Ultralight Particle Dark Matter.

Andreas Ringwald (DESY)

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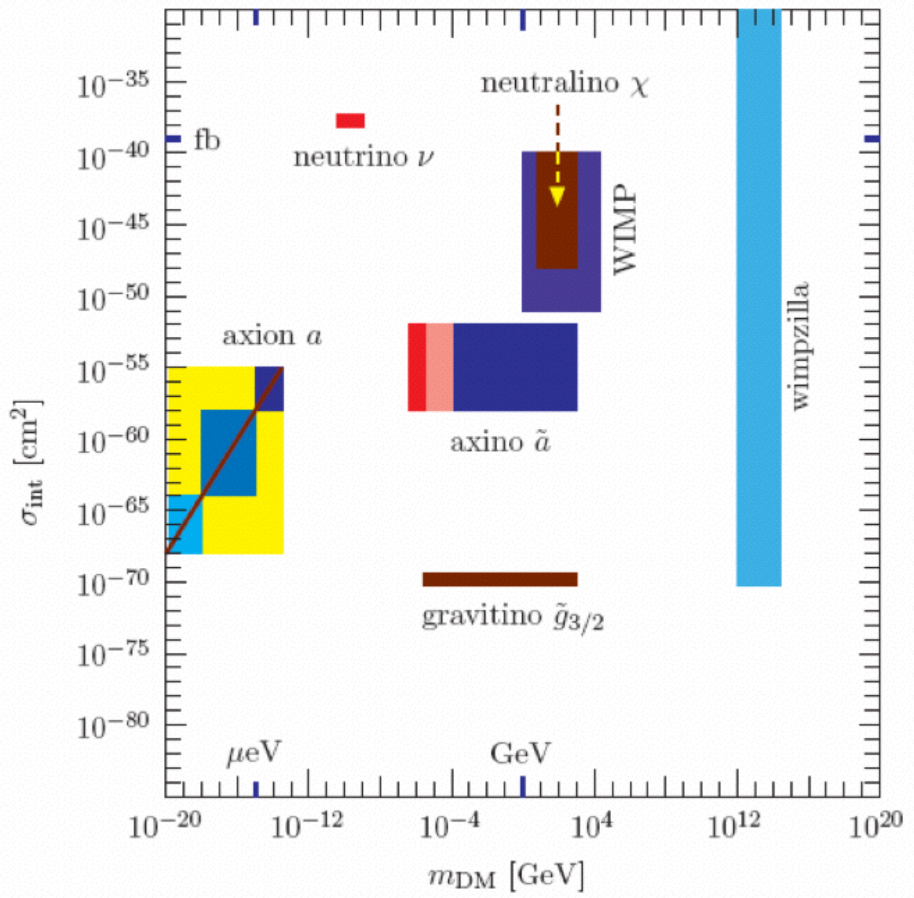
HELMHOLTZ ASSOCIATION

DESY

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:

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

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

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

- Theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ violates P and T, and thus CP
- 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:

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

Physics case for axions: Strong CP problem

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

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

  has localised minimum at vanishing theta parameter:

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

- Introduce field A(x) as dynamical theta parameter, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry, i.e. a shift symmetry, $A(x) \to A(x) + {\rm const.}$ broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \left(\bar{\theta} + \frac{A}{f_A} \right) G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

  - Can eliminate theta by shift $A(x) \to A(x) - \bar{\theta} f_A$; QCD dynamics (see above) leads then to vanishing vev, $< A >= 0$, i.e. P, T, and CP conserved
  - Particle excitation of A: Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Strength of its interactions with SM controlled by PQ scale f_A

Physics case for axions: Strong CP problem

- Because of mixing with the neutral pion, described by the chiral QCD Lagrangian, the axion is a pseudo Nambu-Goldstone boson, with see-saw relation between chiral symmetry breaking scale and PQ scale f_A,

$$m_A \sim \frac{m_\pi f_\pi}{f_A} \sim \mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)$$

  It has a universal coupling to photons

$$\mathcal{L} \supset -\frac{g_{A\gamma}}{4}\, A\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

  of size $g_{A\gamma} \sim \frac{\alpha}{2\pi f_A} \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)$

- For large PQ scale: axion prime paradigm of a WISP [Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81]

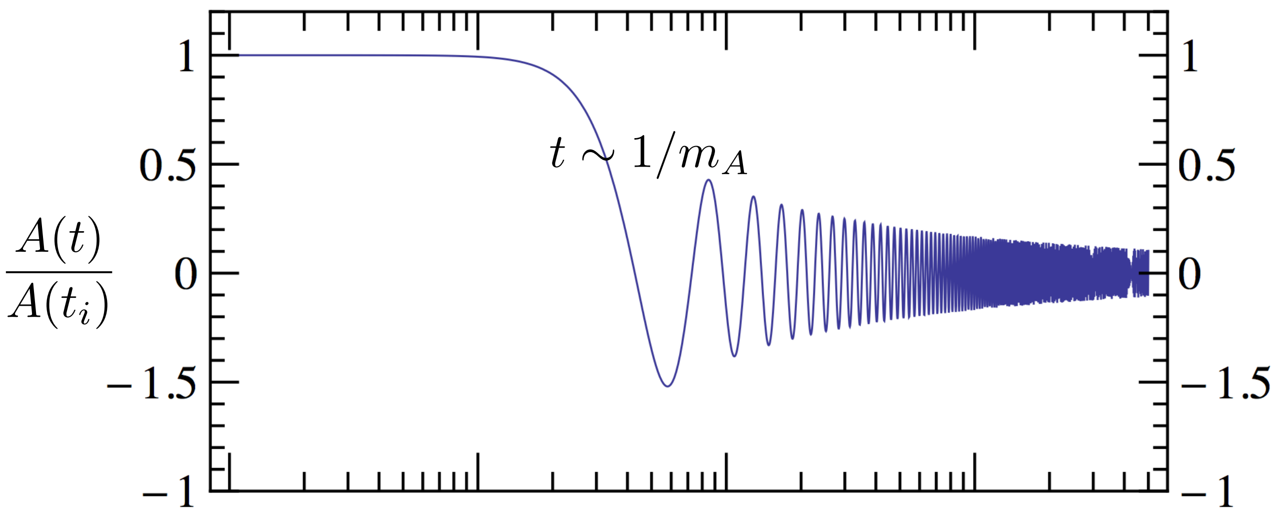
- Constraints from astrophysics (e.g. duration of ν signal of SN1987A) :

$$f_A \gtrsim 4 \times 10^8\,\mathrm{GeV} \Rightarrow m_A \lesssim 16\,\mathrm{meV}$$

Physics case for axions and ALPs: Cold dark matter

- For $f_A \gtrsim 10^9\,\mathrm{GeV}$, axions produced pre-dominantly non-thermally in the early universe by vacuum-realignment and, in some cases and under certain circumstances, also via decay of topological defects

- Vacuum-realignment: [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83]
  - Homogeneous mode of axion field frozen at random initial value, $A(t_i) = \theta_i\, f_A$, because of cosmic expansion, as long as $t \lesssim 1/m_A$. Later, at $t > 1/m_A$, axion field oscillates around zero.
  - Classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter, i.e. cold dark matter



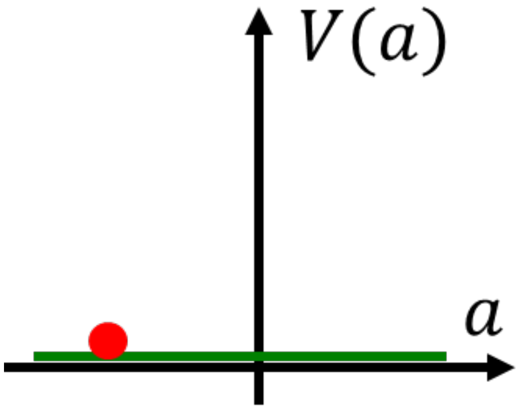
Physics case for axions and ALPs: Cold dark matter

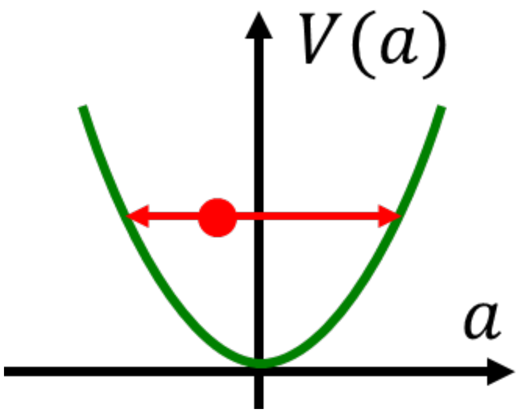
- If reheating temperature after inflation below f_A and no dilution by late decays of particles beyond SM,

$$\Omega_A h^2 \approx 0.71 \left(\frac{f_A}{10^{12}\ \mathrm{GeV}} \right)^{7/6} \left(\frac{\theta_i}{\pi} \right)^2$$

- If reheating temperature after inflation is above f_A, initial misalignment angles take on different values in different patches of universe,

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





[Raffelt]

