On the space of quantum field theories

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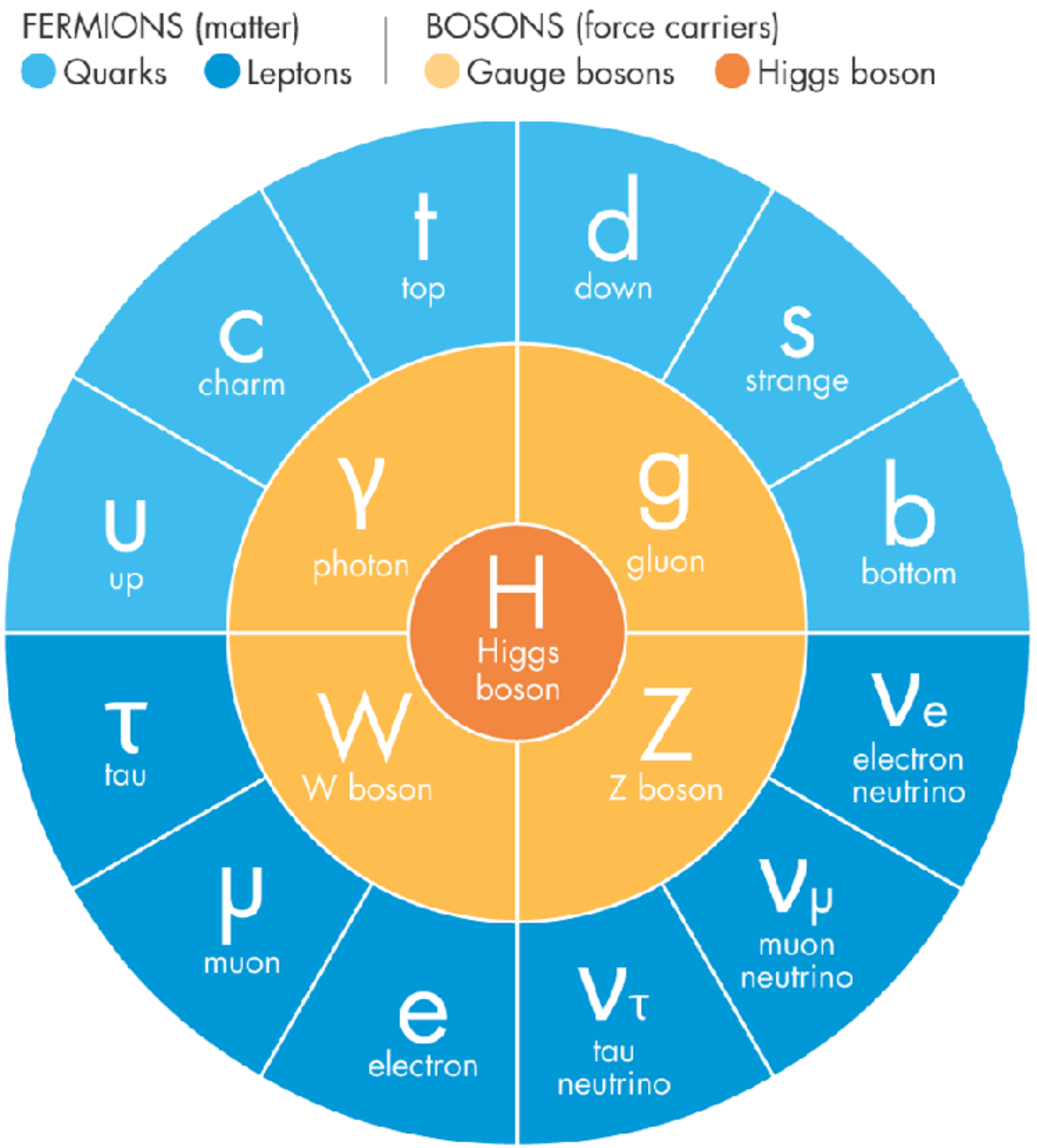
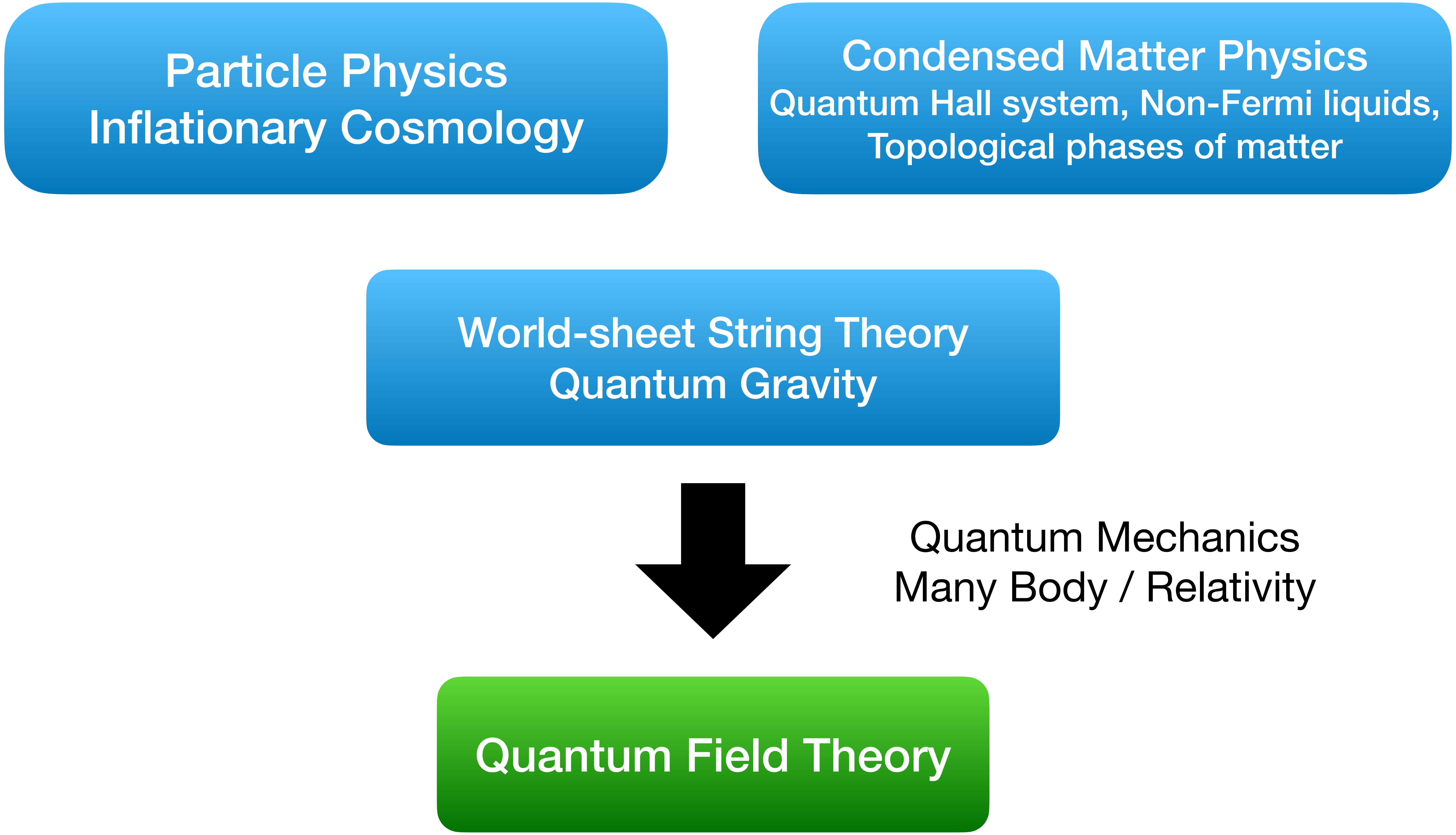
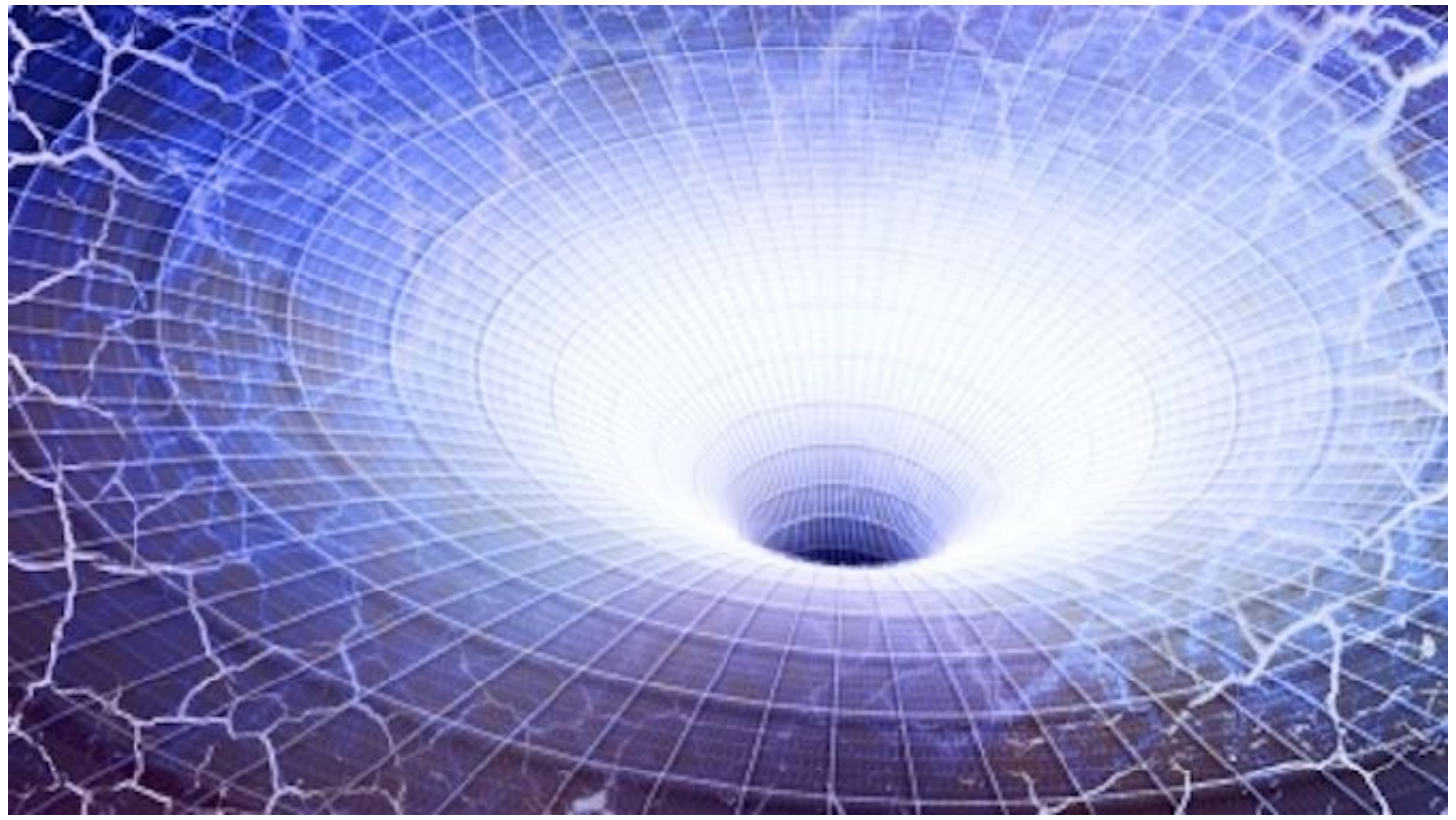
Why quantum field theory?

