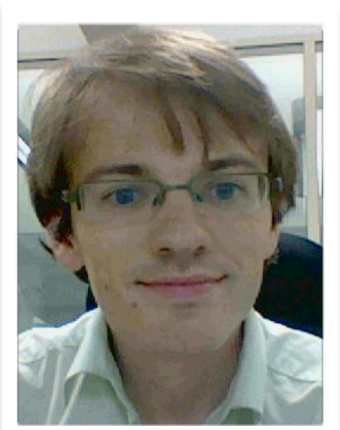
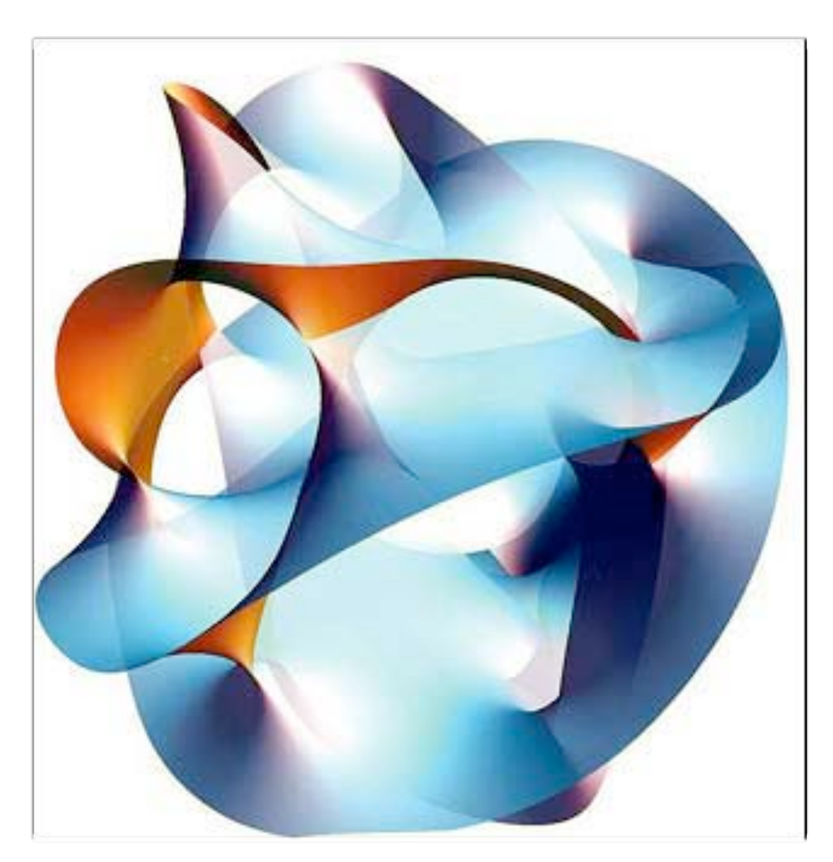
Searching for a 0.1-1 keV Cosmic Axion Background

M.C. David Marsh
University of Oxford



Based on:
J.P. Conlon, D.M.,
arXiv:1304.1804 [hep-ph],
arXiv:1305.3603 [astro-ph.CO].

Reheating in String Theory



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For typical compactification manifolds, there are hundreds of moduli.

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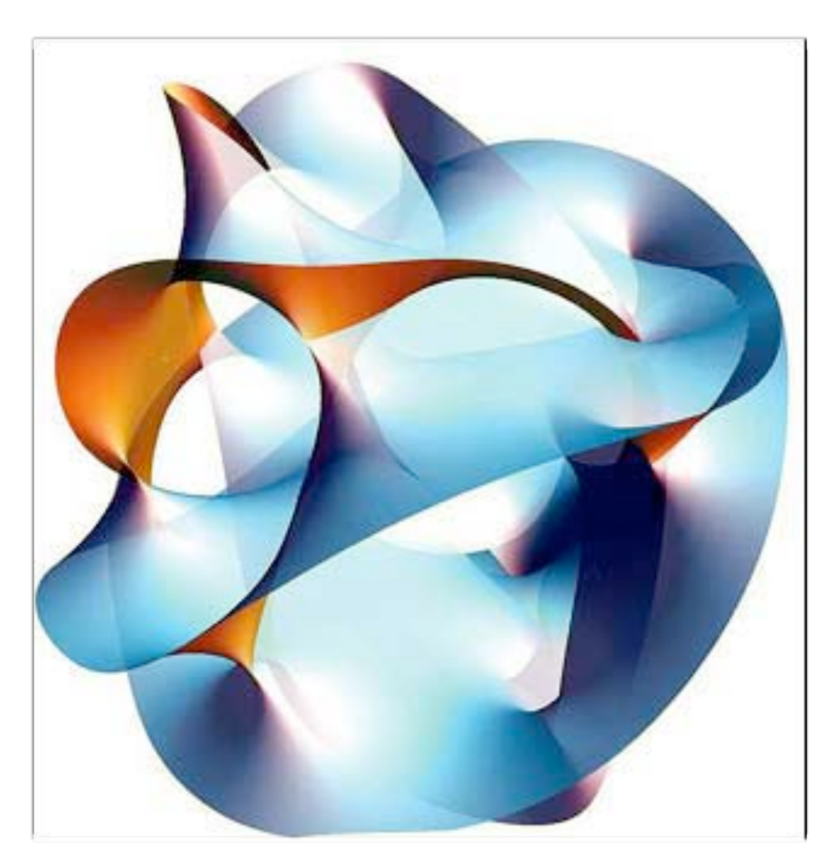

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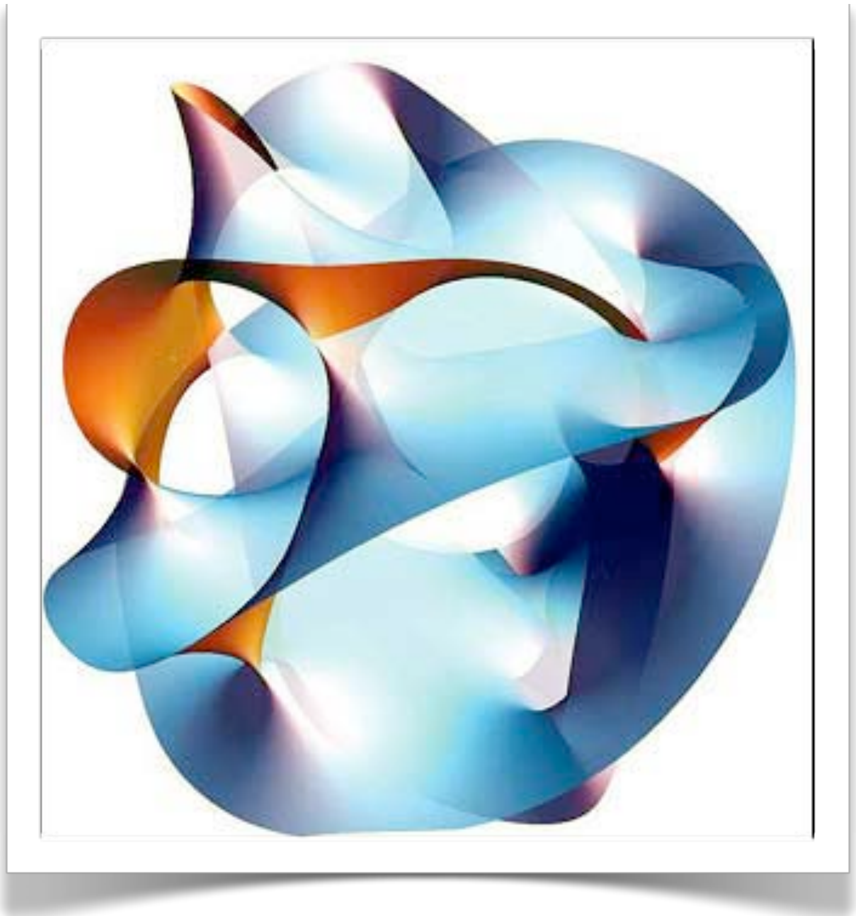
For typical compactification manifolds, there are hundreds of moduli.

Over the past decade, a number of moduli stabilization schemes (such as KKLT and LVS in type IIB) have been developed, in which all moduli are made massive.

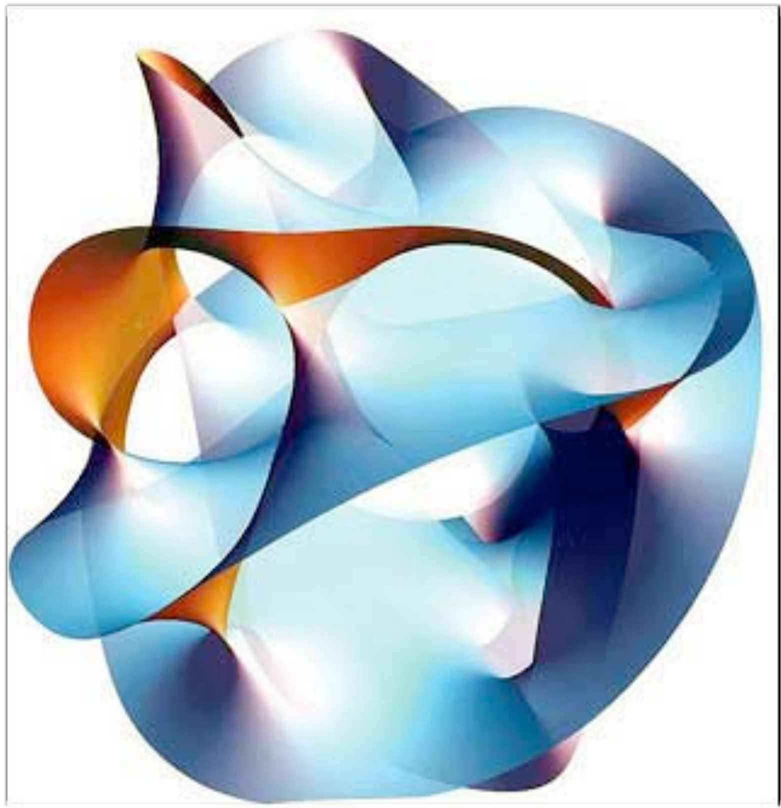
Reheating in String Theory



Though massive, the moduli may be of significant cosmological importance.

