Superheavy Dark Matter in R^2-modified Gravity

Elena Arbuzova

Dubna State University & Novosibirsk State University

based on joint works with A.D. Dolgov, A.A. Nikitenko, R.S. Singh

Supported by the RSF Grant 22-22-00294

XXXV International Workshop on High Energy Physics

From Quarks to Galaxies: Elucidating Dark Sides

28 November - 1 December 2023

Protvino, Moscow region, Russia

Outline

- Dark Matter Mystery
- Cosmological evolution in R^2-gravity
- Kinetics and freezing of massive stable relics in cosmic plasma and bounds on the masses of DM particles
  - Minimally coupled scalars mode
  - Massive fermions mode
  - Gauge bosons mode
- Cosmic rays from heavy particle decays
- Conclusions

Dark Matter Mystery

- invisible form of matter disclosing itself through its gravitational action
- electrically neutral, since doesn't scatter light
- properties are practically unknown

Particles of many different types can be DM candidates

The fractional mass density of dark matter:

$$\Omega_{DM} = \frac{\varrho_{DM}}{\varrho_{crit}} \approx 0.265$$

The critical energy density of the universe:

$$\varrho_{crit} = \frac{3H_0^2 M_{Pl}^2}{8\pi} \approx 5\ \mathrm{keV/cm^3}, \quad M_{Pl} = 1.22 \cdot 10^{19} GeV = 2.18 \cdot 10^{-5} g$$

H_0 is the present day value of the Hubble parameter:

$$H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \approx 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

The observed mass density of DM in contemporary universe:

$$\varrho_{DM} \approx 1\,\mathrm{keV/cm^3}$$

Observational Evidence and Possible Carriers of DM

Independent pieces of data:

- flat rotational curves around galaxies;
- equilibrium of hot gas in rich galactic clusters;
- the spectrum of the angular fluctuations of Cosmic Microwave Background (CMB) Radiation;
- onset of Large Scale Structure (LSS) formation at the redshift $z_{LSS} = 10^4$ prior to hydrogen recombination at $z_{rec} = 1100$.

Possible carriers of dark matter:

- WIMP (Weakly Interacting Massive Particle): axions ($\sim 10^{-5}$ eV), heavy neutral leptons ($\sim$ GeV), particles of mirror matter, the Lightest Supersymmetric Particle (LSP), ...
- MACHO (Massive Astrophysical Compact Halo Object): primordial black holes (PBH) (from 10^{20} g up to tenth $M_\odot$), topological or non-topological solitons, possible macroscopic objects consisting e.g. from the mirror matter, ...

SUSY Dark Matter

Low energy minimal SUSY model:

- Predicts the existence of stable LSPs with mass $M_{LSP} \sim$ 100–1000 GeV
- No manifestation at LHC $\Longrightarrow$ restricted parameter space open for SUSY

The LSP's energy density

$$\varrho_{LSP} \sim \varrho_{DM}^{(obs)} (M_{LSP}/1\ TeV)^2, \quad \varrho_{DM}^{(obs)} \approx 1\ keV/cm^3$$

- For $M_{LSP} \sim 1$ TeV, ϱ_{LSP} is of the order of the observed DM energy density
- For larger masses LSPs would overclose the universe.

LSPs are practically excluded as DM particles in the conventional cosmology.

In $(R + R^2)$-gravity the energy density of LSPs may be much lower $\Longrightarrow$
it reopens for them the chance to be the dark matter, if $M_{LSP} \geq 10^6$GeV.

