Galaxy Clusters as tele-ALP-scopes

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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'

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'3.5 keV lines from ALP conversion in the Milky Way and M31'

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

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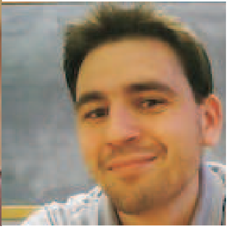
'ALP Conversion and the Soft X-Ray Excess in the Outskirts of the Coma Cluster'

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








I
AXION-LIKE PARTICLES

Moduli

How to connect string compactifications into observations?

It is difficult to single out any preferred extension of the Standard Model as there are so many different approaches to realising the Standard Model.

- Weakly coupled heterotic string
- Free fermionic models
- Rational CFT models (Gepner models)
- IIA intersecting D6 branes
- Branes at singularities
- M-theory on singular G2 manifolds
- IIB magnetised branes with fluxes
- F-theory
- ...

Moduli

These different approaches lead to various extensions of the Standard Model

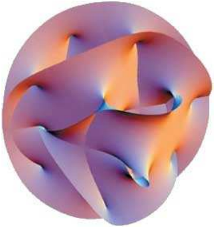
- Traditional SUSY grand unified theories
- Direct versions of the MSSM
- Non-supersymmetric Standard Models
- ...
- all with or without additional vector-like exotics or other gauge groups.

It is also very hard to match the precise couplings of the Standard Model - how would you ever know one approach was correct?

Moduli

How to connect string compactifications to observations?

Most useful to focus on the most generic features:

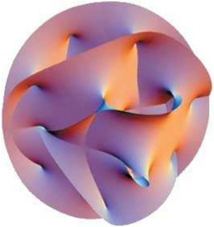


Closed string sector always present and involves modes (moduli or axions) always present in compactified string theory.

Much of the physics of moduli and axions is universal across compactifications.

Moduli

Moduli are the gravitationally coupled modes descending from deformations of extra-dimensional geometry.



These have universal origins (volume or dilaton modulus) and are present in all compactifications.

Unlike extensions of the Standard Model, their existence is not sensitive to the details of the geometry.

Axions

Axions also arise generically in string theory, by reduction of form fields on cycles.

For example, the axionic coupling $\theta F \wedge F$ easily arises from reduction of Chern-Simons action:

$$\int C_4 \wedge F \wedge F$$

on a 4-cycle.

An axion c_i arises from reduction of C_4 on a 4-cycle:

$$c_i = \int_{\Sigma_4} C_4$$

Nomenclature

An axion by any other name would smell as sweet....

1. Any particle with exact $\theta \to \theta + 2\pi$ shift symmetry

   traditional string theory usage

2. The QCD axion (and only that)

   First type of particles are 'axion-like particles'

   experimental/pheno axion community

3. A particle with no $\theta \to \theta + 2\pi$ shift symmetry, but that would have symmetry in absence of fluxes

   monodromy usage

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

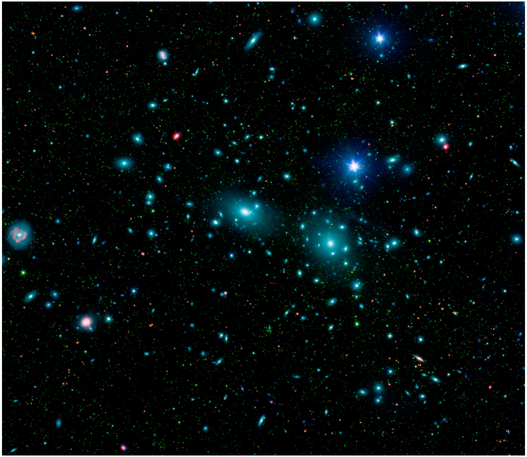
Galaxy Clusters

Galaxy Clusters

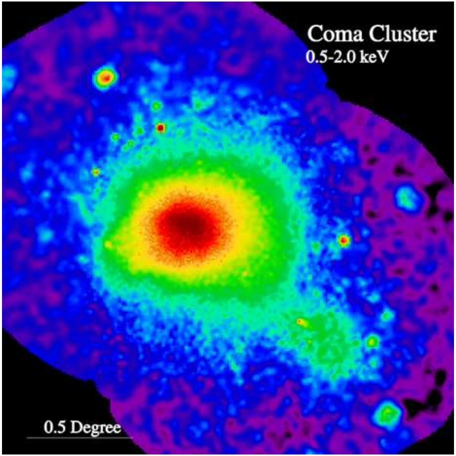
Galaxy clusters are:

- 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.

