Quantum Black Holes

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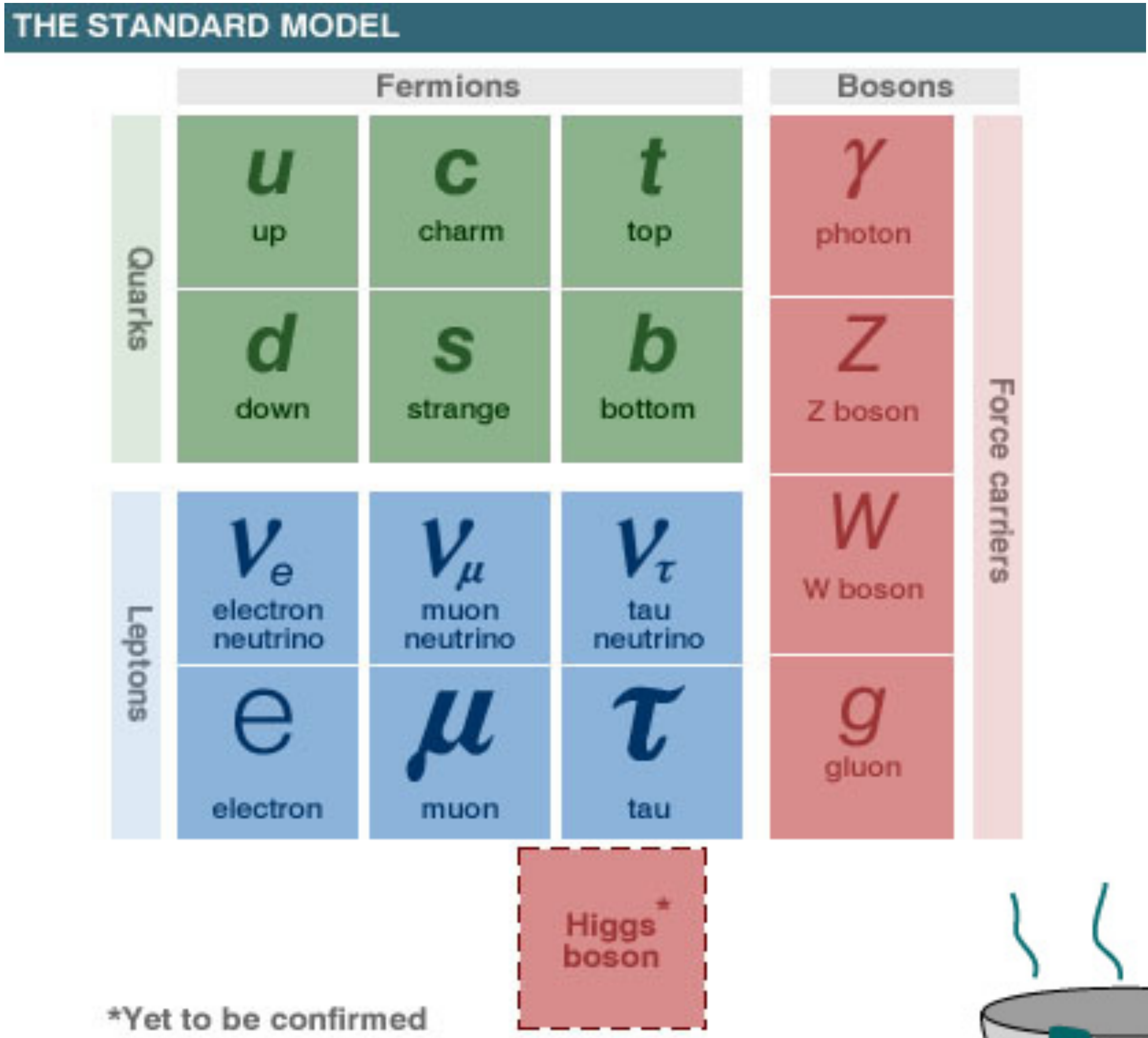
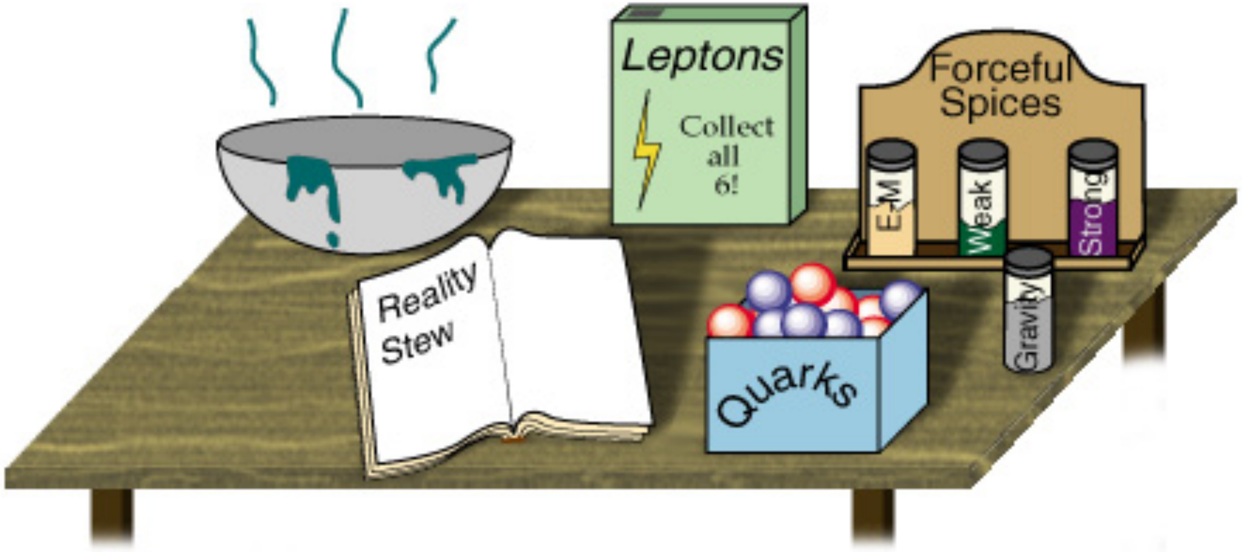


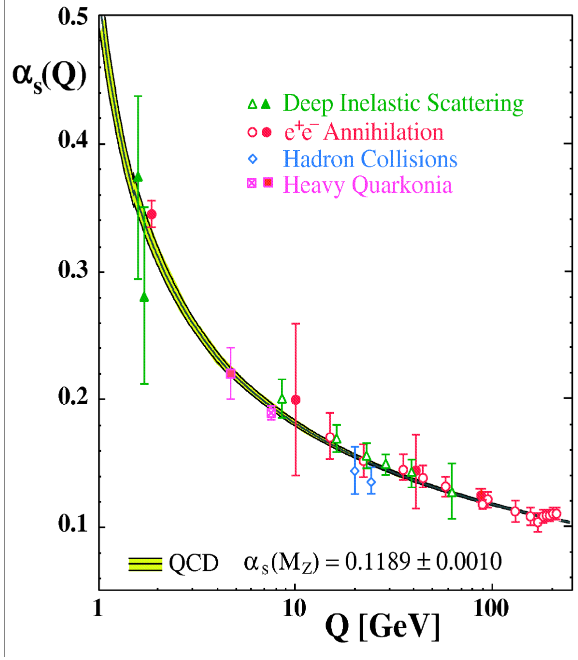
Standard Model of particle physics

It is described by a quantum field theory.



