Phenomenology and Cosmology of Sequestered Scenarios

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Based on:

1. String inflation after Planck: Burgess,MC,Quevedo, arXiv:1306.3512 [hep-th]
2. Non-thermal DM in LVS: Allahverdi,MC,Dutta,Sinha, arXiv:1307.xxxx [hep-th]

Cosmological challenges for strings

Two ubiquitous problems of string compactifications:

- Cosmological moduli problem:
  1. ϕ starts oscillating at $H_{\rm osc} \sim m_\phi$ with $\phi_0 \sim M_P$
  2. ϕ redshifts as matter $\Rightarrow$ dominates the energy density
  3. ϕ decays at $H_{\rm dec} \sim \Gamma \sim \epsilon^2 m_\phi$ where $\epsilon \sim m_\phi/M_P \ll 1$
  4. Reheat temperature $T_{\rm rh} \sim \epsilon^{1/2} m_\phi > T_{\rm BBN} \simeq 3$ MeV $\Rightarrow m_\phi > 50$ TeV
- Axionic dark matter overproduction:
  1. $\mathcal{O}(100)$ axions in string compactifications
  2. Some projected out, eaten up by anomalous $U(1)$s or heavy from NP effects
  3. Some remain light $\Rightarrow$ one can be the QCD axion with $f_a \sim M_s$
  4. Overproduction of axionic cold DM for $f_a > 10^{12}$ GeV

Tension between these two problems:

ϕ heavier/lighter than 50 TeV $\Leftrightarrow$ high/low string scale $\Leftrightarrow$ too much/right axion DM

Non-standard cosmology from strings

Focus on $m_\phi > 50$ TeV $\Rightarrow \phi$ decay dilutes any previous relic:

- Axionic DM diluted if $T_{\rm rh} < \Lambda_{\rm QCD} \simeq 200$ MeV [Fox,Pierce,Thomas]
  $\Rightarrow$ if $T_{\rm rh} \gtrsim T_{\rm BBN}$ can have $f_a \sim 10^{14}$ GeV without tuning
- Standard thermal LSP DM diluted if $T_{\rm rh} < T_{\rm f} \simeq m_{\rm DM}/20 \sim \mathcal{O}(10)$ GeV
- Baryon asymmetry diluted if produced before ϕ decay
  $\Rightarrow$ good if baryogenesis in the early universe is too efficient

Decay products:

- Non-thermal LSP DM from ϕ decay $\Rightarrow$ larger parameter space
  - Annihilation scenario for high $T_{\rm rh}$ (close to $T_{\rm f}$)
    1. abundant initial production of DM
    2. subsequent efficient annihilation $\Rightarrow$ Wino/Higgsino-like DM
  - Branching scenario for low $T_{\rm rh}$ (close to $T_{\rm BBN}$)
    1. smaller initial production of DM
    2. subsequent inefficient annihilation $\Rightarrow$ Bino-like DM
- Baryon asymmetry from ϕ decay $\Rightarrow$ explain baryon-DM coincidence [Dutta et al]

Challenges for moduli decays

Two problems for moduli decays:

- Gravitino problem:
  1. if $m_{3/2} < m_\phi$ the gravitino is produced from ϕ decay
  2. if $m_{3/2} < 50$ TeV $\Rightarrow$ gravitino decays after BBN
  3. if $m_{3/2} > 50$ TeV $\Rightarrow$ gravitini could annihilate into DM $\Rightarrow$ DM overproduction
- Axionic dark radiation overproduction:
  1. moduli are gauge singlets $\Rightarrow$ they do not prefer to decay into visible sector fields
  2. large branching ratio into light axions $\Rightarrow$ large $N_{\rm eff}$

$$\rho_{\rm rad} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

  3. Tight bounds from observations (Planck+WMAP9+ACT+SPT+BAO+HST): $N_{\rm eff} = 3.52^{+0.48}_{-0.45} \Rightarrow \Delta N_{\rm eff} \simeq 0.5$

LARGE Volume Scenario

In type IIB LVS models moduli masses and couplings can be computed explicitly
$\Rightarrow$ can study cosmological history of the universe

Two scenarios:

- Non-sequestered models:
  1. Visible sector in the geometric regime (magnetised intersecting D7-branes)

$$M_{\rm soft} \simeq m_{3/2}/\ln\left(M_P/m_{3/2}\right) \qquad m_\phi \sim M_{\rm soft}\sqrt{M_{\rm soft}/M_P} \ll M_{\rm soft}$$

  2. CMP for volume mode ϕ since $m_\phi \sim \mathcal{O}(1)$ MeV for $M_{\rm soft} \sim \mathcal{O}(1)$ TeV
  3. Intermediate string scale $M_s \simeq M_P\sqrt{\frac{M_{\rm soft}}{M_P}} \ll M_P \Rightarrow$ bad for GUTs and inflation

