Axions and Axion-Like Particles in the Dark Universe.

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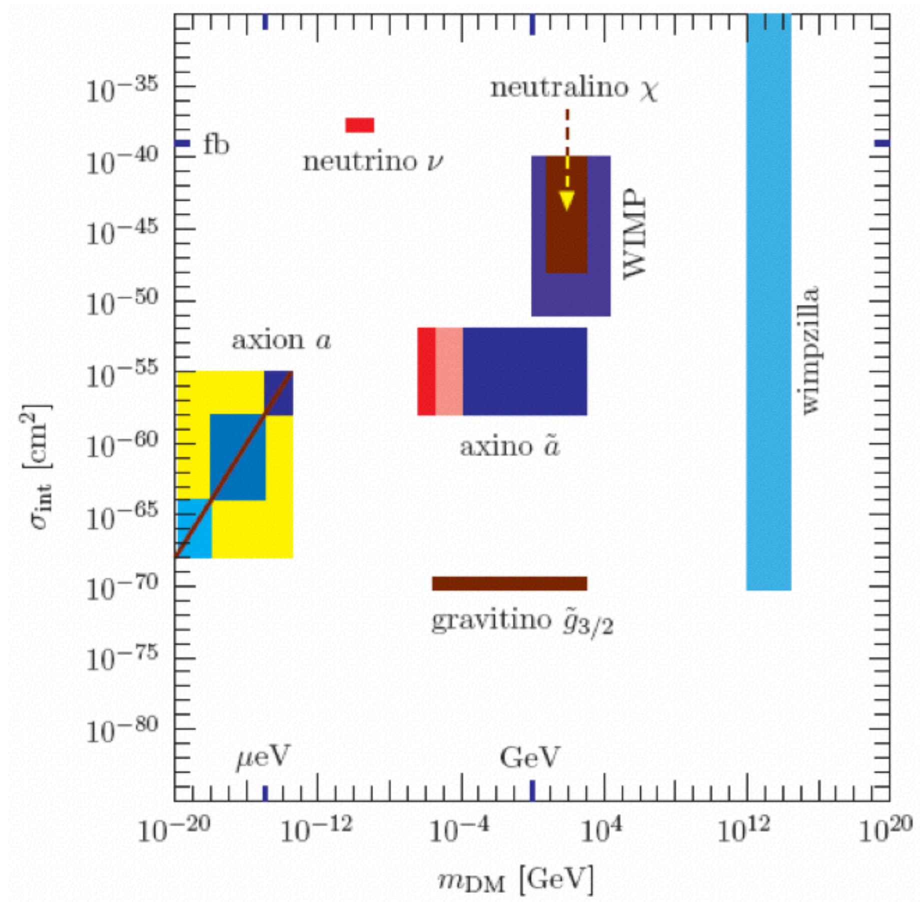
Introduction

- Plenty of dark matter (DM) candidates spanning huge parameter range in masses and couplings
- Two classes stand out because of their convincing physics case and the variety of experimental and observational probes:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions
- Plan:
  - Physics case for axions and axion-like particles (ALPs)
  - Probes of axions and ALPs



[Kim,Carosi `10]

Physics case for axions: Strong CP problem

- Most general gauge invariant Lagrangian of QCD up to dimension four:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \bar{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - Fundamental parameters of QCD: strong coupling α_s, quark masses m_u, m_d, ..., and theta parameter

$$\bar{\theta} = \theta + \arg\,\det\,\mathcal{M}_q$$

- Theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ odd under P and T, i.e. leads to CP violation in flavor conserving interactions
- Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment (EDM) of neutron; experimentally

$$|d_n| < 2.9 \times 10^{-26}\ e\,\mathrm{cm}$$

- Strong CP problem:

$$d_n(\bar{\theta}) \sim \frac{e\bar{\theta} m_u m_d}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17}\ \bar{\theta}\ e\,\mathrm{cm} \Rightarrow |\bar{\theta}| \lesssim 10^{-9}$$

Physics case for axions: Strong CP problem

- Peccei-Quinn solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from effective chiral Lagrangian,

$$V(\overline{\theta}) = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \overline{\theta}^2 + \mathcal{O}(\overline{\theta}^4)$$

  has localised minimum at vanishing theta parameter:

  If theta were a dynamical field, its vacuum expectation value (vev) would dynamically relax to zero

- Introduce field a(x) as dynamical theta parameter, enjoying a shift symmetry, $a \to a + \mathrm{const.}$, broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \, \partial^\mu a - \frac{\alpha_s}{8\pi} \left(\bar{\theta} + \frac{a}{f_a} \right) G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

  - Can eliminate theta by shift $a(x) \to \overline{a}(x) \equiv a(x) + \overline{\theta} f_a$; QCD dynamics (see above) leads to vanishing vev, $\langle \overline{a} \rangle = 0$, i.e. P, T, and CP conserved
  - Elementary particle excitation of field around vev: axion (Weinberg 78; Wilczek 78)

Physics case for axions: Strong CP problem

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- For large decay constant f_a: prime paradigm of a WISP (Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81)

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma} - \frac{2}{3}\,\frac{m_u + 4m_d}{m_u + m_d}\right) \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

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

- Strong constraints from astrophysics (non-excessive energy loss of stars):

$$f_a \gtrsim 10^9\ \mathrm{GeV}$$

Physics case for axions and ALPs: NGBs of SSB

- In 4D field theoretic extensions of the Standard Model (SM), axion field realised as phase of a complex $SU(2)_L \times U(1)_Y$ singlet scalar field whose vev breaks a global anomalous chiral $U(1)_{\rm PQ}$ symmetry,

$$\Phi(x) = \frac{v_{\rm PQ} + \rho(x)}{\sqrt{2}}\, {\rm e}^{i a(x)/f_a}$$

  - At energies much below the symmetry breaking scale $v_{\rm PQ}$ the low-energy effective field theory is that of a (pseudo-)Nambu-Goldstone Boson (NGB) with decay constant

$$f_a = v_{\rm PQ}/C_{ag}$$

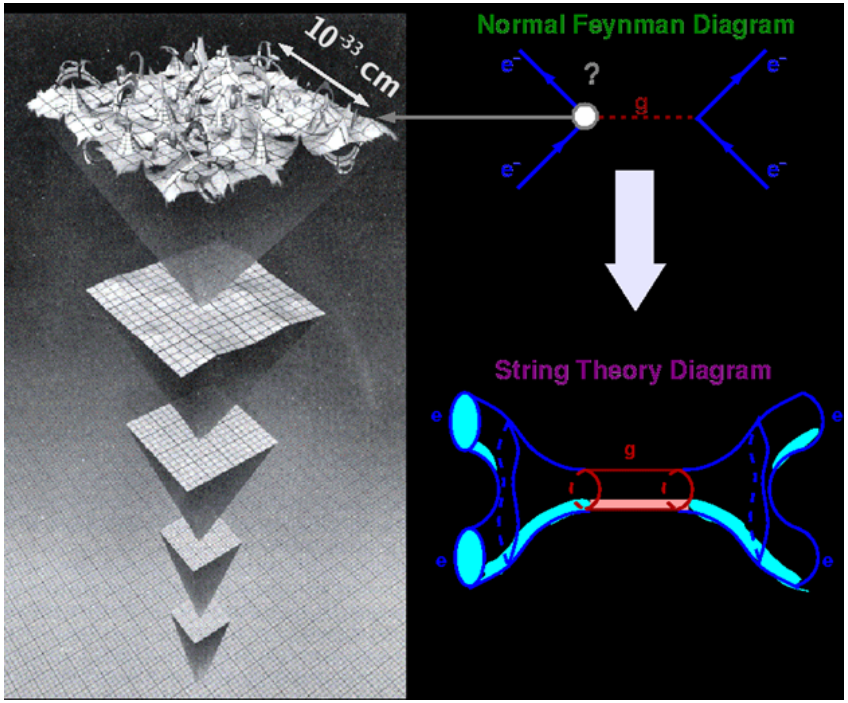
- More axion-like particles (ALPs) may arise as NGBs from the breaking of more than one anomalous $U(1)_{\rm PQ}$

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu a_i\,\partial^\mu a_i - \frac{\alpha_s}{8\pi}\left(\bar\theta + C_{ig}\frac{a_i}{f_{a_i}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{i\gamma}\frac{a_i}{f_{a_i}}\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