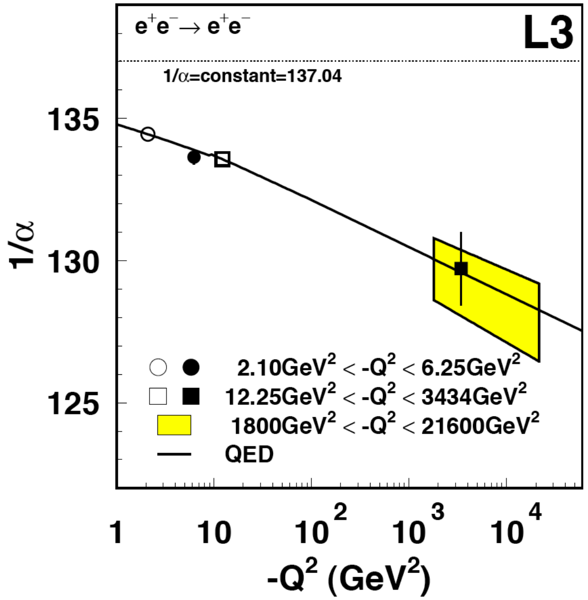
Like athletes, coupling constants run (with energy)….

fast

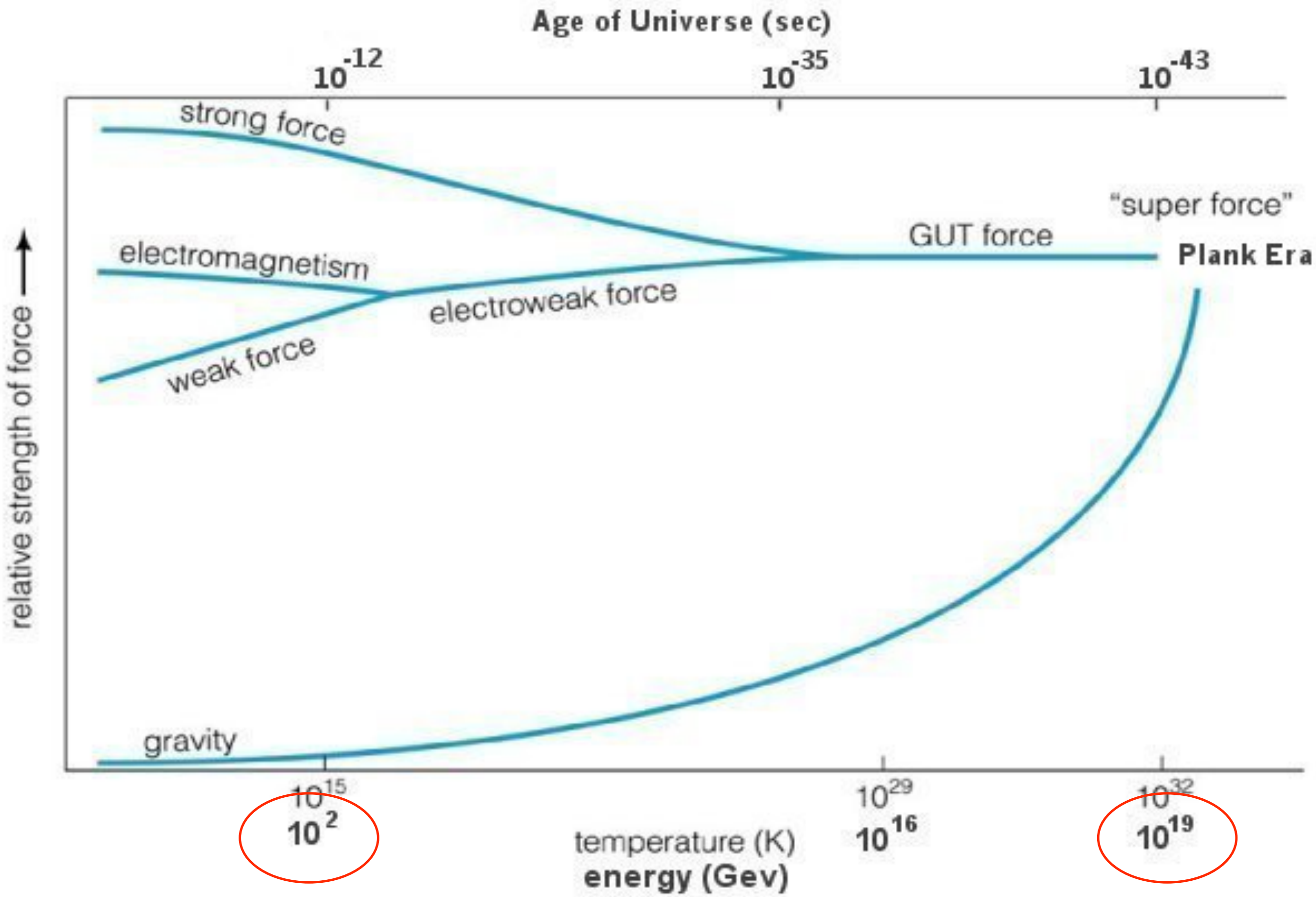


or

slow



When does gravity become important?



A grand unification?
Is there actually only
one fundamental interaction?

