



QMAP

Scale Versus Conformal Invariance of IR Fixed Points

Markus Lüthi

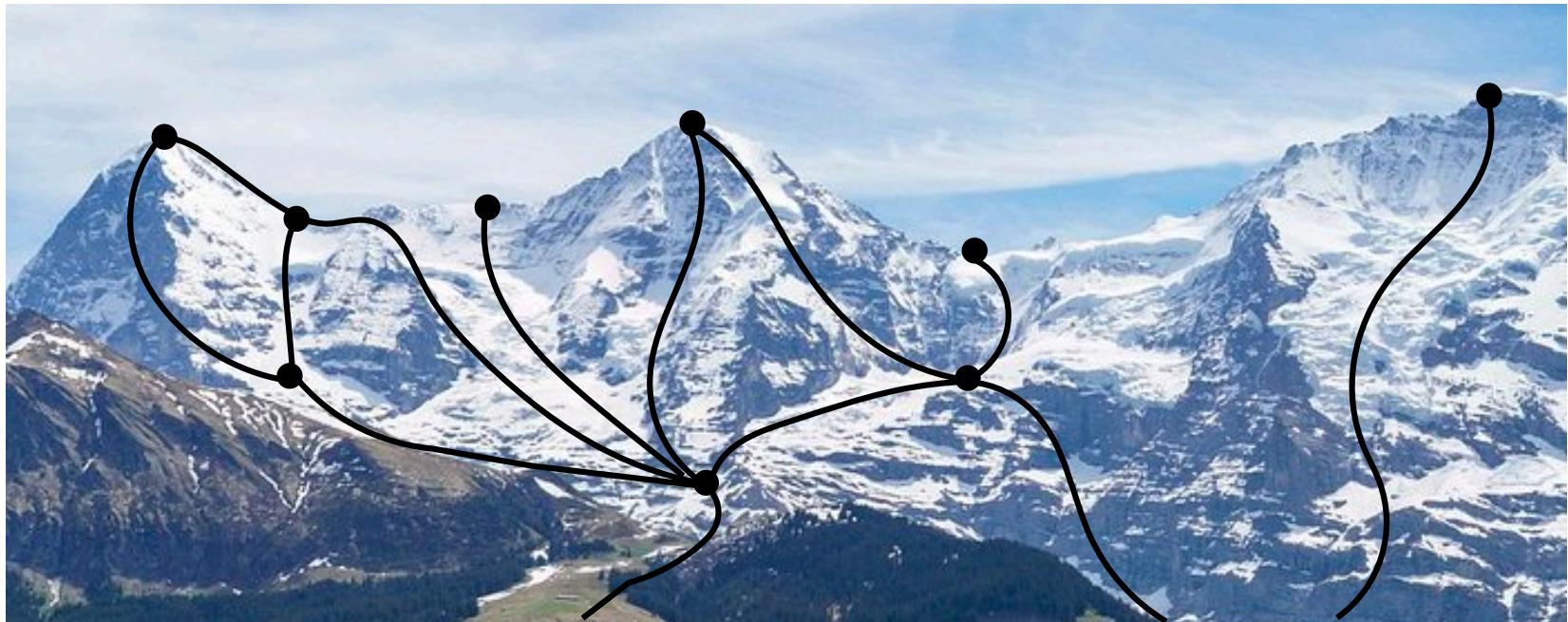
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Outline

- Introduction
- Theorem
- Proof
- Counterexamples?
- Remarks on the Wilson RG
- Conclusions

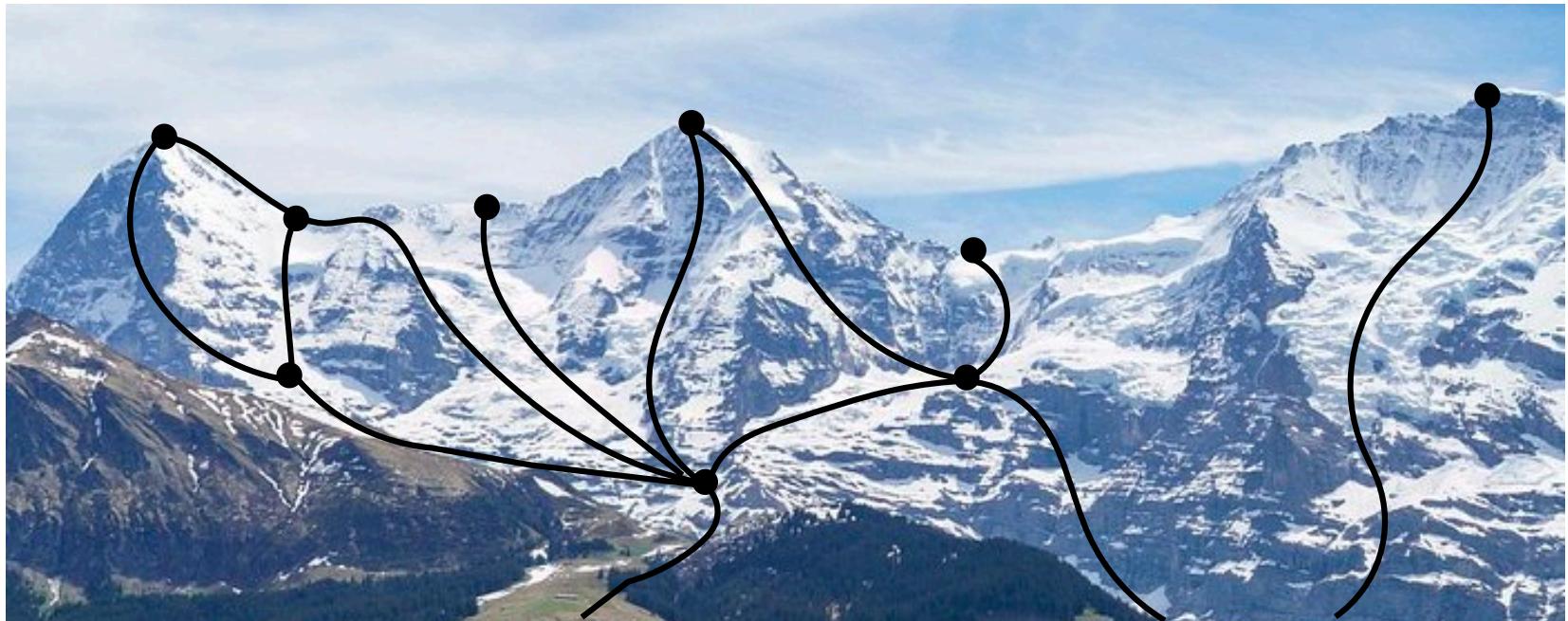
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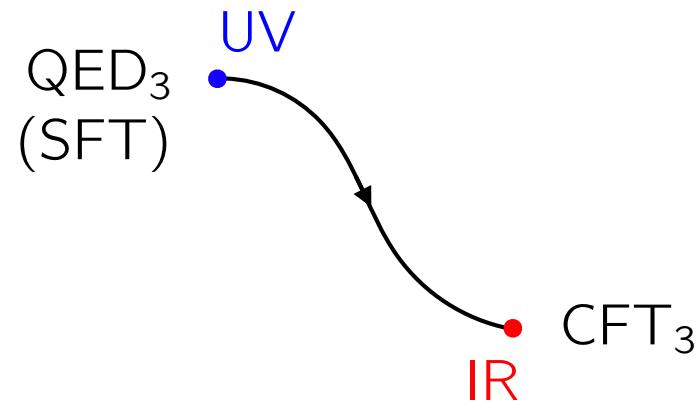


What about scale without conformal invariance (SFTs)?

Are there RG flows that start/end on SFTs?

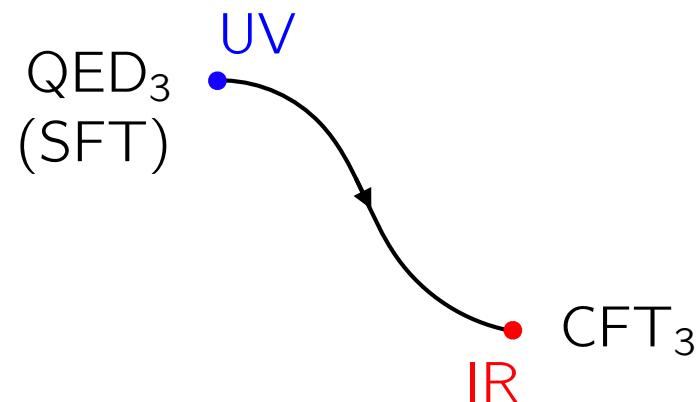
SFT Flows?

Many 3D examples...