Physics case for axions and ALPs: String theory

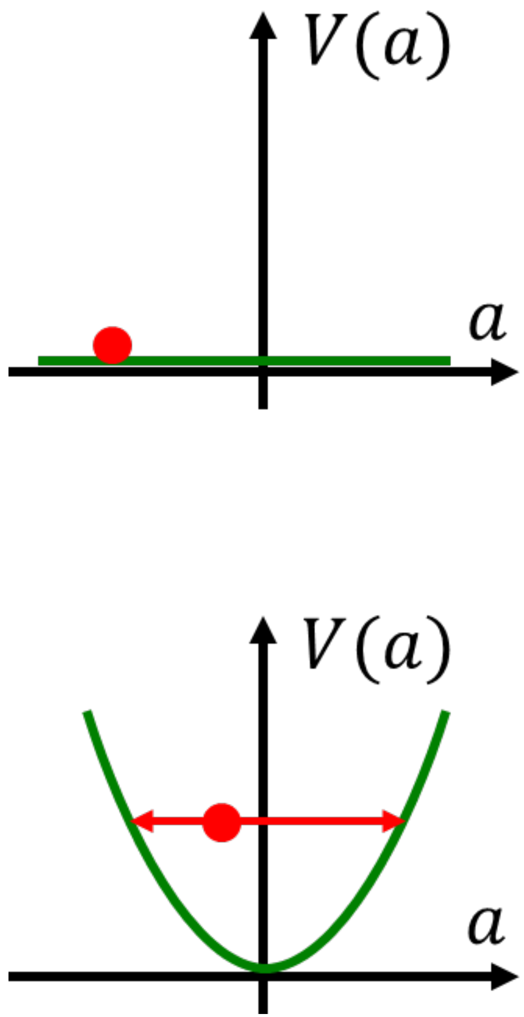
- 4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs
  - KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string

    shift symmetry from gauge invariance in 10D;
    number of ALPs depends on topology of compactified space;
    decay constant of order the string scale, i.e. GUT scale, $10^{16}\ \mathrm{GeV}$,in the heterotic string case, typically lower, the intermediate scale, $10^{10}\ \mathrm{GeV}$, in IIB compactifications realising brane worlds with large extra dimensions
    [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli, Goodsell, AR 12]
  - NGBs from accidental PQ symmetries appearing as low energy remnants of large discrete symmetries from compactification, $f_a \sim v_{\mathrm{PQ}_i}$ [Lazarides,Shafi 86; Choi et al. 09]



Physics case for axions and ALPs: Cold dark matter

- For large decay constant, axion CDM produced non-thermally in the early universe by vacuum-realignment and, in some cases and under certain circumstances, also via decay of topological defects
- Axion field in early universe has random initial state, $a(t) = \theta_a f_a$, fixed by cosmic expansion, as long as $t \lesssim m_a^{-1}$. Later, at $t \gtrsim m_a^{-1}$, axion field responds by attempting to minimise its potential, oscillating around minimum (vacuum-realignment). Classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter, i.e. CDM
[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83]



[Raffelt]

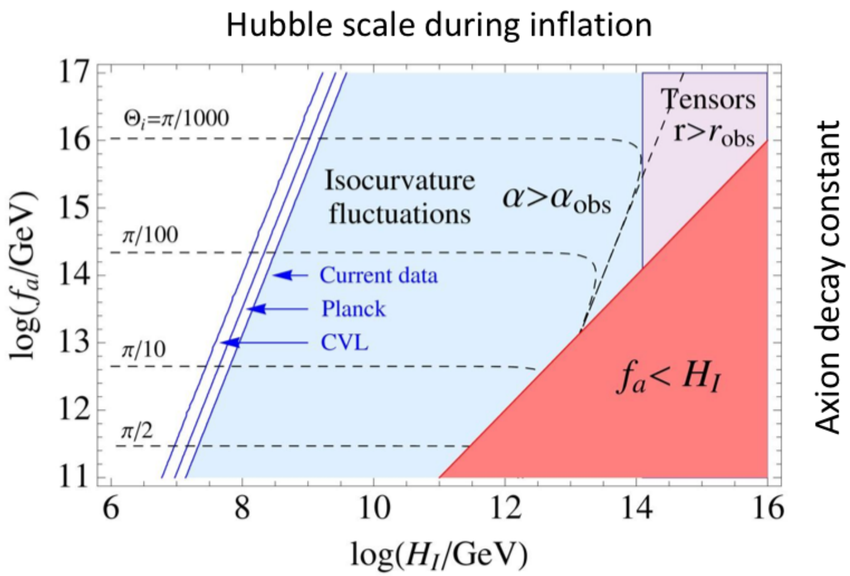
Physics case for axions and ALPs: Cold dark matter

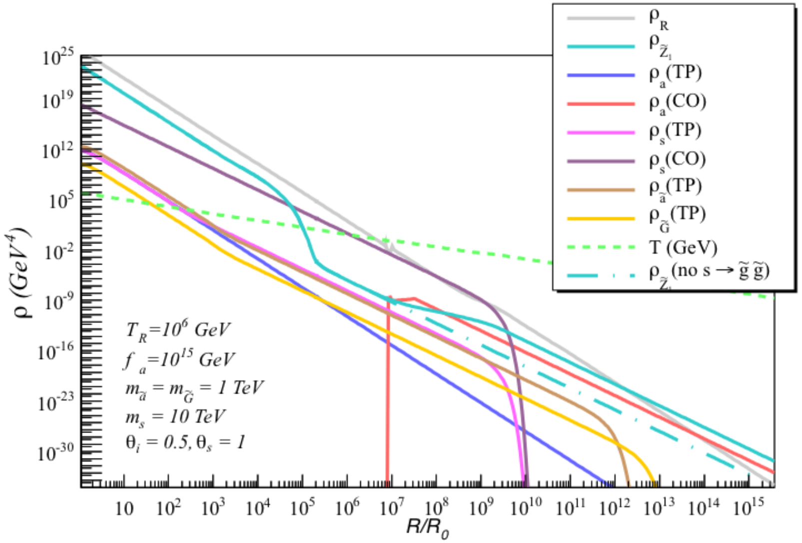
- If reheating temperature after inflation below f_a and no dilution by late decays of particles beyond SM,

$$\Omega_a h^2 \approx 0.71 \times \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{\Theta_a}{\pi}\right)^2$$

  - Axion can be dominant part of CDM if decay constant $f_a \gtrsim 10^{11}\ \mathrm{GeV}$
  - Axion with GUT scale decay constant would overclose universe unless initial misalignment angle very small
  - Axion field present during inflation: its quantum fluctuations lead to isocurvature fluctuations [Fox et al.; Hamann et al. 09]

- Cosmic axion window wider if late dilution occurs, as e.g. in SUSY extensions of PQ mechanism [Baer et al. 12]



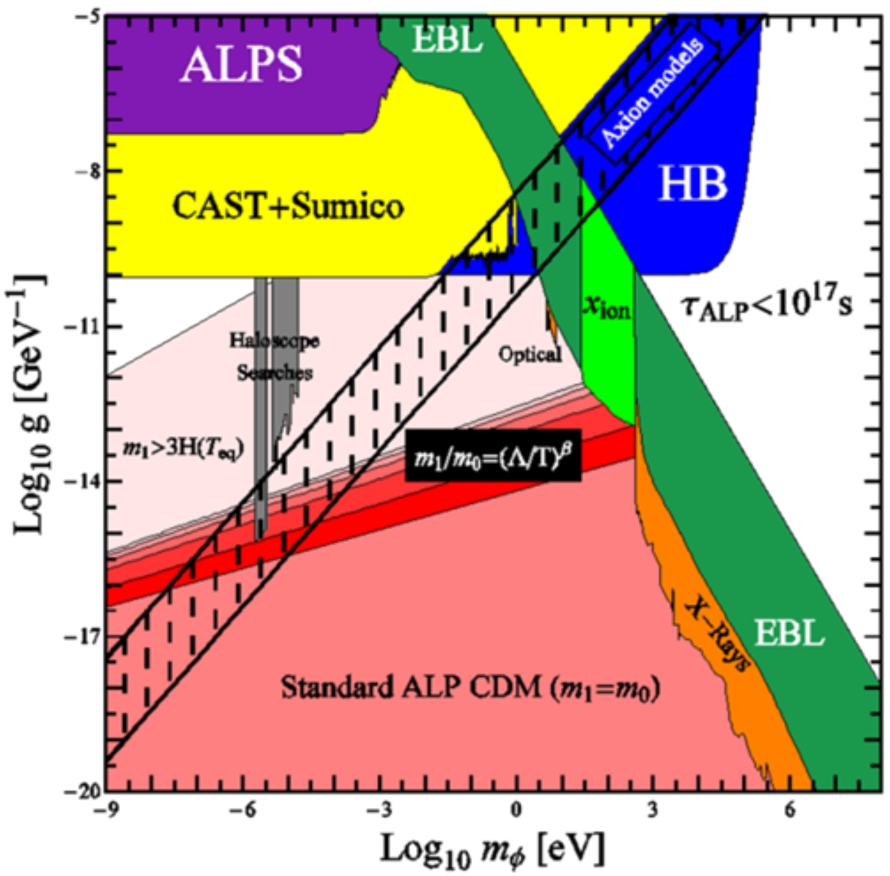


Physics case for axions and ALPs: Cold dark matter

- Other bosonic WISPs such as axion-like particles (ALPs) are also produced via the vacuum-realignment mechanism,

$$\Omega_{a_i} h^2 \approx 0.16 \times \left(\frac{m_i}{\mathrm{eV}}\right)^{1/2} \left(\frac{f_{a_i}}{10^{11}\ \mathrm{GeV}}\right)^2 \left(\frac{\Theta_i}{\pi}\right)^2$$

  - Search space for ALPs CDM quite large



[Arias et al. 12]

