Pre and Post-inflationary String Cosmology

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Based on:

1) Pre-inflation: MC, Downes, B. Dutta, arXiv:1309.3412
   MC, Downes, B. Dutta, Pedro, Westphal, arXiv:1407.1048
2) Inflation: Burgess, MC, Quevedo, arXiv: 1306.3512
   MC, K. Dutta, Maharana, arXiv:1401.2579
   Burgess, MC, Quevedo, Williams, arXiv: 1404.6236
3) Reheating and dark radiation: MC, Conlon, Quevedo, arXiv:1208.3562
4) Stringy axions and the 3.55 keV line: MC, Conlon, Marsh, Rummel, arXiv:1403.2370
5) Non-thermal dark matter: Allahverdi, MC, B. Dutta, Sinha, arXiv:1307.5086
   Allahverdi, MC, B. Dutta, Sinha, arXiv:1401.4364
   Aparicio, MC, B. Dutta, Krippendorf, Maharana, Muia, Quevedo, in preparation

Contents

- String inflation and large vs small tensor modes
- Pre-inflationary string cosmology and power loss at large scales
- Post-inflationary string cosmology

  i) Axionic dark radiation
  ii) Cosmic axion background and soft X-ray excess
  iii) 3.55 keV line
  iv) Non-thermal dark matter

- Particular case: sequestered string models

Focus on phenomenology more than maths

⟶ Indirect predictions from generic features of string compactifications!

Understanding acceleration

Emerging picture from COBE, WMAP, Planck, BICEP: striking simplicity

i) Gaussian scalar fluctuations

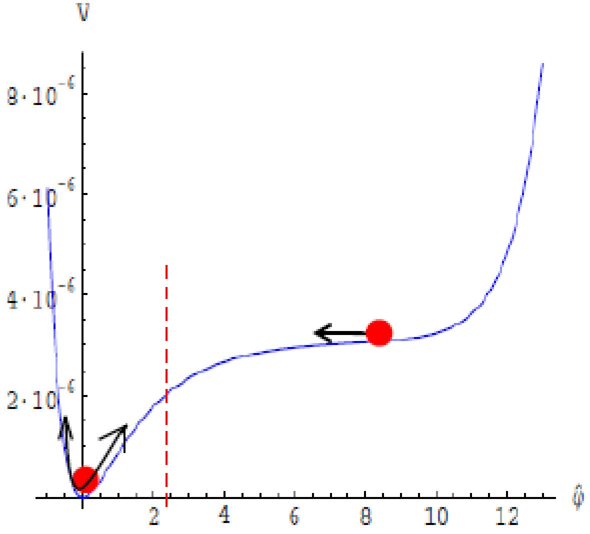
ii) Spectral index close to scale-invariant: $n_s \simeq 0.9655 \pm 0.0062$ (68% CL, Planck 2015)

iii) No evidence for tensor modes: $r < 0.11$ (95% CL, Planck 2015)

→ Early epoch of accelerated expansion driven by a scalar field

Slow-roll inflation:

$$V \approx 3H_{\inf}^2 M_P^2$$



$$\varepsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 << 1 \qquad \eta \equiv M_P^2 \frac{V''}{V} \approx \left(\frac{m_{\inf}}{H_{\inf}}\right)^2 << 1$$

$$N_e = \frac{1}{M_P}\int_{\varphi_{end}}^{\varphi_{in}} \frac{1}{\sqrt{2\varepsilon}}\, d\varphi \approx 60 \qquad P_S(k) \approx A_S^2\, k^{n_s - 1}$$

$$A_S \approx \frac{H_{\inf}}{2\pi\sqrt{2}M_P\sqrt{\varepsilon}} \approx 5\cdot 10^{-5} \qquad n_s - 1 = 2\eta - 6\varepsilon \approx -0.04$$

$$r \equiv \frac{A_T^2}{A_S^2} = 16\varepsilon < 0.11 \qquad \Rightarrow \quad H_{\inf} < 10^{14}\ \text{GeV}$$

$$\Rightarrow \quad M_{\inf} = V^{1/4} < 2\cdot 10^{16}\ \text{GeV} \approx M_{GUT}$$

Why string inflation?

Inflation is UV-sensitive! → complete theory of quantum gravity as string theory

- Abnormally flat potentials: η-problem

Hierarchy problem for Higgs: why $m_H << M_P$? Similarly for the inflaton: why $m_{\text{inf}} << H_{\text{inf}}$?
Need to control quantum gravity interactions → string theory
Slow-roll parameters are sensitive to dim 6 Planck suppressed operators:

$$\Delta V \approx V \frac{\varphi^2}{M_P^2} \quad \Rightarrow \quad \Delta m^2_{\inf} \approx \frac{V}{M_P^2} \approx H^2_{\inf} \quad \Rightarrow \quad \Delta \eta \approx 1$$

- Trans-Planckian field motion

Observable gravitational waves require trans-Planckian distances

Lyth bound: $$\frac{\Delta\varphi}{M_P} \approx \sqrt{\frac{r}{0.001}} \quad \Rightarrow \quad \Delta\varphi > M_P \quad \text{for} \quad r > 0.001$$

How can you trust the low-energy expansion? → need a symmetry → string theory

$$V(\varphi) = V_0 + \frac{m^2}{2}\varphi^2 + \varphi^4 \sum_{i=0}^{\infty} \lambda_i \left(\frac{\varphi}{M_P}\right)^i$$

