Origin and Phenomenology of Dark Radiation

Joseph Conlon, Oxford University

Southampton, 10th May 2013

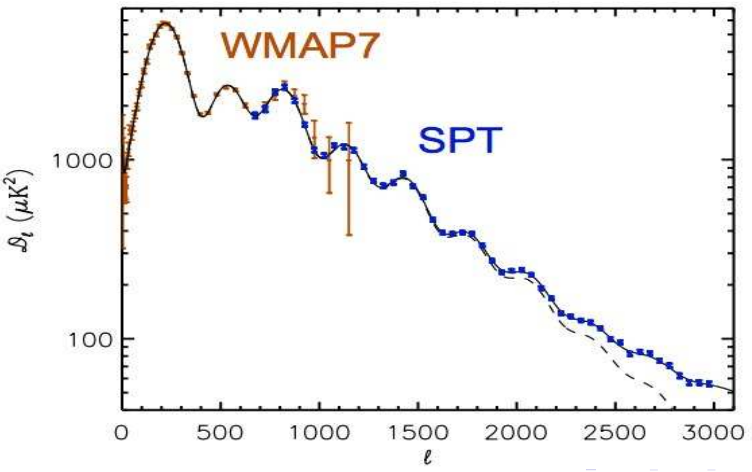
Based on 1208.3562 Cicoli JC Quevedo
1304.1804 JC Marsh
(also see 1208.3563 Higaki Takahashi)

Talk Structure

1. Experimental motivation
2. Reheating in the Early Universe
3. Origin of Axionic Dark Radiation
4. Phenomenology of Axionic Dark Radiation

Experimental Motivation

This is the age of precision cosmology.



Experimental Motivation

The CMB has been extensively measured by

- COsmic Background Explorer (COBE)
- ...
- Wilkinson Microwave Anisotropy Probe (WMAP)
- Atacama Cosmology Telescope (ACT)
- South Pole Telescope (SPT)
- Planck

Cosmology provides the only direct evidence for matter outside the Standard Model.

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

What physics measures N_{eff}?

BBN:

- BBN predictions depend on the expansion rate as a function of temperature.

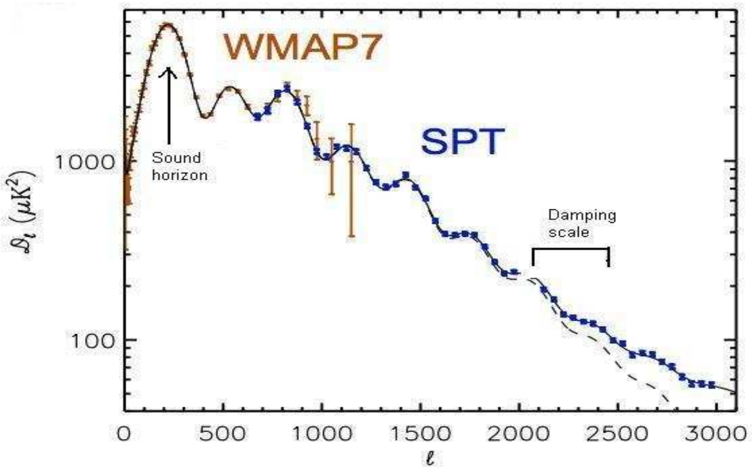
$$\frac{\pi^2}{30} g_*(T_{SM}) T_{SM}^4 + \rho_{dark\ radiation} = \underbrace{3H^2 M_P^2}_{\text{expansion rate}}$$

- This relationship is modified by additional non-SM radiation.

CMB:

- The CMB BAO peaks are damped by photon freestreaming.
- The ratio of the damping scale to the sound horizon is sensitive to additional non-SM radiation.

Experimental Motivation



Experimental Motivation

Observation has tended to hint at the $1 \to 2\sigma$ level for $N_{eff} - N_{eff,SM} > 0$.

