Galaxy Clusters as Tele-ALP-scopes

Joseph Conlon, Oxford University

CTPU Daejeon 2014, 17th October 2014

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'

1410.1867 Pedro Alvarez, JC, Francesca Day, David Marsh, Markus Rummel
'Observational consistency and future predictions for a 3.5 keV ALP to photon line'

Thanks to my collaborators

Talk Structure

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

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 $M \gtrsim 2 \times 10^{11}\mathrm{GeV}$.

review Ringwald 1210.5081

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

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

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

Seeing ALPs

'Astrophysical parameters':

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

'Terrestrial parameters':

$$\text{Small angle: } P_{a\to\gamma} \simeq 2.0\cdot 10^{-23} \times \left(\frac{B_\perp}{10\mathrm{T}} \frac{L}{10\mathrm{m}} \frac{10^{13}\ \mathrm{GeV}}{M} \right)^2 .$$

Astrophysical sources overwhelmingly better

II
GALAXY CLUSTERS

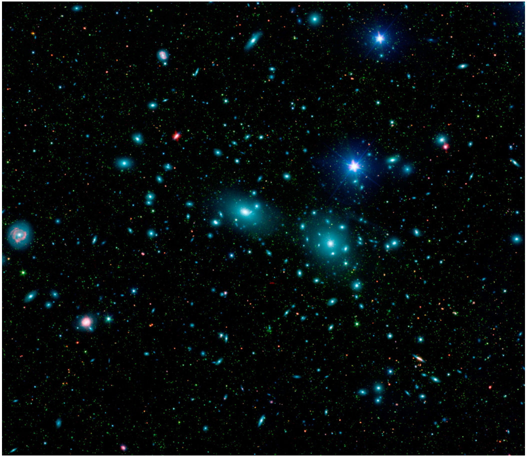
Galaxy Clusters

Galaxy Clusters

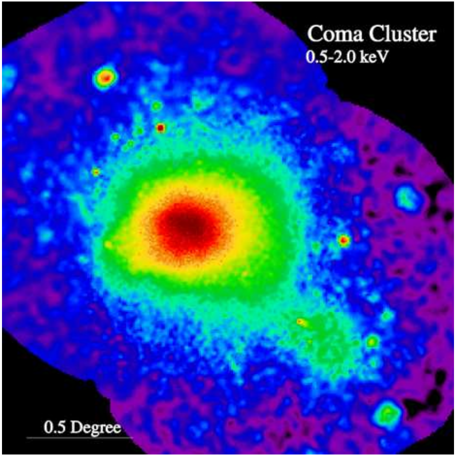
Galaxy clusters are:

- The largest virialised structures in the universe
- Typical size 1 Mpc, 100-1000 galaxies, total mass $10^{14} \div 10^{15} M_{sun}$.
- By mass 1 per cent galaxies, 10 per cent gas, 90 per cent dark matter.
- Suffused by magneto-ionic plasma with $T_{gas} \sim 2 \div 10$keV, emitting in X-rays via thermal bremsstrahlung
- Plasma is magnetised with $B \sim 1 \div 10\mu$G with coherence scales $L \sim 1 \div 10$ kpc.
- Sit at the 'large magnetic fields over large volumes' frontier of particle physics.

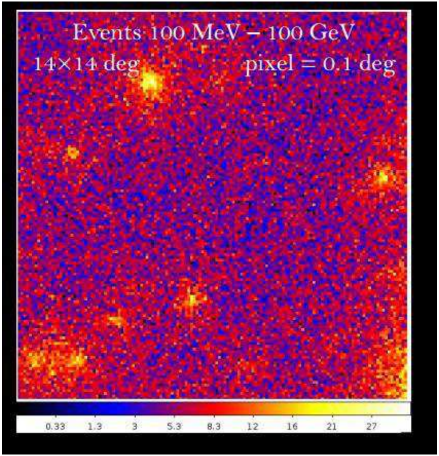
The Coma Cluster in IR/Visible



The Coma Cluster in X-rays



The Coma Cluster in Gamma Rays



(Ando + Zandanel, 1312.1493)

Seeing ALPs

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

The cluster magnetic field $B \sim 1 - 10\mu G$ is more than compensated by coherence lengths $L \sim 1 - 10\text{kpc} \sim 10^{34}\text{GeV}^{-1}$.

