# Fundamental Lessons From String Theory

WPC
Theoretical Physics Symposium 2023
Hamburg
November 2018

Cumrun Vafa

I dedicate this talk to Edward Witten who has played a leading role in what I have to tell you today.

It is too early to present the final formulation of string theory.

It is too early to present the final formulation of string theory.


It is still  work in progress.

It turns out that even the incomplete knowledge we have of string theory nevertheless conveys important new principles of physics.

Many of these new principles are counter-intuitive.

I will try to explain some of these new principles and use examples to illustrate them.

To put things in perspective it is helpful to recall some historical lessons:

Many developments of physics hinge on giving up what we thought as fundamental.

Earth the center of universe — No

Absolute notion of time — False

Absolute notion of state of a system — False

String theory also calls for radical changes of our understanding of fundamentals of physics.

It is surprising that even though we do not know what string theory really is, some of its principles are already in place.

It is reminiscent of the early days of QM after DeBroglie's Discovery, but before Heisenberg and Schroedinger came up with its final formulation.

What have we learnt from string theory?
Can these be summarized as some principles of quantum gravity?

The main lesson is:

UV physics does not decouple from IR physics

Effective Field Theory ideas (for theories without gravity) suggest that you can write the most general allowed theory in the IR only restricted by symmetries at hand. No need to know the details of UV.

This mentality is incorrect when it comes to quantum gravity.

Black holes are a clear example of lack of decoupling:

They are IR solutions to Einstein equation but they know about the UV degrees of freedom through Bekenstein-Hawking entropy:

$$S(M) = A(M)/4$$

UV <—> IR

# Finiteness

The allowed EFT's which arises in IR limit of quantum gravity, is measure zero among all conceivable ones.

Example: Maximally supersymmetric matter theories in 4d (N=4 super-Yang Mills with some gauge group G) coupled to N=4 quantum gravity is inconsistent for almost all G.

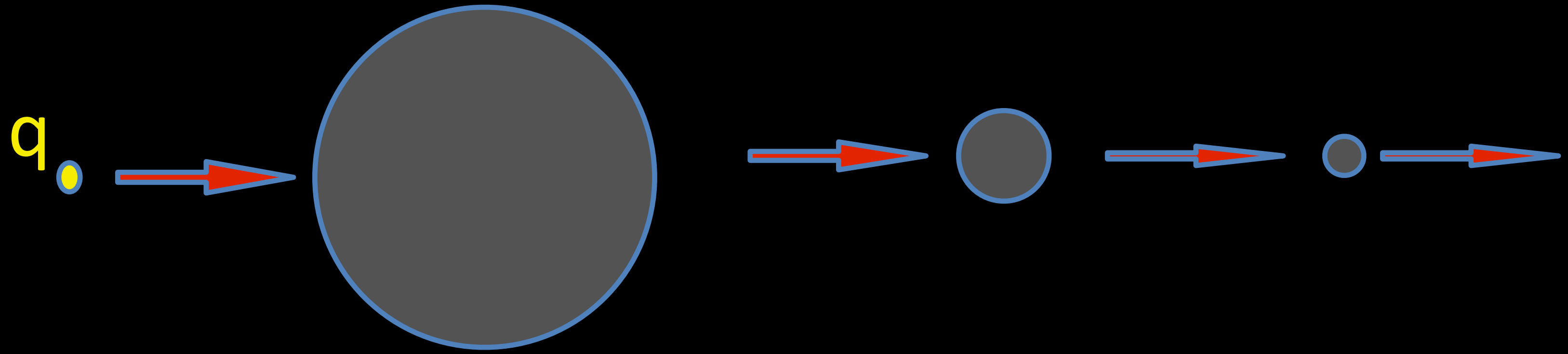
$rank(G) \geq 23$ cannot arise in IR of quantum gravity!

This leads to a more general principle which seems to have been backed by all the examples we know:

The list of consistent IR theories of quantum gravity is finite!

