Black Holes and Particle Species

Gia Dvali

CERN Theory Division and New York University

With: M.Redi;
G. Farrar;
D. Luest;
M. Redi, S. Sibiryakov, A. Vainshtein.

Outline

1) The Hierarchy Problem and Dark Matter motivation for Beyond the Standard Model Physics at LHC.

2) The Idea of a TeV-scale quantum gravity. (“Old “ Example: Large Extra Dimensions).

3) Power of the black hole physics: What lowers the quantum gravity scale is the number of particle species.

4) Pandora’s box of possibilities: Any theory with 10^{32} species will do the job!

5) Experimental signatures at LHC: Production of mini black holes, with hair.

6) 10^{32} Copies of the Standard Model also (automatically) solve the Strong CP Problem .

7) Cosmology of Species: up to 10^{32} New Dark Sectors?

THE SEARCHES OF THE NEW (BEYOND THE STANDARD MODEL) PHYSICS AT THE LARGE HADRON COLLIDER (LHC) ARE 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 ABOUT THE UV STABILITY OF THE VERY SMALL NUMBER

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

It is well established, that for the energies $E < M_W$ the world of (known) elementary particles is described by the STANADARD MODEL

GAUGE FORCES → SU(3)xSU(2)xU(1)

MATTER:

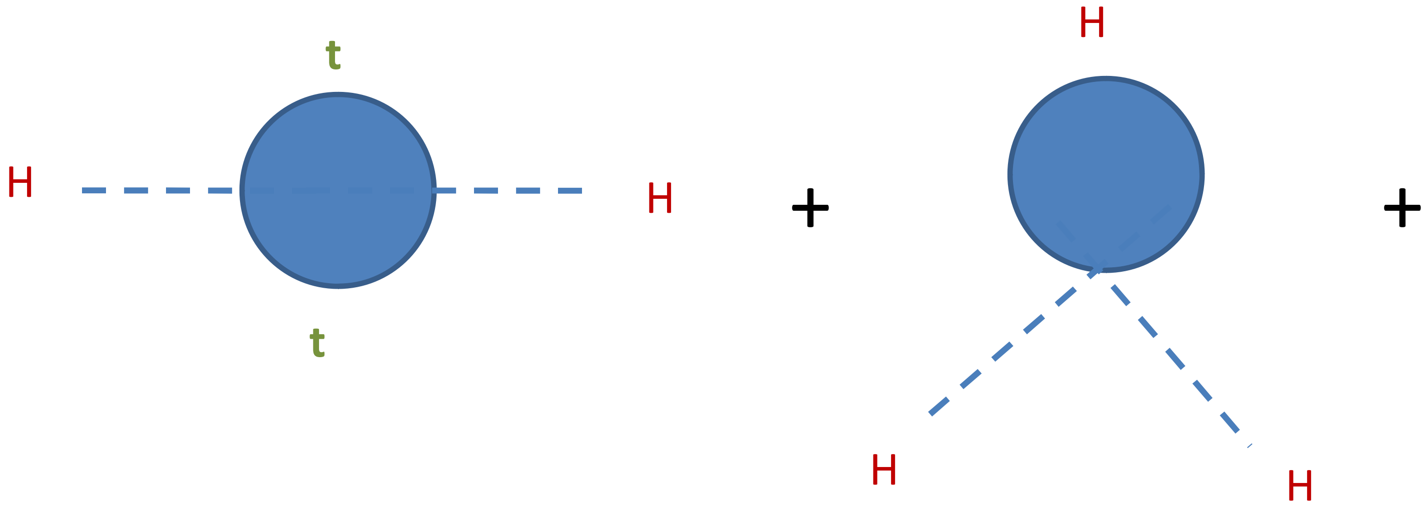
QUARKS : (u,d) (c,s) (t,b), LEPTONS: (e,ν_e) (μ, ν_μ) (τ, ν_τ)

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



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

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, THERE MUST BE SOME NEW PHYSICS NOT FAR ABOVE THE WEAK SCALE , THAT STABILIZES THE HIGGS MASS, AND LHC SHOULD PROBE IT.

