Gravitational baryogenesis and high energy cosmic rays

Elena Arbuzova

Dubna State University & Novosibirsk State University

joint works with A.D. Dolgov, K. Dutta, R. Rangarajan, A.A. Nikitenko

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Baryogenesis

Dominance of matter over antimatter in the universe

- The local universe is clearly matter dominated.
- On the other hand, matter and antimatter seem to have similar properties $\Longrightarrow$ we could expect a matter-antimatter symmetric universe.
- A satisfactory model of our universe should be able to explain the origin of the matter-antimatter asymmetry.

The term **baryogenesis** is used to indicate the generation of the asymmetry between baryons and antibaryons.

Sakharov Principles (1967):

1. Non-conservation of baryonic number
2. Breaking of symmetry between particles and antiparticles
3. Deviation from thermal equilibrium (Th.Eq.)

SBG and GBG do not demand an explicit C and CP violation and can proceed in Th.Eq.

Spontaneous Baryogenesis (SBG)

Cosmological baryon asymmetry can be created by SBG in thermal equil.:

- A. Cohen, D. Kaplan, Phys. Lett. B 199, 251 (1987); Nucl.Phys. B308 (1988) 913. A.Cohen, D.Kaplan, A. Nelson, Phys.Lett. B263 (1991) 86-92

"spontaneous" $\Longrightarrow$ spontaneous breaking of underlying symmetry of the theory

- Unbroken phase: the theory is invariant with respect to the global $U(1)$-symmetry, which ensures conservation of total baryonic number.

Spontaneous symmetry breaking: the Lagrangian density acquires the term

$$\mathcal{L}_{SBG} = (\partial_\mu \theta) J^\mu_B \Longrightarrow \mathcal{L}_{SB} = \dot{\theta}\, n_B\,, \quad n_B \equiv J^0_B \quad (\theta = \theta(t))$$

$\boldsymbol{\theta}$ is the (pseudo) Goldstone field and $\boldsymbol{J^\mu_B}$ is the baryonic current of matter fields.

- n_B is the baryonic number density, so it is tempting to identify $\dot{\boldsymbol{\theta}}$ with the chemical potential, $\boldsymbol{\mu_B}$, of the corresponding system.

Such identification is questionable. It depends upon the representation chosen for the fermionic fields.

- E.V. Arbuzova, A.D. Dolgov, V.A. Novikov, Phys. Rev. D **94** (2016) 123501

Gravitational Baryogenesis (GBG)

Stimulated by SBG the idea of gravitational baryogenesis (GBG) was put forward:

- H. Davoudiasl et al. Phys. Rev. Lett. **93** (2004) 201301, hep-ph/0403019.

The scenario of SBG was modified by the introduction of the coupling of the baryonic current to the derivative of the curvature scalar $\boldsymbol{R}$:

$$\mathcal{L}_{GBG} = \frac{1}{M^2}(\partial_\mu R) J_B^\mu$$

- M is a constant parameter with the dimension of mass.

GBG mechanism can successfully explain the magnitude of the cosmological baryon asymmetry of the universe.

The addition of curvature dependent term to the Lagrangian of GR leads to higher order gravitational EoM which are strongly unstable w.r.t. small perturbations.

- EA, A.D. Dolgov, Phys.Lett. B769 (2017) 171-175, arXiv:1612.06206. JCAP 1706 (2017) no.06, 001, arXiv:1702.07477.

GBG with scalars

The action of the scalar model:

$$S = -\int d^4x \sqrt{-g}\left[\frac{m_{Pl}^2}{16\pi}R + \frac{1}{M^2}(\partial_\mu R)J^\mu - g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi^* + U(\phi,\phi^*)\right] + S_m$$

- where $m_{Pl} = 1.22 \cdot 10^{19}$ GeV is the Planck mass, S_m is the matter action.

The baryonic number is carried by scalar field ϕ with potential $U(\phi,\phi^*)$.

