Searching for axions and ALPs from string theory.

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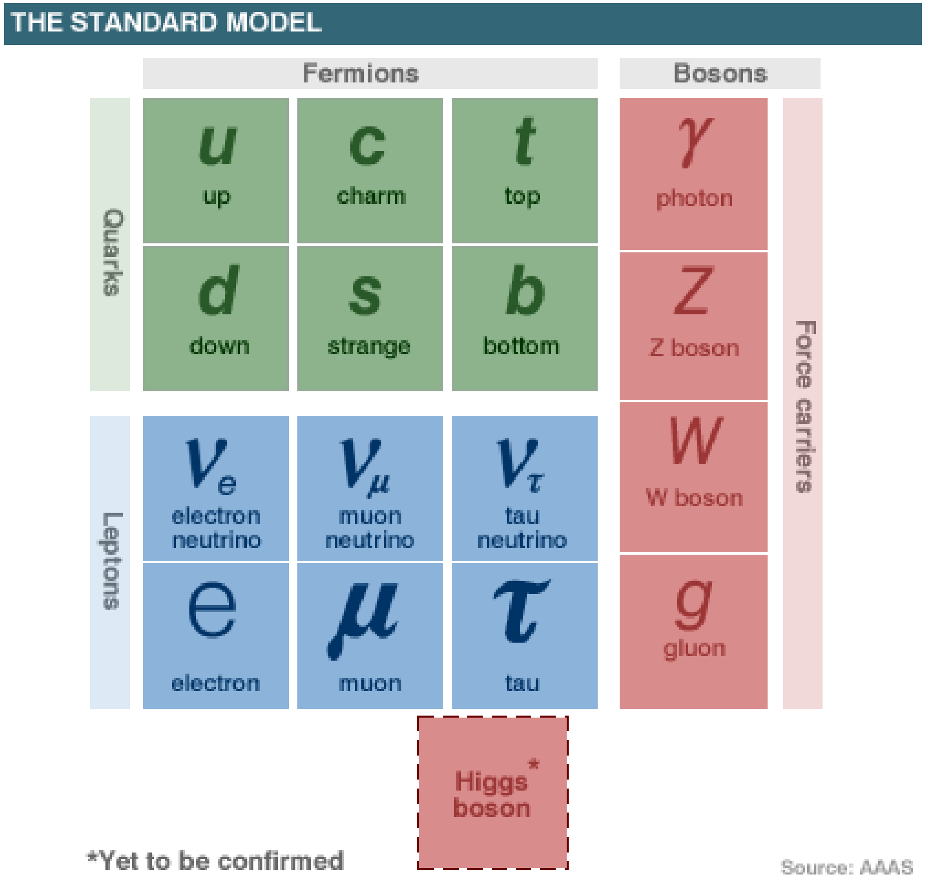
Particles beyond the Standard Model?!

- Standard Model of Particle Physics: Fundamental description of known matter particles and gauge forces



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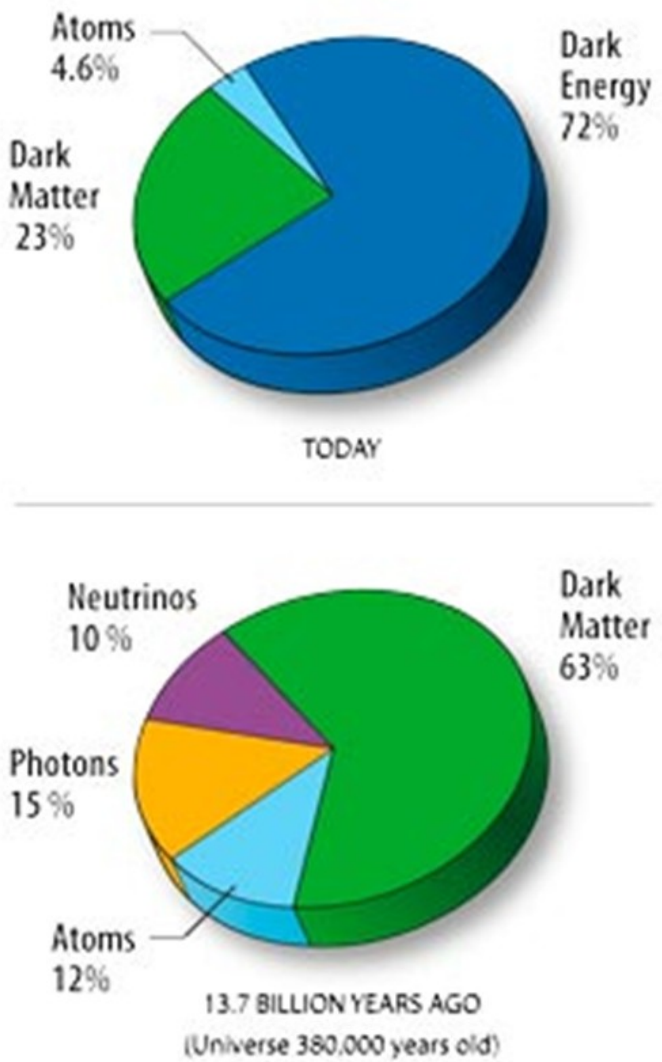
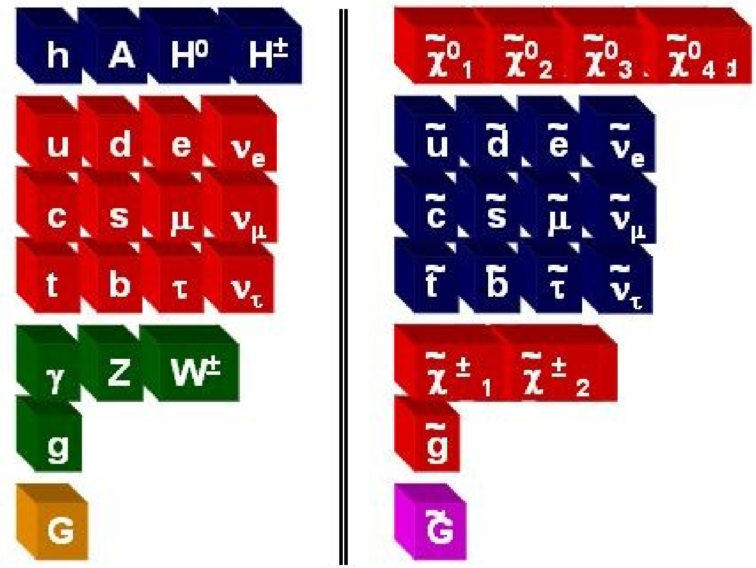
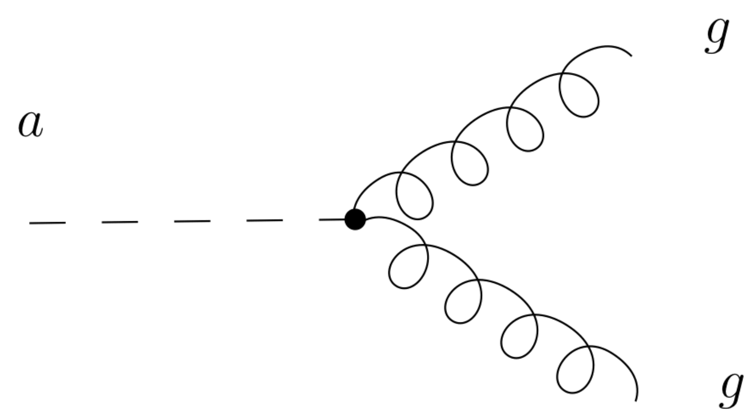


Particles beyond the Standard Model?!

- Standard Model of Particle Physics: Fundamental description of known matter particles and gauge forces
- Standard Model of Cosmology: only about 5 % of energy content of present universe consists of known particles
- Extensions of the Standard Model of Particle Physics: several good motivated candidates for constituents of dark matter
  - SUSY: Neutralino, Gravitino
  - Peccei Quinn: Axion



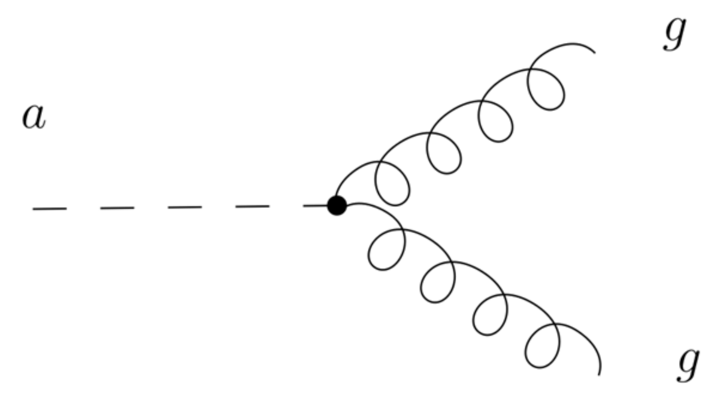


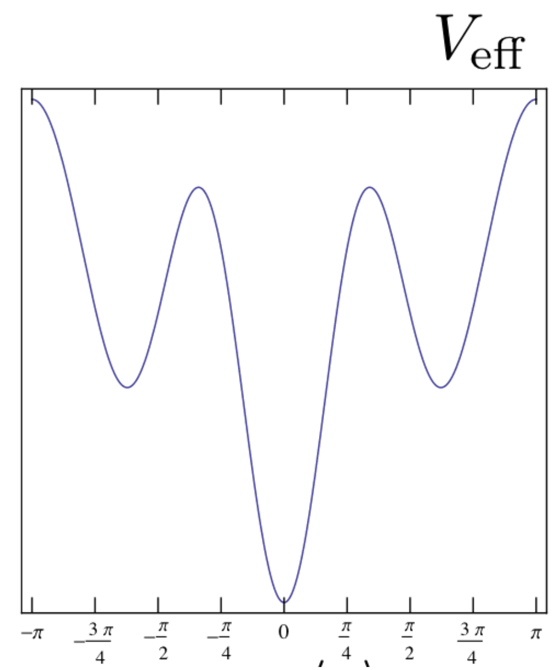
Peccei-Quinn extension of the Standard Model

- Motivation:
  Explanation of unnatural smallness, $\theta < 10^{-10}$, of CP-violating topological term in QCD Lagrangian,

$$\mathcal{L}_{\rm CP-viol.} = \frac{\alpha_s}{4\pi}\,\theta\,{\rm tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Axion field $\theta \to a(x)/f_a$
  - $\langle a \rangle = 0$





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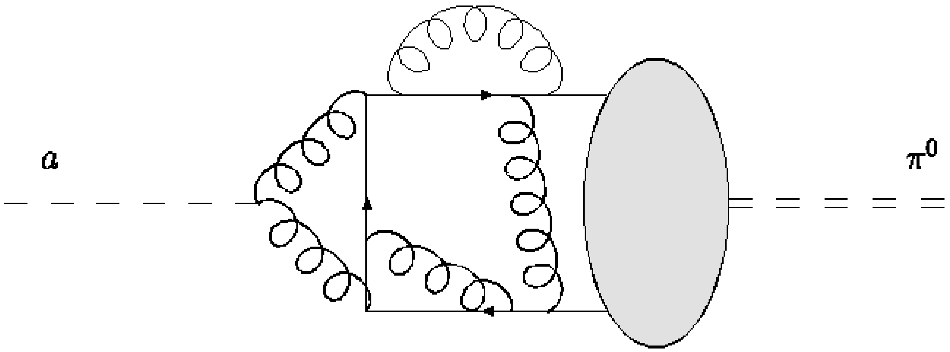

$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

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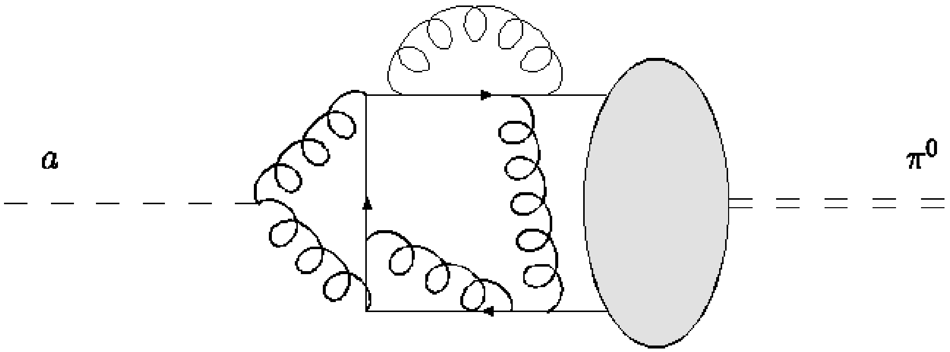

