Searches for Axion-Like Particles with NGC1275

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Axion-Like Particles

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}m_a^2 a^2$$

- Generically arise in string compactifications
- For general ALPs $g_{a\gamma\gamma}$ and m_a are unspecified and unrelated (unlike for the QCD axion)
- $g_{a\gamma\gamma} \lesssim 5 \times 10^{-12}\ \mathrm{GeV}^{-1}$ Supernova Bound
- Coupling to electromagnetism:

$$g_{a\gamma\gamma}\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

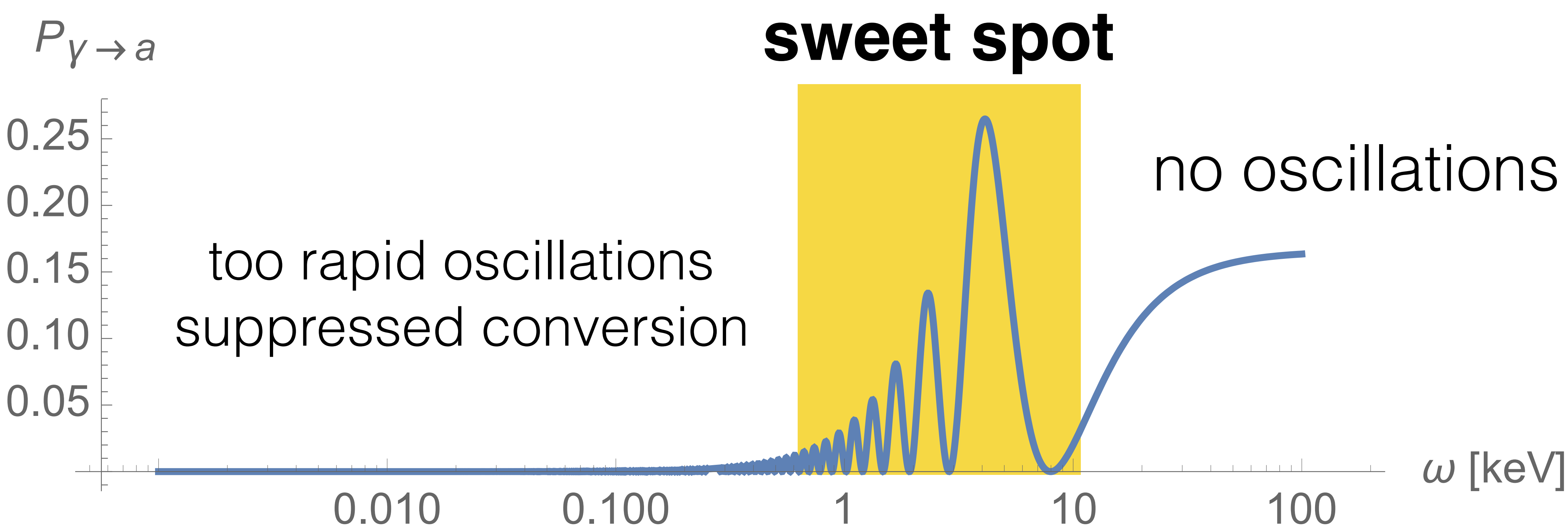
ALP photon conversion

General conversion formula in transverse magnetic field $B_\perp$ of domain size L for very light ALPs $m_a \lesssim 10^{-12}\mathrm{GeV}$:

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

with $\Theta \simeq 0.28\left(\frac{B_\perp}{1\mu\mathrm{G}}\right)\left(\frac{\omega}{1\mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{g_{a\gamma\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)$

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



ALP photon conversion

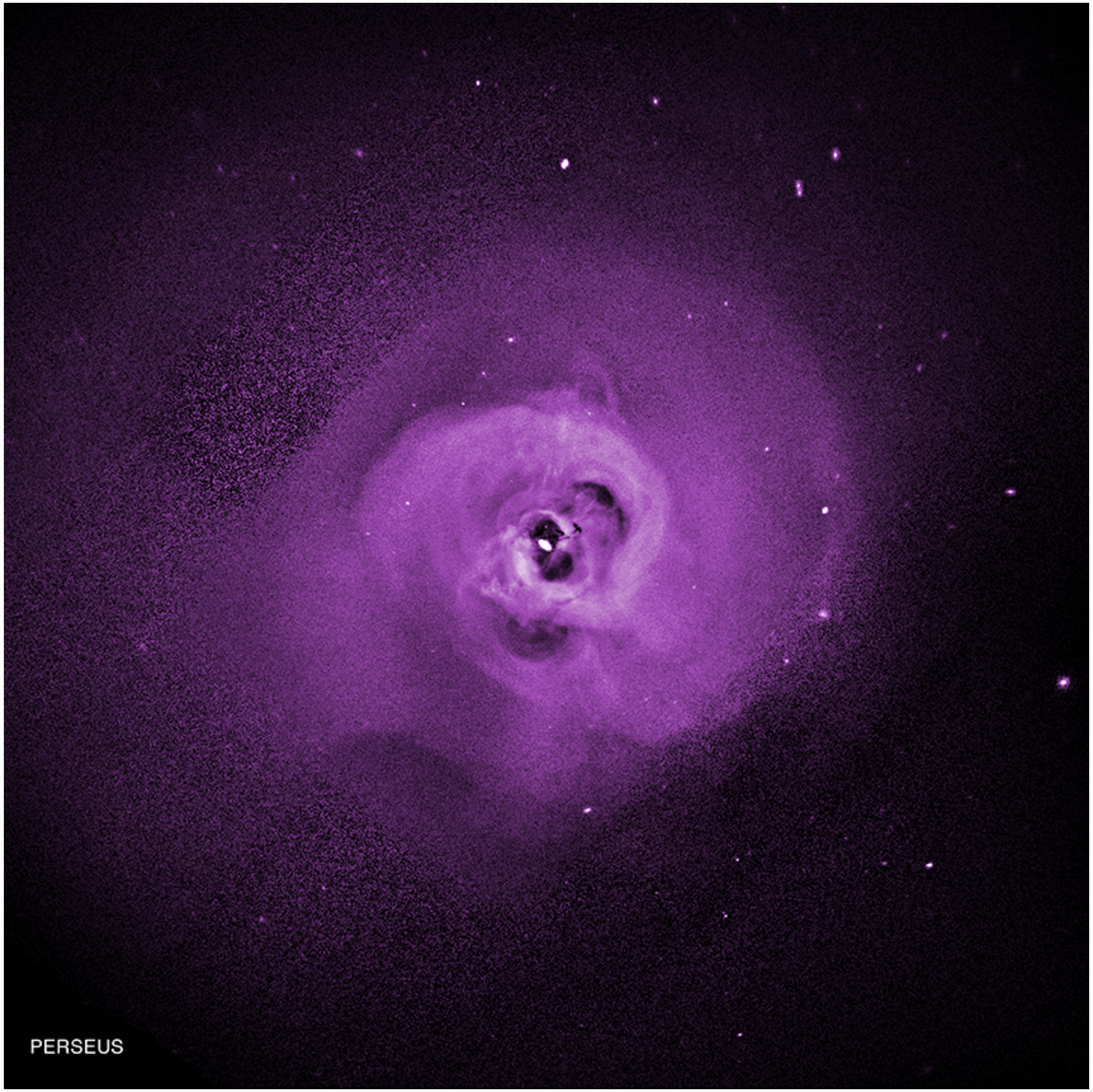
General scaling of conversion probability in coherent magnetic fields:

$$P(\gamma \to a) \sim g_{a\gamma\gamma}^2 \, B^2 \, L^2$$

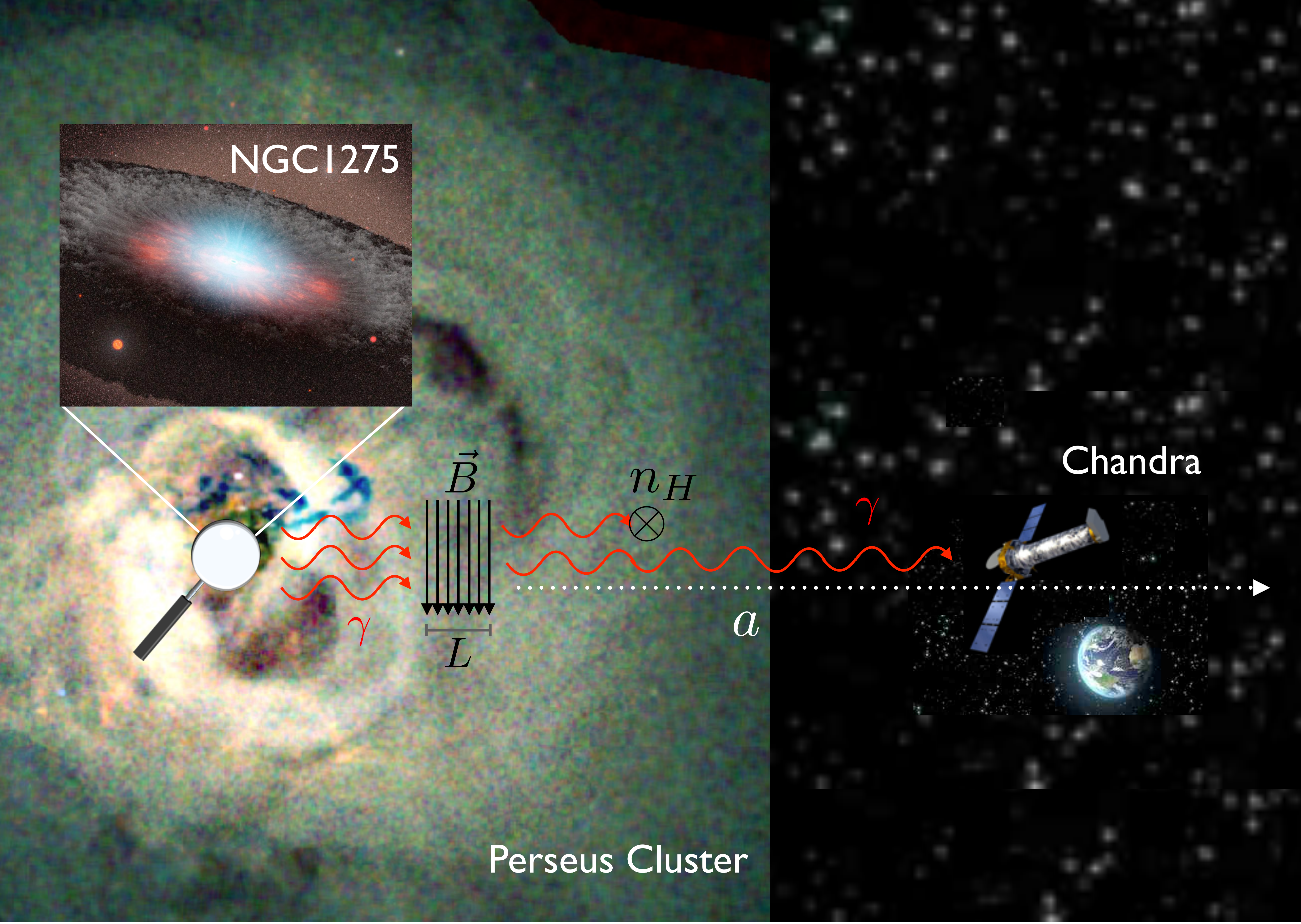
Needs

- BIG magnetic fields B^2 and/or
- LONG coherence length L^2
- Suppressed by weak couplings $g_{a\gamma\gamma}^2$

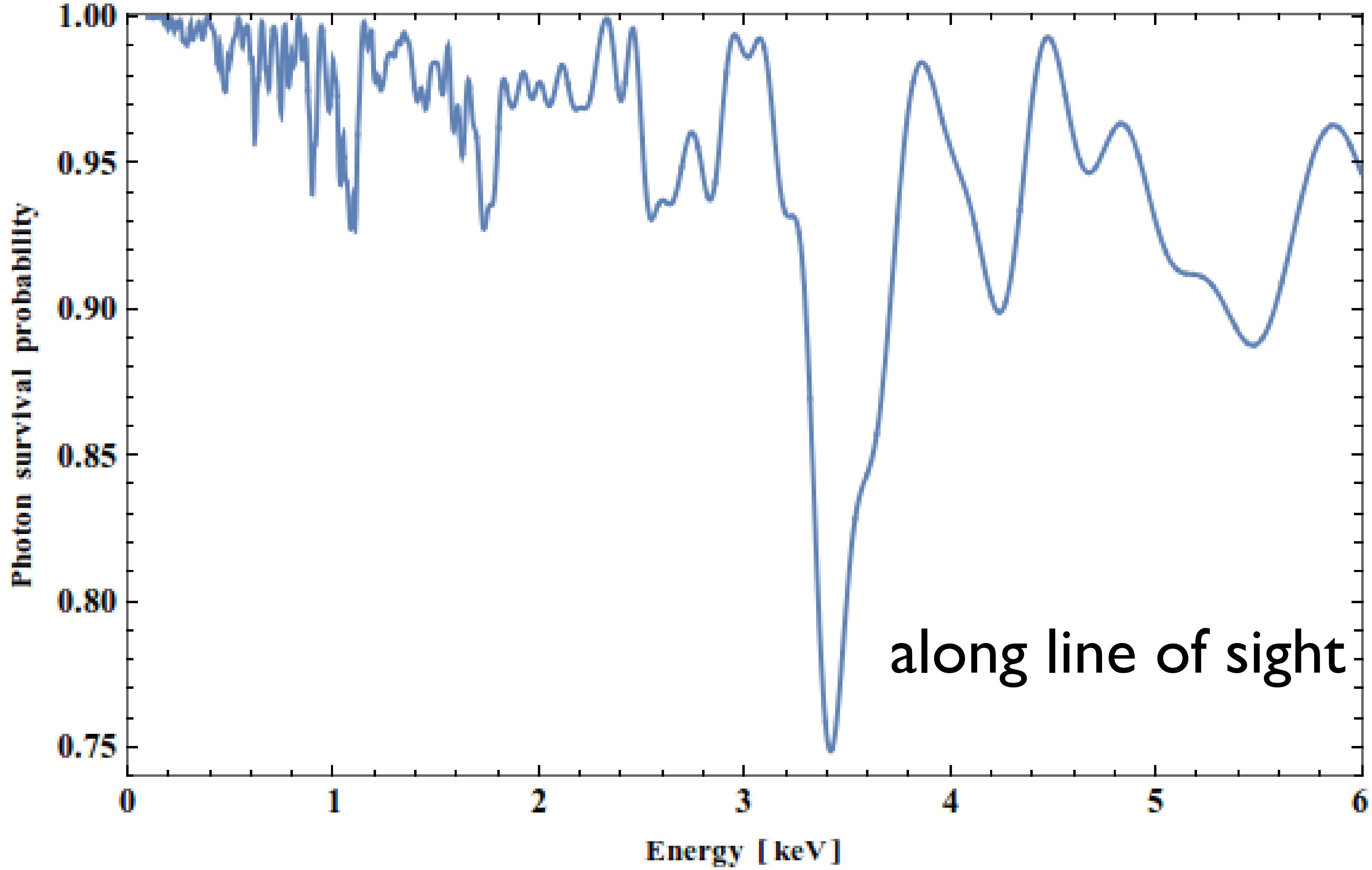
Perseus and NGC1275



- Perseus is a galaxy cluster (z=0.017)
- NGC1275 is the central galaxy (with AGN)
- $\mu\mathrm{G}$ magnetic fields on Mpc scales with kpc coherence scales