- EA, A. D. Dolgov and R. S. Singh, "Dark matter in $R + R^2$ cosmology," JCAP **04** (2019) 014, arXiv:1811.05399 [astro-ph.CO]

Cosmological evolution in R^2-gravity

- EA, A.D. Dolgov, R. Singh, *"Distortion of the standard cosmology in $R + R^2$ theory"*, JCAP **07** (2018) 019 ; arXiv: 1803.01722 [gr-qc]
- EA, A.D. Dolgov, L. Reverberi, *"Cosmological evolution in R^2 gravity,"* *JCAP* **02**, (2012), 049, arXiv:1112.4995 [gr-qc]

General Relativity (GR):

$$S_{EH} = -\frac{M_{Pl}^2}{16\pi} \int d^4x \sqrt{-g}\, R$$

Beyond the frameworks of GR:

$$S_{tot} = -\frac{M_{Pl}^2}{16\pi} \int d^4x \sqrt{-g} \left[R - \frac{R^2}{6M_R^2} \right] + S_m$$

Magnitude of temperature fluctuations of CMB demands $M_R \approx 3 \times 10^{13}$ GeV.

- R^2-term leads to exponential cosmological expansion (Starobinsky inflation).
- It creates considerable deviation from the Friedmann cosmology in the post-inflationary epoch.
- Kinetics of massive species and the density of DM particles differ significantly from those in the conventional cosmology.

The modified Einstein equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \frac{1}{3M_R^2} \left(R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu} + g_{\mu\nu} D^2 - D_\mu D_\nu \right) R = \frac{8\pi}{M_{Pl}^2} T_{\mu\nu}$$

FLRW: $ds^2 = dt^2 - a^2(t)\left[dr^2 + r^2 d\vartheta^2 + r^2 \sin^2\vartheta \, d\varphi^2\right], \;\; H = \dot{a}/a$

Trace equation:

$$D^2 R + M_R^2 R = -\frac{8\pi M_R^2}{M_{Pl}^2} T_\mu^\mu$$

For homogeneous field, $R = R(t)$, and with equation of state $P = w\varrho$:

$$\ddot{R} + 3H\dot{R} + M_R^2 R = -\frac{8\pi M_R^2}{M_{Pl}^2}(1-3w)\varrho$$

w is usually a constant parameter:

- non-relativistic: $w = 0$, relativistic: $w = 1/3$, vacuum-like: $w = -1$

The curvature scalar:

$$R = -6\dot{H} - 12H^2$$

The covariant conservation condition $D_\mu T_\nu^\mu = 0$ in FLRW-metric:

$$\dot{\varrho} = -3H(\varrho + P) = -3H(1+w)\varrho$$

Equation for the Curvature Scalar Evolution

$$\ddot{R} + 3H\dot{R} + M_R^2 R = -\frac{8\pi M_R^2}{M_{Pl}^2}(1-3w)\varrho$$

- does not include the effects of particle production by the curvature scalar;
- is a good approximation at inflationary epoch, when particle production by $R(t)$ is absent, because R is large and friction is large, so $R \to 0$ slowly.

At some stage, when $\boldsymbol{H}$ becomes smaller than $\boldsymbol{M_R}$, $\boldsymbol{R}$ starts to oscillate efficiently producing particles.

- It commemorates the end of inflation, the heating of the universe, and the transition from the accelerated expansion (inflation) to a de-accelerated one.
- The latter resembles the usual Friedmann matter dominated expansion regime but differs in many essential features.

Curvature $\boldsymbol{R(t)}$ can be considered as an effective scalar field (scalaron) with the mass $\boldsymbol{M_R}$ and with the decay width Γ.

Dimensionless Equations

Dimensionless time variable and dimensionless functions

$$\tau = tM_R, \quad H = M_R h, \quad R = M_R^2 r, \quad \varrho = M_R^4 y$$

The system of dimensionless equations

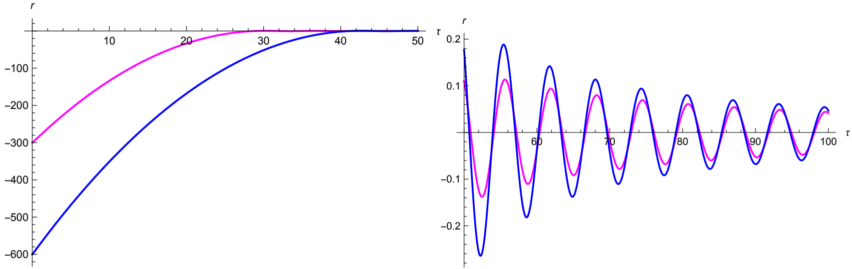
$$\begin{aligned} & r'' + 3hr' + r = -8\pi\mu^2(1-3w)y \\ & h' + 2h^2 = -r/6 \\ & y' + 3(1+w)h\,y = 0 \end{aligned}$$

- prime denotes derivative over τ, $\mu = M_R/M_{Pl}$

Inflationary stage: $y = 0$ ($\varrho = 0$) – "empty" Universe.