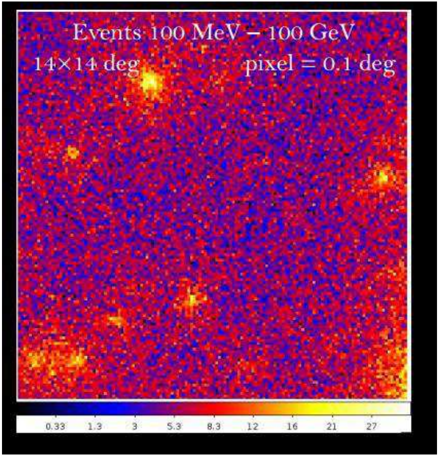
The Coma Cluster in IR/Visible



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 $L \sim 1 - 10\mathrm{kpc} \sim 10^{34}\mathrm{GeV}^{-1}$.

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 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):

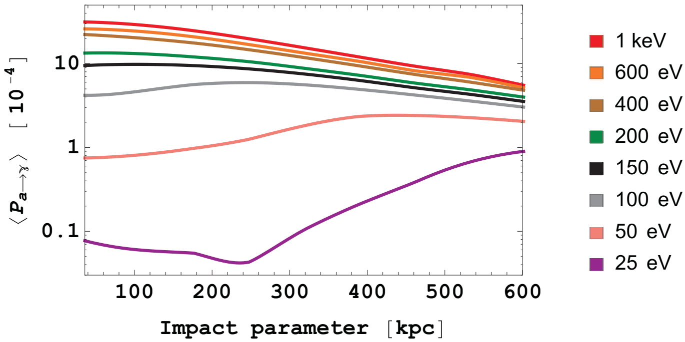
- Magnetic field has Kolmogorov spectrum, $|B(k)| \sim k^{-11/3}$, generated between $k_{max} = \frac{2\pi}{2\text{kpc}}$ and $k_{min} = \frac{2\pi}{34\text{kpc}}$.
- Spatial magnetic field has Gaussian statistics.
- Central magnetic field $\langle B \rangle_{r<291kpc} = 4.7\mu\text{G}$
- Equipartition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

ALP Propagation through Clusters

Three applications:

1. A Primordial Cosmic ALP Population and the Cluster Soft Excess

   no time...

2. The 3.5 keV Line

3. Improved bounds on ALP parameter space (1509.06748 JC Marsh Powell)

III
THE 3.5 KeV LINE

Dark Matter in X-rays?

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Jun 2014

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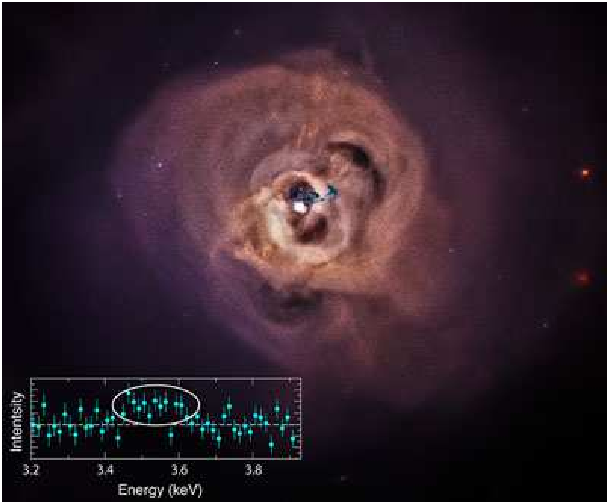
We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies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

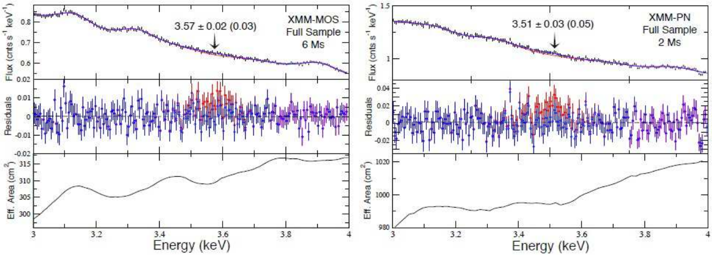
1402.2301, 1402.4119

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?

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)

Dark Matter in X-rays?

Subsequently:

- Suzaku data also show line in Perseus, no line in Coma, Virgo, Ophiuchus (1411.0050)
- Perseus line strongest in centre of the cluster (1411.0050)
- XMM-Newton line in Perseus concentrated in cool core, galactic centre morphology incompatible with dark matter (1411.1758)
- Reply to comment on comment on..... (1411.1759)

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 $\to a \to \gamma$

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.

DM $\rightarrow a \rightarrow \gamma$

Among clusters, Perseus is a nearby cool core cluster:

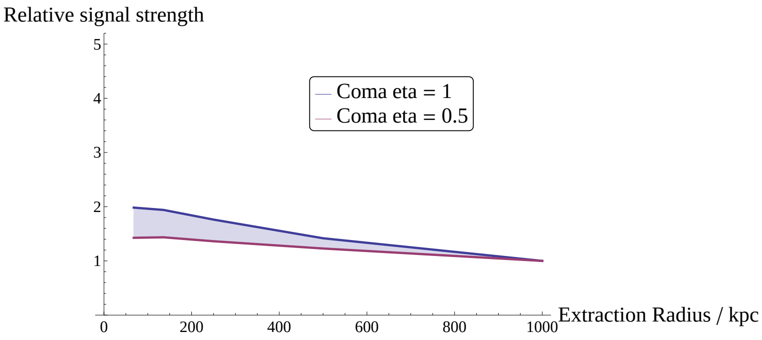
- Stronger magnetic field in the centre of the cluster
- Nearby cluster, so only central region of cluster fits in telescope field of view