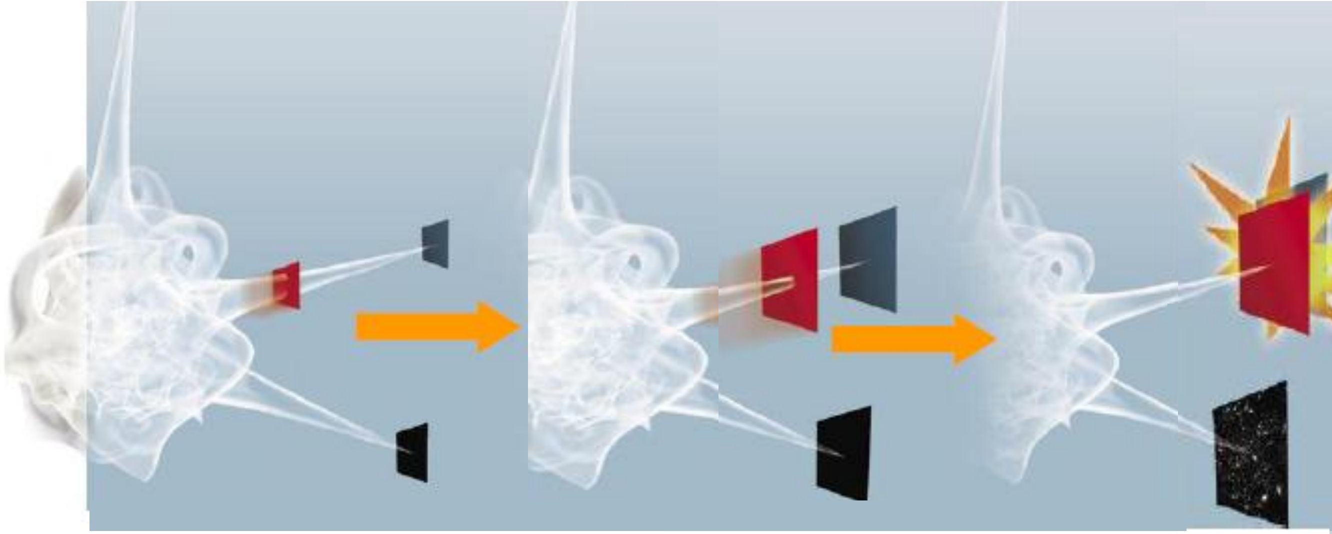
String inflationary scenarios

Two classes of models:

- Open string inflation – inflaton is a brane position modulus

i) No symmetry solving the η-problem → fine-tuning

ii) Upper bounds on field range from size of EDs → no detectable tensor modes



- Closed string inflation

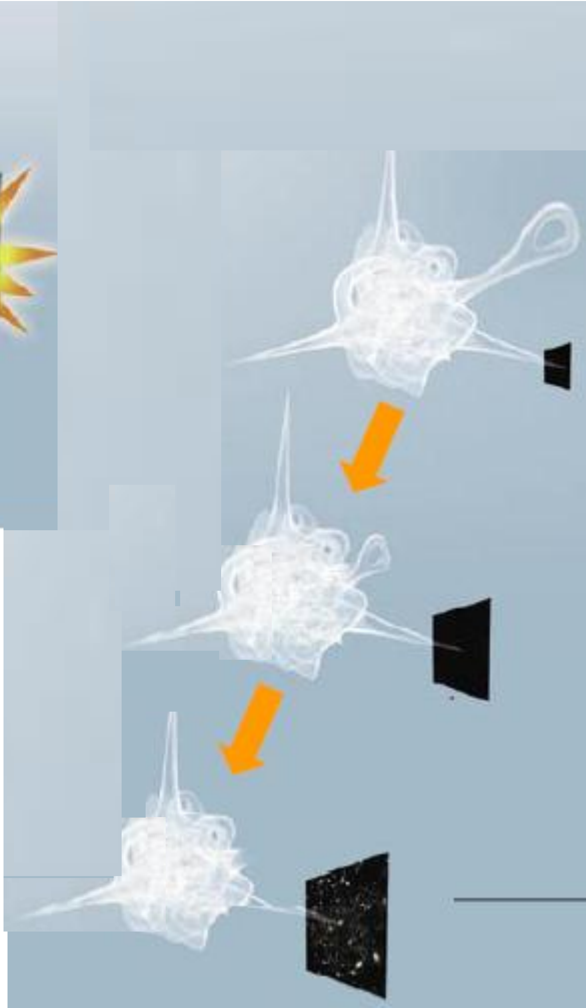
i) Approximate symmetries solving the η-problem

ii) Models with detectable tensor modes

Inflaton:

a) volume modulus (accidental shift symmetry from no-scale)

b) axion (shift symmetry)



String inflation from volume moduli

i) Kahler potential:

$$K_{\rm tree}+K_{g_s}+K_{\alpha'}=-2\ln\mathcal{V}+g_s\sum_i\frac{t_i}{\mathcal{V}}+\frac{1}{\mathcal{V}}$$

➡ suppressed higher dim. operators due to approximate shift symmetry for moduli $\neq\mathcal{V}$

ii) Potential from dim. 4 operators: flat at tree-level + leading g_s effect – Extended no-scale

➡ α' correction lifts only $\mathcal{V}$

➡ naturally flat potential for fields φ orthogonal to $\mathcal{V}$!

iii) Typical potential: $V\approx V_0\left(1-\kappa\, e^{-\kappa\varphi}\right)$ with κ model-dependent

iv) Implications:

$$\varepsilon\approx\frac{\eta^2}{2\kappa^2}\quad\text{and}\quad\eta\approx-\kappa^3e^{-\kappa\varphi}<0\quad\Rightarrow\quad\varepsilon<<|\eta|<<1$$

$$r\approx\frac{2}{\kappa^2}(n_s-1)^2\quad\Rightarrow\quad\text{for}\quad n_s\approx0.96\quad\Rightarrow\quad r\approx\frac{0.0032}{\kappa^2}$$

v) 3 models:

1) Kahler moduli inflation: $\kappa\simeq\mathcal{V}^{1/2}>>1$ ➡ $r\simeq10^{-10}$ [Conlon,Quevedo]

2) Fibre inflation: $\kappa\simeq O(1)$ ➡ $0.005<r<0.007$ [MC,Burgess,Quevedo]

3) Poly-instanton inflation: $\kappa\simeq\ln\mathcal{V}>1$ ➡ $r\simeq10^{-5}$ [MC,Pedro,Tasinato]

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: $\varepsilon \simeq \eta$

$$n_s - 1 \approx 2\eta - 6\varepsilon \approx -4\varepsilon \approx -0.04 \quad \Rightarrow \quad \varepsilon \approx 0.01 \quad \Rightarrow \quad r \approx 16\varepsilon \approx 0.16$$

→ tensor modes should soon be observed!