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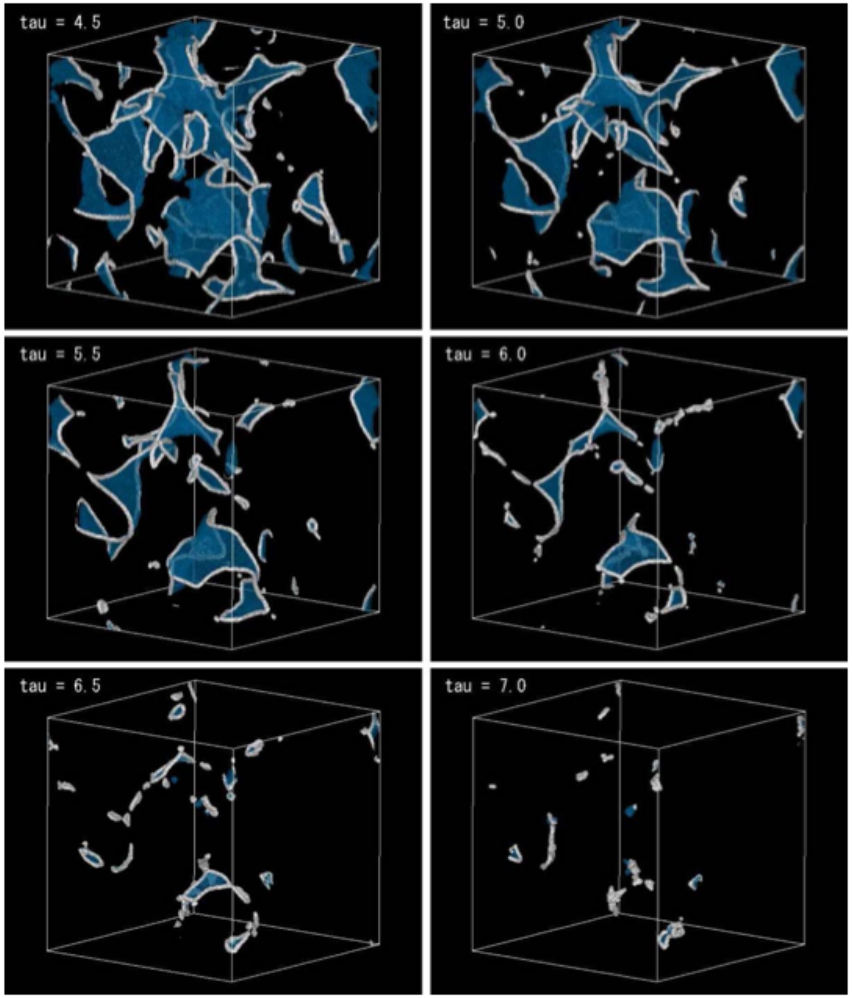
Decay of cosmic strings and domain walls may provide for additional sources for axion CDM



[Hiramatsu et al. 12]

Physics case for axions and ALPs: Cold dark matter

- Other bosonic WISPs, such as axion-like particles (ALPs) (pseudo NG bosons from further $U(1)_{\mathrm{PQ}_i}$s) would also be produced via the vacuum-realignment mechanism,

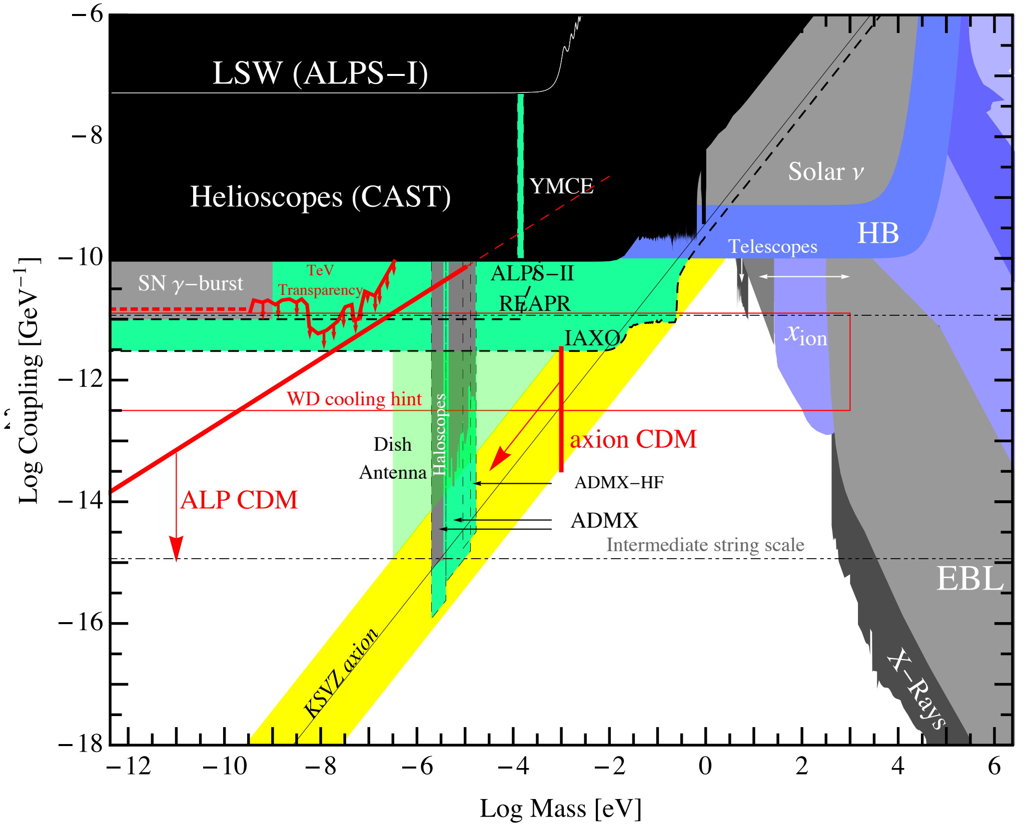
$$\Omega_a h^2 \approx 0.16 \left(\frac{m_a}{\mathrm{eV}}\right)^{1/2} \left(\frac{f_a}{10^{11}\ \mathrm{GeV}}\right)^2 \left(\frac{\theta_i}{\pi}\right)^2$$

- Natural range for axion/ALP CDM: cosmic axion window,

$$10^9\ \mathrm{GeV} \lesssim f_A, f_a \lesssim 10^{12}\ \mathrm{GeV}$$

- Large search space for axion and ALP CDM in photon coupling $g_{i\gamma} \sim \alpha/(2\pi f_i)$ vs. mass

[Arias et al. 12]



adapted from [Hewett et al. 1205.2671]

Physics case for axions and ALPs: NGBs of SSB

- In 4D field theoretic extensions of the Standard Model (SM), axion and ALP fields realised as phases of complex SM singlet scalar fields whose vevs break global anomalous chiral $U(1)_{\mathrm{PQ}_i}$ symmetries,

$$\Phi_i(x) = \frac{v_{\mathrm{PQ}_i} + \rho_i(x)}{\sqrt{2}} \mathrm{e}^{i a_i(x)/f_{a_i}}$$

  - At energies much below the symmetry breaking scales v_{PQ_i} the low-energy effective field theory is that of (pseudo-)Nambu-Goldstone bosons (NGB) with decay constants

$$f_{a_i} = v_{\mathrm{PQ}_i}$$

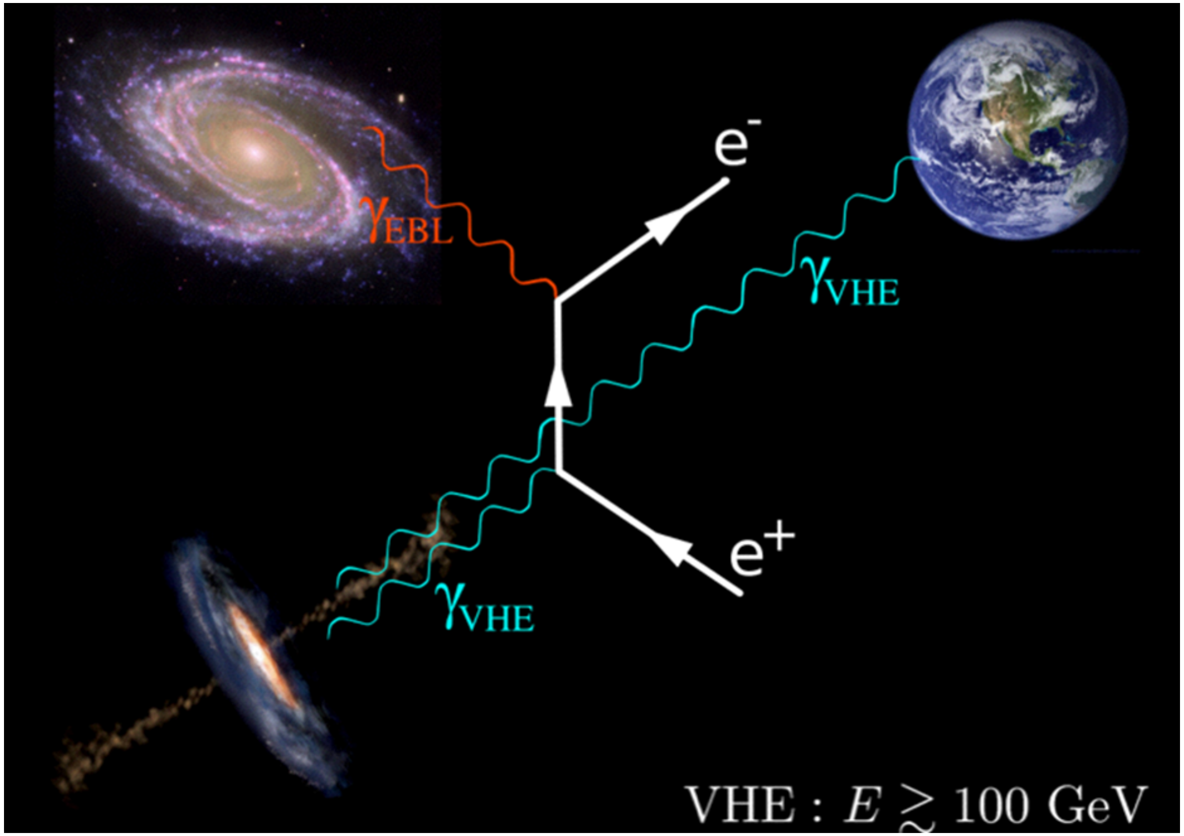
- Decay constants naturally in cosmic axion window

$$10^9\ \mathrm{GeV} \lesssim f_{a_i} \lesssim 10^{12}\ \mathrm{GeV}$$

  - in models where PQ symmetry breaking scales are tied to the scale of lepton number violation, featuring intermediate scale Majorana neutrinos to explain the masses of SM neutrinos via seesaw mechanism [Mohapatra,Senjanovic 83; Shafi,Stecker 84; Langacker,Peccei,Yanagida 86;...;Dias,Pleitez 05;...;Altarelli,Meloni 13]; axion plus ALPs plus heavy Majorana neutrinos occur automatically in big classes of heterotic string orbifold compactifications [Buchmüller et al. 07; Choi et al. 09]
  - in Large Volume IIB string scenarios; in these the axion plus ALPs are occuring automatically [Conlon 06; Cicoli,Goodsell,AR 12]