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\,g_{a\gamma}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\,a\,\vec{E}\cdot\vec{B},$$

$$g_{a\gamma} \simeq \frac{\alpha}{2\pi f_a} \sim 10^{-12}\ {\rm GeV}^{-1}\left(\frac{10^9\ {\rm GeV}}{f_a}\right)$$

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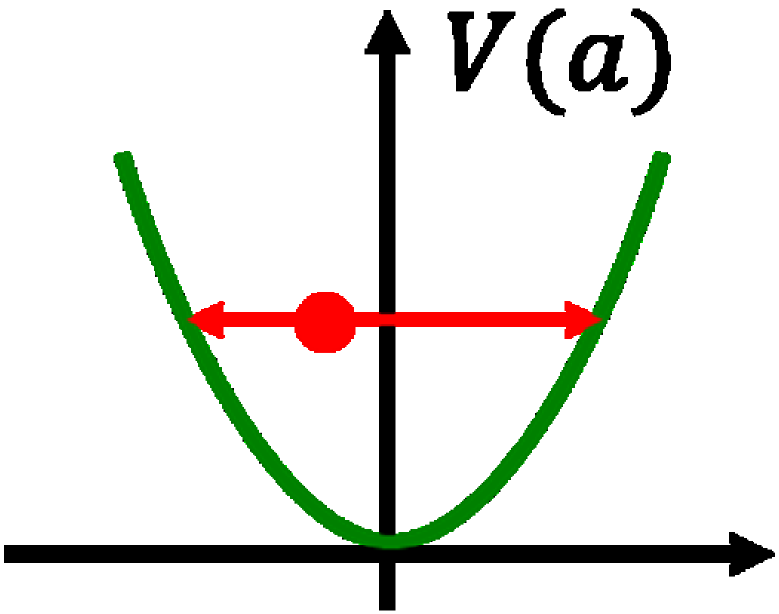
- Welcome side effect:
  - Axion: candidate for dark matter: created non-thermally via misa-lignment mechanism in form of coherent oscillations of axion field



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

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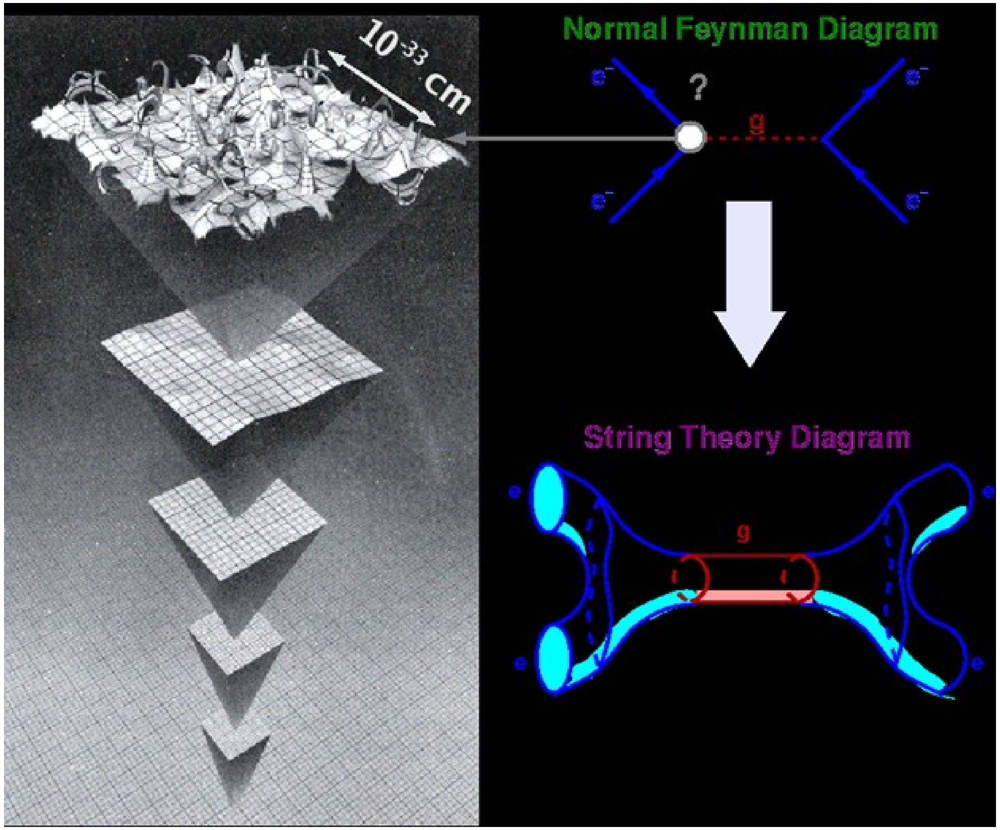
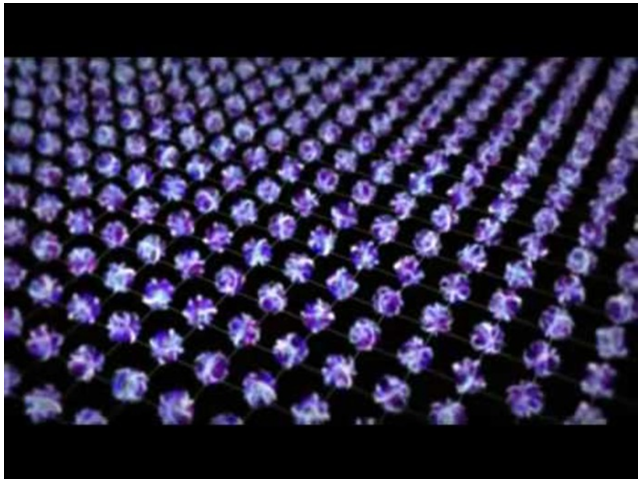
Coexistence: SUSY and PQ extension in string theory

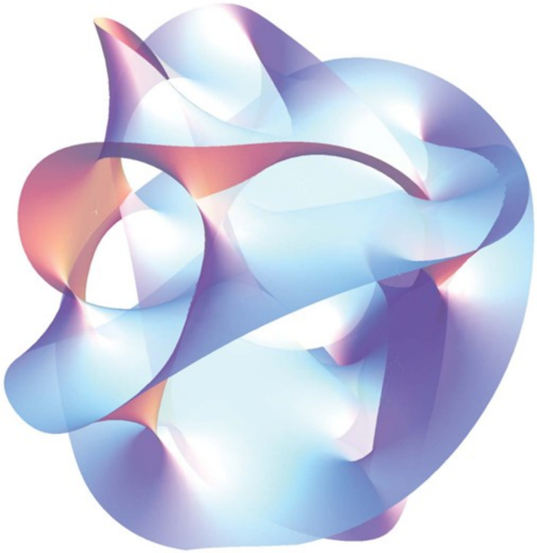
- Particularly strongly motivated extensions of Standard Model based on string theory:
  - Unification of all forces
  - Quantum gravity



Coexistence: SUSY and PQ extension in string theory

- Particularly strongly motivated extensions of Standard Model based on string theory:
  - Unification of all forces
  - Quantum gravity
- Spectrum of low-energy effective theory in (3+1)-dimensions is supersymmetric and possibly contains several kinds of very weakly interacting slim particles (WISPs): Axion, ALPs (Axion-Like Particles
  - if the compact space comprised of the 6 extra dimensions has certain geometrical and topological properties (Calabi-Yau; several cycles)





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: cf. Witten `84

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

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

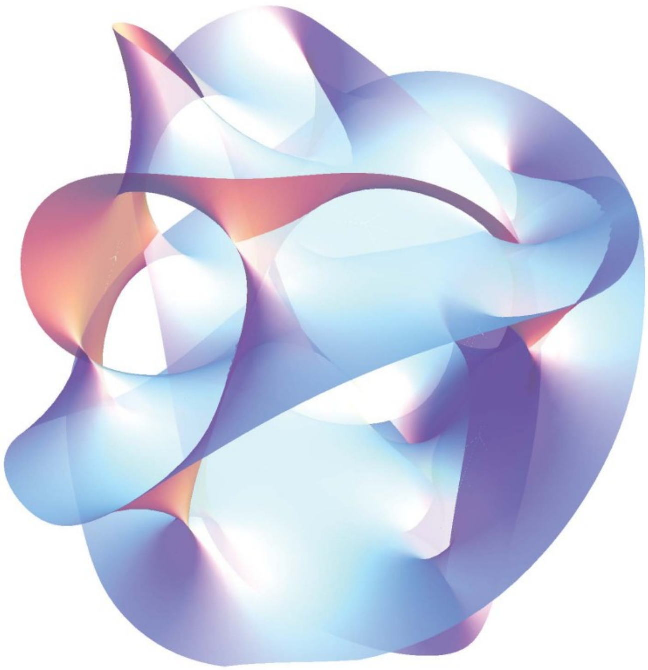
Axions in IIB string theory

- Concentrate on IIB case (moduli stabilisation best understood):
  Realisation of brane-world scenarios in string theory

- KK reduction (expansion in harmonic forms):

$$C_2 = c^a(x)\omega_a, \quad a = 1, \ldots, h_-^{1,1}$$

$$C_4 = c_\alpha(x)\tilde{\omega}^\alpha + \ldots, \quad \alpha = 1, \ldots, h_+^{1,1}$$



- Number of axionic fields determined by topology of CY orientifold: number of topologically non-equivalent 2-cycles or 4-cycles

Axions in IIB string theory

- Number of cycles generically O(100):