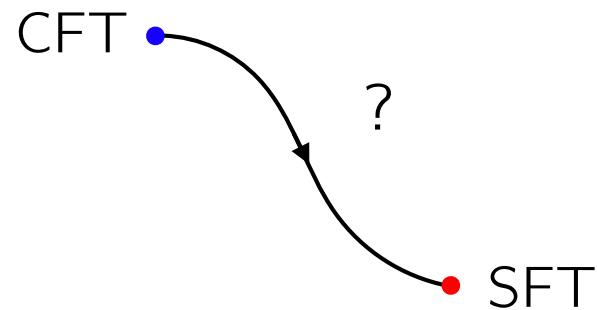


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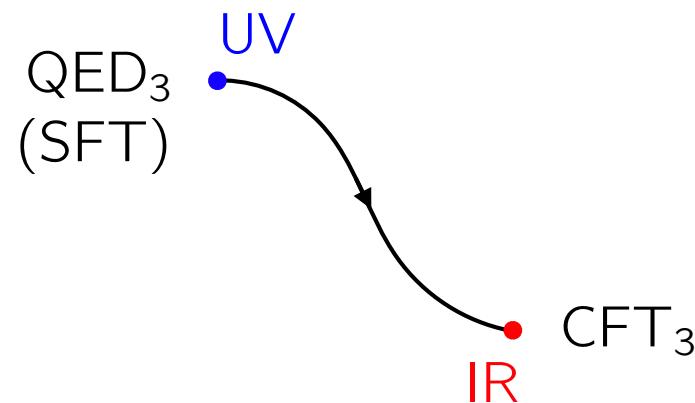


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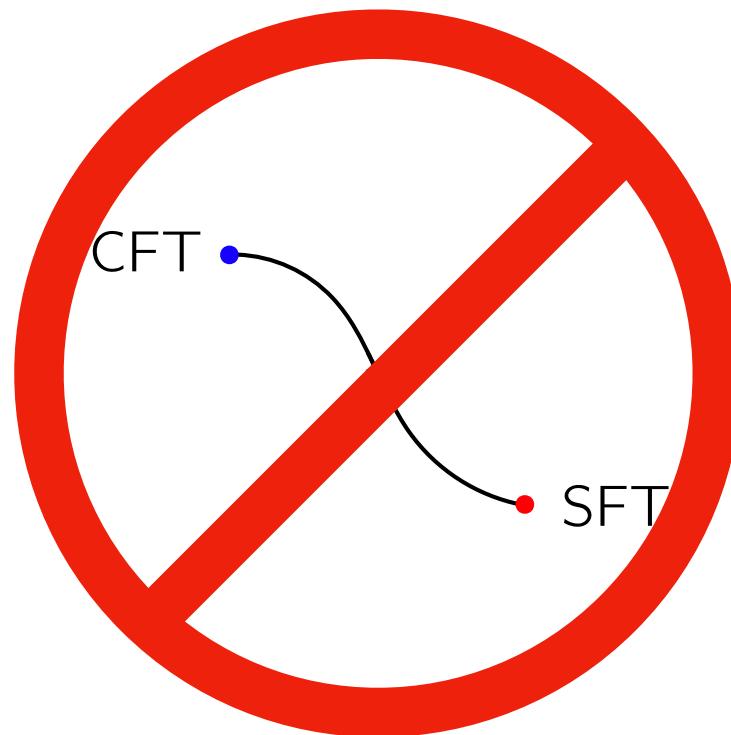


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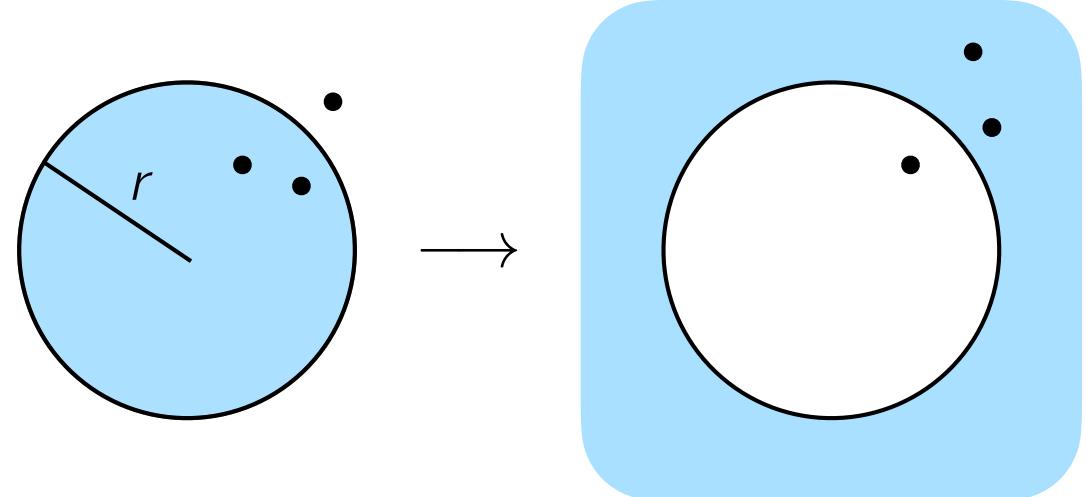
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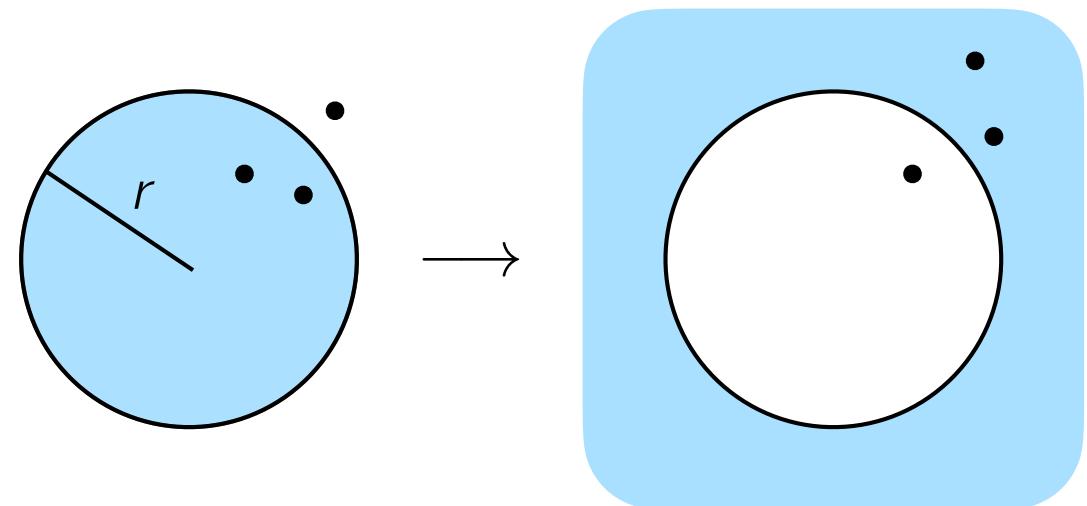


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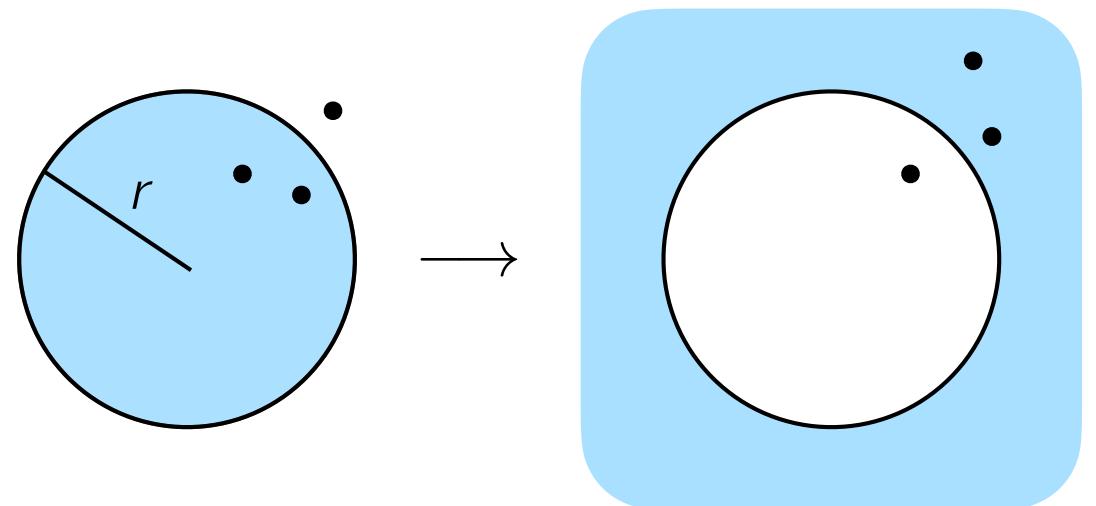
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Then: IR fixed point is a CFT (not SFT)

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 - ⇒ IR fixed point is conformally invariant

Radial Quantization

...for non-conformal QFTs [Fubini, Hanson, Jackiw (1973)]

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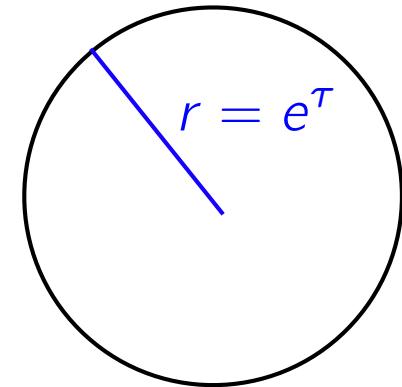
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Tune $m^2/\lambda^2 \Rightarrow$ flows to 3D Ising CFT in IR

