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

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Based on (also see poster by Francesco Muia)

1605.01043

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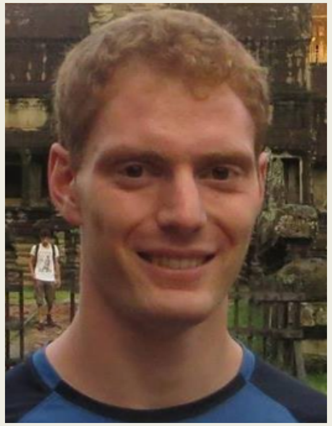
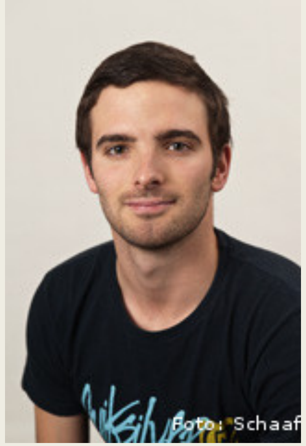
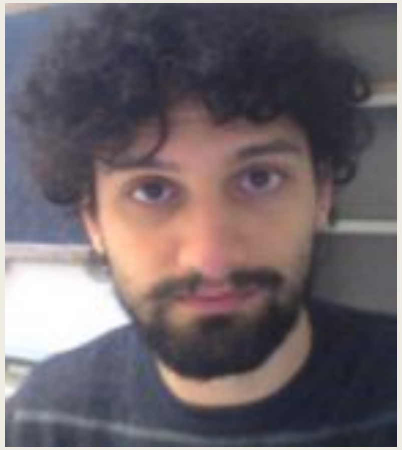
1608.01684

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







I. The Targets

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

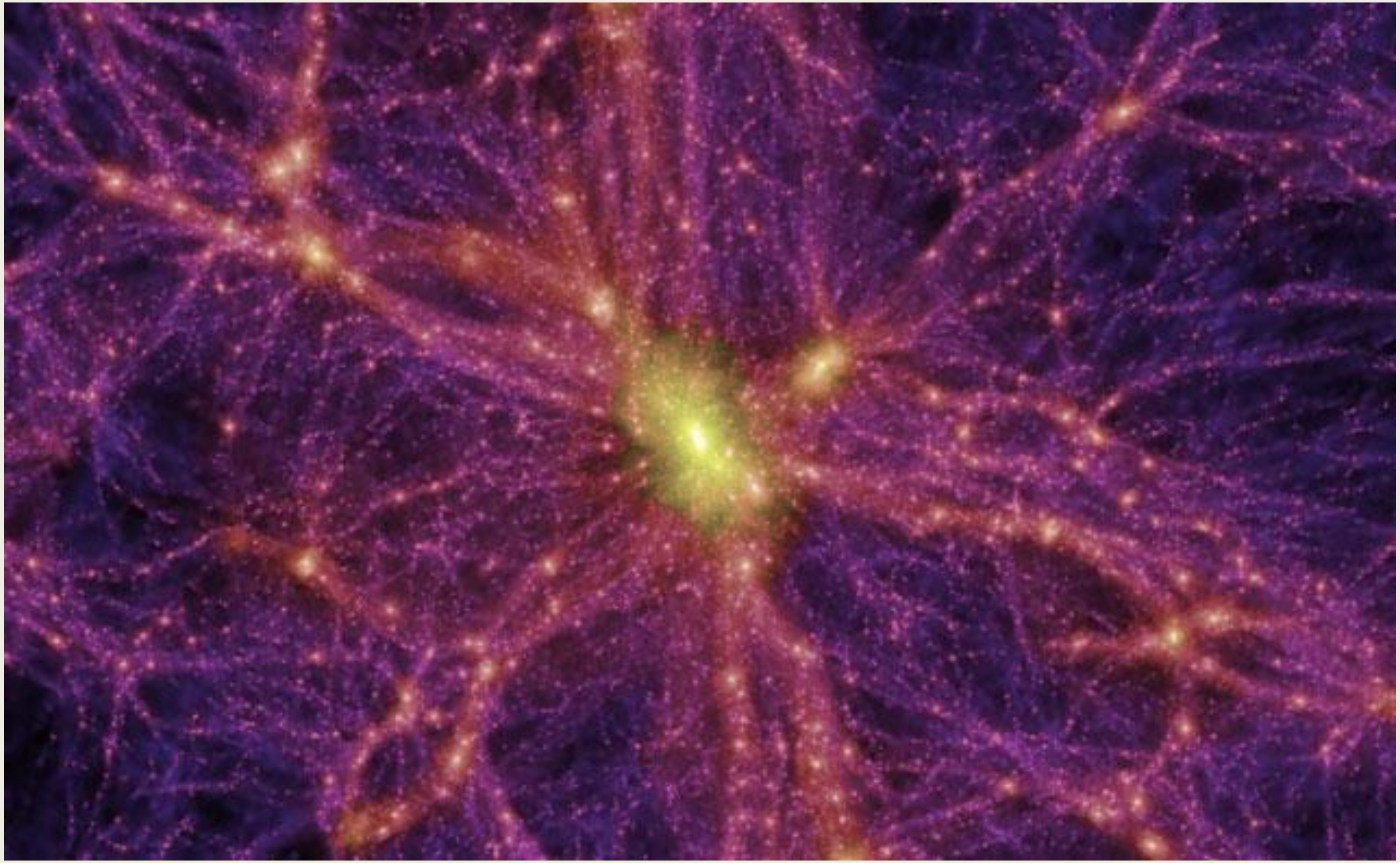
Axion-like particles

- Light axion-like particles (ALPs) are one of the most motivated ways to extend the Standard Model
- They arise generically in string theory – e.g. a light ALP is always present in the Large Volume Scenario.
- 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)