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

$$r \approx 0.1 \left(\frac{M_{\inf}}{M_{GUT}} \right)^4$$

i) M_{inf} could be anywhere between 100 GeV and 10^{15} GeV
ii) No intrinsic reason to prefer any scale

→ no preference for observable or unobservable r

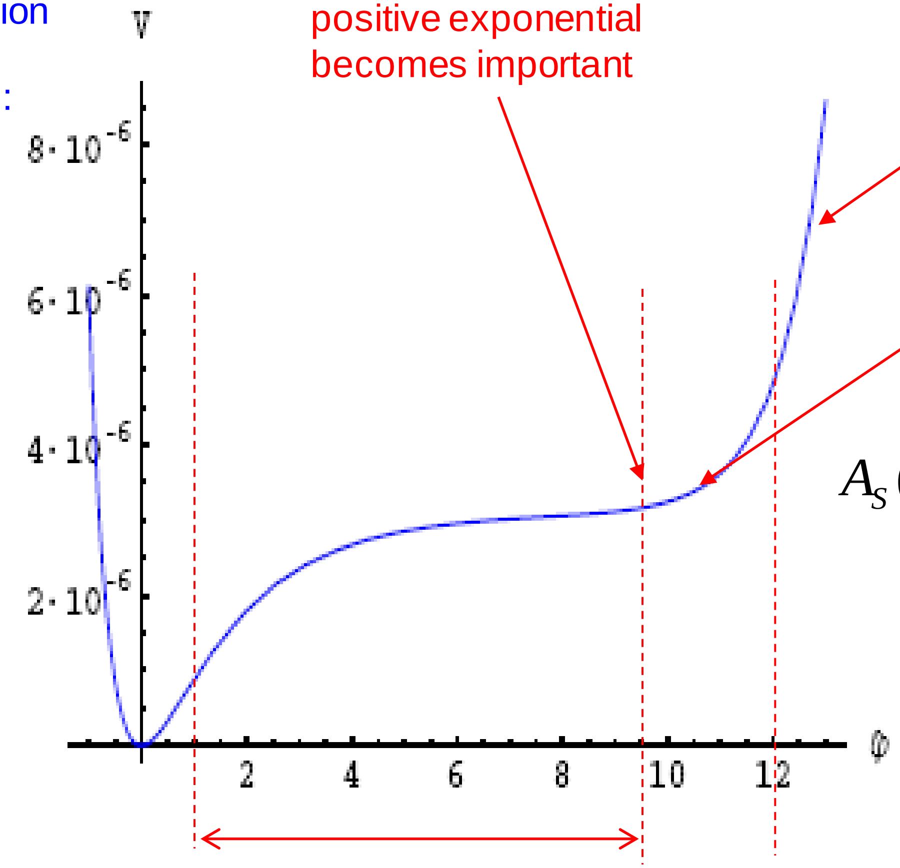
Stringy point of view: Trans-Planckian fields to obtain large r
i) Consistent EFT?
ii) Difficulty to find large r (no-go theorems)
iii) Majority of known string models do not predict large r

→ expect r to be smaller than 0.01

Strings and power loss at large scales

- Qualitative behaviour of closed string inflation with volume moduli

Fit Planck high-precision data at ℓ >50, predict power at ℓ <50: Suppressed power at low-ℓ! 10% deficit at 2.5 σ



positive exponential becomes important

do not trust EFT

departure from slow-roll

$N_e \simeq 60$

$$A_S\,(\text{large scales}) \approx \frac{V^{3/2}}{M_P^3 V'} << 10^{-5}$$

Power loss at low-ℓ!
[MC, Downes, B. Dutta]

In Fibre Inflation:

$$N_e \approx g_s^{-4/3} >> 1$$

$$\delta \approx g_s^{4} << 1$$

- Typical potential:

$$V = V_0\left(1 - \kappa\, e^{-\kappa\varphi} + \delta\, e^{+\mu\varphi}\right)$$

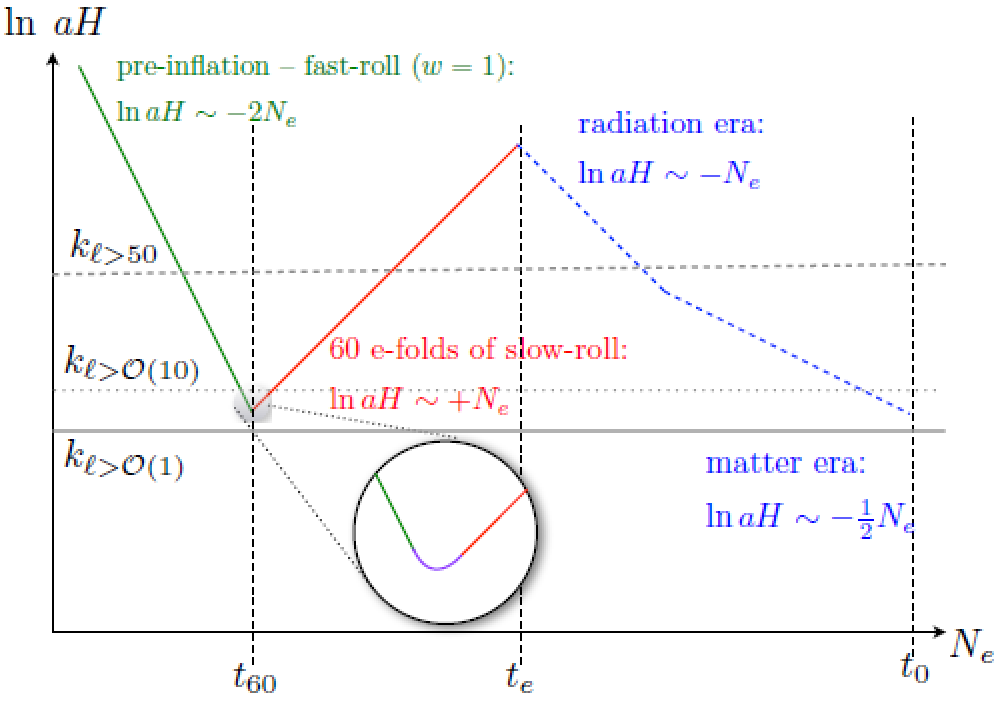
Explicit realisation of fast to slow-roll transition [Contaldi, Kofman, Linde, Peloso]

