On SUSY Breaking and Cosmology in IIB String Compactifications

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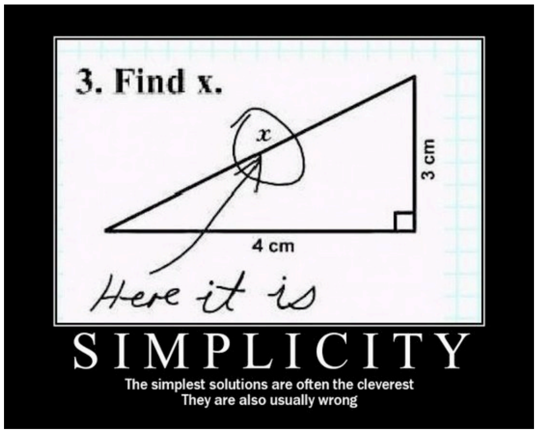
R. Kallosh, FQ + A. Uranga arXiv:1507.07556
I. Garcia-Etxebarria, FQ + R. Valandro arXiv:1512.06926
L. Aparicio, FQ + R. Valandro arXiv:1511.08105
M.Cicoli, K. Dutta, A. Maharana, FQ arXiv:1604.08512
L. Aparicio, M. Cicoli, B Dutta, F. Muia + FQ arXiv:1607.00004

Approaches to BSM



Simplicity

Follow your nose

Top-down

Bottom-up

Outline

- General introduction
- Moduli Stabilisation + de Sitter + SUSY breaking
- Two concrete scenarios (KKLT, LVS)
- Cosmology (inflation scenarios + non-standard postinflationary cosmology)
- Phenomenology (SUSY breaking scenarios)

On SUSY Breaking and Moduli Stabilisation

Why SUSY?

- SUSY does not solve the cc problem
- SUSY may not solve the hierarchy problem
- SUSY B,L + flavour problem
- SUSY complicates cosmology (cosmological moduli problem, gravitino problem)
- Best dark matter candidates not neutralino?
- Unification: other options
- Stability of Higgs potential? No tachyons?

SUSY Challenges for String Scenarios

- **Explicit $\mathcal{N}$=1 Compactification**
- **Concrete SUSY breaking mechanism**
- **Moduli Stabilisation (small cc)**
  (+ avoid CMP (plus gravitino+ dark radiation excess,etc!))
- **Chiral visible sector**
- **Computable soft terms**

String Scenarios

- IIB (+F-theory)

  KKLT
  LVS

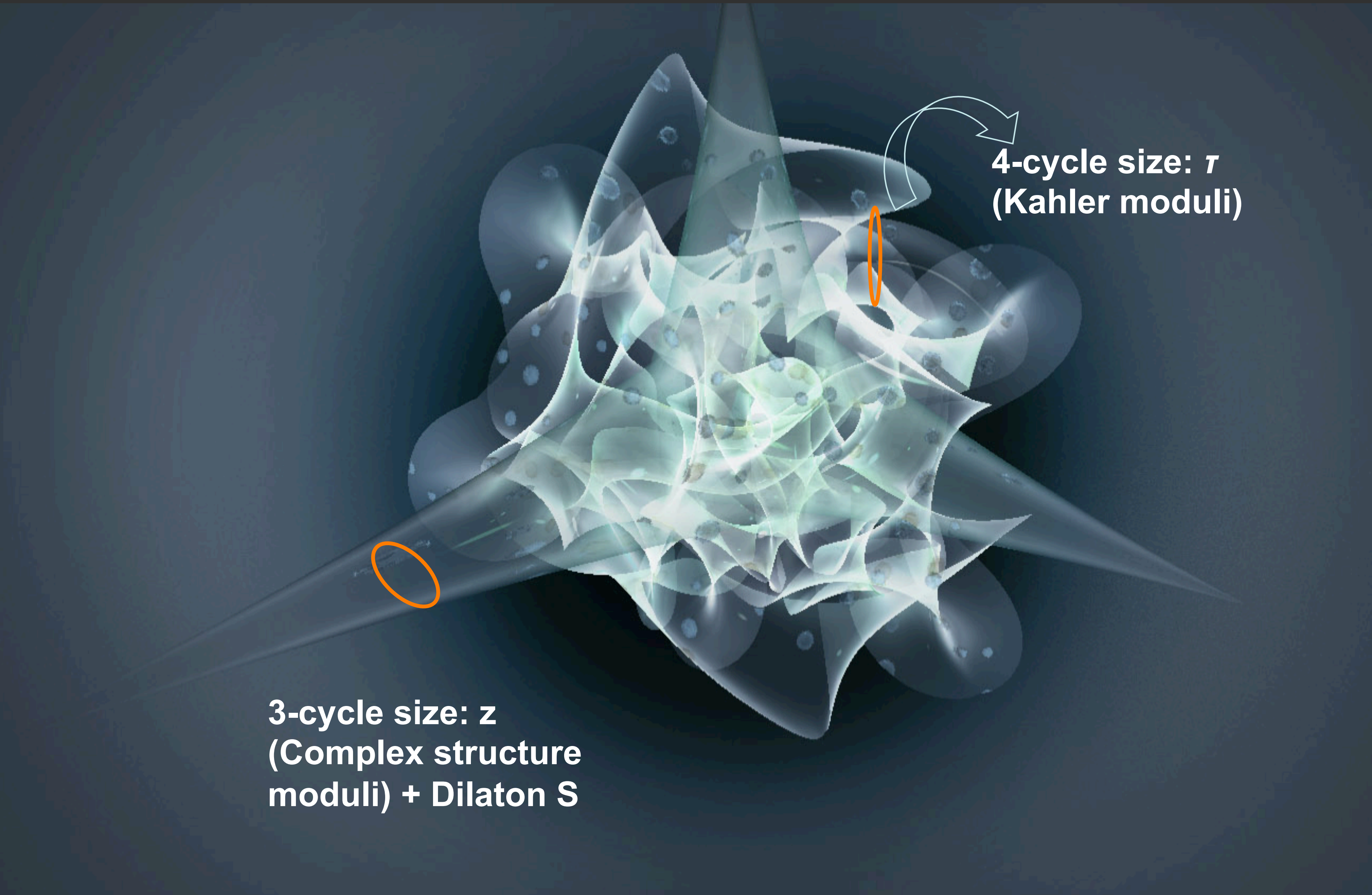
  $\left.\begin{array}{l} \text{KKLT} \\ \text{LVS} \end{array}\right\}$ Moduli Stabilisation

- IIA

- Heterotic

- G2 manifolds

IIB MODULI STABILISATION



GKP Overview

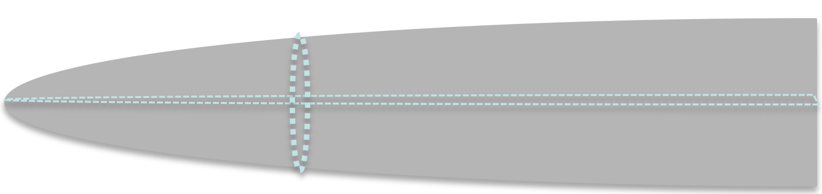
1. Fluxes: GVW $$W = \int G \wedge \Omega$$

$$G_3 = F_3 - iSH_3, \int F_3 = 2\pi M, \int H_3 = -2\pi K$$

Fix CS moduli: z and dilaton: S (but runaway in T directions?)

2. Warped throats

$$z^{1/3} = e^{A} = e^{-\frac{2\pi K}{3 g_s M}} \equiv e^{-\alpha}$$



KKLT Overview

- Nonperturbative effects: $W_{np} = \sum A_i e^{-a_i T_i}$

SUSY AdS Vacua: DW=0

- Anti D3 brane (SUSY breaking+uplift)

$$V_{\text{uplift}} = \frac{D^2}{(T+T^*)^\alpha} = \frac{D^2}{\mathcal{V}^{2\alpha/3}} \qquad \begin{cases} \alpha = 3 & \text{KKLT} \\ \alpha = 2 & \text{KKLMMT} \end{cases}$$

LARGE Volume Scenario

Fluxes determine superpotential W_0 (U,S) (GKP 2002)

Perturbative corrections to K: $K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right)$

Nonperturbative contributions to W: $\boxed{W_{np} = \sum_i A_i e^{-a_i T_i}}$

$$V_F \propto \left(\frac{K^{S\bar{S}}|D_S W|^2 + K^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W}}{\mathcal{V}^2}\right) + \left(\frac{Ae^{-2a\tau}}{\mathcal{V}} - \frac{Be^{-a\tau} W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\boxed{\mathcal{V} \sim e^{a\tau}} \quad \text{with} \quad \tau \sim \mathrm{Re\ S} \sim 1/\mathrm{g_s} > 1.$$

Exponentially large volume for weak coupling

(SUSY broken by Fluxes, AdS) BBCQ, CQS 2005

Other de Sitter 'Uplift'

- **From F/D terms, hidden matter** CKKMQV 2013

  T-branes (Cicoli, FQ, Valandro arXiv:1512.04558)