Physics case for ALPs: VHE transparency of universe

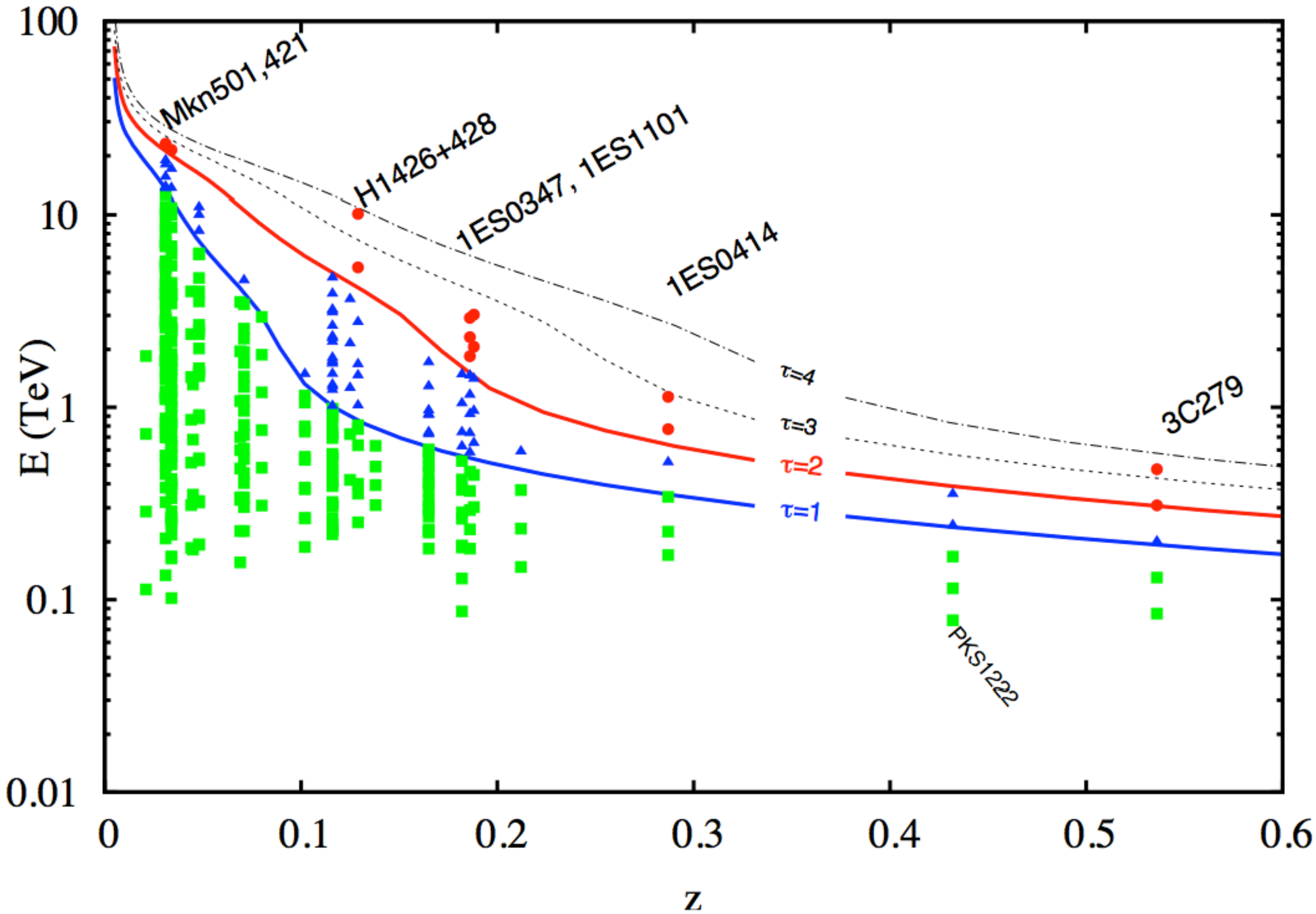
- VHE photon spectra from distant Active Galactic Nuclei (AGN) should show absorption features due pair production at Extragalactic Background Light (EBL)



[Manuel Meyer 12]

Physics case for ALPs: VHE transparency of universe

- In conflict with observations? [Aharonian et al. 07; Albert et al. 08; Mirizzi et al. 07;...]



[Horns,Meyer 12]

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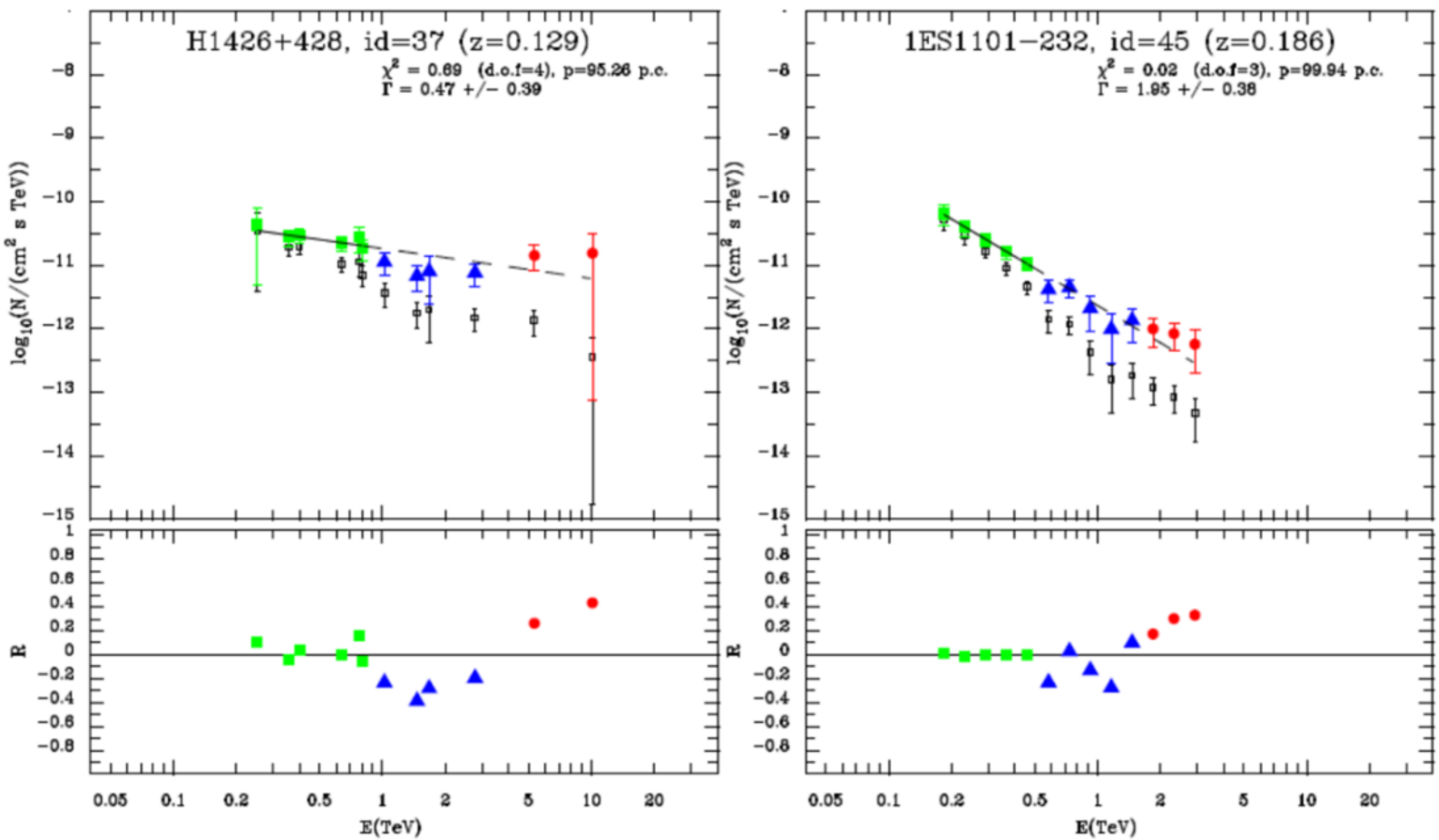
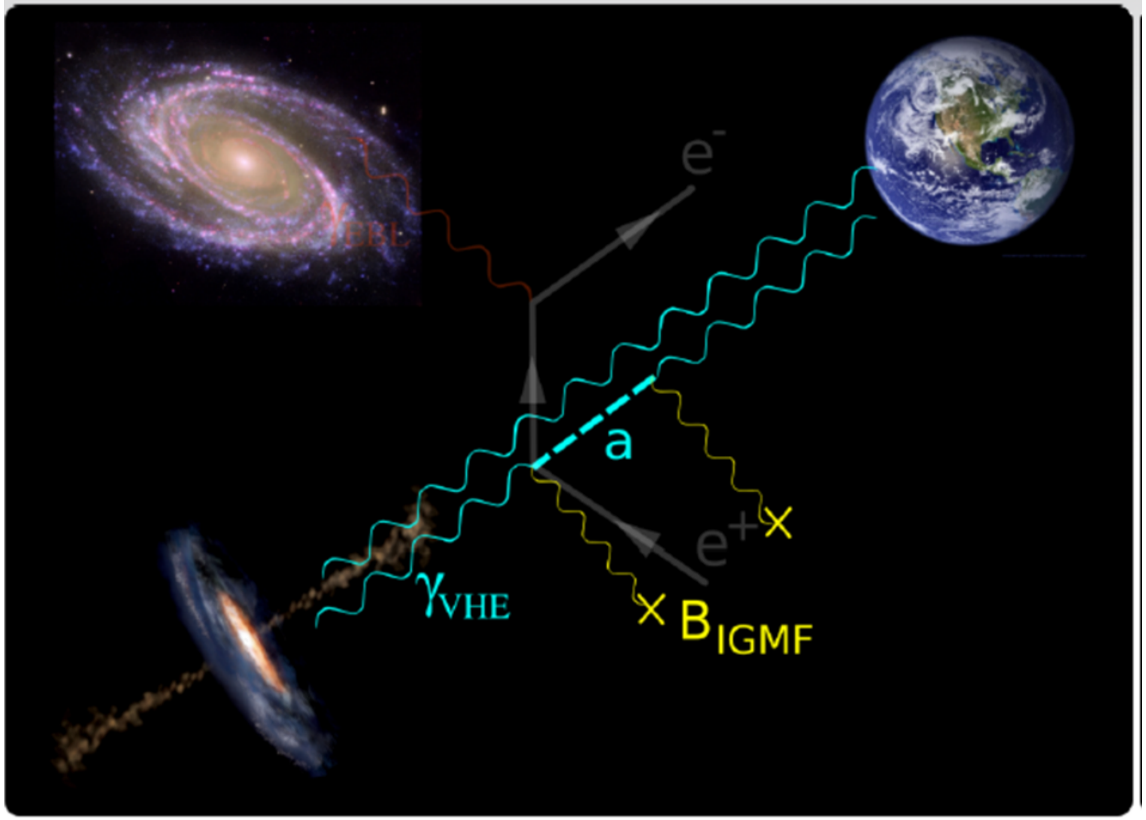


