Axions and AGN

On the evidence for axion-like particles

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March 24, 2011

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Looking for evidence of non-Gaussianity

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Motivation

C. Burrage, A. Davis & D. Shaw, PRL 102 201101 (2009)

recently introduced a new method for searching for axion-like particles using the luminosities of astrophysical objects.

- They applied this method to real AGN data, finding ‘evidence strongly suggestive of the existence of a very light ALP.’
- In a subsequent analysis using a larger data set, they raised the evidence of this claim to the 5 sigma level (though they acknowledge that there could be another explanation.)

I will describe our re-analysis of the claim and the extension of the analysis to a new data set:

Guido W. Pettinari & RC, arXiv:1007.0024

Phys. Rev. D 82, 083502 (2010)

Scalar field couplings

Cosmologists use scalar fields to solve a range of problems:

- Initial conditions -- Inflaton
- Dark Matter -- E.g. Axions
- Late acceleration -- Quintessence field

These fields may have couplings to ordinary particles, which is useful for reheating; but any strong couplings would either cause the fields not be dark, or would not cause acceleration.

Such couplings, if not forbidden by some symmetry, are expected to exist at some level, and they can lead to interesting phenomenology:

- Time/space dependent couplings (e.g. fine structure constant)
- Tired light models
- Fifth force constraints

E.g. Carroll (1998), Csaki et al (2002), Bassett & Kunz (2004), etc.

Axions and the like

The axion is pseudo Nambu-Goldstone boson invented to solve the strong CP problem. It is a potential candidate for dark matter.

It has a coupling to photons of the form:

$$\mathcal{L}_{A\gamma\gamma} = -G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$$

Pseudo-scalar coupling

The coupling is constrained in many ways:

- Solar energy loss
- Direct searches for solar axions
- Conversion to photons from SN1987A $\longrightarrow$ $G_{A\gamma\gamma} \leq 10^{-10}\,\mathrm{GeV}^{-1}$
- Searches assuming it is dark matter

Scalar particles can have similar interactions and these are even more constrained by fifth force tests. Generically particles with such couplings will be called axion-like particles (ALPs).

$$\mathcal{L}_{A\gamma\gamma} = G_{A\gamma\gamma}\phi_A\left(\mathbf{B}^2 - \mathbf{E}^2\right)$$

Scalar coupling

Chameleon fields

Most of the constraints on ALPs can be avoided if the fields are ***chameleon-like***, with masses which depend on the local density.

$$\mathcal{L} = \sqrt{-g}\left[-\frac{1}{2}M_{PL}^2\mathcal{R} + \frac{1}{2}(\partial\phi)^2 + V(\phi)\right] + \mathcal{L}_m(\psi^{(i)}, \tilde{g}_{\mu\nu})$$

Kouray & Weltman *PRD* ***69*** *044026 (2004)*

Here $\tilde{g}_{\mu\nu} = e^{2\beta\phi/M_{pl}}g_{\mu\nu}$ and the potential takes a particular form.

This interaction arises when the scalar field is non-minimally coupled to gravity and you transform to a frame where the gravity is simple.

The impact of the interaction is that the evolution depends on the local matter density:

$$V_{eff}(\phi) = V(\phi) + \rho e^{\beta\phi/M_{pl}}$$

Limits made in high density environments no longer apply!

Low density constraints

Most constraints on axions are made from earth, in the sun, or in centers of supernovae, which are all relatively high density environments.

The Chameleon mechanism suggests it is interesting to try to constrain the axion coupling where the interaction is in low density environments.

One possibility is looking at photons travelling through magnetic fields associated with cluster of galaxies. The coupling terms can lead to photons partially converting into axions, reducing the observed luminosity of the sources.

Galaxy clusters are modeled as having many (>>1) randomly oriented magnetic domains with $B \sim 1\text{-}10\ \mu G$ and $L_{coh} \sim 1\text{-}100\ kpc.$

Mixing and magnetic fields

The probability of converting photons to axions is:

$$P_{\gamma\leftrightarrow\phi} = \frac{1}{1 + E_{crit}^2/E^2}\sin^2\left(\frac{\mu L}{2}\sqrt{1 + E_{crit}^2/E^2}\right)$$

Here, $\mu \equiv BG_{A\gamma\gamma}$ and $E_{crit} = m_{eff}^2/2\mu$

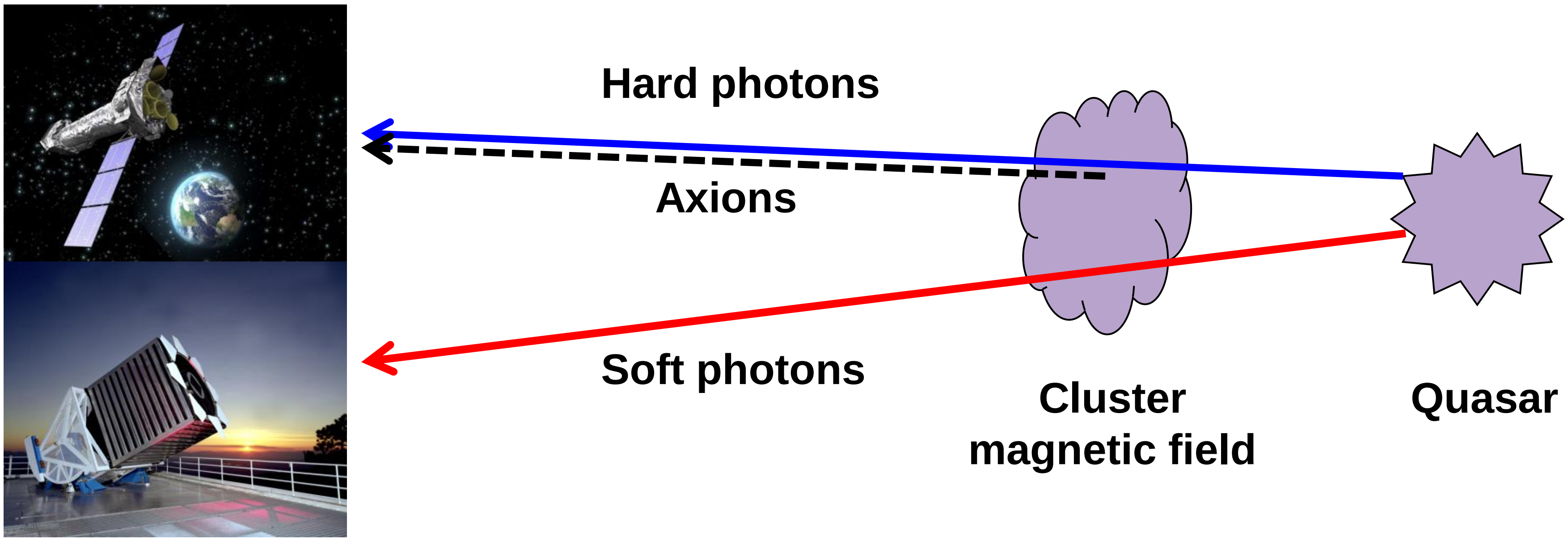
In the strong mixing limit $(LBG_{A\gamma\gamma} \geq 2)$ the mixing becomes energy independent at high energies.