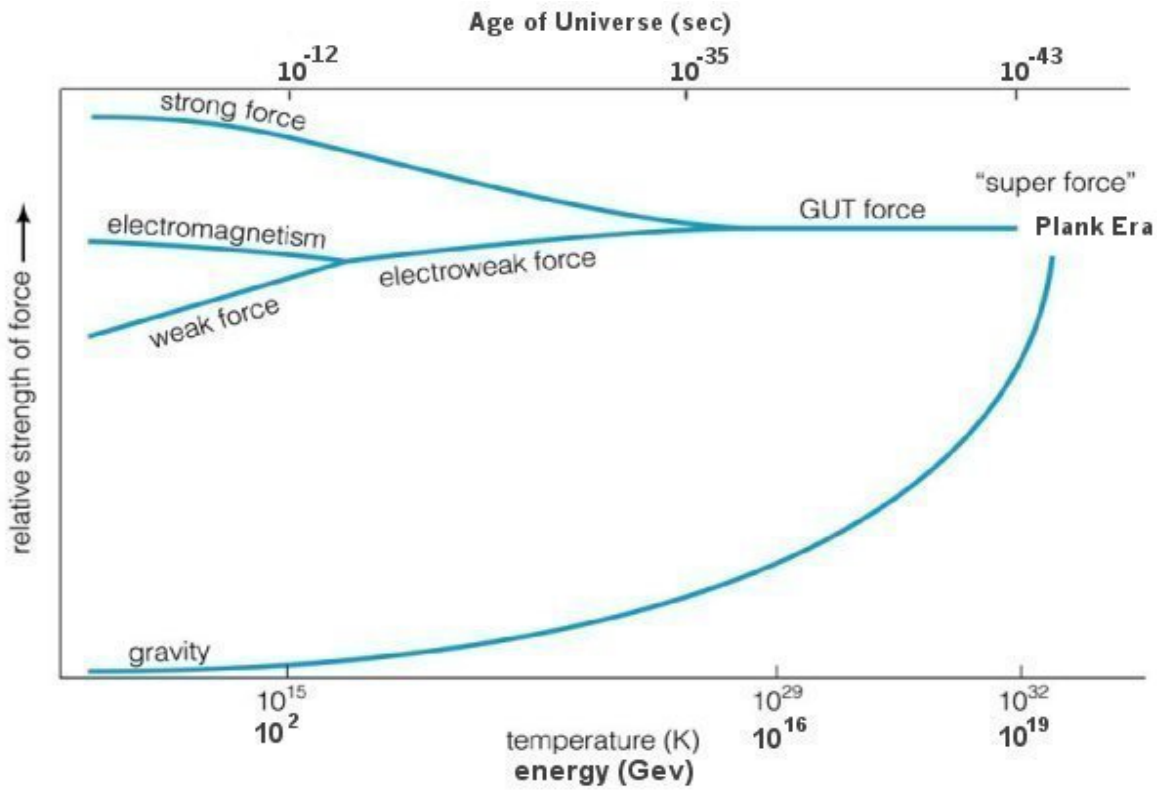
$$M_P = \sqrt{\frac{\hbar c}{G_N}}$$

The Planck mass is the energy scale at which quantum gravitational effects become important.

Doing quantum gravity is challenging

- We do not know how to do calculations in quantum gravity.
- Unifying gravity and quantum mechanics is difficult.
- One can however show a few features such a theory should have, most notably: there is a minimal length in nature (e.g. XC, M. Graesser and S. Hsu) which corresponds to the size of the quantum fluctuations of spacetime itself.
- New tools/theories are needed: string theory, loop quantum gravity, noncommutative geometry, nonperturbative quantum gravity… maybe something completely different.

Quantization of gravity is an issue in the high energy regime which is tough to probe experimentally

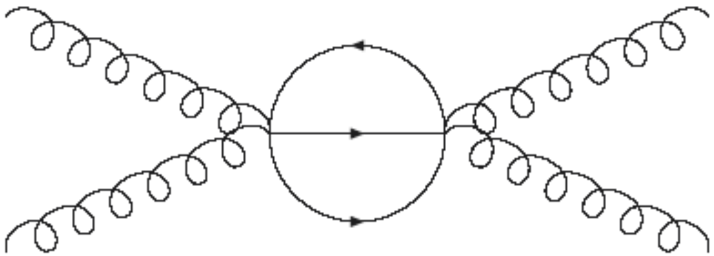


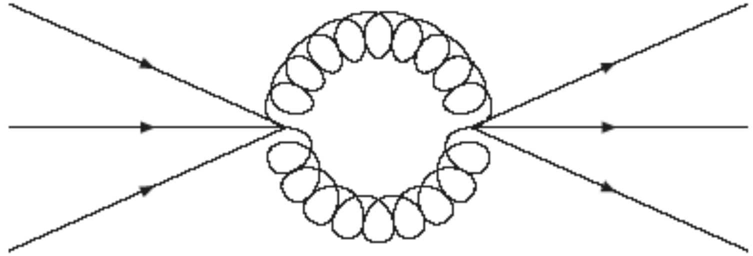
Dimensional analysis:
$M_P \sim 10^{19}$ GeV
but we shall see
that it does not need
to be the case.

Since we do not have data: thought experiments can give us some clues.

Why gravity do we need to quantize gravity?

One example: linearized gravity coupled to matter (described by a quantum field theory) is problematic:





See talk of Claus Kiefer

We actually do not even know at what energy scale quantum gravity becomes strong!

Let me give you two examples

TeV gravity extra-dimensions

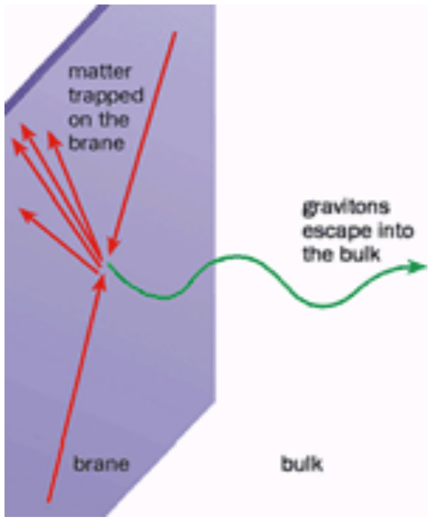
$$\int d^4x\, d^{d-4}x' \sqrt{-g}\ \left(M_*^{d-2}\mathcal{R} + \cdots\ \right)$$

