Forecasting the Axiverse

David J. E. Marsh, Edward Macaulay, Maxime Trebitsch and Pedro G. Ferreira,
arXiv:astro-ph/1110.0502.

David J. E. Marsh,
Berkeley, 1/12/11

Oxford Physics

Outline

- Introduction: standard models
- The "String Axiverse"
- Axions and Cosmology
- Forecasts ("Euclid-like")
- Conclusions and outlook

The Concordance Model

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- Radiation: T_{CMB} Photons

  $N_{\rm eff}$ Relativistic species, e.g. massless neutrinos

- Ordinary matter: Ω_b Baryons

- Dark sector: Ω_d Dark matter

  Ω_Λ Dark energy

$$\Omega_m = \Omega_b + \Omega_d$$

- Initial conditions:

  n_s, A_s … Inflation

The Standard Model

- Gauge forces: EM, strong and weak forces.

  nucleosynthesis, recombination…

- Matter: quarks and leptons

  baryons, massless neutrinos

- Neutrino masses?
- Strong CP problem and axions?

The Dark Sector

- Standard model has no candidates.
- Cosmology: CDM and a c.c. can fit all data.
  Komatsu et al (WMAP 7, 2011)
- Extra relativistic species?
  Dunkley et al (ACT, 2010)
- DE equation of state or EDE?
- Particle Physics: CDM = WIMP (e.g. LSP).
- In addition, need massive neutrinos (observationally) and possibly axions (theoretically).
  Giunti, arXiv:1106.4479 (2011)
  Peccei and Quinn, PRL 38,1440 (1977)

Dark Matter is multi-component!

The Axiverse: what?

Arvanitaki et al PRD 81, 123530 (2010)

"String theory suggests the simultaneous presence of many ultra-light axions, possibly populating each decade of mass down to the Hubble scale, 10^{-33} eV"

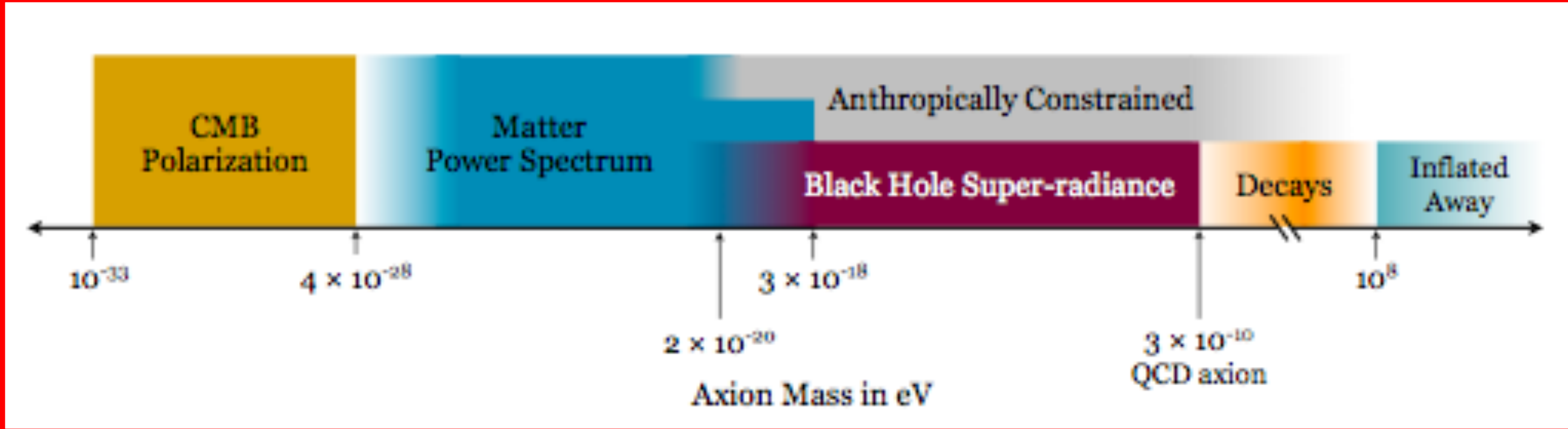
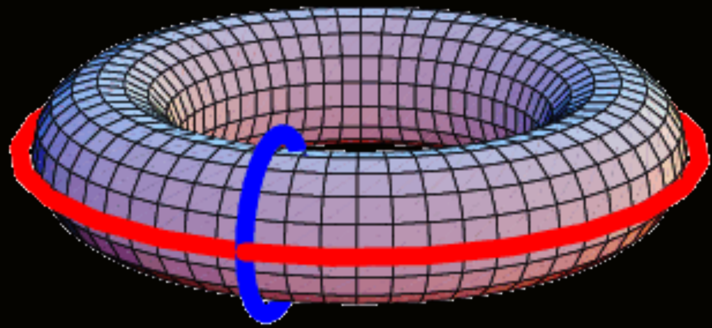


Figure: Arvanitaki et al

The Axiverse: how?

Svrcek and Witten, arXiv:hep-th/0605206

- String theory has extra dimensions: compactify.



- Axions are KK zero-modes of antisymmetric tensor fields compactified on closed cycles.

- Potentials from non-perturbative physics (D-branes, instantons etc.).

Many pseudo Goldstone bosons

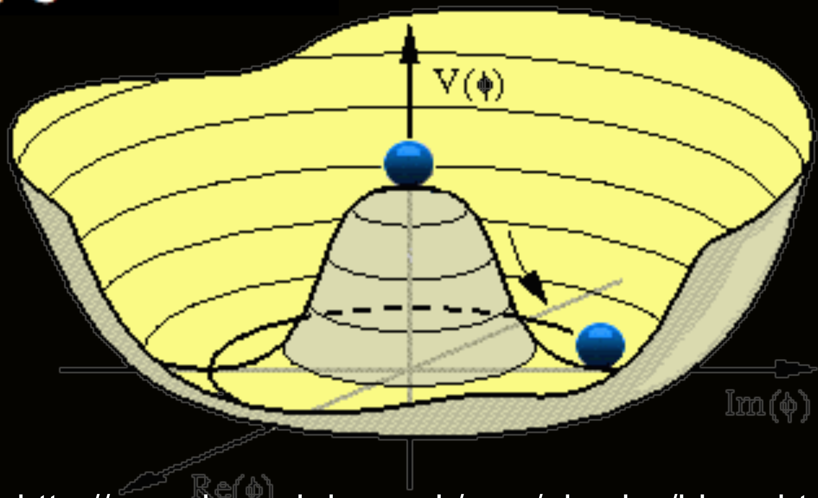
The Axiverse and QCD

- Require the QCD axion to solve strong CP:

$$\mathcal{L} \supset \theta \tilde{F}_{\mu\nu} F^{\mu\nu}$$

$$\theta = \theta_T + \theta_M$$

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



http://www.hep.ph.ic.ac.uk/cms/physics/higgs.html

- SSB at scale f_a, then instantons tilt the hat.

- The QCD axion must remain light to achieve this.

Many axions will remain light

The Axiverse in this work (and why)

- Scales depend on the action of the instantons:

$$\mathcal{L} = \frac{f_a^2}{2}(\partial\theta)^2 - \Lambda^4 U(\theta)$$

$$f_a \sim \frac{M_{pl}}{S} \quad f_a \sim 10^{16}\mathrm{GeV} \quad \Lambda^4 = \mu^4 e^{-S}$$

- Instanton action scales with the area of a cycle.

