Approaching the Planck scale by the astronomical observations

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24 April, 2010

The general opinion among the physicists is that the Planck scale effects are far from any *empirical* verification. Many of them say simply: "it is impossible!".

It can be a true, but only if you identify the world *empirical* with an *experiment*. The difference between the Planck scale energy $1.22 \cdot 10^{19}$ GeV and the highest energies (as the $7 \cdot 10^{3}$ GeV at the LHC) available experimentally is really dispiriting!

This is like probing the atomic structure with resolution of the size of Earth. The difference is enormous!

So, is there truly no access to the Planck scale physics? If "yes", the branch of quantum gravity can be to a good place to do math, unconstrained by any barriers. You can freely develop your crazy ideas here! So in this case, is quantum gravity a science or just Science Fiction?

The goal of this talk is to show that the quantum gravity have a real chance to become a true science. How? In short, the theory must get married with astronomy...

The clue is that the empirical means also *observational*!

Right now, the cosmology and astrophysics experience a rapid advancement. Much higher than the high energy physics do, which is limited by the technological barriers. The high energy physics develops much rapidly as high energy astrophysics etc.

Can we take the advantage of this fast progress in searching for quantum gravity effects? The possibility exist. The task is to extract the proper information from the available data and start to compare them with the theories.

So, what astronomy can proffer...

The are three main possible ways to investigate observationally the Planck scale physics:

- Modified dispersion relation (violation of the Lorentz symmetry)

  - time-lags from the γ-ray bursts (GRB)

  - thresholds on the cosmic particles production

  - impact on GZK cut-off

- Stochastic effects

  - broadening of the spectral lines

  - modifications of spectra (e.g. impact on the black body CMB spectrum)

- Impact on cosmic microwave background radiation

  - temperature anisotropies

  - polarization (e.g. footprints of the primordial gravitational waves)

  - effects on the comic inflation

  - non-Gaussian effects

Modified dispersion relation

The quantum gravity effects may manifest themselves as a violation of the Lorentz invariance. The modified relation of dispersion for the photons can be written as follows

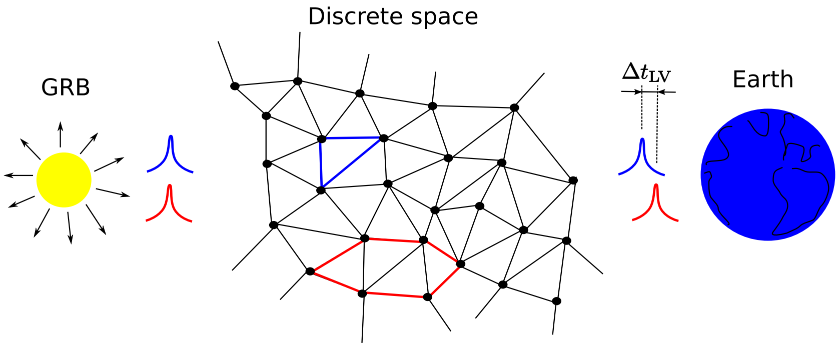
$$p^2 = E^2 \left(1 + \frac{E}{E_{\rm QG}} \right).$$

This implies energy-dependent speed of light

$$v_{\rm gr} = \frac{\partial E}{\partial p} \simeq 1 - \frac{E}{E_{\rm QG}}.$$

Therefore we expect delays in arrivals of photons

$$\Delta t_{\rm LV} = \frac{\Delta E}{E_{\rm QG}} L = \frac{\Delta E}{E_{\rm QG}} \frac{1}{H_0} \int_0^z \frac{dz'}{H(z')}.$$


Discrete space
GRB
Δt_{LV}
Earth

Based on BATSE, HETE and SWIFT data it was shown that [1]

$$E_{\mathrm{QG}} \geq 1.4 \cdot 10^{16}\mathrm{GeV}$$

In 2005, MAGIC recorded VHE $\gamma-$ray flares of Mkn 501 (z=0.034). Based on these observations it was shown that [2]

$$E_{\mathrm{QG}} \geq 0.21 \cdot 10^{18}\mathrm{GeV}$$

In 2006, HESS observed a giant outburst of the blazar PKS 2155-304 (z=0.116). Based on these observations it was shown that [3]

$$E_{\mathrm{QG}} \geq 0.72 \cdot 10^{18}\mathrm{GeV}$$

[1] J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov and E. K. G. Sarkisyan, Astropart. Phys. **25** (2006) 402 [arXiv:astro-ph/0510172].

