The Importance of Pure Theory

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Physics is an experimental science

Why do theory?

Because we are not smart enough!

Because we are not smart enough!

If we were, then we would derive immediately the consequences of experimental results.

Or we would immediately derive the consequences of our fundamental theories.

already a long time ago it was said…

The book of nature is written in the language of mathematics

Kepler, Galileo 1620s

Fundamental physics is described in the language of quantum field theory

20th century

This language is hard!

We need to understand it!

We need people who are fluent…

Interpreting experiments
takes a vibrant theoretical physics
community!

Theory can motivate new experiments

Grand goal of high energy particle physics

Find the quantum field theory describing nature

Particles and their interactions (presumes weak coupling, which is the case in the SM)

Understanding quantum field theory

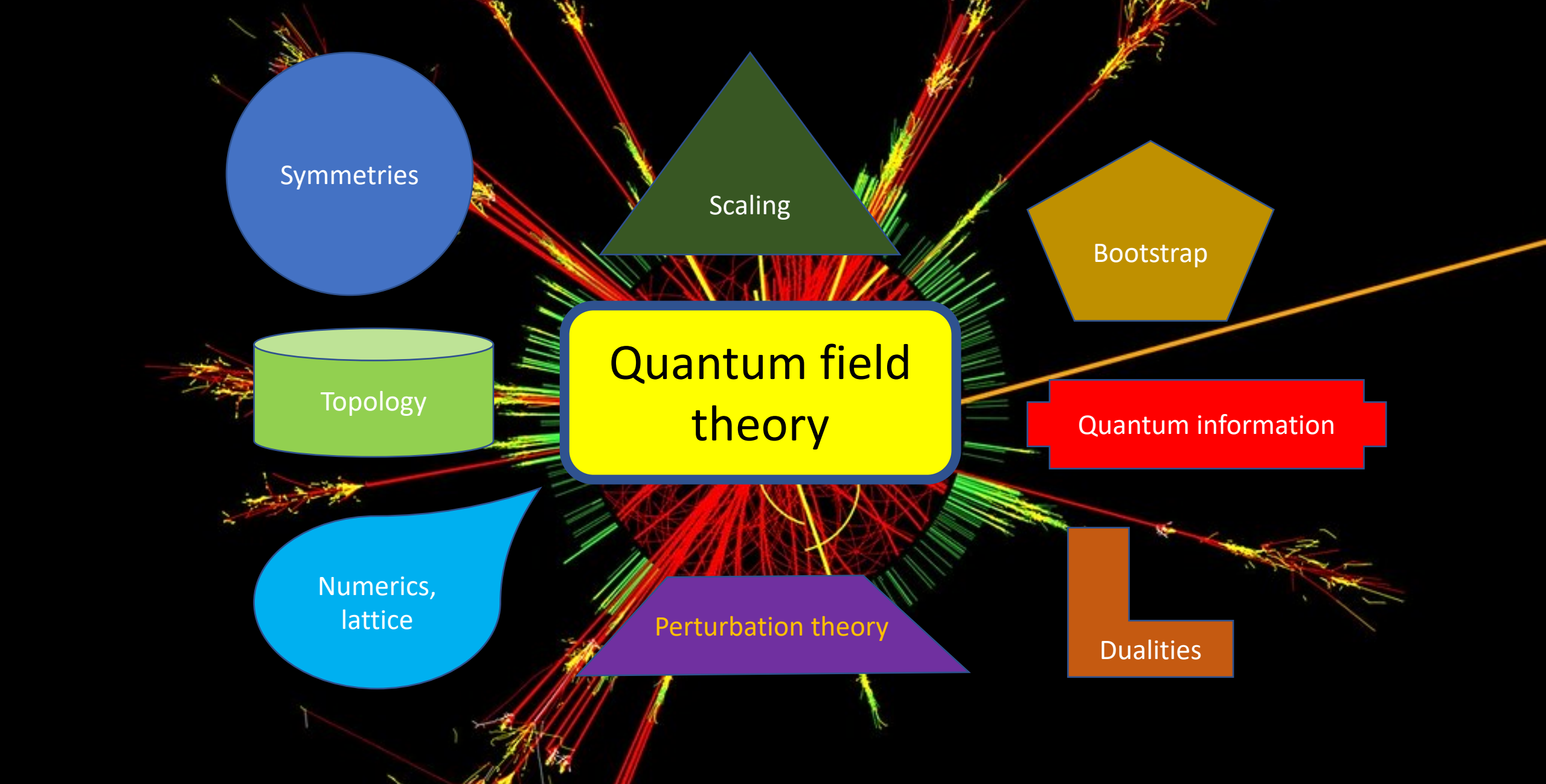
- Generate possible of QFTs.
- Doing computations in a given QFT.

