Soft terms in string models

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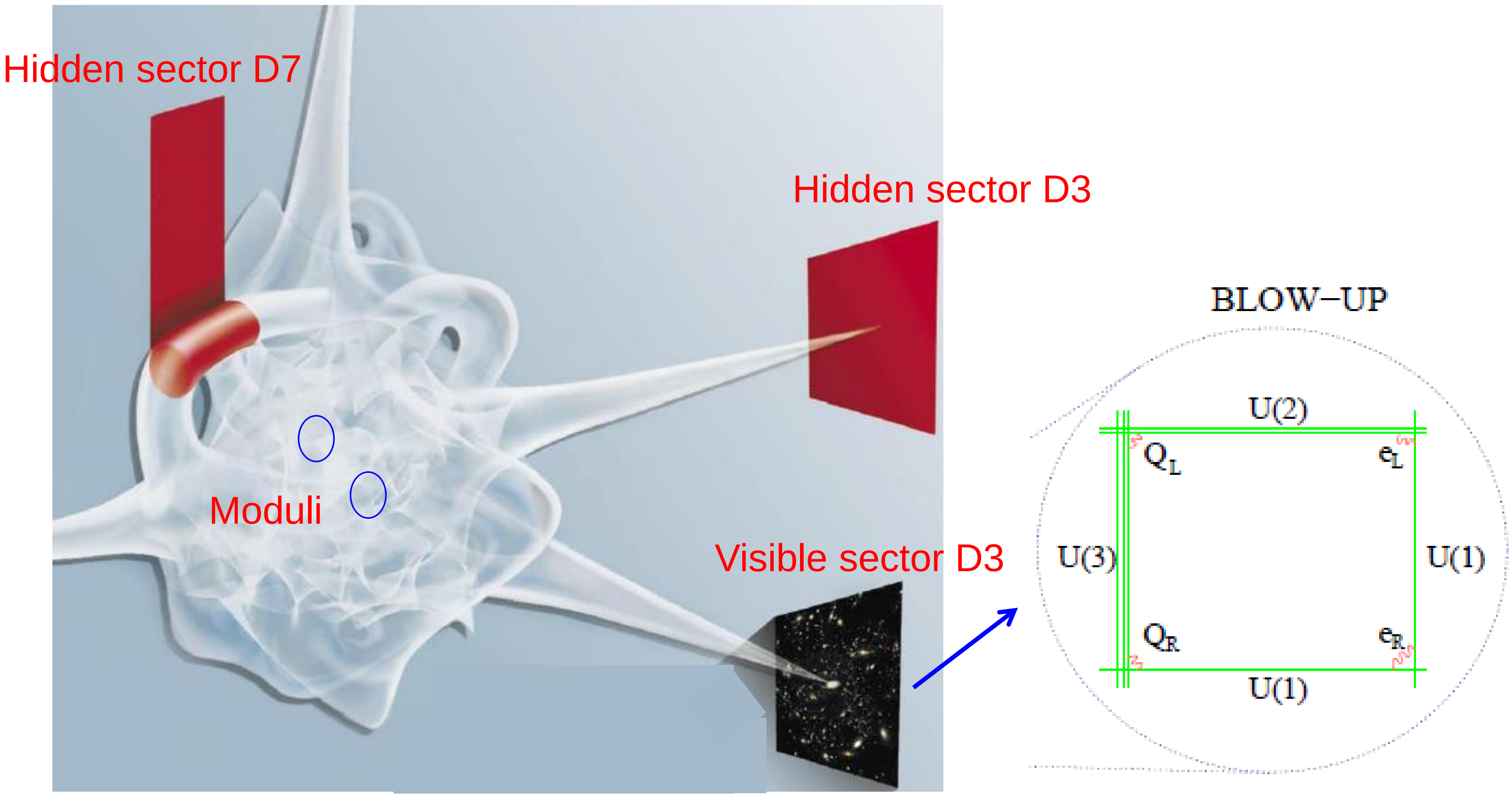
Based on papers written in collaboration with:

Allahverdi, Aparicio, Burgess, Ciupke, Conlon, deAlwis, Dutta, Krippendorf, Maharana, Marsh, Muia, Pedro, Quevedo, Rummel, Valandro

String models

- Ubiquitous presence of geometric moduli (closed strings)
- Branes provide non-Abelian gauge symmetries and chiral matter (open strings)
- Standard Model (or MSSM/GUT theories) localised on branes (D3/D7 in type IIB)

→ model-building is a local issue while moduli stabilisation/SUSY breaking is a global issue



Generic problems

- Cosmological moduli problem [Coughlan et al] [Banks et al] [de Carlos et al]

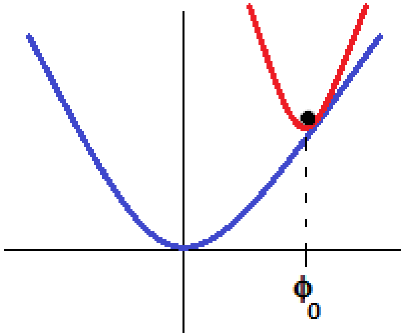
  i) During inflation ϕ displaced from $\phi = 0$ to $\phi = \phi_0 \sim M_p$

  ii) ϕ starts oscillating when $H \sim m_\phi$ ⟶ ϕ stores energy

  iii) ϕ redshifts as matter ⟶ dominates energy density

  iv) ϕ decays when $H \sim \Gamma \sim \varepsilon^2 m_\phi$ where $\varepsilon \sim m_\phi / M_p << 1$

  v) Reheat temperature $T_{rh} \sim \varepsilon^{1/2} m_\phi > T_{BBN} \sim 3$ MeV ⟶ $m_\phi > 50$ TeV



- Gravitino problem [Endo,Hamaguchi,Takahashi] [Nakamura, Yamaguchi]

  i) Gravitino production from ϕ decay if $2m_{3/2} < m_\phi$

  ii) If $m_{3/2} < 50$ TeV ⟶ gravitino decay after BBN/overclosure

  iii) If $m_{3/2} > 50$ TeV ⟶ DM overproduction from gravitino decay/annihilation (unless $T_{3/2} > T_f$)

Simplest way-out: $m_{3/2} > m_\phi > 50$ TeV

Generic problems

- Generically in string compactifications:

  i) ~~SUSY~~ generates $m_\phi \sim m_{3/2}$ → can avoid gravitino problem? [KKLT: $m_{3/2} \sim m_\phi /(16\pi^2)$]

  ii) Moduli mediate ~~SUSY~~ via gravitational interactions → $M_{soft} \sim m_{3/2}$

  iii) For $M_{soft} \sim m_{3/2} > m_\phi > 50$ TeV → do not get low-energy SUSY!

