Dark radiation in IAXO

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1. The *axiverse* from string theory
2. *Moduli* and dark radiation
3. The cosmic axion background and IAXO

References:

- Arvanitaki et al., PRD 81 (2010)
- Conlon & Marsch, JHEP 10 (2013), PRL 111 (2013)
- J. Conlon, talk at ESQG (Frankfurt, 2016)
- J. Redondo, private communication

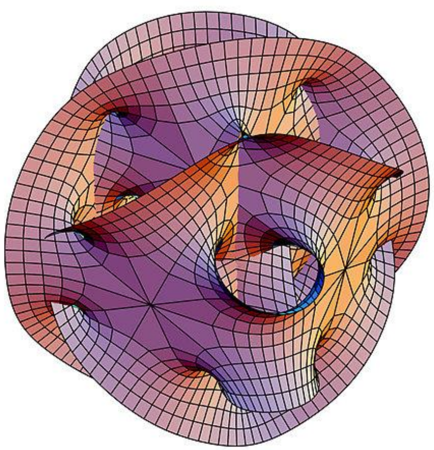
Fine-tuning and the strong CP problem

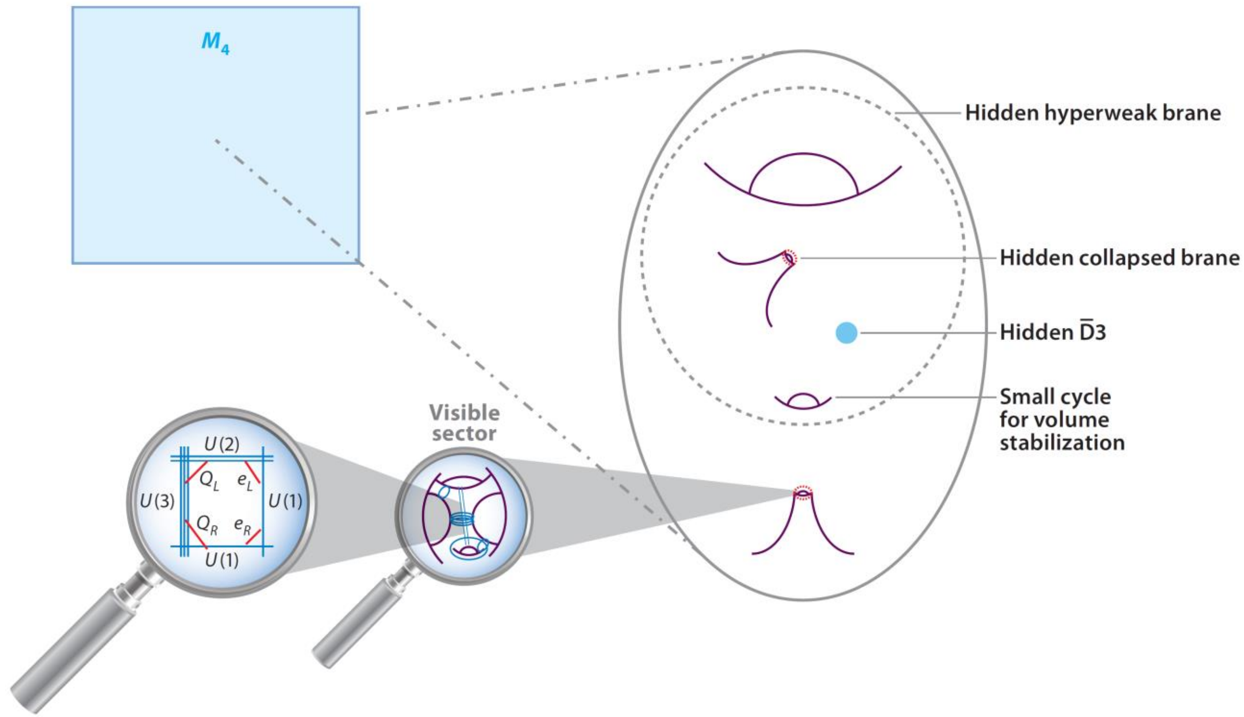
- $\bar{\theta} = \theta + \arg\det m_q$ and $\bar{\theta} \leq 10^{-10}$ seems like a big fine-tuning: strong CP problem
  - Moreover, no symmetry of the SM is restored as $\bar{\theta} \to 0$
- Other similar apparent fine-tunings: cosmological constant, hierarchy problem
- However, $\bar{\theta} \ll 1$ has no anthropic solution: call for a dynamical mechanism