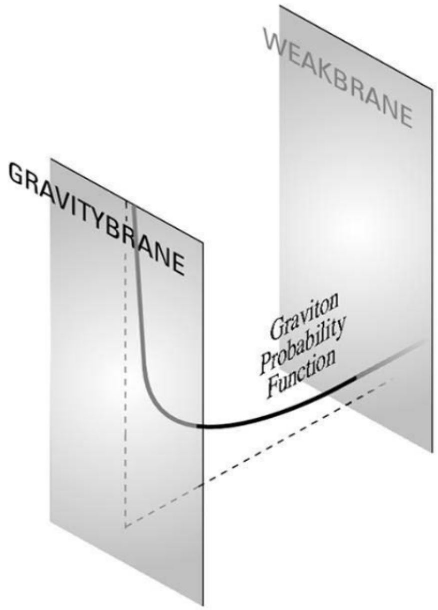
$$M_P^2 = M_*^{d-2} V_{d-4}$$

where M_P is the effective Planck scale in 4-dim

ADD brane world

RS warped extra-dimension





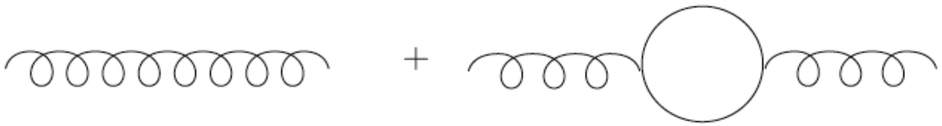
Running of Newton's constant

XC, Hsu & Reeb (2008)

- Consider GR with a massive scalar field

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{16\pi G}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{m^2}{2}\phi^2\right)$$

- Let me consider the renormalization of the Planck mass:



$$M(\mu)^2 \;=\; M(0)^2 - \frac{\mu^2}{12\pi}\left(N_0 + N_{1/2} - 4N_1\right)$$

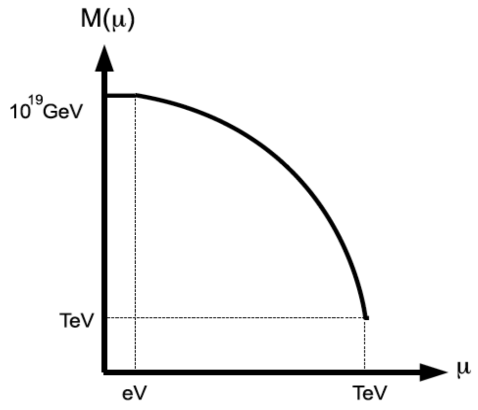
Like any other coupling constant: Newton’s constant runs!

Theoretical physics can lead to anything…
even business ideas!

NEWTON®
running

A large hidden sector!

- Gravity can be strong at 1 TeV if Newton's constant runs fast somewhere between eV range and 1 TeV.



- Strong gravity at μ_{*}=1 TeV takes N=10^{33} fields.

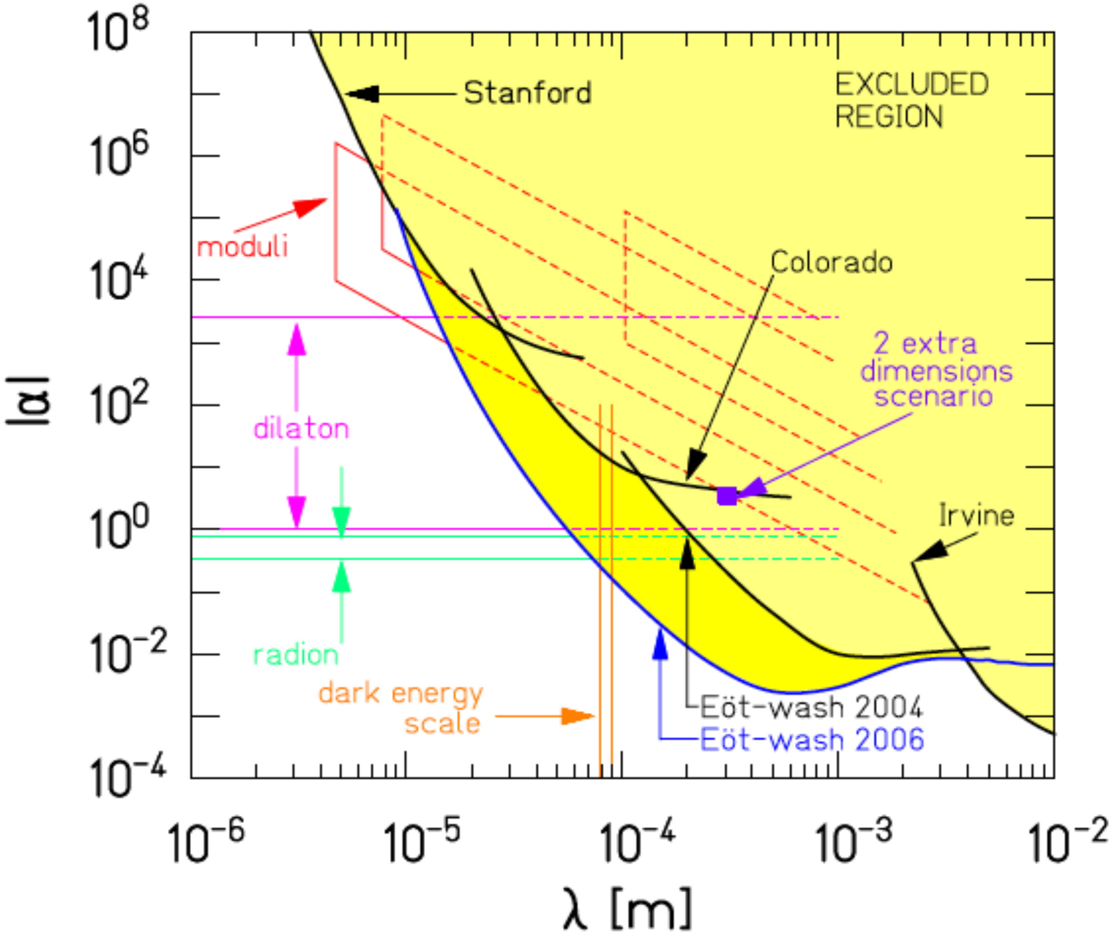
- We assume that these new fields only interact gravitationally with the standard model.

