Title: Searches for ALPs with Current and Future X-ray Satellites - Nicholas Jennings

Date: Sep 26, 2017 01:00 PM

URL: http://pirsa.org/17090073

Abstract: <p>Galaxy clusters represent excellent laboratories to search for Axion-Like Particles (ALPs). They contain magnetic fields which can induce quasi-sinusoidal oscillations in the X-ray spectra of AGNs situated in or behind them. Ultra-deep Chandra observations of the Perseus cluster contain over 5 x 105 counts from the central NGC1275 AGN, and represent an extraordinary dataset for ALP searches. In this talk I will describe how we used these to search for spectral irregularities from the AGN. No irregularities were found at the ~30% level, allowing us to place leading constraints on the ALP-photon mixing parameter gaÎ³Î³ <1.5 Ã— 10âˆ'12GeVâˆ'1 for ma < 10-12 eV. I will move on to discuss the upcoming Athena X-ray Observatory, due for launch in 2028. The X-ray Integral Field Unit (X-IFU) instrument onboard will be far better able to constrain ALPs than Chandra, due to its excellent energy resolution. Using the SIXTE simulation software, we estimate that non-observation of spectral modulations for a 200ks observation of NGC1275 will constrain gaÎ³Î³ <1.5 Ã— 10âˆ'13GeVâˆ'1 , an order of magnitude improvement over that derived from Chandra data.</p>

Searches for ALPs with current and future X-ray satellites

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Perimeter Institute, September 26 2017

Searches for ALPs with satellites

- Chandra analysis 1605.01034 with M. Berg, J. Conlon, F. Day, S. Krippendorf, A. Powell and M. Rummel.
- Athena analysis 1707.00176 and other point source analysis 1704.05256 with J. Conlon, F. Say, S. Krippendorf and F. Muia.

Axion-Like Particles

- Light pseudo-scalars arising from the breaking of a U(1) symmetry at a high scale.
- Well motivated from string theory: always arise in the Large Volume Scenario.
- ALPs couple to electromagnetism via the Lagrangian term:

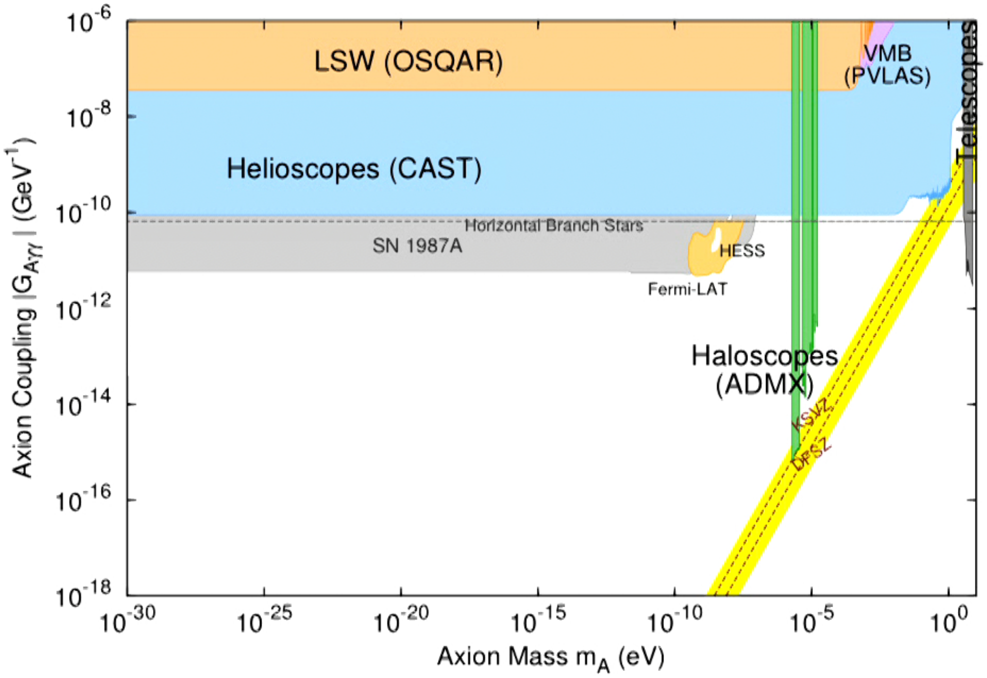
$$\frac{a}{M}\mathbf{E}\cdot\mathbf{B} = a\, g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$$

- In magnetic fields leads to photon-ALP interconversion.

$$|\gamma(E)\rangle \rightarrow \alpha|\gamma(E)\rangle + \beta|a(E)\rangle$$

Previous bounds

- Best previous bounds on ALP-photon coupling $g_{a\gamma\gamma}$ for masses $m_a \lesssim 10^{-12}\mathrm{eV}$ from SN1987a: $g_{a\gamma\gamma} \lesssim 5\times 10^{-12}\mathrm{GeV}^{-1}$.



Photon-ALP oscillations

- Probability of photon-ALP conversion (for $m_a \lesssim 10^{-12}\mathrm{eV}$):

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

$$\Theta = 0.28\left(\frac{\mathrm{B}_\perp}{1\mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right)$$

$$\Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\ \mathrm{keV}}{\omega}\right)$$

Photon-ALP oscillations

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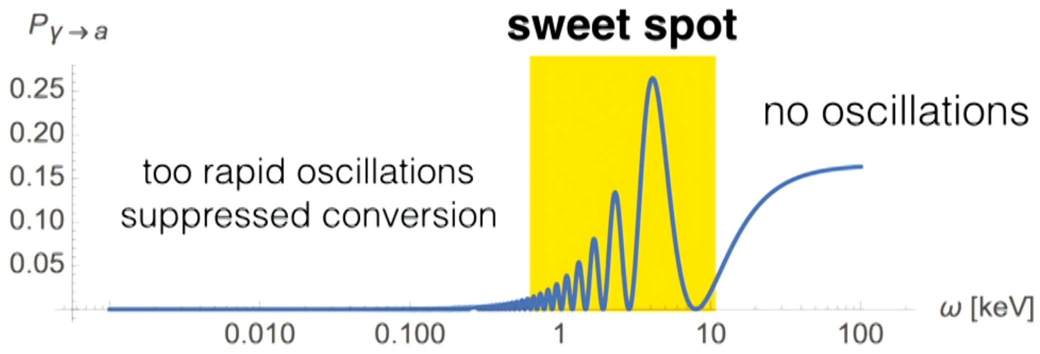
- In cluster magnetic fields leads to photon-ALP oscillations at X-ray energies.



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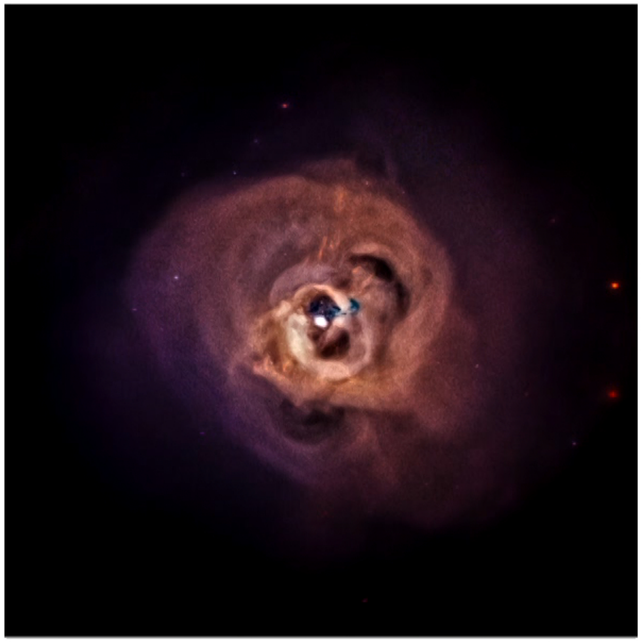
Perseus Cluster

- Magnetic field approximately 1 Mpc across.
- Coherence lengths 3.5-10 kpc.
- Magnetic field strength estimated at 10-25 μG at the centre [astro-ph/0602622], and 1-10 μG across the cluster.
- Very efficient converter of photons to ALPs.



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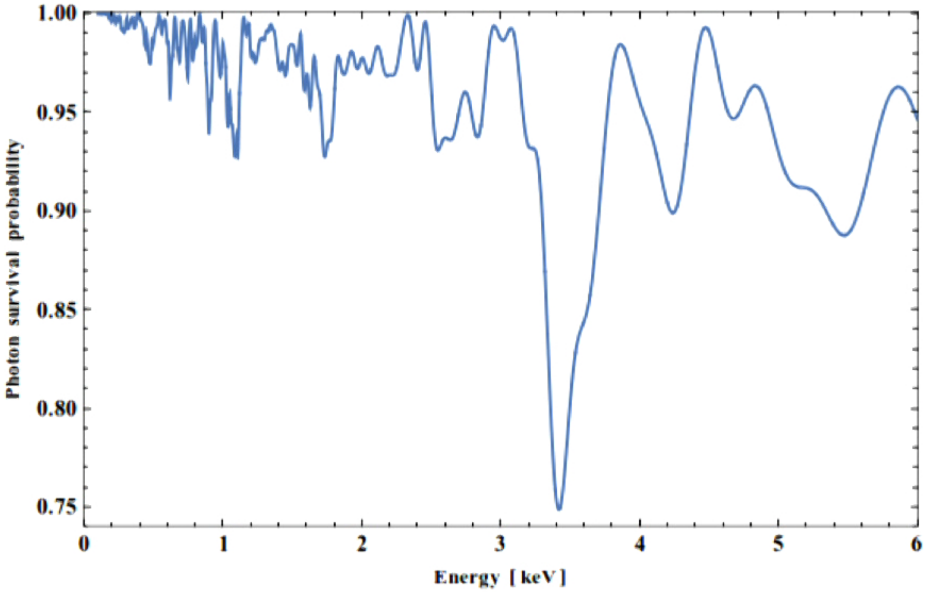
Photon survival probability in Perseus



300 domains, lengths: 3.5-10 kpc (total: 1860kpc), $\mathrm{B}_0 = 25\ \mu\mathrm{G}$

