Searches for Dark Matter and Axion-Like Particles in Active Galactic Nuclei

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University of Aveiro, March 2017

Based on

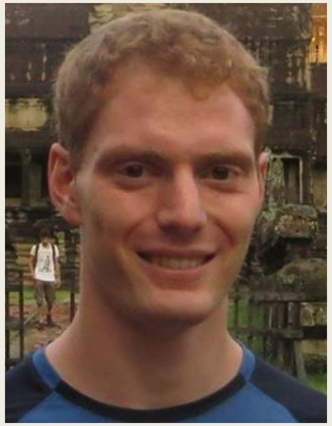
1605.01043

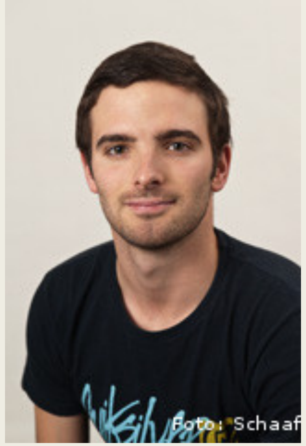
Marcus Berg, JC, Francesca Day, Nick Jennings, Sven Krippendorf, Markus Rummel

1608.01684

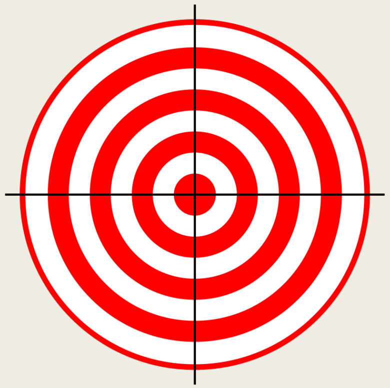
JC, Francesca Day, Nick Jennings, Sven Krippendorf, Markus Rummel







I. The Targets



Axion-like particles

- Light axion-like particles (ALPs) are one of the most motivated ways to extend the Standard Model
- They arise generically in string theory.
- Phenomenologically, they are parametrised by the coupling

$$a \, g_{a\gamma\gamma} \mathbf{E.B} \equiv \frac{\boldsymbol{a}}{\boldsymbol{M}} \mathbf{E.B}$$

- In the presence of a background **B** field, the ALP *a* and photon γ eigenstates mix, leading to photon-ALP oscillations (cf neutrino oscillations)

Axion-Like Particles in String Theory

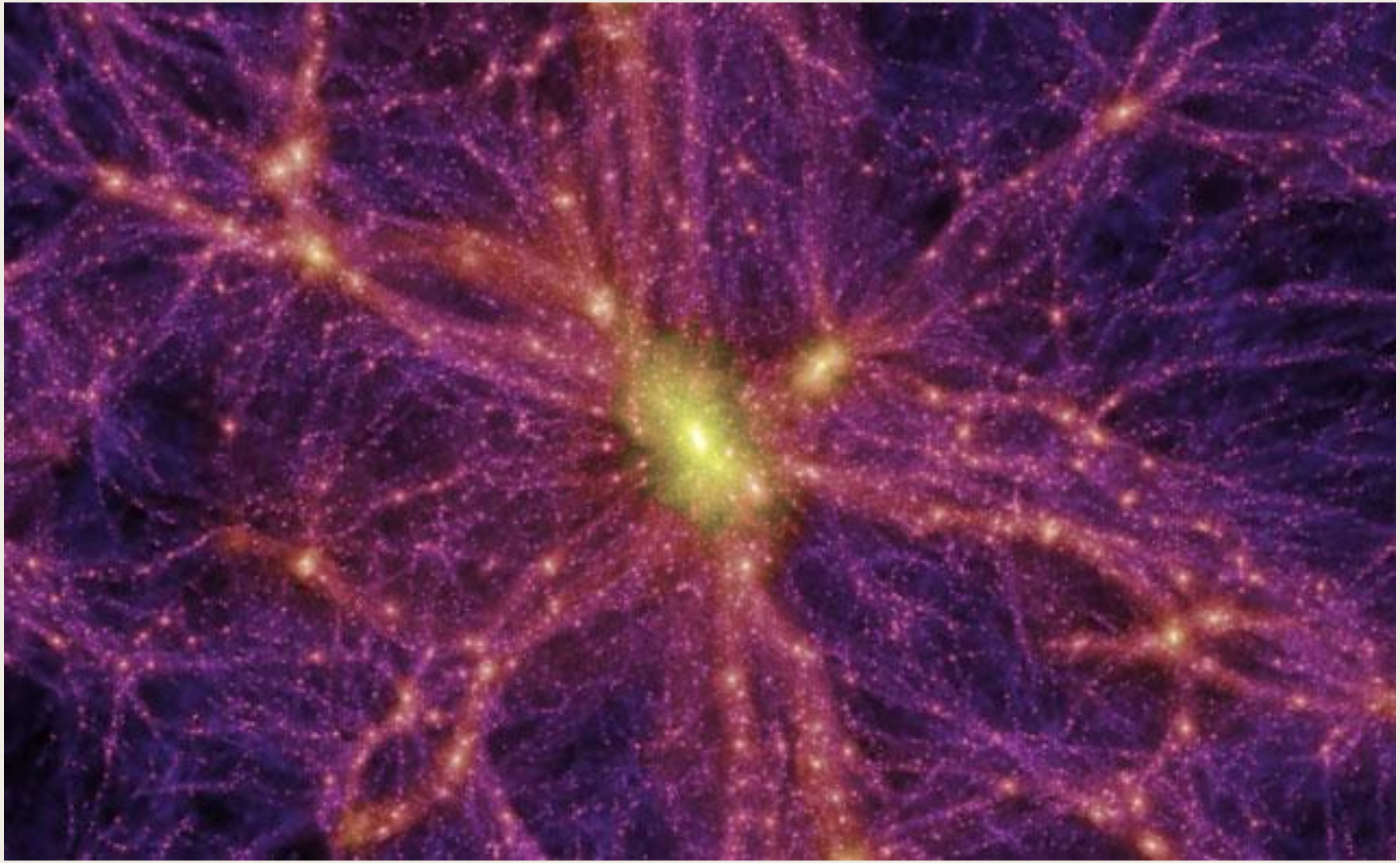
- 30-year old result:

  String compactifications lead to a plenitude of axions in the low-energy theory

- ’Model-dependent‘ axions number O(100) for typical compactifications

- Axion-like particles are one of the most motivated targets in looking for signatures of string compactifications

Dark Matter



Dark, unknown part of the energy budget of the universe

Constitutes approx 25% of total energy in the universe

II. The Methods

Two probes of fundamental physics

- I focus in this talk on two uses of the spectra of Active Galactic Nuclei to search for new physics residing in dark, weakly coupled hidden sectors

1. Searches for ALPs using spectral irregularities induced by ALP-photon mixing (original motivation for this work)

2. Search for dark matter absorption lines (secondary post-data motivation)

How to search for ALPs?

- The basic physics used here to look for ALPs is very simple.

  1. Send photons from A to B

  2. Have a magnetic field inbetween A and B

  3. Photon-ALP interconversion causes some of these photons to oscillate into ALPs

  4. The photon spectrum on arrival at B will show modulations compared to the source photon spectrum at A.

- In our case, the source A will be the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope

Originally Wouters + Brun 2013

AGN

Milli- parsec

NGC1275

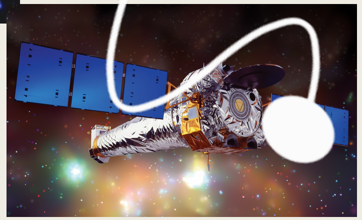
Hundred kilo-parsecs

Perseus cluster

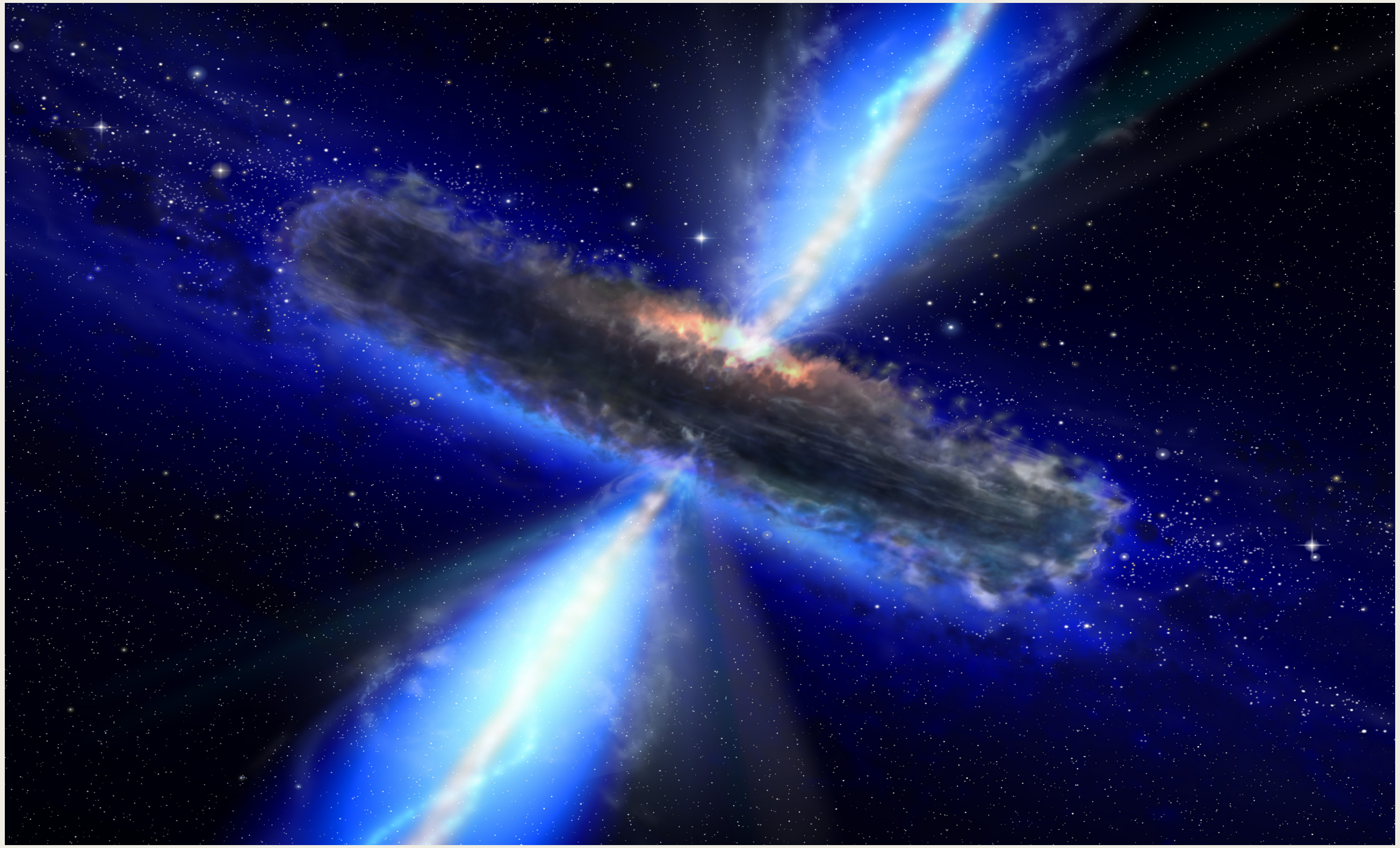
Megaparsecs

68 Mpc

Chandra



AGNs: the standard Unified Model



Credit ESA/NASA, AVO project, Paolo Padavani

AGNs are point sources

- X-ray emission from AGNs comes from extremely small physical region
- This follows from the time variability of AGN spectra: intensities fluctuate on hour to day timescales, implying emission originates from within a light-day
- Basic components to X-ray spectrum are

  1. Power-law

  2. Reflection spectrum (incident photons illuminate accretion disc, resulting in fluorescent emission) – in practice manifest as neutral Fe Kα line at 6.4 keV.