WHAT IS THIS NEW PHYSICS?

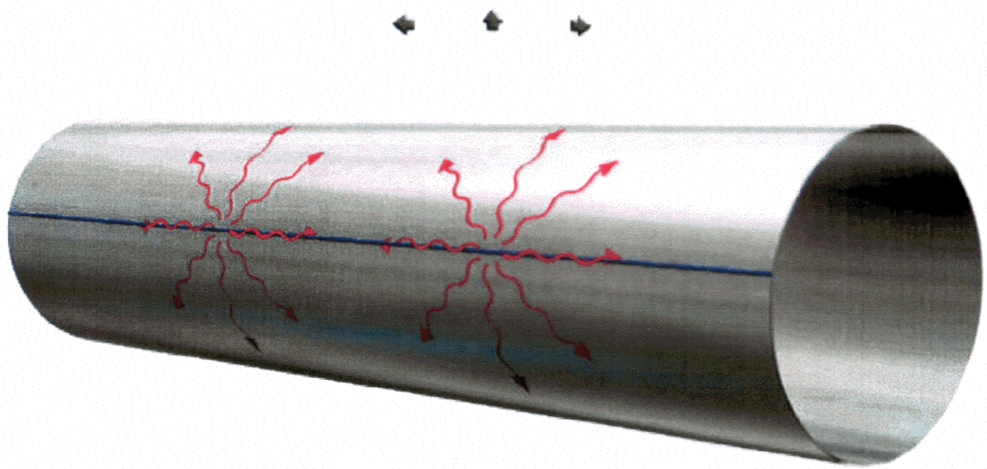
‘98 ADD solution:

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

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

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 was understood recently that the class of low scale quantum gravity theories is much wider and is not, a priory, limited by the large extra dimensional models.

In any theory with large number (N >> 1) of species the scale of quantum gravity is inevitably lowered, relative to the Planck mass [G.D.; G.D. and Redi, '07]

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

This follows from the consistency of the black hole physics and can be proven by the following black hole thought experiment .

THE BLACK HOLE PROOF:

Consider N species of the quantum fields.

$$\Phi_j \quad j = 1, 2 \ldots N$$

of mass Λ.

Assume that this system is invariant under an exact (gauged) discrete symmetry

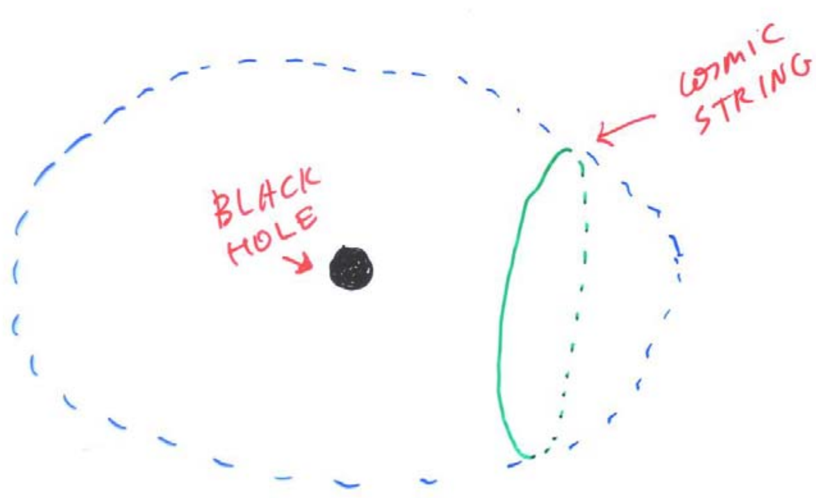
$$Z_2^N \equiv Z_2^{(1)} \times Z_2^{(2)} \times \ldots \times Z_2^{(N)}$$

