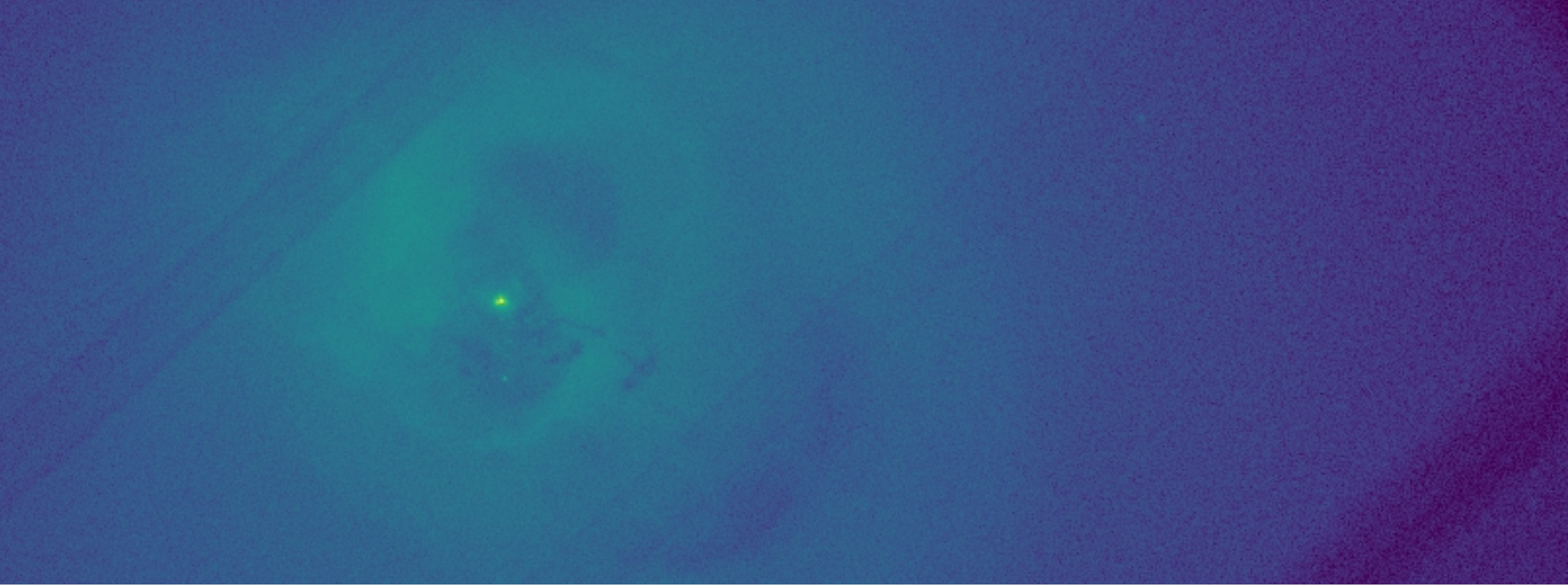


Searches for ALPs with NGC 1275

Sven Krippendorf

Rudolf Peierls Centre for Theoretical Physics

PATRAS 2016, Jeju Island Korea, June 2016

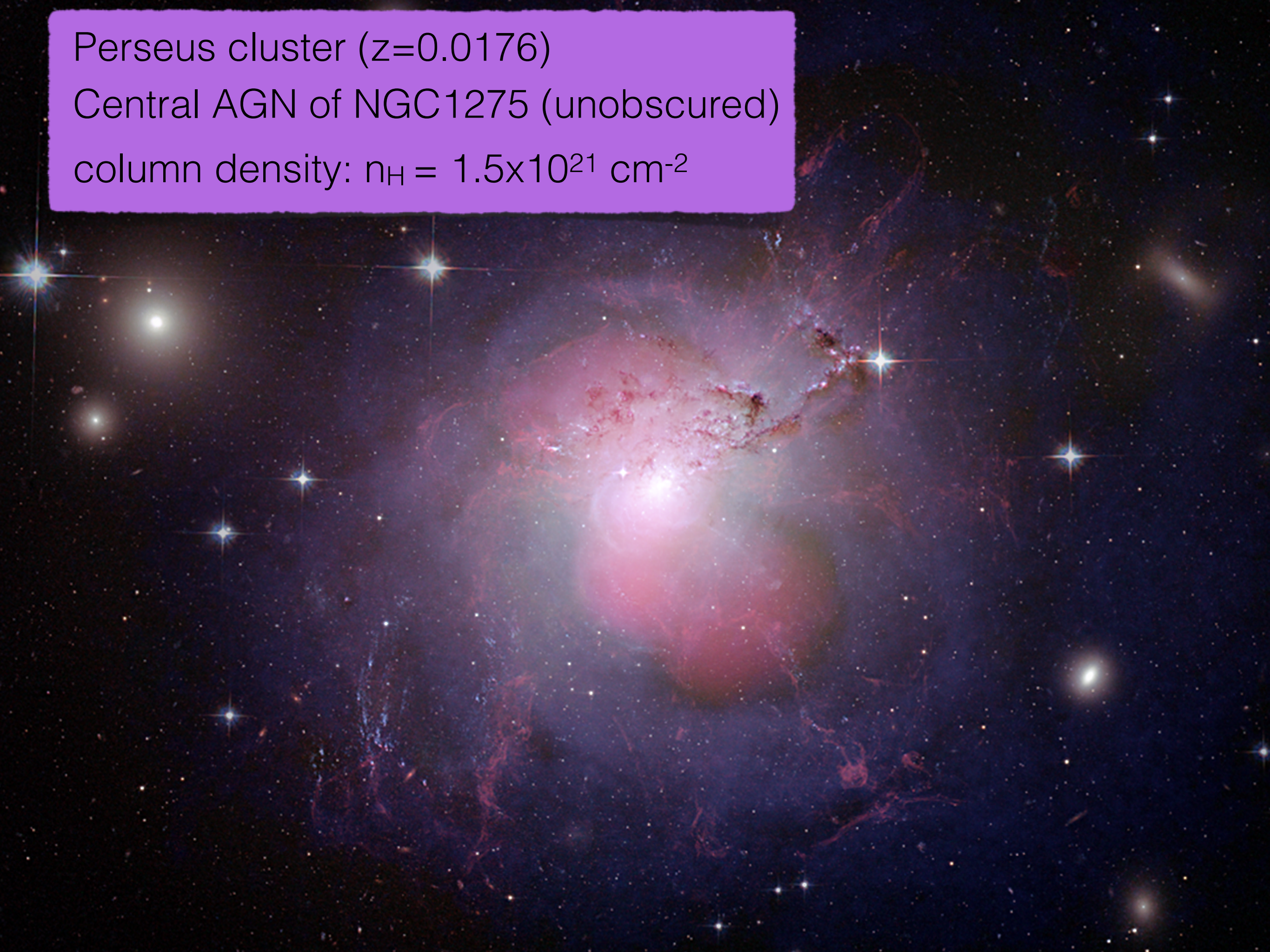
based on: arXiv:1605.01043

in collaboration with:
M. Berg, J. Conlon, F. Day, N. Jennings, A. Powell, M. Rummel

Perseus cluster (z=0.0176)

Central AGN of NGC1275 (unobscured)

column density: $n_H = 1.5 \times 10^{21}$ cm^{-2}



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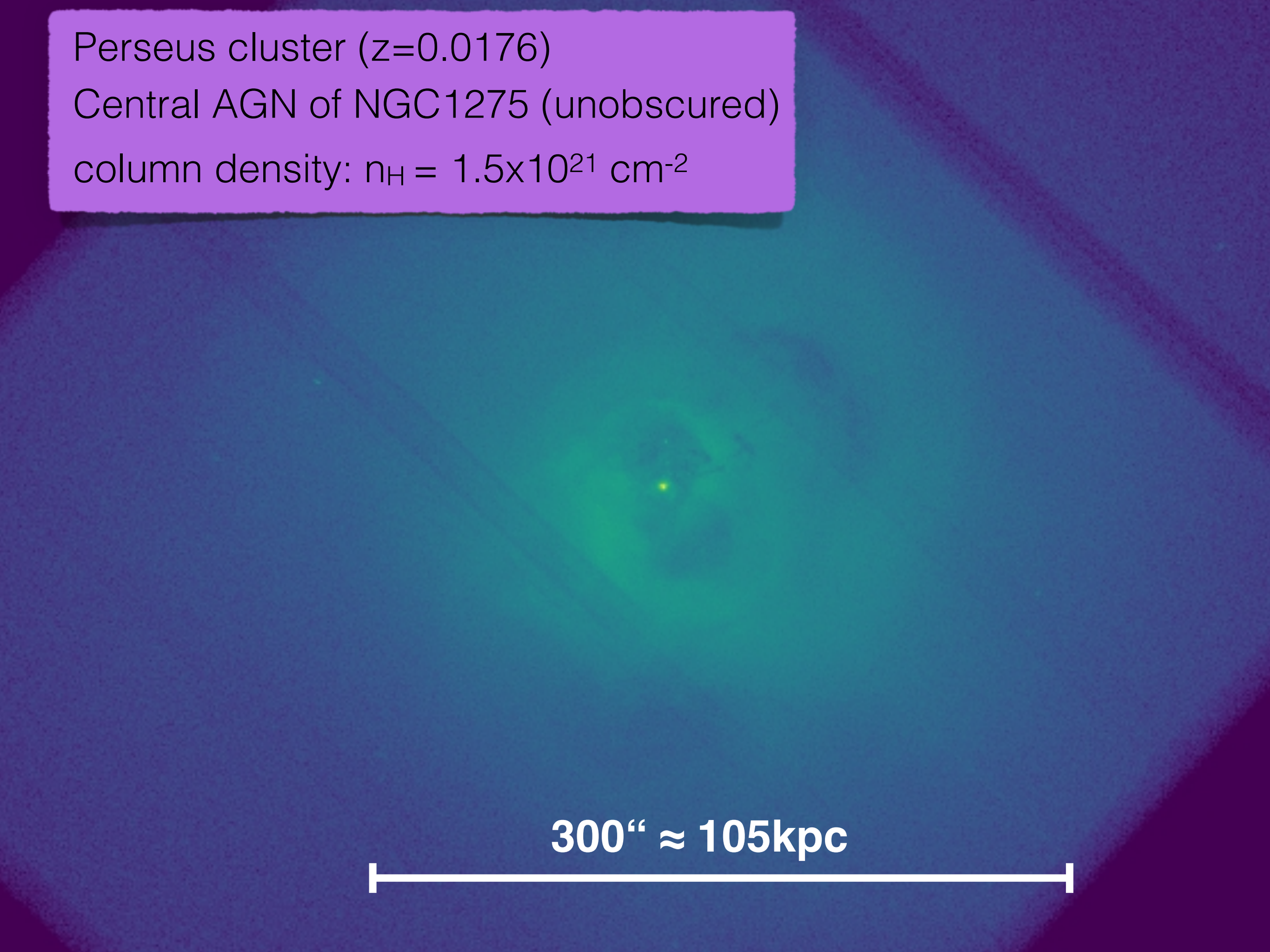


What are we interested in?