If the potential $U(\phi)$ is not invariant w.r.t. the $U(1)$-rotation $\phi \to e^{i\beta}\phi \Longrightarrow$ the baryonic current defined in the usual way is not conserved.

$$J_\mu = iq(\phi^*\partial_\mu\phi - \phi\partial_\mu\phi^*)$$

- Here q is the baryonic number of ϕ

The corresponding equation of motion for the curvature scalar:

$$\frac{m_{Pl}^2}{16\pi}R + \frac{1}{M^2}\left[(R + 3D^2)D_\alpha J^\alpha + J^\alpha D_\alpha R\right] - D_\alpha\phi\, D^\alpha\phi^* + 2U(\phi) = -\frac{1}{2}T^\mu_\mu$$

- D_μ is the covariant derivative, T^μ_μ is the trace of EM tensor of matter

EoM in FLRW background: $ds^2 = dt^2 - a^2(t)d\mathbf{r}^2$

In the homogeneous case the equation for the curvature scalar:

$$\frac{m_{Pl}^2}{16\pi} R + \frac{1}{M^2}\left[(R + 3\partial_t^2 + 9H\partial_t) D_\alpha J^\alpha + \dot{R}\, J^0\right] = -\frac{T^{(tot)}}{2}$$

- J^0 is the baryonic number density of the ϕ-field, $H = \dot{a}/a$ (Hubble par.)
- $T^{(tot)}$ is the trace of the energy-momentum tensor of matter including contribution from the ϕ-field.

The covariant divergence of the current in the homogeneous case:

$$D_\alpha J^\alpha = \frac{2q^2}{M^2}\left[\dot{R}\,(\phi^*\dot{\phi} + \phi\dot{\phi}^*) + (\ddot{R} + 3H\dot{R})\,\phi^*\phi\right] + iq\left(\phi\frac{\partial U}{\partial \phi} - \phi^*\frac{\partial U}{\partial \phi^*}\right)$$

The expectation values of the products of the quantum operators ϕ, ϕ^*, and their derivatives after the thermal averaging:

$$\langle \phi^*\phi \rangle = \frac{T^2}{12}\,, \quad \langle \phi^*\dot{\phi} + \dot{\phi}^*\phi \rangle = 0$$

- T is the plasma temperature

Exponential instability of GBG with scalars

Equation of motion for the classical field ***R*** in the cosmological plasma:

$$\frac{m_{Pl}^2}{16\pi} R + \frac{q^2}{6M^4}\left(R + 3\partial_t^2 + 9H\partial_t\right)\left[\left(\ddot{\boldsymbol{R}} + 3H\dot{R}\right)T^2\right] + \frac{1}{M^2}\dot{R}\langle J^0\rangle = -\frac{T^{(tot)}}{2}$$

- $\langle J^0 \rangle$ is the thermal average value of the baryonic number density of ϕ.
- This term can be neglected, since it is small initially and subdominant later.

Keeping only the linear in R terms we obtain the linear fourth order equation:

$$\frac{d^4 R}{dt^4} + \mu^4 R = -\frac{1}{2}\, T^{(tot)}, \quad \mu^4 = \frac{m_{Pl}^2 M^4}{8\pi q^2 T^2}$$

The homogeneous part of this equation has exponential solutions:

$$R \sim e^{\lambda t}, \quad \lambda = |\mu| e^{i\pi/4 + i\pi n/2}, \quad n = 0, 1, 2, 3$$

- There are two solutions with positive real parts of $\boldsymbol{\lambda}$.

Curvature scalar is exponentially unstable w.r.t. small perturbations, so ***R*** should rise exponentially fast with time and quickly oscillate around this rising function.

Stabilization of GBG in R^2-modified gravity

- EA, A.D. Dolgov, K. Dutta, and R. Rangarajan, *"Gravitational Baryogenesis: Problems and Possible Resolution"*, Symmetry 15 (2023) 2, 404.

