Constraining the MSSM-inflation

CosPT - IJCLab

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11 October 2021

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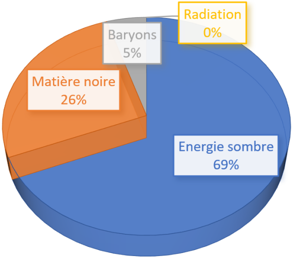
Contents

Contents

Successes and problems of Λ-CDM

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\mathcal{K}}{a^2} + \frac{\Lambda}{3}, \qquad (1)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}, \qquad (2)$$



- Predicts the **temperature history**.
- In Λ-CDM, we include **initial fluctuations**,
  - we describe their **evolution**,
  - we predict with a high accuracy the **CMB** anisotropies and the **structures distribution** visible today.

- What is their **primordial origin** ?

$\Longrightarrow$ **Inflation, accelerated expansion** $\ddot{a} > 0$ with **e-folds number** $N = \ln \frac{a_{end}}{a_{in}} > 50$.

Single scalar field inflation

If **a single fluid** parametrized by $\omega = \frac{P}{\rho}$ dominates during inflation,

- $\ddot{a} > 0$ and $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(1 + 3\omega)\ \rho \implies \omega < -1/3.$
- Single **scalar field** "inflaton" ϕ evolving in a potential $V(\phi)$.

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \tag{3}$$

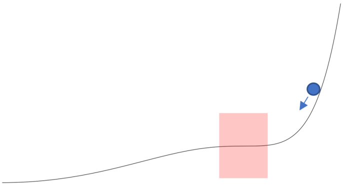
$$P = \frac{1}{2}\dot{\phi}^2 - V(\phi). \tag{4}$$

- **Slow-roll condition** : $\frac{\dot{\phi}^2}{2} \ll V(\phi)$ and $\ddot{\phi} \ll V'(\phi)$,
  $\implies \rho = -P$, so $\omega = -1 < -1/3$,
  $\implies$ **Inflation !**

Single scalar field inflation

- "**de Sitter** universe", ie. dominated by **cosmological constant**.

$\Longrightarrow$ Rewriting the *slow-roll* condition thanks to the **slow-roll parameters**:



$$\epsilon_0 \equiv \frac{H_{in}}{H} = H_{in}\sqrt{\frac{3M_{PL}^2}{V}}, \tag{5}$$

$$\epsilon_1 \equiv \frac{\mathrm{d}\ln|\epsilon_0|}{\mathrm{d}N} = \frac{M_{PL}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \tag{6}$$

$$\epsilon_{n+1} \equiv \frac{\mathrm{d}\ln|\epsilon_n|}{\mathrm{d}N} \ll 1. \tag{7}$$

Cosmological constraints on inflation

We can express the **cosmological observables** describing the primordial perturbations with a first order expansion in the **slow-roll parameters**:

- the *scalar fluctuations amplitude*:

$$A_S = \frac{H^{\star 2}}{8\pi^2 \epsilon_1^\star M_{PL}^2} \in \Lambda CDM, \tag{8}$$

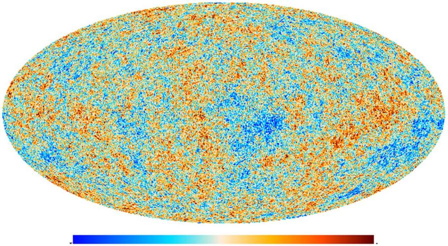
- the scalar *spectral index*,

$$n_S = 1 - 2\epsilon_1^\star - \epsilon_2^\star \in \Lambda CDM, \tag{9}$$

- the *Tensor-to-scalar* ratio,

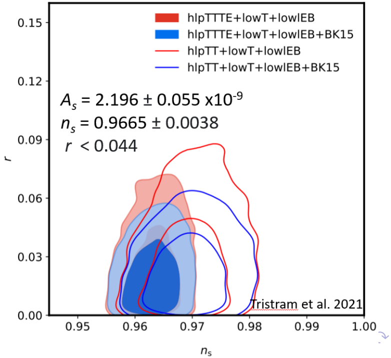
$$r = 16\epsilon_1^\star \tag{10}$$

The Cosmic Microwave Background (CMB)



- CMB : emitted **300000 years after the Big-Bang**.
- **Electrons and photons decouple** and recombine with nuclei.

Below the (n_s, r) constraints by **Planck**.

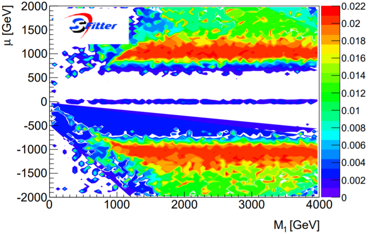


- Perturbations:
  - **Scalar**:
    Leads to plasma **inhomogeneities** and **E modes**. Observed.
  - **Tensor**:
    Gravitational waves leading to **B modes**. Not yet detected.
- **BICEP**: $r < 0.036$ (95% CL)

  [**BICEP/Keck Collaboration** 2021]
- FUTURE: **CMB-S4**, **LiteBIRD**.