# No Global Symmetries

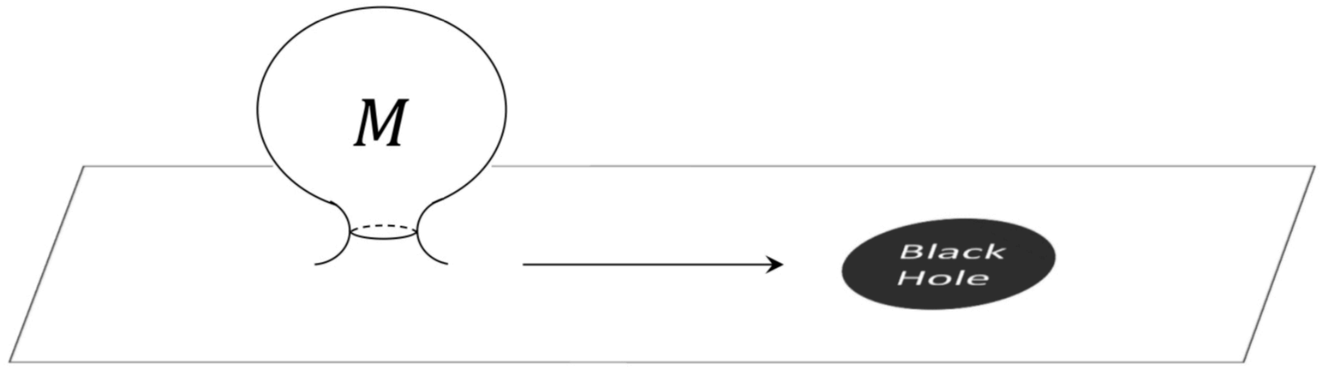
A consistent theory of quantum gravity cannot have global symmetries and all symmetries are gauged. Follows from black hole evaporation:




Global charge falling into a black hole will evaporate away leading to violation of global charge (since evaporation process is independent of global charge inside).

# Uniqueness of Quantum Gravity (Triviality of Cobordism Group)

A simple generalization of this implies that all compactification manifolds carry no charge and one can go from any of them to any other:



# Completeness of Spectrum

Another application of this is that if we have gauge symmetries, all allowed charges appear. Otherwise one can define global symmetries.

For U(1) gauge theories the existence of charged BH solutions and the fact that they carry Bekenstein-Hawking entropy is another argument for this.

# Weakness of gravity

Gravity is always the weakest force: There are elementary charged states whose mass (in fundamental units) is lower than their charge:

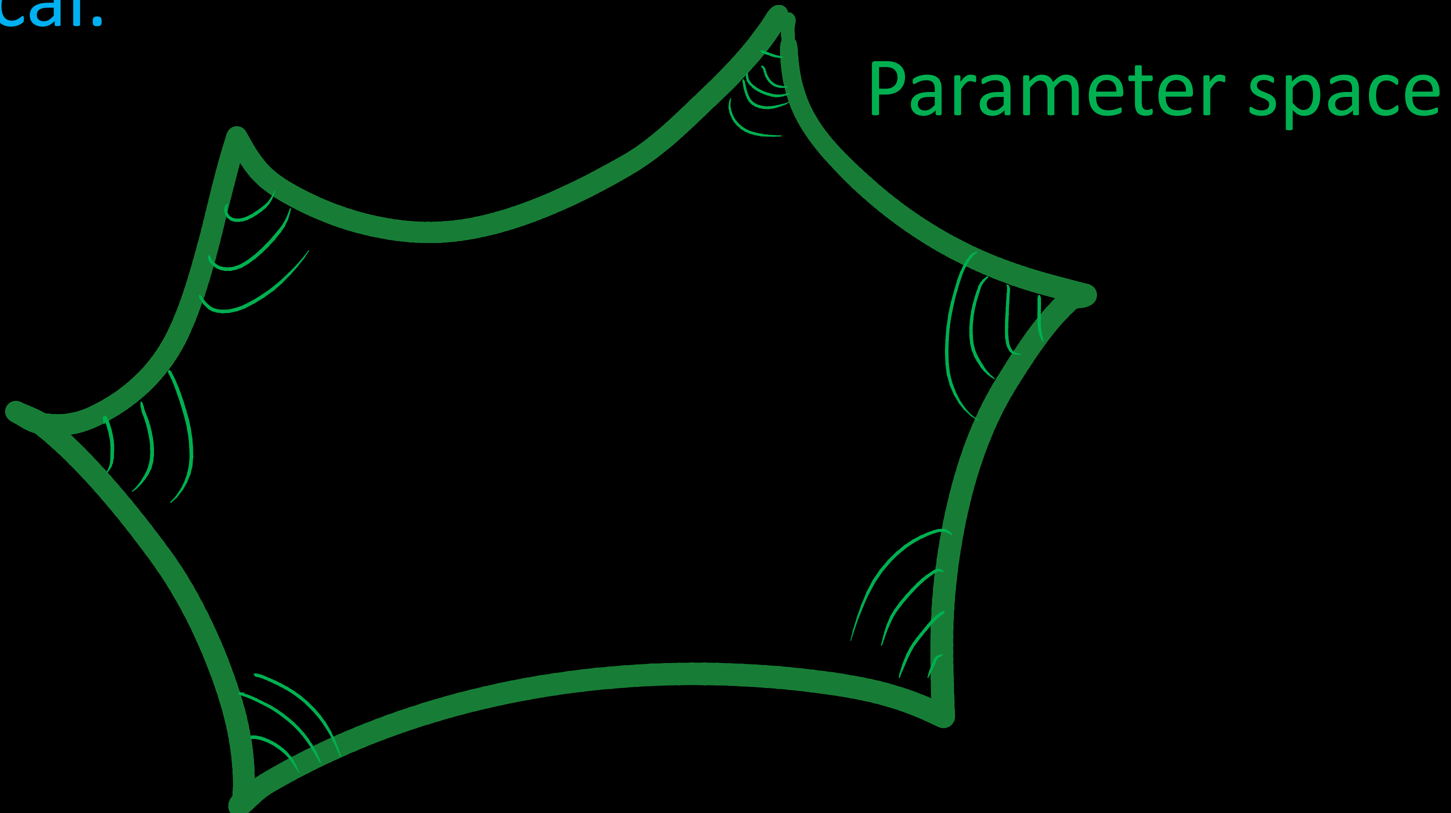
$$m \leq q$$

I.e. gravitational attraction is less than the Coulomb repulsion. A heuristic argument for this again relies on black holes: Start from extremal BH $M = Q$, and use the assumption that it needs to be able to decay to states $M - m \geq Q - q$.

Kinematics of emission requires this.

