Title: A minimalist's approach to the physics of emergence

Speakers: Liujun Zou

Collection: Quantum Criticality: Gauge Fields and Matter

Date: May 18, 2022 - 5:50 PM

URL: https://pirsa.org/22050068

Abstract: One of the central themes of quantum many-body physics and quantum field theory is the emergence of universality classes. In general, determining which universality class emerges in a quantum many-body system is a highly complex problem. I will argue that the perspective of quantum anomaly provides powerful insights to the understanding of the landscape of universality classes that can emerge in a quantum matter, and I will present some interesting applications.

# Key message

Anomaly supremacy: landscape of universality classes in a quantum matter

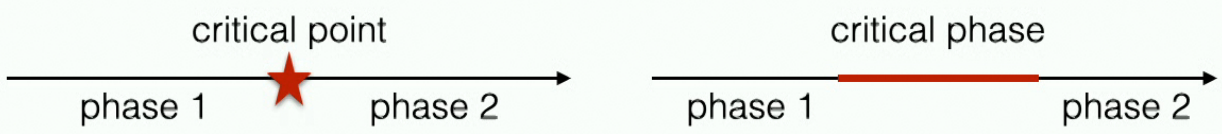
# Emergence of universality class

Many-body system → zoom out → Universality class (QFT)

zoom out →

Refs: da Vinci, 15??.
Picasso, 1927.

# Manifesto of Quantum Criticality



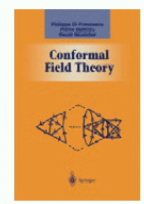

- Features: Enlarged symmetries and nontrivial dynamics
- As a parent state: unified understanding of the nearby phases

# Example: Emergence of $SU(2)_1$ CFT

Universality class (QFT)

=

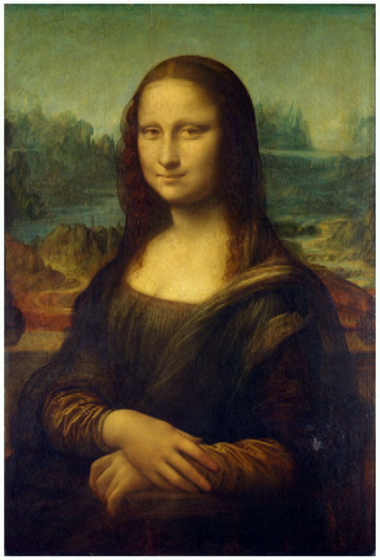
a (1+1)-d CFT defined by **intrinsic** data:
central charge, operator spectrum, OPE

(Ref: 

)

# Example: Emergence of $SU(2)_1$ CFT

Many-body system



$$H = J \sum_i \vec{S}_i \cdot \vec{S}_{i+1}$$ (the most common one)

$$H = J_1 \sum_i \vec{S}_i \cdot \vec{S}_{i+1} + J_2 \sum_i \vec{S}_i \cdot \vec{S}_{i+2}$$

(Ref: Anders' talk)

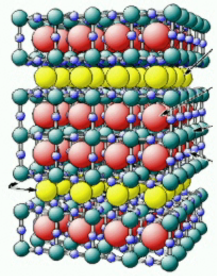
$$H = t \sum f_{i+1}^\dagger e^{i a_i} f_i + \cdots$$

(Ref: Fakher's talk)