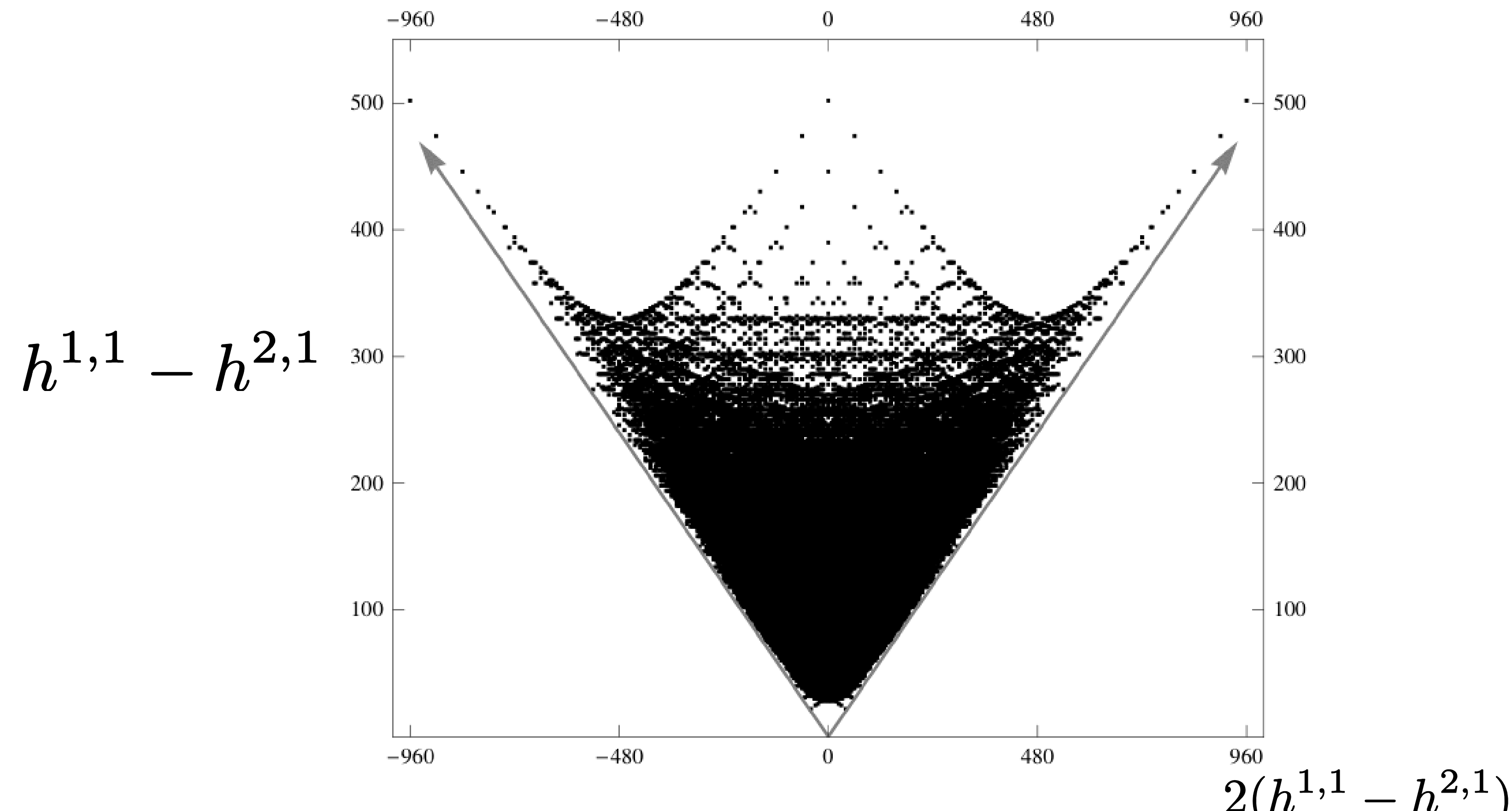
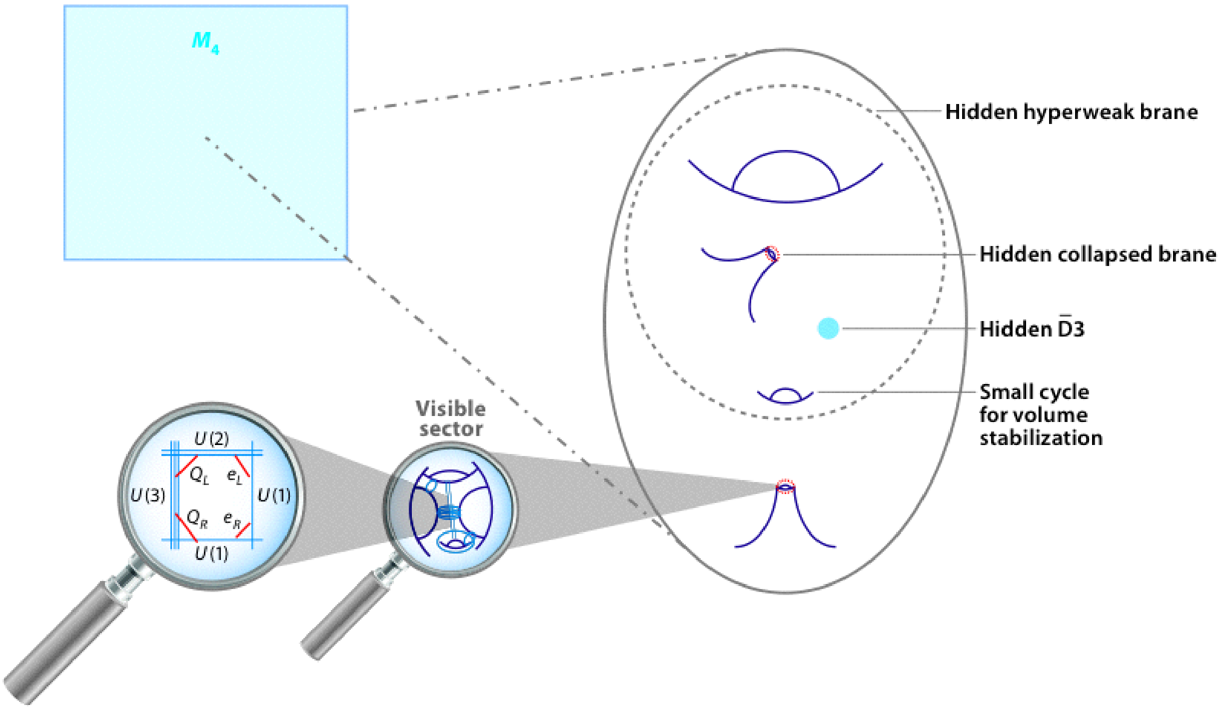


Figure 1: A plot of the Hodge numbers of the Kreuzer–Skarke list. $\chi = 2(h^{11} - h^{21})$ is plotted horizontally and $h^{11} + h^{21}$ is plotted vertically. The oblique axes bound the region $h^{11} \geq 0$, $h^{21} \geq 0$.

Axions in IIB string theory

> Cycles can be wrapped by space-time filling D-branes



> Each of these branes gives rise to a gauge theory at low energy

- Visible sector gauge theory realized by stacks of D7 branes wrapping small 4-cycles
- Hidden sectors, in particular hidden photons, realized by branes wrapping cycles not intersecting visible sector branes

Axions in IIB string theory

- Each axionic field 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 4-cycle α
- 4D EFT from 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

$$S \supset -dc_\alpha \frac{\mathcal{K}_{\alpha\beta}}{8} \wedge \star dc_\beta - \frac{r^{i\alpha}\tau_\alpha}{4\pi M_P}(F_i \wedge \star F_i) + \frac{r^{i\alpha} c_\alpha}{4\pi M_P}(F \wedge F),$$

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

- Decay constants and coupling to gauge bosons via canonical normalization of axion and gauge kinetic terms and matching to:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a_i\, \partial^\mu a_i - \frac{g_3^2}{32\pi^2}\left(\theta_0 + C_{i33}\frac{a_i}{f_{a_i}}\right) F^b_{3,\mu\nu}\tilde{F}^{b,\mu\nu}_3$$

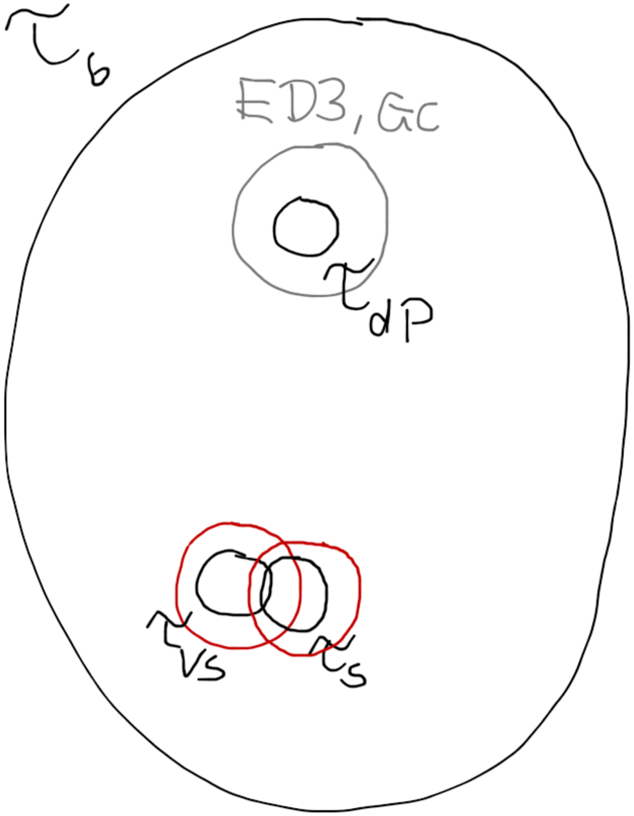
$$- \frac{g_2^2}{32\pi^2} C_{iWW}\frac{a_i}{f_{a_i}} F^b_{W,\mu\nu}\tilde{F}^{b,\mu\nu}_W - \frac{g_Y^2}{32\pi^2} C_{iYY}\frac{a_i}{f_{a_i}} F_{Y,\mu\nu}\tilde{F}^{\mu\nu}_Y$$

IIB axiverse

- An axiverse - QCD axion plus possibly many ultra-light ALPs whose mass spectrum is logarithmically hierarchical – may naturally arise from strings, cf. Arvanitaki et al. `09
- Challenges to obtain an axiverse:
  - Only axions which are not projected out by orientifold projection appear in LE EFT
  - Only axions which do not get too heavy by Kähler moduli stabilisation can be candidates for QCD axion and other light ALPs, cf. Conlon `06
  - Only axions which are not eaten by Stückelberg mechanism to give masses to brane-localized anomalous U(1) gauge bosons will appear in LE EFT
- Acharya, Bobkov, Kumar `11: Moduli stabilisation via single non-perturbative correction to superpotential (cf. Bobkov,Braun, Kumar, Raby `10) fixes all Kähler moduli plus one axion combination: axiverse with $W_0 \ll 1$ and $f_a \sim 10^{16}\,\mathrm{GeV}$
- Cicoli, Goodsell, AR, 1206.0819: Moduli stabilisation of the so-called LARGE Volume Scenario (LVS) which exploits both perturbative and non-perturbative effects to fix Kähler moduli gives rise to an axiverse with $W_0 \sim 1$ and $f_a \sim 10^{10}\,\mathrm{GeV}$

LVS axiverse

- Strategy to fix moduli in LVS:
  (cf. Cicoli, Mayrhofer, Valandro `11)
  - Exploit del Pezzo four-cycle supporting single non-perturbative effect; dP modulus fixed at small size, dP saxion and axion heavy; interplay with leading order alpha´ correction yields exponentially large CY volume
  - Visible sector with chirality built by wrapping magnetised D7-branes around rigid but not del Pezzo four cycles; D-term conditions stabilise d combinations of Kähler moduli, leaving
    $$n_{\rm ax} \equiv h^{1,1} - 1 - d \geq 1$$
    flat directions; latter fixed by pert. corrections
  - LVS requires $n_{\rm ax} \geq 2$: one of the remaining cycles should be small to obtain correct value of $g_{\rm vs}^2 \sim 1/\tau_{\rm vs}$, while there should be at least one further which can be large; latter fixed at
    $$\mathcal{V} \sim \tau_b^{3/2} \sim W_0\, e^{2\pi\tau_{\rm dP}}$$
- More on this: talk by Michele Cicoli



LVS axiverse

- Mass scales for $g_s \sim 0.1, W_0 \sim 1, \mathcal{V} \sim 10^{14}$:

$$M_s \sim \frac{M_P}{\sqrt{4\pi\mathcal{V}}} \sim 10^{10}\,\mathrm{GeV}$$

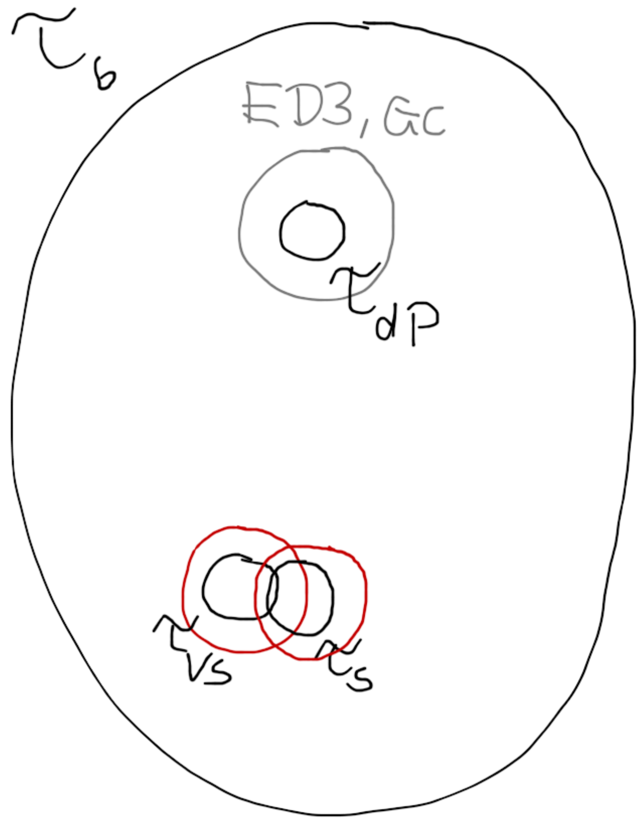
$$m_{\tau_s} \sim \frac{M_P}{\mathcal{V}^{1/2}} \sim 10^{10}\,\mathrm{GeV}$$

$$m_{\tau_{\mathrm{dP}}} \sim \frac{M_P}{\mathcal{V}} \ln\mathcal{V} \sim 30\,\mathrm{TeV}$$

$$m_{3/2} \sim \sqrt{g_s/(4\pi)}W_0\frac{M_P}{\mathcal{V}} \sim 1\,\mathrm{TeV}$$

$$m_{\tau_{\mathrm{vs}}} \sim \alpha_{\mathrm{vs}} m_{3/2} \sim 40\,\mathrm{GeV}$$

