

A Telescope Search for Decaying Relic Axions

astro-ph/0611502

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Stanford Cosmology Meeting, 2/22/07

Outline

- [Whence axions?
- [Axionic Dark Matter
- [Clusters are Axion Laboratories
- [VLT Search for Axions in A2667/A2390
- [Prying open parameter space (modified reheating!)
- [Results/Prospects

CP violation in the strong sector

— [Naive QCD Vacuum contains degenerate family of pure gauge vacua connected by instantons (tunneling).

— [Periodic symmetry demands θ – vacuum: $|\theta\rangle = \sum_n e^{in\theta} |\mathbf{A}_n\rangle$

— [Amplitudes in θ – vacuum have additional term in $\mathcal{L}_{\text{effective}}$:

$$\mathcal{L}_{CPV} = \left(\frac{\theta g^2}{32\pi^2} G\tilde{G} \rightarrow \text{CP violation!} \right)$$

$$d_n \sim 10^{-16} \theta \text{ e cm}$$

— [Neutron electric dipole moment (NEDM) is highly constrained by exp't:

$$\theta \ll 10^{-10}$$

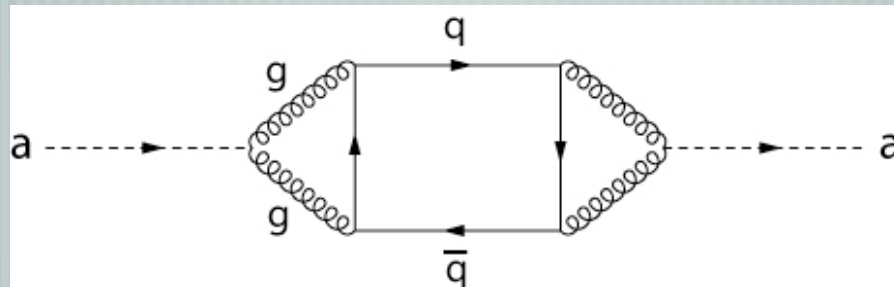
Axions solve the strong CP problem

- [Unnatural? Throw in a (pseudo) scalar! $L_a = - (a/f_{PQ}) G\tilde{G}$
- [Axions have mass:

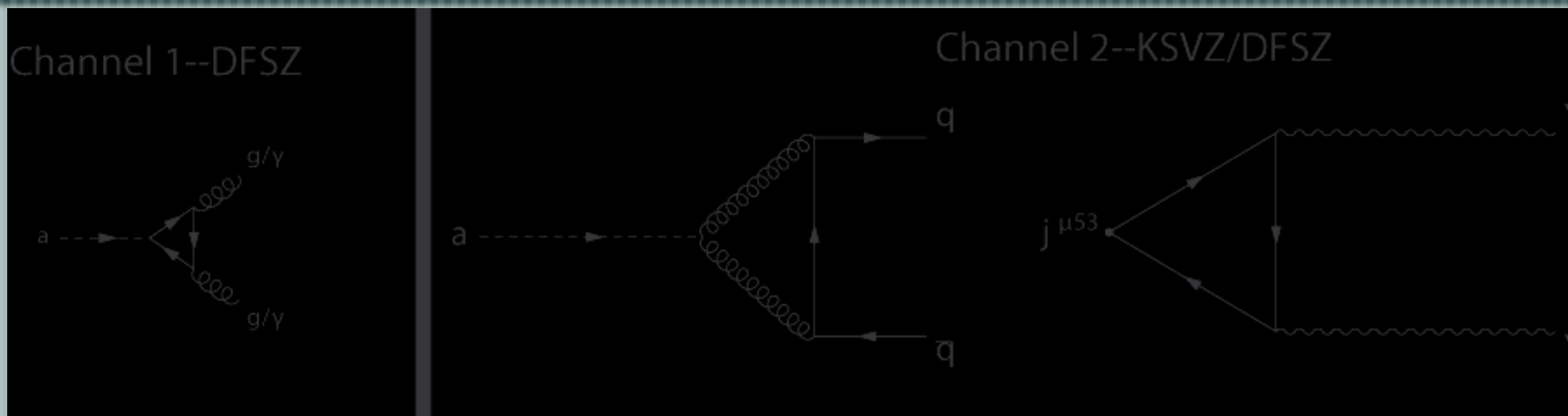
$$m_a \simeq \frac{m_\pi f_\pi}{(f_{PQ}/N)} \frac{\sqrt{z}}{1+z}$$

$$z \equiv \frac{m_u}{m_d}$$

$$V(a) = m_\pi^2 f_\pi^2 \frac{z}{(1+z)^2} \left\{ 1 - \cos \left[\left(\frac{a}{f_{PQ}/N} \right) + \theta \right] \right\}$$