  3. Thermal soft excess (origin not entirely known)

AGNs are Unique Probes of Fundamental Physics

- Light comes from within a FEW SCHWARZSCHILD RADII of the central black hole – interesting physics
- Black holes are fundamental objects - cf superradiance
- Large number of photon counts – high statistics
- Photons experience an identical line of sight through the host galaxy and galaxy cluster – uniform effect
- They experience a dark matter column density larger than almost any other line of sight in the local universe – extreme conditions
- Sensitive to milli-parsec dark matter spikes near central Black Hole – unique sensitivity

NGC 1275

- NGC1275 is the central supergiant elliptical galaxy of the Perseus cluster
- It is located at a redshift of 0.0176 (68 Mpc distant)
- At its centre is a very bright AGN, powered by accretion onto the supermassive black hole.
- The AGN brightness is time-variable (1980 brightness was 20x bigger than in 2001, progressive increase in brightness since 2001)
- The AGN is unobscured, and shines to us through both NGC1275 and the Perseus cluster

AGN

Milli- parsec

NGC1275

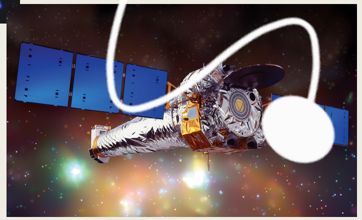
Hundred kilo-parsecs

Perseus cluster

Megaparsecs

68 Mpc

Chandra



The Perseus Cluster

- The Perseus galaxy cluster is the brightest X-ray galaxy cluster in the sky, and is located at a redshift of 0.0176
- It is a cool-core cluster centred around the Seyfert galaxy NGC1275 and its Active Galactic Nucleus.
- The Milky Way column density along the line of sight to Perseus is high, at $n_H = 1.5 \times 10^{21} cm^{-2}$ (implies significant absorption of soft X-rays).
- The Perseus cluster is the subject of enormous observation time with the *Chandra* X-ray telescope, totalling 1.5 Ms – gives over 500,000 photon counts from the central AGN

Optical image of Perseus, credit *R. Jay GaBany,* Cosmotography.com

Perseus in X-rays (NASA, Chandra)

X-ray image of the Perseus cluster: NGC1275 AGN is the central white dot

The AGN jets blow bubbles into the surrounding intra-cluster medium

Photon-ALP Conversion

- The fundamental ALP-photon coupling is

$$a\, g_{a\gamma\gamma}\mathbf{E.B} \equiv \frac{\boldsymbol{a}}{\boldsymbol{M}}\mathbf{E.B}$$

- In a magnetic field, this gives a 2-particle interaction between the ALP and the photon
- The ALP and photon eigenstates mix – the 'mass' eigenstates are no longer the same as the 'flavour' eigenstates (a and γ)
- Propagating through the magnetic field, photon eigenstates oscillate into ALP eigenstates

Photon-ALP Conversion

- Source is NGC1275, destination is earth: intervening magnetic field is magnetic field of the Perseus cluster.
- Galaxy clusters are particularly good locations for photon-ALP interconversion
- Magnetic fields extend over approx. 1 Mpc regions, with coherence lengths in 1- 10kpc region.
- Magnetic field strengths are 1 – 10 microGauss.
- Photon-ALP couplings $g_{a\gamma\gamma}$ of 10^{-12} to 10^{-11} GeV^{-1} generate conversion probabilities of order 10 – 50%.
- No exact knowledge of Perseus magnetic field; central value should be in range 10 – 25 microGauss.

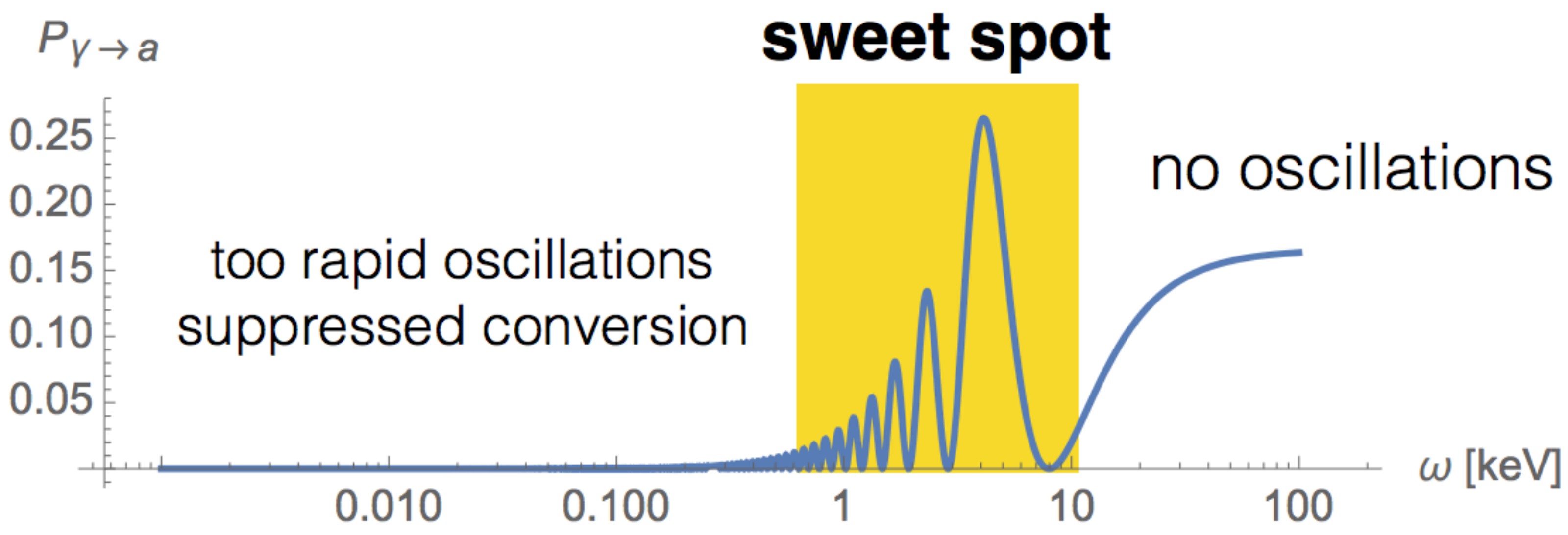
Photon-ALP Conversion – why X-rays?

- Axion-photon interconversion (for $m_a<10^{-12}$eV, effectively massless) in galaxy clusters:

$$P_{\gamma\to a} = \frac{1}{2}\frac{\Theta^2}{1+\Theta^2}\sin^2\left(\Delta\sqrt{1+\Theta^2}\right)$$

$$\Theta = 0.28\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\mathrm{keV}}{\omega}\right)$$

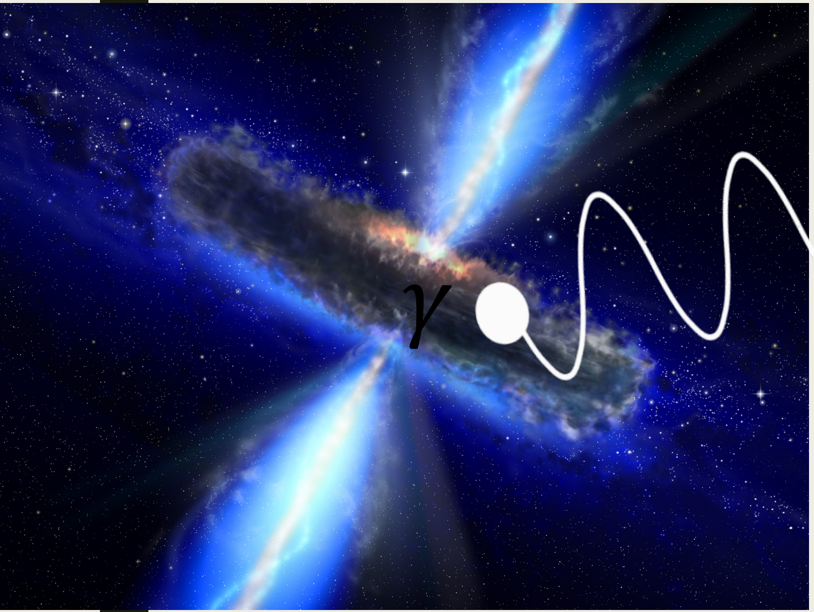
- Sweet spot at X-ray energies:

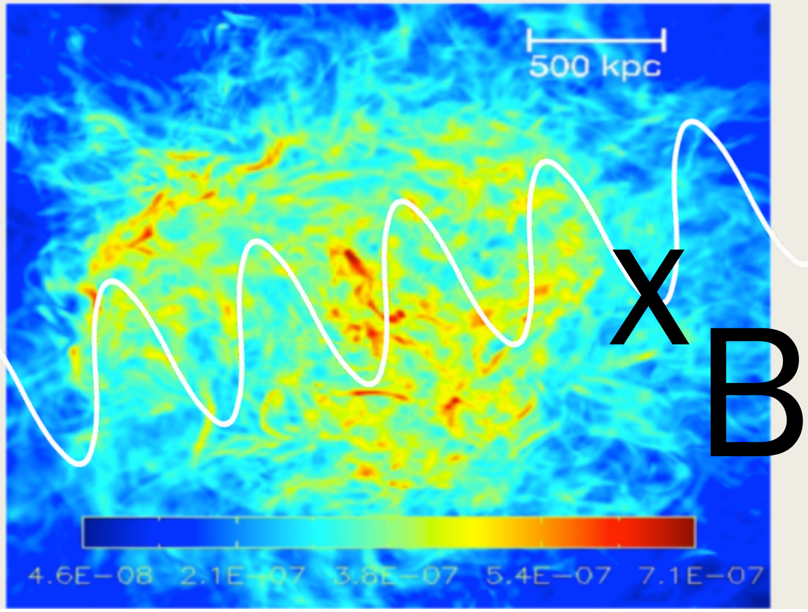


ALPS

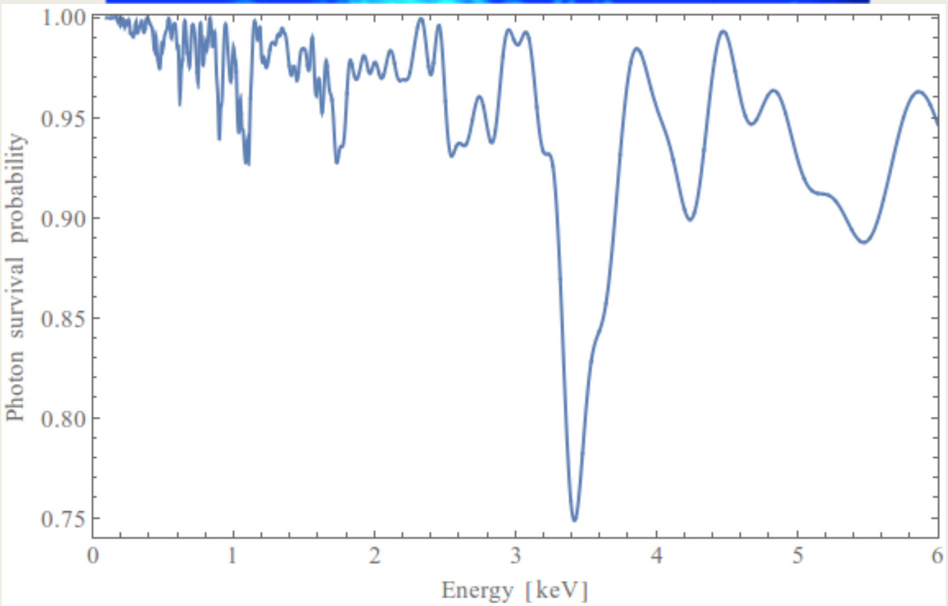
Photons pass through galaxy cluster magnetic field