- Sequestered models:
  1. Visible sector in the singular regime (fractional D3-branes at singularities)

$$M_{\rm soft} \simeq m_{3/2}\left(\frac{m_{3/2}}{M_P}\right) \ll m_{3/2} \qquad m_\phi \sim M_{\rm soft}\left(\frac{M_P}{M_{\rm soft}}\right)^{1/4} \gg M_{\rm soft}$$

  2. NO CMP for ϕ since $m_\phi \sim \mathcal{O}(10^{6-7})$ GeV for $M_{\rm soft} \sim \mathcal{O}(1)$ TeV
  3. High string scale $M_s \simeq M_P\left(\frac{M_{\rm soft}}{M_P}\right)^{1/4} \Rightarrow$ good for GUTs and inflation

Sequestered LVS

- Explicit LVS compactifications with fluxes, D3/D7-branes and O3/O7-planes
- Description of the compact CY by toric geometry [MC,Kreuzer,Mayrhofer]
- Global consistency: D5- & D7-tadpole, torsion charges and FW anomaly cancellation
- Moduli fixing compatible with chirality within the regime of validity of EFT
- D-term induced shrinking of the cycles supporting the visible sector
- Visible sector D3s at del Pezzo singularities [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]
- Minkowski vacua from D-terms or E(-1) instantons [MC,Maharana,Quevedo,Burgess]
- Study of SUSY breaking with running down to TeV scale [Aparicio et al in progress]
- Study of axion phenomenology with explicit QCD axion candidates [MC,Goodsell,Ringwald]
- Interesting cosmology:
  - Inflation using Kähler moduli fits Planck data very well [Burgess,MC,Quevedo]
  - Axion dilution and non-thermal dark matter from moduli decays [Allahverdi,MC,Dutta,Sinha]
  - Dark radiation from light axions [MC,Conlon,Quevedo][Higaki,Takahashi]
  - $\mathcal{O}(200\,\mathrm{eV})$ cosmic axion background [Conlon,Marsh]

Global embedding of D-branes at sing

- ‘Diagonal’ dPs crucial to embed quiver theories [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]:
- Consider them to support the visible sector and turn on a non-zero flux:
  $\xi_{\rm dP} \propto \int_{D_{\rm dP}} J \wedge \mathcal{F}_{\rm dP} = k_{{\rm dP}jk} \mathcal{F}^k_{\rm dP} t^j \propto t_{\rm dP} = 0 \Rightarrow t_{\rm dP} \to 0$
- Need 2 dP divisors exchanged by the orientifold involution $\Rightarrow h^{1,1}_- \geq 1$
- 2 dPs do not intersect each other $\Rightarrow$ they do not touch the O7 $\Rightarrow$ $U(N)$ groups
- Involution-invariant ‘diagonal’ dP for non-pert. effects (generation of $W_{\rm np}$ guaranteed)
- Minimal set-up involves $h^{1,1} = 4$:
  1. $h^{1,1}_- = 1$ G-modulus (reduction of B_2 and C_2)
  2. $h^{1,1}_+ = 3$ T-moduli (1 local blow-up + 1 NP cycle + volume mode)
- A dP divisor has 2 anomalous $U(1)$s
  $\Rightarrow d = 2$ moduli fixed by D-terms (G-modulus and local blow-up)
  $\Rightarrow$ local axions eaten up
- Other ‘diagonal’ dP and volume mode fixed by NP + α' effects

Simplest sequestered LVS model

- Volume form: $\mathcal{V} = \tau_b^{3/2} - \tau_{\rm np}^{3/2} - \tau_{\rm vs}^{3/2} \simeq \tau_b^{3/2}$
- Visible sector cycle shrinks to zero size due to D-terms: $\xi \propto \tau_{\rm vs} \Rightarrow \tau_{\rm vs} \to 0$
- Corresponding axion gets eaten up
- Sources for Kähler moduli stabilisation:

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right) \qquad \text{and} \qquad W = W_0 + A\, e^{-\frac{2\pi}{N} T_{\rm np}}$$

- Leading F-term potential from α' + non-pert. corrections:

$$V \sim \frac{\sqrt{\tau_{\rm np}}}{\mathcal{V}}\, e^{-\frac{4\pi\tau_{\rm np}}{N}} - W_0\, \frac{\tau_{\rm np}}{\mathcal{V}^2}\, e^{-\frac{2\pi\tau_{\rm np}}{N}} + \frac{W_0^2 \xi}{g_s^{3/2}\mathcal{V}^3}$$

- Fix $\mathcal{V}$ and $\tau_{\rm np}$ at $\tau_{\rm np} \sim g_s^{-1}$ and $\mathcal{V} \sim W_0\, e^{\frac{2\pi}{N g_s}}$
- a_b is a light axion whereas $a_{\rm np}$ is heavy
- AdS minimum with spontaneous SUSY breaking
- Minkowski vacua via D-term uplifting or instantons at sing. [MC,Maharana,Quevedo,Burgess]

