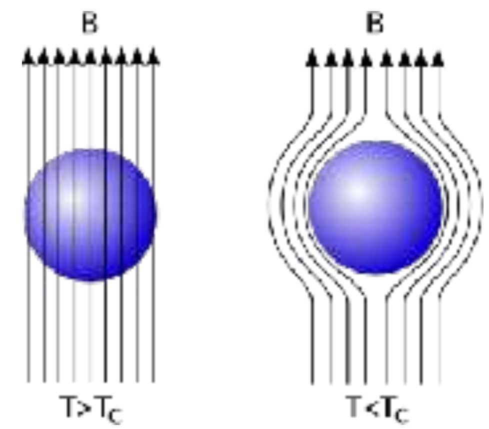
Landau-Ginzburg-Wilson theory: Successes

Ansatz works remarkably well ...



... magnets ($\vec{\varphi}$)

[Wilson & Fisher, PRL '72]



... superconductors (ϕ, ϕ^*, a_μ)

[Halperin, Lubensky, Ma, PRL '74]

... Mott transition in Fermi-point systems $(\vec{\varphi}, \psi^\dagger, \psi)$

2D Dirac:

[Herbut, PRL '06]

[Raghu, Qi, Honerkamp, Zhang, PRL '08]

[Assaad & Herbut, PRX '13]

[LJ & Herbut, PRB '14]

[Otsuka, Yunoki, Sorella, PRX '16]

...

2D QBT:

[Sun *et al.*, PRL '09]

[Scherer, Uebelacker, Honerkamp, PRB '12]

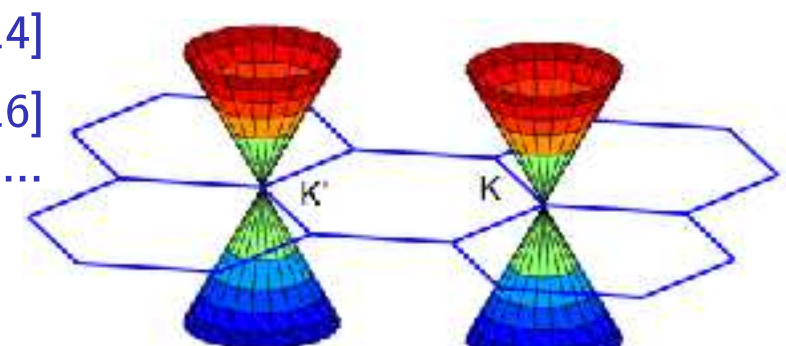
[Pujari, Lang, Murthy, Kaul, PRL '16]

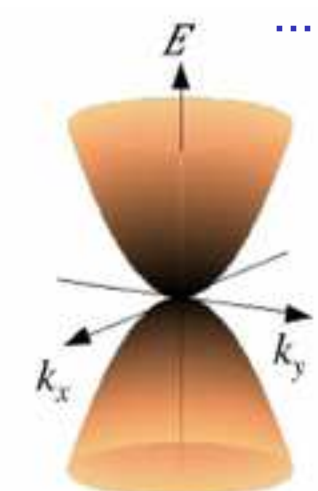
...

3D QBT:

[Herbut & LJ, PRL '14]

...





... and more

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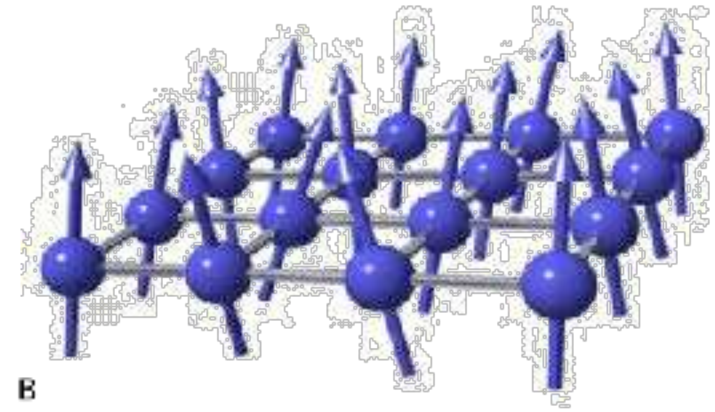

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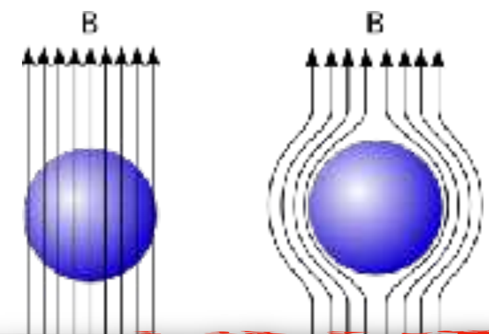


… M

2D Dir

PRL '14]

…

[Raghu

[Assaad & Herbut, PRX '13]

[LJ & Herbut, PRB '14]

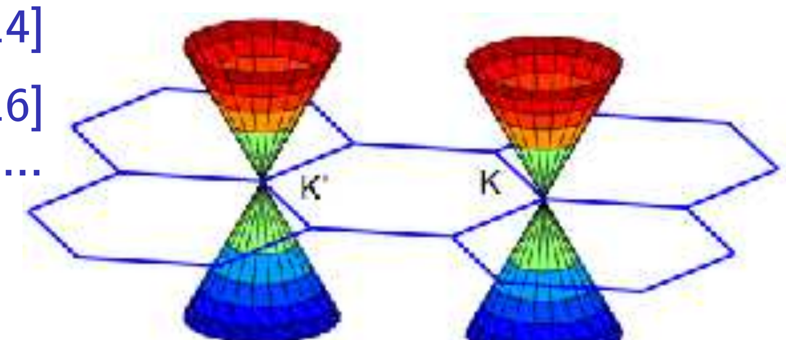
[Otsuka, Yunoki, Sorella, PRX '16]

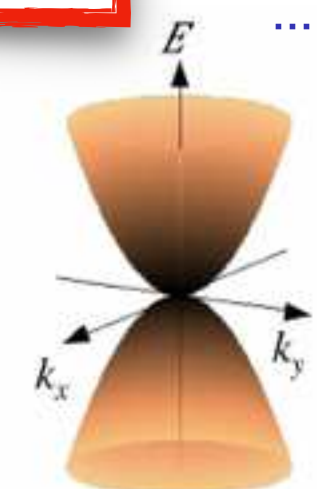
…

[Pujari, Lang, Murthy, Kaul, PRL '16]

…

Exceptions possible?





… and more

Challenging Landau's paradigm

(1) "Fluctuation-induced" quantum criticality

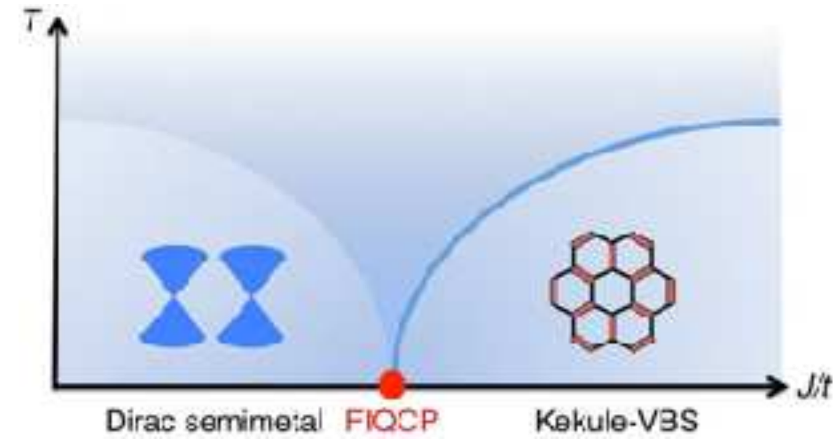
... i.e., mean-field theory becomes invalid

... Kekulé QCP

... despite the presence of cubic term in S[Φ]

[Li, Jiang, Jian, Yao, Nat. Comm. '17]

[Classen, Herbut, Scherer, PRB '17]

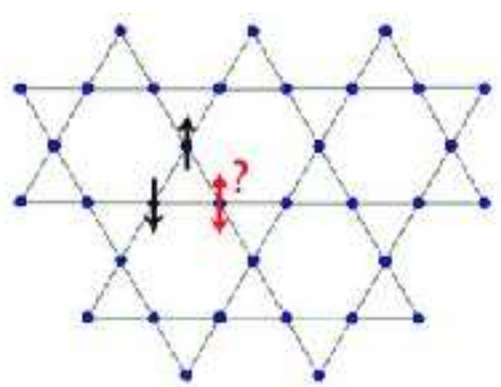


(2) "Topological" quantum criticality

... adjacent phase characterized by topological order

... i.e., no local order parameter

... Kagome spin liquid



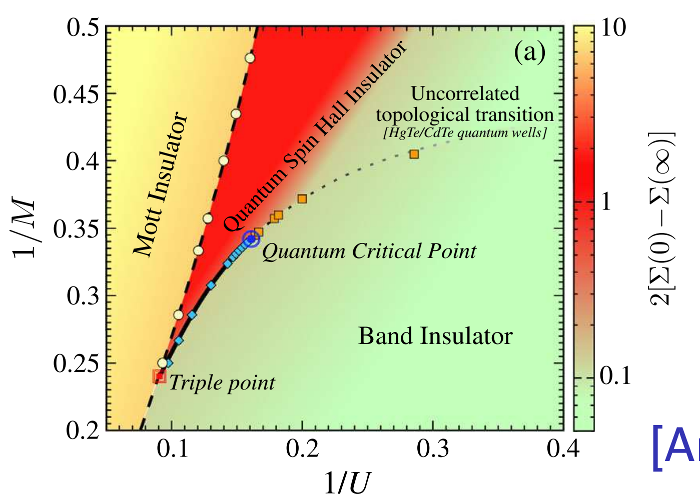
[Hastings, PRB '00]

[He & Chen, PRL '15]

[He *et al.*, PRX '17]

...

