Fundamental physics asks philosophers new questions

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The breakthroughs of the last 40-45 years in fundamental physics

1. Cosmology has become a precise quantitative science due to the emergence of inflation models, the associated theory of cosmological perturbations, and precision experimental data capable of verifying these models.

2. The development of quantum information science, which makes intensive use of entangled quantum states and decoherence theory.

3. The emergence of a large number of meaningful theoretical models of quantum gravity, including string theory, loop quantum gravity with spin foam models, etc.

- Several new methodological issues have arisen in the depths of these new directions that have not been given sufficient attention by the philosophy of scince.

- Are all these issues really noticed by philosophers?

- A few of these problems without trying to solve them will be formulated here.

Preliminaries

- About the notions and meanings of experiment, measurement and state in quantum physics (ansemble approach, D.I. Blokhitsev)

- The nature of mathematics and the mathematical reality

About the notions and meanings of *experiment*, *measurement* and *state* in quantum physics (ansemble approach, Dmitry Blokhitsev)

Theoretical physics produces models that provide observable predictions.

Experiments test the predictions of the theories, confirming the theories or disproving them

The cycle of empirical science

- An experiment is something that can test a theory
- A quantum theory ***generally*** cannot predict the result of a single quantum measurement. QT produces statisticl predictions.
- A single quantum measurement cannot test the prediction of quantum theory
- A single quantum measurement has no status of an experiment within quantum theory

$\psi(x) = \rho(x)e^{i\varphi(x)}$

May be measured separately:

- coordinate probability distribution $X(x)$
- momentum probability distribution $P(p)$

$X(x), P(p) \Rightarrow \rho(x), \varphi(x)$ (up to a constant)

- An experiment in quantum theory is a measurement over an ensemble of systems prepared in the same initial state.
- The ensemble is potentially as large as you want collection of systems in the same state
- In the measurement over the ensemble the statistical predictions of quantum theory can be checked with any accuracy.
- It is possible to apply any mutual-additive (and mutual-excluding) quantum measurements to the same ansamble of states, that allows to reconstruct the structure of the wave function of the system with any accuracy in all details.
- The wave function of a quantum system is an operationally defined quantity within the formalism of quantum theory.

The nature of mathematics and the mathematical reality (a sketch)

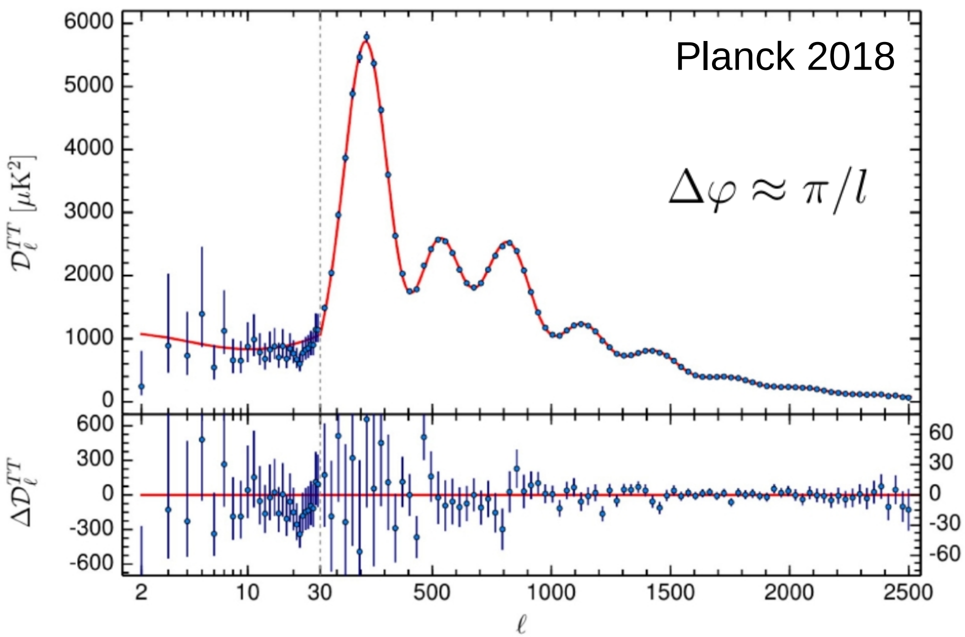
- Consider the trillionth decimal expansion digit of the number $\sqrt{4711}$
- Nobody knows it now, it is not written down anywhere (simply because nobody needs it)
- However, if different people start calculating this digit, they will get the same result.
- Why?
- Because this result objectively ***existed*** before anyone started to calculate it.
- Where did it exist? - In an objectively existing mathematical reality.
- Mathematical reality exists objectively, but not in space-time like matter and energy.
- To exist objectively does not mean to exist necessarily in space and time.
- The existence of an objective world of mathematical forms is not a metaphysical statement, since it is falsifiable in Popper's sense.
- Actually, it is enough to present two different correct calculations of the same mathematical object with different results, and the objective existence of mathematical reality will be disproved (falsifyed).
- *Objection:* But the consistent nature of mathematics guarantees that the result will be the same!
- *Reply:* Gödel's second incompleteness theorem says that if mathematics is indeed consistent, then it is impossible to prove its consistence.
- We cannot be sure of the consistency of mathematics, so comparing the results of different calculations of the same object is always non-trivial.
- Confidence in the consistency of mathematics is based only on experience, and on nothing else (Bourbaki, Volume I)