Mass spectrum

- Main difference with geometric case: no local SUSY breaking since $F^{\mathrm{vs}} \propto \xi = 0$
- Sequestered soft terms: $M_{\mathrm{soft}} \sim m_{3/2}/\mathcal{V} \sim M_P/\mathcal{V}^2 \ll m_{3/2}$
- Get TeV-scale SUSY for $\mathcal{V} \sim 10^7 \Rightarrow$ high string scale $M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
- Right GUT scale: $M_{\mathrm{GUT}} \sim M_s \mathcal{V}^{1/6} \sim 10^{16}$ GeV [Conlon,Palti]
- Mass spectrum:
  - $m_{\tau_{\mathrm{vs}}} \sim m_{a_{\mathrm{vs}}} \sim M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
  - $m_{\tau_{\mathrm{np}}} \sim m_{a_{\mathrm{np}}} \sim M_P \ln \mathcal{V}/\mathcal{V} \sim 10^{12}$ GeV
  - $m_{3/2} \sim M_P/\mathcal{V} \sim 10^{11}$ GeV
  - $m_{\tau_b} \sim M_P/\mathcal{V}^{2/3} \sim 5 \times 10^6$ GeV
  - $M_{\mathrm{soft}} \sim M_P/\mathcal{V}^2 \sim 1$ TeV
  - $m_{a_b} \sim M_P e^{-2\pi \mathcal{V}^{2/3}} \sim 0$
- No CMP since $m_{\tau_b} \gg 50\,\mathrm{TeV}$ + No gravitino problem since $m_{3/2} \gg m_{\tau_b}$
- Successful inflation with $N_e \simeq 60$, $n_s \simeq 0.96$, $r \ll 1$, right amount of density perturbations and possibly power loss at large scales [Burgess,MC,Conlon,Pedro,Quevedo,Tasinato]
- Reheating driven by decay of lightest modulus τ_b

Closed string inflation

Inflation using Kähler moduli:

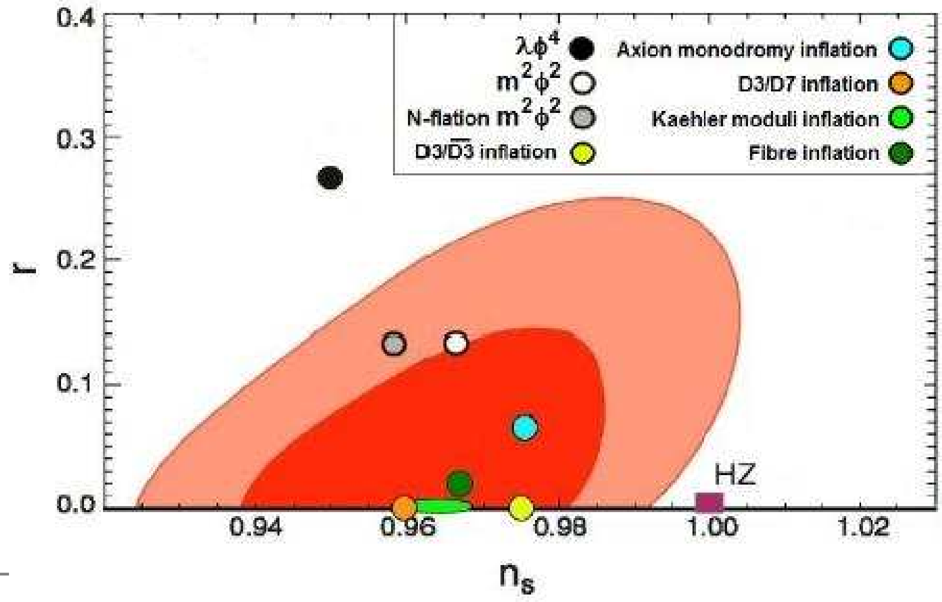
- No-scale structure broken by perturbative effects only by lifting $\mathcal{V}$ direction $\Rightarrow$ naturally flat potential for fields ϕ orthogonal to $\mathcal{V}$!
- Suppressed higher dim. operators due to approximate shift symmetry for ϕ
- Typical potential (in inflationary region):

$$V = V_0\left(1-\beta\kappa e^{-\kappa\phi}+\delta e^{+\mu\phi}\right)\simeq V_0\left(1-\beta\kappa e^{-\kappa\phi}\right) \qquad \beta\sim\mathcal{O}(1),\,\delta\propto g_s^4\ll 1$$

- κ depends on the details of the model: topology of ϕ and effects to generate V
- Implications of V: $\epsilon\simeq\frac{\eta^2}{2\kappa^2}$ and $\eta\simeq-\beta\kappa^3 e^{-\kappa\phi}<0 \quad\Rightarrow\quad \epsilon\ll|\eta|\ll 1$
- Typical prediction: $r=\frac{2}{\kappa^2}\left(n_s-1\right)^2 \quad\Rightarrow$ for $n_s\simeq 0.96 \quad\Rightarrow\quad r\simeq\frac{0.0032}{\kappa^2}$
- Three models:
  1. Kähler moduli inflation: $\kappa\sim\mathcal{V}^{1/2}\gg 1\Rightarrow r\simeq 10^{-10}$ [Conlon,Quevedo]
  2. Fibre inflation: $\kappa\sim\mathcal{O}(1)\Rightarrow 0.005<r<0.007$ [MC,Burgess,Quevedo]
  3. Poly-instanton inflation: $\kappa\simeq\ln\mathcal{V}>1\Rightarrow r\simeq 10^{-5}$ [MC,Pedro,Tasinato]