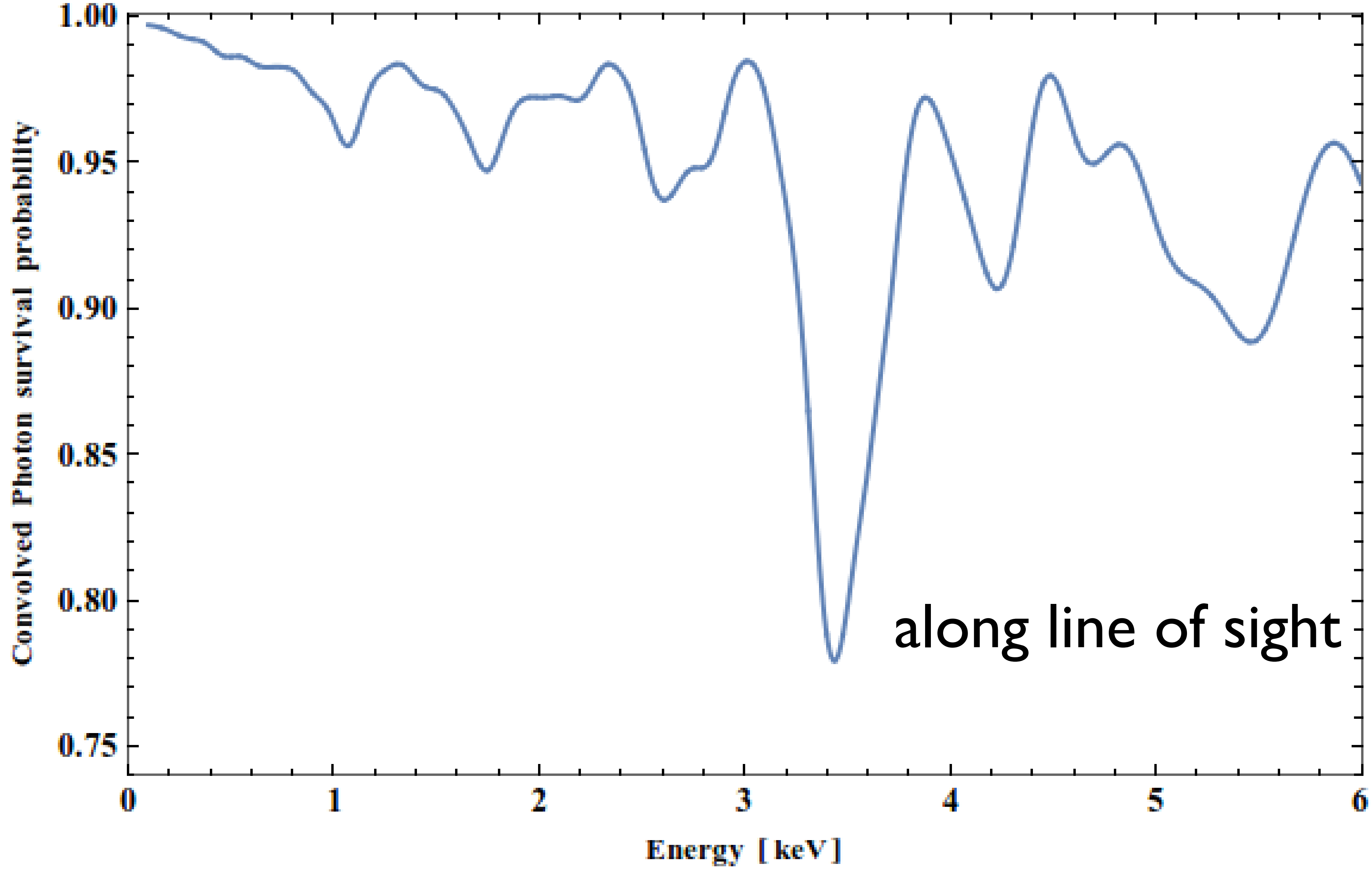

NGC1275
$\vec{B}$
n_H
γ
Chandra
a
γ
L
Perseus Cluster

Photon survival in Perseus



$$g_{a\gamma\gamma} = 1.5 \cdot 10^{-12}\ \mathrm{GeV}^{-1},\ B_0 = 15\mu G,\ \langle B(r) \rangle \sim n_e(r)^{0.7},$$
$$3.5\ \mathrm{kpc} < L < 10\ \mathrm{kpc\ over\ 100\ domains}$$

Photon survival in Perseus

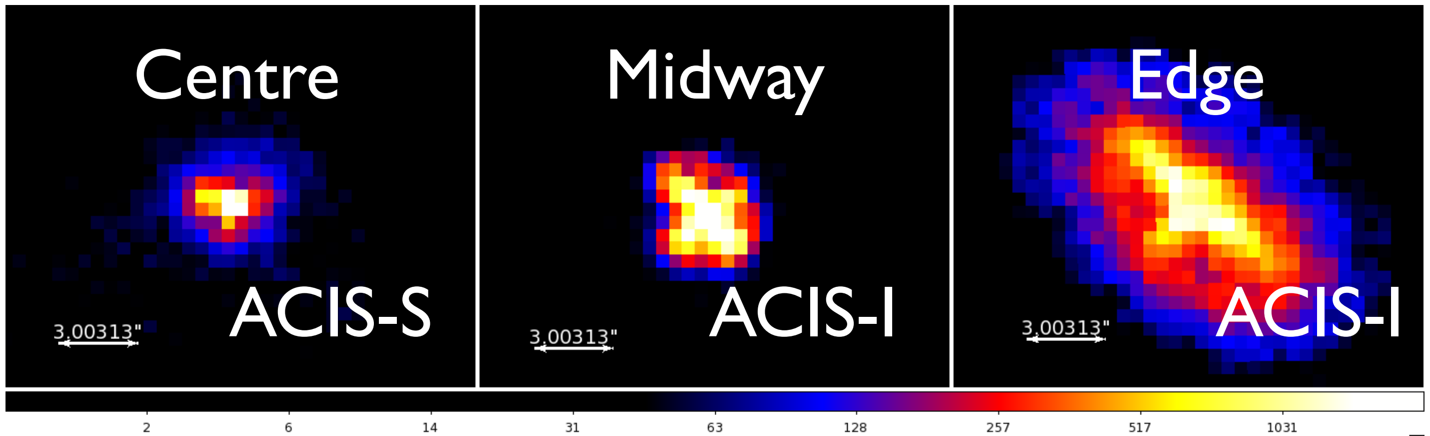


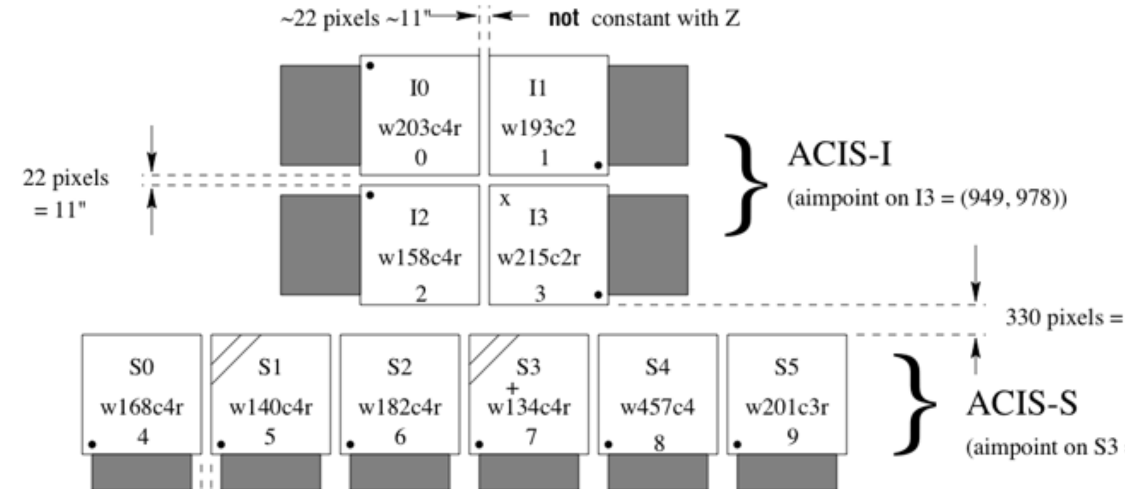
convolved with Gaussian with FWHM of 150 eV

Similar analyses

- [Wouters & Brun '13] searched for spectral modulations in AGN in Hydra A (only 1% of the data used here)
- [Fermi-LAT '16] looked at NGC1275 in GeV where $P(\gamma \to a)$ depends strongly on m_a ($m_a \simeq 10^{-9} - 10^{-8}\mathrm{eV}$ different region in ALP parameter space)
- see also [H.E.S.S. '13] analysis of PKS 2155-304

