Some open questions in physics

Krzysztof A. Meissner
Instytut Fizyki Teoretycznej UW
Instytut Problemów Jądrowych

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- Quantum Mechanics
- Standard Model
- dark matter and dark energy
- quantum gravity
- summary
The most incomprehensible fact about the Universe is that it is comprehensible

A. Einstein
Introduction

- (part of) reality can be described by numbers
- there are correlations among these numbers – physical laws
- with proper idealization these laws seem to be universal and rigorous
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- (part of) reality can be described by numbers
- there are correlations among these numbers – physical laws
- with proper idealization these laws seem to be universal and rigorous
- we have no idea why these statements hold the answer belongs to meta-physics rather than physics...
Introduction

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• but mathematics gives us also a rigorous proof that cognition has its limits:

Gödel theorem + finite resources

“Theory of Everything” is impossible
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• how far can we go?
Cube of theories

Fundamental dimensionful constants: $1/c, \hbar, G$
Quantum Mechanics

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Quantum Mechanics

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- conceptual foundations (and limits) of locality, causality, Heisenberg relations unclear
- problem of measurement (Copenhagen, Everett, Bohm, Penrose, ...) totally unclear...
Particles of the Standard Model

- Leptons (spin 1/2, $q_\nu = 0$, $q_e = -1$):

  \[
  \begin{pmatrix}
  \nu_e \\
  e
  \end{pmatrix}_L, \quad
  \begin{pmatrix}
  \nu_\mu \\
  \mu
  \end{pmatrix}_L, \quad
  \begin{pmatrix}
  \nu_\tau \\
  \tau
  \end{pmatrix}_L
  \]

  $e_R$, $\nu_e R$, $\mu_R$, $\nu_\mu R$, $\tau_R$, $\nu_\tau R$

- Quarks (3 colors, spin 1/2, $q_u = 2/3$, $q_d = -1/3$):

  \[
  \begin{pmatrix}
  u \\
  d
  \end{pmatrix}_L, \quad
  \begin{pmatrix}
  c \\
  s
  \end{pmatrix}_L, \quad
  \begin{pmatrix}
  t \\
  b
  \end{pmatrix}_L
  \]

  $u_R$, $d_R$, $c_R$, $s_R$, $t_R$, $b_R$

- Spin 1:
  - 8 gluons $g$
  - $W^\pm$ and $Z^0$, photon $\gamma$

- Spin 0: Higgs $H$
Standard Model

- extremely successful theory
  - no single experimental deviation
  - verified to unbelievable precision
but it cannot be the ultimate theory...
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  # of leptons = # of quarks
  but why 3 generations???
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  any change ⇒ we are not here...
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  # of leptons $=$ # of quarks
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- why the observed values of masses and coupling constants???
  any change $\Rightarrow$ we are not here...

- why $CP$ violation (and why not enough)???
Standard Model

- why spontaneous symmetry breaking
  \[ \langle H \rangle = \nu \neq 0 \]
Standard Model

• why spontaneous symmetry breaking
  \( \langle H \rangle = v \neq 0 \)??

• why such huge differences in masses???

\[
\frac{m_t}{v} \approx 1, \quad \frac{m_e}{v} \approx 3 \cdot 10^{-6}, \quad \left( \frac{m_{\nu}}{v} \approx 10^{-12} \right)
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  (main source of luminous mass)
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- why proton mass \(\approx 1\) GeV???
  (main source of luminous mass)

- hierarchy problem \[\frac{v}{M_P} \approx 10^{-16}\]
  (supersymmetry, conformal symmetry)
Present content of the Universe

- radiation: $p \approx \frac{\rho}{3}$, negligible
- luminous matter: $p \approx 0$, 4%
  - (stars) 0.5%
  - interstellar gas 0.5%
  - intergalactic gas 3%
- dark matter: $p \approx 0$, 23%
- dark energy: $p \approx -\rho$, 73%
Nucleosynthesis abundances

![Graph showing element abundances relative to hydrogen compared to density of ordinary matter.](image-url)
Dark Matter and Dark Energy

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$$\frac{\rho_{DM}}{M_P^4} \approx 10^{-120}, \quad \frac{\rho_{DM}}{M_W^4} \approx 10^{-54}$$

- the answer probably requires new (not QFT like) physics – quantum gravity?
Galaxy collision
Gravity

- gravitational interaction between elementary particles is extremely weak – why???

$$\alpha_G = \frac{G m_p^2}{\hbar c} \approx 10^{-38}$$

(for EM interactions $$\alpha = e^2/(4\pi \epsilon_0 \hbar c) \approx 1/137$$)
Gravity

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  \[ \alpha_G = \frac{G m_p^2}{\hbar c} \approx 10^{-38} \]
  (for EM interactions \( \alpha = \frac{e^2}{4\pi \epsilon_0 \hbar c} \approx \frac{1}{137} \))
- \( \alpha_G \) is so small \( \Rightarrow \) stars are so large
  \[ M_C \approx \frac{m_p}{\alpha_G^{3/2}} \approx 10^{30} \text{kg} \]
  (Chandrasekhar limit)
Quantum Gravity

• when gravity $\approx$ EM? (G. Stoney, 1881)

$$\frac{G m^2_S}{r^2} = \frac{e^2}{4\pi\varepsilon_0 r^2} \Rightarrow m_S \approx 1.86 \cdot 10^{-9} \text{ kg}$$
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• black hole entropy may be the key issue pointing to QG (as black body radiation did)
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- String Theory
- Loop Quantum Gravity
  - both claim solving BH entropy problem
  - neither solved the CC problem
  - nor the initial singularity and initial conditions problems ...
String theory

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- no single new result relevant for “low energy” particle physics or cosmology
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- problems of initial singularity, existence (or emergence) of time and space at distances $\sim l_P$, interpretation of the “wave function of the Universe” etc. totally unclear
- we are still very far away from understanding quantum gravity
Summary

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• probably the biggest challenges in physics (that we know of!)
  • measurement problem in QM
  • explanation of values of physical constants
  • cosmological constant and quantum gravity
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- the biggest (meta-physical) mystery: why anything is subject to any law at all?
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  • measurement problem in QM
  • explanation of values of physical constants
  • cosmological constant and quantum gravity
• the biggest (meta-physical) mystery: why anything is subject to any law at all?
• Socrates’ statement invariably true: “I neither know nor think that I know”