Formation of conserved charges at the de Sitter space

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

NRNU MEPhI
Department of Elementary Particle Physics

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Plan

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1. Conserved charges and nubmers in Kaluza-Klein-like theories

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2. Apple-like extra space models with U(1)-symmetry

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6. Conclusion

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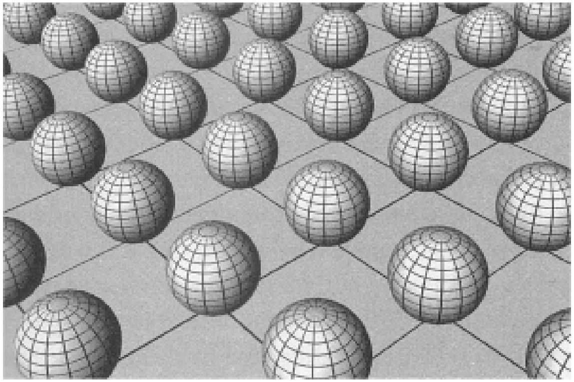

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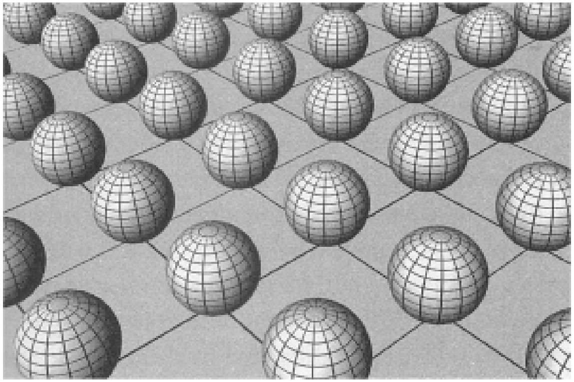

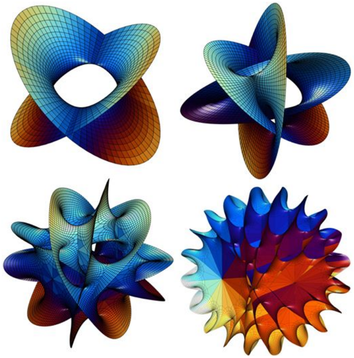

Spatial isometries of extra space

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu + k_{mn}(y)dy^m dy^n \,, \tag{1}$$

$$\nabla_a \xi_b - \nabla_b \xi_a = 0 \,. \tag{2}$$

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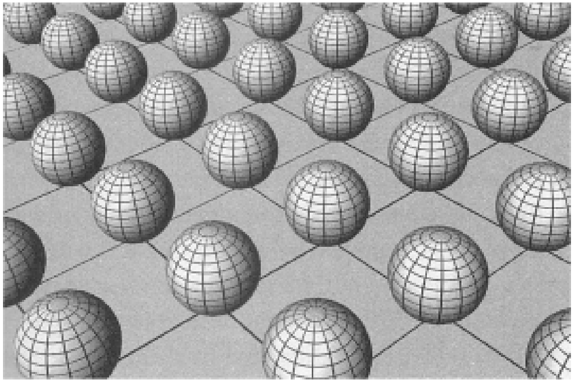

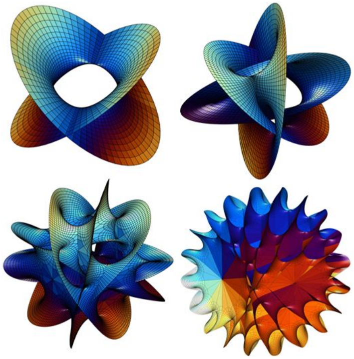

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Neother's current and charge (number)

$$J^a = \frac{\partial L_\mathrm{m}(\chi)}{\partial(\partial_a \chi)} \xi^b \partial_b \chi - \xi^a L_\mathrm{m}(\chi) \,, \tag{3}$$