AGNs are bright point sources of photons



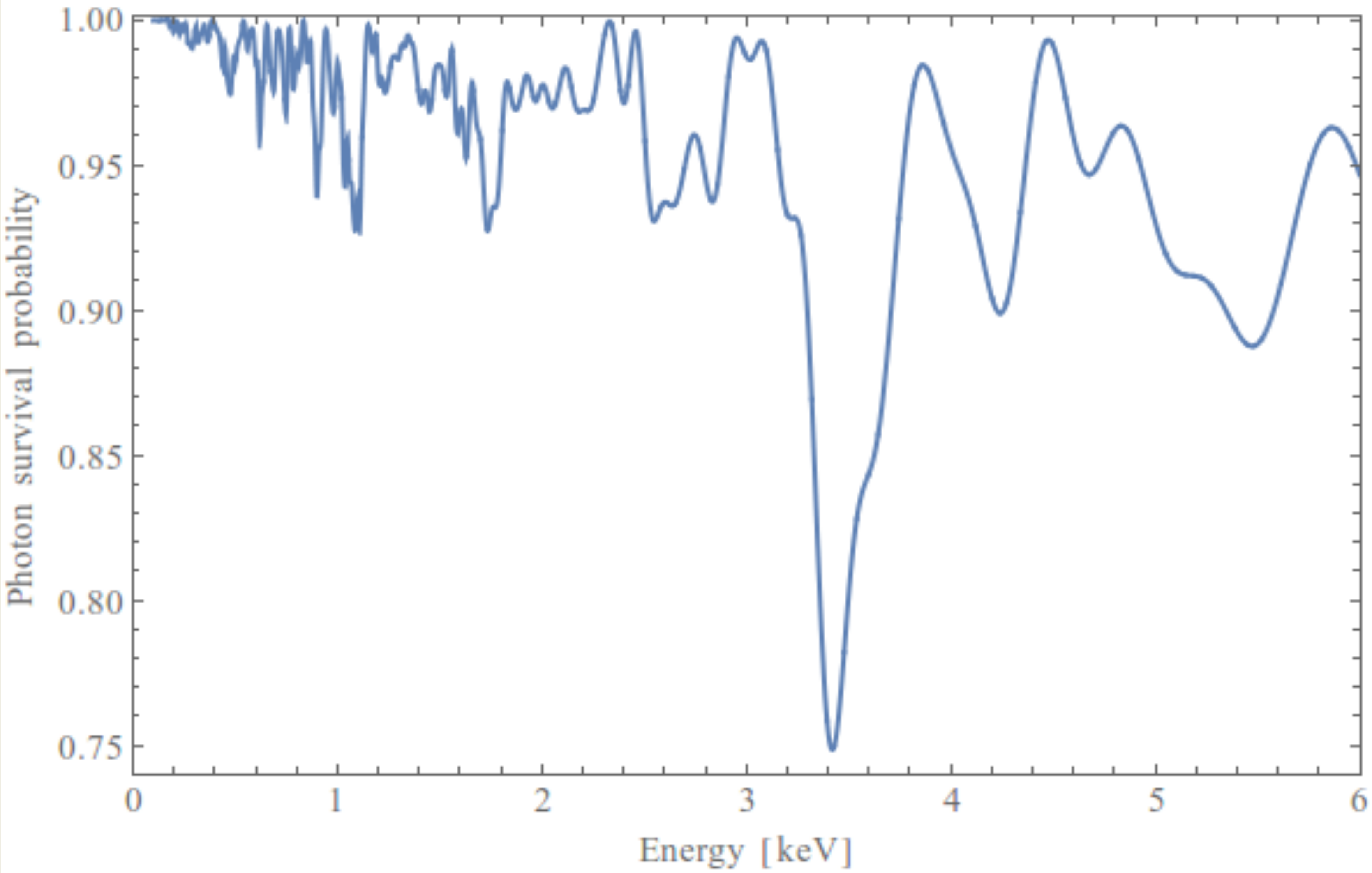


ALP-Photon conversion induces irregularities in observed X-ray spectrum



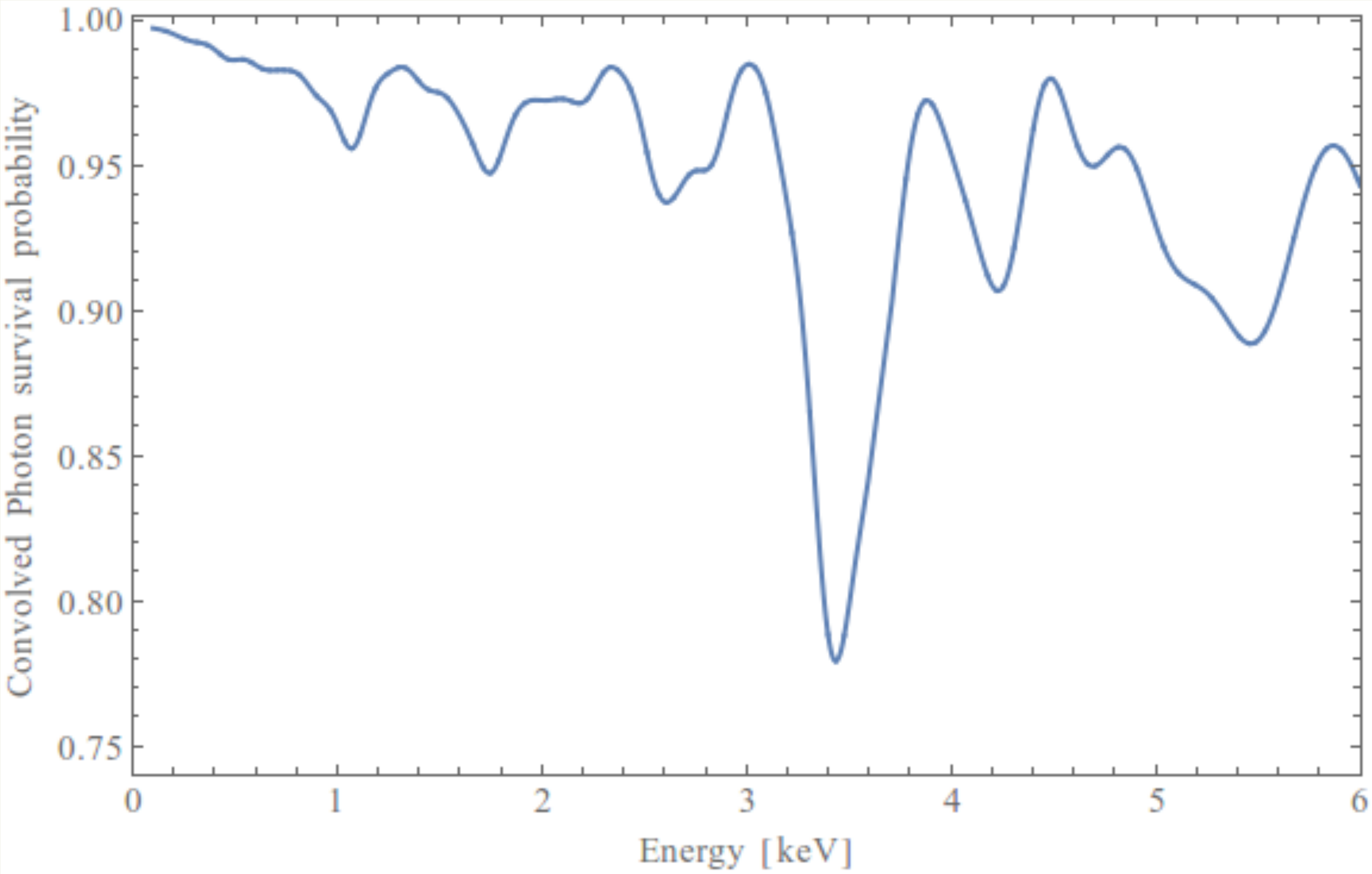
Precise form of modulations depends on cluster magnetic field

Simulated photon survival probability…



This would modulate the true spectrum

…now convolved with detector resolution



This would modulate the true spectrum

III. The Results

A. ALP Searches

Chandra X-ray telescope

~1.5 billion USD

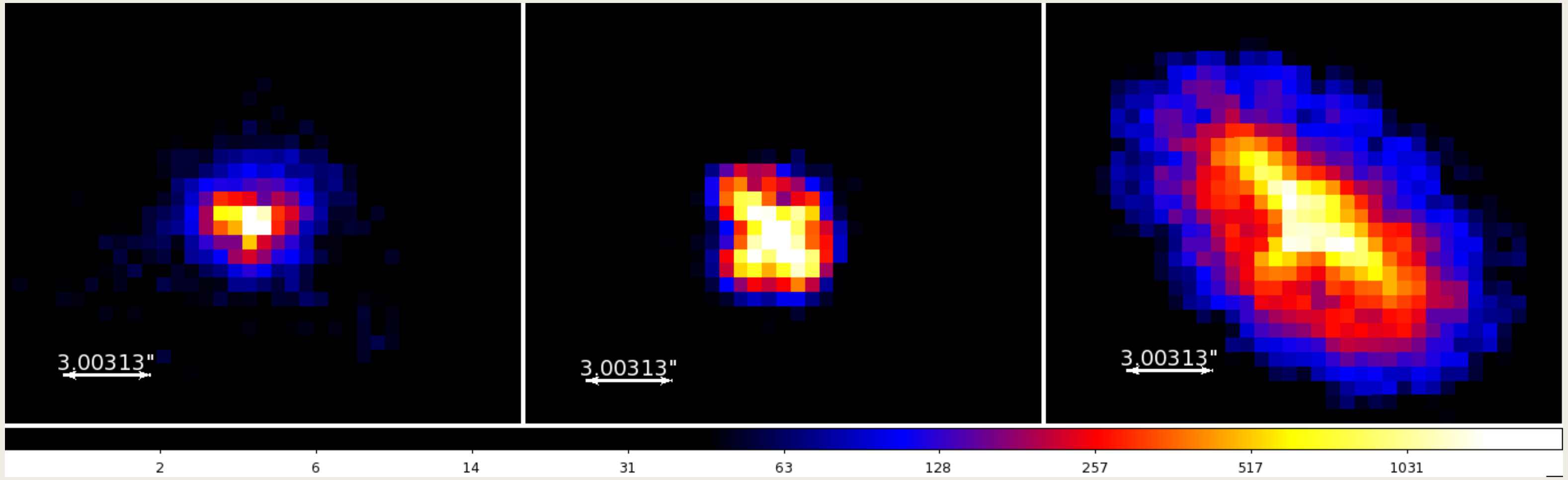
15 years operation

Mature, well understood instrument

Large public observational data archive

The Observations

- NGC1275 observed by *Chandra* in 2002 and 2004 for 1Ms with ACIS-S and 0.5 Ms in 2009 with ACIS-I.
- In ACIS-S observations, NGC1275 is on-axis, in 2009 observations 300ks with NGC1275 around 4 arcmin off-axis and 200ks with NGC1275 around 8 arcmin off-axis.
- Treat these three sets separately, focus on last case.
- *Chandra* on-axis point spread function is around 0.5 arcsec diameter on-axis, broadening to around 10 arcsec diameter when source is around 8 arcmin off-axis.