During inflation, the moduli will generically be displaced from the final vacuum by the energy density of the inflaton.

Reheating in String Theory



Though massive, the moduli may be of significant cosmological importance.

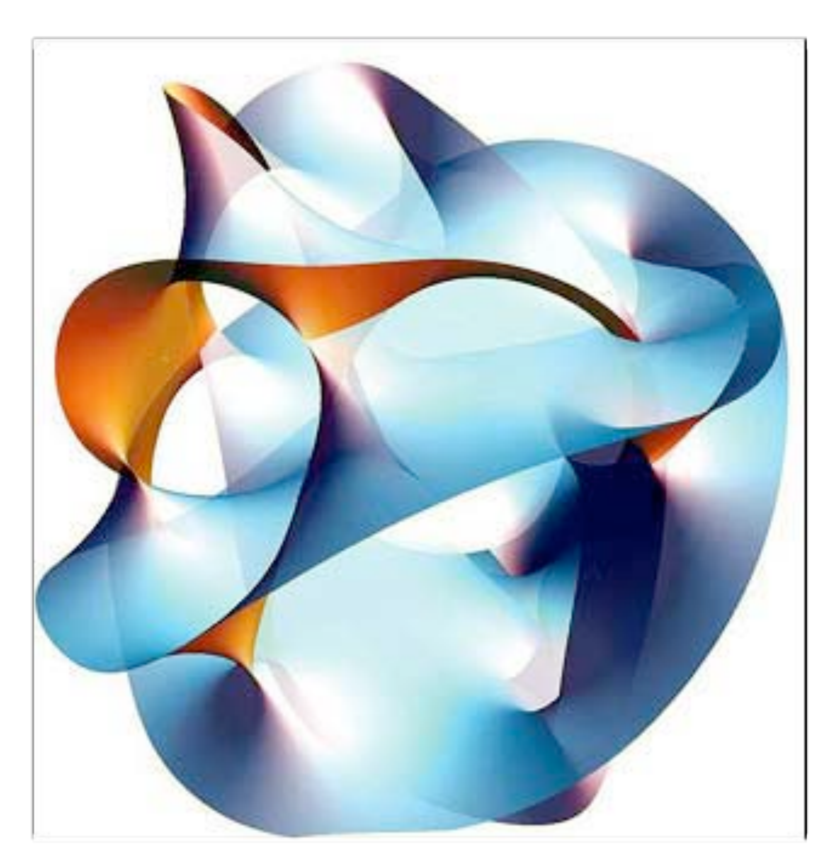
During inflation, the moduli will generically be displaced from the final vacuum by the energy density of the inflaton.

After inflation, these moduli will oscillate around the final vacuum and red-shift like non-relativistic matter:

$$\rho_\Phi \sim 1/a^3 \,,$$

thus coming to dominate over any initial radiation.

Reheating in String Theory



The decay of the most long-lived (*i.e.* lightest) modulus, determines the final reheat temperature of the subsequent Big Bang cosmology:

$$T_{reheat} \sim \frac{m_{\Phi}^{3/2}}{M_{Pl}^{1/2}} \sim 0.6\ \text{GeV} \left(\frac{m_{\Phi}}{10^6 \text{GeV}} \right)^{3/2} .$$

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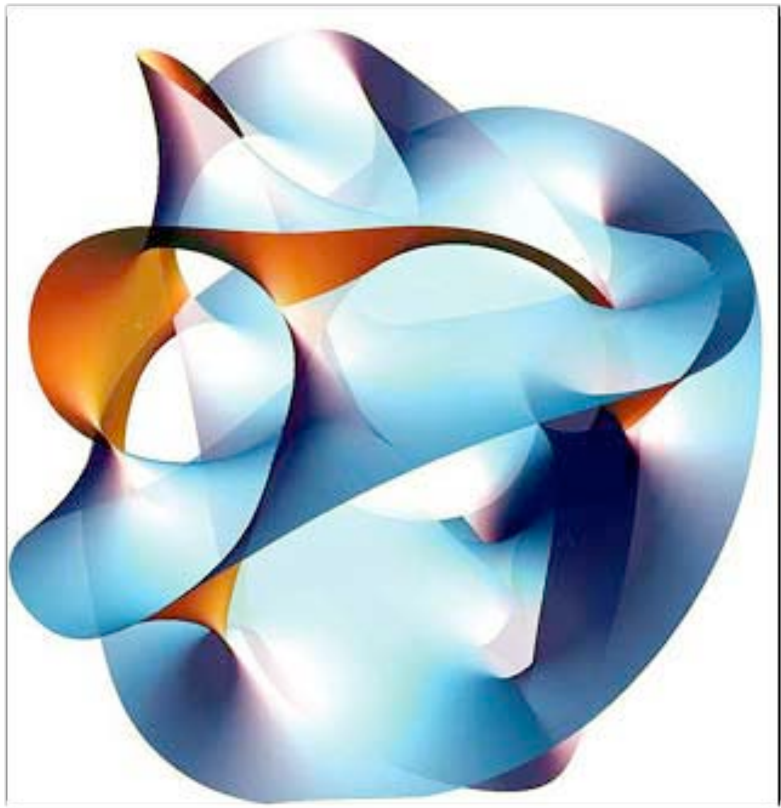

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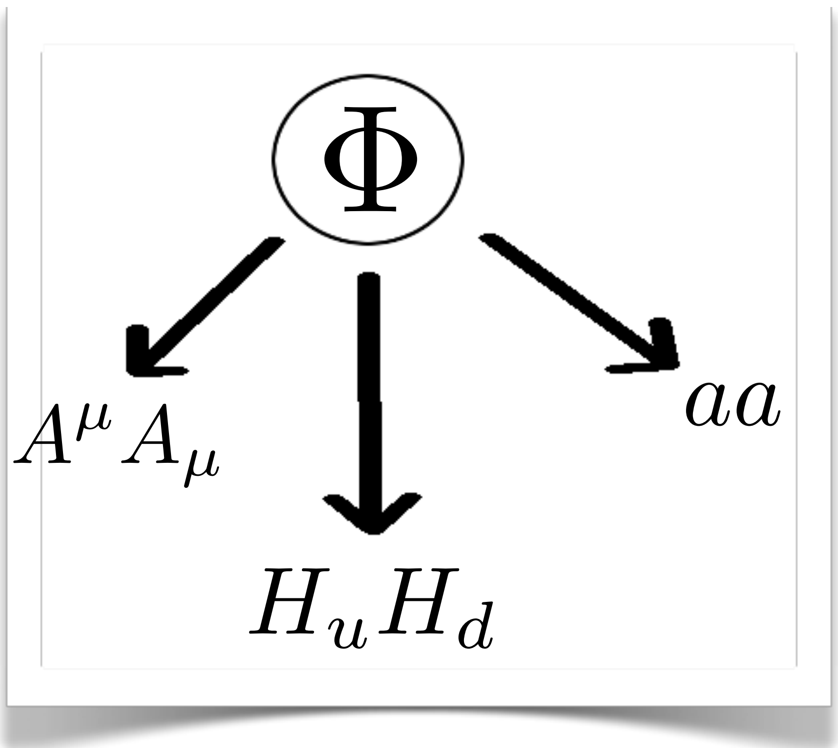
Most of what I will discuss is not tied to any specific moduli stabilization scenario but rather results from the *mere existence of moduli*. However, in a number of moduli stabilization scenarios with TeV-scale soft terms, $m_\Phi \sim 10^6 \text{ GeV}$.

