Supersymmetry and the CMB observables

Ioannis Dalianis

National Technical University of Athens

Based on a work [in progress] in collaboration with
F. Farakos (U.Padua) and Y. Watanabe (U. Tokyo & Gunma Tech)

Motivation and Outline

Supersymmetry...

is one of the most compelling and influential BSM theories

Motivation and Outline

Supersymmetry...

is one of the most compelling and influential BSM theories

Experiments

Until today no evidence of supersymmetry has been discovered

Motivation and Outline

Supersymmetry...

is one of the most compelling and influential BSM theories

Experiments

Until today no evidence of supersymmetry has been discovered

SUSY Energy Scale

LHC disfavours EW scale supersymmetry only

Motivation and Outline

Supersymmetry...

is one of the most compelling and influential BSM theories

Experiments

Until today no evidence of supersymmetry has been discovered

SUSY Energy Scale

LHC disfavours EW scale supersymmetry only

Predictions

*SUSY predicts stable particles that contribute to the **dark matter** and **scalars***

Motivation and Outline

Supersymmetry...

is one of the most compelling and influential BSM theories

Experiments

Until today no evidence of supersymmetry has been discovered

SUSY Energy Scale

LHC disfavours EW scale supersymmetry only

Predictions

*SUSY predicts stable particles that contribute to the **dark matter** and **scalars***

Cosmological Implications

Ultra TeV scale SUSY generally implies a "complicated" cosmology

Motivation and Outline

Supersymmetry...
is one of the most compelling and influential BSM theories

Experiments
Until today no evidence of supersymmetry has been discovered

SUSY Energy Scale
LHC disfavours EW scale supersymmetry only

Predictions
*SUSY predicts stable particles that contribute to the **dark matter** and **scalars***

Cosmological Implications
Ultra TeV scale SUSY generally implies a "complicated" cosmology

CMB
Can provide us with information about the evolution of the very early universe

In which energy scale is SUSY realized?

Natural SUSY ?

LHC, Direct detection[1] : No

A classification of scenarios.[2]

Quasi-Natural SUSY

SUSY particles close to the EW scale, about 1-30 TeV

Split Scale SUSY

The scalar sparticles are much heavier than gauginos and higgsinos [3]

High Scale SUSY

The sparticles have masses around a common scale $\tilde{m}$

---

[1] Badziak, Olechowski,Szczerbiak 2017

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

[3] 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:

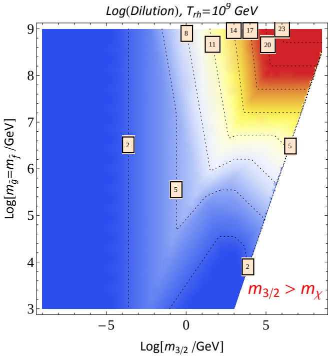
Neutralino Dark matter

$$\Omega_{\tilde{\chi}}^{(\mathrm{th})} h^2 \sim 0.1 \left(\frac{m_{\tilde{\chi}}}{\mathrm{TeV}}\right)^2 \left(\frac{10^{-3}}{c}\right) \left(\frac{x_f}{28}\right)$$

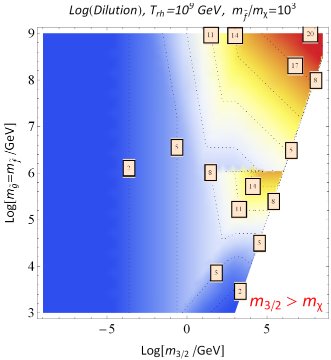
Gravitino Dark matter

$$\Omega_{3/2} h^2 \sim 0.1 \left(\frac{m_{3/2}}{\mathrm{TeV}}\right) \left[1 + \left(\frac{m_{\tilde{g}_3}^2}{3 m_{3/2}^2}\right)\right] \left(\frac{T_{\mathrm{rh}}}{10^{10}\mathrm{GeV}}\right)$$

"Unnatural" SUSY, Gravitino DM and viable cosmology



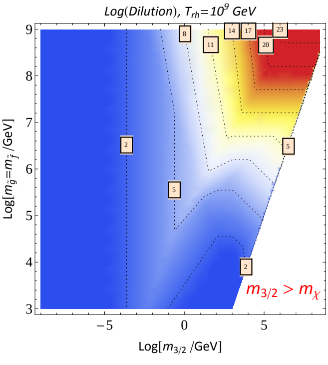
(a)