... topological insulator



[Amaricci *et al.*, PRL '15]

(3) "Deconfined" quantum criticality

[Senthil, Vishwanath, Balents, Sachdev, Fisher, Science '04]

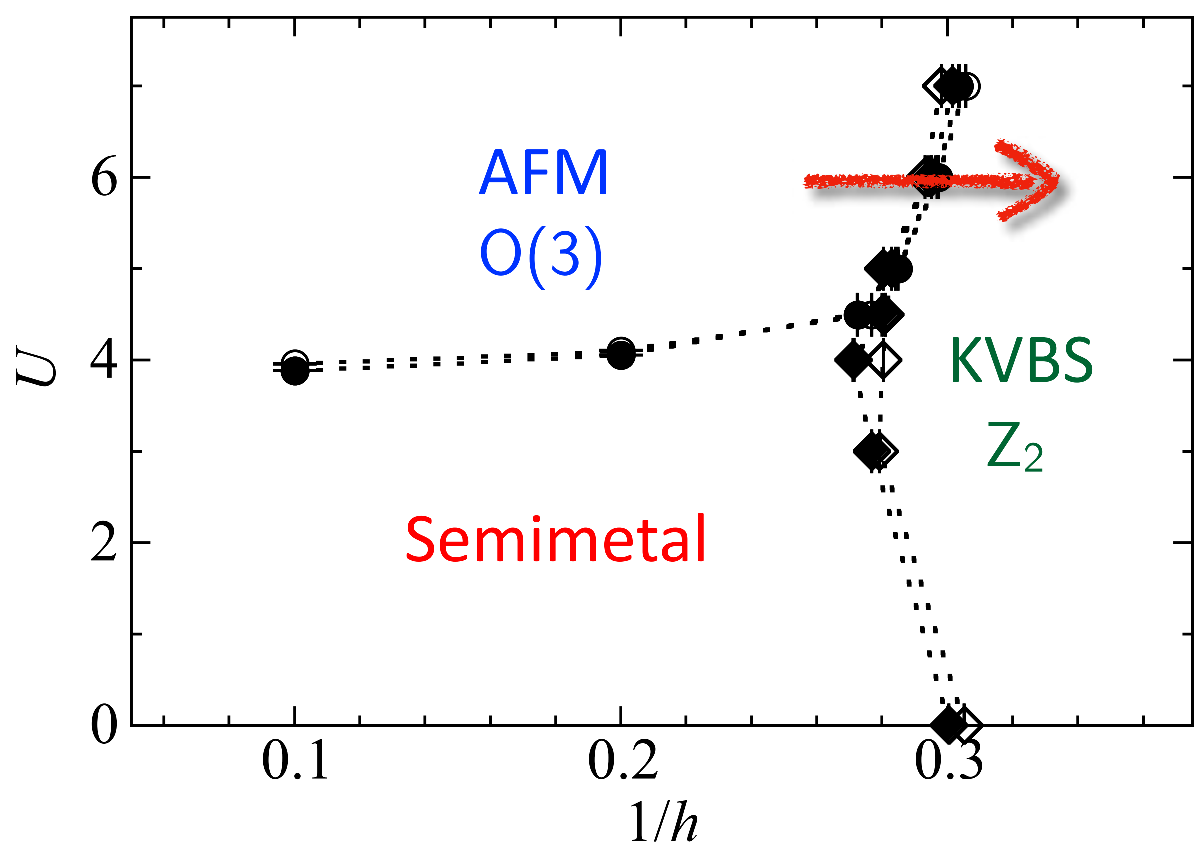
... continuous order-to-order transition

... characterized by fractionalized excitations

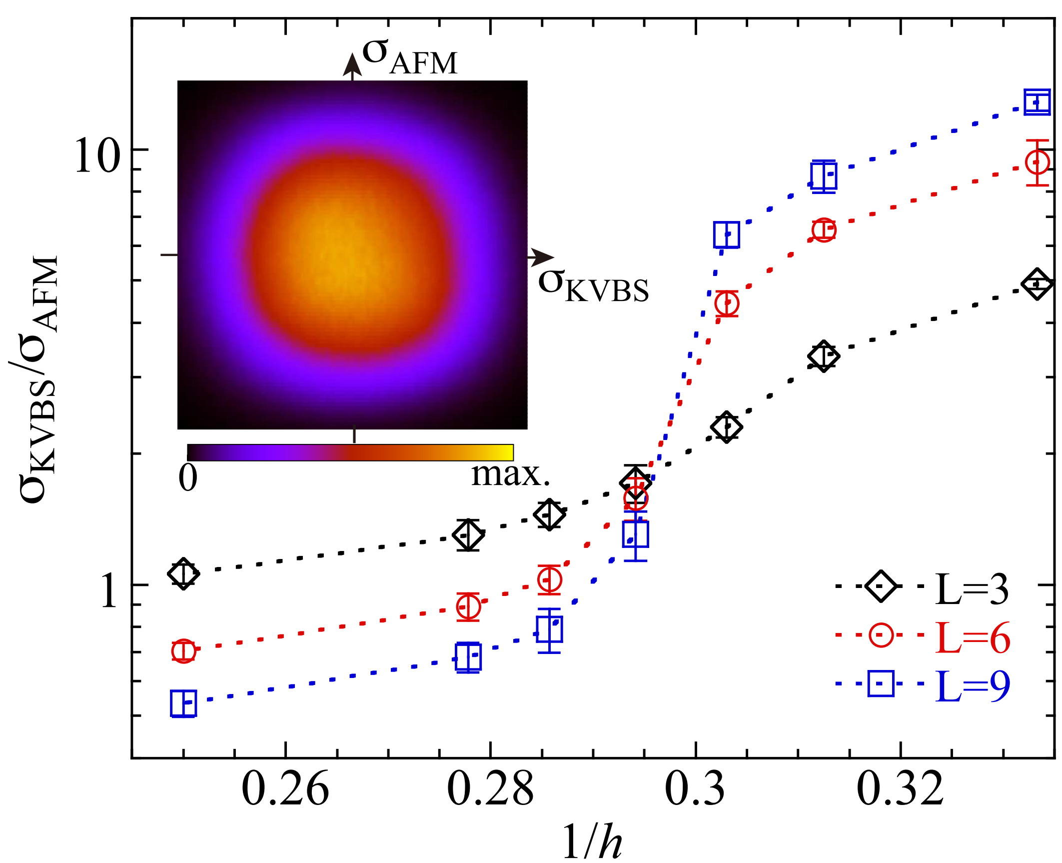
Deconfined quantum criticality

(1) Néel-to-Kekulé transition on honeycomb lattice

... anticommuting masses



standard deviation



... direct continuous transition?

... emergent SO(4)?

[Sato, Hohenadler, Assaad, PRL '17]

→ talk by F. Assaad @ SIFT17

(2) Strong-coupling limit $U \to \infty$:

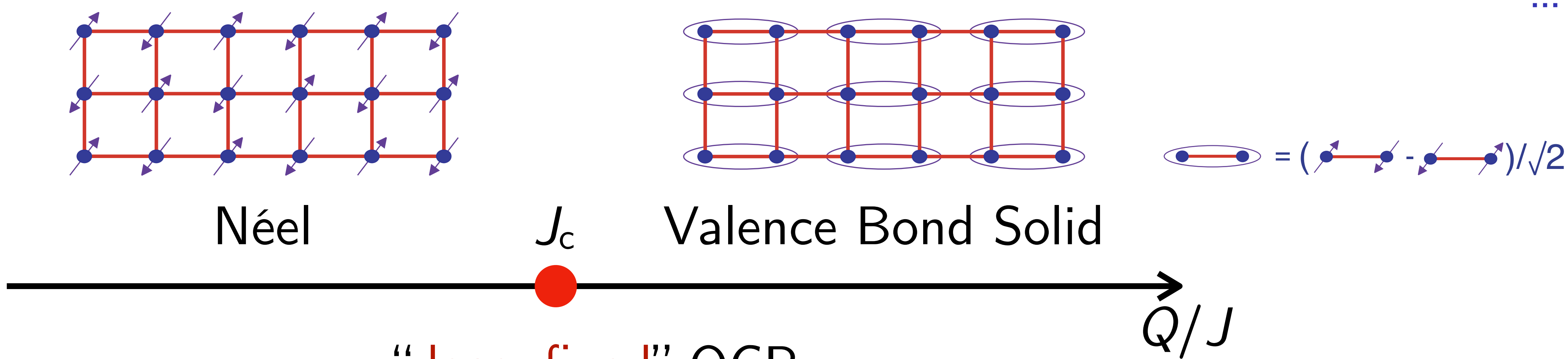
[Senthil *et al.*, Science '04]

$$\mathcal{H} = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j - Q \sum_{\langle ijkl \rangle} \left(\vec{S}_i \cdot \vec{S}_j - \tfrac{1}{4} \right) \left(\vec{S}_k \cdot \vec{S}_l - \tfrac{1}{4} \right)$$

[Sandvik, PRL '07; PRL '10]

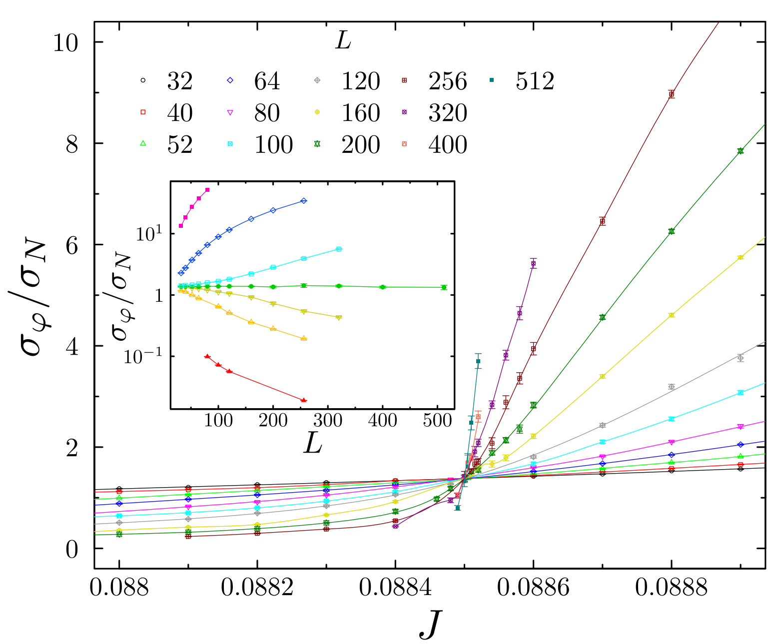
[Nahum *et al.*, PRX '15]

...

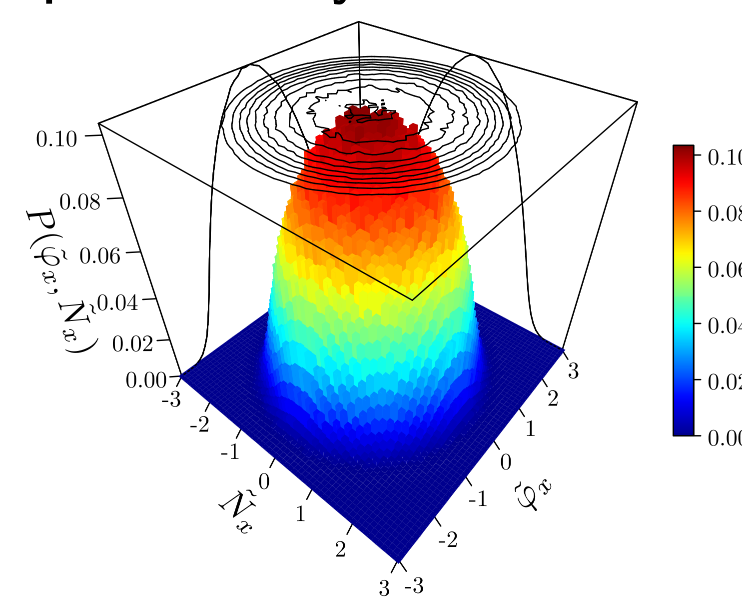


"deconfined" QCP

standard deviation



probability distribution



... isotropic!

