

## Inflating the MSSM

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APC, IJCLab, ITP, L2C,...& DMLab 😊

(Gilbert Moutaka)

DMLab kickoff meeting, DESY-Zoom, 9-10 Dec '21



No Outline

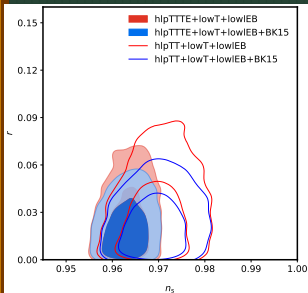


No Outline

TEASER  
TALK

Is there a relation between...?





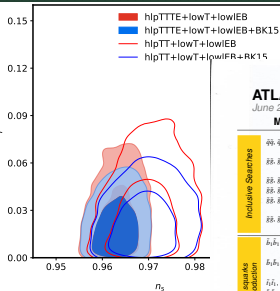
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Is there a relation between...?

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	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{t}^0$	0 $e, \mu$ mono-jet	2-6 jets $E_{T,miss}^{min}$ 139 1-3 jets $E_{T,miss}^{min}$ 36.1	$\tilde{t} \rightarrow [b, \tau, \text{Br Depr}]$ 1.0 1.85 $\tilde{t} \rightarrow [b, \text{Br Depr}]$ 0.9
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{q}\tilde{t}^0$	0 $e, \mu$	2-6 jets $E_{T,miss}^{min}$ 139	Forbidden $\tilde{e} \rightarrow [b, \tau]$ 1.15-1.95 2.3
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{q}W\tilde{t}^0$	1 $e, \mu$	2-6 jets 139	$\tilde{e} \rightarrow [b, \tau]$ 2.2
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{q}\tilde{t}^0\tilde{t}^0$	$e, \mu, \tau$	2 jets $E_{T,miss}^{min}$ 36.1	$m(\tilde{t}) - m(\tilde{t}^0) = 50$ GeV $m(\tilde{t}^0) = 450$ GeV
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{q}WZ\tilde{t}^0$	0 $e, \mu$	7-11 jets $E_{T,miss}^{min}$ 139	$m(\tilde{t}) - m(\tilde{t}^0) = 200$ GeV
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{q}WZ\tilde{t}^0$	SS $e, \mu$	6 jets 139	$m(\tilde{t}^0) = 200$ GeV
	$\tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$ SS $e, \mu$	0 jets $E_{T,miss}^{min}$ 79.8 6 jets 139	$\tilde{e} \rightarrow [b, \tau]$ 1.25 2.25 $m(\tilde{t}^0) = 400$ GeV $m(\tilde{t}^0) = 200$ GeV
	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 b $E_{T,miss}^{min}$ 139	$\tilde{b}_1 \rightarrow [b, \tau]$ 0.68 1.255 $m(\tilde{t}^0) = 400$ GeV 10 GeV $< m(\tilde{b}_1) - m(\tilde{t}^0) < 20$ GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{t}^0 \rightarrow bb\tilde{t}^0$	0 $e, \mu$ 2 $\tau$	6 b $E_{T,miss}^{min}$ 139 2 b $E_{T,miss}^{min}$ 139	$\tilde{b}_1 \rightarrow [b, \tau]$ 0.13-0.85 0.23-1.55 $\Delta m(\tilde{t}^0, \tilde{t}^0) = 130$ GeV, $m(\tilde{t}^0) = 100$ GeV $\Delta m(\tilde{t}^0, \tilde{t}^0) = 130$ GeV, $m(\tilde{t}^0) = 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}^0$	0-1 $e, \mu$	$\geq 1$ jet $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 1.25
3 $\gamma$ and squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{t}^0$	1 $e, \mu$	3 jets+1 b $E_{T,miss}^{min}$ 139	Forbidden 0.65
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b, \tilde{t}_1 \rightarrow \tau G$	1-2 $\tau$	2 jets+1 b $E_{T,miss}^{min}$ 139	Forbidden 1.4
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	2 mono-jet $E_{T,miss}^{min}$ 36.1	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.85
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	mono-jet $E_{T,miss}^{min}$ 139	$m(\tilde{t}^0) = 0$ GeV $m(\tilde{t}^0) = 100$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	1-2 $e, \mu$	1-4 b $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.067-1.18
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	3 $e, \mu$	1 b $E_{T,miss}^{min}$ 139	Forbidden 0.86 $m(\tilde{t}^0) = 360$ GeV, $m(\tilde{t}^0) = m(\tilde{t}^0) = 40$ GeV
	$\tilde{t}_1^0\tilde{t}_1^0$ via WZ	Multiple $\ell$ jets $e, \mu, \tau$	$\geq 1$ jet $E_{T,miss}^{min}$ 139	$\tilde{t}_1^0 \rightarrow [b, \tau]$ 0.205 0.96 $m(\tilde{t}^0) = 0$ , wino-bino $m(\tilde{t}^0) = m(\tilde{t}^0) = 50$ GeV, wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via WW	2 $e, \mu$	$E_{T,miss}^{min}$ 139	$\tilde{t}_1^0 \rightarrow [b, \tau]$ 0.42 $m(\tilde{t}^0) = 0$ , wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via Wb	Multiple $\ell$ jets	$E_{T,miss}^{min}$ 139	Forbidden 1.06 $m(\tilde{t}^0) = 70$ GeV, wino-bino
	$\tilde{t}_1^0\tilde{t}_1^0$ via $\tilde{t}_1\tilde{t}_1$	2 $e, \mu$	$E_{T,miss}^{min}$ 139	1.0 $m(\tilde{t}^0) = 0.5(m(\tilde{t}^0) + m(\tilde{t}^0))$
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	2 $\tau$	$E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau, \text{Br L}]$ 0.16-0.3 0.12-0.39 $m(\tilde{t}^0) = 0$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	2 $e, \mu$	0 jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.7
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	$e, \mu, \tau$	$\geq 1$ jet $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.256 0.7 $m(\tilde{t}^0) = 0$ $m(\tilde{t}^0) = m(\tilde{t}^0) = 15$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 3$ b $E_{T,miss}^{min}$ 36.1	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.13-0.23 0.29-0.88
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	4 $e, \mu$	0 jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.55 0.29-0.88
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 2$ large jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.45-0.93
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 2$ large jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.45-0.93
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 2$ large jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.45-0.93
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 2$ large jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.45-0.93
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	0 $e, \mu$	$\geq 2$ large jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.45-0.93
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1$	Disapp. birk	1 jet $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.21 0.66 Pure Wino Pure Higgsino
	Stable $\tilde{t}_1$ R-hadron	Multiple	36.1	$\tilde{t}_1 \rightarrow [b, \tau]$ 2.0 $m(\tilde{t}^0) = 100$ GeV
	Metastable $\tilde{t}_1$ R-hadron, $\tilde{t}_1 \rightarrow e\tilde{q}\tilde{t}^0$	Multiple	36.1	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.34 0.7 $m(\tilde{t}^0) = 0.1$ ms $m(\tilde{t}^0) = 0.1$ ms
RPV	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	Displ. lep	$E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.34 0.7 $m(\tilde{t}^0) = 0.1$ ms $m(\tilde{t}^0) = 0.1$ ms
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	3 $e, \mu$	0 jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.21 0.66 Pure Wino Pure Higgsino
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	4 $e, \mu$	0 jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.21 0.66 Pure Wino Pure Higgsino
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow e\tilde{t}^0\tilde{t}^0$	3 $e, \mu$	0 jets $E_{T,miss}^{min}$ 139	$\tilde{t}_1 \rightarrow [b, \tau]$ 0.21 0.66 Pure Wino Pure Higgsino
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\*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<sup>-1</sup>

