# Making Light from the Dark Universe

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Oxford University Physics Society, 1st May 2014

# Talk Structure

1. Prelude: What is Dark Radiation?
2. Experimental motivation for dark radiation: CMB and BBN
3. Theoretical motivation for dark radiation: reheating and modulus decays
4. A 0.1 - 1 keV Cosmic Axion Background
5. Observing a Cosmic Axion Background and the Cluster Soft Excess

# I

# THE DARK UNIVERSE

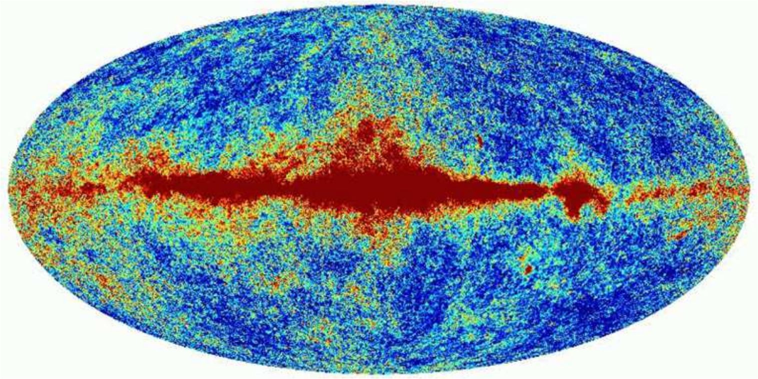
# The Visible Universe

The optical universe...(Hubble deep field)

# The Visible Universe

The X-ray universe...(Chandra deep field)

# The Visible Universe



The microwave universe...(Planck)

# The Universe

## However....

This is the age of precision cosmology.

We know that the energy density of the universe lies

- Approx. 70 % in dark energy
- Approx 25 % in dark matter
- Approx 5 % in baryons
- Approx 0.1 % in neutrinos
- Approx 0.001 % in the CMB

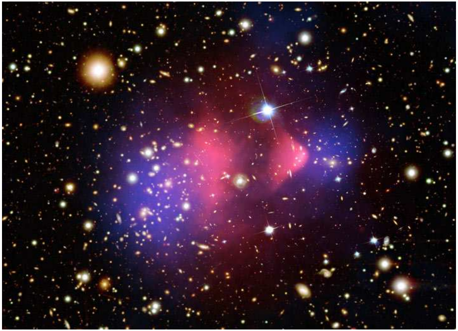
Most of the universe we can't see.

# The Universe

Most of the universe is dark: it has no known electromagnetic interactions.

We cannot see it - we infer its existence by weighing it.

Dark matter is non-relativistic matter not present in the Standard Model.



# The Universe

We do not know what dark matter is, although there are many candidates (eg WIMPs, axions, ALPs, sterile neutrinos, ....) and many experiments that are searching for dark matter.

This talk is not about dark matter.

This talk is about dark radiation - possible new relativistic matter not present in the Standard Model.

What new non-Standard Model relativistic species exist?

# Prelude

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 (not necessarily connected to neutrinos).

At CMB times,

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

For a canonical Hot Big Bang, $N_{eff} = 3.046$: $\Delta N_{eff} = N_{eff} - 3.046$ represents dark radiation - additional radiation decoupled from SM thermal bath.

# II
# EXPERIMENTAL MOTIVATION

# Experimental Motivation: Physics

Both the CMB and primordial BBN abundances are sensitive to additional radiation in the early universe (which changes the expansion rate).

In the CMB, $\Delta N_{eff}$ modifies the detailed properties of the CMB - in particular the damping tail on small scales.

At BBN times, extra radiation modifies the expansion rate at a given temperature.

This affects the primordial Helium and Deuterium abundances: $(D/H)_p$ (where $N_{eff}$ is degenerate with $\Omega_b h^2$) and $Y_p$.

Recent observations have tended to hint at the $1 \div 3\sigma$ level for $\Delta N_{eff} > 0$.

# Experimental Motivation: CMB

Various (non-independent) measurements, 1 $\sigma$ error bars:

- CMB + BAO
  - $3.55 \pm 0.60$ (WMAP9 + eCMB + BAO, 1212.5226)
  - $3.50 \pm 0.47$ (SPT + CMB + BAO, 1212.6267)
  - $2.87 \pm 0.60$ (WMAP7 + ACT + BAO, 1301.0824)
  - $3.30 \pm 0.27$ (Planck + eCMB + BAO, 1303.5076)
- CMB + BAO + $H_0$
  - $3.84 \pm 0.40$ (WMAP9 + eCMB + BAO + H0, 1212.5226)
  - $3.71 \pm 0.35$ (SPT + CMB + BAO + H0, 1212.6267)
  - $3.52 \pm 0.39$ (WMAP7 + ACT + BAO+ H0, 1301.0824)
  - $3.52 \pm 0.24$ (Planck + eCMB + BAO + H0, 1303.5076)

# Experimental Motivation: CMB and $H_0$

Planck fit to $\Lambda$CDM 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 $\Lambda$CDM-dependent prediction not a measurement - must be tested directly by observations.

