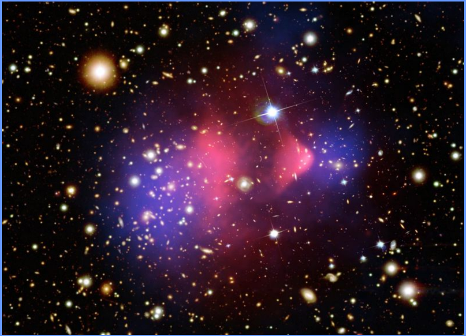
Unsolved Mysteries of Fundamental Physics



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By **fundamental physics**, I mean the search for a small set of laws which *in principle* determine everything we can calculate about the universe. The reductionist dream — not always practical, but very seductive.

Where do we stand in the search for these laws? What do we know, and what are the mysteries?

The most fundamental question:

WHY?

Some say that science does not tell us *why* things happen, just *what* happens. There's some truth to that.

And yet, science often moves forward by asking "why?"

Q: Why is the sky blue?

A: More than light of other colors, blue light is scattered in all directions by the Earth's atmosphere.

Q: Why is blue light scattered more?

A: Because blue light has a shorter wavelength than most other visible light.

Q: Why does blue light have a shorter wavelength?

A: No reason: we just call visible light with short wavelengths ‘blue’.

Q: But why does light with short wavelengths *look* blue?

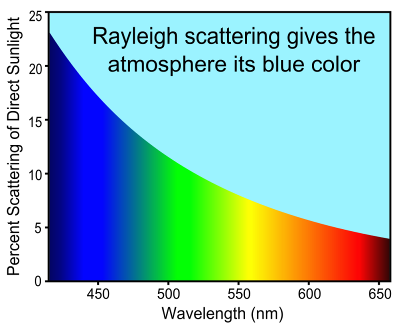
A: Umm, err... that’s not a physics question.

Q: So why does light with short wavelengths scatter more?

A: It scatters off oxygen and nitrogen molecules with an intensity proportional to wavelength^{-4}.

Q: Why does light do that?

A: Electromagnetic waves scatter off particles much smaller than their wavelength with an intensity proportional to wavelength^{-4}.



Q: Why wavelength^{-4}?

A: Now that's a good question!

I won't do the calculation here, but Rayleigh showed this in 1871 using dimensional analysis. It boils down to space being 3-dimensional and the energy density of an electromagnetic wave being proportional to its amplitude squared. If space were 2-dimensional, the intensity would go like wavelength^{-3}.

Q: Why is space 3-dimensional?

A: Nobody knows.

There are many questions in physics that seem *too hard* for us now:

Q: Why is space 3-dimensional?

Q: Why is time 1-dimensional?

Q: Are there any truly fundamental laws, or only succession of better and better approximate laws?

Q: What are the fundamental laws, if they exist?

But some questions that looked too hard were actually answered!

Q: Why is time so different from space?

A: Because the 'interval' between two spacetime points is

$$(\Delta s)^2 = -(\Delta t)^2 + (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2$$

in units where $c = 1$.

It's hard to guess which questions we'll answer next, but it helps to know where we stand now.

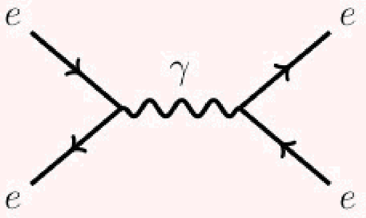
Our best theories of fundamental physics today:

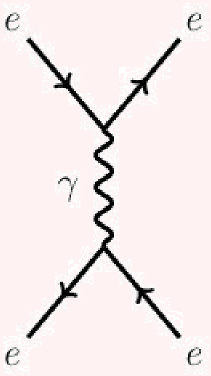
STANDARD MODEL	**GENERAL RELATIVITY**
Electromagnetic Force Weak Force Strong Force	Gravity

The Standard Model describes all the forces *except* gravity using quantum mechanics.

General relativity describes gravity, ignoring quantum mechanics.

The Standard Model describes *particles* and their *interactions* using special relativity and quantum mechanics.