Possible stabilization mechanism might be achieved in R^2-modified gravity:

$$S_{Grav} = -\frac{m_{Pl}^2}{16\pi} \int d^4x \sqrt{-g} \left(R - \frac{R^2}{6M_R^2} \right)$$

R^2-term:

- In the early universe generates inflation (Starobinsky) and density perturbations.
- leads to excitation of the scalar degree of freedom: scalaron with the mass M_R.
- Amplitude of the observed density perturbations demands: $M_R = 3 \cdot 10^{13}$GeV.

Bosonic case: baryonic number is carried by a complex scalar field ϕ:

$$S_{tot}[\phi] = -\int d^4x \sqrt{-g} \left[\frac{m_{Pl}^2}{16\pi} \left(R - \frac{R^2}{6M_R^2} \right) + \frac{1}{M^2} (\partial_\mu R) J^\mu_{(\phi)} \right] -$$

$$\int d^4x \sqrt{-g} \left[g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi^* - U(\phi, \phi^*) \right] + S_{matt}$$

Stabilization: Bosonic Case

The equation for the curvature evolution in spatially flat FLRW-metric:

$$\frac{m_{Pl}^2}{16\pi}\left[R+\frac{1}{M_R^2}(\partial_t^2+3H\partial_t)R\right]+\frac{1}{M^2}\left[(R+3\partial_t^2+9H\partial_t)D_\alpha J^\alpha_{(\phi)}+\dot{R}\,J^0_{(\phi)}\right]$$
$$+2U(\phi)-(D_\alpha\phi)(D^\alpha\phi^*)=-\frac{T^\mu_\mu(\phi)}{2}$$

With the divergence of the baryonic current:

$$D_\alpha J^\alpha_{(\phi)}=\frac{2q^2}{M^2}\left[\dot{R}\,(\phi^*\dot{\phi}+\phi\dot{\phi}^*)+(\ddot{R}+3H\dot{R})\,\phi^*\phi\right]+iq\left(\phi\frac{\partial U}{\partial\phi}-\phi^*\frac{\partial U}{\partial\phi^*}\right)$$

we obtain the 4th order differential equation:

$$\frac{m_{Pl}^2}{16\pi}\left(R+\frac{1}{M_R^2}D^2R\right)+\frac{q^2}{6M^4}\left(R+3\partial_t^2+9H\partial_t\right)\left[\left(\ddot{R}+3H\dot{R}\right)T^2\right]=-\frac{T^\mu_\mu(\phi)}{2}$$

Keeping only the dominant terms we simplify the above equation to:

$$\frac{d^4R}{dt^4}+\frac{\kappa^4}{M_R^2}\frac{d^2R}{dt^2}+\kappa^4R=-\frac{1}{2}\,T^\mu_\mu(\phi),\qquad \kappa^4=\frac{m_{Pl}^2M^4}{8\pi q^2T^2}$$

Stability condition

The characteristic equation for the solution $R \sim \exp(\lambda t)$:

$$(*) \quad \lambda^4 + \frac{\kappa^4}{M_R^2}\lambda^2 + \kappa^4 = 0 \qquad \Longrightarrow \lambda^2 = -\frac{\kappa^4}{2M_R^2} \pm \kappa^2 \sqrt{\frac{\kappa^4}{4M_R^4} - 1}$$

No instability, if $\lambda^2 < 0$ and Eq. $(*)$ has only oscillating solutions.

Stability condition (boson case):

$$\kappa^4 = \frac{m_{Pl}^2 M^4}{8\pi q^2 T^2} > 4M_R^4 \implies M > 3 \cdot 10^4 \text{ GeV} \left(\frac{q\,T}{\text{GeV}}\right)^{1/2}$$

The value of λ depends upon the relation between κ and M_R:

- $\kappa \sim M_R \Longrightarrow$ the frequency of oscillations is of the order of M_R, $|\lambda| \sim M_R$.
- $\kappa \gg M_R \Longrightarrow$ 2 possible solutions: $|\lambda| \sim M_R$ and $|\lambda| \sim M_R(\kappa/M_R)^2 \gg M_R$.