This can also happen if the photons pass through *N* independent domains, as long as $NP_{\gamma\leftrightarrow\phi} \gg 1$

Strong mixing occurs when *E > 0.3-3 keV* (x-rays) given typical parameters describing the magnetic fields and coupling strength.

Cartoon picture

Light from distant sources passes through cluster magnetic fields, and the more energetic photons experience strong mixing into axion-like particles, reducing the luminosity in photons.



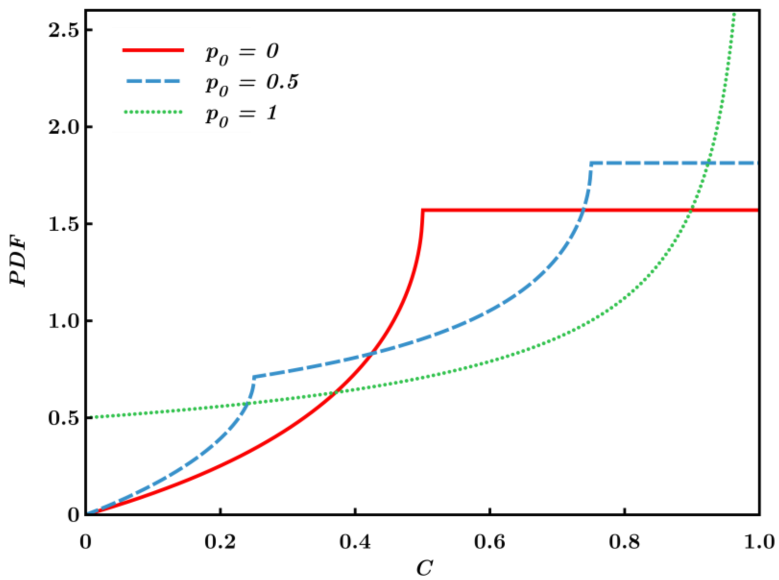
Less energetic light is not mixed, leaving it unaffected. The ratio of luminosities is reduced by 1/3 on average, but the precise amount varies depending on magnetic field strength and orientation on the LOS.

Resulting distribution

Assuming that strong mixing occurs, the final photon luminosity is suppressed by a factor which varies from one line of sight to another.

The distribution of this suppression can be predicted given the degree of the initial polarization. Some sources may not be affected while others may be damped fully.

Burrage, Davis and Shaw proposed to look for this characteristic distribution in the ratios of different energy photons.



C := ratio of final to initial intensity.

In the analysis that follows, the initial photon polarization has marginal impact, so I will ignore it.

Intrinsic scatter

There is not a one to one correspondence between high and low energy luminosities, as they may be emitted via different physical mechanisms.

- In the absence of a full underlying model, the relationship is often modeled phenomenologically,

$$\log(L_{high}) = a + b\log(L_{low}) + S$$

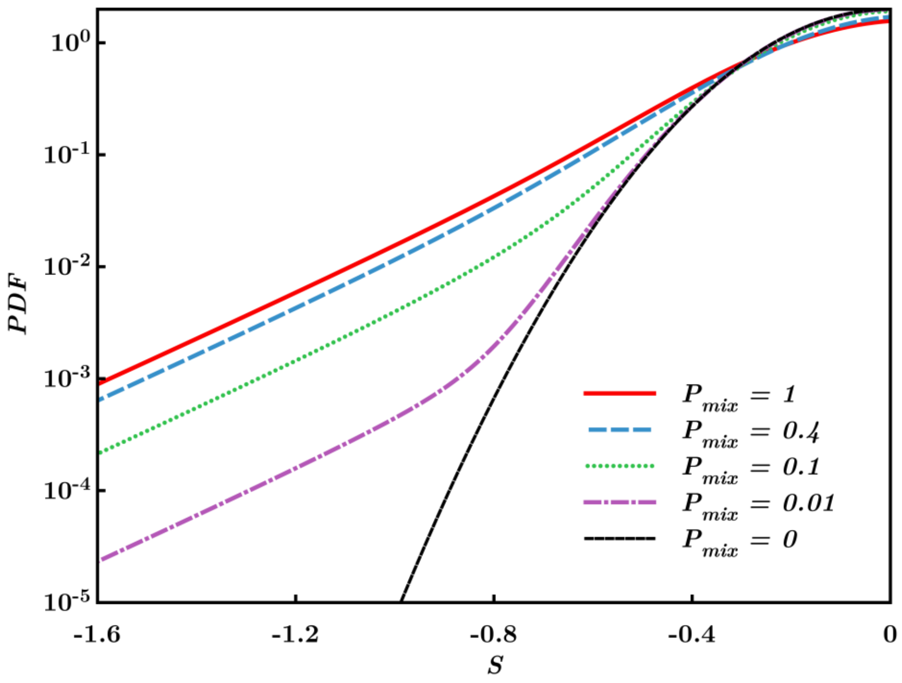
- Here, *a* and *b* describe the average calibration, which are derived from the data. *S* describes the scatter around this fit, which is *often reasonably described by a Gaussian distribution.*

Here we focus on the scatter rather than the average behavior. Thus, the average 1/3 reduction in luminosity is absorbed in the calibration.