- This will reproduce a lot of the phenomenology of models with large extra-dimensions

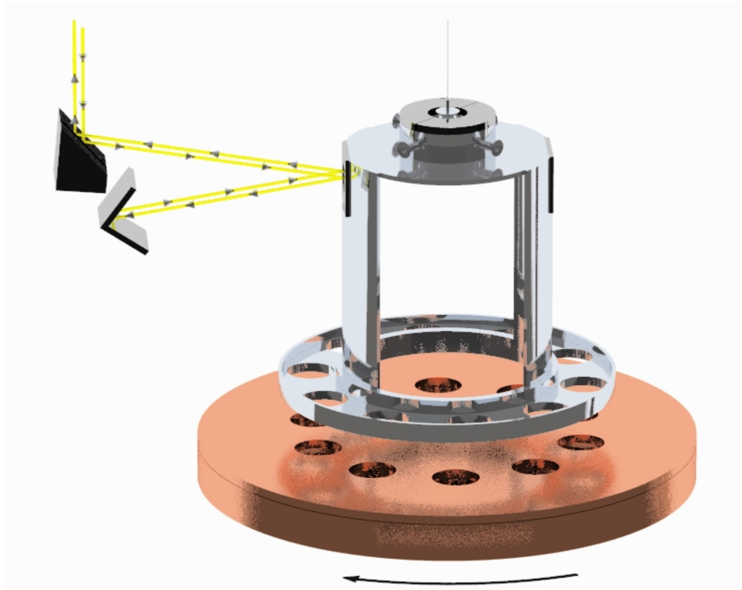
Quantum gravity effects could become important at any energy scale!

It is really an experimental question.

Why are these models viable?



Gravity has only been tested up to distances of the order of 10^{-3} eV!

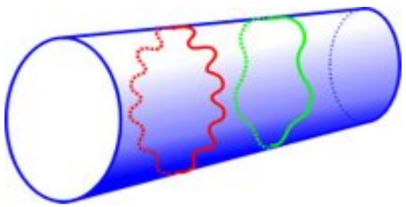


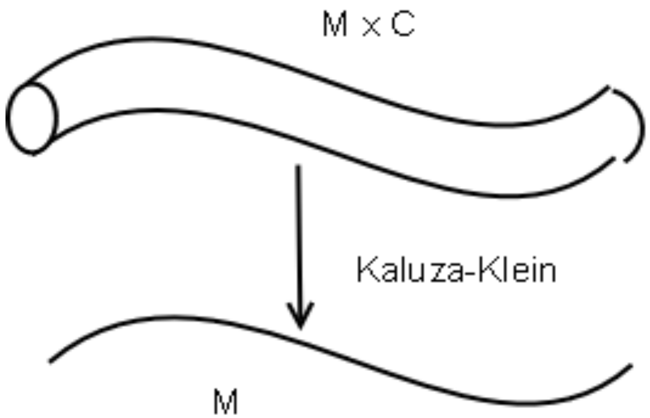
Schematic drawing of the Eöt-Wash Short-range Experiment

$$V(r) = -G_N \frac{m_1 m_2}{r} \left[1 + \alpha \exp\left(-r/\lambda\right)\right]$$

Typical problems of models with TeV Quantum Gravity:

- Light Kaluza-Klein gravitons in ADD:





- Graviton KKs lead to astrophysical constraints: supernovae cooling and neutron stars heating: limits on the scale/number of dimensions

Bounds (orders of magnitude) on ADD brane-world model

n	1	2	3	4	5	6
Gravity exp.	10^7 km	0.2mm				0.1 fm
LEP2		1 TeV	1 TeV	1 TeV	1 TeV	1 TeV
Tevatron		1 TeV	1 TeV	1 TeV	1 TeV	1 TeV
Astro. SN +NS		10^3 TeV	10^2 TeV	5 TeV	none	none
Cosmic rays	1 TeV	1 TeV	1 TeV	1 TeV	1 TeV	1 TeV

Note: mass gap grows with n. In RS bounds of the order of 1 TeV due to mass gap.

One of the key signature of quantum gravity would be the observation of a small quantum black hole.

A brief review on the formation of black holes

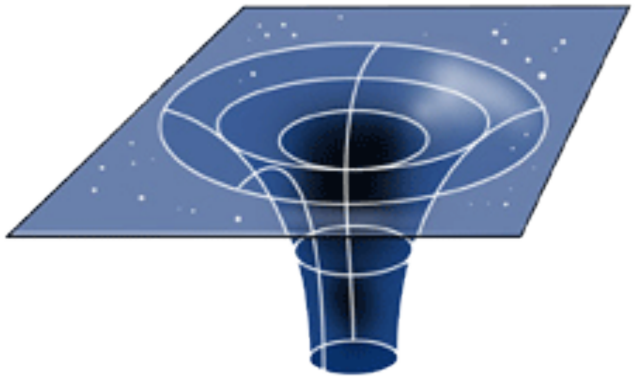
(see talk of Peter D'Eath for details)

When does a black hole form?

This is well understood in general relativity with symmetrical distribution of matter:

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{r_s}{r}} - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$r_s = \frac{2GM}{c^2}$$



But, what happens in particle collisions at extremely high energies?

Small black hole formation

(in collisions of particles)

- In trivial situations (spherical distribution of matter), one can solve explicitly Einstein's equations e.g. Schwarzschild metric.
- In more complicated cases one can't solve Einstein equations exactly and one needs some other criteria.
- Hoop conjecture (Kip Thorne): if an amount of energy E is confined to a ball of size R, where R < E, then that region will eventually evolve into a black hole.

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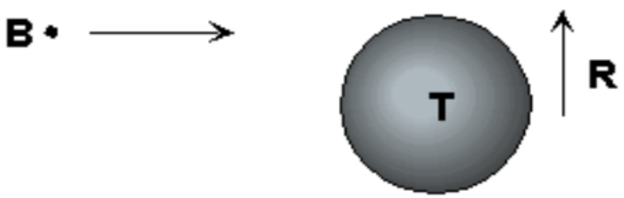
- Cross-section for semi-classical BHs (closed trapped surface constructed by Penrose; D'Eath & Payne; Eardley & Giddings):

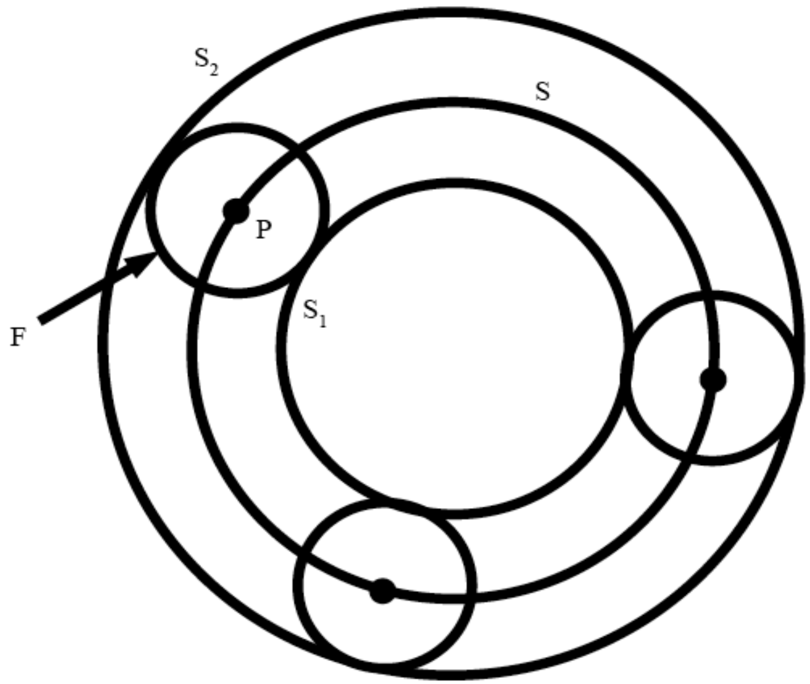
$$\hat{\sigma} \approx \pi r_s^2 \qquad r_s(M_{\rm BH}) = \frac{1}{M_D}\left[\frac{M_{\rm BH}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n \pi^{(n-3)/2}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{1+n}}$$



