Origin and Phenomenology of Dark Radiation

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Thanks to my collaborators

1208.3562 Michele Cicoli, JC, Fernando Quevedo
'Dark Radiation in LARGE Volume Models'

1304.1804 JC, David Marsh
'The Cosmophenomenology of Axionic Dark Radiation'

1305.3603 JC, David Marsh
'Searching for a 0.1-1 keV Cosmic Axion Background'

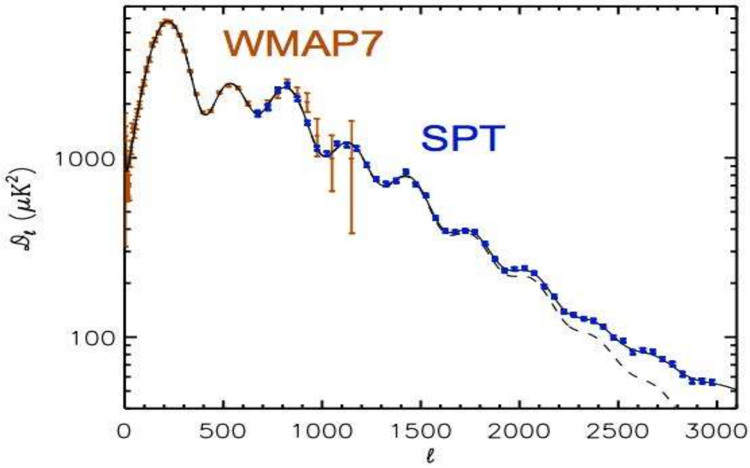
1305.4128 Stephen Angus, JC, Uli Haisch, Andrew Powell
'Loop corrections to ΔN_{eff} in large volume models'

Talk Structure

1. Experimental and theoretical motivation
2. Dark Radiation in the LARGE Volume Scenario
3. A Cosmic Axion Background

Experimental Motivation

This is the age of precision cosmology.



Experimental Motivation

This is the age of precision cosmology.

- 80% of the non-relativistic matter content of the universe does not come from the Standard Model.

  This implies the existence of new non-relativistic species not present in the Standard Model.

- ?? % of the relativistic radiation content of the universe does not come from the Standard Model ($0 < ?? \lesssim 10$)

  If dark matter, why not dark radiation?

  What new non-Standard Model relativistic species exist?

Experimental Motivation

The observable sensitive to non-Standard Model radiation is N_{eff}.

N_{eff} measures the 'effective number of neutrino species' at BBN/CMB: in effect, any hidden radiation decoupled from photon plasma.

At CMB times,

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

Dark radiation refers to additional radiation decoupled from SM thermal bath.

Experimental Motivation

Observations have hinted at the $1 \div 2\sigma$ level for $N_{eff} - N_{eff,SM} > 0$.

Various (non-independent) measurements:

- CMB alone
  - 3.55 ± 0.60 (WMAP9 + eCMB + BAO + H0, 1212.5226)
  - 3.50 ± 0.47 (SPT + CMB + BAO + H0, 1212.6267)
  - 2.87 ± 0.60 (WMAP7 + ACT + BAO+ H0, 1301.0824)
  - 3.30 ± 0.27 (Planck + eCMB + BAO + H0, 1303.5076)
- CMB + H_0
  - 3.84 ± 0.40 (WMAP9 + eCMB + BAO + H0, 1212.5226)
  - 3.71 ± 0.35 (SPT + CMB + BAO + H0, 1212.6267)
  - 3.52 ± 0.39 (WMAP7 + ACT + BAO+ H0, 1301.0824)
  - 3.62 ± 0.25 (Planck + eCMB + BAO + H0, 1303.5076)

Theoretical Motivation

How should we think about dark radiation?

The Accepted Big Picture of the early universe is

1. Inflation
2. End of inflation and inflaton oscillation
3. Inflaton decay
4. Reheating of SM and recovery of Hot Big Bang

Decays of the inflaton to massless weakly coupled hidden sectors (axions, hidden photons, etc), generate dark radiation.

Visible/hidden inflaton branching ratio sets magnitude of dark radiation.

Theoretical Motivation

Matter redshifts as a^{-3} and radiation redshifts as a^{-4}.

Reheating is dominated by the last matter fields to decay.

