Axion Cosmology.

Axion cold dark matter, axions from string theory, and all that …

Andreas Ringwald (DESY)

Implications of the early LHC for cosmology,
DESY, Hamburg, 18-20 April 2012

HELMHOLTZ | ASSOCIATION

Cold Dark Matter Candidates

Best motivated cold dark matter (CDM) candidates

> Lightest Supersymmetric Particle (LSP) in SUSY with R-parity
  - neutralino
  - gravitino

> dynamical theta-parameter
  - axion

arise in extensions of the Standard Model (SM) which are build in order to solve other problems than CDM

> Hierarchy problem

> Strong CP problem

Cold Dark Matter Candidates

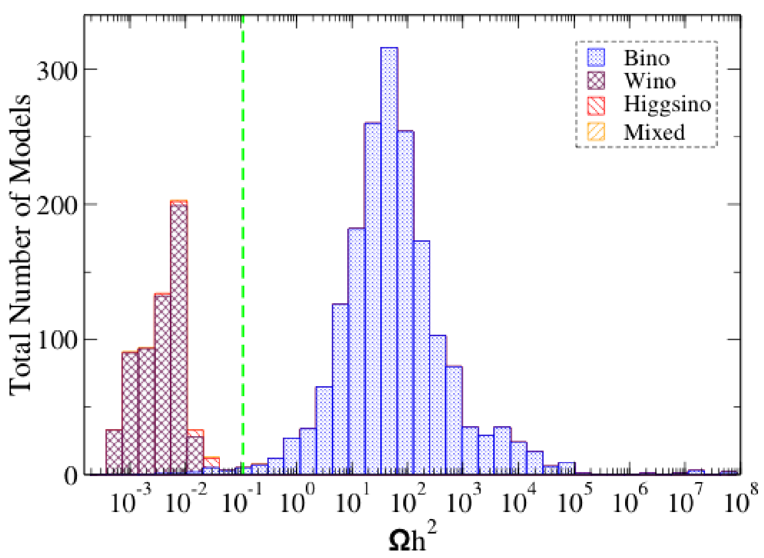
MSSM neutralino LSP CDM scenario has problems:

> Fine tuning:

General scan over 19 param. MSSM

- ★ dimensionful param's defined at M_{GUT}
- $m_{Q_1}, m_{U_1}, m_{D_1}, m_{L_1}, m_{E_1} : 0 \to 3500$ GeV
- $m_{Q_3}, m_{U_3}, m_{D_3}, m_{L_3}, m_{E_3} : 0 \to 3500$ GeV
- $M_1, M_2, M_3 : 0 \to 3500$ GeV
- $A_t,\ A_b,\ A_\tau : -3500 \to 3500$ GeV
- $m_{H_u},\ m_{H_d} : 0 \to 3500$ GeV
- $\tan\beta : 2 \to 60$
- ★ $m_{\widetilde{W}_1} > 103.5$ GeV
- ★ $m_{\widetilde{W}_1} > 91.9$ GeV (wino-like)
- ★ $m_h > 111$ GeV
- ★ HB, Box, Summy, JHEP 1010:023,2010

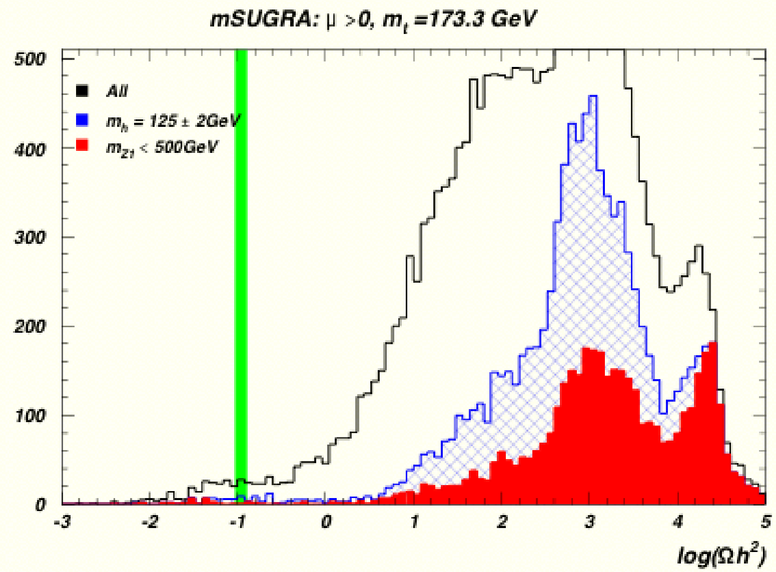
- histogram of models vs. $\Omega_{\tilde{Z}_1} h^2$ with $m_{\tilde{Z}_1} < 500$ GeV



Cold Dark Matter Candidates

MSSM neutralino LSP CDM scenario has problems:

- Fine tuning:
  - from scan over mSUGRA(CMSSM) space
  - require as well $m_h = 125 \pm 2$ GeV
  - $\Omega_{\tilde{Z}_1} h^2 \sim 0.11$ exceedingly improbable, no miracle: HB, V. Barger, A. Mustafayev, arXiv:1202.4038.



Cold Dark Matter Candidates

MSSM neutralino LSP CDM scenario has problems:

- Fine tuning
- Gravitino problem: overproduction of gravitino followed by late gravitino decay can destroy successful BBN predictions unless $T_R < 10^5$ GeV

Gravitino LSP CDM scenario has problems:

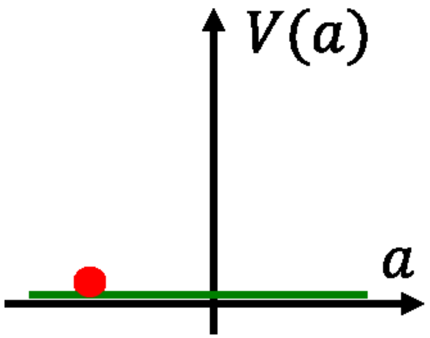
- Long-lived NLSP can destroy BBN

What about axion CDM scenario?

Axion CDM via displacement mechanism

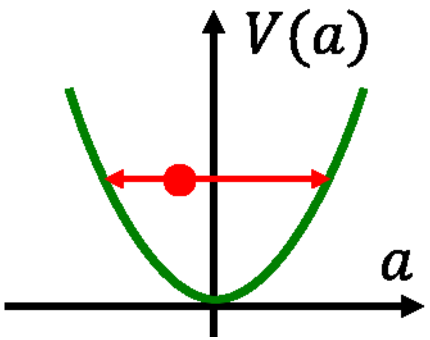
At $T \sim f_a \gtrsim 10^9$ **GeV**

- Axion field fixed at $a_i = \theta_i f_a$



At $T \sim 1$ **GeV**

- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Non-relativistic, classical field oscillations: very small mass, yet cold dark matter



Axion CDM via displacement mechanism

- If entropy conserved since start of oscillations,

$$\Omega_a h^2 \approx 0.7 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{7/6} \left(\frac{\theta_i}{\pi} \right)^2$$

- Classic window: axion main component of CDM, for

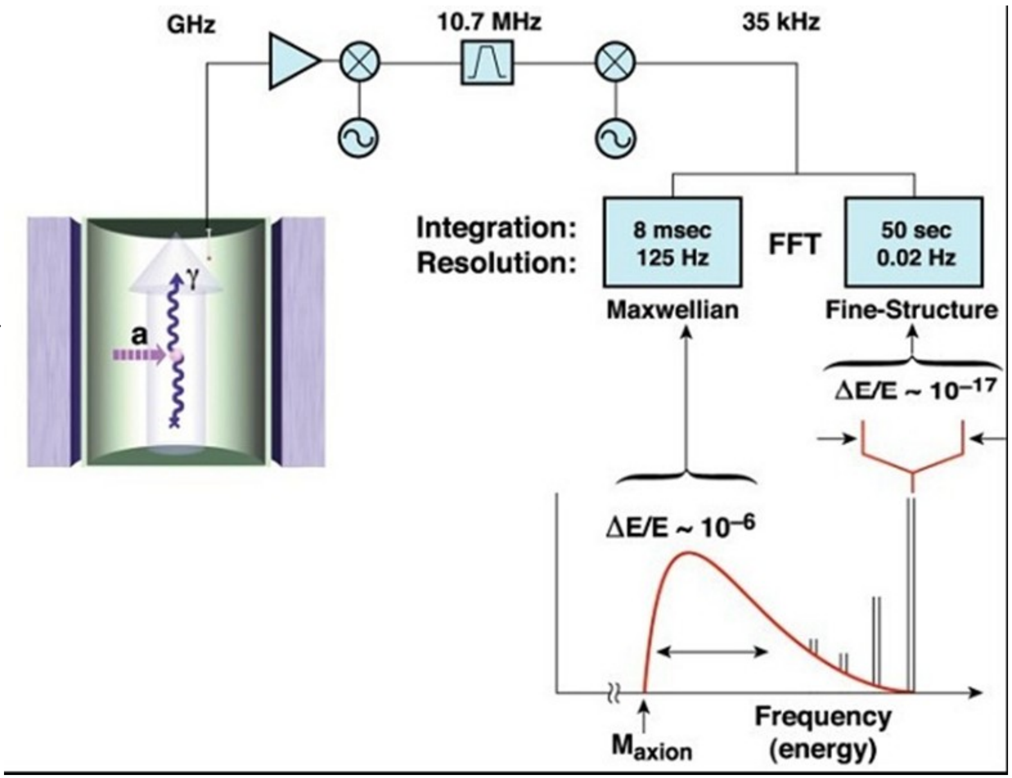
$$f_a \sim 10^{12}\ \mathrm{GeV}, m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 10\ \mu\mathrm{eV} \left(\frac{10^{12}\ \mathrm{GeV}}{f_a} \right), \theta_i \sim 1$$

Direct Axion CDM Searches with Haloscopes

- Axion CDM -> photon conversion in a resonant cavity, $m_a = 2\pi\nu \sim 4\ \mu\mathrm{eV}\left(\frac{\nu}{\mathrm{GHz}}\right)$ based on coupling to two photons, cf. Sikivie `83

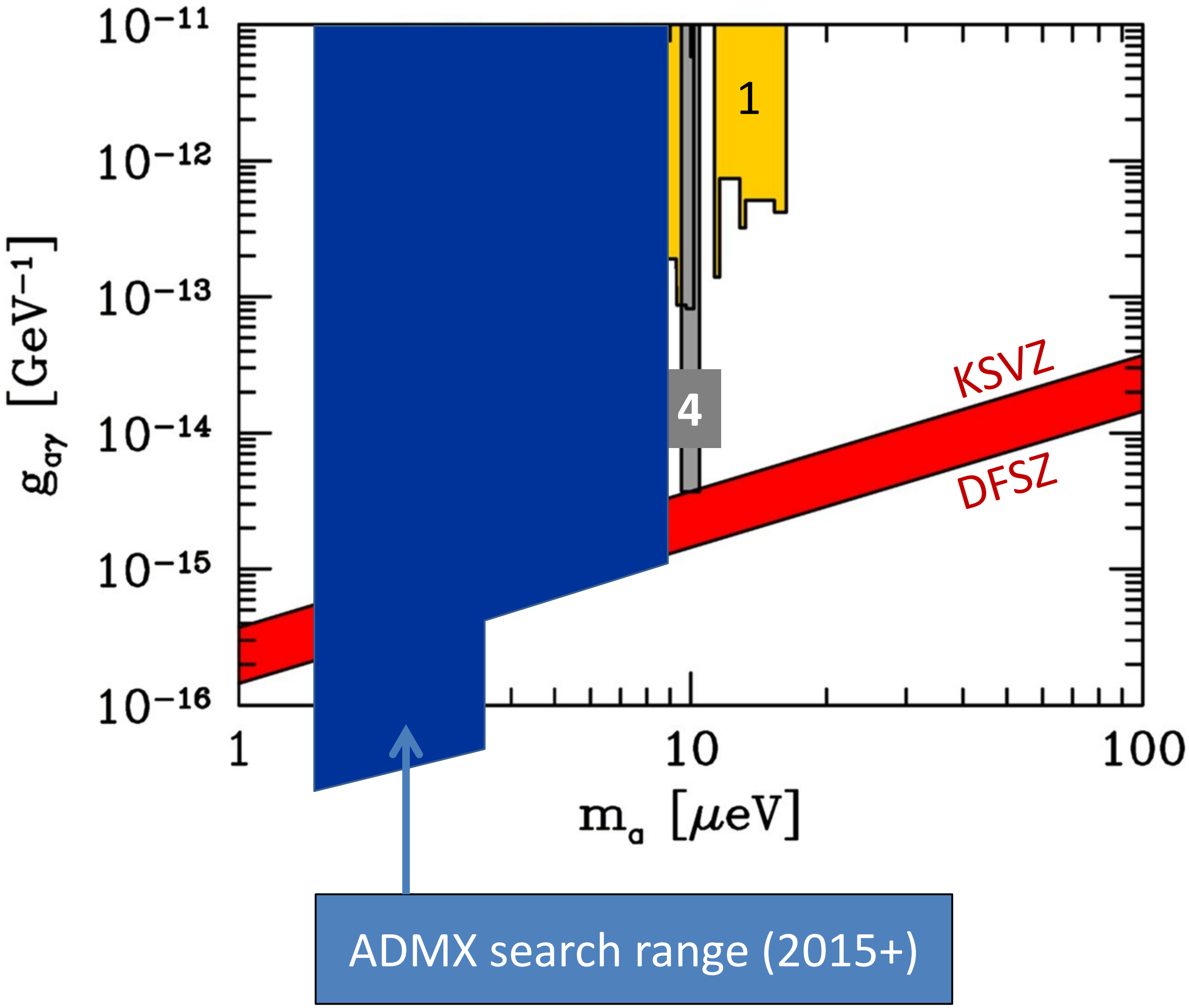
$$\mathcal{L} \supset -\underbrace{\frac{1}{4}\,\frac{\alpha}{2\pi}\,\frac{C_{a\gamma}}{f_a}}_{g_{a\gamma}}\; a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= g_{a\gamma}\; a\; \mathbf{E}\cdot\mathbf{B}$$



