

Inflating the MSSM...work in progress

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APC, IJCLab, ITP, L2C &... DMLab 😊

(Gilbert Moutaka)

CosPT meeting, IJCLab, May 10, 2022

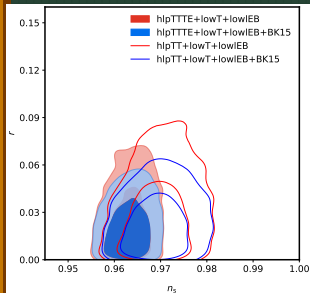


Outline

- Introductory motivations
- SUSY flat directions
- The saddle point MSSM-Inflation model
- The Effective Potential & RGEs
- Towards the CMB constraints
- Implementation in SUSPECT3
- Conclusion

Is there a relation between...?





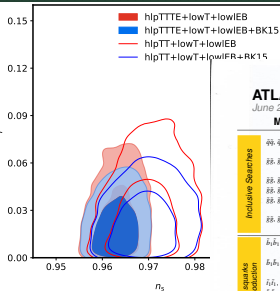
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Is there a relation between...?

M. Tristram *et al*, A&A 647, A128 (2021)

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Is there a relation between...?



ATLAS SUSY Searches* - 95% CL Lower Limits

June 2021

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{g}\tilde{g}^0$	0 ϵ, μ 2-6 jets $E_{T,miss}^{min}$	139 \tilde{g} [1% Br Dipole] 1.0 1.85 $m(\tilde{t}_1^0) < 400$ GeV
	mono-jet	1-3 jets $E_{T,miss}^{min}$	36.1 \tilde{g} [3% Dipole] 0.9 $m(\tilde{g}) < 600$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{g}^0$	0 ϵ, μ 2-6 jets $E_{T,miss}^{min}$	139 \tilde{g} $m(\tilde{t}_1^0) < 0$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	1 ϵ, μ 2-6 jets	139 \tilde{g} Forbidden 1.15-1.95 2.3 $m(\tilde{t}_1^0) < 1000$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	1 ϵ, μ 2-6 jets	139 \tilde{g} 2.2 $m(\tilde{t}_1^0) < 400$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	2 jets $E_{T,miss}^{min}$	36.1 \tilde{g} 1.2 $m(\tilde{t}_1^0) < 50$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	0 ϵ, μ 7-11 jets $E_{T,miss}^{min}$	139 \tilde{g} 1.97 $m(\tilde{t}_1^0) < 600$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	SS ϵ, μ 6 jets	139 \tilde{g} 1.15 $m(\tilde{g}) < 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	0 ϵ, μ 6 jets $E_{T,miss}^{min}$	139 \tilde{g} 1.25 2.25 $m(\tilde{t}_1^0) < 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{W}\tilde{Z}^0$	0 ϵ, μ 6 jets $E_{T,miss}^{min}$	139 \tilde{g} 1.25 2.25 $m(\tilde{t}_1^0) < 400$ GeV
3 γ jets, squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 ϵ, μ 2b $E_{T,miss}^{min}$	139 \tilde{b}_1 0.68 1.255 $m(\tilde{t}_1^0) < 400$ GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{t}_1^0$	0 ϵ, μ 6b $E_{T,miss}^{min}$	139 \tilde{b}_1 Forbidden 0.13-0.85 0.23-1.55 $m(\tilde{t}_1^0) < 100$ GeV
	2τ	2b $E_{T,miss}^{min}$	139 \tilde{b}_1 10 GeV $< m(\tilde{b}_1) < 130$ GeV, $m(\tilde{t}_1^0) < 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{b}\tilde{t}_1^0$	0-1 ϵ, μ ≥ 1 jet $E_{T,miss}^{min}$	139 \tilde{t}_1 1.25 $m(\tilde{t}_1^0) < 1$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow W\tilde{b}\tilde{t}_1^0$	1 ϵ, μ 3 jets+1 b $E_{T,miss}^{min}$	139 \tilde{t}_1 Forbidden 0.65 $m(\tilde{t}_1^0) < 400$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tau\tilde{b}\tilde{t}_1^0$	1-2 τ 2 jets+1 b $E_{T,miss}^{min}$	139 \tilde{t}_1 Forbidden 1.4 $m(\tilde{t}_1^0) < 800$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1$	0 ϵ, μ 2 mono-jet $E_{T,miss}^{min}$	36.1 \tilde{t}_1 0.85 $m(\tilde{t}_1^0) < 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1$	0 ϵ, μ mono-jet $E_{T,miss}^{min}$	139 \tilde{t}_1 0.55 $m(\tilde{t}_1^0) < 100$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1$	1-2 ϵ, μ 1-4 b $E_{T,miss}^{min}$	139 \tilde{t}_1 0.067-1.18 $m(\tilde{t}_1^0) < 400$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{t}_1\tilde{t}_1$	3 ϵ, μ 1b $E_{T,miss}^{min}$	139 \tilde{t}_1 Forbidden 0.86 $m(\tilde{t}_1^0) < 360$ GeV, $m(\tilde{t}_1^0) < 40$ GeV
