# Effective theories for deformable superconductors via Holography

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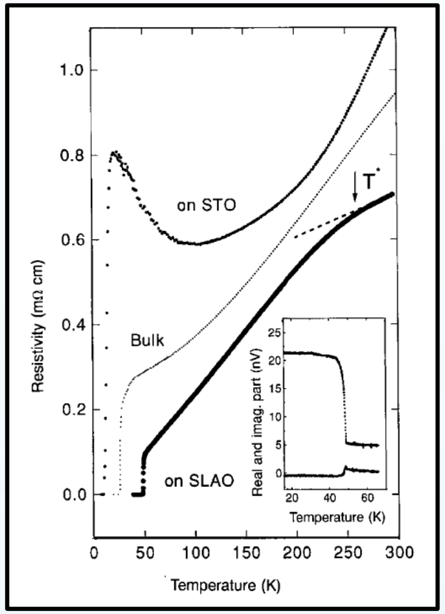
## Outline

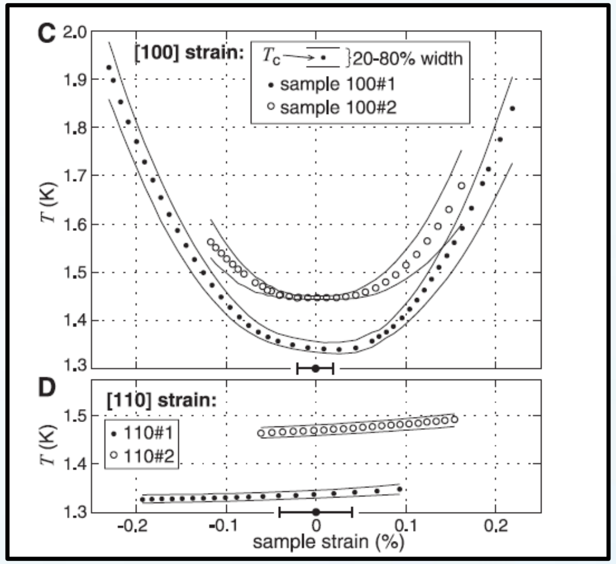
- Introduction / Motivation
- Guidelines to build EFTs w/ Holography
- Construction of the model and (some) results
- Conclusions and prospective developments

# Introduction / Motivation

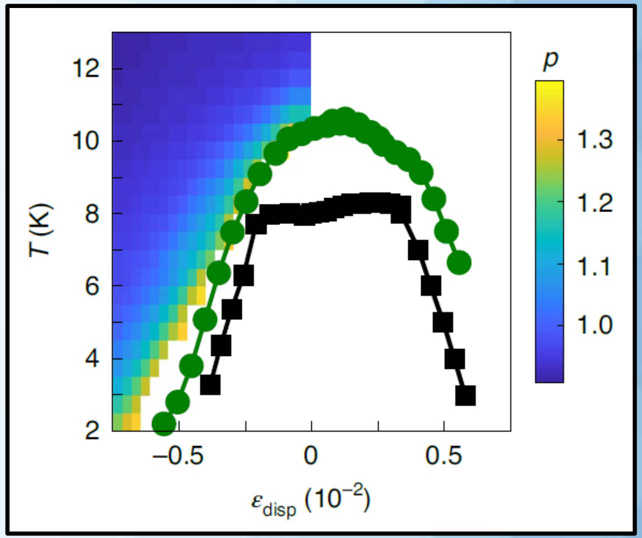
- Experimental studies suggest a rich interplay between strain deformations and SC




Locquet *et al.* (1998) [LSCO]




Hicks *et al.* (2014) [$Sr_2RuO_4$]




Malinowski *et al.* (2020) [$Ba(Fe_{1-x}Co_x)_2As_2$]

- Holography provides an effective description for SC (Hartnoll *et al.*, 2008)

***⇒ Can we make it strain-sensitive? What behaviour does it show?***

## Basics of Holography

- Holography is a conjectured duality:

| (*d+1*)-dimensional theory of gravity | $\Leftrightarrow$ | *d*-dimensional QFT |
|---|---|---|
| ○ $g_{AB}$ is a dynamical degree of freedom | | ○ $g_{\mu\nu}$ is fixed (usually to $\eta_{\mu\nu}$) |
| ○ lives in $\mathcal{M}$ | | ○ lives in $\partial\mathcal{M}$ |