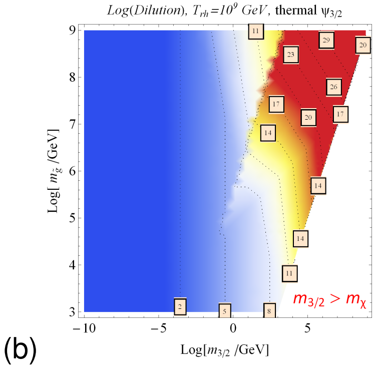


(b)

(Density)-contour plot of the required dilution for reheating temperature after inflation $T_{rh} = 10^9$ *GeV and gravitno the stable LSP. Thermal production of helicity* $\pm 3/2$ *gravitinos from scatterings in the plasma, thermal production of helicity* $\pm 1/2$ *gravitinos from MSSM scatterings, non-thermal production from decays of sfermions and of the NLSP to helicity* $\pm 1/2$ *gravitinos have been taken into account. The contributions to the gravitino abundance have been conditionally added, i.e. in the parts of the contour that thermal equilibrium is achieved the total abundance is replaced by the thermal one.*

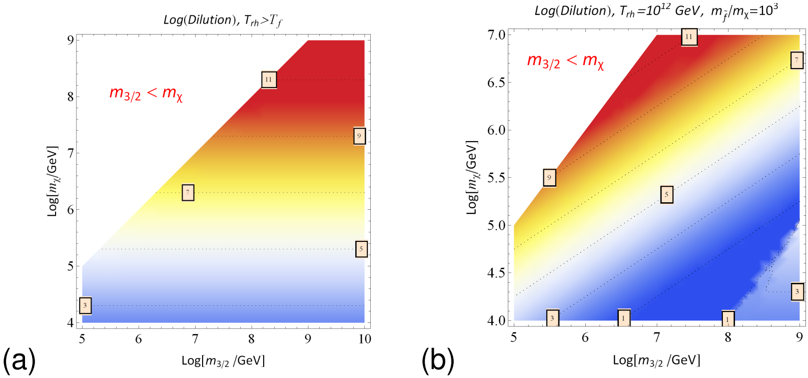
"Unnatural" SUSY, Gravitino DM and viable cosmology





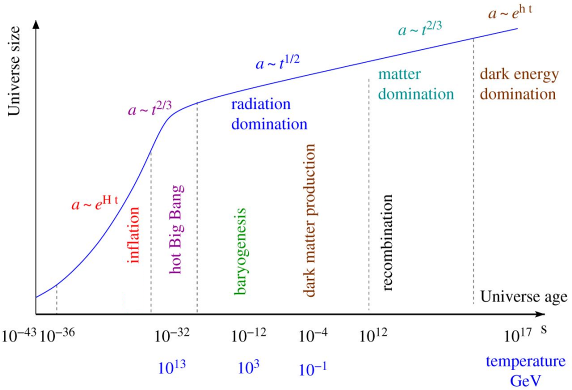
(Density)-contour plot of the required dilution for reheating temperature after inflation $T_{rh} = 10^9$ GeV and gravitno the stable LSP. Thermal production of helicity $\pm 3/2$ gravitinos from scatterings in the plasma, thermal production of helicity $\pm 1/2$ gravitinos from MSSM scatterings, non-thermal production from decays of sfermions and of the NLSP to helicity $\pm 1/2$ gravitinos have been taken into account. The contributions to the gravitino abundance have been conditionally added, i.e. in the parts of the contour that thermal equilibrium is achieved the total abundance is replaced by the thermal one.
Right: Thermal gravitinos due to thermalized messengers (Dalianis 2013).

"Unnatural" SUSY, Neutralino DM and viable cosmology



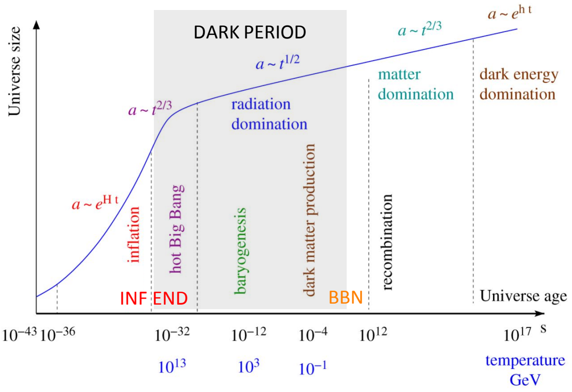
Left: Thermal neutralinos. Right: The neutralinos are produced from the decays of gravitinos (no-annihilation scenario). The gravitinos, that source the neutralino population via their decay, are produced both from thermal scatterings in the plasma and from sfermion decays (when $m_{\tilde{f}} > m_{3/2}$).

