Black holes:
From astrophysics to the Large Hadron Collider

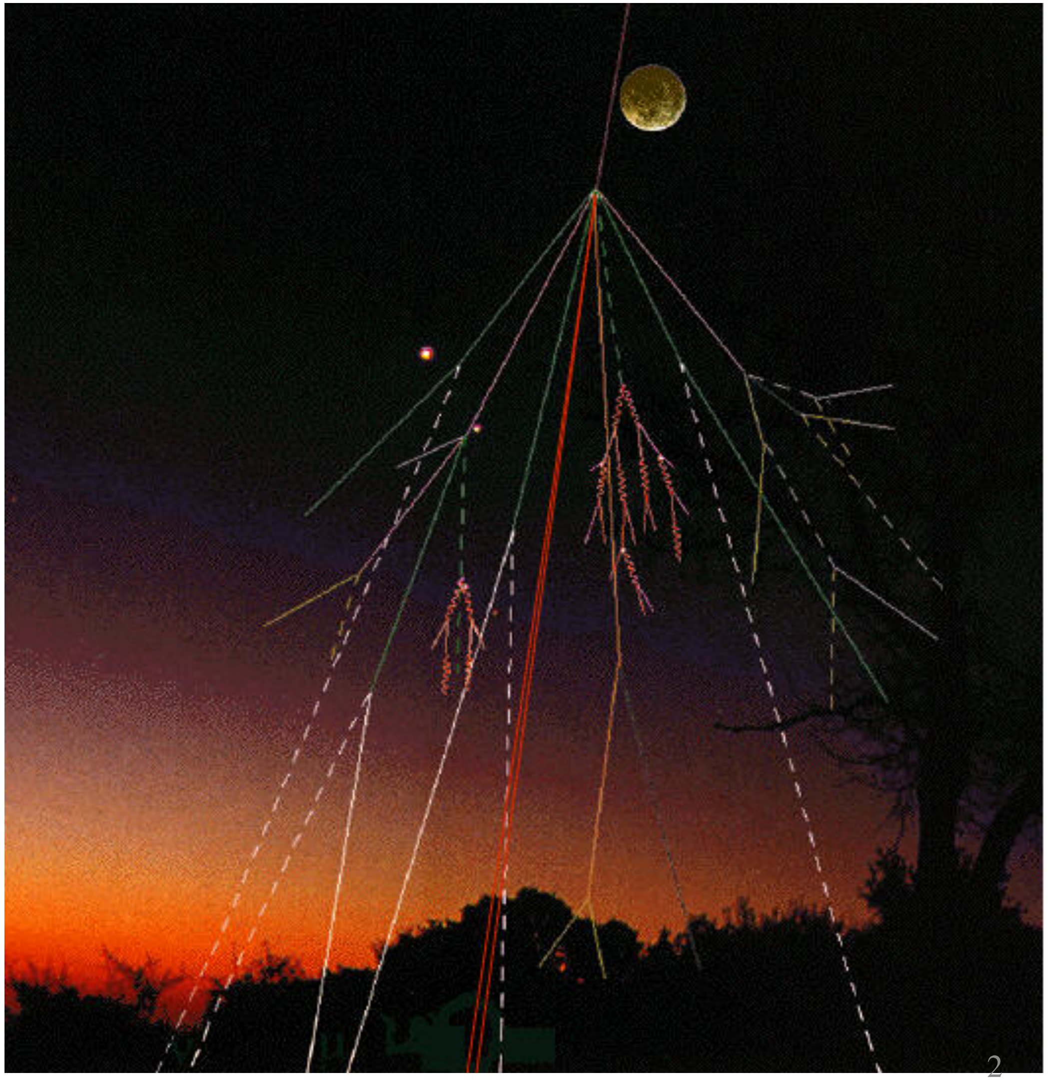
Xavier Calmet

Physics & Astronomy
University of Sussex

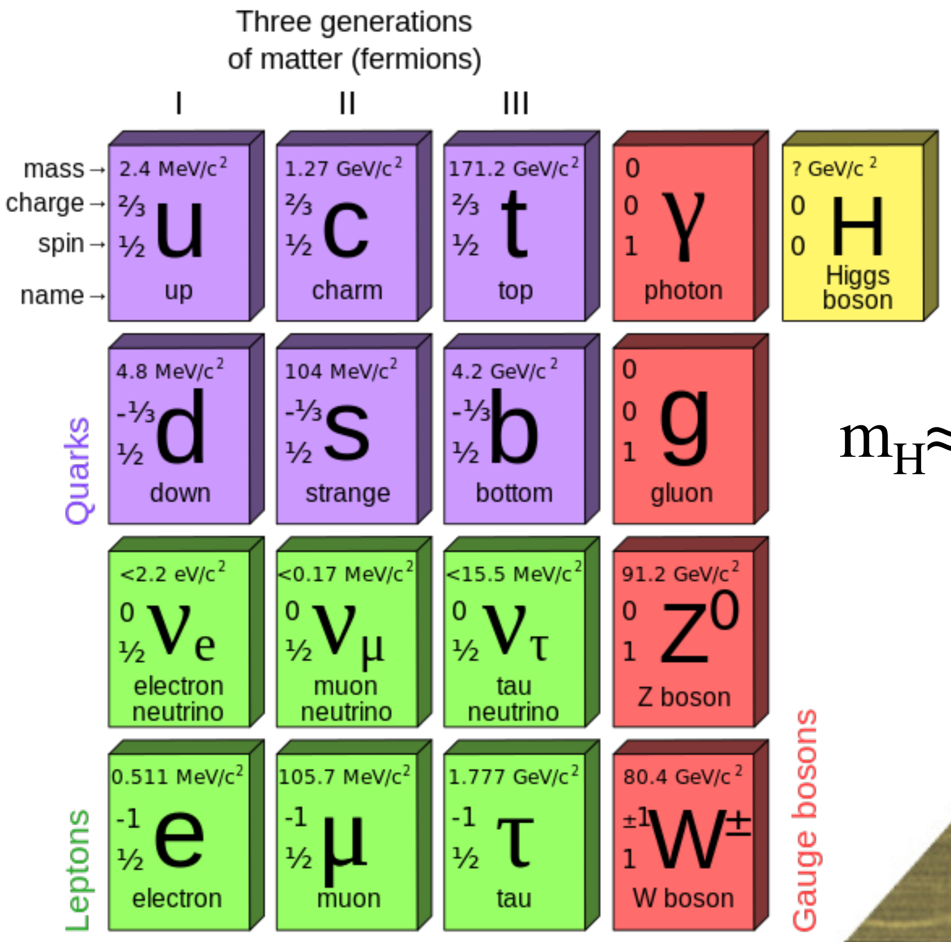
Progress in physics in the last 100 years has been amazing

We went from chaos and a plethora of particles to the standard model of particle physics.

In this talk, I would like to show you how black holes might lead us to the next scientific revolution.



Standard Model

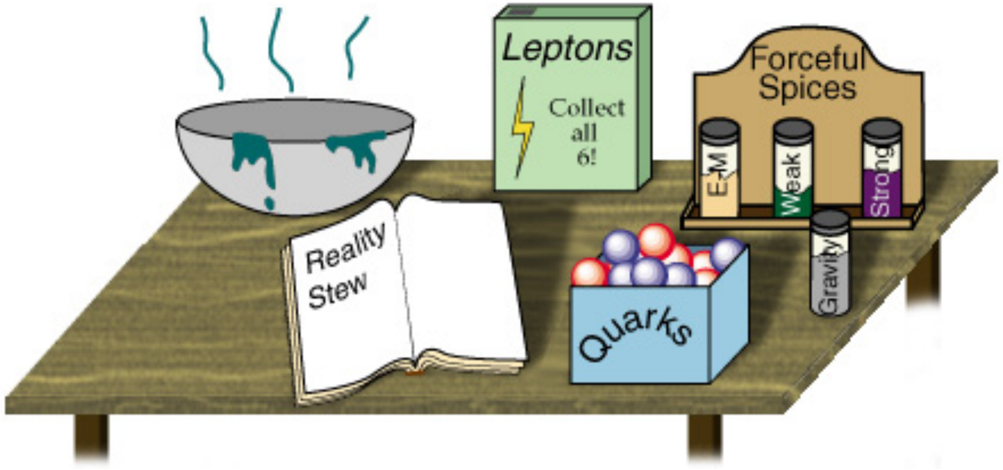


Three generations of matter (fermions)

	I	II	III		
mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	? GeV/c^2 0 0 H Higgs boson
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson	
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson	

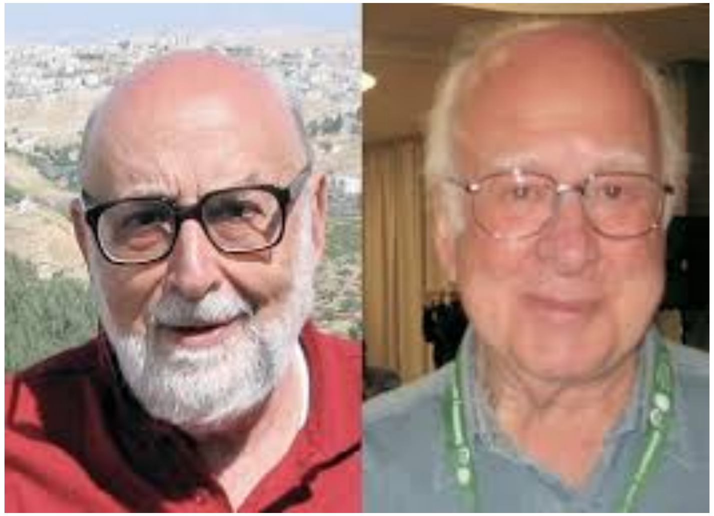
Gauge bosons

$m_H \approx 125$ GeV



40 years between prediction and discovery

Nobel prize 2013 for François Englert and Peter Higgs



Many people have contributed

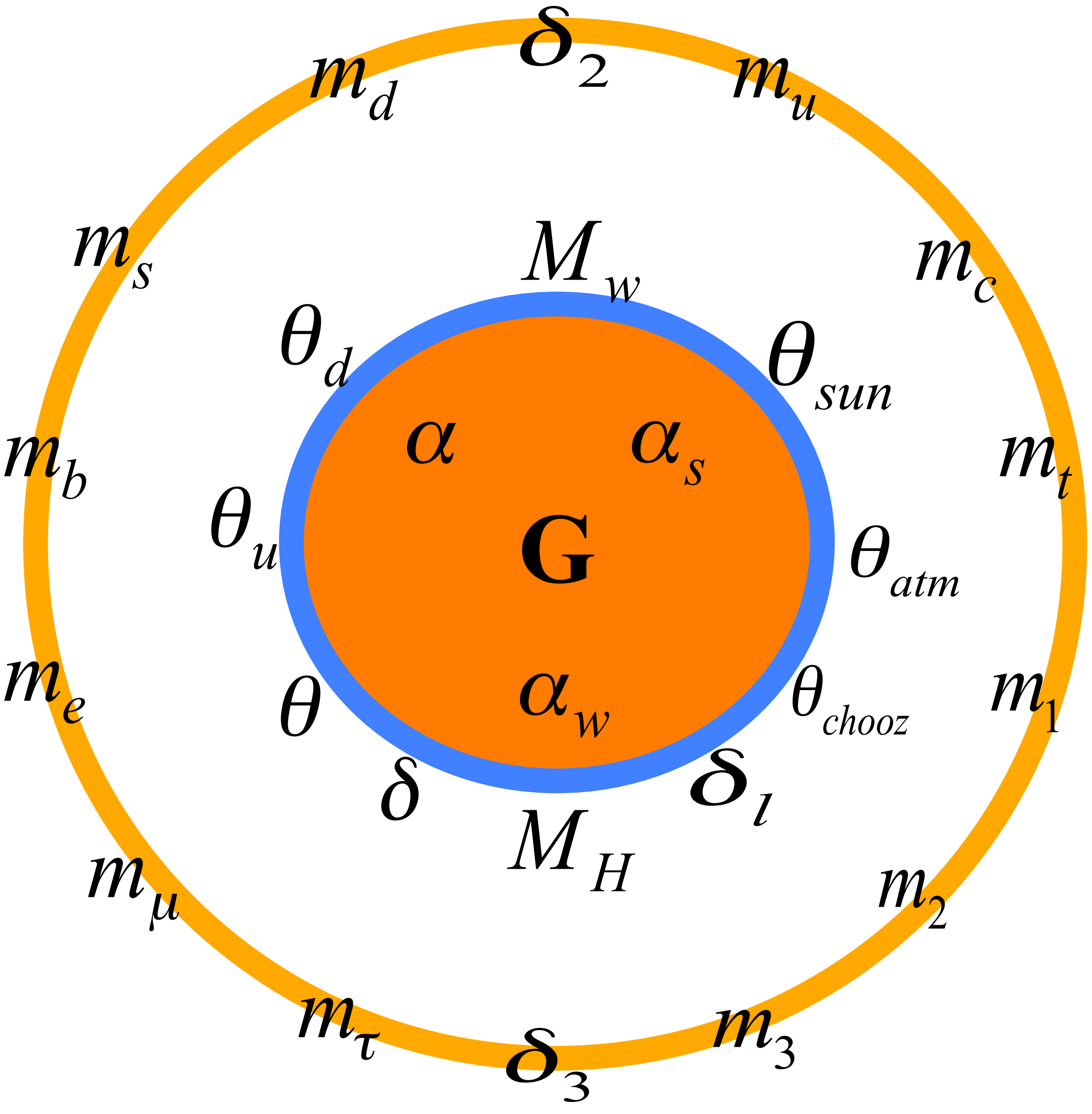
Kibble, Guralnik, Hagen, Englert, and Brout

Anderson

So the standard model works (maybe too well), what do we next?