Inflationary stage: numerical solutions

Evolution of the dimensionless curvature scalar $\boldsymbol{r(\tau)}$ for
$\boldsymbol{r_{in} = -300}$ (magenta) and $\boldsymbol{r_{in} = -600}$ (blue)



- *Left panel*: evolution during inflation.
- *Right panel*: evolution after the end of inflation, the curvature scalar starts to oscillate (scale differs from the left graph).

Curvature oscillations lead to the creation of particles and to the heating of the Universe.

Universe Heating in R^2-gravity

Particle production: friction term approximation for harmonic oscillations of $R(t) \Longrightarrow \Gamma\dot{R}$-term

$$\ddot{R} + (3H + \Gamma)\dot{R} + M_R^2 R = -\frac{8\pi M_R^2}{M_{Pl}^2}(1 - 3w)\varrho$$

Particle production leads to an emergence of the source term in Eq. for ϱ:

$$\dot{\varrho} + 3H(1 + w)\varrho = \bar{S}[R] \neq 0.$$

The system of dimensionless equations:

$$h' + 2h^2 = -r/6$$
$$r'' + (3h + \gamma)r' + r = -8\pi\mu^2(1 - 3w)y$$
$$y' + 3(1 + w)h\,y = S[r]$$

- $\mu = M_R/M_{Pl}$, $\Gamma = M_R\gamma$.

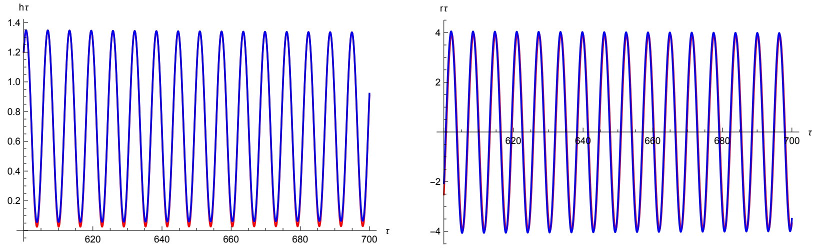
The value of Γ depends on the decay channel of the scalaron

Evolution of $H(t)$ and $R(t)$ at post-inflationary stage

Asymptotic solutions:

$$h = \frac{2}{3\tau}\left[1 + \sin\left(\tau + \theta\right)\right], \quad r = -\frac{4\cos(\tau + \theta)}{\tau} - \frac{4}{\tau^2}$$

Comparison of numerical calculations with analytical estimates for the adjusted "by hand" phase $\theta = -2.9\pi/4$



- *Left panel*: comparison of numerical solution for $h\tau$ (red) with analytic estimate (blue). *Right panel*: the same for numerically calculated $r\tau$.

The difference between the red and blue curves is not observable.

Cosmological evolution in R^2-modified gravity: 4 distinct epochs

1. Inflation: R slowly decreases from large value $R/M_R^2 \gtrsim 10^2$ down to zero.
2. Curvature oscillations:

$$R(t) = 4M_R \frac{\cos(M_R t+\theta)}{t}$$

leading to efficient particle production through the scalaron decay and consequently to the universe heating (scalaron dominated regime)

During this time the universe evolution was quite different from GR.

It opens the window for heavy LSPs to be the cosmological DM, modifies high temperature baryogenesis, leads to reconsideration of PBHs formation, *etc.*

3. Transition of the scalaron domination regime to the dominance of the produced matter of mostly relativistic particles.
4. Onset of the conventional cosmology governed by General Relativity.