The expansion history of the Universe



Schematic evolution of the size of the Universe with respect to the temperature. The key stages are depicted.

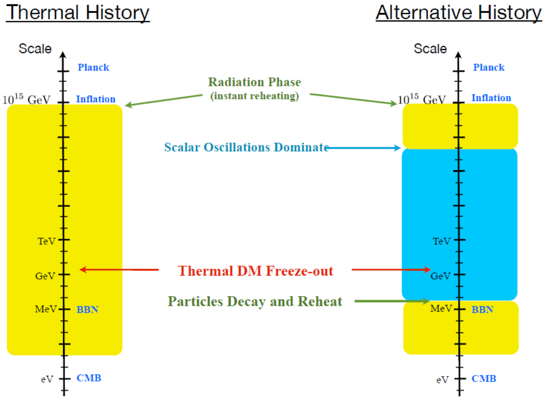
The expansion history of the Universe



Schematic evolution of the size of the Universe with respect to the temperature. The key stages are depicted.

Expansion history effects

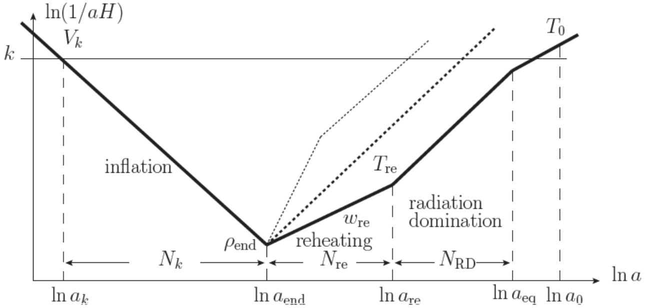
A non-thermal history scenario where a scalar field dominates the energy density of the universe. The low entropy production dilutes the DM relic abundance. (Figure[4])



[4] Easther, Galvez, Oszoy, Watson 2013

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]



[5] Liddle, Leach 2003

Quantifying the effects of the **dark period**

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

$$N_{\rm dark} \equiv \ln\left(\frac{a_{\rm BBN}}{a_{\rm end}}\right) \equiv \frac{1}{3(1+\bar{w}_{\rm dark})} \ln \frac{\rho_{\rm end}}{\rho_{\rm BBN}}$$

- The number of efolds before the end of inflation

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

or

$$N_* \approx 60.8 + \frac{1}{4}\ln\epsilon_* + \frac{1}{4}\ln\frac{V_*}{\rho_{\rm end}} - \Delta N_{\rm dark}\,,$$

where

$$\Delta N_{\rm dark} \equiv \frac{1-3\bar{w}_{\rm dark}}{4} N_{\rm dark} = \Delta N_{\rm rh} + \Delta N_X + \Delta N_{\rm th}$$

- The scalar spectral index

$$n_s(k_*) = 1 - \frac{\alpha}{N_*}\,, \qquad N_* = N^{(0)} - \Delta N_X$$

Dilution and the spectral index value n_s

- Dilution due to scalar oscillation

$$D_X = 1 + \frac{g_s(T_X^{\rm dec})}{g_*(T_X^{\rm dec})}\frac{g_*(T_X^{\rm dom})}{g_s(T_X^{\rm dom})}\frac{T_X^{\rm dom}}{T_X^{\rm dec}} \simeq \frac{T_X^{\rm dom}}{T_X^{\rm dec}} \geq 1$$

- The change of efolds

$$\Delta N_X = \frac{1}{3}\ln\left[\left(\frac{g_*(T_X^{\rm dom})}{g_*(T_X^{\rm dec})}\right)^{1/4} D_X\right] \equiv \frac{1}{3}\ln\tilde{D}_X\,.$$

- Thermal inflation

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

- The change of efolds

$$\Delta N_X|_{\rm FD} = \ln\left[\frac{g_*^{1/4}(T_1)}{g_*^{1/4}(T_2)}\frac{T_1}{T_2}\right] + \frac{1}{3}\ln\left[\frac{g_*^{1/4}(T_1)}{g_*^{1/4}(T_X^{\rm dec})}\frac{T_1}{T_X^{\rm dec}}\right] \equiv \frac{1}{3}\ln\tilde{D}_X^{\rm FD}$$