  → neutralino DM and gauge coupling unification do not work!

  Way-out: $M_{soft} << m_{3/2}$ due to sequestering

- Axion DM overproduction [Preskill et al] [Abbott, Sikivie]

  i) O(100) axions in string compactifications

  ii) Some projected out, eaten up by anomalous U(1)s or heavy from SUSY stabilisation

  iii) Some remain light (perturbative stabilisation) → one can be QCD axion with $f_a \sim M_s$

  iv) GUTs and inflation need $M_s \geq 10^{16}$ GeV → DM overproduction for $f_a \sim M_s > 10^{12}$ GeV

  Way-out: $f_a << M_s$ due to sequestering

Dimensional reduction: $m_{3/2} \sim M_s \, (M_s / M_p) \geq 10^{13}$ GeV for $M_s \geq 10^{16}$ GeV

→ sequestering with more than a loop-factor!

Light moduli from no-scale

- Light moduli due to no-scale structure in type IIB string models:

$$K = -3\ln\left(T+\bar{T}\right) \qquad W = W_0$$

$$V = e^K\left(K^{T\bar{T}} D_T W D_{\bar{T}} \bar{W} - 3|W|^2\right) = \underbrace{e^K |W_0|^2}_{= m_{3/2}^2} \underbrace{\left(K^{T\bar{T}} K_T K_{\bar{T}} - 3\right)}_{=0}$$

→ No-scale gives $m_\phi \sim \varepsilon\, m_{3/2} << m_{3/2}$ → no gravitino problem

$\varepsilon \sim$ size of no-scale breaking effects (α', loop or non-perturbative corrections)

- More generically: $K = -p\ln f(\tau_i) \qquad \tau^i f_i = k\, f \qquad \tau^i f_{ij} = (k-1)\, f_j$

$$K_i = -\frac{p}{f} f_i \qquad K_{ij} = -\frac{p}{f} f_{ij} + \frac{p}{f^2} f_i f_j$$

$$\tau^i K_{ij} = -\frac{p}{f}\left(\tau^i f_{ij}\right) + \frac{p}{f^2}\left(\tau^i f_i\right) f_j = \frac{p}{f} f_j = -K_j$$

$$\tau^k = \tau^i \delta_i^k = \tau^i K_{ij} K^{jk} = -K_j K^{jk}$$

→ $$\boxed{K_j K^{jk} K_k = -\tau^k K_k = \frac{p}{f}\tau^k f_k = k\, p}$$

- Type IIB:

$$K = -2\ln\mathcal{V} \qquad \mathcal{V} = \frac{k_{ijk}}{3!} t^i t^j t^k \qquad \tau_i = \frac{\partial\mathcal{V}}{\partial t^i} = \frac{k_{ijk}}{2!} t^j t^k$$

→ $$p = 2 \qquad k = \frac{3}{2}$$

Sequestering from no-scale

- SUSY breaking from non-zero moduli F-terms:

$$F^T = e^{K/2} K^{T\bar{T}} D_{\bar{T}} \bar{W} = e^{K/2} \bar{W} \; K^{T\bar{T}} K_{\bar{T}} \neq 0$$

- D3 branes at singularities ⟶ locality:

$$\mathcal{K} = -3\ln\left(T+\bar{T}-\varphi\bar{\varphi}\right) = -3\ln\left(T+\bar{T}\right) - 3\ln\left(1-\frac{\varphi\bar{\varphi}}{T+\bar{T}}\right)$$

$$\simeq -3\ln\left(T+\bar{T}\right) + 3\frac{\varphi\bar{\varphi}}{T+\bar{T}} \equiv K + \tilde{K}(T+\bar{T}) \; \varphi\bar{\varphi} \quad \longrightarrow \quad \boxed{\tilde{K}(T+\bar{T}) = 3\, e^{K/3}} \; (*)$$

- Sequestering due to no-scale structure:

$$m_0^2 = m_{3/2}^2 - F^T \bar{F}^{\bar{T}} \partial_T \partial_{\bar{T}} \ln \tilde{K} = m_{3/2}^2 - \frac{1}{3} e^K \left|W_0\right|^2 K^{T\bar{T}} K_{\bar{T}} K_T K^{\bar{T}T} K_{T\bar{T}}$$

$$= m_{3/2}^2 \left(1 - \frac{1}{3} K^{T\bar{T}} K_{\bar{T}} K_T\right) = 0$$

No-scale gives $m_0 \sim \varepsilon\, m_{3/2} << m_{3/2}$ ⟶ can have high $m_{3/2}$ (⟶ high M_s) and low m_0

$\varepsilon \sim$ size of effects breaking (*) (α', loop or non-perturbative corrections)

- More generically: $\boxed{\tilde{K} = c\, e^{K/3}}$

⟶ $$m_0^2 = m_{3/2}^2 - F^i \bar{F}^{\bar{j}} \partial_i \partial_{\bar{j}} \ln \tilde{K} = m_{3/2}^2 - \frac{1}{3} K_{i\bar{j}} F^i \bar{F}^{\bar{j}} = m_{3/2}^2 - \frac{1}{3}\left(V_0 + 3m_{3/2}^2\right) = 0$$

Mass spectrum

[Aparicio, MC, Krippendorf, Maharana, Muia, Quevedo]
[Reece, Xue]