The Observations

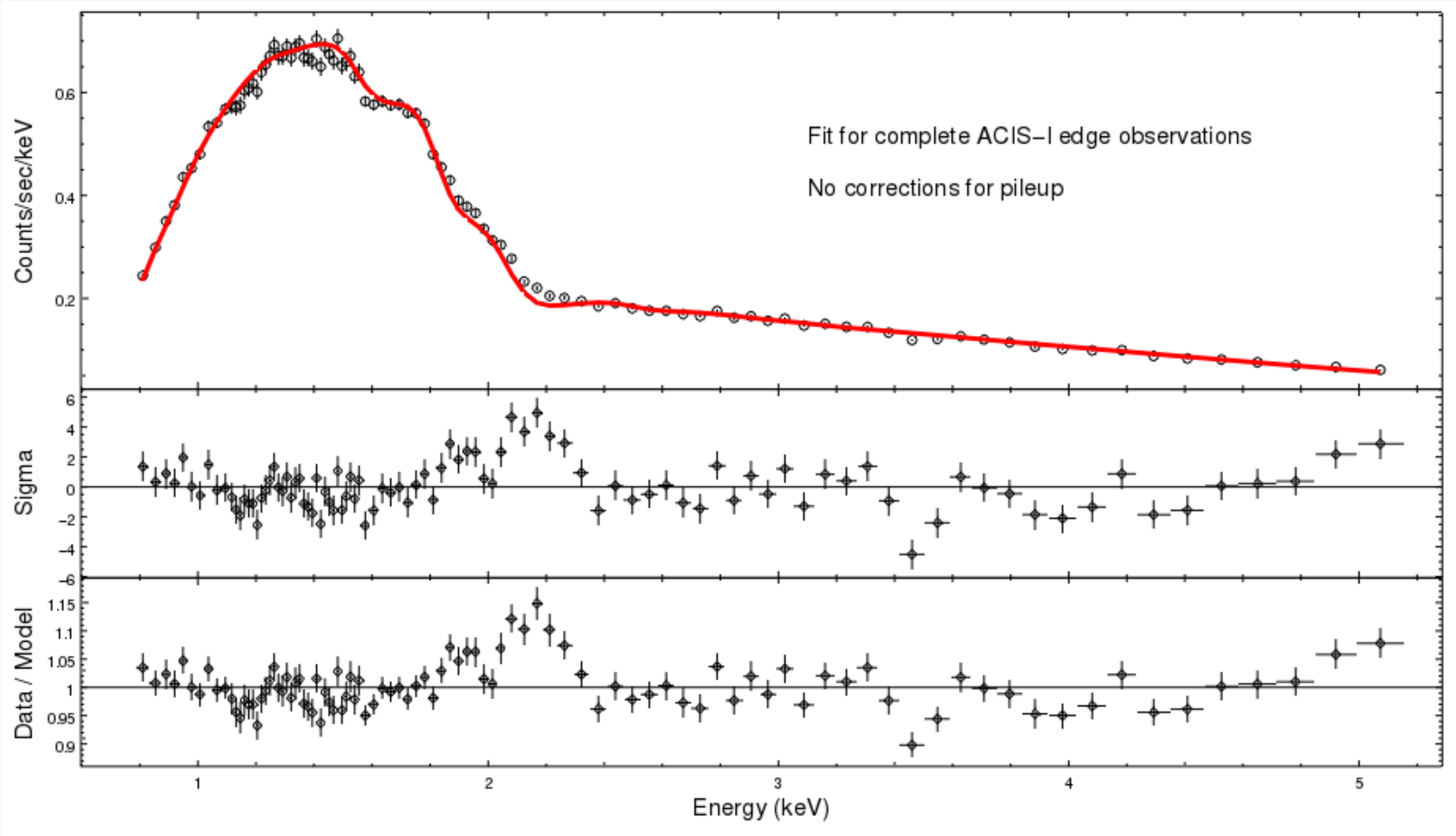
- We extract the AGN spectrum and subtract nearby cluster emission for background.
- We fit the AGN spectrum between 0.8 and 5 keV with an absorbed power law
- We examine these spectra and look for residuals
- Counts are grouped so that there are approximately one hundred bins in total
- Total counts from AGN is

1. 230000 for 2009 ACIS-I ‘edge’ observations (cleanest dataset) FOCUS ON THIS!

2. 242000 for 2009 ACIS-I ‘midway’ observations – heavy pileup contamination

3. 183000 for 2002-4 ACIS-S on-axis observations – heavy pileup contamination

Complete extraction for ACIS-I edge



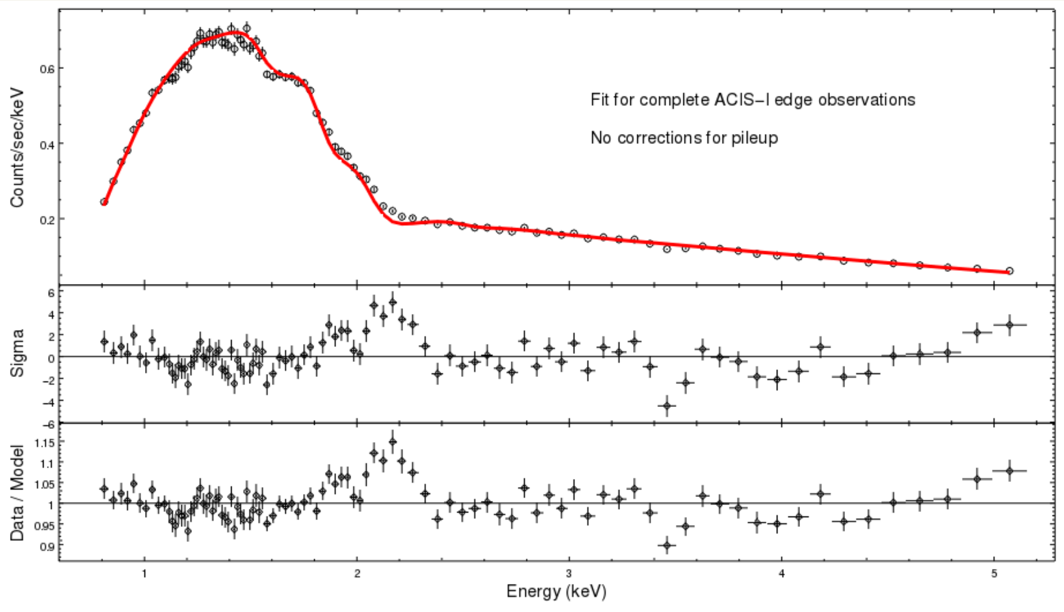
Fit to absorbed power law gives two main features – excess at 2 – 2.2 keV, deficit at 3.4 – 3.5 keV

Features in ACIS-I Edge Data

Two main features:

1. Excess at 2 – 2.2 keV

Subtle because of effective area dip at these energies



Possible to generate fake excesses via energy mismeasurement

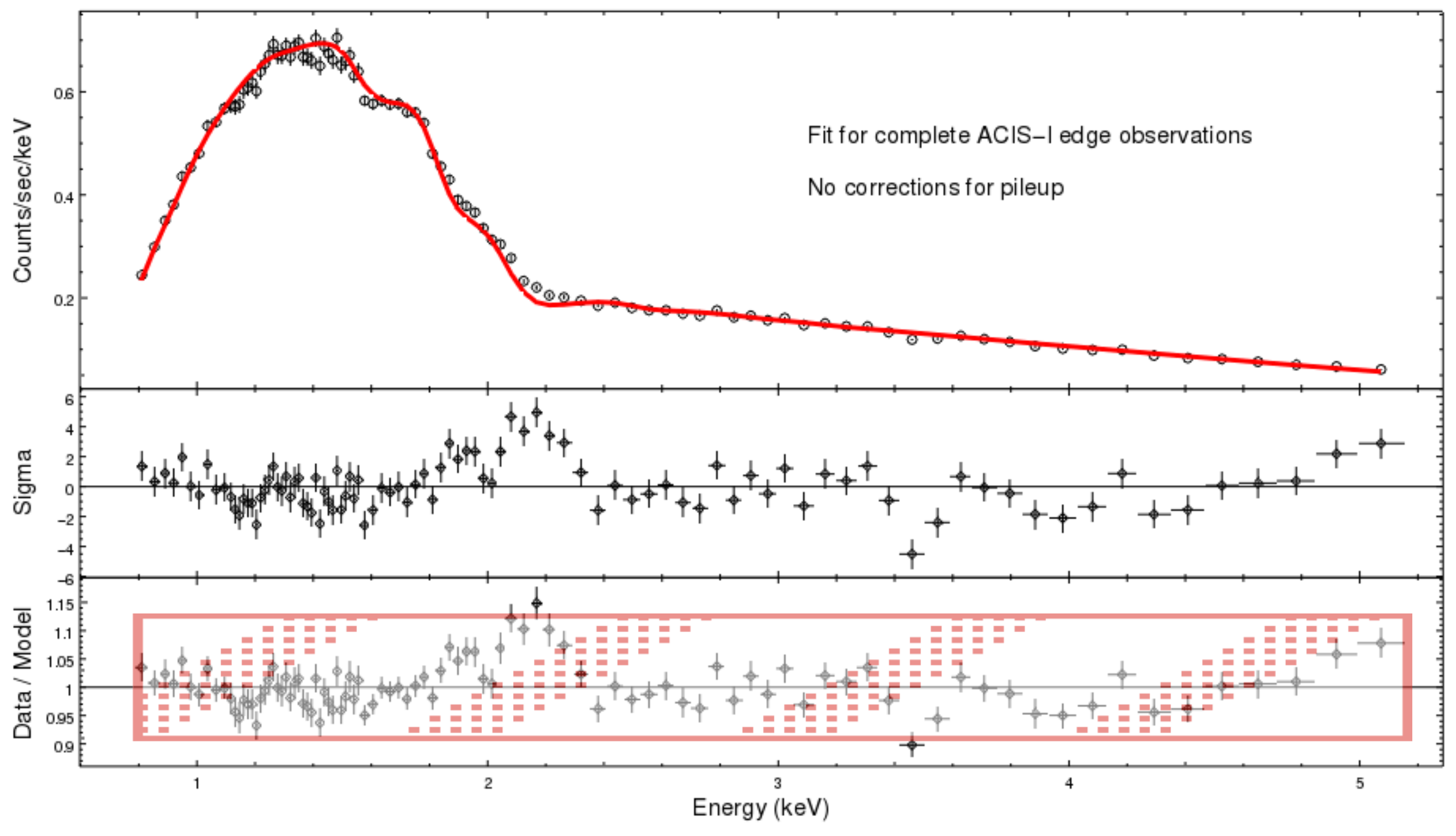
2. Deficit at 3.4 – 3.5 keV

No obvious systematic effects - will discuss in detail below!

ALP Constraints

Unambiguous statement – there are no spectral irregularities greater than 10%

ALP couplings leading to 20-30% irregularities are excluded



ALP Constraints

Exact Perseus magnetic field along line of sight is unknown. We consider three magnetic field cases:

1. B_central = 25 μG, 100 domains between 3.5 and 10kpc (reasonable)
2. B_central = 15 μG, 100 domains between 0.7 and 10kpc (conservative)
3. B_central = 10 μG , 100 domains between 0.7 and 10kpc (ultra-conservative)

We generate simulated magnetic fields, compute the photon-ALP conversion probability and generate spectra corresponding to them.

We say $g_{a\gamma\gamma}$ is ruled out at 95% confidence if 95% of simulated spectra have worse chi-squared fits to an absorbed power-law than the actual data does.