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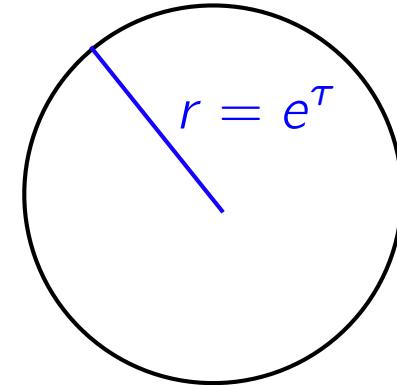
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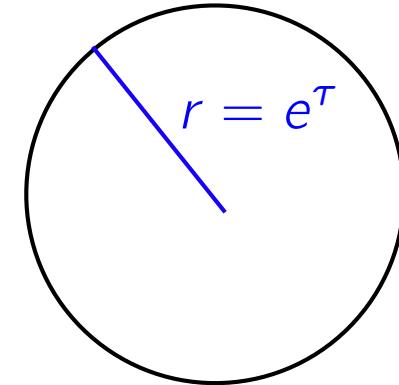
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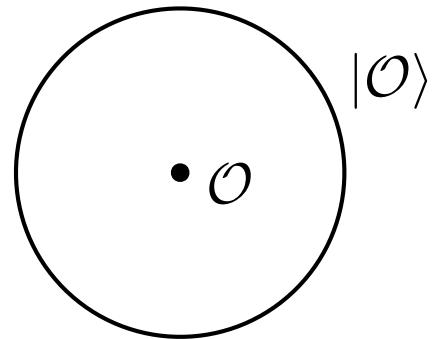


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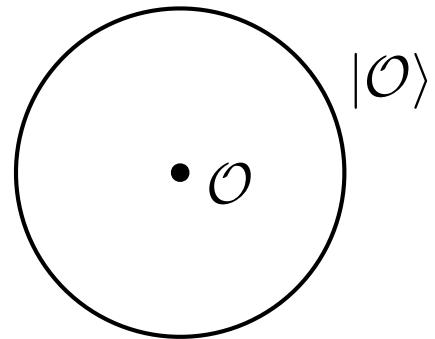
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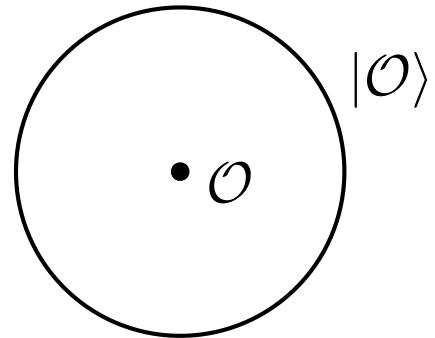


3D ϕ^4 : $\tau \rightarrow -\infty \Rightarrow$ free field theory

$$\hat{\phi}(\tau, \Omega) = \sum_{\ell, m} \frac{y_{\ell m}(\Omega)}{\sqrt{2\Delta_\ell}} \left[a_{\ell m} e^{-\Delta_\ell \tau} + a_{\ell m}^\dagger e^{\Delta_\ell \tau} \right] \quad \Delta_\ell = \ell + \frac{1}{2}$$

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$$|\ell_1, m_1, \dots, \ell_n, m_n\rangle \longleftrightarrow (\partial^{\ell_1} \phi) \cdots (\partial^{\ell_n} \phi)$$

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General condition for \top invariance:

$$\begin{aligned} H(P, Q) &= \underbrace{H(P, Q)^*}_{=} \\ &= H(-P, Q) \end{aligned}$$

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3D ϕ^4 :

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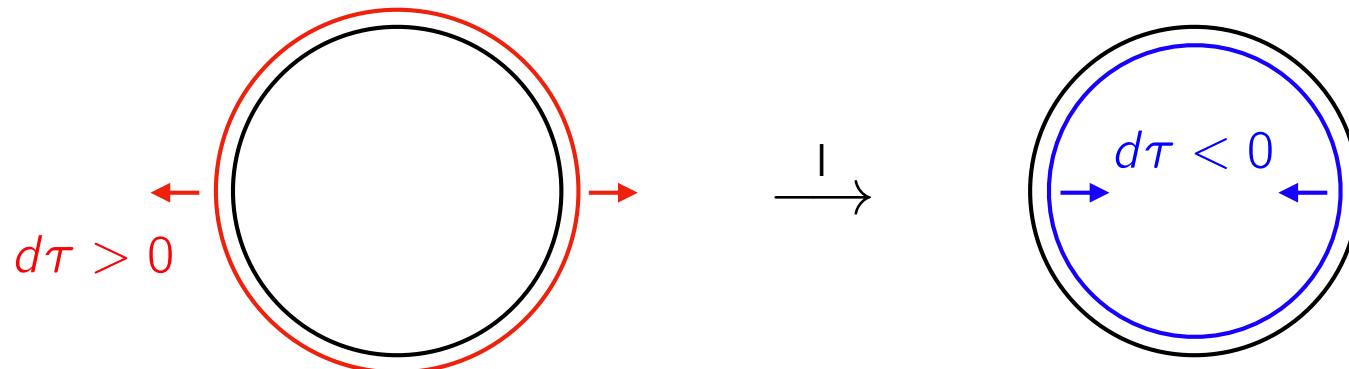
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Physical meaning:

- I is broken only by explicit τ dependence
- Microscopic time reversal invariance all along flow



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Formally: time evolution is a similarity transformation

$$\mathcal{O}(\tau) = S(\tau)^{-1} \mathcal{O}(\tau \rightarrow -\infty) S(\tau)$$

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$H(\tau)^* = H(\tau) \Rightarrow$ observables transform correctly under $d\tau \rightarrow -d\tau$

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Described by scale invariant effective Hamiltonian

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$[H(\tau)]_{\Delta_{\max}}$ = truncation to eigenspace with $\Delta(\tau) < \Delta_{\max}$

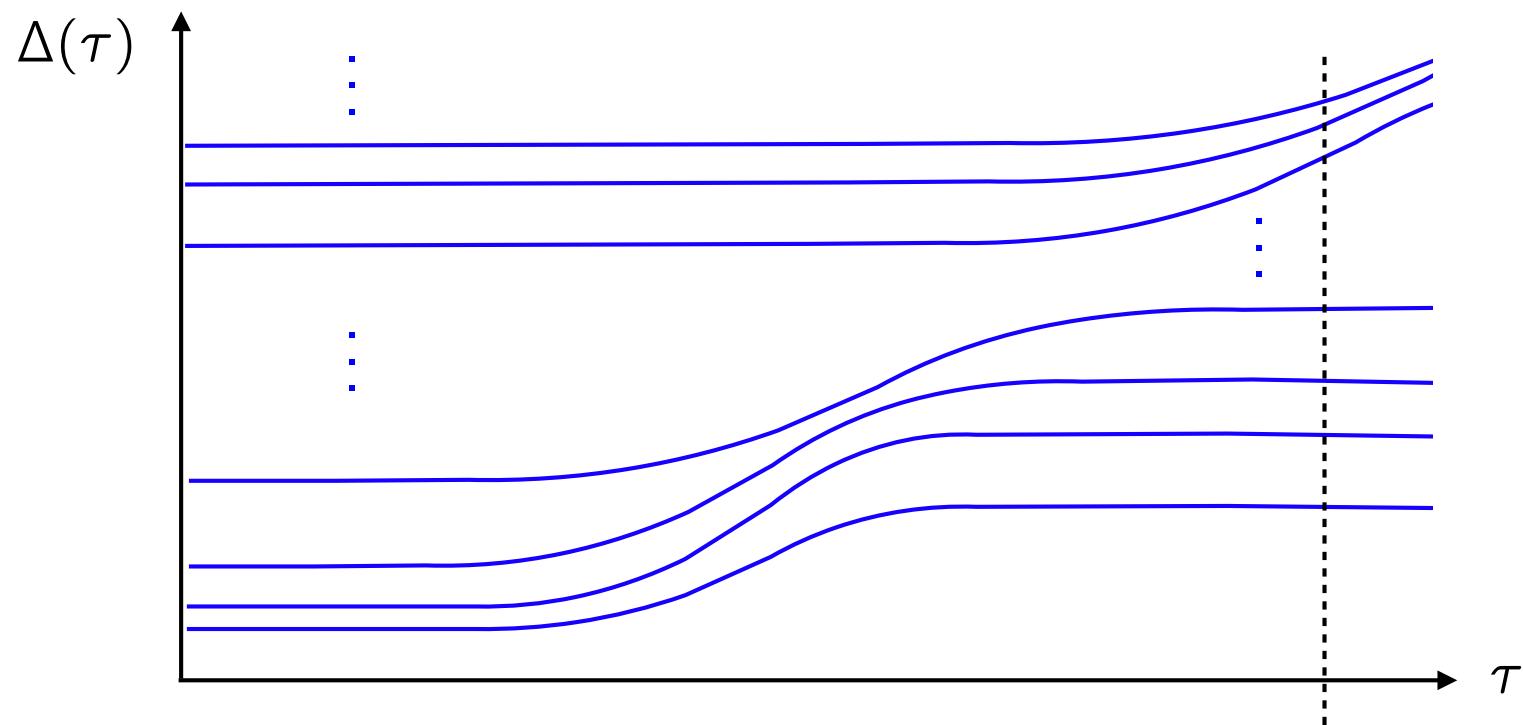
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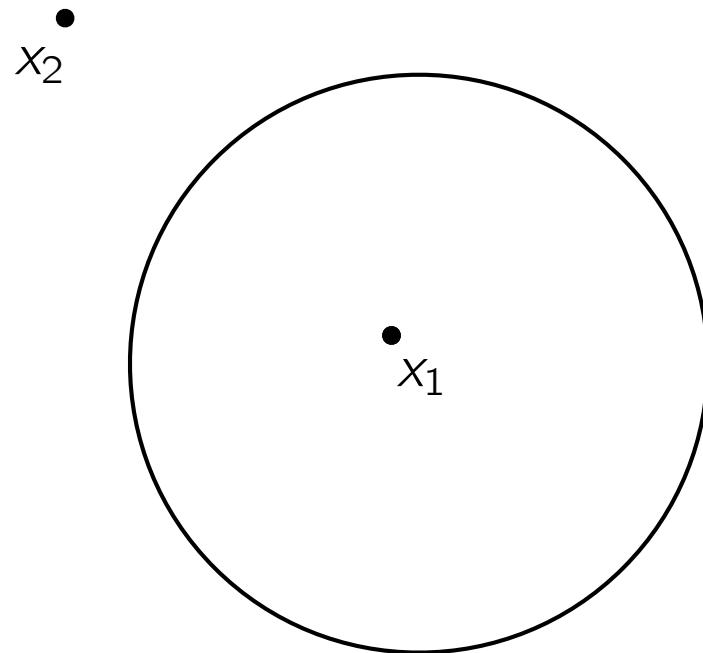
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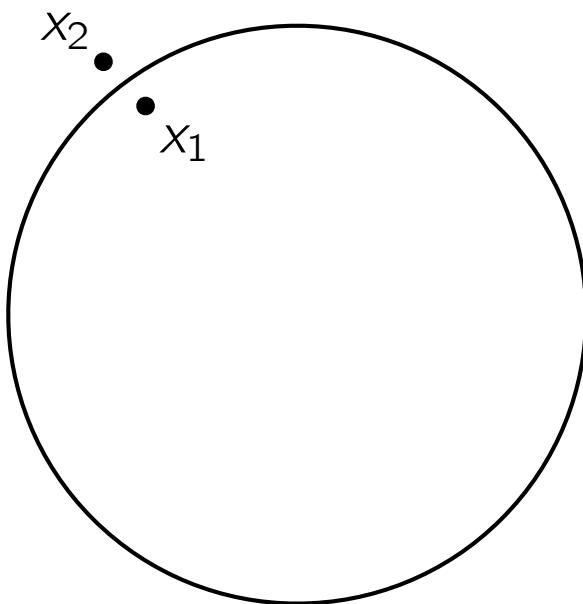