Matter (moduli) whose couplings are suppressed by M_P^{-1} live longest and decay latest.

If massive Planck-coupled particles exist post-inflation, they will almost inevitably come to dominate the universe energy density.

Independent of initial conditions, the universe will pass through a stage where it is matter dominated by Planck-coupled particles.

Theoretical Motivation

Planck-coupled particles are the string theory moduli and their decays initiate the Hot Big Bang.

Direct couplings $\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu}$ give a typical decay rate:

$$\Gamma \sim \frac{1}{16\pi} \frac{m_\phi^3}{M_P^2}, \qquad \tau \sim \left(\frac{40\text{TeV}}{m_\phi} \right)^3 1 \text{ s}.$$

At decay time $H_{decay} \sim \tau_{decay}^{-1}$ and so

$$T_{reheat} \sim (3 H_{decay}^2 M_P^2)^{1/4} \sim 0.6 \text{ GeV} \left(\frac{m_\Phi}{10^6 \text{ GeV}} \right)^{1/2}$$

Theoretical Motivation

We expect reheating to be driven by the late-time decays of massive Planck-coupled particles.

$$\Phi \to \textit{hidden} \text{ with branching ratio } f_{hidden}$$
$$\Phi \to gg, \gamma\gamma, qq, \ldots \text{ with branching ratio } 1 - f_{hidden}$$

$$\Delta N_{eff} = \frac{43}{7} \frac{f_{hidden}}{1 - f_{hidden}} \left(\frac{g(T_{\nu\, dec})}{g(T_{reheat})} \right)^{1/3}.$$

Dark radiation arises from hidden sector decays of moduli

Dark Radiation in the LARGE Volume Scenario

1208.3562 Michele Cicoli, JC, Fernando Quevedo,

1305.4128 Stephen Angus, JC, Uli Haisch, Andrew Powell

General string/UV-complete models have lots of moduli - easily $\mathcal{O}(100)$.

This makes a systematic analysis of reheating very hard.

- Which moduli dominate the energy density?
- Which moduli decay last?
- What are their branching ratios?
- How do you treat a coupled system of $\mathcal{O}(100)$ particles?

Dark Radiation in the LARGE Volume Scenario

LARGE Volume Scenario:

- There is a distinguished lightest modulus (the overall volume modulus).
- All other moduli are much heavier than the volume modulus.
- There is also a single universal massless axion (the volume axion) that is effectively massless.

Bulk volume modulus outlives all other moduli by at least a factor $\sqrt{\mathcal{V}} (\ln \mathcal{V})^3 \gg 1$.

Therefore volume modulus τ_b comes to dominate energy density of universe independent of post-inflationary initial conditions.

Reheating comes from decays of τ_b.

Dark Radiation in the LARGE Volume Scenario

Decay to bulk volume axion induced by $K = -3 \ln(T + \bar{T})$:

$$\mathcal{L} = \frac{3}{4\tau^2}\partial_\mu \tau \partial^\mu \tau + \frac{3}{4\tau^2}\partial_\mu a \partial^\mu a$$

For canonically normalised fields, this gives

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2}\partial_\mu a \partial^\mu a - \sqrt{\frac{8}{3}}\frac{\Phi}{M_P}\frac{\partial_\mu a \partial^\mu a}{2}$$

and

$$\Gamma_{\Phi \to aa} = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Dark Radiation in the LARGE Volume Scenario

Decay to Higgs fields are induced by Giudice-Masiero term:

$$K = -3\ln(T+\bar{T}) + \frac{H_u H_u^*}{(T+\bar{T})} + \frac{H_d H_d^*}{(T+\bar{T})} + \frac{Z H_u H_d}{(T+\bar{T})} + \frac{Z H_u^* H_d^*}{(T+\bar{T})}$$

Effective coupling is

$$\frac{Z}{2}\sqrt{\frac{2}{3}}\left(H_u H_d \frac{\partial_\mu \partial^\mu \Phi}{M_P} + H_u^* H_d^* \frac{\partial_\mu \partial^\mu \Phi}{M_P}\right)$$

This gives

$$\Gamma_{\Phi \to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Dark Radiation in the LARGE Volume Scenario

Important general points:

- All other visible sector decays (squarks, quarks, gauge bosons....) are mass/chirality-suppressed.
- The only non-suppressed decay modes to Standard Model matter are to vector-like Higgs fields via the Giudice-Masiero term.
- There is a guaranteed dark radiation component from the bulk axion.
- As M_P suppressed operators are democratic, both decay modes are comparable.

