Dark Radiation in Sequestered String Models

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Based on:

1) Reheating and dark radiation: MC, Conlon, Quevedo, arXiv:1208.3562
2) Stringy axions and the 3.5 keV line: MC, Conlon, Marsh, Rummel, arXiv:1403.2370
3) Sequestered SUSY-breaking: Aparicio, MC, Krippendorf, Maharana, Muia,Quevedo, arXiv:1409.1931
4) General analysis of dark radiation: MC, Muia, arXiv:1511.05447

Contents

- Post-inflationary string cosmology:

  i) Cosmological moduli problem
  ii) Reheating from moduli decay
  iii) Non-thermal dark matter
  iv) Axionic dark radiation
  v) Cosmic axion background
  vi) Soft X-ray excess in galaxy clusters
  vii) 3.5 keV line in galaxy clusters

- Explicit example: sequestered type IIB models with D3s at singularities

Focus on phenomenology more than maths

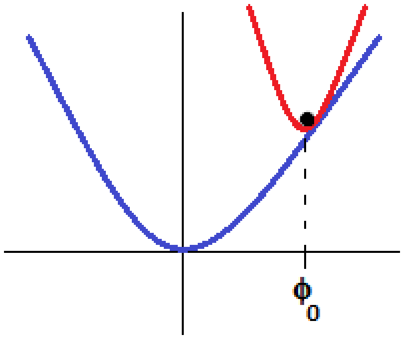
→ Indirect predictions from generic features of string compactifications!

Cosmological moduli problem

- Moduli potential: $$V = \frac{1}{2} m^2 \phi^2 \quad \text{with} \quad m \approx m_{3/2} \approx M_{soft} \approx O(1)\,\text{TeV}$$
- Extra contribution during inflation

$$V = \frac{1}{2} m^2 \phi^2 + c H_{\inf}^2 (\phi - \phi_0)^2 \approx c H_{\inf}^2 (\phi - \phi_0)^2 \quad \text{for} \quad m << H_{\inf}$$

→ ϕ displaced from $\phi = 0$ during inflation



- ϕ behaves as harmonic oscillator with friction $$\ddot{\phi} + 3H\dot{\phi} + m^2 \phi = 0$$
- End of inflation: friction wins → ϕ frozen at $\phi = \phi_0$
- Reheating → thermal bath with temperature T and $H \approx T^2 / M_P$
- Universe expands and cools down → H decreases
- ϕ starts oscillating when $H \approx m$ → ϕ stores energy $\rho_\phi \approx m^2 \phi_0^2 \approx H^2 M_p^2 \approx T^4 \approx \rho_{\text{rad}}$
- ϕ redshifts as $\rho_\phi \propto T^3$ while thermal bath redshifts $\rho_{\text{rad}} \propto T^4$

→ ϕ dominates energy density of the Universe → dilutes everything when it decays!

- ϕ decays when $H \approx \Gamma \approx m^3 / M_P^2$ → Reheating temperature $T_{\text{rh}} \approx \sqrt{\Gamma M_P} \approx m\sqrt{m / M_P}$
- Need $T_{rh} > T_{BBN} \approx$ 3 MeV → m > 50 TeV

Non-standard cosmology from strings

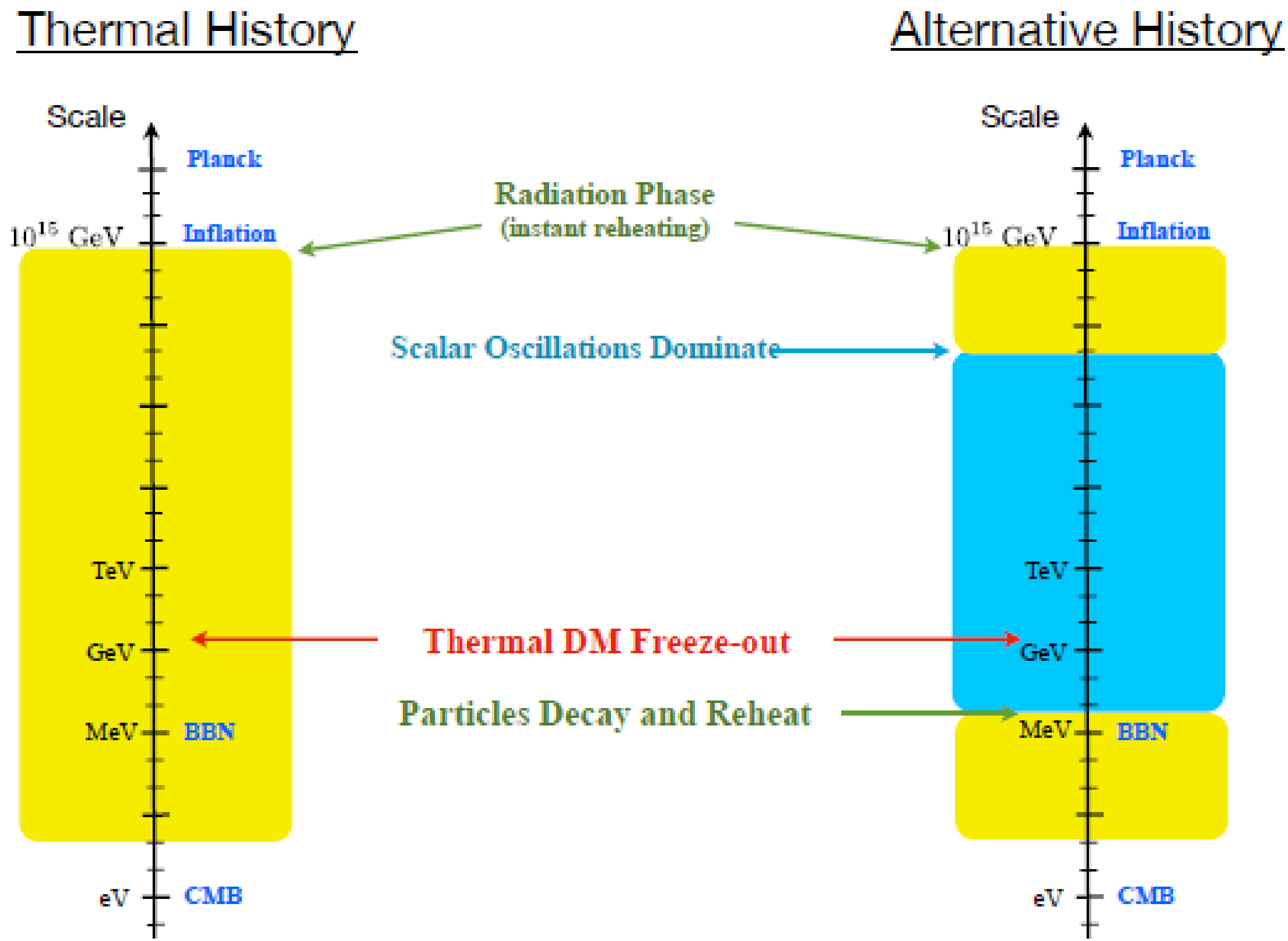
Focus on $m_\phi > 50$ TeV $\Rightarrow$ ϕ decay dilutes any previous relic [Moroi,Randall]:

- 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 $O(\mathrm{TeV})$ coulored particles with B- and CP-violating couplings [Allahverdi,Dutta,Sinha]

Thermal vs Non-thermal cosmology



Non-thermal dark matter from strings

Q: What is generic value of T_{rh} from strings?