$$Z_2^{(j)} \Rightarrow \quad \Phi_j \to -\Phi_j.$$

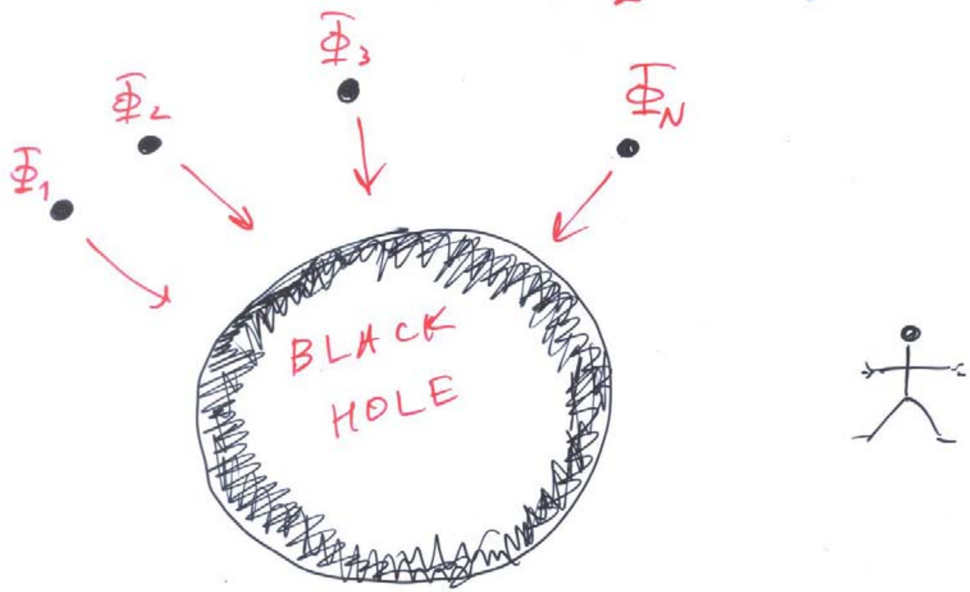
Because Z_2^N is gauged, it is respected by the black hole physics.

This is because black holes can carry a Z_N quantum mechanical hair, which can be measured at infinity by the Aharonov-Bohm effect.

Krauss & Wilczek.



Now, let us prepare an arbitrarily-large black hole that carries a maximal Z_2^N-charge



and wait.

Because Hawking evaporation is thermal, for

$$T_H = \frac{M_P^2}{M_{BH}} \ll \Lambda,$$

the emission probability of Λ-species is Boltzmann-suppressed by

$$\sim e^{-\frac{\Lambda}{T_H}}.$$

So no matter how large is N, the black hole can only start "giving back" the Z_2^N-charge after

$$T_H \gtrsim T_H^* \sim \Lambda.$$

At this point the mass is:

$$M_{BH}^* = \frac{M_P^2}{\Lambda}$$

Now use conservation of energy.
Then, the maximum number of species that can be returned is

$$N_{MAX} = \frac{M_P^2}{\Lambda^2}.$$

Because by Z_2^N-conservation,

$$N_{MAX} \geq N,$$

we prove the bound

$$M_P^2 \geq N \Lambda^2$$

THE BLACK HOLE EVAPORATION RATE IS

$$\frac{dM_{BH}}{dt} = N\, T_H^2$$

$$\Downarrow$$

So the life time is

$$\tau_{BH} \sim \frac{1}{N} \frac{M_{BH}^3}{M_P^4} \sim \Lambda^{-1} \;!$$

THIS IS REMARKABLE

In fact, in a theory with N particle species, the quantum gravity scale is

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

This can be seen by number of arguments, perhaps the most elegant being, that black holes of size

$R_g = M^{-1}_*$, have the lifetime

$$t_{BH} = M^{-1}_*$$

and thus, cannot be regarded as semi-classical states of the Hawking temperature $T_H = M_*$!

Thus, black holes of this size are quantum objects.

WE THOUGHT WE WERE DEALING WITH A BIG FAT CLASSICAL BLACK HOLE,

BUT IT DECAYS WITHIN THE TIME-SCALE OF ITS SIZE!

