Probing Quantum Field Theory at Strong Coupling

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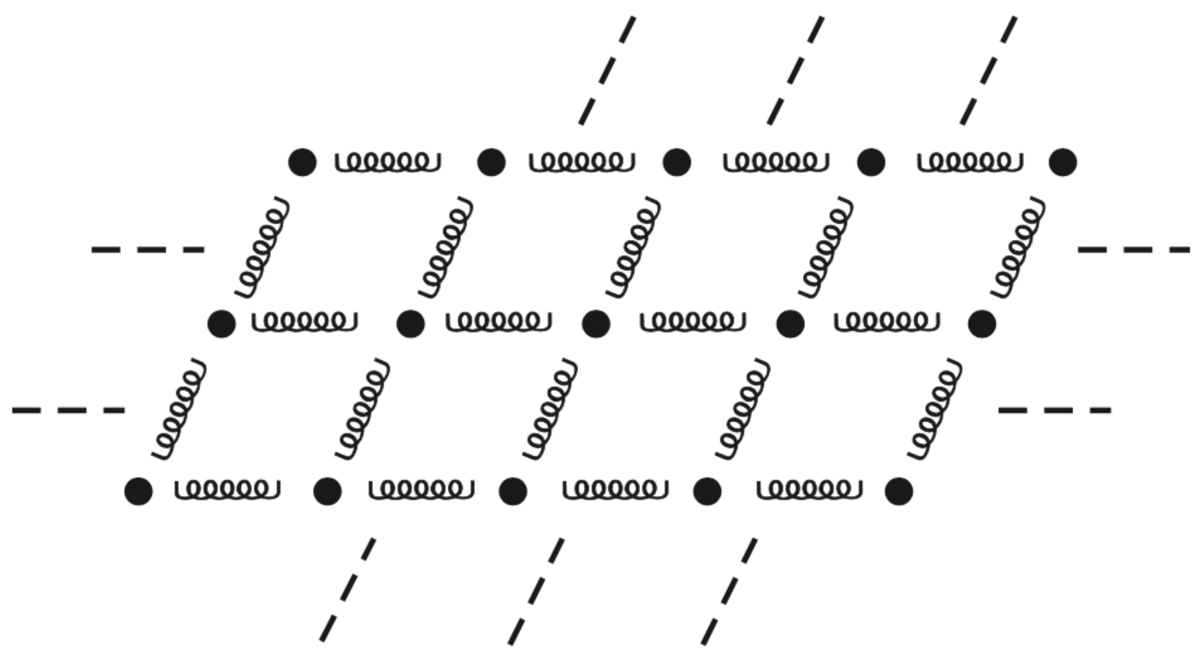
What is QFT?

- **Quantum Field Theory** is the fundamental language of a wide variety of physical systems, utilized in:
  - Particle physics, condensed matter physics, cosmology, …
  - Provides an accurate framework for computing observables.

A deeper understanding of QFT is an essential endeavor of modern physics

Textbook QFT

- When interactions are weak, we can use **perturbation theory** around a free field Lagrangian.

