Testing BSM Scenarios with the CMB Precision Cosmology

Ioannis Dalianis

National Technical University of Athens

In collaboration with Y. Watanabe (Gunma Tech & U. Tokyo)

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Motivation

A historic paradigm: *The Helium abundance and Neutrino families*

- The helium abundance depends sensitively on the expansion rate of the universe during the BBN and epansion rate depends on the number of types of relativistic particles present at $T \simeq 1$ MeV
- Roughly speaking, the primordial abundance of Helium increases by 1% for each additional neutrino family[1]

$$N_\nu \lesssim 3 \qquad (1977)$$

- Accelerator results on the decay of the Z^0 particle[2] lead to the limit

$$N_\nu(Z^0) \leq 3 \qquad (1989)$$

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[2] L3 collaboration 1989

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Is it possible nowadays to test BSM theories?

- Target at which observable?
- Which theory to test?

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Target

Is it possible nowadays to test BSM theories?

- Target at which observable? $\rightarrow$ CMB [3]
- Which theory to test? $\rightarrow$ SUPERSYMMETRY [4] (or your theory!)

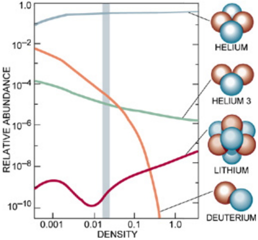
[3] Talks of A. Notari, D. Gorbunov, P. Serpico

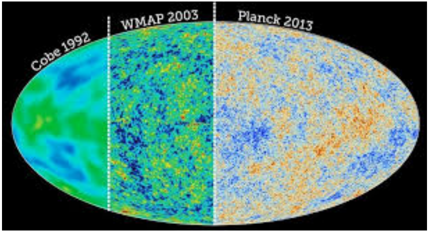
[4] At least seven talks

First Part:

CMB

From BBN to CMB





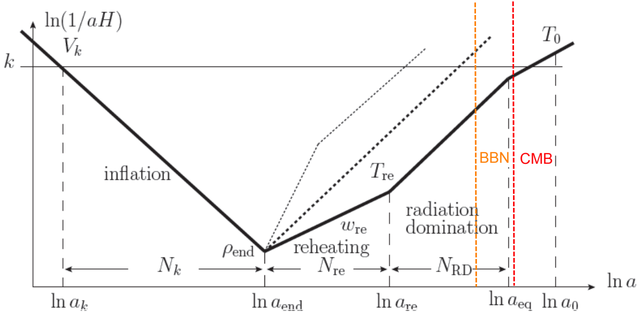
Cosmological assumptions:

- BBN: Big Bang (in ’70s)
- CMB: Cosmic Inflation (today)

Expansion history effects on the CMB

Different reheating-thermal-history influences the mapping of the CMB observed scales back to the horizon exit during inflation. Uncertainty between the end of inflation and the BBN leads to an uncertainty in the number of e-folds after the end of inflation [5] [6]

$$n_s(k_*) = 1 - \frac{\alpha}{N_*}$$



[5] Liddle & Leach 2003

[6] J. Martin & C. Ringeval and V. Vennin 2015

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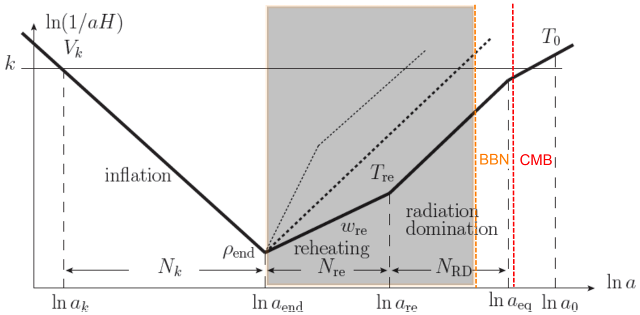

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The scalar spectral index value

The scalar spectral index value dependence on the number of efolds (*large N expansion*)

$$n_s(k_*) = 1 - \frac{\alpha}{N_*}$$

- 1st Generation Observations, COBE: $n_s \approx 1 \pm 0.5$
- 2nd Generation Observations, WMAP : $n_s \approx 0.97 \pm 0.02$
- 3rd Generation Observations, Planck: $n_s = 0.965 \pm 0.004, \quad r < 0.07$