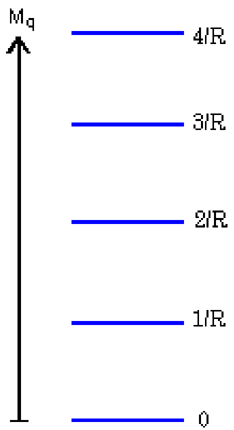
$$Q = \int J^0 \sqrt{|g|}\sqrt{|k|}\, d^3x\, d^d y = \mathrm{const}\,. \tag{4}$$

Conserved charges and nubmers in Kaluza-Klein-like theories

Transition to effective 4-dim theory

$$\chi(x,y) = \sum_{q=0}^{\infty} \chi_q(x) Y_q(y)\,, \quad \begin{cases} \Box_d Y_q(y) = M_q^2 Y_q(y)\,, \\ M_q \approx q/R\,, \quad q \in \mathbb{N}\,. \end{cases} \tag{5}$$

$$\begin{aligned} S &\simeq \int d^4x d^dy \sqrt{|g|}\sqrt{|k|}\,\frac{1}{2}\left[\partial_A\chi\,\partial^A\chi - \mu^2\chi^2\right] = \\ &= \int d^4x \sqrt{|g|} \sum_{q=0}^{\infty} \frac{1}{2}\left[(\partial\chi_q)^2 - (M_q^2+\mu^2)\chi_q^2\right]\,. \end{aligned} \tag{6}$$



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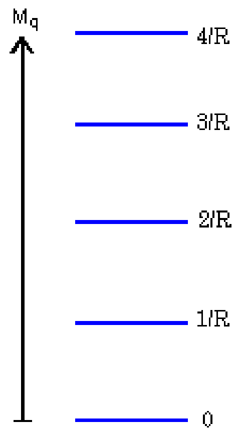

Effective 4-dim Neother's current and charge (number)

$$j^\alpha = \frac{\partial \mathcal{L}_4}{\partial(\partial_\alpha \phi^n)} (t)^n_m \phi^m\,, \qquad (t_i)^n_m = \int Y_n \xi^a \partial_a Y_m \sqrt{|k|}\, d^d y \tag{7}$$

$$Q = \int j^0 \sqrt{|g|}\, d^3 x = \text{const}\,. \tag{8}$$

Apple-like extra space models with U(1)-symmetry

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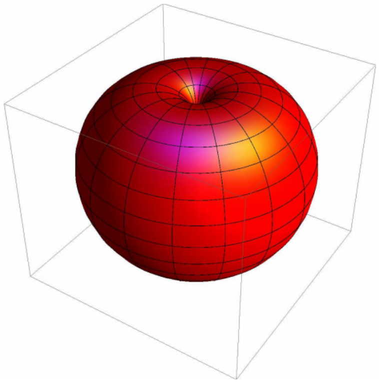