X-ray data: Chandra



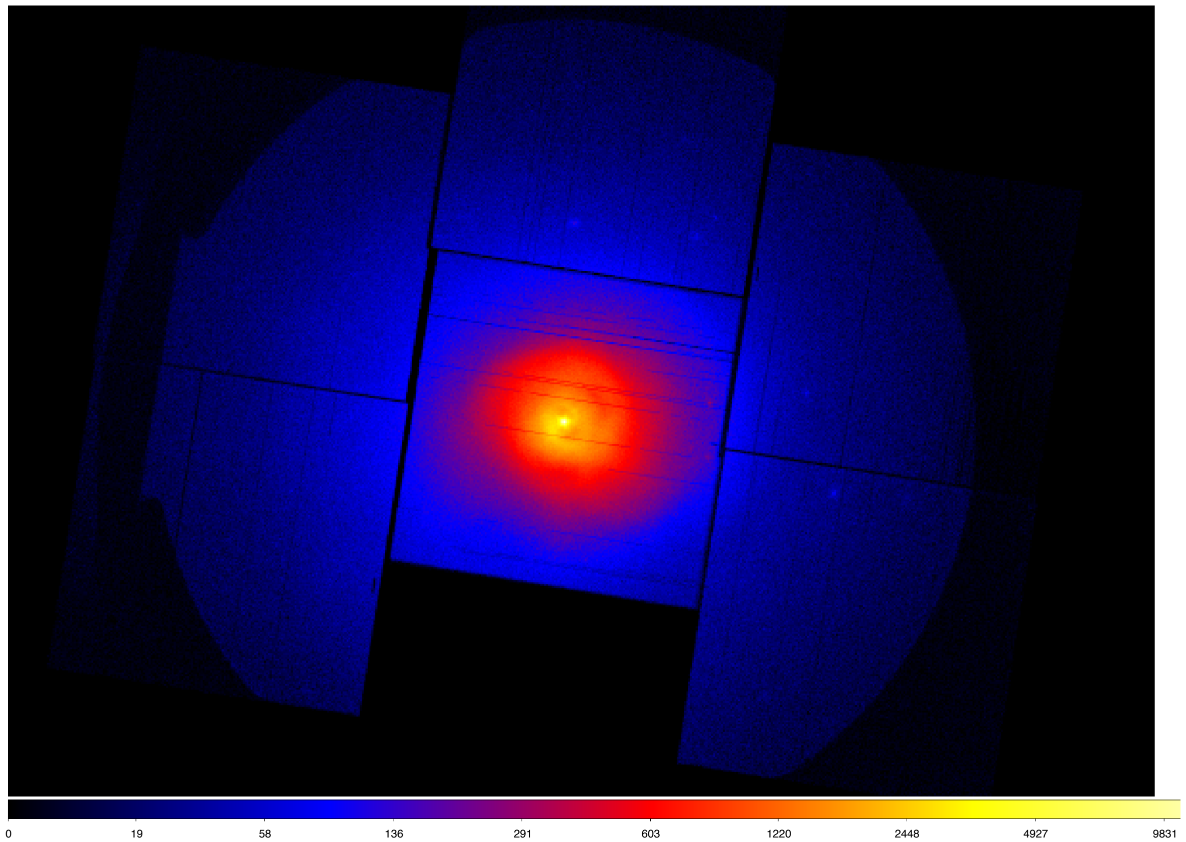


Three data groups:

- 1 Ms/ 230 000 counts ACIS-S Centre
- 300 ks/ 250 000 counts ACIS-I Midway
- 200 ks/ 250 000 counts ACIS-I Edge

Pileup: 2 (or more) photons arriving at the same time, registered as an event with $E = E_1 + E_2$

X-ray data: XMM-Newton



180 ks/ 100 000 counts of EPIC MOS data

- Angular resolution: 8.5” vs 0.5” Chandra

$\Rightarrow$ Worse Signal/Background contrast for XMM

- Effective Area: 1000 cm2 vs 340 cm2 Chandra

- Pileup is an issue here too

Spectral Analysis

- The spectral shape of an AGN is modelled by

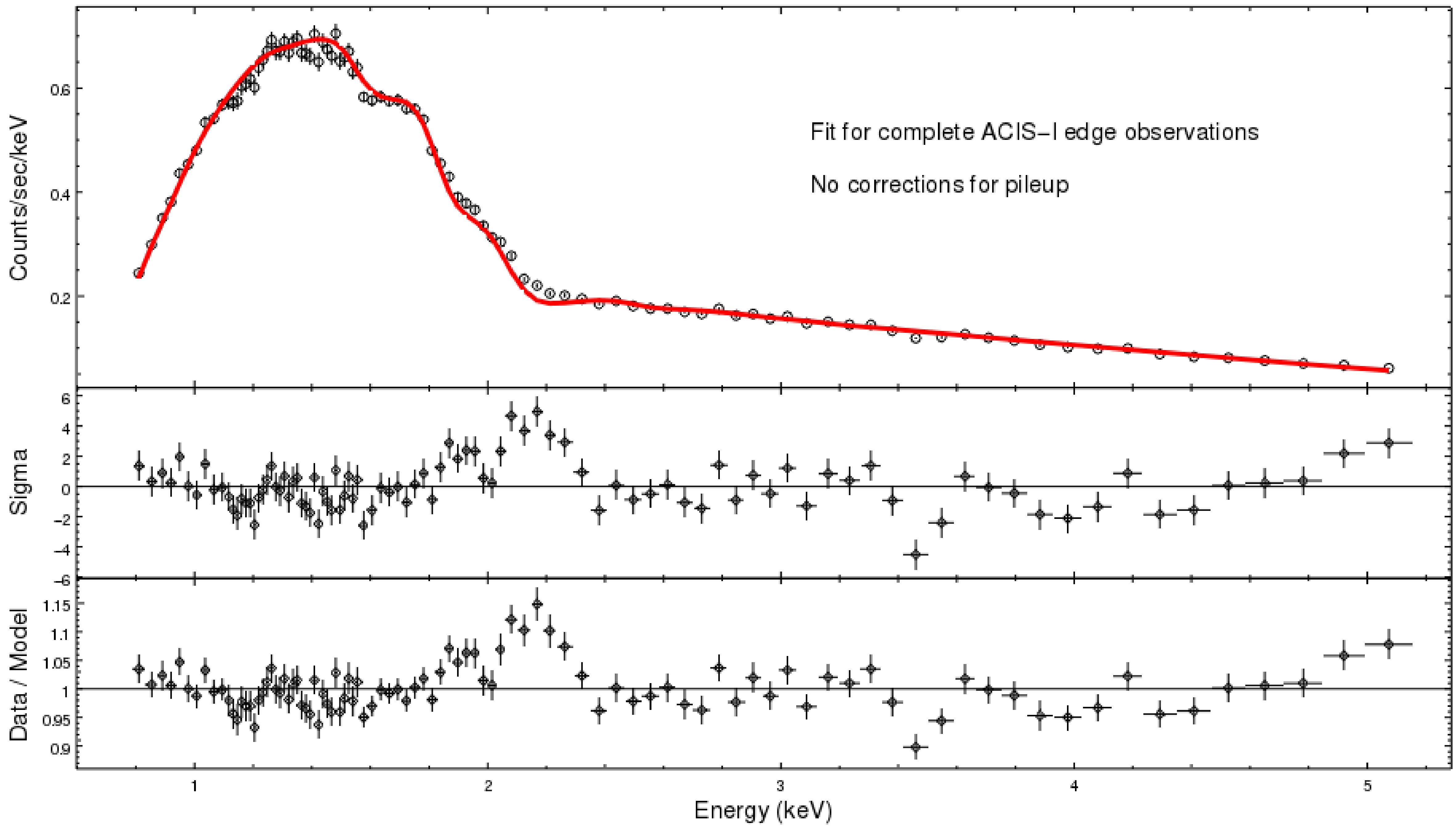
$$AE^{-\gamma} \times e^{-n_H \sigma(E)}$$

- where γ is the powerlaw index and n_H is the hydrogen column density, σ the photoelectric cross-section

- Pileup can be dealt with in two ways:

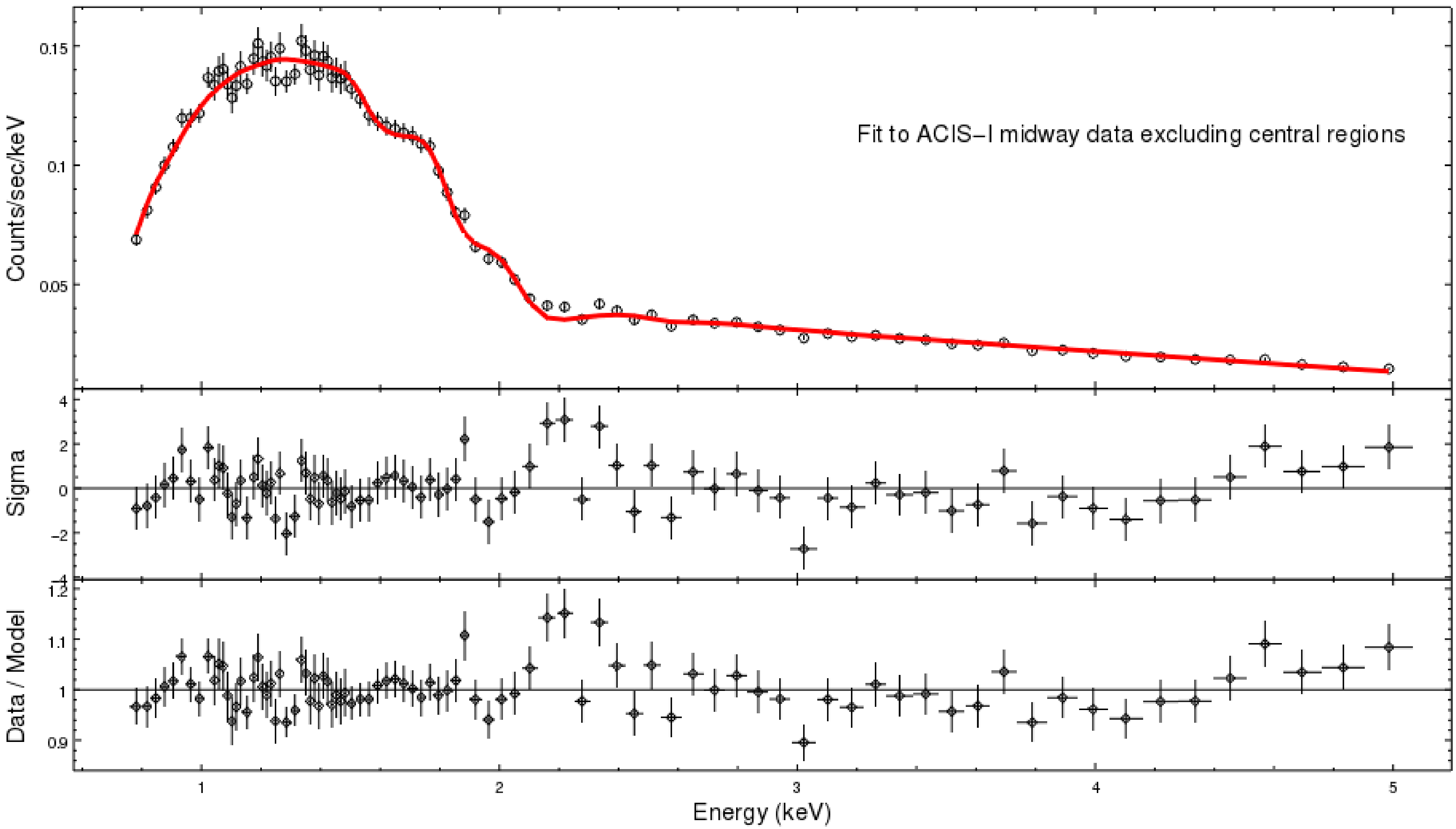
1. Exclude central piled up pixels
2. Model the effects of pileup (jdpileup) [Davis '01]

