# Outlook for New Physics at LHC

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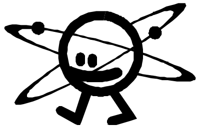
Hadron Collider Physics Symposium 2009
Evian, France

THE SEARCHES OF THE NEW (BEYOND THE STANDARD MODEL) PHYSICS AT THE LARGE HADRON COLLIDER ARE (Mainly) MOTIVATED BY THE HIERARCHY PROBLEM, AN INEXPLICABLE STABILITY OF THE WEAK INTERACTION SCALE ($M_W = 10^2$ GeV) VERSUS THE PLANCK MASS ($M_P = 10^{19}$ GeV),

WHY IS $M^2{}_W/M^2{}_P = 10^{-34}$ ?

THE HIERARCHY PROBLEM IS NOT ABOUT BIG/SMALL NUMBERS!

THERE ARE PLENTY OF BIG/SMALL NUMBERS IN NATURE THAT ARE OF NO MYSTERY.

$L$  $= 10^{12} L$ 

ELEPHANTS (OR HUMANS) ARE BIG, BECAUSE THEY CARRY A HUGE BARYON NUMBER.

THE HIERARCHY PROBLEM IS ABOUT THE UV STABILITY OF THE VERY SMALL NUMBER

$$M^2_W/M^2_P = 10^{-34}$$

# STANADARD MODEL

GAUGE FORCES: → SU(3)xSU(2)xU(1)

MATTER:

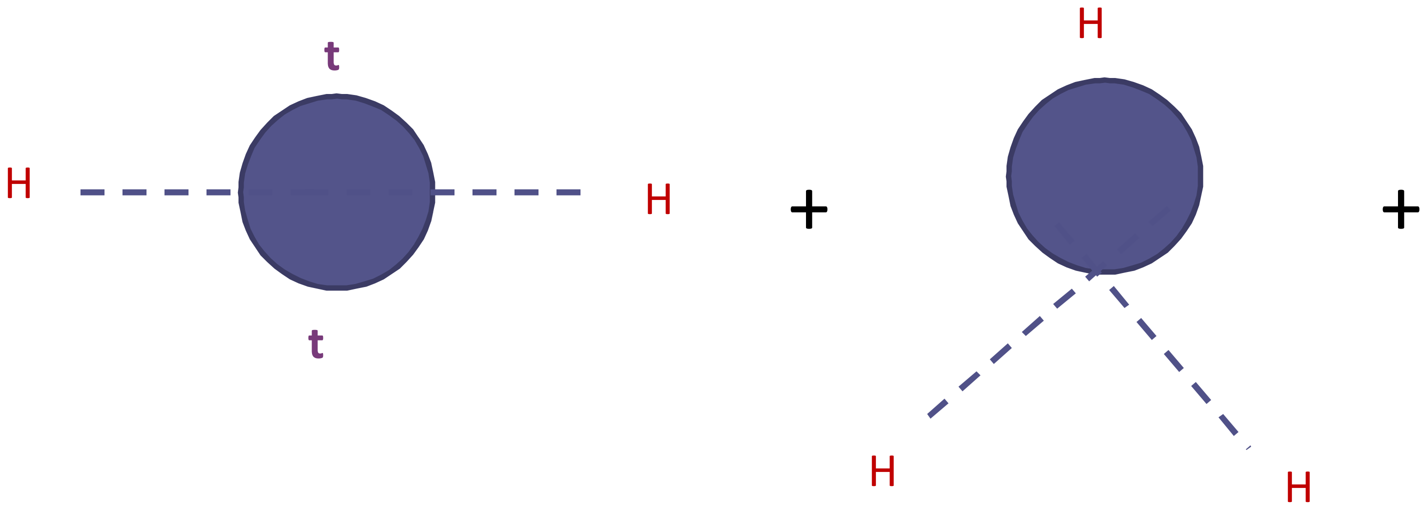
QUARKS : (u,d) (c,s) (t,b), LEPTONS: $(e,\nu_e)$ $(\mu, \nu_\mu)$ $(\tau, \nu_\tau)$

HIGGS: H

The weak scale is set by the vacuum expectation value of the Higgs field, which is related to the mass of the Higgs boson, $m_H$ .

This mass is UV-unstable!

# UV-instability of the Higgs mass

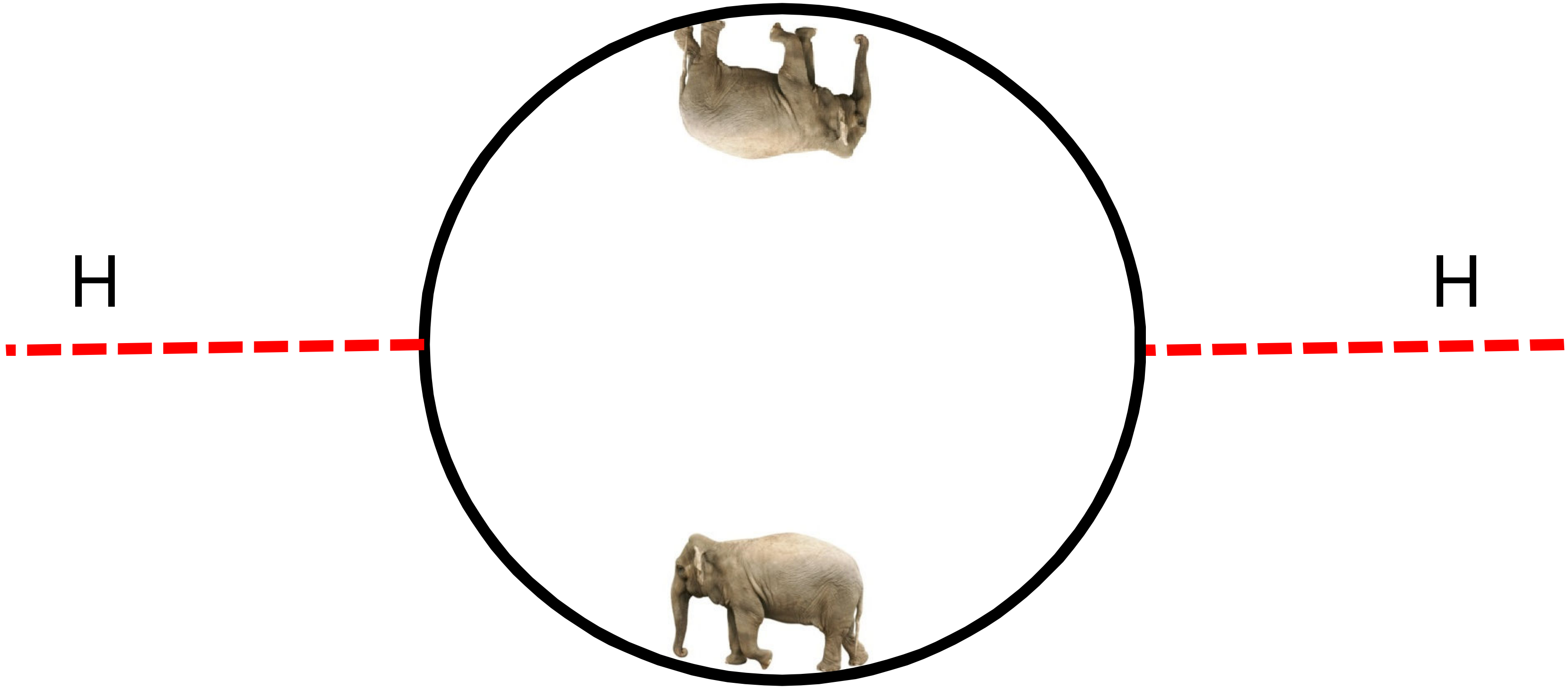


$$\delta m^2_H \quad \approx \; \Lambda^2 \quad !$$

The natural cutoff is the gravity scale $\Lambda = M_P$

Without gravity the problem could have been less severe, but with gravity there is no way out:

The particles running in the loop cannot have arbitrarily high energies without becoming big black holes!



Thus, unless some measures are taken, any correction to the Higgs mass would be cutoff at the Planck scale, and it's a mystery what keeps it lighter.

THUS, THERE MUST BE SOME NEW PHYSICS, NOT FAR ABOVE THE WEAK SCALE , WHICH STABILIZES THE HIGGS MASS,

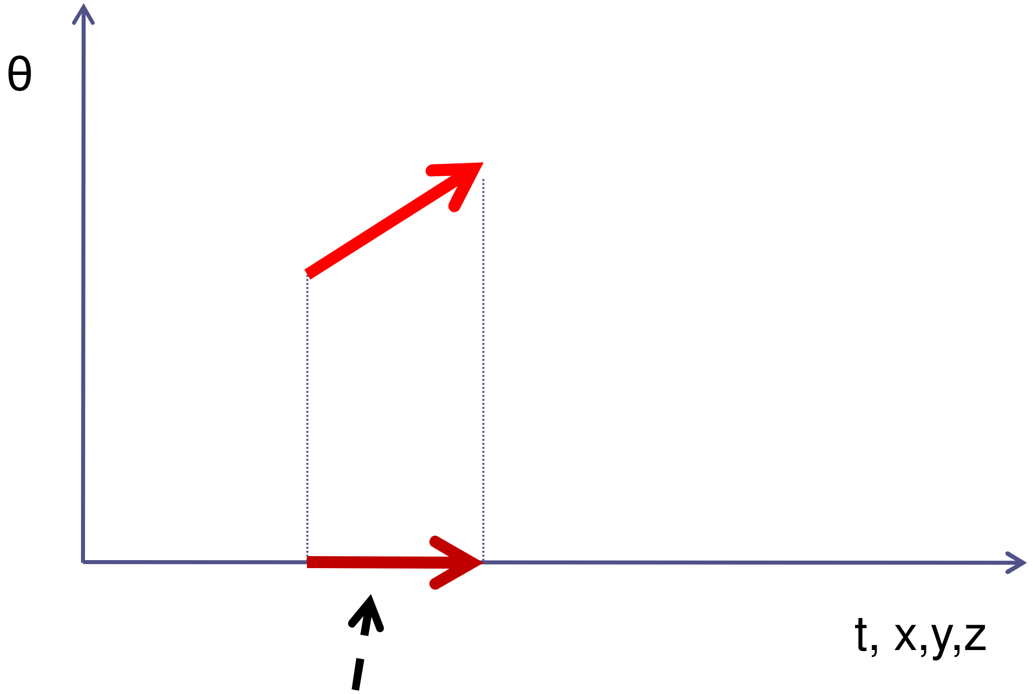
AND LHC SHOULD PROBE IT.

WHAT IS THIS NEW PHYSICS?

# It may be something with no observed analog in physics:

An extra dimension with anti-commuting coordinates - SUSY

$$\{ \theta_\alpha \theta_\beta \} = 0$$



Bosons and Fermions

The superpartners are analogs of KK excitations in θ-dimension.

But,

- Translations in $\theta$ - dimension are broken at low energies:
  SUSY is not an exact symmetry of nature.

  WHY?

- Generic breaking of SUSY would violate flavor. So, whatever dynamics broke SUSY, it cared to conserve the flavor.

  WHY?

- Generic SUSY would violate baryon (and lepton) number already at the renormalizable level. Again, some underlying mechanism took care of B-conservation.

  WHY?

The list goes on and on

Great thing about low energy SUSY:

Once the boundary conditions are specified in UV, computations can be done in a weakly-coupled theory, largely avoiding cutoff sensitivities.

E.g., prediction of the gauge coupling unification (Dimopoulos, Raby, Wilczek; Einhorn & Jones; Marciano & Senjanovic)

There are other little beautiful things.

E.g., electroweak symmetry breaking can be triggered radiatively.

One thing is crystal clear : the new physics will come in form of the new degrees of freedom (new particles species) .