IR Limit

$\langle \mathcal{O}(x_1)\mathcal{O}(x_2) \rangle$ in radial quantization:



Dominated by $\Delta(\tau) \sim 1$



Sensitive to $\Delta(\tau) \gg 1$

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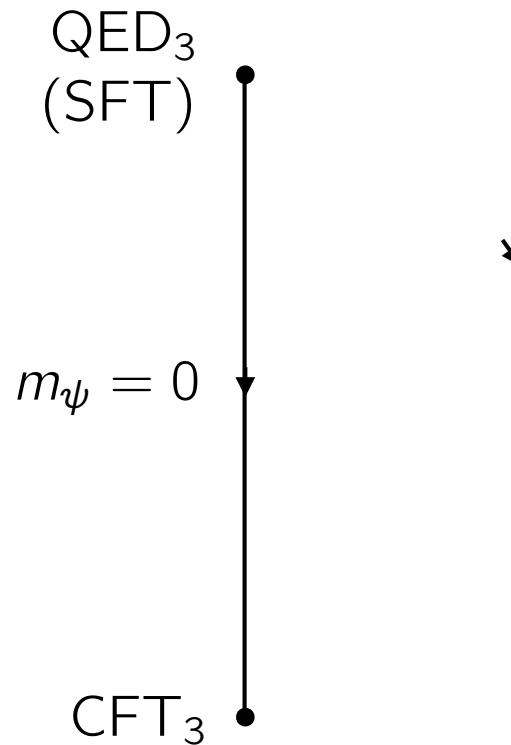
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\Rightarrow conformal invariance

QED

Counterexamples?

