Galaxy Clusters as Tele-ALP-scopes

Joseph Conlon, Oxford University

Johns Hopkins Workshop 2014, Heidelberg, 22nd July 2014

Talk Structure

1. Axion-like Particles
2. Galaxy Clusters and $a \rightarrow \gamma$ Conversion
3. Dark Radiation, a 0.1 - 1 keV Cosmic ALP Background and the Cluster Soft Excess
4. The 3.5 keV line

Thanks to my collaborators

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'

1312.3947 Stephen Angus, JC, David Marsh, Andrew Powell, Lukas Witkowski
'Soft X-Ray Excess in the Coma Cluster from a Cosmic Axion Background'

1403.2370 Michele Cicoli, JC, David Marsh, Markus Rummel
'A 3.5 keV photon line and its morphology from a 3.5 keV ALP line'

1404.7741 JC, Francesca Day
'3.5 keV lines from ALP conversion in the Milky Way and M31'

1406.5518 JC, Andrew Powell
'The 3.5 keV line from $\mathrm{DM} \to a \to \gamma$*: predictions for cool-core and non-cool-core clusters'*

1406.5188 David Kraljic, Markus Rummel, JC
'ALP Conversion and the Soft X-Ray Excess in the Outskirts of the Coma Cluster'

I

AXION-LIKE PARTICLES

Axion-Like Particles

Light, weakly coupled particles represent one of the most interesting ways to extend the Standard Model

- Search strategies entirely decoupled from collider physics
- Such particles (axion-like particles, hidden photons...) arise generically in string compactifications
- No immediate technological obstruction to searches
- Ability to probe the far UV using low energy experiments
- Plenty of (theoretical) low-lying fruit
- Several current interesting hints exist

Axion-Like Particles

Basic ALP Lagrangian is

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

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

Will assume $m_a \lesssim 10^{-12}\mathrm{eV}$ in this talk.

Coupling to electromagnetism is

$$\frac{1}{M}a\mathbf{E}\cdot\mathbf{B}$$

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

Axion-Like Particles

ALPs convert to photons in coherent magnetic fields.

In small angle limit,

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

Conversion

- Grows with B^2 - big fields
- Grows with L^2 - coherent over large distances
- Drops off with M^2 - suppressed by weak couplings

Note heavy suppression (M^{-4}) for any physics based on $\gamma \to a \to \gamma$ - eg light shining through walls, solar axion production.....

Seeing ALPs

ALP-to-photon conversion probability for ALP 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

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

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

Small angle: $P_{a\to\gamma} = 2.0 \cdot 10^{-5} \times \left(\frac{B_\perp}{3\ \mu\mathrm{G}}\frac{L}{10\ \mathrm{kpc}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2.$

II

GALAXY CLUSTERS

Seeing ALPs

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

Galaxy clusters are superb locations:

- 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.

Seeing ALPs

The magnetic field of clusters is relatively small - $B \sim 1 - 10 \mu G$.

This is more than compensated by the large coherence lengths $L \sim 1 - 10\mathrm{kpc} \sim 10^{34}\mathrm{GeV}^{-1}$.

Quantum mechanical coherence:

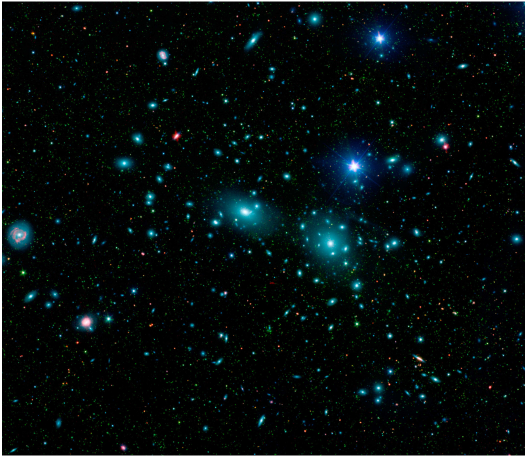
$$\mathcal{A}(a \to \gamma) \propto L$$

$$P(a \to \gamma) \propto L^2$$

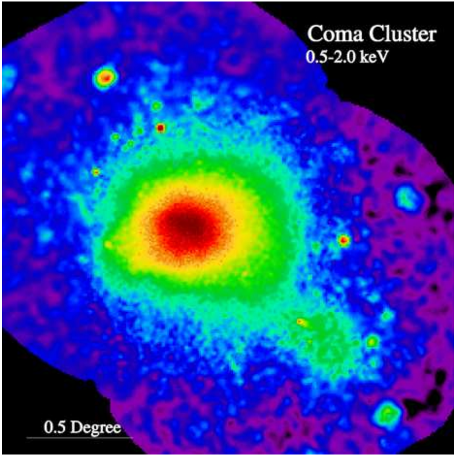
For $E_a \sim 1\mathrm{keV}$ and $M \sim 10^{13}\mathrm{GeV}$, a relativistic ALP has $P(a \to \gamma) \sim 10^{-3}$ passing through a cluster.