And in many potentially-possible cases it may be a matter of the point of view whether to think about them in terms of the new geometry (new dimensions, classical or quantum), point-particles, or the extended object (strings, membranes, black holes…).

But in certain cases, the distinction between the quantum-particles and the semi-classical object can be pretty blurry, or even non-existent in principle.

For example, it will be virtually-impossible to tell the difference between quantum black holes and elementary particles with the same quantum Numbers. Rather only at higher masses the familiar black-holeness will set in (See below) .

There are ways in which nature is known to have already worked.

Some approaches to the Hierarchy Problem employ the generalizations of such known phenomena of nature, which are taking place at different energies.

In fact, QCD does trigger the breaking

$$SU(2)_W x U(1)_Y \rightarrow U(1)_{EM}$$

by the quark condensate

$$<Q_L Q_R> = \Lambda_{QCD} \quad ,$$

which has exactly the quantum numbers of the Higgs doublet!

$Q_L = (u_L, d_L)$ ← Weak-doublet

$Q_R = u_R, d_R$ ← Singlets

Quark condensate gives small masses to $W^+$, $W^-$ and Z,
and $\pi^+$, $\pi^-$, $\pi^0$ become a little bit their longitudinal components.

So, why not use the same mechanism at the weak scale?
This is the idea of the Technicolor
(Weinberg; Susskind; Dimopoulos & Susskind…).

This approach (provided a phenomenologicaly consistent model can be constructed) predicts the tower of QCD-type resonances above the weak scale.

In fact, these resonances can be viewed as part of internal geometry.

Indeed, the role of the elephant's large baryonic charge in technicolor (or QCD) is played by the slow (log) running of the gauge couplings (Politzer; Gross, Wilczek)

$$\alpha_S\,(k^2) \approx 1/\,\beta_0 \ln\,(k^2/\Lambda^2\,)$$

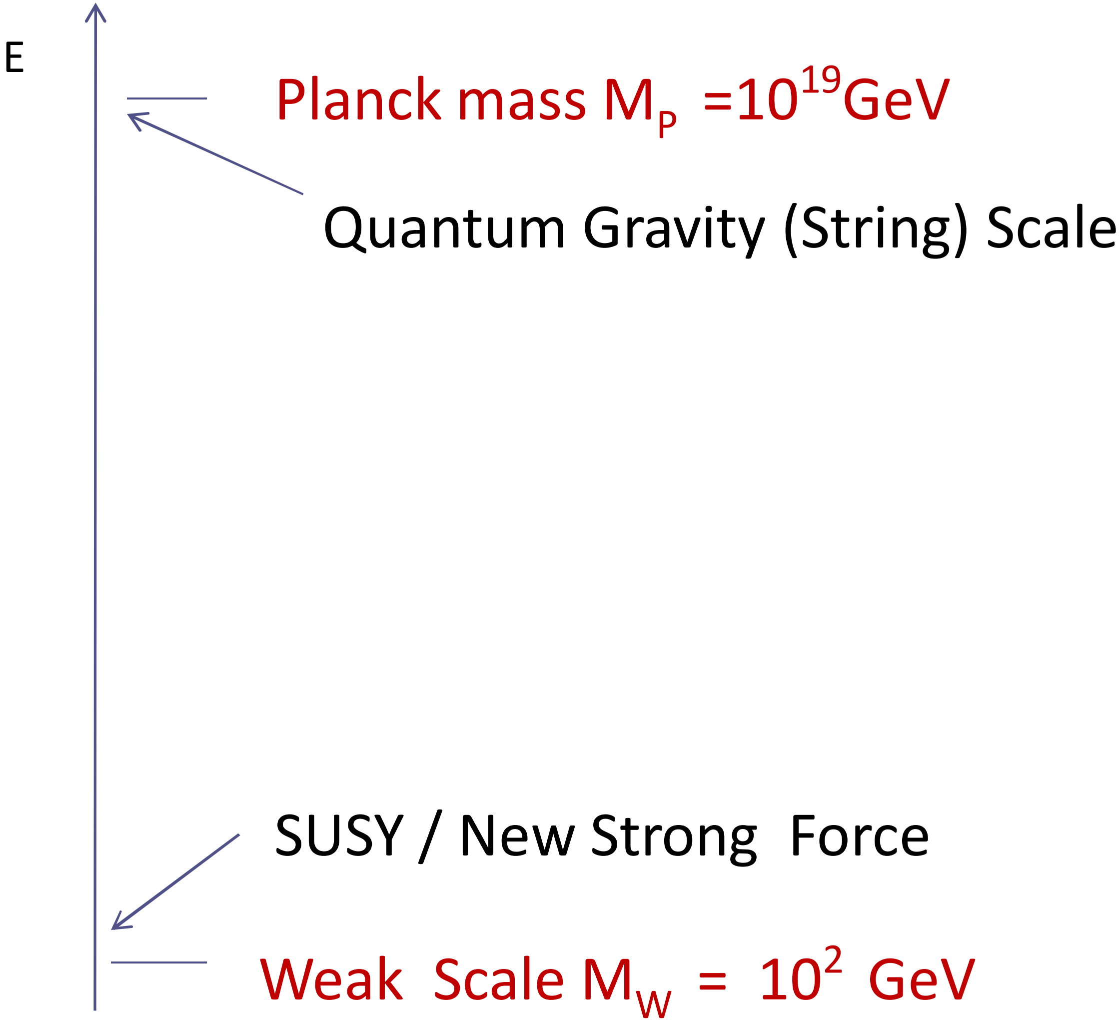
This is why $\Lambda_{QCD} << M_P$ .

Running with energy can be thought of as the motion in the strongly warped gravitational extra dimension (Randall-Sundrum). Then the role of the resonances is played by the tower of KK excitations.

In this language the weak scale is small because the internal dimension is very strongly curved.

But no matter how we look at it, experimentally one must observe the tower of strongly coupled resonances.

# Approaches we discussed so far share the philosophy of the ``Standard Paradigm”    ‘74



E

Planck mass $M_P = 10^{19}$GeV

Quantum Gravity (String) Scale

SUSY / New Strong  Force

Weak  Scale $M_W = 10^2$ GeV

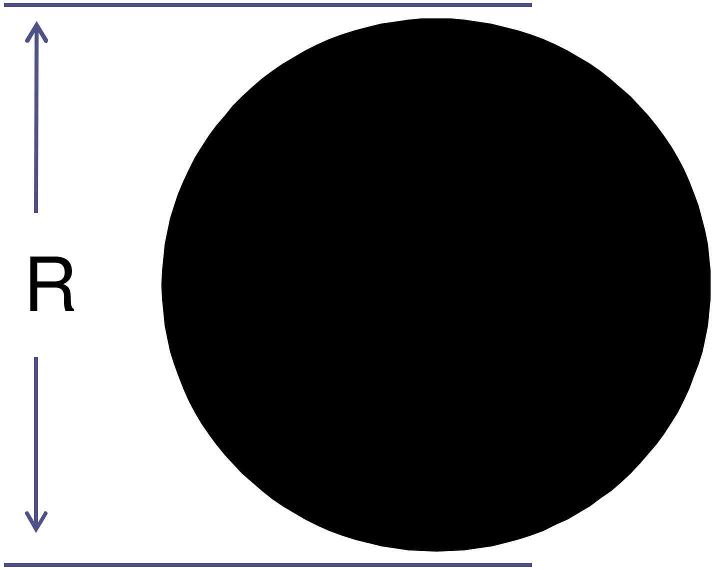
There is an alternative approach that makes use of a known phenomenon in Einstenian (or Newtonian) gravity.

As said above, in Einstein's gravity $M_P$ is the scale where gravitational interactions of elementary particles become strong.

In any sensible theory of gravity, which at large distances reduces to Einstein's GR, a point-like elementary particle heavier than $M_P$ makes no sense.

In fact we know very well what such an object is:
Because its gravitational Schwarzschild radius exceeds its Compton wavelength,

$$R = m/M_P^2 > 1/m ,$$



it is a macroscopic classical black hole!
And becomes more and more classical with the growing mass.

This is an exceptional power of gravity, it provides us with a shortest distance scale, beyond which things again become classical!

So, in SM + GR if Higgs had a mass of order $M_P$ , nobody would ask the question, why it’s not even heavier. Because, if it were heavier, it would stop to be a particle and become something fuzzy and classical.

Now, given that we know that strong gravity scale is an universal regulator of particle masses, let’s ask:

How do we know that gravity is waiting all the way till $M_P$ energies for becoming strong?

Well, we don’t.

So why not at TeV?

# ’98 Quantum Gravity at TeV Idea:

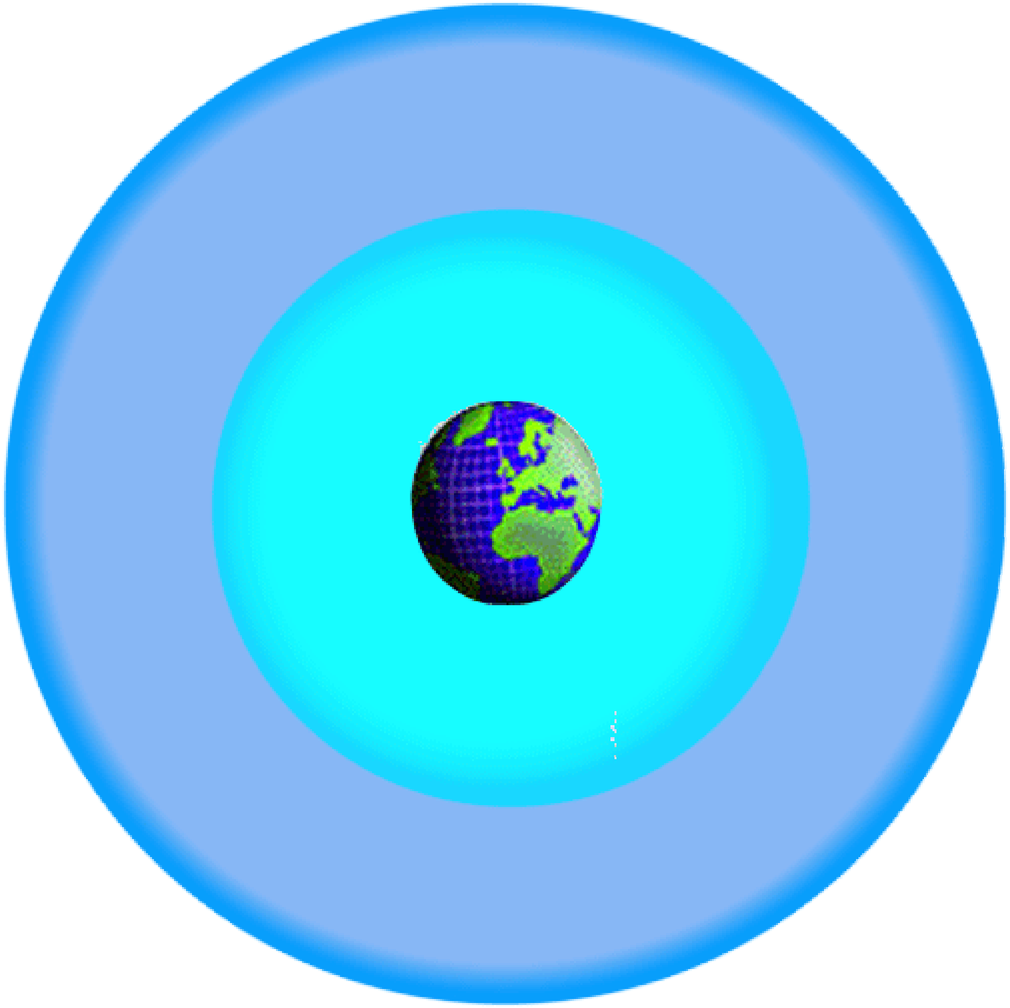
Weak scale is stable, because the quantum gravity scale $M_* \approx$ TeV !