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

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

Tension can be relieved by increasing $\Delta N_{eff}$ as this is degenerate with $H_0$.

# Experimental Motivation: BBN

An independent probe of $N_{eff}$ is via BBN primoridal abundances -

$$\begin{aligned} Y_P &= 0.254 \pm 0.003 & \text{(1308.2100, Izotov et al)} \\ (D/H)_P &= (2.53 \pm 0.04) \times 10^{-5} & \text{(1308.3240, Cooke et al)} \end{aligned}$$

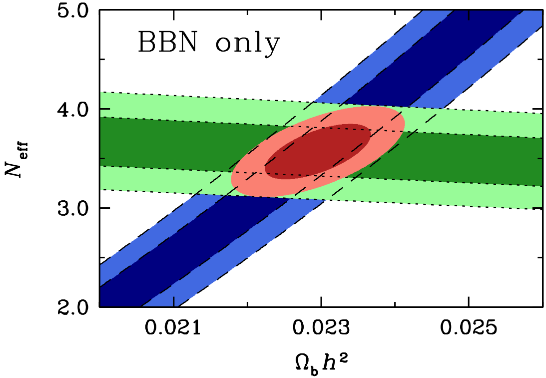
Updated bounds: $(D/H)_P +$ CMB

$$N_{eff} = 3.28 \pm 0.28 \qquad \text{(updates } 3.02 \pm 0.27 \text{ from Planck XVI)}$$

BBN alone $(D/H)_P + Y_P$:

$$N_{eff} = 3.57 \pm 0.18 \qquad \text{(1308.3240, Cooke et al)}$$

# Experimental Motivation: BBN



Based on $Y_P$ and $(D/H)_P$ : $N_{eff} = 3.57 \pm 0.18$ (1308.3240)

(figure from Cooke, Pettini, Jorgensen, Murphy, Steidel 1308.3240)

# Experimental Motivation: BICEP-2

Recent claim of detection of primordial B-mode polarisation in the CMB:

If correct, then CMB estimate of $\Delta N_{eff}$ becomes $3.85 \pm 0.35$ - significant additional support for dark radiation.

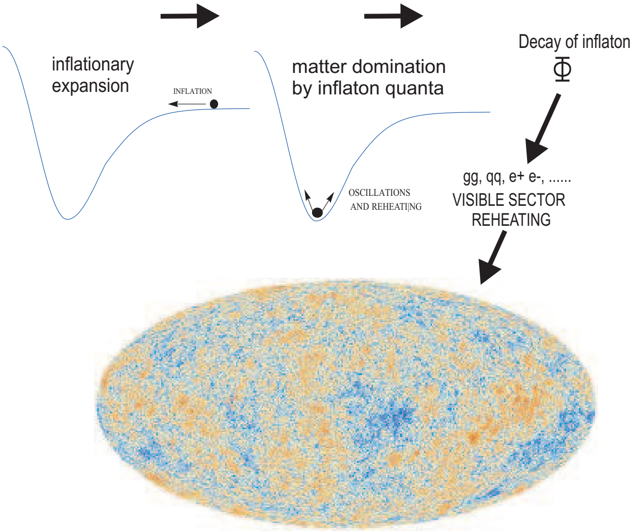
# Experimental Motivation: Summary

- Essentially all determinations of $N_{eff}$ have come in high, although not with decisive significance.
- Two independent channels $CMB + H_0$ and BBN hint for $\Delta N_{eff} \neq 0$ at $2 \div 3\sigma$ level.
- Central value roughly $\Delta N_{eff} \sim 0.5$
- Not 'evidence' let alone 'discovery', but consistent hints all pointing in the same direction.
- Projected experimental sensitivity $\Delta N_{eff} \sim 0.02$ over next decade.

# III

# THEORY MOTIVATION

# The Standard Cosmology



inflationary expansion

matter domination by inflaton quanta

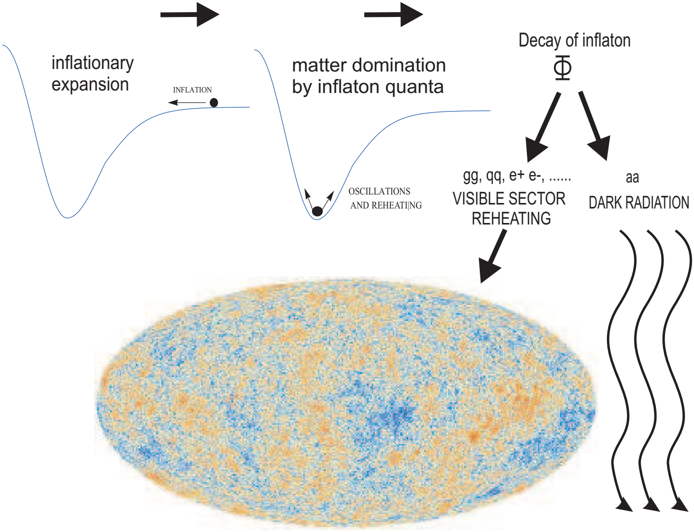
Decay of inflaton

$\Phi$

gg, qq, e+ e-, ......

