SEARCHING FOR ALPS IN GALAXY CLUSTERS

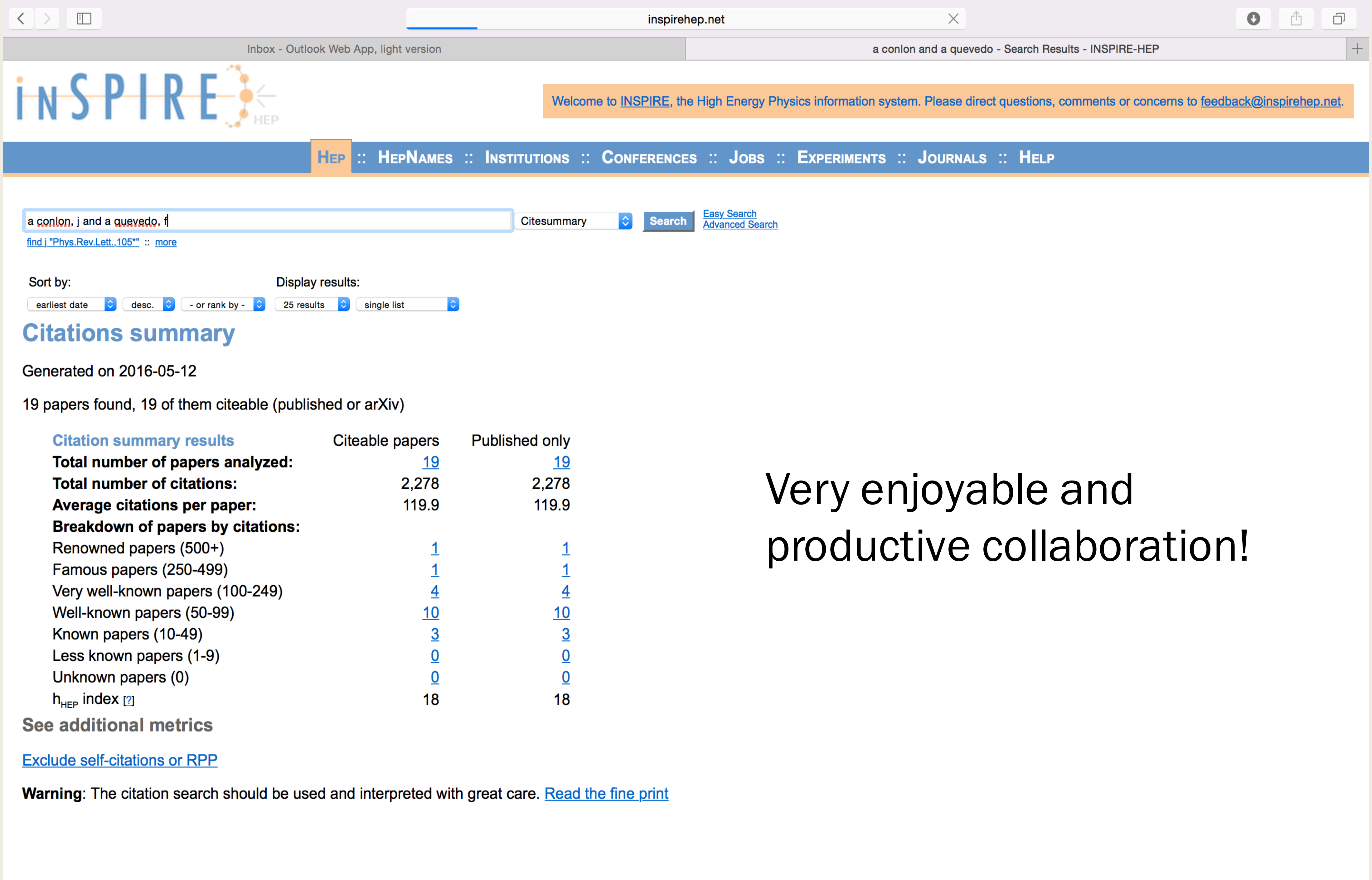
JOSEPH CONLON

QUEVEDO FEST, MAY 2016


EXIT

Happy birthday Fernando!

- Great privilege to have worked with Fernando over a decade
- Lots of fun and lots of learning
- My scientific development owes more to Fernando than I can easily express
- I have been moulded by Fernando’s commitment to string theory as a theory of physics – where physics means experiments and data.
- Fernando is also an extremely good human being,



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a conlon, j and a quevedo, f

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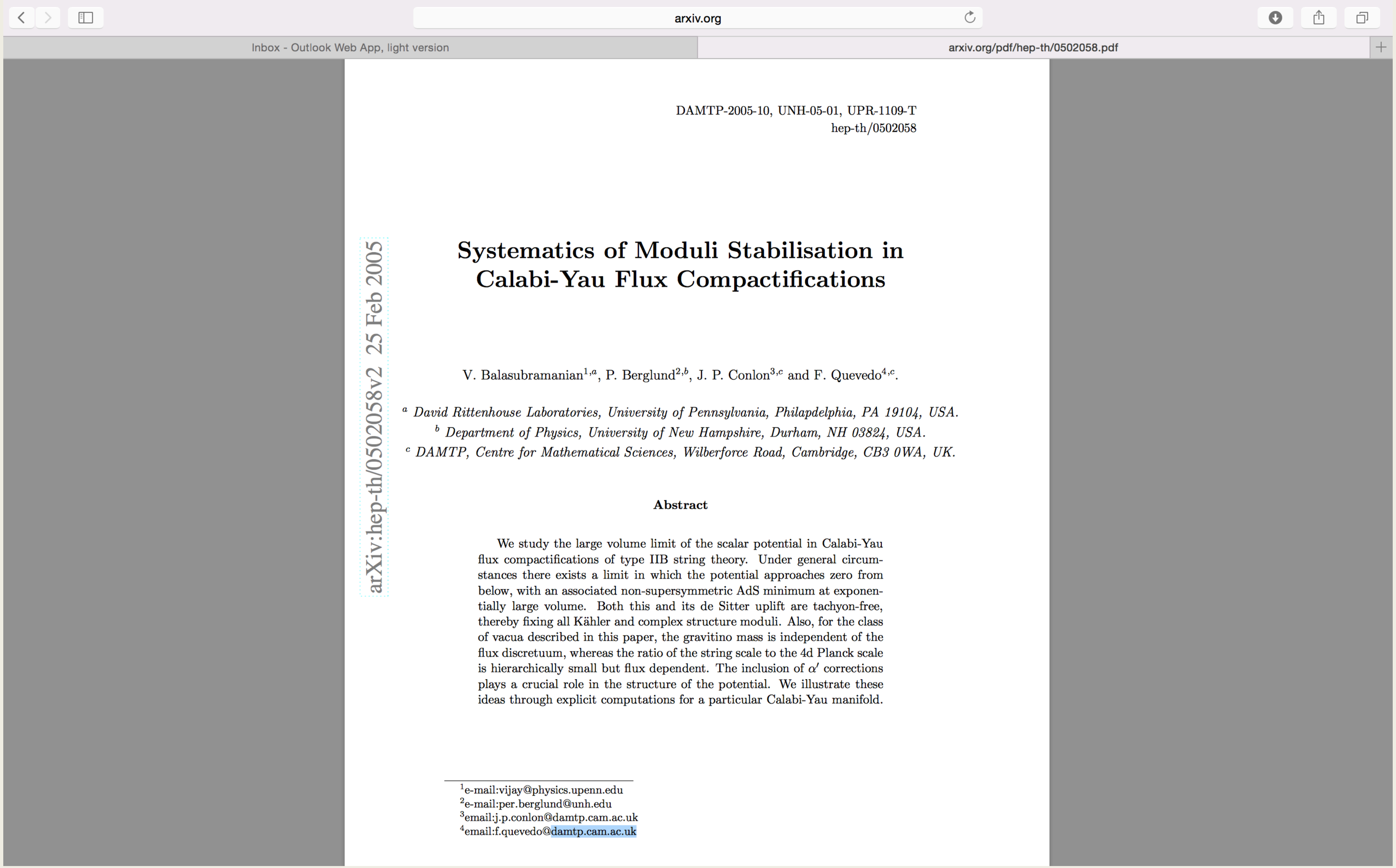
Very enjoyable and productive collaboration!



DAMTP-2005-10, UNH-05-01, UPR-1109-T
hep-th/0502058

Systematics of Moduli Stabilisation in Calabi-Yau Flux Compactifications

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Abstract

We study the large volume limit of the scalar potential in Calabi-Yau flux compactifications of type IIB string theory. Under general circumstances there exists a limit in which the potential approaches zero from below, with an associated non-supersymmetric AdS minimum at exponentially large volume. Both this and its de Sitter uplift are tachyon-free, thereby fixing all Kähler and complex structure moduli. Also, for the class of vacua described in this paper, the gravitino mass is independent of the flux discretuum, whereas the ratio of the string scale to the 4d Planck scale is hierarchically small but flux dependent. The inclusion of α' corrections plays a crucial role in the structure of the potential. We illustrate these ideas through explicit computations for a particular Calabi-Yau manifold.