- The shift of the spectral index

$$\Delta n_s = -\frac{1-n_s^{(0)}}{3N^{(0)}}\ln\tilde{D}_X\left[1 + \frac{1-n_s^{(0)}}{3\alpha}\ln\tilde{D}_X + \left(\frac{1-n_s^{(0)}}{3\alpha}\ln\tilde{D}_X\right)^2\right]$$

The methodology for the estimation of the Δn_s

- We consider a specific reheating temperature motivated by particular inflationary models

[6] Dalianis, Farakos 2017

The methodology for the estimation of the Δn_s

- We consider a specific reheating temperature motivated by particular inflationary models
- We compute the amount of the **minimum *required*** dilution for
  1. different SUSY dark matter scenarios and
  2. different SUSY breaking schemes
  3. different dark matter production mechanisms[6]

  focusing only on the MSSM (*model independent predictions*)

[6] Dalianis, Farakos 2017

The methodology for the estimation of the Δn_s

- We consider a specific reheating temperature motivated by particular inflationary models
- We compute the amount of the **minimum *required*** dilution for
  1. different SUSY dark matter scenarios and
  2. different SUSY breaking schemes
  3. different dark matter production mechanisms[6]

  focusing only on the MSSM (*model independent predictions*)
- We stay **agnostic** about the X scalar field that dilutes the thermal plasma (it can be a modulus, the saxion, ...)

[6] Dalianis, Farakos 2017

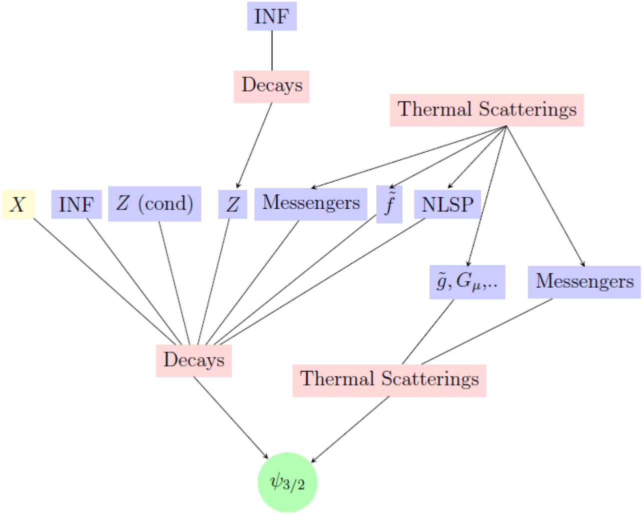
The methodology for the estimation of the Δn_s

- We consider a specific reheating temperature motivated by particular inflationary models
- We compute the amount of the **minimum *required*** dilution for
  1. different SUSY dark matter scenarios and
  2. different SUSY breaking schemes
  3. different dark matter production mechanisms[6]

  focusing only on the MSSM (*model independent predictions*)
- We stay **agnostic** about the X scalar field that dilutes the thermal plasma (it can be a modulus, the saxion, ...)

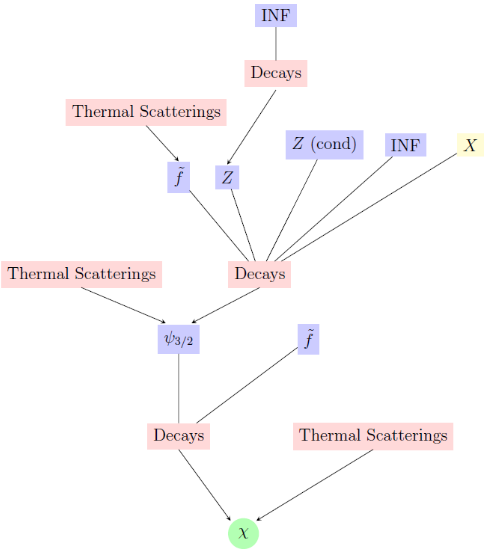
[6] Dalianis, Farakos 2017

Gravitino dark matter



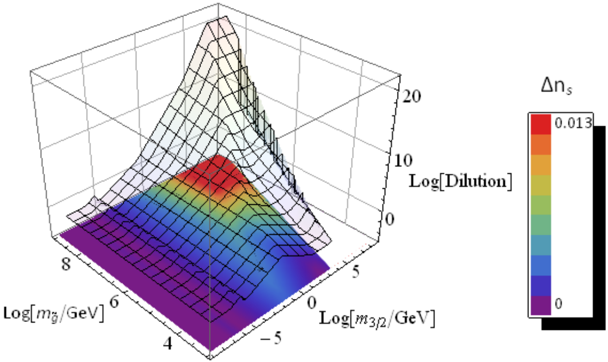
Graphic of the gravitino production chain