[Horns,Meyer 12]

Physics case for ALPs: VHE transparency of universe

- Possible explanation in terms of photon <-> ALP conversions in astro-physical magnetic fields with $g_{a\gamma} \gtrsim 10^{-12}\ \mathrm{GeV}^{-1};\ m_a \lesssim 10^{-7}\ \mathrm{eV}$

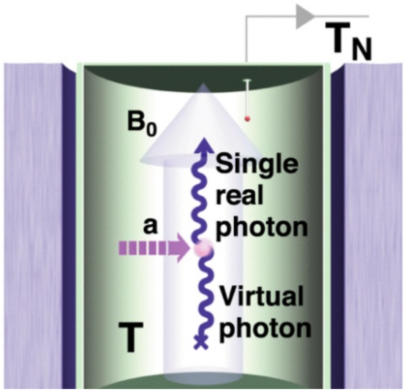
[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Horns,Meyer,Raue 13]



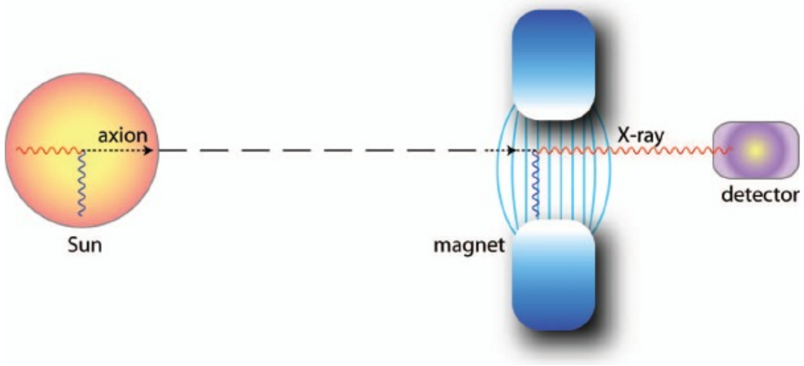
[Manuel Meyer 12]

Experimental probes of axions and ALPs

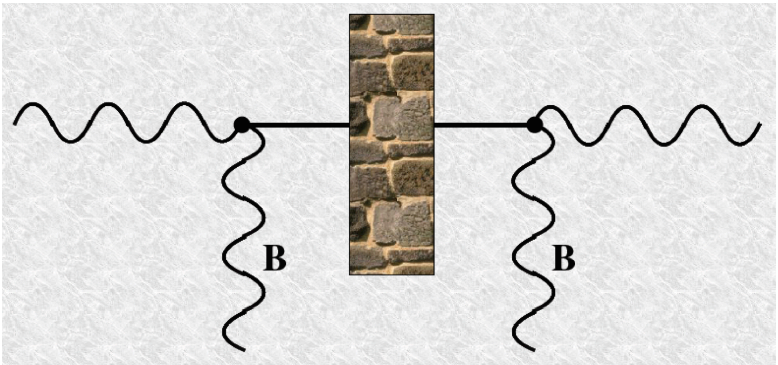
- Direct detection of dark matter axions or axion-like particles (ALPs) (haloscopes)



- Detection of solar axions and ALPs (helioscopes)