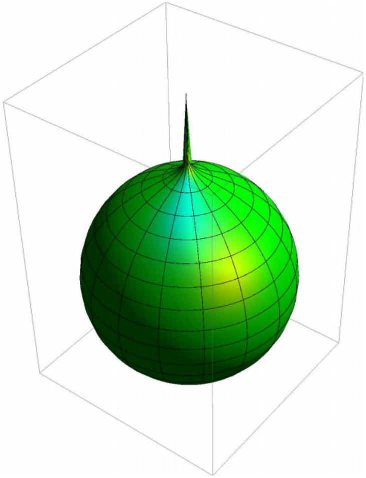

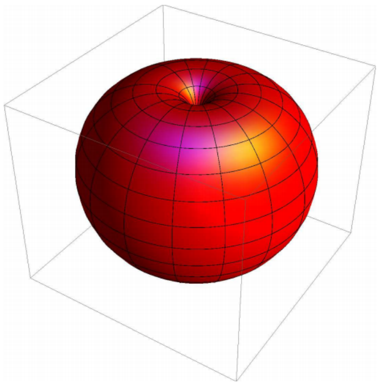

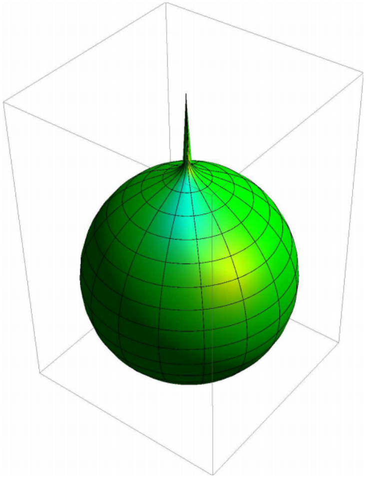

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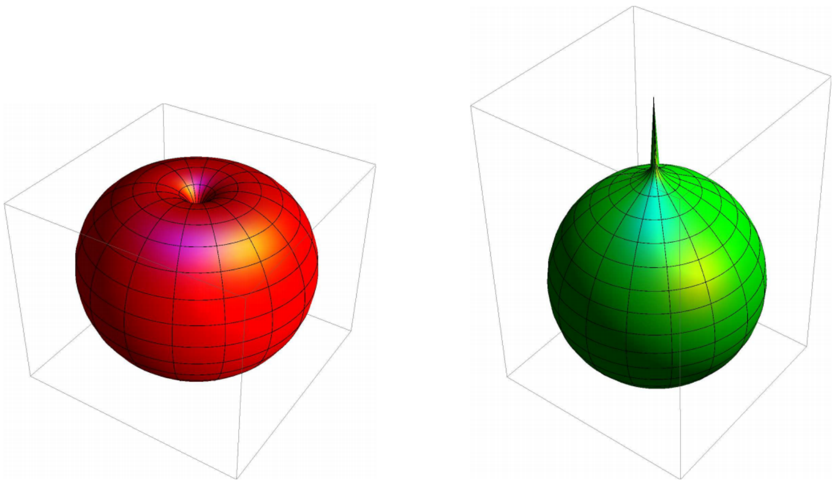
Apple-like extra space models with U(1)-symmetry



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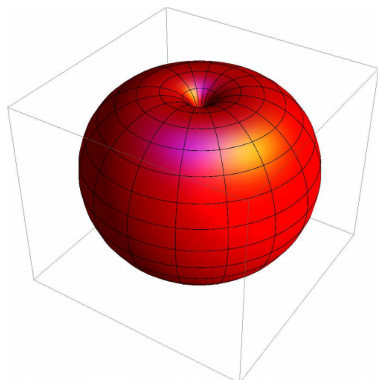
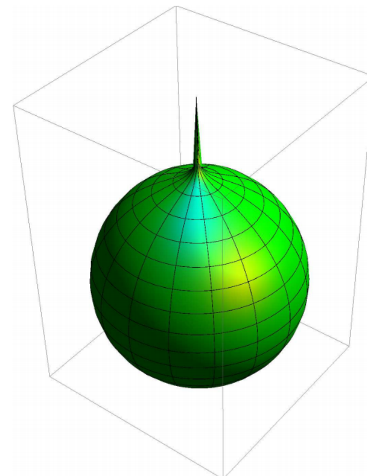
- Unlike the one-dimensional compact extra space, a 2-dim manifold has a non-zero Ricci scalar and can be perturbed.





- Compact 2-dim apple-like manifold have U(1)–symmetry associated with polar rotational isometry.
- Unlike the one-dimensional compact extra space, a 2-dim manifold has a non-zero Ricci scalar and can be perturbed.
- Considered in the framework of warped extra dimensions. It is developed in different works: arxiv:0706.0676, arxiv:1511.01869, arxiv:hep-th/0302067, etc.

