ALPs and the X-ray Universe

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PERIMETER INSTITUTE

Outline

- Axion-like particles
- Galaxy Clusters and ALP conversion
- Search for spectral distortions

Axion-Like Particles

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a$$

- Has shift-symmetry $a \to a + \mathrm{const}$
- This is expected to be broken at some level ("no global continuous symmetries in Quantum Gravity") [Banks, Seiberg '10]
- Generically arise in string compactifications (often even $\mathcal{O}(100)$ or more)
- Explore the light and weakly interacting frontier!

Axion-Like Particles

Breaking to discrete symmetry can be described by

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \Lambda^4 (1 - \cos \frac{a}{f_a})$$

with parameters f_a (decay constant) and scale Λ

Also possible: Explicit breaking e.g. via

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{2} m^2 a^2$$

Axion-Like Particles

Consider remaining discrete symmetry (ALPs):

What are possible values for f_a and $m_a = \frac{\Lambda^2}{f_a}$?

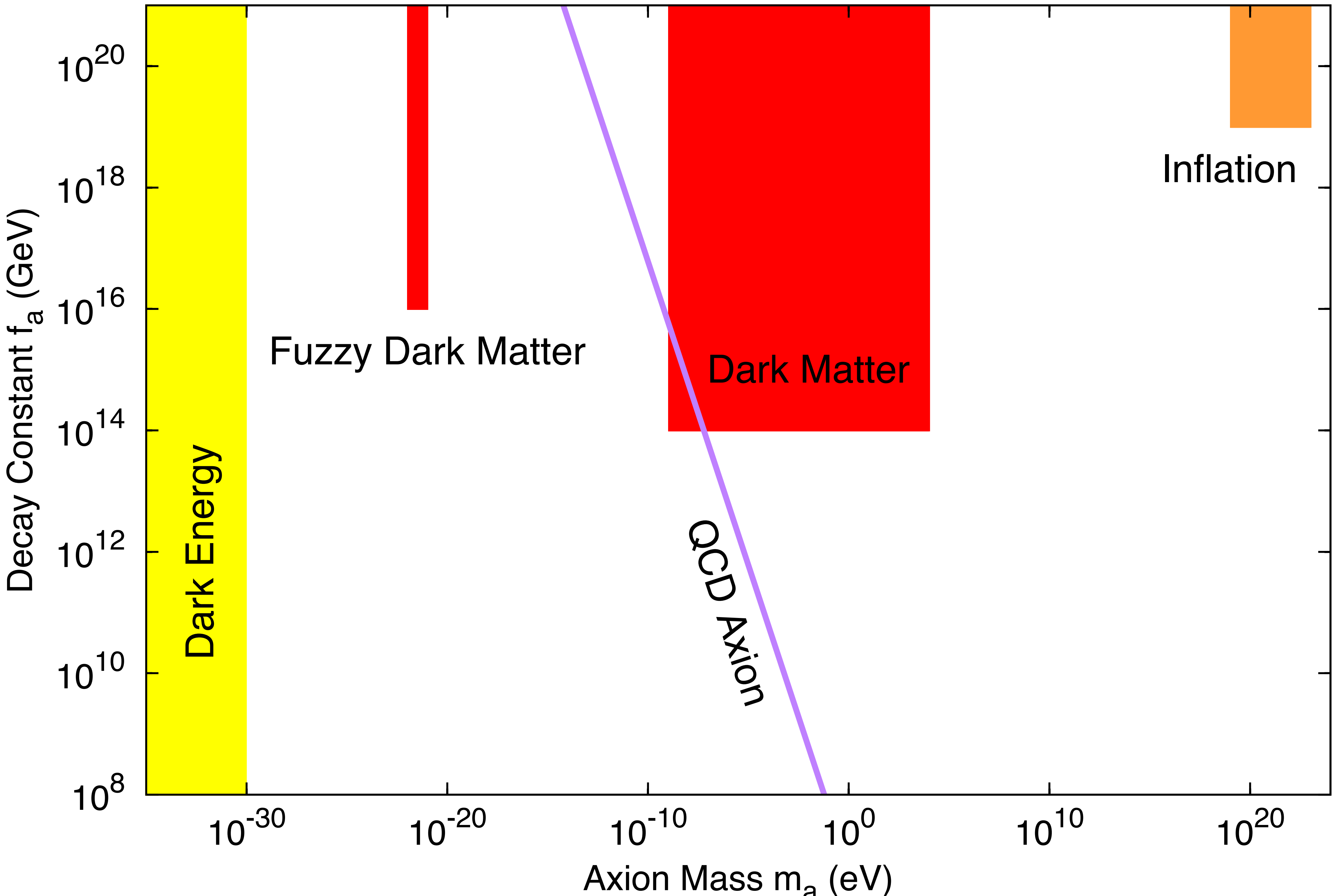
- f_a naturally $\mathcal{O}(M_S)$ to $\mathcal{O}(M_P)$, higher and lower hard but possible(?) [Svrcek, Witten '06]
- m_a anything really, since $\Lambda^4 \sim M_P^2 \Lambda_S^2 e^{-S_{\rm inst}}$ for example $\Lambda_S = 10^{11}$ GeV, $f_a = 10^{17}$ GeV and $S_{\rm inst} = 2\pi/\alpha_G$, $\alpha_G = 0.04$ gives $m_a \sim 10^{-15}$ eV
- also various couplings to SM

Axion-Like Particles

- Strong CP problem (axions) [Peccei, Quinn '77]
- Viable dark matter candidate [Abbott,Sikivie '83; Turner '83; Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald '12,…]
- Inflation [Freese, Friedman, Olinto '90, Silverstein, Westphal '06…]
- Collider constraints [Alekhin et al '15, Jaeckel, Spannowsky '15; Bauer, Neubert, Thamm '17,…]
- "Direct detection" constraints: Madmax, Abracadabra, … SuperCDMS, Lux,…[Agnese et al '13, Kahn et al '16, Caldwell et al '17, Akerib et al '17]

Axion-Like Particles

Rich phenomenology:



Axion-Like Particles

We will explore the phenomenology arising from the coupling to Electromagnetism: [Sikivie ’83; Raffelt, Stodolsky ‘88]

$$\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

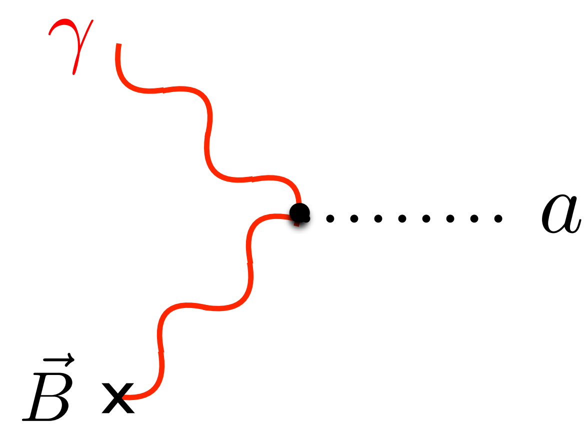
with $g_{a\gamma\gamma} = c_{a\gamma}/f_a$

Don’t have to assume any cosmological abundance, just that they exist!

Axion-Like Particles

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

- Coupling to EM: $g_{a\gamma\gamma}\, a\, \boldsymbol{E}\cdot\boldsymbol{B}$

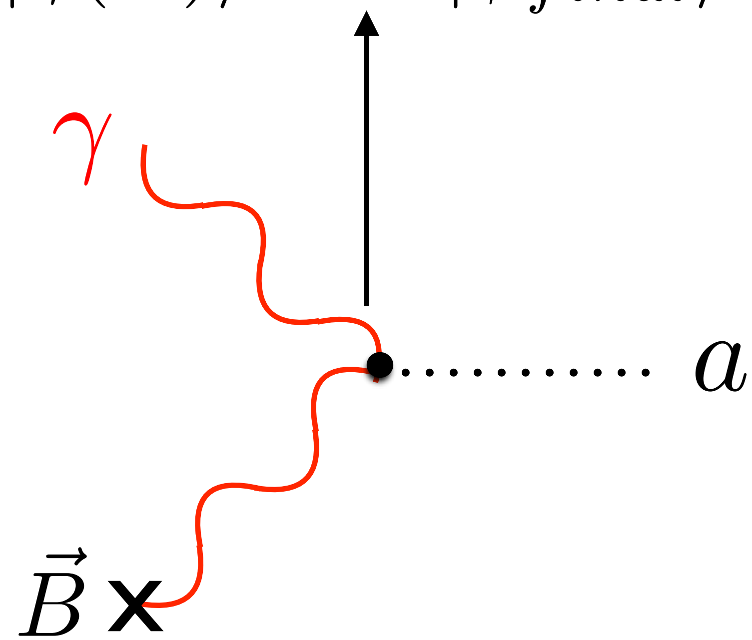


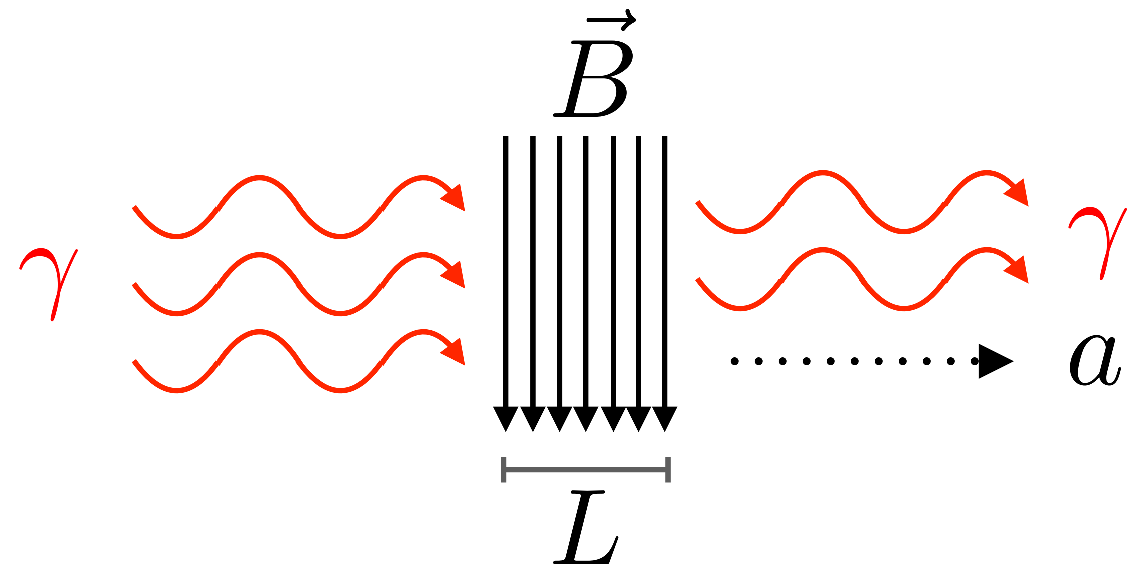
- For general ALPs $g_{a\gamma\gamma}$ and m_a are unspecified and unrelated (unlike for the QCD axion)
- $g_{a\gamma\gamma} \lesssim 5 \times 10^{-12}\ \mathrm{GeV}^{-1}$ Supernova 1987A Bound

[Brockway, Carlson, Raffelt ’96; Grifols, Massó, Toldrà ’96, Payez, Evoli, Fischer, Giannotti, Mirizzi ’15]

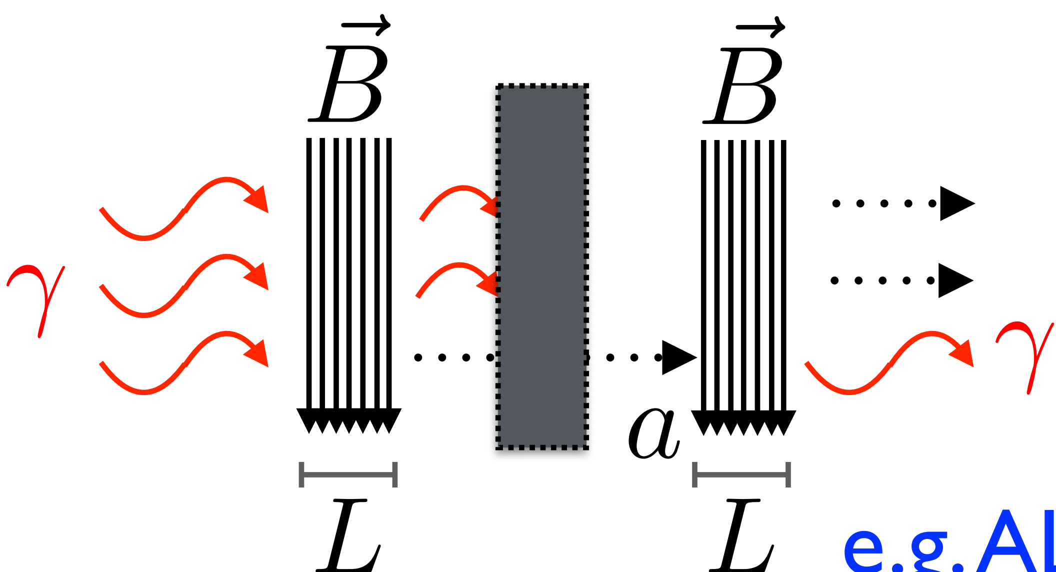
How could we see ALPs?

$$|\psi_{init}\rangle = |\gamma(E)\rangle \longrightarrow |\psi_{final}\rangle = \alpha|\gamma(E)\rangle + \beta|a(E)\rangle \qquad P_{\gamma\to a} \equiv |\beta|^2$$

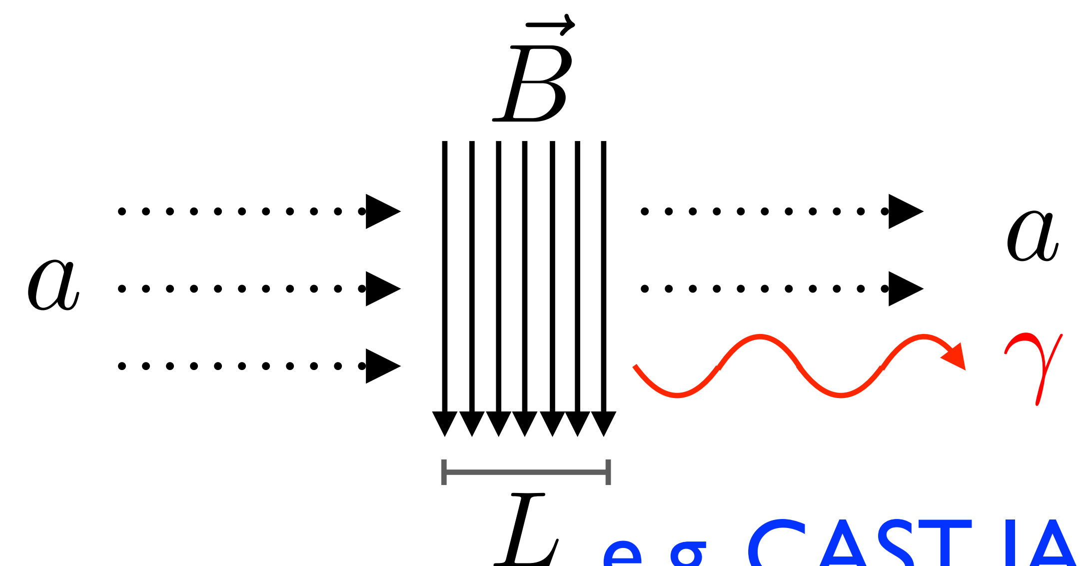




e.g. spectral distortions



e.g. ALPS II



e.g. CAST, IAXO

ALP to photon conversion

- Can be expressed as linearized Schrödinger equation [Raffelt, Stodolsky '88]

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_\mathrm{F} & \Delta_{\gamma a x} \\ \Delta_\mathrm{F} & \Delta_\gamma & \Delta_{\gamma a y} \\ \Delta_{\gamma a x} & \Delta_{\gamma a y} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} |\gamma_x\rangle \\ |\gamma_y\rangle \\ |a\rangle \end{pmatrix} = 0$$

$\Delta_\gamma = -\omega_{\mathrm{pl}}^2/2\omega$ $\quad \omega_{\mathrm{pl}} = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$ $\quad \Delta_a = -m_a^2/\omega$

$\Delta_{\gamma a i} = g_{a\gamma\gamma} B_i/2$

- similar to neutrino oscillations for two generations

ALP to 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 $g_{a\gamma\gamma}^2$

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- Axion-like particles
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- Search for spectral distortions

Why Clusters are good for seeing ALPs

- Astrophysical parameters at X-ray energies:

$$P_{a\to\gamma} = 2P_{\gamma\to a} = 2.0 \cdot 10^{-5} \times \left(\frac{B_\perp}{3\mu\mathrm{G}} \frac{L}{10\mathrm{kpc}} \frac{g_{a\gamma\gamma}}{10^{-13}\mathrm{GeV}^{-1}} \right)^2$$

- Terrestrial parameters at X-ray energies

$$P_{a\to\gamma} = 2P_{\gamma\to a} = 2.0 \cdot 10^{-23} \times \left(\frac{B_\perp}{10\mathrm{T}} \frac{L}{10\mathrm{m}} \frac{g_{a\gamma\gamma}}{10^{-13}\mathrm{GeV}^{-1}} \right)^2$$