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

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Current satellite: Chandra

Image credit: NASA

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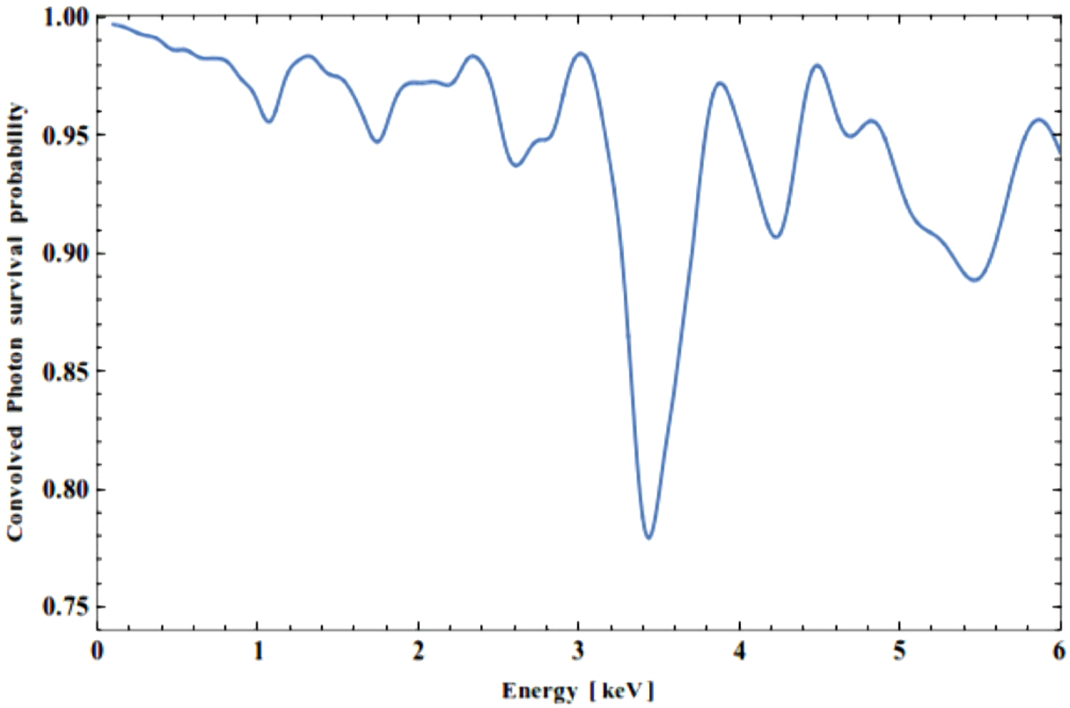
Current satellite: Chandra

	Chandra (ACIS-I detector)
Energy range	0.3-10 keV
Energy resolution	~150 eV
Angular resolution	0.5”
Read-out time	0.2s (2.8ms single row)
Effective area	600 cm^2

Photon survival probability in Perseus



Convolved with Gaussian FWHM (150 eV)

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NGC 1275

- Central galaxy of Perseus, with an AGN unobscured in our direction.

- 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).

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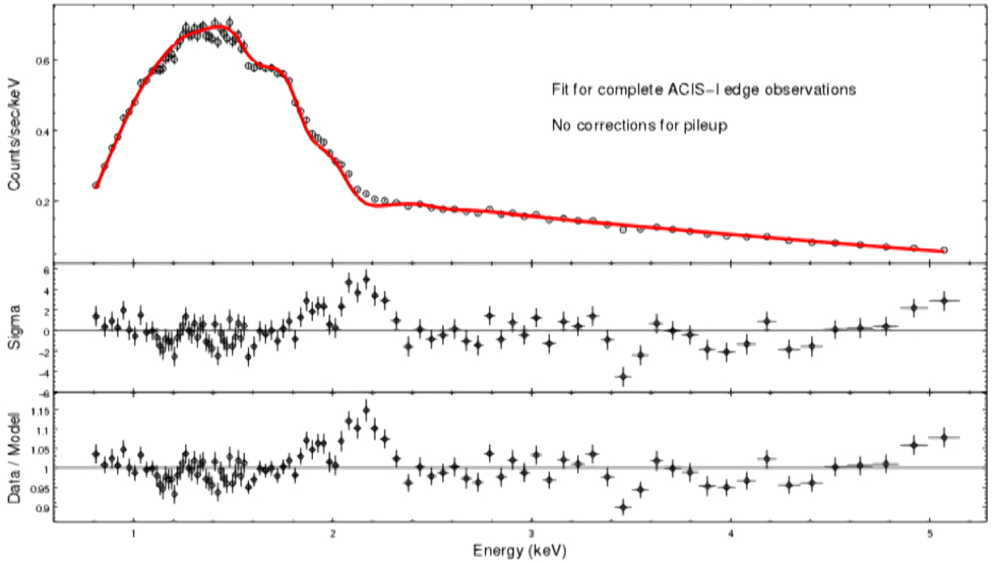
Fitting the data

- We fit to an absorbed power law plus thermal background.

$$(AE^{-\gamma} + \mathrm{APEC})\times e^{-n_H\sigma(E)}$$

- The background cluster thermal emission is modelled directly with APEC, using parameters derived from the *Hitomi* observations of Perseus.

Complete extraction for ACIS-I edge



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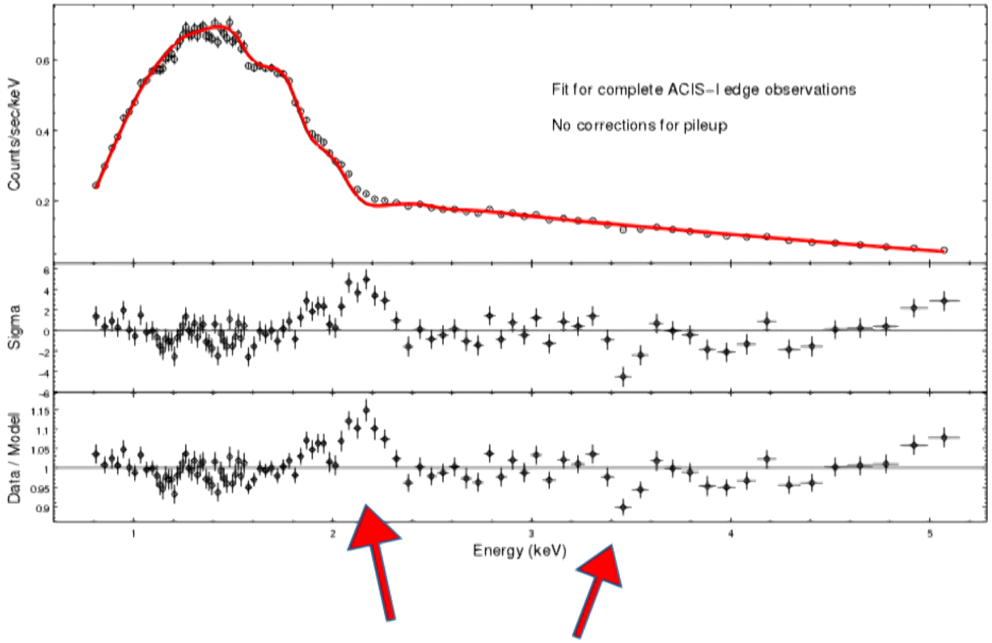
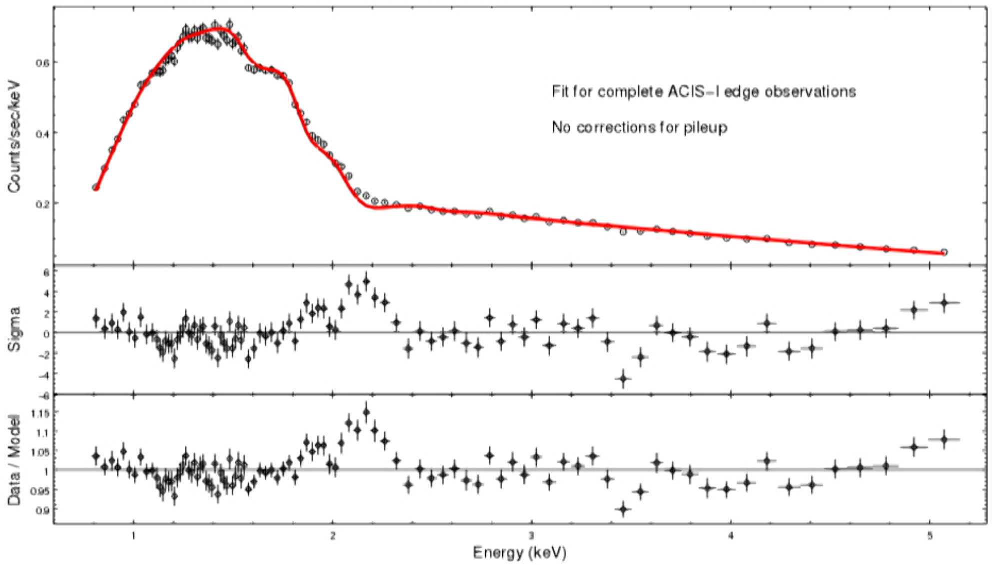
Complete extraction for ACIS-I edge



Features!

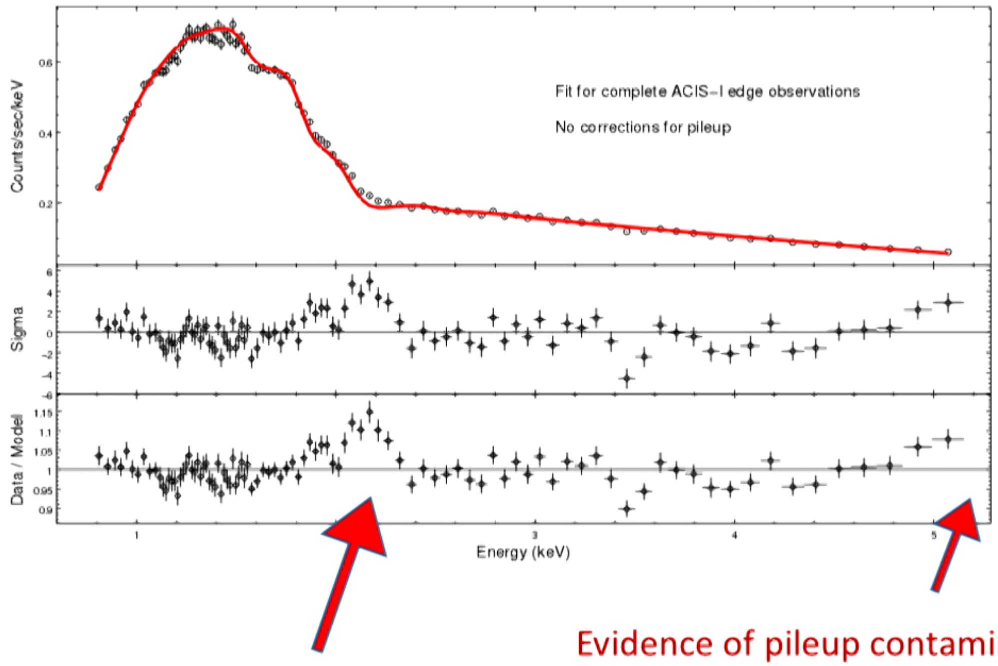
Complete extraction for ACIS-I edge



At 2.0–2.2 keV: five data points in a row 3-5 sigma high

At 3.4–3.5 keV: two data points low, 4.5, 2.6 sigma

Complete extraction for ACIS-I edge



Evidence of pileup contamination

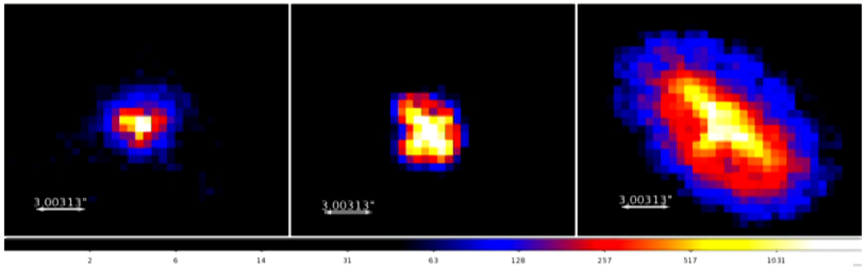
Effective area edge

Pileup contamination

- If two or more photons arrive during the detector read-out time (3.1s), they are registered as one photon.