Apple-like extra space models with U(1)-symmetry

Space-time setting

$$S = \frac{m_D^{D-2}}{2} \int d^D X \sqrt{|G|} \left[f(R) + L_{\rm m} \right] , \quad f(R) = aR^2 + R + c \,. \tag{9}$$

$$ds^2 = G_{MN} dX^M dX^N = g_{\mu\nu}(x) dx^\mu dx^\nu + k_{mn}(x,y) dy^m dy^n \,, \tag{10}$$

$$g_{\mu\nu} = diag(1, -e^{2Ht}, -e^{2Ht}, -e^{2Ht}) \,, \tag{11}$$

$$k_{mn}(x,y) \xrightarrow{t\to\infty} k^{\rm st}_{mn}(y) \tag{12}$$

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Extra space configuration

$$k_{mn}(x,y) = r(\theta, \phi, t)^2 (d\theta^2 + \sin\theta \, d\phi^2) \quad \xrightarrow{t \to \infty} \tag{13}$$

$$\xrightarrow{t \to \infty} \qquad k^{\mathrm{st}}_{mn}(y) = r_0(\theta)^2 (d\theta^2 + \sin\theta \, d\phi^2) \,, \tag{14}$$

$$r(\theta, \phi, t) = r_0(\theta) \, e^{\delta\beta(\theta,\phi,t)} = r_0 \, e^{\beta(\theta) + \delta\beta(\theta,\phi,t)} \tag{15}$$

Inflationary extra space relaxation in the presence of (scalar) field

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Matter content

$$L_{\rm m} = \frac{1}{2} G^{MN} \partial_M \chi \partial_N \chi - V(\chi) \,, \quad V(\chi) = \frac{1}{2} m^2 \chi^2 \,. \tag{16}$$

$$T_{MN} = -2 \frac{\partial L_{\rm m}}{\partial G^{MN}} + G_{MN} L_{\rm m} \,. \tag{17}$$

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Dinamical equations

$$R_{MN} f' - \frac{1}{2} f(R)\, k^{\rm st}_{MN} + \nabla_M \nabla_N f' - k^{\rm st}_{MN} \Box f' = \frac{1}{m_D^{D-2}} T_{MN} . \tag{18}$$

$$\Box_d \chi = -V'(\chi) \,, \tag{19}$$

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- To reduce the order of the PDEs system, we take the standard equation for the connection of Ricci scalar with the metric as the third equation. We also compute the trace of Einstein's equations to simplify. As a result we obtain a second order system of 3 equations for 3 unknown functions: $\beta(t, \theta, \phi)$, $R(t, \theta, \phi)$, $\chi(t, \theta, \phi)$.

Stationary symmetrical equations for metric $k_{mn}^{\mathrm{st}}(y)$: $\beta_{\mathrm{st}}(\theta)$, $R_{\mathrm{st}}(\theta)$, $\chi_{\mathrm{st}}(\theta)$

$$e^{2\beta}r^2\Big(3\big(aR^2+c+R\big)-6H^2\big(2aR+1\big)-3\kappa m^2\chi^2\Big)+4\big(2aR+1\big)\beta_\theta\cot\theta+ \\ +4\big(2aR+1\big)\beta_{\theta\theta}-8a\big(\cot\theta R_\theta+R_{\theta\theta}\big)+4\big(2aR+1\big)+\kappa\chi_\theta^2=0\,, \tag{20}$$

$$e^{2\beta}r^2\big(12H^2-R\big)-2\big(\beta_\theta\cot\theta+\beta_{\theta\theta}-1\big)=0\,, \tag{21}$$

$$e^{2\beta}m^2r^2\chi-\chi_\theta\cot\theta+\chi_{\theta\theta}=0\,, \tag{22}$$

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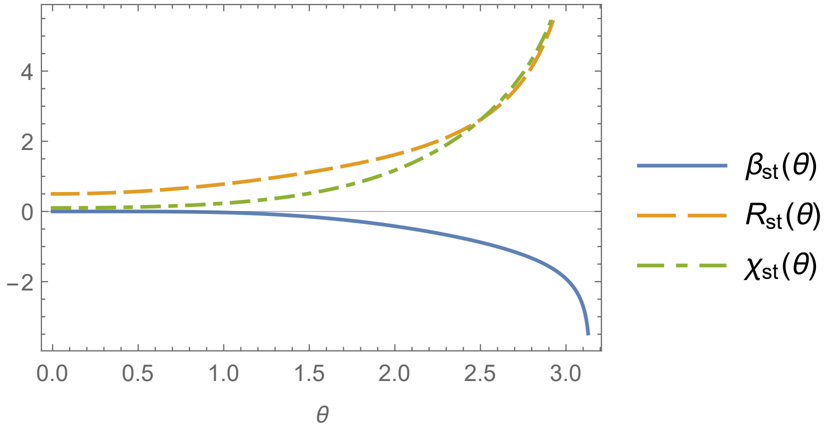