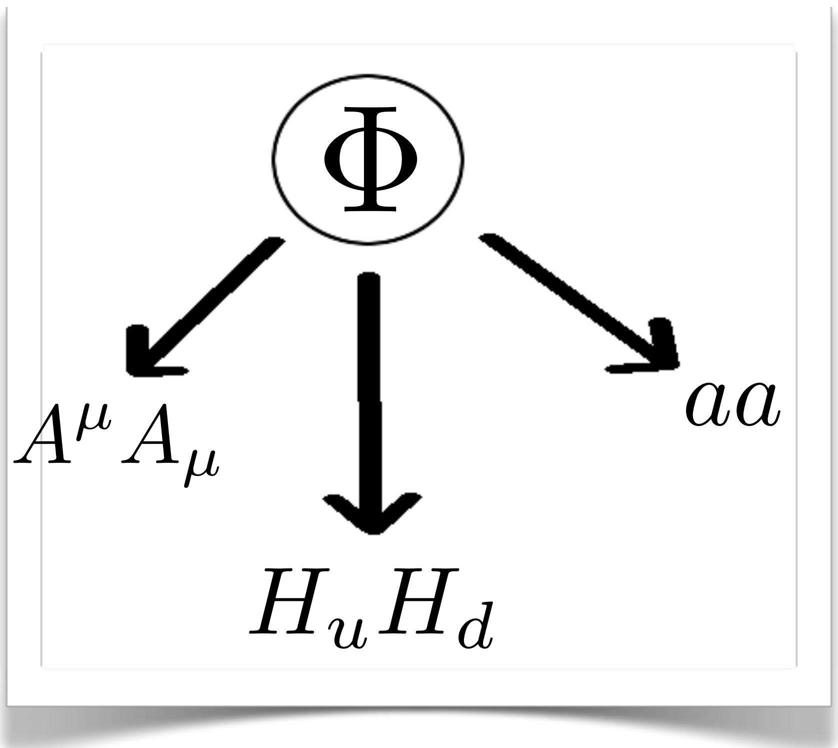
Blumenhagen, Conlon, Krippendorf, Moster, Quevedo, 2009.
Choi, Falkowski, Nilles, Olechowski, 2005.
Acharya, Kumar, Bobkov, Kane, Shao, Watson, 2008.

Reheating in String Theory



Moduli are typically gravitationally coupled to *everything*, including any potentially light hidden sectors, such as e.g. *axion-like particles*.

Reheating in String Theory



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Two-body decay of a modulus into axions,

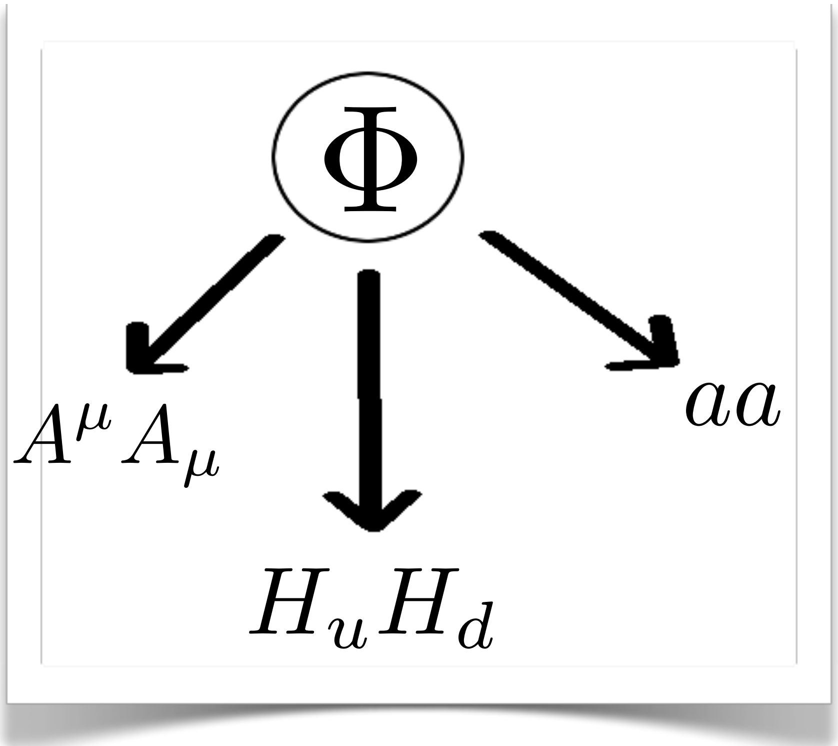
$$\Phi \to aa\,,$$

gives rise to axions with initial energy

$$E_a^{(0)} = m_\Phi/2 \sim \left(\frac{M_{Pl}}{m_\Phi}\right)^{1/2} T_{reheat}\,.$$

$$\sim 10^6\; T_{reheat}\; \left(\frac{10^6\ \text{GeV}}{m_\Phi}\right)^{1/2}\,.$$

Axionic Dark Radiation



These highly relativistic axions will contribute to the *dark radiation* of the universe, conventionally parametrized as an effective number of neutrino species:

$$N_{eff} = 3.046 + \Delta N_{eff} \,.$$

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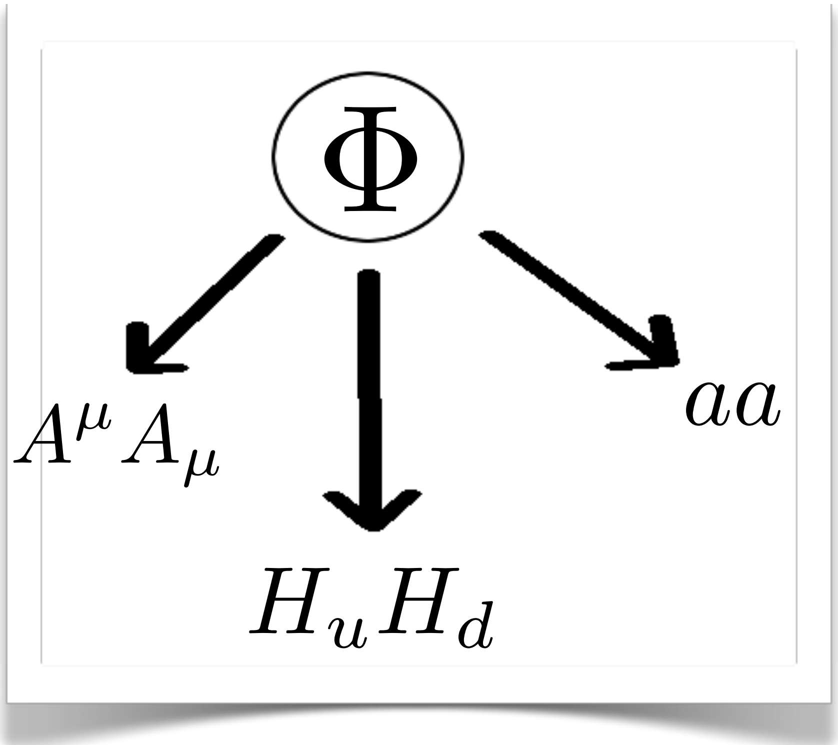

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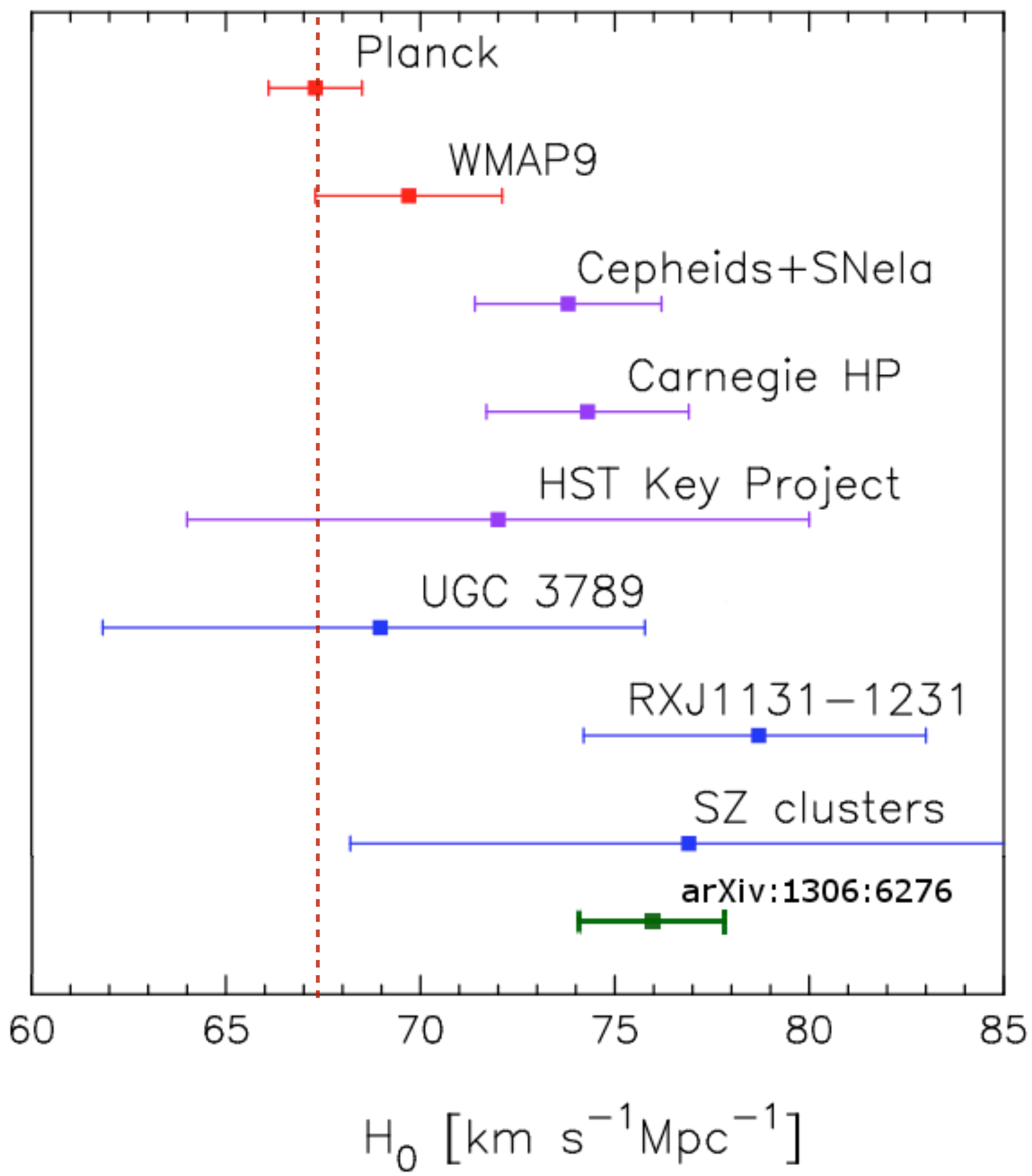
Theoretically, there is no general *a priori* reason for ΔN_{eff} to be small.