Generically in string compactifications :

i) SUSY breaking generates m_ϕ

ii) Moduli mediate SUSY breaking to MSSM via gravitational interactions $\longrightarrow$ $M_{soft} = k\, m_\phi$

iii) Since m_ϕ > 50 TeV, can get TeV-scale SUSY only for $k \ll 1$

iv) $k = O(10^{-2})$ from loop suppression or $k = O(10^{-3} - 10^{-4})$ from sequestering

v) For $M_{soft} = O(1)$ TeV, reheating temperature is

$$T_{\mathrm{rh}} \approx m\sqrt{m/M_P} \approx k^{-3/2} M_{\mathrm{soft}} \sqrt{M_{\mathrm{soft}}/M_P} \approx k^{-3/2} O(10^{-2})\ \mathrm{MeV}$$

$$\text{for } 10^{-4} \le k \le 10^{-2} \quad \longrightarrow \quad 10\ \mathrm{MeV} \le T_{\mathrm{rh}} \le 10\ \mathrm{GeV}$$

Below freeze-out temperature for LSP masses between O(100) GeV and O(1) TeV!

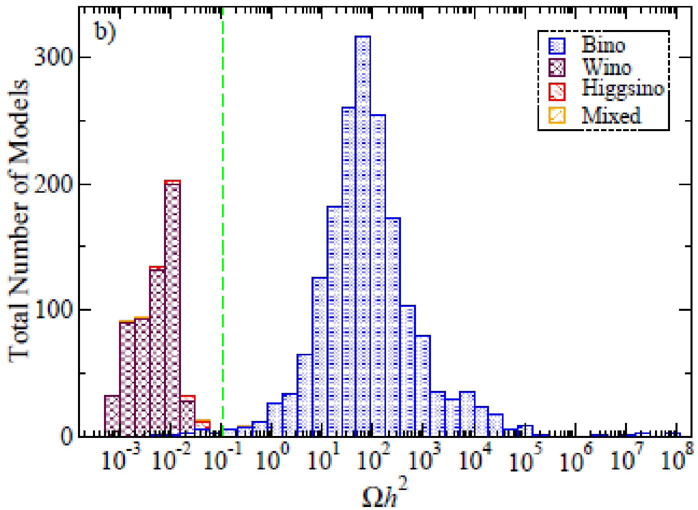
$$10\ \mathrm{GeV} \le T_{\mathrm{f}} \approx m_{\mathrm{DM}}/20 \le 100\ \mathrm{GeV}$$

$\longrightarrow$ Non-thermal dark matter from strings!

Non-thermal dark matter production

• ϕ decay dilutes thermal DM

→ larger parameter space



[Baer et al]

• Non-thermal DM from ϕ decay:

$$\frac{n_{\rm DM}}{s} = \left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \frac{\langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}}{\langle \sigma_{\rm ann} v \rangle_{\rm f}} \left(\frac{T_{\rm f}}{T_{\rm rh}}\right)$$

where $\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \approx 5 \cdot 10^{-10} \left(\frac{1\,\mathrm{GeV}}{m_{\rm DM}}\right)$ and $\langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th} \approx 3 \cdot 10^{-26} cm^3 s^{-1}$

i) Need $\langle \sigma_{\rm ann} v \rangle_{\rm f} = \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th} (T_{\rm f} / T_{\rm rh})$

ii) Since $T_{\rm rh} < T_{\rm f}$ → $\langle \sigma_{\rm ann} v \rangle_{\rm f} > \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}$

→ Wino/Higgsino-like LSP DM

iii) Bino-like LSP: $\langle \sigma_{\rm ann} v \rangle_{\rm f} < \langle \sigma_{\rm ann} v \rangle_{\rm f}^{\rm th}$ → DM overproduction

Non-thermal MSSM

- Consider CMSSM with non-thermal LSP dark matter
- Impose: [Aparicio, MC, Dutta, Krippendorf, Maharana, Muia, Quevedo]

i) radiative EW symmetry breaking + Higgs mass around 125 GeV

ii) no dark matter overproduction

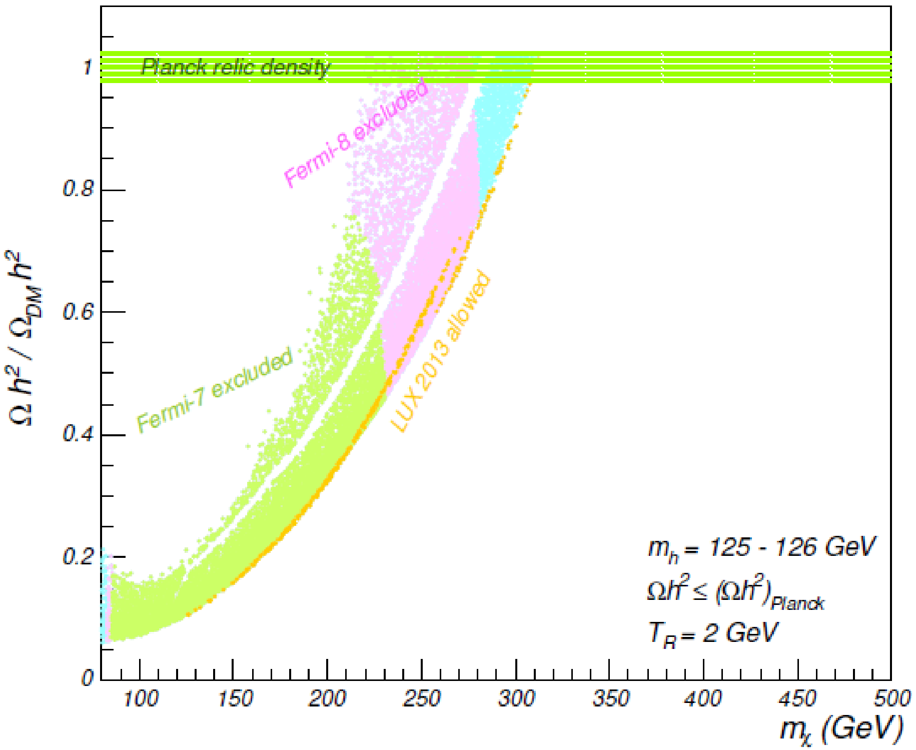
iii) bounds from colliders (LHC), CMB (Planck), direct (LUX) and indirect (Fermi) DM searches