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- 4rth Generation Observations. LiteBIRD, Core+, CMB-S4, PRISM, PIXIE
  The sensitivity **forecasts** for n_s and r is of the order of 10^3 and such a measurement will account for a substantial leap forward at the observational side

$$n_s = 0.96?? \pm 0.0010, \quad r < 0.003$$

Quantifying the effects of the **pre-BBN period**

- We define $N_{\rm dark}$ the number of e-folds from the end of inflation until the beginning of the BBN
- The number of efolds before the end of inflation

$$N_* \approx 66.7 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_{\rm Pl}^4 \rho_{\rm end}}\right) - \frac{1-3\bar{w}_{\rm dark}}{4} N_{\rm dark} - \frac{1}{12}\ln(g_*)$$

$$n_s = 1 - \frac{\alpha}{N_*}$$

- The uncertainty on the N_* comes mainly from the post-accelaration stage and induces an uncertainty on the spectral index value given by the n_s running that reads

$$\Delta n_s = \alpha \frac{\Delta N_*}{{N_*}^2}$$

For $\Delta N_* \sim 1 - 10$ the Δn_s is of size $\mathcal{O}(0.1 - 1)\%$, that is within the accuracy of the future observations.

Pre-BBN cosmic history and Dark Matter

- The reheating temperature T_{rh}
- The Dilution magnitude D

Dilution and the spectral index value n_s

Q: What is the shift in the spectral index for an arbitrary dilution size?

Answer:

- Dilution due to scalar field oscillations

$$D_X \equiv 1 + \frac{S_{\rm after}}{S_{\rm before}} \simeq \frac{T_X^{\rm dom}}{T_X^{\rm dec}} \geq 1$$

- Due to thermal inflation

$$D_X{}^{\rm FD} \simeq 1 + \frac{T_1^4}{T_2^3\, T_X^{\rm dec}}\,.$$

- The shift of the spectral index for

$$n_s = 1 - \alpha/N_*$$

$$\Delta n_s = -\frac{1-n_s^{\rm (th)}}{3N^{\rm (th)}} \ln \tilde{D}_X \left[1 + \frac{1-n_s^{\rm (th)}}{3\alpha} \ln \tilde{D}_X + \left(\frac{1-n_s^{\rm (th)}}{3\alpha} \ln \tilde{D}_X\right)^2\right]$$

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- If $\Delta N_X \sim 10$ then $D_X \sim 10^{13}$ and $\Delta n_s \sim 0.01$
- If $\Delta N_X \sim 1$ then $D_X \sim 10$ and $\Delta n_s \sim 0.001$

Precision improvement

Since precision is expected to increase in the future it is worthwhile to consider next-to-leading corrections. Due to the large number of inflationary models there is no common form for the next-to-leading term [9]. A phenomenological way to parametrize it is based on the large N expansion

$$n_s = 1 - \frac{\alpha}{N_*} + \frac{\beta(N_*)}{{N_*}^2} + \mathcal{O}\left(\frac{1}{{N_*}^3}\right)$$

[9] Martin & Ringeval & Vennin 2016

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The shift in the spectral index, with accuracy $|\Delta n_s|/n_s \lesssim 0.1\%$, due to a post-inflationary dilution of the thermal plasma

$$\Delta n_s = -\left(1 - n_s^{(\mathrm{th})}\right)^2 \frac{\gamma}{3\alpha} \ln \tilde{D}_X \left[\sum_{p=0}^{2} \left(\gamma \frac{1 - n_s^{(\mathrm{th})}}{3\alpha} \ln \tilde{D}_X \right)^p - \frac{\beta\gamma^2}{\alpha^2} \left(1 - n_s^{(\mathrm{th})}\right) + \frac{\beta'\gamma}{\alpha} \right]$$

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The shift in the tensor-to-scalar ratio, coming from the phenomenological parametrization of the scalar tilt

$$\Delta r = \frac{\left(r^{(\mathrm{th})}\right)^2}{16}\left[2(\alpha - 1)^{-1} + \alpha A N^{\alpha - 1}\right] \Delta N_X \,, \qquad (1)$$

[9] Martin & Ringeval & Vennin 2016

Second Part:

BSM scenario

Test a BSM theory

Choose a candidate BSM theory

[10] E. Bagnaschi, G. F. Giudice, P. Slavich and A. Strumia 2004

[11] J.D. Wells 2003; N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino 2004; A. Arvanitaki, N. Craig, S. Dimopoulos and G. Villadoro 2013