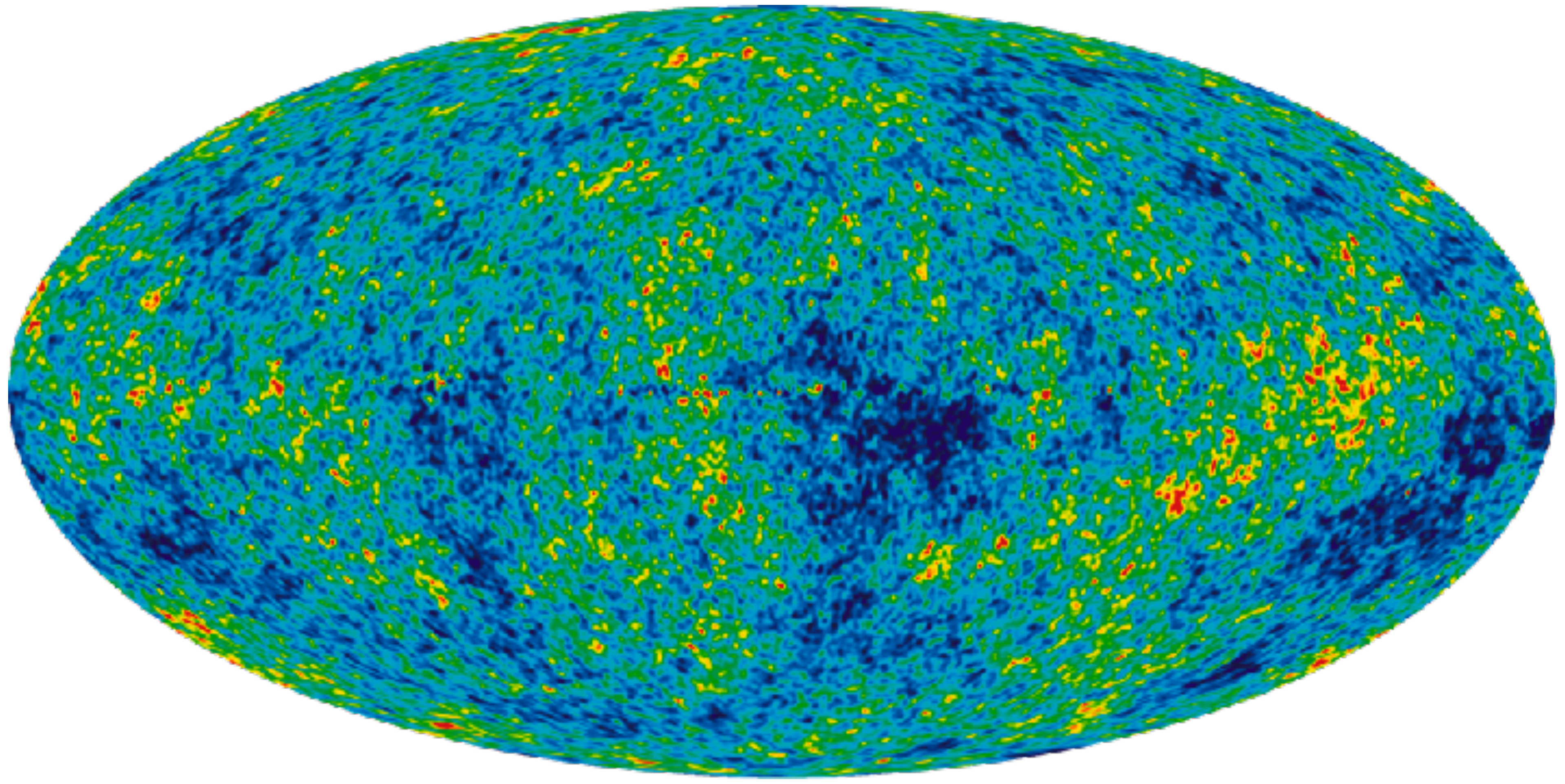
- Nature is described in terms of quantum field theory.
- Standard Model of Particle physics is spectacularly successful.
- (Almost) No experimental signature that violates the Standard Model.
- QFT arises naturally when we consider a relativistic quantum system.