Quantum mechanical coherence:

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

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

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

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

ALP Propagation through Centre of Coma Cluster

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

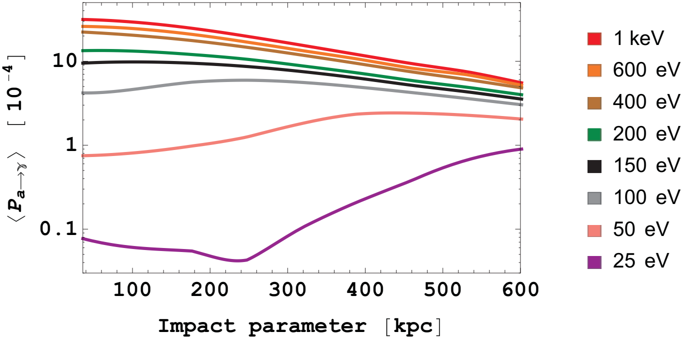
- Magnetic field has Kolmogorov spectrum, $|B(k)| \sim k^{-11/3}$, generated between $k_{max} = \frac{2\pi}{2\text{kpc}}$ and $k_{min} = \frac{2\pi}{34\text{kpc}}$.
- Spatial magnetic field has Gaussian statistics.
- Central magnetic field $\langle B \rangle_{r<291kpc} = 4.7\mu$G
- Equipartition radial 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 Cluster



$a \to \gamma$ 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 at $M \gtrsim 10^{11}\mathrm{GeV}$, ALP-to-photon conversion in a cluster is unsuppressed.

Any primary population of relativistic ALPs will give a large photon signal

III
THE 3.5 KeV LINE

Dark Matter in X-rays?

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

ESRA BULBUL[1,2], MAXIM MARKEVITCH[3], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2,4], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, USA
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[4] Department of Astronomy, University of Maryland, College Park, MD, USA

Submitted to ApJ, 2014 February 10, Accepted 2014 April 28

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.

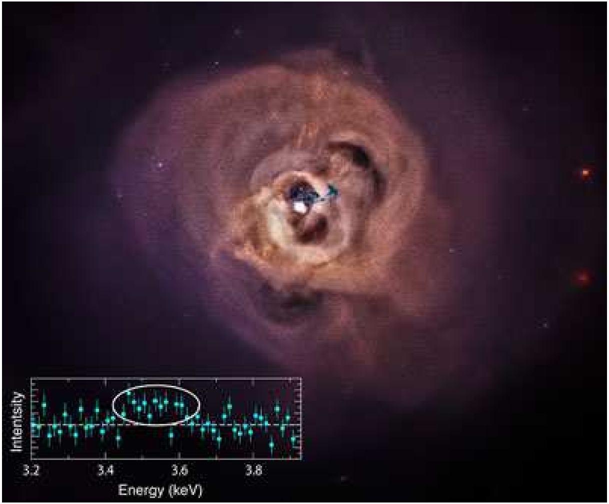
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[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.

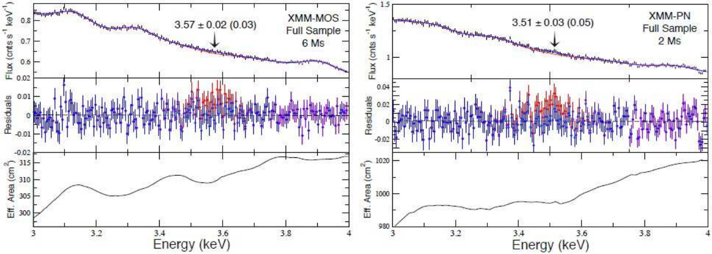
1402.2301, 1402.4119

Dark Matter in X-rays?