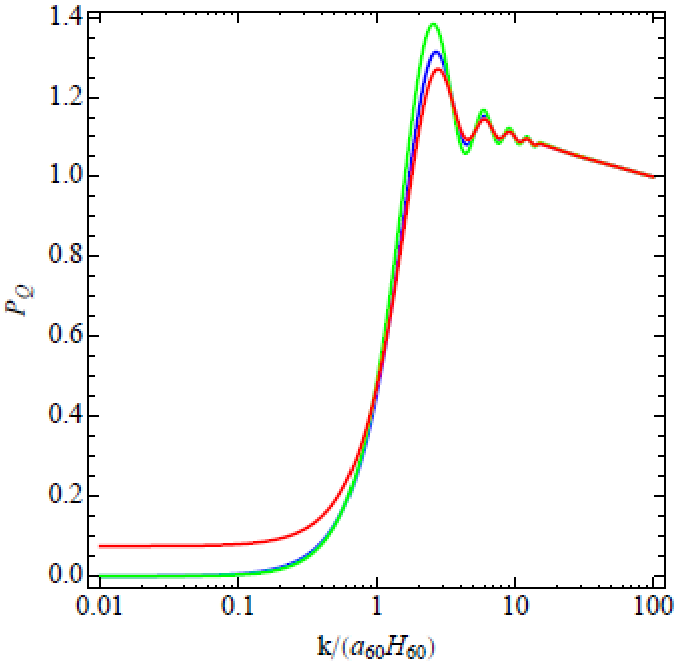
Power loss from just enough inflation

- Power loss at large scales typical of models of just enough inflation [MC, Downes, KB. Dutta, Pedro, Westphal]
- Model-independent analysis of any non-slow-roll background evolution prior to slow-roll inflation
- Universality: power loss at large scales for most common backgrounds:
  - i) fast-roll (w=1, green)
  - ii) matter dominance (w=0, red)
  - iii) radiation dominance (w=1/3, blue)
- Peak with oscillations around start of inflation
- Importance of initial conditions

$$P(k) \propto k^{n_s - 1} C(k, w)$$

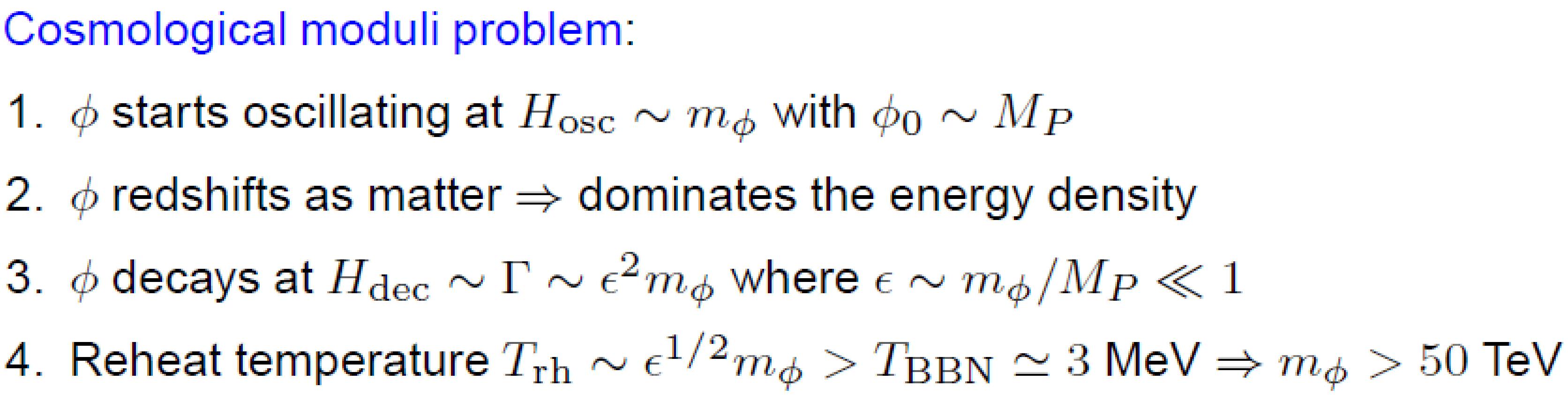
$$n_s - 1 = 3\left(1 - \left|\frac{w-1}{1+3w}\right|\right) = \begin{cases} 0 & \text{for } w = -1, 0 \\ 3 & \text{for } w = 1 \\ 2 & \text{for } w = 1/3 \end{cases}$$





Post-inflationary string cosmology

- Reheating after the end of inflation driven by decay of lightest modulus
- Not necessarily by the inflaton decay



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

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 - O(100) GeV
- Baryon asymmetry diluted if produced before ϕ decay
  $\Rightarrow$ good for Affleck-Dine baryogenesis which can be too efficient [Kane,Shao,Watson,Yu]

Generically in string compactifications :