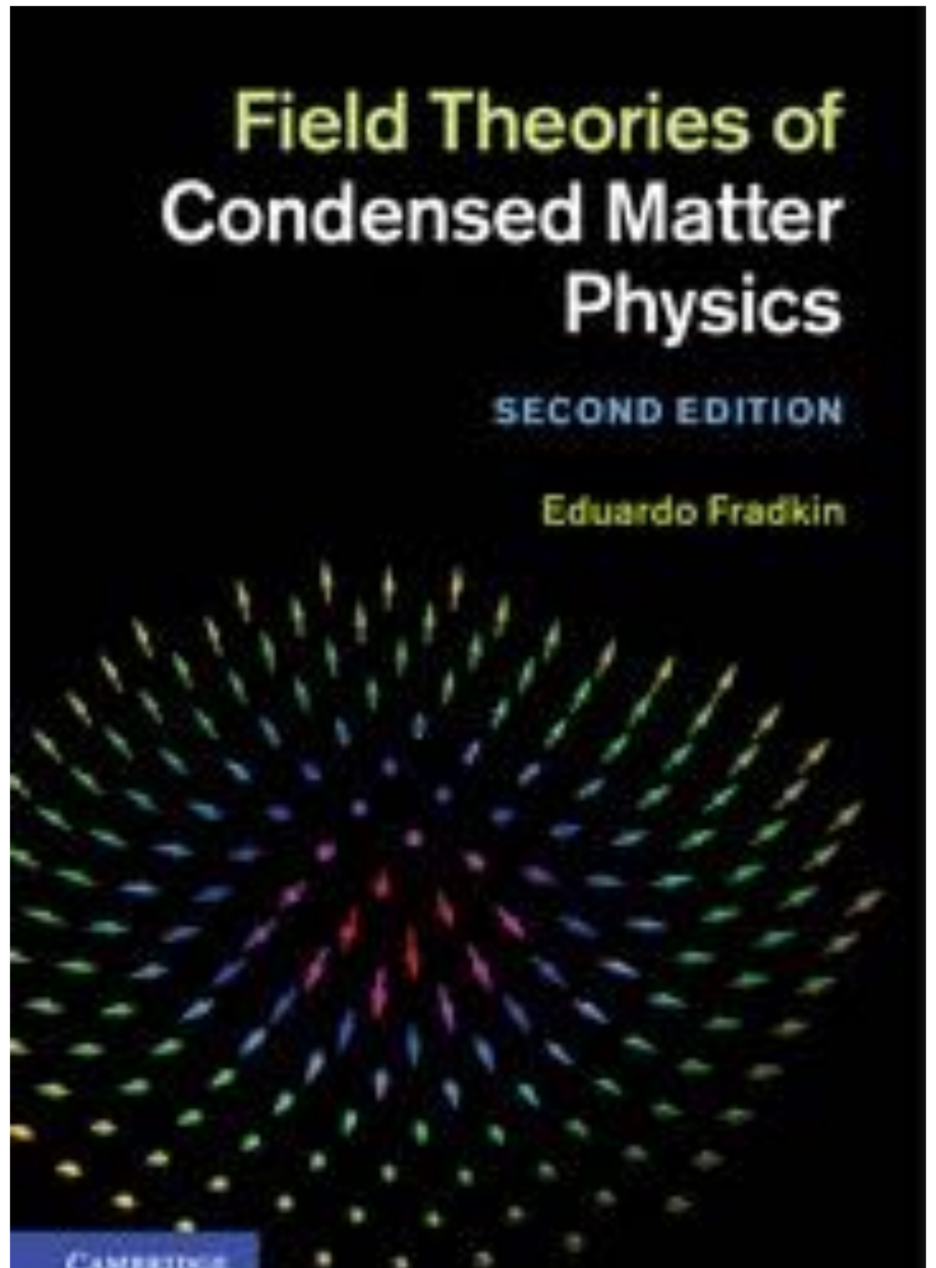



Particle Physics
Inflationary Cosmology
Condensed Matter Physics
Quantum Hall system, Non-Fermi liquids,
Topological phases of matter
World-sheet String Theory
Quantum Gravity
Quantum Mechanics
Many Body / Relativity
Quantum Field Theory