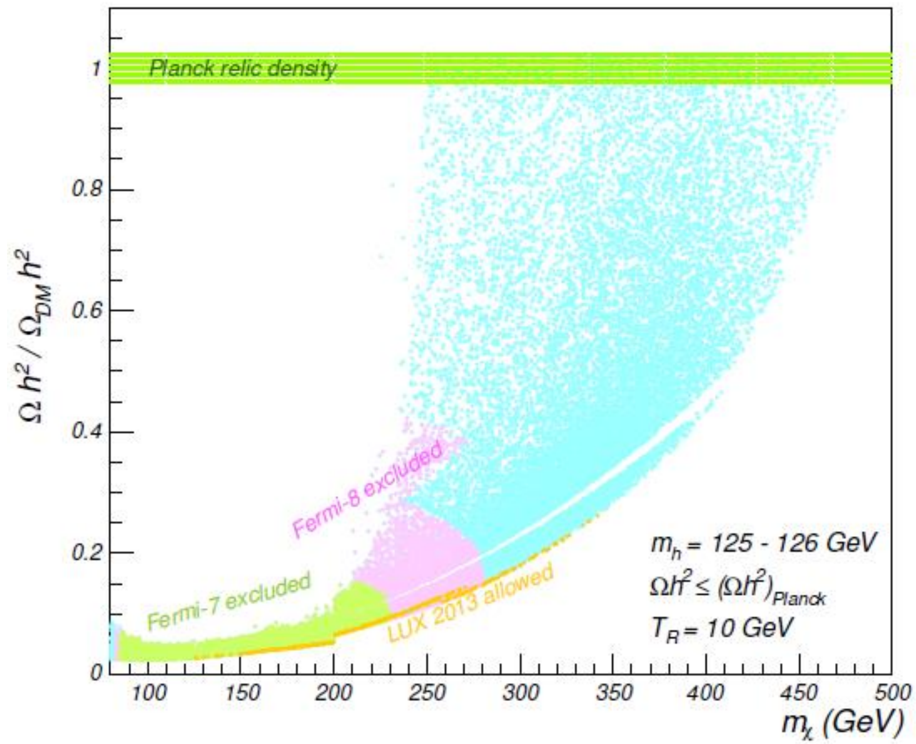
   a) observed DM content saturated for T_R = 2 GeV and 300 GeV Higgsino-like LSP

   b) MSSM case: 300-600 GeV Higgsino LSP saturating DM for T_R = 2-10 GeV

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

   d) realised in string models with sequestered SUSY breaking





Sequestered string models

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

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: $M_s \simeq \mathcal{O}(10^{16})$ GeV
   $\Rightarrow$ good for GUTs and inflation [MC,Burgess,Quevedo]

good (numerically) for inflation? Otherwise need volume evolution during or after inflation

A challenge for moduli decays

GENERIC feature of string compactifications: presence of light axionic degrees of freedom UNAVOIDABLE in most string models [Allahverdi, MC, Dutta,Sinha]

- 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_{eff}

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

  3. Tight bounds from observations (Planck+WMAP9+ACT+SPT+BAO+HST):
     $N_{\text{eff}} = 3.52^{+0.48}_{-0.45} \Rightarrow \Delta N_{\text{eff}} \simeq 0.5$ (95% CL)

GENERIC PREDICTION of string compactifications: axionic dark radiation production from ϕ decay is UNAVOIDABLE in most string models!

Planck 2015: $N_{\text{eff}} = 3.13 \pm 0.32$ (68% CL)
reduced evidence for dark radiation BUT……

Dark radiation and Planck 2015 data

- Positive correlation between N_{eff} and H_0
- Planck indirect value of H_0 :

$H_0 = 67.3 \pm 1.0$ km s^{-1} Mpc^{-1} (68% CL)

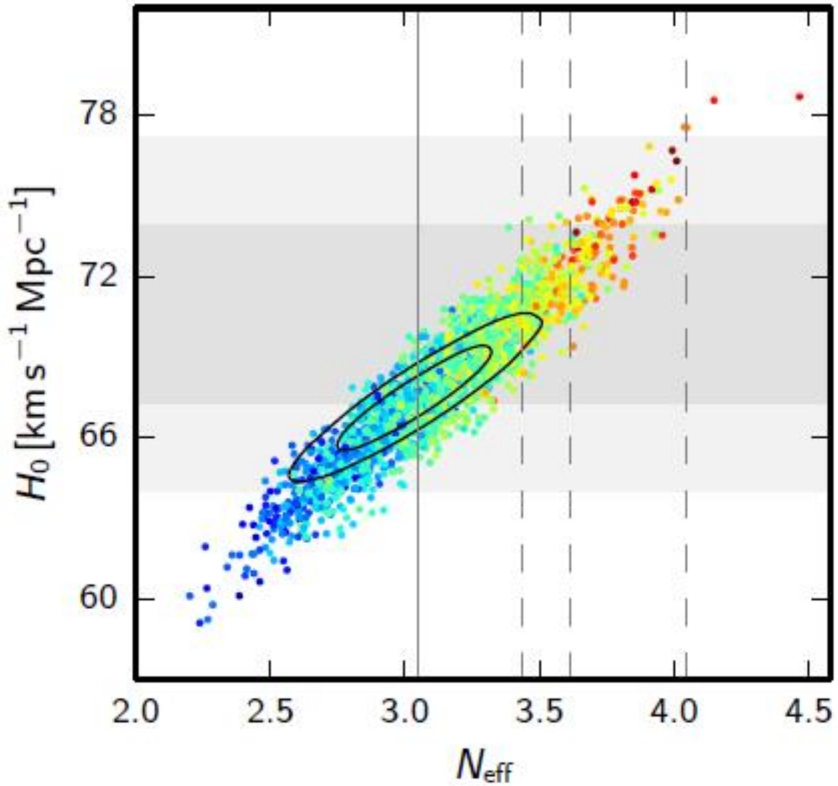
- HST direct value of H_0 :

$H_0 = 73.8 \pm 2.4$ km s^{-1} Mpc^{-1} (68% CL)

2.4 σ tension ⟶ need new physics: $\Delta N_{eff} > 0$

BUT HST data reanalysed by Efstathiou:

$H_0 = 70.6 \pm 3.3$ km s^{-1} Mpc^{-1} (68% CL)



only 1 σ away from Planck value ⟶ no need new physics: $\Delta N_{eff} \to 0$

BUT $\Delta N_{eff} > 0$ still allowed by Planck! (HST value of H_0 still controversial)

E.g.: for $\Delta N_{eff} = 0.39$ Planck data give (68% CL):

$H_0 = 70.6 \pm 1.0$ km s^{-1} Mpc^{-1} ⟶ better agreement with HST!

