Dark Radiation and Dark Matter from String Compactifications

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Based on:

1. Dark radiation: MC,Conlon,Quevedo, arXiv:1208.3562 [hep-th]

   $\longrightarrow$ See talks by Nakayama + Marsh + Kersten + Angus

2. Dark matter: Allahverdi,MC,Dutta,Sinha, arXiv:1307.5086 [hep-ph]

   $\longrightarrow$ See talk by Watson

Cosmological challenges for strings

Two ubiquitous problems of string compactifications:

- Cosmological moduli problem [Coughlan et al][Banks et al][de Carlos et al]:
  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 $\epsilon \equiv m_\phi / M_P \ll 1$
  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 [Preskill et al] [Abbott,Sikivie]:
  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 $\Rightarrow$ ϕ decay dilutes any previous relic [Moroi,Randall]:

- 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 for Affleck-Dine baryogenesis which can be too efficient [Kane,Shao,Watson,Yu]

Decay products:

- Non-thermal LSP DM from ϕ decay [Acharya et al][Allahverdi,MC,Dutta,Sinha]
  - 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 $\Rightarrow$ Co-genesis of DM and baryogenesis due to new $O(\rm TeV)$ coulored particles with B- and CP-violating couplings [Allahverdi,Dutta,Sinha]

Challenges for moduli decays

Two problems for moduli decays:

- Gravitino problem [Endo,Hamaguchi,Takahashi] [Nakamura,Yamaguchi]:
  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 [MC,Conlon,Quevedo][Higaki,Takahashi]:
  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):
     $N_{\rm eff} = 3.52^{+0.48}_{-0.45}$ 95% CL $\Rightarrow \Delta N_{\rm eff} \simeq 0.5$

LARGE Volume Scenario

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

- Lightest modulus mass:

$$m_\phi \simeq m_{3/2}\sqrt{\epsilon} \ll m_{3/2} \qquad \text{where} \qquad \epsilon \equiv \frac{m_{3/2}}{M_P} \simeq \frac{W_0}{\mathcal{V}} \simeq e^{-\frac{2\pi}{N g_s}} \ll 1$$

  1. NO gravitino problem
  2. CMP if $m_{3/2} \simeq \mathcal{O}(M_{\rm soft}) \simeq \mathcal{O}(1)$ TeV $\Rightarrow m_\phi \simeq \mathcal{O}(1)$ MeV

- Way-out: focus on sequestered models [Blumenhagen et al]:
  1. Visible sector in the singular regime (fractional D3-branes at singularities)

$$M_{\rm soft} \simeq m_{3/2}\epsilon \ll m_\phi \simeq m_{3/2}\sqrt{\epsilon} \ll m_{3/2}$$

  2. NO CMP for $\epsilon \simeq 10^{-7}$
     $\Rightarrow M_{\rm soft} \simeq \mathcal{O}(1)\,\text{TeV} \ll m_\phi \simeq \mathcal{O}(5 \cdot 10^6)\,\text{GeV} \ll m_{3/2} \simeq \mathcal{O}(10^{11})\,\text{GeV}$
  3. High string scale: $M_s \simeq M_P\sqrt{\epsilon} \simeq \mathcal{O}(10^{15})$ GeV
     $\Rightarrow$ good for GUTs and inflation

Reheating

- Reheating driven by ϕ decays when $H \sim \Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2}$

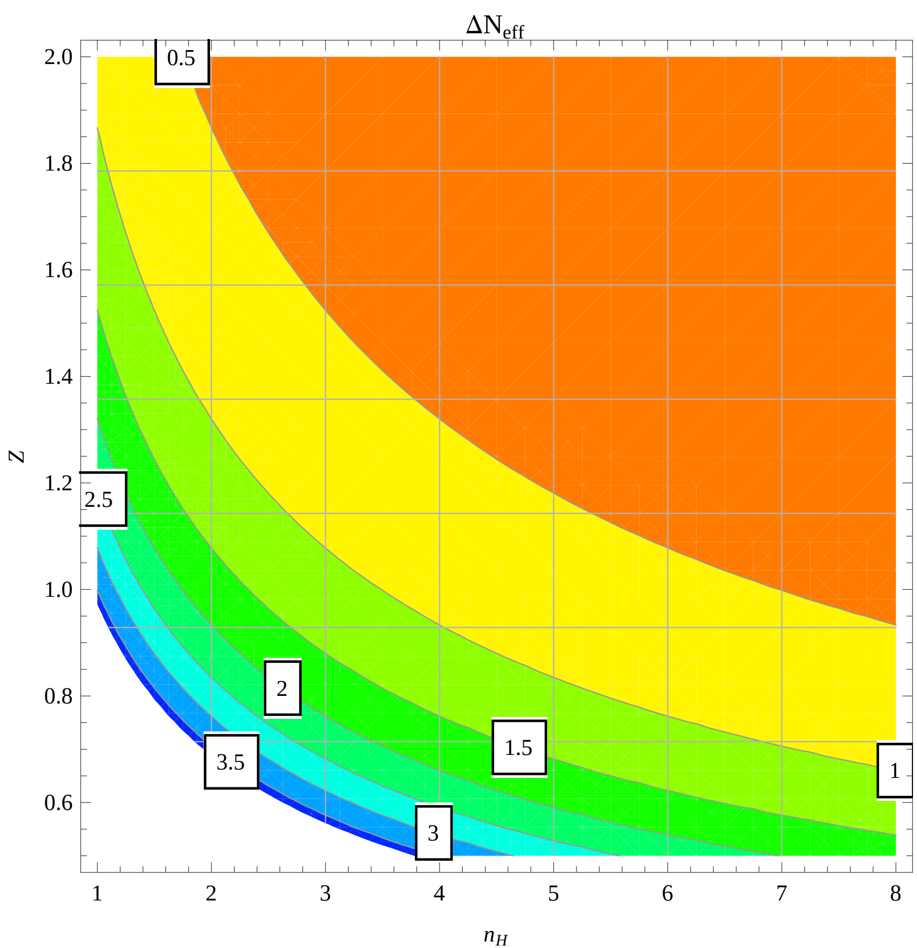
$$T_{\rm rh} = c^{1/2}\left(\frac{m_\phi}{5\cdot 10^6\,{\rm GeV}}\right)^{3/2}\mathcal{O}(1)\,{\rm GeV}$$

