The Low-Energy Frontier

Searching for axions and other very light particles beyond the Standard Model

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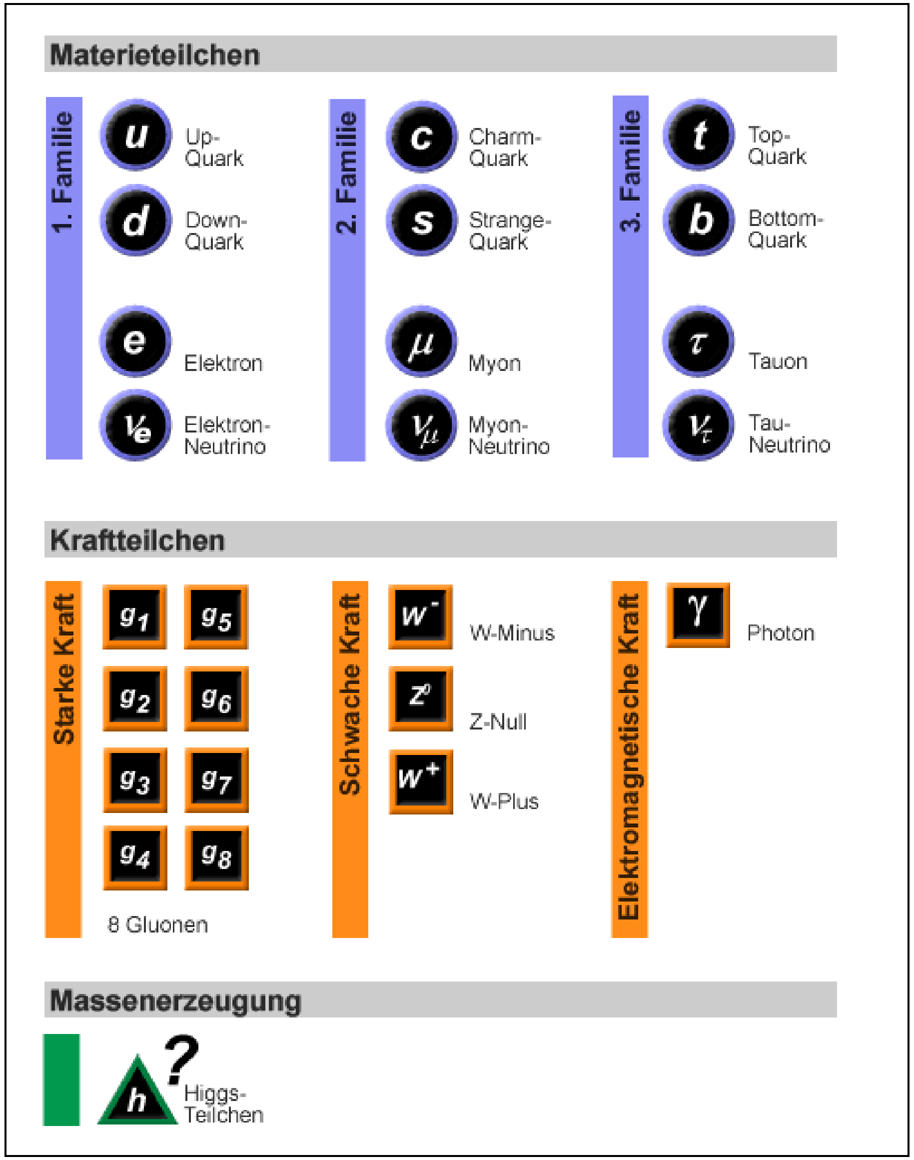
6 December 2007, Wuppertal, D

1. Introduction

- Most successful theory of all times: Standard Model



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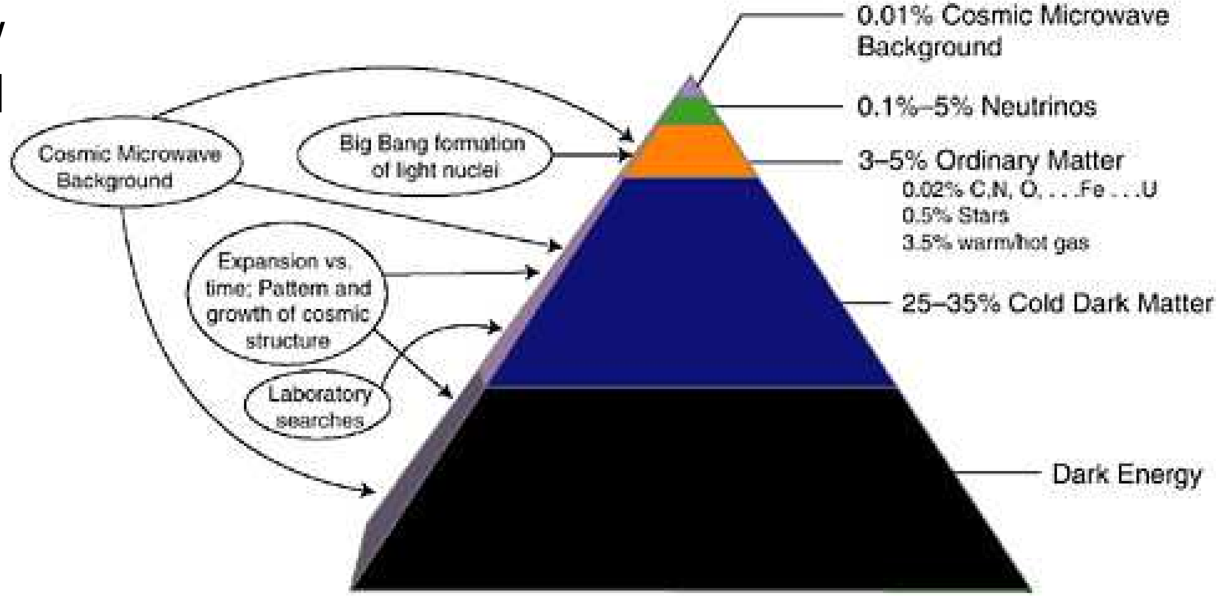
- Hints for existence of new particles beyond the Standard Model:
  – Dark universe



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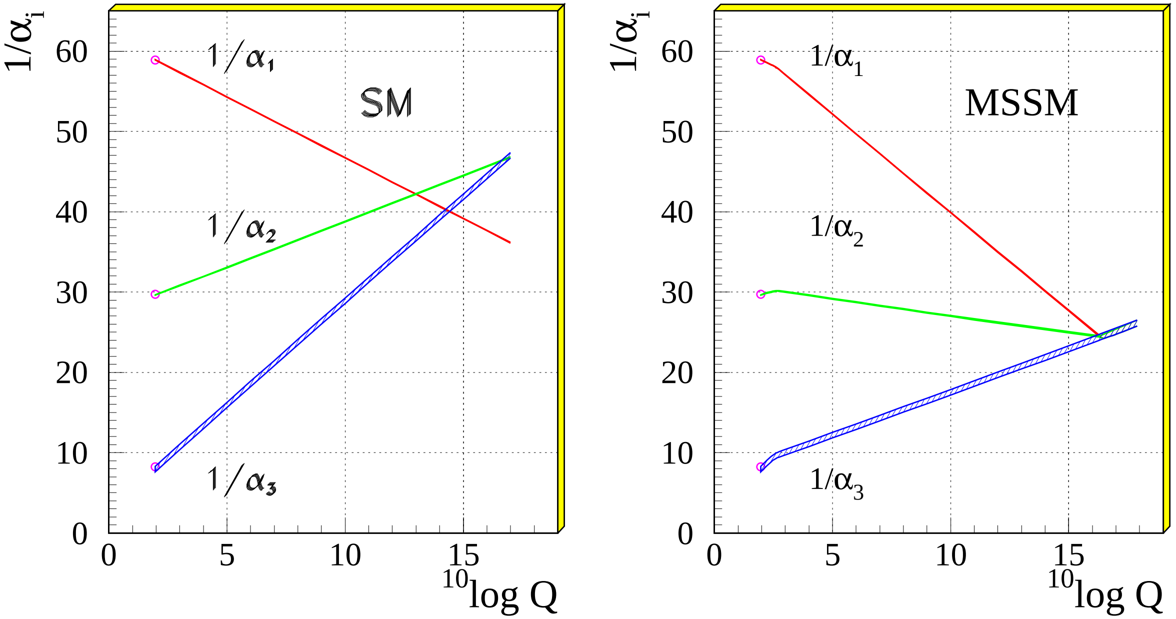
  - Unification of forces

Unification of the Coupling Constants in the SM and the minimal MSSM



[Amaldi, de Boer, Fürstenau '91]

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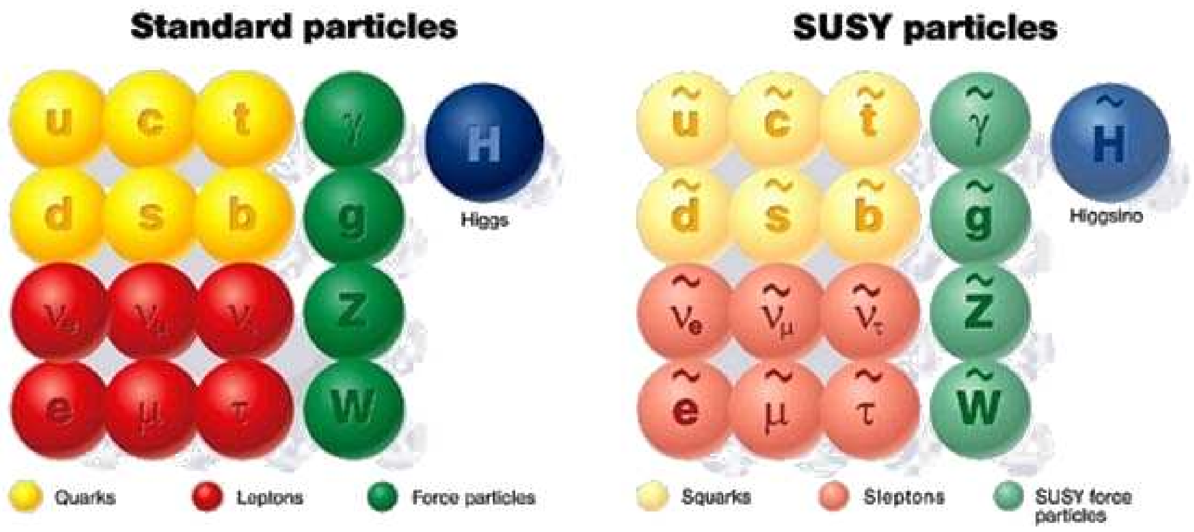

