From string theory to Active Galactic Nuclei: searching for axions with X-rays

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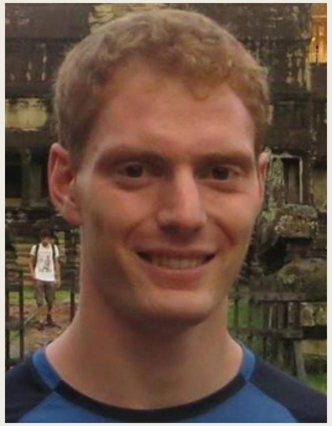
Primarily based on (but also earlier work with Angus, Marsh, Powell, Witkowski)

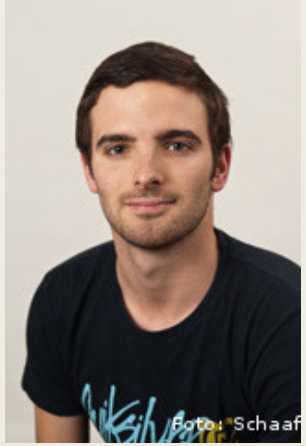
1605.01043

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

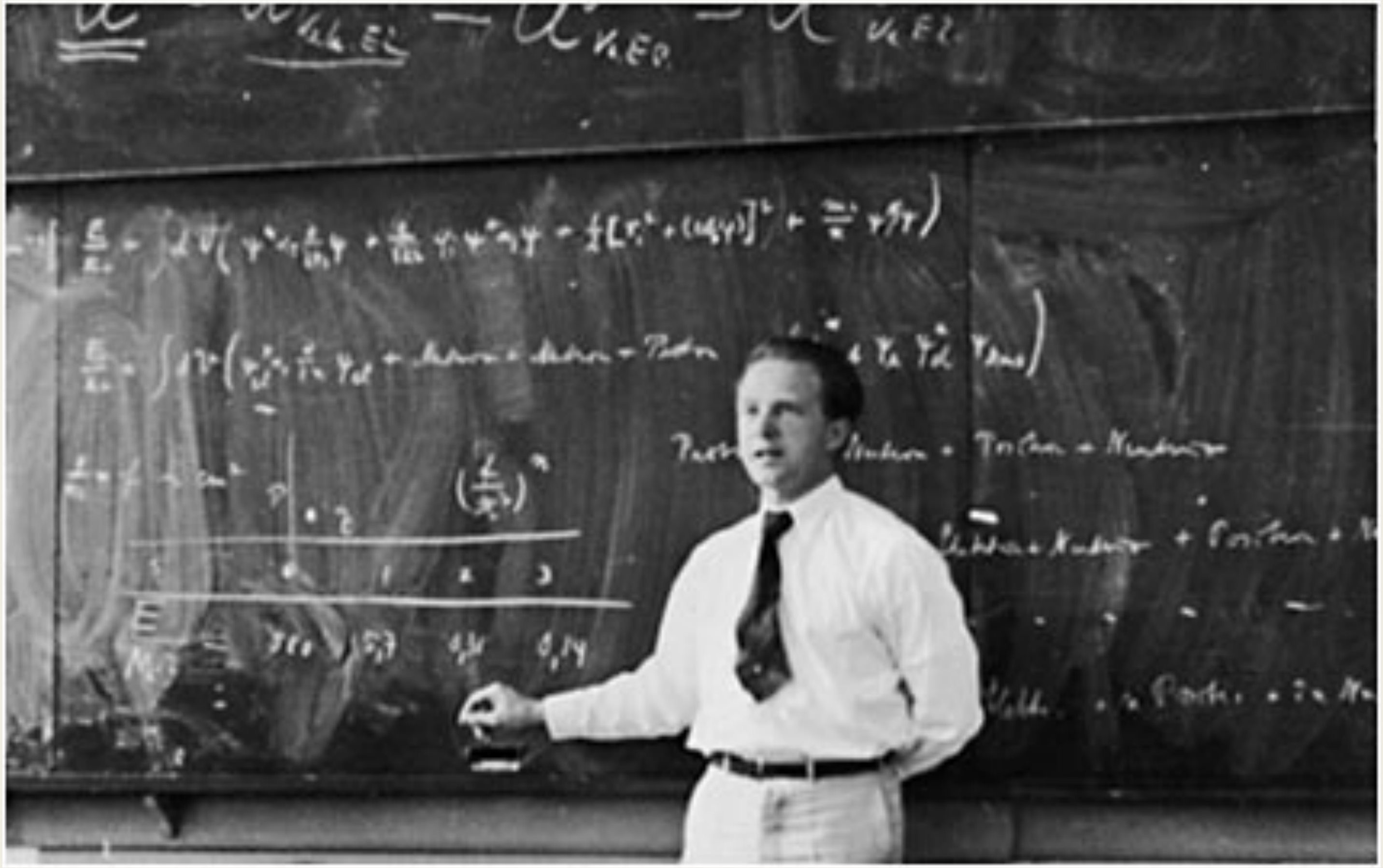
1608.01684

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





I. Frontiers of New Physics



One of the fundamental questions of particle physics:

$$\mathcal{L}_{world} = \mathcal{L}_{Standard\ Model} + \mathcal{L}_{General\ Relativity} + \mathcal{L}_{????}$$

What is $\mathcal{L}_{????}$?

What new particles, interactions or forces lie beyond our current knowledge?

There are many reasons $\mathcal{L}_{????}$ should be present.

1. Dark matter

2. Replication of three chiral generations

3. Baryogenesis – the origin of the matter/antimatter symmetry in the universe

4. The need for a *quantum* theory of the gravitational interactions rather than a classical one

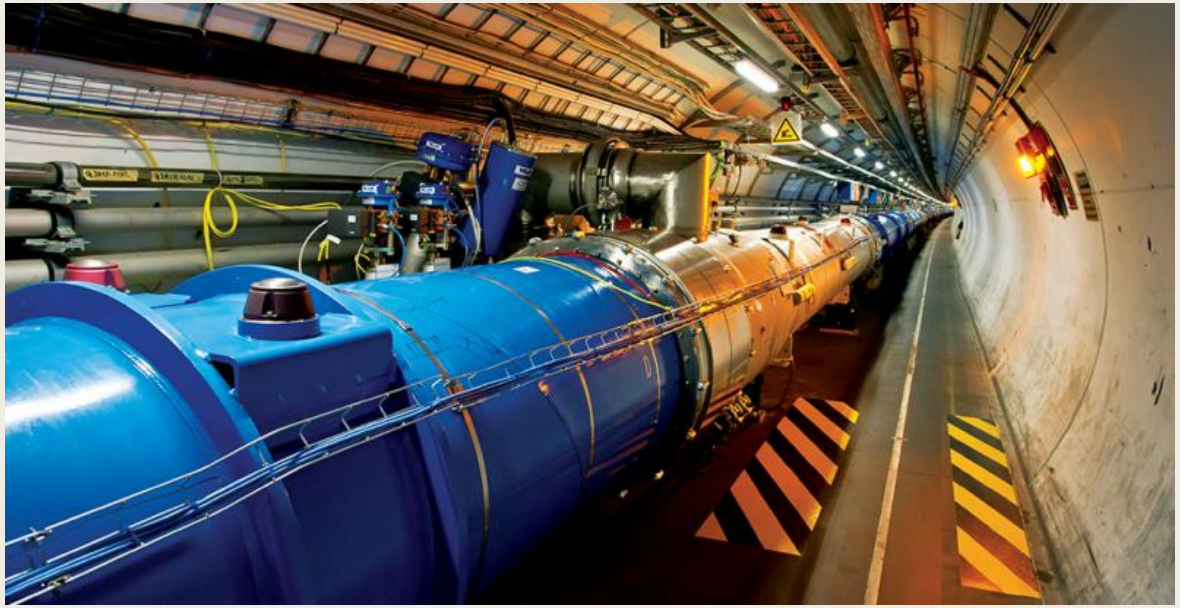
5. The strong CP problem – why is the Theta angle in the Quantum Chromodynamics Lagrangian

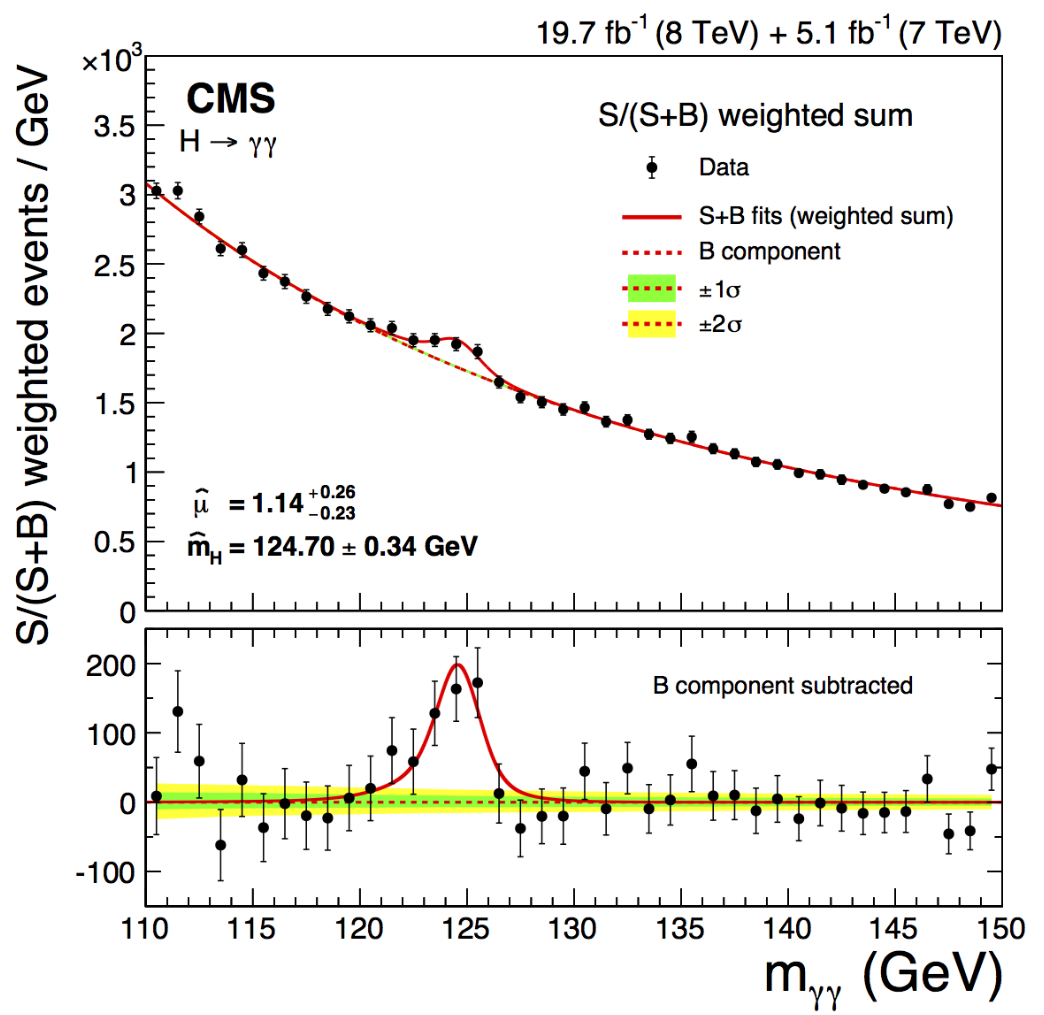
$$\mathcal{L}_{QCD} = \frac{1}{4g^2} F_{\mu\nu}F^{\mu\nu} + \frac{\theta}{8\pi^2}\epsilon_{\alpha\beta\gamma\delta}F_{\mu\nu}F^{\mu\nu} + \Sigma_i m_i \bar{q}_i q_i$$

so close to zero?

Search Strategy I

- Search for *heavy,* relatively *strongly interacting* particles, where *the barrier to discovery is insufficiently energetic phenomena.*





- LHC and Higgs discovery prime example of this

Search Strategy II

- For *light, extremely weakly interacting* particles, LHC-style searches are not useful.

  (collisions at the LHC do not probe the gravitational force)

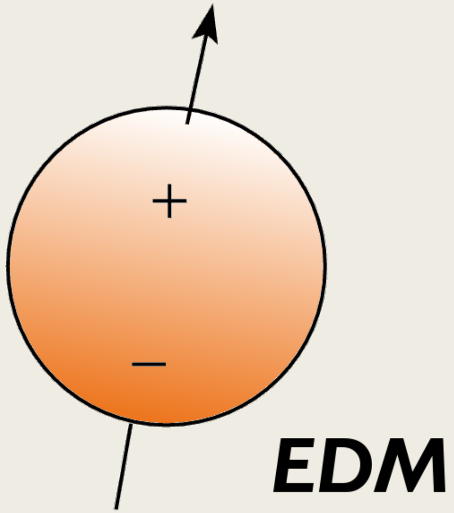
- For new physics with no energetic costs to production, but that is just very weakly coupled to the Standard Model, new strategies are needed.

- The *weak coupling* frontier of particle physics is almost orthogonal to the direction represented by the Large Hadron Collider.

