Review on Swampland
in condensed matter physics

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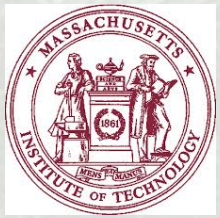
Thanks!
for the excellent
talk and slides



Xiao-Gang Wen (MIT)

Strings 2021, ICTP-SAIFR, São Paulo

A ~~The~~ Big Question in condensed matter

Which EFT can describe condensed matter system?

What Effective Field Theories (EFTs) ~~weakly coupled to Einstein gravity~~ can be UV completed in ~~quantum gravity?~~

- emergent gauge field
- emergent fermions
- emergent standard model
- emergent gravitons (?)

local qubit model (LQM) without any symm

UV completion

Gu, Wen arXiv:0907.1203

EFT valid up to Λ

(low energy description)

?

~~Quantum Gravity theory~~ valid at ~~M_p~~ 10eV

(higher energy description)

as a LQM

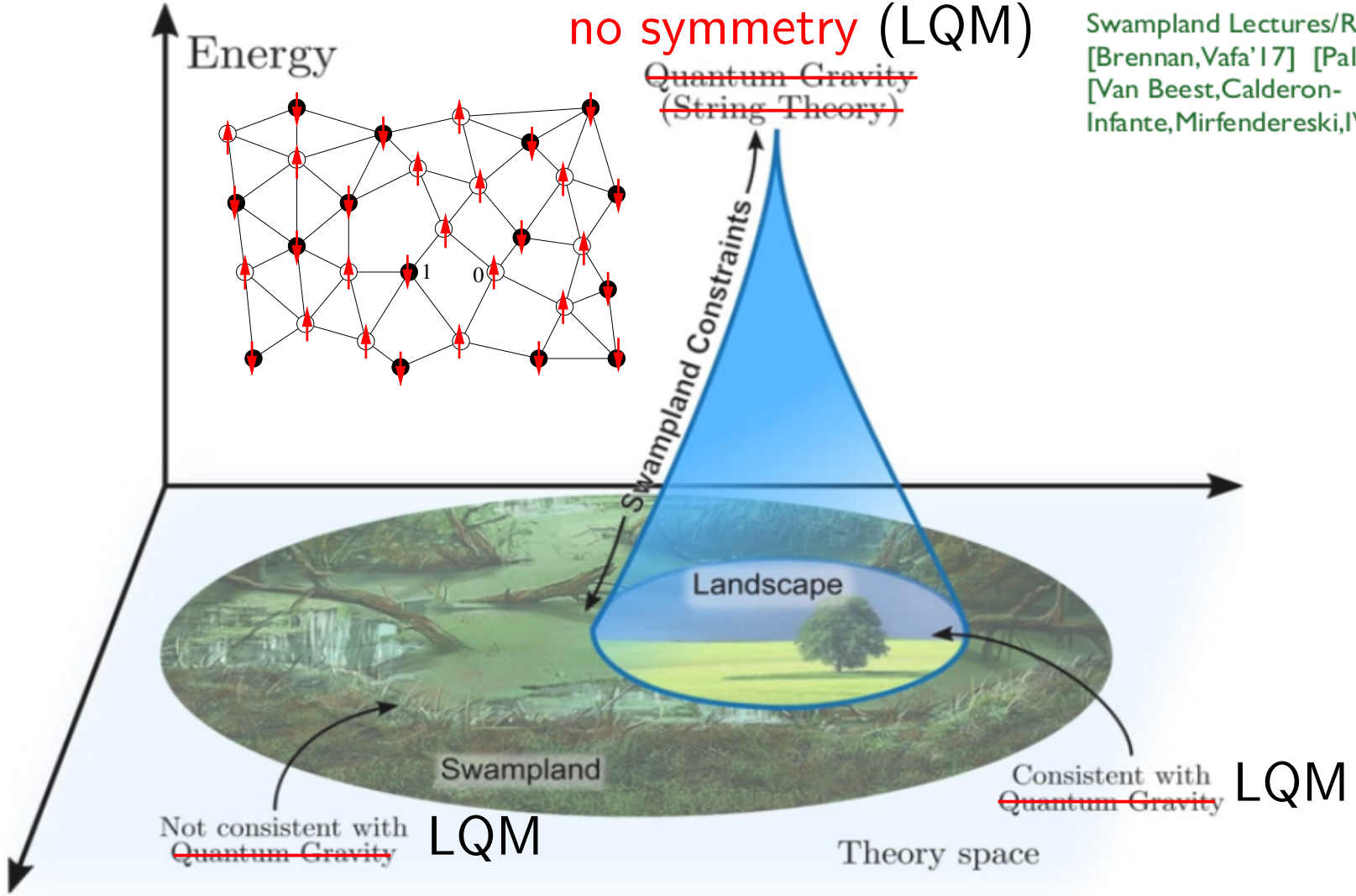
Not every EFT can be UV completed in ~~a Quantum Gravity theory~~

unless it satisfies additional constraints (beyond anomaly cancellation)