The Axiverse in this work (and why)

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- Canonically normalised axions are weakly coupled

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

$$V(\phi) = \frac{1}{2}m_a^2\phi^2 \qquad m_a^2 = \frac{\Lambda^4}{f_a^2}$$

- Masses distribute on a log scale:

$$10^{-33}\text{eV} \lesssim m_a \lesssim 10^{-28}\text{eV}$$

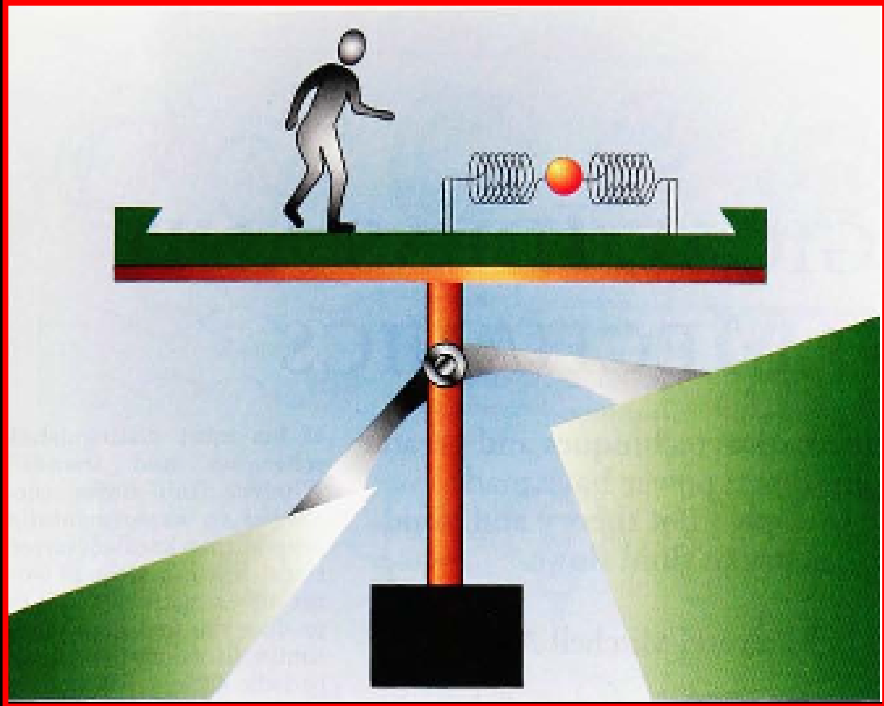
A source of ultra-light scalar dark matter

Interlude

Sikivie, Physics Today, Dec. '96

• You observe a flat table in a room with a slanted floor. How?

• You propose a mechanism to straighten it accurately: gravity.



• The required accuracy requires a long arm and heavy weight.

• How can you test this? Look for relic oscillations from production.

Comments on Axions

- Well defined measure for abundance.

  Tegmark et al, PRD (2006)

- Fine tuning? Mack and Steinhardt, JCAP (2011)

- Isocurvature and gravity waves give constraints.

  Fox et al, hep-th/0409059

- Motivated as dark matter in many different contexts.

  Sikivie, arXiv:1003.2426

- Couplings give further constraints.

  Mortsell and Goobar, JCAP (2003)

- Axions and inflation.

  Linde, PLB (1991)

- Monodromy quintessence, BH superradiance, …

  Panda et al, arXiv:1011.5877

  Arvanitaki and Dubovsky, PRD (2011)

Axiverse Extended

DJEM, PRD (2011)

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- Coupling to a modulus:

$$V(\phi,\chi) = Be^{-2C\chi} - De^{-C\chi} + \frac{1}{2}e^{-\tilde{C}\chi}M^2\phi^2$$

- Stabilisation in an attractor.
- Potential to solve initial conditions problem for axion?
- EDE and dark energy dynamics.
- Collapsing universe is asymptotic future.

Cosmology of the Axiverse I

- Equations of motion:

Ma and Bertschinger, APJ (1995)

Hu, APJ (1998)

$$\ddot{\phi}_0 + 2\mathcal{H}\dot{\phi}_0 + m_a^2 a^2 \phi_0 = 0$$

$$\ddot{\phi}_1 + 2\mathcal{H}\dot{\phi}_1 + (m^2 a^2 + k^2)\phi_1 = -\frac{1}{2}\dot{\phi}_0 \dot{h}$$

- Stress energy tensor:

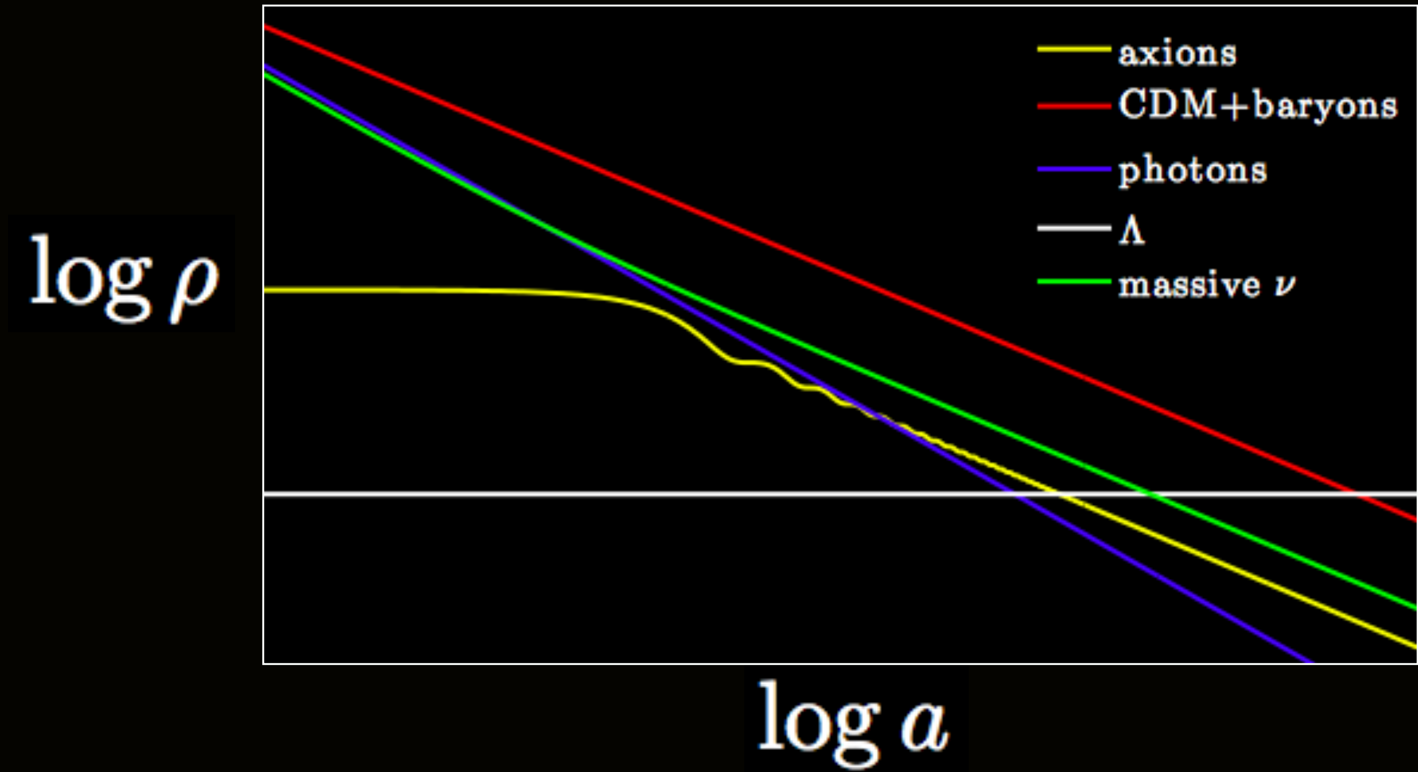
$$\rho_a = \frac{a^{-2}}{2}\dot{\phi}_0^2 + \frac{m_a^2}{2}\phi_0^2 \qquad P_a = \frac{a^{-2}}{2}\dot{\phi}_0^2 - \frac{m_a^2}{2}\phi_0^2$$

$$\delta\rho_a = a^{-2}\dot{\phi}_0\dot{\phi}_1 + m_a^2 \phi_0 \phi_1$$

$$\delta P_a = a^{-2}\dot{\phi}_0\dot{\phi}_1 - m_a^2 \phi_0 \phi_1$$

$$(\rho + P)\theta_a = a^{-2}k^2\dot{\phi}_0$$

Background Evolution



- Different background scaling implies different effects on matter-radiation equality, and hence on the CMB.
- Relic density is non-thermal.

