Are primordial black holes formed during reheating after R2 inflation?

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Based on Work with H. Jeong, R. Jinno, J. Yokoyama

The Dark Side of the Universe (DSU 2024)

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CMB observations and BSM physics

- \cdot (n_s, r) precision measurements from CMB
- No signal of physics beyond the Standard Model (BSM) at the LHC

Planck Collaboration: Constraints on Inflation **CMB constraint on inflation models** √ \overline{a} n \overline{b} lation m Dn∣ a de la $\overline{}$

[Fig. from Planck 2018]

- Fig. 8. Marginalized joint 68 % and 95 % CL regions for *n*^s and *r* at *k* = 0.002 Mpc¹ from *Planck* alone and in combination with Monomial potentials ($p \ge 2$) in GR are disfavored.
- $B = 10/b$ ot if μ a could poil down to further predicion? • What if we could nail down to further precision?

Starobinsky R2 Inflation [Starobinsky 1980; Mukhanov & Chibisov 1981]

$$
S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left(R + \frac{R^2}{6M^2} \right) + S_m
$$

$$
S_m = \int d^4x \sqrt{-g} \left[-\frac{1}{2} (\nabla \sigma)^2 - V(\sigma) \right] \quad \leftarrow \text{Higgs}
$$

+ minimally coupled SM, RHN + "*desert"* **or BSM**

- One of the oldest models of Inflation, before models of Sato and Guth
- A single parameter **M** characterizes the model.

R2 Inflation as scalar-tensor theory

[Whitt 1984; Maeda 1988]

$$
S_J = \frac{1}{2\kappa^2} \int d^4x \sqrt{-\hat{g}} \left(\hat{R} + \frac{\hat{R}^2}{6M^2} \right) + S_m
$$

$$
S_m = \int d^4x \sqrt{-\hat{g}} \left[-\frac{1}{2} (\hat{\nabla}\hat{\sigma})^2 - V(\hat{\sigma}) \right]
$$

R² Inflation as scalar-tensor theory

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$$

Jordan frame
$$
\hat{g}_{\mu\nu}
$$

\n
$$
g_{\mu\nu} = \hat{g}_{\mu\nu} \Omega^2 \qquad \Omega^2 = 2\kappa^2 \left| \frac{\partial \mathcal{L}_J}{\partial \hat{R}} \right| = 1 + \frac{\hat{R}}{3M^2} \equiv e^{\sqrt{\frac{2}{3}}\kappa \varphi}
$$
\nEinstein frame $g_{\mu\nu}$

\n
$$
\hat{R} = \Omega^2 [R + 3\Box(\ln \Omega^2) - \frac{3}{2} g^{\mu\nu} \partial_\mu (\ln \Omega^2) \partial_\nu (\ln \Omega^2)]
$$

$$
S_E = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2} (\nabla \varphi)^2 - U(\varphi) - \frac{1}{2} e^{-\sqrt{\frac{2}{3}}\kappa \varphi} (\nabla \hat{\sigma})^2 - e^{-\sqrt{\frac{8}{3}}\kappa \varphi} V(\hat{\sigma}) \right]
$$

$$
U(\varphi) = \frac{3}{4}M^2M_p^2\left(1 - e^{-\sqrt{\frac{2}{3}}\kappa\varphi}\right)^2 = \begin{cases} \frac{3}{4}M^2M_p^2 & \text{for } \varphi \gg \varphi_f\\ \frac{1}{2}M^2\varphi^2 & \text{for } \varphi \ll \varphi_f \end{cases}
$$

 φ : Scalaron = Inflaton

Starobinsky R² Inflation

 $Chibisc$ *f dtH* ' [Starobinsky 1980; Mukhanov & Chibisov 1981]

where the number of e-folds is given by $\mathcal{L}_\mathcal{D}$ is given by $\mathcal{L}_\mathcal{D}$

 $\overline{\mathbf{a}}$ the end of $\overline{\mathbf{b}}$ The primordial and the primordial and provide of gravitational waves in the set of gravitation of gravitational waves in the set of gravitational waves in the set of gravitation of the set of gravitation of the set of the Scalaron mass M is fixed by CMB temp. anisotropy

$$
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$$

Starobinsky R2 Inflation

[Starobinsky 1980; Mukhanov & Chibisov 1981]

