Title: Emergent fractons in Elusive Bose Metal --- When IR theory blends with UV physics

Speakers: Yizhi You

Series: Quantum Matter

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Abstract: The entanglement pattern of a quantum many-body system can be characterized by quasiparticles and emergent gauge fields, much like those found in Maxwell's theory. My talk begins with the basic aspects of symmetry fractionalization and emergent gauge fields in strongly correlated systems. I will further extend this paradigm into a new type of quantum many-body state, dubbed "fracton phase," from a quantum melting transition of plaquette paramagnetic crystals. These exotic states contain fractionalized sub-dimensional quasiparticles with constraint motion and emergent higher-rank gauge fields. Such constraint dynamics of the quasiparticles bring about an intriguing Bose metal phase with quasi-long range order and yields non-local quantum entanglement. In particular, the key peculiarities of this phase is the UV/IR mixing, where the short wavelength physics controls the low energy theory and hence challenges the standard notion of the renormalization group perspective.

Emergent Fractons in Elusive Bose Metals

Yizhi You

Princeton University

PRINCETON CENTER FOR THEORETICAL SCIENCE

PRINCETON UNIVERSITY

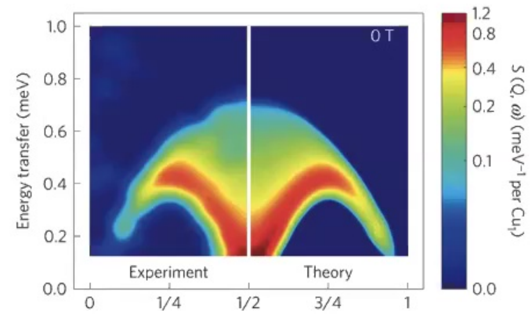
(UV) Hamiltonian → →→ (*IR) effective field theory*

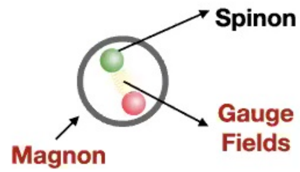
Emergence!

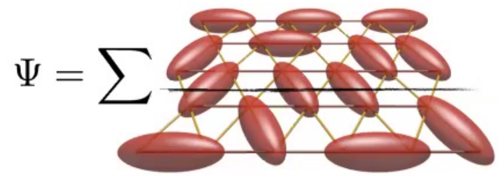
Emergent phenomena → richer context

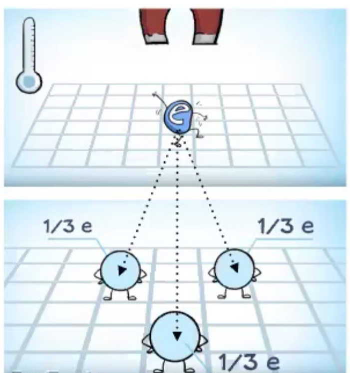
✓Fractionalization

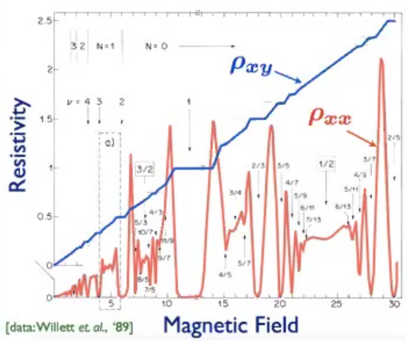
✓Emergent gauge field

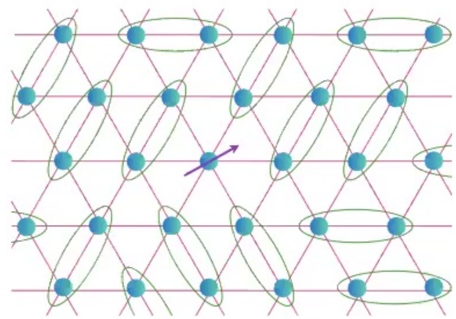












Outline

- ♦ *Emergence of fractionalization?*
- ♦ *Effective theory to describe them?*

1) Melting transition of Valence Bond Solid

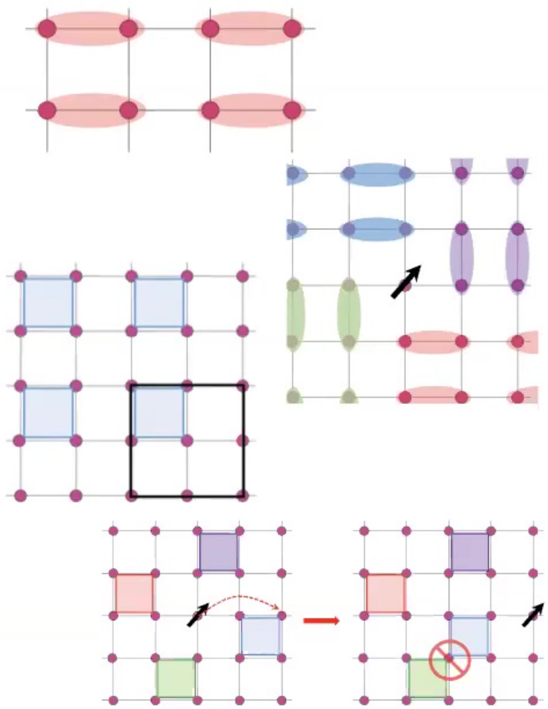
Critical theory = spinon + emergent gauge field

2) Phase transition: Valence Plaquette Solid → Bose metal

✓ *Spinon with* ***constrain dynamics***

✓ *Emergent gauge field:* ***Higher-rank gauge theory***

- *UV-IR mixing!*
- *Short wavelength physics control IR*

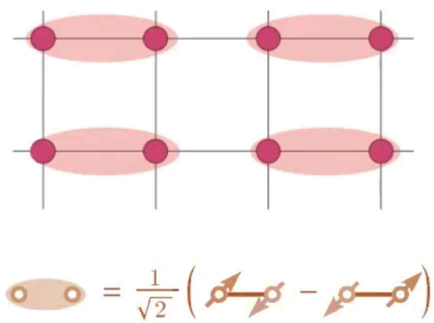


Emergence of fractionalization & Gauge fields?

Where to find them?