VISIBLE SECTOR REHEATING

# The Standard Cosmology + $\Delta N_{eff}$



inflationary expansion

matter domination by inflaton quanta

Decay of inflaton

$\Phi$

gg, qq, e+ e-, ......

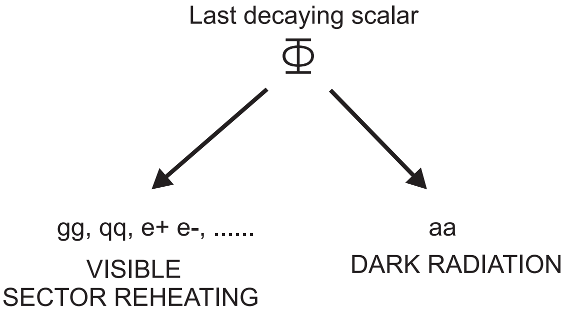
VISIBLE SECTOR REHEATING

aa

DARK RADIATION

# Candidates for Dark Radiation

Dark radiation occurs whenever reheating involves decays to a massless hidden sector as well as the Standard Model.



Last decaying scalar

$\Phi$

gg, qq, e+ e-, ......

VISIBLE
SECTOR REHEATING

aa

DARK RADIATION

Such massless hidden sectors exist in many BSM constructions - QCD axion, axion-like particles, hidden photons, WISPs, chiral fermions....

# Candidates for Dark Radiation

We focus on one particular type of particle: axions (or technically axion-like particles).

The axion probably solves the 'strong CP' problem of the Standard Model: why does the neutron have no electric dipole moment?

The Standard Model Lagrangian contains a topological term

$$\int d^4 x \theta F^a_{\mu\nu} \tilde{F}^{\mu\nu,a}$$

and the angle $\theta < |10^{-10}|$.

The axion, if it exists, solves this problem and dynamically sets $|\theta| = 0$.

# Candidates for Dark Radiation

The existence of axion particles (more generally axion-like particles) is a generic prediction of string theory.

Ten-dimensional string theory compactified to four dimensions predicts many very light or massless axion-like particles.

We will be interested in the mass range

$$m_a \lesssim 10^{-12}\text{eV}$$

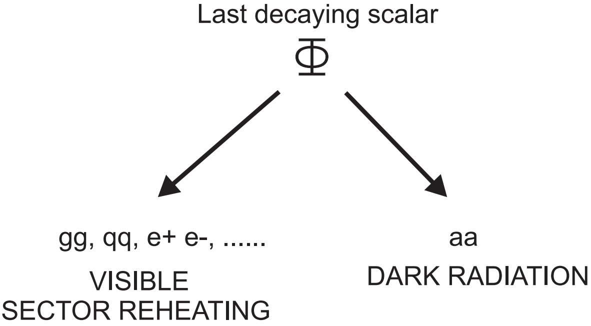
Although light, such particles are very hard to detect as they interact extremely weakly (at least $10^{20}$ times more weakly than neutrinos!)

# IV

# A COSMIC AXION BACKGROUND

# Properties of Dark Radiation

String theory says we expect reheating to be driven by the late-time decays of massive Planck-coupled particles.



Last decaying scalar

$\Phi$

gg, qq, e+ e-, ......

VISIBLE
SECTOR REHEATING

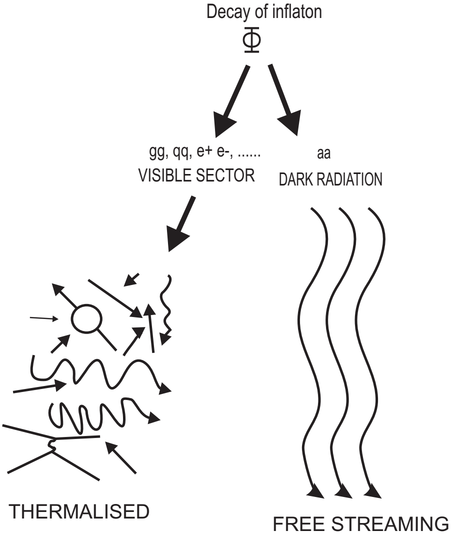
aa

DARK RADIATION

Dark radiation arises from hidden sector decays of moduli

Ideal subject for string phenomenology!

# A Cosmic Axion Background



Decay of inflaton

$\Phi$

gg, qq, e+ e-, ......

VISIBLE SECTOR

aa

DARK RADIATION

THERMALISED

FREE STREAMING

# 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!

# Properties of Dark Radiation

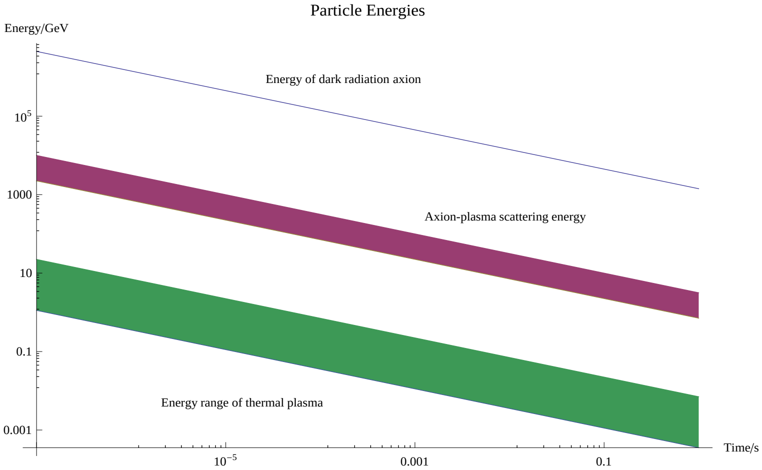
Ratio of axion energy to photon temperature is

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

No absolute prediction, but a modulus mass $m \sim 10^6$GeV arises in many string models.

