Inflation, dark energy, and dark matter in supergravity

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WHAT'S UP?

- we consider inflation, dark energy (DE), dark matter (DM) in the standard approach (single-field inflation governed by the inflaton scalar potential, the DE as the positive cosmological constant (c.c.), the specific Cold DM particle)

- in supergravity ALL that is non-trivial because of SUSY of the action and required stability of non-inflaton scalars that can spoil inflation

Natural questions: why supergravity ???

- How to describe the Dark Universe in the minimal way in supergravity?? What is inflaton, DM, and SUSY breaking scale?

Why supergravity?

SUSY is the leading candidate for new physics beyond the SM. Supergravity is the field theory with local SUSY that automatically implies the general coordinate invariance. The minimal (N=1) supergravity is chiral that is necessary for particle phenomenology and CP violation. Supergravity has many attractive features:

- SUSY unifies bosons and fermions,
- supergravity automatically includes GR,
- supergravity is the conservative extension of GR and field theory, which restricts the number of independent parameters (coupling constants),
- SUSY GUT resuts in the perfect unification of electro-weak and strong interactions,

- the spectrum of matter-coupled supergravities with spontaneously broken SUSY has the natural DM candidate given by the lightest SUSY particle (LSP), provided that R-parity is conserved,

It is unknown how many d.o.f. were present during inflation? Supergravity may be the answer.

- SUSY helps to stabilize the fundamental scales (the hierarchy problem), such as the electro-weak scale and the GUT scale.
- SUSY leads to cancellation of the quadratic UV-divergences in quantum loops

Supergravity is the only way to consistently describe spin 3/2 particle

- supergravity can be considered as the low-energy effective action of superstrings (quantum gravity) in String Landscape.

Not all of these arguments may survive!

CONTRA

SUPERSYMMETRY

- m_B and m_F unequal, SUSY must be broken
- No spartners to SM particles found at LHC
- the observed cosmological constant positive
- the CP violation rules out extended SUSY
- huge matter-over-antimatter abundance
- Superstring Landscape of over 10^{500} vacua

PLAN of the TALK (main part)

- Standard Approach to Cosmology in Supergravity, and its Problems

- Our Approach and its Tools, old and new (hep-th)

- Spontaneous SUSY breaking after inflation

- Hierarchy of DE and SUSY scales

- Gravitino LSP and PBHs as DM, in High-Scale SUSY (hep-ph)

- Conclusion

My Collaborators

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Modified gravity and Starobinsky model

The successful inflationary model, using only gravitational interactions, was proposed by Starobinsky (1980) with

$$S_{\mathrm{Star.}} = \frac{M_{\mathrm{Pl}}^2}{2} \int \mathrm{d}^4x \sqrt{-g} \left(R + \frac{1}{6m^2} R^2 \right) , \qquad (1)$$

where we have introduced the reduced Planck mass $M_{\mathrm{Pl}} = 1/\sqrt{8\pi G_{\mathrm{N}}} \approx 2.4 \times 10^{18}$ GeV, and the scalaron (inflaton) mass m as the only parameter. We use the spacetime signature $(-,+,+,+,)$.

The $(R+R^2)$ gravity model (1) is the simplest extension of the standard Einstein-Hilbert action in the context of the (modified) $F(R)$ gravity theories with

$$S_F = \frac{M_{\mathrm{Pl}}^2}{2} \int \mathrm{d}^4x \sqrt{-g}\, F(R) , \qquad (2)$$

in terms of the real function $F(R)$ of the scalar curvature R.

Equivalence between $F(R)$ gravity and scalar-tensor gravity I

The $F(R)$ gravity action (2) is classically equivalent to

$$S[g_{\mu\nu},\chi] = \frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-g}\,\left[F'(\chi)(R-\chi)+F(\chi)\right] \tag{3}$$

with the real scalar field χ, provided that $F'' \neq 0$ that we always assume. The primes denote the derivatives with respect to the argument.