Valence Bond Solid

✓ Paramagnetic crystal
✓ Breaks T_x and C_4



The Quantum melting of VBS?

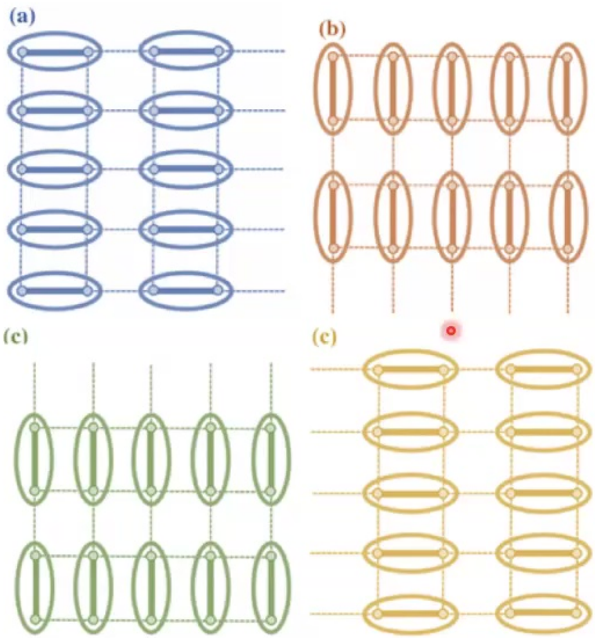
= Disorder the VBS pattern ?

→ develop topological defects

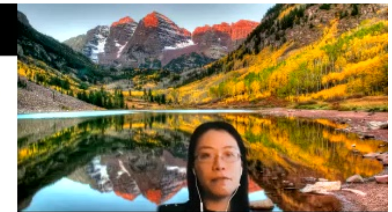
→ fluctuation between distinct patterns

Magic appears!

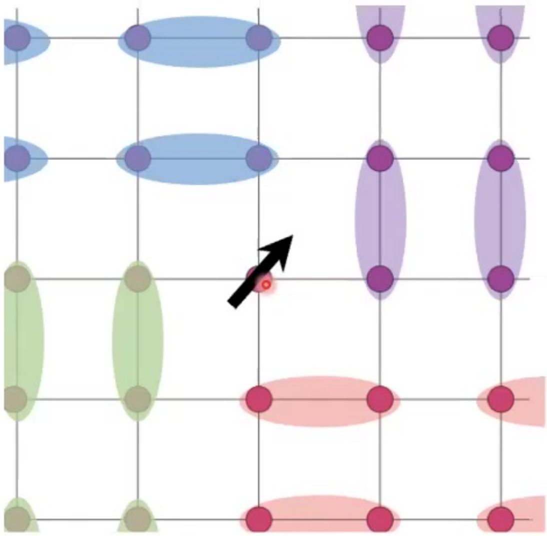
Valence Bond Solid



4 patterns, related by C_4 rotation



VBS Pattern Melting



Z_4 Vortex defect of VBS

Destroy the VBS *(Senthil-2004)*

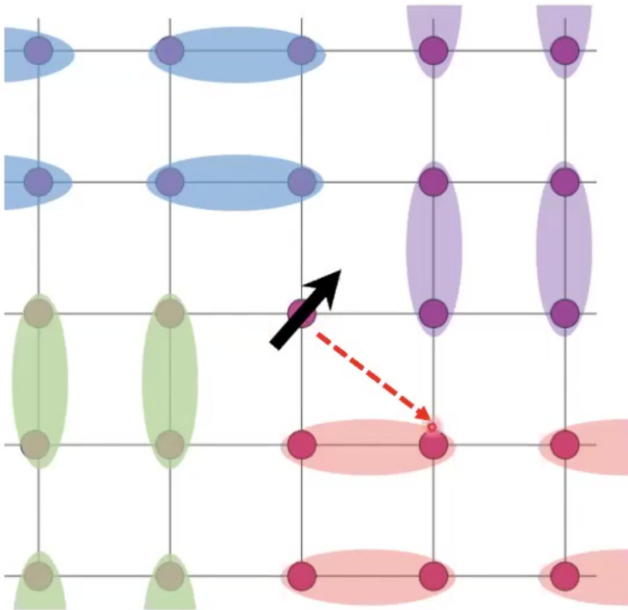
→ Proliferate the defect (vortex)

Defect of the VBS order:
Carry a **spinon** !

Spinon: Carry ½ S_z charge
→ fractionalization at QCP!

Compare to Magnon excitation:
Change S_z number by integer!

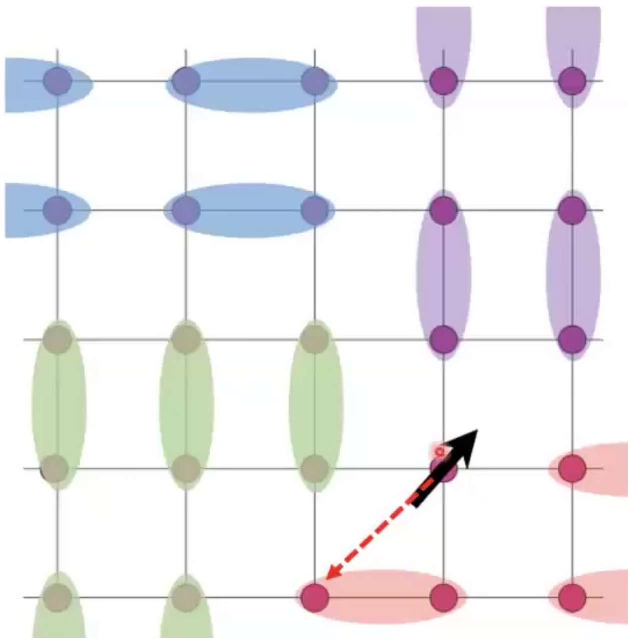
Where is the emergent gauge field?