Axion Dark Matter Searches

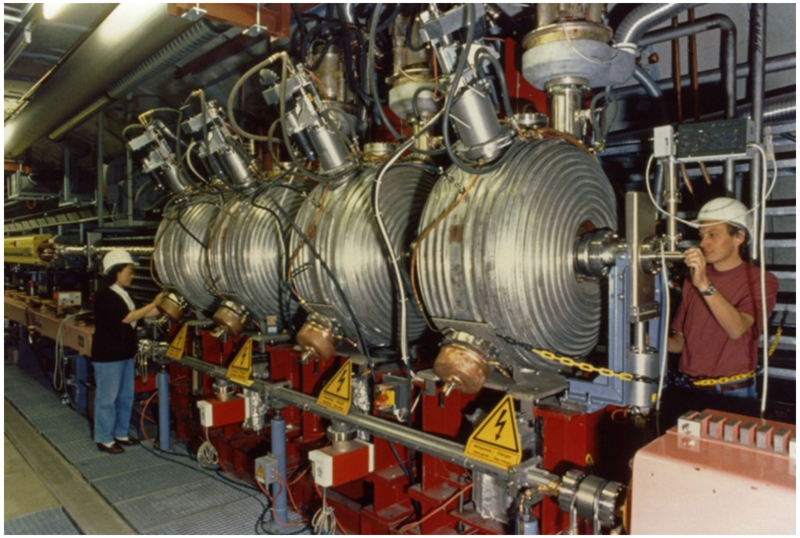
Limits assuming axions are the galactic dark matter with standard halo

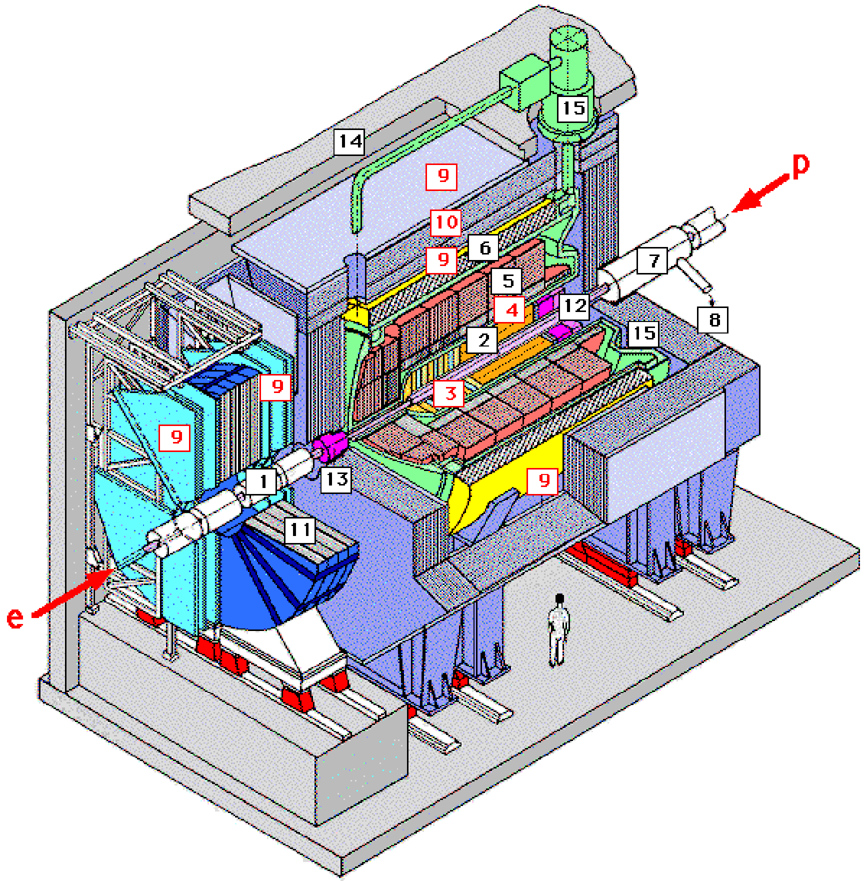


1. Rochester-Brookhaven-Fermilab, PRD 40 (1989) 3153
2. University of Florida PRD 42 (1990) 1297
3. US Axion Search ApJL 571 (2002) L27
4. CARRACK I (Kyoto) hep-ph/0101200

Haloscope Opportunity in Hamburg

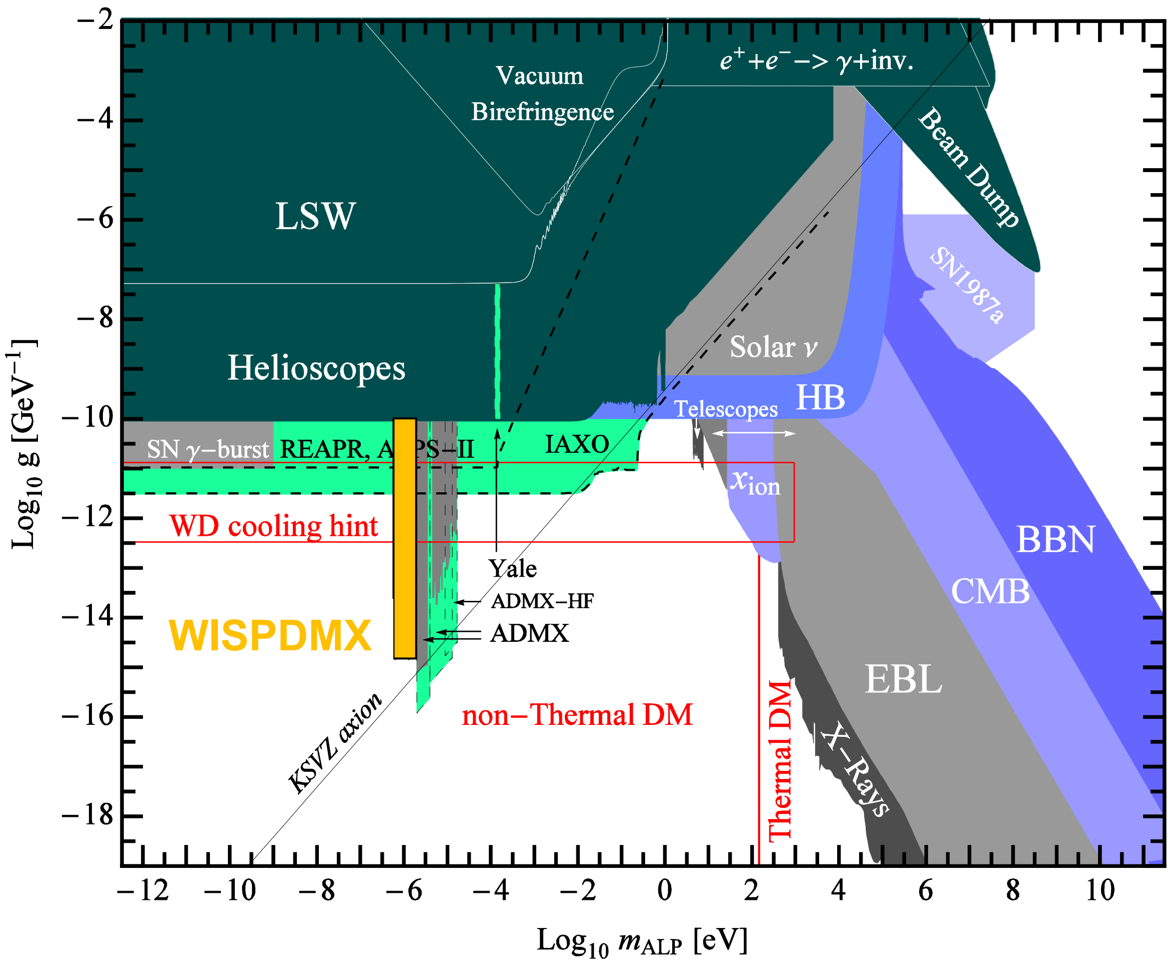
- Available building blocks (DESY)
  - HERA proton ring cavities
  - H1 superconducting solenoid
- Interested partner (MPIfR Bonn)
  - receiver, amplifier, FFT, …





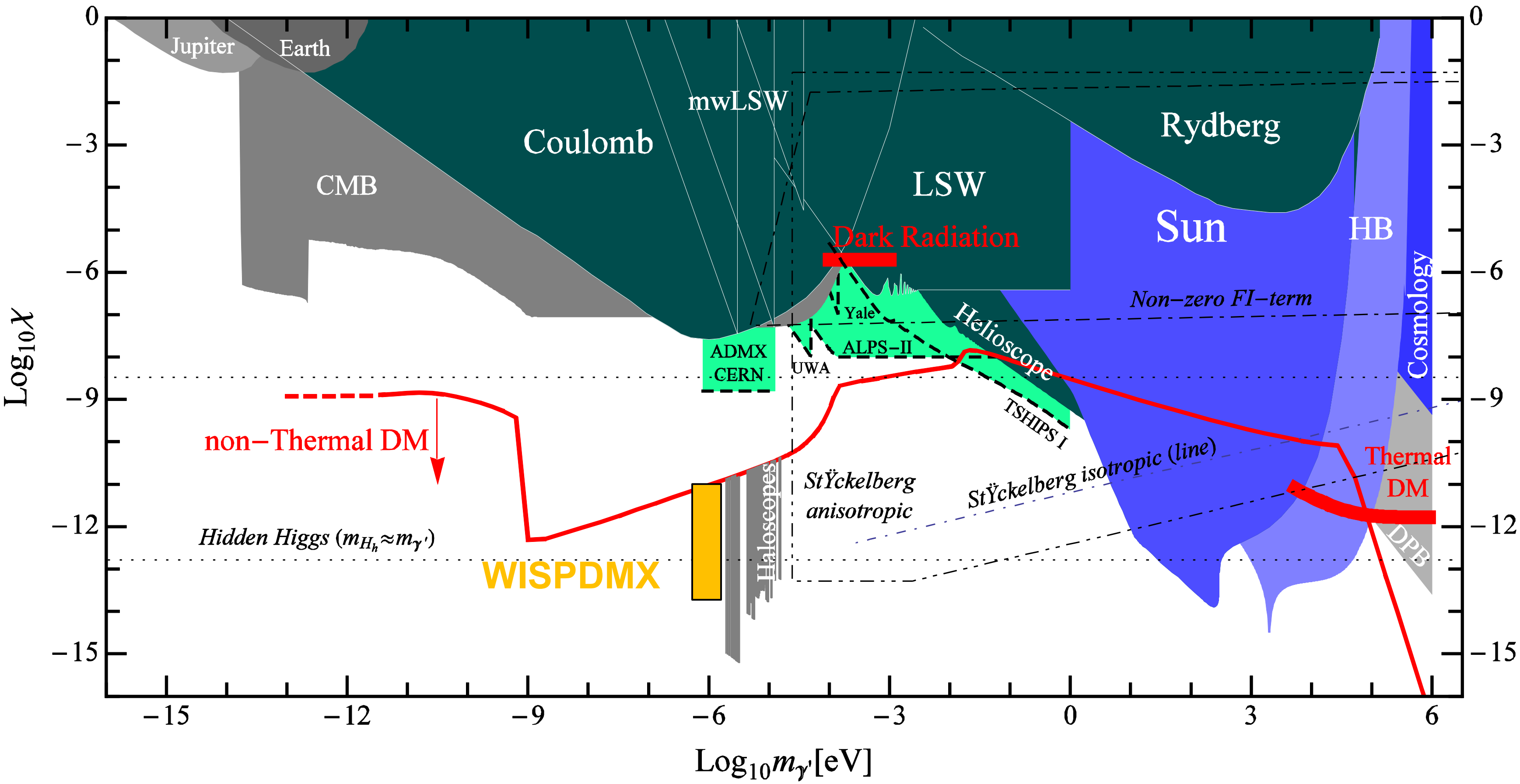
Discovery Reach of Axion and ALP CDM Experiment