Our basic laws are a bit like riddles:

If you solve this mathematical problem→ you can figure out what will happen in your experiment.

Basic tools

- Mathematical constraints → Unitarity, positivity, causality, (UV completion).
- Physical and phenomenological constraints → match experiments and observations.

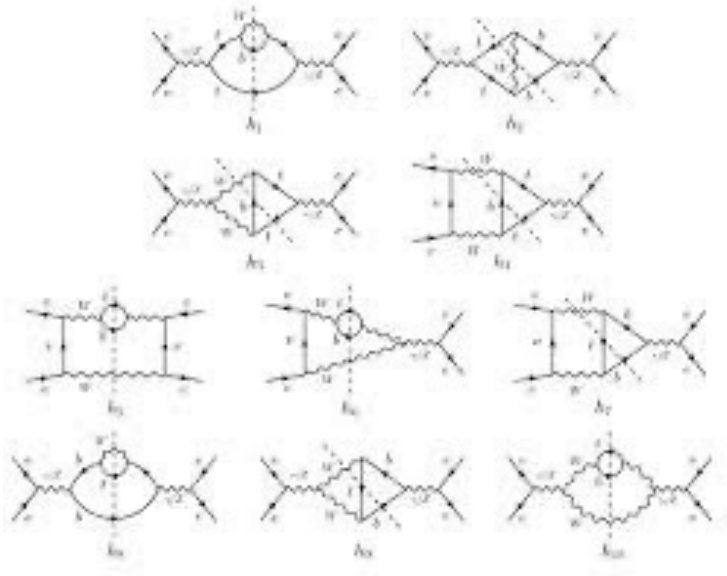


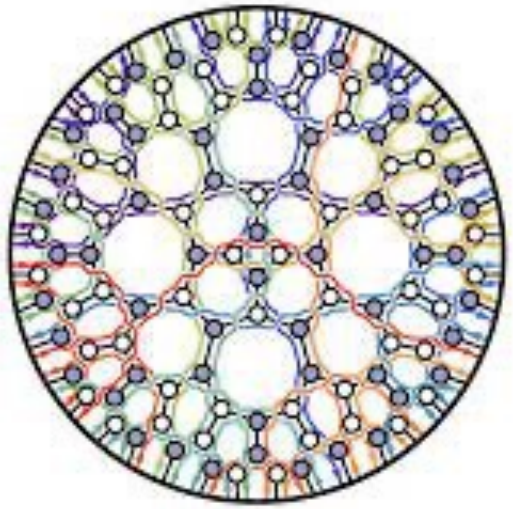
Different pieces of the puzzle

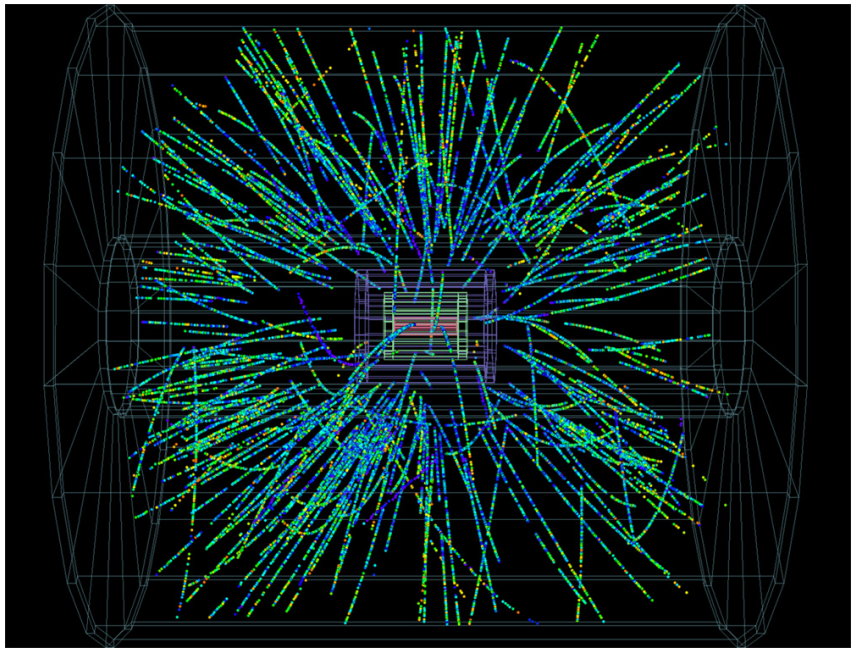
A few comments on some of them

Diving deep into perturbation theory

- Sophisticated mathematical ideas are turning into practical computational techniques for colliders.
- Twistors, Grassmanians, etc.



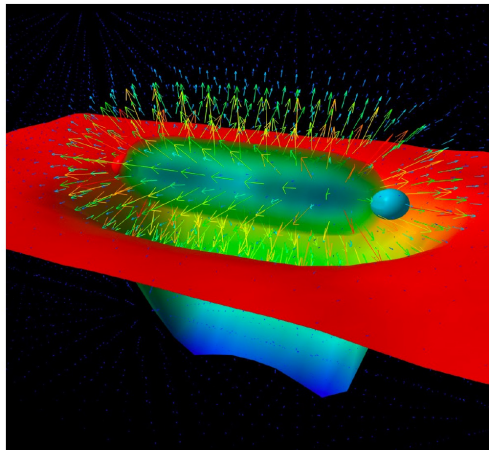




The strong coupling frontier

- How do we treat or analyze strongly coupled field theories?
  - We are lucky that the SM is weakly coupled.