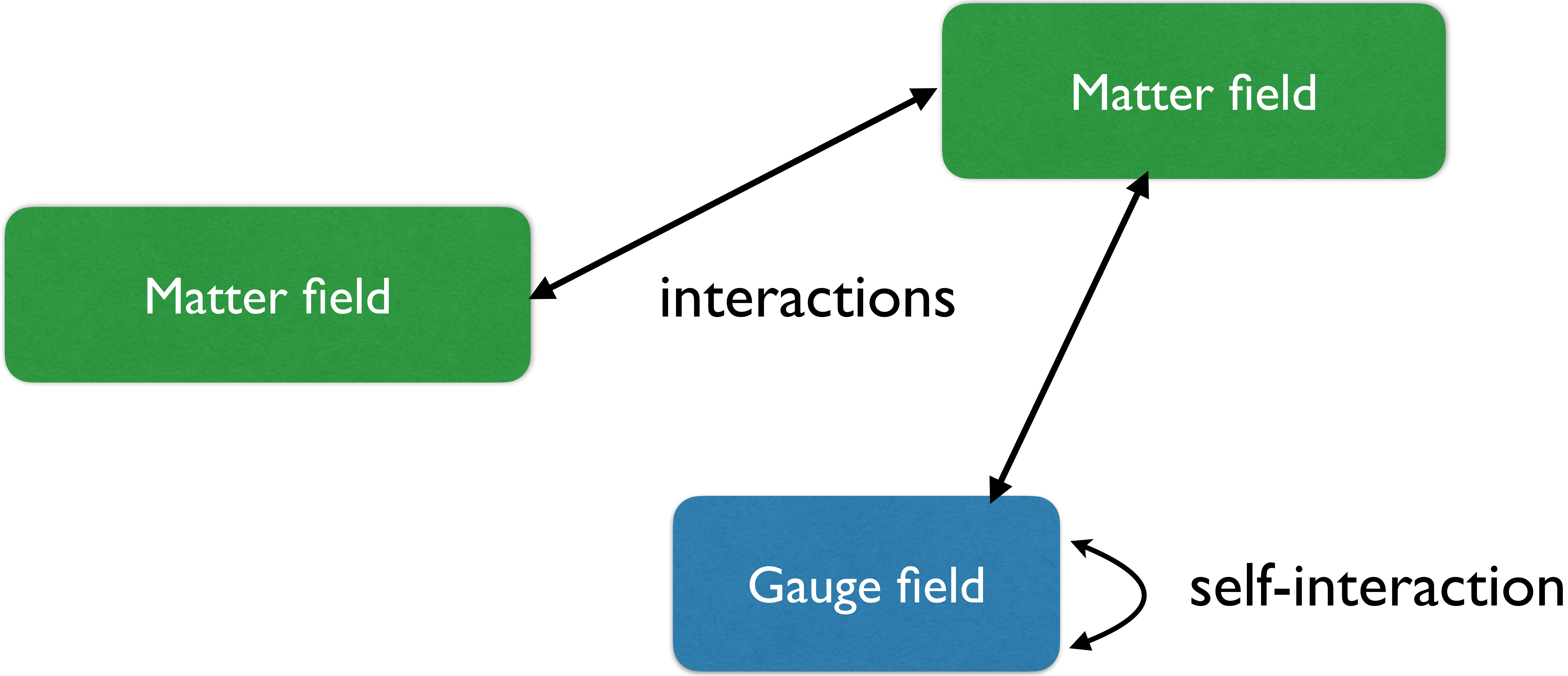


Quantum field theory is a universal language of theoretical physics





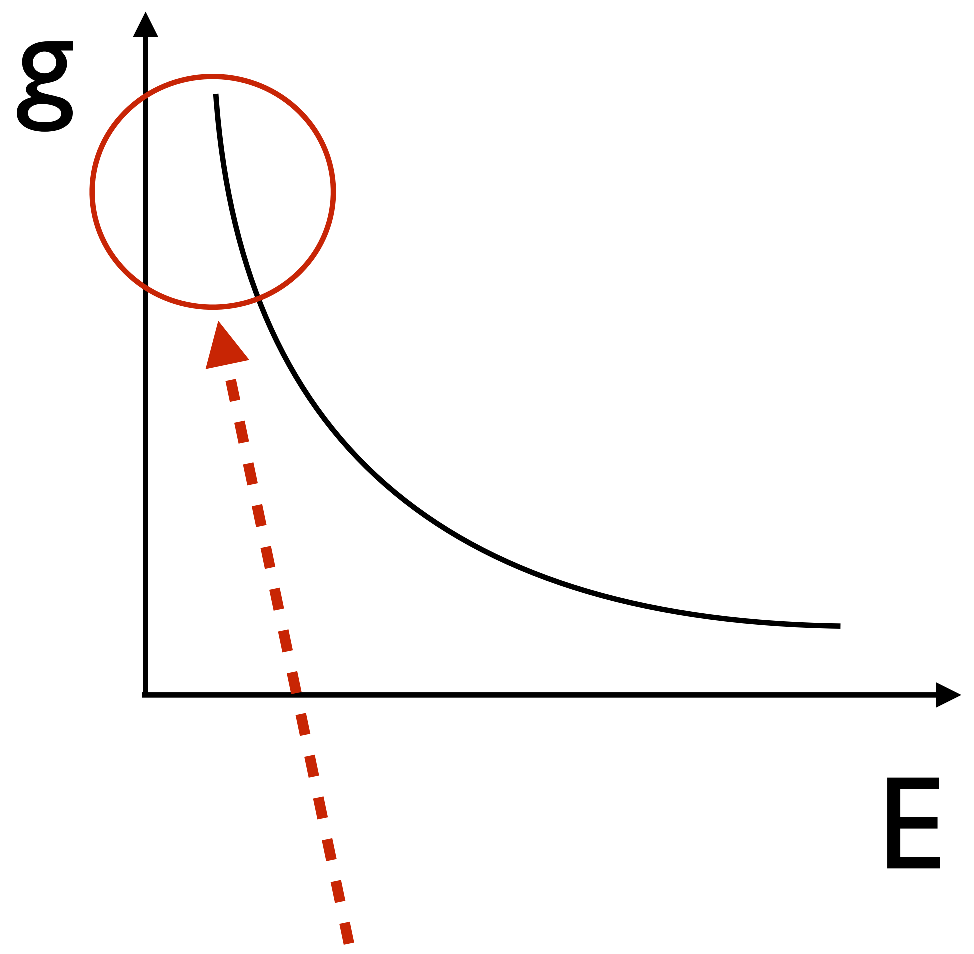
Typical structure of a QFT



When the interactions are weak, one can use perturbation theory.

Challenge: strong coupling

- **Strong-coupling dynamics** underlie the most challenging questions in physics.
  - Color confinement
  - Black Holes
  - High-temperature superconductivity
  - Fractional quantum Hall effect



Perturbation theory
not applicable here.

Challenge: Quantum systems with no path-integral description

- Conventionally, QFT is defined in terms of a path-integral over the field configurations.

$$Z = \int [D\phi] e^{iS[\phi]} \qquad \langle \mathcal{O} \rangle = \int [D\phi] \mathcal{O} e^{iS[\phi]}$$

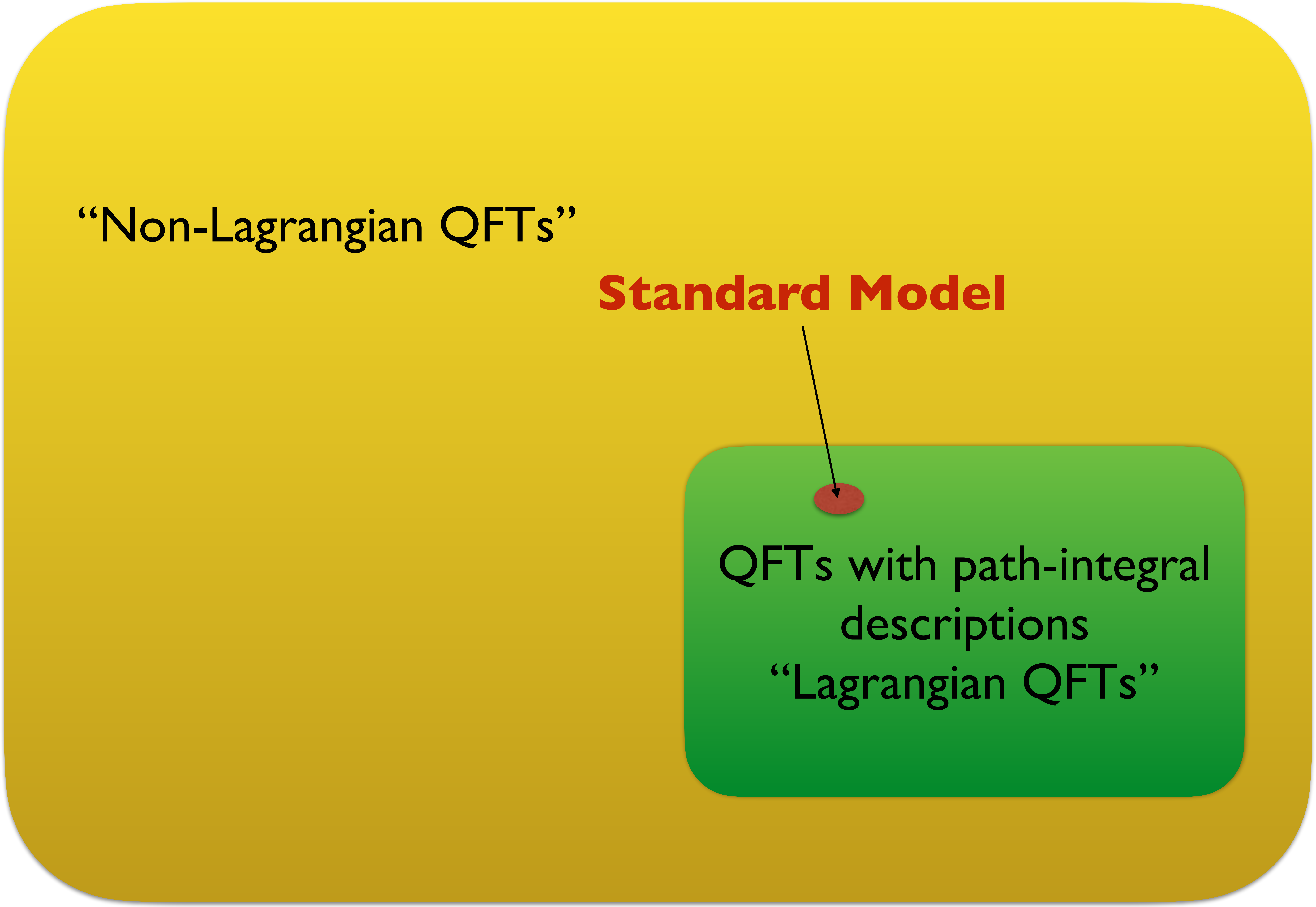
- Recently, it became evident that there is a vast landscape of QFTs with no path-integral formulation!

- Sometimes called “**non**-Lagrangian” theories.

Examples of “non-Lagrangian” QFTs
- partial list of such theories

- 4d Argyres-Douglas theory [Argyres-Douglas ’95]…
- Limits of string/M-theory compactifications at strong coupling.
  eg) 6d $\mathcal{N}$=(2, 0) theories [Witten ’95], $E_{6,\,7,\,8}$ theories [Minahan-Nemeschansky ’97]
- Certain QFTs at infinite coupling limits. [Argyres-Seiberg ’07][Gaiotto ’09]
- CFT duals of numerous supergravity solutions with AdS geometry.
- 4d $\mathcal{N}$=3 SCFTs [Garcia-Etxebarria & Regalado ’15]
- the list goes on and on… and it is growing very rapidly!

