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Abelian LGT in 1D insights from MPS

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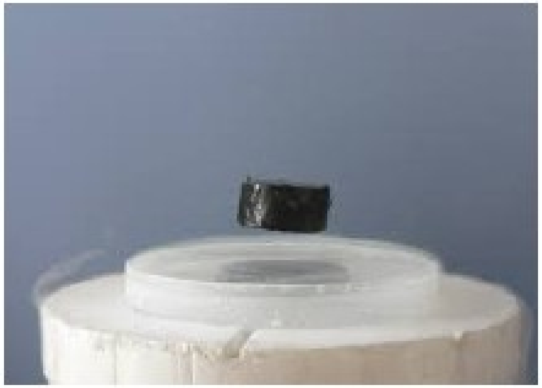
Two key aspects

Out of equilibrium

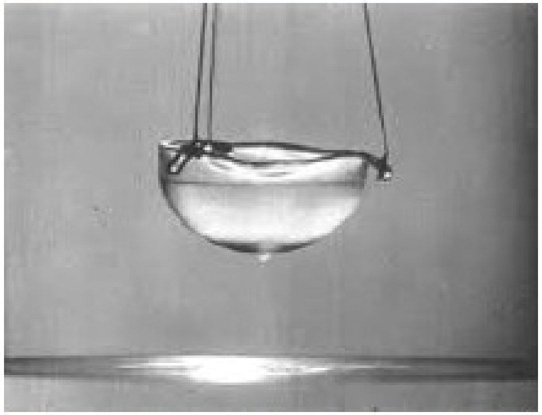
Universality

Exotic Emerging phenoma

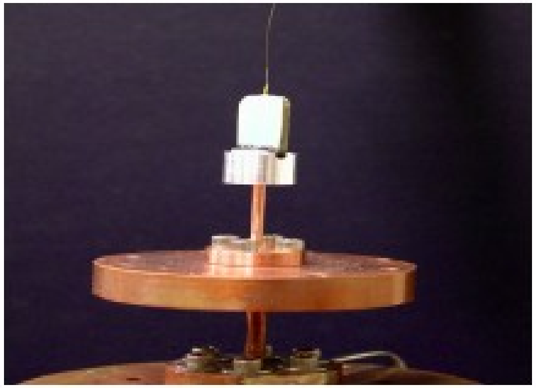
- Superconductor



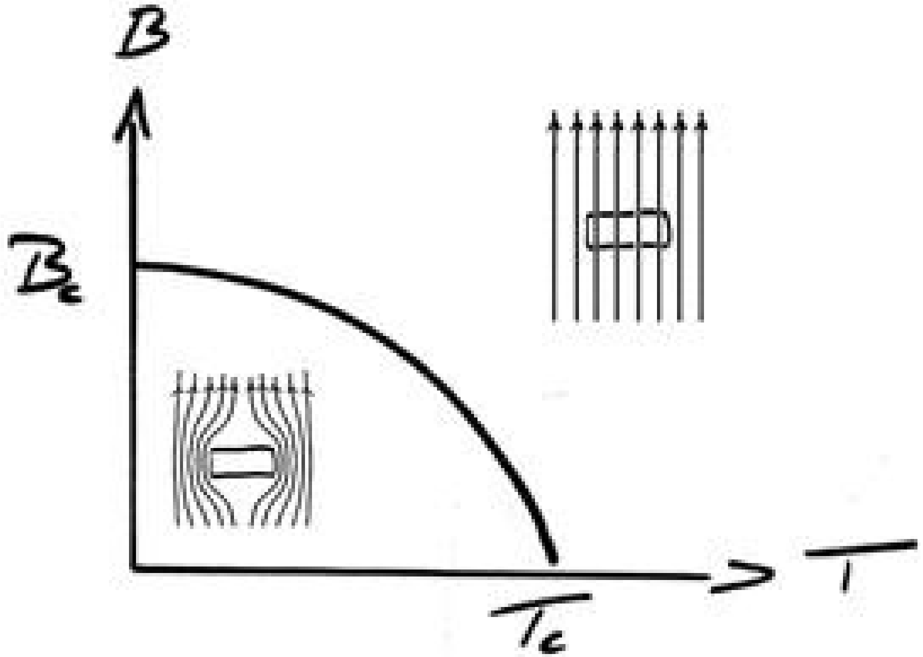
- Super-fluid



- Super-solid

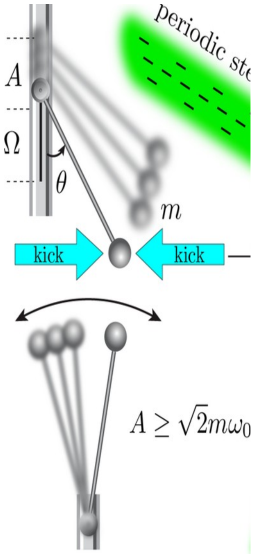


$$H = U - TS$$

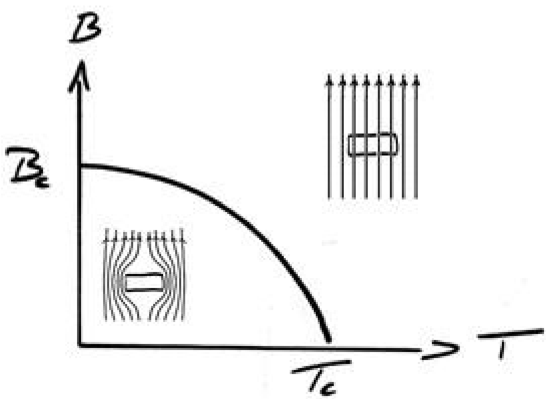


Classical
Kapitsa pendulum

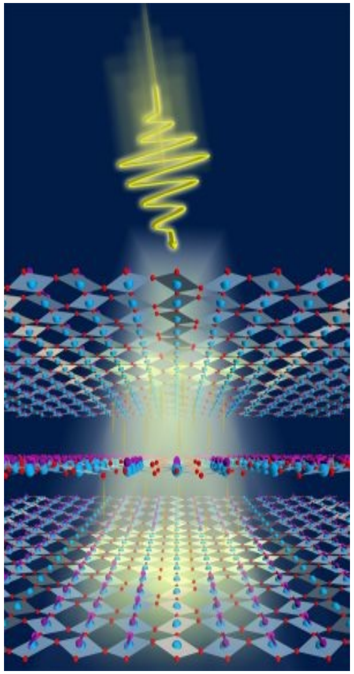
Bukov



Quantum light induced
superconductors



Cavallieri

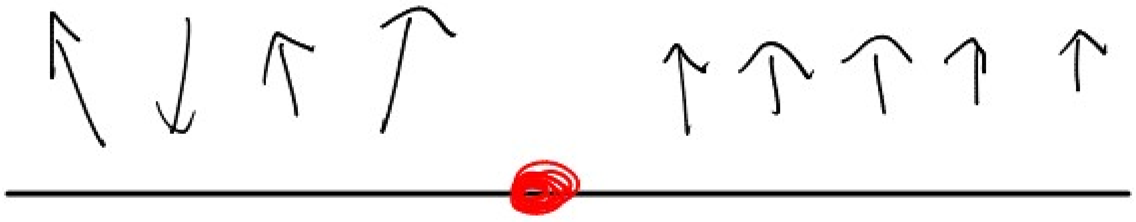


Few tuning knobs

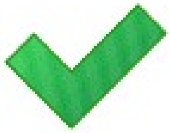
Power laws

Universality classes

Robustness



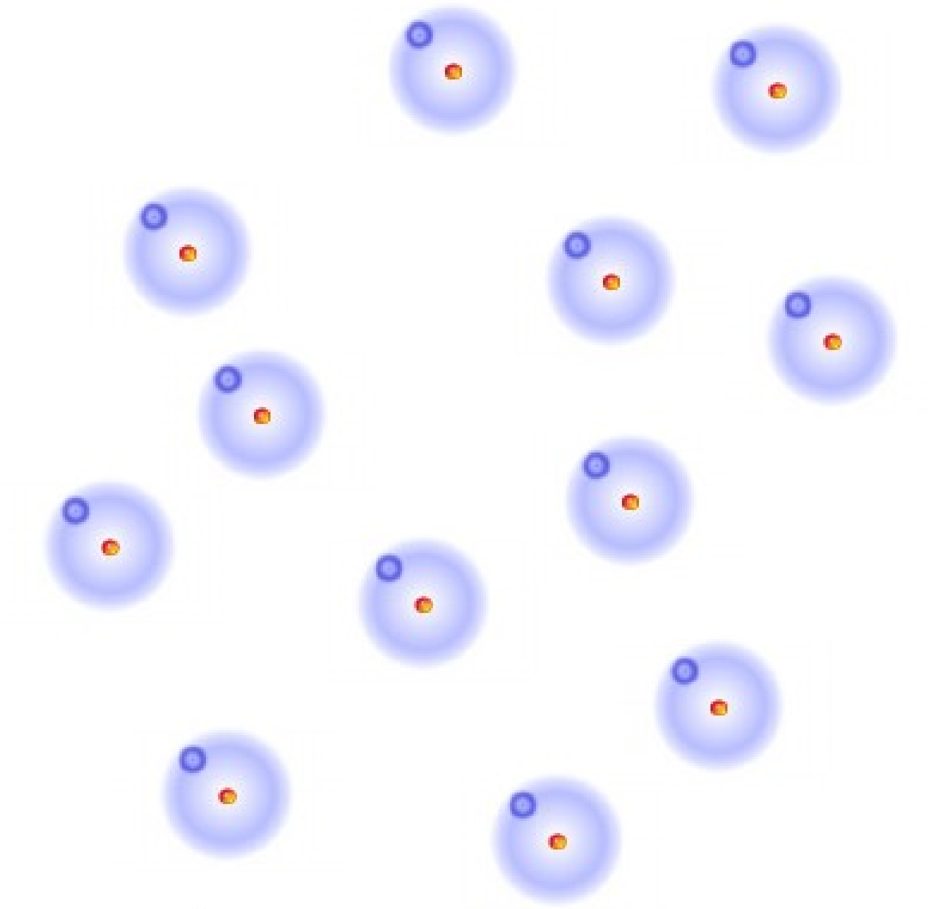
Many Body quantum systems

- Hamiltonian 

$$H = \sum_i H_i + \sum_{ij} V_{ij}$$

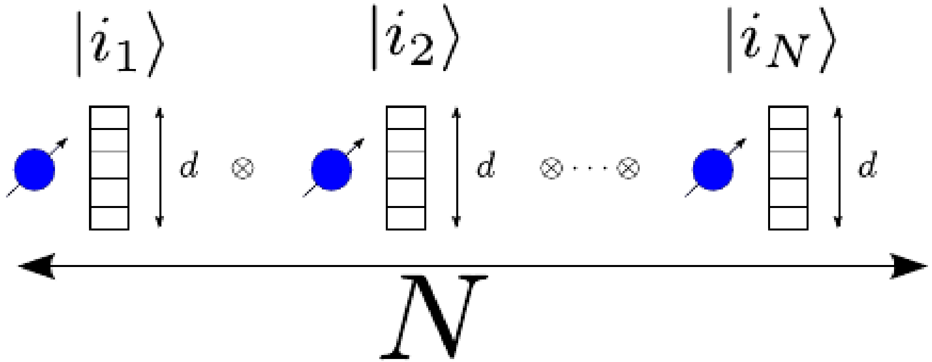
Quantum state is exponentially hard to represent 

$$|\psi\rangle = \sum_{\{\alpha\}} c^{\alpha_1 \alpha_2 \cdots \alpha_L} |\alpha_1 \alpha_2 \cdots \alpha_L\rangle$$



$$|\psi\rangle = \sum_{i_1 \cdots i_N} c^{i_1 \cdots i_N} |i_1 \cdots i_N\rangle$$

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \cdots \otimes \mathcal{H}_N$$



$$c^{i_1 \cdots i_N}$$

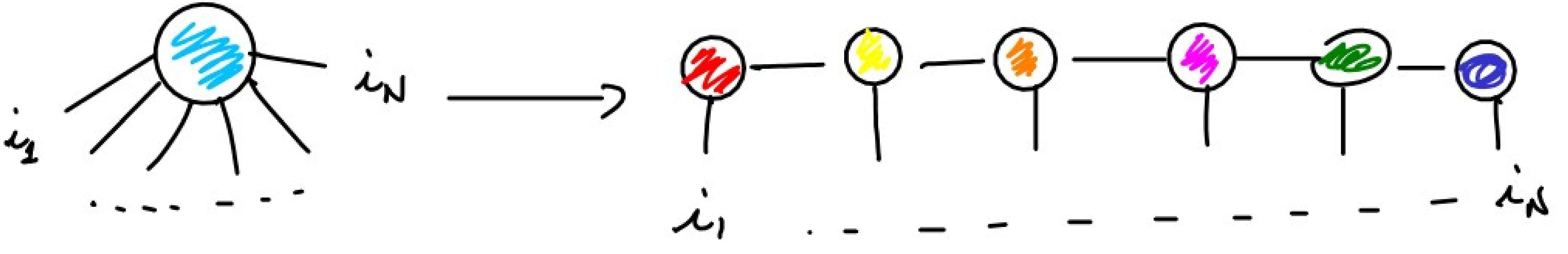