There are different forces but also many fundamental constants!

28



δ_2

m_d m_u

m_s M_w m_c

θ_d θ_{sun}

α α_s

m_b m_t

θ_u $\mathbf{G}$ θ_{atm}

m_e θ α_w θ_{chooz} m_1

δ δ_l

M_H

m_μ m_2

m_τ δ_3 m_3

The exact
number
depends
on what
one includes.
Here:
only SM+gravity

Note: 22 parameters for the fermion masses only!

$$L = T - V$$

The reason for the large number of coupling constants is that physics is based on classical concepts:

Kinetic term: T

potential/interaction term: V

In a sense, the coupling constants are proportionality constants between these two terms.

They cannot be calculated.

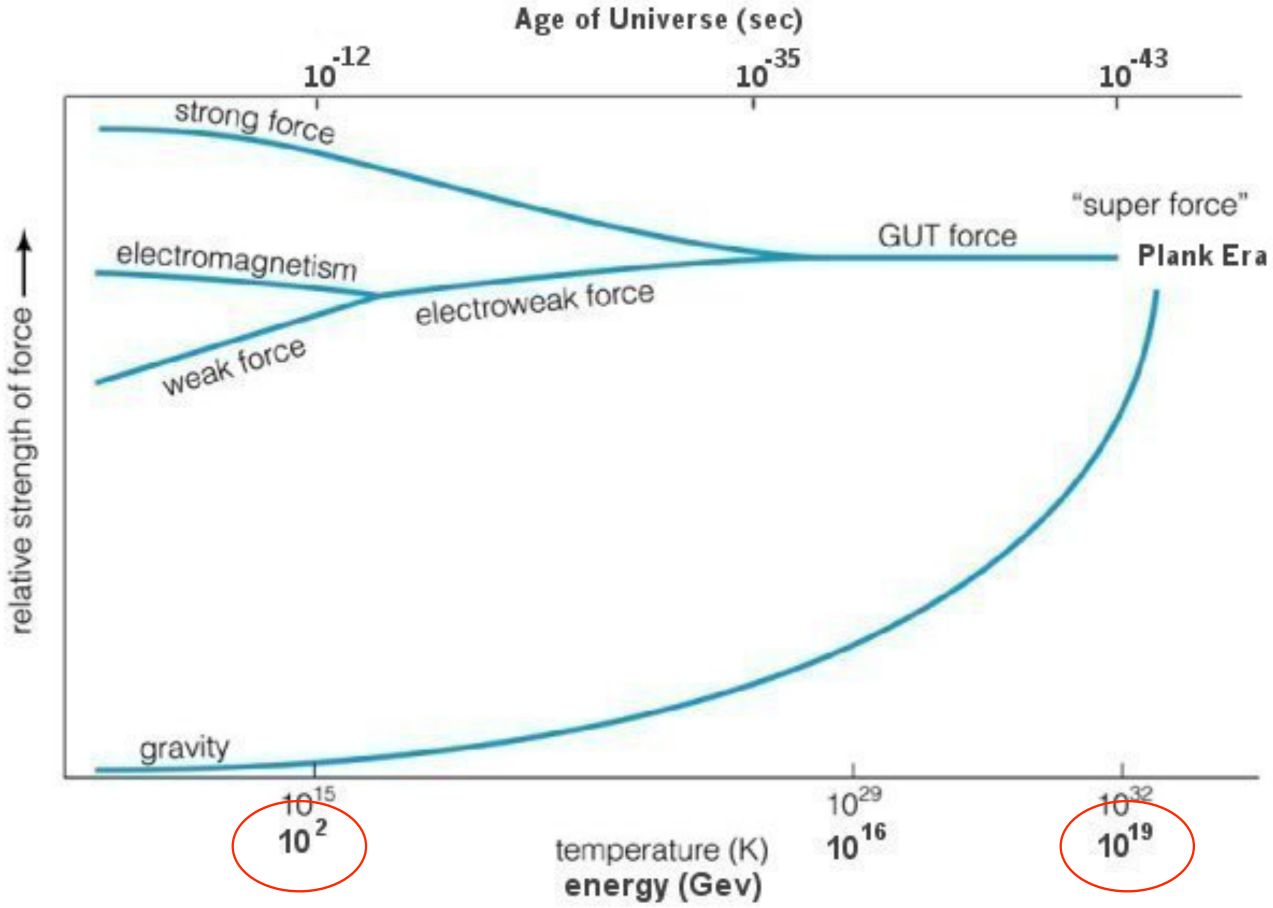
We will focus on Newton's constant G_N

or equivalently on the Planck scale:

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

We will see that it fixes the scale at which quantum gravity effects become important. That's important for black holes.

A reduction of the number of parameters of the standard model requires more unification: Grand Unification Theories.



N.B.: This is the standard picture. I will show you that the Planck mass i.e. 10^{19} GeV could be much smaller!

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.

The situation in theoretical physics is similar to that of 100
years ago in particle physics with the difference
that we don't have data (modulo dark matter and dark energy).

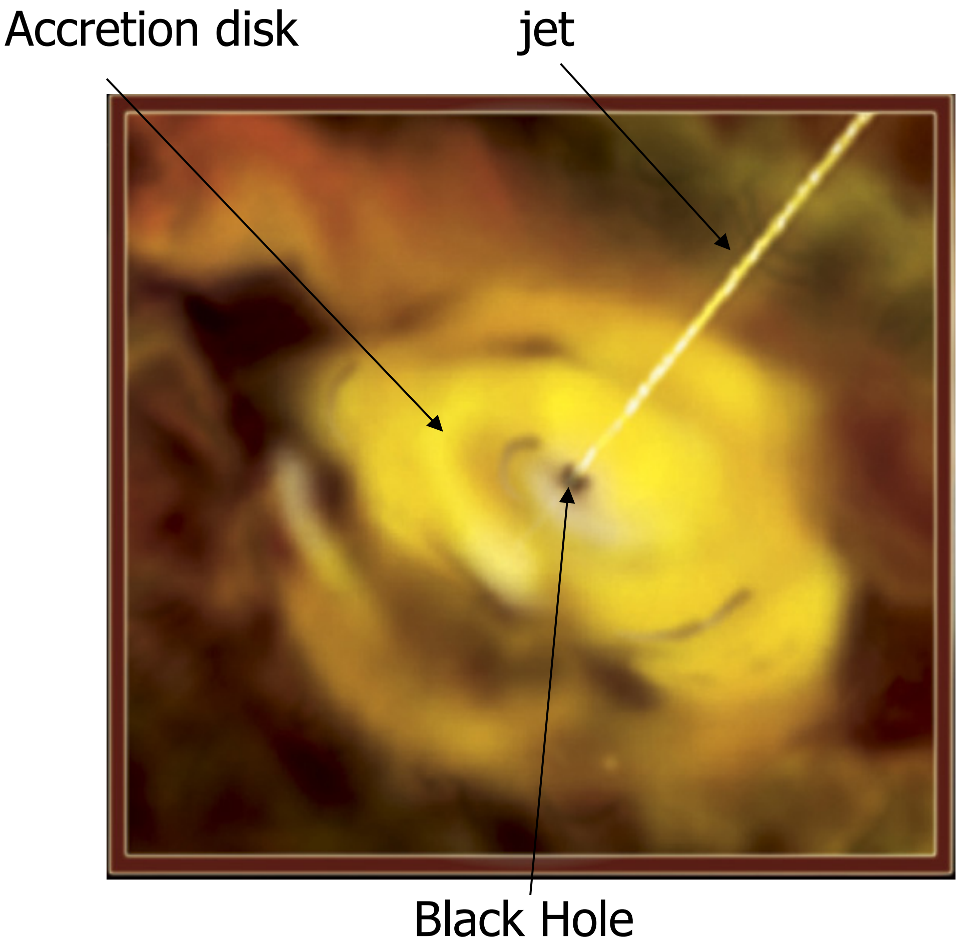
However we have thought experiments to guide us.

Also we have many free parameters which need to be understood?

We need new guiding principles.

What can we learn from black holes?

One of the manifestation of strong gravity is the formation of black holes

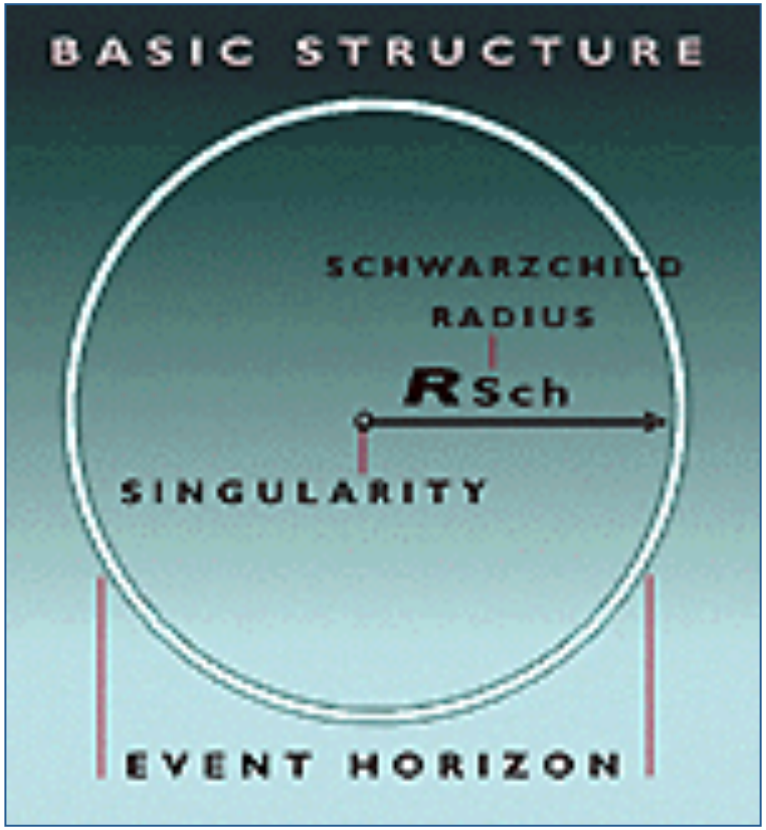


What is a black hole?

- From a mathematical point of view it is a vacuum solution to the equations of Einstein’s general relativity.
- It is a very simple object uniquely defined by its mass, its charge and its angular momentum: it has no hair!
- What falls into a black hole remains into a black hole.
- However, quantum mechanically it is not black, but it will radiate: Hawking radiation, it has a temperature.
- It is an ideal system to study the unification of quantum mechanics (standard model) and gravity!

Black Hole Structure

- Schwarzschild radius defines the event horizon
- $R_{sch} = 2GM/c^2$
- Not even light can escape, once it has crossed the event horizon
- Cosmic censorship prevails (you cannot see inside the event horizon)