$n_s \simeq 0.983 \pm 0.006$ ⟶ different predictions for tensor modes!

⟶ Need reliable direct measurements of H_0 !

Axionic dark radiation from strings

- Low-energy theory: many closed string axions of order $h^{1,1} \simeq O(100)$

  $\longrightarrow$ expect many axions

  i) closed string axions (KK zero modes of antisymmetric forms)

  ii) open string axions (phase θ of a matter field $\phi = |\phi|\, e^{i\theta}$)

- BUT axions can be:

  i) removed from the spectrum by orientifold projection

  ii) eaten up by anomalous U(1)s

    a) open string axions eaten up on cycles in geometric regime

    b) closed string axions eaten up for branes at singularities

  iii) too heavy if fixed supersymmetrically

    (saxion has to get a mass larger than O(50) TeV)

- Moduli stabilisation:

  i) axions are light if saxions are fixed perturbatively because of shift symmetry

  ii) axions are heavy if saxions are fixed non-perturbatively

Note: Non-perturbative stabilisation hard because of tuning, deformation zero-modes, chirality and non-vanishing gauge fluxes (Freed-Witten anomaly cancellation)

$\longrightarrow$ GENERIC PREDICTION: dark radiation production is UNAVOIDABLE in models with perturbative moduli stabilisation! [Allahverdi, MC, Dutta,Sinha]

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 scales in sequestered models

- D3s at singularties $\longrightarrow$ 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):

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

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

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

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

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

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

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

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

1) TeV scale SUSY
2) Standard GUTs
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) $T_{rh} \sim 1$ GeV
8) Non-thermal dark matter
9) Axionic dark radiation

MSSM

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

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

$\longleftrightarrow$

Split SUSY

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

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

$$m_{a_{open}} \approx 1\,\text{meV} \ \text{ for } \ f_{a_{open}} \approx M_s \sqrt{\tau_{vs}} << M_s$$

$$m_{a_b} \approx 0$$

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]
- String realisation of QCD axion [MC,Goodsell,Ringwald]:
  Open string QCD axion θ: $C = \rho\, e^{\mathrm{i}\theta}$
  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

NB: Global embedding: 2 del Pezzo's exchanged by orientifold involution

$\longrightarrow$ 2 light open string axions with intermediate scale f

$\longrightarrow$ 1 is the QCD axion, the other is a massless ALP good for X-ray excess and 3.5 keV line!

Volume decays to axions

1. **Decays to volume axions**

$$K = -3\ln(T_b + \bar{T}_b) \quad \Rightarrow \quad \mathcal{L} = \frac{3}{4\tau_b^2}\partial_\mu \tau_b \partial^\mu \tau_b + \frac{3}{4\tau_b^2}\partial_\mu a_b \partial^\mu a_b$$

Canonical normalisation $\Phi = \sqrt{\frac{3}{2}}\ln\tau_b \Rightarrow \mathcal{L} = \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \frac{3}{4}\exp[-2\sqrt{\frac{2}{3}}\Phi]\partial_\mu a_b \partial^\mu a_b$

Decay rate: $\Gamma_{\Phi\to a_b a_b} \sim \frac{m_\Phi^3}{M_P^2}$ source for dark radiation

2. **Decays to local axions** (if not eaten by $U(1)$s or lifted non-perturbatively)

$$\mathcal{L} = \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \frac{1}{2}\partial_\mu a_s\partial^\mu a_s - \sqrt{\frac{3}{2}}\frac{1}{4M_P}a_s^2\Box\Phi \quad \Rightarrow \quad \Gamma_{\Phi\to a_s a_s} \sim \frac{m_\Phi^3}{M_P^2}$$

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

$$\mathcal{L} \supset -\sqrt{\frac{2}{3}}\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \Phi\theta\Box\theta + \frac{4}{3}\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \Phi\partial_\mu a_b\partial^\mu\theta$$

- $\Phi \to \theta\theta$ decays are mass suppressed
- $\Phi \to \theta a_b$ decays compete with $\Phi \to a_b a_b$ for $\langle\rho\rangle \sim M_P$ BUT $\left(\frac{\langle\rho\rangle}{M_P}\right)^2 \sim \xi \sim \frac{1}{\mathcal{V}} \ll 1$

Volume decays to Higgs bosons

- Giudice-Masiero coupling in the Kähler potential

$$K = -3\ln(T_b + \bar{T}_b) + \frac{H_u\bar{H}_u + H_d\bar{H}_d}{(T_b + \bar{T}_b)} + \left(\frac{ZH_uH_d}{(T_b + \bar{T}_b)} + \text{h.c.}\right)$$

- If Higgs sector has a shift symmetry [Hebecker,Knochel,Weigand]:

$$K \supset \frac{(H_u + \bar{H}_d)(\bar{H}_u + H_d)}{(T_b + \bar{T}_b)} \quad \Rightarrow \quad Z = 1$$

After canonical normalisation:

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \partial_\mu H_u\partial^\mu\bar{H}_u + \partial_\mu H_d\partial^\mu\bar{H}_d \\ &+ \frac{1}{\sqrt{6}}\left[\Phi\left(\bar{H}_u\Box H_u + \bar{H}_d\Box H_d\right) + ZH_uH_d\Box\Phi + h.c.\right]\end{aligned}$$

Last term gives the decay $\Phi \to H_uH_d$ with $\Gamma_{\Phi\to H_uH_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}$

Volume decays to visible sector

1. **Decays to gauge bosons**

   Tree-level: $f_a = S + h_a T_{\rm vs}$ (independent of T_b) – Loop level: $\frac{b_a \alpha_{\rm vs}}{4\pi} \ln \mathcal{V}$

$$\mathcal{L} \supset \frac{\lambda_a \alpha_{\rm vs}}{4\pi} \Phi F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \quad \Gamma_{\Phi\to\gamma\gamma} \sim \left(\frac{\alpha_{\rm vs}}{4\pi}\right)^2 \frac{m_\Phi^3}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

2. **Decays to matter scalars** C

$$K = -3\ln(T_b + \bar{T}_b) + \frac{C\bar{C}}{(T_b + \bar{T}_b)} \quad \Rightarrow \quad \mathcal{L} \supset \frac{1}{2}\sqrt{\frac{2}{3}}\,\Phi\left(\bar{C}\Box C + C\Box\bar{C}\right)$$

   $\Phi \partial_\mu C \partial^\mu C$ couplings vanish! Decay rate: $\Gamma_{\Phi\to CC} \sim \frac{m_0^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$

   For MSSM case
   but not for split SUSY
   where $m_0 \approx m_\phi$!