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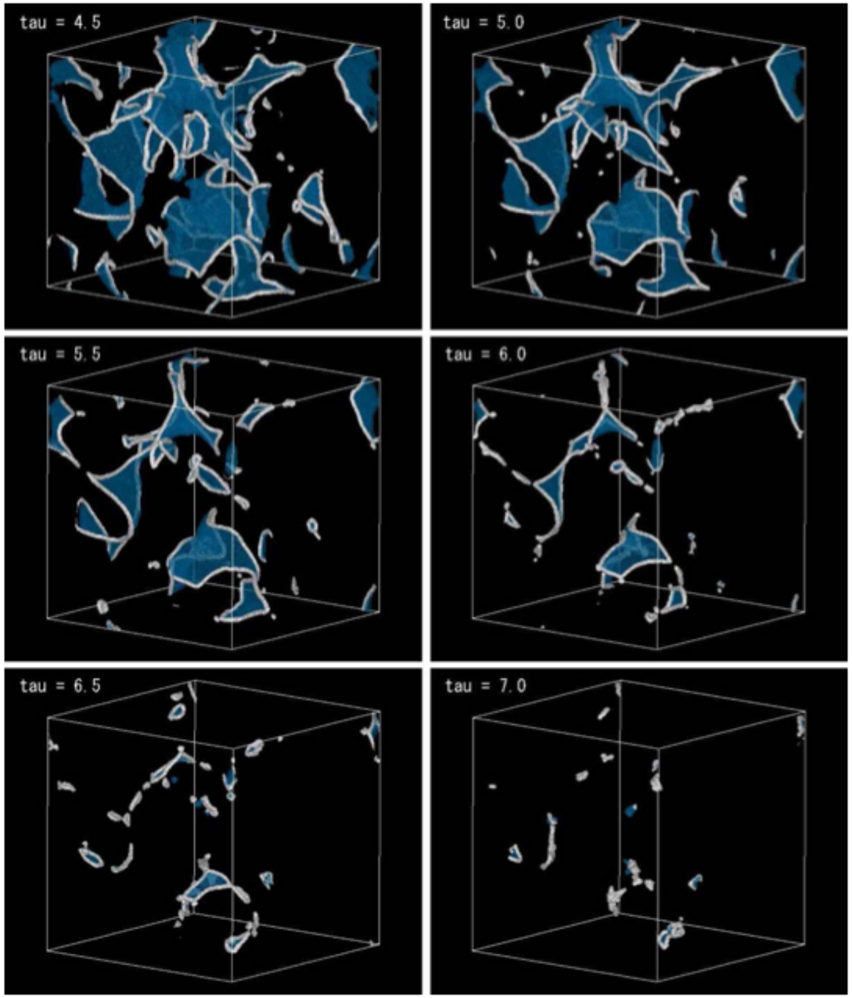
  - Search space for ALPs CDM quite large

- If reheating temperature after inflation is above f_a, initial misalignment angles take on different values in different patches of universe, leading to average contribution

$$\Omega_a h^2 \approx 0.3 \times \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

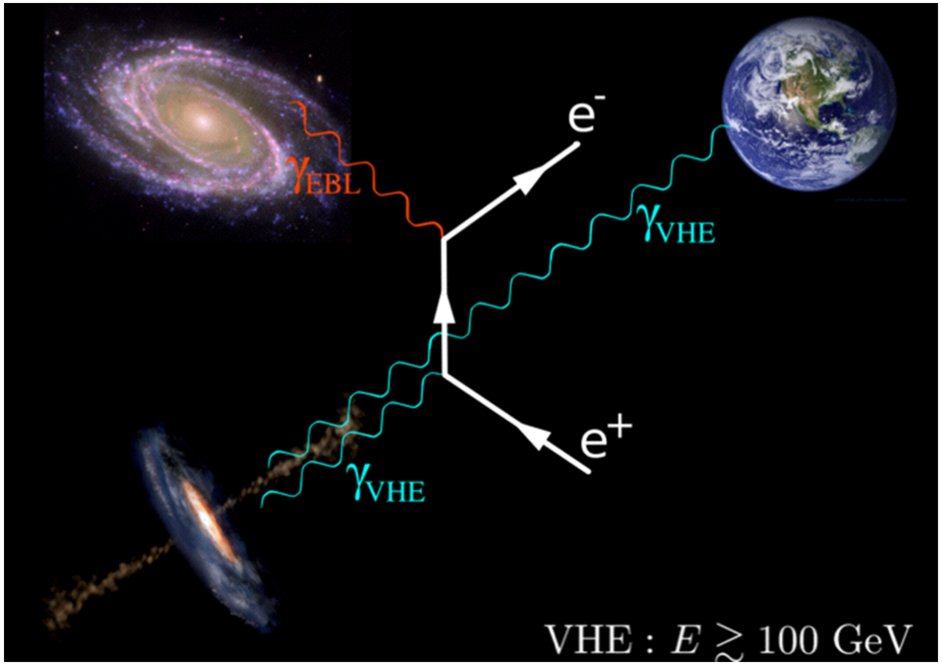
  - Decay of cosmic strings and domain walls may provide for additional sources for axion CDM



[Hiramatsu et al. 12]

Physics case for ALPs: VHE transparency of universe

- VHE photon spectra from distant Active Galactic Nuclei (AGN) should show absorption features due pair production at Extragalactic Back-ground Light (EBL)



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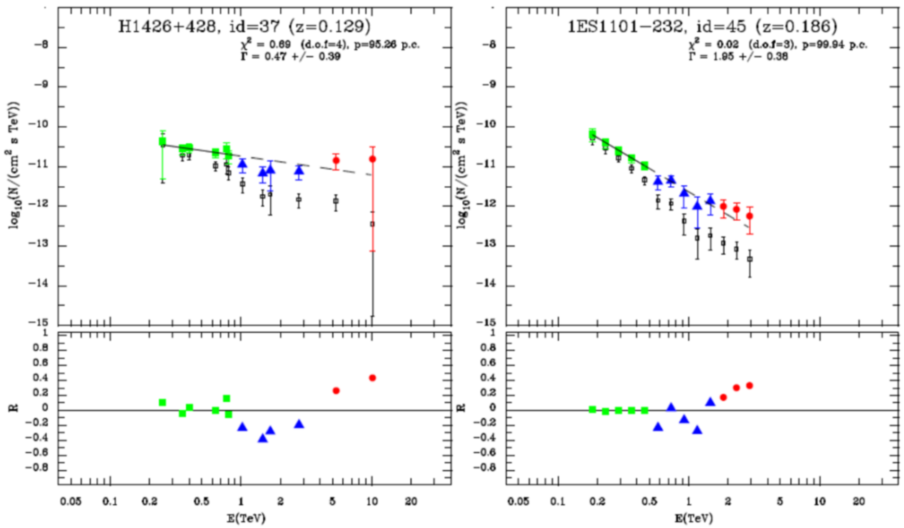

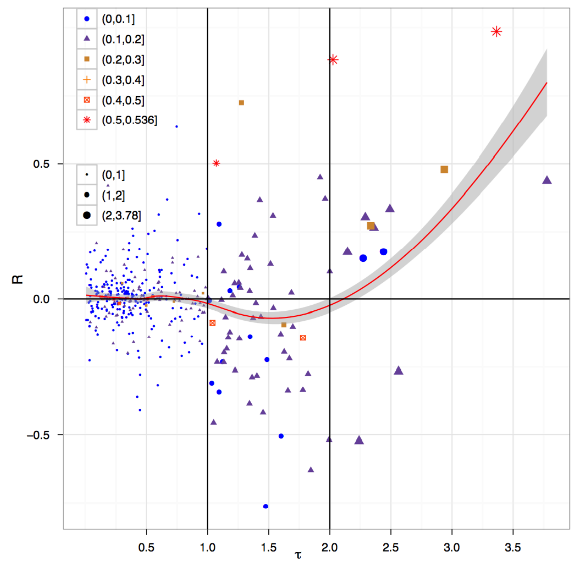

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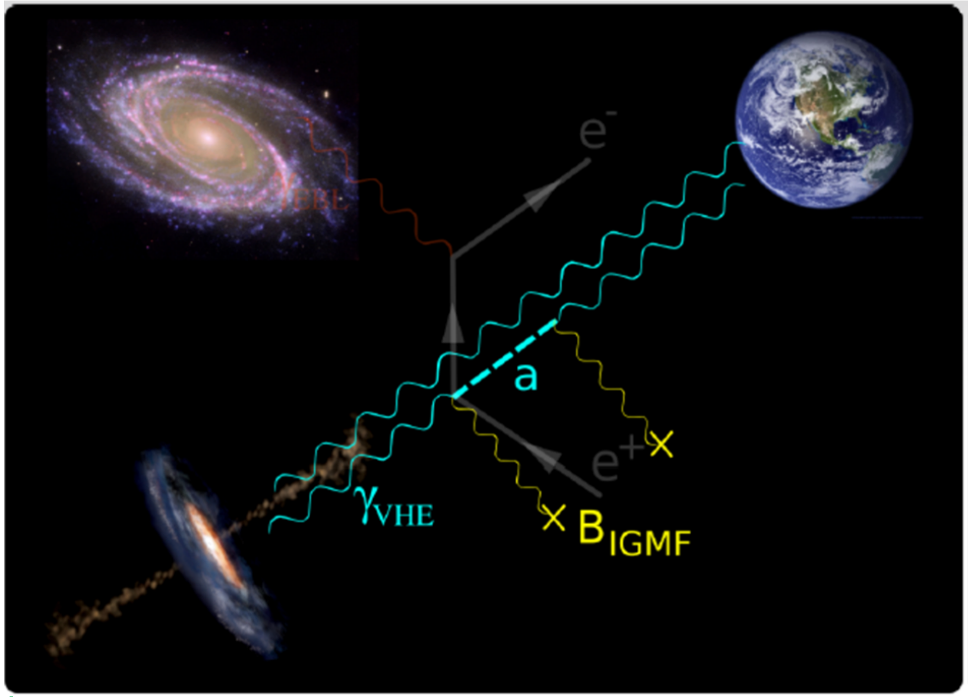
- Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields [Roncadelli et al 07; Simet et al 08; Sanchez-Conde et al 09; Horns et al 12; Horns,Meyer 13]



