Stringy Axions and the 3.5 keV line

Michele Cicoli

Bologna Univ., INFN and ICTP

Frascati, 18 April 2016

Istituto Nazionale di Fisica Nucleare

The Abdus Salam International Centre for Theoretical Physics

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Based on:

MC, Conlon, Marsh, Rummel, Phys.Rev. D90 (2014) 023540, arXiv:1403.2370 [hep-ph]

Contents

- 4D moduli and axions from string theory
- Non-standard post-inflationary string cosmology
- Axionic dark radiation
- Cosmic Axion Background
- Soft X-ray excess in galaxy clusters
- 3.5 keV line from galaxy clusters

String Moduli

- String theory lives in 10D and needs supersymmetry for consistency
- Compactified extra dimensions: $X_{10D} = M_{4D} \times Y_{6D}$
- 4D EFT for $E << M_{KK} \approx \mathrm{Vol}(Y_{6D})^{-1/6}$
- Geometrical and topological properties of Y_{6D} determine 4D physics
- N=1 SUSY in 4D if Y_{6D} is a Calabi-Yau manifold $\longrightarrow$ chiral theory $\longrightarrow$ realistic!
- Y_{6D} can de deformed in size and shape remaining CY

i) Maths: deformations parameterised by moduli

ii) 4D Physics: moduli are new scalar particles with only gravitational couplings to matter

- Moduli ϕ massless at classical level $\longrightarrow$ flat potential $V(\phi)=0$ $\longrightarrow$ $<0|\phi|0>$ unfixed!
- Two big problems:

i) Unobserved long-range forces (for $m < 1$ meV)

ii) Unpredictability since $g_s = g_s(\phi)$, $g_{YM} = g_{YM}(\phi)$, $Y_{ijk} = Y_{ijk}(\phi)$ and mass spectrum depends on ϕ

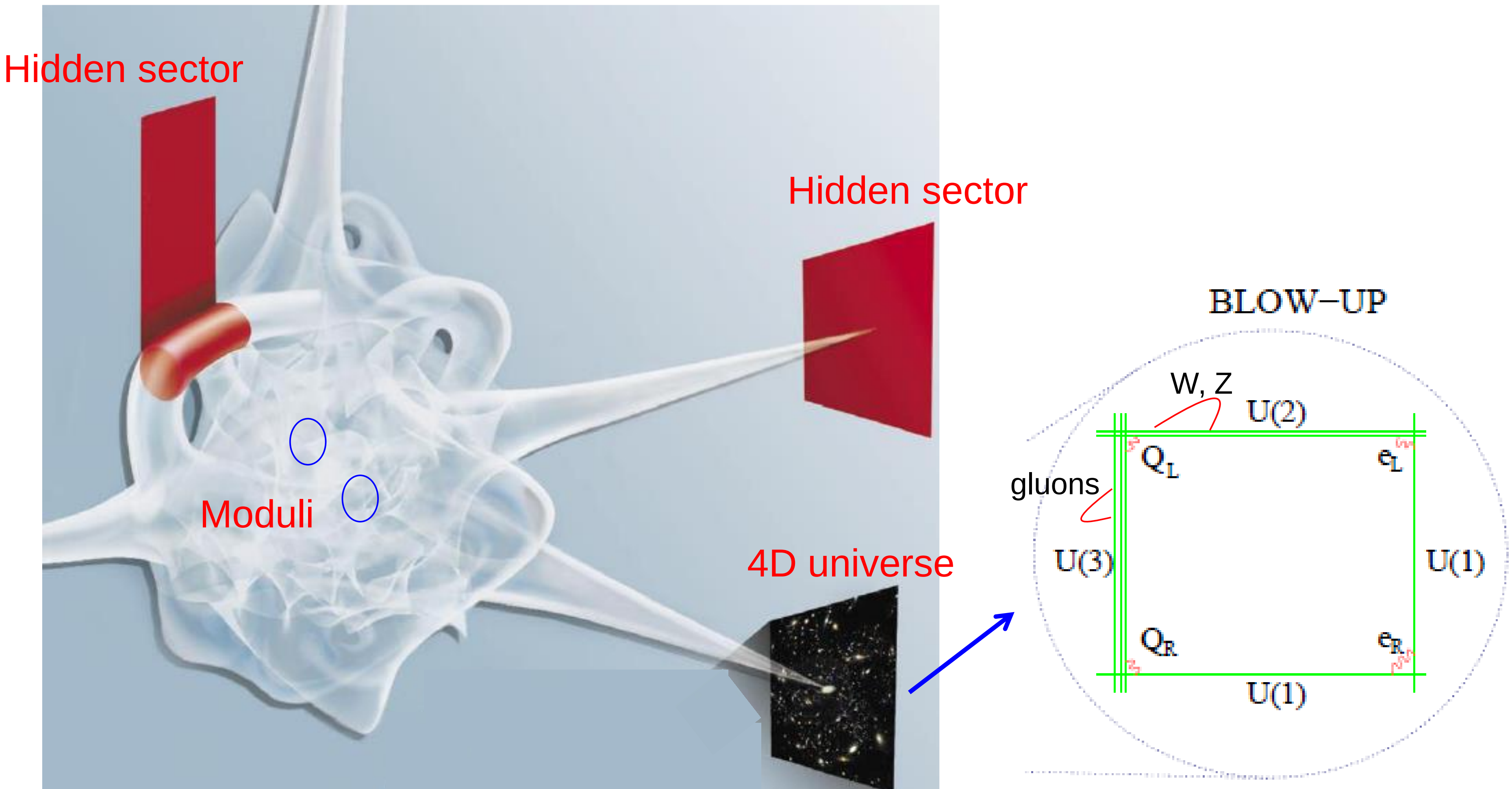
$\longrightarrow$ need to develop $V(\phi)\neq 0$ via quantum corrections $\longrightarrow$ fix $<0|\phi|0>$