# A Cosmic Axion Background

The ‘Hot Big Bang’ looks like

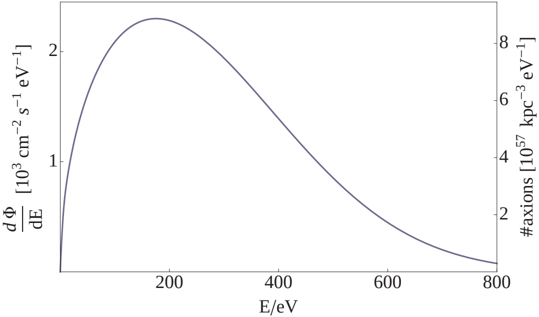


# A Cosmic Axion Background

Axions originate at $z \sim 10^{12} (t \sim 10^{-6}$ s) and freestream to today.

PREDICTION: Cosmic Axion Background

Energy: $E \sim 0.1 \div 1\text{keV}$ 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 such axionic dark radiation 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 $E \gg T_{CMB}$ comes from very simple and general properties of moduli.

This Cosmic Axion Background would today have energies lying in extreme ultraviolet / soft X-ray wavebands.

Could we see it?

# V

# OBSERVING A COSMIC AXION BACKGROUND

# Seeing Axions

If a Cosmic Axion Background exists, how could one see it?

Axion-photon conversions come from axion coupling to electromagnetism:

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

In background magnetic fields, axions convert (oscillate) into photons.

This oscillation is very similar to the physics of neutrino oscillations.

# Seeing Axions

The CAST experiment - point an LHC magnet at the sun and look for axions converting to photons

# Seeing Axions

Axion-to-photon conversion probability for axion energy $E_a$ in transverse magnetic field $B_\perp$ of domain size $L$ is:

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

where

$$\theta \approx 2.8\cdot 10^{-5} \times \left(\frac{10^{-3}\text{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{E_a}{200\ \mathrm{eV}}\right)\left(\frac{10^{14}\ \mathrm{GeV}}{M}\right),$$

$$\Delta = 0.27 \times \left(\frac{n_e}{10^{-3}\text{cm}^{-3}}\right)\left(\frac{200\ \mathrm{eV}}{E_a}\right)\left(\frac{L}{1\ \mathrm{kpc}}\right).$$

# Seeing Axions

$$P(a \to \gamma) \sim 2.3 \times 10^{-8} \left( \frac{B}{1\mu\mathrm{G}} \right)^2 \left( \frac{L}{1\mathrm{kpc}} \right)^2 \left( \frac{10^{13}\mathrm{GeV}}{M} \right)^2$$

Not large - but not that small either....

An illustration of the importance of quantum mechanical coherence.

Amplitudes grow with length - probabilities grow with length squared.

# Seeing Axions

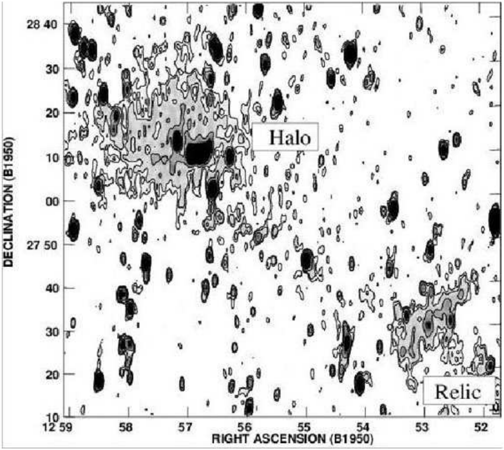
Axions convert to photons in coherent magnetic field domain: want large magnetic fields supported over large volumes.

Galaxy Clusters:

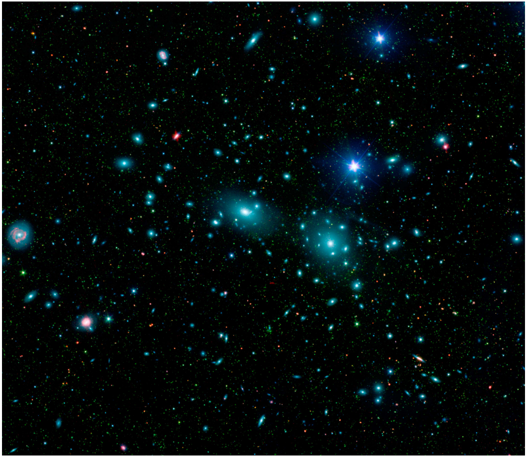
- The largest virialised structures in the universe
- Typical size 1 Mpc, typical mass $10^{14} \div 10^{15} M_{sun}$.
- Large magnetic fields $B \sim 1 \div 10 \mu\text{G}$ coherent over $L \sim 1 \div 10$ kpc.
- Hot intracluster gas, $T_{gas} \sim 2 \div 10\text{keV}$.
- By mass 1 per cent galaxies, 10 per cent gas, 90 per cent dark matter.
- Sit at the ‘large magnetic fields over large volumes’ frontier of particle physics.