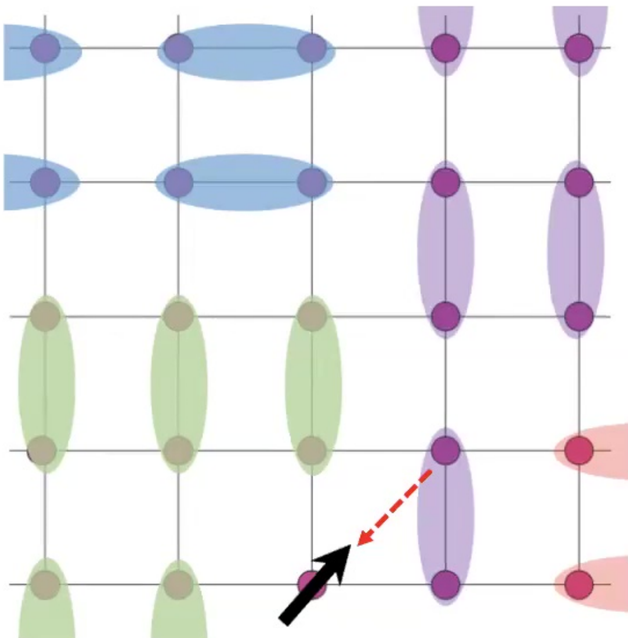


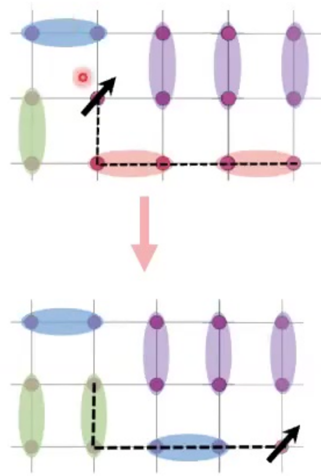
Spinon's kinetics

If spinon is energetically deconfined,

It can fluctuate in the dimer background!





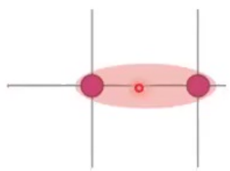


Moving spinon **requires changing VBS pattern !**

→ **Emergent gauge field**

Mapping *(Moessner, Kivelson)*

Dimer ←→ U(1) gauge theory



VB coverage = ***E*** field

$$E_i(\boldsymbol{r}) = (-1)^{i_r} D_i(\boldsymbol{r})$$

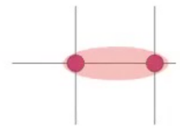
Gauss Law → charge conservation

$$\partial_i E_i(\boldsymbol{r}) = (-1)^{i_r}(1 - q(\boldsymbol{r}))$$

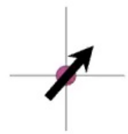
No dimer adjacent to site → spinon

1 dimer adjacent to site → no spinon

Emergent gauge field ←→ constraint !!!



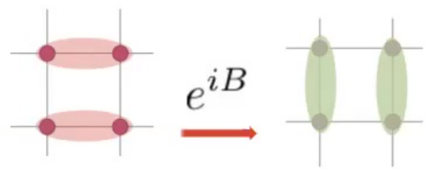
q=0



q=1

$$[A_i(\boldsymbol{x}), E_j(\boldsymbol{y})] = \frac{i}{2\pi}\delta_{ij}\delta_{\boldsymbol{xy}}$$

Create/annihilate VB

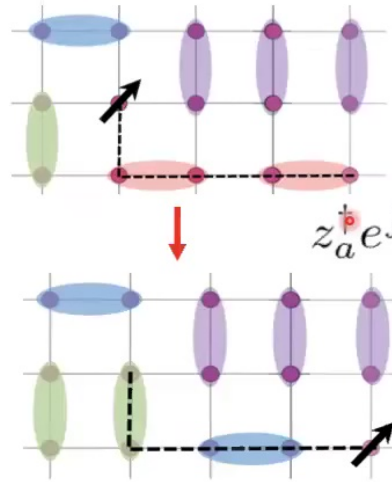


VB fluctuation = ***B*** field

Emergence of fractionalization & Gauge fields?

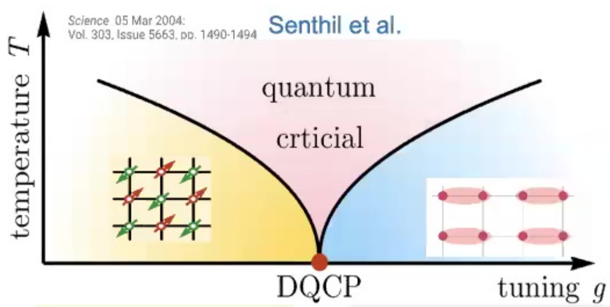
✓ **Spinon** couple with the **emergent gauge field**

✓ Moving spinon requires changing VBS pattern



$$z_a^\dagger e^{\int_a^b A_i dx_i} z_b$$

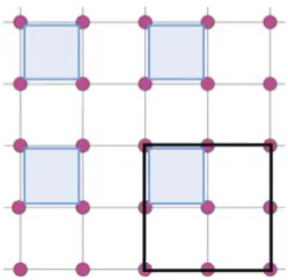
VBS melting → VBS defect + spinon condensate → Magnetic order



Deconfined Quantum Criticality

- ✓ *Spinon ~ half-Magnon*
- ✓ *Emergent U(1) gauge theory*

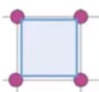
Beyond fractionalization & Gauge fields?



Valence Plaquette Solid

✓ Breaks T_x , T_y and C_4

($SrCu_2(BO_3)_2$)



$$|1010\rangle + |0101\rangle$$

The Quantum melting of VPS?

✓Fractionalization

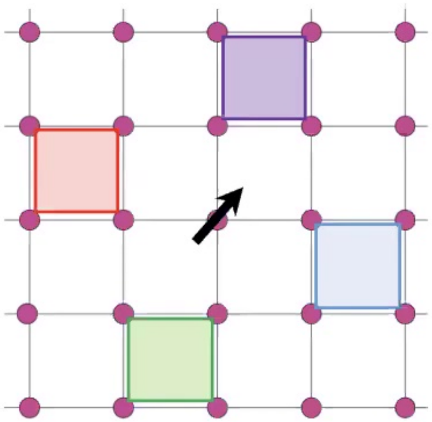
*Spinon with **constraint dynamics***

✓Emergent gauge field

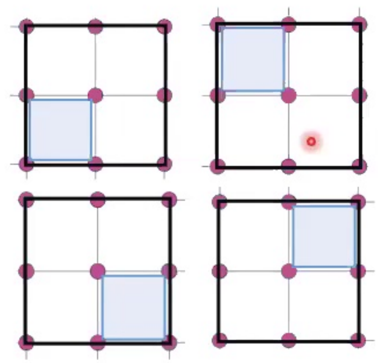
Higher-rank gauge theory

VPS melting !