Axion flavors



- [DFSZ (strongly coupled) vs KSVZ (hadronic) axion models
- [$\tau(a \rightarrow \gamma\gamma) \simeq 6.8 \times 10^{24} \xi^{-2} m_{a,\text{eV}}^{-5} \text{ sec}$, $\xi \equiv \frac{4}{3} (E/N - 1.92 \pm 0.08)$
- [Weak couplings to SM \rightarrow Axions are dark matter! $\Gamma, \sigma \propto \alpha^2$
- [Cold and bound today:
 $\langle v_a^2/c^2 \rangle^{1/2} = 4.3 \times 10^{-4} m_{a,\text{eV}}^{-1}$

Axionic dark matter: More on ξ

$$\xi = \frac{4}{3} \left\{ \frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right\}$$

Two-photon coupling plagued by high *theoretical* uncertainties:
Moroi and Murayama 1998

[Kaplan-Manohar ambiguity: m_π^i are invariant under $m_u \rightarrow m_u + \epsilon m_d^*$
 $m_d \rightarrow m_d + \epsilon m_u^*$.

Baryon masses help but $\delta z \sim \mathcal{O}(50\%)$.

[Chiral perturbation theory is only good to about 10% for f_π .

[$\xi \equiv (4/3) [E/N - 1.92 \pm 0.75]$ may be closer to truth.

So even for DFSZ models ($E/N=8/3$), ξ may vanish in theory.

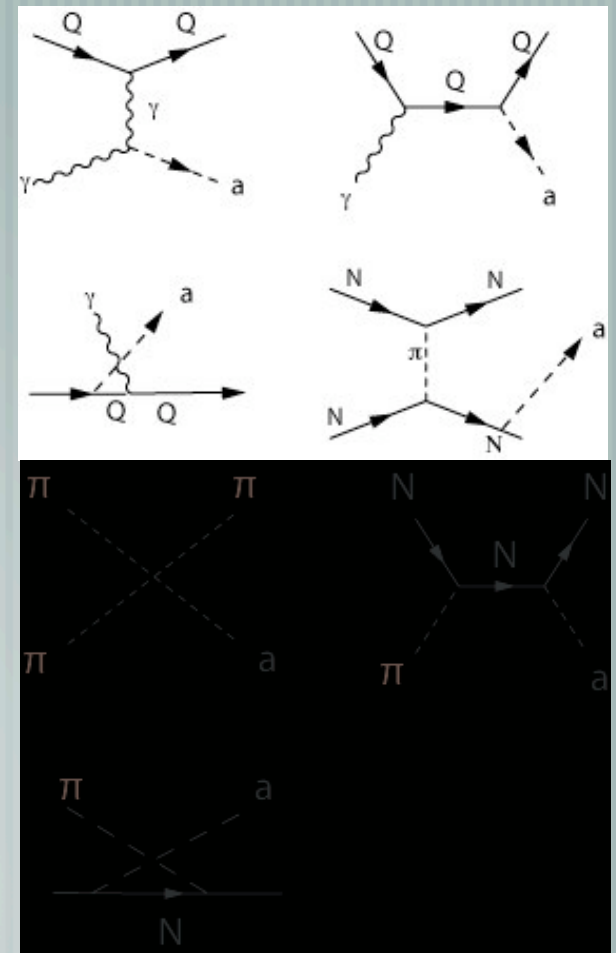
Axionic dark matter: Thermal production

— [If $m_{a,\text{eV}} \geq 10^{-2} \text{ eV}$, then axions are produced thermally.

— [$T_d \simeq 30 - 50 \text{ MeV}$

Chang/Choi (1993) follow relevant reactions numerically

— [In this regime, $\Omega_a h^2 = 0.007 m_{a,\text{eV}} (10/g_{*,D})$.



Axionic dark matter: Non-thermal production

- [After axions pick up mass at QCD phase transition, coherent oscillations follow: $\ddot{a} + 3H\dot{a} + m_a^2(T) a = 0$.
- [Eventually axions settle to their zero-T rest-mass (‘freeze-out’), yielding an abundance: $\Omega_a h^2 = 1.1 \times 10^{-6} m_{a,\text{eV}}^{-1.175}$
- [These axions form a zero-momentum condensate, and thus behave like CDM.