[Nahum *et al.*, PRL '15]

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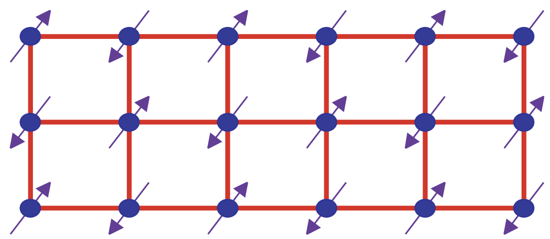
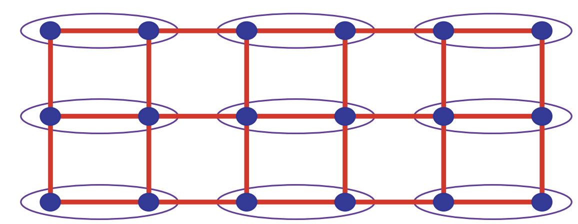
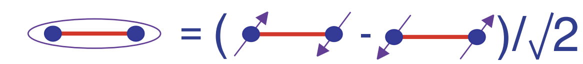
[Sandvik, PRL '07; PRL '10]

[Nahum *et al.*, PRX '15]

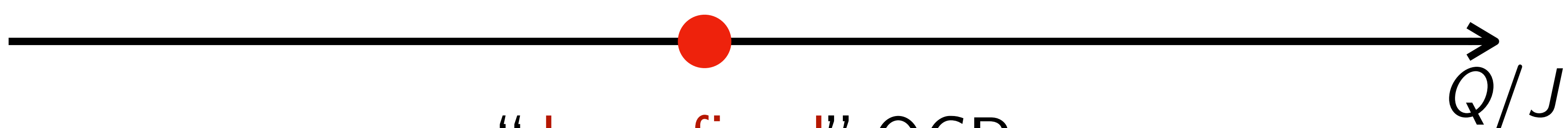
...







Néel J_c Valence Bond Solid

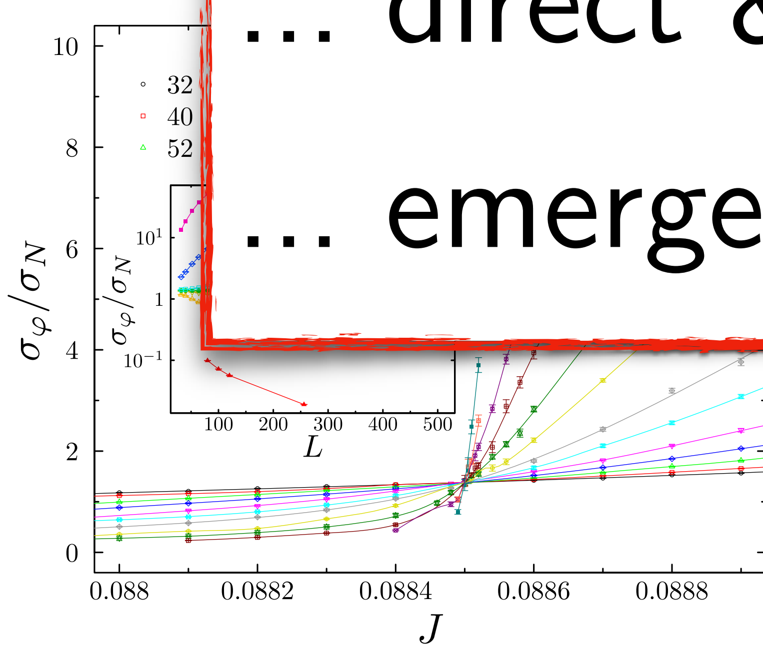


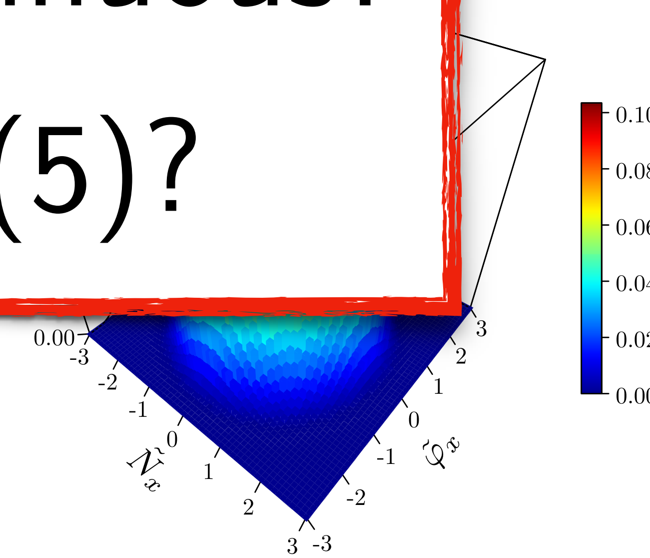
"deconfined" QCP

sta ... bution

... direct & continuous?

... emergent SO(5)?





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[Nahum *et al.*, PRL '15]

Breakdown of Landau-Ginzburg-Wilson

Continuum field theory for Néel phase: [Senthil *et al.*, Science '04; PRB '04]

$$S_{\vec{n}} = \frac{1}{2g} \int d^2 r d\tau (\partial_\mu \vec{n})^2 + S_\mathrm{B}$$

... O(3) nonlinear σ model
... with nonlocal S_B

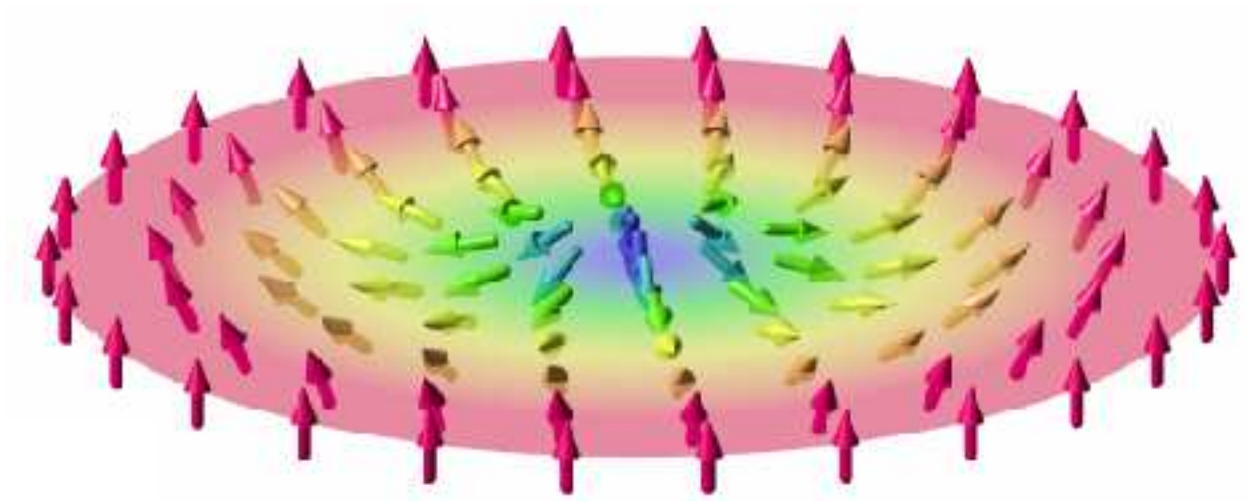
Néel order parameter: $\vec{n} \propto (-1)^r \vec{S}_r$

r ... lattice site

Spin Berry phase: $S_\mathrm{B} = iS \sum_r (-1)^r A_r$

A_r ... area enclosed by $\vec{n}_r(\tau)$

... nonvanishing for monopole events:



... e.g., creation of skyrmion with $Q = \frac{1}{4\pi} \int d^2 r\, \vec{n} \cdot (\partial_x \vec{n} \times \partial_y \vec{n})$

Order parameters: Néel: (n_1, n_2, n_3) VBS: $(\mathrm{Re}\,\mathcal{M}, \mathrm{Im}\,\mathcal{M})$

$\mathcal{M}$ ... monopole operator

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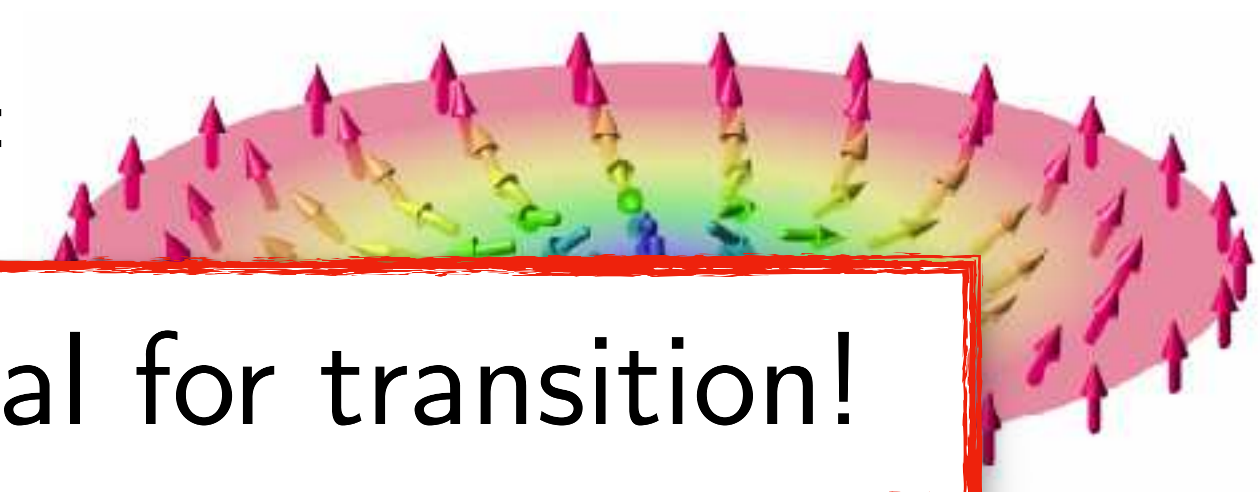

Berry phase crucial for transition!