ACIS-I edge



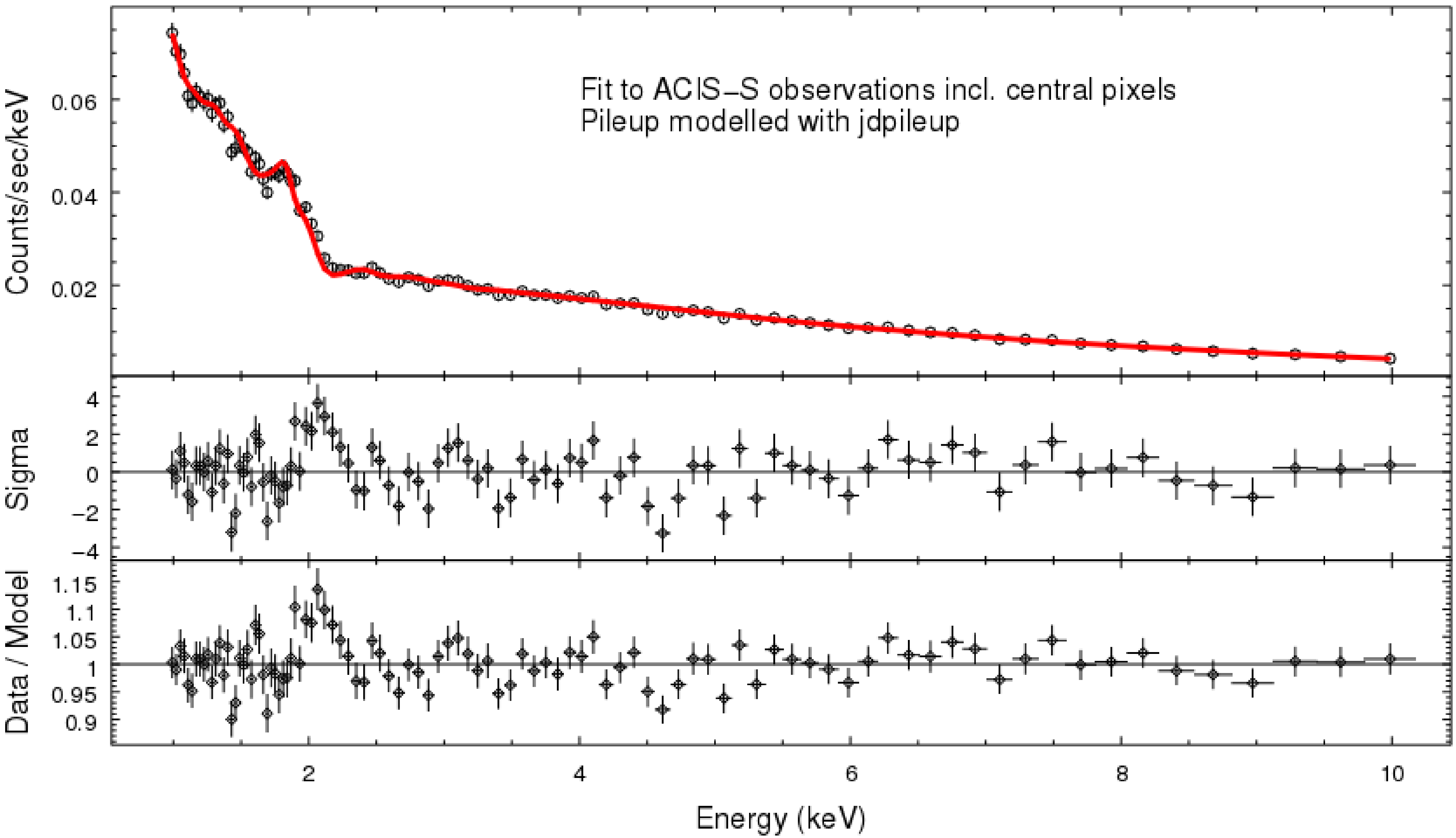
$$229000 \text{ counts}, \ \gamma = 1.77, \ n_H = 2.1 \cdot 10^{21} \text{cm}^{-2}, \ \text{AGN/Cluster} = 6.5/1$$

ACIS-I Midway



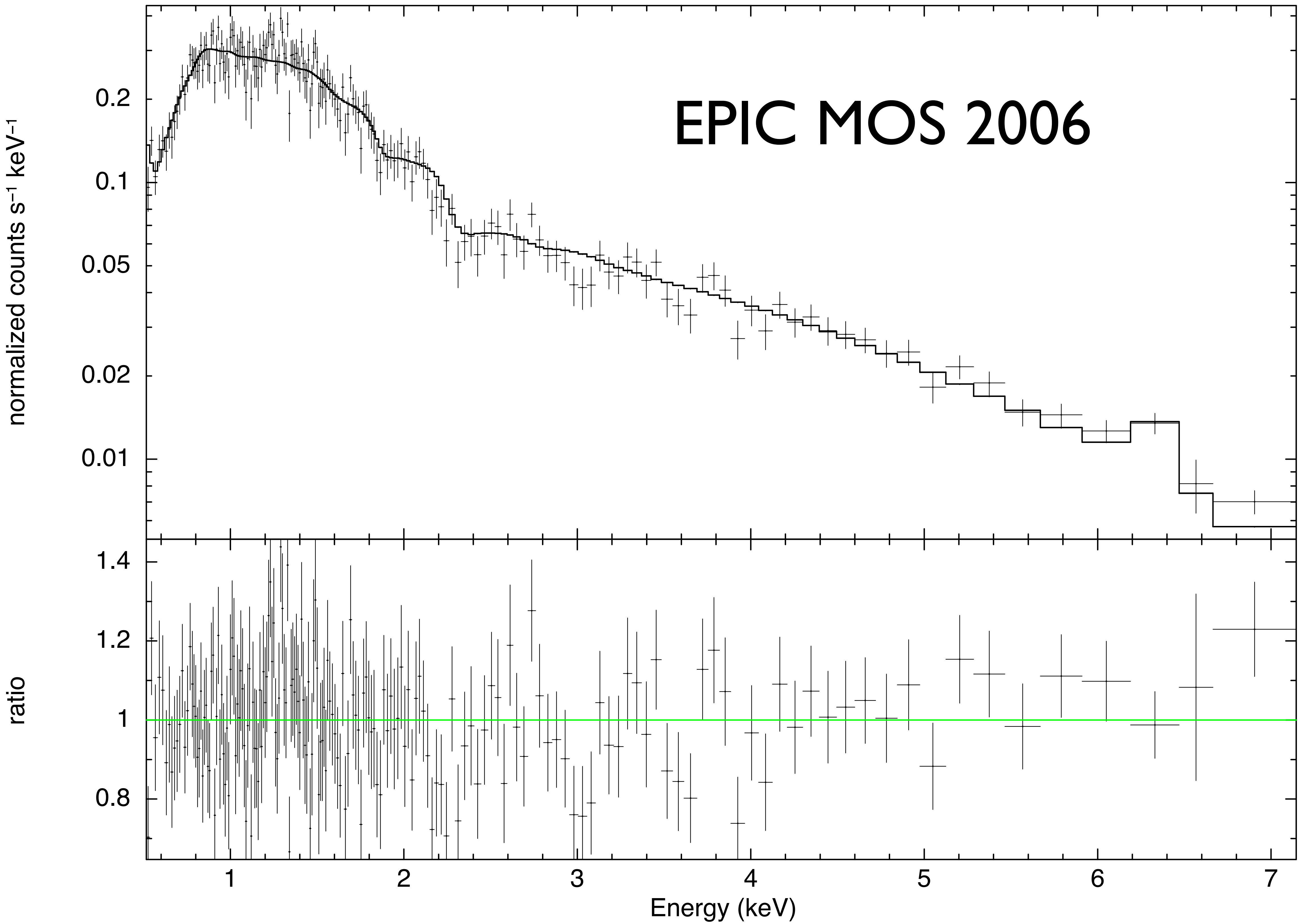
$$74000 \text{ counts}, \ \gamma = 1.64, \ n_H = 1.4 \cdot 10^{21} \text{cm}^{-2}, \ \text{AGN/Cluster} = 5.3/1$$