- PQ mechanism: a new (anomalous) spontaneously broken chiral symmetry $U(1)_{PQ}$
  - QCD axion: the NG boson of the SSB, $\langle a \rangle = -(f_a/\xi)\bar{\theta}$
- BUT: all other sources of explicit $U(1)_{PQ}$ breaking should be at least 10 orders of magnitude down with respect to the potential generated by the QCD anomaly
  - Quantum gravity effects? ⟶ String theory

Axions in string theory

- Massless fields arise in string theory under compactification of M_6 as Kaluza-Klein zero modes of antisymmetric tensor fields, present in all string theories
  - Number of massless scalar fields is determined by the topology of the compactification (e.g., number of 2-cycles in M_6, usually more than one hundred)





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  - Number of massless scalar fields is determined by the topology of the compactification (e.g., number of 2-cycles in M_6, usually more than one hundred)
  - Anomaly-cancellation conditions result in axion-like couplings for these fields

→ *String compactifications have plenty of candidates for axion-like particles*

But… do they really predict the QCD axion?

Difficulties:

1. String axions can be removed from the low-energy spectrum by different mechanisms (presence of fluxes, branes,…)
2. A QCD axion from string theory would have a cosmologically non-allowed large value of the SSB scale f_a

The QCD axion in string theory

- Standard limits on f_a:

$$f_a > 10^9\,\text{GeV (lab/astrophysics), and } f_a < 10^{12}\,\text{GeV (cosmology)}$$

[large f_a → axion oscillations start later → larger energy density of axions today]

- Non-perturbative corrections to the string theory axions (couplings to e.g. worldsheet / membrane instantons) must not spoil PQ mechanism:

$$\mu^4 \exp(-S_{\text{inst}}) < 10^{-10} \xi f_\pi^2 m_\pi^2 \quad \Rightarrow \quad S_{\text{inst}} \geq 200$$

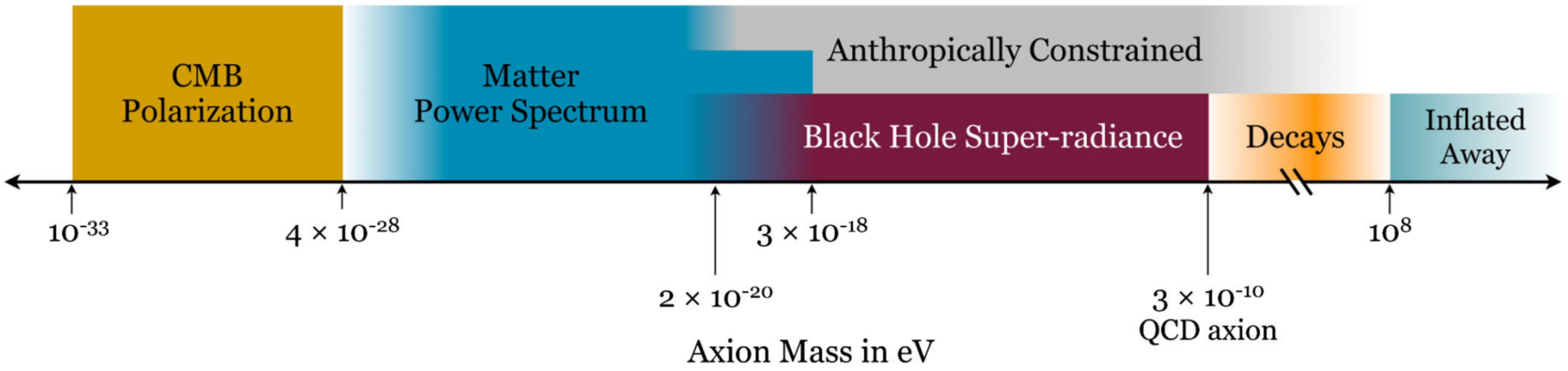
This is a significant constraint for string theory models

- Quite generally, $f_a \sim M_{\text{P}}/S_{\text{inst}} \quad \rightarrow \quad f_a \sim M_{\text{GUT}} \simeq 2 \times 10^{16}\,\text{GeV}$

- Possible solutions:
    - The cosmological constraint is not valid (e.g., different axion initial conditions in different patches of the Universe)
    - f_a can be lowered significantly if a large amount of warping is present

The string *axiverse*

- No anthropic origin of the solution to strong CP problem:
  - No fine tuning in the existence of the QCD axion & extreme smallness of all non-QCD contributions to its potential: dynamical consequence
  - String theory compactifications have a potential or producing hundreds of light axions
- The QCD axion as a solution of the strong CP problem implies the existence of many light axions, homogeneously distributed on a log scale