Minimal Supersymmetric Model (MSSM)

- **MSSM** is a theory **beyond the HEP SM**.
- MSSM is constrained by the mass and the couplings of the **Higgs boson**, **direct searches** at colliders, direct search for **dark matter** and the measurement of the **relic density** [Henrot-Versillé 2014].
- Some regions are still unconstrained:

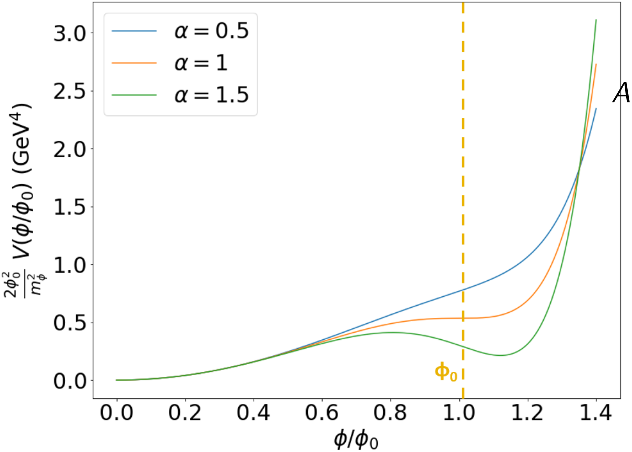


- IDEA: Add the **inflation** into the game. What implications?
- **Two types of scalar fields** combining MSSM sparticles are candidates to have produced an **inflation** :
  - $\phi_{\tilde{L}} = \frac{\tilde{L}+\tilde{L}+\tilde{e}}{\sqrt{3}}$,
  - $\phi_{\tilde{q}} = \frac{\tilde{u}+\tilde{d}+\tilde{d}}{\sqrt{3}}$.

MSSM potential at tree level

The **potential** in which the MSSM inflatons evolve reads

$$V(\phi) \equiv \frac{1}{2} m_\phi^2 \phi^2 - A \frac{\lambda \phi^6}{6 M_p^3} + \lambda^2 \frac{\phi^{10}}{M_p^6}, \tag{11}$$



m_ϕ ϕ **mass**,
A its associated **coupling**,
$V''(\phi_0) = 0$.

slow-roll

$\Longleftrightarrow$

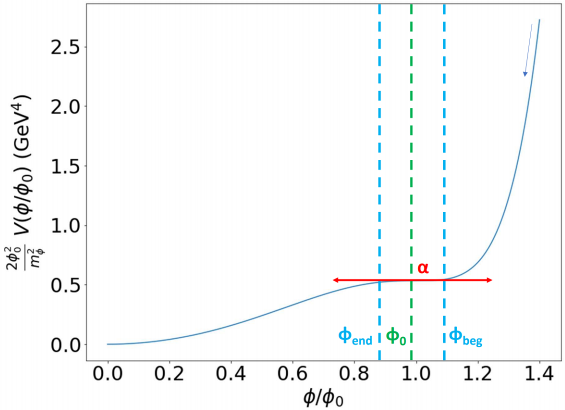
$\alpha \equiv \frac{A^2}{40 m_\phi^2} \simeq 1$

(sharply)

Contents

Problem and methodology

PROBLEM: What is the allowed **parameter space** **(m_ϕ, A, λ) by A_s et n_s** ?



Fix ϕ_0

$\xrightarrow{n_s^{cosmo}} \alpha$

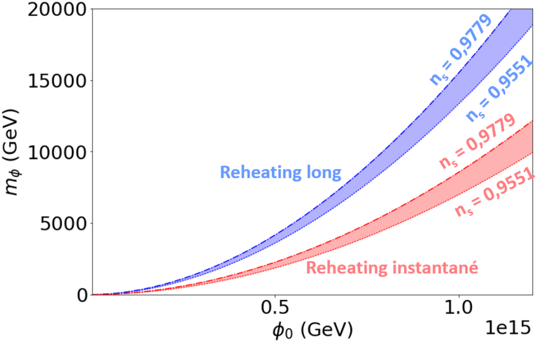
$\xrightarrow{A_s^{cosmo}}$ Norm.

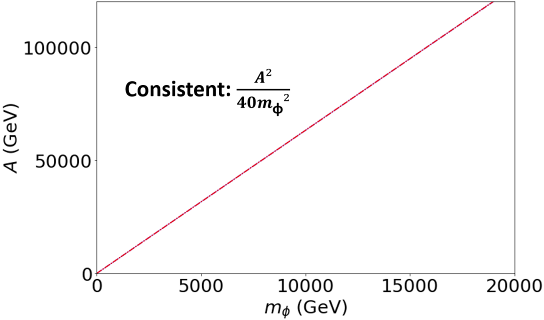
$\rightarrow$ (m_ϕ, A, λ).