  - But new physics could be strongly coupled. How do we explore it?
  - QCD becomes strongly coupled at low energies.

Confinement



- Confinement is essential for describing the real world.

- Can we understand it better? Conceptually and practically?
  - Lattice, quantum computers
  - Toy models (different dimensions, different matter contents, supersymmetry, large N)

A very basic tool..

Symmetries

- Conservation laws, selection rules.
- Spontaneous symmetry breaking.
- Anomalies
- Topology
- Larger gauge symmetries → GUT theories, etc.
- Supersymmetry.

- Emergent accidental symmetries.
  - Proton decay?

- Higher form symmetry.
- Integrability (in two dimensions, or in large N (planar) theories)

One symmetry plays a crucial role in QFT

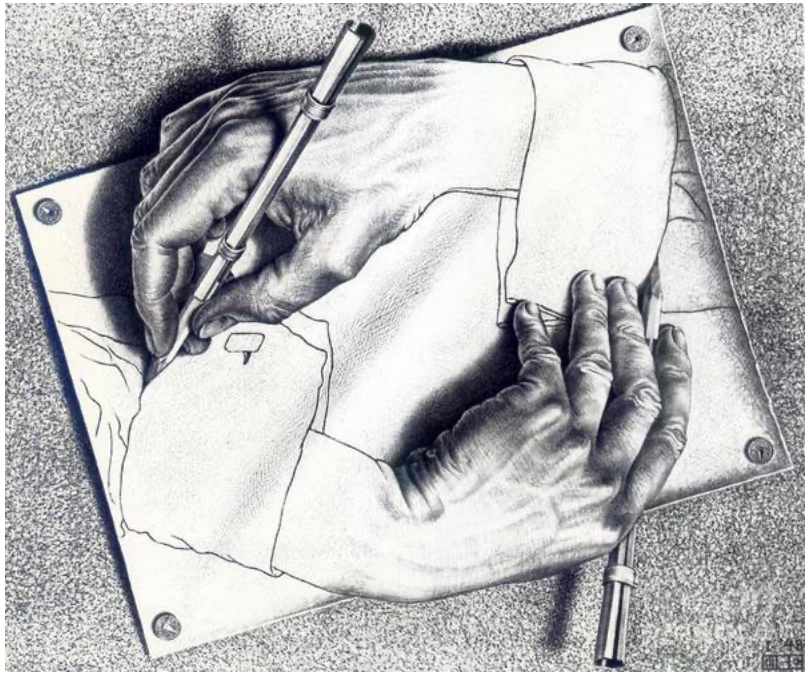
Scaling symmetries

- Scaling is an important symmetry, or approximate symmetry.