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

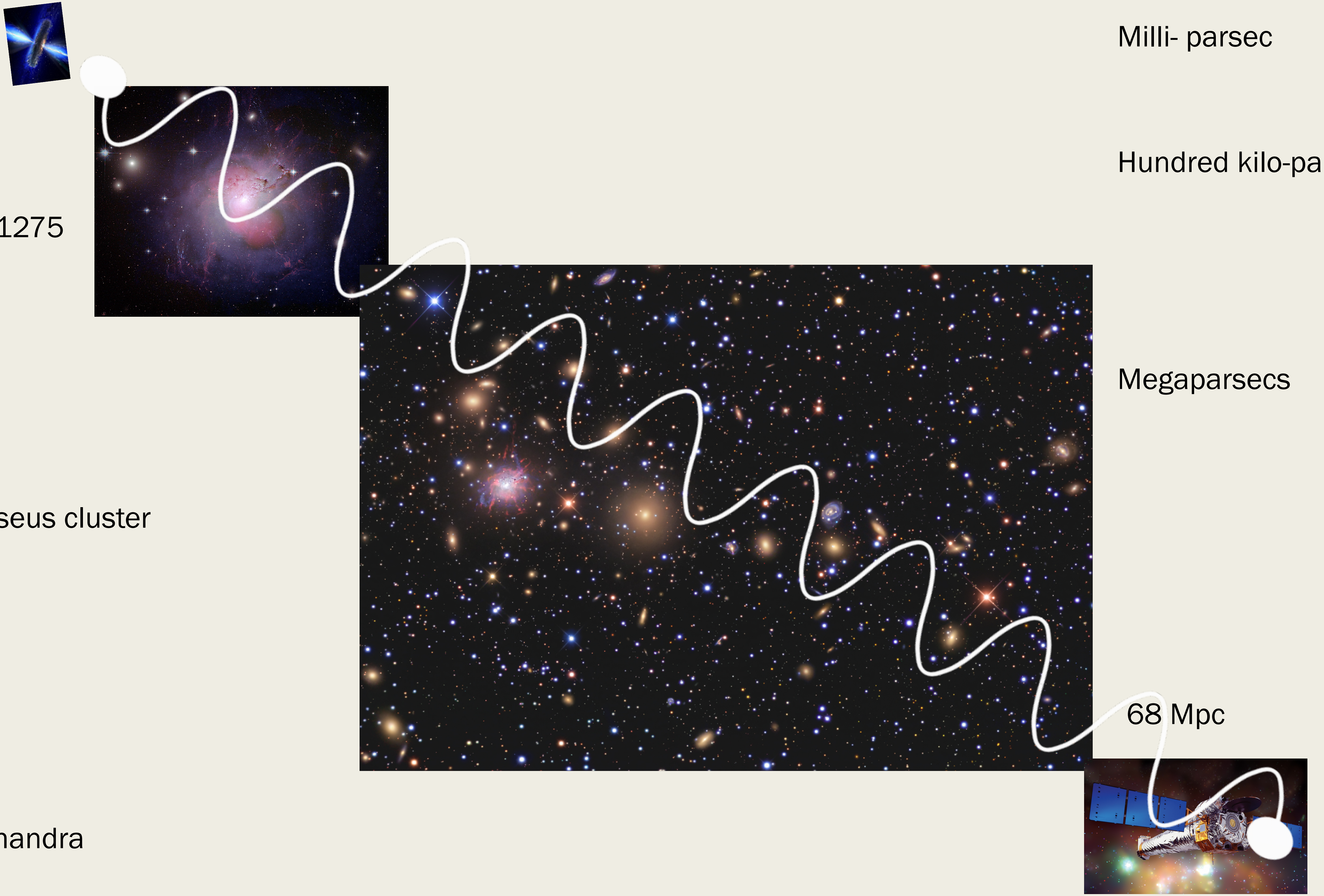
Originally Wouters + Brun 2013

AGN

Milli- parsec

NGC1275

Hundred kilo-parsecs



Perseus cluster

Megaparsecs

Chandra

Active Galactic Nuclei are point sources

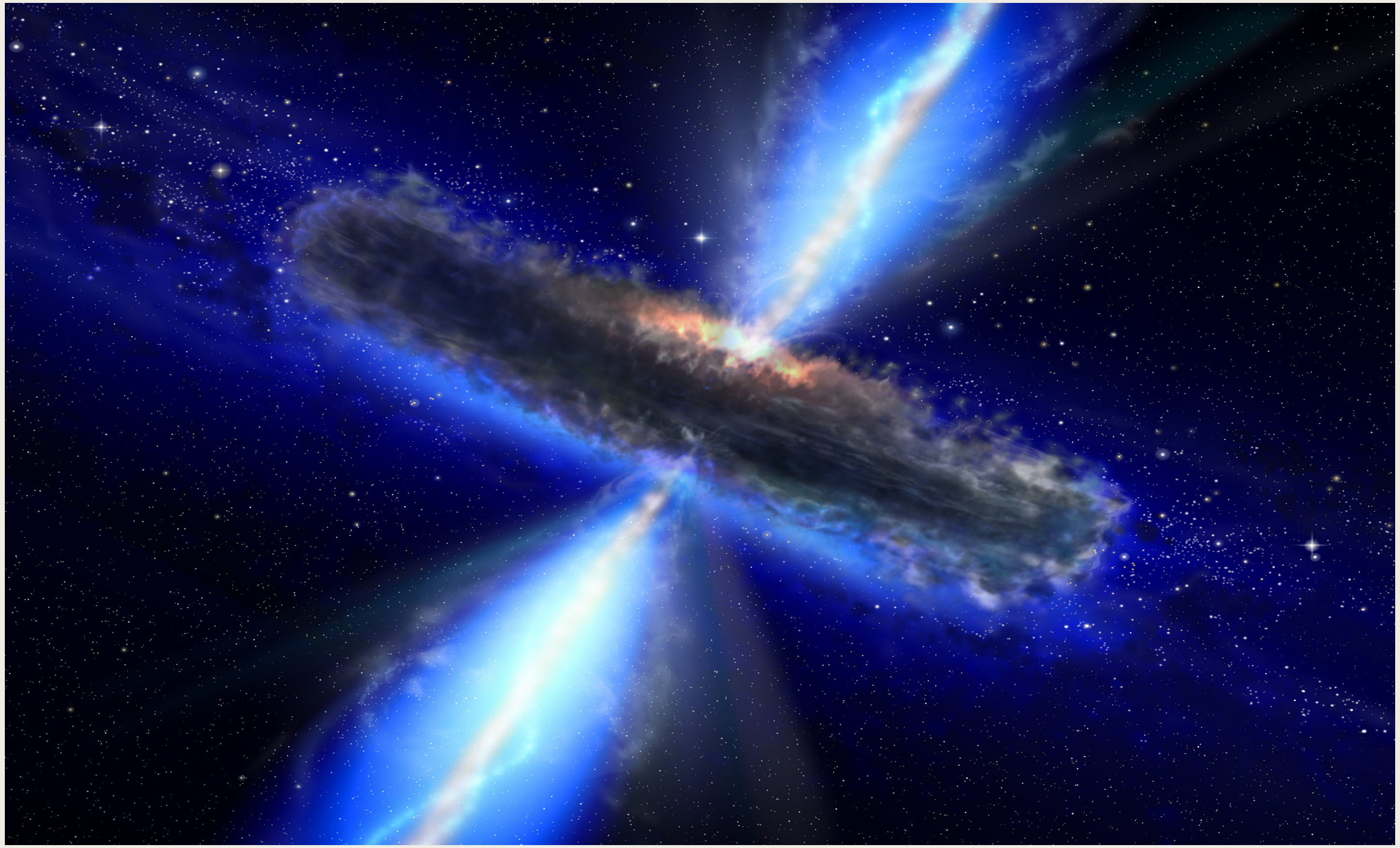
- X-ray emission from AGNs comes from extremely small physical region
- This follows from the time variability of AGN spectra: intensities fluctuate on hour to day timescales, implying emission originates from within a light-day
- Basic components to X-ray spectrum are

  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: the standard Unified Model



Credit ESA/NASA, AVO project, Paolo Padavani

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

- 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.

Cluster Magnetic Fields

- Cluster magnetic fields are measured through Faraday rotation measurements of radio sources that shine through galaxy clusters

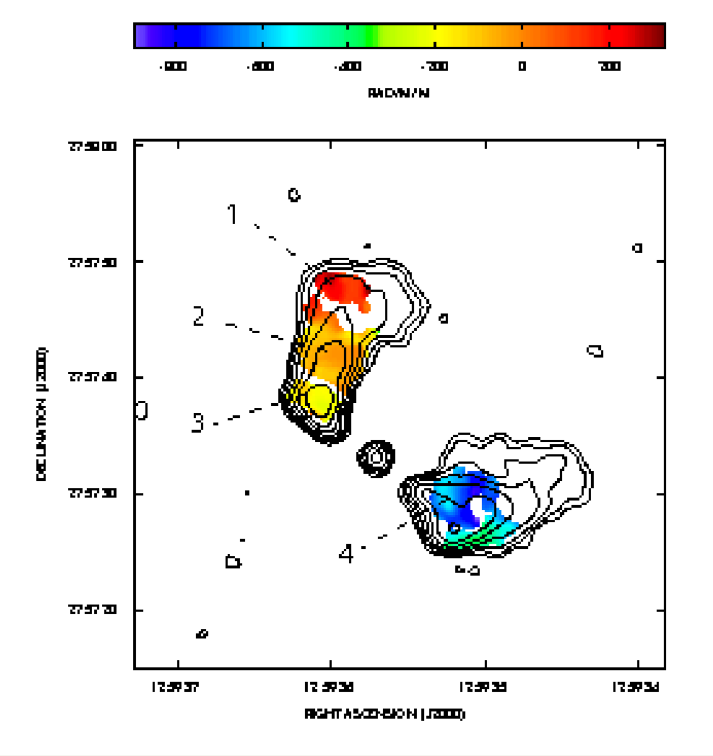
$$RM = 812\, rad\, m^{-2} \int \left(\frac{n_e}{10^{-3} cm^{-3}}\right)\left(\frac{B_{\parallel}}{1\, \mu G}\right) d(kpc)$$

- Electron density n_e is determined from X-ray maps.
- The size of the RM and the scale over which it varies gives statistical information on the magnitude and coherence scales of the intracluster magnetic field.
- Despite uncertainty, these allow measurements of

  Central cluster magnetic field B_0

  Range of scales Λ_{min} to Λ_{max} over which the magnetic field varies.

  Normally assume a Kolmogorov spectrum of power in the magnetic field



Cluster Magnetic Fields

- Typical cluster magnetic fields are 1-10 microGauss
- Reaching up to 50 microGauss for the centre of cool core clusters
- In longer term, knowledge will improve with Square Kilometre Array (measure more radio sources that are in or behind clusters)

Cluster	$\langle B_0 \rangle$ (μG)	n_0 (cm^{-3})	T (keV)	References
Abell 194	1.5	0.69	2.4	This work
Abell 119	5.96	1.40	5.6	Murgia et al. (2004)
Abell 2199	11.7	101.0	4.1	Vacca et al. (2012)
Abell 2255	2.5	2.05	6.87	Govoni et al. (2006)
Abell 2382	3.6	5.0	2.9	Guidetti et al. (2008)
3C31	6.7	1.9	1.5	Laing et al. (2008)
3C449	3.5	3.7	0.98	Guidetti et al. (2010)
Coma	4.7	3.44	8.38	Bonafede et al. (2010)
Hydra	45.2	62.26	4.3	Laing et al. (2008)

Col. 1: Cluster; Col. 2: Central magnetic field; Col. 3: Central electron density;

From 1703.08688 Govoni et al

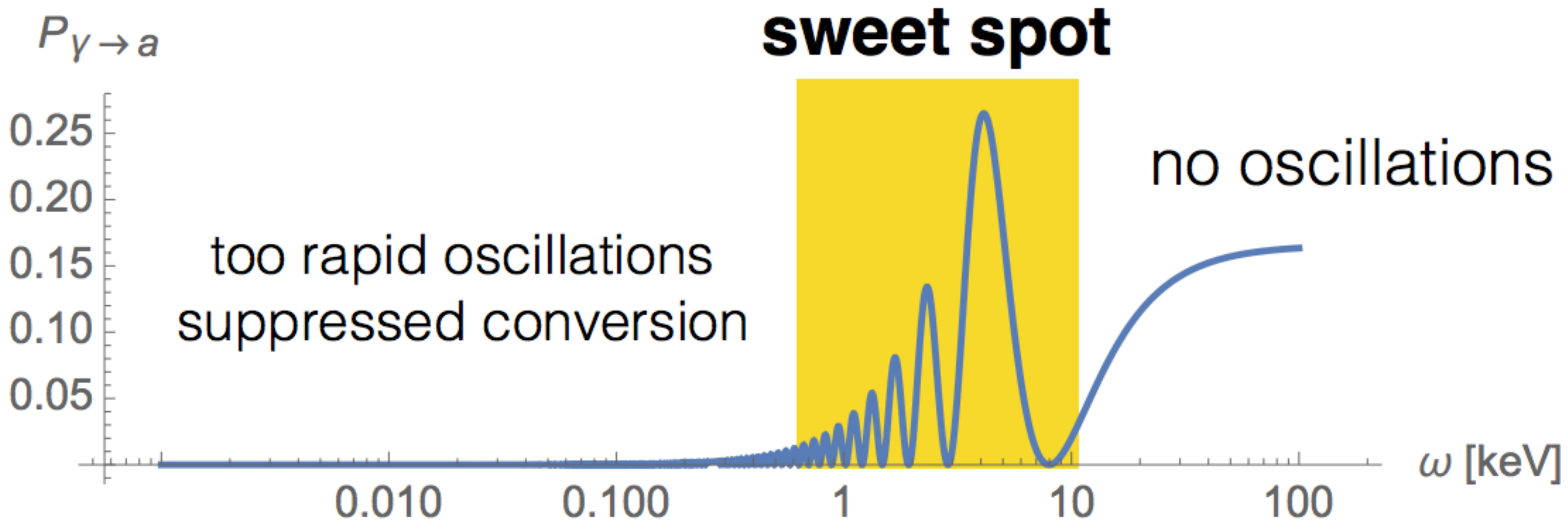
Photon-ALP Conversion – why X-rays?

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

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

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

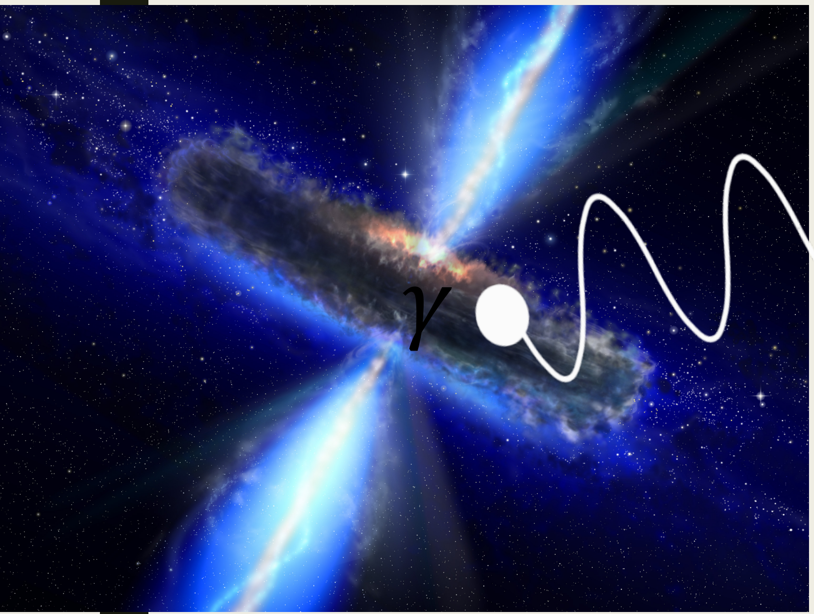
- Sweet spot at X-ray energies:

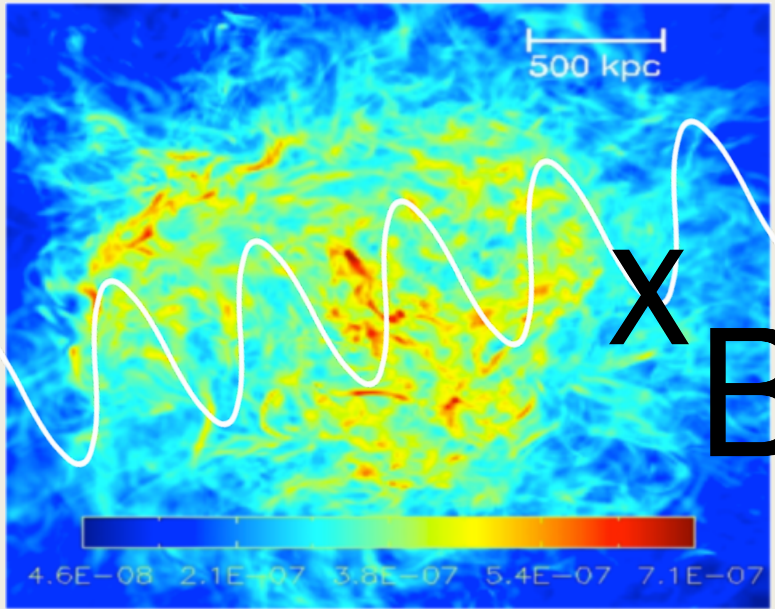


ALPS

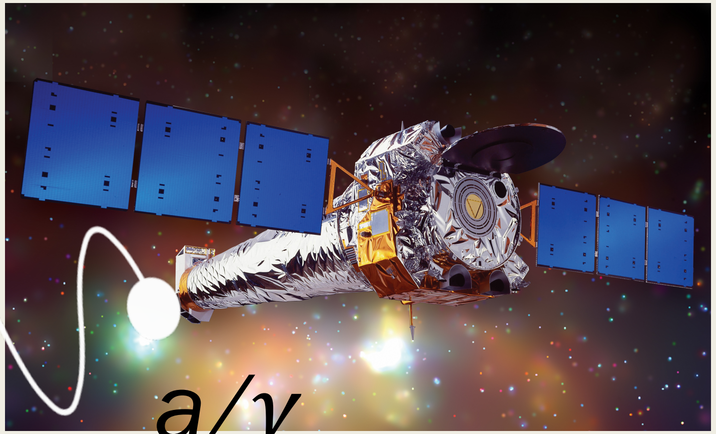
Photons pass through galaxy cluster magnetic field