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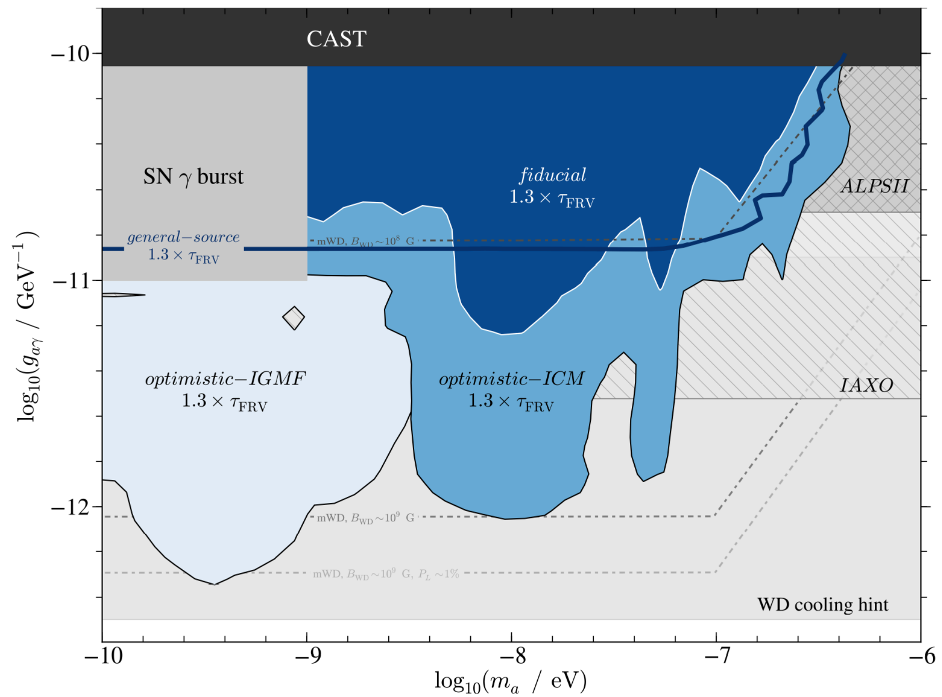
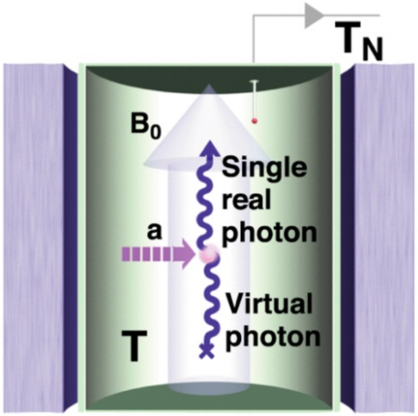


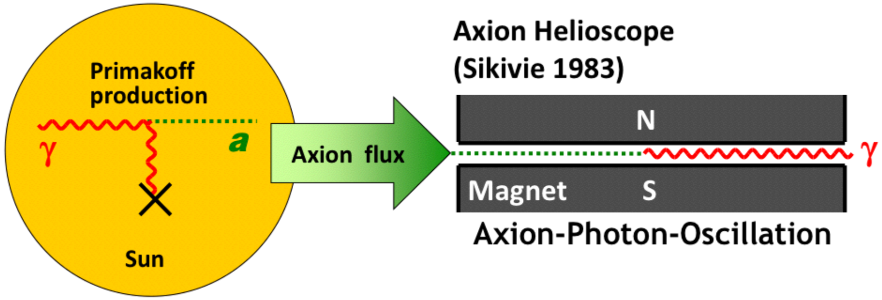
$$g_{i\gamma} \gtrsim 10^{-11}\ \mathrm{GeV}^{-1}, \qquad m_{a_i} \lesssim 10^{-7}\ \mathrm{eV}$$

Probes of axions and ALPs

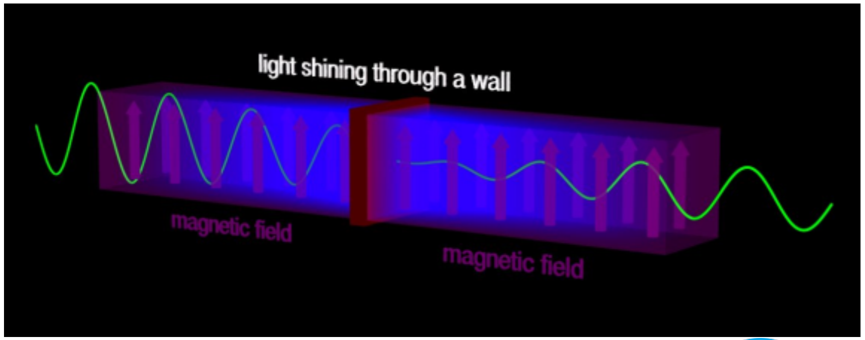
- Direct detection of dark matter axions or axion-like particles (ALPs) (haloscopes)



- Indirect detection of solar axions and ALPs (helioscopes)



- Direct production and detection of ALPs (light shining through walls experiments)

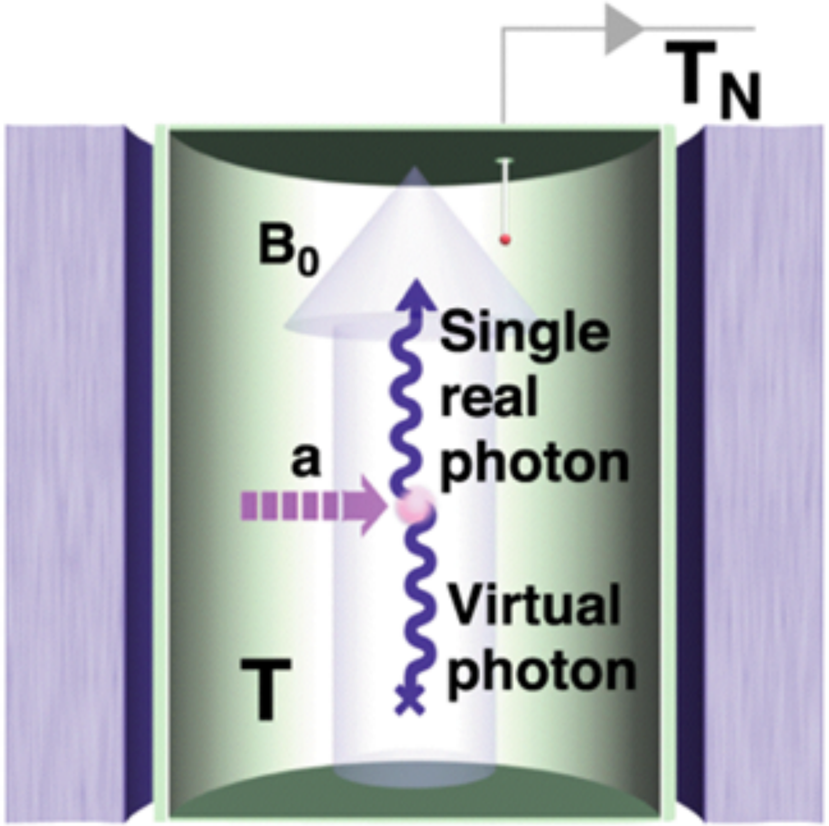


Direct detection of axion or ALP dark matter: Cavities

- Axion or ALP DM -> photon conversion in electromagnetic cavity placed in a magnetic field [Sikivie `83]
- Best sensitivity : mass = reso-nance frequency

$$m_a = 2\pi\nu \sim 4\ \mu\text{eV} \left(\frac{\nu}{\text{GHz}}\right)$$

$$P_{\text{out}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\text{DM}} V Q / m_a$$