$\longrightarrow$ get $m > 50$ TeV via moduli stabilisation to avoid cosmological problems

Where is the Standard Model?

- Ordinary particles are open strings living on branes
- Branes provide non-Abelian gauge symmetries and chiral matter
- Standard Model (or MSSM/GUT theories) localised on branes

  ⟶ model-building is a local issue while moduli stabilisation is a global issue

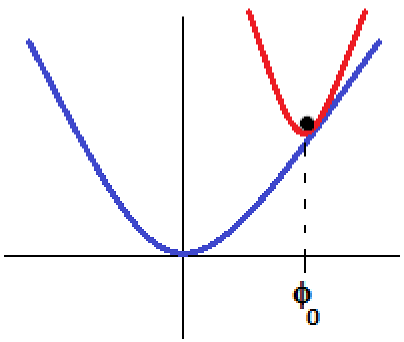


Cosmological Moduli Problem

- Lightest modulus 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

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

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

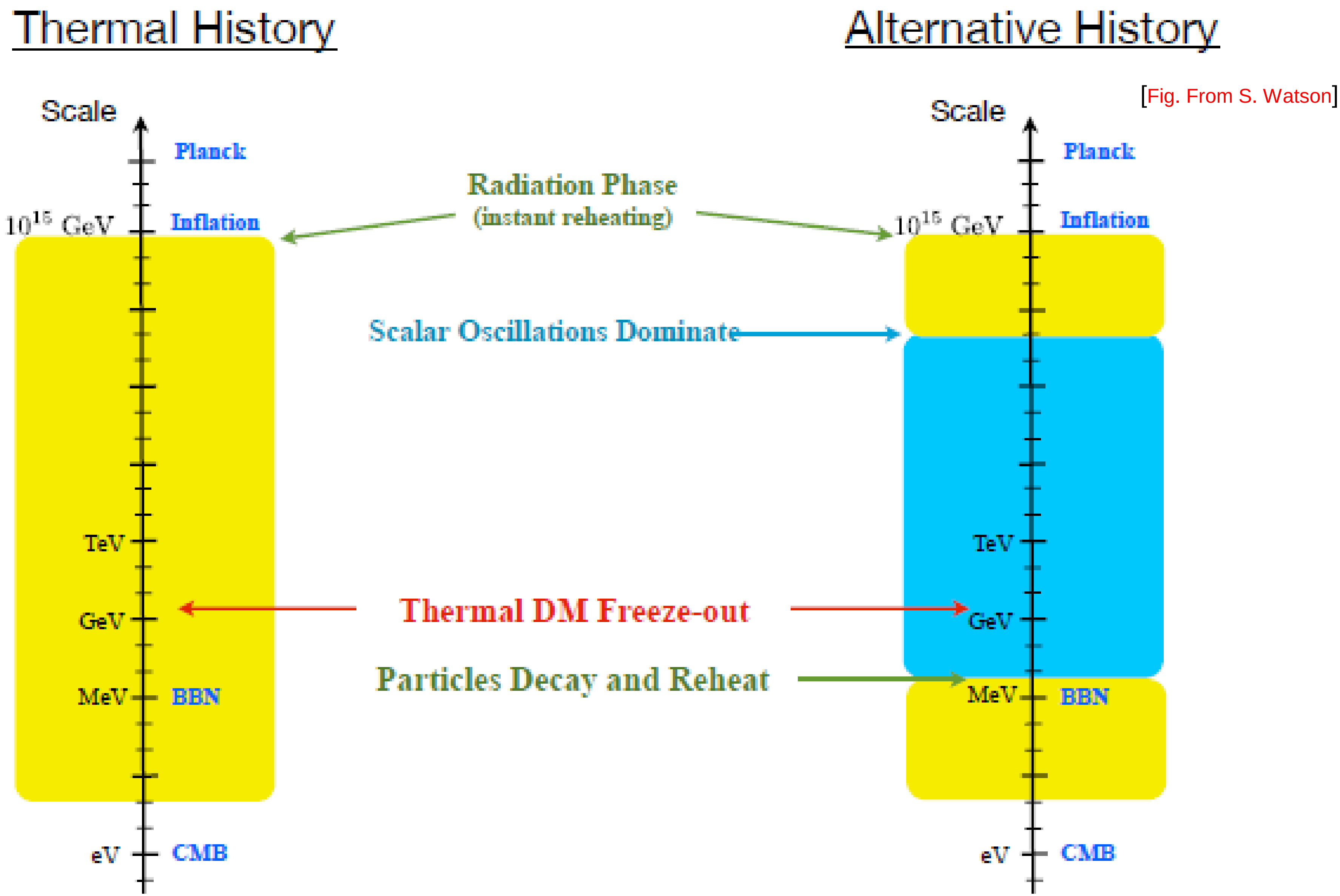


- ϕ behaves as harmonic oscillator with friction $\ddot{\phi} + 3H\dot{\phi} + m^2 \phi = 0$
- End of inflation: friction wins $\longrightarrow$ ϕ frozen at $\phi = \phi_0$
- Reheating $\longrightarrow$ thermal bath with temperature T and $H \approx T^2 / M_P$
- Universe expands and cools down $\longrightarrow$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

$\longrightarrow$ ϕ dominates energy density of the Universe $\longrightarrow$ dilutes everything when it decays!

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

Non-thermal String Cosmology



Axions from Strings

- Low-energy theory: $h^{1,1} \simeq O(100)$ string axions [MC,Ringwald,Goodsell]
  i) closed string axions a (KK zero modes of antisymmetric forms $\Phi = \phi + i\, a$)
  ii) open string axions θ (phase 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 for branes wrapping internal cycles
    b) closed string axions eaten up for branes at singularities
  iii) too heavy if fixed supersymmetrically
    (saxion ϕ has to get a mass larger than 50 TeV)

- Axions enjoy a shift symmetry $\longrightarrow$ moduli stabilisation:
  i) axions are heavy ($m_a \simeq m_\phi > 50$ TeV) if saxions are fixed non-perturbatively
  ii) axions are light ($m_a \ll m_\phi$) if saxions are fixed 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: presence of light axions is unavoidable in models with perturbative moduli stabilisation! [Allahverdi, MC, Dutta,Sinha]