II. Axions and Axion-Like Particles (ALPs)

The original QCD axion

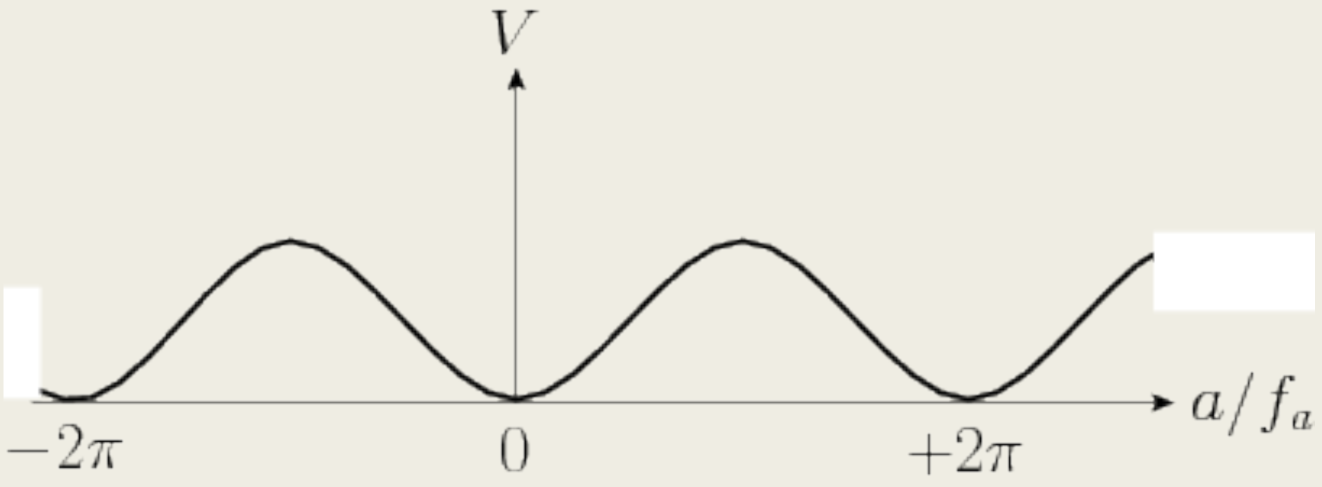
- $$\mathcal{L}_{QCD} = \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} + \frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F^{\alpha\beta} F^{\gamma\delta} + \Sigma_i m_i \bar{q}_i q_i$$
- The θ term in the QCD Lagrangian violates parity. Its experimental consequence is an electric dipole moment for the neutron.



- For typical values of θ (between 0 and 2π) this generates a neutron electric dipole moment of $\sim 10^{-17} e$ cm
- Current bound on neutron dipole moment is $< 3\times10^{-26} e$ cm - θ is very close to zero.

Non-perturbative QCD effects lead to a potential that depend on the θ angle

$$V_{axion}(a) = \Lambda_{QCD}^4\left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$



Promote the θ angle to a dynamical quantity $\left(\theta = \frac{a}{f_a}\right)$. This dynamically minimises θ at zero, and generates a mass term for the QCD axion a

$$m_a^2 = V''(a) = \frac{\Lambda_{QCD}^4}{f_a^2}, \qquad m_a \sim \left(\frac{10^{11}\text{GeV}}{f_a}\right) 10^{-3}\text{eV}$$

The QCD Axion (if it exists) is very light and has very weak interactions with the Standard Model

Axions

- The axions is valued on a circle and so has an angular periodicity
- The basic axion Lagrangian is

$$\mathcal{L}_{ALP} = -\frac{1}{2}\partial_\mu a \partial^\mu a + V(a)$$

  subject to $V(a) \equiv V(a + 2\pi f_a)$
- The angular periodicity implies that direct 'perturbative' contributions to the potential such as $m_a a^2$or λa^4 are forbidden by the periodicity
- The leading contributions to axion potentials come from (small) non-perturbative terms such as $\Lambda^4 \sin(\frac{a}{f_a})$ where Λ arises from exponentially suppressed effects.
- This has the key consequence that axions are naturally very light (or massless).

Axions 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

- Axions are one of the most motivated targets in looking for signatures of string compactifications

Axions in String Theory

- In higher-dimensional theory, dimensional reduction of terms like (as one example)

$$\int C_4 \wedge F_2 \wedge F_2 \; d^8x$$

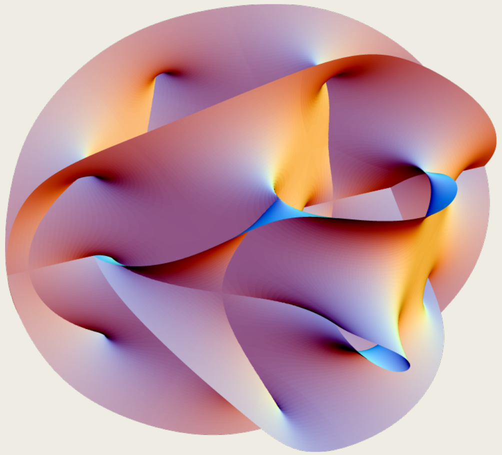
gives rises to lower-dimensional axionic couplings

$$\int a_i \, F_2 \wedge F_2 \; d^4x$$

with a separate axion $a_i = \int_{\Sigma_i} C_4$ for each 4-cycle Σ_i the field C_4 is reduced on

- Number of axions ~ topological complexity of extra dimensions

and 6-dimensional Calabi-Yaus can be rather topologically complex



Axion-Like Particles (ALPs)

- The original, QCD axion is defined by the additional coupling to the strong force

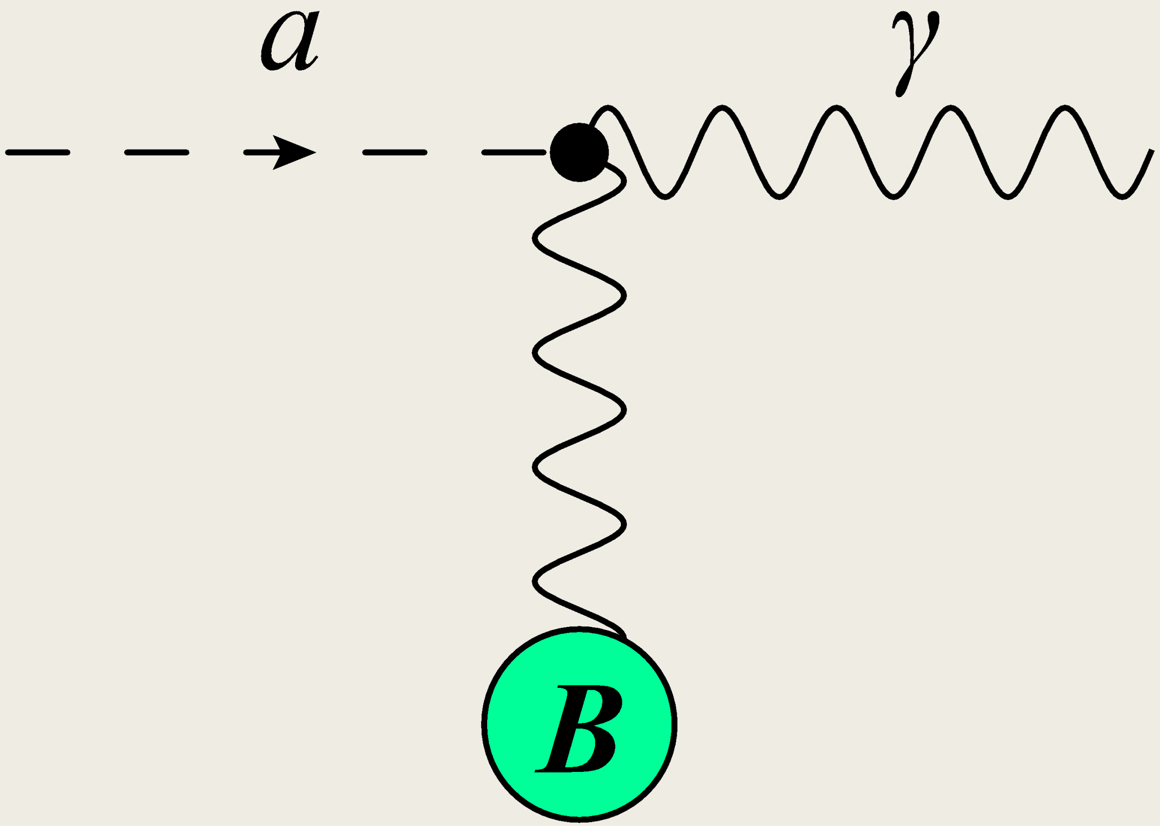
$$aF_{QCD}\tilde{F}_{QCD}$$

  when the θ angle is promoted to be a dynamical variable.
- *Axion-like particles (ALPs)* have no coupling to the strong force.
- *The key coupling for axion-like particles* is the coupling to electromagnetism

$$\frac{a}{8\pi^2 f_a}\epsilon_{\alpha\beta\gamma\delta}F^{\alpha\beta}F^{\gamma\delta} \equiv a\, g_{a\gamma\gamma}\mathbf{E.B}$$

- This coupling sets the interaction between the ALP a and the Standard Model fields.

III. Axion Phenomenology



Axion Phenomenology

- The coupling

$$a\, g_{a\gamma\gamma} \mathbf{E}.\mathbf{B}$$

  is key to searches for ALPs.

- In a fixed background magnetic field, this mixes the ALP a and the photon γ mass eigenstates.

$$\begin{array}{ccc} |\gamma_1> & & |\gamma_1> \\ |\gamma_2> & \rightarrow & \cos\phi|\gamma_2> + \sin\phi\ |a> \\ |a> & & \cos\phi\,|a> - \sin\phi\,|\gamma_2> \end{array}$$

- Analogous to neutrino oscillations, there are oscillations between the 'flavour' eigenstates a and γ, while the 'mass' eigenstates are linear combinations of a and γ

- We restrict to light/massless ALPs in our discussion

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

Sikivie
Raffelt + Stodolsky

where B is transverse magnetic field

L is magnetic field coherence length

$g_{a\gamma\gamma}$ is (dimensional) ALP-photon coupling

$$P(\gamma \to a) \sim 1.2 \times 10^{-8} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{1\,\mu G}\right)^2 \left(\frac{L}{1\,\mathrm{kpc}}\right)^2$$

Astrophysical environments (B = $10^{-10} T$ L = 1 kpc) are overwhelmingly better than terrestrial environments (B = 10T, L = 10m)

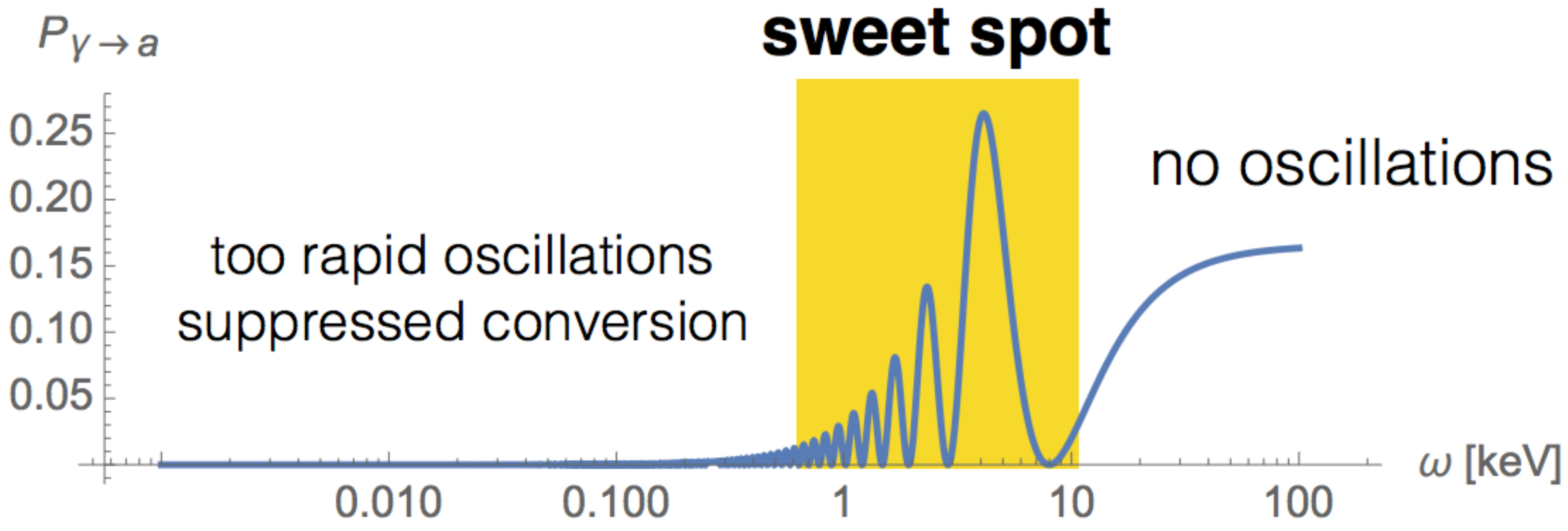
Photon-ALP Conversion – why X-rays?

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

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

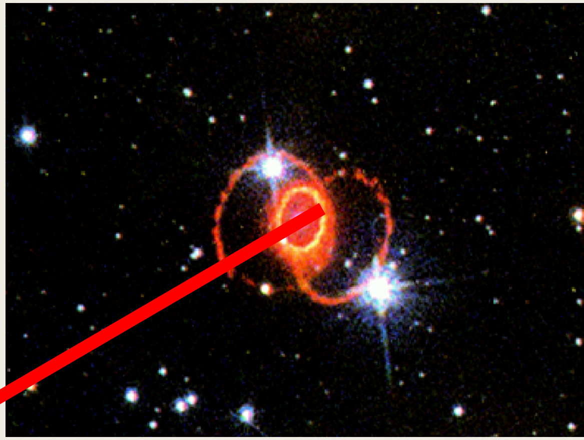
$$\Theta = 0.28\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\mathrm{keV}}{\omega}\right)$$

- Sweet spot at X-ray energies:



SN1987A constrains $g_{a\gamma\gamma} < 5 \times 10^{-12}$ GeV^{-1}

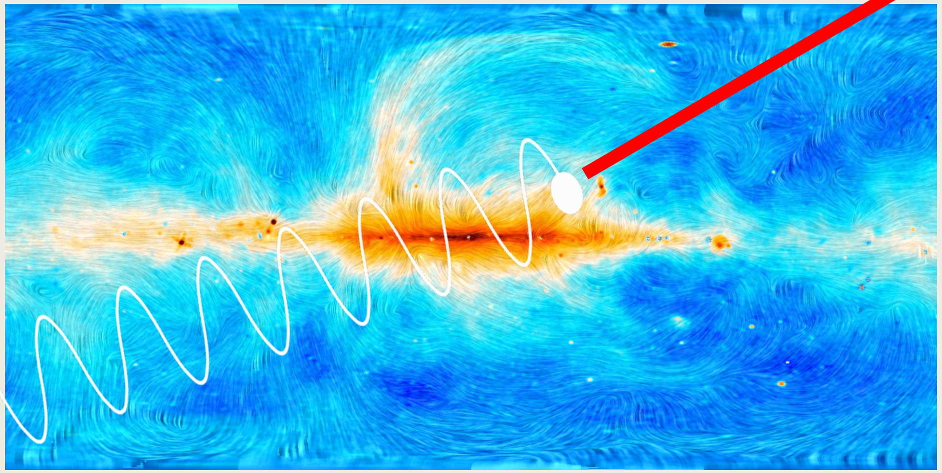
Brockway, Carlson, Raffelt astro-ph/9605197
Grifols, Masso, Toldra astro-ph/9606028
Payez et al 1410.3747



SN1987A

a

Milky Way B Field



Solar Maximum Mission

γ

IV. Using AGNs to search for ALPs

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.