EW direct	$\tilde{t}_1^0\tilde{t}_1^0$ via WZ	Multiple ℓ jets ϵ, μ, τ ≥ 1 jet $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.205 0.96 $m(\tilde{t}_1^0) < 0$, wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via WW	2 ϵ, μ $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.42 $m(\tilde{t}_1^0) < 70$ GeV, wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via Wb	Multiple ℓ jets $E_{T,miss}^{min}$	139 \tilde{t}_1^0 Forbidden 1.06 $m(\tilde{t}_1^0) < 70$ GeV, wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	2 ϵ, μ $E_{T,miss}^{min}$	139 \tilde{t}_1^0 1.0 $m(\tilde{t}_1^0) < 0.5(m(\tilde{t}_1^0) + m(\tilde{t}_1^0))$
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	2 τ $E_{T,miss}^{min}$	139 \tilde{t}_1^0 [P, P, L] 0.16-0.3 0.12-0.39 $m(\tilde{t}_1^0) < 0$
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	2 ϵ, μ 0 jets $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.7 $m(\tilde{t}_1^0) < 0$
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	ϵ, μ, τ ≥ 1 jet $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.256 0.7 $m(\tilde{t}_1^0) < 150$ GeV
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	0 ϵ, μ ≥ 3 b $E_{T,miss}^{min}$	36.1 \tilde{t}_1^0 0.13-0.23 0.29-0.88 $BR(\tilde{t}_1^0 \rightarrow b\tilde{t}_1^0) < 1$
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	4 ϵ, μ 0 jets $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.55 0.29-0.88 $BR(\tilde{t}_1^0 \rightarrow Z\tilde{t}_1^0) < 1$
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	0 ϵ, μ ≥ 2 large jets $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.45-0.93 $BR(\tilde{t}_1^0 \rightarrow Z\tilde{t}_1^0) < 1$
Long-lived particles	Direct $\tilde{t}_1^0\tilde{t}_1^0$ prod., long-lived \tilde{t}_1^0	Disapp. brik 1 jet $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.21 0.66 Pure Wino Pure Higgsino
	Stable \tilde{g} R-hadron	Multiple	36.1 \tilde{g} 2.0 $m(\tilde{t}_1^0) < 100$ GeV
	Metastable \tilde{g} R-hadron, $\tilde{g}\tilde{g}\tilde{g}^0$	Multiple	36.1 \tilde{g} (if $\tau > 10$ ns, 0.2 ns) 2.05 2.4 $m(\tilde{t}_1^0) < 100$ GeV
RPV	$\tilde{t}_1^0\tilde{t}_1^0$ via $Z\tilde{t}_1\tilde{t}_1$	3 ϵ, μ $E_{T,miss}^{min}$	139 \tilde{t}_1^0 1.05 1.05 Pure Wino
	$\tilde{t}_1^0\tilde{t}_1^0$ via $W\tilde{Z}\tilde{t}_1\tilde{t}_1$	0 jets $E_{T,miss}^{min}$	139 \tilde{t}_1^0 0.96 1.55 $m(\tilde{t}_1^0) < 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{g}^0$	4-5 large jets	36.1 \tilde{g} [if $\tau > 200$ GeV, 1100 GeV] 1.3 1.9 $m(\tilde{t}_1^0) < 200$ GeV, Large \tilde{t}_1^0
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{g}^0$	Multiple	36.1 \tilde{g} 0.55 1.05 $m(\tilde{t}_1^0) < 200$ GeV, bino- \tilde{g}
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}\tilde{g}^0$	$\geq 4b$	139 \tilde{g} Forbidden 0.95 $m(\tilde{t}_1^0) < 400$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{b}$	2 jets + 2b	36.7 \tilde{t}_1 [if $\tau > 1$ ns] 0.42 0.61 $BR(\tilde{t}_1 \rightarrow b\tilde{t}_1) < 20\%$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{b}$	2b	36.1 \tilde{t}_1 1.0 1.6 $BR(\tilde{t}_1 \rightarrow b\tilde{t}_1) < 100\%$, $cos\theta < 1$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{b}$	1 μ DV	136 \tilde{t}_1 0.2-0.32 Pure Higgsino
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{b}$	1-2 ϵ, μ ≥ 6 jets	139 \tilde{t}_1 1.0 1.6 Pure Higgsino