Well-defined string scenarios may be constrained by bounds on the amount of dark radiation produced in light hidden sectors (such as axions or hidden photons), *c.f. talk by Nakayama*.

Cicoli, Conlon, Quevedo, 2012.
Higaki, Nakayama, Takahashi, 2012, 2013.
Angus, Conlon, Haisch, Powell, 2013.

Hints of Dark Radiation



Adapted from "*Planck 2013 results XVI*", and Fiorentino, Musella, Marconi, 2013.

The existence of dark radiation may already be hinted by cosmological data.

The Planck collaborations fit of the ΛCDM-model *predicts* a value of H_0 which appears discrepant with local measurements at ~ *2-4.6* σ.

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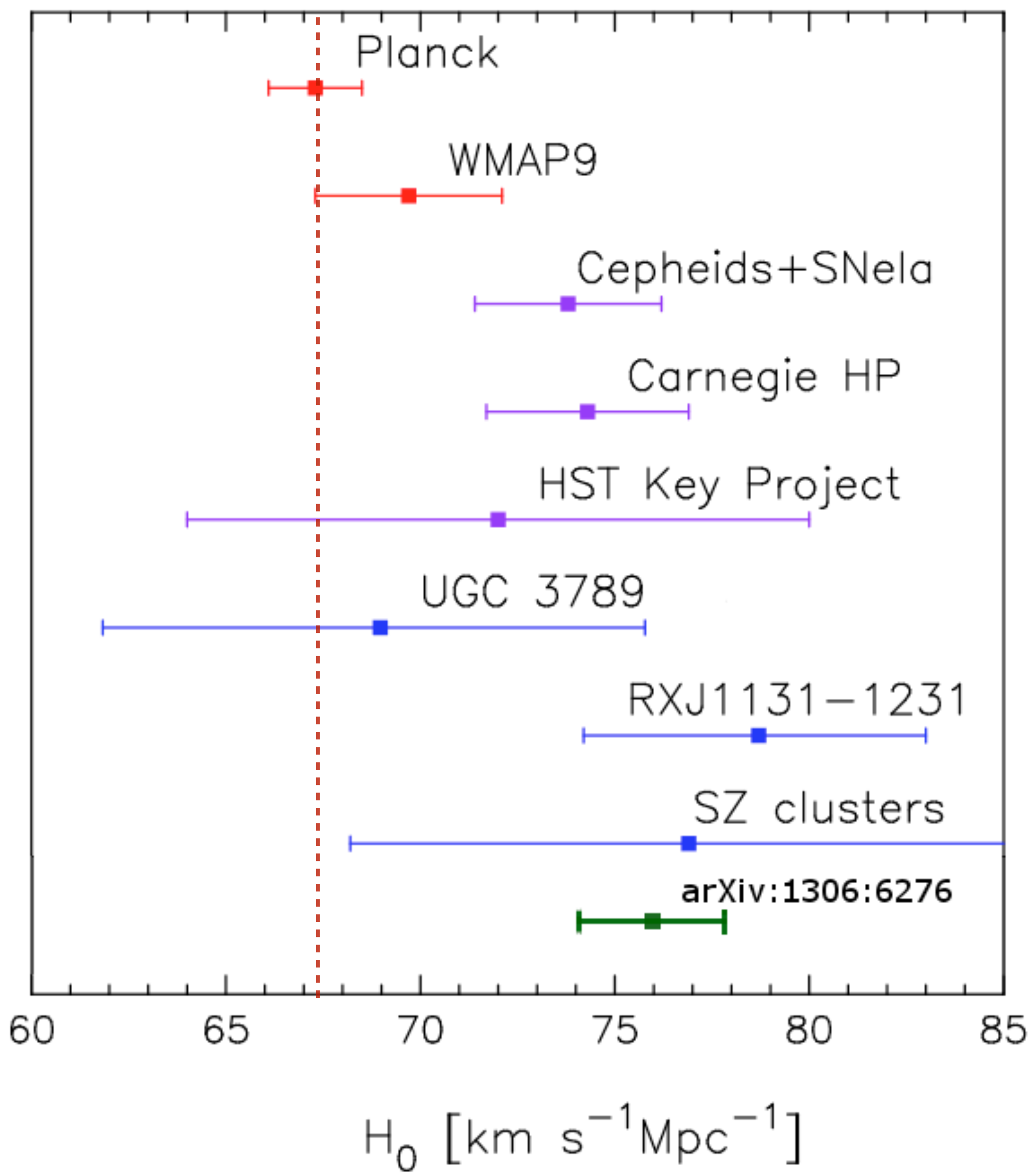

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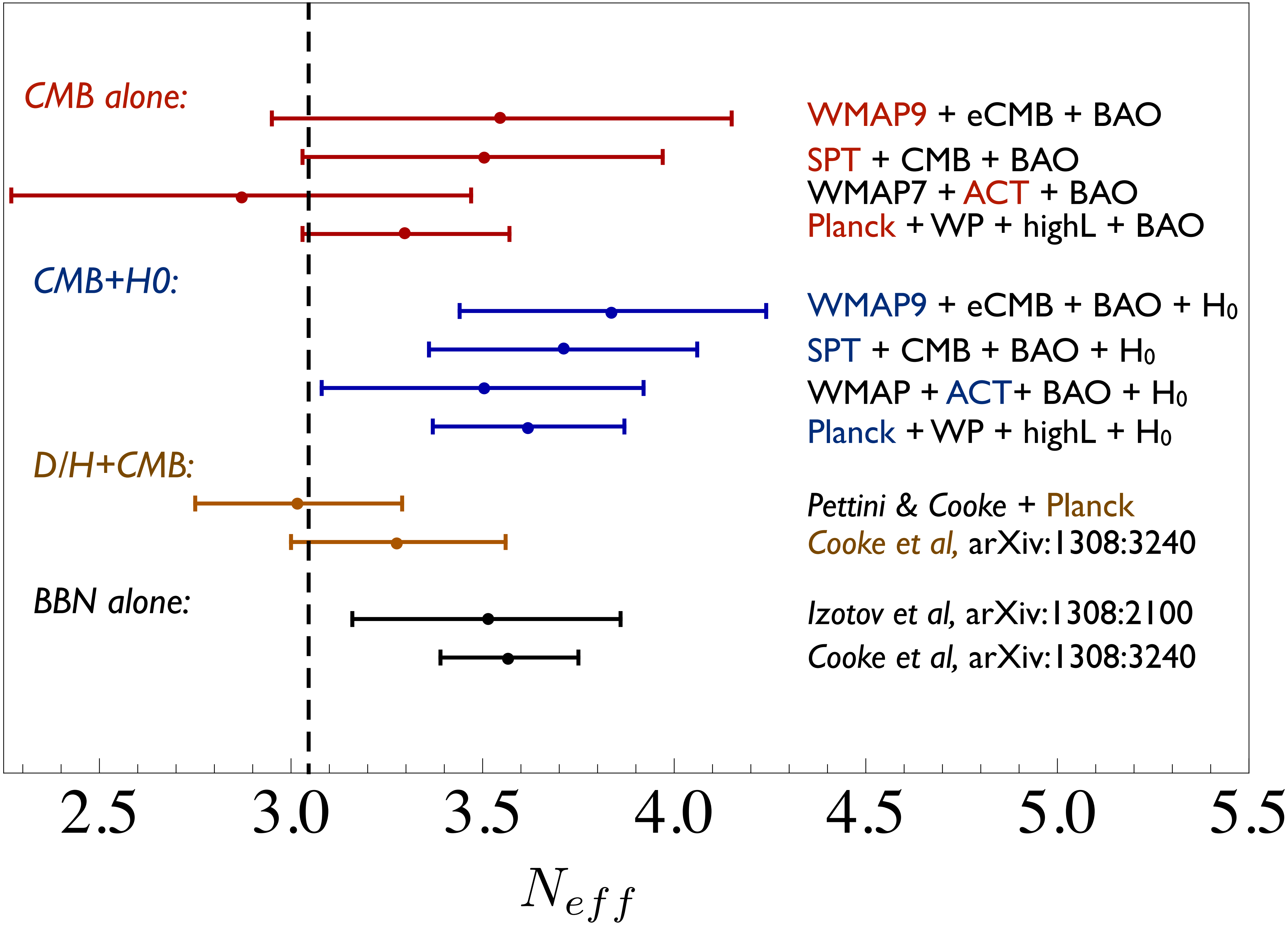
The CMB estimate of H_0 is highly dependent on the ΛCDM-model, and the tension with actual local measurements of H_0 can be ameliorated by the inclusion of dark radiation.

There are hints of dark radiation at *1-2.9* σ.