New phase of matter. If gapped liquid $\rightarrow$ **Topological order**

Local qubit model with
no symmetry (LQM)

Swampland Lectures/Reviews:
[Brennan,Vafa'17] [Palti'19]
[Van Beest,Calderon-Infante,Mirfendereski,IV'21]



Condensed-matter-physics (CMP)

Swampland: Apparently consistent (~~anomaly-free~~) EFTs that cannot be UV completed in ~~quantum gravity~~ LQM

[Vafa'05]

(they cannot arise as low energy limits of ~~string theory~~) LQM

Local qubit model with
no symmetry (LQM)

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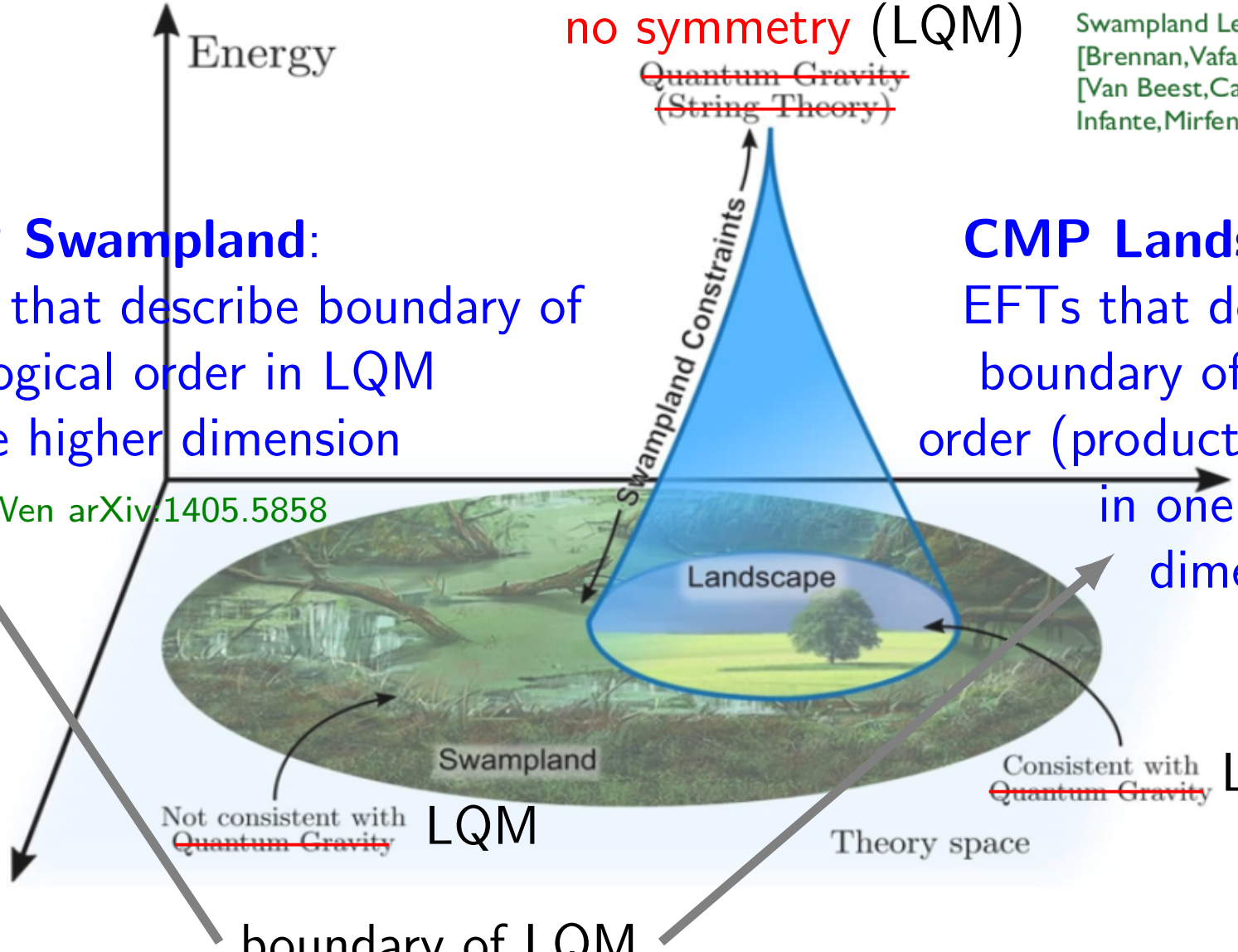