ACIS-S



$$177000 \text{ counts}, \; \gamma = 1.81, \; n_H = 2.6 \cdot 10^{21} \text{cm}^{-2}, \; \text{AGN/Cluster} = 3.7/1$$

XMM



$$63000 \text{ counts}, \; \gamma = 1.65, \; n_H = 1.3 \cdot 10^{21} \text{cm}^{-2}, \; \text{AGN/Cluster} = 1/3$$

Data Summary

- 2.2 keV excess is prevalent in all Chandra datasets with 3-5 sigma (ACIS-I Edge/Midway, ACIS-S, pileup modelled, central pixels included)
- 3.5 keV dip is present in most Chandra datasets with 2-4 sigma (Not in ACIS-I Midway)
- Neither is (strongly) present in XMM **but** background subtraction problematic and less data $\Rightarrow$ no contradiction with Chandra

Bounds

$$AE^{-\gamma} \times e^{-n_H \sigma(E)} \text{ vs } AE^{-\gamma} \times e^{-n_H \sigma(E)} \times P_{\gamma \to a}$$

- Pure power law is good fit up to residuals $\mathcal{O}(10\%)$

$\Rightarrow$ Modulations $\langle P_{\gamma \to a} \rangle \lesssim 20\%$

- To get more detailed bounds we need to put in a magnetic field model $B \propto B_0 n_e^\eta$

- $\eta = 0.7$ (conservative)

[Churazov et al '03]

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

Bounds

Three cases:

1. $B_0 = 25\mu\text{G},\ 3.5\ \text{kpc} < L < 10\ \text{kpc}$ [Taylor et al '06, Vacca et al '12]

   $\Rightarrow g_{a\gamma\gamma} \lesssim 1.5 \times 10^{-12}\ \text{GeV}^{-1}\ (95\%)$

2. $B_0 = 15\mu\text{G},\ 0.7\ \text{kpc} < L < 10\ \text{kpc}$ (very conservative)

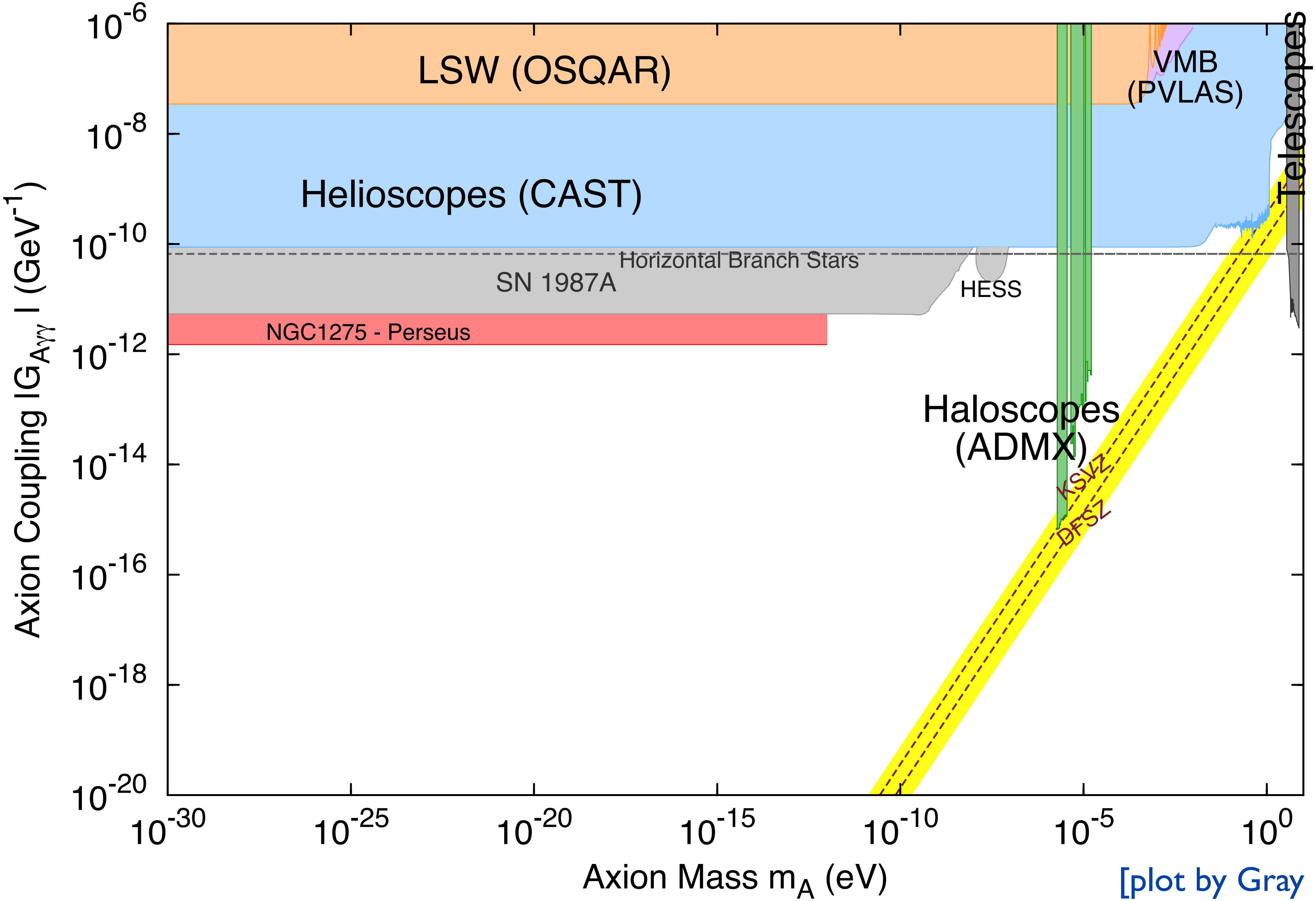
   $\Rightarrow g_{a\gamma\gamma} \lesssim 3.8 \times 10^{-12}\ \text{GeV}^{-1}\ (95\%)$

   $B_0 = 10\mu\text{G},\ 0.7\ \text{kpc} < L < 10\ \text{kpc}$ (ultra conservative)

   $\Rightarrow g_{a\gamma\gamma} \lesssim 5.9 \times 10^{-12}\ \text{GeV}^{-1}\ (95\%)$

Supernova bound: $g_{a\gamma\gamma} \lesssim 5 \times 10^{-12}\ \text{GeV}^{-1}\ (95\%)$

ALP Parameter Space



[plot by Gray Rybka]