High frequency oscillations of R would lead to **efficient gravitational particle production** and, as a result, to damping of the oscillations.

Production of dark matter particles by oscillating curvature

Heavy DM particles have been created in the model of the Starobinsky inflation:

$$S(R^2) = -\frac{M_{Pl}^2}{16\pi} \int d^4x \sqrt{-g} \left[R - \frac{R^2}{6M_R^2} \right]$$

The width of the scalaron decay into a pair of fermions with mass m_f:
(EA, A.D. Dolgov, A.S. Rudenko, 2112.11288 [hep-ph])

$$\Gamma_f = \frac{m_f^2 M_R}{6 M_{Pl}^2}$$

- This result is obtained for particles with masses $m_f \ll M_R$.

We are interested in the case when the scalaron decays create particles with mass about 10^{20} eV, that is the energy of UHECR.

- EA, A.D. Dolgov, A.A. Nikitenko, "*Cosmic rays from annihilation of heavy dark matter particles*", e-Print: 2405.12560 [hep-ph] ; "*Cosmic rays from heavy particle decays*", e-Print: 2305.03313 [hep-ph], Phys.Atom.Nucl. 87 (2024) 1, 49-55.

The problem of the origin of the ultra high energy cosmic rays (UHECR)

Registered events with enegies $\gtrsim 10^{20}$ eV: Extremely High Energy Cosmic Rays (EHECR).

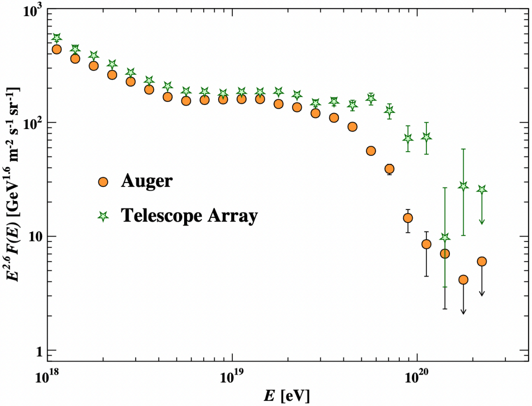

Figure: UHECR fluxes measured by Pier Auger Observatory and Telescope Array (Fig. 30.10, PDG, 2020)

Scalaron decay into extremely heavy DM

For decay width $\Gamma_{m_f} = m_f^2 M_R/(6M_{Pl}^2)$ the energy density of heavy fermions would be much larger than the averaged cosmological density of DM:

$$\varrho_f \gg \varrho_{DM} \approx 1 \text{ keV/cm}^3$$

The probability of the decay would be strongly suppressed if the fermion mass M_f is extremely close to $M_R/2$:

$$\Gamma_f = \frac{M_f^2 M_R}{6M_{Pl}^2}\sqrt{1 - \frac{4M_f^2}{M_R^2}}, \quad M_f \sim \frac{M_R}{2}$$

- The phase space factor $(1 - 4M_f^2/M_R^2)^{1/2}$ allows to arrange the energy density of presumably DM particles f to be equal to the observed energy density of DM:

$$\varrho_f \approx \varrho_{DM}$$

Annihilation of superheavy dark matter particles

The flux of high energy particles is determined by the cross-section of annihilation of heavy fermions:

$$\sigma_{ann} v \sim \alpha^2 g_* / M_f^2 ,$$

- v is the centre-of-mass velocity, α is the coupling constant, $\alpha \sim 10^{-2}$, and g_* is the number of the open annihilation channels, $g_* \sim 100$.
- With $M_f = 1.5 \cdot 10^{13}$ GeV we estimate $\sigma_{ann} v \sim 2 \cdot 10^{-56} \mathrm{cm}^2$.