ALP Constraints

1. Reasonable case (B_central = 25 μG, 100 domains between 3.5 and 10kpc)

   $g_{a\gamma\gamma}$ < 1.5 x 10^{-12} GeV^{-1}

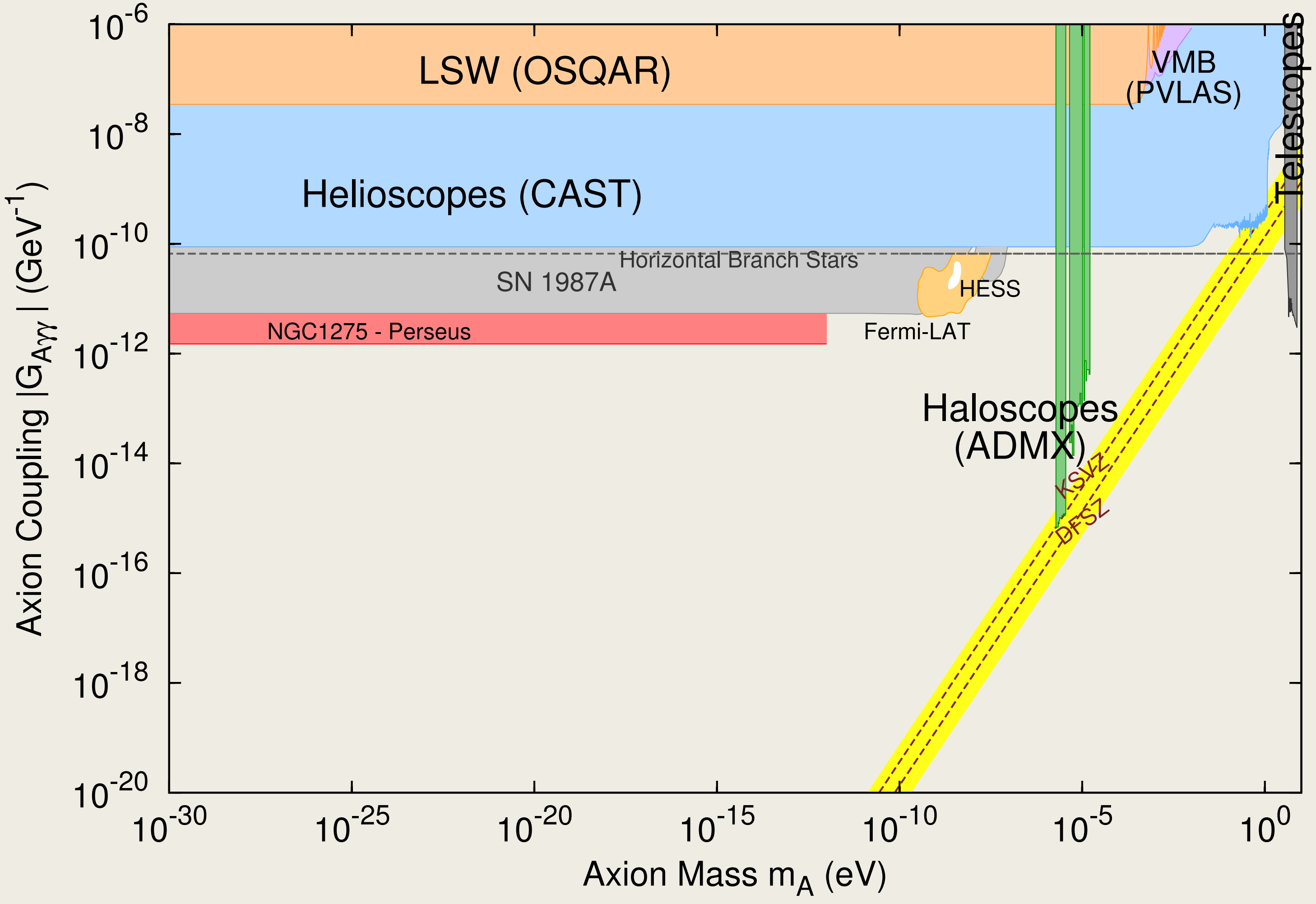
2. Conservative case: (B_central = 15 μG, 100 domains between 0.7 and 10kpc)

   $g_{a\gamma\gamma}$ < 3.8 x 10^{-12} GeV^{-1}

3. Ultra-conservative: (B_central = 10 μG , 100 domains between 0.7 and 10kpc)

   $g_{a\gamma\gamma}$ < 5.6 x 10^{-12} GeV^{-1}

Absence of any spectral modulations at 20-30% level gives leading bounds on ALP-photon coupling at small mass



Bounds would be stronger still if we knew that either

2 - 2.2 keV feature

or

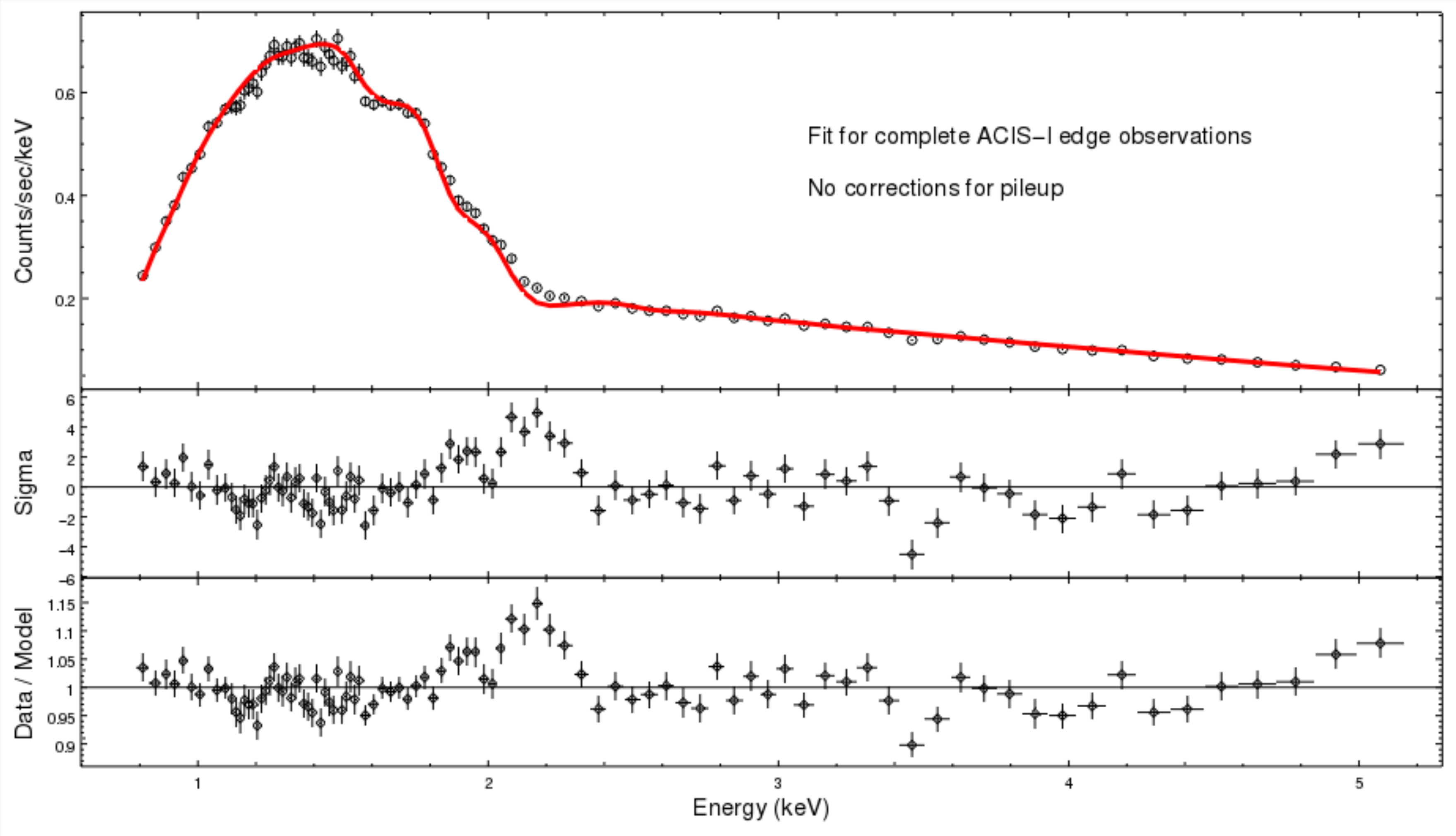
3.4 – 3.5 feature

were definitely not real……

III. The Results

B. Dark Matter and the 3.5 keV Line

Complete extraction for ACIS-I edge



Two main features – excess at 2 – 2.2 keV, deficit at 3.4 – 3.5 keV

Look at 3.4 – 3.5 keV feature more closely…

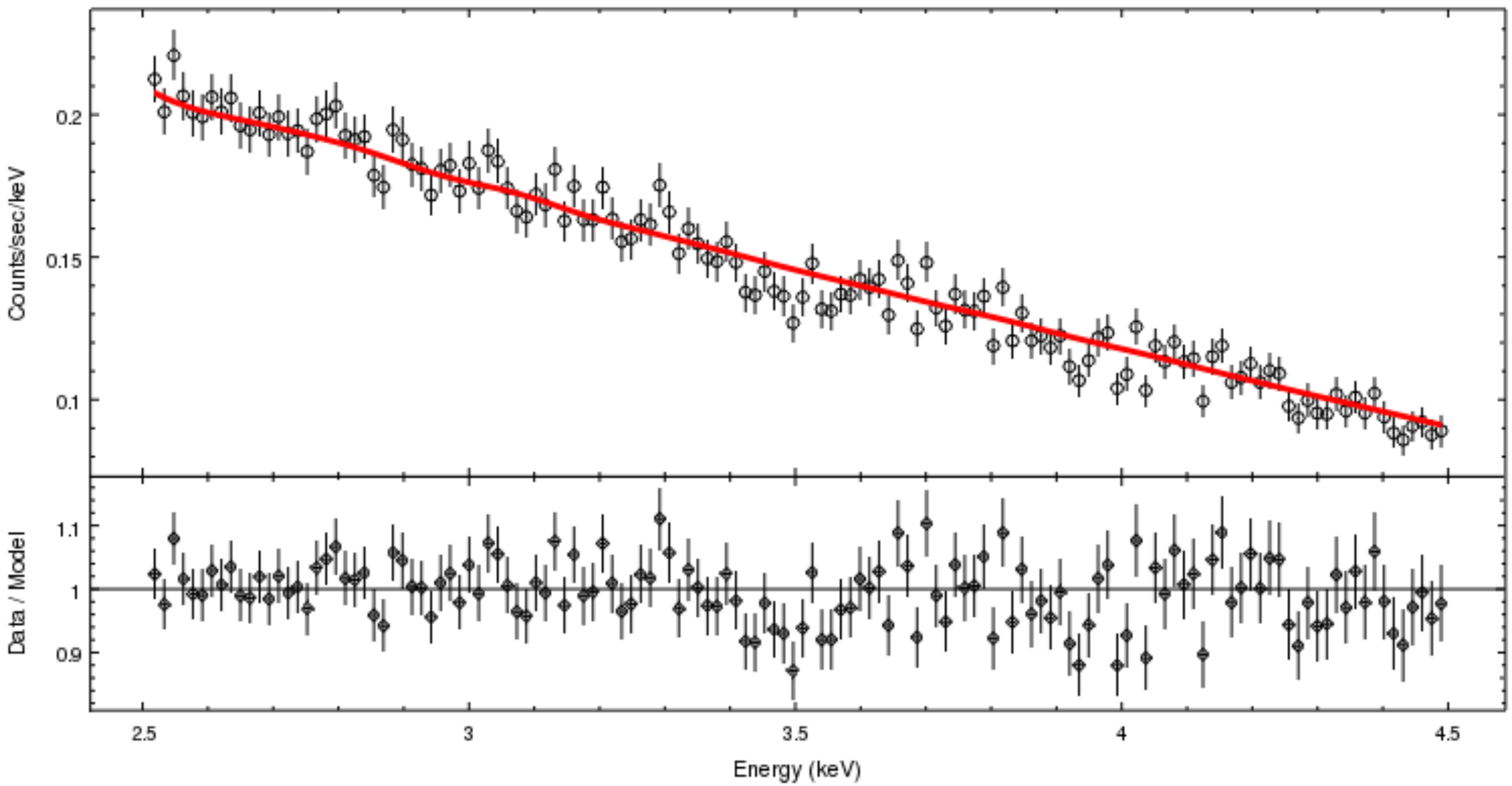
We fit from 0.8 to 5 keV and cut out 1.8 – 2.3 keV region to avoid biasing the fit.