SUCH OBJECTS CANNOT BE REGARDED AS (QUASI) CLASSICAL BLACK HOLES, WITH WELL DEFINED HAWKING TEMPERATURE:

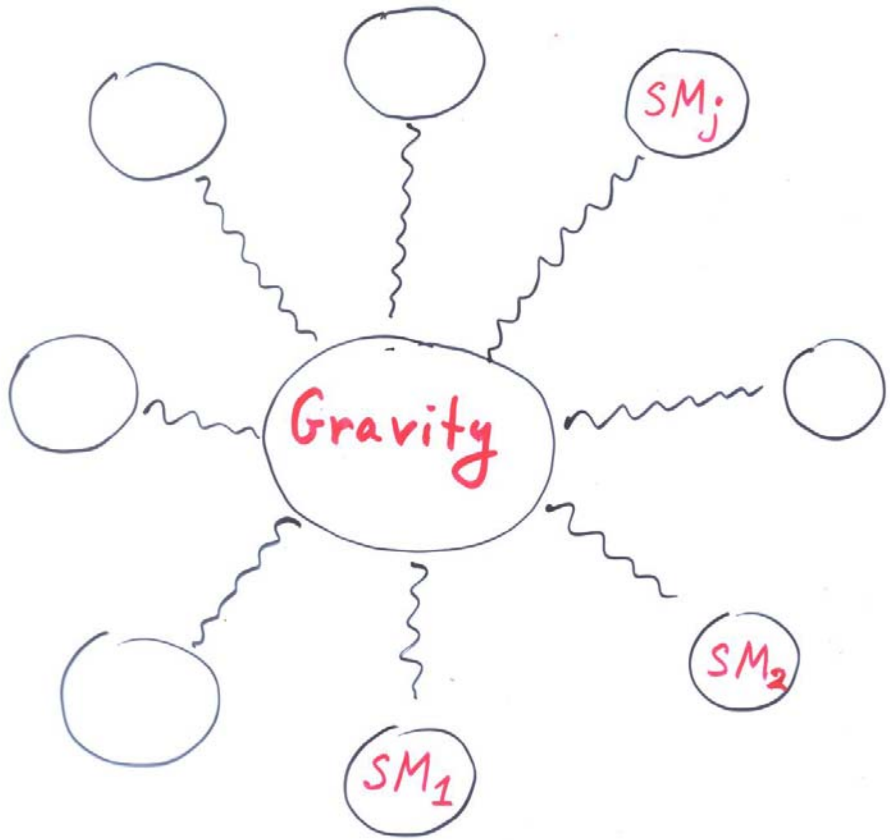
THEIR T_H CHANGEL OVER THE TIME SCALE $\sim T_H^{-1}$.

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.

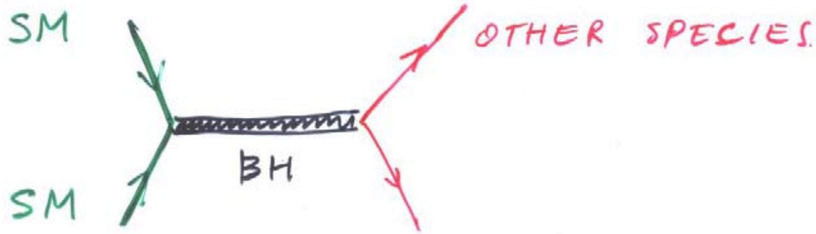
The role of these 10^{32} species, can equally well be played by 10^{32} Kaluza-Klein gravitons from large extra dimensions, or by 10^{32} copies of the Standard Model!

$N \sim 10^{32}$ Copies of the Standard Model



Gravity becomes weak by $\frac{1}{N}$ because of "Spreading" in the space of Species!

BUT IF Λ IS THE SCALE OF QUANTUM GRAVITY, LHC MUST SEE PRODUCTION OF THE BLACK HOLES.



IN FACT, THE BH PRODUCED AT LHC MUST HAVE A MEMORY OF THEIR "SPECIES OF ORIGIN"!

THE SMALL BLACK HOLES CARRY HAIR!