Problems

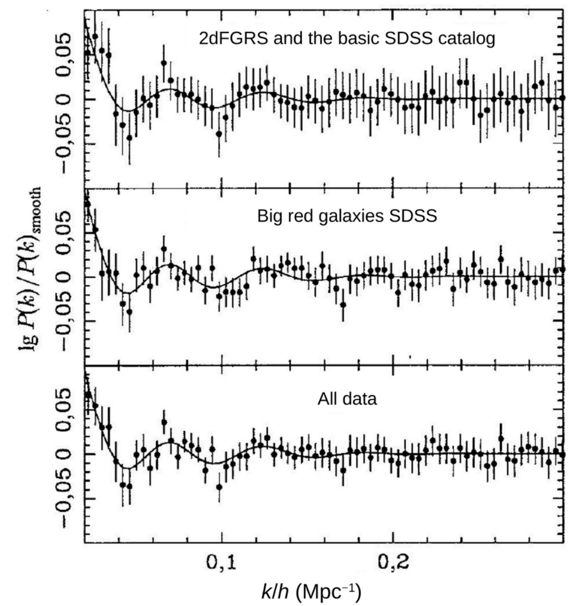
- **Problem 1. Cosmic variance and the meaning of the theoretical cosmology**
- **Problem 2. The epistemological status of the Multiverse and "other universes"**
- **Problem 3. Operational status of quantum macrostates**
- **Problem 4. The final theory and the meaning of physical reality**
- **Application of the philosophy of the final theory for understanding superstring theory**

Problem 1.
Cosmic variance and the meaning of the theoretical cosmology

Among the modern cosmoly data very important are the data on anisotropy of the Cosmology Microwave Bacground (CMB) and data on the distribution of baryonic matter in the Universe.



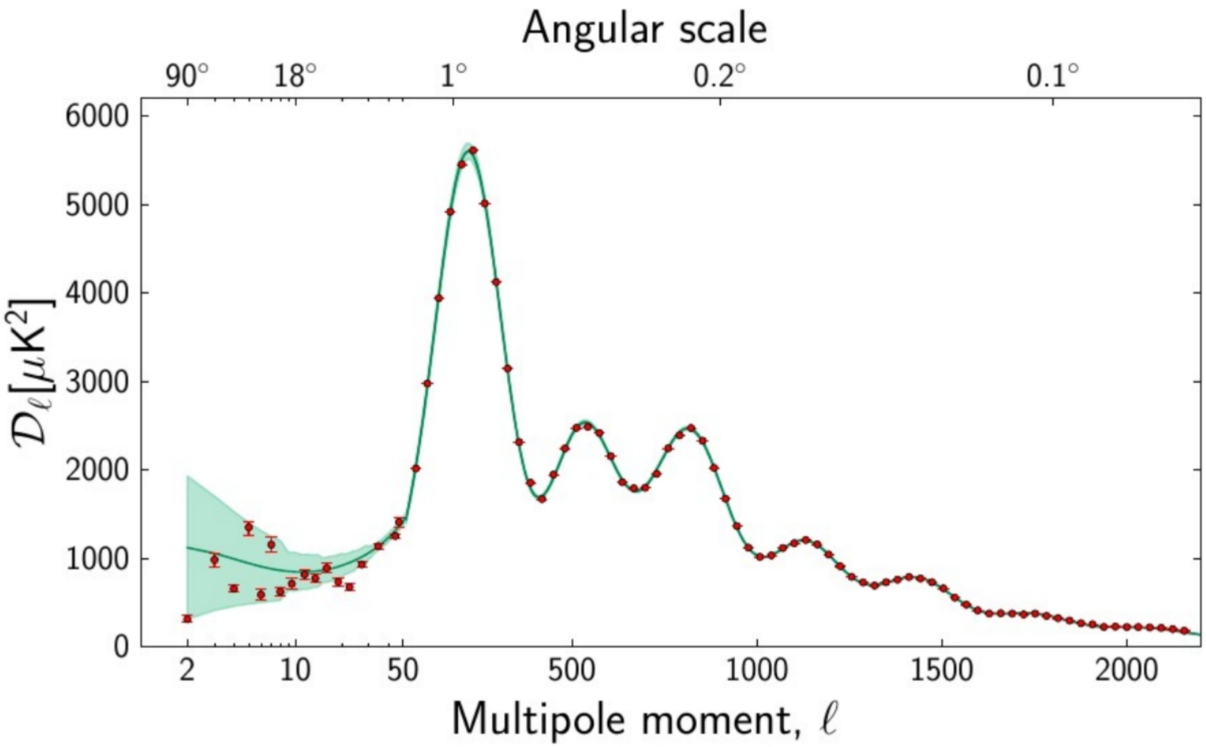
Anisotropy of the temperature of (CMB)