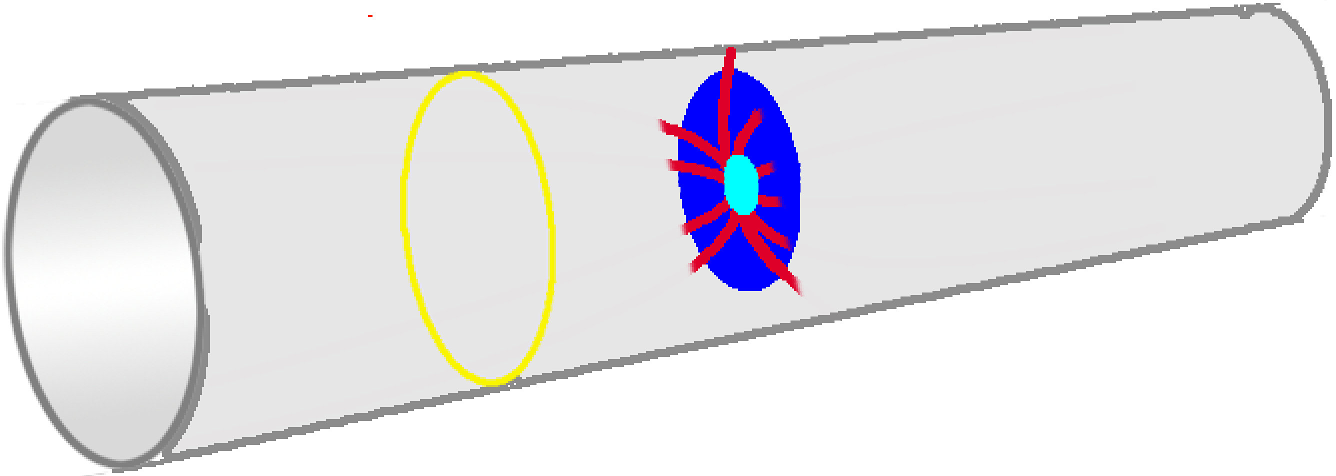
**(Arkani-Hamed, Dimopoulos, GD;**
**Antoniadis, Arkani-Hamed, Dimopoulos, GD)**

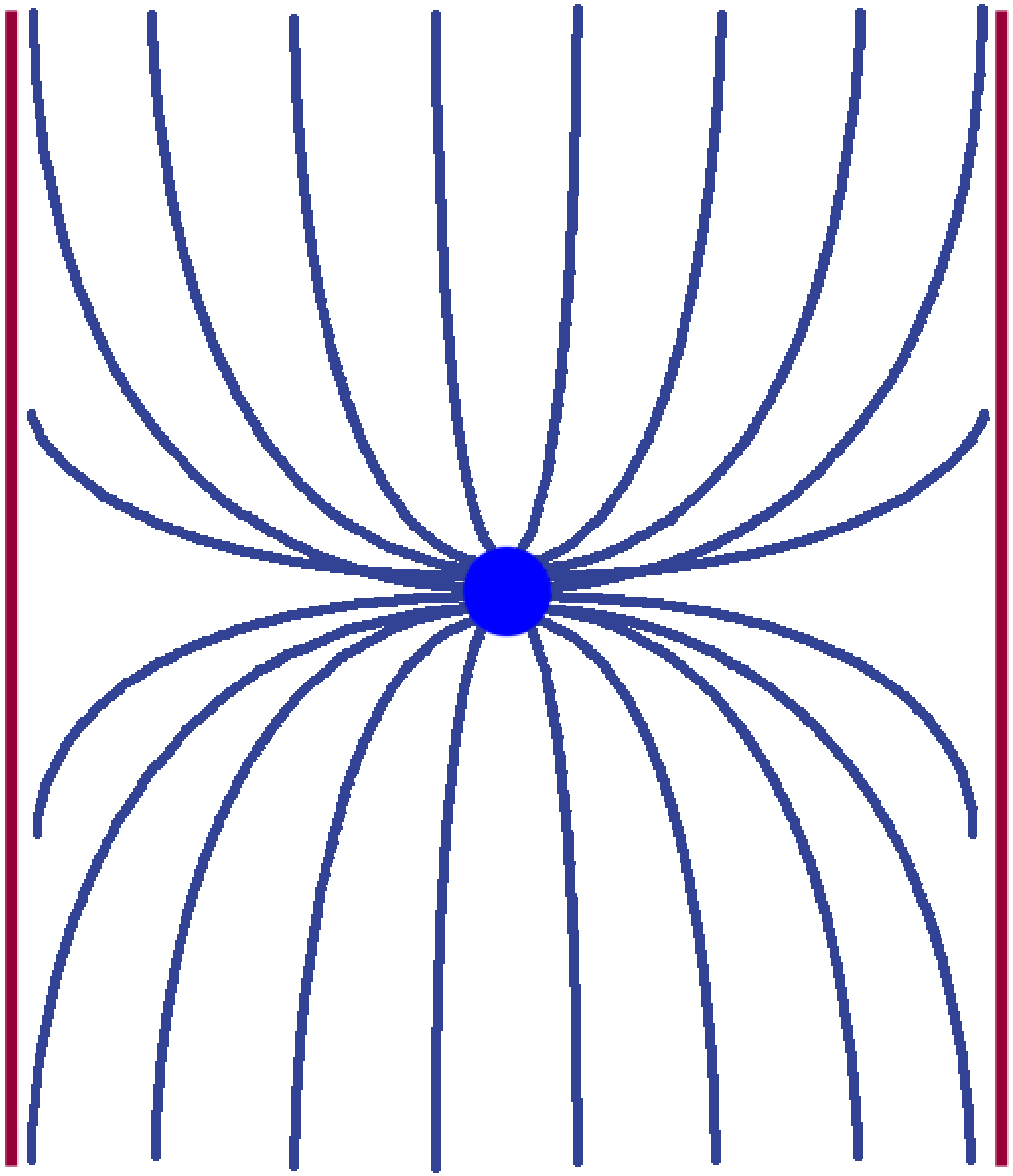
But, if gravity becomes strong around the TeV scale, why is the large distance gravity so much weaker than all the other forces of nature?

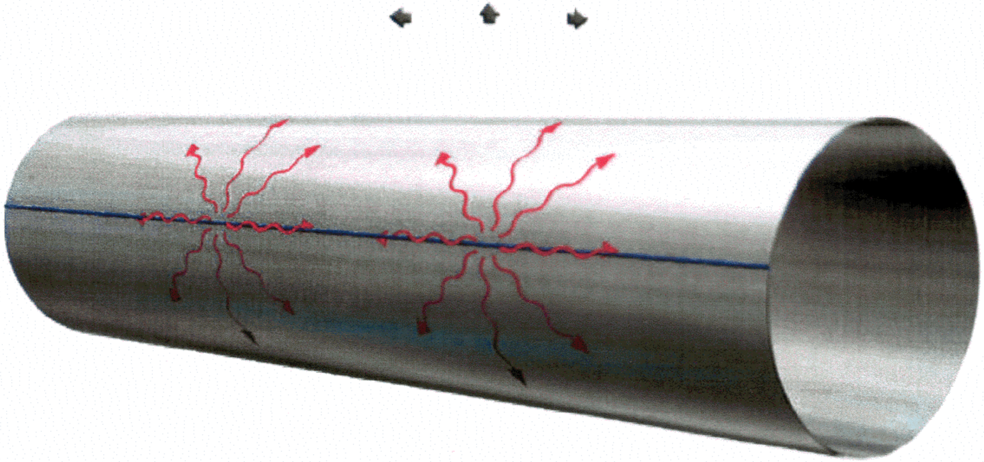
For example, gravitational attraction between the two protons at 1 m distance is $10^{37}$ times weaker of their Coulomb repulsion!