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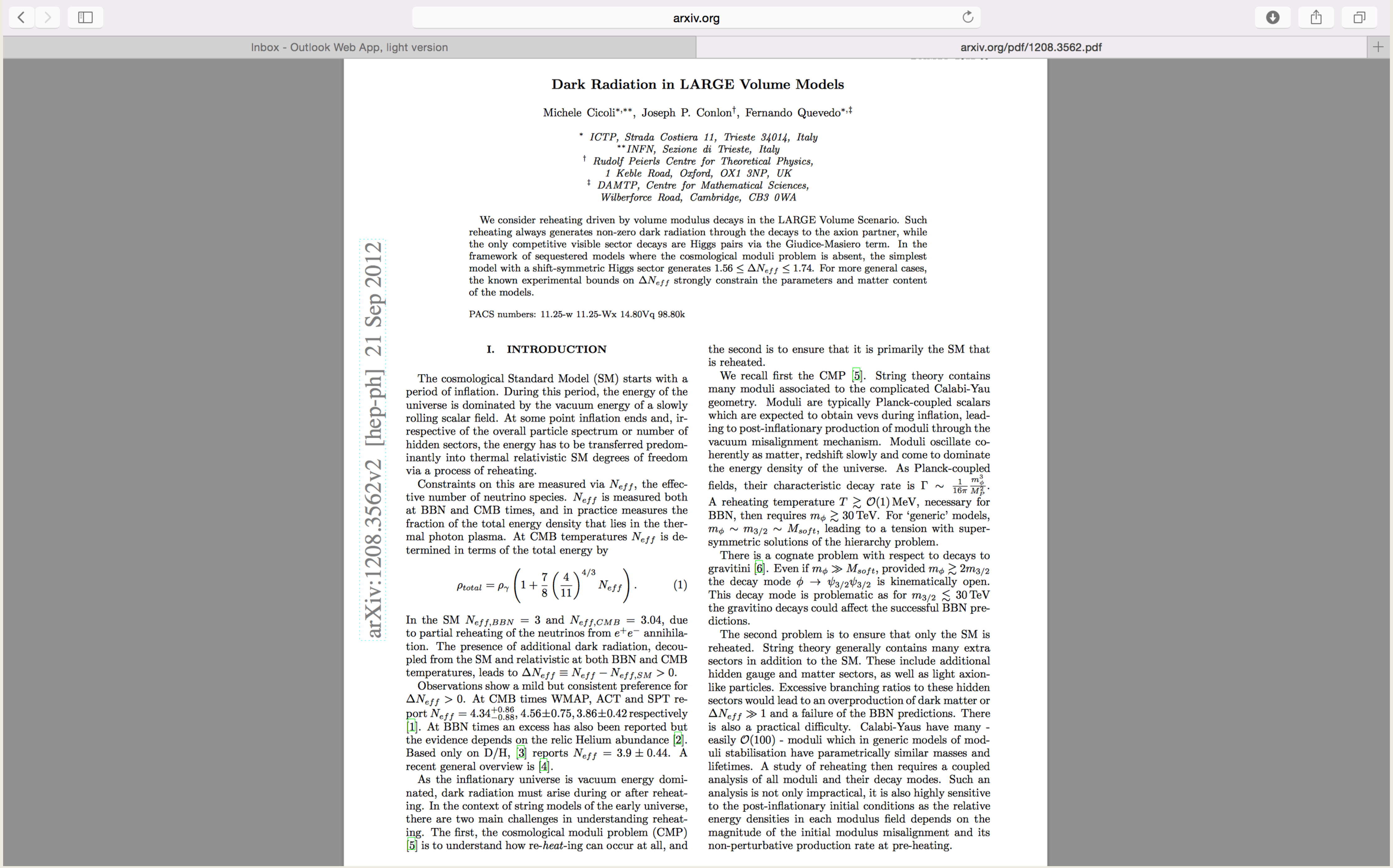

Dark Radiation in LARGE Volume Models

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We consider reheating driven by volume modulus decays in the LARGE Volume Scenario. Such reheating always generates non-zero dark radiation through the decays to the axion partner, while the only competitive visible sector decays are Higgs pairs via the Giudice-Masiero term. In the framework of sequestered models where the cosmological moduli problem is absent, the simplest model with a shift-symmetric Higgs sector generates $1.56 \leq \Delta N_{eff} \leq 1.74$. For more general cases, the known experimental bounds on ΔN_{eff} strongly constrain the parameters and matter content of the models.

PACS numbers: 11.25-w 11.25-Wx 14.80Vq 98.80k

I. INTRODUCTION

The cosmological Standard Model (SM) starts with a period of inflation. During this period, the energy of the universe is dominated by the vacuum energy of a slowly rolling scalar field. At some point inflation ends and, irrespective of the overall particle spectrum or number of hidden sectors, the energy has to be transferred predominantly into thermal relativistic SM degrees of freedom via a process of reheating.

Constraints on this are measured via N_{eff}, the effective number of neutrino species. N_{eff} is measured both at BBN and CMB times, and in practice measures the fraction of the total energy density that lies in the thermal photon plasma. At CMB temperatures N_{eff} is determined in terms of the total energy by

$$\rho_{total} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right). \qquad (1)$$

In the SM $N_{eff,BBN} = 3$ and $N_{eff,CMB} = 3.04$, due to partial reheating of the neutrinos from e^+e^- annihilation. The presence of additional dark radiation, decoupled from the SM and relativistic at both BBN and CMB temperatures, leads to $\Delta N_{eff} \equiv N_{eff} - N_{eff,SM} > 0$.

Observations show a mild but consistent preference for $\Delta N_{eff} > 0$. At CMB times WMAP, ACT and SPT report $N_{eff} = 4.34^{+0.86}_{-0.88}, 4.56 \pm 0.75, 3.86 \pm 0.42$ respectively [1]. At BBN times an excess has also been reported but the evidence depends on the relic Helium abundance [2]. Based only on D/H, [3] reports $N_{eff} = 3.9 \pm 0.44$. A recent general overview is [4].

As the inflationary universe is vacuum energy dominated, dark radiation must arise during or after reheating. In the context of string models of the early universe, there are two main challenges in understanding reheating. The first, the cosmological moduli problem (CMP) [5] is to understand how re-*heat*-ing can occur at all, and the second is to ensure that it is primarily the SM that is reheated.

We recall first the CMP [5]. String theory contains many moduli associated to the complicated Calabi-Yau geometry. Moduli are typically Planck-coupled scalars which are expected to obtain vevs during inflation, leading to post-inflationary production of moduli through the vacuum misalignment mechanism. Moduli oscillate coherently as matter, redshift slowly and come to dominate the energy density of the universe. As Planck-coupled fields, their characteristic decay rate is $\Gamma \sim \frac{1}{16\pi}\frac{m_\phi^3}{M_P^2}$. A reheating temperature $T \gtrsim \mathcal{O}(1)\,\text{MeV}$, necessary for BBN, then requires $m_\phi \gtrsim 30\,\text{TeV}$. For 'generic' models, $m_\phi \sim m_{3/2} \sim M_{soft}$, leading to a tension with supersymmetric solutions of the hierarchy problem.

There is a cognate problem with respect to decays to gravitini [6]. Even if $m_\phi \gg M_{soft}$, provided $m_\phi \gtrsim 2m_{3/2}$ the decay mode $\phi \rightarrow \psi_{3/2}\psi_{3/2}$ is kinematically open. This decay mode is problematic as for $m_{3/2} \lesssim 30\,\text{TeV}$ the gravitino decays could affect the successful BBN predictions.

The second problem is to ensure that only the SM is reheated. String theory generally contains many extra sectors in addition to the SM. These include additional hidden gauge and matter sectors, as well as light axion-like particles. Excessive branching ratios to these hidden sectors would lead to an overproduction of dark matter or $\Delta N_{eff} \gg 1$ and a failure of the BBN predictions. There is also a practical difficulty. Calabi-Yaus have many - easily $\mathcal{O}(100)$ - moduli which in generic models of moduli stabilisation have parametrically similar masses and lifetimes. A study of reheating then requires a coupled analysis of all moduli and their decay modes. Such an analysis is not only impractical, it is also highly sensitive to the post-inflationary initial conditions as the relative energy densities in each modulus field depends on the magnitude of the initial modulus misalignment and its non-perturbative production rate at pre-heating.

~~SEARCHING FOR~~ FINDING ALPS IN GALAXY CLUSTERS

JOSEPH CONLON
QUEVEDO FEST, MAY 2016

My collaborators!

- This talk is directly based on 1605.01034 (with Marcus Berg, Francesca Day, Nicholas Jennings, Sven Krippendorf, Andrew Powell, Markus Rummel)
- I also acknowledge much previous collaboration on the physics of ALPs in galaxy clusters, particularly with David Marsh
- My interest in ALPs arose from understanding the low-energy phenomenology of the Large Volume Scenario, and the desire to connect string theory to experiment.

- The method described is very similar to previous work by Wouters and Brun 1304.0989 – but they use a much less luminous AGN (data sample less than 1% of that presented here)

Axion-like particles

- Light axion-like particles (ALPs) are one of the most motivated ways to extend the Standard Model
- They arise generically in string theory – e.g. a light ALP is always present in the Large Volume Scenario.
- Phenomenologically, they are parametrised by the coupling

$$a\ g_{a\gamma\gamma}\mathbf{E.B} \equiv \frac{\boldsymbol{a}}{\boldsymbol{M}}\mathbf{E.B}$$

- In the presence of a background **B** field, the ALP a and photon γ eigenstates mix, leading to photon-ALP oscillations (cf neutrino oscillations)

How to search for ALPs?

- The basic physics underlying this talk 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.

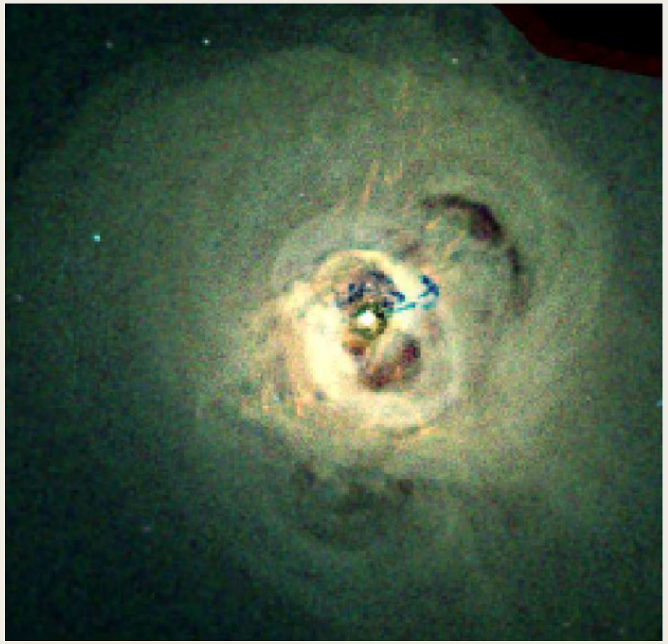
- In our case, the source A is the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope

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

NGC 1275

- NGC1275 is the central galaxy of the Perseus cluster
- At its centre is a very bright AGN, powered by accretion onto the supermassive black hole.
- The brightness of NGC1275 is time-variable (1980 brightness was 20x bigger than in 2001, progressive increase in brightness since 2001)
- AGN is unobscured, shining to us through the Perseus galaxy cluster



