Cosmological baryon/lepton assymmetry in terms of Kaluza-Klein extra dimensions

V.V.Nikulin (Speaker)   S.G.Rubin

NRNU MEPhI
Department of Elementary Particle Physics

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Plan

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6. Conclusion

Introduction. Common 4-dim theories.

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Internal symmetries in common 4-dim theories

$$S[\,\phi(x) \to \hat{g}\,\phi(x)\,] = \mathrm{inv}\,, \qquad \hat{g} = e^{i\hat{t}\alpha}\,, \tag{1}$$

$$\hat{g} \in G - \text{internal symmetry group}\,,$$
$$\phi(x) \in V - \text{internal space (of representation)}\,.$$

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Conserved currents and numbers/charges in common 4-dim theories

$$\Longrightarrow \qquad \partial_\mu j^\mu = 0\,, \qquad j^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)}\hat{t}\,\phi\,,$$
$$Q = \int j^0\, d^3x = \text{const}\,. \tag{2}$$

Introduction. Extra spatial symmetries in KK-like theories.

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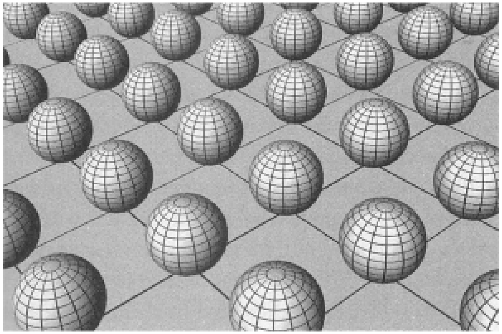

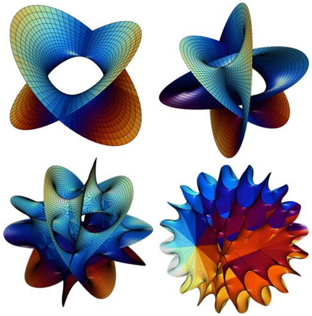

Isometries of extra space

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu + k_{mn}(y)dy^m dy^n\,, \tag{3}$$

$$\nabla_m\,\xi_n(y) - \nabla_n\,\xi_m(y) = 0\,. \tag{4}$$

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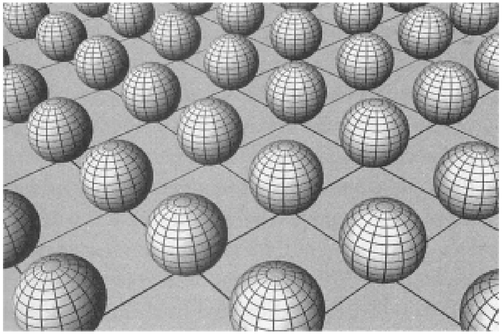

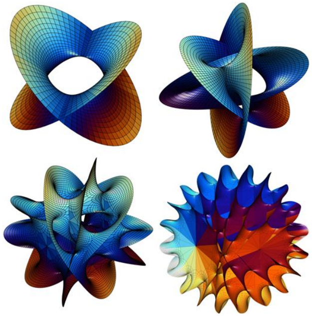

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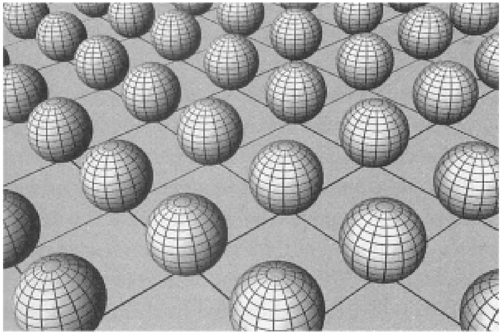

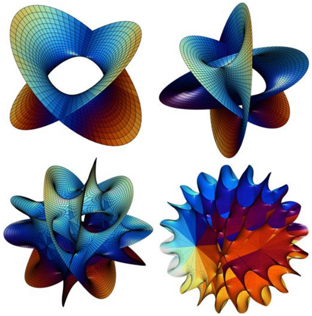

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In terms of higher-dim theory