contains d^N parameters

- $2^2 = 4$
- $2^3 = 8$
- $2^4 = 16$
- $2^5 = 32$
- $2^6 = 64$
- ...
- $2^{40} = 1.0995116e+12$

- Express exponentially large tensors

$$C^{i_1 \cdots i_N}$$

- As contraction of small elementary tensors, example matrix product state



Bosonic gauge theories 1+1D

- Probably easier to get in cold atoms

2D Photons

$$S = \int d^2x \ -\frac{1}{2e^2}F_{01}F^{01} + A_\mu j^\mu$$

$$\partial_0 F^{01} = \partial_1 F^{01} = 0$$

$$A_0 = 0.$$

Only constant no wave

Adding Matter

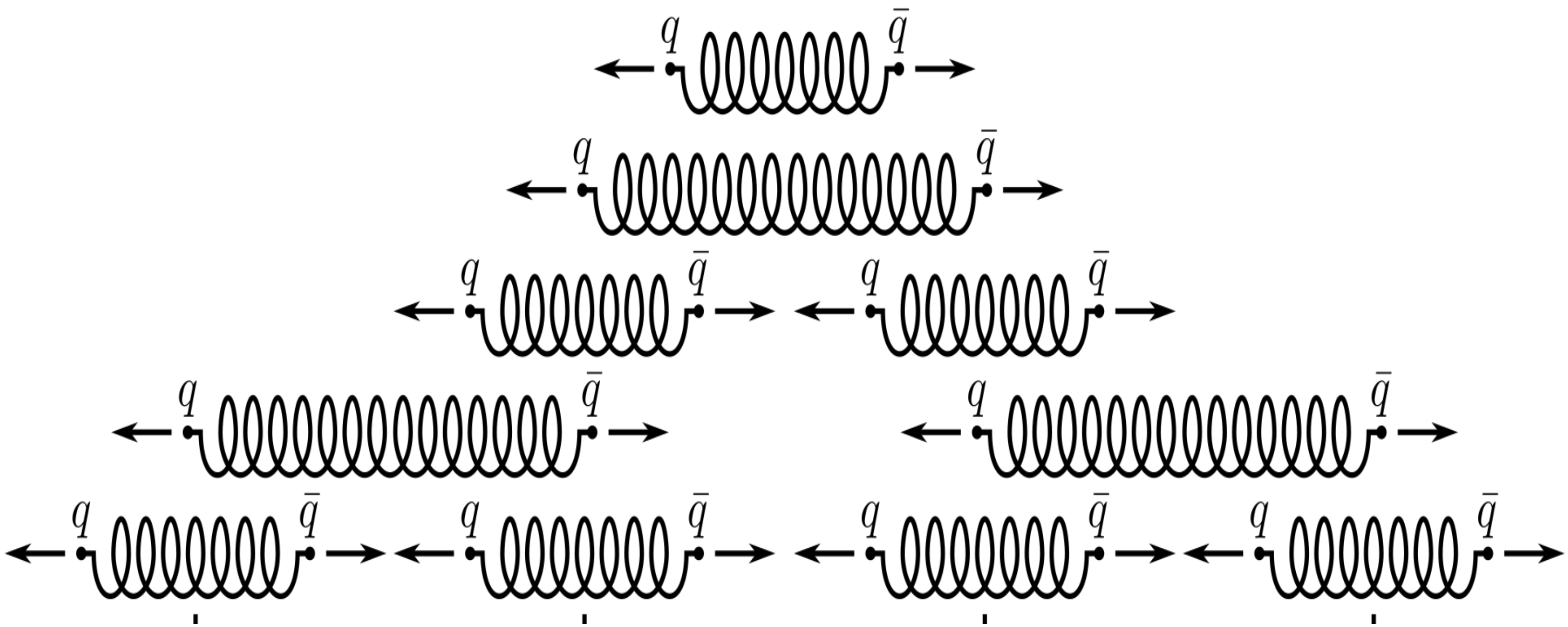
$$\frac{1}{e^2}\partial_1 F^{01} = q\delta(x) \quad \Rightarrow \quad F^{01} = qe^2\theta(x) + \mathcal{E}$$

$$H = \int dx \, \frac{1}{2e^2} F_{01}^2$$

$$\frac{1}{e^2}\partial_1 F^{01} = q\left[\delta(-L/2) - \delta(+L/2)\right] \quad \Rightarrow \quad F^{01} = \begin{cases} qe^2 & x \in (-L/2, +L/2) \\ 0 & \text{otherwise} \end{cases}$$

$$H = \frac{q^2 e^2}{2} L$$

String breaking



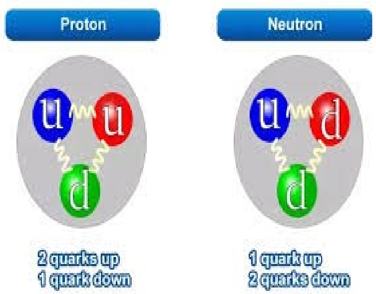
$$L \geq 4\frac{m^2}{e^2}$$

Wikipedia

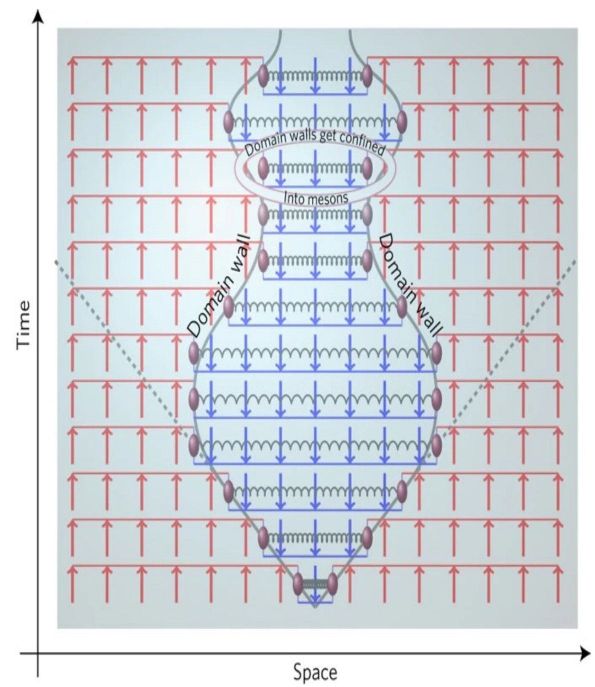
Evading thermalization through confinement

Basic idea

- Confined theories, are those in which excitations are bound to live close together



- If you create those excitations, they will stay close together for long times, they don't radiate, as a consequence of energy conservation.