AGNs are point sources

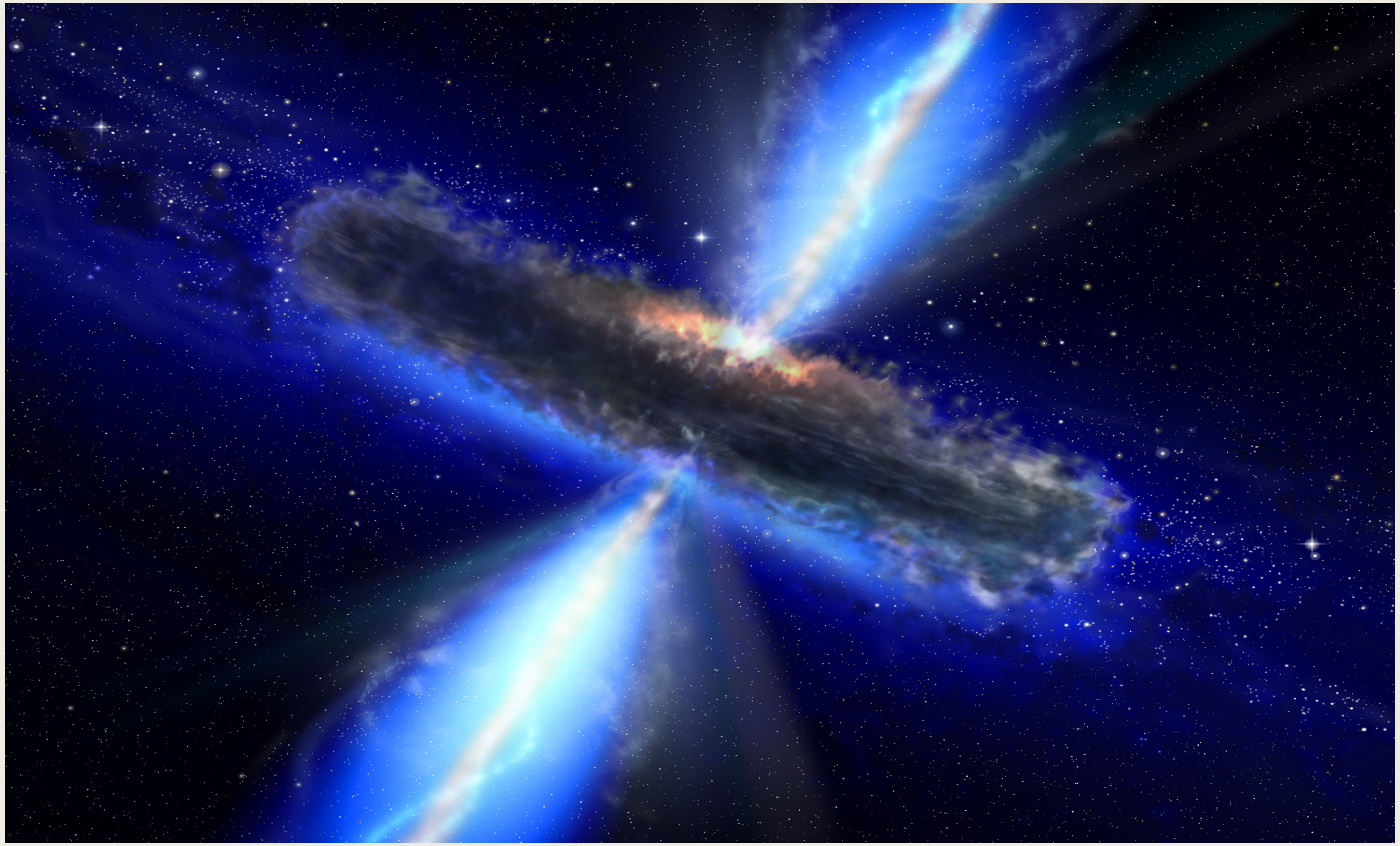
- X-ray emission from AGNs comes from extremely small physical region
- We know this because of the time variability observed in AGN: AGN intensities can vary on day timescales, implying emission originates
- Various observations imply X-ray emission comes from innermost region of accretion disc, a few Schwarschild radii of black hole.
- 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: the standard Unified Model