Axionic dark matter: Big picture

Thermal production ($m_{a,\text{eV}} > 10^{-2}$):

$$\Omega_a h^2 = 0.08 \left(\frac{m_{a,\text{eV}}}{11} \right) \left(\frac{10}{g_{*,D}} \right)$$

Nonthermal production ($m_{a,\text{eV}} < 10^{-2}$):

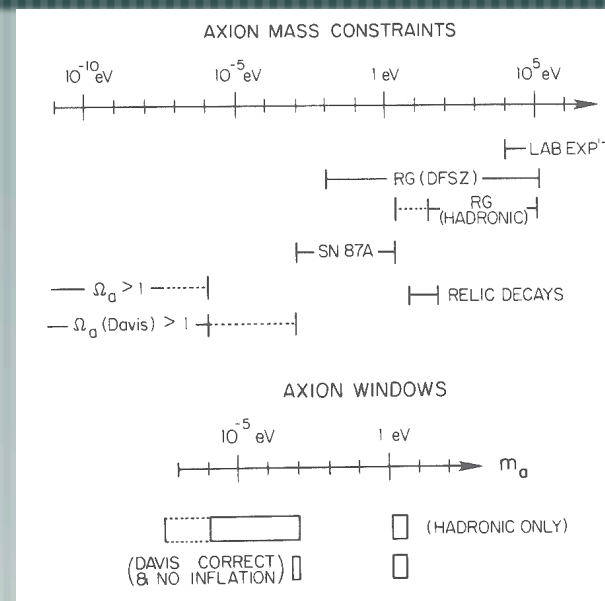
$$\Omega_{\text{mis}} h^2 \approx 1.1 \times 10^{-6} m_{a,\text{eV}}^{-1.175}.$$

Mass windows of interest:

$$5 \times 10^{-5} < m_{a,\text{eV}} < 10^{-3} \quad 0.004 < \Omega_a < 0.25$$

$$3 < m_{a,\text{eV}} < 8 \quad 0.04 < \Omega_a < 0.12$$

$$8 < m_{a,\text{eV}} < 14 \quad 0.12 < \Omega_a < 0.21$$



Galaxy clusters are axion laboratories

[Phase space aplenty:

$$x_a^{\max} = 10^{-2} m_{a,\text{eV}}^4 a_{250}^2 g_a \sigma_{1000}$$

$$x_a = \frac{\Omega_a}{\Omega_m}$$

[Density vs. lifetime

[Detectability:

$$\lambda_a = 24,800 \text{Å} (1 + z_{\text{cl}}) m_{a,\text{eV}}^{-1}$$

$$I_\lambda = \frac{6.8 \times 10^{-21} m_{a,\text{eV}}^7 \xi^2 \Sigma / (g \text{ cm}^{-2}) e^{\frac{-(\lambda_r - \lambda_a)^2}{\lambda_a^2} \frac{c^2}{2\sigma^2}}}{\sigma_{1000} (1 + z_{\text{cl}})^4 S^2(z_{\text{cl}})} \text{cgs}$$

[First attempts-A2218/A1413/A2256 at KPNO (2.1m) :

$$3 < m_{a,\text{eV}} < 8, \xi \leq 0.08 \text{ (Bershady et al. 1991).}$$

Galaxy clusters are axion laboratories: Why does it pay to look again?