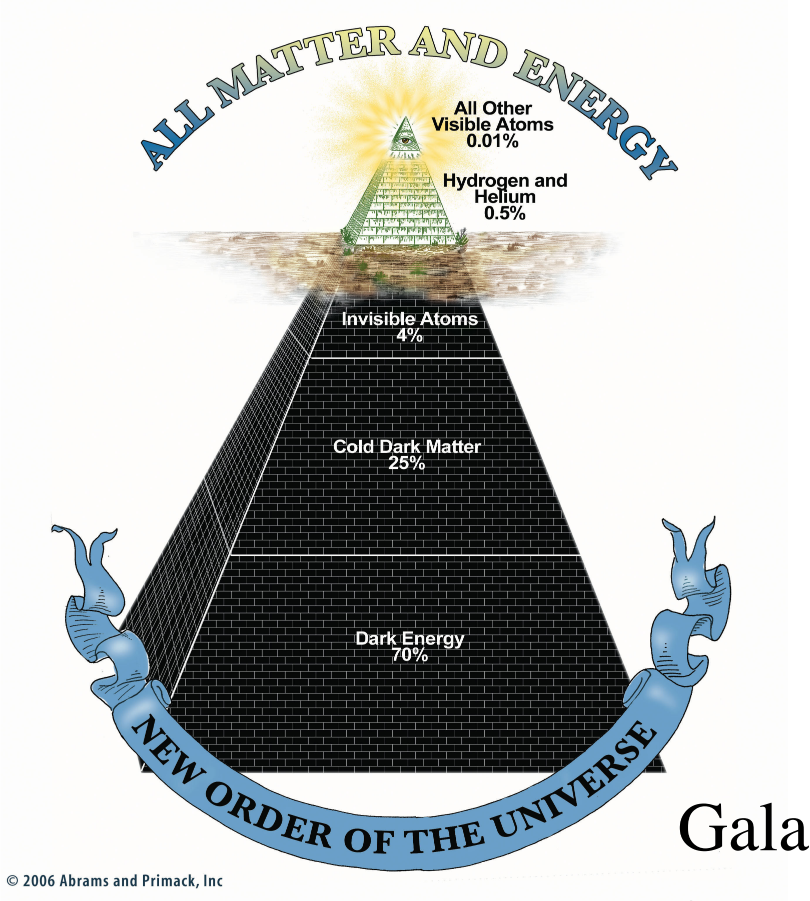


Schwarzschild BH

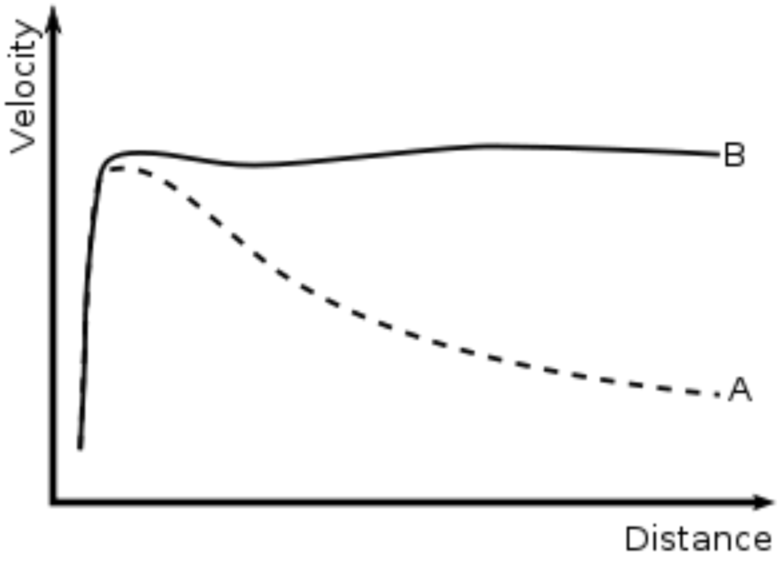
Masses of Black Holes

- Primordial – can be any size, including very small (If >10^{14} g, they would still exist today)
- "Stellar-mass" black holes – must be at least 3 M_o (~10^{34} g) – many examples are known
- Intermediate black holes – range from 100 to 1000 M_o - located in normal galaxies – many seen
- Massive black holes – about 10^6 M_o – such as in the center of the Milky Way – many seen
- Supermassive black holes – about 10^{9-10} M_o - located in Active Galactic Nuclei, often accompanied by jets – many seen

We know that the standard model is not complete: black holes could complete it!



Dark matter is not explained by the Standard Model



Galaxy rotation curves are an indication that some matter is dark

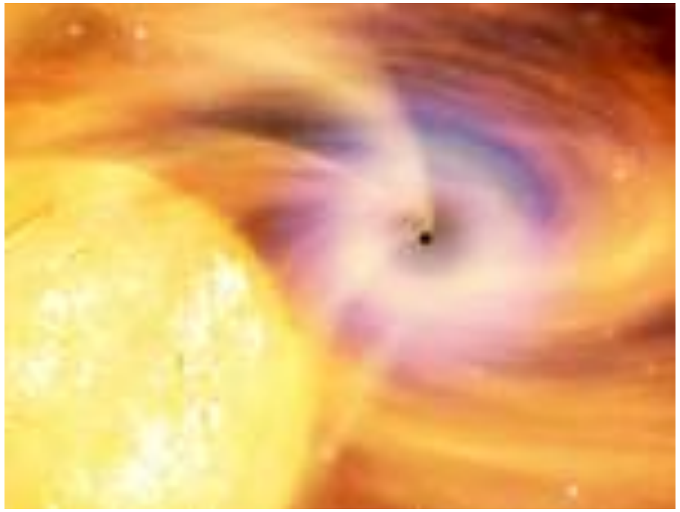
Primordial black holes could be dark matter!

Black hole temperature

One can define a temperature for black holes

$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

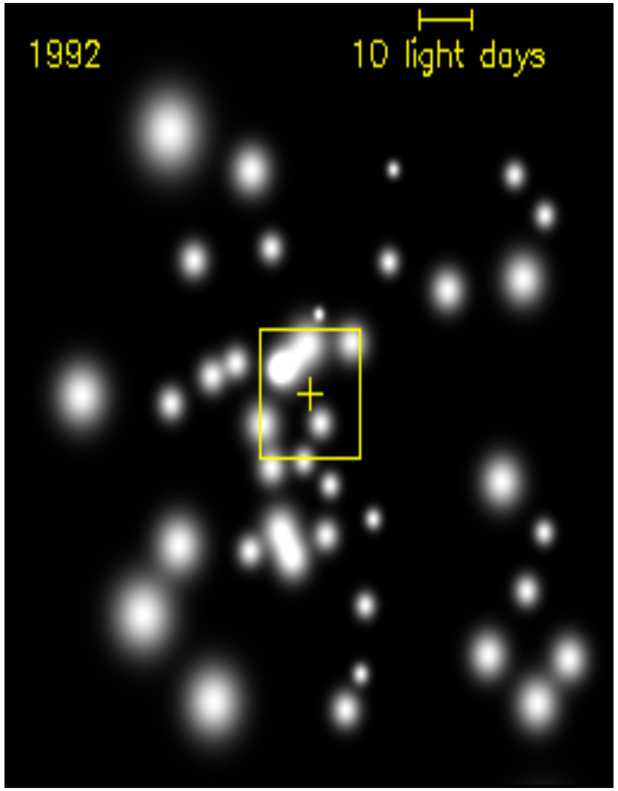
Hawking radiation



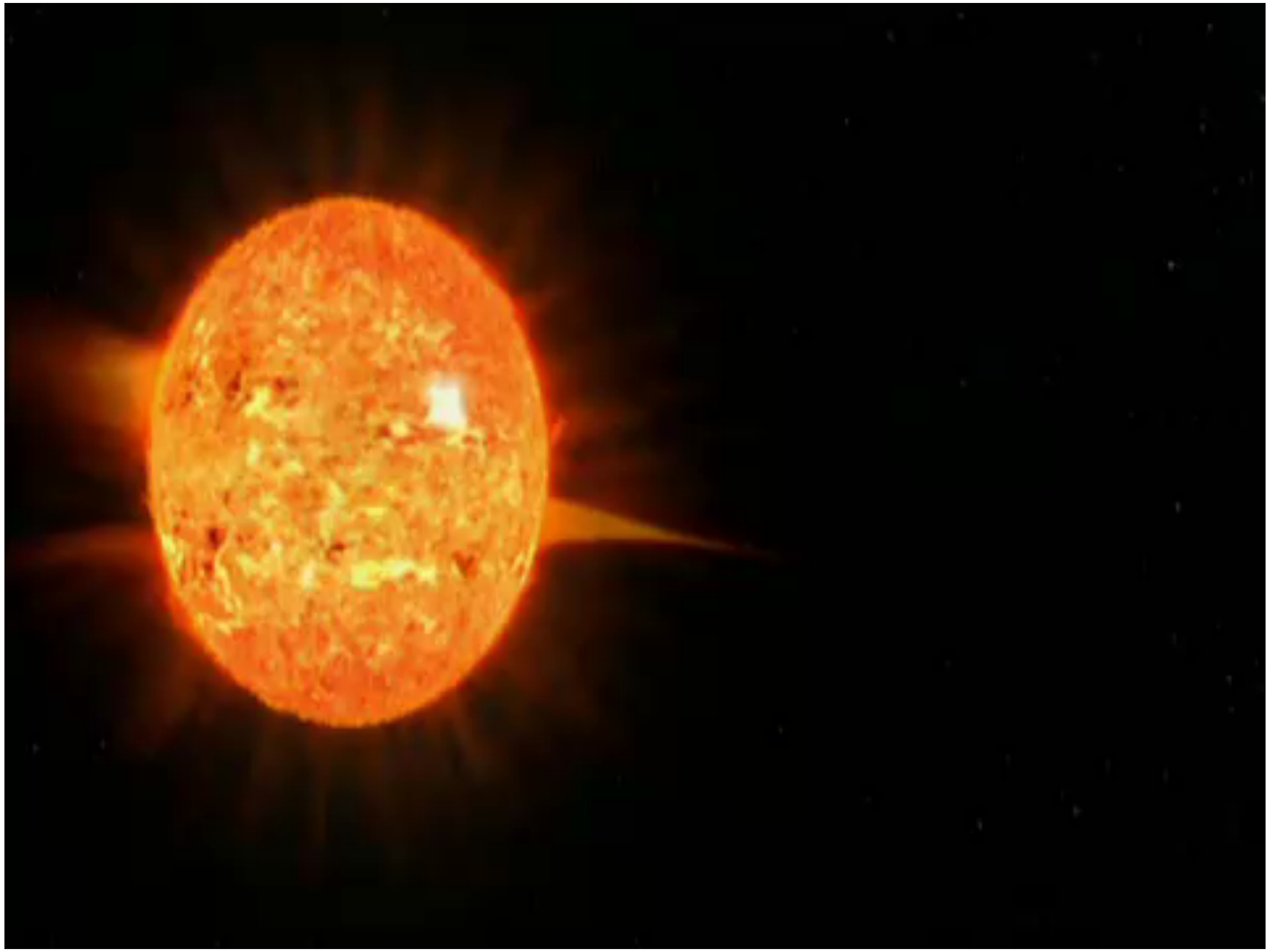
The heavier a black holes the cooler it is!

Evidence for astrophysical holes

Zooming in to see the stars in the central parsec of the Milky Way galaxy, orbiting around – the BH!



How do you see black holes?



Can we probe strong gravity (high space-time curvature) with astrophysical black holes?

- No! The larger the mass of the black hole, the smaller the curvature at the horizon.
- For astrophysical black holes, space-time is rather flat at the horizon.
- Curvature is only high at the singularity which is inside the horizon: you cannot see it!
- We need to look for light black holes.
- How light can a black hole be?

What happens when you fall into a black holes?

- Traditionally we thought nothing too dramatic (till you get closer to the singularity). You will get stretched a bit…

Ren
and
Stimpy

What happens when you fall into a black holes?

- Traditionally we thought nothing too dramatic (till you get closer to the singularity). You will get stretched a bit…

- Recent idea: there might be a firewall?

Firewall

- A single emission of Hawking radiation involves two mutually entangled particles.

- The outgoing particle escapes and is emitted as a quantum of Hawking radiation; the infalling particle is swallowed by the black hole.

- Susskind has shown that the outgoing particle must be entangled with all the Hawking radiation the black hole has previously emitted.

- This creates a paradox: a principle called "monogamy of entanglement" requires that, like any quantum system, the outgoing particle cannot be fully entangled with two independent systems at the same time; yet here the outgoing particle appears to be entangled with both the infalling particle and, independently, with past Hawking radiation.

Firewall

- In order to resolve the paradox, one may be forced to give up one of three time-tested principles of physics: Einstein's equivalence principle, unitarity, or existing quantum field theory

- Firewall resolution of the paradox:

  - Entanglement must somehow get immediately broken between the infalling particle and the outgoing particle.

  - Breaking this entanglement would release inconceivable amounts of energy, thus creating a searing "black hole firewall" at the black hole event horizon.

- What happens when you pass the horizon is an open question!

How can we probe the Planck scale using black holes?

First of all: What is so special about the Planck scale?

$$M_P = \sqrt{\frac{\hbar c}{G}} = 1.2209 \times 10^{19} \mathrm{GeV}/c^2 = 2.176 \times 10^{-8} \mathrm{kg}$$

$$l_P = \sqrt{\frac{\hbar G}{c^3}} = 1.616252 \times 10^{-35} \mathrm{m}$$

$$t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.39121 \times 10^{-44} \mathrm{s}$$

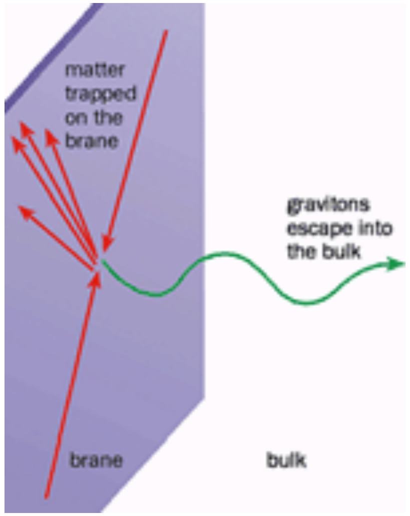
- We usually assume that it is the scale at which gravity becomes strong.
- Could the scale for quantum gravity be much lower than expected from naïve dimensional analysis?
- In more than four dimensions, it is well-known that it is the case!
- Is it also possible in four-dimensions.