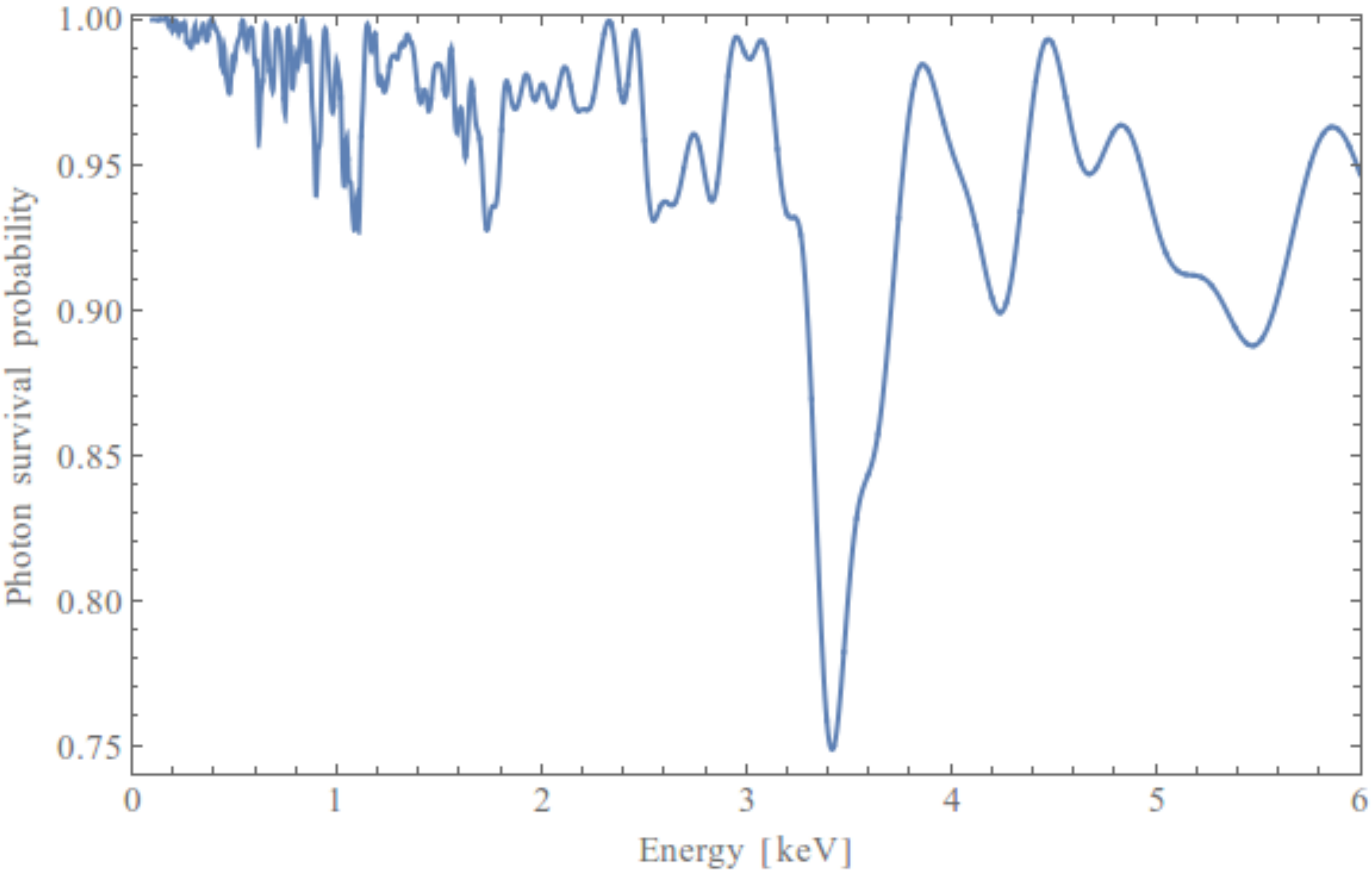


Credit ESA/NASA, AVO project, Paolo Padavani

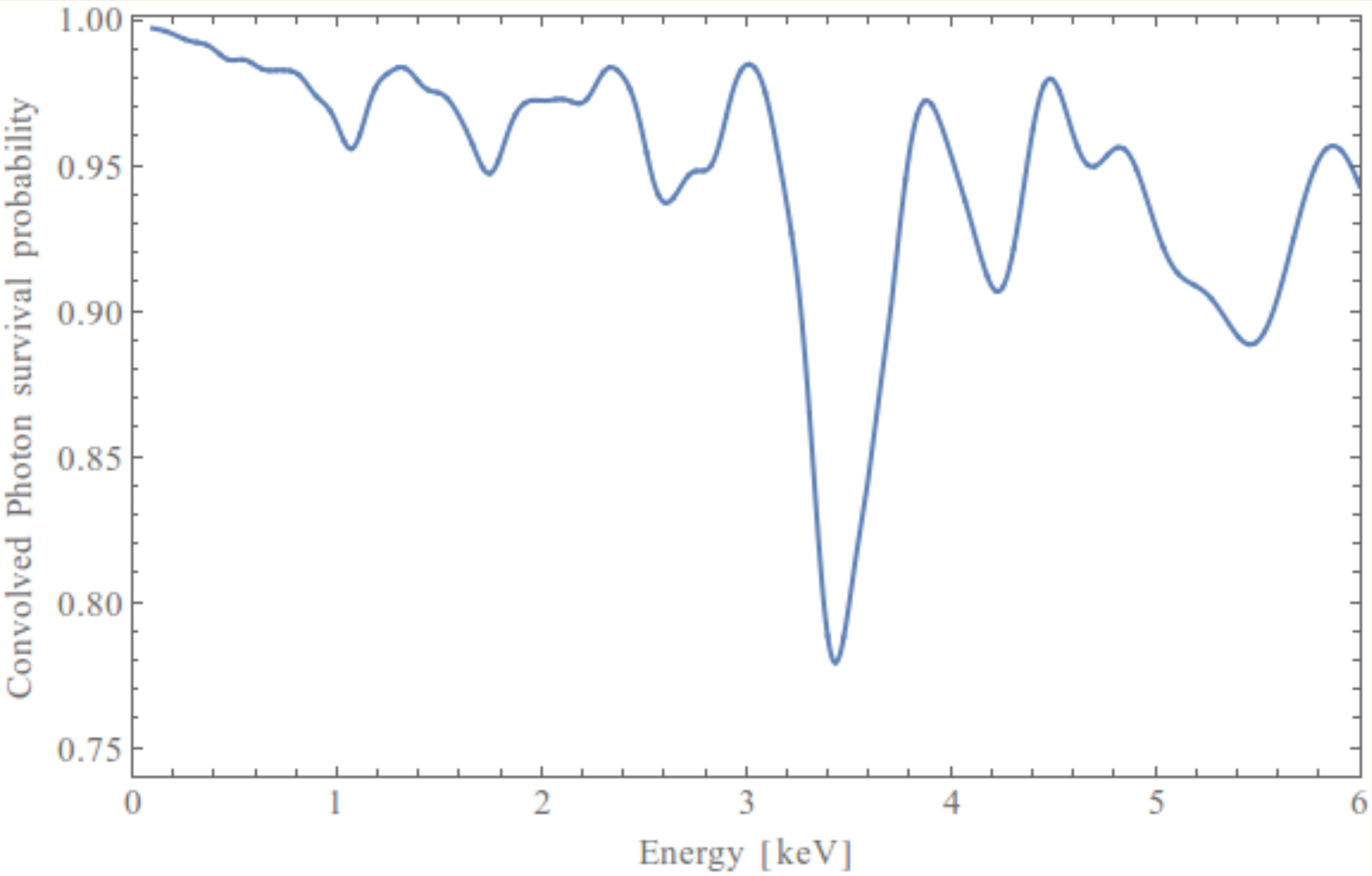
Photon-ALP Conversion

- Source is NGC1275, destination is earth: intervening magnetic field is the magnetic field of the Perseus cluster.
- Galaxy clusters are particularly good location 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.
- Allowed values of photon-ALP coupling $g_{a\gamma\gamma}$ can lead to conversion probabilities of order 10 – 50%.
- No detailed knowledge of exact value of Perseus magnetic field; central value should be in range 10 – 25 microGauss.

Simulated photon survival probability…

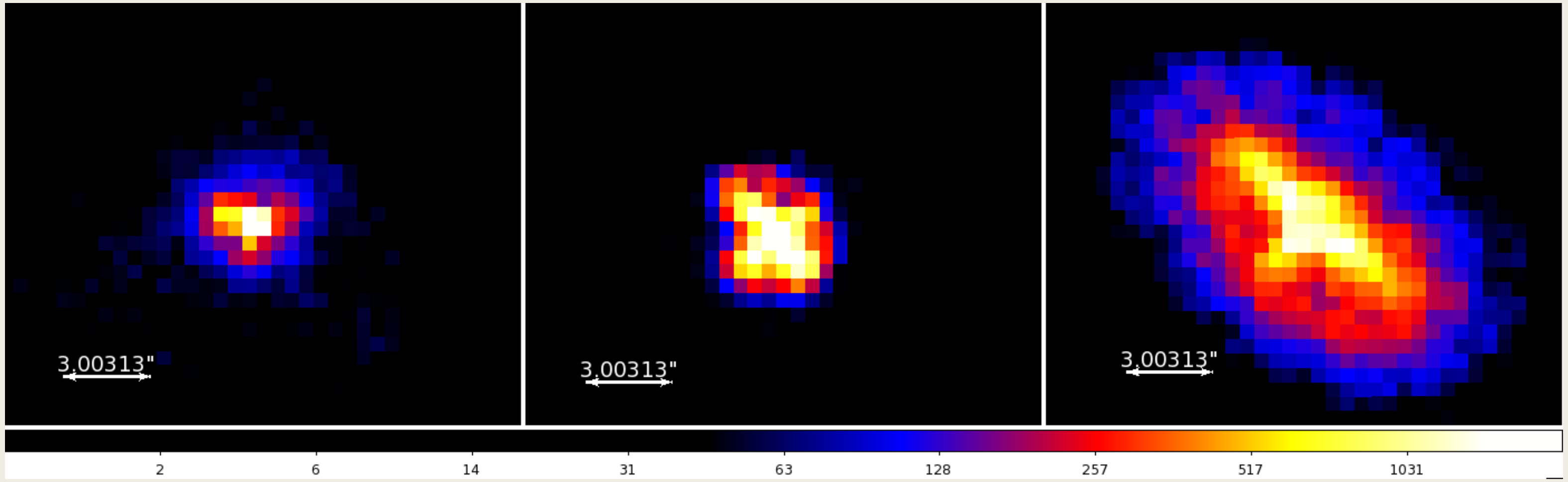


…now convolved with detector resolution



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.
- We treat these three 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.



The Observations

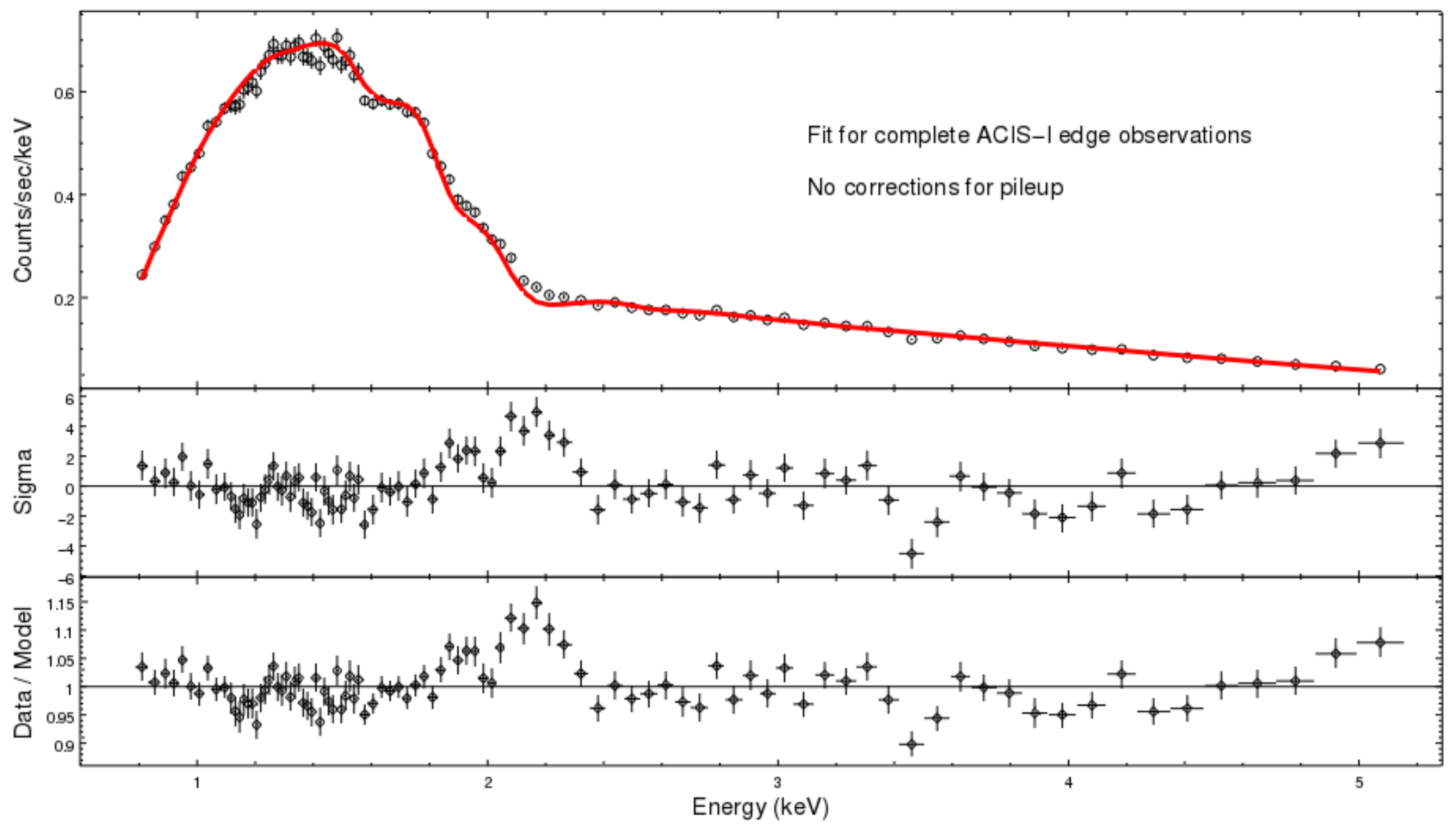
- We extract the AGN spectrum and subtract nearby cluster emission for background.
- We then fit the AGN spectrum between 0.8 and 5 keV with an absorbed power law, supplemented if necessary by a soft thermal component.
- We then examine these spectra and look for residuals
- Counts are grouped so that there are approximately one hundred bins in total
- Total counts from AGN is