3. **Decays to matter fermions, gauginos and Higgsinos**

$$\mathcal{L} \supset \lambda \frac{\Phi}{M_P} \bar{\chi}\bar{\sigma}^m D_m \chi \quad \Rightarrow \quad \Gamma_{\Phi\to ff} \sim \frac{m_f^2 m_\Phi}{M_P^2} \ll \frac{m_\Phi^3}{M_P^2}$$

Reheating

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

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

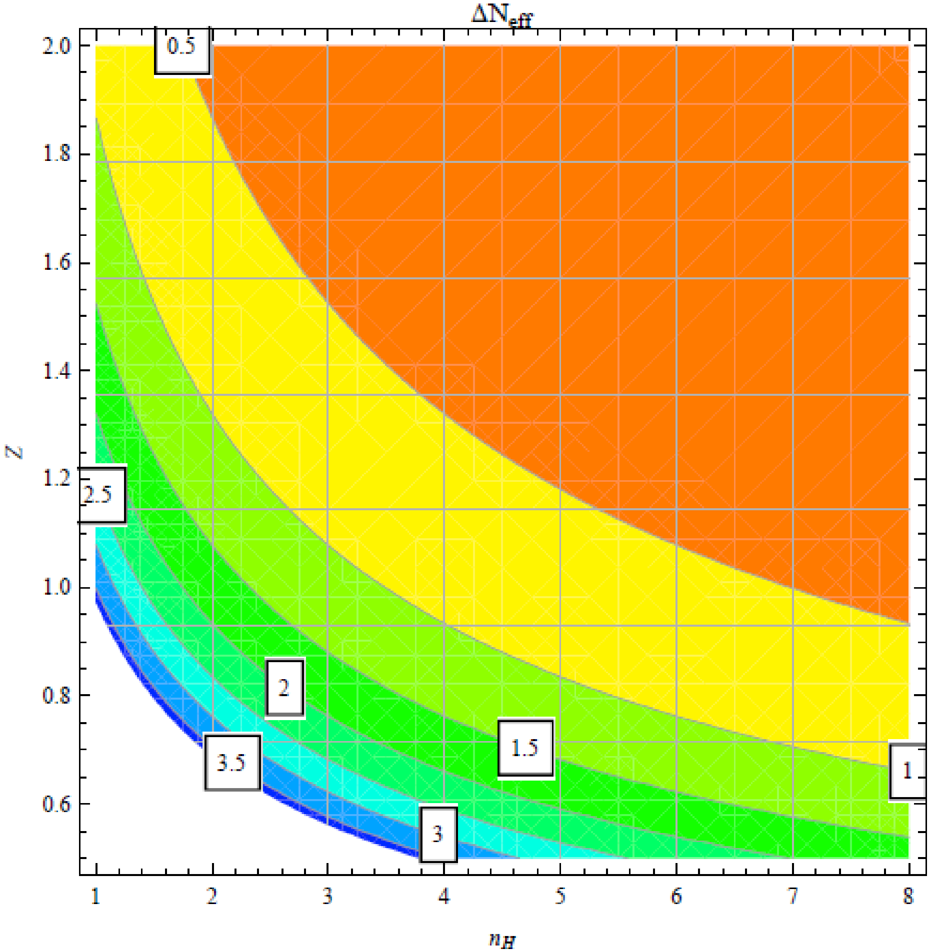
- Leading decay channels:
  - **Higgses:** $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions:** $c_{\phi\to a_b a_b} = 1/24$
- Subleading decay channels:
  - **Gauge bosons:** $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm vs}^2}{8\pi} \ll 1$
  - **Other visible sector fields:** $c_{\phi\to\psi\psi} \simeq \left(\frac{M_{\rm soft}}{m_\phi}\right)^2 \simeq \frac{1}{\mathcal{V}} \ll 1$ Only for MSSM case!
  - **Local open string axions:** $c_{\phi\to a_b\theta} \simeq \left(\frac{M_s}{M_P}\right)^4\tau_{\rm sing}^2 \simeq \left(\frac{\tau_{\rm sing}}{\mathcal{V}}\right)^2 \ll 1$

MSSM predictions for dark radiation

Prediction for $\Delta N_{\rm eff}$ for n_H Higgs doublets:

[MC, Conlon, Quevedo] [Higaki, Takahashi]

$$\Delta N_{\rm eff} = \frac{3.48}{n_H Z^2}$$



$\Delta N_{eff} \leq 1$ for $n_H = 2$

if $Z \geq 1.22$

Split SUSY predictions for dark radiation

- In split SUSY $m_0 = c m_\phi$ and $\mu = \tilde{c} m_\phi$ with $c \approx \tilde{c} \approx O(1)$ [MC, Muia]

  → ϕ can decay to squarks, sleptons and Higgsinos if $c \leq 1/2$ and $\tilde{c} \leq 1/2$

- Kinematic condition satisfied due to string loop corrections to K
- Interaction Lagrangian:

$$\mathcal{L}_{\rm cubic} \simeq \frac{7c^2}{2\sqrt{6}} \frac{m_\Phi^2}{M_P} \hat{\Phi} \left[\sigma^\alpha \sigma_\alpha + \chi^\alpha \chi_\alpha + \left(1 + \frac{6\tilde{c}^2}{7c^2}\right) h_i h^i + 2Z \left(c_{B,K} - \frac{1}{7c^2}\right) \sum_{i=1}^{4} (-1)^{i+1} h_{2i-1} h_{2i} \right]$$
$$+ \tilde{c} \sqrt{\frac{2}{3}} \frac{m_\Phi}{M_p} \hat{\Phi} \left(\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0 \right) + \text{h.c.}.$$

- New contributions to visible sector branching ratio:

  i) Decays to squarks and sleptons
  ii) Mass term contribution to decays to (heavy) Higgses
  iii) $B\mu$-term contribution to decays to Higgses
  iv) Decays to Higgsinos

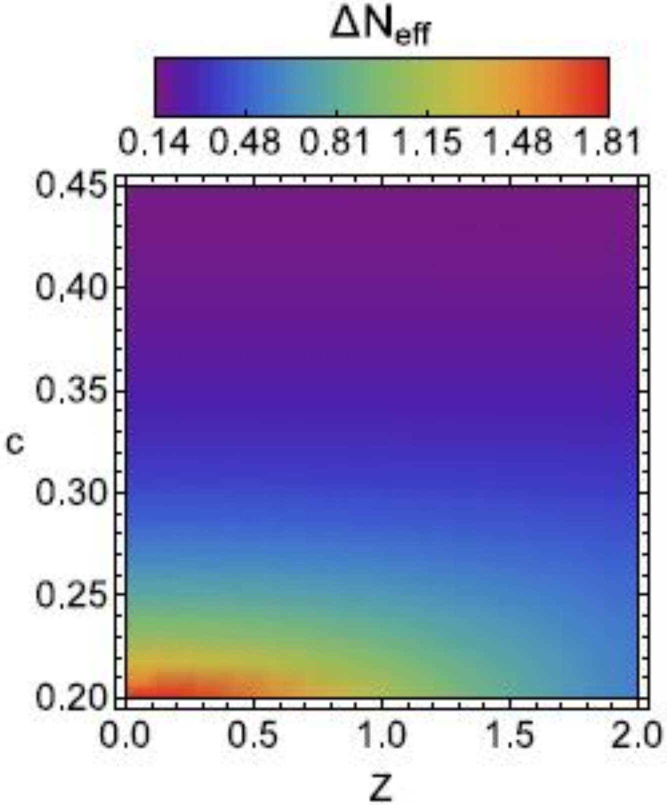
- Significant reduction of extra dark radiation!

