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

Speakers: Liujun Zou

Collection: Quantum Matter Workshop

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Abstract: One of the central themes of condensed matter physics is the emergence of universality classes. In general, it is highly complex to determine which universality class emerges in a quantum matter based on its microscopic properties. In this talk, I will argue that the perspective of quantum anomaly provides powerful insights into the understanding of the landscape of universality classes that can emerge in a quantum matter, and I will present some interesting applications. Along the way, I will discuss the notions of entanglement-enabled symmetry-breaking orders, non-Lagrangian quantum criticality, quantum spin liquids beyond the usual parton description, etc.

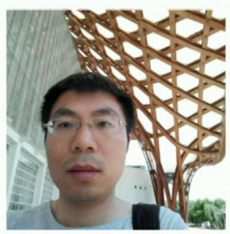
PERIMETER INSTITUTE

A **minimalist's** approach to the physics of **emergence**

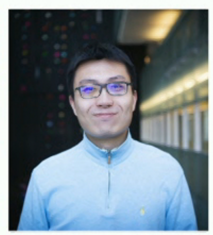
Liujun Zou
(Quantum Matter Workshop, 11/15/2022)

Weicheng Ye

Meng Guo



Yin-Chen He



Chong Wang

Cheng-Ju Lin

Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097
Lin, **Zou**, 2207.08828
Ye, **Zou**, 2210.02444

Take-home message

Anomaly supremacy: landscape of universality classes in a quantum matter

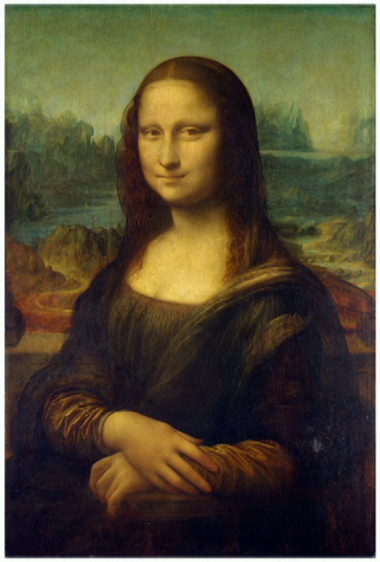
Along the way…

Entanglement-enabled symmetry-breaking orders: intrinsically entangled

Non-Lagrangian quantum criticality: ultra quantum matter

Emergence of universality class

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



→ zoom out →

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

Example: Emergence of Fermi liquids

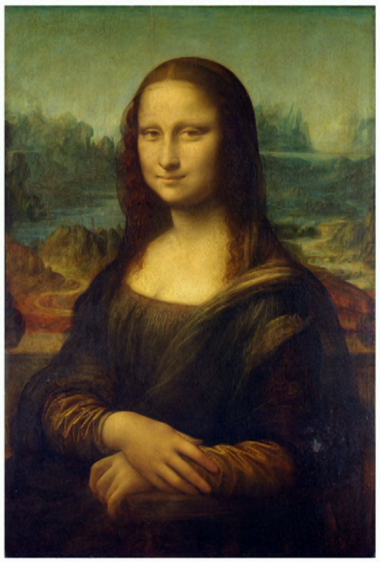
Universality class (QFT)

=

a Fermi liquid defined by **intrinsic** data:
Fermi velocity, Landau parameters, etc

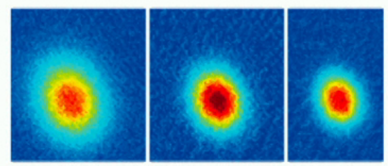
Example: Emergence of Fermi liquids

Many-body system



(gold)

(mercury)



(^{167}Er gas)

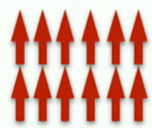
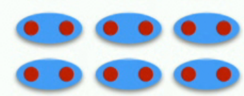
other possibilities

Interesting universality classes?

