Searching for a Cosmic Axion Background

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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'

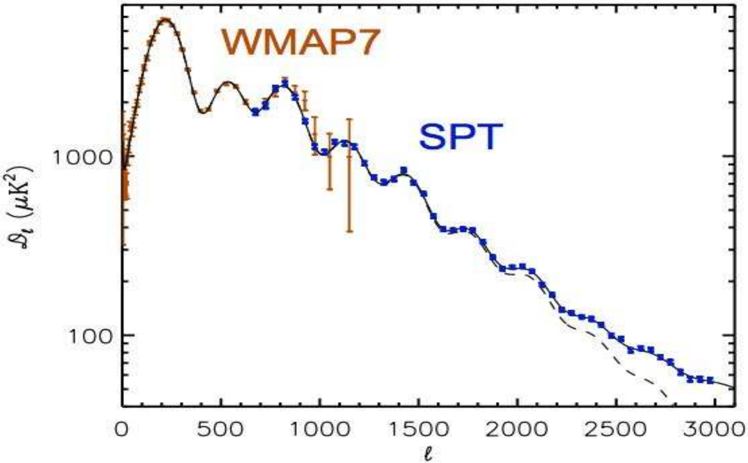
1305.3603 JC, David Marsh
'Searching for a 0.1-1 keV Cosmic Axion Background'

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

See talks here by Angus, Higaki, Takahashi and also 1208.3563, 1304.7987, 1306.6518

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)

Experimental Motivation

Planck fit to ΛCDM predicts value of H_0 in local universe as

$$H_0 = 67.3 \pm 1.2 \text{km s}^{-1}\text{Mpc}^{-1}$$

This is a ΛCDM-dependent prediction not a measurement - must be tested directly by observations.

This prediction is $\sim 2.5\sigma$ discrepant from direct measurements of H_0:

$$\begin{aligned} H_0 &= 73.8 \pm 2.4 \text{ (Riess et al 2011)} \\ H_0 &= 74.3 \pm 1.5 \pm 2.1 \text{ (Freedman et al, 2012)} \\ H_0 &= 76.0 \pm 1.9 \text{ (recent claim - 1306.6276)} \end{aligned}$$

Tension can be relieved by increasing ΔN_{eff} as this is degenerate with H_0.

Theoretical Motivation

How should we think about dark radiation?

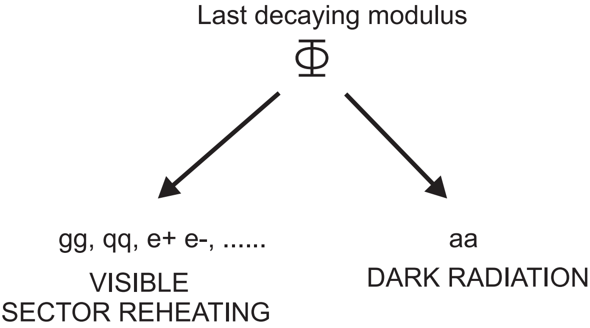
In the inflationary universe, reheating proceeds from decays of a scalar field. However

- Matter redshifts as $\rho_\Phi \sim a^{-3}$
- Radiation redshifts as $\rho_\gamma \sim a^{-4}$
- $3 < 4$

Reheating is dominated by the LAST scalar to decay NOT the first.

Theoretical Motivation

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



Dark radiation arises from hidden sector decays of moduli

Ideal subject for string phenomenology!

Properties of Dark Radiation

Decays of the inflaton to massless weakly coupled hidden sectors (axions, hidden photons, RR $U(1)$s etc), generate dark radiation.

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

$$\Phi \to \textit{hidden} \text{ with branching ratio } f_{hidden}$$

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

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

Properties of Dark Radiation

Independent of susy breaking scale in string models reheating is driven by decays of the lightest moduli, and dark radiation arises from hidden sector decays of these moduli.