AGNs are bright point sources of photons

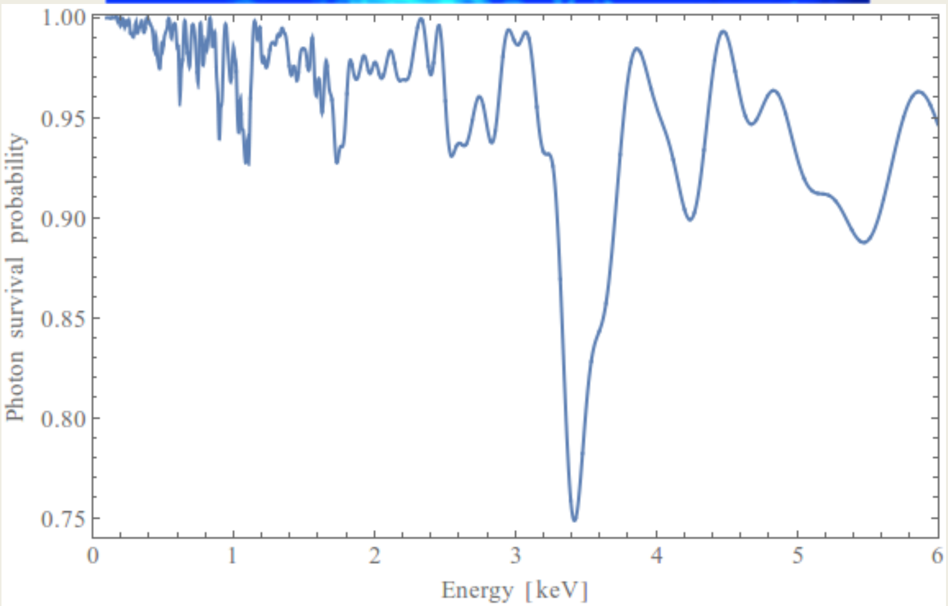




X B

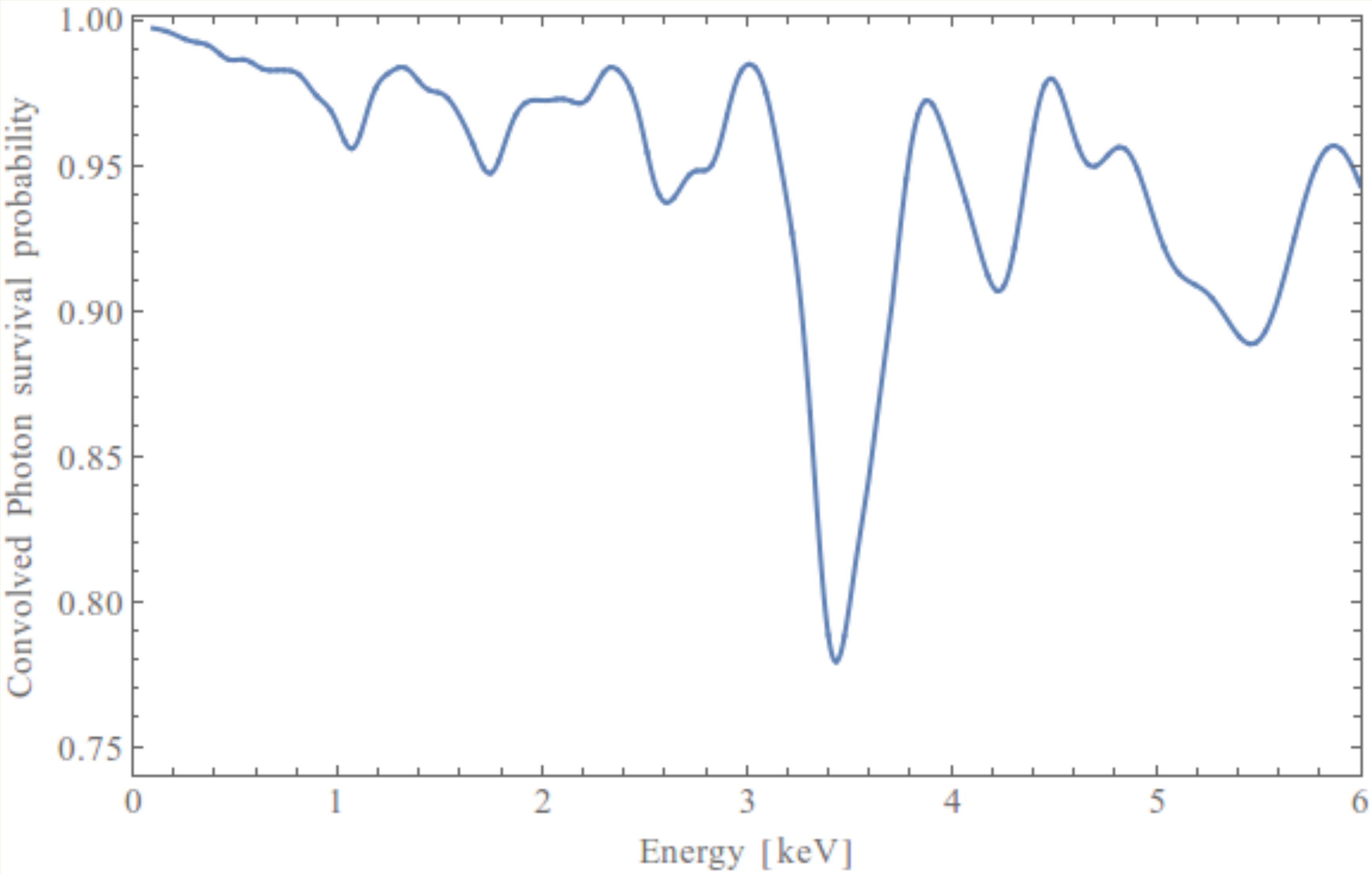


ALP-Photon conversion induces irregularities in observed X-ray spectrum



Precise form of modulations depends on cluster magnetic field

Simulated photon survival probability



This would modulate the true spectrum

III. The Results

A. ALP Searches

Chandra X-ray telescope

~1.5 billion USD

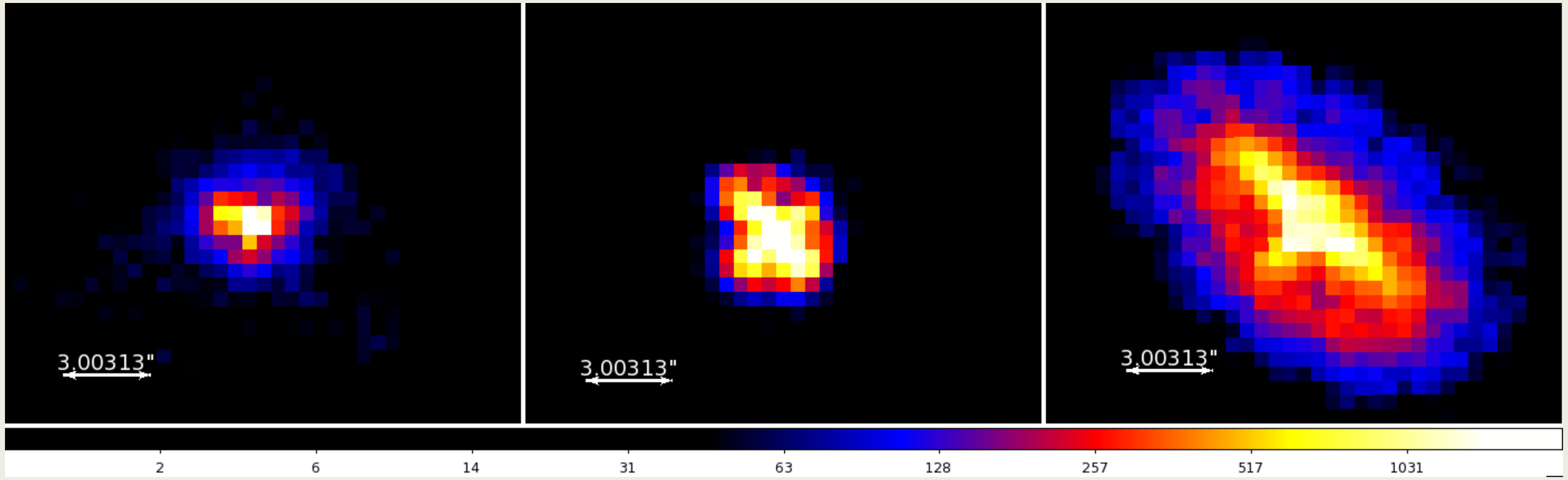
15 years operation

Mature, well understood instrument

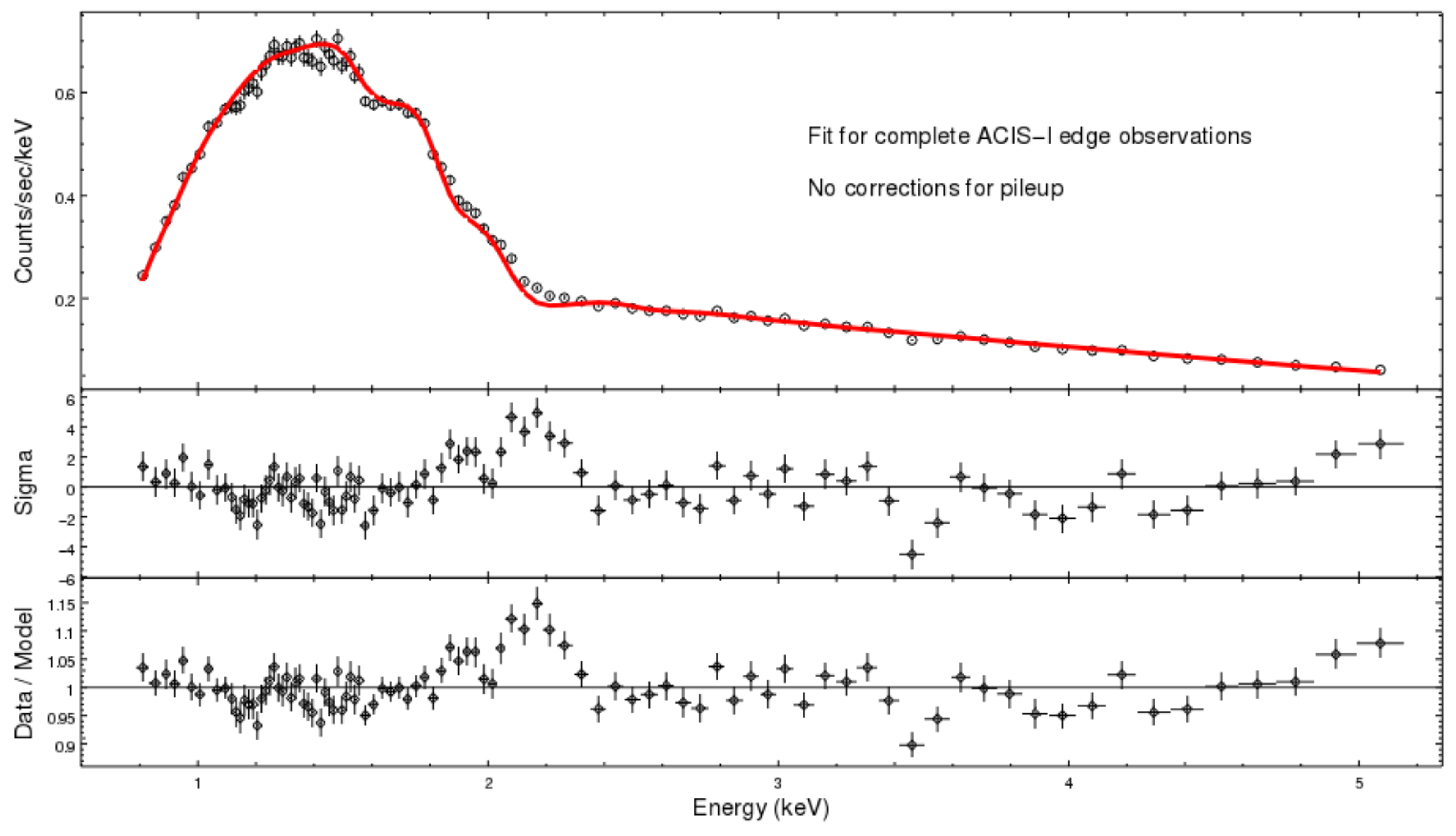
Large public observational data archive

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.



Complete extraction for ACIS-I edge



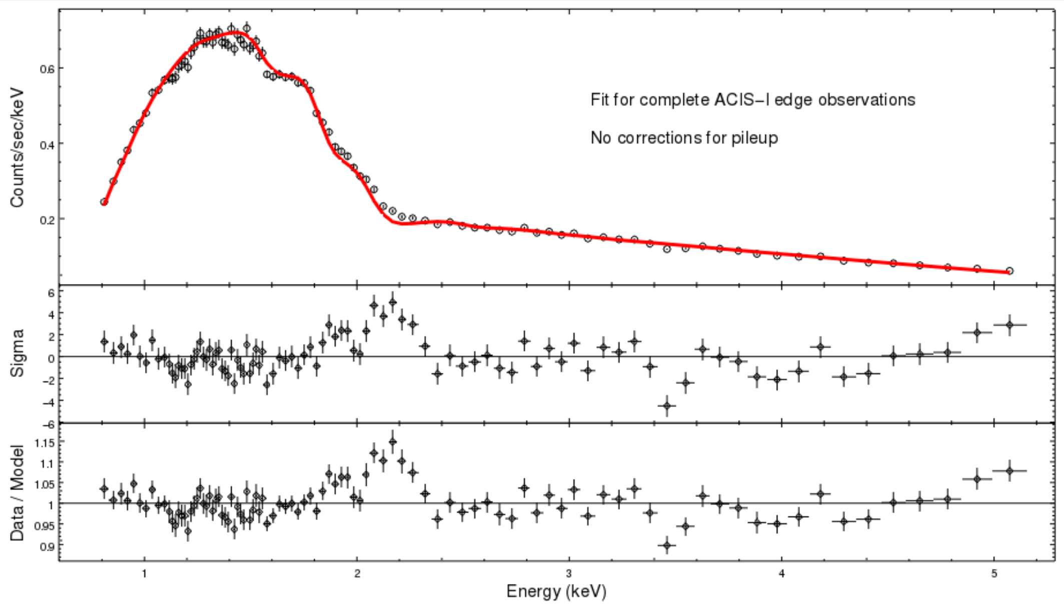
Fit to absorbed power law gives two main features – excess at 2 – 2.2 keV, deficit at 3.4 – 3.5 keV