However, the mixing provides an extra contribution to the scatter which is non-Gaussian and can be measured!

Predictions for the scatter

Assuming the intrinsic scatter is Gaussian, we can predict the distribution for how the observed scatter should look after strong mixing:



Derived initially by Burrage, Davis & Shaw, 09.

The impact depends on two factors:

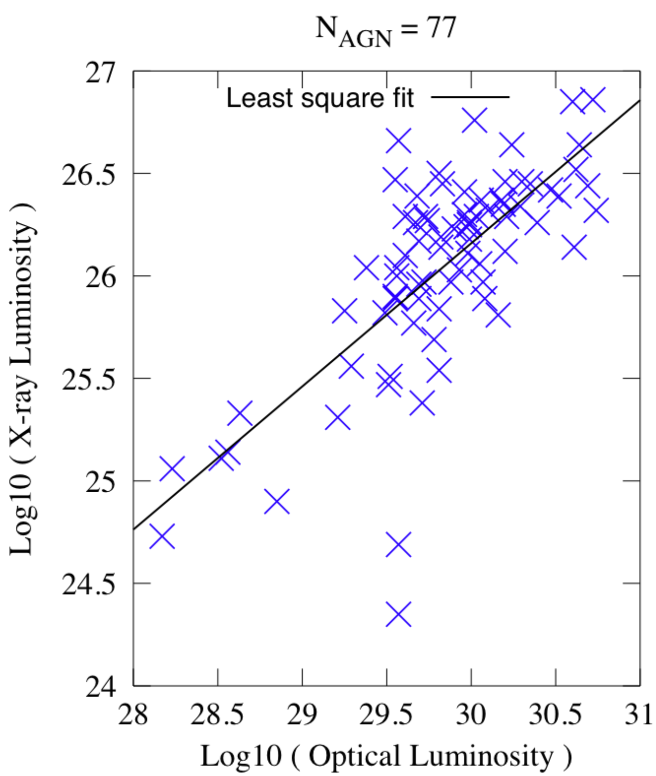
- the degree of intrinsic scatter
- the fraction of lines of sight

to experience strong mixing – P_{mix}

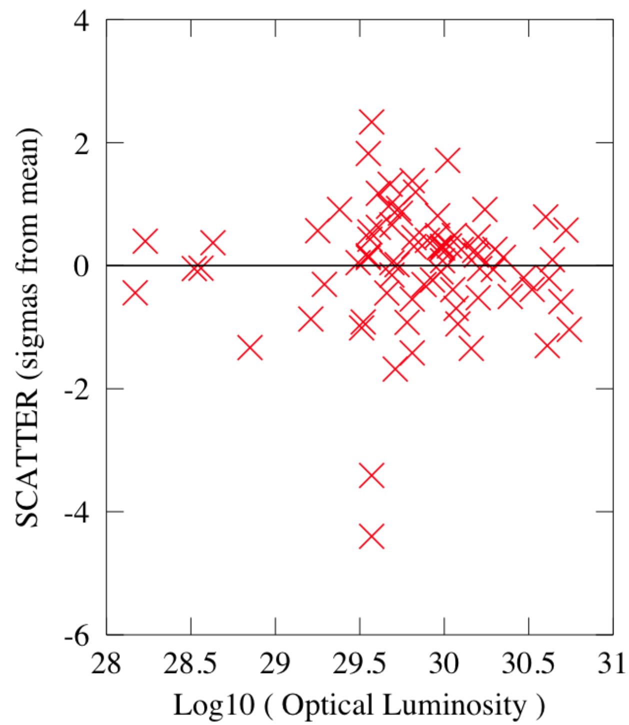
Mixing increases the variance of the scatter by a fixed amount, and also adds to the low luminosity tail, skewing the distribution.

Searching for the effect

To search for the effect, BDS analyzed a sample of 77 AGNs with optical and X-ray luminosities (measured with ROSAT & Chandra at 2keV.)



Original data.



After best fit has removed average behaviour.

Searching for the effect

They examined the ratio between the likelihoods for two hypotheses:

- Simple Gaussian scatter with the observed variance
- Intrinsic Gaussian scatter, folded with additional scatter from mixing, but with the same total variance.

They defined a statistic which is effectively the difference in chi-squared.

$$r \equiv 2 \ln \left(\frac{\mathcal{L}_{ALP}}{\mathcal{L}_{Gauss}} \right)$$

Positive values indicate a preference for the mixing hypothesis!

For their data set, they found *r = 14*

➢ 3.7 σ evidence for the scattering model.

For an extended data set with 203 AGN, they found *r = 25*

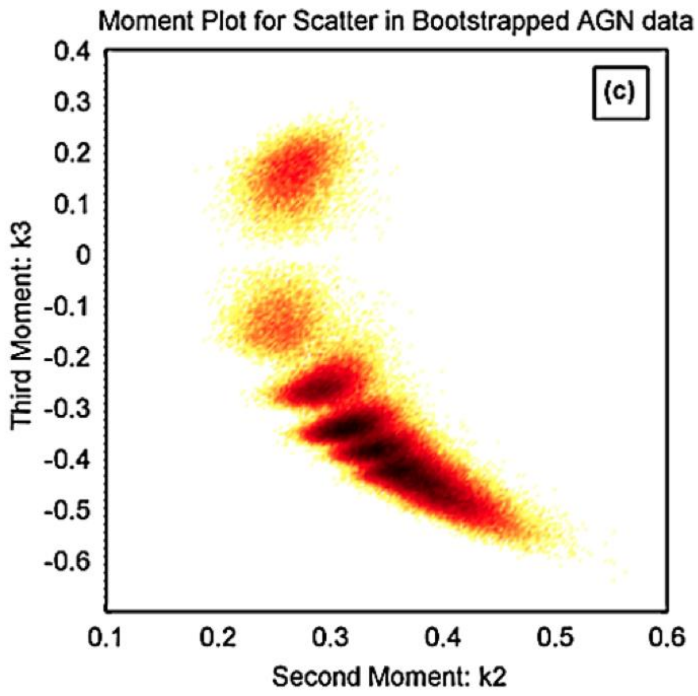
➢ 5 σ evidence for the scattering model!