Entanglement-enabled symmetry-breaking orders: intrinsically entangled

Non-Lagrangian quantum criticality: ultra quantum matter

Spontaneous symmetry breaking

Order	Ferromagnet	Valence bond solid
Original symmetry	SO(3) x translation	
Unbroken symmetry	U(1) x translation	SO(3) x $(\text{translation})^2$
Picture		

( = spin singlet)

<u>Common feature</u>: can be represented by "product states" and are thus "classical"

Entanglement-enabled symmetry-breaking orders (EESBO)

Original symmetry	SO(3) x translation
Unbroken symmetry	Z_n x translation (not U(1) x translation!)
Picture	???

EESBO: cannot be represented by product states and are thus intrinsically entangled

Lin, **Zou**, arXiv: 2207.08828

Non-Lagrangian theories: ultra quantum matter

	mean field = renormalizable UV Lagrangian			**Non-Lagrangian**
UV	weakly coupled	strongly coupled	weakly coupled	strongly coupled
↓	↓	↓	↓	↓
IR	weakly coupled	weakly coupled	strongly coupled	strongly coupled
	E.g.: free fermion	E.g.: QED_4	E.g.: (2+1)-d Wilson-Fisher	E.g.: Stiefel liquid

Zou, He, Wang, 2101.07805

Non-Lagrangian theories: ultra quantum matter

Non-Lagrangian

strongly coupled

↓

strongly coupled

E.g.:
Stiefel liquid

1. IR fixed point without renormalizable UV Lagrangian
   (no such Lagrangian can match its symmetry and anomaly)

2. Strongly coupled from UV to IR

3. Not connected to any semi-classical mean field

Zou, He, Wang, 2101.07805

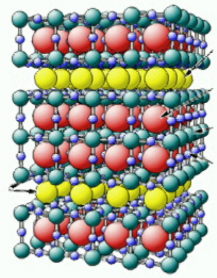
Why do we care?

- Expand the horizon of physics
- Mandate more powerful theoretical tools
- Potentially realizable in a lab

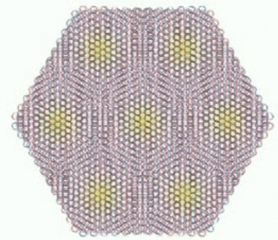

WANTED!
Lattice systems with emergent interesting universality classes

To see the world from a grain of sand

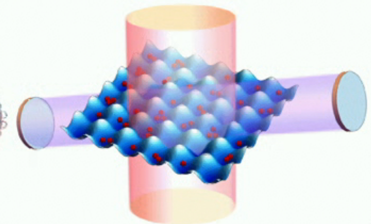
physical universe



YBCO



twisted bilayer graphene



cold atom

……

tunable artificial universes

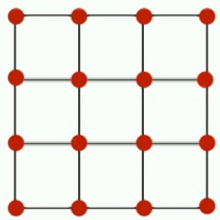
your favorite theories may emerge

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

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

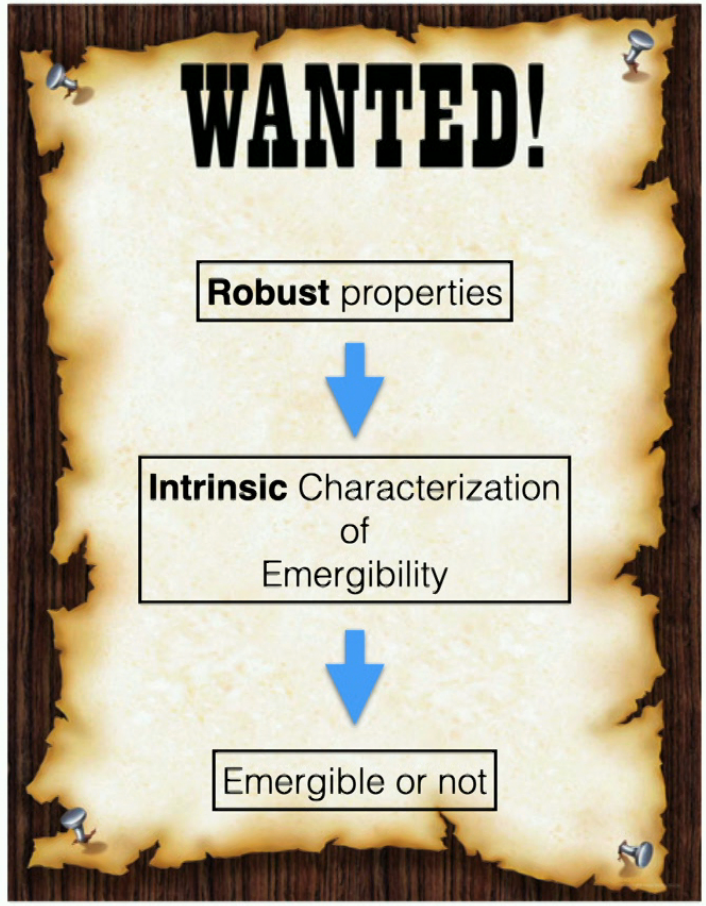
How can we answer it?