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$$

Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

$$
\sigma \equiv e^{-\frac{\kappa}{\sqrt{6}}\varphi} \hat{\sigma}
$$
\n
$$
\mathcal{L}_{\text{scalar}} = -\frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - \frac{\kappa \sigma}{\sqrt{6}} \partial_{\mu} \sigma \partial^{\mu} \varphi - \frac{\kappa^{2} \sigma^{2}}{12} \partial_{\mu} \varphi \partial^{\mu} \varphi - \frac{m_{\sigma}^{2}}{2} e^{-\frac{2}{\sqrt{6}}\kappa \varphi} \sigma^{2}
$$
\n
$$
\psi \equiv e^{-\frac{3\kappa}{2\sqrt{6}}\varphi} \hat{\psi}
$$
\n
$$
\mathcal{L}_{\text{fermion}} = -\bar{\psi} \mathcal{D} \psi - e^{-\frac{1}{\sqrt{6}}\kappa \varphi} m_{\psi} \bar{\psi} \psi
$$

Gravitational reheating by scalaron decay

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Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

Based on the above gravitationally induced couplings, the scalaron decay rate is given by $\mathbf{S}^{3,3}$ Gravitational reheating by scalaron der Gravitational reheating by scalaron ded Gravitational reheating by scalaron decay

1503.08430] [YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

^p10*Mp*). To get *^T*rh ⁼ *^O*(10⁹ GeV), we have

1*/*2

*T*rh =

$$
\Gamma(\varphi \to \sigma \sigma) = \frac{\mathcal{N}_{\sigma} (M^2 + 2m_{\sigma}^2)^2}{192 \pi M_{\text{Pl}}^2 M}
$$

\n
$$
\simeq \frac{\mathcal{N}_{\sigma} M^3}{192 \pi M_{\text{Pl}}^2} + \frac{\mathcal{N}_{\sigma} m_{\sigma}^2 M}{48 \pi M_{\text{Pl}}^2} \qquad \Gamma(\varphi \to \bar{\psi}\psi) = \frac{\mathcal{N}_{\psi} m_{\psi}^2 M}{48 \pi M_{\text{Pl}}^2}
$$

\n**Leading term**
\n
$$
T_{\text{rh}} \simeq 0.1 \sqrt{\Gamma_{\text{tot}} M_p} \left(\frac{\mathcal{N}_{\text{tot}}}{100}\right)^{-1/4} \sim 10^{-9} M_p,
$$

\n
$$
N_* \simeq 54 + \frac{1}{3} \ln \left(\frac{T_{\text{rh}}}{10^9 \text{ GeV}}\right),
$$

ں
ior le If we know the matter sector (e.g. SM minimally coupled to gravity), made inflationary predictions can be made without uncertainty. ed to gravity),
certainty.

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⌘ ¹

Predictions depend on reheating temperature dominated portions at the number of the number of the control state \sim *MPre* $\overline{\mathsf{dist}}$ *N*⇤ \ln s den \sim \sim \sim \sim ◆¹*/*² neating temperature zalar pahanting tamparatura by the Cobe-William of the Couplet of the contraction of the amplitude of the amplitude of the amplitude of the

e-folds of inflation the realaron re e-folds of inflation scalaron mass

of heavy charged modes.

scalard

$$
N_* \simeq 54 + \frac{1}{3} \ln \left(\frac{T_{\rm rh}}{10^9 \text{ GeV}} \right), \qquad M \simeq 10^{-5} M
$$

$$
M \simeq 10^{-5} M_p \frac{4\pi \sqrt{30}}{N_*} \left(\frac{\mathcal{P}_{\zeta}(k_*)}{2 \times 10^{-9}}\right)^{1/2}
$$

$$
\sim 10^{13} \text{GeV}
$$

and spin-1 (*Aµ*) are rescaled as

ˆ

characterized by the ratio by the ratio between Eqs. (16) and (16) and (15): (16): (grav. waves tilt and running of spectra

curvature perturbations as \mathbb{R}^2 , \mathbb{R}^2 ,

$$
r = \frac{\mathcal{P}_{\gamma}(k)}{\mathcal{P}_{\zeta}(k)} \simeq 16\epsilon \simeq \frac{12}{N_*^2}.
$$

$$
n_s - 1 = \frac{d \ln \mathcal{P}_{\zeta}(k)}{d \ln k} \simeq -6\epsilon_V + 2\eta_V \simeq -\frac{2}{N_*},
$$