The rate of the decrease of the f-particle density per unit time and volume:

$$\dot{n}_f = \sigma_{ann} v n_f^2 = \alpha^2 g_* n_f^2 / M_f^2 \approx const ,$$

The annihilation of heavy f-particles leads to a continuous contribution to the rate of cosmic ray production per unit time and unit volume equal to:

$$\dot{\varrho}_f^{(ann)} = 2 M_f \dot{n}_f .$$

Energy distribution of the CR particles produced by $f\bar{f}$-ann

We postulate the differential energy spectrum of the number density flux:

$$\frac{d\dot{n}_{PP}(E)}{dE} = \mu^3 \exp\left[-\frac{(E - 2M_f/\bar{n})^2}{\delta^2}\right]\theta(2M_f - E)$$

- μ is a normalisation factor with dimension of mass, δ is the width of distr.
- $\bar{n}$ is the average number of particles created by $f\bar{f}$ - annihilation, $\bar{n} \sim 10^3$

The contribution from the heavy particle annihilation into cosmic ray flux:

$$\frac{d\dot{\varrho}_{PP}(E)}{dE} = E\,\frac{d\dot{n}_{PP}(E)}{dE}$$

The total flux of the energy density of the produced particles:

$$\dot{\varrho}_{PP} = \int_0^{2M_f} E\left(\frac{d\dot{n}_{PP}(E)}{dE}\right) dE \approx \sqrt{\pi}\,\mu^3\,\bar{M}\delta\,, \quad \bar{M} = 2M_f/\bar{n}$$

The normalisation factor μ^3 can be calculated from the condition:

$$\dot{\varrho}_f^{(ann)} = \dot{\varrho}_{PP} \implies \mu^3 = \frac{1.48\cdot 10^{-54}\,\bar{n}}{2\sqrt{\pi}\,\mathrm{GeV}\,\mathrm{cm}^6 M_f\delta} = \frac{2.2\cdot 10^{-109}\,\bar{n}}{\mathrm{cm}^3}\left(\frac{\mathrm{GeV}}{\delta}\right)$$

Flux of cosmic rays from homogeneous dark matter

Let us estimate the energy flux of the products of the annihilation of DM particles "in the entire Universe" and reaching Earth's detectors, assuming that the dark matter in the Universe is distributed uniformly and isotropically.

Flux created by source S from the spherical layer with radius R and width ΔR:

$$\Delta L = \frac{S}{4\pi R^2} \times 4\pi R^2 \Delta R = S \Delta R.$$

Integrating over the homogeneity scale we find the total flux:

$$L_{hom} = S_{hom} R_{max}, \quad S_{hom} = \frac{d\dot{n}_{PP}}{dE}, \quad R_{max} \approx 10^{28} cm$$

The contribution to the flux of high energy CR, emerging from the $f\bar{f}$ ann.:

$$L_{hom} = \frac{2.23 \cdot 10^{-81} \bar{n}}{cm^2} \left(\frac{\mathrm{GeV}}{\delta} \right) \exp\left[-\frac{(E - 2M_f/\bar{n})^2}{\delta^2} \right] \theta(2M_f - E)$$

A crude order of magnitude estimate assuming $\bar{n} = 10^3$ and $\delta \sim 1$ GeV would be:

$$L_{hom} \sim 10^{-78}\, cm^{-2} \quad vs \quad L_{obs} \sim 10^{-55}\, cm^{-2} (PDG)$$

The resonance effect in DM particle annihilation

The annihilation can be strongly enhanced due to resonance process of $f\bar{f}$-transition to scalaron, since $2M_f$ is very close to M_R.

- 1. P. Gondolo, G. Gelmini, Nucl. Phys.B 360 (1991) 145
- 2. K. Griest, D. Seckel, Phys. Rev. D 43 (1991) 3191

The thermally averaged cross-section [1]:

$$\langle \sigma_{ann} v \rangle = \frac{1}{8M_f^4 T [K_2(M_f/T)]^2} \int_{4M_f^2}^{\infty} ds\,(s - 4M_f^2)\sigma_{ann}(s)\sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right)$$

- T is the cosmic plasma temperature, $s = (p_f + p_{\bar{f}})^2$ is the center of mass energy squared, and $K_{(1,2)}$ are the modified Bessel functions.