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

2. 242000 for 2009 ACIS-I ‘midway’ observations

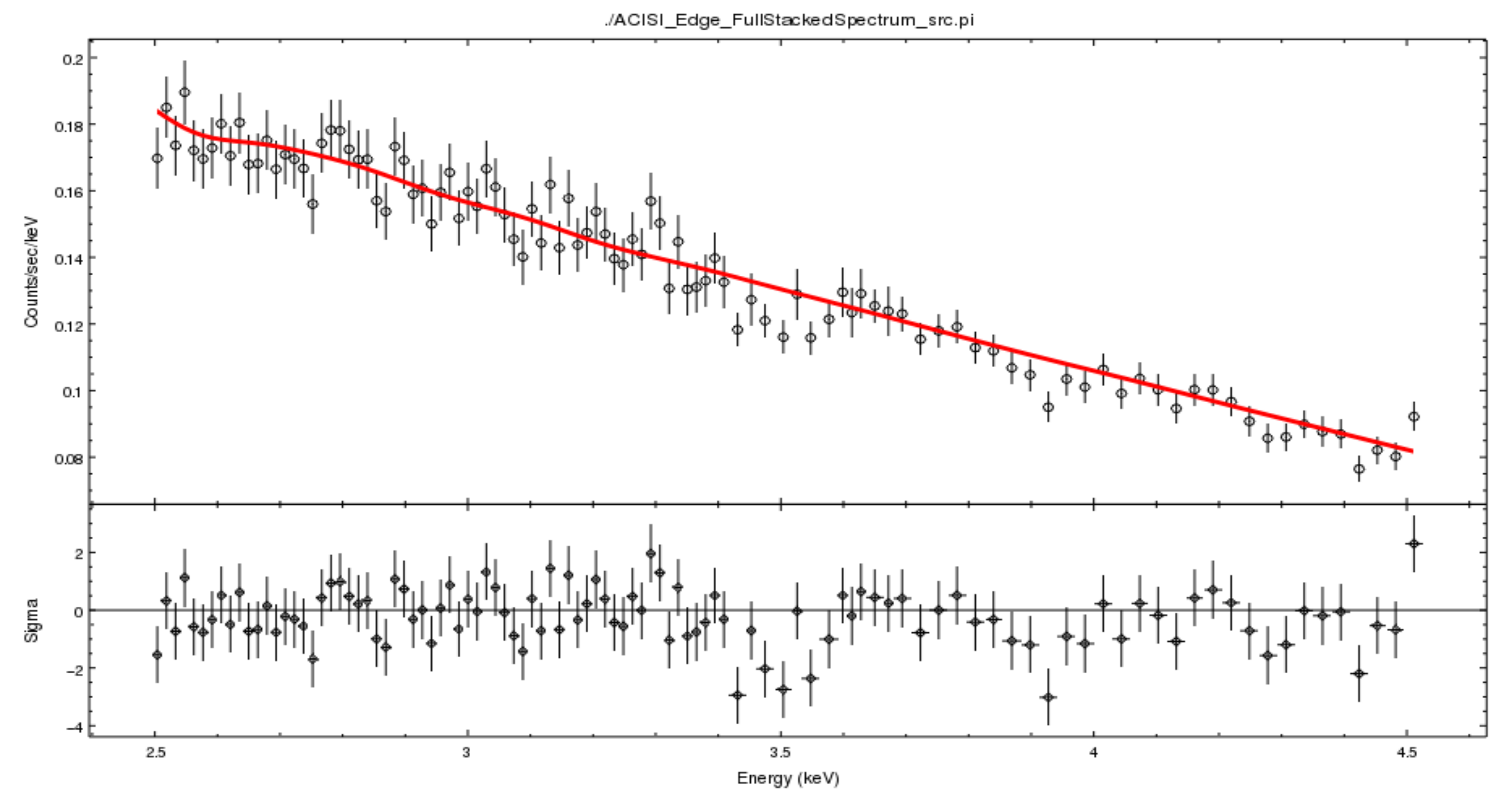
3. 183000 for 2002-4 ACIS-S on-axis observations

Complete extraction for ACIS-I edge



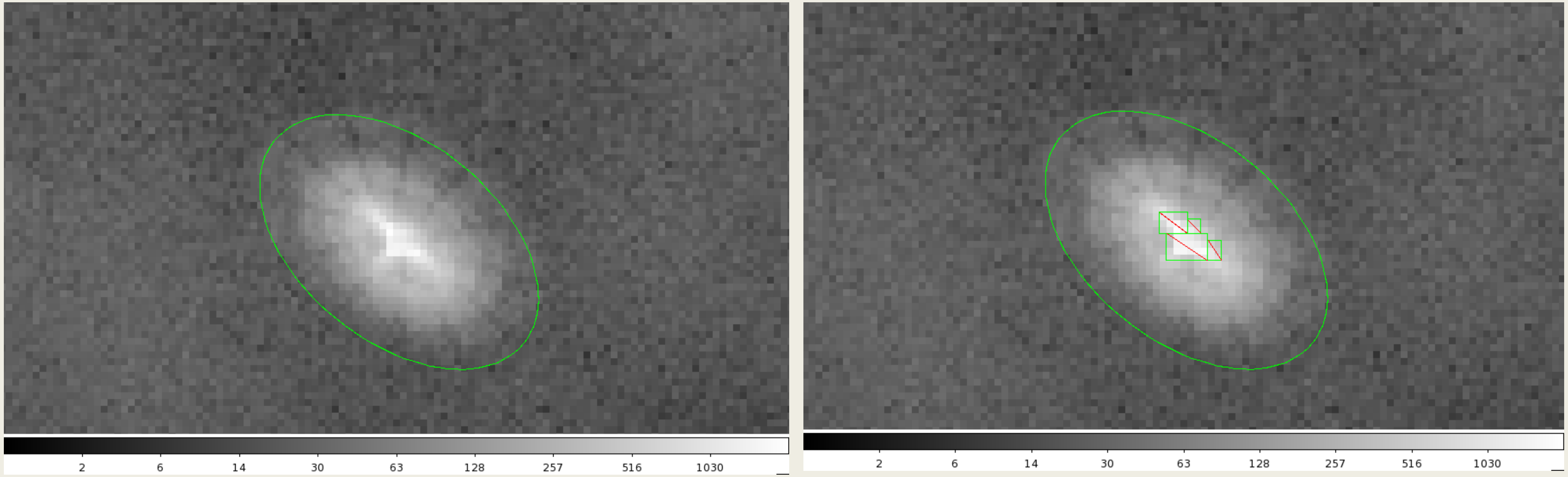
At 2 – 2.2 keV: five data points in a row 3-5 sigma high
At 3.4 – 3.5 sigma: two data points low, 4.5, 2.6 sigma

Zoom-in on 3.5 keV region



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

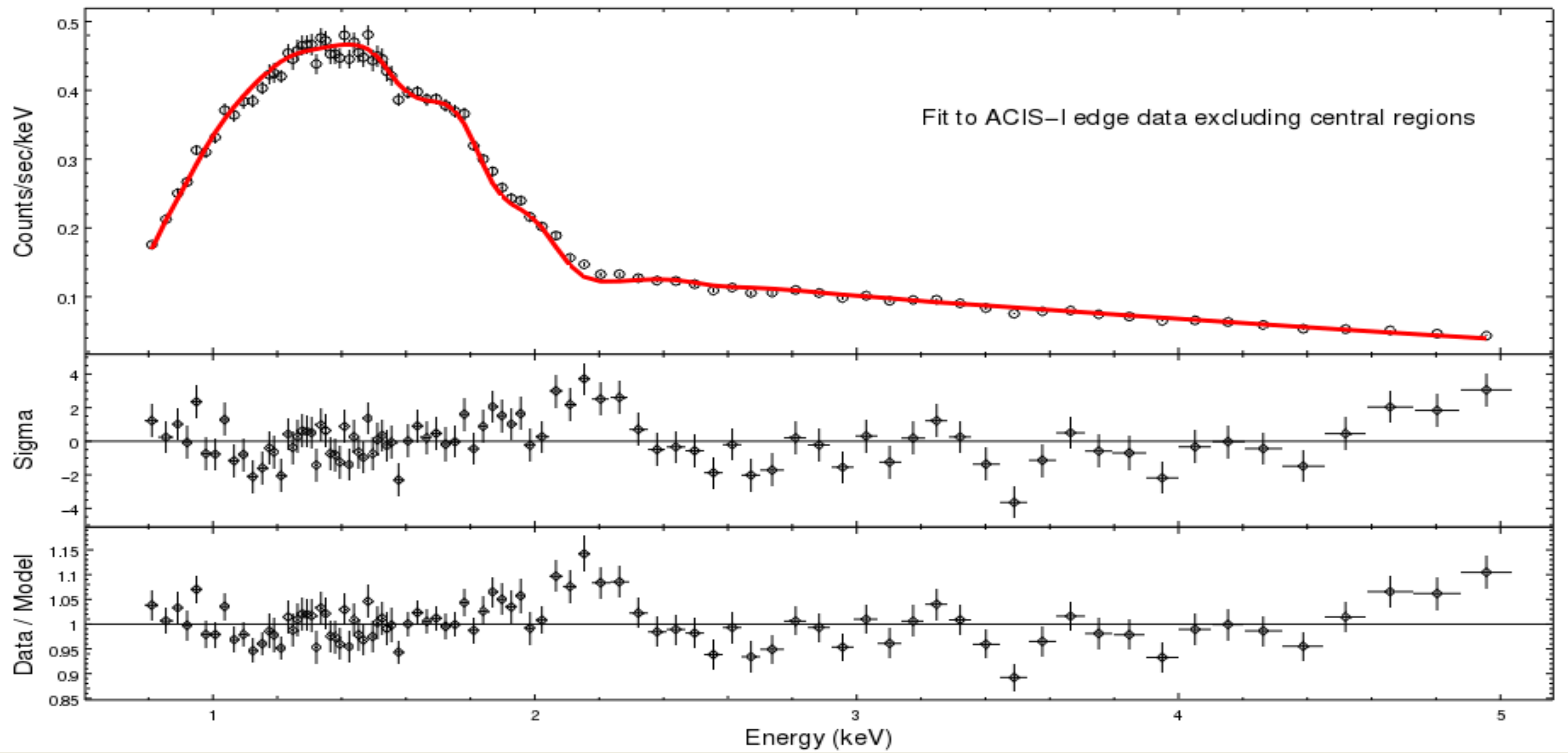
- Care is needed with pileup as 2 – 2.2 keV region is near a detector feature
- Do features arises from pileup (arrival of multiple photons in a single readout time)?
- We clean the spectrum by removing central regions of highest pile-up.