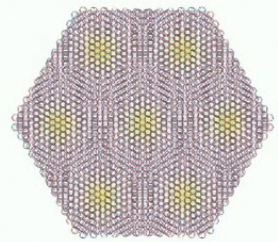
other possibilities

# To see the world from a grain of sand

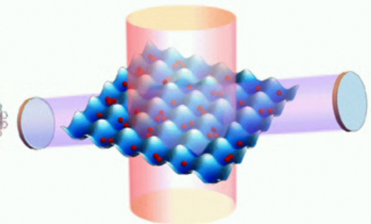
physical universe



YBCO



twisted bilayer graphene



cold atom

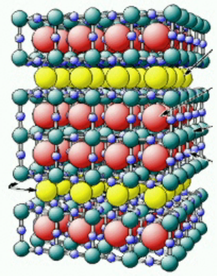
……

**tunable** artificial universes

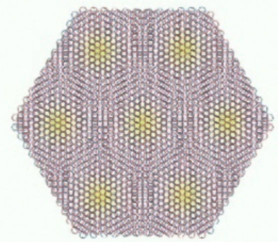
**your** favorite theories may emerge

# To see the world from a grain of sand

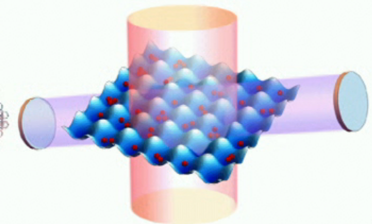
physical universe



YBCO



twisted bilayer graphene



cold atom

……

**tunable** artificial universes

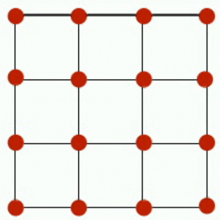
**your** favorite theories may emerge

# The emergibility problem

- Question: can a given QFT emerge in the ground state of a given lattice system?
- Example: can the O(3) Wilson-Fisher CFT ($\mathcal{L} = \frac{1}{2}(\partial_\mu \vec{n})^2 + u(\vec{n}^2)^2$) emerge in the ground state of a square lattice spin-1/2 system with all symmetries?

Possible Hamiltonian: $H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + \cdots$

**any** local interactions
respecting all symmetries
(spin rotation and lattice symmetries)



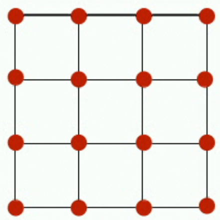
●: localized spin-1/2 particle

# The emergibility problem

- Question: can a given QFT emerge in the ground state of a given lattice system?
- Example: can the O(3) Wilson-Fisher CFT ($\mathcal{L} = \frac{1}{2}(\partial_\mu \vec{n})^2 + u(\vec{n}^2)^2$) emerge in the ground state of a square lattice spin-1/2 system with all symmetries?

Possible Hamiltonian: $H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + \cdots$

**any** local interactions respecting all symmetries (spin rotation and lattice symmetries)



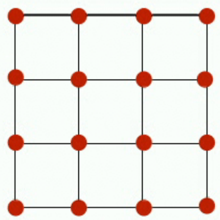
●: localized spin-1/2 particle

# The emergibility problem

- Question: can a given QFT emerge in the ground state of a given lattice system?
- Example: can the O(3) Wilson-Fisher CFT ($\mathcal{L} = \frac{1}{2}(\partial_\mu \vec{n})^2 + u(\vec{n}^2)^2$) emerge in the ground state of a square lattice spin-1/2 system with all symmetries?

Possible Hamiltonian: $H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + \cdots$

**any** local interactions respecting all symmetries (spin rotation and lattice symmetries)



●: localized spin-1/2 particle

# Robust vs. detailed microscopic properties

**Robust** properties

1. Symmetries (spin rotation and lattice symmetries)
2. Representation of the degrees of freedom (spin-1/2)
3. Locations of the degrees of freedom (vertices of the square lattice)

**Detailed** properties

1. Specific form of the Hamiltonian (E.g.: Heisenberg, commuting projector…)
2. Magnitude and range of the interaction (E.g.: up to next-nearest-neighbor…)

…

…

# Why do we care?

- Fundamental: landscape of universality classes in a many-body system
- Useful: realizing a specific universality class in many-body systems