[2] J. Albert *et al.* [MAGIC Collaboration and Other Contributors Collaboration], Phys. Lett. B **668** (2008) 253 [arXiv:0708.2889 [astro-ph]].

[3] J. Bolmont, R. Buhler, A. Jacholkowska and S. J. Wagner [the H.E.S.S. Collaboration], arXiv:0904.3184 [gr-qc].

Stochastic effects - quantum gravitational Brownian motions

Random motion of the test particle due to the foamy structure of the space at the Planck scale $\rightarrow$ in case of photon, smearing of the light cone.

If we assume that the random motion is of the Brownian type, then the smearing in position is given by

$$\sigma_x = \sqrt{cl_{\text{Pl}}}\sqrt{t} = \sqrt{Ll_{\text{Pl}}}.$$

A spectra line becomes broader due to the smearing of the light cone, according to

$$\frac{\Delta\nu}{\nu} = \frac{\nu}{c}\sqrt{Ll_{\text{Pl}}}$$

where $l_{\text{Pl}} = 1.6 \cdot 10^{-35}$m.

Let us take the X-ray K-α Fe emission line from NGC 4258. Based on the observations of the XMM-Newton satellite we have

$$\frac{\Delta\nu}{\nu} = \frac{250 \text{ eV}}{6.4 \text{ keV}} \approx 0.04.$$

The source is at distance $L = 7.3 \pm 0.5$ Mpc. To compare, our prediction from the Brownian type quantum fluctuations of space is

$$\frac{\Delta\nu}{\nu} \approx 6000.$$

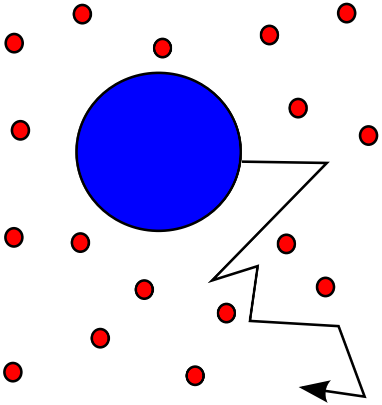
The predicted effect is much bigger than the observed broadening. Therefore, even with such a simple data, some possible Planck scale effects can be just excluded! We can learn something about the Planck scale physics.

For the model based on linearized quantum gravity, the effect of broadening is however much more weaker, then

$$\frac{\Delta\nu}{\nu} \approx \frac{\nu}{c} l_{\text{Pl}} \sqrt{\ln\left(\frac{L}{l_{\text{Pl}}}\right)}.$$

Brownian motions and reality of atoms

A little more than 100 years ago most people - and most scientists - thought of matter as continuous. Although since ancient times some philosophers and scientists had speculated that if matter were broken up into small enough bits, it might turn out to be made up of very tiny atoms, few thought the existence of atoms could ever be proved. Then Einstein (1905) and Smoluchowski (1906) independently presented a way to indirectly confirm the existence of atoms and molecules by study of Brownian motions.



Theory of Einstein and Smoluchowski has been proved experimentally by Perrin in 1908.

Impact on cosmic microwave background radiation

The observations of the cosmic microwave background (CMB) radiation indicate that the power spectrum of primordial scalar perturbations is in the broad range *nearly* scale-invariant. Therefore, the spectrum can be written in the power-law form

$$\mathcal{P}_{\mathrm{s}}(k) = A_{\mathrm{s}} \left(\frac{k}{k_0} \right)^{n_{\mathrm{s}}-1},$$

where the spectral index n_{s} is close to unity. The seven years of observations made by the WMAP satellite give the following values of the amplitude and spectral index of the scalar perturbations [4]

$$A_{\mathrm{s}} = 2.441^{+0.088}_{-0.092} \cdot 10^{-9},$$
$$n_{\mathrm{s}} = 0.963 \pm 0.012,$$

at the pivot scale $k_0 = 0.002\ \mathrm{Mpc}^{-1}$.