YY-2019



Z_4 Vortex defect of VPS



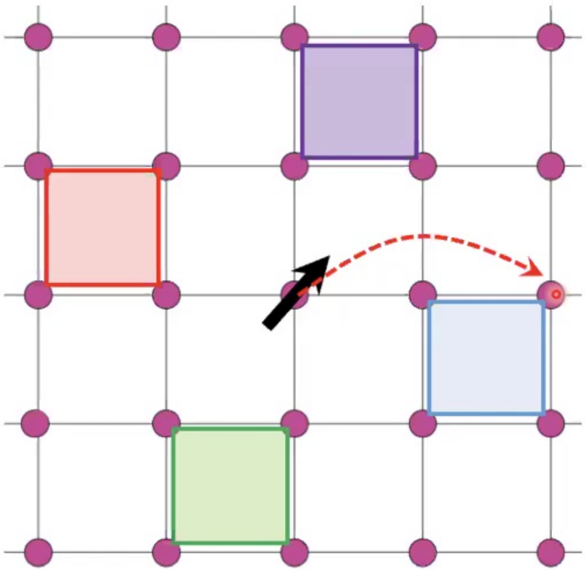
Four
Valence Plaquette patterns

Defect of the VPS order: Carry a **spinon** !

Spinon: Carry ½ S_z charge→ fractionalization!

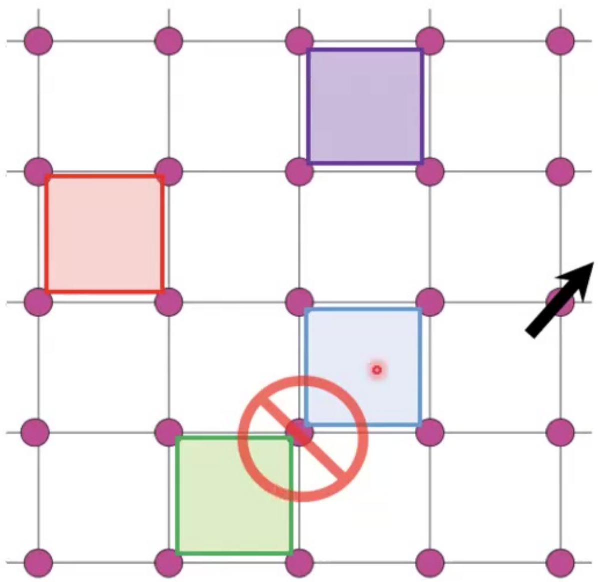
Where is the emergent gauge field?

Look for the spinon's kinetics and VPS pattern change!



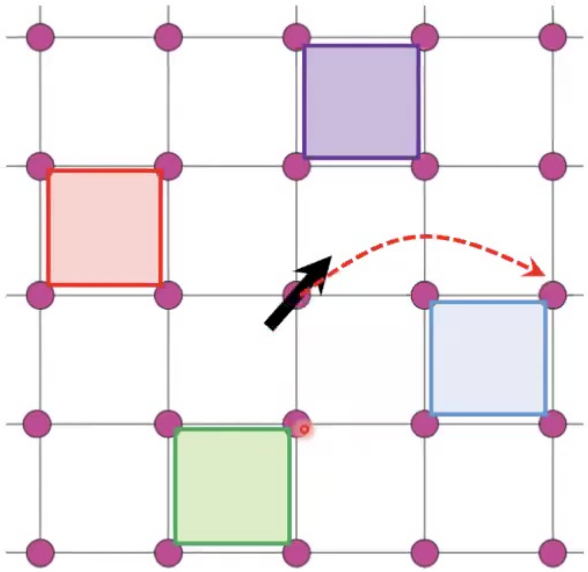
Spinon's kinetics

How to move a spinon???



How to move a spinon???

Spinon is stuck?



Spinon's kinetics

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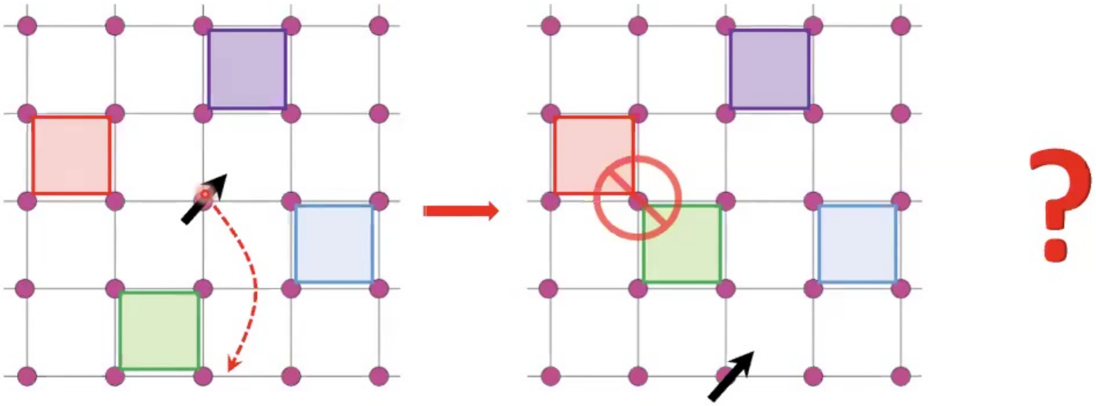