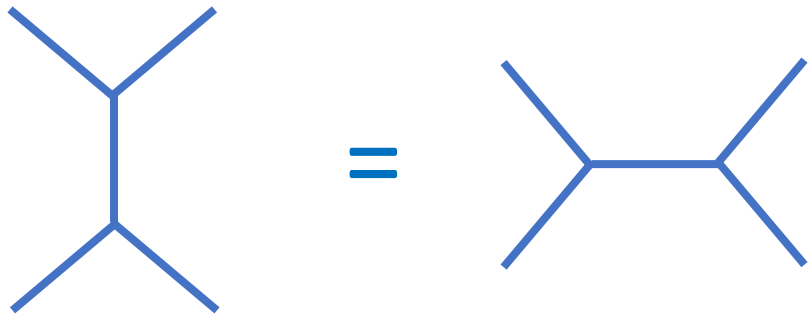
- Renormalization group.

Bootstrap ideas

- Exploiting mathematical consistency conditions to constrain theories strongly enough to get some predictions.



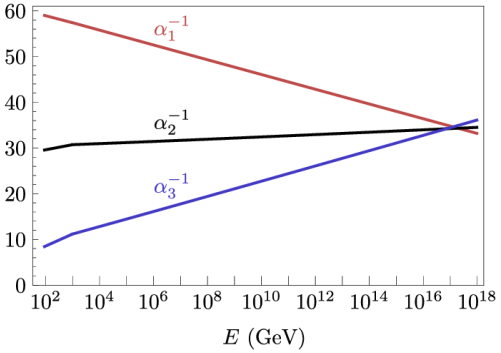
The conformal bootstrap



- Well established results in d=2
- Very interesting new tool to study CFTs in d>2. Concrete results in 2+1 and 3+1 dimensions.

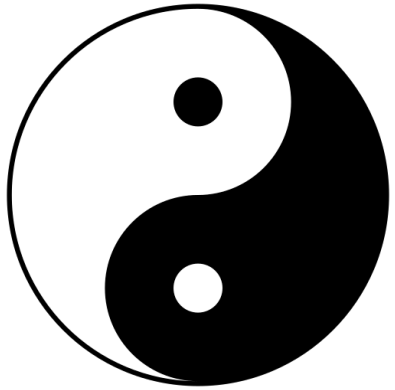
Supersymmetry?

- Solvable models
- Leads to exact solutions. Window to strong coupling.
- Useful for the exploration of many aspects of quantum field theory, confinement, dualities, amplitudes, collider physics, etc.
- Is it the ultimate explanation of the electroweak hierarchy?



Dualities in quantum field theory

- Strong coupling → weak coupling.
- Complicated → Simple.
- Connections with condensed matter physics.



Tools from quantum information

beyond quantum simulations…

Quantum field theory through the lens of quantum information

- How does quantum information constrain QFT?
  - Puts some order in the renormalization group flows.
  - Subtle positive energy conditions.