\n
$$
n_t = \frac{d \ln \mathcal{P}_{\gamma}(k)}{d \ln k} \simeq -2\epsilon_V \simeq -\frac{3}{2N_*^2},
$$

\n
$$
\frac{dn_s}{d \ln k} \simeq 16\epsilon_V \eta_V - 24\epsilon_V^2 - 2\xi_V^2 \simeq -\frac{2}{N_*^2},
$$

\n
$$
\frac{dn_t}{d \ln k} \simeq 4\epsilon_V \eta_V - 8\epsilon_V^2 \simeq -\frac{3}{N_*^3},
$$

PBH formation after R² inflation?

Necessary for the PBH formation

These modes re-enter the horizon & grow during the long inflaton-oscillation epoch

Perturbations during the inflaton-oscillation era

[Finelli, Brandenberger 1999; Jedamzik, Lemoine, Martin 2010]

Perturbations during the inflaton-oscillation era

[Finelli, Brandenberger 1999; Jedamzik, Lemoine, Martin 2010]

[Martin, Papanikolaou, Venin 2020]

Another condition

Mass fraction of PBHs

$$
\beta(k(M))=2\int_{\delta_{\rm th}}^{\infty}P(\delta)d\delta
$$

Our viewpoint

The evolution of the anisotropy

Pancake Collapse Effect

[Khlopov, Polnarev 1980; Harada, Yoo, Kohri, Jhingan 2016]

If \exists perimeter $> 2\pi \times$ (Schwarzchild radius) \rightarrow cannot collapse

$$
\beta_0^{\text{pancake}} = \int_0^\infty d\alpha \int_{-\infty}^\alpha d\beta \int_{-\infty}^\beta d\gamma \,\theta (1 - h(\alpha, \beta, \gamma)) w(\alpha, \beta, \gamma)
$$

$$
\simeq 0.071 \sigma_H^5
$$

$$
\sigma_H = \sqrt{\mathcal{P}_\delta}
$$

The Spin Effect

[Harada, Yoo, Kohri, Nakao 2017]

PBH production is suppressed very very very much!!!

Result: No PBH dominant era

Conclusion

MODEL: R^2 inflation model

FOCUS: The density perturbation ω inflaton-oscillation epoch

Appendix: SUSY Scenarios

the above action to matter sector. We take the minimal coupling between the minimal coupling between the SUGRA s

$$
S = \int \mathrm{d}^4 x \mathrm{d}^4 \theta E \left(N(\mathcal{R}, \bar{\mathcal{R}}) + J \left(\phi, \bar{\phi} e^{gV} \right) \right) \phi, \text{ V are the matter sector} + \left[\int \mathrm{d}^4 x \mathrm{d}^2 \Theta 2 \mathscr{E} \left(F(\mathcal{R}) + P(\phi) + \frac{1}{4} h_{AB}(\phi) W^A W^B \right) + \text{H.c.} \right]
$$

duality trans. b **↓ duality trans. by T, S (T is the Lagrange multiplier)**

$$
S = \int d^4x d^2\Theta 2\mathscr{E} \frac{3}{8} (\bar{\mathscr{D}}\bar{\mathscr{D}} - 8\mathcal{R}) e^{-K/3} + W + \frac{1}{4} h_{AB} W^A W^B + \text{H.c.}
$$

$$
\text{Kahler pot:} \quad K = -3\ln\left(\frac{T+\bar{T}-N(S,\bar{S})-J(\phi,\bar{\phi}e^{gV})}{3}\right),
$$

 $\frac{1}{2}$ is from a first, non-holomorphic term action as it is from D-component of $\frac{1}{2}$ **Superpot:** $W = 2TS + F(S) + P(\phi)$.