Baryonic Acoustic Oscillations (BAO)
W.J. Percival et al MNRAS 381(2007)1053

- The standard cosmological model ΛCDM describes all observations very well using only 6 free parameters.
- The ΛCDM predicts probability distributions and expected magnitudes of cosmological perturbations.
- The predicted probability distributions are distributions over the ***ensemble of universes***. It is in the nature of the theory of cosmological perturbuations.

- We must have access to an infinite ensemble of universes to test the predictions of the ΛCDM cosmology with exhaustive accuracy.
- But we have access only to a single instance of the universe
- So we fundamentally cannot test the predictions of cosmological models with exhaustive accuracy - this is the ***cosmic variance*** problem



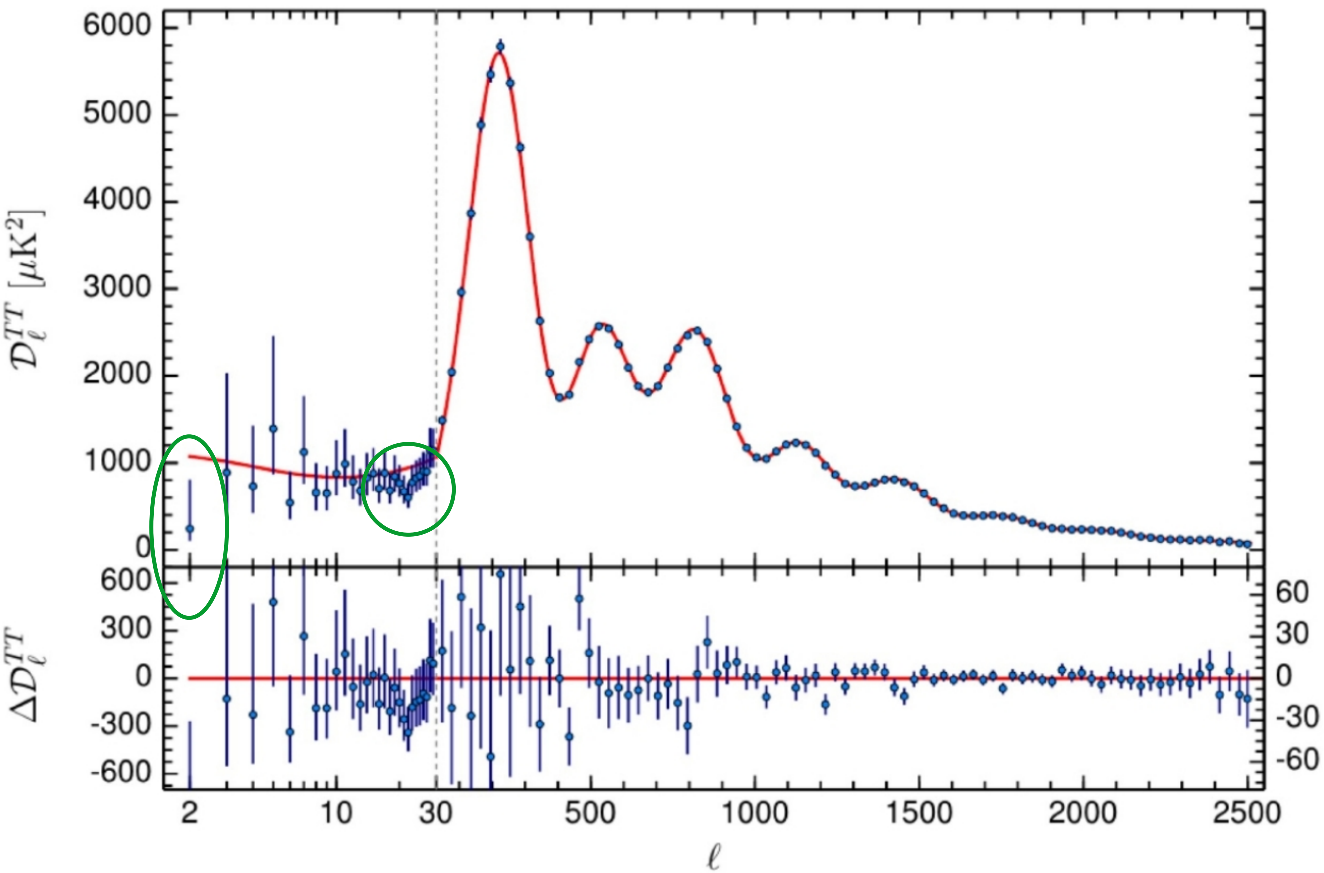
Red error bars — experimental errors of amplitudes of temperature fluctuations in our sky