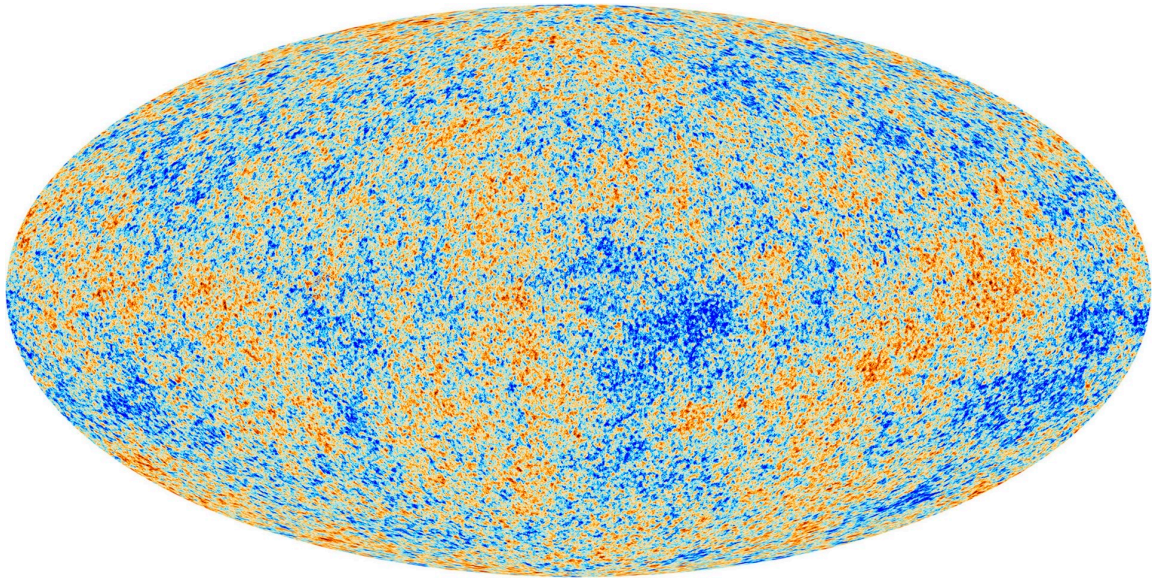
Let’s pause for a comment…

...but theorists have their heads in clouds..