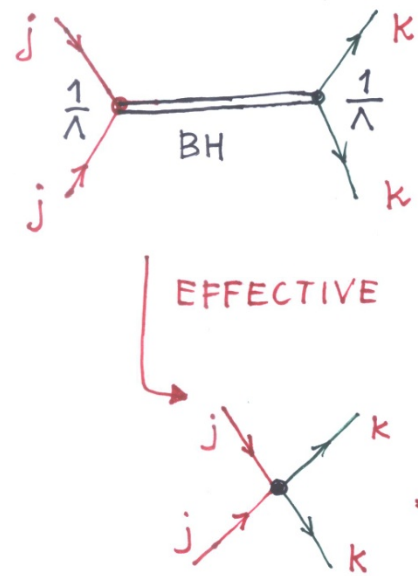
BH PRODUCED IN COLLISION OF OUR STANDARD MODEL PARTICLES AT ENERGY $\sim \Lambda$, WILL DECAY WITH THE RATE

$$\Gamma_{BH \to SM} \sim \Lambda$$

BACK INTO THE STANDARD MODEL SPECIES, AND ONLY WITH VERY SUPPRESSED RATE INTO THE OTHER INDIVIDUAL COPIES

$$\Gamma_{BH \to OTHERS} \lesssim \frac{\Lambda^5}{M_P^4}$$

INDEED, IF SMALL BLACK HOLES COULD DECAY DEMOCRATICALLY, WE WOULD RUN INTO A FIELD-THEORETIC CONTRUDICTION.



EFFECTIVE OPERATOR

$$\Rightarrow \frac{1}{\Lambda^2}\,\psi_j\psi_j\,\psi_k\psi_k$$

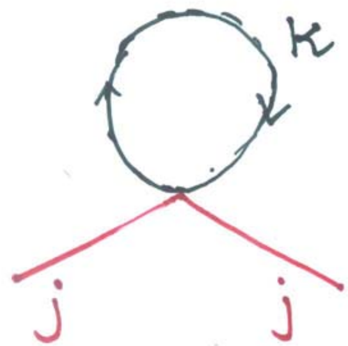
RATE OF TRANSITION:

$$\sum_k \Gamma_{j\to k} \sim \frac{E^5}{\Lambda^4} N \sim \frac{E^5 M_p^2}{\Lambda^6}$$

WOULD BLOW UP AT:

$$E_* \sim \Lambda\sqrt{\frac{\Lambda}{M_p}} \ll \Lambda \quad !$$

RENORMALIZATION OF SM KINETIC TERMS WOULD BE **HUGE**:

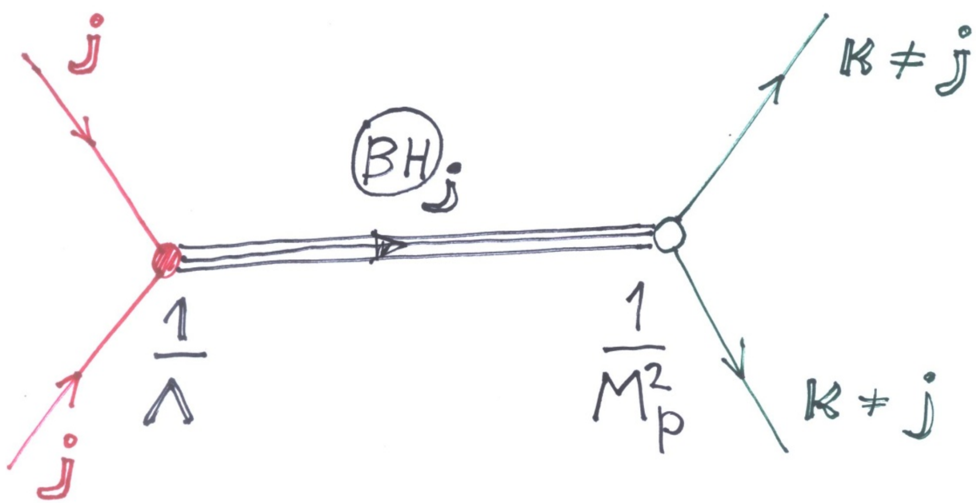
$\sum_k$ 

$\Longrightarrow \left(\frac{M_p}{\Lambda}\right)^2 \bar{\psi}_j \not{\partial} \psi_j$