Followed first thanks to a **semi-analytical code for inflation**, ASPIC [Martin 2013], to get the **constraints in the planes** (ϕ_0, m_ϕ) and (m_ϕ, A).

(n_s, A_s) constraints with reheating

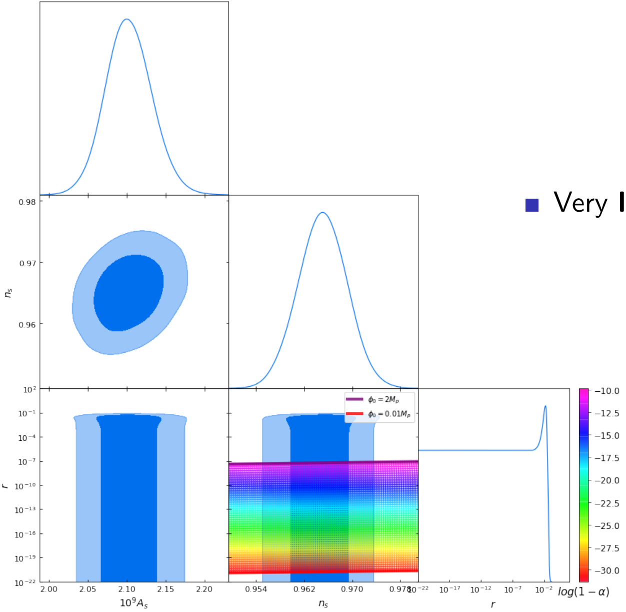
- **News:** **Reheating**.
- In the (ϕ_0, m_ϕ) plane.





- In the (m_ϕ, A) plane.
- These constraints will be included in the **SUSY analysis**.

Constraining the cosmology from MSSM



- Very **low** predicted r.

Renormalization Group Equations for LLe inflaton

ϕ dependency of $(m_\phi,\ A,\ \lambda)$: correction at first order of the **Renormalization Group Equations** (here for $\tilde{L}\tilde{L}\tilde{e}$) :

$$\phi\frac{\mathrm{d}m_\phi^2}{\mathrm{d}\phi} = -\frac{1}{6\pi^2}\left(\frac{3}{2}\tilde{m}_1^2 g_1^2 + \frac{3}{2}\tilde{m}_2^2 g_2^2\right),$$

$$\phi\frac{\mathrm{d}A}{\mathrm{d}\phi} = -\frac{1}{2\pi^2}\left(\frac{3}{2}\tilde{m}_1 g_1^2 + \frac{3}{2}\tilde{m}_2 g_2^2\right),$$

$$\phi\frac{\mathrm{d}\lambda}{\mathrm{d}\phi} = -\frac{1}{4\pi^2}\lambda\left(\frac{3}{2}g_1^2 + \frac{3}{2}g_2^2\right),$$

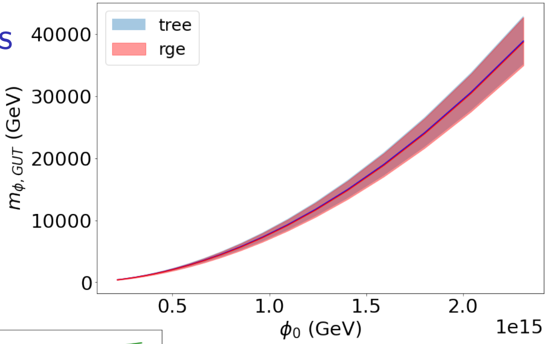
$$\phi\frac{\mathrm{d}g_1}{\mathrm{d}\phi} = \frac{11}{16\pi^2}g_1^3,$$

$$\phi\frac{\mathrm{d}g_2}{\mathrm{d}\phi} = \frac{1}{16\pi^2}g_2^3,$$

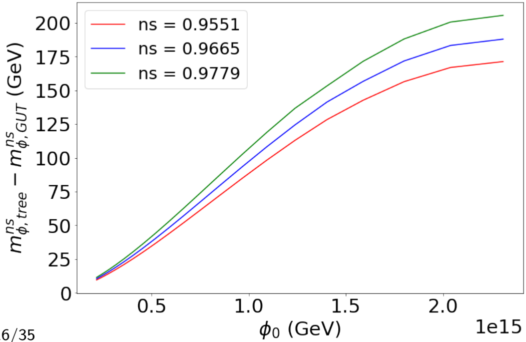
$$\frac{\mathrm{d}}{\mathrm{d}\phi}\left(\frac{\tilde{m}_1}{g_1^2}\right) = \frac{\mathrm{d}}{\mathrm{d}\phi}\left(\frac{\tilde{m}_2}{g_2^2}\right) = 0.$$

- $\tilde{m}_1$ et $\tilde{m}_2$ $U(1)_Y$ **and** $SU(2)_W$ **gauginos masses**,
- g_1 and g_2 associated **gauge couplings**,
- At **GUT** energy of $\phi_{GUT} \simeq 3\times 10^{16}$ GeV, $\tilde{m}_1 = \tilde{m}_2 = m_\phi$, $g_1 = \sqrt{\frac{\pi}{10}}$ et $g_2 = \sqrt{\frac{\pi}{6}}$.