The resonance cross-section has the form [2]:

$$\sigma_{ann}^{(res)} v = \frac{\alpha^2 s}{(M_R^2 - s)^2 + M_R^2 \Gamma_R^2}$$

- $M_R = 3 \cdot 10^{13}$ GeV is the scalaron mass and $\Gamma_R = \frac{M_f^2 M_R}{6 M_{Pl}^2}$ is its decay width.

Thermally averaged resonance cross-section:

$$\langle \sigma_{res} v \rangle = \int_0^\infty dzze^{-z} \frac{\alpha^2 s}{(M_R^2 - s)^2 + M_R^2 \Gamma_R^2} \approx \frac{\alpha^2}{M_R^2} \int_0^\infty \frac{dzze^{-z}}{\gamma^2 + \eta^2 z^2}$$

- dimensionless variable z is defined according to $s = 4M_f^2(1 + Tz/M_f)$.

For $M_f = 1.5 \cdot 10^{13}$ GeV and $T = T_{CMB} = 2.7K = 2.35 \cdot 10^{-4}$ eV:

$$\gamma^2 = \frac{\Gamma_R^2}{M_R^2} = \frac{1}{36} \left(\frac{M_f}{M_{Pl}} \right)^4 \approx 6.7 \cdot 10^{-26} \quad \text{vs} \quad \eta^2 = \left(\frac{T}{M_f} \right)^2 \approx 2.45 \cdot 10^{-52}$$

- We can neglect the term $\eta^2 z^2$ and conclude that the annihilation cross-section is 26 orders of magnitude higher than the estimate made above.
- The contribution to the flux of the cosmic rays might be at the sufficient level to explain the origin of UHECR with $E \gtrsim 10^{20}$ eV.

The effect is even stronger in the case of annihilation of $f\bar{f}$ in denser regions of the Galaxy (galactic center) with realistic distribution of DM.

Flux of UHECR from DM annihilation in the galactic center (GC)

Local density of DM in GC is much larger than the average cosmological density:

- Y. Sofue, arXiv:2004.11688 [astro-ph.GA]

$$\varrho_{GC} = 840 \text{ GeV/cm}^3 \gg \varrho_{obs} = 1\text{keV/cm}^3$$

Since the flux of the cosmic rays from DM annihilation is proportional to the square of the DM particle density, smaller objects with the number density larger than the average one can create a larger flux of the cosmic rays.

The result for L_{hom} should be rescaled as follows:

$$L_{GC} = L_{hom} \times \left(\frac{n_{GC}}{\bar{n}_{DM}} \right)^2 \frac{r_{cl}^3/(3\, d_{gal}^2)}{R_{max}} \approx 10^3\, L_{hom}$$

- $r_{cl} = 10$ pc $\approx 3 \cdot 10^{19}$ cm and $4\pi r_{cl}^3/3$ is volume of high density cluster in GC
- $4\pi d_{gal}^2$ is the area of the sphere at the distance d_{gal} from GC, $d_{gal} = 8$ kpc $= 2.4 \cdot 10^{22}$ cm, $R_{max} = 10^{28}$ cm.

Realistic Dark Matter distribution in the Galaxy

The commonly accepted shape of dark matter distribution (Gunn, 1972):

$$\varrho(r) = \varrho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1} \equiv \varrho_0 q(r),$$

- ϱ_0 denotes the finite central density and r_c the core radius.