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

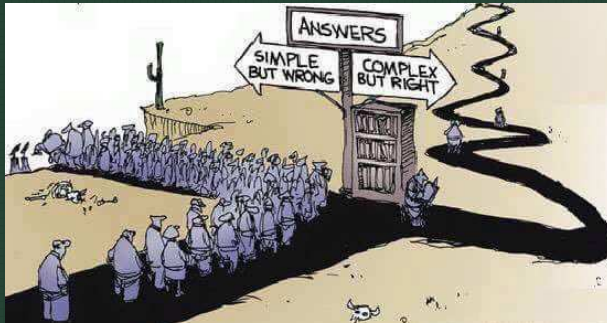
M. Tristram et al, A&A 647

and this →

Introductory motivations

Where is –Is there– (TeV) New Physics ??

message from (the) BSM at the LHC (?)



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- In its (next-to-)minimal versions, (N)MSSM, possible relations between constraints from inflation (prediction of the scalar spectral index, the power spectrum normalization, etc.), and constraints from particle physics searches ?
- SUSY DM candidates still viable, even for (relatively) light LSP, despite direct / indirect search limits and LHC constraints.



SUSY flat directions



SUSY flat directions

$$V_{susy} = \sum_k |F_{\phi_k}|^2 + \frac{1}{2} \sum_A g_A^2 \vec{D}^A \cdot \vec{D}^A$$

$$F_{\phi_k} := \frac{\partial W}{\partial \phi_k}, \quad \vec{D}^A := \Phi^\dagger \vec{T}^A \Phi, \quad (\Phi \text{ multiplet of } \phi_k \text{'s})$$

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→ in the space of 49 complex scalar fields ϕ_k (squarks, sleptons, Higgses).

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→ The (R_p -conserving) MSSM potential has $\mathcal{O}(300)$ flat directions!

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BUT...

SUSY flat directions

a flat direction:

- has to be lifted...
- and by not too much → slow-roll/enough e-folding to fit observations

→ three main lifting sources:

- renormalizable superpotential (MSSM)
- soft SUSY breaking masses (MSSM)
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e.g. → LLe or udd flat directions lifted by

$$W^{LLe} = \frac{\lambda}{M_p^3} (LLe)(LLe) \text{ resp. } W^{udd} = \frac{\lambda}{M_p^3} (udd)(udd)$$

SUSY flat directions

- $\epsilon_{\alpha\beta} L_i^\alpha L_j^\beta e_k$ [$SU(3)_c \times SU(2) \times U(1)_Y$ gauge inv.] \rightarrow 'LLe' D-flat direction

$$L_i = \begin{pmatrix} \varphi \\ 0 \end{pmatrix}, L_j = \begin{pmatrix} 0 \\ \varphi \end{pmatrix}, e_k = \varphi, \varphi \text{ complex-valued}$$