The equivalence is easy to verify because the χ-field equation implies $\chi = R$. In turn, the factor F' in front of the R in (3) can be (generically) eliminated by a Weyl transformation of metric $g_{\mu\nu}$, that transforms the action (3) into the action of the scalar field χ minimally coupled to Einstein gravity and having the scalar potential

$$V = \left(\frac{M_{\rm Pl}^2}{2}\right)\frac{\chi F'(\chi)-F(\chi)}{F'(\chi)^2}\quad . \tag{4}$$

Equivalence between $F(R)$ gravity and scalar-tensor gravity II

The kinetic term of χ becomes canonically normalized after the field redefinition $\chi(\varphi)$ as

$$F'(\chi) = \exp\left(\sqrt{\tfrac{2}{3}}\varphi/M_{\rm Pl}\right) \ , \quad \varphi = \frac{\sqrt{3}M_{\rm Pl}}{\sqrt{2}} \ln F'(\chi) \ , \tag{5}$$

in terms of the canonical inflaton field φ, with the total acton

$$S_{\rm quintessence}[g_{\mu\nu},\varphi] = \frac{M^2_{\rm Pl}}{2}\int d^4x\sqrt{-g}R - \int d^4x\sqrt{-g}\left[\tfrac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + V(\varphi)\right] \ . \tag{6}$$

The classical and quantum stability conditions of $F(R)$ gravity theory are given by

$$F'(R) > 0 \quad \text{and} \quad F''(R) > 0 \ . \tag{7}$$

They are obviously satisfied in Starobinsky model (1) for $R > 0$. Equations (7) also guarantee the existence of the Weyl transformation and, hence, the equivalence.

The inverse transformation

The inverse transformation reads (and clearly shows the relevance of R^2 for slow roll)

$$R = \left[\frac{\sqrt{6}}{M_{\rm Pl}} \frac{dV}{d\varphi} + \frac{4V}{M_{\rm Pl}^2} \right] \exp\left(\sqrt{\tfrac{2}{3}} \varphi / M_{\rm Pl} \right) , \tag{8}$$

$$F = \left[\frac{\sqrt{6}}{M_{\rm Pl}} \frac{dV}{d\varphi} + \frac{2V}{M_{\rm Pl}^2} \right] \exp\left(2\sqrt{\tfrac{2}{3}} \varphi / M_{\rm Pl} \right) . \tag{9}$$

In the case of Starobinsky model (1), one finds the inflaton potential

$$V(\varphi) = \frac{3}{4} M_{\rm Pl}^2 m^2 \left[1 - \exp\left(-\sqrt{\tfrac{2}{3}} \varphi / M_{\rm Pl} \right) \right]^2 . \tag{10}$$

This scalar potential is bounded from below (non-negative and stable), and it has the absolute minimum at $\varphi = 0$ corresponding to a Minkowski vacuum. The scalar potential (10) has a plateau of the positive height related to the inflationary scale $H_{\rm inf.}/M_{\rm Pl} = 1.06 \times 10^{-4} \sqrt{r}$.

Inflationary features

A duration of inflation is measured in the slow roll approximation by the e-foldings number

$$N_e \approx \frac{1}{M_{\rm Pl}^2}\int_{\varphi_{\rm end}}^{\varphi_*} \frac{V}{V'} d\varphi \ , \tag{11}$$

where φ_* is the inflaton value at the reference scale (horizon crossing), and $\varphi_{\rm end}$ is the inflaton value at the end of inflation when one of the slow roll parameters

$$\varepsilon_V(\varphi) = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \quad \text{and} \quad \eta_V(\varphi) = M_{\rm Pl}^2\left|\frac{V''}{V}\right| \ , \tag{12}$$

is no longer small (close to 1).

The amplitude of scalar perturbations at horizon crossing is given by

$$A = \frac{V_*^3}{12\pi^2 M_{\rm Pl}^6 ({V_*}')^2} = \frac{3m^2}{8\pi^2 M_{\rm Pl}^2}\sinh^4\left(\frac{\varphi_*}{\sqrt{6}M_{\rm Pl}}\right) = 2.1\times 10^{-9} \ . \tag{13}$$

Starobinsky inflation and Planck data

Starobinsky model (1) is the excellent model of cosmological inflation, in very good agreement with the Planck data. The Planck satellite mission measurements (2018) of the Cosmic Microwave Background (CMB) radiation give the scalar perturbations tilt as $n_s \approx 1 + 2\eta_V - 6\varepsilon_V \approx 0.9649 \pm 0.0042$ and restrict the tensor-to-scalar ratio as $r \approx 16\varepsilon_V < 0.064$ (95% CL). The Starobinsky inflation yields $r \approx 12/N_e^2 \approx 0.004$ and $n_s \approx 1 - 2/N_e$, where N_e is the e-foldings number between 50 and 60, with the best fit at $N_e \approx 55$.