(n_s, A_s) constraints with simple *LLe* RGE's



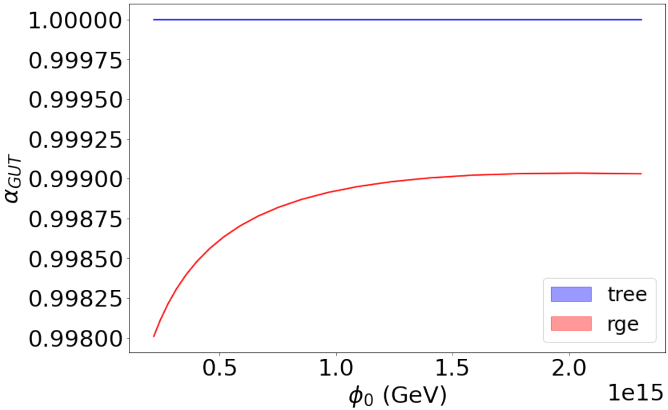
- In the (ϕ_0, m_ϕ) plane.



- Still need to study the **RGE impact** on the SUSY-analysis.

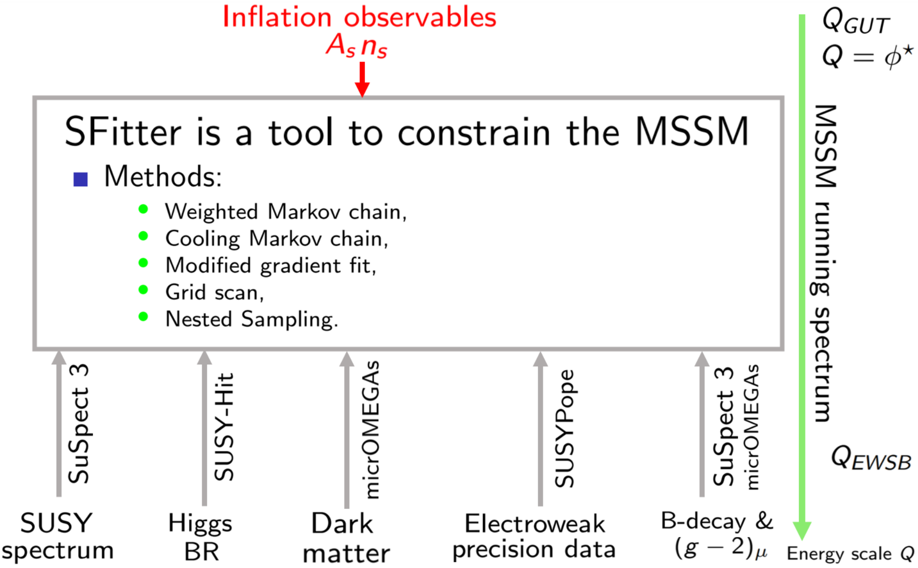
Relaxing the fine-tuning thanks to RGE's

- Compare α_{tree} vs ϕ_0 with α_{GUT} vs ϕ_0:



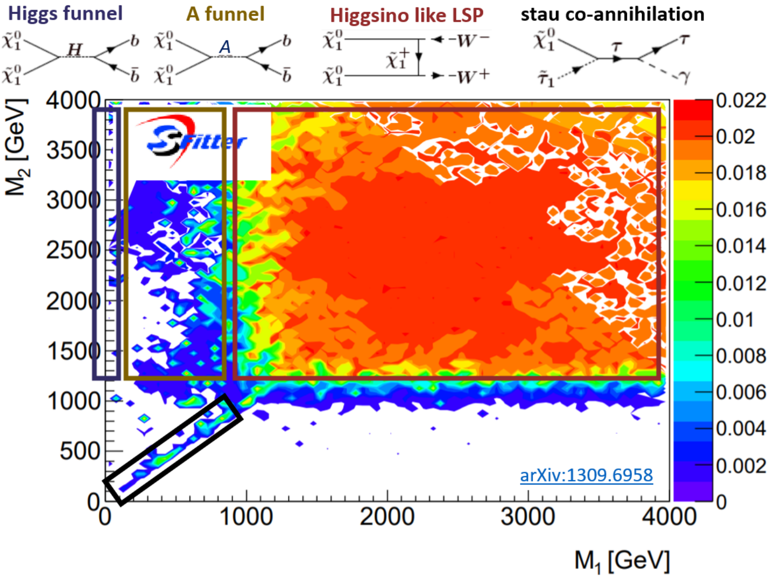
$\Longrightarrow$ Relaxing of the α_{GUT} fine-tuning!