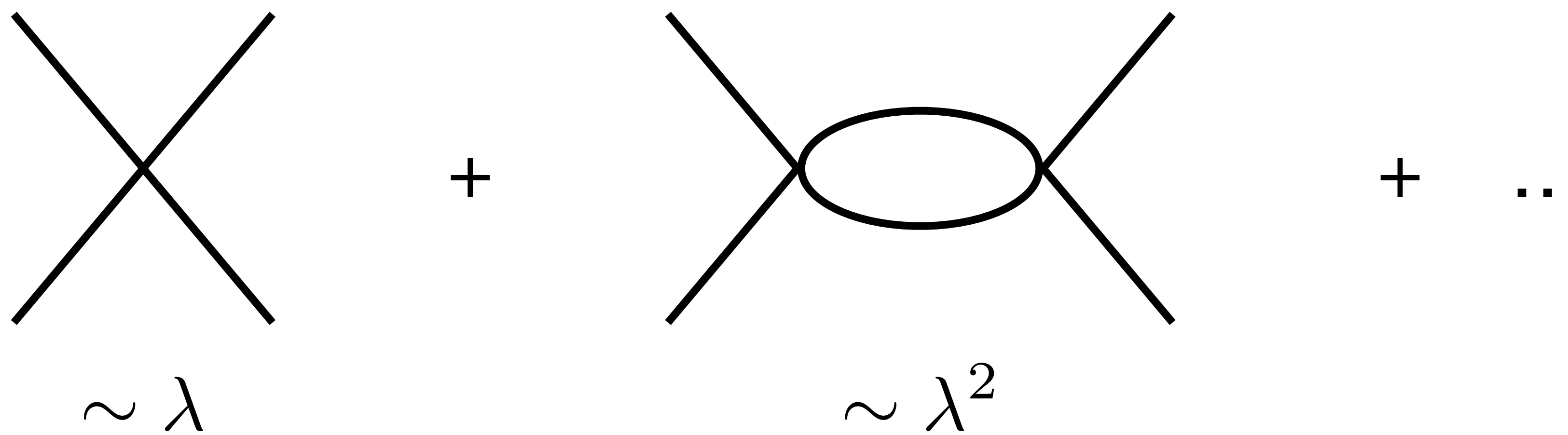


+ perturbation

"Mattress model" - Zee's QFT in a Nutshell

Beyond Textbook QFT

- For example, we can compute scattering amplitudes in perturbation theory with the machinery of Feynman diagrams.



- The coupling λ determines the strength of force of interactions between fields.
- Perturbation theory is valid when $\lambda \ll 1$.

Motivating Question: Can we solve for the dynamics of QFT at strong coupling?

Physics depends on the energy scale

- The strength of the couplings depend on the energy scale. The **Renormalization Group** tells you how the couplings **run** ("**flow**") as a function of energy.