Typical moduli couplings $\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu}$ generate decay rates:

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

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

A Cosmic Axion Background

$\Phi \to gg, \ldots$: 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:

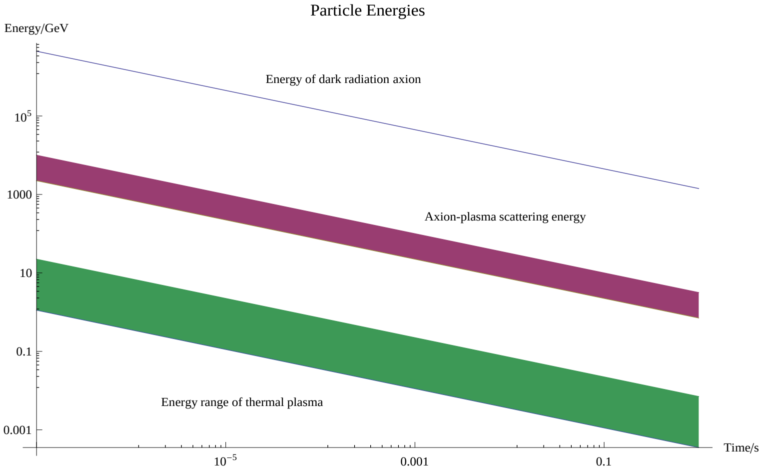
Ratio of axion energy to photon temperature is

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

Retained through cosmic history!

A Cosmic Axion Background

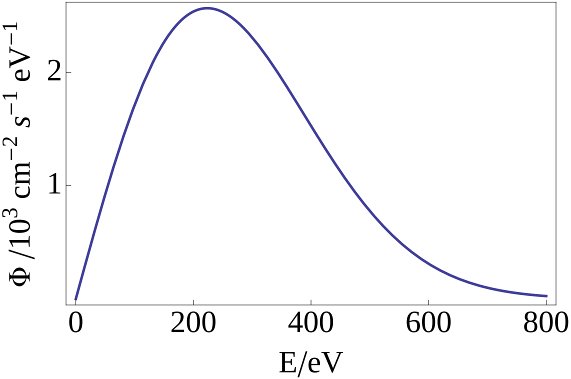
The 'Hot Big Bang' looks like



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 $\sim \left(\frac{\Delta N_{eff}}{0.57}\right) 10^6 \text{cm}^{-2}\text{s}^{-1}$.



A Cosmic Axion Background

The current energy of the dark radiation axions is

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

The expectation that there is a dark analogue of the CMB at extreme ultraviolet / soft X-ray energies comes from very simple and general properties of moduli.

This is not tied to particular models of moduli stabilisation, approaches to getting the Standard Model, choice of string theory, etc

It is not even particularly tied to string theory.

A Cosmic Axion Background

How to observe a CAB?

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 coherent magnetic field domain: want large magnetic fields supported over large volumes.

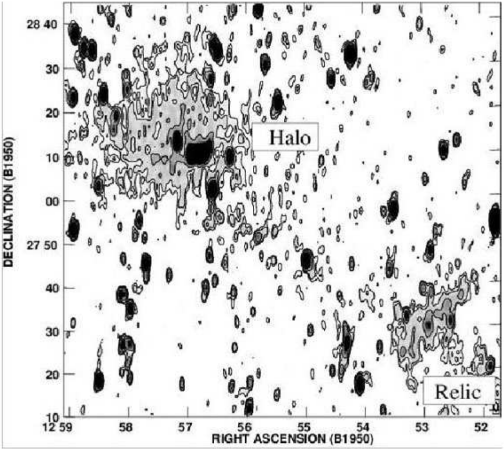
Galaxy clusters have large-scale coherent magnetic fields: $B \sim 1\mu$G, coherence length $L \sim 1 \div 10$ kpc.

What are clusters and what do they look like?

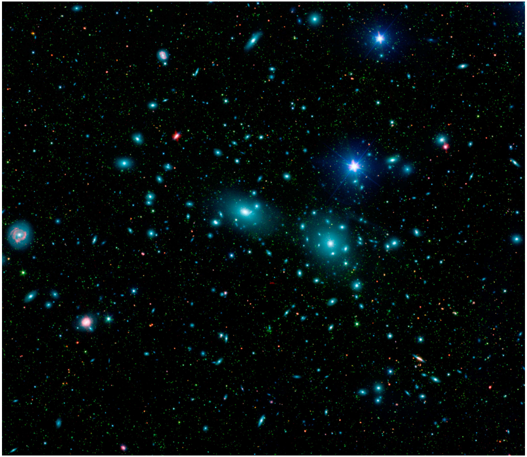
- The largest virialised structures in the universe
- Typical size 1 Mpc, typical mass $10^{14} \div 10^{15} M_{sun}$.
- Hot intracluster gas, $T_{gas} \sim 2 \div 10$keV.
- By mass 1 per cent galaxies, 10 per cent gas, 90 per cent dark matter.
- Sit at the 'large magnetic fields over large volumes' frontier.