The mass parameter of the Starobinsky model (1) is fixed by the observed CMB amplitude (13) as

$$m \approx 3 \cdot 10^{13}\ \text{GeV} \quad \text{or} \quad \frac{m}{M_{\text{Pl}}} \approx 1.2 \cdot 10^{-5}\ . \tag{14}$$

A numerical analysis of (11) with the potential (10) yields

$$\sqrt{\frac{2}{3}}\varphi_*/M_{\text{Pl}} \approx \ln\left(\frac{4}{3}N_e\right) \approx 5.5\ , \quad \sqrt{\frac{2}{3}}\varphi_{\text{end}}/M_{\text{Pl}} \approx \ln\left[\frac{2}{11}(4+3\sqrt{3})\right] \approx 0.5\ , \tag{15}$$

where we have used $N_e \approx 55$.

Standard approach to inflation and DE in supergravity

is based on the use of chiral superfields (max. spin 1/2), which requires complexification of inflaton. Two chiral superfields are generically needed, the one including inflaton, and another one including goldstino.

It is possible to identify the two superfields, thus getting inflaton and goldstino in a single chiral superfield (Ketov and Terada 2014). The *sinflaton* scalar has to be stabilized, with its mass beyond the Hubble value (non-trivial!), in order to get the *single-field* inflation favored by Planck data.

Slow-roll inflation and a de Sitter vacuum (DE) are obtained by carefully engineering the scalar potential V in terms of a Kähler potential K and a superpotential W as $(M_{\mathrm{Pl}} = 1)$

$$V_F = e^K \left(|DW|^2 - 3\,|W|^2 \right) \quad \text{with} \quad DW = W' + K'W \ ,$$

and avoiding the η-problem! *Stability* of inflation (enough e-foldings) is a major concern (difficult to achieve). The other options were also considered in the literature, such as the nilpotent chiral superfields and the non-linearly realized supersymmetry. We do not employ them (unitarity bound, quantum corrections).

Modified gravity and supergravity

The popular way of describing viable inflation and dark energy is given by modified gravity, as e.g., the $F(R)$ gravity models with the action

$$S[g] = \int d^4x\sqrt{-g}\, F(R) \ . \tag{1}$$

The most straightforward way of extending the $F(R)$ gravity to supergravity is

$$S = \int d^4x d^4\theta E^{-1} N(\mathcal{R},\bar{\mathcal{R}}) + \left[\int d^4x d^2\Theta 2\mathcal{E} F(\mathcal{R}) + h.c. \right] \tag{2}$$

in terms of the $\mathcal{N}=1$ supergravity chiral superfield $\mathcal{R}$ having the scalar curvature R among its field components at Θ^2.

The action (2) can be transformed into the standard matter-coupled Einstein supergravity action with two chiral matter superfields (Cecotti 1987, SVK 2009). However, it cannot embed the $(R+R^2)$ gravity (= Starobinsky inflationary model) because of extra propagating scalars, whose potential is generically unbounded from below. These scalars have to be stabilized either by introducing more superfields or tuning the function N, without good example ever found.

Modified Electrodynamics and its N=1 SUSY Extension

$$S_{\text{BI}}[A_\mu] = -M_{\text{BI}}^4 \int d^4x \sqrt{-\det\left(g_{\mu\nu} + M_{\text{BI}}^{-2} F_{\mu\nu}\right)}\,, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

This Born-Infeld nonlinear theory reduces to Maxwell electrodynamics in flat spacetime, has taming of Coulomb self-energy of a point-like electric charge, the limited values of the electromagnetic field F, the electric-magnetic self-duality, causal propagation (no shock waves, no superluminal signals); and also arises from strings and D-branes as the effective theory.