(n_s, r)-plane

- Almost unanimous prediction of small r
- Well agreement with observations



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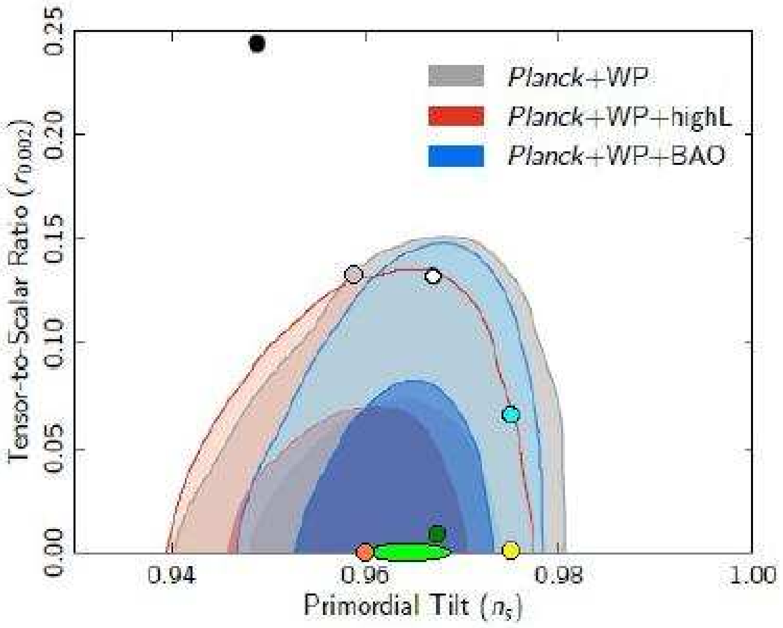

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Prospects for measuring r

- Observations more sensitive to r in near future: what might be found?
- Two theoretical points of view:
  1. Flat prior: ϵ and η similar in size: $\epsilon \simeq \eta$

$$n_s - 1 \simeq 2\epsilon - 6\eta \simeq -4\epsilon \simeq -0.04 \qquad \Rightarrow \qquad \epsilon \simeq 0.01 \qquad \Rightarrow \qquad r \simeq 16\epsilon \simeq 0.16$$

  $\Rightarrow$ tensor modes should soon be observed!

  2. Flat log prior: size of tensor perturbations set by inflationary energy scale

$$r \sim (M_{\rm inf}/M_{\rm GUT})^4$$

    - $M_{\rm inf}$ could be anywhere between 100 and 10^{15} GeV
    - No intrinsic reason to prefer any scale

      $\Rightarrow$ no preference for observable or unobservable r

- Stringy point of view: Trans-Planckian fields to obtain large r
  - Consistent EFT? Answer in string theory
  - Difficulty to find large r – no-go theorems
  - Majority of known string models do not predict large r

    $\Rightarrow$ expect r to be too small to be visible

Non-Gaussianities

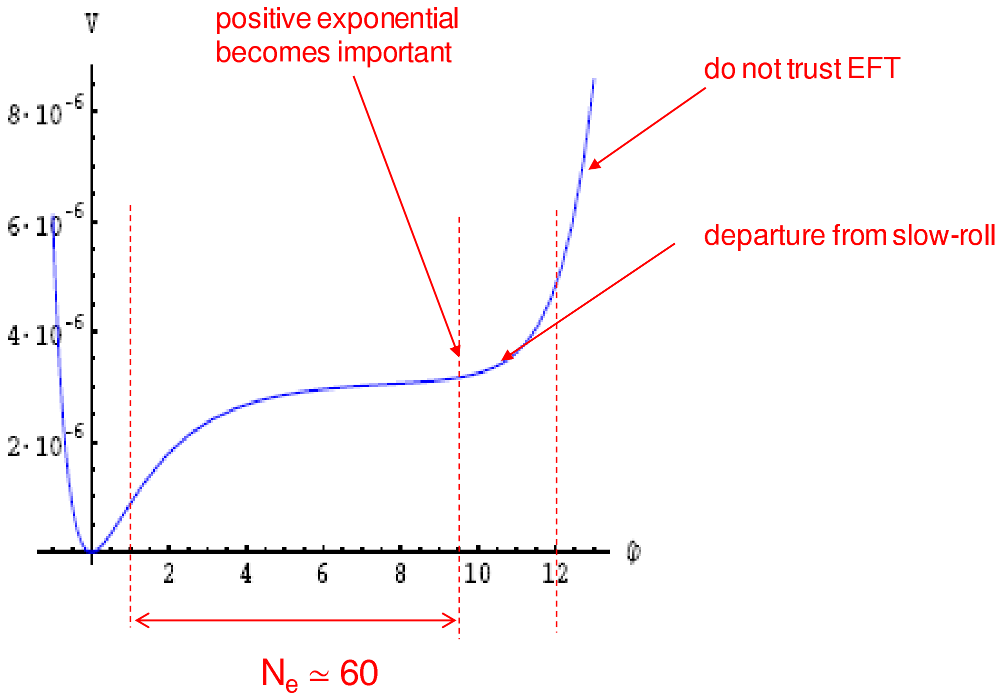
Two mechanisms for non-Gaussianity in string inflation:

1. Non-canonical kinetic terms (DBI inflation)
   - Large NG due to departure from slow-roll
   - Tension with the data due to prediction of large equilateral and orthogonal NG
2. Multi-field dynamics
   - Large NG due to large self-interaction of fields which generate NG
   - A generic compactification has many moduli
     $\Rightarrow$ some of them heavier and some lighter than $H_{\rm inf}$
   - During inflation light fields get large quantum fluctuations
   - Non-standard generation of density perturbations + large local NG
   - Examples: curvaton or modulated reheating [Burgess,MC,Gomez-Reino,Quevedo,Tasinato,Zavala]

But in most cases multi-field models do NOT generate isocurvature perturbations due to an effective single-field dynamics – motion is along a trough!
$\Rightarrow$ partial explanation of why inflationary models describe the data so well
$\Rightarrow$ observational evidence for single-field models is not against multi-field models

Strings and power loss at large scales

- Qualitative behaviour of closed string inflation with volume moduli
- Typical potential: $V = V_0 \left(1 - \beta\kappa e^{-\kappa\phi} + \delta e^{+\mu\phi}\right) \qquad \beta \sim \mathcal{O}(1),\, \delta \propto g_s^4 \ll 1$
- Amplitude of scalar fluctuations: A_s(large scales) $\simeq \frac{V^{3/2}}{M_P^3 V'} \ll 10^{-5}$



positive exponential becomes important

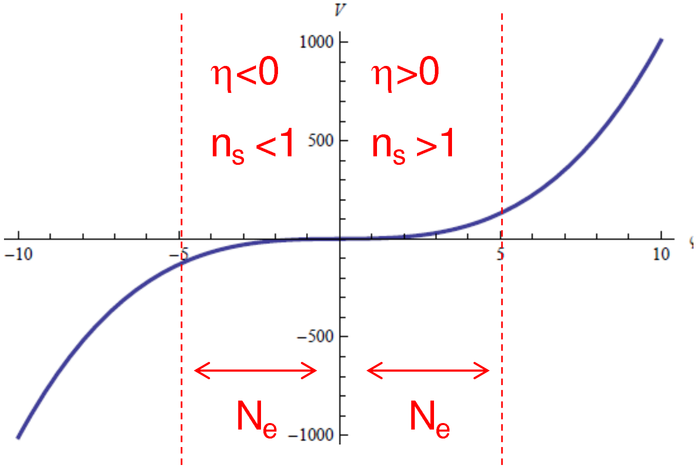
do not trust EFT

departure from slow-roll

$N_e \simeq 60$

No power loss in symmetric potentials

- Brane-antibrane inflation: fine-tuning to solve η-problem $\Rightarrow$ inflection point inflation
- Typical potential: $V = V_0 \left(1 + \lambda_1 \phi + \lambda_3 \phi^3 + \lambda_4 \phi^4 + ...\right)$
- Right n_s if $N_e > \mathcal{O}(140)$ and $r \ll 1$ [Baumann, McAllister et al]
- But blue-spectrum statistically favoured since $P(N_e) \propto 1/N_e^3$
- Power loss at large scales needs $N_e \sim \mathcal{O}(60-70) \Rightarrow$ tension with n_s



Leading volume decays

Reheating driven by decay of lightest modulus τ_b
Leading decay channels for τ_b (ϕ is the canonically normalised modulus)

1. Higgses
2. closed string axions

- **Decays to Higgs bosons**: $\phi \to H_u H_d$ decays induced by the Giudice-Masiero term, $K \supset Z\,\frac{H_u H_d}{2\tau_b}$, with $Z \sim \mathcal{O}(1)$:

$$\Gamma_{\phi\to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\phi^3}{M_\mathrm{P}^2}$$

- **Decays to bulk axions** (if not eaten by anomalous $U(1)$s):

$$\Gamma_{\phi\to a_b a_b} = \frac{1}{48\pi}\frac{m_\phi^3}{M_\mathrm{P}^2}$$

- **Decays to local closed string axions** (if not eaten by $U(1)$s or lifted by NP effects):

$$\Gamma_{\phi\to a_\mathrm{loc} a_\mathrm{loc}} = \frac{9}{16}\frac{1}{48\pi}\frac{m_\phi^3}{M_\mathrm{P}^2}$$