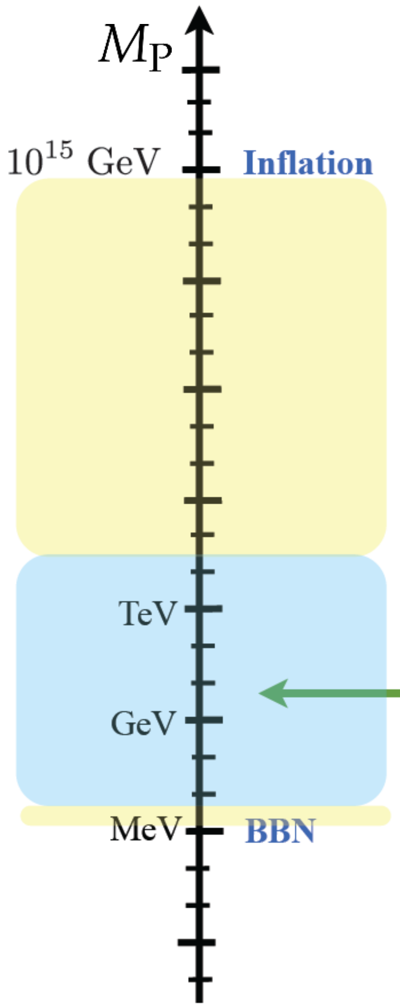
Compactifications and moduli

- String compactifications generically predict scalar particles: moduli
  - The vacuum expectation values of massless scalar fields determine the geometry of the internal manifold
  - They need to be stabilized to get a sensible low-energy theory; depending on the stabilization mechanism, they can get masses from $O(\text{TeV})$ to M_P
- Since moduli interact with gravitational strength, they live long and decay late:
  1. Moduli oscillation after inflation dominate the energy density of the universe (modification of calculation of freeze-out relic densities of DM)
  2. Reheating comes from the decays of these moduli

$$T_\text{rht} \sim \left(\frac{m_\phi}{100\,\text{TeV}}\right)^{3/2} 3\,\text{MeV}$$

Potential problem with BBN (cosmological moduli problem)

A non-standard thermal history of Universe



Radiation domination era

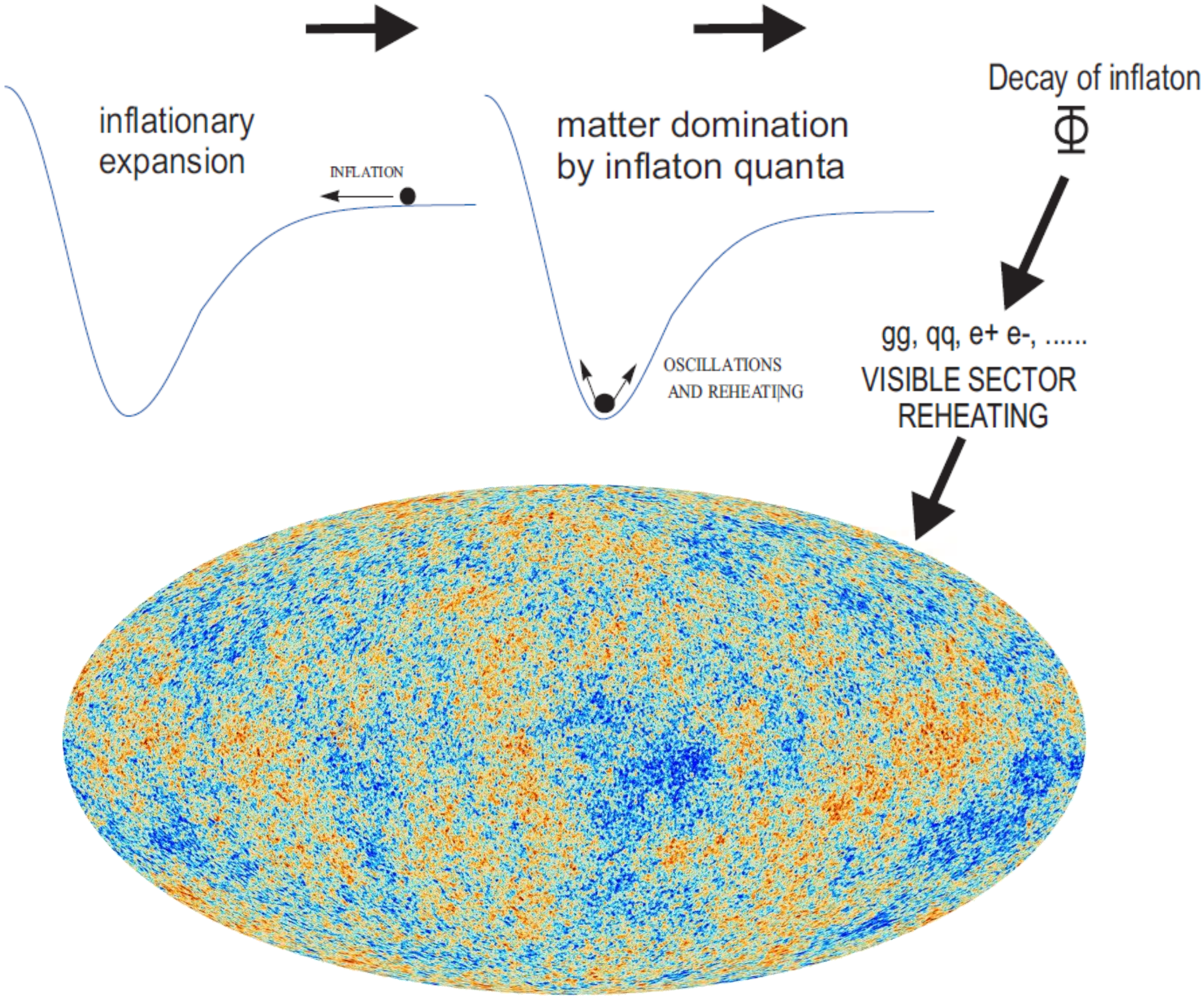
Moduli domination begins $H \sim m_\phi$