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 0.1\,\mathrm{MeV}$$



  - No cosmological moduli problem since τ_b diluted by entropy production due to decay of τ_{vs} reheating universe to O(GeV)

LVS axiverse

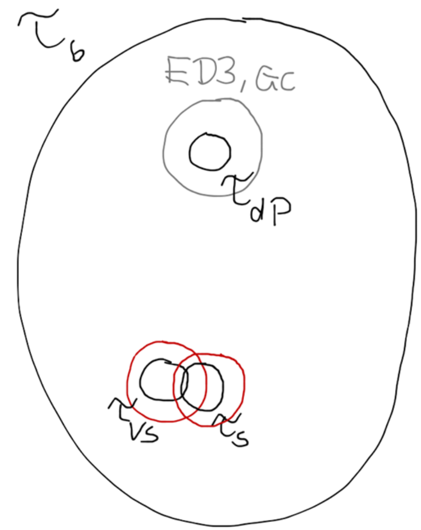
> Scaling of axion decay constants and couplings:

$$f_{a_b} = \frac{\sqrt{3}}{4\pi} \frac{M_P}{\tau_b} \simeq \frac{M_P}{4\pi \mathcal{V}^{2/3}} \simeq \frac{M_{\rm KK}^{\rm 10D}}{4\pi}, \qquad f_{a_s} = \frac{1}{\sqrt{6}\,(2\tau_s)^{1/4}} \frac{M_P}{4\pi\sqrt{\mathcal{V}}} \simeq \frac{M_s}{\sqrt{4\pi}\tau_s^{1/4}},$$

$$C_{bbb} \simeq g_b^{-2} \frac{f_{a_b}}{M_P} \simeq \mathcal{O}(1), \qquad C_{sbb} \simeq g_b^{-2} \frac{f_{a_s}\tau_s^{3/4}}{\mathcal{V}^{1/2} M_P} \simeq \mathcal{O}(\epsilon) \simeq \mathcal{O}\left(\mathcal{V}^{-1/3}\right),$$

$$C_{bss} \simeq g_s^{-2} \frac{f_{a_b}}{M_P} \simeq \mathcal{O}(\epsilon^2) \simeq \mathcal{O}\left(\mathcal{V}^{-2/3}\right), \qquad C_{sss} \simeq g_s^{-2} \frac{f_{a_s}}{\tau_s^{3/4} M_s} \simeq \mathcal{O}(1).$$

- $a_{\rm vs}$: QCD axion with $f_{a_{\rm vs}} \sim f_{a_s} \sim 10^{10}\,{\rm GeV}$
- a_b : essentially massless ALP with $f_{a_b} \sim 10^8\,{\rm GeV}$, but nearly decoupled, $C_{bss} \sim 10^{-10}$



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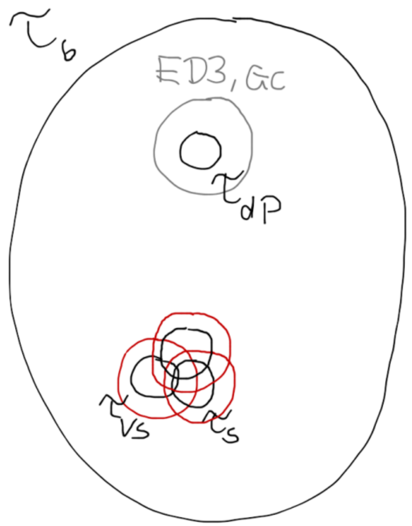
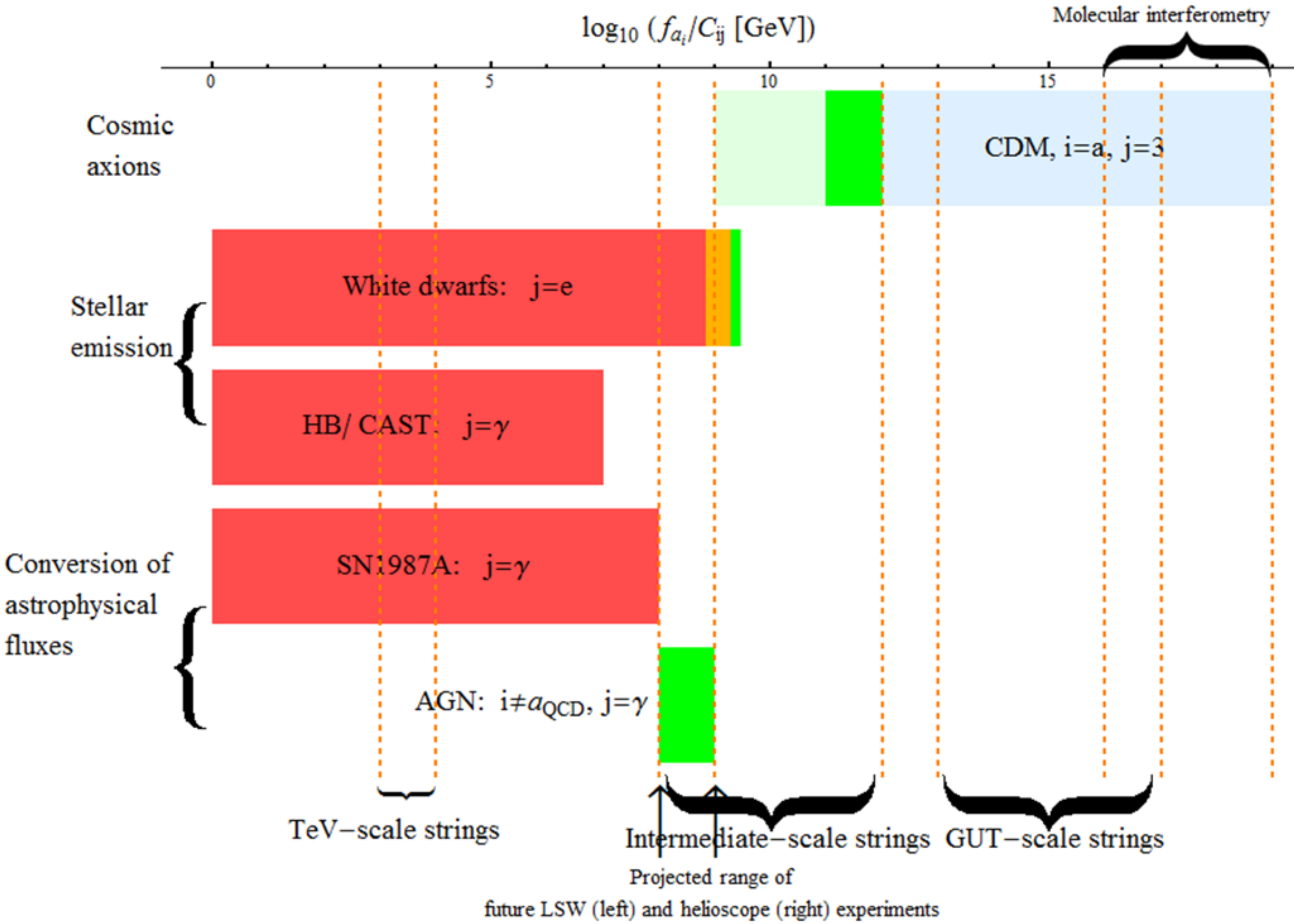
- a_b : essentially massless ALP with $f_{a_b} \sim 10^8\,{\rm GeV}$, but nearly decoupled, $C_{bss} \sim 10^{-10}$
- Possibly more ultralight, $m_{a_b} \ll m_a$, ALPs with

$$f_{a_s} \sim 10^{10}\,{\rm GeV}, C_{sss} \sim 1$$



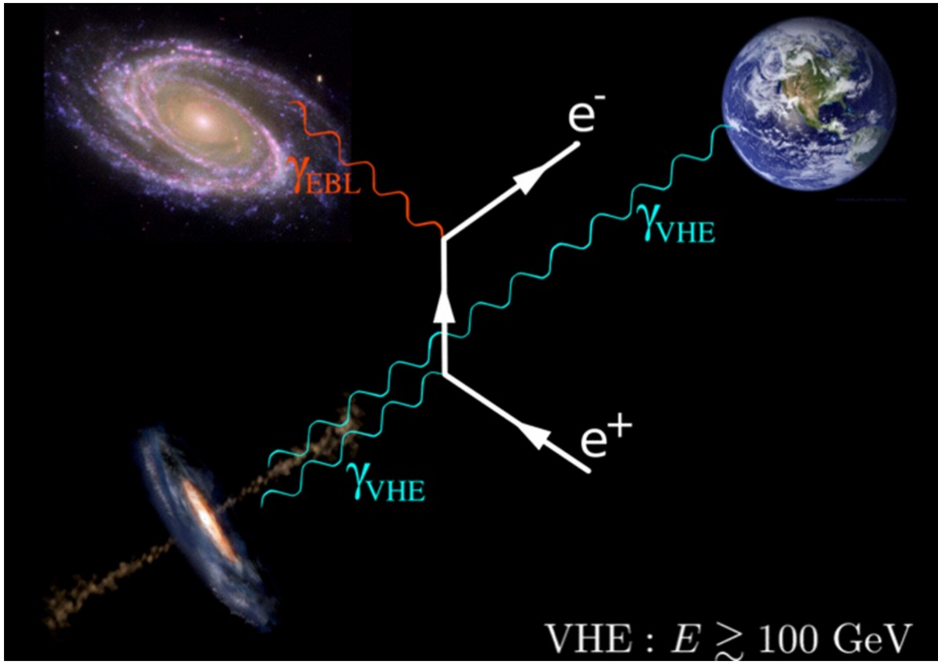
Axion and ALPs with intermediate scale decay constant?

> Current limits and possible hints from astrophysics and cosmology:



Hints for axion or ALP effects in propagation of TeV photons through universe?

- TeV photons of distant Active Galactic Nuclei (AGN) should feature absorption breaks due to electron-positron pairproduction on the Extragalactic Background Light (EBL)



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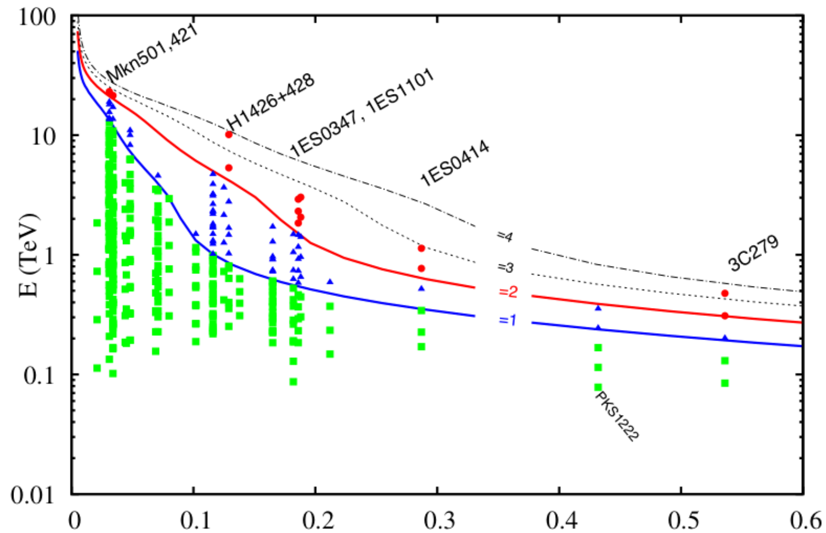
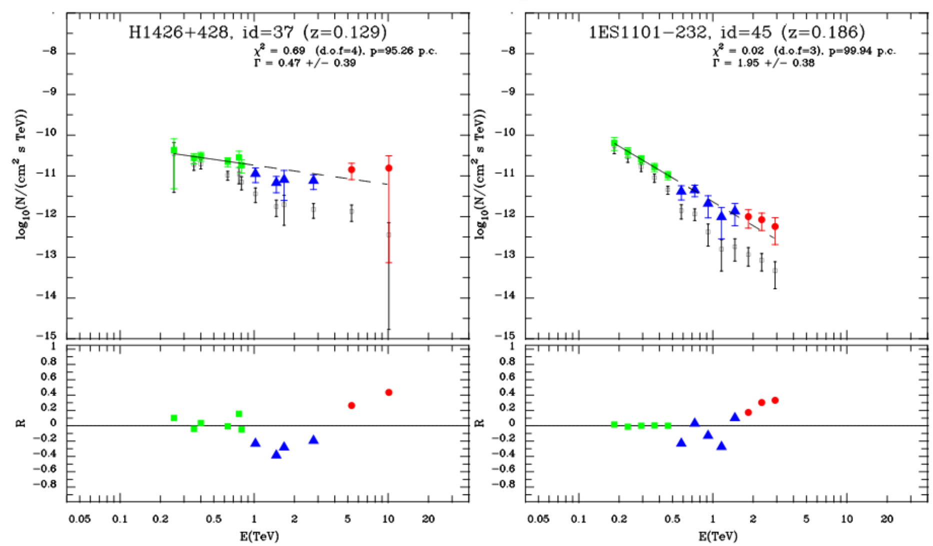
  - 50 spectra (HESS, MAGIC, Veritas), assumption: minimal EBL; absorption ruled out by more than 4 sigma