- Two ways to ameliorate this:

  - Model pile-up effects with jdpileup model.
  - Discard central pixels with highest flux.



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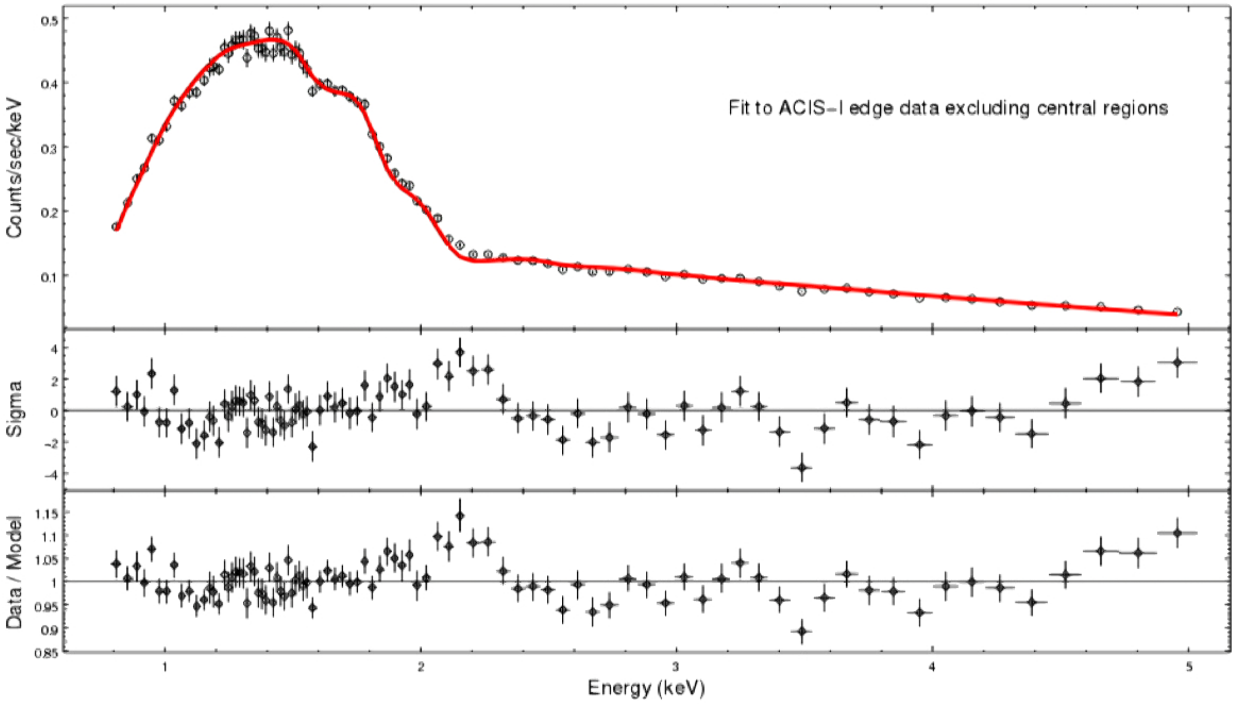
Extraction for ACIS-I edge excluding centre



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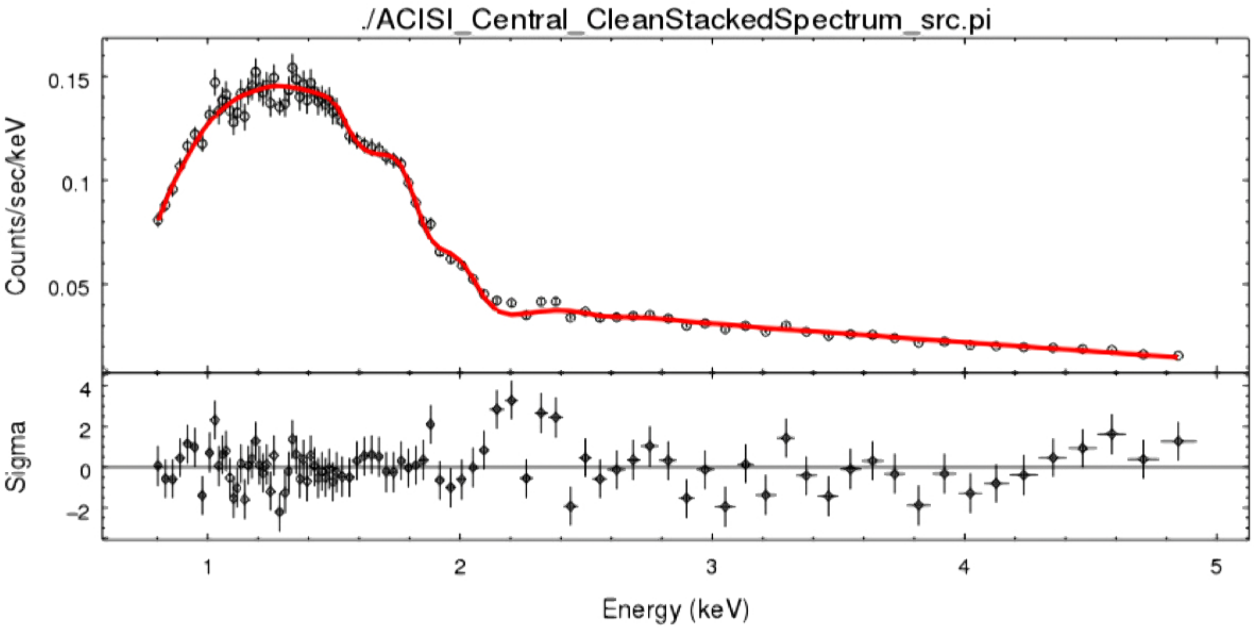
ACIS-I midway excluding centre



50% reduction in data when central regions are excluded.

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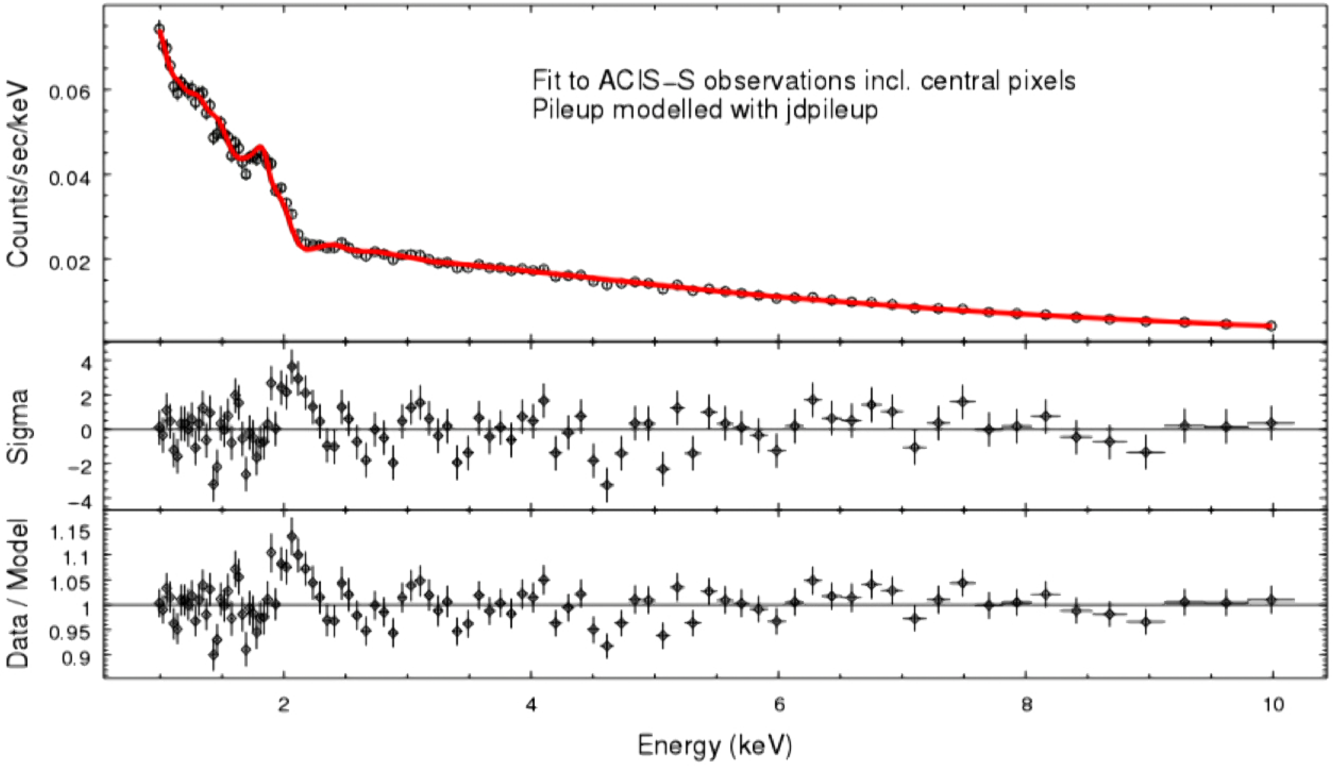
Extraction for ACIS-S with pileup model