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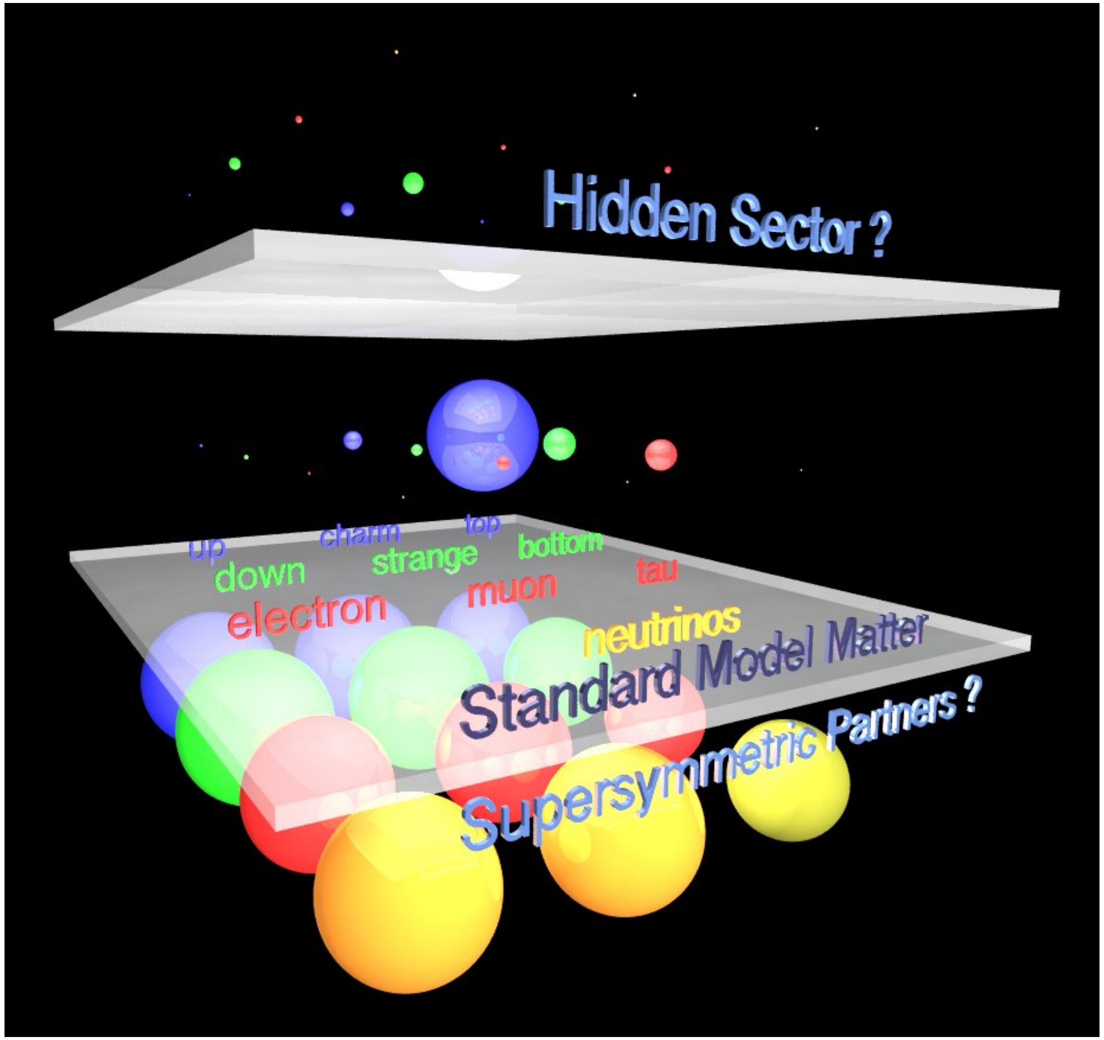
- Hints for existence of new particles beyond the Standard Model:
  - Dark universe
  - Unification of forces
  - Neutrino masses
  - Strong CP problem
- Some of these new particles may be WISPs (Weakly Interacting Sub-eV Particles) rather than WIMPS (Weakly Interacting Massive Particles)

⇒ Hidden sectors of nature?



[Ahlers (unpubl.)]

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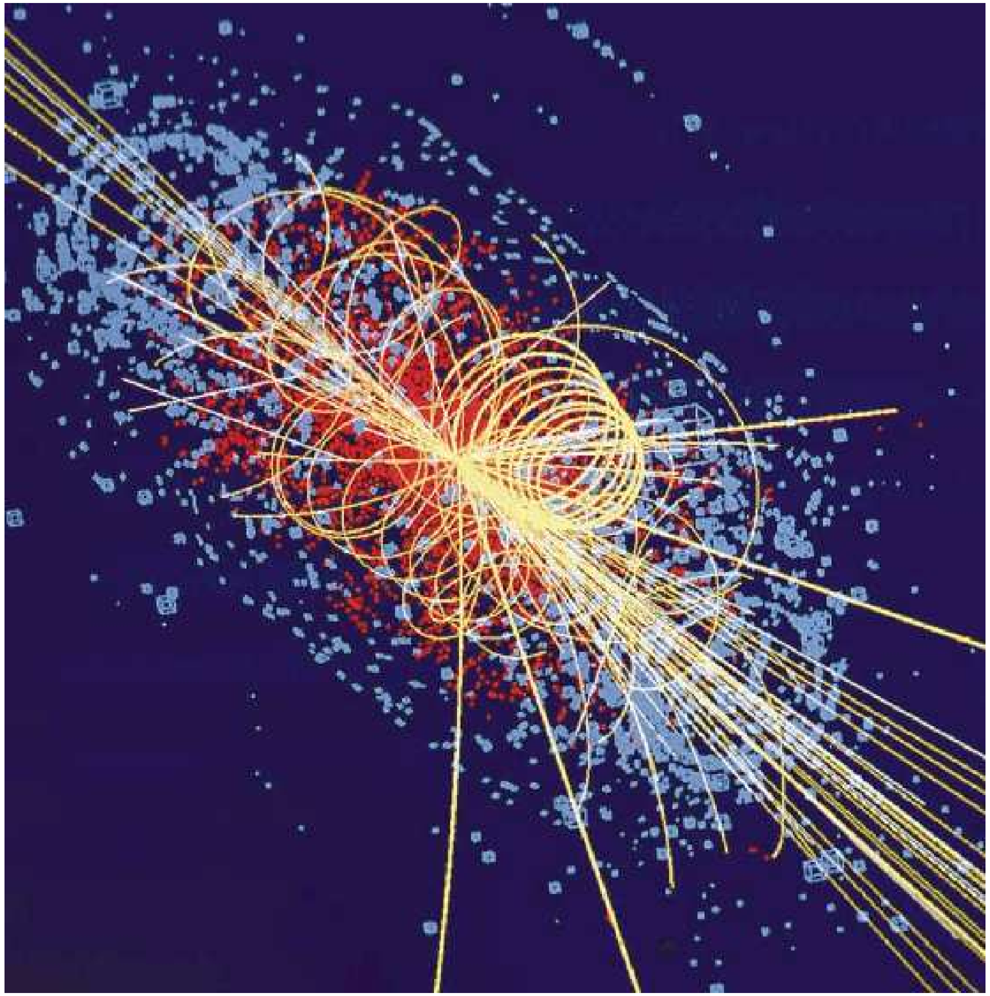
- Large Hadron Collider (LHC) will probe physics at the TeV scale at an unprecedented level
  - Origin of particle masses?



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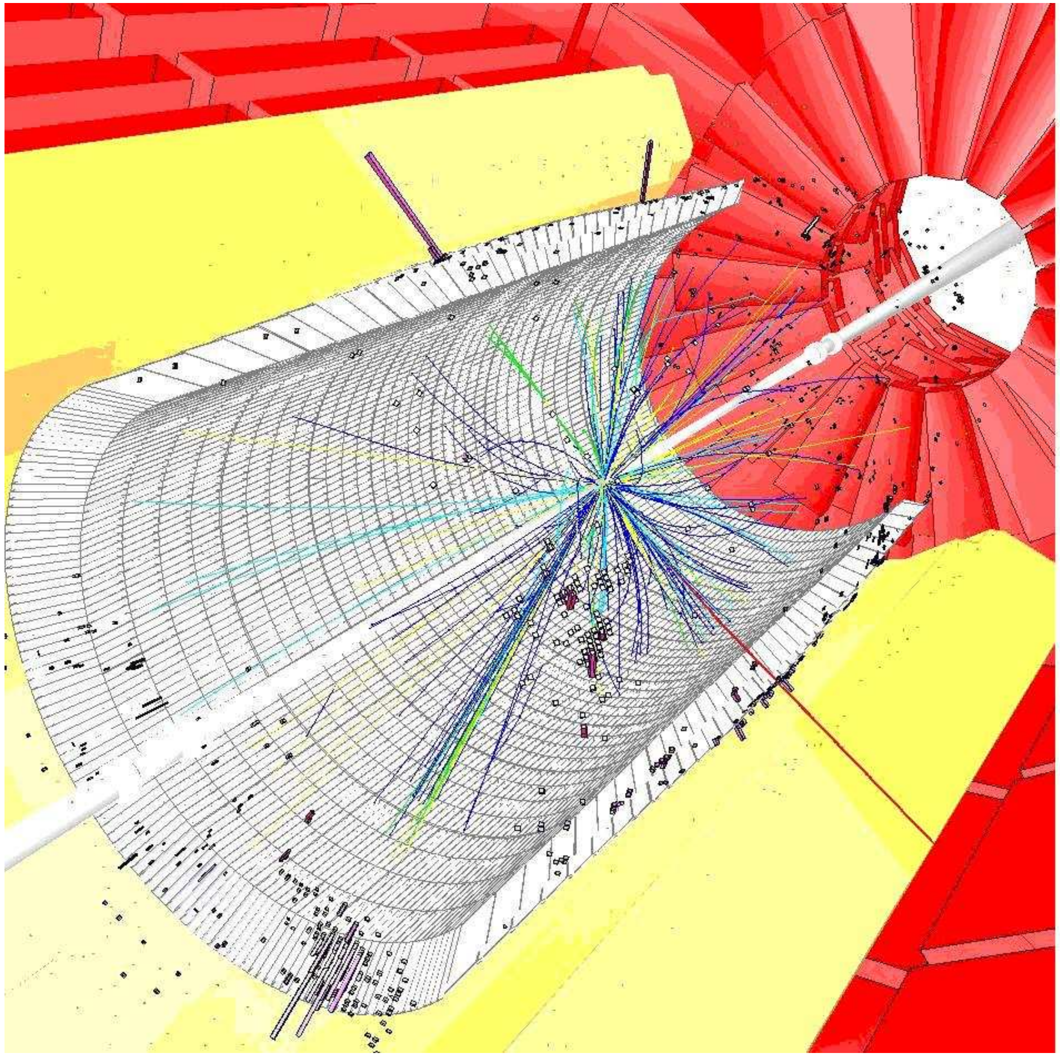