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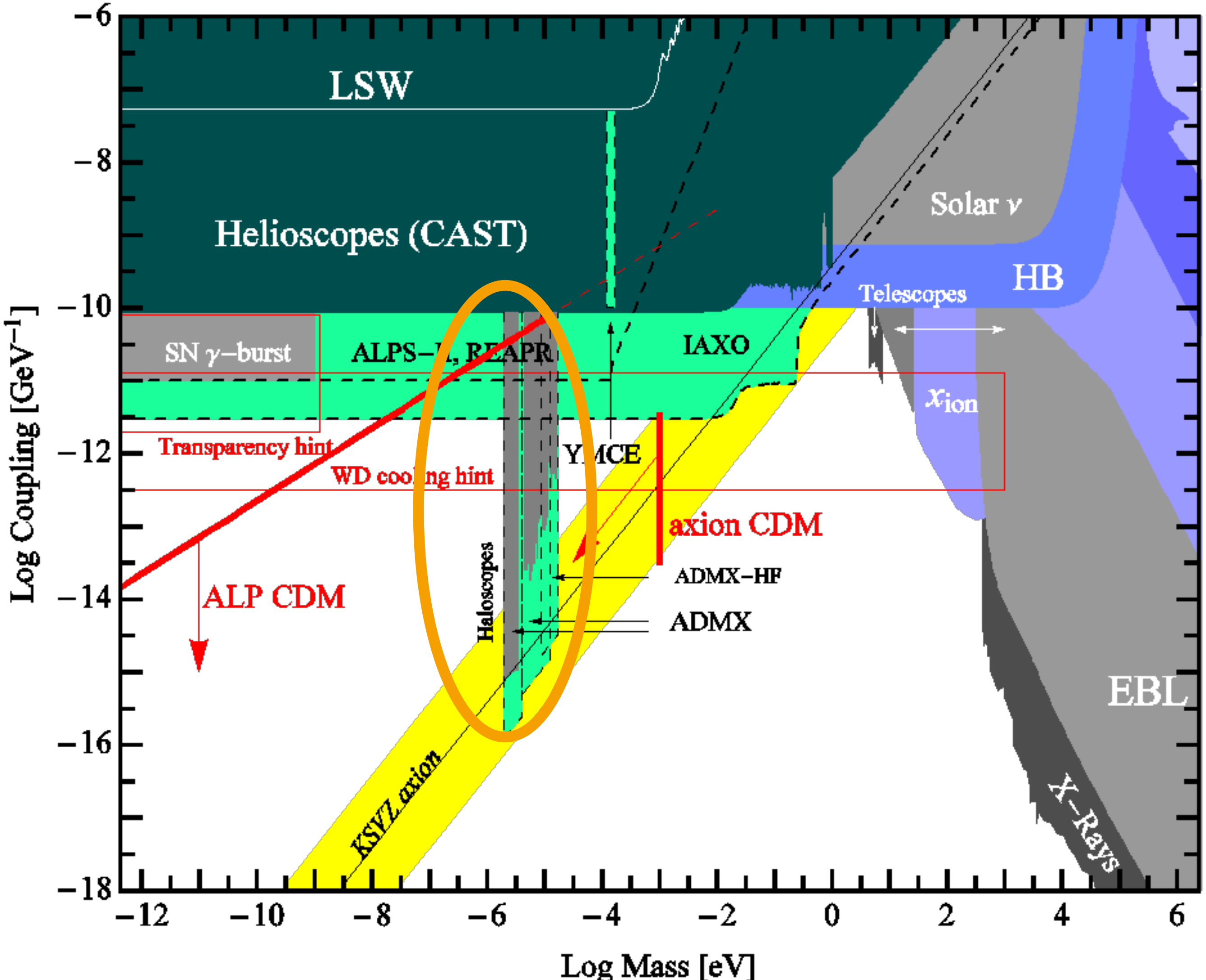
- Ongoing: ADMX (Seattle), takes decade for mass scan over two orders of magnitude

Direct detection of axion or ALP dark matter: Cavities



(Hewett et al 12)

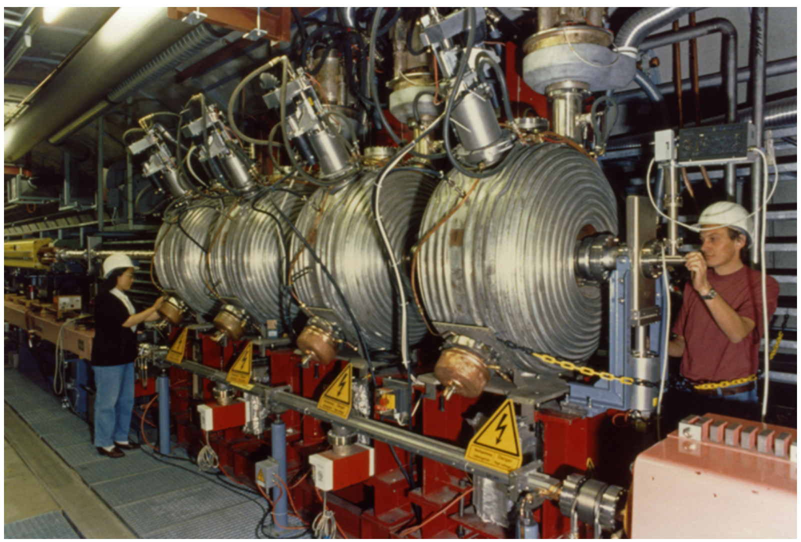
Direct detection of axion or ALP dark matter: Cavities

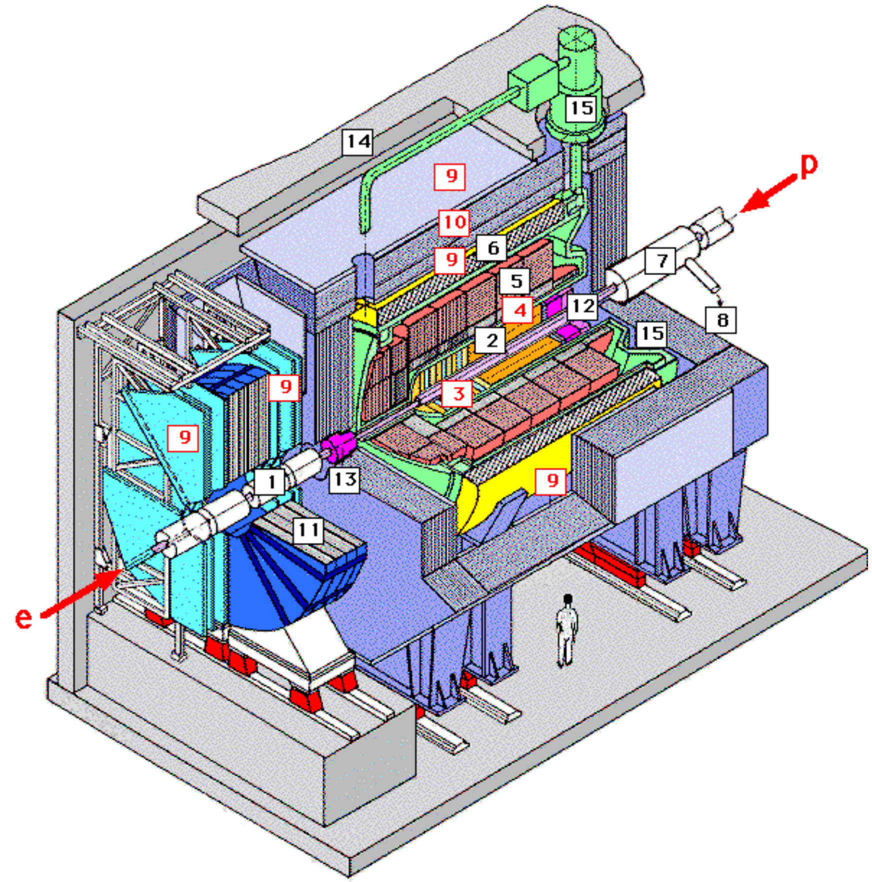
> Available building blocks (DESY)

- HERA proton ring accelerator cavity
- H1 superconducting solenoid

> Interested partner institute (MPIfR)