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

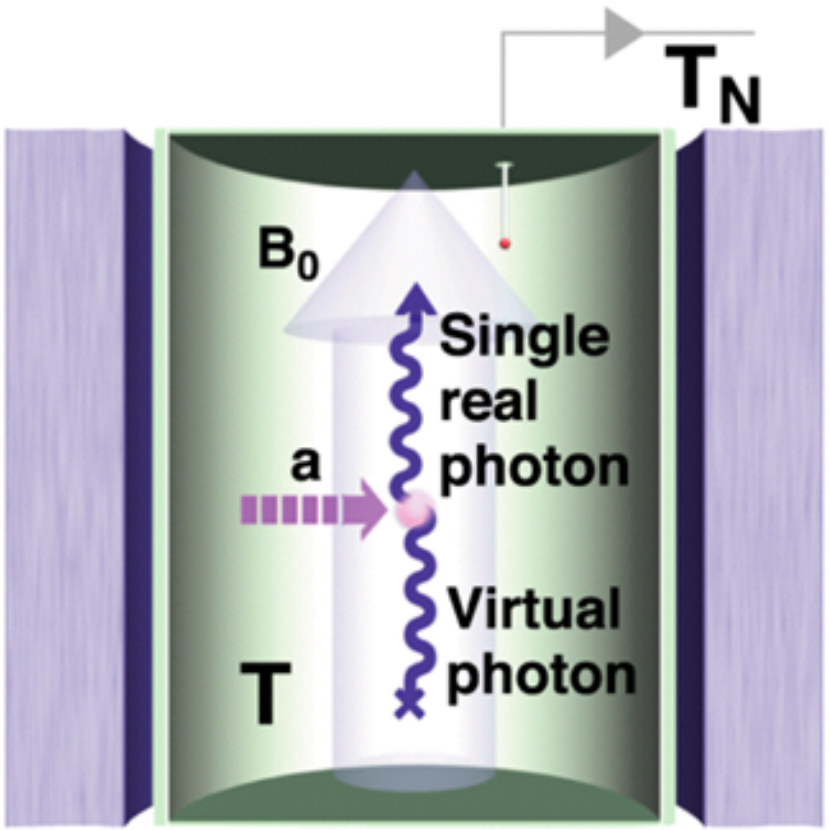


Direct detection of axion or ALP dark matter: Cavities

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

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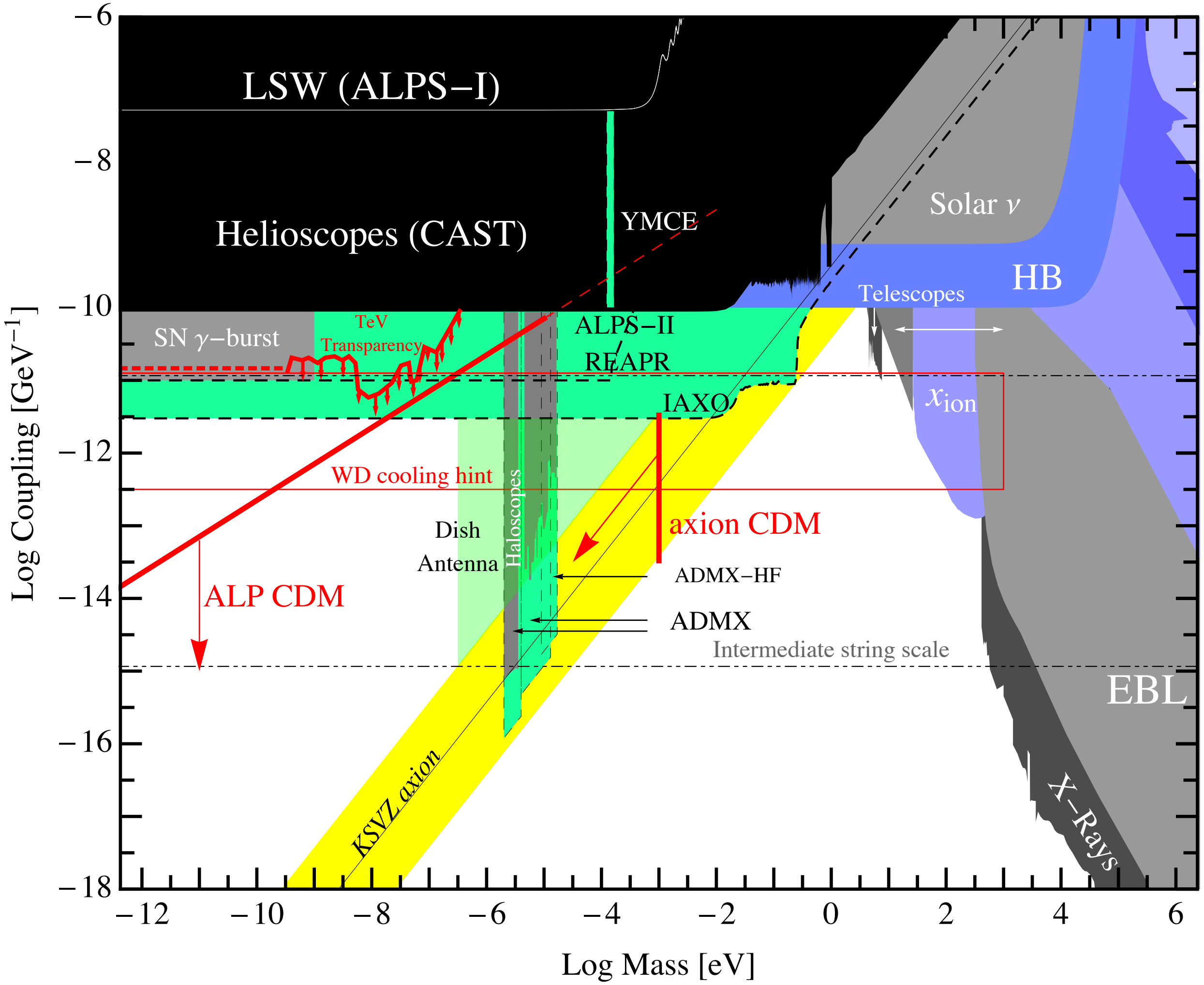
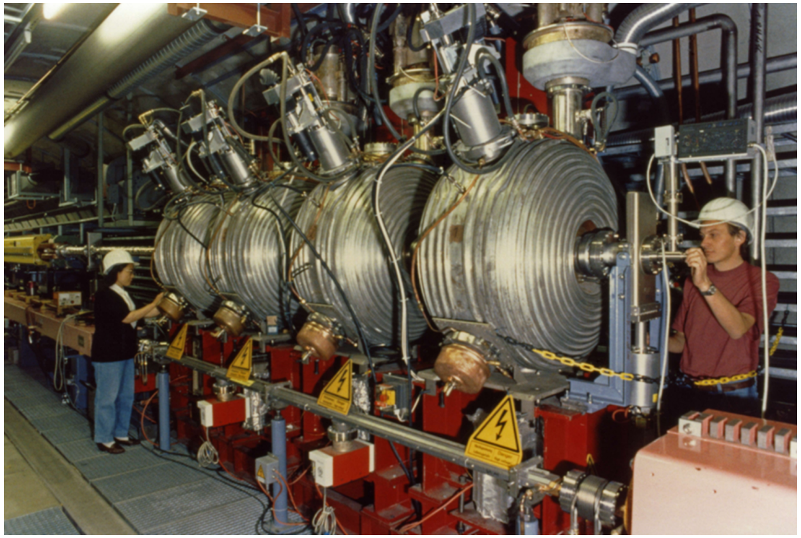
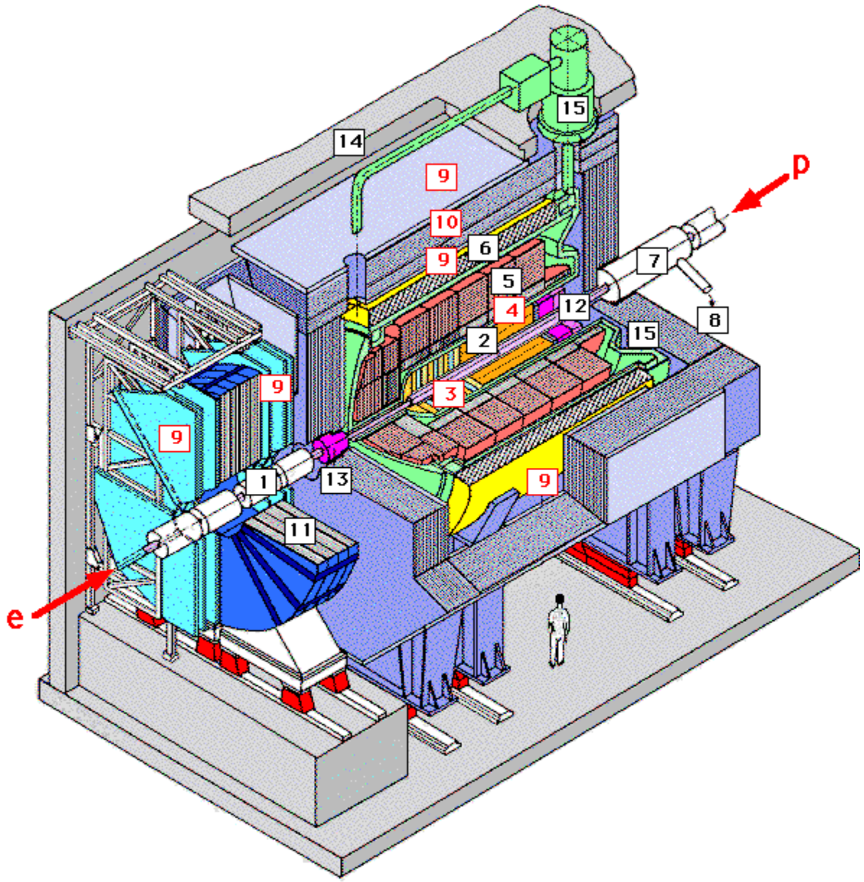


adapted from [Hewett et al 12]

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, …

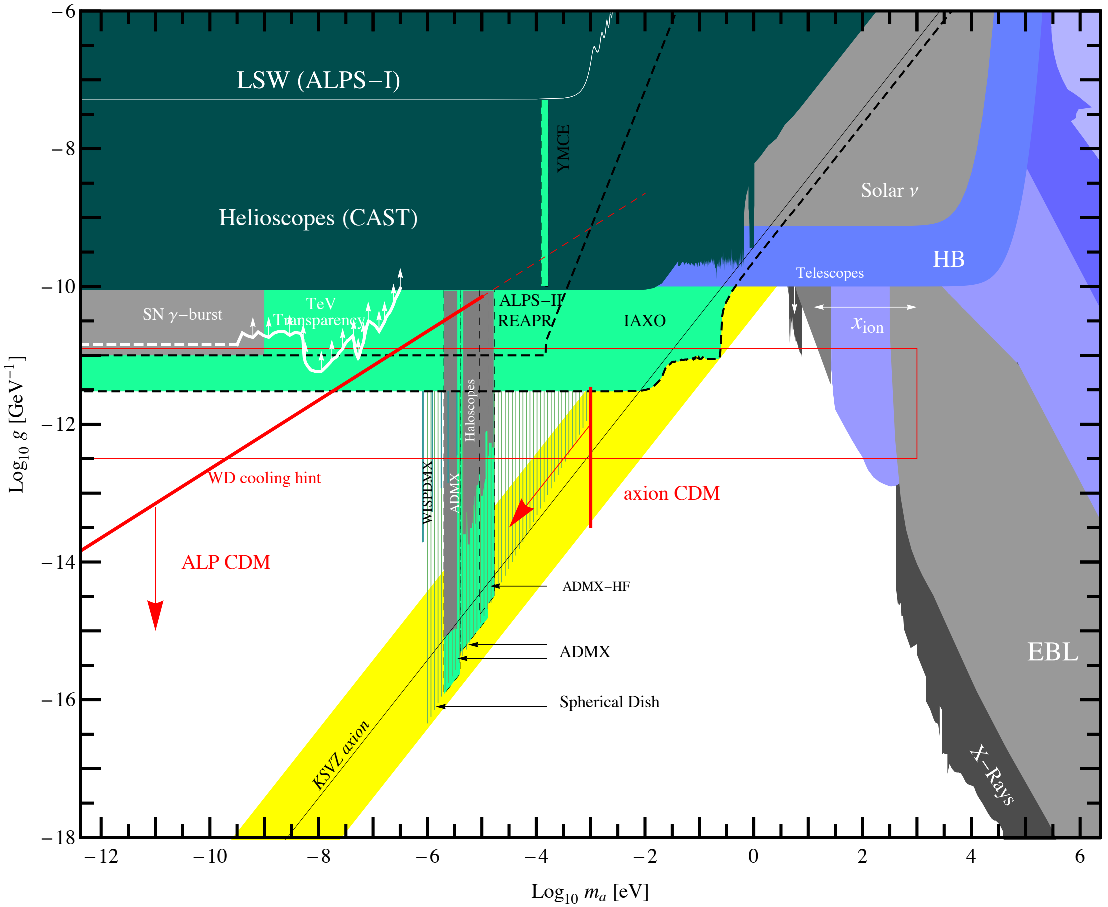




- Operational: pilot study for WISPDMX

Direct detection of axion or ALP dark matter: Cavities

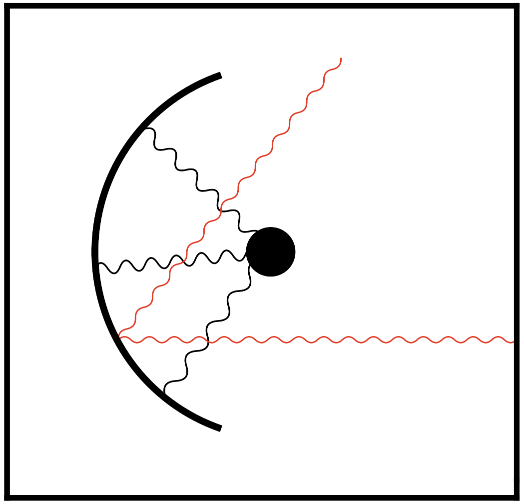
> WISPDMX may probe mass region below ADMX:
[Horns et al. (DESY,MPIfR,UHH]