Light green corridor — irreducible erorrs of cosmic variance

$$\Delta\mathcal{D}_l = \frac{\mathcal{D}_l}{\sqrt{l+\frac{1}{2}}}$$

- The theory of cosmological perturbations is a statistical theory, as well as quantum mechanics.
- Moreover, the source of cosmological perturbations are irreducible quantum fluctuations of the inflaton field (or fields) at the inflation stage of the history of Universe.
- The source of statisticality in the theory of cosmological perturbations is fundamentally the same as the source of statisticality in quantum theory.

- The quantum theory admits the use of arbitrary large ensembles of quantum systems for exact test of predictions of the theory.
- However, unlike quantum theory, in the theory of cosmological perturbations only one element of the infinite ensemble of universes, which is described by this theory, is accessible.
- The consequences of this - the impossibility of exact verification of predictions of cosmological models - are absolutelly dramatic.



- **The quadrupole problem:**
  - Why is the amplitude of the quadrupole ($l = 2$) so low?
  - Is it an accident event, or may be a consequence of the unusual topology of the Universe?

- **The $l = 20$ problem:**
  - What explains the dip of the curve in the $l = 20$ region?
  - Is it an accident, or is it a defect of ΛCDM theory?

- There is NO way to answer these questions and there NEVER will be.

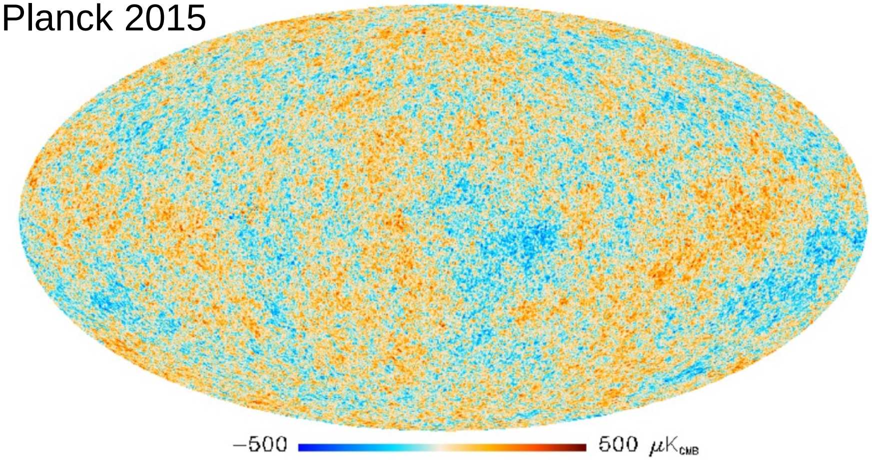
- Somewhere in the Universe there are places where for accidental reasons (unusual fluctuation of the inflaton field) the CMB anisotropy has nothing in common with the ΛCDM predictions. What should the inhabitants of such places in the Universe think?