- 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

Key

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

↕

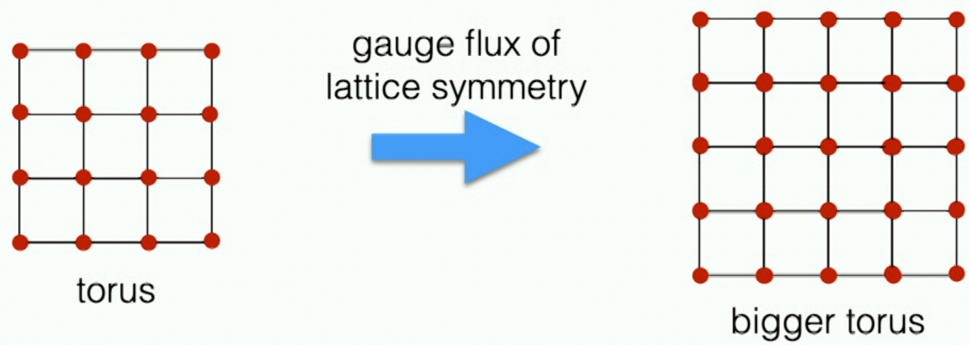
Anomaly of lattice systems

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

Anomaly of QFT

- Inconsistency when coupled to gauge field
- Intrinsic property of a QFT
- Example: anomaly associated with U(1) x U(1) symmetry in Weyl semimetal

Example: lattice translation and SO(3) spin rotation

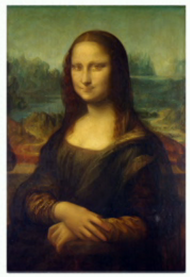


Anomaly: spin changes by 1/2 when coupled to lattice symmetry gauge field

Metlitski, et al, 1707.07686.

Anomaly-matching condition of emergibility

Many-body system



zoom out →

Universality class (QFT)

⇕

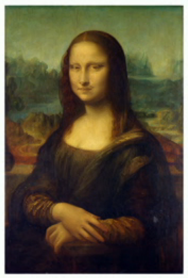
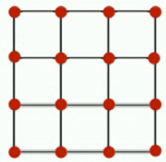
$\omega = \Omega$

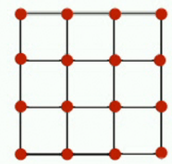
ω: characterizing anomaly of the lattice system

Ω : characterizing anomaly of the universality class

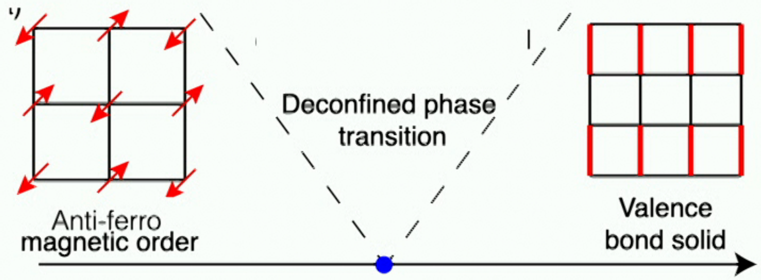
Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097
Ye, **Zou**, 2210.02444

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
$\approx$ weakly coupled lattice gauge theory