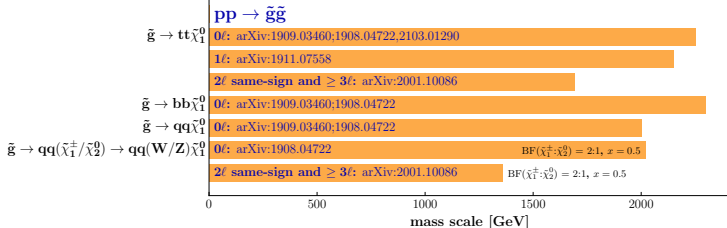
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Mass scale [TeV]

M. Tristram et al, A&A 647

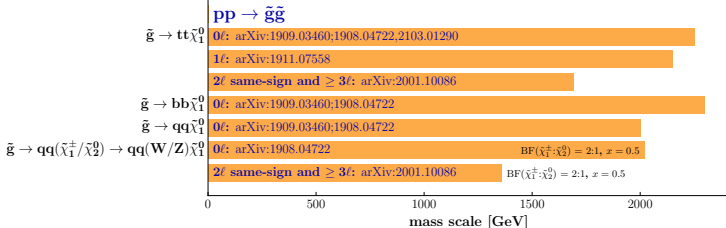
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## Overview of SUSY results: gluino pair production