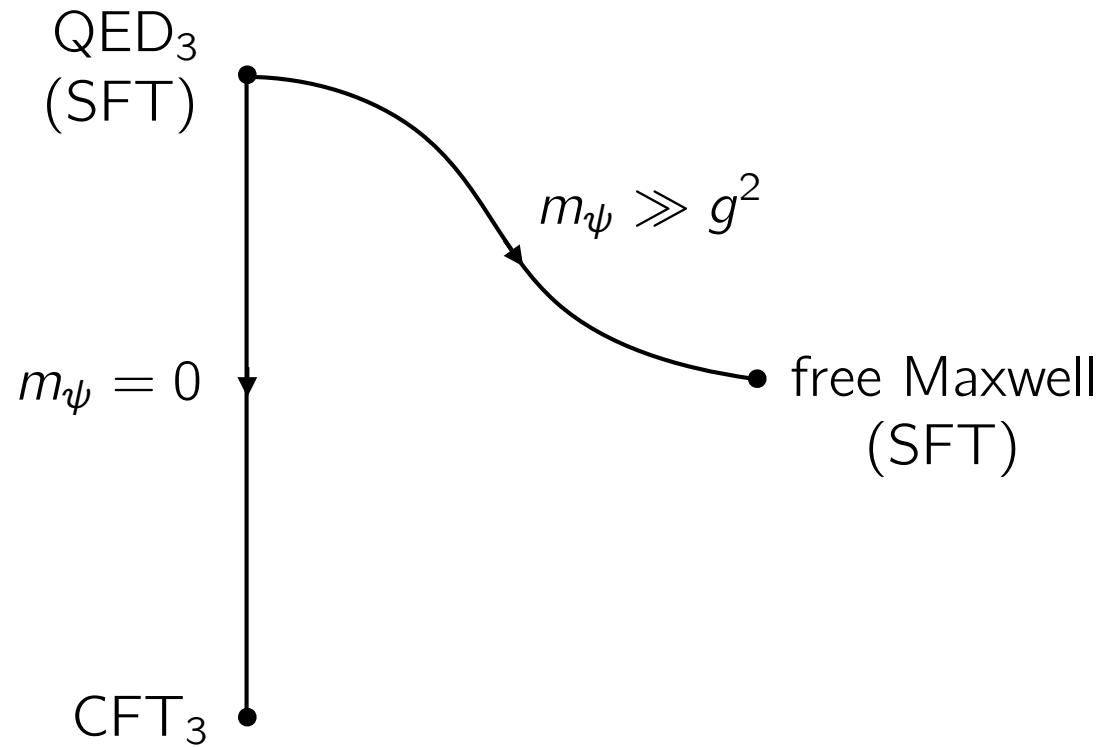
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Flow is weakly coupled in $1/N_f$ expansion
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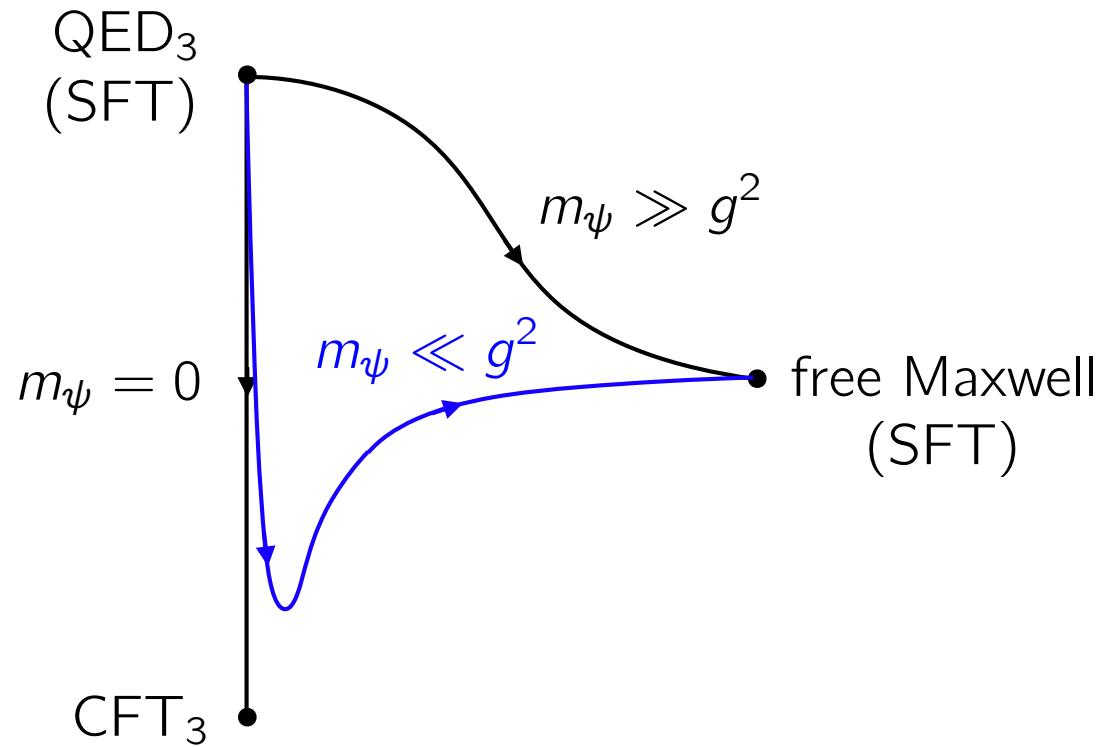
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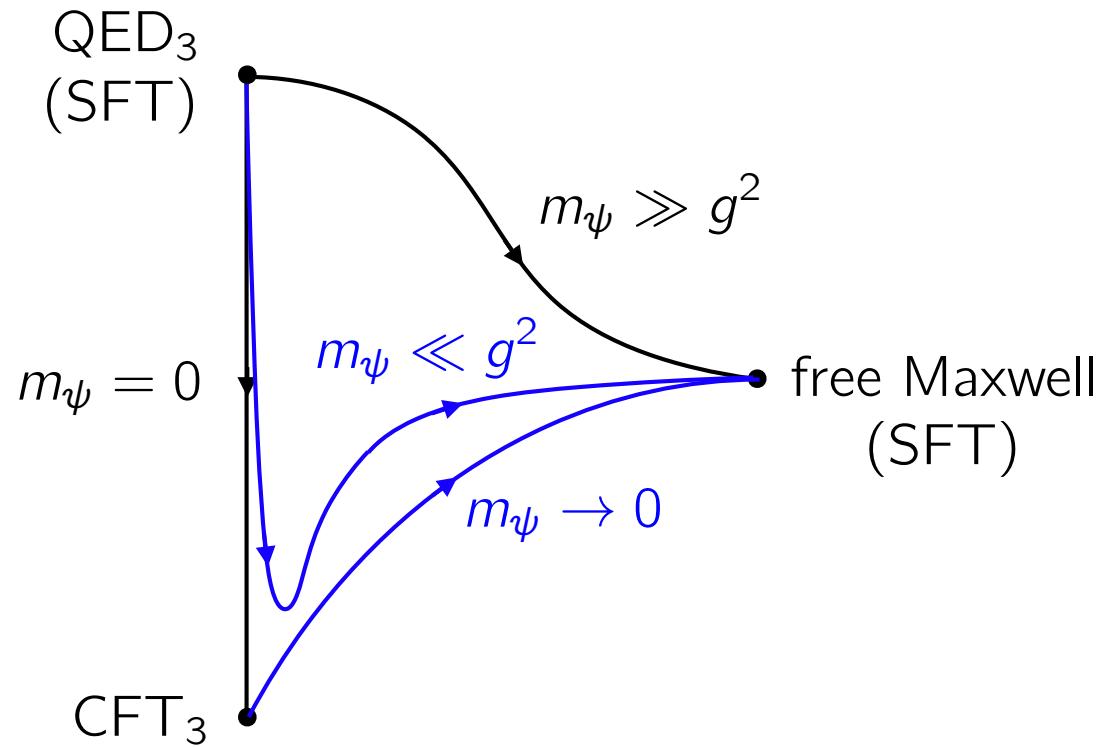
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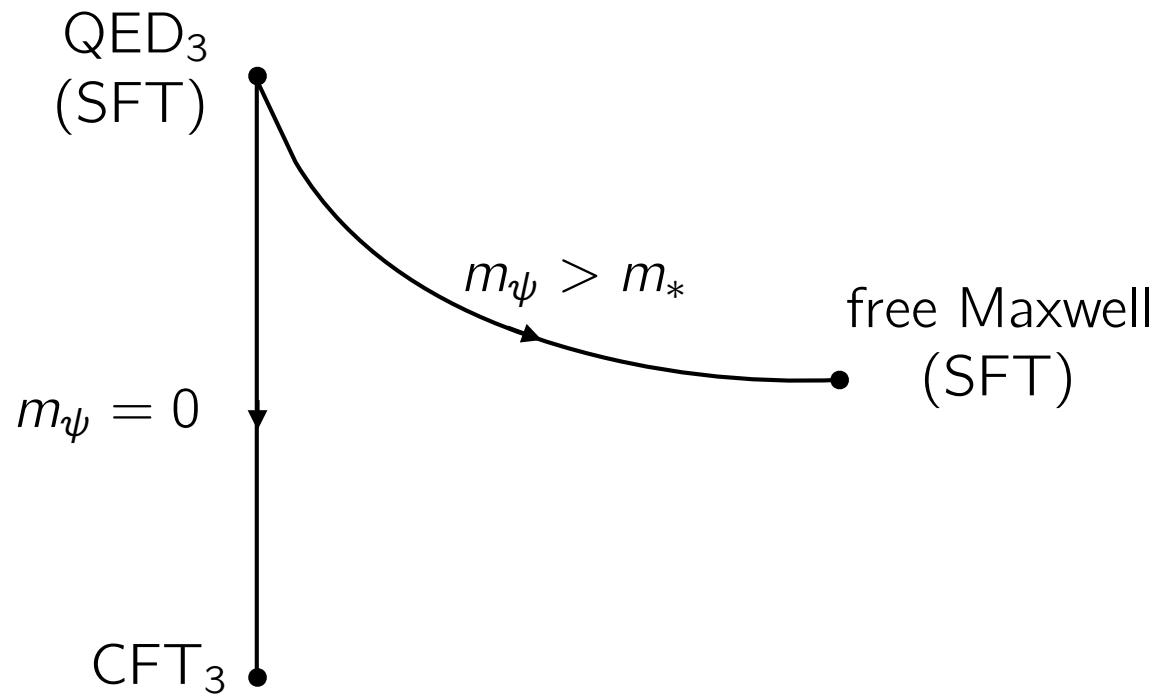
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Dangerously Irrelevant

- QCD: $\Delta\mathcal{L}_{\text{QCD}} = \sum_A G_A |\psi_L^\dagger T_A \psi_R|^2$
 $Z_{2L} \times Z_{2R}$ forbids quark mass
Breaks continuous chiral symmetries \Rightarrow all pions massive
- 3D counterexample:

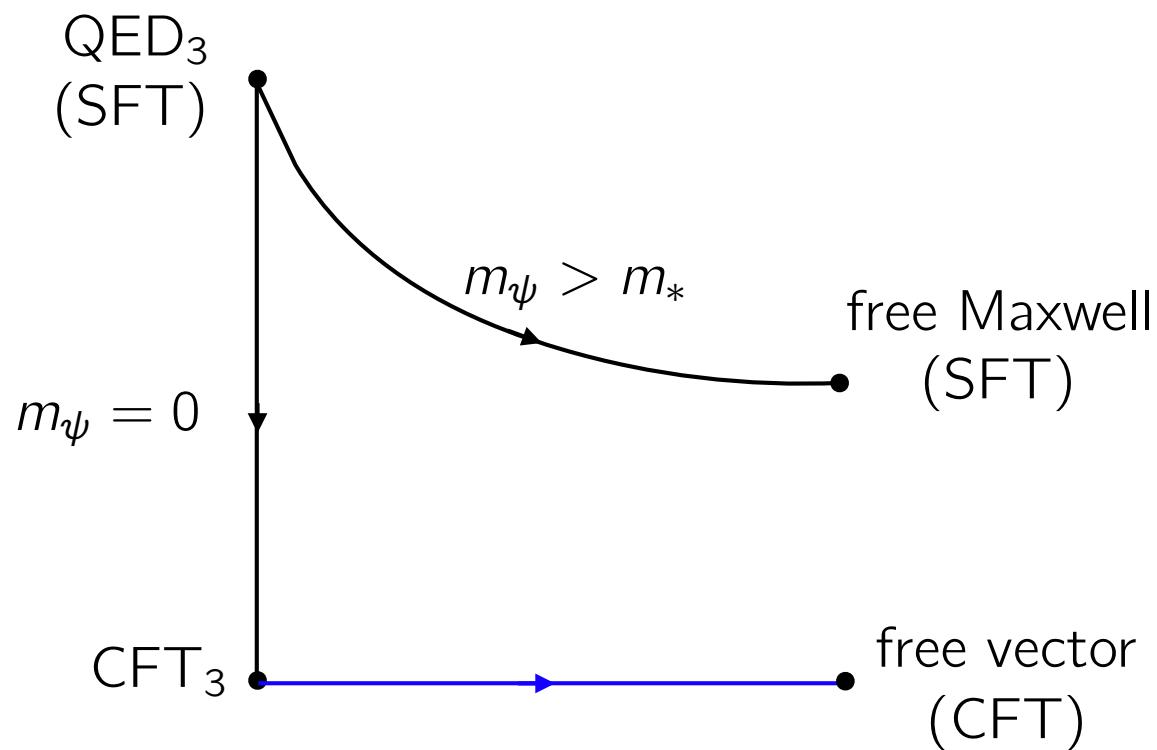
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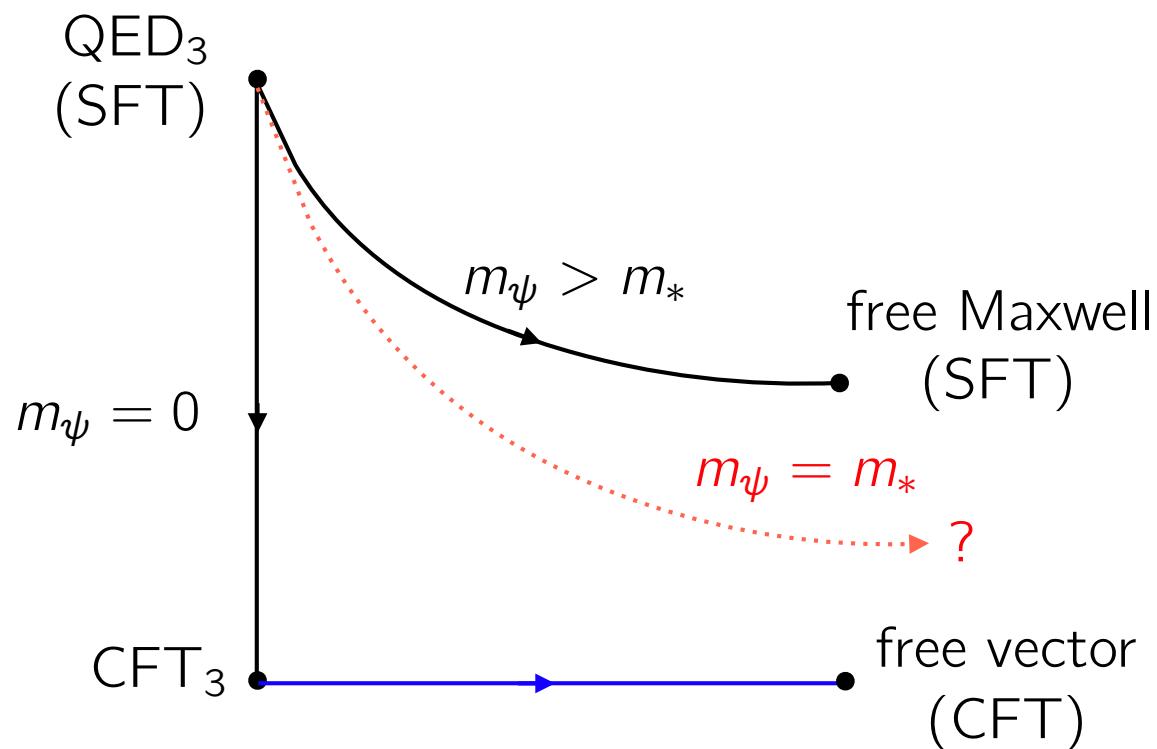
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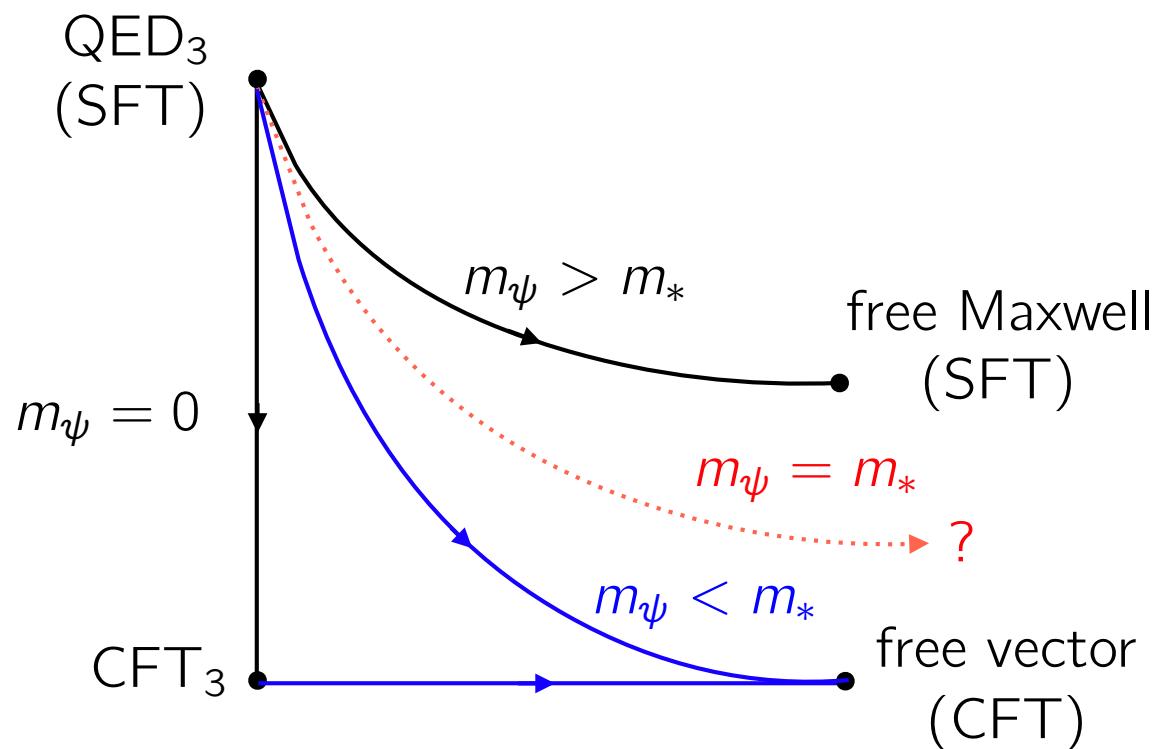
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3D QED

$N_f \rightarrow \infty$ limit:

$$\text{---} \circ \text{---} = \text{---} + \text{---} \circ \text{---} + \text{---} \circ \text{---} \circ \text{---} + \dots$$

$$\sim \frac{1}{p^2 + \Pi(p)}$$

3D QED

$N_f \rightarrow \infty$ limit:

$$\text{Diagram with shaded loop} = \text{Diagram with wavy line} + \text{Diagram with one loop} + \text{Diagram with two loops} + \dots$$

$$\sim \frac{1}{p^2 + \Pi(p)}$$

$$\Pi(p) \sim \underbrace{g^2 N_f}_{= \lambda} \int d^3 k \frac{1}{(\not{k} + m_\psi)(\not{k} + \not{p} + m_\psi)} \sim \lambda p^2 \begin{cases} \frac{1}{|p|} & |p| \gg m_\psi \\ \frac{1}{m_\psi} & |p| \ll m_\psi \end{cases}$$

3D QED

$N_f \rightarrow \infty$ limit:

$$\text{Diagram: } \text{Wavy line} \circlearrowleft = \text{Wavy line} + \text{Wavy line} \circlearrowleft + \text{Wavy line} \circlearrowleft \text{Wavy line} + \dots$$

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$m_\psi = 0$: flows to Gaussian CFT

$$\Gamma_{1\text{PI}} = \int d^3 x \left[\lambda F_{\mu\nu} \frac{1}{\Box^{1/2}} F_{\mu\nu} + \bar{\psi} i \not{\partial} \psi \right]$$

$$f_{\mu\nu} = \lambda^{1/2} F_{\mu\nu} = \text{primary}$$

$$\Delta_f = 2$$

3D QED

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$$\text{---} \circlearrowleft = \text{---} + \text{---} \circlearrowleft + \text{---} \circlearrowleft \text{---} \circlearrowleft + \dots$$

$$\sim \frac{1}{p^2 + \Pi(p)}$$

$$\Pi(p) \sim \underbrace{g^2 N_f}_{= \lambda} \int d^3 k \frac{1}{(\not{k} + m_\psi)(\not{k} + \not{p} + m_\psi)}$$

$$\sim \lambda p^2 \begin{cases} \frac{1}{|p|} & |p| \gg m_\psi \\ \frac{1}{m_\psi} & |p| \ll m_\psi \end{cases}$$