- **From non-perturbative effects on hidden brane at singularities**

  BCMQ 2011

- **...**

dS Kahler Moduli Stabilisation

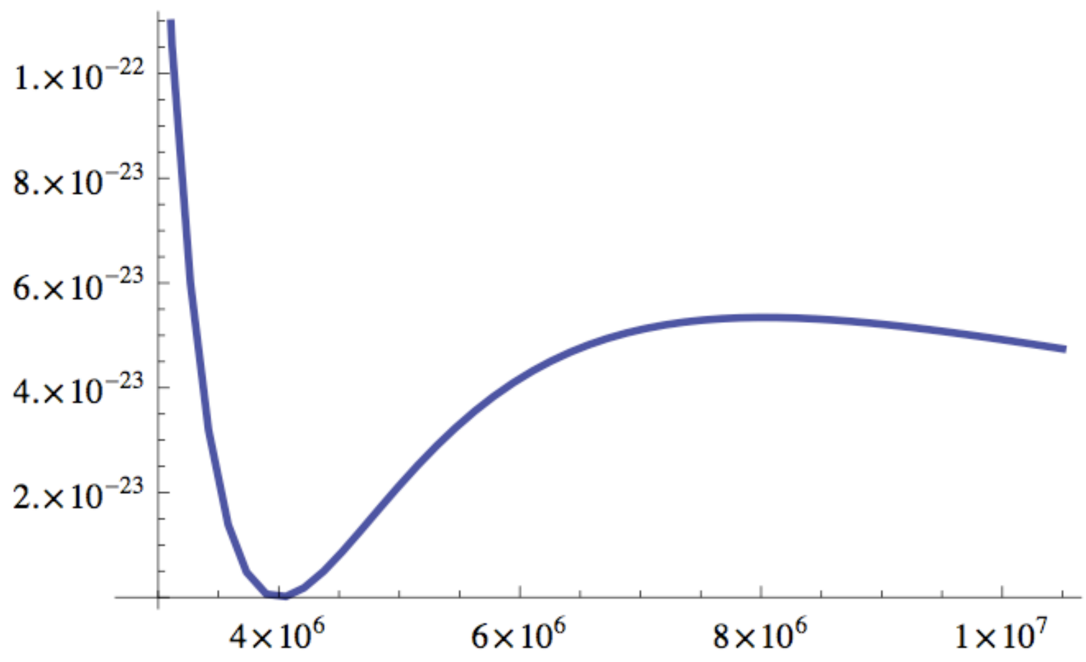
$$\boxed{V_F^{\rm tot} = V_{\rm np} + V_{\alpha'} + V_{\rm uplift}}$$

$$V_{\rm np} = \frac{8}{3\lambda}(a_s A_s)^2\sqrt{\tau_s}\,\frac{e^{-2\,a_s\tau_s}}{\mathcal{V}} - 4\,a_s A_s|W_0|\tau_s\frac{e^{-a_s\tau_s}}{\mathcal{V}^2}$$

$$V_{\alpha'} = \frac{3}{4}\frac{\zeta|W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

$V_{\rm uplift} = A/\mathcal{V}^{a}$

$1<a<3$



Relevant Scales

String Scale $$M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi\mathcal{V}}},$$

Kaluza Klein Scale $$M_{KK} \simeq \frac{M_P}{\sqrt{4\pi}\mathcal{V}^{2/3}},$$

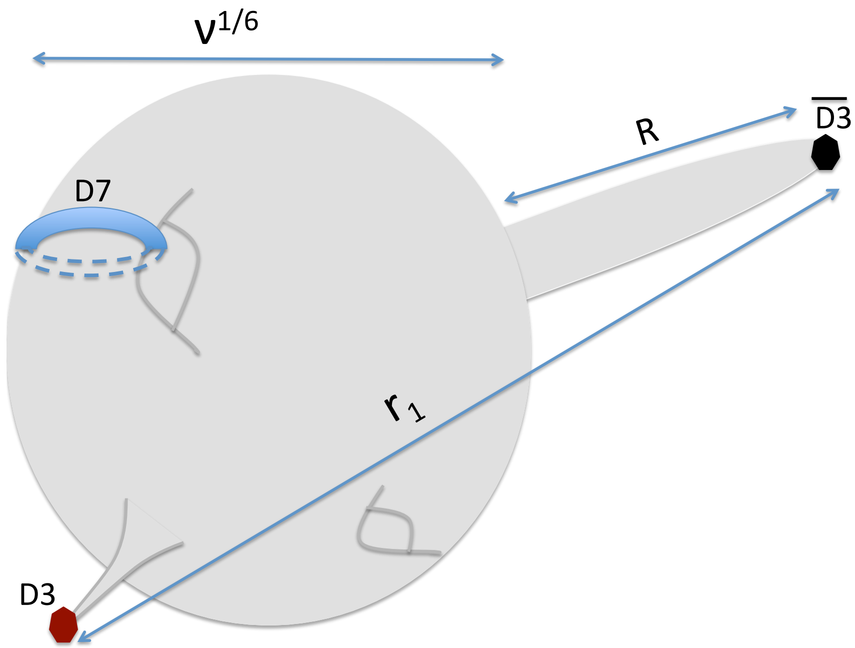
Gravitino mass $$m_{3/2} \simeq \left(\frac{g_s^2}{2\sqrt{2\pi}}\right)\frac{W_0 M_P}{\mathcal{V}}.$$

Volume modulus mass $$m_{\mathcal{V}} \simeq m_{3/2}/\sqrt{\mathcal{V}}.$$

Vacuum decay rates $$\Gamma \sim e^{-\mathcal{V}^3}$$

Revisiting Anti D3 Brane Uplift

Brane-Antibrane interaction



$$V = \frac{e^{-4\alpha}}{\mathcal{V}^{4/3}}\left(1 - \frac{e^{-4\alpha}}{\mathcal{V}^{4/3}(<\varphi> + \delta\varphi)^4}\right)$$

$$\sim \frac{e^{-4\alpha}}{\mathcal{V}^{4/3}}\left(1 + 4e^{-4\alpha}\mathcal{V}^{1/3}\,\delta\varphi\right)$$

Stability of D-branes at Singularities

Inter- brane attraction

$$\delta V(\hat{\varphi}) = \frac{e^{-8\alpha}}{\mathcal{V}} \hat{\varphi} M_p^3 + m_0^2 |\hat{\varphi}|^2 \qquad \hat{\varphi} \sim \frac{e^{-8\alpha} M_p^3}{2 m_0^2 \mathcal{V}}$$

$$\Delta r \ll \ell_s \text{ if } \quad \begin{cases} \frac{m_0^2}{M_p^2} \gg \frac{W_0^4}{\mathcal{V}^{11/6}} & \text{for KKLT} \\ \frac{m_0^2}{M_p^2} \gg \frac{1}{\mathcal{V}^{23/6}} & \text{for LVS} \end{cases}$$

No tachyons:

$$\begin{cases} m_0 \gg \frac{W_0^2}{\mathcal{V}^{4/3}} M_p \sim \frac{m_{3/2}^2}{M_{KK}} & \text{for KKLT} \\ m_0 \gg \frac{W_0^2}{\mathcal{V}^2} M_p \sim \frac{m_{3/2}^2}{M_p} & \text{for LVS} \end{cases}$$

Nilpotent Super fields

Kallosh et al 2013-2015
(Also: Bergshoeff, van Proeyen,
Wrase, Dudas, D'allagata,
Zwirner, Ferrara, etc.)

Nilpotent Superfields EFT

$$X = X_0(y) + \sqrt{2}\psi(y)\theta + F(y)\theta\bar{\theta}$$

$$\boxed{X^2 = 0} \qquad X_0 = \frac{\psi\psi}{2F}$$

$$K = K_0 X X^* \qquad W = \rho X + W_0$$

$$V = K_0^{-1} \left\| \frac{\partial W}{\partial X} \right\|^2 = \frac{|\rho|^2}{K_0} \geq 0$$

$$\mathcal{L} = -\rho^2 + i\partial_a \bar{\psi}\bar{\sigma}^a \psi + \frac{1}{4\rho^2}\bar{\psi}^2\partial^2\psi^2 - \frac{1}{16\rho^6}\psi^2\bar{\psi}^2\partial^2\psi^2\partial^2\bar{\psi}^2$$

~ Volkov-Akulov !

Nilpotent Superfields and KKLT

Goldstino: Nilpotent chiral superfield

$$X^2(x,\theta) = 0.$$

Rocek,...,Komargodski, Seiberg,...