MSSM-like		Split SUSY-like
M_p	10^{18} GeV	M_p
$M_s \sim M_p\, \varepsilon$	$10^{14\text{-}15}$ GeV	$M_s \sim M_p\, \varepsilon$
$m_{3/2} \sim M_p\, \varepsilon^2$	$10^{10\text{-}11}$ GeV	$m_{3/2} \sim M_p\, \varepsilon^2$
$m_\phi \sim M_p\, \varepsilon^3$	$10^{6\text{-}7}$ GeV	$m_\phi \sim m_0 \sim M_p\, \varepsilon^3$
$M_{1/2} \sim m_0 \sim M_p\, \varepsilon^4$	$10^{2\text{-}3}$ GeV	$M_{1/2} \sim M_p\, \varepsilon^4$

Leading order no-scale breaking: α' effects → $\varepsilon \sim \mathcal{V}^{-1/2} \sim 10^{-3/-4}$

Unification scale in D3-brane models: $M_{GUT} \sim M_s\, \varepsilon^{-1/3} \sim 10^{16}$ GeV [Conlon, Palti]

No flavour problem (for MSSM-like): flavour and ~~SUSY~~ from two decoupled sectors [Conlon]

Non-standard post-inflationary cosmology

- Lightest modulus mass: $m_\phi \sim 10^{6-7}$ GeV >> 50 TeV $\longrightarrow$ $T_{rh} \sim 1 - 10$ GeV
- ϕ decay dilutes any previous relic: [Moroi,Randall]

i) Baryon asymmetry $\longrightarrow$ good if AD baryogenesis is too efficient [Kane,Shao,Watson,Yu] [MC, Muia]

ii) Standard thermal WIMP DM since $T_{rh} < T_f \sim m_{DM}/20 \sim 10$ GeV - 100 GeV

[Allahverdi, Acharya, MC, Dutta, Kane,Kumar,Sinha,Watson]

- Products from ϕ decay:

i) Non-thermal DM

$$\frac{n_{DM}}{s} = \left(\frac{n_{DM}}{s}\right)_{obs} \frac{\langle \sigma_{ann} v \rangle_f^{th}}{\langle \sigma_{ann} v \rangle_f} \left(\frac{T_f}{T_{rh}}\right) \quad \text{where} \quad \left(\frac{n_{DM}}{s}\right)_{obs} \approx 5 \cdot 10^{-10} \left(\frac{1\,\text{GeV}}{m_{DM}}\right) \quad \text{and} \quad \langle \sigma_{ann} v \rangle_f^{th} \approx 3 \cdot 10^{-26} cm^3 s^{-1}$$

a) Need $\langle \sigma_{ann} v \rangle_f = \langle \sigma_{ann} v \rangle_f^{th} \left(T_f / T_{rh}\right)$

b) Since $T_{rh} < T_f$ $\longrightarrow$ $\langle \sigma_{ann} v \rangle_f > \langle \sigma_{ann} v \rangle_f^{th}$ $\longrightarrow$ Higgsino-like DM

c) Bino-like LSP: $\langle \sigma_{ann} v \rangle_f < \langle \sigma_{ann} v \rangle_f^{th}$ $\longrightarrow$ DM overproduction