Cosmology of the Axiverse II

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- WKB approx. gives a scale dependent sound speed:

$$c_s^2 = \frac{k^2}{4m_a^2 a^2}; \quad k < 2m_a a$$

$$c_s^2 = 1; \quad k > 2m_a a$$

Hu et al, PRL (2000)

Amendola and Barbieri, PLB (2006)

- Process analogous to neutrino free-streaming:

$$\frac{k_m}{H_0} = (2\Omega_m)^{1/3}\left(\frac{m_a}{H_0}\right)^{1/3}; \quad k_m < k_{eq}$$

$$\frac{k_m}{H_0} = \left(\frac{4\Omega_m}{1+z_{eq}}\right)^{1/4}\left(\frac{m_a}{H_0}\right)^{1/2}; \quad k_m > k_{eq}$$

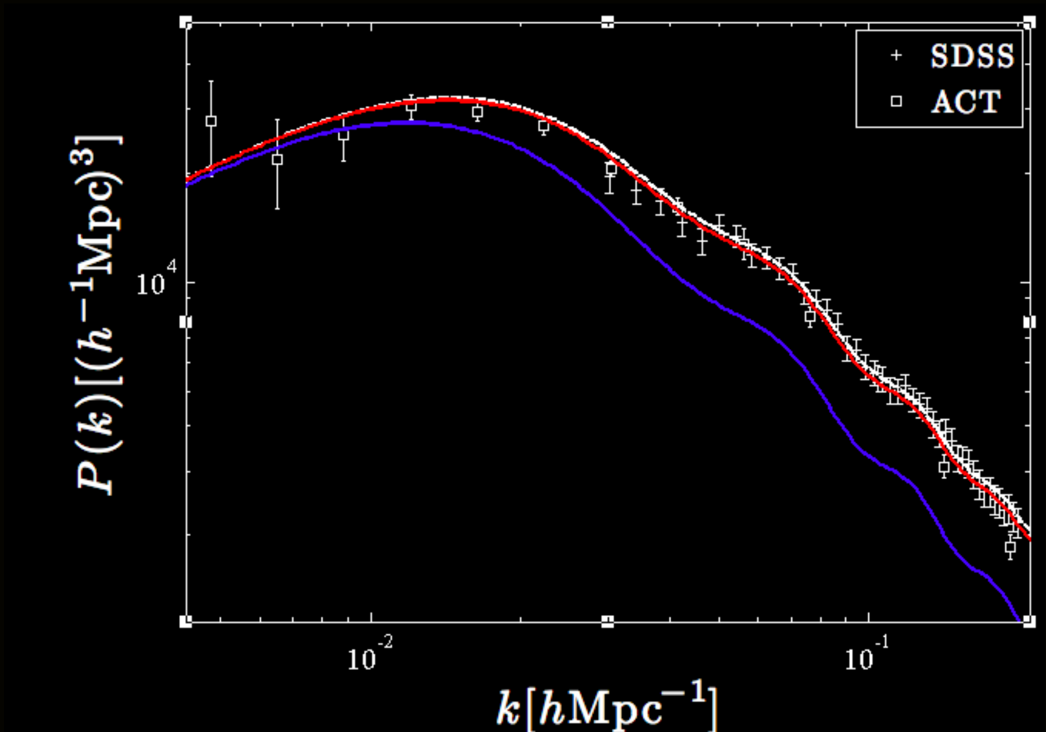
Axion "Free-Streaming"

DJEM and Ferreira, PRD (2010)

- This leads to steps in the matter power spectrum:

$$T_m(k,z,\tilde{f}_{ax}) = \tilde{f}_d T_{ax}(k,z,\tilde{f}_{ax}) T_c(k,\tilde{f}_{ax}=0) + \tilde{f}_b T_b(k,\tilde{f}_{ax})$$

DJEM and Ferreira, PRD (2010) Eisenstein and Hu, APJ (1997)



- Many degeneracies as for massive neutrinos.

Hu, Eisenstein, Tegmark, PRL (1998)

Important Scales

m_a (eV)	$k_m (h\text{Mpc}^{-1})$	$\bar{k}_m (h\text{Mpc}^{-1})$	z_{osc}
10^{-29}	0.0058	0.0575	350
10^{-30}	0.0027	0.0267	74
10^{-31}	0.0012	0.0124	15
10^{-32}	0.0006	0.0057	2.4

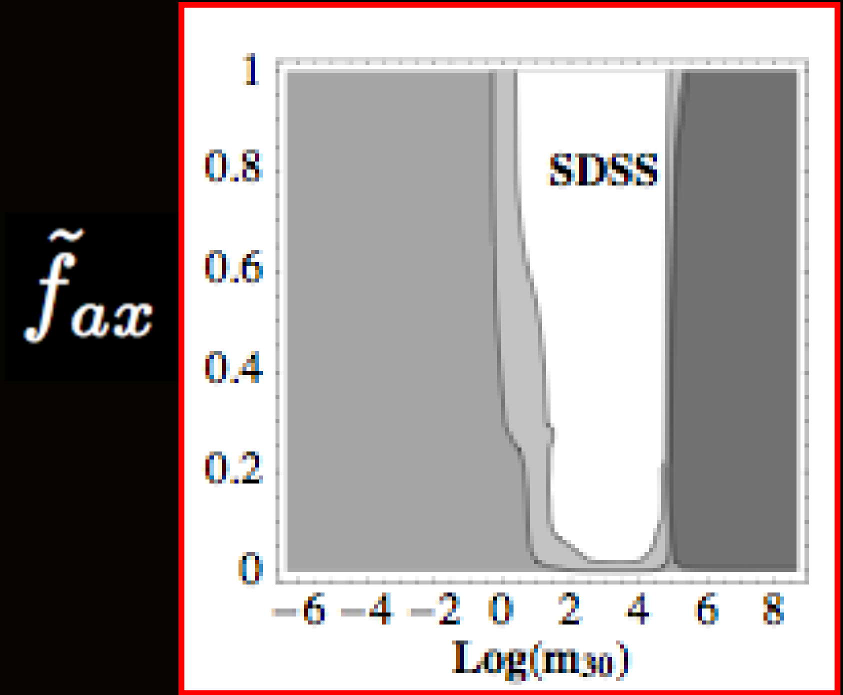
$$k_{eq}(f_{ax} = 0) = 0.0136h\,\text{Mpc}^{-1}$$
$$k_{eq}(f_{ax} = 0.01) = 0.0135h\,\text{Mpc}^{-1}$$
$$k_{FS}(m_\nu = 0.055\,\text{eV}, z = 0) = 0.0451h\,\text{Mpc}^{-1}$$

DJEM et al, arXiv:1110.0502

$$\tilde{f}_{ax} = \frac{\Omega_a}{\Omega_m} \qquad f_{ax} = \frac{\Omega_a}{\Omega_d}$$

Implementation

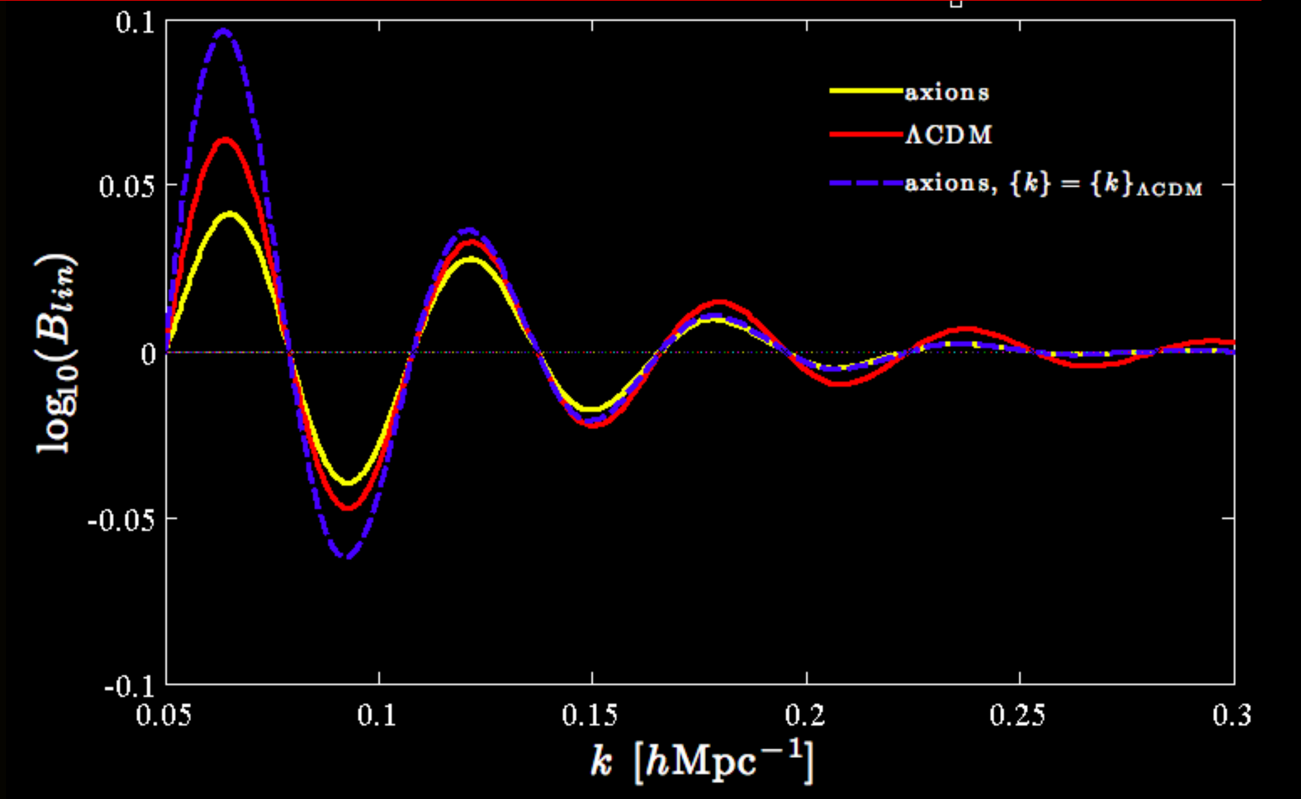
- Module for CAMB solves field equations and oscillations.
- Mass range restricted by this choice.