Various measurements:

- BBN
  - 3.71 ± 0.45 (BBN Y_p, 1208.0032)
  - 3.9 ± 0.44 (CMB + BBN + D/H, 1112.2683)
- CMB
  - ~~3.26 ± 0.35~~ 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)

WMAP 9-year results: A 'slight' change

Draft version December 21, 2012
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NINE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (*WMAP*) OBSERVATIONS: COSMOLOGICAL PARAMETER RESULTS

G. Hinshaw[1], D. Larson[2], E. Komatsu[3,4,5], D. N. Spergel[6,4], C. L. Bennett[2], J. Dunkley[7], M. R. Nolta[8], M. Halpern[1], R. S. Hill[9], N. Odegard[9], L. Page[10], K. M. Smith[6,11], J. L. Weiland[2], B. Gold[12], N. Jarosik[10], A. Kogut[13], M. Limon[14], S. S. Meyer[15], G. S. Tucker[16], E. Wollack[13], E. L. Wright[17]

Draft version December 21, 2012

ABSTRACT

We present cosmological parameter constraints based on the final nine-year *WMAP* data, in conjunction with a number of additional cosmological data sets. The *WMAP* data alone, and in combination, continue to be remarkably well fit by a six-parameter ΛCDM model. When *WMAP* data are combined with measurements of the high-l cosmic microwave background (CMB) anisotropy, the baryon acoustic oscillation (BAO) scale, and the Hubble constant, the matter and energy densities, $\Omega_b h^2$, $\Omega_c h^2$, and Ω_Λ, are each determined to a precision of ~1.5%. The amplitude of the primordial spectrum is measured to within 3%, and there is now evidence for a tilt in the primordial spectrum at the 5σ level, confirming the first detection of tilt based on the five-year *WMAP* data. At the end of the *WMAP* mission, the nine-year data decrease the allowable volume of the six-dimensional ΛCDM parameter space by a factor of 68,000 relative to pre-*WMAP* measurements. We investigate a number of data combinations and show that their ΛCDM parameter fits are consistent. New limits on deviations from the six-parameter model are presented, for example: the fractional contribution of tensor modes is limited to $r < 0.13$ (95% CL); the spatial curvature parameter is limited to $\Omega_k = -0.0027^{+0.0039}_{-0.0038}$; the summed mass of neutrinos is limited to $\sum m_\nu < 0.44$ eV (95% CL); and the number of relativistic species is found to lie within $N_{\rm eff} = 3.26 \pm 0.35$, when the full data are analyzed. The joint constraint on $N_{\rm eff}$ and the primordial helium abundance, $Y_{\rm He}$, agrees with the prediction of standard Big Bang nucleosynthesis. We compare recent *Planck* measurements of the Sunyaev–Zel'dovich effect with our seven-year measurements, and show their mutual agreement. Our analysis of the polarization pattern around temperature extrema is updated. This confirms a fundamental prediction of the standard

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The Big Picture

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

Any hidden sector decays of the inflaton generate dark radiation.

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

Deep Result Number One

$$4 > 3$$

Deep Result Number One

$$4 > 3$$

Non-relativistic matter redshifts as a^{-3}

Radiation redshifts as a^{-4}

As universe expands, non-relativistic matter comes to dominate over radiation.

A radiation-dominated universe does not occur until this matter decays.

Deep Result Number Two

$$\frac{1}{M_P} < \frac{1}{M_{GUT}}, \frac{1}{f_{PQ}}, \frac{1}{M_W}, \ldots$$

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$$\frac{1}{M_P} < \frac{1}{M_{GUT}}, \frac{1}{f_{PQ}}, \frac{1}{M_W}, \ldots$$

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

For direct couplings $\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu}$ the 'typical' such decay rate is

$$\Gamma \sim \frac{1}{16\pi} \frac{m_\phi^3}{M_P^2}$$

with a lifetime

$$\tau \sim \left(\frac{40\text{TeV}}{m_\phi} \right)^3 1 \text{ s}.$$

Implications

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.

Such particles are ubiquitous in string theory - they are the moduli - higher dimensional modes of the graviton.

Decays of these particles give the radiation-dominated Hot Big Bang.

Implications

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

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

$$\text{Lifetime: } \tau \sim \left(\frac{40\text{TeV}}{m_\phi}\right)^3 1 \text{ s.}$$

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

Decays to hidden relativistic particles give dark radiation.

What is dark radiation?

Dark radiation requires a particle relativistic at CMB times - $m \lesssim 10\text{eV}$.

We know three good ways of keeping particles light.

- Chirality - charged chiral fermions cannot acquire a mass term without symmetry breaking.
- Gauge symmetries - unbroken $U(1)_{em}$ explains why $m_\gamma \simeq 0$.
- Shift symmetries and axions - the symmetry $a \to a + \epsilon$ forbids perturbative mass terms

$$\frac{1}{2} m_a^2 a^2 \in \mathcal{L}$$

What is dark radiation?

