Constraining Axion Properties using Galaxy Clusters

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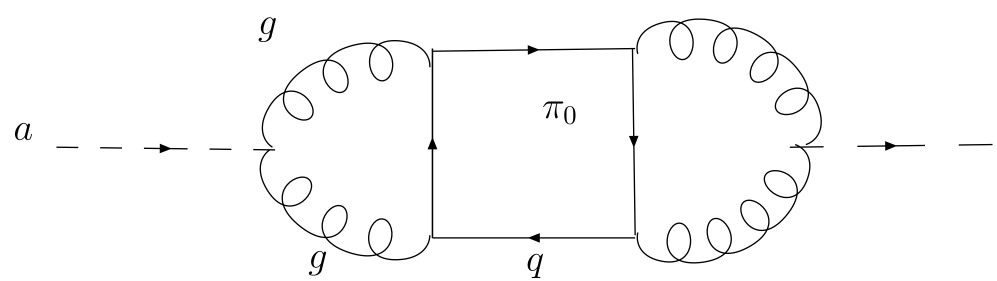
The Strong CP Problem

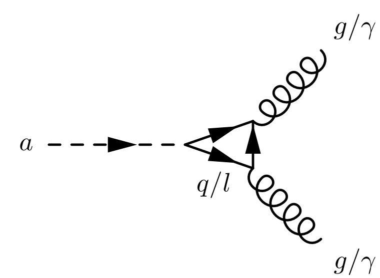
- QCD picks up CP violating terms due to tunneling between different vacua and weak-sector anomalies $\mathcal{L}_{QCD_{CPV}} = \frac{\bar{\theta} g^2}{32\pi^2} Tr(F_{\mu\nu}\tilde{F}^{\mu\nu})$
- The CP violating term predicts an electric dipole moment $|n\rangle$ for the neutron, which is not seen in nature. Best experimental limits require $\theta \lesssim 10^{-10}$.
- Near-vanishing of θ would seem to require a conspiracy between strong/weak sectors: Preferable to seek a dynamical solution!

Axions: A possible solution to the Strong CP Problem

- Peccei-Quinn (1977) propose a second Higgs field with symmetry breaking scale $10^{19} GeV \gtrsim f_{PQ} \gtrsim 1 TeV$. The Goldstone boson of this field would be the axion.
- The axion (a) directly couples to fermions via $a\overline{\Psi}\gamma_5\Psi$.
Anomaly diagrams lead to a coupling with gluons/photons: $-\frac{\alpha_s}{8\pi f_{PQ}} aF\tilde{F}$
This term cancels out the CP-violating term in the ground state.
- By coupling to pions, axions would acquire a mass $m_a = .62eV \frac{10^7 GeV}{f_{PQ/N}}$ set by the PQ symmetry breaking scale.



Axion mass via pion coupling



Direct Axion coupling to gluons/photons

Axions as Dark Matter Particles

- Axions with $m_{a_{eV}} > 10^{-2}$ can be produced thermally by $N + \pi \rightarrow N + a$ They freeze out to yield an abundance: $\Omega_a h^2 = \frac{m_{a_{ev}}}{130} \frac{60}{g_d^*}$
- After freeze out, Axion temperatures redshift as $1/a$. At $T = m_a/3$, axions become non-relativistic, and then their velocity scales as $1/a$ yielding a velocity today of $\langle v_a^2 \rangle \approx 2.7 \times 10^{-4} c \times (60/g_d^*)^{1/3}$.
- With lower velocity than a typical galaxy cluster velocity dispersion, axions will fall into cluster potential wells, contributing Ω_a/Ω_m of the cluster mass density.
- Axions with $m_{a_{eV}} < 10^{-2}$ would be produced non-thermally by oscillations of an initially misaligned, θ yielding an abundance of

$$\Omega_a h^2 \approx .13 \times \Lambda_{200}^{-0.7} f(\theta_1) \theta_1^2 (m_{a_{eV}}/10^{-5})^{-1.18}$$

- Axions and WIMPs (possibly the supersymmetric neutralino) are theoretically well-motivated candidates for Cold Dark Matter (CDM).