- Receiver, amplifier, FFT, …

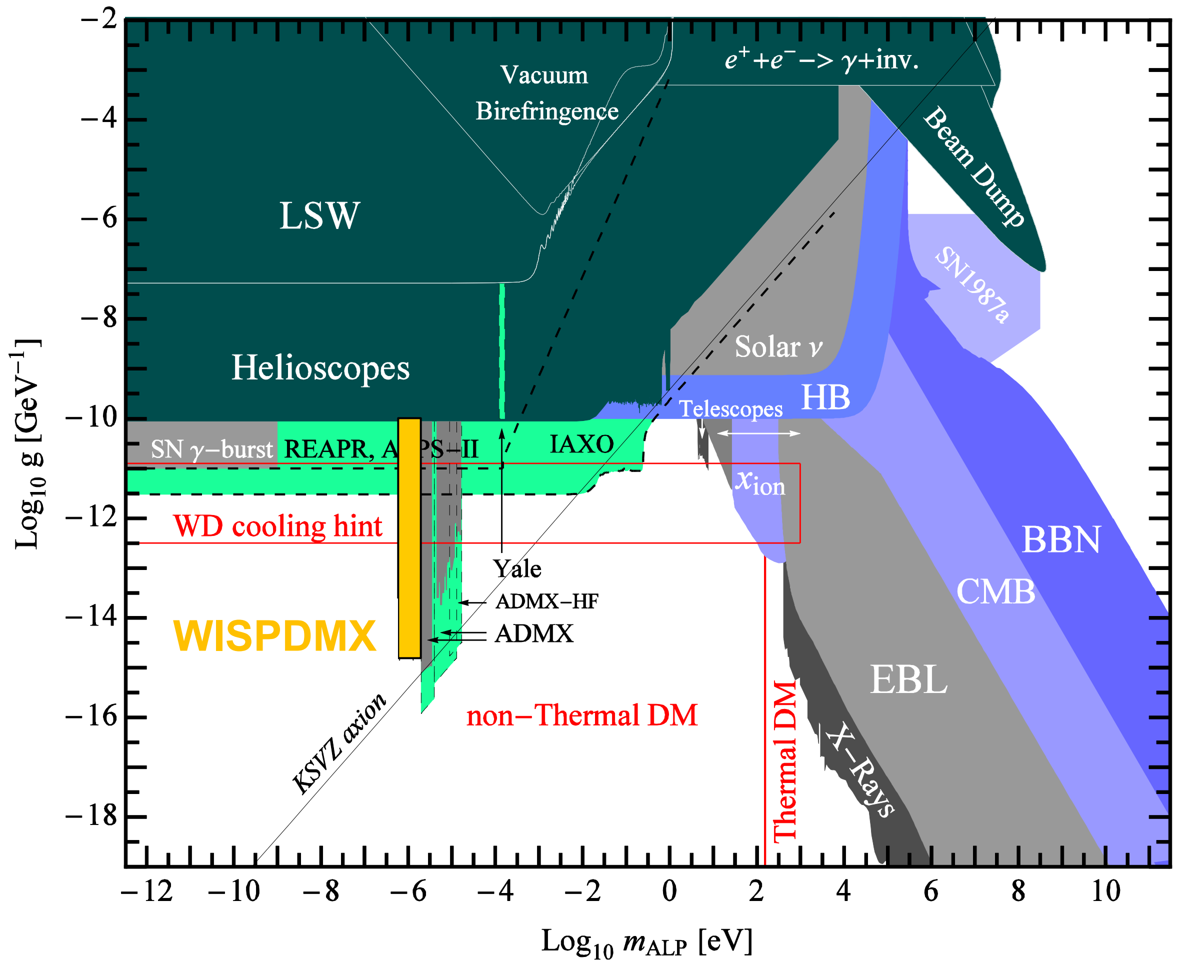




> Ongoing pilot study for WISPDMX

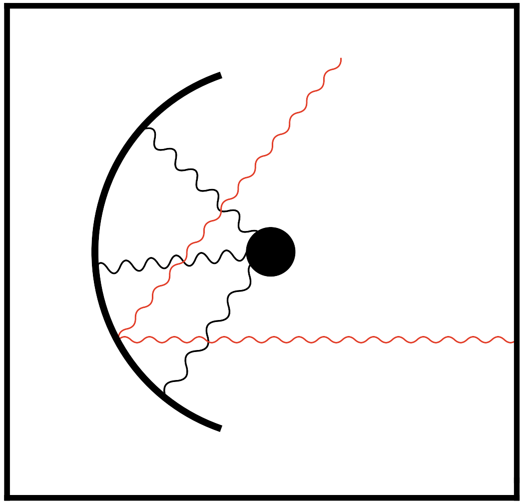
Direct detection of axion or ALP dark matter: Cavities

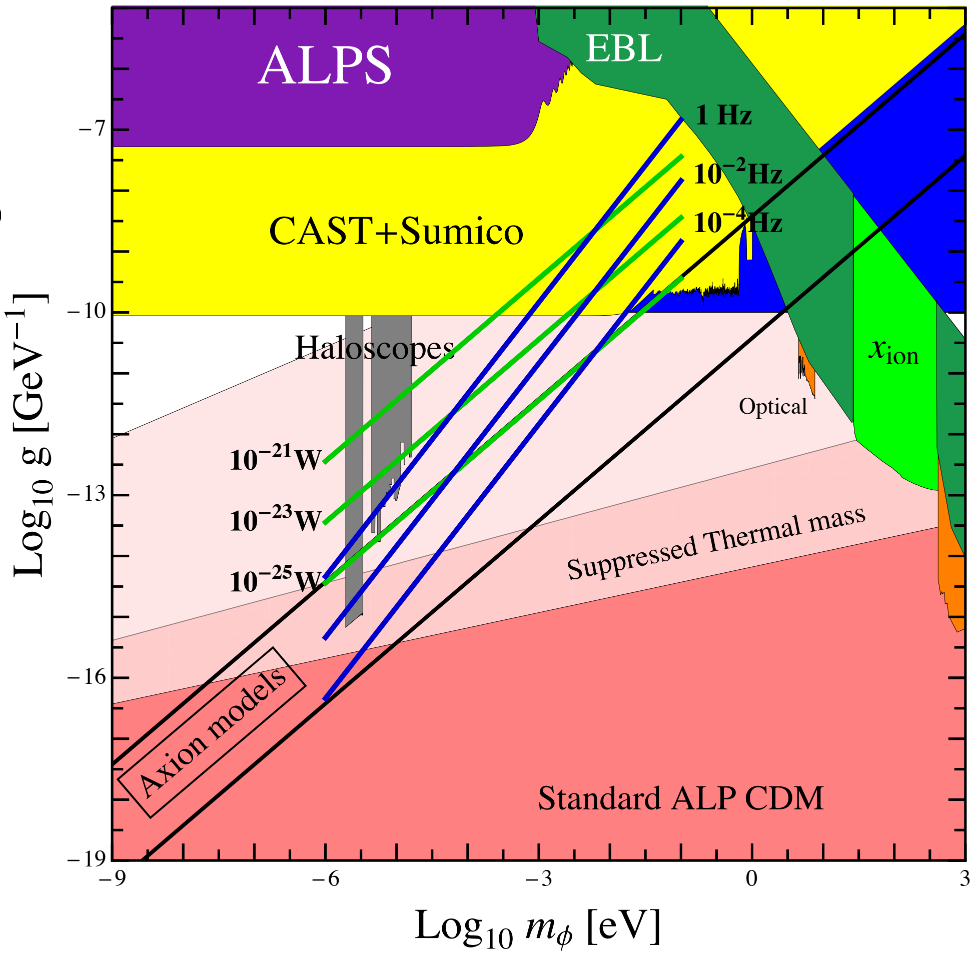
> WISPDMX may probe mass region below ADMX:
[Horns et al. (DESY,MPIfR,UHH]



Direct detection of axion or ALP DM: Dish Antenna

- Proposed broadband search method, based on
  - radiation emitted by conducting surfaces when excited by axionic DM
  - focussed into detector by using spherically shaped surface (dish antenna)





$$P_{\text{center}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\text{DM}} A_{\text{dish}} / m_a^2$$

[Horns et al 12]

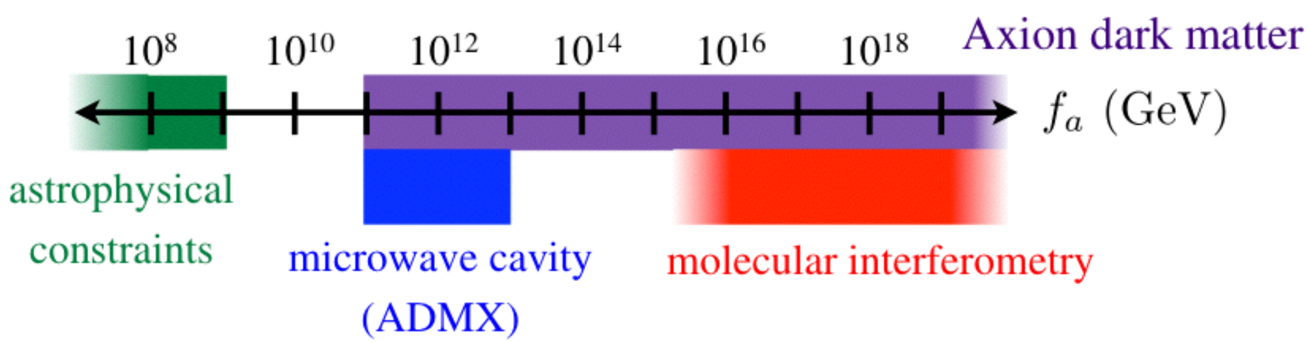
Direct detection of axion DM: Molecular interferometry

> Axion DM: all nucleons have a rapidly oscillating electric dipole moment

$$d_N \sim e \frac{m_u m_d}{(m_u + m_d) m_N^2} \theta_{\rm eff}(t) \sim 10^{-16}\, \theta_{\rm eff}(t)\, e\, {\rm cm}$$

$$\theta_{\rm eff}(t) \sim \frac{a(t)}{f_a} \sim \frac{\sqrt{\rho_{\rm DM}}}{m_a f_a} \cos(m_a t) \sim \frac{\sqrt{\rho_{\rm DM}}}{m_\pi f_\pi} \cos(m_a t) \sim 10^{-19} \cos(m_a t)$$

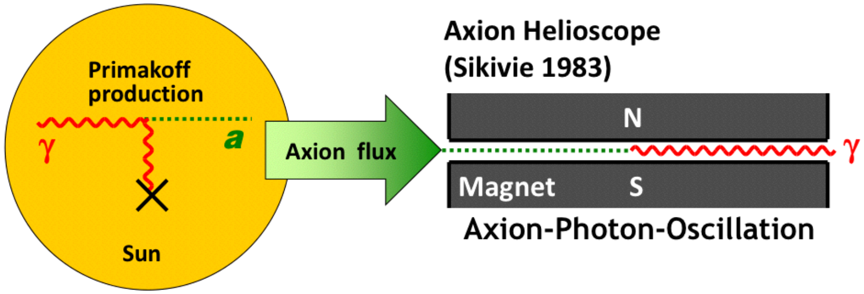
- Window of opportunity for $m_a \sim m_\pi f_\pi / f_a \sim {\rm MHz}\, (10^{16}\, {\rm GeV}/f_a)$:
- Molecular interferometric search for oscillating shifts of atomic energy levels due to the coupling between internal atomic fields and time varying CP-odd nuclear moments, $\delta E \sim E_{\rm int} d_N \sim 10^{-24}$ eV



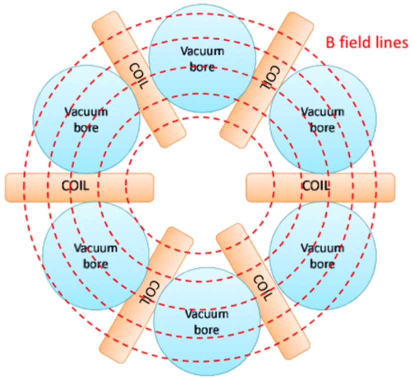
[Graham, Rajendran 11]