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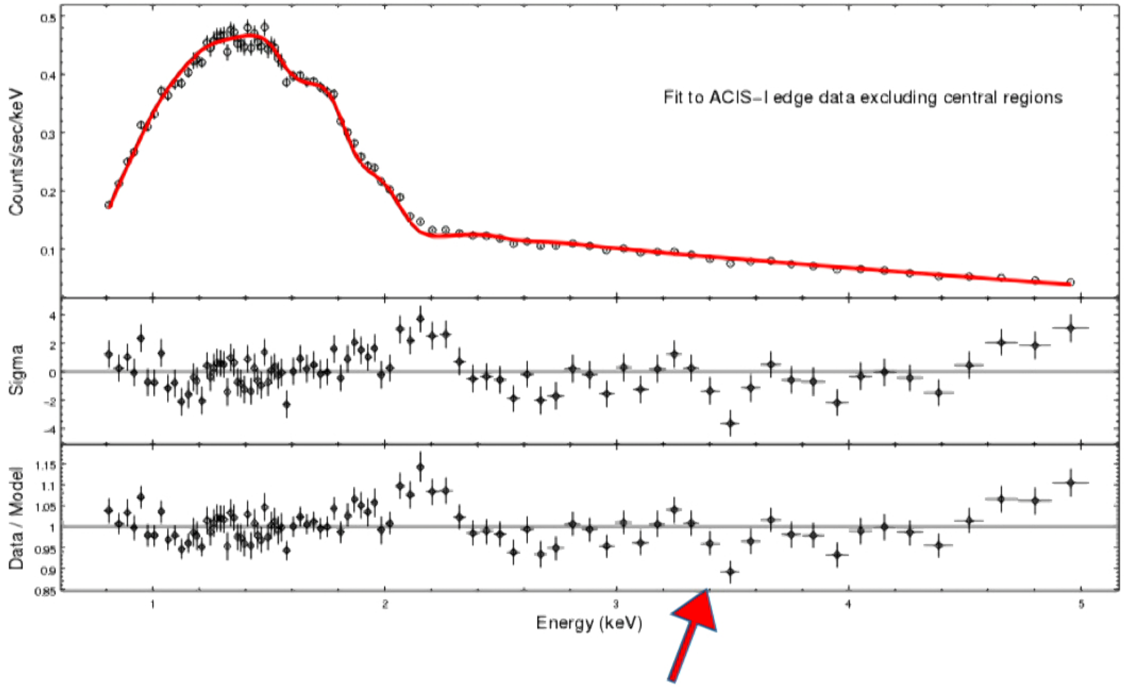
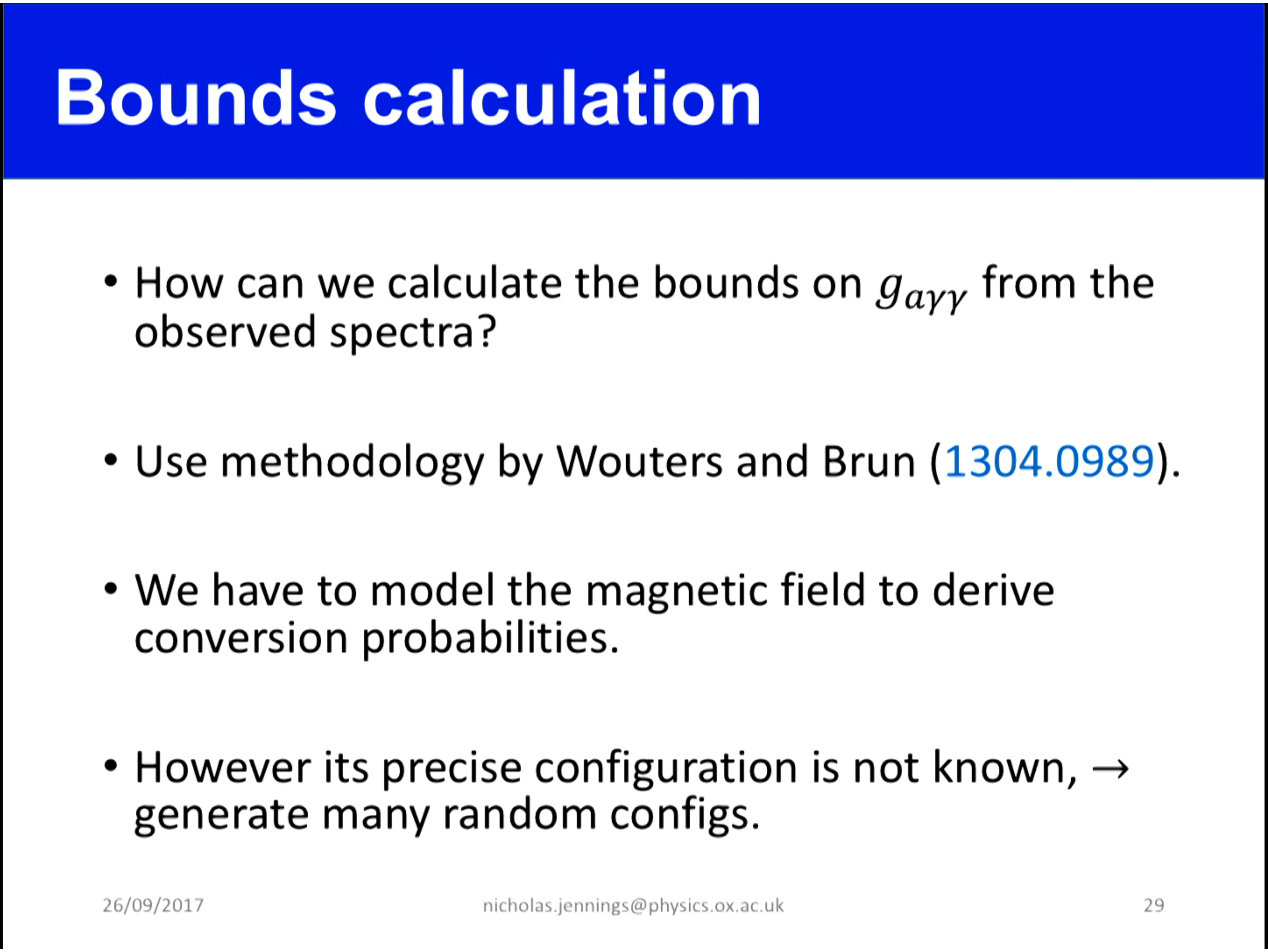
Excess around 2 keV

- At location of effective area dip due to Iridium edge.
- Highly sensitive to effects of pileup.
- We include it in our bounds calculation, ensuring they remain conservative.

Side note: 3.5 keV dip

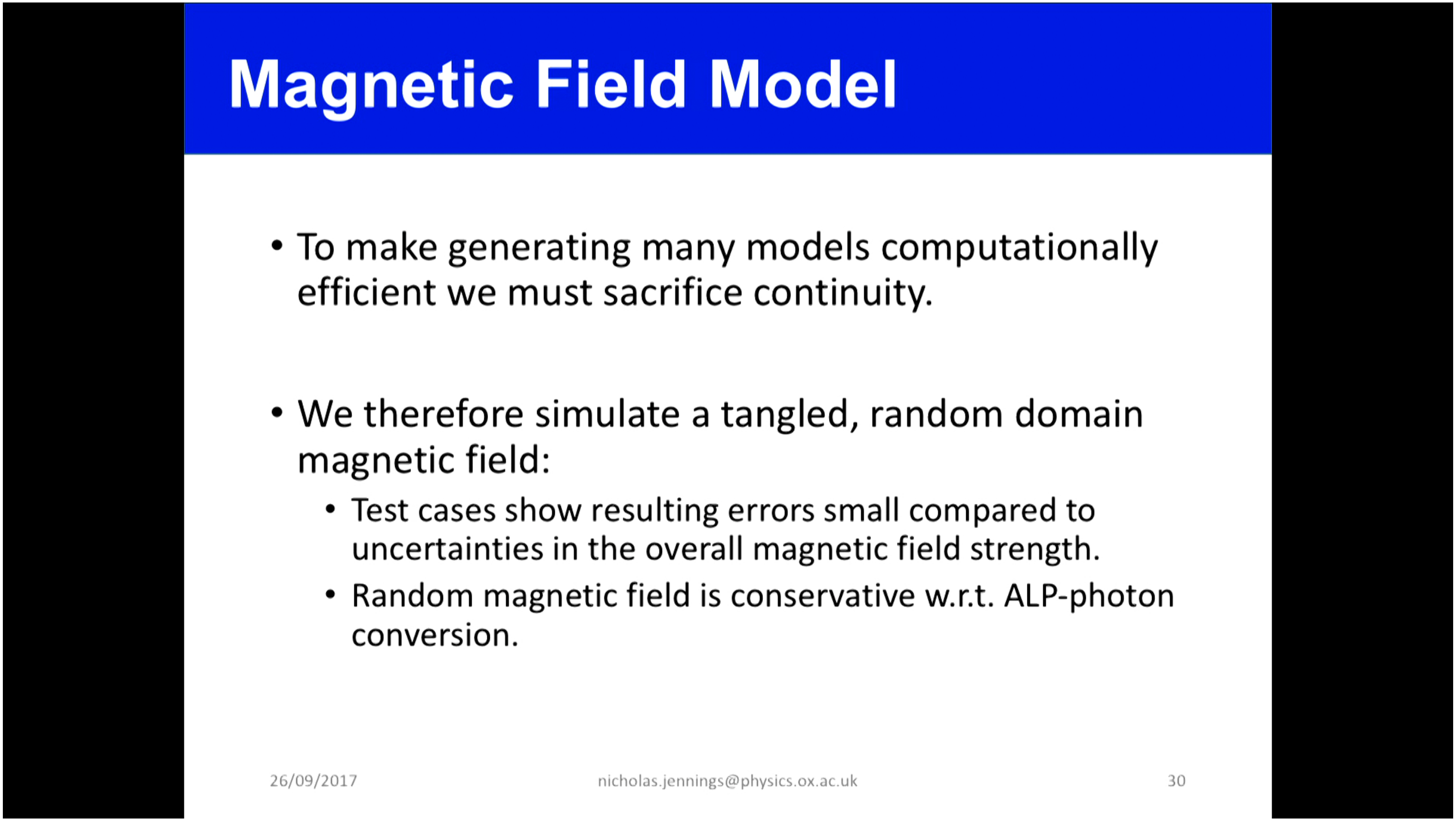


Possible connection to 3.5 keV excess seen in cluster emission.
Could be explained by Fluorescent Dark Matter, see 1608.01684