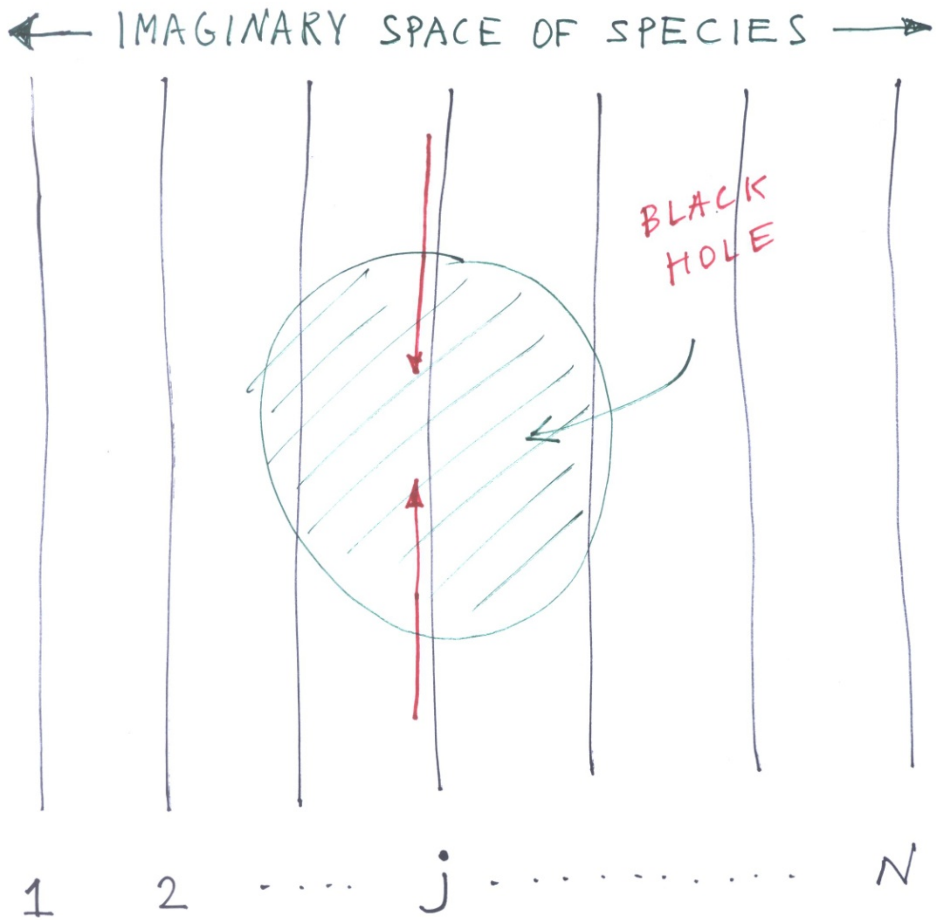
SM PARTICLES WOULD BE EXTREMELY WEAKLY COUPLED!

THE ONLY CONSISTENT POSSIBILITY IS THAT SMALL BH-S HAVE A "MEMORY OF THE PLACE OF ORIGIN" IN THE SPACE OF SPECIES.

THAT IS, THEY CARRY N FLAVORS OF HAIR



WITH THE GROWING SIZE OF A BH, THE MEMORY BECOMES SHORTER AND SHORTER.



Experimental signatures of low scale quantum gravity theories are pretty spectacular.

One model-independent prediction is the formation of mini black holes in particle collisions. The small black holes carry ``hair”, which becomes ``shorter’’ with their increasing size. In the same time the cross-sections soften out with the increase of the collision energy. This is very different from supersymmetry.

In some realizations, the black holes can be semi-classical (G.D., Sibiryakov, ‘08), and live very long. For us, such black holes will look as very long lived charged states, with continuously decreasing mass, that at the final stage explode in very energetic Standard Model particles.

Another signature is production of string vibrations, and emission of particles in Extra Dimensions.