1. Introduction

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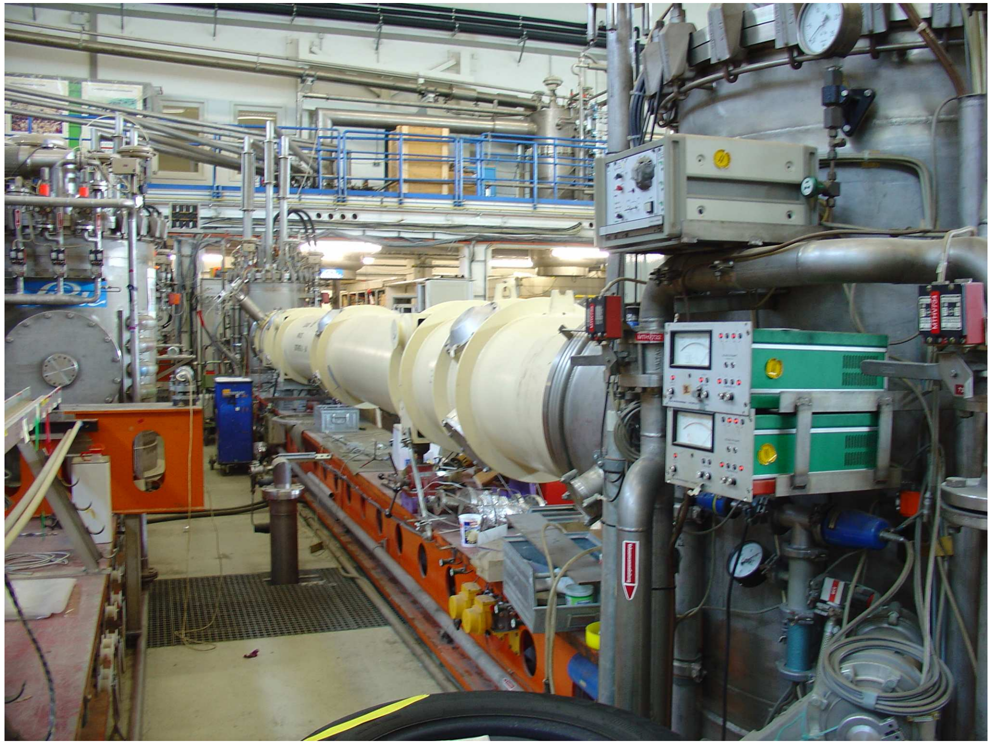
  - Origin of particle masses?
  - Nature of dark matter? Neutralinos as weakly interacting massive particles (WIMPs)?
- Experiments exploiting low-energy photons and/or large electromagnetic fields may yield complementary information on physics at the sub-eV scale
  - New very weakly interacting sub-eV particles (WISPs): axions, light hidden-sector particles, ...?



2. Motivation for/Constraints on Axions and Other WISPs

- Axion-Like Particles (ALPs):

  New light spin-zero particles, very weakly coupled to ordinary matter

  – Arise naturally as Goldstone bosons if there was a global continuous symmetry in the theory that is spontaneously broken in the vacuum

    * Axion, arising from the breaking of a U(1) Peccei-Quinn symmetry introduced to explain the non-observation of CP violation in strong interactions [Peccei, Quinn (1977); S. Weinberg (1978); Wilczek (1978)]

$$m_A = [z^{1/2}/(1+z)]\, m_\pi f_\pi / f_A = 0.6\,\mathrm{meV} \times (10^{10}\,\mathrm{GeV}/f_A),$$

$$\text{where} \quad z = m_u/m_d = 0.56$$

    * Other examples: familon, majoron, dilaton, modulus, ...

– Such neutral spin-zero particles couple to two photons via

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

$$\mathcal{L}_{\phi^{(+)}\gamma\gamma} = -\frac{1}{4}\, g\, \phi^{(+)}\, F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\, g\, \phi^{(+)}\, \left(\vec{E}^2 - \vec{B}^2\right)$$

⇒ In the presence of a magnetic field $\vec{B}$, a photon of frequency ω may oscillate into a neutral spin-zero particle of mass $m_\phi < \omega$, and vice versa

[Sikivie (1983);Ansel'm (1985);van Bibber *et al.* (1987);Raffelt,Stodolsky (1988)]

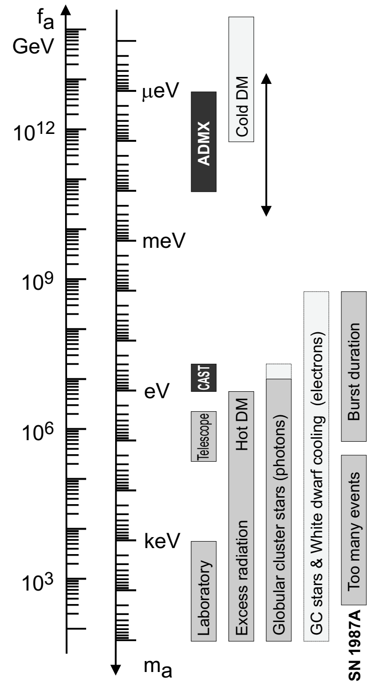
– Coupling suppressed by energy scale f of symmetry breaking,

$$g \propto \frac{\alpha}{2\pi f},$$

e.g. for the QCD axion, [Weinberg '78; Bardeen,Tye '78; . . .]

$$g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{2}{3}\frac{4+z}{1+z} - \frac{E}{N}\right)$$

- QCD axion is candidate for dark matter
- Astrophysical constraints
  - ALPs are generated in hot plasmas and lead there to energy losses
  - Observed limits of star evolution scales ⇒ constraints on interaction strengths with photons, electrons, nucleons ⇒ constraints on g vs. m_ϕ



[Raffelt '06]

- Constraints based on photon-ALP conversion:

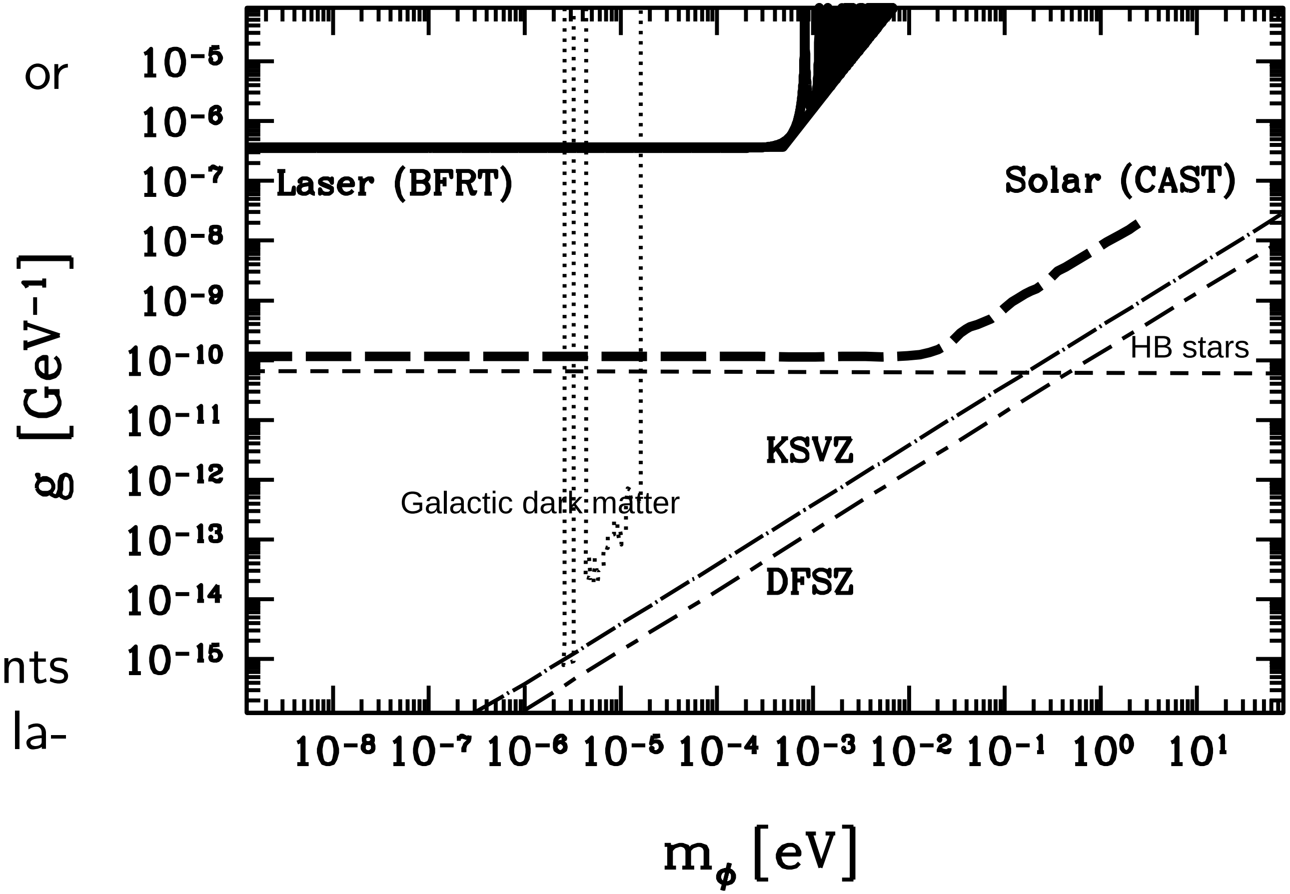
  Strongest bounds:
  Production in early universe or in astrophysical sources; detection in laboratory:

  – Search for dark matter
    - ∗ Microwave cavity experiments: RBF, UF, ADMX, CARRACK

  – Search for solar axions
    - ∗ Germanium: SOLAX, COSME
    - ∗ Magnetic: Tokyo helioscope, CAST

  Much less sensitivity:
  Pure laboratory experiments (detection and production in laboratory):

  – Laser experiments
    - ∗ Photon regeneration: BFRT, ...
    - ∗ Polarization experiments: BFRT, ...



[PDG (2004); AR '07]

- The need for pure laboratory limits:
  - In the center of sun/stars where most ALPs are produced, the environment is different from the environment of laboratory experiments:
    * high temperature $\sim$ keV
    * high density (at least compared to vacuum)
    * large electromagnetic fields involved in the Primakoff process

$\Rightarrow$ If g and/or m_ϕ are generated by new physics at scales much below $\mathcal{O}(\mathrm{keV})$, solar physics can be unaffected by ALPs, which instead can become visible in laboratory experiments at sub-eV scale

[Masso,Redondo '05; Jäckel *et al.* '06; Mohapatra,Nasri '06; Brax *et al.* '07; ...]