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In terms of effective 4-dim theory

$$\Longrightarrow \qquad \partial_\alpha j^\alpha = 0\,, \qquad j^\alpha = \frac{\partial \mathcal{L}_4}{\partial(\partial_\alpha \phi^n)} (t)^n_m \phi^m\,, \tag{8}$$

$$(t_i)^n_m = \int Y_n (\xi^a \partial_a) Y_m \sqrt{|k|}\, d^d y\,,$$

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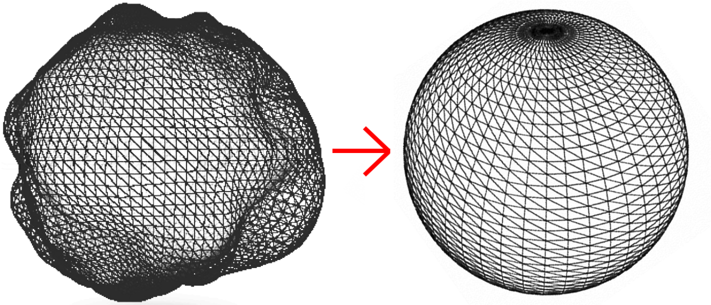
Violation of KK-symmetries in early Universe and lepton assymmetry



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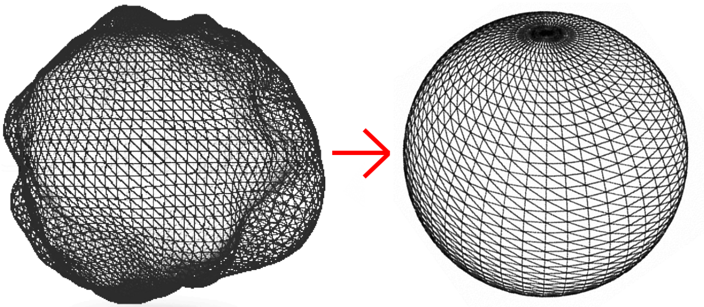

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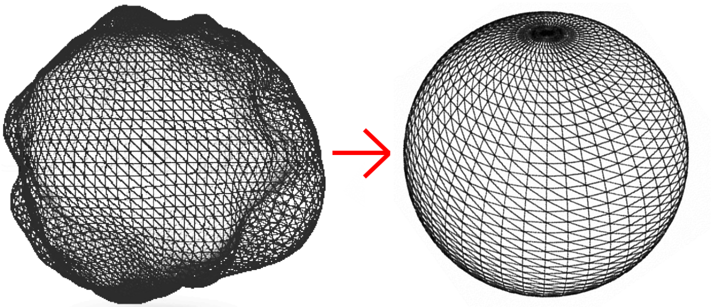

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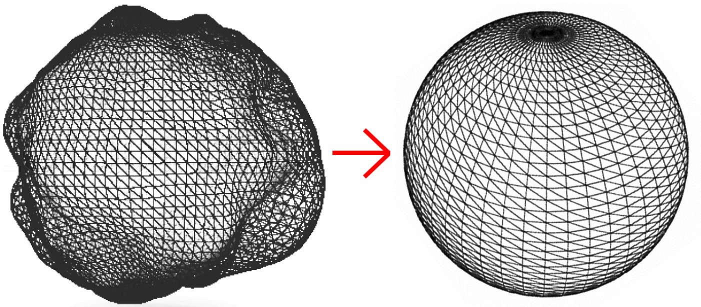

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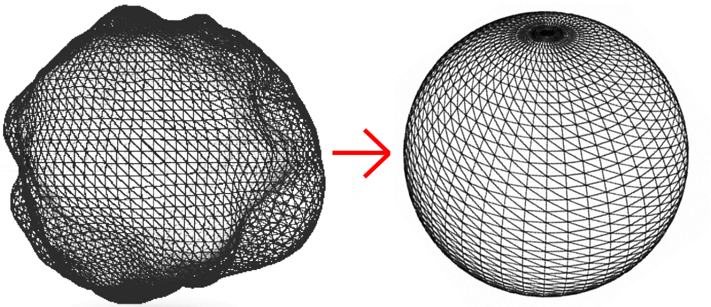

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- However, if $1/r_0 < H$, the fluctuations of the metric will distort the extra space, and consiquently break its symmetry. As a result, some initial accumulation of the numbers/charges will occur during inflation.
- After the inflation (in low-energetic physics) relaxation of the metric occurs and symmetry is restored. The corresponding numbers are conserved again.

