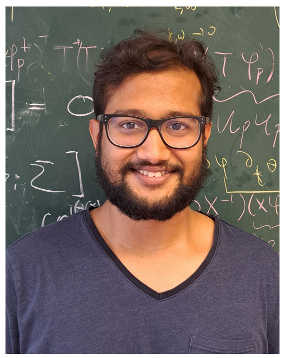
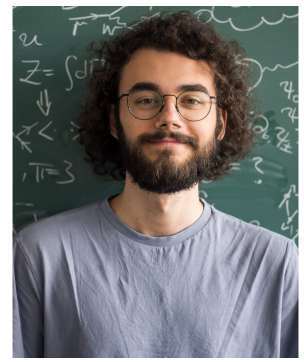
QOpen Kickoff workshop
April 30, 2026
Lisbon, Portugal

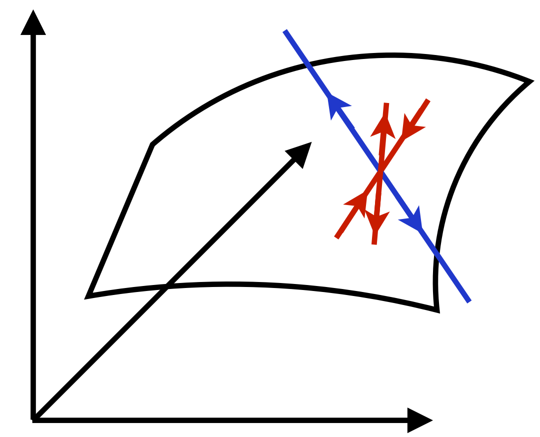
Universität zu Köln

Fermion quantum criticality far from equilibrium


R. Mittal


J. Lang


T. Zander



Mittal, Zander, Lang, SD, PRX (2026) — Viewpoint in Physics by P. Zhang

Sebastian Diehl

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QOpen Many-body Open Quantum Systems

COST Action CA24109 – QOpen https://cost.eu https://qopen.eu/

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Motivation

active matter

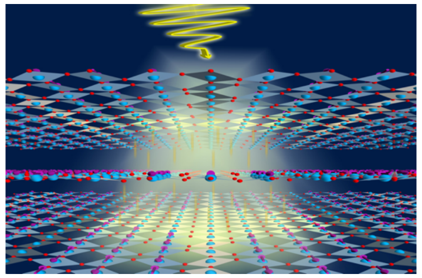
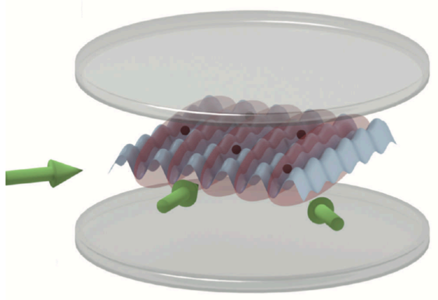
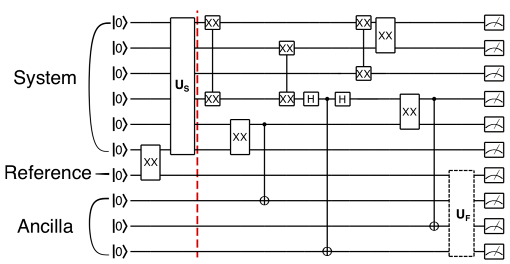
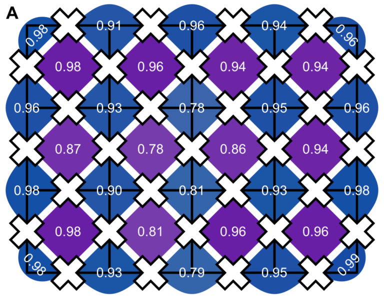
- many mobile agents:
  flocking birds, colonies of bacteria, traffic,…
- loose definition:
  (1) emergent collective behavior
  (2) no detailed balance on a microscopic level

Hohenberg, Cross, RMP (1993)

Bowick, Fakhri, Marchetti, Ramaswamy, PRX (2023)

active condensed / synthetic matter?

- systems with broken detailed balance on microscopic level: driven & open quantum systems

solid state	cold atoms	NISQ platforms	
			
light induced superconductors/ ferromagnets	quantum gases and materials in optical cavities	trapped ion quantum simulators	superconducting circuits / Rydberg arrays
Mitrano et al. Nature (2016) Bloch et al. Nature (2022)	Baumann et al., Nature (2010) Hübener et al. Nat, Mat. (2020)	Noel et al. Nat. Phys. (2022) Monroe et al. RMP (2021) Blatt, Roos, Nature (2012)	Satzinger et al. Science (2021) Semeghini et al. Science (2021)

What are the novel states of matter & phenomena?
Are there universal quantum effects?

The question, refined: equilibrium vs. non-equilibrium

microscopic breaking of detailed balance —> universal macroscopic non-equilibrium phenomena

micro coarse graining macro

equilibrium

non-equilibrium

equilibrium emergent

(the usual case)

?

non-equilibrium state of matter

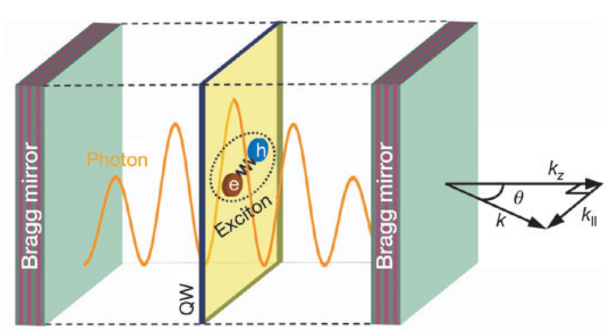
(the interesting case)

guiding principle: activate soft modes
(critical, Goldstone, …)

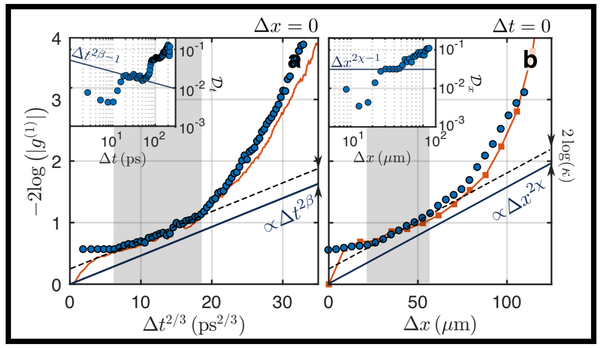
Universality in driven open quantum matter,
Sieberer, Buchhold, Marino, SD, Rev. Mod. Phys. (2025)

working example

exciton-polariton driven condensates —> Kardar-Parisi-Zhang (KPZ) universality class



Kasprzak et al., Nature (2006)



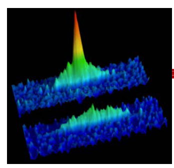
Fontaine et al., Nature (2022)
Th: Altman, Chen, Sieberer, SD, Toner, PRX (2015); He, Sieberer, SD, PRL (2017)

The question, refined: equilibrium vs. non-equilibrium

microscopic breaking of detailed balance —> universal macroscopic non-equilibrium phenomena

micro — coarse graining — macro

equilibrium

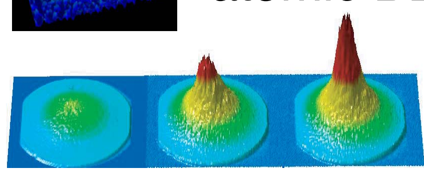


atomic BEC

equilibrium
emergent

(the usual case)

non-equilibrium



polariton BEC

?

non-equilibrium
state of matter

(the interesting case)

guiding principle: activate soft modes
(critical, Goldstone, …)

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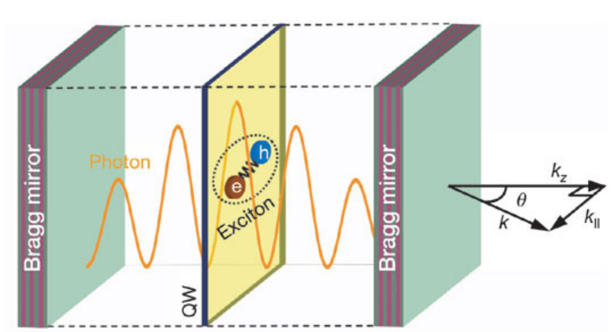
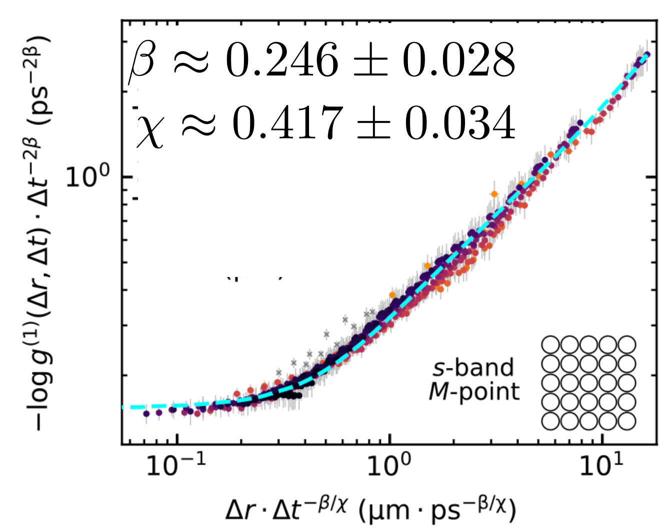
working example

exciton-polariton driven condensates —> Kardar-Parisi-Zhang (KPZ) universality class



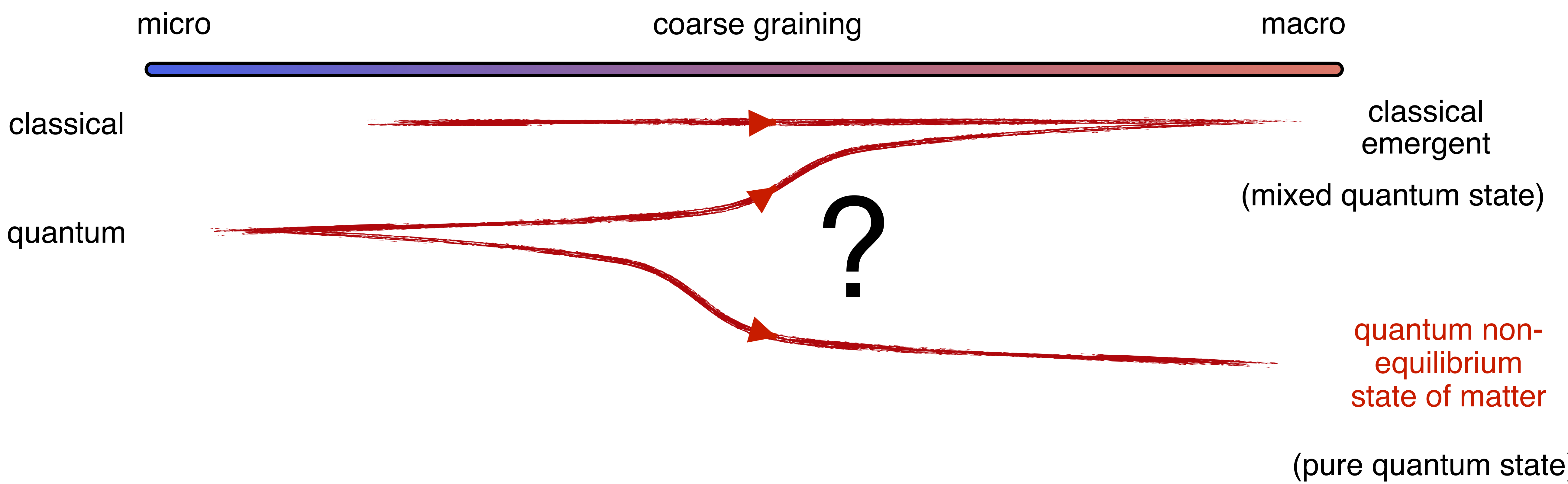
Kasprzak et al., Nature (2006)



2D KPZ quantitatively seen in polaritons!
Dam et al. Science (2026)

The question, refined: classical vs. quantum

microscopic breaking of detailed balance —> universal macroscopic non-equilibrium phenomena

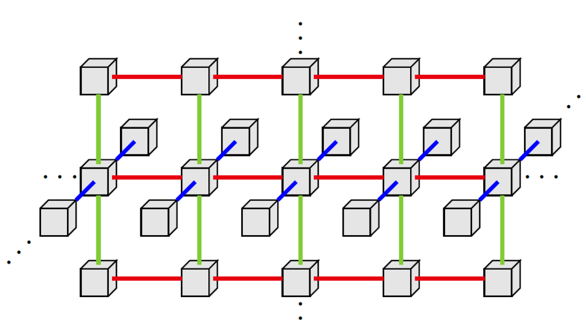


this talk:

Far from equilibrium & quantum

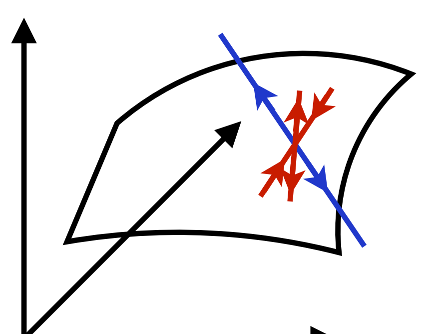
microscopic model

- fermion topological dark states
- competition and dark-to-dark transition



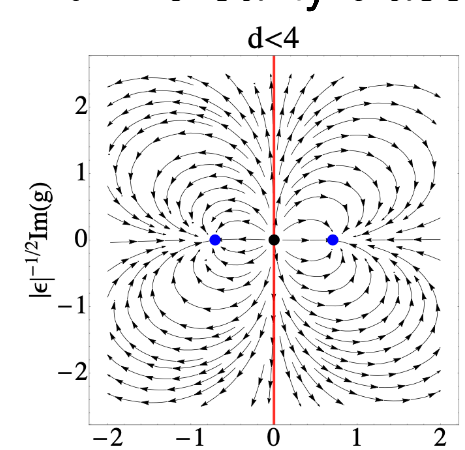
mesoscopic field theory

- fermion-boson action
- emergent symmetry protecting state's purity



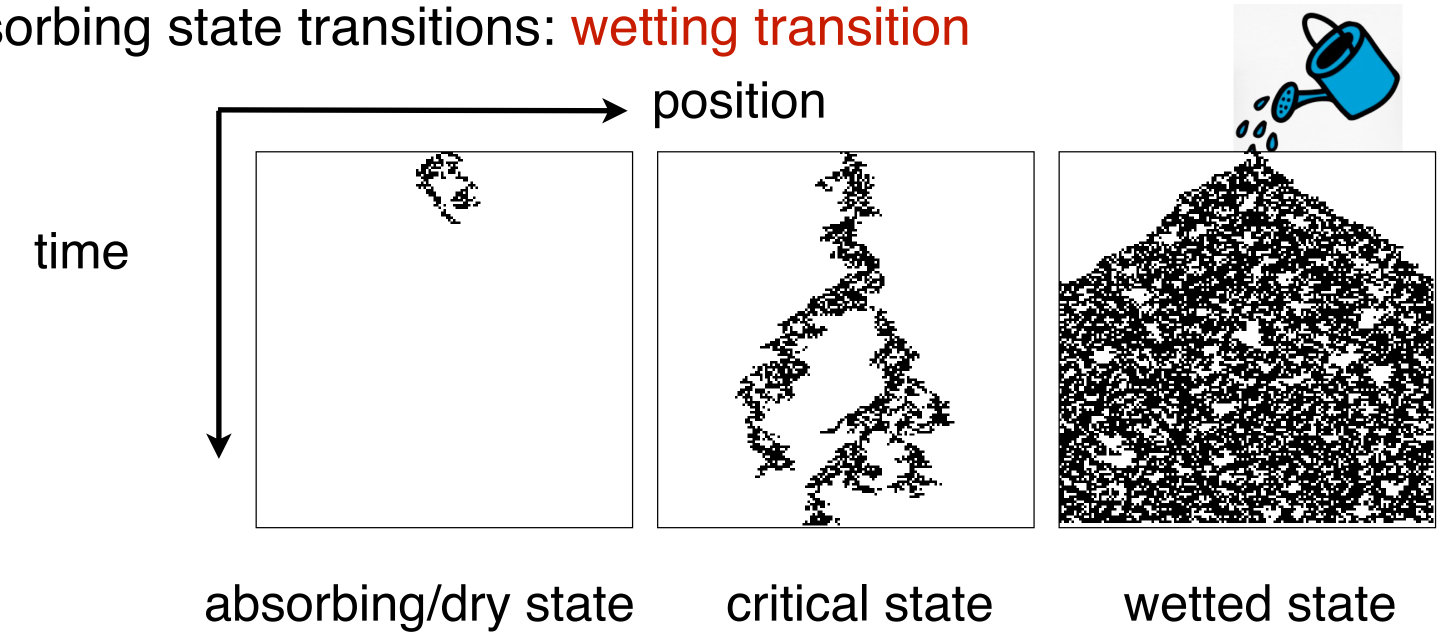
macroscopic phenomenology

- quantum critical fermions far from equilibrium
- new universality class



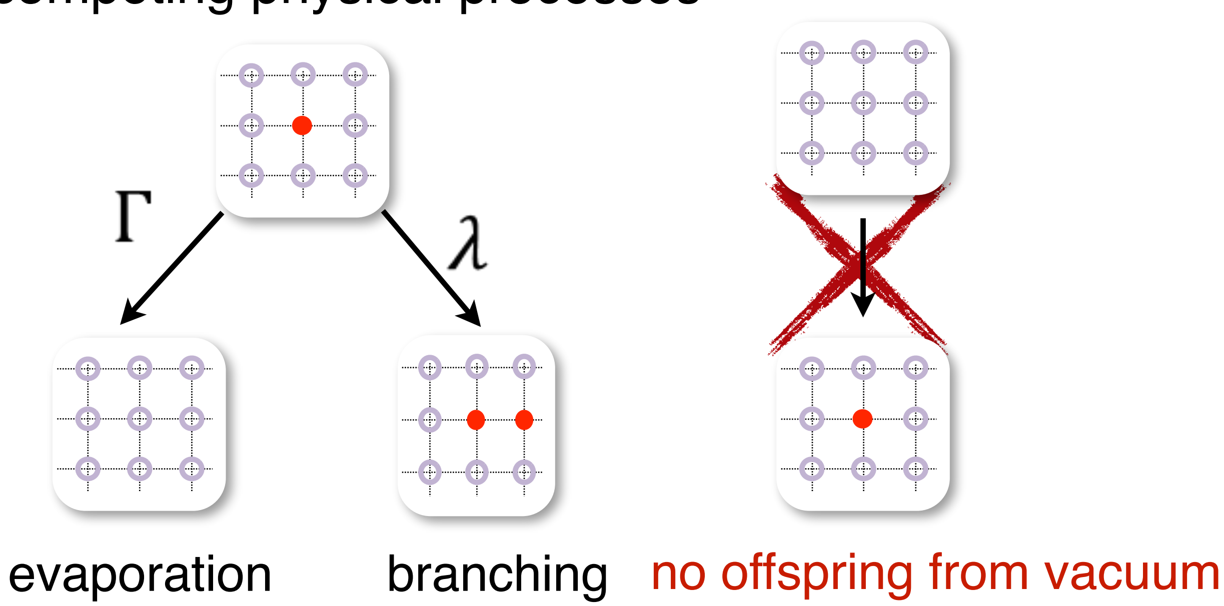
Classical active matter scenario: Absorbing state transitions

- classical absorbing state transitions: wetting transition

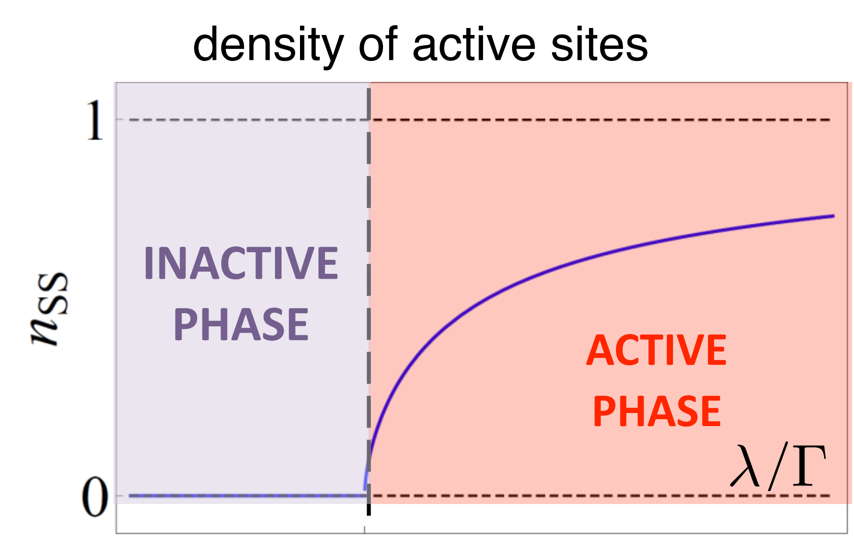


H. Hinrichsen, Adv. Phys. (2000);
G. Odor, RMP (2004)

- competing physical processes



- phase transition:



➡ absorbing state = uncorrelated empty ‘trivial vacuum'

➡ non-equilibrium dynamics: not every process comes with its reverse (no detailed balance)

Classical active matter scenario: Non-equilibrium universality

- wetting transition in directed percolation (DP) universality class
- Grassberger-Janssen conjecture: all absorbing state transitions in DP class

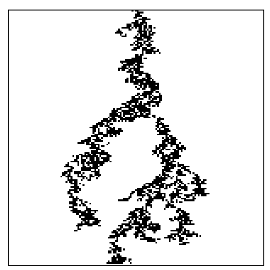
Grassberger, Z. Phys. B (1982); Janssen, Z. Phys. B (1985)

microscopic

—> water, bacteria, driven atoms/ions

wetting

G. Odor, RMP (2004)

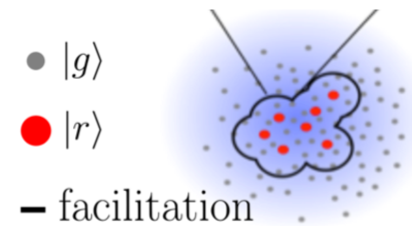


epidemic spreading

Pastor et al., RMP (2015)

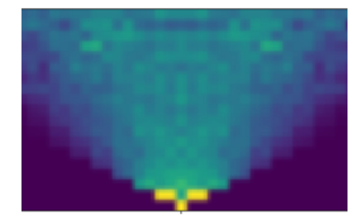
Rydberg atoms

Gutierrez et al., PRA (2017)



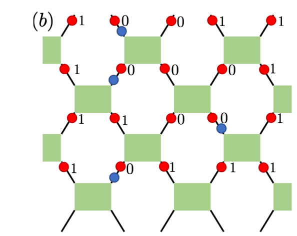
trapped ions

Chertkov et al., Nat. Phys. (2023)



measurement induced phase transitions

Piroli et al. PRB (2021); O'Dea et al. PRB (2024)



coarse graining

mesoscopic

—> (bosonic) activity order parameter

directed percolation field theory

$$Z = \int \mathscr{D}(\tilde{\phi}, \phi) e^{iS[\tilde{\phi},\phi]} \qquad S[\tilde{\phi}, \phi] = \int_{t,\mathbf{x}} [\tilde{\phi}(\partial_t + K\nabla^2 + r)\phi + g(\tilde{\phi}\phi^2 - i\tilde{\phi}^2\phi)]$$

fluctuation effects

macroscopic

—> critical degrees of freedom

length

non-equilibrium universality class w/o equilibrium counterpart

Marcuzzi, Buchhold, SD, Lesanovsky, PRL (2016); Carollo, Gillman, Weimer, Lesanonvsky, PRL (2019)

➡ emergent classical: quantum problems can map to classical DP

➡ clean & quantitative realizations possible ('non-equilibrium simulators')

➡ can we beat Grassberger-Janssen by quantum mechanics?

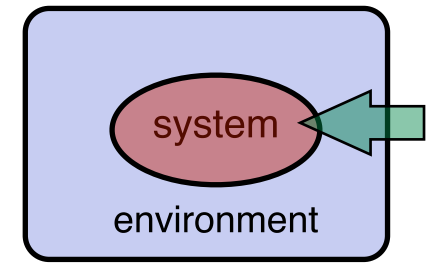
Quantum analog: Dark states in Lindblad equations

- Lindblad quantum master equation for driven open quantum system

spin, lattice site, …

$$\partial_t \hat{\rho} = \underbrace{-i[\hat{H}, \hat{\rho}]}_{\text{coherent evolution}} + \sum_i \underbrace{\gamma_i [2\hat{L}_i \hat{\rho} \hat{L}_i^\dagger - \hat{L}_i^\dagger \hat{L}_i \hat{\rho} - \hat{\rho} \hat{L}_i^\dagger \hat{L}_i]}_{\text{driven-dissipative evolution}}$$

$$\equiv \hat{\mathcal{L}}[\hat{\rho}]$$



- interpretation:

$$\partial_t \hat{\rho} = -i(\hat{H} - i \sum_i \gamma_i \hat{L}_i^\dagger \hat{L}_i)\hat{\rho} + \text{h.c.} + 2 \sum_i \gamma_i \hat{L}_i \hat{\rho} \hat{L}_i^\dagger$$

energy

decay (dissipation)

ensures probability conservation (fluctuation)

$$\text{“}E - i\Gamma\text{”}$$

$$\partial_t \mathrm{tr} \hat{\rho}(t) = 0$$

Quantum analog: Dark states in Lindblad equations

- Lindblad quantum master equation for driven open quantum system

spin, lattice site, …

$$\partial_t \hat\rho = \underbrace{-i[\hat H, \hat\rho]}_{\text{coherent evolution}} + \sum_i \underbrace{\gamma_i [2\hat L_i \hat\rho \hat L_i^\dagger - \hat L_i^\dagger \hat L_i \hat\rho - \hat\rho \hat L_i^\dagger \hat L_i]}_{\text{driven-dissipative evolution}}$$

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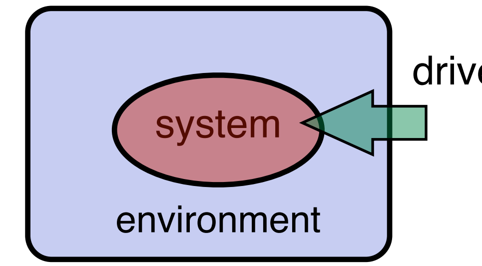
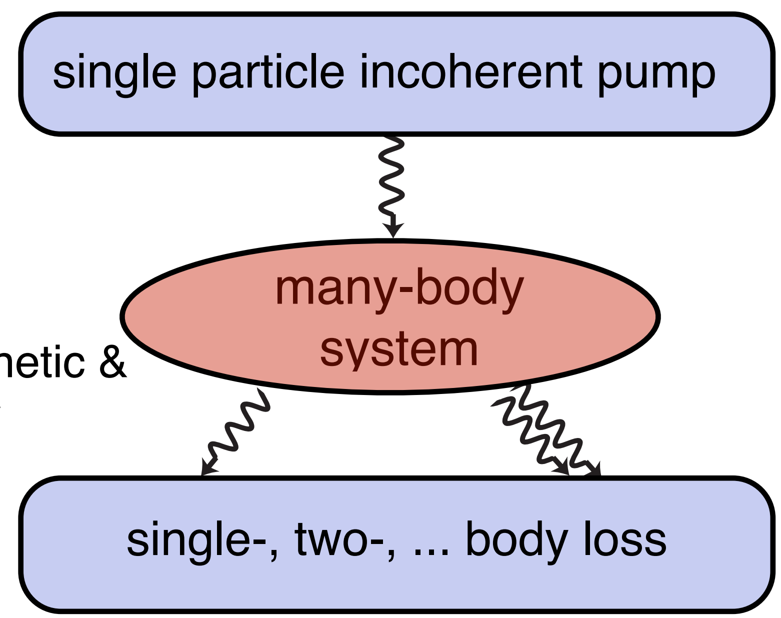


- Lindbladians break equilibrium conditions

$\hat L = \hat a_i^\dagger$

H

e.g. Bose-Hubbard: kinetic & potential energy



$\hat L = \hat a_i$ $\qquad$ $\hat L = \hat a_i^2$

- driven open system: dissipation channels from independent microscopic processes
- system is ‘confused’ which bath to thermalise to
- sharply defined by violation of thermal / KMS symmetry of Lindblad-Keldysh path integral

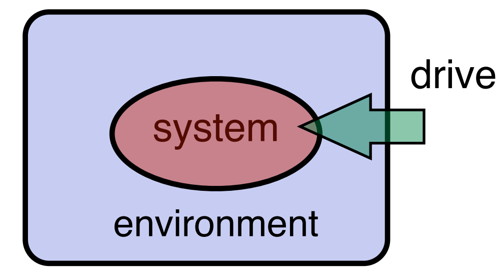
Sieberer, …, SD, PRB (2015); Haehl et al. JHEP (2016); Crossley et al., JHEP (2016); Aron et al. SciPost (2018)

Quantum analog: Dark states in Lindblad equations

- Lindblad quantum master equation for driven open quantum system

spin, lattice site, …

$$\partial_t \hat{\rho} = \underbrace{-i[\hat{H}, \hat{\rho}]}_{\text{coherent evolution}} + \kappa \underbrace{\sum_\alpha \left(\hat{L}_\alpha \hat{\rho} \hat{L}_\alpha^\dagger - \frac{1}{2}\{\hat{L}_\alpha^\dagger \hat{L}_\alpha, \hat{\rho}\}\right)}_{\text{driven-dissipative evolution}}$$



$$\equiv \hat{\mathcal{L}}[\hat{\rho}]$$

- Dark states

$$\hat{L}_\alpha |D\rangle = 0 \quad \forall\, \alpha \qquad\qquad H|D\rangle = E|D\rangle$$

➡ time evolution stops when $\rho = |D\rangle\langle D|$

Quantum analog: Dark states in Lindblad equations

- Lindblad quantum master equation for driven open quantum system

$$\partial_t \hat{\rho} = \underbrace{-i[\hat{H}, \hat{\rho}]}_{\text{coherent evolution}} + \kappa \underbrace{\sum_\alpha \left(\hat{L}_\alpha \hat{\rho} \hat{L}_\alpha^\dagger - \frac{1}{2}\{\hat{L}_\alpha^\dagger \hat{L}_\alpha, \hat{\rho}\}\right)}_{\text{driven-dissipative evolution}}$$

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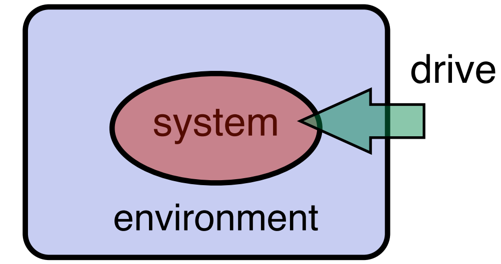
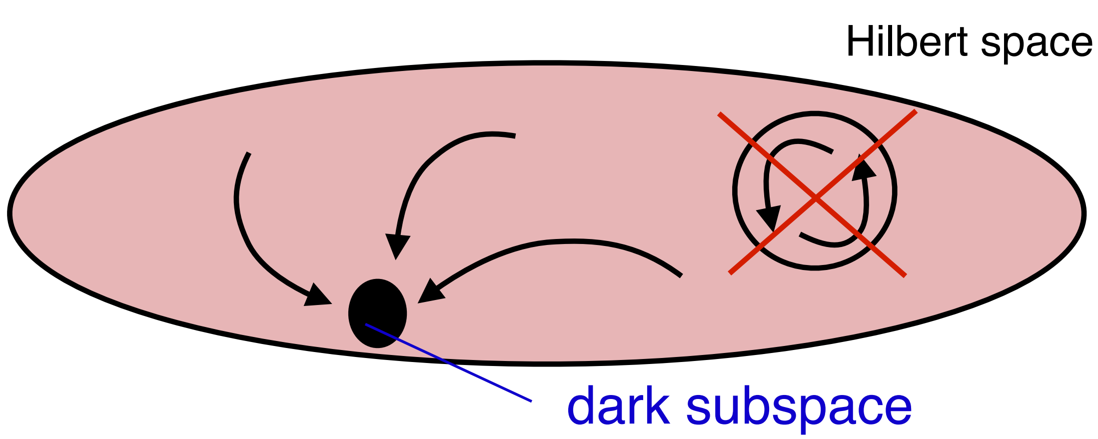


- Interesting situation: unique dark state solution



➡ you can enter, but never leave (cf. absorbing state)

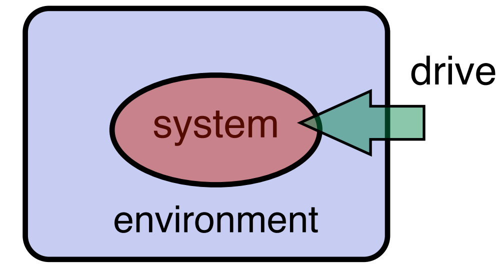
➡ directed motion in Hilbert space $\rho \xrightarrow{t\to\infty} |D\rangle\langle D|$

➡ dissipation removes entropy, increases purity

Quantum analog: Dark states in *many-body* Lindblad equations

- Lindblad quantum master equation for driven open quantum system

$$\partial_t \hat\rho = \underbrace{-i[\hat H, \hat\rho]}_{\text{coherent evolution}} + \underbrace{\kappa \sum_\alpha (\hat L_\alpha \hat\rho \hat L_\alpha^\dagger - \tfrac{1}{2}\{\hat L_\alpha^\dagger \hat L_\alpha, \hat\rho\})}_{\text{driven-dissipative evolution}}$$



$$\equiv \hat{\mathcal{L}}[\hat\rho]$$

- simple example: lossy cavity

$$\hat H = \omega_0 a^\dagger a, \quad \hat L = a \qquad \Longrightarrow \quad |D\rangle = |0\rangle$$

➡ 'trivial vacuum' empty state (like in classical absorbing states)

- many-body example ('dissipation engineering')

$$\hat L_i = (a_i^\dagger + a_{i+1}^\dagger)(a_i - a_{i+1})$$

$\forall i,$ lattice sites

bosons

$$\Longrightarrow \quad |D\rangle = |BEC, N\rangle$$

fixed number BEC

SD et al., Nat. Phys. (2008); Verstraete et al., Nat. Phys. (2009)

fermions

$$\Longrightarrow \quad |D\rangle = |BCS, N\rangle$$

fixed number Kitaev chain

SD et al., Nat. Phys. (2011)

➡ 'non-trivial vacuum' (particle non-empty, quantum correlated)

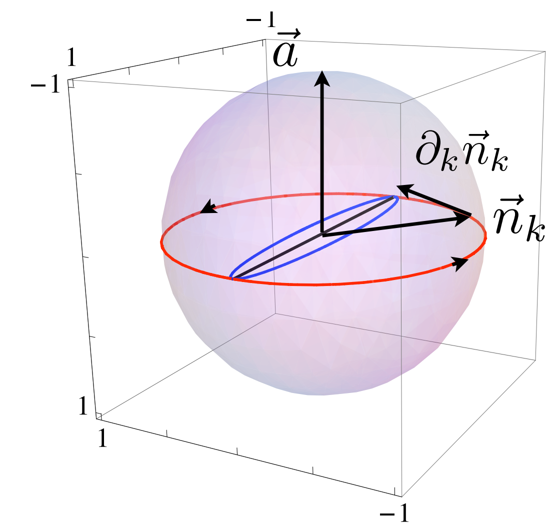
Non-trivial vacuum: topological insulator dark state

Goldstein, SciPost (2019); Shavit, Goldstein, PRB (2020)
Tonielli, Budich, Altland, SD, PRL (2020)

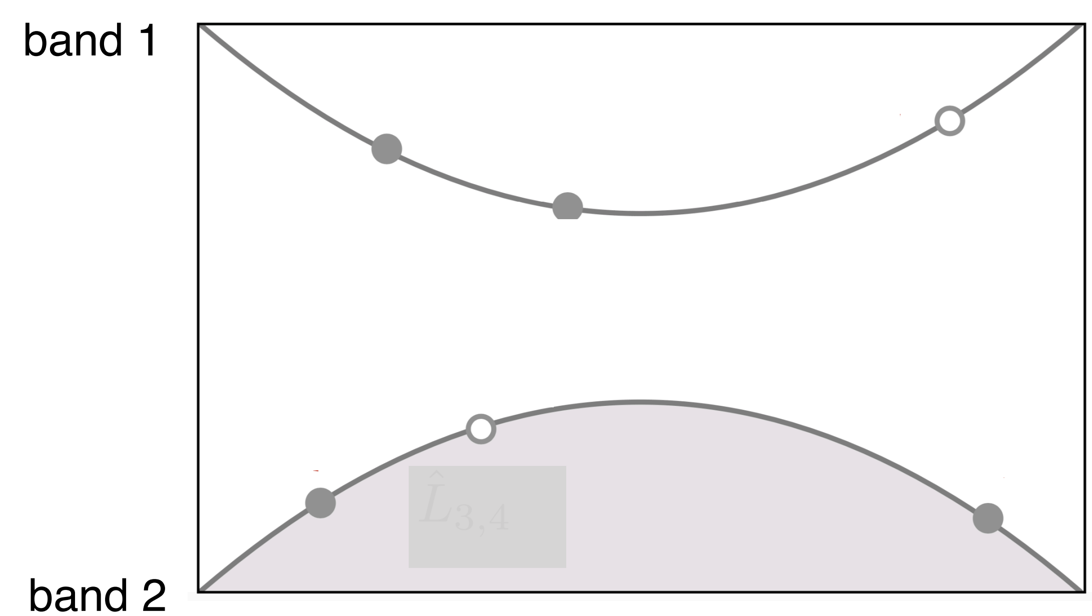
- nontrivial vacuum state, example: dissipative chiral topological insulator 1D

$$|D\rangle = \prod_{\mathbf{x}} l^{\dagger}_{2,\mathbf{x}} |0\rangle \qquad d = 1\text{: 2 bands, e.g. SSH state}$$

- quantum correlations, characterized by topological chiral winding number $W \in \mathbb{Z}$
    - e.g. SSH state: winding on grand circle of Bloch sphere



winding number in 1d



Non-trivial vacuum: topological insulator dark state

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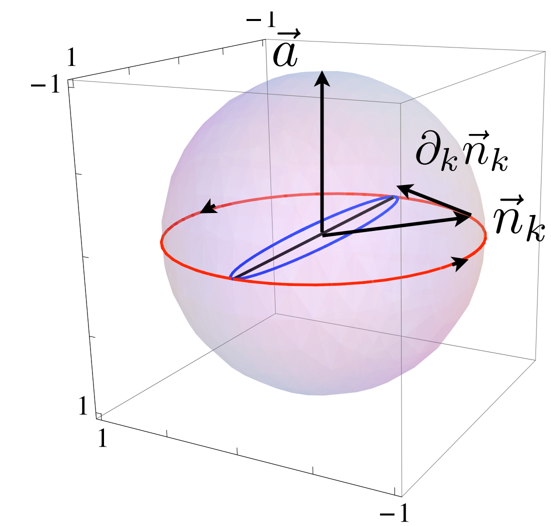


winding number in 1d

- parent Lindblad operators cooling into this vacuum:

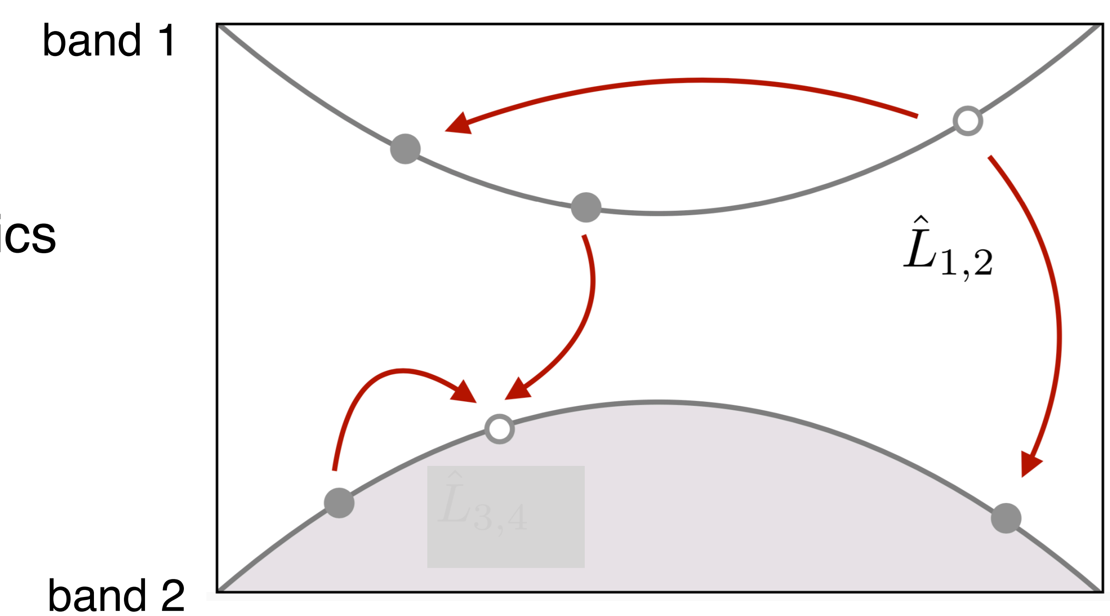
$$\hat{L}_{a,1} = \hat{\psi}^{\dagger}_a \hat{l}_1 \quad \hat{L}_{a,2} = \hat{\psi}_a \hat{l}^{\dagger}_2 \qquad a = 1,2 \ \text{band}$$

- interpretation: IF-THEN condition

IF band 1 empty $\Longrightarrow \hat{l}_1|\psi\rangle = 0$, band 2 occupied $\Longrightarrow \hat{l}^{\dagger}_2|\psi\rangle = 0$ THEN stop dynamics

otherwise recycle into evolution

➡ dynamics stops once above dark state is reached



Altland, Fleischhauer, SD, PRX (2021)

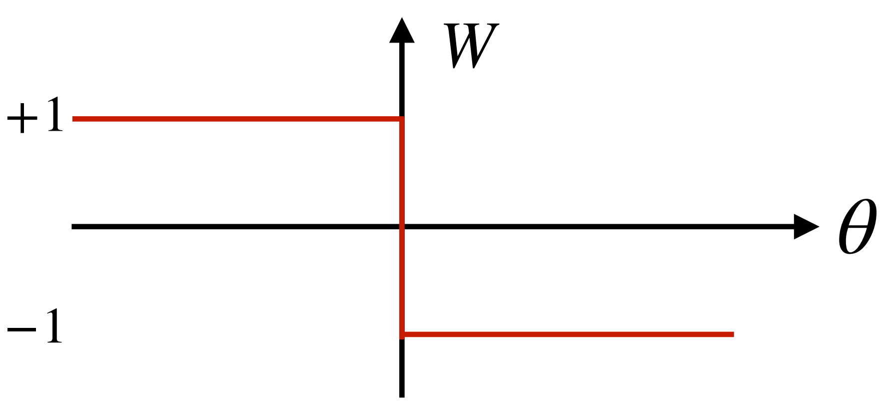
Topological quantum phase transition far from equilibrium

- Competition by superposition of left and right winding Lindblad operators

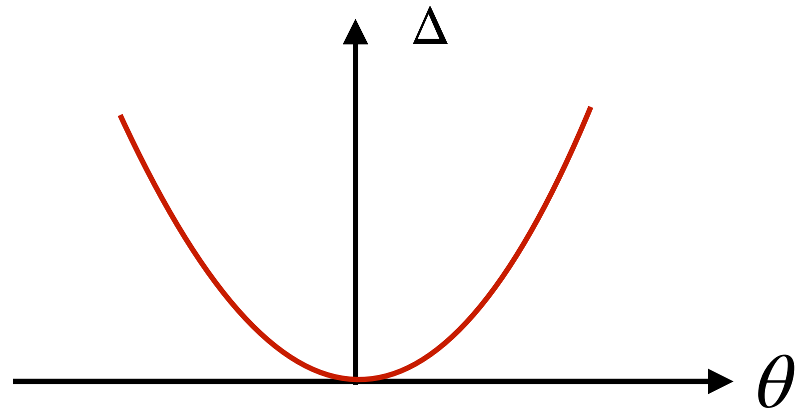
$$\hat{L}_i = \cos\theta \hat{L}_i^+ + \sin\theta \hat{L}_i^-$$

stabilises $W = +1$ stabilises $W = -1$

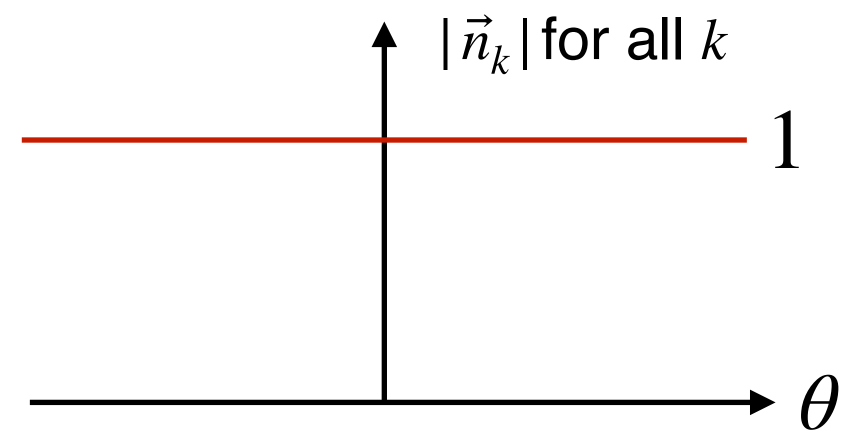
winding number



dissipative gap



purity



➡ topological phase transition at $\theta = \pi/4$ via gap closing

➡ state pure across transition (canonical transformation)

➡ between two non-trivial vacua: absorbing-to-absorbing state transition (cf. directed percolation: absorbing to active)

➡ interacting (quartic) Lindbladian: quantum critical behavior far from equilibrium?

Theoretical approach

- map dark state Lindbladian into equivalent Lindblad-Keldsh field theory (Keldysh = Feynman for density matrix)

$$\partial_t \hat{\rho} = -i[\hat{H}, \hat{\rho}] + \kappa \sum_i (\hat{L}_i \hat{\rho} \hat{L}_i^\dagger - \tfrac{1}{2}\{\hat{L}_i^\dagger \hat{L}_i, \hat{\rho}\})$$

$$\Updownarrow$$

$$Z = \mathrm{tr}\rho(t) = \int \mathcal{D}\psi_\pm e^{iS[\psi_\pm]}$$

length

microscopic — lattice Lindblad-Keldysh field theory

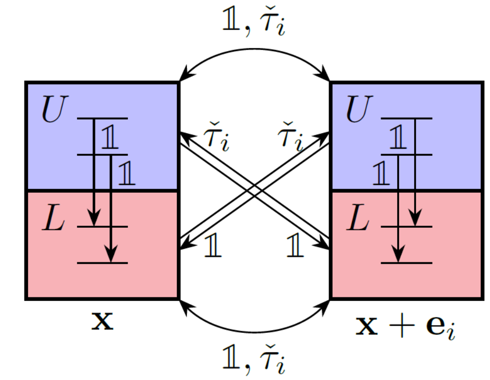
mesoscopic — near quantum critical continuum action

➡ identify relevant degrees of freedom for quantum phase transition

macroscopic — fixed point action

➡ determine universality class (set of critical exponents)

Microscopic fermion model

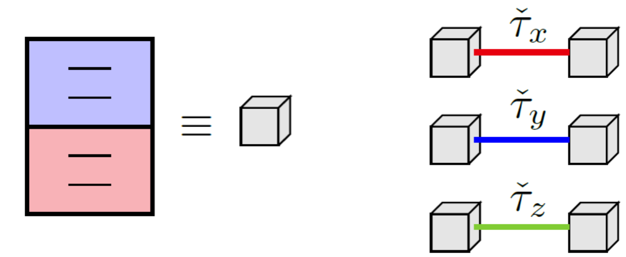


- chiral topological insulator models in all odd spatial dimensions (class AIII)

$$\hat{L}^{(U)}_{\alpha,\beta}(\mathbf{x}) = \hat{\psi}^\dagger_\alpha(\mathbf{x})\hat{x}_\beta(\mathbf{x}), \quad \beta \in U,\ \alpha \in I\,,$$
$$\hat{L}^{(L)}_{\alpha,\beta}(\mathbf{x}) = \hat{\psi}_\alpha(\mathbf{x})\hat{x}^\dagger_\beta(\mathbf{x}), \quad \beta \in L,\ \alpha \in I$$

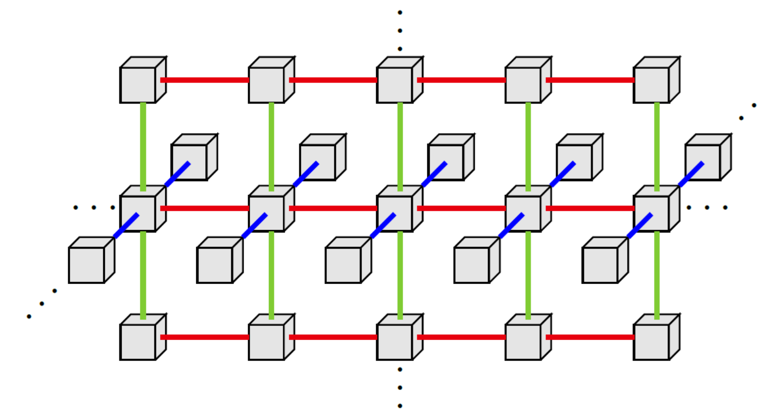
$$I = (U, L)$$

upper, lower bands



superposition realising competition

$$\hat{x}_\beta = \cos(\theta)\hat{l}_\beta + \sin(\theta)\hat{r}_\beta = W_{\beta\delta}(\theta)\hat{\psi}_\delta$$



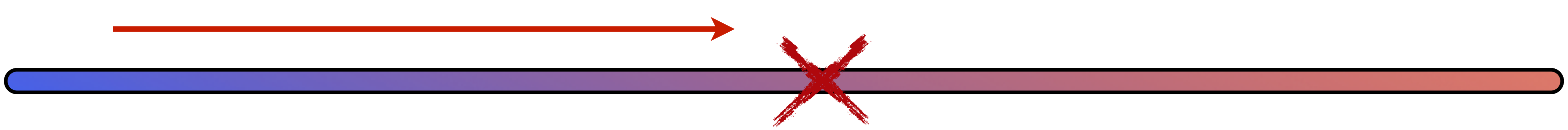
Realization in 3D

- Important feature: conserves total number of particles

➡ expect diffusive slow mode to couple to fermions

- two ways to derive 'mesoscopic' near critical action
  - direct calculation: Hubbard-Stratonovich decoupling

  ➡ provides parameters & identify symmetries



micro

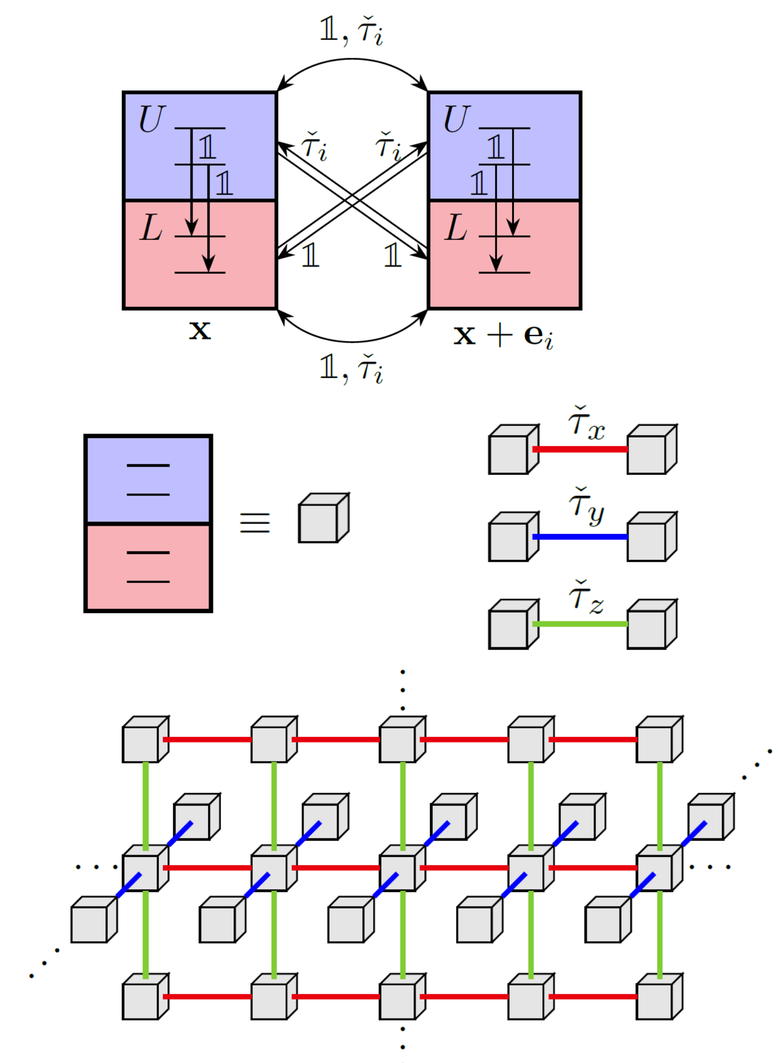
meso

macro

  - symmetry based construction

  ➡ promote identified symmetries to construction principle for intermediate scale action

Microscopic fermion model



Realization in 3D

- chiral topological insulator models in all odd spatial dimensions

$$\hat{L}^{(U)}_{\alpha,\beta}(\mathbf{x}) = \hat{\psi}^\dagger_\alpha(\mathbf{x})\hat{x}_\beta(\mathbf{x}), \quad \beta \in U,\ \alpha \in I\,,$$
$$\hat{L}^{(L)}_{\alpha,\beta}(\mathbf{x}) = \hat{\psi}_\alpha(\mathbf{x})\hat{x}^\dagger_\beta(\mathbf{x}), \quad \beta \in L,\ \alpha \in I$$

$I = (U, L)$

upper, lower bands

superposition realising competition

$$\hat{x}_\beta = \cos(\theta)\hat{l}_\beta + \sin(\theta)\hat{r}_\beta = W_{\beta\delta}(\theta)\hat{\psi}_\delta$$

- Important feature: conserves total number of particles

➡ expect diffusive slow mode to couple to fermions

- symmetries (in part emergent in continuum limit):

  - unitary symmetries
    - weak Pin(d) symmetry (spatial subgroup of Lorentz transformations)
    - chiral symmetry

  } dissipative Dirac insulators

  - new anti-unitary symmetry: fermion dark state symmetry

Symmetry based derivation: fermion sector

- near critical effective action in d+1 dimensions in diagonal basis

$$S = S_F + S_B + S_Y$$

(1) unitary symmetries (weak Pin(d) and chiral)

(2) fermion dark state symmetry: emergent dynamical symmetry with two components

- anti-unitary dynamical involution (squares to 1)

$$\chi(\mathbf{x},t) \to T_F \chi(\mathbf{x},-t) \qquad \mathrm{i} \to -\mathrm{i}$$
$$\bar{\chi}(\mathbf{x},t) \to \bar{T}_F \bar{\chi}(\mathbf{x},-t)$$

$$T_F = \begin{pmatrix} -\mathbb{1} & 0 \\ F & \mathbb{1} \end{pmatrix}, \quad \bar{T}_F = \begin{pmatrix} -\mathbb{1} & 0 \\ -F & \mathbb{1} \end{pmatrix}$$

only possible for Grassmann fields

$$F = F^\dagger,\ F^2 = \mathbb{1}$$

- weak global U(1)

$$\chi \to \mathcal{U}_z(\theta)\chi \qquad \mathcal{U}_z(\theta) = \exp(i\theta\tau_z)$$

➡ cooling into Dirac insulator pure state

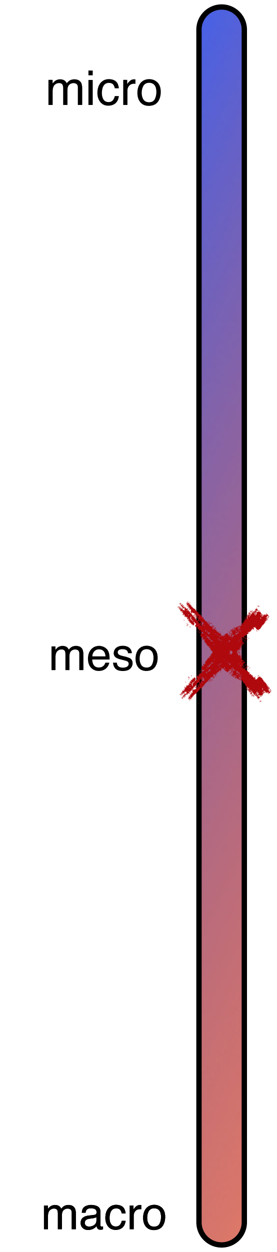
➡ action has single relevant parameter!

$$S_F = \int_{\mathbf{q},\omega} \bar{\chi}^\top(\omega,\mathbf{q}) \begin{pmatrix} 0 & \omega - K(\mathbf{q}) \\ \omega - K^\dagger(\mathbf{q}) & 2\mathrm{i}P(\mathbf{q}) \end{pmatrix} \chi(\omega,\mathbf{q})$$

$$K(\mathbf{q}) = H(\mathbf{q}) + \mathrm{i}D(\mathbf{q})$$

$$D(\mathbf{q}) = (\Delta_d + K_d \mathbf{q}^2)\mathbb{1}$$
$$H(\mathbf{q}) = (\Delta_c + K_c \mathbf{q}^2)\mathbb{1}$$
$$P(\mathbf{q}) = D(\mathbf{q})\tau_z\ ,$$

in diagonal basis, in line with microscopic derivation



Result: Quantum critical fermion-boson action

- near critical effective action in d+1 dimensions

$$S = S_F + S_B + S_Y$$

- critical fermions: cooling into Dirac non-trivial vacuum

$$S_F = \int_{\mathbf{q},\omega} \bar{\chi}^\top(\omega,\mathbf{q}) \begin{pmatrix} 0 & \omega - K(\mathbf{q}) \\ \omega - K^\dagger(\mathbf{q}) & 2\mathrm{i}P(\mathbf{q}) \end{pmatrix} \chi(\omega,\mathbf{q})$$

- gapless bosons: diffusive modes of conserved particle number

$$S_B = \int_{t,\mathbf{x}} (n_c, \theta_q) \begin{pmatrix} 0 & \partial_t - D\partial_x^2 \\ \partial_t + D\partial_x^2 & -i2DT\partial_x^2 \end{pmatrix} \begin{pmatrix} n_c \\ \theta_q \end{pmatrix}$$

- cubic fermion-boson coupling

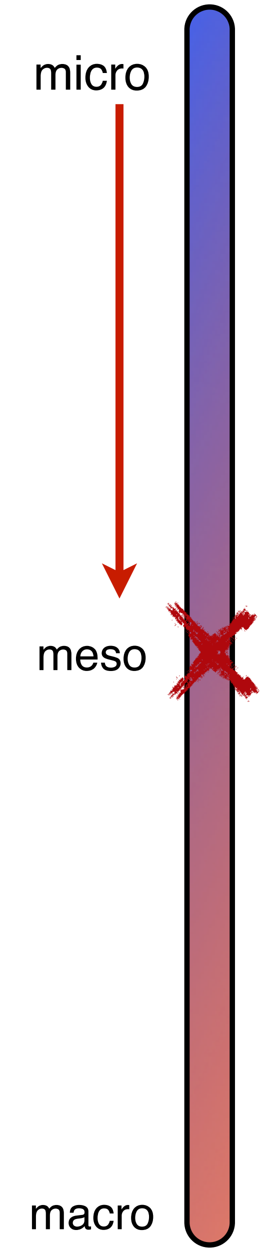
$$S_Y = \int_{\mathbf{x},t} n_c(\mathbf{x},t) \bar{\chi}^\top(\mathbf{x},t) \begin{pmatrix} 0 & g\mathbf{1} \\ g^*\mathbf{1} & \mathrm{i}(g^* - g)\tau_z \end{pmatrix} \chi(\mathbf{x},t)$$

  - compare non-linearities:

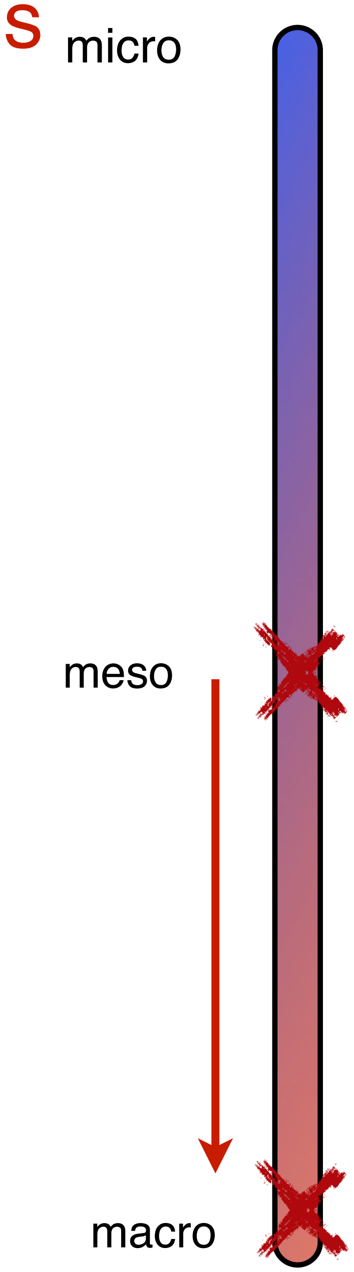
$$n_c \bar{\chi}_c \chi_q + h.c. + n_c \bar{\chi}_q \chi_q$$

vs. directed percolation

$$\phi_c \phi_c \phi_q + \phi_c \phi_q \phi_q$$



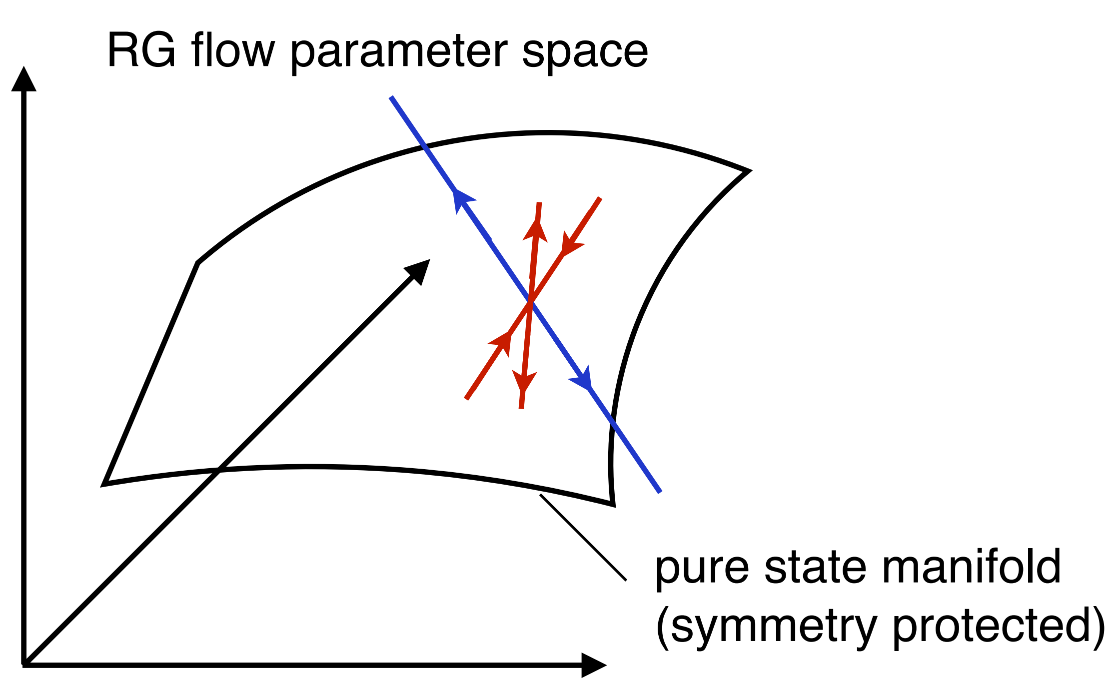
Towards macroscopic physics I: symmetry principle for pure states



- analysis guided by fermion dark state symmetry
- implication I: protecting the fermion state's purity
  - Ward identity: non-thermal fluctuation-dissipation relation $\underbrace{G^K}_{\text{correlation}} \overset{\text{FDS}}{=} F\underbrace{(G^R - G^A)}_{\text{response}}$
  - equal-time: $G^K(t,t) = \Gamma, \quad F^2 = \mathbf{1}$

    $\Longrightarrow$ full renormalized covariance matrix $\Gamma^2 = \mathbf{1}$, pure state

- implication II: constraining RG flow
  - forbids activation of a relevant direction (noise)

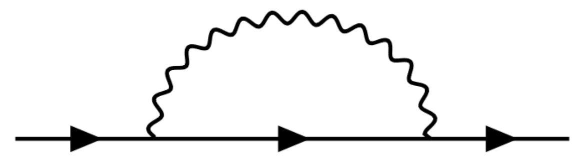


  - non-Gaussian fixed point reached by single fine tuning
  - unlike previous instances of non-equilibrium quantum criticality (bicritical points)

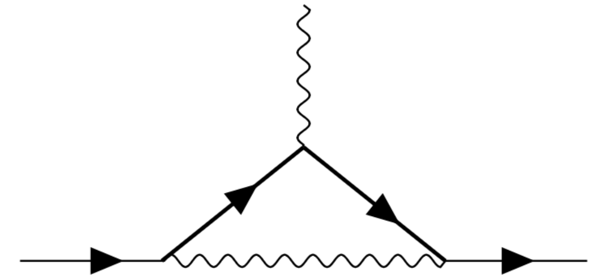
non-Markovian: Dalla Torre et al. Nat. Phys. (2012)
Markovian: Marino, SD, PRL (2016)

Towards macroscopic physics II: RG analysis

- flow equations at one-loop order



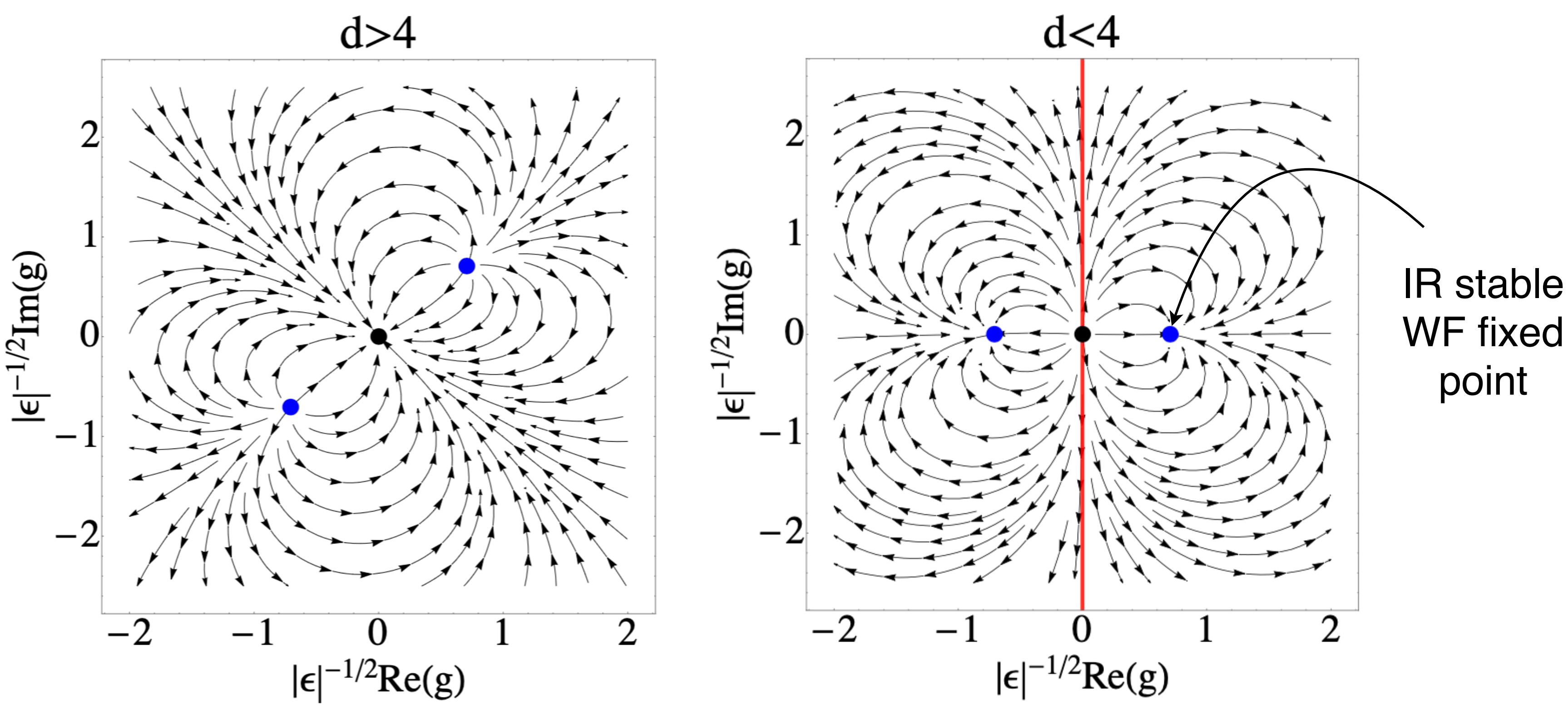
complex fermion self energy



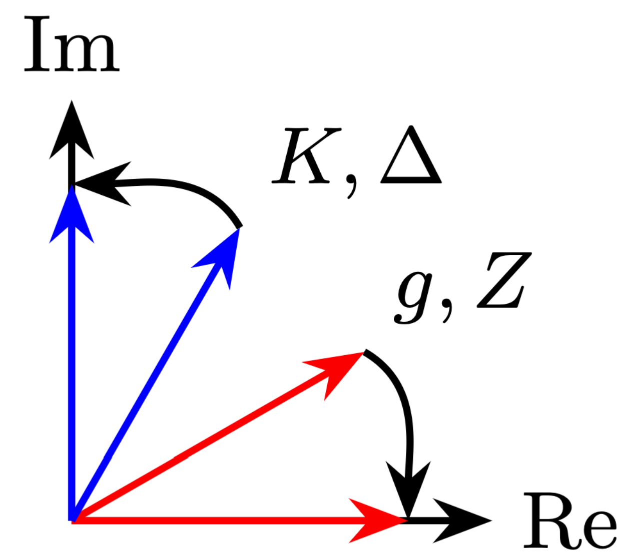
complex Yukawa coupling

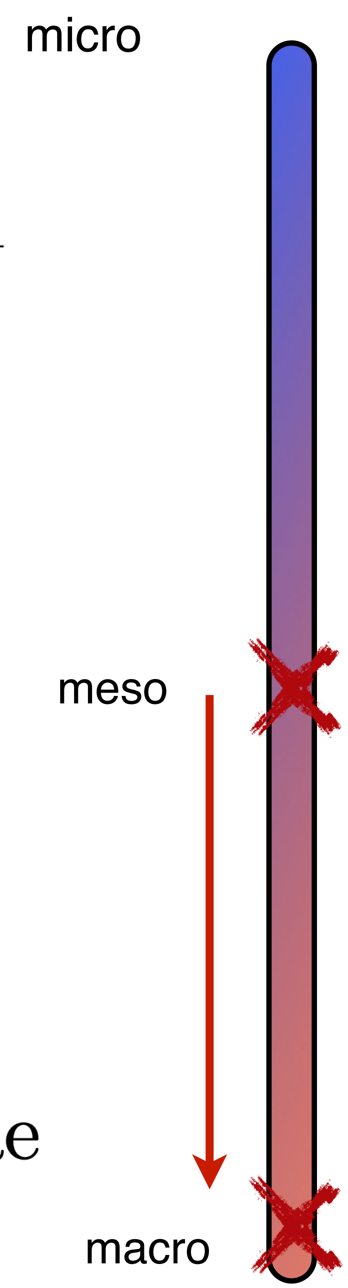
- fixed point structure

Flow of Yukawa coupling



fixed point with reversible and irreversible couplings



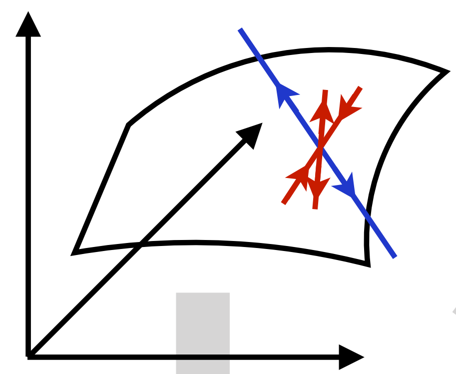


- set of one-loop critical exponents for new universality class

correlation length exponent	$\nu = \frac{1}{2} - \frac{\epsilon}{4}$
dynamical exponent	$z = 2 + \frac{\epsilon}{2}$
anomalous dimension	$\eta = -\frac{\epsilon}{4}$

Discussion: related symmetry structures at critical points

- symmetry constrains flow in pure states



in quantum sytems:

Marcuzzi et al., PRL (20016); Piroli et al. PRB (2021), O'Dea et al., PRB (2024)

quantum directed percolation:

Carollo, Gillman, Weimer, Lesanonvsky, PRL (2019); Thompson, Kamenev, SciPost (2024)

quantum criticality

- thermal/KMS symmetry for $T = 0$

Sieberer, …, SD, PRB (2015); Haehl et al. JHEP (2016); Crossley et al., JHEP (2016); Aron et al. SciPost (2018)

fermion dark state transitions

- fermionic dark state symmetry

absorbing state transitions

- rapidity inversion

U.C. Täuber, Critical Dynamics (2014)

➡ further commonalities:

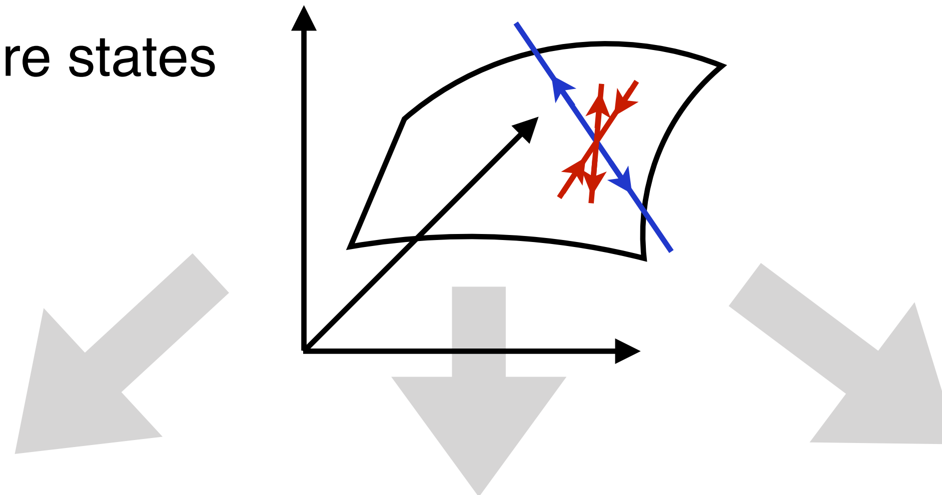
➡ implication: fluctuation-dissipation relations fixing system in pure state

➡ all symmetries reminiscent of time reversal:

- $\mathbb{Z}_2$ antiunitary involution
- involve $t \to -t$

Discussion: related symmetry structures at critical points

- symmetry constrains flow in pure states



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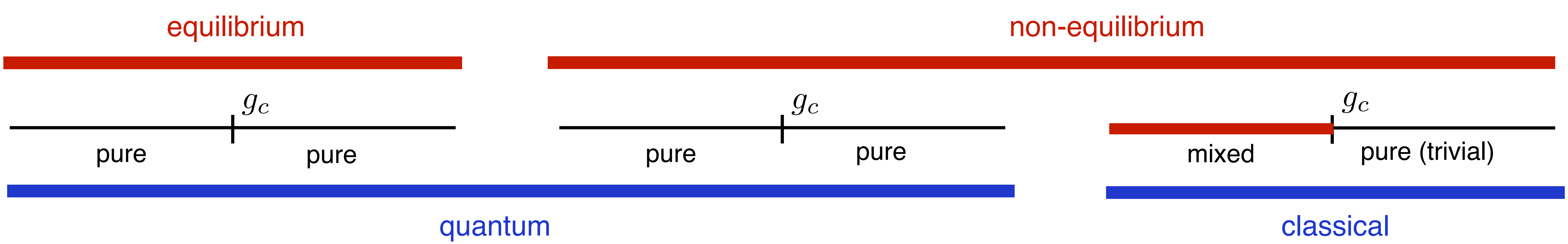
➡ further comparison:



➡ new intersection: non-equilibrium quantum

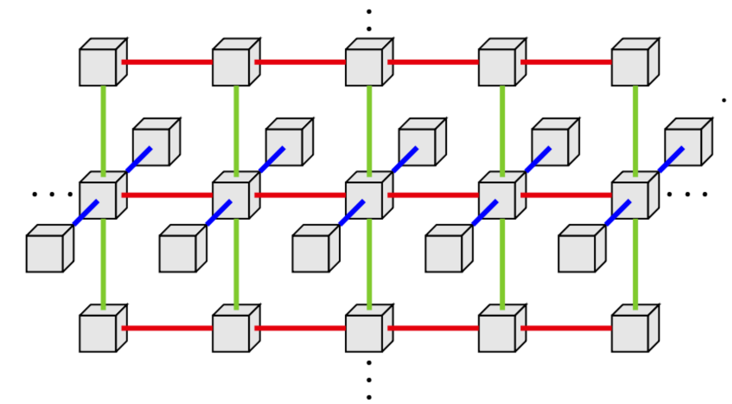
➡ caveat: symmetry protection $\neq$ physical protection

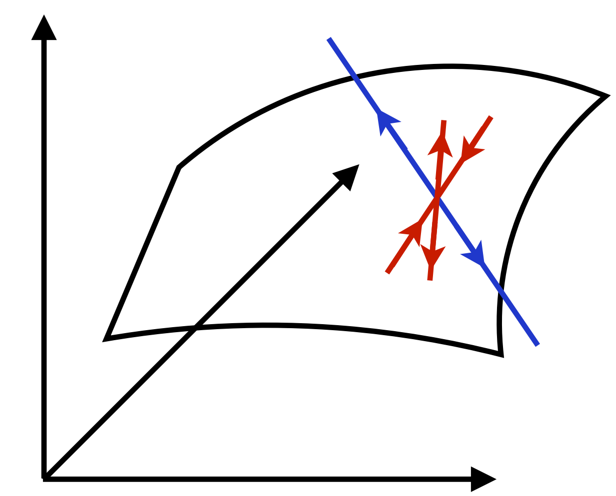
Fermion quantum criticality far from equilibrium

R. Mittal, T. Zander, J. Lang, SD, PRX (2026)

microphysics — macrophysics

- microscopic ingredients:
  - fermion dark state, interactions, breaking of equilibrium, particle number conservation
  - building blocks available in Floquet driven solid state platforms





- mesoscopic symmetries:
  - protection of pure quantum states
  - fermion-boson theory analogous to DP action

- macroscopic physics:
  - new intersection, parallels to equilibrium quantum criticality and absorbing state transitions
  - quantum criticality far from equilibrium