... e.g., creation of skyrmion with $Q = \frac{1}{4\pi}\int d^2r\, \vec{n}\cdot(\partial_x \vec{n} \times \partial_y \vec{n})$

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Field theory for deconfined criticality

Reformulation:

... CP^1 parametrization

$$\vec{n} = z^\dagger \vec{\sigma} z$$

$z = (z_1, z_2)$ ... complex "spinon"

CP^1 model:

$$S_z = \int d^2\vec{r} d\tau \left[\sum_{\alpha=1,2} |(\partial_\mu - i a_\mu) z_\alpha|^2 - \left(|z_1|^2 + |z_2|^2\right)^2 \right]$$

a_μ ... "photon"

... monopoles = instantons in a_μ

Senthil *et al.*: $\boxed{\text{Monopoles irrelevant at critical point!}}$

[Senthil *et al.*, Science '04; PRB '04]

Natural field theory: noncompact CP^1 model ($NCCP^1$)

Field theory for deconfined criticality

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[Senthil *et al.*, Science '04; PRB '04]

Natural field theory: noncompact CP¹ model (NCCP¹)

Deconfined QCP = critical point with fractionalized excitations

... with fractionalized excitations being "confined" in either phase

Field theory for deconfined criticality

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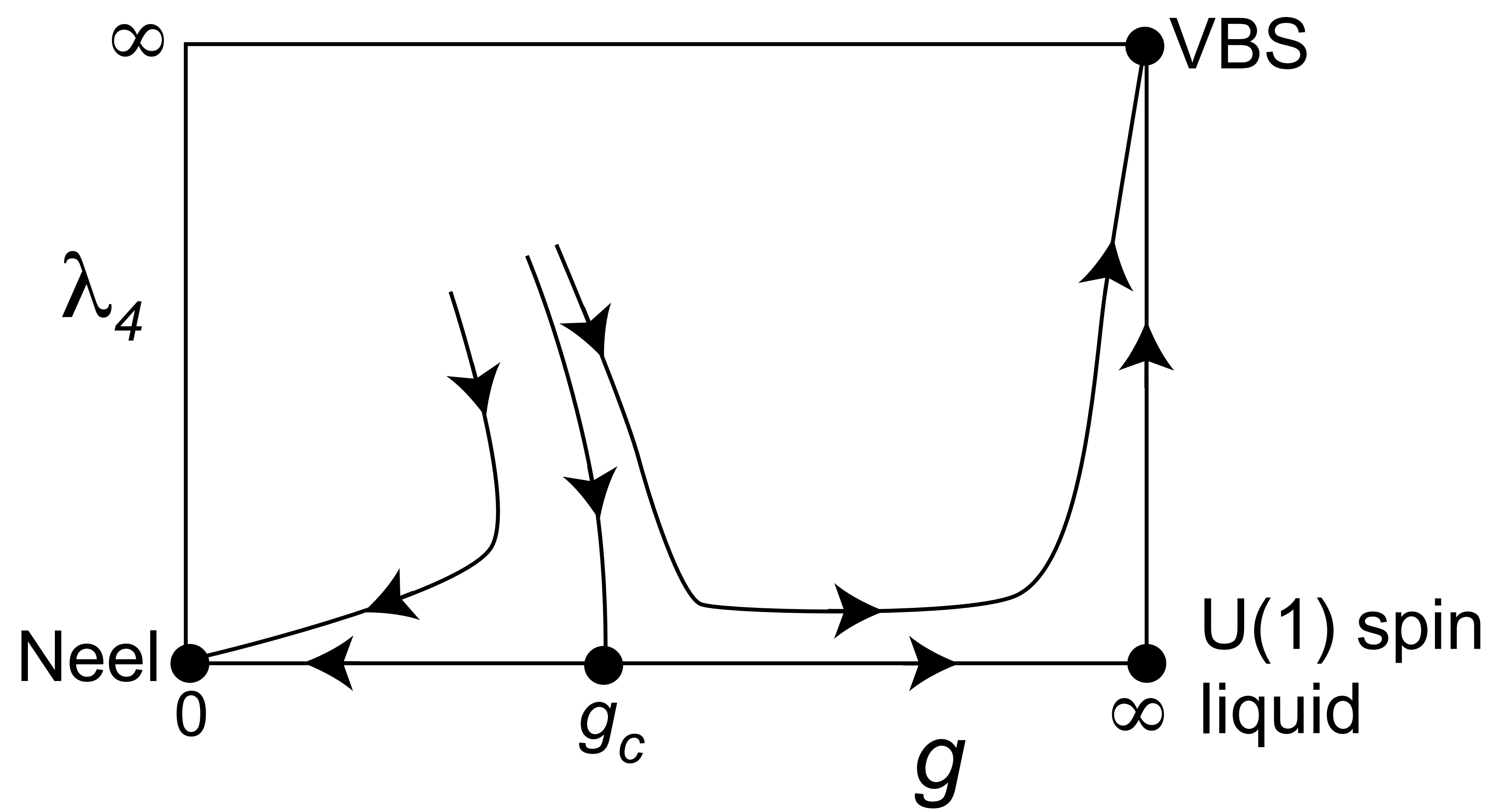


[Senthil *et al.*, JPSJ '05]

Deconfined QCP = critical point with fractionalized excitations

... with fractionalized excitations being "confined" in either phase

Alternative formulations of deconfined QCP

Duality conjecture:

[Wang, Nahum, Metlitski, Xu, Senthil, PRX '17]

$$\boxed{\text{noncompact } CP^1 \text{ model} \quad \Longleftrightarrow \quad QED_3\text{-Gross-Neveu model}}$$

$$(z_1, z_2, z_1^\dagger, z_2^\dagger, b_\mu) \quad \Leftrightarrow \quad (\psi_1, \psi_2, \bar\psi_1, \bar\psi_2, a_\mu)$$

$$\sum_{\alpha=1,2} |D_b z_\alpha| - \left(|z_1|^2 + |z_2|^2\right)^2 \quad \Leftrightarrow \quad \sum_{i=1,2} \left(\bar\psi_i \not{D}_a \psi_i + \phi \bar\psi_i \psi_i\right) + V(\phi)$$

... with $V(\Phi)$ tuned to criticality

Explicitly:

$$(n_1, n_2, n_3, n_4, n_5) \sim (\overbrace{2\,\mathrm{Re}\,\mathcal{M}_b, 2\,\mathrm{Im}\,\mathcal{M}_b}^{U(1)}, \overbrace{z^\dagger\sigma_x z, z^\dagger \sigma_y z, z^\dagger \sigma_z z}^{O(3)})$$

$$\sim \left[\underbrace{\mathrm{Re}\,(\psi_1^\dagger \mathcal{M}_a), -\mathrm{Im}\,(\psi_1^\dagger \mathcal{M}_a), \mathrm{Re}\,(\psi_2^\dagger \mathcal{M}_a), \mathrm{Im}\,(\psi_2^\dagger \mathcal{M}_a)}_{U(2)}, \phi\right]$$

... naturally explains emergent SO(5)!

... part of "duality web" in 2+1D:

[Seiberg, Senthil, Wang, Witten, Ann. Phys. '16]

[Karch & Tong, PRX '16]

[Thomson & Sachdev, arXiv '17]

...

Consequences of $\mathrm{NCCP}^1 \Longleftrightarrow \mathrm{QED}_3$-Gross-Neveu

Predictions for critical behavior:

[Wang, Nahum, Metlitski, Xu, Senthil, PRX '17]

(1) $[z^\dagger \sigma^z z] = [\phi] \quad \Rightarrow \quad \eta_{\mathrm{QED}_3\text{-GN}} = \eta_{\text{Néel}} = \eta_{\mathrm{VBS}}$ ... from $\phi \sim z^\dagger \sigma^z z$

... $\eta_{\text{Néel}} = \eta_{\mathrm{VBS}}$ consistent with QMC

[Sandvik, PRL '07]

(2) $[z^\dagger z] = [\phi^2] \quad \Rightarrow \quad \nu_{\mathrm{QED}_3\text{-GN}} = \nu_{\text{Néel-VBS}}$ ... from $(\phi^2, \dots) \sim (z^\dagger \sigma^z z, z^\dagger z, \dots)$

(3) $[\bar\psi \sigma^z \psi] = [\phi^2] \quad \Rightarrow \quad [\bar\psi \sigma^z \psi] = 3 - 1/\nu_{\mathrm{QED}_3\text{-GN}}$ ... from $\bar\psi \sigma^z \psi \sim z^\dagger z$

... nontrivial prediction fully within QED_3-GN

... allows quantitative test of duality conjecture

Here: (a) Existence of QCP in QED_3-GN model? ... prerequisite for duality

(b) Critical behavior? ... & comparison with NCCP^1

QED3-Gross-Neveu model: GN limit

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - \cancel{iea}_\mu)\gamma_\mu\psi_i + g\phi\bar{\psi}_i\psi_i\right] + \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4$$

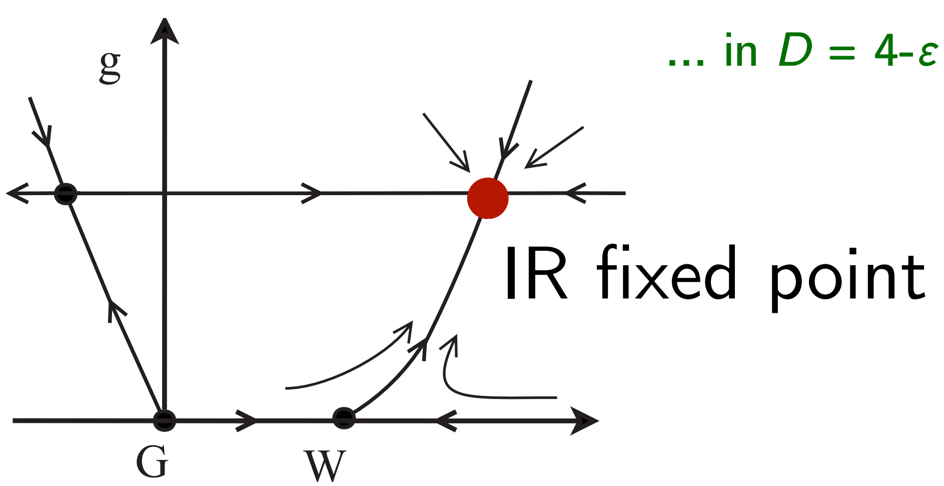
... in D = 2+1

... i = 1,...,2N

Gross-Neveu limit $(e^2 \to 0)$:

Gross-Neveu-Yukawa theory

... in D = 4-ε



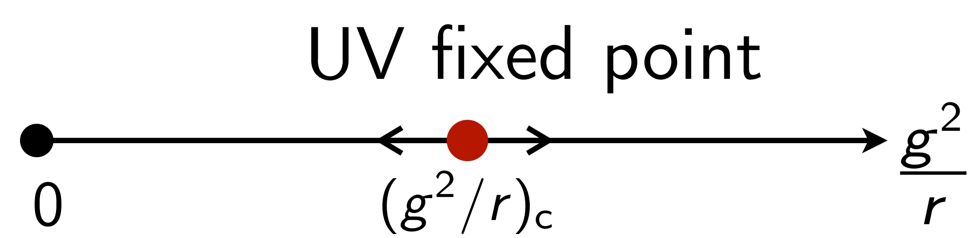
[Herbut, Juricic, Vafek, PRB '09]

$\Leftrightarrow$

Gross-Neveu theory

... in D = 2+ε

$$g\phi\bar{\psi}\psi + \frac{r}{2}\phi^2 \sim -\frac{g^2}{r}(\bar{\psi}\psi)^2$$



GN-QCP exists for all $2 < D < 4$ and can be understood as either ...