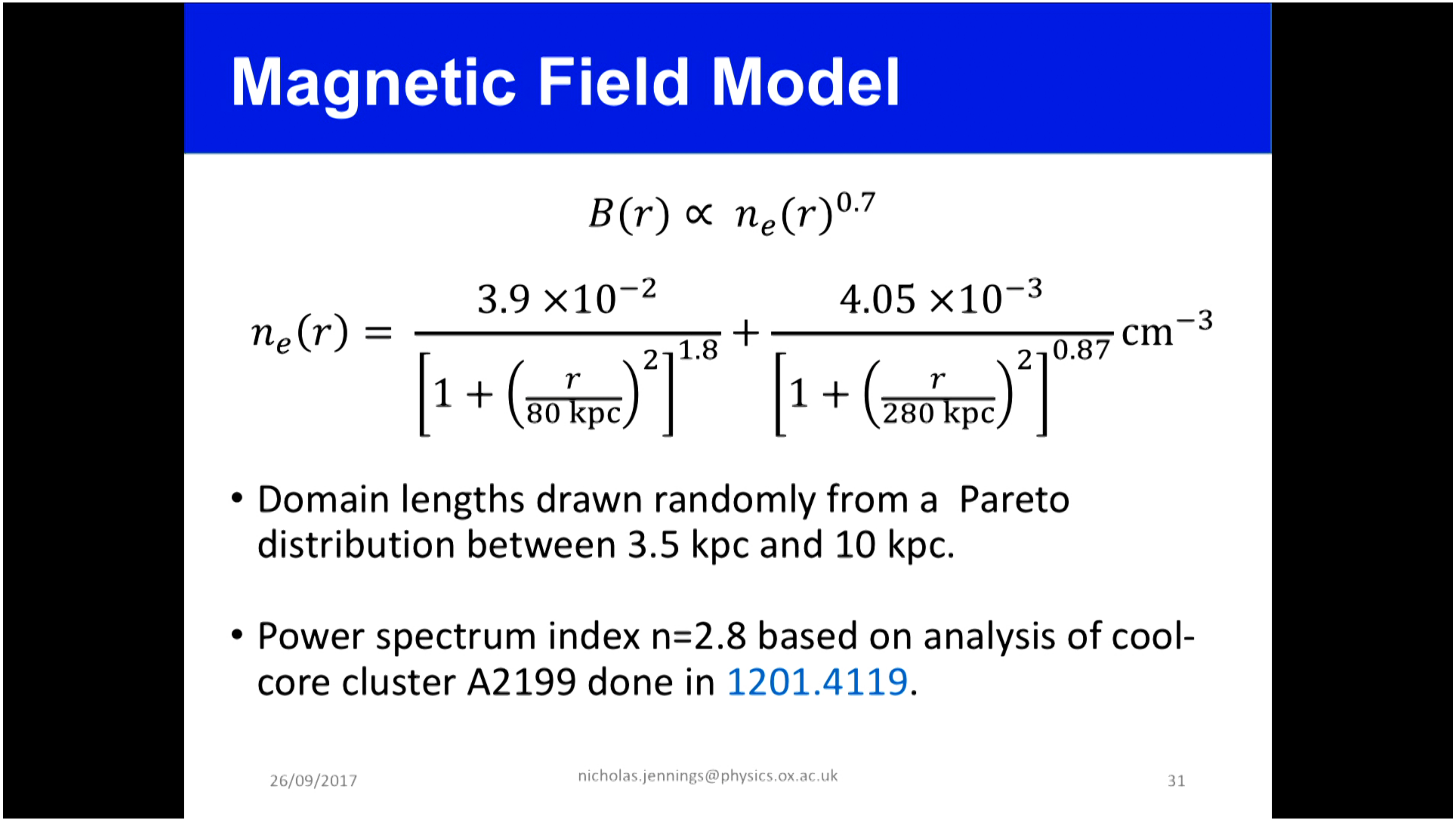
Bounds calculation

- How can we calculate the bounds on $g_{a\gamma\gamma}$ from the observed spectra?
- Use methodology by Wouters and Brun (1304.0989).
- We have to model the magnetic field to derive conversion probabilities.
- However its precise configuration is not known, → generate many random configs.



Magnetic Field Model

- To make generating many models computationally efficient we must sacrifice continuity.
- We therefore simulate a tangled, random domain magnetic field:
  - Test cases show resulting errors small compared to uncertainties in the overall magnetic field strength.
  - Random magnetic field is conservative w.r.t. ALP-photon conversion.



Magnetic Field Model

$$B(r) \propto \; n_e(r)^{0.7}$$

$$n_e(r) = \frac{3.9 \times 10^{-2}}{\left[1 + \left(\frac{r}{80 \text{ kpc}}\right)^2\right]^{1.8}} + \frac{4.05 \times 10^{-3}}{\left[1 + \left(\frac{r}{280 \text{ kpc}}\right)^2\right]^{0.87}} \text{cm}^{-3}$$

- Domain lengths drawn randomly from a Pareto distribution between 3.5 kpc and 10 kpc.
- Power spectrum index n=2.8 based on analysis of cool-core cluster A2199 done in 1201.4119.

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Bounds calculation: methodology

- Consider two models:
  - Model 0: $F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)}$
  - Model 1: $F_0(E, \boldsymbol{B}) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to \gamma}(E, \boldsymbol{B}, M)$

- Procedure:
  1. Calculate $P_{\gamma \to \gamma}$ for 50 random magnetic field configurations.
  2. For each mag. field config. generate 10 fake data sets from Model 1.
  3. Fit Model 0 to each of the 500 fake data sets.
  4. Fit Model 0 to actual data to find ${\chi_{data}}^2$.
  5. If ${\chi_{model}}^2 < {\chi_{data}}^2$ for less than 5% of configs, Model 1 excluded at 95% confidence.

Bounds calculation

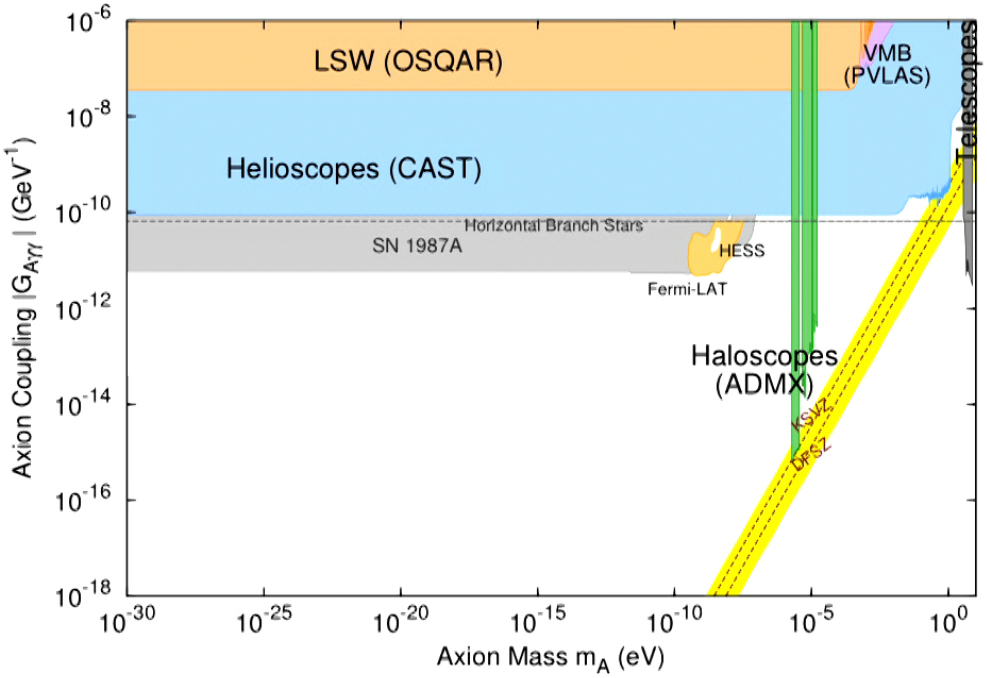
- We scan in the range

$$g_{a\gamma\gamma} = (1 \rightarrow 5) \times 10^{-12}\ \mathrm{GeV}^{-1}$$

with intervals of $1 \times 10^{-13}\ \mathrm{GeV}^{-1}$.

Previous bounds

- Best previous bounds on ALP-photon coupling $g_{a\gamma\gamma}$ for masses $m_a \lesssim 10^{-12}\text{eV}$ from SN1987a: $g_{a\gamma\gamma} \lesssim 5 \times 10^{-12}\text{GeV}^{-1}$.



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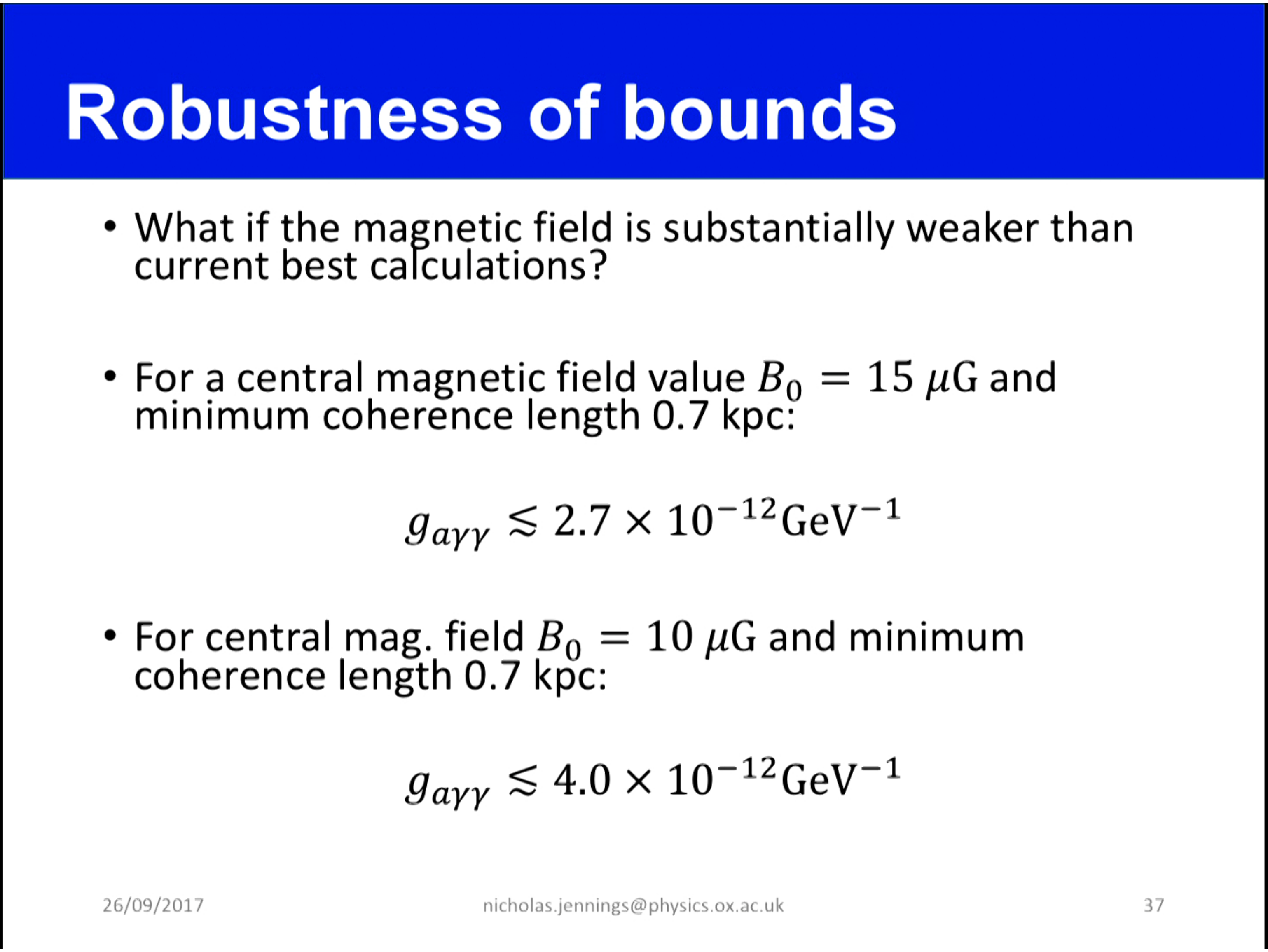
New bounds