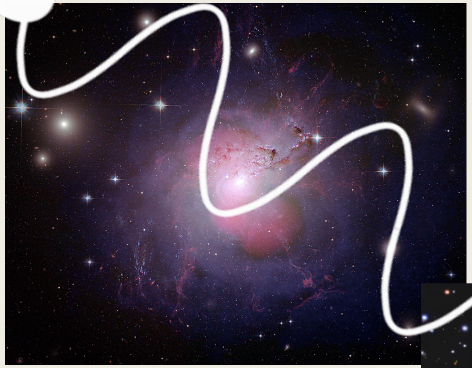
- In our case, the source A will be the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope

Originally Wouters + Brun 2013

AGN

Milli- parsec

NGC1275



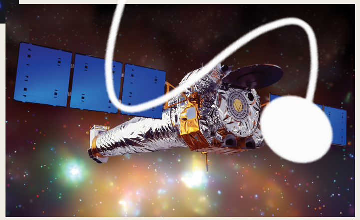
Hundred kilo-parsecs

Perseus cluster

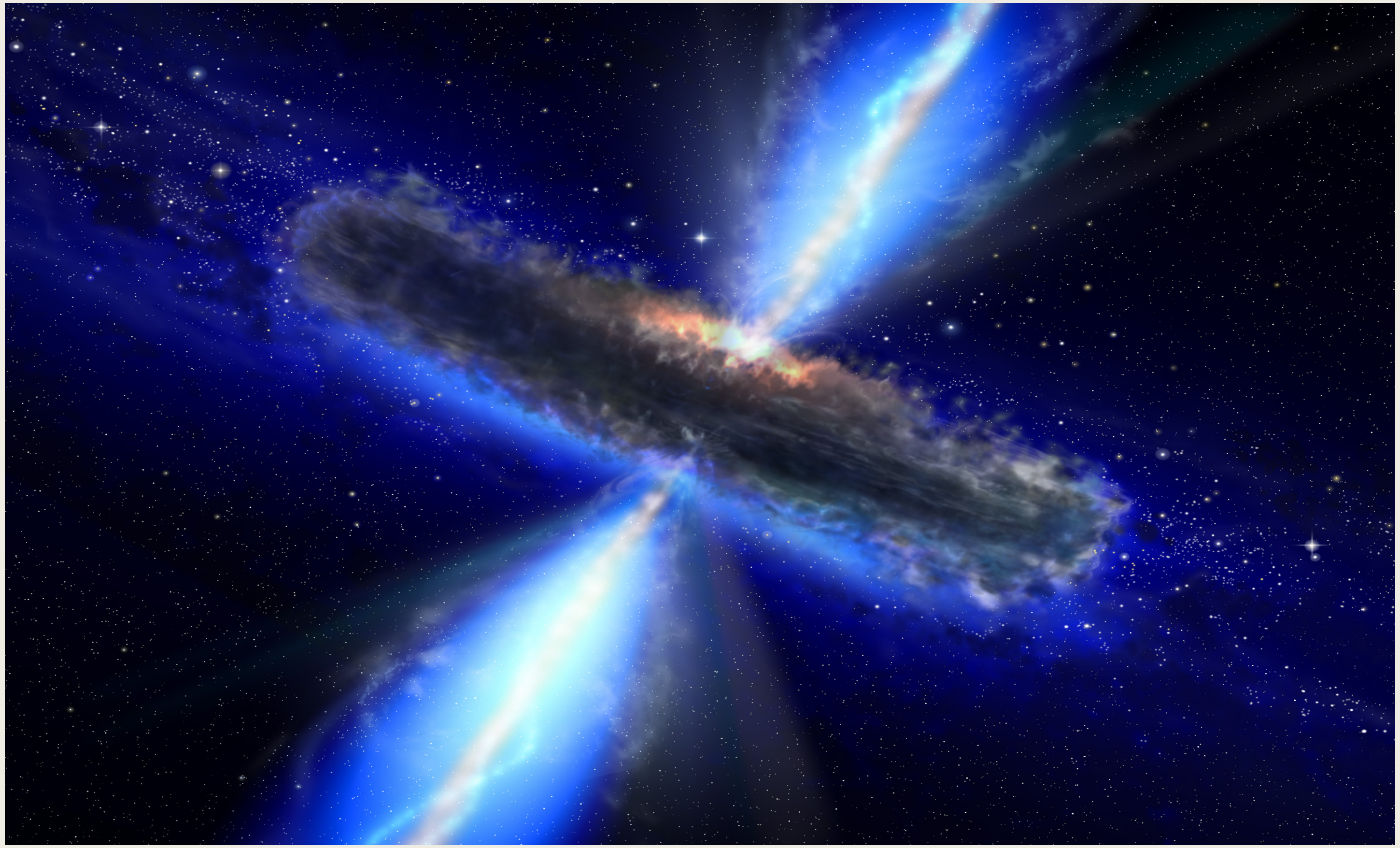
Megaparsecs

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

- 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 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

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 $n_H = 1.5 \times 10^{21} \mathrm{cm}^{-2}$ (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

Cluster Magnetic Fields

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

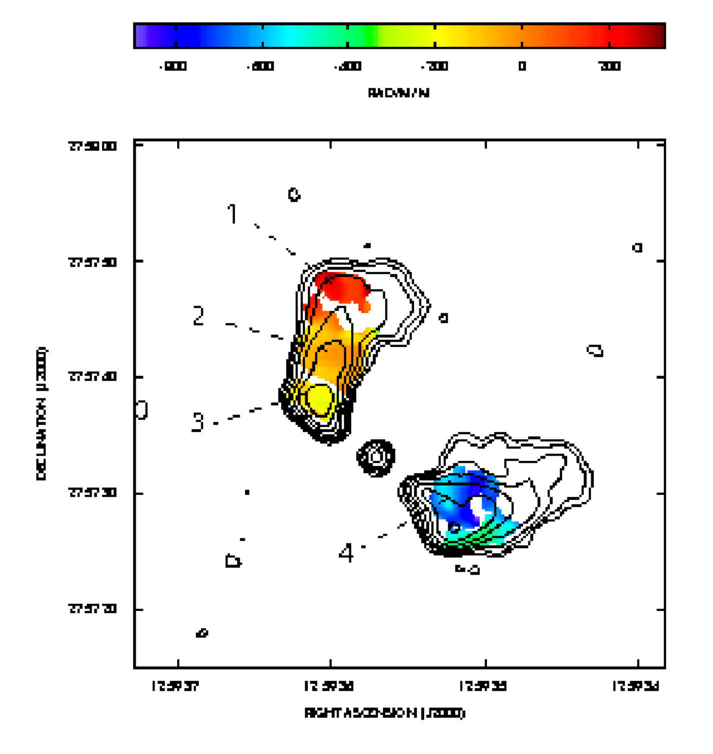
$$RM = 812\, rad\, m^{-2} \int \left(\frac{n_e}{10^{-3} cm^{-3}}\right)\left(\frac{B_{\|}}{1\ \mu G}\right) d(kpc)$$

- 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

Perseus Magnetic Field

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)

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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.

AGN 

Milli- parsec

NGC1275

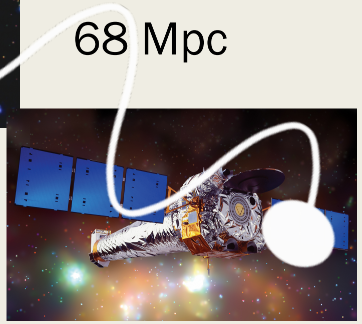
Hundred kilo-parsecs

Perseus cluster

Megaparsecs

68 Mpc

Chandra



Chandra X-ray telescope

~1.5 billion USD

15 years operation

Mature, well understood instrument

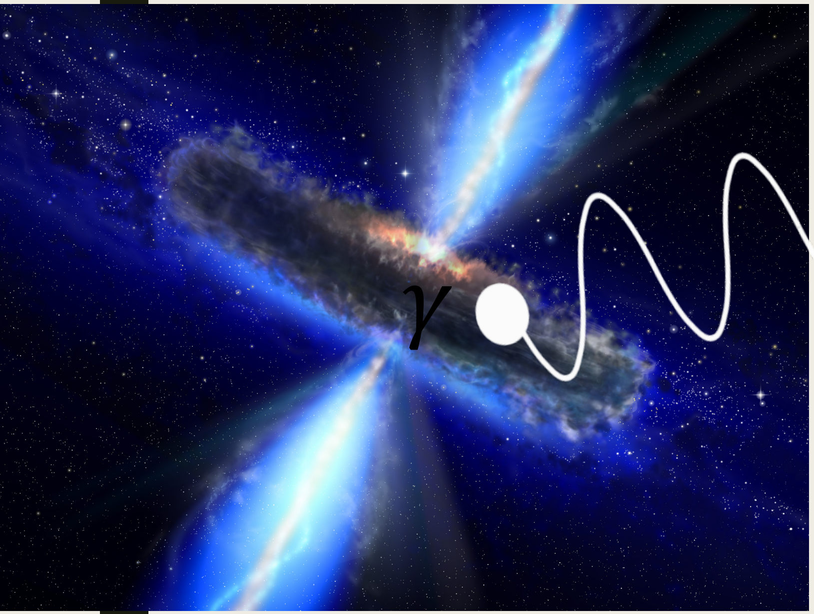
Large public observational data archive

Photon-ALP Conversion

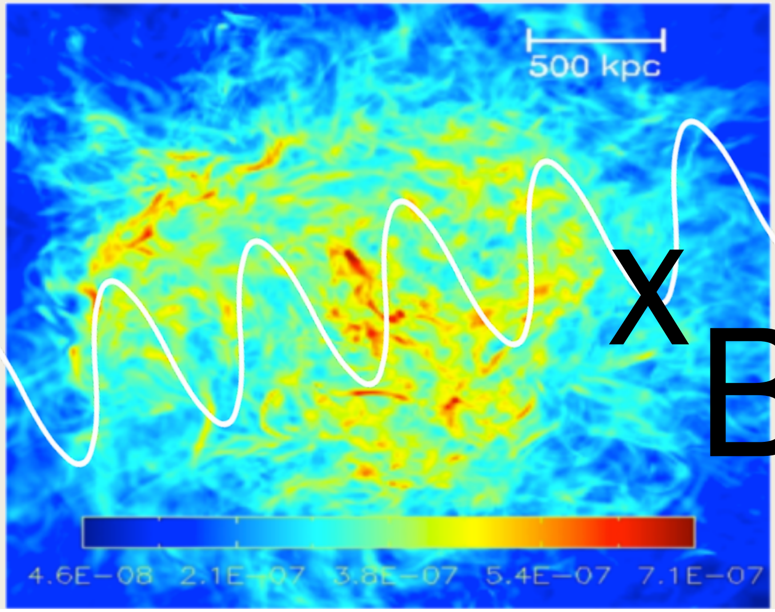
- Source is NGC1275, destination is earth: intervening magnetic field is magnetic field of the Perseus cluster.
- Galaxy clusters are particularly good locations for photon-ALP interconversion
- Magnetic fields extend over approx. 1 Mpc regions, with coherence lengths in 1- 10kpc region.
- Magnetic field 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.