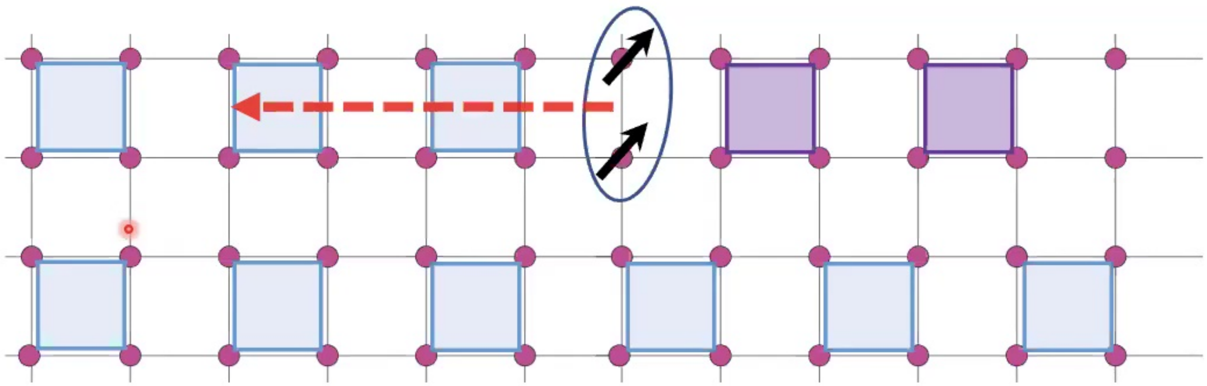
Spinon is stuck! Cannot move!

Immobile particle → Fracton

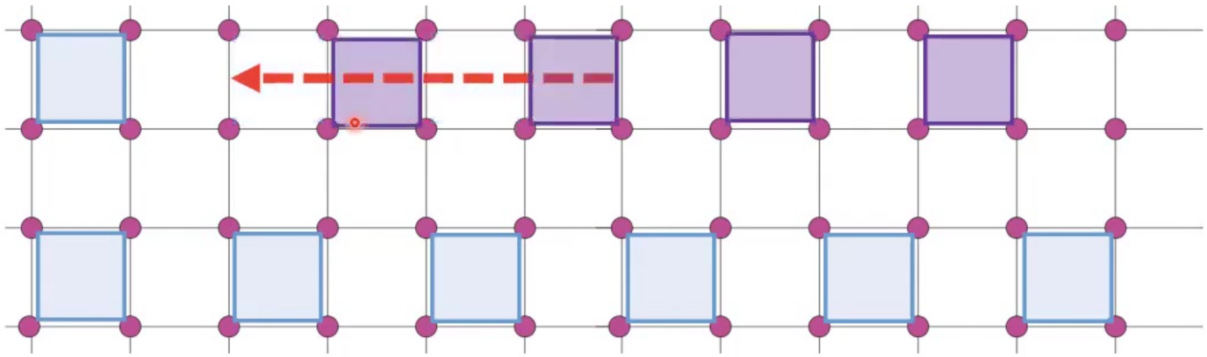
Fracton Phases of Matter

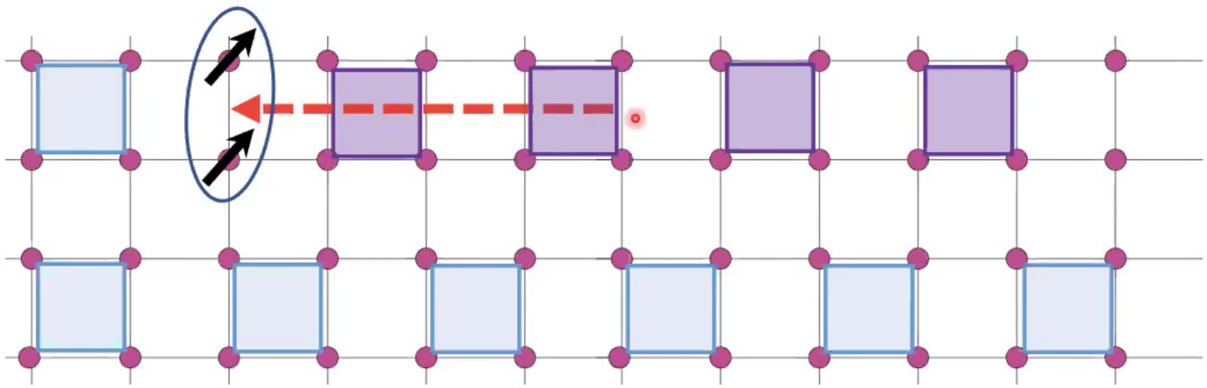
Michael Pretko, Xie Chen, Yizhi You

Fractons are a new type of quasiparticle which are immobile in isolation, but can often move by forming bound states.



How to move a spinon-pair (dipole)???



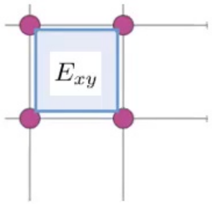


Moving **dipole requires changing VPS pattern !**

→ **Emergent gauge field?**

Mapping *(YY-2019)*

VP ←→ Higher-rank gauge theory



VP coverage
= E_{xy} field

$$E_{xy}(\boldsymbol{r}) = (-1)^{i_{\boldsymbol{r}}} P(\boldsymbol{r})$$

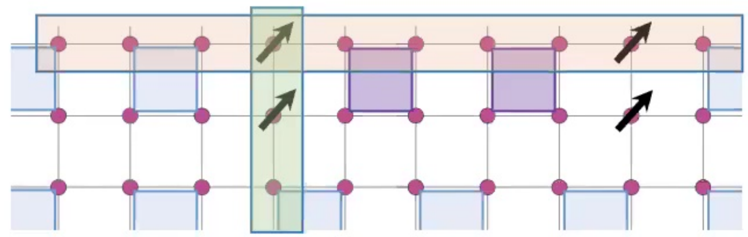
`Gauss Law ' → Charge Conservation

$$\partial_x \partial_y E_{xy}(\boldsymbol{r}) = (-1)^{i_{\boldsymbol{r}}} (1 - q(\boldsymbol{r}))$$

Charge conservation on each row !