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 et al. 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
- Boyarsk et al finds line in outskirts of Perseus cluster (XMM-MOS, XMM-PN)
- Line also found in M31 by Boyarsky et al

Significance Counting

Sample	Instrument	$\Delta\chi^2$	N
Bulbul et al.			
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 et al.			
Perseus outskirts	XMM-MOS	9.1	2
Perseus outskirts	XMM-PN	8.0	2
Andromeda galaxy	XMM-MOS	13.0	2

Data Evaluation

- (+) 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?

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

Dark Matter in X-rays?

Subsequently:

- No 3.5 keV line in Chandra data of Milky Way centre (1405.7943)
- 3.5 keV line in XMM-Newton data of Milky Way centre (1408.1699, 1408.2503) - K XVIII or dark matter?
- No line in M31 from 3-4 keV fit, bananas in clusters (1408.1699)
- No 3.5 keV line in dwarf spheroidals, stacked galaxies (1408.3531, 1408.4115)
- Yes line in M31, 3-4 keV fit lacks precision (1408.4388)
- No bananas in clusters - use correct atomic data instead (1409.4143)

Sterile Neutrino?

Sample	Instrument	$\sin^2 2\theta$ $\times 10^{-11}$
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	$23.3^{+7.6}_{-8.9}$
Perseus	XMM-PN	< 18 (90 %)
Coma + Centaurus + Ophiuchus	XMM-MOS	$18.2^{+4.4}_{-5.9}$
Coma + Centaurus + Ophiuchus	XMM-PN	< 11(90%)
Perseus	Chandra ACIS-I	$28.3^{+11.8}_{-12.1}$
Perseus	Chandra ACIS-S	$40.1^{+14.5}_{-13.7}$
M31 on-centre	XMM-Newton	2–20
Stacked galaxies	XMM-Newton	< 2.5 (99%)
Stacked galaxies	Chandra	< 5 (99%)
Stacked dwarves	XMM-Newton	< 4 (95%)

Sterile Neutrino?

Models of form $\mathrm{DM} \to \gamma + X$ do not fit the data.

Challenges for BSM explanations:

- Clusters are special: signal stronger in clusters than in galaxies
- Nearby / cool-core clusters are special: signal is stronger than in distant stacked sample
- Among galaxies, M31 is special
- Milky Way centre: dark matter or atomic physics?

Focus here on the $\mathrm{DM} \to a \to \gamma$ explanation (1403.2370 Cicoli, JC, Marsh, Rummel) that can explain all these features.

Model is $\mathrm{DM} \to a + X$ followed by $a \to \gamma$ in transverse magnetic field

DM $\rightarrow a \rightarrow \gamma$

Proposal: DM decays to a monoenergetic 3.5 keV ALP, which converts to a 3.5 keV photon in astrophysical magnetic field.

Signal traces both magnetic field and the dark matter distribution

1. Clusters are special because magnetic field extends over 1 Mpc compared to 30 kpc for galaxies.
2. Nearby clusters are special because field of view covers central region with largest B fields.
3. Cool-core clusters are special because they have large central B fields.
4. M31 is special because it is an edge-on spiral galaxy with an unusually coherent regular magnetic field.
5. MW centre may/may not give observable signal

$\mathrm{DM} \to a \to \gamma$ pre-dictions

From 1403.2370: Cicoli, JC, Marsh, Rummel

'In environments with high dark matter densities but low magnetic fields, such as dwarf galaxies, the line should be suppressed.....'

From 1404.7741 JC, Day

'We note that - within the $\mathrm{DM} \to a \to \gamma$ scenario - the above points make M31 an unusually favourable galaxy for observing a 3.55 keV line. For general galaxies in this scenario, the signal strength of the 3.55 keV would be much lower than for galaxy clusters, and the fact that for M31 these can be comparable is rather uncommon.'