 ϕ and vector superfields ϕ and ϕ

Starobinsky SUGRA R2 inflation Starobinsky SUGRA R2 inflation

The inflaton (or SUGRA) sector (T and S) of this class of this class of this class of \mathbb{R}^d

 $[1 \text{GHz}, 1 \text{yy}, 1 \text{a}$, Yokoyama 1411
 46, Dalia
" , (9) [Terada, YW, Yamada, Yokoyama 1411.6746; Dalianis & YW 1801.05736]

$$
\mathcal{L} = -3M_P^2 \int d^4\theta \, E \left[1 - \frac{4}{m_\Phi^2} \Re \bar{\mathcal{R}} + \frac{\zeta}{3m_\Phi^4} \Re^2 \bar{\mathcal{R}}^2 \right]
$$

$$
N(S, \bar{S}) = -3 + \frac{12}{m_\Phi^2} S \bar{S} - \frac{\zeta}{m_\Phi^4} (S \bar{S})^2 \qquad \frac{1}{S, \text{ Im } T \text{ are stabilized.}}
$$

$$
F(S) = 0,
$$

The above action can be recast into the following form $\mathcal{S}^{\mathcal{S}}$ into the following form $\mathcal{S}^{\mathcal{S}}$ Real part of T becomes the inflaton $\Phi: V = \frac{\partial^{\eta} u_{\Phi}}{4}$ ($1 -$ |
|-Real part of T becomes the inflaton Φ : $V = \frac{3m_{\Phi}}{4} \left(1 - e^{-\sqrt{2}/3 \text{Re} \theta} \right)$ S and stabilizes its potential. The real part of T becomes the inflaton, and the inflaton, and the canonically $3m_\Phi^2$ 4 $\sqrt{2}$ $1 - e^ \sqrt{2/3{\rm Re}T}$ $\overline{T}\setminus{}^2$ \vert Real part of T becomes the inflaton Φ: $V = \frac{3m_{\Phi}}{4} \left(1 - e^{-\sqrt{2/3}\text{Re}T}\right)$ pair of auxiliary fields: the complex scalar *M* and the real vector *bm*. Lagrangian (59) when expanded

$$
S = \int d^4x d^2\Theta 2\mathscr{E} \frac{3}{8} (\mathscr{D}\mathscr{D} - 8\mathcal{R}) e^{-K/3} + W + \frac{1}{4} h_{AB} W^A W^B + \text{H.c.}
$$

$$
K = -3\ln\left(\frac{T + \bar{T} - N(S, \bar{S}) - J(\phi, \bar{\phi}e^{gV})}{3}\right),
$$

W = 2TS + F(S) + P(\phi). **Grav. coupling to matter** ϕ , V

Starobinsky SUGRA R2 inflation Starobinsky SUGRA R2 inflation Starobinsky SUGRA R2 inflation and masses otherwise other particles.

The inflaton (or S UGRA) sector (T and S) of this class of this class of models was of models was $\mathcal{S}(\mathcal{S})$

 $[1 \text{GHz}, 1 \text{yy}, 1 \text{a}$, Yokoyama 1411
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$$
\mathcal{L} = -3M_P^2 \int d^4\theta E \left[1 - \frac{4}{m_\Phi^2} \Re \bar{\mathcal{R}} + \frac{\zeta}{3m_\Phi^4} \Re^2 \bar{\mathcal{R}}^2 \right]
$$

$$
N(S, \bar{S}) = -3 + \frac{12}{m_\Phi^2} S \bar{S} - \frac{\zeta}{m_\Phi^4} (S \bar{S})^2
$$

$$
F(S) = 0,
$$

Real part of T becomes the inflaton $\Phi: V = \frac{3m_{\Phi}^2}{\sigma^2}$ ($1 - e^{-\sqrt{2}/3}$ \mathcal{S} and stabilizes its potential. The real part of T becomes the inflaton, and the canonically canonically continued by 3m² # ————————
√2/3Re \$2 Real part of T becomes the inflaton Φ : $\big\vert V =$ $3m_\Phi^2$ 4 $\sqrt{2}$ $1 - e^ \sqrt{2/3{\rm Re}T}$ $\overline{T}\setminus{}^2$ \vert T = 10 is the canonical inflation in the canonical inflation of the sGoldstino of the sGoldsti Real part of T becomes the inflaton Φ : $V = \frac{\partial m_{\Phi}}{4} \left(1 - e^{-\sqrt{2/3 \text{Re} T}}\right)$, pair of auxiliary fields: the complex scalar *M* and the real vector *bm*. Lagrangian (59) when expanded $\sqrt{2}$ SUSY breaking sector as general as possible, but occasionally we assume a simple SUSY breaking Real part of T becomes the inflaton Φ:

SUSY breaking field: **R22 SUSY breaking field: R2** terms for the "auxiliary" fields *R2* $\frac{1}{2}$ and $\frac{1}{2}$

$$
J(z,\bar{z}) = |z|^2 - \frac{|z|^4}{\Lambda^2},
$$
Z may dominate after inflation.

$$
P(z) = \mu^2 z + W_0,
$$

Inflaton decay after SUGRA R2 inflation ' ' flat ' ' '
' 2 ≃2 **'** ' **Γ**
Γιάσης της Προσφαλής της Προσφαλής της Ανατολίας της Προσφαλής της Προσφαλής της Προσφαλής της Προσφαλής της Π √3 $\overline{ }$!
!!
! l**y** $\overline{}$ \mathbf{a} $\overline{\mathbf{z}}$ |
|-
| 1 33
33 SU m² z ЯПМ Г
△ p … " $\overline{}$ $\overline{\mathbf{f}}$ n_{II} $\overline{12}$ \overline{a} − 4GzGzWo
− 4GzGzWords Words Words
− 4GzGzWords Words Words Words This means the interaction that the interaction terms are proportion to the mass terms of scalars. The mass te ^M˜ij [≃] ^Pij/W ⁺ ^Jij [−] ^Jijz¯Gz¯ where ^z is the SUSY breaking field. Under the same approximation, $\begin{array}{l} \hline \textbf{Inflaton domain of}\textbf{for CILCDA DO inflation} \end{array}$

where tilded indexes may take both of holomorphic and anti-holomorphic indexes like $\mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L}$

 $\frac{1}{2}$ induction is a contract of $\frac{1}{2}$ in $\$ m² (1 W¯)' same order contribution from the contribution from the daughter of the mass of the mass of the mass of the mas
Mass of the mass of the mass of the daughter particle quality of the daughter particle particle particle parti [Terada, YW, Yamada, Yokoyama 1411.6746; Dalianis & YW 1801.05736]

 p and p a

 $\frac{1}{2}$ $\frac{3m^4}{2}$ ^JzG^z [∓] Figure coupling is the effective coupling is simplified when $8\pi M_P^2 m_\Phi$ is in particular 96π $\Gamma(T\to \phi^i \bar{\phi}^{\bar{i}})=\frac{3m_i^4}{8\pi M^2\eta^2}$ \dot{i} $8\pi M_{\bm{\mathcal{P}}}^2 m_{\Phi}$ $\Gamma(T \to \phi^i \phi^j) = \frac{m_{\Phi}}{96\pi M^2} |J_{ij}|^2.$ $\phi^j) = \frac{m_{\Phi}^3}{2c}$ $\overline{\Phi}$ $96\pi M_{\bm{\mathsf{P}}}^2$ $|J_{ij}|$ $\frac{2}{\cdot}$ \sim $\frac{1}{2}$ $\frac{3m^4}{1000}$ **bcalars:** $I(T \to \phi^{\circ} \phi^{\circ}) = \frac{1}{8\pi M^2 m^2}$, $I(T \to \phi^{\circ} \phi^{\circ}) = \frac{1}{96\pi M^2} |J_{ij}|^2$. $\overline{\cdot}$ $\overline{\$ $\overline{2}$ where $8\pi M_{\tilde{P}}^2 m_{\Phi}$ and $96\pi M_{\tilde{P}}^2$ ^c_J¹ Scalars:

Φ

Fermions:
$$
\Gamma(T \to \chi^i \bar{\chi}^{\bar{i}}) = \frac{m_i^2 m_{\Phi}}{192 \pi M_P^2},
$$