Test a BSM theory

Choose a candidate BSM theory
SUSY is a compelling BSM scenario

- Natural SUSY?
- Quasi-Natural SUSY [10]
- Split Scale SUSY: *The scalar sparticles are much heavier than gauginos and higgsinos* [11]
- High Scale SUSY *The sparticles have masses around a common scale* $\tilde{m}$

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[10] E. Bagnaschi, G. F. Giudice, P. Slavich and A. Strumia 2004

[11] J.D. Wells 2003; N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino 2004; A. Arvanitaki, N. Craig, S. Dimopoulos and G. Villadoro 2013

SUSY Dark Matter and Relic Abundances

Two well-known examples:

For gravitino and neutralino LSP one can collectively write down a general scaling with respect to the mass parameters and temperature

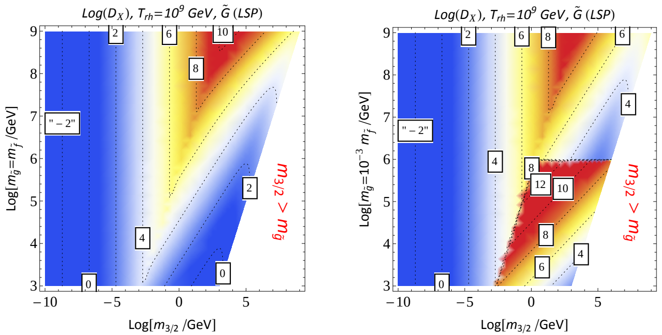
$$\Omega_{3/2} \propto m_{3/2}^{\alpha} \left(\frac{m_{\tilde{g}}}{m_{3/2}}\right)^{\beta} \left(\frac{m_{\tilde{f}}}{m_{3/2}}\right)^{\gamma} T_{\rm rh}^{\delta} \; , \qquad m_{3/2} < m_{\tilde{g}}, m_{\tilde{f}} \; ,$$

and

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

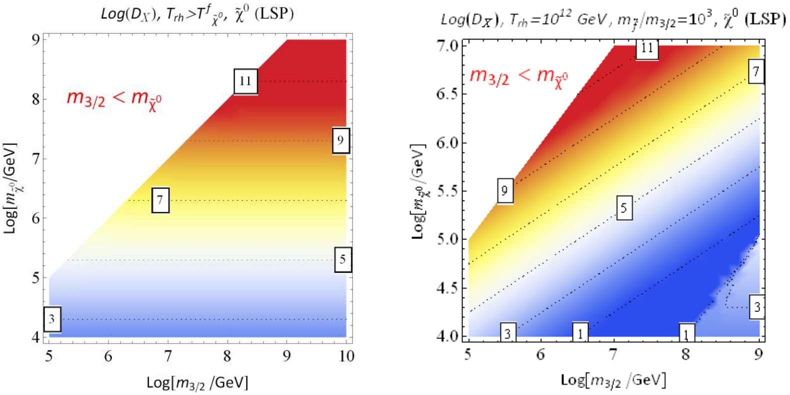
where the exponents $(\alpha, \beta, \gamma, \delta)$ and $(\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}, \tilde{\delta})$ are either positive or zero, depending on the dark matter production mechanism considered.

Multi-TeV SUSY, Gravitino DM and viable cosmology



Density and contour plot of the logarithm of the *required* dilution for $T_{\rm rh} = 10^9$ GeV reheating temperature after inflation and gravitno the stable LSP. Thermal production of helicity $\pm 3/2$ and $\pm 1/2$ gravitinos from scatterings in the plasma, non-thermal production from decays of sfermions and the NLSP to helicity $\pm 1/2$ gravitinos have been taken into account.

Multi-TeV SUSY, Neutralino DM and viable cosmology



Density and contour plot of the *required* dilution for neutralino stable LSP. In the left panel the neutralino abundance is the thermal one. In the right the neutralino yield is dominated by the decay of gravitinos produced from sfermion decays. The gravitino mass is taken to be $m_{3/2} > 10^5$ GeV to avoid BBN constraints.

Q: How can we relate the SUSY BSM scenarios with the CMB observables?