DM $\rightarrow a \rightarrow \gamma$

Among clusters, Perseus is a nearby cool core cluster:

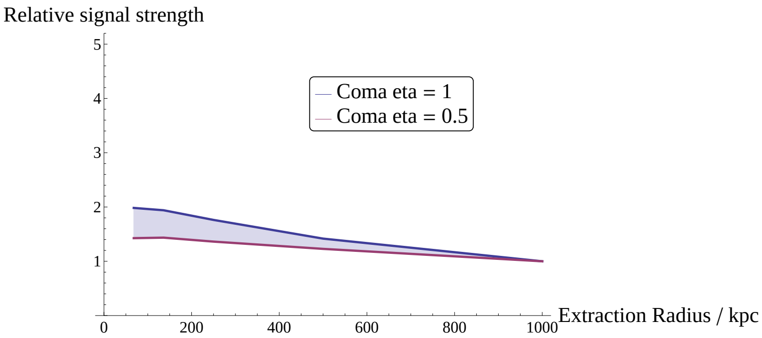
- Stronger magnetic field in the centre of the cluster
- Nearby cluster, so only central region of cluster fits in telescope field of view

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

We also expect stronger signals for these

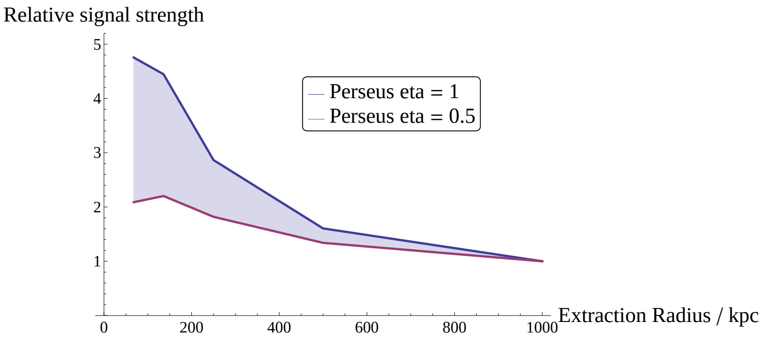
We can quantify differences between cool-core and non-cool-core clusters JC, Powell

Non-Cool-Core Clusters - 'Coma'



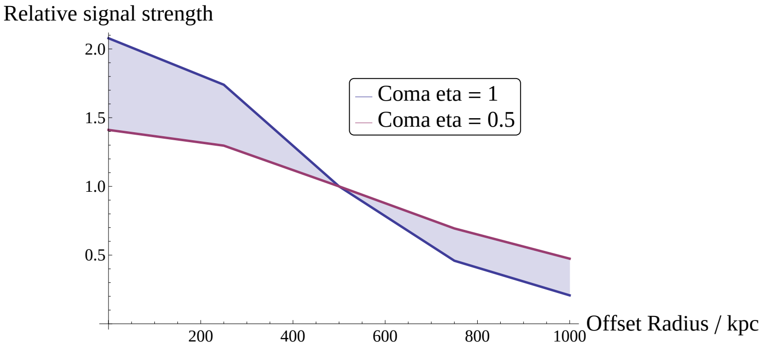
Relative signal strength as function of extraction radius

Cool Core Clusters - 'Perseus'



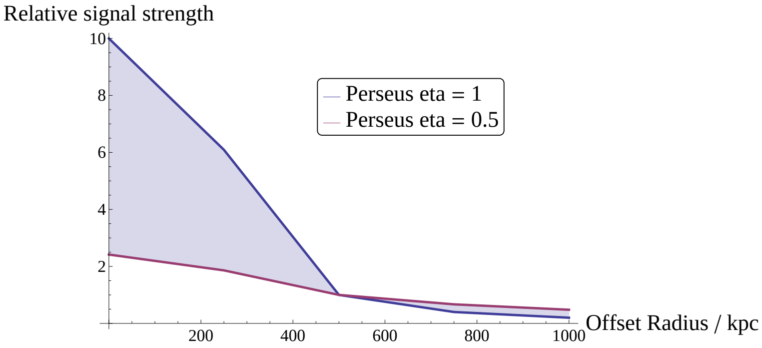
Relative signal strength as function of extraction radius

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)

The Milky Way

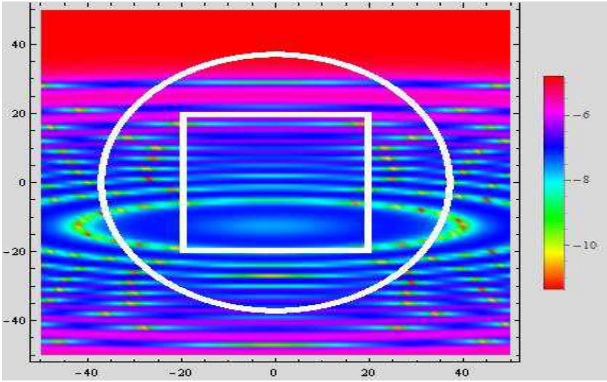
Using Jansson+Farrar magnetic field, we showed that no observable signal can arise from bulk Milky Way halo JC, Day

Results do not apply for MW centre as this magnetic field model excludes central 1kpc - sets B=0 there.