i) SUSY breaking generates m_ϕ and $M_{\rm soft}$ ⟶ $M_{\rm soft} = k\, m_\phi$

ii) Since $m_\phi > 50$ TeV, can get TeV-scale SUSY only for $k << 1$

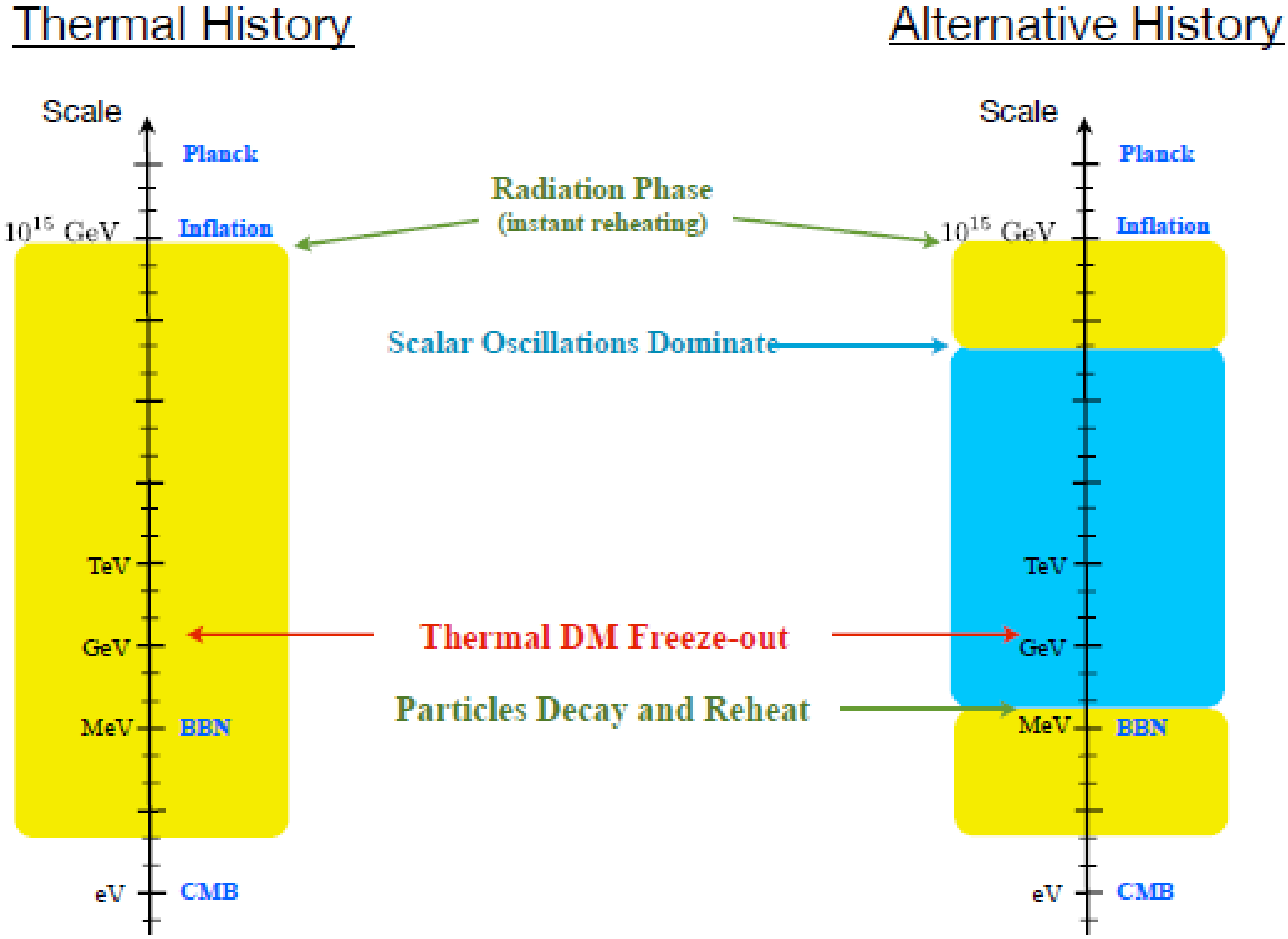
iii) $k = O(10^{-2})$ from loop suppression or $k = O(10^{-3} – 10^{-4})$ from sequestering

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

$$T_R \sim \frac{M_{\rm soft}}{\kappa^{3/2}}\sqrt{\frac{M_{\rm soft}}{M_P}} \sim \kappa^{-3/2}\,\mathcal{O}(10^{-2})\ {\rm MeV} \qquad \text{for } 10^{-4} \le k \le 10^{-2} \Rightarrow 10\,{\rm MeV} \le T_R \le 10\,{\rm GeV}$$

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

Thermal vs Non-thermal cosmology



Radiation Phase
(instant reheating)

Scalar Oscillations Dominate

Thermal DM Freeze-out

Particles Decay and Reheat

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 $\Rightarrow \Delta N_{\rm eff} \simeq 0.5$

Planck 2015: $N_{\rm eff}$ = 3.13 ± 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)

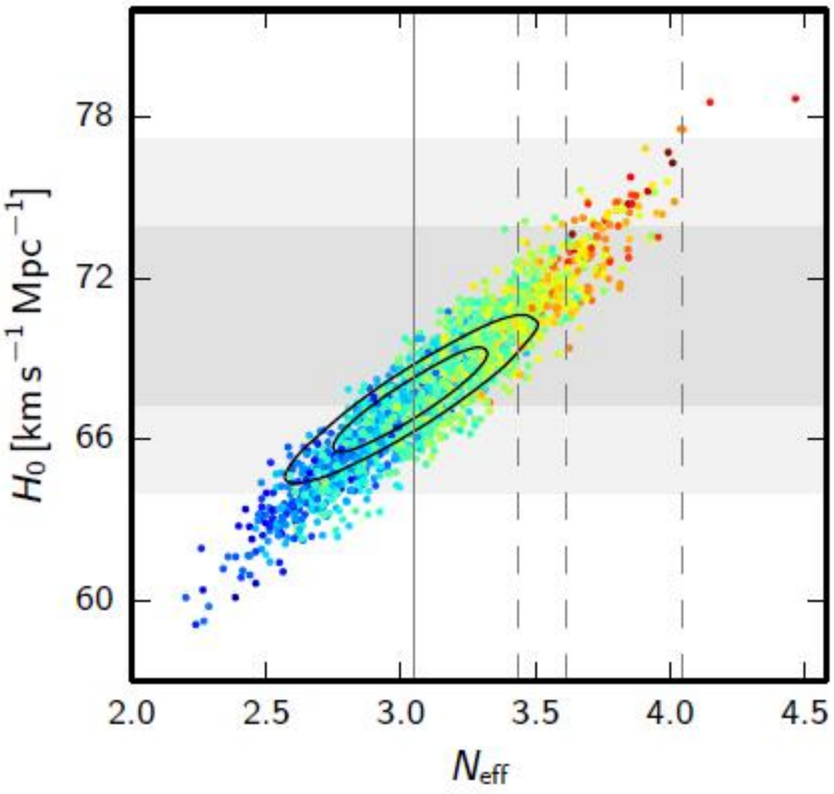
- HST direct value of H_0 :

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

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

BUT HST data reanalysed by Planck:

$H_0 = 70.6 \pm 3.3$ 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!

$n_s \simeq 0.983 \pm 0.006$ → can allow larger tensors: $r \sim 0.01$ in Fibre Inflation

→ Need reliable direct measurements of H_0 !