- First check in a quantum quench @ SISSA

Real-time confinement following a quantum quench to a non-integrable model

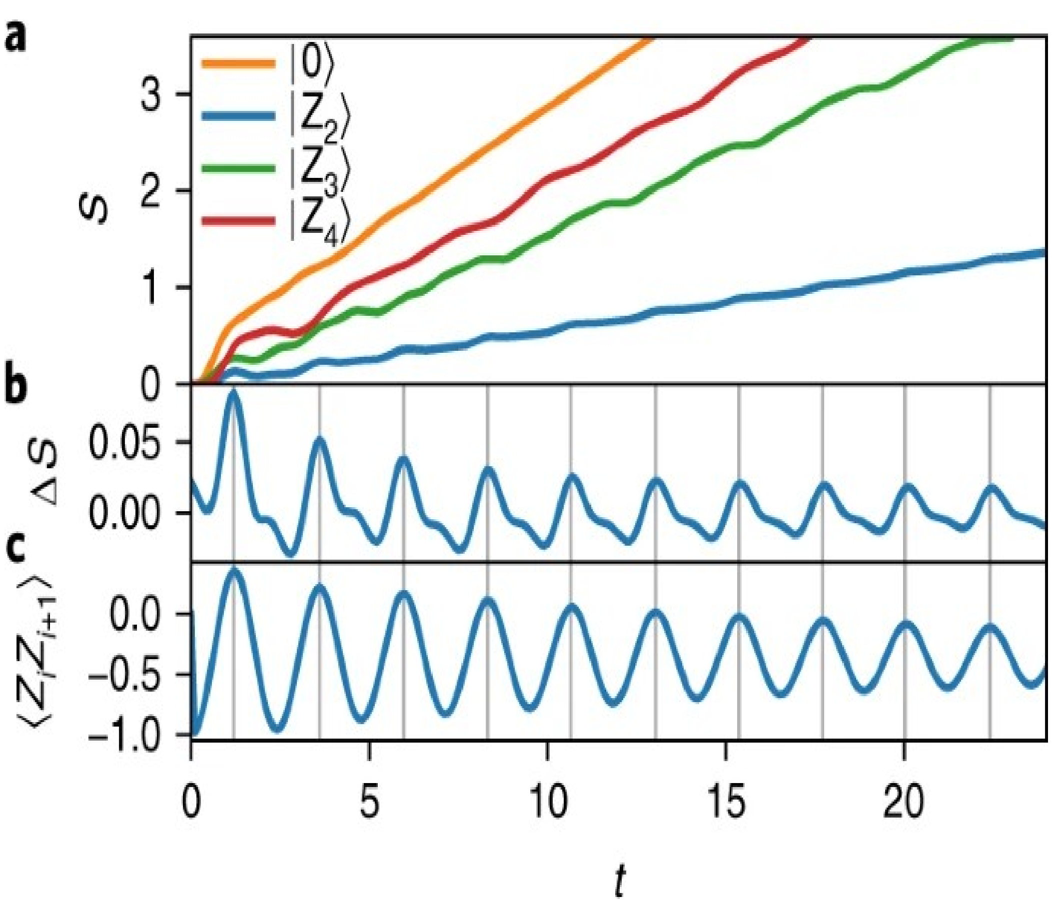
Marton Kormos, Mario Collura, Gabor Takács & Pasquale Calabrese

Nature Physics 13, 246–249(2017) | Cite this article

See also Robinson… Surace…

Quantum scars

Some initial states are different, generic states thermalize, but some don’t



Article | Published: 14 May 2018

Weak ergodicity breaking from quantum many-body scars

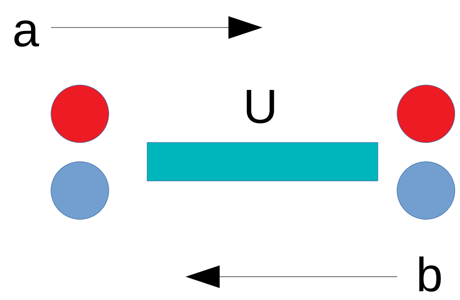
C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn & Z. Papić

Nature Physics **14**, 745–749(2018) | Cite this article

$$H = \sum_{i=1}^{L} P_i X_{i+1} P_{i+2}$$

$$|\mathbb{Z}_2\rangle = |\bullet \circ \bullet \circ \ldots\rangle, \ |\mathbb{Z}_2'\rangle = |\circ \bullet \circ \bullet \ldots\rangle$$

On the lattice, non interacting



$$x = 1/(a^2 q^2)$$

$$\hat{H} = \sum_j \hat{L}_j^2 + 2\left(x\left((m/q)^2 + 2x\right)\right)^{1/2} \sum_j \left(\hat{a}_j^\dagger \hat{a}_j + \hat{b}_j \hat{b}_j^\dagger\right)$$
$$- \frac{x^{3/2}}{\left((m/q)^2 + 2x\right)^{1/2}} \sum_j \left[\left(\hat{a}_{j+1}^\dagger + \hat{b}_{j+1}\right)\hat{U}_j\left(\hat{a}_j + \hat{b}_j^\dagger\right) + \text{h.c.}\right], \tag{1}$$