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[but if R_p -violation is allowed \rightarrow lifted by the renormalizable operators,
 $W \sim LLe$ resp. udd]

The saddle point MSSM-Inflation model

Inflation along either of these directions (Enqvist & collab. '06 +)

$$\varphi \rightarrow \frac{\varphi}{\sqrt{3}}, \quad \phi = |\varphi|$$



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$$\varphi \rightarrow \frac{\varphi}{\sqrt{3}}, \quad \phi = |\varphi|$$
$$V_{inflation}^{tree} = \frac{1}{2} m_\phi^2 \phi^2 - |A| \lambda \frac{\phi^6}{6 M_p^3} + \lambda^2 \frac{\phi^{10}}{M_p^6}, \quad (\lambda > 0)$$

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$V_{inflation}^{tree}$ has now a non-trivial minimum at $\phi = \phi_0 \neq 0$.

→ Adjust the parameters to make this minimum as shallow as possible
+ initial condition for the inflaton field ϕ to get slow-roll.

→ exact saddle-point at $\phi_0 = \left(\frac{M_p^3 m_\phi}{\lambda \sqrt{10}}\right)^{1/4}$ with $|A| = \sqrt{40}m_\phi$.

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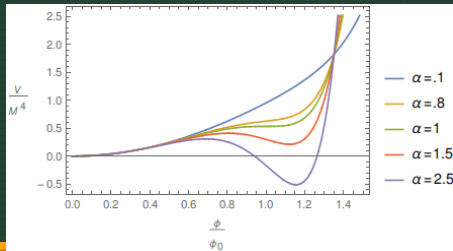
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→ relate A to the MSSM soft tri-linear couplings at the SUSY breaking scale, e.g. $A_t = a m_{3/2}$, $A = (3 + a)m_{3/2}$ in minimal SUGRA.



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 $m_\phi^2 = \frac{1}{3}(m_{L_1}^2 + m_{L_2}^2 + m_{e_1}^2)$, running at all scales.

→ link between the inflation requirements/constraints and the MSSM spectrum and SUSY DM.



The saddle point MSSM-Inflation model

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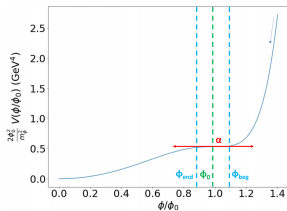
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→ variance with the literature:

- $-|A| \rightarrow -2|A|$... $A\lambda \frac{\varphi^6}{6M_p^3} + h.c.$
- $|\varphi|$ kinetic term normalization, $\varphi \rightarrow \frac{\varphi}{\sqrt{6}}$.
- full RG improved effective potential, + yukawa sector.
- effects of the reheating era.

Towards the CMB constraints

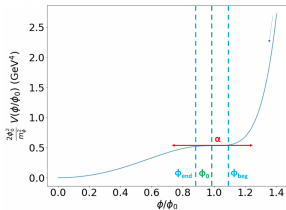
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Gilles Weymann-Despres (IJCLab)

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Slow-roll parameters

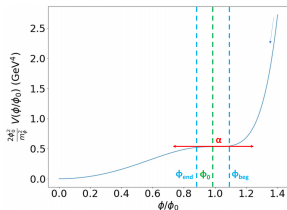
$$\epsilon_1 \simeq \frac{M_P^2}{2} \left(\frac{V'(\phi)}{V(\phi)} \right)^2$$

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Scalar perturbations power spectrum

$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

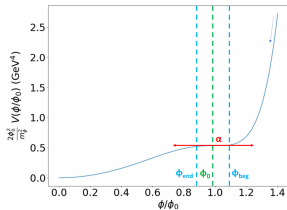
Planck:

$$n_s = 0.9665 \pm 0.0038,$$

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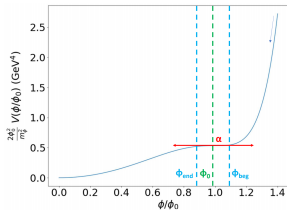
$$n_s = 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