Axionic dark radiation from strings

- Low-energy theory: many closed string axions of order $h^{1,1} \simeq O(100)$ for a generic CY
  → 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 the geometric regime
    b) closed string axions eaten up for branes at singularities
  iii) too heavy if they are 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

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

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

Non-thermal dark matter

- ϕ decay dilutes thermal DM → larger parameter space
- Non-thermal DM produced from ϕ decay: [Allahverdi,MC,Dutta,Sinha]

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

  - $\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \simeq 5\times10^{-10}\left(\frac{1\ {\rm GeV}}{m_{\rm DM}}\right)$
  - $\langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th} \simeq 3\times10^{-26}{\rm cm}^3\,{\rm s}^{-1}$ is the thermal value
  - $Y_\phi \equiv \frac{3T_{\rm rh}}{4m_\phi}$ and ${\rm Br}_{\phi\to{\rm DM}}$ is the branching ratio into R-parity odd particles

- First term on RHS side: Annihilation Scenario

  1. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} = \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}(T_{\rm f}/T_{\rm rh})$
  2. 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: Branching Scenario

  1. Need $\langle\sigma_{\rm ann} v\rangle_{\rm f} < \langle\sigma_{\rm ann} v\rangle_{\rm f}^{\rm th}(T_{\rm f}/T_{\rm rh})$
  2. 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
  3. Need $T_R \leq 10$ MeV → suppress coupling to visible sector

     → dark radiation overproduction rules out this scenario!

Non-thermal CMSSM

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

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

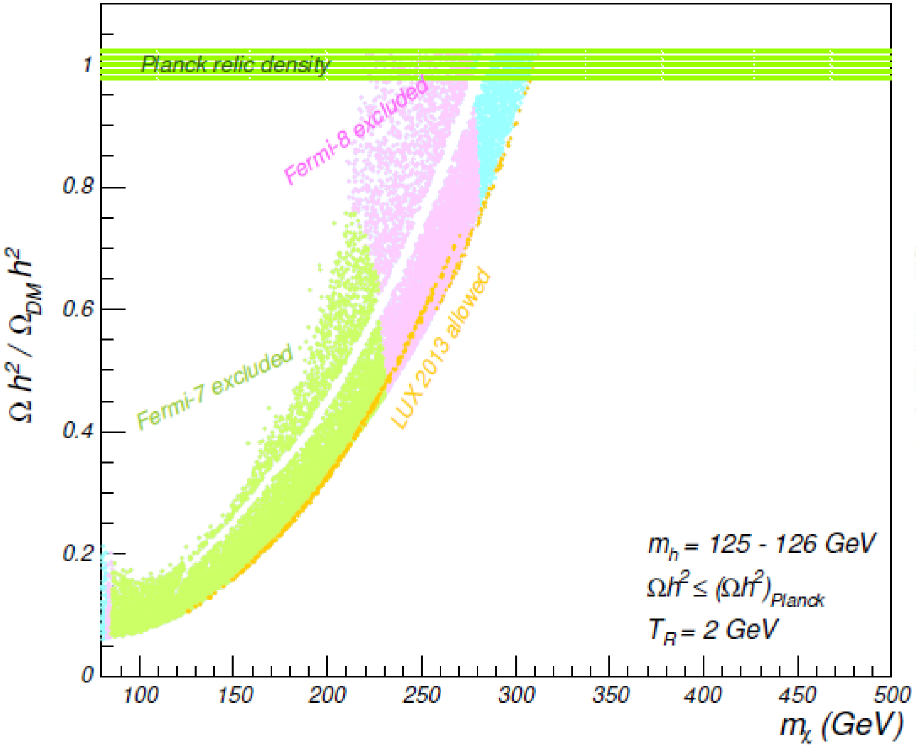
ii) no dark matter overproduction

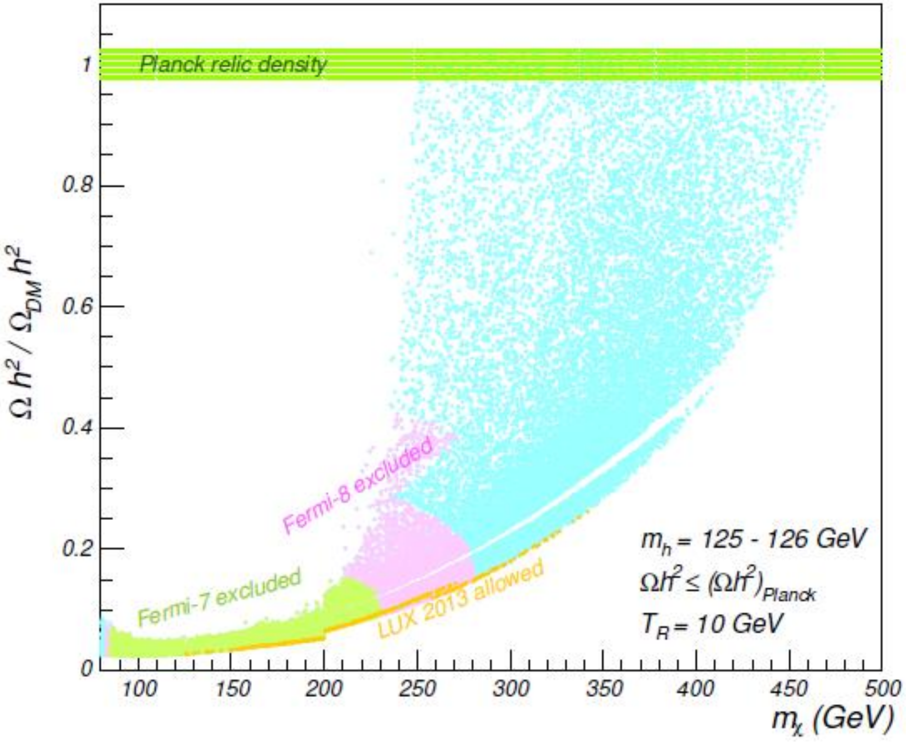
iii) bounds from colliders (LHC), CMB (Planck), direct (LUX) and indirect (Fermi) DM searches