... **IR** fixed point of GNY or ... **UV** fixed point of GN

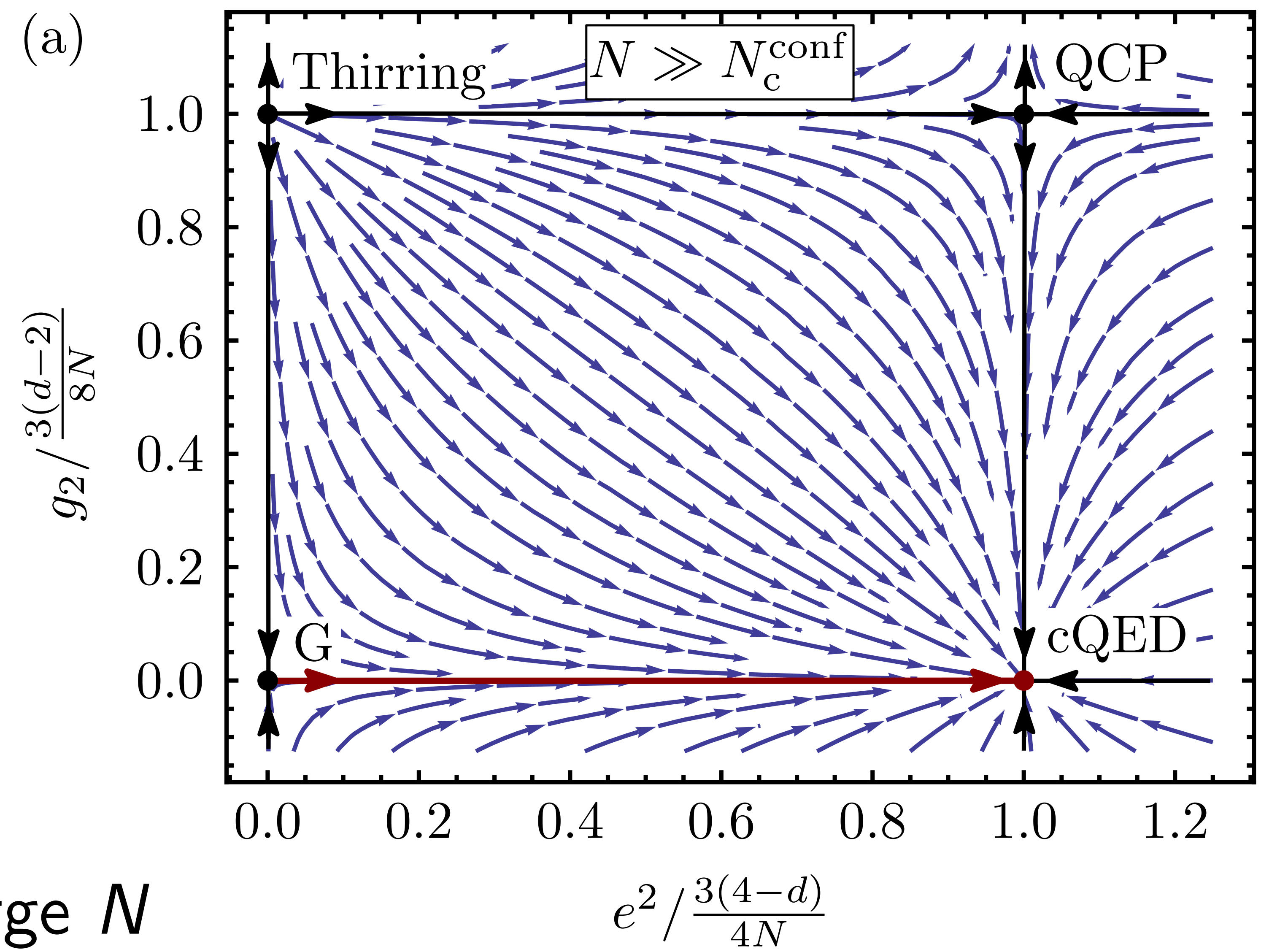
[Zinn-Justin, NPB '91] [Braun, Gies, D Scherer, PRD '11] [LJ, Herbut, PRB '14]

QED$_3$-Gross-Neveu model: QED$_3$ limit

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + g\phi\bar{\psi}_i\psi_i\right] \cancel{+ \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4}$$

QED$_3$ limit $(g \to 0)$:



... conformal phase at large N

[LJ, PRD '16]

QED$_3$-Gross-Neveu model: QED$_3$ limit

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + \cancel{g\phi\bar{\psi}_i\psi_i\right] + \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4}$$

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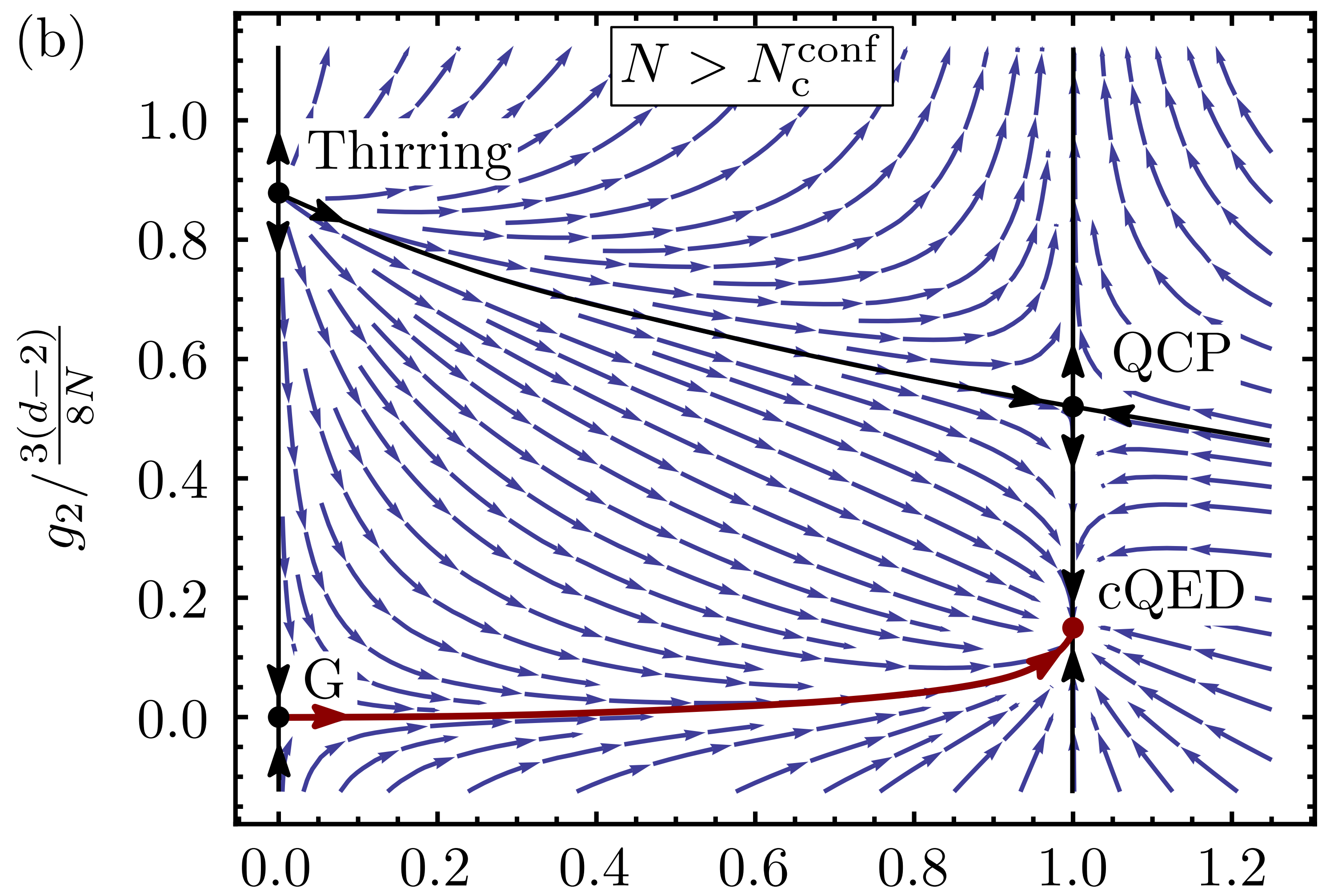


... QCP and cQED approach each other

[LJ, PRD '16]

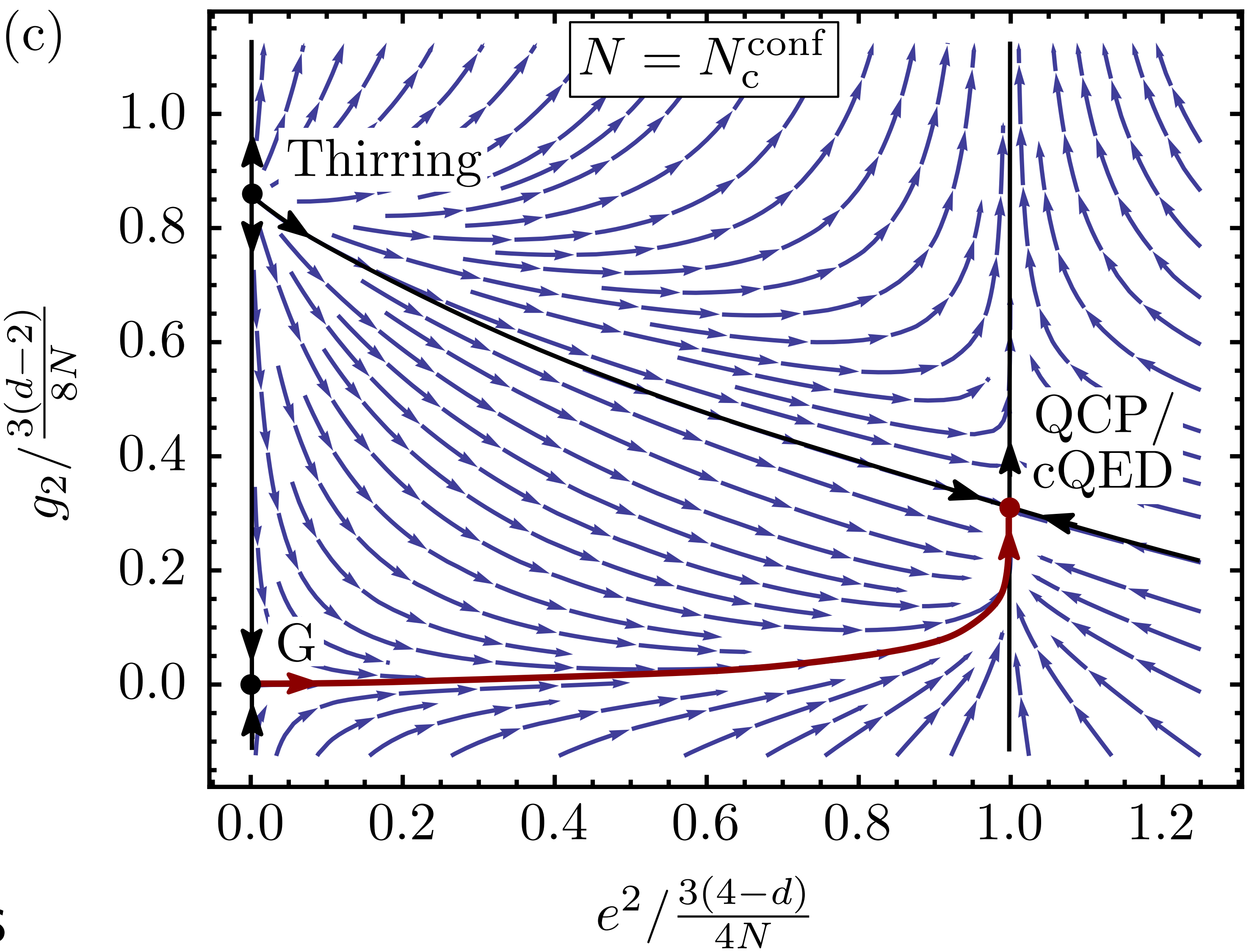
QED$_3$-Gross-Neveu model: QED$_3$ limit