Axions are

- Generic in string compactifications - may easily be $\mathcal{O}(100)$ in number
- Naturally light - the shift symmetry $a \to a + 2\pi f_a$ forbids a perturbative mass term.
- Not part of the Standard Model - uncharged under SM gauge group

Axions are a outstanding and well motivated candidate for dark radiation.

Reheating and N_{eff} in LVS

General string/UV-complete models have lots of moduli.

Calabi-Yaus give rise to $\mathcal{O}(100)$ moduli, which may all have comparable masses and decay widths.

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?

LARGE Volume Models

LARGE Volume Scenario (Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058) : stabilises volume at exponentially large values in 'Swiss cheese' geometry

$$\mathcal{V} \sim |W| e^{c/g_s}, \qquad \tau_s \sim \ln \mathcal{V}.$$

The minimum is at exponentially large volume and non-supersymmetric.

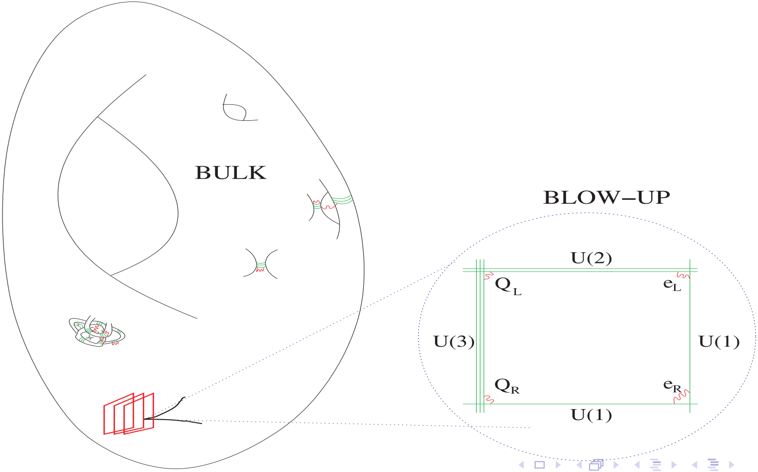
The large volume lowers the string scale and supersymmetry scale through

$$m_{string} \sim \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} \sim \frac{M_P}{\mathcal{V}}.$$

An appropriate choice of volume generates TeV scale soft terms and allow a supersymmetric solution of the hierarchy problem.

LARGE Volume Models

SM at local singularity:



LARGE Volume Models

The basic mass scales present (in sequestered scenario) are

Planck scale:	M_P	$2.4 \times 10^{18}\text{GeV}.$
String scale:	M_S	$M_P \times \mathcal{V}^{-\frac{1}{2}}.$
KK scale	M_{KK}	$M_P \times \mathcal{V}^{-2/3}.$
Gravitino mass	$m_{3/2}$	$M_P \times \mathcal{V}^{-1}.$
Small modulus	m_{τ_s}	$M_P \times \mathcal{V}^{-1} \times \ln \mathcal{V}.$
Complex structure moduli	m_U	$M_P \times \mathcal{V}^{-1}.$
Volume modulus	m_{τ_b}	$M_P \times \mathcal{V}^{-3/2}.$
Soft terms	M_{soft}	$M_P \times \mathcal{V}^{-2}.$
Volume axion	m_{a_b}	$M_P \times e^{-\mathcal{V}^{2/3}}.$

LARGE Volume Models

The key points are:

- 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.

Reheating and N_{eff} in LVS

In LVS reheating is driven by decay modes of τ_b.

We can quantify dark radiation through hidden/visible sector decays of τ_b.

As the lightest modulus is the overall volume modulus, couplings are model-independent.

One guaranteed contribution to dark radiation:

bulk volume axion $\mathrm{Im}(T_b)$ which is massless up to effects exponential in $\mathcal{V}^{2/3} \gg 1$.

Reheating and N_{eff} in LVS

Decay to bulk axion is induced by $K = -3\ln(T + \bar{T})$. This induces a Lagrangian

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

For canonically normalised fields, this gives

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

This gives

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

Reheating and N_{eff} in LVS

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

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

Reheating and N_{eff} in LVS

Other decays:

- Decays to SM gauge bosons are loop suppressed and so negligible, $\Gamma \sim \left(\frac{\alpha}{4\pi}\right)^2 \frac{m_\phi^3}{M_P^2}$
- Decays to SM fermions are chirality suppressed and so negligible, $\Gamma \sim \frac{m_f^2 m_\phi}{M_P^2}$
- Decays to MSSM scalars are mass suppressed and so negligible, $\Gamma \sim \frac{m_{\tilde{Q}}^2 m_\phi}{M_P^2}$.
- Decays to RR U(1) gauge fields are volume suppressed and negligible $\Gamma \sim \frac{m_\phi^3}{\mathcal{V}^2 M_P^2}$.
- Decays to bulk gauge bosons are not suppressed but are model dependent.
- Decays to other axions are not suppressed but are model dependent.