Original Realization: Extra Dimensions







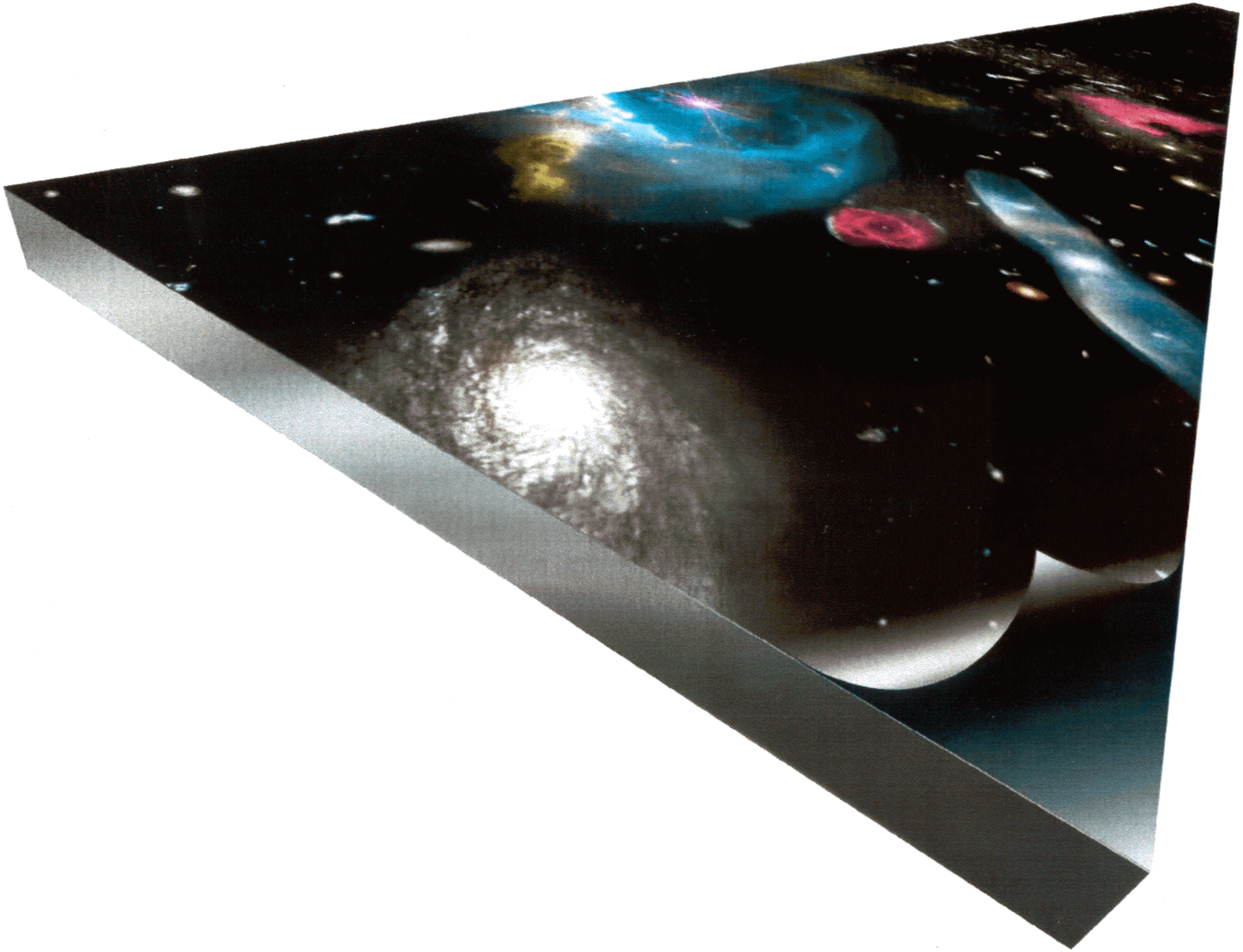


$$G_N = G_{NF}/V_{EXTRA}$$

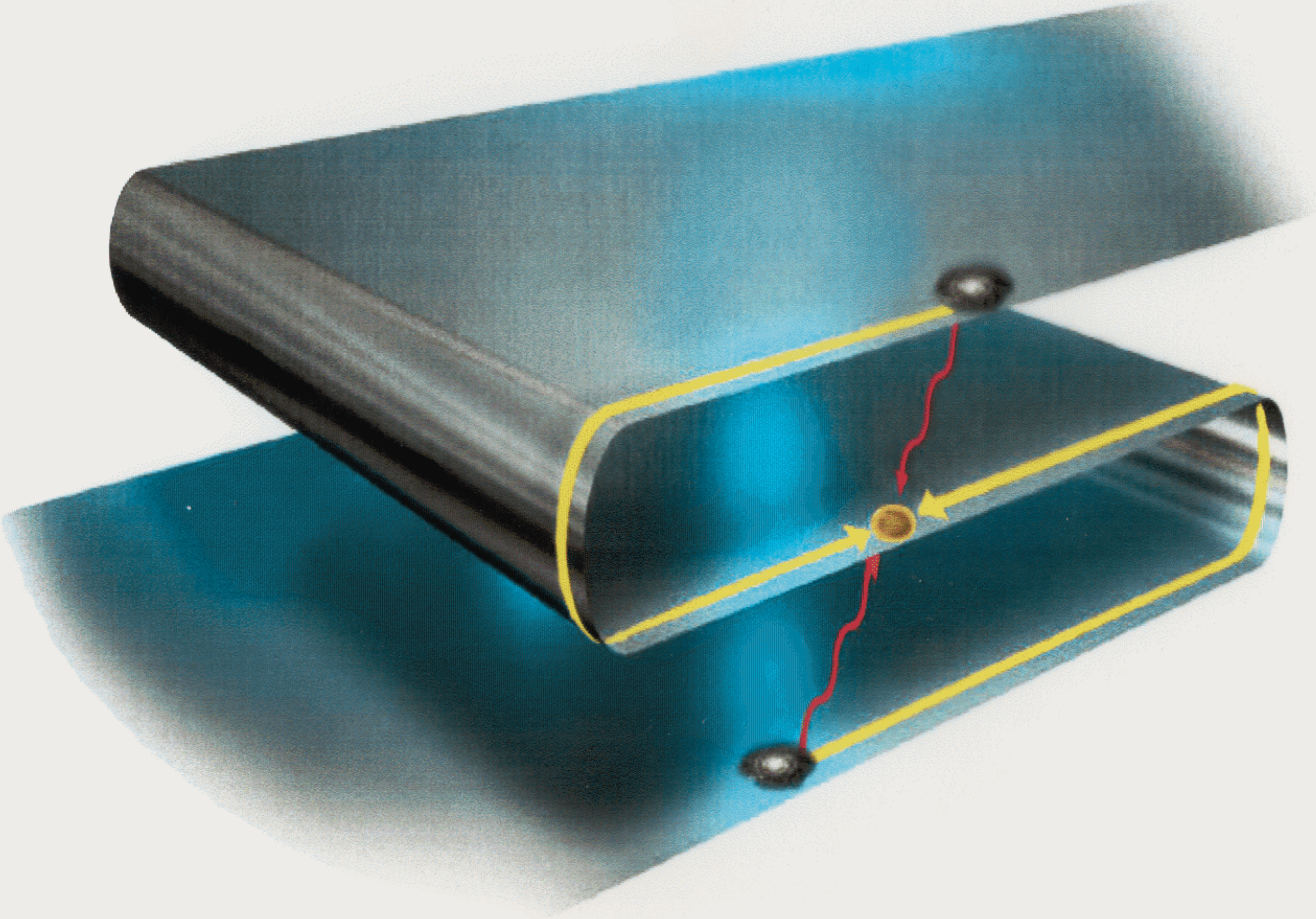
As a result of the dilution, there is a simple relation between the true quantum gravity scale and the Planck mass measured at large distances:

$$M^2_P = M^2_* (M_* R)^n$$

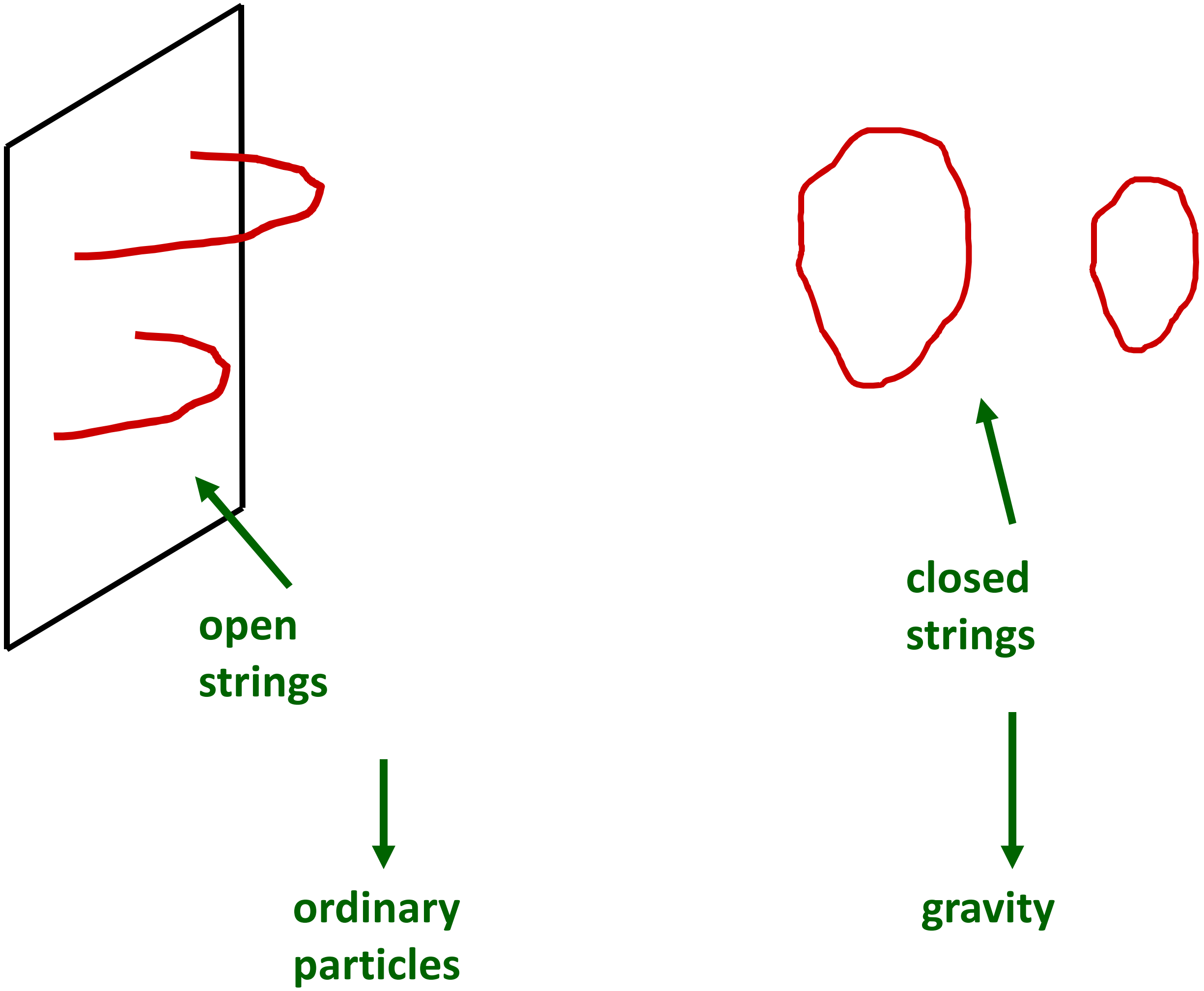
Volume of extra space



# Gravitational shortcut



# STRING THEORY PICTURE



open strings

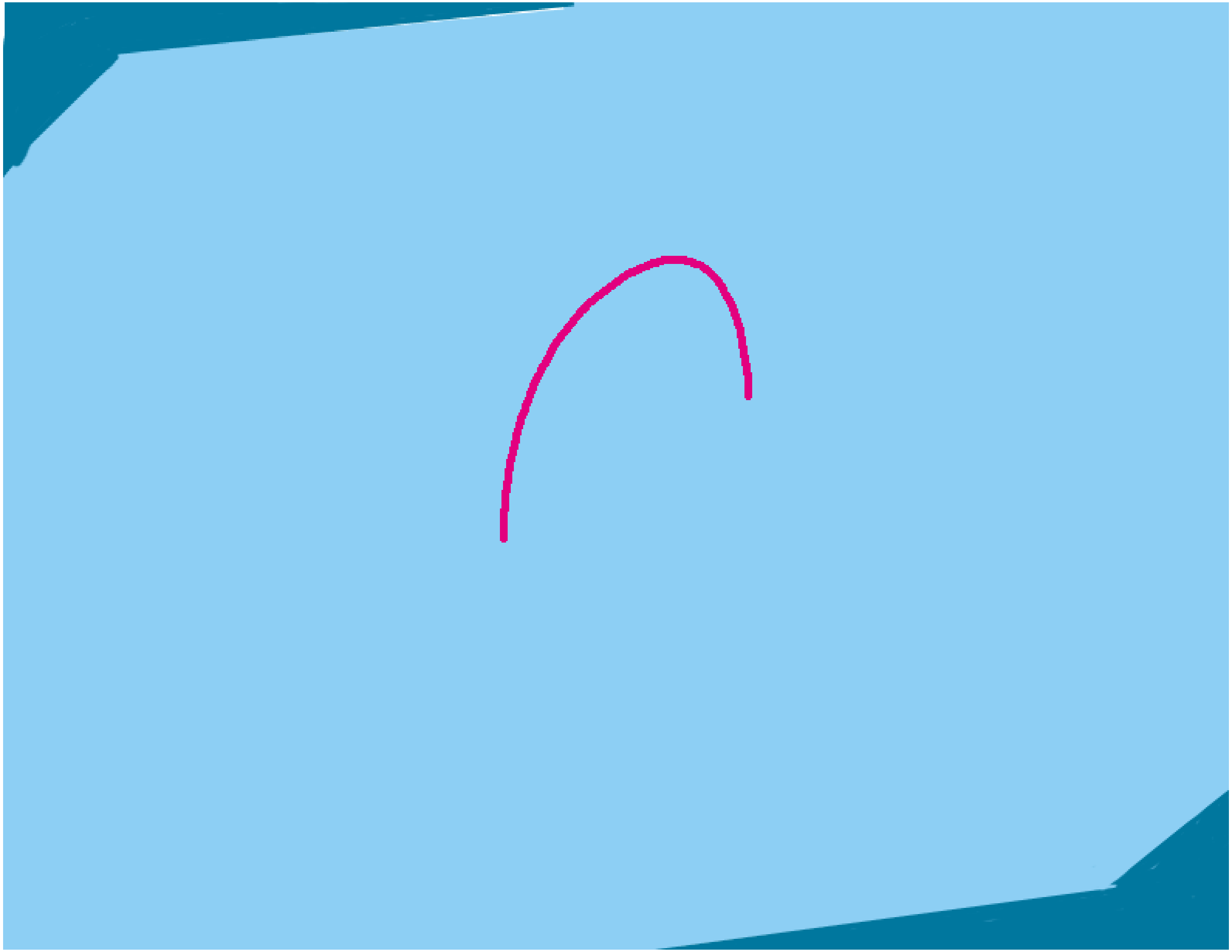
↓

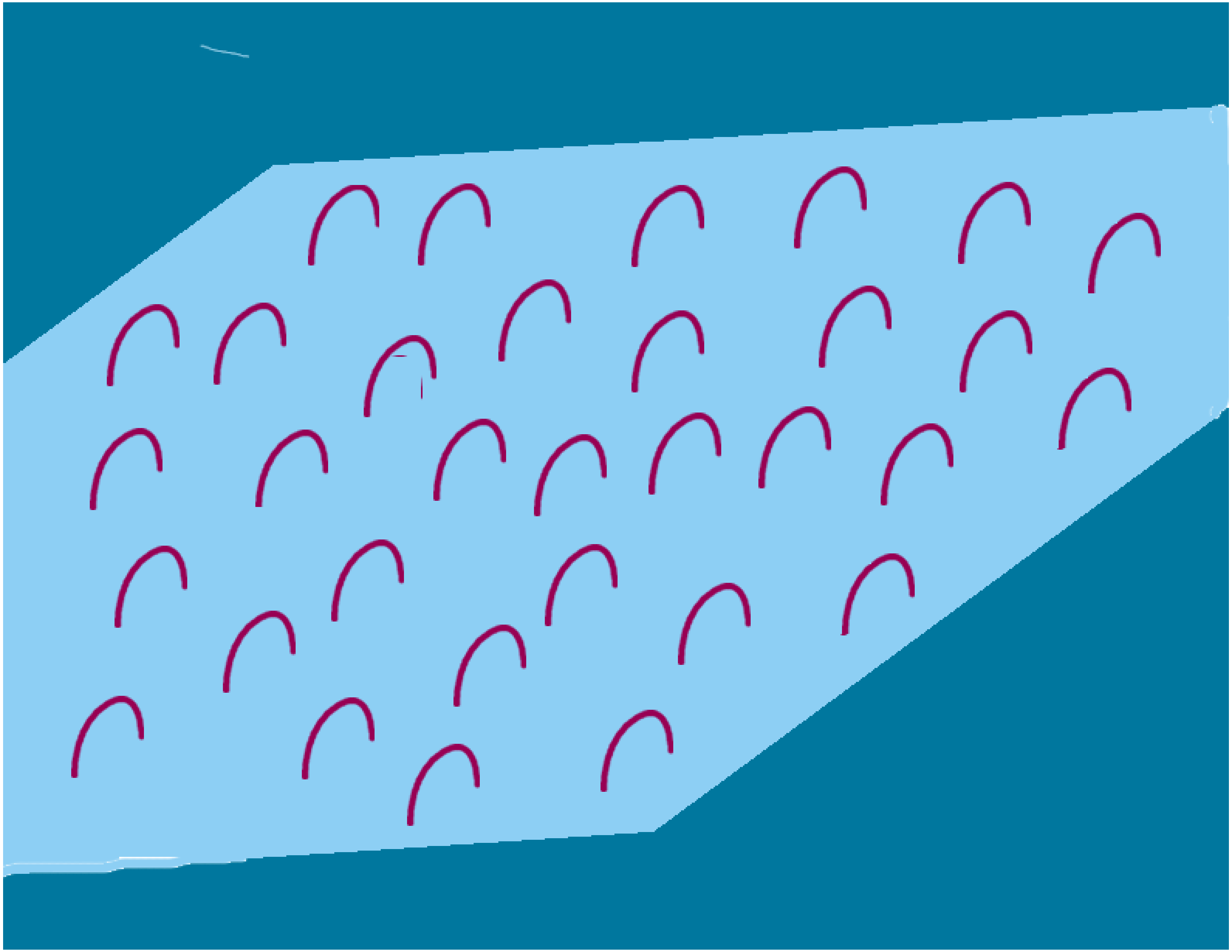
ordinary particles

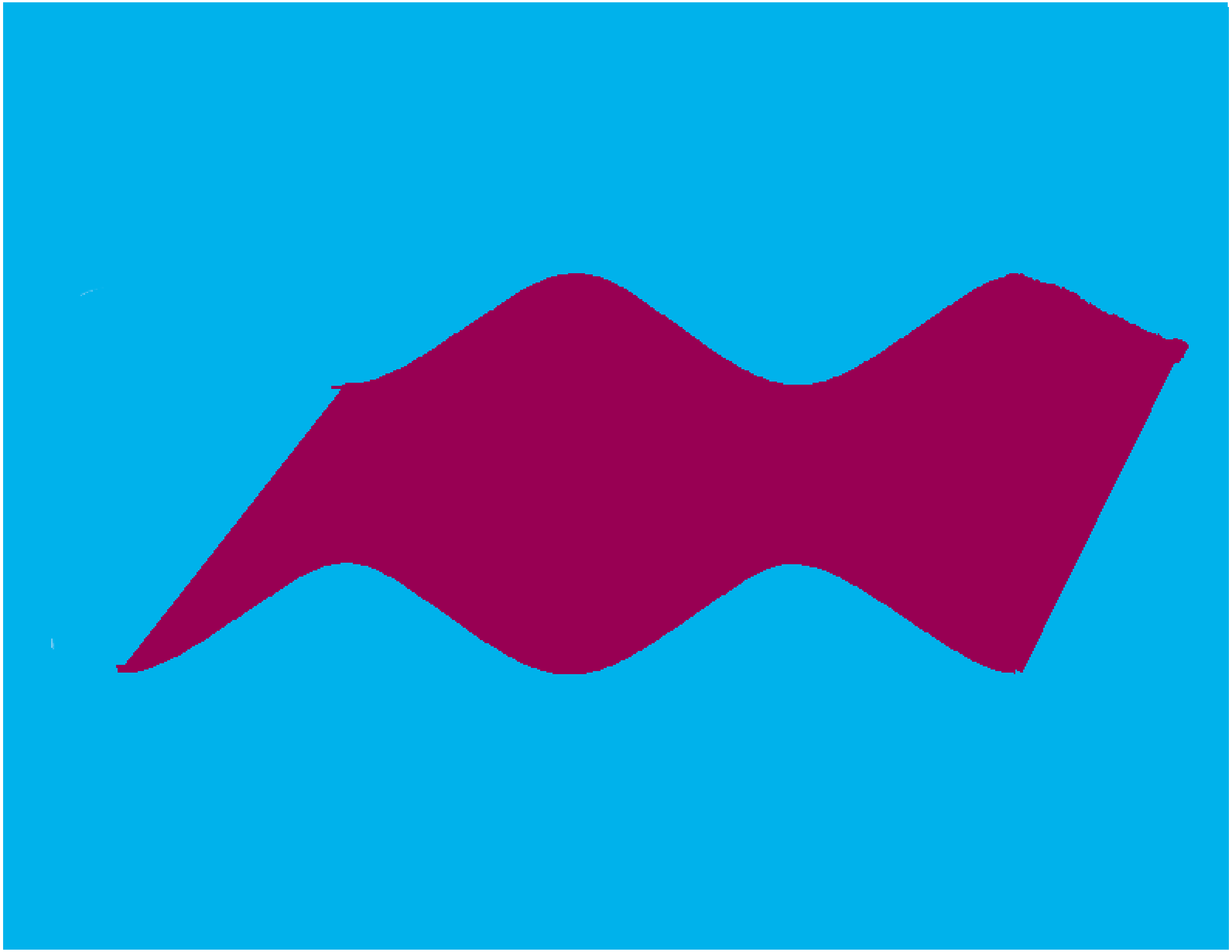
closed strings

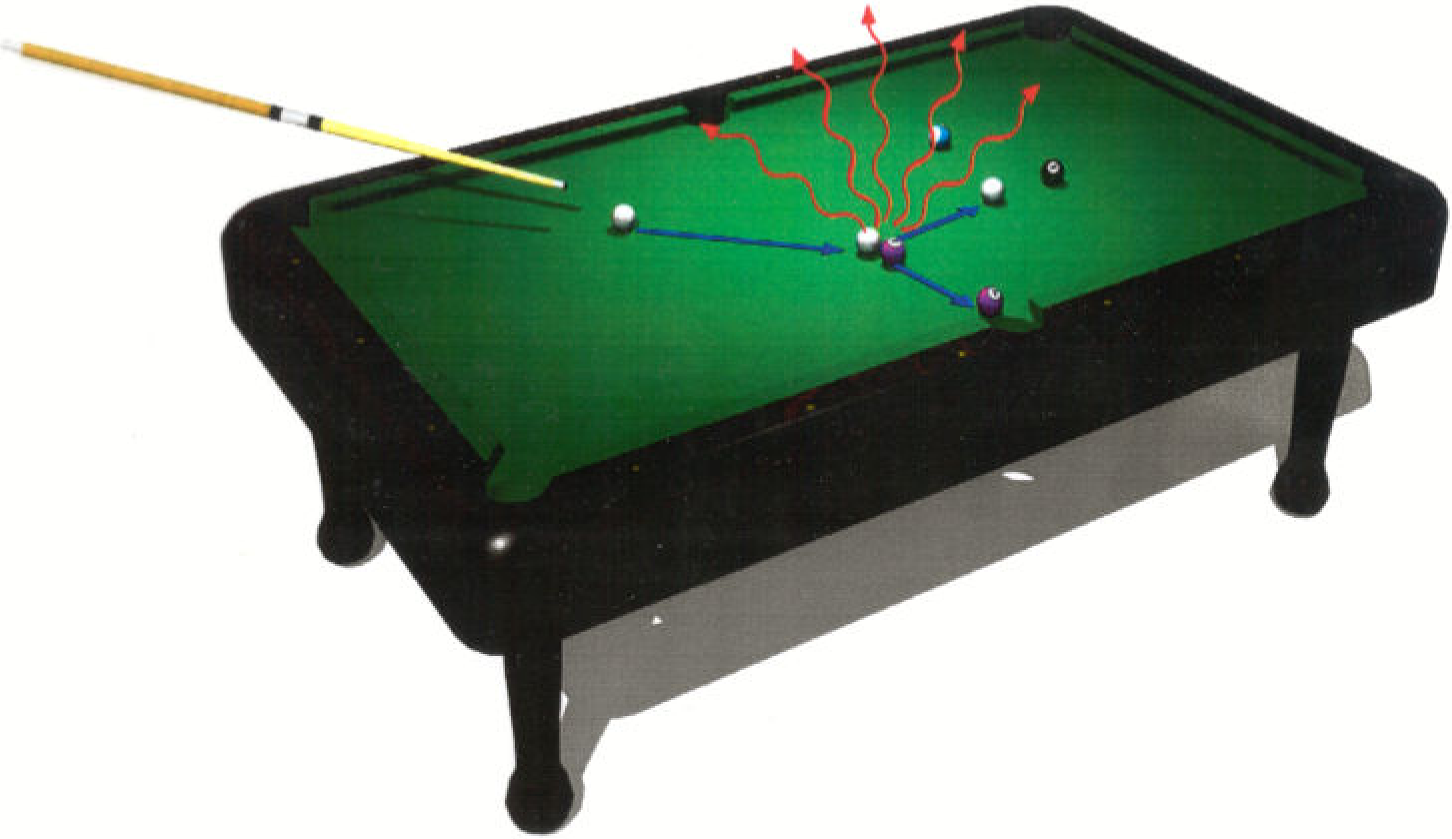
↓

gravity





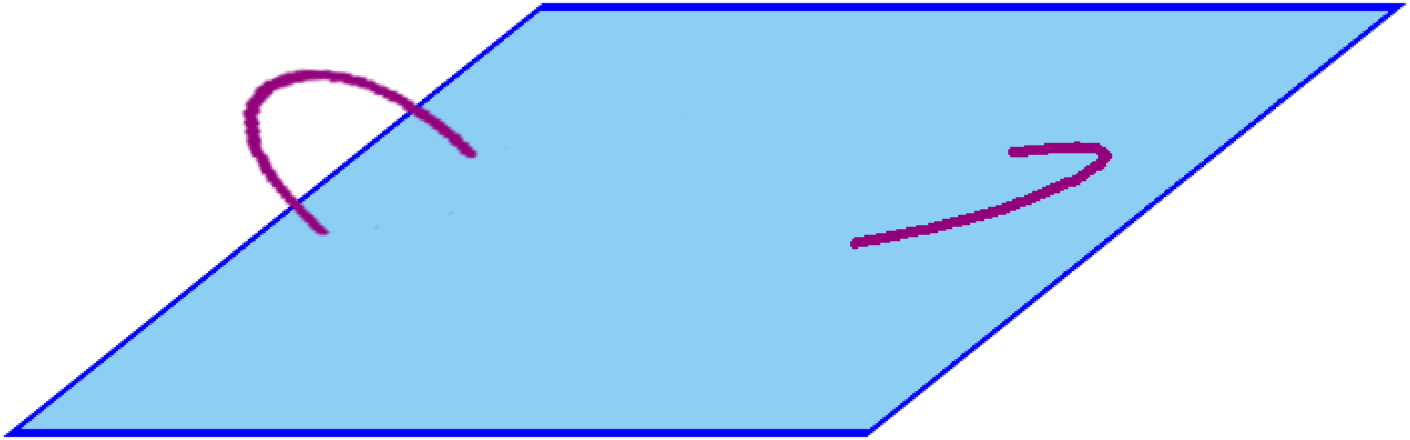


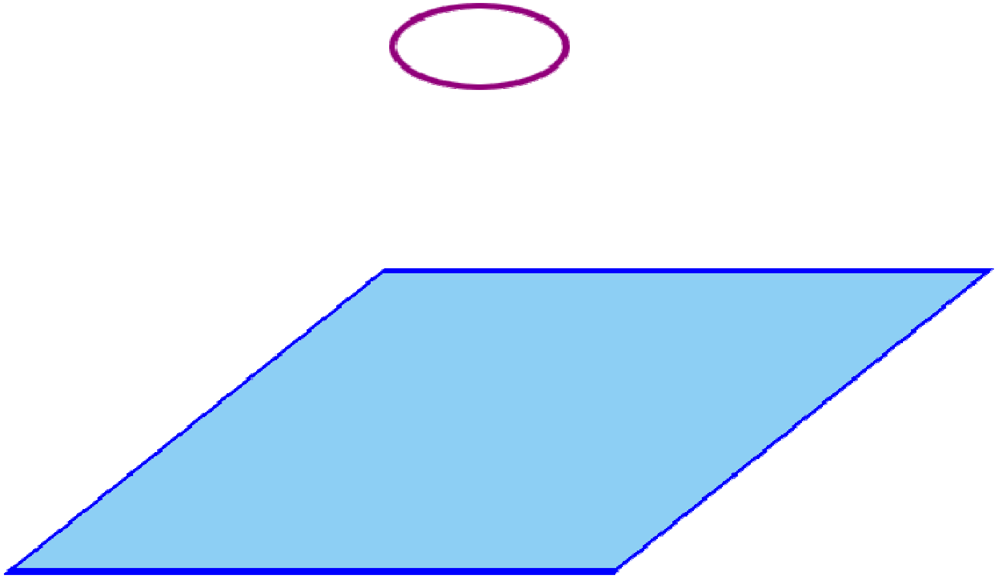


Experimental signatures of low scale quantum gravity are pretty spectacular.

These include formation of mini black holes, Kaluza-Klein gravitons, and string vibrations in particle collisions (e.g., high spin recurrences of ordinary particles).

(For a recent detailed study of string production within type II strings see work by, Lust, Stieberger, Taylor; ... )





# The Role of Particle Species in Lowering Gravity Scale.

$$M^2_P = M^2_* \, (M_* R)^n$$

Volume of extra space

Notice, that the above relation can be rewritten as,

$$M^2_P = M^2_* \, N,$$

Where N is the number of Kaluza-Klein species . This very important, because the latter expression turns out to be more general than the former:

What matters is the number of species!

**It follows from the consistency of Black Hole physics that in any theory with N species the scale of quantum gravity is inevitably lowered, relative to the Planck mass**

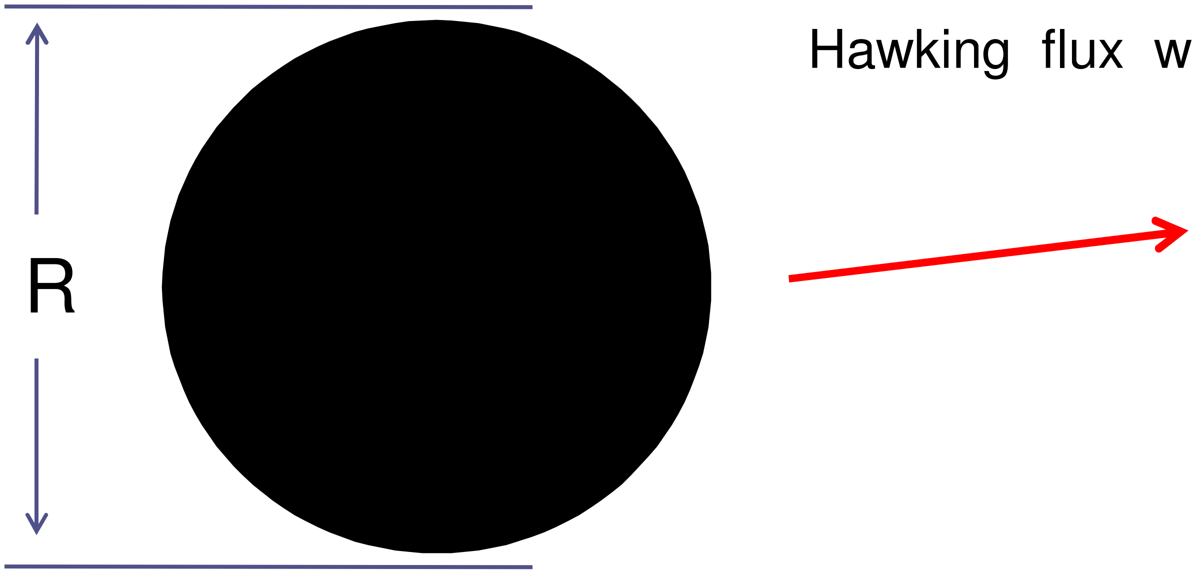
[GD; GD & Redi ’07; GD & Lüst ‘08]

$$M^2_* = M^2_P / N \quad !$$

The fundamental length scale at which classical gravity is getting strong is

$$L_* = M^{-1}_* = \sqrt{N} / M_P \ .$$