- From the clean ACIS-I observations, at 95% confidence we derive the bound:

$$g_{a\gamma\gamma} \lesssim 1.4 \times 10^{-12}\mathrm{GeV}^{-1}$$



Robustness of bounds

- What if the magnetic field is substantially weaker than current best calculations?
- For a central magnetic field value $B_0 = 15\ \mu\mathrm{G}$ and minimum coherence length 0.7 kpc:

$$g_{a\gamma\gamma} \lesssim 2.7 \times 10^{-12}\mathrm{GeV}^{-1}$$

- For central mag. field $B_0 = 10\ \mu\mathrm{G}$ and minimum coherence length 0.7 kpc:

$$g_{a\gamma\gamma} \lesssim 4.0 \times 10^{-12}\mathrm{GeV}^{-1}$$

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Robustness of bounds

- Could pileup mask the appearance of ALP oscillations?
- We simulate the AGN spectra (with and without ALPs) using MARX and derive bounds.
- We find that $g_{a\gamma\gamma} = 2 \times 10^{-12}\mathrm{GeV}^{-1}$ is strongly excluded, with $g_{a\gamma\gamma} = 1.5 \times 10^{-12}\mathrm{GeV}^{-1}$ borderline.
- We compare MARX simulations with *ChaRT* simulations, and find similar results.

Robustness of bounds

- Could the effective area dip interfere with bounds?
- The effect of the excess is to weaken the bounds we can derive, so they are conservative.
- Removing the energy range 1.8-2.3 keV would lead to a (spurious) bound of:

$$g_{a\gamma\gamma} \lesssim 1.1 \times 10^{-12}\ \mathrm{GeV}^{-1}$$

Other point sources

- We performed an analysis of other good point sources in 1704.05256.

- Best sources for constraining ALPs from this dataset:

2E3140: $g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-12}\ \mathrm{GeV}^{-1}$

NGC3862: $g_{a\gamma\gamma} \lesssim 2.4 \times 10^{-12}\ \mathrm{GeV}^{-1}$

Work by other research groups

- M. Marsh et al. (1703.07354) look at M87, find a bound of:

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

- Fermi-LAT analysis of NGC1275 (1603.06978) and H.E.S.S. (PKS 2155-304, 1311.3148).
  - Probes higher mass range $\sim 10^{-9}$ eV.

How to improve these bounds

- Take more data of NGC1275 and others with Chandra, using a shorter readout time to minimise pileup.

- The main limitation of Chandra is its energy resolution.

- Future satellites with improved energy resolution would be able to vastly improve these bounds.

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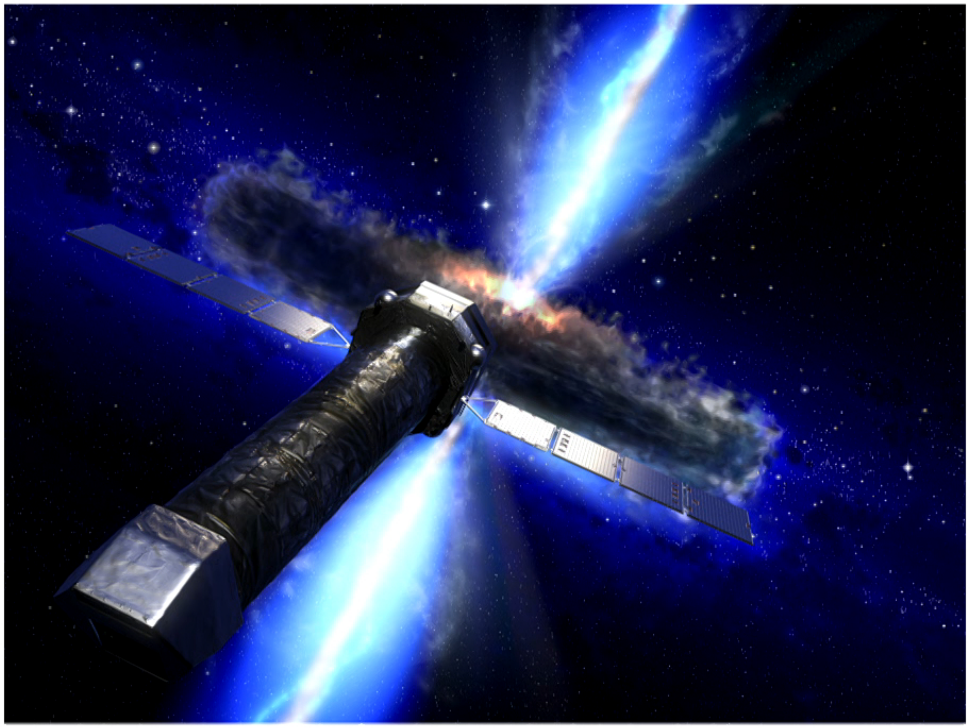
Future Satellite: ATHENA



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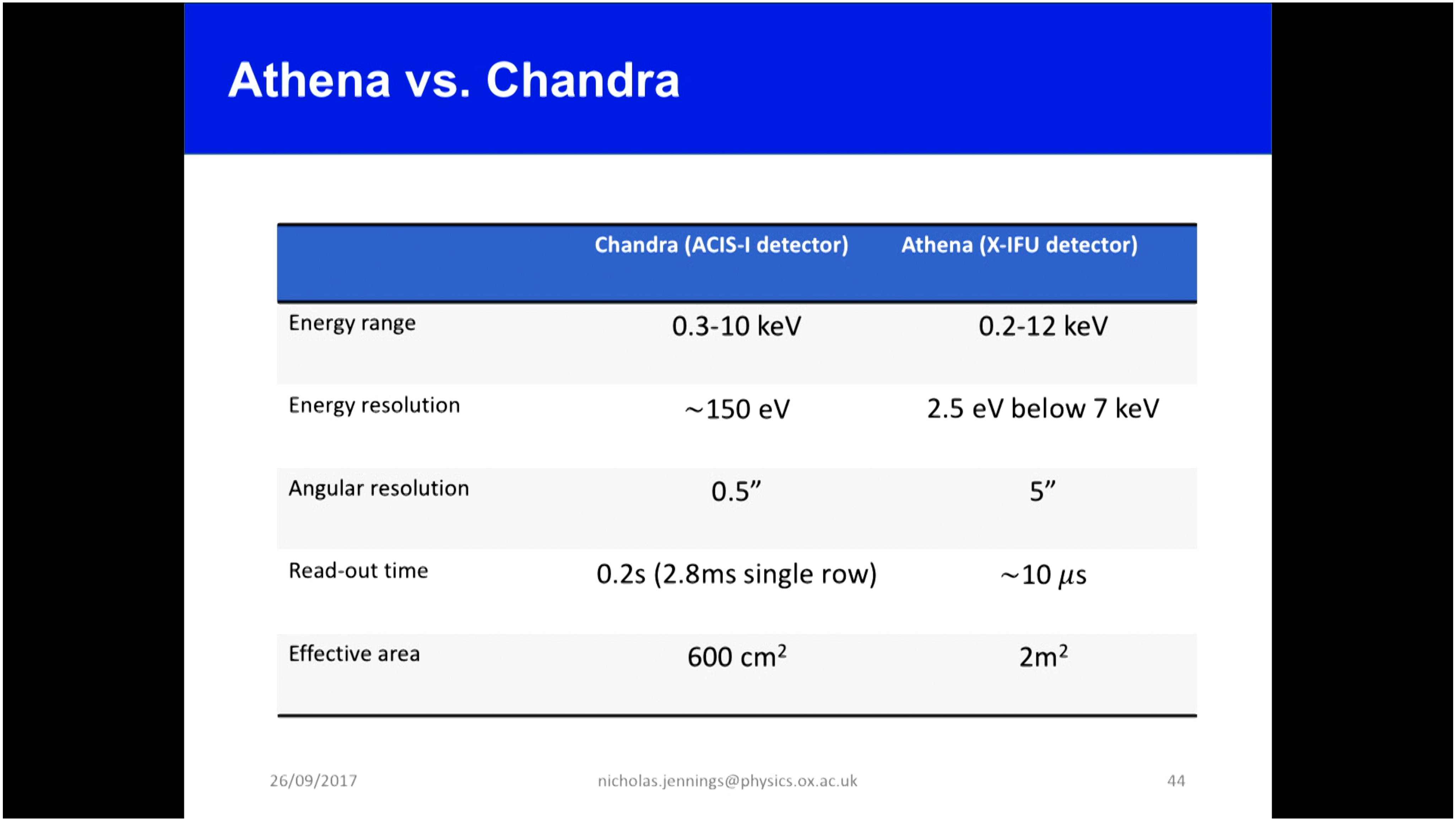

Athena vs. Chandra

	Chandra (ACIS-I detector)	Athena (X-IFU detector)
Energy range	0.3-10 keV	0.2-12 keV
Energy resolution	~150 eV	2.5 eV below 7 keV
Angular resolution	0.5”	5”
Read-out time	0.2s (2.8ms single row)	~10 μs
Effective area	600 cm^2	2m^2