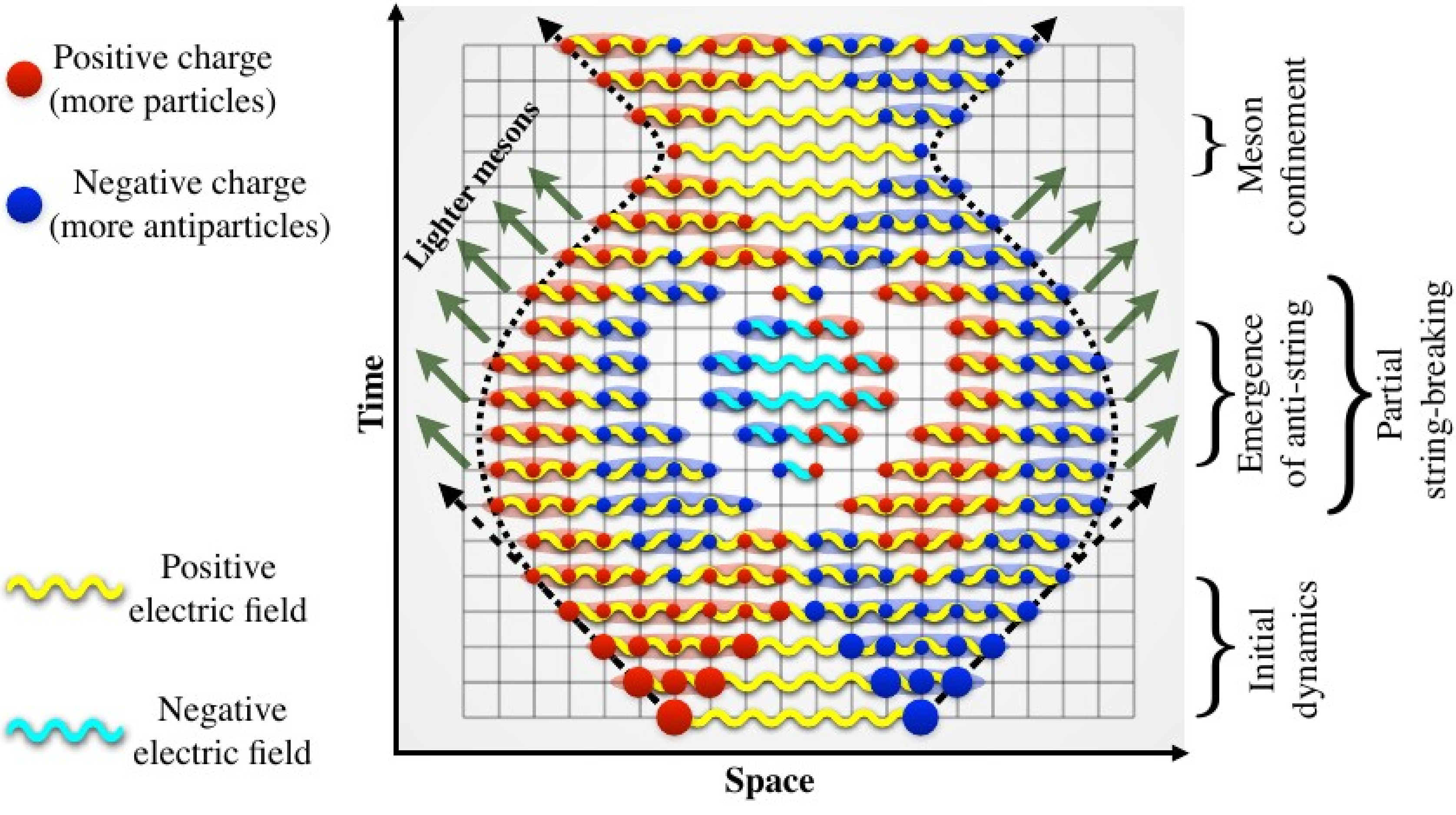
Quench protocol

- We obtain the ground state of H with MPS
- Act with the operator

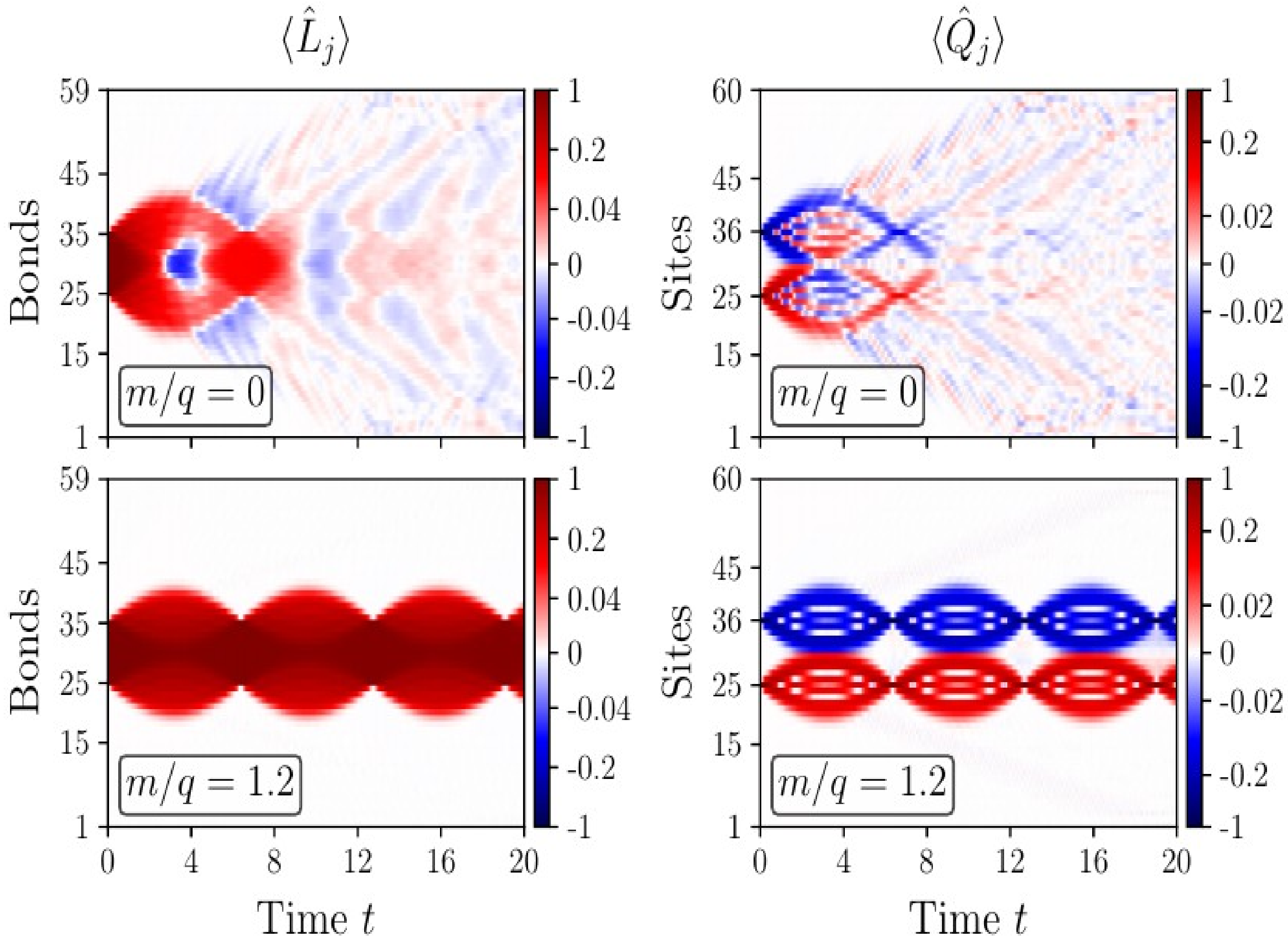
$$\hat{M}_R \equiv \left(\hat{a}^{\dagger}_{\frac{N}{2}-R} + \hat{b}_{\frac{N}{2}-R}\right)\left[\prod_{j=\frac{N}{2}-R}^{\frac{N}{2}+R} \hat{U}_j^{\dagger}\right]\left(\hat{a}_{\frac{N}{2}+R+1} + \hat{b}^{\dagger}_{\frac{N}{2}+R+1}\right) \tag{2}$$

^

Long lived finite energy states



Numerical results

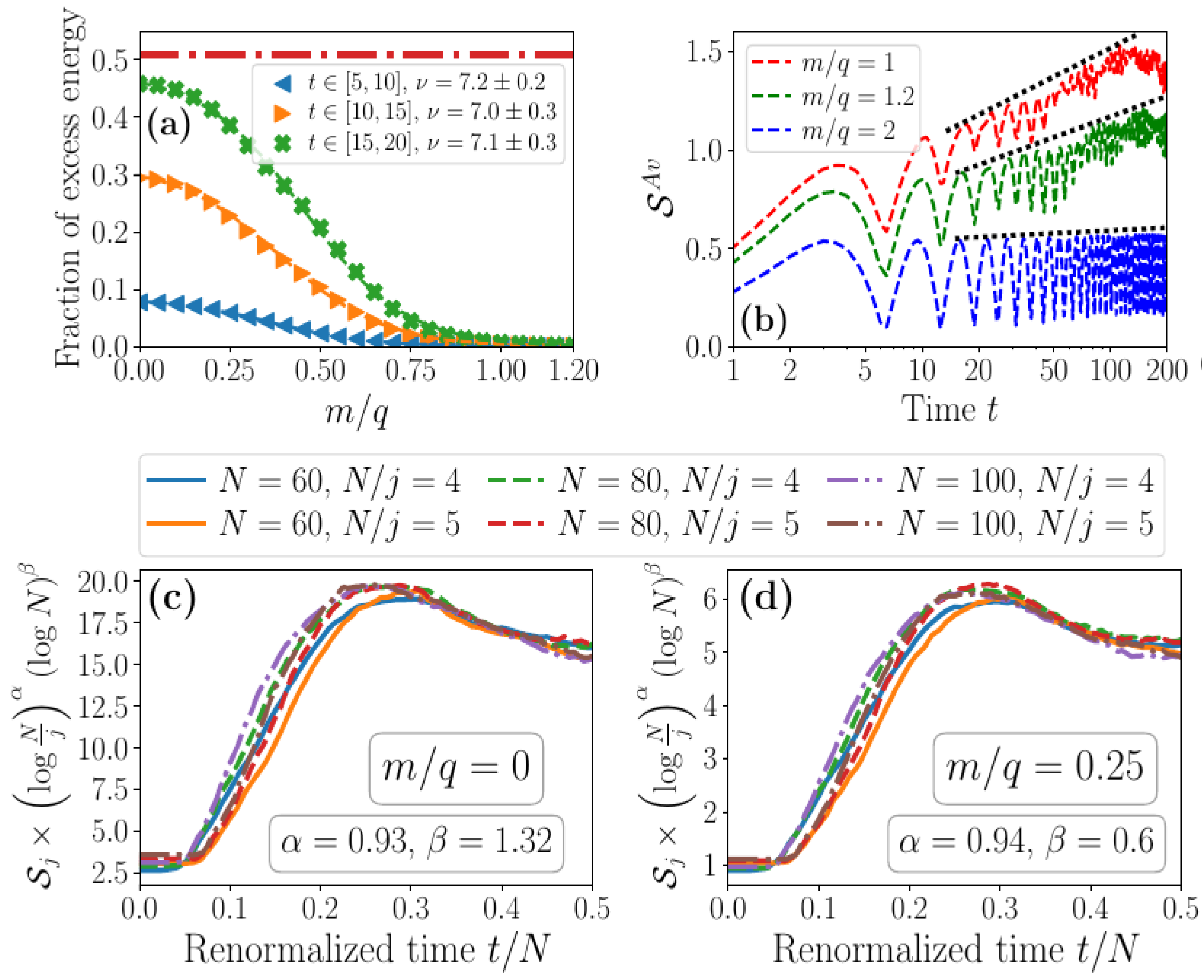


Thermal?