Indirect detection of solar axions and ALPs: Helioscopes

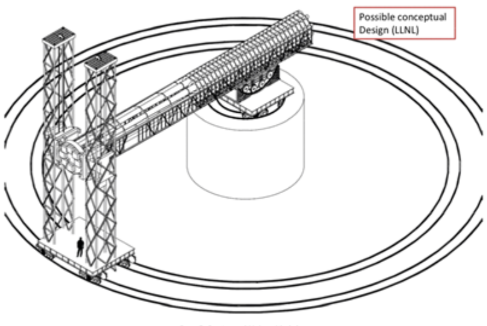
- Sun strong source of axions and ALPs
- Helioscope searches for axions and ALPs



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



- Ongoing: CAST … CERN Axion Solar Telescope



- LoI: IAXO … International Axion Observatory

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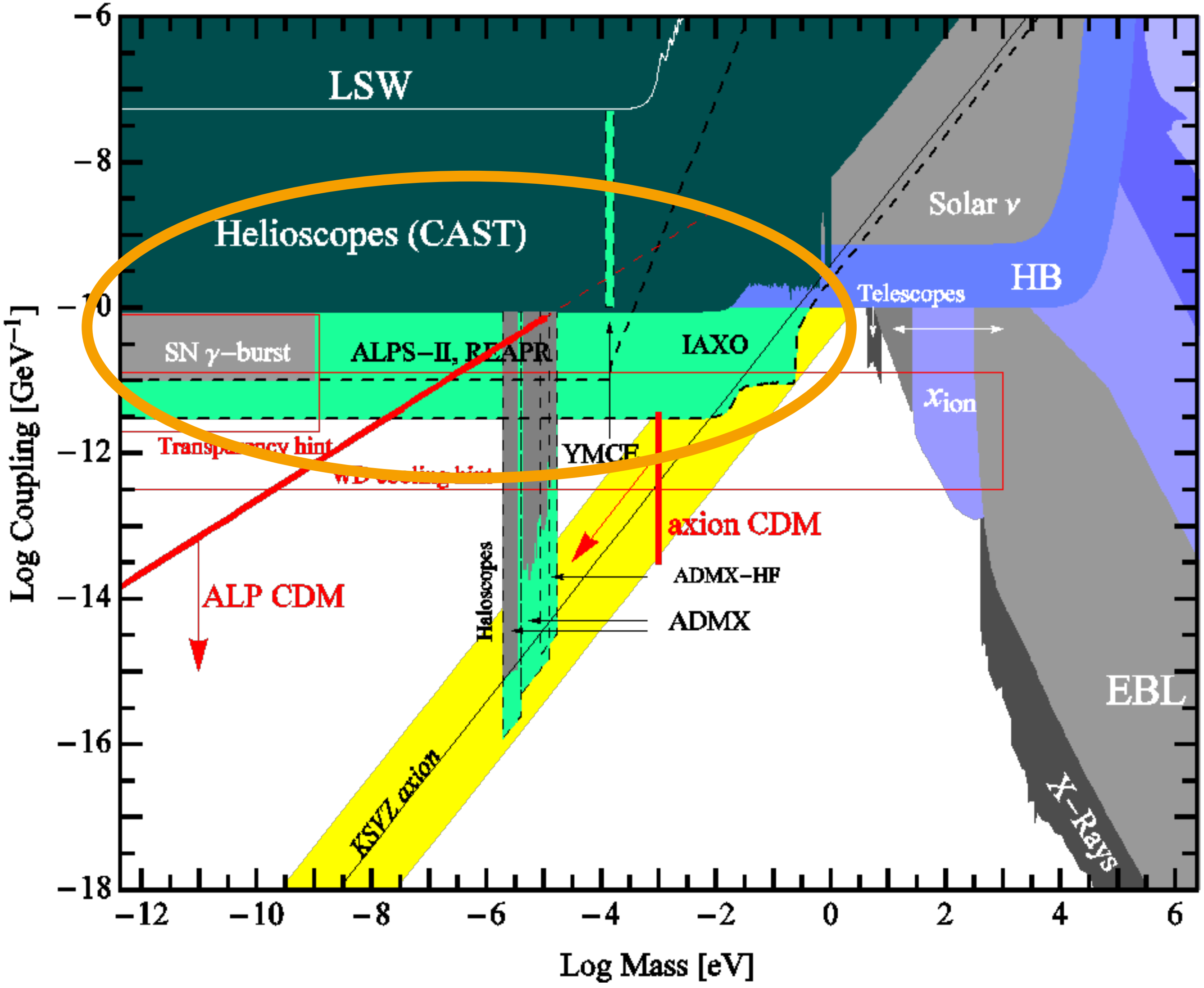
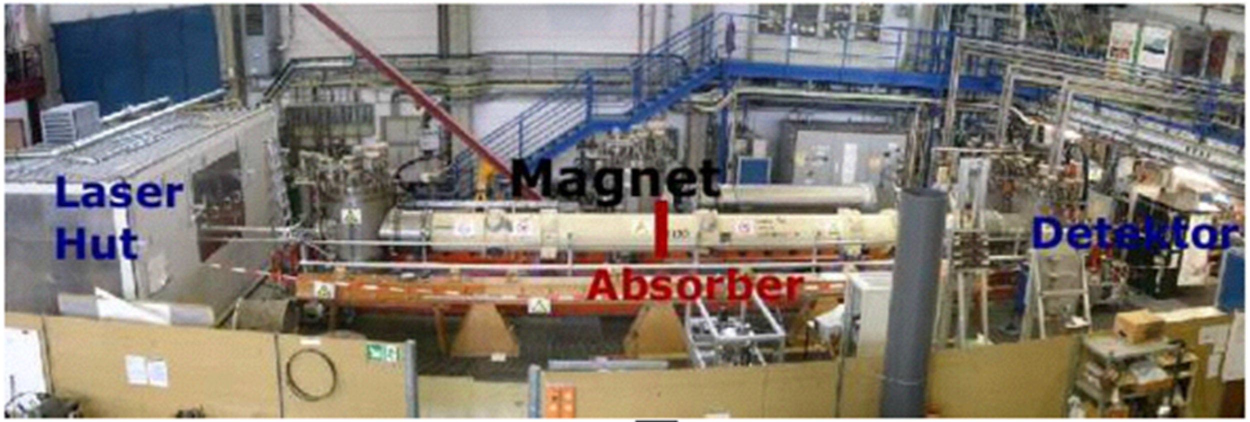
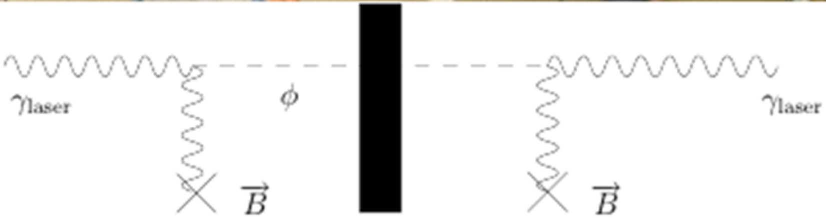


Direct production and detection of ALPs: LSW

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





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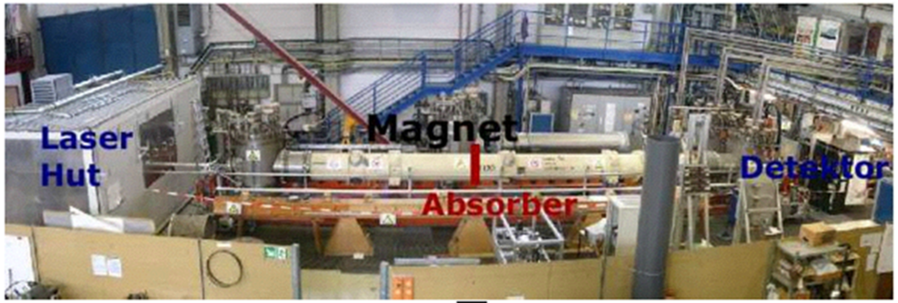
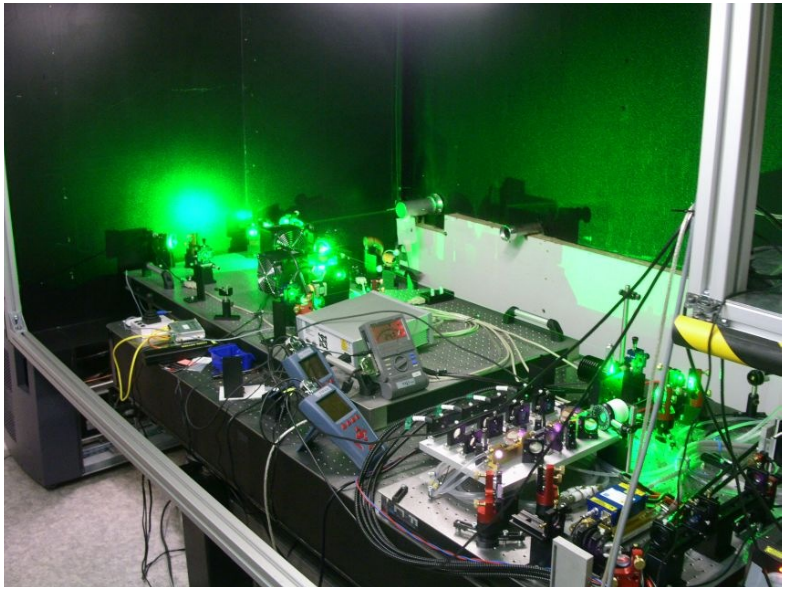
Direct production and detection of ALPs: LSW