Standard thermal WIMP freeze-out

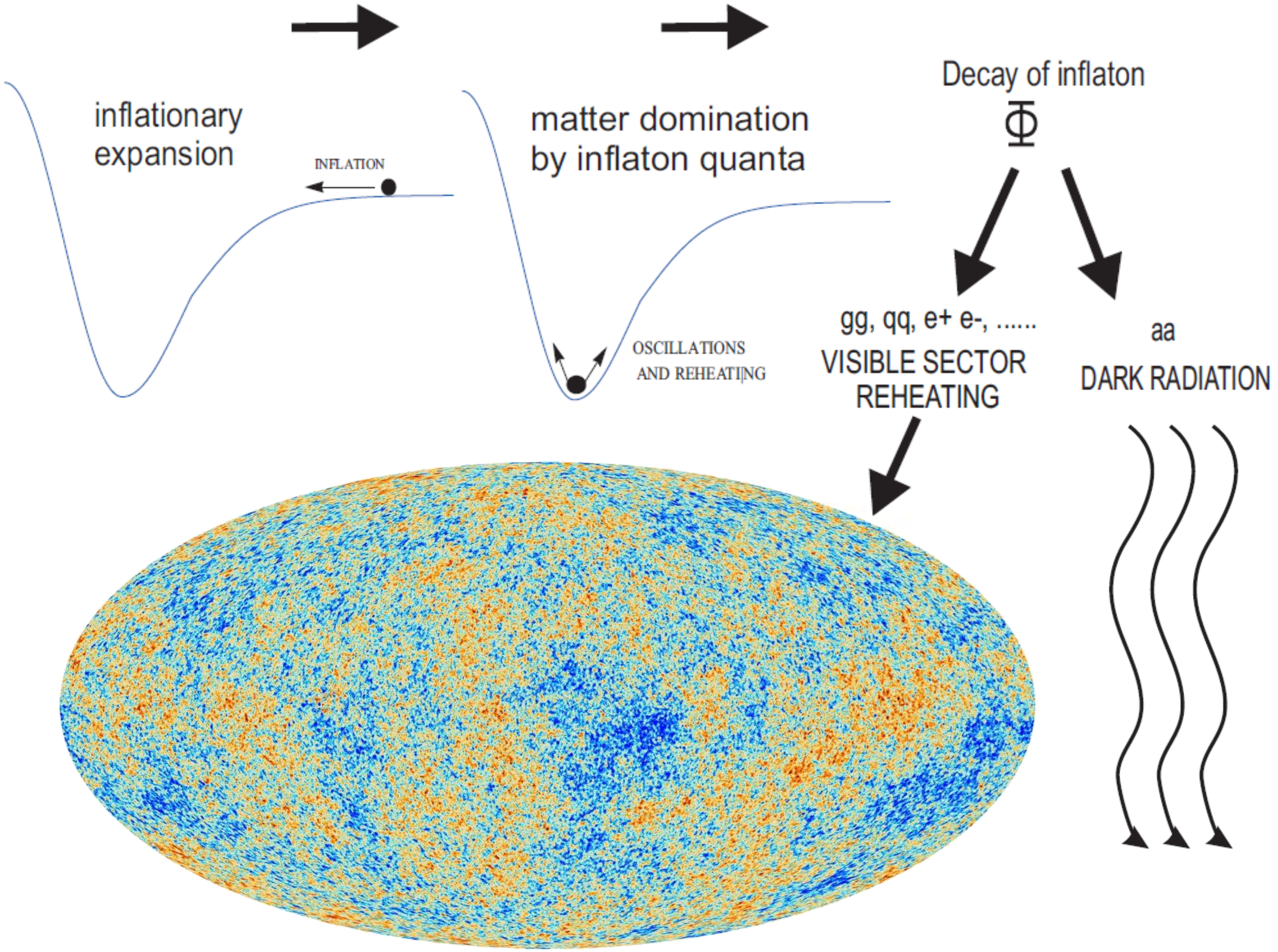
Moduli decay and reheat $H \sim \Gamma = \tau^{-1}$