The space of QFTs



- There is no reason to believe that every physical system can be written in terms of free fields + interactions.

- There may be a strongly-coupled quantum system that exists in nature that does not allow a path-integral description.

- We have to consider such QFTs and search for a way to understand them.

- Let me illustrate this point by focusing on a simple quantum system, which exemplifies the limitations of the conventional paradigm for the QFT.

Electric-Magnetic duality

$$\nabla \cdot E = \rho$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times B = J + \frac{\partial E}{\partial t}$$

$$\Longrightarrow$$

$$\nabla \cdot E = \rho_e$$
$$\nabla \cdot B = \rho_m$$
$$\nabla \times E = -J_m - \frac{\partial B}{\partial t}$$
$$\nabla \times B = J_e + \frac{\partial E}{\partial t}$$

If there is a magnetic monopole, the Maxwell's equations are modified.

It is invariant under the duality transformation

$$E \to -B \quad B \to E$$

Magnetic monopoles

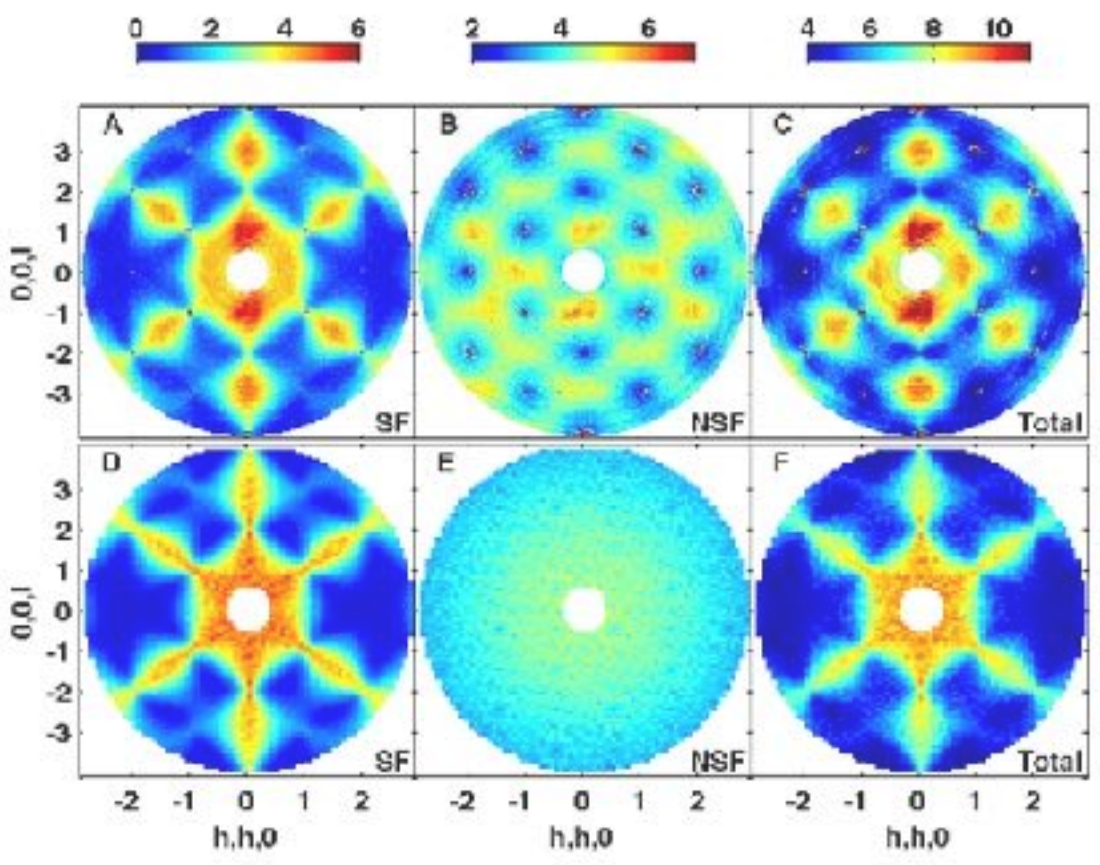
- Magnetic monopole can be realized theoretically (and experimentally!).

[t' Hooft-Polyakov]

- Grand Unified Theory: Created when the universe undergoes a phase transition from Grand Unification to Electroweak epoch.

- It exists in a condensed-matter system as a collective-excitation. (experimentally realized!)

- They are indispensable in string theory.



[Fennel et al, Science '09]

Electron-Monopole system

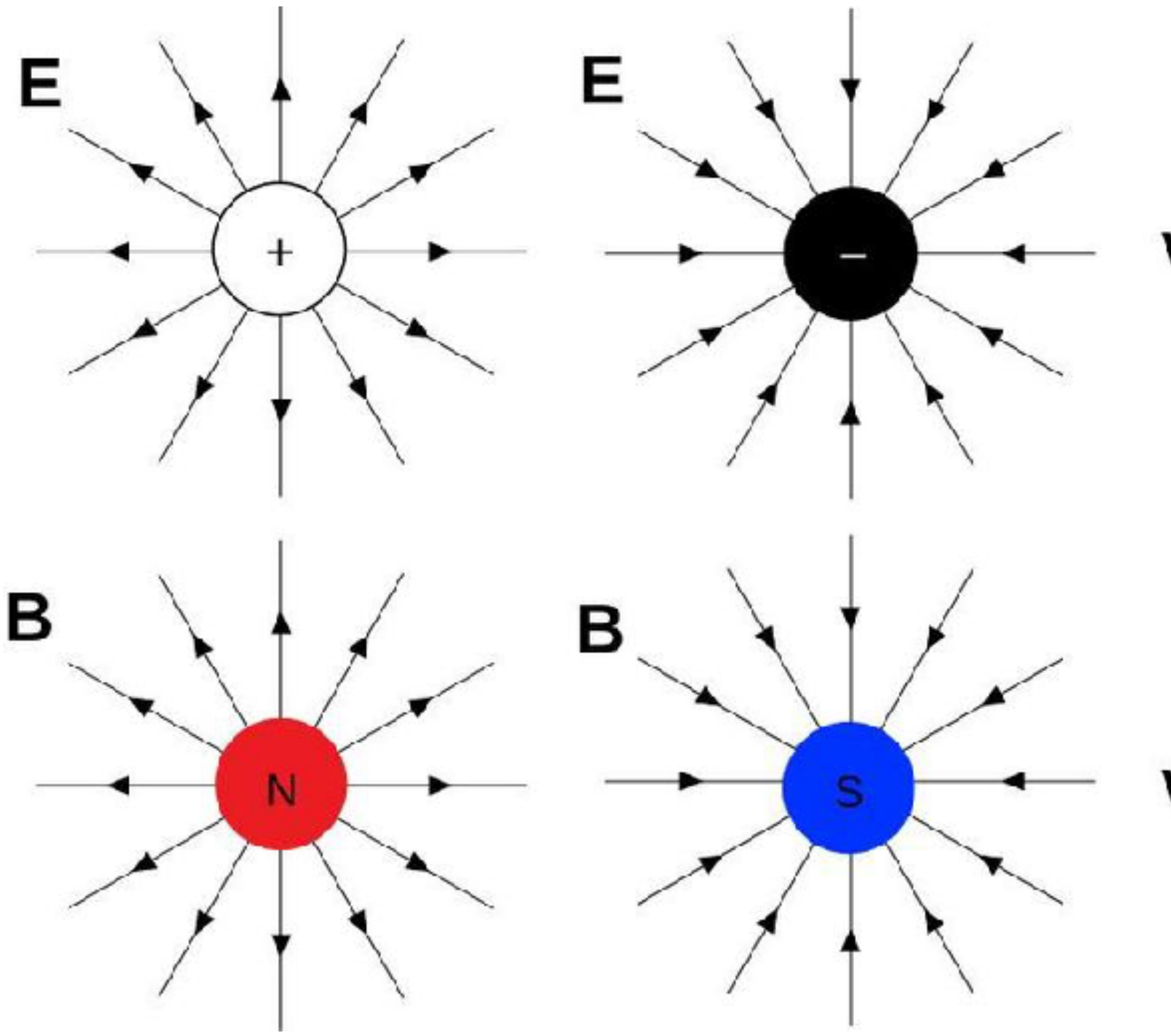
A simple toy model QFT?