Fit with xswabs * (xspowerlw + xsbapec)

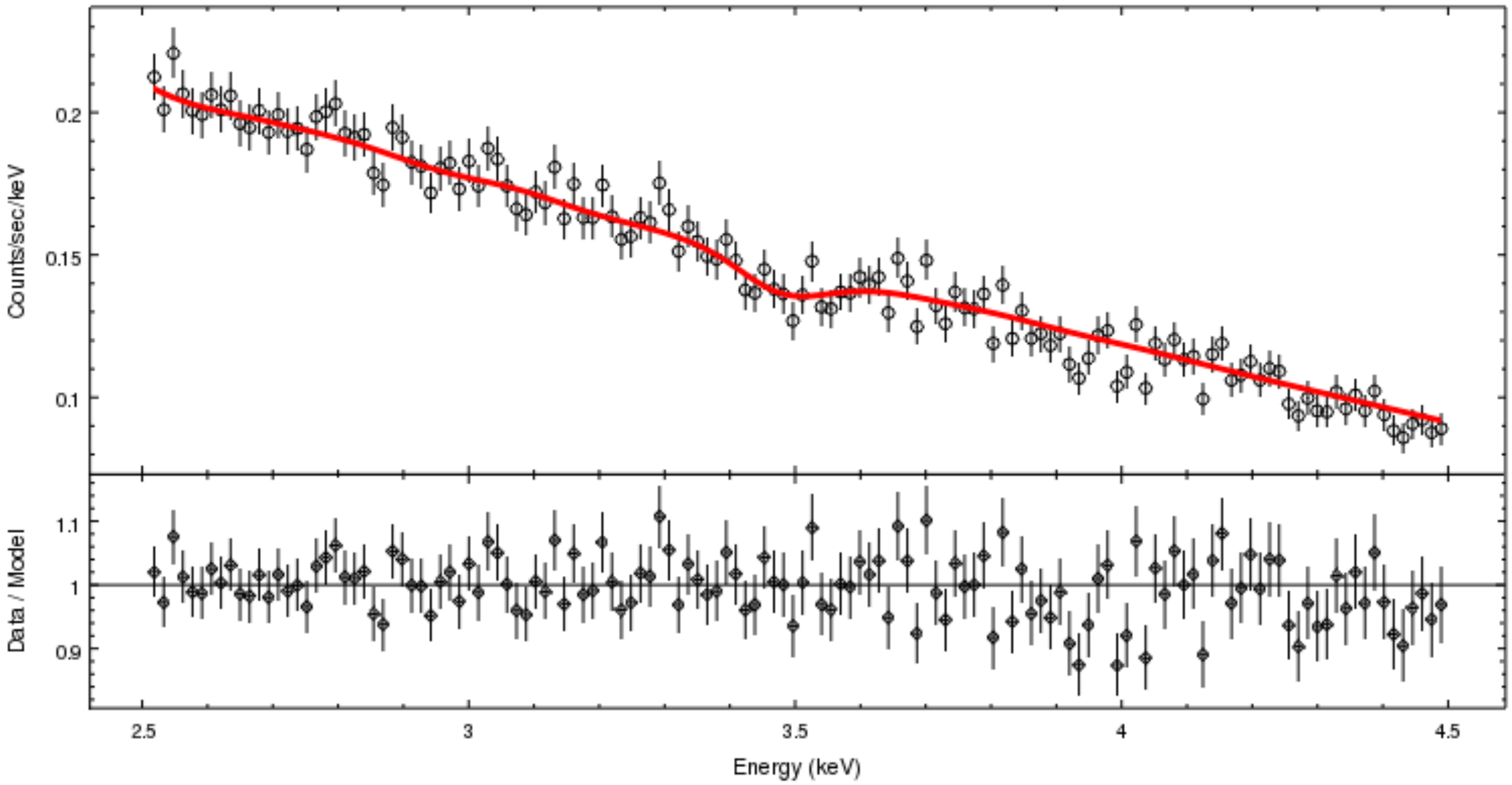
i.e. Absorption * (power law + thermal cluster emission)

Use thermal emission cluster parameters determined by Hitomi

For convenience, only show fit from 2.5 – 4.5 keV



Good fit – chi squared of 273/250 dof – with dip clearly visible at 3.5 keV



Now include a negative Gaussian……$\Delta\chi^2 = 20.0$ for 2 dof

Over 4 sigma preference for dip/absorption at (3.54 +- 0.02) keV! (cluster frame)

The 3.5 KeV Line….

Exactly the same energy as the 3.5 keV line excess….

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

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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

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

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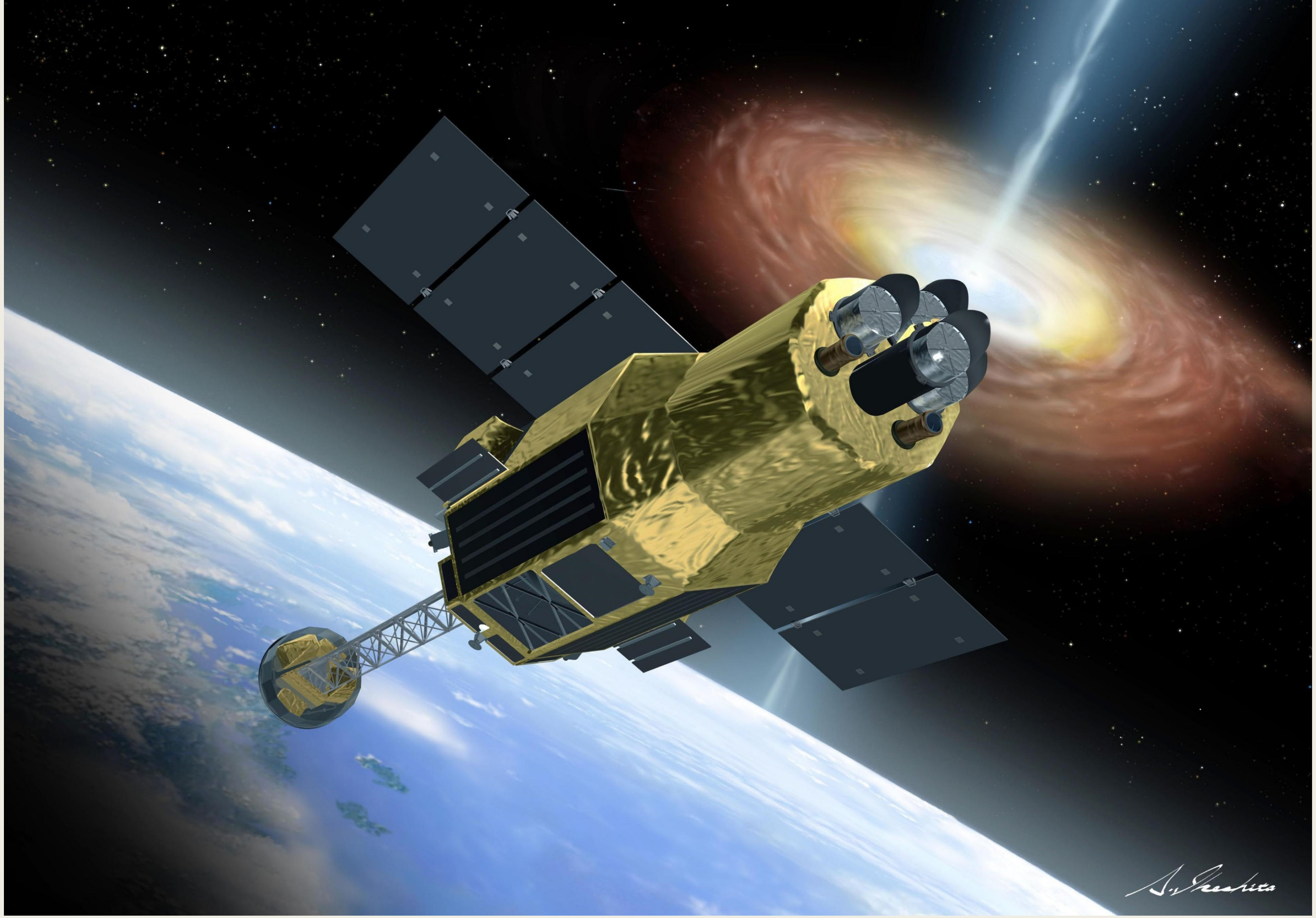
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We report a weak line at 3.52 ± 0.02 keV in X-ray spectra of M31 galaxy and the Perseus galaxy cluster observed by MOS and PN cameras of XMM-Newton telescope. This line is not known as an atomic line in the



3.5keV line was expected to be resolved by Hitomi.....

Launch of Hitomi from Tanegashima Space Centre

17th February 2016

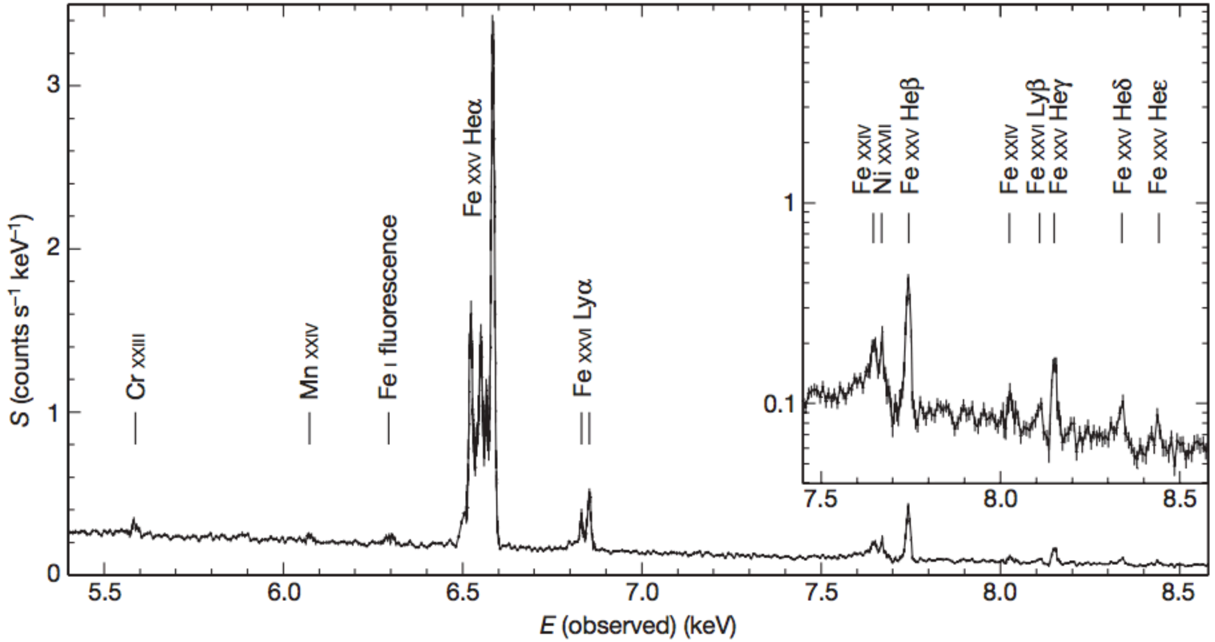
LETTER

doi:10.1038/nature18627

The quiescent intracluster medium in the core of the Perseus cluster

The Hitomi collaboration*

Clusters of galaxies are the most massive gravitat objects in the Universe and are still forming. They are