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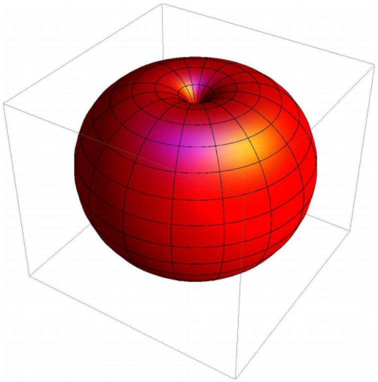

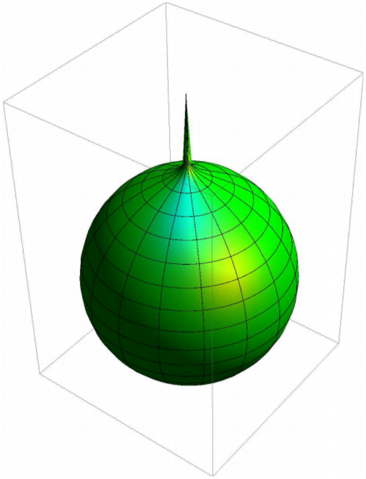

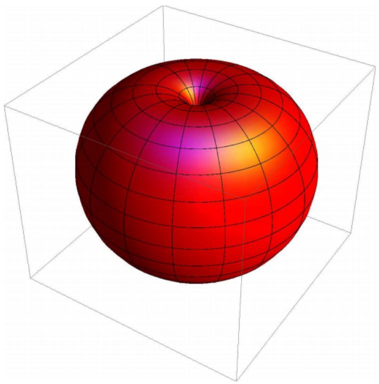

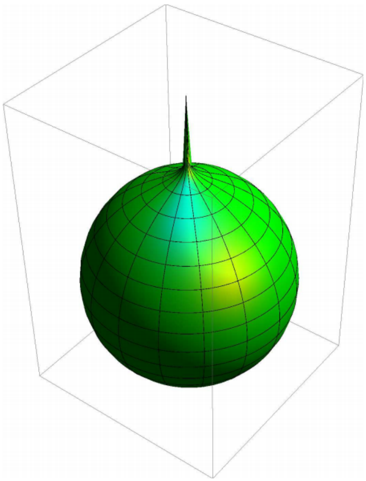

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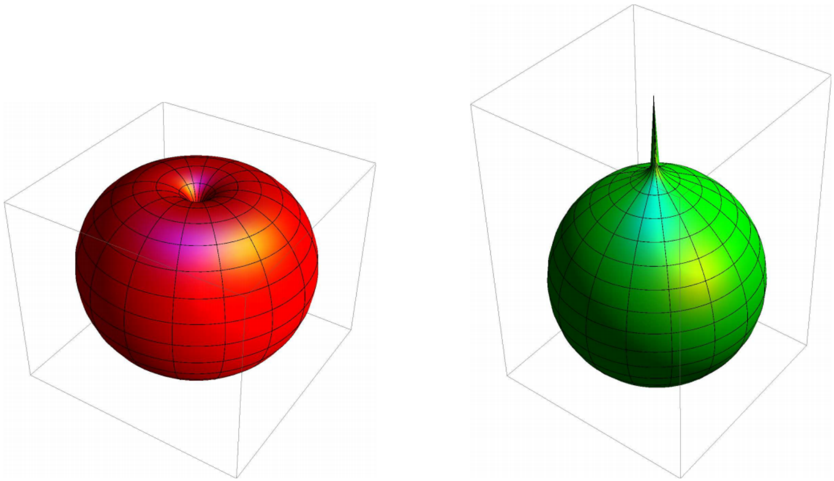

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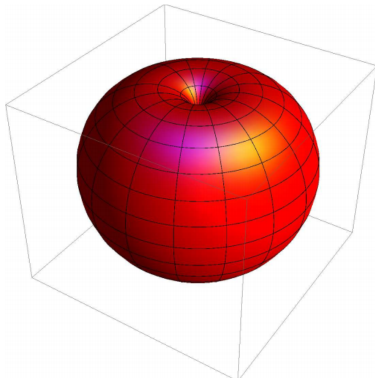

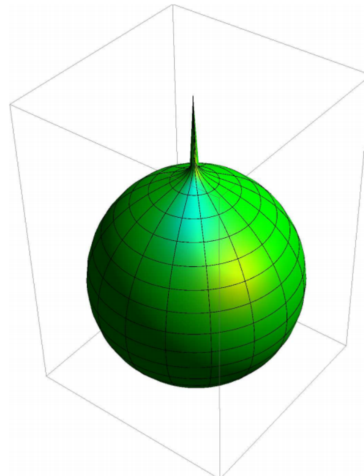

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- Such configurations considered in the framework of warped extra dimensions. It is developed in different works including ours: arxiv:0706.0676, arxiv:2006.01329, arxiv:hep-th/0302067, etc.