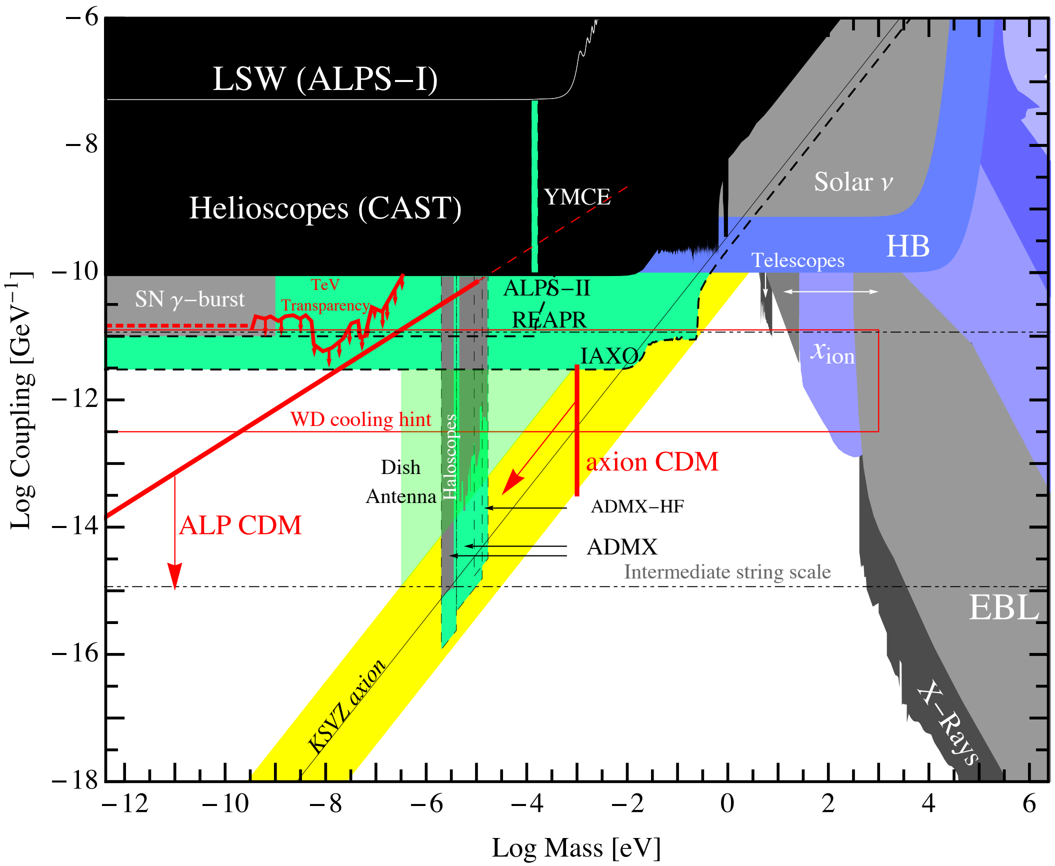


adapted from [Hewett et al 12]

Direct detection of axion or ALP DM: Dish Antenna

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





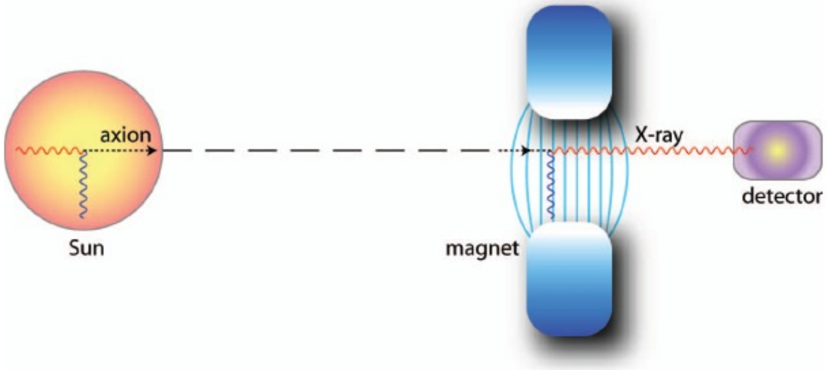
adapted from [Hewett et al 12]

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

[Horns et al. 12]

Detection of solar axions and ALPs: Helioscopes

- Sun strong source of axions and ALPs
- Helioscope searches for axions and ALPs [Sikivie 83]



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

  - Ongoing: CAST … CERN Axion Solar Telescope

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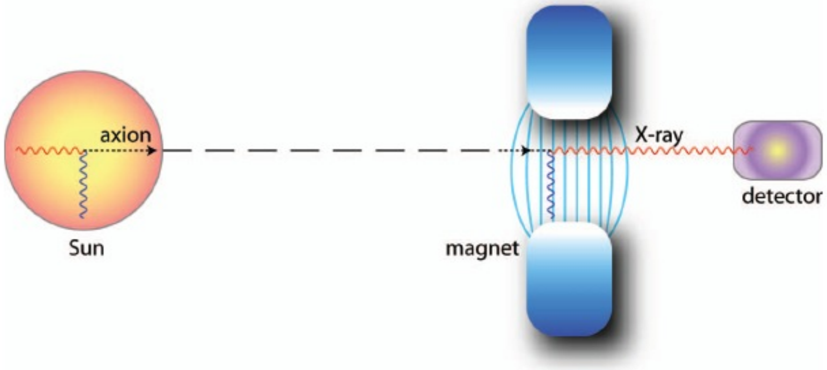
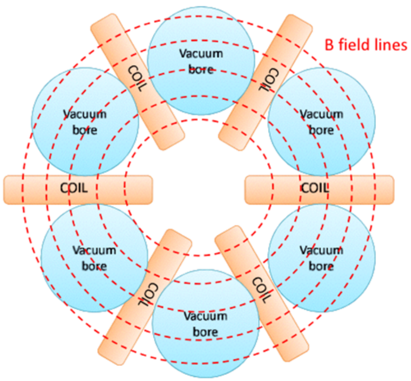
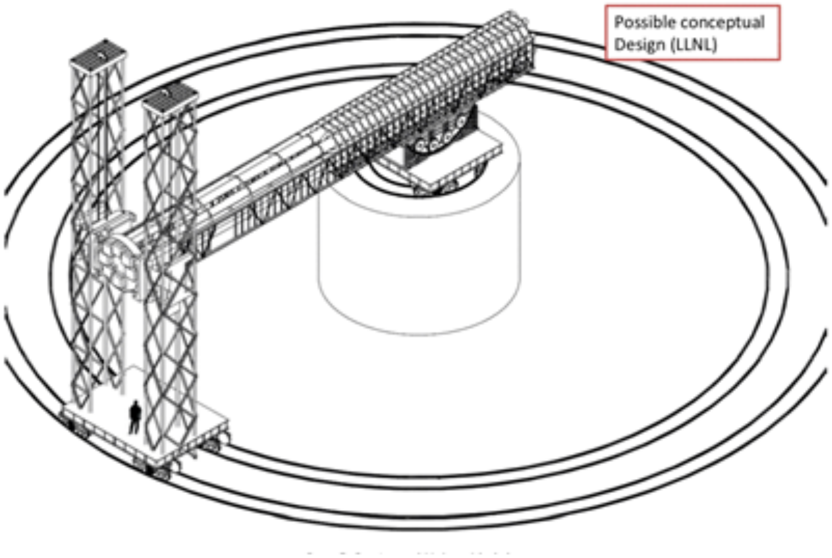
  - LoI currently written: IAXO (International Axion Observatory)