Fingerprints of mixing

Burrage et al also introduce a new plot, which they describe as a ‘fingerprint’ of the distribution.

This is a plot of the skewness versus the variance for a collection of realisations of the data.

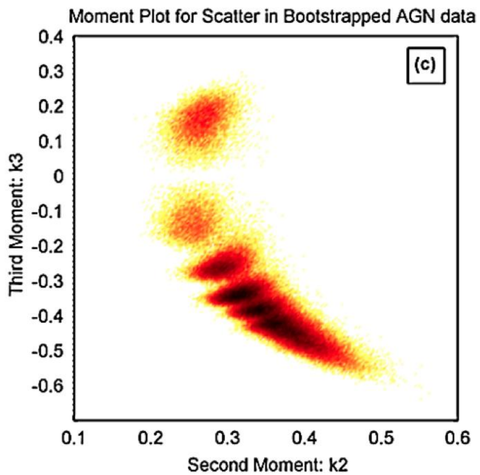
These realisations are generated through `bootstrap resampling` of the actual observations.



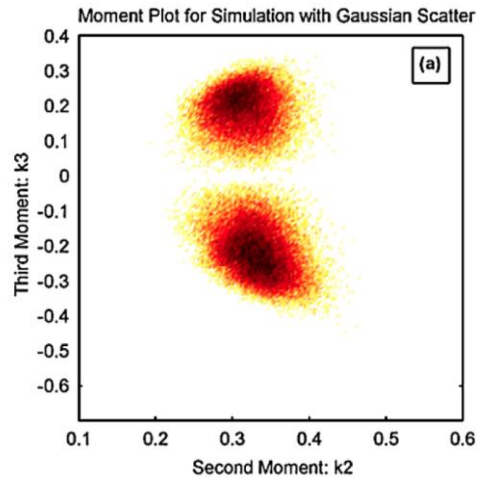
Bootstraps are a resamplings of the original data set, *with replacement,* so that a single point may appear numerous times or not at all in any particular realisation.

Fingerprints of mixing

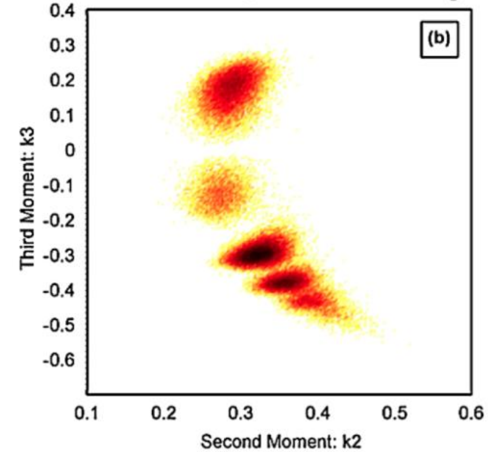
Data



Gaussian realization



Axion mixing realization



The data fingerprints resemble the ALP realization much more closely than the Gaussian one, though BDS do not try to quantify it.

Two significant similarities:

- Large skewness when variance is large.
- Similar substructure seen which is not present in Gaussian bootstraps.

With this and the r-statistic, Burrage et al. 09 seem to make a strong case for the detection of axion mixing.

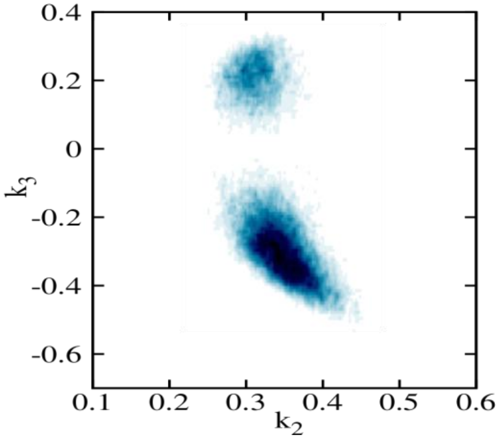
What's going on?

Where is the substructure coming from?

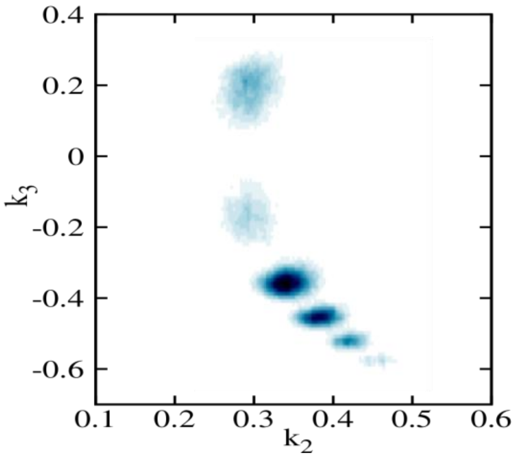
We reproduced their results, but found the substructure only arose in simulations where there were large outliers.

One or two outliers are being re-sampled, and re-sampling them more than once increases the variance and skewness, and so creates a new substructure.

These fingerprints show that the data likely has one or two outliers which are skewed to lower luminosity.