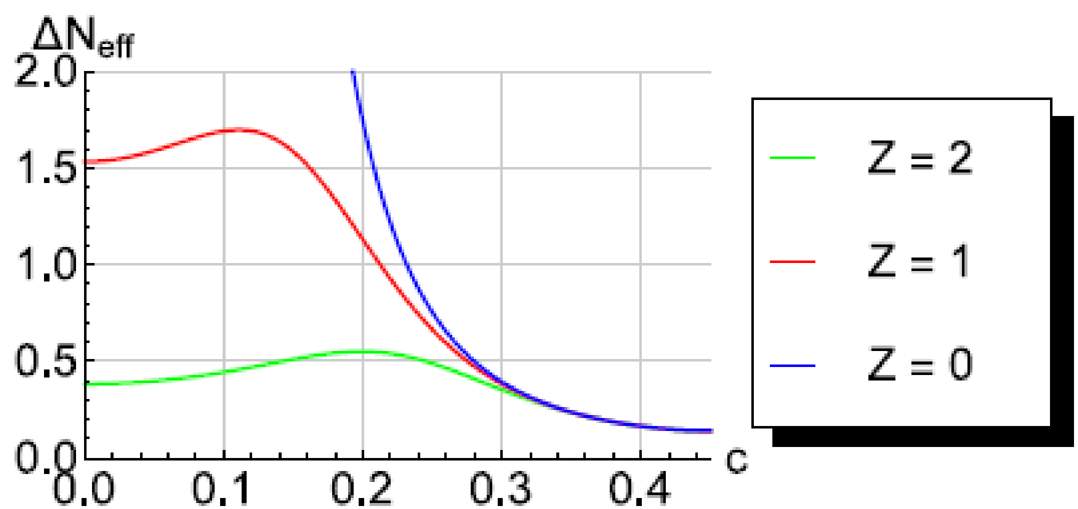
$$0.14 \leq \Delta N_{eff} \leq 1.60 \quad \text{for} \quad Z = 1$$

Split SUSY predictions for dark radiation

- Conservative predictions for $\tilde{c} = 0$

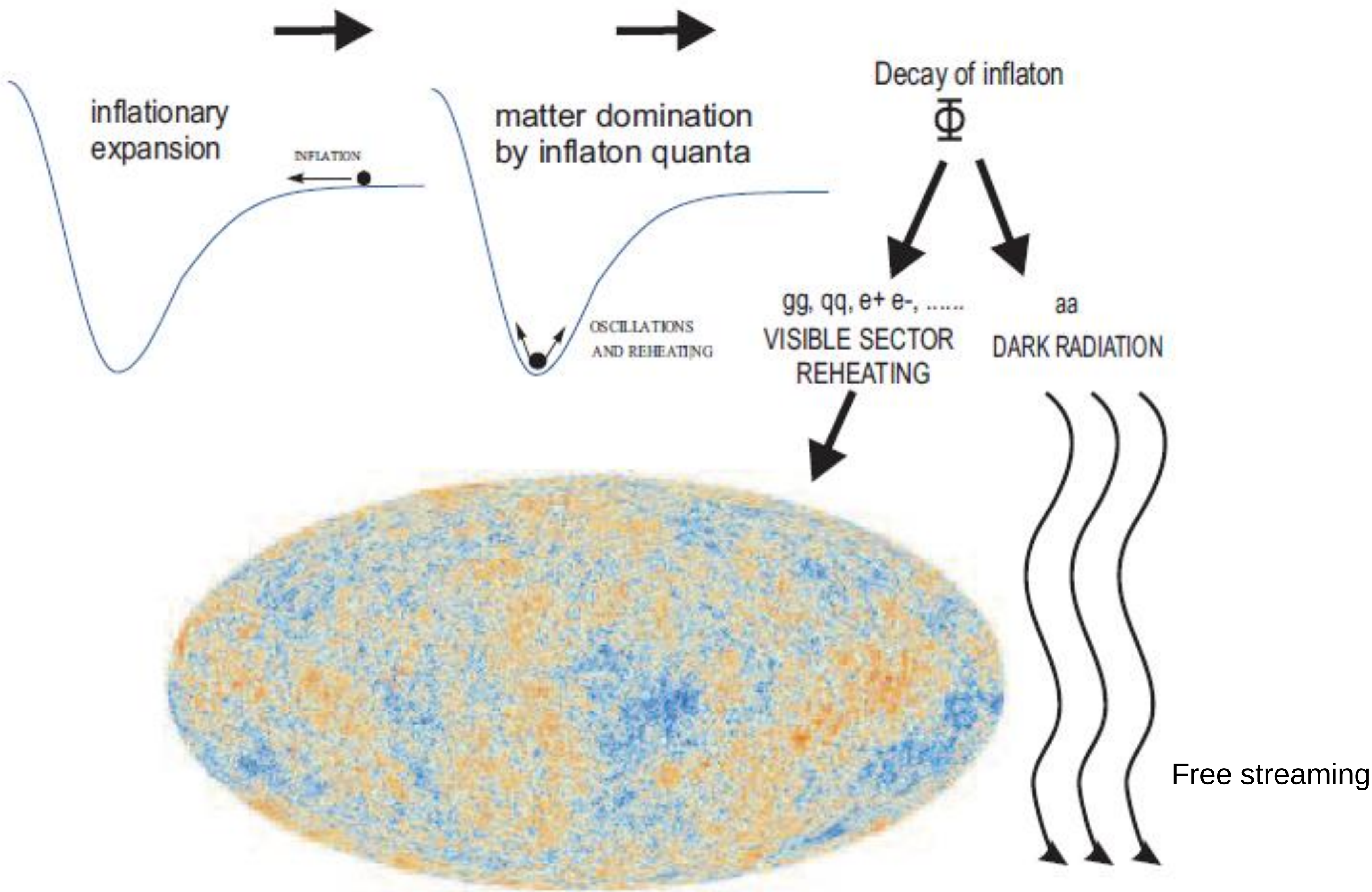
[MC, Muia]





$$\Delta N_{eff} \leq 1 \quad \text{for} \quad Z = 0 \quad \text{if} \quad c \geq 0.23$$