$m_\psi = 0$: flows to Gaussian CFT

$$\Gamma_{1\text{PI}} = \int d^3 x \left[\lambda F_{\mu\nu} \frac{1}{\square^{1/2}} F_{\mu\nu} + \bar{\psi} i \not{\partial} \psi \right]$$

$$f_{\mu\nu} = \lambda^{1/2} F_{\mu\nu} = \text{primary}$$

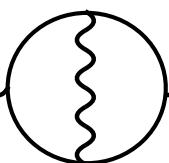
$$\Delta_f = 2$$

$m_\psi \neq 0$: flows to free Maxwell

$$\Gamma_{1\text{PI}} = \int d^3 x \frac{\lambda}{m_\psi} F_{\mu\nu}^2$$

$$\Rightarrow m_* = 0 \dots$$

$1/N_f$ Corrections

$$\Delta\Pi(p) = \text{---} + \dots$$


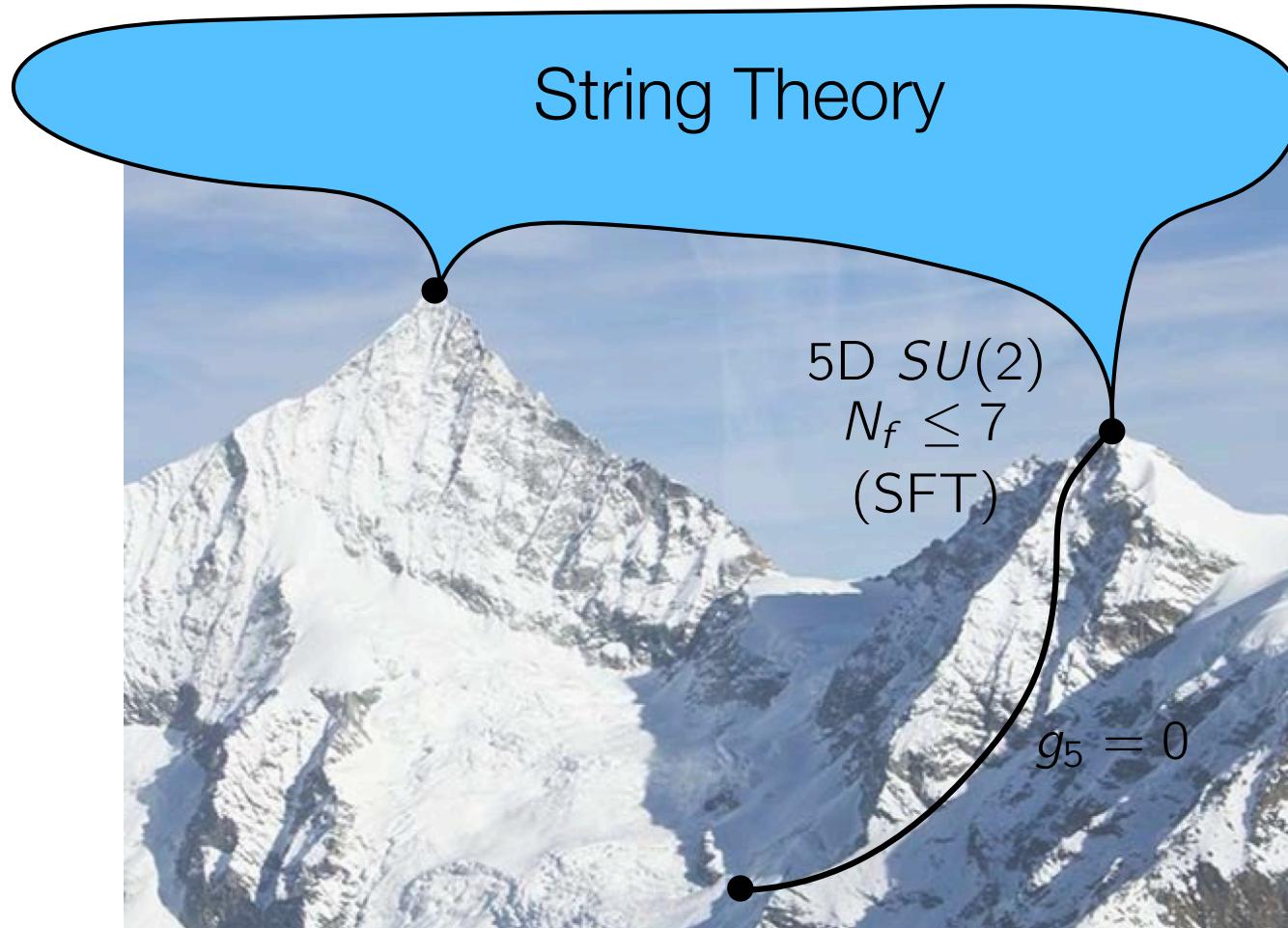
$$\sim \frac{\lambda^2}{N_f} \times \frac{p^2}{m_\psi^2} \quad |p| \ll m_\psi$$

$m_\psi \ll \frac{\lambda}{N_f} \Rightarrow 1/N_f$ expansion breaks down

Suggests $m_* \sim \frac{\lambda}{N_f}$

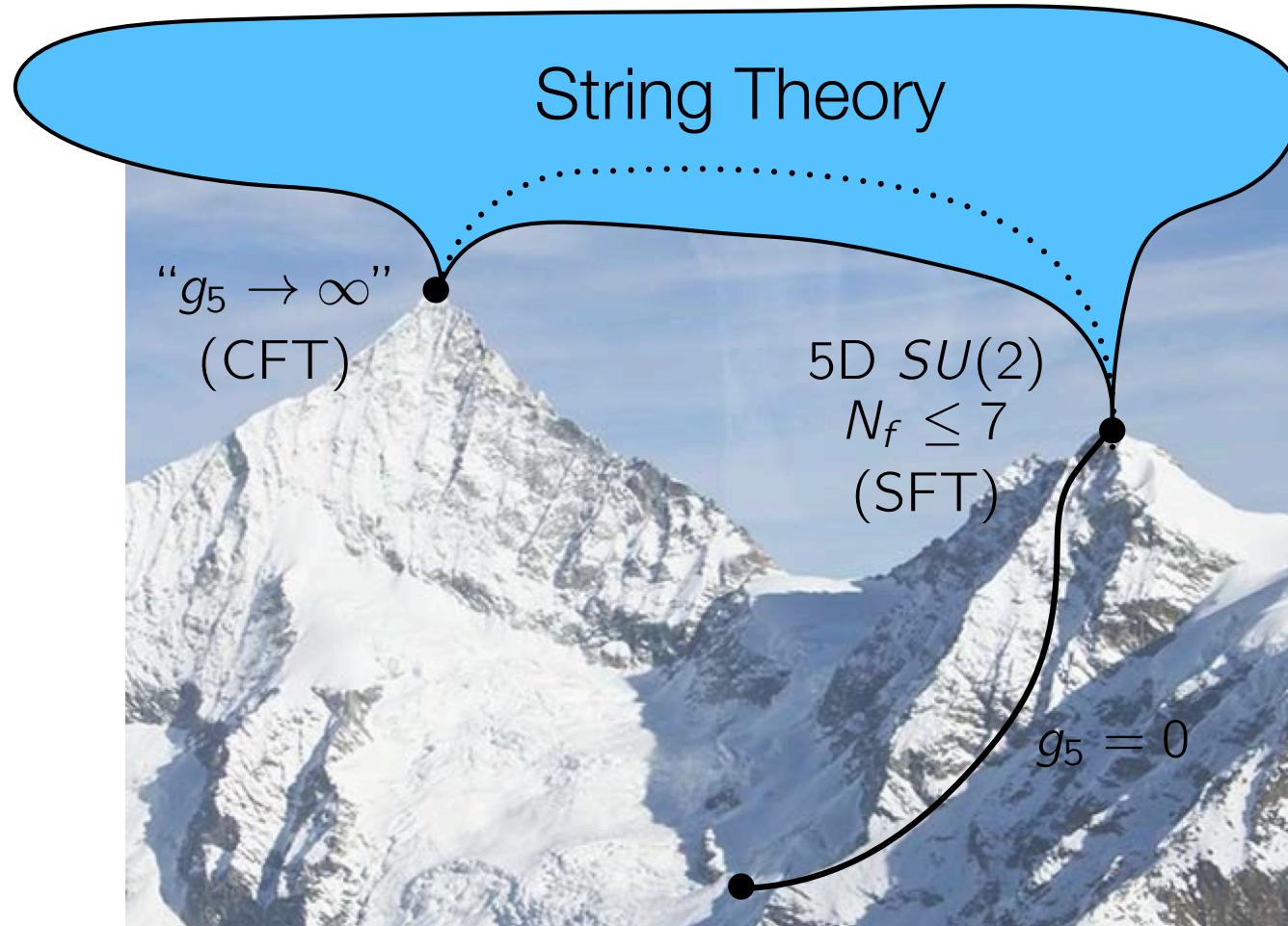
More Counterexamples?

[Seiberg (1996); Intriligator, Morrison, Seiberg (1997)...]



More Counterexamples?