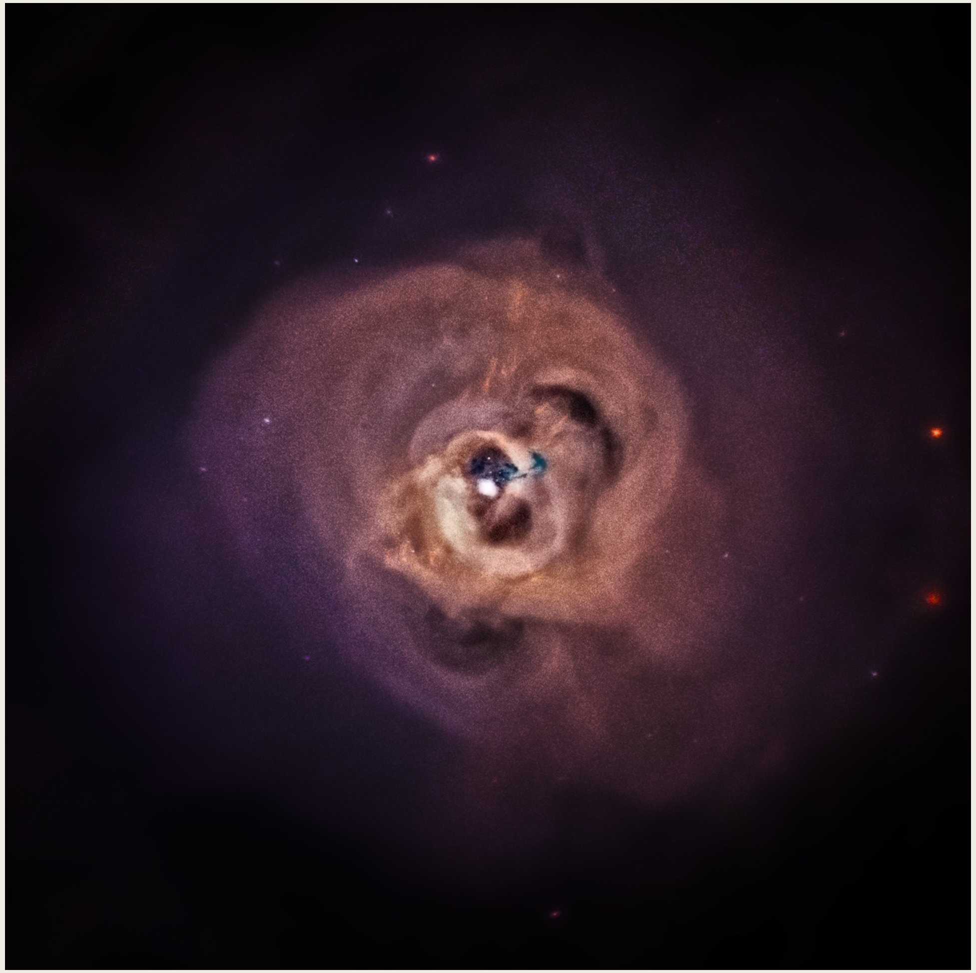


Hitomi returned a ground-breaking spectrum of Perseus before its tragic loss in March 2016

Energy resolution around 5eV, 20x better than Chandra or XMM!

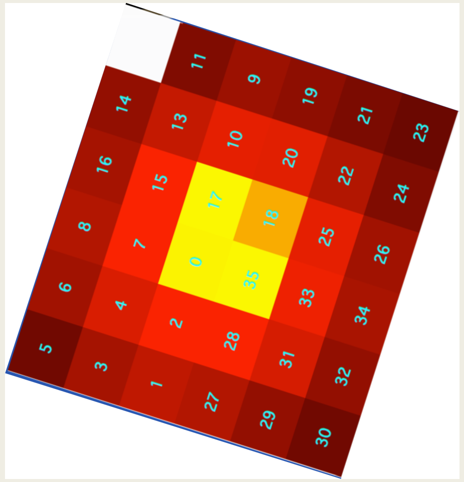
Images of the centre of Perseus

CHANDRA



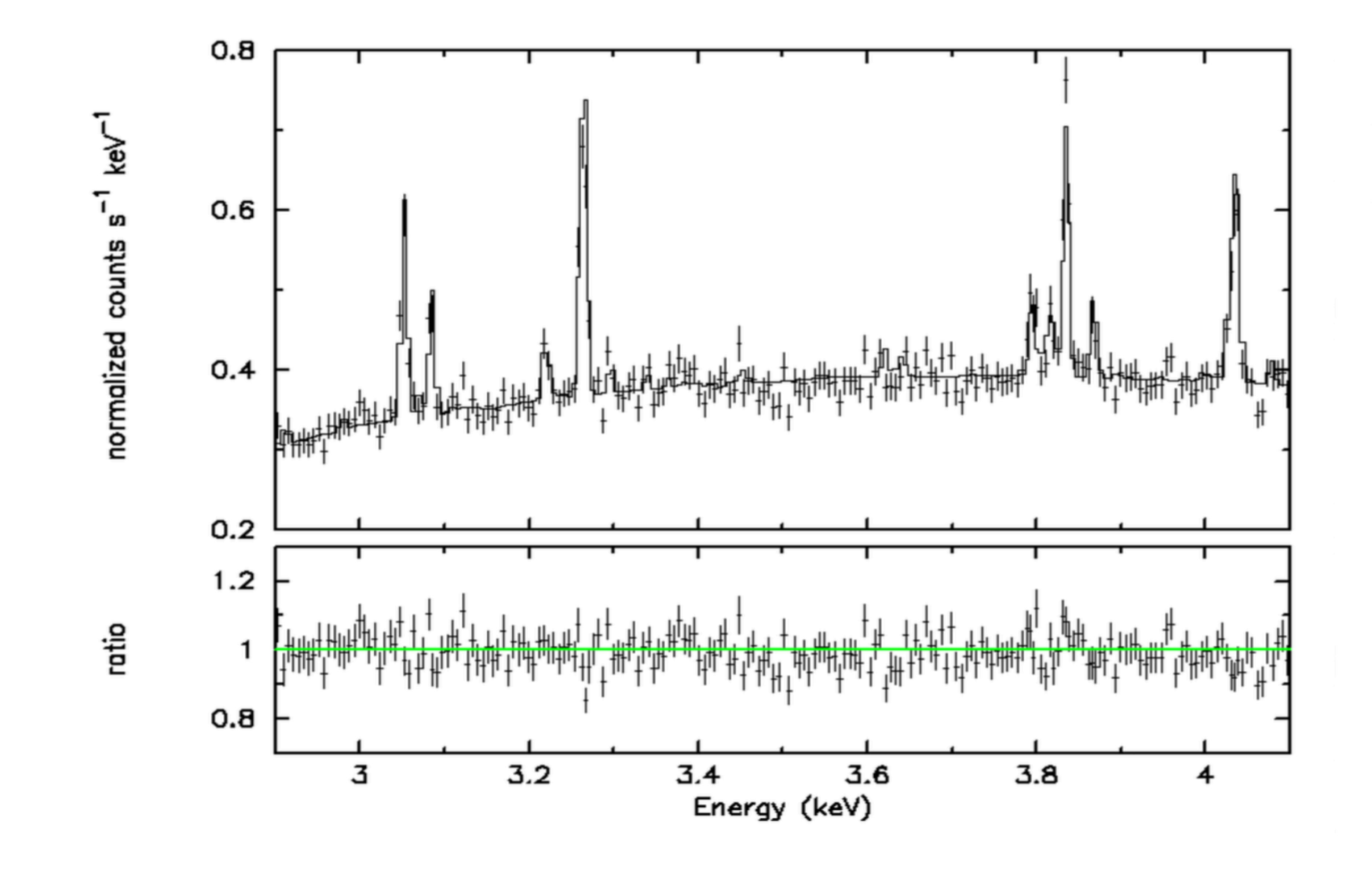
Best angular resolution

HITOMI



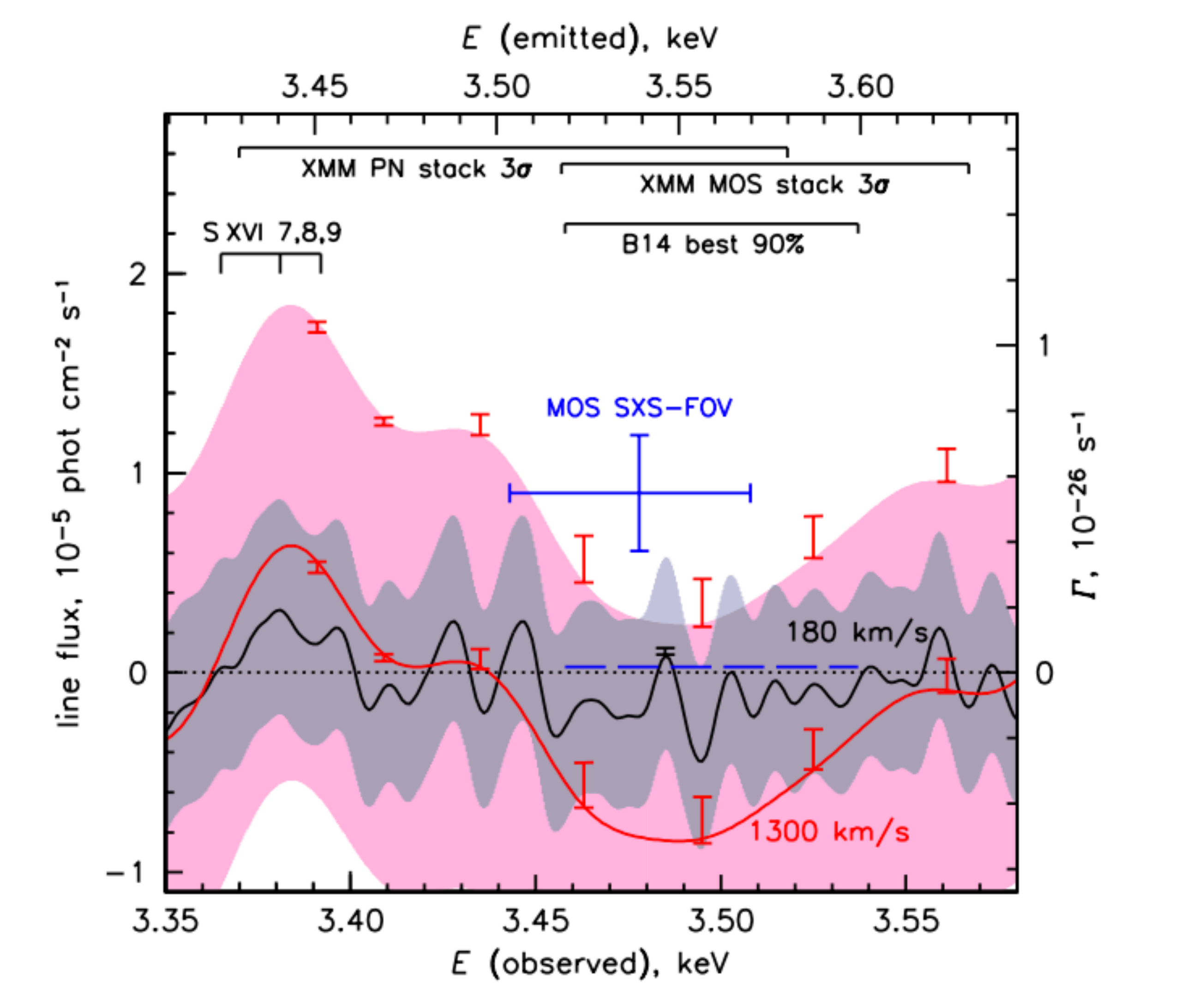
Best energy resolution

Hitomi Spectrum of Perseus Cluster



But look closely near 3.5 keV.....