$N \sim 10^{32}$ COPIES OF THE STANDARD MODEL ALSO SOLVES THE STRONG CP PROBLEM.

Θ - ANGLE MEASURES THE ELECTRIC FLUX OF THE QCD CHERN-SIMONS 3-FORM

$$\Theta = \frac{\langle G\tilde{G}\rangle}{\Lambda_{QCD}^4} \equiv \frac{{}^*dC}{\Lambda_{QCD}^4}$$

WHERE

$$C_{\alpha\beta\gamma} \equiv A_\alpha A_\beta A_\gamma - \frac{3}{2} A_\alpha \partial_\beta A_\gamma$$

BUT WITH $N = 10^{32}$ COPIES OF QCD, THE TOTAL FLUX CANNOT EXCEED

$$\Lambda \equiv \frac{M_P}{\sqrt{N}}$$

THUS,

$$\overline{\Theta} = \frac{1}{\sqrt{N}} \left(\frac{\Lambda}{\Lambda_{QCD}} \right)^4 \lesssim 10^{-10}$$

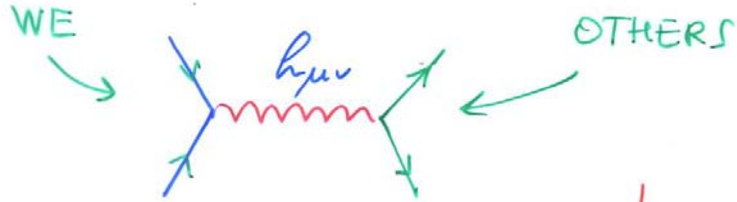
Cosmology of Species

Normalcy temperature.

Imagine we start out hot at temperature T and all the other sectors are empty.

The production rate of other species:

$$\Gamma_{WE \to OTHERS} = \frac{T^5}{M_P^4} N = \frac{T^5}{M_P^2 \Lambda^2}$$



At $\mathbf{T_*} = (M_P \Lambda^2)^{\frac{1}{3}} \sim 10^8\,\text{GeV}$

$$\Gamma_{WE \to OTHERS} = H = \frac{T^2}{M_P}$$

For $T < T_*$, we cool down as normal (due to Universe's expansion).

For $T > T_*$ we cool because of decay into the other species!

Because $T_* \gg T_{BBN} \sim 10\,\text{MeV}$, $T \gg T_*$ is not a problem.

In fact, the baryons in the other sectors can be a dark matter.

For being dark matter, there must be $\sim 10^{80}$ baryons of the other copies.

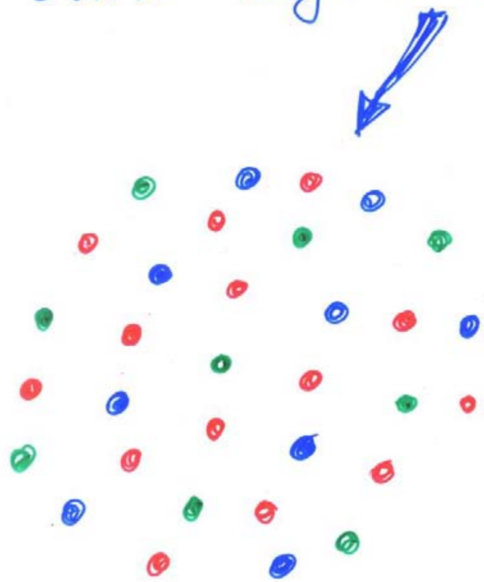
10^{48} baryons per SM copy.

This is 10^{31} times less than the density of the normal baryons.

So the "hidden" baryons never interact and are the perfect DM candidate!

$SM \otimes SM \otimes SM \otimes \ldots\ldots$

Dark baryon cloud



$$N_{TOTAL} = 10^{31} \times 10^{48} = 10^{80}$$

(4) This solutions will be tested by LHC, or else there is a BIG puzzle.

(5) We shall discuss some interesting open questions, and implications for other hierarchies

$$\frac{M_{GUT}}{M_P}, \quad \frac{M_{STRING}}{M_P} \ldots$$

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.