There are particles that carry forces:

electromagnetism	γ (photon)
weak force	W, Z
strong force	g (gluon)

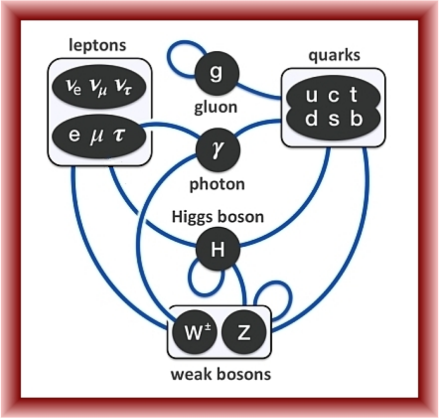
and particles that constitute ‘matter’:

	leptons	quarks
1st generation	e, ν_e	d, u
2nd generation	μ, ν_μ	s, c
3rd generation	τ, ν_τ	b, t

There is also one more:

H (Higgs boson)

They interact in various ways:



The strengths of their various interactions are described by 25 constants. 22 involve the Higgs boson!

The most obvious mysteries seem very hard to solve.

Q: Why are there 3 forces?

Q: Why does each generation include 2 leptons and 2 quarks?

Q: Why are there 3 generations of matter particles?

Q: Why do the 25 constants have the values they do?

Some “grand unified theories” offer plausible answers to the first two questions. The third seems harder, and the fourth even harder. For more, type

the algebra of grand unified theories

into Google.

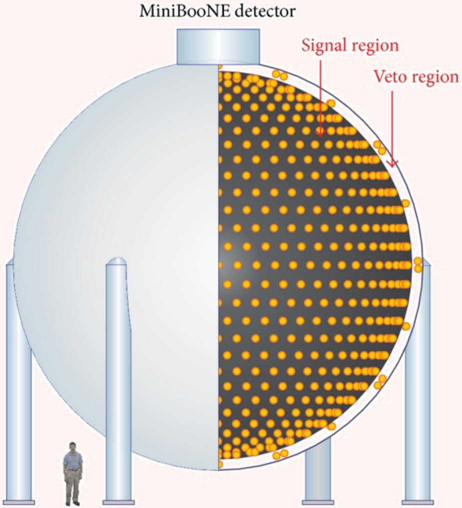
It seems easier to make progress on other puzzles.

Q: What's up with neutrinos?

Once we thought they were massless. Now we know they have masses and the 3 kinds $(\nu_e, \nu_\mu, \nu_\tau)$ can turn into each other.

In the Standard Model all this is described by their interactions with the Higgs... using 7 of the 25 constants in this model.

But there are anomalies in the data!



MiniBooNE: 800 tons of mineral oil in a tank bombarded with muon neutrinos from a distance of 500 meters... for 16 years.

At MiniBooNE and an earlier experiment, muon neutrinos seem to be turning into electron neutrinos too fast to be explained by the Standard Model!

A fourth kind of neutrino could be to blame... or the experiments could be wrong... or something else.

Next: MicroBooNE, with 170 tons of liquid argon!

General relativity says that freely falling objects trace out paths in spacetime that are ‘as straight as possible’, but that matter curves spacetime according to **Einstein’s equation**:

Given any small ball of freely falling test particles initially at rest relative to each other, the rate at which its volume begins to shrink is proportional to: the energy density at the center of the ball, plus the sum of the pressures in all three directions.

or more precisely:

$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = -\frac{1}{2}(\rho + P_x + P_y + P_z)$$

in units where $c = 8\pi G = 1$.

From this one can derive Newton's law of gravity in the limit of slowly moving objects and weak gravitational fields. One also can understand:

- black holes
- gravitational waves
- the Big Bang

To illustrate the simplicity of general relativity, let's *sketch* how the Big Bang works. For more details, type

the meaning of Einstein's equation

into Google!