- Could probe axion CDM up to ADMX mass region:
  [Horns,Jaeckel,Lindner,Lobanov,Möller,AR,Sekutowicz,Trines,Westphal]



Discovery Reach of Hidden Photon CDM Experiment

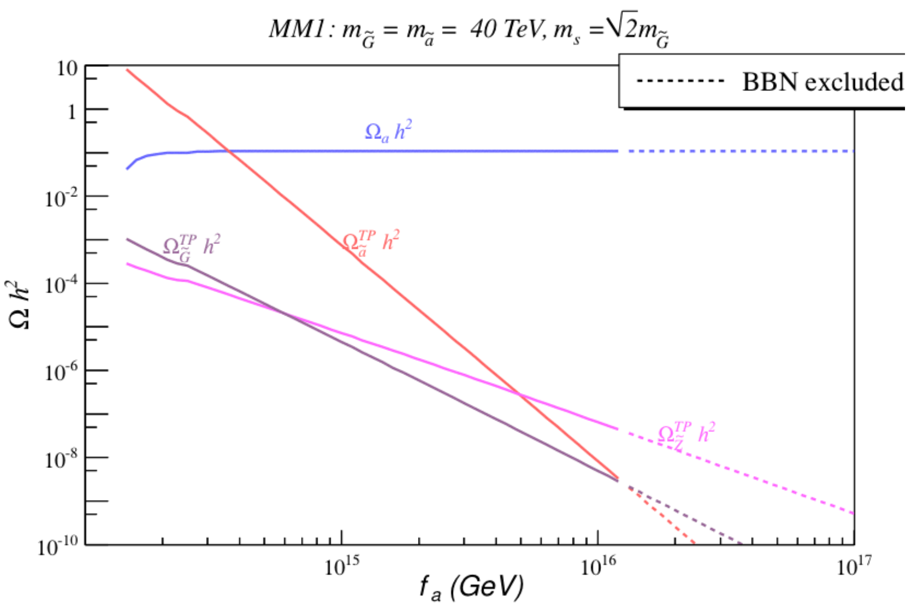
- First stage without magnet: could probe Hidden Photon CDM, cf. Nelson,Scholtz `11; Arias et a. `12, up to ADMX mass region
  [Horns,Jaeckel,Lindner,Lobanov,Möller,AR,Sekutowicz,Trines,Westphal]



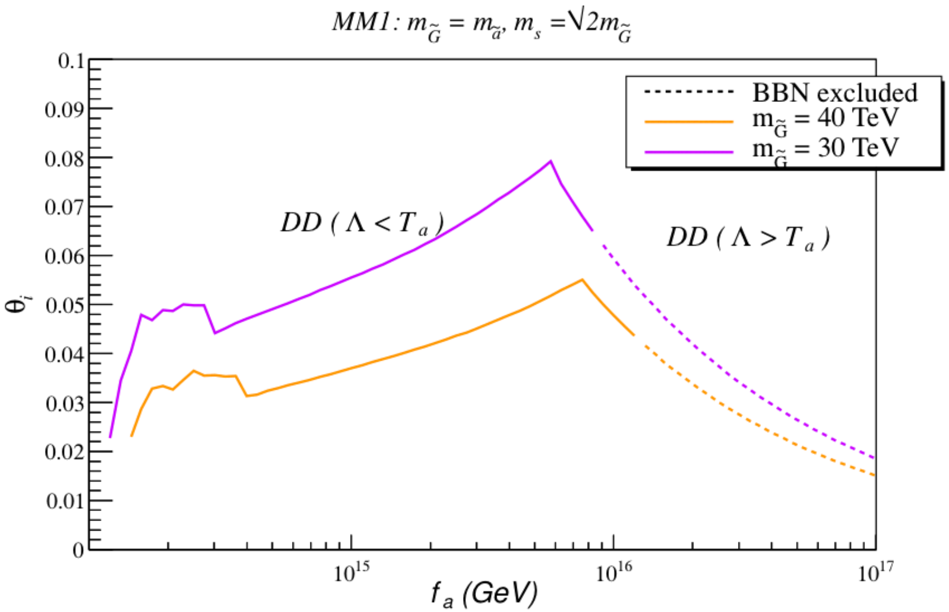
GUT scale axion CDM

> Ways to allow for $f_a \sim 10^{16}\,\mathrm{GeV}$ without overclosing the universe:

- small $\theta_i \sim 10^{-3}$ (anthropic window)
- dilution by late decaying particles (after beginning of oscillations, but before BBN)
- both … , cf. e.g. Baer, Lessa `11



MM1: $m_{\tilde G} = m_{\tilde a}$, $m_s = \sqrt{2} m_{\tilde G}$



Searching for Axions in the Anthropic Window

Assume axions are galactic dark matter: 300 MeV/cm^3

( ) ( )

Independently of expect

( ) ( )

Expect time-varying neutron EDM, MHz frequency for GeV

Experimental limit on static EDM

Use much larger electric fields within atoms, small energy shifts within polarized molecules: Molecular interferometry techniques may work, a factor 100 off at present. Best in kHz-MHz regime (anthropic window).

Graham & Rajendran, arXiv:1101.2691

Axions in String Theory

- String compactifications generically contain pseudo-scalar fields with axionic coupling to gauge fields and anomalous global shift symmetry

$$a_i F\tilde{F} \qquad\qquad a_i \longrightarrow a_i + \epsilon$$

- These axion and axion-like particle (ALP) candidates arise in string compactifications as KK zero modes of antisymmetric tensor fields:

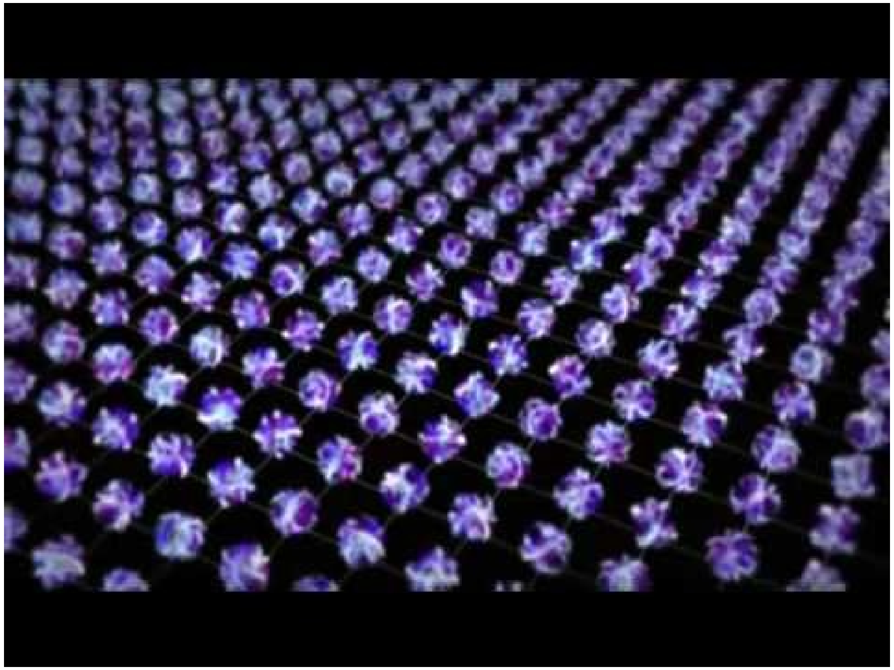
$$\text{heterotic string}: \quad B_2$$

$$\text{IIB string}: C_2, C_4$$

Axions in IIB String Theory

- Concentrate on IIB case (moduli stabilisation best understood): realisation of brane-world scenarios in string theory
- Assume that 4D theory arising from compactification has N=1 SUSY:

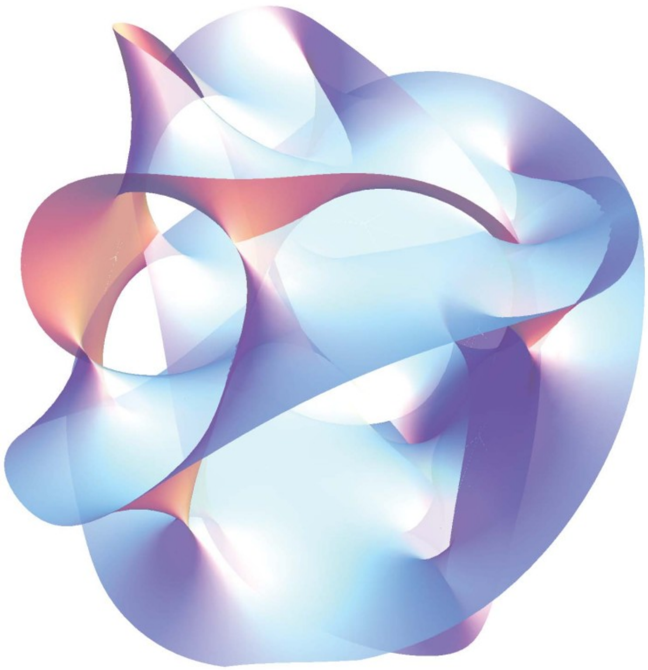
$$10\ \mathrm{D} \rightarrow 4\ \mathrm{D} + \mathrm{CY}_3$$



Axions in IIB String Theory

- KK reduction (expansion in harmonic forms):

$$C_2 = c^a(x)\omega_a, \quad a = 1, ..., h^{1,1}_-$$
$$C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \ldots, \quad \alpha = 1, ..., h^{1,1}_+$$



- Number of axionic fields determined by topology of CY manifold (number of topologically non-equivalent 2-cycles or 4-cycles)

Axions in IIB String Theory

> Number of cycles generically O(100):

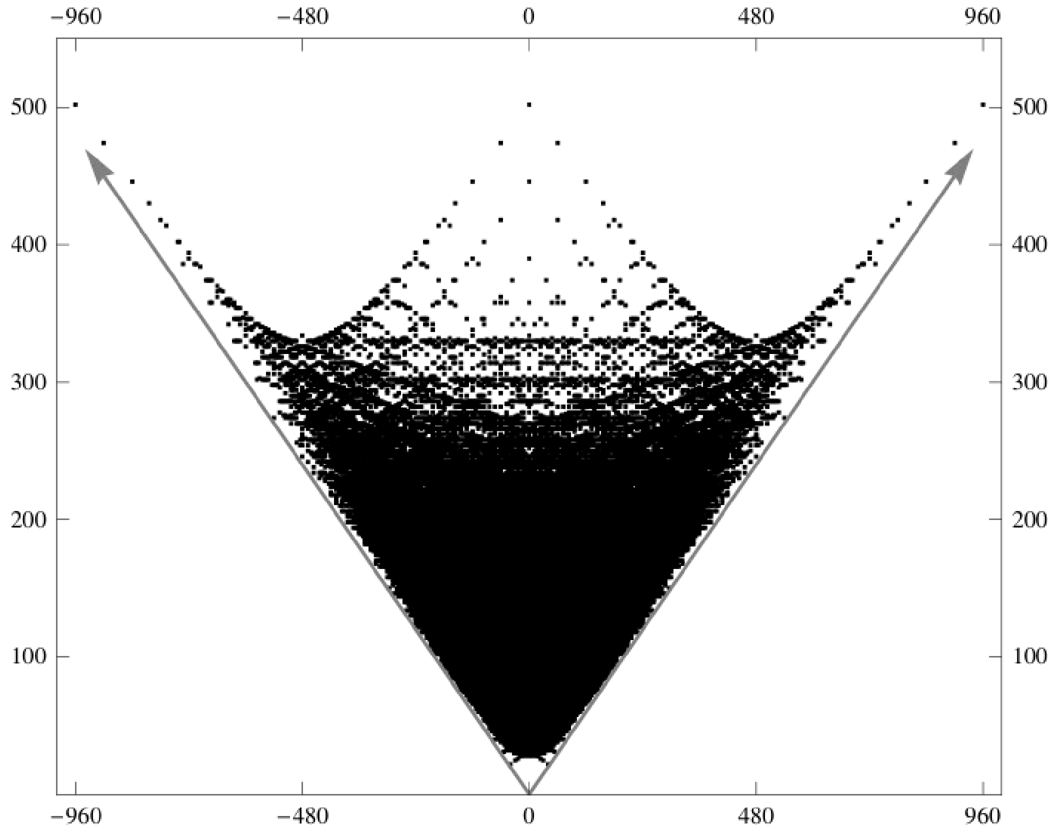


Figure 1: A plot of the Hodge numbers of the Kreuzer–Skarke list. $\chi = 2(h^{11} - h^{21})$ is plotted horizontally and $h^{11} + h^{21}$ is plotted vertically. The oblique axes bound the region $h^{11} \geq 0$, $h^{21} \geq 0$.