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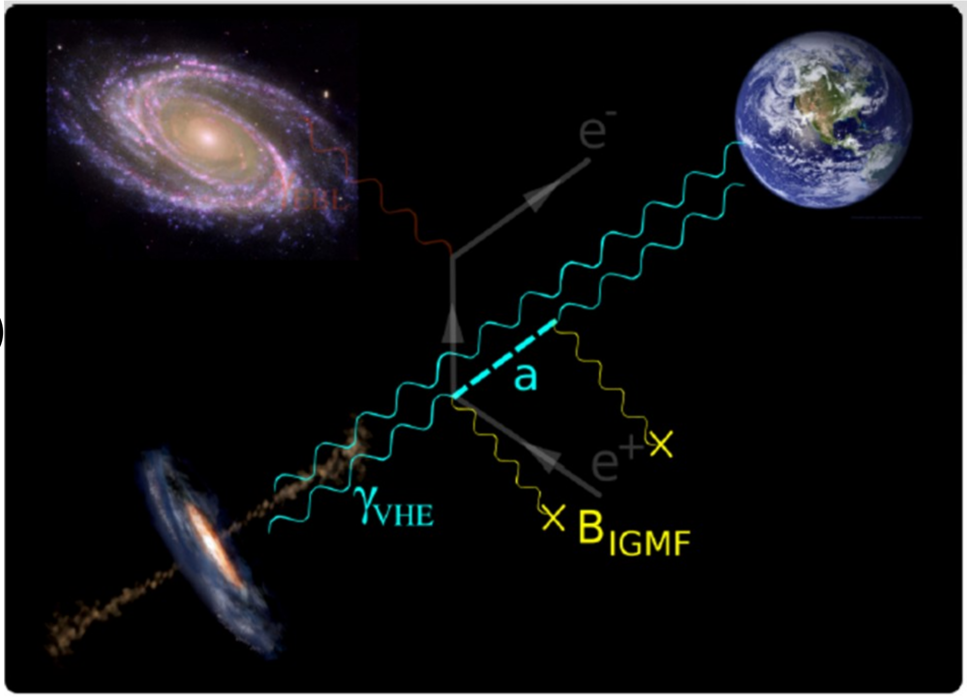

$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

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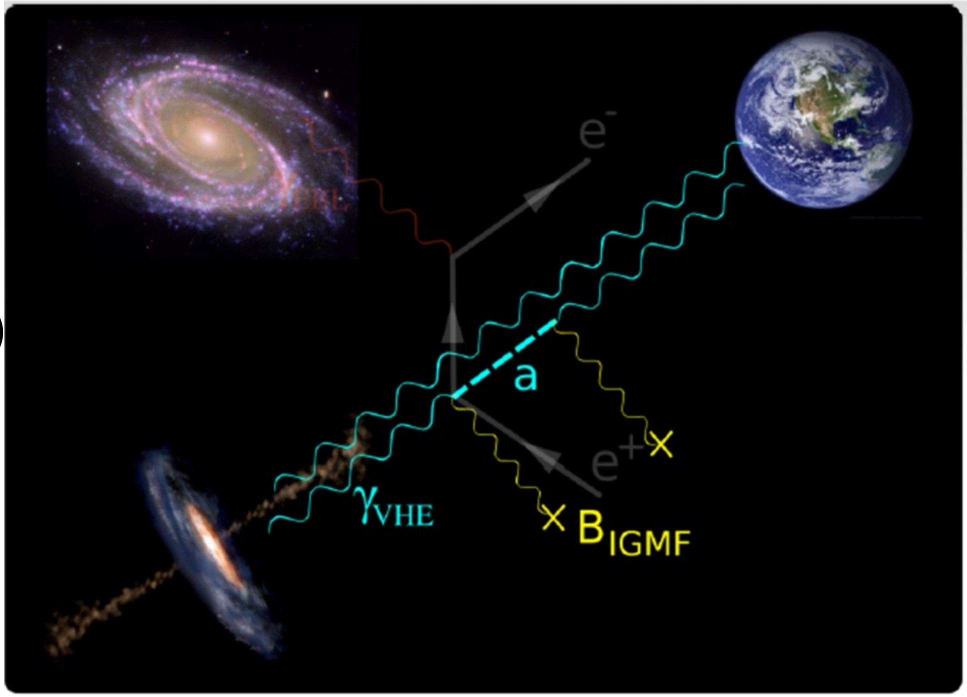
- Has to be an ALP: too light for a QCD axion with such a decay constant



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

$$\rightarrow \frac{f_{a_i}}{C_{i\gamma}} \simeq 10^8 \div 10^9\,\mathrm{GeV}$$

$$\text{for} \quad m_{a_i} \lesssim \mathrm{neV}$$

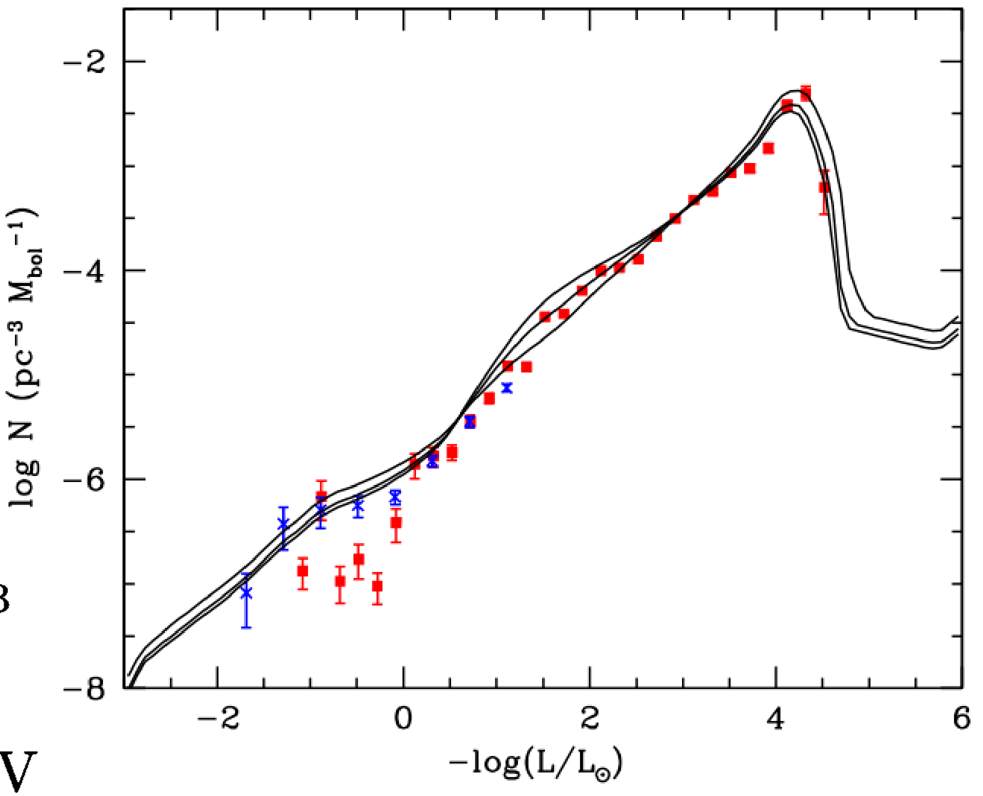
Hint for axion/ALP-production in white dwarfs?

- Non-standard energie-loss mechanism in white dwarfs, cf. Isern et al.
- Compatible with axion or ALP production in electron-bremsstrahlung

$$g_{ie} \equiv \frac{C_{ie} m_e}{f_{a_i}} = (2.0 \div 7.0) \times 10^{-13}$$

$$\rightarrow \frac{f_{a_i}}{C_{i,e}} \simeq (0.7 \div 2.6) \times 10^9 \ \mathrm{GeV}$$

$$\text{for} \quad m_{a_i} \lesssim \mathrm{keV}$$



Can we explain these hints within IIB axiverse?

- Anomalous transparency of universe and anomalous energy loss of white dwarfs could be explained by

$$C_{i\gamma}/C_{ie} \simeq 10, \qquad f_{a_i}/C_{i\gamma} \simeq 10^8 \text{ GeV}, \qquad m_{\rm ALP} \lesssim 10^{-9} \div 10^{-10} \text{ eV}.$$

- Model where visible sector build from intersecting branes in geometric regime

$$\frac{C_{i\gamma}}{C_{ie}} \sim \frac{8\pi\tau_*}{3}, \qquad \frac{f_{a_i}}{C_{i\gamma}} = \frac{1}{8\pi N_{i\gamma}\tau_*^{1/4}} \frac{M_P}{\sqrt{\mathcal{V}}} = \frac{1}{8\pi N_{i\gamma}\tau_*^{1/4}} \sqrt{\frac{g_s M_P m_{3/2}}{W_0}}.$$

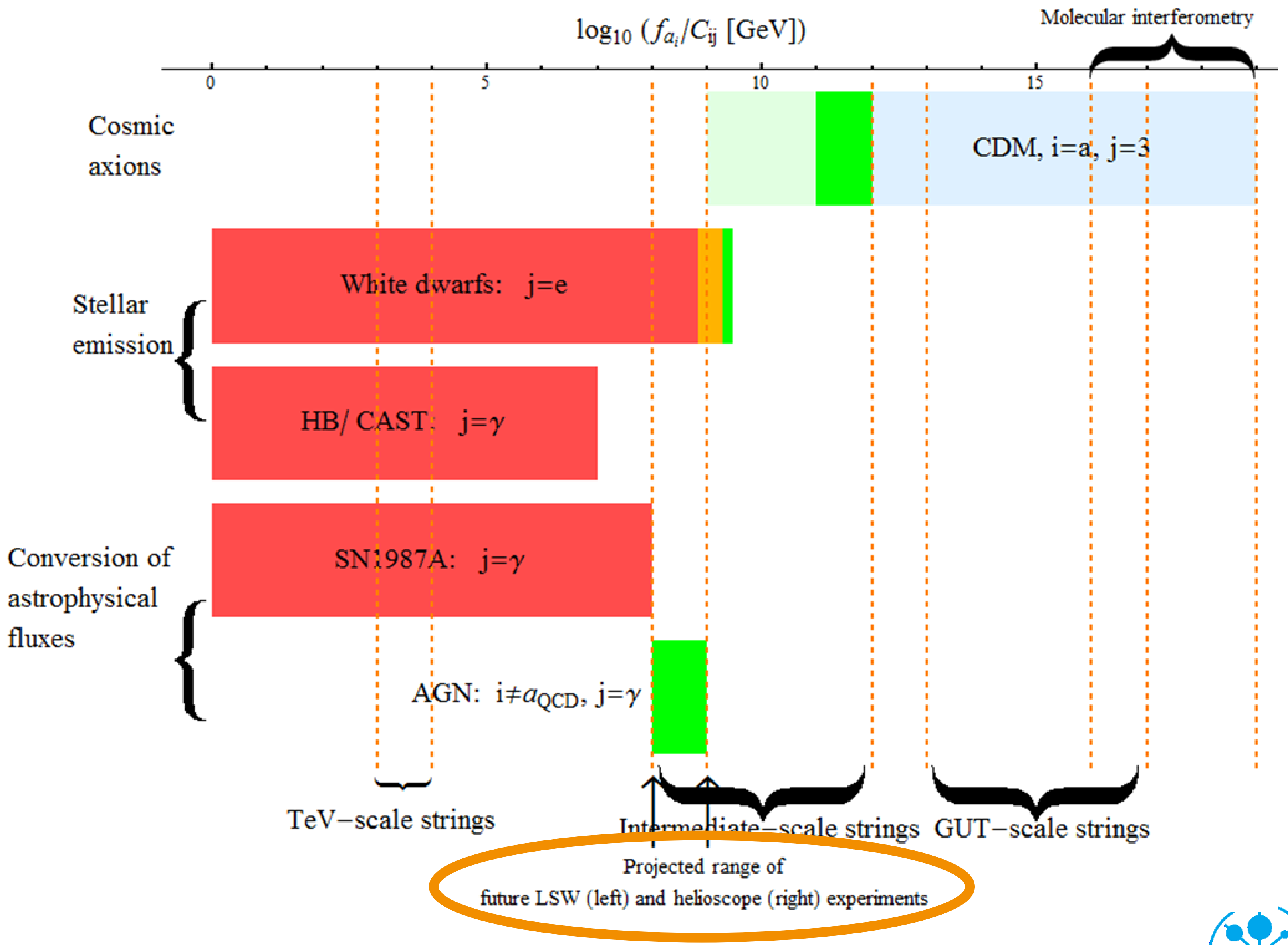
- Yields required values for $m_{3/2} = 10 \text{ TeV}, \; g_s \simeq 0.1 \text{ and } W_0 \sim 10$