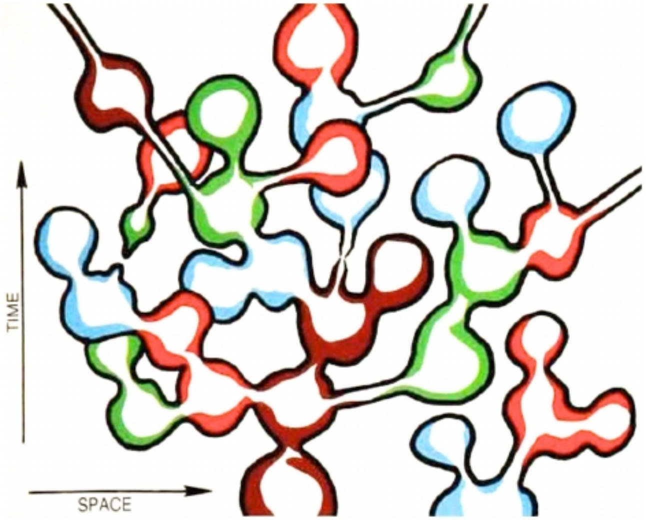
Summary and questions.

- Unlike the rest of all other physics (including quantum theory), theoretical cosmology, especially the theory of cosmological perturbations, cannot be precisely verified by experiment due to the internal structure of the theory.
- What then is the epistemological status of cosmology?
- Can cosmology be regarded as a true empirical science?
- Does it mean the limit of empirical cognition?

Problem 2:
The epistemological status of the Multiverse and "other universes"

Planck 2015

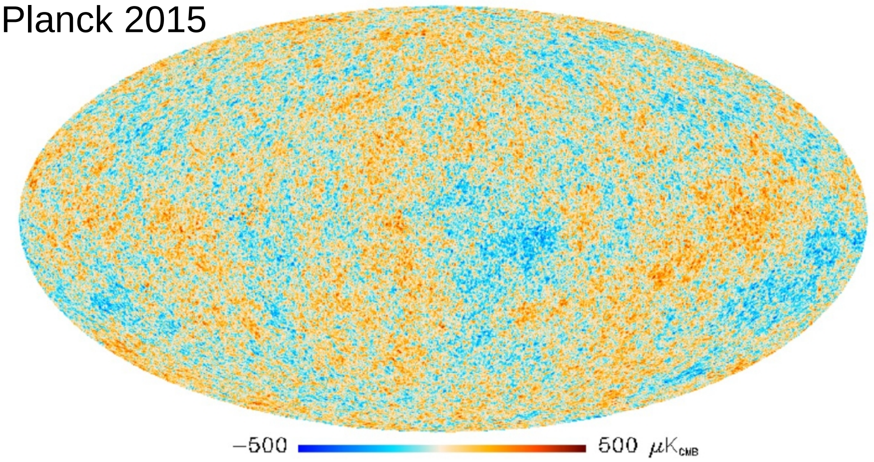


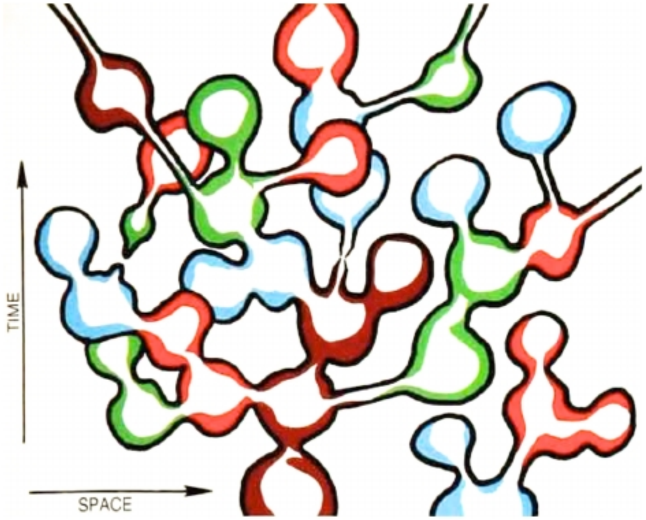


Global structure of a chaotic,
self-reproducing inflationary universe.
Different colors mean different physics
(different symmetry breaking)
Picture of Andrei Linde, arXiv:1512:01203

- The inflation model explains CMB anisotropy, and, within the standard ΛCDM model, quantitatively describes CMB anisotropy and other observations very well.
- Moreover, CMB anisotropy was predicted in the inflation model before it was discovered.
- CMB anisotropy is the imprinting of irreducible quantum fluctuations of the inflaton field into the picture in our sky.
- Therefore, without the idea of quantum fluctuations of the inflaton field, what we see in the sky cannot be explained.
- However, the same irreducible quantum fluctuations, which lead to the visible picture of CMB anisotropy, lead to another conclusion: the inflation process generates not only one (our) Universe, but also many other "local" universes, which may or may not be similar to our Universe.
- This multitude of other universes is called the Multiverse.
- ***Conclusion:*** it is impossible (very difficult?) to explain the observed CMB anisotropy and explain all other observed phenomena without simultaneously predicting the existence of the Multiverse.

