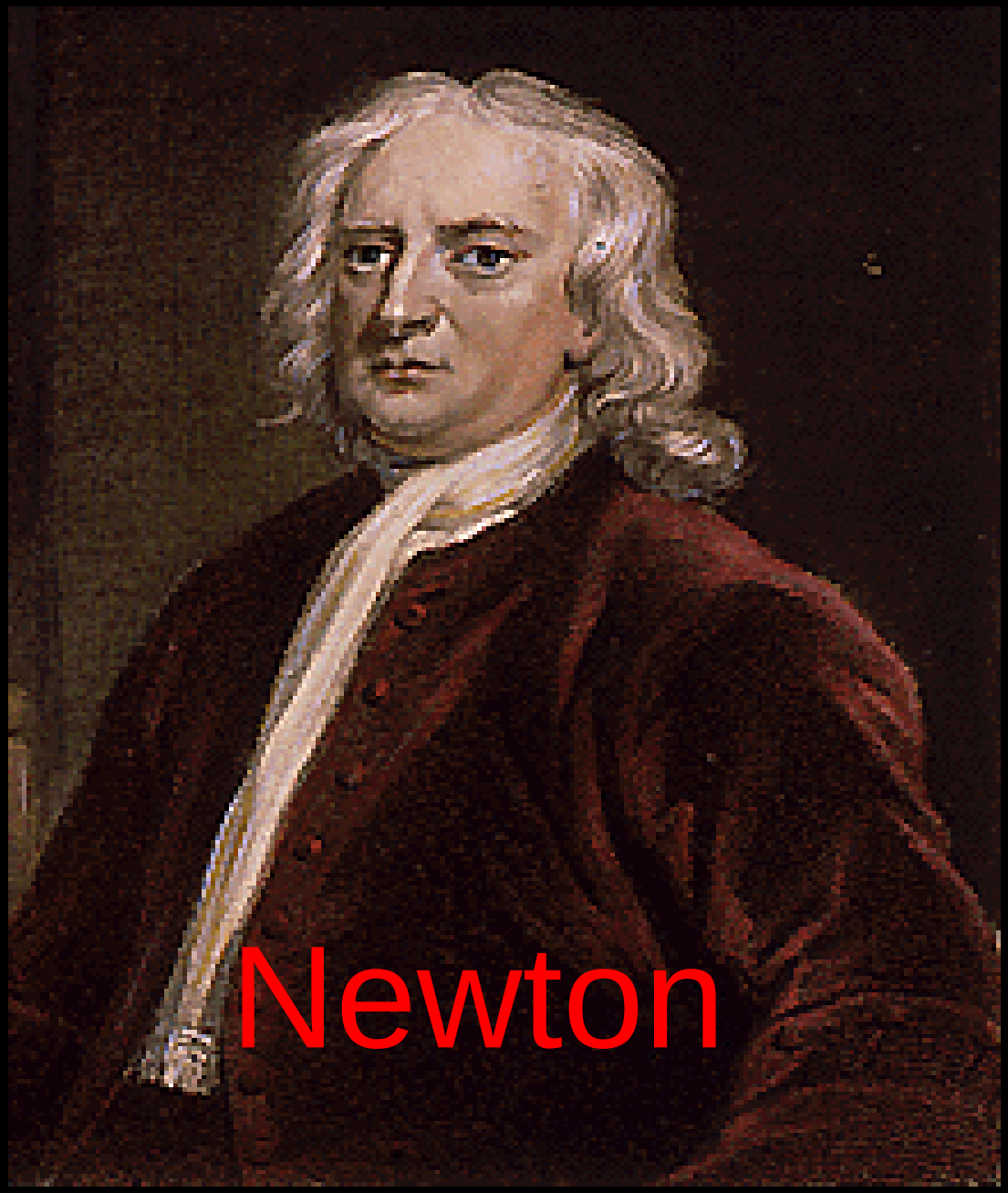
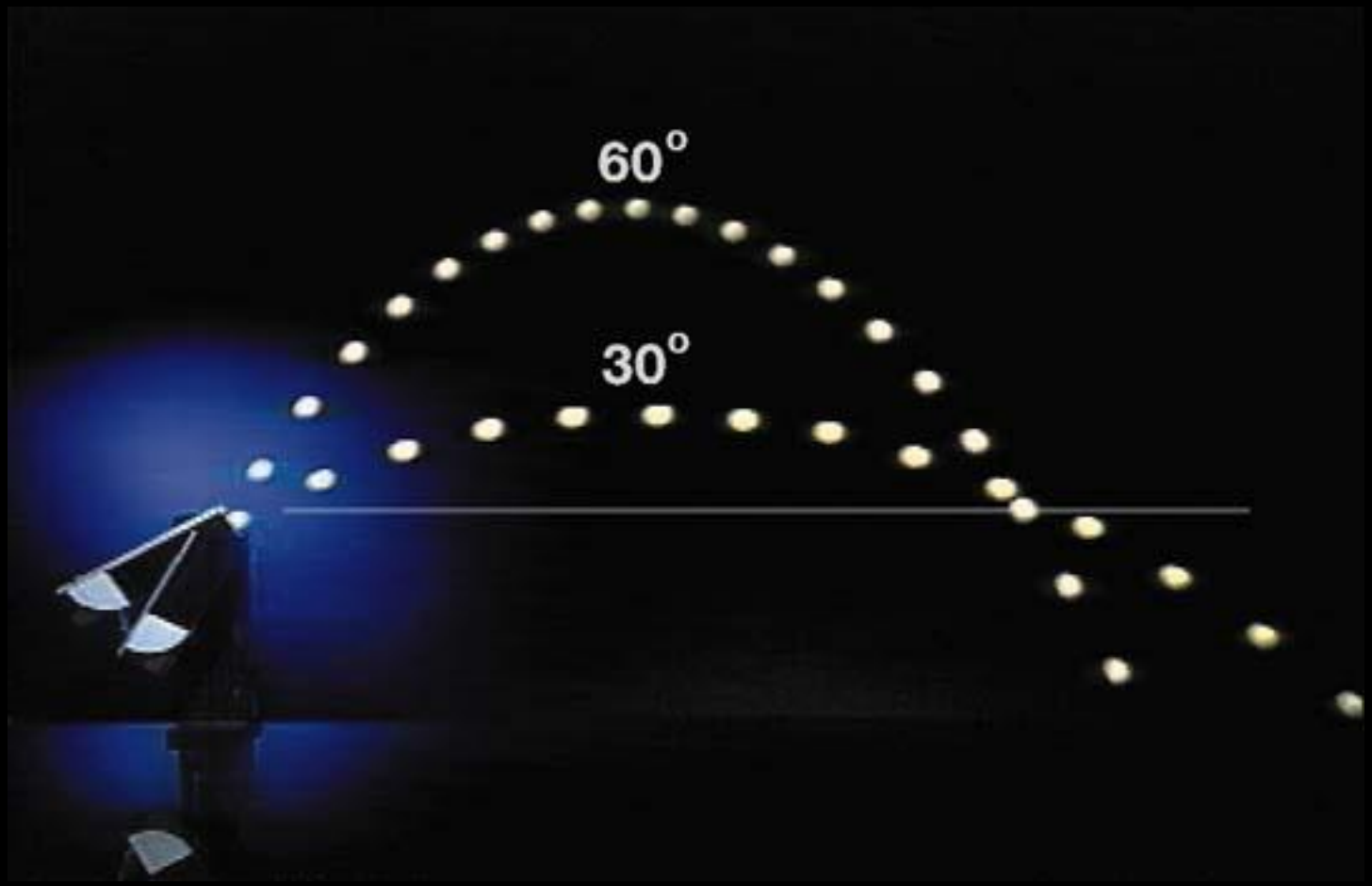
Strings, And the magic of Extra Dimensions

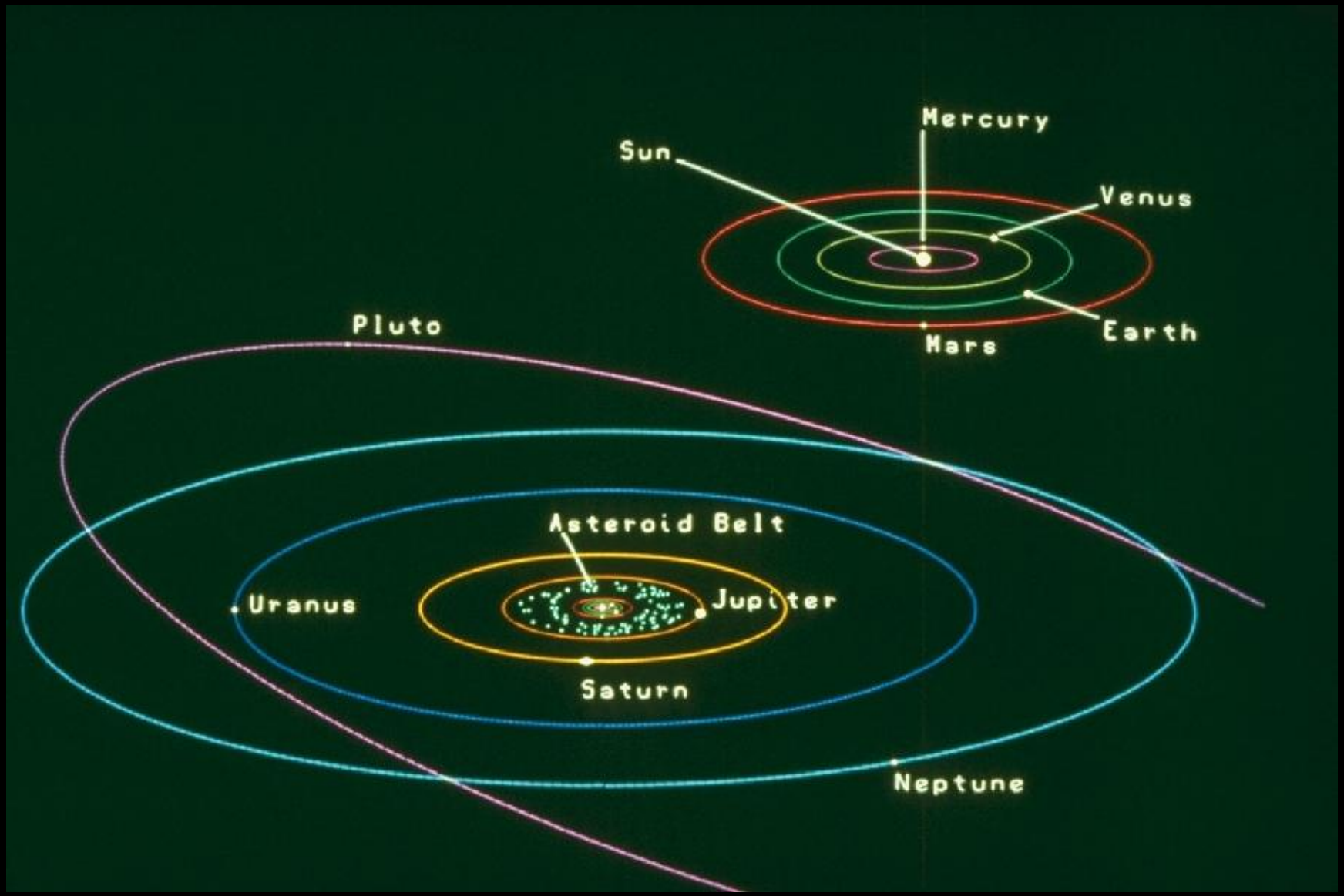
ICTS, Bangalore
June 5, 2013
Cumrun Vafa

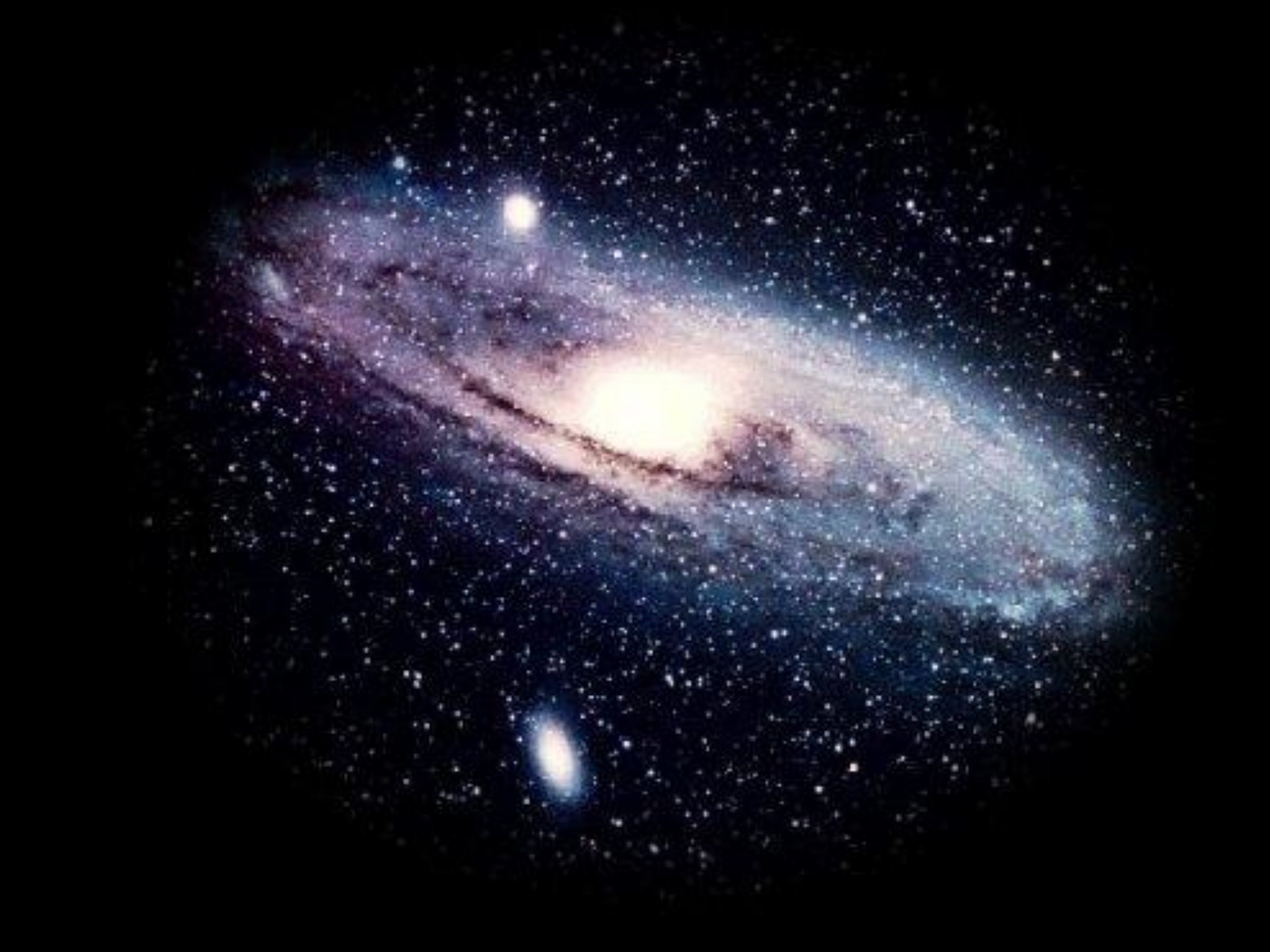

Newton

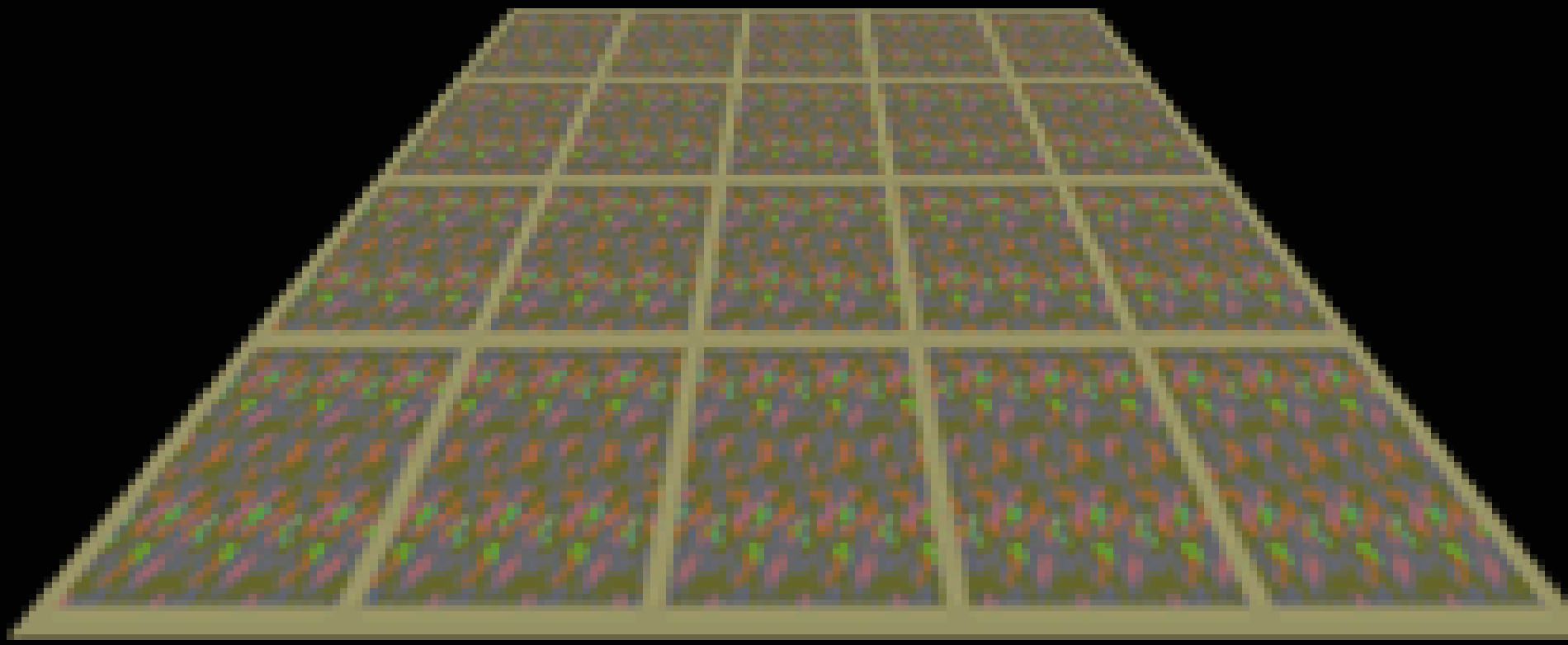
Apple: Where it all starts!