- ALP mass could be generated by single Kähler potential instanton, e.g. $m_{\rm ALP} \sim m_{3/2}\, e^{-\pi\tau_*} \sim 10^{-10}\,\text{eV}$ requires

$$\tau_* \sim \frac{1}{\pi} \ln\left(\frac{g_s m_{3/2}}{m_{\rm ALP}}\right) \sim 16.$$

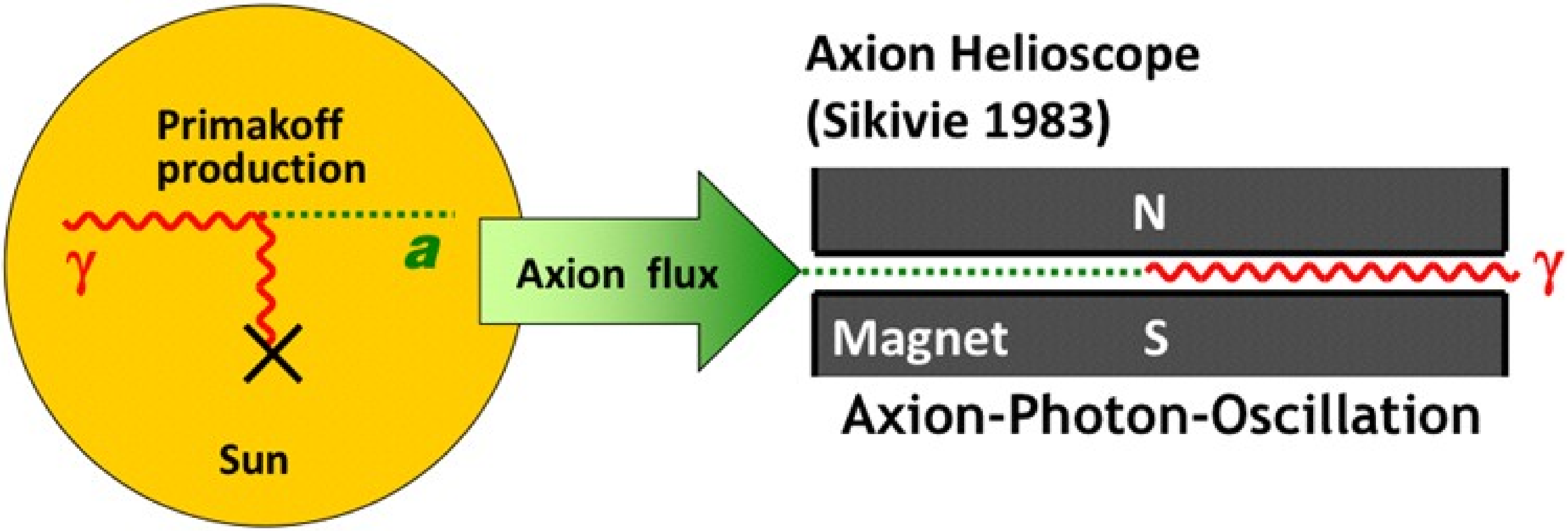
- Astrophyical hints compatible with intermediate string-scale scenario

Laboratory probes of axion and ALPs with intermediate scale decay constant?



Search for solar axions and ALPs

- Sun strong source of axions and ALPs
- Helioscope searches for axions/ALPs and HPs



$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

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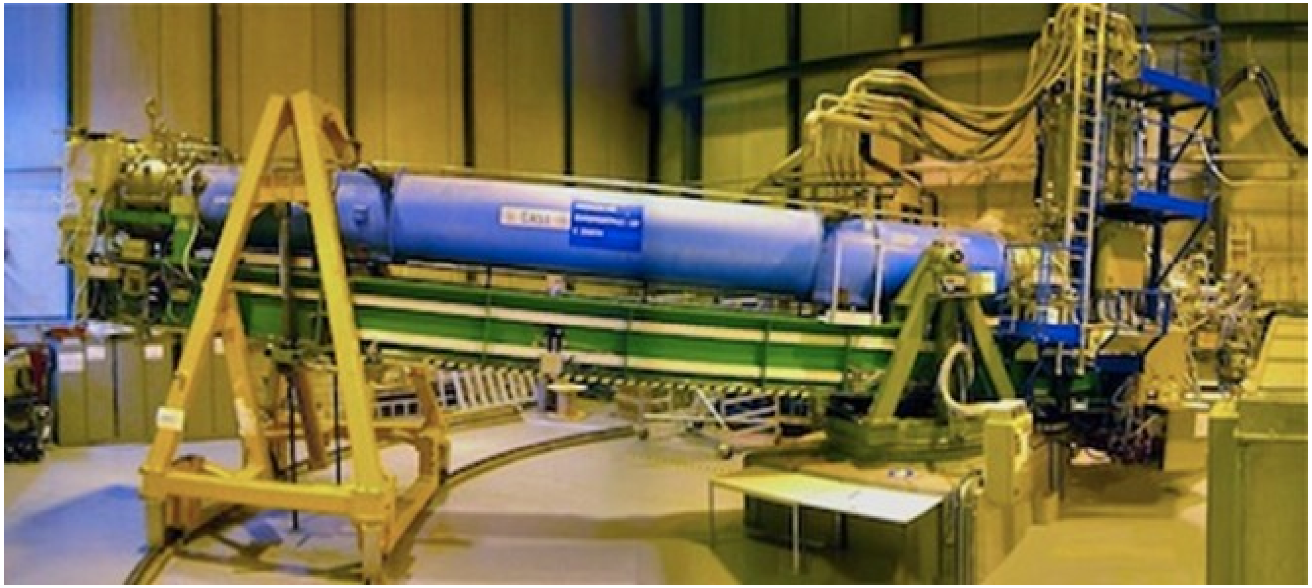

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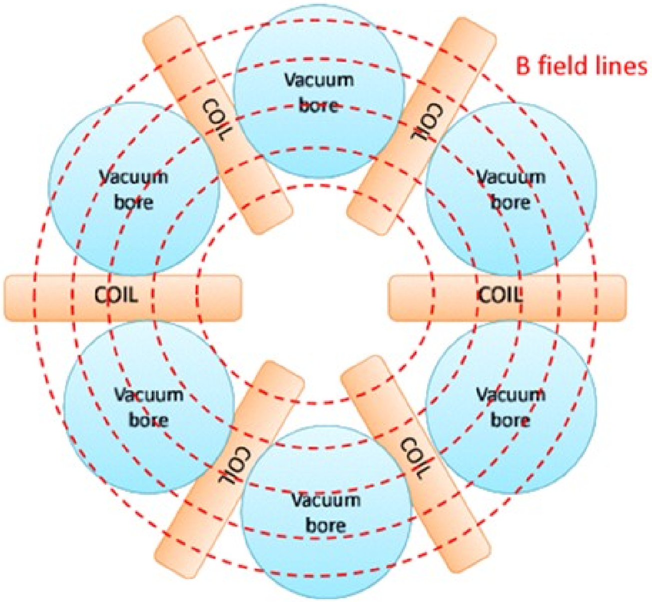
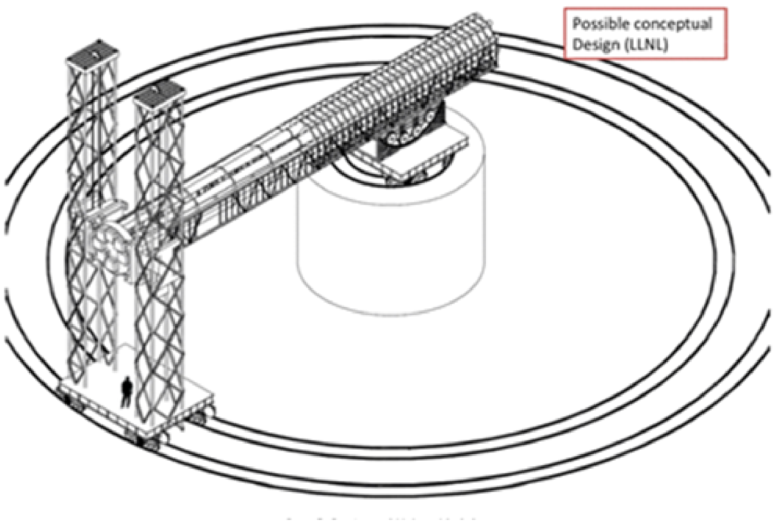
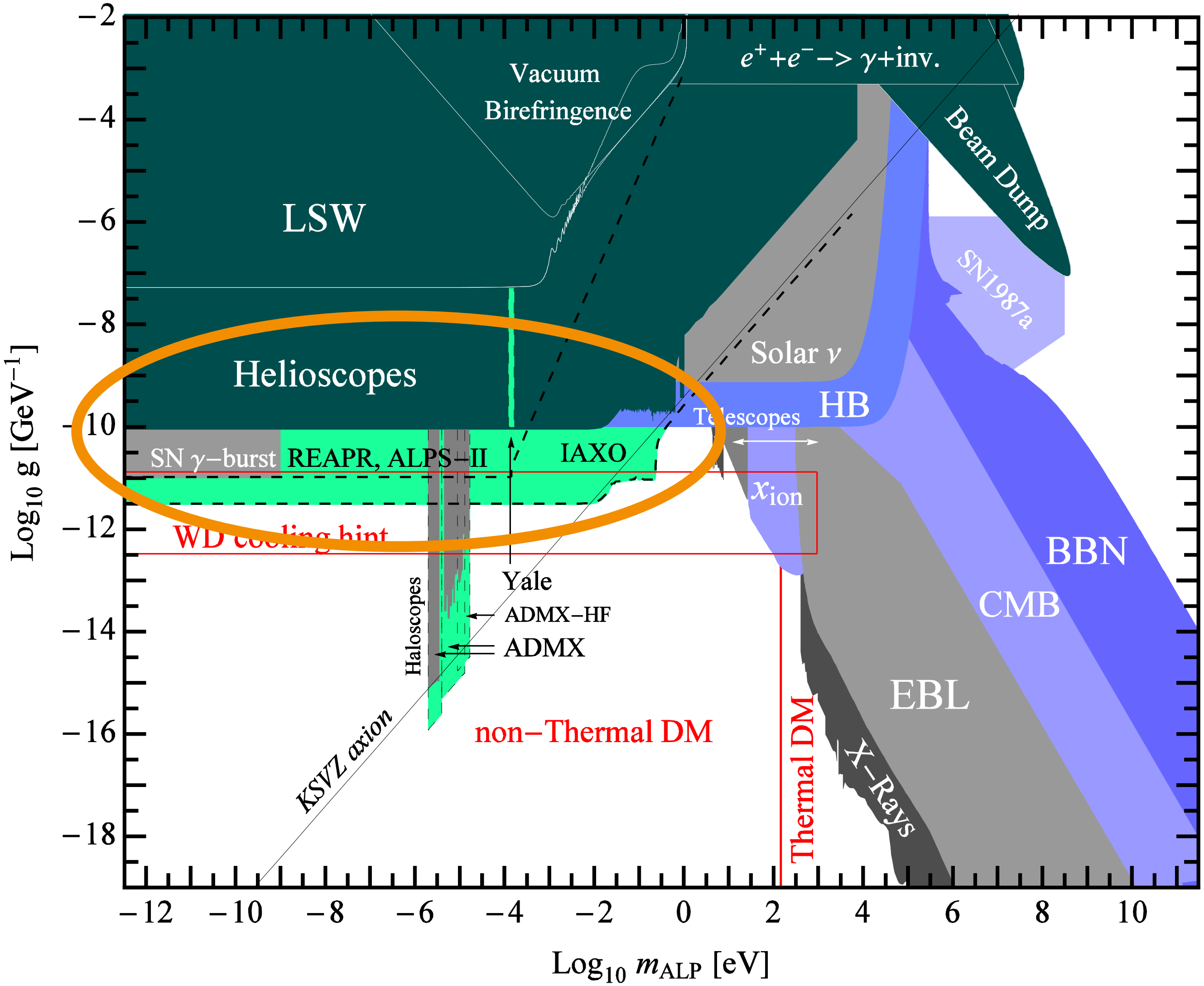