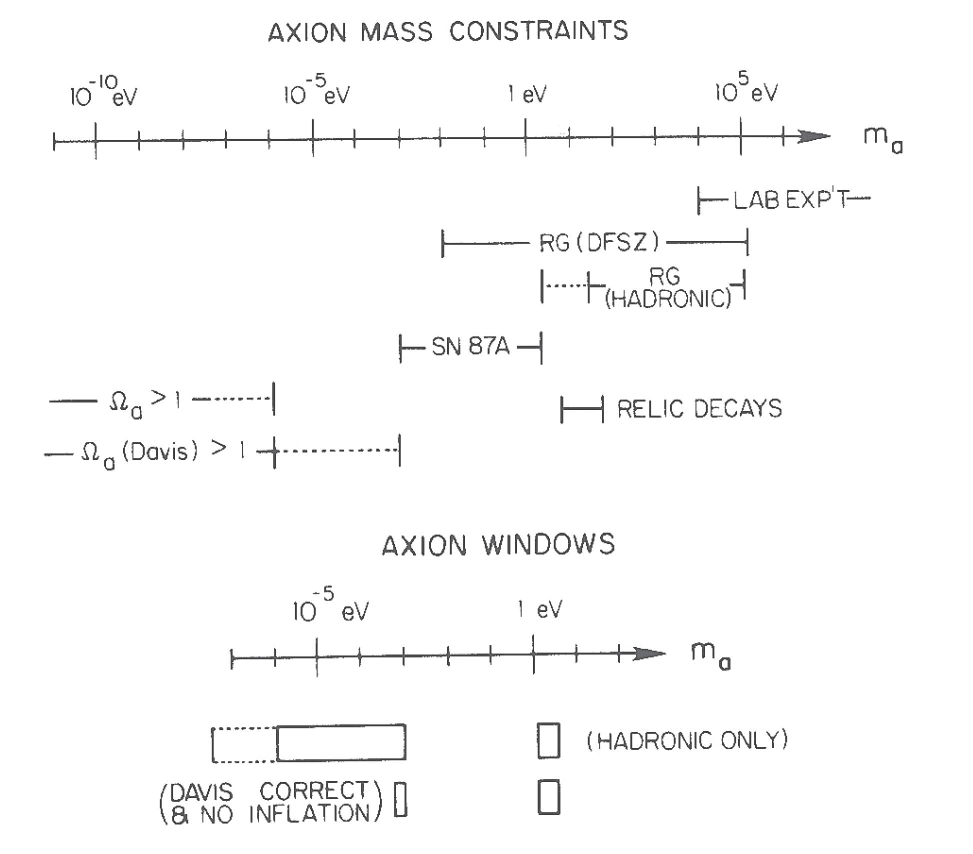
Axion Decay to Photons:

$$a \rightarrow \gamma\gamma$$

- The cumulative effect is an axion decay with lifetime
$$\tau(a \rightarrow \gamma\gamma) \approx 6.8 \times 10^{24} \xi^{-2} m_{a_{ev}}^{-5}\, s$$
where the axion-photon coupling strength $\xi = \frac{4}{3}\left(\frac{E}{N} - 1.92 \pm .08\right)$, where $E = 2\sum_j X_j Q_j^2 D_j$ and N (the total PQ charge of all fermions that couple to the axion) are counting factors accounting for the number of ways the axion can couple directly to standard model fermions and then photons or via pions to photons.

- Although this lifetime is extremely long, one might hope to see the photons produced by axion decays in high density environments, such as galaxy clusters.