Reheating and N_{eff} in LVS

Important points are:

- The only non-suppressed decay modes to Standard Model matter are to the Higgs fields via the Giudice-Masiero term.
- There is always a hidden radiation component from the bulk axion.
- Both rates are roughly comparable and unsuppressed.

Reheating and N_{eff} in LVS

Assuming $Z = 1$ (as in shift-symmetric Higgs) and just volume axion gives

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

Volume axion remains massless and is entirely decoupled from Standard Model.

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

This is a tree level result - there are large logs at loop level which need to be included (Angus, JC, Haisch, Powell in progress)

Reheating and N_{eff} in LVS

- The LVS framework gives a natural and calculable origin for dark radiation.

- Dark radiation occurs as the volume axion from the $\Phi \to aa$ modulus decay.

  We now turn to a more general study of the phenomenology of axionic dark radiation.

Universe Constituents

Reheating is driven by modulus decay:

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

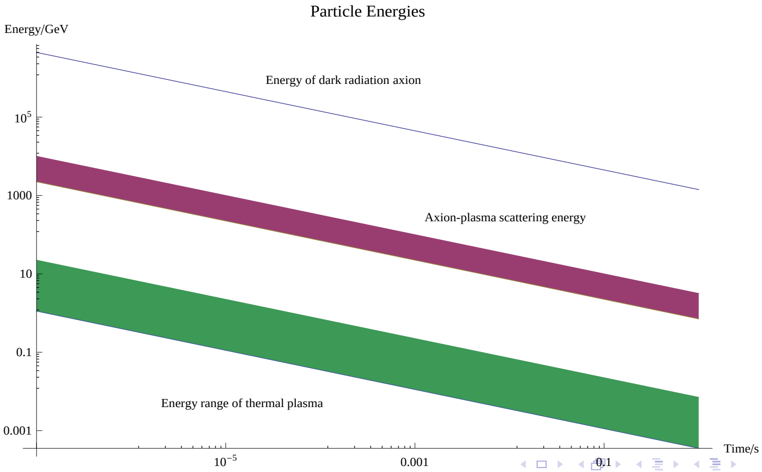
$$\text{Lifetime: } \tau \sim \left(\frac{40\text{TeV}}{m_\phi}\right)^3 1 \text{ s.}$$

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

Visible sector has $\langle E \rangle \sim T$, axions have $\langle E \rangle = m_\phi/2$.

Universe Constituents

The 'Hot Big Bang' looks like



Universe Constituents

There is a large energy difference $E_a \gg T_{SM}$.

Axion-SM collision energy is $E_{CoM} \sim \sqrt{E_a T_{SM}} \gg T_{SM}$.

Scattering of axions off the thermal plasma accesses processes kinematically inaccessible in standard cosmology.

This includes:

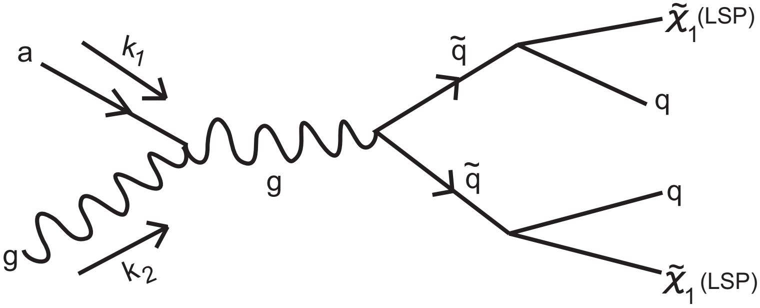
1. Late time energy injection through $a + \gamma \to q\bar{q}$
2. Late time dark matter production through $a + g \to \tilde{q}\tilde{q}^*, \ldots$

Focus on the latter....

Dark Matter Production

Once $T_{SM} < T_{decoupling}$, any axion-SM scattering into susy particles will produce dark matter.