- Leading decay channels:
  - **Higgses**: $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions**: $c_{\phi\to a_b a_b} = 1/24$
  - **Local closed string axions** (if not eaten by $U(1)$s): $c_{\phi\to a_{\rm loc} a_{\rm loc}} = 9/384$
- Subleading decay channels:
  - **Gauge bosons**: $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm vs}^2}{8\pi} \ll 1$
  - **Other visible sector fields**: $c_{\phi\to\psi\psi} \simeq \left(\frac{M_{\rm soft}}{m_\phi}\right)^2 \simeq \frac{1}{\mathcal{V}} \ll 1$
  - **Local open string axions**: $c_{\phi\to a_b\theta} \simeq \left(\frac{M_s}{M_P}\right)^4 \tau_{\rm sing}^2 \simeq \left(\frac{\tau_{\rm sing}}{\mathcal{V}}\right)^2 \ll 1$

Predictions for dark radiation

Prediction for $\Delta N_{\rm eff}$ for n_H Higgs doublets and n_a local closed string axions:

$$\Delta N_{\rm eff} = \frac{3.48}{n_H Z^2}\left(1 + \frac{9 n_a}{16}\right) \xrightarrow[n_a=0]{} \frac{3.48}{n_H Z^2}$$



Axions in sequestered models

- In LVS $\mathcal{V}$ fixed by perturbative effects $\Rightarrow$ light a_b because of shift symmetry
- Open string axions eaten up by anomalous $U(1)$s on bulk cycles
  $\Rightarrow$ light bulk closed string axions are a model-independent feature of LVS
  $\Rightarrow$ dark radiation is a model-independent prediction of LVS!
- $\mathcal{O}(200)\,\mathrm{eV}$ cosmic axion background + X-ray excess in galaxy cluster [Conlon,Marsh]
- Two options for QCD axion [MC,Goodsell,Ringwald]:
  - **Open string QCD axion** θ: $C = \rho\, e^{i\theta}$
    1. Subleading ϕ decay to $\theta \Rightarrow$ No DR overproduction
    2. D-terms: $V_D \simeq g^2 \left(\rho^2 - \xi\right)^2 \Rightarrow f_a = \langle\rho\rangle = \sqrt{\xi} \simeq \sqrt{\langle\tau_{\rm sing}\rangle}\, M_s$
    3. Subleading F-terms: $\langle\tau_{\rm sing}\rangle = 1/\mathcal{V} \ll 1$
       $\Rightarrow f_a \simeq M_s/\sqrt{\mathcal{V}} \simeq \mathcal{O}(10^{11-12})\,\mathrm{GeV} \Rightarrow$ No DM overproduction
  - **Closed string QCD axion** $a_{\rm sing}$: $T_{\rm sing} = \tau_{\rm sing} + {\rm i} a_{\rm sing}$
    1. All local closed string axions eaten up by anomalous $U(1)$ in dP singularities
    2. $a_{\rm sing}$ could be left over for more complicated singularities
    3. $f_{a_{\rm sing}} \simeq M_s/\sqrt{4\pi} \simeq 10^{14}$ GeV
    4. Needs to be diluted by ϕ decay or tune initial misalignment angle
    5. $a_{\rm sing}$ could give DR overproduction

Non-thermal dark matter from ϕ decay

- Non-thermal DM produced from ϕ decay [Allahverdi,MC,Dutta,Sinha]
- ϕ decay dilutes thermal DM by a factor of order $(T_{\rm f}/T_{\rm rh})^3 \gtrsim 10^6$
- Parameter space larger than the one for thermal DM
- DM production from ϕ decay:

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

where:

- $\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \simeq 5 \times 10^{-10} \left(\frac{1\ {\rm GeV}}{m_{\rm DM}}\right)$
- $\langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th} \simeq 3 \times 10^{-26} {\rm cm}^3\, {\rm s}^{-1}$ is the thermal value
- $Y_\phi \equiv \frac{3 T_{\rm rh}}{4 m_\phi} = \frac{0.9}{\pi} \sqrt{\frac{c\, m_\phi}{M_P}}$
- ${\rm Br}_{\phi \to {\rm DM}}$ is the branching ratio for ϕ decays into R-parity odd particles

Non-thermal DM scenarios

- DM abundance:

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

- First term on RHS side $\Rightarrow$ Annihilation Scenario
  1. DM produced from ϕ decay undergo some annihilation
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} = \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \left(T_{\rm f}/T_{\rm rh}\right)$
  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 is produced directly from ϕ decay
  2. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \left(T_{\rm f}/T_{\rm rh}\right)$
  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
     $\Rightarrow$ can accommodate also Wino/Higgsino DM

Annihilation Scenario

- FERMI bounds from dwarf spheroidal galaxies [Geringer-Sameth, Koushiappas]:
  - For $m_{\rm DM} < 40\,{\rm GeV}$, $\langle \sigma_{\rm ann} v \rangle_{\rm f} < \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}$ $\Rightarrow$ No ‘annihilation scenario’
  - For $m_{\rm DM} > 40\,{\rm GeV}$, $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$ $\Rightarrow$ $T_{\rm rh} \gtrsim 70\,{\rm MeV}$
- $T_{\rm rh} \simeq 0.8\,Z$ GeV for $m_\phi \simeq 5 \times 10^6$ GeV $\Leftrightarrow$ TeV-scale SUSY
- Two cases:

1. QCD axion is an open string mode θ with $f_a \simeq 10^{11-12}$ GeV
   - Subleading ϕ decays to $\theta \Rightarrow$ No DR is produced
   - DR from ϕ decays to bulk closed string axions $\Rightarrow$ suppress $\Delta N_{\rm eff} \simeq 1.74/Z^2$
   - $\Delta N_{\rm eff} \simeq 0.5 \Rightarrow Z \simeq 1.8 \Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)$ GeV
   - $T_{\rm rh} > \Lambda_{\rm QCD} \Rightarrow$ axion DM is not diluted
   - Multicomponent DM (Wino/Higgsino + open string axions)
2. QCD axion is a local closed string mode $a_{\rm loc}$ with $f_a \simeq 10^{14}$ GeV
   - $\phi \to a_{\rm loc} a_{\rm loc}$ is a leading decay channel $\Rightarrow$ suppress $\Delta N_{\rm eff} \simeq 2.72/Z^2$
   - $\Delta N_{\rm eff} \simeq 0.5 \Rightarrow Z \simeq \sqrt{5} \simeq 2.2 \Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)$ GeV
   - Axion DM is not diluted $\Rightarrow$ tune initial misalignment angle
   - Multicomponent DM (Wino/Higgsino + closed string axions)

Branching Scenario

- Low $T_{\rm rh}$ regime: $3\,{\rm MeV} \lesssim T_{\rm rh} \lesssim 70\,{\rm MeV}$
- Need very small ϕ decay width
- $Z \simeq 2$ to avoid DR problems $\Rightarrow T_{\rm rh} \simeq \mathcal{O}(1)\,{\rm GeV}$
- Cannot lower $T_{\rm rh}$ if $Z = 0$ from loop-suppressed ϕ decays to gauge bosons
- Lower $T_{\rm rh}$ for smaller values of $m_\phi \Rightarrow M_{\rm soft} \ll \mathcal{O}(1)\,{\rm TeV}$
- No DR overproduction + TeV-scale SUSY forbid branching scenario
- Rule out models with Bino LSP $\Rightarrow$ non-thermal DM overproduction
- Way-out: focus on cases where the LSP is unstable
- DM is QCD axion

Conclusions

- Sequestered LVS models
- Superpartner spectrum in the TeV range
- High string scale $M_s \simeq 10^{15}\,\mathrm{GeV} \Rightarrow$ Good inflationary scenarios
- No CMP and no gravitino problem since $m_{3/2} \simeq 10^{11}\,\mathrm{GeV} \gg m_\phi \simeq 5 \times 10^6\,\mathrm{GeV}$
- Reheating driven from ϕ decay with $T_{\mathrm{rh}} \simeq \mathcal{O}(1)\,\mathrm{GeV}$
- Generic dark radiation production from ϕ decay to light bulk closed string axions
- Non-thermal DM from ϕ decay which increases DM parameter space
- ‘Annihilation scenario’ with multicomponent DM: Wino/Higgsino + QCD axion
- Two options for QCD axion:
  - Open string QCD axion with $f_a \simeq 10^{11-12}\,\mathrm{GeV}$
    $\Rightarrow$ No extra DR contribution + no DM overproduction
  - Closed string QCD axion with $f_a \simeq 10^{14}\,\mathrm{GeV}$
    $\Rightarrow$ Extra DR contribution + tune initial misalignment angle
- No ‘Branching scenario’ with $T_{\mathrm{rh}} \simeq 10\,\mathrm{MeV}$ due to DR + TeV-scale SUSY constraints
  $\Rightarrow$ rule out models with stable Bino-like LSP