Non-thermal

Seen through entanglement

Entanglement entropy



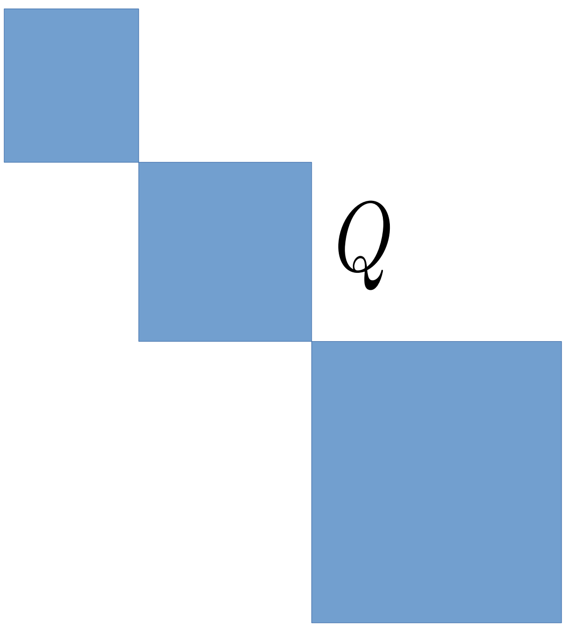
No linear increase, long lived oscillations

No volume law

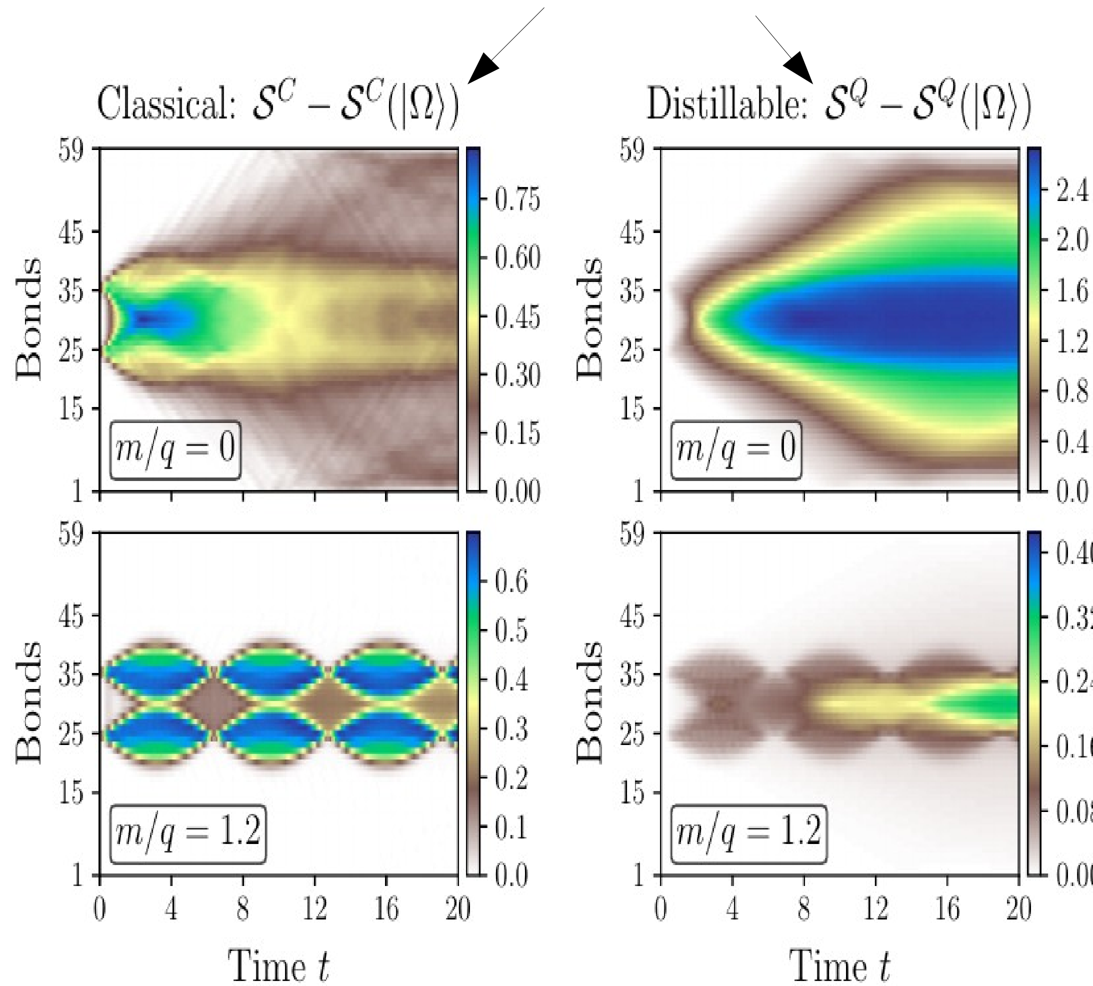
NON THERMAL !!!

Various entropy contributions

$$S(\rho) = -\sum_Q p_Q \ln p_Q + \sum_Q p_Q \mathcal{S}(\rho_Q)$$



$$\rho = \rho_1 \oplus \rho_2 \oplus \ldots$$



Summary 1

- Also in Abelian QED 2, despite the existence of string breaking, there are initial states that fail to thermalize.

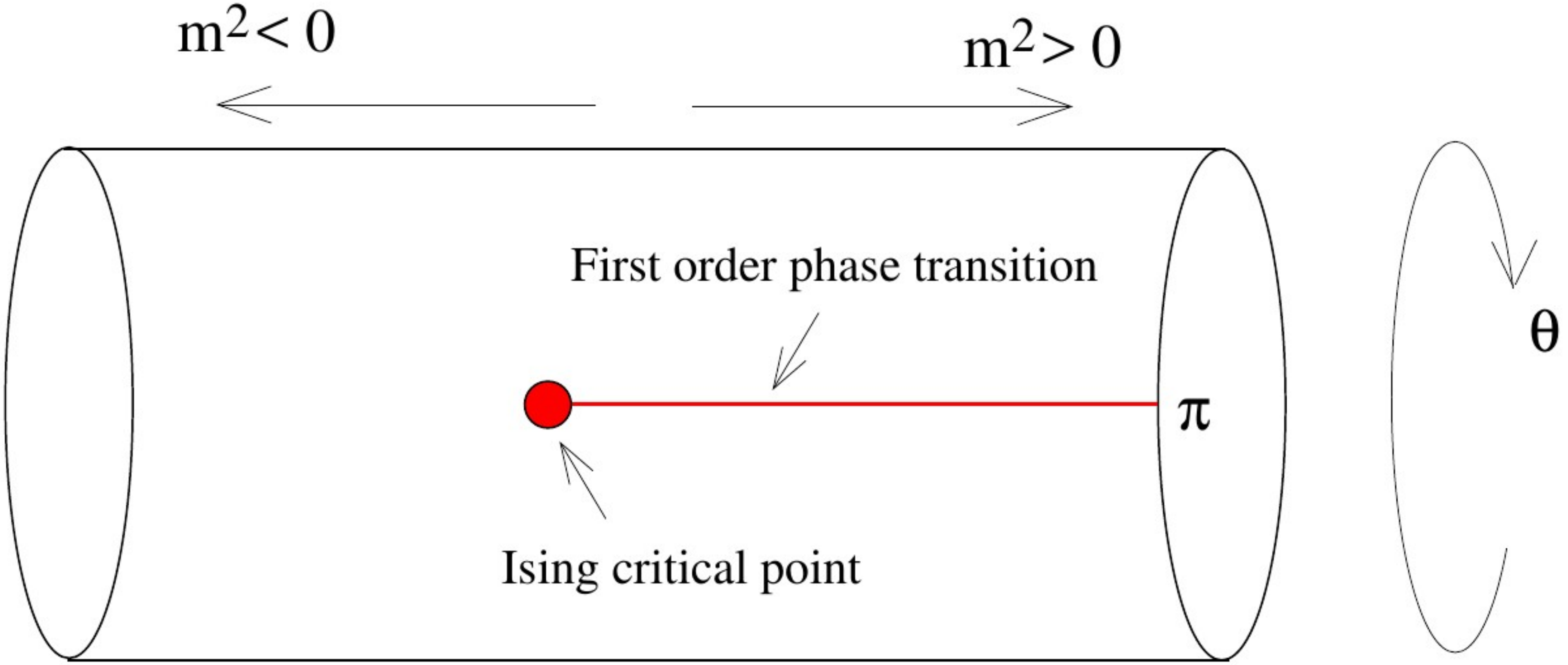
- A particle-antiparticle pair even when radiating into mesons leave behind strongly correlated non-thermal regions

New critical point, absent in the continuum

- Probably easier to get in cold atoms

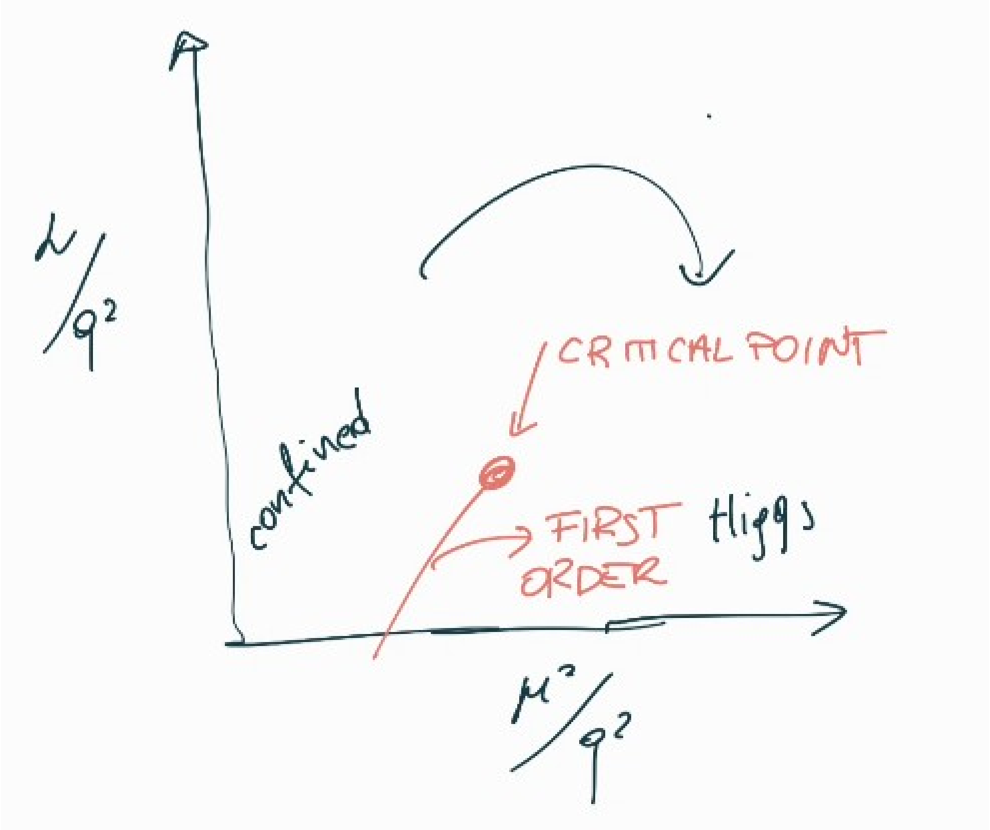
The full Abelian Higgs model

$$S = \int d^2x \; \frac{1}{2e^2} F_{01}^2 + \frac{\theta}{2\pi} F_{01} + |\mathcal{D}_\mu \phi|^2 - m^2|\phi|^2 - \frac{\lambda}{2}|\phi|^4$$