Non-standard post-inflationary cosmology

- Reheating from lightest modulus decay: $m_\phi \sim 10^6$ GeV >> 50 TeV $\longrightarrow$ $T_{rh} \sim 1$ GeV > 3 MeV
- ϕ decay dilutes any previous relic: [Moroi,Randall]

i) Baryon asymmetry $\longrightarrow$ good if AD baryogenesis is too efficient [Allahverdi, MC, Muia]
ii) Axion DM if $T_{rh} < \Lambda_{QCD} \sim 200$ MeV $\longrightarrow$ can have $f_a \sim 10^{14}$ GeV without tuning [Fox, Pierce, Thomas]
iii) Standard thermal WIMP DM since $T_{rh} < T_f \sim m_{DM}/20 \sim 10$ GeV - 100 GeV

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

- Products from ϕ decay:

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

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

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

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

ii) Axionic dark radiation

[MC, Conlon ,Quevedo]

a) Moduli are gauge singlets $\longrightarrow$ non-zero branching ratio into hidden fields

b) Light axions unavoidable in most string models $\longrightarrow$ generic prediction $\Delta N_{eff} > 0$

Planck 2013 + HST: $N_{eff} = 3.52 \pm 0.48$ (95% CL) Planck 2015: $N_{eff} = 3.13 \pm 0.32$ (68% CL) BUT…

N_{eff} and Planck vs HST data

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

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

- HST direct value of H_0 :

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

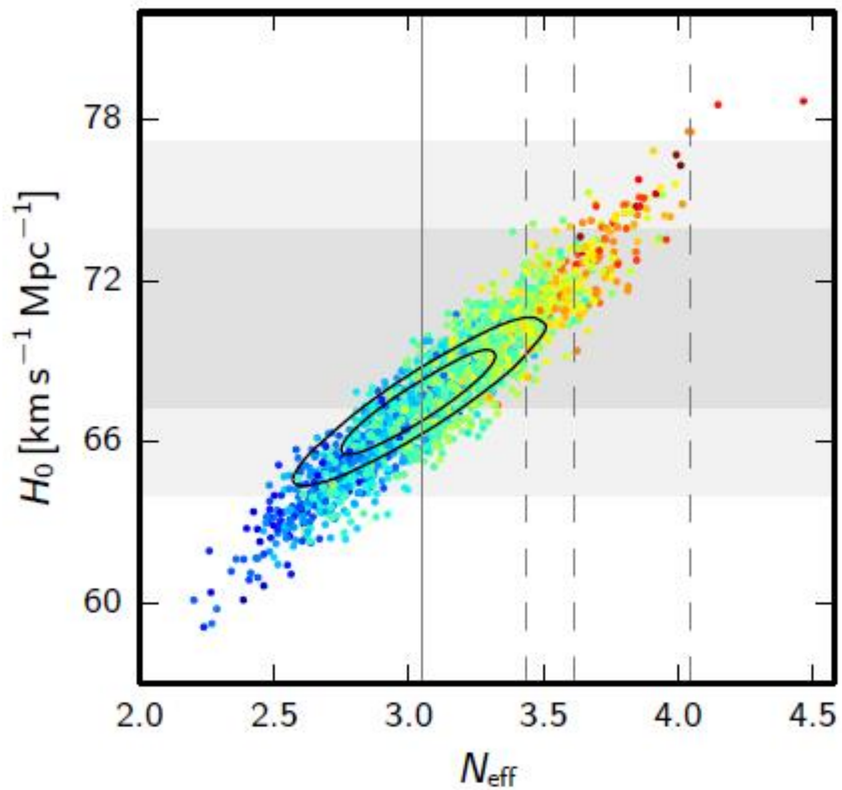
2.4 σ tension ⟶ need new physics: $\Delta N_{eff} > 0$

But HST data reanalysed by Efstathiou:
H_0 = 70.6 ± 3.3 km s^{-1} Mpc^{-1} (68% CL)

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

But $\Delta N_{eff} > 0$ still allowed by Planck!