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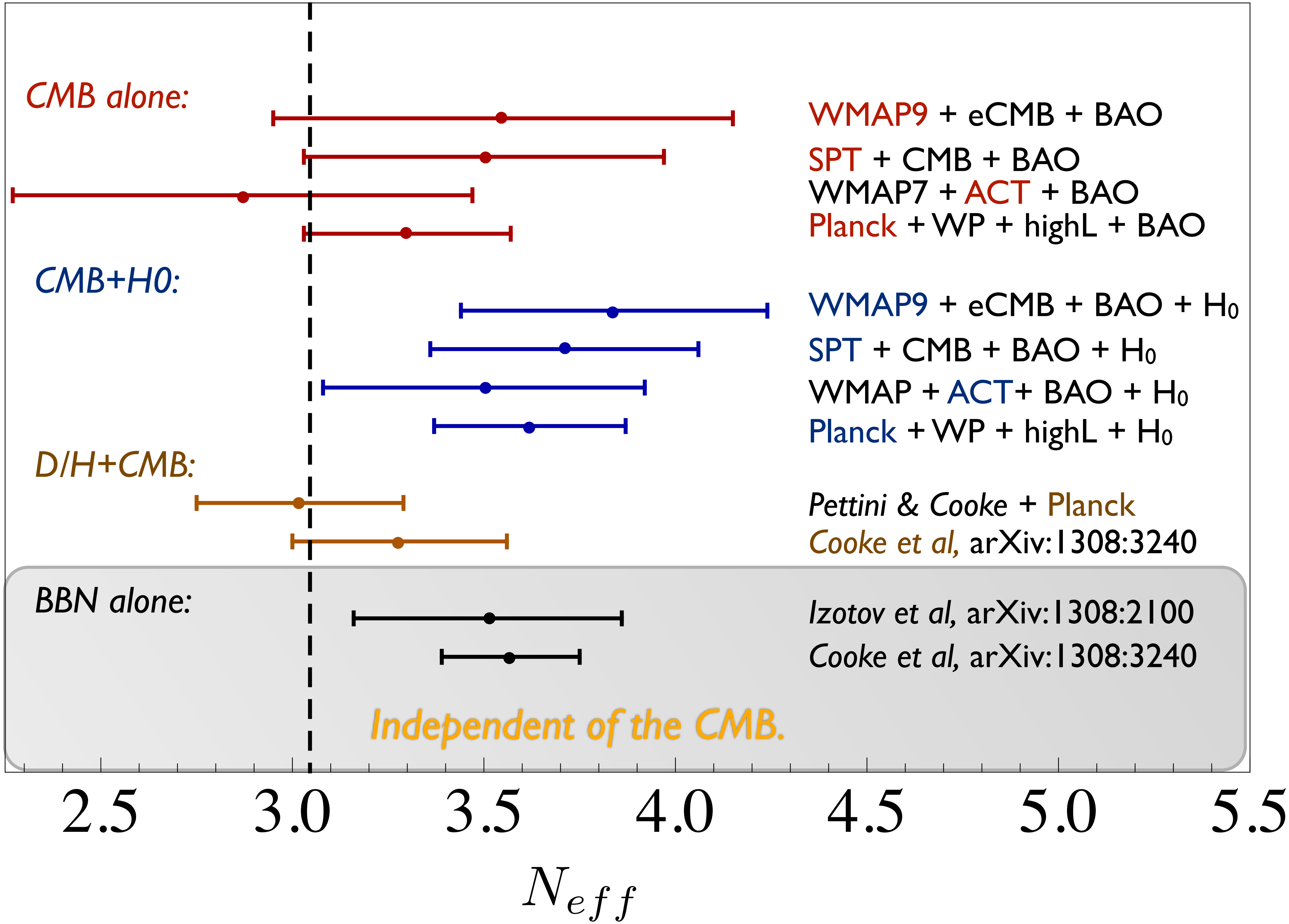
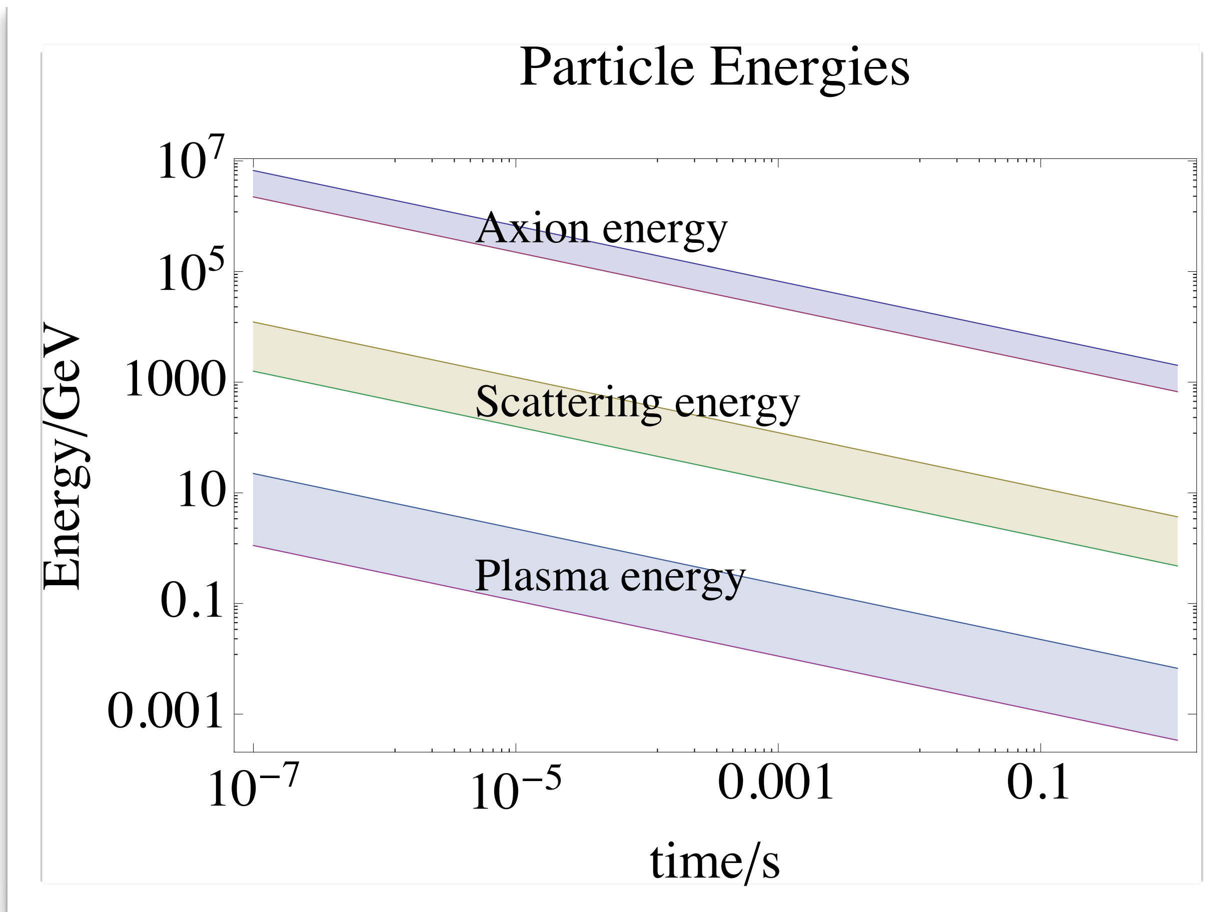


The Cosmophenomenology of Axionic Dark Radiation



J.Conlon, M.C.D.M., arXiv:1304.1804 [hep-ph]

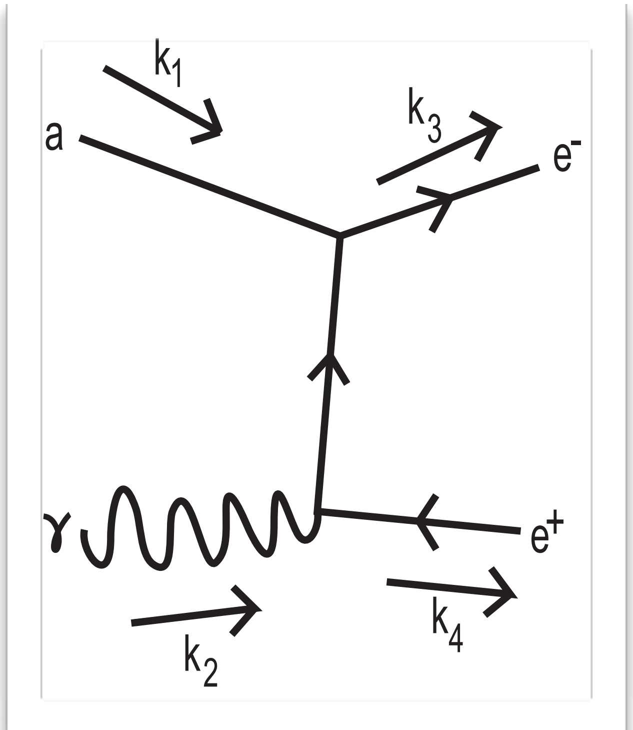
Thus, the existence of dark radiation is both theoretically and observationally well-motivated.