Axions in IIB String Theory

- Each axion comes along with a real scalar field – saxion – which is real part of lowest component of chiral superfield,

$$T_\alpha = \tau_\alpha + i\, c_\alpha$$

- τ_α … Kähler modulus measuring the volume of four-cycle α
- KK reduction of D-brane action

$$S_p = \frac{-2\pi}{(2\pi\sqrt{\alpha'})^{p+1}} \left(\int_\Sigma d^{p+1}\xi e^{-\phi} \sqrt{\det(g + B + 2\pi\alpha' F)} + i \int_\Sigma e^{B + 2\pi\alpha' F} \wedge \sum_q C_q \right)$$

- T_α is gauge kinetic function for theory on D7-brane:
  - volume measures gauge coupling, $\tau_\alpha \sim g^{-2}$
  - c_α has axionic coupling, $\sim c_\alpha F \wedge F$

Axions in IIB String Theory

- 4D effective field theory, cf. Jockers, Louis `05

$$\mathcal{L} \supset -dc_\alpha \frac{\mathcal{K}_{\alpha\beta}}{8} \wedge \star dc_\beta + \frac{\tau_i}{8\pi} F_i \wedge \star F_i + \frac{1}{4\pi M_P} c_\alpha r^{i\alpha} (F_i \wedge F_i)$$

$$\text{with} \quad \mathcal{K}_{\alpha\beta} \equiv \frac{\partial^2 K}{\partial \tau_\alpha \partial \tau_\beta}, K = -2 \ln \mathcal{V}, r^{i\alpha} \equiv \ell_s^{-4} \int_{D_i} \tilde{\omega}^\alpha$$

- Decay constants via canonical normalization of axion kinetic terms:

$$f_a \sim \begin{cases} M_P/\tau_a & \text{non} - \text{local axion} \\ M_s \sim M_P/\sqrt{\mathcal{V}} & \text{local axion} \end{cases}$$

  - Local axion: corresponding 4-cycle does not intersect any divisor which controls the overall volume

- Coupling to gauge bosons via canonical normalization of gauge kinetic terms, ~ C_ia/f_a .

Axions in IIB String Theory

- Ultra-light axions – an axiverse - guaranteed? cf. Arvanitaki et al. `09
- Caveat: Saxions should be heavy, > 10 TeV, in order to avoid cosmological moduli problem
- Only axions which do not get too heavy by moduli stabilisation can be candidates for QCD axion and other light ALPs, cf. Conlon `06
- Cicoli, Goodsell, AR, DESY 12-058, 1205.nnnn:
  - Moduli stabilisation mechanism of Large Volume Scenario accomplishes this
  - Verified also in explicit globally consistent chiral model examples (CYs with h_11=4,5,few, plus brane setups and fluxes), cf. Cicoli,Mayrhofer,Valandro `11:

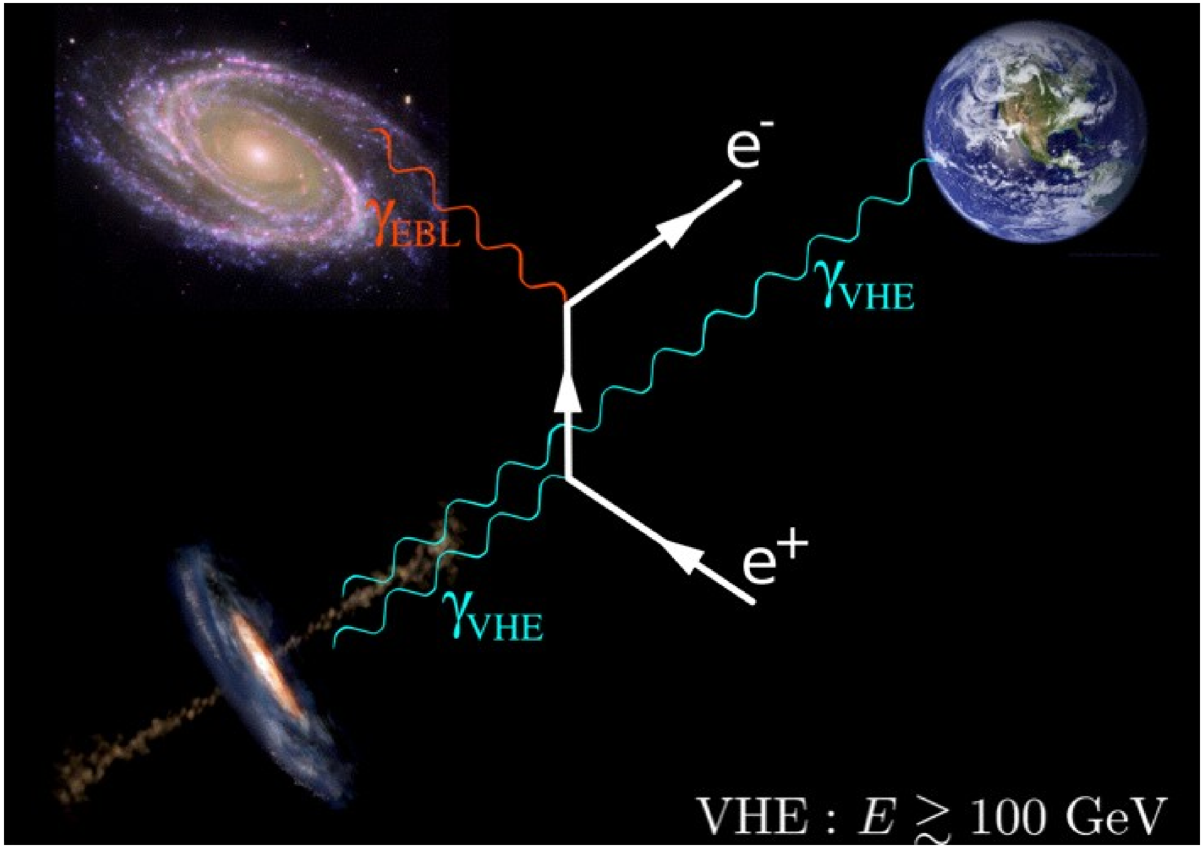
    GUT-like model with 5 magnetised D7 branes: one axion with f~10^16 GeV
    MSSM-like model: two light axions, both have f/C ~ 10^16 GeV
    Chiral model with 3 light axions with f/C ~ 10^18 GeV, 10^16 GeV, and M_s ~ 10^11 GeV
    Chiral model with two light axions with f ~ M_s ~ 10^11 GeV

Axions in IIB String Theory

- Possible intermediate string scale scenarios:
  - axion plus few lighter ALPs (local axions) with $f \sim M_s \sim M_P/\sqrt{V} \sim 10^{11}$ GeV
  - plus saxions of mass $M_P/V \sim 10$ TeV
  - plus few light ALPs (non-local ones) with $f/C \sim M_P \sim 10^{18}$ GeV
  - only one non-local ALP may have $f > M_s \sim 10^{11}$ GeV
  - volume modulus of mass $M_P/V^{3/2} \sim$ MeV
- QCD axion in the classic window, $f_a \sim 10^{11}$ GeV, plus lighter ALP(s), with comparable coupling to photons
- Opportunities:
  - QCD axion DM can be detected with microwave cavities
  - Axion and/or ALP can explain some astro-puzzles (see below)
  - ALP can be detected with light-shining-through wall experiments (see below)

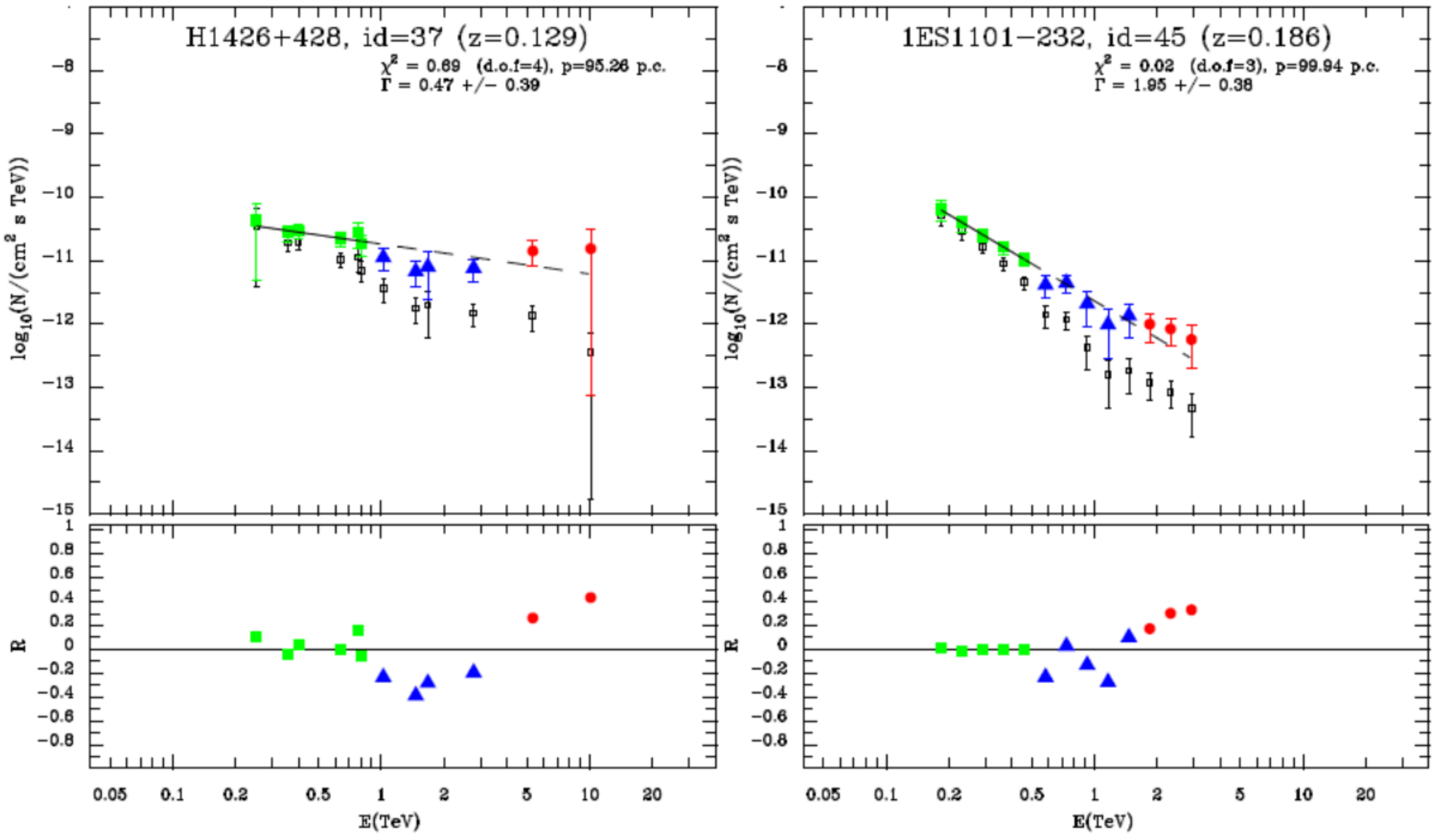
Hints for f ~ 10^10 GeV

- TeV photon spectra of distant AGNs should show absorption feature due to electron-positron pair production on extra-galactic background light