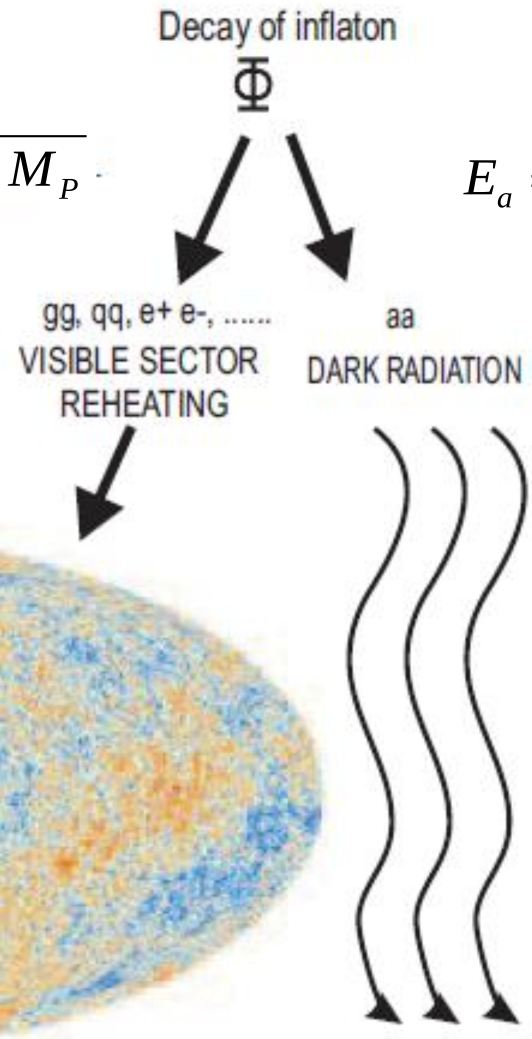
E.g.: for $\Delta N_{eff} = 0.39$ Planck data give (68% CL):
H_0 = 70.6 ± 1.0 km s^{-1} Mpc^{-1} ⟶ better agreement with HST!
$n_s \simeq 0.983 \pm 0.006$ ⟶ different spectral index (and tensor-to-scalar ratio r)



New HST release: H_0 = 73.03 ± 1.79 km s^{-1} Mpc^{-1} (68% CL)
3 σ tension ⟶ need $\Delta N_{eff} > 0$ in range 0.4 - 1