Classical Mechanics

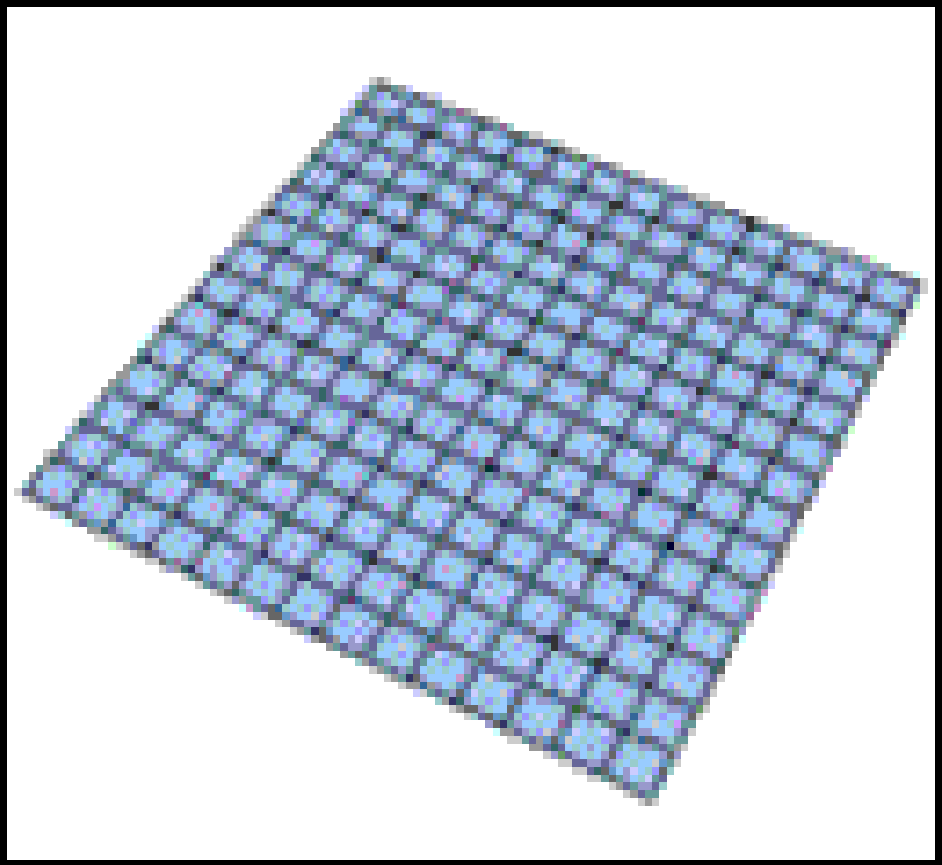

Mercury
Sun
Venus
Earth
Mars
Pluto
Asteroid Belt
Uranus
Jupiter
Saturn
Neptune



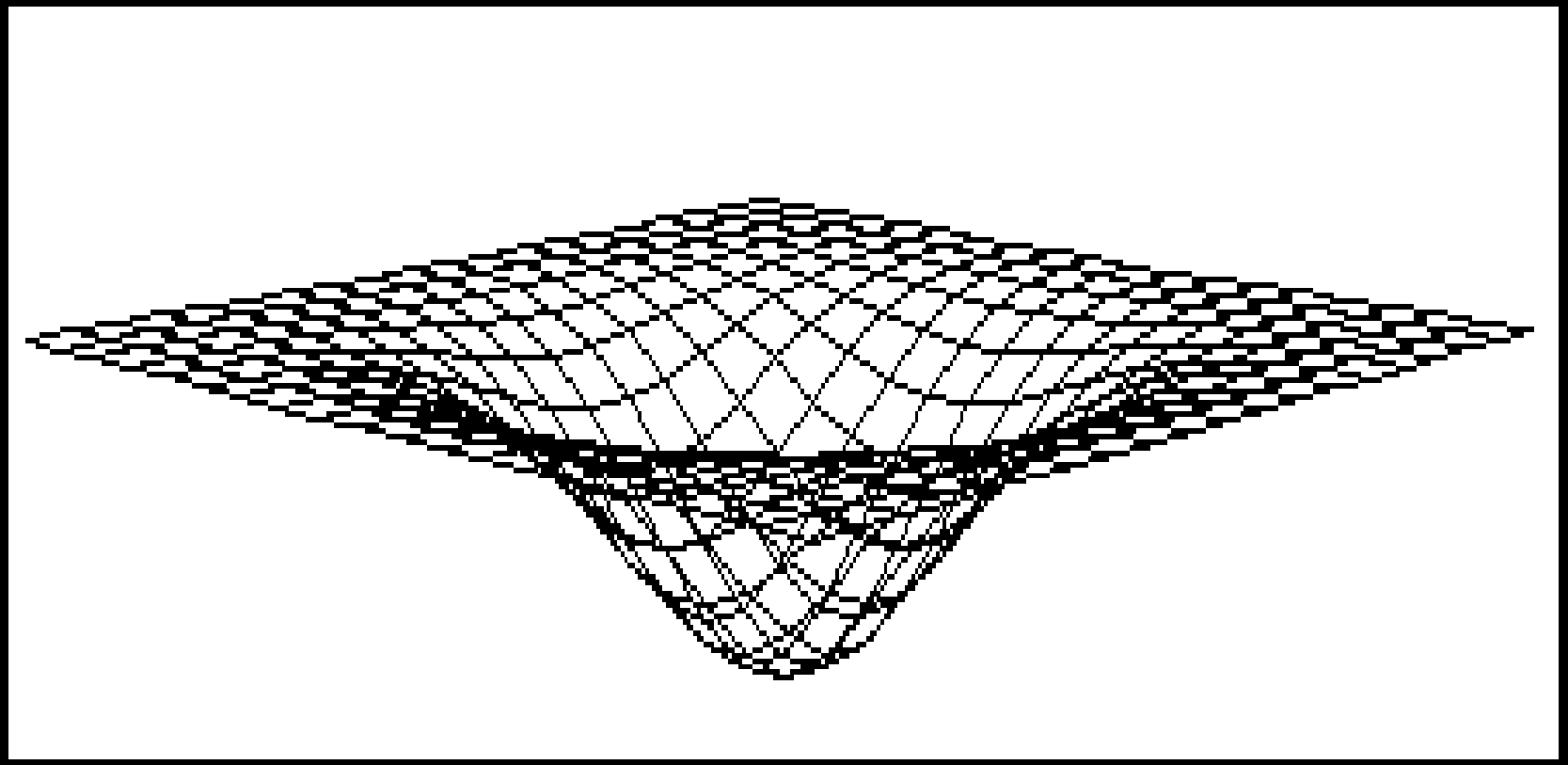


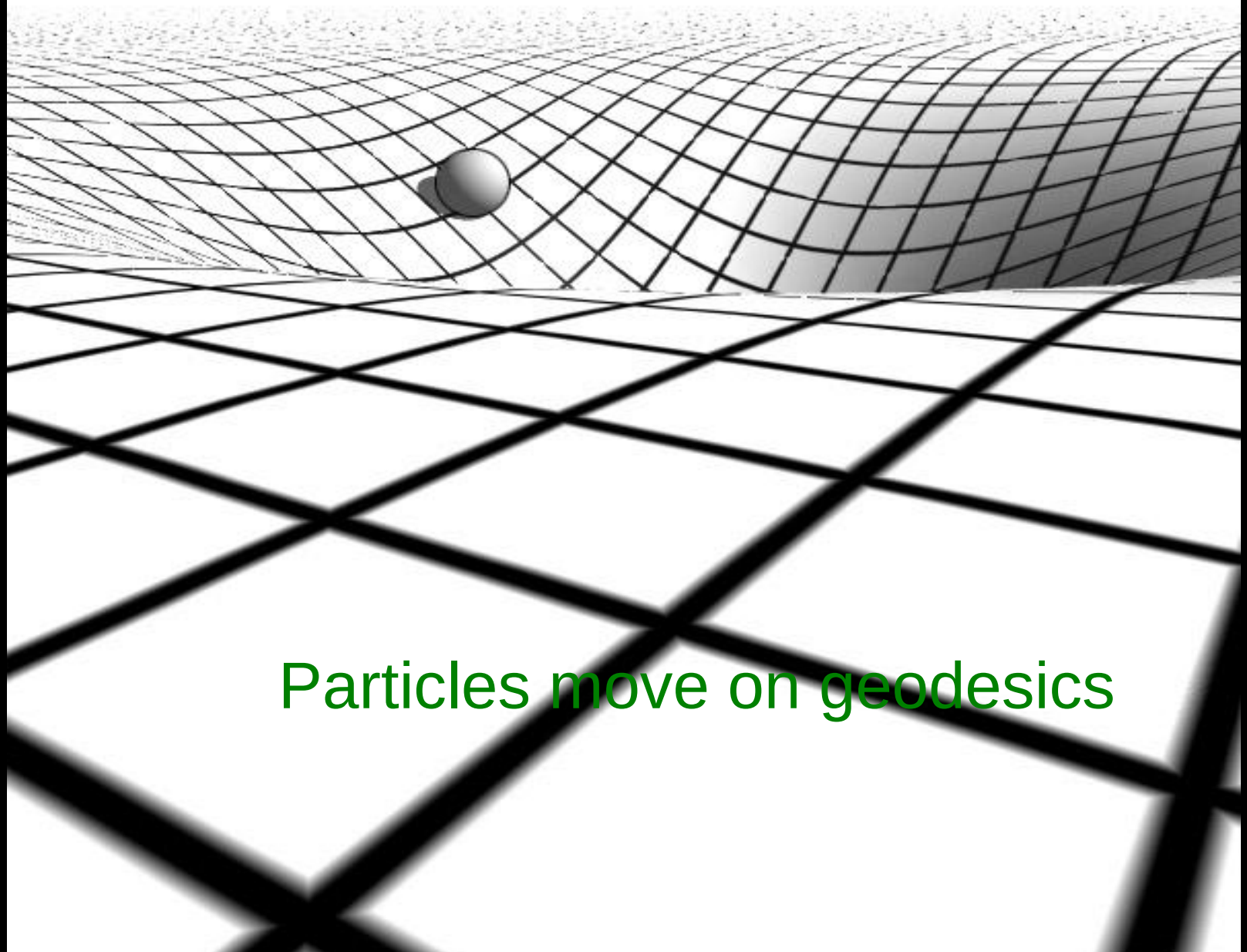
FLAT SPACE

Add Time + Space Not Flat!

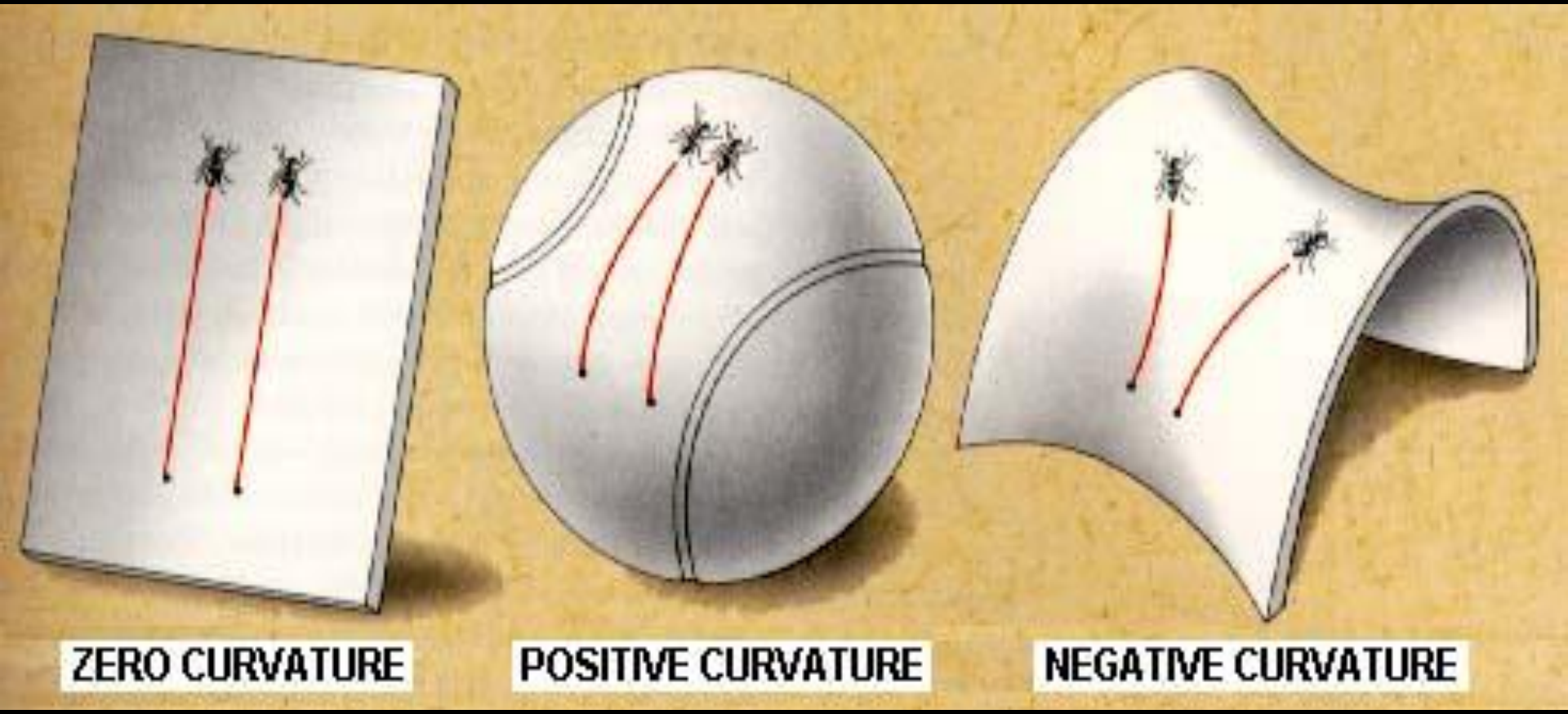


Geometry of Space and Time is Curved

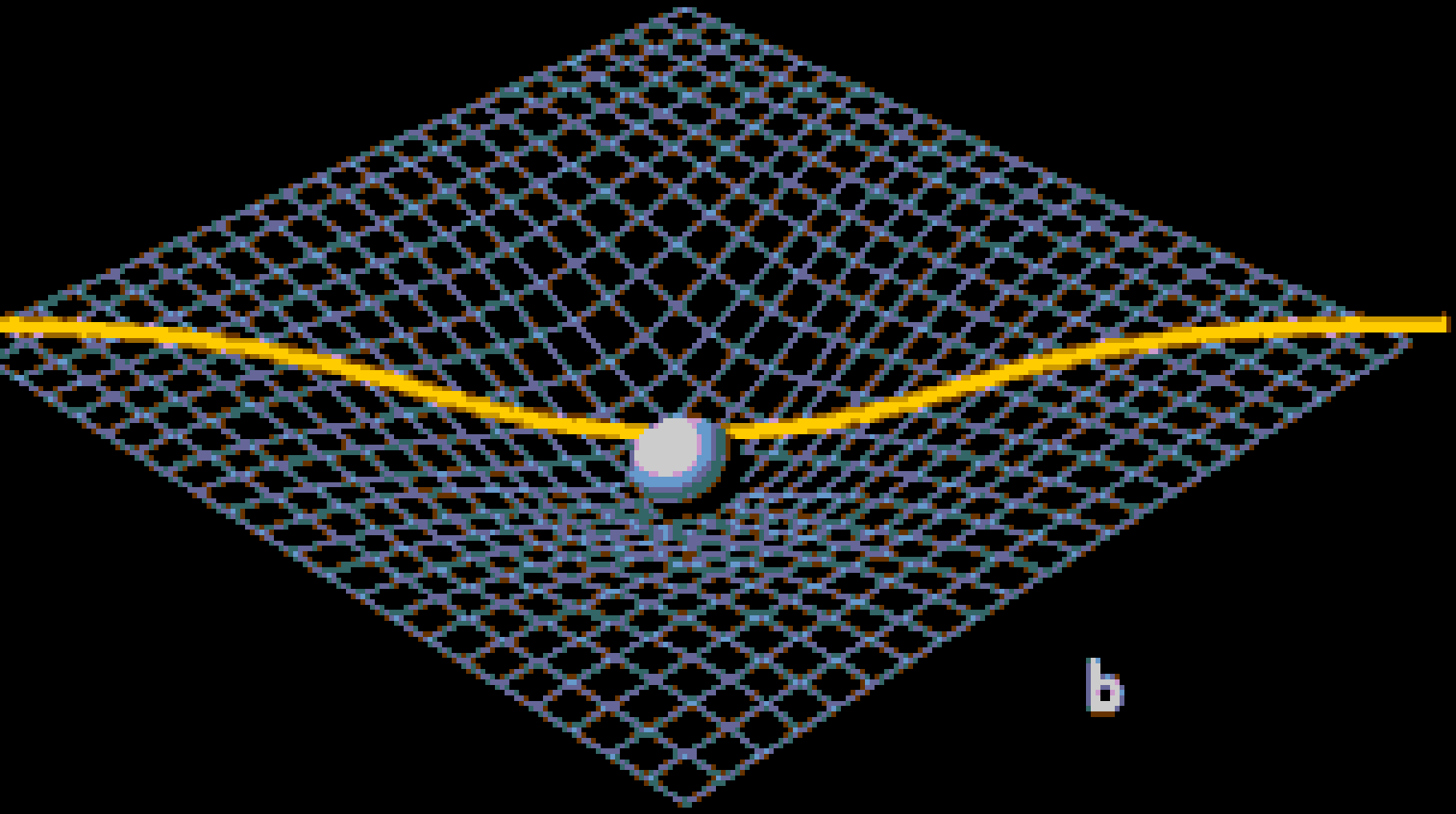




Particles move on geodesics

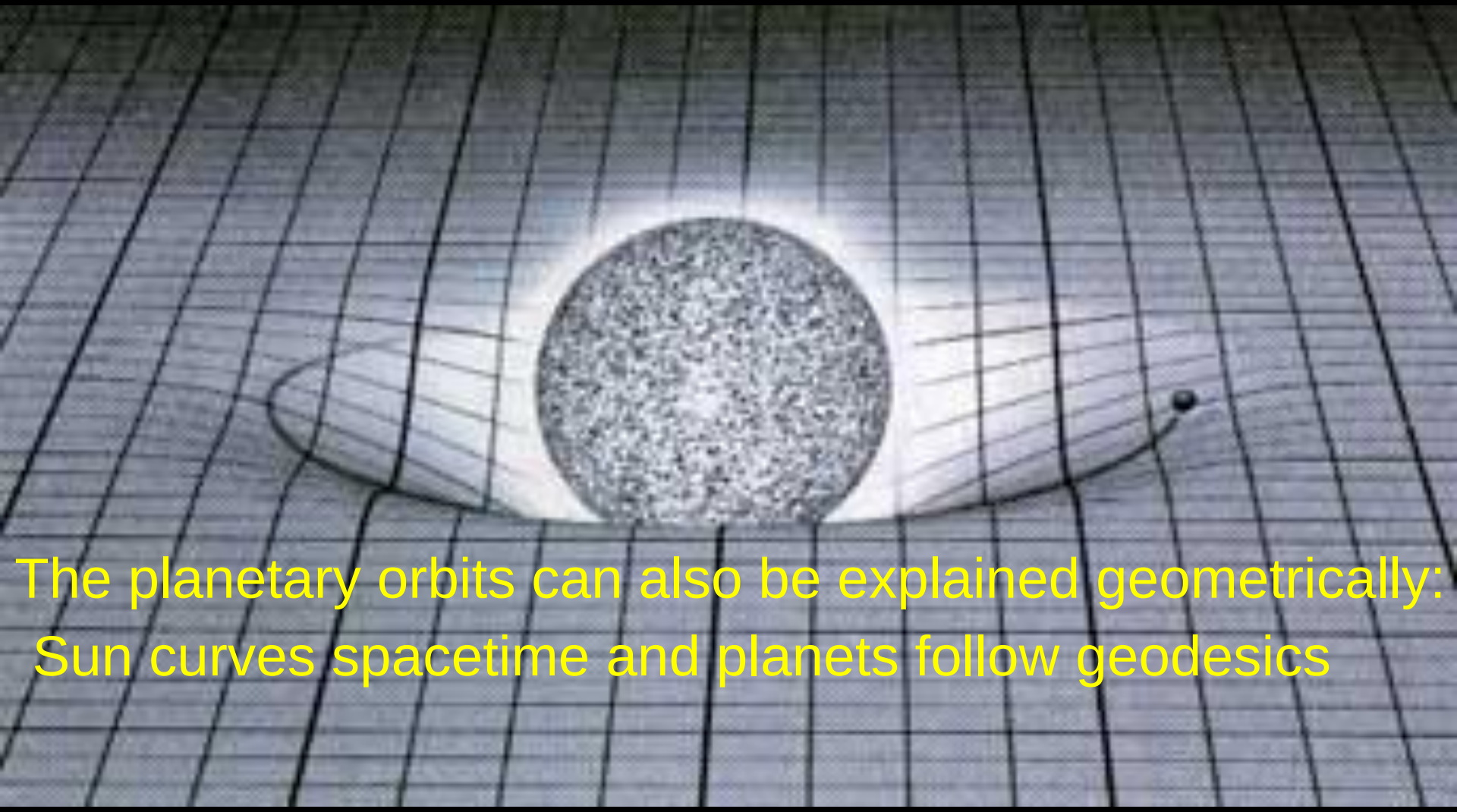


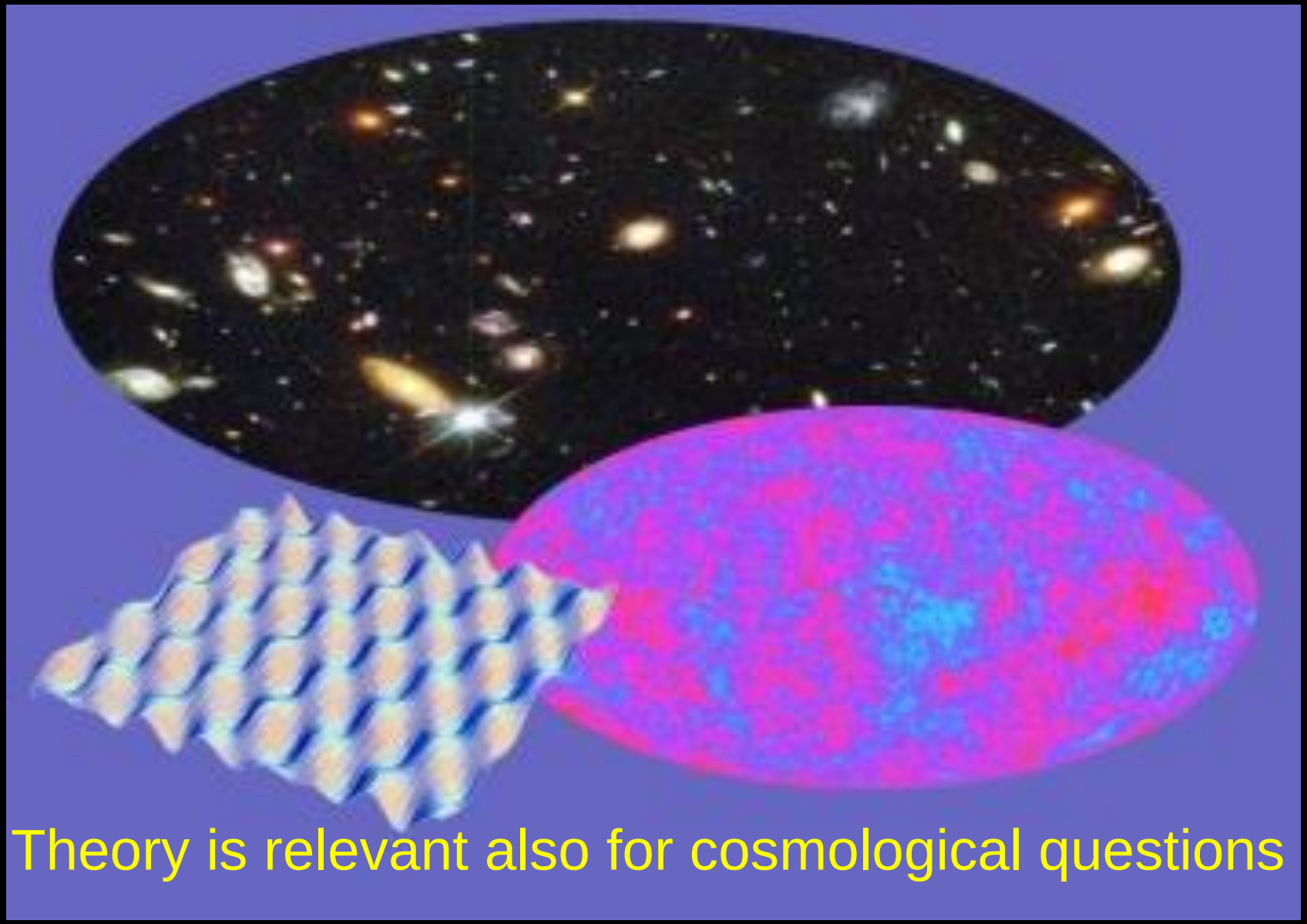
curvature + geodesic → looks like force

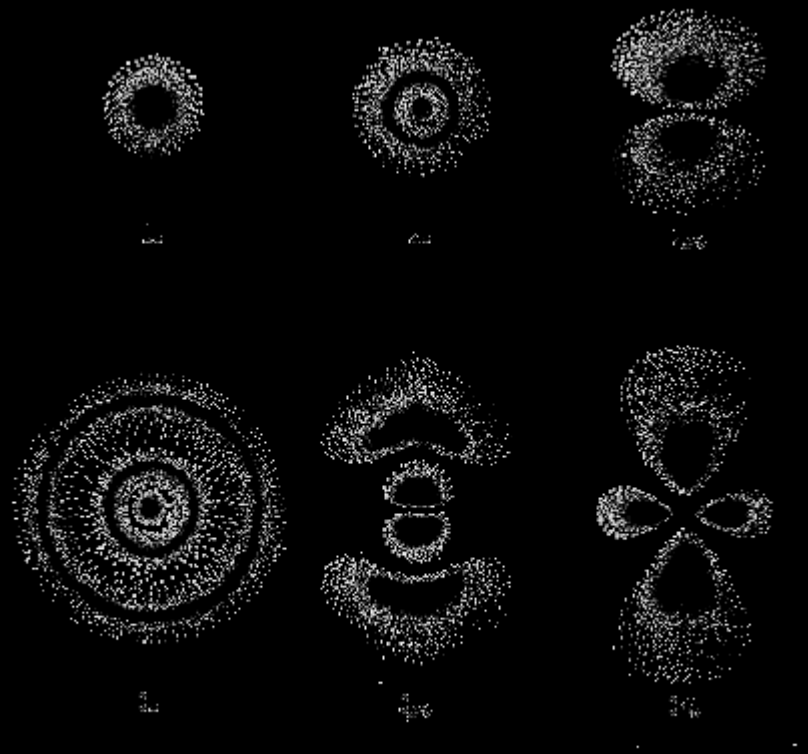


Matter → Curvature

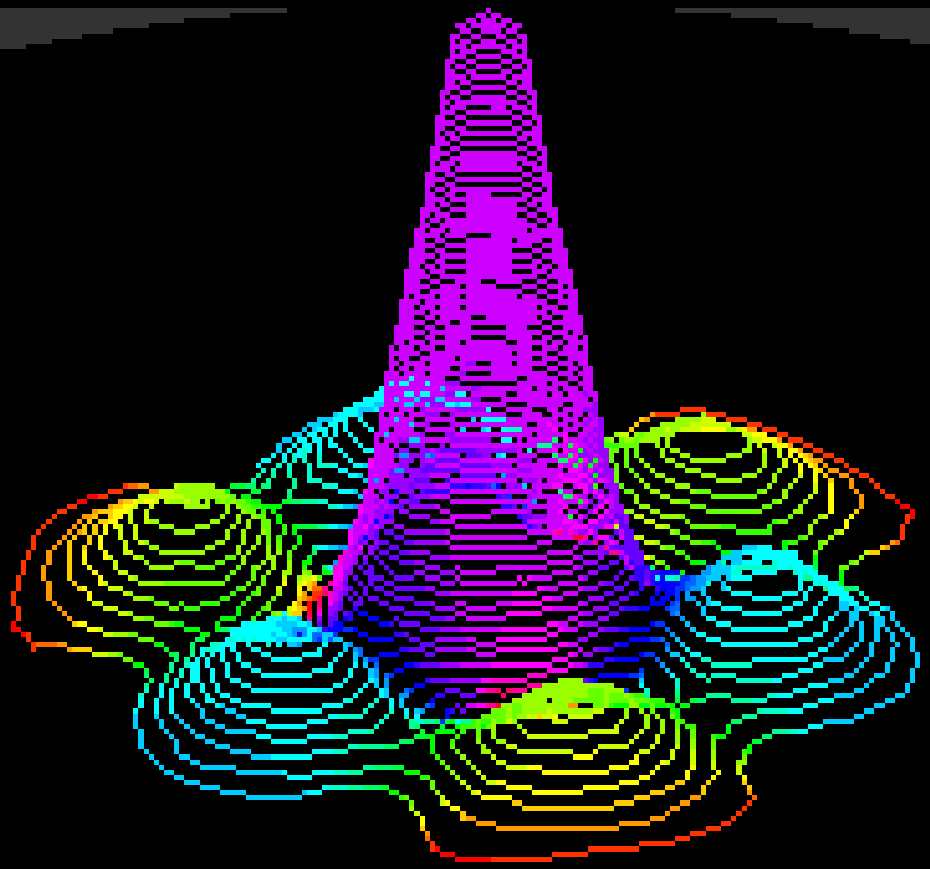

Even light bends as it moves on geodesics


The planetary orbits can also be explained geometrically:
Sun curves spacetime and planets follow geodesics