# Duality

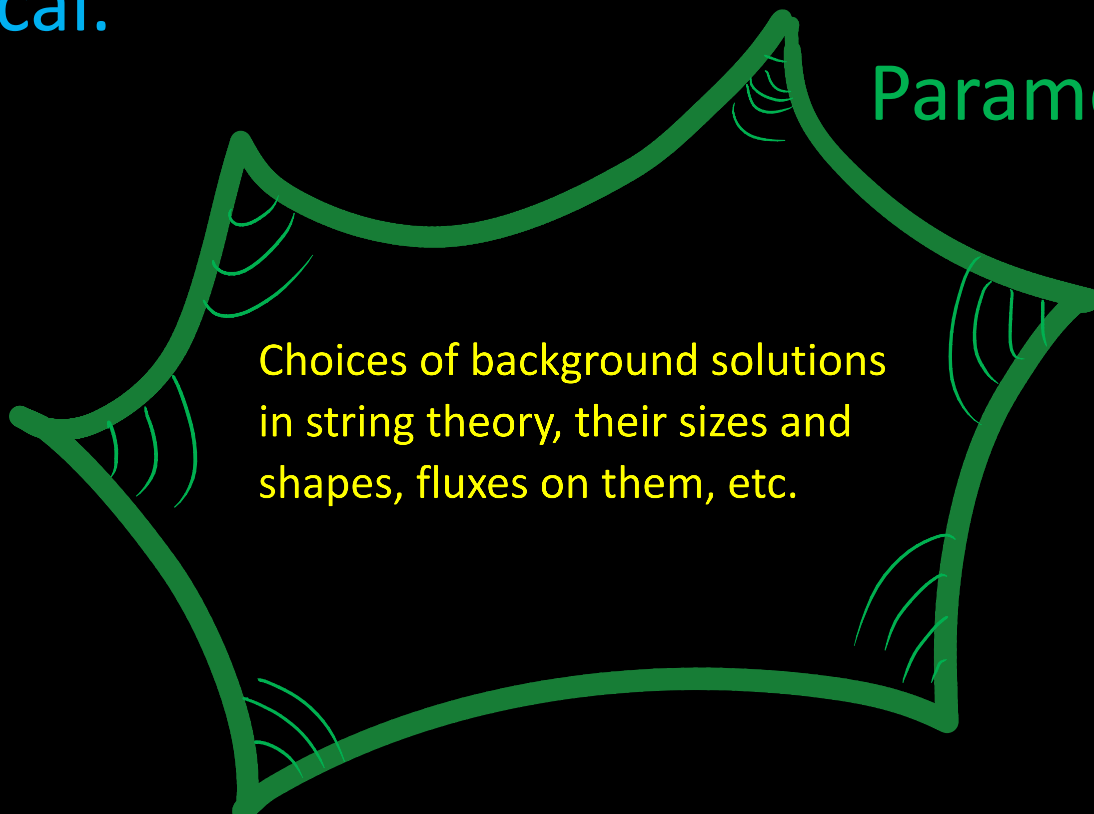
This is the general phenomenon that two very different looking physical systems can nevertheless be identical.



# Duality

This is the general phenomenon that two very different looking physical systems can nevertheless be identical.