- Two ways to employ it:
  - Top-down (*strong conjecture*): action is known on both sides
  - Bottom-up (*weak conjecture*): only one side is solvable

## Basics of Holography

- In a QFT, compute a partition function as a function of sources:

$$\mathcal{Z}_{QFT}[J] \quad \Longrightarrow \quad \langle \mathcal{O}(x_1)...\mathcal{O}(x_n)\rangle = \frac{\delta^n \log \mathcal{Z}}{\delta J(x_1)...\delta J(x_n)}$$

- The idea is to breath life into the sources of the theory…

$$J(x) \longrightarrow \phi_G(x,u) \text{ with suitable BCs}$$

- …and to make the following identification (GPKW formula, 1998):

$$\mathcal{Z}_{QFT}[J] = \mathcal{Z}_{QG}[\phi_G : \text{"}\phi_G \to J\text{" on } \partial\mathcal{M}]$$

## Basics of Holography

$$\mathcal{Z}_{QFT}[J] = \mathcal{Z}_{QG}[\phi_G : "\phi_G \to J" \text{ on } \partial\mathcal{M}]$$

- We will focus on the limit where: QG → GR $\mathcal{Z}_{QFT}[J] \simeq e^{iS_{\text{on-shell}}[\phi_G]}\Big|_{"\phi_G \to J"}$
  - The corresponding QFT is strongly coupled, with no quasiparticle excitation
  - However, fundamental degrees of freedom are unknown

⇒ ***We still can write an Effective Field Theory!***

## Writing a holographic EFT down

- Symmetries specify which operators are surely present in the QFT:
  - Noether's theorem → conserved currents
  - Goldstone's theorem → order parameters
- We need to select suitable corresponding fields for the GR side

***⇒ Strategy: write down an action, solve EOMs, retrieve VEVs****

*Regularizing the action of the theory reveals that each dual gravitational field contains info about both source and VEV of the corresponding QFT operator

## EFT for superconductivity: operators

- A U(1) global symmetry… ⇒ add a U(1) gauge field $A_A(x,u)$
- …spontaneously breaks down ⇒ add a charged complex scalar (s-wave) $\psi(x,u)$
- Translational symmetry is spontaneously broken ⇒ add a set of real scalars $\phi^I(x,u),\ I \in \{x_1, ..., x_{d-1}\}$
- The QFT lives in flat space ⇒ add a (negative) cosmological constant $\Lambda$

# EFT for superconductivity: action

- The simplest dual action (for a (2+1)-dimensional QFT) we can write:

$$\mathcal{S}_{grav} = \int d^4x\sqrt{-g}\left\{\frac{1}{2\kappa^2}\left(R - 2\Lambda - 2m^2 X^N\right) - \frac{1}{4e^2}F_{AB}F^{AB} - (D_A\psi)^*(D^A\psi) - M^2|\psi|^2\right\}$$

QFT is (2+1)-dimensional

Theory of gravity with flat boundary

Breaking translations

$$X = \sum_{i\in\{x,y\}} \frac{1}{2} g^{AB}\left(\partial_A\phi^I\partial_B\phi^I\right), \; N > \frac{5}{2}$$