TeV gravity extra-dimensions

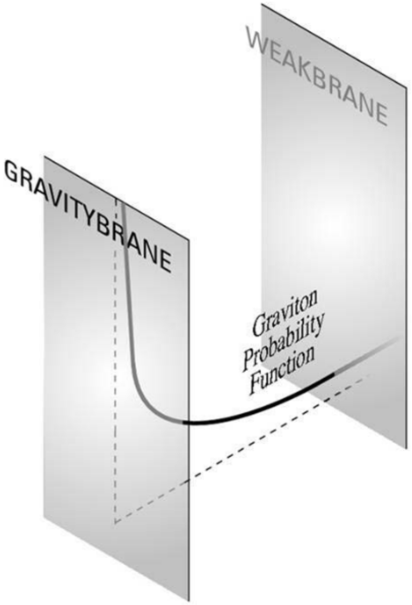
$$S = \int d^4x d^n x' \sqrt{-g}(M_\star^{n+2}\mathcal{R} + ...) \qquad M_P^2 = M_\star^{n+2} V_n$$

where M_P is the effective Planck scale in 4-dim

Arkani-Hamed,
Dimopoulos,
Dvali (ADD) brane world

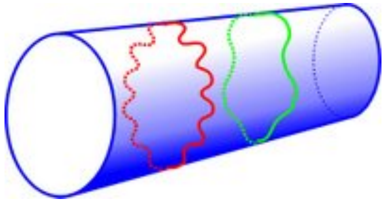


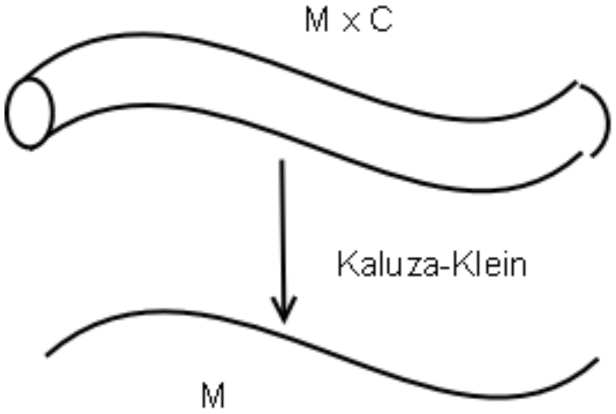
Randall Sundrum (RS) warped extra-dimension



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

Low scale quantum gravity in 4 dim using the “running” of Newton’s constant

-Uncertainty principle of Quantum Mechanics: particles can pop out of the vacuum for very brief periods of time and affect the value of the original coupling constant.

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

-Quantum field theory: particles + anti-particles come in pairs.

E.g. in quantum electrodynamics, the electric coupling constant runs (i.e. is renormalized) and depends on the energy scale at which it is measured:

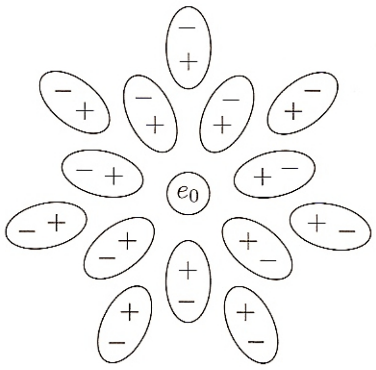


Figure 7.8. Virtual e^+e^- pairs are effectively dipoles of length $\sim 1/m$, which screen the bare charge of the electron.

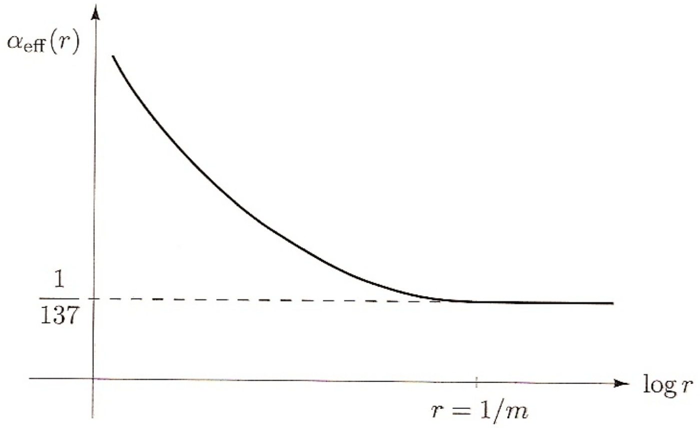
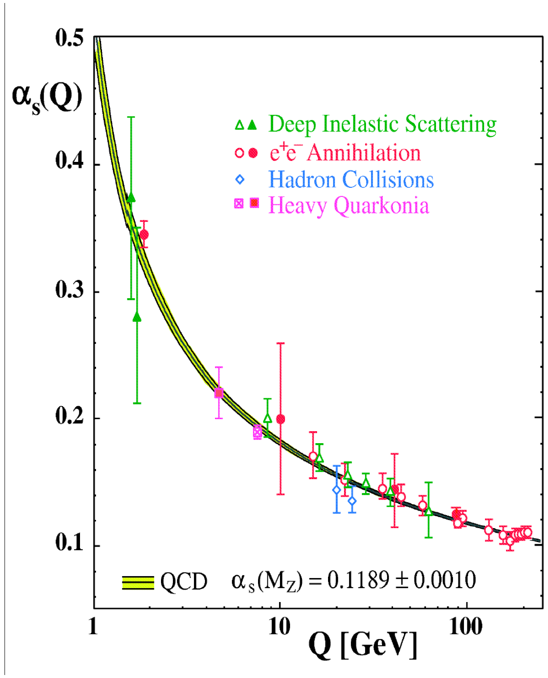


Figure 7.10. A qualitative sketch of the effective electromagnetic coupling constant generated by the one-loop vacuum polarization diagram, as a function of distance. The horizontal scale covers many orders of magnitude.

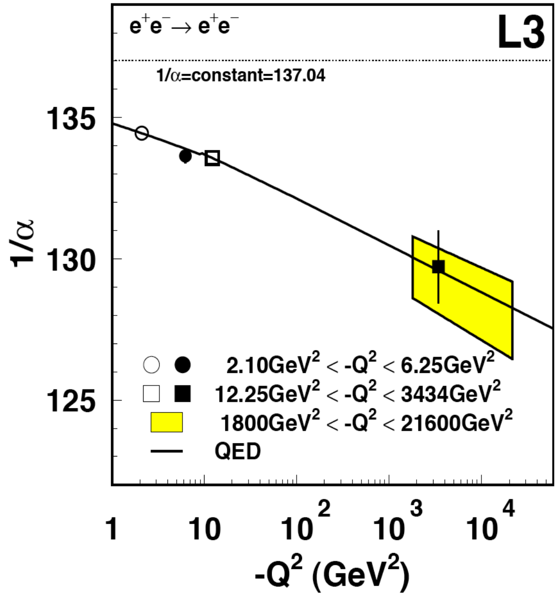
Like athletes, coupling constants can run….

fast



or

slow



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

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Theoretical physics can lead to anything…
even business ideas!

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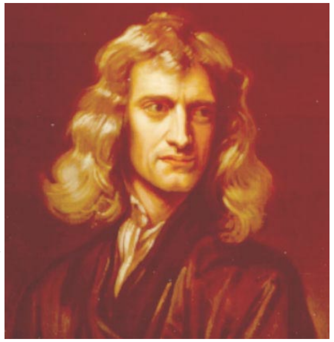
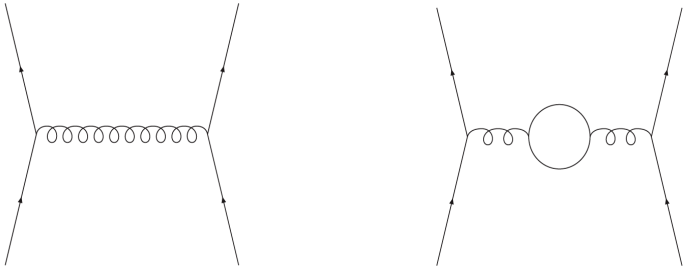
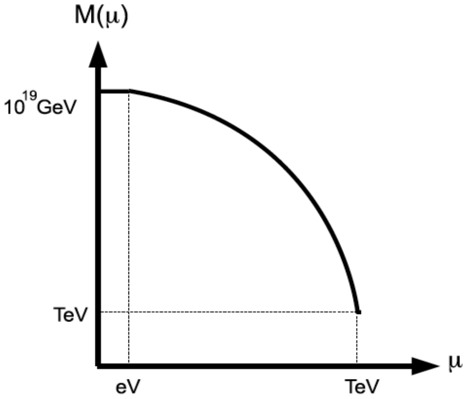
Low scale quantum gravity in 4 dim: Running of Newton's constant



- Consider usual gravity: graviton exchange between two slowly moving particles:



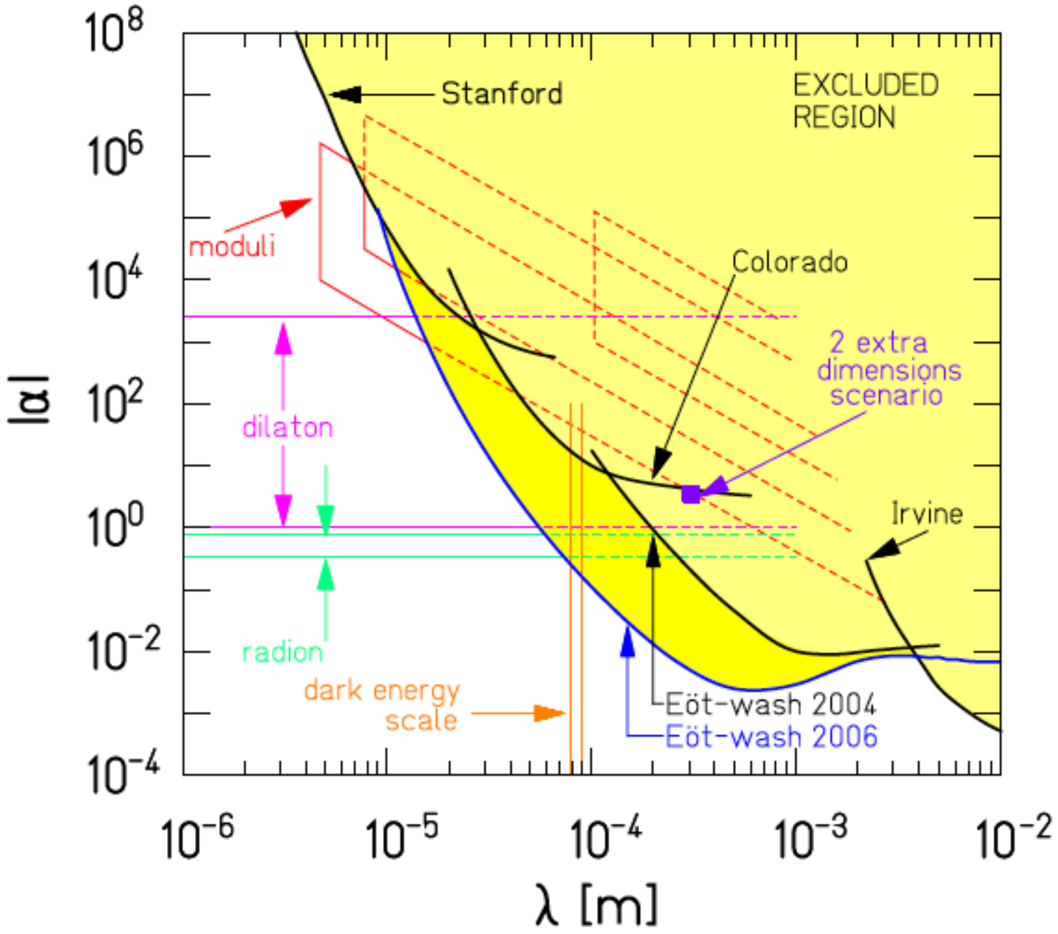
- The Planck scale runs with energy



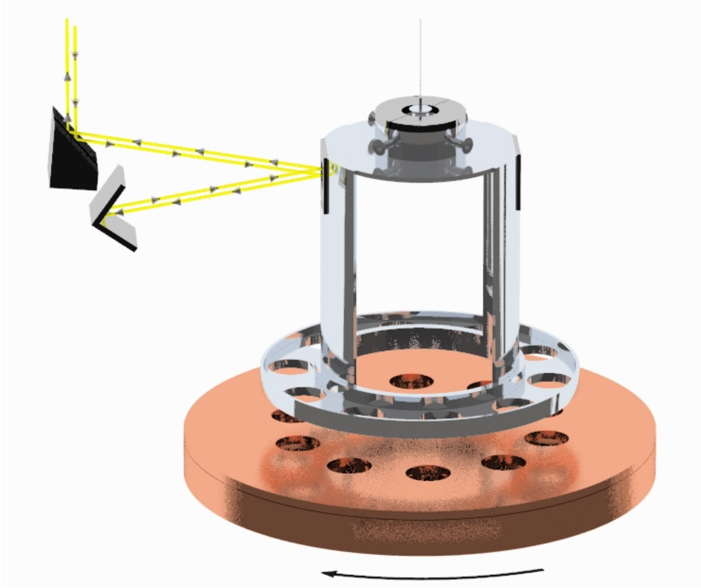
- The scale at which gravity becomes strong depends on the number of particles in the model!

xc, S. Hsu, D. Reeb, Phys.Rev. D77 (2008) 125015

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

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

Low scale quantum gravity

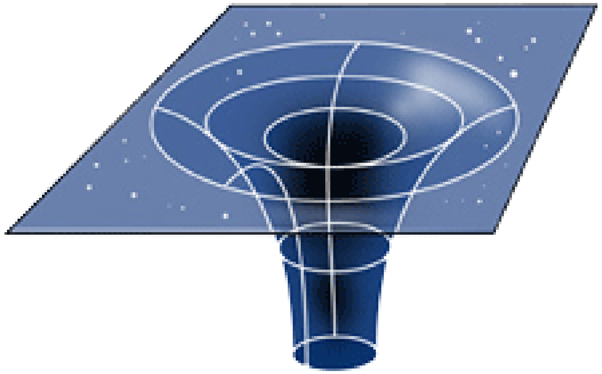
- Provide solutions to hierarchy problem (if geometry explained by e.g. string theory).
- Rich phenomenology at LHC.
- In particular black holes might be created at LHC.