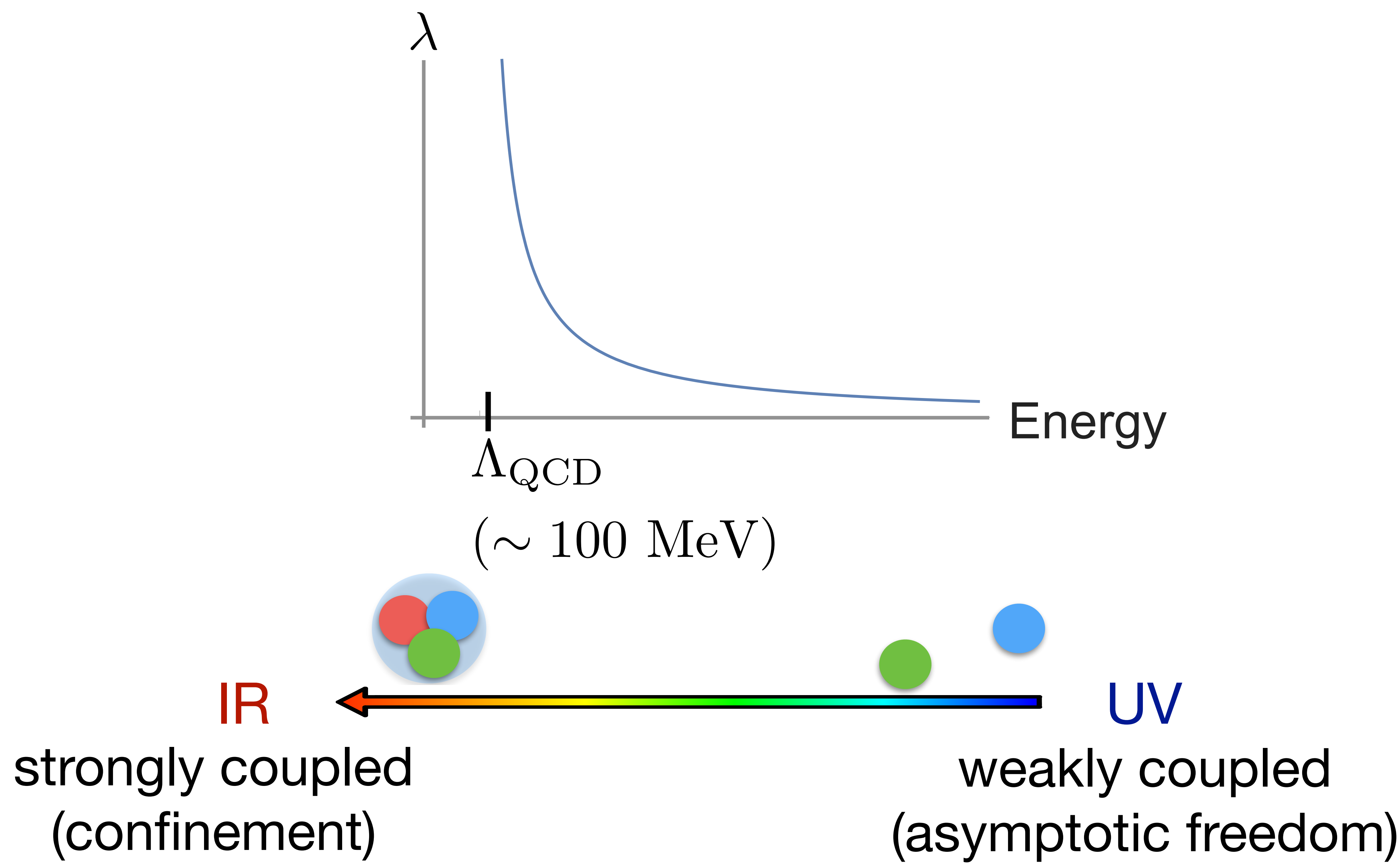
UV

high energy = short distance

IR

low energy = long distance

Confinement in Quantum Chromodynamics (QCD)



- Can we analytically understand confinement in QCD and other non-Abelian gauge theories?

Symmetry is a powerful organizing principle and tool

- To make progress, it is useful to use **simplifying assumptions**, by restricting to QFTs with certain symmetries.
- Fields in QFT are classified by how they transform under the symmetries of the physical system.

Perspective: Study theories with additional symmetries as a laboratory for studying general QFTs.

Supersymmetry

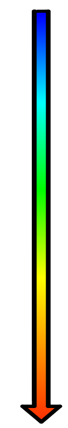
- SUSY is the only spacetime extension of Poincaré symmetry in a consistent QFT. [Haag, Lopuszanski, Sohnius '75]
- Introduce fermionic generators (supercharges) Q^A, A=1,.., $\mathcal{N}$. Schematically,

$$Q|\text{boson}\rangle = |\text{fermion}\rangle, \qquad Q|\text{fermion}\rangle = |\text{boson}\rangle$$

- With supersymmetry, we can often analyze **non-perturbative** aspects of QFTs exactly, *e.g*. using holomorphicity.

Constraining the phases of gauge theories using SUSY

Interesting arena: Supersymmetric QFT_1



+ perturb with ~~SUSY~~ term
in a protected multiplet

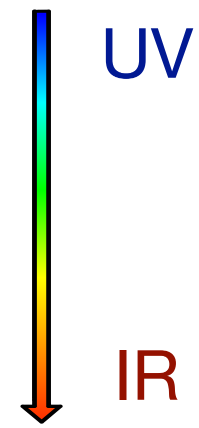
Less-supersymmetric QFT_2

- Famous example: $\mathcal{N}=2$ super Yang Mills $\rightarrow \mathcal{N}=1$. Confinement in the $\mathcal{N}=1$ vacua can be understood from this perspective.

[Seiberg, Witten ’94]