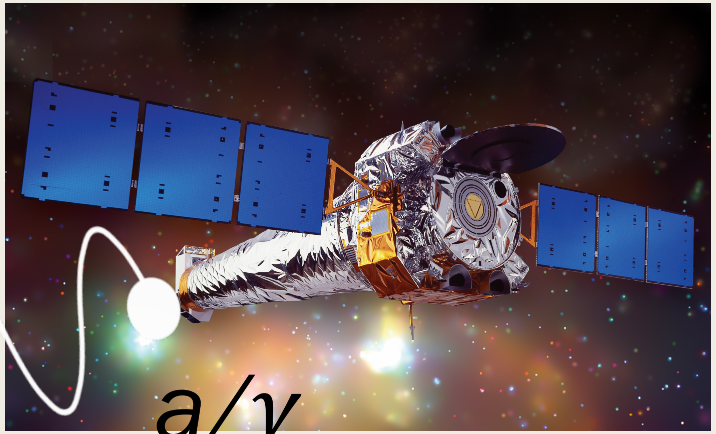
ALPS

AGNs are bright point sources of photons

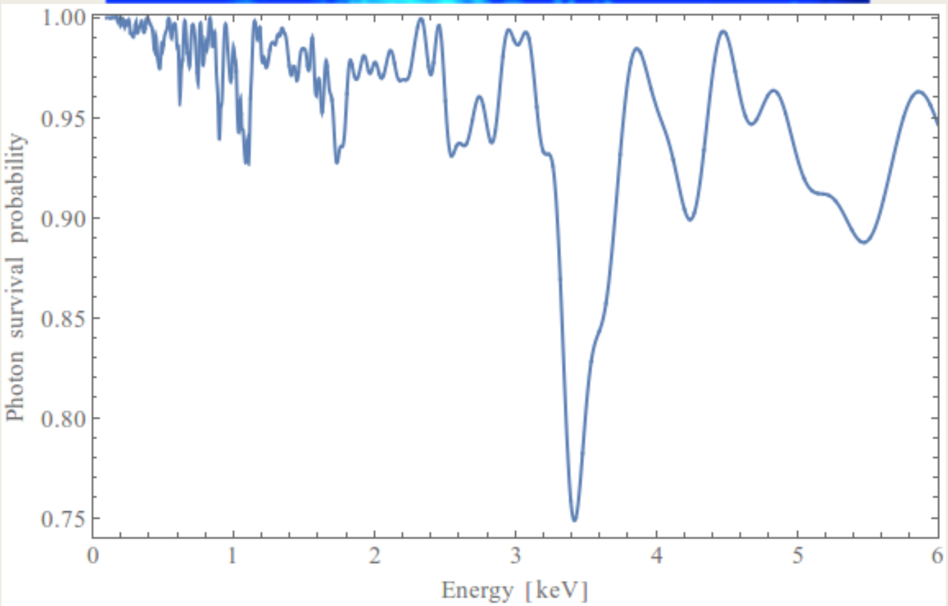


Photons pass through galaxy cluster magnetic field



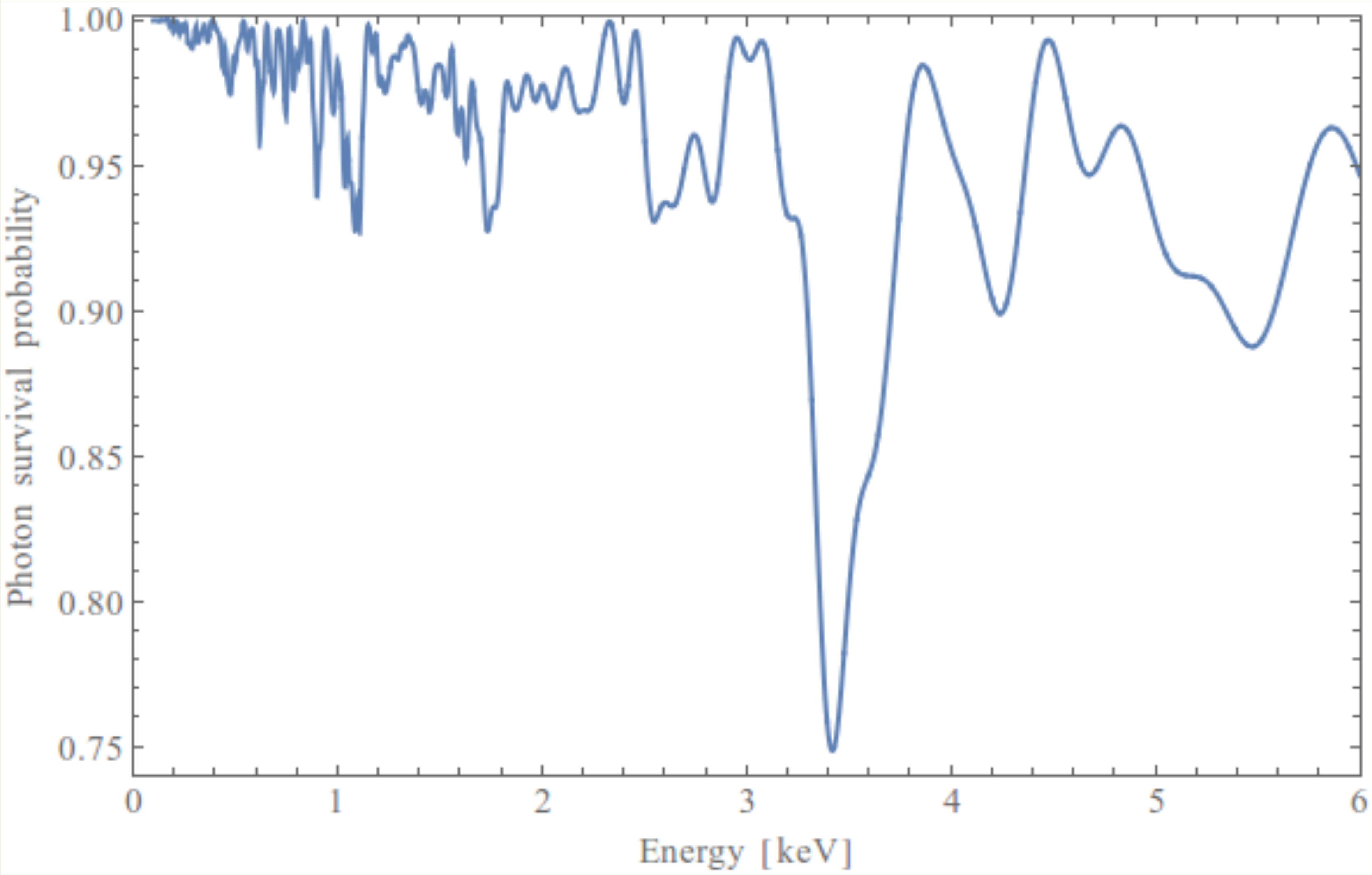


ALP-Photon conversion induces irregularities in observed X-ray spectrum



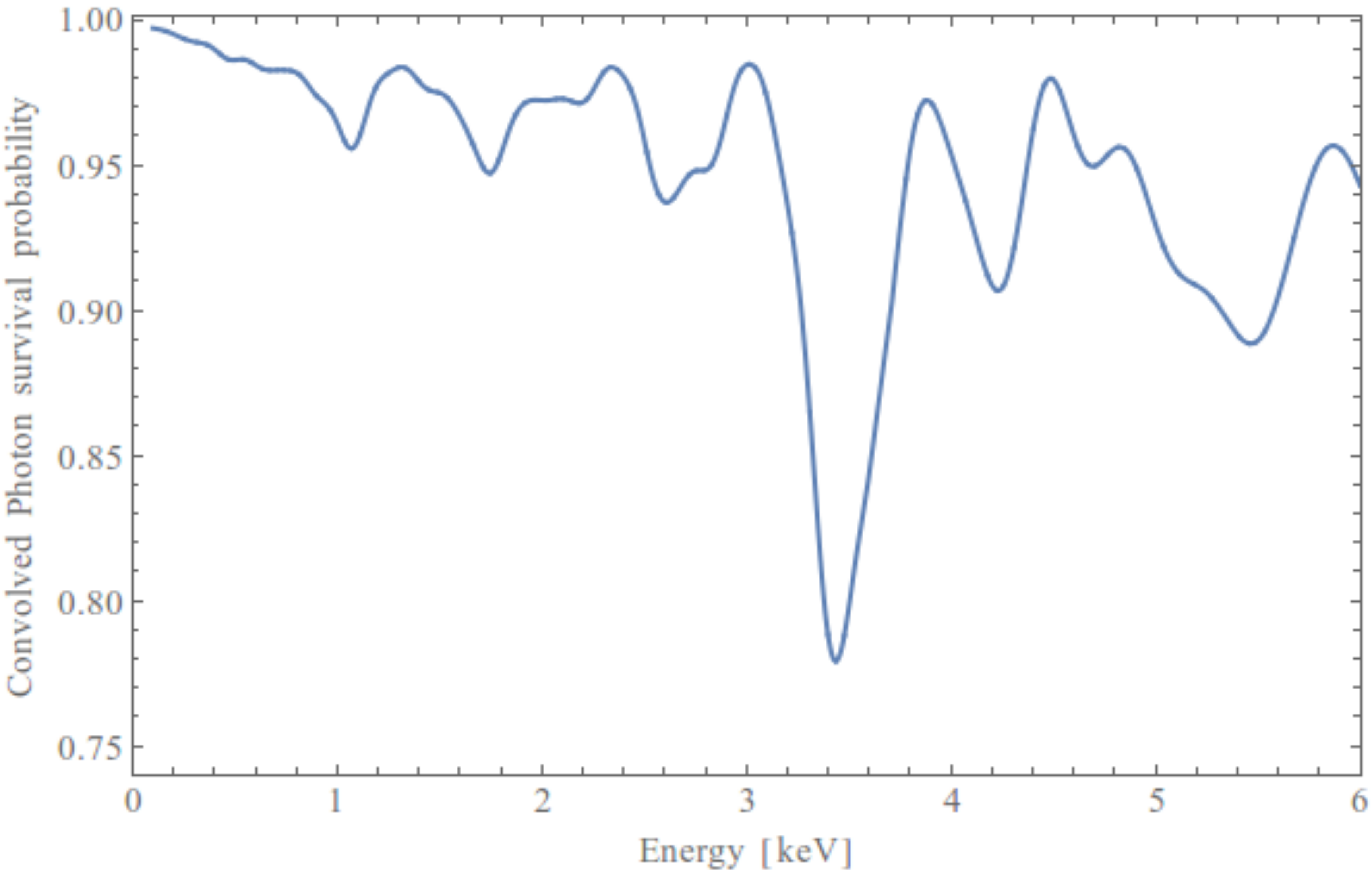
Precise form of modulations depends on cluster magnetic field

Simulated photon survival probability…



This would modulate the true spectrum

…now convolved with detector resolution

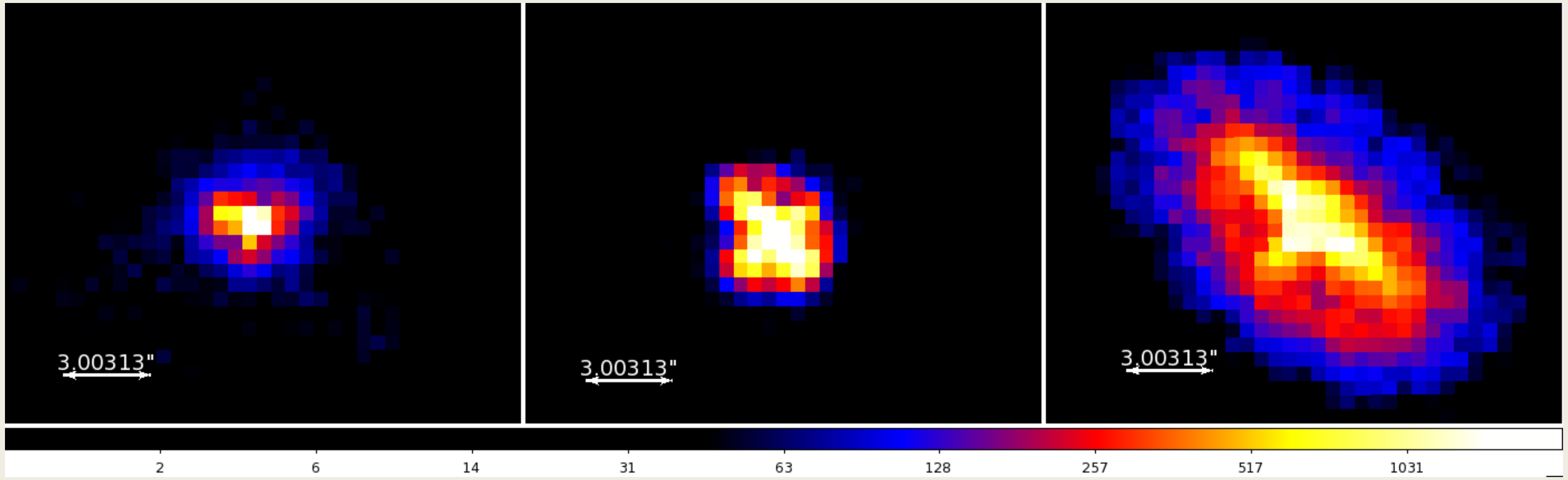


This would modulate the true spectrum

V. Data

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

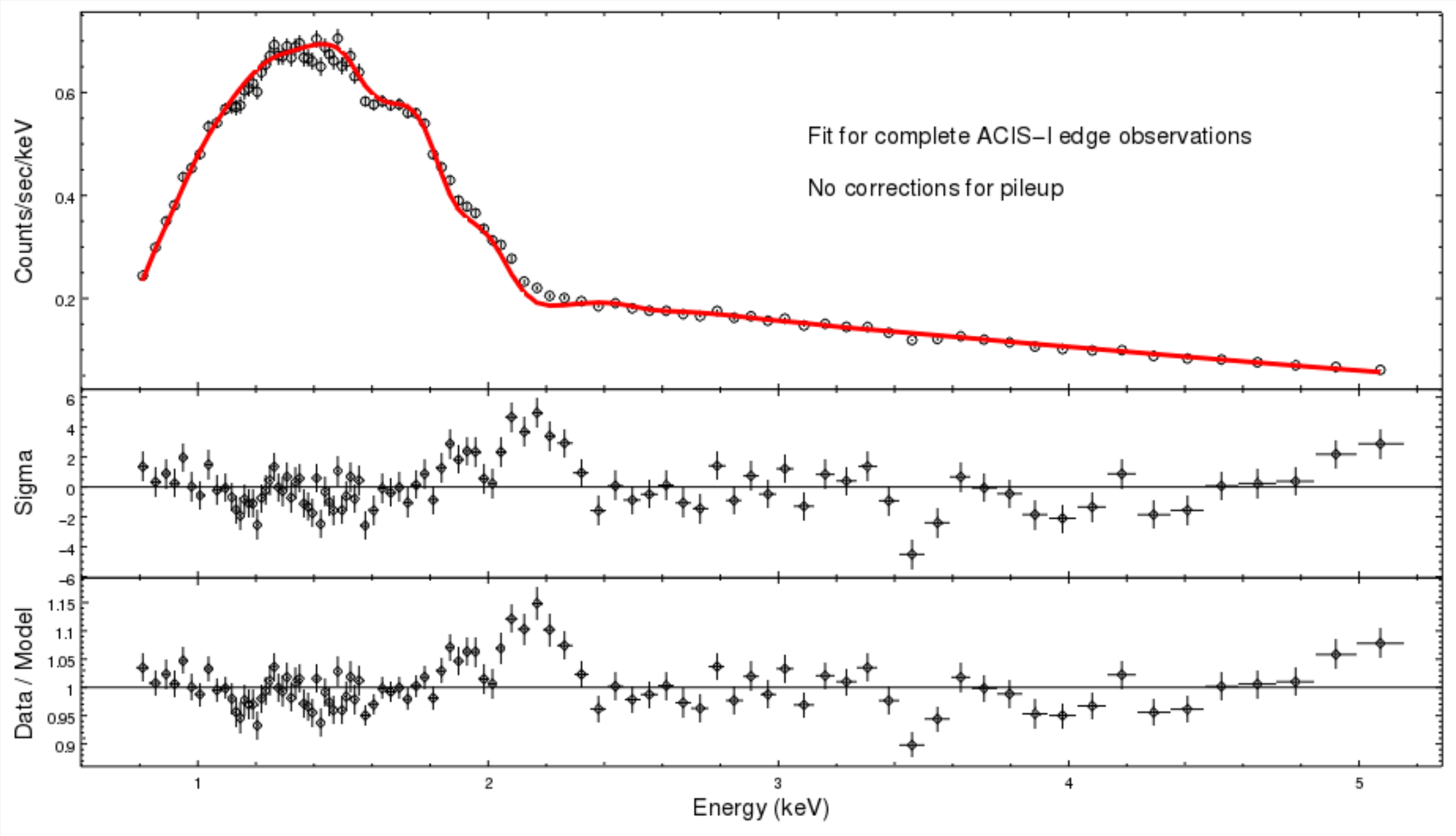
1. 230000 for 2009 ACIS-I ‘edge’ observations (cleanest dataset)