This can be proven by black hole thought experiments.



Hawking flux with $T = 1/R$

In Einstein’s GR Black holes are strongly gravitating objects with escape velocity at the horizon $>$ speed of light. Therefore, classically, they are absolutely black.

However, quantum mechanically Black Holes evaporate with the Hawking temperature

$$T = 1/ R$$

Evaporation of Einsteinian Black Holes is thermal and is fully democratic in all the particle species (flavors).

The rate of mass change is:

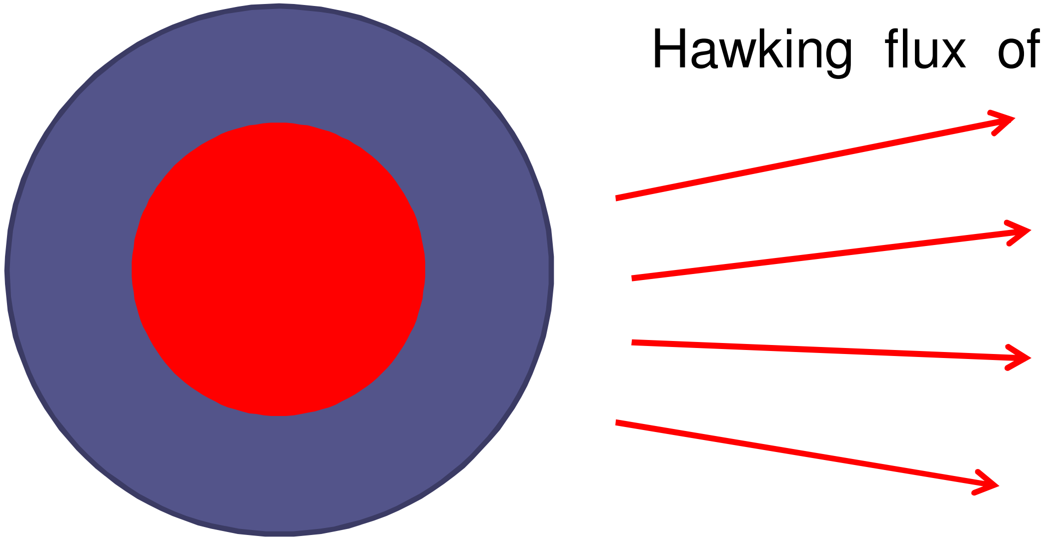
$$dM/dt = T^4 R^2 N = T^2 N ,$$

where N is the number of particle flavors.

The condition of quasi-classicality: The rate of temperature-change is slower than the temperature-squared,

$$dT/dt < T^2 .$$

The Black Holes that violate this condition cannot be quasi-classical, because they half-evaporate faster than their size!


Hawking flux of N species with $T = 1/R$

The black holes of size

$$R < L_* = \sqrt{N} / M_P$$

cannot afford to be semi-classical, because they half-evaporate Faster than their size!

Equivalently, the rate of temperature-change is faster than the temperature-squared

$$dT/dt > T^2$$

Thus, the fundamental length scale below which no semi-classical black holes can exist in any consistent theory with N species is

$$L_* = \sqrt{N} / M_P$$

and the corresponding mass scale marks the cutoff.

$$M^2_* = M^2_P / N$$

Alternative proof of the bound comes from species resolution experiments
[G.D., Gomez, `08]

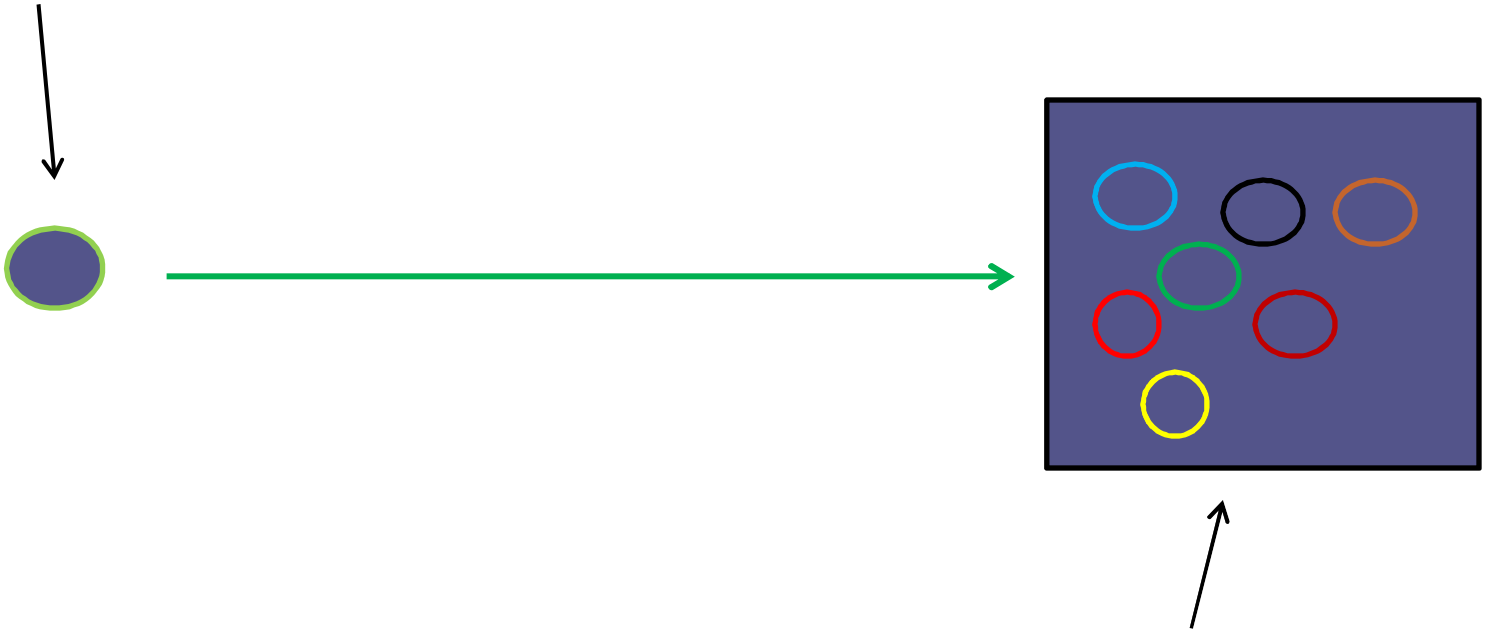
N species exist as long as we can distinguish them by physical measurements.