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + g\phi\bar{\psi}_i\psi_i\right] \cancel{+ \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4}$$

QED$_3$ limit $(g \to 0)$:

(c)



... collision of fixed points

[LJ, PRD '16]

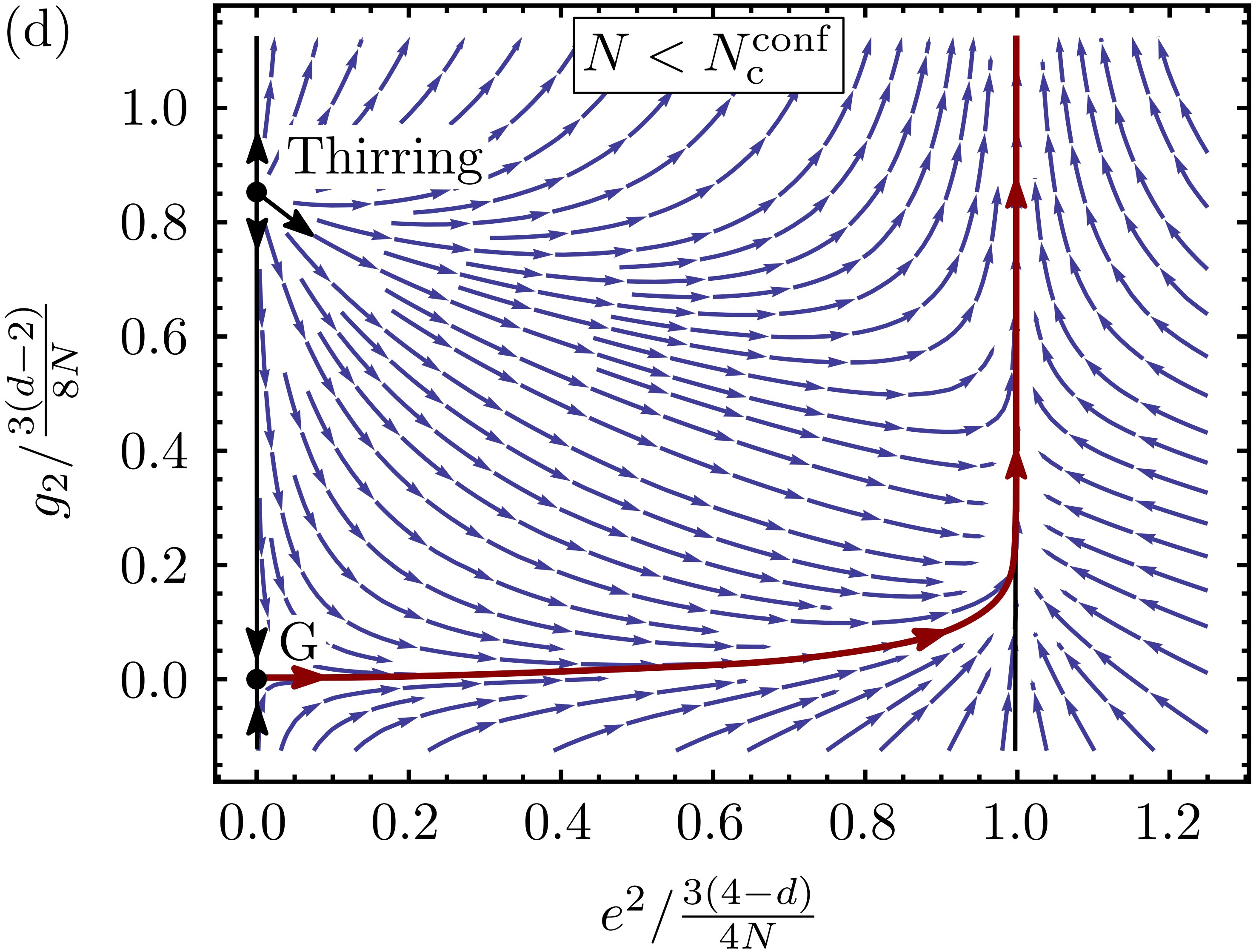
QED3-Gross-Neveu model: QED3 limit

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + g\phi\bar{\psi}_i\psi_i\right] \cancel{+ \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4}$$

QED3 limit $(g \to 0)$:

(d)



... runaway flow!

[LJ, PRD '16]

QED$_3$-Gross-Neveu model: QED$_3$ limit

Lagrangian:

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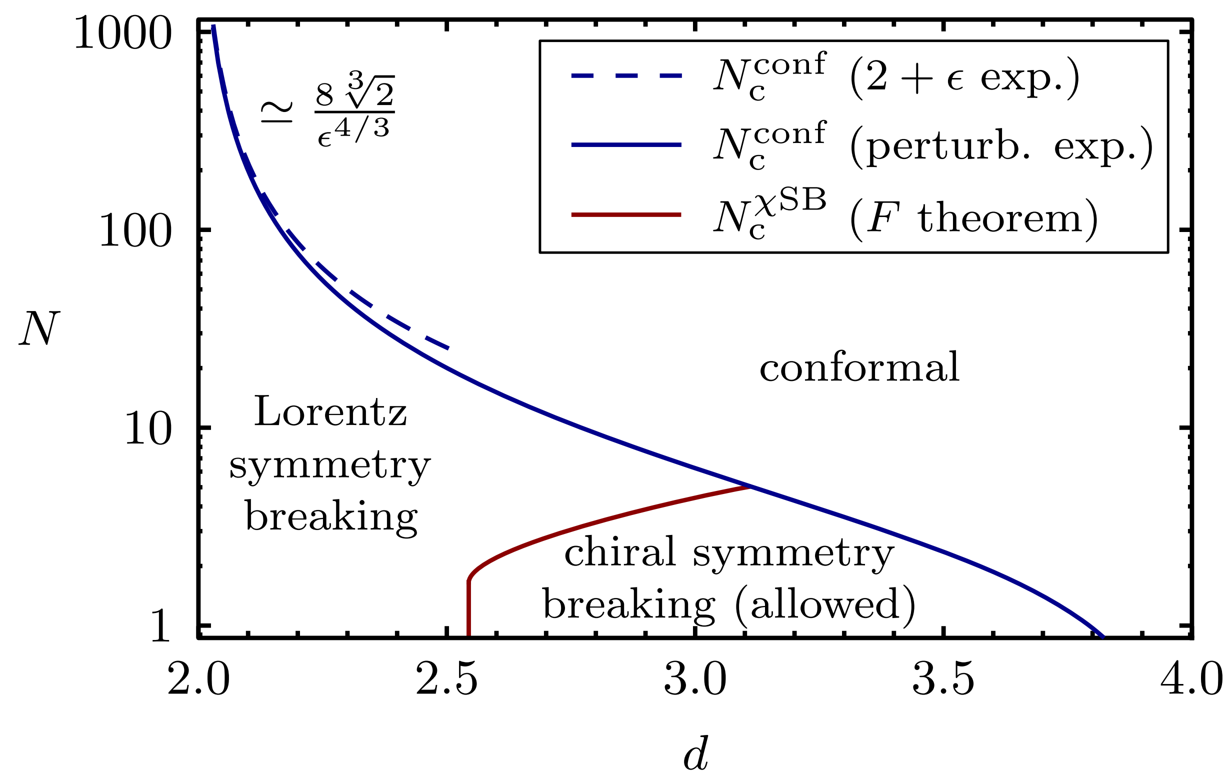
QED$_3$ limit $(g \to 0)$:

[LJ, PRD '16]



... QED$_3$ (potentially) unstable at low N!

→ talk by I. Herbut @ SIFT17

[Appelquist, Nash, Wijewardhana, PRL '88]
[Braun, Gies, LJ, Roscher, PRD '14]
[Di Pietro *et al.*, PRL '16]
[Herbut, PRD '16]
...

QED3-Gross-Neveu model: QED3 limit

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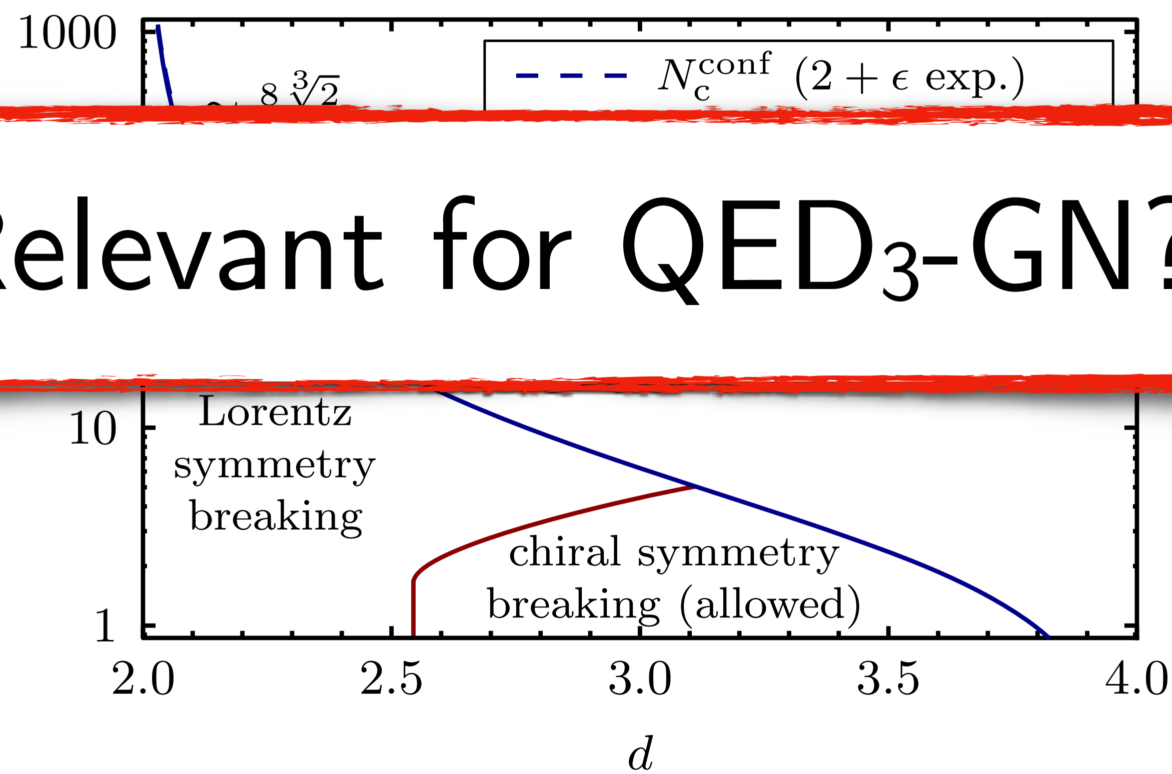
$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + \cancel{g\phi\bar{\psi}_i\psi_i}\right] \cancel{+ \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4}$$

QED3 limit $(g \to 0)$:

[LJ, PRD '16]



Relevant for QED3-GN?