CMP Swampland:
EFTs that describe boundary of topological order in LQM in one higher dimension

Kong, Wen arXiv:1405.5858

CMP Landscape:
EFTs that describe boundary of trivial order (product state) in one higher dimension

LQM

LQM

boundary of LQM

Swampland: [Vafa'05]
Apparently consistent (anomaly-free) EFTs that cannot be UV completed in quantum gravity LQM
(they cannot arise as low energy limits of string theory) LQM

Goal of the Swampland program: in condensed matter

What are the constraints that a low energy EFT must satisfy to be consistent with ~~quantum gravity~~? LQM

What distinguishes the landscape from the swampland?

UV imprint of ~~quantum gravity~~ at low energies

LQM

in condensed matter

Proposals: **Swampland Conjectures**

EFTs in swampland are boundary of bulk gapped quantum liquids.

~~Motivated by String Theory as well as Black Hole physics~~

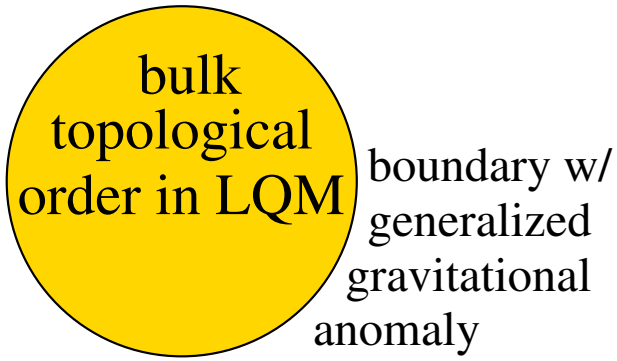
The bulk topological order in bulk quantum liquid is the obstruction for the EFT be consistent with LQM in the same dimension.

The bulk topological order of an EFT = generalized (gravitational) anomaly in the EFT

- The bulk topological order of an EFT is the additional constrains (beyond anomaly cancellation) for an EFT to be consistent with LQM in the same dimension.

  Wen arXiv:1303.1803
  Kong, Wen arXiv:1405.5858

  → **Generalized anomaly** in the EFT is the **bulk topological order** (the Drinfeld center in 1+1D) of an EFT



- Generalized gravitational and gauge anomalies are defined without spacetime manifold/bundle
- Usual anomaly = invertible bulk top. order
- Generalized anomaly includes non-invertible bulk topological order

- An EFT is consistent with LQM in the same dimension iff
- it is free of generalized anomaly **Anomaly-free condition:**
- it satisfies the **remote detectability principle**
- it is connected to the trivial phase through a domain wall

Remote detectability principle

~~Completeness Hypothesis~~

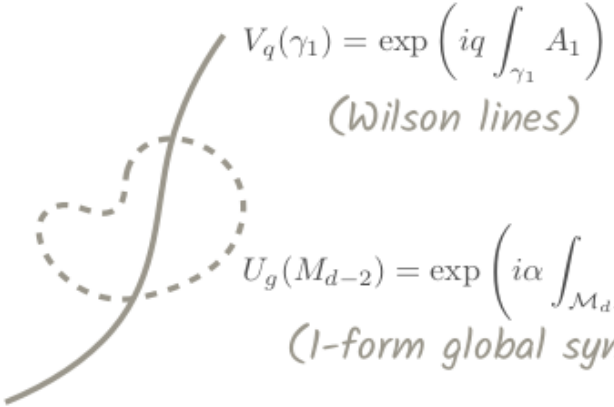
There are physical charged states in all representations of gauge group consistent with Dirac quantisation [Polchinski, Dirac…]

Does it follow from the absence of global symmetries?

No global symmetries = *No topological operators*

Complete spectrum = *All charged operators can end*

example: Maxwell theory



Example: Emergent gauge charge and gauge flux can fully detect each other via remote braiding, in order for the EFT to be consistent with LQM (*ie* to be free of the generalized anomaly).