Amendola and Barbieri, PLB (2006)

Observables: P(k) and BAO

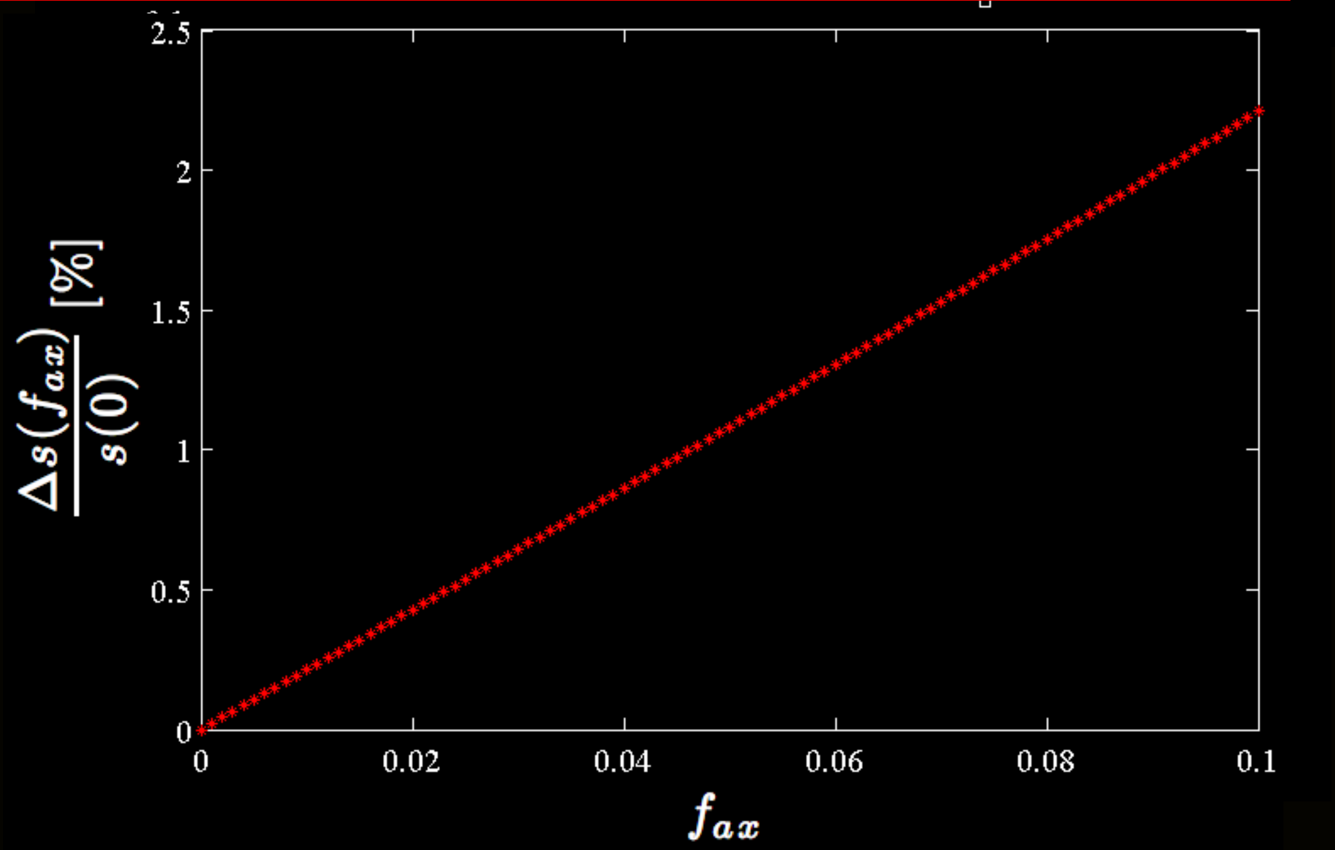
DJEM et al, arXiv:1110.0502



$$B_{lin} = \frac{T^2_{m,\mathrm{full}}(k)}{T^2_{m,\mathrm{no\ osc}}(k)}$$

Observables: P(k) and BAO

DJEM et al, arXiv:1110.0502



- Model for smooth part changes: bias?
- Small change in sound horizon from background.