Planck 2015





Global structure of a chaotic,
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- Each local universe of the Multiverse is completely unreachable for us, since it is separated from us by a space-like interval.
- We fundamentally have no empirical way to directly test the existence of other universes of the Multiverse, unless there exist some passable "bridges" between local universes like wormholes.

Questions:

- Given that all other universes of the Multiverse lie beyond the reach of empirical methods, what is the epistemological status of these objects?
- Should we consider the other universes of the Multiverse to be only objects of mathematical reality arising in the context of the theory of eternal chaotic inflation?
- Or are other universes "more real" than just the mathematical objects of the world of objective mathematical forms?

Problem 3
Operational status of quantum macrostates

- It is supposed in quantum theory that for any quantum state there is a possibility to create an ensemble of any size.
- In other words, it is supposed the procedure of preparation of a quantum state to be reproducible.
- Due to this all quantum probabilities and the very notion of quantum state acquire a clear operational (ensemble) meaning.
- Macroobjects consist of quantum microsystems and, it would seem, should be quantum objects as well.
- However (generally speaking) the decoherence time of quantum states of macroobjects is so small that it is fundamentally impossible either to prepare an ensemble of systems in a given state and, even more, to make a measurement over the system.
- *Example:* Decoherence time of a 10 μm dust particle:
  300K + 1 atm air 10^{-31} sec;
  300K + absolute vacuum 10^{-11} sec
- Question: what is the meaning of the statement that a macroobject has a quantum state if this quantum state does not lead to any operationally definable characteristics?
- Clarification: The only type of states of macrosystems for which a reproducible ensemble can be prepared are statistical mixtures indistinguishable from classical probability distributions
  (the density matrix is strictly diagonal).
- Should we assume that macrosystems can be characterized by classical states only?
- Is it correct that ***any*** macrostates are operationally indefinable?
- It is incorrect: there are macrostates separated from the environment and protected from decoherence by an energy gap. For example, superfluids or superconductors. There are other ways: topological protection, quantum correction codes in quantum computing.
- But generally there is no protection against decoherence, therefore decoherence is very strong and operationally-defined quantum description is impossible.
- Possible objection: Let's isolate macrosystem from environment completely. We can use a chamber with walls at absolute zero temperature +
  absolute vacuum +
  protection from all radiation, including neutrinos.
- This does not solve the problem in the general case, since
  1) not all macrosystems make even sense under such deep isolation conditions
  2) it is not always possible to reproducibly prepare the initial state of the macroscopic system even if there is isolation of the system from the environment due to an energy gap or other methods.

Example 1.
Quantum information in biological objects.

- Quantum informatics allowed to create the first working prototypes of quantum computers.
- For quantum computers the conditions of quantum coherence conservation and reproducibility of initial state preparation are fulfilled.
- Question: Could similar quantum modes of information processing play a role in the brain or even just in any living cell?
  (Sir Roger Penrose, Stuart Hameroff)
- Problem: Even if there are quantum modes in a neuron or in a living cell, sufficiently isolated from the environment (it is, in principle, not impossible), we cannot transfer a living cell to a given quantum initial state in a reproducible way.
- Therefore it is impossible to create an ensemble of quantum states for a living cell, therefore quantum modes of information processing of a living cell can not have ensemble operational sense.

Example 2.
Quantum state of the Universe

- CMB anisotropy is defined by quantum fluctuations of the inflaton field of the scale of the visible event horizon of the Universe.
- To describe the CMB anisotropy the use of quantum states of the infation field of the scale of the visible Universe looks inevitable.
- However, we observe a single instance of the Universe, so it is fundamentally impossible to create an ensemble of quantum states for the visible part of the Universe to study it
- The quantum state for the visible part of the Universe is operationally indefinable, but we must use this concept for prediction of CMB anisotropy.
- The situation is very similar to the origin of the phenomenon of *cosmic variance* - in fact it is the same *cosmic variance*, but translated into the language of quantum ensembles.

Macroscopic quantum states:
Summary and Questions.