A sample process for dark matter production:



Dark Matter Production

Basic estimates:

Plasma particle density $$n \sim T^3$$

Axion scattering cross-section $$\sigma \sim \left(\frac{\alpha}{4\pi} \frac{1}{f_a} \right)^2$$

Axion scattering rate $$\Gamma = \langle n \sigma v \rangle \sim \left(\frac{\alpha}{4\pi} \right)^2 \frac{T^3}{f_a^2}$$

Hubble scale $$H \sim \frac{T^2}{M_P}$$

Total scattering fraction $$\sim \frac{\Gamma}{H} \sim \left(\frac{\alpha}{4\pi} \right)^2 \frac{T M_P}{f_a^2}.$$

Dark Matter Production

Basic estimates:

Axion abundance	$Y_a \equiv \frac{n_a}{s} \sim \frac{n_a}{n_\gamma} \sim \frac{f_{hidden} T_{reheat}}{m_\Phi}$
Dark matter/ scattering event	2
Dark matter abundance	$Y_{DM} \sim Y_a \times 2 \times \frac{\Gamma}{H}$
	$\sim f_{hidden} \left(\frac{\alpha}{4\pi}\right)^2 \frac{T_{reheat}^2 M_P}{f_a^2 m_\Phi}$

This gives the approximate dark matter abundance from axion-plasma scattering (cf $Y_{WIMP\,DM} \sim 2 \times 10^{-12}$),

$$Y_{DM} \sim 10^{-10} \left(\frac{T_{reheat}}{1\text{GeV}}\right)^2 \left(\frac{10^9\text{GeV}}{f_a}\right)^2 \left(\frac{10^6\text{GeV}}{m_\Phi}\right).$$

Dark Matter Production

Calculate scattering rate via interactions

$$\begin{aligned} \mathcal{L}_{a\gamma\gamma} &= a g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} \equiv \frac{1}{8} a g_{a\gamma\gamma} \epsilon_{\mu\nu\lambda\rho} F^{\mu\nu} F^{\lambda\rho}, \\ \mathcal{L}_{agg} &= \frac{a}{f_{PQ}} \left(\frac{\alpha}{16\pi} \right) \epsilon_{\mu\nu\lambda\rho} F_a^{\mu\nu} F_a^{\lambda\rho}. \end{aligned}$$

Take axion of energy $E = \frac{m_\Phi}{2}$ scattering off a thermal plasma at temperature T to charged scalars, $a + \gamma/g \to \tilde{q}\tilde{q}^*$.

Dark Matter Production

Scattering via photons:

$$\Gamma_{a+\gamma\to\tilde{q}\tilde{q}^*} = \langle n\sigma v\rangle = \frac{1}{\pi^2}\int_0^2 d\lambda \frac{1}{e^{\frac{2m^2}{E\lambda T}}-1}\frac{8m^6}{E^3\lambda^4}\times\frac{1}{128}\frac{e^2 g_{a\gamma\gamma}^2}{24\pi}\Big(2(4-5\lambda)\sqrt{4-2\lambda} +6\lambda^2\ln\left(\sqrt{2}+\sqrt{2-\lambda}\right)-3\lambda^2\ln\lambda\Big).$$

Scattering via gluons

$$\Gamma_{a+\gamma\to\tilde{q}\tilde{q}^*} = \langle n\sigma v\rangle = \frac{1}{\pi^2}\int_0^2 d\lambda \frac{1}{e^{\frac{2m^2}{E\lambda T}}-1}\frac{8m^6}{E^3\lambda^4}\times\frac{1}{128}\frac{\alpha_s^3}{48\pi^2 f_{PQ}^2}\Big(2(4-5\lambda)\sqrt{4-2\lambda} +6\lambda^2\ln\left(\sqrt{2}+\sqrt{2-\lambda}\right)-3\lambda^2\ln\lambda\Big).$$

Dark Matter Production

Results: Assume reheating via modulus decay with

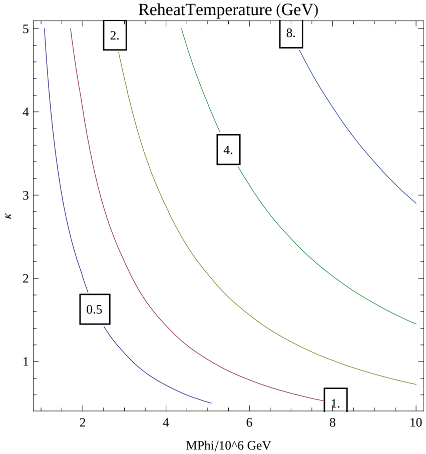
$$\Gamma = \frac{1}{4\pi} \frac{m_\Phi^3}{(M_P/\kappa)^2}$$

Γ fixes reheat H_{decay} and thus T_{reheat}.