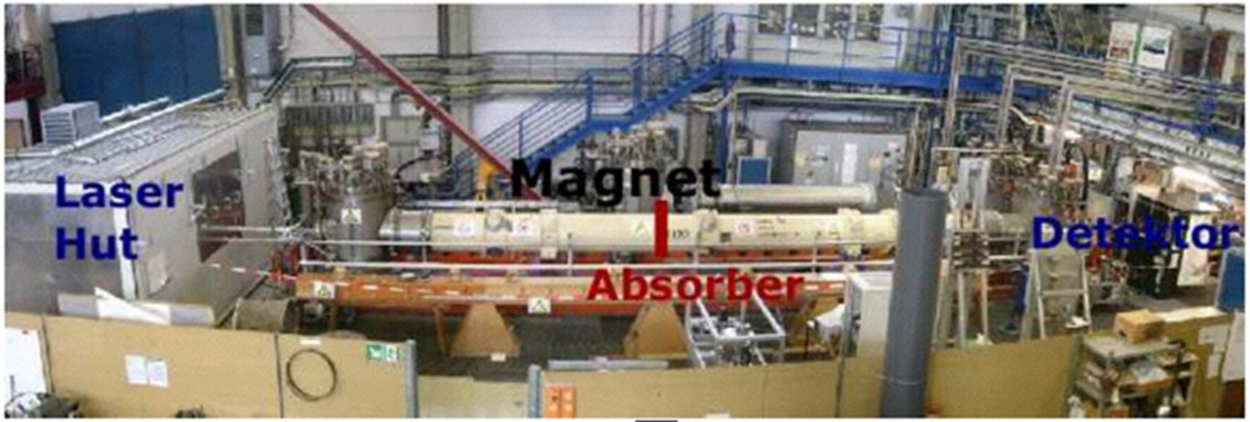
  - CAST … CERN Axion Solar Telescope
  - IAXO … International Axion Observatory (under investigation)

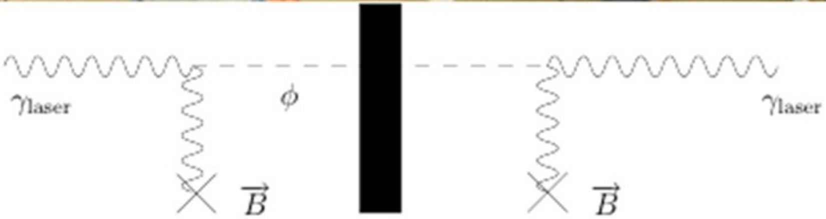
Search for solar axions and ALPs



Search for ALPs via light-shining-through-walls

- ALPs can pass walls
- Light-shining-through-walls experiments: (here ALPS (@DESY)):





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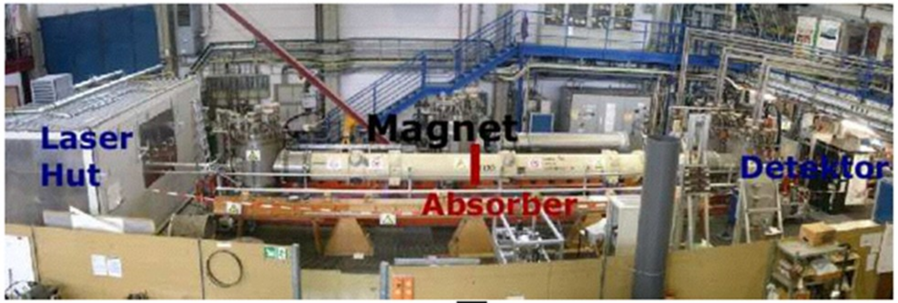
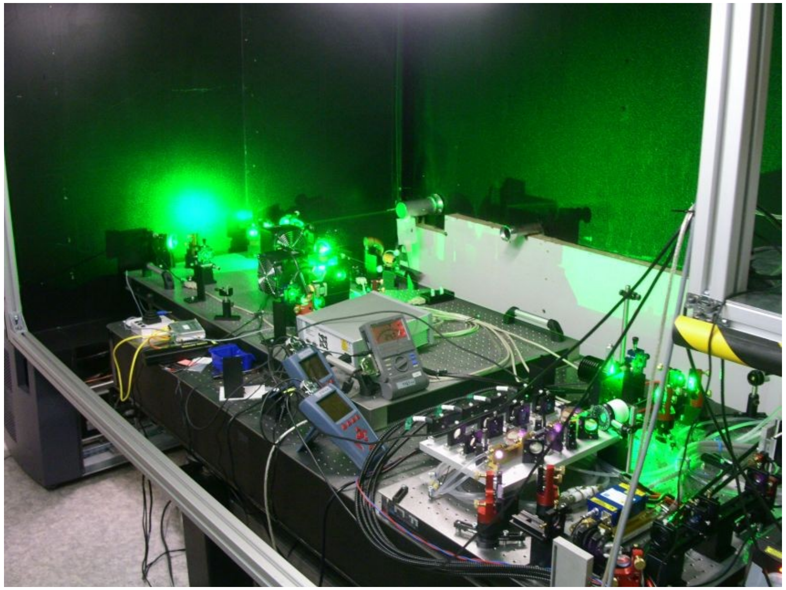
Search for ALPs via light-shining-through-walls

> ALPS:

- HERA dipole (8.4 m, 5 T)
- Primary laser: enhanced LIGO laser (1064 nm, 35 W)
- Frequency doubled: 523 nm
- 300-fold power build-up in cavity





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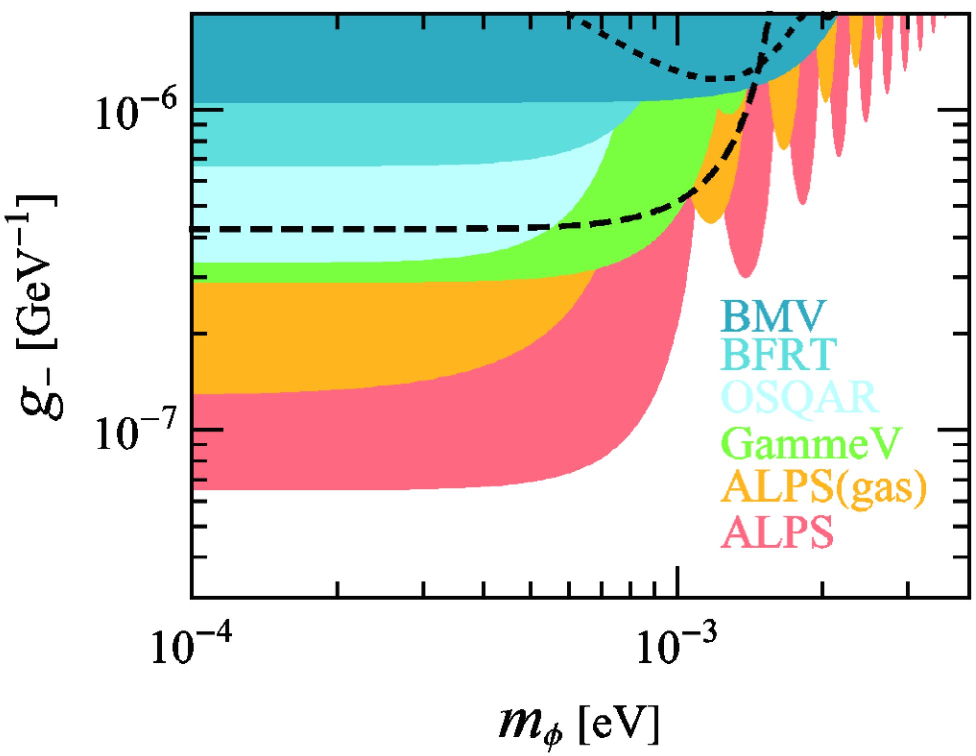

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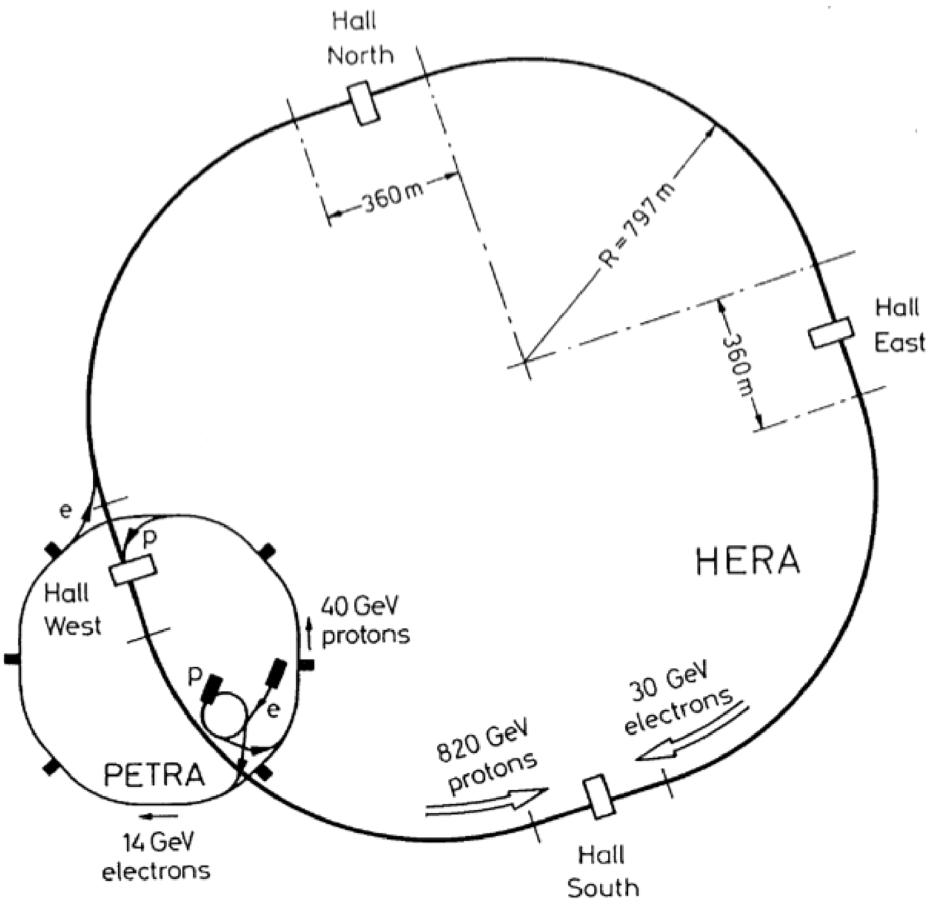
- 12 + 12 HERA dipoles
- Increased power build-up (~5000)
- Cavity also on regeneration part