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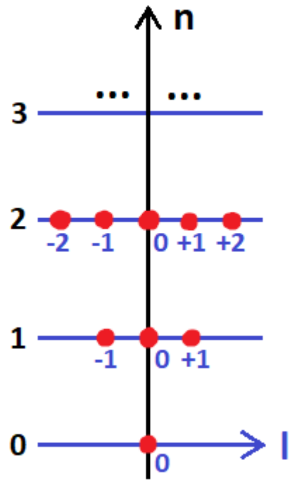

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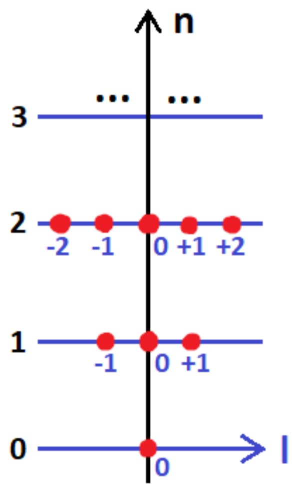

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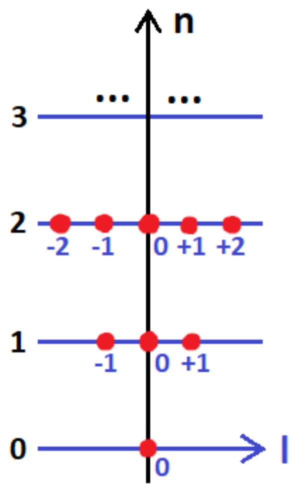

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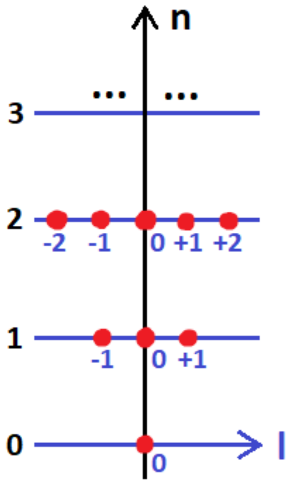

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- However, to observe low-energy lepton asymmetry, we need to have massless (ground-level $n = 0$) states with a nonzero angular momentum l.
- The idea of possible such configurations is used in work arxiv:0706.0676 for other purposes. It is based on compact extra spaces with an excess of angle.

Splitting of the ground fermionic KK-level in spaces with angle excess

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Angle profuse extra space

$$ds^2 = g_{\mu\nu}\left(x^\alpha\right) dx^\mu dx^\nu - r^2(\theta)\left(d\theta^2 + b^2 \sin^2\theta \, d\varphi^2\right)\ , \tag{10}$$

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Higher-dimentional fermionic action

$$S_\Psi = \int d^6X \sqrt{|G|}\, i\overline{\Psi} h^B_{\tilde{A}} \Gamma^{\tilde{A}} \nabla_B \Psi\,, \tag{11}$$

where $\Gamma^{\tilde{A}}$ is flat 8×8 (in 6-dim) gamma matrices

$$\Gamma_\nu = \begin{pmatrix} \gamma_\nu & 0 \\ 0 & -\gamma_\nu \end{pmatrix}, \quad \Gamma_\theta = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad \Gamma_\varphi = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}, \tag{12}$$

and $h^B_{\tilde{A}}$ is the frame field:

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- You can find a detailed derivation of fermion splitting in the paper arxiv: 0706.0676.

Splitting of the ground KK-level of fermions in spaces with angle excess

Kaluza-Klein decomposition

$$\Psi\left(x^A\right) = \sum_j Y_j(\theta,\varphi)\Psi_j(x) = \sum_{nl} e^{il\varphi} \begin{pmatrix} Y_{nl}^{+}(\theta)\psi_{nl}(x) \\ Y_{nl}^{-}(\theta)\xi_{nl}(x) \end{pmatrix}, \tag{14}$$

where the Y_{nl}^{+} and Y_{nl}^{-} is the eigenfunctions are computed from Dirac equation:

$$ih_{\tilde{A}}^{B}\hat{\Gamma}^{\tilde{A}}\nabla_B\Psi = ih_{\tilde{\mu}}^{\nu}\hat{\Gamma}^{\tilde{\mu}}\nabla_\nu\Psi + \underbrace{ih_{\tilde{m}}^{n}\hat{\Gamma}^{\tilde{m}}\nabla_n}_{\text{mass operator}}\Psi = 0\,. \tag{15}$$