- Consider a field theory with massless electron and monopole interacting via photon.

- Possibly the simplest interacting QFT.
  (no non-abelian gauge bosons)

- It is ***very difficult to construct such a QFT*** having (light) electrons and monopoles simultaneously.
  [Dirac '30][Schwinger '60][Zwanziger '60]

- Is it a fundamental limitation of **Nature** or just a short-coming of the gauge theory **description**?



The electron-monople QFT is strongly-coupled

- Such a system is **inevitably strongly-coupled**, due to the Dirac-quantization condition:

$$eg = 2\pi\hbar n\ , \quad n \in \mathbb{Z}$$

- This QFT (if it exists) **does not have a classical limit**!
No Lagrangian. No path-integral formulation.

- [Argyres-Douglas '95] showed for the first time that such a QFT (with extended supersymmetry) **indeed exists**.

- This type of 'non-Lagrangian' QFTs play a prominent role in understanding strong-coupling phase of string/M-theory.

So, what should we do to understand this theory?

One way: Find a Lagrangian!

(hey, didn’t you just say you can’t?)

It was recently found that there exists a Lagrangian theory that flows to the enigmatic Electron-Monopole theory!

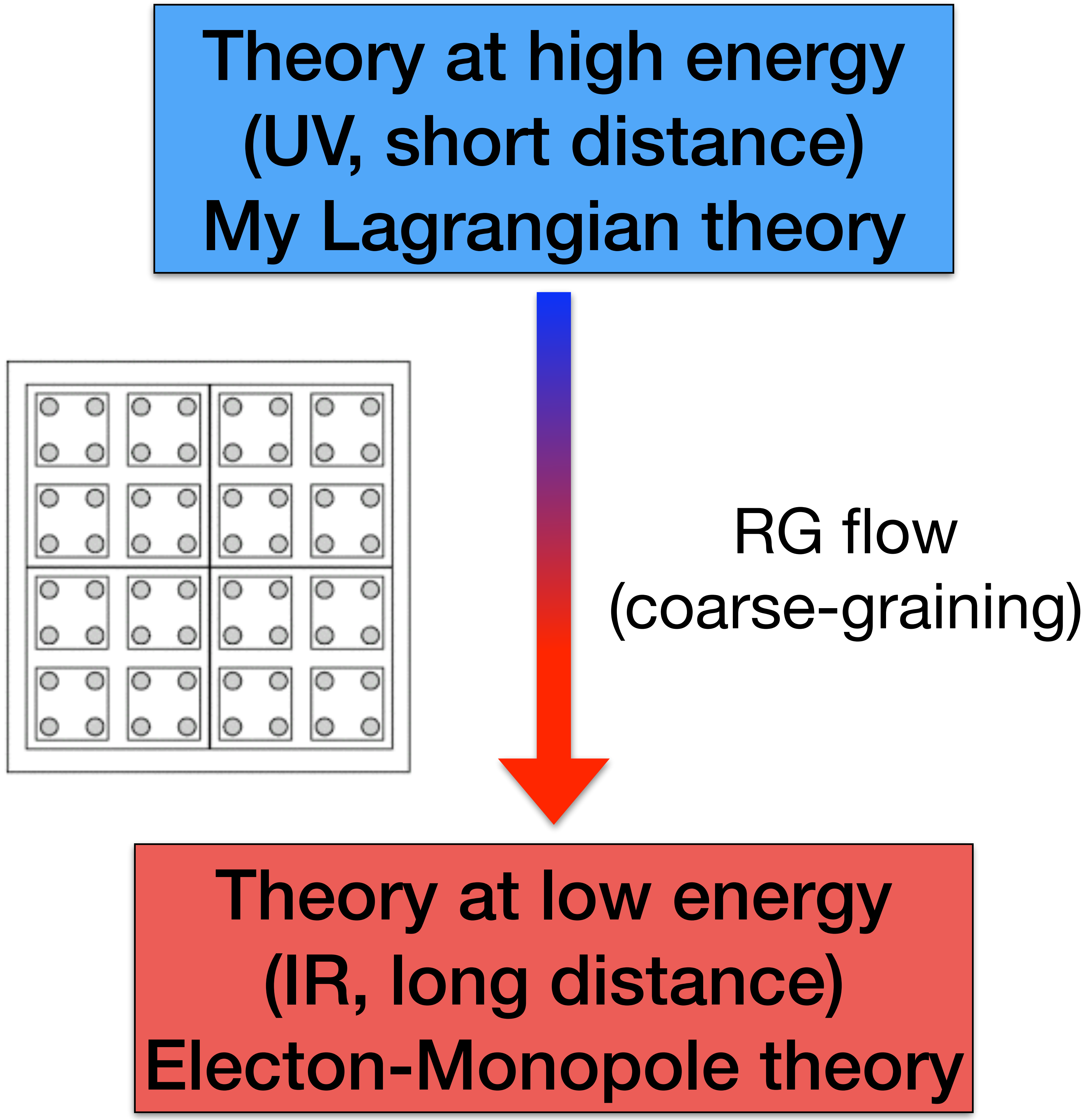
[Maruyoshi-JS '17]

A "Lagrangian" for a "non-Lagrangian" theory

What does it mean?

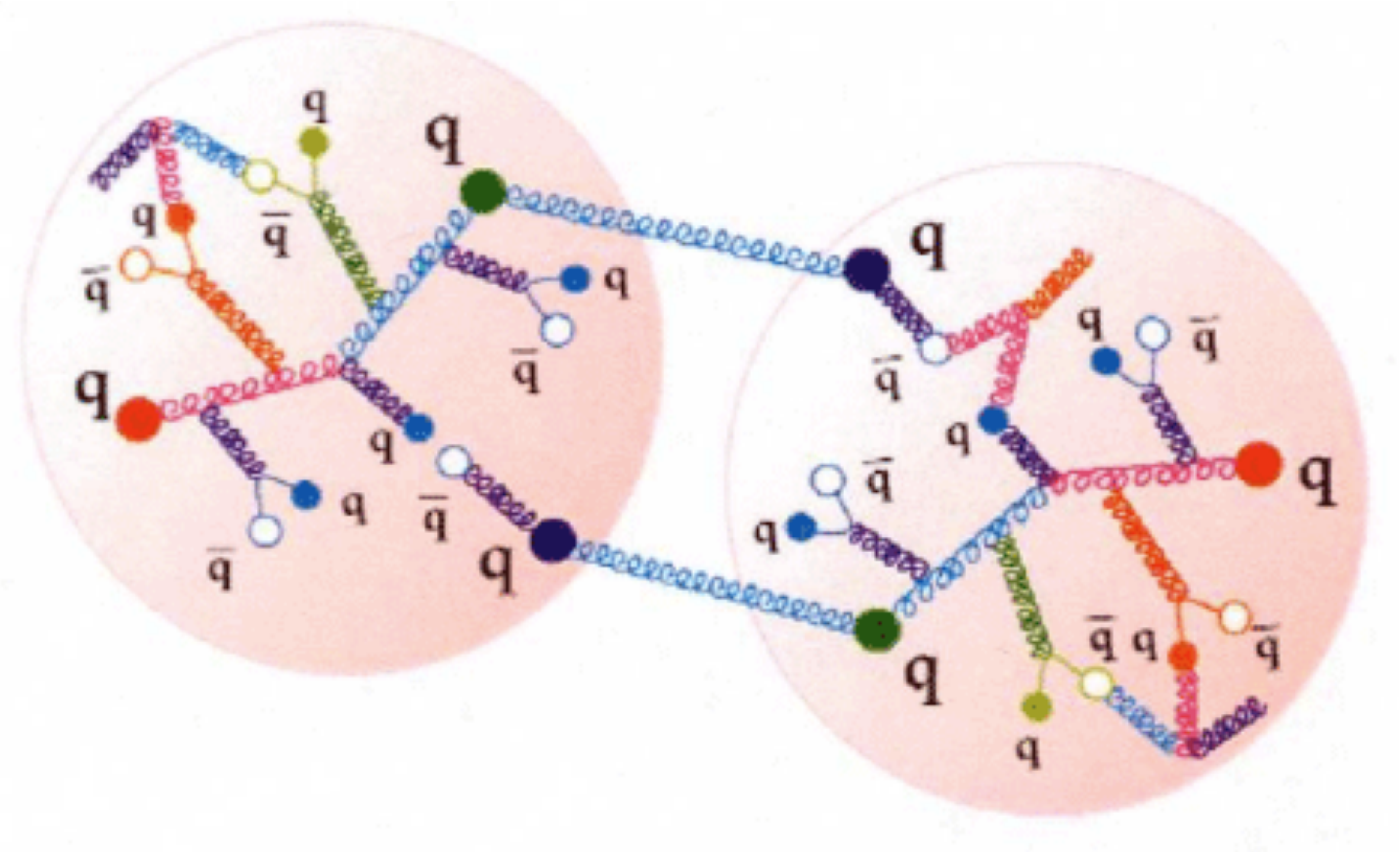
Wilsonian Renormalization Group (RG) Flow