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

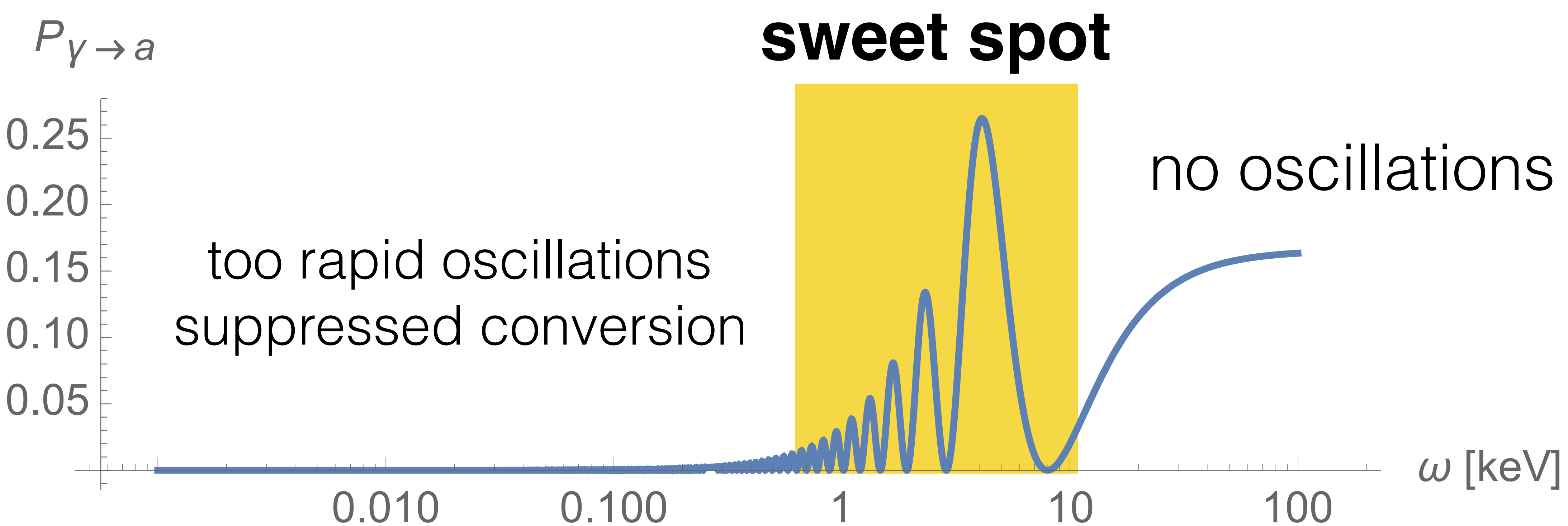
ALP photon conversion

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

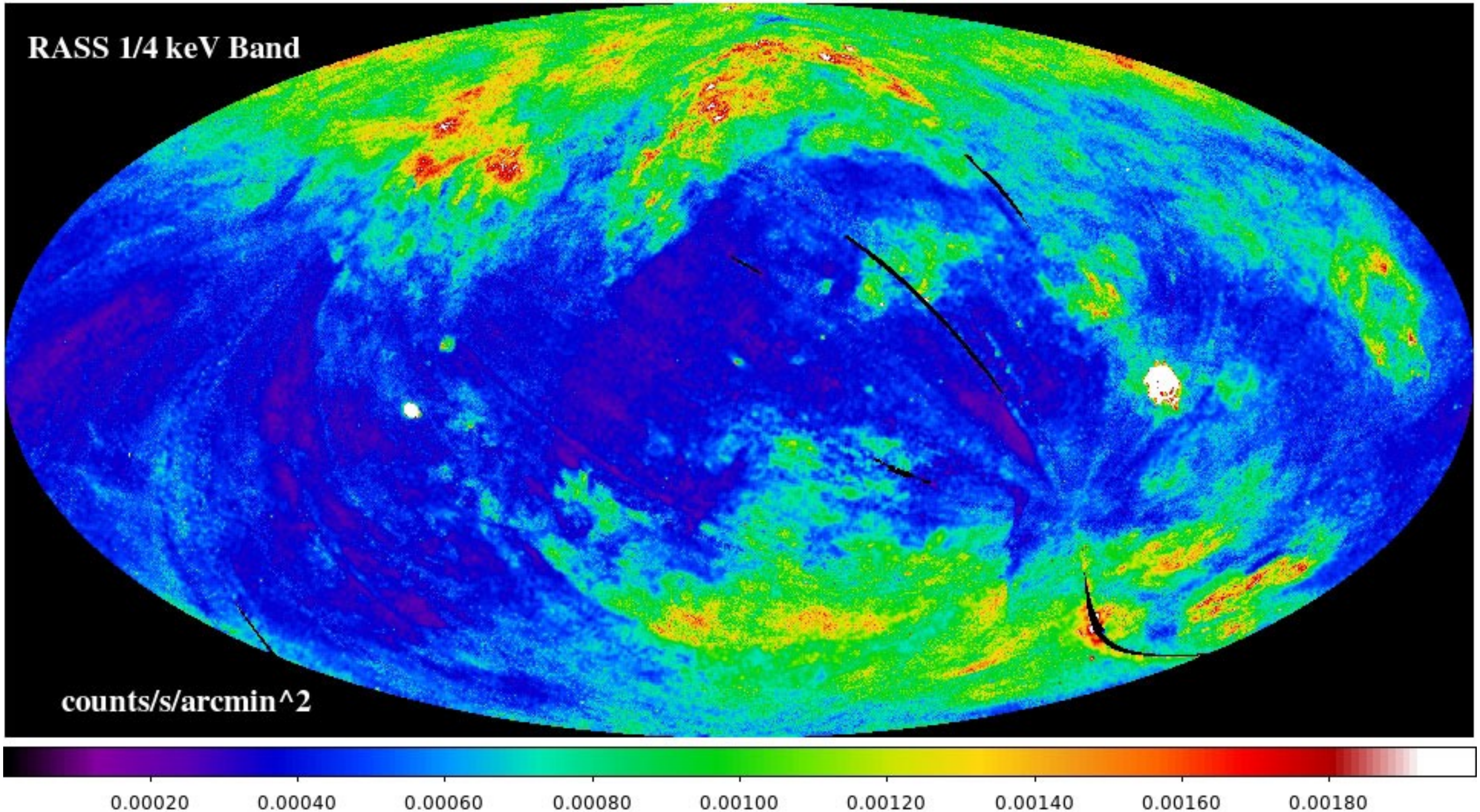
$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

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

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

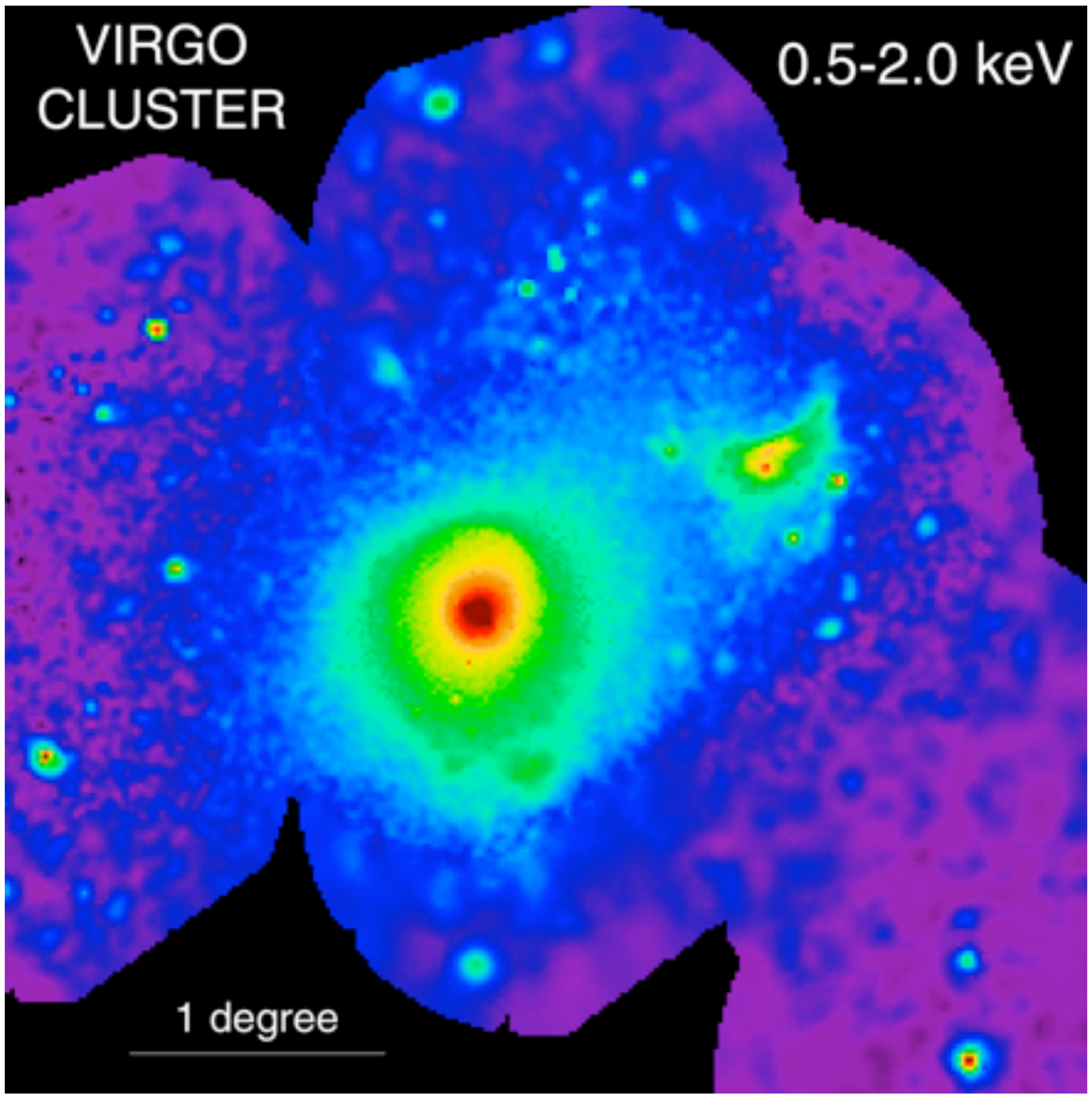


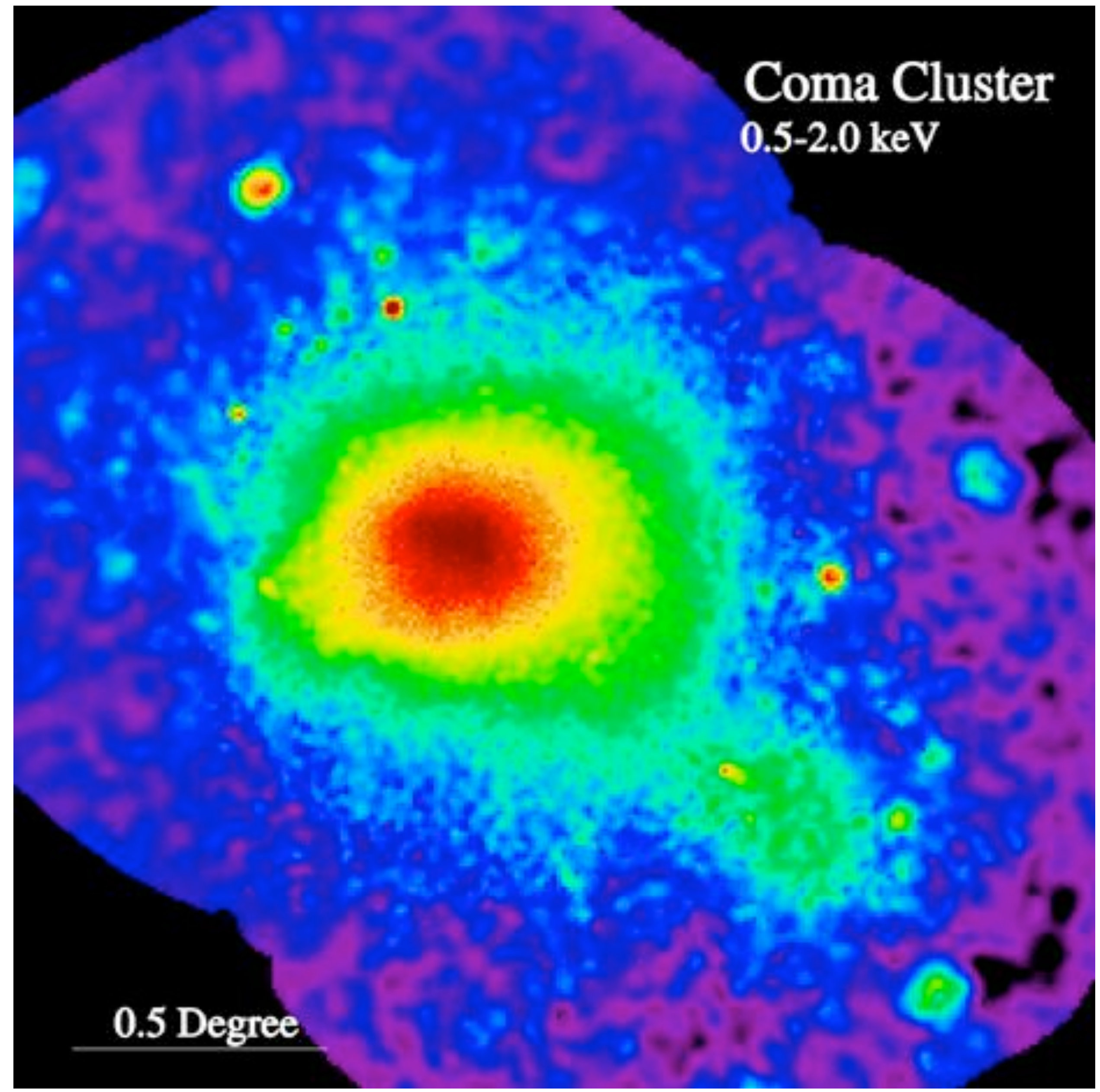
The X-ray universe



ALP-photon conversion

⇒ Look at Galaxy Clusters in X-ray!

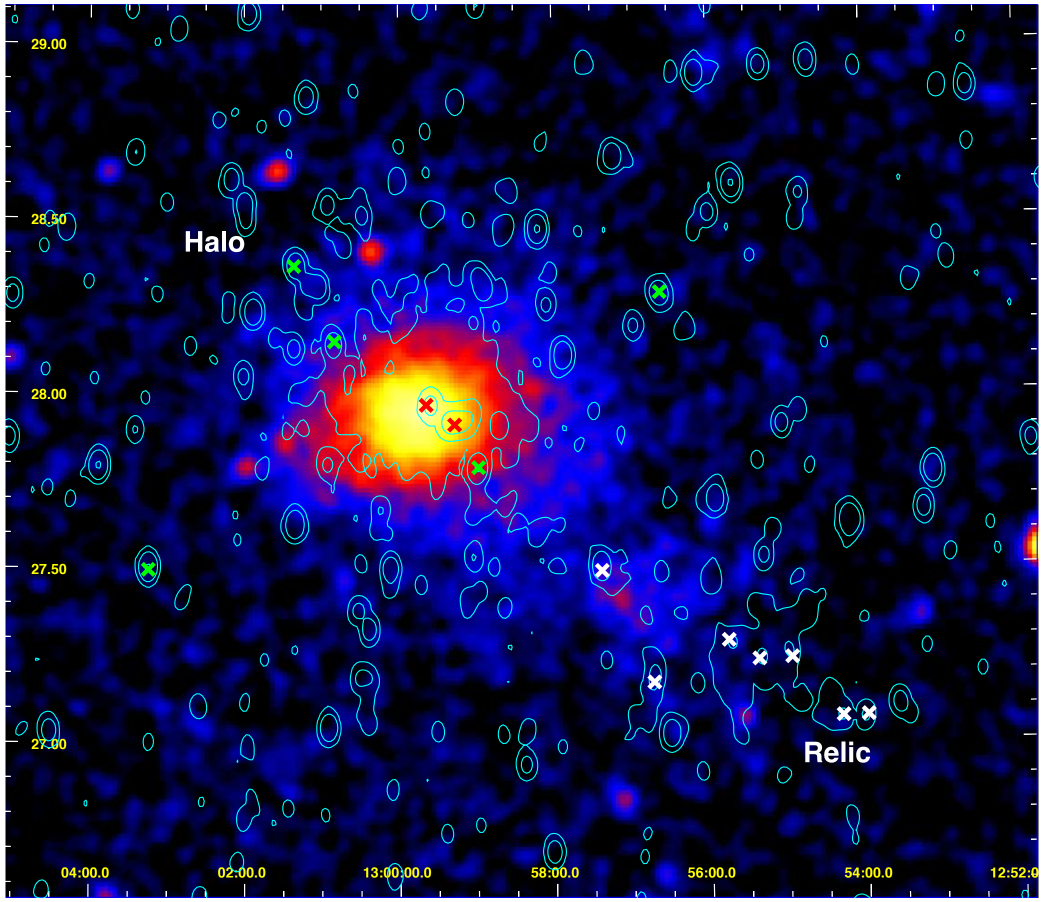




Magnetic Fields in Galaxy Clusters

- Electron density via X-ray brightness profile

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



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

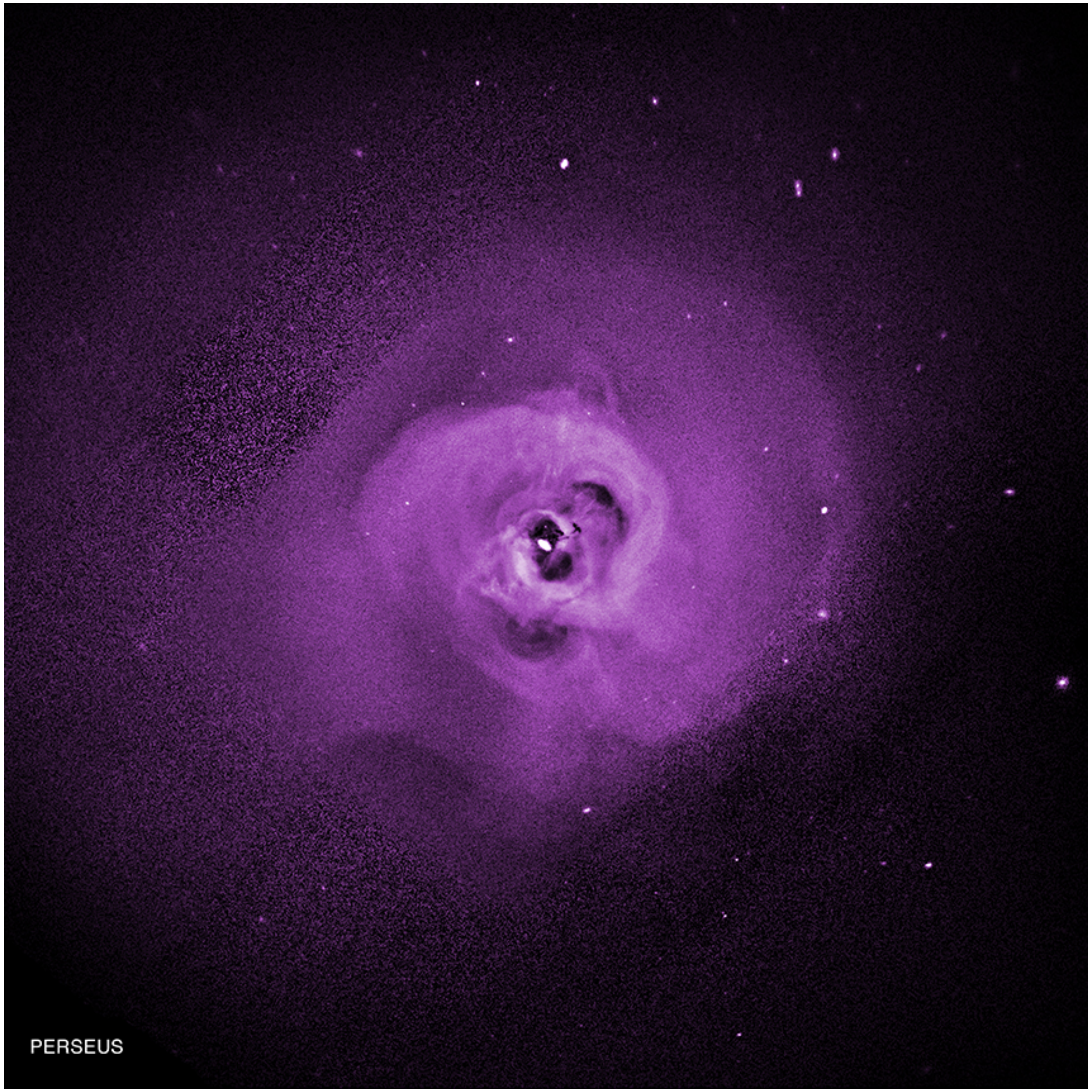
- Magnetic field via Faraday rotation $RM = \frac{e^3}{2\pi m_e^2}\int_{l.o.s} n_e(l) B_{\|}(l)\mathrm{d}l$