Contents


Inflation observables
$A_s\, n_s$
SFitter is a tool to constrain the MSSM
Methods:
Weighted Markov chain,
Cooling Markov chain,
Modified gradient fit,
Grid scan,
Nested Sampling.
SuSpect 3
SUSY-Hit
micrOMEGAs
SUSYPope
SuSpect 3
micrOMEGAs
SUSY spectrum
Higgs BR
Dark matter
Electroweak precision data
B-decay & $(g-2)_\mu$
Q_{GUT}
$Q = \phi^\star$
MSSM running spectrum
Q_{EWSB}
Energy scale Q

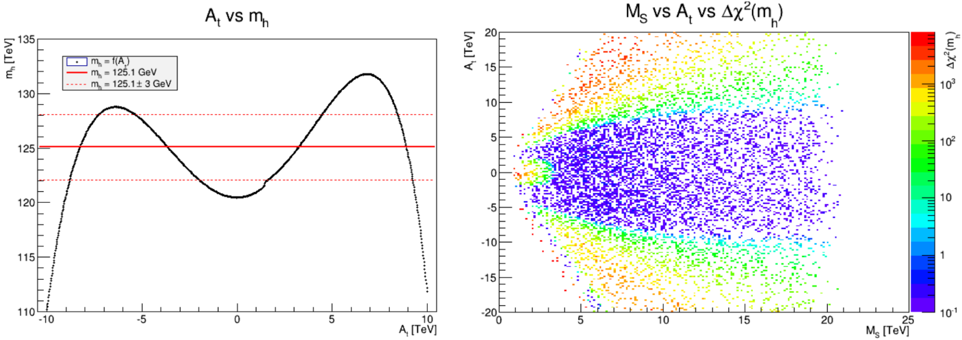
Constraints from a LSP dark matter

Planck: $\Omega_{CDM}h^2 = 0.1187 \pm 0.0017 \pm 0.0120_{th}$.



1) Higgs mass and A_t

- **Loop corrections** depend on A_t and stop masses (among others).
- The measured m_h determines A_t in the fit.

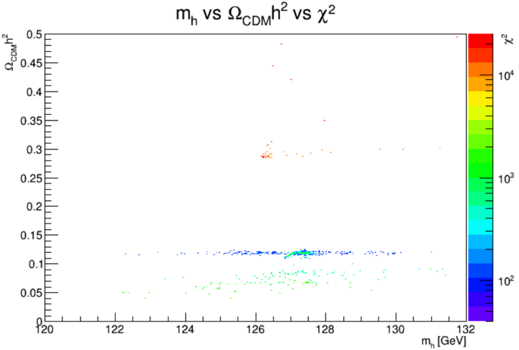


- Large $|At|$ leads to large corrections on the measured m_W

$\Longrightarrow$ 2 of 4 solutions excluded.

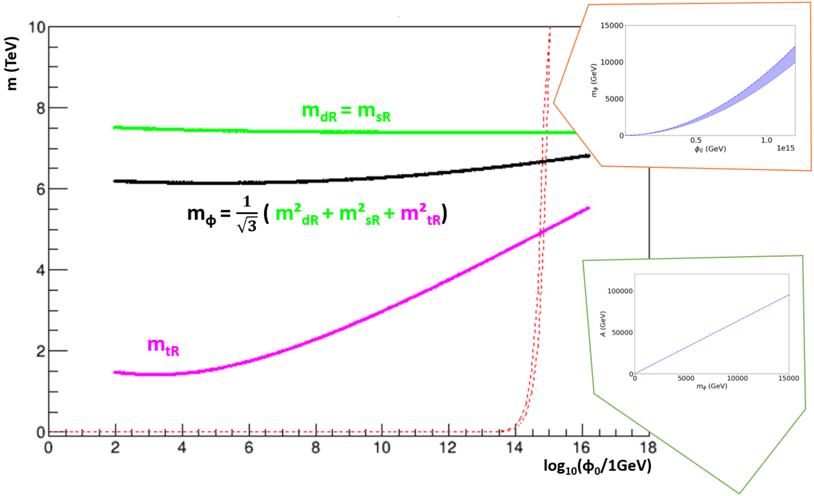
2) Dark matter and M_1 tuning

- Assume **bino-like dark matter** decaying through A-funnel. So $m_A = 2m\chi$.
- M_1 has a **negligible effect** on m_h.
- We can **adjust it** with a gradient method to get $m_A = 2m\chi$.



- We verify that the **selected points** satisfy m_h and Ω_{CDM}.