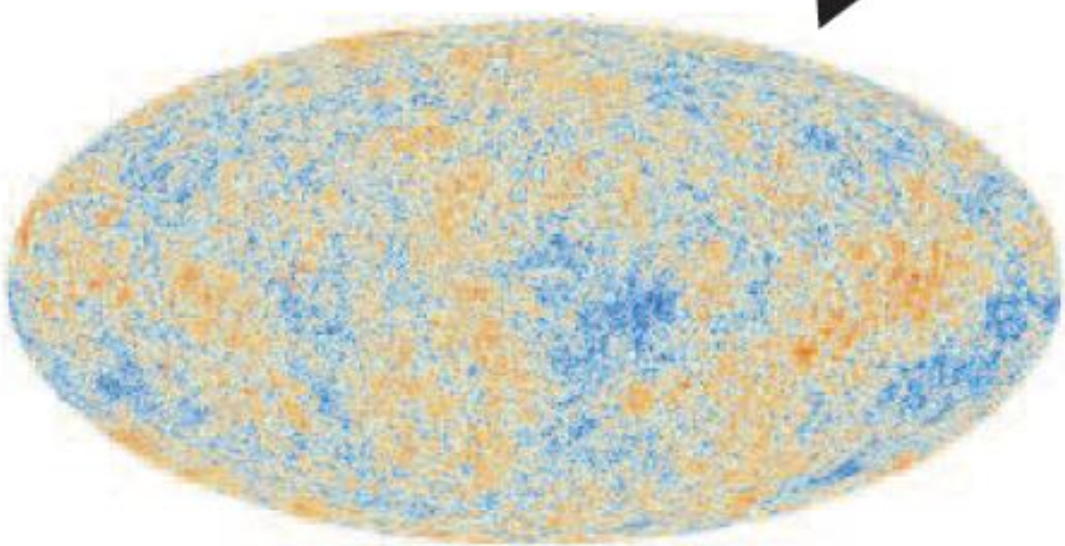
Dark radiation production

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



$$E_a = m_\phi / 2$$

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



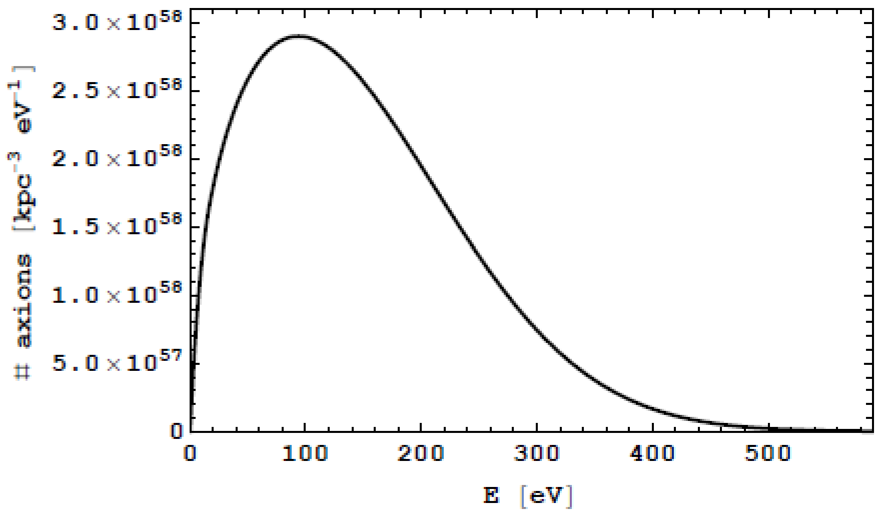
Free streaming

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

Cosmic Axion Background

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 $m_a >> \omega_{pl}$

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

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) $B \sim 1 \div 10\ \mu$G
iv) $L \sim 1 \div 10$ 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)

- Very large statistical significance

- No fully convincing 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

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 $\longrightarrow$ clear prediction

$$F_i \propto \Gamma_{\mathrm{DM}\to\gamma\gamma}\,\rho_{\mathrm{DM},i} \quad \Rightarrow \quad \frac{F_i}{F_j} \propto \frac{\rho_{\mathrm{DM},i}}{\rho_{\mathrm{DM},j}} \quad \text{fixed}$$

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 $\longrightarrow$ they should give cleanest DM decay line

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

Alternative explanation: DM $\to$ ALP $\to \gamma$

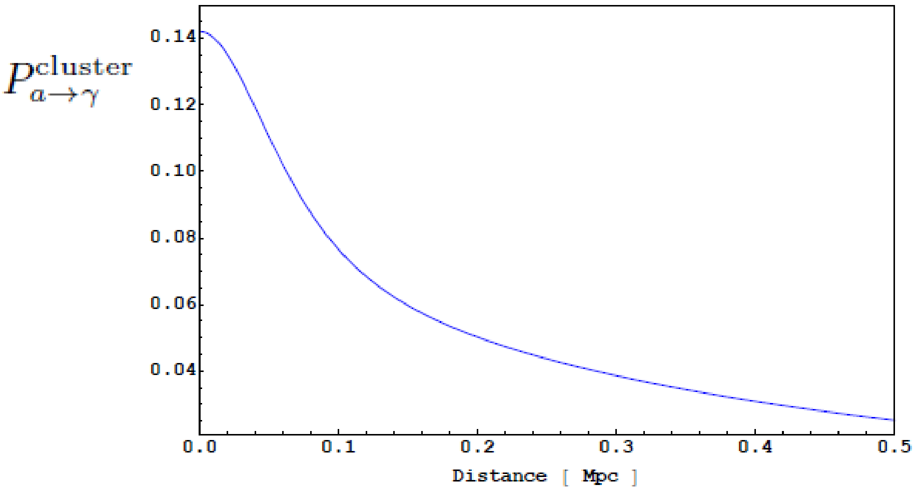
- Monochromatic 3.5 keV axion line from DM decay with $m_{DM} \sim 7$ keV