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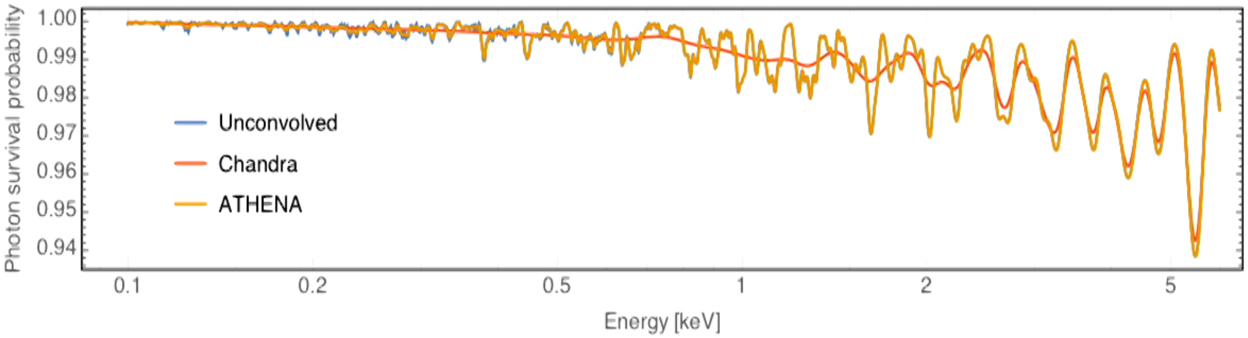
Photon survival probability in Perseus

$$g_{a\gamma\gamma} = 5\times 10^{-13}\mathrm{GeV}^{-1}$$



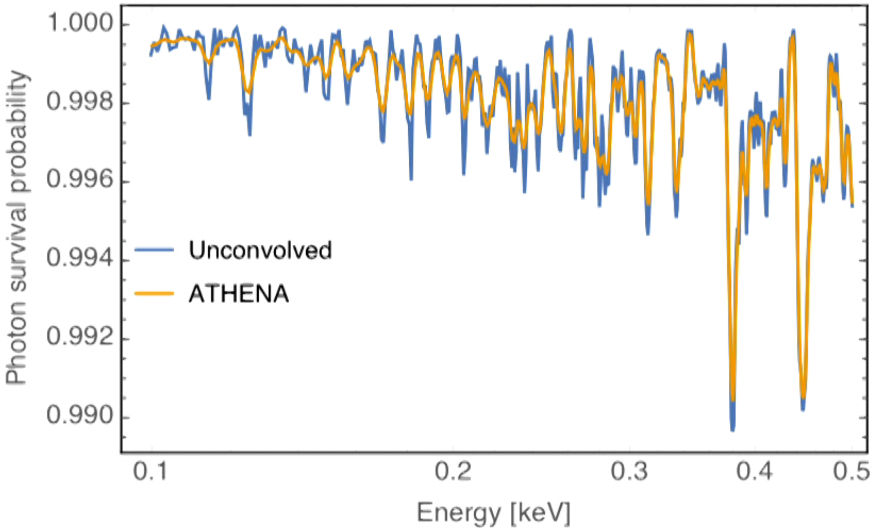
300 domains, lengths: 3.5-10 kpc (total: 1860kpc), $\mathrm{B}_0 = 25\ \mu\mathrm{G}$

Red convolved with 150 eV FWHM Gaussian (*Chandra)*

Orange convolved with 2.5 eV FWHM Gaussian (*Athena)*

Photon survival probability in Perseus

$$g_{a\gamma\gamma} = 5\times 10^{-13}\text{GeV}^{-1}$$



Blue unconvolved

Orange convolved with 2.5 eV FWHM Gaussian (*Athena)*

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Simulating using SIXTE

- SImulation of X-ray TElescopes software.
- End-to-end simulator for X-IFU on *Athena.*
- Methodology: Create 2 `Xspec` models:
    - Model 0: `zwabs*(powerlaw + bapec)`
    - Model 1: `zwabs*(powerlaw + bapec)*` $P_{\gamma\rightarrow\gamma}(E,\boldsymbol{B})$
- Parameters based on *Chandra* and *Hitomi* observations.
- Simulate X-IFU response using `xifupipeline`.
- Fit both sets of data to Model 0, compare.

Simulating the data

- We generate the AGN spectrum and cluster background using the same model as before:

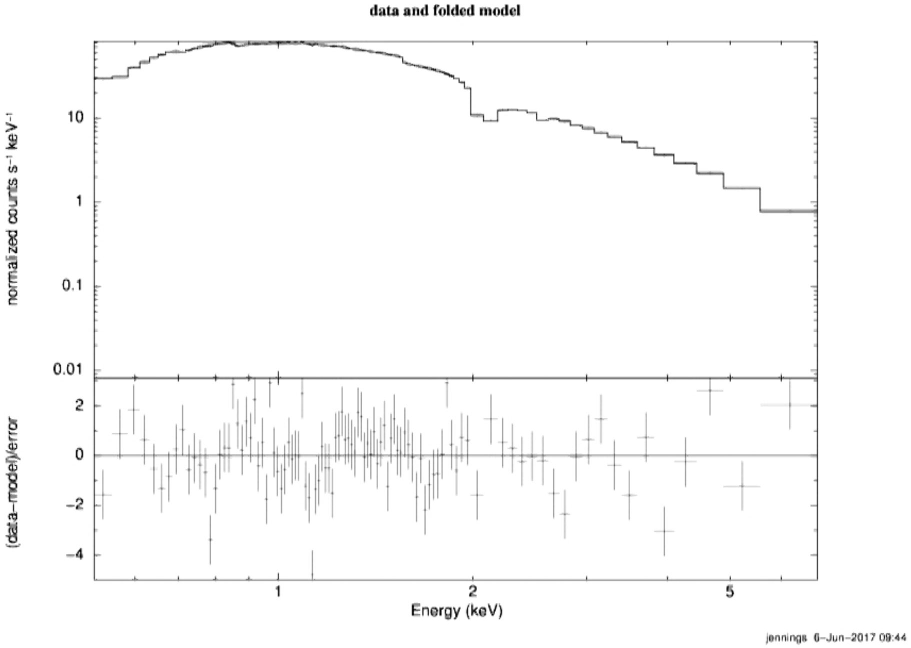
$$(AE^{-\gamma} + \mathrm{APEC})\times e^{-n_H\sigma(E)}$$

- However Hitomi observations show the AGN is twice as bright as it was for the Chandra observations. We use this measured brightness in our simulation.

Simulated spectrum

10 ks observation with ALP modulations

$$g_{a\gamma\gamma} = 5\times 10^{-13}\mathrm{GeV}^{-1}$$



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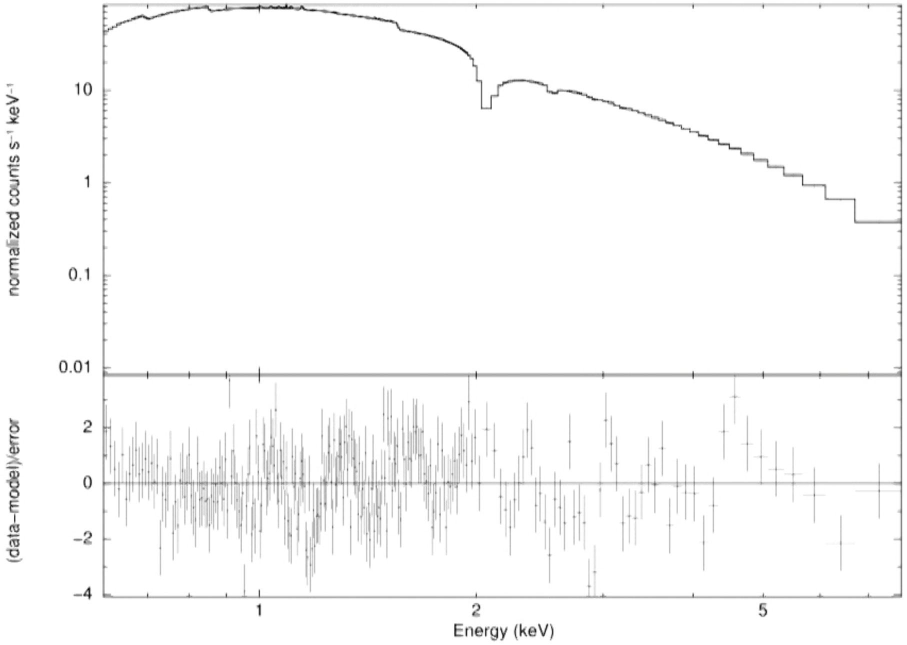
Simulated spectrum

200 ks observation with ALP modulations

$$g_{a\gamma\gamma} = 3\times 10^{-13}\mathrm{GeV}^{-1}$$



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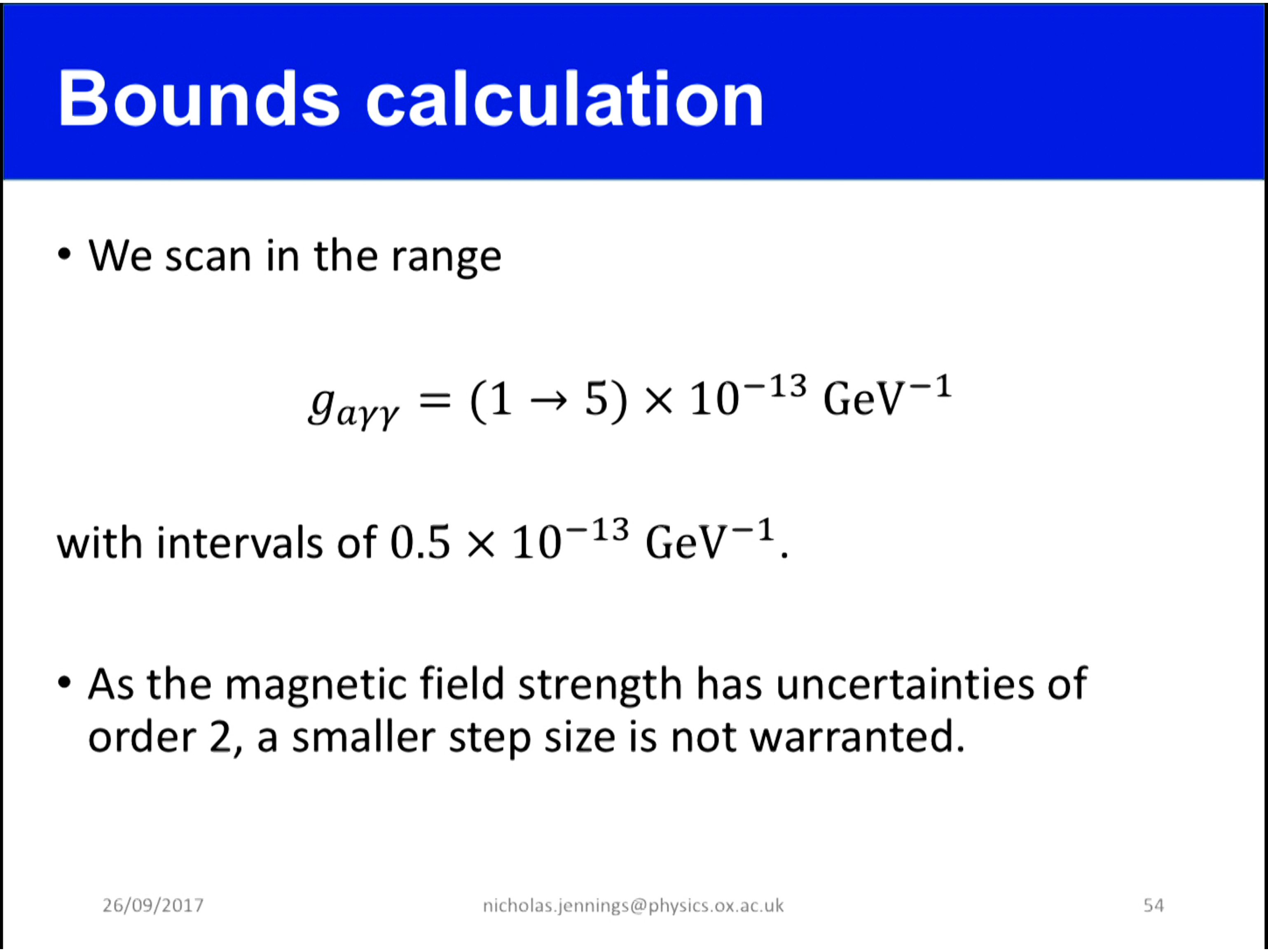
Bounds calculation