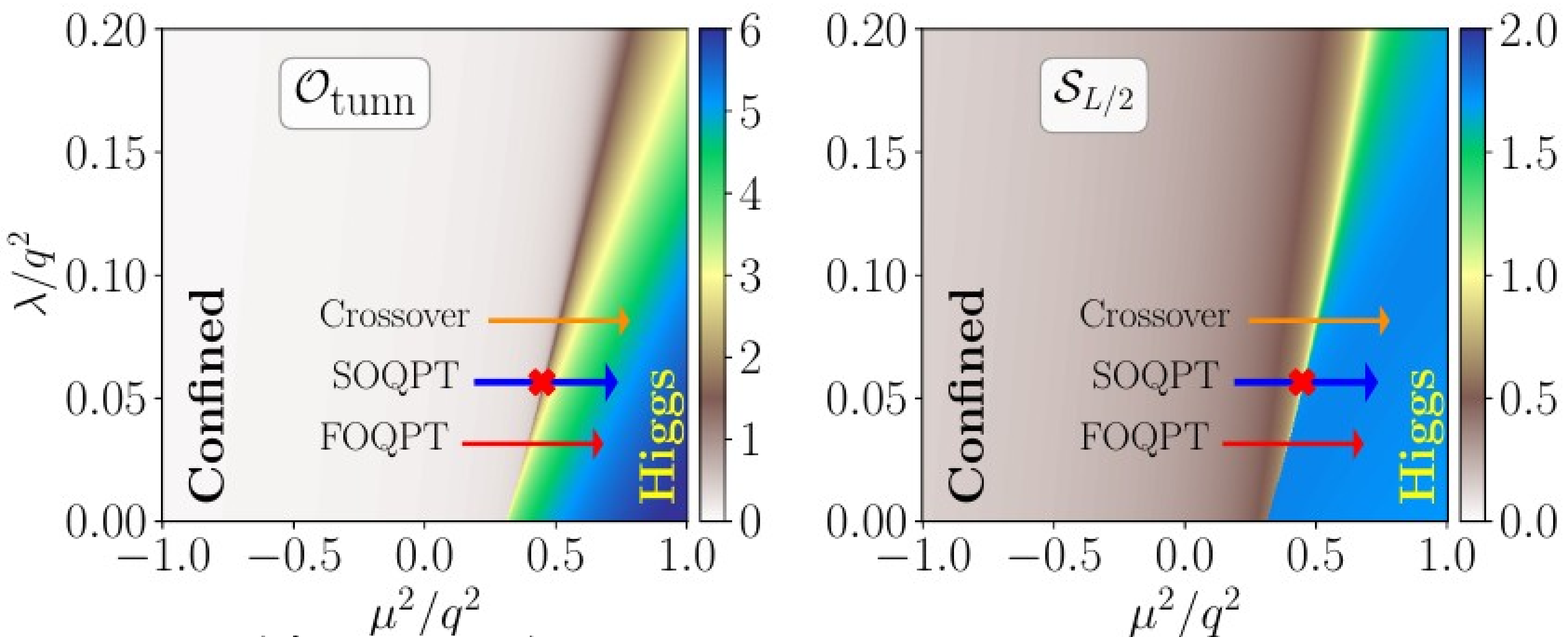


On the lattice

$$+\frac{\lambda}{q^2}(\hat{\phi}_j^\dagger)^2\hat{\phi}_j^2 \,. \qquad \theta = 0$$



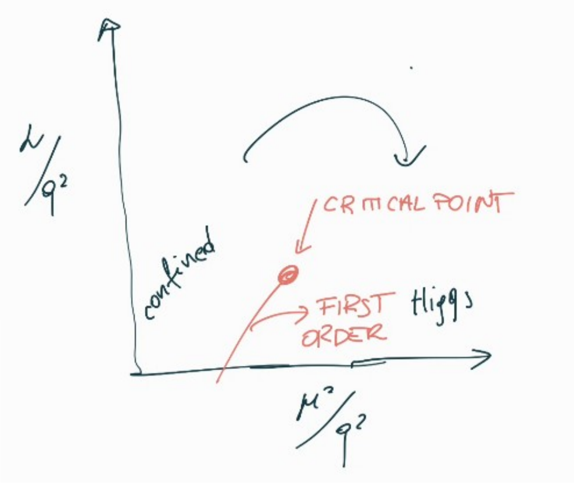
Unexpected phase diagram

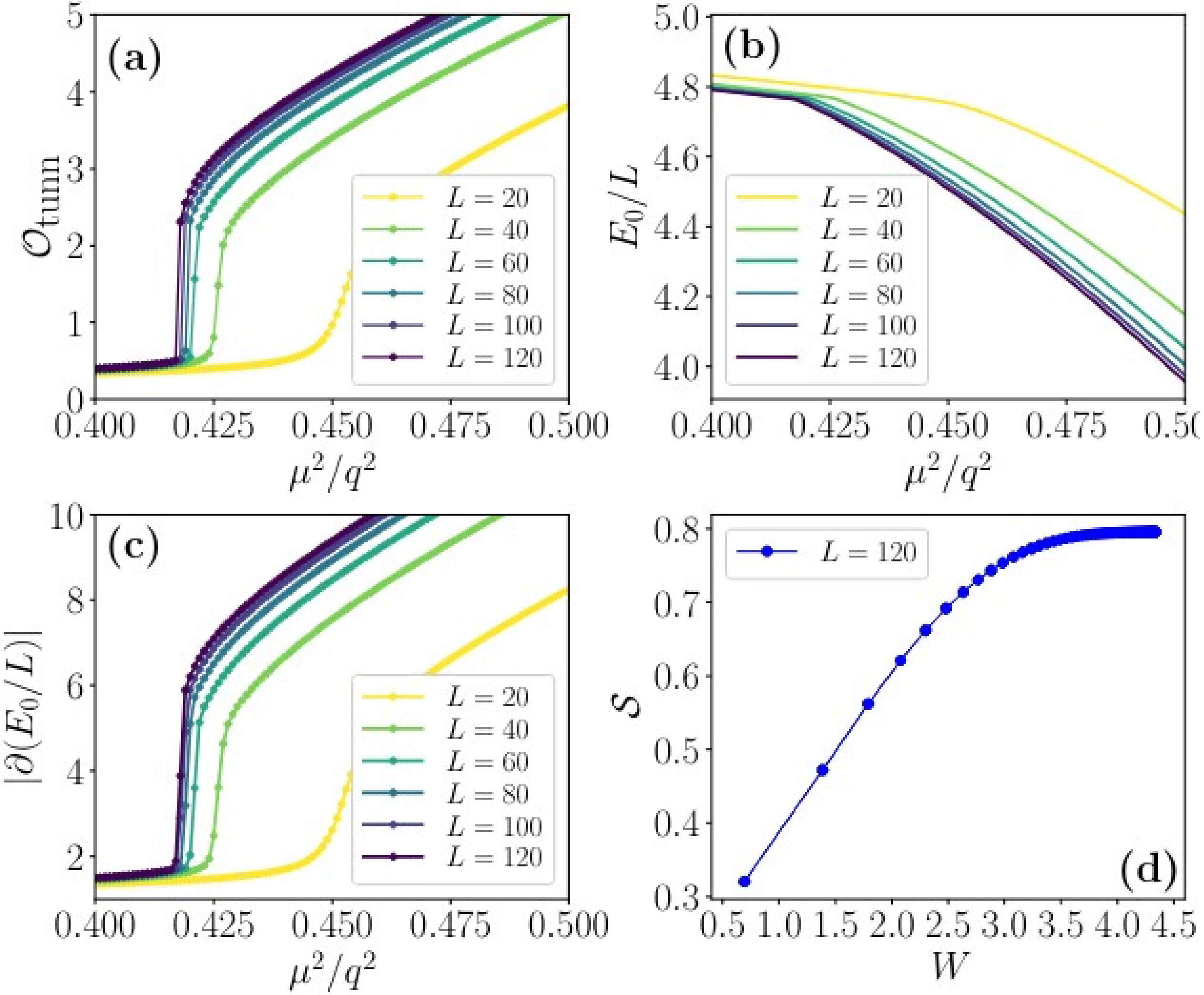


$$\frac{1}{2L}\sum_j \langle \hat{\phi}^\dagger_{j+1}\hat{U}_j\hat{\phi}_j + h.c.\rangle$$

$$\hat{\phi}_j = \frac{1}{\sqrt{2}}\left(\hat{a}_j + \hat{b}_j^\dagger\right),\ \hat{\Pi}_j = \frac{i}{\sqrt{2}}\left(\hat{a}_j^\dagger - \hat{b}_j\right),$$