- Photon axion conversion in astrophysical objects:

$$g_{a\gamma\gamma}\ a\ \mathbf{E}\cdot\mathbf{B}$$

- here: point sources (e.g. AGNs & Quasars) in galaxy clusters (X-ray spectrum)

- Look for energy dependent modulations in the spectrum

- Similar analysis by Wouters and Brun but with a less luminous AGN (Hydra A) than NGC1275 (~1% of data used here)

- Fermi-LAT analysis of NGC1275 (talk Meyer, 1603.06978) and H.E.S.S. (PKS 2155-304, 1311.3148)

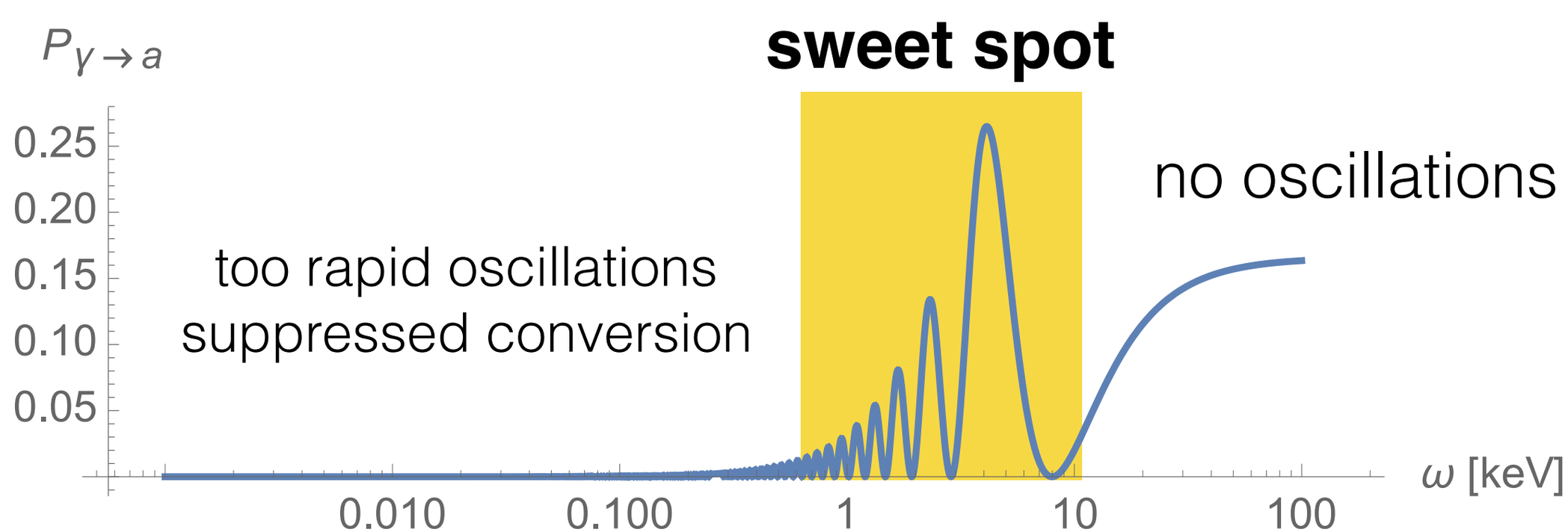
Why X-rays?

- 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:



let’s look at Perseus

Magnetic Field - Perseus

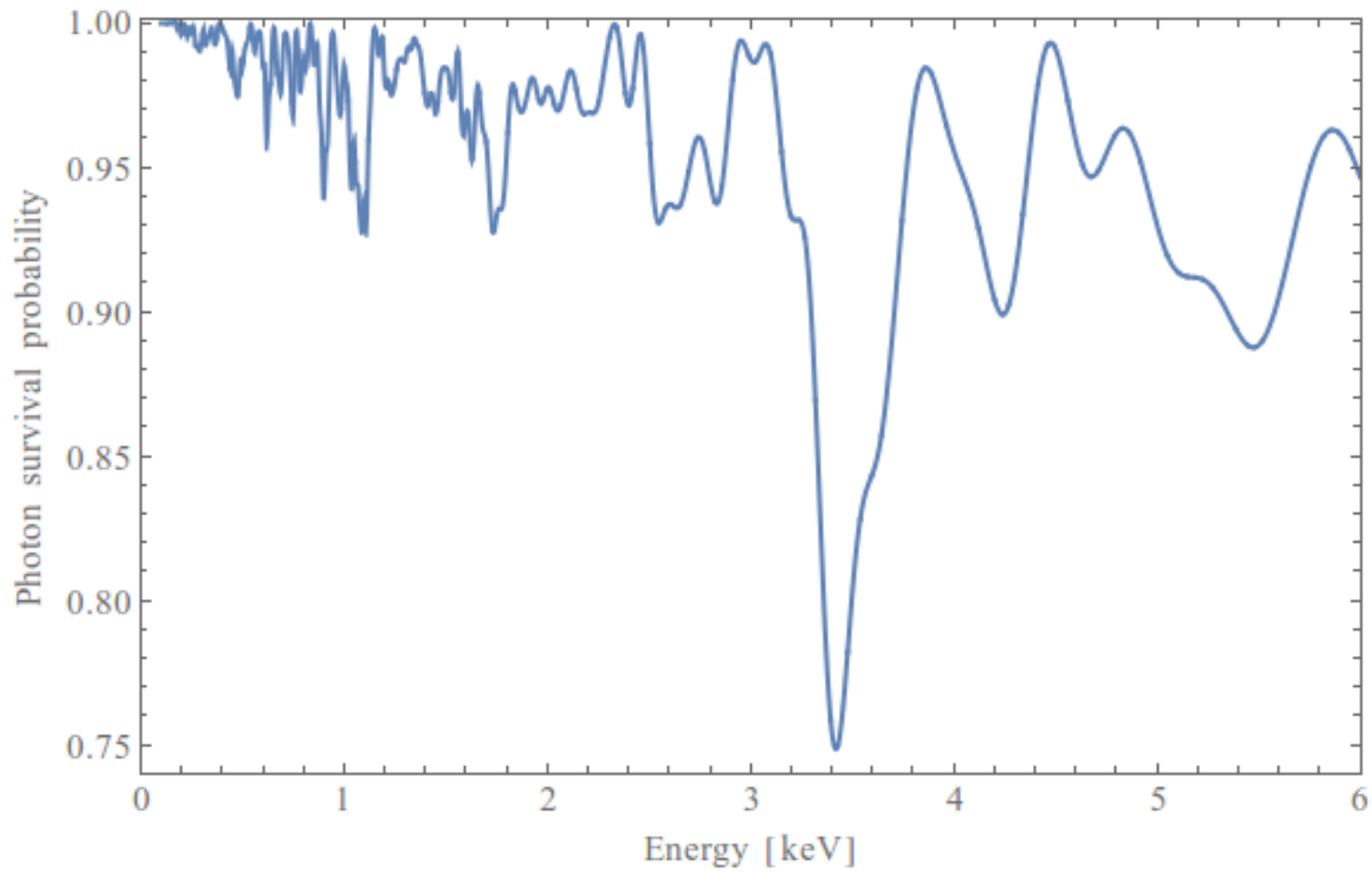
- Magnetic field extends over approx. 1 Mpc regions with coherence lengths in 1-10 kpc.
- No detailed knowledge of exact value of Perseus magnetic field; central value should be in range 10-25 μG (astro-ph/0602622).
- Magnetic field strengths are 1-10 μG.
- Allowed values of photon-ALP coupling $g_{a\gamma\gamma}$ can lead to conversion probabilities of order 10 - 50 %.

$$B \propto n_e^{0.7}$$

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

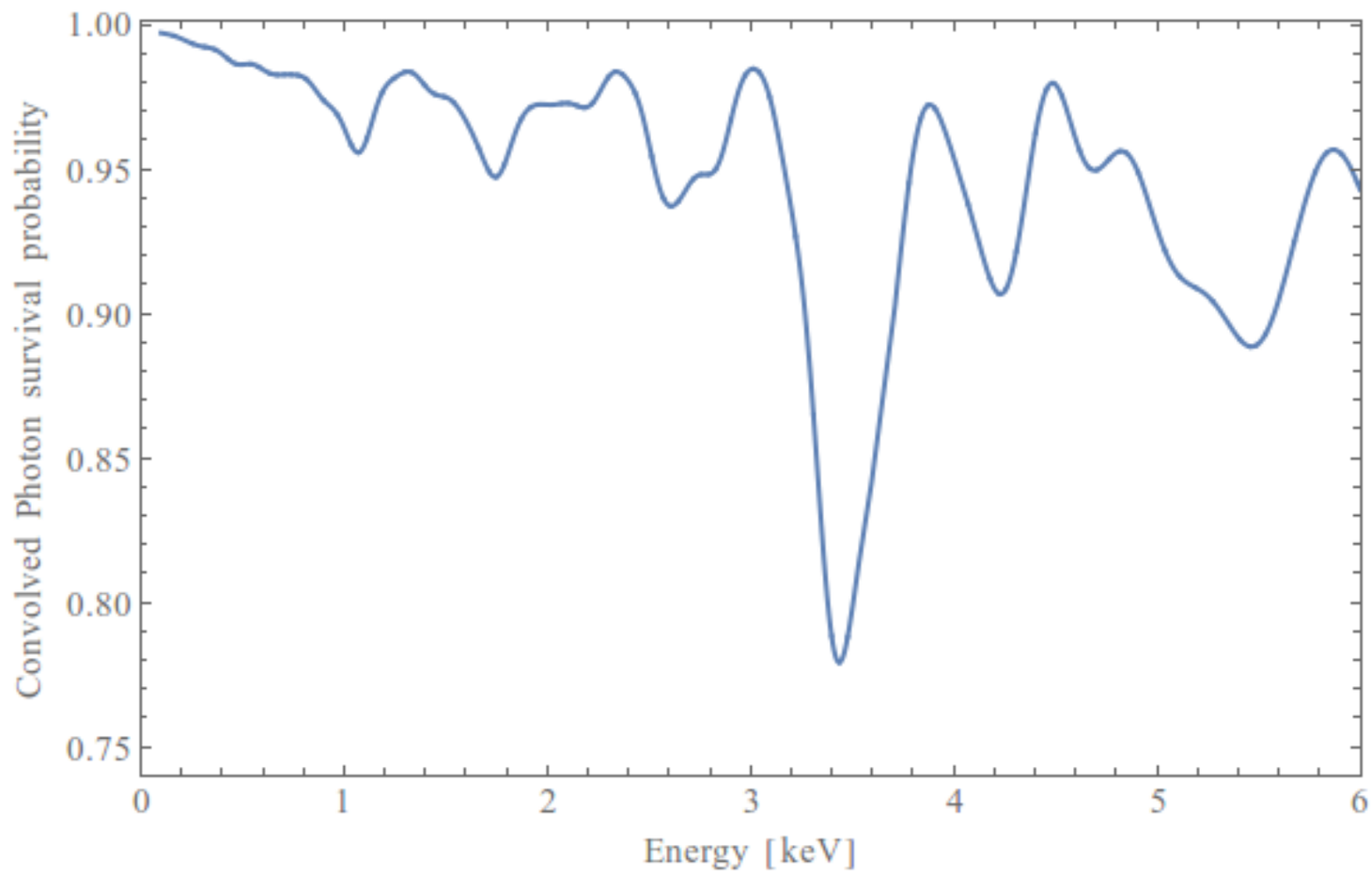
astro-ph/0301482

Photon survival probability - Perseus



100 domains, lengths: 3.5-10 kpc (total: 620kpc), B_0=15μG

Photon survival probability - Perseus



convolved with Gaussian FWHM (150 eV)