The N=1 BI theory is obtained by extending $F_{\mu\nu}$ to $W_\alpha = -\frac{1}{4}\left(\bar{\mathcal{D}}^2 - 4\mathcal{R}\right)\mathcal{D}_\alpha V$ in N=1 superspace. The super-BI action can be nicely written down as

$$S_{\text{sBI}}[V] = \frac{1}{4}\int d^4x d^2\theta\, \mathcal{E} X + \text{h.c.}\,, \quad \text{where} \quad X + \frac{M_{\text{BI}}^{-4}}{16} X\left(\bar{\mathcal{D}}^2 - 4\mathcal{R}\right)\bar{X} = W^2.$$

This action has the extra hidden (nonlinearly realized) SUSY, and includes the goldstino (Volkov-Akulov) action, with $M_{\text{SUSY}} = M_{\text{BI}}$.

Alternative supergravity tools: basic ideas

- use a massive vector multiplet (instead of a chiral multiplet) to unify real inflaton scalar and goldstino (max. spin 1);

- use the super-Higgs-effect to give mass to the vector multiplet;

- use Born-Infeld kinetic term instead of Maxwell term for the vector multiplet, in order to generate the goldstino action and F-type spontaneous SUSY breaking after inflation;

- use new Fayet-Iliopoulos terms, without gauging the R-symmetry, for D-type spontaneous SUSY breaking after inflation, and uplifting Minkowski vacuum to a de Sitter vacuum (dark energy).

Inflaton in a massive vector multiplet

Consider arbitrary real function $\tilde{J}(He^{2gV}\overline{H})$ with Higgs chiral superfield H, which is invariant under the gauge transformations (van Proeyen 1989)

$$H \to H' = e^{-igZH} \;, \quad \overline{H} \to \overline{H}e^{ig\overline{Z}\overline{H}} \;, \quad V \to V' = V + \tfrac{i}{2}(Z - \bar{Z}) \;, \qquad (3)$$

whose gauge parameter Z itself is a chiral superfield. The V is manifestly massive in the gauge $H = 1$. The Lagrangian reads (Farakos, Kehagias and Riotto 2013)

$$\mathcal{L} = \int d^2\theta 2\mathcal{E}\left\{\tfrac{3}{8}(\overline{\mathcal{D}}\overline{\mathcal{D}} - 8\mathcal{R})e^{-\frac{2}{3}J} + \tfrac{1}{4}W^{\alpha}W_{\alpha}\right\} + \text{h.c.} \;, \qquad (4)$$

with the bosonic part (after elimination of the auxiliary field D, and $F = dA$)

$$e^{-1}\mathcal{L} = -\tfrac{1}{2}R - \tfrac{1}{4}F_{mn}F^{mn} - \tfrac{1}{2}J''\partial_m C\partial^m C - \tfrac{1}{2}J''B_m B^m - \tfrac{g^2}{2}J'^2 \;, \qquad (5)$$

the inflaton $C = V|$, the function $J = J(C)$ and $W_{\alpha} = -\frac{1}{4}\left(\overline{\mathcal{D}}\overline{\mathcal{D}} - 8\mathcal{R}\right)\mathcal{D}_{\alpha}V$.

The D-type potential of Starobinsky inflationary model arises when choosing

$$J(C) = \tfrac{3}{2}(C - \ln C) \quad \text{and} \quad C = \exp\left(\sqrt{2/3}\phi\right) \;. \qquad (6)$$

SUSY breaking after inflation by Polonyi superfield

In all the models above, SUSY is restored after inflation. To avoid it, we can add Polonyi chiral superfield (the hidden sector) with

$$K = \Phi\overline{\Phi}\,, \qquad \mathcal{W} = \mu(\Phi + \beta)\,. \tag{7}$$

The total Lagrangian of this Polonyi-Starobinsky supergravity reads

$$\mathcal{L} = \int d^2\theta 2\mathcal{E}\left\{\tfrac{3}{8}(\overline{\mathcal{D}}\overline{\mathcal{D}} - 8\mathcal{R})e^{-\frac{1}{3}(K+2J)} + \tfrac{1}{4}W^\alpha W_\alpha + \mathcal{W}(\Phi)\right\} + \text{h.c.} \tag{8}$$

and leads to a Minkowski vacuum after inflation, though with spontaneously broken SUSY. However, this also leads to the the F-type contribution of Polonyi scalar to the inflationary scalar potential, due to its mixing with the inflaton. A possible cure (Aldabergenov and SVK, 2017) is adding a field-dependent FI term and changing the (Starobinsky) J-function, thus loosing the connection to the $(R + R^2)$ gravity, or modifying the Kaehler potential by the higher-order terms.