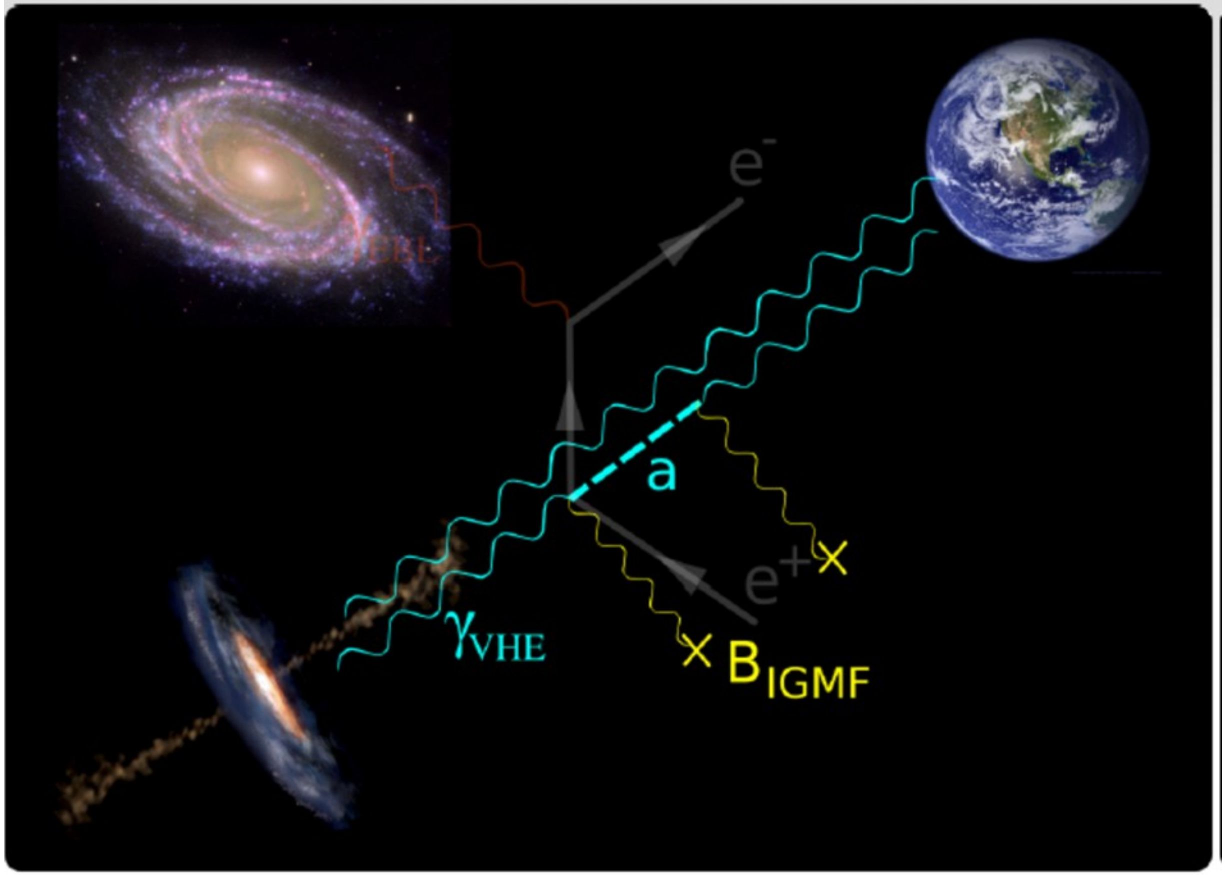
Hints for f ~ 10^10 GeV

- They don´t (cf. e.g. Horns, Meyer `12: more than 4 sigma effect)



Hints for f ~ 10^10 GeV

- Possible explanation: photon <-> ALP oscillations in astrophysical magnetic fields, cf. de Angelis et al. `07; Mirizzi, Montanino `09;…



Hints for f ~ 10^10 GeV

- Required parameters:

$$m_{a_i} \lesssim \mathrm{neV}, \;\; g_{i\gamma} \equiv \frac{\alpha}{2\pi} \frac{C_{i\gamma}}{f_{a_i}} \sim 10^{-12} \div 10^{-11}\ \mathrm{GeV}^{-1}$$

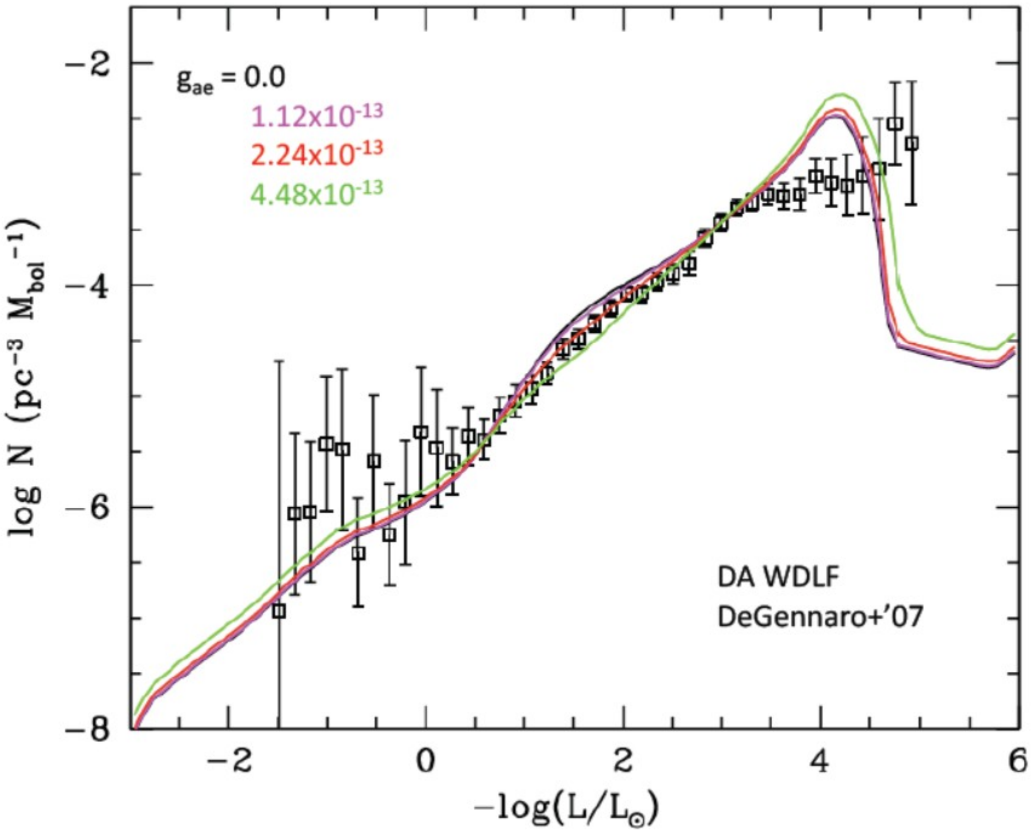
$$\Rightarrow f_{a_i} \sim 10^{8} \div 10^{9}\ C_{i\gamma}\ \mathrm{GeV}$$

- Must be an ALP, too light for an axion with such a decay constant

Non-Standard Energy Loss in White Dwarfs

- Standard model does not fit to white dwarf luminosity function
- Extra energy loss compatible with axion or ALP bremsstrahlung

Isern et al. `08



Hints for f ~ 10^10 GeV

- Required parameters:

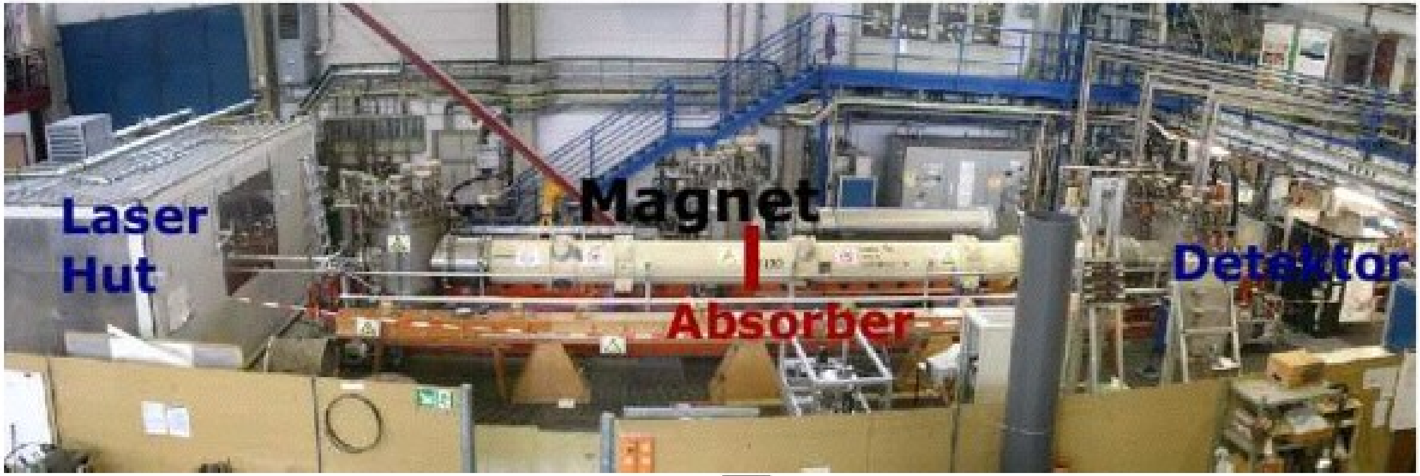
$$m_{a_i} \lesssim \mathrm{keV}, \;\; g_{ie} \equiv \frac{C_{ie} m_e}{f_{a_i}} = (0.6 \div 1.7) \times 10^{-13}$$

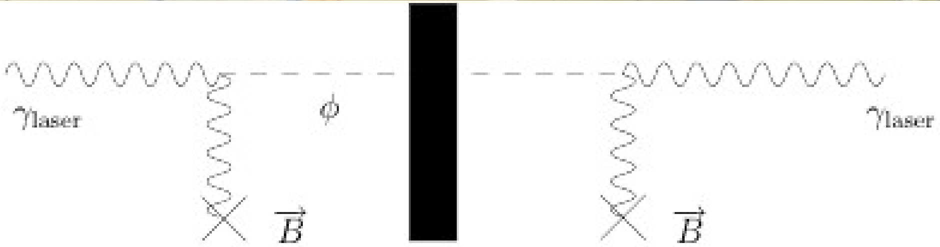
$$\Rightarrow f_{a_i} \sim 10^{10} \; C_{ie} \; \mathrm{GeV}$$

- Can be axion or ALP

Light-shining-through-walls

- Parts of this parameter space accessible at next generation of light-shining-through-walls experiments such as ALPS-II proposed at DESY or REAPR proposed at Fermilab (using e.g. 12 + 12 HERA magnets)





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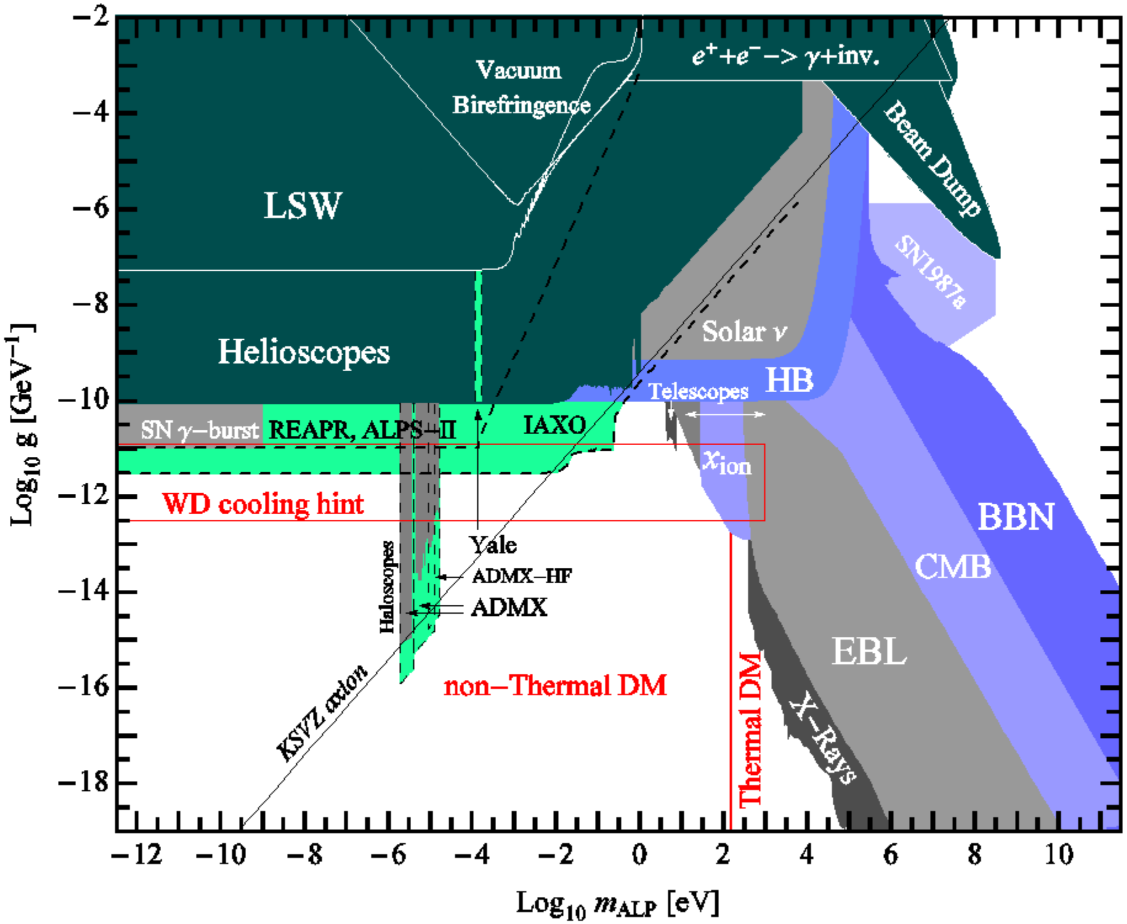
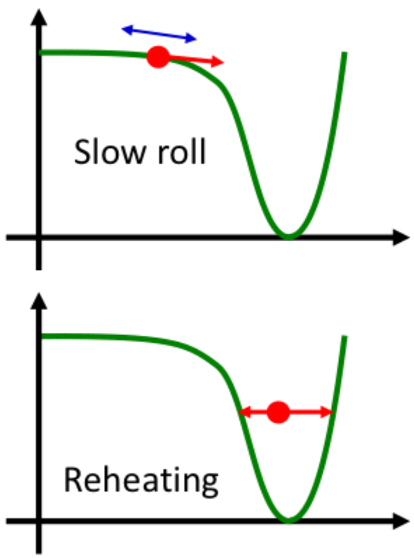