First order line



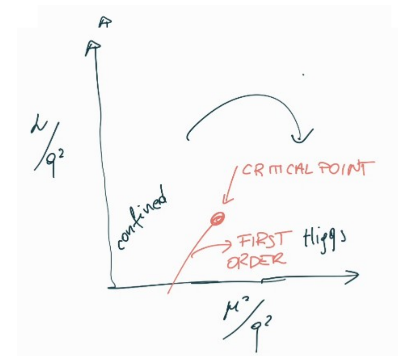


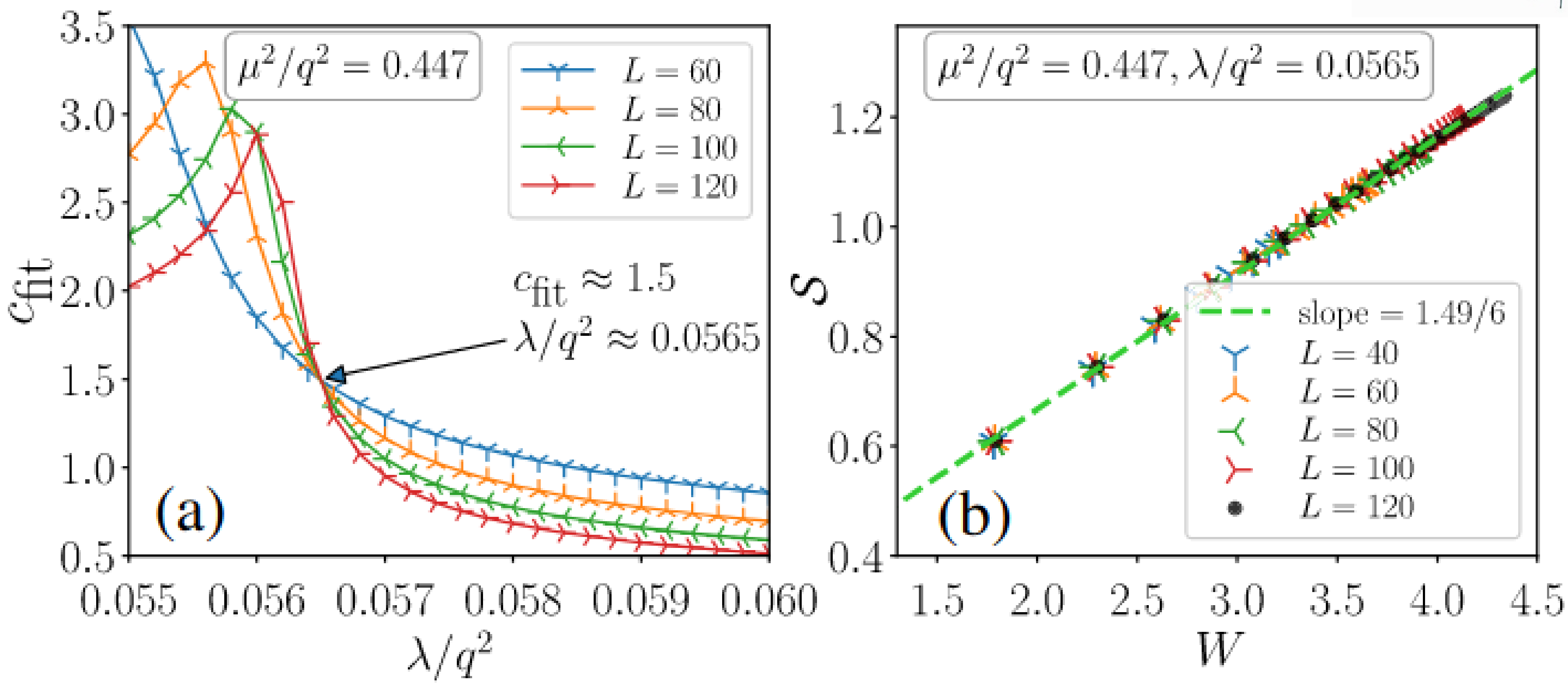
Locating the critical point

$$\mathcal{S}(l, L) = \frac{c}{6} W + b',$$

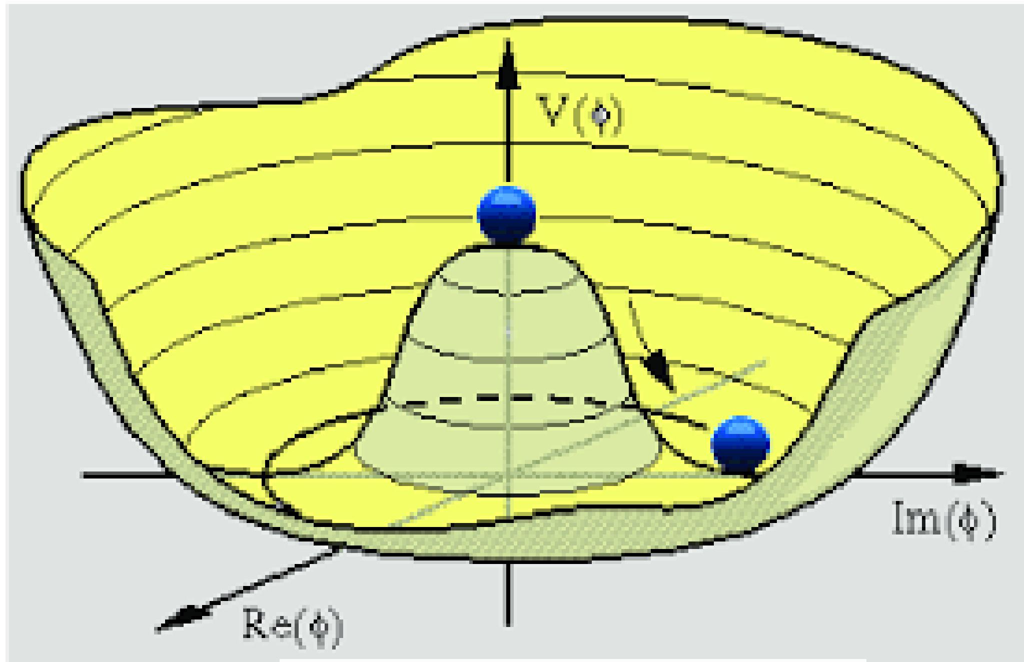
$$W(l, L) = \ln\left[(2L/\pi)\sin(\pi l/L)\right]$$

Calabrese Cardy, Rico ….