Subleading volume decays

- **Decays to gauge bosons**: Tree-level: $f_a = S + h_a T_{\rm vs}$ (independent of T_b) – Loop level: $\left(\frac{\alpha_{\rm vs}}{4\pi}\right) \ln \mathcal{V} \Rightarrow$ loop suppressed decay width

$$\Gamma_{\phi \to A^\mu A^\mu} = \lambda \left(\frac{\alpha_{\rm vs}}{4\pi}\right)^2 \frac{m_\phi^3}{M_{\rm P}^2}$$

- **Decays to other visible sector fields**: mass suppressed decays to matter scalars, fermions, gauginos and Higgsinos (commonly denoted as ψ):

$$\Gamma_{\phi \to \psi\psi} \simeq \frac{M_{\rm soft}^2 m_\phi}{M_{\rm P}^2} \ll \frac{m_\phi^3}{M_{\rm P}^2}$$

- **Decays to local open string axions** θ: ($C = \rho\, e^{i\,\theta}$ with $\langle\rho\rangle \neq 0$):

$$\mathcal{L} \supset \left(\frac{\langle\rho\rangle}{M_{\rm P}}\right)^2 \phi\theta\Box\theta$$

suppressed by tiny axion mass of the axion and $(\langle\rho\rangle/M_{\rm P})^2 \simeq \xi \sim 1/\mathcal{V} \ll 1$

Axions in sequestered models

- Unsuppressed decays to bulk and local closed string axions can cause problems with DR overproduction $\Rightarrow$ constraints on hidden sector model building
- In globally consistent chiral brane models in explicit compact CYs these axions tend to be eaten up by anomalous $U(1)$s due to consistency reasons $\Rightarrow$ no DR overproduction!
- Two options for QCD axion:
  - **Closed string QCD axion**
    1. In dP singularities all local closed string axions are eaten up
    2. Focus on singularities more complicated than dP
    3. A local closed string axion left over with $f_{a_{\rm loc}} \simeq M_s/\sqrt{4\pi} \simeq 10^{14}$ GeV
    4. Needs to be diluted by ϕ decay or tune initial misalignment angle
    5. $a_{\rm loc}$ should not cause any problem with DR overproduction
  - **Open string QCD axion**
    1. The phase θ of a matter field ϕ can be the QCD axion
    2. Subleading ϕ decay to $\theta \Rightarrow$ No DR production
    3. D-terms: $V_D \simeq g^2 \left(|\phi|^2 - \xi\right)^2$ with $\xi = \tau_{\rm vs}/\mathcal{V} \Rightarrow f_a = \langle|\phi|\rangle = \sqrt{\xi} \simeq \langle\sqrt{\tau_{\rm vs}}\rangle\, M_s$
    4. Subleading F-terms: $\langle\tau_{\rm vs}\rangle = \mathcal{V}^{-2\alpha} \ll 1$ with $0 < \alpha < 1 \Rightarrow f_a = \langle|\phi|\rangle \simeq M_s/\mathcal{V}^{\alpha}$
    5. For $\alpha = 1/2$, one has $f_a \simeq 10^{11}$ GeV $\Rightarrow$ OK for DM

Non-thermal dark matter from ϕ decay

- Non-thermal DM produced from ϕ decay with $\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_{\rm P}^2}$
- ϕ decays when $H \sim \Gamma_\phi$ and reheats the universe to a temperature

$$T_{\rm rh} = c^{1/2}\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{m_\phi}{50\ {\rm TeV}}\right)^{3/2} T_{\rm BBN}$$

- ϕ decay dilutes thermal DM by a factor of order $(T_{\rm f}/T_{\rm rh})^3 \gtrsim 10^6$
  $\Rightarrow$ need DM production from modulus decay:

$$\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs}\frac{\langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}}\left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi {\rm Br}_{\rm DM}\right]$$

where $\langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th} \simeq 3\times 10^{-26}{\rm cm}^3\,{\rm s}^{-1}$ is the value needed in the thermal case

$$\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \simeq 5\times 10^{-10}\left(\frac{1\ {\rm GeV}}{m_{\rm DM}}\right) \qquad \text{and} \qquad Y_\phi \equiv \frac{3T_{\rm rh}}{4m_\phi} = \frac{0.9}{\pi}\sqrt{\frac{c\,m_\phi}{M_{\rm P}}}$$

${\rm Br}_{\rm DM}$ is the branching ratio for ϕ decays into R-parity odd particles which decay to DM

Non-thermal DM scenarios

- DM abundance:

$$\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}} \left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi {\rm Br}_{\rm DM}\right]$$