We consider the epoch of the universe heating and calculate the freezing of the massive species $\boldsymbol{X}$ in plasma, created by the scalaron decays into heavier particles, and find the range of the allowed X-masses to form the cosmological DM.

Kinetics and freezing of massive supersymmetry-kind relics in cosmic plasma and bounds on masses of DM particles

- EA, A.D. Dolgov, R. Singh, *"Dark matter in $R+R^2$ cosmology,"*, JCAP **04** (2019), 014, arXiv:1811.05399 [astro-ph.CO]
- EA, A.D. Dolgov, R. Singh, *Superheavy dark matter in $R+R^2$ cosmology with conformal anomaly,"* Eur. Phys. J. C **80**, (2020), 1047, arXiv: 2002.01931 [hep-ph]
- EA, A.D. Dolgov, R. Singh, *"R^2-Cosmology and New Windows for Superheavy Dark Matter,"*, Symmetry **13** (2021) 5, 877

Cosmological energy density for different decay channels

Scalaron decay into 2 massless scalars minimally coupled to gravity:

$$\Gamma_s = \frac{M_R^3}{24 M_{Pl}^2}, \qquad \varrho_s = \frac{M_R^3}{240\pi t}$$

Scalaron decay into a pair of fermions with mass m_f:

$$\Gamma_f = \frac{M_R m_f^2}{6 M_{Pl}^2}, \qquad \varrho_f = \frac{M_R m_f^2}{120\pi t}$$

Scalaron decay into gauge bosons induced by the conformal anomaly:

$$\Gamma_{an} = \frac{\beta_1^2 \alpha^2 N}{96\pi^2} \frac{M_R^3}{M_{Pl}^2}, \qquad \varrho_{an} = \frac{\beta_1^2 \alpha^2 N}{4\pi^2} \frac{M_R^3}{120\pi t}$$

β_1 is the first coefficient of the beta-function, N is the rank of the gauge group
α is the gauge coupling constant (at high energies it depends upon the theory).

Much slower decrease of the energy density of matter than normally for relativistic matter is ensured by the influx of energy from the scalaron decay.

- Normally for relativistic matter: $\varrho \sim 1/a^4(t) \sim 1/t^{8/3}$, since $a(t) \sim t^{(2/3)}$ at SD.

Connection of the temperature with time: GR $\Longleftrightarrow$ R^2

In thermalized plasma with $\varrho_{therm} = \pi^2 g_* T^4/30$

$$\varrho_{GR} = \frac{3M_{Pl}^2}{32\pi t^2} = \frac{\pi^2 g_* T^4}{30} \implies (tT^2)_{GR} = \left(\frac{90}{32\pi^3 g_*}\right)^{1/2} M_{Pl} = const$$

- g_* is the number of relativistic species in the plasma, $g_* \sim 100$.

R^2-theory:

$$\varrho_s = \frac{M_R^3}{240\pi t} = \frac{\pi^2 g_* T^4}{30} \implies (tT^4)_s = \frac{M_R^3}{8\pi^3 g_*} = const$$

$$\varrho_{an} = 2.6 \cdot 10^{-2} \alpha_R^2 \frac{M_R^3}{t} \implies (tT^4)_{an} = \frac{0.78}{\pi^2 g_*} \alpha_R^2 M_R^3 = const$$

- The coupling $\boldsymbol{\alpha_R}$ is taken at the energies equal to the scalaron mass.

Correspondingly

$$\left(\frac{\dot{T}}{T}\right)_{GR} = -\frac{1}{2t} \qquad \left(\frac{\dot{T}}{T}\right)_{s;an} = -\frac{1}{4t}$$

Evolution of X-particles in thermal plasma

Freezing of massive species $X \Longrightarrow$ Zeldovich Eq., 1965 (Lee-Weinberg, 1977):

$$\dot{n}_X + 3Hn_X = -\langle \sigma_{ann} v \rangle \left(n_X^2 - n_{eq}^2 \right), \;\; n_{eq} = g_s \left(\frac{M_X T}{2\pi} \right)^{3/2} e^{-M_X/T}$$

- $\langle \sigma_{ann} v \rangle$ is the thermally averaged annihilation cross-section of X-particles
- n_{eq} is their equilibrium number density, g_s is the number of spin states.