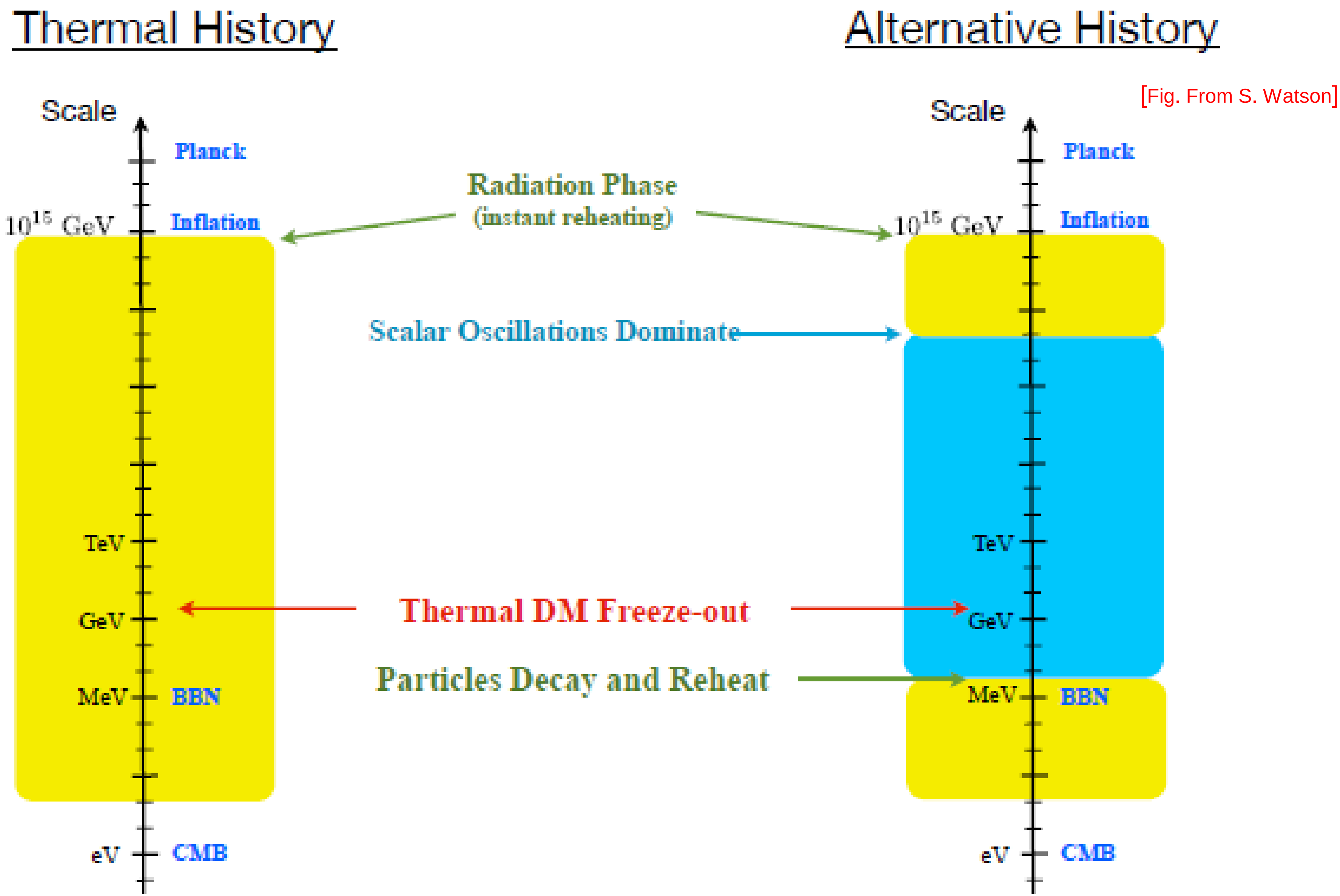
ii) Axionic dark radiation

a) Moduli are gauge singlets $\longrightarrow$ non-zero branching ratio into hidden fields [MC, Conlon,Quevedo] [Higaki, Takahashi]

b) Light axions unavoidable in models with perturbative moduli stabilisation [Allahverdi, MC, Dutta,Sinha]

$\longrightarrow$ $\Delta N_{eff} > 0$ unavoidable $\quad$ $\Delta N_{eff} \leq 1$ within 2σ

Thermal vs Non-thermal cosmology



Non-thermal CMSSM

[Aparicio,MC,Dutta,Krippendorf,Maharana,Muia,Quevedo]

- Consider CMSSM with non-thermal LSP DM
- Impose:

i) radiative EWSB + 125 GeV Higgs mass

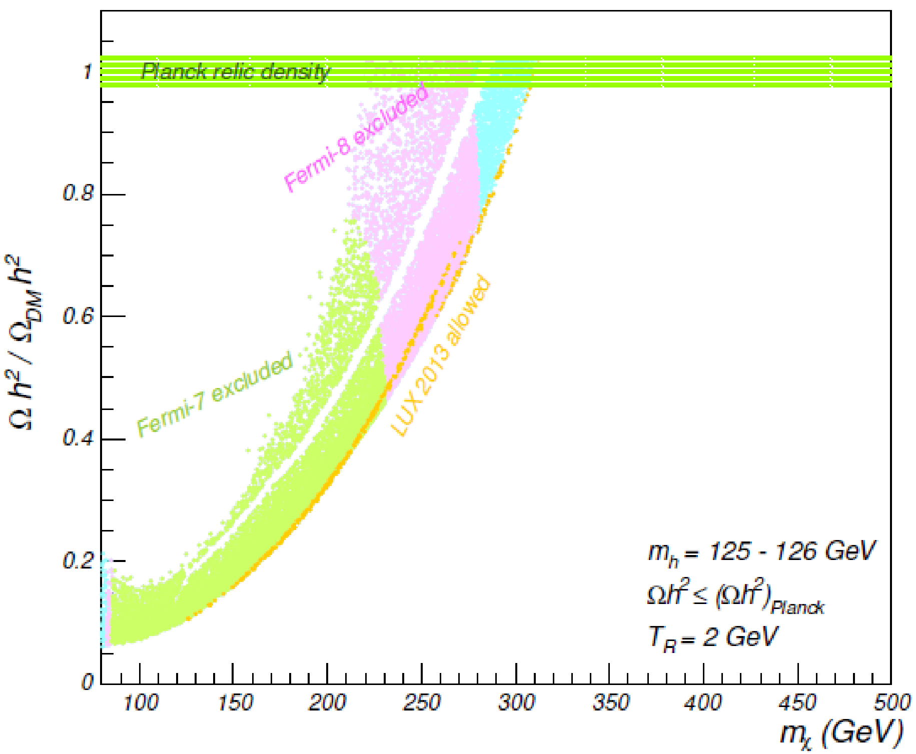
ii) no DM overproduction

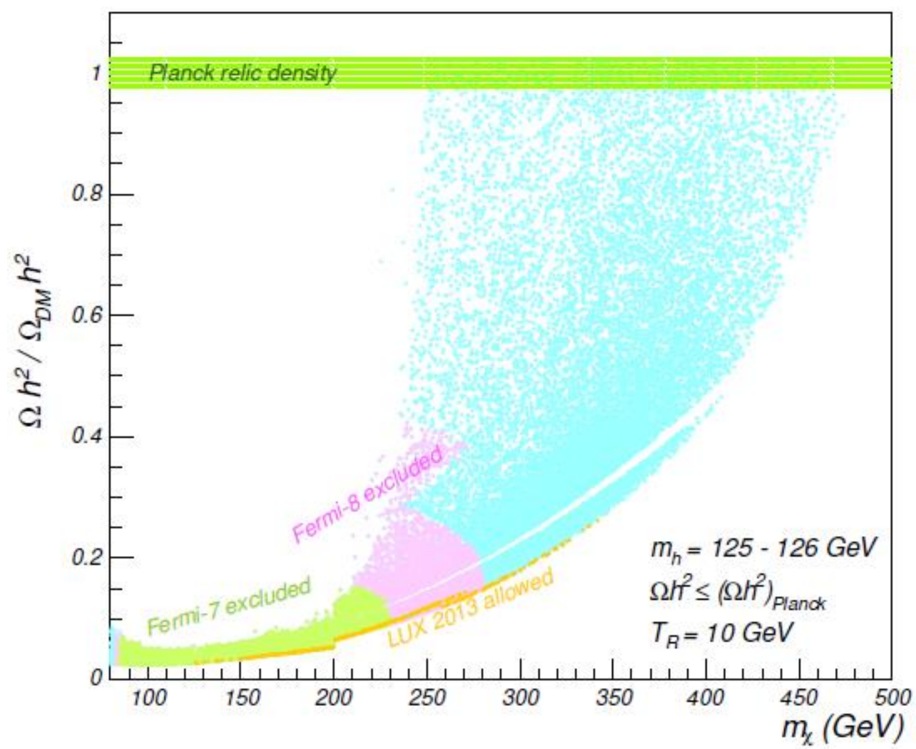
iii) bounds from colliders (LHC), CMB (Planck), direct (LUX) and indirect (Fermi) DM searches

a) observed DM content saturated for $T_{rh} = 2$ GeV and 300 GeV Higgsino LSP

b) stops around 4-5 TeV, gluinos around 2-3 TeV + light degenerate neutralinos

c) realised in type IIB sequestered string models





Non-thermal Higgsinos

- Model independent analysis of Higgsino LSP (for MSSM, NMSSM, split SUSY, …)
- Impose (no radiative EWSB and no 125 GeV Higgs mass): [Aparicio,MC,Dutta,,Muia,Quevedo]

i) no DM overproduction

ii) bounds from colliders (LHC), CMB (Planck), direct (LUX) and indirect (Fermi) DM searches