Converts energy to light 1000 times more rapidly than the sun....

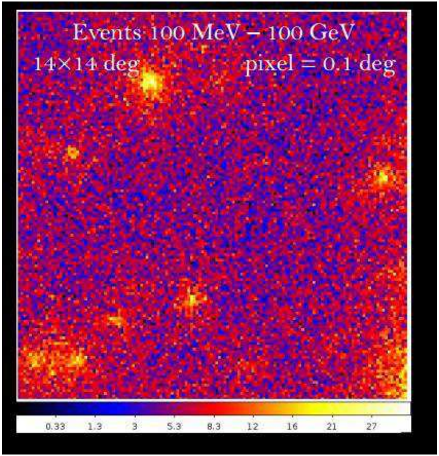
The Coma Cluster in IR/Visible



The Coma Cluster in X-rays



The Coma Cluster in Gamma Rays



(Ando + Zandanel, 1312.1493)

ALP Propagation through Center of Coma Cluster

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

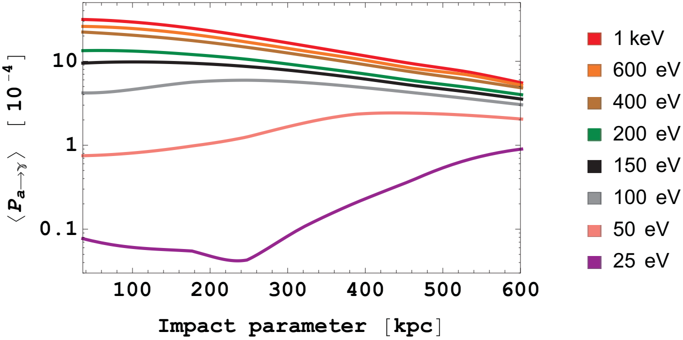
- Magnetic field has Kolmogorov spectrum, $|B(k)| \sim k^{-11/3}$, generated between $k_{max} = \frac{2\pi}{2\text{kpc}}$ and $k_{min} = \frac{2\pi}{34\text{kpc}}$.
- Spatial magnetic field has Gaussian statistics.
- Central magnetic field $\langle B \rangle_{r<291kpc} = 4.7\mu\text{G}$
- Equipartition radial scaling of B, $B(r) \sim n_e(r)^{1/2}$
- Electron density taken from β-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 ALPs with $E = 25\text{eV} \div 25000\text{eV}$ and determination of $P(a \to \gamma)$.

ALP Propagation through Centre of Coma



$a \to \gamma$ conversion probabilities for different ALP energies as a function of radius from the centre of Coma with $M = 10^{13}\mathrm{GeV}$

Note the high suppression for $E_a < 100\mathrm{eV}$

Angus JC Marsh Powell Witkowski 1312.3947

ALP Propagation through Clusters

Main Point: even up to large values of M, ALP-to-photon conversion is relatively unsuppressed through a galaxy cluster

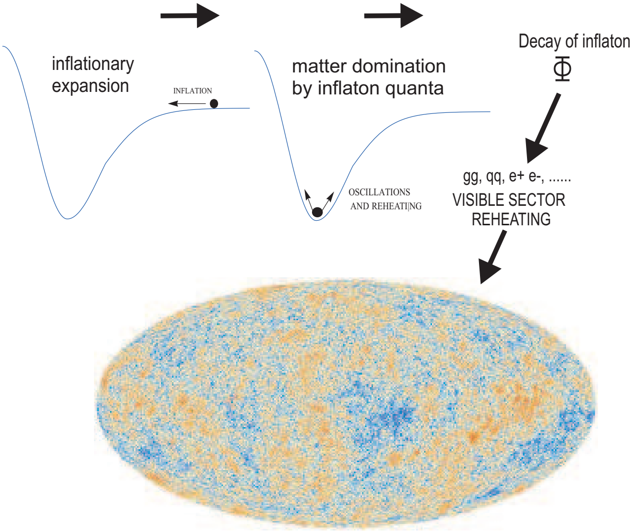
Any initial population of relativistic axion-like particles will convert to photons at reasonably large rates

III

DARK RADIATION AND THE CLUSTER SOFT EXCESS

The Standard Cosmology

The Standard Cosmology:



inflationary expansion

matter domination by inflaton quanta

Decay of inflaton

Φ

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

VISIBLE SECTOR
REHEATING

The Cosmological Moduli Problem

Polonyi 81, Coughlan Ross 83, Banks Kaplan Nelson 93, de Carlos Casas Quevedo Roulet 93

Hot Big Bang starts when universe becomes radiation dominated.

This occurs 'when inflaton decays'. However:

- Non-relativistic matter redshifts as $\rho_\Phi \sim a(t)^{-3}$
- Radiation energy density redshifts as $\rho_\gamma \sim a(t)^{-4}$
- Therefore as $a(t) \rightarrow \infty$, $\frac{\rho_\gamma}{\rho_\Phi} \rightarrow 0$

Long-lived matter comes to dominate almost independent of the initial conditions.