Constraining the phases of gauge theories using SUSY

$\mathcal{N} = 2$ super Yang-Mills



+ perturb with ~~SUSY~~ term
in a protected multiplet

"adjoint" QCD

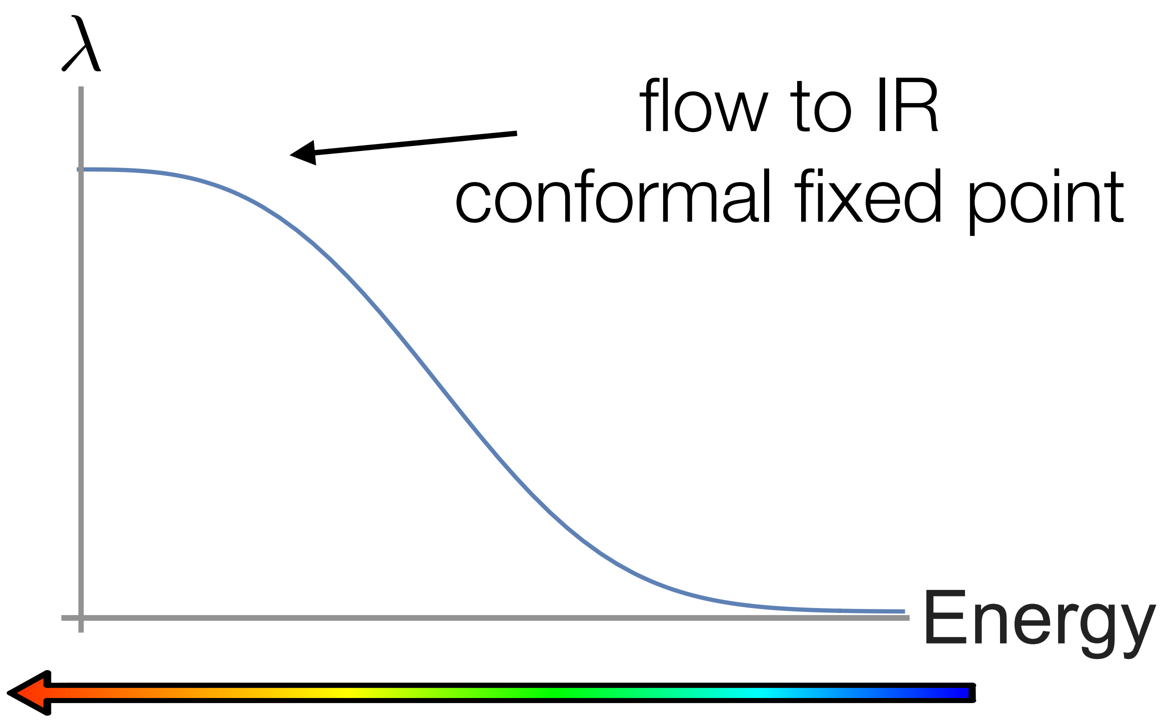
- I've been analyzing the IR phase structure of a cousin of (non-supersymmetric!) QCD with this approach.

- We give evidence for confinement in the IR gauge theory.

[D'Hoker, Dumitrescu, Gerchkovitz, **EN** '20 + to appear]

Conformal symmetry

- QFTs can flow to a **fixed point** of the renormalization group, where the couplings no longer change with scale.
- Scale invariance is usually enhanced to conformal invariance at such a fixed point.