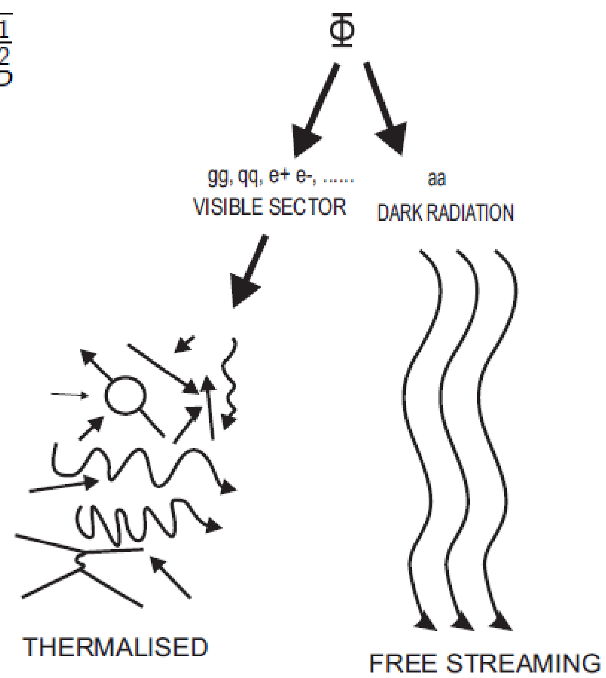
Dark radiation production



Cosmological evolution of dark radiation

$\Phi \to gg, \ldots$: Decays thermalise $T_\gamma \sim T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$

$\Phi \to aa$: Axions never thermalise $E_a = \frac{m_\Phi}{2}$



Thermal bath cools into the CMB while axions never thermalise and freestream to the present day:

Ratio of axion energy to photon temperature is

$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\Phi}\right)^{\frac{1}{2}} \sim 10^6 \left(\frac{10^6\text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$

Retained through cosmic history!

No absolute prediction, but a lightest modulus mass $m \sim 10^6$GeV arises in many string models - often correlated with SUSY approaches to the weak hierarchy problem.

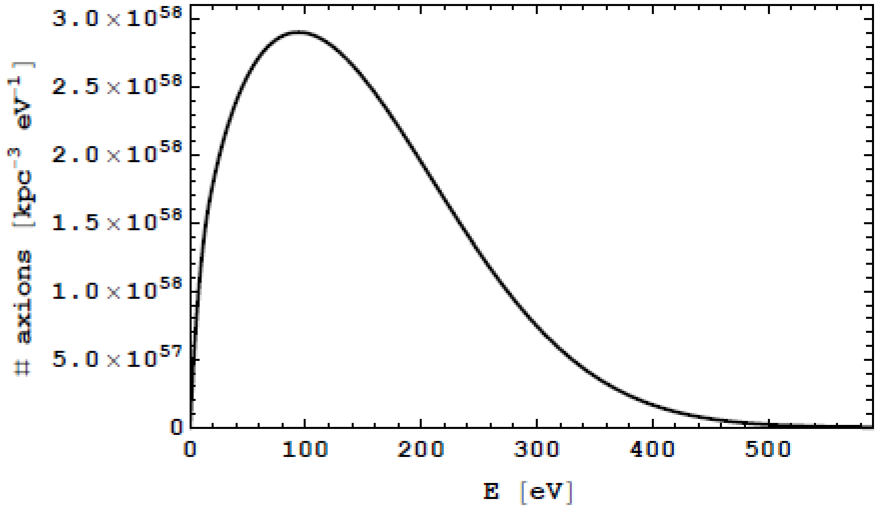
No CMP requires m>$10^{4\text{-}5}$ GeV!

- KKLT hep-th/0503216 Choi et al
- Sequestered LVS 0906.3297 Blumenhagen et al + 1409. 1931 Aparicio, MC, Krippendorf, Maharana, Muia, Quevedo
- 'G2 MSSM' 0804.0863 Acharya et al

Cosmic Axion Background

PREDICTION: Cosmic Axion Background

$$E_a \sim 200\text{eV} \left(\frac{10^6 \text{ GeV}}{m_\Phi} \right)^{\frac{1}{2}}$$



The expectation that there is a dark analogue of the CMB at $E \gg T_{CMB}$ comes from very simple and general properties of moduli.

It is not tied to precise models of moduli stabilisation or choice of string theory etc.

It just requires the existence of massive particles only interacting gravitationally.

For $10^5\text{GeV} \lesssim m_\Phi \lesssim 10^8\text{GeV}$ CAB lies today in EUV/soft X-ray wavebands.

Axion-photon conversion

- Axion-photon conversion in coherent magnetic fields

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{a}{4M}F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2 a^2$$

M $\geq 10^{11}$ GeV from supernovae cooling

- Axion-photon conversion probability in plasma with frequency ω_{pl}

i) for $m_a < \omega_{pl}$

$$P_{a\to\gamma} \approx \frac{1}{4}\left(\frac{B\,L}{M}\right)^2$$

ii) for $m_a >> \omega_{pl}$

$$P'_{a\to\gamma} \approx P_{a\to\gamma}\left(\frac{\omega_{\rm pl}}{m_a}\right)^4 << P_{a\to\gamma}$$

negligible

- Need large B and L to have large conversion probability $\longrightarrow$ galaxy clusters

i) typical size $R_{cluster} \sim 1$ Mpc

ii) ICM plasma frequency $\omega_{pl} \sim 10^{-12}$ eV

$\longrightarrow$ axions with $m_a >> 10^{-12}$ eV (QCD axion) give negligible conversion

iii) B ~ 1 ÷ 10 μG

iv) L ~ 1 ÷ 10 kpc

CAB evidence in the sky

- Soft X-ray excess in galaxy clusters above thermal emission from ICM observed since 1996 by several missions (EUVE, ROSAT, XMM-Newton, Suzaku and Chandra)

- Statistical significance around 100σ!

- No good astrophysical explanation

- Typical excess luminosity

$$\mathcal{L}_{\text{excess}} \approx 10^{43}\ \text{erg s}^{-1}$$

- CAB energy density

$$\rho_{\text{CAB}} = 1.6 \times 10^{60}\ \text{erg Mpc}^{-3} \left(\frac{\Delta N_{\text{eff}}}{0.57}\right)$$

- Soft X-ray luminosity from axion-photon conversion

$$\mathcal{L}_{a\to\gamma} = \rho_{\text{CAB}} P^{\text{cluster}}_{a\to\gamma} = 3.16 \times 10^{43}\ \text{erg s}^{-1} \left(\frac{\Delta N_{\text{eff}}}{0.5}\right) \left(\frac{B}{\sqrt{2}\,\mu\text{G}} \frac{10^{12}\,\text{GeV}}{M}\right)^2 \left(\frac{L}{1\,\text{kpc}}\right)$$

- 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

- Detection of a 3.5 keV line from:

i) Stacked galaxy clusters (XMM-Newton) and Perseus (Chandra) [Bulbul et al. 1402.2301]

ii) Perseus and Andromeda (XMM-Newton) [Boyarsky et al. 1402.4119]

iii) Perseus (Suzaku) [Urban et al. 1411.0050]

- Non-detection of a 3.5 keV line from:

i) Dwarf spheroidal galaxies (XMM-Newton) [Malyshev et al. 1408.3531]

ii) stacked galaxies (XMM-Newton and Chandra) [Anderson et al. 1408.4115]

- Simplest explanation: DM with $m_{DM} \sim 7$ keV (sterile neutrinos, axions, axinos,…..) decaying into photons [Higaki, Jeong, Takahashi] [Jaeckel,Redondo, Ringwald]

- Astrophysical explanation: new atomic transition line from ICM plasma – less plausible: line seen in Andromeda where there is no ICM!