- First term on RHS side $\Rightarrow$ **Annihilation Scenario**
  1. DM particles produced from ϕ decay undergo some annihilation
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} = \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \, (T_{\rm f}/T_{\rm rh})$
  3. Since $T_{\rm rh} < T_{\rm f}$, need $\langle\sigma_{\rm ann} v\rangle_{\rm f} > \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ $\Rightarrow$ Wino/Higgsino DM
- Second term on RHS side $\Rightarrow$ **Branching Scenario**
  1. DM annihilation is inefficient and DM abundance is produced form ϕ decay
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \, (T_{\rm f}/T_{\rm rh})$
  3. Always the case for $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ $\Rightarrow$ Bino DM
  4. Can also happen for $\langle\sigma_{\rm ann} v\rangle_{\rm f} > \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}$ if $T_{\rm rh}/T_{\rm f}$ is too small

Observational constraints

- Fermi results place tight constraints on the ‘annihilation scenario’
- Limits from dwarf spheroidal galaxies:
  1. $T_{\rm f} \lesssim 30\, T_{\rm rh}$ for $m_{\rm DM} > 40$ GeV ⇒ $T_{\rm rh} > 70$ MeV
  2. For $m_{\rm DM} < 40$ GeV, need $\langle \sigma_{\rm ann} v \rangle_{\rm f} < \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}$, if DM annihilates into $b\bar{b}$
     ⇒ ‘annihilation scenario’ cannot work in this case

  ⇒ the ‘branching scenario’ is the only option for $m_{\rm DM} < 40$ GeV
- Since $5 \times 10^{-3} \lesssim {\rm Br}_{\rm DM} \lesssim 1$, (lower bound set by three-body decay of ϕ into R-parity odd particles), need $Y_\phi \lesssim 10^{-8}$ to obtain correct DM abundance
- For $m_\phi \simeq 5 \times 10^6$ GeV, this requires $T_{\rm BBN} \lesssim T_{\rm rh} \lesssim 70$ MeV

⇒ two interesting regimes for $T_{\rm rh}$:

1. Annihilation scenario for $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$;
2. Branching scenario for $T_{\rm BBN} \lesssim T_{\rm rh} \lesssim 70$ MeV.

Annihilation Scenario

- High $T_{\rm rh}$ regime: $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$
- ϕ decays mainly to Higgses with $c = Z^2/12$
  $\Rightarrow T_{\rm rh} \simeq 0.8\, Z$ GeV for $m_\phi \simeq 5 \times 10^6$ GeV $\Leftrightarrow$ TeV-scale SUSY
- Focus on cases where bulk axions are removed from the spectrum

1. QCD axion is a local closed string mode $a_{\rm loc}$ with $f_a \sim 10^{14}$ GeV
   - $\phi \to a_{\rm loc} a_{\rm loc}$ is a leading decay channel $\Rightarrow$ suppress $\Delta N_{\rm eff} \simeq 1/Z^2$
   - $\Delta N_{\rm eff} \simeq 0.5 \Rightarrow Z \simeq \sqrt{2} \Rightarrow T_{\rm rh} \simeq 1$ GeV
   - $T_{\rm rh} < T_{\rm f}$ if $m_{\rm DM} > 20\, T_{\rm rh} \simeq 20$ GeV
   - Reheat temperature larger than QCD scale: $T_{\rm rh} \simeq 1\,{\rm GeV} > \Lambda_{\rm QCD}$
     $\Rightarrow$ axion cold DM is not diluted $\Rightarrow$ tune initial misalignment angle or $a_{\rm loc}$ eaten up by an anomalous $U(1)$ (QCD axion is then an open string mode)
   - Multicomponent DM (Wino/Higgsino + closed string axions)
2. QCD axion is an open string mode θ with $f_a \simeq 10^{11-12}$ GeV:
   - $\phi \to \theta\theta$ is a subleading decay channel $\Rightarrow$ No DR is produced
   - Reheat temperature larger than QCD scale $\Rightarrow$ axion cold DM is not diluted
   - but f_a is intermediate $\Rightarrow$ No need to tune initial misalignment angle
   - DM can be multicomponent (Wino/Higgsino + open string axions)

Branching Scenario

- Low $T_{\rm rh}$ regime: $3\,{\rm MeV} \lesssim T_{\rm rh} \lesssim 70$ MeV $\Rightarrow$ very small modulus decay width
- If QCD axion is a closed string $\Rightarrow Z \geq \sqrt{2}$ to avoid DR problems $\Rightarrow T_{\rm rh} \gtrsim 1$ GeV
- Lower $T_{\rm rh}$ for smaller values of $m_\phi \Rightarrow M_{\rm soft} \ll 1$ TeV
- Way-out: focus on cases where closed string axions are removed by anomalous $U(1)$s $\Rightarrow$ QCD axion is an open string which does not cause any DR problem
- $T_{\rm rh} \ll \Lambda_{\rm QCD} \Rightarrow \phi$ decay dilutes axion oscillations $\Rightarrow$ negligible QCD axion DM
- Two ways to lower the reheat temperature:
  1. $Z = 0$ if Giudice-Masiero term forbidden by some symmetries $\Rightarrow$ leading decay channel to gauge bosons is loop-suppressed
  2. $Z \simeq 0.1$ in the absence of symmetries forbidding ϕ decays to Higgses