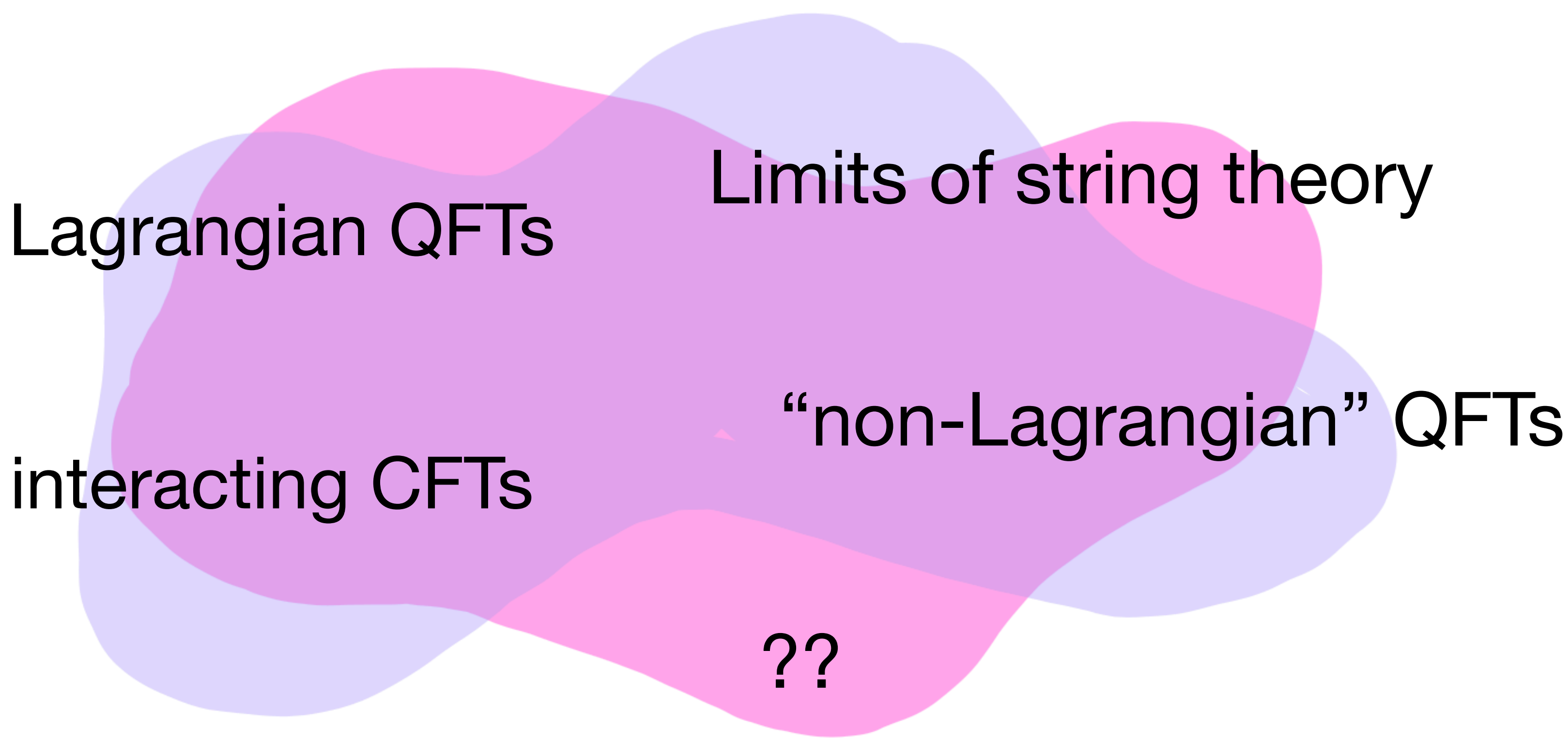


Conformal Field Theory (CFT)

- CFTs are important in modeling physical phenomena.
- QFTs are **generically** conformally invariant at long distances.
  - Trivial example: if all fields are massive, they decouple in the IR.
  - Especially combined with SUSY, there exist many examples of nontrivial, interacting supersymmetric CFTs!

What is the space of QFT?

- Today we know that textbook perturbation theory around weakly coupled Lagrangians is just one small corner of QFT!