Theory is relevant also for cosmological questions



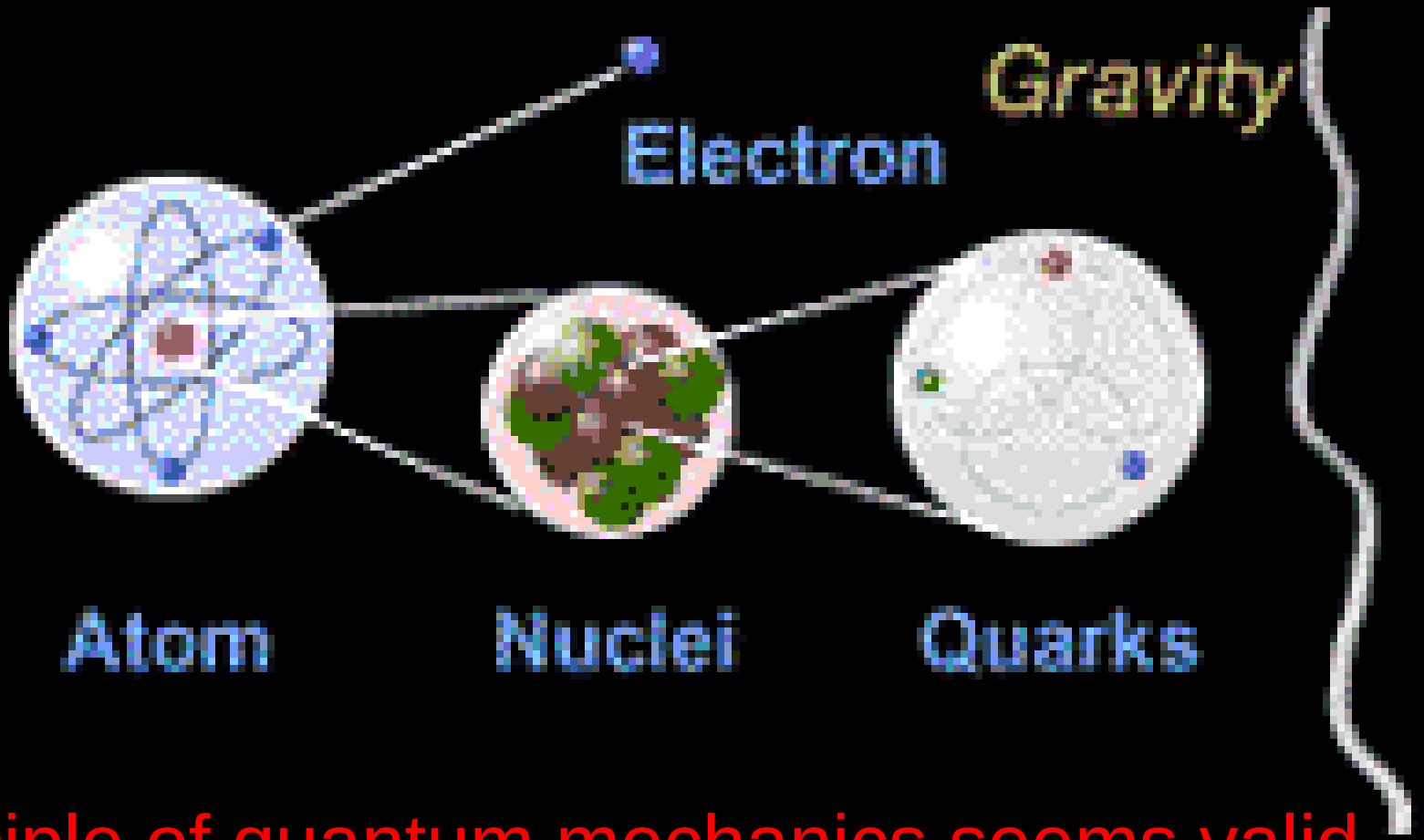
Particles are ``fuzzy'' at smaller scales



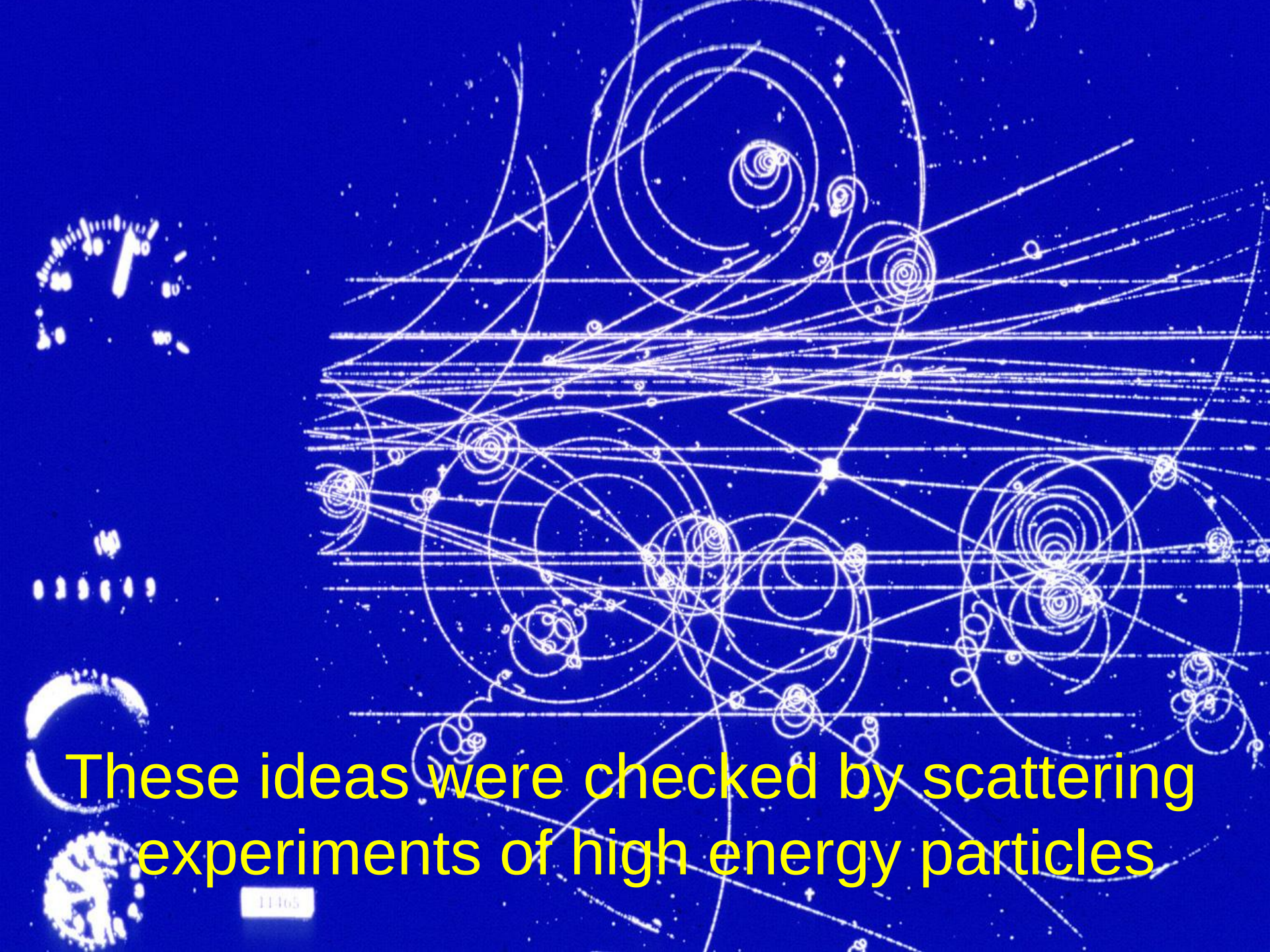
Quantum mechanics was born


Bohr

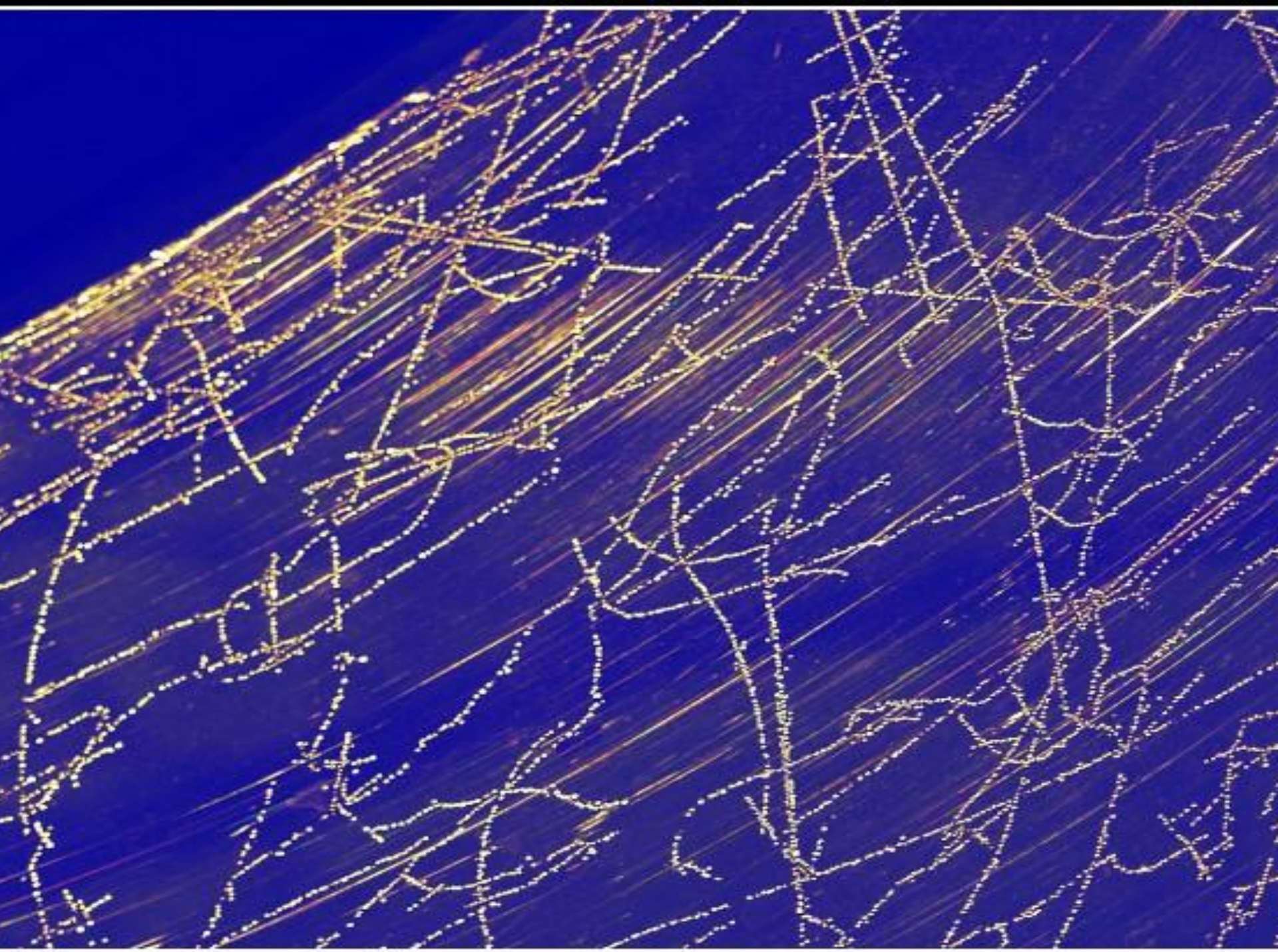
This was so radical, even Einstein was intrigued!

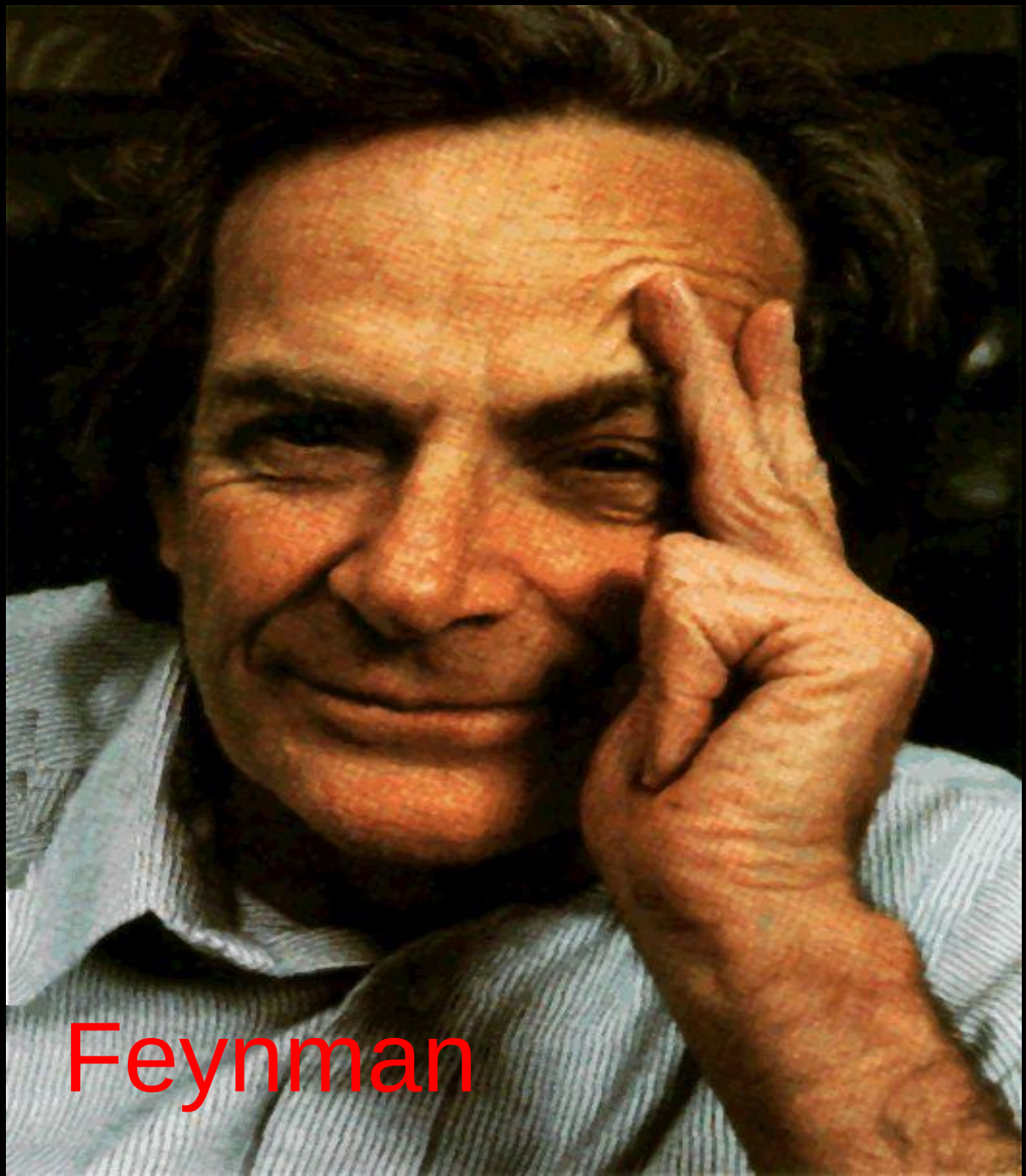


Principle of quantum mechanics seems valid even at nuclear and subnuclear scales

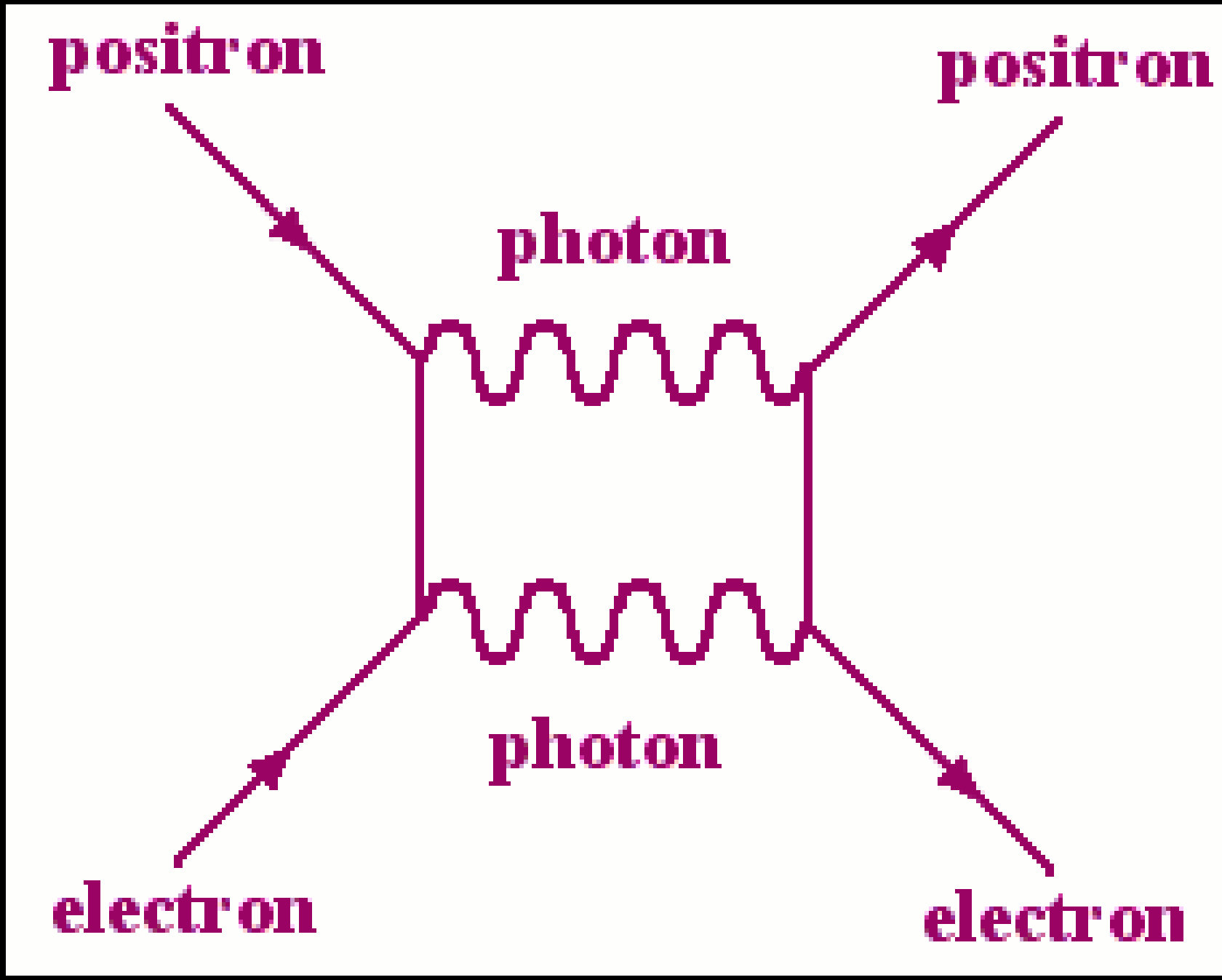


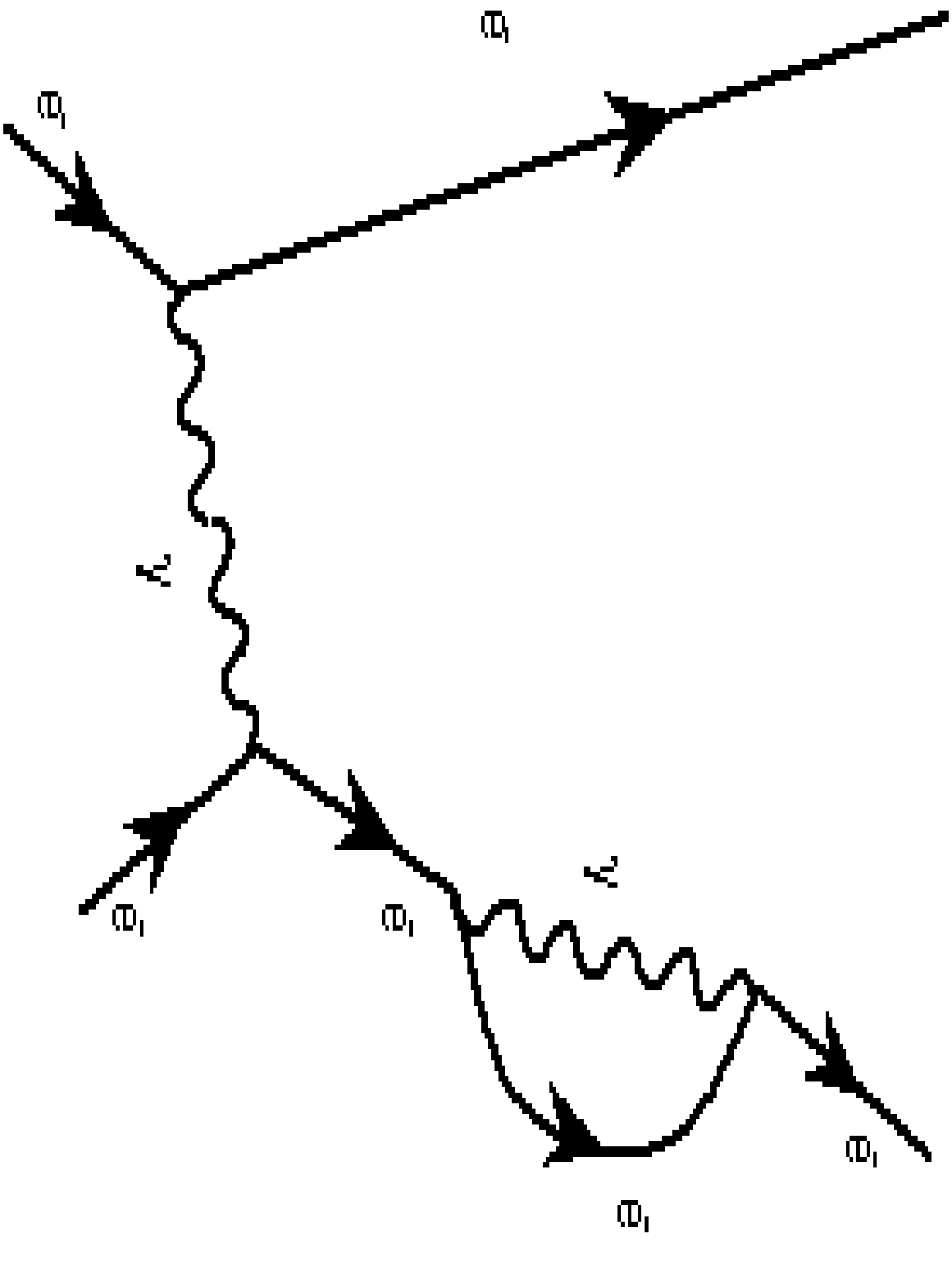
These ideas were checked by scattering experiments of high energy particles