[Ryu, Schleicher, Treumann, Tsagas, Widrow '11]

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

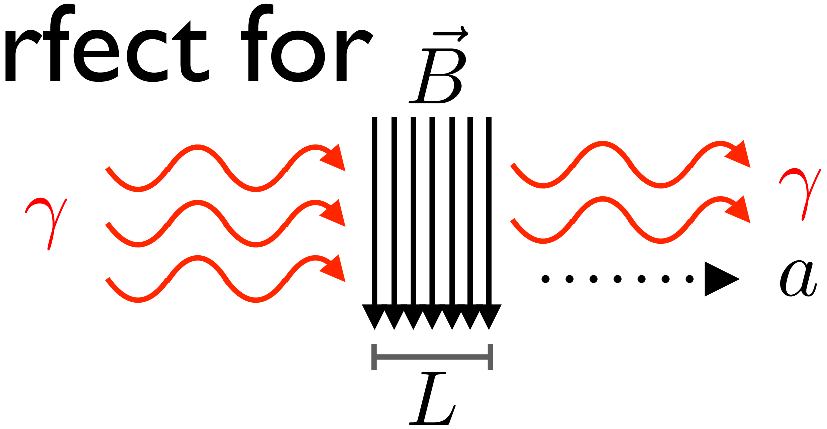
$$\Rightarrow \text{turbulent } B \sim \mathcal{O}(\mu\text{G}) \text{ with } L \sim \mathcal{O}(10\text{kpc})$$

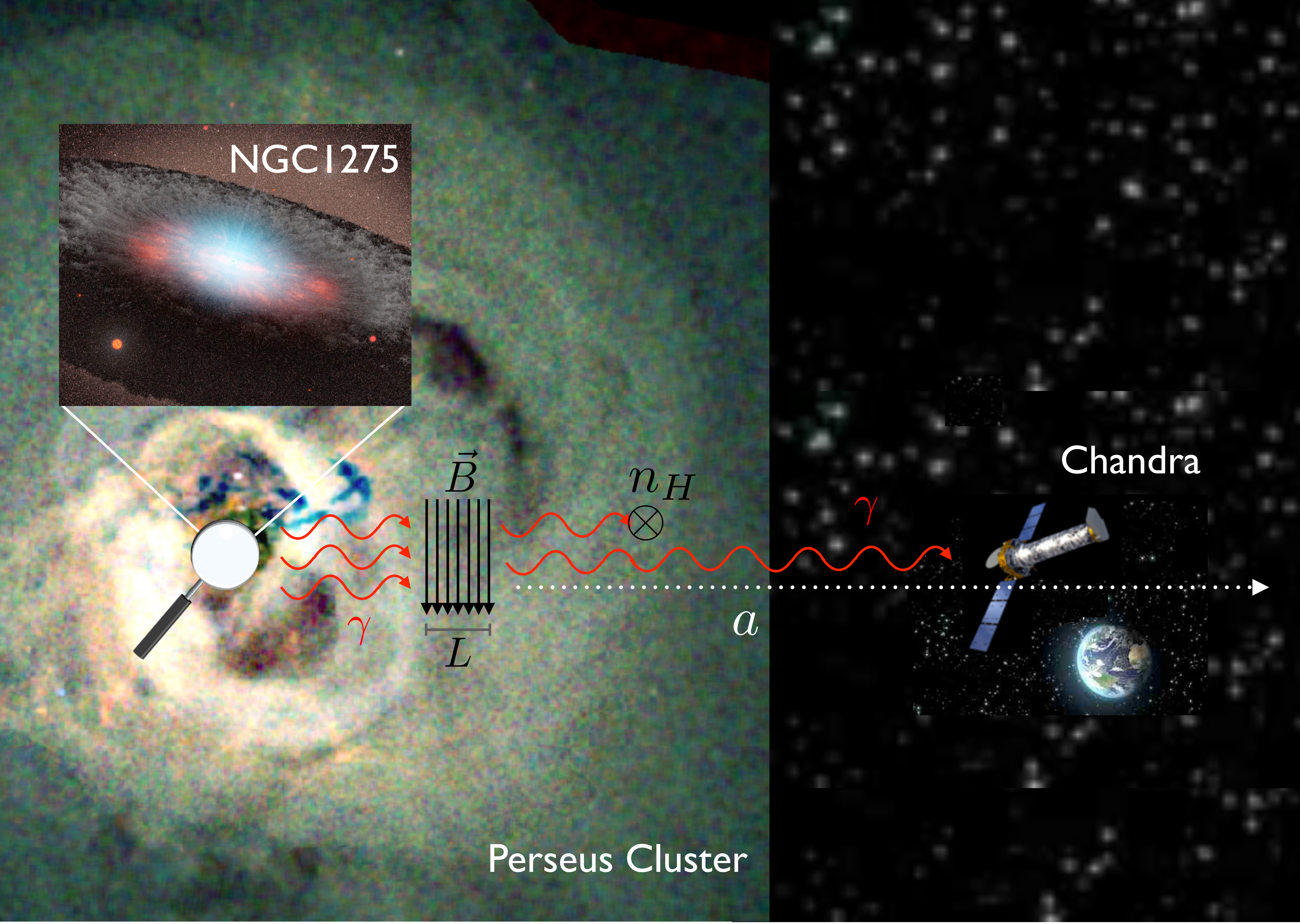
Perseus and NGC1275



- Perseus is close (z=0.017) and bright
- Central galaxy NGC1275 has a very bright AGN
- μG magnetic fields on Mpc scales with kpc coherence scales

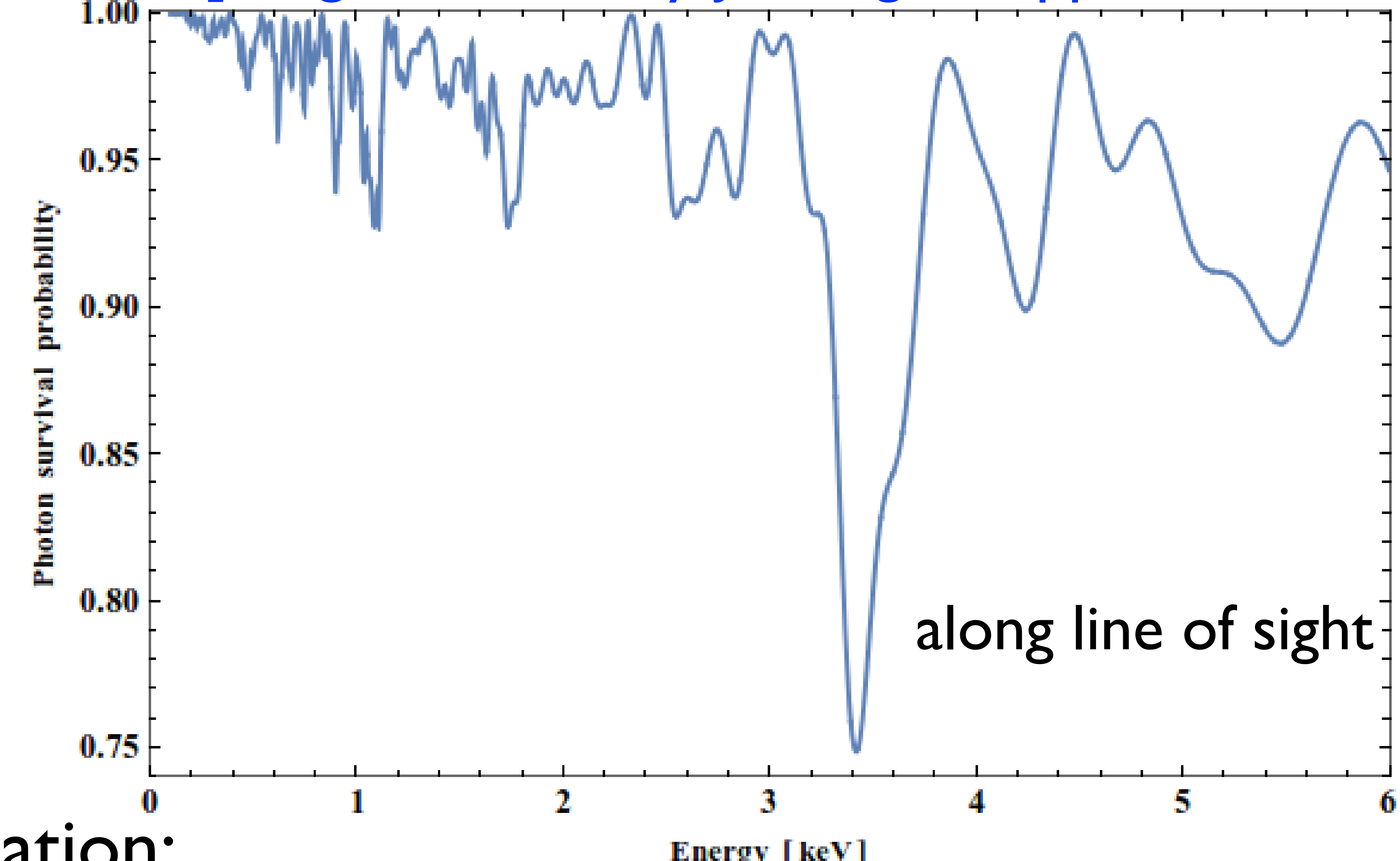
$\Rightarrow$ Perfect for




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

Modulations

[Berg, Conlon, Day, Jennings, Krippendorf, Powell, MR '16]



Simulation:

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

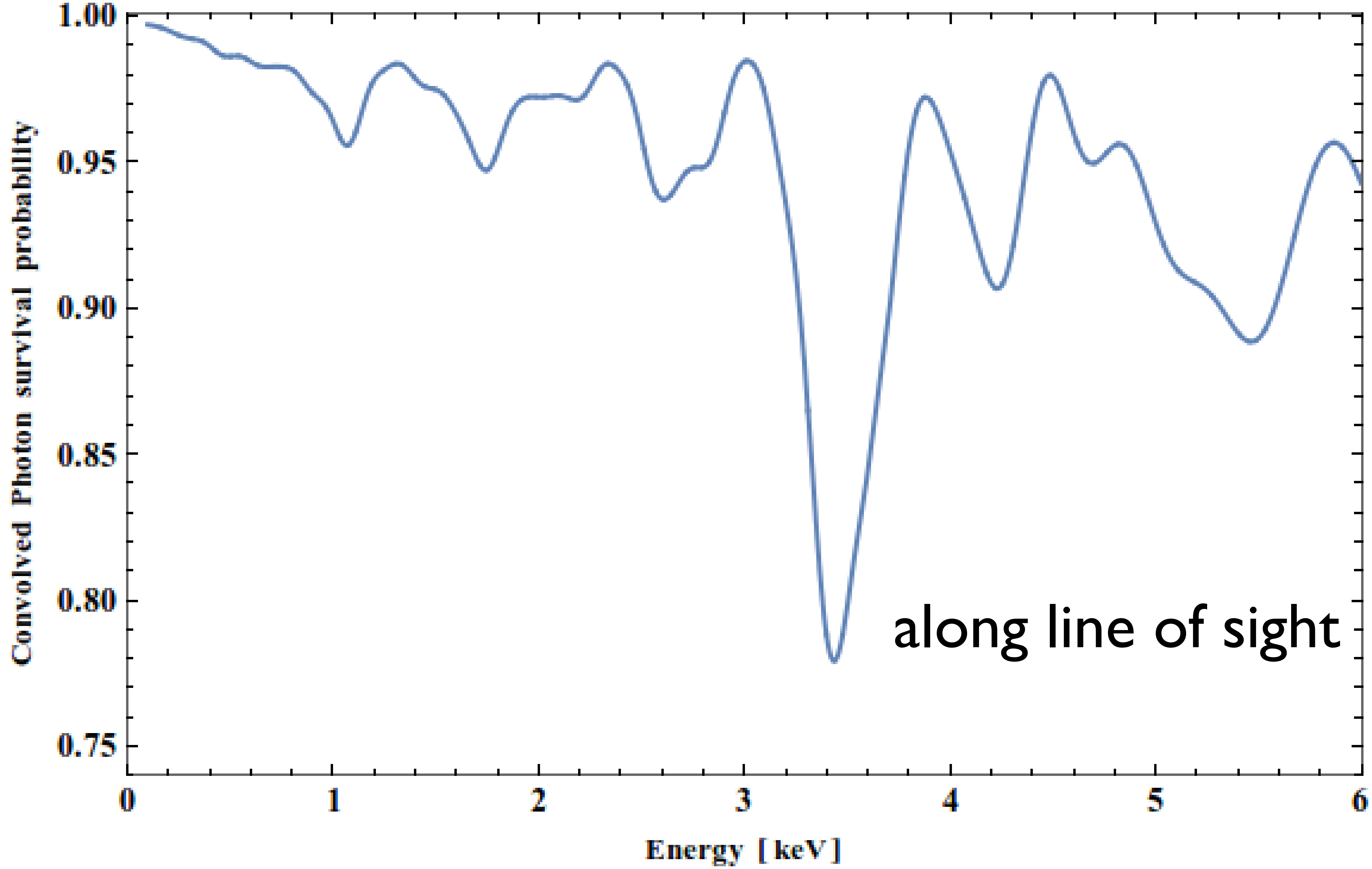
$$3.5\ \mathrm{kpc} < L < 10\ \mathrm{kpc\ over\ 100\ domains}$$

Modulations

Effects that can wash out modulations:

- Finite energy resolution of the telescope

Modulations



convolved with Gaussian with FWHM of 150 eV

Modulations

Effects that can wash out modulations:

- Finite energy resolution of the telescope
- Destructive interference from different lines of sight whenever $l_{\text{Region}} \gtrsim L_{\text{Coherence}}$
- Insufficient statistics: Oscillations $(\mathcal{O}(10\%))$ are indistinguishable from Poisson Errors $1/\sqrt{\text{Counts}}$

$\Rightarrow$ Sufficient counts from small region

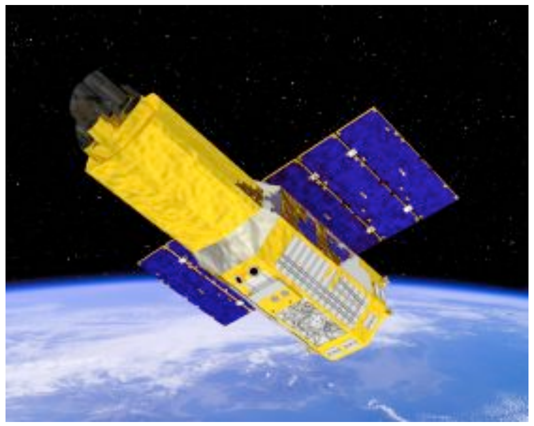
$\Rightarrow$ AGNs in/behind Galaxy Clusters

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 $P(\gamma \to a)$ can be resonantly large if $m_a \simeq 10^{-10} - 10^{-8}\ \mathrm{eV}$ (different region in ALP parameter space)
- see also [H.E.S.S. '13] analysis of PKS 2155-304

Which telescope?