Constraints on Axions



The two remaining mass windows are $10^{-6} \leq m_{a_{eV}} \leq 10^{-3}$ and $1 \leq m_{a_{eV}} \leq 20$. A telescope search for decaying axions in clusters is of interest even in the case of a null detection, because the one remaining mass range is one in which the freeze out abundance of axions is just right for axions to be a substantial fraction (perhaps all!) of the dark matter: $\Omega_a h^2 \approx .13 \times \Lambda_{200}^{-0.7} f(\theta_1)\theta_1^2 (m_{a_{eV}}/10^{-5})^{-1.18}$

Using Galaxy Clusters to constrain Axion Properties

- $\lambda_a = 24800 \mathring{A} m_{a_{eV}}^{-1}$
- Natural line width $\approx 1/\tau \approx 10^{-24} s^{-1}$ is negligible compared to the typical Doppler width $\approx 10^{19} s^{-1}$.

$$I_\lambda = \frac{6.8\times10^{-21} m_{a_{eV}}^7 \xi^2 \Sigma/(gcm^{-2}) e^{\frac{-(\lambda_r-\lambda_a)^2}{\lambda_a^2}\frac{c^2}{2\sigma^2}}}{\sigma_{1000}(1+z_{cl})^4}$$, where Σ is

projected surface mass density. This idea is due to Turner (1987).

First Attempts

- Bershady, Ressell, and Turner--Telescope search for axions using Clusters A1413(z=.143),A2218(z=.171) and A2256(z=.0601) (KPNO 2.1 m). 160 spectra averaged at 3 slit positions. Wavelength coverage-->3.7 to 7.8eV in axion mass.
- 30 spectra taken 5 core radii away from the cluster core subtracted from 30 spectra taken near cluster core in order to subtract sky.
- No obvious axion line was seen.
- Limits on ξ obtained by looking for peaks in the cross-correlation between cluster spectra at the appropriate lag. Gaussian noise assumed to evaluate the statistical significance of each observed peak. Then template spectra with axion lines were convolved with observed spectra to determine the uppermost ξ allowed by the data. King profiles were assumed for the clusters.
- Limits could be improved with longer integration time, use of an IFU to cover more of a cluster, and by more careful modeling of the expected intensity.

The Data

- The VIMOS IFU (1600 fibers X 4 quadrants-0.66" fiber diameter on the sky has been used to take spectra of A2667 (z=.234) and A2390 (z=0.230) (Kneib, Covone, Jullo).
- HST WFPC2 (F450W/5X2400s/F814/4x1000s) images.
- Ray-tracing fits to locations to locations of strongly lensed background galaxies (giant arcs and arclets) used to fit the cluster potential as a sum of truncated PIEMDs. Galaxy mass assumed to trace light, constant M/L, added in to produce projected mass map for clusters. Relevant to weighting of IFU data.
- Andrew Blain has been advising me on the data analysis.

Analysis Technique

- IFU Fibers falling on known galaxy locations (source or lens) are masked.
- Noise cube estimated by adding Poisson noise to 5% of the mean flux (estimated adjacent fiber cross-talk on CCD) from adjacent fibers.
- We are interested only in line emission-->continuum emission fitted in 2X $\Delta\lambda = 3\frac{\sigma}{c}\lambda_a(1+z_{cl})$ sized windows on either side of the candidate line location andsubtracted.
- Data cube resampled in wavelength to optimize signal to noise for candidate axion line locations (optimum bin size is estimated with a simple simulation).

Analysis (cont'd)

- Projected mass map avoids pitfalls of assuming density distribution, allows weighting signal to optimize S/N.