Supersymmetric Massive Born-Infeld theory

The (Maxwell) kinetic term (W^2) is generalized to the Born-Infeld kinetic term, leading to the Lagrangian ($M_{\text{Pl}} = g = 1$, $\omega = \frac{1}{8}\mathcal{D}^2 W^2$, and $\alpha^{-1} = M_{\text{BI}}^4$)

$$\mathcal{L}_{\text{mBI}} = -3\int d^4\theta E e^{-2\mathcal{J}(V)/3} + \left(\tfrac{1}{4}\int d^2\Theta 2\mathcal{E} W^2 + \text{h.c.}\right) + \\ + \tfrac{1}{4}\int d^4\theta E \frac{W^2 \bar{W}^2}{1 + 8\alpha(\omega+\bar{\omega}) + \sqrt{1 + 8\alpha(\omega+\bar{\omega}) + 16\alpha^2(\omega-\bar{\omega})^2}} \ . \tag{9}$$

The vector kinetic terms sum up to the BI action with ($F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$)

$$S_{\text{BI}} = M_{\text{BI}}^4 \int d^4x \left[\sqrt{-\det(g_{\mu\nu})} - \sqrt{-\det\left(g_{\mu\nu} + M_{\text{BI}}^{-2} F_{\mu\nu}\right)}\right] \ . \tag{10}$$

The fermionic kinetic terms are equivalent to the Akulov-Volkov (AV) action for goldstino, up to field redefinition.

New Fayet-Iliopoulos (FI) terms

The standard FI term (Freedman 1977) leads to the gauged R-symmetry in supergravity and, hence, is not very useful for model building (no scalar couplings). There exist new FI terms without gauging the R-symmetry, after decomposing the vector multiplet as $V = \mathcal{V} + G$, where G is the nilpotent goldstino superfield, $G^2 = 0$. The new FI term is proportional to G, while its coupling constant can be generalized to a real function $\mathcal{I}(V)$. The first such new FI term was found by Cribiori et al. (2017):

$$\mathcal{L}_{\text{I}} = 2 \int d^4\theta E \frac{W^2 \bar{W}^2}{\mathcal{D}^2 W^2 \bar{\mathcal{D}}^2 \bar{W}^2} \mathcal{I} \quad \text{with} \quad G_{\text{I}} = \frac{W^2 \bar{W}^2}{\mathcal{D}^2 W^2 \bar{\mathcal{D}}^2 \bar{W}^2} \ . \tag{11}$$

Soon after, another new FI term was found (Kuzenko 2018; Aldabergenov, SVK and Knoops, 2018):

$$\mathcal{L}_{\text{II}} = 2 \int d^4\theta E \frac{W^2 \bar{W}^2}{(\mathcal{D}W)^3} \mathcal{I} \quad \text{with} \quad G_{\text{II}} = \frac{W^2 \bar{W}^2}{(\mathcal{D}W)^3} \, . \tag{12}$$

Our full Lagrangian now reads

$$\mathcal{L}_{\text{I}} = \mathcal{L}_{\text{mBI}} + 2 \int d^4\theta E \frac{W^2 \bar{W}^2}{\mathcal{D}^2 W^2 \bar{\mathcal{D}}^2 \bar{W}^2} \mathcal{I} \, , \tag{13}$$

The bosonic terms

After eliminating the auxiliary fields and Weyl rescaling to Einstein frame, $e \to e^{4\mathcal{J}/3}e$ and $g^{mn} \to e^{-2\mathcal{J}/3}g^{mn}$, the bosonic part reads

$$\begin{aligned} e^{-1}\mathcal{L}_{\mathsf{I}} = & \tfrac{1}{2}R - \tfrac{1}{2}\mathcal{J}''\partial_a C\partial^a C - \tfrac{1}{2}\mathcal{J}'' B_a B^a \\ & + \frac{e^{4\mathcal{J}/3}}{8\alpha}\left[1 - \sqrt{1+8\alpha Z^2}\sqrt{1+4\alpha F^2 e^{-4\mathcal{J}/3} + 4\alpha^2 (F\tilde{F})^2}\right] , \end{aligned} \tag{14}$$

where $Z \equiv \frac{\mathcal{I}}{4} - \mathcal{J}' e^{-2\mathcal{J}/3}$, $\tilde{F}_{ab} \equiv -\frac{i}{2}\epsilon_{abcd}F^{cd}$, B_a is the vector field whose field strength is F_{ab}. The absence of ghosts requires $\mathcal{J}'' > 0$.