When does a black hole form?

This is well understood in general relativity with symmetrical symmetry:

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

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



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

Small black hole formation

- In 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.

Small black hole formation

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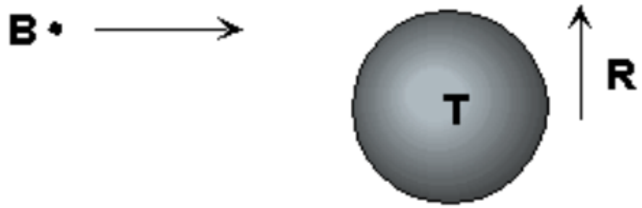
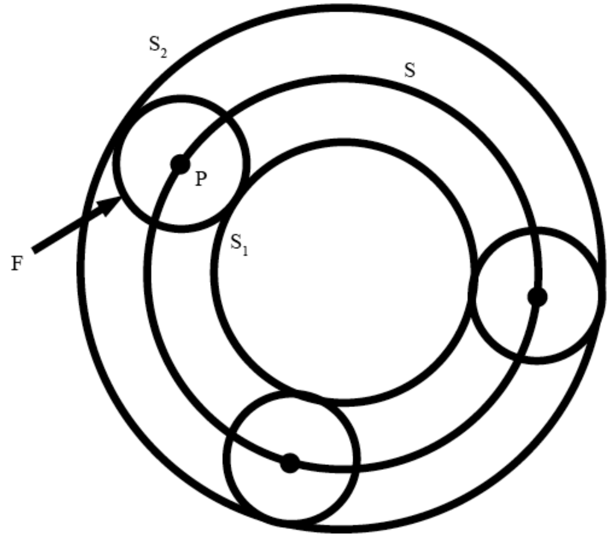
- Cross section:

$$\hat{\sigma} \approx \pi r_s^2 \qquad r_s = \frac{2GM}{c^2}$$



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.

- In 2002, Eardley and Giddings have proven that a closed trapped surface (CTS) forms in the collision of two particles with a non-zero impact parameter.
- A CTS is a compact spacelike two-surface in space-time such that outgoing null rays perpendicular to the surface are not expanding.

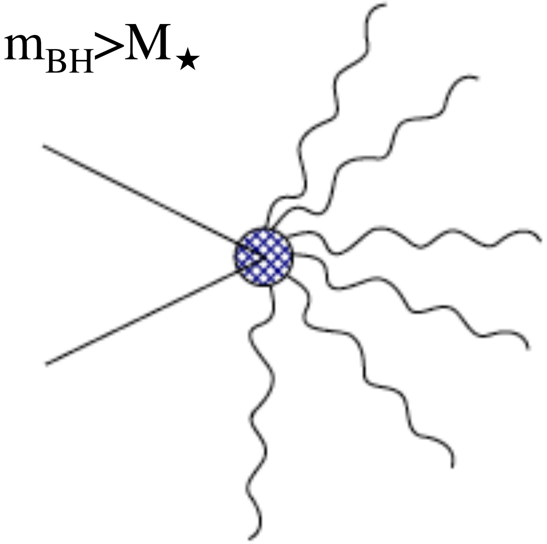


- At some instant, the sphere S emits a flash of light. At a later time, the light from a point P forms a sphere F around P, and the envelopes S_1 and S_2 form the ingoing and outgoing wavefronts respectively. If the areas of both S_1 and S_2 are less than of S, then S is a closed trapped surface.

- This is enough to prove gravitational collapse

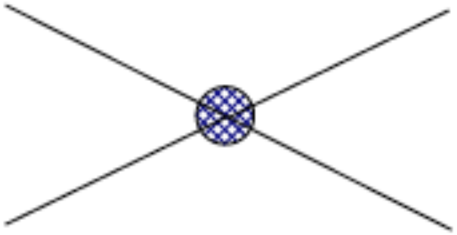
Semi-classical (thermal) versus quantum black hole: calculate the entropy!

$m_{BH} > M_\star$



thermal black hole
large entropy

$m_{BH} \sim M_\star$



quantum black hole
small entropy

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

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

Semi-classical BHs can’t be produced at LHC but quantum BHs could

Use symmetries to predict how QBHs are produced or decay!

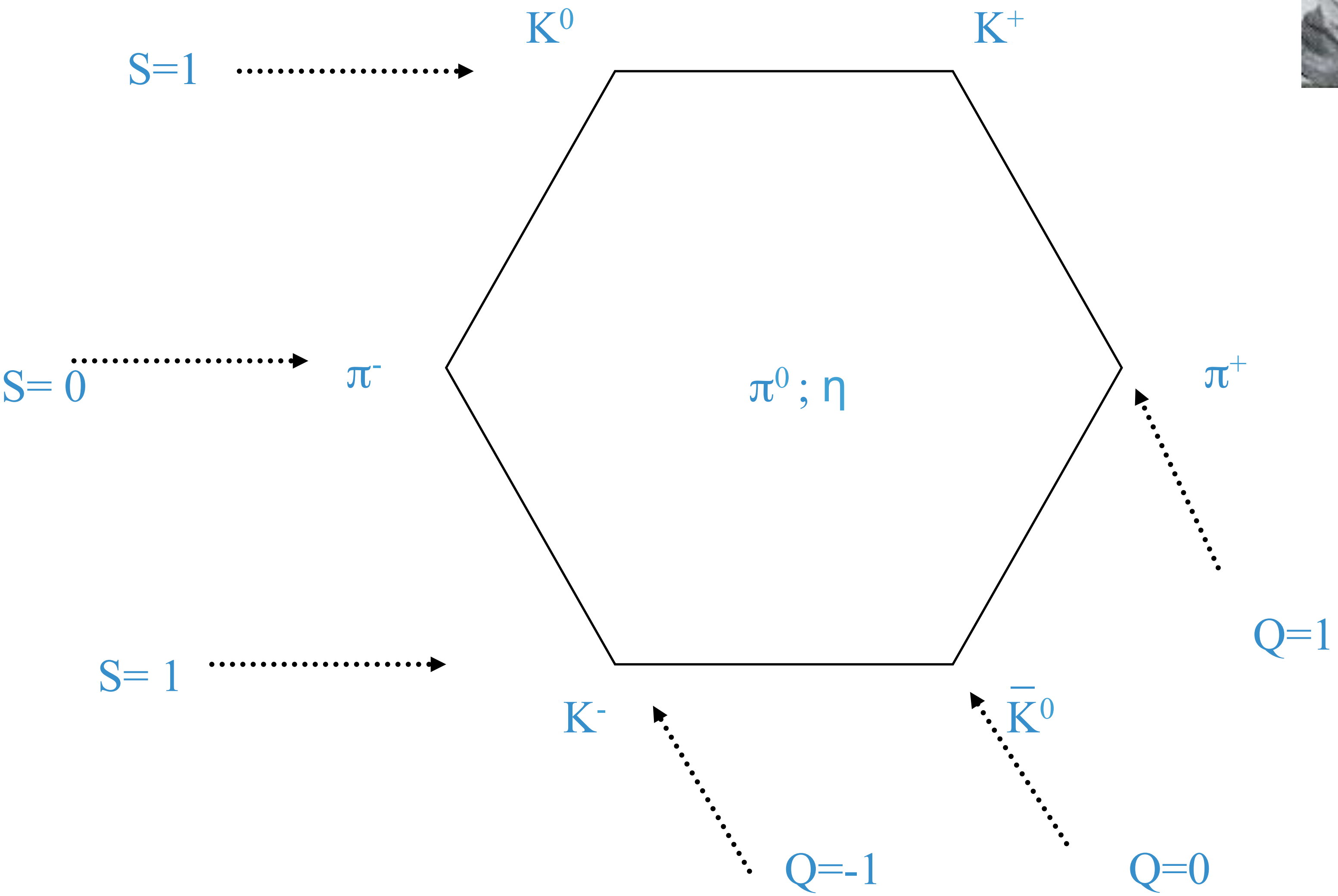
QCD for Quantum Black Holes

XC, W. Gong & S. Hsu

- Quantum Black Holes created at the LHC would carry the quantum numbers of the particles (quarks and gluons) which created them.
- They can have non-integer electric charges.
- They can carry color charges.
- If you know the quantum numbers: you can predict precisely how they would be created and how they would decay.

THE EIGHTFOLD WAY (1961)

The Meson Octet



K^0 K^+

S=1

S= 0 π^- π^0 ; η π^+

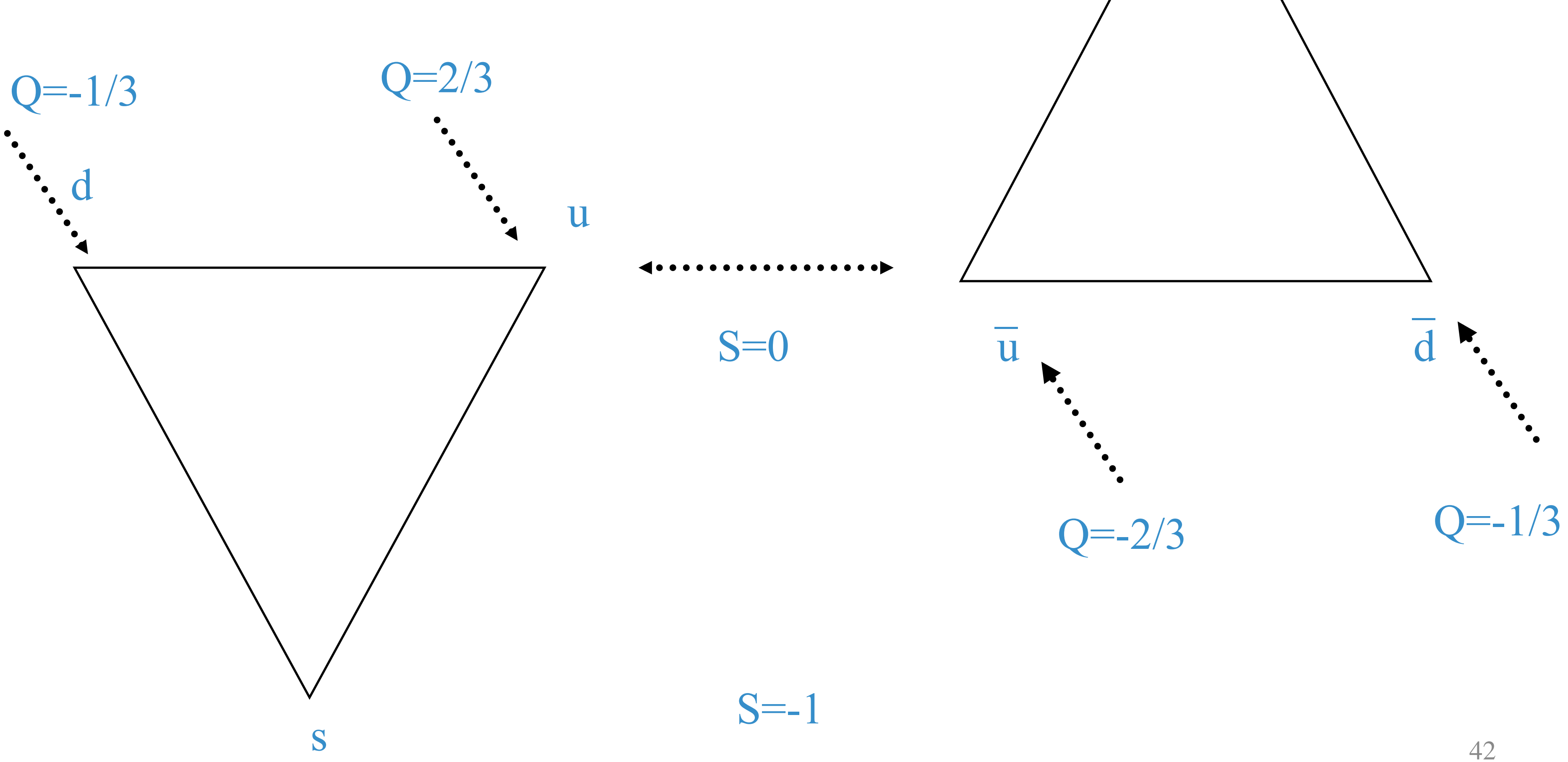
S= 1

K^- $\bar{K}^0$

Q=1

Q=-1 Q=0

The Quark Model (1964)