Probes of f ~ 10^16 GeV

- Direct axion CDM detection: time varying EDM of neutron
- Isocurvature perturbations in CMB:

Inflaton field

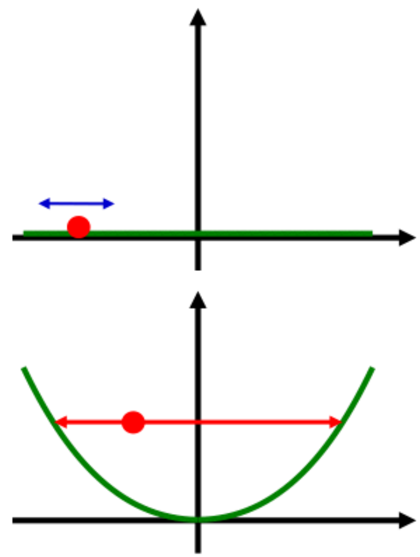
De Sitter expansion imprints
scale invariant fluctuations



Inflaton decay matter & radiation
Both fluctuate the same:
Adiabatic fluctuations

Axion field

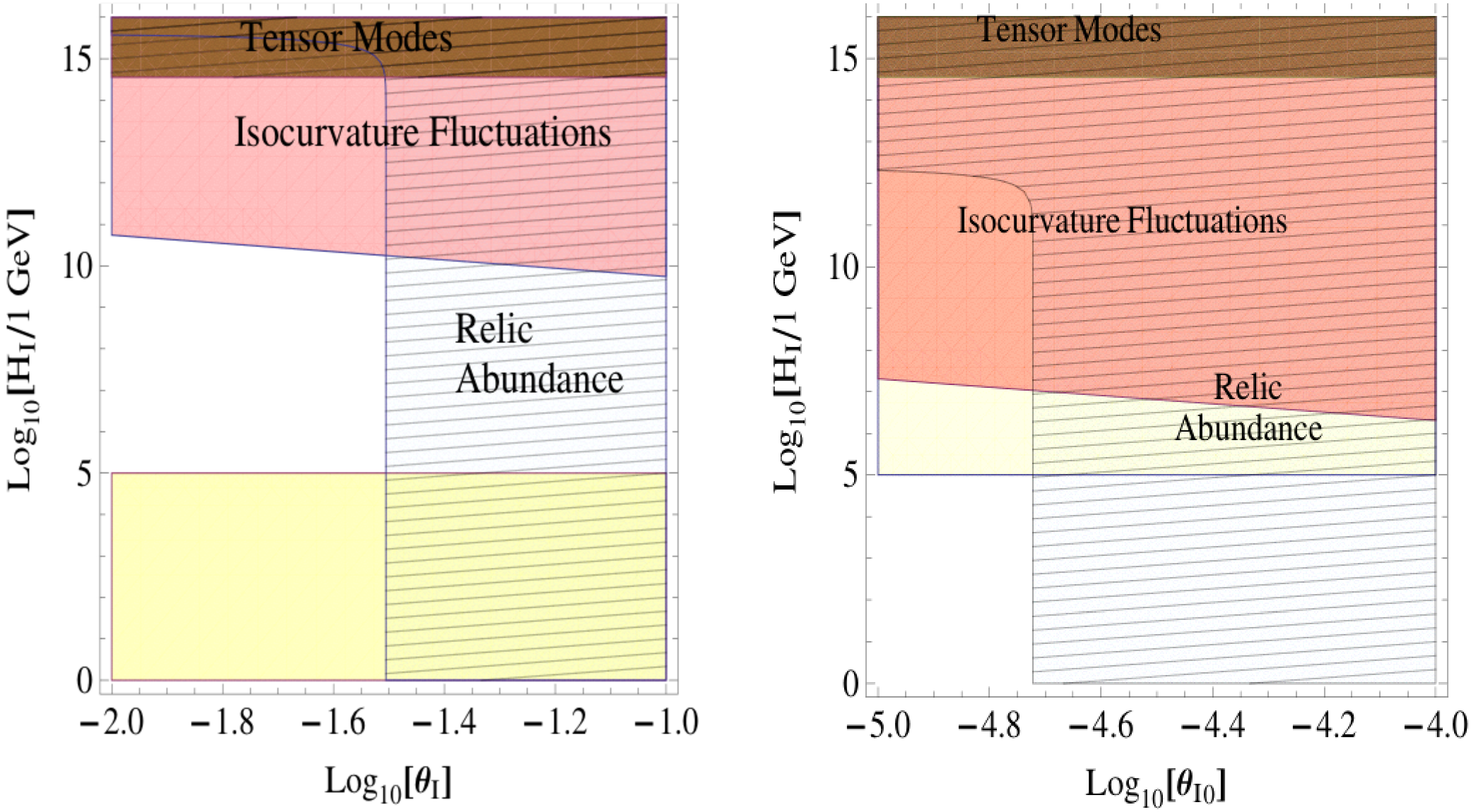
De Sitter expansion imprints
scale invariant fluctuations



Inflaton decay radiation
Axion field oscillates late matter
Matter fluctuates relative to radiation:
Entropy fluctuations

Probes of f ~ 10^16 GeV

- Direct CDM detection: time varying EDM of neutron
- Isocurvature perturbations in CMB, two scenarios (H_I>(<) M_mod):



Cf. Acharya, Bobkov, Kumar `10

Other probes of f ~ 10^16 GeV (cf. Arvanitaki et al. `09)

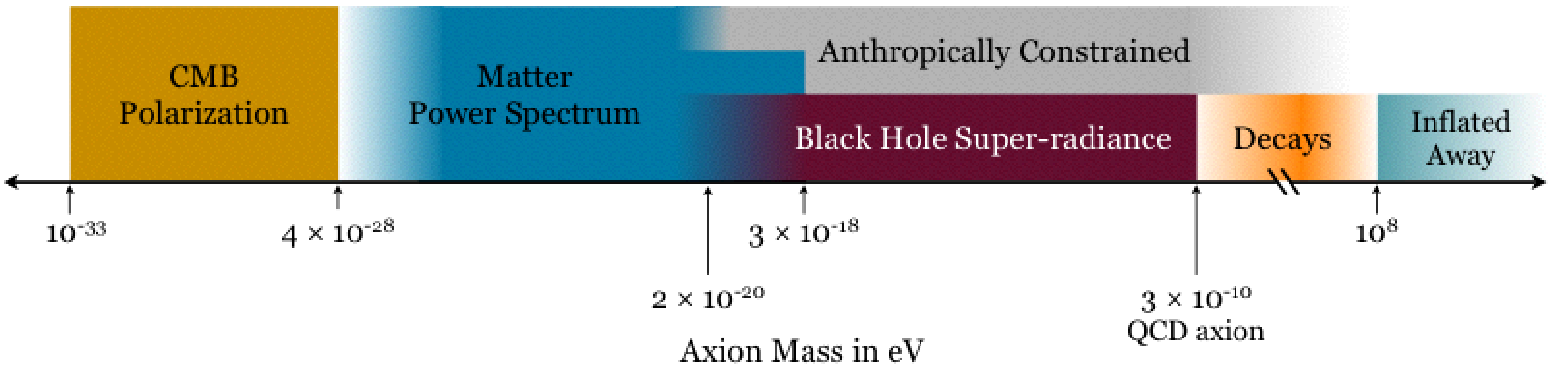


Figure 1: **Map of the Axiverse:** The signatures of axions as a function of their mass, assuming $f_a \approx M_{GUT}$ and $H_{inf} \sim 10^8$ eV. We also show the regions for which the axion initial angles are anthropically constrained not to over-close the Universe, and axions diluted away by inflation. For the same value of f_a we give the QCD axion mass. The beginning of the anthropic mass region (2×10^{-20} eV) as well as that of the region probed by density perturbations (4×10^{-28} eV) are blurred as they depend on the details of the axion cosmological evolution (see Section 2.3). 3×10^{-18} eV is the ultimate reach of density perturbation measurements with 21 cm line observations. The lower reach from black hole super-radiance is also blurred as it depends on the details of the axion instability evolution (see Section 2.5). The region marked as "Decays", outlines very roughly the mass range within which we expect bounds or signatures from axions decaying to photons, if they couple to $\vec{E} \cdot \vec{B}$. We will discuss axion decays in detail in a companion paper.

Conclusions

- Axions and ultralight axion-like particles strongly motivated both from bottom up as well as from top-down perspective
- May play important role in cosmology and astrophysics
- Next generation of experiments start to probe axions and ALPs with intermediate scale decay constant f ~ 10^10 – 10^12 GeV
- Opportunities in Hamburg:
  - Light-shining-through-walls: ALPS-II
  - Haloscope?
  - Helioscope?

Backup Slides

Cold Axion Populations

Case 1:
Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

Dependence on initial misalignment angle

Dark matter density a cosmic random number ("environmental parameter")

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMB bounds on isocurvature fluctuations
- Scale of inflation required to be small