Cleaned spectrum has same features: excess at 2 – 2.2keV and deficit at 3.4 – 3.5 keV

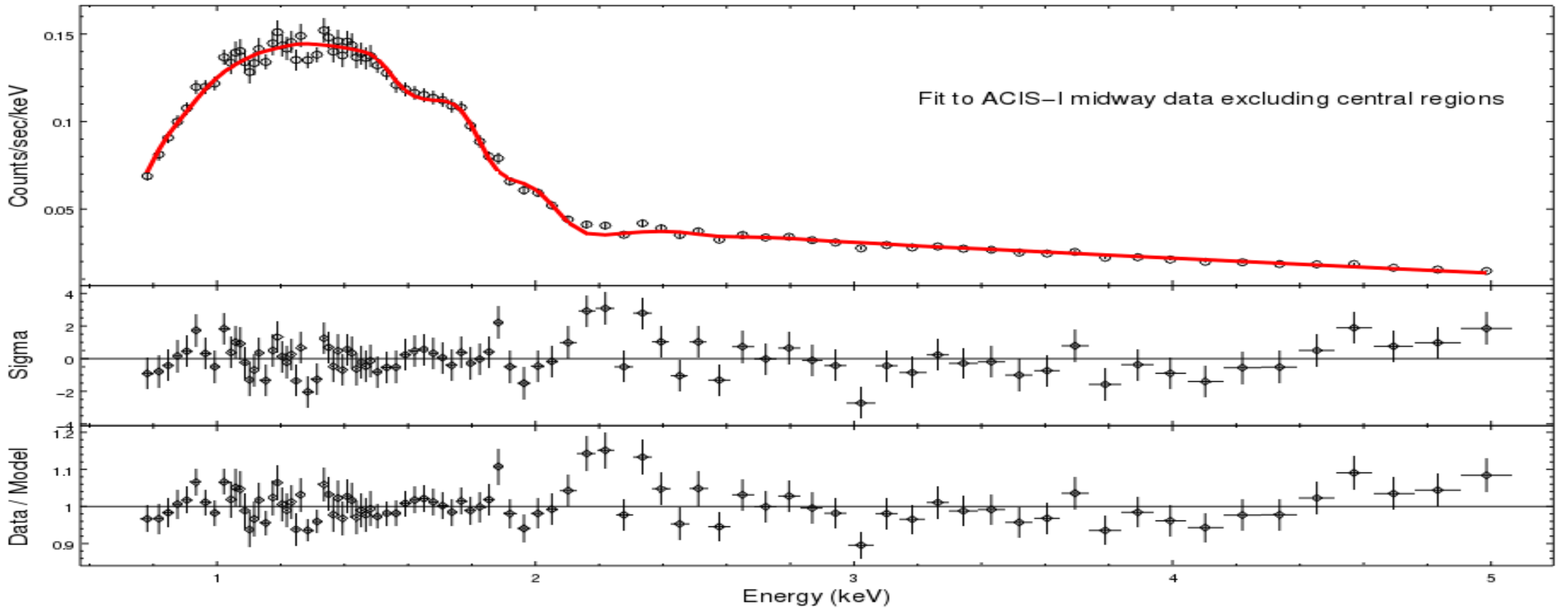
1. Statistical significance reduces slightly (consistent with reduction in the amount of data)

2. *Magnitude* of excess remains the same (data/model ratio) – suggesting pile-up is not the origin.



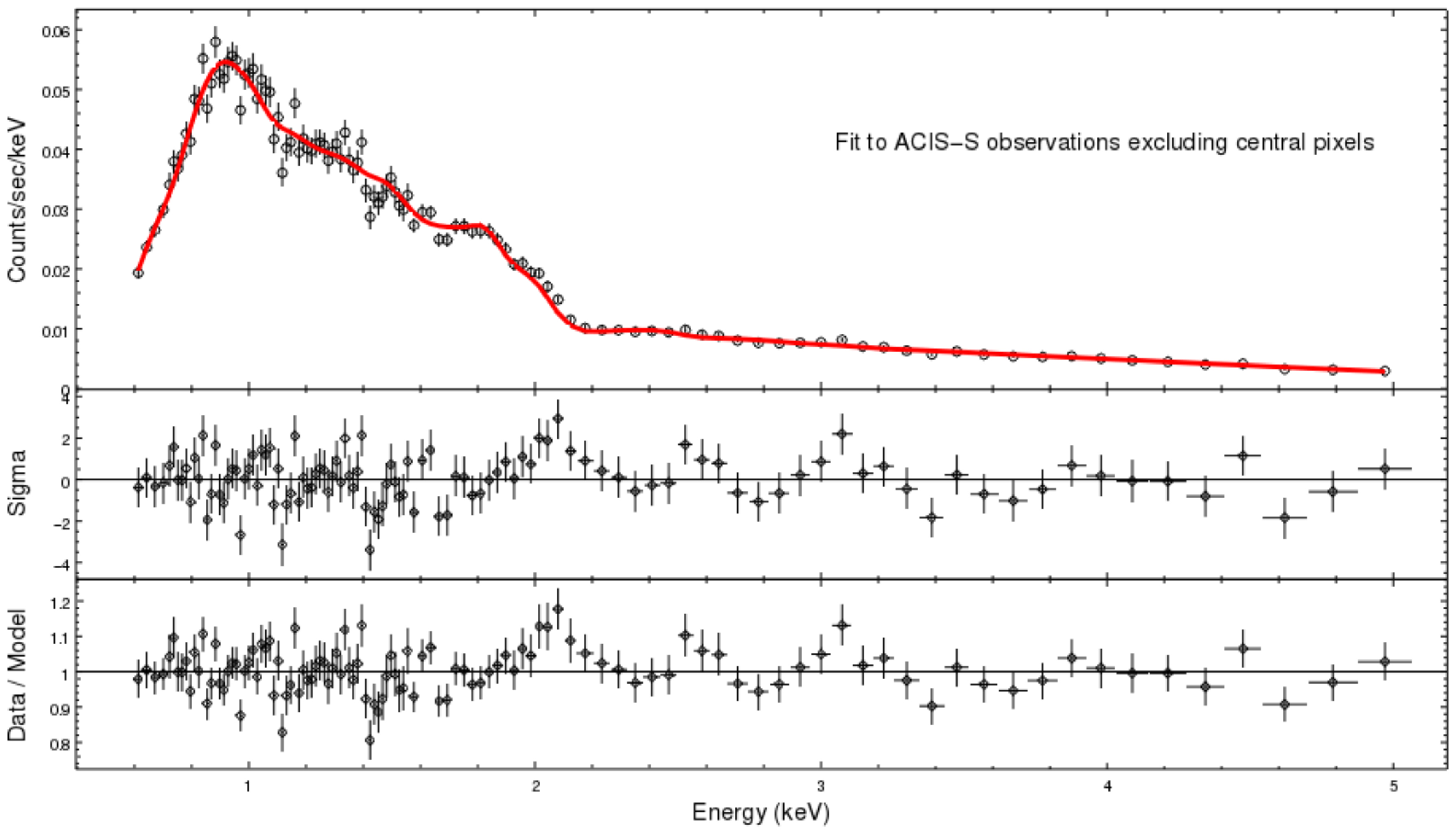
2009 ACIS-I midway data is consistent with clear feature near 2 keV.

Statistical significance reduces with less data (over 50% less once cleaned than for ACIS-I edge data)



2002-4 cleaned ACIS-S observations are all also consistent

Excess at 2 – 2.2 keV and deficit at 3.4 keV



Basic 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

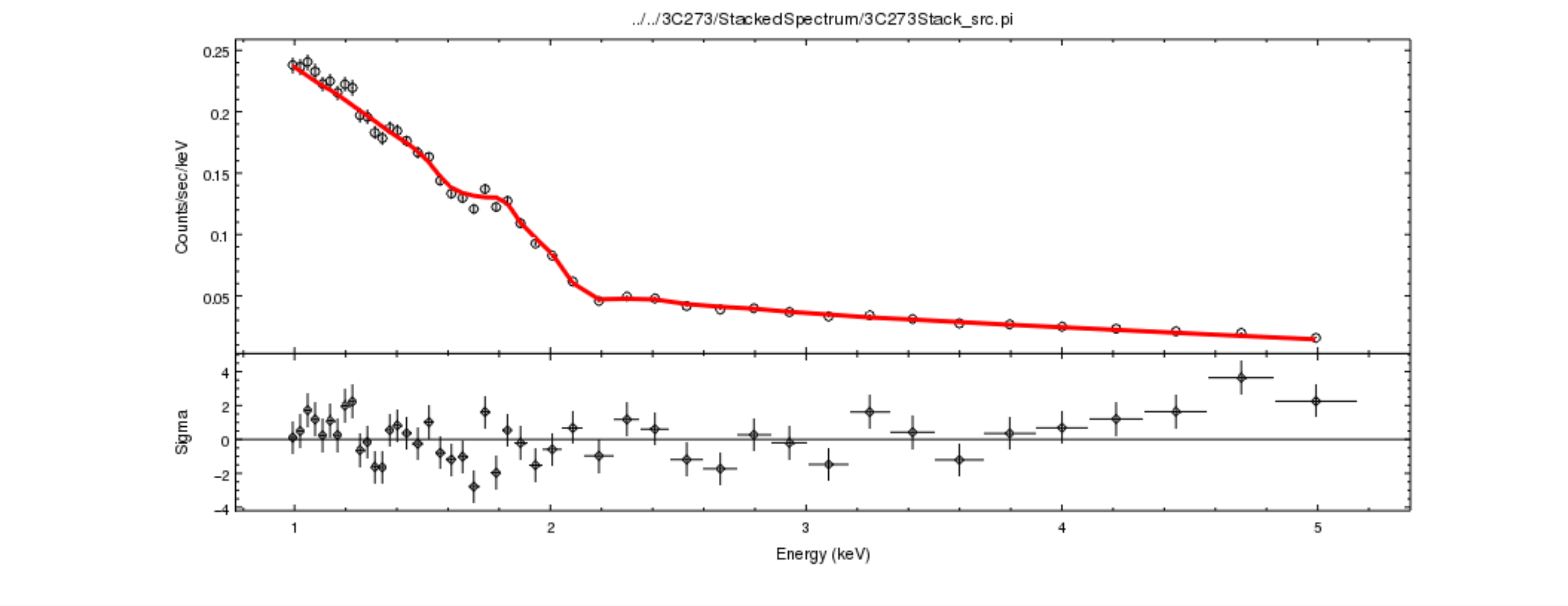
  2. Deficit at approx 5- 10% level in 3.4 – 3.5 keV region

- *Statistical* significance of 2 – 2.2 keV excess is overwhelming (far beyond 5 sigma)
- *Statistical* significance of 3.4 – 3.5 keV deficit is 'only' around 5 sigma
- High statistical significance means think hard about systematic / instrumental effects

Quick summary of systematics

- Pileup – but magnitude of excess is the same across different spectra on different instruments with widely differing levels of pileup
- Effective area miscalibration – but excess is not present in the background spectra,
- Missubtraction 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
- Miscalibration of gain in high-flux regions – but level of flux is very different in the different spectra, and features remain at consistent level.
- Emission line (2 – 2.2 keV) from soft thermal component – no plausible lines in relevant region
- Absorption line (3.4 - 3.5 keV) – no plausible lines, absorption comes from Milky Way, no absorption seen in diffuse cluster spectra
- Fluorescent emission (2 – 2.2keV) from S Kα line at 2.31 keV – energy too high and line not strong enough