Amplitude

$$A_s = \frac{H_*^2}{8\pi^2 \varepsilon_{1*} M_p}$$

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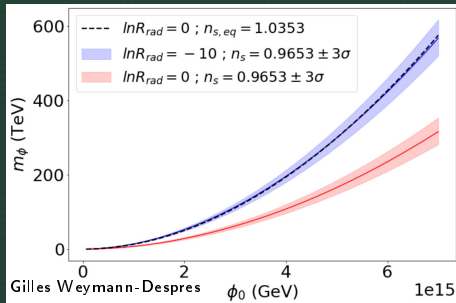
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$$V'(\phi_0) \neq 0, V''(\phi_0) = 0 \rightarrow \alpha \text{ extremely fine-tuned: } \alpha \neq 1 \text{ and } 1 - \alpha < 10^{-8}$$

Martin, Ringeval, Vennin '13



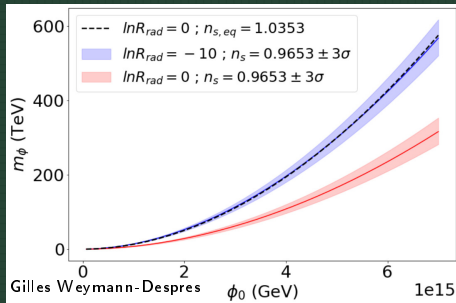
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$$\begin{aligned}
 \Delta N_* &= -\frac{1}{M_{\text{Pl}}^2} \int_{\phi_*}^{\phi_{\text{end}}} \frac{V(\phi)}{V'(\phi)} d\phi \\
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Martin, Ringeval '06

Towards the CMB constraints

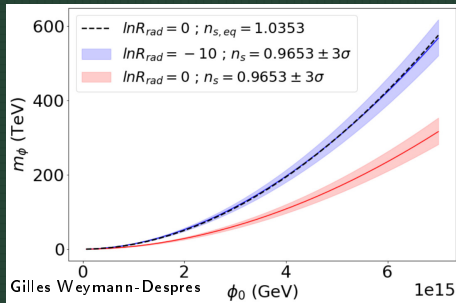


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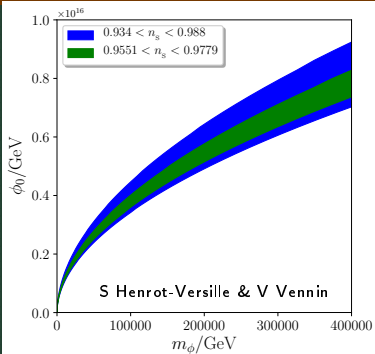
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$$V'(\phi_*) = \sum c_n(\phi_0)(\phi_* - \phi_0)^n + \mathcal{O}((\phi_* - \phi_0)^9)$$

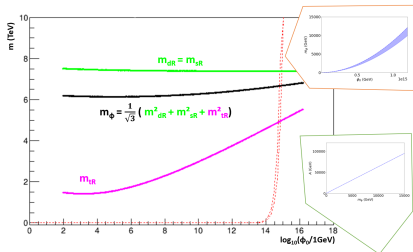
The Wall



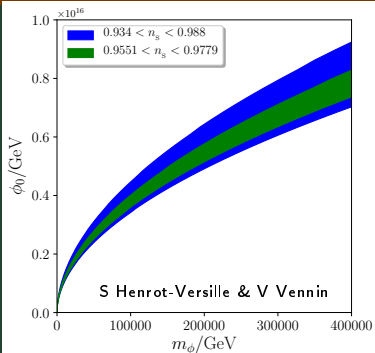
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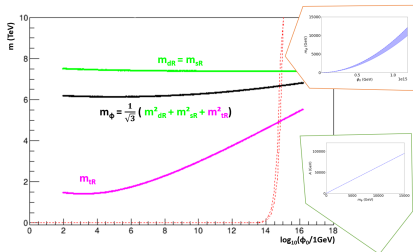
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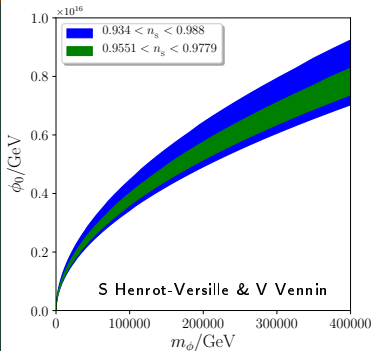
Richard von Eckardstein & D Zerwas



The Wall



Richard von Eckardstein & D Zerwas



There is always a solution!