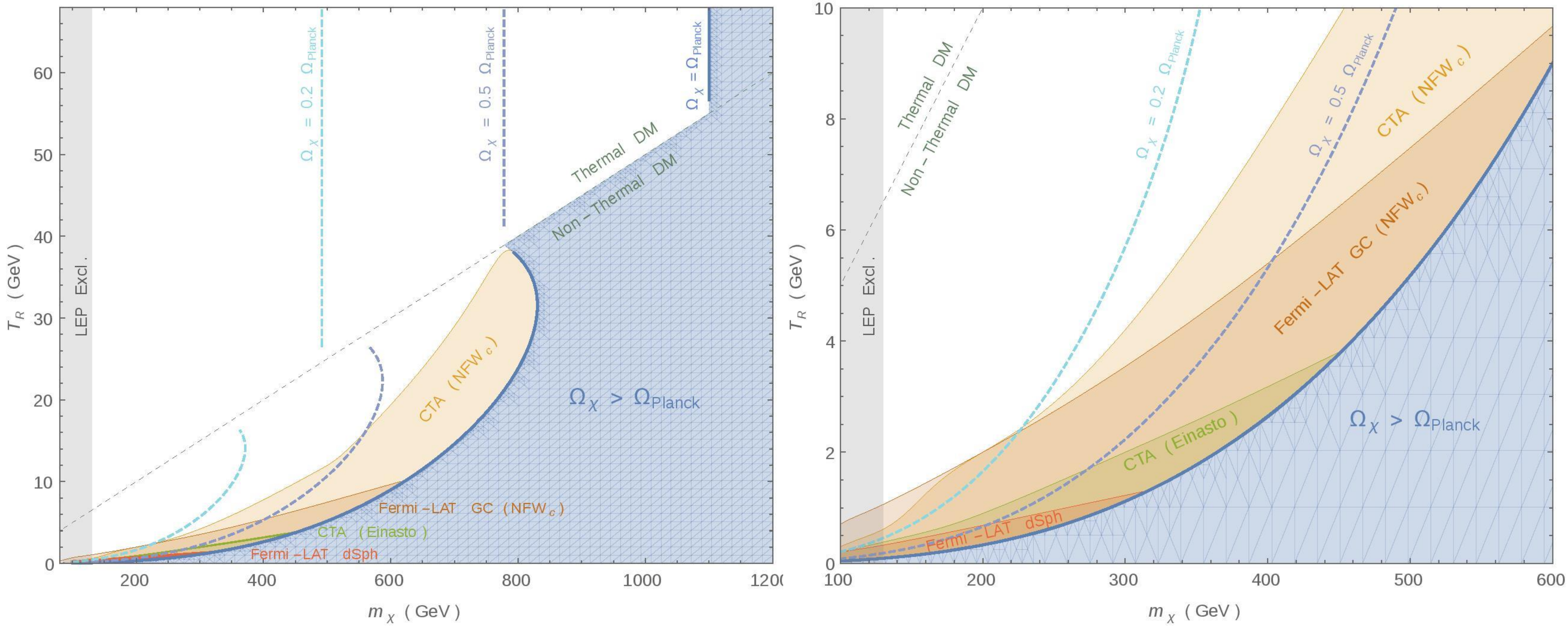
a) observed DM content saturated for T_{rh} = 2-40 GeV and 300-850 GeV Higgsino LSP

b) light degenerate neutralinos/charginos + rest heavier (model dependent)

c) collider signature: monojet + missing energy + soft leptons

LHC14: μ < 200 GeV (at 5σ) [Baer, Mustafayev, Tata] 100 TeV machine: μ < 850 GeV [Low, Wang]