$$T_{\rm rht} > 1\,\text{MeV (BBN)} \;\Rightarrow m_\phi \geq 30\,\text{TeV}$$

Dark radiation



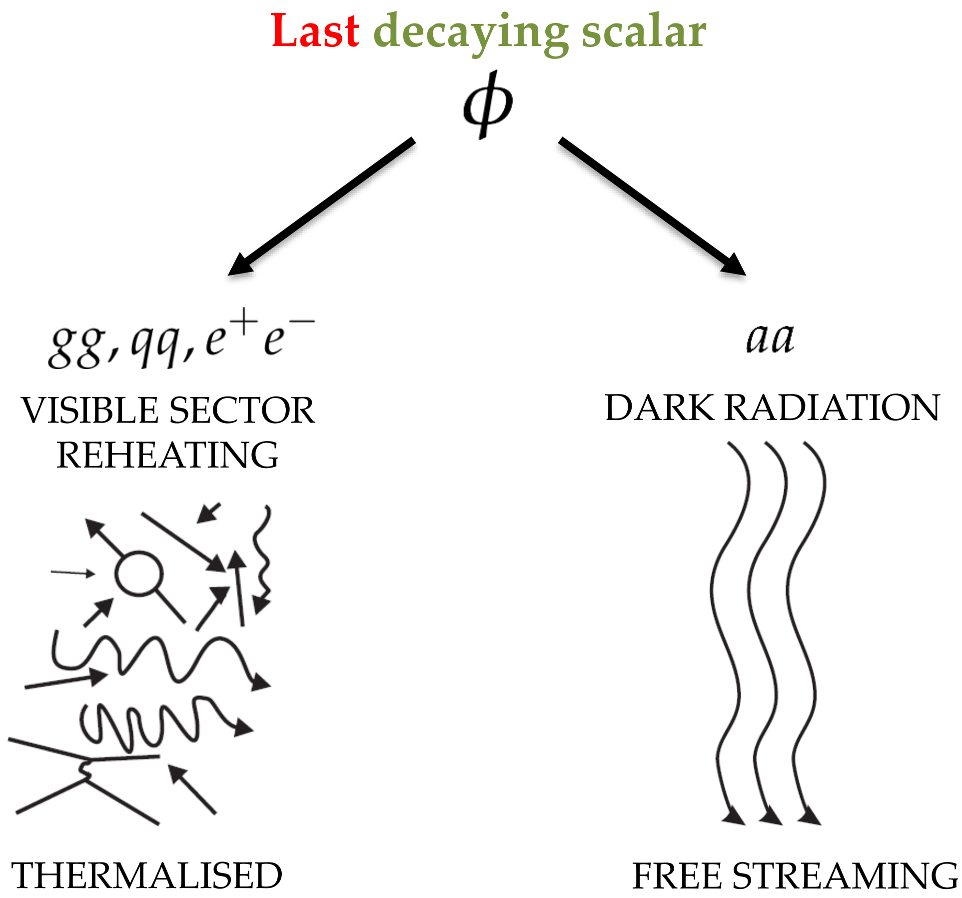
Dark radiation



Moduli decay and dark radiation

- Dark radiation modify CMB and BBN; however, current observational values from WMAP, ACT, SPT, Planck leave room for $\Delta N_{\rm eff} \sim 0.1 - 0.3$
- Dark radiation is well-motivated in string theory:
  - Moduli generally couple to everything with $1/M_{\rm P}$ couplings
  - There is no reason to expect vanishing couplings to hidden sectors
- Explicit studies of string effective field theories support axionic decay modes with branching ratios $B_a(\phi \to aa) \sim 0.01 \to 1$
- Therefore, in string theory we should expect reheating to be driven by the late-time decays of massive Planck-coupled particles
- As radiation redshifts as a^{-4} and matter redshifts as a^{-3}, we expect reheating to be driven by the last scalar field to decay
- Since it does not interact, dark radiation propagates freely after this