... QED3 (potentially) unstable at low N!

→ talk by I. Herbut @ SIFT17

[Appelquist, Nash, Wijewardhana, PRL '88]
[Braun, Gies, LJ, Roscher, PRD '14]
[Di Pietro *et al.*, PRL '16]
[Herbut, PRD '16]
...

QED$_3$-GN model: Fermionic RG

Integrate out ϕ:

$$g\phi\bar{\psi}_i\psi_i + \frac{r}{2}\phi^2 \mapsto u(\bar{\psi}_i\psi_i)^2$$

... u will also generate other four-fermion terms

General four-fermion theory compatible with U($2N$):

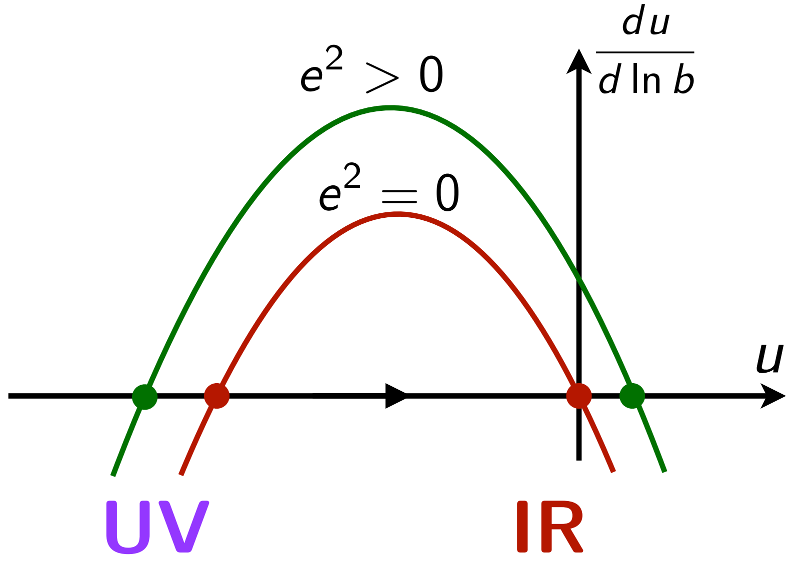
[Gies & LJ, PRD '10]

$$\mathcal{L}_\psi = \bar{\psi}_i\gamma_\mu(\partial_\mu - ia_\mu)\psi + u(\bar{\psi}_i\psi_i)^2 + v(\bar{\psi}_i\gamma_\mu\psi_i)^2$$

One-loop RG:

... at large N

$$\frac{du}{d\ln b} = -u - 8u^2 + 2e^4$$



QED$_3$-GN model: Fermionic RG

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One-loop RG: ... at large N

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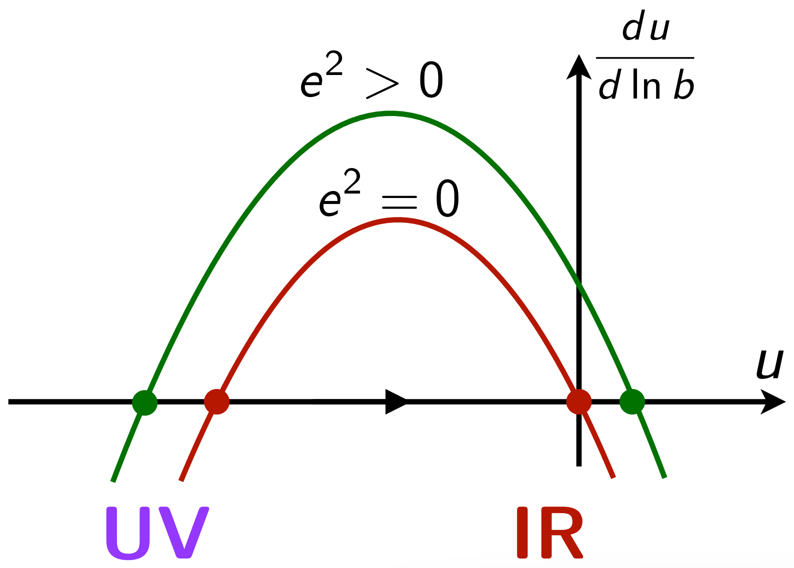


... gauge fluctuations stabilize QED$_3$-GN fixed point!

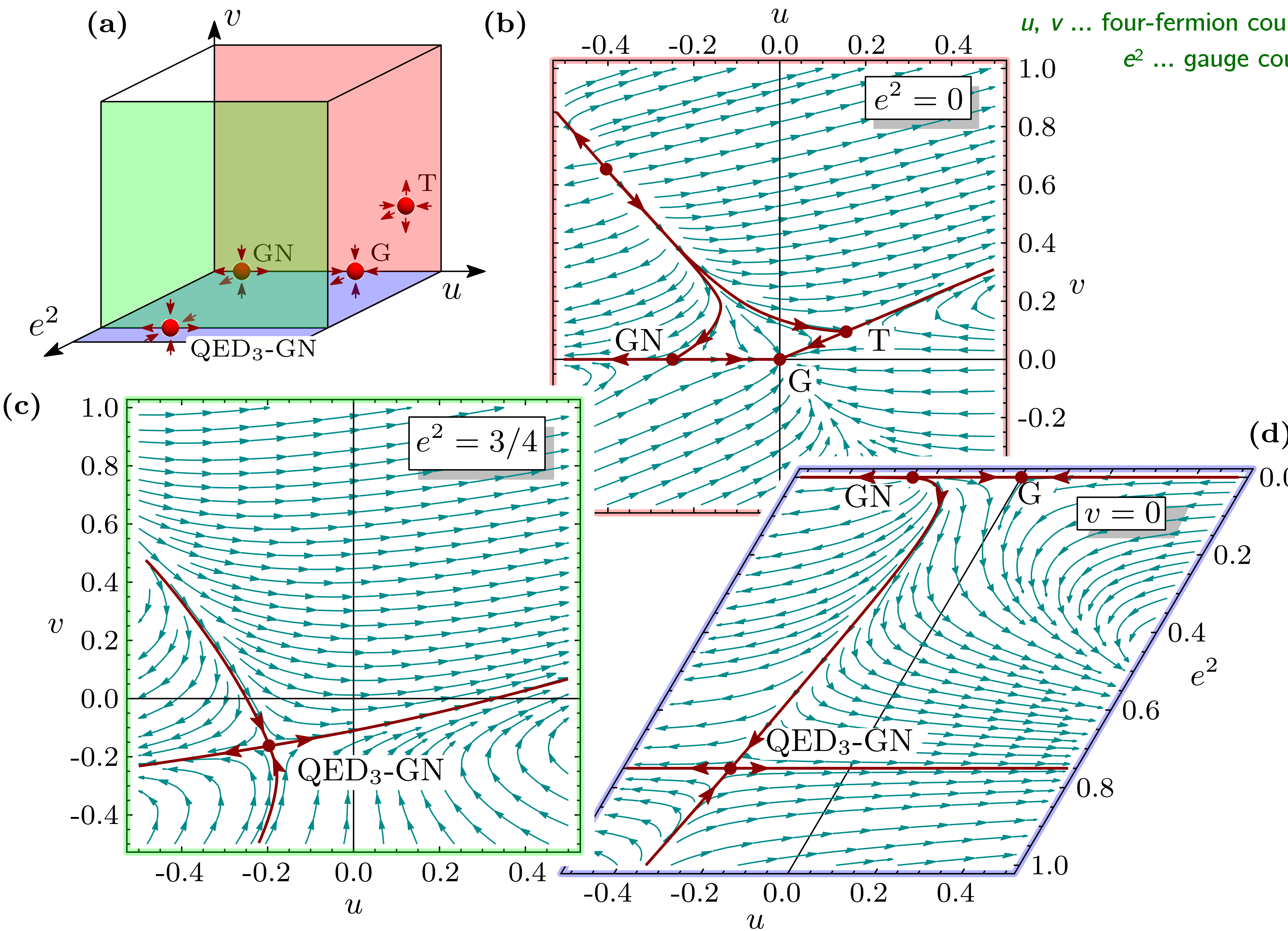
... in contrast to QED$_3$-Thirring fixed point

Fermionic RG: Flow diagram

[LJ & Y-C He, PRB '17]

u, v ... four-fermion couplings

e^2 ... gauge coupling



Fermionic RG: Flow diagram

[LJ & Y-C He, PRB '17]

u, v ... four-fermion couplings

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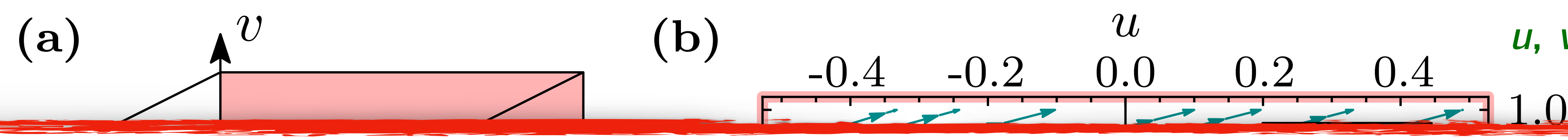
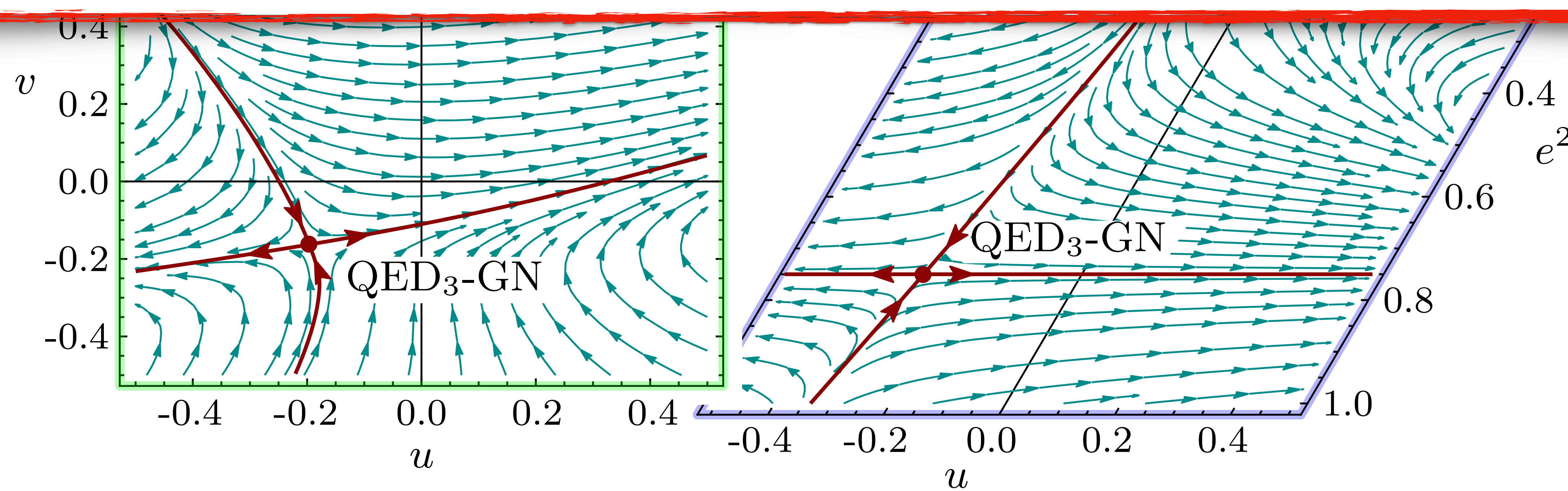


