Fundamental Physics: Where We Stand Today

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for more see: http://math.ucr.edu/home/baez/madison

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?

Why do many physicists feel stuck?

Let us start around 1983, when the W and Z particles were discovered and the Standard Model and general relativity seemed triumphant, after a century of rapid and revolutionary discoveries.

These theories describe 4 forces:

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

The Standard Model describes all the forces *except* gravity using quantum mechanics. General relativity describes gravity, ignoring quantum mechanics.

General relativity is a beautiful work of pure thought. The Standard Model is a baroque mess: we live in an interesting world.

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 starts shrinking 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 sentence (and lots of hard work!) one can derive everything we know about gravity, including:

- black holes
- gravitational waves
- the Big Bang

For example, let's sketch how the Big Bang works.

For more details, type

the meaning of Einstein's equation

into Google!

Assume the universe is homogeneous and isotropic. At any time $t = 0$, pick a small ball of freely falling particles centered at the Earth and initially at rest relative to it. The pressure is the same in all directions, so:

$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = -\frac{1}{2}(\rho + 3P)$$

and $V \propto R^3$, so:

$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = \left.\frac{3\ddot{R}}{R}\right|_{t=0}$$

and thus:

$$\left.\frac{3\ddot{R}}{R}\right|_{t=0} = -\frac{1}{2}(\rho + 3P)$$

This applies at any time. By homogeneity it applies to a ball of any size. So, it describes the expansion or contraction of the universe!

What does

$$\frac{3\ddot{R}}{R} = -\frac{1}{2}(\rho + 3P)$$

imply? Until recently, it seemed that pressure is negligible except in the very early universe, giving:

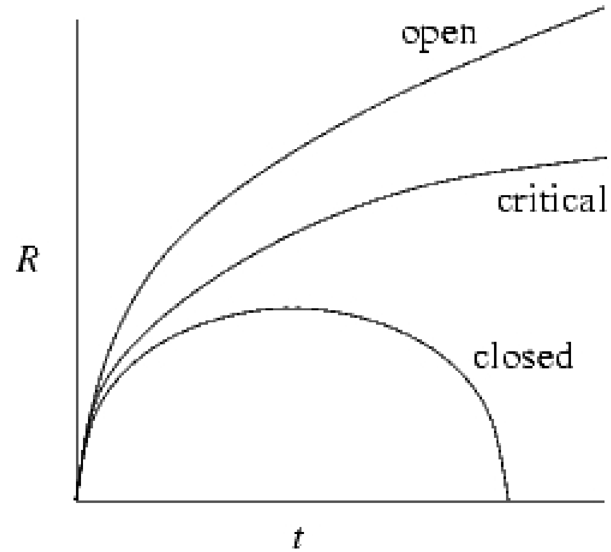
$$\frac{3\ddot{R}}{R} = -\frac{\rho}{2}$$

Conservation of energy says ρR^3 is some constant k, 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, astronomers recently discovered that *none of these matches reality.* It seems the universe is expanding faster and faster!

Mystery 1. What is making the expansion of the universe accelerate?

Maybe it's the energy of empty space!

The vacuum's pressure P is related to its energy density ρ by:

$$P = -\rho$$

So, ignoring matter:

$$\frac{3\ddot{R}}{R} = -\frac{1}{2}(\rho + 3P) = \rho$$

Thus: if the energy density of the vacuum is positive, the expansion of the universe tends to accelerate!

Mystery 2. Is the vacuum energy density positive? (If so, this is called **dark energy**.)

Next, the Standard Model. This is a list of *particles* and *interactions*. 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

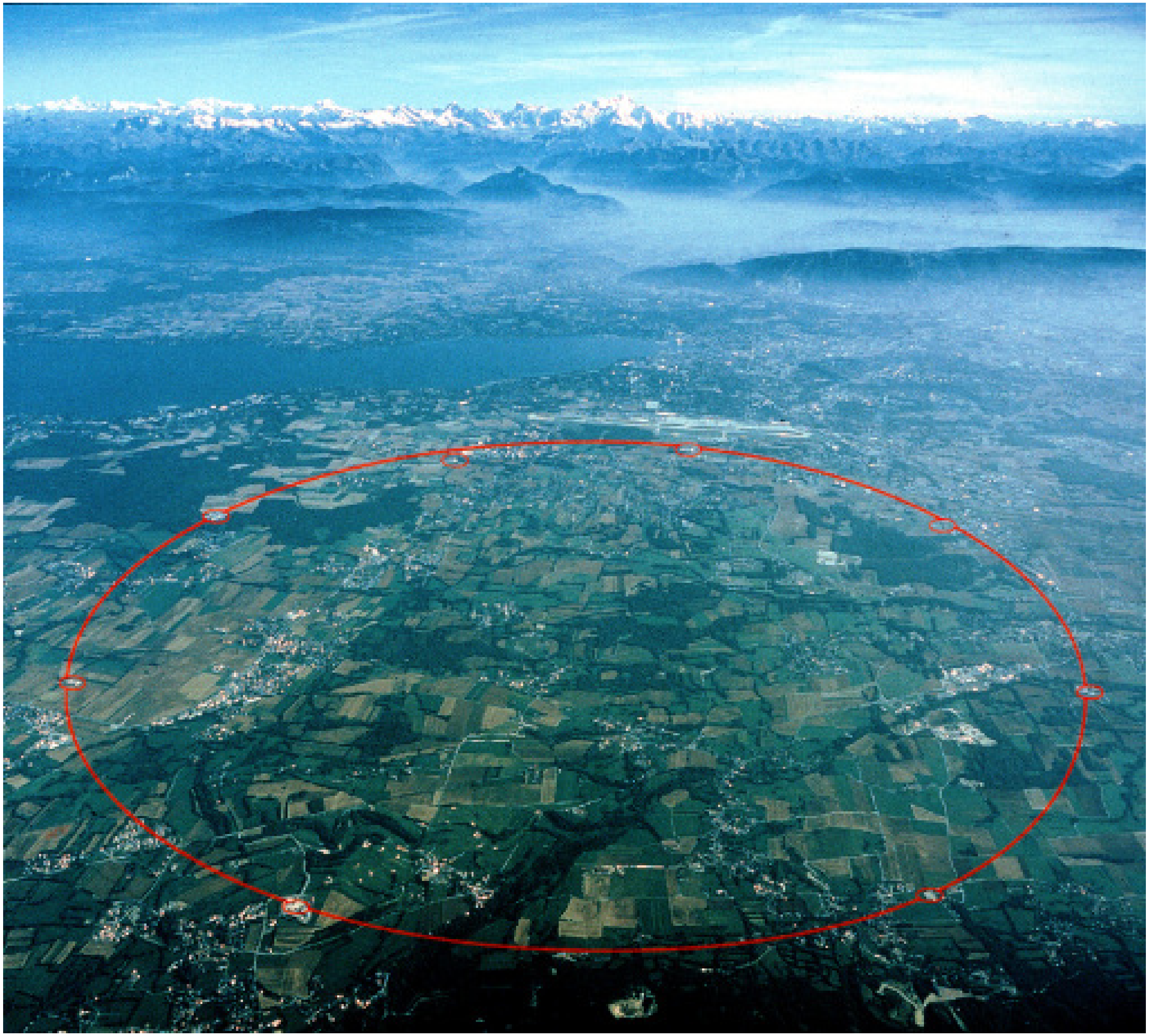
3 generations of leptons and quarks. Quarks interact via the strong force; leptons don't. All have antiparticles – e.g. the electron's antiparticle is the positron e^+.

There is also one *not yet seen* particle called the Higgs, which interacts with other particles and gives them their mass!

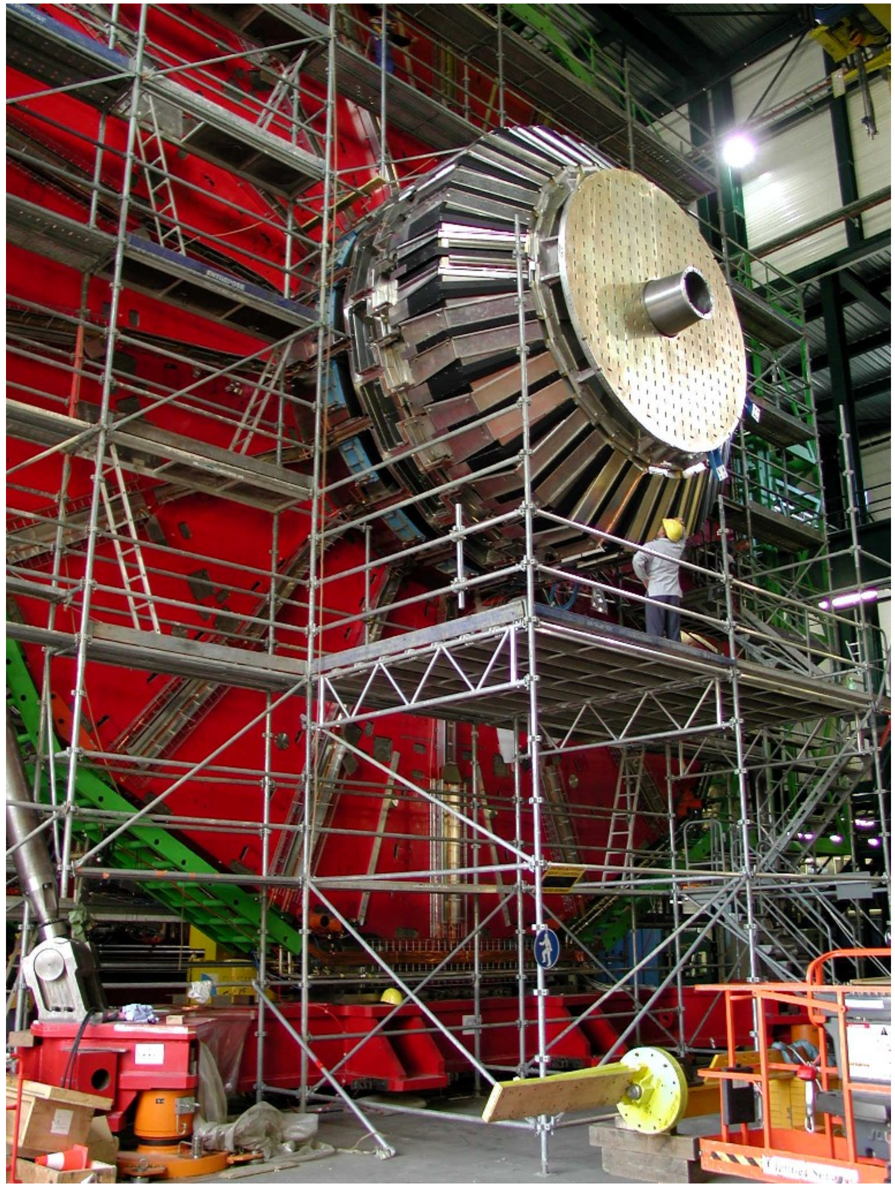
We hope to see this – *or not!* – when the Large Hadron Collider (LHC) starts operating around 2007.

Like the existing accelerator at the same site near Geneva, the LHC will be 17 kilometers in diameter... but it will collide protons instead of electron-positron pairs, and thus reach higher energies. Each proton will carry the kinetic energy of seven flying mosquitos (7 TeV).

The craftsmanship found in great cathedrals, but missing in most modern art, can now be seen here – underground.

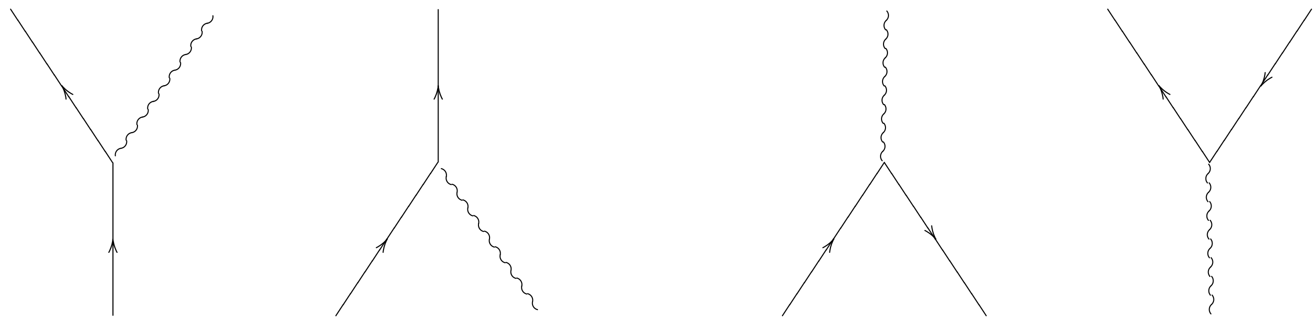


CERN image

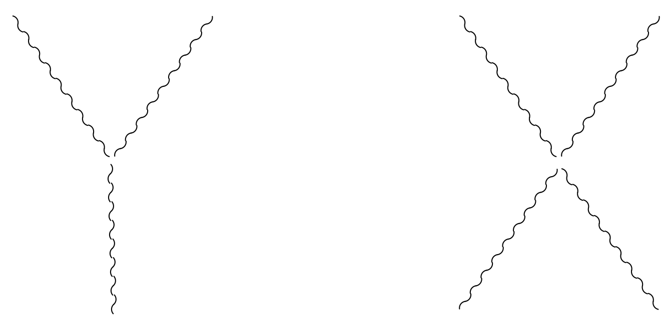


CMS electromagnetic calorimeter

Finally, there are lots of interactions. Most involve one 'force' and two 'matter' particles:



This is dictated by 'gauge invariance', a principle linking the Standard Model and general relativity. Gauge invariance also implies that most force particles interact with themselves:



The Higgs interacts with every particle that has mass.

It takes 18 fundamental constants to describe the strengths of all these interactions. All but 3 involve the unseen Higgs.

By constrast, general relativity requires just 1 constant: the energy density of the vacuum, usually called the **cosmological constant**.

Mystery 3. Does the Higgs really exist? What is the origin of mass?

Mystery 4. Why do these 18 numbers have the values they do? Does this question even have an answer?

While it seems to have been designed by a committee, the Standard Model works quite well – *too well* for frustrated physicists who want to find something simpler.

String theory is very beautiful, but we must add complications by hand to make it fit reality. To get the 'supersymmetric Standard Model' from string theory requires lots of arbitrary choices. The result still doesn't match experiment until one 'breaks supersymmetry' by hand, introducing ~ 105 extra constants. Is this an improvement?

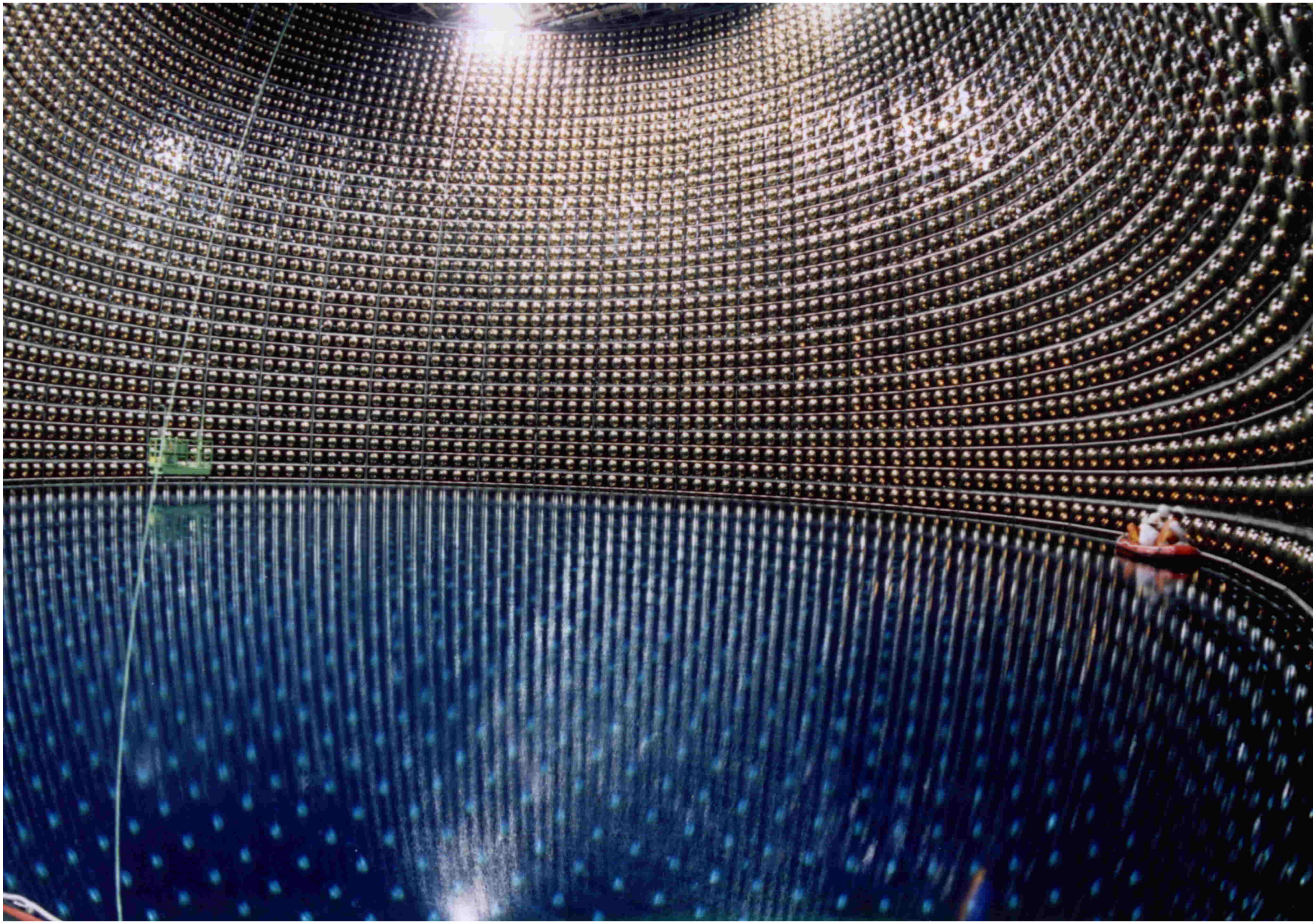
Perhaps right now beautiful theories are less useful than *new data*. To go beyond the Standard Model and general relativity, nothing is better than experiments that find flaws in these theories.

Where can we find flaws in the Standard Model, before the LHC fires up?

In the heavens!

For the last 20 years, our most shocking discoveries about the very small world of particles have come from astronomy. We now have amazing observatories: some on Earth, some in space, some buried deep underground.

For example, in Kamiokande there is a neutrino detector consisting of 50,000 tons of water buried beneath the Japanese Alps, carefully watched by 13,000 photodetectors. When neutrinos hit this water, a few interact with it, and emit tiny pulses of light:



Super-Kamiokande experiment

Since the 1960s, people have seen *fewer electron neutrinos coming from the Sun than expected!*

The Sun is powered by nuclear fusion. In fusion,

$$p \longrightarrow n + e^{+} + \nu_e$$

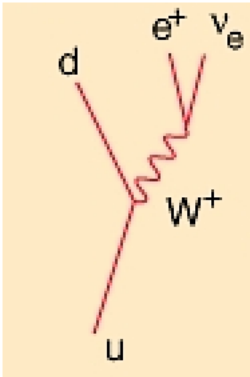
but really

$$p = u + u + d, \quad n = u + d + d$$

and the process at work is:

$$u \longrightarrow d + e^{+} + \nu_e$$

mediated by the weak interaction:



In the Standard Model neutrinos are massless and stable. So, we should see a certain number of ν_e's coming from the Sun... but by 1997, experiments had proved that we see only 1/3 of that number.

Since there are 3 kinds of neutrinos, maybe they 'oscillate' between different kinds! This can only happen if they have mass and suitable interactions exist.

In 1998, the detector in Kamiokande saw that ν_μ's produced by cosmic rays hitting the atmosphere turn into something else... probably ν_τ's. Many experiments are now studying neutrinos.

Mystery 5. Do neutrino oscillations fit into a slightly modified Standard Model – now requiring 25 dimensionless numbers – or must the theory be changed more drastically?

Astronomy also raises questions about general relativity: the accelerating expansion of the universe is one. We also see many black holes. Most galaxies have one at their center. The Milky Way has one about 3×10^6 times the mass of the Sun.

Ironically, it's easier to see the black hole in NGC1097, a galaxy 45 mega-lightyears away:

NASA image

The Very Large Telescope in Chile can see dust and gas spiralling into the center of NGC1097:

ESO image

In the galaxy's center, a black hole slowly swallows matter, emitting enough hot hydrogen to create hundreds of new stars in a ring 5500 light years across:

ESO image

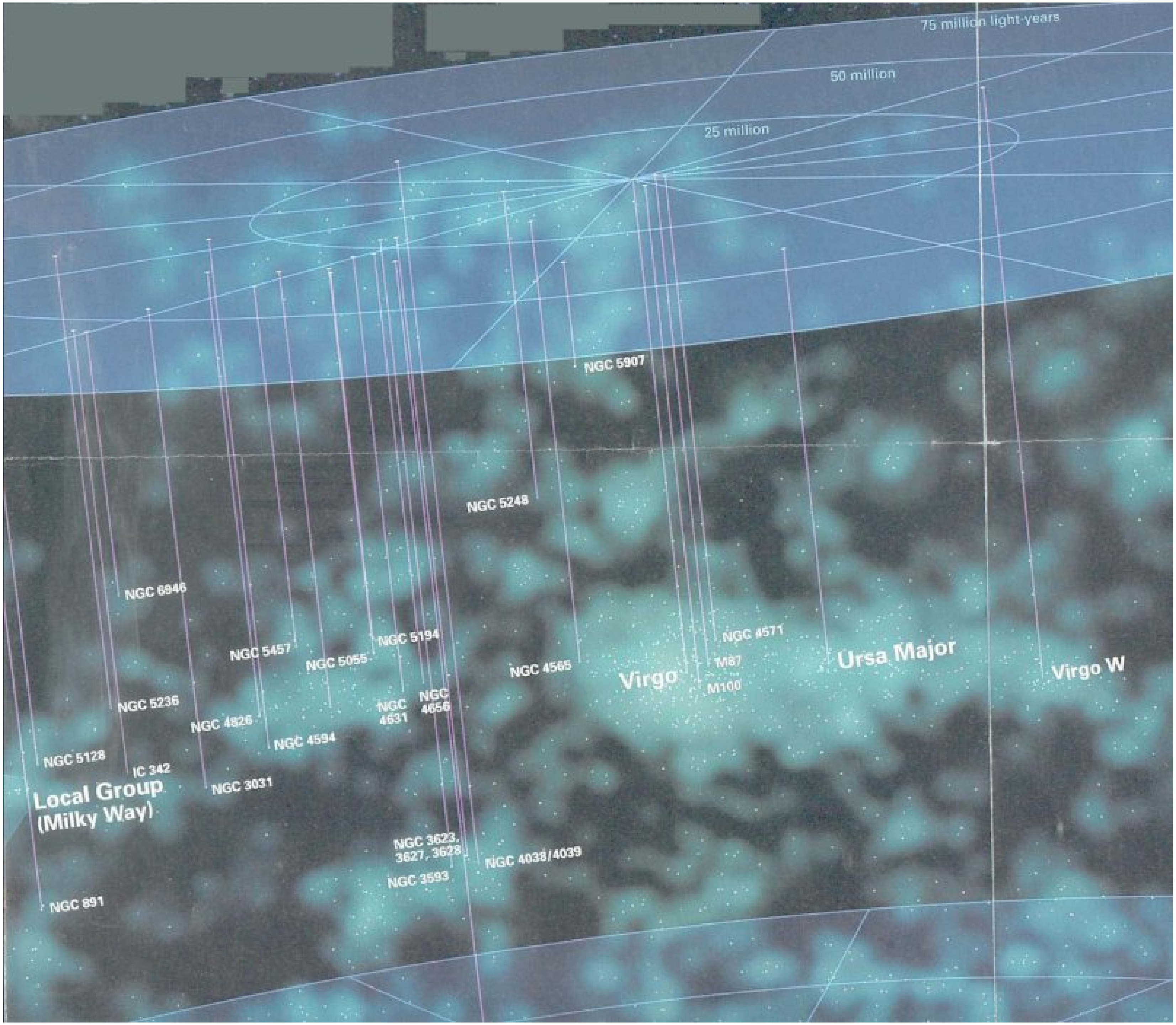
All this *confirms* general relativity...but it makes a certain puzzle very real:

Mystery 6. What happens to things when they fall into a black hole?

Nobody knows – we may need a good theory combining quantum mechanics and gravity to answer this. Hawking has argued that black holes eventually radiate away their energy, with a solar-mass black hole taking 10^{66} years to do so. This does not fully solve the mystery.

The real triumph of modern astronomy is that at last we can survey the *entire observable universe*…seeing back in time to just 400,000 years after the Big Bang, when the gas cooled enough to let light through.

From the cosmic viewpoint, our galaxy and NGC1097 are next-door neighbors, part of the Virgo Supercluster, a gravitationally bound collection of galaxy clusters 200 mega-lightyears in diameter.


75 million light-years
50 million
25 million
NGC 5907
NGC 5248
NGC 6946
NGC 5457
NGC 5194
NGC 4571
NGC 5055
NGC 4565
Ursa Major
M87
Virgo
Virgo W
M100
NGC 4631
NGC 4656
NGC 5236
NGC 4826
NGC 4594
NGC 5128
IC 342
Local Group (Milky Way)
NGC 3031
NGC 3623, 3627, 3628
NGC 4038/4039
NGC 3593
NGC 891

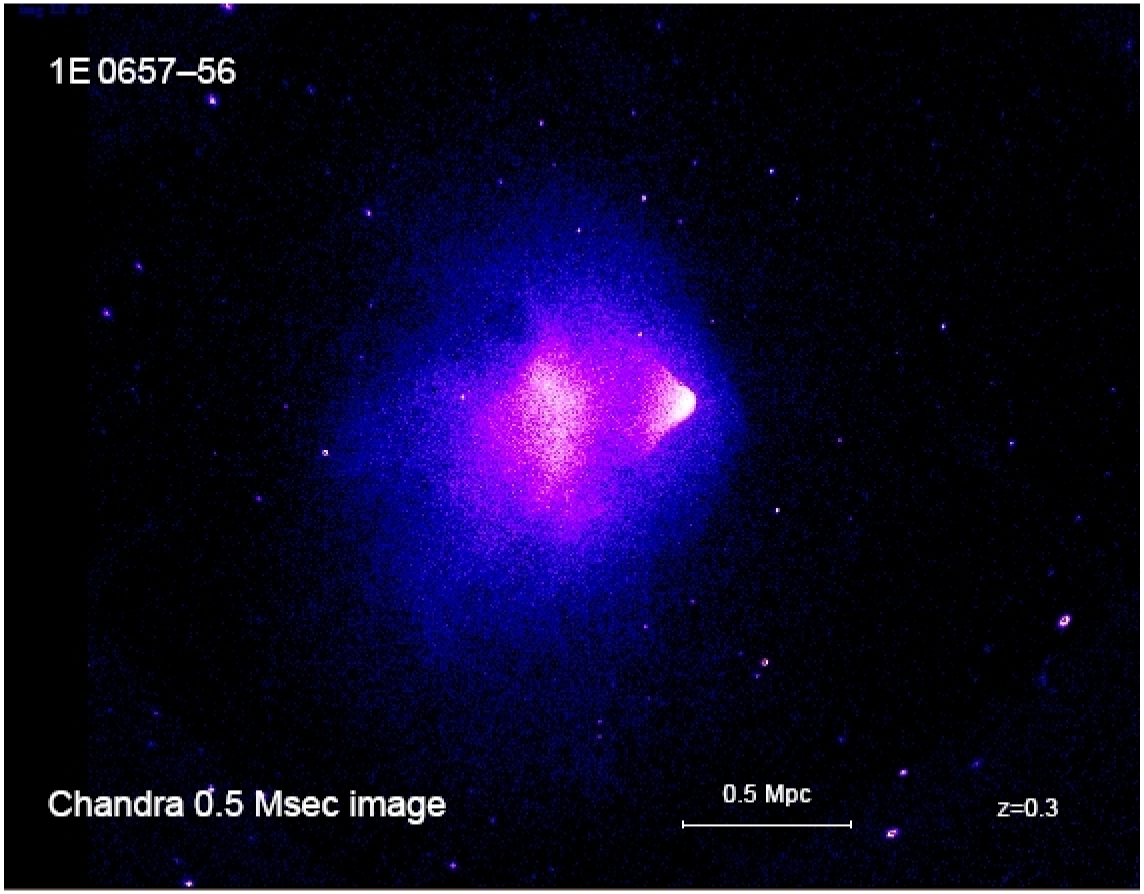
The Virgo Supercluster contains about 200 trillion (2×10^{14}) stars. But, its mass is about 10^{15} times that of the Sun. Since most stars are not huge, *there are not enough stars to explain the mass of the Virgo Supercluster!*

This 'missing mass problem' is also evident in other ways:

- 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.

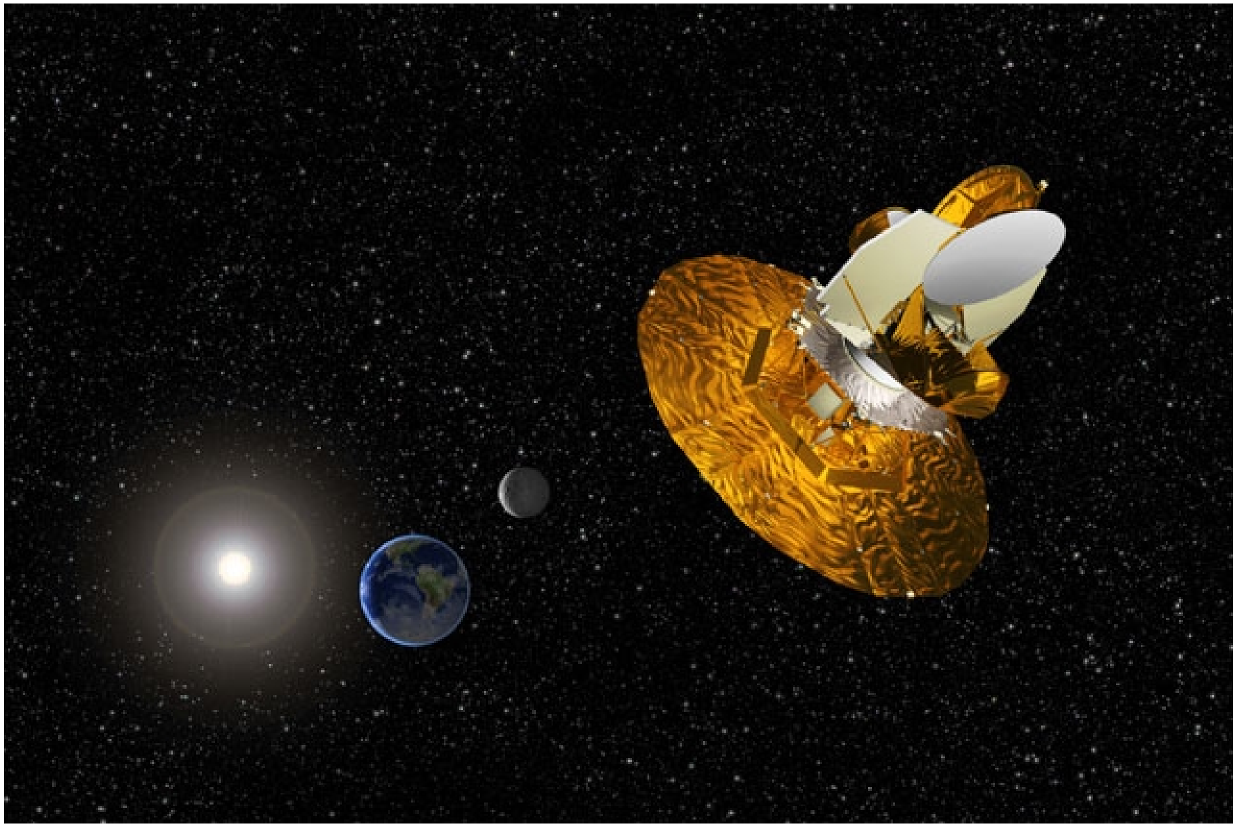
We need at least 5 times more cold dark matter than normal matter! *Or perhaps something more radical!* Maybe general relativity is wrong.

In 2005, scientists found evidence that cold dark matter is real, thanks to gravitational lensing in the Bullet Cluster:



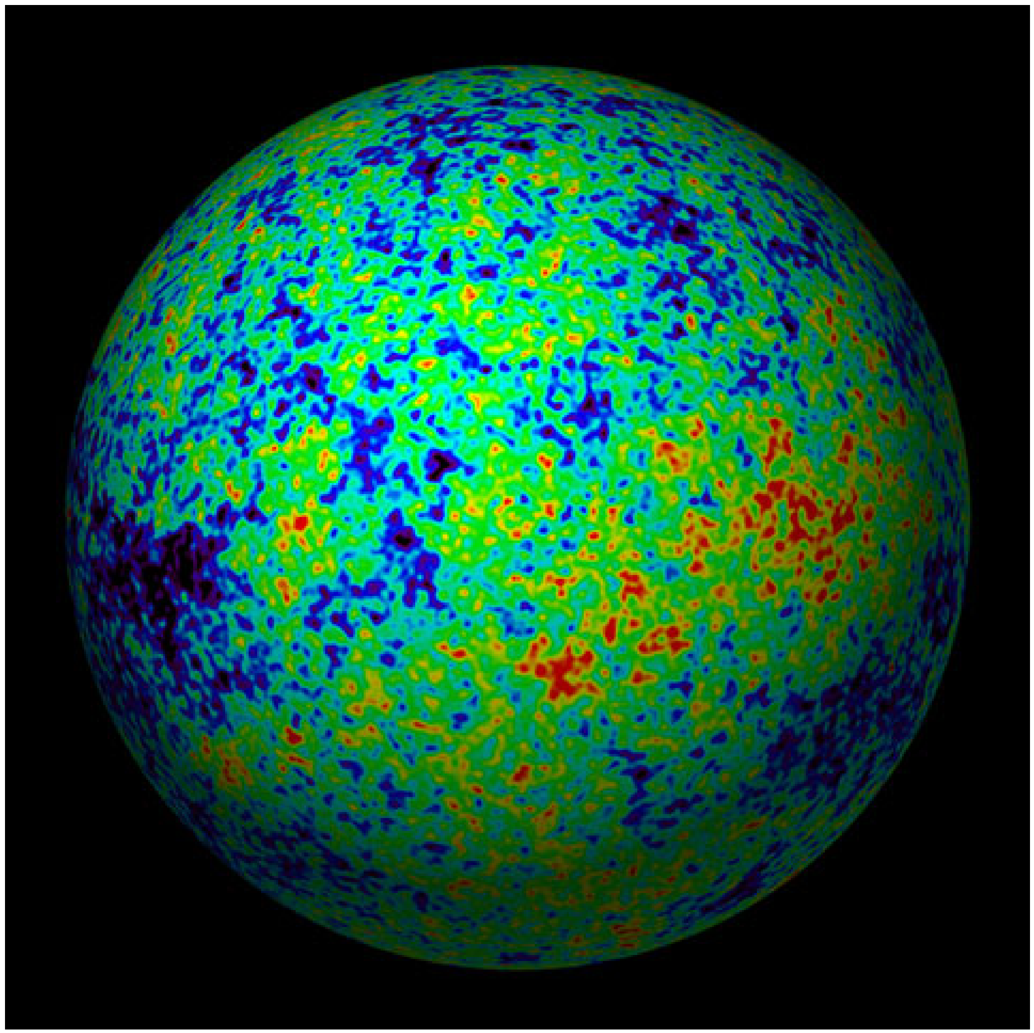
0.5 Mpc = 1.6 mega-lightyears

How much dark matter is there? The Wilkinson Microwave Anisotropy Probe (WMAP) gives the best estimates so far. This is a satellite in orbit with the Earth always between it and the Sun. Facing out into the night, it can measure temperature variations of 10^{-6} kelvin in the chilly radiation left over from the early universe:



NASA image

400,000 years after the Big Bang, the hydrogen in the Universe cooled and thinned enough to let radiation travel freely! As the Universe expanded, this radiation cooled to 2.73 kelvin... but it kept an imprint of that early moment:



NASA image

In 2003, the WMAP team estimated that the energy of our universe, including $E = mc^2$, is made of:

- **4% normal matter**
- **23% cold dark matter**
- **73% vacuum energy (= "dark energy")**

In fact, they estimate the density of vacuum energy is about 10^{-9} joules per cubic meter – equivalent to about 10^{-26} kilograms per cubic meter!

Mystery 7. What is cold dark matter – or what else explains what this hypothesis tries to explain?

For more mysteries, type

open questions in physics

into Google.

We can see that since the 1980s, *theory* has contributed much less to fundamental physics than *observations*. Theorists continue to make predictions, but they are usually wrong or not yet testable. This has led to a feeling of malaise. Why are they failing?

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.*

When string theory arose as a candidate for the final theory, many theorists became excited. In 1980, Hawking said he thought there was a 50% chance that we would know the final theory in 20 years!

This soon proved to be overoptimistic. But when their theories made incorrect or untestable predictions, many theorists failed to rethink their position. It is difficult to publicly retract bold claims.

Instead, some focused more and more attention on the *mathematical beauty* of their theories...some becoming mathematicians in disguise. (There are worse fates.) Others made the theory *more and more complicated* to try to fit the data — without much success.

Psychologically, the fate of string theory depends greatly on the results from LHC. Supersymmetry or not? Time will tell.

But meanwhile, experiments and observations continue, showing that we live in a universe that is *far from understood*, even at the simple level of fundamental physics!

This is not bad. It merely leaves more fun for our children and grandchildren. . . if we leave them a world in which they can afford to study such questions.