- Start with a theory defined at short-distance. (UV theory)
- As one integrate-out the high-energy modes, the effective Hamiltonian/ Lagrangian change. “RG flow”
- There is a fixed point where the couplings no longer change. “IR fixed point”



It is analogous to QCD

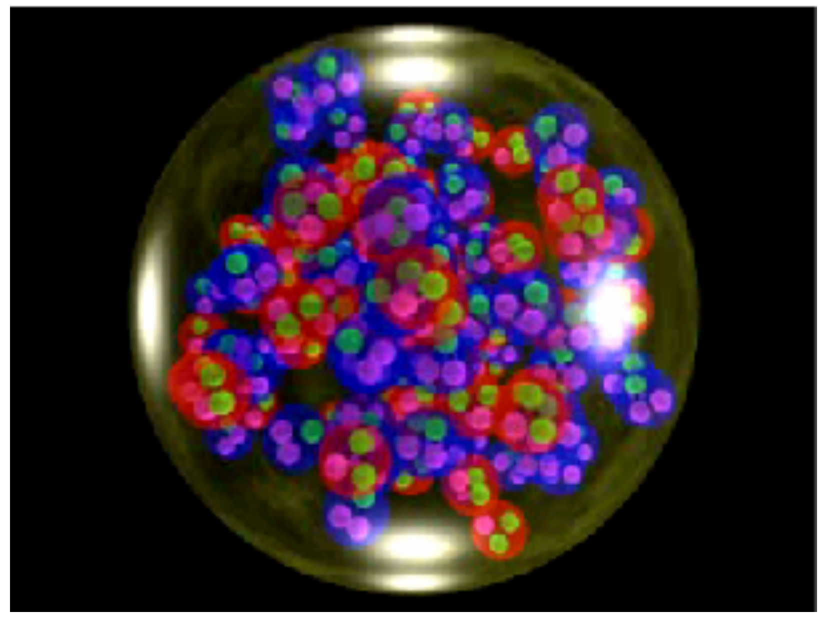
- Our theory provides a microscopic description for the “macroscopic” theory of monopoles and electrons.
- Analogous to the QCD (quark and gluon) as a microscopic description for the macroscopic proton and neutron.



The microscopic theory contains gauge bosons (‘gluons’) and matters (‘quarks’) similar to QCD.

No photon/electron/monopoles to begin with.

Photon/electron/monopole emerge at strong coupling!



(+ Emergent SUSY enhancement)

Monopole
Electron
Photon

↔

Composite of Quarks & Gluons

Such phenomenon is quite ubiquitous!

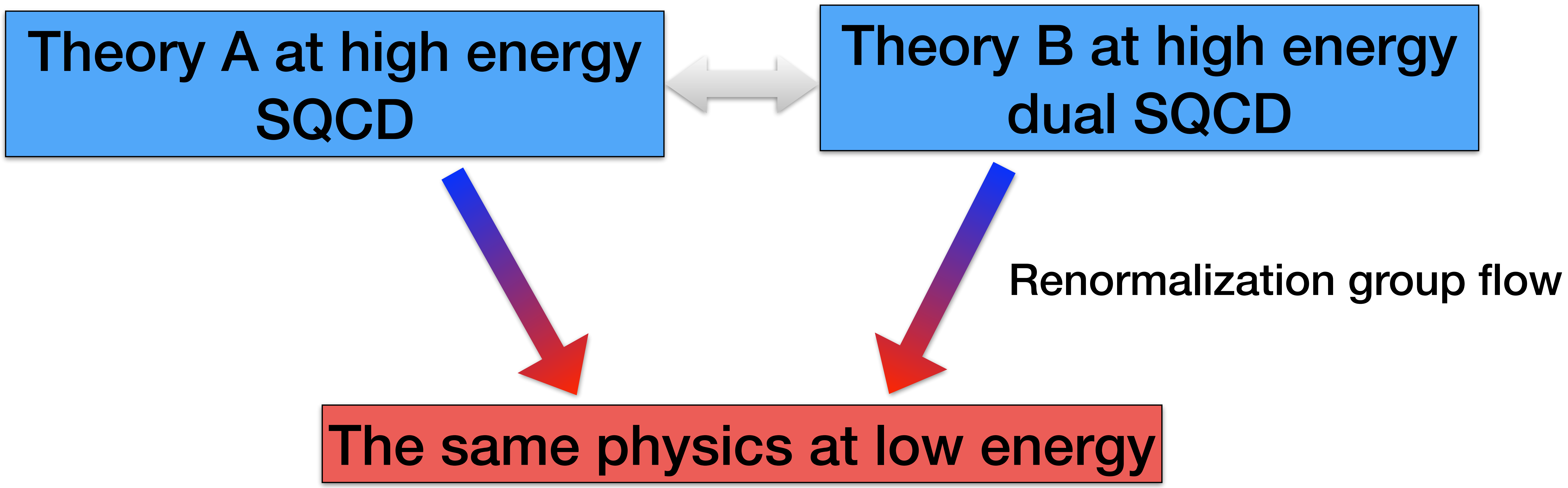
[Agarwal-Maruyoshi-JS][Benvenutti-Giacomelli]…
[Maruyoshi-Nardoni-JS ’19]
[Razamat-Zafrir][Agarwal-KH Lee-JS ’20]

What do they all mean?