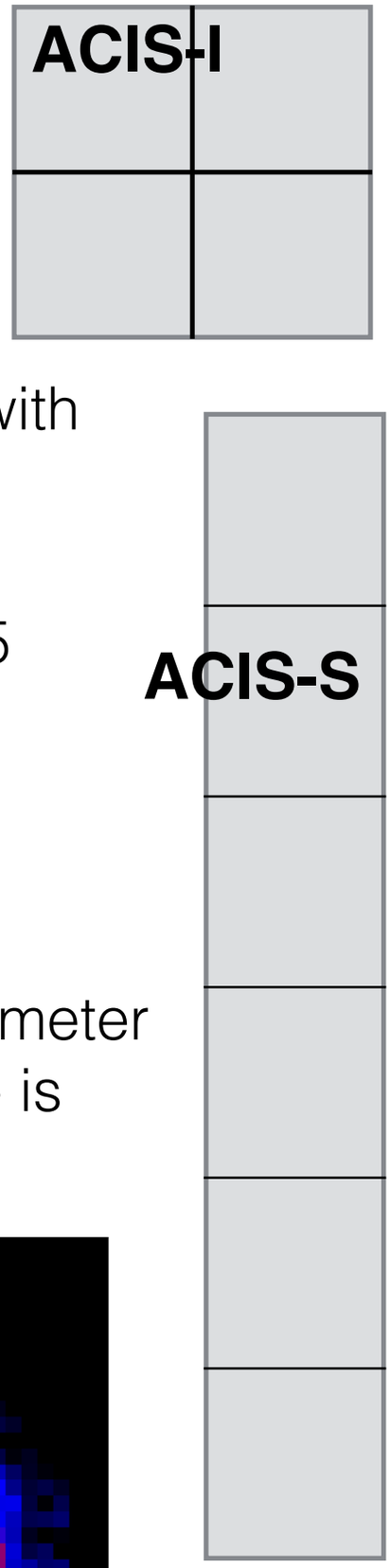
100 domains, lengths: 3.5-10 kpc (total: 620kpc), B_0=15μG

Observations

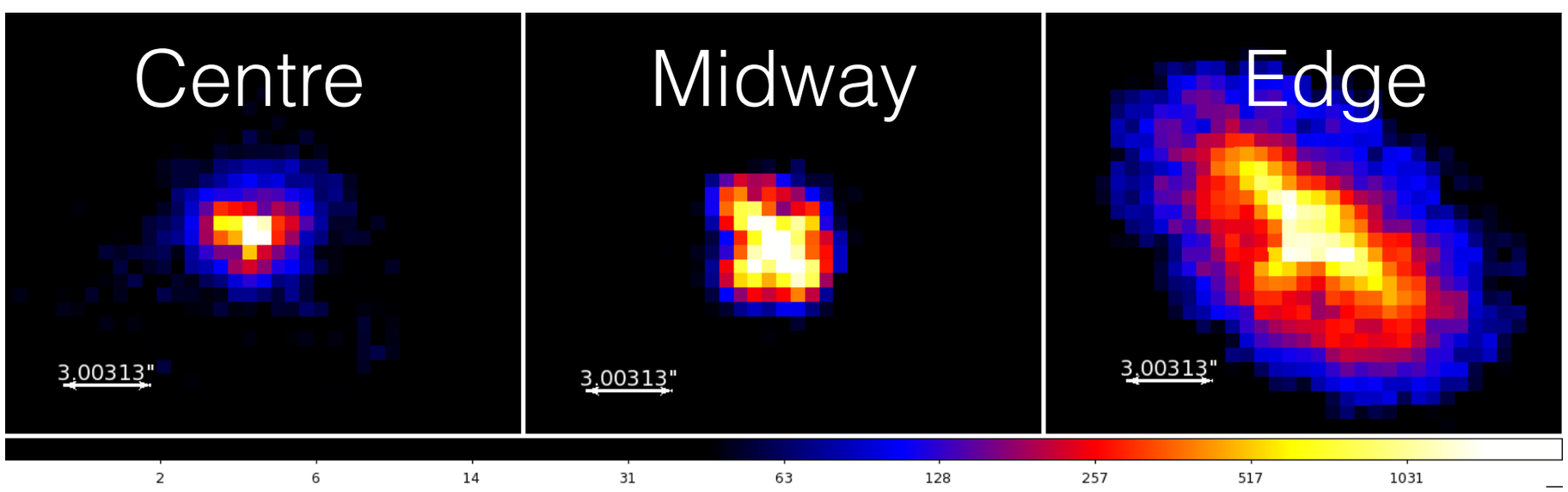
Chandra

XMM Newton

Observation



- NGC1275 observed by Chandra in 2002 and 2004 for 1 Msec with ACIS-S and 0.5 Msec in 2009 with ACIS-I:
  1. Centre: ACIS-S observations, NGC1275 is on-axis
  2. Midway: 2009 ACIS-I observations 300 ksec with NGC1275 around 4 arcmin off-axis
  3. Edge: 200 ksec with NGC1275 around 8 arcmin off-axis.
- We treat these three data sets separately.
- 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.



Spectral analysis

- We extract the AGN spectrum and subtract nearby cluster emission for background.

- We fit the AGN spectrum (0.8 - 5 keV) with an absorbed power-law (supplemented by a soft thermal component).

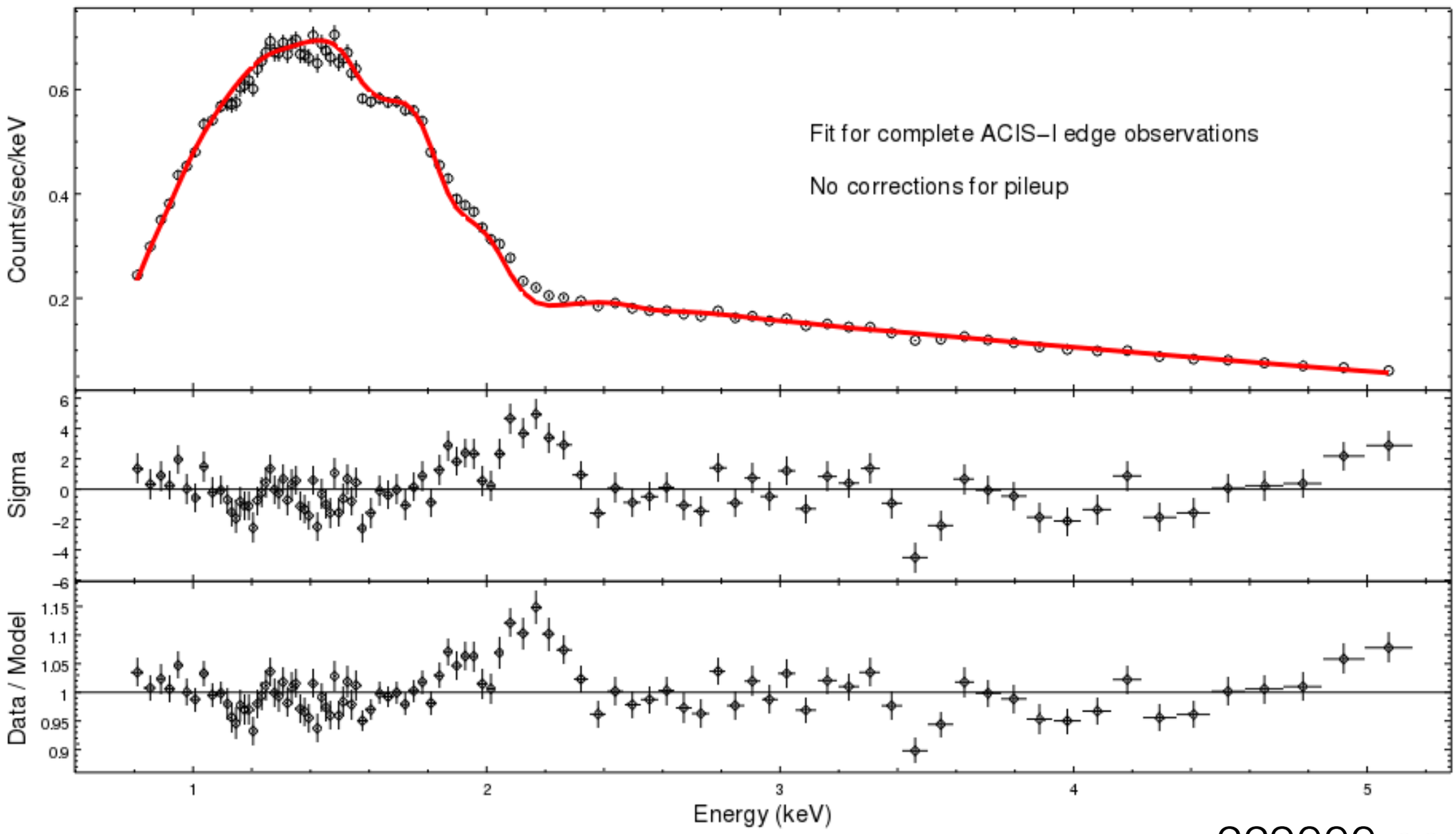
$$F_0(E) = A\ E^{-\gamma} \times e^{-n_H \sigma(E)}$$

- We then examine these spectra and look for residuals.

- Counts are grouped such that there are approx. 100 bins in total.