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

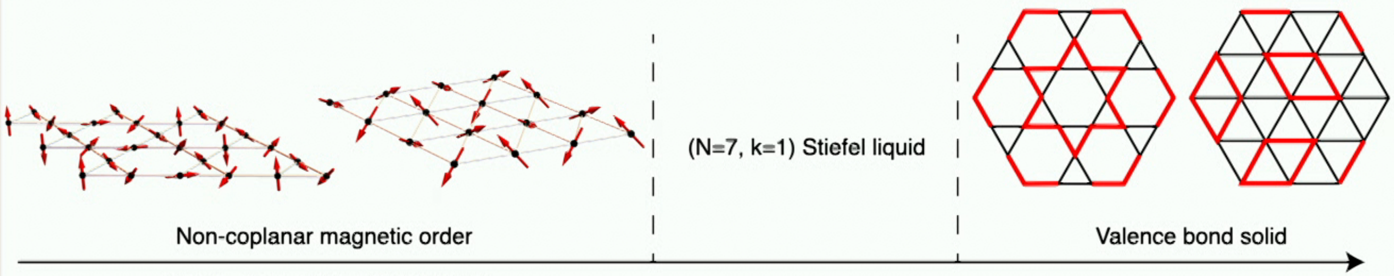
Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

Application 3

Q: In which lattice systems can non-Lagrangian Stiefel liquid emerge?

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

A:



Gong, et al, arXiv: 1705.00510
Yu, et al, arXiv: 2003.13709
Gong, et al, arXiv: 1412.1571

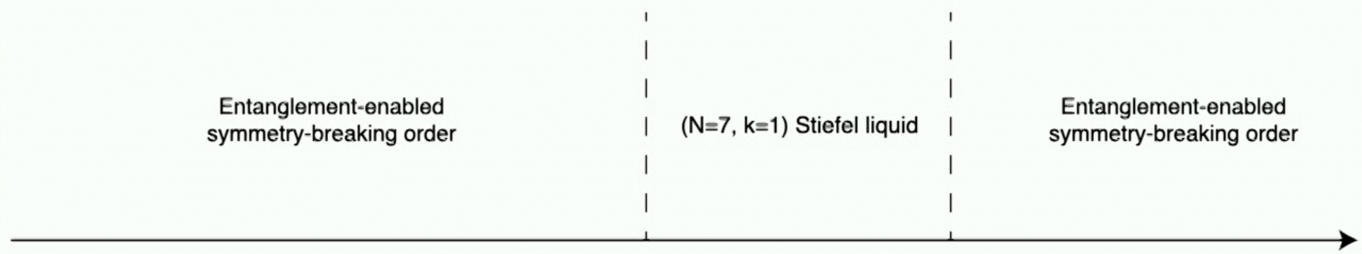
Refs: **Zou**, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

Application 3

Q: In which lattice systems can non-Lagrangian Stiefel liquid emerge?

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

A:



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

Exhaustive search

$G_s = p6m$

	spin-1/2 position	DQCP	DSL	$SL^{(7)}$	DSL_{quad}	$SL^{(7)}_{quad}$
honeycomb	0	10(2)	76(1)	453(0)	1(1)	12(2)
triangular	a	0	3(3)	41(8)	0	0
kagome	c	0	3(3)	35(9)	0	0
	$a\&c$	2(1)	23(5)	176(2)	0	2(0)
	total	12 (3)	105 (12)	705 (19)	1 (1)	14 (2)

$G_s = p4m$

	spin-1/2 position	DQCP	DSL	$SL^{(7)}$	$SL^{(7)}_{incom}$	DSL_{quad}	$SL^{(7)}_{quad}$
square	0	19(0)	217(0)	1849(0)	2(0)	1(1)	22(4)
	a	1(1)	23(3)	299(2)	3(2,1)	0	1(1)
	b	1(1)	23(3)	299(2)	3(2,1)	0	1(1)
	c	3(0)	56(4)	632(0)	2(2)	0	3(1)
	$a\&b$	1(1)	22(0)	279(0)	11(11)	0	1(0)
	$a\&c$	0	6(6)	117(6)	0	0	0
	$b\&c$	0	6(6)	117(6)	0	0	0
	$a\&b\&c$	1(1)	19(2)	227(0)	6(6)	0	1(0)
	total	26 (4)	372 (24)	3819 (16)	27 (23,2)	1 (1)	29 (7)