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

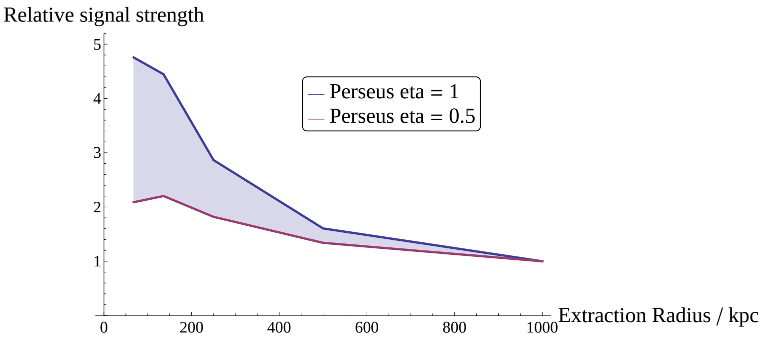
We can quantify differences between cool-core and non-cool-core clusters JC, Powell

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

The Future

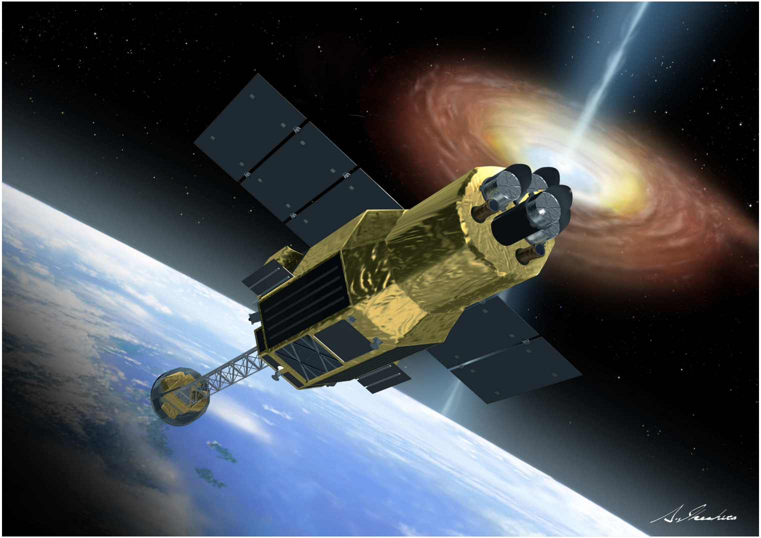
More X-ray data will appear in the relatively near future:

Boyarksy, Ruchayskiy: deep XMM-Newton observation (> 1 Ms) of Draco dwarf galaxy in progress

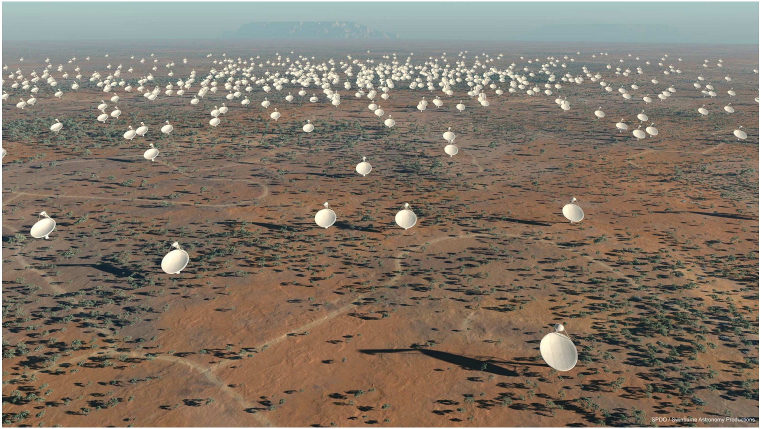
Bulbul et al: stacked archival Suzaku observations of galaxy clusters (in progress)

ASTRO-H flies January 2016 - will offer a decisive test of dark matter interpretation

ALPs and Galaxy Clusters: The Future



ALPs and Galaxy Clusters: The Future



ALPs and Galaxy Clusters: The Future

The future is bright:

- JAXA satellite Astro-H launches next year, offering unprecedented energy resolution ($\Delta E \sim 7\mathrm{eV}$ compared to $\Delta E \sim 100\mathrm{eV}$).
- The Square Kilometer Array will gradually come on line from 2020, ultimately providing tomographic magnetic field information for galaxy clusters
- ATHENA has been approved by ESA for L-class 2028 launch slot

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
- New X-ray satellite (ASTRO-H) in 1 year, vast increase in magnetic field data on decade timescale (SKA), means bright observational future