For annihilation of non-relativistic particles:

$$\langle \sigma_{ann} v \rangle = \sigma_{ann} v = \frac{\pi \alpha^2 \beta_{ann}}{2M_X^2} \;\; \text{(S-wave)},$$

$$\langle \sigma_{ann} v \rangle = \frac{3\pi \alpha^2 \beta_{ann}}{2M_X^2} \frac{T}{M_X} \;\; \text{(P-wave, Majorana fermions)}$$

- M_X is a mass of X-particle, $\boldsymbol{\alpha}$ is a coupling constant, in SUSY theories $\boldsymbol{\alpha \sim 0.01}$
- $\boldsymbol{\beta_{ann}}$ is a numerical parameter $\sim$ the number of annihilation channels, $\boldsymbol{\beta \sim 10}$.

We assume that direct X-particle production by $\boldsymbol{R(t)}$ is suppressed in comparison with inverse annihilation of light particles into $X\bar{X}$-pair.

Some comments

Two possible channels to produce massive stable X-particles:

- Directly through the scalaron decay into a pair $X\bar{X}$,
- By inverse annihilation of relativistic particles in thermal plasma.

Direct production of $X\bar{X}$-pair by scalaron gives

$$\varrho_X^{(0)} \approx \varrho_{DM} \approx 1\mathrm{keV}/\mathrm{cm}^3, \text{ if } M_X \approx 10^7 \text{ GeV}$$

"Catch-22":

- For such small mass thermal production results in too large $\boldsymbol{\varrho_X}$.
- For larger masses $\varrho_X^{(0)}$ would be unacceptably larger than ϱ_{DM}.

A possible way out:

- Since oscillating curvature scalar creates particles only in symmetric state, the direct ***X***-particles is forbidden, if they are Majorana fermions, which must be in antisymmetric state.

Scalaron decay into massless non-conformal scalars

Dimensionless Zeldovich equation

$$\frac{df}{dx} = -\frac{0.03 g_s \alpha^2 \beta_{ann}}{\pi^3 g_*} \left(\frac{M_R}{M_X}\right)^3 \frac{f^2 - f_{eq}^2}{x^5}, \quad n_X = n_{in}\left(\frac{a_{in}}{a}\right)^3 \boldsymbol{f}, \quad x = \frac{M_x}{T}$$

For $g_* = 100$, $\alpha = 0.01$, $\beta_{ann} = 10$, $M_R = 3 \times 10^{13}$ GeV, and $n_\gamma = 412/\text{cm}^3$

The present day energy density of the X-particles:

$$\boldsymbol{\varrho_X = M_X n_\gamma f_{fin} \approx 10^{10}} \left(\frac{\mathbf{10^{10} GeV}}{\boldsymbol{M_X}}\right) \text{GeV}/\text{cm}^3$$

To be compared with the observed energy density of DM: $\boldsymbol{\varrho_{DM} \approx 1}$ keV/cm^3.

- X-particles must have mass $M_X \gg M_R$ to make reasonable DM density.
- If $\boldsymbol{M_X > M_R}$, then classical scalaron field can still create X-particles, but the probability of their production would be strongly suppressed $\Longrightarrow$ such LSP with the mass somewhat larger than $\boldsymbol{M_R}$ could successfully make the cosmological DM.

Scalaron decay into a pair of fermions

The decay width and the energy density:

$$\Gamma_f = \frac{M_R m_f^2}{6 M_{Pl}^2}, \qquad \varrho_f = \frac{M_R m_f^2}{120 \pi t}$$

The largest contribution into the cosmological energy density at scalaron dominated regime is presented by the decay into the heaviest fermion species.

We assume:

- The mass of the LSP is considerably smaller than the masses of the other decay products, $\boldsymbol{m_X < m_f}$, at least as $\boldsymbol{m_X \lesssim 0.1 m_f}$.
- The direct production of X-particles by $\boldsymbol{R(t)}$ can be neglected.