$\Rightarrow$ Pure laboratory searches for ALPs based on their couplings to photons are urgently needed and still complementary to the searches involving astrophysical or cosmological considerations

- Hidden-sector photons (γ's) and Minicharged Particles (MCPs):
  - γ': New light spin-one boson mixing with the photon [Okun '82]
  - MCP: New particle with electric charge $Q = \epsilon\, e \ll e$

- Motivation for γ's and MCPs:
  - Most supersymmetric (SUSY) extensions of Standard Model invoke "hidden sector" of particles which interact with Standard Model particles ("visible sector") only via feeble, gravity-like interactions
  - Not all the particles in the hidden sector are necessarily very heavy:
    * Hidden sector gauge group may contain unbroken U(1) gauge factors ($\Rightarrow \gamma'$), which may mix kinetically with the visible sector U(1)
    * Chiral symmetries may keep some hidden sector matter particles light
    * If the latter are charged under the above U(1), they acquire small electric charge due to above mixing ($\Rightarrow$ MCP) [Holdom '85]

- Simplest model:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\mathrm{U(1)}_{\mathrm{visible}}} \underbrace{-\frac{1}{4}B^{\mu\nu}B_{\mu\nu}}_{\mathrm{U(1)}_{\mathrm{hidden}}} \underbrace{-\frac{1}{2}\chi\, F^{\mu\nu}B_{\mu\nu}}_{\text{kinetic mixing}} \underbrace{+\bar{v}(\mathrm{i}\partial\!\!\!/ + e A\!\!\!/)v}_{\text{visible matter}} \underbrace{+\bar{h}(\mathrm{i}\partial\!\!\!/ + e B\!\!\!/)h}_{\text{hidden matter}}$$

  – Dimensionless kinetic mixing parameter χ:

    * kinetic mixing generically appears in theories with several U(1) factors (renormalizable term respecting gauge and Lorentz symmetry)
    * Integrating out heavy particles generically tends to generate $\chi \neq 0$

  – Diagonalization of kinetic term:

$$B^\mu \to \tilde{B}^\mu - \chi A^\mu$$

U(1)$_{\mathrm{visible}}$ unaffected, up to renormalization, $e^2 \to e^2/(1-\chi^2)$

– Hidden sector charged particle gets induced electric charge:

$$e\bar{h}\not{B}h \quad\rightarrow\quad e\bar{h}\tilde{\not{B}}h - \chi e\bar{h}\chi e\not{A}h$$

$$\Rightarrow\quad Q_h^{\rm vis} \equiv \epsilon e = -\chi e$$

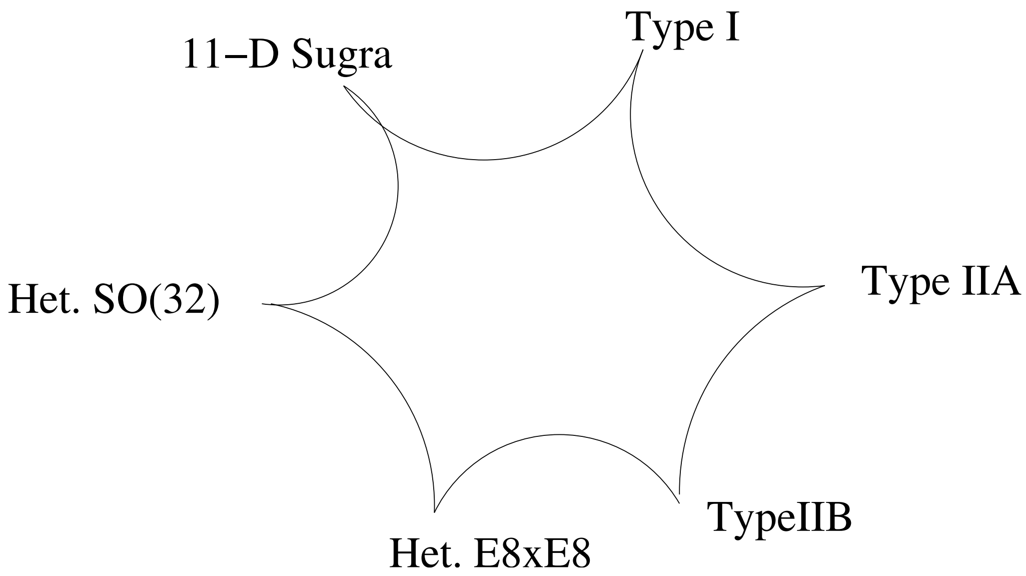
* may be fractional
* may be tiny, if $\chi \ll 1$: h is MCP

- Value of χ in well-motivated extensions of Standard Model?

- Gauge kinetic mixing in extensions of Standard Model based on string theory

  [Abel,Jaeckel,Khoze,AR ‘06]

  – Additional U(1) factors in hidden sectors: generic prediction



[Abel,Santiago ‘04]

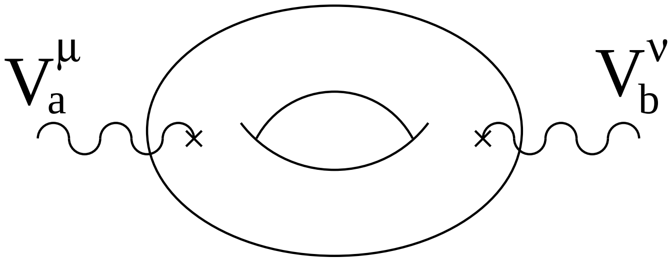
- Gauge kinetic mixing in extensions of Standard Model based on string theory

  [Abel,Jaeckel,Khoze,AR '06]

  – Additional U(1) factors in hidden sectors: generic prediction
  – Expected size of χ in particular string theory setting: one-loop calculation
    - ∗ Weakly coupled heterotic closed string models

      [Dienes,Kolda,March-Russell '97]

Heterotic string models:



$$\chi \simeq \frac{e e_h}{8\pi^2} C \frac{\Delta m_{\rm SUSY}^{\rm hidden}}{M_P}$$

$$\simeq e_h \underbrace{C}_{10\div 100} (\underbrace{10^{-16}}_{\rm GM} \div \underbrace{10^{-9}}_{\rm SUGRA})$$

[Dienes,Kolda,March-Russell '97]

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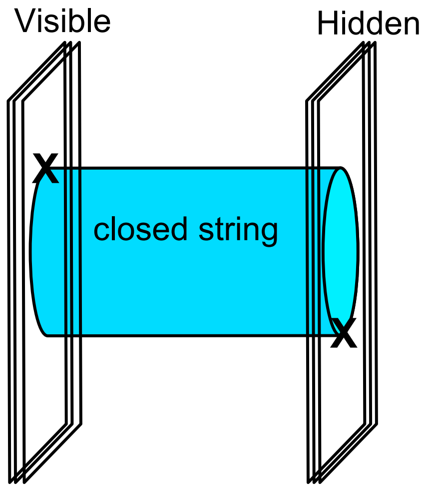
    * Weakly coupled heterotic closed string models

      [Dienes,Kolda,March-Russell '97]

    * Open string models involving stacks of Dirichlet branes and antibranes

      [Abel,Schofield '04]

IIA/IIB string models:



$$\chi \sim e\, e_h \left(\frac{2^{(8-p)/2}}{\alpha_p} \frac{M_s}{M_P} \right)^{\frac{2(5-p)}{6-p}} \left(\frac{R}{r} \right)^{\frac{d-p+3}{6-p}}$$

[Abel,Schofield '04]

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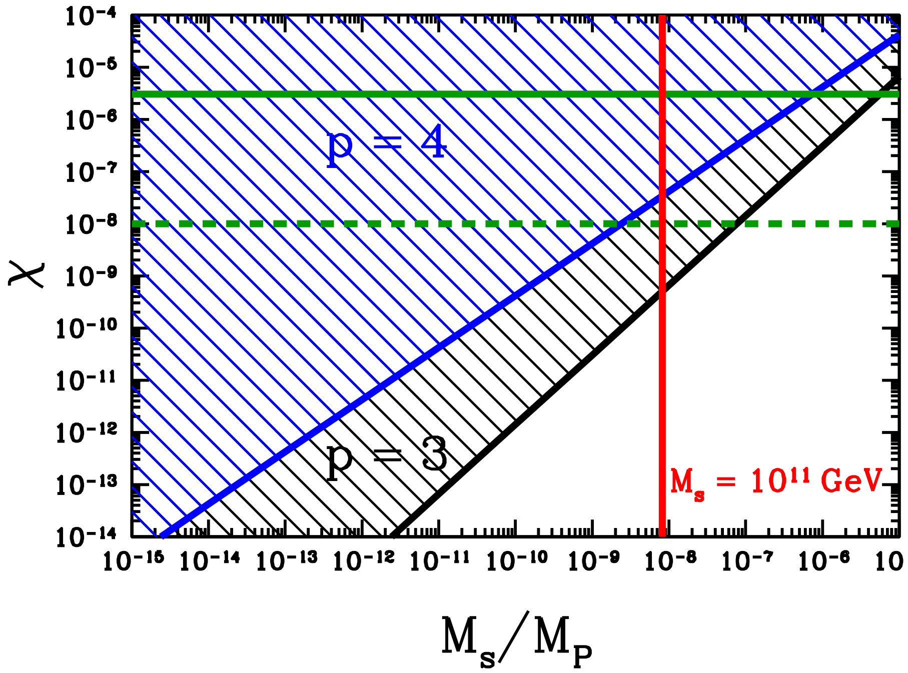
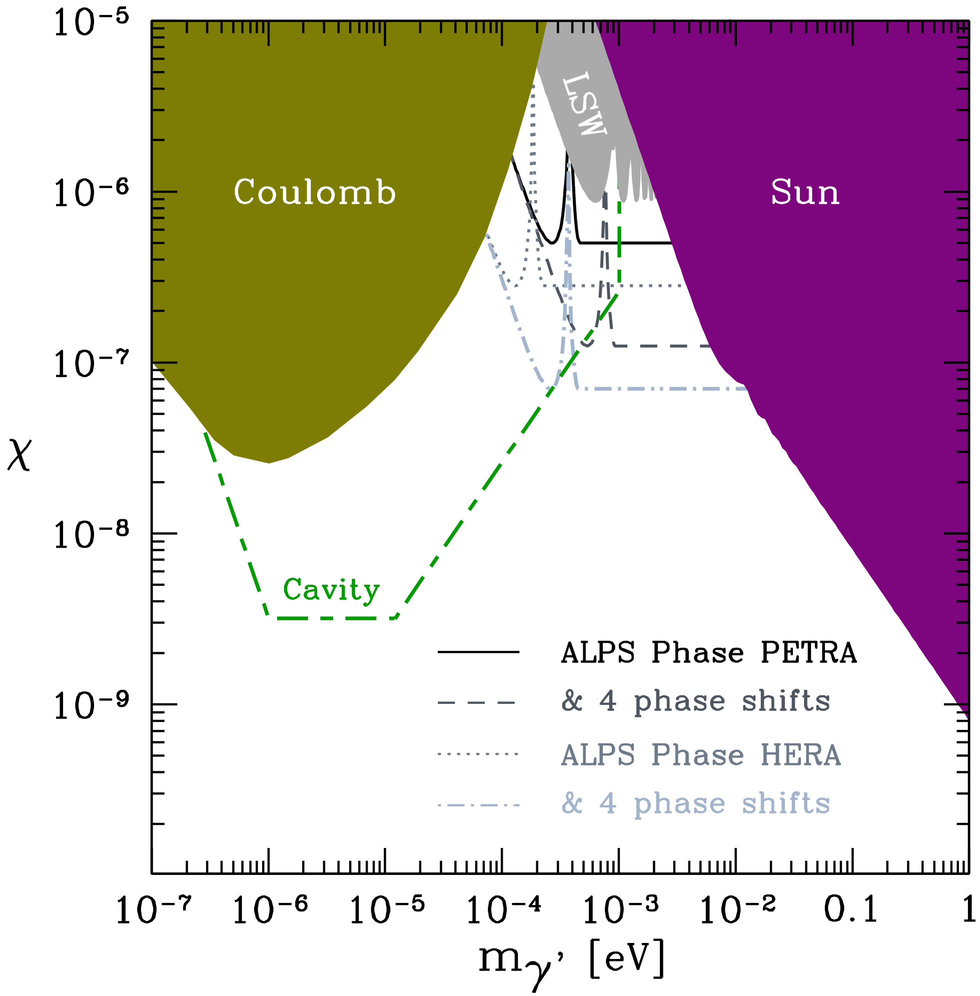