- There is an operationally definable part of quantum theory, where all predicted quantities and the very notion of quantum state has a well-defined ensemble operational sense.

- At the same time, there are a lot of situations in which it looks inevitably to use operationally indefined quantum probabilities or quantum states.

Questions:

- Is it true that we have two different quantum theories (ensemble QT and "Bayesian" QT)?

- Can the "Bayesian" version of quantum theory be considered as a true part of normal empirical science?

Problem 4
The *final theory* and the meaning of physical reality

- Physical theories are represented by mathematical models, and mathematical models are consistent mathematical systems belonging to the objective world of mathematical forms.
- All confirmed physical theories (Standard Model, ΛCDM-cosmology) are considered as ***approximate*** descriptions of reality, none of them claiming to be "complete" or "final".
- It is assumed that a deeper description of physical reality is possible, from which existing theories may be derived as approximations or limiting cases. This is called the correspondence principle.
- **Question:** is there a limit to the refinement of physical theories in depth?
- **Answer:** It's unknown.

- However, it is widely believed that such a "regression to infinity" is impossible. In particular, the limit may be related to the Planck scale of energies, distances and times
- If "regression to infinity" is impossible, then there must be a ***final theory*** that provides an exhaustive description of physical reality at the deepest level and does not allow for refinements.
- All other physical theories must be deduced from the ***final theory*** as some emergent phenomenology, or, in other words, they all can be reduced to the ***final theory***.
  Hence another name for the final theory is the ***theory of everything***.
- The search for a ***final theory*** is actively pursued. It is supposed that the final theory is some form of quantum gravity plus the unification of gravitation and all other interactions into a single united theory.

- If the ***final theory*** really exists and admits a mathematical description, there is nothing outside this mathematical description.
- Therefore the mathematical description of the ***final theory*** turns out to be identical to the physical reality it describes.
- Unlike all existing theories, which are approximate mathematical models, the ***final theory*** is not a model of anything, but is identical with the object of its description.
- **Question:** what does this mean? Answer options:

1. The physical reality of the ***final theory*** is nothing more than a consistent mathematical system (Max Tegmark).
2. The mathematical system corresponding to the ***final theory***, while conserves its reality in the world of mathematical forms, also acquires the additional status of physical reality.
3. The ***final theory*** is a synthetic object of a new type, which is neither a physical reality nor a mathematical system, but it disintegrates into physical reality and a set of mathematical models of physics in the "low-energy limit".
4. May be all answers 1-3 are true at the same time?
5. Could there be something else?

- Max Tegmark was one of the first who clearly posed this question.
- According to Max Tegmark the answer is obvious, it is the answer number 1. In this case we have the following implication:
- If the ***final theory*** exists, then we live in a «mathematical matrix» and are ourselves mathematical objects.
- This is NOT a hypothesis, it is a simple logical conclusion from 1) the existence of the ***final theory*** plus 2) answer number 1.
- Max Tegmark asks: what distinguishes the mathematical system of the ***final theory*** from other mathematical systems? Why just this system is a physical reality?
- Max Tegmark's answer was "the mathematical democracy": All consistent mathematical systems ***are*** physical realities, and our mathematical system is only one of those that are complex enough to support the existence within it an observer.
- Mathematical democracy is by no means a trivial thing. For example, answer number 3 does not lead to mathematical democracy in a simple way.
- Rather, option 3 leads to a **different question**:
- Might there be a common root to all mathematics (not just mathematical models of physics) and all physics that is itself neither physics nor mathematics?
  May it be that there is a common root of physical reality and mathematical reality?

Application of the philosophy of the *final theory* for understanding superstring theory (M-theory)

- In the general relativity, space and time appear to be dynamical objects, and like any dynamical objects, must be subject to the quantum theory.
- It follows from quantum theory that space-time must fluctuate very strongly on the Planck scales of length, time and energy.
- There is no smooth spacetime on Planck scale.
- Therefore, to describe spacetime on Planck scale we need a quantum theory of spacetime (quantum gravity).
- *Absence of smooth spacetime on Planck scale is the initial prerequisite of any quantum theory of gravity.*

- **Superstring theory** is one of the candidates for quantum theories of gravity.
- At the same time, superstring theory is developed as a quantum theory of motion of one-dimensional ***Planck-scale*** objects (strings) in ***smooth spacetime***.