6

 C ougo fioldo Gauge fields

'

Gauge fields
&**gauginos:**
$$
\Gamma(T \to AA) + \Gamma(T \to \lambda \lambda) \simeq \frac{3N_{\rm g}\alpha^2 m_{\Phi}^3}{128\pi^3 M_P^2} \left(T_G - \frac{1}{3}T_R\right)^2
$$

z

\$

 $\overline{}$

2. (19)
2. (19)
2. (19)

#

m²

)'

8πM²

^Gm^Φ

2

 $\Gamma(\Phi_{\rm R\pm} \to \psi_{3/2}\psi_{3/2}) \simeq$ m_Φ^3 $48\pi M_{\textit{P}}^2$ × $\sqrt{2}$ \int $\overline{\mathcal{L}}$ $16 \left(\frac{m_{3/2}}{m_{\phi}} \right)$ m_Φ \setminus^2 $\left(m_z^2\ll m_\Phi m_{3/2}\right)$ $\left(m_z \right)$ m_{Φ} \setminus^4 $\left(3m_\Phi m_{3/2} \ll m_z^2 \ll m_\Phi^2\right)$ \sum 1 $\left(m_{\Phi}^2 \ll m_z^2\right)$ $\overline{ }$ $\mathbf{\bar{p}}$ **phase Space 6** $\frac{1}{3}$. $\frac{1}{3}$ $\frac{1}{3}$ The inflaton T has the Lagrange multiplier origin so that it never appears in the gauge \sim Gravitinos: (Φ is inflaton) *P*

Constraints from gravitino abundance

[Terada, YW, Yamada, Yokoyama 1411.6746]

Gravitinos generated from:

- inflaton decay
- thermal scatterings
- 3) decay of particles
- 4) decay of oscillating Z

Neutralino LSP (~TeV WIMP) is assumed for:

gravitino mass $> 10⁴$.5 GeV \rightarrow anomaly mediation

gravitino mass < 10^4.5 GeV \rightarrow gravity mediation

CMB uncertainties from the post-inflationary evolution [Easther, Galvez, Ozsoy, Watson 2013] Into antoortaminoo nomi tho poot minational y of olation
IFasther Galvez Ozsov Watson 20131 where $\overline{}$ the running and the running of the running of the scale of the scale one can assume that the scale of the scale
In general one can assume that the scale of t \sim spectral index to be given at leading order by the expression of the exp **n** 2013]

N⇤

Thermal History al F spectral index to be given at leading order by the expression σ at leading order by the expression σ

Alternative History ◆*ⁿs*1+(1*/*2)(*dns/d* ln *^k*) ln(*k/k*⇤)+(1*/*6)(*d*2*ns/d* ln *^k*2)(ln(*k/k*⇤))2+*...*

Shift in (ns, r) due to late entropy production *^X* . It is *D^X* = 1 when no dilution takes **b** Shift in (ns, r) due to late entropy pl **In order the Shift in (ns. r) due to late entropy production and** \mathbf{r} **scalar cosmic evolution** When the scalar X *coherently oscillates about the minimum of a e*
Oscillates about the minimum of a e⊿ectively quadratic potential it is in the minimum of a e⊿ectively quadratic

1
1
1

1
1
1

and entropy respectively and can be taken to be approximately equal. The *T* dec

is found to be subdominant with respect to be subdominant with respect to the μ -dependent terms. The μ

• After inflaton decay, a diluter field X (modulus, flaton) may dominate the universe until BBN. Decays of X produce **entropy**: $\frac{1}{2}$ \mathbb{H} H ^{*N* α f} el $\frac{1}{4}$ ⇢dec *X w* and the cosmic the cosmic telement of α is the cosmic the set of a cosmic the cosmic the cosmic than the cosmic telement of α where when **DDIY.** Decays of A produce entropy. t mor minater accely, a sincter from r (frocaler, fellow, press, abundances and of the relativistic degrees of freedom at the time of the *X* decay. The *X* field decays and reheats