- Total counts:
    1. 230 000 for 2009 ACIS-I ‘edge’ observations (cleanest dataset)
    2. 242 000 for 2009 ACIS-I ‘midway’ observations
    3. 183 000 for 2002-2004 ACIS-S on-axis observation

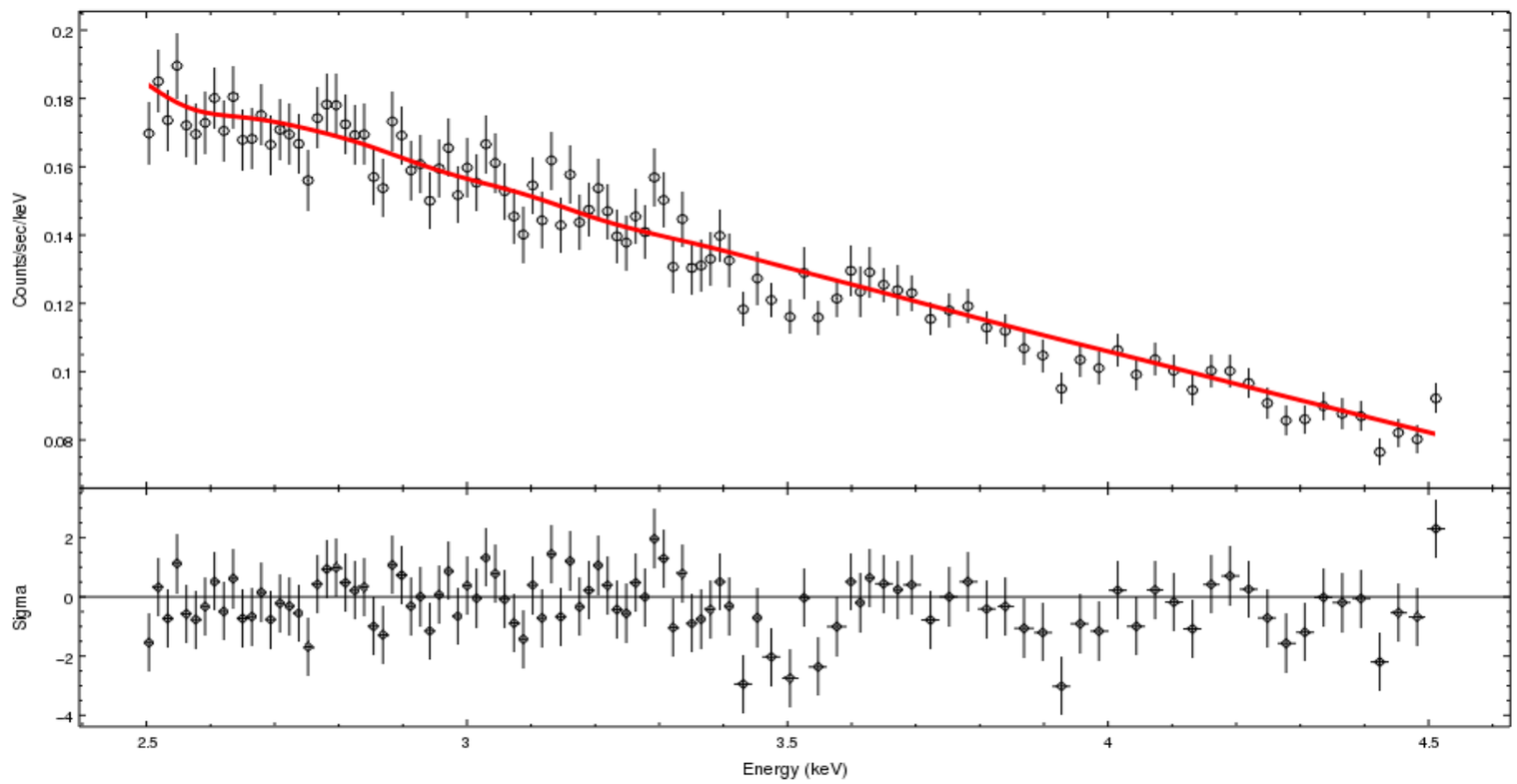
ACIS-I edge



229000 counts
$n_H = 2.1\ 10^{21}\ cm^{-2}$
$\gamma = 1.82$
AGN/cluster: 6.51:1

2-2.2 keV: five data points in a row 3-5 sigma high.
3.4-3.5 keV: two data points low, 4.5 sigma, 2.6 sigma

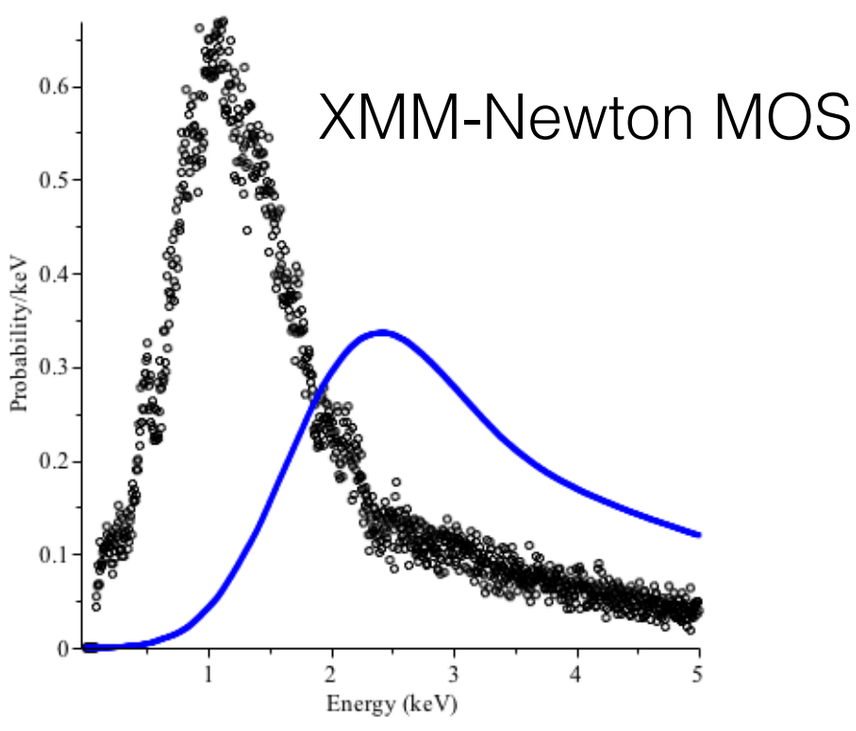
Zoom-in on 3.5 keV

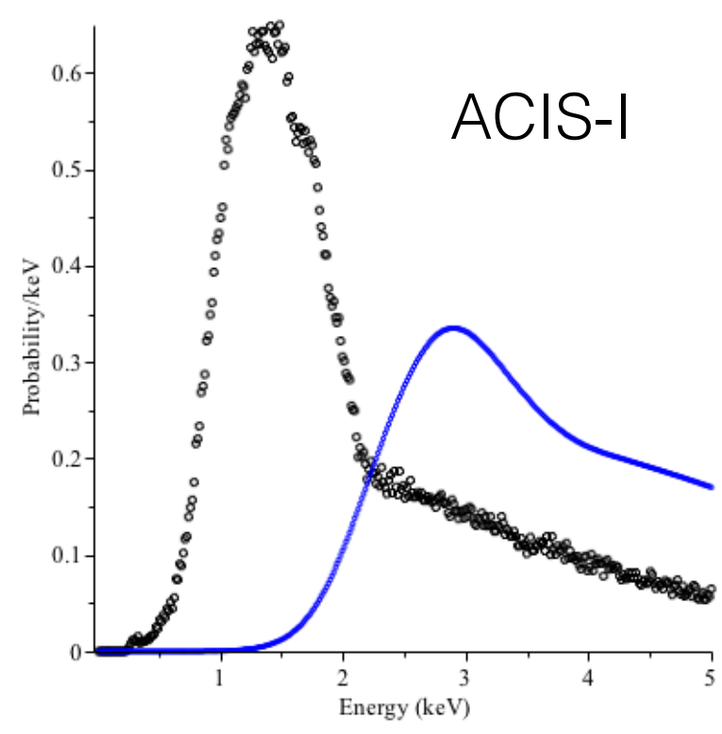


Possibly a connection to observation of 3.5 keV excess from diffuse cluster emission (Bulbul et al, Boyarsky et al)

Pile-up

- Care is needed as 2-2.2 keV region is near a detector feature
- Do features arise from pile-up (multiple photons arriving within a single read-out time)?
- Clean spectrum by removing regions of highest pile-up (and model pile-up with *jdpileup*)