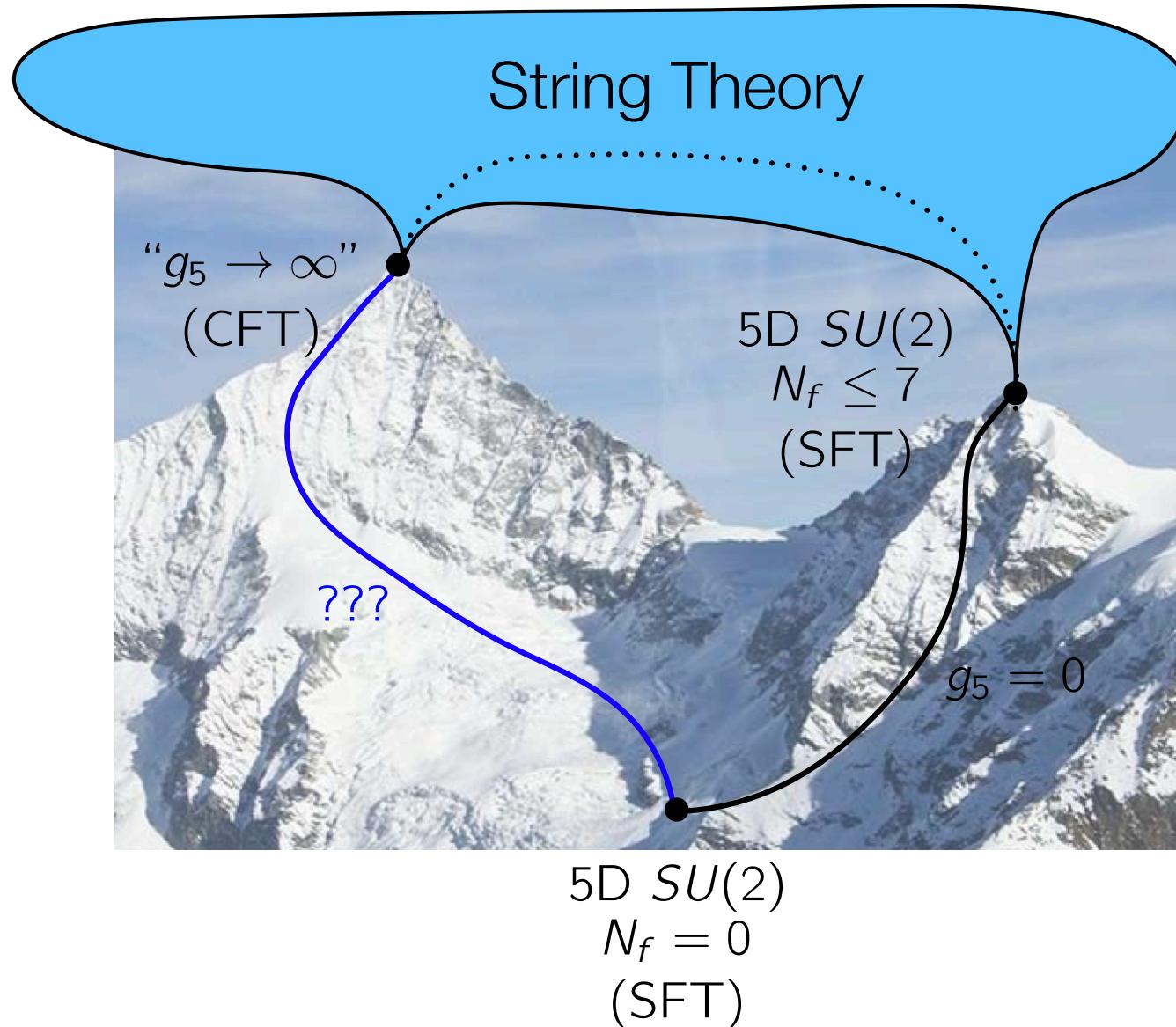
[Seiberg (1996); Intriligator, Morrison, Seiberg (1997)...]



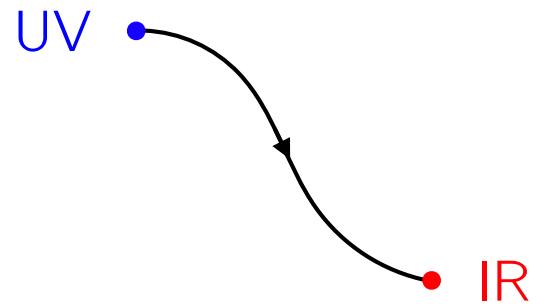
5D $SU(2)$
 $N_f = 0$
(SFT)

More Counterexamples?

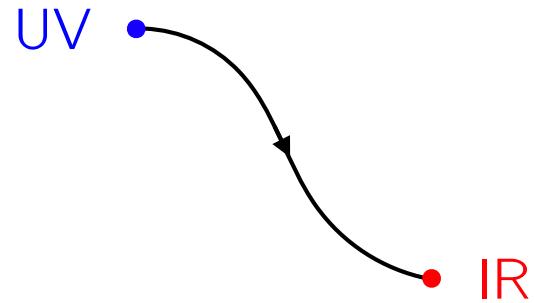
[Seiberg (1996); Intriligator, Morrison, Seiberg (1997)...]



Radial Quantization = Wilson RG

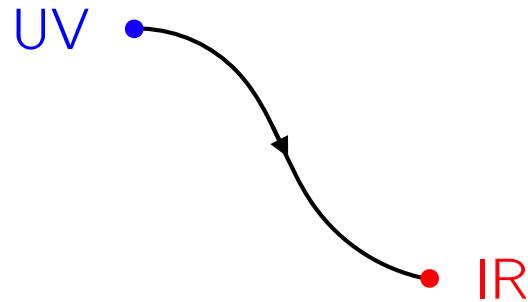


Radial Quantization = Wilson RG



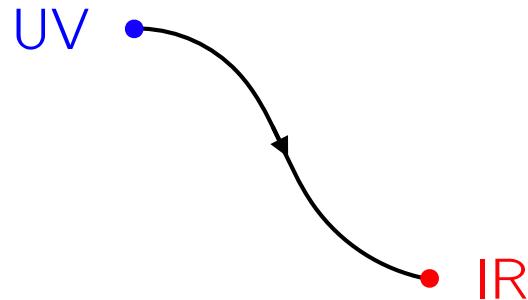
- $\tau \rightarrow \pm\infty \Rightarrow$ Spectrum of $H(\tau) \rightarrow$ UV/IR fixed point
(even for SFT...)

Radial Quantization = Wilson RG



- $\tau \rightarrow \pm\infty \Rightarrow$ Spectrum of $H(\tau) \rightarrow$ UV/IR fixed point
(even for SFT...)
- Mathematically precise formulation of Wilson RG

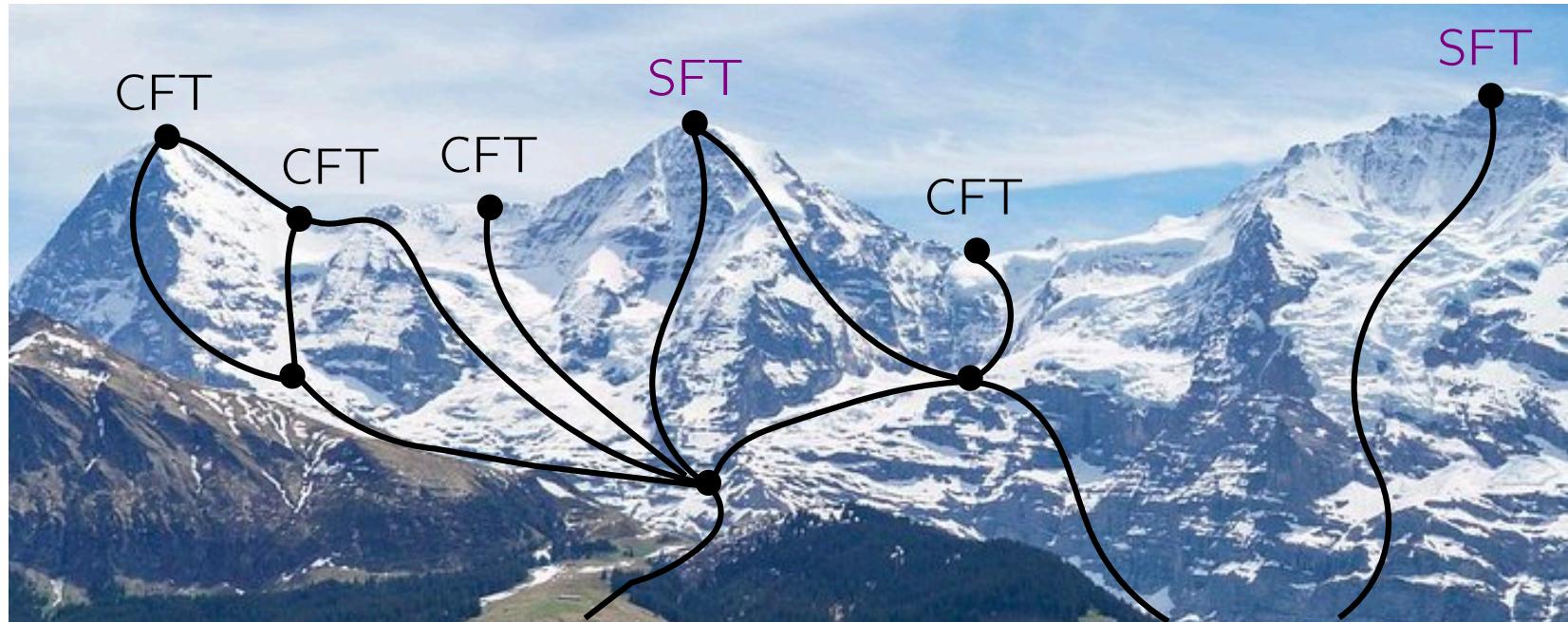
Radial Quantization = Wilson RG



- $\tau \rightarrow \pm\infty \Rightarrow$ Spectrum of $H(\tau) \rightarrow$ UV/IR fixed point
(even for SFT...)
- Mathematically precise formulation of Wilson RG
- Can be put on a computer
e.g. Lattice on $S^{D-1} \times R$

[Brower, Berger, Fleming, Gasbarro, Owen (2022)]

Conclusions



The landscape of QFTs can contain SFTs,
but only on the peaks?

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