- **ALPS:** [AEI,DESY,UHH]
  - 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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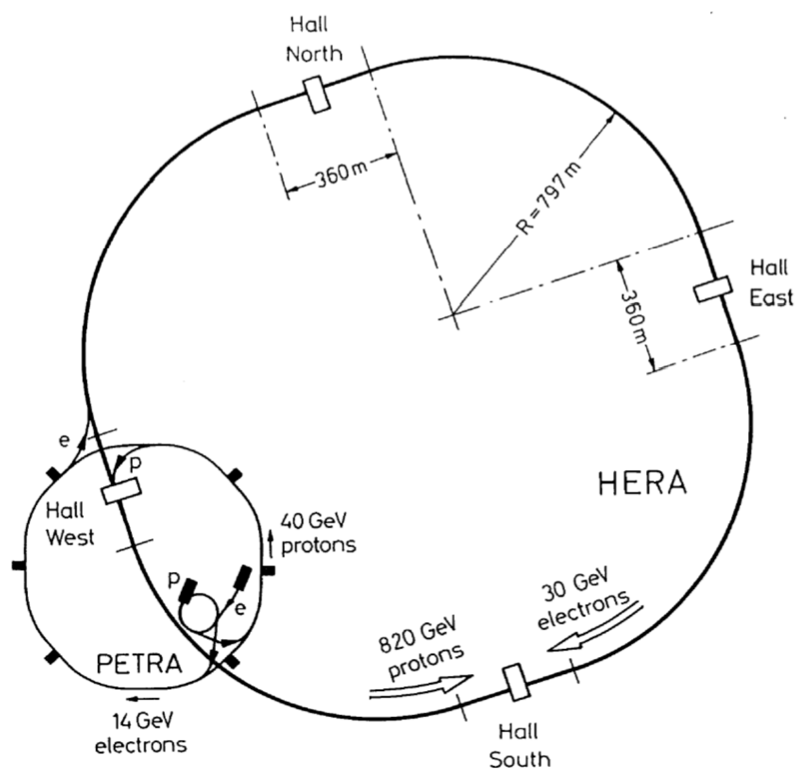
- ALPS-II:
  - 5000-fold power build-up in cavity
  - cavity also on regeneration part with 40000-fold power build-up (2014)
  - 10 + 10 HERA dipoles (2017)
- Similar plans also at Fermilab (REAPR)
- Next-to-next generation: sensitivity improvement by another order of magnitude in coupling



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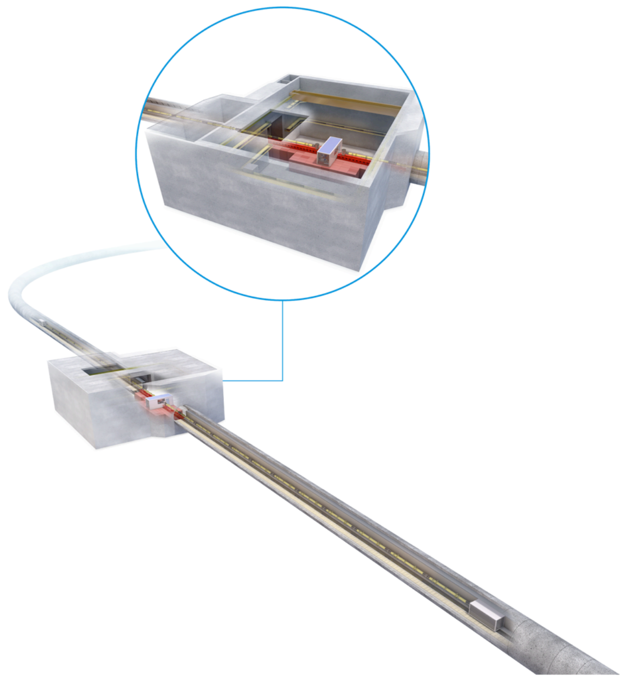
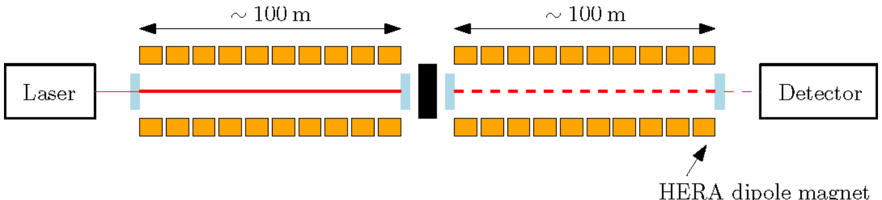
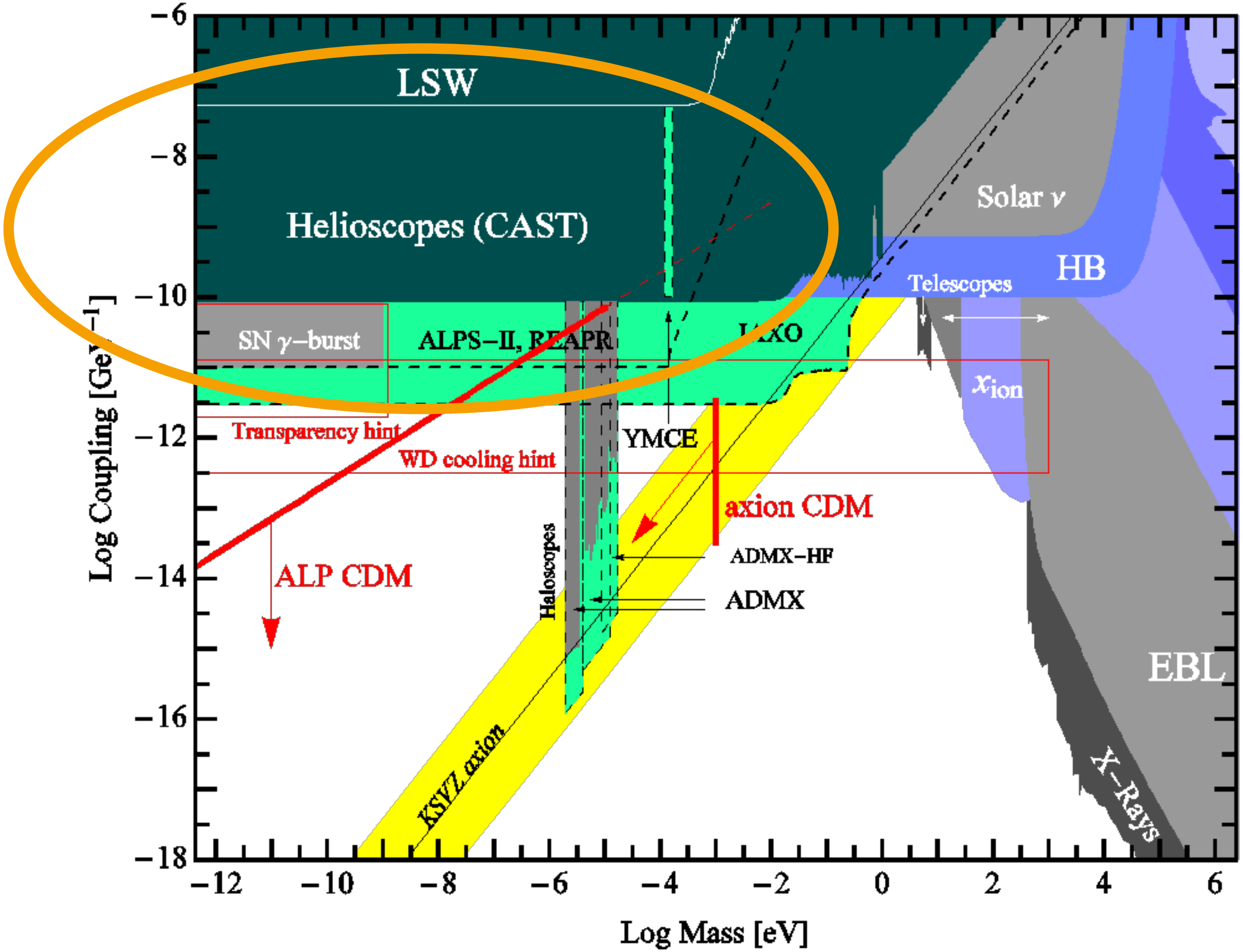
- Similar plans also at Fermilab (REAPR)
- Next-to-next generation: sensitivity improvement by another order of magnitude in coupling





Direct production and detection of ALPs: LSW



Summary

- Strong physics case for axion and ALPs:
  - Solution of strong CP problem gives particularly strong motivation for existence of axion
  - In many UV completions of SM, in particular in completions arising from string theory, there are many axion-like particle candidates
  - Axion and ALPs can be the observed cold dark matter
  - ALPs can explain the anomalous transparency of the universe for VHE gamma rays
- Important regions in axion and ALPs parameter space can be tackled in the upcoming decade by a number of experiments:
  - Haloscopes
  - Helioscopes
  - Light-shining-through-a-wall experiments
- Stay tuned!