Suzaku



$\Delta E = 100\ \text{eV},$
$\Delta\phi = 60''$

XMM-Newton

$\Delta E = 100\ \text{eV},$
$\Delta\phi = 5''$

Chandra

$\Delta E = 100\ \text{eV},$
$\Delta\phi = 0.5''$

Hitomi

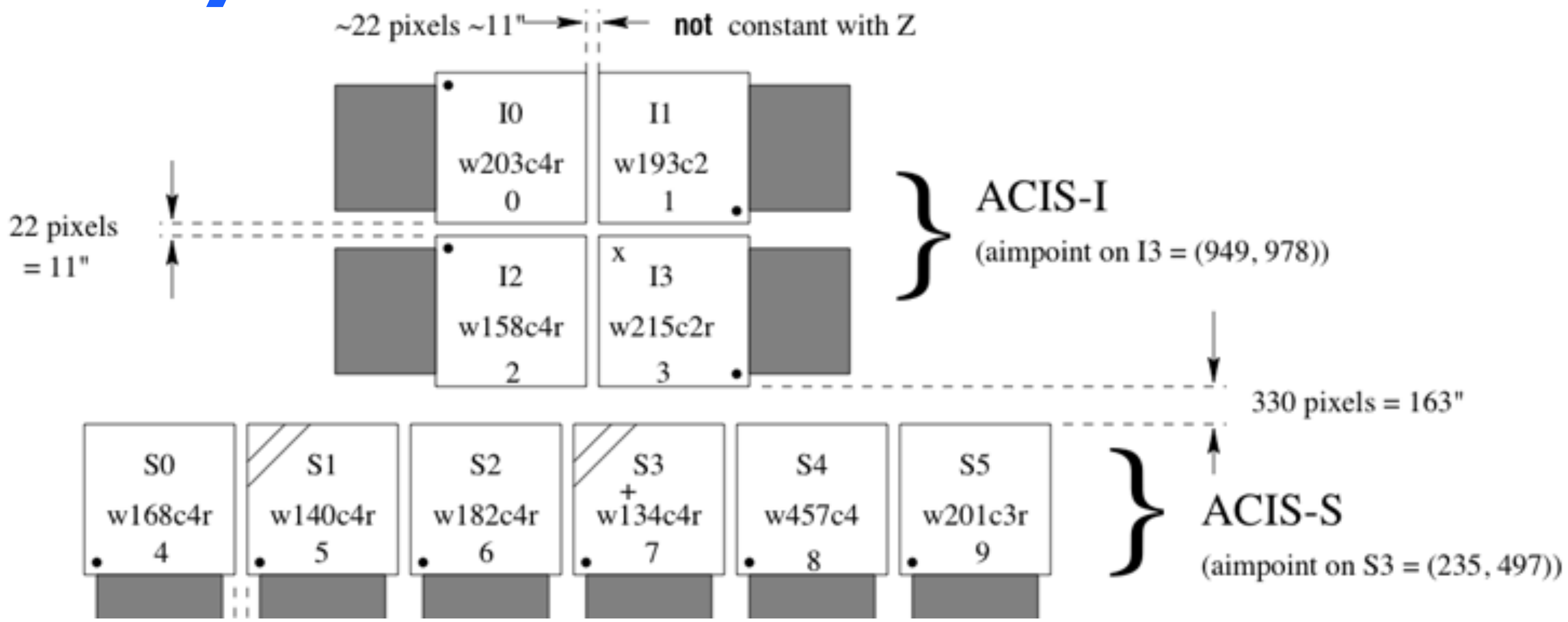
$\Delta E = 5\ \text{eV},\ \Delta\phi = 60''$

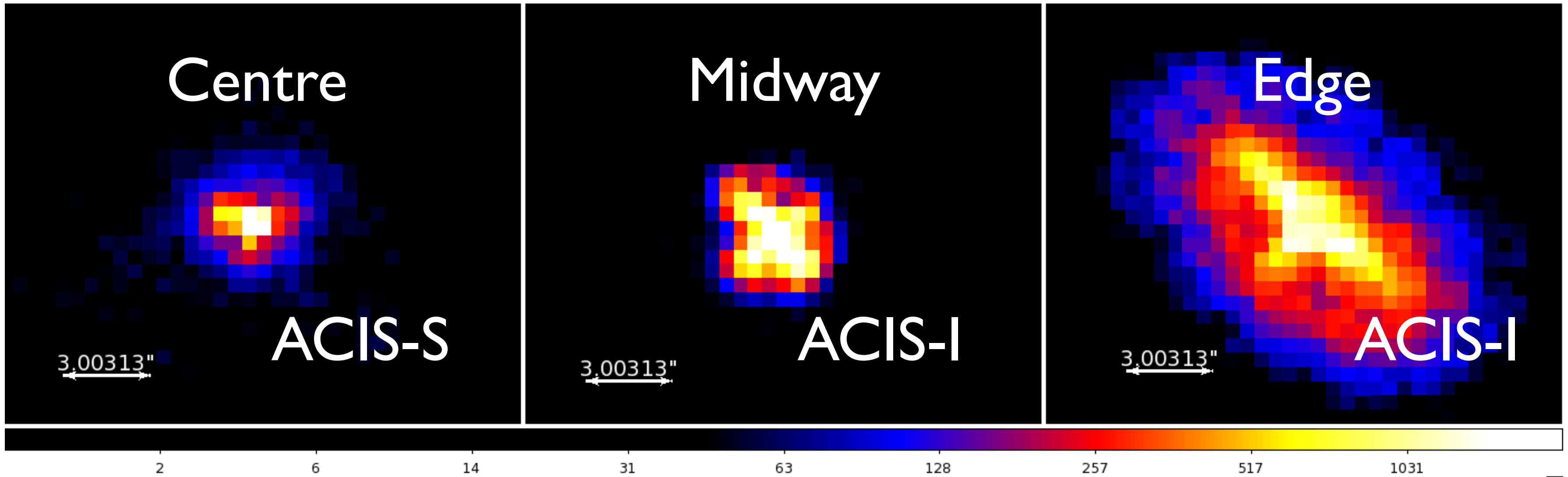
Wishlist:

- Many counts
- Avoid Pileup
- Good Signal / Background

X-ray data: Chandra

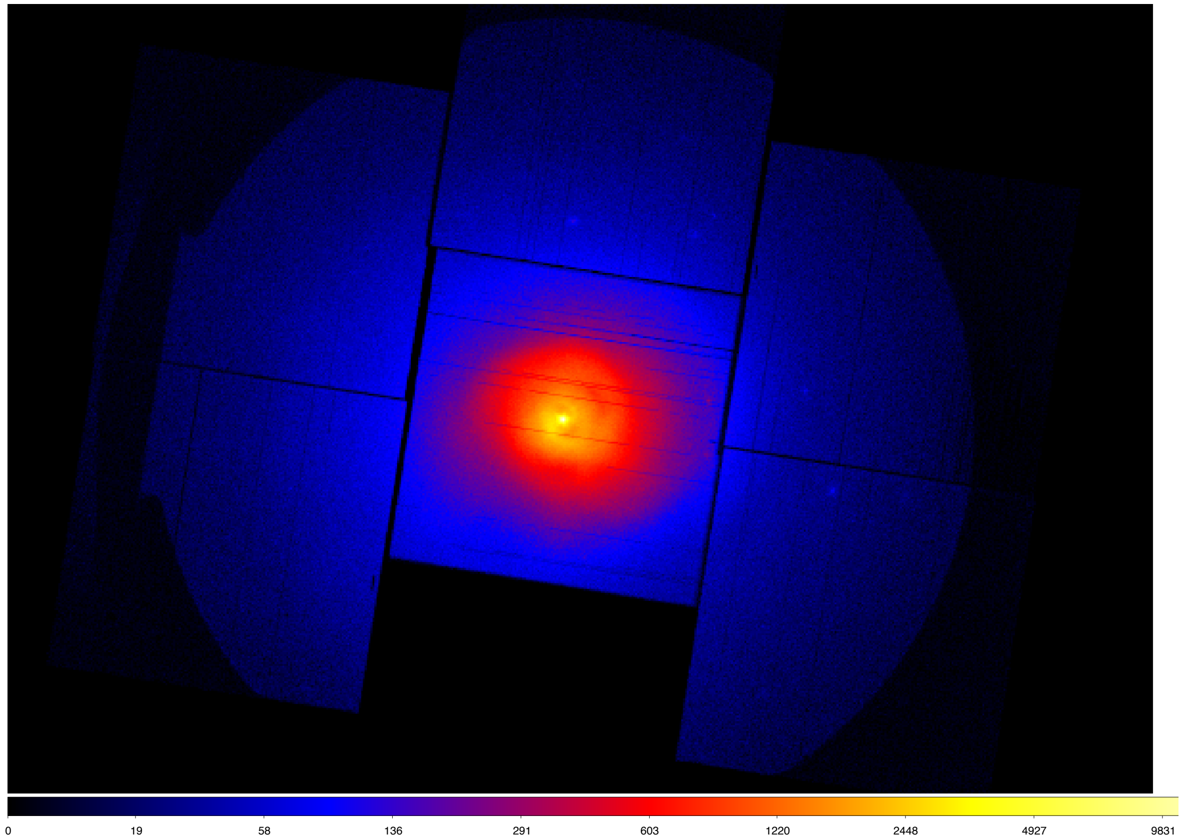
1.5 MS/
750 000
counts
of ACIS-I/S
data





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

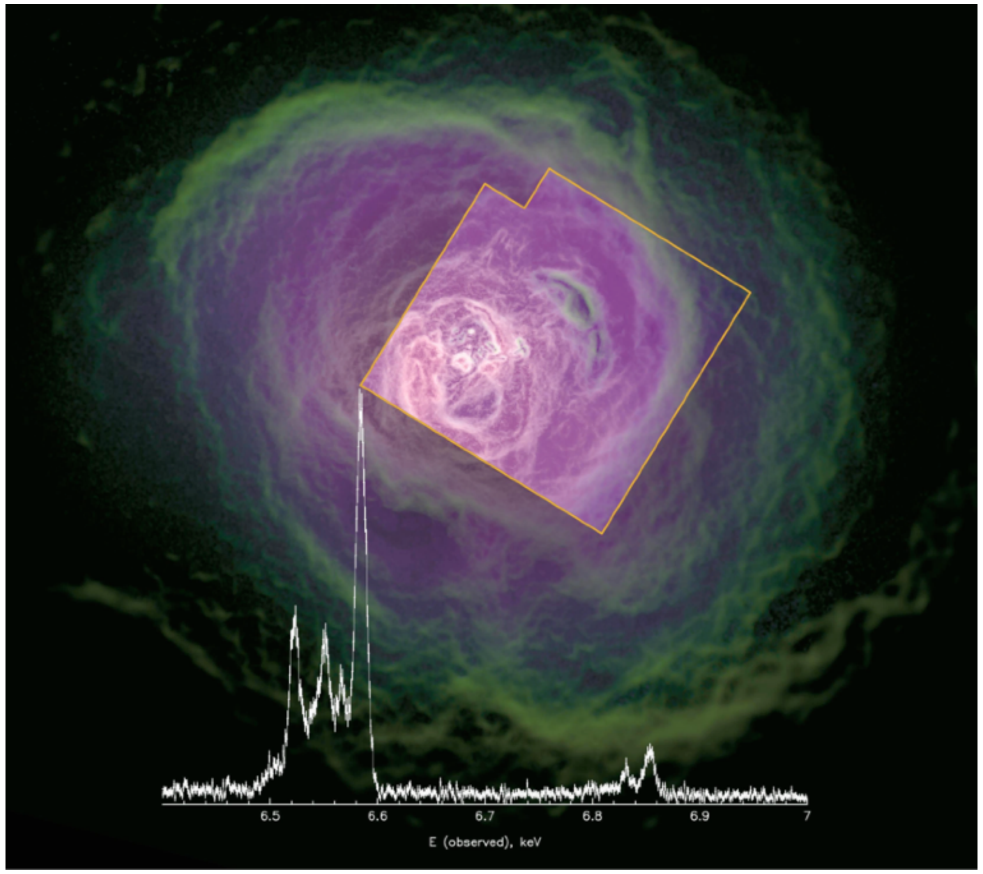
- Angular resolution: 8.5” vs 0.5” Chandra

$\Rightarrow$ Worse Signal/Background contrast for XMM

- Effective Area: 1000 cm2 vs 340 cm2 Chandra

- Pileup is an issue here too

X-ray data: Hitomi



275 ks of data

[Hitomi Collaboration '16]

- Angular resolution: 60" vs 0.5" Chandra

$\Rightarrow$ AGN cannot be resolved

- 20 times better Energy resolution
- Died just after a few weeks in operation

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Spectral Analysis

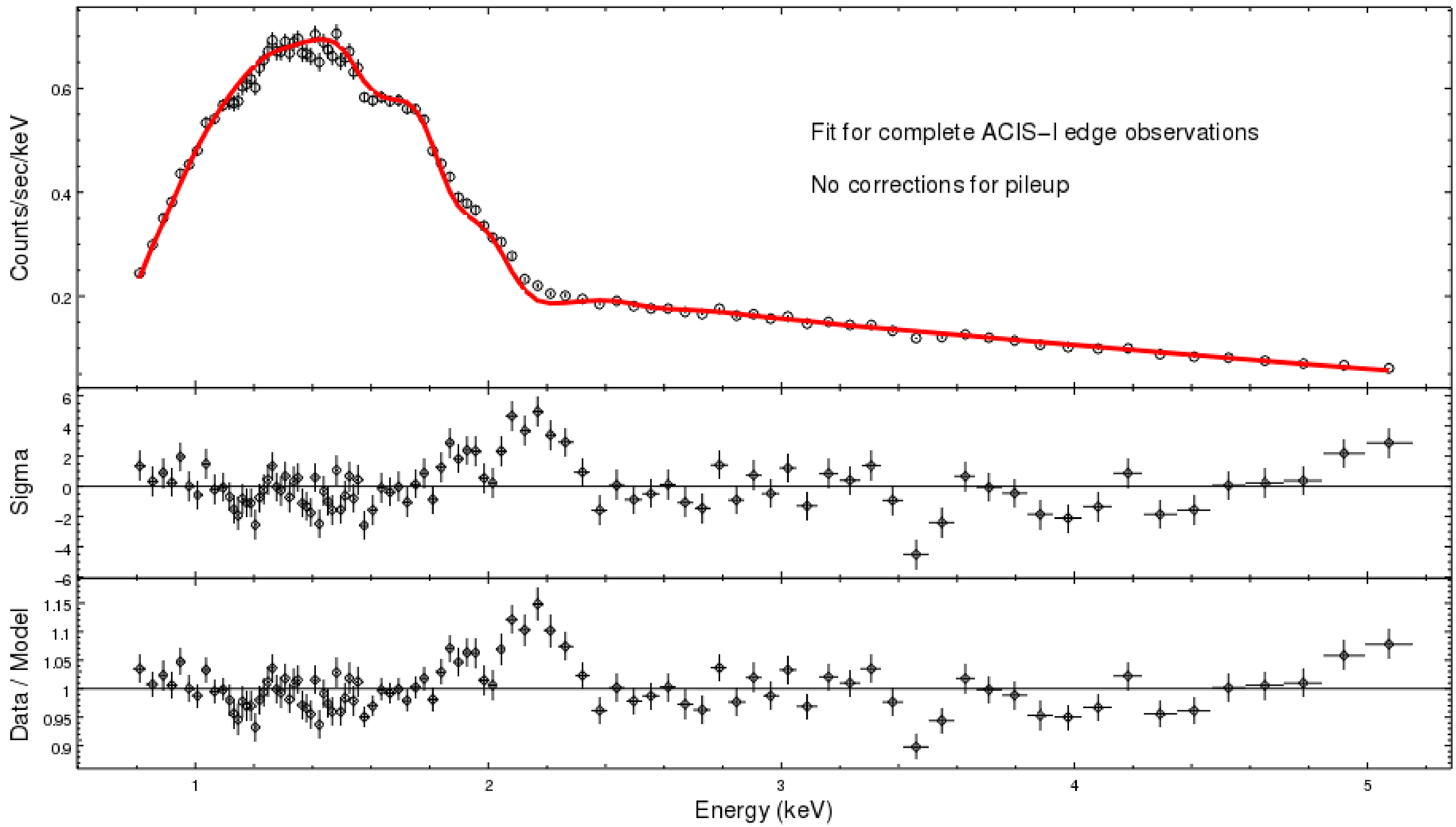
- The spectral shape of an AGN is modelled by

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

- 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:

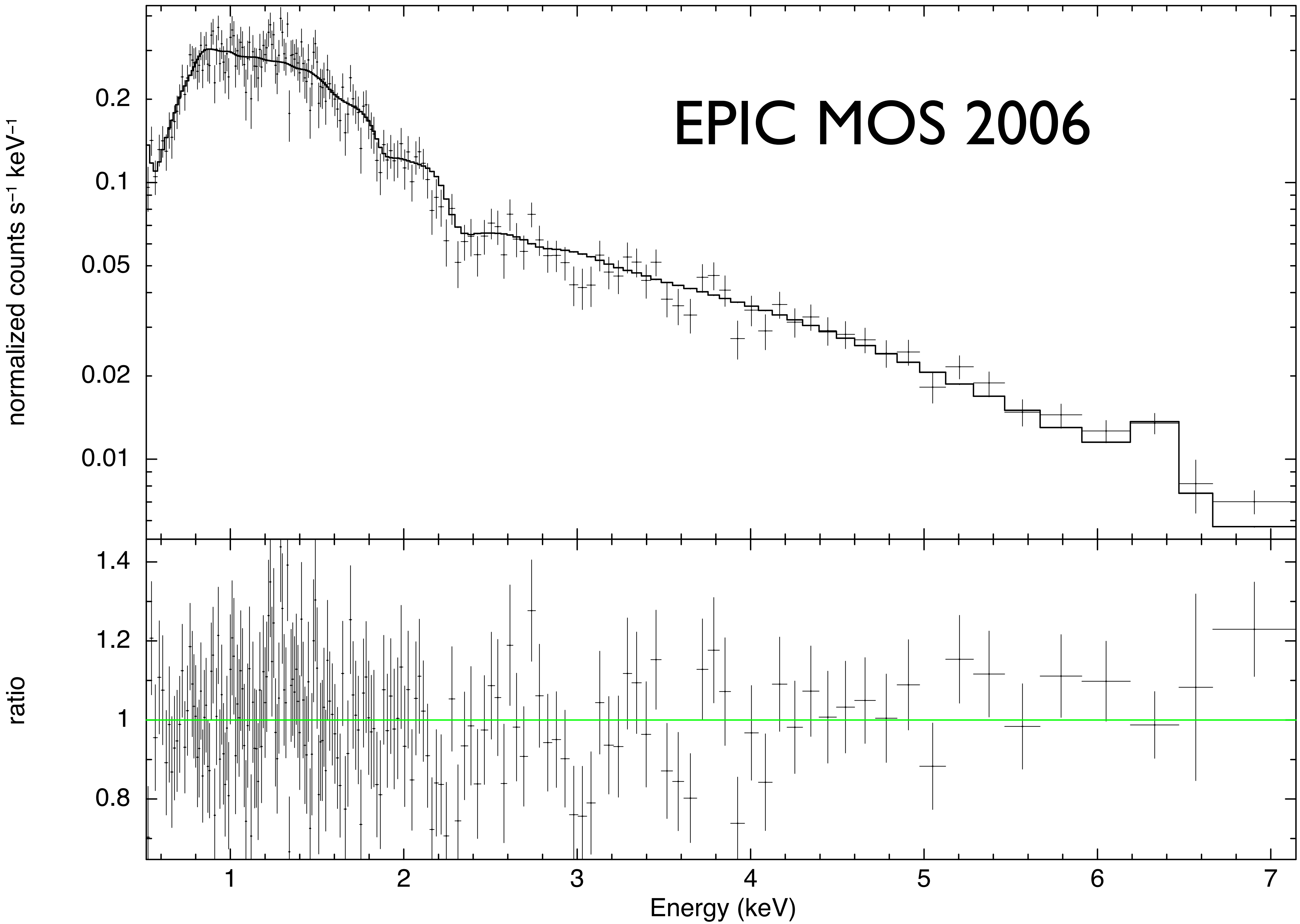
1. Exclude central piled up pixels
2. Model the effects of pileup (jdpileup) [Davis '01]