[4] E. Komatsu *et al.*, arXiv:1001.4538 [astro-ph.CO].

The primordial perturbations were formed during the phase of cosmic inflation. The simplest model of inflation bases on the single massive scalar field theory. In this model, the primordial perturbations were formed from the quantum fluctuations of the field ϕ during the phase of *slow-roll* inflation. Based on the latest WMAP observations one can determine e.g. the mass of inflaton field [5]

$$
\begin{aligned}
m &\simeq m_{\mathrm{Pl}} \frac{1}{4} \sqrt{3\pi A_{\mathrm{s}}}(1-n_{\mathrm{s}}) \\
&= (1.4 \pm 0.5) \cdot 10^{-6} m_{\mathrm{Pl}} \\
&= (1.7 \pm 0.6) \cdot 10^{13} \mathrm{GeV}.
\end{aligned}
$$

This could suggest that the energy scale of inflation have something to do with the Grand Unification Theory (GUT).

[5] J. Mielczarek, M. Kamionka, A. Kurek, M. Szydlowski, "Observational hints on the Big Bounce"

Problems of the standard cosmology:
1) Initial Big Bang singularity.
2) Initial conditions for inflation (in particular for the slow-roll period).

Solutions given by loop quantum cosmology (LQC):
1) The initial singularity is replaced by the quantum Big Bounce.
2) A bounce gives mechanism to set the proper initial conditions for inflation! Moreover, inflation is generic in loop quantum cosmology! [6] [7] [8] [9].

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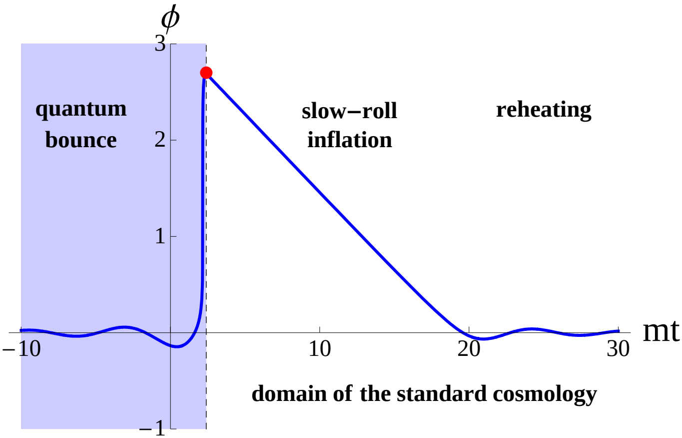
[6] J. Mielczarek, "Possible observational effects of loop quantum cosmology," Phys. Rev. D **81** (2010) 063503 .[arXiv:0908.4329]

[7] A. Ashtekar and D. Sloan, "Loop quantum cosmology and slow roll inflation," arXiv:0912.4093 [gr-qc].

[8] D. W. Chiou and K. Liu, "Cosmological inflation driven by holonomy corrections of loop quantum cosmology," arXiv:1002.2035 [gr-qc].

[9] J. Mielczarek, T. Cailleteau, J. Grain, A. Barrau, "Inflation in loop quantum cosmology: dynamics and spectrum of gravitational waves," .[arXiv:1003.4660]

Inflation in LQC - the *shark fin* scenario



Dynamics of the massive *inflaton* field is governed by:

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0.$$

Gravitational waves in LQC

$$\frac{d^2}{d\eta^2}h_a^i + 2aH\frac{d}{d\eta}h_a^i - \nabla^2 h_a^i + m_Q^2 h_a^i = 0,$$