The Effective Potential & RGEs

Improve the Potential \rightarrow loop corrections \rightarrow $\log \frac{\phi}{\phi_0}$ resummation.

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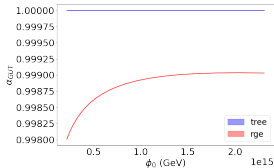
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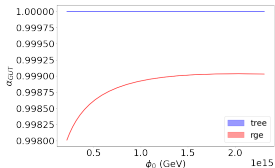
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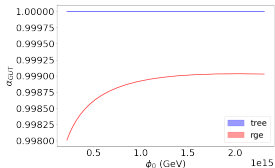
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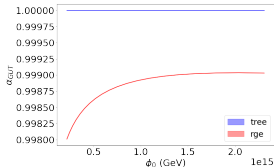
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In fact α should be redefined!

The Renormalization Group Equations

Can be adapted from RPV results

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tds:

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tsb:

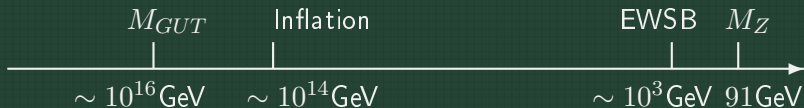
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Implemented in SUSPECT3

- Inflation scale
- High scale boundary conditions relating A to MSSM soft breaking couplings.
- RGEs for m_ϕ^2 , A and λ for all LLe and udd directions, including 3rd generation Yukawa effects.

Ready for a full-fledged analysis:



Outlook

- Although (particularly) fine-tuned, the saddle-point MSSM inflation is an interesting set-up → relates high scale inflation to low scale susy particle physics.
- The on-going collaboration: brings together exp & theo/cosmo & particle, expertise and related analysis tools (private Python and Mathematica codes and ASPIC/SuSpect3/SFitter)
- Extension to other SUSY scenarios; comparison of theoretical predictions to future experimental HEP, cosmology and DM searches.

THANK YOU FOR YOUR ATTENTION



BACKUP SLIDES



Relating \mathcal{A} to the soft MSSM trilinear couplings

→ Minimal SUGRA (minimal Kähler potential)

At the 'high' scale:

$$V = \sum_a |F_{\phi_a}|^2 + m_{3/2}^2 |\phi_a|^2 + m_{3/2} \left(\sum_a \phi_a F_{\phi_a} + (\mathcal{A} - 3)W + h.c. \right)$$

→ soft terms in ϕ_b^3 and ϕ_c^6 are thus related

$$A_3 = \mathcal{A} m_{3/2}, \quad A_6 = (3 + \mathcal{A}) m_{3/2}$$

→ in the simplest calculable case (Polonyi superpotential)

$$\mathcal{A} = 3 - \sqrt{3} \Rightarrow A_6 = A_3 \frac{6 - \sqrt{3}}{3 - \sqrt{3}} \quad \text{used in the study}$$

CAUTION: valid only for universal soft terms @ GUT !!

The saddle point MSSM-Inflation model

Inflation along these directions (Enqvist & collab. '06 +)



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\rightarrow normalization $\phi \rightarrow \frac{\phi}{\sqrt{3}}$?

The saddle point MSSM-Inflation model

Inflation along these directions (Enqvist & collab. '06 +)

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choose phases such that

$$(\phi \equiv |\varphi|)$$

$$V_{inflation} = \frac{1}{2} m_\phi^2 \phi^2 - 2 |A| \lambda \frac{\phi^6}{6M^3} + \lambda^2 \frac{\phi^{10}}{M^6}$$

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