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

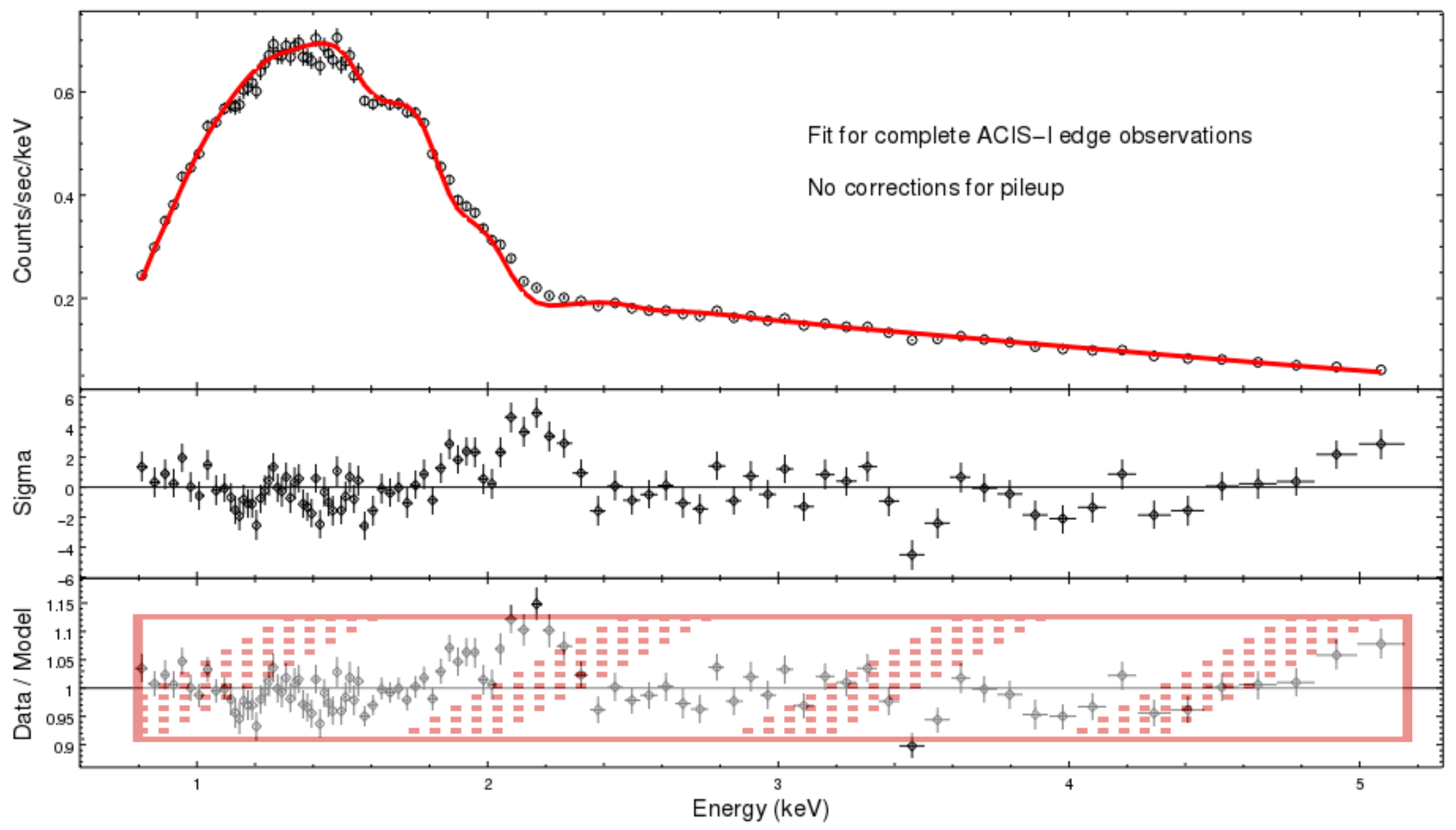
2. Deficit at 3.4 – 3.5 keV

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

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

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

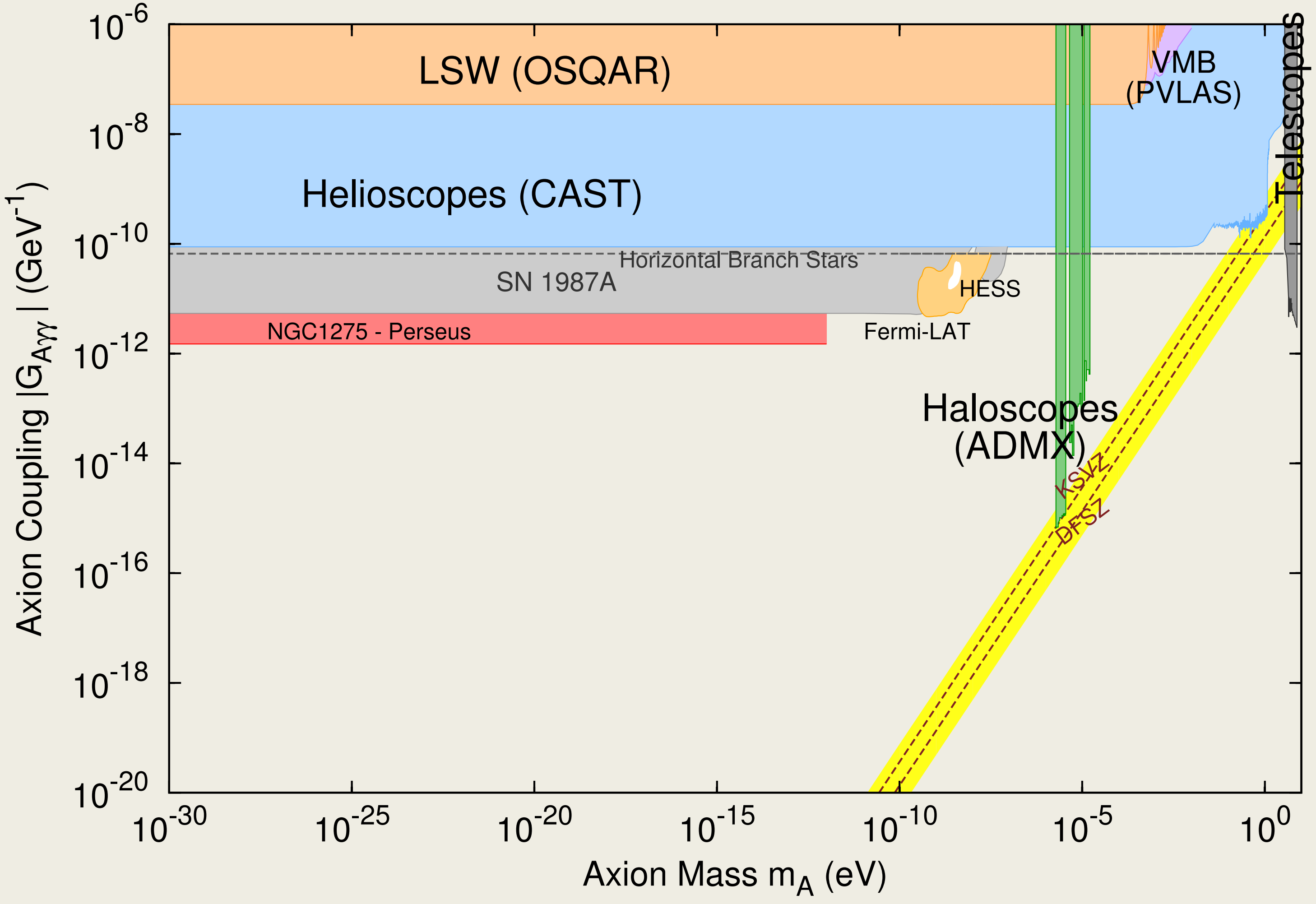
2. Conservative: (B_central = 15 μG, 100 domains between 0.7 and 10kpc)

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

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

   $g_{a\gamma\gamma} < 5.6 \times 10^{-12}$ 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

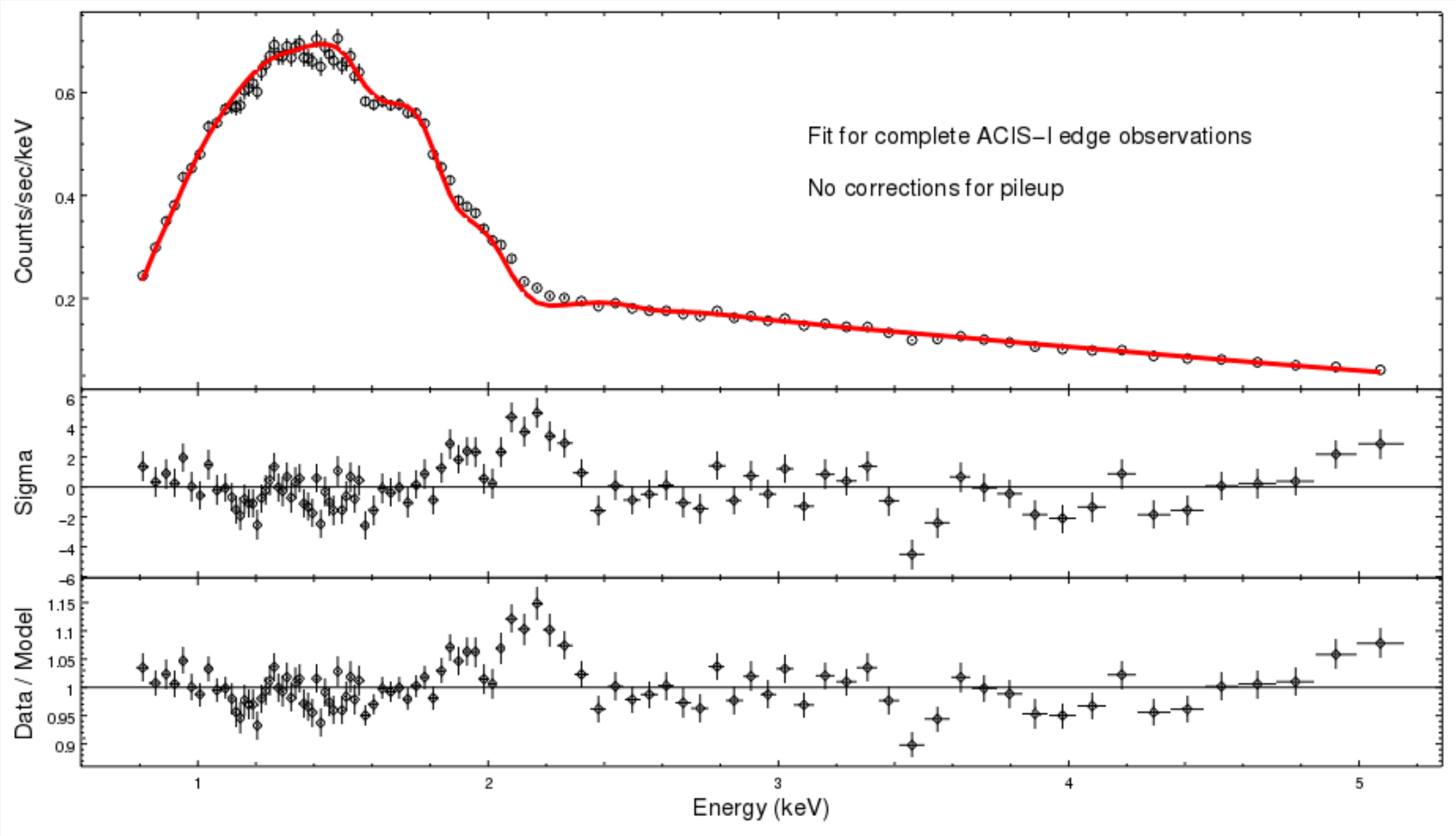
3.4 – 3.5 feature

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…

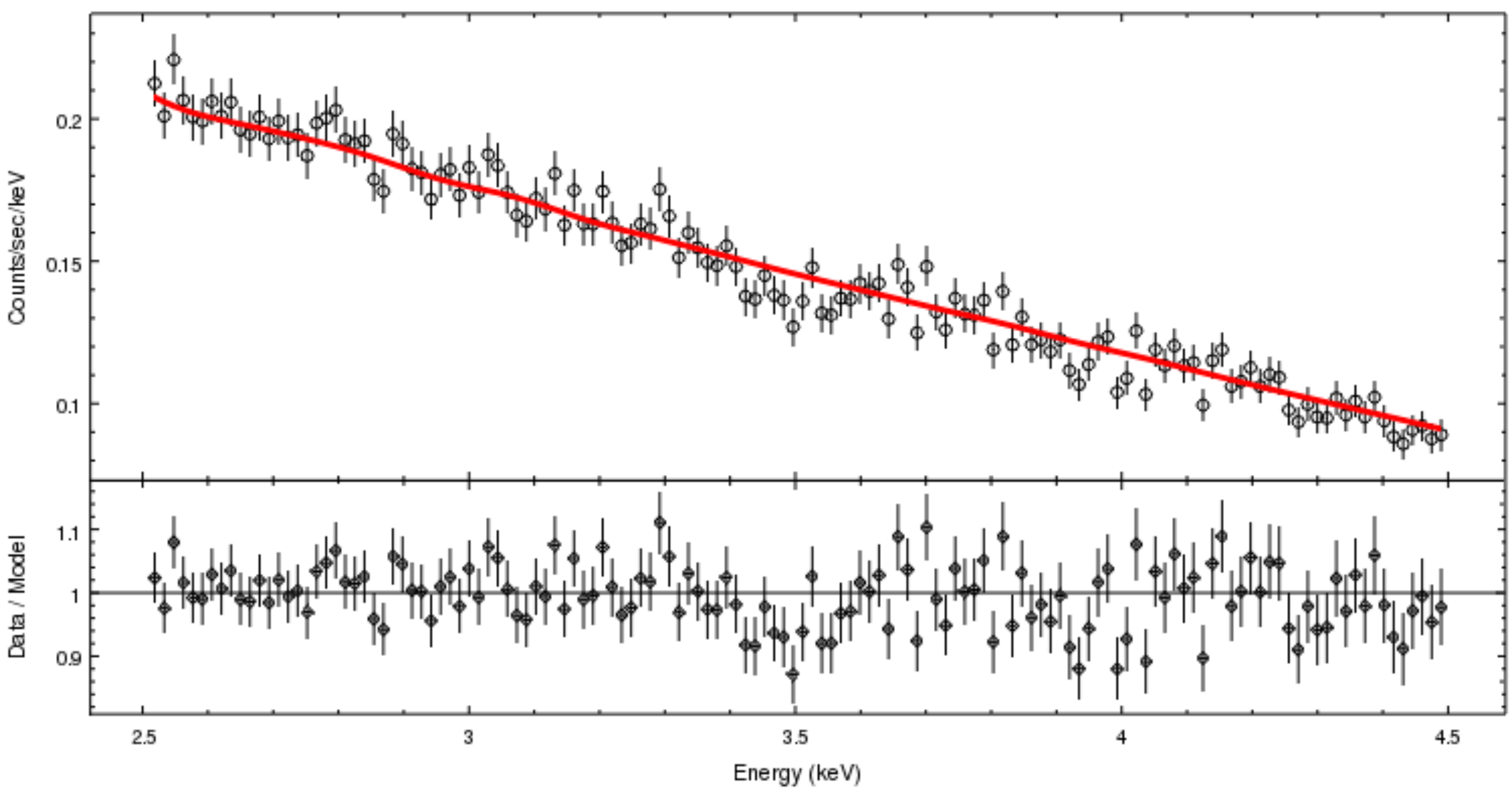
We fit from 0.8 to 5 keV and cut out 1.8 – 2.3 keV region to avoid biasing the fit.