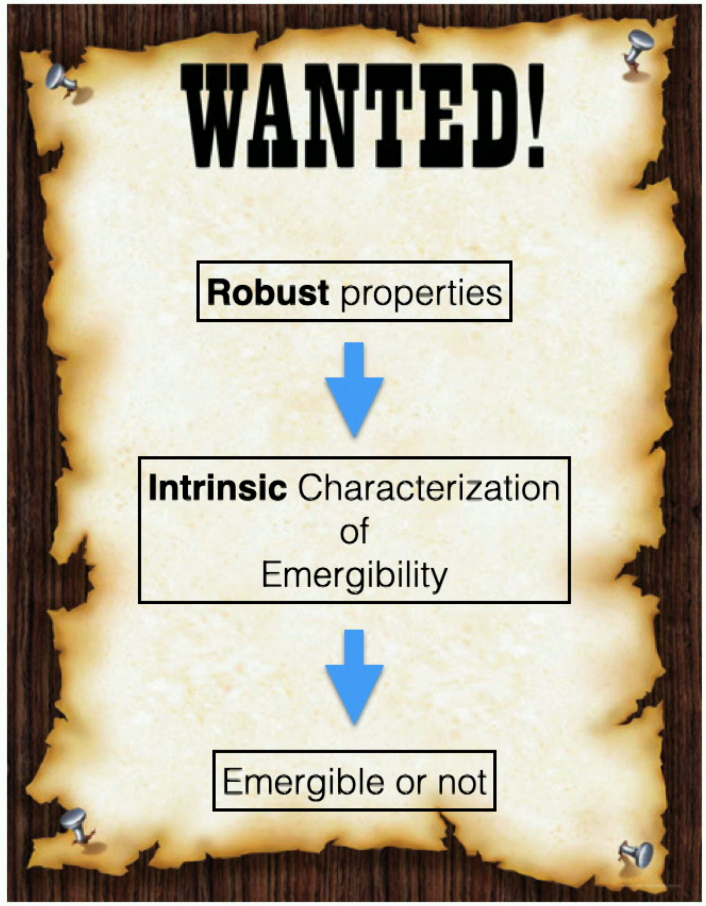
# How can we answer it?

- Q: Solving all possible lattice Hamiltonians?
  - A: Not practical.
- Q: Explicit construction of an effective QFT?
  - A: Often case-by-case and uncontrolled.
  - A: No known explicit construction for **non-Lagrangian** theories.

(ultra quantum matter beyond any semi-classical mean field)

Ref: **Zou**, He, Wang, 2101.07805


WANTED!
**Intrinsic** Characterization
of
Emergibility


WANTED!
**Robust** properties
**Intrinsic** Characterization
of
Emergibility
Emergible or not

# Input: robust properties

1. Symmetries
2. Representation of the degrees of freedom
3. Locations of the degrees of freedom

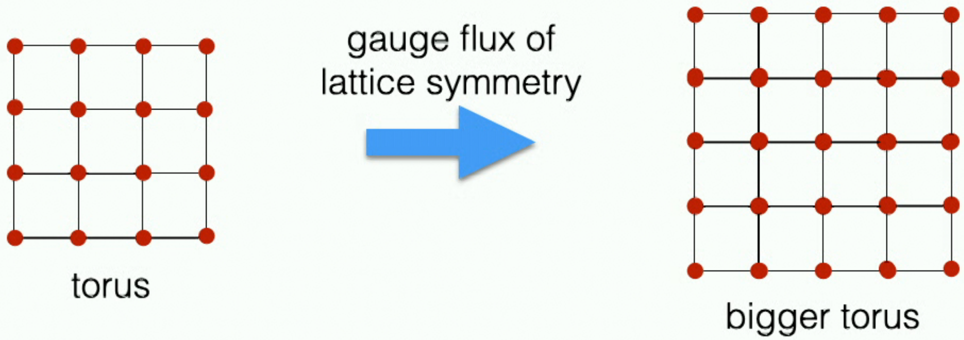
# Key

1. Symmetries
2. Representation of the degrees of freedom
3. Locations of the degrees of freedom

Anomaly of lattice systems

**Zou**, He, Wang, 2101.07805.
Ye, Guo, He, Wang, **Zou**, 2111.12097.

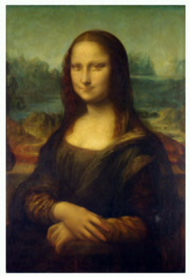
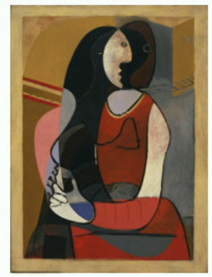
# Example: lattice translation and SO(3) spin rotation




Anomaly: spin changes by 1/2 when coupled to lattice symmetry gauge field

Metlitski, et al, 1707.07686.