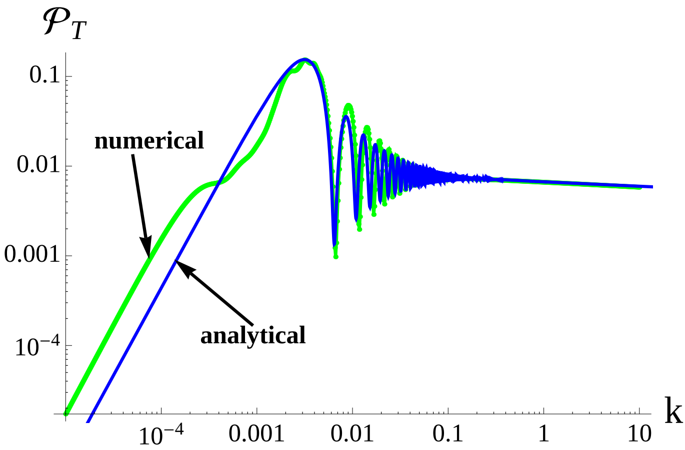
where $h_1^1 = -h_2^2 = h_\oplus$, $h_2^1 = h_1^2 = h_\otimes$ in the TT gauge. The quantum gravitationally induced "effective mass" is given by

$$m_Q^2 := 16\pi G a^2 \frac{\rho}{\rho_c}\left(\frac{2}{3}\rho - V\right).$$

Quantization promotes the field h_a^i to be the operator $\hat{h}_a^i$. The correlation function of the $\hat{h}_a^i$ field is defined as follows

$$\langle 0|\hat{h}_b^a(\mathbf{x},\eta)\hat{h}_a^b(\mathbf{y},\eta)|0\rangle = \int_0^\infty \frac{dk}{k}\mathcal{P}_{\mathrm{T}}(k,\eta)\frac{\sin kr}{kr}.$$

Power spectrum of gravitational waves.



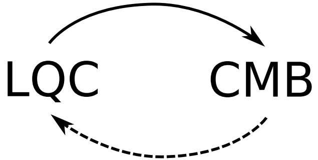
In the IR region the spectra behave as $\mathcal{P}_{\rm T} \propto k^2$ while in the UV region they behave as $\mathcal{P}_{\rm T} \propto k^{-2\epsilon}$, where $\epsilon \ll 1$ is the slow-roll parameter. Here $m = 10^{-2} m_{\rm Pl}$.

From LQC to CMB

LQC - loop quantum cosmology gives an applicative framework to investigate evolution of the Universe at the Planck epoch (When the characteristic energies are of the order 10^{19}GeV). This theory base on the non-perturbative approach to quantise gravitational degrees of freedom, called loop quantum gravity (LQG).

CMB - cosmic microwave background (radiation)

We derive predictions from the theory and then we try to confront them with observational data.



This can give us the feedback on the theory and can learn us something about the Planck scale physics.

Observational constraint on the Barbero-Immirzi parameter

The critical energy density in LQC is defined as follows

$$\rho_{\mathrm{c}} = \frac{\sqrt{3}}{16\pi^2\gamma^3}\rho_{\mathrm{Pl}},$$

where $\rho_{\mathrm{Pl}} := m_{\mathrm{Pl}}^4$ and $m_{\mathrm{Pl}} \approx 1.22 \cdot 10^{19}$ GeV is the Planck mass. Based on the seven years observations of the WMAP satellite

$$\rho_{\mathrm{obs}} = \frac{m^2\phi_{\mathrm{obs}}^2}{2} \approx 8 \cdot 10^{-12} m_{\mathrm{Pl}}^4.$$

Based on this, we infer that $\rho_{\mathrm{c}} > \rho_{\mathrm{obs}}$. We see also that $\rho_{\mathrm{obs}} \ll \rho_{\mathrm{Pl}}$. Therefore the observed constraint on the energy scale of the bounce is very weak. However since $\rho_{\mathrm{c}} \sim 1/\gamma^3$, the constraint on the parameter γ can be much stronger. We find

$$\gamma < 1100.$$

The value obtained from consideration of black hole entropy $\gamma = 0.239$ places well within the observational bound.

The work is ongoing with the French group

- Aurelien Barrau (Grenoble)
- Thomas Cailleteau (Grenoble)
- Julien Grain (Paris)

as well with the Polish group

- Michał Kamionka (Wrocław)
- Aleksandra Kurek (Kraków)
- Marek Szydłowski (Kraków)