Fit with xswabs * (xspowerlw + xsbapec)

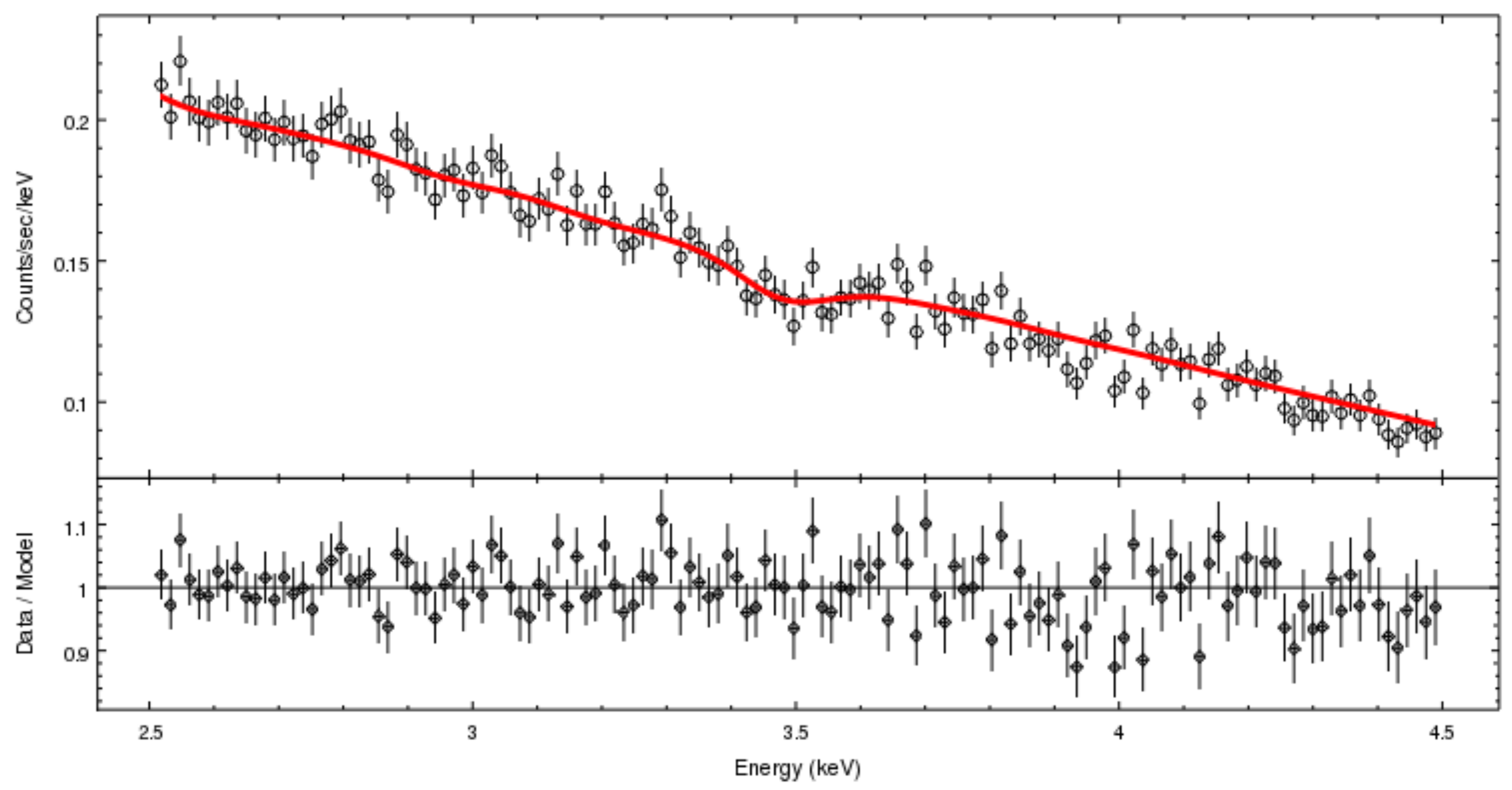
i.e. Absorption * (power law + thermal cluster emission)

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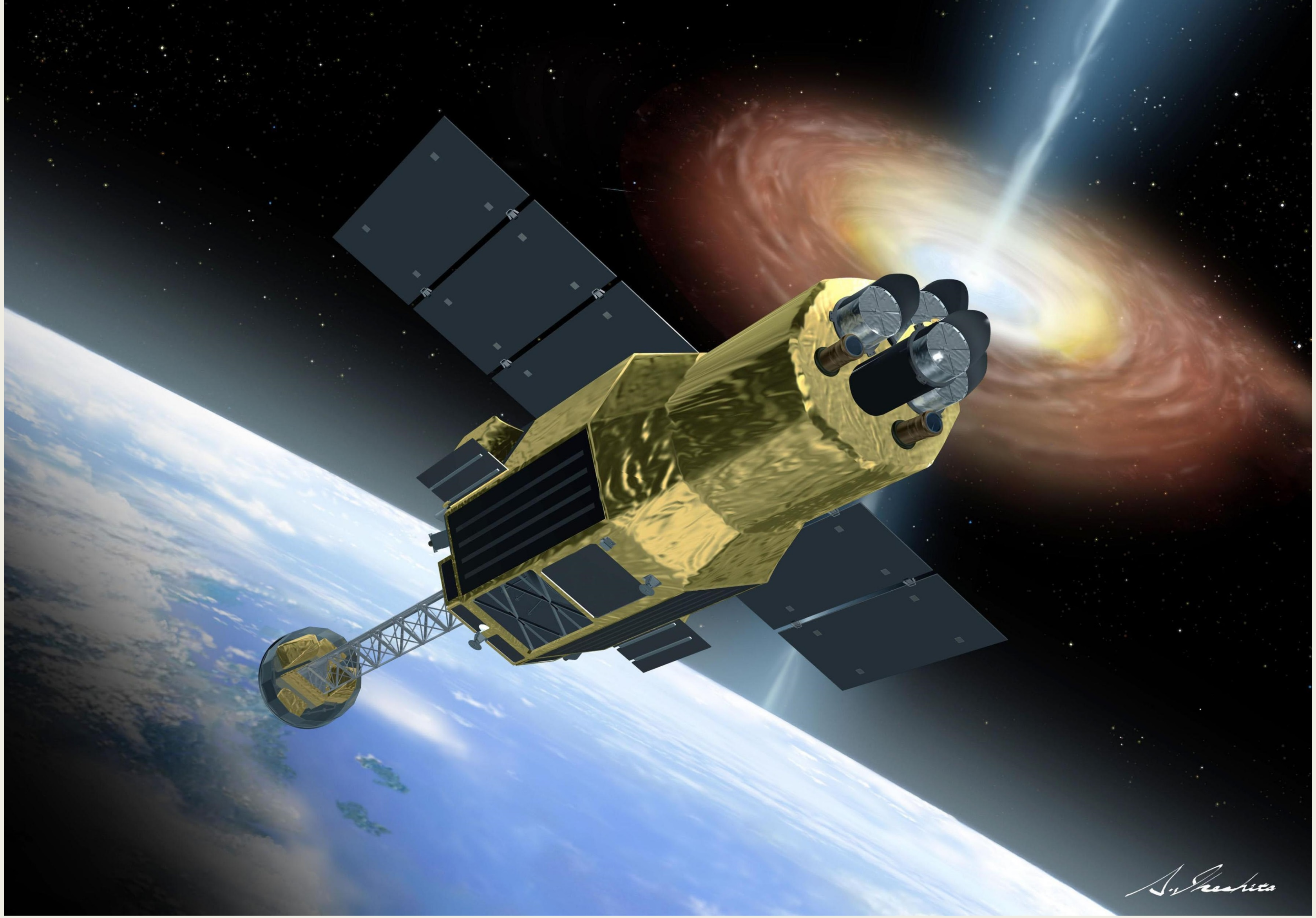
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

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

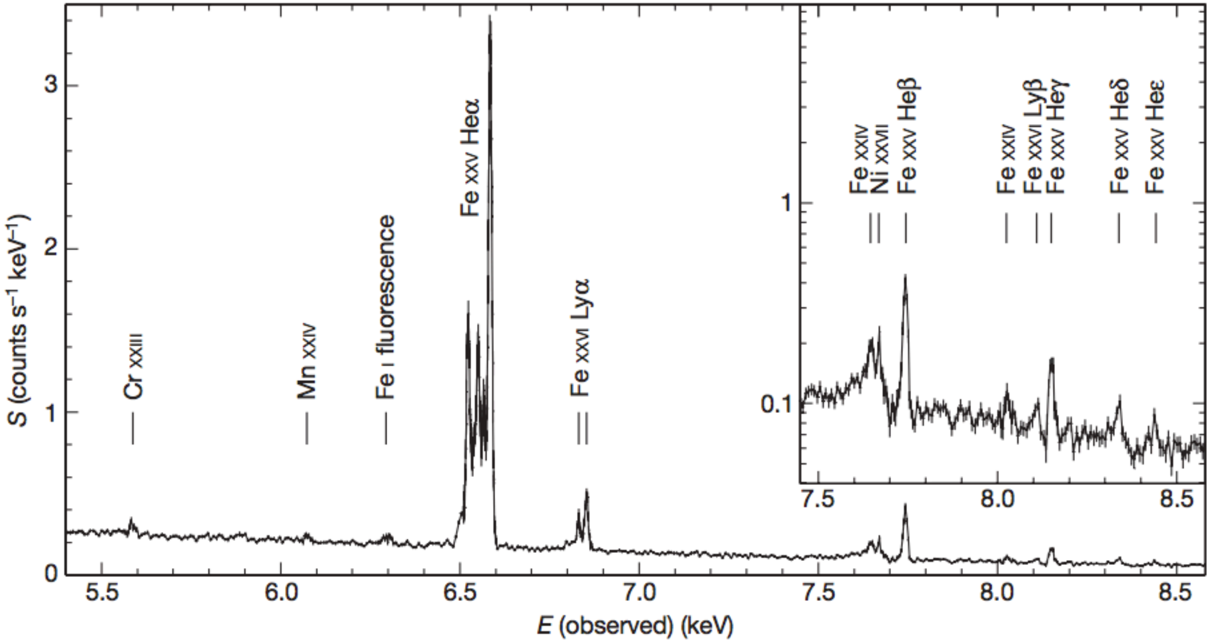
LETTER

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 gravita[...] objects in the Universe and are still forming. They are