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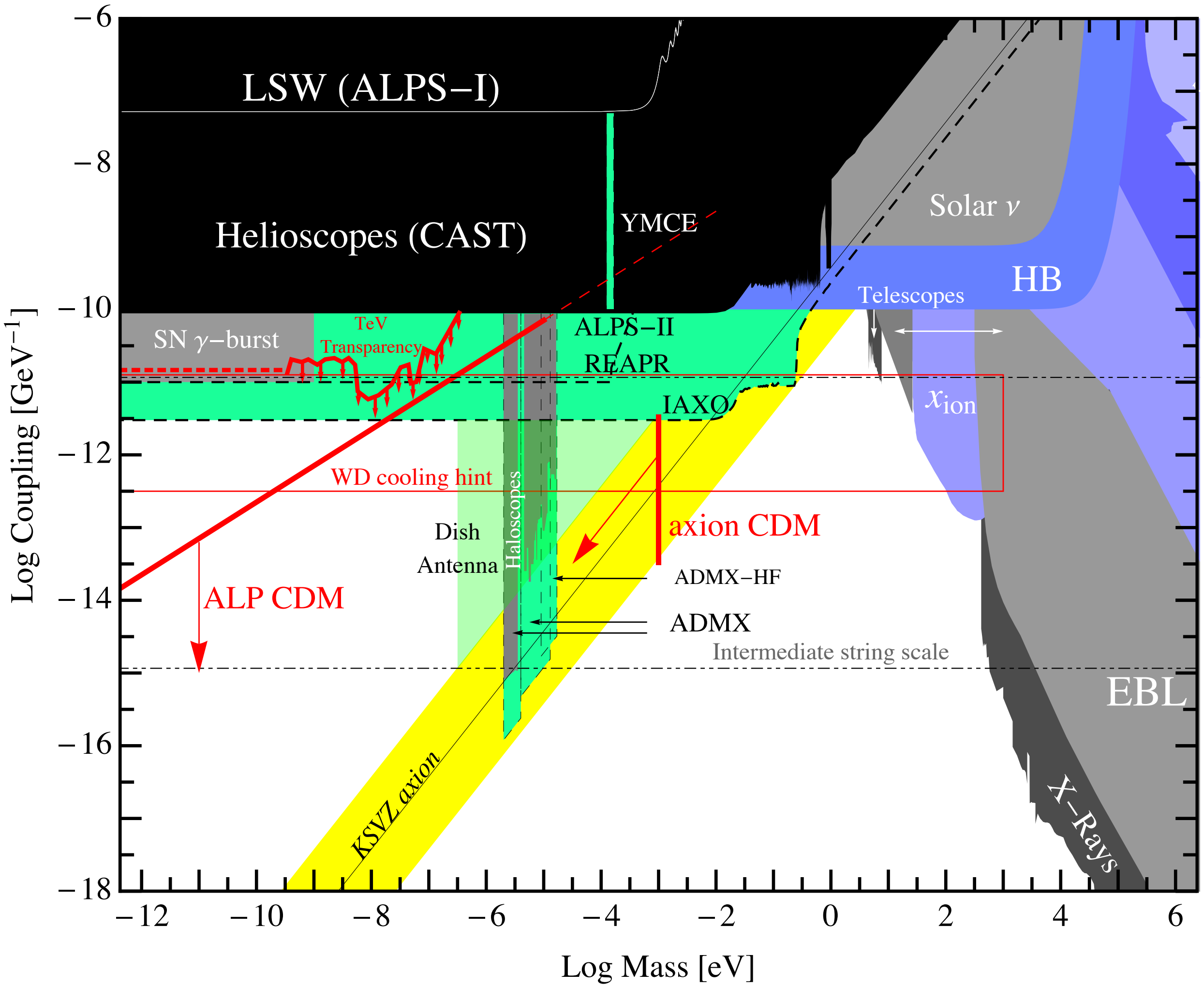
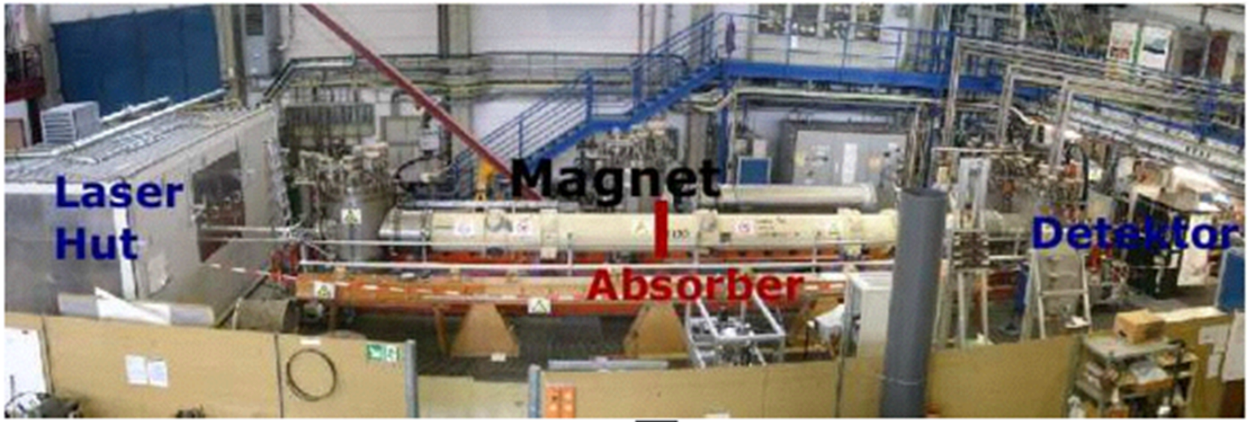
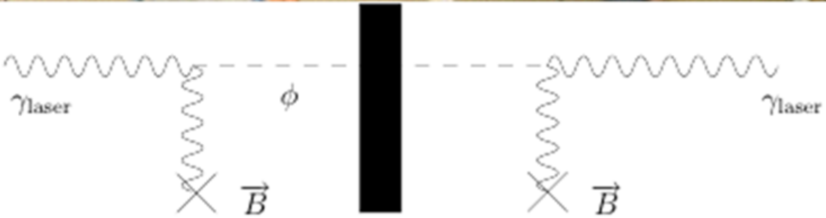


adapted from [Hewett et al 12]

Direct production and detection of ALPs: LSW

- ALPs can pass walls [Anselm 85; van Bibber et al. 87]
- Light-shining-through-walls experiments: (here ALPS-I (@DESY)):





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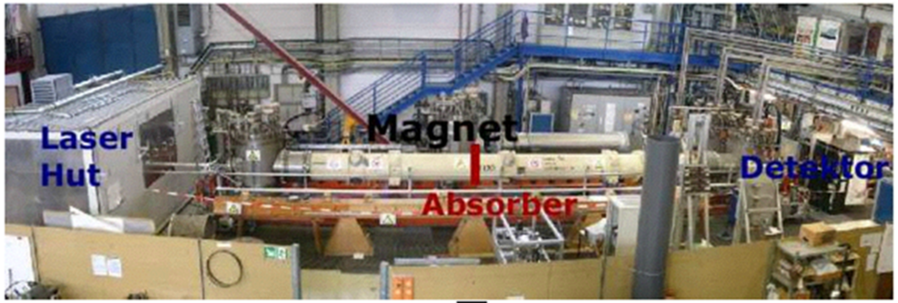
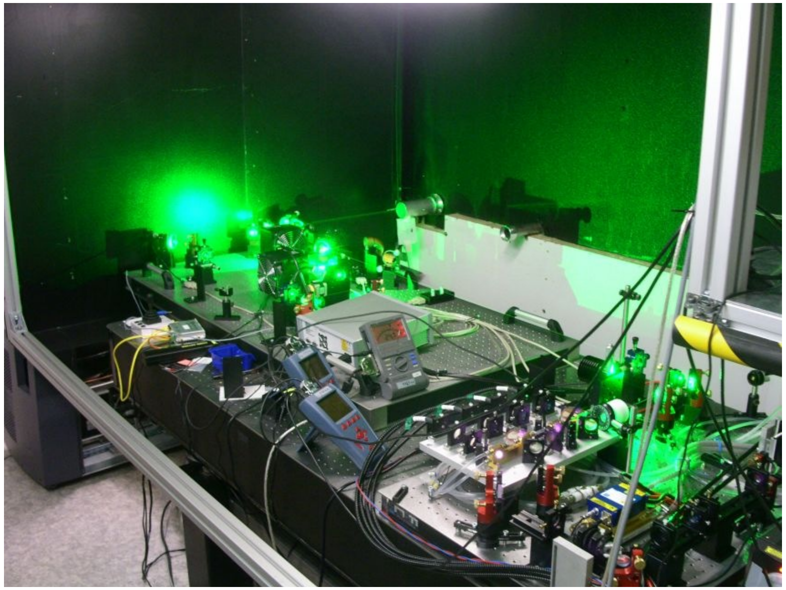
Direct production and detection of ALPs: LSW

- ALPS-I: [AEI,DESY,UHH]
  - HERA dipole (8.4 m, 5 T)
  - Primary laser: enhanced LIGO laser (1064 nm, 35 W)
  - Frequency doubled: 532 nm
  - 300-fold power build-up in cavity





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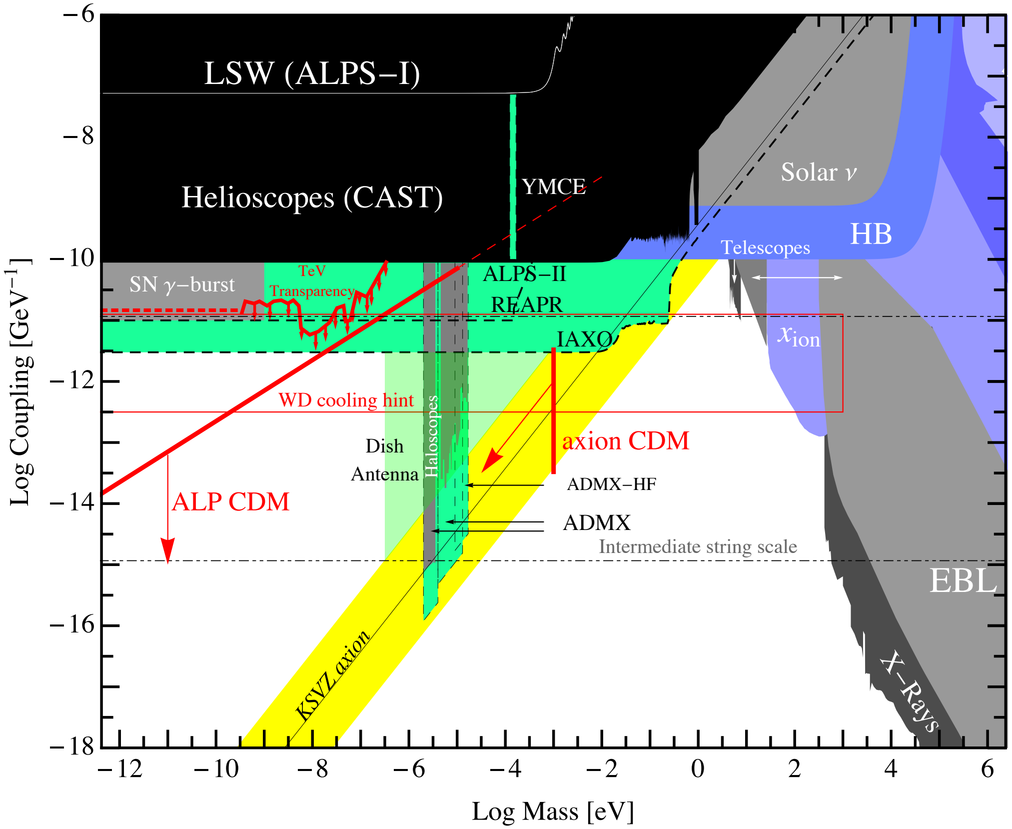