Conserved current

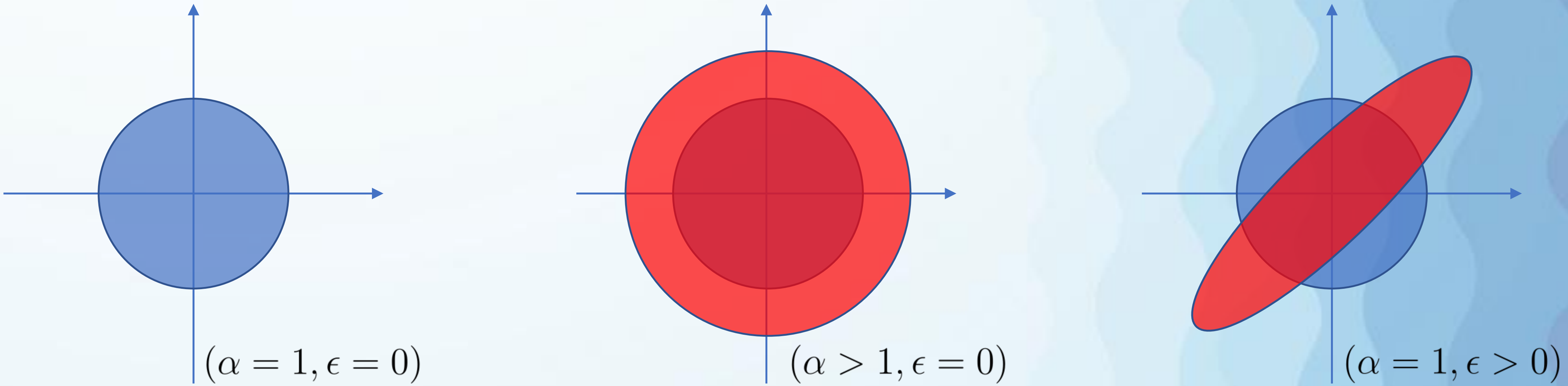
Charged order parameter

$$D_A = \partial_A - iqA_A$$

- What we need to do is "just" solving the (classical) EOMs for these fields!

# EFT for superconductivity: solutions

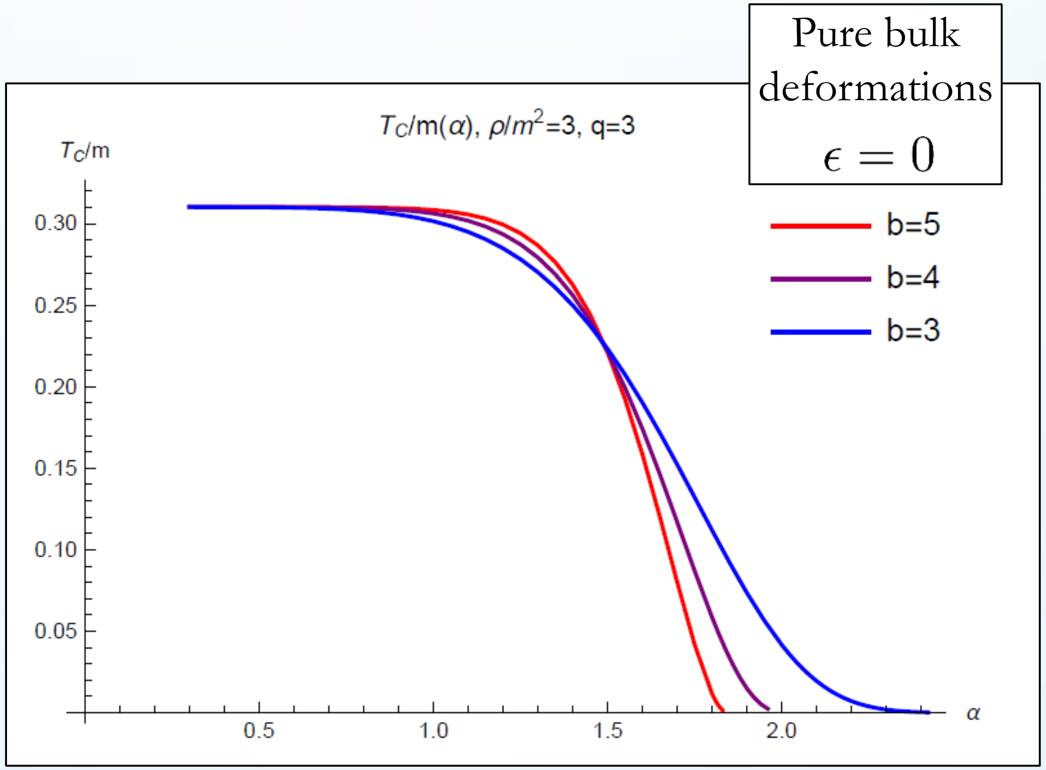
- For $\phi^I(x,u)$ restrict to: $$\begin{pmatrix}\phi^x\\ \phi^y\end{pmatrix} = \alpha \begin{pmatrix}\sqrt{1+\epsilon^2/4} & \epsilon/2 \\ \epsilon/2 & \sqrt{1+\epsilon^2/4}\end{pmatrix}\begin{pmatrix}x\\ y\end{pmatrix}$$