KKLT $K = -3\log(T+T^*) + c\,(T+T^*)^n\; XX^* + ZCC^* + \cdots$

$$Z = (T+T^*)^m + b\,(T+T^*)^k\, XX^*$$

$$W = W_0 + W_{\rm matter} + W_{np} + \boxed{\rho X}$$

Plug into SUGRA expression for V, V= V_{KKLT} + V_{uplift} :

$$V_{\rm uplift} = \frac{|\rho|^2}{c(T+T^*)^{n+3}}$$

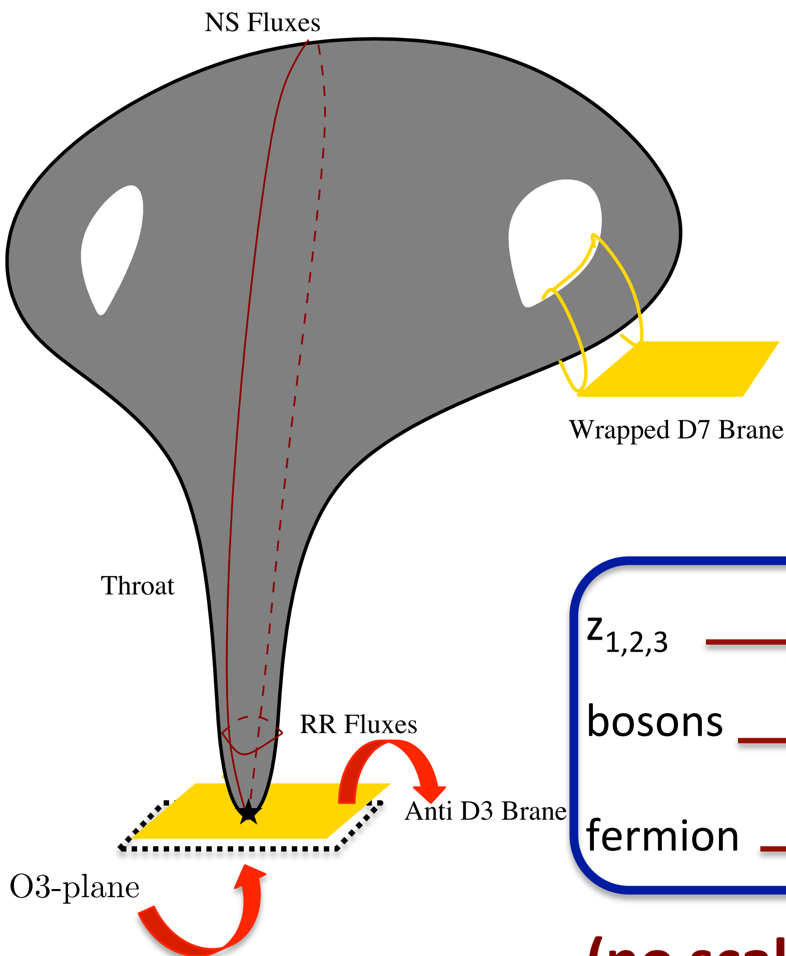
(like KKLT, KKLMMT)

Kallosh et al. 2013-15
see also Polchinski
@ SUSY 2015

Antibrane uplift from manifestly SUSY EFT!

Anti D3 Brane/O3$^-$ Spectrum

Kallosh, Uranga, FQ
arXiv:1507.07556



$z_{1,2,3}$	$\longrightarrow$	$-z_{1,2,3}$
bosons	$\longrightarrow$	-bosons
fermion	$\longrightarrow$	fermion

⇒ **Massless spectrum:**
Fermion=Goldstino

(no scalars, no gauge fields)

Spectrum on (anti) D3 brane

Field	$SO(3,1)$	$SO(6)$	$U(N)$	
Gauge boson	vector	$\mathbf{1}$	Adj	
Scalar	$\mathbf{1}$	$\mathbf{6}$	Adj	
Fermion	spinor	$\mathbf{4}$	Adj	$\bar{4}$ **for anti D3 brane**

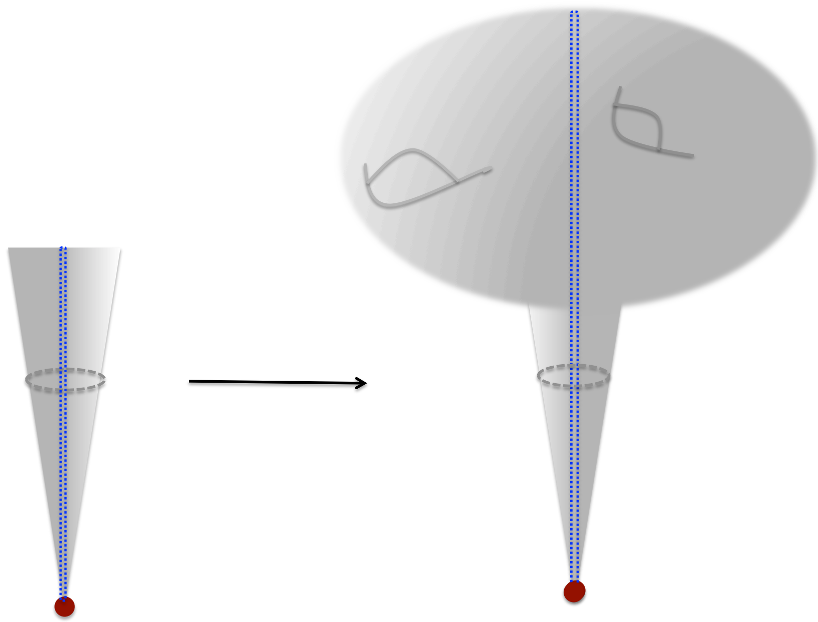
Masses from fluxes $G_3\,\lambda\lambda$

G3=10 (ISD) + $\overline{10}$ (IASD)

Mass term $\bar{4}\cdot\bar{4}\cdot 10$ **(10=6+3+1 and 4=3+1 of SU(3))**

3 massive 1 massless fermion (N=1 goldstino)

Local to Global Throats



Garcia-Etxebarria, FQ, Valandro
arXiv:1512.06926

e.g.

$$\begin{array}{c|cccccccc|c} & W_1 & W_2 & W_3 & W_4 & W_5 & Z & X & Y & D_{\mathrm{H}} \\ \hline \mathbb{C}^*_1 & 0 & 0 & 0 & 0 & 0 & 1 & 2 & 3 & 6 \\ \mathbb{C}^*_2 & 1 & 1 & 1 & 0 & 0 & 0 & 6 & 9 & 18 \\ \mathbb{C}^*_3 & 0 & 1 & 0 & 1 & 0 & 0 & 4 & 6 & 12 \\ \mathbb{C}^*_4 & 0 & 0 & 1 & 0 & 1 & 0 & 4 & 6 & 12 \end{array},$$

First concrete realisation of warped throats in compact CY?

SUSY Breaking

SUSY Breaking from moduli

General soft terms: Moduli z, matter φ

$$K_T(z^I, \bar{z}^J, \phi_\alpha, \bar{\phi}_\beta) = K(z^I, \bar{z}^J) + Z_{\alpha\beta}(z^I, \bar{z}^J)\, \phi_\alpha \bar{\phi}_\beta + \cdots$$

$$\mathcal{L}_{\not{S}\mathrm{USY}} \;=\; \underbrace{m_0^2\, \varphi^*\, \varphi}_{\text{scalar masses}} \;+\; \left(\underbrace{M_\lambda\, \lambda\lambda}_{\text{gaugino masses}} \;+\; h.c. \right) \;+\; (A\, \varphi^3 \;+\; h.c.)$$

$$\boxed{\begin{aligned} M_{1/2} &= \frac{1}{f + f^*} F^I \partial_I f \\ A_{\alpha\beta\gamma} &= F^I K_I + F^I \partial_I \log Y_{\alpha\beta\gamma} - F^I \partial_I \log\left(Z_\alpha Z_\beta Z_\gamma\right) \\ m_0^2 &= V_0 + m_{3/2}^2 - F^I F^J \partial_I \partial_J \log Z \end{aligned}}$$

Soni+Weldom, Kaplunovsky-Louis, Brignole-Ibanez-Munoz

Original KKLT SUSY Breaking

Choi-Falkowski-Nilles-Olechowski 2005

$$S_{N=1} = \int d^4x \sqrt{g^C} \left[\int d^4\theta \, CC^* \left(-3 \exp(-K_{eff}/3)\right) + \left\{ \int d^2\theta \left(\frac{1}{4} f_a W^{a\alpha} W^a_\alpha + C^3 W_{eff} \right) + \text{h.c.} \right\} \right],$$

$$S_{\bar{D}3} = \int d^4x \sqrt{g^C} \int d^4\theta \left[-\frac{1}{2} e^{4A_{min}} C^2 C^{2*} \theta^2 \bar{\theta}^2 P(\Phi^m, \Phi^{m*}) + e^{3A_{min}} C^3 \bar{\theta}^2 \Gamma(\Phi^m, \Phi^{m*}) + \text{h.c.} \right],$$

$$e^{4A_{min}} e^{2K_0/3} P = \frac{D}{(T+T^*)^2} \qquad e^{3A_{min}} \Gamma \sim \sqrt{m_{3/2}/M_{Pl}}\, W_0, \ll W_0$$