ACIS-I edge



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

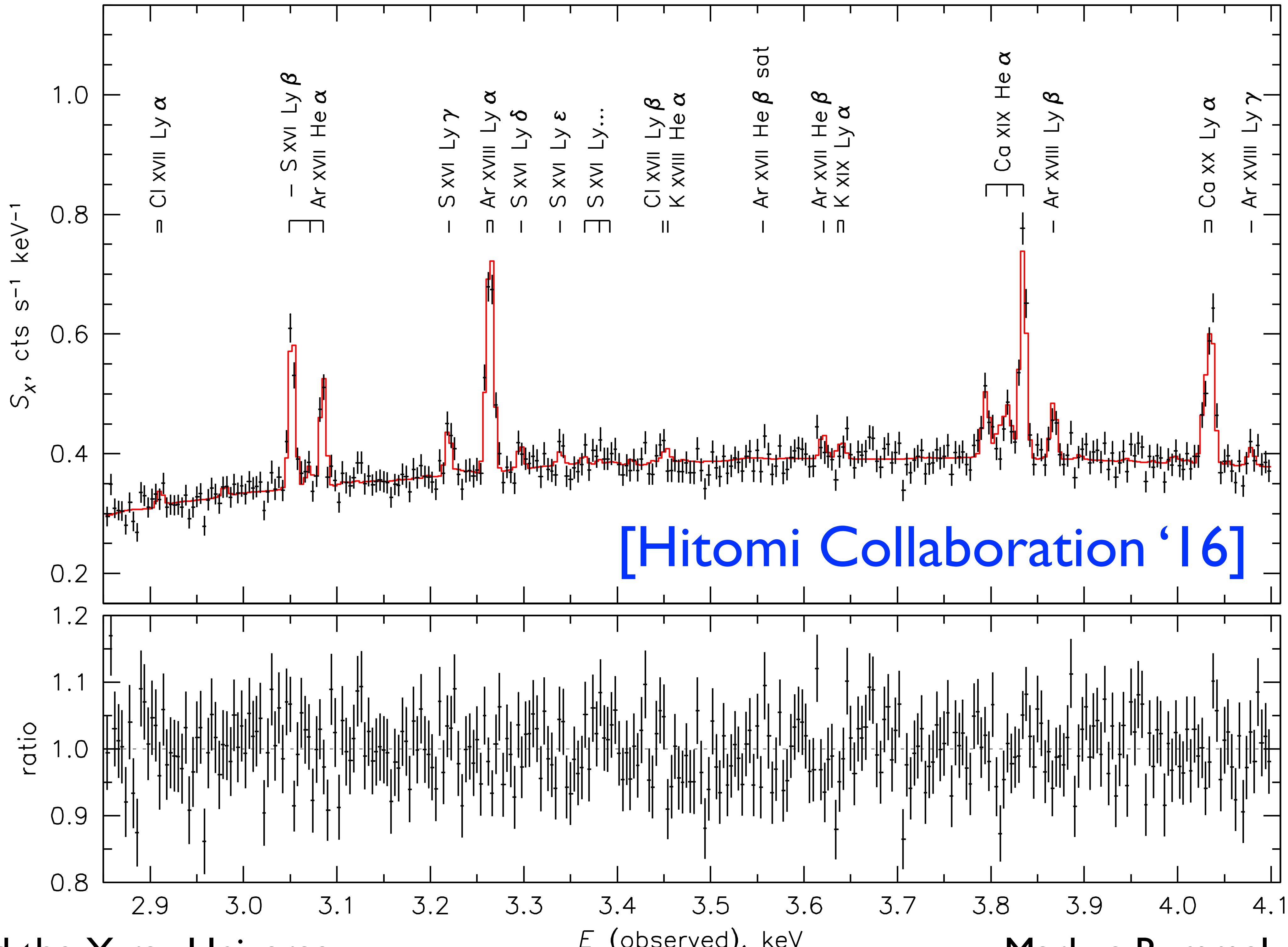
XMM



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

Hitomi

AGN only ~15% ⇒ No constraints on modulations



[Hitomi Collaboration '16]

Bounds

[Berg, Conlon, Day, Jennings, Krippendorf, Powell, MR '16]

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

- 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]

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

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)

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

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

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

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

Bounds from other AGN

[Conlon, Day, Jennings, Krippendorf, MR '17]

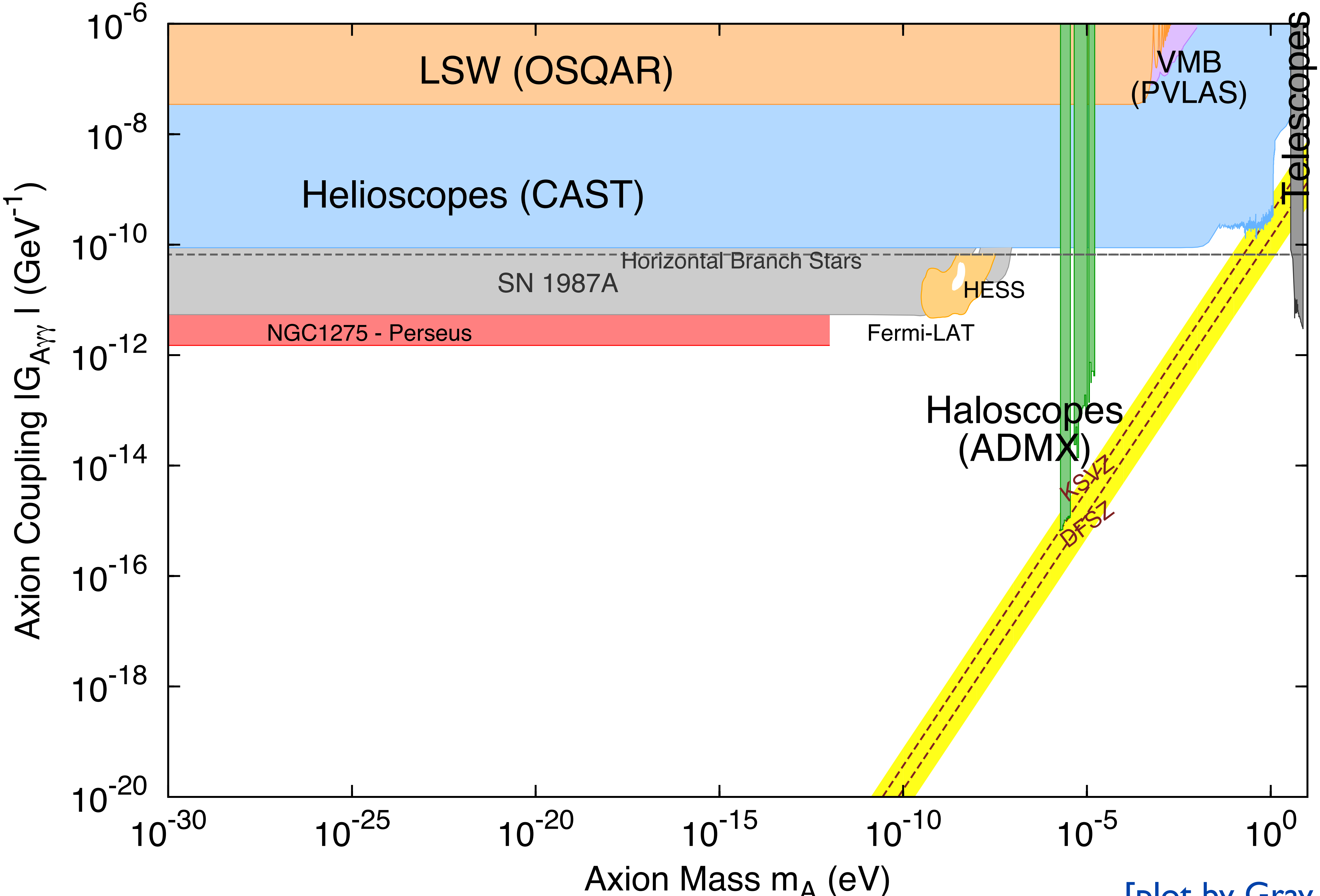
- extended NGC1275 to other sources in or behind Galaxy clusters

Source	Cluster	$n_{e,0}$ $(10^{-3}\mathrm{cm}^{-3})$	r_c (kpc)	β	B_0 μG	L_{total} (Mpc)
B1256+281	Coma	3.44	291	0.75	4.7	2
SDSS J130001.47+275120.6	Coma	3.44	291	0.75	4.7	2
NGC3862	A1367	1.15	308	0.52	3.25	1
IC4374	A3581	20	75	0.6	1.5	1
2E3140	A1795	50	146	0.631	20	1
CXOUJ134905.8+263752	A1795	50	146	0.631	20	2
UGC9799	A2052	35	32	0.42	11	1

$$g_{a\gamma\gamma} \lesssim 1.5\times10^{-12}\mathrm{GeV}^{-1} \text{ and } g_{a\gamma\gamma} \lesssim 2.4\times10^{-12}\mathrm{GeV}^{-1}$$

similar bound from [Marsh,Russell,Fabian, McNamara,Nulsen,Reynolds '17] from M87 (Virgo cluster)

ALP Parameter Space



[plot by Gray Rybka]

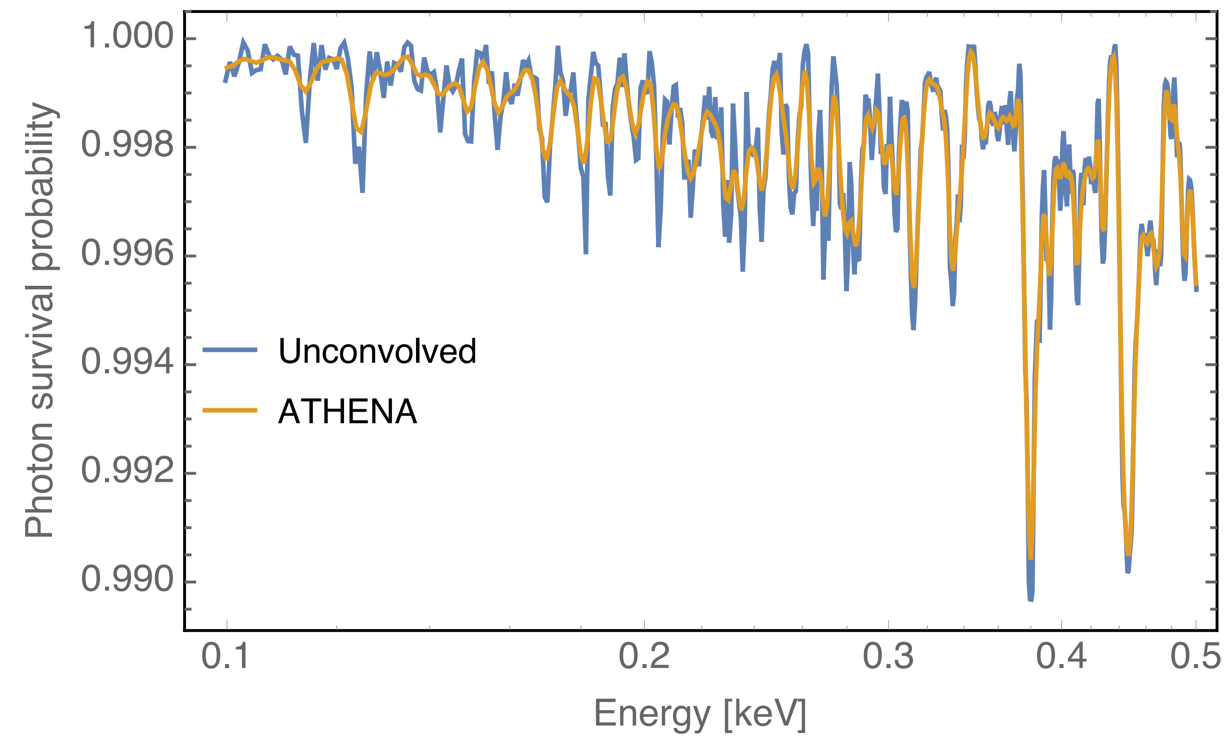
Data Outlook

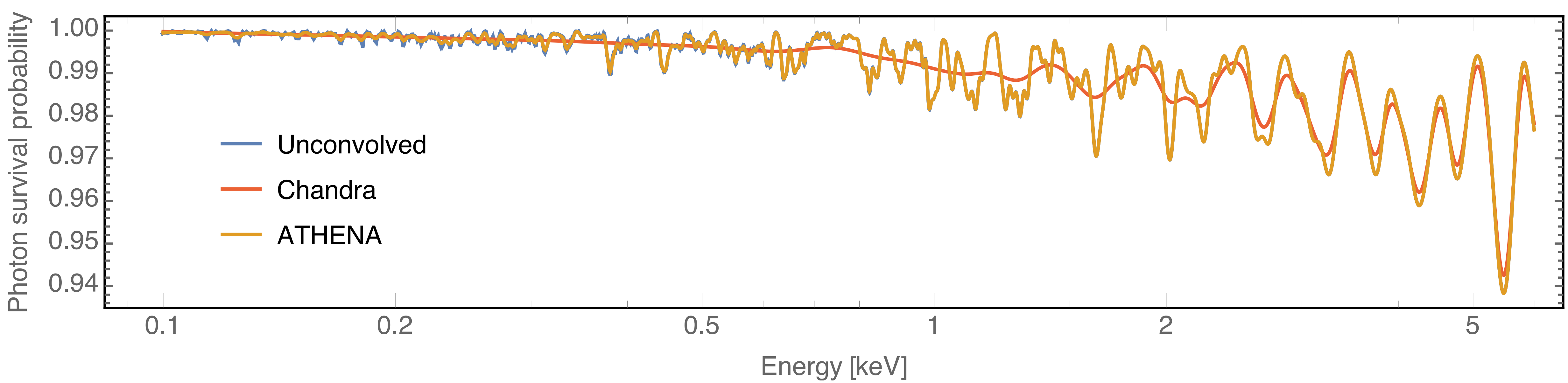
A clean, deep spectrum of NGC1275 doesn't exist yet

- i.e. spectrum that is not piled up
- AGN has increased it's intensity in recent years
- XMM would have signal / background of 9 / 1 now
- XMM has "small window mode" $\Rightarrow$ max count rate without pileup is 25 cts/s (10 cts/s expected)
- Hitomi/Athena can potentially resolve line width

Athena (late 2020s)

- ~10 time effective area than XMM
- 2.5 eV Energy resolution
- 5” angular resolution



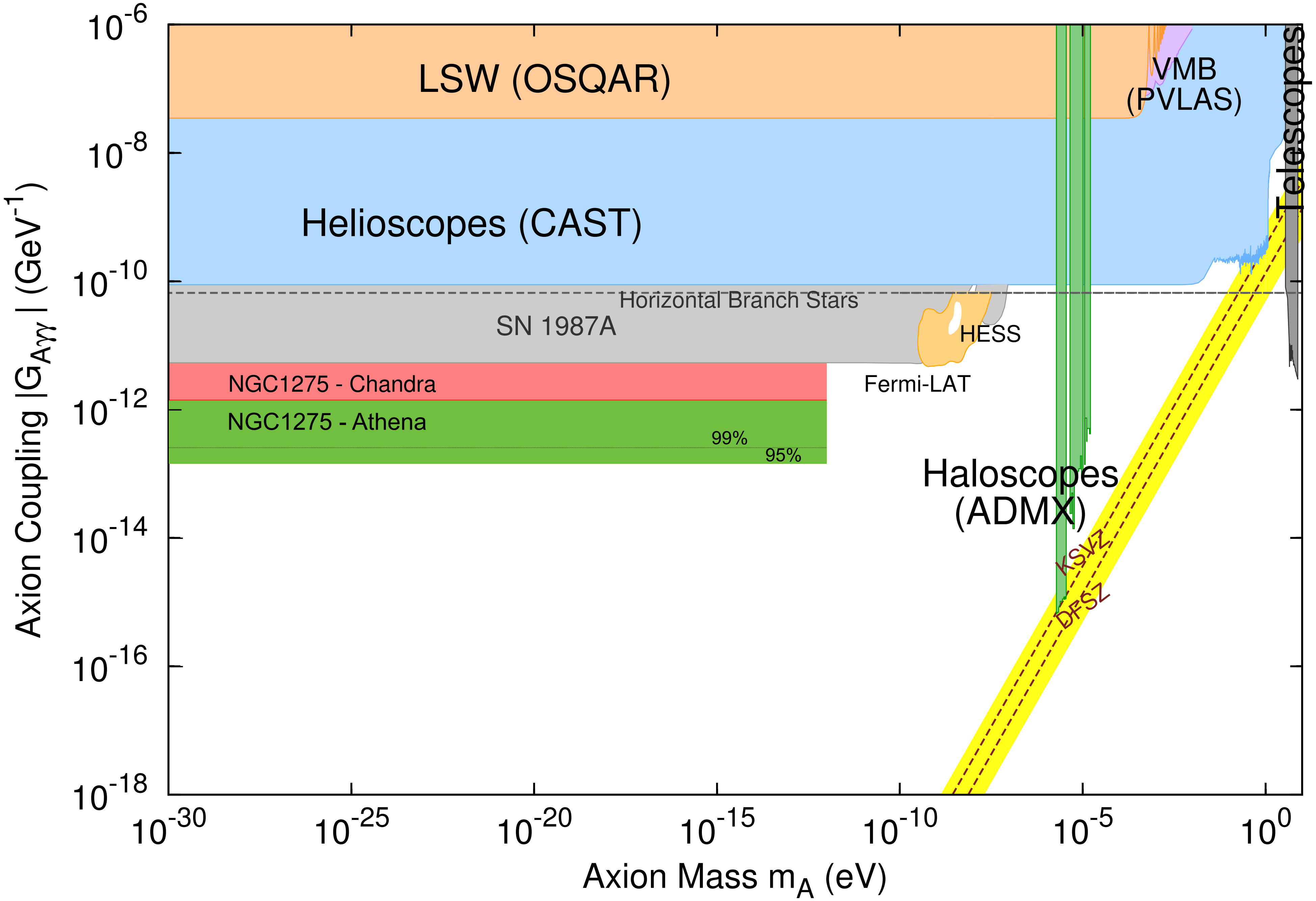


[Conlon, Day, Jennings, Krippendorf, Muia ‘17]

Outlook: Athena

Projected bounds:

[Conlon, Day, Jennings, Krippendorf, Muia '17]



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%, $\chi^2_i < \chi^2_{\mathrm{data}}$

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

Improving analysis method

[Conlon, MR '18]

Residuals: $$\mathcal{F}(\omega) \simeq \sum_i \frac{\epsilon_i}{2}\left(\frac{\omega}{\omega_0}\right)^2 \cos\left[2\Delta_i\left(\frac{\omega_0}{\omega}\right)\right]$$