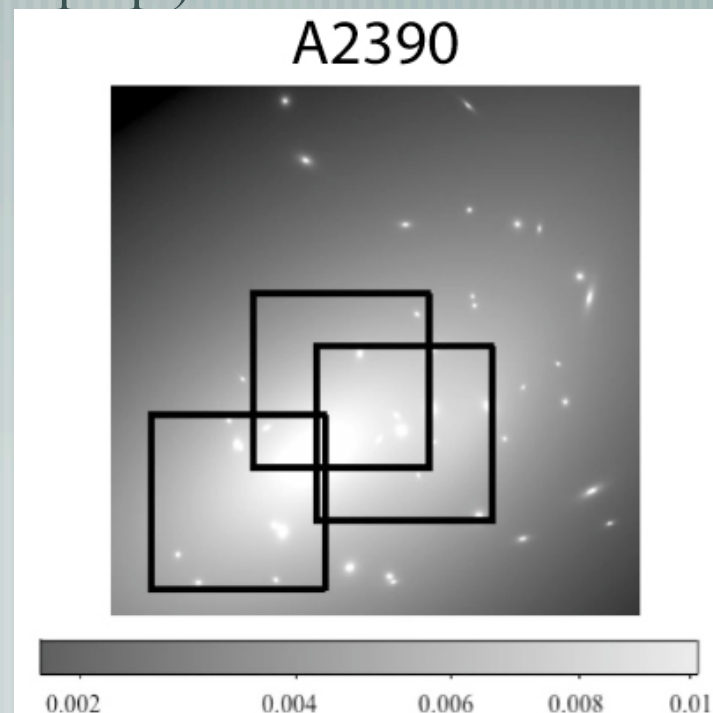
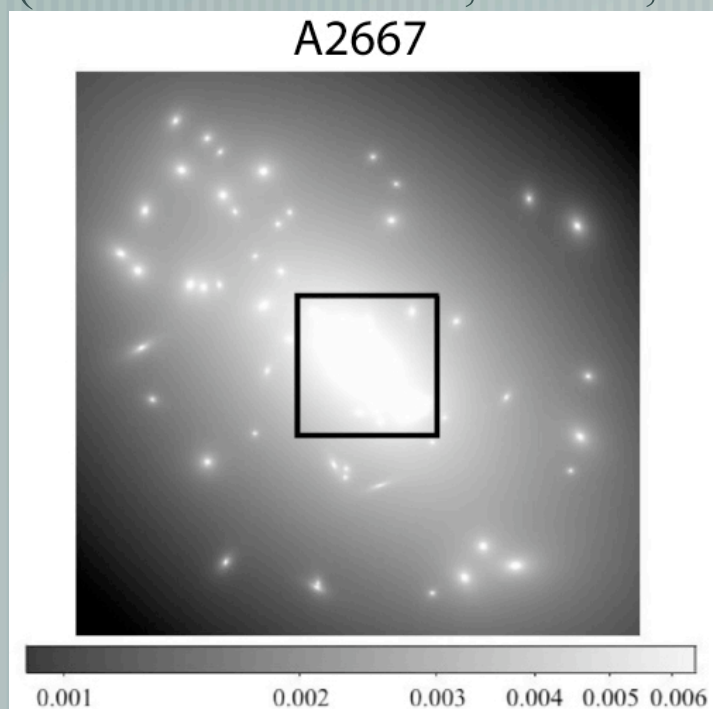
- [Better telescopes: 8.1m vs 2.0 m!
- [Better spectrographs: Integral field spectroscopy allows optimal use of cluster density profile to optimize S/N and sky subtraction
- [Better mass profiles: Cluster lensing maps
- [Parameter space is wide open

Data: VIMOS spectroscopy

- [Visible Multi-Object Spectrograph (VIMOS) IFU, mounted at UT3 at Paranal (largest fov of any IFU). 6400 fibers in 4 quadrants.
- [A2667/A2390 observed 06/27/06-06/30/06.
0.67''/fiber resolution mode used $\rightarrow 54'' \times 54''$ covered by IFU
- [LR-Blue grism (sufficient to resolve 195\AA $\sigma_{1000} m_{a,\text{eV}}^{-1}$ FWHM of axion line)
- [A2667: 10.8 ksec integration time (1 pointing)
A2390: 10.8 ksec integration (3 pointings)
- [Cosmic Rays are removed

Data: Cluster mass maps

- [Multi-component mass model constructed using lenstool (Kneib 1993)
- [PIEMD (pseudo-isothermal spheres) used for each component
- [Faber-Jackson like scaling relations used for smaller scale components (Covone et al. 2006, A2667; A2390 in prep)



Data Analysis I

- [4.5-7.7 eV window probed ($z \simeq 0.23$, $4000\text{\AA} < \lambda < 6800\text{\AA}$)
- [Bright sources are masked (HST images)
- [Using lensing map (HST), extract density-correlated signal.
Data Cube \longrightarrow 1D mean spectrum of clusters:

$$I_{\lambda,i}^{\text{mod}} = \langle I_{\lambda} / \Sigma_{12} \rangle \Sigma_{12,i} + b_{\lambda}$$