Focus on Coma - large, well observed, nearby cluster.

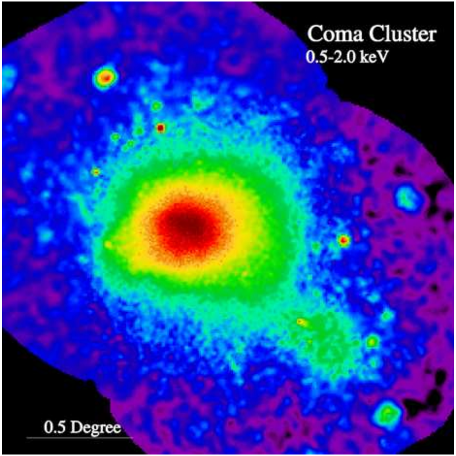
Coma in Radio



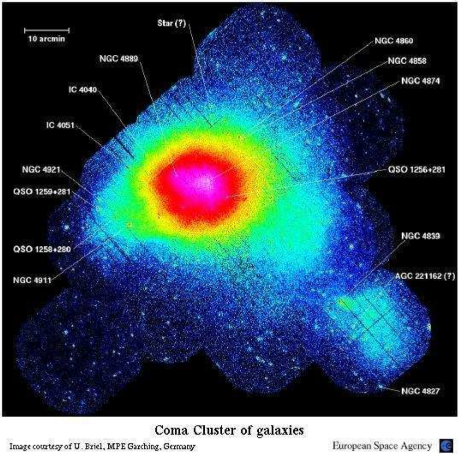
Coma in IR/Visible



Coma in X-rays (ROSAT)



Coma in X-rays (XMM-Newton)



A Cosmic Axion Background

Energy density of Cosmic Axion Background is

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

Typical cluster X-ray luminosity (typical scale 1 Mpc) is

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

In small mixing approximation,

$$\begin{aligned} P(a \to \gamma) &= \frac{B^2 L^2}{4M^2} \text{ per domain} \\ &= 2.3 \cdot 10^{-19} \text{s}^{-1} \times \left(\frac{B_\perp}{1\ \mu\text{G}} \frac{10^{13}\ \text{GeV}}{M} \right)^2 \left(\frac{L}{1\ \text{kpc}} \right). \end{aligned}$$

A Cosmic Axion Background

$a \to \gamma$ 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 gives a luminosity ruled out by four orders of magnitude!

Axions that are everywhere are much easier to detect than axions that must be first produced in stars or supernovae.

A Cosmic Axion Background

In fact there exists a long-standing (since 1996) EUV/soft x-ray excess from galaxy clusters (Lieu 1996). 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 - principally EUVE and ROSAT, also XMM-Newton, Suzaku, Chandra.

Statistical significance ($> 100\sigma$) not an issue.

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

Astrophysical Explanations

Two main proposals for astrophysical explanations:

1. A warm thermal gas with $T \sim 0.2\text{keV}$.

   Interpret soft excess as thermal bremmstrahlung emission from this warm gas.

2. A large non-thermal relativistic electron population with $E \sim 200 - 300$ MeV.

   Interpret soft excess as inverse Compton scattering of electrons on CMB.

Astrophysics: $T \sim 0.2$keV warm gas

The original proposal. However:

1. Such a gas is pressure unstable against the hot ICM gas.

   It rapidly cools away on a timescale much shorter than cluster timescales.

2. A thermal $T \sim 0.2$keV gas would also have thermal emission lines - particularly O_{VII} at 560 eV.

   No such lines have been observed - some early claimed detections have gone away.

Astrophysics: non-thermal $E \sim 150$ MeV electrons

A more promising propsal: a large population of non-thermal electrons scattering off the CMB. However:

1. If this population continues to $E \sim 2$GeV, its synchrotron radio emission is above level of Coma radio halo.

   This necessitates a sharp spectral cutoff between ~ 200MeV and ~ 2GeV.