Consider scattering to MSSM scalar particles via s-channel photon and gluons, and take a universal scalar mass of 1TeV.

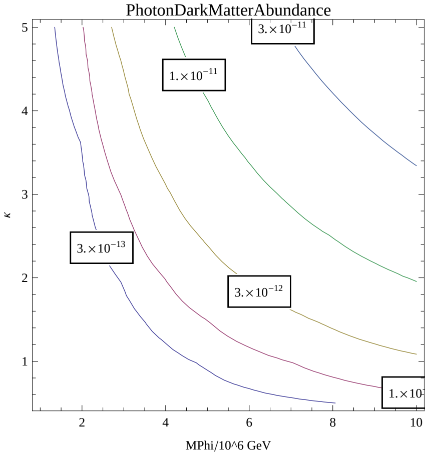
Vary M_Φ (modulus mass) and κ (coupling to matter).

Dark Matter Production



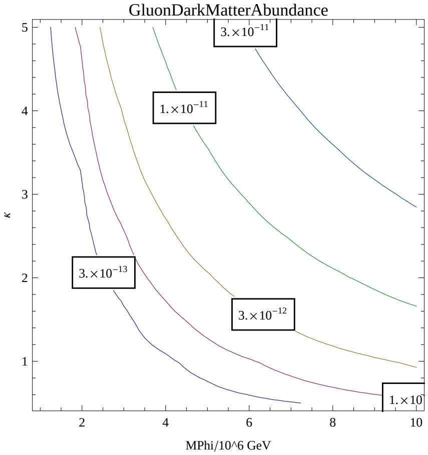
Natural reheat temperature is $\mathcal{O}(GeV)$

Dark Matter Production



$a\gamma\gamma$ scattering, $g_{a\gamma\gamma} = 10^{-10} \text{GeV}^{-1}$

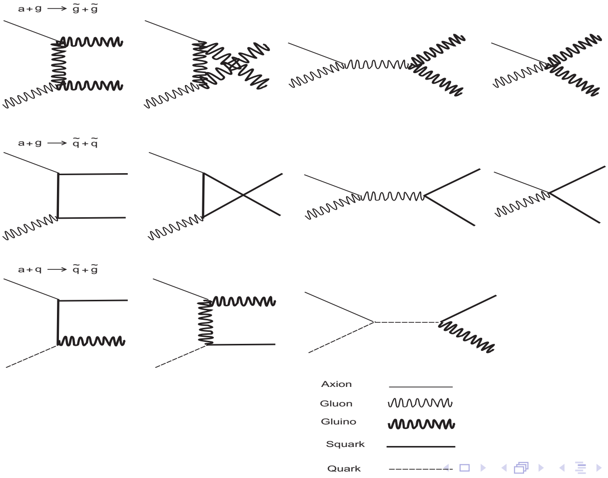
Dark Matter Production



agg scattering, $f_{PQ} = 10^9\,\mathrm{GeV}$

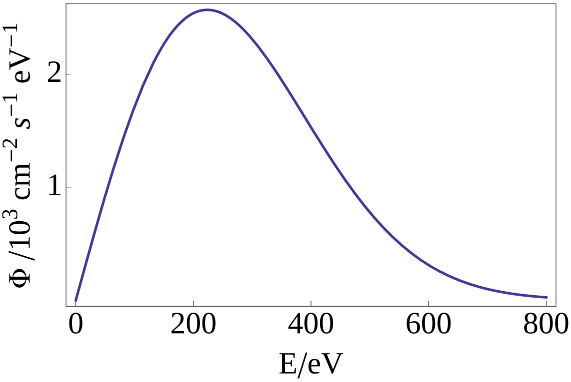
Dark Matter Production

There are many more diagrams that can be included...



Cosmic Axion Background

Axions survive today as a Cosmic Axion Background with energies $E \sim \mathcal{O}(200 \text{ eV})$.



Analysis of CAB to appear next week in Conlon + Marsh 1305.xxxx

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 $\Phi \to aa$.
- Axionic dark radiation is highly energetic compared to the thermal plasma.
- Axion-plasma scattering can produce the observed dark matter abundance.
- Prediction of soft X-ray CAB background.