In such a case LSPs are dominantly produced by the secondary reactions in plasma, which was created by the scalaron production of heavier particles.

Kinetic equation for freezing of fermionic species

$$\frac{df}{dx} = -\frac{\alpha^2 \beta_{ann}}{2\pi^3 g_*} \frac{n_{in} M_R m_f^2}{m_X^6} \frac{f^2 - f_{eq}^2}{x^5}$$

$n_{in} = 0.09 g_s m_X^3$ is the initial number density of X-particles at $T \sim m_X$.

$$\boldsymbol{\varrho_X \approx 7 \cdot 10^{-9} \frac{m_f^3}{m_X M_R}\,\mathrm{cm}^{-3}}$$

- $\alpha = 0.01$, $\beta_{ann} = 10$, $g_* = 100$, $g_s = 2$
- If we take $\boldsymbol{m_f = 10^5}$ GeV and $\boldsymbol{m_X = 10^4}$ GeV, then $\boldsymbol{\varrho_X \ll \varrho_{DM}}$.

$\boldsymbol{\varrho_X}$ becomes comparable with the energy density of the cosmological DM, $\varrho_{DM} \approx 1$ keV/cm^3, if $m_X \sim 10^6$ GeV, $m_f \sim 10^7$ GeV:

$$\varrho_X \approx 2.1 \left(\frac{m_f}{10^7\,\mathrm{GeV}}\right)^3 \left(\frac{10^6\,\mathrm{GeV}}{m_X}\right) \frac{\mathrm{keV}}{\mathrm{cm}^3}$$

Scalaron decay into gauge bosons due to conformal anomaly

- $X, \bar{X}$ are Majorana fermions $\Longrightarrow$ direct production by scalaron is forbidden.
- $X\bar{X}$-pairs are produced through the inverse annihilation of relativistic particles in the thermal plasma.

X-particles may be viable candidates for the carriers of the cosmological dark matter, if their mass $\boldsymbol{M_X \sim 10^{11}}$ GeV.

The range of allowed masses of X-particles to form cosmological DM depends upon the dominant decay mode of the scalaron.

Dominant decay channel of the scalaron	Allowed M_X to form DM
Minimally coupled scalars mode: $$\Gamma_s = \frac{M_R^3}{24 M_{Pl}^2}$$	$M_X \gtrsim M_R \approx 3 \cdot 10^{13}$ GeV
Massive fermions mode: $$\Gamma_f = \frac{m_f^2 M_R}{6 M_{Pl}^2}$$	$M_X \sim 10^6$ GeV
Gauge bosons mode: $$\Gamma_{an} = \frac{\beta_1^2 \alpha^2 N}{96\pi^2} \frac{M_R^3}{M_{Pl}^2}$$	$M_X \sim 10^{11}$ GeV

Possible observations

According to our results, the mass of DM particles, with the interaction strength typical for supersymmetric ones, can be in the range from 10^6 to 10^{13} GeV.

Possibilities to make X-particles visible:

1. The decay of superheavy DM particles, which could have a lifetime long enough to manifest themselves as stable DM, but at the same time lead to the possibly observable contribution to the UHECR spectrum.
2. Furthermore, instability of superheavy DM particles can arise due to Zeldovich mechanism through virtual black holes formation.
3. Annihilation effects in clusters of dark matter in galaxies and galactic halos, in which, according to
   - V. S. Berezinsky, V. I. Dokuchaev and Y. N. Eroshenko, *Small-scale clumps of dark matter*, *Phys. Usp.* **57** (2014) 1 [arXiv:1405.2204]

   the density of DM is many times higher than DM cosmological density.

Cosmic rays from heavy particle decays

- EA, A.D. Dolgov, A.A. Nikitenko,
  "*Cosmic rays from heavy particle decays*", e-Print: 2305.03313 [hep-ph], accepted in *Phys.Atom.Nucl.*

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:

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

- This result is obtained for particles with masses $m_f \ll M_R$.
- X-particles created by the scalaron decay into heavier fermions could form DM, if $m_f \sim 10^7$ GeV, $M_X \sim 10^6$ GeV

We are interested in the case when the scalaron decays create particles with mass about 10^{21} eV, that is the energy of UHECR.