2. This population necessarily produces gamma rays through non-thermal bremmstrahlung.

   It was predicted that these gamma rays would be easily observable by Fermi (Atoyan + Volk 2000)

   But - Fermi does not see any clusters:

$$\mathcal{F}^{Coma}_{>100 \text{ MeV}} < 2.5 \times 10^{-9} \text{ph cm}^{-2} \text{ s}^{-1}$$

Astrophysics: non-thermal $E \sim 150$ MeV electrons

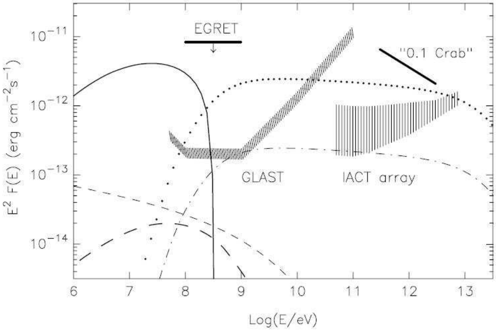


FIG. 6.—Expected γ-ray fluxes expected from the Coma Cluster. The

from Atoyan + Volk, 2000

Astrophysics: non-thermal $E \sim 150$ MeV electrons

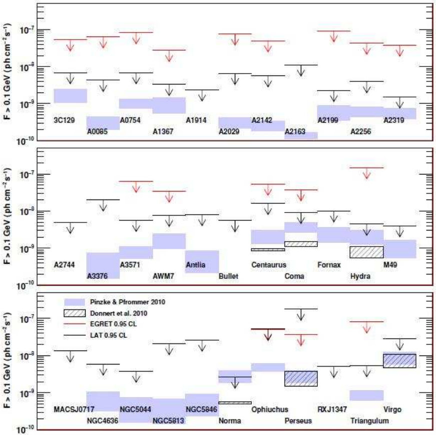
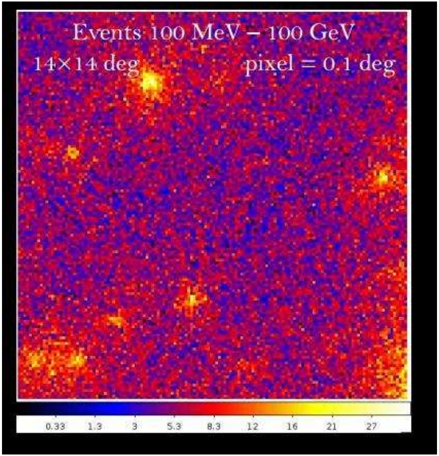


Figure 1. Photon flux upper limits derived from *Fermi*-LAT observations of galaxy clusters (assuming unresolved gamma-ray emission) are compared with EGRET

Fermi 18 month limits, Ackermann 2010

Coma in Gamma Rays



(Ando + Zandanel, to appear 2013)

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

Necessary energy and luminosity easy to obtain and also matches large spatial extent of excess.

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 is constant across clusters and varies only with redshift ($E_a \sim (1+z)$).

In progress: detailed model of axion propagation through turbulent Coma magnetic field.

A Cosmic Axion Background

What would observation of CAB axions at $\sim 200\text{eV}$ tell us?

Allowing the last modulus to decay with

$$\Gamma \sim \frac{1}{4\pi} \frac{m_\Phi^3}{\Lambda^2}$$

and requiring a reheat temptperature $T \gtrsim 1\text{MeV}$:

This implies the existence of a particle with mass $m_\Phi \gtrsim 10\text{TeV}$ and coupling $\Lambda \gtrsim 10^{17}\text{GeV}$.

If we restrict $\Lambda \lesssim M_P$, then we can bound

$$10\text{TeV} \lesssim m_\Phi \lesssim 10^6\text{GeV}$$

$$10^{17}\ \text{GeV} \lesssim \Lambda \lesssim 2.4 \times 10^{18}\text{GeV}$$

- can establish the existence of moduli!

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 $\Phi \rightarrow aa$.
- Modulus decays to dark radiation predict a Cosmic Axion Background with $E_a \sim 0.1 \div 1$ keV.
- CAB can be detected through $a \rightarrow \gamma$ conversion in magnetic fields and may already be visible through long-standing astrophysics EUV excess in galaxy clusters.