Critical exponents:

$$1/\nu = 1 + \mathcal{O}(1/N)$$

$$[\bar\psi\psi] = 1 + \mathcal{O}(1/N) \quad \Rightarrow \quad \eta_\phi = 1 + \mathcal{O}(1/N)$$ ... large anom. dimension!

$$[\bar\psi\sigma^z\psi] = 2 + \mathcal{O}(1/N) \quad \Rightarrow \quad \eta_{\bar\psi\sigma^z\psi} = \mathcal{O}(1/N)$$ ... trivial



QED$_3$-GN model: 4-ε expansion

Lagrangian:

$$\mathcal{L}_{\psi\phi} = \sum_{i=1,2} \left[\bar{\psi}_i(\partial_\mu - iea_\mu)\gamma_\mu\psi_i + g\phi\bar{\psi}_i\psi_i\right] + \frac{1}{2}\phi(r - \partial_\mu^2)\phi + \lambda\phi^4$$

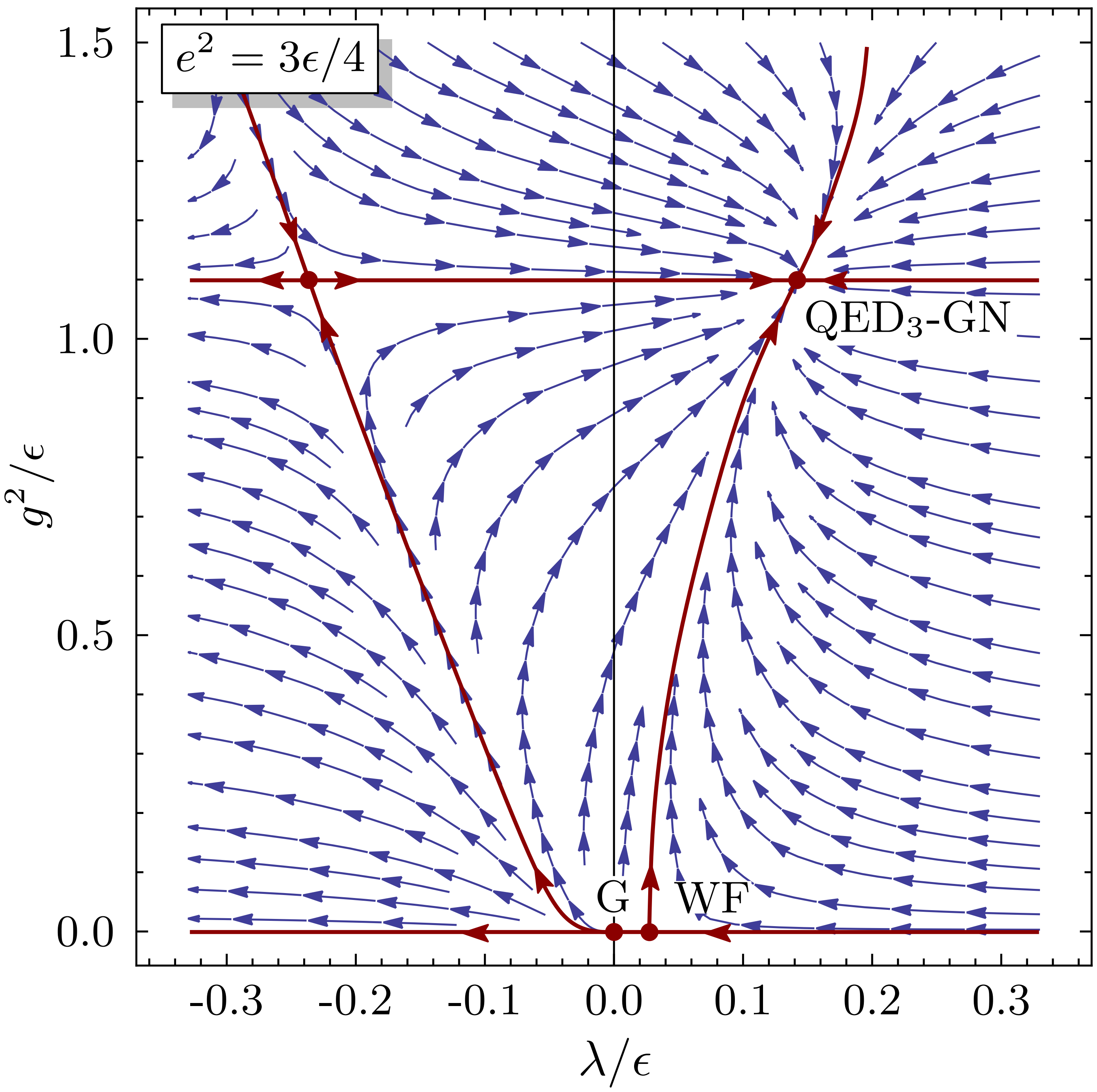
Engineering dimensions:

$$[e^2] = 4 - D, \qquad [g] = \frac{4-D}{2}, \qquad [\lambda] = 4 - D$$

... become simultaneously marginal near $D = 3+1$!

$\boxed{\varepsilon \text{ expansion in } D = 4\text{-}\varepsilon \text{ possible!}}$

QED$_3$-GN model: Flow diagram in $D = 4$-ε



... for $N = 1$

... fully IR stable fixed point

[LJ & Y-C He, PRB '17]

QED$_3$-GN model: Critical exponents

$D = 4 - \epsilon$:

$$\eta_a = \epsilon$$

$$\eta_\phi = \frac{2N+9}{2N+3}\epsilon + \mathcal{O}(\epsilon^2)$$

$$\nu = \frac{1}{2} + \frac{10N^2 + 39N + f(N)}{24N(2N+3)}\epsilon + \mathcal{O}(\epsilon^2)$$

... with $f(N) \equiv \sqrt{4N^4 + 204N^3 + 1521N^2 + 2916N}$

$$[\bar{\psi}\sigma^z\psi] = 3 - \frac{2N+6}{2N+3}\epsilon + \mathcal{O}(\epsilon^2)$$

... large $\mathcal{O}(\epsilon)$ corrections

Combine with results from $D = 2 + \epsilon$:

$$\eta_\phi = 2 - (D-2) + \mathcal{O}(1/N, (D-2)^2)$$

$$1/\nu = (D-2) + \mathcal{O}(1/N, (D-2)^2)$$

$$[\bar{\psi}\sigma^z\psi] = 1 + (D-2) + \mathcal{O}(1/N, (D-2)^2)$$

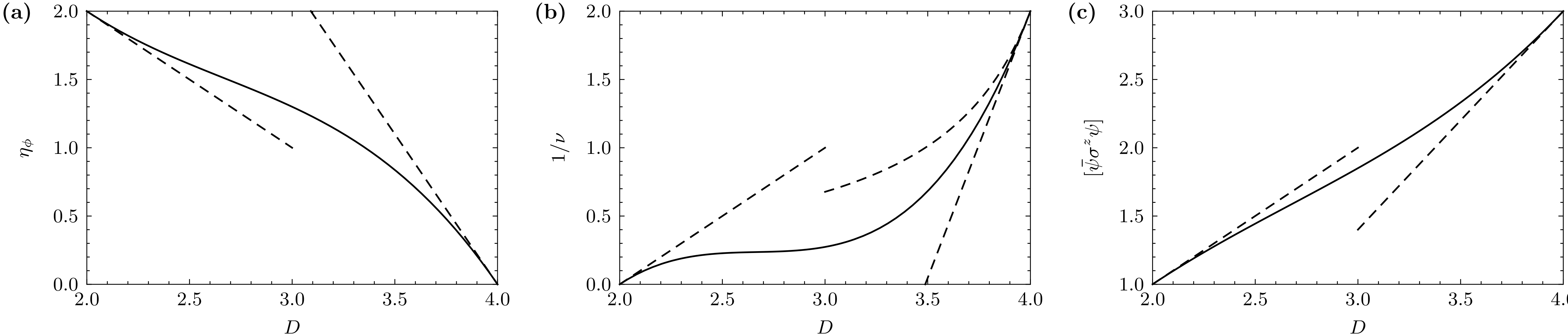
QED$_3$-GN model: Critical exponents

[LJ & Y-C He, PRB '17]

$N = 1:$

dashed: ε-expansion results

solid: interpolation



$\eta_\phi \approx 1.3(9)$ $\quad 1/\nu \approx 0.3(4)$ $\quad [\bar{\psi}\sigma^z\psi] \approx 1.8(5)$

... error: difference to plain extrapolation

Comparison: QED$_3$-GN vs. NCCP^1

QED$_3$-GN	SU(2) NCCP^1	
$[\phi] \approx (1+1.3(9))/2$	$[z^\dagger \sigma^z z] \approx (1+0.26(3))/2$	[Sandvik, PRL '07]
	$\approx (1+0.35(3))/2$	[Melko & Kaul, PRL '08]
	$\approx (1+0.25(3))/2$	[Nahum *et al.*, PRX '15]
	$\approx (1+0.22)/2$	[Bartosch, PRB '13]
$[\bar\psi\sigma^z\psi] \approx 3-1.2(5)$	$[z^\dagger z] \approx 3-1.28(5)$	[Sandvik, PRL '07]
	$\approx 3-1.47(9)$	[Melko & Kaul, PRL '08]
	$\approx 3-1.99(4)$	[Nahum *et al.*, PRX '15]
	$\approx 3-1.79$	[Bartosch, PRB '13]
$[\phi^2] \approx 3-0.3(4)$	$[z^\dagger z] \approx$ —*see above*—	

... $[\phi] \sim [z^\dagger \sigma^z z] = (1+\eta)/2$

... $[\bar\psi\sigma^z\psi] \sim [\phi^2] = 3 - 1/\nu$

... $[\bar\psi\sigma^z\psi]$ not inconsistent, but large deviations for $[\phi]$ and $[\phi^2]$

Conclusions

QED_3-Gross-Neveu model ...

... interesting due to possible duality with NCCP[1]

... i.e., theory of Néel-VBS deconfined critical point

... has a stable fixed point

... even when cQED_3 collides with another QCP

... prerequisite for duality to hold

... critical behavior computable within 4-ε expansion

... all couplings simultaneously marginal

... but higher orders necessary to test of duality

... large anomalous dimension η_ϕ

... however: large η_ϕ necessary for emergent SO(5)

[Nakayama & Ohtsuki, PRL '16]

$\rightarrow$ poster by B. Ihrig @ SIFT17