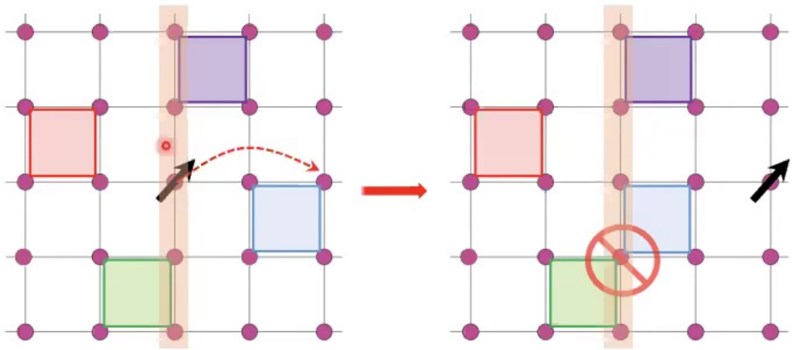
$\int dx_i \;\rho = 0$ ***Subsystem symmetry***

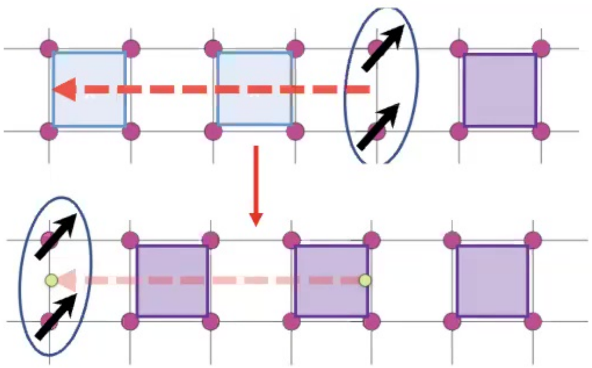
Emergent gauge field ←→ constraint !!!



Spinon inside VPS defect appear in quartet

Conserved in each row/column!





Spinon **is a fracton:**
Cannot move!

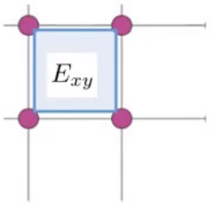
Charge conserved on row/columns

✓A pair of spinon (dipole) **only** fluctuate along the transverse stripe!

✓Such dynamics is accompanied by the plaquette flipping along the path

Mapping

VP ←→ Higher-rank U(1) gauge theory



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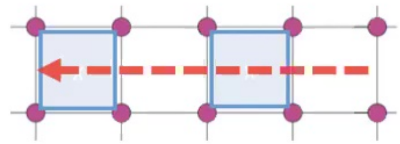
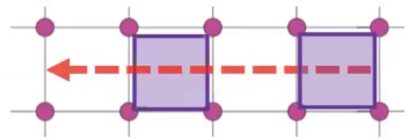
Charge conservation on each row !

$\int dx_i \;\; \rho = 0$ ***Subsystem symmetry***

$\boxed{A_{xy}} \to A_{xy} + \partial_x \partial_y \alpha,$ Create/annihilate VP

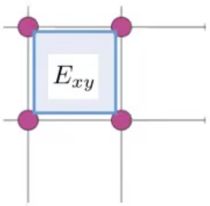


$e^{i \int dy A_{xy}}$ *VPS Pattern flip*



Mapping

VP ←→ Higher-rank U(1) gauge theory



VP coverage
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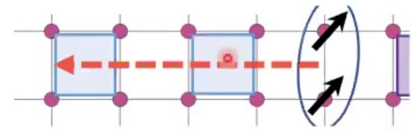
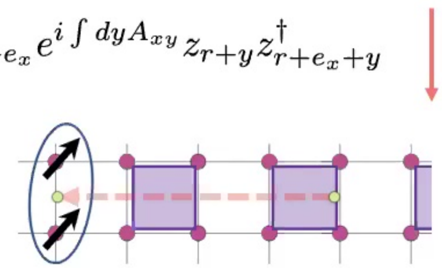
Charge conservation on each row !

$$\int dx_i \; \rho = 0$$



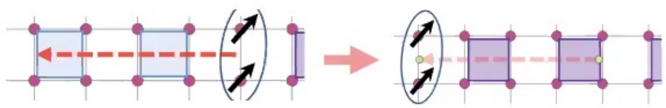
$$z_r^\dagger z_{r+e_x} e^{i \int dy A_{xy}} z_{r+y} z_{r+e_x+y}^\dagger$$

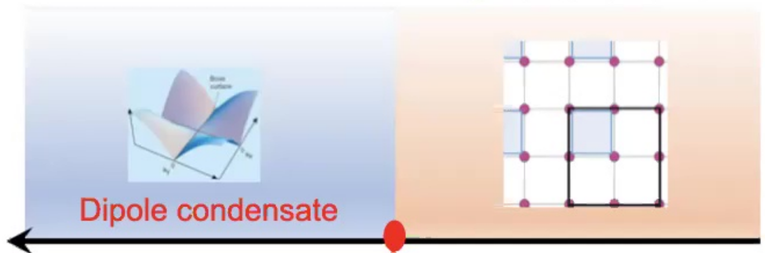


✓ Moving dipole requires changing VPS pattern along the path!

→ Dipole current minimal couple with emergent higher-rank gauge field!

What happens after plaquette melting? *(YY-2020)*

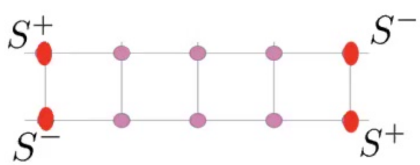




Algebraic liquid | VPS

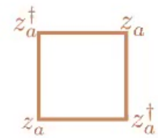
Fractonic KT transition

$$\langle S^+(r)S^-(r+e_y)S^+(r+x)S^-(r+e_y+x)\rangle$$
$$= \frac{1}{(x)^{1/(K\pi^2)}}$$



Gaussian theory

$$\mathcal{L} = \frac{K}{2}\sum_{a=1,2}(\partial_t\theta_a)^2 - \frac{K}{2}\sum_{a=1,2}(\partial_x\partial_y\theta_a + A_{xy})^2$$



Dipole fluctuation
= ring-exchange

✓ Dipole: fluctuate in **1d,** condense?
→ No long-range order → Mermin-Wagner theorem
→ Quasi-long-range order between dipoles!