Limitation on the number l comes from the normalization condition:

$$\int |Y_{nl}|^2\sqrt{|k|}\,d^2y < +\infty \qquad \underset{n=0}{\Longrightarrow} \qquad l = -\lceil b/2\rceil, ..., 0, .., +\lfloor b/2\rfloor \in \mathbb{Z}\,. \tag{16}$$

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Low-energy (n=0) effective 4-dim action

$$S = \int d^6X\sqrt{|G|}\,i\overline{\Psi}h^B_{\tilde{A}}\Gamma^{\tilde{A}}\nabla_B\Psi \sim \int\sqrt{-g}\,d^4x\sum_{l=-1}^{+1}\left(i\overline{\psi}_l\gamma^\mu\partial_\mu\psi_l + i\overline{\xi}_l\gamma^\mu\partial_\mu\xi_l\right)\,. \tag{17}$$

Fermion splitting in extra space with angle profuse

Correspondence of currents

$$J_\Psi^m = \frac{\partial \mathcal{L}}{\partial(\partial_m \Psi)} \partial_\varphi \Psi = i\overline{\Psi} h_{\tilde{A}}^m \Gamma^{\tilde{A}} \partial_\varphi \Psi \implies$$

$$j_\psi^\mu = \frac{\partial \mathcal{L}_4}{\partial(\partial_\mu \psi_l)} t_{ll'} \psi_{l'} = i \sum_l l \, \overline{\psi_l} \gamma^\mu \psi_l \,, \qquad t_{ll'} = \int Y_l \, \partial_\varphi Y_{l'} \sqrt{k} \, d^2 y = il\delta_{ll'} \,, \tag{18}$$

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U(1)-number

Take the angle profuse parameter $b = 4$ for example.
Then we have triplet splitting: $l = -1, 0, +1$.

$$\begin{aligned} Q_{\Psi} &= \int J_{\Psi}^{0} \sqrt{|G|}\, d^3 x d^2 y = \int j_{\psi}^{0} \sqrt{|g|}\, d^3 x = \\ &= \int i(\psi_{+1}^{\dagger} \psi_{+1} - \psi_{-1}^{\dagger} \psi_{-1}) d^3 x = N_{\psi_{+1}} - N_{\psi_{-1}} = \mathrm{const}\,. \end{aligned} \tag{19}$$

Momentum (lepton number) transfer from a scalar field to fermions

Scalar field action and interaction

The Lagrangian of the scalar field and its interaction with the fermion field can be chosen as simple as possible:

$$S_\Phi + S_{\text{int}} = \int d^6x \sqrt{|G|} \left[\frac{1}{2} \partial_M \Phi \partial^M \Phi + f \Phi \bar{\Psi} \Psi \right] \xrightarrow{\int d^2y} \tag{20}$$

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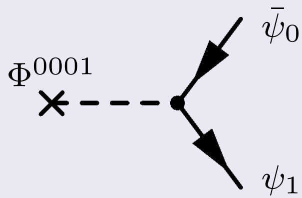

Internal momentum (leptonic number) conservation

$$Q = \int J^0\sqrt{|G|}\,d^3xd^2y = Q_\Psi + Q_\Phi = N_{\psi_{+1}} - N_{\psi_{-1}} + Q_\Phi = \text{const}\,. \tag{22}$$

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- The accumulated charges (numbers) are then conserved due to symmetry restoration. However, in the usual case, the charge is realized in massive KK-modes with $l \neq 0$, which is stable due to the momentum conservation. Such a mechanism is suitable for generating stable massive dark matter particles, but is not suitable for explaining the low-energetic lepton assymetry.

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- It is possible to avoid this limitation in the extra space model where the massless fermionic KK-level splits into a multiplet. This splitting becomes possible in extra spaces with an angle profuse $b > 4$. The massless components of the triplet can carry internal momentum $l = \pm 1$ - that is, carry an effective 4-dim charge (number), in our case - leptonic.

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- But this charge cannot accumulate in the fermion field. Due to Fermi-Dirac statistics, fermions cannot exist in the form of coherent oscillations in which charge (number) is accumulated. Therefore, we need to introduce an interaction with a scalar field. Then, the condensate of the scalar field carrying the internal momentum (lepton number) will decay into leptons, forming a lepton asymmetry.

Thanks for you attention!

Any questions?