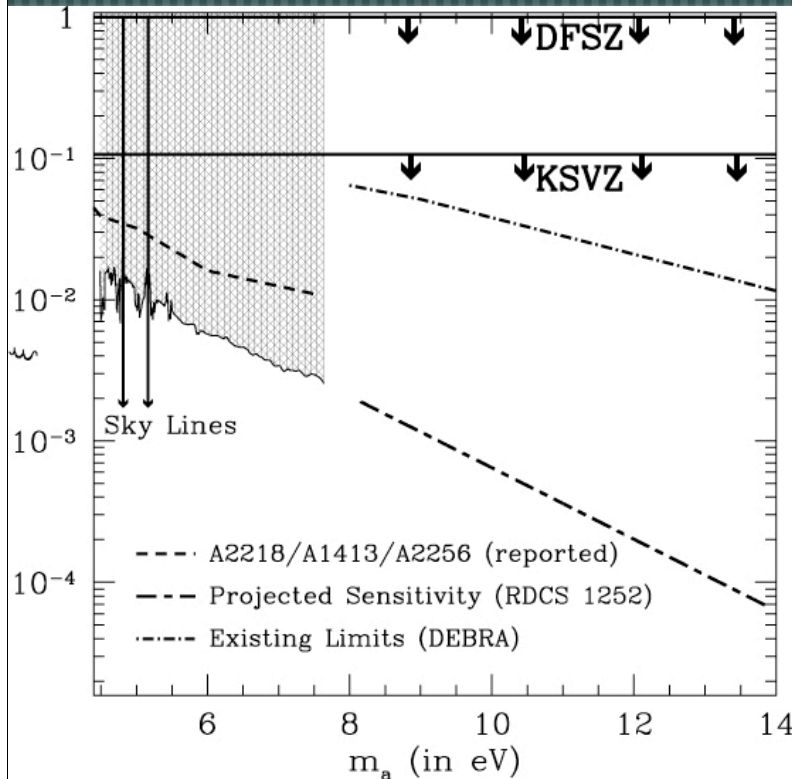
Data analysis II

- [Careful noise model] includes: Poisson Noise, fiber cross-talk, read-noise, flat-fielding, bias, statistical errors in mass map.
- [Signal sought via visual inspection, cross-correlation methods

$$g(l) = \frac{\int I_1(x) I_2(x+l) dx}{\left[\int I_1^2(x) dx \int I_2^2(x) dx \right]^{1/2}},$$

$x = \ln \lambda$

Results



Limit imposed via:

$$\xi \leq \sqrt{\frac{\sigma_{1000}(1+z_{cl})^4 S^2(z_{cl}) m_{a,\text{eV}}^7(\lambda) \langle I_\lambda / \Sigma_{12} \rangle}{2.30 \times 10^{-18} \text{ cgs}}}$$

Higher redshift clusters sensitive to weaker coupling

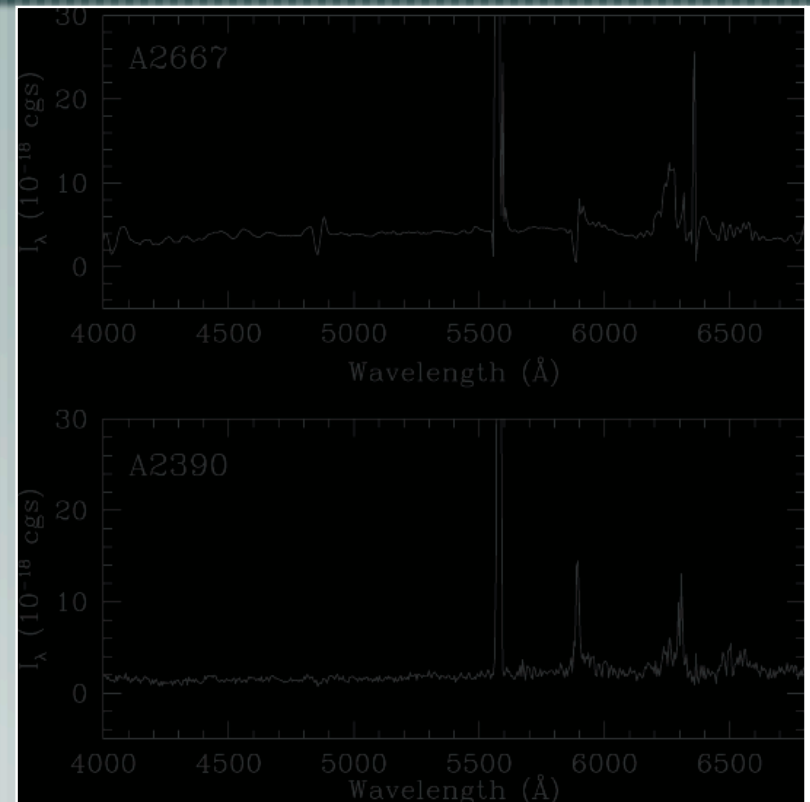
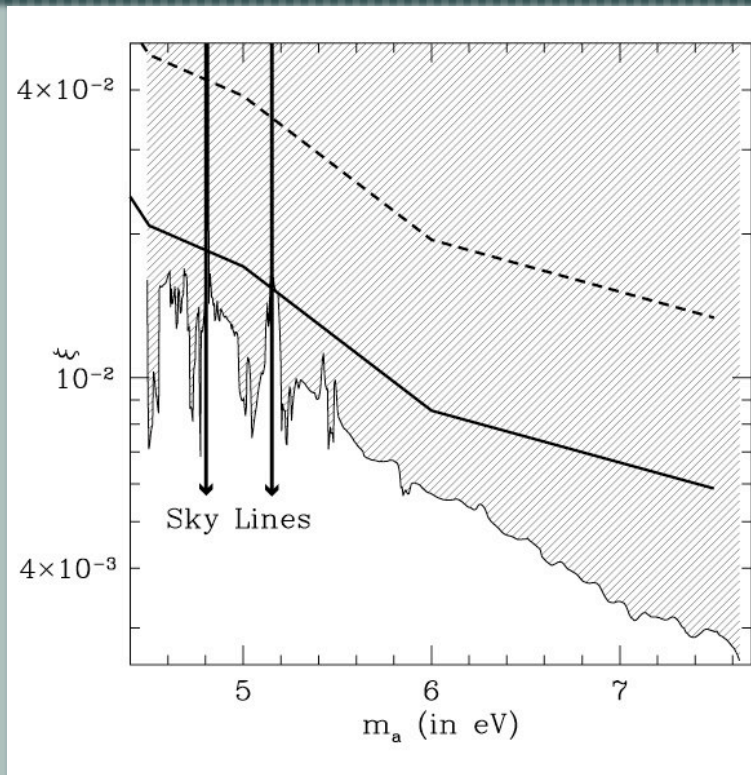
$$I_\lambda \propto m_a^7 (1+z_{cl})^{-4} \xi^2$$