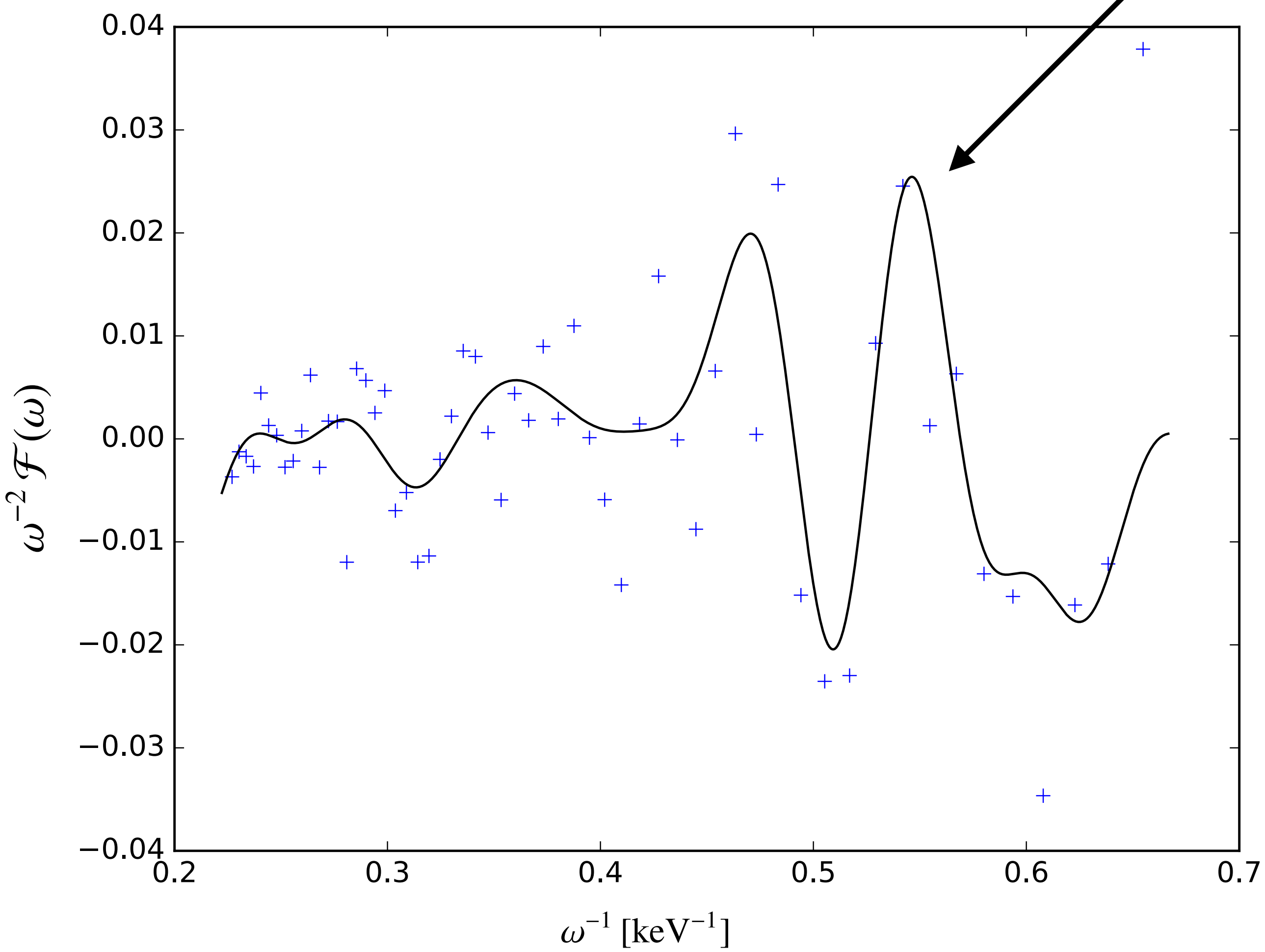
unknown, depend on B field realization

- Fourier analysis of $(u_i, y_i) \quad = \quad \left(\omega_i^{-1}, \omega_i^{-2}\mathcal{F}(\omega_i)\right)$
- Sinusodial fit
- Machine learning (deep neural network)

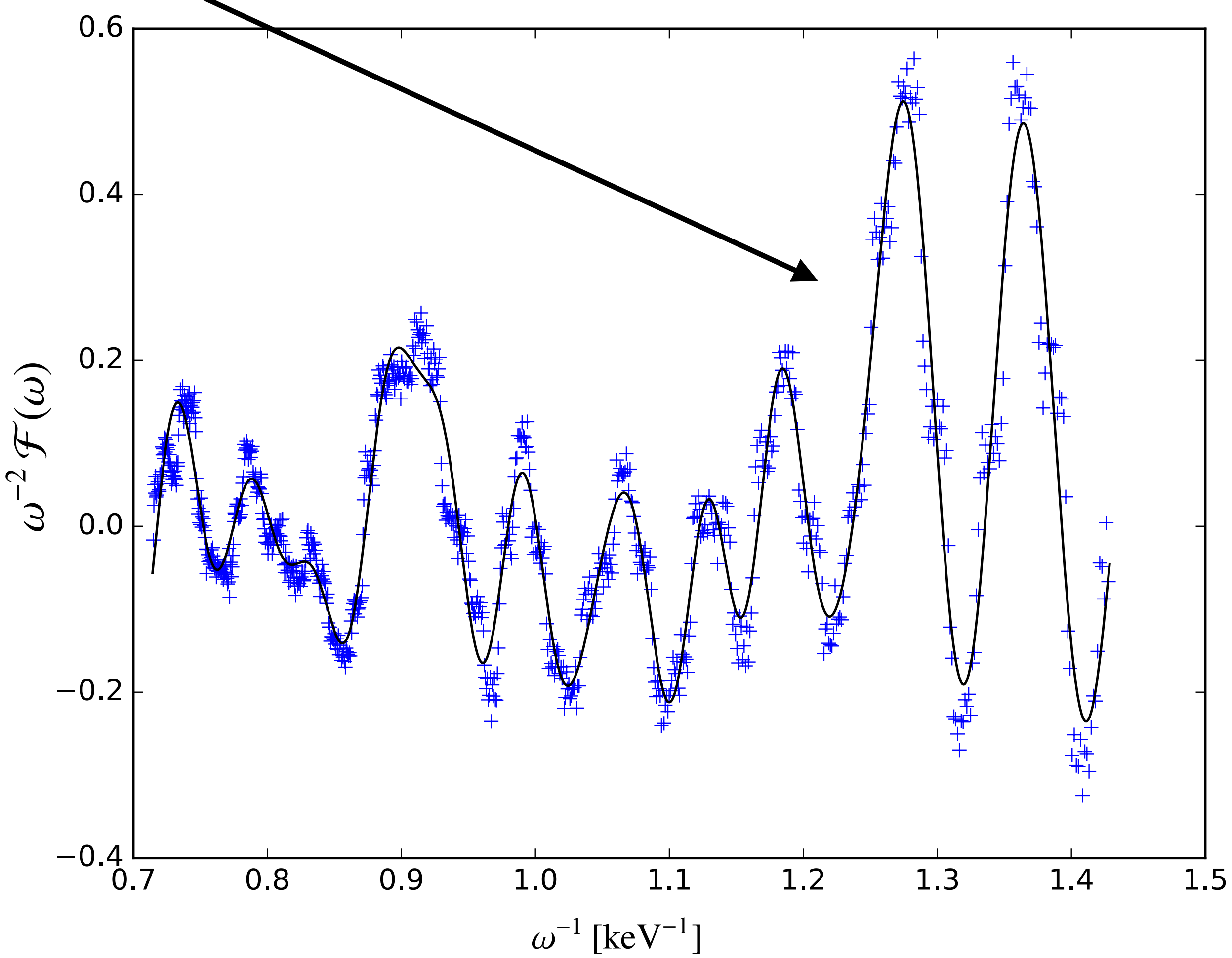
Improving Analysis method

simulated data of NGC1275

$$y^{(K)}(x) \equiv \mathrm{Re}\left(\sum_{k=-K}^{K-1} \hat{y}_k\, e^{-2\pi i k x}\right)$$



XMM

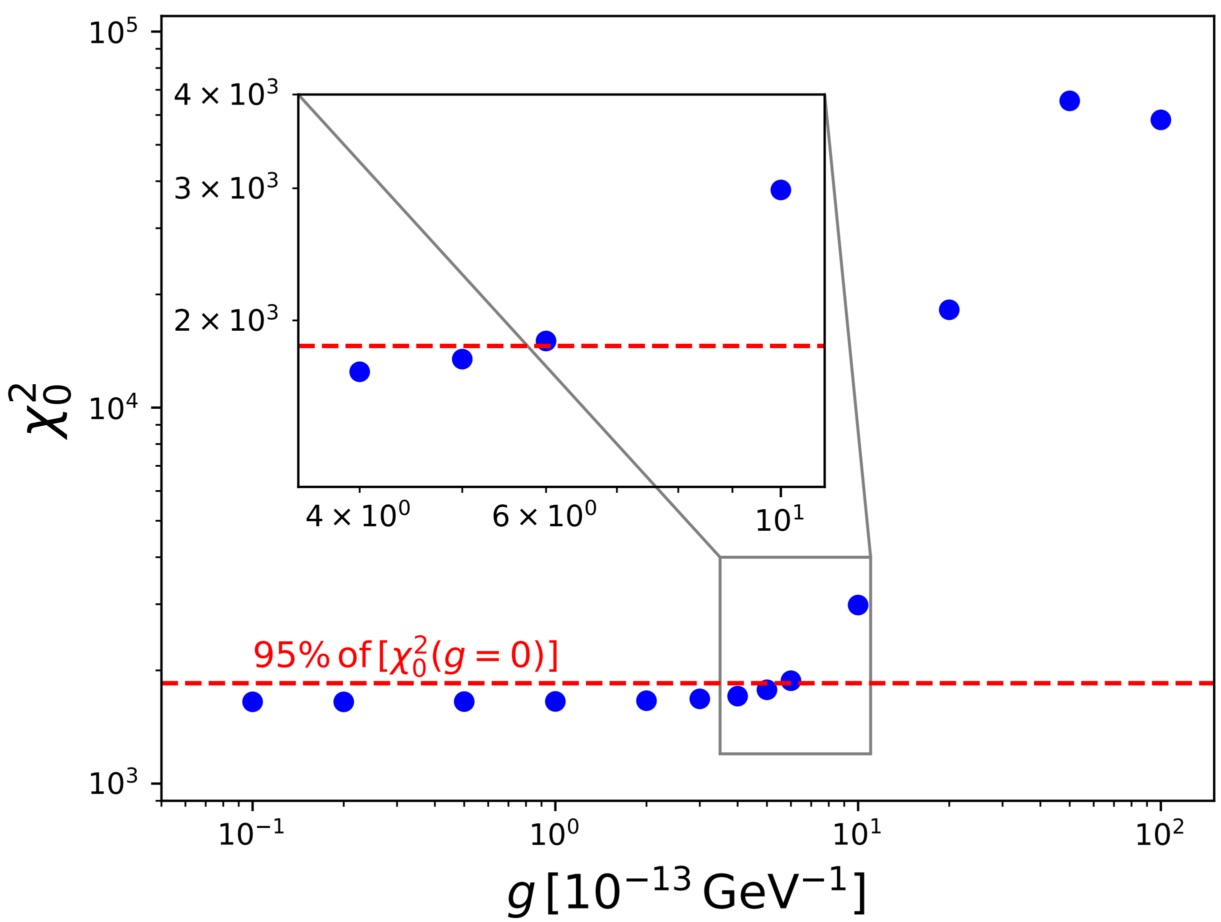


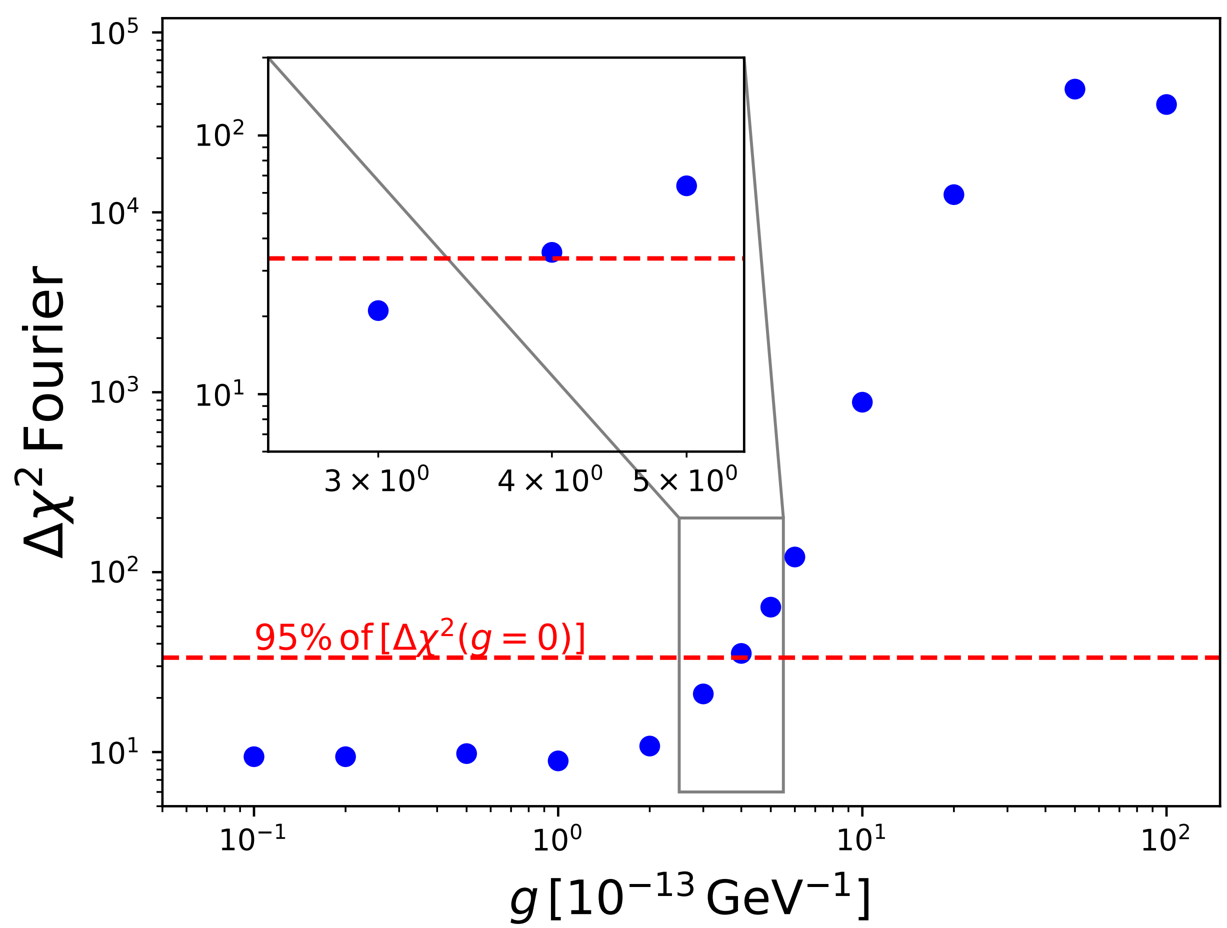
Athena

Improving Analysis method

$$\Delta\chi^2(g) \quad = \quad \chi_0^2(g) - \chi_1^2(g).$$

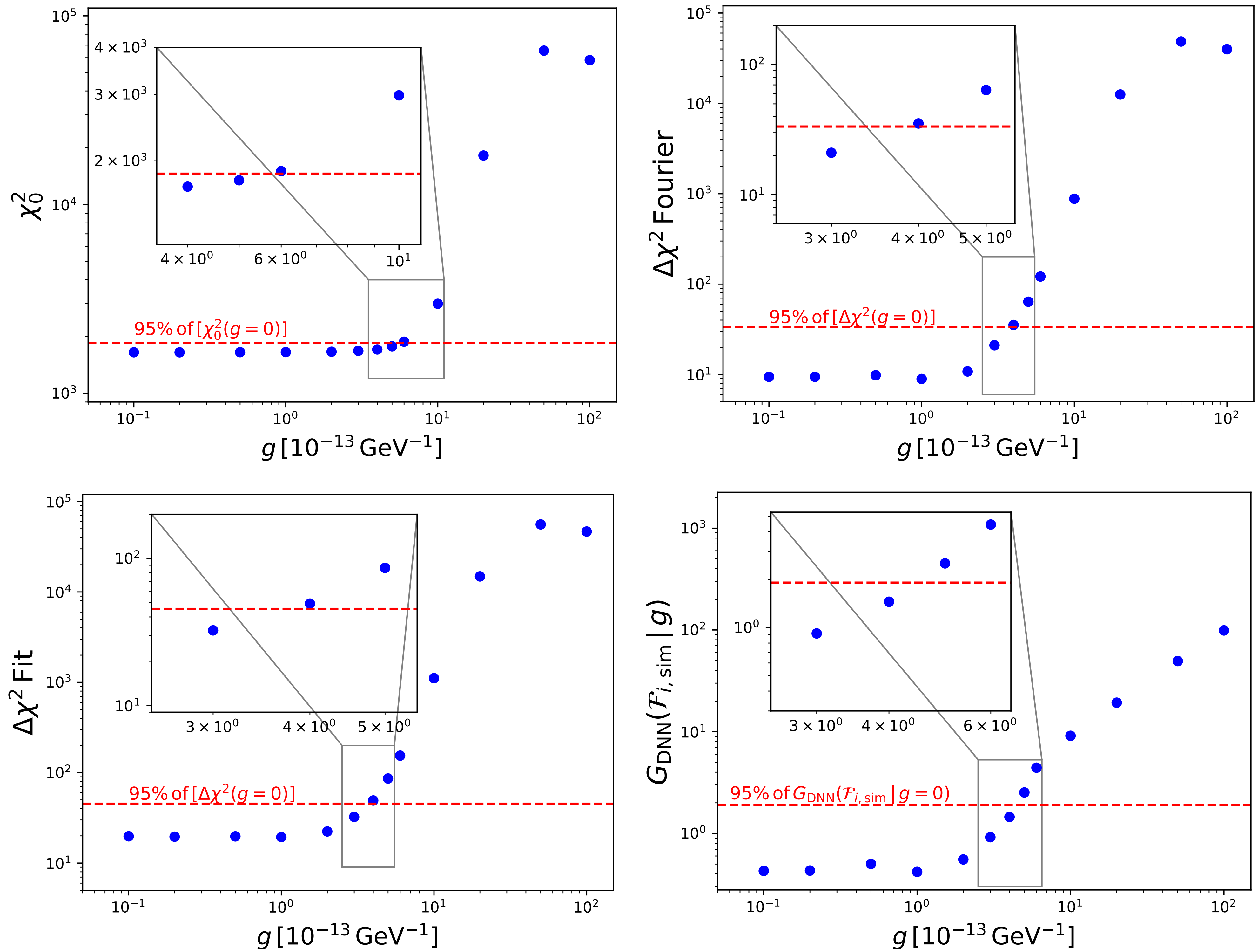
if null hypothesis can't be excluded: $\text{5th percentile}\left[\Delta\chi^2(g_{\text{bound}})\right] = \Delta\chi^2_{\text{obs}}$