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



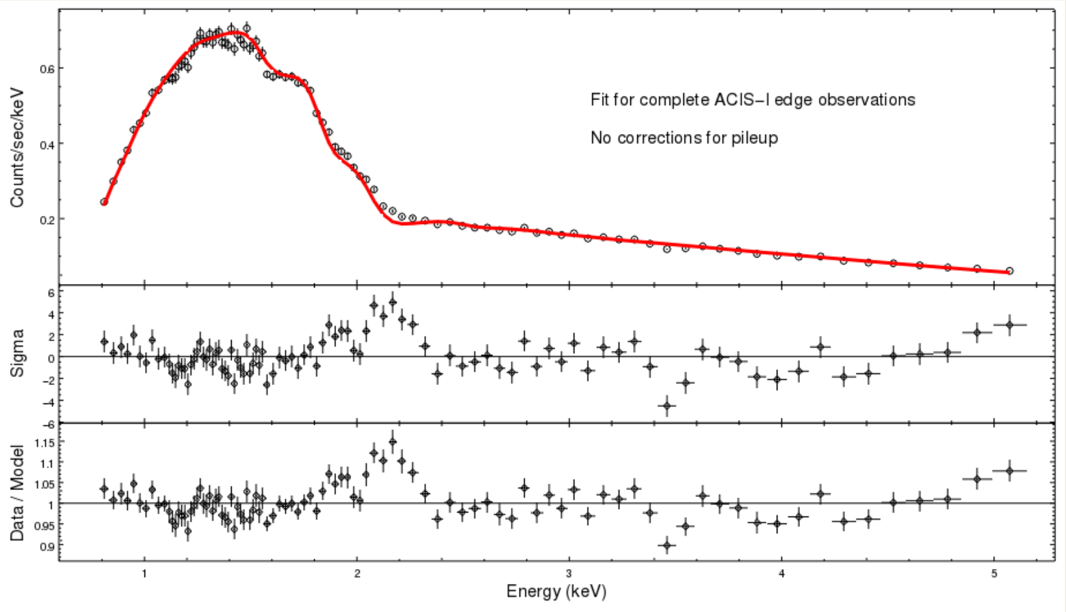
Fit to absorbed power law gives two main features – excess at 2 – 2.2 keV, deficit at 3.4 – 3.5 keV

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

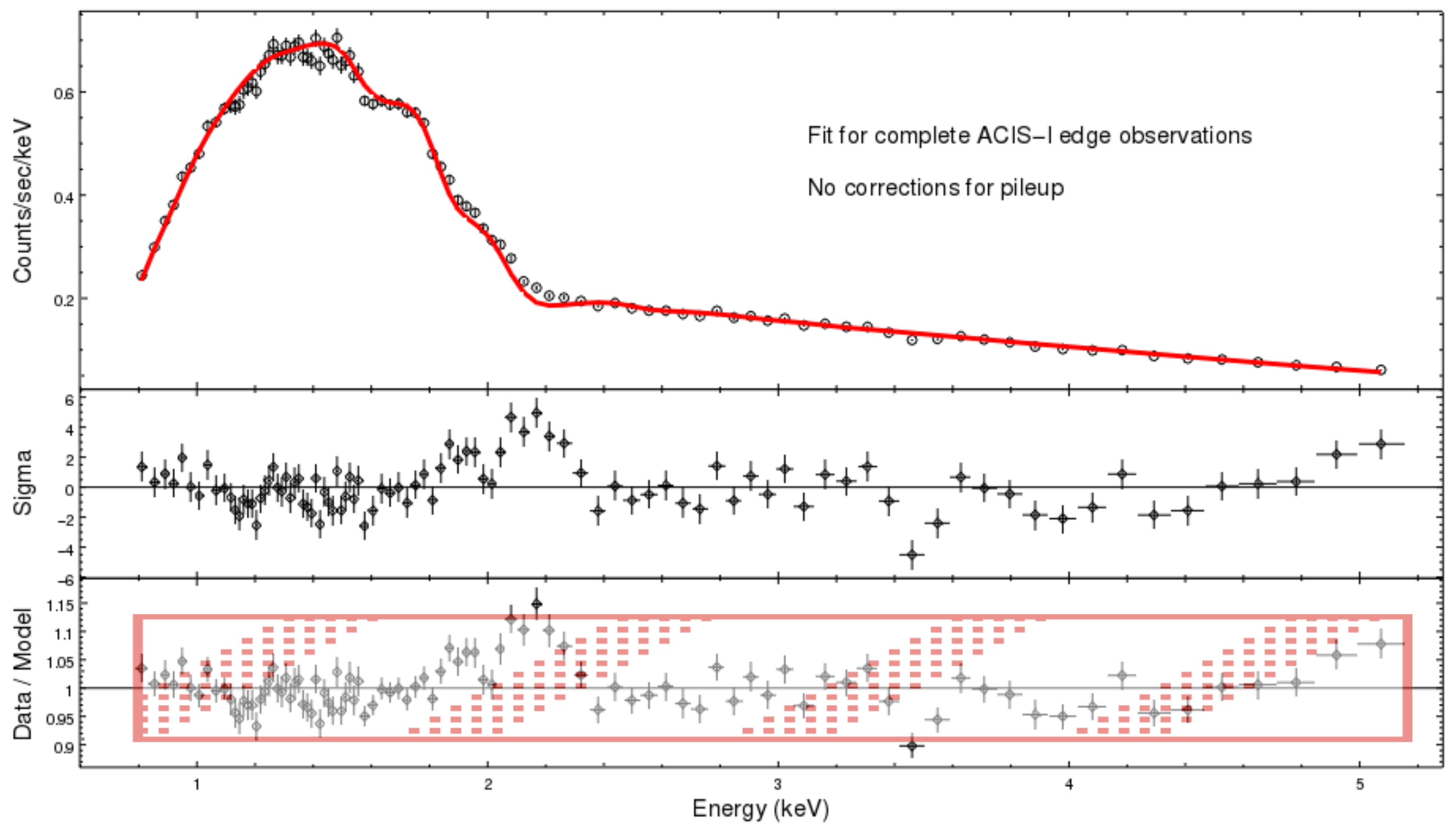
2. Deficit at 3.4 – 3.5 keV

No obvious systematic effects – connection to 3.5 keV line?

ALP Constraints

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

ALP couplings leading to 20-30% irregularities are excluded



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ALP Constraints

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

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

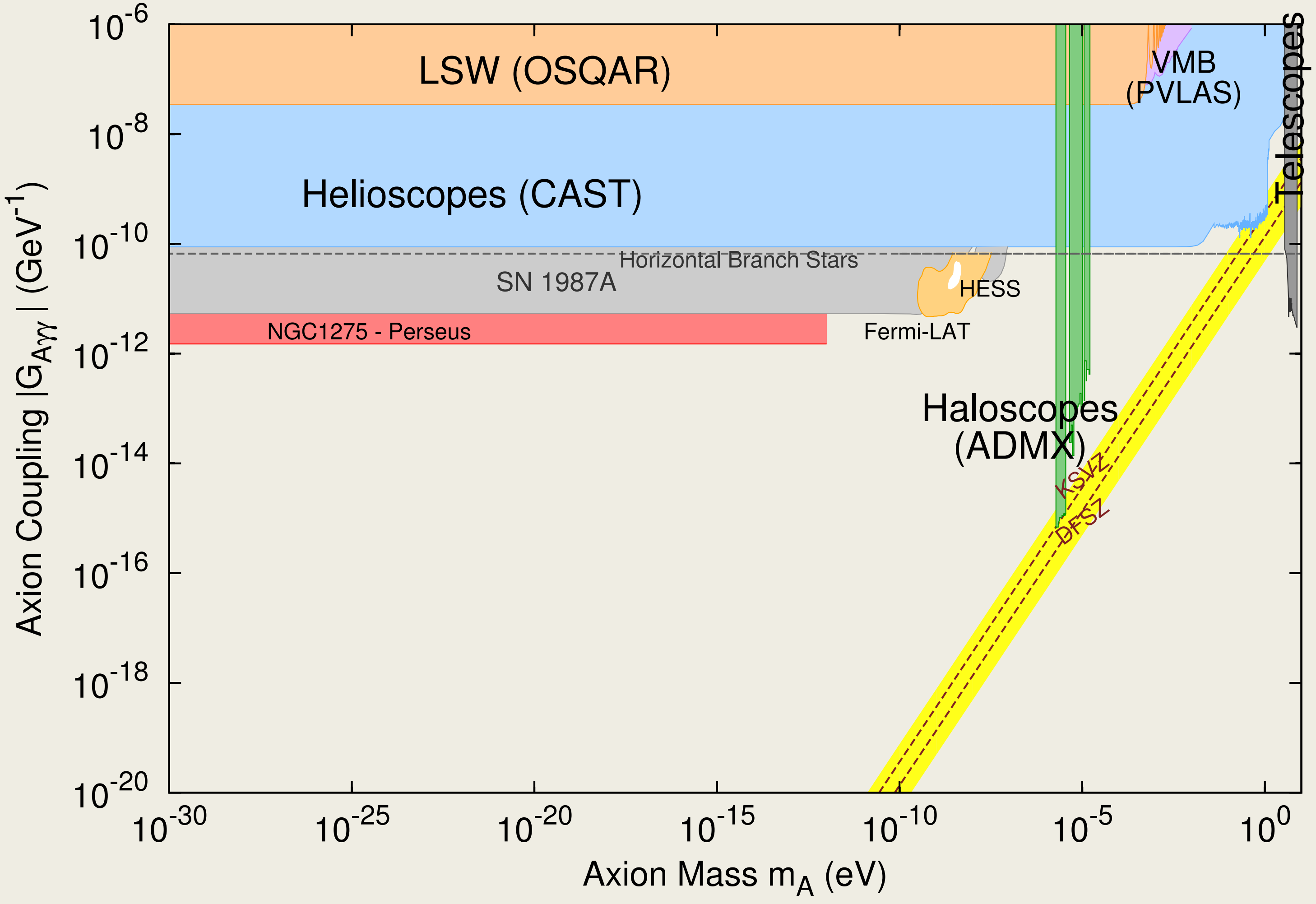
2. Conservative case: (B_central = 15 μG, 100 domains between 0.7 and 10kpc)

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

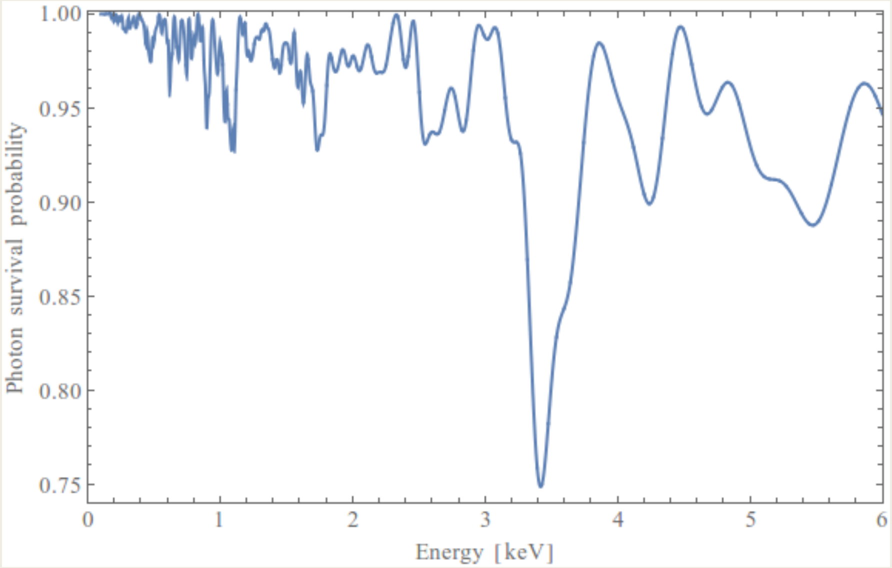
ALP Constraints

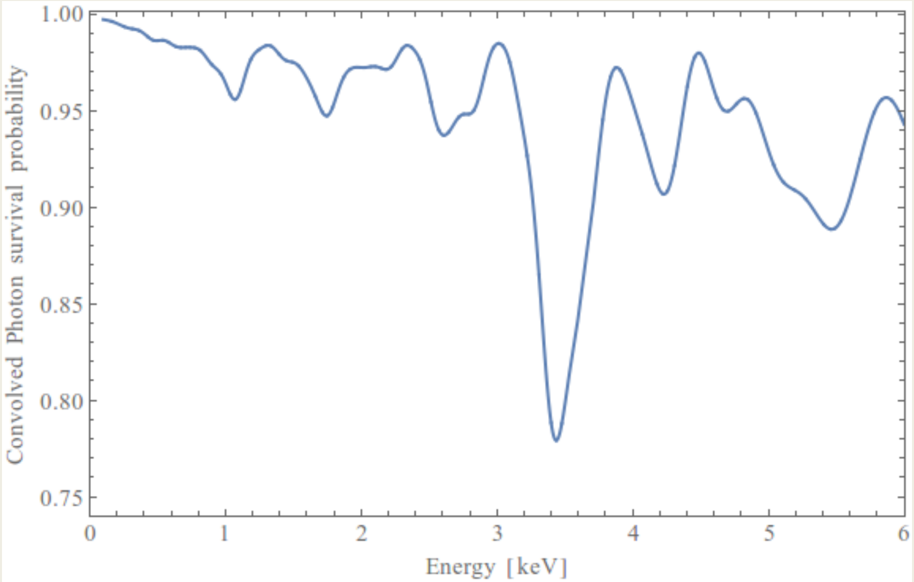
- A similar recent analysis has used data from M87 at centre of Virgo cluster to obtain similar bounds (1703.07354 Marsh et al)
- We recently extended these to various other sources in or behind galaxy clusters (using Coma, A1795, A2052, A3581, A1367) (1704.05256)

  Produces comparable (although weaker) constraints, consistent with sources that are not as bright