$$\boxed{m_T \sim 4\pi^2 m_{3/2} \sim (4\pi^2)^2 m_{soft}\,.}$$

Soft Terms from Nilpotent: KKLT

$$F^X = e^{K/2} K^{-1}_{XX^*} D_X W = M/\left(T+T^*\right)^{n+3/2}$$

$$F_T = e^{K/2} D_T W \sim \frac{3W_0}{(T+T^*)^{3/2}}\epsilon$$

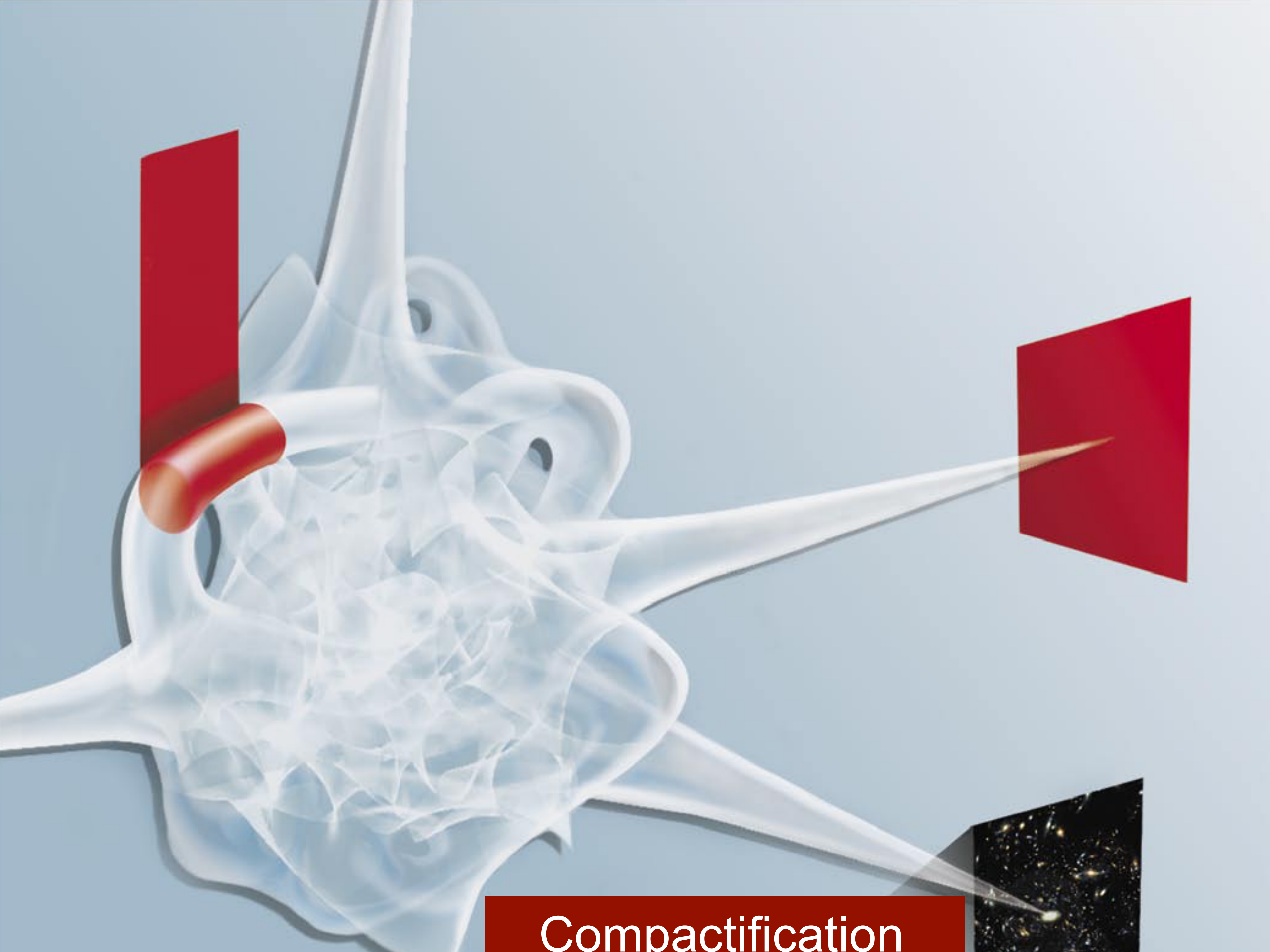
$$\begin{aligned} M_{1/2} &= \frac{1}{f+f^*} F^I \partial_I f \\ A_{\alpha\beta\gamma} &= F^I K_I + F^I \partial_I \log Y_{\alpha\beta\gamma} - F^I \partial_I \log\left(Z_\alpha Z_\beta Z_\gamma\right) \\ m_0^2 &= V_0 + m_{3/2}^2 - F^I F^J \partial_I \partial_J \log Z \end{aligned}$$

$$M_{1/2}, A \;= m_{3/2}/\log\left(\frac{M_{planck}}{m_{3/2}}\right) \qquad m_0^2 \sim m_{3/2}^2$$

or $\quad m_{soft} \sim m_{3/2}/\log\left(\frac{M_{planck}}{m_{3/2}}\right)$

SUSY Breaking in LVS

- **Fluxes break SUSY**
- **In EFT: F-terms of Kahler moduli (plus subdominant F_S, F_U)**
- **Uplifting only relevant if cancellations (sequestering) (anomaly mediation subdominant).**
- **Several scenarios studied + nilpotent**



Compactification

Summary of Soft terms

	KKLT	**LVS**
Soft term	D3	D3
$M_{1/2}$	$\pm\left(\frac{3}{2a\mathcal{V}^{2/3}}\right)\ m_{3/2}$	$\pm\left(\frac{3s^{3/2}\xi}{4\mathcal{V}}\right)\ m_{3/2}$
m_0^2	$\left(\frac{s^{3/2}\xi}{4\mathcal{V}}\right) m_{3/2}^2$	$\left(\frac{5s^{3/2}\xi}{8\mathcal{V}}\right)\ m_{3/2}^2$
A_{ijk}	$-(1 - s\partial_s \log Y_{ijk})\, M_{1/2}$	$-(1 - s\partial_s \log Y_{ijk})\, M_{1/2}$

	KKLT	**LVS**
Soft term	D7	D7
$M_{1/2}$	$\pm\left(\frac{1}{a\mathcal{V}^{2/3}}\right) m_{3/2}$	$\pm\left(\frac{3}{4a\tau_s}\right) m_{3/2}$
m_0^2	$(1 - 3\omega)\, m_{3/2}^2$	$\left(\frac{9(1-\lambda)}{16a^2\tau_s^2}\right)\ m_{3/2}^2$
A_{ijk}	$\frac{3}{2}(2\lambda - 1 - s\partial_s \log Y_{ijk})\, M_{1/2}$	$-3(1-\lambda)\, M_{1/2}$

Phenomenology

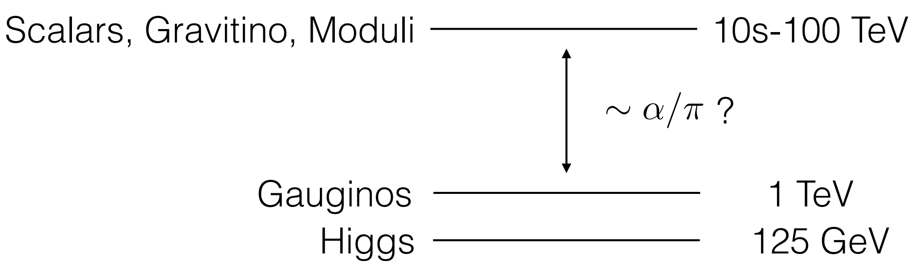
KKLT Phenomenology

- **D3: Anomaly vs α' effects (tachyons?)**
- **D7:** $m_0 \sim m_{3/2} >> m_{3/2}/\log\left(M_{Planck}/m_{3/2}\right)$
- **Modulus heavier than gravitino (gravitino problem)**
- **Gaugino masses: suppression implies anomaly mediation is relevant (mirage?)**
- **Split spectrum ($m_0/M_{1/2}$~50)**

LVS Phenomenology

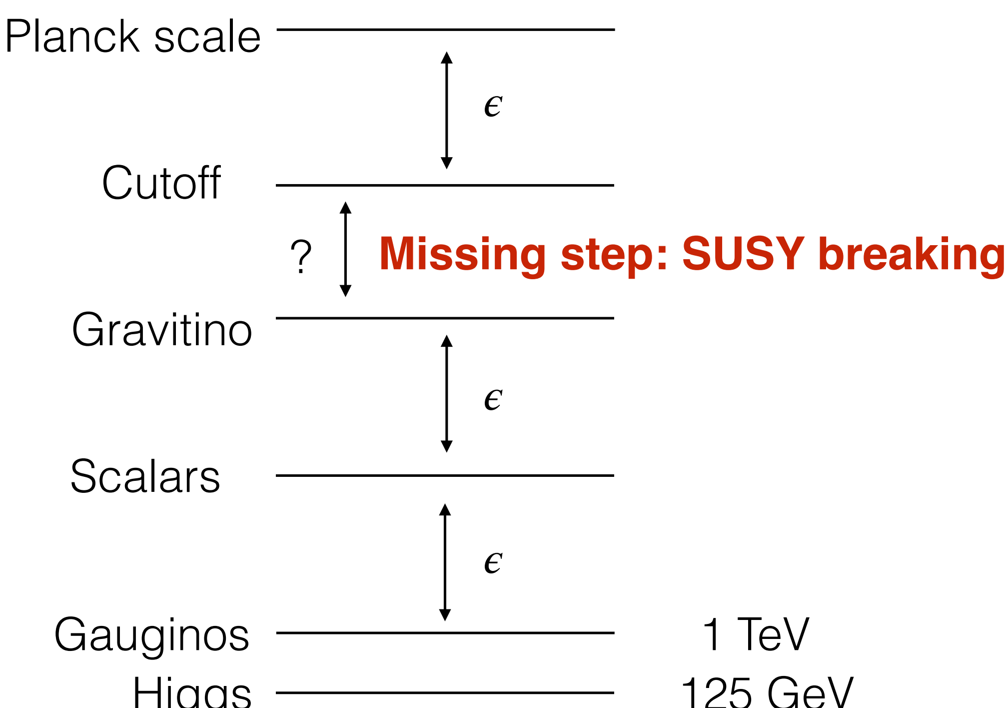
- D7: modulus lighter than soft terms (CMP?)
- D3: modulus heavier
- D3: split SUSY ($m_0/M_{1/2}$~100-1000)
- Anomaly mediation sub-subdominant (no-scale)