Spectrum from bright quasar 3C273



Extracted in similar way to ACIS-S observations, but no excesses seen

New Physics Interpretations

- ALPs – can explain and generate modulations for $g_{a\gamma\gamma}$ in $1\ -5\times10^{-12}GeV^{-1}$ region
- For 3.4 – 3.5 keV deficit, can also consider a dark matter absorption line

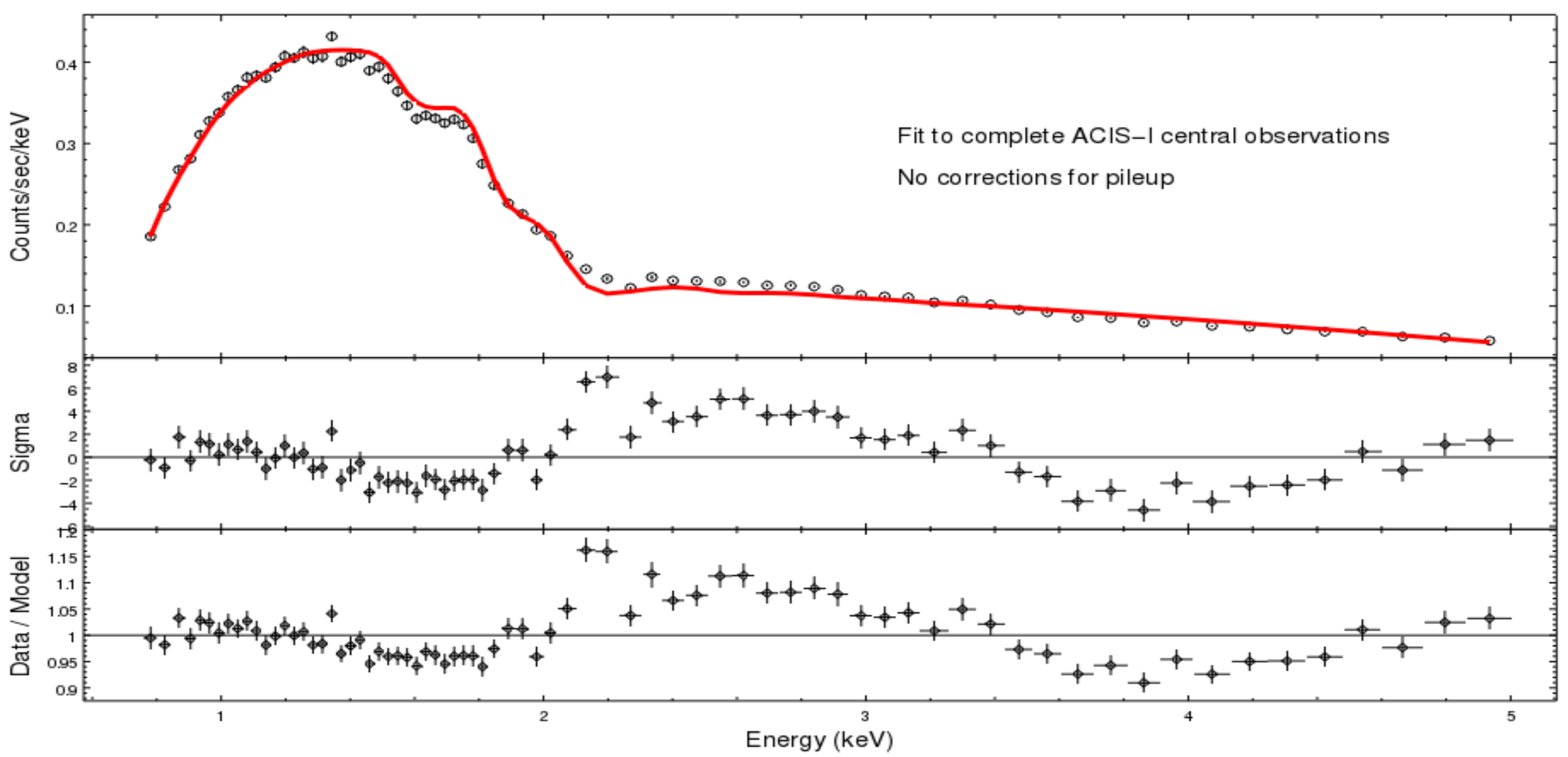
  1. Relevant for models of excited dark matter used to explain 3.5 keV cluster emission line

  2. Dark matter column density along line of sight to NGC1275 is higher than almost anywhere else
- Perhaps *Hitomi* observation of Perseus centre will add more useful information

Conclusions

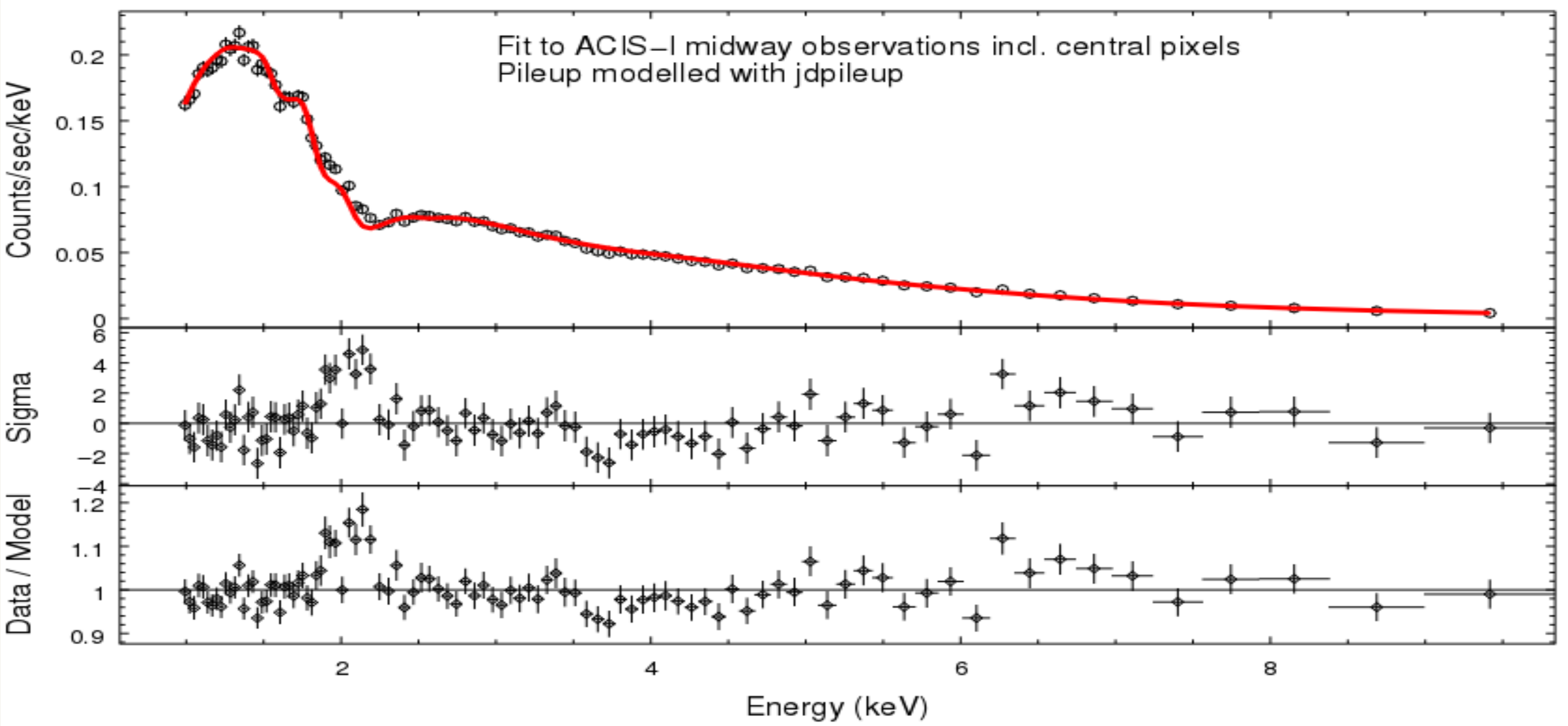
- This dataset is *really, really good*.
- It provides the best current bounds on ALP-photon interactions.
- It also contains a possible signal.
- Statistical significance is enormous – what other systematics are there?
- Immediate next step: what is in *Hitomi* data for AGN? Is there enough to shed further light on these questions?

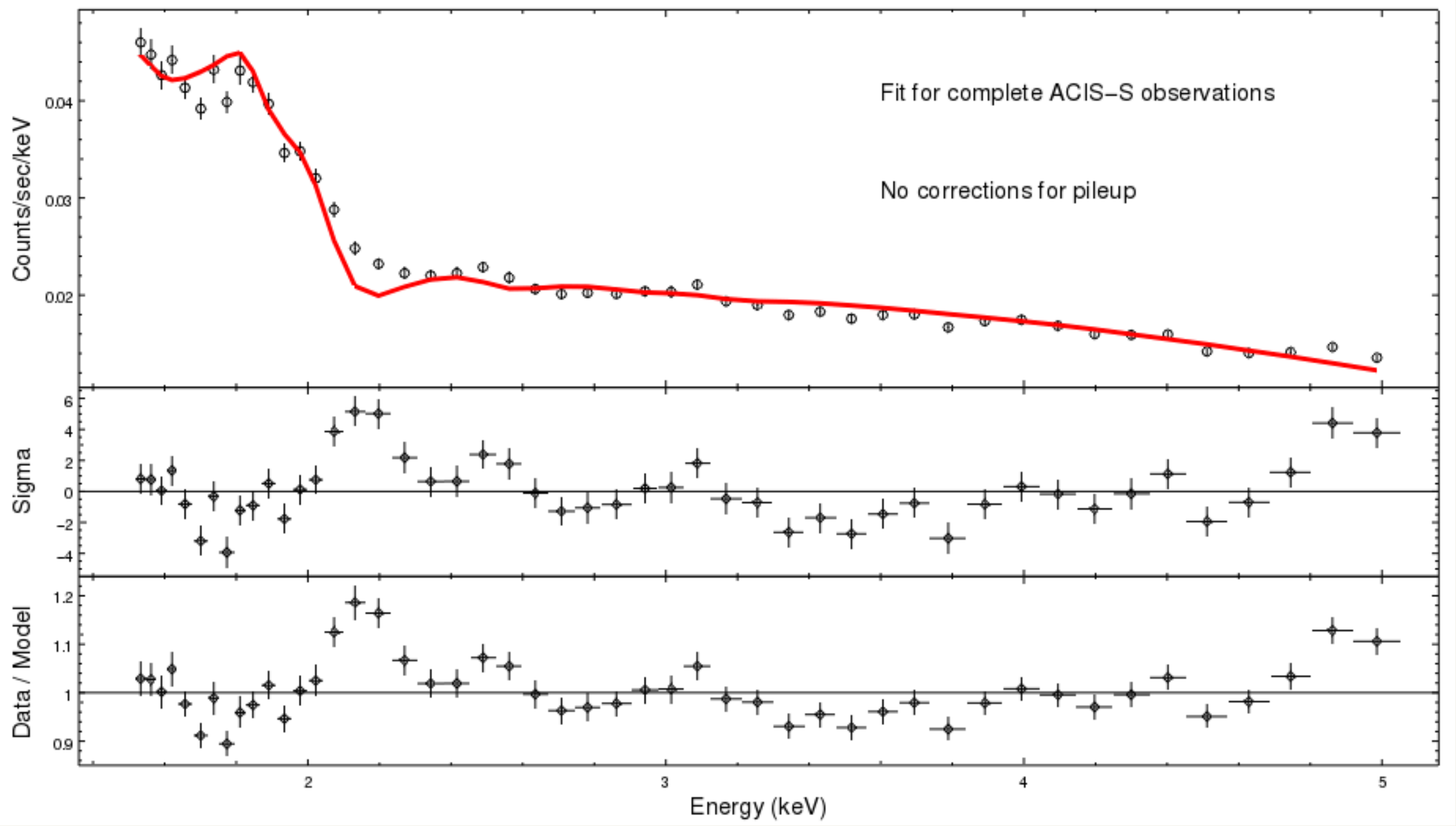
HAPPY BIRTHDAY FERNANDO!