- **Question:** What is the smooth background spacetime, in which the motion of ***Planck-size*** strings is considered, given the fact that any quantum gravity must start from ***absence*** of smooth space-time on ***Planck scale***?
- One would expect any monograph on string theory to begin with a discussion of what this smooth spacetime background means, given that there can be no physical spacetime on the Planck scale. However, no monograph (that are known for me) discusses this issue at the very beginning or anywhere else.
- The smooth "spacetime" of the string theory background cannot relate to physical spacetime. It is by construction a ***purely abstract*** background, in which the dynamics of ***purely formal*** objects - strings - is ***purely formally*** considered.
- It is not defind *a priori* what all this can have to do with real space-time.
- The background space of string theory is much more similar to isotopic spaces for describing internal degrees of freedom of elementary particles than to physical spacetime.
- Rather it looks that this background space somehow describes something like the internal degrees of freedom of a "quantum of spacetime", just as isotopic spaces describe the internal degrees of freedom of elementary particles.

- It is known that a consistent superstring theory can be constructed only in the background spacetime of dimension 10 or 11.

- On this basis string theorists very often say (especially in popular publications) that "our space is 10-dimensional or 11-dimensional, but some space dimensions are compactified on Calabi-Yau manifolds of Planck scale, so these dimensions are not visible to us".

- Actually there is no compactification of ***our*** space on Planck-size manifolds and there cannot be, because on Planck scales there is no space-time at all, space is not a smooth differentiable manifold, so there is no notion of space dimension and there is simply nothing to compactify.

- This is directly seen in such quantum theories of gravity as loop quantum gravity or the theory of causal sets where smooth space-time is an emergent phenomenon at large distances only, but the same must take place also in the general case.

- The string theorists' claims about 10 or 11 dimensions refer actually only the formal mathematical structure of the background of string theory, not to physical spacetime.

- How ***physical*** space-time is related to string theory is a difficult question.

Back to the philosophy of the *final theory*

- In the ***final theory*** the most fundamental level of physical reality is some mathematical structure identical to the physical reality at the deepest level.

- All other physics is obtained from this structure in some ***emergent and unknown beforehand way***.

- It is important that this mathematical structure itself does not have to have any characteristics directly corresponding to emergent physical concepts of higher level.

- The structure of string theory is very similar to the expected structure of the ***final theory***.

- There is nothing wrong in the fact that string theory is built in an abstract smooth background space, which has no direct relation to physical space-time. It is only necessary to realize that the background space of string theory is not the physical space.

- Quantum dynamics of strings in formal smooth background "space-time" can be those consistent mathematical system, which defines the fundamental physical reality. ***Physical spacetime*** can be obtained from here in some emergent way, but this way is not predeafined in advance and may not be simple.

- String theory is not the only candidate for a ***final theory*** (quantum gravity)

- Other candidates are:

  - different forms of loop quantum gravity and spin foam models
  - different forms of causal set theory,
  - the Regge calculus and tranguagltions,
  - Vitaly Vanchurin's network theory.
  - etc.…

- All of them have some features of the ***final theory*** in that they are based on formal mathematical structures rather far from observations, and these mathematical structures often have even an abstract combinatorial nature, not space-time or field nature, as in the string theory.

- We do not know whether there is a "correct candidate" among the applicants for the role of the true ***final theory***.

Thank you!

To the minimal length

$$\text{Unsertainty relation: } \Delta x \cdot \Delta p \geq \frac{1}{2}\hbar$$

$$\text{Maximal momentum uncertainty: } \Delta p_{max} = mc$$

$$\text{Minimal spatial uncertainty: } \Delta x_{min} \cdot \Delta p_{max} \geq \frac{1}{2}\hbar \;\Rightarrow$$

$$\Delta x_{min}(m) \geq \frac{1}{2}\frac{\hbar}{mc} = \frac{1}{2}L_C(m)$$

The greater m the less Δx_{min}

But the greater m, the greater Shwartzshildt radius of particle: $r_g(m) = \dfrac{2Gm}{c^2}$

The maximal possible point-like mass is defined by $r_g(m) = \Delta x_{min}(m) \;\Rightarrow$

$$\frac{2Gm}{c^2} = \frac{1}{2}\frac{\hbar}{mc} \;\Rightarrow\; m = \frac{1}{2}\sqrt{\frac{\hbar c}{G}} = \frac{1}{2}M_{Pl}$$

For the absolutely minimal Δx_{min} we obtain:

$$\Delta x_{min} = \frac{\hbar}{M_{Pl}c} = \sqrt{\frac{\hbar G}{c^3}} = X_{Pl}$$