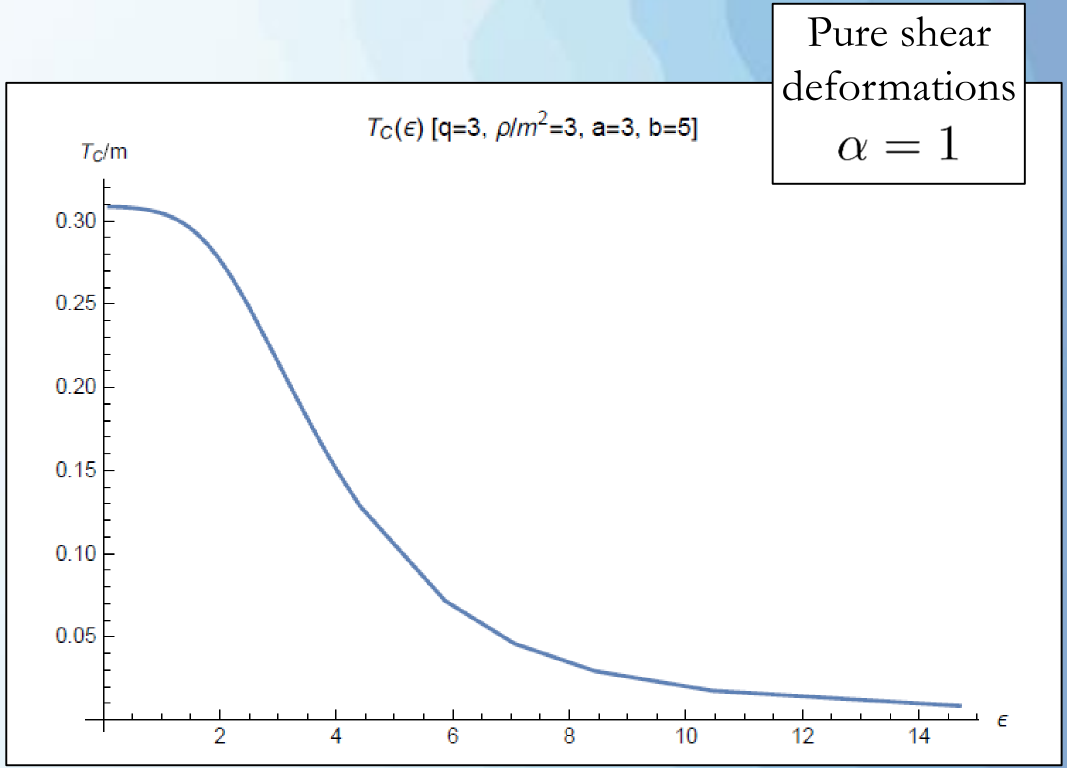



- This allows us to restrict to time-independent, QFT-homogeneous ansatzes for the other fields

# EFT for superconductivity: some results

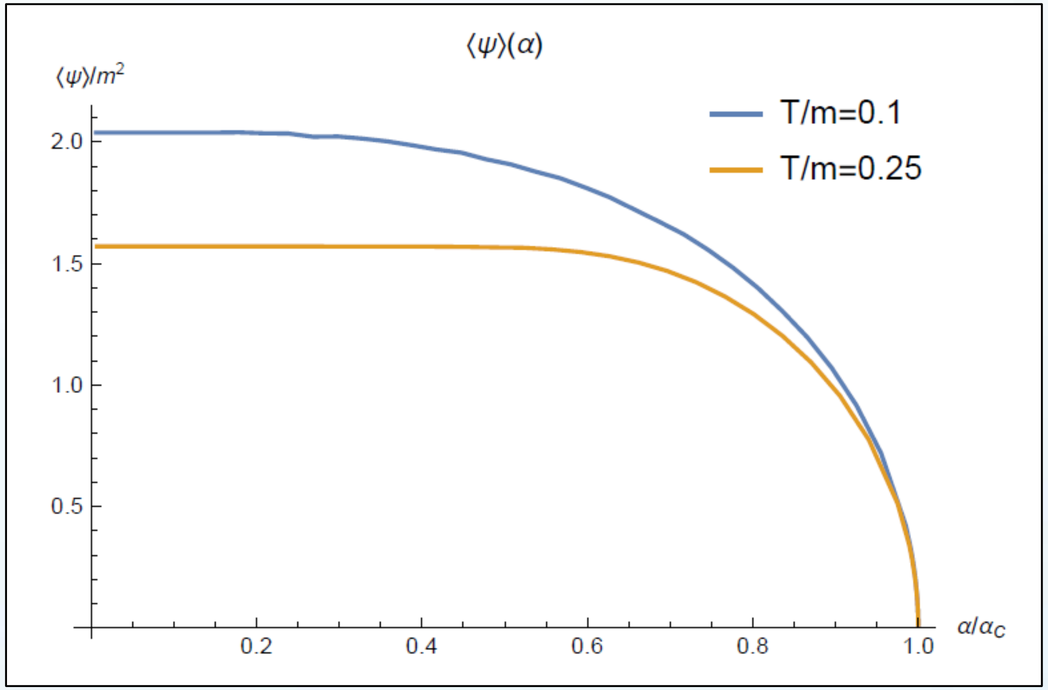
- We can see that there is a strong interplay between deformations and SC