[Abel,Jaeckel,Khoze,AR '06]

Constraints:

- γ's:
  - Sun (lifetime and helioscope)
  - Coulomb $1/r^2$ law
  - Light shining through a wall



[Ahlers *et al.* '07]

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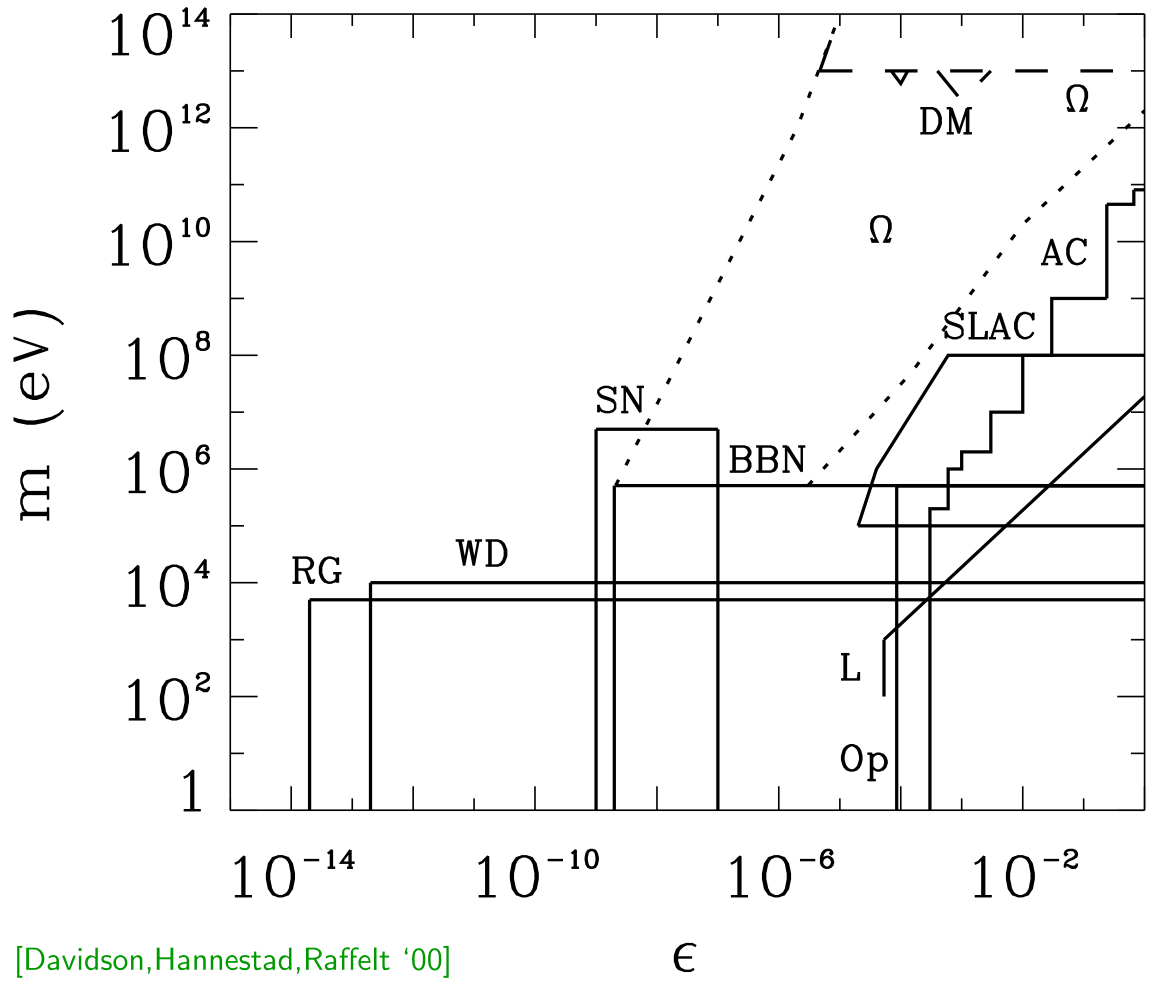
  - Lifetime of stars (RG,WD)
  - Big bang nucleosynthesis
  - Lamb shift (L)
  - Orthopositronium (Op)



[Davidson,Hannestad,Raffelt '00]

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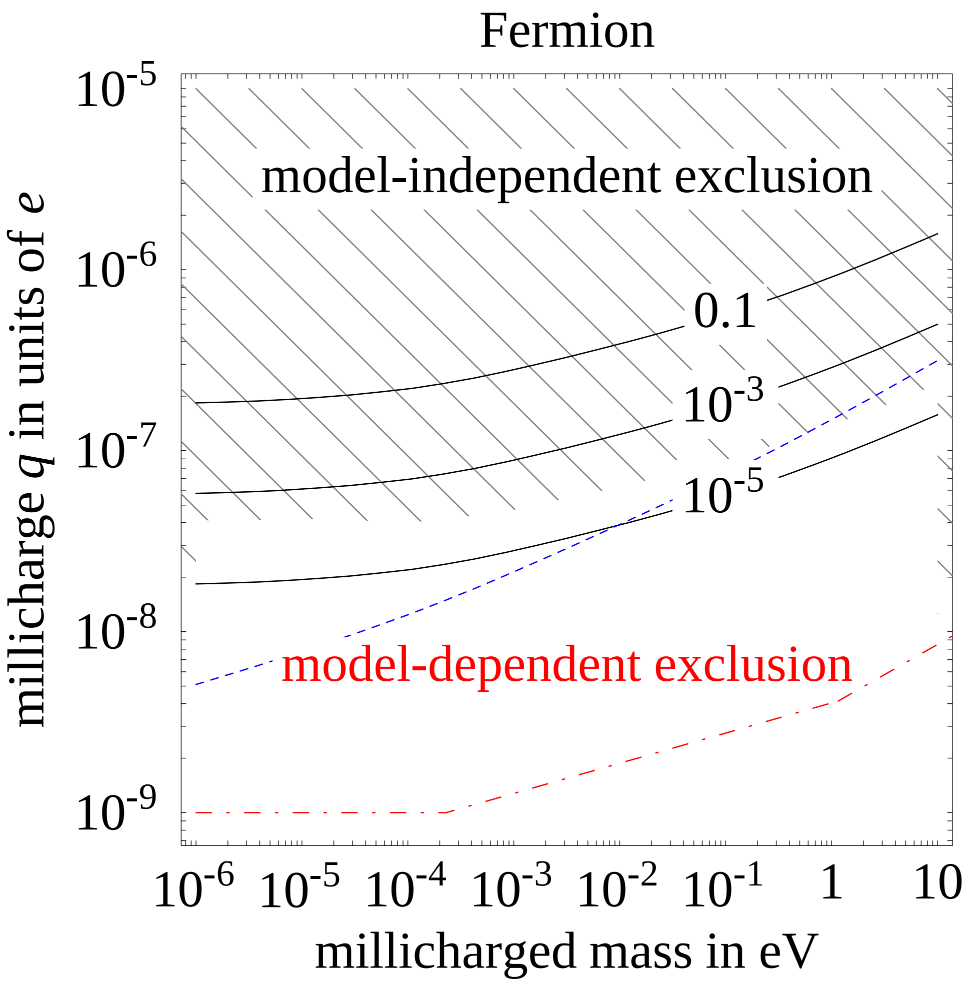
  - CMB

$\Rightarrow$ Model-independent laboratory searches start to probe interesting range in χ and ϵ

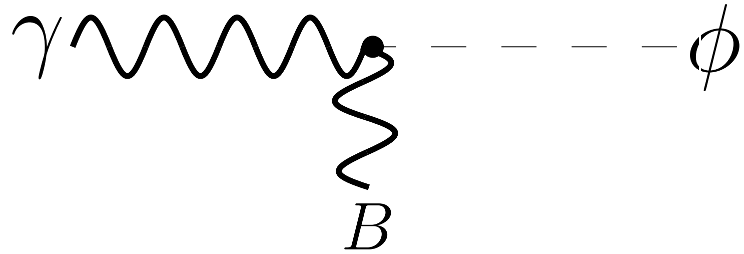


[Melchiorri,Polosa,Strumia '07]

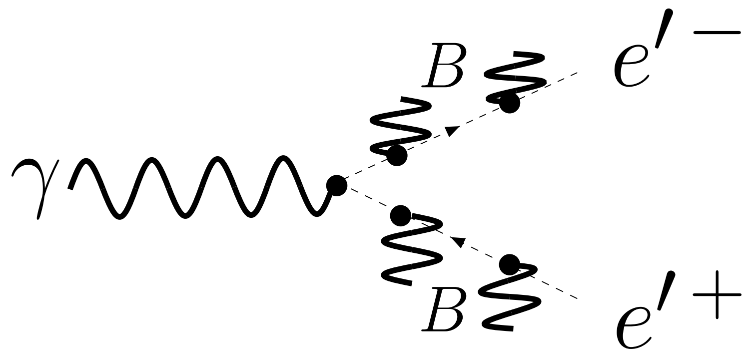
3. Laser Polarization Experiments

- Linearly polarized laser beam along transverse magnetic field:
  - Real conversion of laser photons in WISPs

Photon → ALP:



Photon → MCP:



$\gamma \rightarrow \gamma'$

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- Linearly polarized laser beam along transverse magnetic field:
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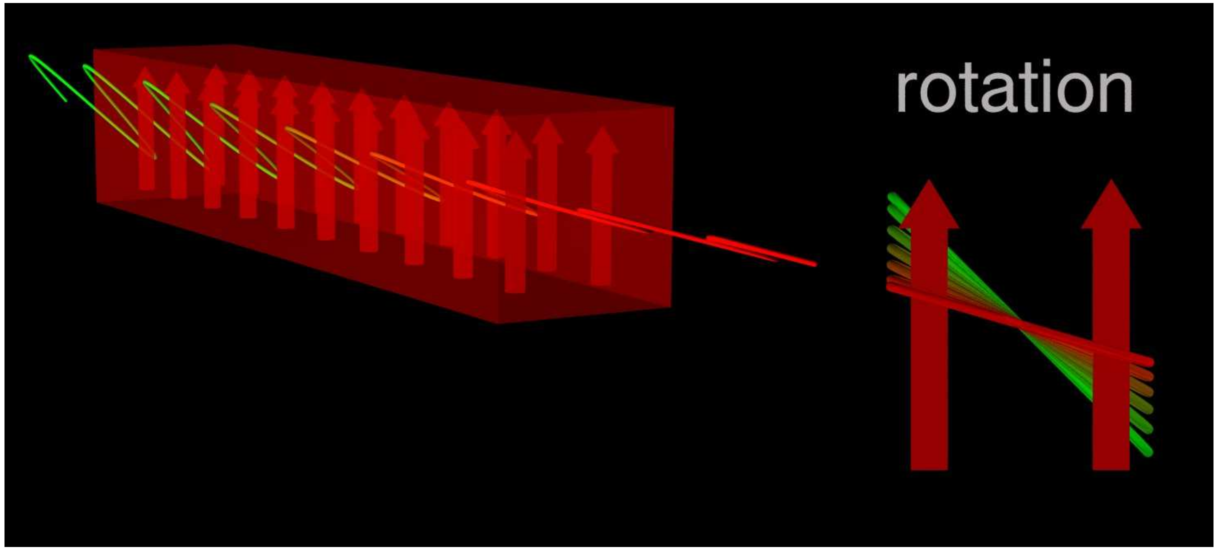

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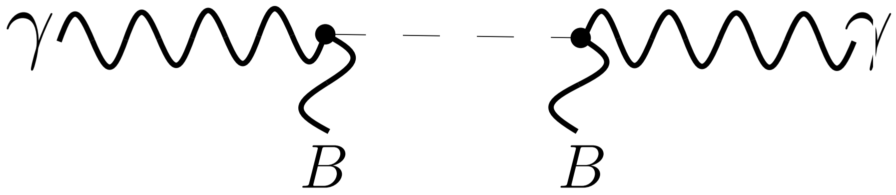
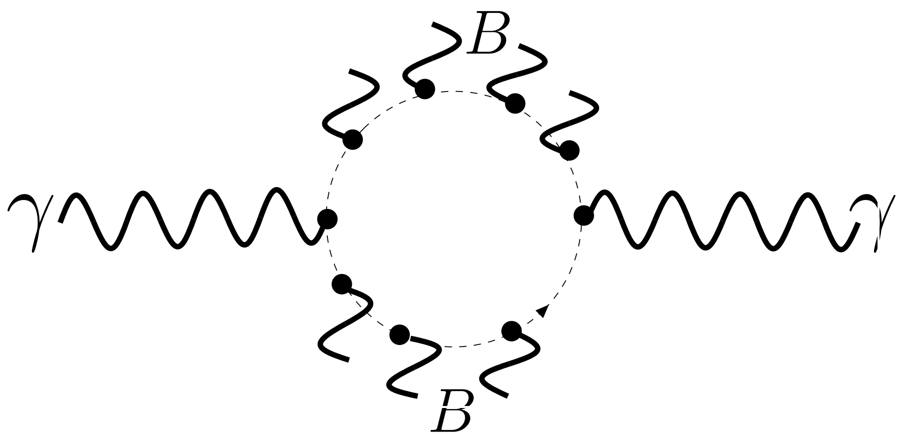
  - Virtual conversion of laser photons in WISPs





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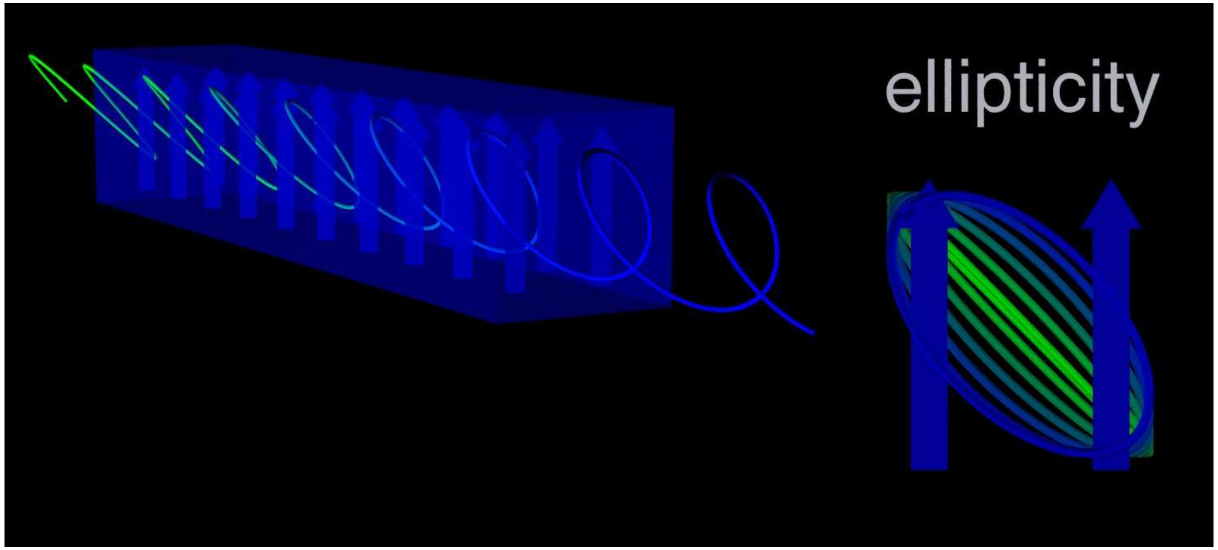
  - Virtual conversion of laser photons in WISPs ⇒ elliptical polarization, since phase velocity depends on relative orientation between polarization and magnetic field



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BFRT experiment: [Cameron *et al.* '93]
(Brookhaven, Fermilab, Rochester, Trieste)

$B \sim 2\ \mathrm{T}, \ell = 8.8\ \mathrm{m}, \omega = 2.4\ \mathrm{eV}, N_{\mathrm{pass}} = 34 - 254$

PVLAS experiment: [Zavattini *et al.* '06]

$B = 5\ \mathrm{T}, \ell = 1\ \mathrm{m}, \omega = 1.2\ \mathrm{eV}, N_{\mathrm{pass}} = 44000$

Q&A experiment: [Chen,Mei,Ni '06]

$B = 2.3\ \mathrm{T}, \ell = 1\ \mathrm{m}, \omega = 1.2\ \mathrm{eV}, N_{\mathrm{pass}} = 18700$

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- Interpretation in terms of real and virtual production of
  - light neutral spin-zero boson (Axion-Like Particle (ALP)),

$$(g/4)\,\phi^{(-)}\,F_{\mu\nu}\tilde{F}^{\mu\nu}\ \ \left(\phi^{(+)}\,F_{\mu\nu}F^{\mu\nu}\right)$$

Effects of Nearly Massless, Spin Zero Particles on Light Propagation in a Magnetic Field

[Maiani,Petronzio,Zavattini '86]

$$-\Delta\theta^{(+)} = \Delta\theta^{(-)} = N_{\rm pass}\left(\frac{gB\omega}{m_\phi^2}\right)^2 \sin^2\left(\frac{Lm_\phi^2}{4\omega}\right)\sin 2\theta$$

$$-\psi^{(+)} = \psi^{(-)} = \frac{N_{\rm pass}}{2}\left(\frac{gB\omega}{m_\phi^2}\right)^2\left(\frac{Lm_\phi^2}{2\omega} - \sin\left(\frac{Lm_\phi^2}{2\omega}\right)\right)\sin 2$$

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$$\partial_\mu \to \partial_\mu - \mathrm{i}\epsilon e A_\mu$$

Polarized Light Propagating in a Magnetic Field as a Probe for Millicharged Fermions [Gies,Jaeckel,AR '06]

$$\psi = \frac{\omega}{2}\,\ell_B\,\Delta n\,\sin(2\theta), \quad \Delta\theta = \frac{1}{4}\,\ell_B\,\Delta\kappa\,\sin(2\theta)$$

$$\Delta n = -\frac{\epsilon^2\alpha}{4\pi}\left(\frac{\epsilon\,eB}{m_\epsilon^2}\right)^2 \Delta I(\lambda), \quad \Delta\kappa = \frac{1}{2}\epsilon^3 e\alpha\frac{B}{m_\epsilon}\,\Delta T(\lambda)$$

$$\Delta I^{\rm Dsp}(\lambda) = \frac{1}{2^{\frac{2}{3}}}\left(\frac{3}{\lambda}\right)^{\frac{4}{3}}\int_0^1 \mathrm{d}v\,(1-v^2)^{\frac{2}{3}}\,\tilde{e}_0'\left[-\left(\frac{6}{\lambda}\frac{1}{1-v^2}\right)^{\frac{2}{3}}\right]$$

$$\Delta T^{\rm Dsp}(\lambda) = \frac{2\sqrt{3}}{\pi\lambda}\int_0^1 \mathrm{d}v\;K_{2/3}\left(\frac{4}{\lambda}\frac{1}{1-v^2}\right)$$

$$\lambda \equiv \frac{3}{2}\frac{\omega}{m_\epsilon}\frac{\epsilon e B}{m_\epsilon^2}$$

cf. [...;Toll '52;...;Adler '71;...;Tsai,Erber '74,'75;...]