$\Rightarrow$ Bounds on $g^2_{a\gamma\gamma}$ improved by factor ~ 2

Improving Analysis method



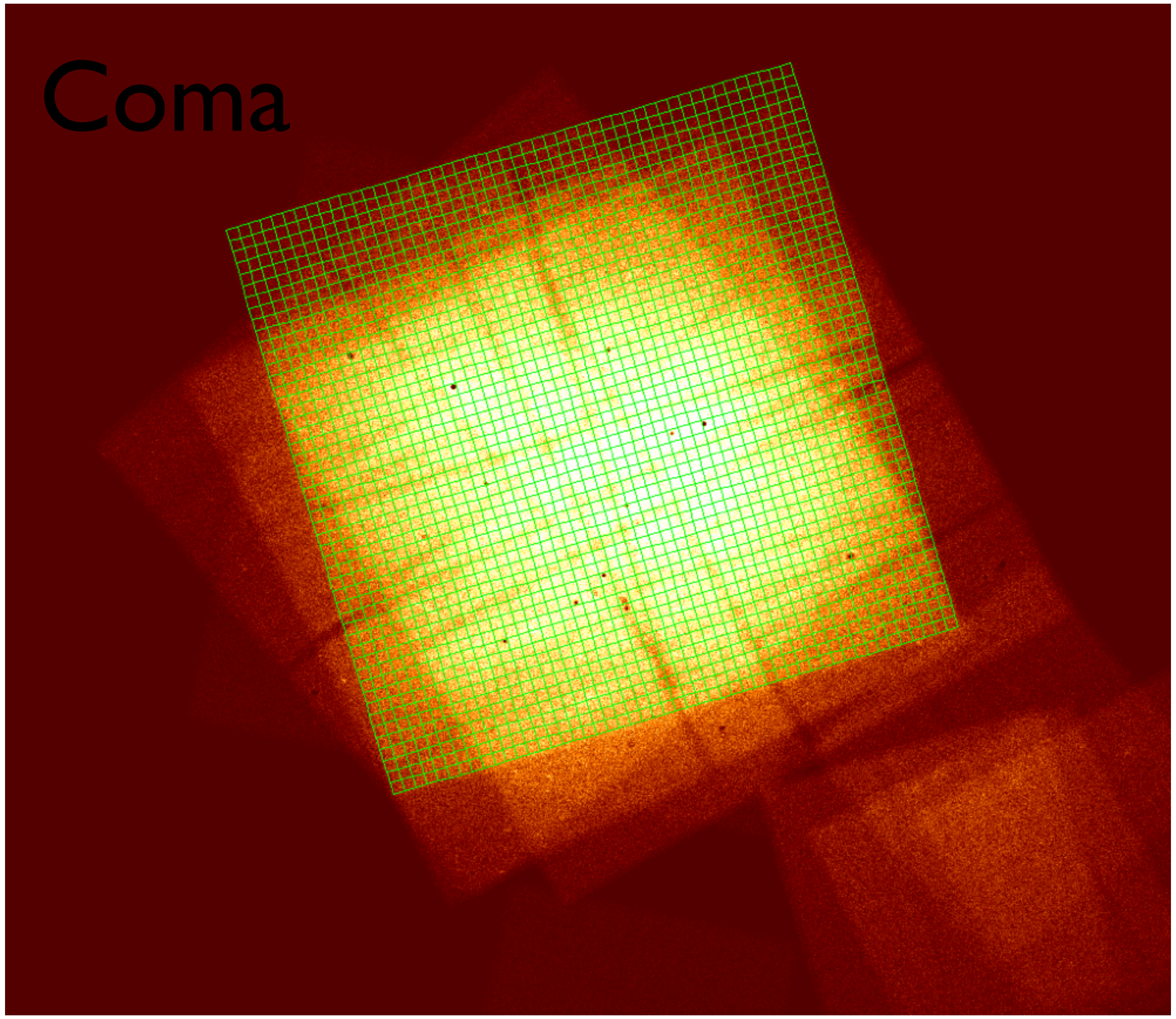
Conclusions & Outlook

- ALP properties can be probed via ALP-photon conversion, particularly well in galaxy clusters
- AGNs in/behind Galaxy Clusters have an extraordinary amount of X-ray data
- Absence of $\gtrsim 10\%$ deviations from expected spectrum allows the most competitive bounds yet on $g_{a\gamma\gamma}$ for $m_a \lesssim 10^{-12}$ eV
- Outlook: More data (Hitomi, XMM, Chandra, Athena; SKA) better analysis methods

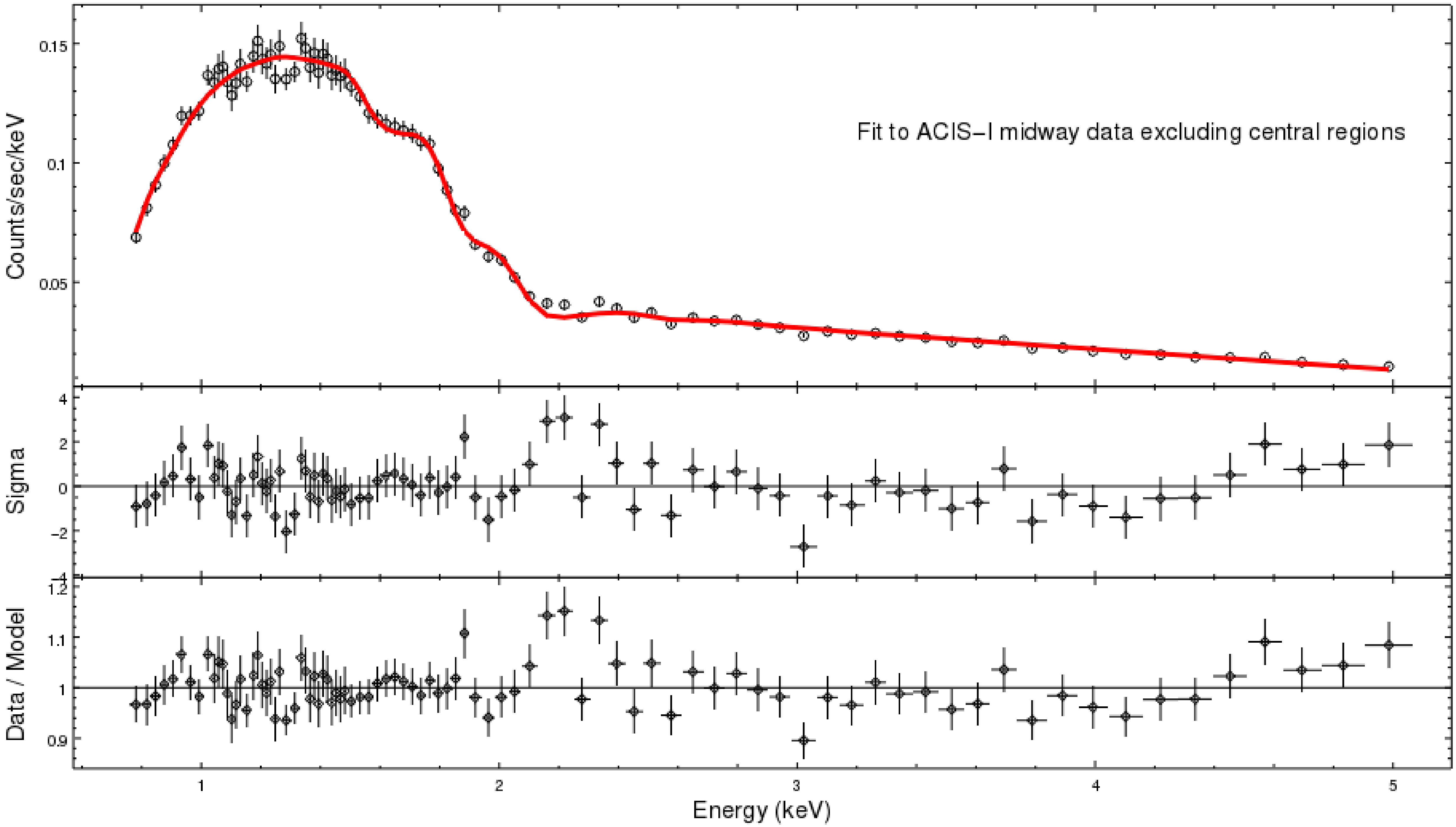
Backup Slides

Outlook

- Hitomi and Athena data to come
- Continuum in clusters with known magnetic field
- Other point sources in the universe

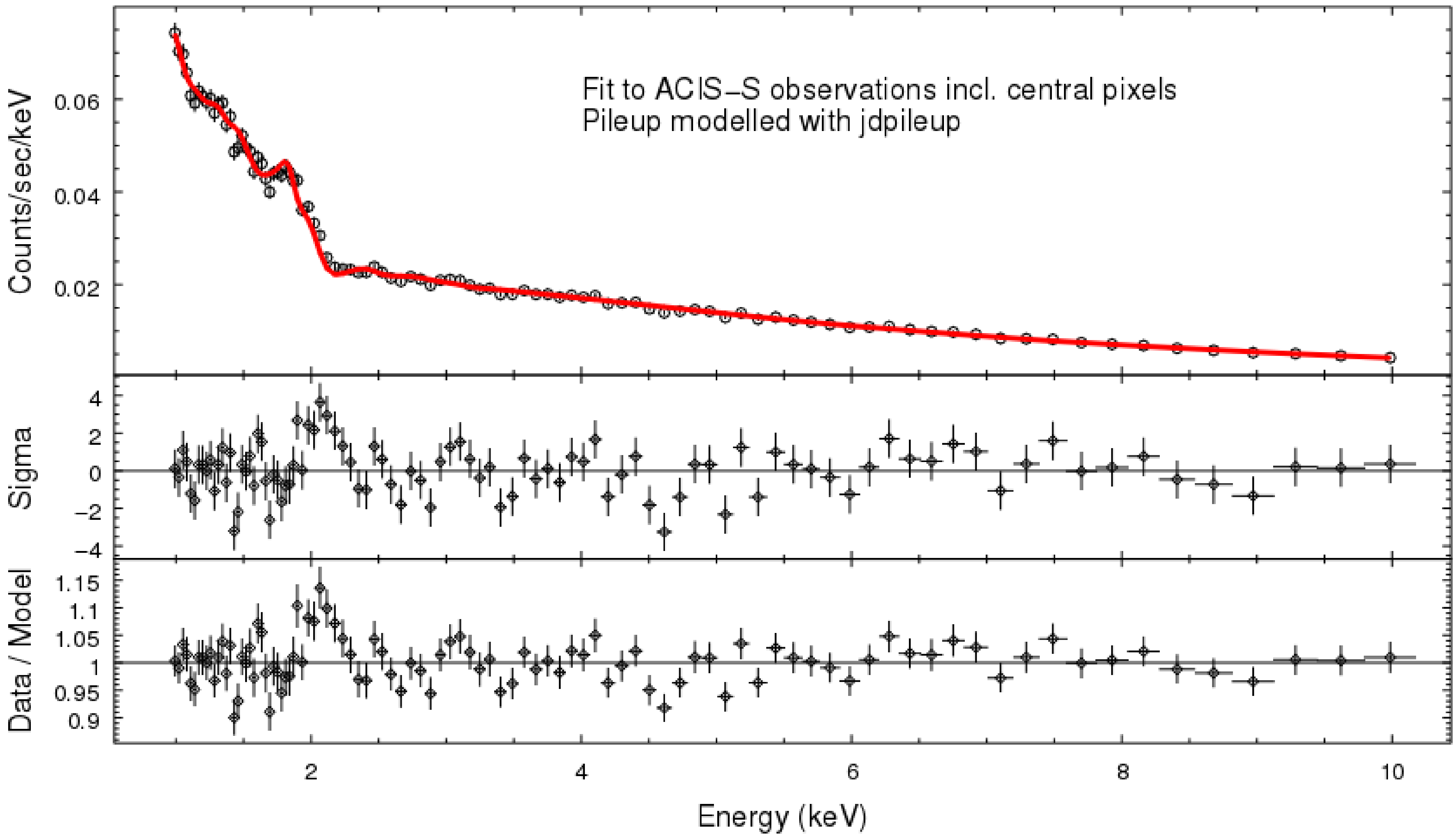


ACIS-I Midway



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

ACIS-S

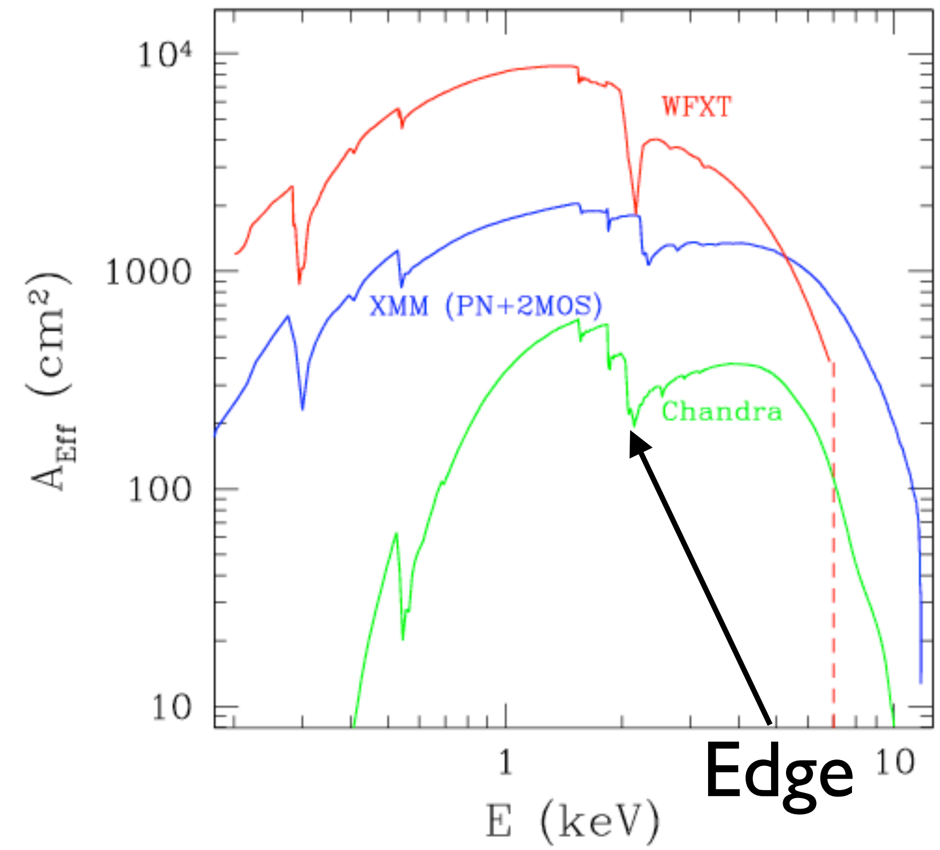


177000 counts, $\gamma = 1.81$, $n_H = 2.6 \cdot 10^{21} \mathrm{cm}^{-2}$, $\mathrm{AGN/Cluster} = 3.7/1$

2.2 keV excess explanations

Instrumental:

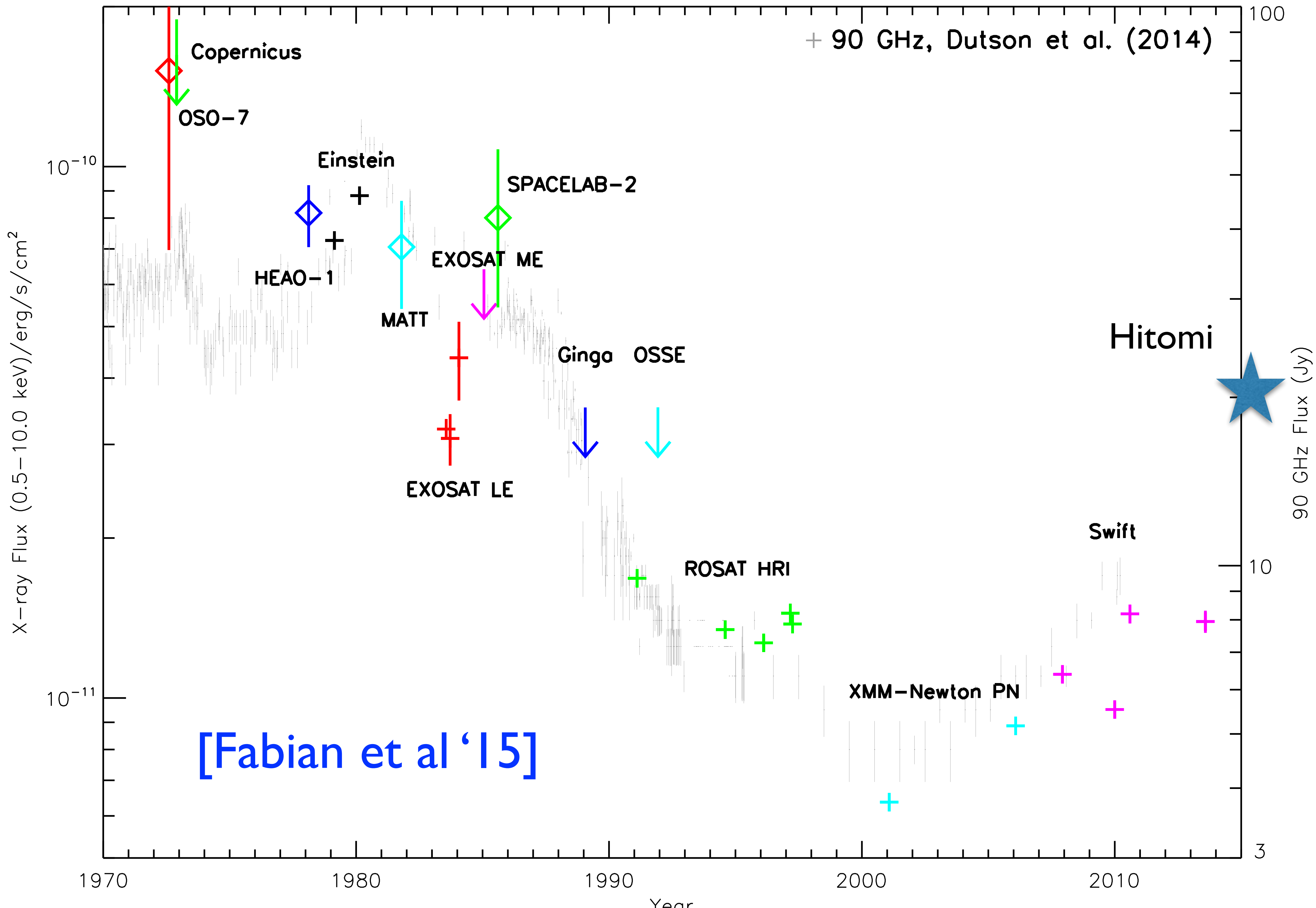
- Effective area miscalibration
- Gain miscalibration