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We have to work in a particular inflationary framework

Starobinsky model of inflation

- Higher curvature gravitation [12]

$$e^{-1}\mathcal{L} = \frac{1}{2}R + \frac{\alpha}{4}R^2.$$

- That is recast into Einstein gravity coupled to a scalar (the scalaron)

$$e^{-1}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\varphi\partial\varphi - \frac{1}{4\alpha}\left(1 - e^{-\sqrt{\frac{2}{3}}\varphi}\right)^2.$$

- The rehating temperature is found to be[13]

$$T_{\rm rh} \sim 10^9 \text{GeV}$$

[12] Starobinsky '80, Whitt '84

[13] Gorbunov and Panin 2011

The Supergravity Starobinsky inflation model

- Standard supergravity: 4 new scalar DOF that reside inside appropriate superfields.
- The Higher Derivative supergravity is equivalent to standard supergravity with Kähler potential[14]

$$K = -3 \ln \left\{ \mathcal{T} + \bar{\mathcal{T}} + f\left(\mathcal{S}, \bar{\mathcal{S}}\right) \right\},$$

  and superpotential

$$W = 6\mathcal{T}\mathcal{S}.$$

- During inflation $\langle S \rangle = \langle \mathrm{Im}\, T \rangle = 0$ are strongly stabilized and the model becomes

$$e^{-1}\mathcal{L} = -\frac{M_P^2}{2} R - \frac{1}{2}\partial\varphi\partial\varphi - \frac{3}{2} m^2 M_P^2 \left(1 - e^{-\sqrt{\frac{2}{3}}\varphi/M_P}\right)^2$$

- The reheating temperature is found to be[15]

$$T_{\mathrm{rh}} \sim 10^9 \mathrm{GeV}$$

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[14] Cecotti '87, Kallosh, Linde '13; Farakos, Kehagias, Riotto '13; Dalianis, Farakos, Kehagias, Riotto, von Unge '14

[15] Terada, Watanabe, Yamada, Yokoyama 2014; Takeda, Watanabe 2014

The Starobinsky model CMB predictions

Going at next-to-leading order we could probe $\Delta N_X \sim 1$ changes that could shed light on the pre-BBN cosmic history. For the Starobinsky model the expression reads

$$n_s = 1 - \frac{\alpha_{R^2}}{N} + \frac{\beta_{R^2}(N)}{N^2} = 1 - \frac{2}{N} + \frac{0.81 + 3/2\ln(N)}{N^2}$$

To order $1/N^3$ the tensor-to-scalar ratio reads

$$r = \frac{12}{N^2} - \frac{18}{N^3}(2.1 + \ln N)$$

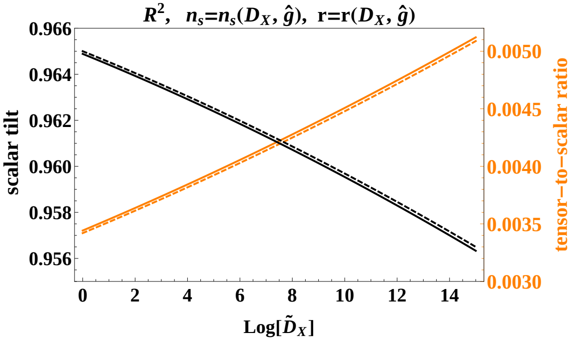
Plugging $N = 54$ the *thermal* scalar tilt value is obtained

$$n_s^{(\mathrm{th})}\Big|_{R^2} = 0.965\,, \qquad r^{(\mathrm{th})}\Big|_{R^2} = 0.0034$$

that is 0.2% larger than the leading order prediction. We also take at next-to-leading order Note that the r value is 17% smaller than the value obtained at leading order. Furthermore, going to accuracy level $1/N^3$ the $r = r(n_s)$ relation reads

$$r - 3(1 - n_s)^2 + \frac{23}{4}(1 - n_s)^3 = 0$$

The shift in n_s and r for the Starobinsky model



The size of the shift due to a non-thermal phase that lasts $\tilde{N}_X = [(1-3\bar{w}_X)/4]^{-1}\Delta N_X$ e-folds after the inflaton decay for the Starobinsky model is

$$\Delta n_s(D_X, \hat{g}) = -2 \times 10^{-4}\,(\ln D_X + \hat{g})\left[1 + \frac{2}{300}(\ln D_X + \hat{g})\right] \,,$$

The shift in the tensor-to-scalar reads

$$\Delta r(D_X, \hat{g}) = 3.9 \times 10^{-5}\,(\ln D_X + \hat{g})\left[1 + 8.2 \times 10^{-3}(\ln D_X + \hat{g})\right] \,.$$

