Quantum Physics confronts Einstein's Gravity

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Science Saturdays
13 October 2001

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Abstract:

The search for an overall master theory that is compatible both with quantum physics and with Einstein's theory of gravity (the general relativity) is still the single biggest theoretical problem facing physics at the turn of the millennium.

Both string theory (also called brane theory) and its competitors will be described (in a non-technical way) — there is still a lot we do not understand.

Public Perceptions:

- Quantum physics is very weird and abstract.
- Relativity is bizarre and abstract.

Reality:

- Quantum physics is part of everyday technology.
- Special relativity — speed of light limitations — are part of everyday technology.
- General relativity — Einstein's gravity — is central to at least some off-the-shelf technology.
- Quantum gravity?

Quantum technology:

- Transistors: solid state electronics *versus* thermionic valves.

- Computer memory, CPU's.

- All household electronics.

- Ignore philosophy and metaphysics.

- Quantum physics works.

- We can and do use it on a regular basis to design our technology.

- The end user does not need to know the details...

Special relativistic technology:

- Lasers. (Pointers; CD's; CD-ROM)
- Satellite time delays. (Phone system)
- Physical size of computers.
- Length of computer cables.

Special relativity most often shows up in the speed of light limitation.

And yes, our technology really is sensitive to speed of light limits.

Special relativistic technology:

- Computer clock speed 2.0 Giga–Hertz.

- Implies one computing cycle, one "tick", every 1/(2,000,000,000) seconds.
(Half a nano-second.)

- In each "tick" of the clock, light (and electrical signals) can travel at most 15 centimetres (6 inches).

- To do the job properly, you need to be able to send a electrical pulse from one side of the CPU to the other and back in less than one "tick" of the clock.

- CPU's *must* be less than 3 inches across.

General relativistic technology:

- GPS — Navstar.

- Useful for knowing where you are.

- Useful for finding the target.

- General relativity (Einstein's gravity) is an essential component of getting the system to work. (Design phase.)

- General relativity is actually a bigger effect than special relativity.

- The end user does not need to know the details...

- This is why the US Air Force keeps a few experts on general relativity on tap...

Penrose classification:

Something that does not often make it past the science reporters:

— Not all theories are created equal. —

Roger Penrose splits theories into:

- Superb.
- Useful.
- Tentative.

Some theories are bedrock.

As you get closer to the frontier, the theories become more uncertain and tentative.

That's why it's called research.

Penrose classification:

The key observation is:

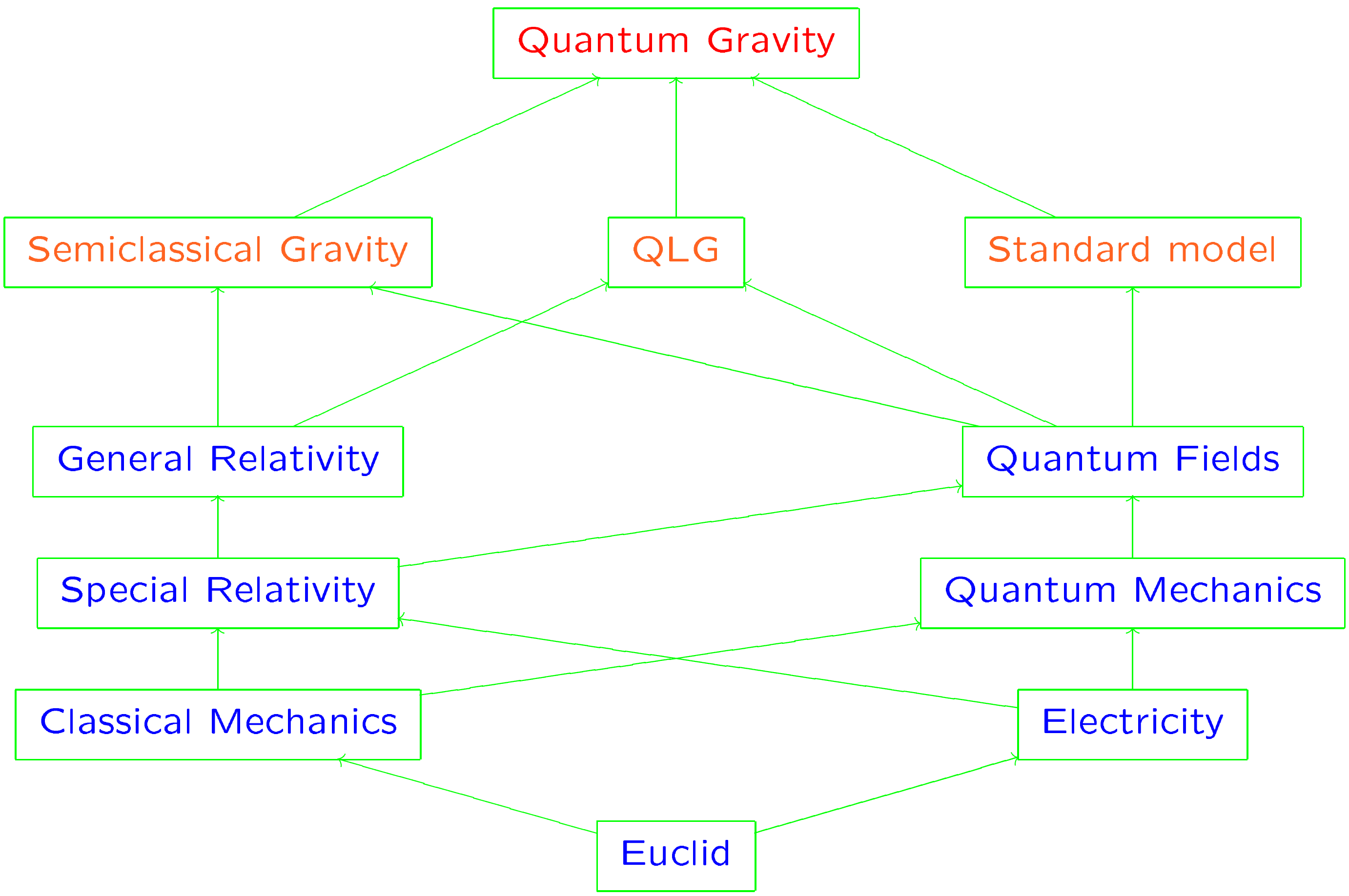
- Quantum physics is "Superb".

- Einstein gravity (general relativity) is "Superb".

- Put them together and the results are a mess.

- Quantum gravity is *at best* "Tentative".

Penrose classification:



This diagram describes the logical relationships between the major fundamental theories of physics that are currently extant or under development. Note that the lowest four layers are all Superb theories, the next to top layer is Useful, while the topmost layer is very definitely Tentative.

Why do we need quantum gravity?

There is this thing called the Planck scale.

First discussed by Max Planck in 1899.

Quantum physics was in its infancy.

Planck constant — then only an empirical way of parameterizing the unexpected behaviour of black-body radiation.

Planck scale — seemed to be merely an accident of "algebraic numerology" — you put $\hbar$, c, and G together in various ways and out popped masses, times, and distances.

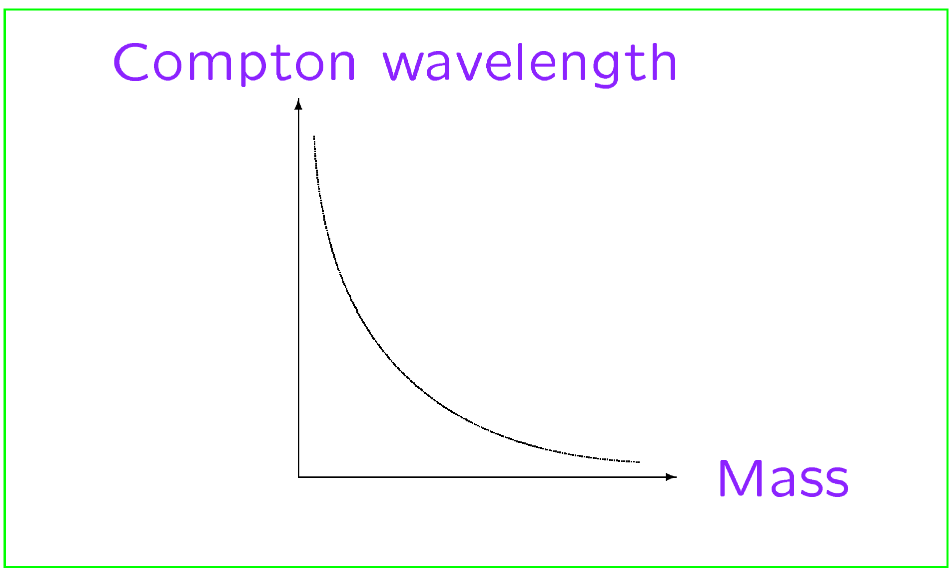
After the development of quantum physics (1925): The significance of the Planck scale as the harbinger of quantum gravity was appreciated.

The Planck scale: Compton wavelength

Quantum mechanics tells us that an elementary particle of mass M can be reasonably easily localized within a distance

$$\lambda_{\text{Compton}} = \frac{\hbar}{M\,c}$$

known as the Compton wavelength.

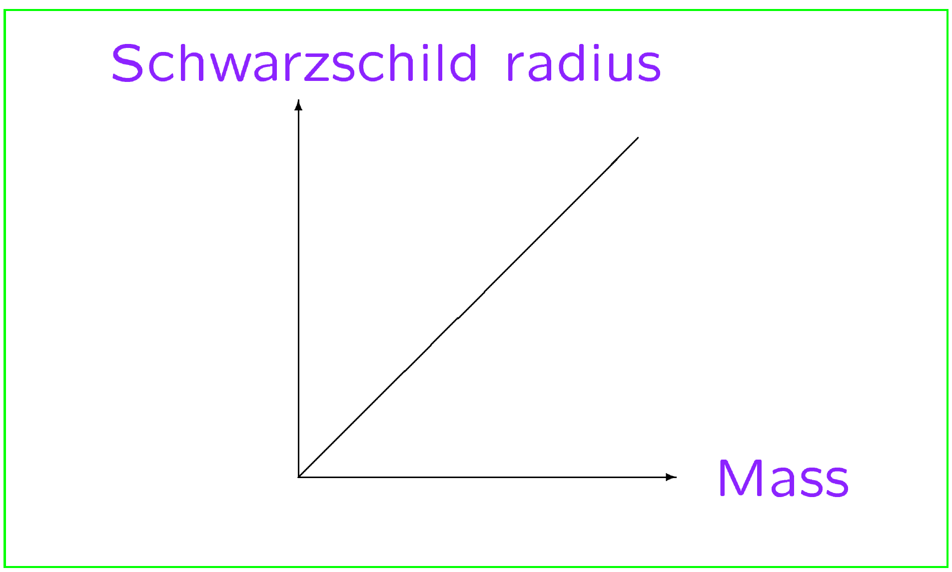


Compton wavelength as a function of mass.

The Planck scale: Schwarzschild radius

Classical gravity tells us that a particle of mass M will disappear down a black hole if the particle is smaller than its Schwarzschild radius

$$r_{\text{Schwarzschild}} = \frac{2\,G\,M}{c^2}.$$

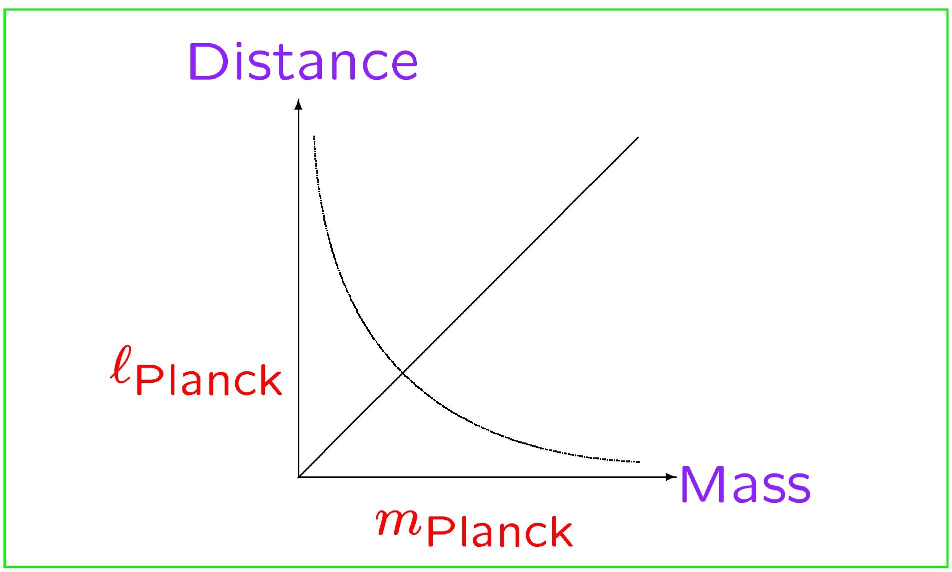


Schwarzschild radius as a function of mass.

The Planck scale: Crossover

Plot the Compton wavelength as a function of mass, and the Schwarzschild radius as a function of mass.

The Planck mass is the place that the two graphs cross.



The Planck scale is the crossing point of Compton wavelength and Schwarzschild radius as a function of mass.

The Planck scale: Crossover

We expect that a heavy enough elementary particle should disappear down its own little black hole.

We expect this to happen when the Compton wavelength equals the Schwarzschild radius.

Set $\lambda_{\text{Compton}} = r_{\text{Schwarzschild}}$:

$$\frac{\hbar}{M\ c} = \frac{G\ M}{c^2}.$$

Solve for the mass M of the particle.

This defines the Planck mass:

$$M_{\text{Planck}} = \sqrt{\frac{\hbar\ c}{G}}.$$

The Planck scale: Formulae

Planck mass:

$$M_{\text{Planck}} = \sqrt{\frac{\hbar\ c}{G}}.$$

The Planck energy is now easy:
take $E_{\text{Planck}} = m_{\text{Planck}} c^2$ to get:

$$E_{\text{Planck}} = \sqrt{\frac{\hbar\ c^5}{G}}.$$

The Compton wavelength of a Planck mass particle $\lambda_{\text{Planck}} = \hbar/(m_{\text{Planck}} c)$ is defined to be the Planck length:

$$\ell_{\text{Planck}} = \sqrt{\hbar\ c\ G}.$$

Finally the Planck time is defined to be the time required for light to travel one Planck length $T_{\text{Planck}} = \ell_{\text{Planck}}/c$, so that:

$$T_{\text{Planck}} = \sqrt{\frac{\hbar\ G}{c}}.$$

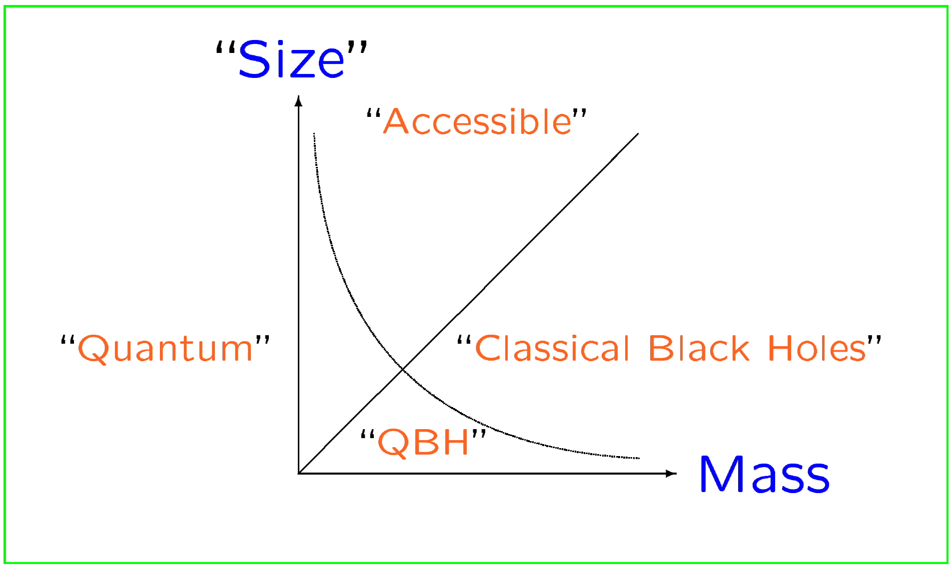
The Planck scale.

Symbol	Name	Value
m_{Planck}	Planck mass	2.18×10^{-8} kilogram 21.8 micro-grams 1.22×10^{19} GeV/c^2
E_{Planck}	Planck energy	1.22×10^{19} GeV
ℓ_{Planck}	Planck length	1.62×10^{-35} metres
T_{Planck}	Planck time	5.39×10^{-44} seconds

Values of the various Planck units.

Classical–Quantum transition:

- The physically accessible region.



Accessible region for “effective radius” as a function of mass.

- The region that lies *above* both curves is physically accessible.

Why is quantum gravity so difficult?

- Lack of experimental guidance.

- Our technology is so good in some ways that it's easy to forget what's impossible; now or for the foreseeable future.

- The really interesting experiments are in an energy regime that we simply cannot access.

From the theorists' perspective, one of the most frustrating aspects of our times is that all the interesting physics (interesting from the point of view of quantum gravity that is) seems to be taking place at or above the Planck scale — but our current technology is simply not up to the task of building a Planck scale accelerator.

Where we are:

- Accelerators (atom smashers): 10,000 GeV.
- Cosmic rays (top end of spectrum): 10,000,000,000,000 GeV.
- Planck energy: 10,000,000,000,000,000,000 GeV.
- Laboratory accelerators are too weak by a factor 1,000,000,000,000,000.
- That's a US quadrillion [UK 1,000 billion].
- And waiting for those very few highest energy cosmic rays to pass by has its own problems...

How to proceed?

- Without experiments, we have to rely on simplicity, elegance, and internal consistency.

- This is a dangerous game.

- Einstein made it work, once...
  (When he developed general relativity.)

- (Special relativity had plenty of experimental guidance from the outset.)

- Even Einstein could not make the "elegance trick" work a second time.

- No-one else has *ever* gotten the "elegance trick" to work.

Main contenders:

- Brane theory (*aka* "string theory"):
  *n*ee "dual resonance model".
  Recycled QFT that did not work the first time round.

- Quantum geometry:
  quantum geometrodynamics — can we work with a wildly fluctuating geometry instead of a more or less fixed geometry?

- Lattice quantum gravity:
  Approximate spacetime by a discrete lattice — "atoms" of geometry.
  Analogy:
  Continuum mechanics $\to$ molecular physics.

Common themes:

- Everyone agrees you have to do something drastic at short distances to keep the physics under control...

- You should be ecstatic if the large-distance limit reproduces both quantum physics and Einstein gravity...

- Short distances: don't ask...

- These are all "models" not "theories"...

- "Theory" is a technical term that should only be applied in the "Superb" category.

- All current models of quantum gravity are extremely Tentative...

Main tribes:

- Particle physicists (brane models, strings):
  - Quantum physics is supreme...
  - Too bad for Einstein gravity...
- General relativists (quantum geometry):
  - Einstein gravity is supreme...
  - Too bad for quantum physics...
- Lattice physicists:
  - Never yet met anything they couldn't put on a lattice...
  - Too bad for the continuum...

Gravitons *versus* spacetime:

- Which is more fundamental:
  - Quantum physics? (Gravitons.)
  - Einstein gravity? (Curved spacetime.)
  - Neither?

- We simply do not know —
  but whatever happens:
  - Gravitons are a decent approximation, in their appropriate corner of reality.
  - Curved spacetime is a decent approximation, in its appropriate corner of reality.
  - Reality is almost certainly weirder than we think...

Conclusion:

- Quantum physics works, in its corner of reality.

- Einstein gravity works, in its corner of reality.

- There must be some theory, call it "quantum gravity", that reproduces both quantum physics and Einstein gravity in appropriate limits.

- We're still looking.