Our study of MW centre appeared recently (Alvarez, JC, Day, Marsh, Rummel 1410.1867)

Magnetic field in MW centre highly uncertain ($10 - 1000\ \mu$G) - observable line signal attainable only if B field at top range of observational estimates - uniform poloidal milligauss field over central $\sim$ 100pc.

The Sgr A* Region



Relative signal strength as offset from Sgr A*: base 10 logs.

XMM-Newton sees a signal; Chandra does not

'Smoking gun' signal: majority of signal in XMM-Newton field of view is from $z > 20pc$

The Future

More data will appear in the relatively near future:

Analyses known to be in progress:

Bulbul et al: stacked archival Chandra and Suzaku observations of galaxy clusters (grant awarded October 2013)

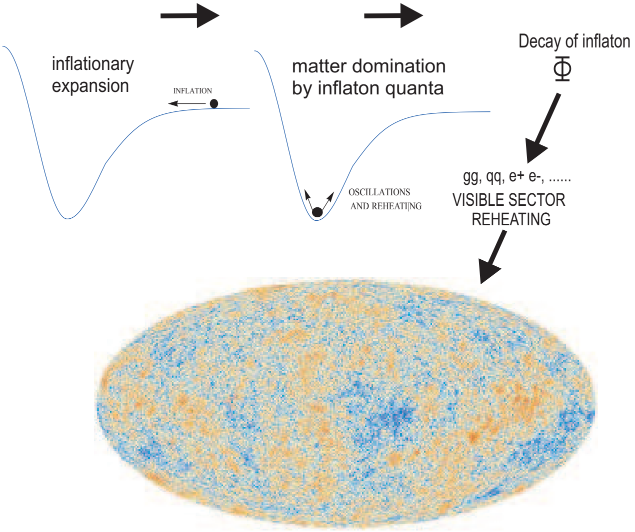
Boyarsky et al: A520 (train wreck cluster, dark matter displaced from hot gas)

Look forward to more observational progress!

IV
DARK RADIATION AND THE CLUSTER SOFT EXCESS

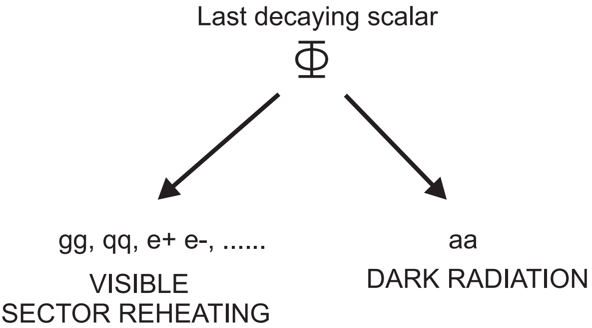
The Standard Cosmology

The Standard Cosmology:



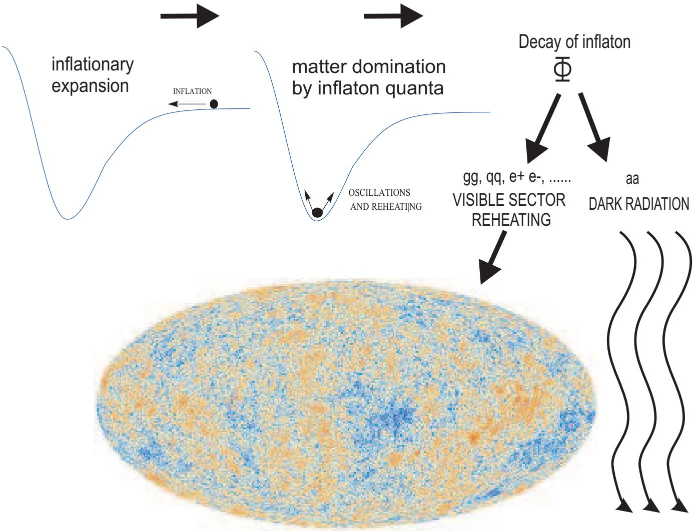
The Cosmological Moduli Opportunity

In any string model we expect reheating to be driven by the late-time decays of massive Planck-coupled particles.