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]

$$F_i \propto \Gamma_{\mathrm{DM}\to a} P^i_{a\to\gamma}\,\rho_{\mathrm{DM},i} \quad \Rightarrow \quad \frac{F_i}{F_j} \propto \frac{\rho_{\mathrm{DM},i}\,P^i_{a\to\gamma}}{\rho_{\mathrm{DM},j}\,P^j_{a\to\gamma}} \propto \left(\frac{B_i}{B_j}\right)^2$$

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



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

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

DM $\rightarrow$ ALP $\rightarrow \gamma$: 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

- 4D string models $\longrightarrow$ Moduli ϕ and light axions a
- Cosmological moduli problem: $m_\phi > 50$ TeV
- Reheating driven by lightest modulus decay
- Non-standard cosmology: dilution of baryon asymmetry and thermal DM
- Non-thermal dark matter with Higgsino-like neutralino
- 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-field of galaxy clusters
- Explain soft X-ray excess in galaxy clusters
- Explain 3.5 keV line from galaxy clusters improving simplest decaying DM interpretation

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 [MC,Burgess,Quevedo]

Reheating from ϕ decay

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

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

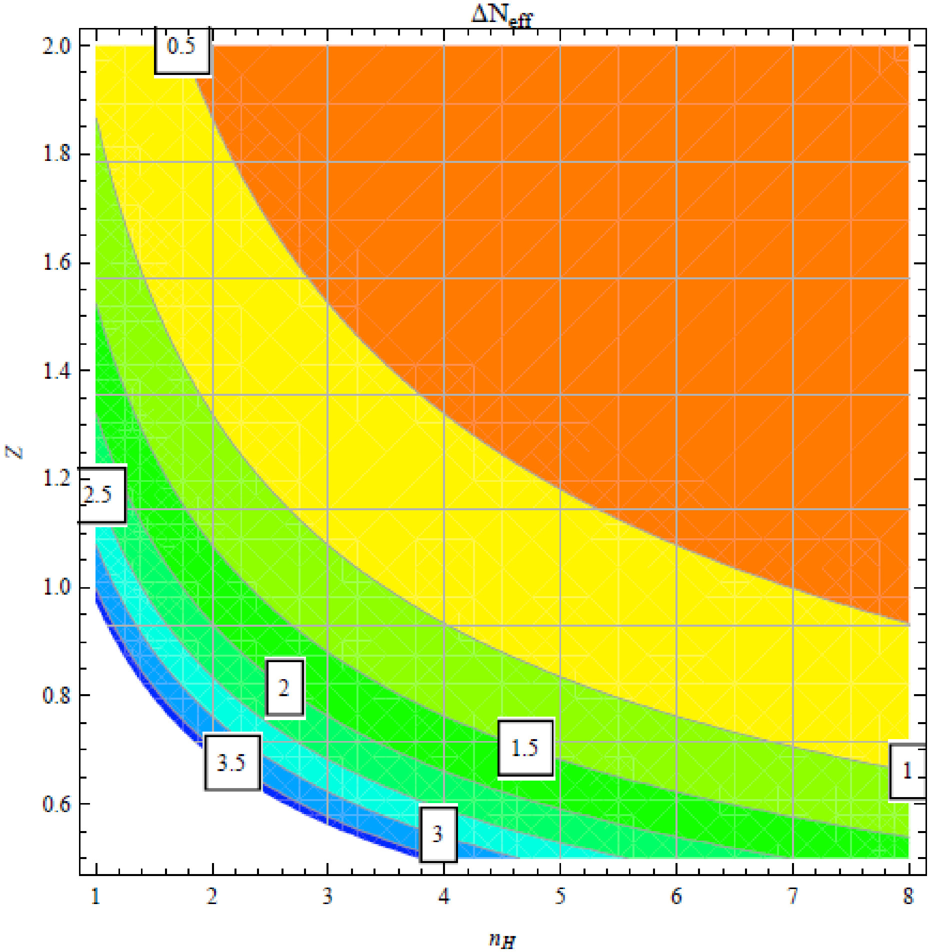
- Leading decay channels:
  - **Higgses:** $c_{\phi\to H_u H_d} = Z^2/12$ from GM term $K \supset Z\,\frac{H_u H_d}{2\mathcal{V}^{2/3}}$
  - **Bulk closed string axions:** $c_{\phi\to a_b a_b} = 1/24$
- Subleading decay channels:
  - **Gauge bosons:** $c_{\phi\to A^\mu A^\mu} = \lambda\frac{\alpha_{\rm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