Moduli decay and dark radiation



Dark radiation arises from hidden sector decays of moduli

A cosmic axion background

- Since moduli couplings to SM particles and axions are of order $1/M_P$: $\Gamma \sim \frac{m_\phi^3}{M_P^2}$
- At decay, $H_{decay} \sim \tau^{-1} = \Gamma$, the energy density and temperature are:

$$H_{decay} = \sqrt{\frac{8\pi G\rho}{3}} \quad \Rightarrow \quad T_{rht} \sim \rho^{1/4} \sim \frac{m_\phi^{3/2}}{M_P^{1/2}} \sim 0.6\,\text{GeV} \left(\frac{m_\phi}{10^6\,\text{GeV}}\right)^{3/2}$$

- The two-body decays $\phi \to aa$ give an energy for these axions:

$$E_a = \frac{m_\phi}{2} = 5 \times 10^5\,\text{GeV} \left(\frac{m_\phi}{10^6\,\text{GeV}}\right)$$

- Thermal bath cools into CMB while axions never thermalize
- The ratio of axion energy to photon temperature is retained through cosmic history!

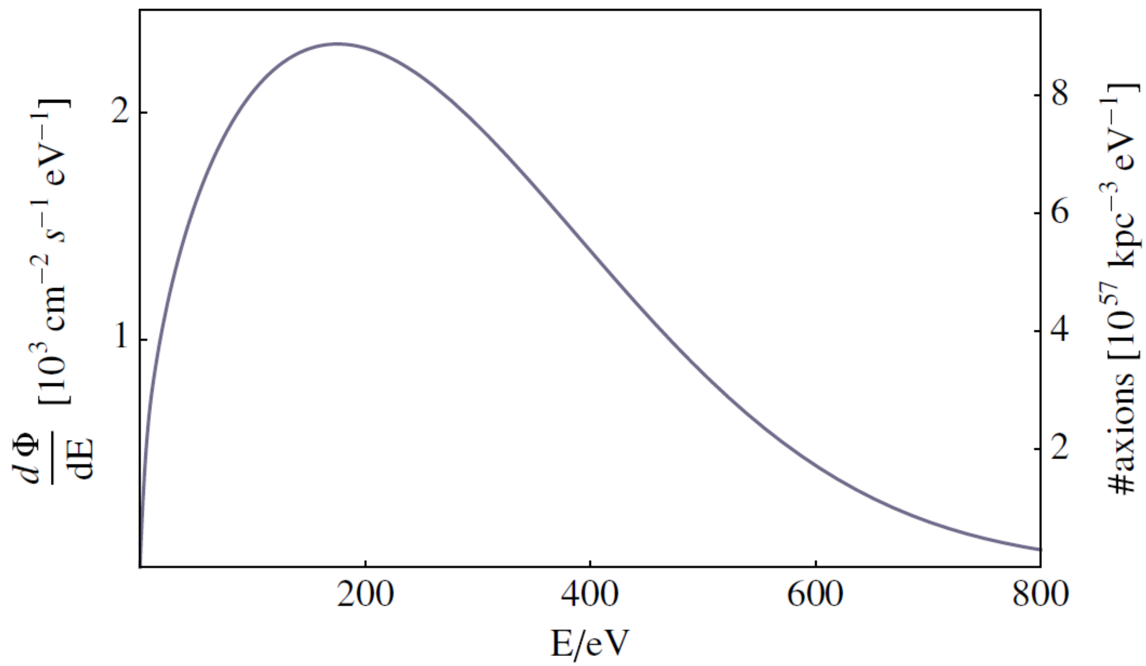
$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\phi}\right)^{1/2} \sim 10^6 \left(\frac{10^6\,\text{GeV}}{m_\phi}\right)^{1/2} \sim \frac{E_a^0}{T_\gamma^0}$$

- Today, these axions have $E_a^0 \sim \mathcal{O}(200\,\text{eV})$

A cosmic axion background

PREDICTION: Cosmic Axion Background (CAB)

$$\text{Energy:} \quad \sim 0.1 \div 1\,\text{keV} \qquad\qquad \text{Flux:} \quad \sim \left(\frac{\Delta N_{\text{eff}}}{0.1}\right) 10^6\,\text{cm}^{-2}\,\text{s}^{-1}$$



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- It is a dark analogue of the CMB at much higher energy
- This expectation comes from simple and general properties of moduli
- It is not tied to any precise model for moduli stabilization
- It just requires the existence of massive particles only interacting gravitationally
- For $10^5\,\text{GeV} \leq m_\phi \leq 10^8\,\text{GeV}$ the CAB lies today in extreme UV/soft X-ray

- Can this CAB be detected? Look for signatures of $a \to \gamma$ conversion in
  - Astrophysical/cosmological magnetic fields (galaxy clusters)
  - Signals in helioscopes?