$$
\Delta N_X = \frac{1}{3} \ln \left[\left(\frac{g_*(T_X^{\text{dom}})}{g_*(T_X^{\text{dec}})} \right)^{1/4} D_X \right] = \frac{1}{3} \ln \tilde{D}_X
$$
\n
$$
D_X \equiv \frac{S_{\text{after}}}{S_{\text{before}}} = 1 + \frac{g_*(T_X^{\text{dec}})}{g_*(T_X^{\text{dec}})} \frac{g_*(T_X^{\text{dom}})}{g_*(T_X^{\text{dom}})} \frac{T_X^{\text{dom}}}{T_X^{\text{dec}}} \simeq \frac{T_X^{\text{dom}}}{T_X^{\text{dec}}} \ge 1
$$
\n
$$
R^2, \ \mathbf{T}_{\text{rh}} = 10^9 \text{ GeV}
$$
\n10²⁰\n10¹⁰\n10¹⁰\n10¹⁰\n10¹⁰\n10¹⁰\n10¹⁰\n10¹⁵\n10¹⁶\n10¹⁶\n10⁵\n10⁵\n10⁵\n10⁵\n10⁵\n10⁶\n10⁷\n10⁸\n10¹⁰\n10¹

^X is the temperature

Supersymmetric dark matter scenarios **Supersymmetric dark matter scenarios** its relic density parameter generally violates the ⌦DM*h*² = 0*.*12 bound, and the essential conclusion scenario as well. Remarkably in these models, the saxion can play the rˆole of the diluter *X* for its compose y condense dan nomation essentiale entropy that successfully decreases that is abundance \sim

Merits: Gauge coupling unification, stable dark matter, baryogenesis, stringy UV completion, … also generate the recent results on the relationship constraints on the relationship constraints on the society Merite: Gauge coupling unification, stable dark matter, harvogenesis

scenario as well. Remarkably in these models, the saxion can play the rˆole of the diluter *X* for its

is that, in general, a special thermal history of the universe is required for the axino dark matter

- 1. Gravitino LSP 1. Gravitino LSP
- 2. Neutralino LSP (WIMP) \mathcal{L} . The outching \mathcal{L} of \mathcal{L} with \mathcal{L}
- Thermal DM (freeze out): thermal scatterings with the MSSM, messenger fields The mass of the predicted religion of supersymmetric data reliefs that matter in section 3 suggests that we have a sugge
- Non-thermal DM (freeze in): decays, thermal scatterings

Light WIMP mass is disfavored by the LHC. Ω_{DM} h² is severely constrained when **sparticle masses increase**: F_{c} is gravitating and neutralino $\frac{1}{2}$ on $\frac{1}{2}$ one can collect the substitution of $\frac{1}{2}$ the mass reserve.
Opub2 is severaly constrain \mathbf{r} and the mass parameters and temperature and temperat **strained when sparti**

$$
\Omega_{3/2} \propto m_{3/2}^{\alpha} \left(\frac{m_{\tilde{g}}}{m_{3/2}}\right)^{\beta} \left(\frac{m_{\tilde{f}}}{m_{3/2}}\right)^{\gamma} T_{\text{rh}}^{\delta}, \qquad m_{3/2} < m_{\tilde{g}}, m_{\tilde{f}},
$$

$$
\Omega_{\tilde{\chi}^0} \propto m_{\tilde{\chi}^0}^{\tilde{\alpha}} m_{3/2}^{\tilde{\beta}} \left(\frac{m_{\tilde{f}}}{m_{3/2}}\right)^{\tilde{\gamma}} T_{\text{rh}}^{\tilde{\delta}}, \qquad m_{\tilde{\chi}^0} < m_{3/2}, m_{\tilde{f}}
$$

Alternative cosmic histories and SUSY *T* dec *^X < T*f.o. ˜⁰ and (ii) *n*˜⁰ h*v*i *< H*(*T* dec *^X*) hold. If not, then in the case (i) the neutralinos might reach **SMIC NISTORIES AND SUSY**

expression generally applies. For the neutralino LSP one should also check whether the conditions (i) α

★ High reheating temp. generally overproduce light LSP *X* and was appropriately discussed by the decay of the scalar \mathcal{X} . On the scalar \mathcal{X}