S=1

$\bar{s}$

Q=-1/3

Q=2/3

d

u

S=0

$\bar{u}$

$\bar{d}$

Q=-2/3

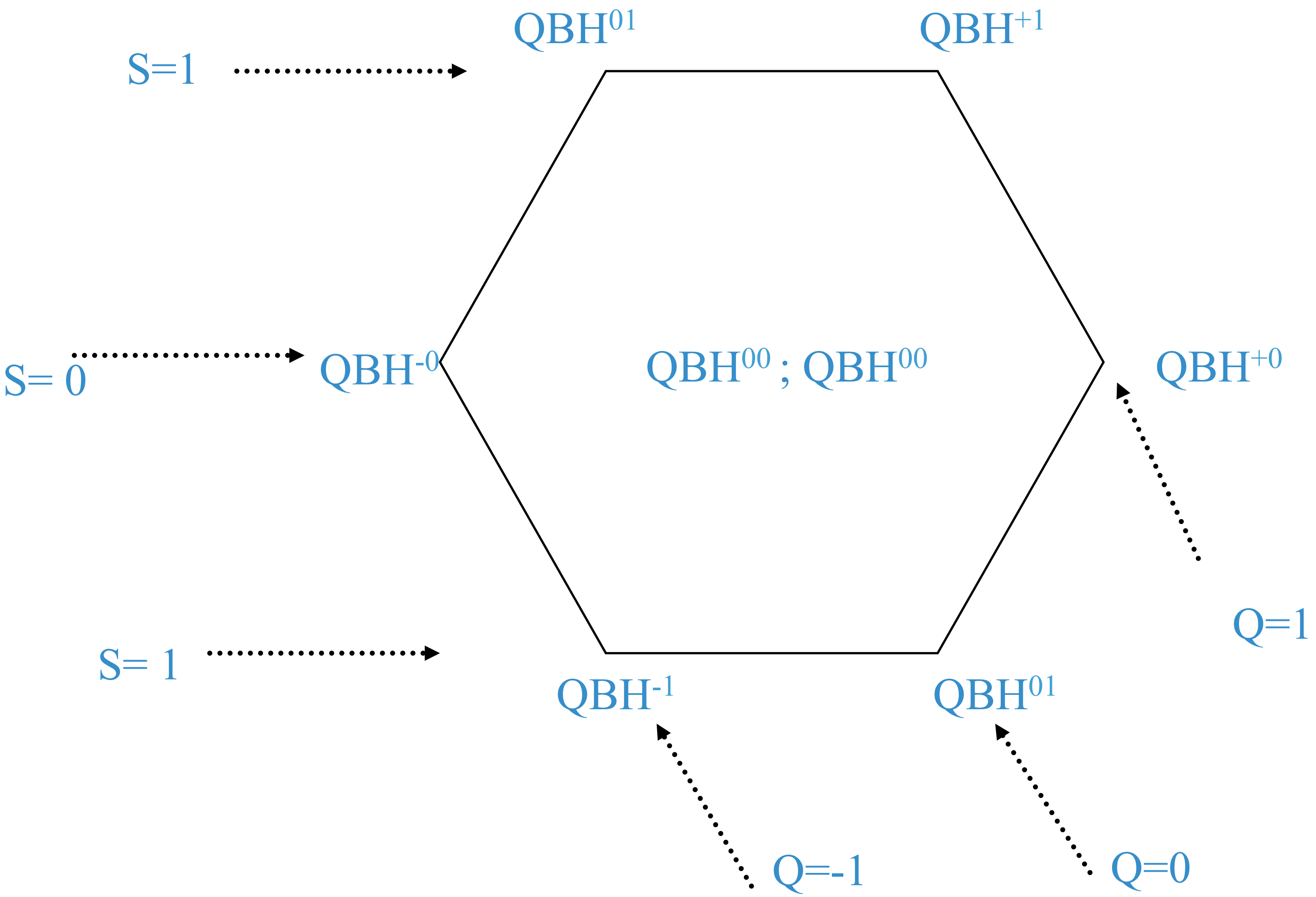
Q=-1/3

s

S=-1

THE EIGHTFOLD WAY FOR QUANTUM BLACK HOLES

The Quantum Black Hole Octet



QBH^{01} QBH^{+1}

S=1

S= 0 QBH^{-0} QBH^{00} ; QBH^{00} QBH^{+0}

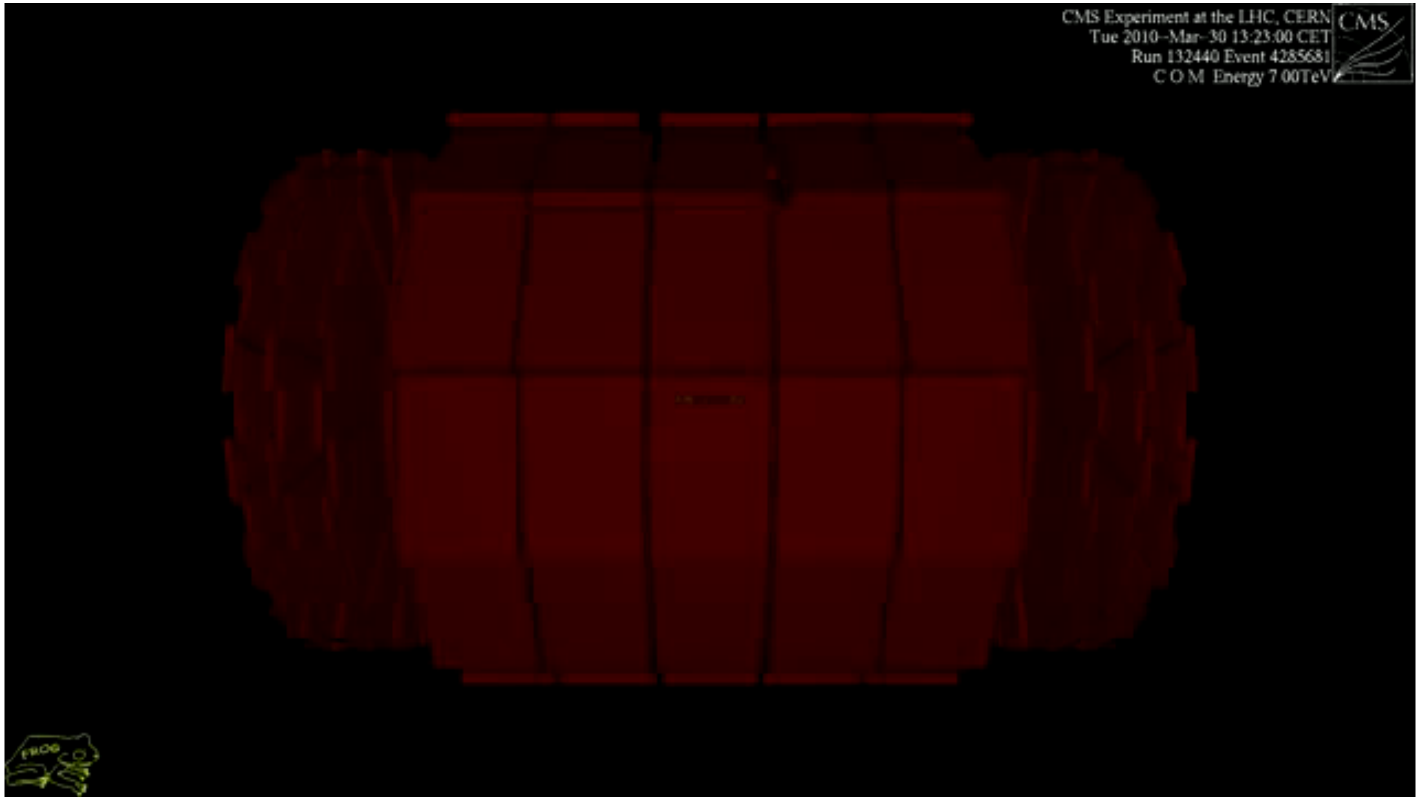
Q=1

S= 1

QBH^{-1} QBH^{01}

Q=-1 Q=0

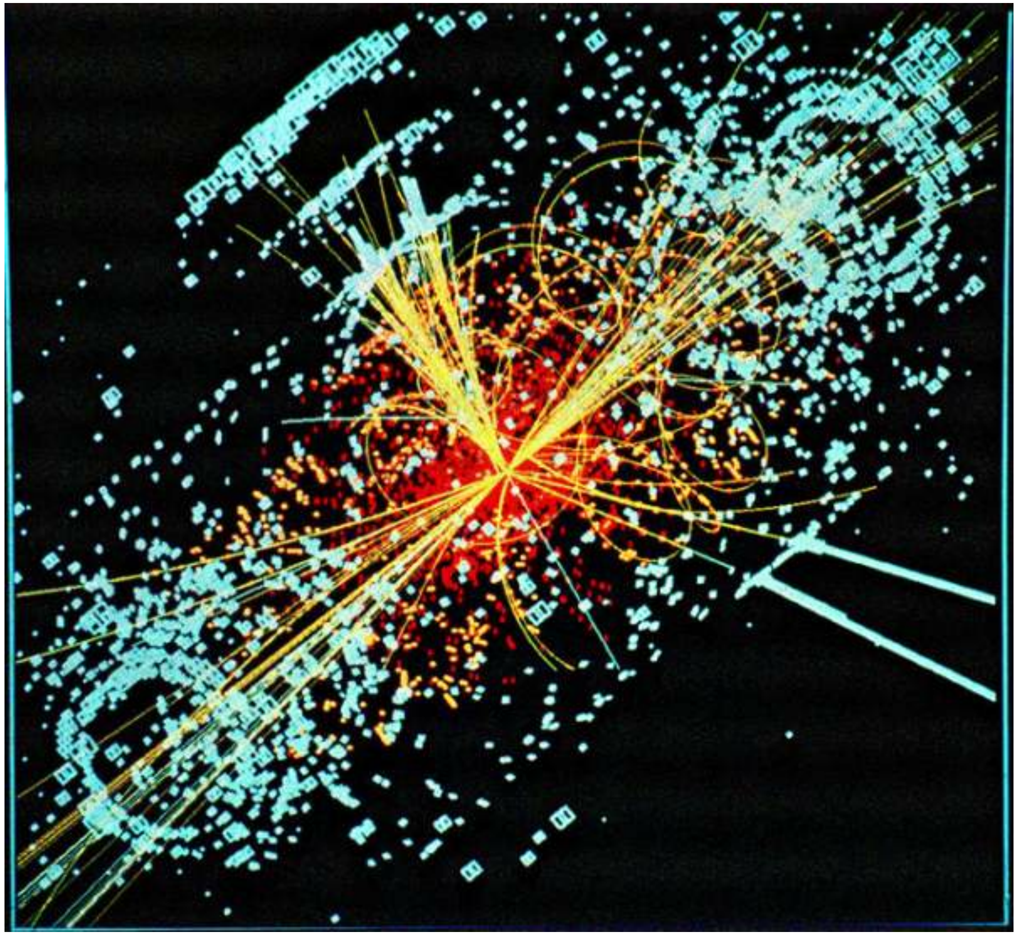
If a BH is produced at the LHC it’s important to understand how it will decay in order to find the needle in the haystack.



Typical reaction at the LHC: many particles are produced!

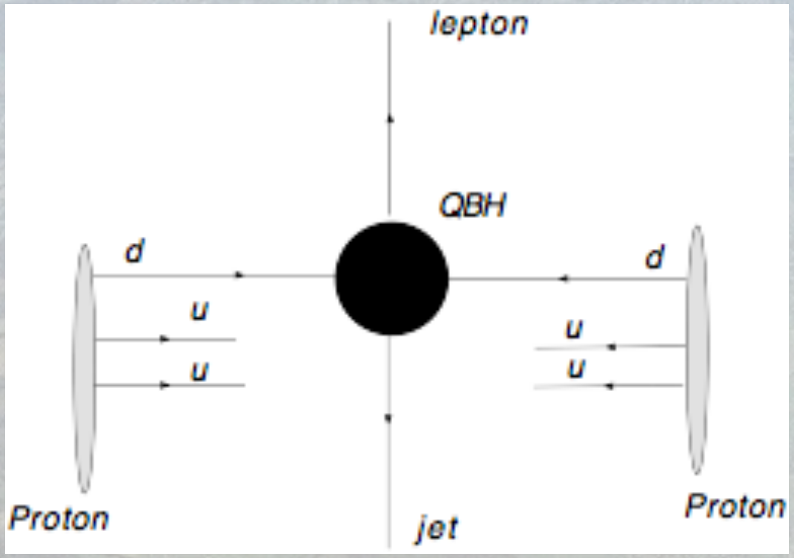
If a BH is produced at the LHC it's important to understand how it will decay in order to find the needle in the haystack.

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



It is important to model the decay of small BHs.