Feynman

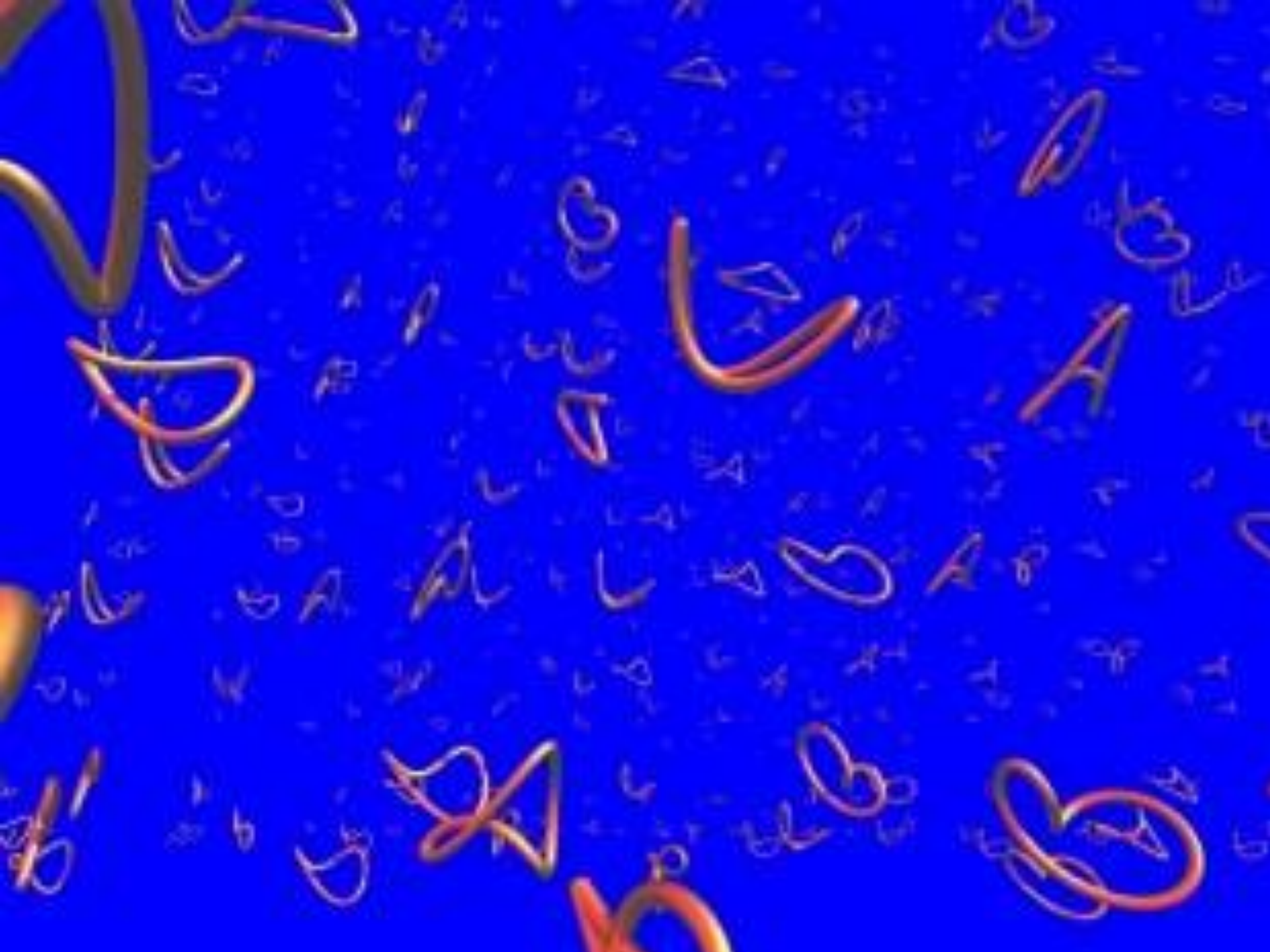
Interaction takes place by exchange of particles


positron
positron
photon
photon
electron
electron

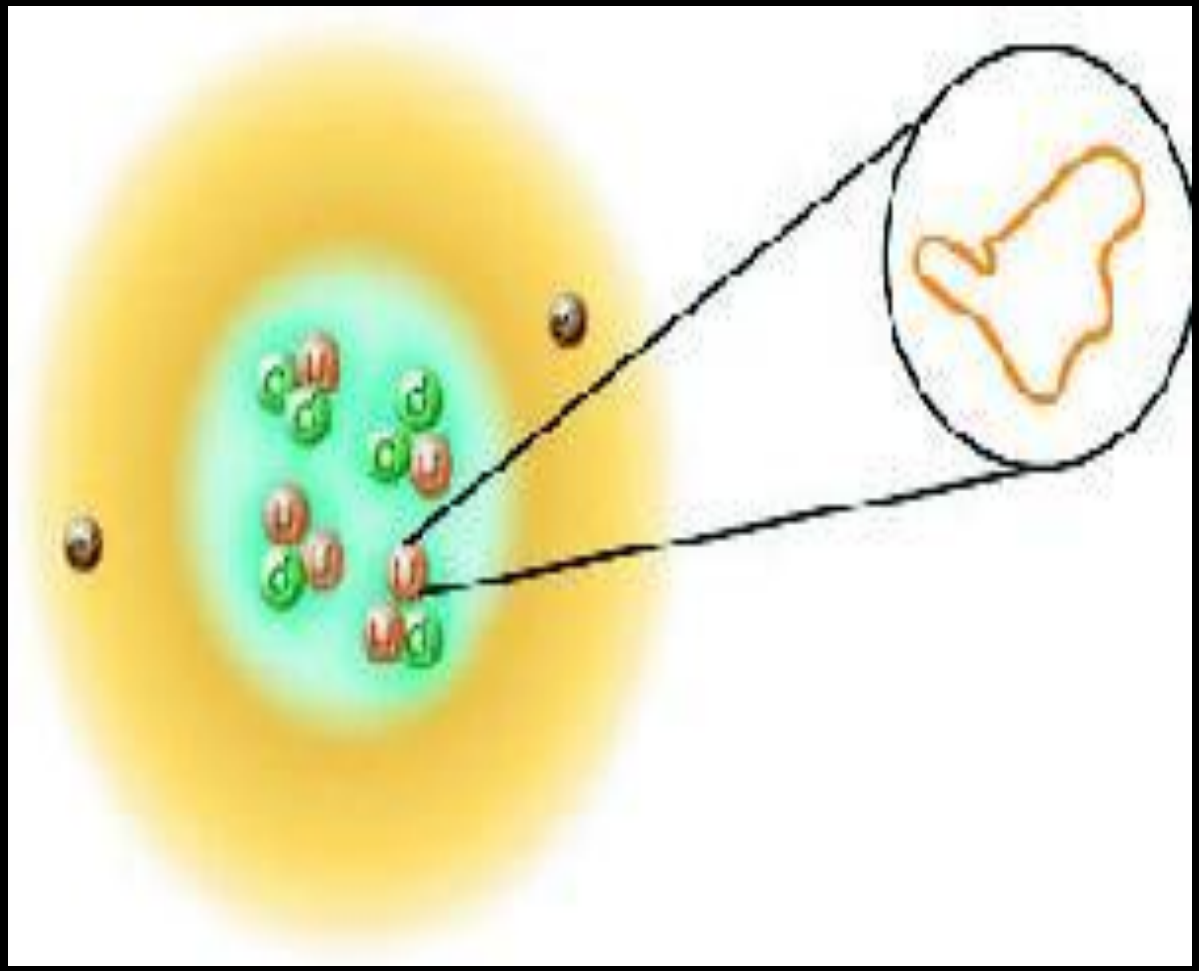



Gravity+Quantum Mechanics→?

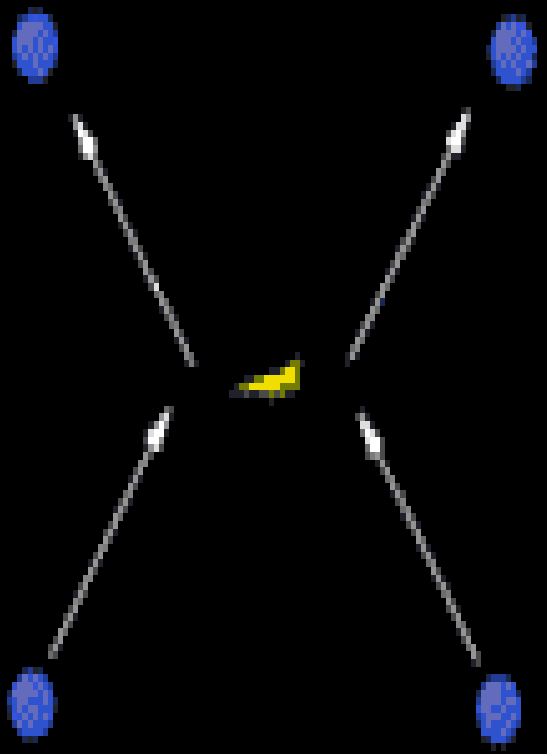
Particles+quantum mechanics+gravity

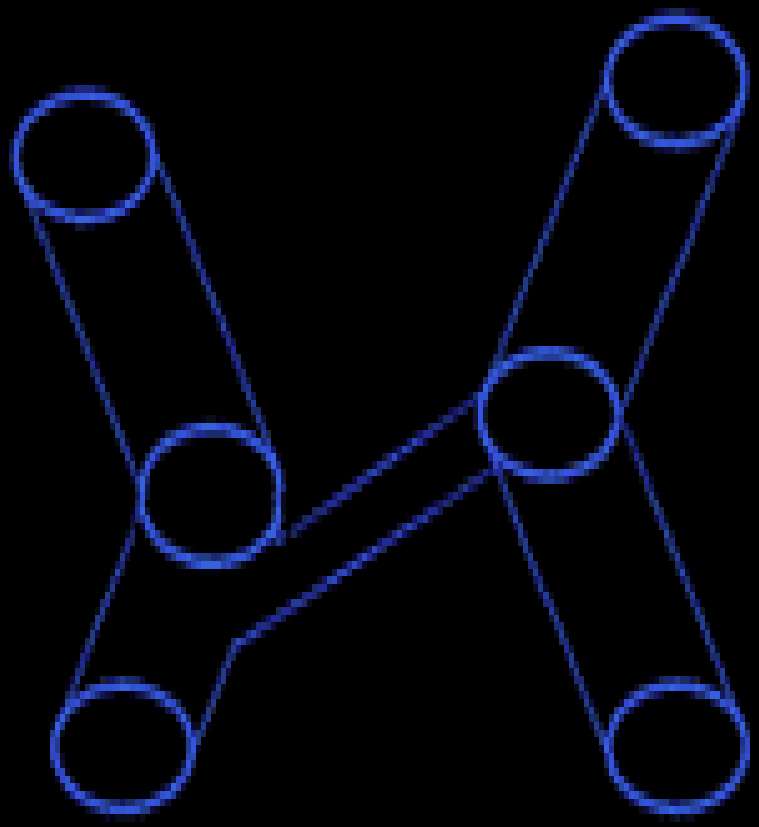


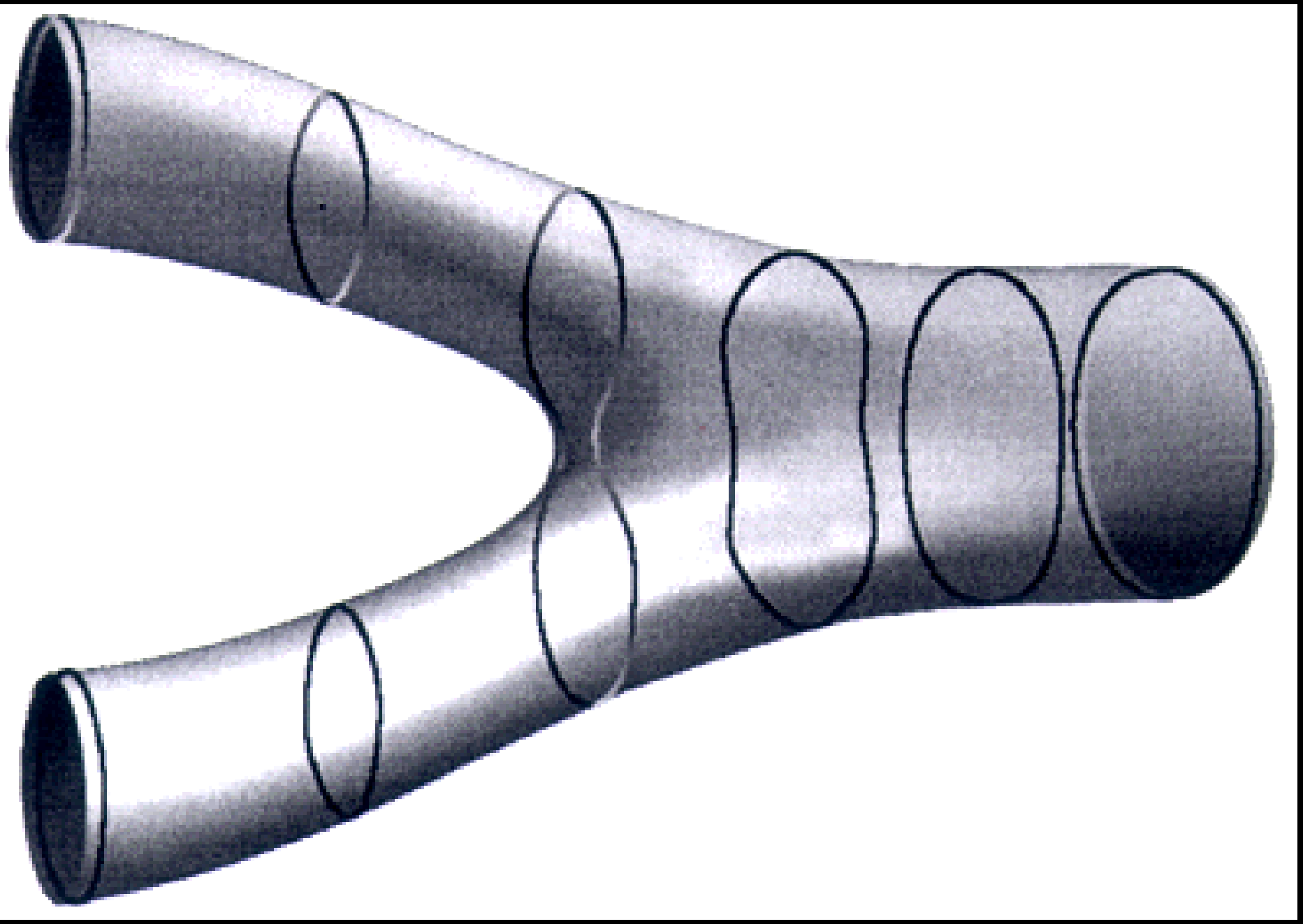
At yet smaller scales ``elementary particles'' look like strings