d) realised in type IIB sequestered string models

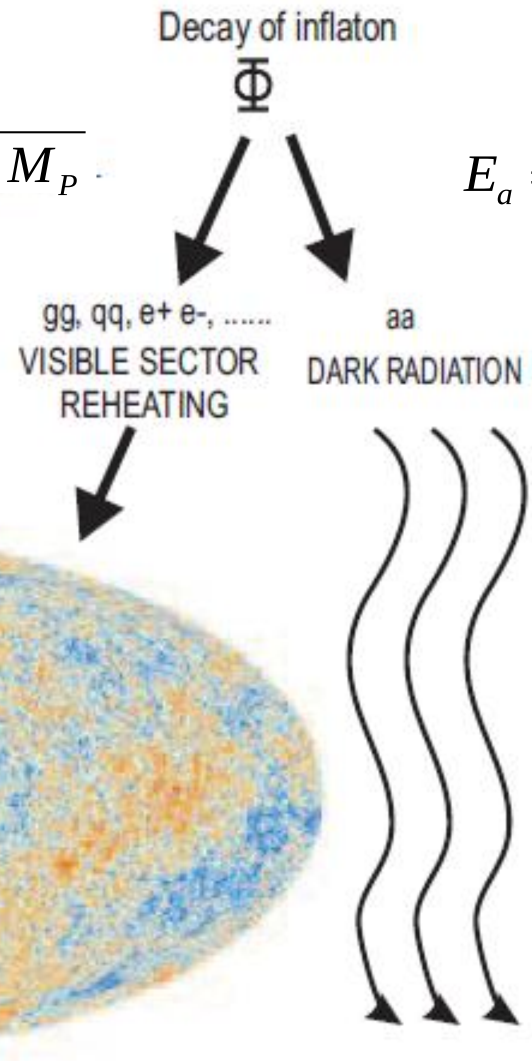


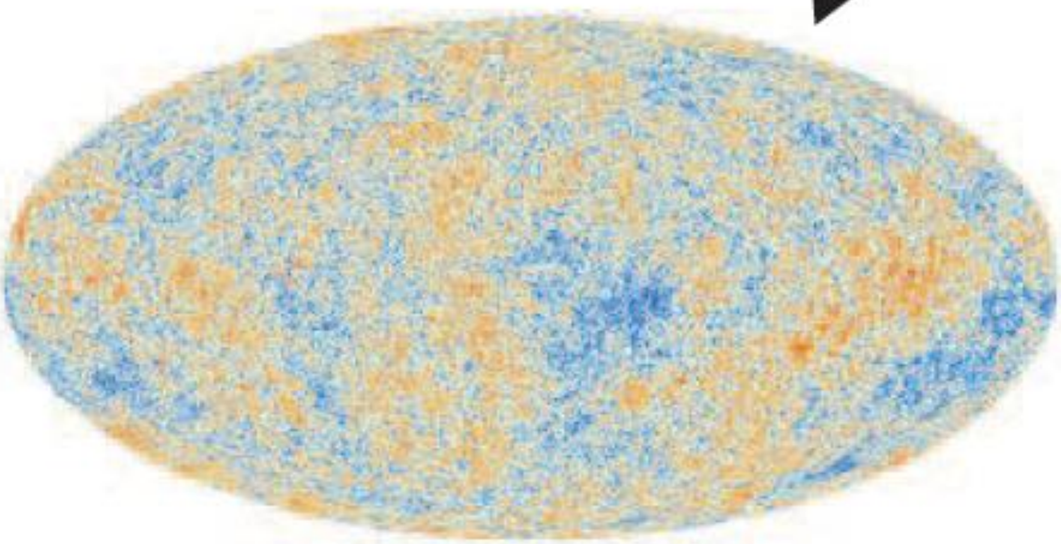
Dark radiation production

$$T_\gamma \approx T_{rh} \approx m_\phi \sqrt{m_\phi / M_P}$$

$$E_a = m_\phi / 2$$

$$\frac{E_a}{T_\gamma} \approx \sqrt{\frac{M_p}{m_\phi}} \approx 10^6 \left(\frac{10^6 \text{ GeV}}{m_\phi} \right)^{1/2}$$





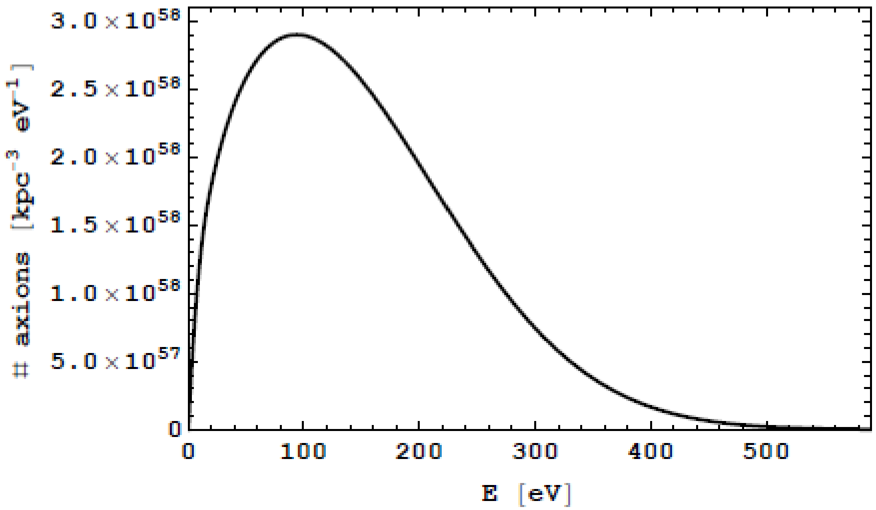
Free streaming

Ratio of energies retained through cosmic history → still valid today!

Cosmic axion background and 3.5 keV line

PREDICTION: Cosmic Axion Background

$$E_a \approx 200\,\text{eV}\left(\frac{10^6\ \text{GeV}}{m_\phi}\right)^{1/2}$$



- For 10^5 GeV ≤ m_φ ≤ 10^7 GeV, CAB lies today in soft X-ray wavebands
- Detectable via axion-photon conversion in astrophysical B-fields

$$\mathcal{L} \supset -\frac{a}{4M} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- Soft X-ray excess in clusters observed since 1996 (EUVE, ROSAT, XMM-Newton, Suzaku, Chandra)
- Match data for

$$\Delta N_{\text{eff}} \approx 0.5 \qquad m_a < 10^{-12}\,\text{eV} \qquad M \approx 10^{12}\ \text{GeV}$$

[Conlon, Marsh]

- 3.5 keV line from galaxy clusters (XMM-Newton, Suzaku ,Chandra) due to DM → aa converting to γ
- Better than simplest explanation: DM → $\gamma\gamma$ for m_{DM} ~ 7 keV due to:

i) Inferred signal strength: flux depends on both DM density and B-field

ii) Morphology: stronger signal from cool core where B-field peaks

iii) Non-observation in dwarf galaxies and galaxies: small size and B-field

iv) Match data for same values which give soft X-ray excess

[MC, Conlon, Marsh, Rummel]

LVS string models

- Tree-level: (i) cx str moduli U and dilaton S fixed by background fluxes at $F^U = F^S = 0$
  (ii) Kahler moduli T flat because of no-scale cancellation
- Corrections beyond tree-level

$$\mathcal{V} = \tau_b^{3/2} - \sum_{i=1}^{n} \tau_i^{3/2} \qquad K = -2\ln\mathcal{V} - \frac{\xi}{g_s^{3/2}\mathcal{V}} \qquad W = W_0 + \sum_{i=1}^{n} A_i\, e^{-a_i T_i}$$