What is the minimal space-time scale L on which we can decode species
identities?

Any decoder contains samples of all N species in each pixel .

So the space-time resolution is set by the size of the pixel.

How small can this size be?



Message encoded in a green flavor

Pixel of size L, with all the sample flavors

Without gravity, there is no limit to the smallness of L.

But with gravity there is, because localization of species costs energy,

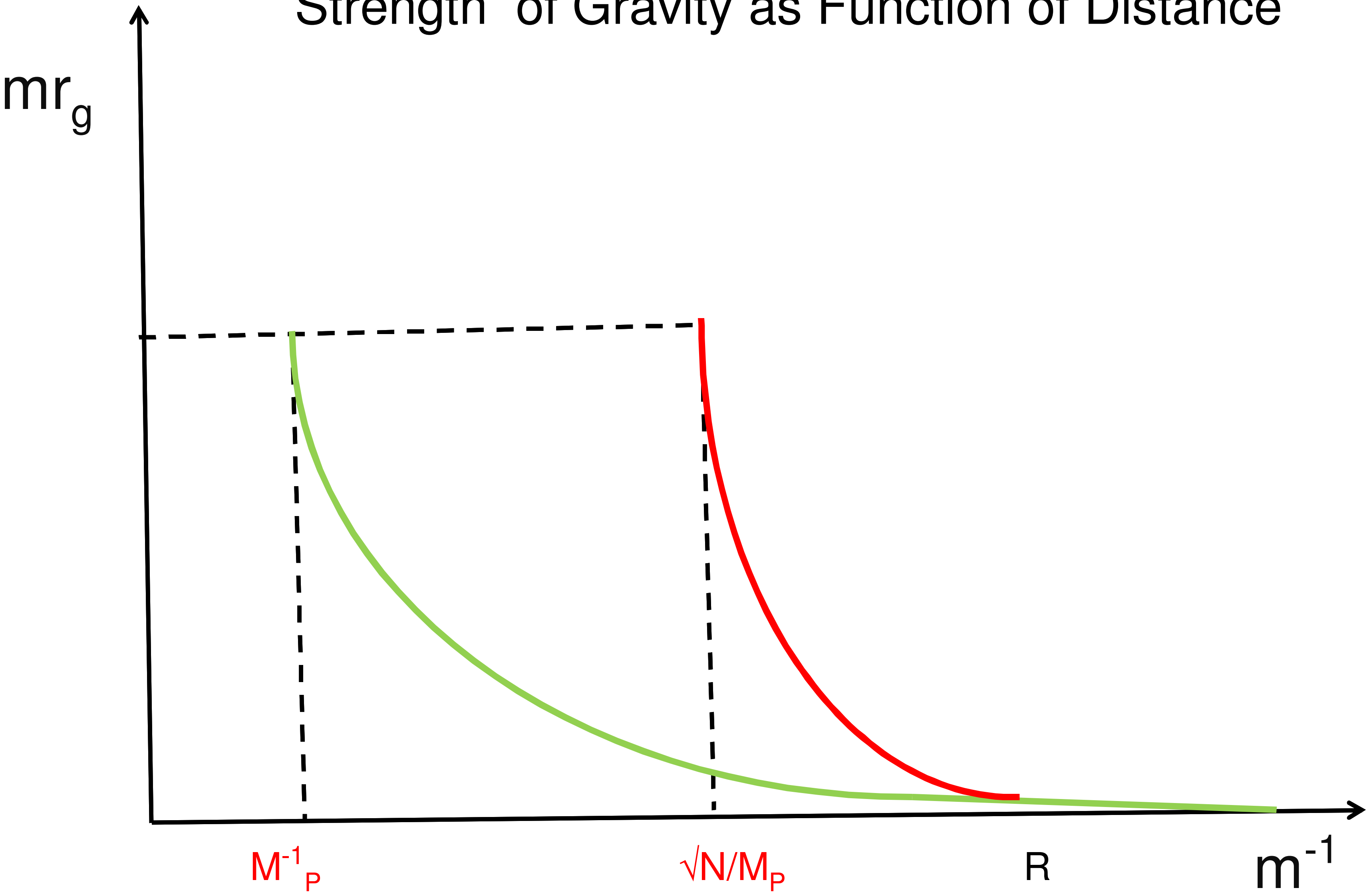
$$E > N/L ,$$

which gravitates and eventually will collapse into a black hole.

We must have $L > \sqrt{N} / M_P$ , or else the processor itself collapses into a black hole!

(By the way, this sets the lower bound on any particle detector that an arbitrarily advances civilization may construct.)

# Strength of Gravity as Function of Distance

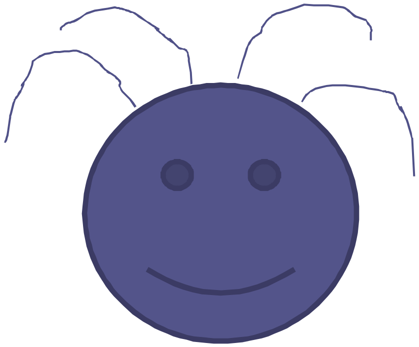


The black hole arguments show, that the class of theories which solve the Hierarchy Problem by TeV quantum gravity scale, is much larger.

In particular, any theory with $N = 10^{32}$ particle species, will do this.

The role of these $10^{32}$ species, can equally well be played by $10^{32}$ Kaluza-Klein gravitons from large extra dimensions, or by $10^{32}$ copies of the Standard Model!

# Einsteinian Black Holes carry no hair



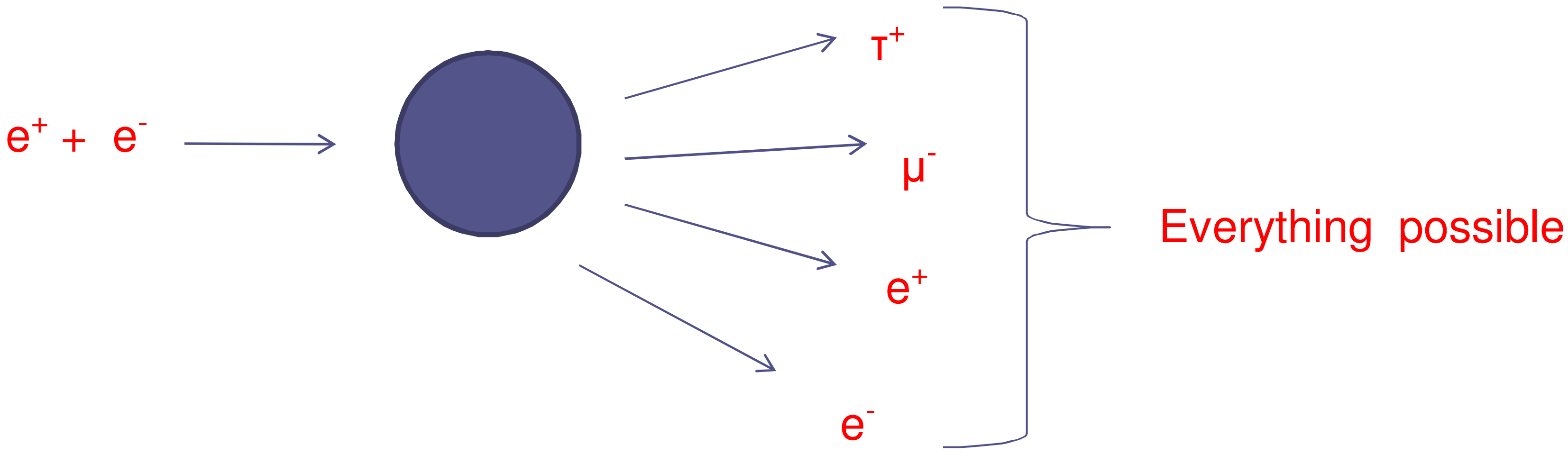
Such Black Holes can only be distinguished by exactly conserved quantum numbers measurable at infinity.

For example, such numbers are the mass of a Black Hole and its electric charge.

On the other hand, quark and lepton flavors in the Standard Model are not exactly-conserved quantum numbers of nature, and are impossible to measure outside the Black Hole horizon.

Flavor -violation by Black Holes can be visualized by the following thought experiment.

In Standard Model we can produce a large classical black hole by colliding particles of a given flavor , e.g., electron-positron. If the Hawking Temperature of this Black Hole is sufficiently high,  it will evaporate in all three lepton generations (and  in other possible species) fully democratically,



$e^+ + e^-$

$\tau^+$

$\mu^-$

$e^+$

$e^-$

Everything  possible

Thus, macroscopic  Black Holes violate flavor  maximally.

# What about the microscopic Black Holes that may be produced at LHC?

It turns out that story for them is different:

The small black holes must carry memory about their origin, and are non-democratic!

The species (label) flavor exhibits locality properties.

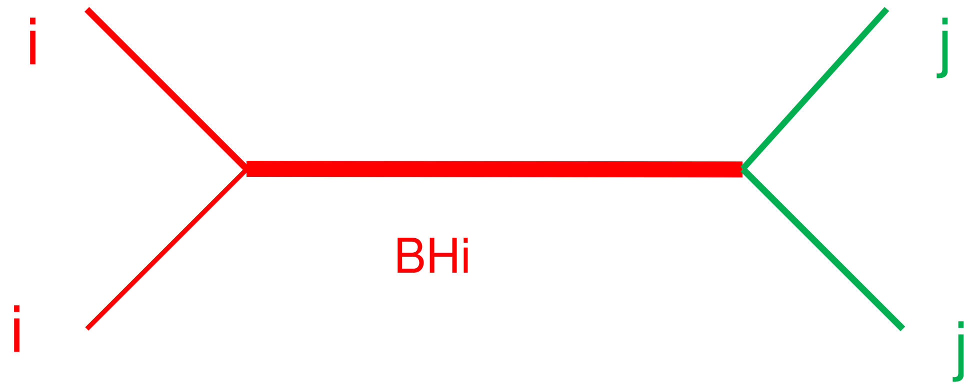
Picture is such as if species are separated in true extra dimensions!

Consider a microscopic black hole of mass $\sim M_*$ , produced in a particle-anti- particle annihilation of $i$-th flavor of species at energies $\sim M_*$ .