Observables: Growth Rate

DJEM et al, arXiv:1110.0502

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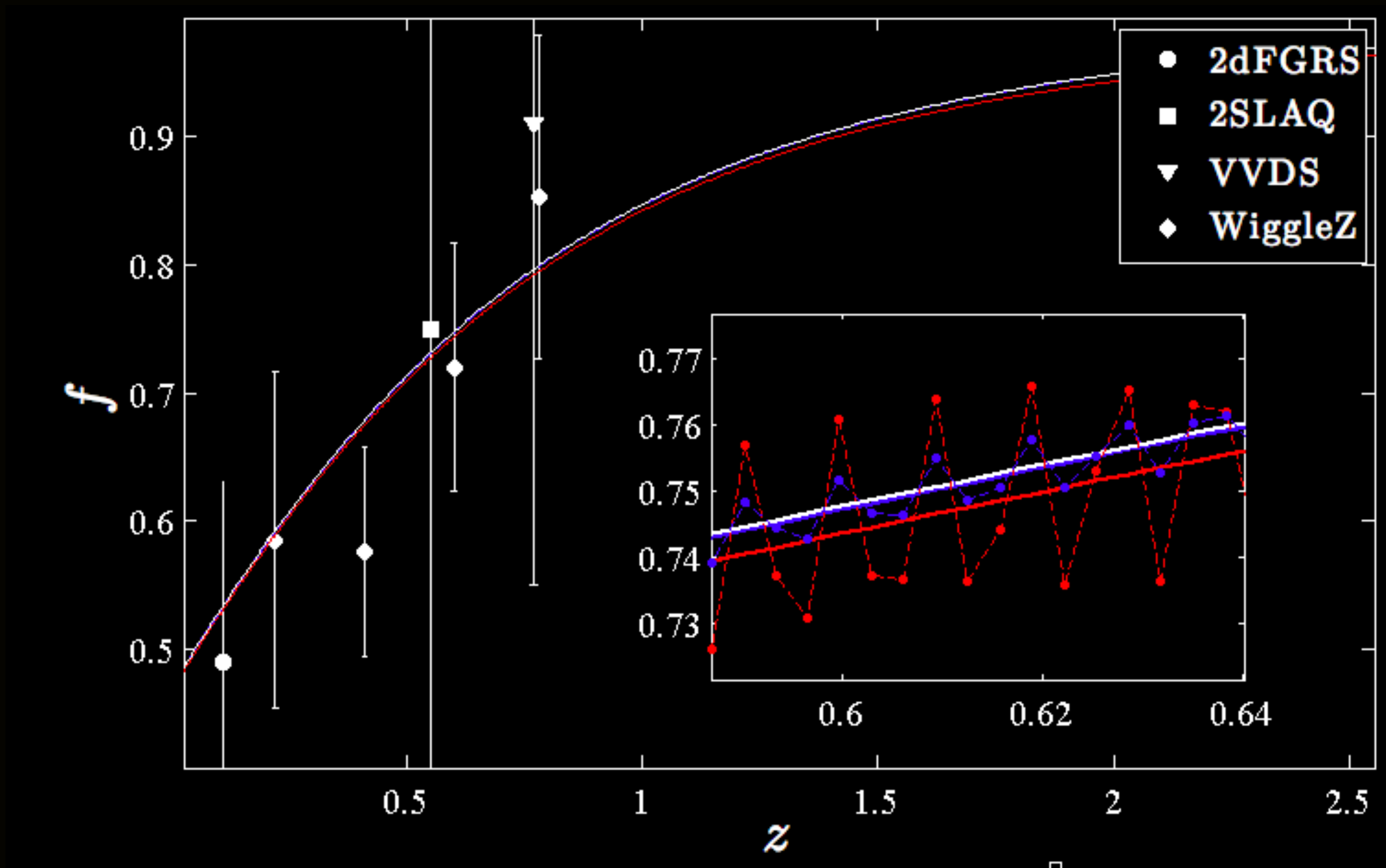
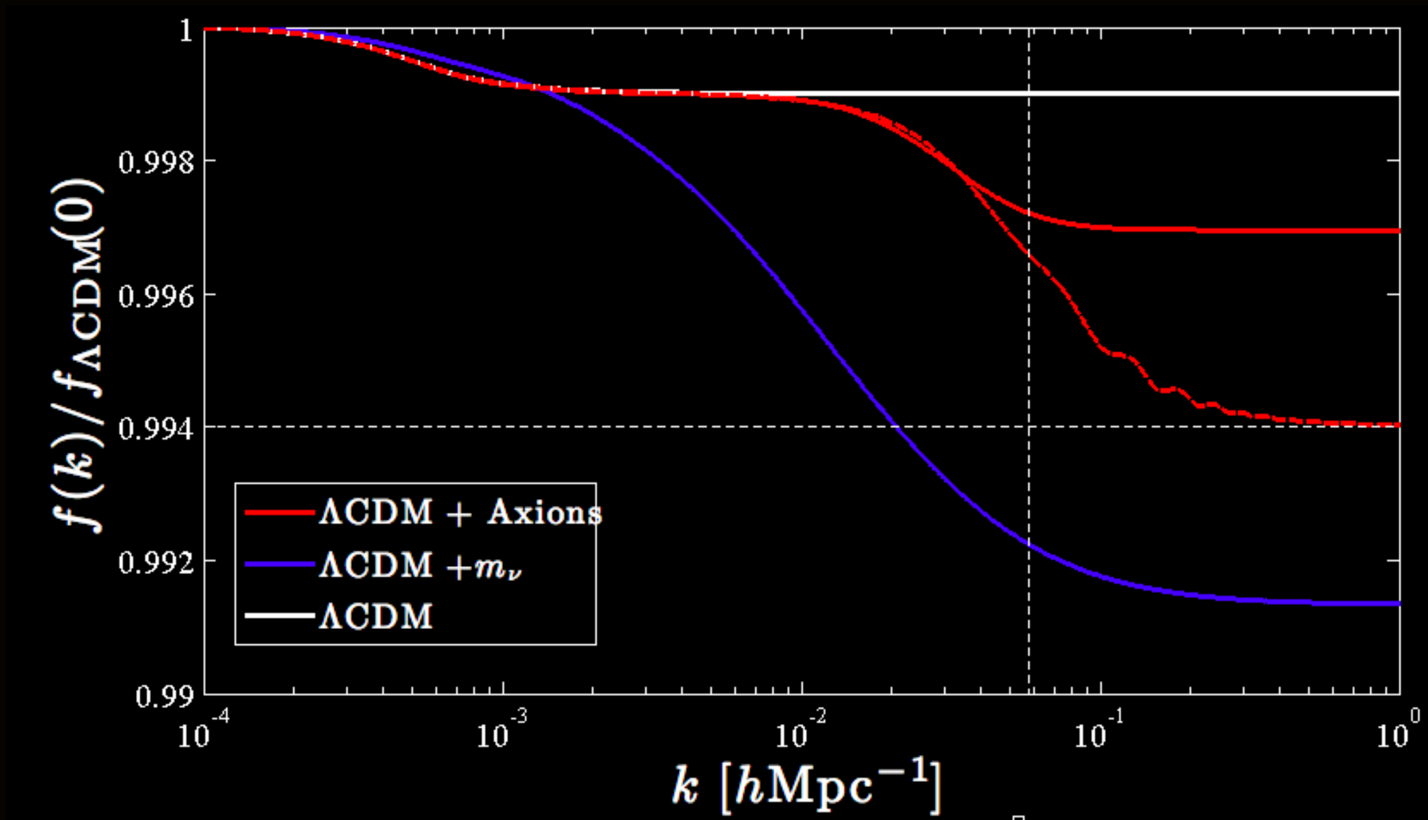


$$f = \frac{d \ln \delta}{d \ln a} = \frac{\dot{\delta}}{\mathcal{H}\delta}$$

Observables: Growth Rate

DJEM et al, arXiv:1110.0502



- Scale dependent growth, degenerate with more CDM.
- Unique signal needs large scale measurement.

Observables: Weak Lensing

DJEM et al, arXiv:1110.0502

Oxford Physics

- Convergence power spectrum measures dark matter density directly from galaxy shear.

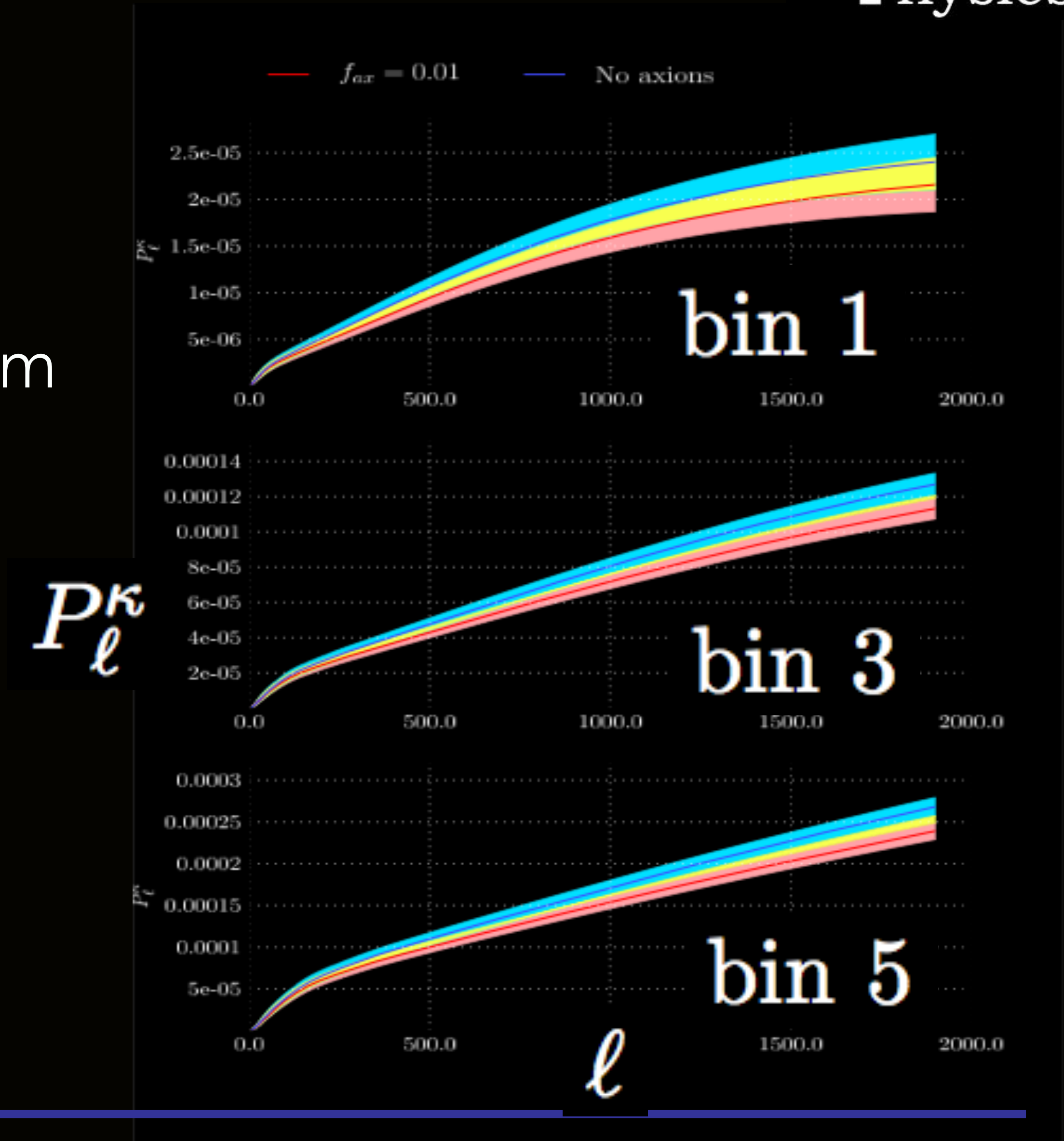
$$P_l^\kappa = \int_0^{\chi_\infty} \mathrm{d}\chi \frac{W^2(\chi)}{r^2(\chi)} P(l/r(\chi), z)$$