Small Black Holes at the LHC



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2013-193
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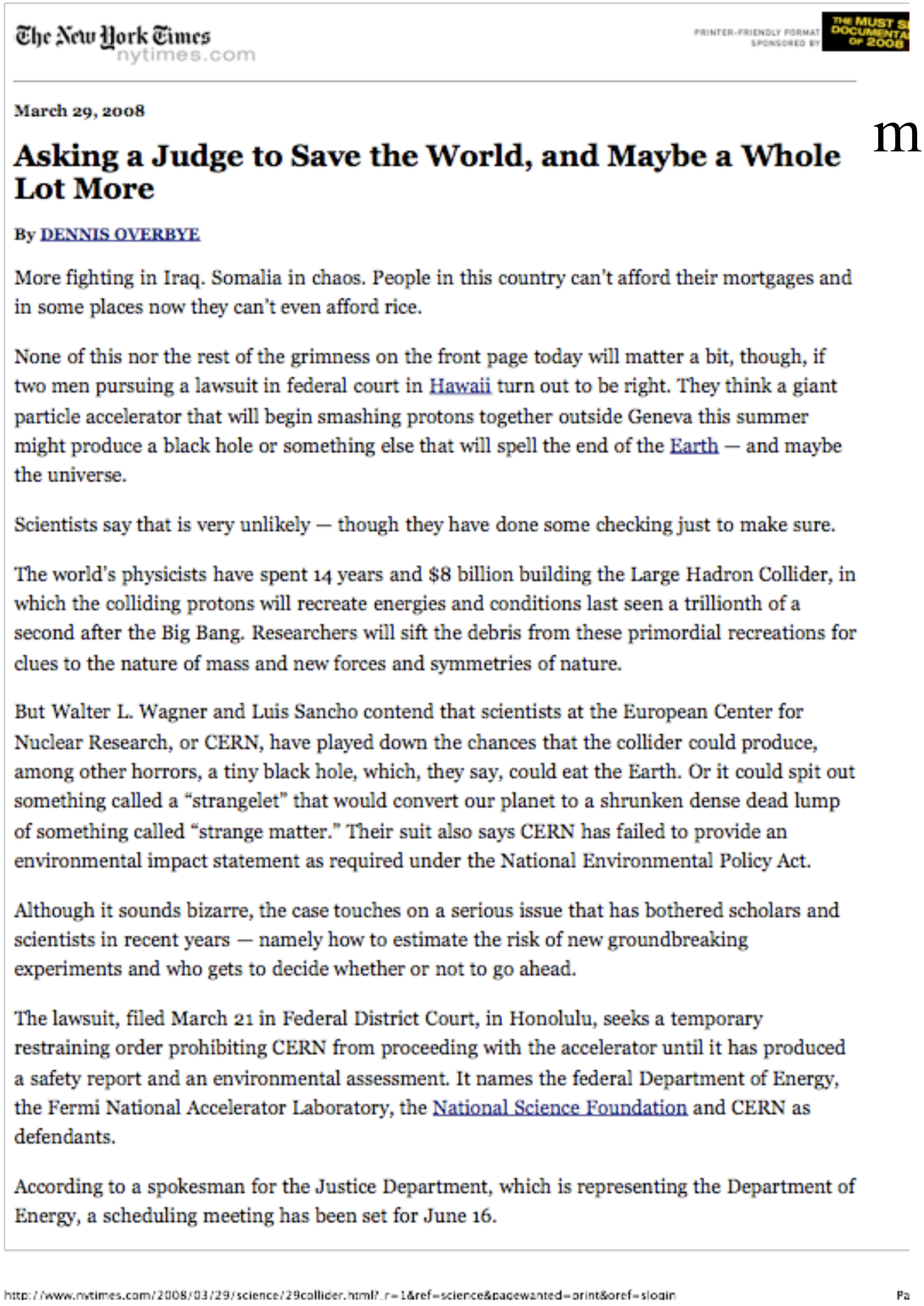
Search for Quantum Black-Hole Production in High-Invariant-Mass Lepton+Jet Final States Using Proton–Proton Collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ and the ATLAS Detector

The ATLAS Collaboration

Abstract

This Letter presents a search for quantum black-hole production using $20.3\,\mathrm{fb}^{-1}$ of data collected with the ATLAS detector in pp collisions at the LHC at $\sqrt{s} = 8\,\mathrm{TeV}$. The quantum black holes are assumed to decay into a lepton (electron or muon) and a jet. In either channel, no event with a lepton–jet invariant mass of $3.5\,\mathrm{TeV}$ or more is observed, consistent with the expected background. Limits are set on the product of cross sections and branching fractions for the lepton+jet final states of quantum black holes produced in a search region for invariant masses above $1\,\mathrm{TeV}$. The combined 95% confidence level upper limit on this product for quantum black holes with threshold mass above $3.5\,\mathrm{TeV}$ is $0.18\,\mathrm{fb}$. This limit constrains the threshold quantum black-hole mass to be above $5.3\,\mathrm{TeV}$ in the model considered.

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.

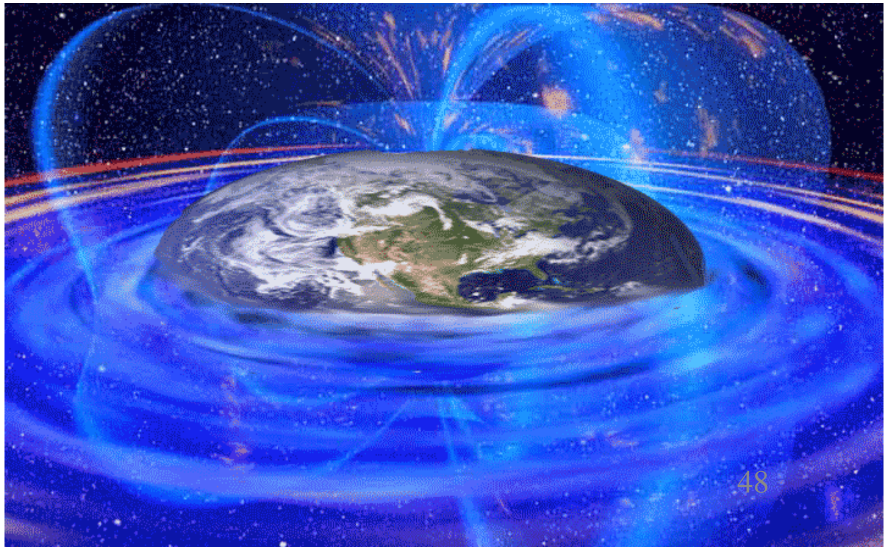
The world's physicists have spent 14 years and $8 billion building the Large Hadron Collider, in which the colliding protons will recreate energies and conditions last seen a trillionth of a second after the Big Bang. Researchers will sift the debris from these primordial recreations for clues to the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

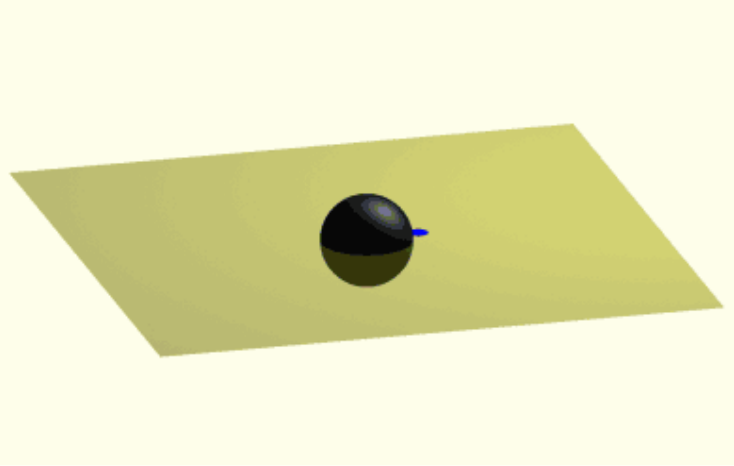
Although it sounds bizarre, the case touches on a serious issue that has bothered scholars and scientists in recent years — namely how to estimate the risk of new groundbreaking experiments and who gets to decide whether or not to go ahead.

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.

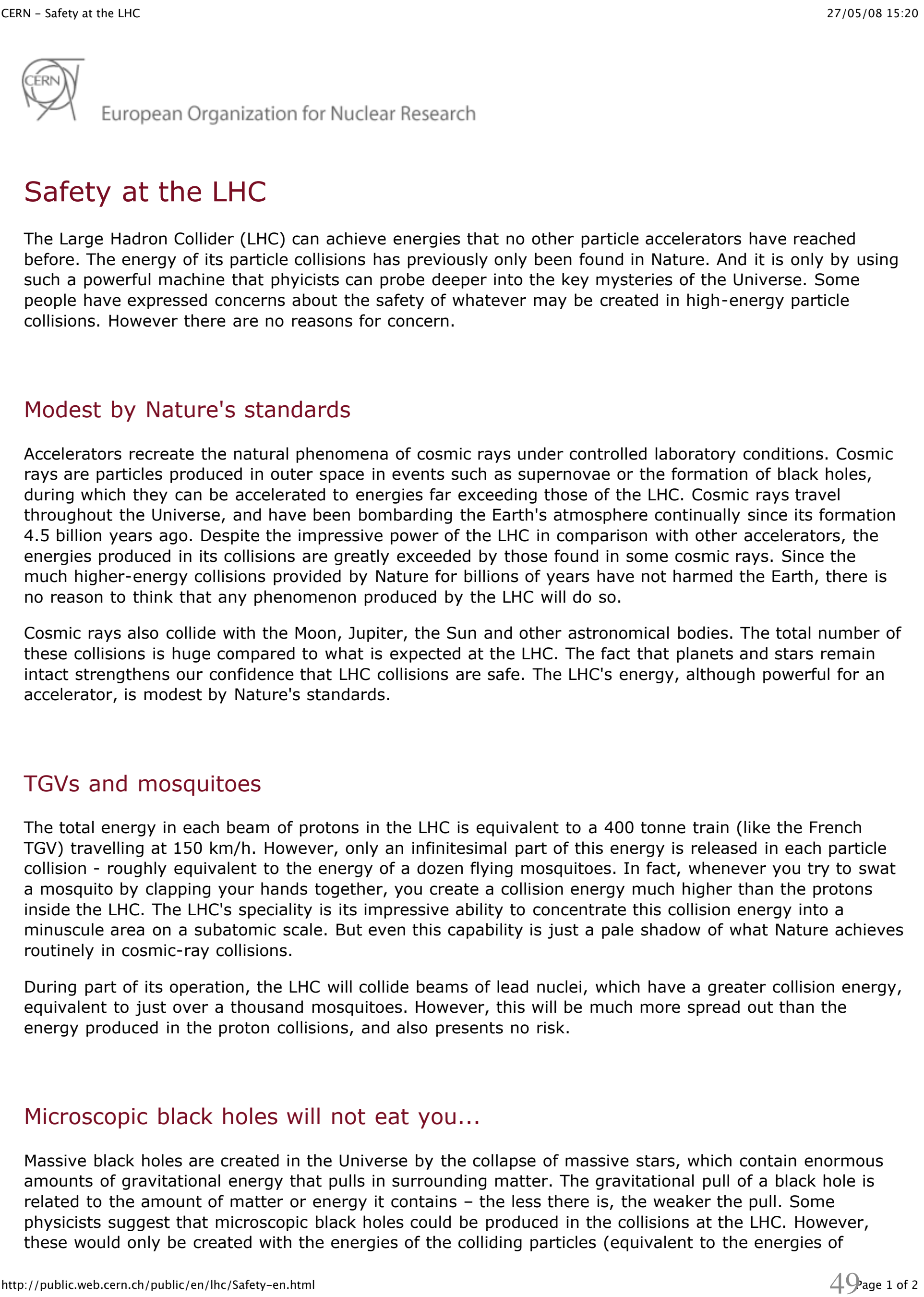
According to a spokesman for the Justice Department, which is representing the Department of Energy, a scheduling meeting has been set for June 16.



black holes decay via Hawking radiations!



CERN had to react!



CERN - Safety at the LHC 27/05/08 15:20

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.