Neutralino dark matter



Graphic of the neutralino production chain

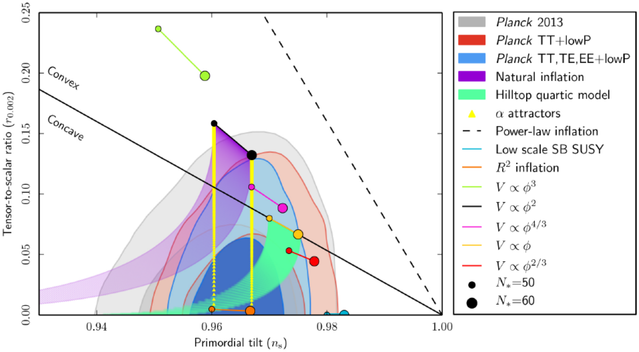
"SUSY effects" on the spectral index



The 3D graph demonstrates the *required* (=minimum) dilution magnitude as a function of the gravitino, which is a Dark Matter particle, and sparticles. **The information that one extracts from this graph is that SUSY models (quasi-natural, split, high scale) can be compatible with the CMB data for particular values for the n_s.**

Inflation: Current Status

Planck constraints on selected inflationary models[7]



[7] Planck collaboration 2015

Starobinsky model of inflation

- Higher curvature gravitation [8]

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

- 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[9]

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

[8] Starobinsky '80, Whitt '84

[9] 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[10]

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

  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[11]

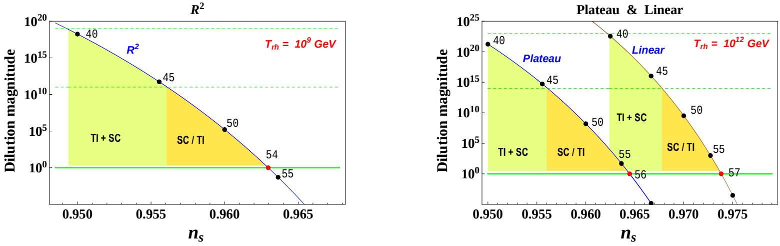
$$T_{\rm rh} \sim 10^9 \mathrm{GeV}$$

---

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

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

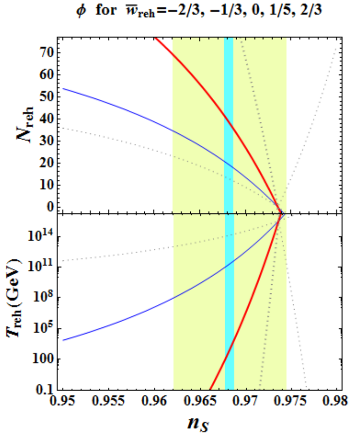
Inflation models and the shift of the spectral index



The shift at the spectral index value and the dilution magnitude due to scalar condensate domination (SC) and/or to thermal inflation (TI) for the Starobinsky R^2 inflation (left panel), and plateau and linear inflationary potentials (right panel).
The maximum number of the dilution is imposed by the ratio T_{rh}/T_{BBN} for scalar condensate domination and the $\Delta N_X|_{TI} \lesssim 10$ constraint for thermal inflation. If there is no entropy production after the decay of the inflaton the e-folds number is expected to be $N_* \simeq 54$ for R^2 inflation and $N_* \simeq 56, 57$ for the plateau and linear potential respectively (red dots).

If the inflaton does not reheat the universe

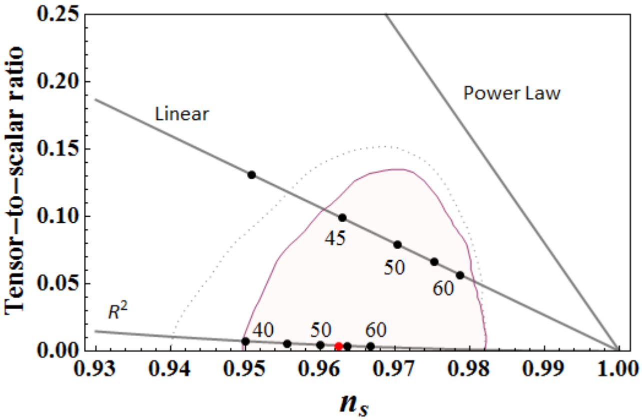
It is possible that the scalar field X dominates the universe before the decay of the inflaton. In such a scenario the production of the dark matter takes place at low temperatures. The measurement of the spectral index is also a measurement of the reheating temperature of the universe[12]