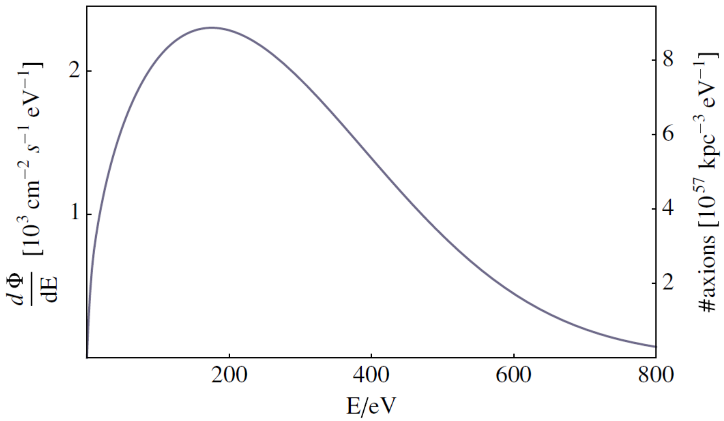
Dark radiation and solar axions

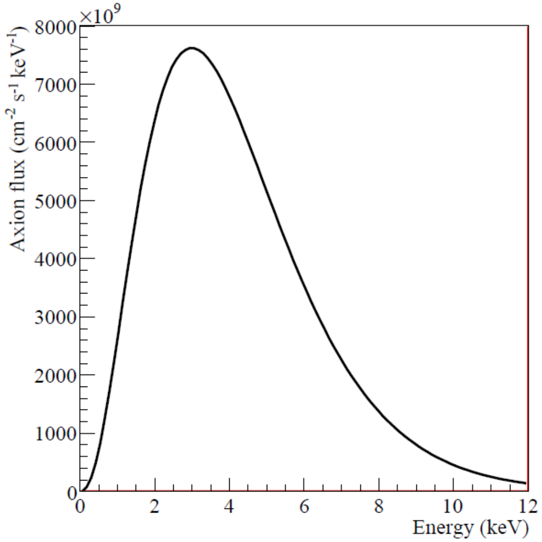
- The flux of dark radiation is isotropic; that of solar axions is directional
- The solar axion flux is suppressed by two powers of the axion decay constant

$$\Phi_{\rm solar} = \left(g_{a\gamma\gamma} \times 10^{10}\,{\rm GeV}\right)^2 3.54 \times 10^{11}\,{\rm cm}^{-2}\,{\rm s}^{-1}$$
$$\equiv 1.91 \times 10^6 \left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)^2 {\rm cm}^{-2}\,{\rm s}^{-1}$$

$$\Phi_a \sim 10^6\,{\rm s}^{-1}\,{\rm cm}^{-2}$$

- DR axions can easily dominate solar axions for non-excluded values of f_a
- The spectrum of solar axions differ from that of dark radiation axions





Dark radiation at IAXO

- Dark radiation axions could be observed by IAXO as an isotropic background
- This background would come however from the magnet bores (in whatever magnet position) and could be switched on/off (or modulated) with the magnetic field
- Dark radiation signatures:
  - Characteristic spectrum; needs low threshold X-ray detectors (200 eV)
  - Loss of coherence starts earlier than in CAST ($m_a \geq 2 \cdot 10^{-3}$ eV) and is steeper
  - However, from the *axiverse* picture, we expect a plethora of axion-like masses, for which there is coherence of the conversion in vacuum
- Since the axion-photon coupling is a free parameter, independent of m_a, it is relevant that IAXO is sensitive to values beyond direct bounds (ie SN/globular clusters)