$$r_s = \frac{2GM}{c^2}$$

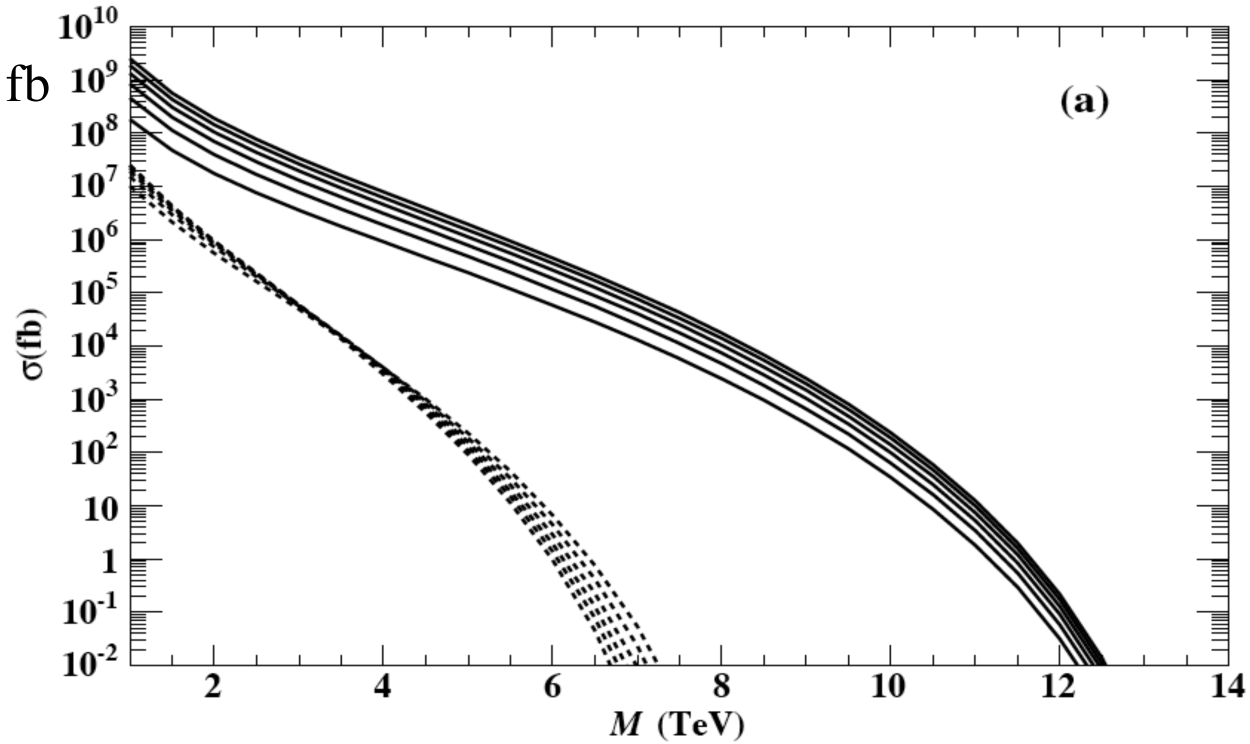
The cross section for point-like particles colliding with a sphere is just the area of the sphere projected onto the transverse plane, that is, a circular disk of radius R.

- A CTS is a compact spacelike two-surface in space-time such that outgoing null rays perpendicular to the surface are not expanding.



- At some instant, the sphere S emits a flash of light. At a later time, the light from a point P forms a sphere F around P, and the envelopes S_1 and S_2 form the ingoing and outgoing wavefronts respectively. If the areas of both S_1 and S_2 are less than of S, then S is a closed trapped surface.

Small BHs @ LHC
(studied by Anchordoqui et al. and many other people, this plot is from Gingrich, hep-ph/0609055)



$$\sigma \sim \frac{1}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^{\frac{2}{1+n}}$$

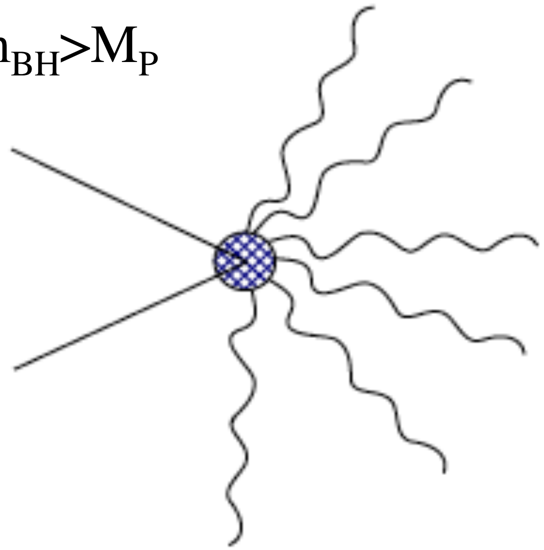
For partons, σ increases with energy but note that PDFs go so fast to zero that they dominate. In other words quantum black holes dominate!

σ(pp->BH+X), M_D=1 TeV

This shows the significance of the inelasticity in BH production

Semi-classical (thermal) versus quantum black hole: calculate the entropy!

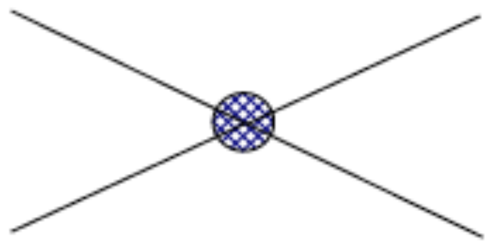
$m_{BH} > M_P$



thermal black hole
large entropy

$m_{BH} \sim M_P$

XC Gong & Hsu (2008)



quantum black hole
small entropy

$$S = \frac{1+n}{2+n}\frac{M_{BH}}{T_{BH}}$$

$$\langle N \rangle \propto \left(\frac{M_{BH}}{M_\star} \right)^{\frac{n+2}{n+1}}$$

Keep in mind that E-G construction only works for $m_{BH} >> M_P$

We need to understand the formation of quantum BHs

Black holes at LHC made it to the New York Times!