Scalaron decay into extremely heavy DM

The width of the scalaron decay into superheavy leptons with mass $M_L \sim M_R/2$:

$$\Gamma_L = \frac{M_L^2 M_R}{6M_{Pl}^2}\sqrt{1 - \frac{4M_L^2}{M_R^2}}$$

- The phase space factor $(1 - 4M_L^2/M_R^2)^{1/2}$ makes it possible to arrange the density of presumably DM particles L equal to the observed density of DM.

However, with the canonical energy scale of gravitational interaction with $M_{Pl} = 1.22 \cdot 10^{19}$ GeV, the life-time of such DM-particles turns out to be too long to allow for any observable consequences of their decays.

A possible way out could be opened by diminishing the fundamental gravity scale at small distances down to a lower value $M_* < M_{Pl}$. This could lead to a considerable increase of decay probability of DM-particles.

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 only a few orders of magnitude longer than the universe age.

Decays of such particles could make essential contribution to 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 $R_* \sim 10^{(4/d)}/M_* > 1/M_*$.

Some comments about M_* and M_R^*

Angular fluctuations of CMBR imply: $M_R \approx 3 \times 10^{13}$ GeV.

The amplitude of the scalar fluctuations is fixed by CMB observations:

$$\delta^2 \sim \left(\frac{M_R}{M_{Pl}}\right)^2$$

Thus, in models where the fundamental gravitational coupling is determined by M_*, instead of M_{Pl}, the scalaron mass should be changed appropriately:

$$M_R^* = 3 \times 10^{13} (M_* / M_{Pl}) \quad GeV$$

We are interested in the case when the scalaron decays create particles with energies 10^{21} eV, that is the energy of UHECR.

$\Longrightarrow$ the scalaron mass, M_R^*, should be at least of the order 10^{12} GeV.

To this end we need to choose:

$$M_* = M_{Pl}/30 \approx 3 \times 10^{17} \quad \mathrm{GeV}$$

Proton decay through virtual Black Hole

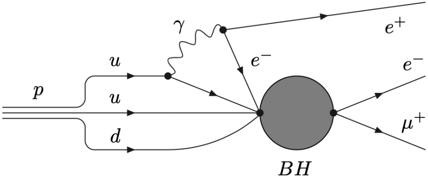


Figure: C. Bambi, A. D. Dolgov and K. Freese, Nucl. Phys. B **763** (2007), 91-114.

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

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

- $m_p \approx 1$GeV, $m_q \sim 300$ MeV, $\Lambda \sim 300$ MeV is the QCD scale parameter, $\alpha = 1/137$, and d is the number of "small' extra dimensions.

Proton life-time: $\tau_p = 7.3 \times 10^{198}$ years $\gg t_U \approx 1.5 \times 10^{10}$ years.

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

Heavy proton type dark matter

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:

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

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 existence of stable particles with interaction strength typical for SUSY and heavier than several TeV is in tension with conventional Friedmann cosmology.
- R^2-gravity opens a way to save life of such X-particles, because in this theory the density of heavy relics with respect to the plasma entropy could be noticeably diluted by radiation from the scalaron decay.
- The range of allowed masses of X-particles to form cosmological DM depends upon the dominant decay mode of scalaron.
- In the model of high dimensional gravity modification may exist superheavy DM particles stable with respect to the conventional particle interactions. However, such DM particles should decay though the virtual BH formation.
- With a proper choice of the parameters the life-time of such quasi-stable particles may be larger than the universe age only by 3-4 orders of magnitude.
- This permits X-particles to make an essential contribution to the flux of high energy cosmic rays.
- The considered mechanism may lead to efficient creation of cosmic ray neutrinos of very high energies observed at IceCube and Baikal detectors.

THE END

THANK YOU FOR ATTENTION