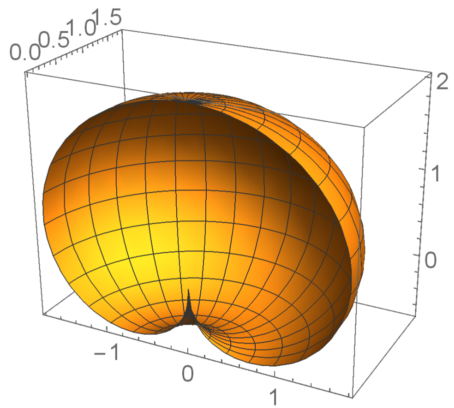

Inflationary extra space relaxation in the presence of (scalar) field

Small pertribations approximation

$$\begin{aligned}
\beta(t,\theta,\phi) &= \beta_{\rm st}(\theta) + \delta\beta(t,\theta,\phi)\,, \quad \delta\beta(t,\theta,\phi) \ll \beta_{\rm st}(\theta)\,,\\
R(t,\theta,\phi) &= R_{\rm st}(\theta) + \delta R(t,\theta,\phi)\,, \quad \delta R(t,\theta,\phi) \ll R_{\rm st}(\theta),\\
\chi(t,\theta,\phi) &= \chi_{\rm st}(\theta) + \delta\chi(t,\theta,\phi)\,, \quad \delta\chi(t,\theta,\phi) \ll \chi_{\rm st}(\theta)\,.
\end{aligned} \tag{23}$$

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Linearized equations

$$\begin{aligned}
&e^{2\beta}r^2\Big(3\delta R\big(4aH^2-2aR-1\big)+8a\delta R_{\phi\phi}\csc^2\theta-8a\delta R\big(\beta_\theta\cot\theta+\beta_{\theta\theta}-1\big)+\\
&+2\Big(3\delta\chi\kappa m^2\chi-3\delta\beta\Big(R\big(-4aH^2+aR+1\big)+c-2H^2-\kappa m^2\chi^2\Big)-12aHR\delta\beta_t+\\
&+4\big(2aR+1\big)\delta\beta_{tt}+18aH\delta R_t-4a\delta R_{tt}+6H\delta\beta_t\Big)\Big)+8a\delta R_\theta\cot\theta-4\delta\beta_{\theta\theta}-\\
&-4\big(2aR+1\big)\delta\beta_{\phi\phi}\csc^2\theta-4\big(2aR+1\big)\delta\beta_\theta\cot\theta+8a\big(\delta R_{\theta\theta}-R\delta\beta_{\theta\theta}\big)+2\kappa\delta\chi_\theta\chi_\theta=0\,,
\end{aligned} \tag{24}$$

$$e^{2\beta}r^2\Big(\delta\beta\big(24H^2-2R\big)+4\big(3H\delta\beta_t+\delta\beta_{tt}\big)-\delta R\Big)-2\Big(\delta\beta_\theta\cot\theta+\delta\beta_{\phi\phi}\csc^2\theta+\delta\beta_{\theta\theta}\Big)=0\,, \tag{25}$$

$$e^{2\beta}r^2\Big(m^2\big(2\delta\beta\chi+\delta\chi\big)+3H\delta\chi_t+\delta\chi_{tt}\Big)-\delta\chi_\theta\cot\theta-\delta\chi_{\phi\phi}\csc^2\theta-\delta\chi_{\theta\theta}=0\,. \tag{26}$$