Satellite view : connecting different ideas

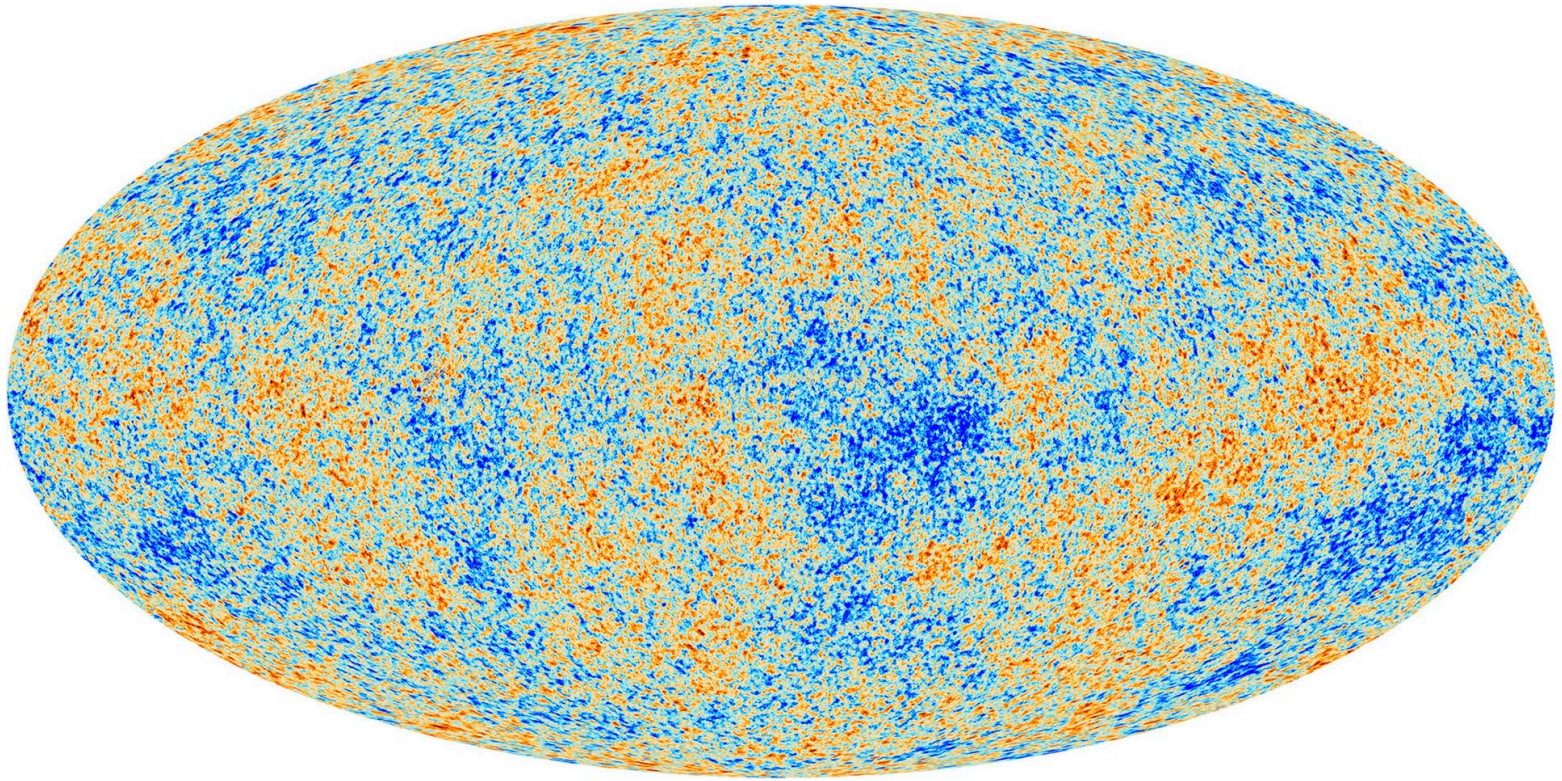
An interesting example is the following

Primordial density fluctuations in cosmology



Theory of inflation developed in the 80’s

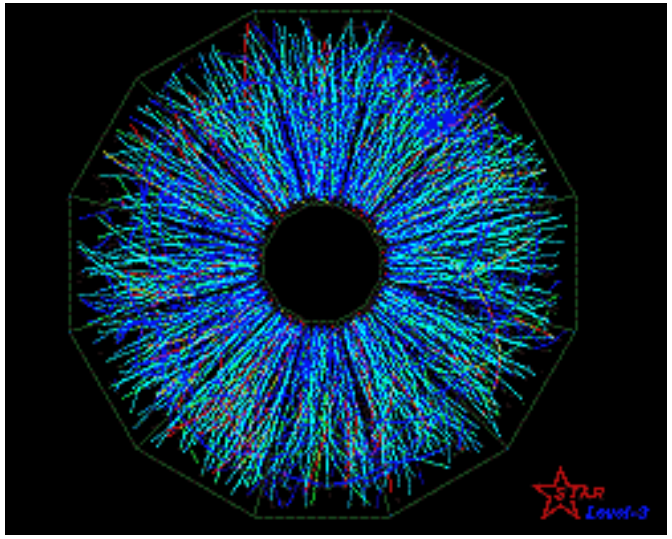
Primordial density fluctuations in cosmology



The shape of the universe is a snapshot of a quantum field !

Inflationary primordial fluctuations

- Quantum field theory techniques → tools for computing subtle signals.



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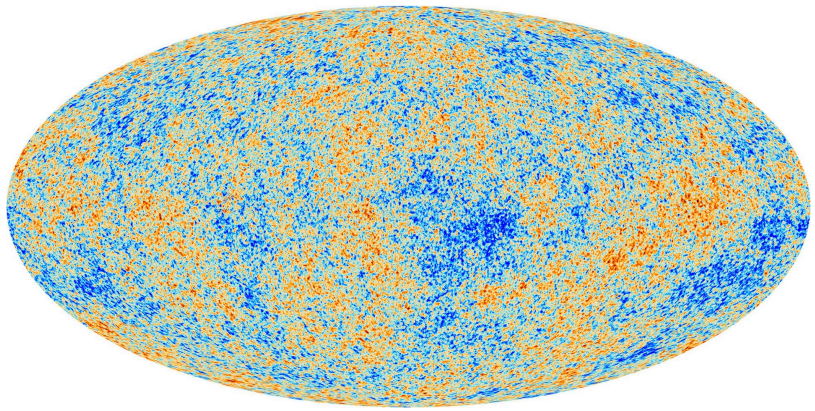
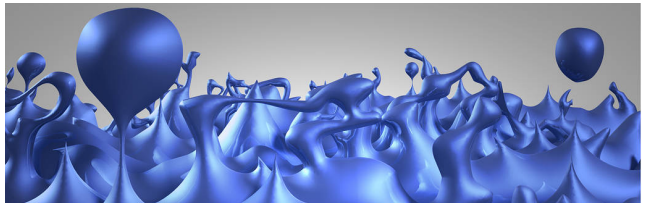


Beyond quantum field theory

into

Quantum Gravity



Why do we care about quantum gravity?