Focus on Coma - large, well observed, nearby cluster at $|b| \gg 0$.

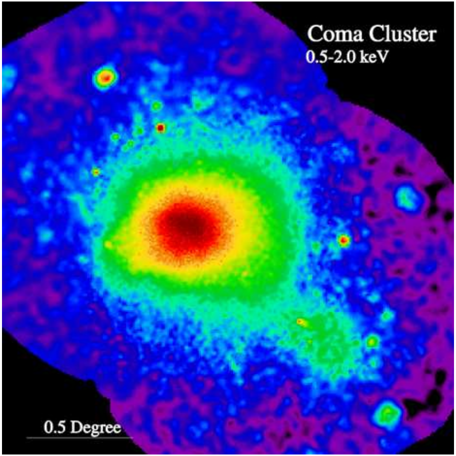
# Coma in Radio



# Coma in IR/Visible



# Coma in X-rays (ROSAT)



# A Cosmic Axion Background

Energy density of Cosmic Axion Background is

$$\rho_{CAB} = \left( \frac{\Delta N_{eff}}{0.57} \right) 1.6 \times 10^{60} \text{erg Mpc}^{-3}$$

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

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

For field $B$ over a domain $L$, in small mixing approximation,

$$\begin{aligned} P(a \to \gamma) &= \frac{B^2 L^2}{4M^2} \text{ per domain} \\ &= 2.0 \cdot 10^{-18} \text{s}^{-1} \times \left( \frac{B_\perp}{3\ \mu\text{G}} \frac{10^{13}\ \text{GeV}}{M} \right)^2 \left( \frac{L}{1\ \text{kpc}} \right). \end{aligned}$$

# 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 $\Delta N_{eff} \sim 0.5$ and $M \sim 10^{11}$GeV, $a \to \gamma$ luminosity outshines entire cluster!

Counterpart - for $M \sim 10^{11}$GeV observable signal can remain even with $\Delta N_{eff} \sim 10^{-4}$.

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

# The Cluster Soft Excess

In fact there exists a long-standing (since 1996) EUV/soft x-ray excess from galaxy clusters (Lieu 1996, review Durret 2008). E.g Coma has

$$\mathcal{L}_{excess} \sim 10^{43} \text{erg s}^{-1}$$

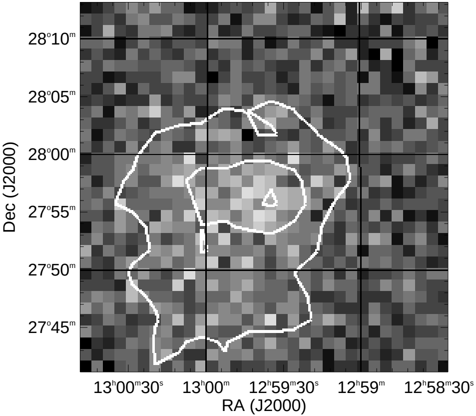
What is observed is excess emission above low-energy tail from thermal Bremmstrahlung emission from hot intracluster gas.

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/Inverse Compton-CMB scattering of relativistic electrons) all have problems.

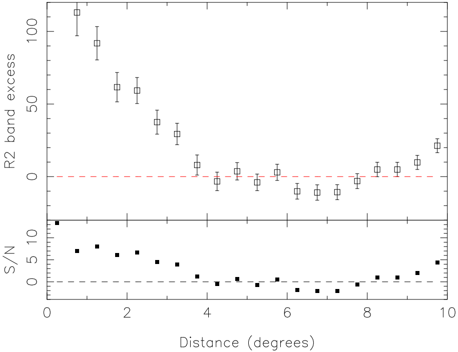
# The Cluster Soft Excess: Coma



from astro-ph/0403081 Bowyer et al, soft excess in Coma as observed by EUVE

# The Cluster Soft Excess: Coma

Soft excess extends well beyond hot gas and cluster virial radius:



from 0903.3067 Bonamente et al, ROSAT R2 band (0.14-0.28keV) observation of Coma

# Cluster Soft Excess: Astrophysical Explanations

Two main proposals for astrophysical explanations:

1. A warm thermal gas with $T \sim 0.2$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.

Both have problems.

# The Cluster Soft Excess and a CAB

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

Necessary energy and luminosity easy to obtain ($M \lesssim 10^{13}\text{GeV}$) and also consistent with 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. $O_{VII}$) associated to excess
- Energy of excess is constant across clusters, varying with redshift as $E_a \sim (1 + z)$.