- Scalar potential

$$V = \sum_{i=1}^{n}\left(\frac{8}{3}\sqrt{\tau_i}\,(a_i A_i)^2\,\frac{e^{-2a_i\tau_i}}{\mathcal{V}} - 4 a_i A_i W_0 \tau_i \frac{e^{-a_i\tau_i}}{\mathcal{V}^2}\right) + \frac{3\xi W_0^2}{4 g_s^{3/2}\mathcal{V}^3}$$

- AdS minimum at

$$\tau_i \approx \left(\frac{\xi}{2n}\right)^{2/3} g_s^{-1} \approx g_s^{-1} \approx O(10) \quad \text{for } g_s \approx 0.1$$

$$\mathcal{V} \approx W_0\, e^{a_i\tau_i} \approx e^{1/g_s} >> 1 \quad \longrightarrow \quad \text{trust approximations}$$

- dS vacua without anti-branes

dS$_1$ case: non-zero hidden matter F-terms induced by D-terms (T-branes) [MC, Quevedo, Valandro]

dS$_2$ case: non-perturbative effects at singularities [MC, Maharana, Quevedo, Burgess]

- Generate hierarchies naturally: $m_{3/2} \approx \frac{W_0 M_p}{\mathcal{V}} \approx M_p\, e^{-1/g_s} << M_p$
- Spontaneous ~~SUSY~~: $F^{T_b} \approx \frac{M_p^2}{\mathcal{V}^{1/3}} \neq 0 \qquad F^{T_i} \approx \frac{M_p^2}{\mathcal{V}} \neq 0 \qquad F^U \approx F^S \approx \frac{M_p^2}{\mathcal{V}^2} \neq 0$

Visible sector on D3s

[MC, Krippendorf, Mayrhofer, Quevedo, Valandro]

- D3s at singularities

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - \tau_{vs1}^{3/2} - \tau_{vs2}^{3/2}$$

- $\tau_{vs1} \leftrightarrow \tau_{vs2}$ orientifold projection
  → get U(N) groups
- D-terms for normalised matter fields $\Phi = \rho\, e^{i\theta}$

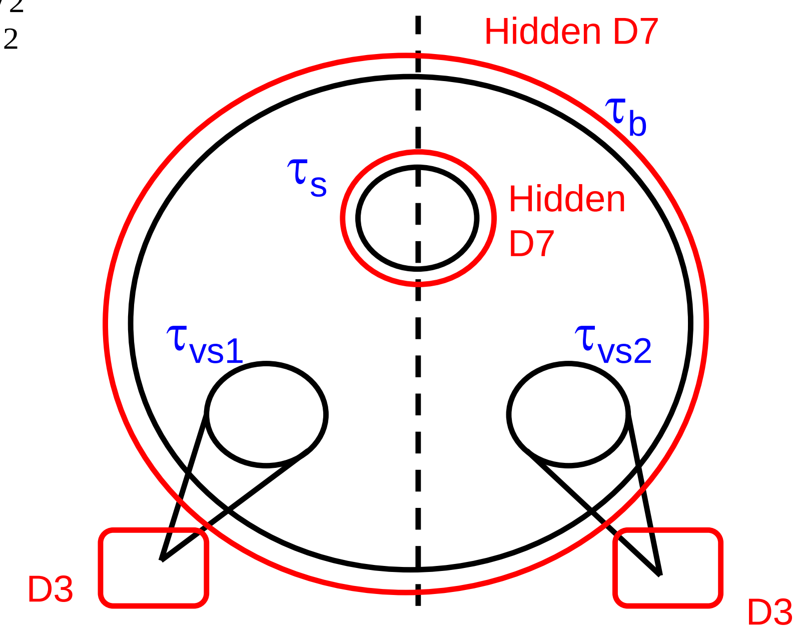
$$V_D \simeq g^2\left(\rho^2 - \xi\right)^2$$

- FI-term

$$\xi \simeq q_i K_i \simeq \frac{\tau_{vs}}{\mathcal{V}}$$

- D = 0 gives

$$\langle \rho \rangle = \sqrt{\xi} \simeq M_s \sqrt{\tau_{vs}}$$



- Closed string axion $Im(T_{vs})$ eaten up by anomalous U(1)s
- Subleading F-terms from SUSY breaking fix:

  a) non-tachyonic scalars: $\rho = 0$ → $\xi = 0$ → $\tau_{vs} = 0$

  b) tachyonic scalar: $\rho \sim 0 + 1/\mathcal{V} \sim M_s / \mathcal{V}^{1/2}$ → $\tau_{vs} \sim 0 + 1/\mathcal{V} << 1$
- Open string axion θ can be QCD axion with $f_a = \rho \sim M_s / \mathcal{V}^{1/2} \sim m_{3/2} \sim 10^{10\text{-}11}$ GeV
  → no DM overproduction
- Non-perturbative + α' effects fix τ_b and τ_s at $\tau_b^{3/2} \approx e^{\tau_s}$ $\quad \tau_s \approx g_s^{-1}$

Mass scales

- D3s at singularties → F-term of τ_{vs} is zero: $F^{vs} \propto \xi_{FI} \propto \tau_{vs} \to 0$
- Soft-terms (depending on matter Kahler metric and dS mechanism):

$$M_{1/2} \approx \frac{M_p}{\mathcal{V}^2} << m_{3/2} \approx \frac{M_p}{\mathcal{V}} \qquad m_0 \approx \begin{cases} \frac{M_p}{\mathcal{V}^{3/2}} \approx m_{\tau_b} \\ \frac{M_p}{\mathcal{V}^2} \end{cases}$$