The New York Times
nytimes.com

March 29, 2008

Asking a Judge to Save the World, and Maybe a Whole Lot More

By DENNIS OVERBYE

More fighting in Iraq. Somalia in chaos. People in this country can't afford their mortgages and in some places now they can't even afford rice.

None of this nor the rest of the grimness on the front page today will matter a bit, though, if two men pursuing a lawsuit in federal court in Hawaii turn out to be right. They think a giant particle accelerator that will begin smashing protons together outside Geneva this summer might produce a black hole or something else that will spell the end of the Earth — and maybe the universe.

Scientists say that is very unlikely — though they have done some checking just to make sure.

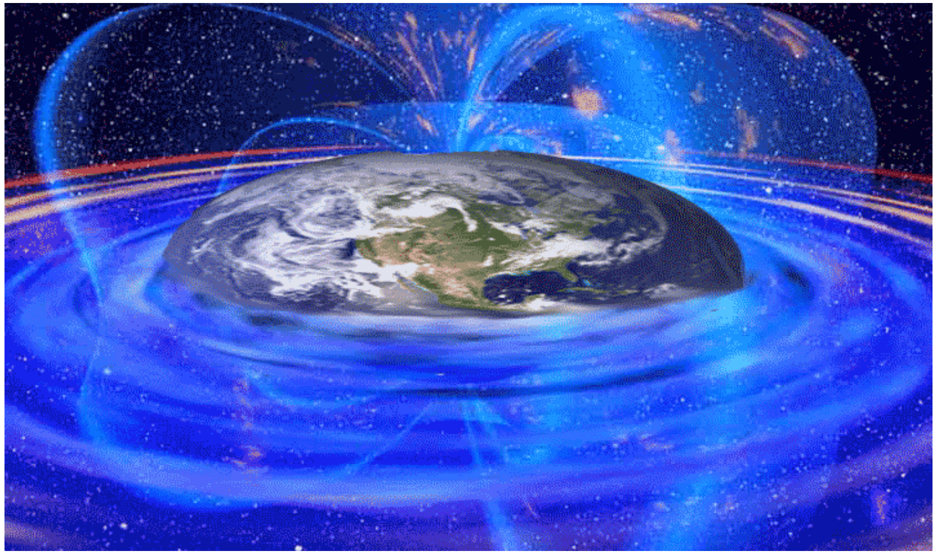
The world's physicists have spent 14 years and $8 billion building the Large Hadron Collider, in which the colliding protons will recreate energies and conditions last seen a trillionth of a second after the Big Bang. Researchers will sift the debris from these primordial recreations for clues to the nature of mass and new forces and symmetries of nature.

But Walter L. Wagner and Luis Sancho contend that scientists at the European Center for Nuclear Research, or CERN, have played down the chances that the collider could produce, among other horrors, a tiny black hole, which, they say, could eat the Earth. Or it could spit out something called a "strangelet" that would convert our planet to a shrunken dense dead lump of something called "strange matter." Their suit also says CERN has failed to provide an environmental impact statement as required under the National Environmental Policy Act.

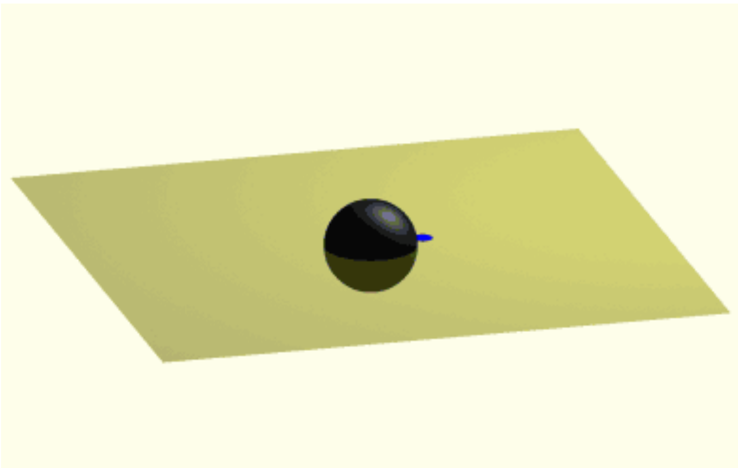
Although it sounds bizarre, the case touches on a serious issue that has bothered scholars and scientists in recent years — namely how to estimate the risk of new groundbreaking experiments and who gets to decide whether or not to go ahead.

The lawsuit, filed March 21 in Federal District Court, in Honolulu, seeks a temporary restraining order prohibiting CERN from proceeding with the accelerator until it has produced a safety report and an environmental assessment. It names the federal Department of Energy, the Fermi National Accelerator Laboratory, the National Science Foundation and CERN as defendants.

According to a spokesman for the Justice Department, which is representing the Department of Energy, a scheduling meeting has been set for June 16.



black holes decay via Hawking radiations!



CERN had to react!

European Organization for Nuclear Research

Safety at the LHC

The Large Hadron Collider (LHC) can achieve energies that no other particle accelerators have reached before. The energy of its particle collisions has previously only been found in Nature. And it is only by using such a powerful machine that phyicists can probe deeper into the key mysteries of the Universe. Some people have expressed concerns about the safety of whatever may be created in high-energy particle collisions. However there are no reasons for concern.

Modest by Nature's standards

Accelerators recreate the natural phenomena of cosmic rays under controlled laboratory conditions. Cosmic rays are particles produced in outer space in events such as supernovae or the formation of black holes, during which they can be accelerated to energies far exceeding those of the LHC. Cosmic rays travel throughout the Universe, and have been bombarding the Earth's atmosphere continually since its formation 4.5 billion years ago. Despite the impressive power of the LHC in comparison with other accelerators, the energies produced in its collisions are greatly exceeded by those found in some cosmic rays. Since the much higher-energy collisions provided by Nature for billions of years have not harmed the Earth, there is no reason to think that any phenomenon produced by the LHC will do so.

Cosmic rays also collide with the Moon, Jupiter, the Sun and other astronomical bodies. The total number of these collisions is huge compared to what is expected at the LHC. The fact that planets and stars remain intact strengthens our confidence that LHC collisions are safe. The LHC's energy, although powerful for an accelerator, is modest by Nature's standards.