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- ALPS-II plans (2016+):
  - 12 + 12 HERA dipoles
  - Increased power build-up (~5000)
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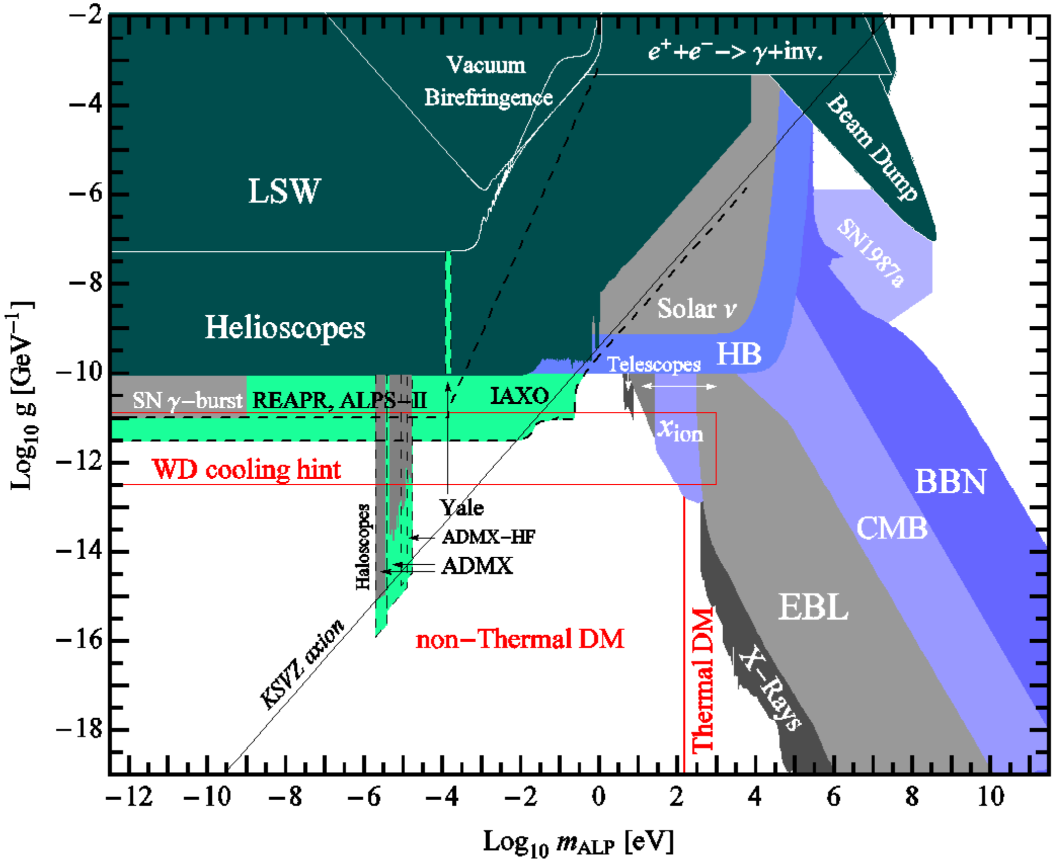
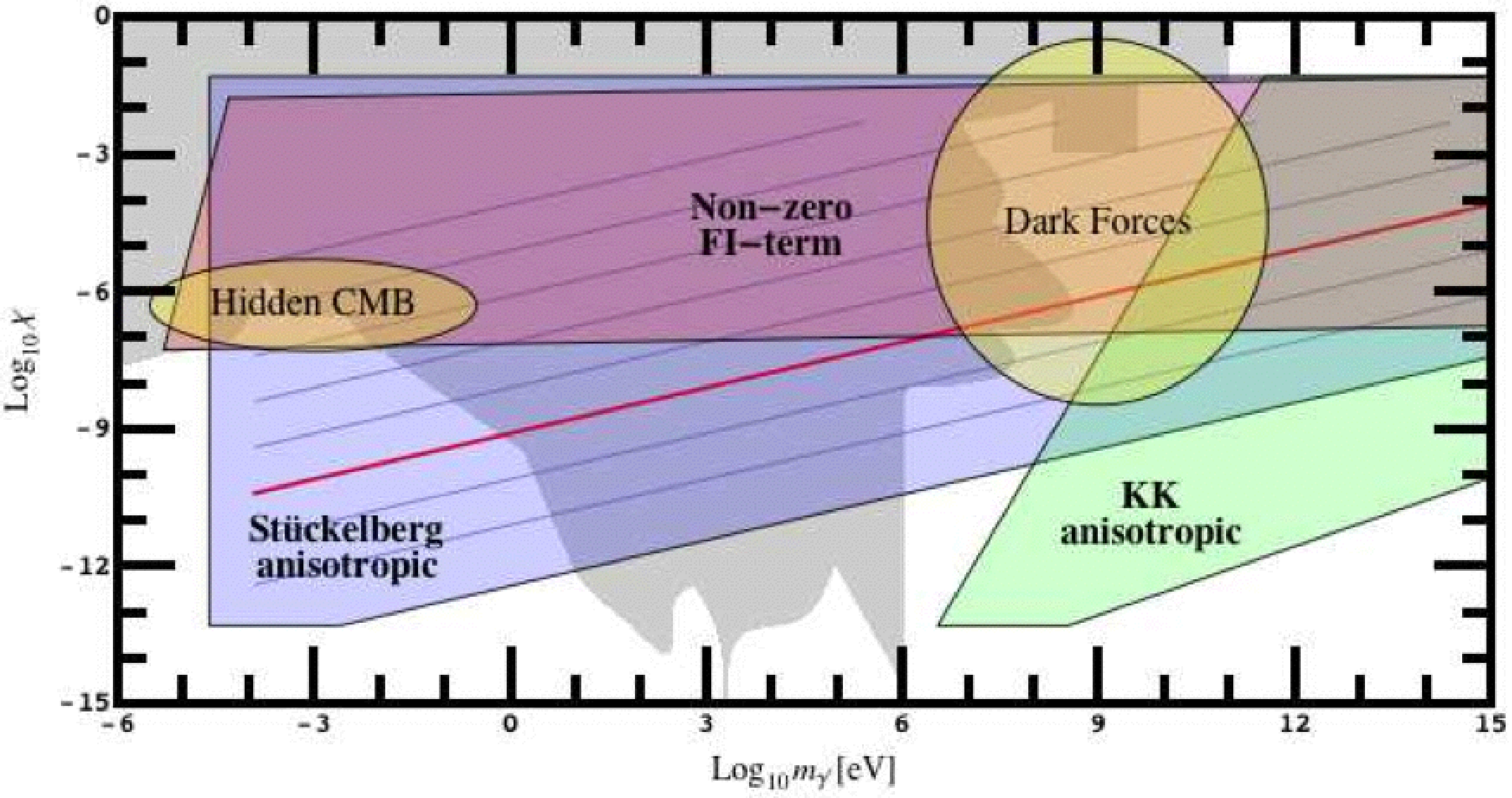
- Similar plans also at Fermilab (REAPR)



Summary and conclusions

- String phenomenology holds the promise of an axiverse – the QCD axion plus a (possibly large) number of further ultralight axion-like particles, possibly populating each decade of mass down to the Hubble scale
- Promise fulfilled in LARGE Volume Scenario of IIB string compactifications
- Models that exhibit a QCD axion with an intermediate-scale decay constant and additional even lighter axion-like particles having the same decay constant and coupling to the photon can explain astrophysical anomalies and be tested in the next generation of helioscopes and light-shining-through-walls experiments
- Cosmology of LVS axiverse still to be investigated in detail

Backup: Hidden photons



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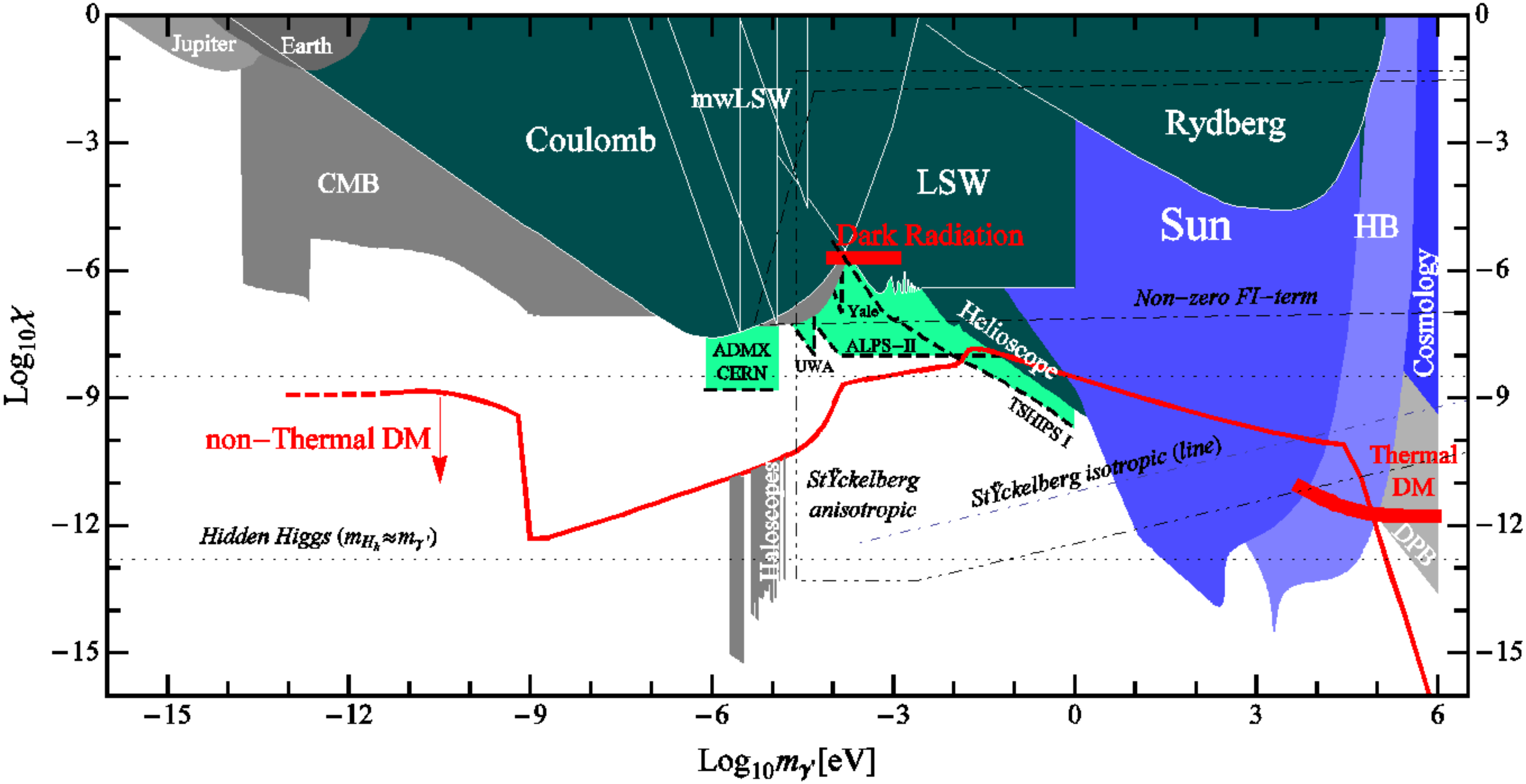
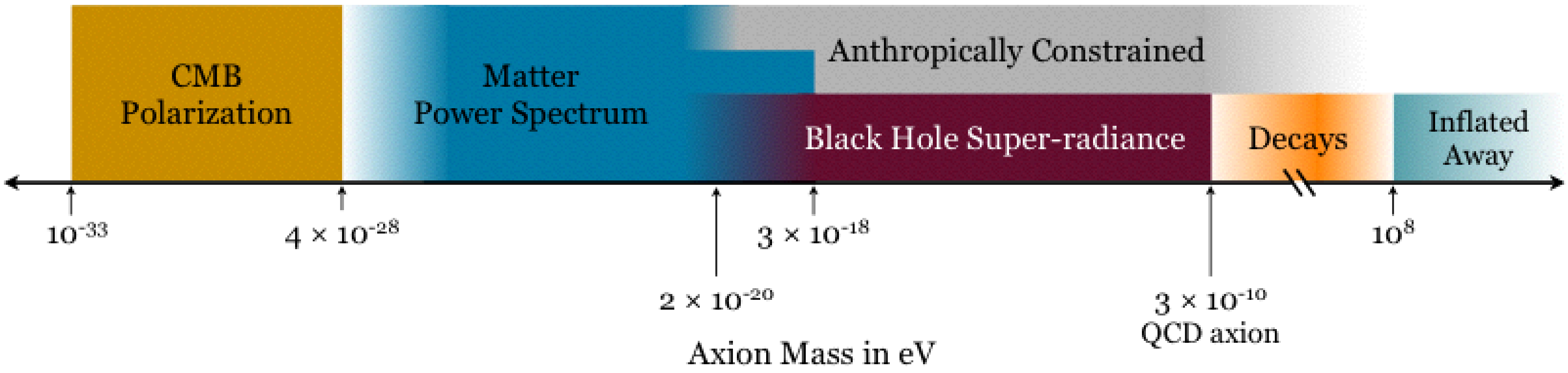


Backup: More probes of ultralight axions and ALPs



cf. Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell `09