# Quantum reality

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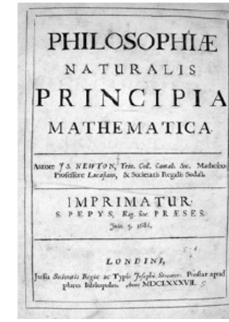
# Quantum century

- Quantum mechanics (and quantum field theory) is the defining physical theory of the 20th century.
- Quantum field theory is one the two fundamental theories of physics at the moment. (The other is general relativity, which describes space, time and gravity.)
- Quantum theory has overturned our conception of reality as concerns matter, being and happening.
- It is the foundation of all modern technology, and its impact on society is difficult to overestimate.

# Classical physics




Principia 1687

- In the 17th century, classical physics was established with Isaac Newton's Principia Mathematica.
- The view of reality of classical mechanics is close to our everyday ideas.

# Classical space and time: the world as a theatre

- Space is a passive stage for action.
- Time indicates at which point of the play we are.
- Both space and time are passive, eternal and unchanging: they do not care about events on-stage (i.e. what matter is doing).

# Classical matter and being: the world as a clockwork

- Matter consists of small grains (particles), stuck together. (Classical electromagnetism also includes *fields*; let's not get into them!)

- The grains exist continuously and have a fixed position in space at each time.
  - The world is *definite*. (The state of the world is unambiguous.)

- The grains interact with each other in such a way that, given the position and velocity of every grain at some time, their future and past is determined.
  - The world is *deterministic*. (Every effect has a cause.)

- There is no special present moment.

# From the classical to the modern

- In the late 19th and early 20th century, observations could not be explained in the framework of classical physics

- Classical physics gave way to modern physics: quantum mechanics and special relativity.

- Special relativity changed the view of space and time, quantum mechanics changed the view of matter and being.

- These evolved into quantum field theory and general relativity.

- Quantum field theory and general relativity have not yet been fully combined.

# Genealogy of modern physics

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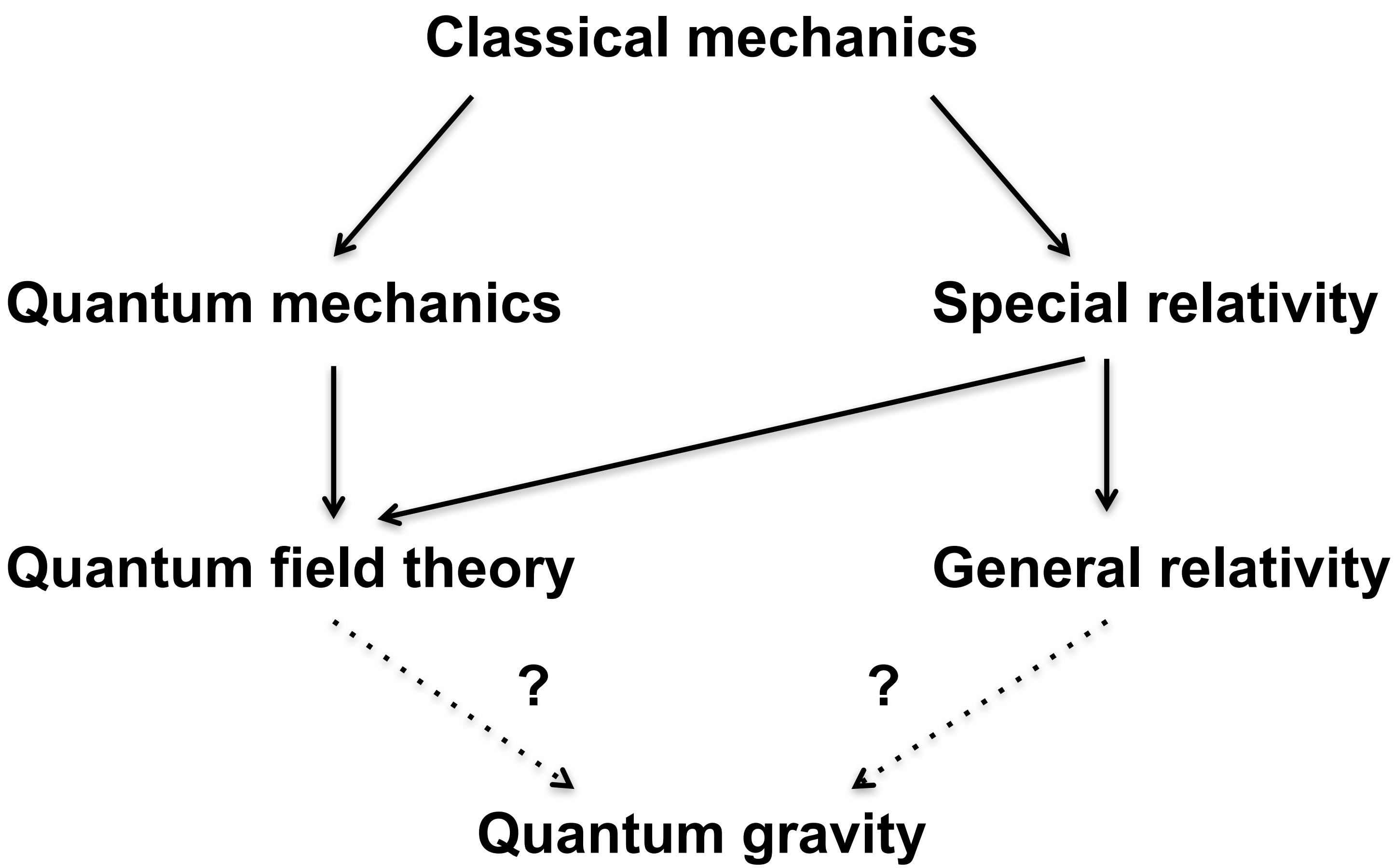
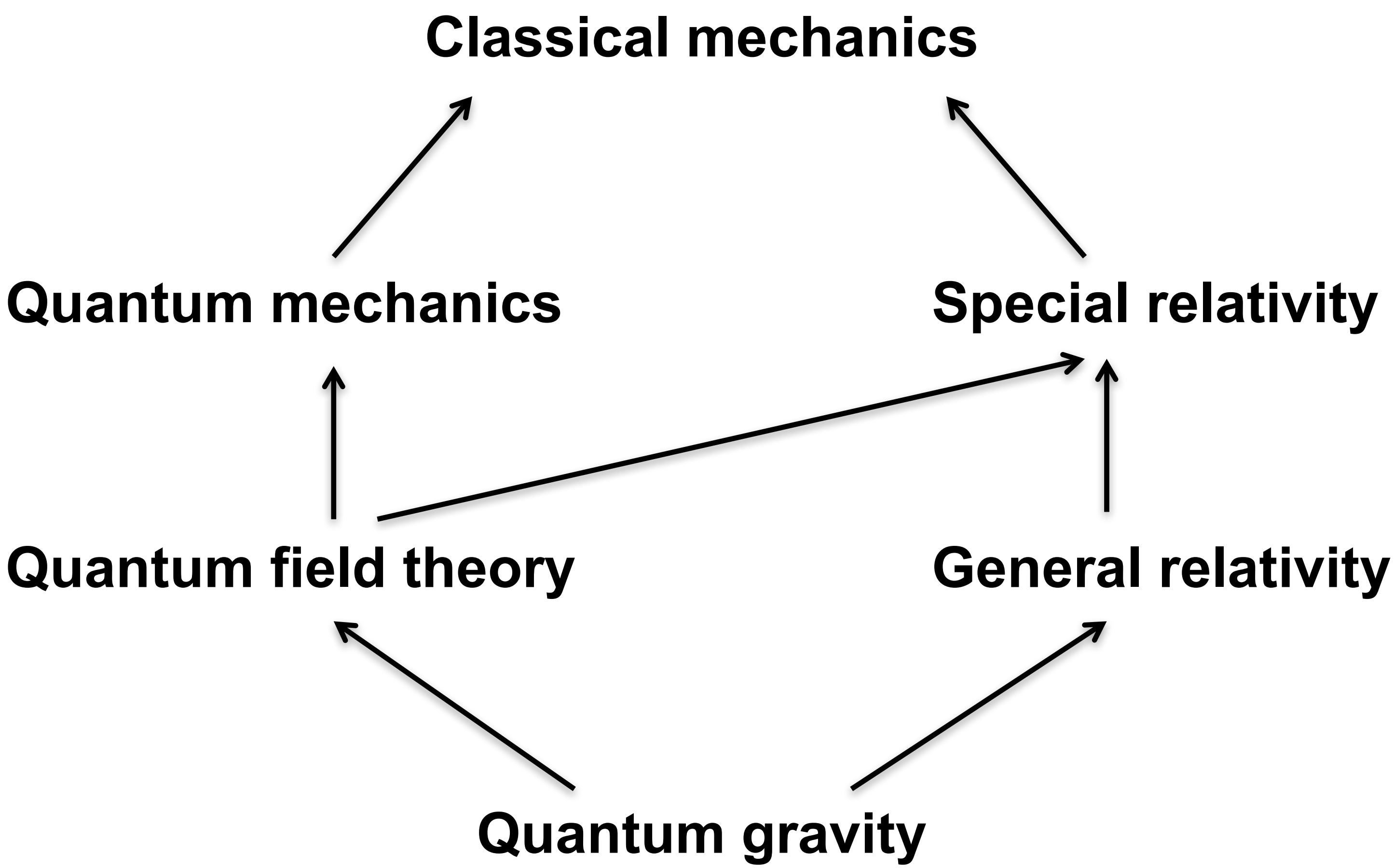


# Limits of physical theories



# Atomic problems

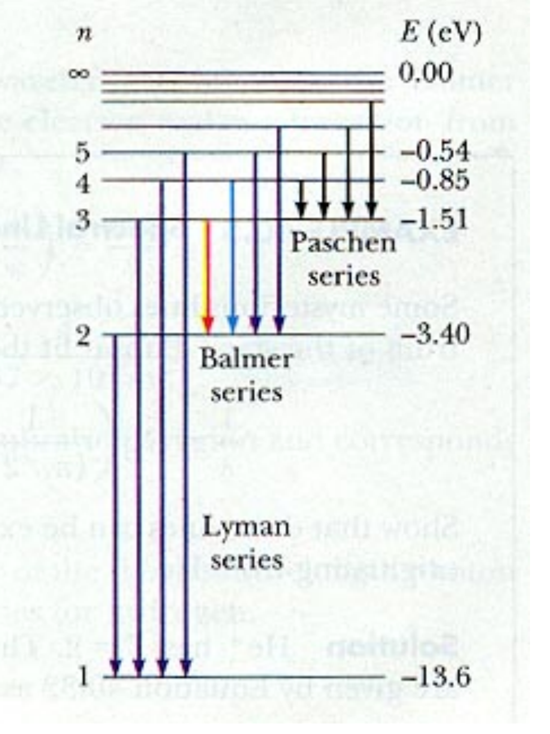
- In 1911, it was found by Ernest Rutherford that atoms have a positively charged nucleus, surrounded by negatively charged electrons.
- The Rutherford model of the atom is like a solar system.
- According to classical electromagnetism, charged objects in accelerated motion emit electromagnetic radiation.
- An electron would lose energy and fall down into the nucleus in less than a billionth of a second.
- Also, atoms were observed to only emit light at certain discrete wavelengths, instead of a continuum.

# Bohr model of the atom

- Niels Bohr proposed a solution in 1913: electrons orbit only at certain discrete distances: *quantisation*.

- If an electron jumps to to a closer orbit, it emits a photon (light particle). It has to absorb a photon to move up.