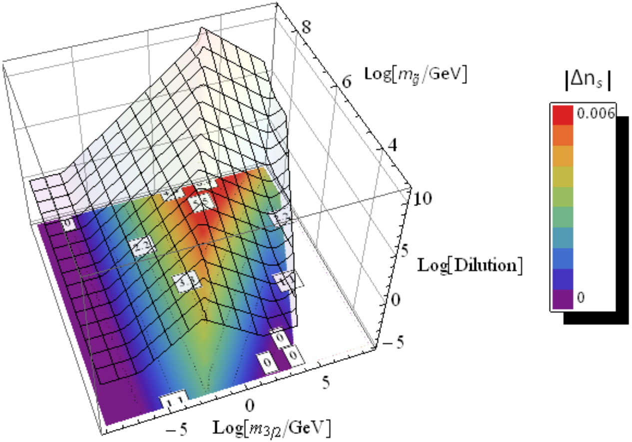
SUSY BSM scenarios: Gravitino LSP

#	m_Z	$m_{\tilde{g}}$	$m_{\tilde{f}}$	$m_{3/2}$ (LSP)	D_X	N_*	n_s	r	Origin
1	10^3	10^3	10^4	10	1	54	**0.965**	**0.0034**	Th
2	10^4	10^4	10^4	10^2	$10^4\|_{\min}$	$51\|_{\max}$	**0.963**$\|_{\max}$	**0.0038**$\|_{\min}$	Th
3	10^6	10^5	10^6	10^4	$10^6\|_{\min}$	$49\|_{\max}$	**0.962**$\|_{\max}$	**0.0041**$\|_{\min}$	Non-th
4	10^4	10^4	10^5	10^3	$10^{10}\|_{\min}$	$46\|_{\max}$	**0.960**$\|_{\max}$	**0.0044**$\|_{\min}$	Th

The n_s and r prediction for gravitino LSP and a gauge mediation scheme for the R^2 supergravity model. In the cases # 1, 2 and 3 the gravitinos are produced from thermal scatterings of messengers and MSSM fields while in the case # 4 from the non-thermal decay of the supersymmetry breaking Z field[16]. In cases # 2, 3 and 4 dilution is required to decrease the LSP abundance below the observational bound. In the case # 1 non-minimal hidden sector features have been assumed. The masses are in GeV units.

$$\mathrm{Br}^{\mathrm{inf}}_{3/2} \equiv \mathrm{Br}(\Phi \to \tilde{G}\tilde{G}) \simeq \frac{1}{48\pi c'} \times \begin{cases} 16\left(\frac{m_{3/2}}{m_\Phi}\right)^2 & \text{for} \quad m_Z \ll (m_\Phi m_{3/2})^{1/2} \\ \left(\frac{m_Z}{m_\Phi}\right)^4 & \text{for} \quad (3m_{3/2}m_\Phi)^{1/2} \ll m_Z \ll m_\Phi \end{cases} \tag{2}$$

[16] Hamaguchi, R. Kitano and F. Takahashi

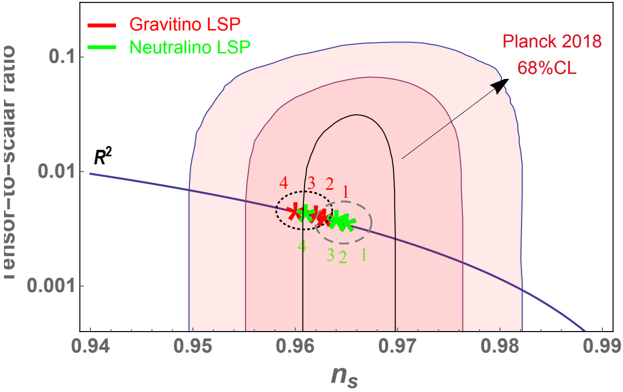


Log[$m_{\tilde{g}}$/GeV]
8
6
4
10
5
0
−5
Log[Dilution]
0
5
−5
Log[$m_{3/2}$/GeV]
$|\Delta n_s|$
0.006
0