Problems with DM decay

- Problems with simplest explanation DM $\longrightarrow \gamma\,\gamma$:

i) Inconsistent inferred signal strength

Line traces only DM quantity in each cluster → clear prediction

$$F^{i}_{\mathrm{DM}\to\gamma} \propto \Gamma_{\mathrm{DM}\to\gamma}\,\rho^{i}_{\mathrm{DM}} \quad \Rightarrow \quad \frac{F^{i}_{\mathrm{DM}\to\gamma}}{F^{j}_{\mathrm{DM}\to\gamma}} \propto \frac{\rho^{i}_{\mathrm{DM}}}{\rho^{j}_{\mathrm{DM}}} \quad \text{fixed}$$

BUT signal strength from Perseus larger than for other stacked galaxy clusters (XMM-Newton and Chandra) and Coma, Virgo and Ophiuchus (Suzaku)

ii) Inconsistent morphology of the signal

Non-zero signal from everywhere in DM halo

BUT stronger signal from central cool core of Perseus (XMM-Newton, Chandra and Suzaku) and Ophiucus + Centaurus (XMM-Newton)

iii) Non-observation in dwarf spheroidal galaxies

Dwarf galaxies are dominated by DM → they should give cleanest DM decay line

BUT the line has not been observed + non-observation in stacked galaxies

Alternative explanation: DM → ALP → γ

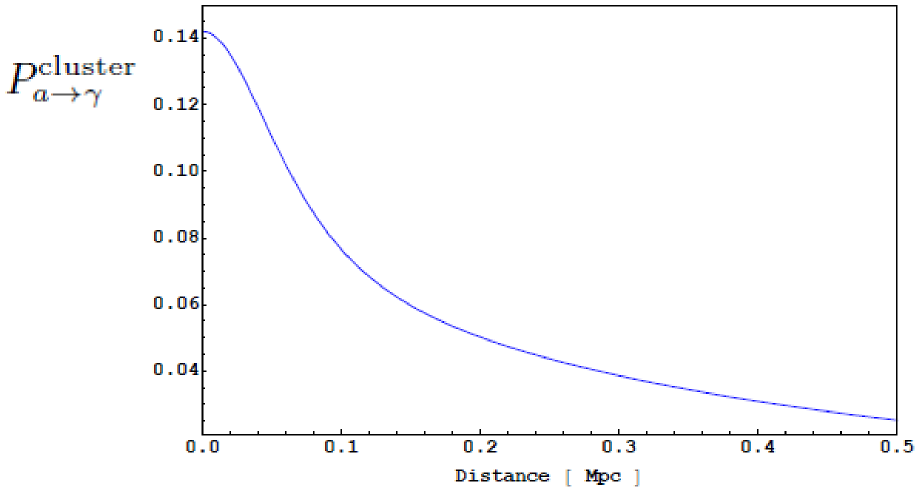
- Monochromatic 3.5 keV axion line from DM decay with m_{DM} ~ 7 keV

a) $\frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a \longrightarrow \Gamma_\Phi = \frac{1}{32\pi}\frac{m_\Phi^3}{\Lambda^2}$ b) $\frac{\partial_\mu a}{\Lambda}\bar{\psi}\gamma^\mu\gamma^5\chi \longrightarrow \Gamma_{\psi\to\chi a} = \frac{1}{16\pi}\frac{(m_\psi^2 - m_\chi^2)^3}{m_\psi^3\Lambda^2}$

- Axion-photon conversion in cluster magnetic field [MC, Conlon, Marsh, Rummel 1403.2370]

$$F^i_{\mathrm{DM}\to\gamma} \propto \Gamma_{\mathrm{DM}\to a} P^i_{a\to\gamma} \rho^i_{\mathrm{DM}} \quad \Rightarrow \quad \frac{F^i_{\mathrm{DM}\to\gamma}}{F^j_{\mathrm{DM}\to\gamma}} \propto \frac{\rho^i_{\mathrm{DM}} P^i_{a\to\gamma}}{\rho^j_{\mathrm{DM}} P^j_{a\to\gamma}} \propto \left(\frac{B^i}{B^j}\right)^2$$

- Morphology of the signal: B-field peakes at centre



$$B(r) = B_0\sqrt{\frac{n_e(r)}{n_e(0)}}$$

- Match data for same values which give soft X-ray excess: $m_a < 10^{-12}\mathrm{eV} \quad M \approx 10^{12}\ \mathrm{GeV}$

$$\Lambda \approx M_{GUT} \approx 10^{16}\ \mathrm{GeV}$$

DM $\rightarrow$ ALP $\rightarrow$ γ: advantages and predictions

- B-dependent line strength can explain:

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

ii) Stronger signal from cool core:
B-field peaks in central cool core in galaxy clusters

iii) Non-observation in dwarf galaxies:
Dwarf galaxies have L and B-field smaller than galaxy clusters
Predicted in MC, Conlon, Marsh, Rummel 1403.2370 $\longrightarrow$ confirmed in Malyshev et al. 1408.3531

iv) Non-observation in galaxies:
Galaxies have L and B-field smaller than galaxy clusters
Predicted in MC, Conlon, Marsh, Rummel 1403.2370 $\longrightarrow$ confirmed in Anderson et al. 1408.4115

v) Observation in Andromeda:
it is almost edge on to us
$\longrightarrow$ axions have significant passage through its disk and enhance conversion probability

Conclusions

- Cosmological moduli problem: $m_\phi > 50$ TeV
- 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 $T_R = 2$ GeV
  ii) MSSM with a 300-600 GeV Higgsino LSP saturating DM for $T_R = 2\text{-}10$ GeV
- Generic production of axionic dark radiation $\longrightarrow$ $\Delta N_{eff} \neq 0$
- Cosmic axion background with $E_a \sim 200$ eV
- CAB detectable via axion-photon conversion in B
- Explain soft X-ray excess in galaxy clusters
- Explain 3.5 keV line from galaxy clusters improving simplest decaying DM interpretation