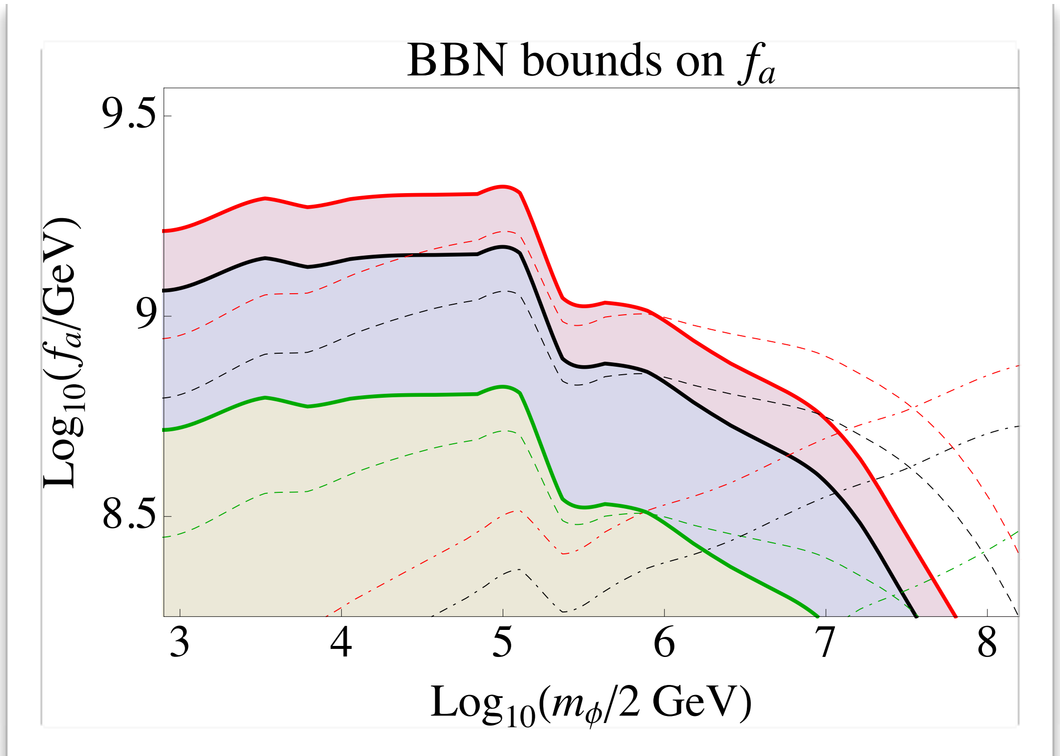
For the rest of this talk, I will entertain the possibility of a non-vanishing density of axionic dark radiation arising from modulus decay.

Since $E_a \gg T$, such axions may scatter off the thermal plasma to access otherwise kinematically forbidden processes.

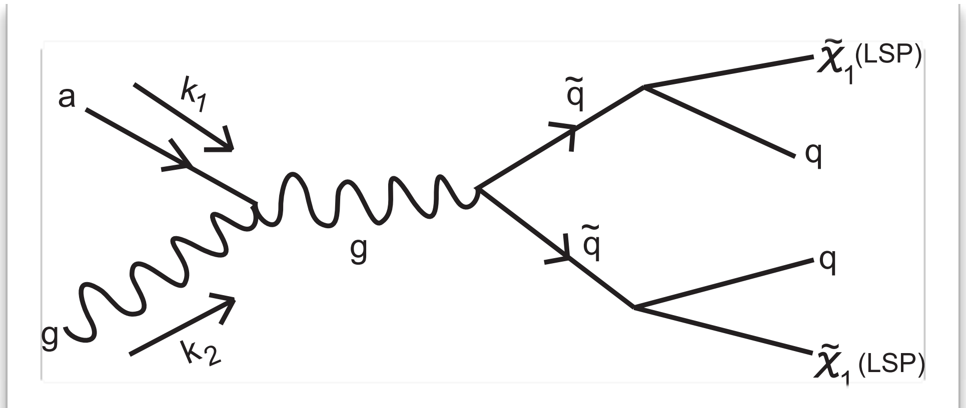
The Cosmophenomenology of Axionic Dark Radiation

BBN bounds from scattering off thermal plasma:





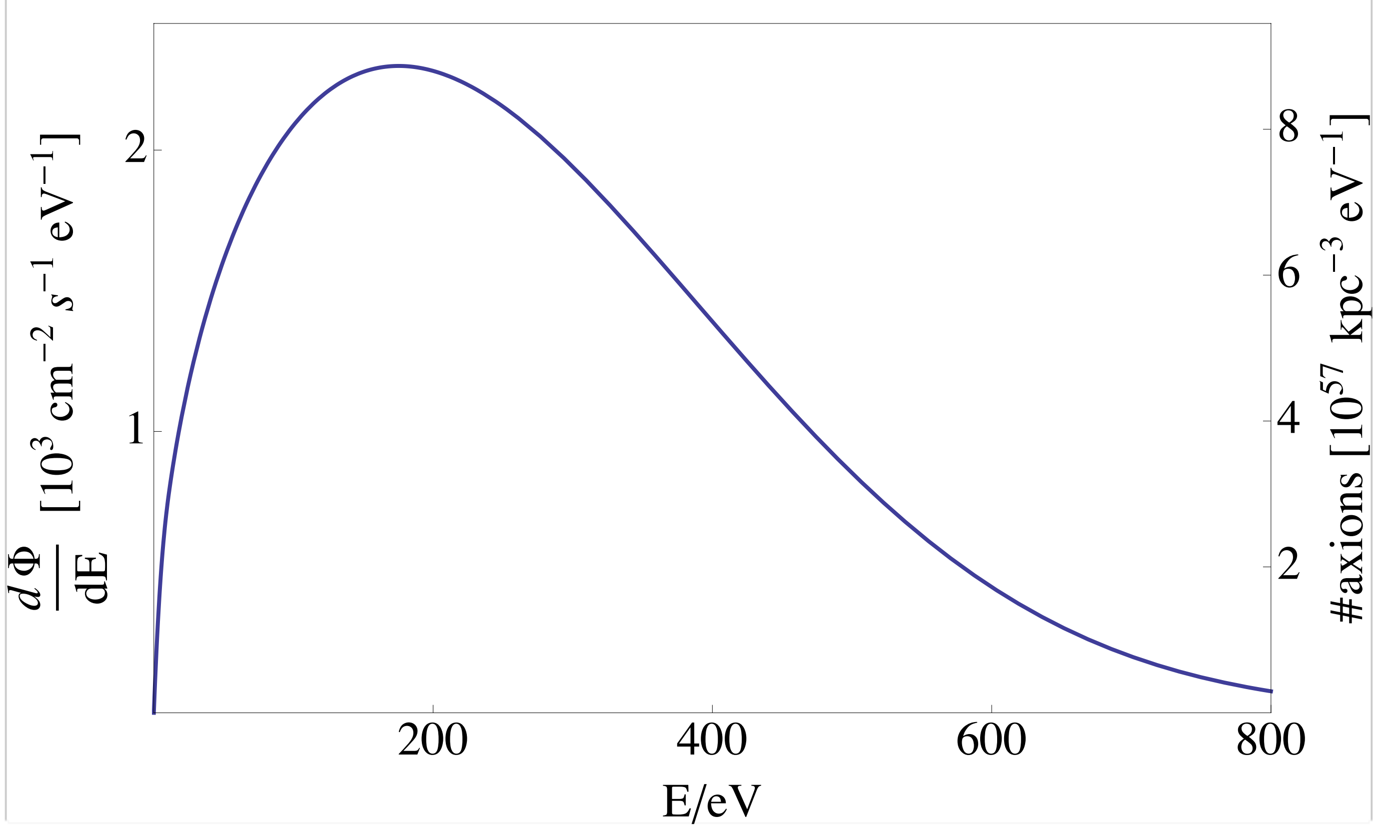
Dark matter generation:



For details, see arXiv:1304.1804 [hep-ph].

The Cosmic Axion Background

Prediction:



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The decay of moduli at

$$t \sim 10^{-6} \left(\frac{10^6 \text{ GeV}}{m_\Phi}\right)^3 \text{ s}$$

(*c.f.* $z \sim 10^{12}$) gives rise to a present day isotropic flux of axions: $\Phi_{\text{today}} \sim 10^6 \text{ cm}^{-2}\text{s}^{-1} \times$

$$\times \left(\frac{\Delta N_{eff}}{0.57}\right)\left(\frac{m_\Phi}{10^6 \text{ GeV}}\right)^{1/2} .$$