The Higgs mechanism



$$\phi = (v+h)\, e^{i \frac{\alpha}{v}}$$

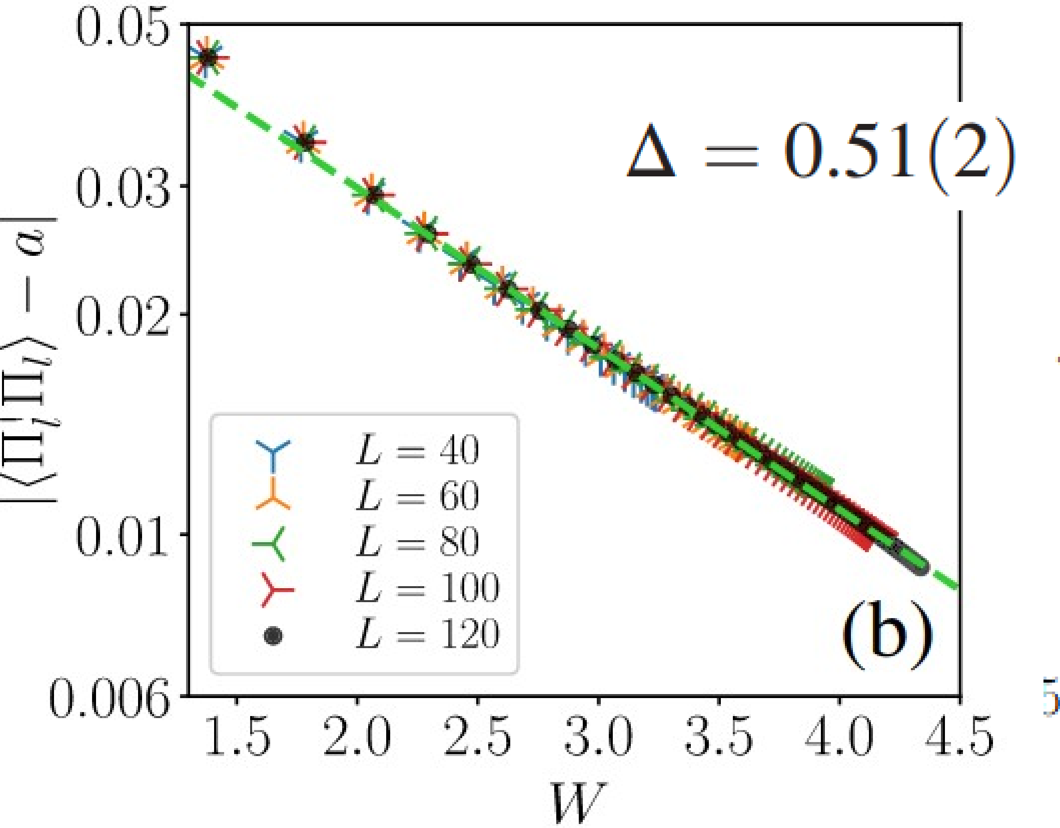
$$\frac{1}{2} \otimes 1$$

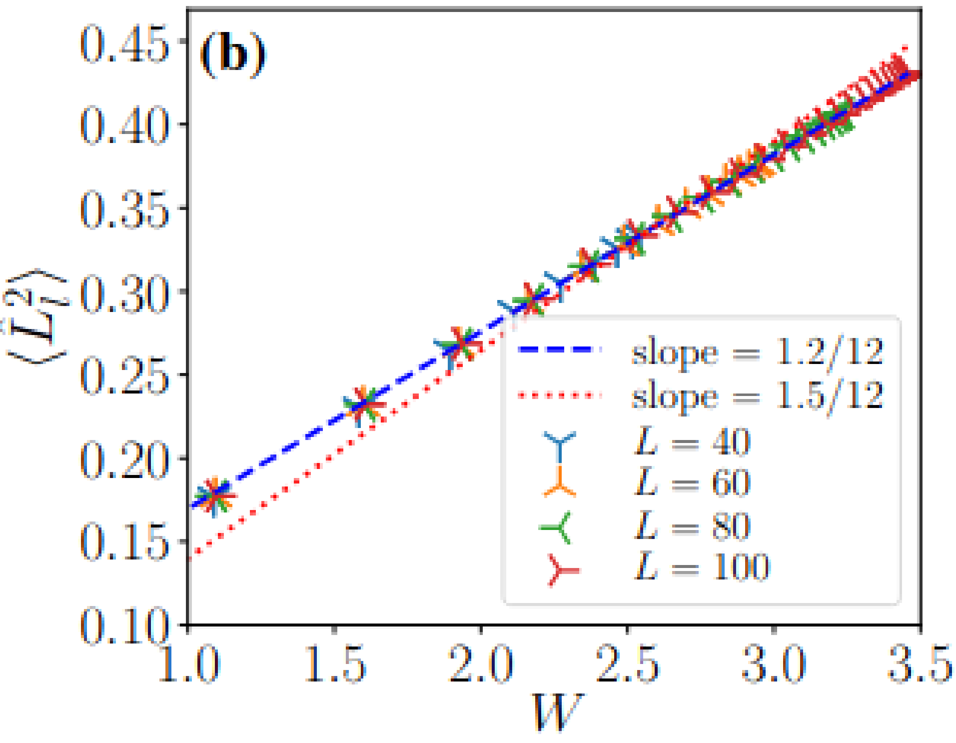
C= ½ free fermion (radial mode softening)
C= 1 free boson Higgs mode + photon

Operators

$$\langle \hat{\Pi}_l^\dagger \hat{\Pi}_l \rangle \simeq a + b[\exp(W)]^{-\Delta},$$

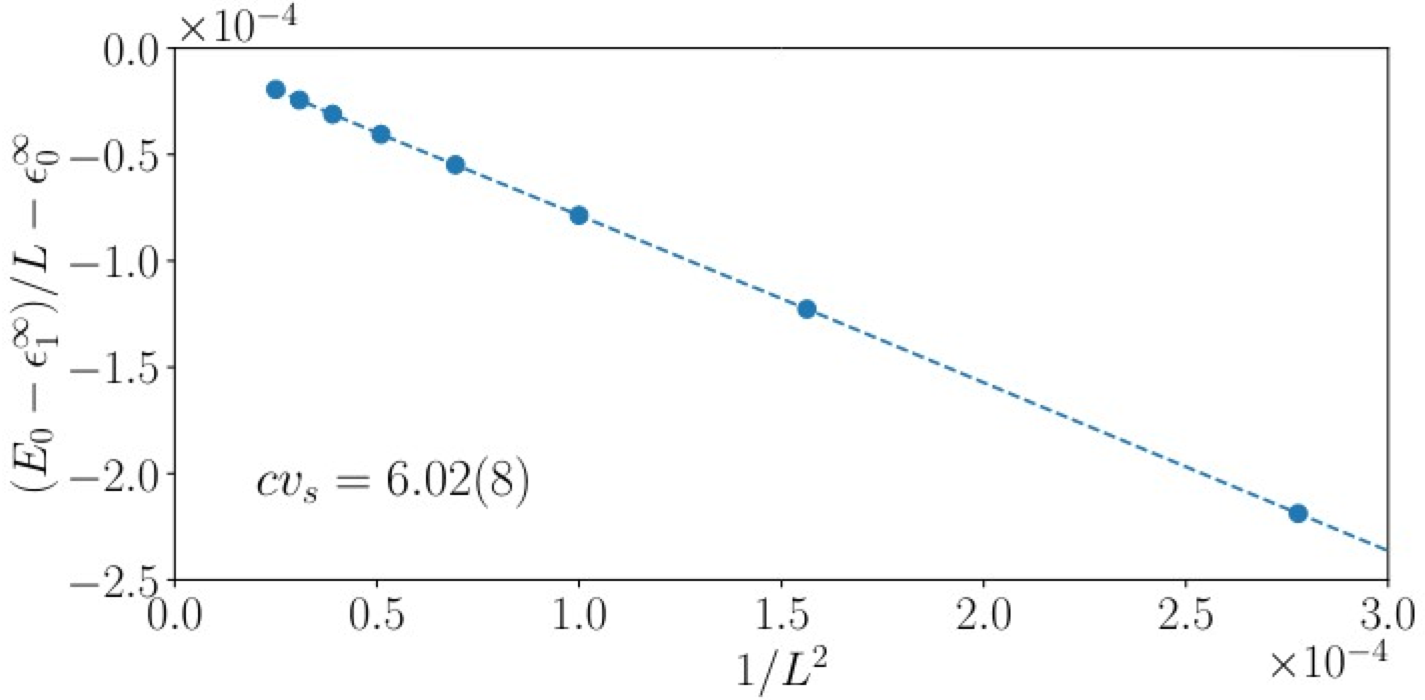
$$\langle L^2 \rangle \propto W$$





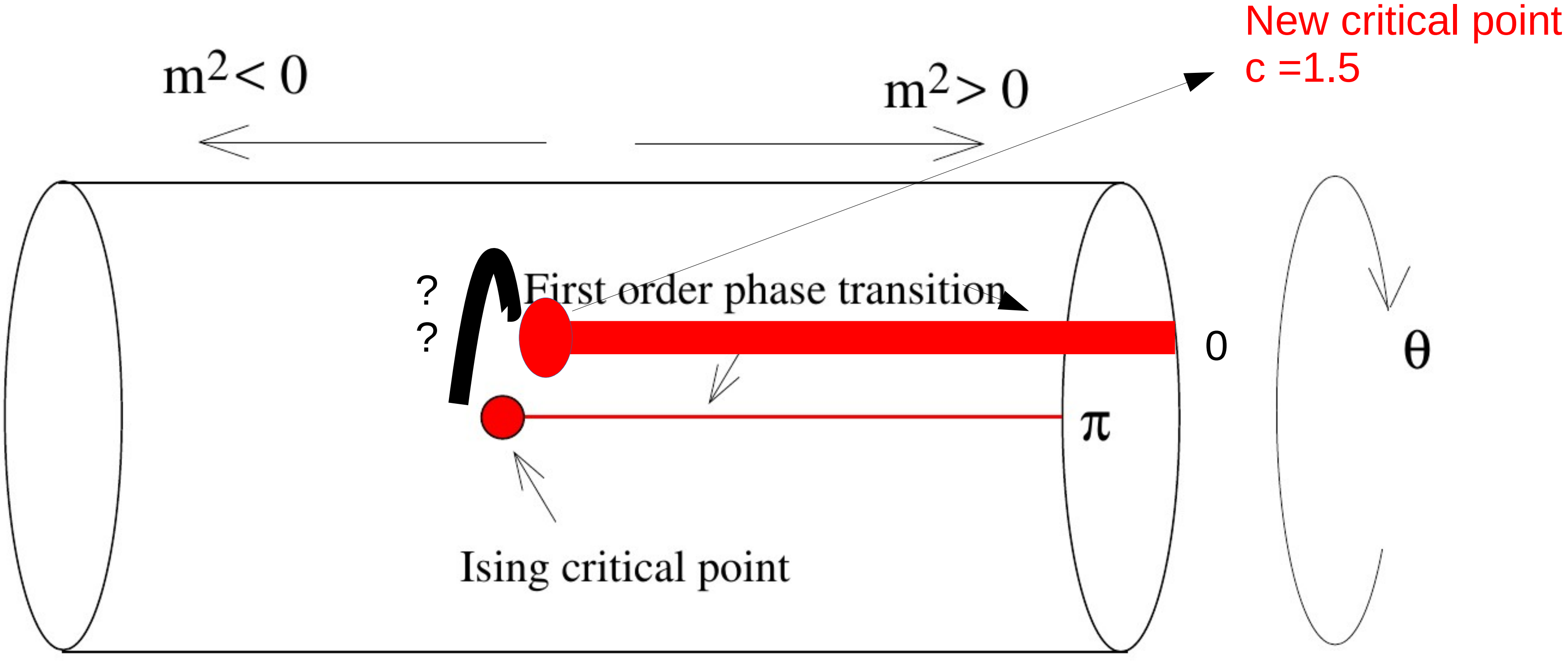
Sound velocity

$$E_0(L) = \epsilon_0^\infty L + \epsilon_1^\infty - \frac{\pi c v_s}{24L},$$



Summary 2

- The lattice version of the Abelian Higgs model 2 has another line of transition



We are hiring, 2 years post-doc available, get in touch: luca.tagliacozzo@iff.csic.es

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