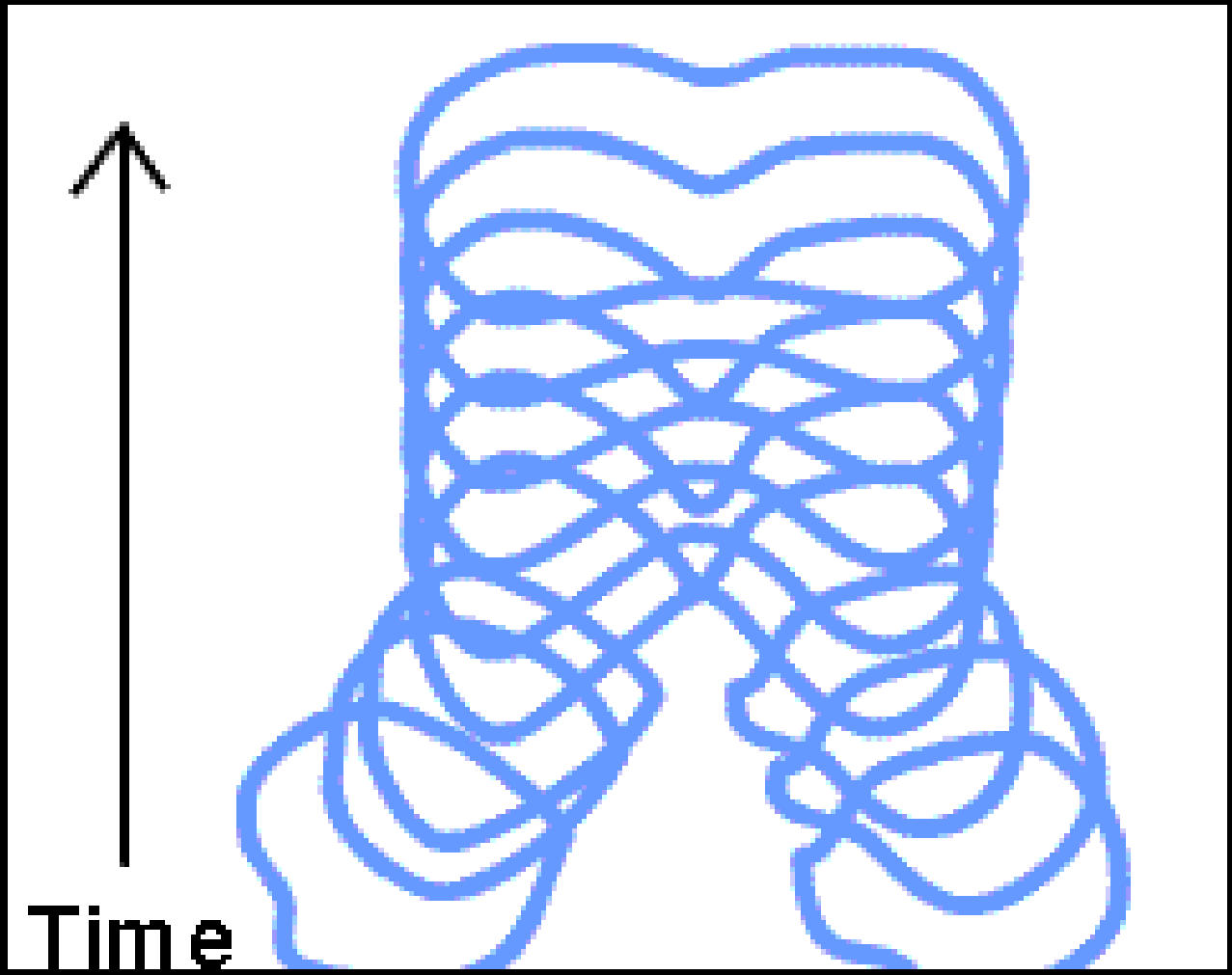


String Interaction

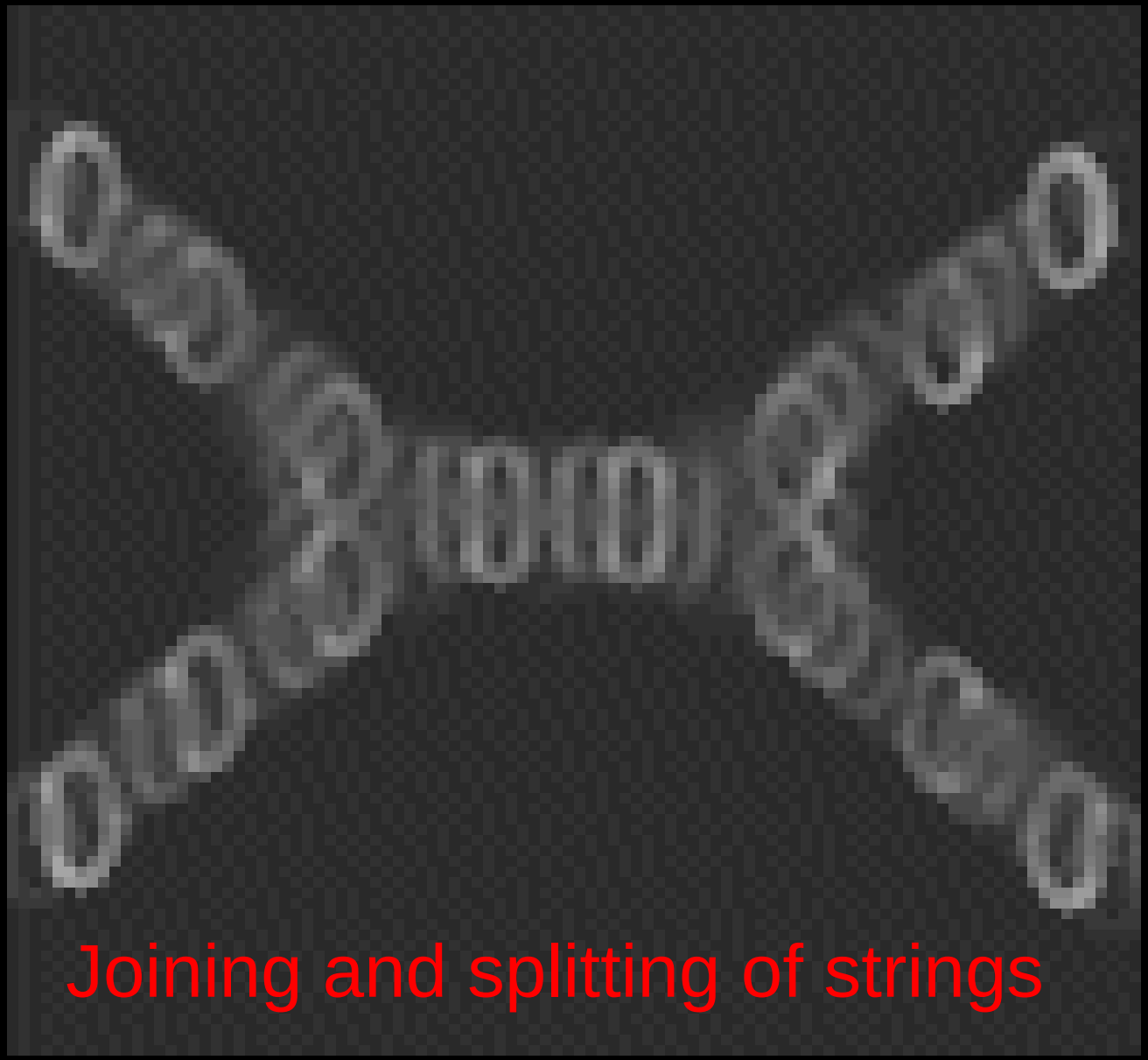








Joining of strings



Joining and splitting of strings

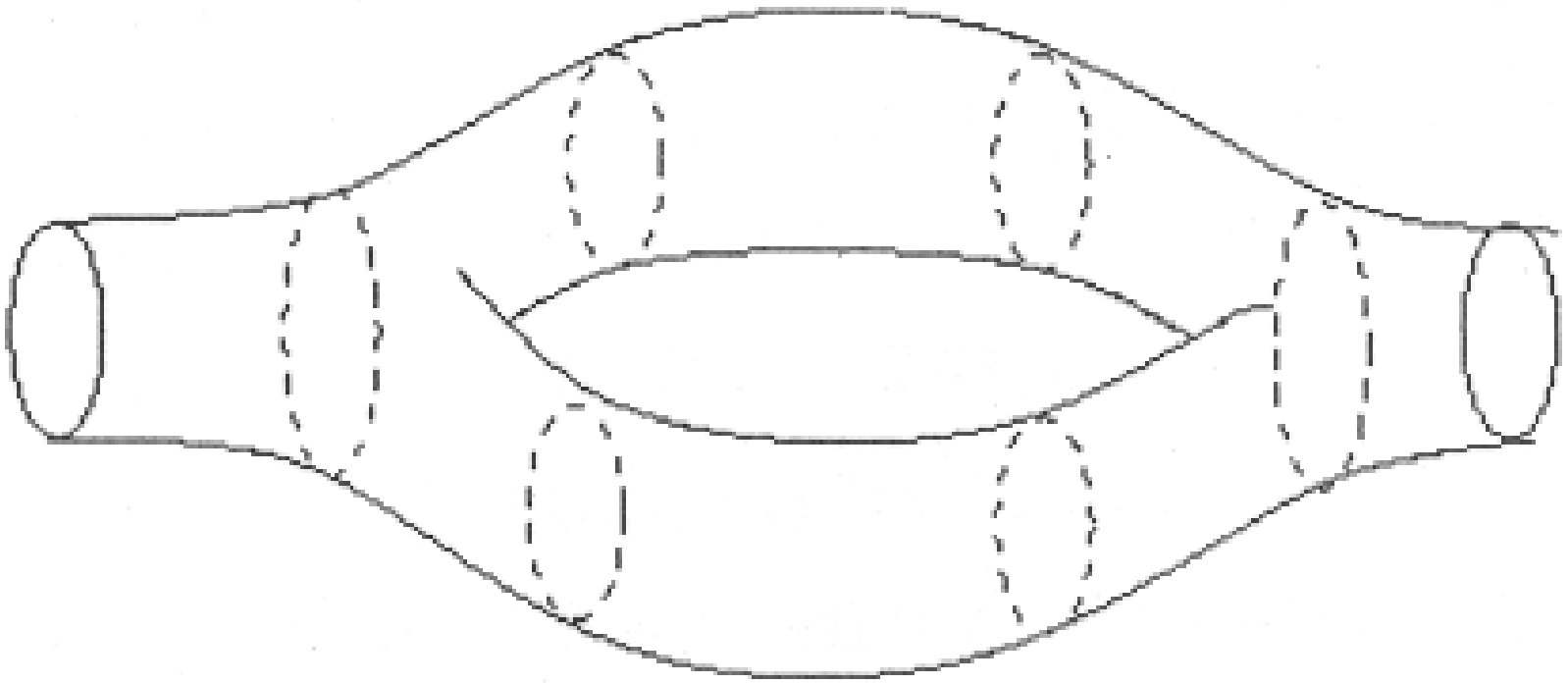
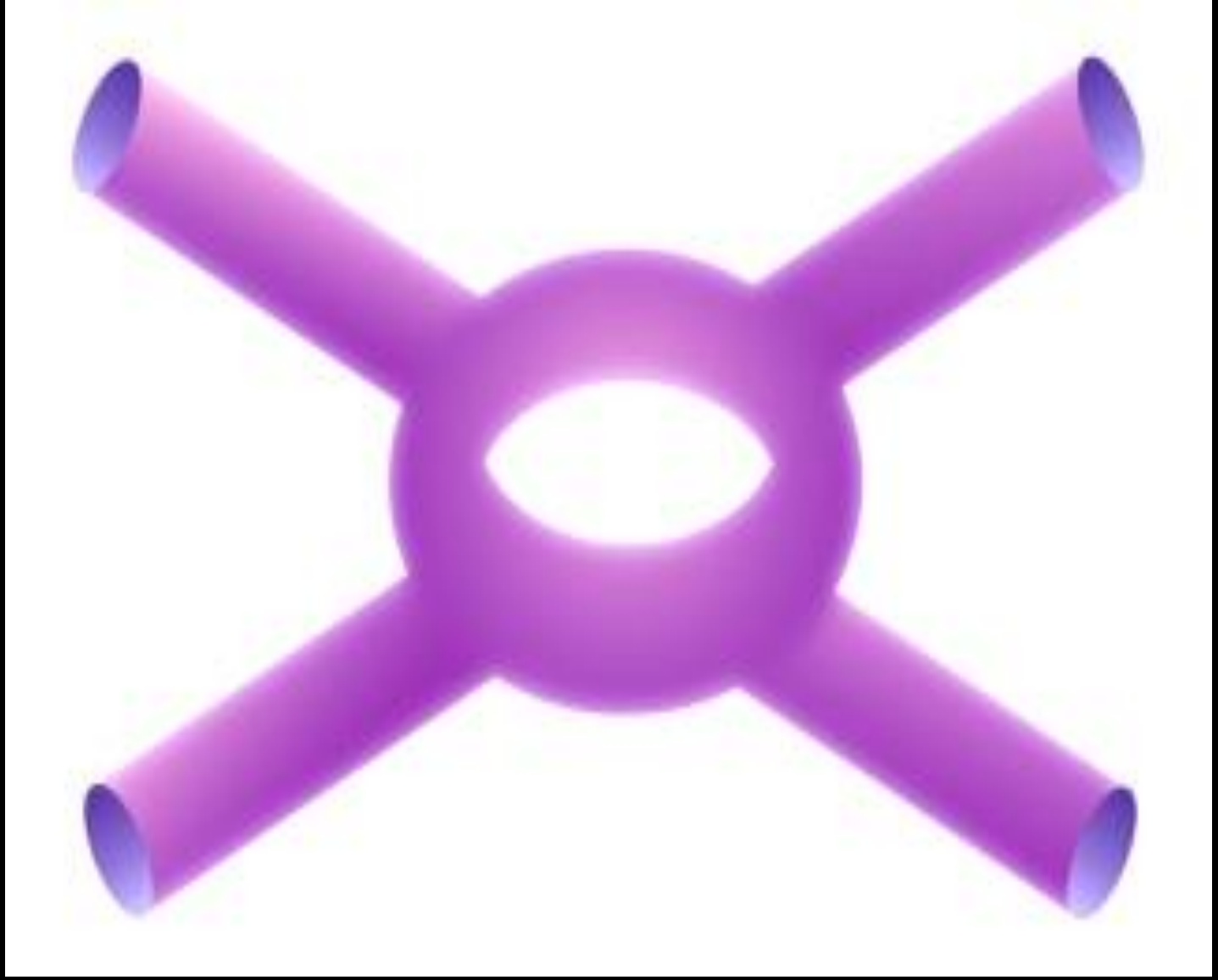
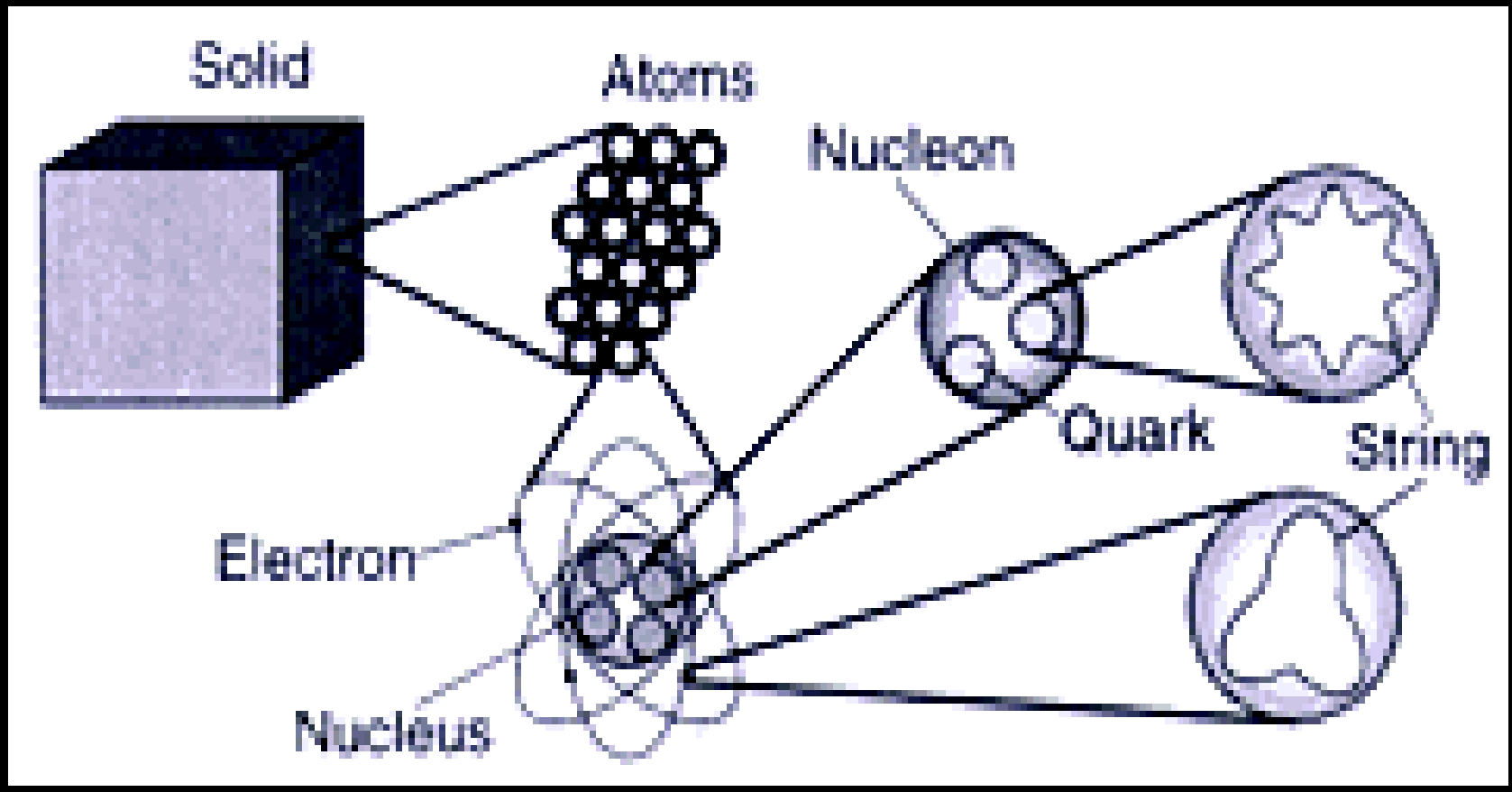


Fig.3 Closed string splitting and rejoining.
(Second order, loop level)



String interactions are described by the beautiful geometry of surfaces



Everything seems to be in place with strings at a very tiny (at present unobservable) scale

Strings:
The prime candidate for quantum gravity

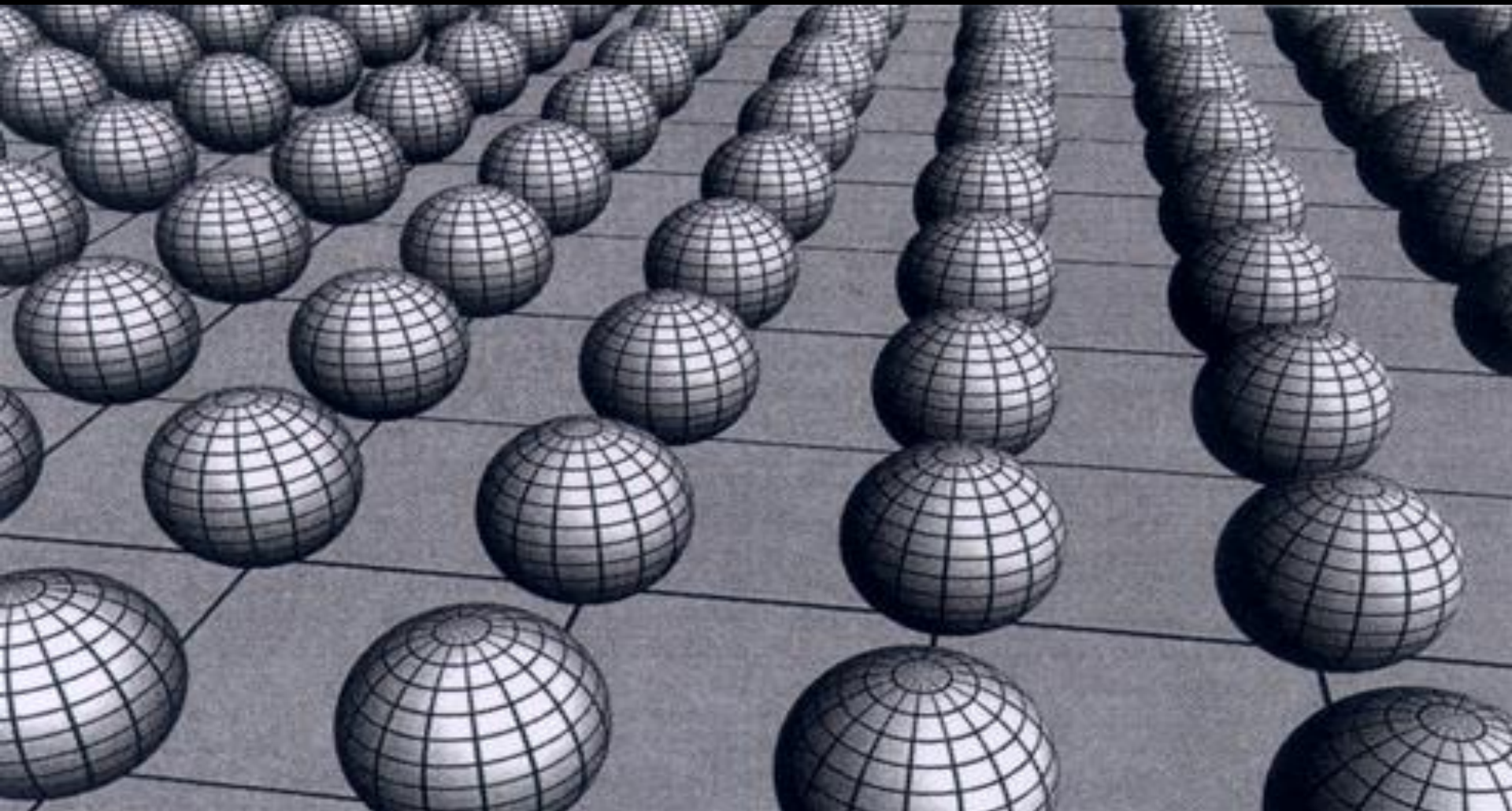
String/geometry connection:
starts on the wrong foot!

String theory demands d=10 but we live in d=4

This seems to raise a dilemma:

How to get rid of extra dimensions?

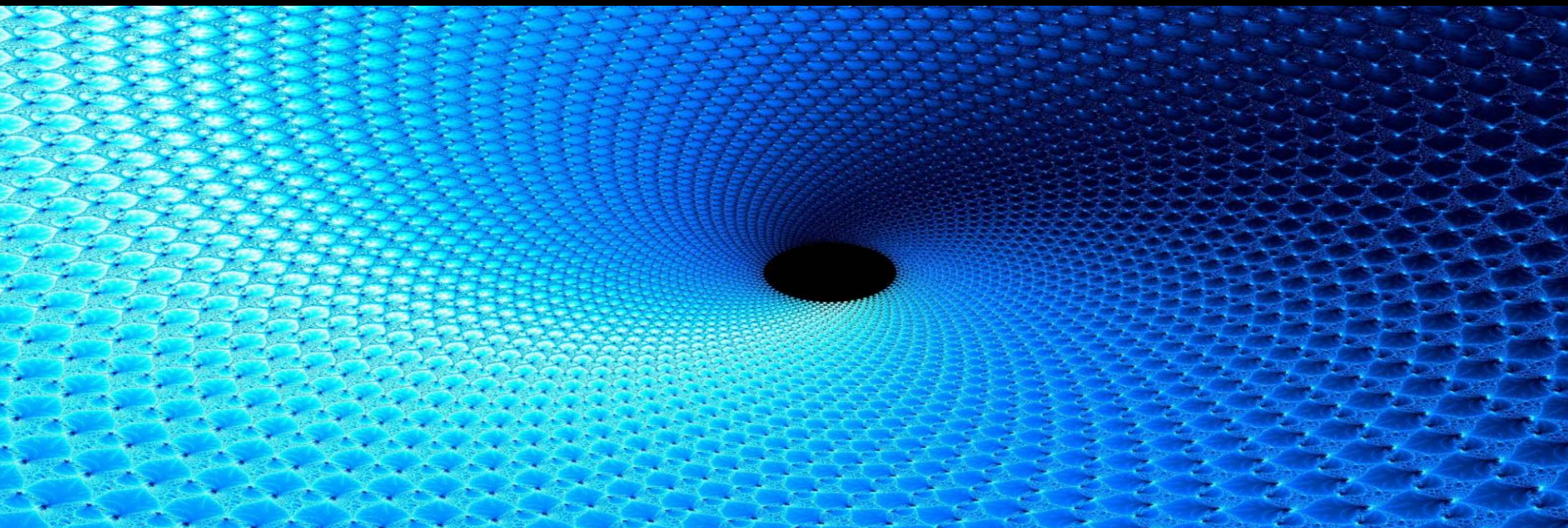
First attempt: Extra dimensions curled up and tiny--unobservable!



But this answer is not totally satisfactory:

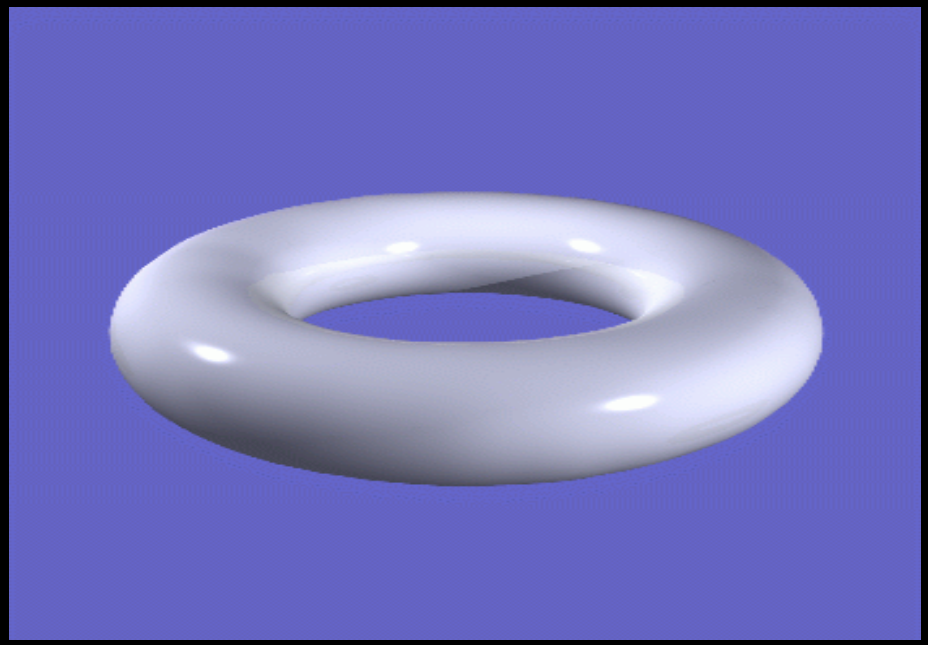
What are the extra dimensions good for?!

1) Black Hole Entropy: Where are the microstates of the black hole hidden?
Bekenstein-Hawking formula:
S=A(horizon)/4 (instead of 0).