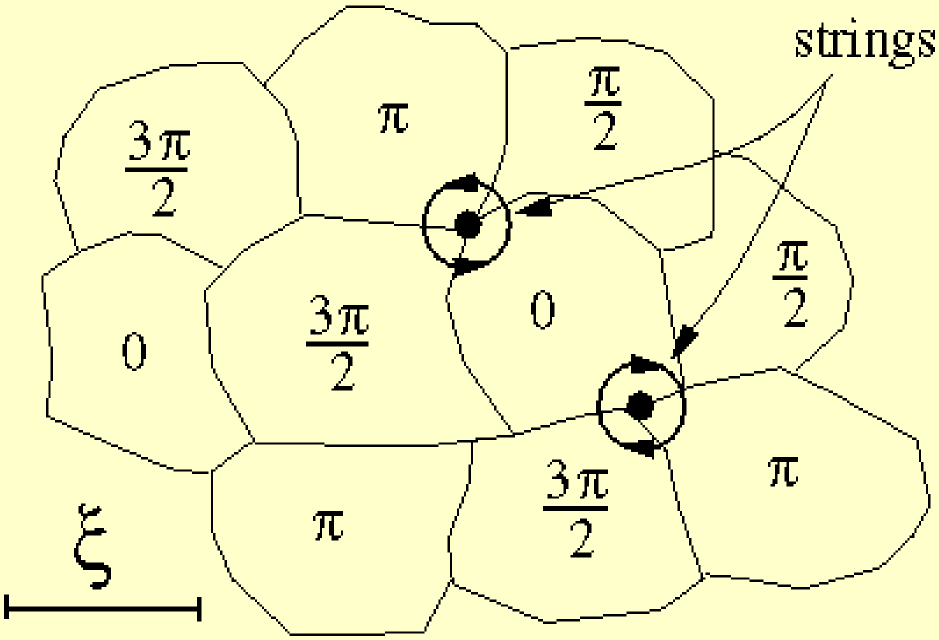
Case 2:
Reheating restores PQ symmetry

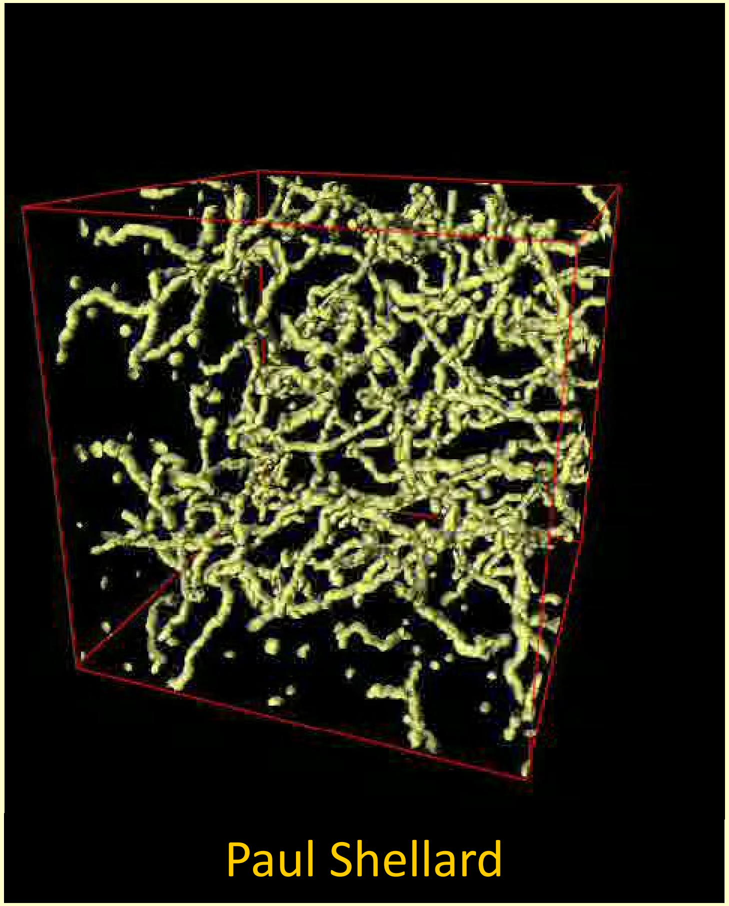
- Cosmic strings of broken $U_{PQ}(1)$ form by Kibble mechanism
- Radiate long-wavelength axions
- independent of initial conditions
- or else domain wall problem

Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters
Typical properties
- Mass
- Radius cm
- Mass fraction up to several 10%

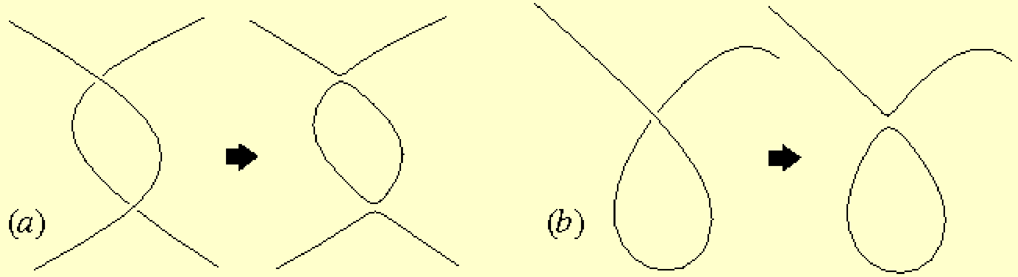
Axions from Cosmic Strings

Strings form by Kibble mechanism after break-down of $U_{PQ}(1)$





Small loops form by self-intersection



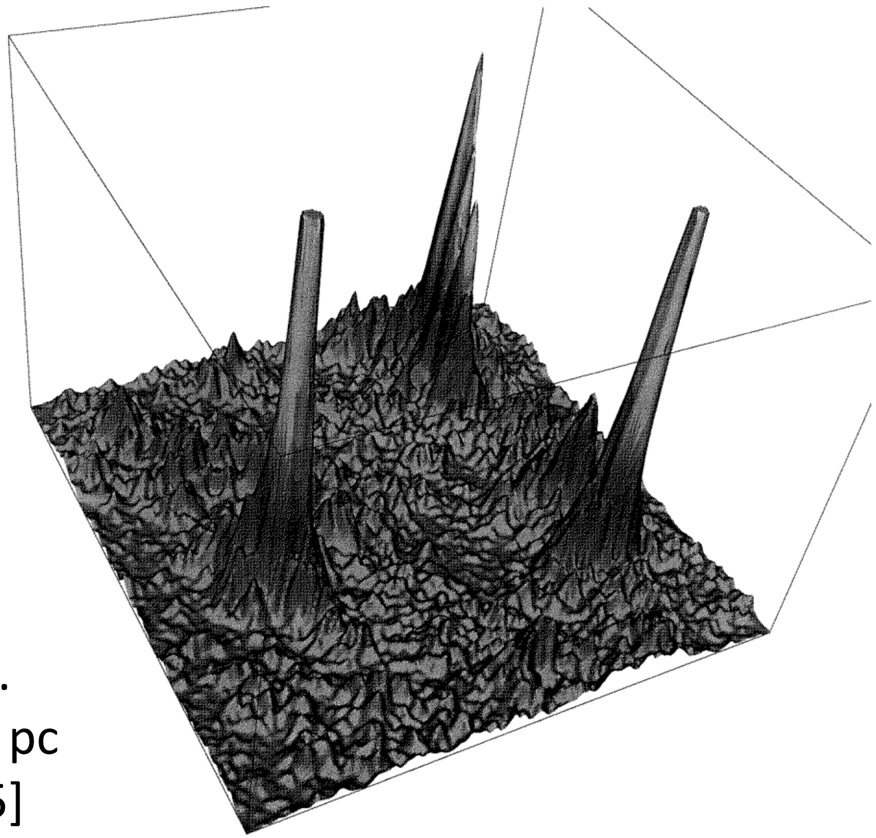
Axion Mini Clusters

The inhomogeneities of the axion field are large, leading to bound objects, "axion mini clusters". [Hogan & Rees, PLB 205 (1988) 228.]
Self-coupling of axion field crucial for dynamics.

Typical mini cluster properties:

Mass $\sim 10^{-12}$ M_{sun}
Radius $\sim 10^{10}$ cm
Mass fraction up to several 10%

Potentially detectable with gravitational femtolensing

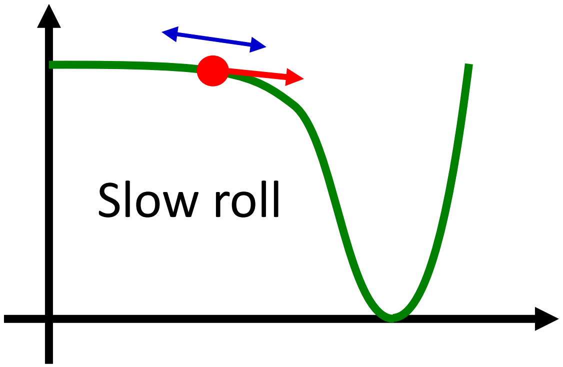


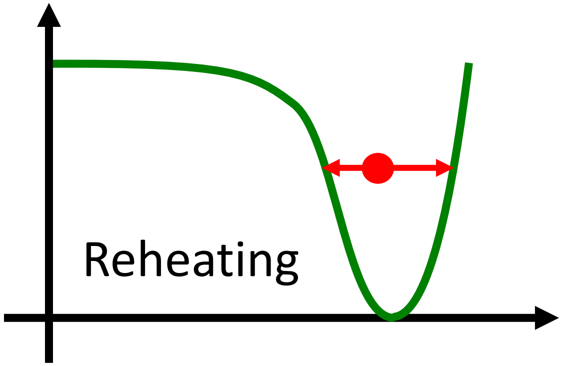
Distribution of axion energy density.
2-dim slice of comoving length 0.25 pc
[Kolb & Tkachev, ApJ 460 (1996) L25]

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field

De Sitter expansion imprints scale invariant fluctuations

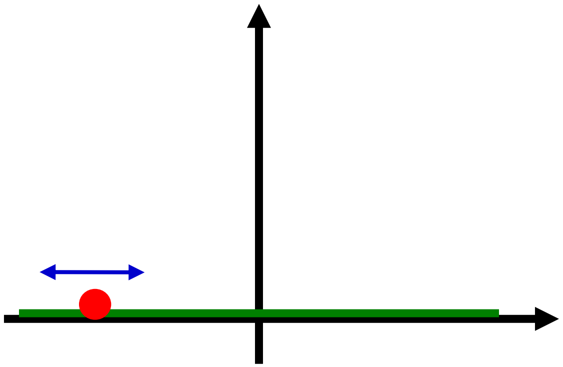


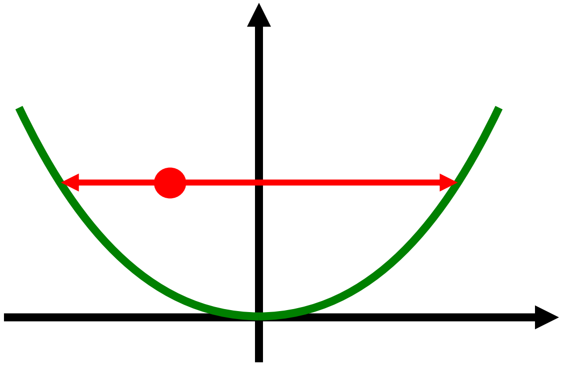


Inflaton decay $\rightarrow$ matter & radiation
Both fluctuate the same:
Adiabatic fluctuations

Axion field

De Sitter expansion imprints scale invariant fluctuations





Inflaton decay $\rightarrow$ radiation
Axion field oscillates late $\rightarrow$ matter
Matter fluctuates relative to radiation:
Entropy fluctuations

Power Spectrum of CMB Temperature Fluctuations

Sky map of CMBR temperature fluctuations

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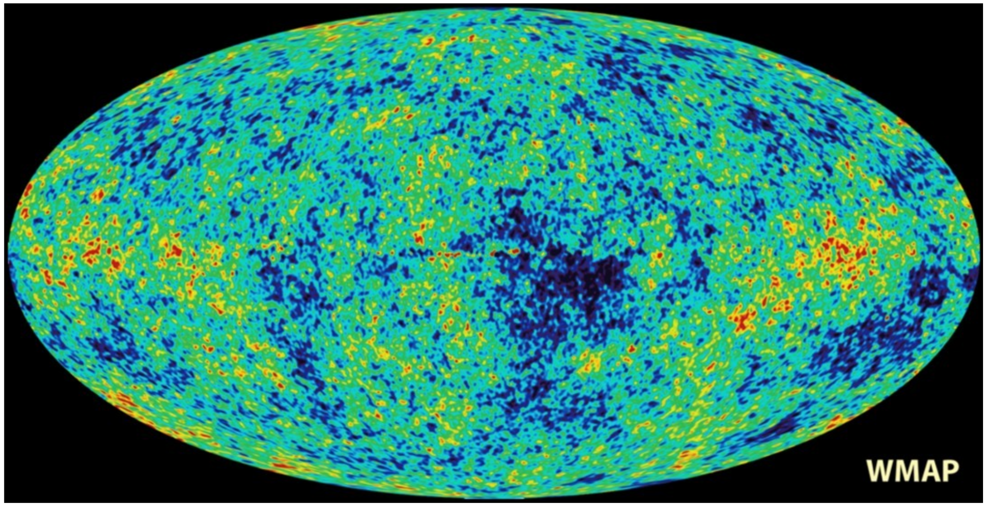

Multipole expansion

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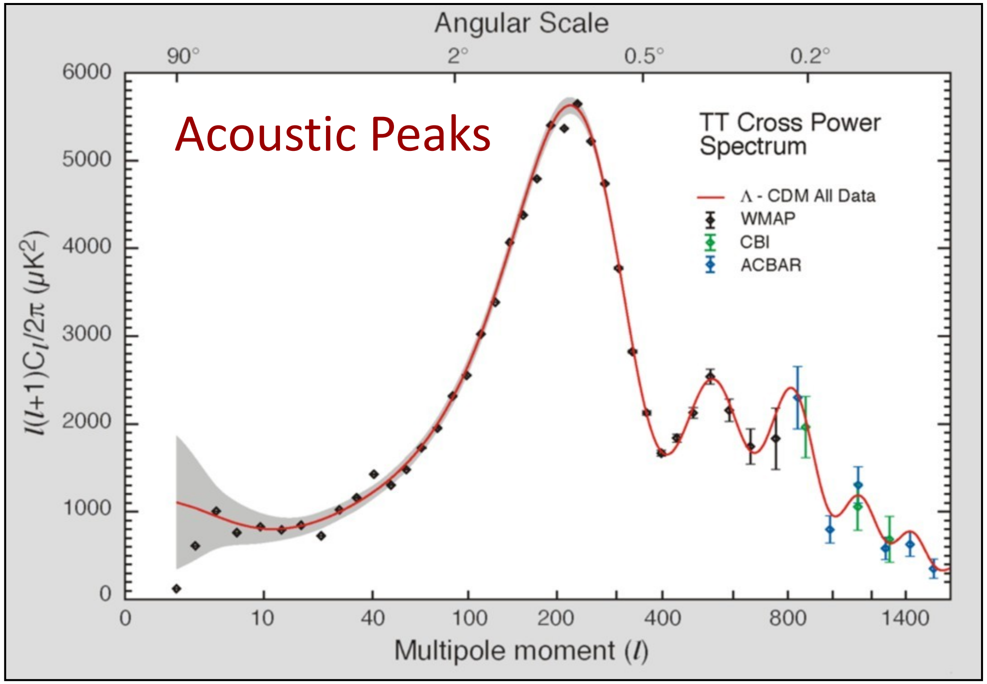