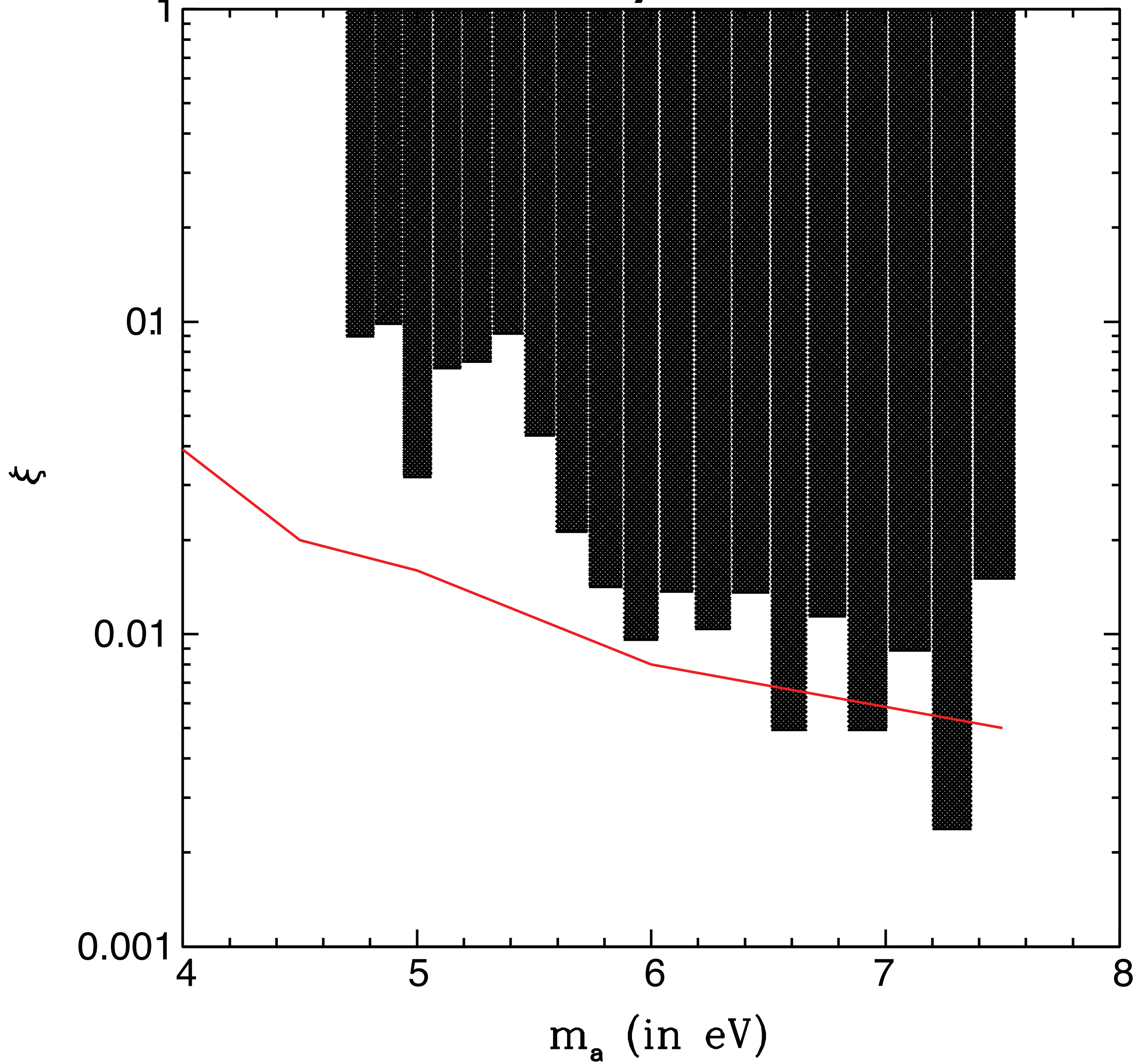
$$\left\langle \frac{I_\lambda}{\rho} \right\rangle_{axion} = \frac{1.29 \times 10^{-18} m_{a_{eV}}^7 \xi^2}{\sigma_{1000} S^2(z_{cl})(1+z_{cl})^4},$$

should be location independent.

Analysis (cont'd)

- The observed emission is modeled $I_{\lambda,i}^{mod} = \left\langle \frac{I_\lambda}{\rho} \right\rangle \rho_i + c_\lambda$, where c_λ accounts for the possibility of legitimate sky emission uncorrelated with density. Weights are chosen to optimize the measurement of $\left\langle \frac{I_\lambda}{\rho} \right\rangle$, and this used to calculate the upper limit on ξ as a function of axion mass.

Preliminary Results



Concerns/Caveats

- My limits are slightly worse than TBR!! A comparison of collecting areas/integration times tells us that we should see about 300 times as many photons from axion decay, so for a given noise level ~~and~~ signal to noise-threshold, we should be able to set an upper limit on ξ that is $\sqrt{\sqrt{300}} \approx 4$ times as stringent.
- The IFU data are not flat-framed. Area of current work.
- Excessive fitting going on? Sky should be masked, not fitted for(?).
- Resampled bins include sky lines--could include sky flux in estimation of axion decay flux--worsen limits.

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