SUSY BSM scenarios: Neutralino LSP

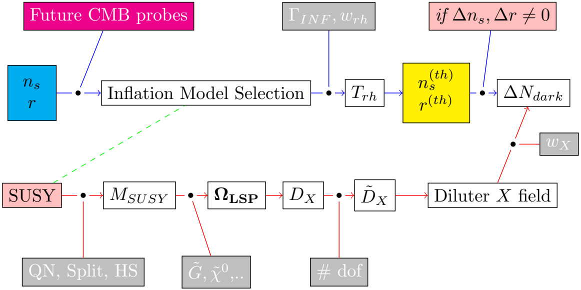
#	m_Z	$m_{3/2}$	$m_{\tilde{f}}$	$m_{\tilde{\chi}^0}$ (LSP)	$D_{(X)}$	N_*	n_s	r	Origin
1	10^5	10^5	10^5	10^3	1	54	**0.965**	**0.0034**	Th
2	10^7	10^6	10^6	10^3	$10^2\vert_{\rm min}$	$52\vert_{\rm max}$	**0.964**$\vert_{\rm max}$	**0.0036**$\vert_{\rm min}$	Non-th
3	10^9	10^8	10^8	10^3	$10^2\vert_{\rm min}$	$52\vert_{\rm max}$	**0.964**$\vert_{\rm max}$	**0.0036**$\vert_{\rm min}$	Th
4	10^8	10^7	10^7	10^5	$10^8\vert_{\rm min}$	$48\vert_{\rm max}$	**0.961**$\vert_{\rm max}$	**0.0042**$\vert_{\rm min}$	Non-th

The n_s and r prediction for neutralino LSP and anomaly/gravity mediation scheme for the R^2 supergravity model. In the case $\#$ 2 the neutralino annihilate after the decay of gravitinos, while in case $\#$ 3 neutralinos acquire a thermal abundance. In the case $\#$ 4 the neutralinos from the gravitino decay are overabundant and a diluter X is required. The case $\#$ 1 is the standard thermal WIMP scenario. The masses are in GeV units.



Constraints on the (n_s, r) contour plane from Planck-2015 in the pink, and the schematic illustration of 2σ forecast constraints from a future CMB probe with sensitivity $\delta n_s \sim 10^{-3}$ and $\delta r \sim 10^{-3}$ depicted with the dotted and dashed ellipsis.

Outline



This graph demonstrates the analysis presented in this talk to probe BSM scenarios via the CMB precision measurements.

Outlook and conclusions

Experimental difficulties

The colliders, the classical strategy for the BSM searches, seem to be unable to probe ultra-TeV energy scales with the current technology and budget. Therefore, BSM physics may remain in darkness unless an (unexpected) LHC signal appears.

Cosmological Observations

There are significant prospects for the current and future CMB probes to constrain the n_s and r values with high enough precision.

BSM physics and the Cosmic Expansion History

A unified description of the early universe cosmic evolution yields improved CMB predictions and BSM scenarios can be tested

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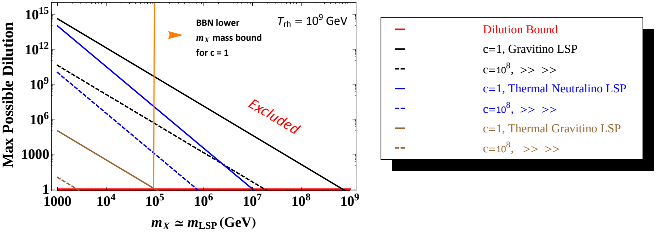
THANK YOU!

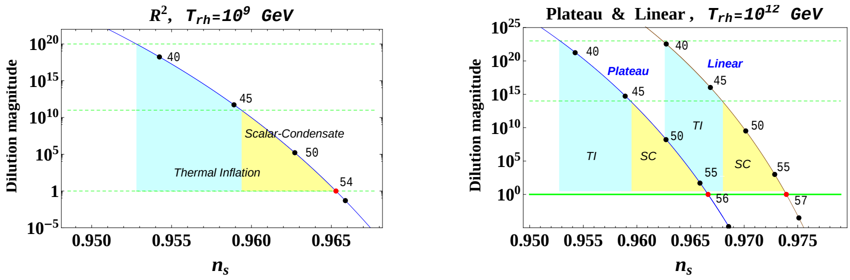
The maximum possible dilution due to a scalar condensate



- The X domination, either due to its nearly constant potential energy or due to the energy stored in its oscillations about the vacuum, dilutes the LSP abundance D_X times and supplements it with the contribution from the diluter decay

$$\Omega^{<}_{\rm LSP} \to \frac{\Omega^{<}_{\rm LSP}}{D_X} + \Omega^{X}_{\rm LSP} \equiv \Omega_{\rm LSP} \,,$$

The shift in the spectral index value and the dilution magnitude



The shift in the n_s and the D_X due to scalar condensate domination (SC) and due to thermal inflation (TI) for the Starobinsky R^2 inflation (left panel), general plateau and linear inflationary potentials (right panel).