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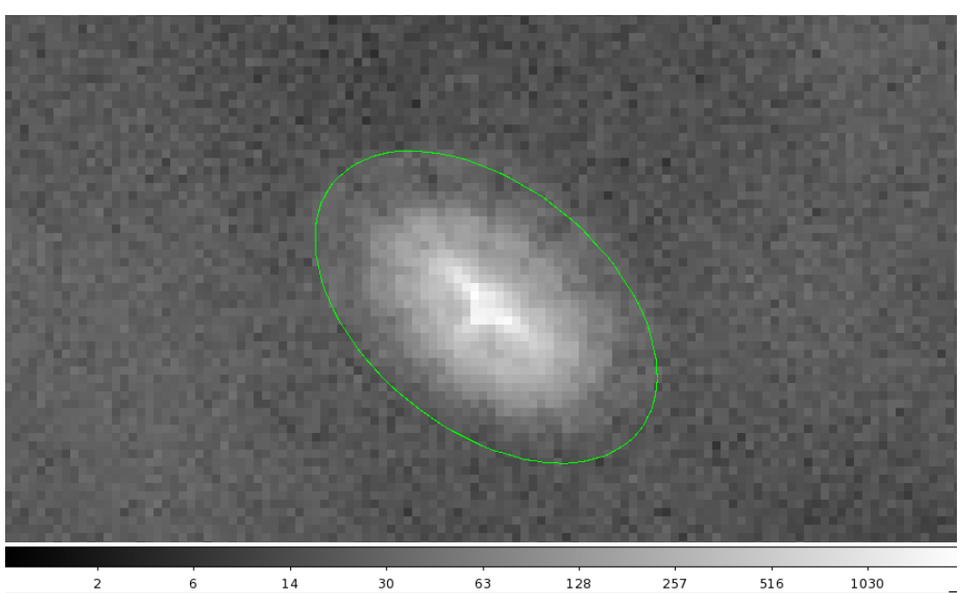
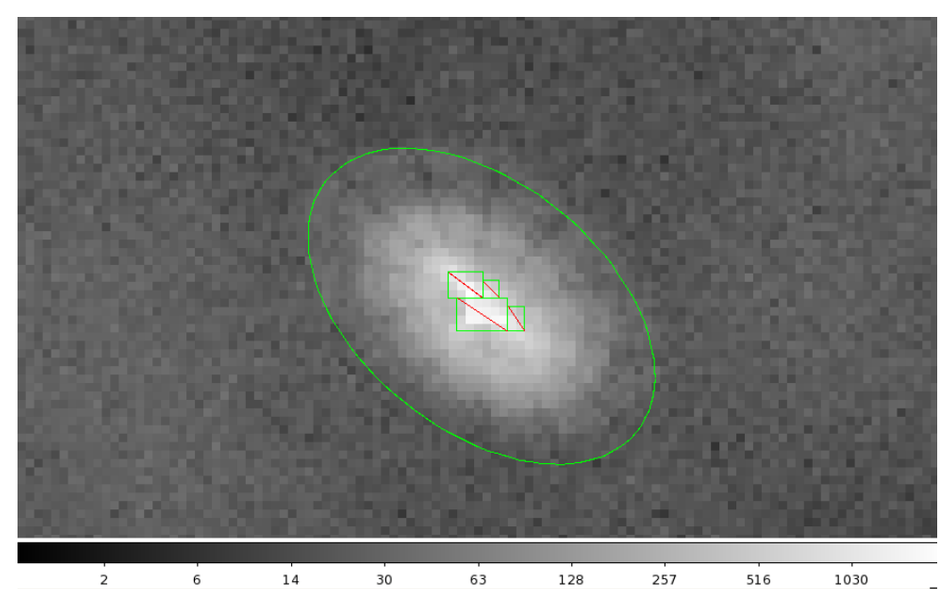
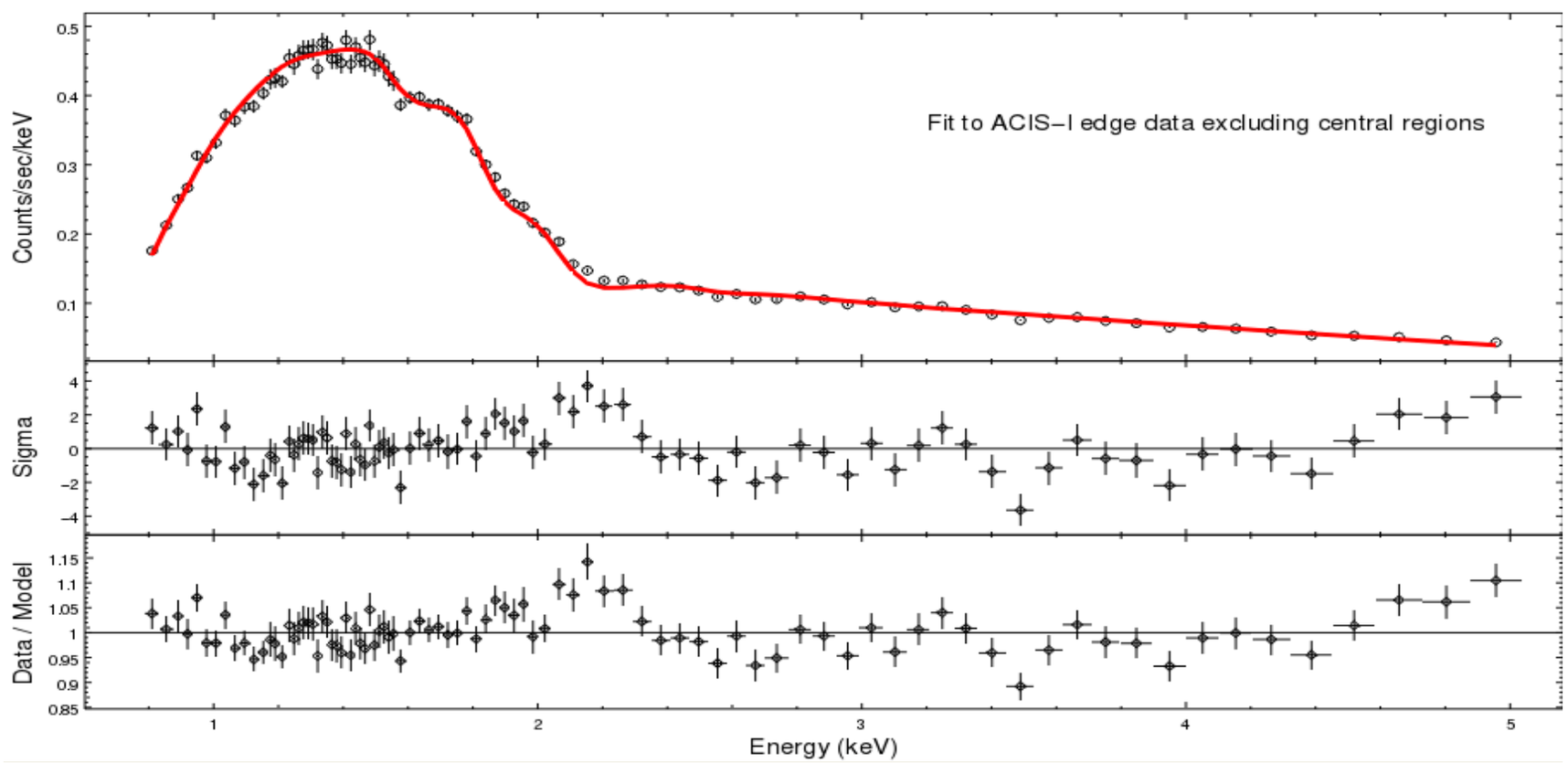




Cleaned edge spectrum

Cleaned spectrum has same features:

1. Statistical significance reduces slightly (consistent with reduction in the amount of data)
2. Magnitude of excess remains the same (data/model ratio) - suggesting pile-up is not the origin.