- Particles still have definite positions and velocities.



# Quantum mechanics

- The Bohr model was experimentally successful, but limited, and had no solid basis. It postulated quantisation, instead of explaining it.
- The full theory of *quantum mechanics* was found in 1925.
- Erwin Schrödinger formulated it in terms of the *wave function*, Werner Heisenberg, Max Born, and Pascual Jordan in terms of matrices.
- Both are ways of describing the *state* of the system.

# Deterministic state evolution

- The state of the system is the information that describes the system fully.
- In classical mechanics, the state is the positions and velocities of all grains.
- In quantum mechanics, the state cannot be expressed in terms of classical grains of matter.
- In both cases, state evolution is deterministic: given the initial state, the future state can be predicted. (In QM, the past cannot be determined, though.)

# Indefiniteness and indeterminism

- In quantum mechanics, two things are new:
  - The state does not correspond one-to-one to observable quantities. (Lack of definiteness.)
  - Relation of the state to observations is not deterministic.(Lack of determinism.)

# Wave function

- The state of the system can be represented by a wave function.

- The wave function says:
  - what are the possible results of observations (e.g. which kind of light an atom can emit)
  - what are the probabilities of the possible results

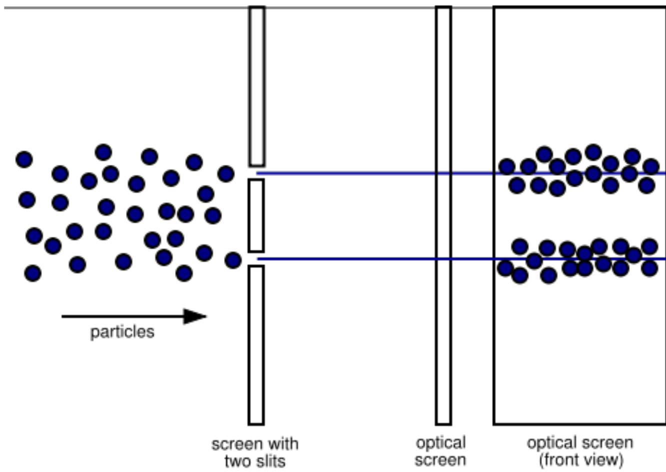
# Limits of being, not knowledge

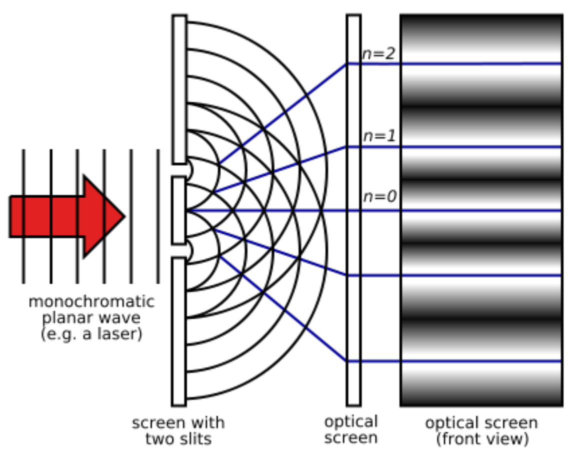
- In classical mechanics, a particle is modelled by a pointlike grain, and the state is its position and velocity.
- In quantum mechanics, a particle is modelled by a wave function. The wave function determines the probability of observing the particle at different points, and with different velocities.
- That is all.
- This is not a question of *not being able to know* more about the particle, but that *there is nothing else to be known*.

# Quantum mechanical model of the atom

- Bohr avoided the problem of atom instability (due to electromagnetic emission) by postulating discrete orbits.
- Bohr was wrong.
- In quantum mechanics, there is no problem because particles have no orbits. They do not have definite positions unless they are observed. Hence, they do not move in space along trajectories.

# The two-slit experiment




Interference pattern

light: 1803

electron: 1961

# To be and not to be

- The following statements about the electron are all incorrect:
  - It goes through the upper hole.
  - It goes through the lower hole.
  - It goes through both of the holes.
  - It doesn’t go through either of the holes.