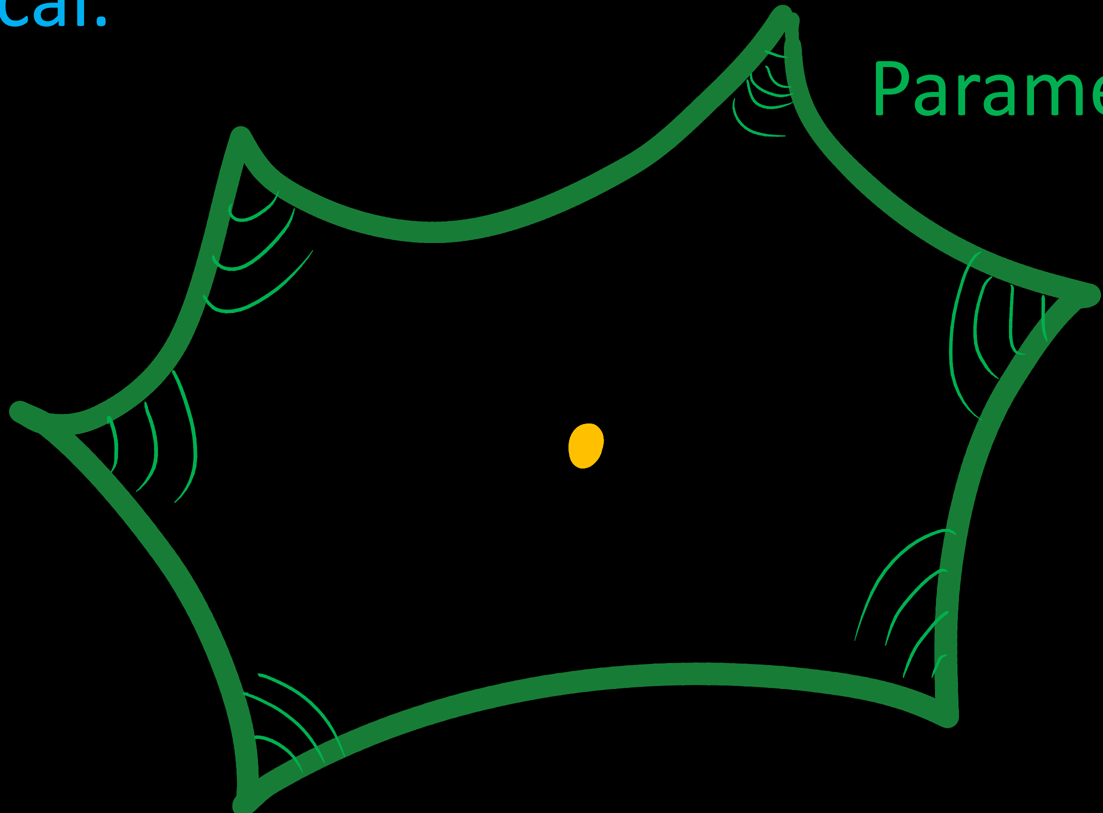
Parameter space



# Duality

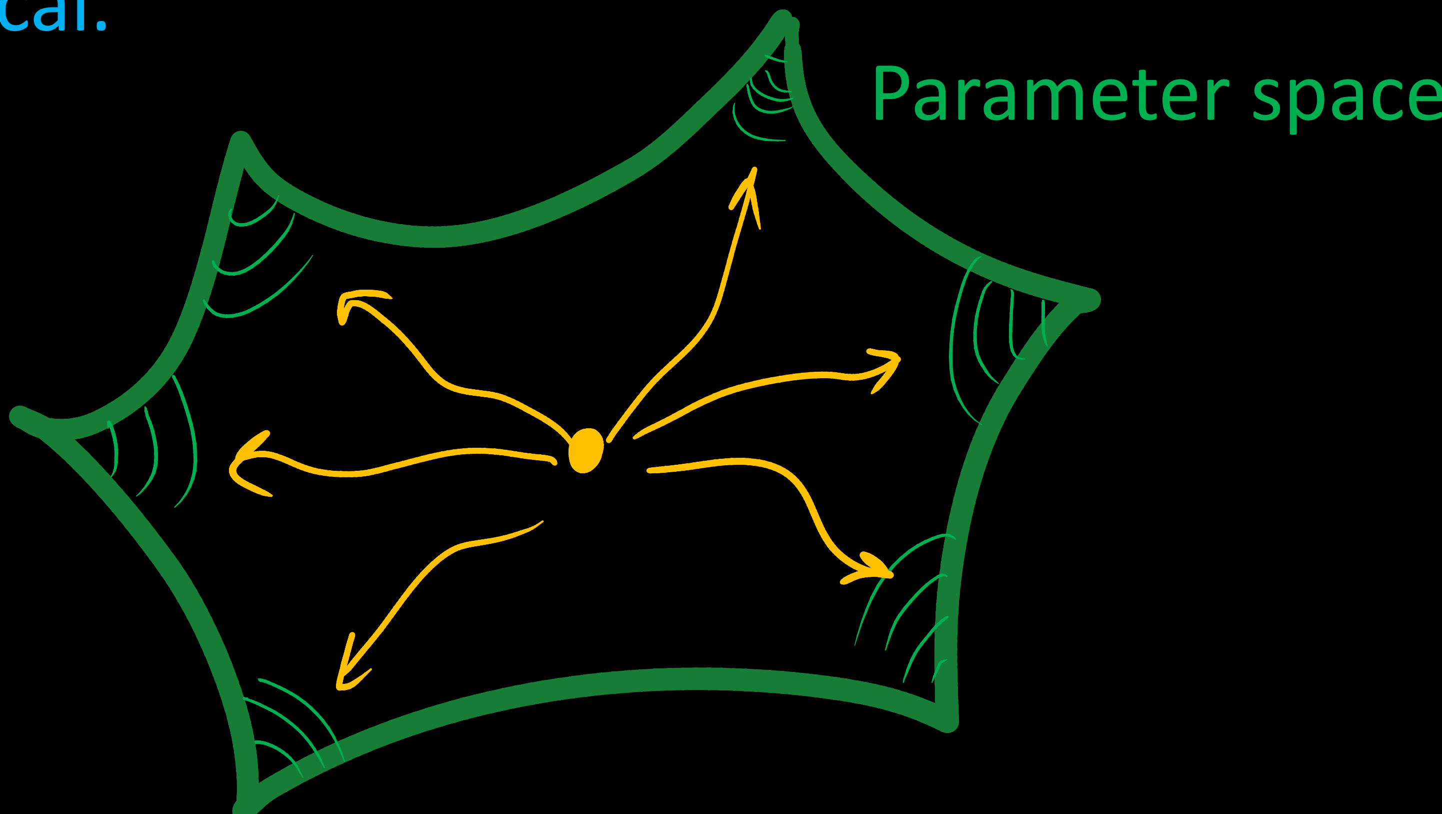
This is the general phenomenon that two very different looking physical systems can nevertheless be identical.

Parameter space



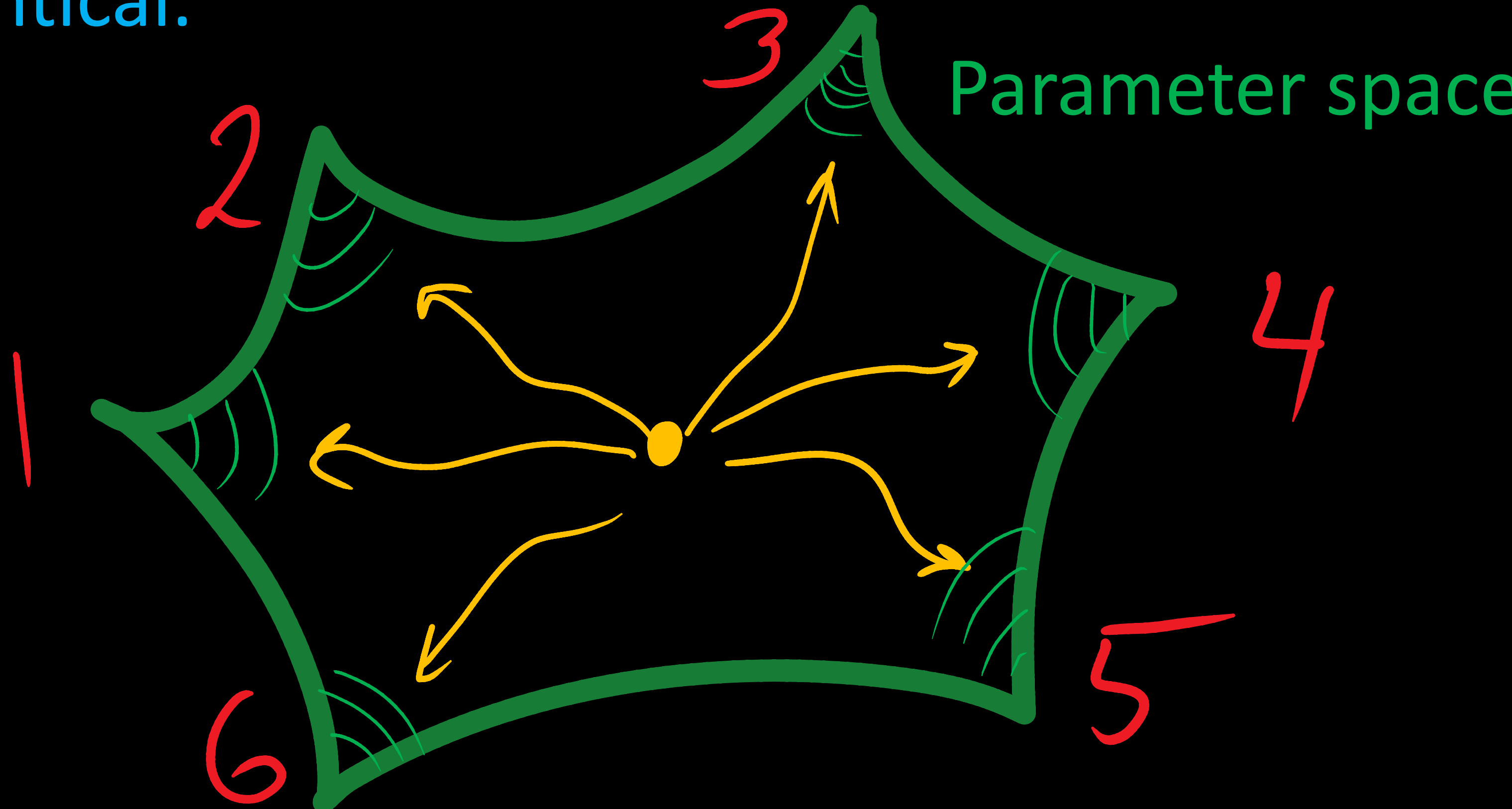
# Duality

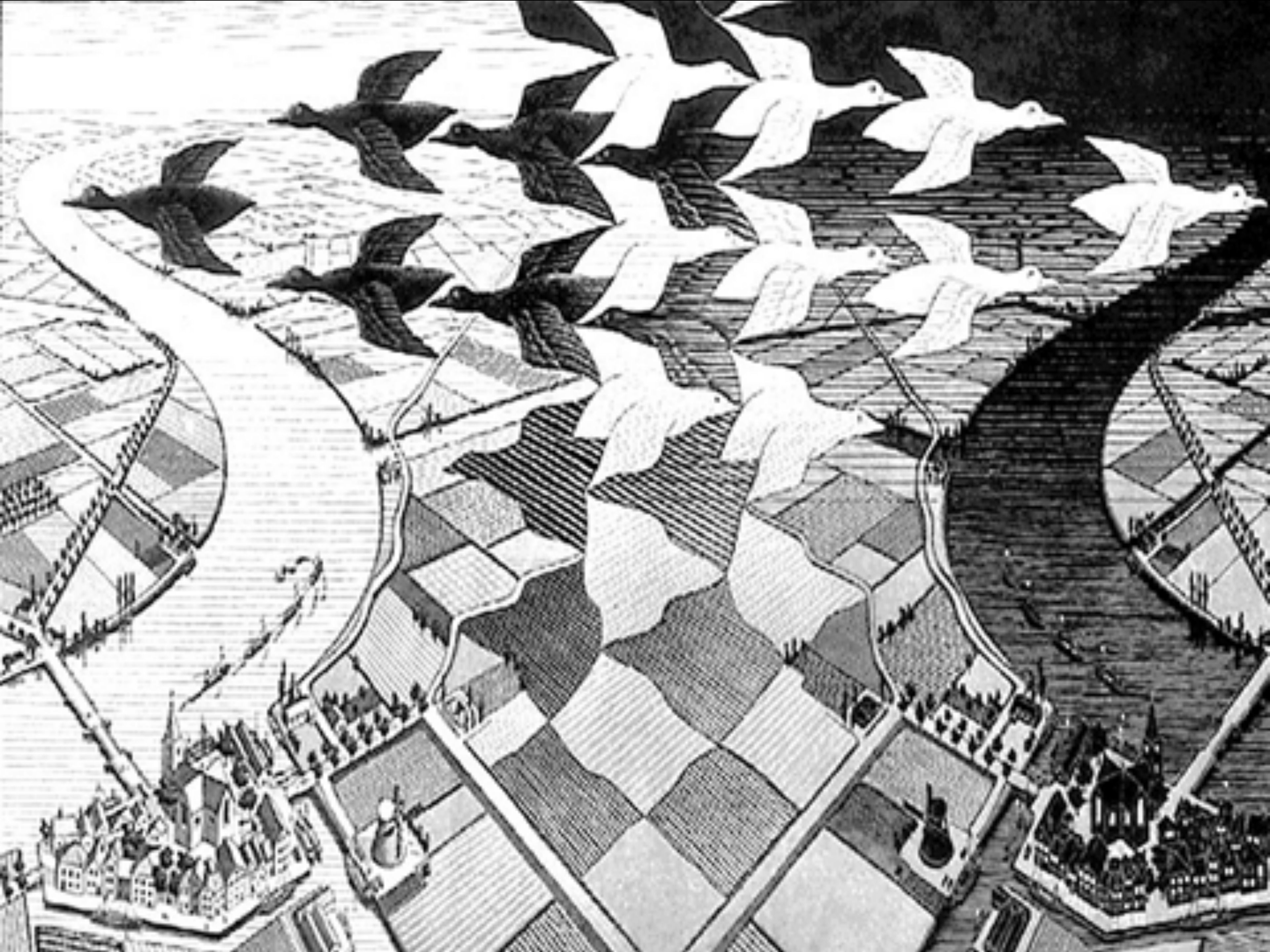
This is the general phenomenon that two very different looking physical systems can nevertheless be identical.