Limits on constraints

- Existing CCD technology has around 100eV energy resolution

Blurs 

to 

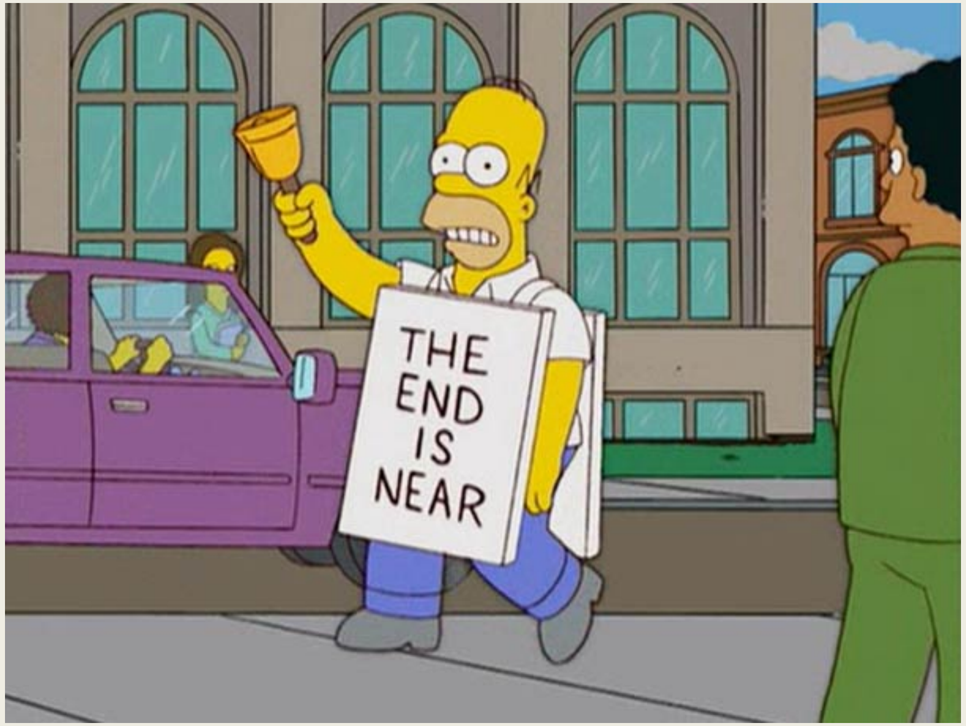
Better constraints will come from satellites with microcalorimeter technology and ~ 5eV

Microcalorimeters were on-board ASTRO-E (crashed), Suzaku (helium leak), Hitomi (lost after 1 month).....

In 2028 ESA will launch the L-class mission ATHENA as the next generation X-ray satellite

We estimate this will deliver a further factor of ten improvement in sensitivity to $g_{a\gamma\gamma}$

VI. Conclusions



Conclusions

- Axions (and more generally ALPs) are well-motivated extensions of the Standard Model that require search strategies orthogonal to those used at high-energy colliders

- ALPs interconvert with photons in magnetic fields

- This conversion is highly efficient at X-ray energies and passing through galaxy cluster environments

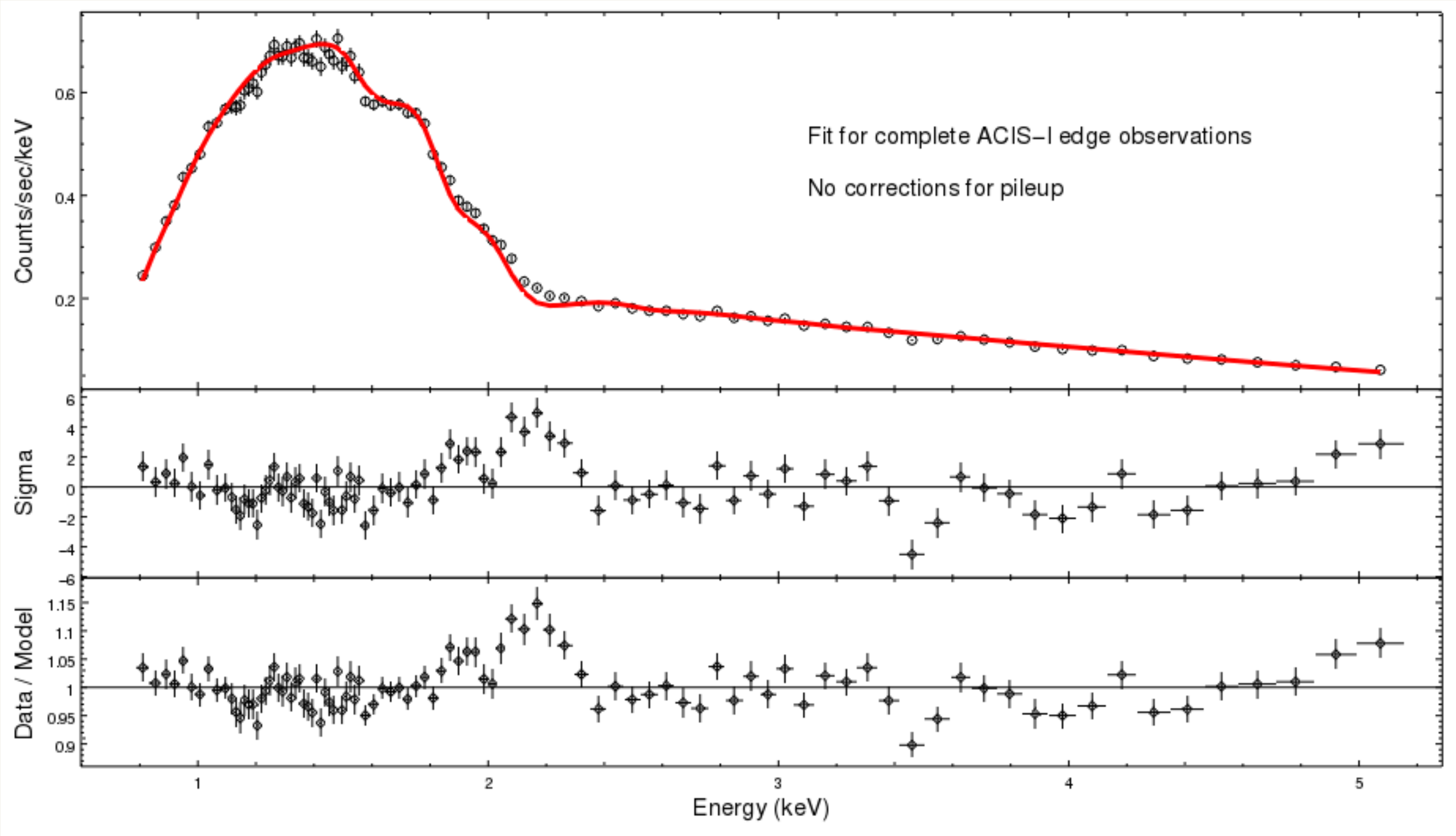
- Existing and future X-ray observations of Active Galactic Nuclei located in or behind galaxy clusters offer leading sensitivity to the ALP-photon coupling $g_{a\gamma\gamma}$

- X-ray astronomy offers novel and powerful ways to search for new fundamental physics

VII. Extra Slides

Connection to 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…

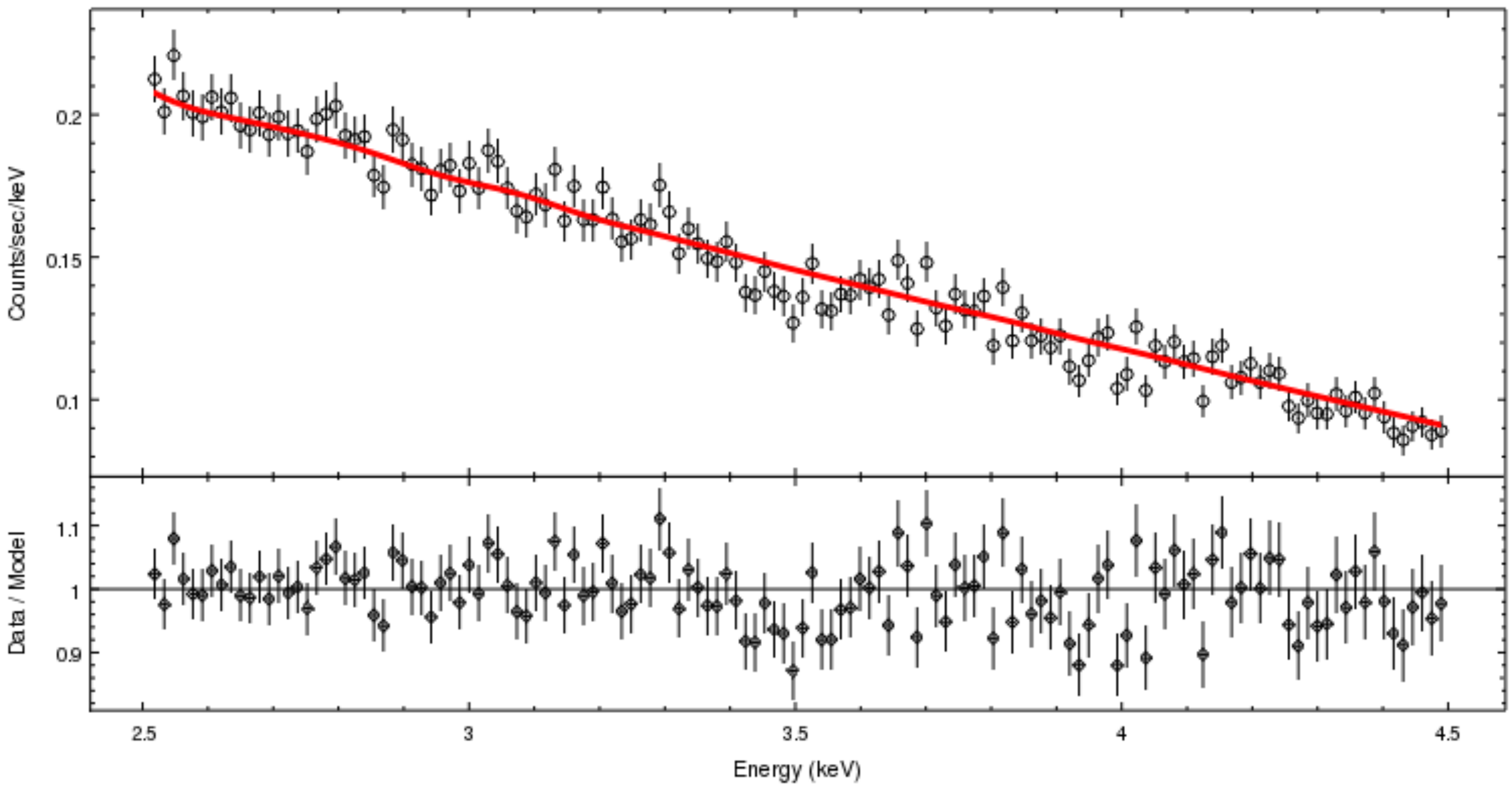
We fit from 0.8 to 5 keV and cut out 1.8 – 2.3 keV region to avoid biasing the fit.

Fit with xswabs * (xspowerlw + xsbapec)

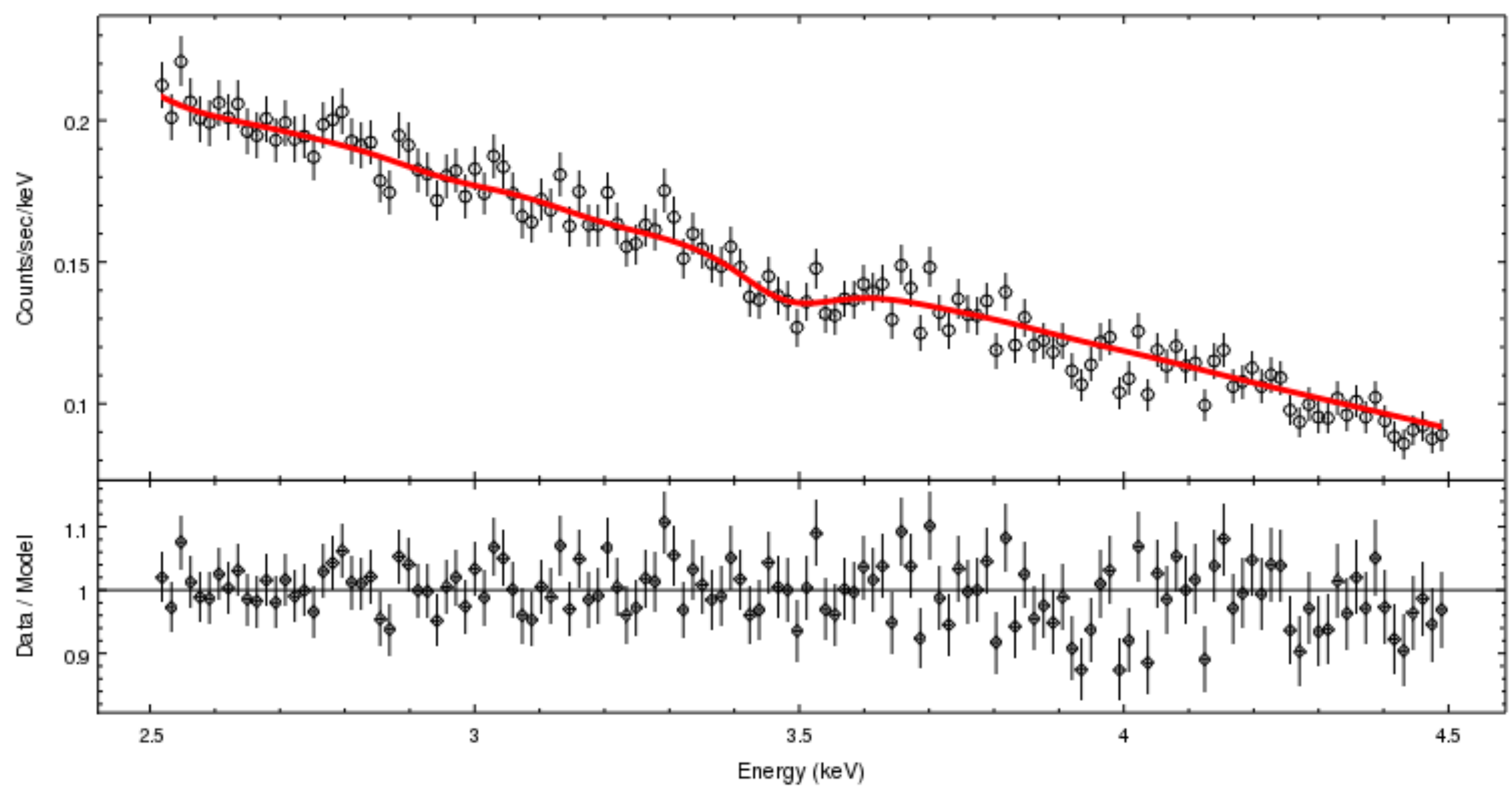
i.e. Absorption * (power law + thermal cluster emission)