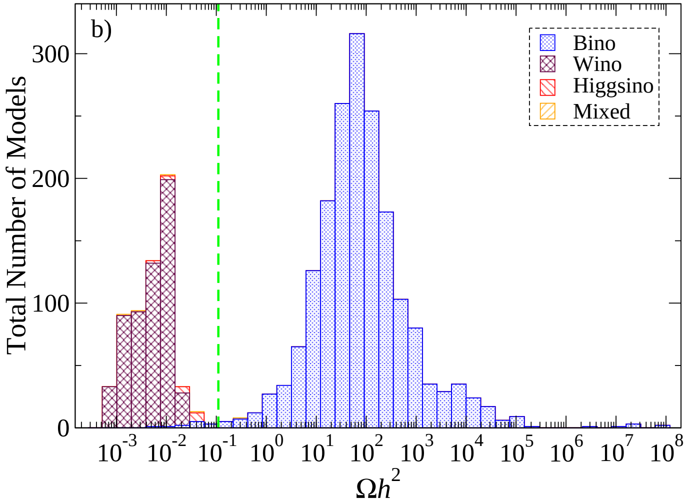
Branching Scenario

Two cases:

1. $Z = 0$
   - Loop-suppressed decay to gauge bosons via a two-body final state: $c = \lambda \frac{\alpha_{\rm vs}^2}{8\pi}$
   - If $\lambda \simeq 1$, $\alpha_{\rm vs} \simeq 1/137$, and $m_\phi \simeq 5 \times 10^6$ GeV $\Rightarrow T_{\rm rh} \simeq 4$ MeV $\Rightarrow Y_\phi \simeq 6 \times 10^{-10}$
   - Gauginos produced in three-body decays of the modulus ($\phi \rightarrow 1 \ {\rm gluon} + 2 \ {\rm gluinos}$) with ${\rm Br}_{\rm DM} \sim 5 \times 10^{-3}$
   - ${\rm Br}_{\rm DM} \simeq 5 \times 10^{-3} \Rightarrow$ DM abundance matches observed value for $m_{\rm DM} \simeq 165$ GeV
   - Keep m_ϕ fixed at $m_\phi \lesssim 2 \times 10^7$ GeV (to get TeV-scale SUSY) and vary λ
   - $T_{\rm rh} \gtrsim 3$ MeV $\Rightarrow \lambda \gtrsim 0.01$ and in turn $m_{\rm DM} \lesssim 900$ GeV
2. $Z \simeq 0.1$
   - $m_\phi \simeq 5 \times 10^6$ GeV $\Rightarrow T_{\rm rh} \simeq 80$ MeV $\Rightarrow m_{\rm DM} \simeq 10$ GeV
   - Larger $m_{\rm DM}$ requires smaller Z keeping m_ϕ fixed to get low-energy SUSY
   - $Z \simeq 0.01 \Rightarrow m_{\rm DM} \simeq 100$ GeV

Thermal dark matter and baryogenesis

- Thermal DM gets diluted: good since not very generic model-wise!
- Simplified MSSM version: SUGRA with 19 parameters [Baer,Box,Summy]



- Also any previous matter-antimatter asymmetry gets diluted!
  - Welcomed effect for Affleck-Dine baryogenesis which can be too efficient
  - If no asymmetry left over after ϕ decay $\Rightarrow$ Can address baryon-DM coincidence
  - Co-genesis of DM and baryogenesis from the moduli decay in the presence of new $O(\mathrm{TeV})$ coulored particles with B- and CP-violating couplings [Allahverdi,Dutta,Sinha]

Conclusions

- Sequestered LVS models:
  - Superpartner spectrum in the TeV range
  - Good inflationary scenarios
  - Non-thermal DM from ϕ decay which increases DM parameter space
  - No moduli-induced gravitino problem since $m_{3/2} \simeq 10^{10}\,\mathrm{GeV} \gg m_\phi \simeq 5 \times 10^6$ GeV
- Two regimes for $T_{\rm rh}$ depending on ϕ couplings:
  1. ‘Annihilation scenario’ for high $T_{\rm rh} \simeq 1$ GeV
     - ϕ decays mainly to Higgses
     - Axionic DR overproduction avoided either by anomalous $U(1)$s or by suitable couplings in the Giudice-Masiero term
     - Non-thermal DM: Wino/Higgsino with $m_{\rm DM} > 40$ GeV + QCD axion
  2. ‘Branching scenario’ for low $T_{\rm rh} \simeq 10$ MeV
     - ϕ decays mainly to gauge bosons (or if the decay to Higgses is suppressed)
     - QCD axion can only be an open string mode diluted by ϕ decay since $T_{\rm rh} < \Lambda_{\rm QCD}$
     - Both over and under-abundance DM scenarios can be accommodated
     - Bino DM mass can vary from $\mathcal{O}(\mathrm{GeV})$ to $\mathcal{O}(\mathrm{TeV})$