The (non-thermal) axion spectrum has energies in the extreme UV to X-ray range:

$$E_a \sim 200 \text{ eV} .$$

The Cosmic Axion Background

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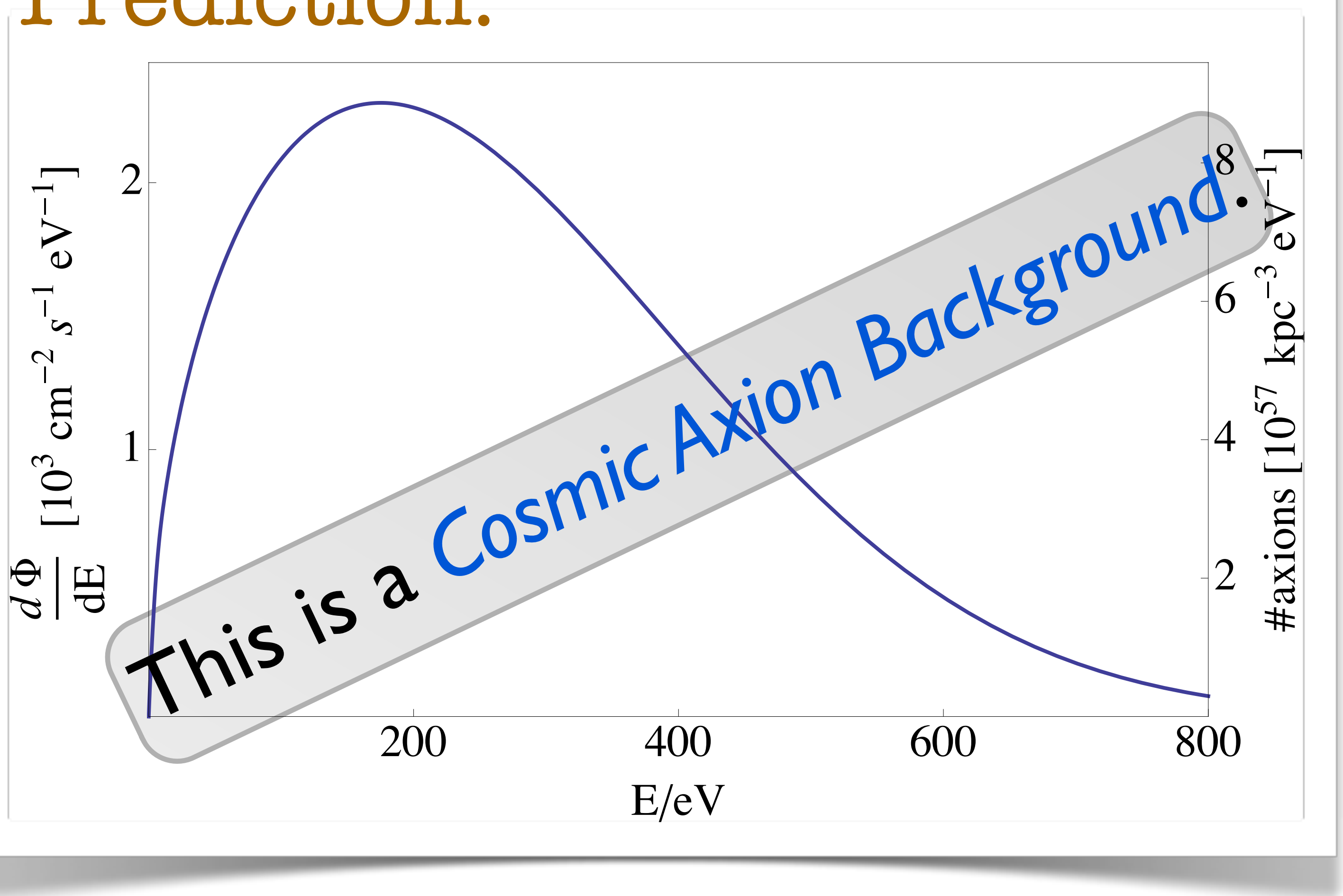

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Can a CAB be directly observed?

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Surely not this easy ...

Can a CAB be directly observed?

... but perhaps it's hiding in this picture.

Searching for a Cosmic Axion Background

Key property: Axions may convert into photons in the presence of a magnetic field.

The axion-photon part of the Lagrangian is given by,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4M}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2\,,$$

where we consider axion-like particles with $m_a \approx 0,$ and require $M > 10^{11}\ \mathrm{GeV}$ to avoid supernova bounds.

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To leading order, the probability of axion-photon conversion in an external magnetic field with coherence length *L* is given by,

$$P(a \to \gamma) \approx \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2 \,.$$

Sikivie, 1983.

Searching for a Cosmic Axion Background

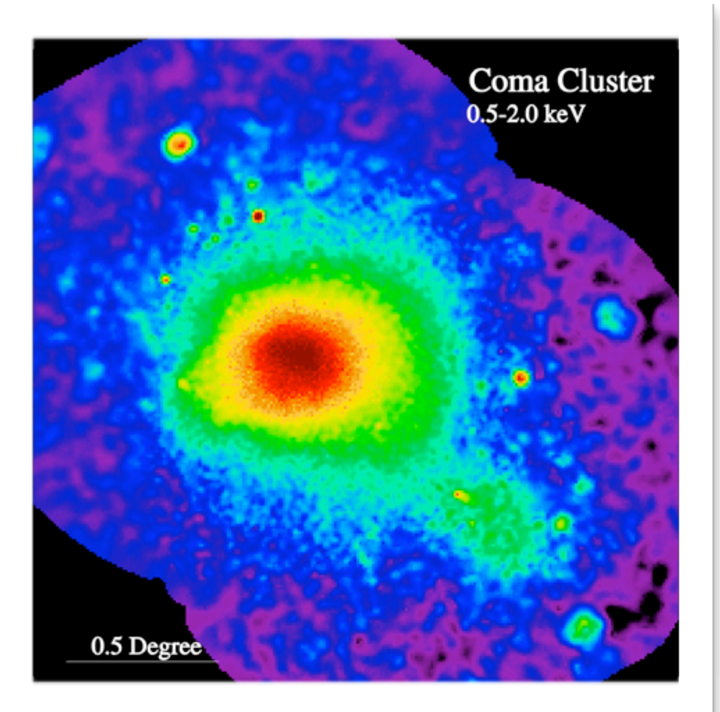
Coma as seen by HST.

Galaxy clusters typically have magnetic fields of μG strength coherent over scales of several kiloparsec, and thus provide an excellent laboratory to search for a Cosmic Axion Background.

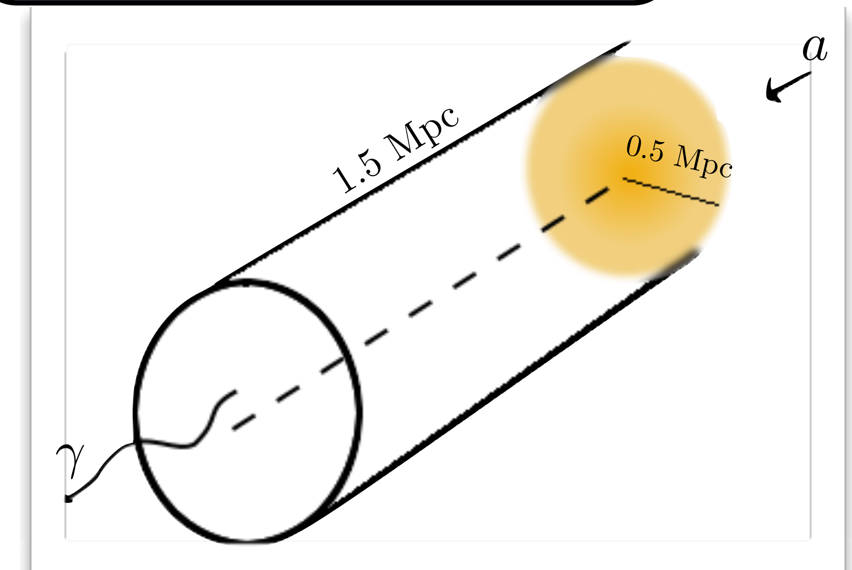
In fact, soft X-ray excess above the hot cluster medium has been observed by a number of experiments *(EUVE, ROSAT, BeppoSAX, XMM-Newton, Suzako, Chandra)* in a large number of galaxy clusters since 1996.

Review: Durret et al, arXiv:0801:0977.

Searching for a Cosmic Axion Background



Coma as seen by Rosat.

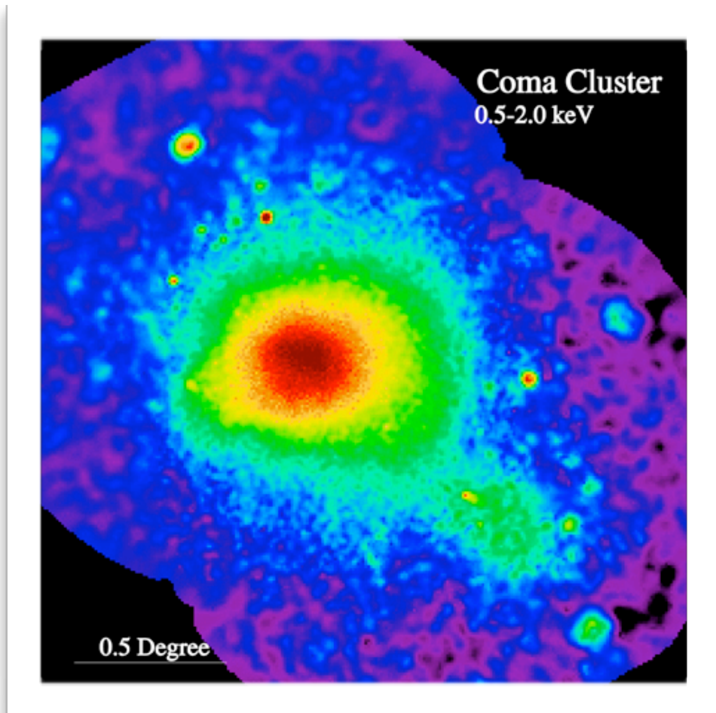


Expl.: Coma cluster:

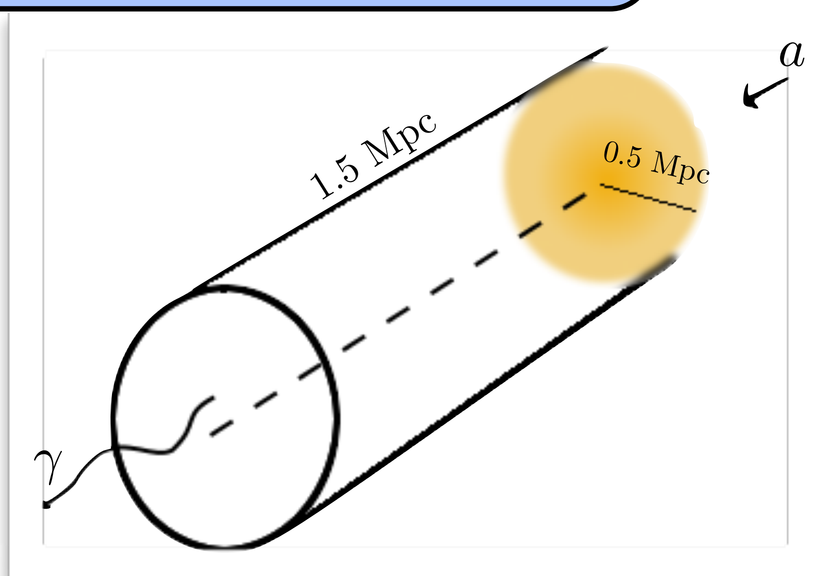
Observed excess from central region:

$$\mathcal{L}_{obs.\ excess} \approx 10^{42} \text{ erg s}^{-1}\,.$$

Searching for a Cosmic Axion Background



Coma as seen by Rosat.