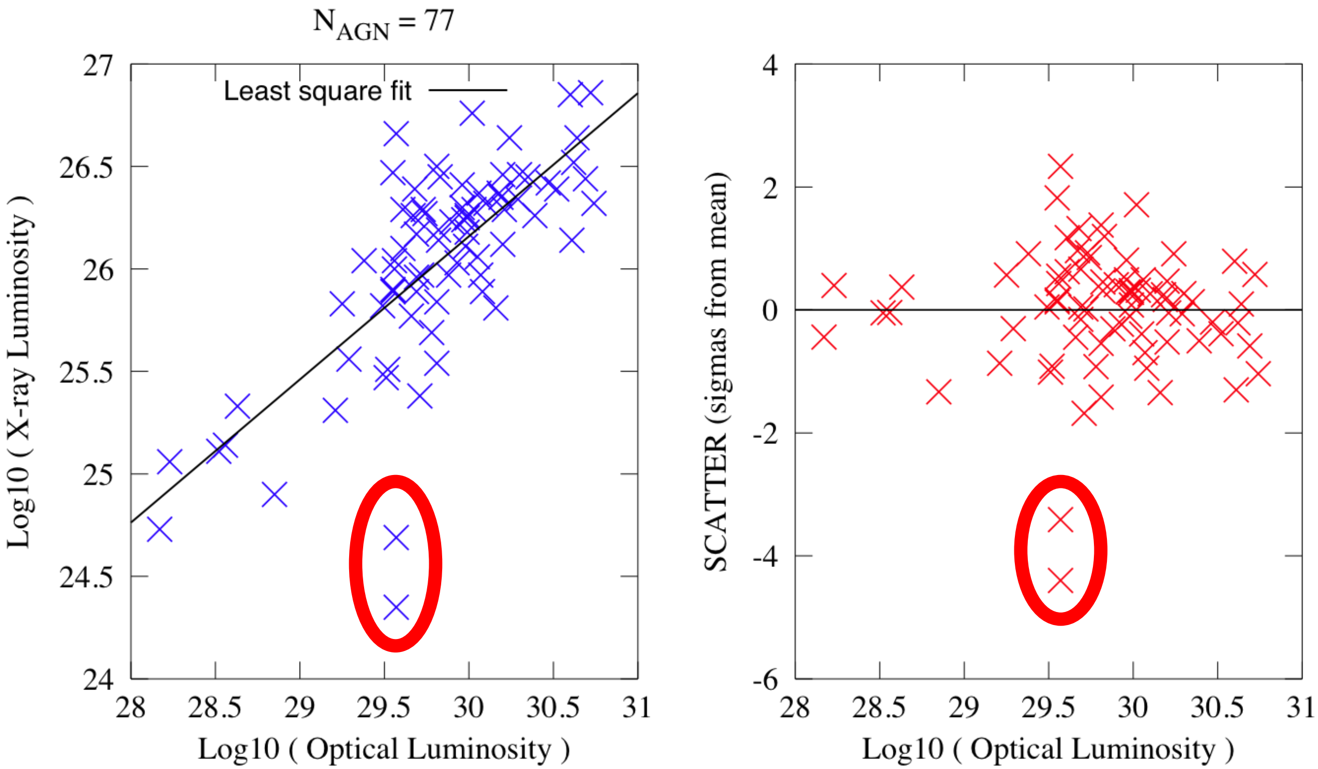
Typical realization



Realization with 1 large outlier

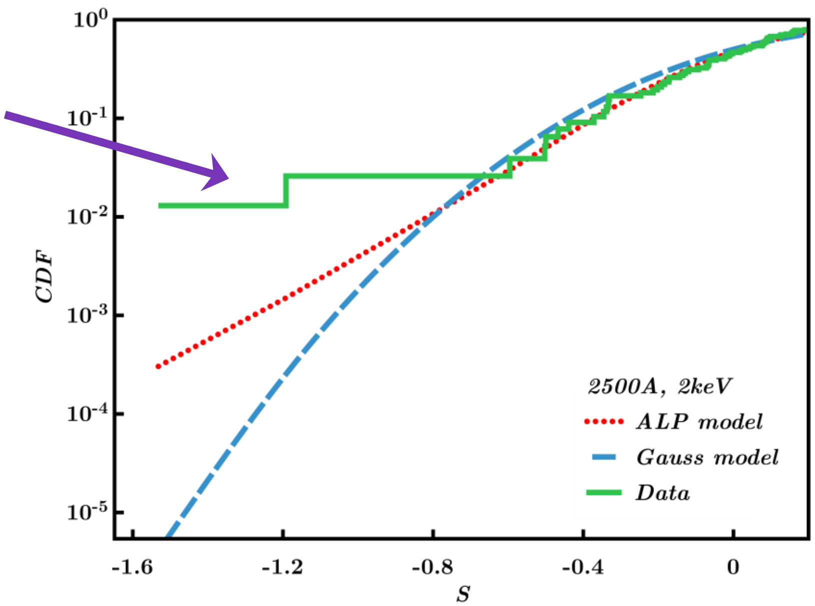
The outliers

There are indeed two big outliers in BDS dataset:



The cumulative distribution

These outliers can be clearly seen in the CDF. One or two outliers dominate the tail of the distribution.



Notably, the mixing model is more likely to have these outliers because it has a wider tail and is skewed towards lower ratios, just as the data is.

However, the outliers far exceed what is expected in the ALP model.

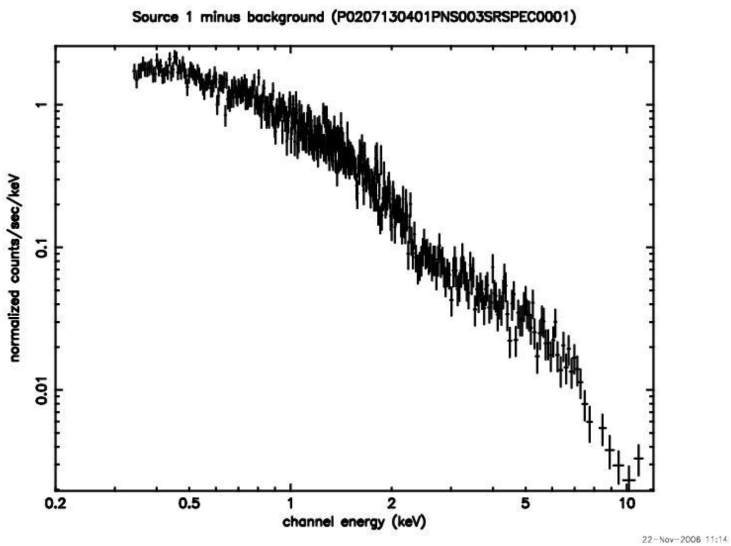
So, while mixing is a much better fit than Gaussian, neither really works!

These outliers dominate both the ratio of likelihoods and the fingerprint plots.