Fit to complete ACIS−I central observations

No corrections for pileup


Fit to ACIS−I midway observations incl. central pixels
Pileup modelled with jdpileup
Counts/sec/keV
0
0.05
0.1
0.15
0.2
Sigma
−4
−2
0
2
4
6
Data / Model
0.9
1
1.1
1.2
2
4
6
8
Energy (keV)


Fit for complete ACIS−S observations
No corrections for pileup
Counts/sec/keV
0.04
0.03
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Data / Model
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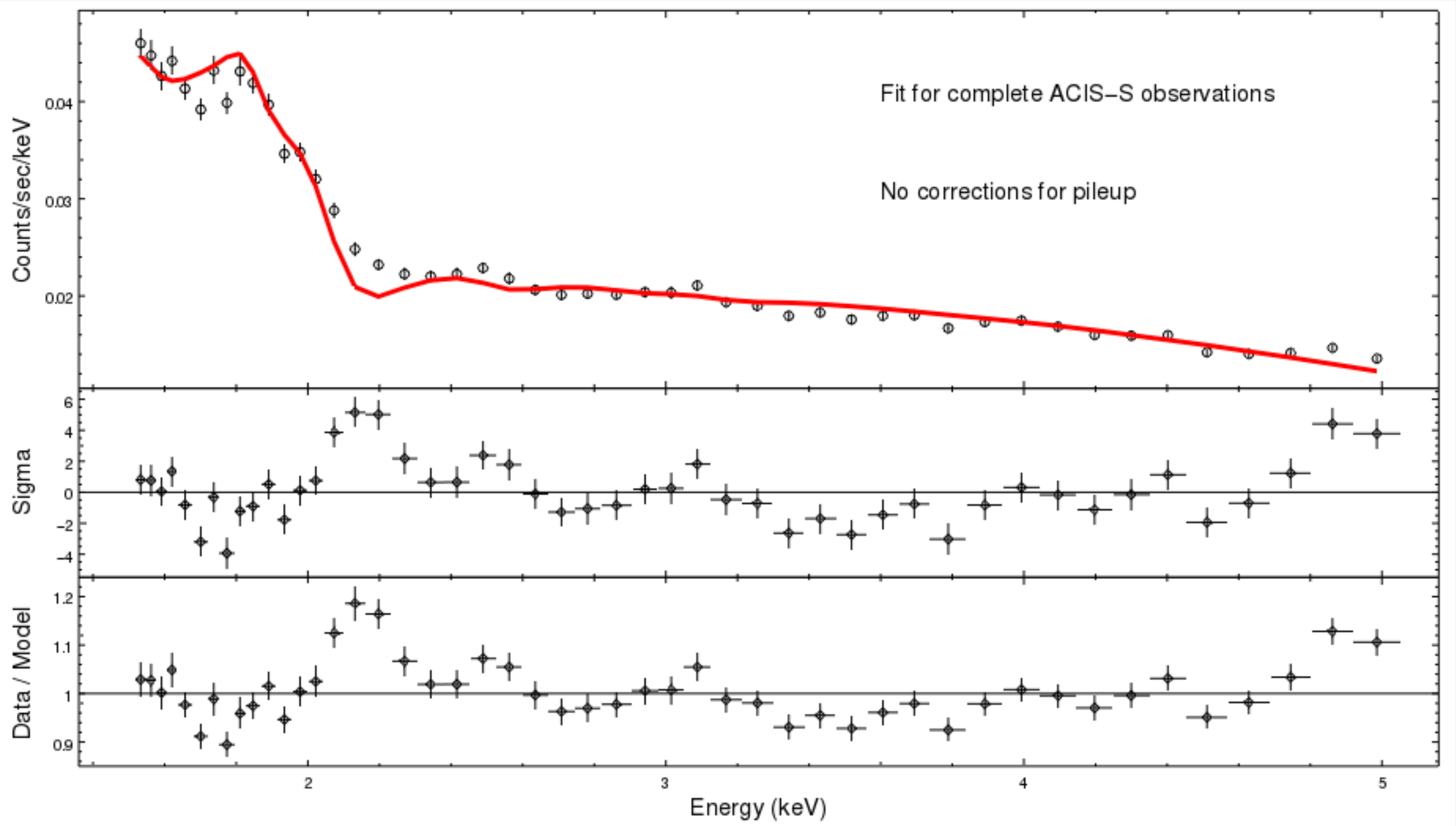
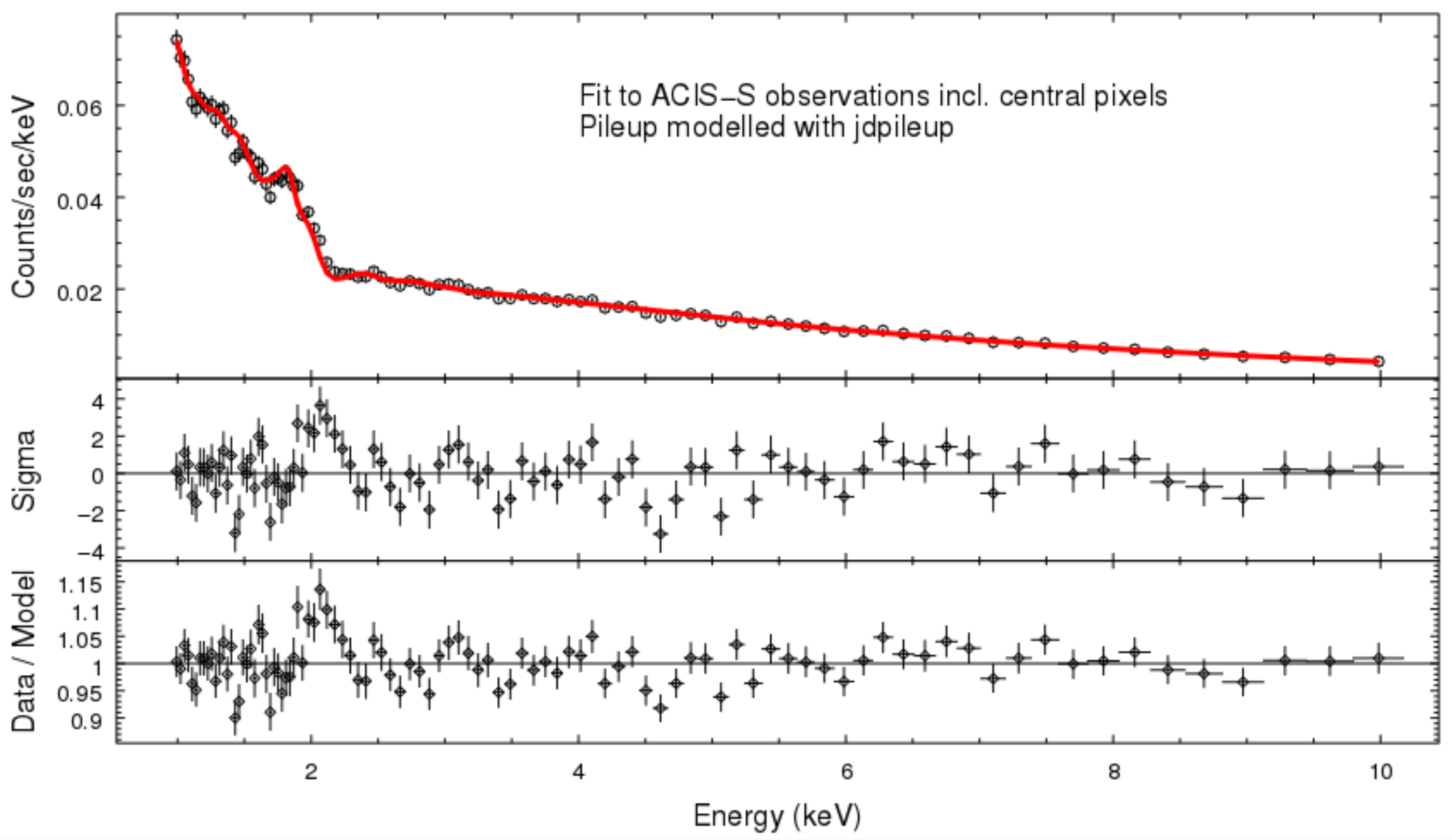
Energy (keV)



Fit for complete ACIS−S observations

No corrections for pileup


Fit to ACIS−S observations incl. central pixels
Pileup modelled with jdpileup
Counts/sec/keV
0.06
0.04
0.02
Sigma
4
2
0
−2
−4
Data / Model
1.15
1.1
1.05
1
0.95
0.9
2
4
6
8
10
Energy (keV)