- Set $\mathcal{V} \sim 10^7$ to get $M_{1/2} \sim O(1)$ TeV :

$$M_p \approx 10^{18} \text{ GeV}$$

$$M_{GUT} \approx M_s \mathcal{V}^{1/6} \approx 10^{16} \text{ GeV}$$

$$M_s \approx m_{\tau_{vs}} \approx m_{a_{vs}} \approx 10^{15} \text{ GeV}$$

$$M_{KK} \approx 10^{14} \text{ GeV}$$

$$m_{\tau_s} \approx m_{a_s} \approx 10^{12} \text{ GeV}$$

$$m_{3/2} \approx 10^{11} \text{ GeV}$$

MSSM:

$$m_{\tau_b} \approx 10^7 \text{ GeV}$$

$$M_{1/2} \approx m_0 \approx M_p \mathcal{V}^{-2} \approx 1 \text{ TeV}$$

↔

Split SUSY:

$$m_{\tau_b} \approx m_0 \approx 10^7 \text{ GeV}$$

$$M_{1/2} \approx 1 \text{ TeV}$$

$$m_{a_{open}} \approx 1 \text{ meV}$$

$$m_{a_b} \approx 0$$

1) TeV scale SUSY
2) Standard GUTs and WIMP DM
3) Right inflationary scale
4) No CMP for τ_b and no gravitino problem
5) QCD axion from open string modes
6) Reheating driven by the decay of τ_b
7) $T_{rh} \sim$ 1-10 GeV
8) Non-thermal dark matter
9) Axionic dark radiation
10) Affleck-Dine baryogenesis

(Ultra) - Locality

- Kahler potential

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) + K(U,S)$$

$$\mathcal{K} = K + \tilde{K}_\alpha(U,S,T)\bar{C}^\alpha C^\alpha + \left[Z(U,S,T)H_u H_d + \text{h.c.}\right]$$

- Kahler matter metric from Yukawas

$$\hat{Y}_{\alpha\beta\gamma} = e^{K/2}\frac{Y_{\alpha\beta\gamma}(U,S)}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}}$$

- Locality implies:

$$\tilde{K}_\alpha = f_\alpha(U,S)\, e^{K/3} \qquad (*)$$

- Two limits:

  i) Ultra-local limit: $(*)$ holds exactly

  ii) Local limit: $(*)$ holds only at leading order in $\mathcal{V}$-expansion

$$e^{K/3} = \frac{e^{K(U,S)/3}}{\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right)^{2/3}} = \frac{e^{K(U,S)/3}}{\mathcal{V}^{2/3}}\left(1 - \frac{\hat{\xi}}{3\mathcal{V}} + \ldots\right)$$

- Parametrisation of Kahler matter metric: $\tilde{K}_\alpha = \frac{f_\alpha(U,S)}{\mathcal{V}^{2/3}}\left(1 - c_\xi \frac{\hat{\xi}}{\mathcal{V}} + \ldots\right)$

- Ultra-local limit for $c_\xi = 1/3$

Soft terms

[Aparicio, MC, Krippendorf, Maharana, Muia, Quevedo]

- Gaugino masses

$$f_a = \kappa_a S + \lambda_a T_{\rm SM} \to \kappa_a S \qquad \longrightarrow \qquad M_{1/2} = \frac{F^S}{2s} \simeq \lambda(U,S)\frac{\hat{\xi}\, m_{3/2}}{\mathcal{V}}$$

- Scalar masses:

$$m_\alpha^2 = m_{3/2}^2 + V_0 - F^{T_i}F^{\overline{T}_{\bar{j}}}\partial_{T_i}\partial_{\overline{T}_{\bar{j}}} \ln \tilde{K}_\alpha + \tilde{K}_\alpha^{-1}\sum_a g_a^2 D_a \partial_\alpha \partial_{\bar{\alpha}} D_a \qquad D_a = \sum_J Q_{ja}\phi_j \frac{\partial K}{\partial \phi_j} + \sum_i q_{ia}\partial_{T_i} K$$

- Ultra-local limit:

dS$_1$ case: generated by D-terms at O($\mathcal{V}^{-3}$) $\qquad m_0^2 \simeq \frac{9}{64}\frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V}\ln\mathcal{V}}$

dS$_2$ case: generated by F-terms of U and S at O($\mathcal{V}^{-4}$) $\qquad m_\alpha^2 \simeq Q_\alpha(U,S) M_{1/2}^2$

- Local limit: D-terms are negligible

$$m_0^2 \simeq \frac{15}{4}\left(c_\xi - \frac{1}{3}\right)\frac{\hat{\xi}\, m_{3/2}^2}{\mathcal{V}} \qquad c_\xi > 1/3$$

- A-terms ~ $M_{1/2}$
- Giudice-Masiero or non-perturbative W generate μ-term $\lesssim M_{1/2}$
- Two scenarios:

i) MSSM-like: ultra-local dS$_2$ case $\qquad M_{1/2} \sim m_\alpha \sim A_{\alpha\beta\gamma} \sim \frac{M_p}{\mathcal{V}^2}$

ii) Split SUSY: other cases $\qquad M_{1/2} \sim A_{\alpha\beta\gamma} \sim \frac{M_p}{\mathcal{V}^2} \quad \text{while} \quad m_0 \sim \frac{M_p}{\mathcal{V}^{3/2}}$

with tunable flux-dependent coefficients

Conclusions

- No-scale + locality in 4D string models → sequestering: $M_{1/2} << m_\phi << m_{3/2} << M_s$
- Avoid CMP + gravitino problem + axion DM overproduction
- Allow large M_s and TeV-scale $M_{1/2}$

  → good for GUTs, inflation, WIMP DM
- Split SUSY-like spectra more generic with $m_0 \sim m_\phi \sim 10^{6-7}$ GeV
- Reheating driven by lightest modulus decay
- Non-standard cosmology: dilution of thermal DM
- Non-thermal dark matter:
  i) CMSSM with a 300 GeV Higgsino LSP saturating DM for T_{rh} = 2 GeV
  ii) More in general: 300-850 GeV Higgsino LSP saturating DM for T_{rh} = 2-40 GeV
- Generic production of axionic dark radiation → $\Delta N_{eff} \neq 0$
- Cosmic axion background with $E_a \sim 200$ eV
- CAB detectable via axion-photon conversion in B
- Explain soft X-ray excess and 3.5 keV line in galaxy clusters
- Realised in LVS type IIB compactifications with visible sector on D3-branes