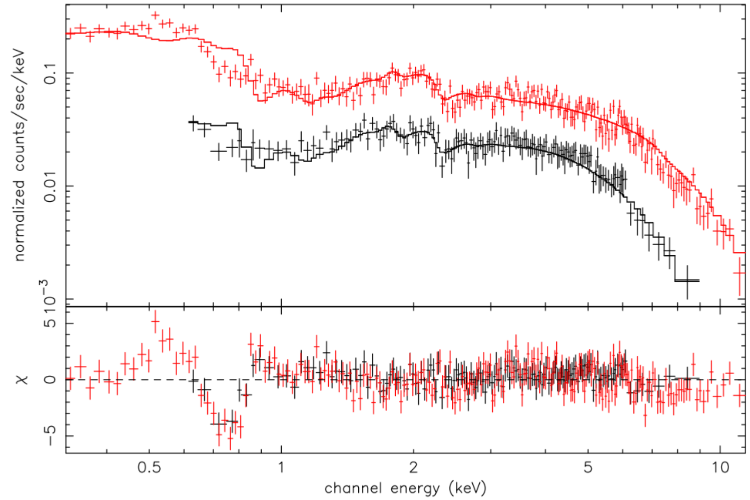
The largest outlier

Are the outliers typical objects, or are there reasons to be suspicious?

XMM-Newton Science Archive



Markarian 304
(Piconcelli et al. 2004)



We investigated the largest outlier (Markarian 304, z = 0.067) and found out it is a highly absorbed AGN. This is a well known class of object with reduced emission in the lower energy X-rays.

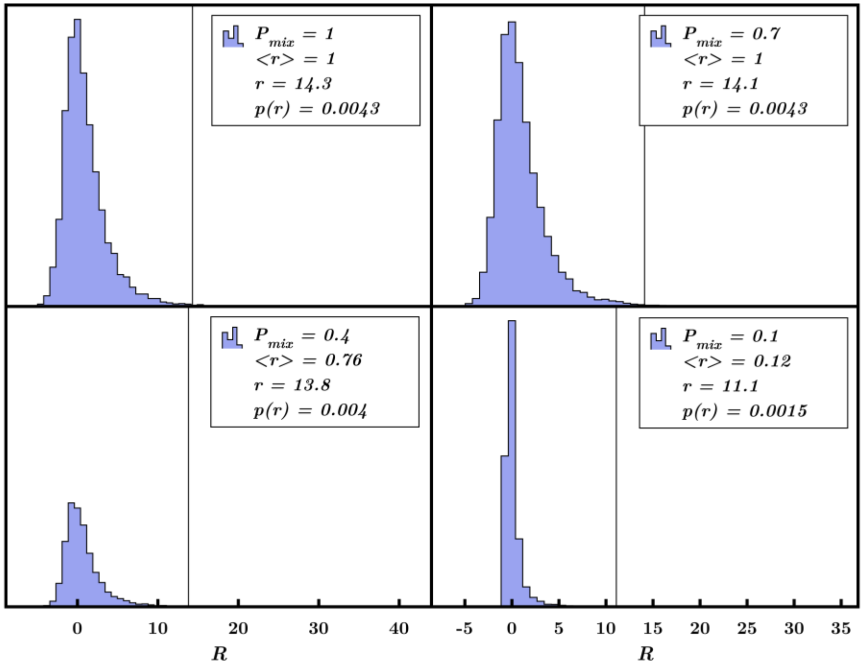
Removing MK304 reduces the r-statistic by 64% in the BDS data set!

What should they have seen?

The measured r value of 14 is much higher than what is predicted in the ALP mixing model!

By Monte Carlo-ing many samples of the model, we find that typically we should not have expected a significant signal with the data set used by BSD.

To get a significant signal, one needs either many more AGN, or a sample with a smaller intrinsic variance, so that the effects of mixing are more obvious.



Four different probabilities for a given line-of-sight to be mixed.

A new sample

Motivated by these issues, we analyzed a new data set based on SDSS and the XMM-Newton quasar survey (M. Young et al, 2009.)

Advantages of the new survey:

- Homogeneous X-ray observations
- Multiple X-ray bands (1, 1.5, 2, 4, 7, 10 keV)
- Many thousands of photons, so that photon shot noise is minimal
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We attempt to make a homogeneous subsample of these, excluding any which:
- Appear to be radio loud or broad line emission sources
- Do not have a significant signal/noise (average 1300 photons)
- X-ray spectra are not well fit by a power law
- Spectral slope might indicate obscured AGN.

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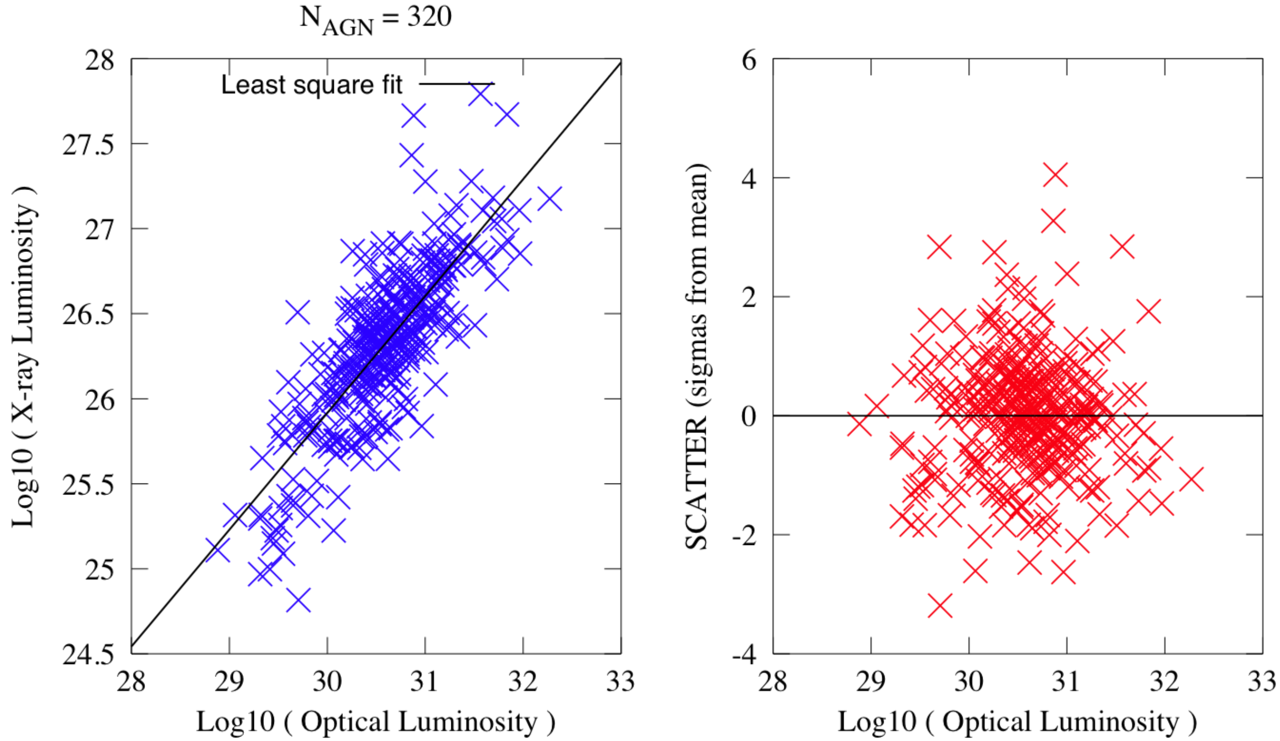
This results in a sample 320 AGN with relatively small variance.