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- ALPS-II:
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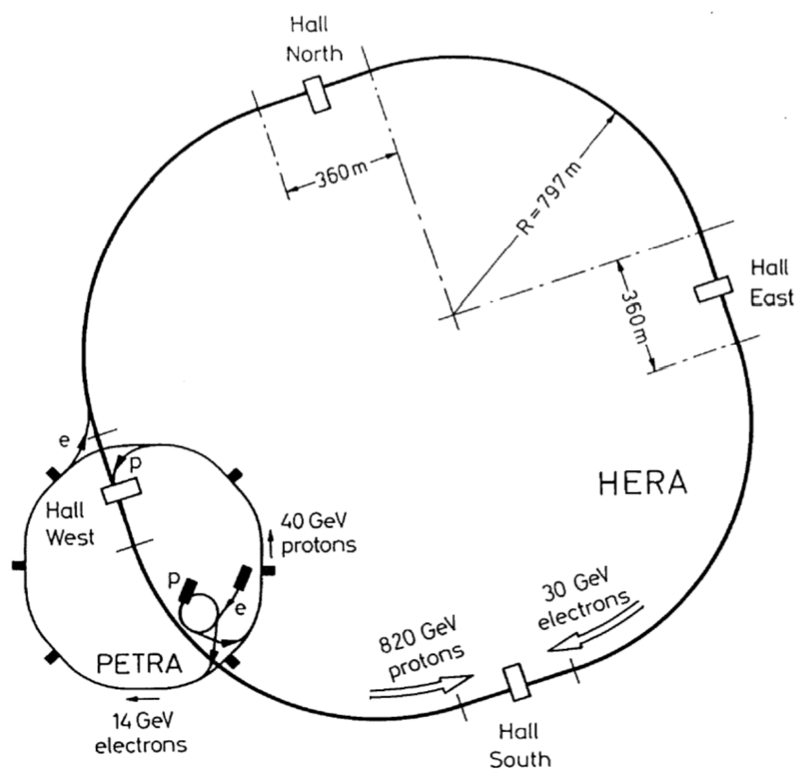
  - cavity also on regeneration part with 40000-fold power build-up (2014)
  - 10 + 10 HERA dipoles (2017)
  - Single photon detection with TES



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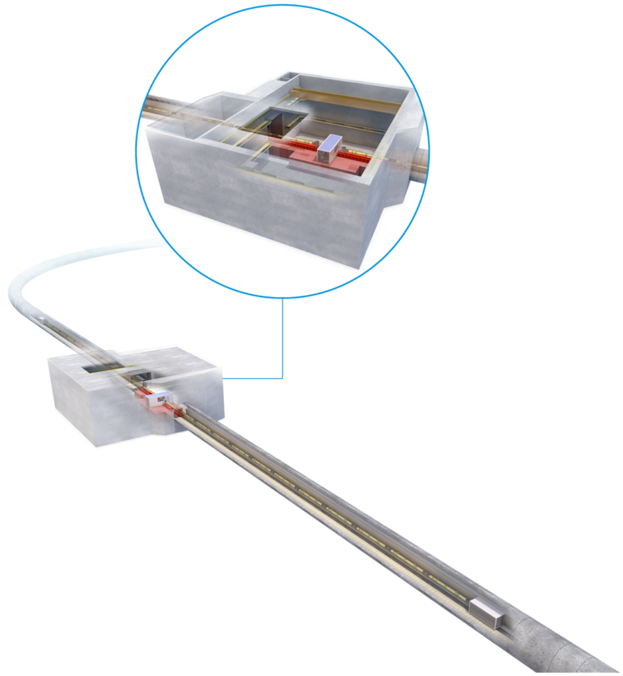
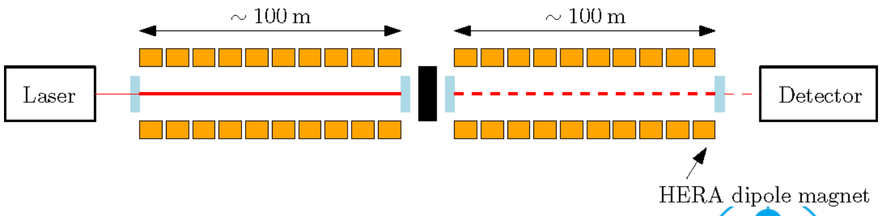
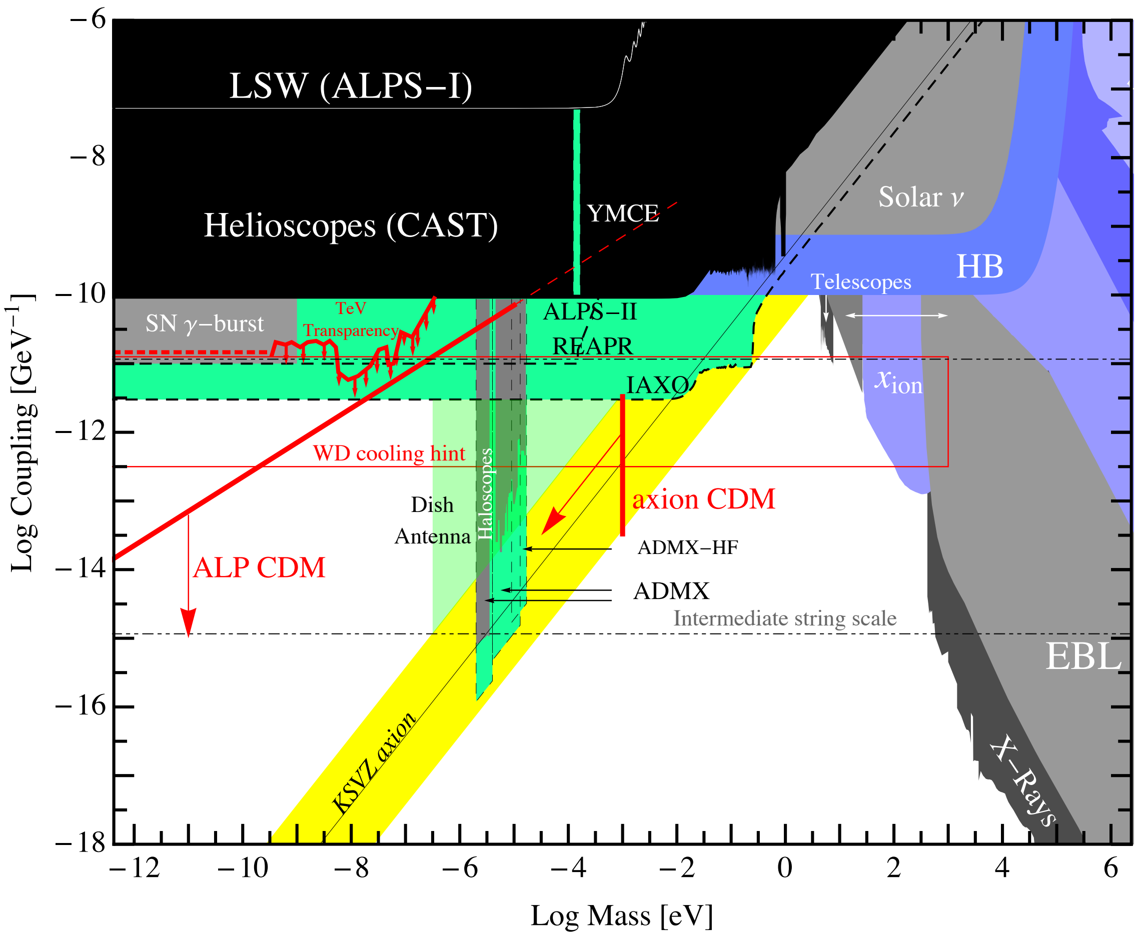




Direct production and detection of ALPs: LSW

- Sensitivity improves by more than 3 orders of magnitude compared to ALPS-I (another order of magnitude doable, but needs new efforts in laser and magnet technology)



adapted from [Hewett et al 12]

Summary

- Strong physics case for axion and ALPs:
  - Solution of strong CP problem gives particularly strong motivation for existence of axion
  - For intermediate scale decay constant, $10^9\,\mathrm{GeV} \lesssim f_A, f_a \lesssim 10^{12}\,\mathrm{GeV}$, axion and ALPs are natural cold dark matter candidates
  - In many theoretically appealing UV completions of SM, in particular in completions arising from strings, there occur intermediate scale axions and ALPs automatically
  - ALPs can explain the anomalous transparency of the universe for VHE gamma rays
- Intermediate scale region 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!