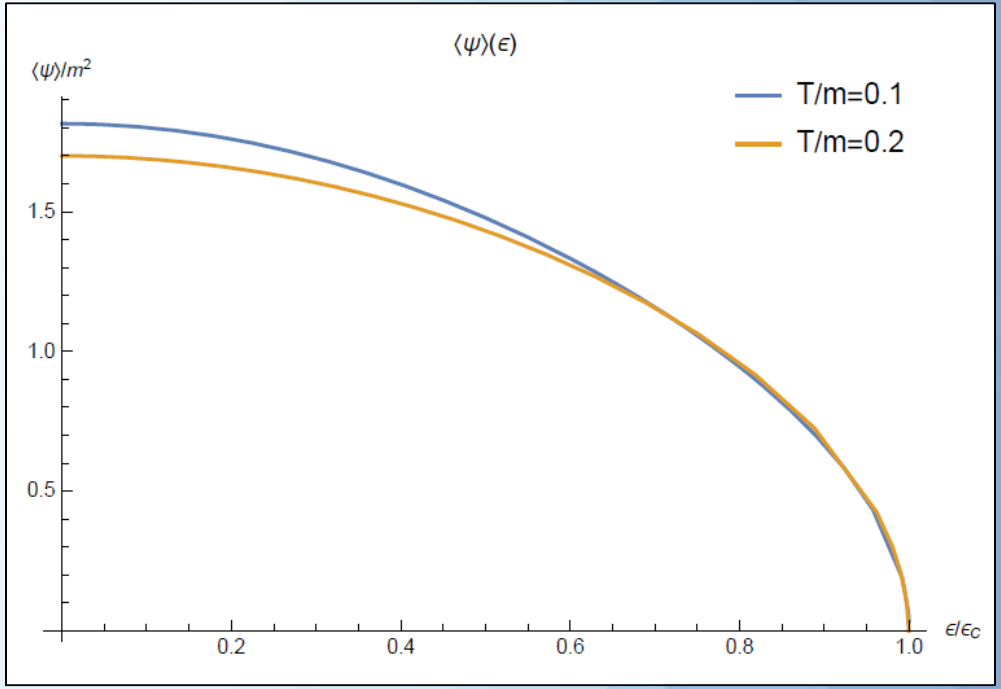


# EFT for superconductivity: some results

- Studying the condensate, it is found that strain-induced transitions are MF ones




$$\langle\psi\rangle(\alpha) \sim (\alpha_C - \alpha)^{\frac{1}{2}} \text{ for } \alpha \to \alpha_C, \quad \langle\psi\rangle(\epsilon) \sim (\epsilon_C - \epsilon)^{\frac{1}{2}} \text{ for } \epsilon \to \epsilon_C$$

## Conclusions

- I showed that it is possible to build strain-sensitive holographic theories of SC
  - Can we find different behaviours? Add couplings, change $\phi^I(x,u)$ term…
  - Is this useful to describe some observed phenomenology?

**Thank you for the attention!**

**谢谢你听我!**