Hidden sector decays of moduli give rise to dark radiation.

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.

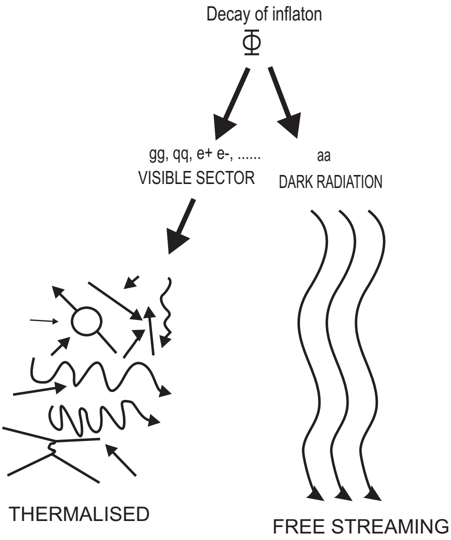
$$\begin{aligned} \text{Visible sector} &: \quad \frac{\Phi}{4M_P} F^{color}_{\mu\nu} F^{color,\mu\nu}, \; \frac{\partial_\mu \partial^\mu \Phi}{M_P} H_u H_d, \ldots \\ \text{Hidden sector} &: \quad \frac{\Phi}{2M_P} \partial_\mu a \partial^\mu a, \; \frac{\Phi}{4M_P} F^{hidden}_{\mu\nu} F^{hidden,\mu\nu}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

This is supported by explicit studies of string effective field theories

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

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

A Cosmic ALP Background



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

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

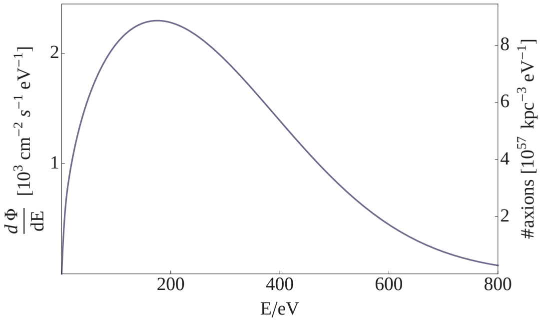
Retained through cosmic history!

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

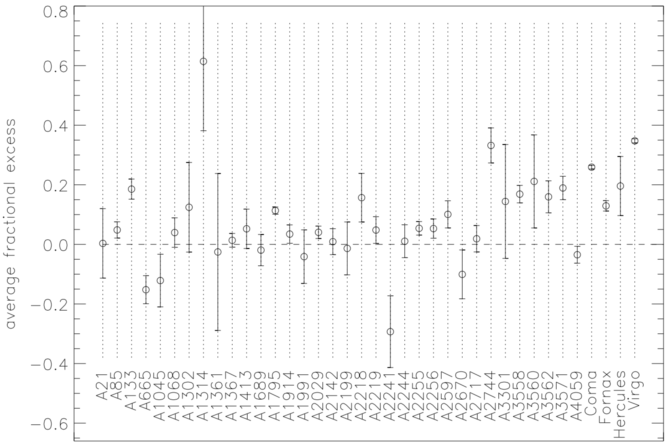
$$\mathcal{L}_{excess} \sim 10^{43} \text{erg s}^{-1}$$