Inflationary extra space relaxation in the presence of (scalar) field

Initial conditions (for example random traveling wave in n=2 mode)

$$\delta\beta(t,\theta,\phi) = \delta\beta_2(t,\theta)\sin(2\phi) + \delta\beta_2\left(t+\frac{n\pi}{2},\theta\right)\cos(2\phi)\,,$$
$$\delta\chi(t,\theta,\phi) = \delta\chi_2(t,\theta)\sin(2\phi) + \delta\chi_2\left(t+\frac{n\pi}{2},\theta\right)\cos(2\phi)\,. \quad (27)$$

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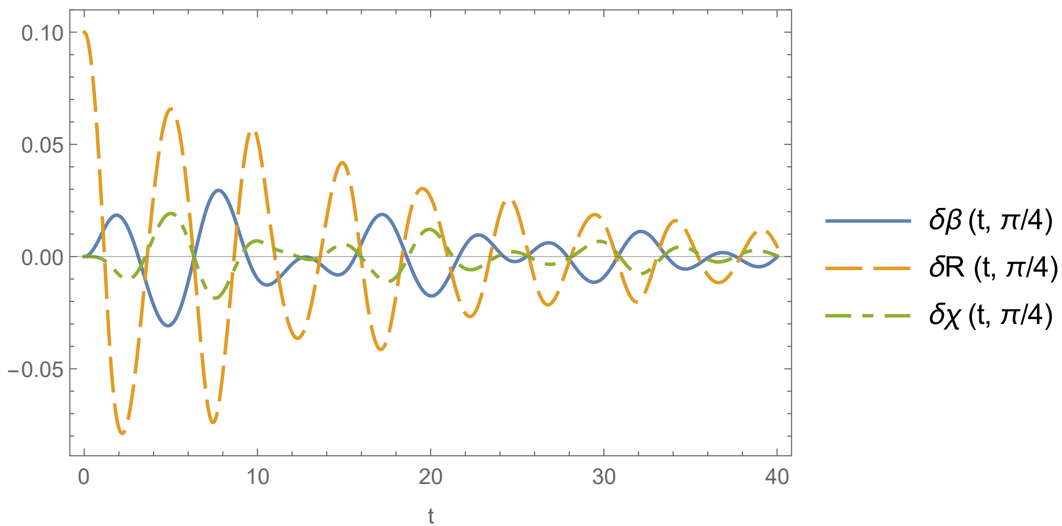

Accumulation of U(1)-number initial asymmetry

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Effective 4-dim U(1)-number before the relaxation ends

$$Q(t) = \int \partial^0 \chi \partial_\phi \chi \, r^2 e^{2\beta} \sin\theta \, d\theta d\phi =$$
$$= \int \partial^0 \delta\chi(t,\theta,\phi) \partial_\phi \delta\chi(t,\theta,\phi) \, r^2 e^{2\left(\beta_{st}(\theta) + \delta\beta(t,\theta,\phi)\right)} \sin\theta \, d\theta d\phi \, . \qquad (28)$$

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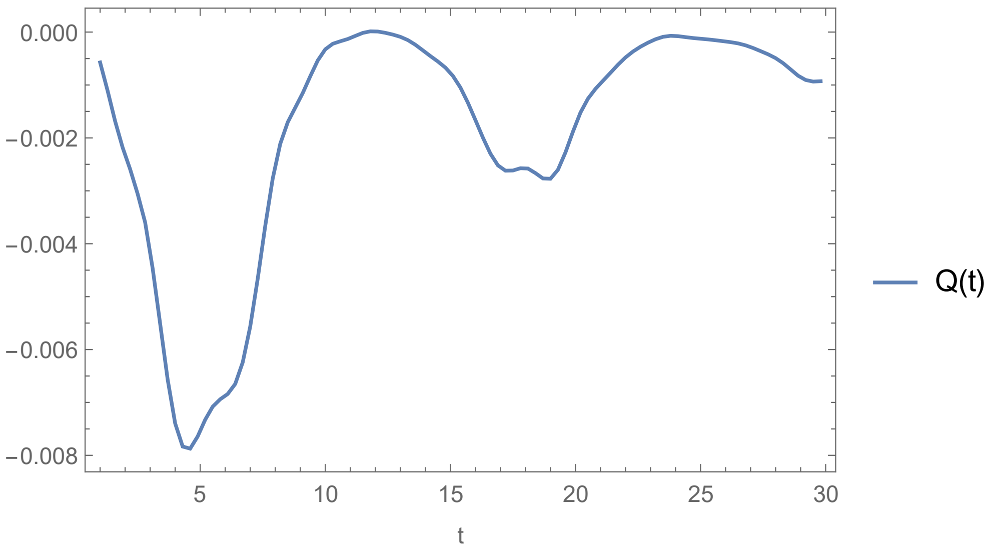