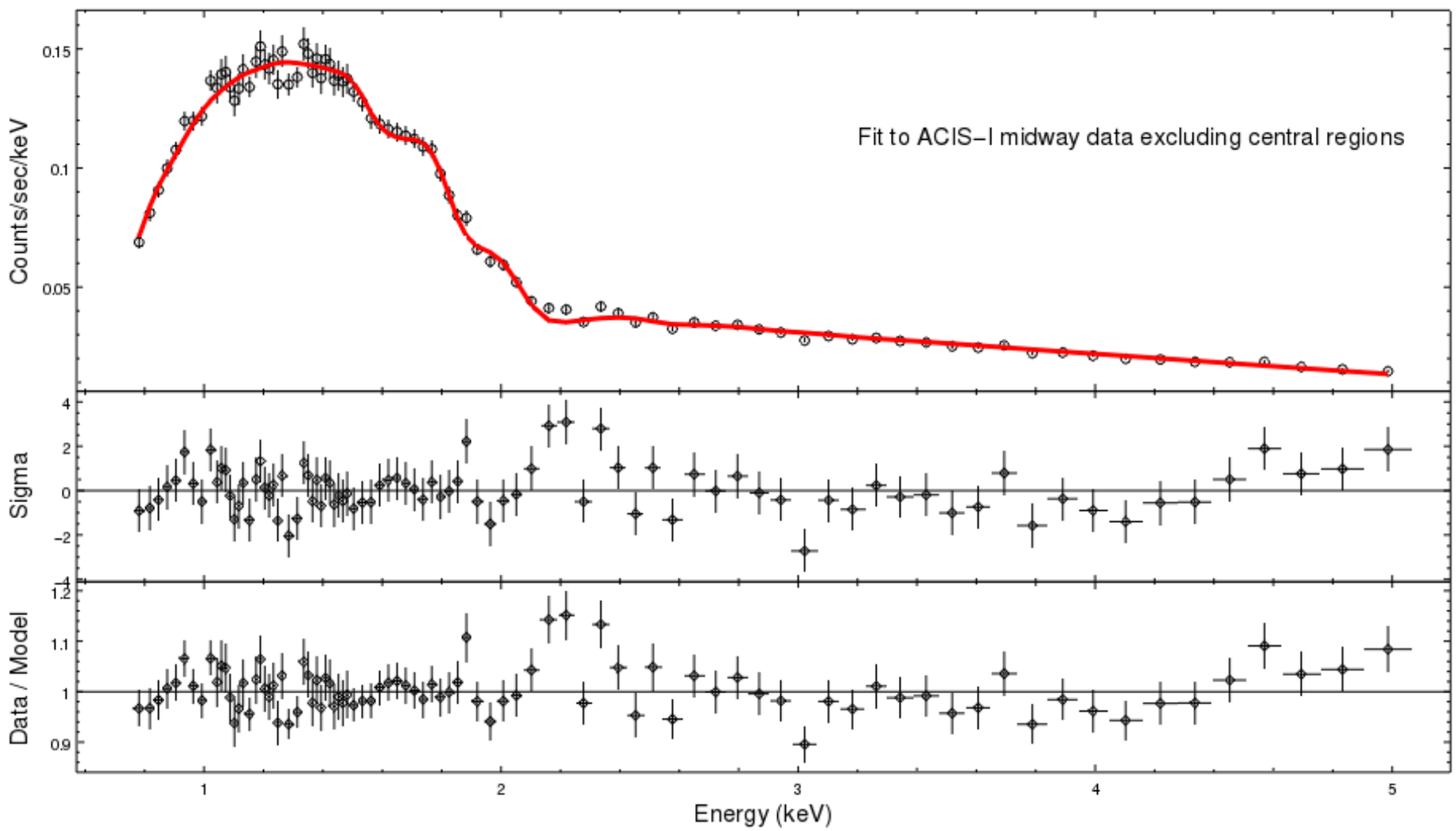
153000 counts

$n_H = 2.2\ 10^{21}\ cm^{-2}$

$\gamma = 1.85$

AGN/cluster: 4.5:1

Midway/Central spectra

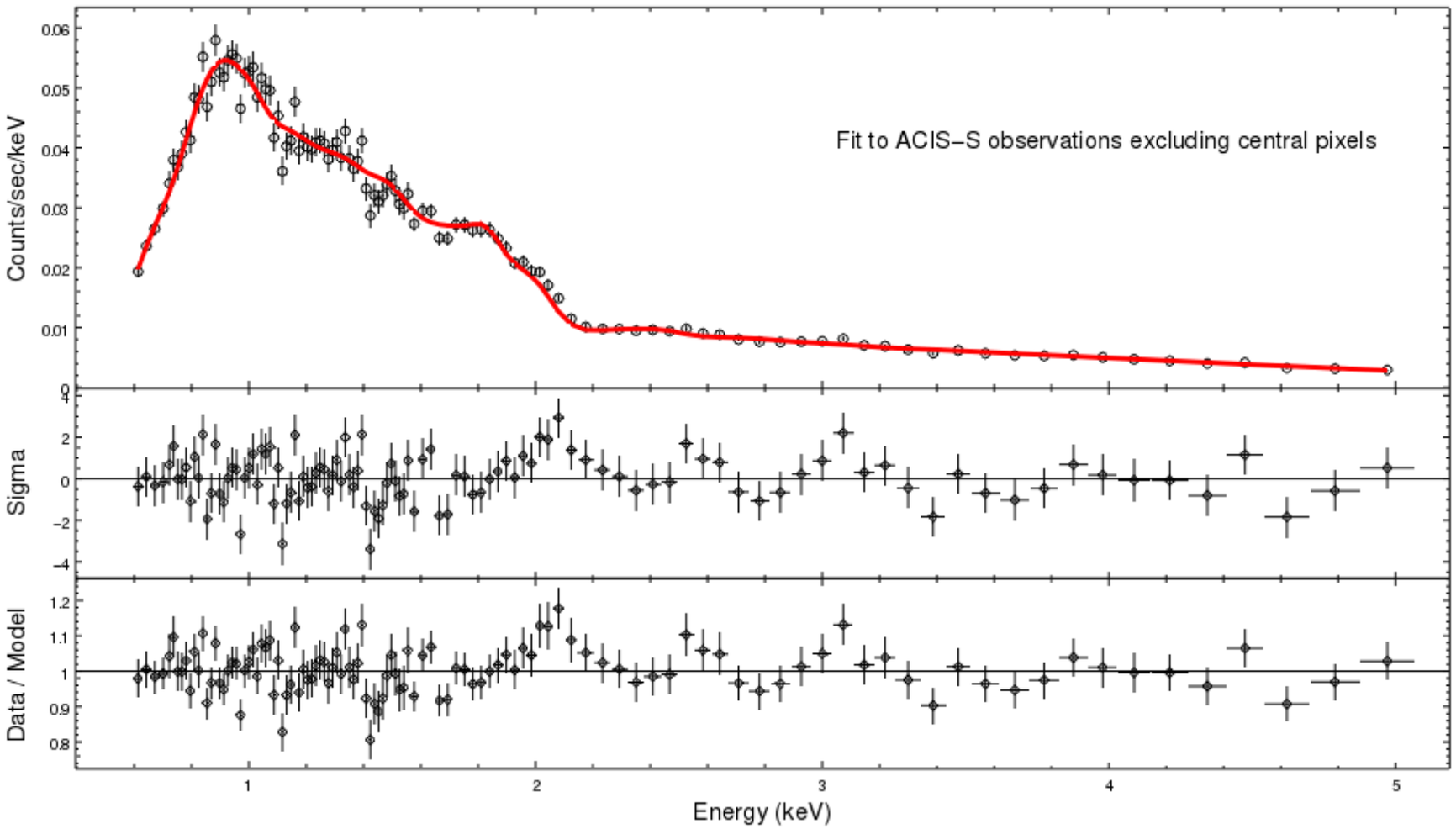


74000 counts

$n_H = 1.3\ 10^{21}\ cm^{-2}$

$\gamma = 1.64$

Midway/Central spectra



74000 counts
$n_H = 1.7\ 10^{21}\ cm^{-2}$
$\gamma = 1.85$
soft-thermal component (T=0.83 keV)

Summary of Data

- Fits of Chandra data on NGC1275 produces two main features:

  1. Excess at approx. 5-15% level in 2-2.2 keV region
  2. Deficit at approx. 5-10% level in 3.4-3.5 keV region

- Statistical significance of 2-2.2 keV excess is overwhelming (far beyond 5σ)

!!! Systematics !!!

- Statistical significance of 3.4-3.5 keV deficit is ‘only’ around 5σ

- XMM-Newton observations contaminated by pile-up

Systematics

- Pileup: magnitude of excess is the same across different spectra on different instruments with widely differing levels of pileup.
- Effective area mis-calibration: excess is not present in the background spectra.
- Mis-subtraction of cluster background: can extract in a way that AGN dominates background cluster emission by 15:1 or even 60:1, but O(10%) features survive.
- Mis-calibration of gain in high-flux region: level of flux is very different in the respective spectra while features remain at consistent level.
- Emission line (2-2.2 keV) from soft thermal component - no plausible lines in relevant region.
- Fluorescent emission from S Kα line at 2.31 keV - energy too high and line not strong enough.
- Absorption line (3.4-3.5 keV): no plausible lines. Absorption from Milky Way? No absorption seen in diffuse cluster spectra.

New Physics

- ALPs can explain and generate modulations for $g_{a\gamma\gamma}$ in 1-5 10^{-12} GeV^{-1} region.

- For 3.4-3.5 keV deficit, can also consider a dark matter absorption line:

    1. Relevant for models of excited dark matter used to explain 3.5 keV cluster emission line.

    2. Dark matter column density along line of sight to NGC1275 is higher than almost anywhere else.

Bounds

- Use absence of large oscillatory features to place rough bounds on $g_{a\gamma\gamma}$:

$$F_0(E) = A\ E^{-\gamma} \times e^{-n_H \sigma(E)}$$

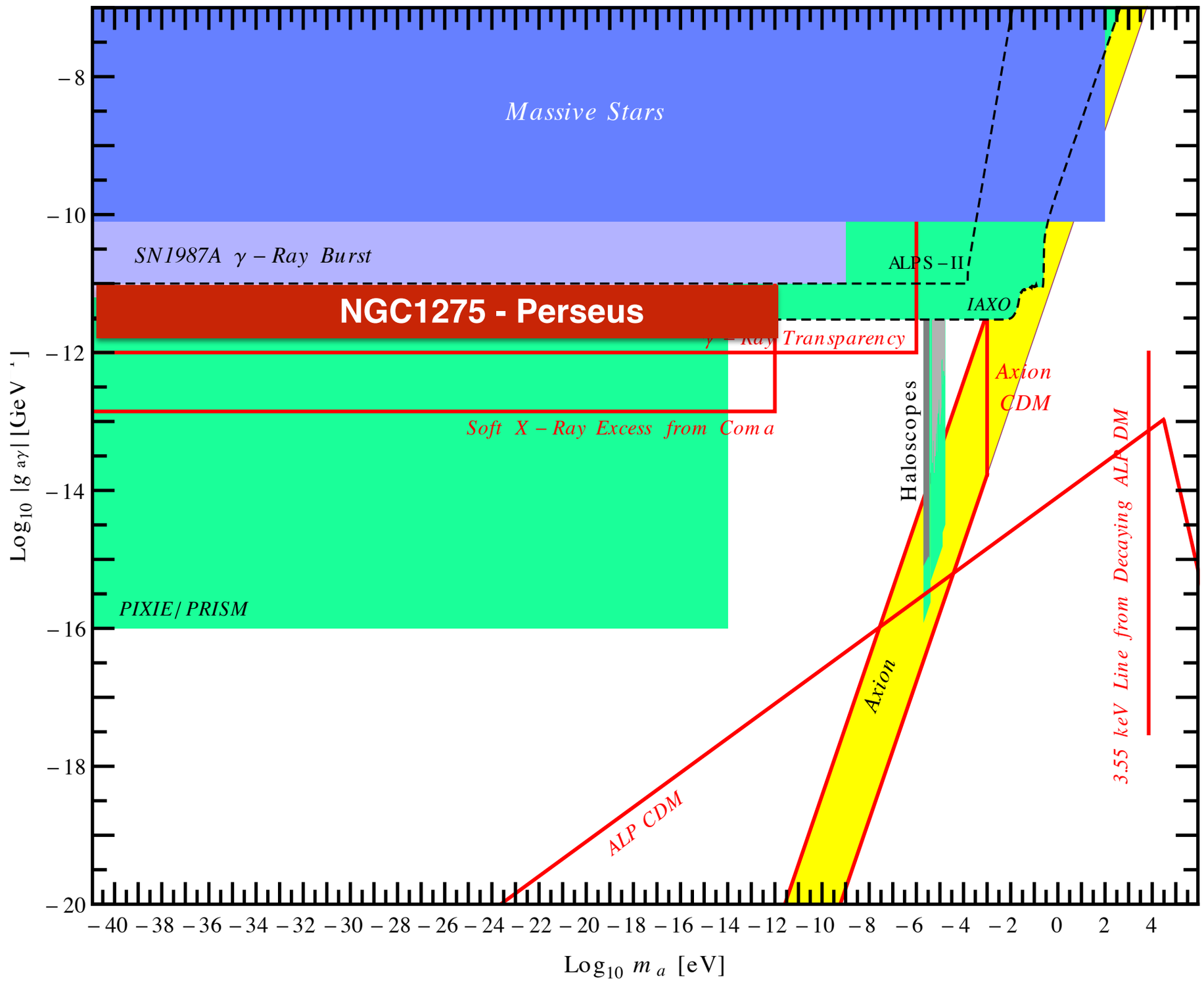
$$F_1(E) = A\ E^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to a}(E, B, g_{a\gamma\gamma})$$

- Assumptions:

$$B \propto n_e^{0.7} \qquad n_e(r) = \frac{3.9 \times 10^{-2}}{\left[1 + (\frac{r}{80\mathrm{kpc}})^2\right]^{1.8}} + \frac{4.05 \times 10^{-3}}{\left[1 + (\frac{r}{280\mathrm{kpc}})^2\right]^{0.87}} \mathrm{cm}^{-3}$$

- Bounds (95% confidence, fake data method):

B_0 [μG]	$x_{\min}$ [kpc]	$g_{a\gamma\gamma}$ [GeV^{-1}]
25	3.5	1.5×10^{-12}
15	0.7	3.8×10^{-12}
10	0.7	5.9×10^{-12}