- Classical language of matter as grains, with fixed position and trajectory, is insufficient.
  - Reality is *indefinite*.

- The wave function does not predict where the particle will fall, only the probability for it.
  - Reality is *indeterministic*.

# Wave function collapse

- When we observe the electron at one point, we know that the electron was there at the observation time.
- It is said that the wave function *collapses*: instead of a continuous probability distribution, the probability is 100% in one place and 0% everywhere else.
- Because the outcome of the observation is random, state evolution at collapse is indeterministic.
- Thus the present state does not determine the past.
- In quantum mechanics, there is a special moment of happening, when indefinite past is transformed into present certainty.

# Schrödinger's cat

- In 1935, Schrödinger illustrated quantum reality with the following thought experiment.
- Put a cat inside a box. In the box, there is a vial of poison gas, attached to a radioactive atom. If the atom decays, the vial is broken and the cat dies. If not, the cat lives.
- If we do not observe inside the box, the atom's state is indefinite. Thus also the state of the cat is indefinite.
- Before we open the box, the cat is neither dead nor alive, it just has a probability of being dead or alive.

# Appearance of definiteness

- Indefinite states are seen in the two-slit experiment.
- Why do we never see them in everyday life, for macroscopic objects? (The largest molecule for which the two-slit experiment has been done has 810 atoms.)

# The Copenhagen interpretation

- According to the Copenhagen interpretation, the state collapses on observation.
- This is a workable rule for most physics purposes.
- Problems:
  - Puts the observer in a special position. Who qualifies as an observer? What if we put Schrödinger in the box and leave the cat outside?
  - Who observers the observers? (Observer is assumed to be in a definite state.)
  - What about the state of the entire universe?

# Decoherence

- Part of the cat problem is solved by *decoherence*.
- System is called decoherent when there is no interference between states corresponding to different observations.
- Interaction between the box and the observers *entangles* them, so that if one is definite, so is the other.
- Thus observers of non-isolated systems see only definite states. (It's difficult to isolate a cat.)
- Decoherence does not explain how the state of the entire system becomes determined (collapse), nor say which of the alternatives is seen (indeterminism).

# Quantum precision

- The quantum mechanics of 1925 made it possible to calculate atomic spectra more precisely than the Bohr model.
- It also allowed to understand and manipulate the structure of atoms (periodic table), nuclei and molecules.
- All electronics and all modern chemistry –in other words, all modern technology– is based on quantum mechanics.
- The societal effects of electronics, chemistry and so on are incalculable.