Algebraic Liquid phase = Elusive 2D Bose metal

Elusive Algebraic Liquid phase: A Bose metal

`Bose Fermi surface'! *(Fisher-2005, Balents-2004, YY-2019)*

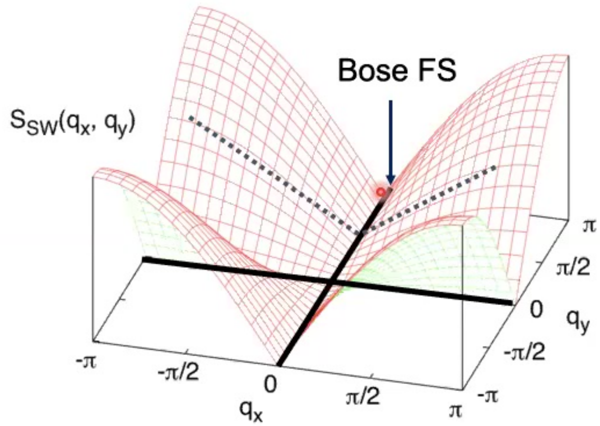
✓Zero-energy branch line on k_x ,k_y axis

Compare to 2D Fermi surface (zero energy points forms a close line)

Transport: Specific heat

$C_v \sim T \ln(1/T)$

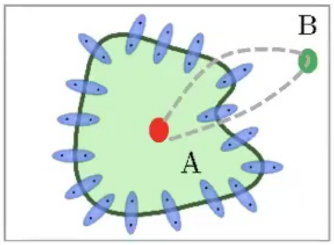
✓Akin to marginal non-Fermi liquid



$E \sim k_x k_y$

Get a 'Fermi surface' from boson!!!

Quantum information viewpoint – **Entanglement & Mutual information**



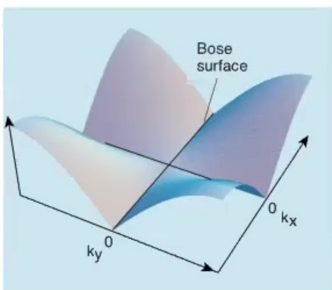
$$\rho_A = \mathrm{Tr}_{\bar{A}} |\Psi\rangle\langle\Psi|$$

$$S(A) = -\mathrm{Tr}_A\left(\rho_A \ln \rho_A\right)$$

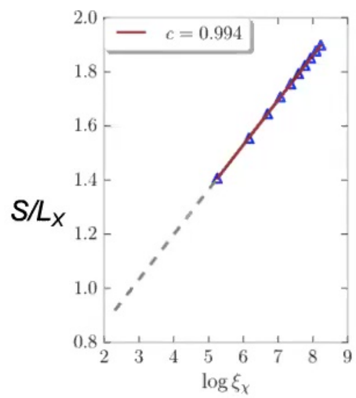
Entanglement Entropy

2D GS → Entanglement area law

EE ~ L (Length of the boundary)



Algebraic Liquid phase



$S_A \sim L\ln(L)$

Algebraic Liquid phase

- ✓ *Violation of the area law !* $L\ln(L)$
- ✓ *long-range mutual information!*
- ✓ *Similar to 2d FS*

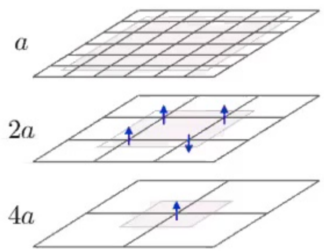
(YY-Pollmann, YY-2019-PRR)

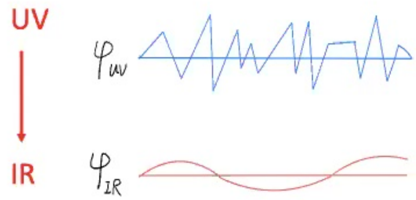
Critical phase *beyond* ***Renormalization Perspective?***

Universality of critical phenomenon

$$\langle C(0,0)\ C(\vec{r},0)\rangle = \boxed{\frac{1}{r^{D-2+\eta}}}$$

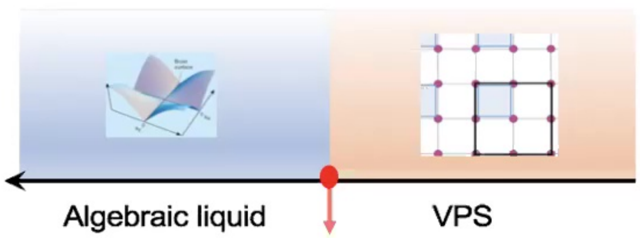
Universal scaling at QCP





Coarse grained = keep long wave-length

→ low energy = long wave-length
→ Scaling & critical exponent is universal



Fractonic KT transition

Charge correlator at the algebraic liquid phase

$$\langle \hat{n}(x,y,0)\ \hat{n}(0,0,0)\rangle \boxed{= \frac{1}{(xy)^2}}$$

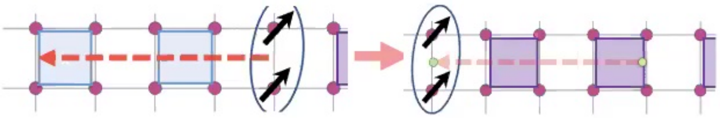
$$\langle S^+(0)S^-(t)\rangle \sim e^{-a(ln(t))^2}$$

$$\langle \partial_x S^+(0)\partial_x S^-(t)\rangle \sim \frac{1}{t^\alpha}$$

?

Why UV blend with IR ?

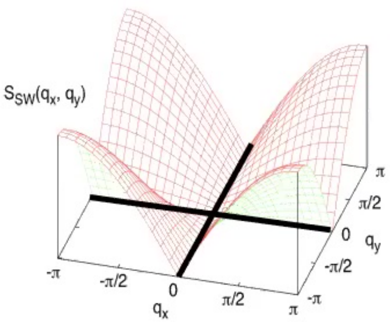
low energy modes from short wave-length physics



$$\mathcal{L} = \frac{K}{2}\sum_{a=1,2}(\partial_t\theta_a)^2 - \frac{K}{2}\sum_{a=1,2}(\partial_x\partial_y\theta_a + A_{xy})^2$$

Subsystem symmetry → local fluctuation with zero energy

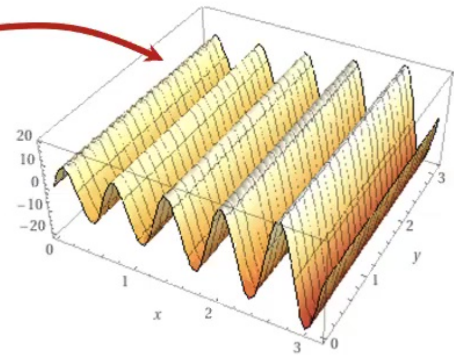
→ low energy modes from short wave-length physics → Bose surface (E=0 at large k)



Rough field fluctuation at low energy

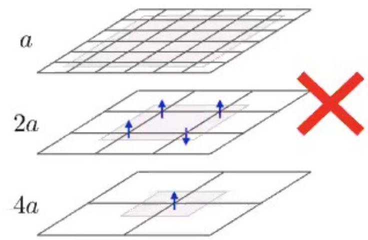
→ Short wave-length physics enter IR

UV-IR mixing! (Seiberg-*2020*)



Short wave-length physics enter IR
→ UV-IR mixing!