Split SUSY, Take 1:



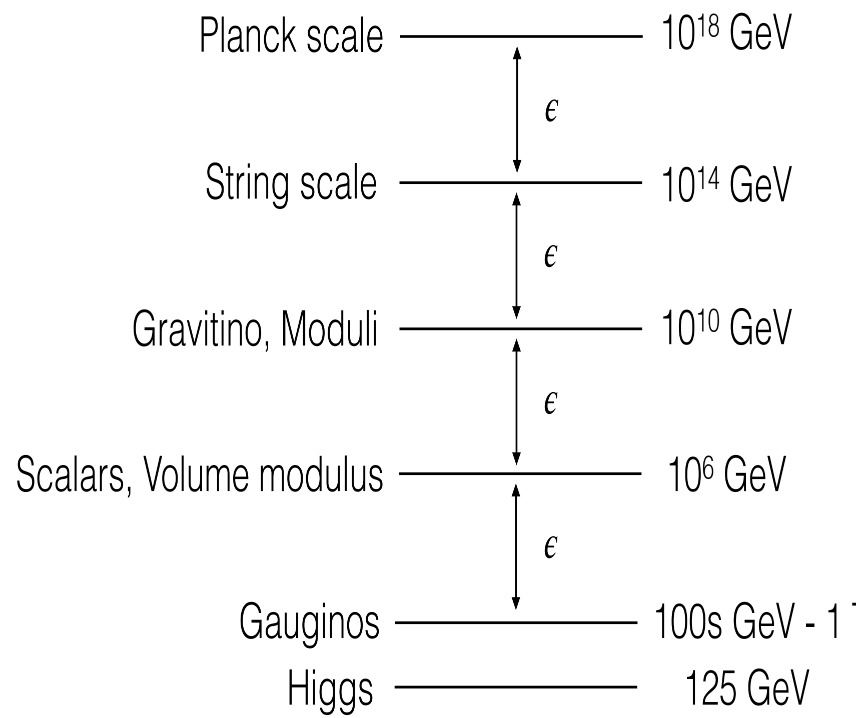
A Bottom-up perspective
M Reece et al
arXiv:1512.04941

Split SUSY, Take 2:



SUSY's Ladder

Possible realization of gravitino decoupling from 10D II



Very few concrete scenarios

- **Split Supersymmetry** $m_0 \sim 50\ M_{1/2}$

  $m_0 \sim 1000\ M_{1/2}$

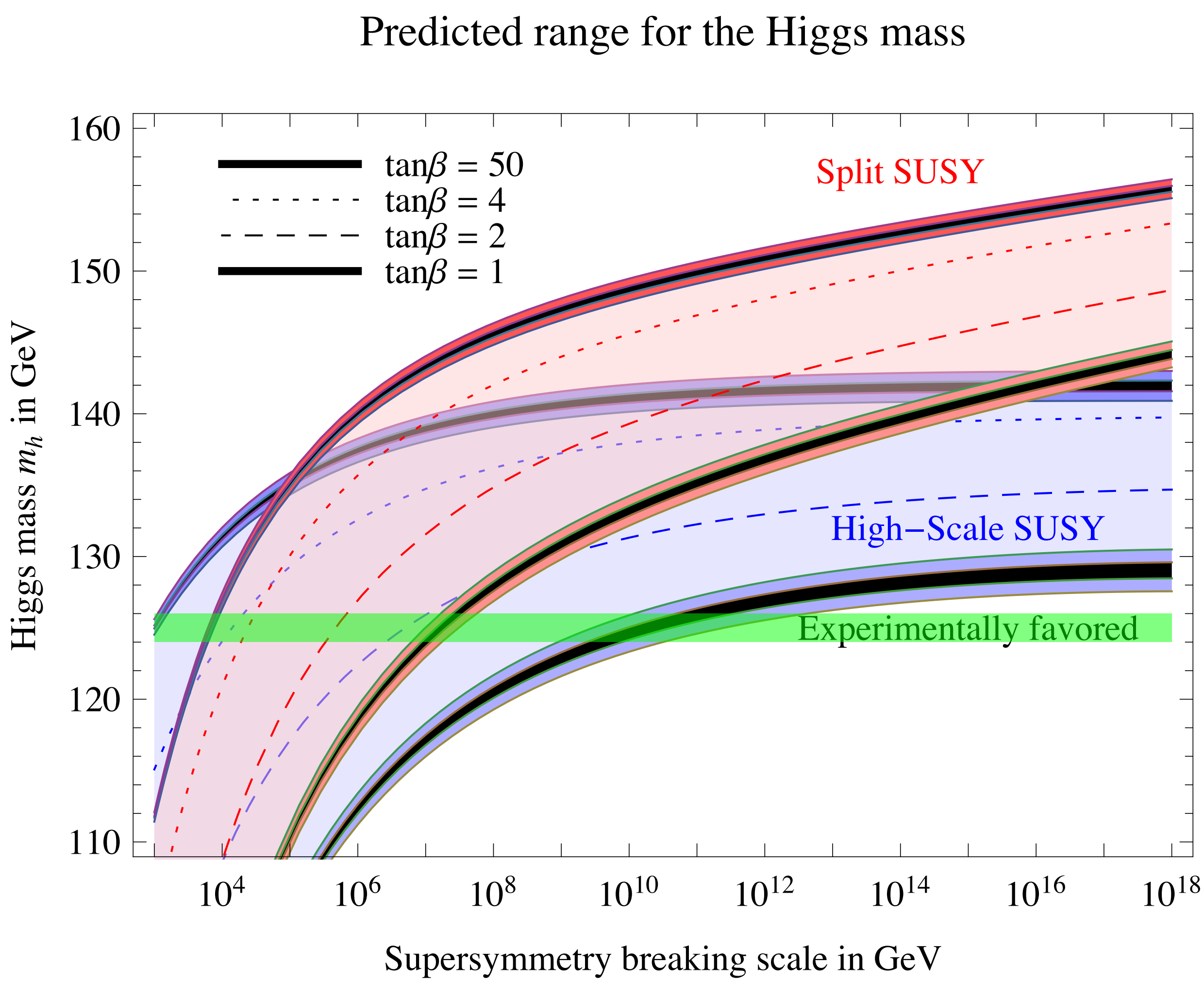
  $M_{1/2} \sim 1$ TeV

(Concrete realisation of split susy in a framework including landscape, relative scales fixed, matching well with experiments...)

- **High energy SUSY** $m_0 \sim M_{1/2} \sim 10^{11}$ GeV

- **Mirage** (anomaly ~gravity mediation (Choi et al))

Split and Large Scale SUSY



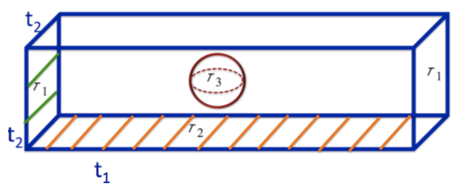
Giudice et al 2012

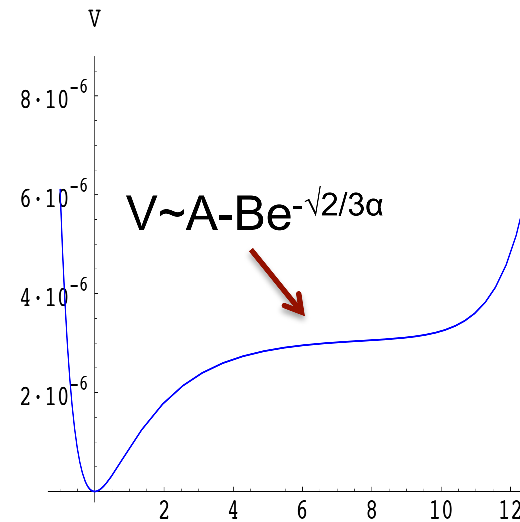
Cosmology:

Kahler+Fibre Inflation

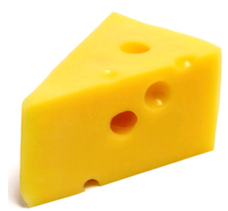
Stringy realisation of α-attractors

- $\alpha=2$ (fibre inflation) Burgess, Cicoli, FQ (2007)