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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[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

Conclusions

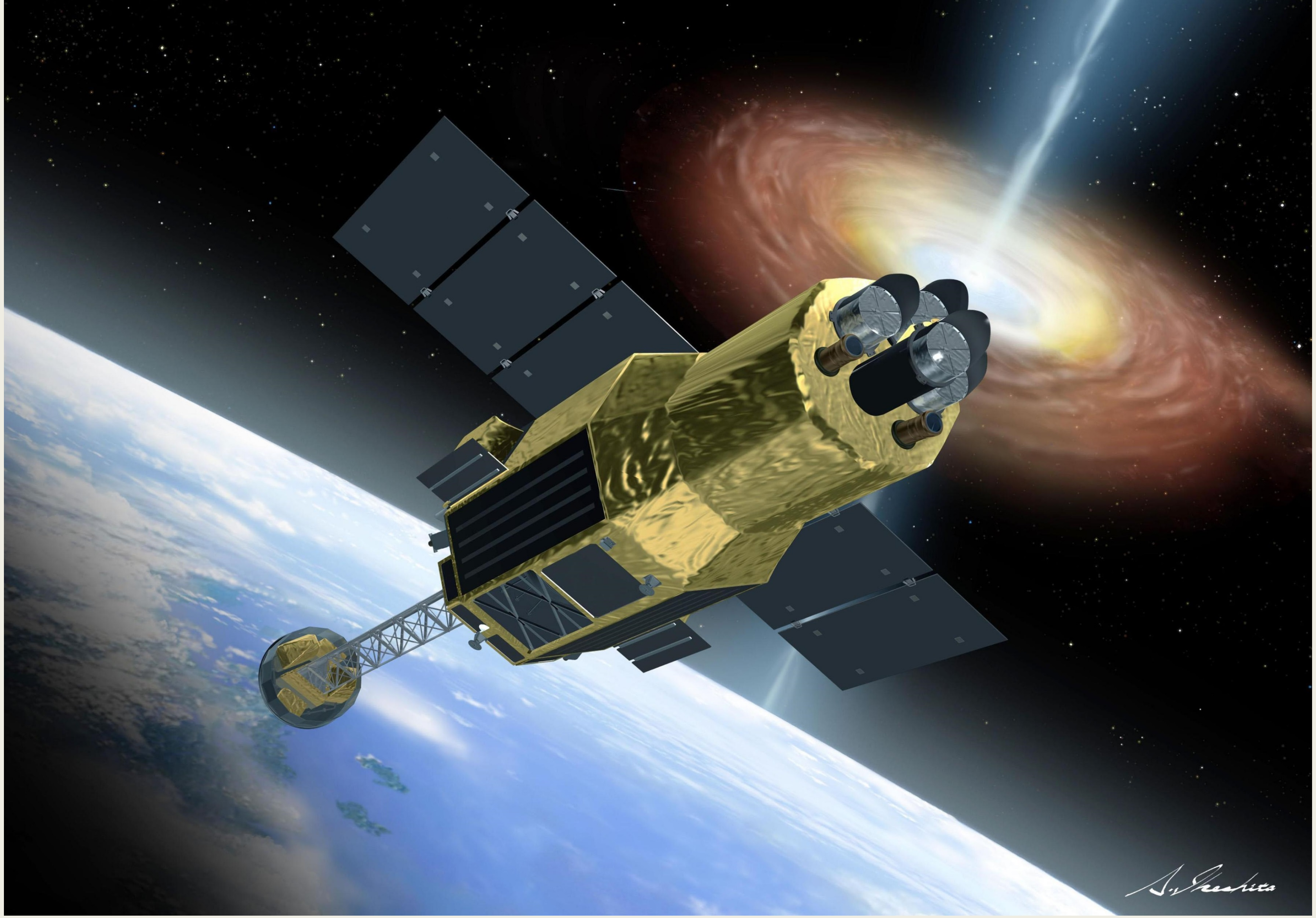
1. X-ray astronomy is a powerful probe of fundamental physics

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!



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


Launch of Hitomi from Tanegashima Space Centre
17th February 2016

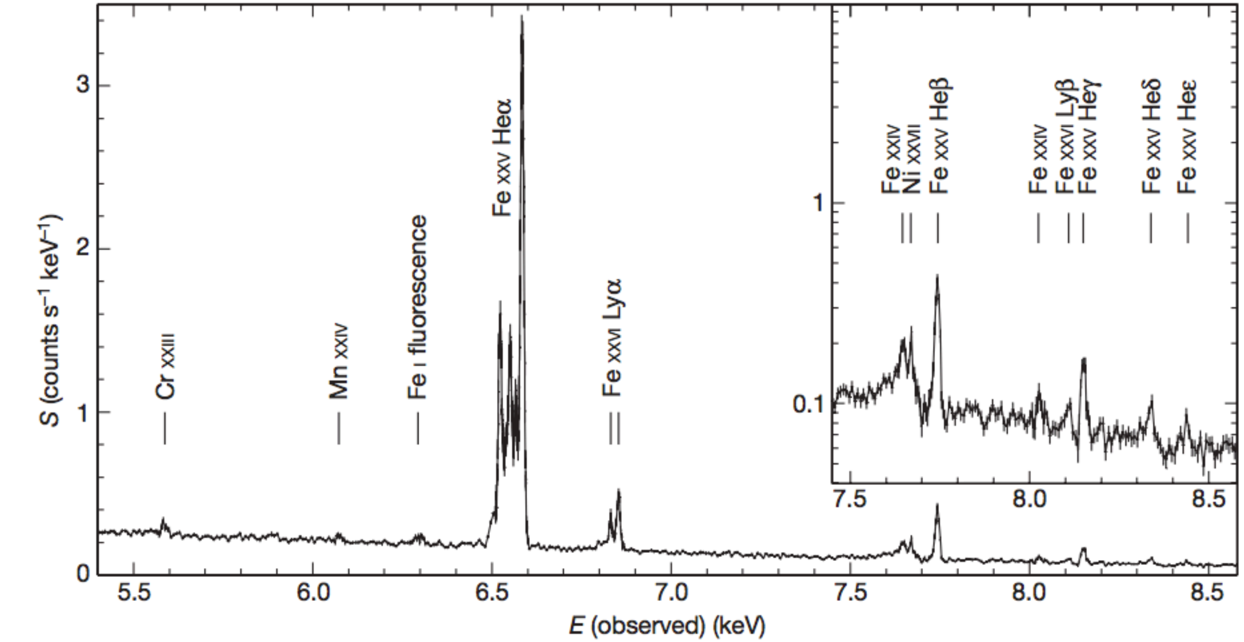
LETTER

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

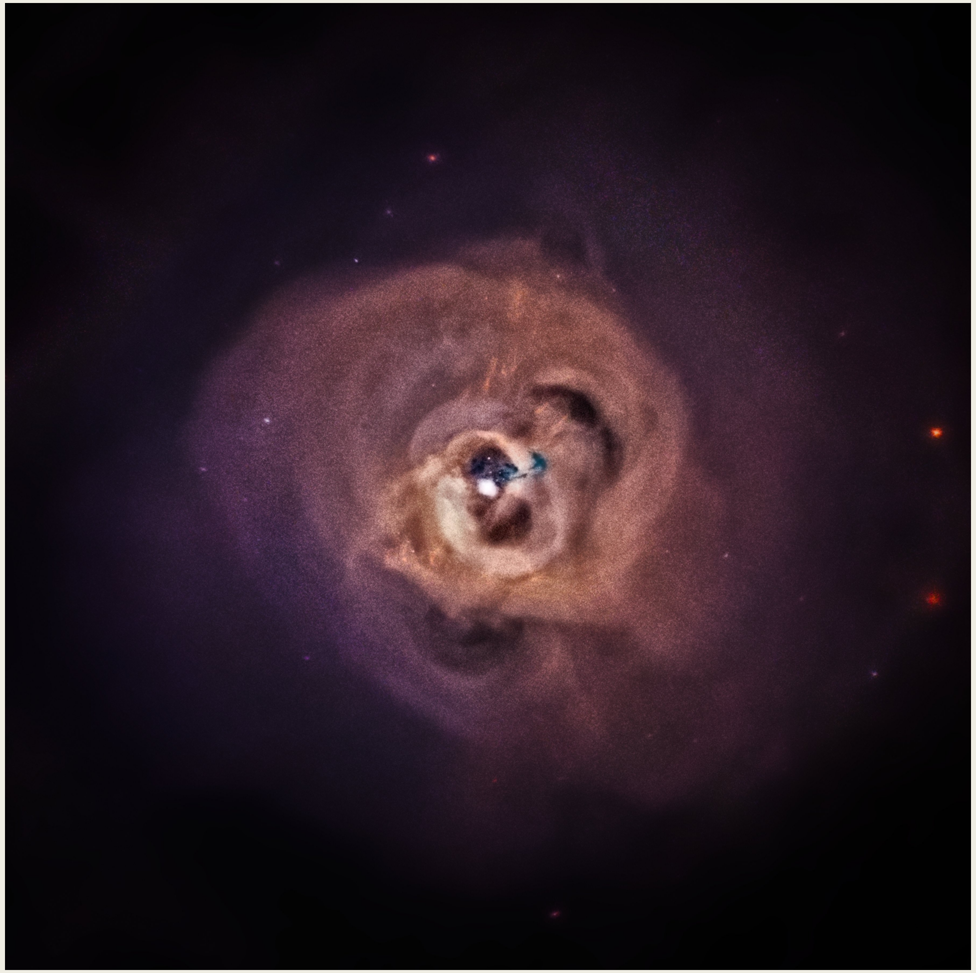


Hitomi returned a ground-breaking spectrum of Perseus before its tragic loss in March 2016