A new sample

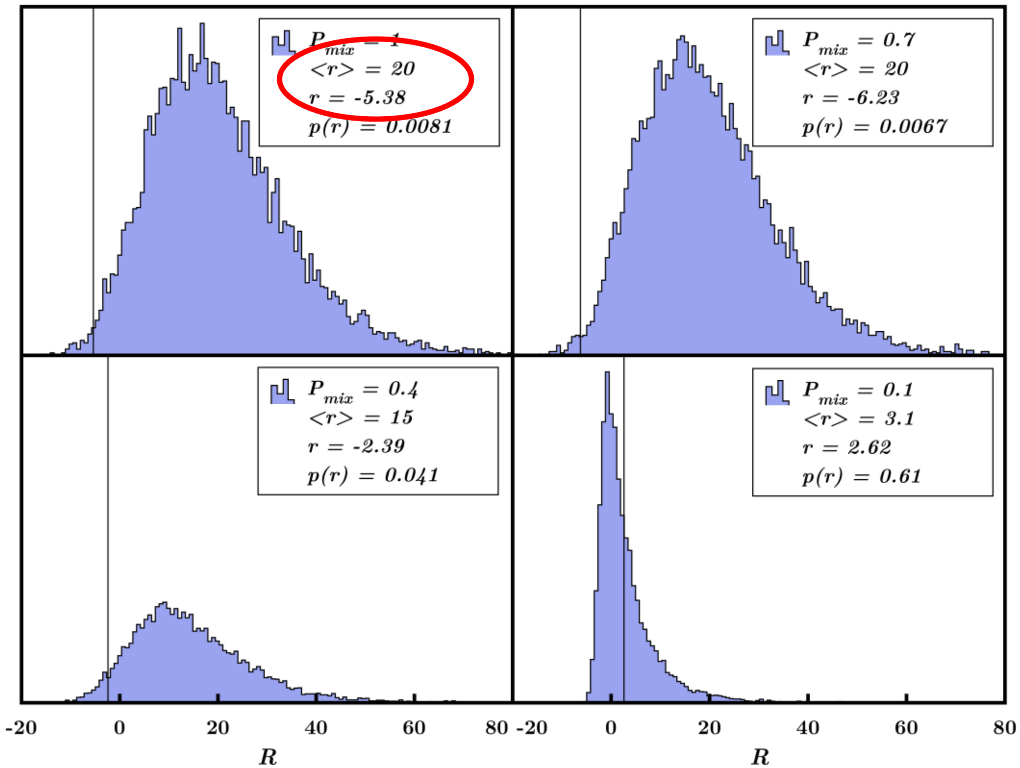
In principle, a cleaner sample will have smaller intrinsic scatter; combined with increased numbers, this should increase the sensitivity to axion mixing.

The distribution of our cleaner sample of 320 active galactic nuclei:



Do we have the sensitivity?

With this new sample, in principle we could find good evidence for mixing, if the probability of mixing is high enough:

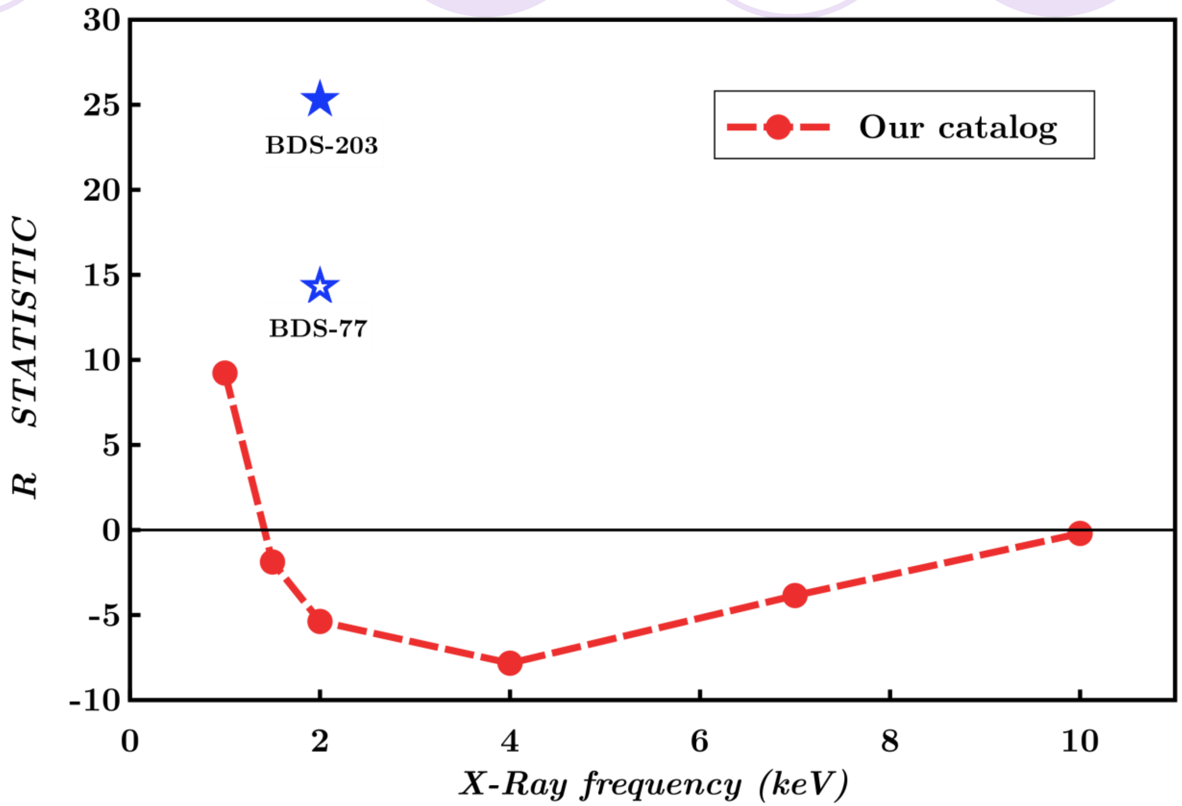


If the probability of mixing is 50% or higher, the signal would be detected at four sigma on average.

Results

The new data allows us to test the evidence for different x-ray energies.

The more energetic x-rays are more likely to be strongly mixed, but this is not what we see in the data.

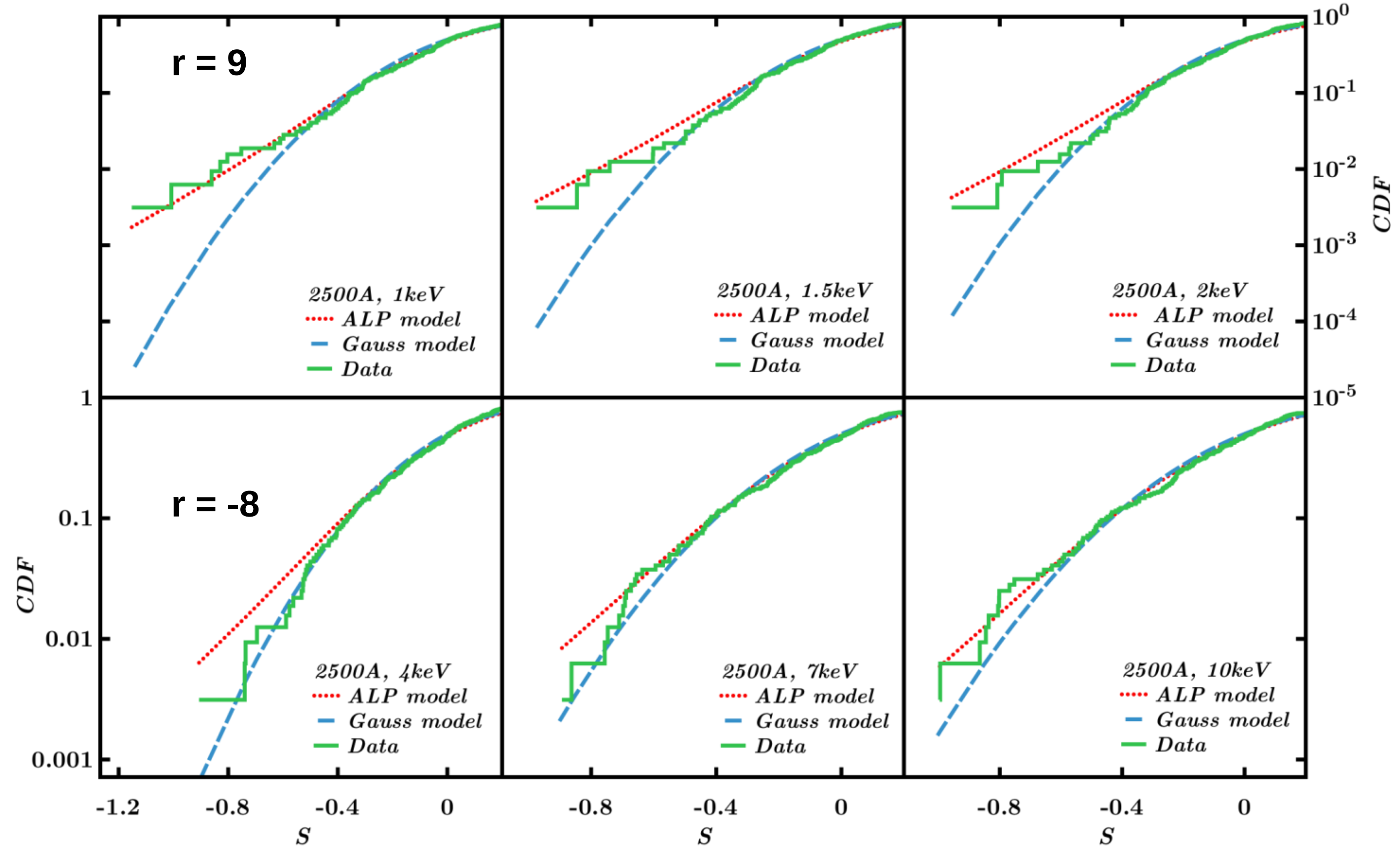


Apart from the 1 keV bin (r = 9), which is most likely to still be affected by absorption, all the other X-ray bins actually prefer the Gaussian distribution (r < 0).

Results

This is demonstrated by looking at the cumulative distributions.

However, neither model really gives great goodness of fit, as quantified by KS, Kuiper and Anderson-Darling test.



Conclusions

- Early indications of evidence for axion mixing were biased by inhomogeneous samples, and in particular the contamination by a few outliers where the X-rays have been strongly absorbed.
- Analysis of more homogeneous samples shows no evidence, indicating either no mixing, or that the probability of mixing is less than 50%.
- The distribution of the ratios of the high and low energy luminosities of objects can in principle give useful bounds on mixing to axion-like particles, but it requires a homogeneous class of objects where the intrinsic scatter is reasonably small and preferably is well understood.
- Given a sufficiently clean sample, even a few objects could be enough if the scatter is small and we can be certain that they should have been strongly mixed by passing through magnetic field regions.

Thanks!

Many thanks to Misao and Takahiro for organising the workshop, as well as to all the others who contributed to the organisation!