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

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

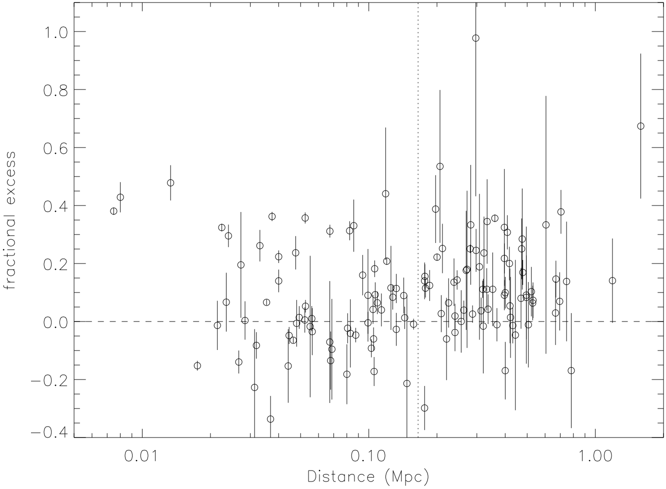
Difficulties with astrophysical explanations - see backup slides.

The Cluster Soft Excess



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

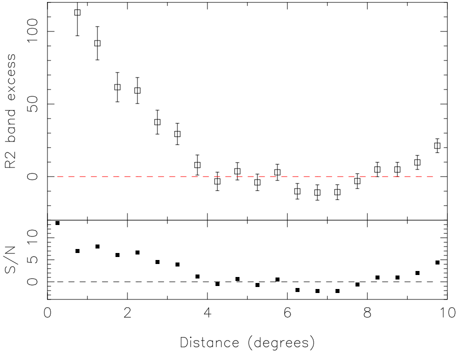
The Cluster Soft Excess



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 $a \to \gamma$ 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

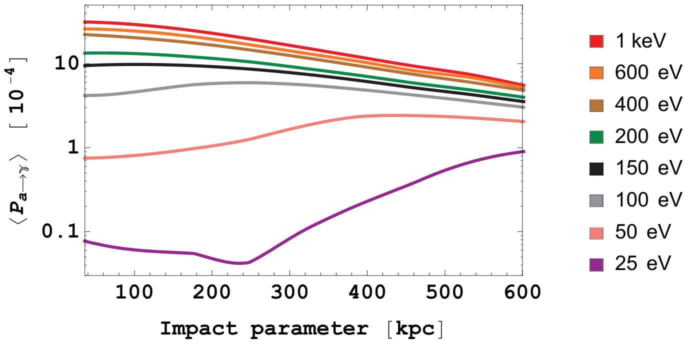
$$\mathcal{L}_{Mpc^3} = 3.6 \cdot 10^{41} \text{ erg Mpc}^{-3}\text{s}^{-1} \times$$
$$\times \left(\frac{\Delta N_{eff}}{0.57}\right) \left(\frac{B}{\sqrt{2}\ \mu\mathrm{G}} \frac{10^{13}\ \mathrm{GeV}}{M}\right)^2 \left(\frac{L}{1\ \mathrm{kpc}}\right),$$

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

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

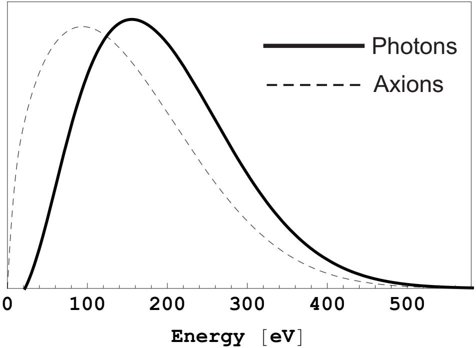


$a \to \gamma$ conversion probabilities for different ALP energies as a function of radius from the centre of Coma