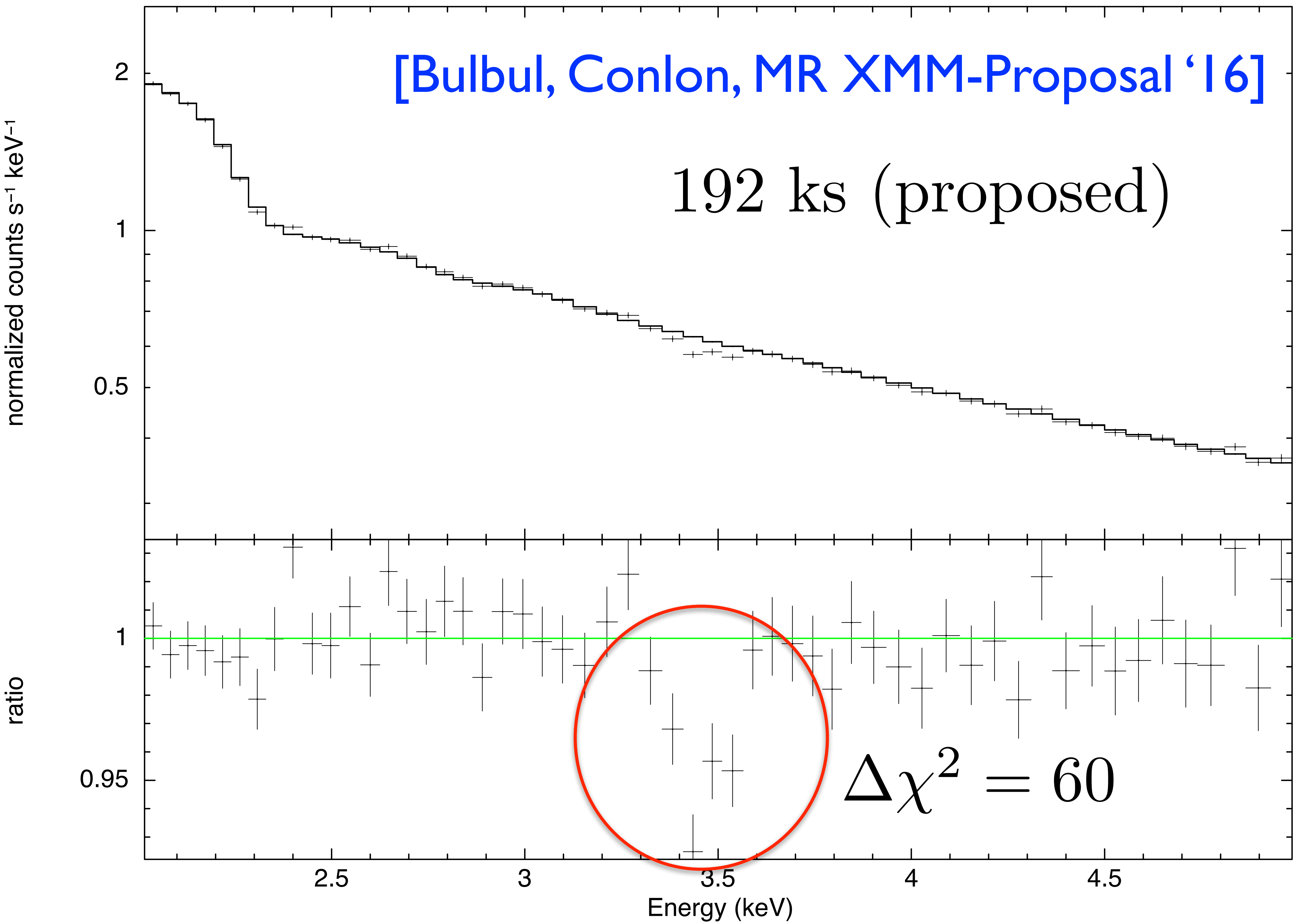
Astrophysical:

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

X-ray variability of NGC1275

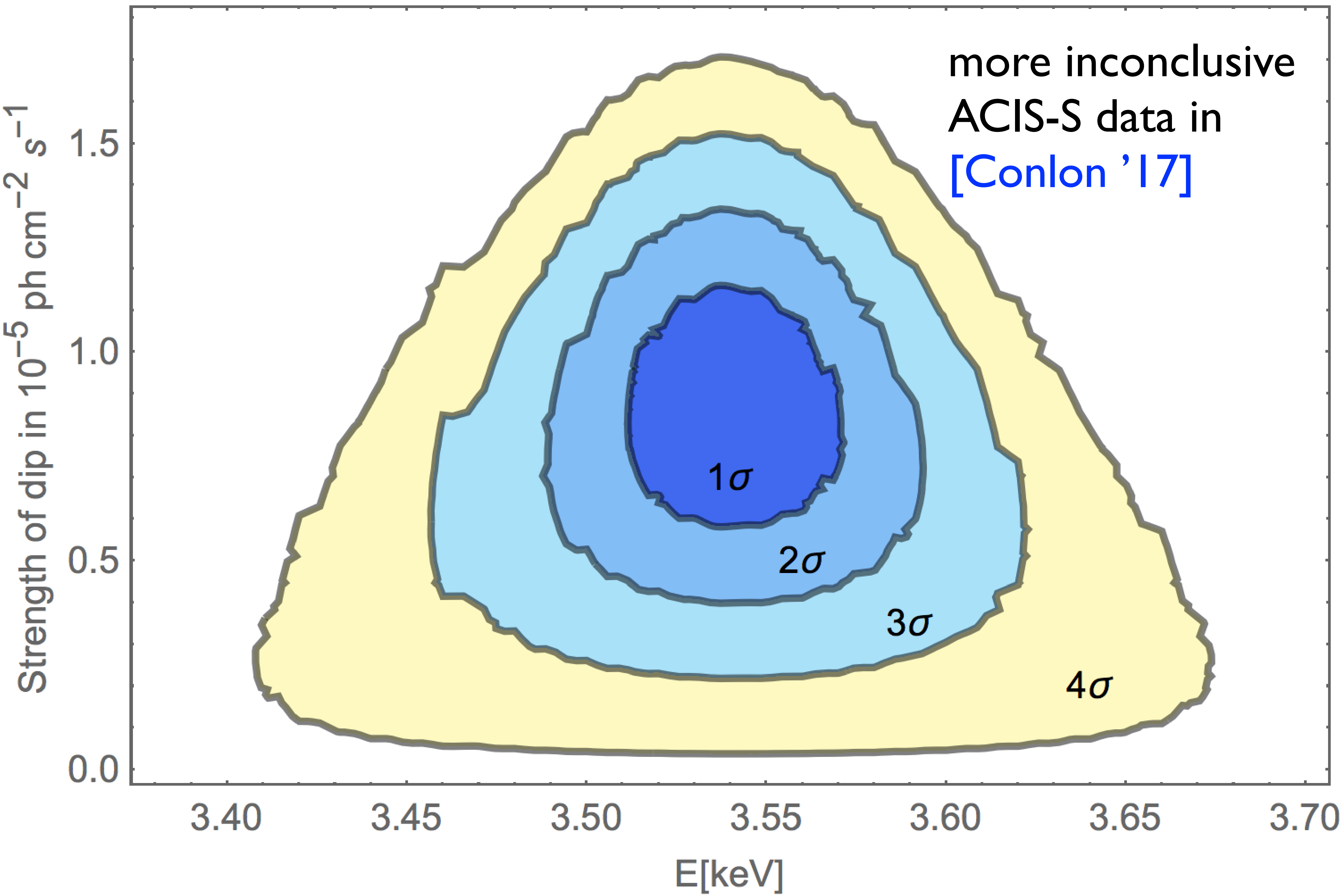


Data Outlook



Closer look at 3.5 keV

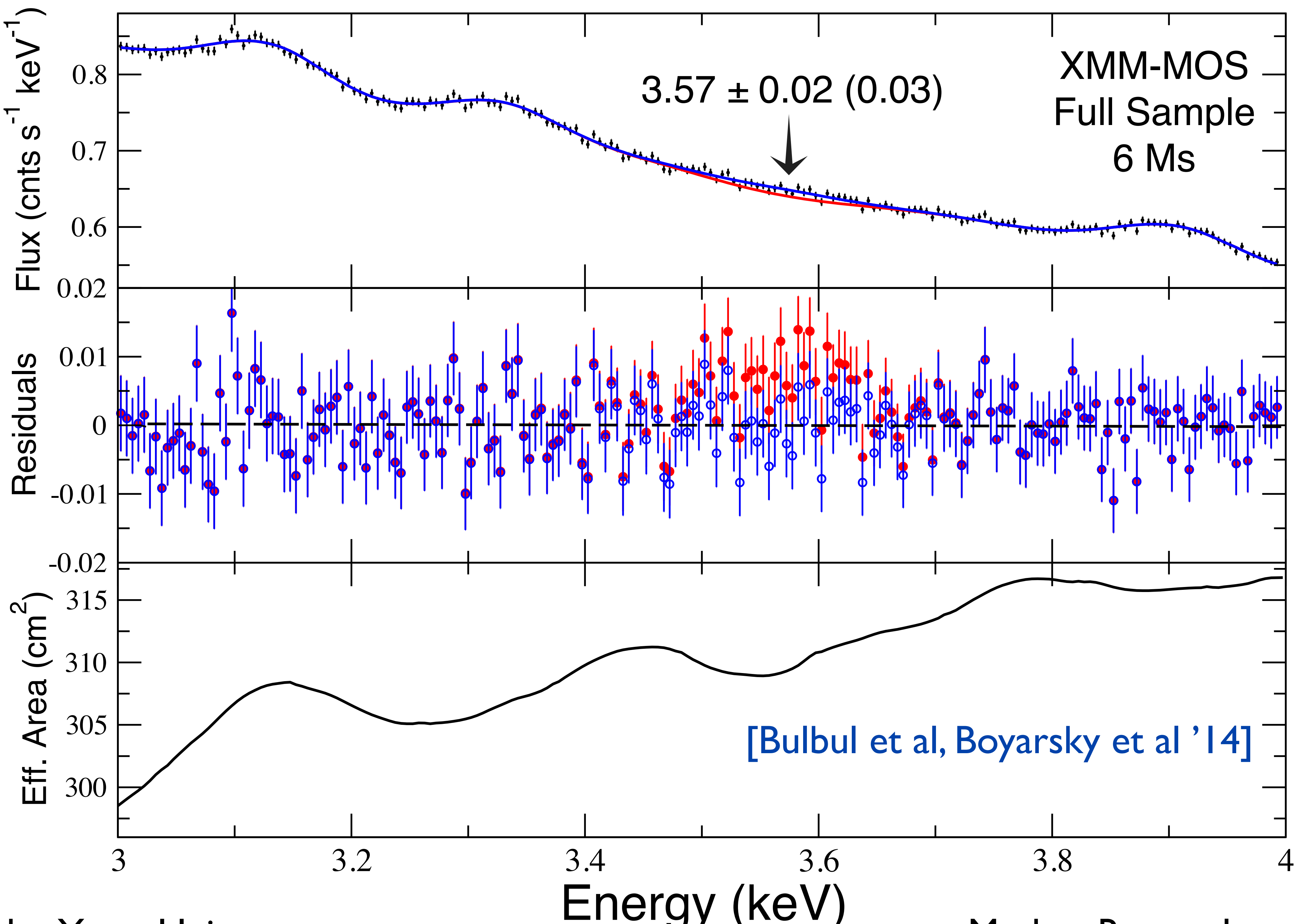
[Conlon, Day, Jennings, Krippendorf, MR '16] edge (least piledup)



more inconclusive ACIS-S data in [Conlon '17]

Closer look at 3.5 keV

Wasn't there something else at 3.5 keV…?

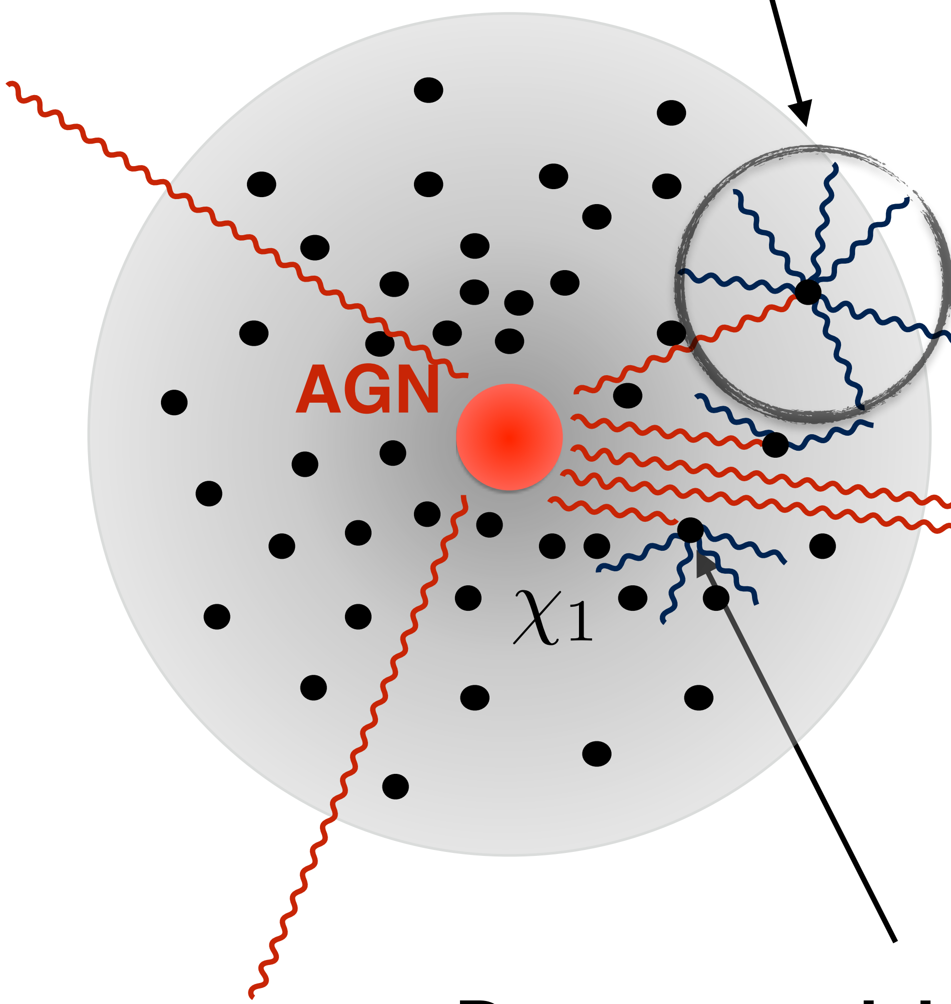


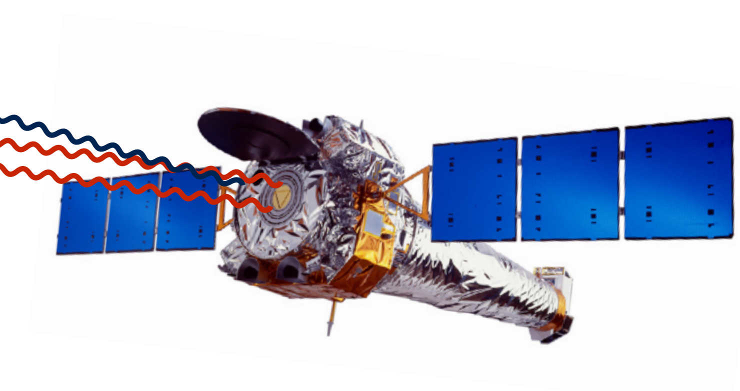
[Bulbul et al, Boyarsky et al '14]

Fluorescent dark matter

[Profumo, Sigurdson '07]

Responsible for line





Responsible for dip

Fluorescent dark matter

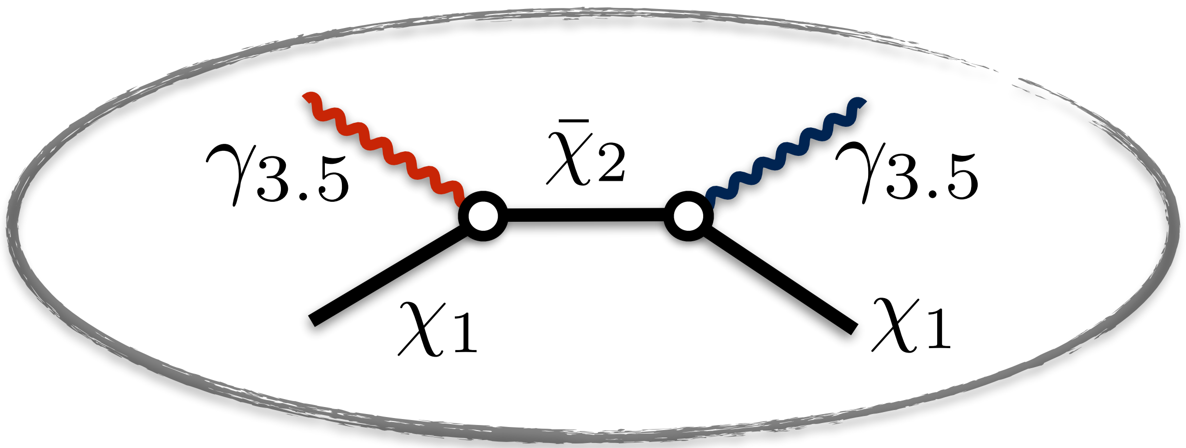
- Chandra sees only absorbed AGN spectrum (dip)
- Hitomi sees sum of diffuse emission + absorbed AGN spectrum (slight dip)
- Observed fluxes are consistent
- Line is broadened by dark matter velocity dispersion

$$v_{DM} \simeq 1300 \text{ km s}^{-1} \Rightarrow \sigma = 15eV$$

- For the cluster gas:

$$v_{\text{Gas}} \simeq 200 \text{ km s}^{-1} \Rightarrow \sigma = 2.4eV$$

Fluorescent dark matter



[D'Eramo, Hableton, Profumo, Stefaniak '16; Conlon, Day, Jennings, Krippendorf, MR '16]

- Simple model: $\mathcal{L} \supset \frac{1}{M}\bar{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$

- Strength of the dip: $\Gamma \geq \left(\frac{m_{DM}}{\mathrm{GeV}}\right) \times 5.8 \times 10^{-10}\mathrm{keV}$

$\Rightarrow$ Strong absorption broadened by DM dispersion

$\Rightarrow$ If real has to be new physics!