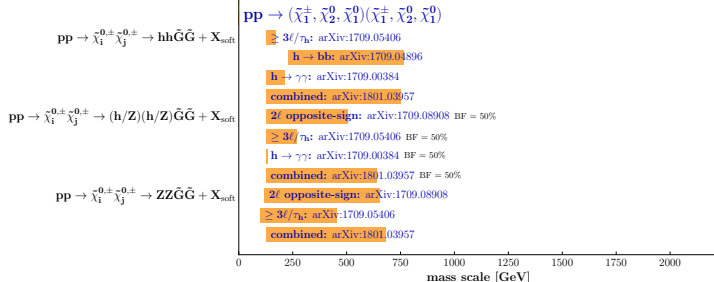
137 fb<sup>-1</sup> (13 TeV)

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities  $\Delta M$  and  $x$  represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to  $\Delta M$ , respectively, unless indicated otherwise.

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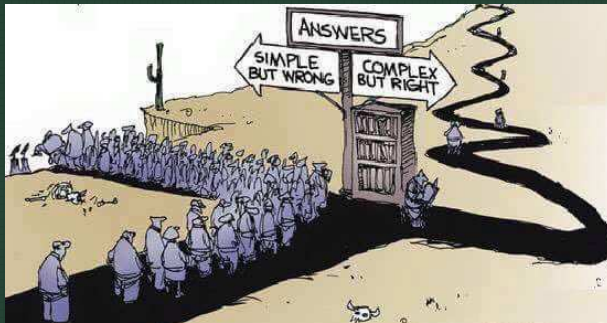
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## Introductory motivations

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

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



Too early to give up on Supersymmetry!



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- unification with Gravity...



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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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## SUSY flat directions

a flat direction:

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

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- renormalizable superpotential (MSSM)
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e.g. →  $LLe$  or  $udd$  flat directions lifted by

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



## The saddle point MSSM-Inflation model

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

$$\phi \sim \tilde{L}_i + \tilde{L}_j + \tilde{e}_k, \quad \phi \sim \tilde{u}_i + \tilde{d}_j + \tilde{d}_k$$



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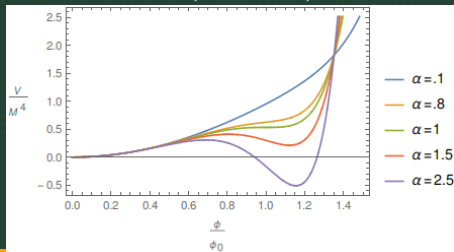
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$$V_{inflation}^{tree} = \frac{1}{2}m_\phi^2\phi^2 - A\lambda\frac{\phi^6}{6M_p^3} + \lambda^2\frac{\phi^{10}}{M_p^6}, \quad (\lambda > 0, A > 0)$$

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

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



# The saddle point MSSM-Inflation model



## The saddle point MSSM-Inflation model

→ 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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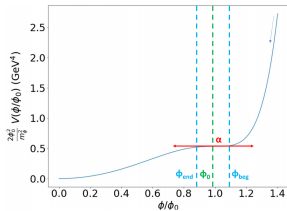
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Boehm et al. '13

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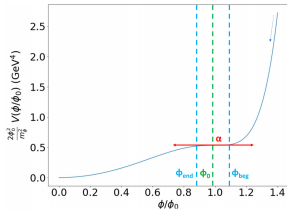
$$V_{inflation}^{tree} = \frac{1}{2} m_\phi^2 \phi^2 - A\lambda \frac{\phi^6}{6M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$$



courtesy Gilles Weymann-Despres (IJCLab)

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Slow-roll parameters

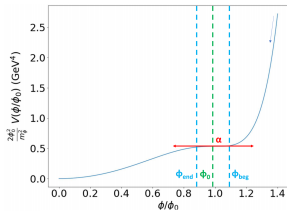
$$\epsilon_1 \simeq \frac{M_P^2}{2} \left( \frac{V'(\phi)}{V(\phi)} \right)^2$$

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Scalar perturbations power spectrum