Subsystem symmetry → local fluctuation zero energy
→ low energy modes from short wave-length physics



Illegal Coarse graining

UV-IR mixing → short wave-length physics survives at low energy
→ IR theory affected by UV

✓ *Critical exponent independent of spacetime, emergent fractal dimension* Zhou, Pollmann, You, to appear

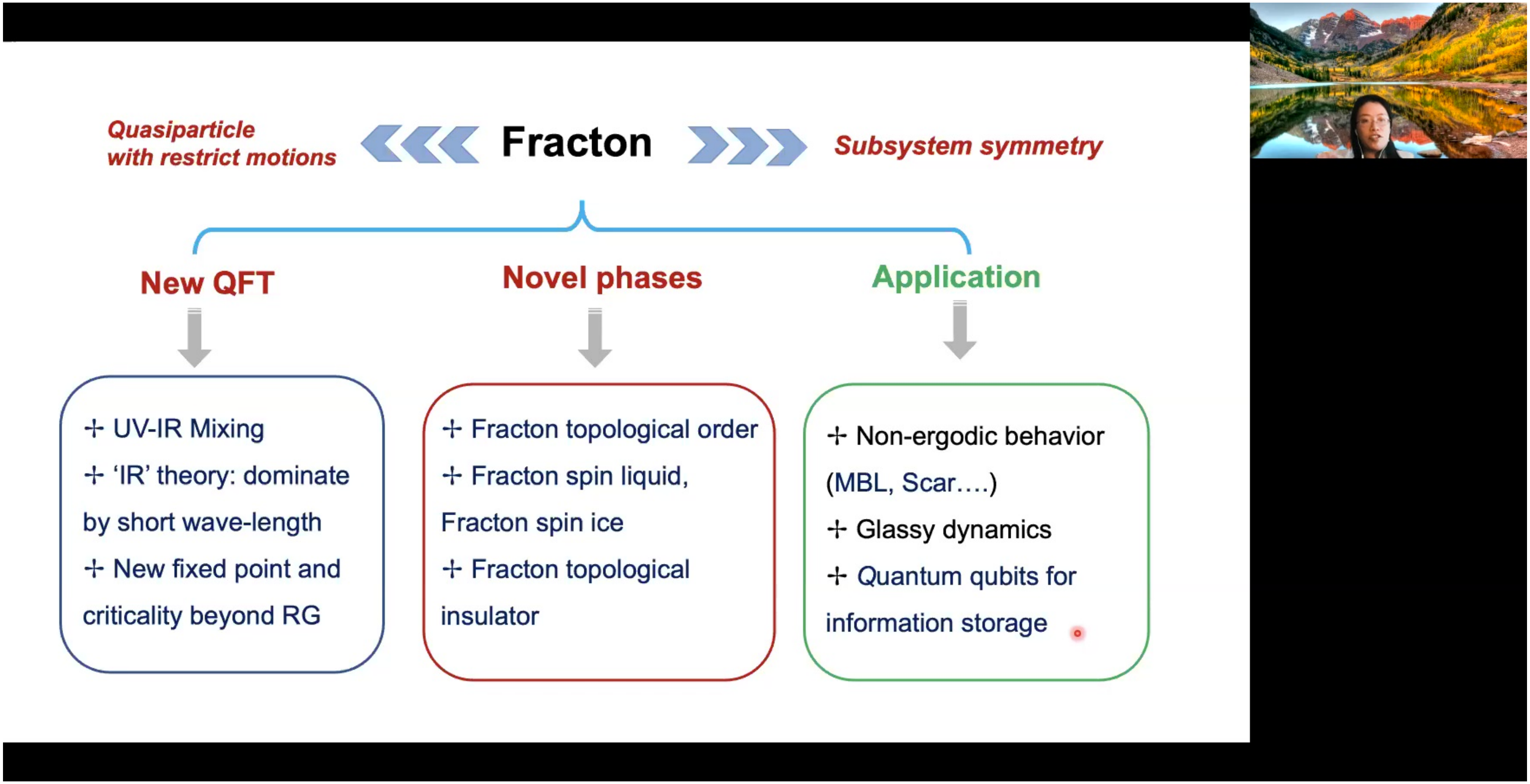
✓ *EFT* Depends on UV cut-off

✓ *Higher order operators could be more relevant!*

Originate from Fracton !

New quantum field theory: IR blend with UV!

(You-2019, Seiberg-2020, Karch-2020)


Quasiparticle
with restrict motions
Fracton
Subsystem symmetry
New QFT
Novel phases
Application
+ UV-IR Mixing
+ 'IR' theory: dominate
by short wave-length
+ New fixed point and
criticality beyond RG
+ Fracton topological order
+ Fracton spin liquid,
Fracton spin ice
+ Fracton topological
insulator
+ Non-ergodic behavior
(MBL, Scar….)
+ Glassy dynamics
+ Quantum qubits for
information storage

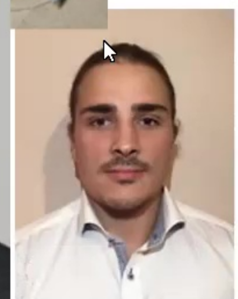
Thank You!

Zhen Bi (MIT)

Mike Pretko (Boulder)

VPS transitions Phys. Rev. Research **2**,013162

Hughes (UIUC)



Pollmann (TUM)

Bibo (TUM)

Emergent fracton at QCP,
arXiv:2008.01746