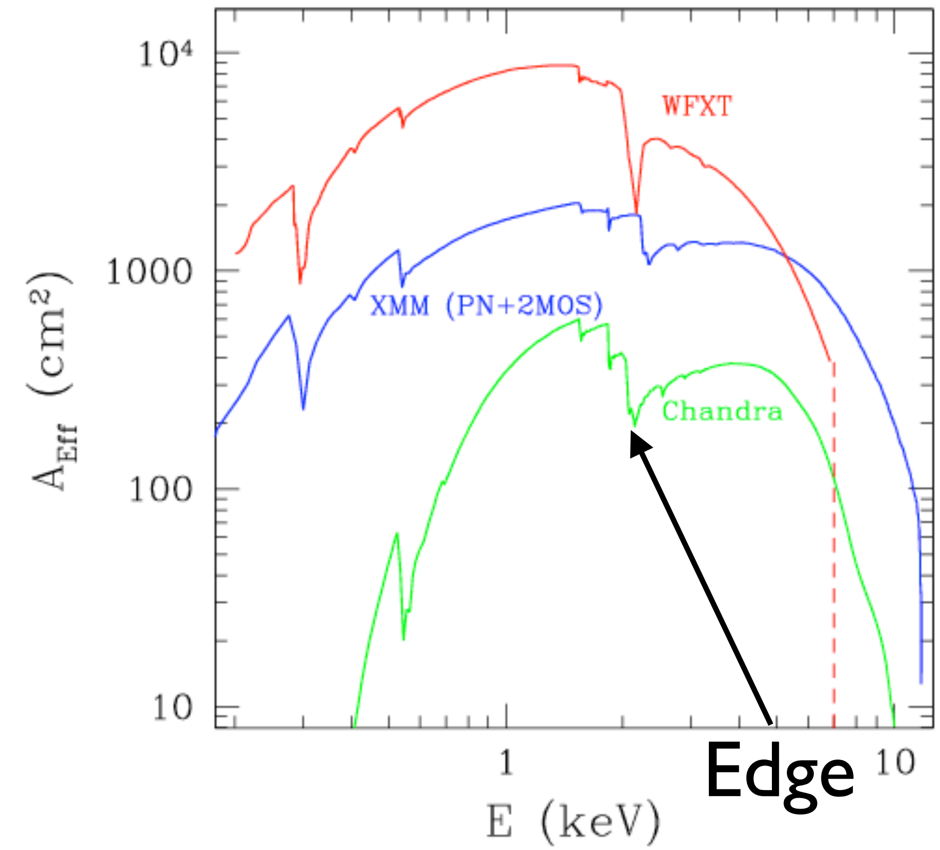
Conclusions & Outlook

- ALP properties can be probed via ALP-photon conversion, particularly well in galaxy clusters
- NGC1275 in the Perseus Cluster has an extraordinary amount of Chandra X-ray data
- Two unexplained features are visible in the spectrum: 2.2 keV excess (3-5 sigma) and 3.5 keV deficit (2-4 sigma)
- Absence of other deviations allows the *most competitive bounds yet* on $g_{a\gamma\gamma}$ for $m_a \lesssim 10^{-12}\mathrm{GeV}$
- Outlook: Other point-sources (in other clusters)

2.2 keV excess explanations

Instrumental:

- Effective area miscalibration
- Gain miscalibration



Astrophysical:

- Thermal emission from ionized gas close to AGN
- $K\alpha$ emission close to AGN

Bounds method

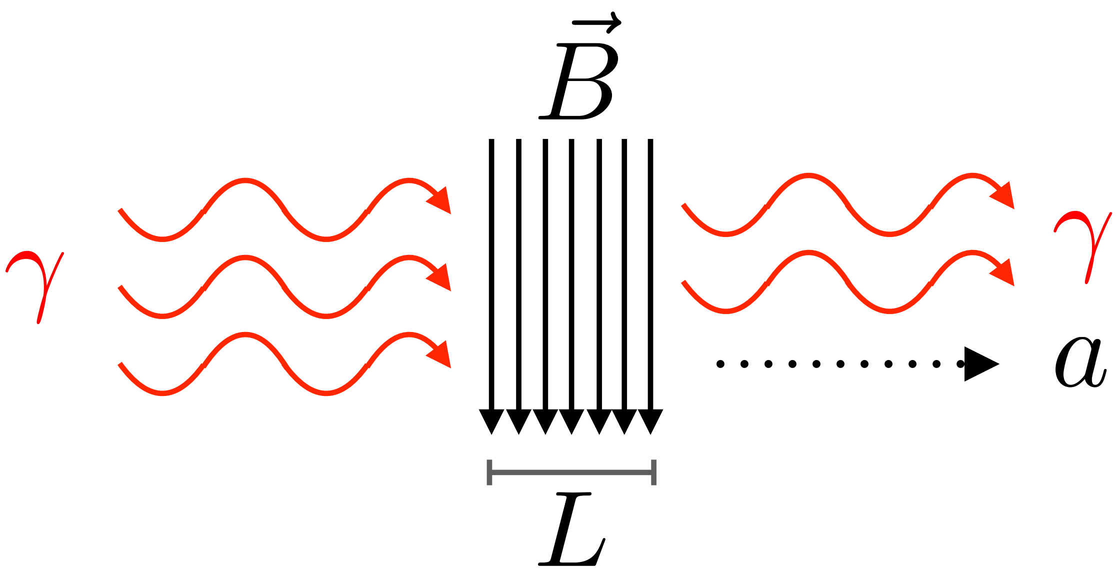
Model 0: no ALPs

Model 1: with ALPs

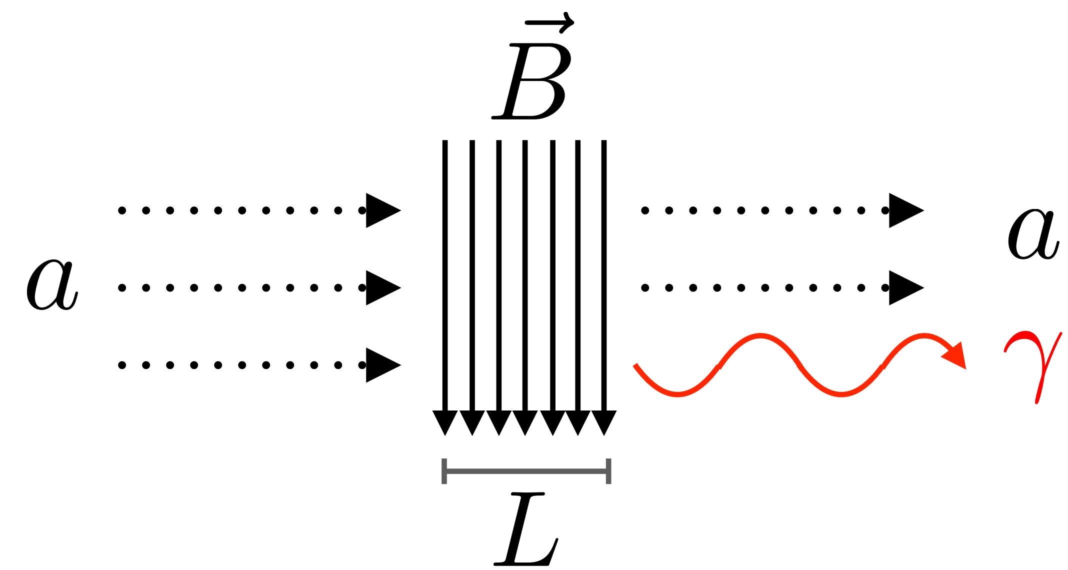
- Fit model 0: χ^2_{data}
- For each $g_{a\gamma\gamma}$: generate 50 different magnetic field realisations with model 1
- For each, generate 10 fake data sets
- Fit model 0: χ^2_i
- If for fewer than 5%, $\chi^2_i < \chi^2_{\mathrm{data}}$

$\Rightarrow$ $g_{a\gamma\gamma}$ excluded at 95%

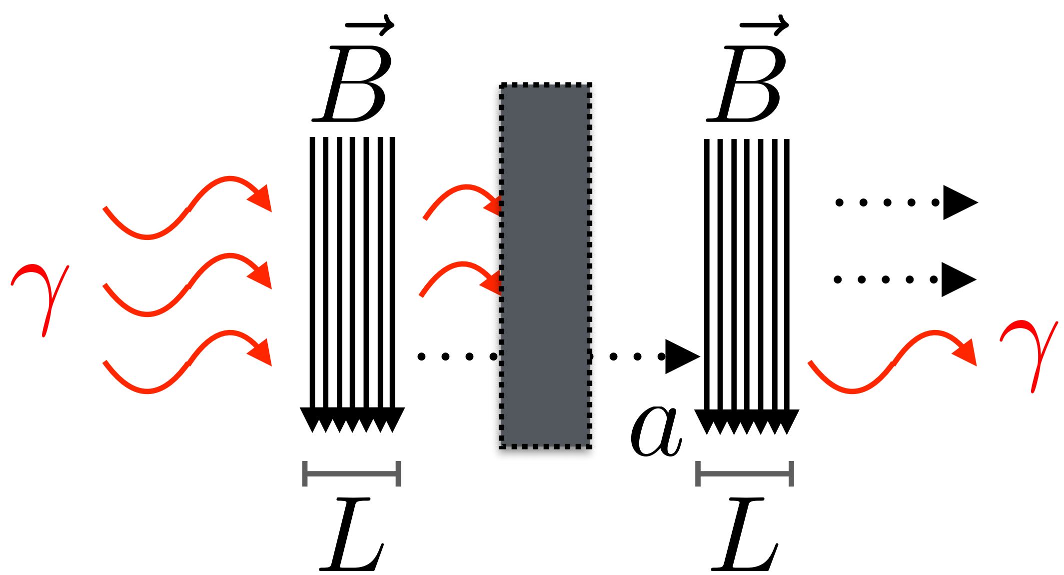
How could we see ALPs?