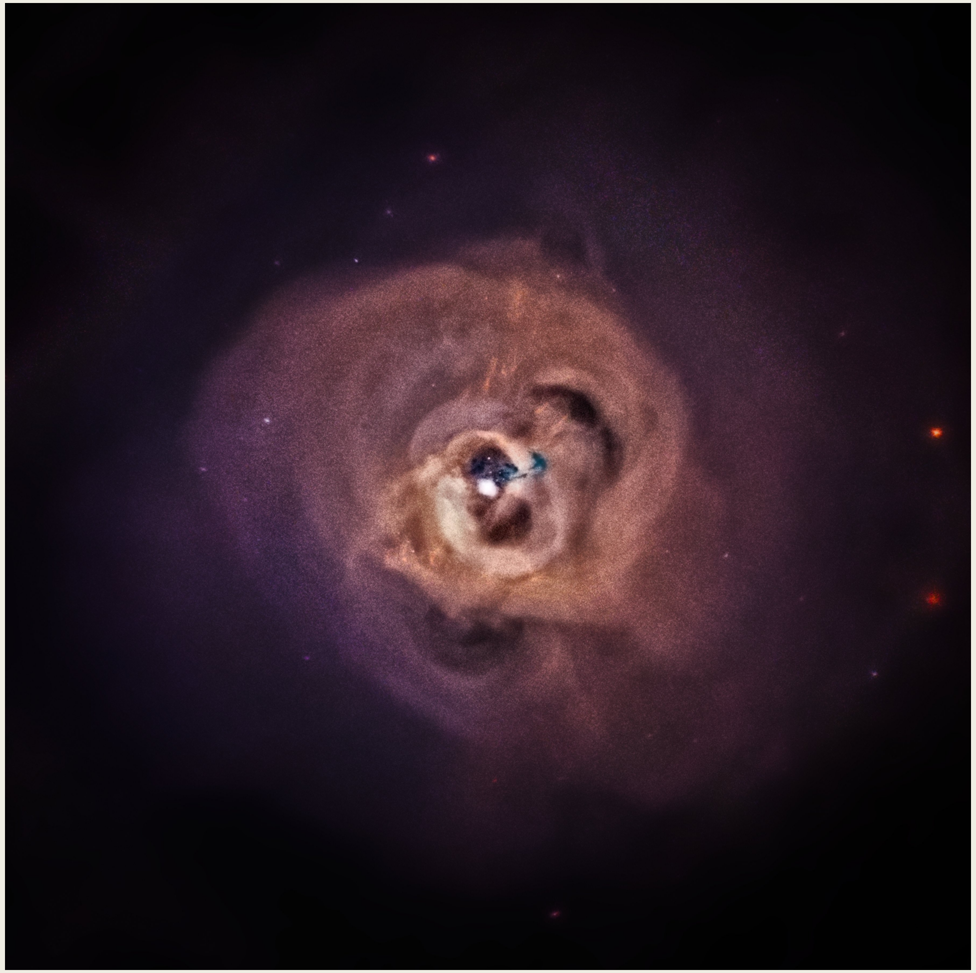


Hitomi returned a ground-breaking spectrum of Perseus before its tragic loss in March 2016

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

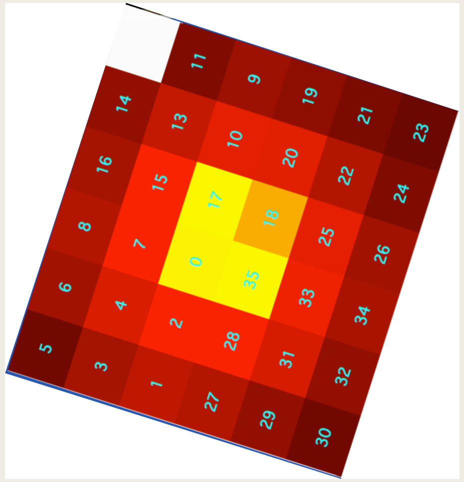
Images of the centre of Perseus

CHANDRA



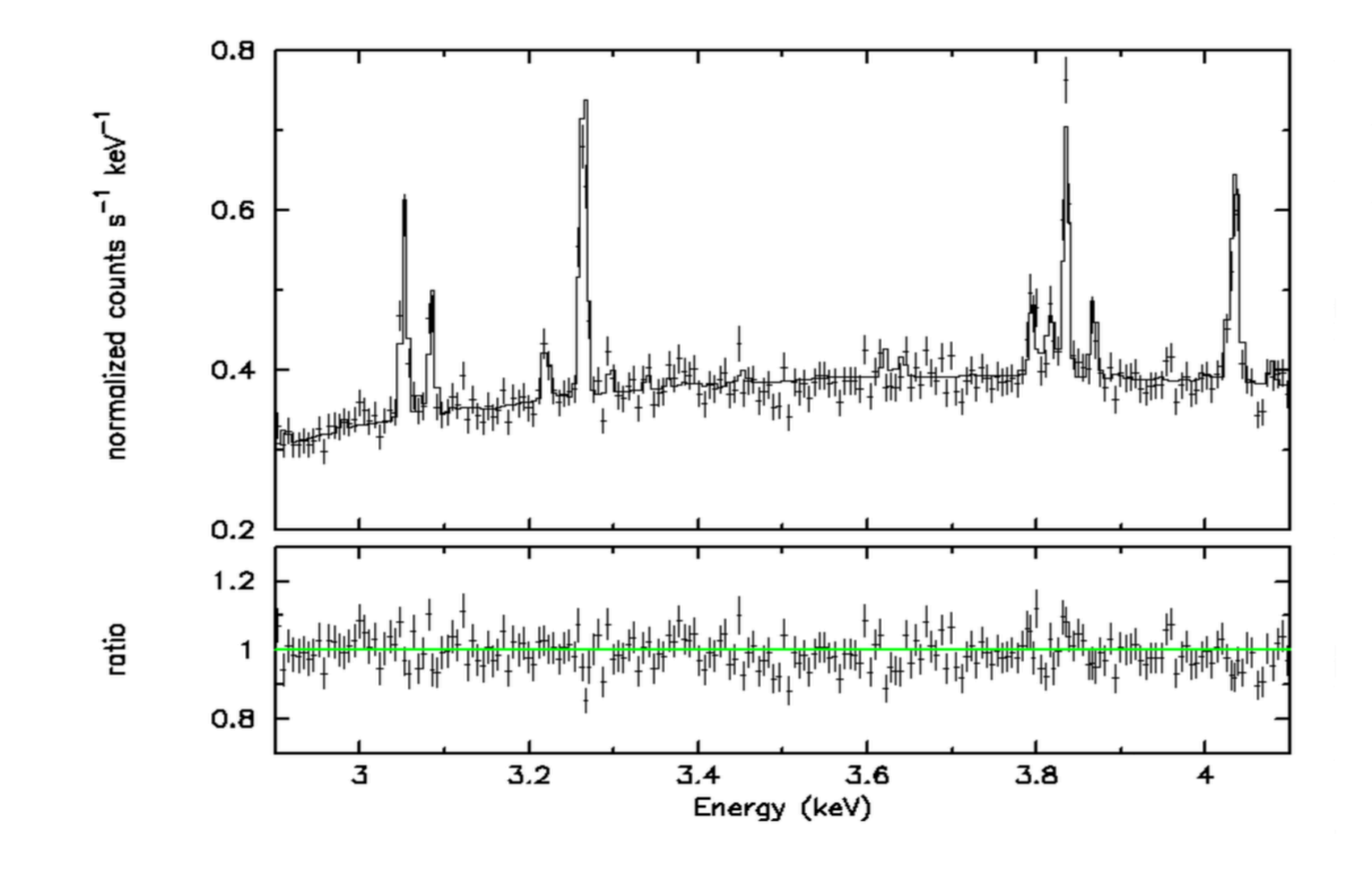
Best
angular
resolution

HITOMI



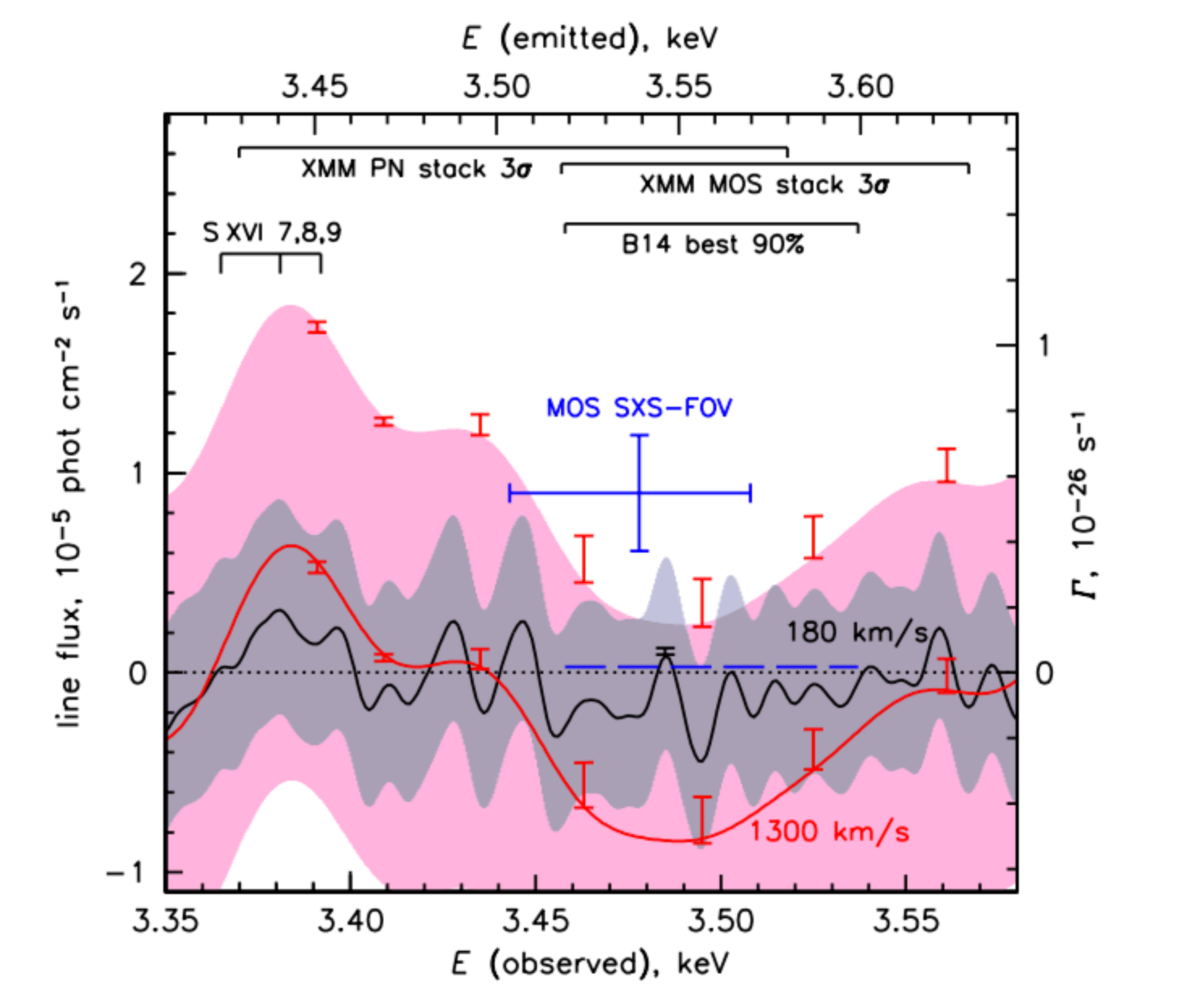
Best energy
resolution

Hitomi Spectrum of Perseus Cluster



But look closely near 3.5 keV.....