- Mystery of the initial cosmological singularity.

- Clarify mysteries around the Standard Model: gauge groups, coupling constants, details of inflation, etc.

String theory as a candidate theory of quantum gravity

- It is a theory under construction.
- At least, it is a very useful toy model.
- It involves involve deep mathematical structures that are intimately connected to various aspects of quantum field theory.

A rich problem to study in quantum gravity

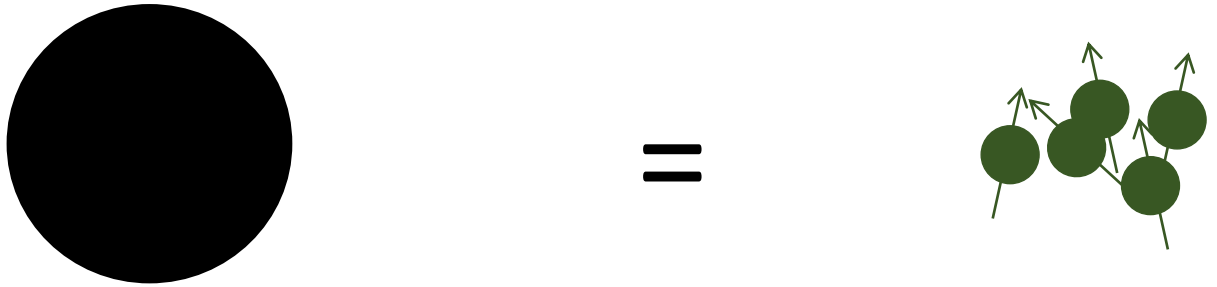
The black hole information problem

- How do black holes work in the quantum theory?

A hypothesis

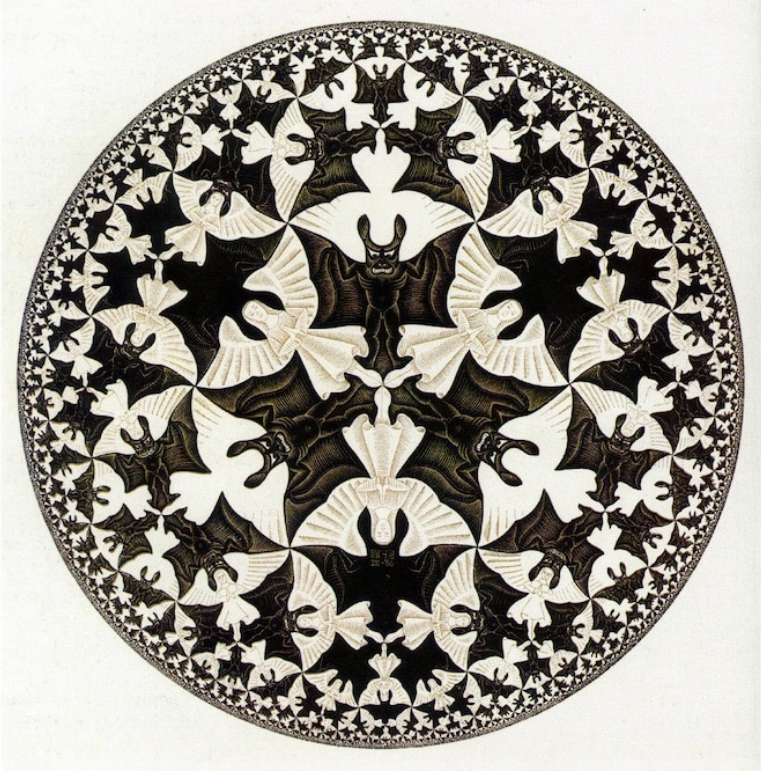
Black holes as quantum systems

- A black hole seen from the outside can be described as a quantum system with S degrees of freedom (qubits). S = Area/4 (l_p =1)



Gravitational holography

- Quantum systems with boundary = quantum theory on the boundary.
- AdS/CFT.