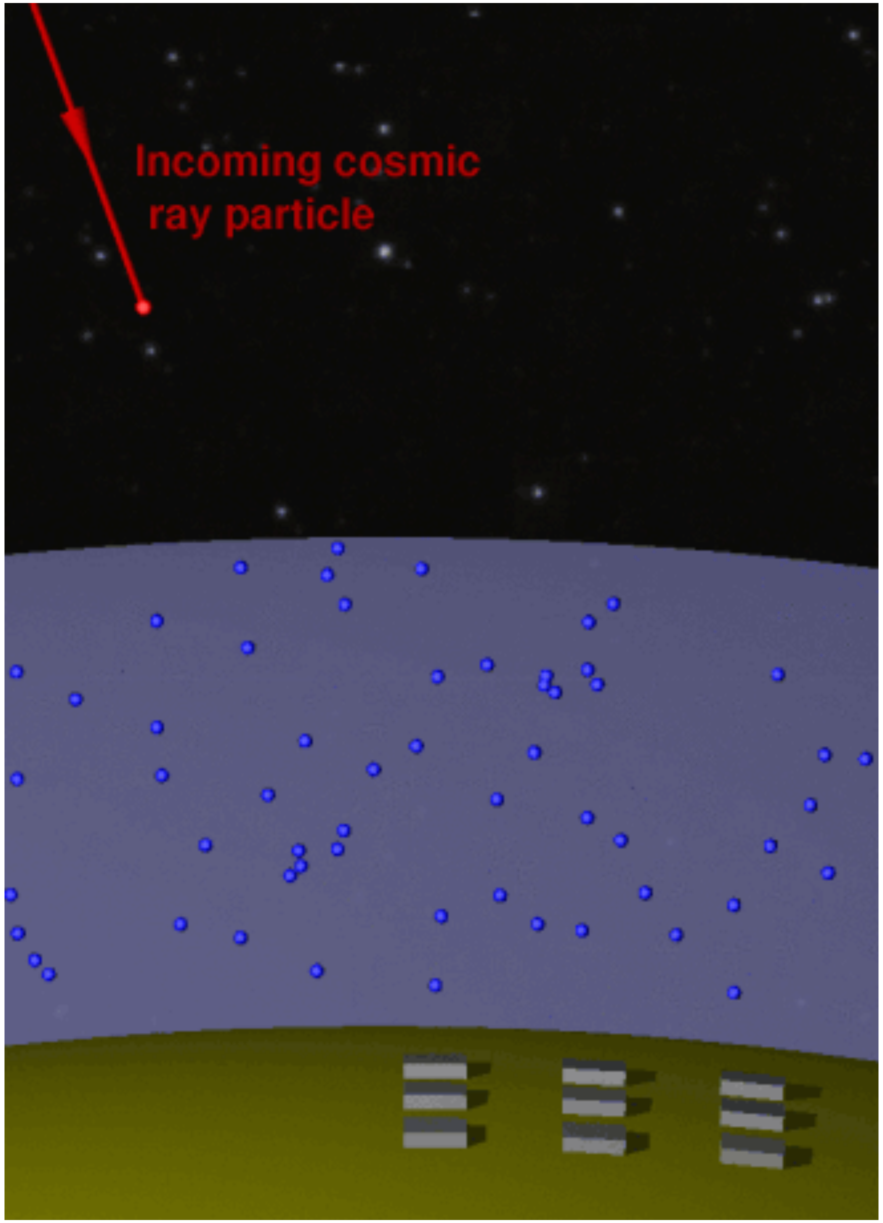
During part of its operation, the LHC will collide beams of lead nuclei, which have a greater collision energy, equivalent to just over a thousand mosquitoes. However, this will be much more spread out than the energy produced in the proton collisions, and also presents no risk.

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

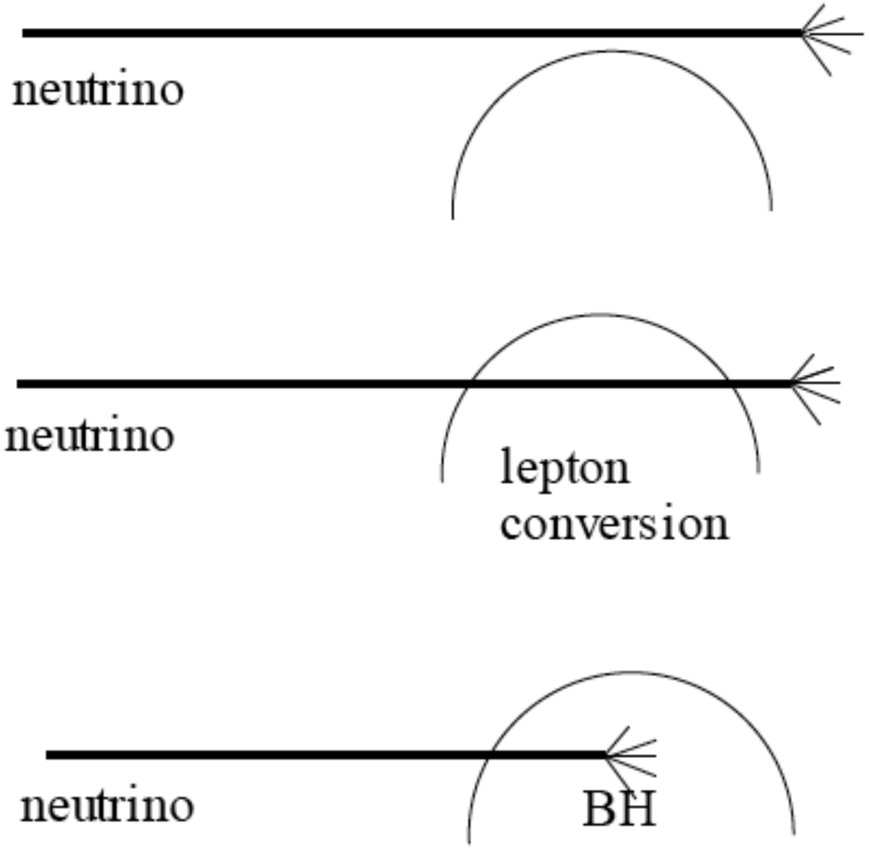
http://public.web.cern.ch/public/en/lhc/Safety-en.html Page 1 of 2

Since the beginning of particle physics, cosmic rays have been used to probe very high energetic reactions and thus discover new particles!



- High energetic cosmic ray (e.g. neutrino) hits an atom in the earth upper atmosphere.
- It could produce a QBH.

Compare SM to BH creation scenario



Shower is detected both by ground arrays and by fluorescence detectors

Because of BH production: there are less showers due to earth-skimming neutrinos

Bounds (orders of magnitude) on brane world models

n	1	2	3	4	5	6
Gravity exp.	10^7 km	0.2mm				0.1 fm
LEP2/ Tevatron		1 TeV	1 TeV	1 TeV	1 TeV	1 TeV
LHC		~5 TeV	~5 TeV	~5 TeV	~5 TeV	~5 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

So far black holes on Earth have only been spotted in Belgium
(my wife is from Belgium)

This is advertisement for a beer called "black hole".

So far Belgium has not imploded…

despite black holes

Black Holes and the unification of QM and GR

- We have few information on what to expect from the unification of quantum mechanics and general relativity.
- Experimental bounds are rather weak.
- Thought experiments can be useful.
- Black hole are often a central argument of these Gedankenexperiments.
- Typical example: the derivation of a minimal length.

A minimal length from QM and GR

Claim: GR and QM imply that no operational procedure exists which can measure a distance less than the Planck length.

Assumptions:

- Hoop Conjecture (GR): 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.
- Quantum Mechanics: uncertainty relation.

Minimal Ball of uncertainty:

Consider a particle of Energy E which is not already a black hole. Its size r must satisfy:

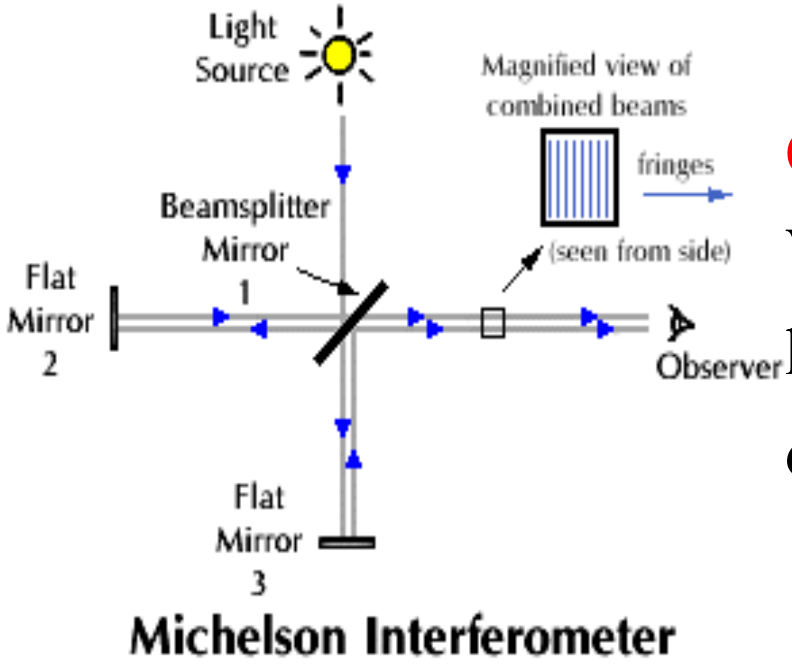
$$r \gtrsim \max\left[1/E\,,\ E\right]$$

where 1/E is the Compton wavelength and E comes from the Hoop Conjecture. We find:

$$r \sim l_P$$

C.Alden Mead, Phys.Rev. 135 (1964) B849-B862

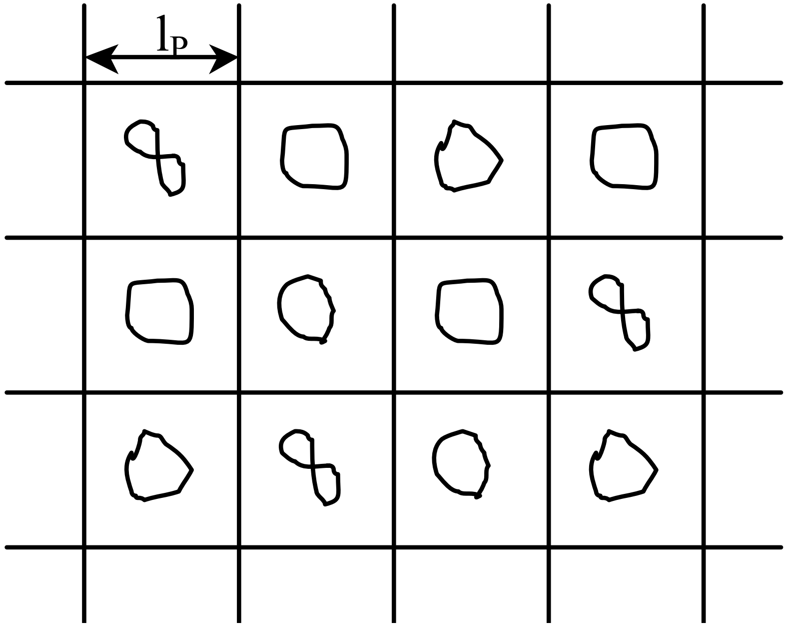
Could an interferometer do better?



Wavelength of light is much bigger than the path length sensitivity!

Our concrete model:

We assume that the position operator has discrete eigenvalues separated by a distance l_P or smaller.



XC, Graesser, Hsu, Phys.Rev.Lett. 93 (2004) 211101

- Let us start from the standard inequality:

$$(\Delta A)^2(\Delta B)^2 \geq -\frac{1}{4}(\langle[A,B]\rangle)^2$$

- Suppose that the position of a test mass is measured at time t=0 and again at a later time. The position operator at a later time t is:

$$x(t) = x(0) + p(0)\frac{t}{M}$$

- The commutator between the position operators at t=0 and t is

$$[x(0), x(t)] = i\frac{t}{M}$$

- Using the standard inequality we have:

$$|\Delta x(0)||\Delta x(t)| \geq \frac{t}{2M}$$

- At least one of the uncertainties Δx(0) or Δx(t) must be larger than:

$$\sqrt{t/2M}$$

- A measurement of the discreteness of x(0) requires two position measurements, so it is limited by the greater of Δx(0) or Δx(t):

$$\Delta x \equiv max\left[\Delta x(0), \Delta x(t)\right] \geq \sqrt{\frac{t}{2M}}$$

- This is the bound we obtain from Quantum Mechanics.

- To avoid gravitational collapse, the size R of our measuring device must also grow such that R > M.

- However, by causality R cannot exceed t.

- GR and causality imply:

$$t > R > M$$

- Combined with the QM bound, they require Δx > 1 in Planck units or

$$\Delta x > l_P$$

- This derivation was not specific to an interferometer - the result is device independent: no device subject to quantum mechanics, gravity and causality can exclude the quantization of position on distances less than the Planck length.

Non-locality in QFT due to QBHs

- One can identify quantum black holes in the propagator of the graviton using effective theory techniques.

$$iD^{\alpha\beta,\mu\nu}(q^2) = \frac{i\left(L^{\alpha\mu}L^{\beta\nu} + L^{\alpha\nu}L^{\beta\mu} - L^{\alpha\beta}L^{\mu\nu}\right)}{2q^2\left(1 - \frac{NG_N q^2}{120\pi}\log\left(-\frac{q^2}{\mu^2}\right)\right)}$$

- This leads to new insights into QFT which must be non-local at energies of the order of the Planck scale. E.g. for a scalar field

$$O_8 \;=\; \frac{2}{15}G_N^2 N\left(\partial_\mu\phi(x)\partial^\mu\phi(x) - m^2\phi(x)^2\right)\log\left(-\frac{\Box}{\mu^2}\right)\left(\partial_\nu\phi(x)\partial^\nu\phi(x) - m^2\phi(x)^2\right)$$

- This is not surprising given the existence of a minimal length (quantum black holes are extended objects).
- We will never probe scales below the Planck scale.
- We need to understand these non-local effects better, they may be the guiding principle we were looking for to go beyond QFT.

Black Holes are truly fascinating!

- The observation of astrophysical black holes are a confirmation of Einstein's general relativity.
- Black holes allow to probe the scale of quantum gravity.
- The tightest bounds to date on the value of this energy scale come from LHC data.
- Black holes are an ideal laboratory to probe the unification of quantum mechanics and general relativity.
- Lots of open questions: what happens when you pass the horizon, is there truly a singularity? What happens to information?
- Black holes + QM lead to the conclusion that there is a minimal length in nature.

Black Holes are truly fascinating!

Thanks for your attention!