By unitarity decay rate of such a black hole back to $i$-th species is

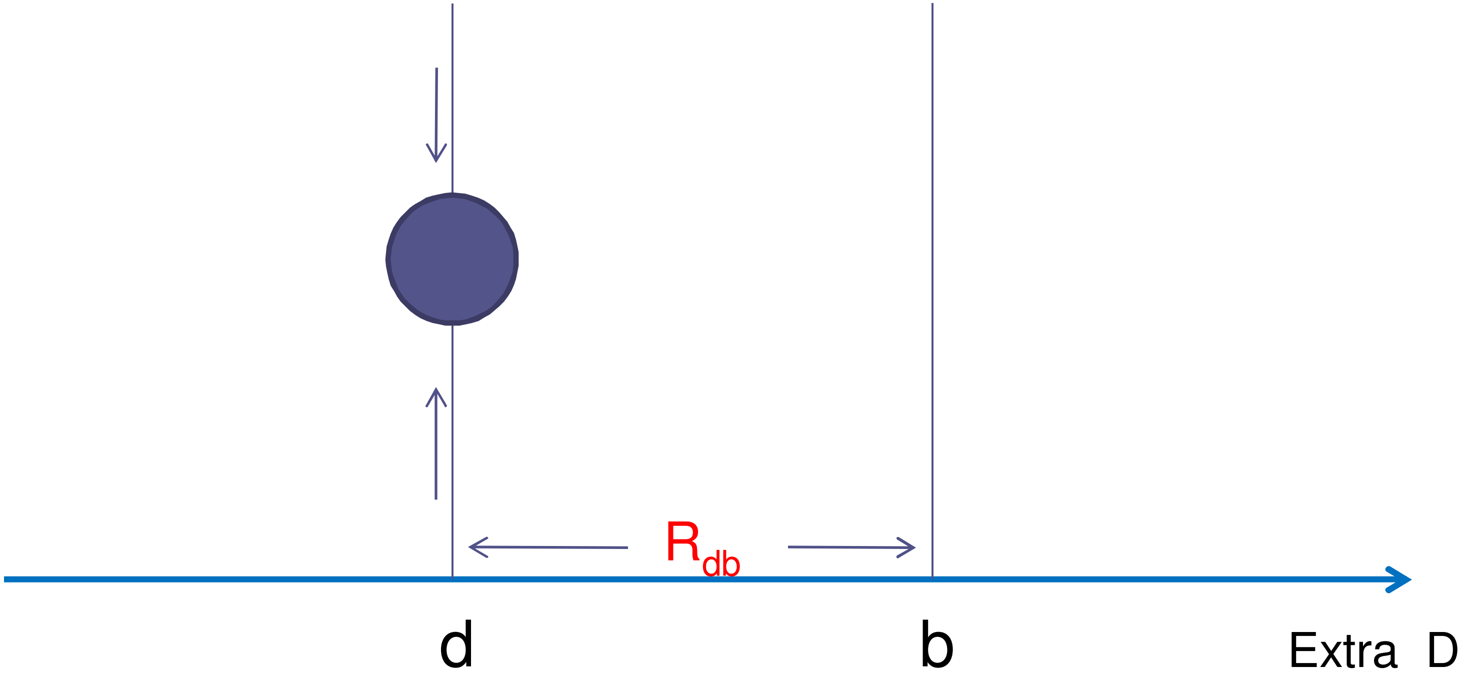
$$\Gamma \sim M_*$$

And the decay rate into all other flavors $j \neq i$ must be suppressed by $1/N$.



So the species label (i,j) behaves like a coordinate!

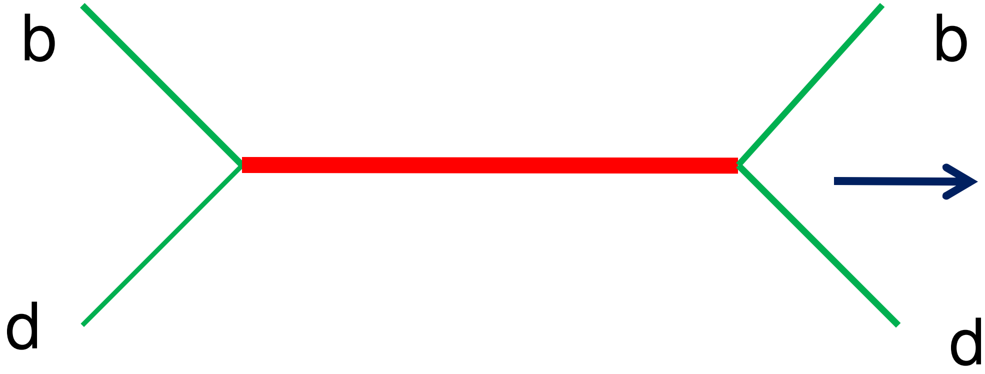
Flavors are displaced in extra dimension (space of species)



Probability to produce b-quarks in a decay of a small (quantum) black hole produced at the d-quark site is exponentially suppressed.

Processes mediated by such Black Holes will be flavor-conserving. However, a quasi-classical Black Hole of $R > R_{db}$, will violate the flavor Maximally.

The low energy decoupling of processes mediated by quasi-classical Black Holes of mass M, are very different from the ones mediated by quantum particles of the same mass:



$$\frac{1}{M^2}\ bd\ bd$$

An analogous process mediated by a virtual quasi-classical black hole of mass $M = M_* (M_* R)^{n+1}$ would be exponentially suppressed at least by the factor

$$\exp(-S_B)$$

Where $S_B = (M_* R)^{n+2}$ is the Beckenstein entropy of a $(4+n)$ - dimensional Black Hole.

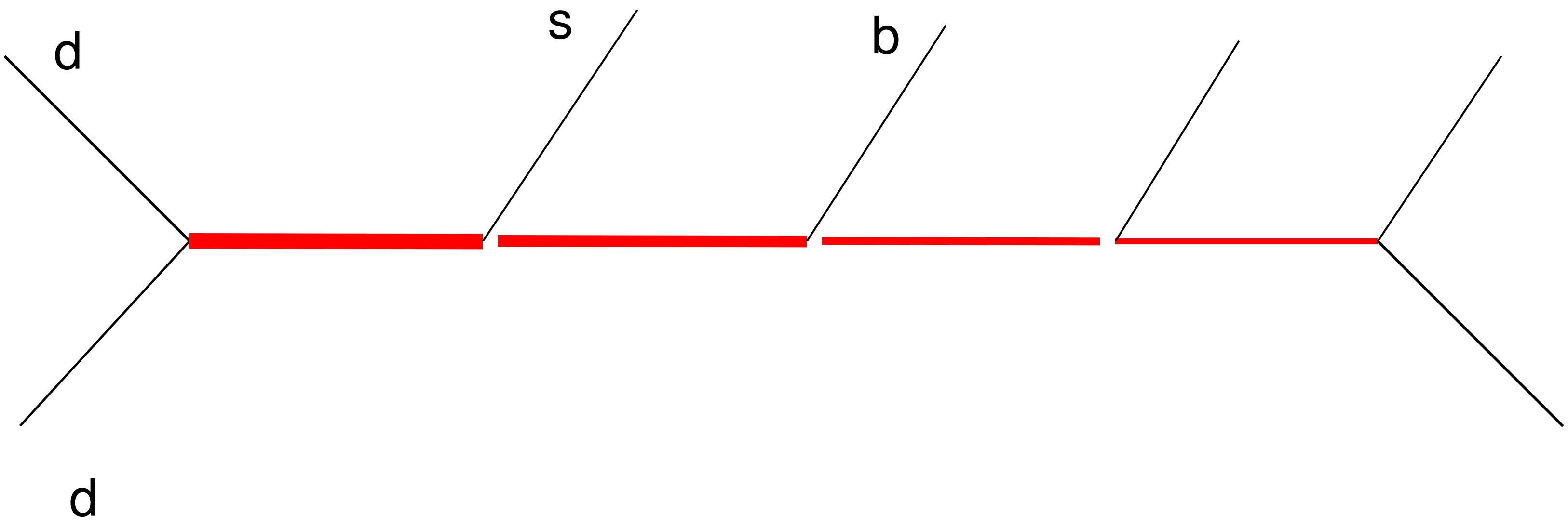
This decoupling is due to he fact that large Black holes are quasi-classical objects.

However, unlike other quasi-classical objects (e.g. solitons) at high energies the black hole mediated processes sharply catch up.

In particular, for center of mass energies

$$E > M_{db} = M_* (M_* R_{db})^{n+1} ,$$

d-b transition processes become order one.



The number of quanta emitted $N_{final} = (E/M_* )^{(n+2)/(n+1)}$

# Generic features:

1) Exponentially sharp increase of flavor-violation in the final states at high energies.

2) Softening of the final state momenta:

$$p_{final} / E = (M_* /E)^{n+2}$$

3) Total number of flavors produced democratically :

$$N_{final} = (E/M_* )^{(n+2)/(n+1)}$$

This physics resonates with some old ideas about the origin of the quark masses and mixing CKM mixing angles:

Nearest neighbor mixing idea

Fritzsch

|  | b |  |
|---|---|---|
| b |  | a |
|  | a | 1 |

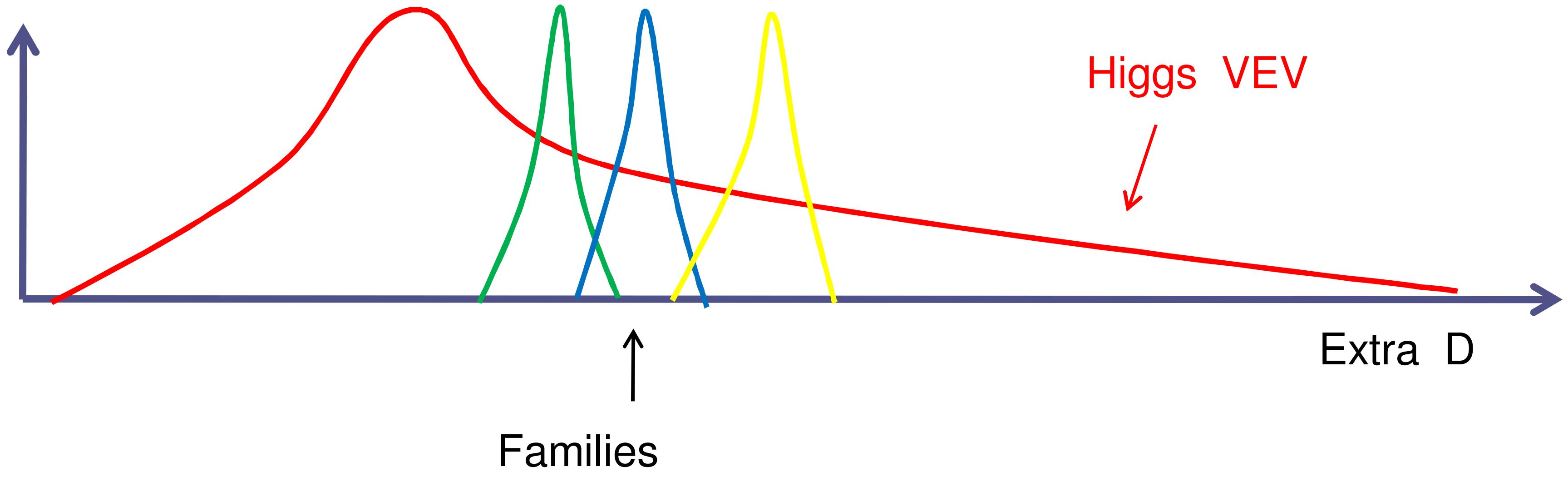
The hierarchy of Quark and Lepton masses may be explained by separation of Standard Model families in extra dimensions.

The hierarchy of masses then can originate from:

1) A small overlap of the left and right handed wave functions (Arkani-Hamed, Schmaltz `99) ,

or

2) localization of different families at different distances from the ``Higgs brane'' (G.D., Shifman `00)



# Conclusions

This is an exciting time for the particle physics community.

LHC will directly probe the mechanism which is responsible for generating the weak interaction scale and masses of the elementary particles.

And, there is a strong theoretical indication, that LHC will also probe physics that is behind the stability of the above scale.

If the ideas presented in this talk have anything to do with nature, LHC has an exceptional chance of experimentally discovering and studying the nature of quantum gravity.