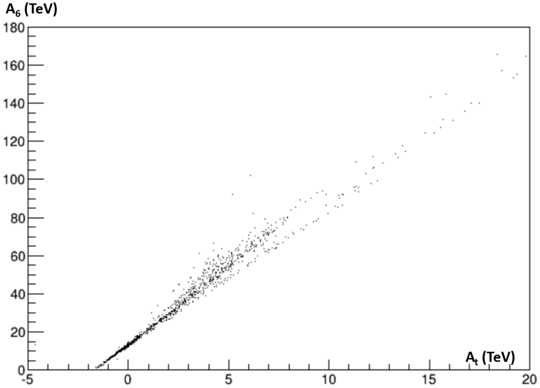
3) $U^3 D^2 D^1$ Inflation constraint, the Wall and $m_{\tilde{q}_{12}}$ tuning



- $\forall m_\phi$, we can find an intersection at $\phi_0 = \mathcal{O}(10^{14})$ GeV.
- Ultimately, we adjust $m_{\tilde{q}_{12}}$ to get the right $\frac{m_\phi(\phi_0)}{A_6(\phi_0)} \simeq 1/\sqrt{40}$.

A_6 constraint on A_t within Polonyi model

- **Inflation** $\Longrightarrow$ $A_6 > 0$,
- **Polonyi model**: $A_{6,GUT} = \frac{6-\sqrt{3}}{3-\sqrt{3}} A_{t,GUT}$.
- After running from GUT to $EWSB$:



$\Longrightarrow$ $A_t(Q_{EWSB}) < -1.5$ TeV are now **excluded**.

Outlook and future work

- Constraints on the MSSM from **inflation so far**
  - **Heavy scalar masses** favored.
  - $U^3D^1D^2$ inflation in the Polonyi model **restricts the parameter space** of A_t.
  - Work in progress!
- Refine the **inflation constraint**
  - Include all **RGE's for other flat directions** *udd* & *LLe*.
  - Include a **non-instantaneous reheating** into the global fit (link it with relics?).
- Write a **paper**.

Thanks!

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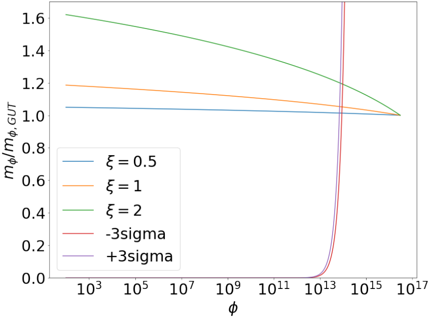
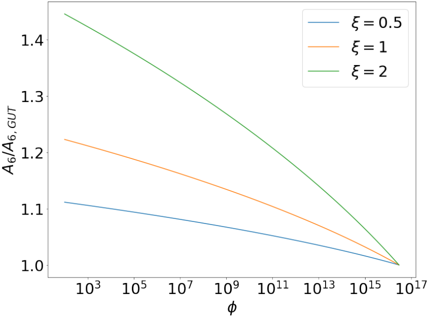
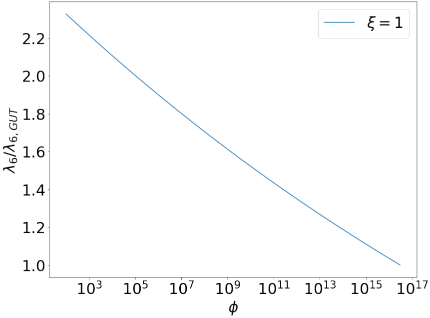
Dépendance en énergie



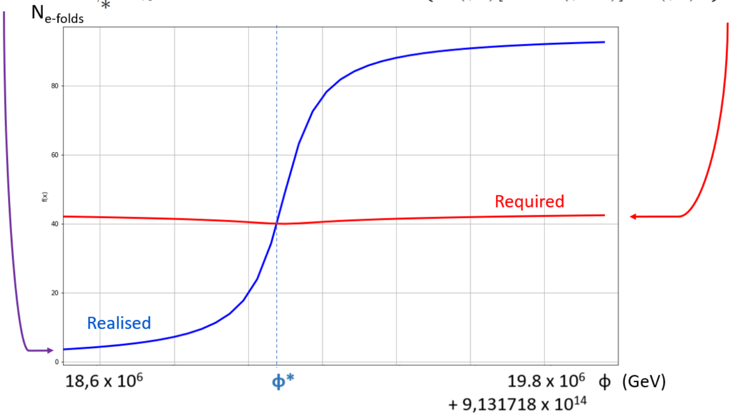




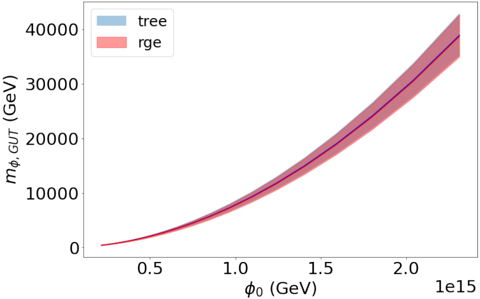
Important step : determination of $\phi\star$