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

# Axion Propagation through Coma

Magnetic field model is best fit to Faraday rotation (Bonafede et al 1002.0594):

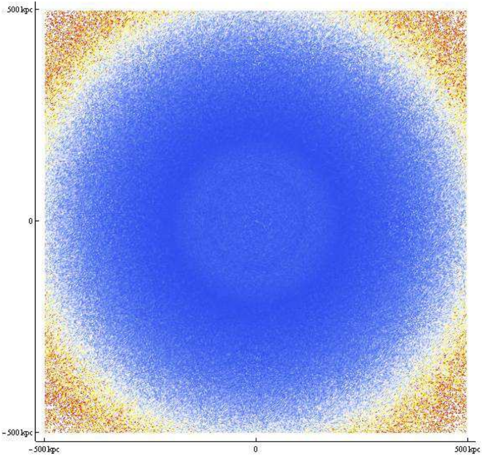
- Magnetic field has Kolmogorov spectrum, $|B(k)| \sim k^{-11/3}$, generated between $k_{max} = \frac{2\pi}{2\text{kpc}}$ and $k_{min} = \frac{2\pi}{34\text{kpc}}$.
- Spatial magnetic field has Gaussian statistics.
- Central magnetic field $\langle B \rangle_{r<291kpc} = 4.7\mu\text{G}$
- Equipartition radial scaling of $B$, $B(r) \sim n_e(r)^{1/2}$
- Electron density taken from $\beta$-model with $\beta = 0.75$,

$$n_e(r) = 3.44 \times 10^{-3} \left( 1 + \left( \frac{r}{291\text{kpc}} \right)^2 \right)^{-\frac{3\beta}{2}} \text{cm}^{-3}$$

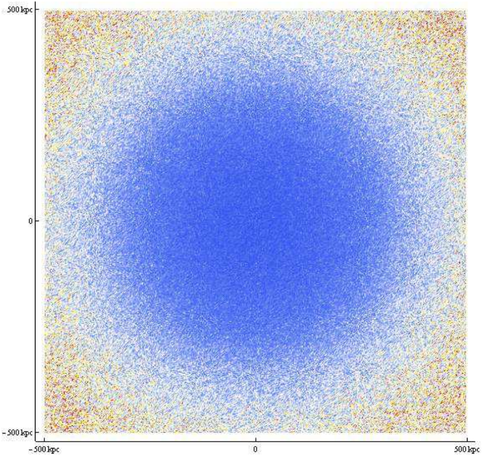
- Numerical $2000^3$ magnetic field with 0.5kpc resolution.

Numerical propagation of axions with $E = 25\text{eV} \div 25000\text{eV}$ and determination of $P(a \to \gamma)$.

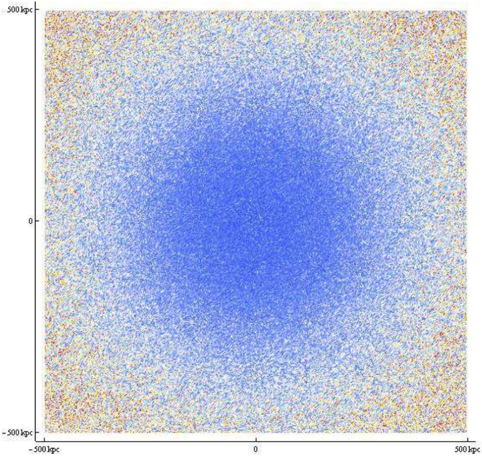
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 25\text{eV}$



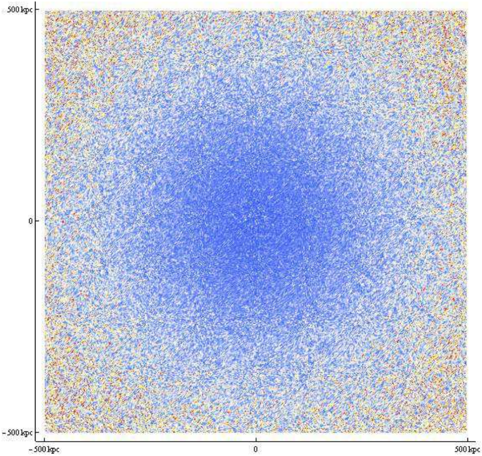
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 50\text{eV}$



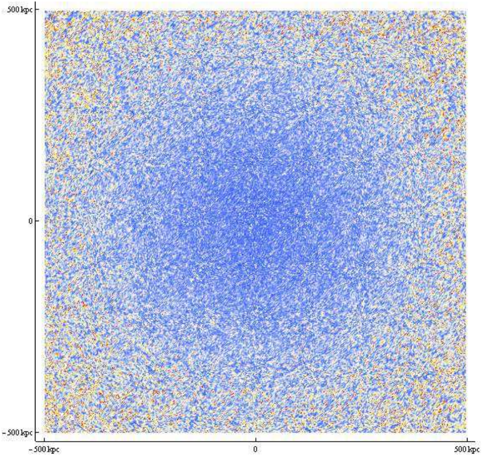
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 75\text{eV}$