We assume that $r_c = 1$ kpc and calculate ϱ_0 from the condition that at the position of the Earth at $r = l_\oplus = 8$ kpc the density of DM is:

- P. Salucci et al., arXiv:1003.3101 [astro-ph.GA]

$$\varrho(l_\oplus = 8\,\text{kpc}) \approx 0.4\,\mathrm{GeV/cm^3} \implies \varrho_0 = 65\varrho(l_\oplus) = 26\,\mathrm{GeV/cm^3}$$

We consider the annihilation of DM particles at the point determined by the radius-vector $\vec{r}$ with the spherical coordinates r, θ, ϕ directed from GC.

The distance of this point to the Earth is:

$$d_\oplus = \sqrt{(\vec{l_\oplus} + \vec{r})^2} = \sqrt{r^2 + l_\oplus^2 - 2r\, l_\oplus \cos\theta}$$

CR flux from annihilation of DM with realistic distribution in Galaxy

We recalculate the flux of cosmic rays rescaling L_{GC} and obtain:

$$L_{real} = L_{GC} \left(\frac{26\mathrm{GeV}}{840\mathrm{GeV}} \right)^2 \frac{3d_{gal}^2}{r_{cl}^3} J$$

where J is the integral over DM distribution:

$$J = \int \frac{d^3 r q(r)}{d_\oplus^2} = 2\pi \int \frac{dr r^2 q(r) d\cos\theta}{r^2 + l_\oplus^2 - 2 r l_\oplus \cos\theta} = 2\pi \int \frac{dr r q(r)}{l_\oplus} \ln \frac{l_\oplus + r}{l_\oplus - r}.$$

After change of variables, $r = x l_\oplus$, the integral is reduced to the expression below and is taken numericallly:

$$J = 2\pi\, l_\oplus \int_0^1 dx x \left(1 + 64x^2\right)^{-1} \ln \frac{1+x}{1-x} = 0.2\, l_\oplus.$$

Thus we obtain $L_{real} = 3 \cdot 10^5 L_{GC}$. This is noticeably larger than the flux from the dense GC and allows for much weaker amplification by the resonance annihilation.

Decays through virtual Black Holes

- Usually dark matter particles are supposed to be absolutely stable.
- Zeldovich mechanism (1976): decay of any presumably stable particles is possible through creation of virtual black holes.
- The rate of the proton decay calculated in the canonical gravity, with the energy scale equal to M_{Pl}, is extremely tiny and the corresponding life-time is by far longer than the universe age.

However, the smaller scale of gravity and huge mass of DM particles both lead to a strong amplification of the Zeldovich effect.

Superheavy DM particles with $M_X \sim 10^{12}$ GeV may decay through the virtual BH with life-time several orders of magnitude longer than the universe age.

Decays of such particles could make essential contribution to the UHECR.

Multidimensional Modification of Gravity

Model: the observable universe with the SM particles is confined to a 4-dim brane embedded in a $(4+d)$-dim bulk, while gravity propagates throughout the bulk.

- N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B **429**, 263 (1998); I.Antoniadis, N.Arkani-Hamed, S.Dimopoulos, G.Dvali, Phys.Lett.B**436**,257(1998).

The Planck mass M_{Pl} becomes a long-distance 4-dimensional parameter and the relation with the effective gravity scale at small distances, M_*, is given by:

$$M_{Pl}^2 \sim M_*^{2+d} R_*^d, \quad R_* \sim \frac{1}{M_*}\left(\frac{M_{Pl}}{M_*}\right)^{2/d},$$

- R_* is the size of the extra dimensions.

We choose $M_* \approx 3 \times 10^{17}$ GeV, so $R_* \sim 10^{(4/d)}/M_* > 1/M_*$.