Dark Radiation in the LARGE Volume Scenario

Assuming $Z = 1$ (as for shift-symmetric Higgs Hebecker-Knochel-Weigand) and just volume axion gives: Tree-level (1208.3562 Cicoli JC Quevedo)

$$BR(\Phi \to \text{hidden}) = \frac{1}{3}$$

This branching ratio corresponds to $N_{eff,tree} \sim 4.7$.

However there are large logs $\frac{\alpha}{4\pi} \ln \left(\frac{M_{string}}{M_{\Phi}} \right) \ldots$

Radiative corrections computed (1305.4128 Angus, JC, Haisch, Powell).

Loop level:

$$N_{eff,loop} \gtrsim 4.4$$

Minimal scenario excluded!

A Cosmic Axion Background

Reheating is driven by modulus decay:

$$\Phi \to aa \text{ with branching ratio } f_{hidden}$$
$$\Phi \to gg, \gamma\gamma, qq, \ldots \text{ with branching ratio } 1 - f_{hidden}$$

Recall

$$H_{decay} \sim \Gamma \sim \frac{1}{16\pi} \frac{m_\Phi^3}{M_P^2}$$

$$T_{reheat} \sim \left(3H_{decay}^2 M_P^2\right)^{1/4} \sim \frac{m_\phi^{3/2}}{M_P^{1/2}} \sim 0.6\text{GeV} \left(\frac{m_\phi}{10^6\text{GeV}}\right)^{3/2}$$

A Cosmic Axion Background

Dark radiation from $\Phi \to aa$: axions produced with

$$E_a = \frac{m_\Phi}{2}$$

and freestream to present day. Thermal reheat temperature is

$$T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$$

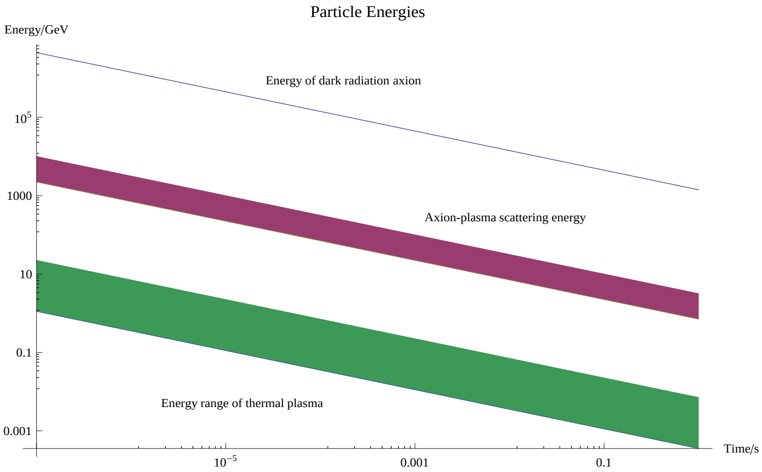
Ratio of axion energy to photon temperature is

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

Retained through cosmic history!

A Cosmic Axion Background

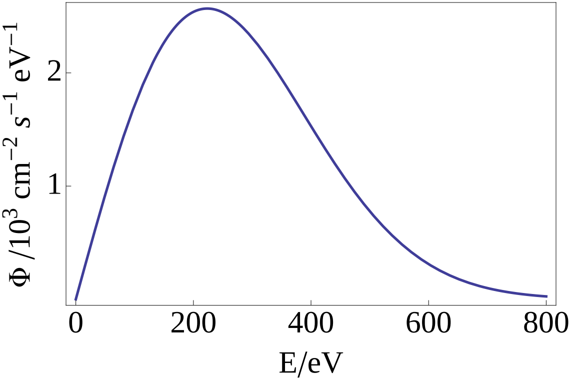
The 'Hot Big Bang' looks like



A Cosmic Axion Background

Axions survive to today.

PREDICTION: Cosmic Axion Background with energies $E \sim 0.1 \div 1\text{keV}$ and a flux $\sim 10^6\text{cm}^{-2}\text{s}^{-1}$.