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

The Cosmological Moduli Problem

Moduli are generically misaligned during inflation, and afterwards oscillate as non-relativistic matter ($\rho \sim a^{-3}$) before decaying.

Lifetime of moduli is determined by M_P-suppressed decay rate:

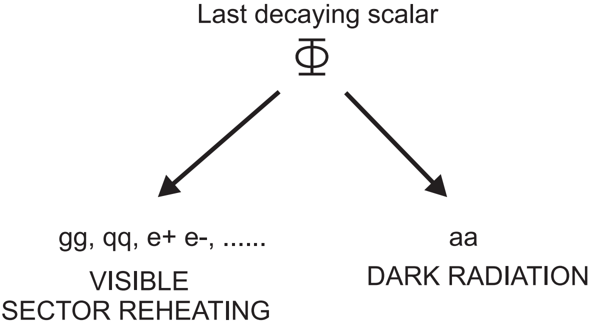
$$\begin{aligned}
\Gamma &\sim \frac{1}{8\pi}\frac{m_\Phi^3}{M_P^2} \\
\tau &= \Gamma^{-1} \sim 8\pi\frac{M_P^2}{m_\Phi^3} = \left(\frac{100\text{TeV}}{m_\Phi}\right)^3 0.1\text{s} \\
T_{decay} &\sim \left(\frac{m_\Phi}{100\text{TeV}}\right)^{3/2} 3\text{ MeV}
\end{aligned}$$

Hot Big Bang does not start until moduli decay.

Side consequence: generic expectation of string compactifications is that the universe passes through a modulus-dominated epoch, and reheating comes from the decays of these moduli.

The Cosmological Moduli Opportunity

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



Last decaying scalar

Φ

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

VISIBLE
SECTOR REHEATING

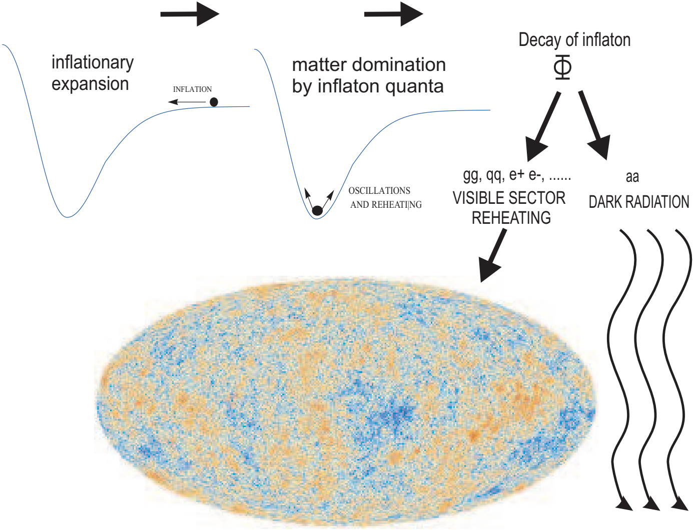
aa

DARK RADIATION

Hidden sector decays of moduli give rise to dark radiation.

Ideal subject for string phenomenology!

The Cosmological Moduli Opportunity



The Cosmological Moduli Opportunity

As gravitationally coupled particles, moduli generally couple to everything with M_P^{-1} couplings and there is no reason to expect vanishing couplings to hidden sectors.

$$\begin{aligned}
\text{Visible sector} \quad &: \quad \frac{\Phi}{4M_P} F_{\mu\nu}^{color} F^{color,\mu\nu}, \ \frac{\partial_\mu \partial^\mu \Phi}{M_P} H_u H_d, \ldots \\
\text{Hidden sector} \quad &: \quad \frac{\Phi}{2M_P} \partial_\mu a \partial^\mu a, \ \frac{\Phi}{4M_P} F_{\mu\nu}^{hidden} F^{hidden,\mu\nu} \ldots
\end{aligned}$$

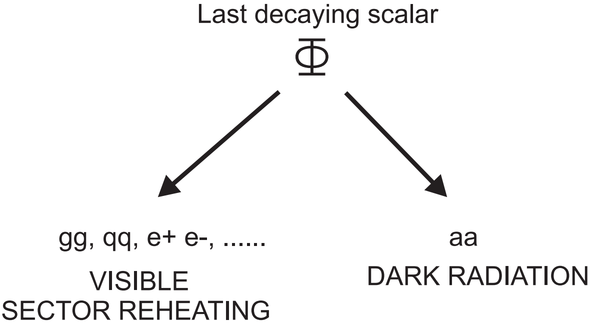
This is supported by explicit studies of string effective field theories

In particular, axionic decay modes naturally arise with $\mathrm{BR}(\Phi \to aa) \sim 0.01 \to 1$.