Heavy proton type dark matter: $X \to L^+ \bar{q}_* q_*$

The width of the proton decay $p \to l^+ \bar{q} q$ via virtual BH:

- C. Bambi, A. D. Dolgov and K. Freese, Nucl. Phys. B **763** (2007), 91-114

$$\Gamma_p = \frac{m_p\,\alpha^2}{2^{12}\,\pi^{13}} \left(\ln \frac{M_{Pl}^2}{m_q^2}\right)^2 \left(\frac{\Lambda}{M_{Pl}}\right)^6 \left(\frac{m_p}{M_{Pl}}\right)^{4+\frac{10}{d+1}} \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}$$

Decay $X \to L^+ \bar{q}_* q_*$: $m_p \Longrightarrow M_X \sim 10^{12}\,GeV$, $m_{q_*} \sim M_X$, $M_{Pl} \Longrightarrow M_*$.

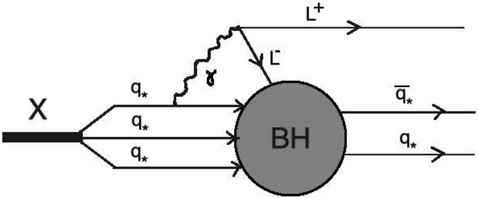

Figure: Diagram illustrated X-particle decay into $L^+ \bar{q}_* q_*$ through virtual BH.

NB. We assume, that BH has vacuum quantum numbers to avoid naked singularity.

Superheavy DM particle decay

The life-time of X-particles:

$$\tau_X \approx 10^{-24}\mathrm{s} \cdot \frac{2^{11}\pi^{13}}{3\alpha_*^2}\left(\frac{\mathrm{GeV}}{\mathrm{M_X}}\right)\left(\frac{\mathrm{M_*}}{\Lambda_*}\right)^6\left(\frac{\mathrm{M_*}}{\mathrm{M_X}}\right)^{4+10/(\mathrm{d}+1)}\left(\ln\frac{\mathrm{M_*}}{\mathrm{m_{q_*}}}\right)^{-2}\mathrm{I(d)}^{-1},$$

where we took $1/\mathrm{GeV} = (2/3)\times 10^{-24}$ s and

$$I(d) = \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}, \quad I(7) \approx 0.0057.$$

Now all the parameters, except for Λ_*, are fixed:

- $M_* = 3 \times 10^{17}$ GeV, $M_X = 10^{12}$ GeV, $m_{q_*} \sim M_X$, and $\alpha_* = 1/50$

The life-time of X-particles can be estimated as:

$$\tau_X \approx 7 \times 10^{12}\ \mathrm{years}\left(10^{15}\,\mathrm{GeV}/\Lambda_*\right)^6 \quad vs \quad t_U \approx 1.5 \times 10^{10}\ \mathrm{years}$$

A slight variation of Λ_* near 10^{15} GeV allows to fix the life-time of DM particles in the interesting range. They would be stable enough to behave as the cosmological DM and their decay could make considerable contribution into cosmic rays at ultra high energies.

Conclusions

- The derivative coupling of baryonic current to the curvature scalar in GBG leads to higher (4th) order equations for gravitational field, which are unstable w.r.t. small perturbations and such instability leads to an exponential rise of the curvature.
- The problem of stability can be solved by adding to the Hilbert-Einstein action the R^2-term that leads to oscillations of curvature and to efficient particle production.
- In R^2-gravity the viable canditates for DM particles could be extremely heavy, up to $M \sim 10^{13}$ GeV. Annihilation and decay of such particles are promising sources of EHECR, which is difficult to explain by the canonical astrophysical mechanisms.
- The contribution to the flux of cosmic rays originated from different cosmological environment (e.g. DM clumps in the galactic centre) might be at the sufficient level to explain the origin of UHECR with $E \gtrsim 10^{20}$ eV.
- The flux of UHECR would be strongly enchanced in the case of the resonance annihilation of superheavy DM particles.
- DM particles are supposed to be stable with respect to the conventional particle interactions, but they could decay though the virtual BH formation. In the model of high dimensional gravity the life-time of such quasi-stable particles may exceed the universe age by several orders of magnitude.
- The considered mechanisms might explain the origin of cosmic rays observed by Pierre Auger and Telescope Array detectors.

THE END

THANK YOU FOR ATTENTION