- Generate data from two models:
  - Model 0: $F_0(E) = AE^{-\gamma} \times e^{-n_H \sigma(E)}$
  - Model 1: $F_0(E, \boldsymbol{B}) = AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to \gamma}(E, \boldsymbol{B}, M)$

- Procedure:
  1. Calculate $P_{\gamma \to \gamma}$ for 50 random magnetic field configurations.
  2. For each mag. field config. generate 10 fake data sets from Model 1.
  3. Fit Model 0 to each of the 500 fake data sets.
  4. Generate 100 fake data sets from Model 0, and fit.
  5. If ${\chi_1}^2 < \max({\chi_0}^2, 1)$ for less than 5% of configs, Model 1 excluded at 95% confidence.



Bounds calculation

- We scan in the range

$$g_{a\gamma\gamma} = (1 \to 5) \times 10^{-13}\ \mathrm{GeV}^{-1}$$

with intervals of $0.5 \times 10^{-13}\ \mathrm{GeV}^{-1}$.

- As the magnetic field strength has uncertainties of order 2, a smaller step size is not warranted.

Bounds calculation

- For a 200ks observation of NGC1275, with $B_0 = 25\ \mu\text{G}$, at 95% and 99% confidence respectively:

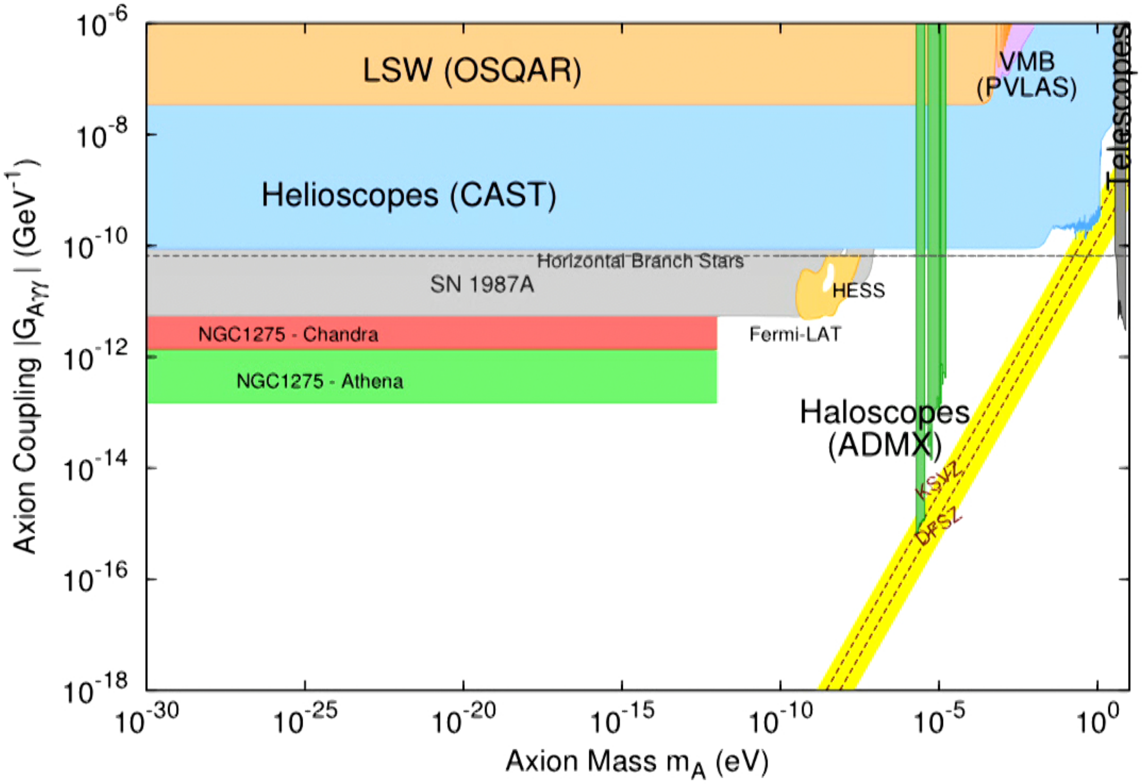
$$g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-13}\ \text{GeV}^{-1}$$

$$g_{a\gamma\gamma} \lesssim 2.5 \times 10^{-13}\ \text{GeV}^{-1}$$

- For a short 10ks observation the bound is:

$$g_{a\gamma\gamma} \lesssim 4.5 \times 10^{-13}\ \text{GeV}^{-1}$$

ATHENA bounds



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Comparison with future experiments

- IAXO
  - Will probe coupling in the region of $g_{a\gamma\gamma} \sim$ a few $\times 10^{-12}\ \mathrm{GeV}^{-1}$.
  - Will be competitive with Chandra bound.

- Dark Matter searches
  - Rely on ALPs/axions comprising some or all of the Dark Matter.
  - CASPEr upgrade could probe ALP-nucleon and ALP-gluon couplings corresponding to $f_a \sim 10^{16}\ \mathrm{GeV}$.
  - ABRACADABRA will probe $g_{a\gamma\gamma} \sim 10^{-16}\ \mathrm{GeV}^{-1}$.

- PIXIE / PRISM
  - Lack of distortions in the CMB would constrain the product $g_{a\gamma\gamma}B < 10^{-16}\ \mathrm{GeV}^{-1}\ \mathrm{nG}$.
  - If the cosmic magnetic field is close to experimental bound $B < \mathrm{nG}$ this could be competitive.

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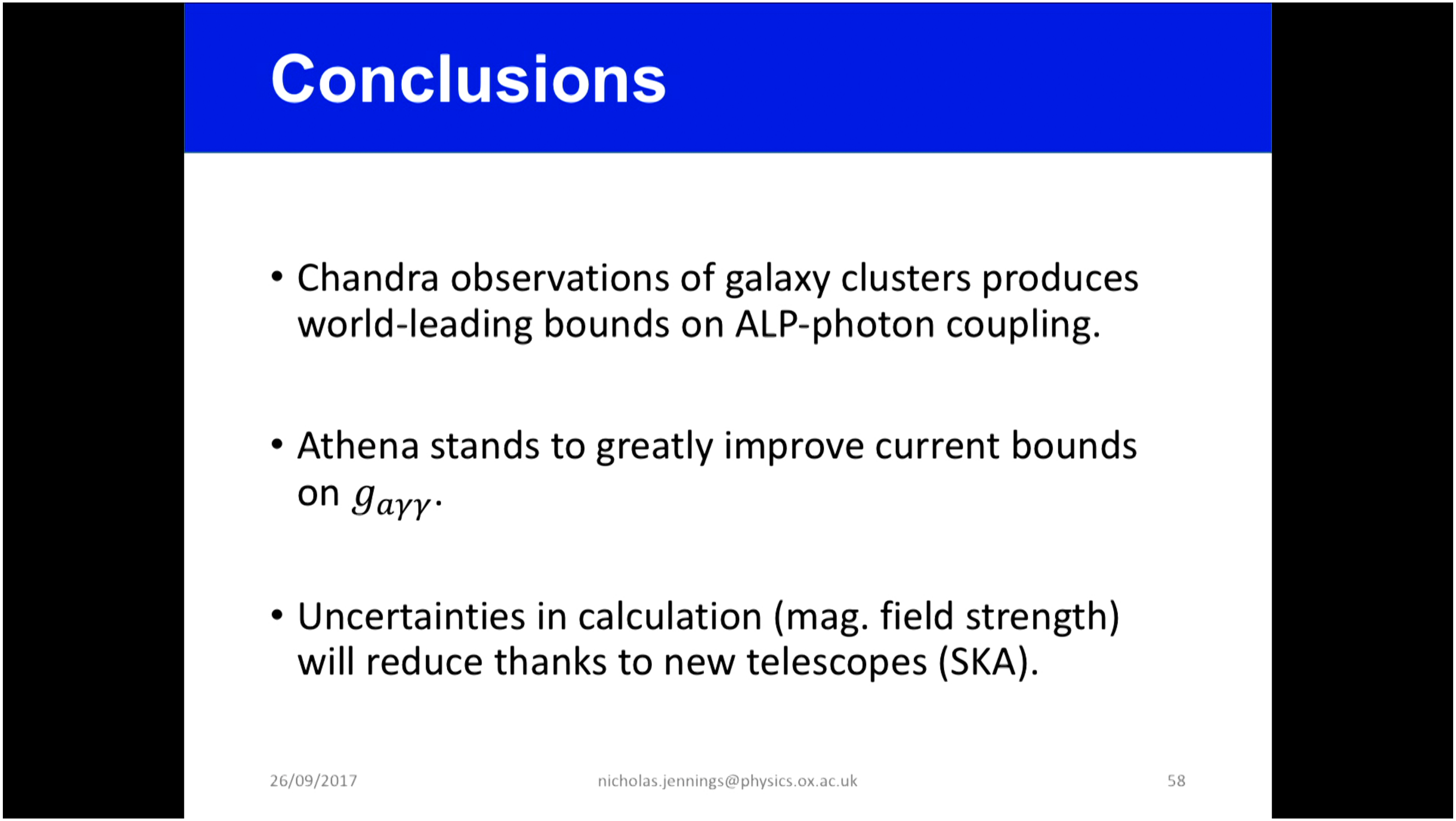

Conclusions

- Chandra observations of galaxy clusters produces world-leading bounds on ALP-photon coupling.
- Athena stands to greatly improve current bounds on $g_{a\gamma\gamma}$.
- Uncertainties in calculation (mag. field strength) will reduce thanks to new telescopes (SKA).