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

→ b) sfermion and gluino masses in the few TeV region

c) realised in string models with sequestered SUSY breaking

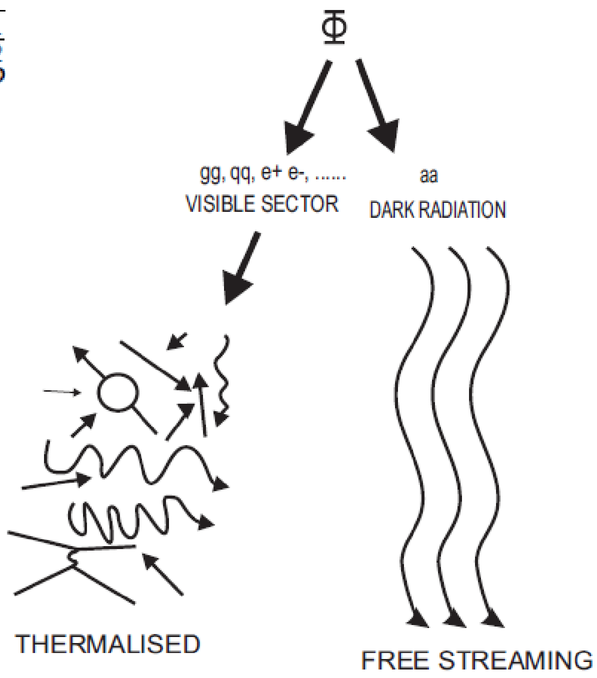




Cosmological evolution of dark radiation

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

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



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

Ratio of axion energy to photon temperature is

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

Retained through cosmic history!

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

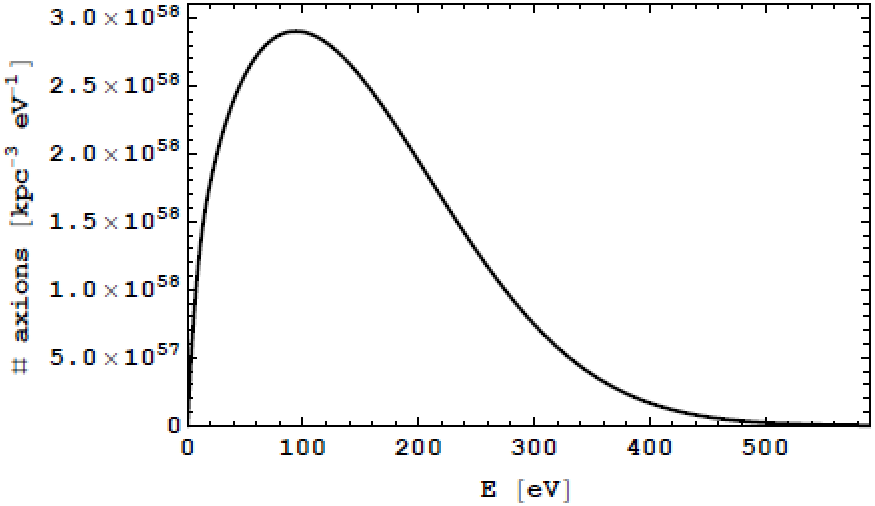
No CMP requires m>$10^{4\text{-}5}$ GeV!

- 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 ≥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 ➡ galaxy clusters

i) typical size $R_{cluster}$ ~ 1 Mpc

ii) ICM plasma frequency ω_{pl} ~ 10^{-12} eV

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

iii) B ~ 1 ÷ 10 μG

iv) L ~ 1 ÷ 10 kpc

- Total conversion probability

$$P^{\rm cluster}_{a\to\gamma} = \sum_i P^{i-\rm th\,domain}_{a\to\gamma} = \frac{B^2 L R_{\rm cluster}}{4M^2}$$

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]

3.55 keV line

- Bulbul et al. 1402.2301: detection of a 3.55 keV line from stacked galaxy clusters (XMM-Newton) and Perseus (Chandra)

- Boyarsky et al. 1402.4119: detection of a 3.55 keV line from Perseus and Andromeda (XMM-Newton)

- Malyshev et al. 1408.3531: non-detection of a 3.55 keV line from dwarf spheroidal galaxies (XMM-Newton)

- Anderson et al. 1408.4115 : non-detection of a 3.55 keV line from stacked galaxies (XMM-Newton and Chandra)

- Urban et al. 1411.0050: detection of a 3.55 keV line from Perseus (Suzaku)

- Simplest explanation: dark matter with m_{DM} ~ 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 also in Andromeda where there is no plasma!

Problems with DM decay

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

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 DM decay rate inferred 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) even if DM is larger + signal from Ophiucus and Centaurus peaks at the cool core (XMM-Newton)

iii) Non-observation in dwarf spheroidal galaxies

Dwarf galaxies are dominated by DM and their interstellar medium is not a source of diffuse X-ray emission ➡ they should provide the cleanest DM decay line signal

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

Alternative explanation: DM → ALP → γ

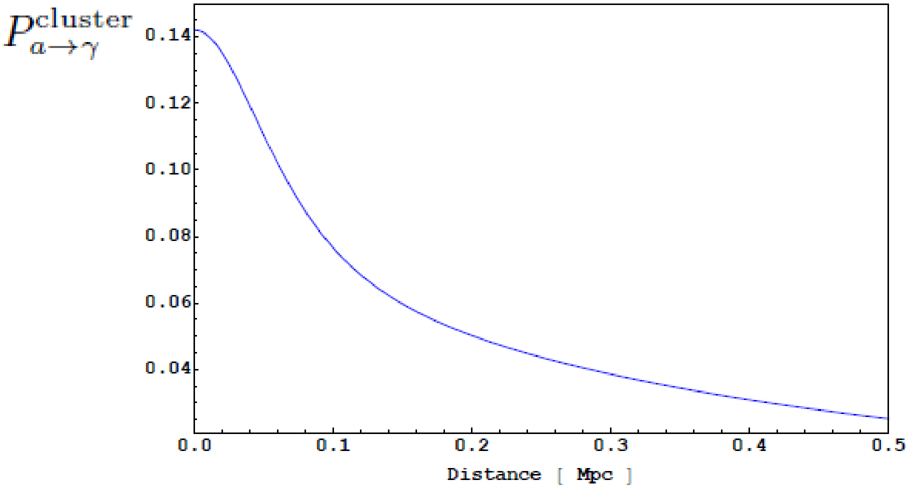
- Monochromatic 3.55 keV axion line from decay of DM with m_{DM} ~ 7 keV