Angular power spectrum

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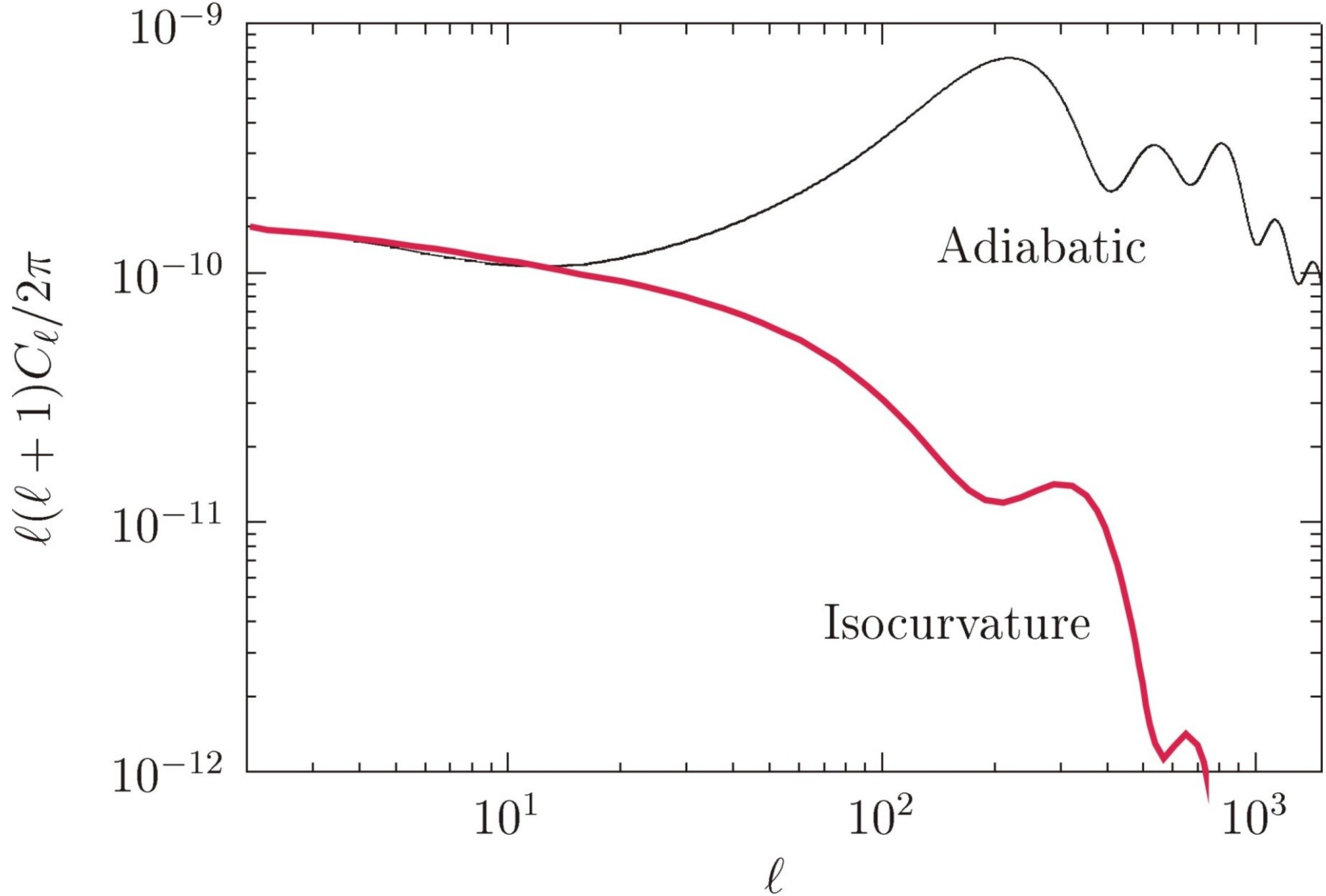
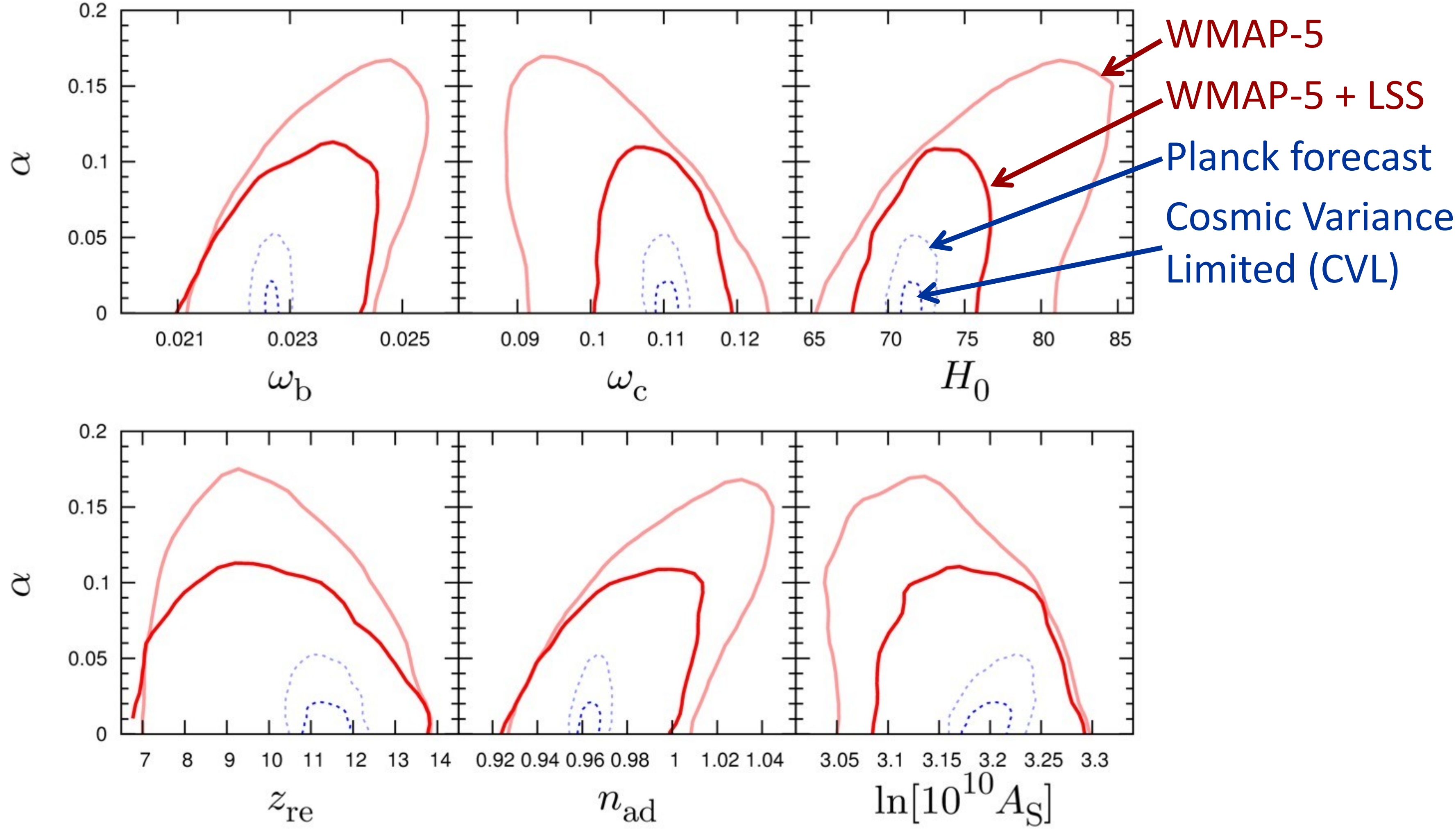
Adiabatic vs. Isocurvature Temperature Fluctuations



Adapted from Fox, Pierce & Thomas, hep-th/0409059

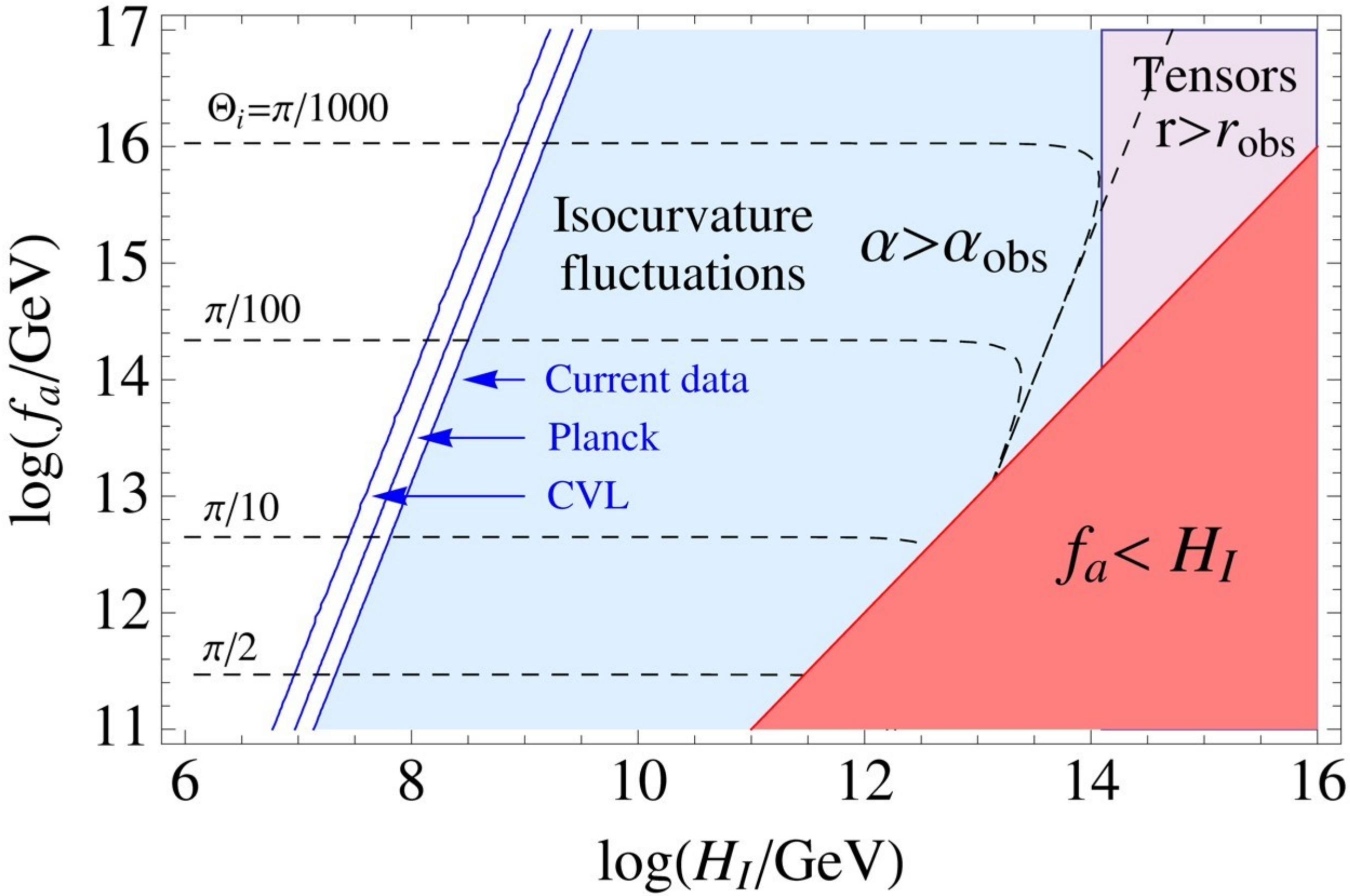
Parameter Degeneracies



Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

Isocurvature Forecast

Hubble scale during inflation



Axion decay constant

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647