1. Reproduced all known realizations of DQCP and DSL
2. Uncoverd many unknown realizations of DQCP and DSL
3. Many realizations of $SL^{(7)}$

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

Summary

- Entanglement-enabled symmetry-breaking orders: intrinsically quantum

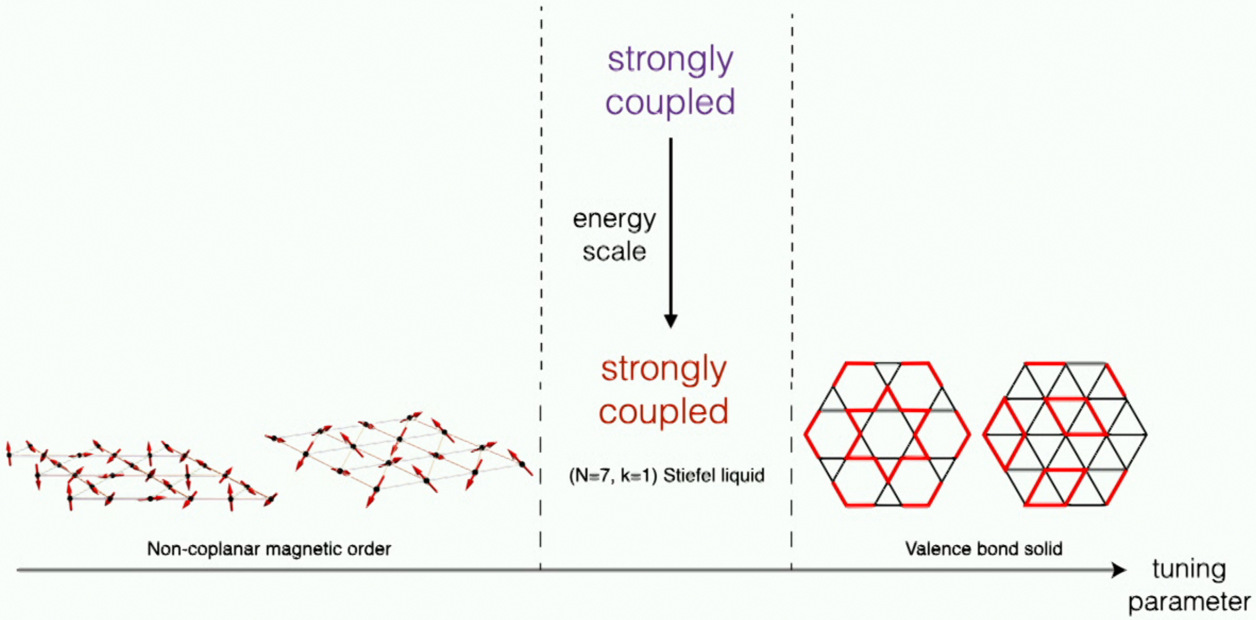
Original symmetry	SO(3) x translation
Unbroken symmetry	Z_n x translation (not U(1) x translation!)
Picture	???

EESBO: cannot be represented by product states and are thus intrinsically entangled

Lin, **Zou**, arXiv: 2207.08828

Summary

- Non-Lagrangian theories: ultra quantum matter

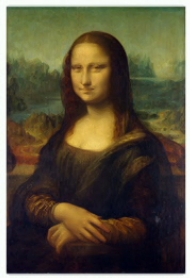


Zou, He, Wang, 2101.07805
Ye, Guo, He, Wang, **Zou**, 2111.12097

Summary

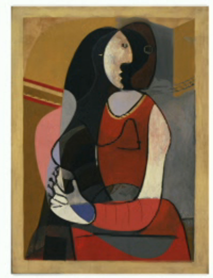
- Anomaly supremacy: landscape of universality classes in a quantum matter

Many-body system



zoom out

Universality class (QFT)



$\Updownarrow$

$$\omega = \varphi^{*}(\Omega)$$

Zou, He, Wang, 2101.07805

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