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]

$$F^i_{\mathrm{DM}\to\gamma} \propto \Gamma_{\mathrm{DM}\to a} P^i_{a\to\gamma}\rho^i_{\mathrm{DM}} \qquad \Rightarrow \qquad \frac{F^i_{\mathrm{DM}\to\gamma}}{F^j_{\mathrm{DM}\to\gamma}} \propto \frac{\rho^i_{\mathrm{DM}}P^i_{a\to\gamma}}{\rho^j_{\mathrm{DM}}P^j_{a\to\gamma}} \propto \frac{B^i}{B^j}$$

- 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: $m_a < 10^{-12}\mathrm{eV} \quad M \approx 10^{12}\,\mathrm{GeV}$

DM → ALP → γ: advantages and predictions

- B-dependent line strength can explain:

i) Inferred signal strength:
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 a small B-field
Predicted in MC, Conlon, Marsh, Rummel 1403.2370 ⟹ confirmed in Malyshev et al. 1408.3531

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

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

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 $\epsilon \simeq 10^{-7}$
   $\Rightarrow M_{\rm soft} \simeq \mathcal{O}(1)\,{\rm TeV} \ll m_\phi \simeq \mathcal{O}(5\cdot 10^6)\,{\rm GeV} \ll m_{3/2} \simeq \mathcal{O}(10^{11})\,{\rm GeV}$
3. High string scale: $M_s \simeq \mathcal{O}(10^{16})$ GeV
   $\Rightarrow$ good for GUTs and inflation

Reheating

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

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

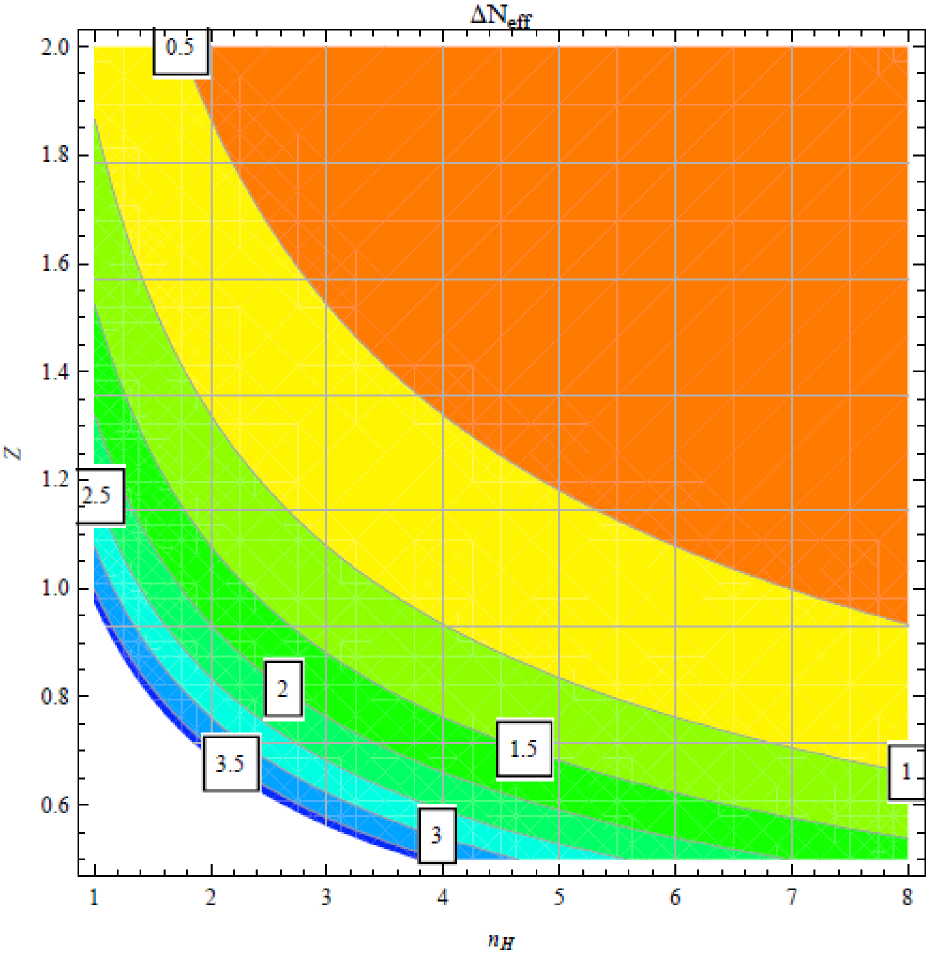
- Leading decay channels:
  - **Higgses:** $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions:** $c_{\phi\to a_b a_b} = 1/24$
- Subleading decay channels:
  - **Gauge bosons:** $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm vs}^2}{8\pi} \ll 1$
  - **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 ΔN_{eff} for n_H Higgs doublets:

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

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



Conclusions

- Need to focus on UV complete theory to trust inflation → string theory
- Hard to get models with large tensor modes and $\Delta\varphi > M_P$
- Good inflaton candidates: volume moduli (effective shift symmetry from no-scale)
- Expect values of tensor-to-scalar ratio $r \leq 0.01$
- Generic power loss at large scales for models of just enough inflation
- Reheating driven by lightest modulus decay
- Non-thermal dark matter: CMSSM with a 300 GeV Higgsino LSP saturating DM for $T_R = 2$ GeV
- Generic production of axionic dark radiation
- 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 3.55 keV line from galaxy clusters improving simplest decaying DM interpretation

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 $F^{\rm vs} \propto \xi = 0$
- Sequestered soft terms: $M_{\rm soft} \sim m_{3/2}/\mathcal{V} \sim M_P/\mathcal{V}^2 \ll m_{3/2}$
- 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: $M_{\rm GUT} \sim M_s \mathcal{V}^{1/6} \sim 10^{16}$ GeV [Conlon,Palti]
- Mass spectrum:
  - $m_{\tau_{\rm vs}} \sim m_{a_{\rm vs}} \sim M_s \sim M_P/\sqrt{\mathcal{V}} \sim 10^{15}$ GeV
  - $m_{\tau_{\rm np}} \sim m_{a_{\rm np}} \sim M_P \ln \mathcal{V}/\mathcal{V} \sim 10^{12}$ 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
  - $M_{\rm soft} \sim M_P/\mathcal{V}^2 \sim 1$ TeV
  - $m_{a_b} \sim M_P e^{-2\pi \mathcal{V}^{2/3}} \sim 0$
- No CMP since $m_{\tau_b} \gg 50\,{\rm TeV}$ + 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