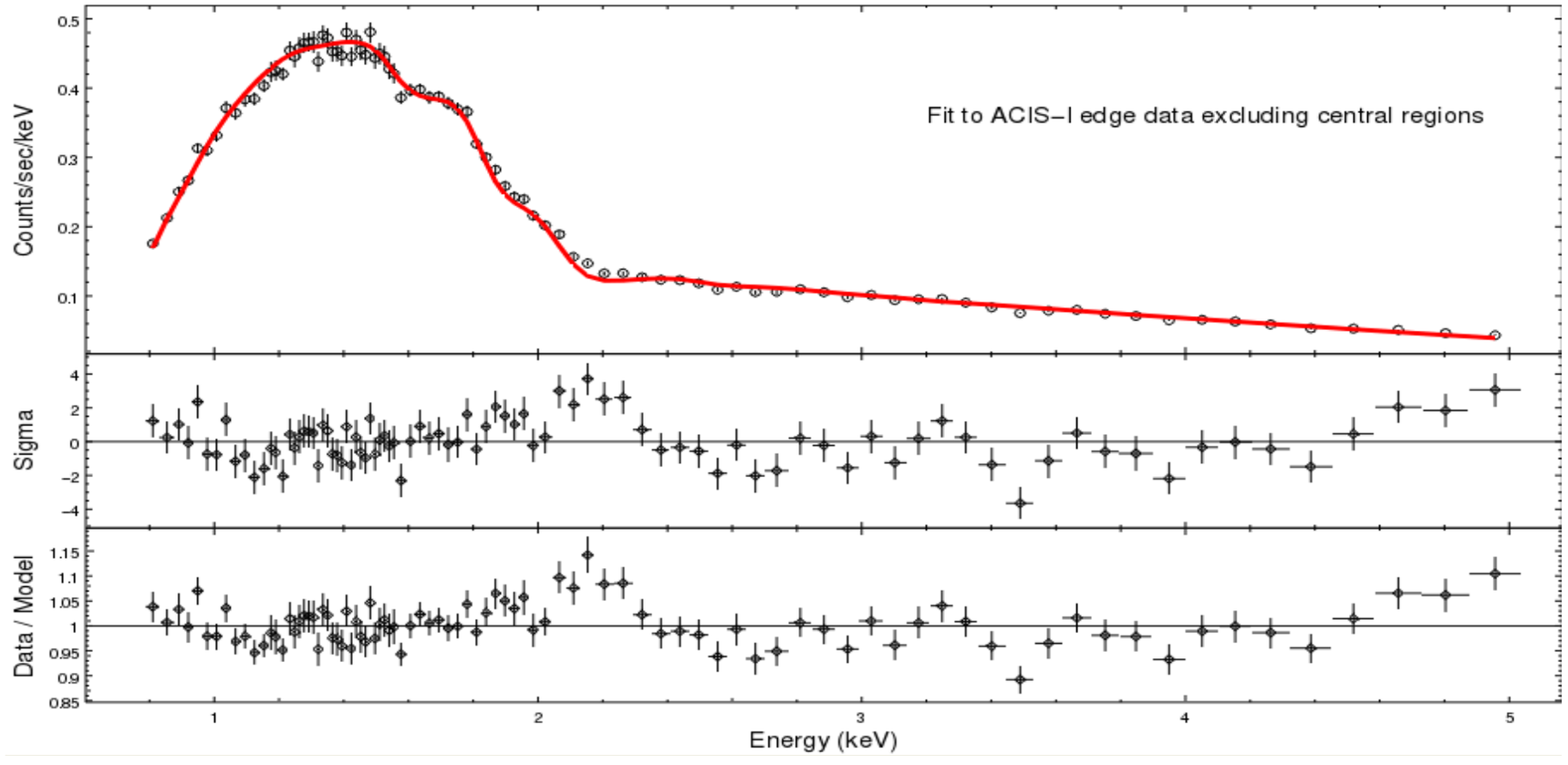


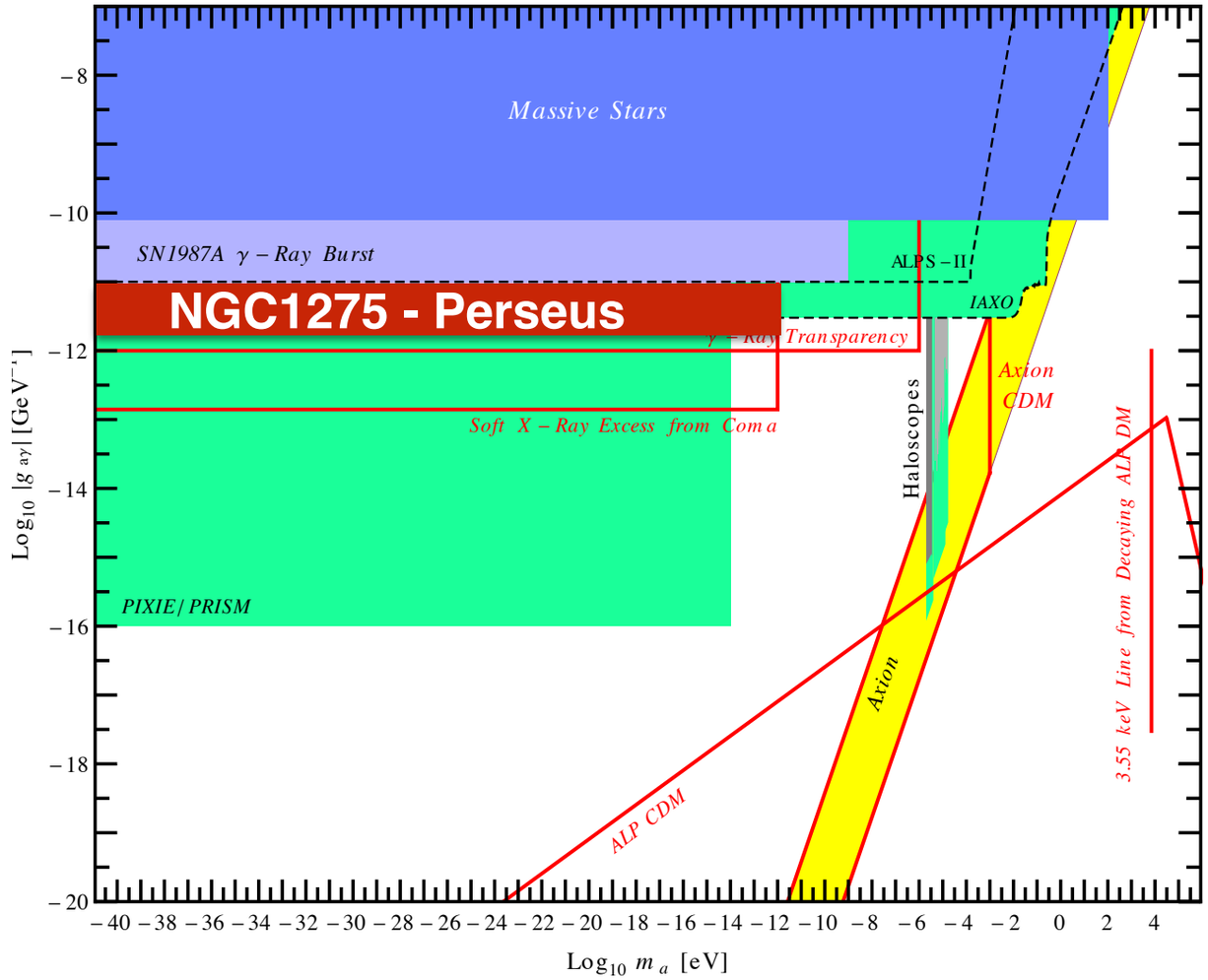
based on Dias et al. (1403.5760)

Conclusions

- This dataset is really, really good.
- It provides the best current bounds on ALP-photon interactions for $m_a<10^{-12}$eV.
- It contains a possible signal with enormous statistical significance - what other systematics are there?
- Very exciting whether Hitomi has something to add, regime IAXO can be sensitive.

고맙습니다!





Thank you!

Extra Slides

More on AGNs

- X-ray emission from AGNs comes from extremely small physical region

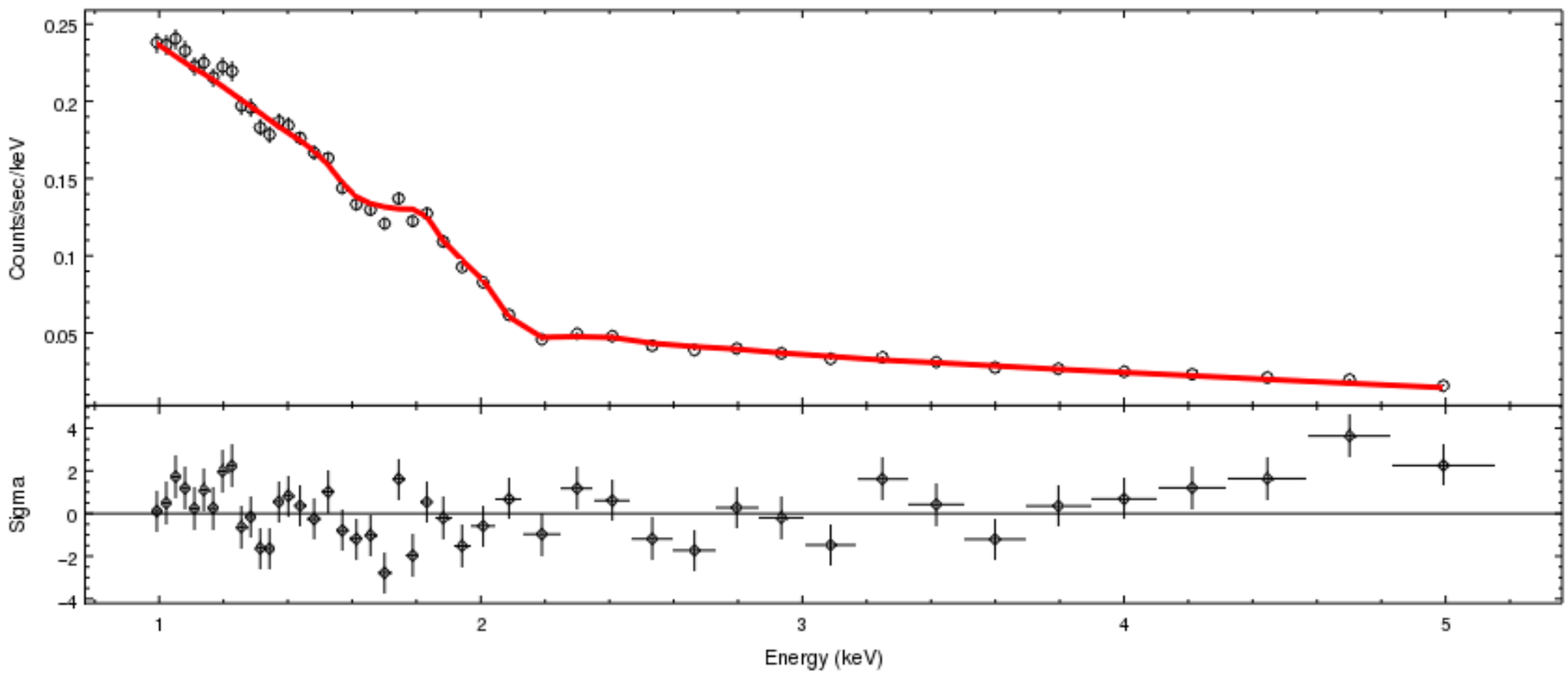
- We know this because of the time variability observed in AGNs: intensities can vary on day timescales, implying emission can only originate from small region.

- Various observations imply X-ray emission comes from innermost region of accretion disc, a few Schwarzschild radii away of BH.

- Basic components of X-ray spectrum:

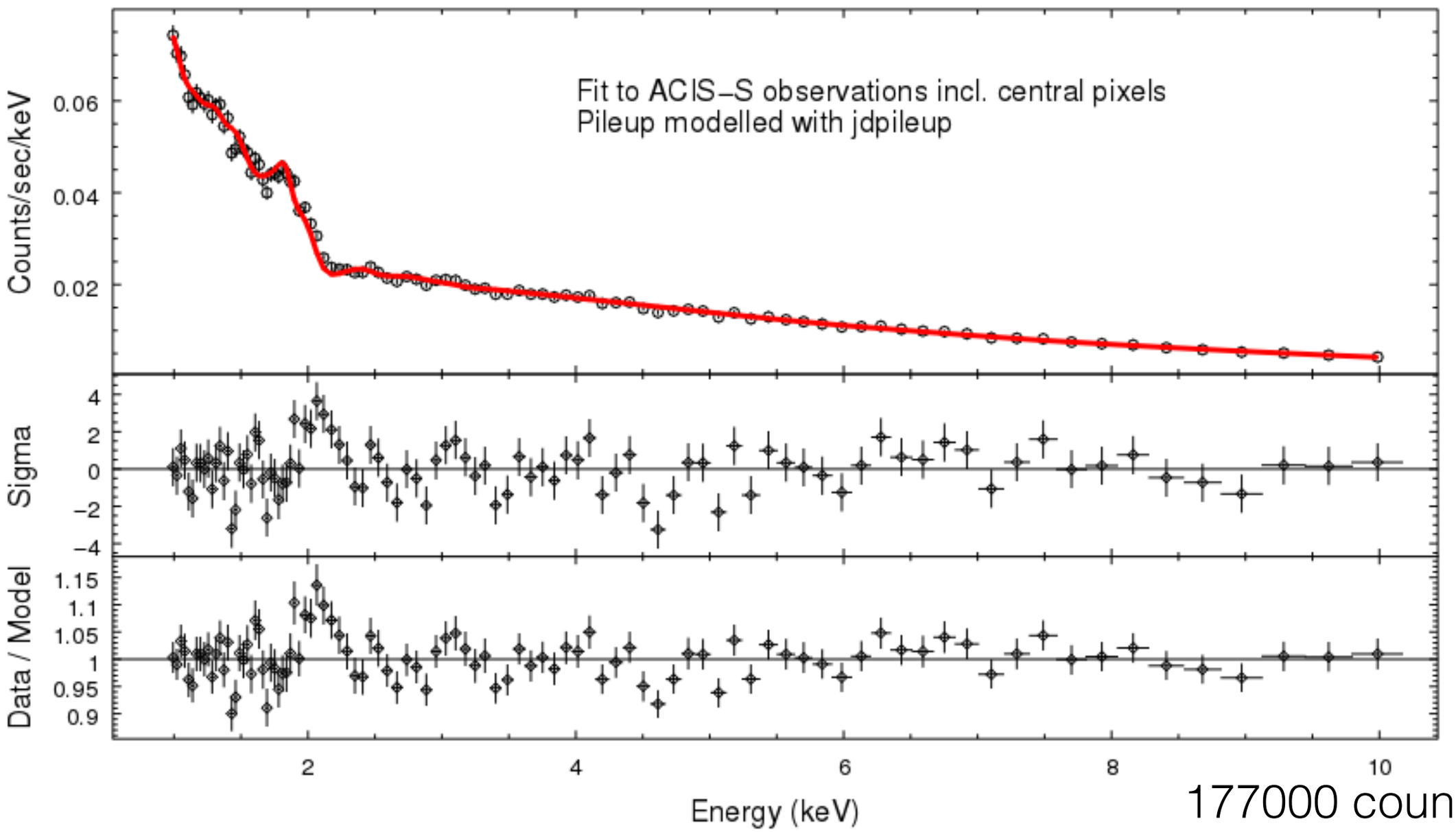
1. Power-law
2. Reflection spectrum (incident photons illuminate accretion disc, resulting in fluorescent emission; in practice: neutral Fe Kα line at 6.4 keV)
3. Thermal soft excess (origin not entirely known)