- Window function sets redshift bin: tomography.

Observables: Weak Lensing

- Indistinguishable from LCDM in single bin.
- Growth amplitude from tomography gives very strong constraints.

Hu, PRD (2002)



Observables: CMB

- Most effects can be removed due to total degeneracy with horizon size and equality redshift.
- Breaks degeneracy with neutrino mass and number.
- Constraining power in ISW due to oscillations near recombination: used in checks.
- Larger effects in lensing not used because of correlations.

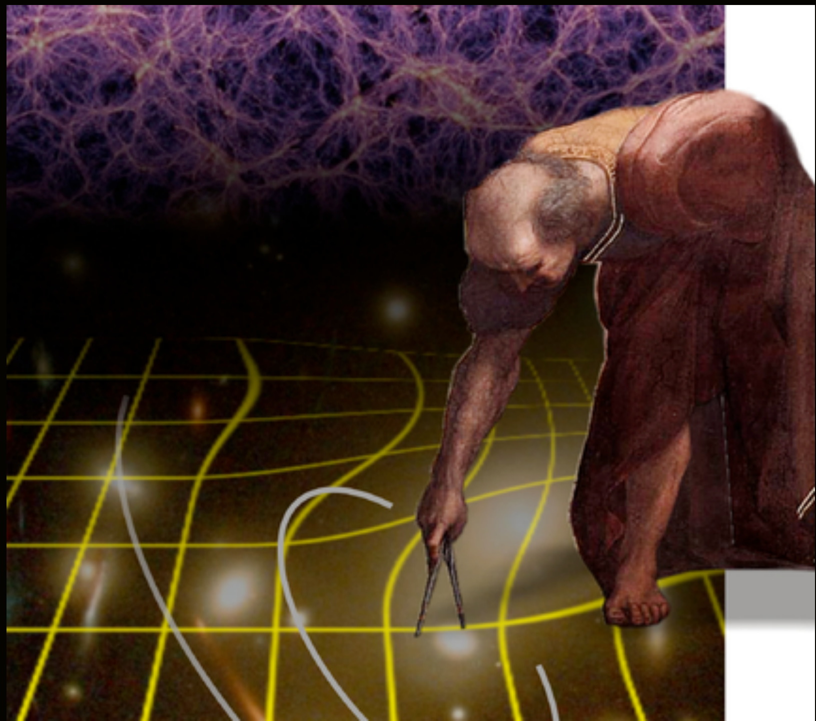
Forecasts: Implementation

- Fisher Matrix forecast for Planck + Euclid.
- CMB uses FIsherCodes by Sudeep Das.

  http://www.astro.princeton.edu/~sudeep/fisherCodesDoc
- GRS and WLT are our own, by Edward and Maxime.

Forecasts: Euclid

http://sci.esa.int/euclid
arXiv:1110.3193



"The Euclid survey can be thought of as the low-redshift, 3-dimensional analogue and complement to the map of the high redshift Universe provided by ESA's Planck mission".

Forecasts: Survey Parameters

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- Planck: TT, TE, EE in 100, 143 and 217 GHz.

$$f_{sky} = 0.8 \qquad \ell_{max} = 2000$$

- Euclid GRS: 15 redshift bins of varying volume.

$$0.5 < z < 2$$

Spectroscopic

$$0.146h \text{ Mpc}^{-1} \leq k_{max} \leq 0.2h \text{ Mpc}^{-1}$$

43.68 million galaxies at a constant density of:

$$1 \times 10^{-3} [h\text{Mpc}^{-1}]$$

- Euclid WLT: 5 redshift bins, with constant # of sources.

$$0 < z < 3$$

Photometric

$$f_{sky} = 0.5 \qquad \ell_{max} = 1900$$

Forecasts: Fiducial Models

- Fixed Hubble: $H_0 = 71.9 \text{ km s}^{-1}\text{Mpc}^{-1}$
- Test 4 axion masses:

$$m_a = 10^{-32}, 10^{-31}, 10^{-30}, 10^{-29}\text{eV}$$

Forecasts: Fiducial Models

Oxford Physics

- Fiducial cosmology:

$$\Omega_b h^2 = 0.02258 \qquad \Omega_c h^2 = 0.1109$$

$$A_s = 2.3 \times 10^{-9} \qquad n_s = 0.963$$

$$N_{\rm eff} = 3.04 \qquad m_\nu = 0.055 \text{ eV}$$

$$f_{ax} = 0.01 \qquad w = -1$$

- Marginalise over:

$$Y_{He} = 0.24 \qquad \tau = 0.166$$

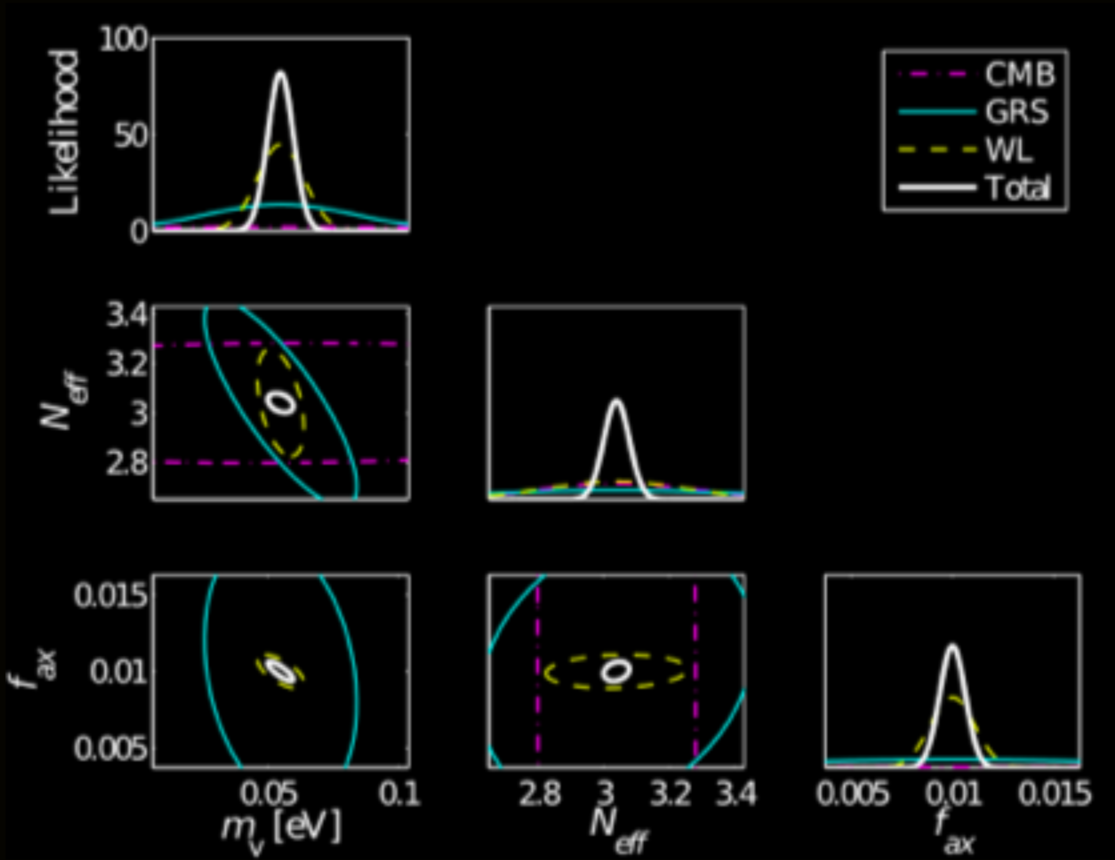
$$b = 1.7 \qquad \sigma_v = 350 \text{ km s}^{-1}$$