$$m_a = 24,800 \text{ \AA} (1+z_{cl}) / \lambda_a$$

$$I_\lambda \propto \xi^2 (1+z_{cl})^3$$

$$\xi \propto I_\lambda^{1/2} (1+z_{cl})^{-3/2}$$

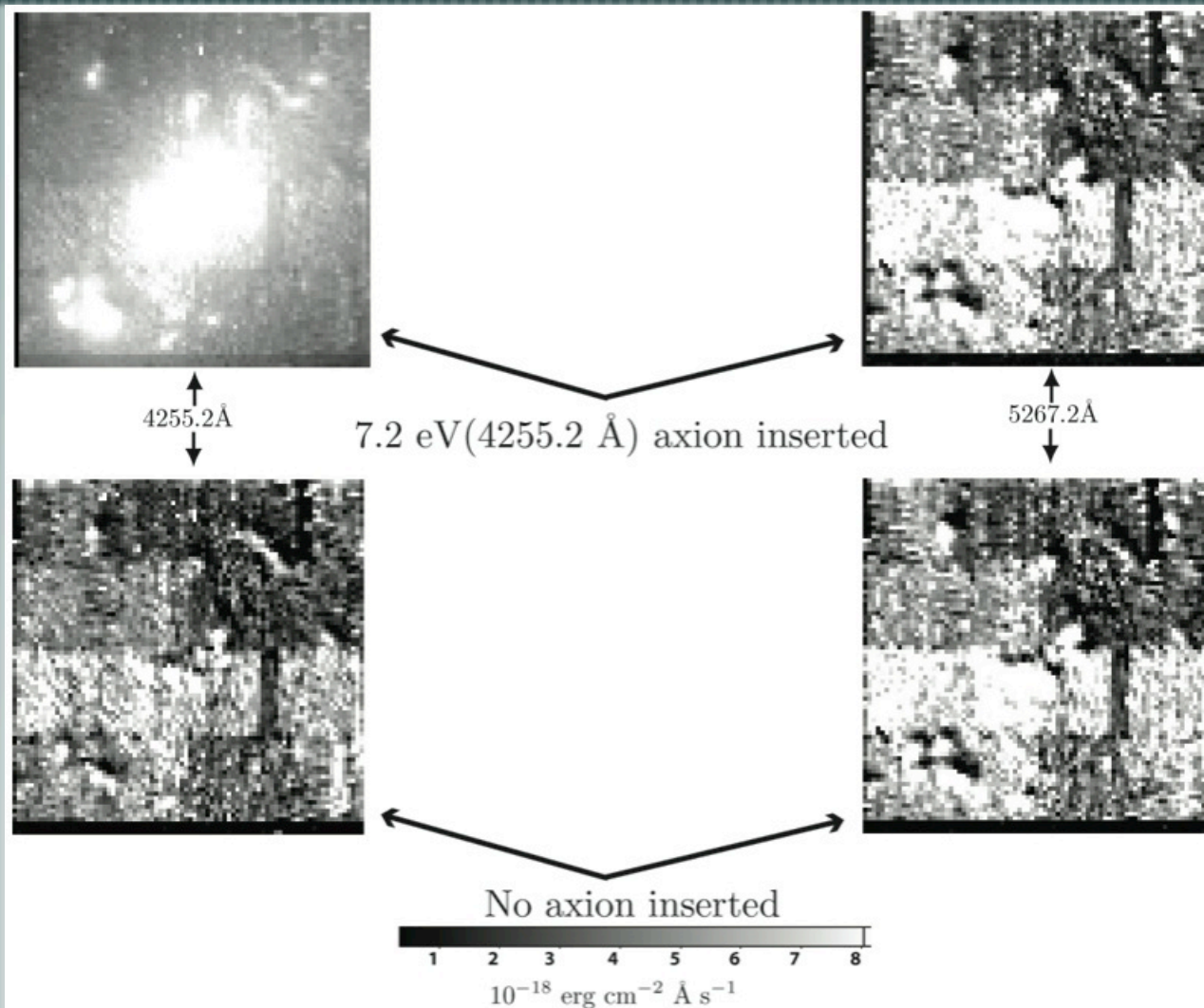
Results



- [Limits implied by past work re-calculated to take account of
- a) Better measurements of cosmo parameters,
 - b) Better measurements of cluster mass profiles

Simulations

- IFUs are messy!
- To model systematics, 'fake' lines inserted with variety of ξ values
- Routine that generates 1D spectra applied to 'fake' cubes.



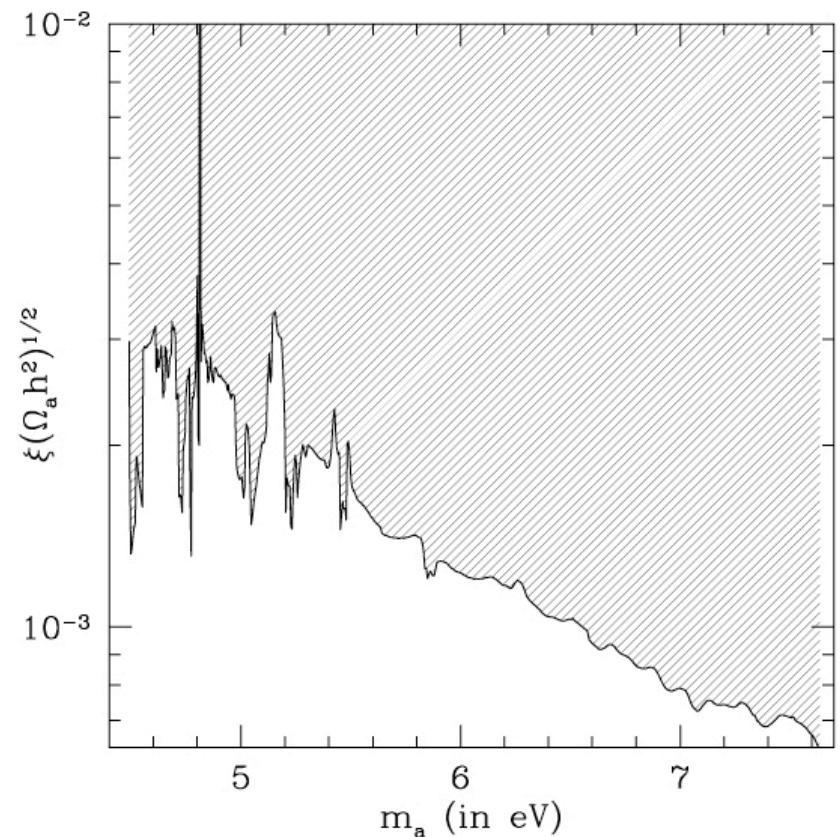
Independent constraints on $\sim\text{eV}$ axions: Axion free streaming/ISW effect

- [Light axions ($\sim\text{eV}$) are relativistic at early times; free-streaming erases structure on comoving scales
$$l < \lambda_{\text{fs}} = [19 \text{ Mpc} / (\Omega_{\text{a}} h^2)] \left\{ 1 + \ln \left[1.2 \left(\frac{\Omega_{\text{a}} h^2}{\Omega_{\text{m}} h^2} \right) \right] \right\},$$
leading to suppression in galaxy power spectrum.
- [Even lighter axions act like radiation at decoupling, amplifying decaying potential modes and leading to an enhanced ISW effect (Hu/Sugiyama 1995).
- [Hannestad et al. 2005 use this idea to derive a constraint $m_{\text{a}} < 1.05 \text{ eV}$.

Relaxing our assumptions

- [LSS/CMB limits assume thermal production (TP)
- [$\Omega_a h^2$ is a free parameter if TP assumption dropped
- [New Constraint:

$$\xi \sqrt{\Omega_a h^2} \leq \left[\frac{\sigma_{1000} (1+z_{cl})^4 S^2(z_{cl}) m_{a,\text{eV}}^6(\lambda) \left\langle \frac{I_\lambda}{\Sigma_{12}} \right\rangle}{3.48 \times 10^{-16} \text{ cgs}} \right]^{1/2}$$



Why relax our assumptions?

Modified reheating....