Problem of charge (number) transfer to the lowest KK-mode

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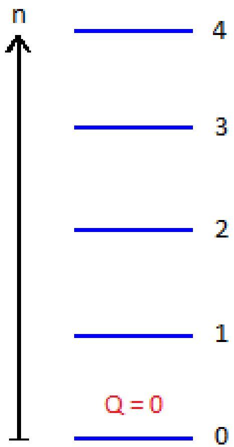
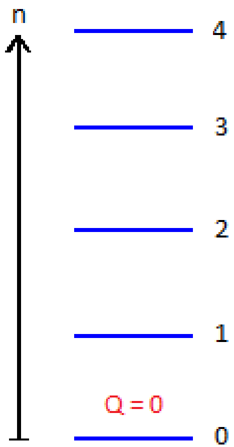


The total charge of the KK-tower

$$\begin{aligned} Q &= \int J^0 \sqrt{|g|}\sqrt{|k|}\, d^3x\, d^d y \; \sim \\ &\sim \int \sum_{n=0}^{\infty} n\; \chi_n^* \partial^0 \chi_n \sqrt{|g|}\, d^3 x \; = \\ &= \int \sum_{n=\mathbf{1}}^{\infty} n\; \chi_n^* \partial^0 \chi_n \sqrt{|g|}\, d^3 x \,. \end{aligned} \tag{29}$$

Problem of charge (number) transfer to the lowest KK-mode



The total charge of the KK-tower

$$Q = \int J^0 \sqrt{|g|}\sqrt{|k|}\, d^3x\, d^dy \sim$$
$$\sim \int \sum_{n=0}^{\infty} n\, \chi_n^* \partial^0 \chi_n \sqrt{|g|}\, d^3x = \tag{29}$$
$$= \int \sum_{n=\mathbf{1}}^{\infty} n\, \chi_n^* \partial^0 \chi_n \sqrt{|g|}\, d^3x\,.$$

- The lower level of the KK-tower does not contribute to the total charge. The charge of its particles is zero - therefore, the massive KK-modes cannot decay into known particles (which should be located at the lower level of the KK-towers).

Fermion splitting in extra space with angle profuse

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Angle profuse extra space

$$ds^2 = g_{\mu\nu}\left(x^{\alpha}\right) dx^{\mu} dx^{\nu} - r_0^2 \left(d\theta^2 + b^2 \sin^2\theta \, d\varphi^2\right) , \tag{30}$$

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Higher-dimentional fermionic action

$$S_\Psi = \int d^6x \sqrt{|G|}\, i\overline{\Psi} h^B_{\tilde{A}} \Gamma^{\tilde{A}} \nabla_B \Psi \,, \tag{31}$$

where $\Gamma^{\tilde{A}}$ is flat gamma matrices

$$\Gamma_\nu = \begin{pmatrix} \gamma_\nu & 0 \\ 0 & -\gamma_\nu \end{pmatrix}, \quad \Gamma_\theta = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad \Gamma_\varphi = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}, \tag{32}$$

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

$$g^{AB} = h^A_{\widetilde{A}} h^B_{\widetilde{B}} \eta^{\widetilde{A}\widetilde{B}} \,. \tag{33}$$