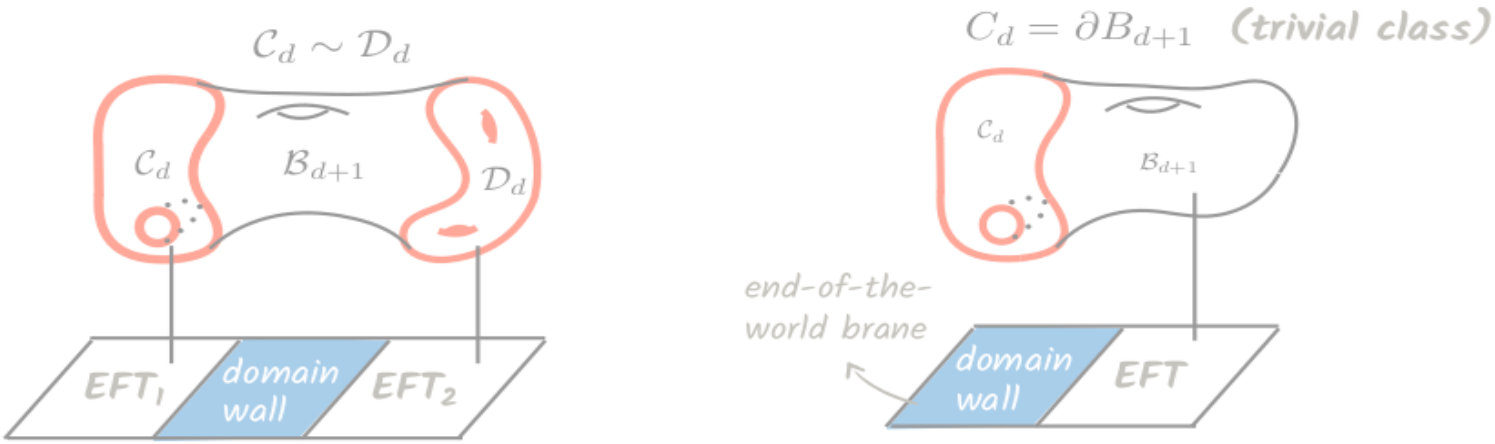
Cobordism conjecture

The cobordism group of a quantum gravity theory must be trivial:

$$\Omega_k^{QG} = 0 \quad \text{[McNamara,Vafa'19]}$$

k : internal dimension
D : total dimension

to avoid a (D-k-1)-form global symmetry with charges $[M] \in \Omega_k^{QG}$



All EFTs from LQM can connect to trivial phase by domain walls

It implies all theories of same dimension are connected by finite energy domain walls, and predicts the existence of new defects in string theory!

Unconnected EFTs must have different generalized anomalies (*ie* have different bulk topological orders)

No global symmetries ~~in q-gravity~~
in LQM without any symmetry

In EFT of LQM, Any global symmetry must be broken or gauged ~~in quantum gravity~~

[Banks-Dixon'88] [Horowitz,Strominger,...] [Susskind] [Banks,Seiberg'11]

New zoo of generalised global symmetries to explore! See Shao's review talk

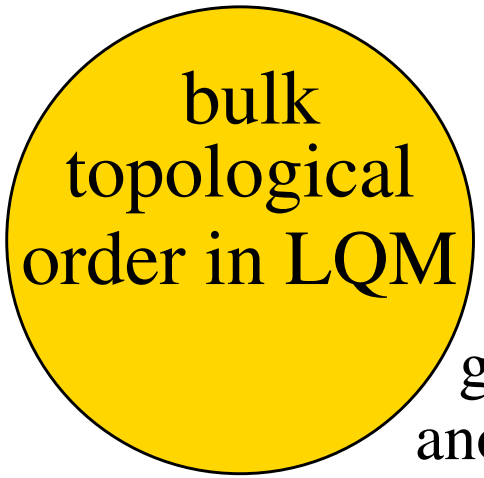
- All emergent symmetry come from the fusion rule of low energy top. excitations (can appear only if EFT describes a top. order)

- Point-like topological excitations $\rightarrow$ group symmetry.
- Extended topological excitations $\rightarrow$ higher-group symmetry.
- Splitting fusion rule $\rightarrow$ Algebraic higher symmetry beyond higher group, described by fusion higher category with fiber functor.

  Also see Casini's and McGreevy's talks Kong,Lan,Wen,Zhang,Zheng arXiv:2005.14178

- The standard **standard model** has $\mathbb{Z}_2$ global symmetry (the fermion number parity). There must be additional $\mathbb{Z}_2$ gauge field. to turn the $\mathbb{Z}_2$ into a gauge symmetry. Levin, Wen cond-mat/0302460

String theory		Condensed matter physics
Quantum gravity	=?=	Local qubit model with no symm (LQM)
EFTs of QG (landscape)	∼	EFTs of LQM (CMP landscape)
String swampland	∼	Boundary theory of top order of bulk LQM (CMP Swampland, EFTs w/ generalized anomaly)
Swampness	∼	**Generalized anomaly = Bulk top. order**
Cobordism conjecture		An EFT is from LQM (*ie* is anomaly-free) iff it has domain wall with trivial phase
Completeness Hypothesis		Remote detectability principle (generalized-anomaly-free condition)
No global symmetries		All low energy emergent symmetry of LQM must come from fusion rule of topological excitations in topological order



boundary w/ generalized gravitational anomaly

LQM

qubit unification