For a long time people thought that pressure is negligible in intergalactic space except in the very early universe, giving:

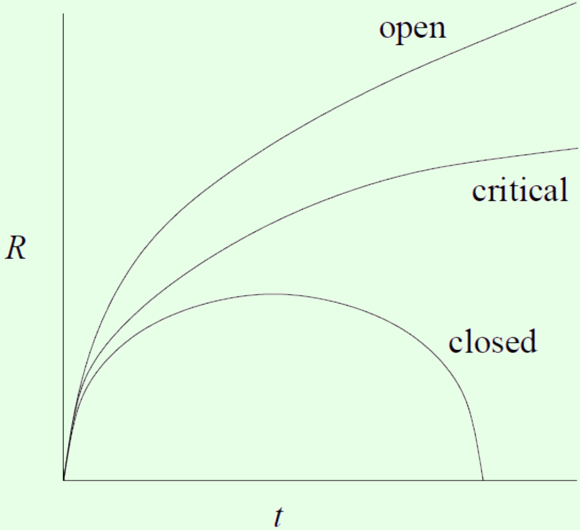
$$\frac{\ddot{V}}{V} = -\frac{\rho}{2}$$

for any ball of galaxies. Conservation of mass says ρR^3 is constant where R is the radius of the ball, so:

$$3\ddot{R} = -\frac{k}{2R^2}$$

Exactly like the motion of a rock thrown upwards from the Earth in good old Newtonian gravity! *What goes up must come down...* unless it exceeds escape velocity.

So, we get 3 possibilities:



However, *none of these matches what we see.* It seems the universe is expanding faster and faster!

Q: What is making the expansion of the universe accelerate? Does the vacuum have negative pressure? If so, why? If not, what is responsible for this apparent effect?

The most popular option is ‘dark energy’ with negative pressure. All we need is $6 \cdot 10^{-10}$ joules/meter^3, equivalent to $7 \cdot 10^{-27}$ kilograms/meter^3.

Gravity holds many other mysteries which seem very hard to solve:

Q: How can we reconcile general relativity and the Standard Model?

Q: What really happened at the Big Bang?

Q: What happens to stuff that falls into black holes?

Q: What’s the ultimate fate of the Universe?

Q: Why is the future so different than the past?

Again, it seems easier to make progress on other puzzles.

Q: Why does it seem that most of the matter in the Universe is invisible?

- Galaxies rotate faster than can be explained by all understood forms of mass.
- Our theories of galaxy formation don't work without positing 'cold dark matter'.
- Fluctuations in the microwave background radiation fit a model with cold dark matter, not a model without.

Whatever the solution to these puzzles, we are lucky that new data keeps coming in — quite quickly.

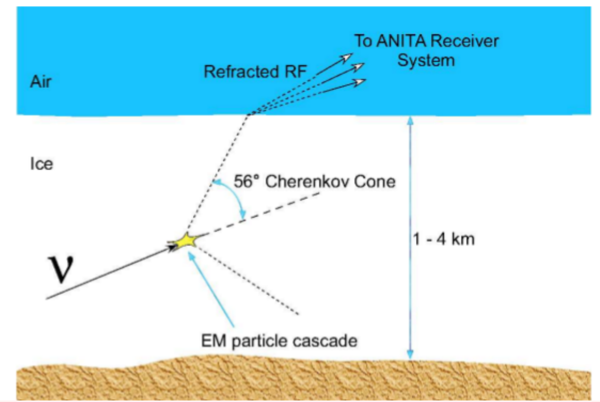
Based on the triumph of the Standard Model and general relativity by the early 1980s, theorists made the mistake of guessing that *we were close to a final theory of fundamental physics*.

They decided to first unify the forces other than gravity, then unify them with gravity. Many hoped that *mathematical aesthetics based on existing theories could quickly finish the job.*

So far, this seems wrong.

Luckily, experiments keep revealing new clues! Just last week, a paper came out on results from ANITA, the Antarctic Impulse Transient Antenna.

They seem to have seen two ultra-high-energy neutrinos — energies of $6 \cdot 10^{17}$ electron volts — *coming up from the ground.*



This seems unlikely if the Standard Model is all there is. Stay tuned!