Forecasts: Results

DJEM et al, arXiv:1110.0502

Oxford Physics

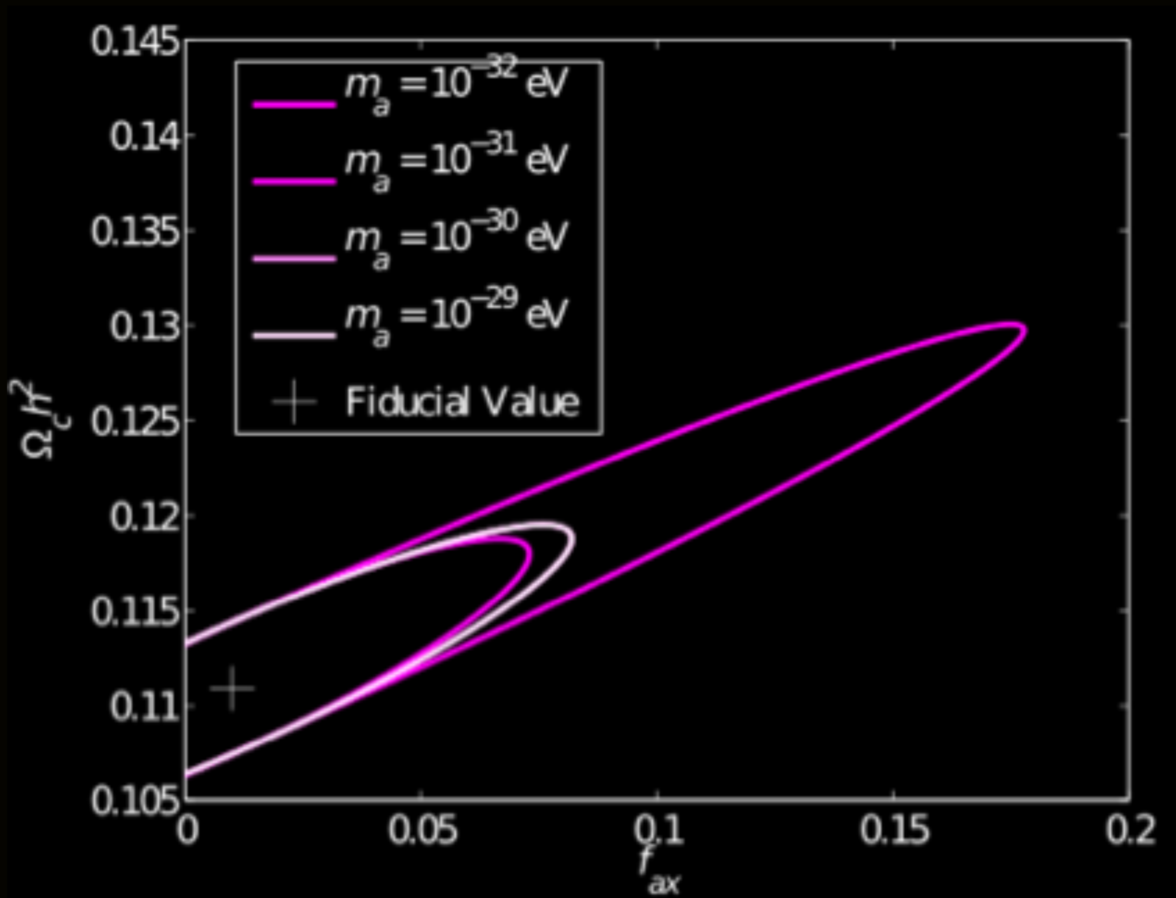
- Compare with massive neutrinos:



Forecasts: Results

DJEM et al, arXiv:1110.0502

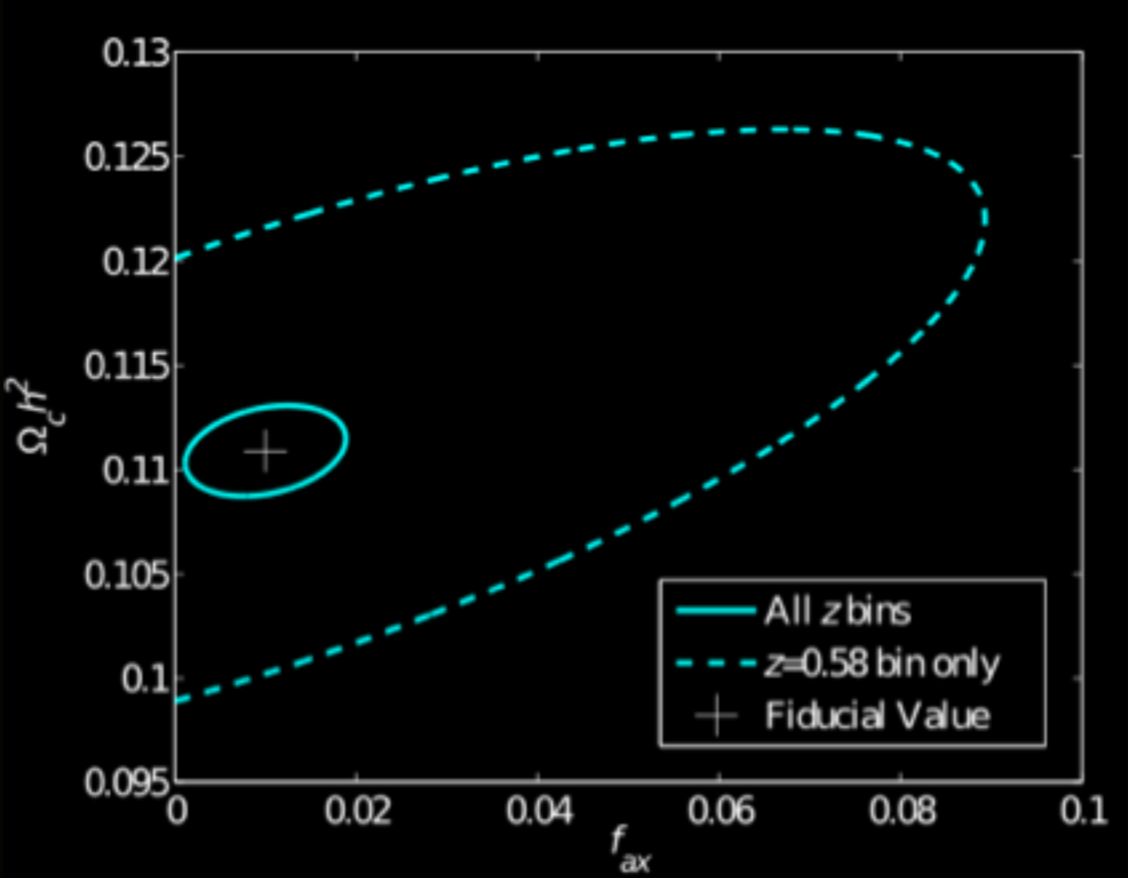
- Strong CMB degeneracies:



Forecasts: Results

DJEM et al, arXiv:1110.0502

- Value of combining redshift information:

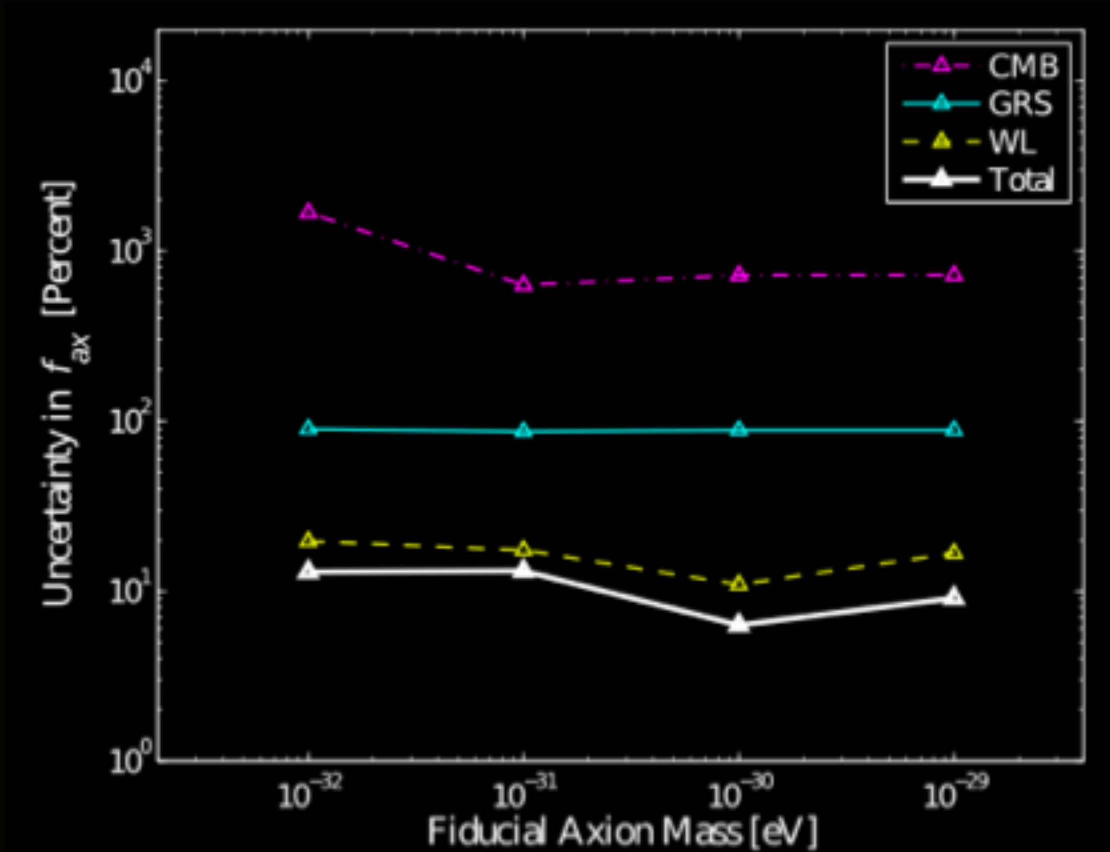


GRS alone can constrain 1% at 1σ

Forecasts: Results

DJEM et al, arXiv:1110.0502

- Combined results:



1σ

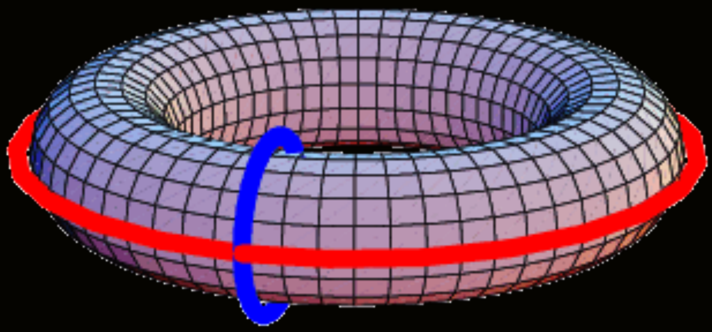
Mass independent constraints

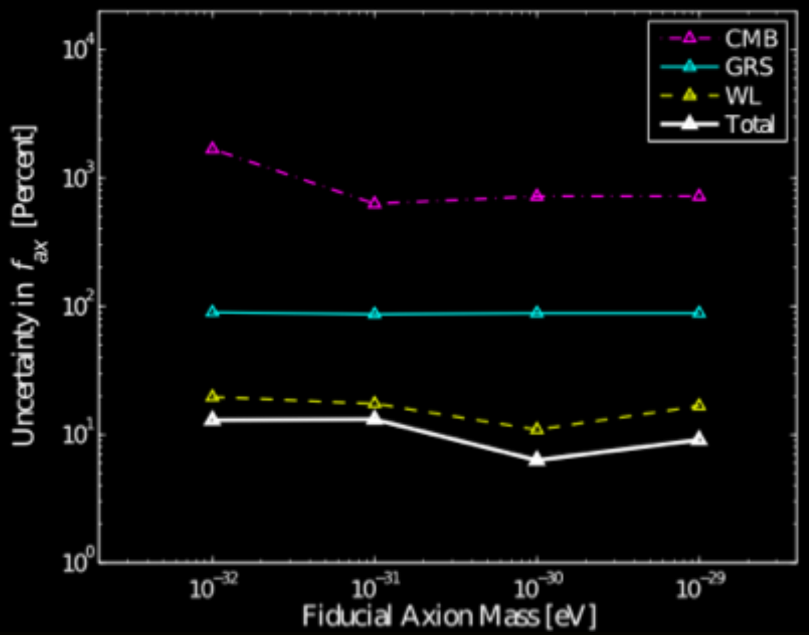
Outlook

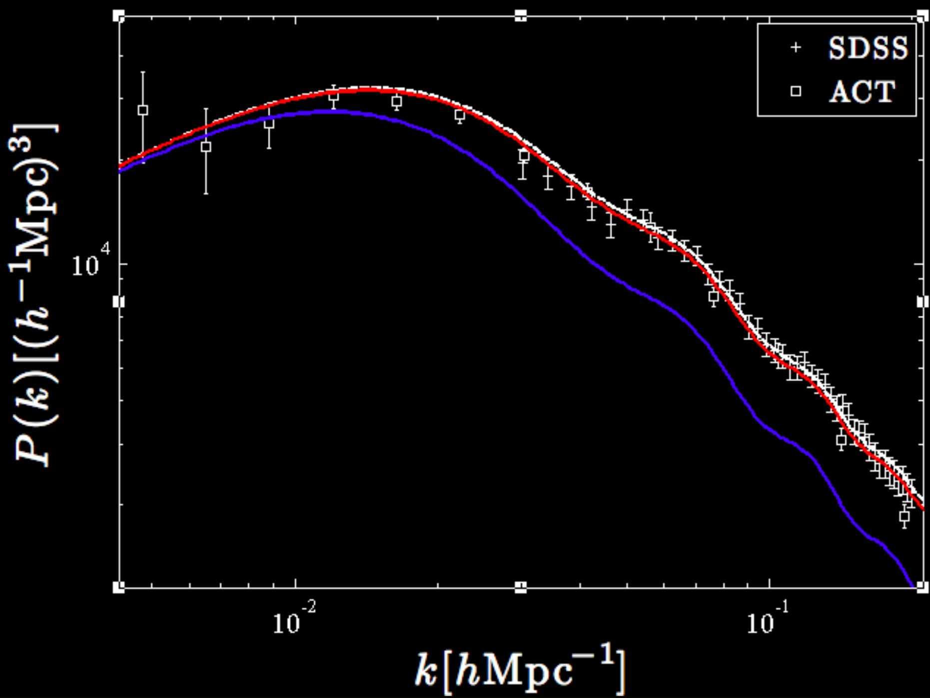
- Still much work to do for param. estimation.
- Fits comparing to specific neutrino models.
- Multiple, heavier species: Ly-alpha?
- Anharmonic potentials.
- Dynamics of extended model.

  DJEM et al, in prep.
- Isocurvature?

Summary




CMB
GRS
WL
Total
Uncertainty in f_{ax} [Percent]
10^4
10^3
10^2
10^1
10^0
10^{-32}
10^{-31}
10^{-30}
10^{-29}
Fiducial Axion Mass [eV]


SDSS
ACT
$P(k)[(h^{-1}\mathrm{Mpc})^3]$
10^4
10^{-2}
10^{-1}
$k[h\mathrm{Mpc}^{-1}]$

Thank You!

Questions?