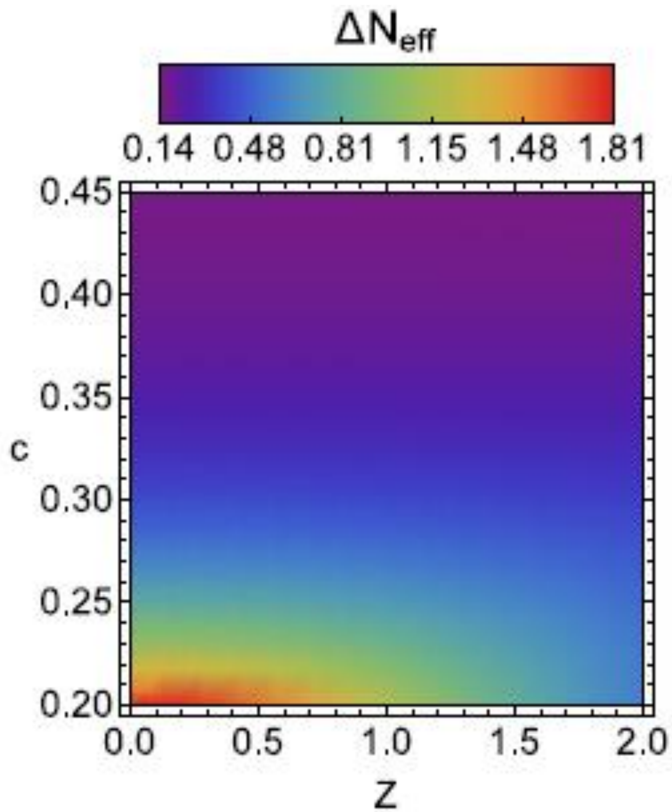
if $Z \geq 1.22$

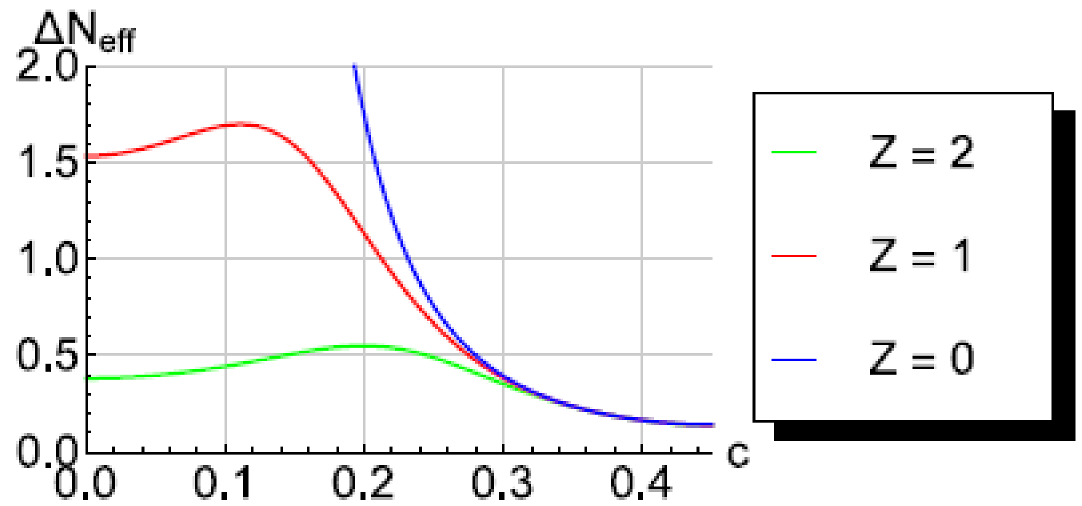
Split SUSY predictions for dark radiation

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

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

- Significant reduction of extra dark radiation!





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

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