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

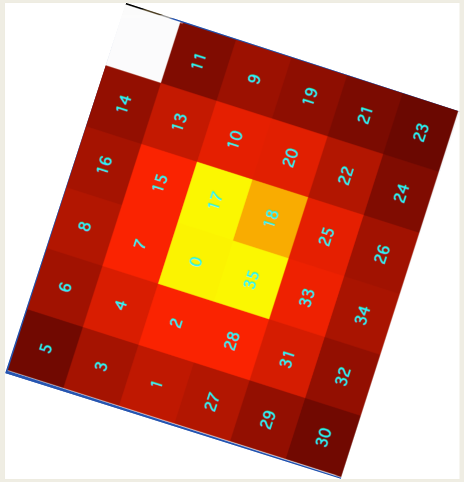
Images of the centre of Perseus

CHANDRA



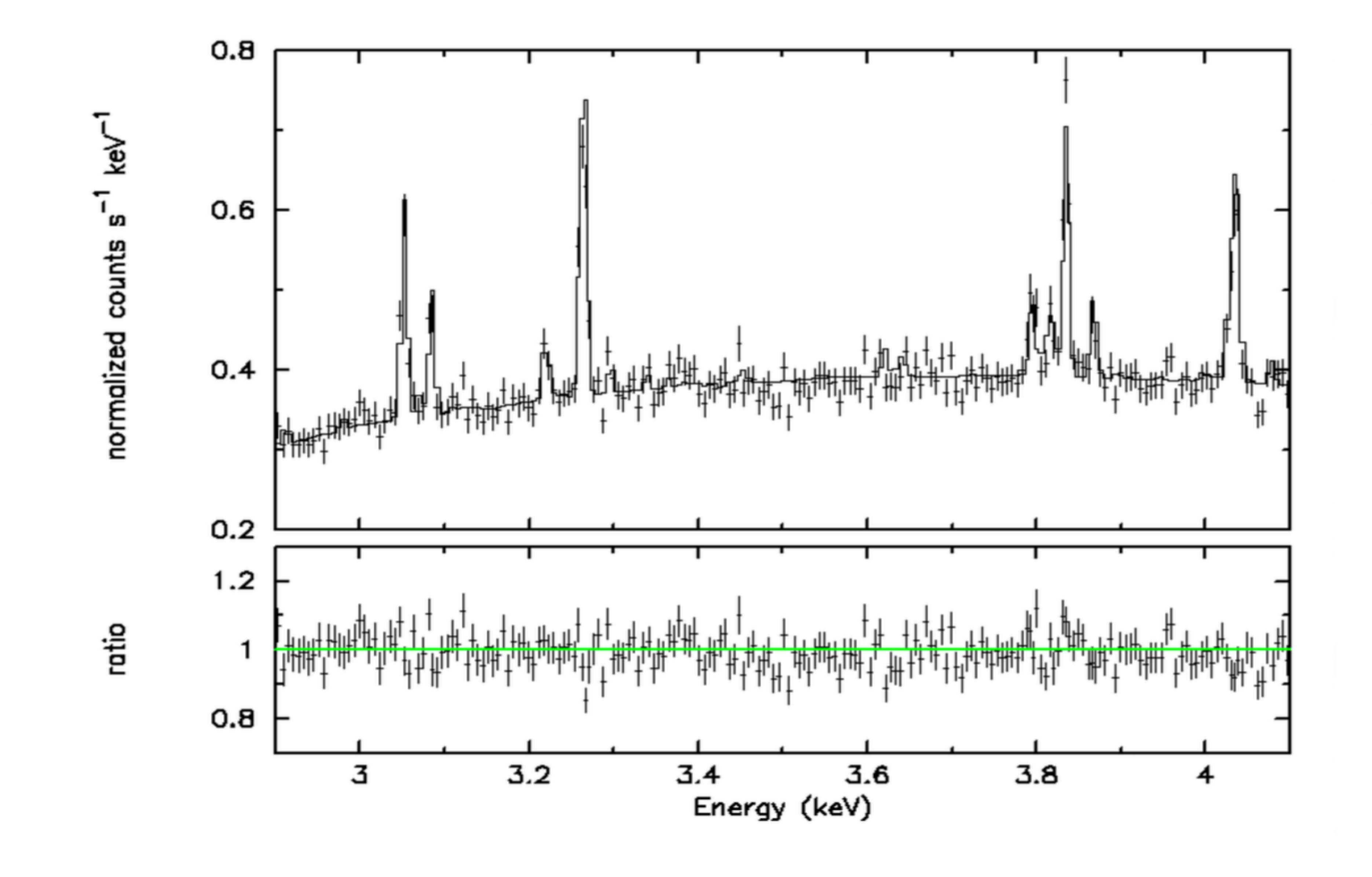
Best
angular
resolution

HITOMI



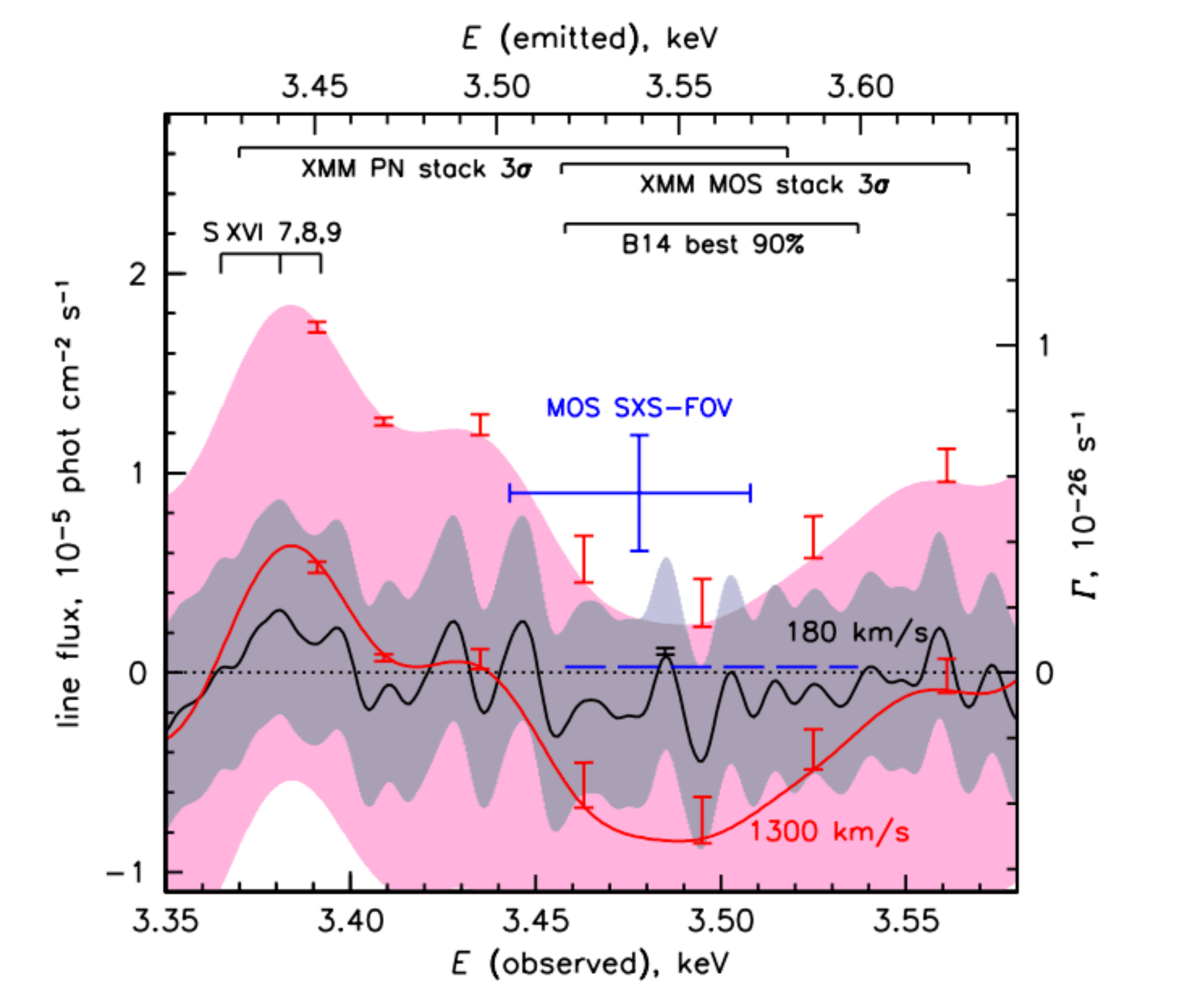
Best energy
resolution

Hitomi Spectrum of Perseus Cluster



But look closely near 3.5 keV.....

Hitomi best-fit line properties



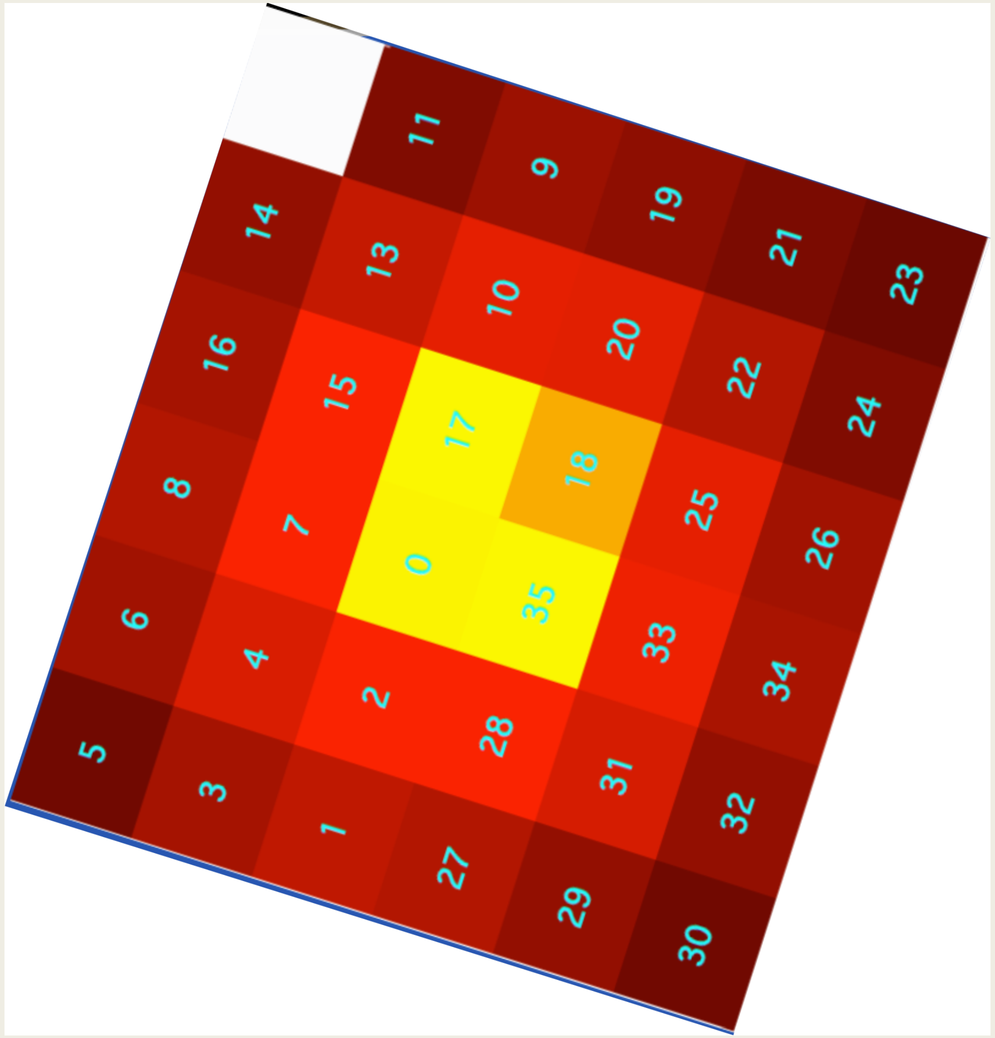
No Excess!

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

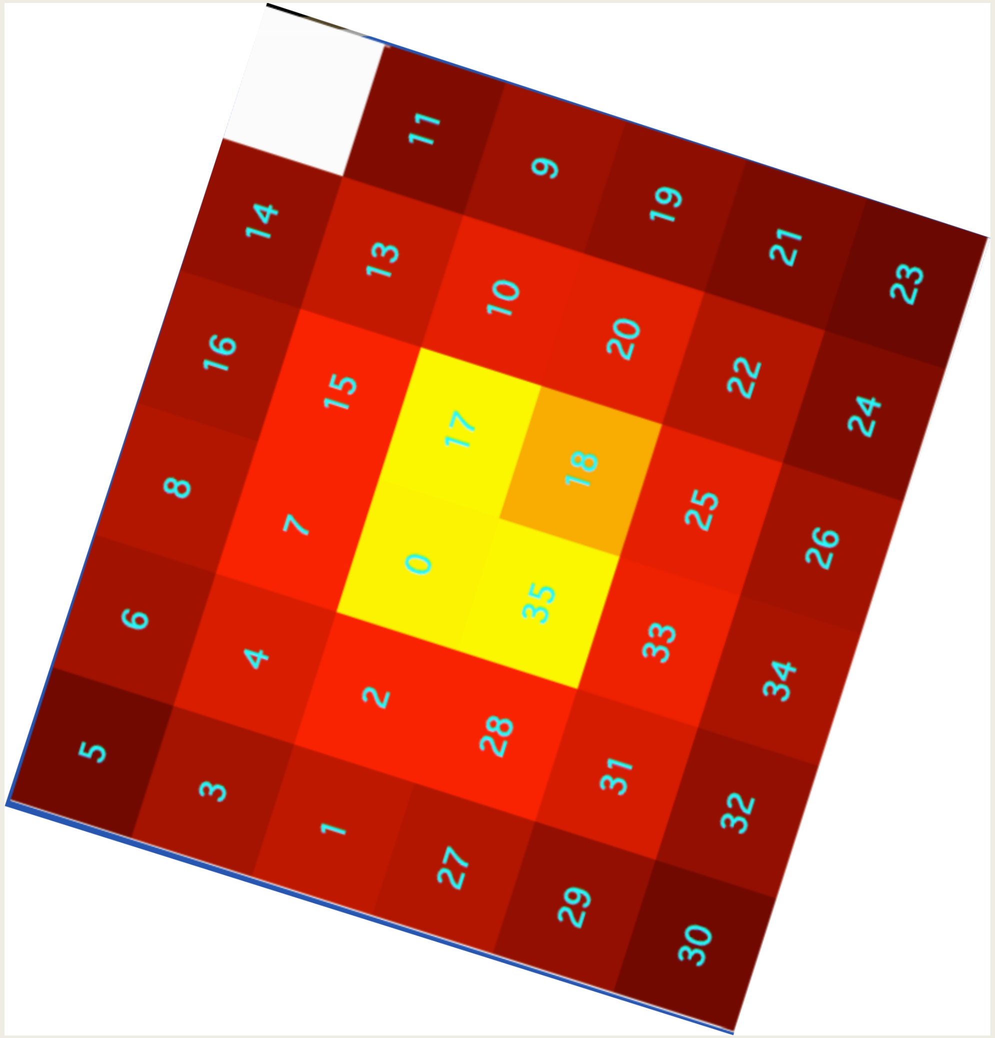
is sensitive only to the SUM of

(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

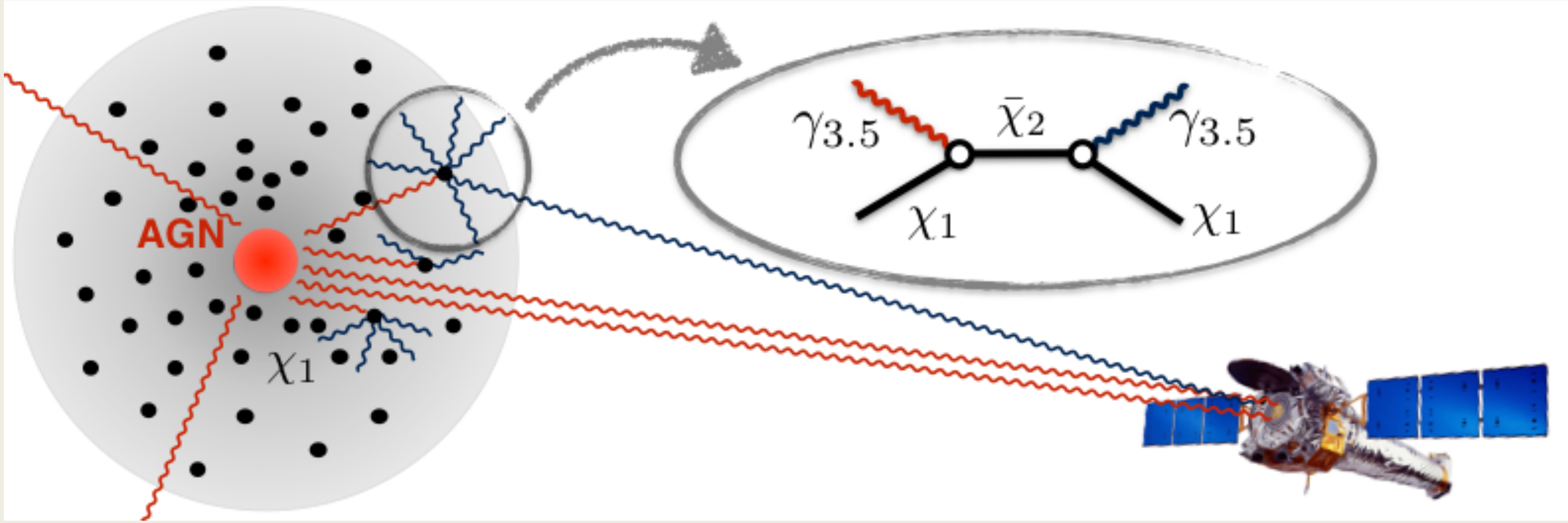
Deficit/absorption in the spectrum of very bright point source

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 $\chi_2 \rightarrow \chi_1\gamma$ leads to diffuse 3.5 keV excess

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