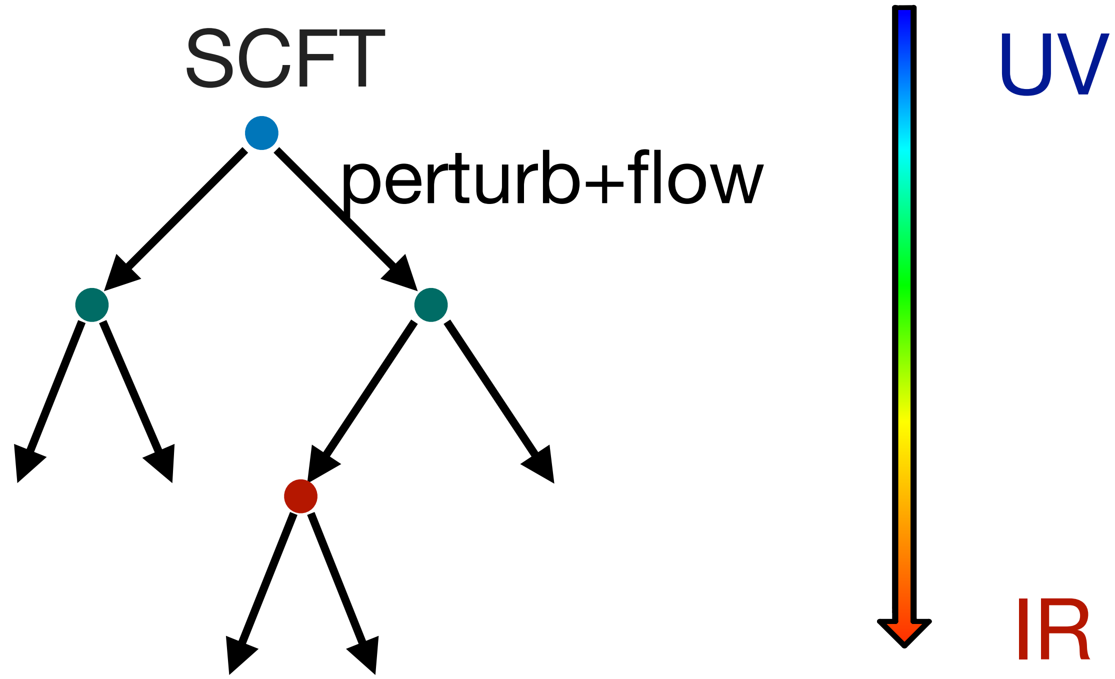


Motivating Question: Can we characterize / constrain the space of QFTs in various spacetime dimensions?

Lamposts in the space of QFT

- Restrict to SUSY + conformal symmetry = SCFT, use the **superconformal algebra** to derive exact results.

- Map SCFTs and their deformations to start to explore the landscape of QFT.



My work: explore the landscape of $\mathcal{N} = 1$ SCFTs in 4d.

[Maruyoshi, **EN**, Song '18 + in progress]

String theory is a powerful tool to generate/study QFT

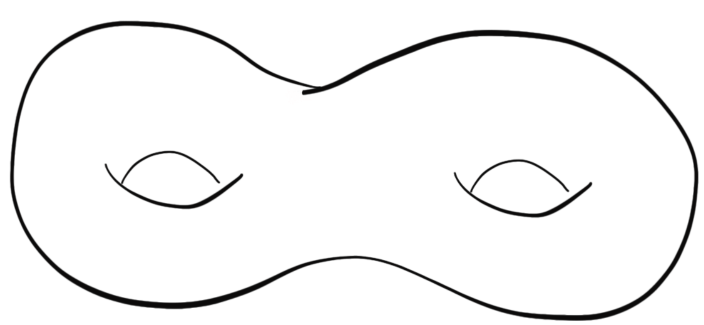
- Many nontrivial, strongly coupled QFTs arise as the low energy limit of **brane configurations** in string theory.

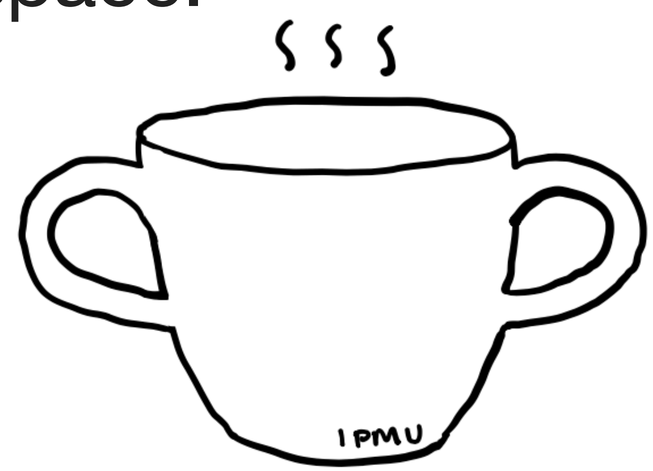
10/11 dimensions

↓ shrink (10/11-*d*) dimensions

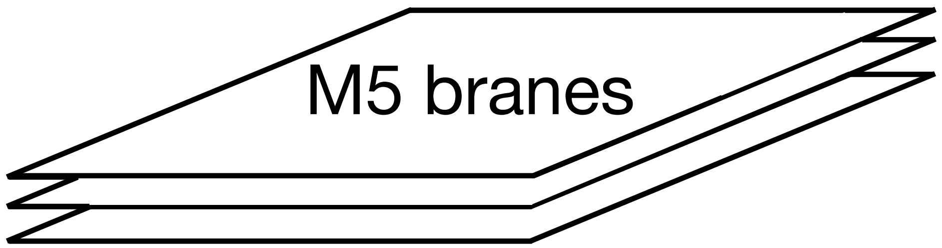
d dimensions

- The *d*-dimensional QFT is characterized by the **topology** of the (10-*d*)-dimensional internal space.