- → Dilution of DM abundance is necessary: diluter field X *Ailuter field X*
- If $D_X = 1$ then $T_{\text{rh}} \lesssim \tilde{m}$ or $\tilde{m} \sim \text{TeV}$ • If $\mathcal{O}(TeV) < (m_{LSP}, \tilde{m}) < T_{rh}$ then $D_X \geq D_X^{\min} \equiv \frac{\mathcal{N}_{LSP}}{0.12 \, h^{-2}}$ where \tilde{m} the sparticle mass scale. Γ Figure 5: The maximum possible distribution size, \tilde{M} conducted by a scalar \tilde{M} • If $D_X = 1$ then $T_{\text{rh}} \lesssim \tilde{m}$ or $\tilde{m} \sim \text{TeV}$ a If $\theta(T_{\theta}V) < (m_{LSP} \tilde{m}) < T$, then $D > D^{\min} - \Omega_{LSP}^{\le}$ • If $O(TeV) < (m_{LSP}, \tilde{m}) < T_{rh}$ then $D_X \ge D_X^{\min} \equiv \frac{\Delta Z_{LSP}}{0.12 h^{-2}}$ where \tilde{m} the sparticle mass scale. L_{hom} $T_{\text{A}} \leq \tilde{m}$ or \tilde{m} or L_{N} ⌦LSP*h*² 0*.*12 implies $\frac{\Omega_{\rm LSP}^<}{0.12 h^{-2}}$

where we she speaked mess because.

CMB observables: SUGRA R2 inflation After the end of the inflationary expansion the inflaton is a homogeneous condensate of scalar *^N*³ (2*.*1 + ln *^N*) and ↵*^s* ⁼ ² *^N*² ⁺ *^N*³ (0*.*68 + 3 ln *^N*)*.* (55) Plugging *N*(th) = 54 in Eq.(54) the *thermal* scalar tilt value is obtained **CMB observables: SUGRA R2 inflation** *^N*² = 1 ²

Also, the tensor spectral tilt and running are respectively *n^t* = 3*/*(2*N*²

⇤), *dnt/d* ln *^k* ' 3*/N*³

^N ⁺

$$
N_{*}|_{R^{2}} = 55.9 + \frac{1}{4}\ln\epsilon_{*} + \frac{1}{4}\ln\frac{V_{*}}{\rho_{\text{end}}} + \frac{1}{12}\ln\left(\frac{g_{*rh}}{100}\right) + \frac{1}{3}\ln\left(\frac{T_{rh}}{10^{9}\,\text{GeV}}\right) - \Delta N_{X}
$$

CMB observables: SUGRA R2 inflation *CMB* observables: SUGRA R2 inflation

approach consists of representation (47). This is achieved by the action $[$ Dalianis & YW 1801.05736] and action $[$

^L ⁼ 3*M*² *P* Z *d*4 ✓ *E* ¹ ⁴ *^m*²RR¯ ⁺ ⇣ 3*m*4R² R¯ 2 *.* (59) + **MSSM, Z, X, (messengers)**

Modifications and further properties can be found in [97, 98, 99, 101, 102, 103, 104, 100, 105, 106, **Gravitino DM (in GeV units)**

Neutralino (WIMP) DM s_{total} and s_{total} and t_{total} are produced from the gravitinos are produced from the gravitinos of s_{total} **Neutralino (WIMP) DM**

integrated out due to the non-linear realization and it is the only dynamic degree of freedom during

CMB observables: SUGRA R2 inflation *CMB* observables: SUGRA R2 inflation

approach consists of representation (47). This is achieved by the action $[$ Dalianis & YW 1801.05736] and action $[$

$$
\mathcal{L} = -3M_P^2 \int d^4\theta \, E \, \left[1 - \frac{4}{m^2} \mathcal{R}\bar{\mathcal{R}} + \frac{\zeta}{3m^4} \mathcal{R}^2 \bar{\mathcal{R}}^2 \right] \quad + \text{MSSM, Z, X,}
$$
\n(messagengers)

Modifications and further properties can be found in [97, 98, 99, 101, 102, 103, 104, 100, 105, 106, **Gravitino DM (in GeV units)**

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CMB observables: SUGRA R2 inflation

[Dalianis & YW 1801.05736]