Unexpected connections to other fields of physics

- Quark gluon plasma
- Condensed matter
- Quantum chaos.
- …

Constraints on effective field theories from quantum gravity

- We suspect that not all effective field theories can be embedded in a full theory of quantum gravity.
- Some properties are rule out by quantum gravity.
- With (hopefully) possible implications for inflation, proton decay, etc.

Conceptual questions in cosmology

- Initial singularity?
- Measure problem?
- Was there anything “before” the singularity?

I would like to end with some comments

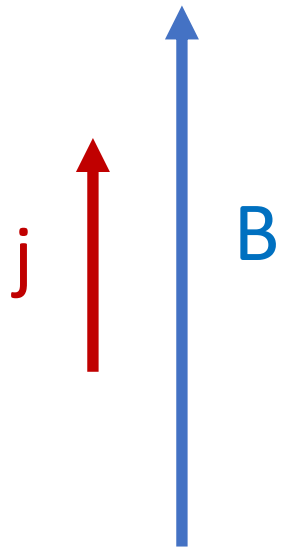
The importance of diversity of approaches

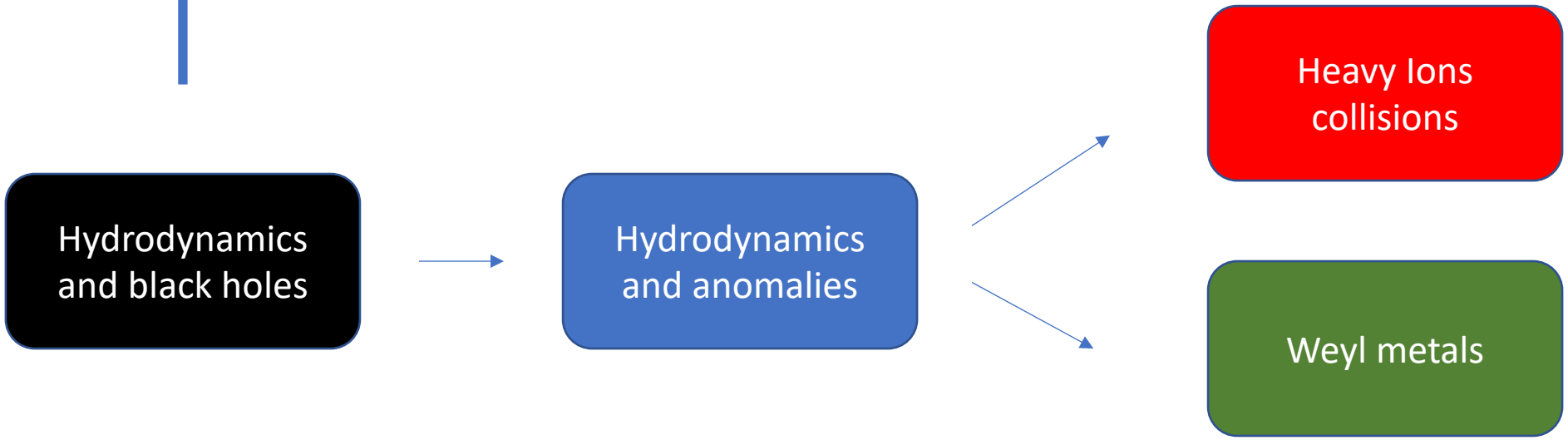
- It is important to follow a diversity of approaches and theoretical methodologies.
- From more phenomenologically oriented.
- To in depth studies of idealized models.

- I only highlighted a sample of the diverse theoretical ideas that are being studied.

Case study

Anomalies and the chiral magnetic effect





Many other cases

- Superconductivity → Higgs boson
- Hawking radiation → Cosmological fluctuations.
- Topology → Instantons, theta term, anyons, quantum computing…
- …

Nurturing the rising talent

- This area attracts outstanding young people
- Supporting junior faculty and postdocs doing high risk/high return research.
- Versatile theorists can contribute in many fields of physics, technology and industry.


We have many exciting opportunities in the road ahead for theoretical discoveries!

We all look forward to the exciting experimental projects that will come out of the P5 process!

Thank you!