1208.3562 Cicoli JC Quevedo, 1208.3563 Higaki Takahashi, 1304.7987 Higaki Nakayama Takahashi

A Cosmic ALP Background

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



Last decaying scalar

Φ

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 ALP Background

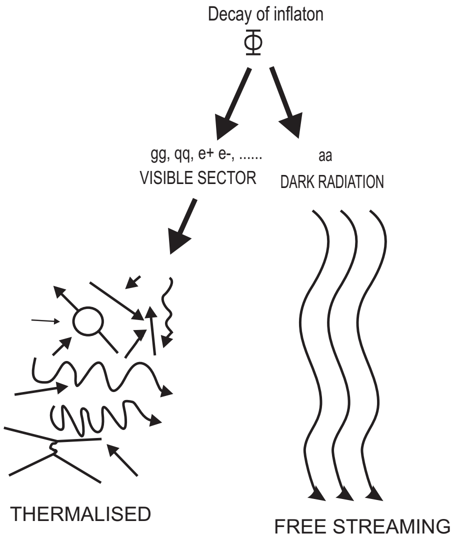
Typical moduli couplings $\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu}$ or $\frac{\Phi}{M_P} \partial_\mu a \partial^\mu a$ give

$$H_{decay} \sim \Gamma \sim \frac{1}{8\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\begin{array}{lcl} T_{reheat} & \sim \left(3H_{decay}^2 M_P^2\right)^{1/4} \sim \frac{m_\phi^{3/2}}{M_P^{1/2}} & \sim 0.6\mathrm{GeV} \left(\frac{m_\phi}{10^6\,\mathrm{GeV}}\right)^{3/2} \\ E_{ALP} & = \left(\frac{m_\Phi}{2}\right) = & 5 \times 10^5\,\mathrm{GeV} \left(\frac{m_\Phi}{10^6\,\mathrm{GeV}}\right) \end{array}$$

Visible sector thermalises: however ALPs propagate freely as universe is transparent to them.

A Cosmic ALP Background



A Cosmic ALP Background

$\Phi \to gg, \ldots$: Decays thermalise $T_\gamma \sim T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$

$\Phi \to aa$: ALPs never thermalise $E_a = \frac{m_\Phi}{2}$

Thermal bath cools into the CMB while ALPs never thermalise and freestream to the present day:

Ratio of ALP 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 ALP Background

Ratio of ALP 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 lightest modulus mass $m \sim 10^6$GeV arises in many string models - often correlated with SUSY approaches to the weak hierarchy problem.

- KKLT hep-th/0503216 Choi et al
- Sequestered LVS 0906.3297 Blumenhagen et al
- ‘G2 MSSM’ 0804.0863 Acharya et al

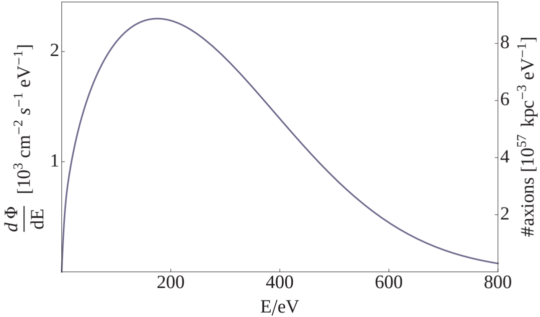
NB Moduli problem requires $m_\Phi \gtrsim 10^5$TeV.

A Cosmic ALP Background

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

PREDICTION: Cosmic ALP Background

Energy: $E \sim 0.1 \div 1\text{keV}$ Flux: $\sim \left(\frac{\Delta N_{eff}}{0.57}\right) 10^6 \text{cm}^{-2}\text{s}^{-1}$.



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

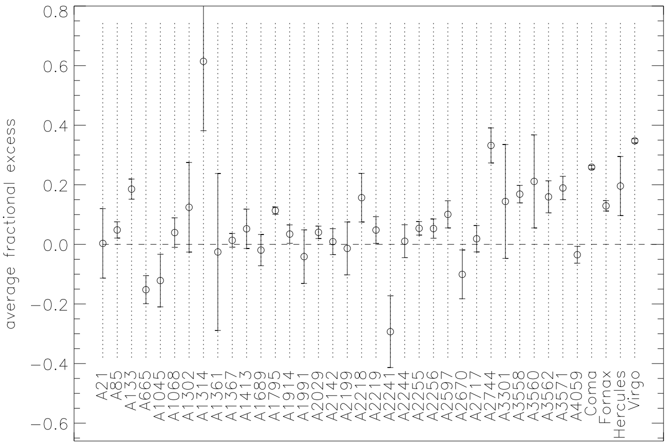
$$\mathcal{L}_{excess} \sim 10^{43} \text{erg s}^{-1}$$

Observed by different satellites - principally EUVE and soft bands of ROSAT.

Has been studied for a large number (~ 40) of clusters, present in ~ 15.