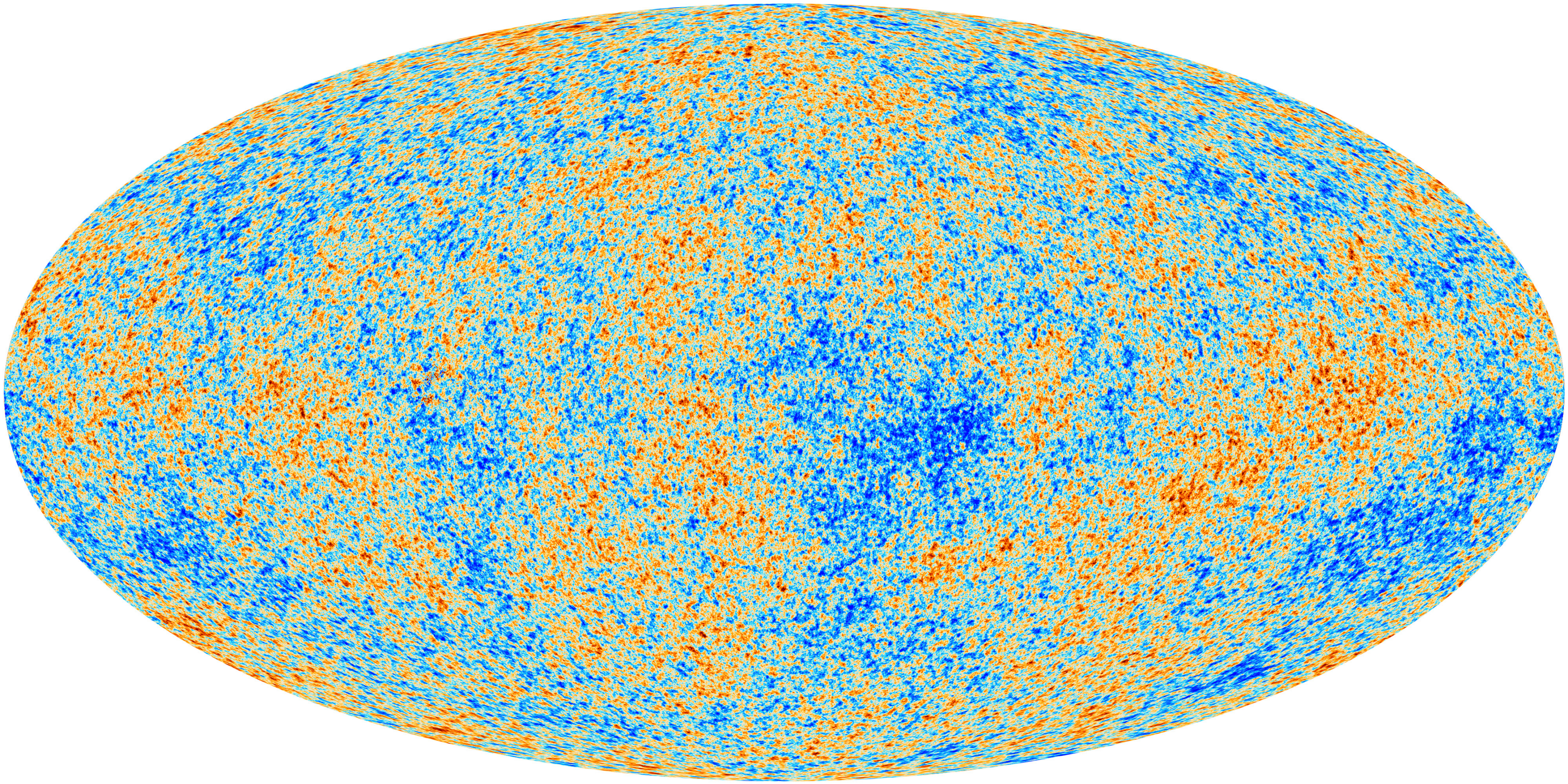
# Beyond quantum mechanics

- In the 1940's quantum mechanics was unified with special relativity in quantum field theory (QFT).
- (Some of the successes credited to quantum mechanics above require QFT.)
- QFT has allowed us to understand the fundamental building blocks of matter and its interactions at a level beyond atoms, nuclei, protons and neutrons.
- QFT is the most precisely tested theory in history, agreeing with observations at the level of one part $10^9$.
- QFT has not been fully united with general relativity.

# Quantum seeds of structure

- Unifying QFT and general relativity has been studied since the 1950s, but remains unaccomplished.
- However, there is one area of overlap where it has been possible to observationally probe quantum gravity.
- In the early universe, during a small fraction of the first second, the expansion of the universe (likely) accelerated.
- The universe, including the probability distribution of perturbations, became smooth.
- As the state became determined (how?), one possibility was realised, and formed the seeds of all cosmic structure.

# The seeds of structure



http://sci.esa.int/planck/51553-cosmic-microwave-background-seen-by-planck/

# Reality beyond imagination

- Quantum theory is the most precisely tested and most technologically fertile theory of physics.
- It has overturned everyday notions of reality in a way that would have been inconceivable a hundred years ago.
- The appearance of definite macroscopic reality is not understood.
- The union of quantum theory and general relativity is yet to be achieved.