e.g. spectral distortions



e.g. CAST, IAXO



e.g. ALPS II

Why Clusters are good for seeing ALPs

- Astrophysical parameters at X-ray energies:

$$P_{a\to\gamma} \equiv 2P_{\gamma\to a} = 2.0\cdot 10^{-5} \times \left(\frac{B_\perp}{3\ \mu\mathrm{G}} \frac{L}{10\ \mathrm{kpc}} \frac{10^{13}\ \mathrm{GeV}}{M} \right)^2$$

- Terrestrial parameters at X-ray energies

$$P_{a\to\gamma} \equiv 2P_{\gamma\to a} \simeq 2.0\cdot 10^{-23} \times \left(\frac{B_\perp}{10\mathrm{T}} \frac{L}{10\mathrm{m}} \frac{10^{13}\ \mathrm{GeV}}{M} \right)^2$$

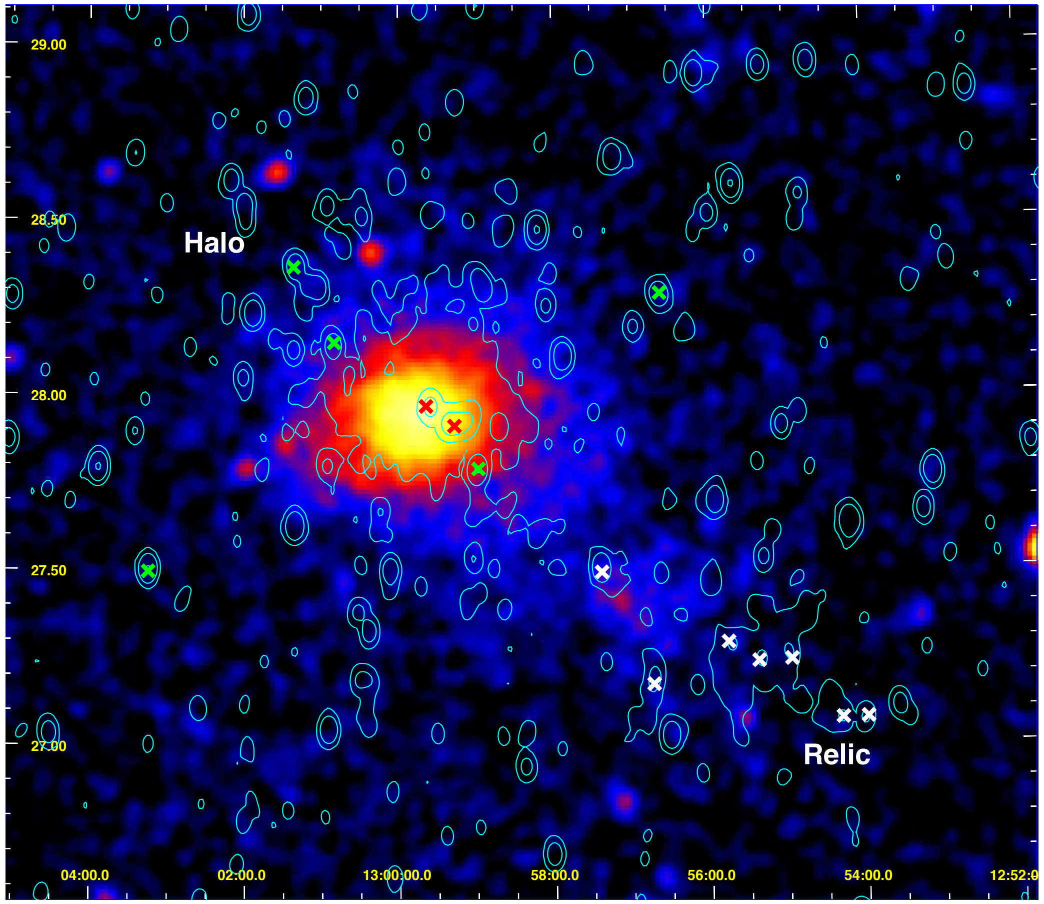
$\Rightarrow$ Much longer coherence length beats stronger magnetic field

Magnetic Fields in Galaxy Clusters

- Electron density via X-ray brightness profile

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

- Magnetic field via Faraday rotation $RM = \frac{e^3}{2\pi m_e^2} \int_{l.o.s} n_e(l) B_{\|}(l) \mathrm{d}l$



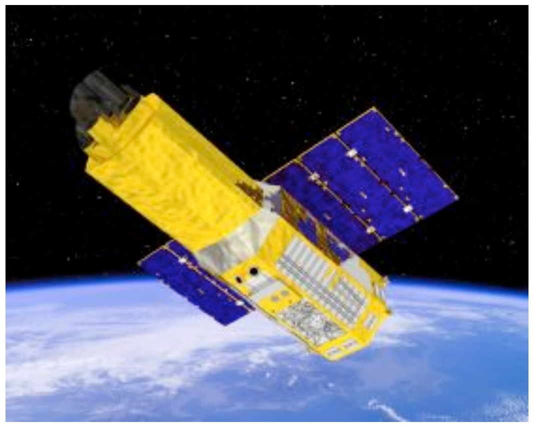
[Bonafede,Vazza,Bruggen,Murgia, Govoni,Feretti,Giovannini,Ogrean'13]

$$\Rightarrow B(r) = C \cdot B_0 \left(\frac{n_e(r)}{n_0}\right)^{\eta}$$ (via simulation vs RM)

$$\Rightarrow \text{turbulent } B \sim \mathcal{O}(\mu\text{G}) \text{ with } L \sim \mathcal{O}(10\text{kpc})$$

Which telescope?

Suzaku



$\Delta E = 100$ eV,
$\Delta\phi = 60''$

XMM-Newton

$\Delta E = 100$ eV,
$\Delta\phi = 5''$

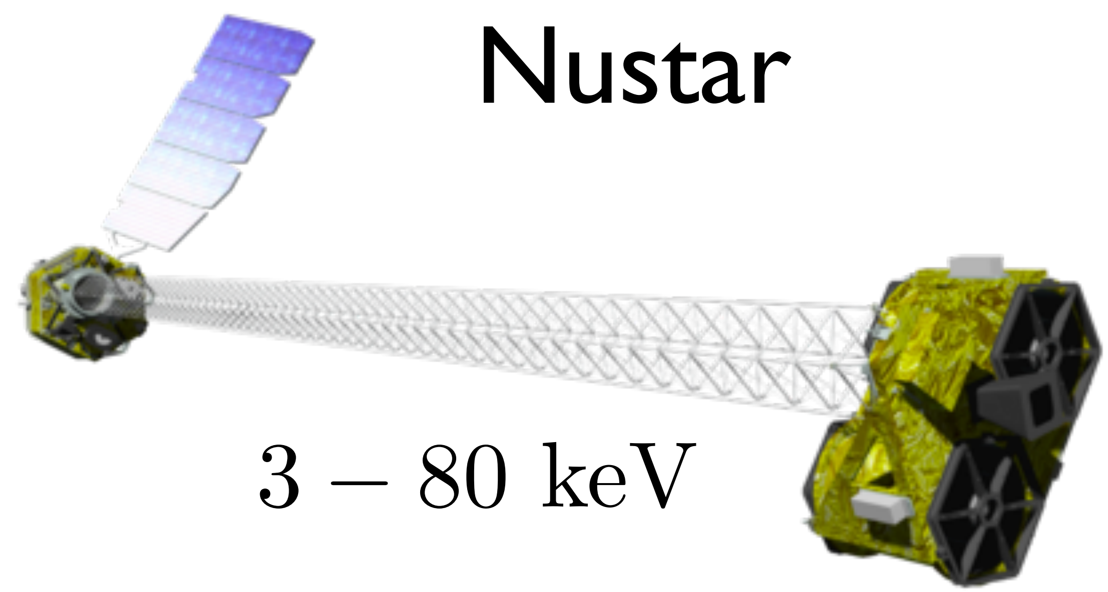
Chandra

$\Delta E = 100$ eV,
$\Delta\phi = 0.5''$

Hitomi/Astro-H

$\Delta E = 5$ eV, $\Delta\phi = 60''$

Nustar



$3 - 80$ keV

$\Delta E = 500$ eV, $\Delta\phi = 10''$