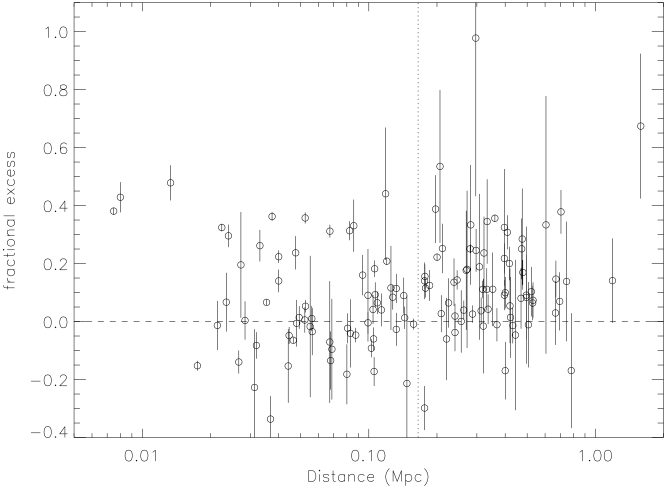
Difficulties with astrophysical explanations - see backup slides.

The Cluster Soft Excess



from Bonamente et al 2002, fractional soft excess in ROSAT 0.14 - 0.28 keV R2 band

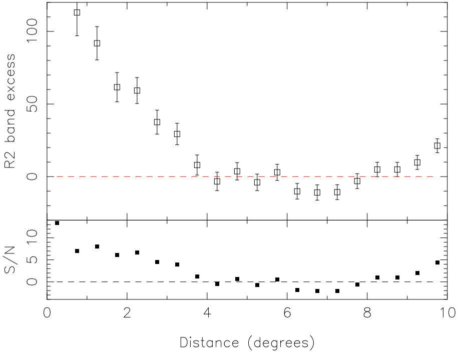
The Cluster Soft Excess



from Bonamente et al 2002, fractional soft excess with radius

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) observations of Coma

The Cluster Soft Excess and a CAB

Proposal: cluster soft excess generated by $a \rightarrow \gamma$ conversion in cluster magnetic field.

Basic predictions:

- Magnitude and morphology of soft excess 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 $E_a \sim (1+z)$.

Test by propagating ALPs through simulated cluster magnetic fields

A Cosmic ALP Background

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

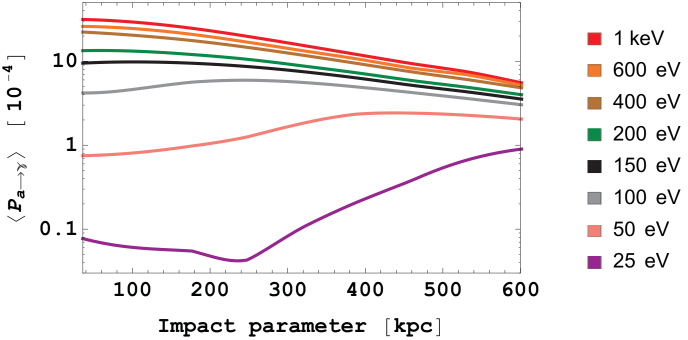
$$\begin{aligned}\mathcal{L}_{Mpc^3} &= 3.6 \cdot 10^{41} \text{ erg Mpc}^{-3}\text{s}^{-1} \times \\ &\times \left(\frac{\Delta N_{eff}}{0.57}\right)\left(\frac{B}{\sqrt{2}\ \mu\mathrm{G}}\frac{10^{13}\ \mathrm{GeV}}{M}\right)^2\left(\frac{L}{1\ \mathrm{kpc}}\right),\end{aligned}$$

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 $\Delta N_{eff} \sim 10^{-4}$.

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

ALP Propagation through Centre of Coma

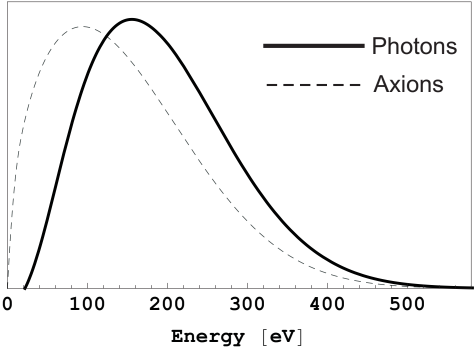


$a \to \gamma$ conversion probabilities for different ALP energies as a function of radius from the centre of Coma