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

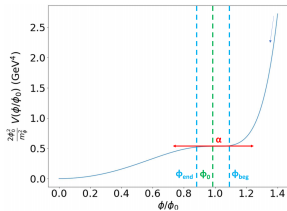
Planck:

$$n_s = 0.9665 \pm 0.0038,$$

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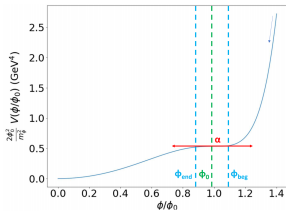
$$n_s = 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

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

Martin, Ringeval, Vennin '13

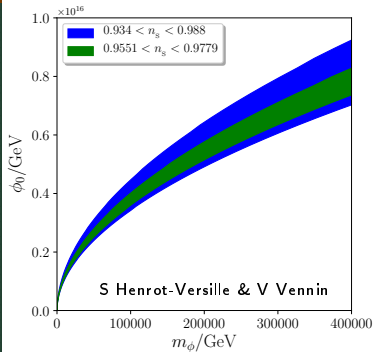


# The Wall

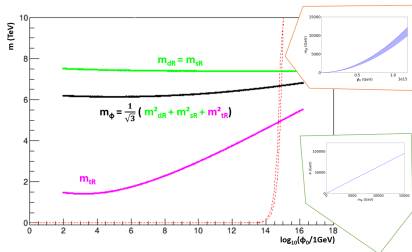




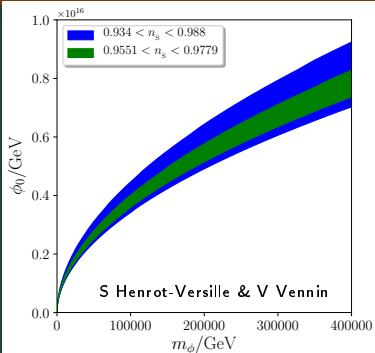
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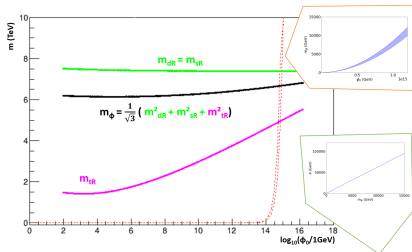
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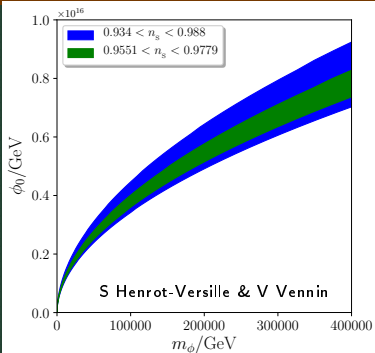
Richard von Eckardstein & D Zerwas



# The Wall



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There is always a solution!

## The Effective Potential

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

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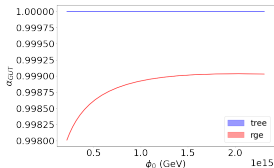
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Gilles Weymann-Despres

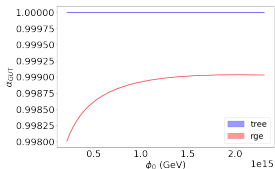
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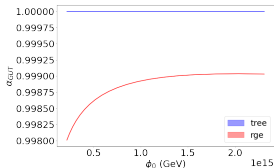
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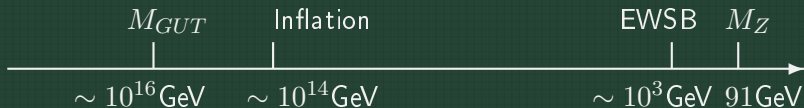
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**In fact  $\alpha$  should be redefined!**

## Implemented in SUSPECT3

- Included Inflation scale
- Included high scale boundary conditions relating  $A$  to MSSM soft breaking couplings.
- Included RGEs for  $m_\phi^2$ ,  $A$  and  $\lambda$  for all  $LLe$  and  $udd$  directions, including 3rd generation Yukawa effects.

Ready for a full-fledged analyses:





## Outlook

- Although (particularly) fine-tuned, the saddle-point MSSM inflation is an interesting set-up → relates high scale inflation to low scale particle physics.
- The on-going collaboration: brings together exp & theo/cosmo & particle, expertise and related analysis tools (ASPIC/SuSpect3/SFitter)
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- Extension to other SUSY scenarios; comparison of theoretical predictions to future experimental HEP, cosmology and DM searches.
- The DMLab as a hub is a real opportunity for us: short-term visits, feedback from experts, the SuSpect/SUSY-HIT project,...

*THANK YOU FOR YOUR ATTENTION*



BACKUP SLIDES