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$$ds^2 = g_{\mu\nu}(x^\alpha)\, dx^\mu dx^\nu - r_0^2 \left(d\theta^2 + b^2 \sin^2\theta\, d\varphi^2\right) , \tag{30}$$

Higher-dimentional fermionic action

$$S_\Psi = \int d^6x \sqrt{|G|}\, i\overline{\Psi} h^B_{\tilde{A}} \Gamma^{\tilde{A}} \nabla_B \Psi \,, \tag{31}$$

where $\Gamma^{\tilde{A}}$ is flat gamma matrices

$$\Gamma_\nu = \begin{pmatrix} \gamma_\nu & 0 \\ 0 & -\gamma_\nu \end{pmatrix}, \quad \Gamma_\theta = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad \Gamma_\varphi = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}, \tag{32}$$

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

$$g^{AB} = h^A_{\tilde{A}} h^B_{\widetilde{B}} \eta^{\widetilde{A}\widetilde{B}} \,. \tag{33}$$

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

Fermion splitting in extra space with angle profuse

Kaluza-Klein decomposition of lowest level

$$\Psi\left(x^A\right) = \sum_l Y_l(\theta,\varphi)\Psi_l(x) = \sum_l \frac{e^{il\varphi}}{\sqrt{2\pi}}\begin{pmatrix} \alpha_l(\theta)\psi_l(x) \\ \beta_l(\theta)\xi_l(x) \end{pmatrix}, \tag{34}$$

where the form of $\alpha_l(\theta)$ and $\beta_l(\theta)$ are computed from extra metric. Effective fermions ψ_l and ξ_l are indistinguishable for the massles KK-level.

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Massles effective 4-dim modes

$$\begin{aligned} S &= \int d^6X\sqrt{|G|}\, i\bar{\Psi} h^B_{\tilde{A}} \Gamma^{\tilde{A}} \nabla_B \Psi \sim \\ &\sim \int \sqrt{-g}\, d^4x \sum_l i\bar{\psi}_l \gamma_\mu \partial^\mu \psi_l \,, \qquad l = -\lceil b/2 \rceil, ..., 0, .., +\lfloor b/2 \rfloor \,. \end{aligned} \tag{35}$$

Limitation of mode number comes from the normalization condition:

$$\int d^6X\sqrt{|G|}\,\bar{\Psi}\Psi = \int d^4x\sqrt{|g|}\sum_l \left(\bar{\psi}_l\psi_l + \bar{\xi}_l\xi_l\right) \,. \tag{36}$$

Fermion splitting in extra space with angle profuse

Correspandence of currents

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

$$j^\mu = \frac{\partial \mathcal{L}_4}{\partial(\partial_\mu \psi_l)} t_{ll'} \psi_{l'} = i \sum_l l \, \overline{\psi_l} \gamma^\mu \psi_l \,, \qquad t_{ll'} = \int Y_l \, \partial_\varphi Y_{l'} \sqrt{k} \, d^2 y = il\delta_{ll'} \,, \tag{37}$$

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U(1)-number

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

$$\begin{aligned} Q &= \int J^0 \sqrt{|G|}\, d^3x d^2y = \int j^0 \sqrt{|g|}\, d^3x = \\ &= \int i(\psi^\dagger_{+1}\psi_{+1} - \psi^\dagger_{-1}\psi_{-1}) d^3x = N_{+1} - N_{-1} = \text{const}\,. \end{aligned} \qquad (38)$$

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- Violation of the extra space symmetry at the inflationary stage leads to the establishment of non-zero initial values of symmetry-associated charges (numbers) after the inflation.
- The accumulated charges (numbers) are then conserved because of the symmetry of effective 4-dimensional theory. However, in the usual case, the charge is realized by massive KK-modes, which are not capable of decaying into known ones due to the symmetry. Such a mechanism is suitable for generating stable dark matter, but is not suitable for explaining the baryon number.

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Thanks for you attention!

Any questions?