Arena of geometric engineering

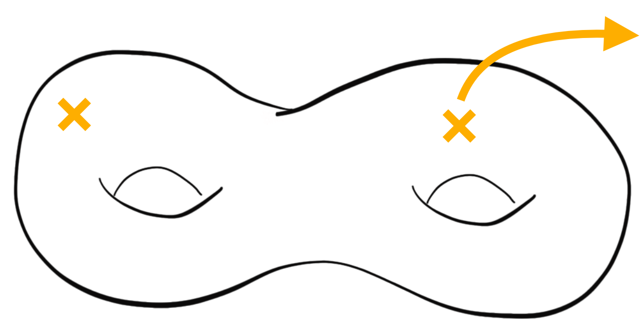


worldvolume limit

6d SCFTs (non-Lagrangian! Big breakthrough of the ~90s)

[Witten] [Strominger] [Seiberg] …

compactify on Riemann surface



4d flavor symmetry

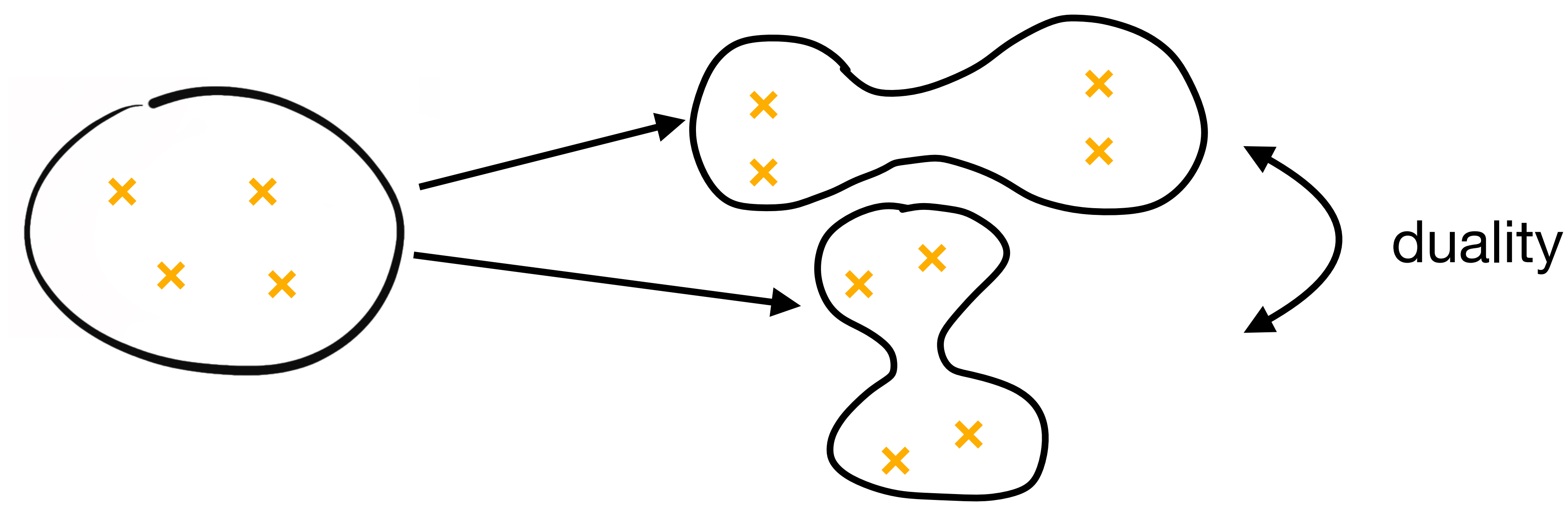
4d SCFT (generically strongly coupled!)