The auxiliary field D is eliminated via its algebraic equation of motion,

$$D = \frac{Z}{\sqrt{1-8\alpha Z^2}}\sqrt{1+4\alpha F^2 e^{-4\mathcal{J}/3} + 4\alpha^2 (F\tilde{F})^2} , \tag{15}$$

and it can have the non-vanishing VEV, $\langle D\rangle \neq 0$ or $\langle Z\rangle \neq 0$, that spontaneously breaks SUSY.

The scalar potential

is given by

$$\mathcal{V} = \frac{e^{4\mathcal{J}/3}}{8\alpha}\left(\sqrt{1+8\alpha Z^2}-1\right) \ . \tag{16}$$

and can be used to realize both slow-roll and Starobinsky-like inflation, as well as a de Sitter vacuum, by properly choosing the real functions $\mathcal{J}$ and Z.

Similarly, as regards the second new FI term, we find the D-depenent terms in Jordan frame as follows:

$$\begin{aligned} e^{-1}\mathcal{L}_{\text{II}}(D) = &-\frac{\mathcal{I}}{16}\left[4D-\frac{4F^2}{D}+\frac{F^4-(F\tilde{F})^2}{D^3}\right]+e^{-2\mathcal{J}/3}\mathcal{J}'D \\ &+\frac{1}{8\alpha}\left(1-\sqrt{1+4\alpha(F^2-2D^2)+4\alpha^2(F\tilde{F})^2}\right) \ . \end{aligned} \tag{17}$$

The generic new features are: (i) the non-polynomial dependence upon D, (ii) the highly non-linear dependence upon F, (iii) the non-trivial coupling to chiral matter for respecting Kähler invariance, and (iv) the rich structure of the scalar potential.

Gravitino LSP as DM in Polonyi-Starobinsky supergravity

- gravitino produced from vacuum during inflation and inflaton/Polonyi decay;
- the matching DM abundance implies $m_{3/2} \approx 7.7 \cdot 10^{12}$ GeV;
- the F-type SUSY breaking scale $\mu^{1/2} \sim \sqrt{m_{3/2} M_{\mathrm{Pl}}}$ is close to M_{GUT};
- a de Sitter vacuum (c.c. or DE) is obtained by tuning FI as $\frac{1}{2}\langle D\rangle^2 = \Lambda_0$;
- no gravitino and Polonyi overproduction problems; avoiding BBN constraints;
- all sparticles masses are above $m_{3/2}$ in the High-Scale SUSY scenario;
- the reheating temperature is about 10^{10} GeV.

Conclusion

- Unification of (inflation, DE and DM), and unification of scales $(\Lambda_0, H_{\text{inf.}}, M_{\text{SUSY}})$ are possible in our supergravity approach to the Dark Side of the Universe;

- the origin of inflaton, DE and DM is all (super)gravitational;

- the non-standard supergravity tools (J,BI,FI) are essential; in particular, the FI terms uplift AdS vacuum to dS, similarly to the KKLT mechanism in string theory;

- High-Scale SUSY is required; its only "low-energy" feature is the gravitino LSP as DM. Hence, accelerator searches for SUSY and WIMPs will give no sign of SUSY, and only indirect cosmoparticle physics probes are possible.

Thank you for your attention!

PBHs as DM in supergravity I

Primordial Black Holes (PBHs) may be formed in the early Universe by collapsing of primordial density perturbations resulting from inflation, when these perturbations reenter the horizon and are large enough, i.e. when gravity forces are larger than pressure. Apart from being considered as another (non-particle) source for DM, some PBHs (of stellar mass) are also considered as the candidates for the gravitational wave effects caused by the binary black hole mergers observed by LIGO/Virgo collaboration.