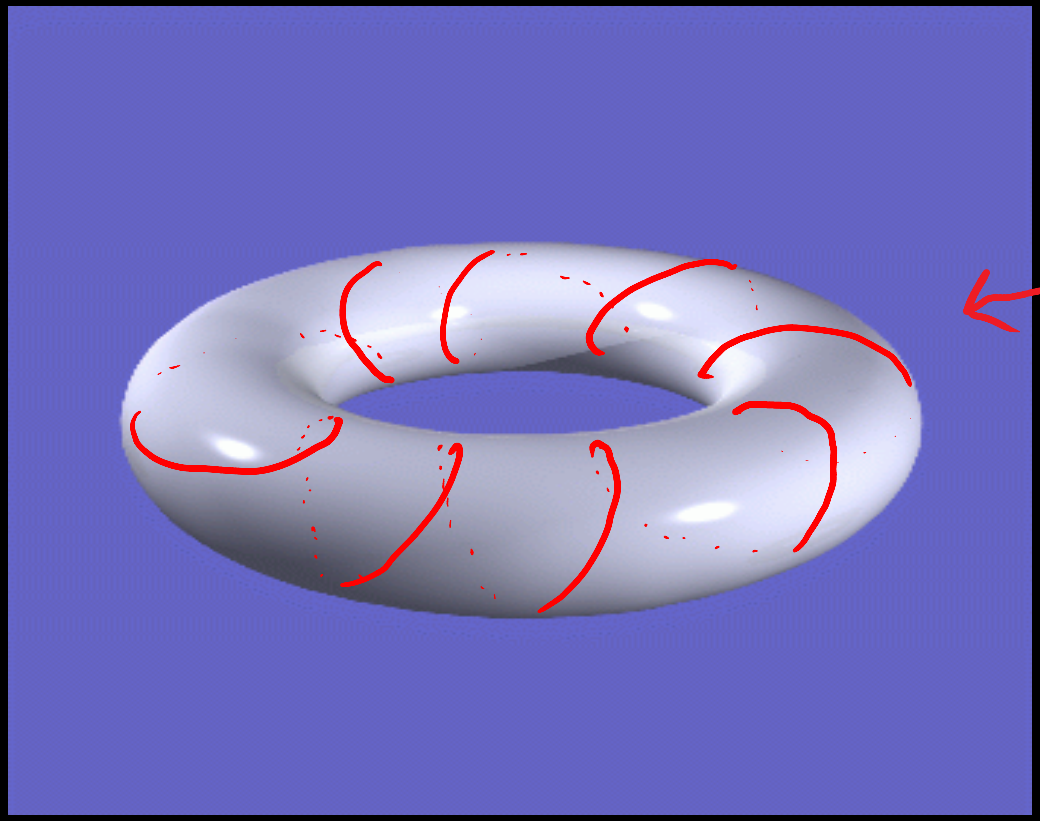


2) What dictates the structure of matter? Number of generations and the types of gauge forces?

3) In solving dynamics of certain 4d theories auxiliary spaces arise (notably Montonen-Olive torus)? Are they physical?



In addition, monopoles and dyons are related to objects on this surface. Are the curves on the surface physical objects?



4) Can one better understand strong interactions and understand how phenomena such as confinement take place.

Until mid 90's the extra dimensions of string theory, were viewed by and large as an embarrassment for string theory, or at best a tolerable feature.

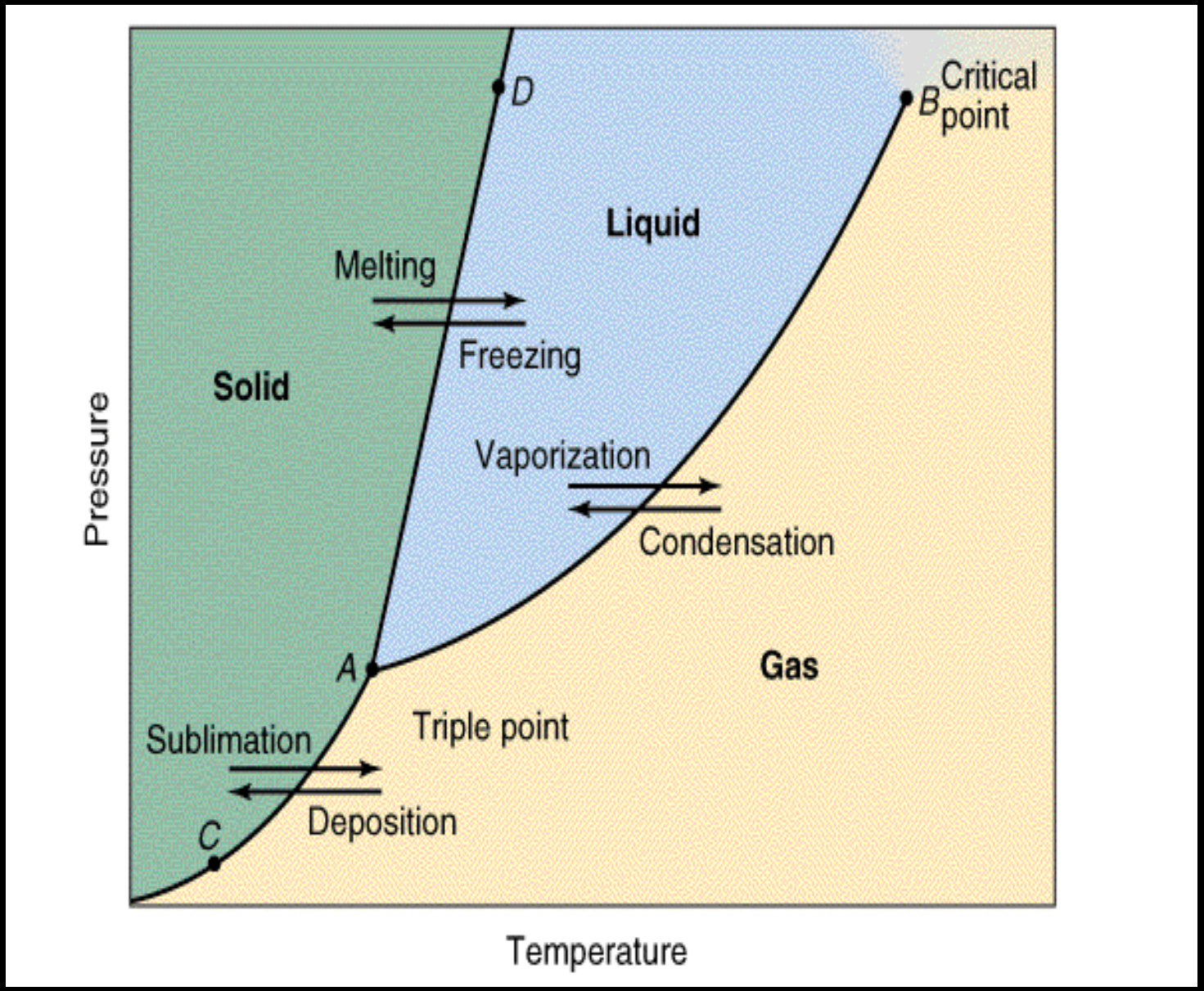
The story changed dramatically with the discovery of string dualities in the mid 90's.

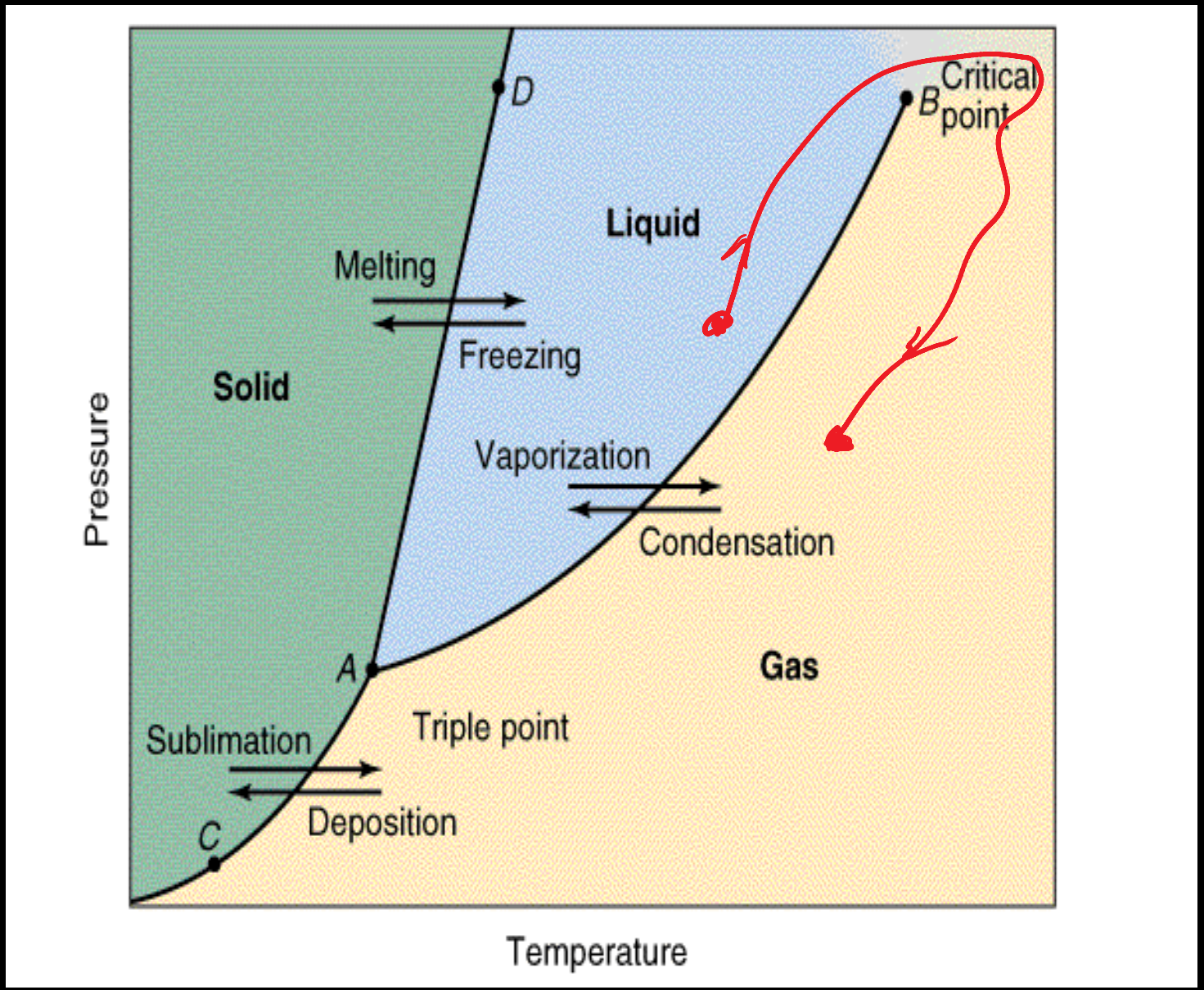
String Dualities:

Upon changing parameters various known string theories unify to one theory (called M-theory).

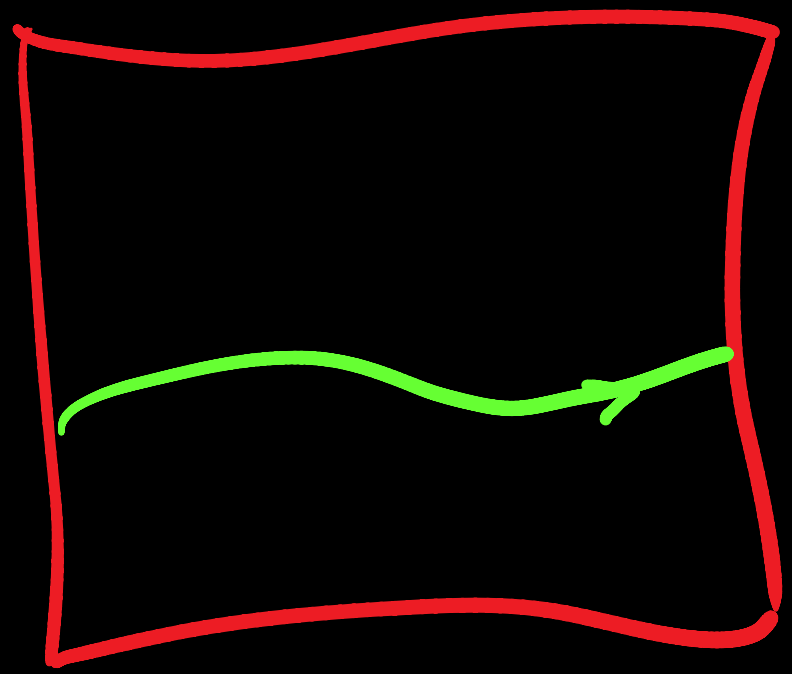
Extended objects (branes) play a key role.

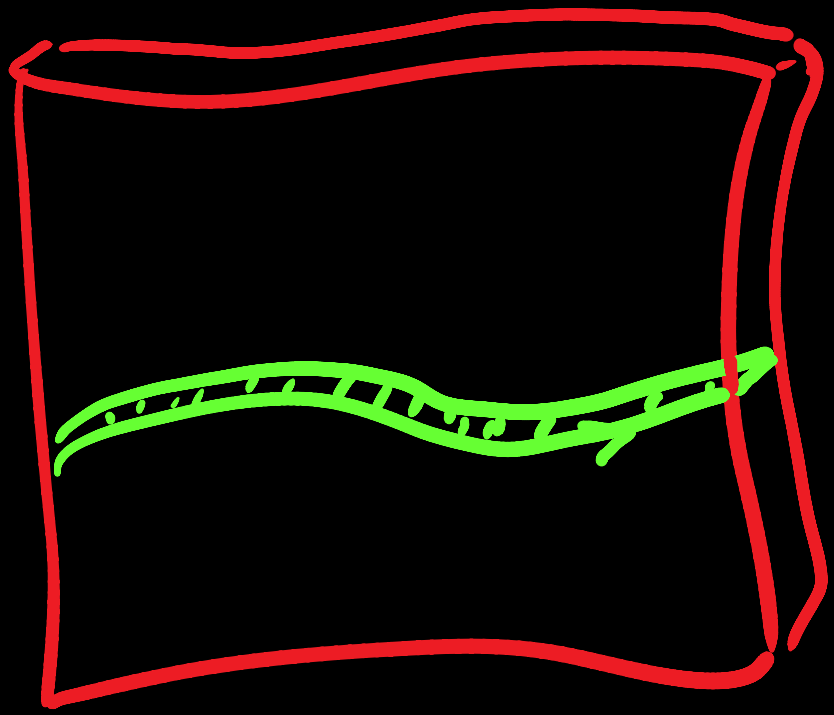
A familiar analogy:

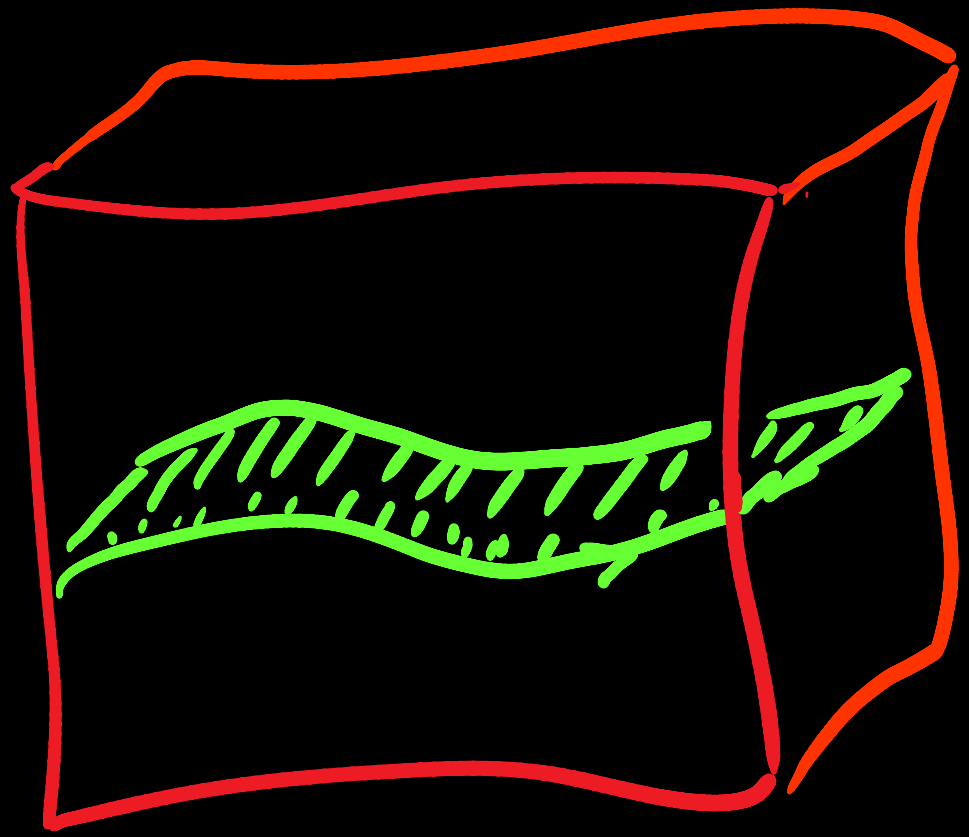


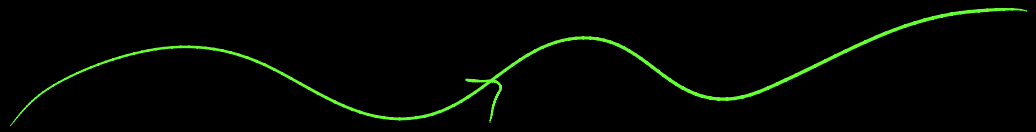

D
B
Critical point
Liquid
Melting
Freezing
Solid
Vaporization
Condensation
Pressure
A
Gas
Triple point
Sublimation
Deposition
C
Temperature

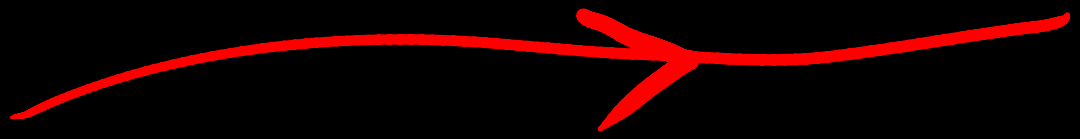
As we change parameters in string theory Dimension of space as well as the objects change:

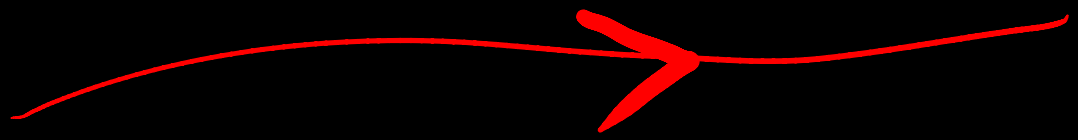


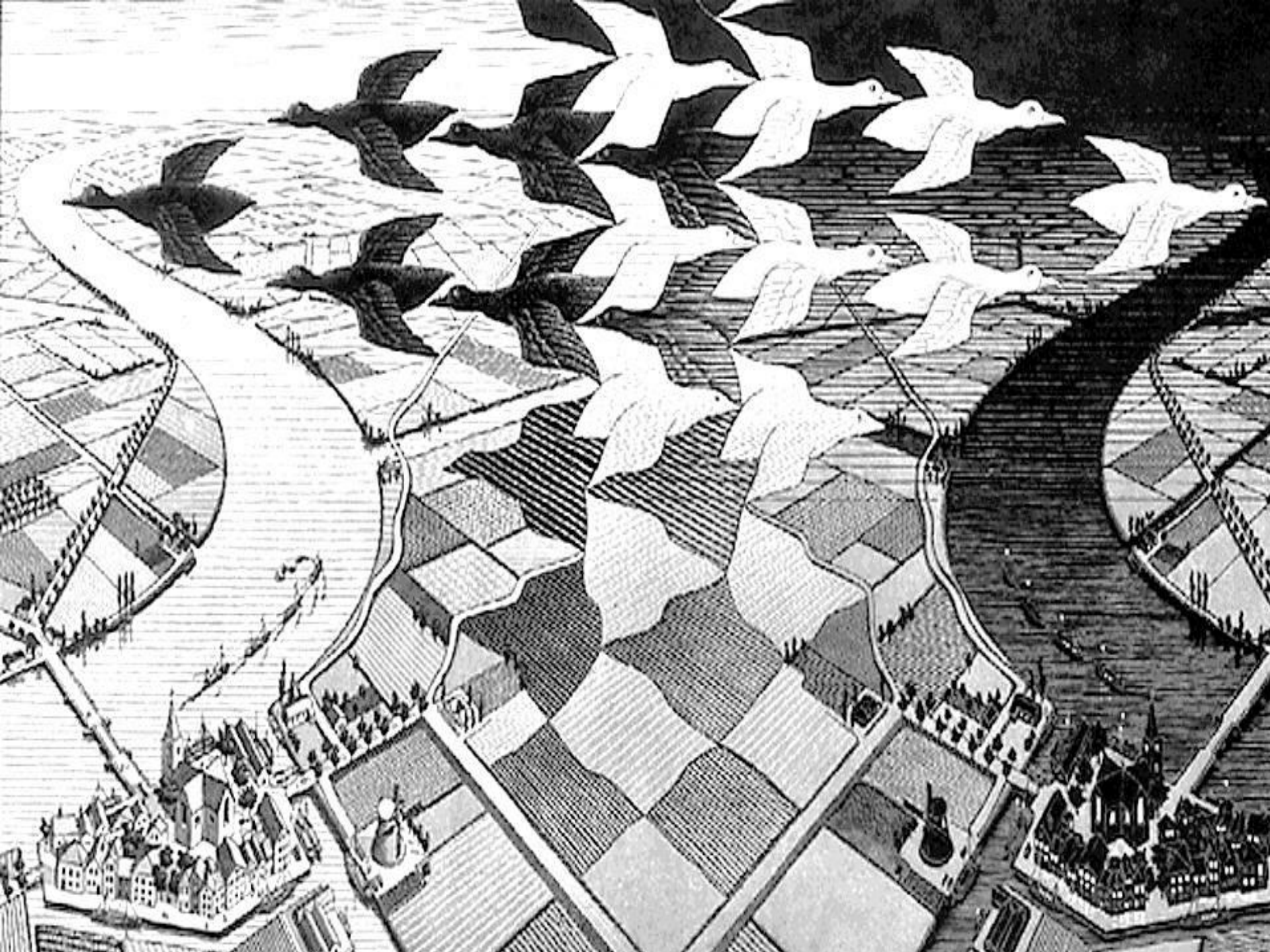


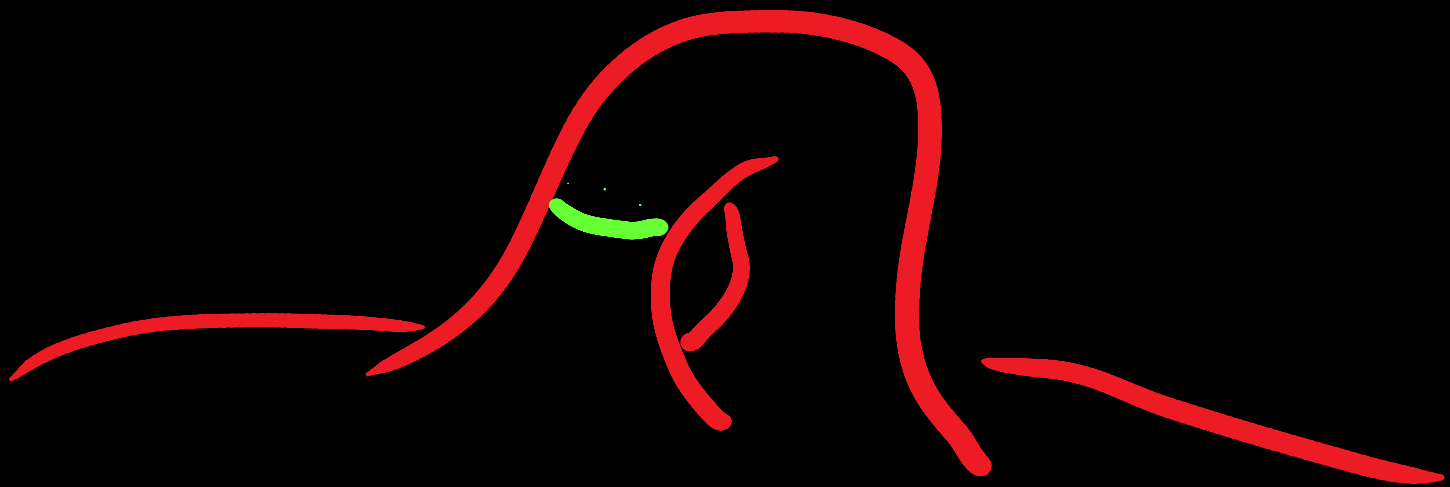


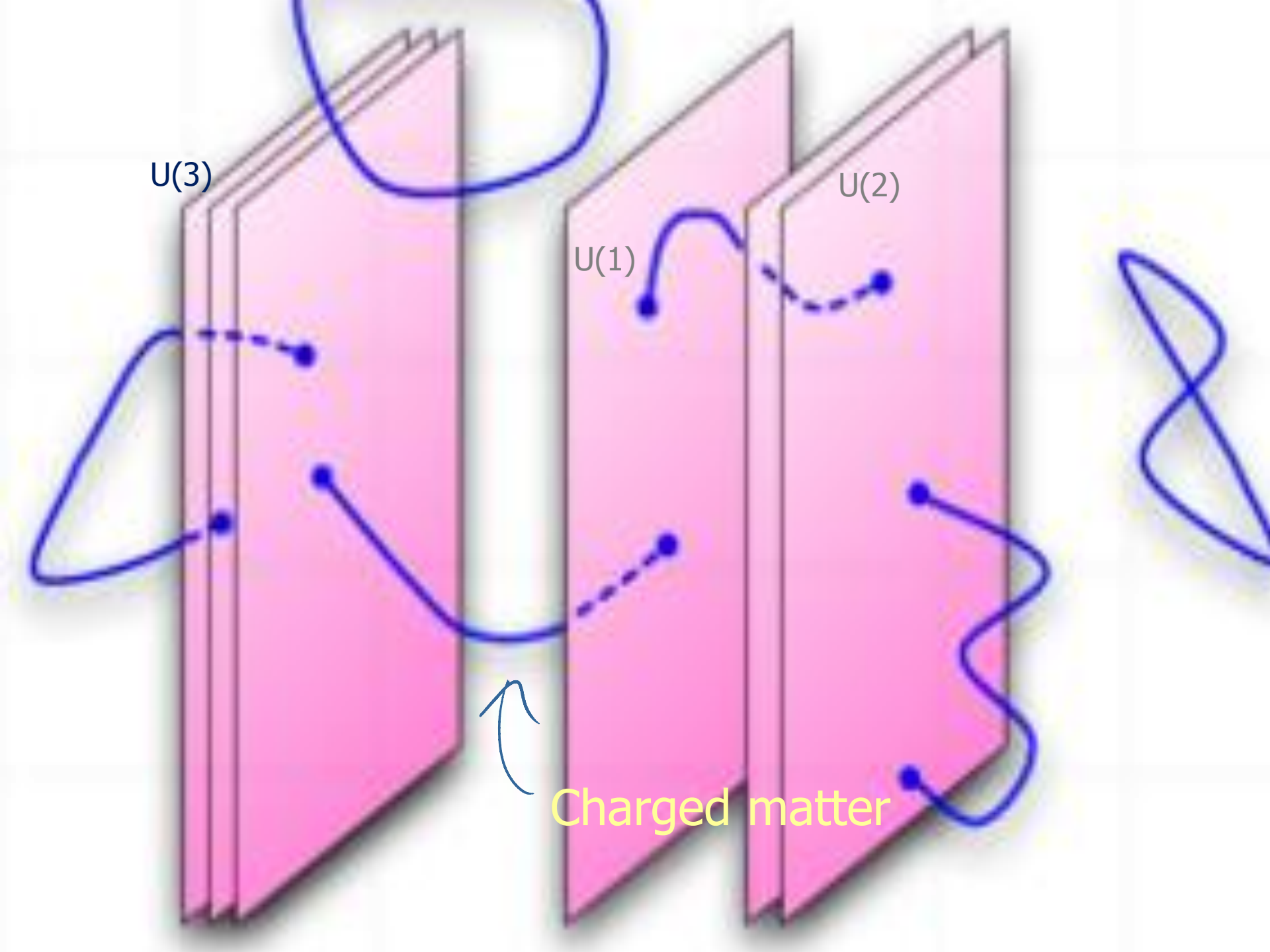






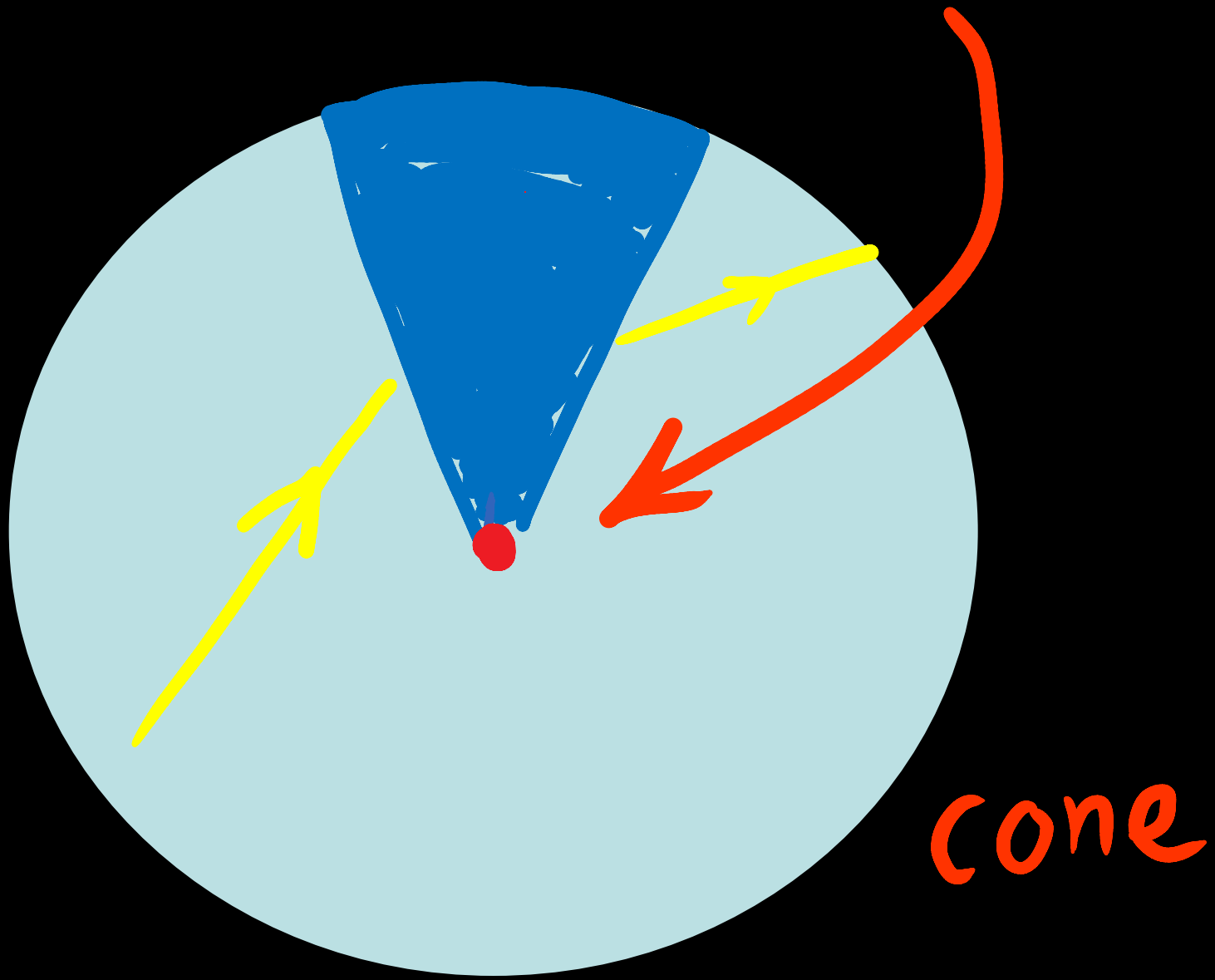




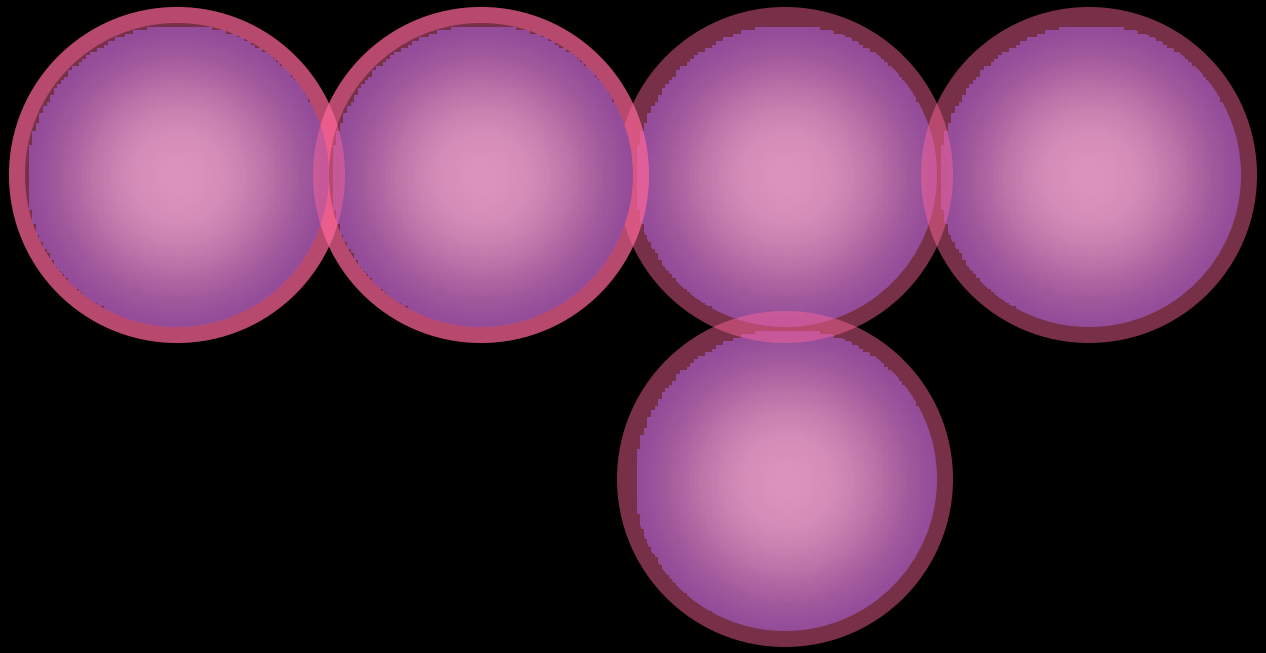

U(3)
U(2)
U(1)
Charged matter

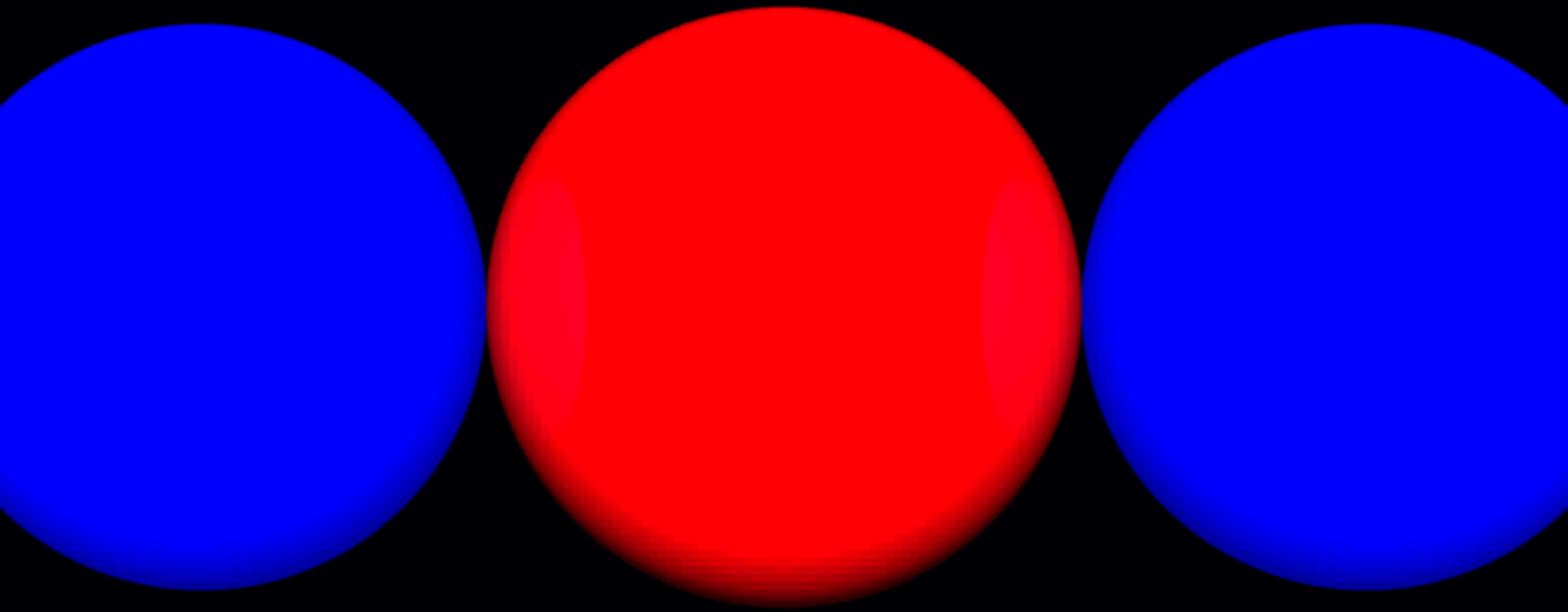
Interplay between geometry and branes:

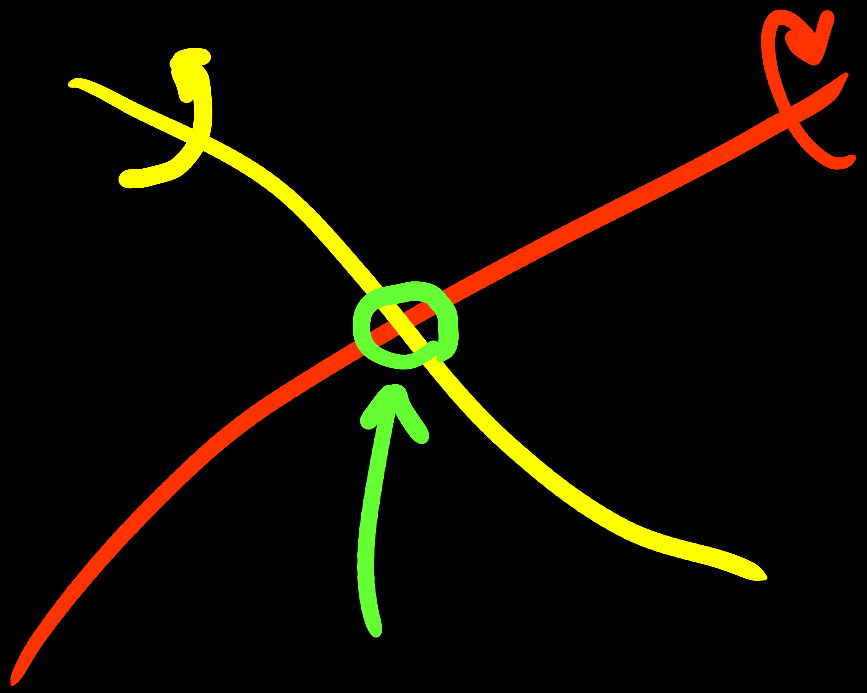
2-Singularities of geometry can be interpreted as branes.

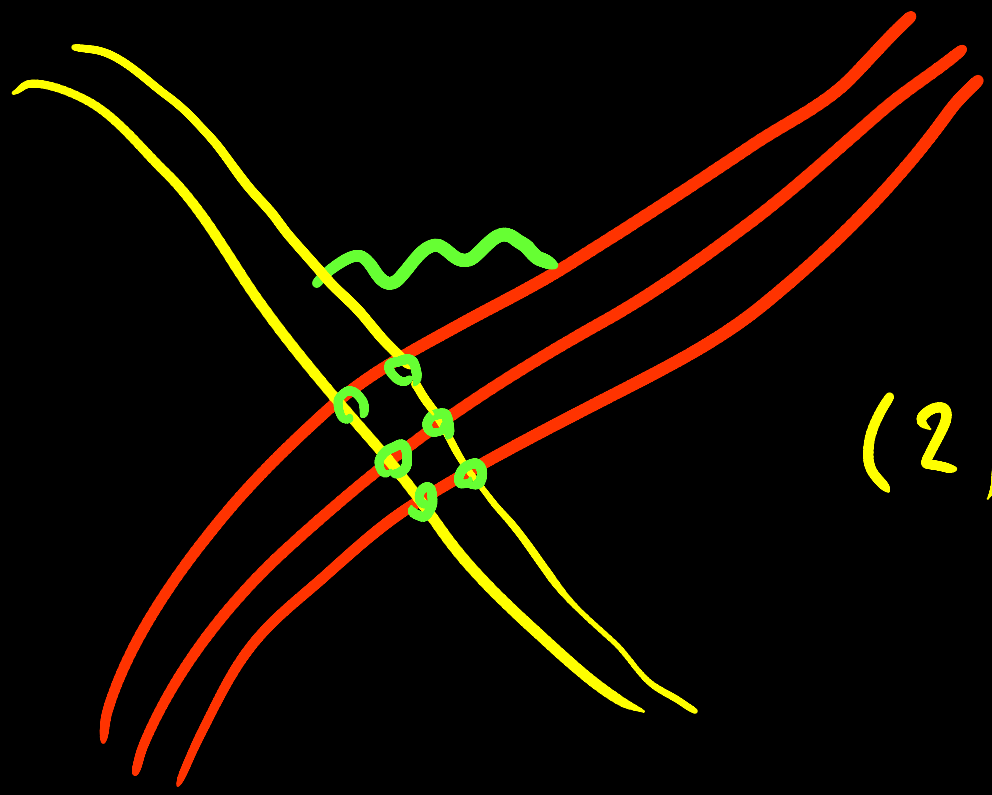

cone

SO(10)

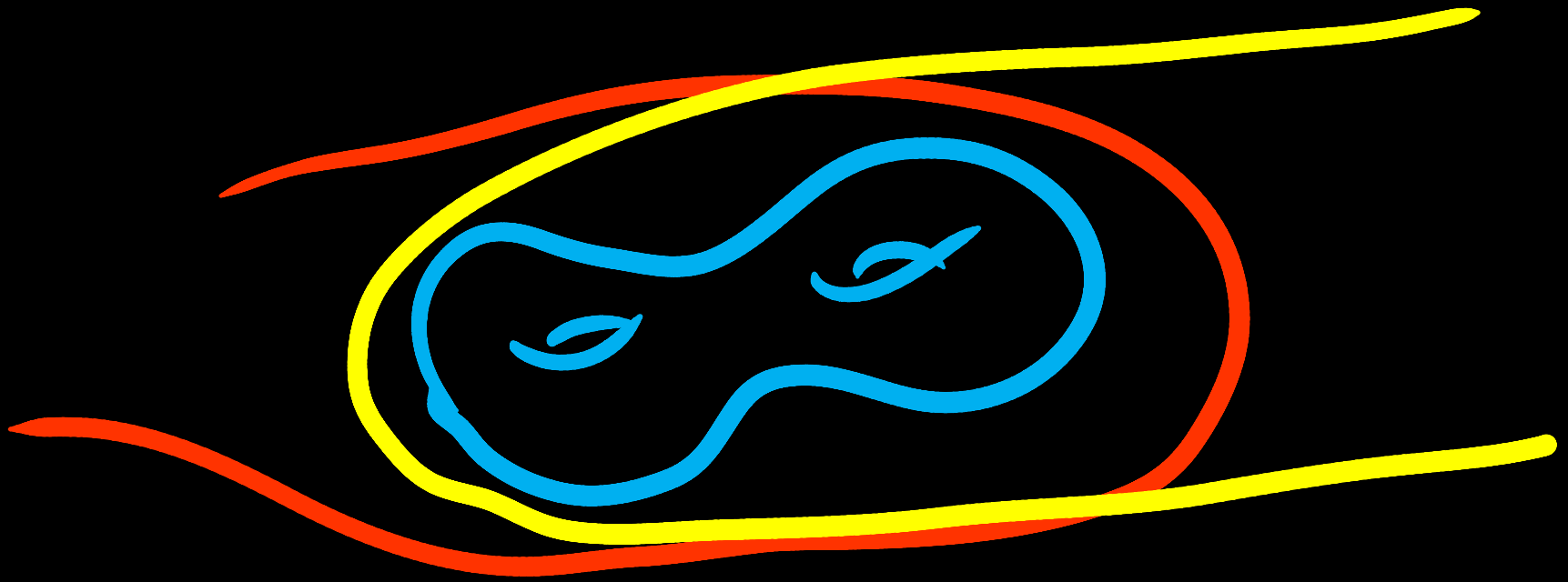





matter


(2,3)

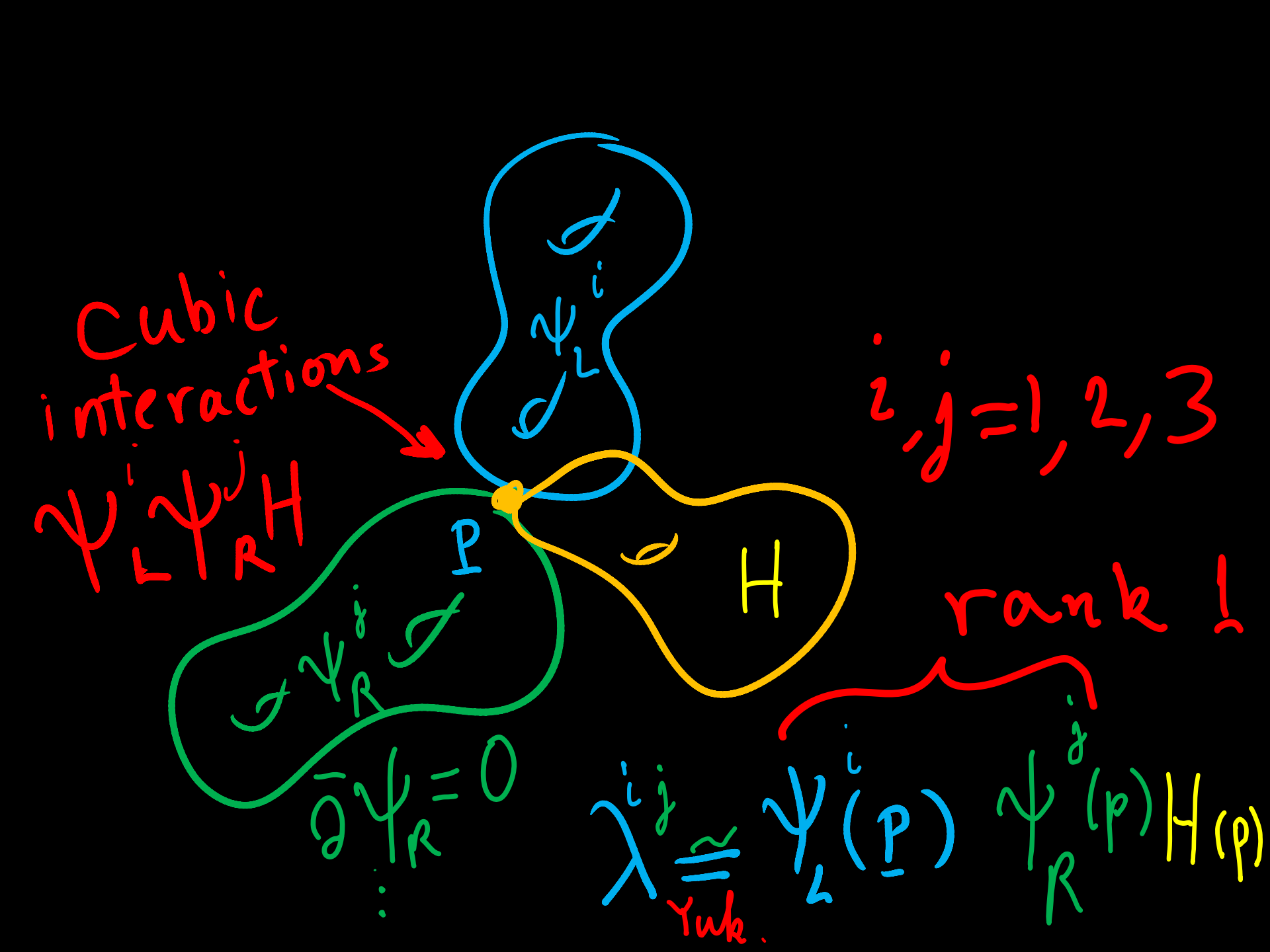
Existence of extra dimensions allows us to create degeneracies → 3 generations



The number of generations =3

The number of zero modes for the Dirac operator on the surface=3

$$\not{D}\psi^i = 0 \qquad i = 1,2,3$$

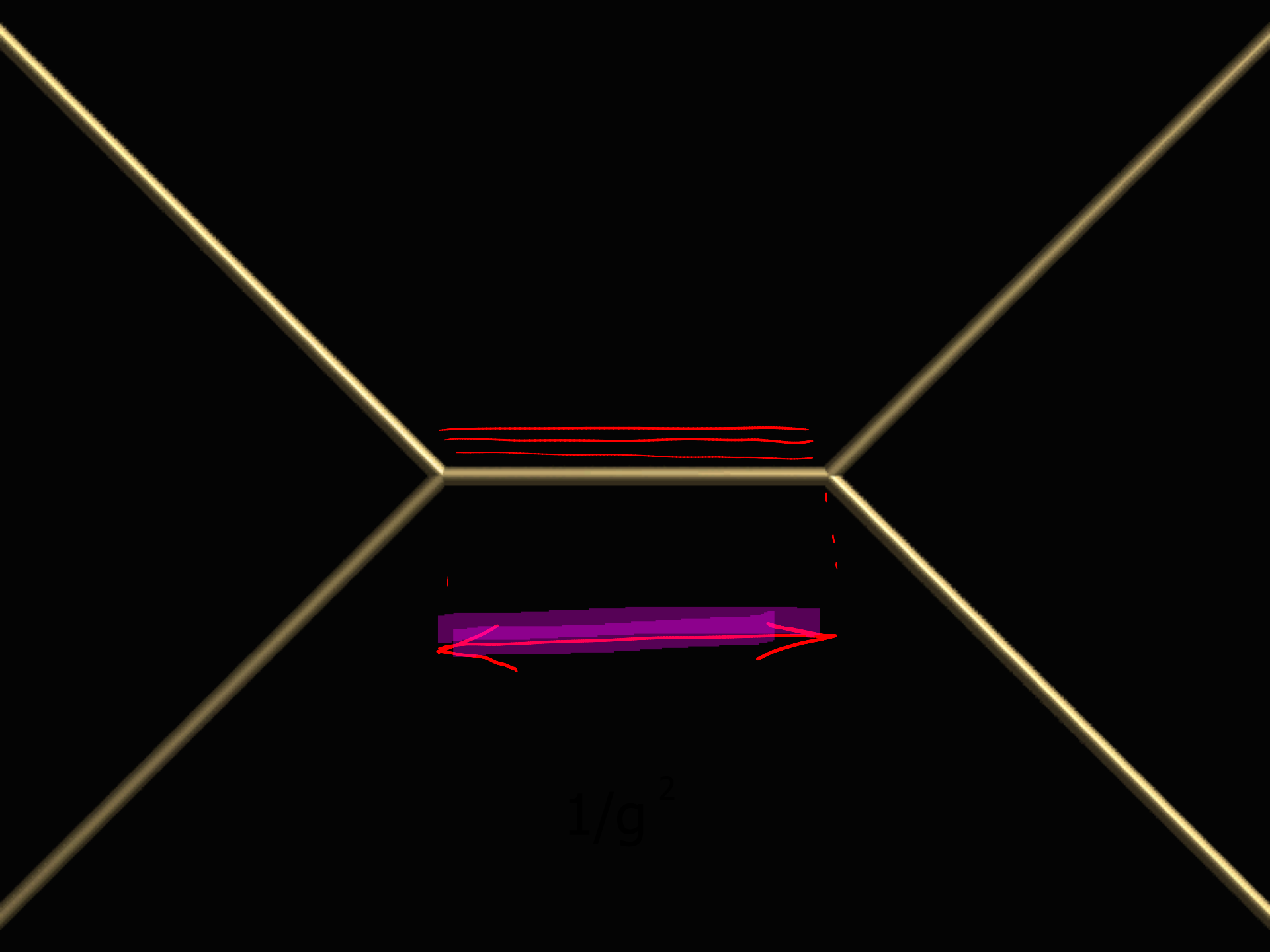

Cubic interactions
$\psi_L^i \psi_R^j H$
$i,j=1,2,3$
ψ_L^i
P
H
ψ_R^i
$\bar{\partial}\psi_R = 0$
$\lambda^{ij} \underset{\text{Yuk.}}{\simeq} \psi_L^i(P)\, \psi_R^j(P)\, H(P)$
rank !

This also leads to semi-quantitative predictions for quark mixing matrix in a class of string models:

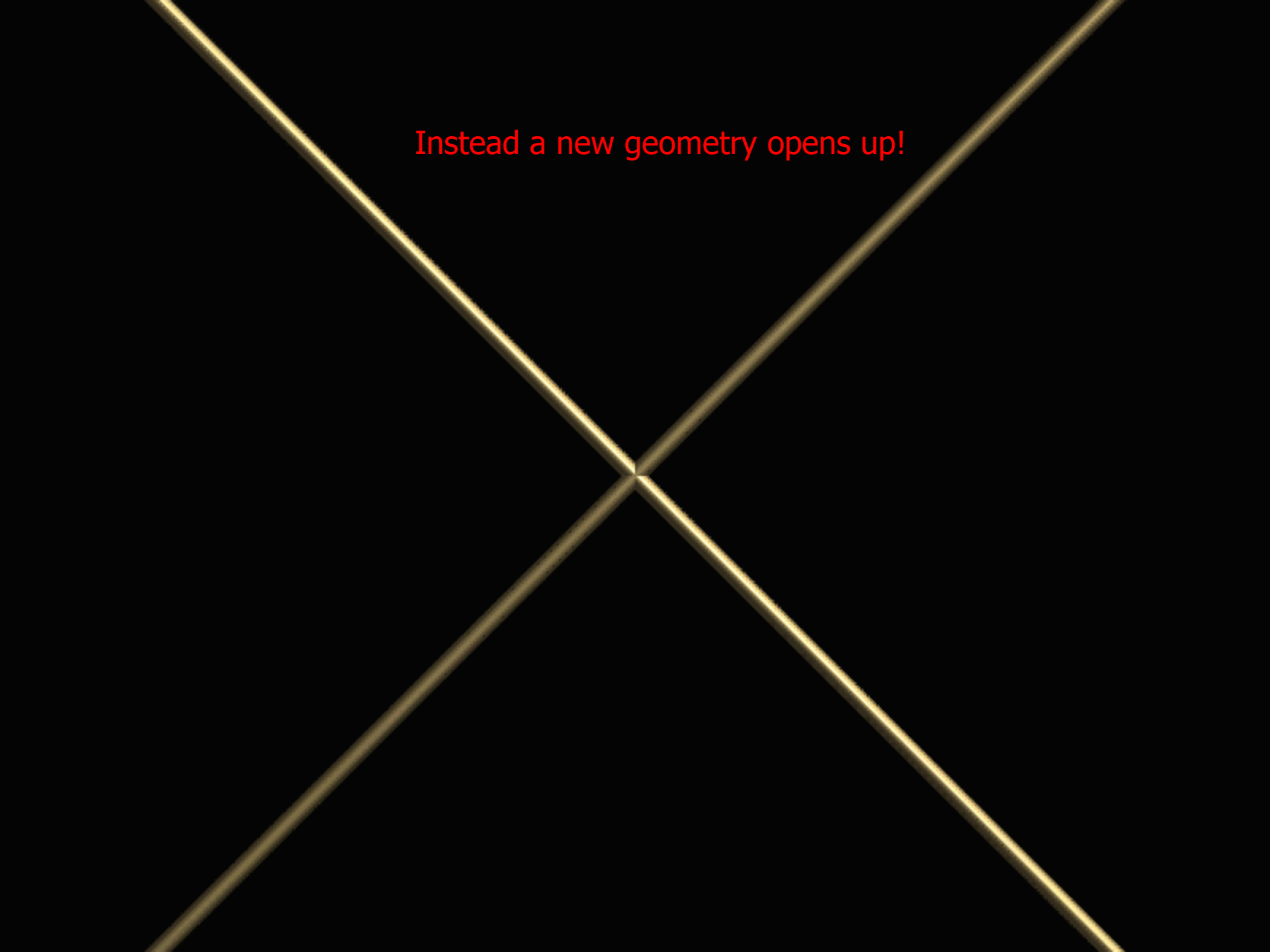
$\alpha_{GUT} \approx 0.04$

$$V_{CKM}^{F-th} \sim \begin{pmatrix} 1 & \alpha_{GUT}^{1/2} & \alpha_{GUT}^{3/2} \\ \alpha_{GUT}^{1/2} & 1 & \alpha_{GUT} \\ \alpha_{GUT}^{3/2} & \alpha_{GUT} & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.008 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

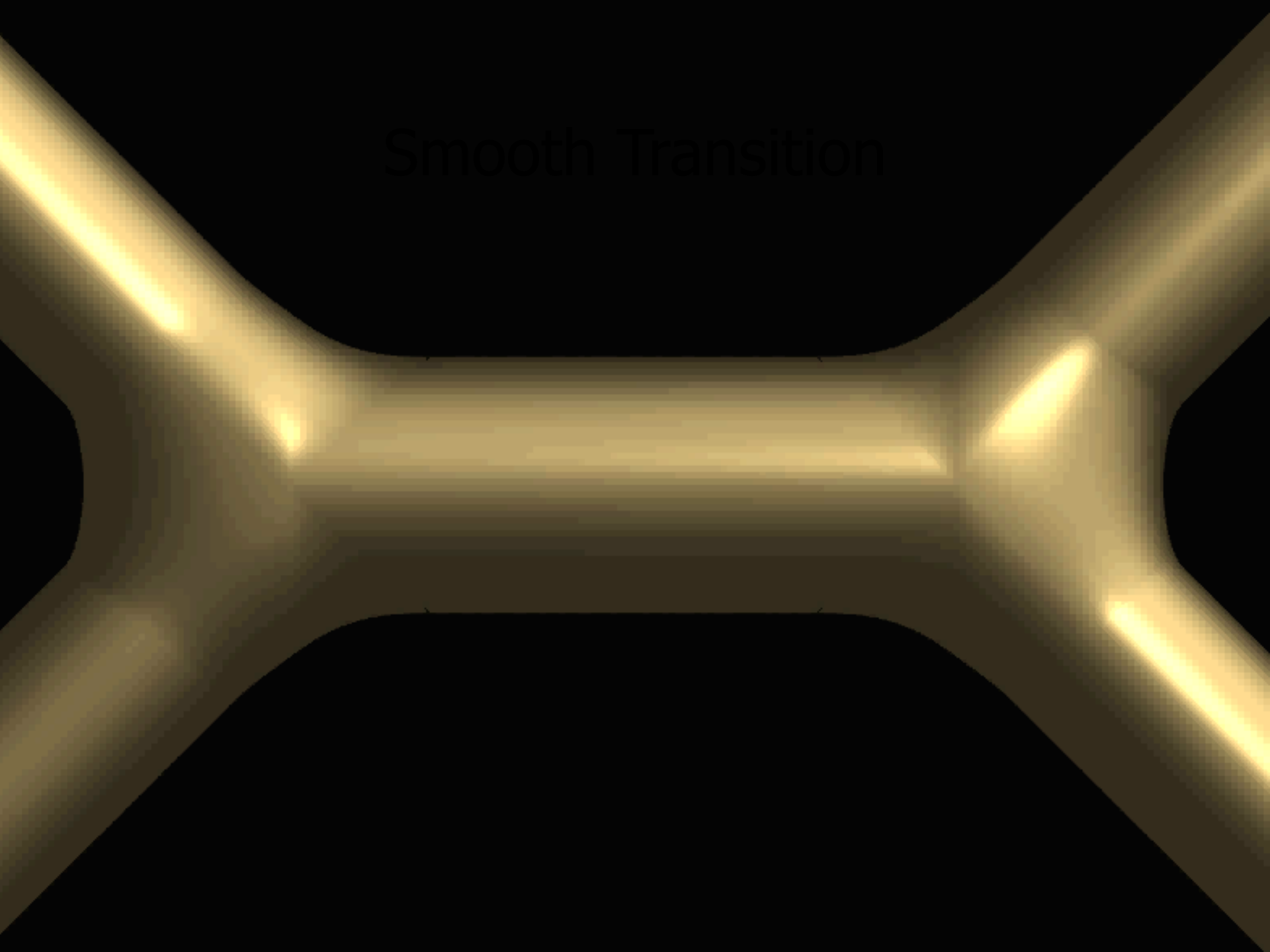
$$|V_{CKM}(M_{weak})| \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix}$$


$1/g^2$


Naïve continuation does not make
geometric sense

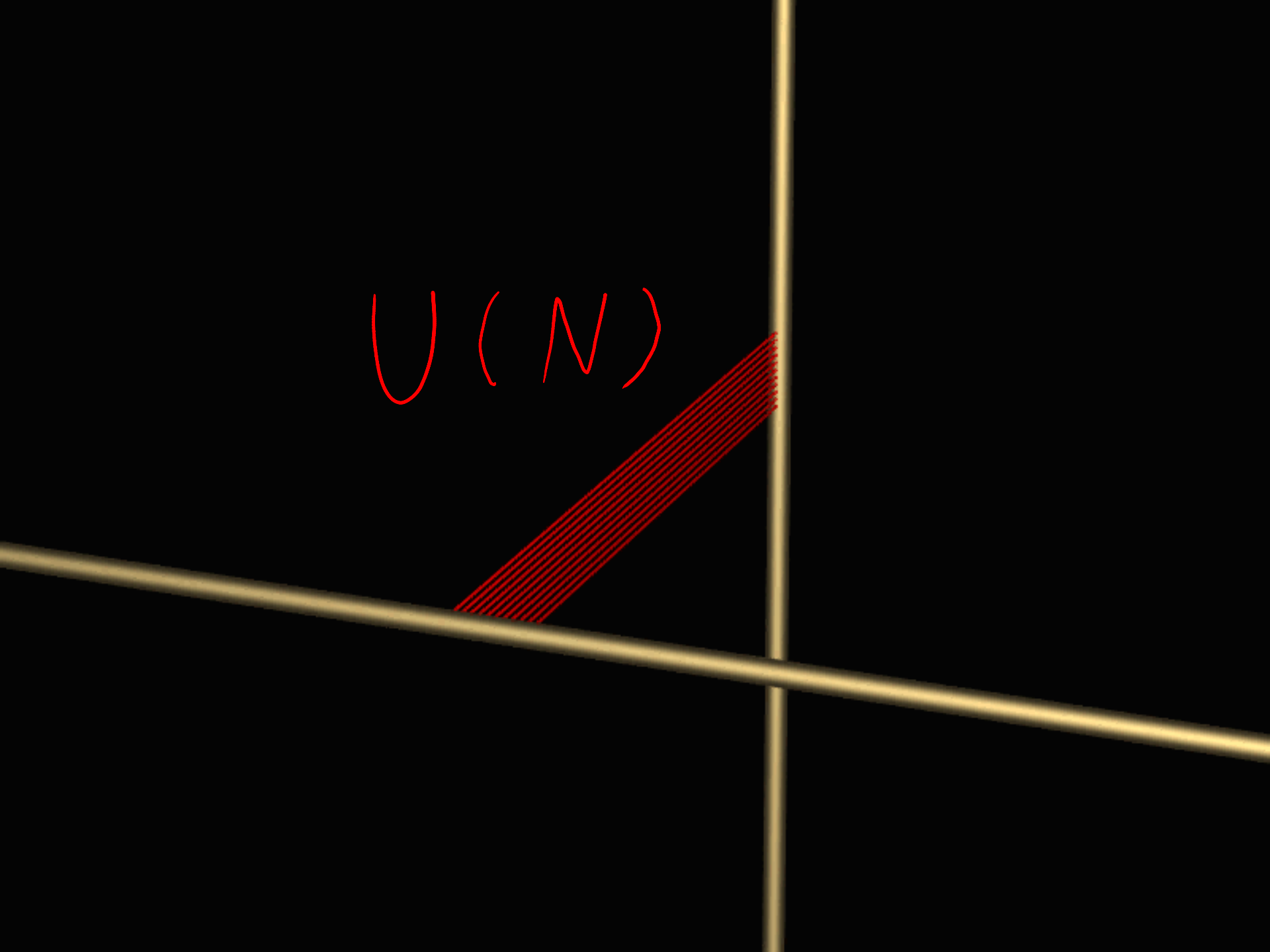

Instead a new geometry opens up!

In many cases the transition is smooth. For example they get mapped to a dual geometry for which there is no sharp transition point and this leads to important insights into strong coupling physics.


Smooth Transition

To get rid of the open string means somehow the D-branes must disappear (because the D-branes are responsible for cutting the closed string open).

A dual description exists where the branes are replaced by flux:

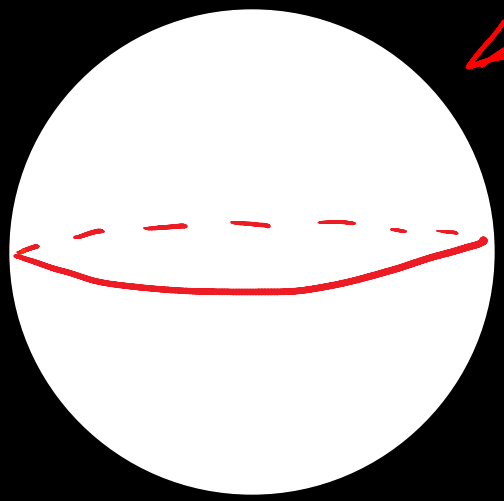

U(N)

Black Holes

How are black holes realized in string theory?

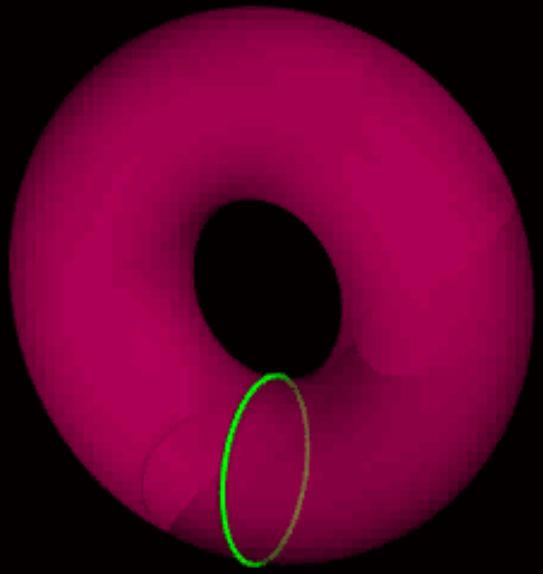
One way is to view them as branes wrapped around cycles of the internal manifold.

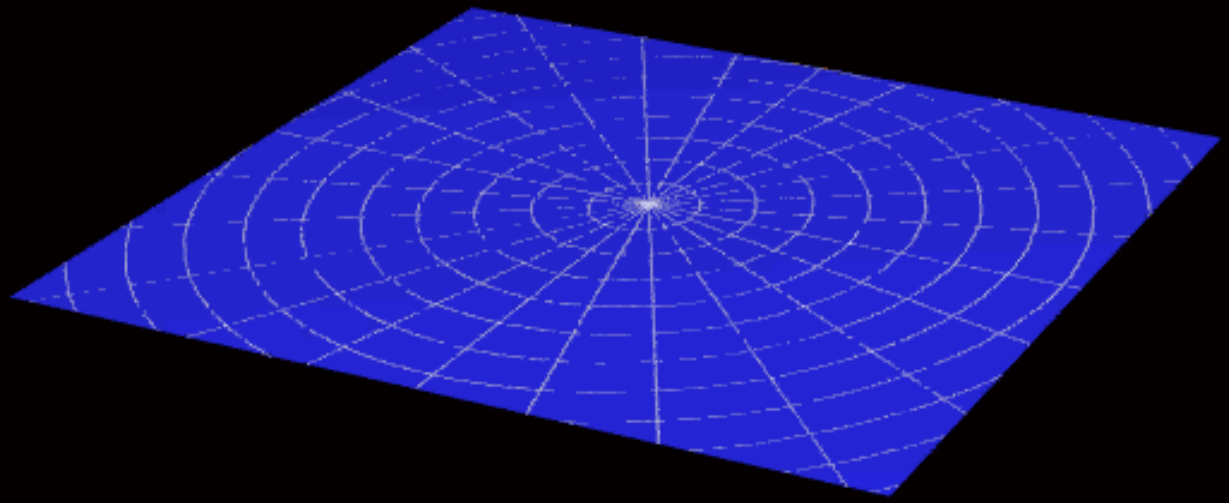
Mass = tension x Volume of the brane



$$S = \frac{1}{4} A$$

Black hole as wrapped branes in the internal dimensions





Conclusion

Strings and Geometry have a beautiful interplay.

This interplay sheds light on 4d physics. Many physical facts have their origin in the internal geometry of string theory.