TGVs and mosquitoes

The total energy in each beam of protons in the LHC is equivalent to a 400 tonne train (like the French TGV) travelling at 150 km/h. However, only an infinitesimal part of this energy is released in each particle collision - roughly equivalent to the energy of a dozen flying mosquitoes. In fact, whenever you try to swat a mosquito by clapping your hands together, you create a collision energy much higher than the protons inside the LHC. The LHC's speciality is its impressive ability to concentrate this collision energy into a minuscule area on a subatomic scale. But even this capability is just a pale shadow of what Nature achieves routinely in cosmic-ray collisions.

During part of its operation, the LHC will collide beams of lead nuclei, which have a greater collision energy, equivalent to just over a thousand mosquitoes. However, this will be much more spread out than the energy produced in the proton collisions, and also presents no risk.

Microscopic black holes will not eat you...

Massive black holes are created in the Universe by the collapse of massive stars, which contain enormous amounts of gravitational energy that pulls in surrounding matter. The gravitational pull of a black hole is related to the amount of matter or energy it contains – the less there is, the weaker the pull. Some physicists suggest that microscopic black holes could be produced in the collisions at the LHC. However, these would only be created with the energies of the colliding particles (equivalent to the energies of

Black holes have already been spotted in Belgium

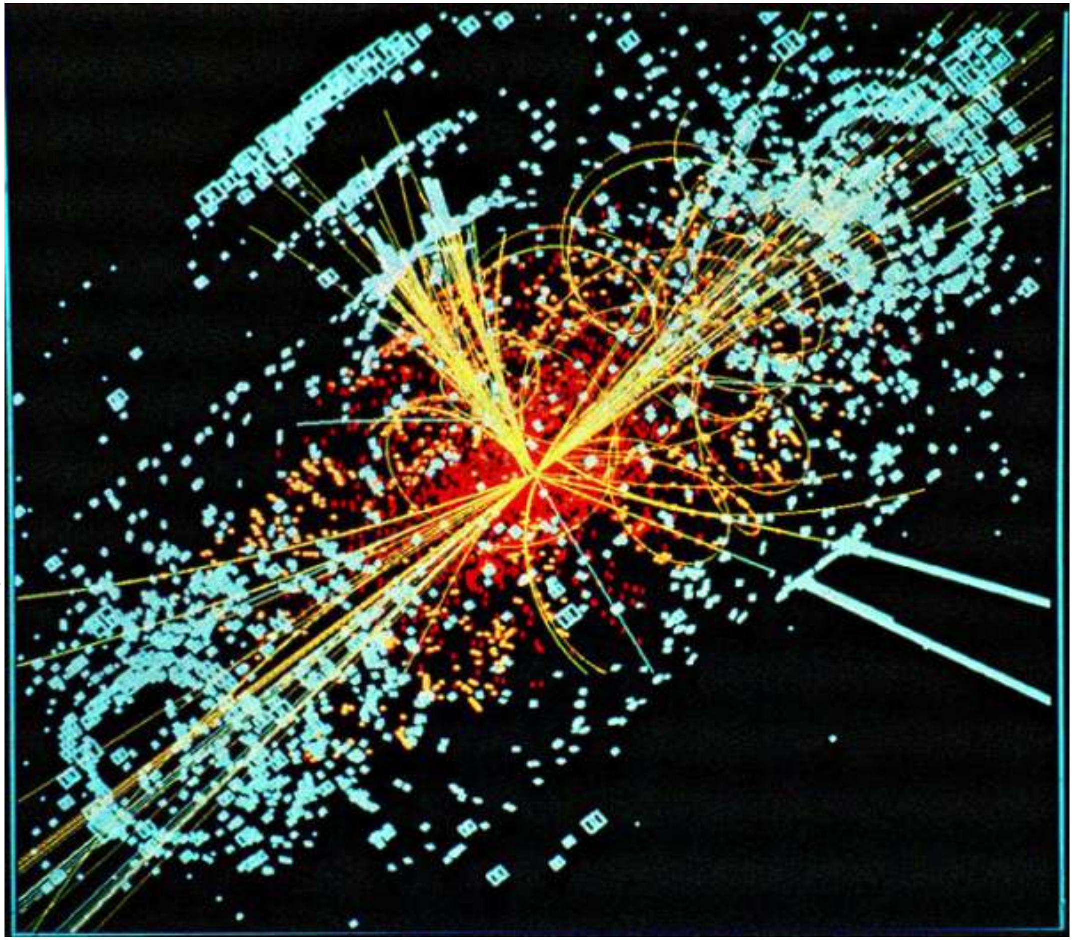
There is a Belgian beer called "black hole".

So far Belgium has not imploded…

despite black holes

If a BH is produced at the LHC it's important to understand how it will decay in order to find the needle in the haystack.

Does it have Spin?
To what particles does it decay (greybody factor)?



It is important to model the decay of small BHs:
see talks of Elizabeth Winstanley for theory and Victor Lendermann monte-carlo/CERN experiment side.

Small black holes at LHC: some open questions

- They would be produced via collisions of quarks&gluons: most of them would be charged under SU(3) and would carry a QED charge: how does this impact the production mechanism? See talk of Octavian Micu.

- Would a minimal length impact BHs solutions and their phenomenology at the LHC? See talk of Piero Nicolini

- What are the correct cross-sections for non-thermal small black holes? What’s the minimal QBH mass? Etc…

Black Hole information problem (over simplified)

- S. Hawking & J. Bekenstein showed that BHs are not black but radiate away energy.
- No hair theorem: black holes are uniquely determined by their mass, angular momentum and charge: they don’t care how they got formed.
- If a pure quantum state enters the BH, the transformation of that state into the mixed state of Hawking radiation would destroy information about the original quantum state.
- If BHs are produced, we would have a unique opportunity of checking whether information is destroyed or not by BHs. See talk of Sabine Hossenfelder.

A few personal remarks/Conclusions

- It is very unlikely that the scale of quantum gravity is really within the LHC reach. We have shown that models with large extra-dimensions or a large hidden sector suffer from unitarity problem (M. Atkins & XC 2010).
- However, there is little theoretical prejudice for the energy scale at which quantum gravity effects become important: It is an experimental physics question.
- LHC physics is a good excuse to think about fundamental gravity questions: a lot of progress has be made that way using thought experiments.
- It remains crucial to find ways to probe quantum gravity experimentally: primordial black holes could be useful (see talk of Agnieska Januik) or maybe systems with strong gravitational fields.
- More interaction between high energy/relativists and astronomers hopefully will lead to new ideas on how to probe quantum gravity.