Hitomi best-fit line properties



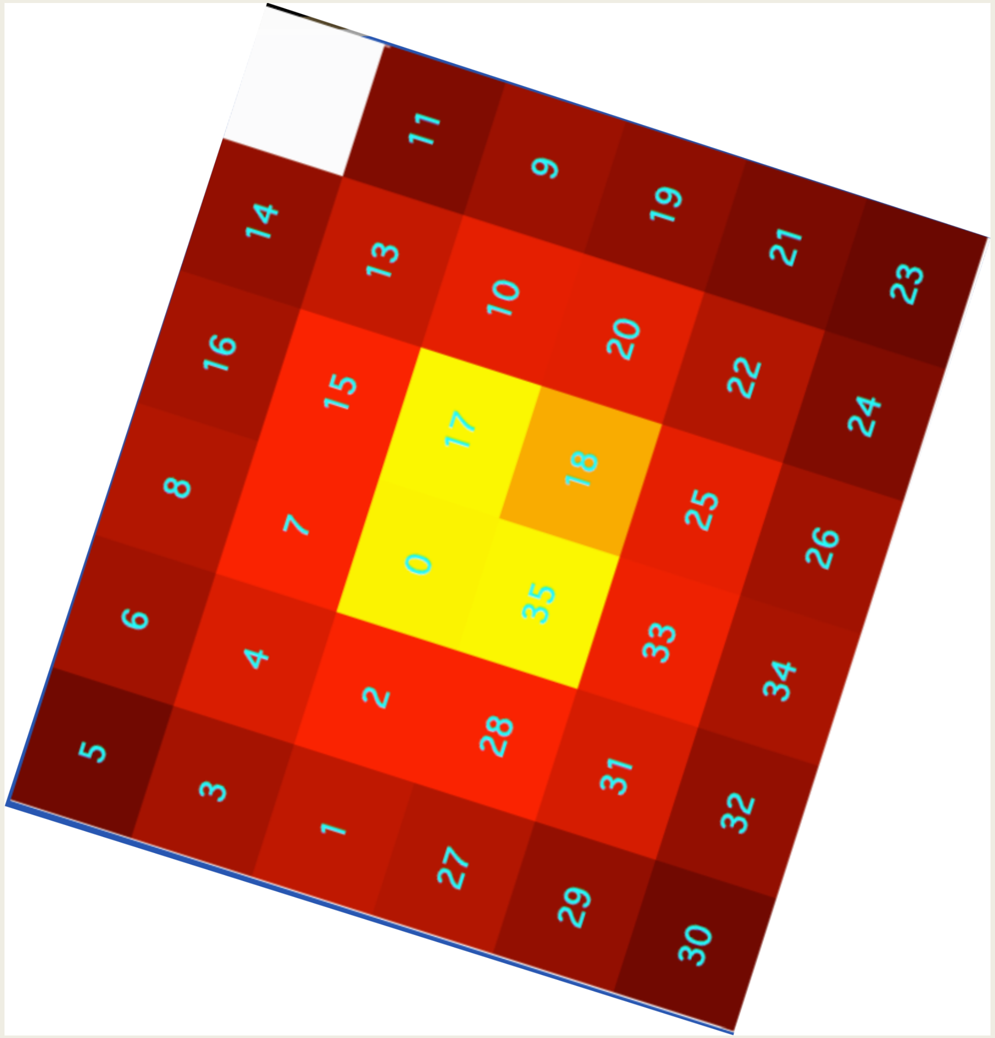
No Excess!

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})

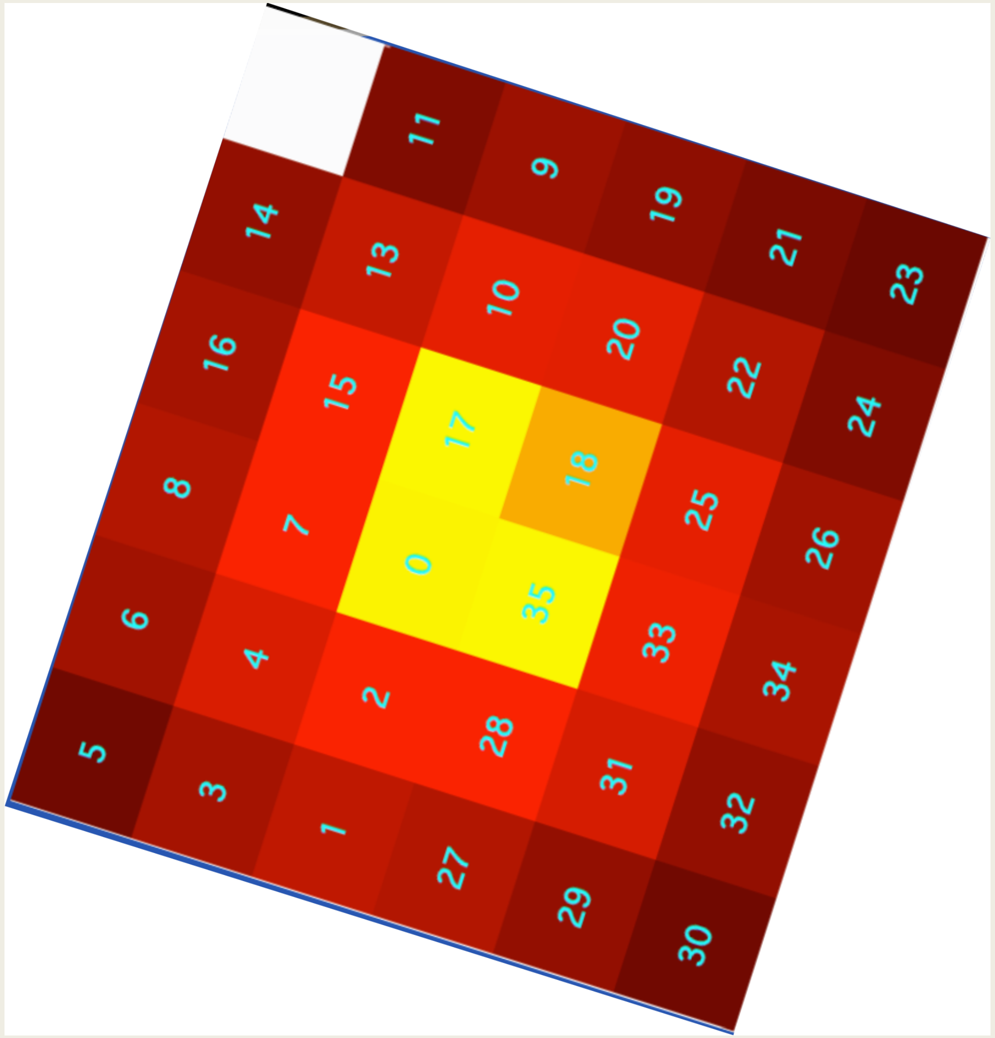
is sensitive only to the SUM of

(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:

(-8×10^{-6} photons cm^{-2} s^{-1})

XMM Excess (excluding AGN) in Hitomi Field of View

(9.0 ± 2.9) $\times 10^{-6}$ photons cm^{-2} s^{-1}

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

(-16.7 ± 3.6) $\times 10^{-6}$ photons cm^{-2} s^{-1}

All consistent!

3.5 keV line in Perseus

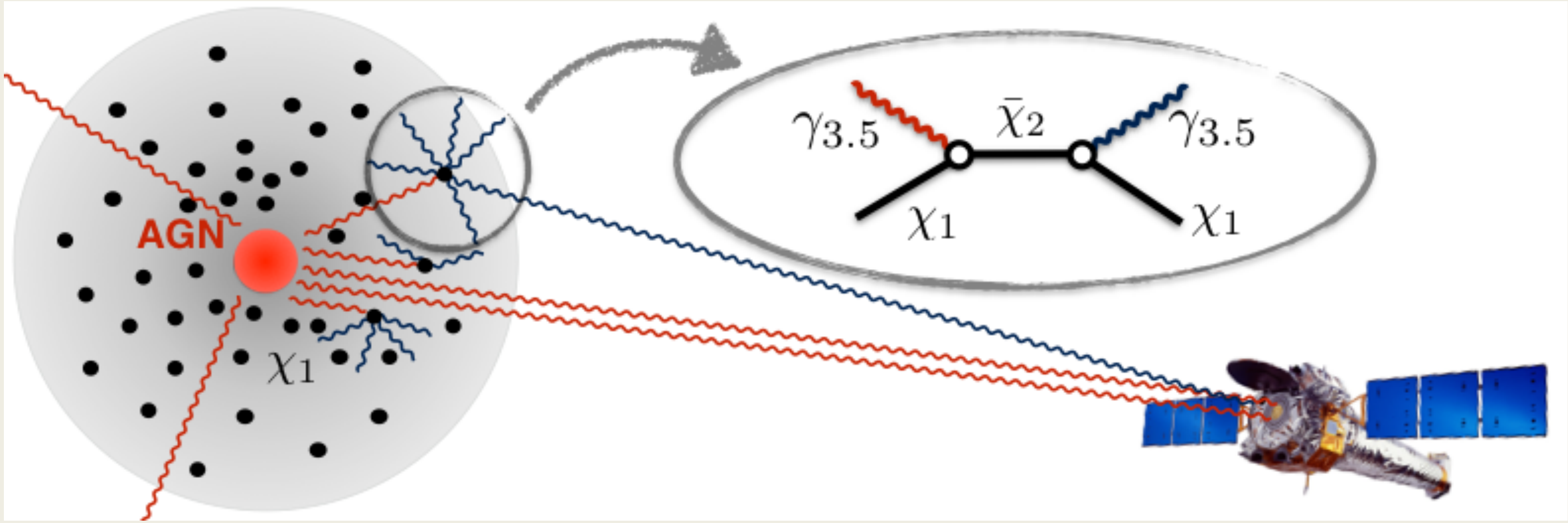
Deficit/absorption in the spectrum of very bright point source

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 $\chi_2 \rightarrow \chi_1\gamma$ 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. 3.5 keV line is compelling evidence for new physics

THANK YOU!