The PBHs abundance $f = \Omega_{PBH}/\Omega_{\rm cr}$ is proportional to the amplitude of the scalar perturbations P_ζ, and is also proportional to $(M_{\rm Sun}/M_{PBH})^{1/2}$. Hence, for the PBH to be the DM, one needs $M_{\rm PBH} \approx 10^{-12} M_{\rm Sun}$, and the enhancement of the perturbation spectrum from 10^{-9} (CMB) to 10^{-2} (PBH) at the last stages of inflation.

PBHs as DM in supergravity II

In a single-field inflation, perturbations are controlled by the inflaton scalar potential, so that large fluctuations are produced when the slow roll parameter $\varepsilon = r/16$ goes to zero, i.e. when the potential has a near-inflection point with $V' \approx V'' \approx 0$.

To unify a copious PBH production with the CMB observables, these events should be "decoupled" by demanding the existence of another ("short") plateau in the scalar potential after the inflationary plateau towards the end of inflation.

This is not the case for the Starobinsky inflation but can be easily achieved in our supergravity framework by allowing the another plateau or spikes of the J'-function in the inflaton scalar potential $V = \frac{1}{2}g^2(J')^2$.

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Review

COSMOLOGICAL PROBES OF SUPERSYMMETRIC FIELD THEORY MODELS

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Abstract: The lack of positive results in searches for SUSY particles at the LHC and in direct searches for WIMPs in the underground experiments may hint to a super-high energy scale of SUSY phenomena beyond the reach of direct experimental probes. At such scales the supergravity models based on Starobinsky inflation can provide the mechanisms for both inflation and superheavy dark matter. However, it makes the indirect methods to be the only way of testing the SUSY models, so that cosmological probes acquire the special role in this context. Such probes can rely on the nontrivial effects of SUSY physics in the early Universe, which are all model-dependent and thus can provide discrimination of the models and their parameters. We discuss non-equilibrium particles and primordial structures like the Primordial Black Holes (PBHs) and antimatter domains in a baryon-asymmetric Universe as the possible cosmological probes for high energy scale SUSY physics.

Keywords: supersymmetric models; supergravity; inflation; superheavy dark matter; Primordial Black Holes; cosmic antinuclei

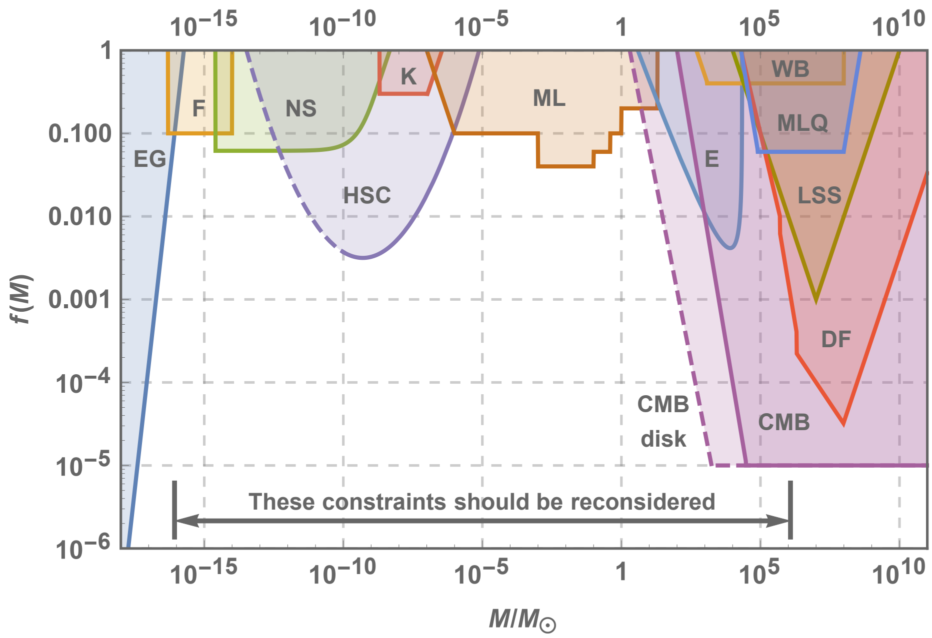

Figure 2. Critical analysis by [67] of constraints on PBH dark matter contribution into the total density by [79] with the account for less stringent CMB constraits by [80].

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