Spectra of other AGN



Quasar: 3C273

Central observation with Pileup-model



177000 counts

$n_H = 2.6\ 10^{21}\ cm^{-2}$

$\gamma = 1.81$

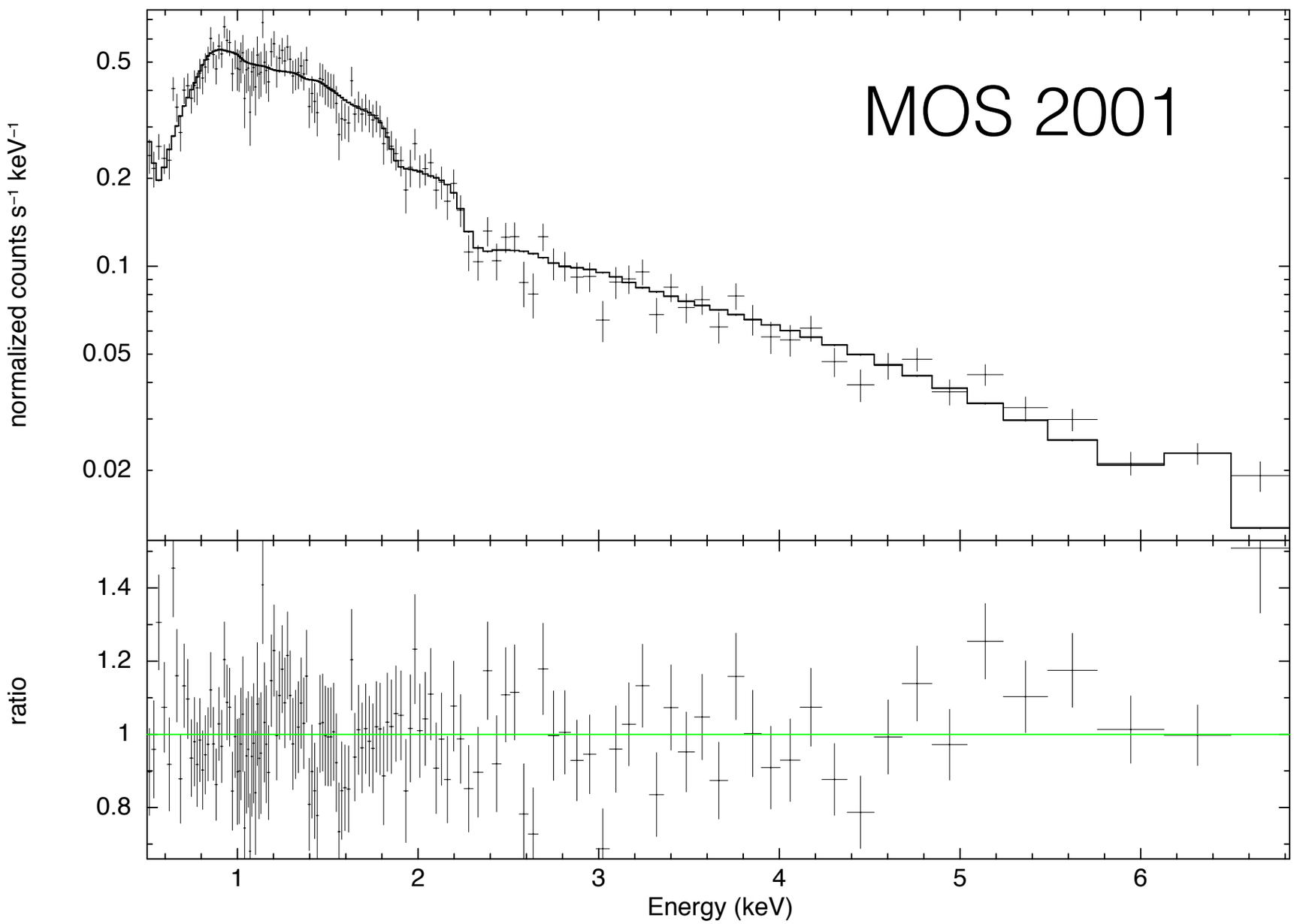
AGN/cluster: 6.51:1

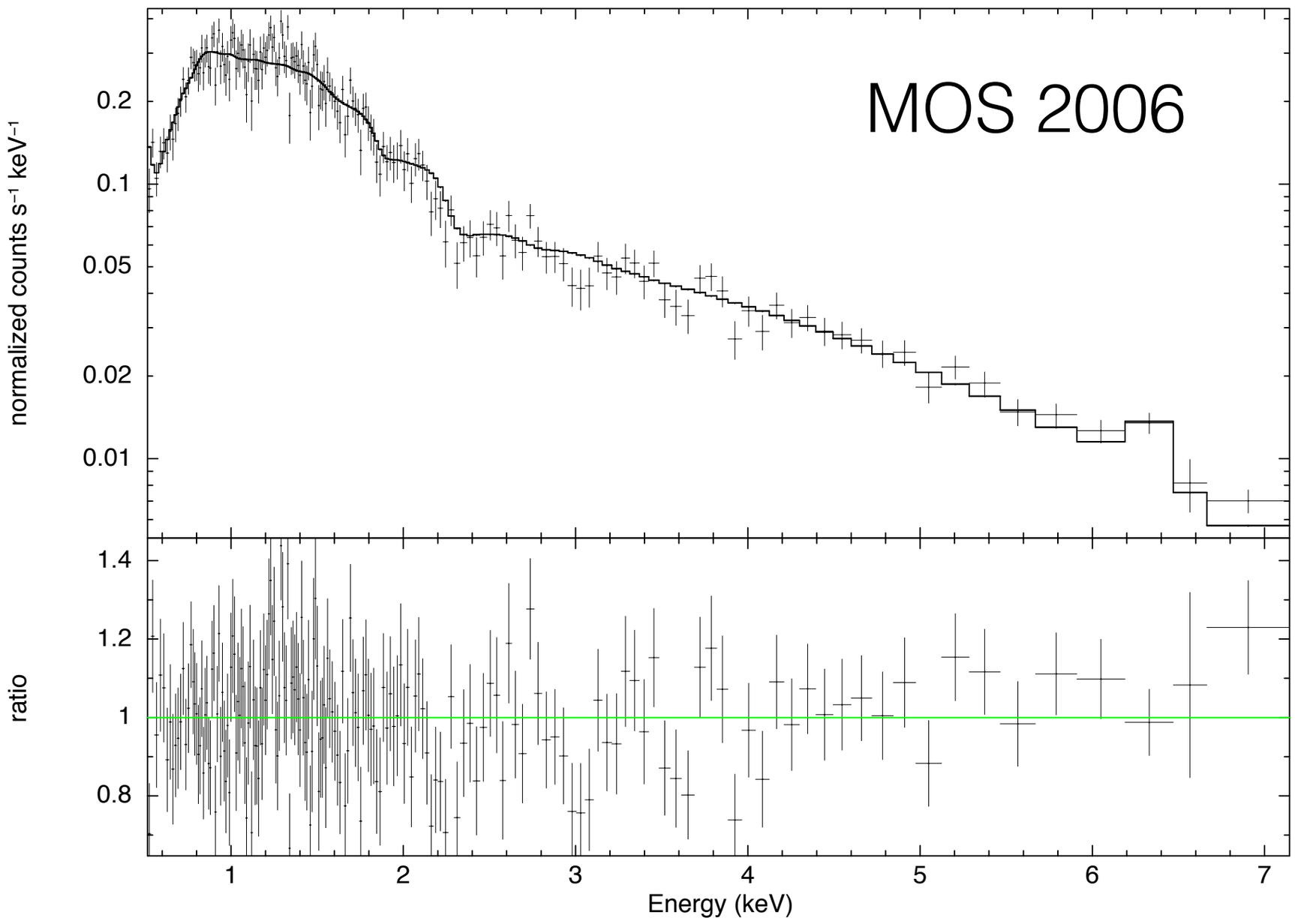
More details on bounds

- Generate fake data from Model1 and access how well it is fit by Model0 (how well oscillations can hide in Poisson noise).
- Fit Model0 to data and find reduced χ^2_{Data} .
- 50 random magnetic fields B_i for l.o.s. to NGC1275 and generate $P_{\gamma\leftrightarrow a}$.
- For each B generate 10 fake data sets from Model1.
- Fit Model0 to each of fake data sets.
- If fewer than 5% of the χ^2 are lower than χ^2_{Data}, $g_{a\gamma\gamma}$ is excluded at 95% confidence level.

XMM spectra

	MOS 2001	MOS 2006
Exposure [ks]	49	118
Counts	$\sim$ 47000	$\sim$ 63000
γ	1.65 $\pm$ 0.03	1.65 $\pm$ 0.03
$T_{\rm soft}$	0.84 $\pm$ 0.06	0.80 $\pm$ 0.06
n_H [10^{22} atoms cm^{-2}]	0.13 $\pm$ 0.03	0.13 $\pm$ 0.03
χ^2/ dof	154 / 131	205 / 178
q-value	0.08	0.08



XMM spectra

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