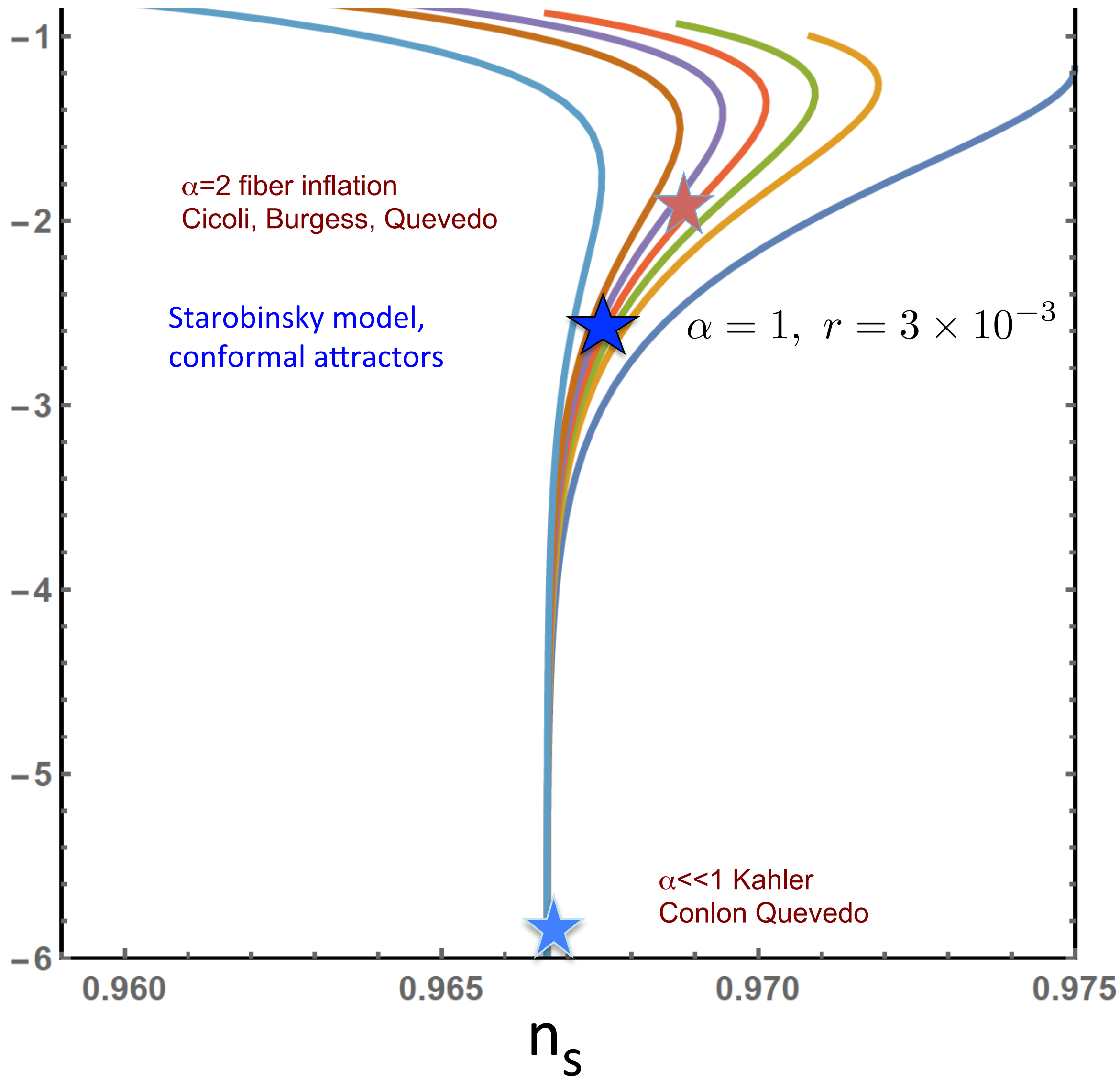


- $\alpha=(V\ln V)^{-1}$ (Kahler blow-up inflation)
- Conlon, FQ (2006)



- ...$\alpha=(\ln V)^{-1}$ (polyinstanton inflation) Cicoli, Pedro, Tasinato (2011)

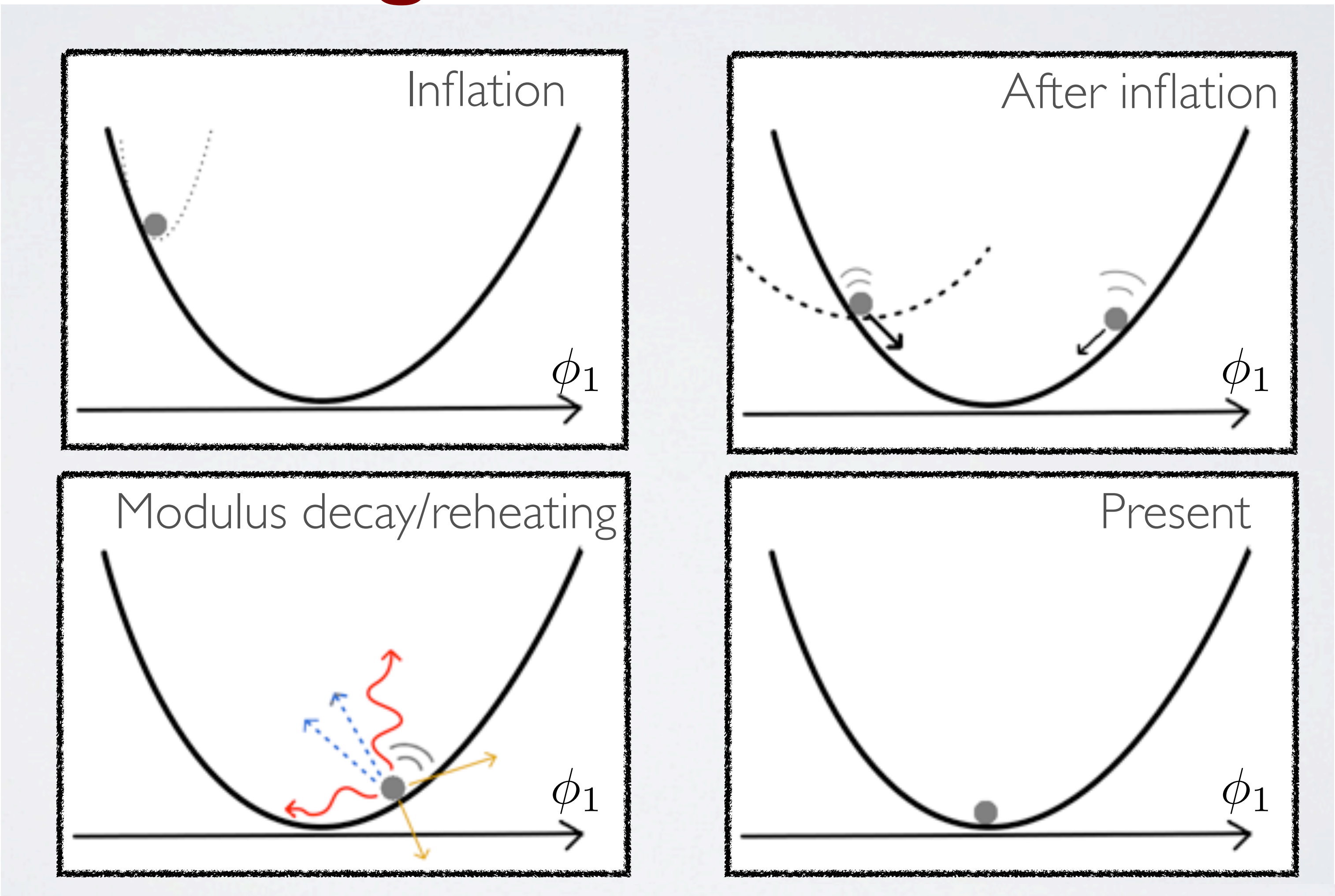
Inflation: Fibre+Kahler



From Kallosh talk

After Inflation

Cosmological Moduli 'Problem'



$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$$

T > O(1 MeV), so $m_\phi \gtrsim 3 \cdot 10^4\ \mathrm{GeV}$

Coughlan et al 1983, Banks et al, de Carlos et al 1993

e.g. After Kahler Inflation

Explicit computation of Vacuum misalignement

$$Y = \frac{\delta\varphi}{M_{\rm pl}} = \sqrt{\frac{2}{3}}\delta\phi \simeq 2\sqrt{\frac{2}{3}}R\phi_* \simeq 0.1 - 1$$

M.Cicoli, K. Dutta, A. Maharana, FQ
arXiv:1604.08512

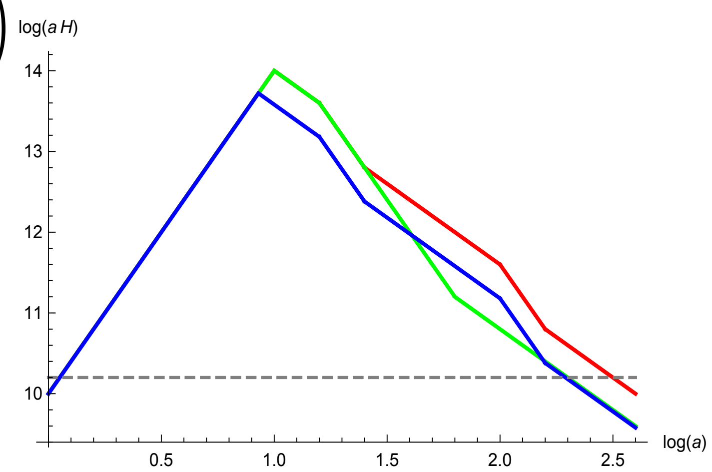
Number of efoldings:

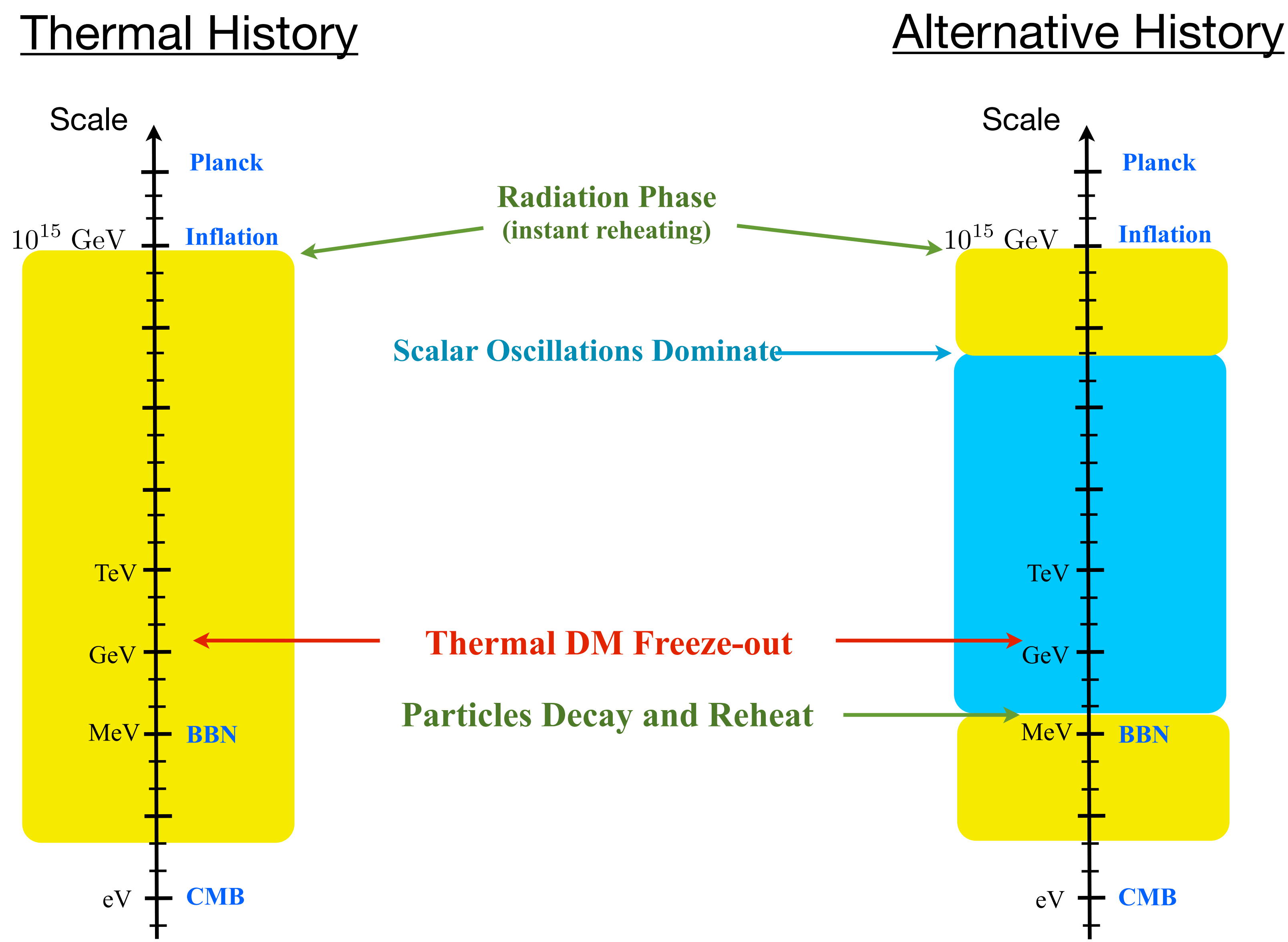
$$N_e + \frac{1}{4}N_{\rm mod} + \frac{1}{4}(1-3w_{\rm re})N_{\rm re} \approx 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{\rm end}}\right)$$

$$\left(55 - \frac{1}{4}N_{\rm mod}\right) \pm 5$$

$$N_{\rm mod2} \approx \frac{2}{3}\ln\left(\frac{16\pi\mathcal{V}^{5/2}(\ln\mathcal{V})^{5/2}Y^4}{10\beta^2}\right)$$

$$N_e \simeq 44.65 + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{\rm end}}\right) \simeq 45 \qquad n_s \simeq 0.955\,.$$

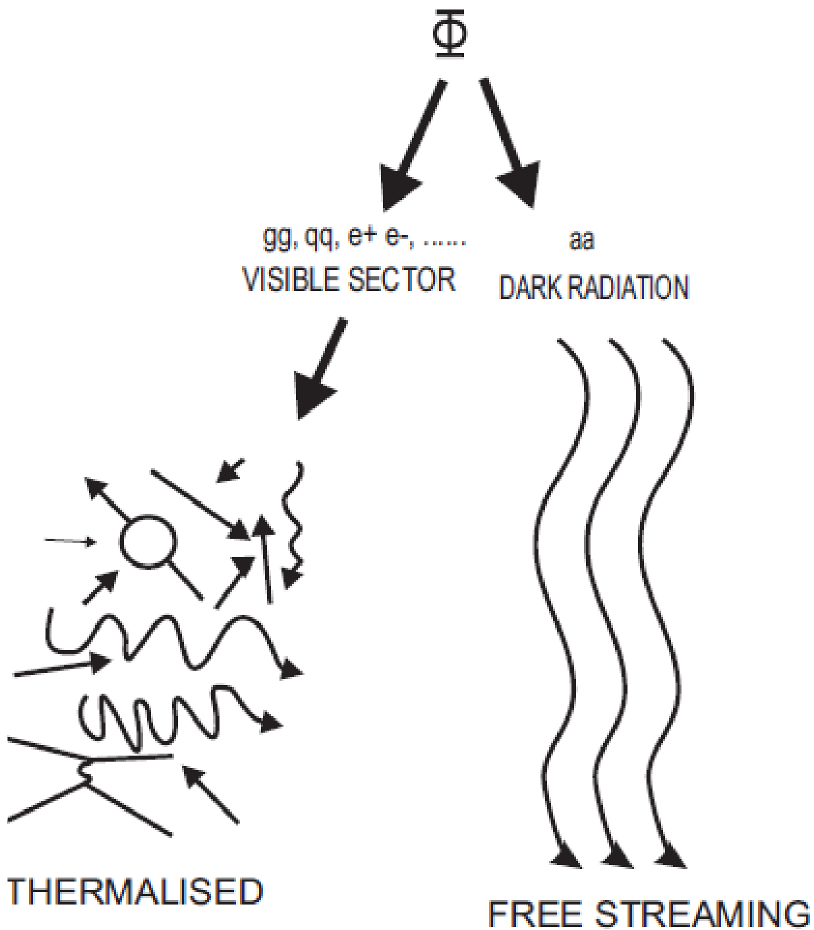




From S. Watson, SUSY 2013

Generic from LVS: very light axion
(dark radiation, matter, energy?)

mass<10^{-22} eV...



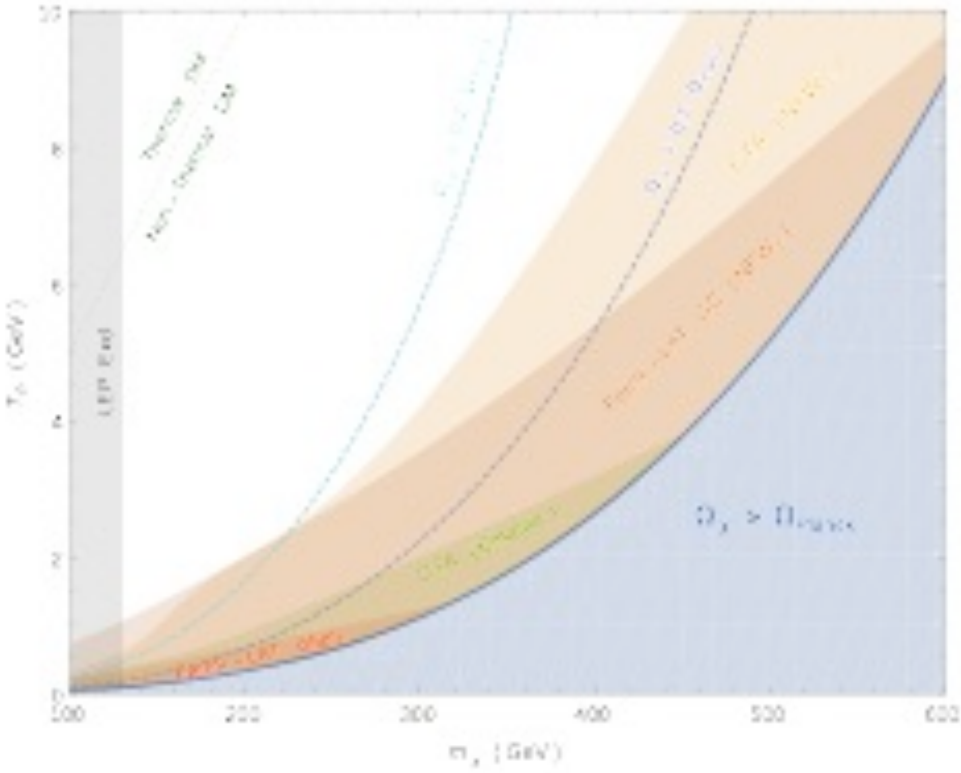
e.g. Non-Thermal Dark-Matter (MSSM)

- KKLT: gravitino decay
- KKLT: D7 Higgsino overproduction
- KKLT:D3 small region allowed Higgsino DM

- LVS: Volume decay
- LVS:D7 Higgsino overproduction
- LVS: D3: allowed region to be constrained by 1Ton (Xenon, CTA) and 100TeV (not LHC).