# Duality

This is the general phenomenon that two very different looking physical systems can nevertheless be identical.





# Dualities

Some opposite corners:

Weak coupling ↔ Strong coupling

Weak coupling ↔ Extra dimension

Small space↔ Large space (T-duality)

Large N QFT ↔ gravity in one higher dimension

…

In a sense we can view the boundary theories which admit perturbative descriptions,

the analog of distinct special `reference frames'.

duality frames

At these corner:

dual description of the physics emerges in terms of tower of weakly interacting light particles or strings

$$m \sim_{\Delta\phi>>1} exp(-\lambda\Delta\phi), \qquad \lambda \geq \frac{1}{\sqrt{d-2}}$$

$$m \sim_{|\Lambda|\to 0} |\Lambda|^{\alpha}, \qquad \alpha \sim \mathcal{O}(1)$$

Where $\Delta\phi$ is distance in field space and $\Lambda$ is the cosmological constant.

# Predictions for our Universe?

It is a well known fact that the ideas of EFT fail to explain various fine-tunings in the standard model of physics.

For example:

Why is the cosmological constant $\Lambda$ so small?

# Predictions for our Universe?

It is a well known fact that the ideas of EFT fail to explain various fine-tunings in the standard model of physics.

For example:

Why is the cosmological constant $\Lambda$ so small?
Why  electroweak scale $M_w$ so small ?

# Predictions for our Universe?

It is a well known fact that the ideas of EFT fail to explain various fine-tunings in the standard model of physics.

For example:

Why is the cosmological constant $\Lambda$ so small?
Why electroweak scale $M_w$ so small ?
Why do we live at a time when dark energy has just taken over?

# Predictions for our Universe?

It is a well known fact that the ideas of EFT fail to explain various fine-tunings in the standard model of physics.

For example:

Why is the cosmological constant $\Lambda$ so small?

Why electroweak scale $M_w$ so small ?

Why do we live at a time when dark energy has just taken over? Why matter/radiation/dark energy densities where almost equal at a particular time?

However as we have explained a main lesson we have learned from string theory is that

EFT should fail!

Could it be that the fine-tunings that appear in the standard model of physics is due to the fact that quantum gravity is not taken into account?

Here I present one example:

I will argue that these ideas lead to a rather interesting perspective on the Dark Sector in our universe.

# A Unification of Dark Sector

The most fine tuned non-zero parameter:

$$\Lambda \sim 10^{-122}$$

But as we already noted extreme parameters predict the existence of a light tower of particles/strings:

$$m \sim \Lambda^{\alpha}$$

# A Unification of Dark Sector

The most fine tuned non-zero parameter:

$$\Lambda \sim 10^{-122}$$

But as we already noted extreme parameters predict the existence of a light tower of particles/strings:

$$m \sim \Lambda^{\alpha}$$

This tower of particle is expected to be weakly coupled! natural candidate for the dark matter!

Indeed combined with other observational input, this leads to the unique prediction of having one of the extra dimensions (the `Dark Dimension') of the length scale

$$l \sim \Lambda^{-\frac{1}{4}} \sim \mu m$$

$$m \sim \Lambda^{\frac{1}{4}} \sim (.1 - .01) eV$$

In this scenario the dark matter will be a combination of the tower of KK modes which is decaying down at a rather slow pace.  Gives rise to a rather rich model for dark matter phenomenology.

# Conclusion

String theory has led to new ideas that  change our understanding of consistency requirements of quantum gravitational theories.

New principles have emerged.  Leads to new predictions.

Can potentially lead to explanation of fine tunings in our universe that is lacking in the context of UV/IR decoupling of EFT's.