A Cosmic Axion Background

How to see this?

Energy density of Cosmic Axion Background is

$$\rho_{CAB} = 1.6 \times 10^{60} \text{erg Mpc}^{-3}$$

Total X-ray luminosity of a galaxy cluster (typical scale 1 Mpc) is

$$\mathcal{L} \sim 10^{42 \div 45} \text{erg s}^{-1}$$

Very small $a \to \gamma$ conversion rates generate enormous luminosities.

How to produce photons?

A Cosmic Axion Background

Axion-photon conversions come from axion coupling to electromagnetism:

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

For general axion-like particles $M \equiv g_{a\gamma\gamma}^{-1}$ and m_a are unspecified.

We take $m_a = 0$ and keep M free.

Direct bounds (axion production in supernovae) are $M \gtrsim 10^{11}\text{GeV}$.

A Cosmic Axion Background

Axions convert to photons in a coherent magnetic field domain.

Galaxy clusters have large-scale coherent magnetic fields:
$B \sim 1\mu$G, coherence length $L \sim 1 \div 10$ kpc.

In small mixing approximation,

$$P(a \to \gamma) = \frac{B^2 L^2}{4M^2}$$

For 1 kpc domains with $B = 1\mu$G:

$$P(a \to \gamma) = 2.3 \cdot 10^{-19} \mathrm{s}^{-1} \times \left(\frac{B_\perp}{1\ \mu\mathrm{G}} \frac{10^{13}\ \mathrm{GeV}}{M} \right)^2 \left(\frac{L}{1\ \mathrm{kpc}} \right)$$

($M \equiv g_{a\gamma\gamma}^{-1}$, coupling $g_{a\gamma\gamma} aE \cdot B$)

A Cosmic Axion Background

$a \rightarrow \gamma$ conversion generates a soft X-ray luminosity

$$\mathcal{L}_{Mpc^3} = 3.6 \cdot 10^{41} \text{ erg Mpc}^{-3}\text{s}^{-1} \times \times \left(\frac{\Delta N_{eff}}{0.57}\right)\left(\frac{B}{\sqrt{2}\ \mu\mathrm{G}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2\left(\frac{L}{1\ \mathrm{kpc}}\right),$$

Extremely luminous - for $\Delta N_{eff} \sim 0.5$, normal limit value $M \sim 10^{11}$GeV ruled out by four orders of magnitude!

A Cosmic Axion Background

In fact there exists a long-standing (since 1996) EUV/soft x-ray excess from galaxy clusters. E.g Coma has

$$\mathcal{L}_{excess} \sim 10^{42} \text{erg s}^{-1}$$

What is observed is excess emission above low-energy tail from thermal Bremmstrahlung emission from hot intracluster gas.

Observed by many missions - EUVE, ROSAT, BeppoSAX, XMM-Newton, Suzaku, Chandra.

Statistical significance not an issue.

Possible astrophysical explanations (thermal warm gas/Compton scattering of relativistic electrons) all have problems.

A Cosmic Axion Background

This excess may be generated by $a \to \gamma$ conversion in cluster magnetic field.

Necessary luminosity easy to obtain.

Many predictions:

- Soft excess magnitude and morphology fully determined by cluster magnetic field and electron density
- Spatial extent of excess conterminous with magnetic field
- No thermal emission lines (e.g. from O_{VII}) can be associated to excess
- 'Energy' of excess grows with redshift as $(1 + z)$.

Has a Cosmic Axion Background been visible and unnoticed for 20 years?

Conclusions

- Dark radiation is an extension of standard cosmology with good experimental and theoretical motivation.
- It is naturally generated in string models through the modulus decay $\Phi \to aa$.
- Minimal LARGE Volume Scenario slightly overproduces dark radiation.
- Modulus decays to dark radiation predict a Cosmic Axion Background with $E_a \sim 0.1 \div 1$ keV.
- CAB can be detected through $a \to \gamma$ conversion in magnetic fields and may already be visible through long-standing astrophysics EUV excess in galaxy clusters.

Conclusions

PREDICTION: Cosmic Axion Background with energies $E \sim 0.1 \div 1\text{keV}$ and a flux $\sim \left(\frac{\Delta N_{eff}}{0.57}\right) 10^6 \text{cm}^{-2}\text{s}^{-1}$.