[12] J. Martin, C. Ringeval and V. Vennin 2015

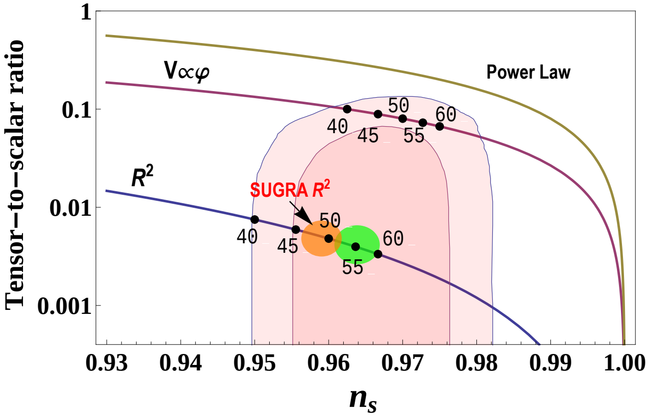
Observational Prospects

Planck VS 4th generation experiments



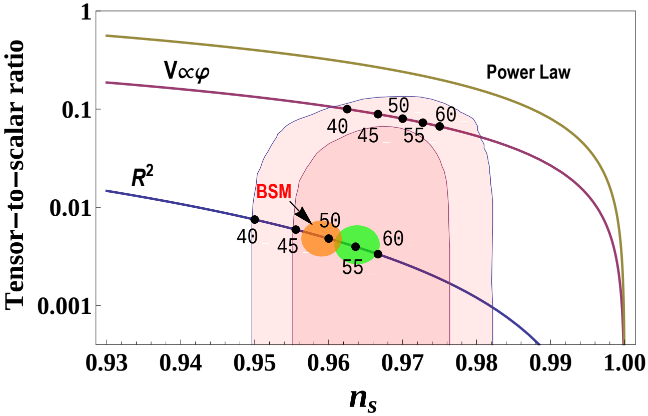
Observational Prospects

Planck VS 4th generation experiments (for a fiducial value $r = 5 \times 10^{-2}$)

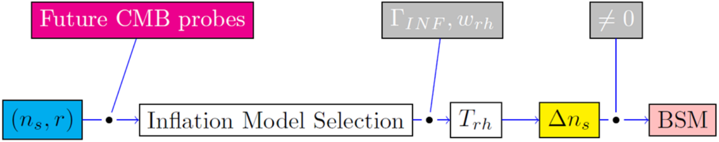


Observational Prospects

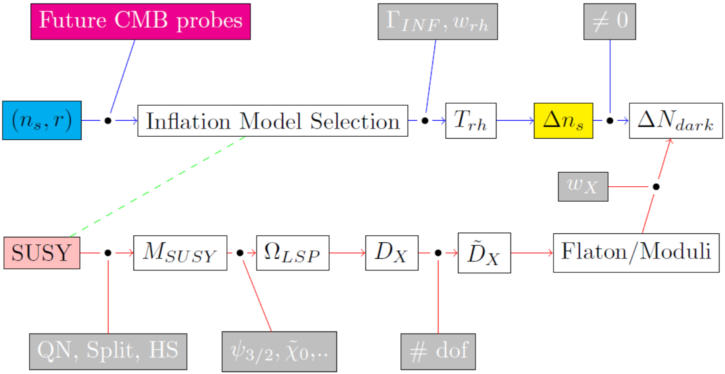
Planck VS 4th generation experiments (for a fiducial value $r = 5 \times 10^{-2}$)



Summary-Outlook



Summary-Outlook



Conclusions

Experimental difficulties

The colliders, the classic 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 of the current and future CMB probes to constrain the n_s and r values with high enough precision.

BSM physics and cosmic evolution

By constraining the uncertainties of the early universe radiation dominated era it is possible to look into the BSM scenarios. Non-trivial information for the BSM physics can be extracted through a combined analysis and minimal assumptions.

Conclusions

Experimental difficulties

The colliders, the classic 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 of the current and future CMB probes to constrain the n_s and r values with high enough precision.

BSM physics and cosmic evolution

By constraining the uncertainties of the early universe radiation dominated era it is possible to look into the BSM scenarios. Non-trivial information for the BSM physics can be extracted through a combined analysis and minimal assumptions.

THANK YOU!