Hitomi best-fit line properties



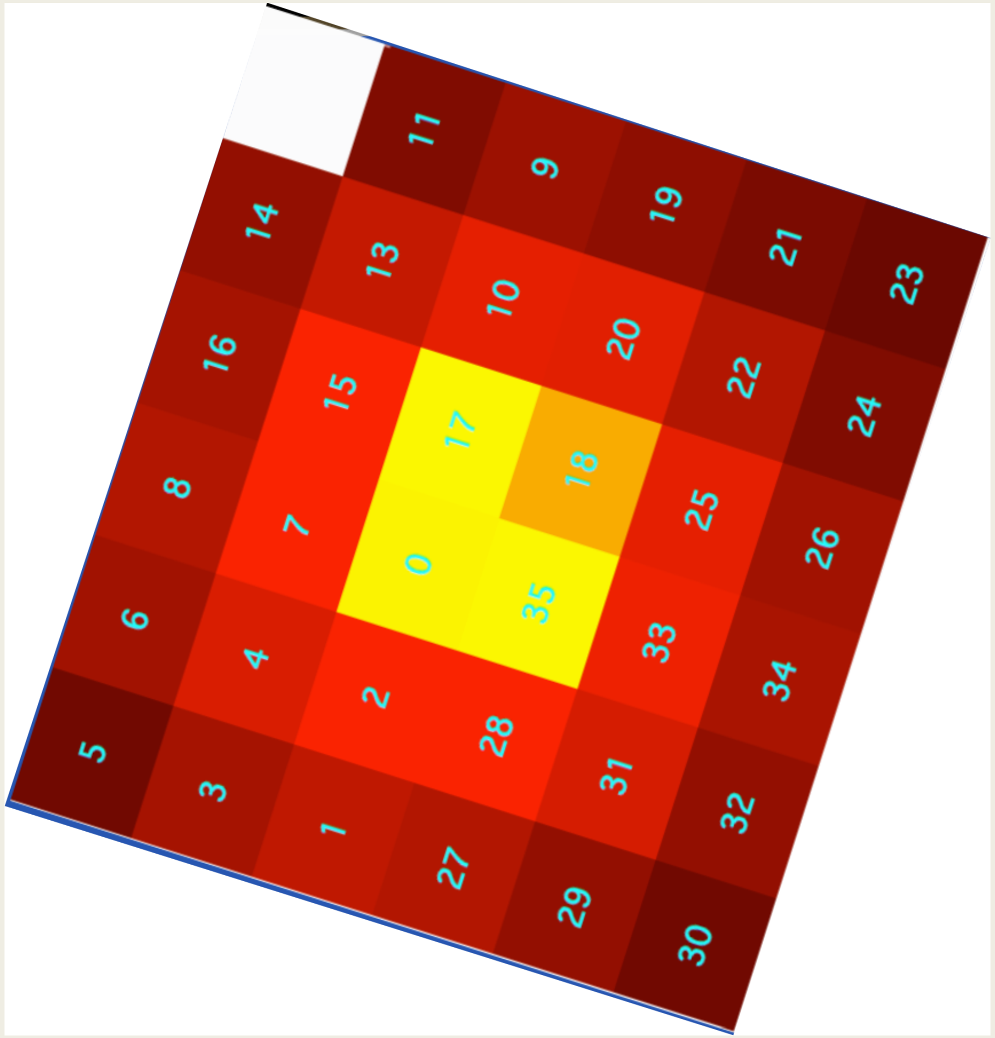
No Excess!

Overall best-fit line is negative at 3.54 keV with normalisation of

-8×10^{-6} photons cm^{-2} s^{-1}

2.5 sigma significance

Hitomi view of Perseus



Hitomi cannot separately resolve AGN and thermal cluster emission

Its best-fit value

(-8×10^{-6} photons cm^{-2} s^{-1})

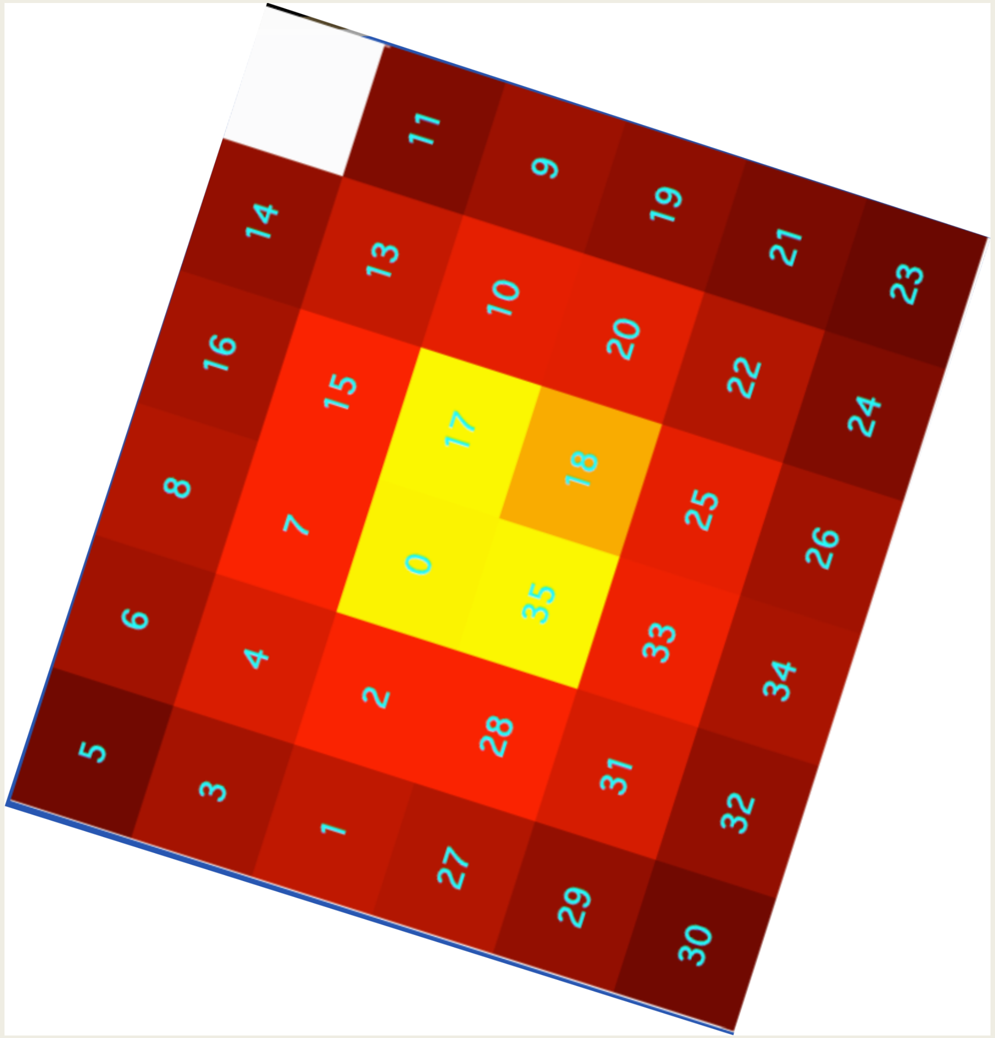
is sensitive only to the SUM of

(3.54 keV features in cluster emission)

PLUS

(3.54 keV features in AGN spectrum)

Hitomi view of Perseus



Hitomi best-fit value at 3.54 keV:

(-8 x 10^{-6} photons cm^{-2} s^{-1})

XMM Excess (excluding AGN) in Hitomi Field of View

(9.0 +- 2.9) x 10^{-6} photons cm^{-2} s^{-1}

Deficit in AGN from Chandra (rescaled from 2009 to 2016 AGN luminosity)

(-16.7 +- 3.6) x 10^{-6} photons cm^{-2} s^{-1}

All consistent!

3.5 keV line in Perseus

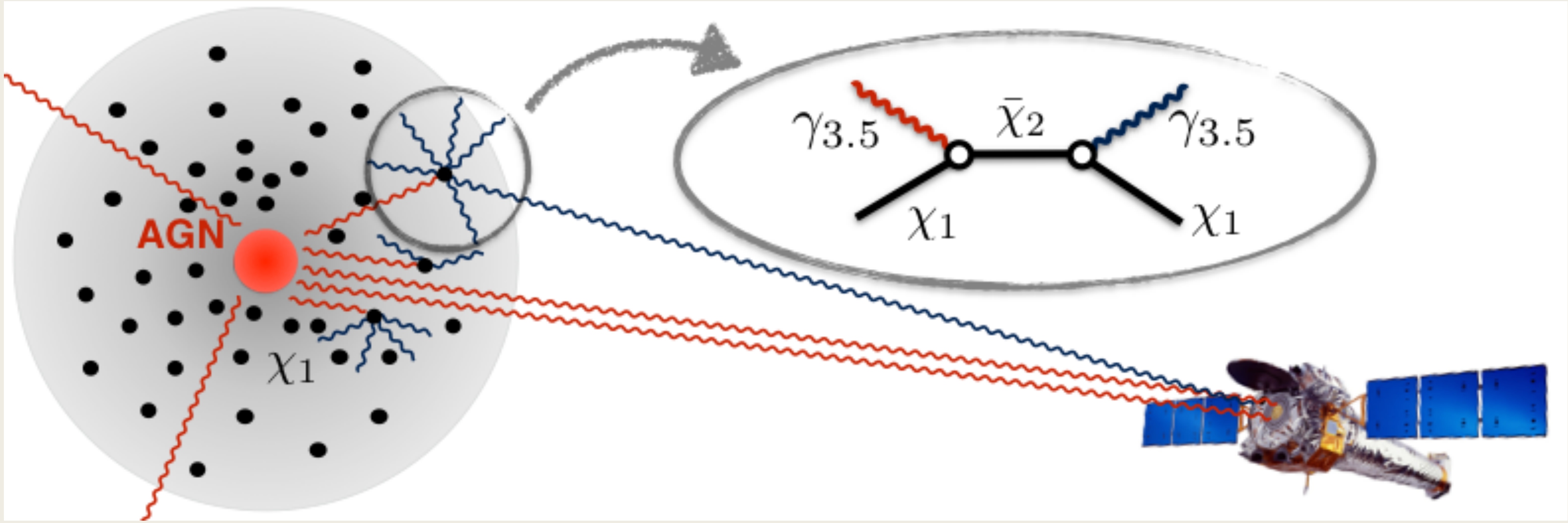
Deficit/absorption in the spectrum of very bright point source

Excess/emission in the diffuse spectrum throughout the cluster

At the same energy – how to explain this in one model?

Fluorescent Dark Matter

Dark matter absorbs and re-emits 3.5 keV photons; generates both AGN deficit and diffuse excess



Fluorescent Dark Matter

$$\mathcal{L} \supset \frac{1}{M}\bar{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu},$$

Simplest model involves two states (χ_1 and χ_2)

Dark matter is in ground state χ_1

Absorption of real 3.5 keV photons takes it to excited state χ_2

Instant decay $\chi_2 \to \chi_1\gamma$ leads to diffuse 3.5 keV excess

(Lots of work on excitation via dark matter collision, but this scenario is surprisingly little studied)

Conclusions

1. X-ray astronomy is a powerful probe of fundamental physics

2. Existing, archival *Chandra* observations of Perseus constraint offer leading constraints on $g_{a\gamma\gamma}$ for light ALPs with m < 10^{-12} eV

3. Data contains a striking dip in the AGN spectrum at (3.54 +- 0.02) keV – dark matter absoprtion?

4. My opinion: 3.5 keV line is compelling evidence for new physics

THANK YOU!