[Gaiotto] [Gaiotto, Moore, Neitzke] [Chacaltana, Distler]…

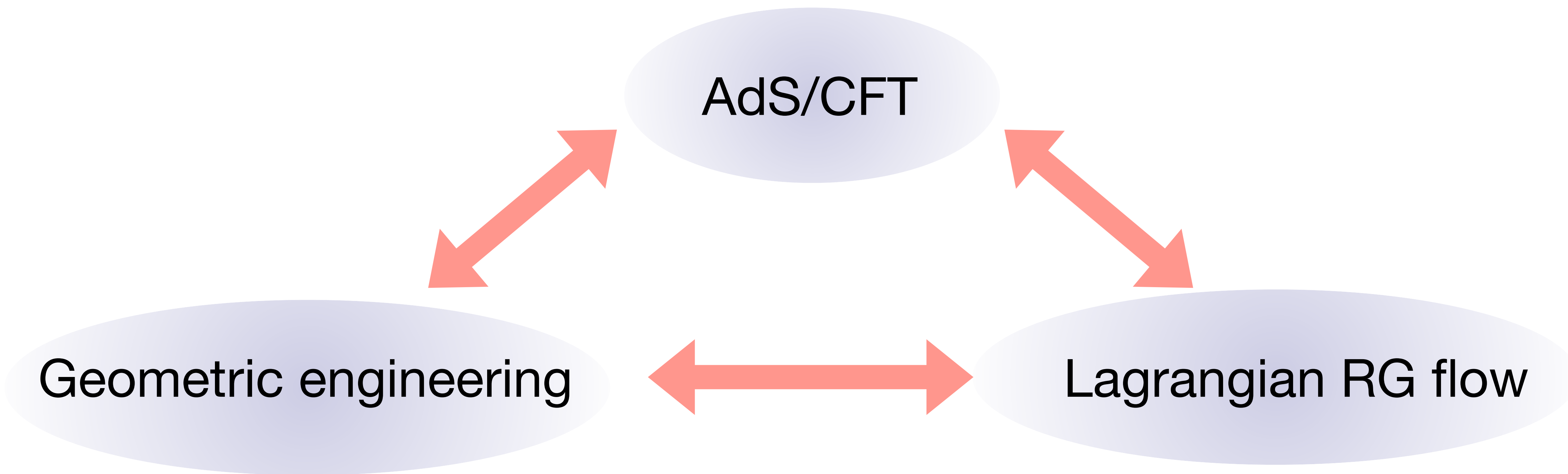
Using geometry to learn about QFT

- This allows us to organize a large space of 4d SCFTs geometrically.
- Provides a geometric interpretation of QFT properties (*e.g.* duality!)

Degeneration limits of the Riemann surface = Dualities of 4d QFTs



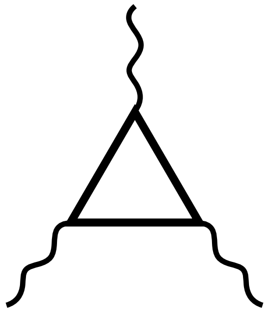
Complementary perspectives yield more insight



e.g. [Bah, Bonetti, Minasian, **EN** '21]

Computing observables

- How to compute observables (operator dimensions, indices, central charges, global symmetries, …)?
- An important observable: **anomalies.**
    - A symmetry has an anomaly when it is conserved classically, but not quantumly.



    - Anomalies in global symmetries can lead to interesting constraints on the QFT, since they are invariant under RG flow.

Anomalies from geometric engineering

- Anomalies are inherently **topological** quantities: encapsulated by a d+2 form **anomaly polynomial** built from characteristic classes.
- Can build a systematic geometric toolkit for computing anomalies in QFTs obtained from wrapped M5-branes.

[Bah, Bonetti, Minasian, **EN** ’18, ’19]

Summary

- The full nature of QFT remains an open question.
- We can make progress in understanding strong coupling phenomena by harnessing symmetries, especially supersymmetry + conformal symmetry.
- In geometric engineering we can develop new tools based on geometry to study a large class of strongly coupled QFTs.
- There is a vast landscape still to explore…

Thank you!