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

Angus JC Marsh Powell Witkowski 1312.3947

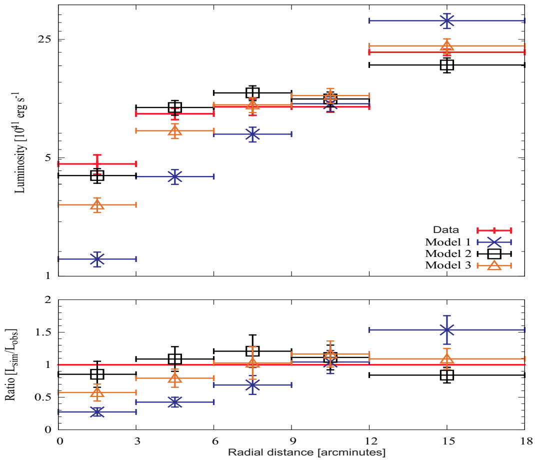
ALP Propagation through Centre of Coma



Comparison of original ALP spectrum and spectrum of converted photons

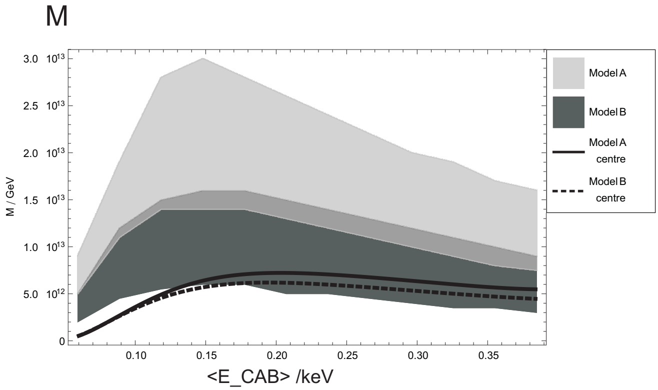
Photon spectrum falls off rapidly at both low and high energies

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



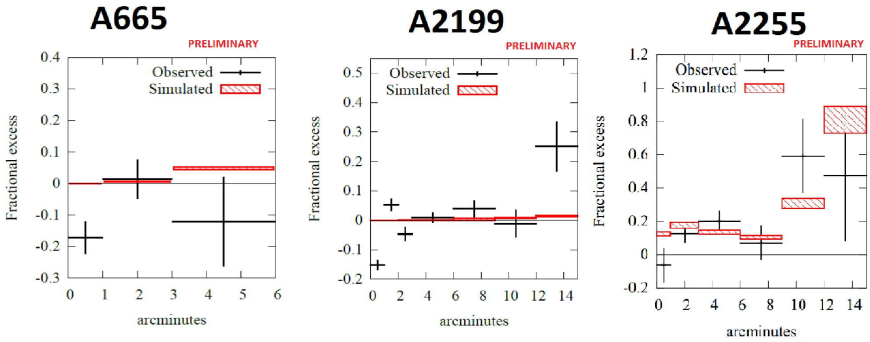
Fit to the outskirts gives a compatible value of $M \sim 10^{13}\mathrm{GeV}$.

Kraljic, Rummel, JC 1406.5188

ALP Propagation through Other Clusters

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

Powell, to appear



Conclusions

- Galaxy clusters are highly efficient converters of axion-like particles ($m \lesssim 10^{-12}\mathrm{eV}$) to photons - that nature has provided for free
- $a \to \gamma$ conversion probabilities are $\mathcal{O}(1)$ for $M \sim 10^{11}\mathrm{GeV}$, and primary ALP signals turn into an easily visible photon signal correlated with cluster magnetic field
- For the 3.5 keV line, the $\mathrm{DM} \to a \to \gamma$ scenario is a highly promising explanation
- String theory suggets a primordial cosmic ALP background at 0.1 - 1 keV, which can explain the long-standing cluster soft excess

BACKUP SLIDES

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 (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 $E \sim$ 2GeV, its synchrotron radio emission is above level of Coma radio halo.

   This necessitates a sharp spectral cutoff between $\sim$ 200MeV and $\sim$ 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

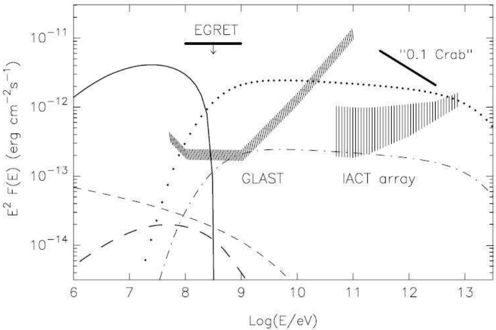


FIG. 6.—Expected γ-ray fluxes expected from the Coma Cluster. The

from Atoyan + Volk, 2000