Note the high suppression for $E_a < 100\text{eV}$

Angus JC Marsh Powell Witkowski 1312.3947

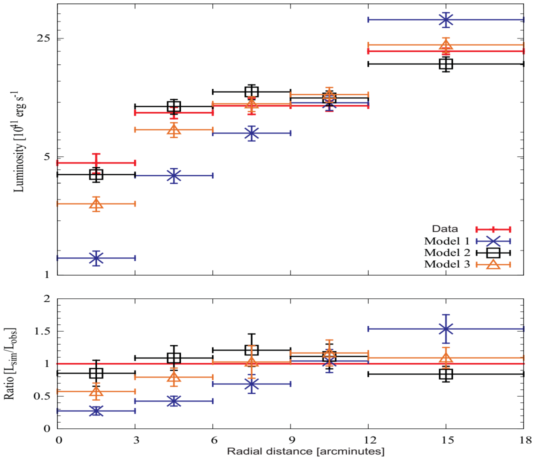
ALP Propagation through Centre of Coma



Comparison of original ALP spectrum and spectrum of converted photons

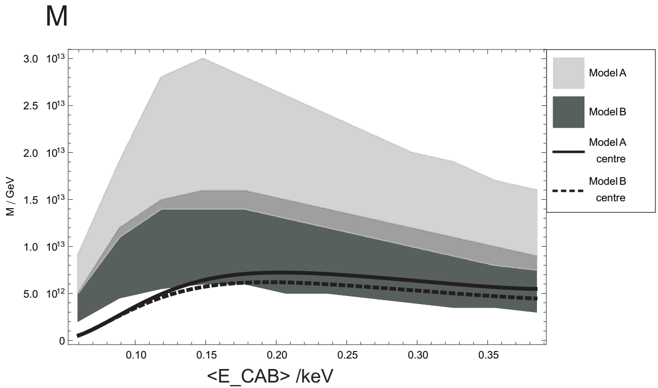
Photon spectrum falls off rapidly at both low and high energies

ALP Propagation through Centre of Coma



Morphology fits reasonably well for $M \sim 7 \times 10^{12}\,\mathrm{GeV}$

ALP Propagation through Outskirts of Coma



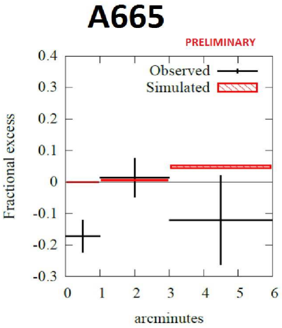
Fit to the outskirts gives a compatible value of $M \sim 10^{13}\mathrm{GeV}$.

Kraljic, Rummel, JC 1406.5188

ALP Propagation through Other Clusters

(Plots assume the Coma best fit value of $M \sim 7 \times 10^{12}\text{GeV}$)

Powell, to appear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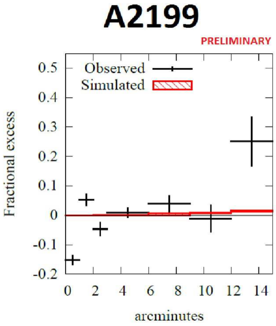
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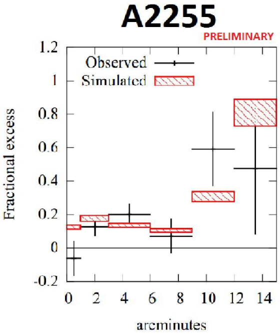
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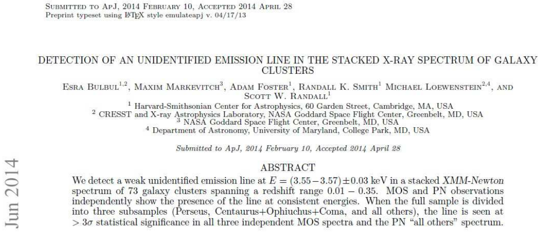
IV
THE 3.5 KeV LINE

Dark Matter in X-rays?



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Preprint typeset using LaTeX style emulateapj v. 04/17/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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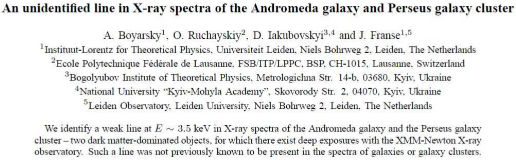
ABSTRACT

We detect a weak unidentified emission line at $E = (3.55-3.57) \pm 0.03$ keV in a stacked *XMM-Newton* spectrum of 73 galaxy clusters spanning a redshift range 0.01 – 0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN "all others" spectrum.



An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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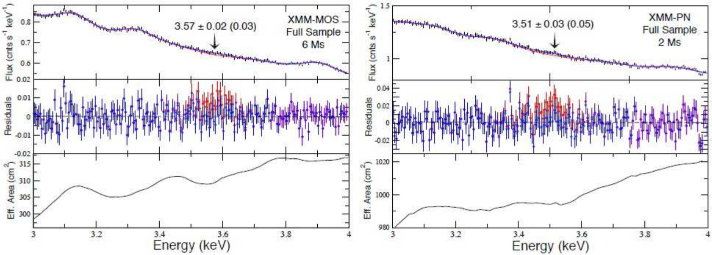
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters.

1402.2301, 1402.4119

Dark Matter in X-rays?

Small signal on a large background



Dark Matter in X-rays?