# Anomaly-matching condition of emergibility

| Many-body system | | Universality class (QFT) |
|---|---|---|
|  | zoom → out |  |

⇕

$\omega = \Omega$

$\omega$: characterizing anomaly of the lattice system

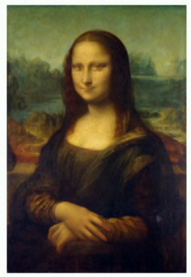
$\Omega$ : characterizing anomaly of the universality class

(Cf: $\partial_\mu j^\mu = \frac{\epsilon_{\mu\nu}F^{\mu\nu}}{2\pi}$ )

Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

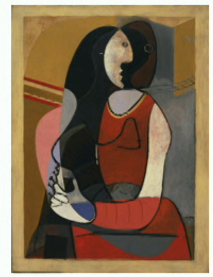
# Anomaly-matching condition of emergibility

Many-body system



zoom out →

Universality class (QFT)



$\Updownarrow$

$$\boxed{\omega = \Omega}$$

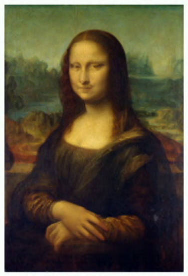
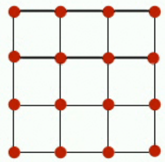
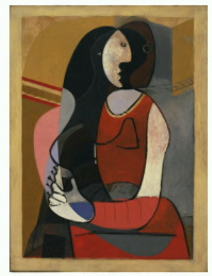
$\omega$: characterizing anomaly of the lattice system

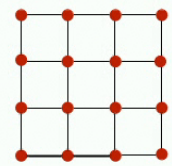
$\Omega$ : characterizing anomaly of the universality class

(Cf: $\partial_\mu j^\mu = \frac{\epsilon_{\mu\nu} F^{\mu\nu}}{2\pi}$ )

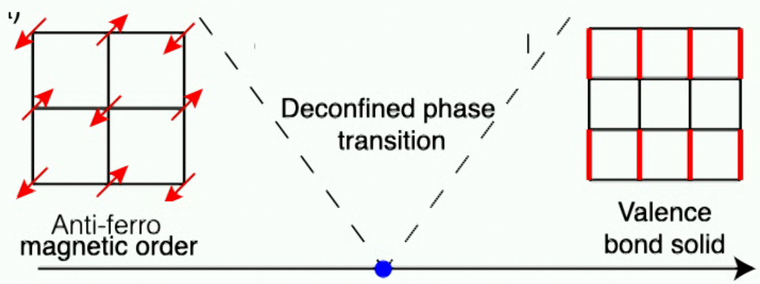
Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

# Application 0

Take  =  and  = O(3) Wilson-Fisher,

→ $\omega \neq 0$, $\Omega = 0$ → O(3) Wilson-Fisher cannot emerge in 

# Application 1




Senthil, et al, cond-mat/0311326

Q: can ● describe a transition between another pair of phases?

(e.g. ferromagnet and VBS)

A: No, for square lattice spin-1/2 system. Yes, for honeycomb lattice spin-1/2 system.

Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

# Application 2

U(1) Dirac spin liquid: $\mathcal{L} = \sum_j \bar{\psi}_j (i\partial_\mu - a_\mu)\gamma^\mu \psi_j + \frac{1}{4e^2} f_{\mu\nu}^2$

"Belief" 1: DSL can be stable on triangular/kagome lattice spin-1/2 systems
cannot honeycomb/square

Our result: DSL can also be stable on honeycomb/square lattice spin-1/2 systems

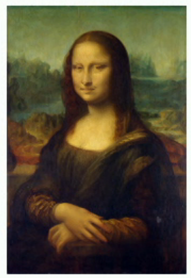
"Belief" 2: DSL can always be described by parton construction
≈ weakly coupled lattice gauge theory

Our result: DSL can actually "go beyond" parton construction.

Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

# Anomaly supremacy:
# landscape of universality classes in a quantum matter

Many-body system



zoom → out

Universality class (QFT)

$\Updownarrow$

$$\omega = \Omega$$

Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097