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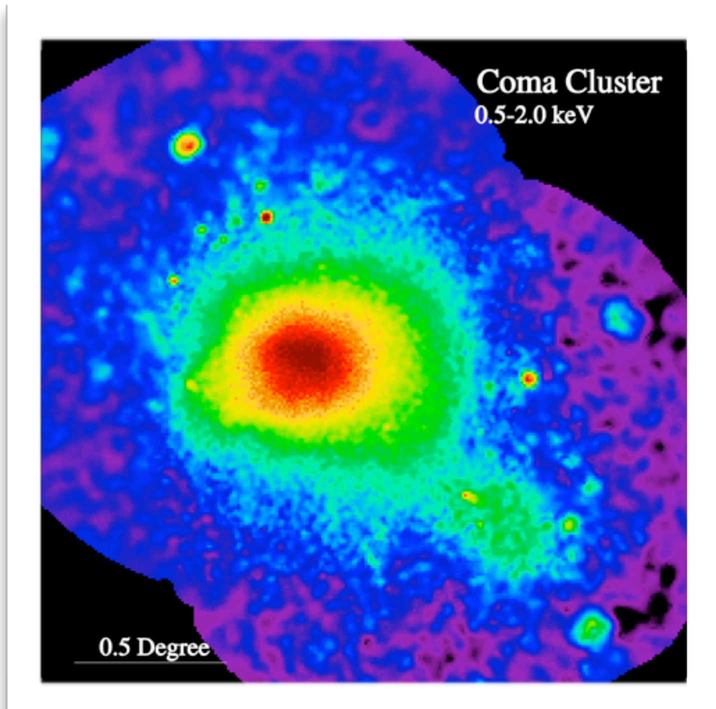
Searching for a Cosmic Axion Background



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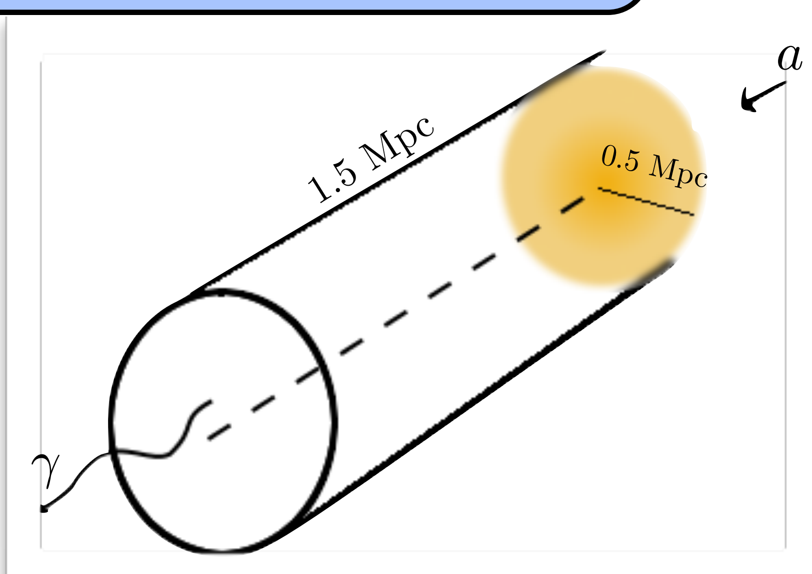

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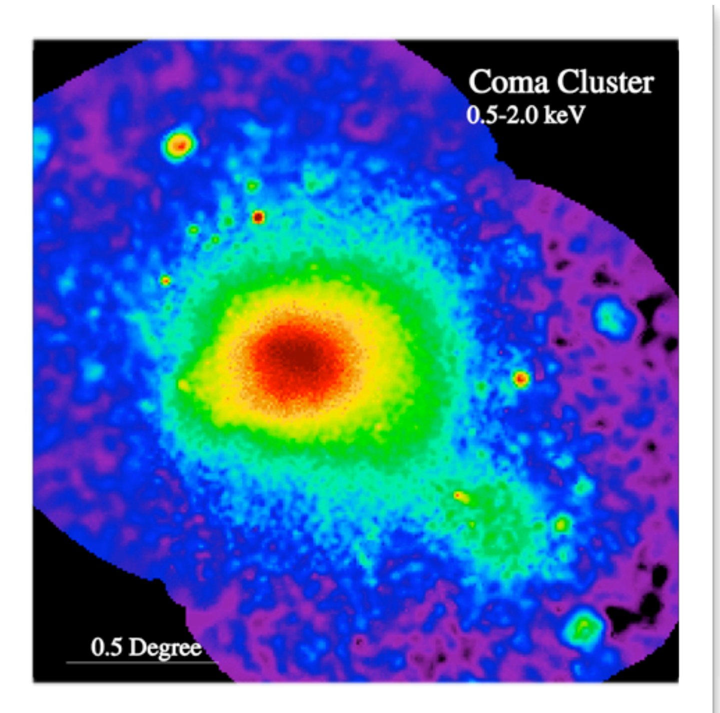
Thus, the soft X-ray excess appears to be easily explained by axion-photon conversion of the CAB.

Searching for a Cosmic Axion Background



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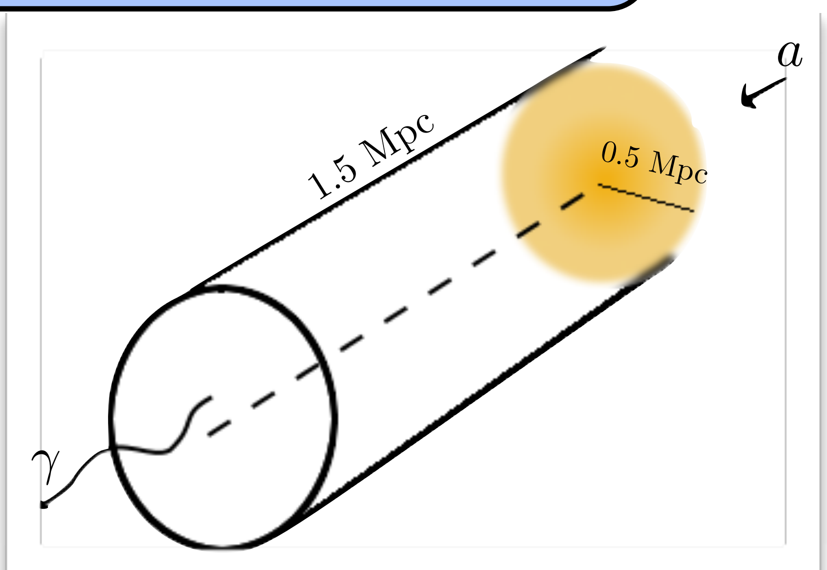

Expl.: Coma cluster:

Has a signs of a Cosmic Axion Background been observed but unnoticed for 17 years?

Searching for a Cosmic Axion Background

This scenario has several correlated predictions:

- Soft excess magnitude and morphology fully determined by cluster magnetic field and electron density. *[More detailed study under way].*
- No thermal emission lines can be associated with the excess. *[In apparent agreement with observations].*
- Spectrum of excess is to leading order given by the non-thermal spectrum of the CAB, and red-shifts like $(1+z)$.

Candidate Astrophysical Explanations

Candidate astrophysical explanations are all struggling:

1. Brehmsstrahlung from additional thermal gas ($T \sim 200$ eV).

   But such a gas would cool too rapidly, and furthermore give rise to unobserved emission lines.

2. Inverse Compton Scattering of CMB photons off non-thermal gas *[c.f. Hwang 1997, Bowyer et al, 2004, ...]*.

   Most such models are now ruled out based on overproduction of radiowaves from synchrotron emission.
   Independently, Fermi has not observed galaxy clusters, yet this model predicts correlated gamma-ray emission [Atoyan, Voelk, 1999].

Conclusions:

Axionic dark radiation is a well-motivated extension of standard cosmology.

Some of the best studied string theory models predict a present day primordial background of relativistic axions with energies $E_a \sim 0.1 - 1$ keV.

This *Cosmic Axion Background* may be detected through axion-photon conversion in magnetic fields, and *may already be visible* through long-standing soft X-ray excess in galaxy clusters.

Conclusions:

Thanks!