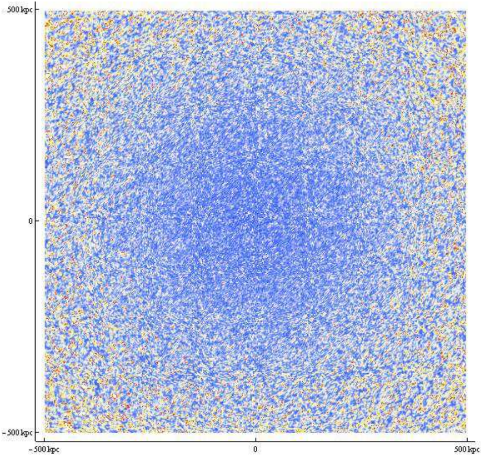
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 100\text{eV}$



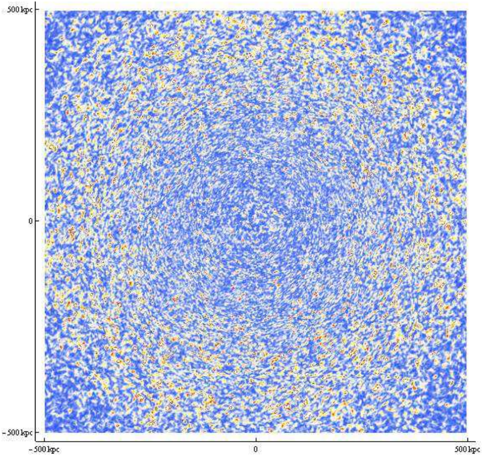
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 150\text{eV}$



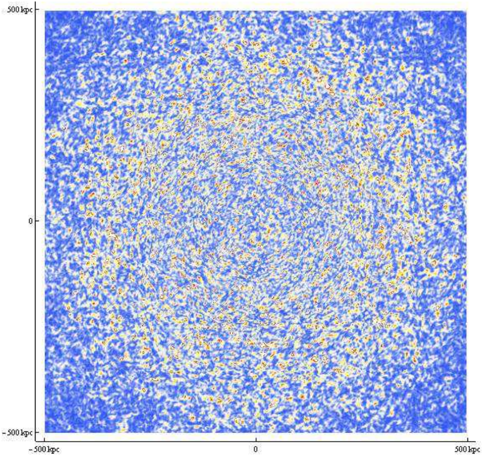
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 200$eV



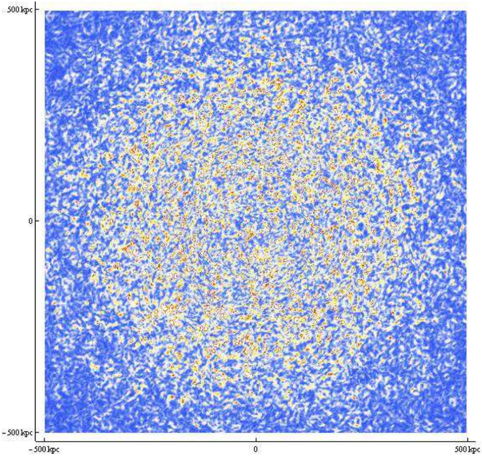
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 400\text{eV}$



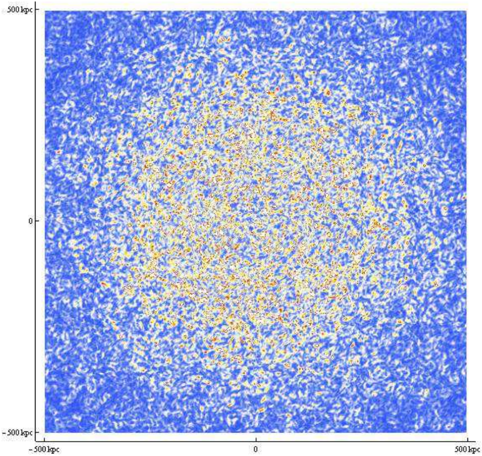
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 600\text{eV}$



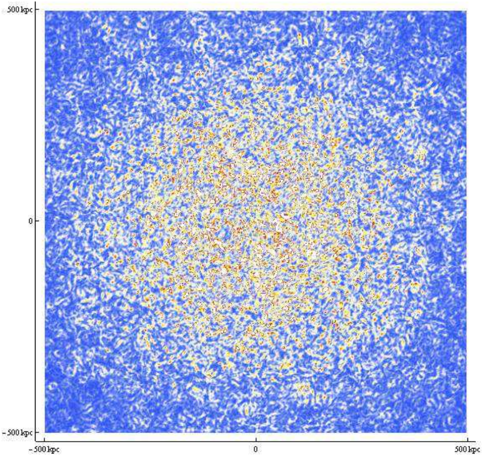
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 800\text{eV}$



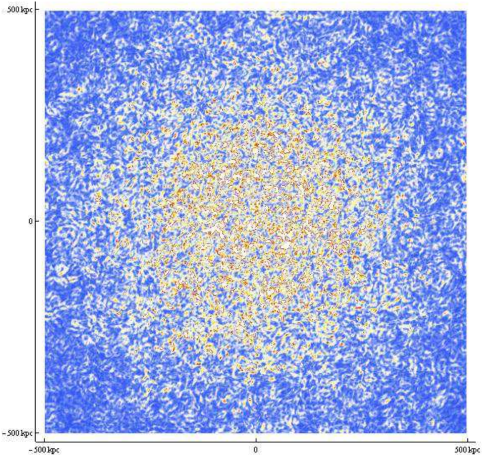
# $P(a \rightarrow \gamma)$ in Coma, central Mpc$^3$: $E_a = 1000\text{eV}$