Most detailed evidence for signal comes from analyses involving galaxy clusters

- Stacked sample of 73 clusters in Bulbul paper
- Two XMM instruments - MOS and PN
- Individual subsamples of Perseus, Coma+Ophiuchus+Centaurus, All Others
- Perseus reconfirmed with deep Chandra observations, both ACIS-S and ACIS-I
- Outskirts of Perseus studied in Boyarsky paper (XMM-MOS, XMM-PN), as well as M31
- More recent paper (Riemer-Sorensen, 1405.7943) finds no signal in Milky Way centre

Significance Counting

Sample	Instrument	$\Delta\chi^2$	N
Bulbul paper			
Perseus	XMM-MOS	15.7	1
Coma + Centaurus + Ophiuchus	XMM-MOS	17.1	1
All others stacked (69 clusters)	XMM-MOS	16.5	1
All others stacked (69 clusters)	XMM-PN	15.8	1
Perseus	Chandra ACIS-I	11.8	2
Perseus	Chandra ACIS-S	6.2	1
Boyarsky paper			
Perseus outskirts	XMM-MOS	9.1	2
Perseus outskirts	XMM-PN	8.0	2
Andromeda galaxy	XMM-MOS	13.0	2

Significance Counting

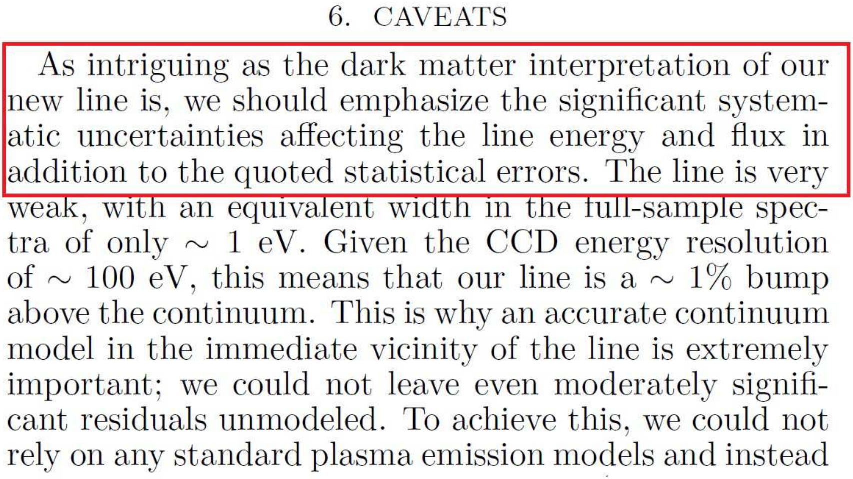
- (+) Line seen by four instruments (XMM-MOS, XMM-PN, Chandra ACIS-I, Chandra ACIS-S)
- (+) Line seen independently by two separate collaborations
- (+) Collaborations do not consist of BSM theorists
- (+) Line seen from at least five different sources at consistent energy
- (+) Line absent in deep 16Ms blank sky observations

However - need excellent control over backgrounds:

- (-) Signal one percent above continuum
- (-) X-ray atomic lines from hot gas at similar energies
- (-) Detector backgrounds also generate X-ray lines
- (-) Effective area wiggles can mimic signal

Dark Matter in X-rays?

Deserves to be taken seriously - time will tell correctness



6. CAVEATS

As intriguing as the dark matter interpretation of our new line is, we should emphasize the significant systematic uncertainties affecting the line energy and flux in addition to the quoted statistical errors. The line is very weak, with an equivalent width in the full-sample spectra of only $\sim$ 1 eV. Given the CCD energy resolution of $\sim$ 100 eV, this means that our line is a $\sim$ 1% bump above the continuum. This is why an accurate continuum model in the immediate vicinity of the line is extremely important; we could not leave even moderately significant residuals unmodeled. To achieve this, we could not rely on any standard plasma emission models and instead

Sterile Neutrino?

The canonical explanation....

Sample	Instrument	$\sin^2 2\theta$ $\times 10^{-11}$
Bulbul paper		
All others stacked (69 clusters)	XMM-MOS	$6.0^{+1.1}_{-1.4}$
All others stacked (69 clusters)	XMM-PN	$5.4^{+0.8}_{-1.3}$
Perseus	XMM-MOS	$23.3^{+7.6}_{-8.9}$
Coma + Centaurus + Ophiuchus	XMM-MOS	$18.2^{+4.4}_{-5.9}$
Perseus	Chandra ACIS-I	$28.3^{+11.8}_{-12.1}$
Perseus	Chandra ACIS-S	$40.1^{+14.5}_{-13.7}$

Signal strength appears different between clusters

In particular, signal is stronger for central regions of bright, nearby cool-core clusters

$\mathrm{DM} \to a \to \gamma$

Proposal: DM decays to a 3.5 keV line ALP, which converts to a 3.5 keV photon in the cluster magnetic field.

Signal then traces magnetic field as well as dark matter distribution

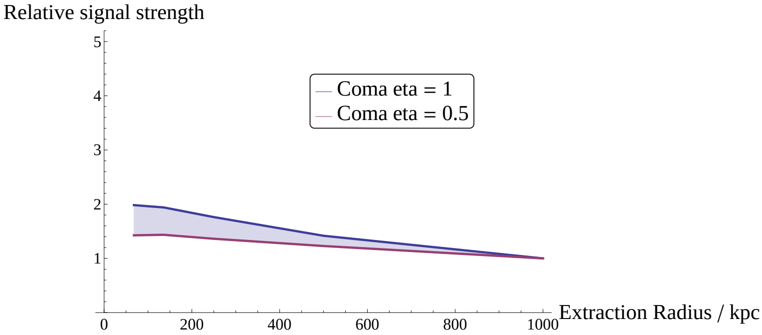
Perseus nearby cool core cluster:

- Stronger magnetic field in the centre of the cluster
- Nearby cluster, so only central region of cluster fits in telescope field of view

Ophiuchus (cool core), Centaurus (cool core), Coma (non-cool-core) also nearby, and XMM-Newton FoV only covers central region

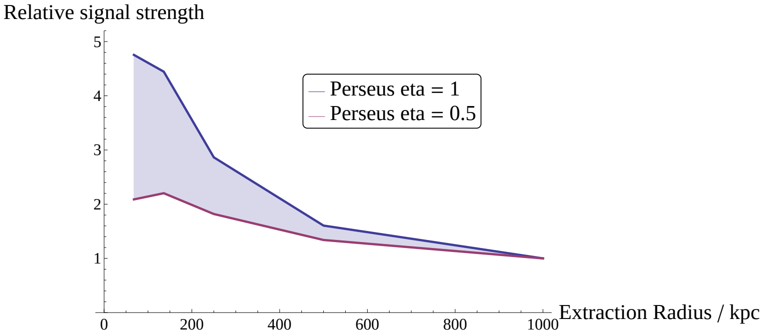
Also expect stronger signals for these

Non-Cool-Core Clusters - ‘Coma’



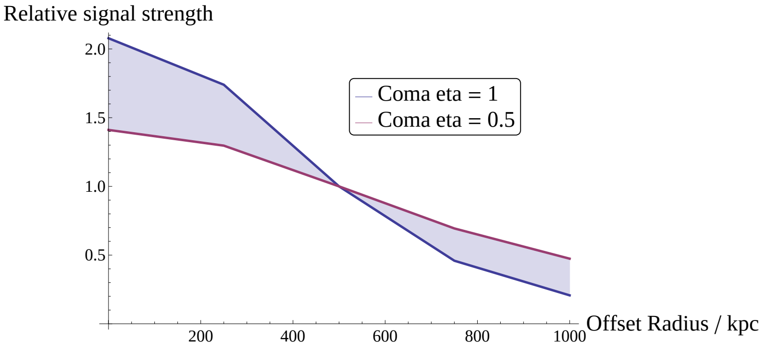
Relative signal strength as function of extraction radius

Cool Core Clusters - ‘Perseus’



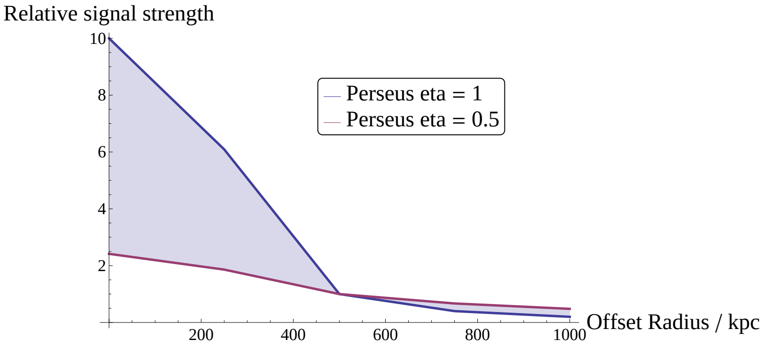
Relative signal strength as function of extraction radius

Non-Cool-Core Clusters - ‘Coma’



Relative signal strength as function of offset radius (250kpc extraction radius)

Cool Core Clusters - 'Perseus'



Relative signal strength as function of offset radius (250kpc extraction radius)

Conclusions

- Galaxy clusters are superb converters of axion-like particles ($m \lesssim 10^{-12}\mathrm{eV}$) to photons
- $a \to \gamma$ conversion probabilities are $\mathcal{O}(1)$ for $M \sim 10^{11}\mathrm{GeV}$
- Primary ALP sources can turn into easily visible photons with signal correlated with cluster magnetic field
- Two examples: a primordial cosmic ALP background, and the process $DM \to a \to \gamma$ for the 3.5 keV line

BACKUP SLIDES

Cluster Soft Excess: 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.

Both have problems (in back-up slides).

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:

$$\mathcal{F}^{Coma}_{>100 \text{ MeV}} < 1.1 \times 10^{-9} \text{ph cm}^{-2} \text{ s}^{-1}$$

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

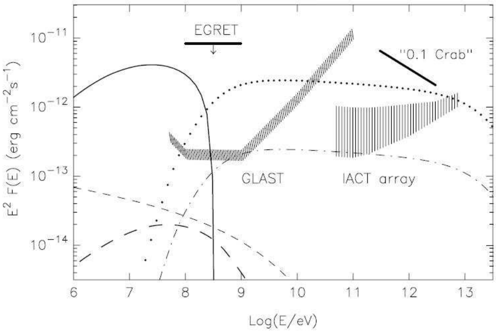


FIG. 6.—Expected γ-ray fluxes expected from the Coma Cluster. The

from Atoyan + Volk, 2000