Duality

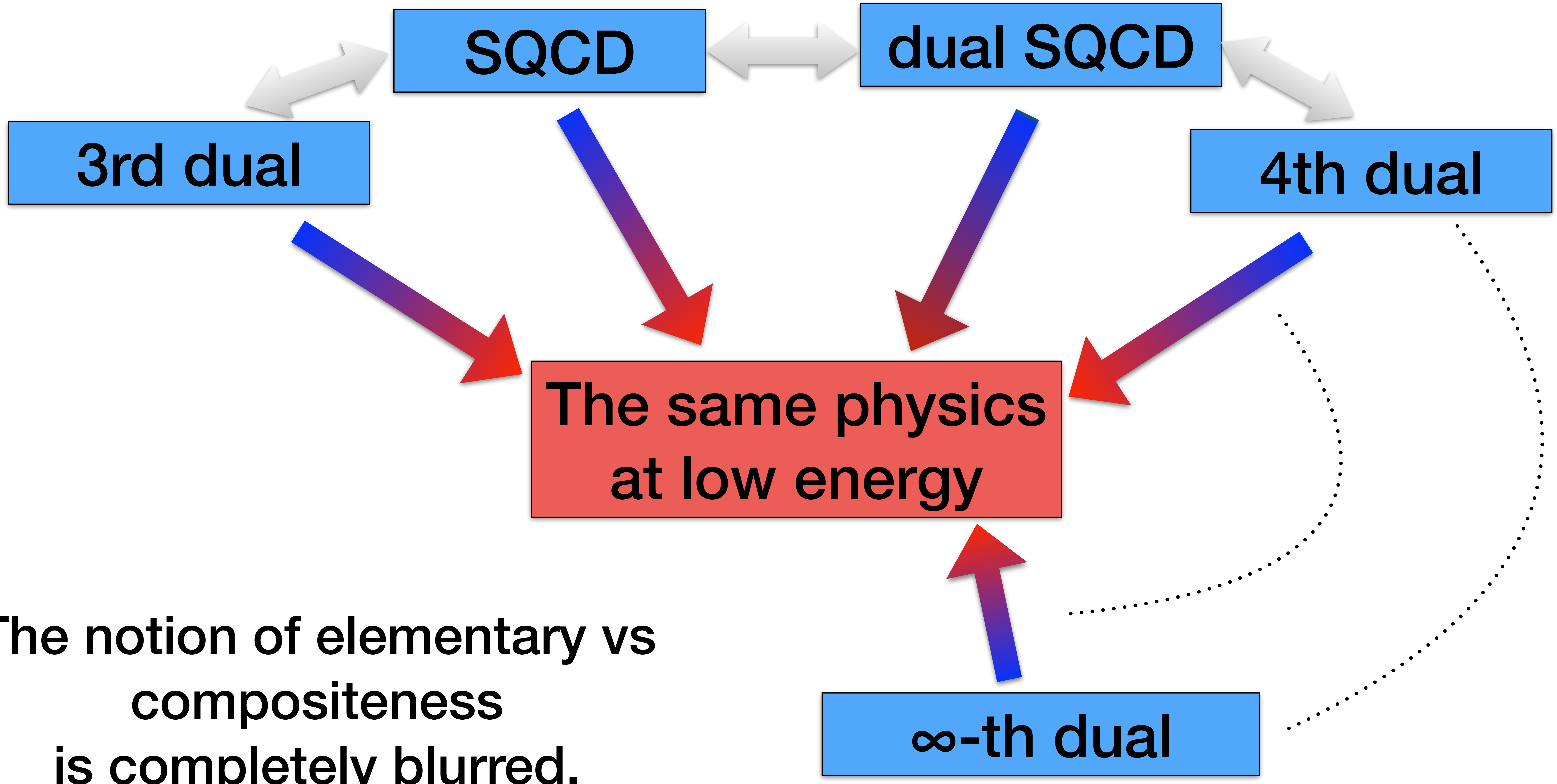
Equivalence of two seemingly different systems

[Seiberg]+…



Weak coupling $\Longleftrightarrow$ Strong coupling

Infinitely many dualities



The notion of elementary vs compositeness is completely blurred.

[Agarwal-Intriligator-JS]

Some implications

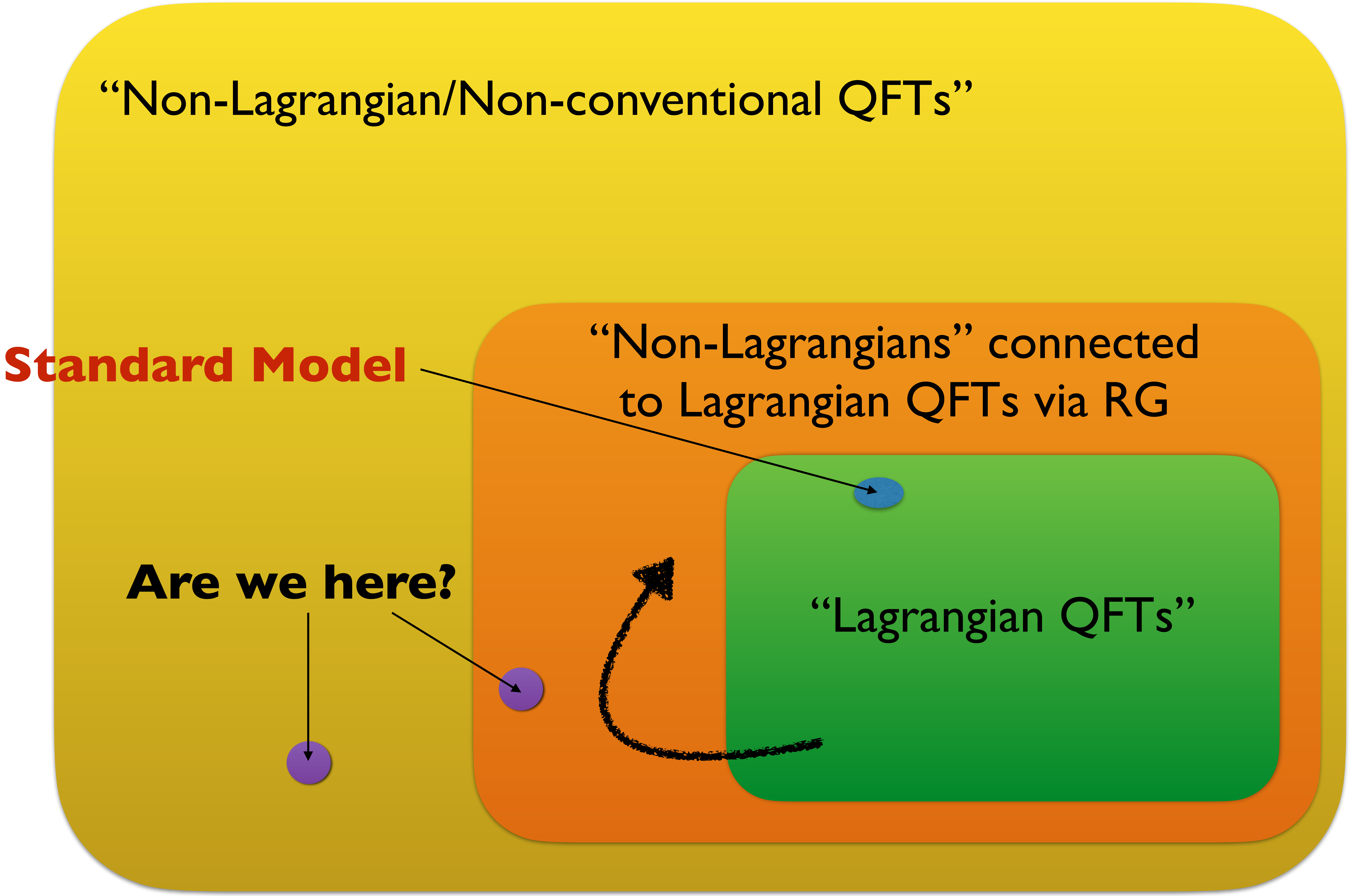
- What is the correct framework of quantum fields?

- No uniform way to describe a quantum system (QFT).
- The notion of elementary and composite is **arbitrary.**

- Conventional way (path-integral) does not fully capture the **power of QFT**.
- We *may* need an **entirely new framework** for the quantum field theories!

- It is **not Nature's limitation**, but our **lack of understanding**.
- Why should we care? Opportunity for **new physics**!

The space of QFTs



Conclusion

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- We know that quantum field theory works very well.
  (It is a universal language of physics)
- There exists **inherently quantum**, **strongly-coupled** QFT that has **no classical/weak-coupling limit**.
- Such “non-Lagrangian” QFTs are **ubiquitous** in the space of QFTs. We have to explore them. Chance for new physics?
- Need to develop new methods to study such theories.
- Quantum field theory is extremely versatile and rich. Exciting discoveries await us in the uncharted territory!