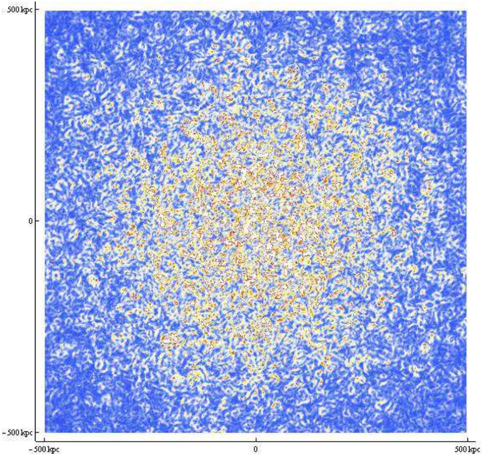
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 1300\text{eV}$



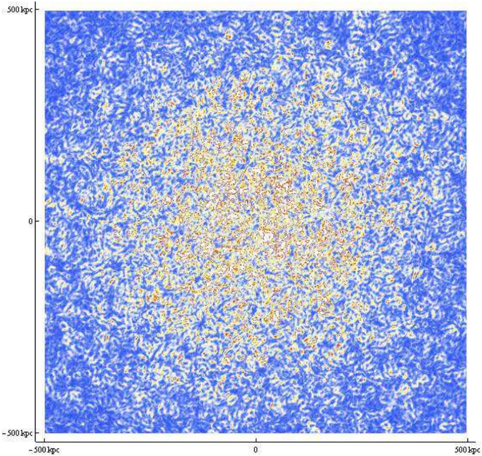
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 1600\text{eV}$



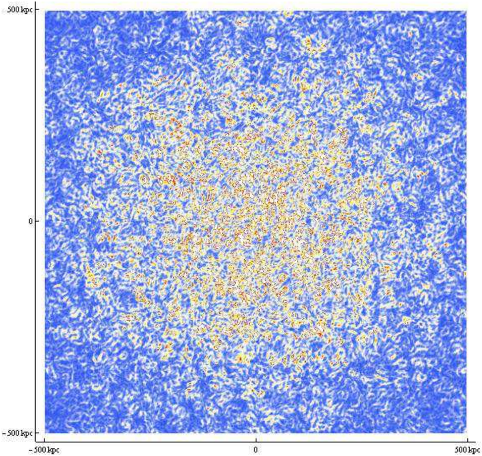
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 2000\text{eV}$



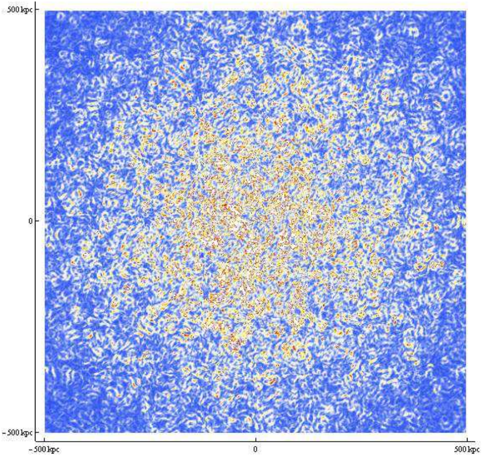
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 4\text{keV}$



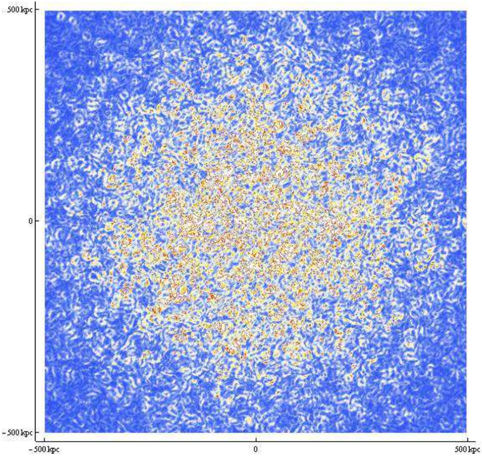
# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 8\text{keV}$



# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 16\text{keV}$



# $P(a \to \gamma)$ in Coma, central Mpc$^3$: $E_a = 25$keV



# Conclusions

- Dark radiation is an extension of standard cosmology with exceptional theoretical motivation and good experimental motivation.
- Its existence requires only a decay mode of the 'inflaton' to a massless hidden sector.
- In string models dark radiation is naturally generated through the modulus decay $\Phi \to aa$.
- For typical moduli masses this predicts a Cosmic Axion Background freestreaming from $z \sim 10^{12}$ to now have $E_a \sim 0.1 \div 1$ keV.
- CAB can be observed through $a \to \gamma$ conversion in magnetic fields and may already be visible through long-standing astrophysics EUV excess from galaxy clusters.