Dark radiation at IAXO

- Dark radiation … background
- This backgrou… whatever magnet position) and … agnetic field
- Dark radiation …
  - Character… (200 eV)
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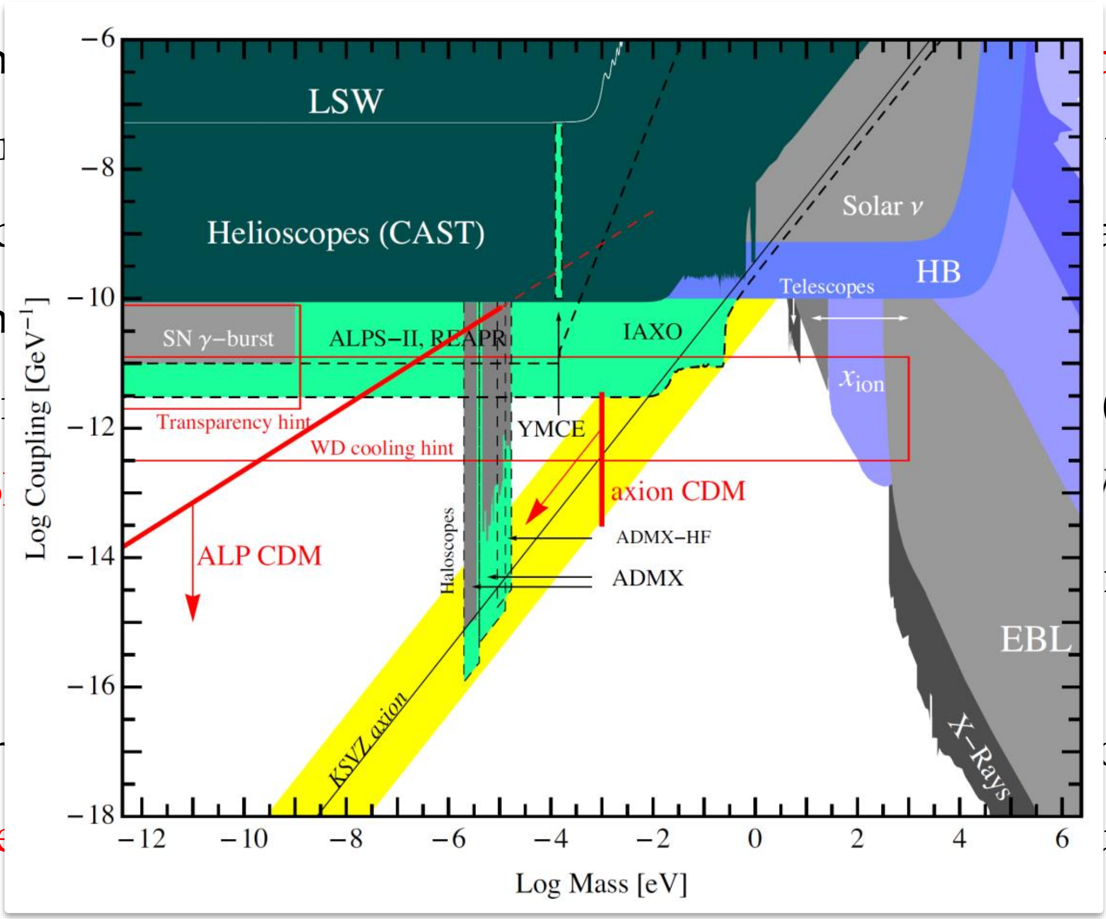

Dark radiation at IAXO

- But… can IAXO be really sensitive to this cosmic axion background?

$$\Phi_a \sim \left(\frac{m_\phi}{5\cdot 10^6\,\mathrm{GeV}}\right)\left(\frac{\Delta N_{\rm eff}}{0.1}\right) 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} = \frac{2\cdot 10^8}{\langle E\rangle [eV]}\left(\frac{\Delta N_{\rm eff}}{0.1}\right)$$

While at $g_{a\gamma\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}, \quad \rightarrow \quad \Phi_{\rm solar} \sim 3.5\times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- To have comparable fluxes: $m_\phi \sim 6\cdot 10^{17}\,\mathrm{GeV} \quad \rightarrow \quad \langle E\rangle \sim 6\cdot 10^{-4}\,\mathrm{eV}!$
- Moreover, $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1} \Rightarrow f_a \sim 2\cdot 10^7\,\mathrm{GeV}$
- To have a rough idea of the sensitivity of IAXO at this scale:

$$\#\,\mathrm{events/year} \sim \frac{450}{\langle E\rangle\,[\mathrm{eV}]}$$

$(B = 3\,\mathrm{T}, L = 20\,\mathrm{m}, 8\ \mathrm{bores\ of}\ 60\,\mathrm{cm\ of\ diam}, \Delta N_{\rm eff} = 0.1, g_{a\gamma\gamma} = 10^{-10}\,\mathrm{GeV}^{-1})$

Conclusions

- String theory supports the existence of axion and axion-like particles
- It also supports the existence of a cosmic axion background coming from the decay of moduli
- However, with "natural" values of the parameters, this CAB would be inobservable in IAXO
- For certain values of the parameters, this CAB could be observable, but would require very low threshold detectors
- The feasibility of this observation needs a more detailed background and detector study