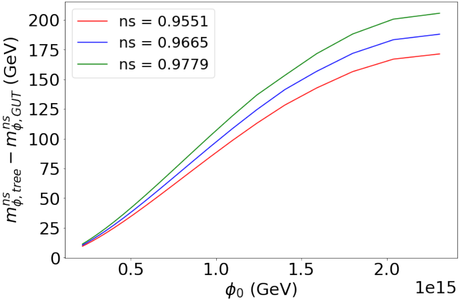
$\phi\star$ is the ϕ such that the perturbation exiting the horizon at this time is a mode $k\star = 0.05$ Mpc^{-1}.

$$N_{\rm end} - N_* = -\frac{1}{M_{\rm Pl}^2}\int_{\phi_*}^{\phi_{\rm end}} \frac{V(\chi)}{V_\chi(\chi)}\,{\rm d}\chi = \ln R_{\rm rad} - N_0 - \frac{1}{4}\ln\left\{\frac{9}{\epsilon_1(\phi_*)[3-\epsilon_1(\phi_{\rm end})]}\frac{V(\phi_{\rm end})}{V(\phi_*)}\right\} + \frac{1}{4}\ln(8\pi^2 P_*)$$



Constraints at one loop





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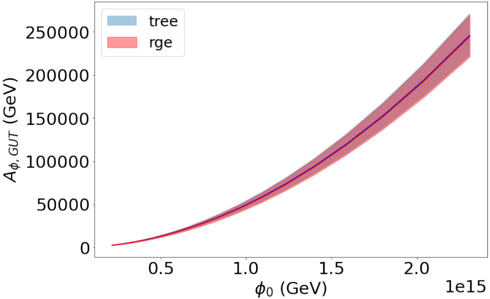
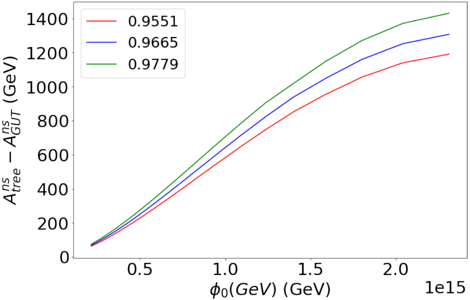
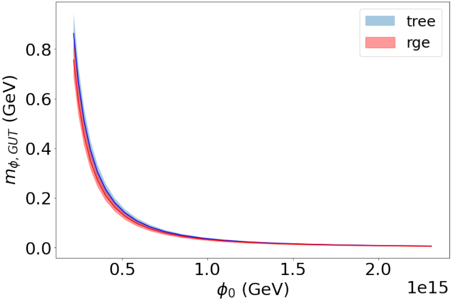
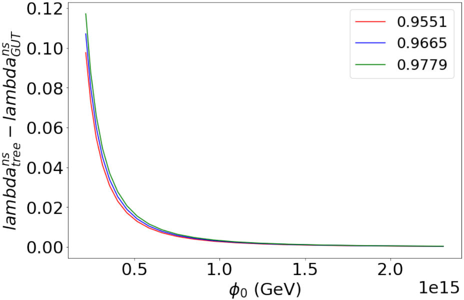


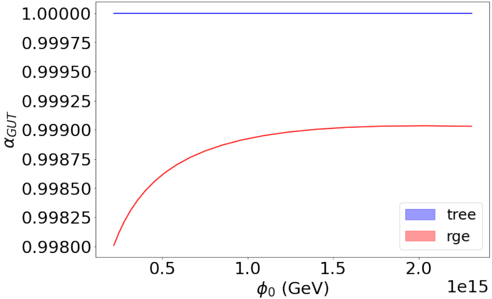


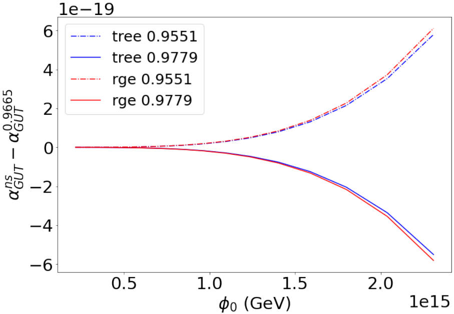
Constraints at one loop





Constraints at one loop





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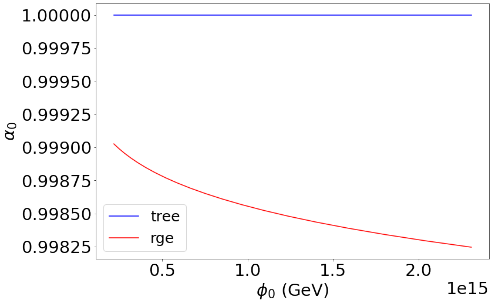
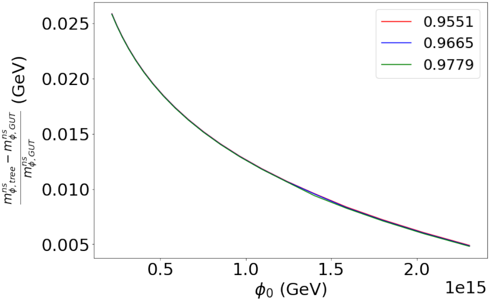