Kawasaki and Kohri 1999,

Giudice, Kolb, Riotto, Semikoz, and Tkachev 2000

- [**Solid** understanding of cosmic thermal history up to 1 MeV (BBN): We should be agnostic at higher energy scales.
- [After inflation, we think the universe (pre)-reheats, creating a finite-temperature radiation bath, in EQ with SM particles. Energy density of this bath defines a temperature T
- [Suppose (pre)-reheating is driven by some decaying scalar field with finite lifetime Γ_ϕ :
 $\phi \rightarrow \gamma\gamma$
 $\gamma\gamma \rightarrow XX$
- [Reheating temperature defined by $\Gamma_\phi = H(T_{\text{rh}})$

More on extended reheating

- [Interesting to consider consequences of lower (\sim MeV) reheating temperature
- [Entropy **continually** dumped from scalar field to radiation
- [Temperature falls slower than $T \propto 1/a \rightarrow T \propto a^{-3/8}$
- [Steeper dependence of scale factor on temperature \rightarrow higher H.
- [Chemical equilibrium requires $n\langle\sigma v\rangle/H > 1$: harder with higher H.

Some species never freeze out at all

Others freeze-out earlier

} Lower abundances for given mass!

Extended reheating conclusions

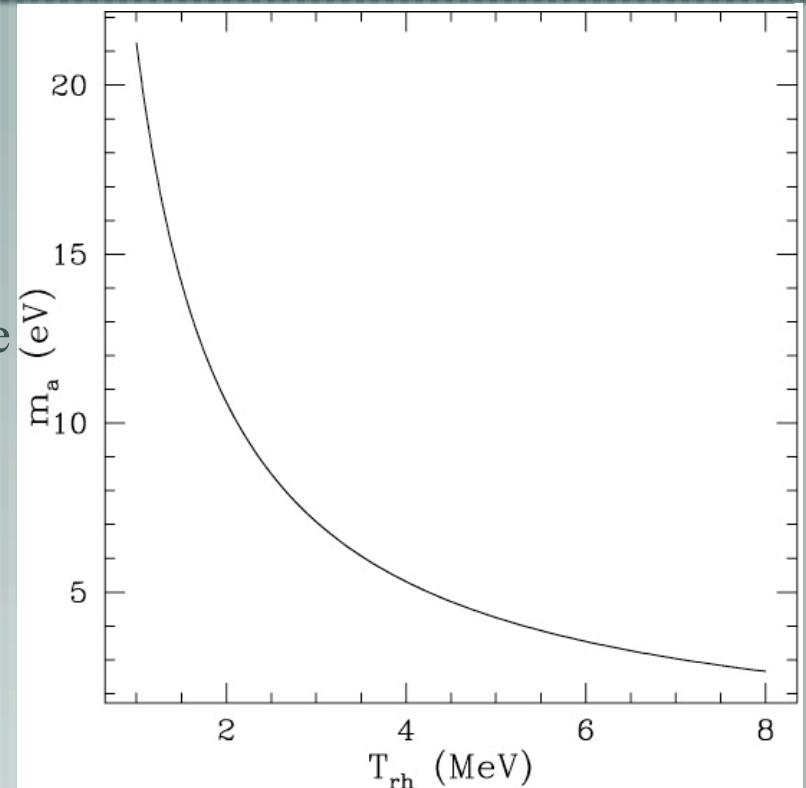
[From solution of Boltzmann equation, can see abundance of hot relics for a given mass is suppressed

[Constraints on neutrino mass from $\Omega_\nu h^2 < (1, 0.007)$ nearly lifted

[Using relevant axion cross section

$$\langle \sigma v \rangle \approx \frac{(1+z)^2 T^2 m_a^2}{z m_\pi^2 f_\pi^2} \rightarrow$$

$$\Omega_a h^2 \approx 7.3 \times 10^{-7} m_{a,\text{eV}}^3 (T_{\text{rh}}/\text{MeV})^3 [10/g_*(T_{\text{rh}})]^{3/2}$$



Recent excitement & future work

- [**Conservative** improvement on past constraints to ξ of ~ 3
- [Results free of dynamical assumptions about cluster
- [Robust exclusion of naive DFSZ/KSVZ models
- [Proof of technique:
RDCS1252 ($z=1.2$) will probe **new swathe of parameter space**.
- [PVLAS- Axion signal?

Summary

- [Axions solve the strong CP problem
- [Axions are a promising dark matter candidate
- [Presently, cluster spectra offer tight constraints to ξ
- [**Future work** on high- z clusters will seek 8-14 eV axions that may have **very weak two-photon couplings**).
- [First use of IFU spectroscopy to constrain nature of DM