L. Aparicio, M. Cicoli, B Dutta, F. Muia + FQ arXiv:1607.00004

Non-thermal Higgsino DM



Model independent indirect search 300-600 GeV Higgsinos
all others multi TeV

Conclusions

- **Two general scenarios of SUSY breaking with computable soft terms** **(fully SUSY EFT with Nilpotent superfield)**
- **KKLT: D7 (similar but not equal to previously studied), D3 (all new)**
- **LVS: Similar to previous studies**
- **Explicit (mini) split SUSY**
- **LVS+KKLT Nonthermal Dark matter**
- **Interesting (testable) phenomenology**

Geometry 1

$$ds^2_{10} = e^{2D}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2D}g_{mn}dy^m dy^n$$

$$e^{2D(y)} \equiv h^{-1/2}(y)$$

$$ds^2_{10} = \mathcal{V}^{1/3}\left(e^{-4A} + \mathcal{V}^{2/3}\right)^{-1/2} ds^2_4 + \left(e^{-4A} + \mathcal{V}^{2/3}\right)^{1/2} ds^2_{CY_0}$$

$$(F_5)_{rtx^1x^2x^3} = \frac{\partial e^{4A}}{\partial r}$$

Giddings-Maharana

$$\boxed{\mathcal{V}^{2/3} \gg e^{-4A}}$$

$$ds^2_{10} = ds^2_4 + \mathcal{V}^{1/3} ds^2_{CY_0} = ds^2_4 + ds^2_{CY}$$

Geometry 2

$$\boxed{e^{-4A} \gg \mathcal{V}^{2/3}}$$

~Klebanov-Strassler

$$ds_{10}^2 = e^{2D_w} ds_4^2 + e^{-2D_w}\left(dr^2 + r^2 ds_{T^{1,1}}^2\right)$$

$$e^{-D_w(r_0)} \sim \frac{R}{r_0} \qquad r_0 \propto \mathcal{V}^{1/6} z^{1/3} \ell_s \sim \mathcal{V}^{1/6} e^{-\frac{2\pi K}{3g_s M}} \ell_s$$

Redshift factor

$$\Omega \sim e^A \mathcal{V}^{1/6} \ll 1. \quad M_s^w \quad \sim \quad \Omega M_s \sim \frac{\mathcal{V}^{1/6} e^A}{\mathcal{V}^{1/2}} = \frac{e^A}{\mathcal{V}^{1/3}} \gg \frac{W_0}{\mathcal{V}}$$

$$\Longrightarrow \boxed{e^{-A} \ll \mathcal{V}^{2/3} \ll e^{-4A}}$$

$$e^{4A_w(r_0)} \sim e^{-\frac{8\pi K}{3g_s M}} \equiv e^{-4\alpha}$$

Geometry 3

$$V_{\rm uplift} = \frac{D^2}{(T+T^*)^\alpha} = \frac{D^2}{\mathcal{V}^{2\alpha/3}} \qquad \begin{cases} \alpha = 3 & \text{KKLT} \\ \alpha = 2 & \text{KKLMMT} \end{cases}$$

$$T_3 \int d^4x \sqrt{-g_4} \sim M_s^4 \frac{\mathcal{V}^{2/3}}{e^{-4A(r_0)} + \mathcal{V}^{2/3}} \sim \begin{cases} \frac{e^{4A(r_{\rm D3})}}{\mathcal{V}^{4/3}} & \text{for } e^{-4A(r_0)} \gg \mathcal{V}^{2/3} \\ \frac{1}{\mathcal{V}^2} & \text{for } \mathcal{V}^{2/3} \gg e^{-4A(r_0)} \end{cases}$$

Giddings-Maharana

$$T_3 = 8\pi^3 g_s \alpha'^2 \sim M_s^4 \sim M_p^4/\mathcal{V}^2.$$

Anti D3 brane sits at tip of throat at r_0 !

Brane-Antibrane Interactions (KKLMMT)

$$S = -T_3 \int d^4x \sqrt{-g} \left(\frac{1}{h} \sqrt{1 - h g^{\mu\nu} \partial_\mu r \partial_\nu r} - \frac{q}{h} \right)$$

q=1 (-1) D3 brane (antibrane)

$$\int d^4x \sqrt{-g_4} \left(\frac{1}{2} T_3 \partial_\mu r_{D3} \partial_\mu r_{D3} - 2T_3 \frac{r_0^4}{R^4} \left(1 - \frac{\ell_s^4}{R^4} \frac{r_0^4}{r_{D3}^4} \right) \right)$$

A curiosity: SUSY KKLMMT

Recall D3/anti D3 Potential

$$V \sim M_p^4 \frac{e^{-4\alpha}}{\mathcal{V}^{4/3}} \left(1 - e^{-4\alpha}\left(1 - 4\mathcal{V}^{1/3}\frac{\varphi}{M_p} + 10\mathcal{V}^{2/3}\frac{\varphi^2}{M_p^2} + \cdots\right)\right)$$

N=1 EFT

$$K = -3\log\left(T + T^* - \phi^*\phi - X^*X\right)$$

$$W = W_0(U,S) + W_{np}(U,S,T) + \boxed{\rho(U,S,\phi)X}$$

$$\rho = \rho_0 + \delta\rho = \rho_0 + \rho_1\phi + \rho_2\phi^2 + \cdots \qquad \hat{\varphi} = \frac{\phi}{\sqrt{3(T+T^*)}} \sim \frac{\phi}{\mathcal{V}^{1/3}}$$

$$V_{F_X} = e^K K^{-1}_{XX^*}\left\|D_X W\right\|^2 = \mathcal{V}^{-2}\mathcal{V}^{2/3}\left\|\frac{\partial W}{\partial X}\right\|^2 = \frac{|\rho|^2}{\mathcal{V}^{4/3}} \sim \frac{|\rho|^2}{(T+T^*)^2}$$
$$\sim \frac{1}{\mathcal{V}^{4/3}}\left(|\rho_0|^2 + 2\mathcal{V}^{1/3}\mathrm{Re}(\rho_0^*\rho_1\hat{\varphi}) + \mathcal{V}^{2/3}|\rho_1|^2|\hat{\varphi}|^2 + 2\mathcal{V}^{2/3}\mathrm{Re}(\rho_0^*\rho_2\hat{\varphi}^2) + \cdots\right)$$

'Reproduces' V for

$$|\rho_0| \sim e^{-2\alpha}, \qquad |\rho_1| \sim |\rho_2| \sim e^{-6\alpha}, \cdots$$

Slightly more general

$$W = W_0(U,S) + W_{np}(U,S,T) + \rho(U,S,\phi)X$$

$$K = -2\log\mathcal{V} + AXX^* + B\phi\phi^* + CXX^*\phi\phi^* + \cdots$$

$$A = \frac{a}{\mathcal{V}^{2/3}} + b(z,z^*) = \frac{a}{\mathcal{V}^{2/3}} + e^{4A}$$

$$V_{up} = e^K K^{-1}_{XX^*}|\rho_0|^2 = \frac{|\rho_0|^2}{\mathcal{V}^2}\frac{\mathcal{V}^{2/3}}{a + b\mathcal{V}^{2/3}}$$

Reproduces Giddings-Maharana uplift ($b=e^{4A}$)!

LVS vs KKLT

- W_0~0.1-100
- AdS non SUSY
- Minimum: perturbative in big cycle vs non-perturb. in small cycle
- Uplift:anti D3 branes, D-terms...
- Small parameter = 1/V
- SUSY broken by fluxes
- Many moduli: need $h_{21}>h_{11}>1$ + one blow up, the rest by loop effects/ D-terms

- W_0<<1
- AdS SUSY
- Minimum: tree-level vs non-perturbative
- Uplift: anti D3 branes...(no D-terms)
- Small parameter W0
- SUSY broken by uplifting mechanism
- Many moduli: non-perturbative effects for each of them or ...

SUSY Challenges for String Scenarios

- **Explicit $\mathcal{N}$=1 Compactification**
- **Concrete SUSY breaking mechanism**
- **Moduli Stabilisation (small cc)**
  (+ avoid CMP (plus gravitino+ dark radiation excess,etc!))
- **Chiral visible sector**
- **Computable soft terms**