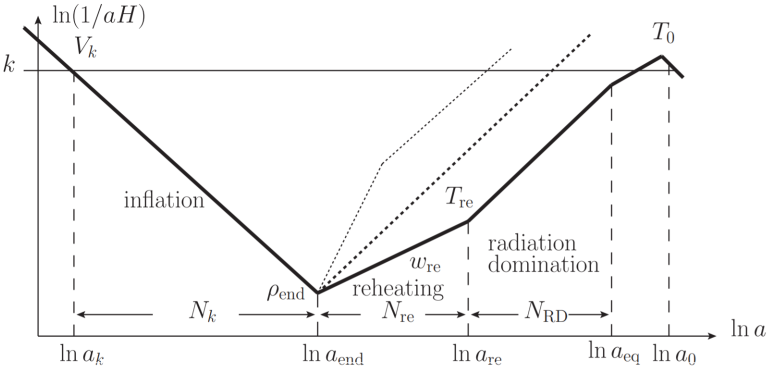


Reheating

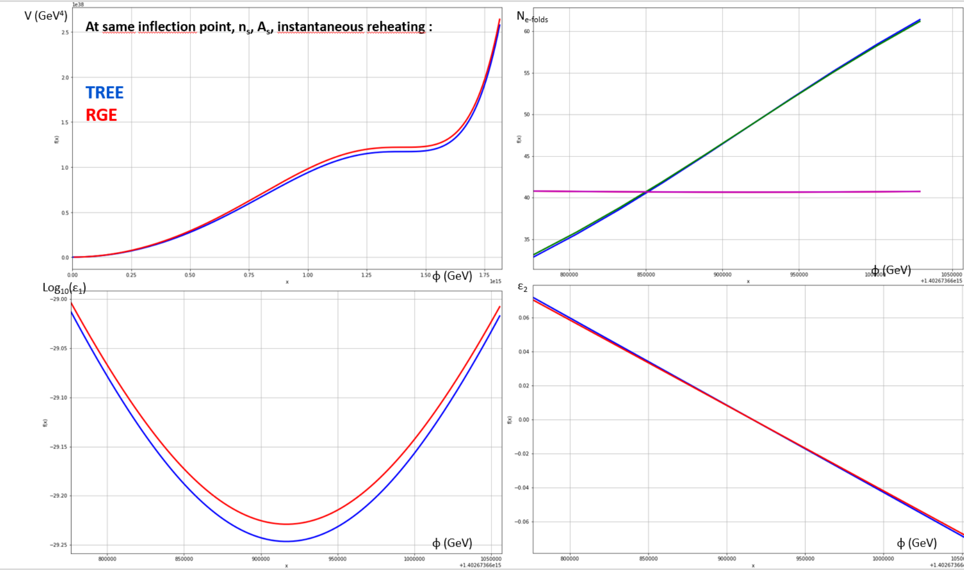
$$-1/3 < \omega_{reh} \equiv \frac{1}{N_{re} - N_{end}} \int_{N_{end}}^{N_{re}} \omega(N)\, \mathrm{d}N < 1 \tag{12}$$

$$\ln \rho_{BBN} < \ln \rho_{reh} < \ln \rho_{end}\,, \tag{13}$$

$$\frac{1}{4} \ln \frac{\rho_{BBN}}{\rho_{end}} < \ln R_{rad} \equiv \frac{1 - 3\omega_{reh}}{12\,(1 + \omega_{reh})} \ln \frac{\rho_{reh}}{\rho_{end}} < -\frac{1}{12} \ln \frac{\rho_{BBN}}{\rho_{end}} \tag{14}$$



$\ln \frac{1}{aH} = \ln \frac{1}{\dot{a}} \propto (1 - \frac{2}{3\,(1+\omega)}) \ln t \propto \frac{1+3\omega}{2} \ln a.$



V (GeV^4)
At same inflection point, n_s, A_s, instantaneous reheating :
TREE
RGE
ϕ (GeV)
$N_{e\text{-folds}}$
ϕ (GeV)
$\text{Log}_{10}(\varepsilon_1)$
ϕ (GeV)
ε_2
ϕ (GeV)