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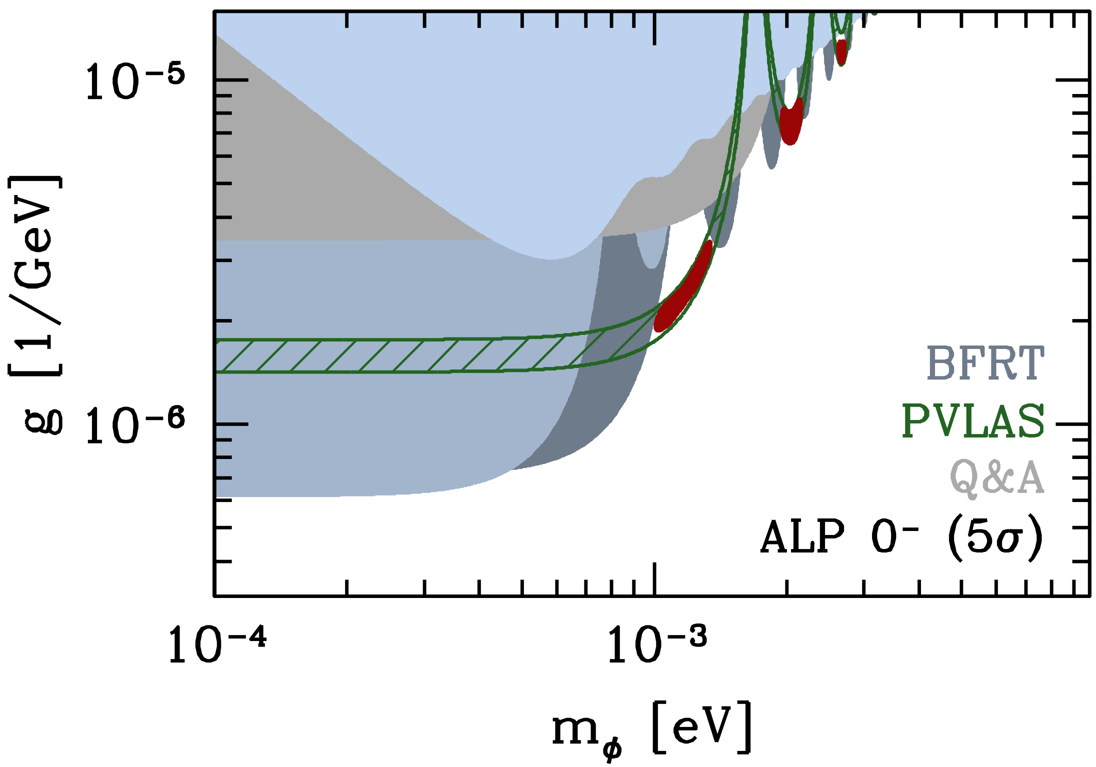
- PVLAS '06 signal + other limits: ALP or MCP?

PVLAS '06 Data:



[Ahlers,Gies,Jaeckel,AR '06]

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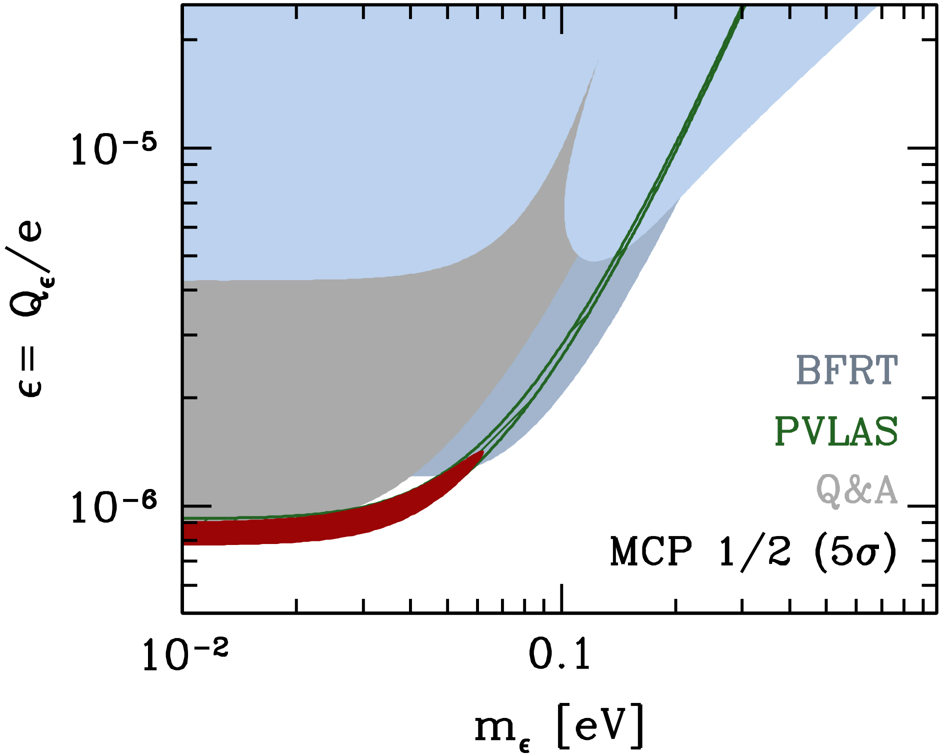

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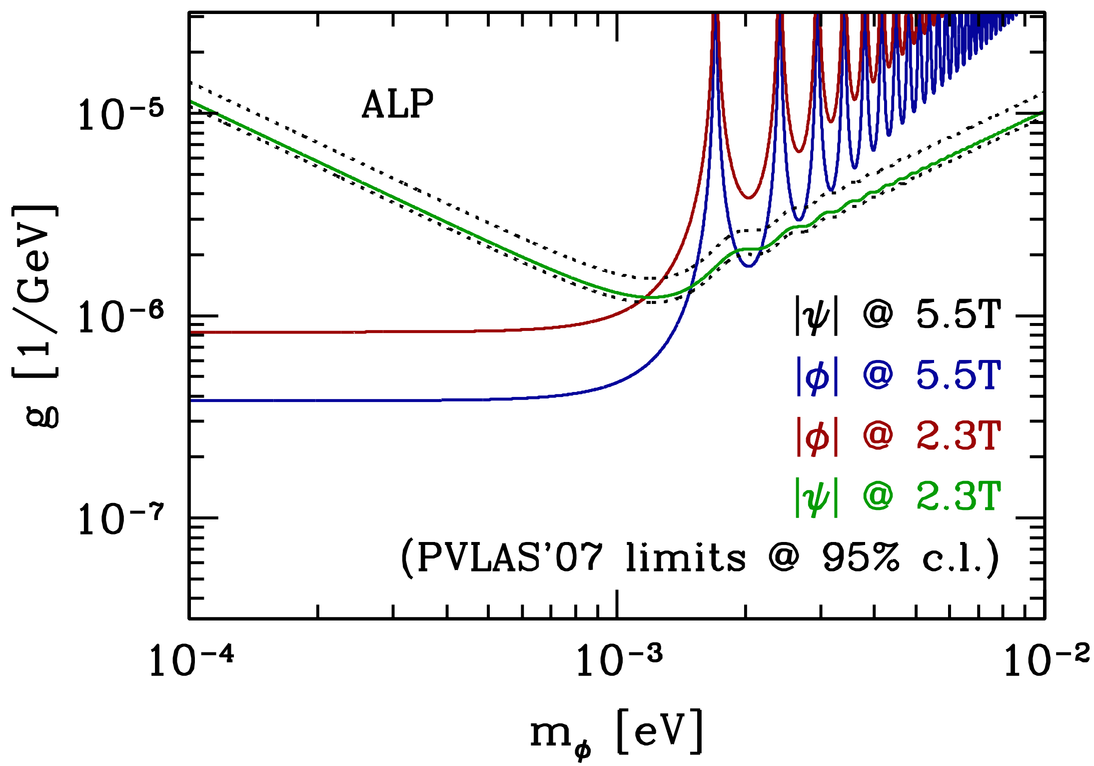

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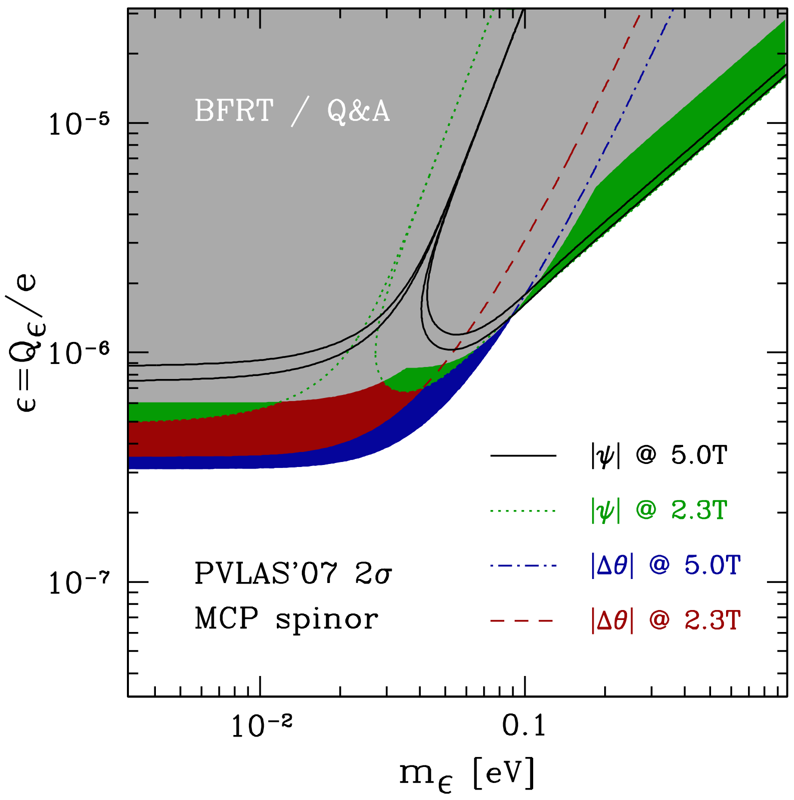

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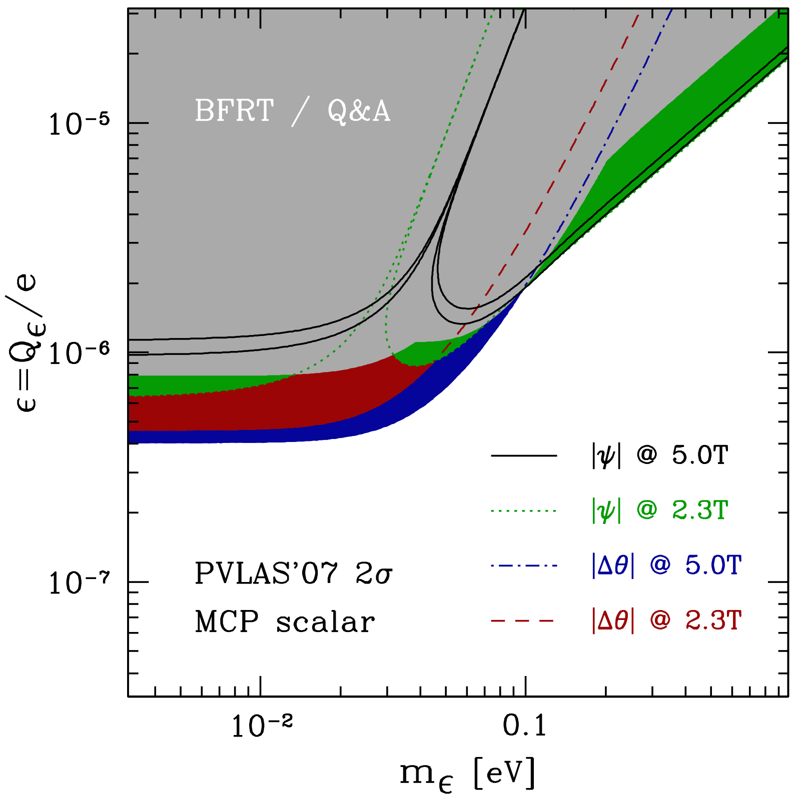
PVLAS '07 Data:



[Ahlers *et al.* '07]

3. Laser Polarization Experiments

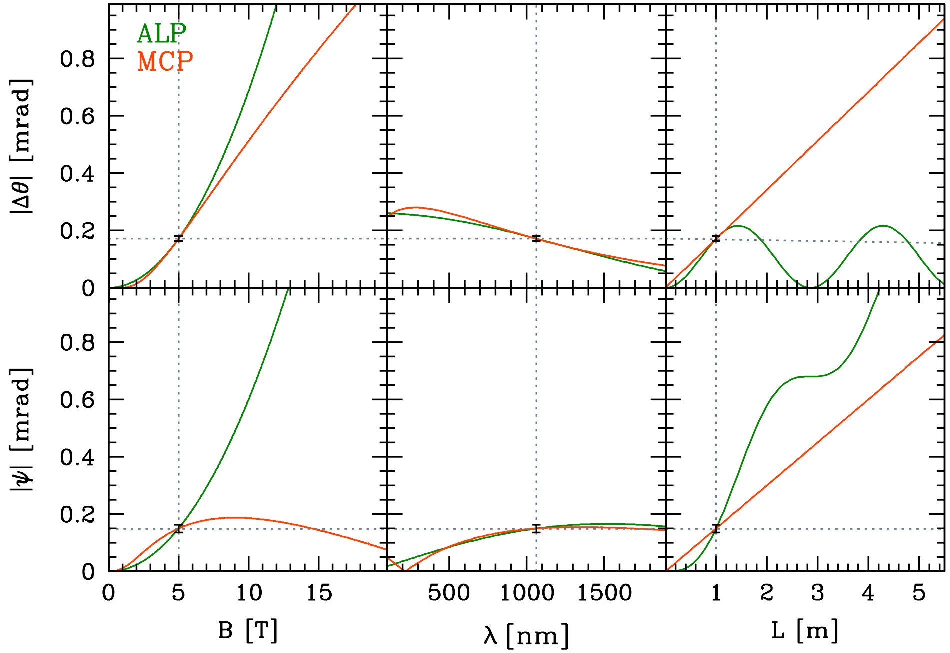
- Interpretation in terms of real and virtual production of
  - light neutral spin-zero boson (Axion-Like Particle (ALP))

  and/or
  - light MiniCharged Particle (MCP) – anti-particle pair,

$$\partial_\mu \to \partial_\mu - \mathrm{i}\epsilon e A_\mu$$

- PVLAS '06 signal + other limits: ALP or MCP?
- PVLAS '07 limit: no(?) sign of ALP or MCP?

Distinguishing ALPs from MCPs:



[Ahlers,Gies,Jaeckel,AR '06]

BMV (Toulouse): 11 T pulsed magnet

OSQAR (CERN): 9.6 T LHC magnet

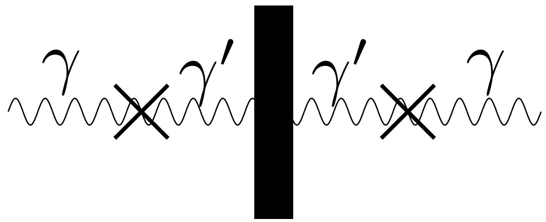
4. Photon Regeneration Experiments

- Linearly polarized laser beam in vacuum or along a transverse magnetic field
- Place wall in beam pipe:
  - laser beam will be absorbed
  - neutral WISPs (Paraphotons, ALPs) fly through wall and
  - reconvert on other side of wall into photons, which can be detected

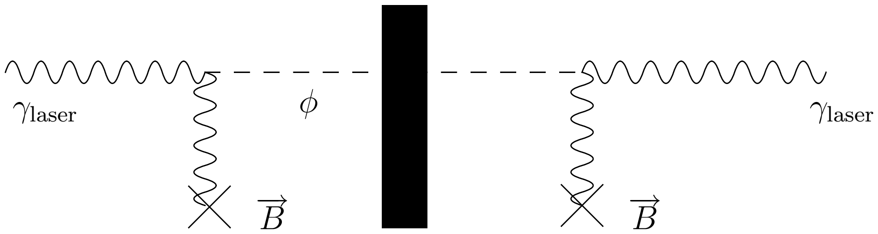
[Okun '82;Sikivie '83;Anselm '85;..]

PR via

- γ-γ' oscillations:



- photon-ALP oscillations:



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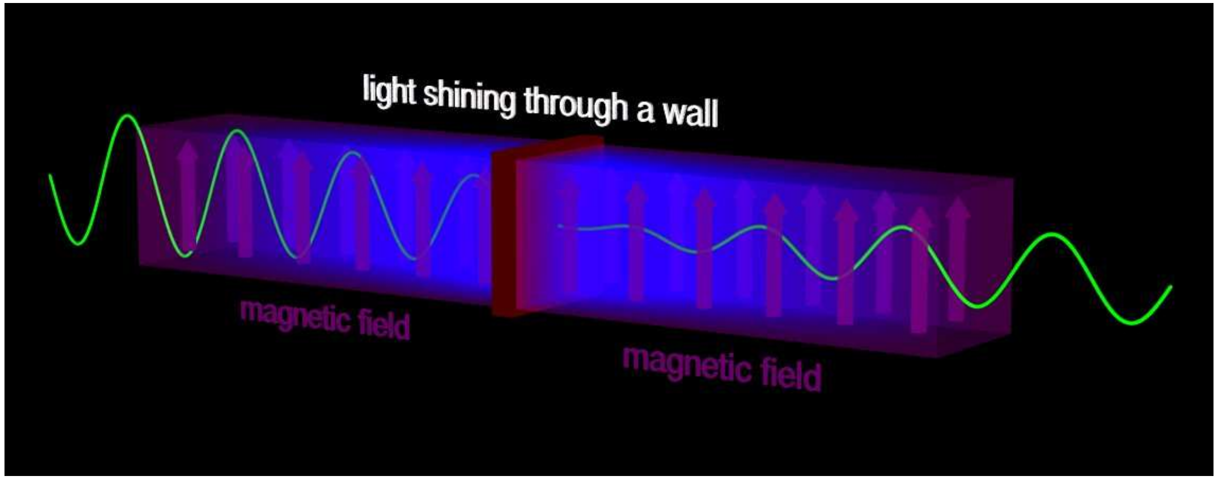

[Ahlers (unpubl.)]

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[Okun '82;Sikivie '83;Anselm '85;..]

- Pioneering experiment: BFRT
- Several ongoing experiments

Experiment	Laser	Cavity	Magnets
ALPS	532 nm; 200 W	–	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m
BFRT	~ 500 nm; 3 W	$N_p = 200$	$B_1 = B_2 = 3.7$ T $\ell_1 = \ell_2 = 4.4$ m
BMV	8×10^{21} γ/pulse	–	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 0.25$ m
GammeV	532 nm; 3.2 W	–	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 3$ m
LIPSS	900 nm; 3 kW	–	$B_1 = B_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m
OSQAR	1064 nm; 1 kW	$N_p \sim 10^4$	$B_1 = B_2 = 9.5$ T $\ell_1 = \ell_2 = 7$ m
PVLAS	1064 nm; 0.02 W	$N_p = 4 \times 10^4$	$B_1 = 5$ T, $\ell_1 = 1$ m $B_2 = 2.2$ T, $\ell_2 = 0.5$ m

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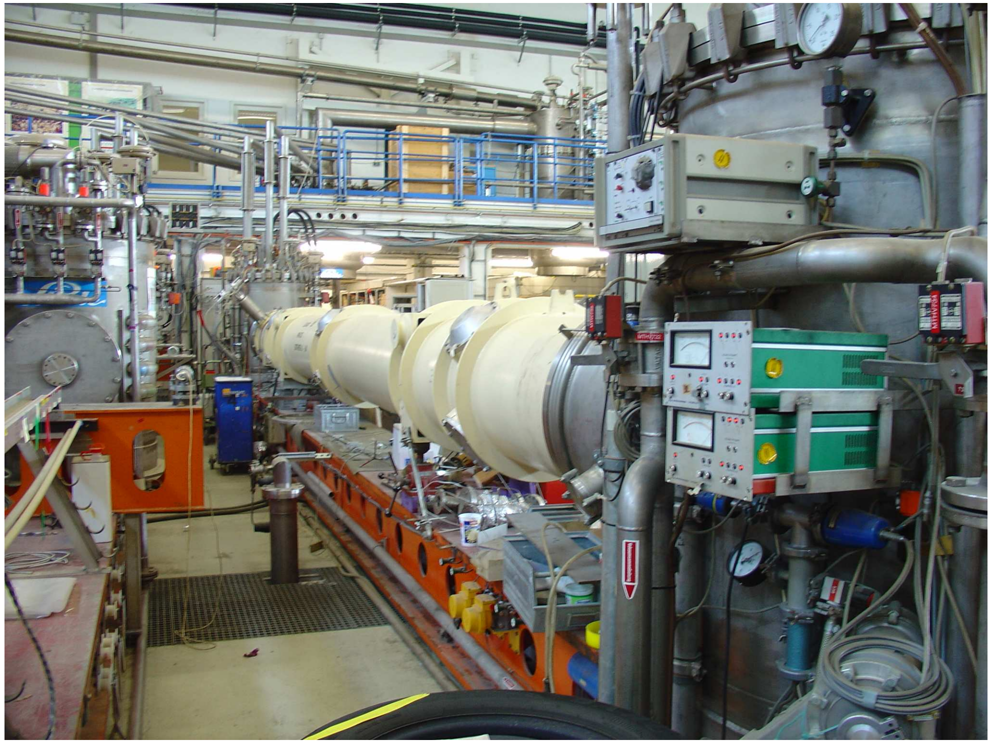
Axion-Like Particle Search:

[DESY, Laser Zentrum Hannover, Sternwarte Bergedorf]



$B = 5\ \mathrm{T}, \ell = 4.2\ \mathrm{m}, \underbrace{\langle P\rangle = 40\ \mathrm{W}, \omega = 2.4\ \mathrm{eV}}_{\dot N_0 \sim 1\times 10^{20}/\mathrm{s}}, N_{\rm pass} = 0$

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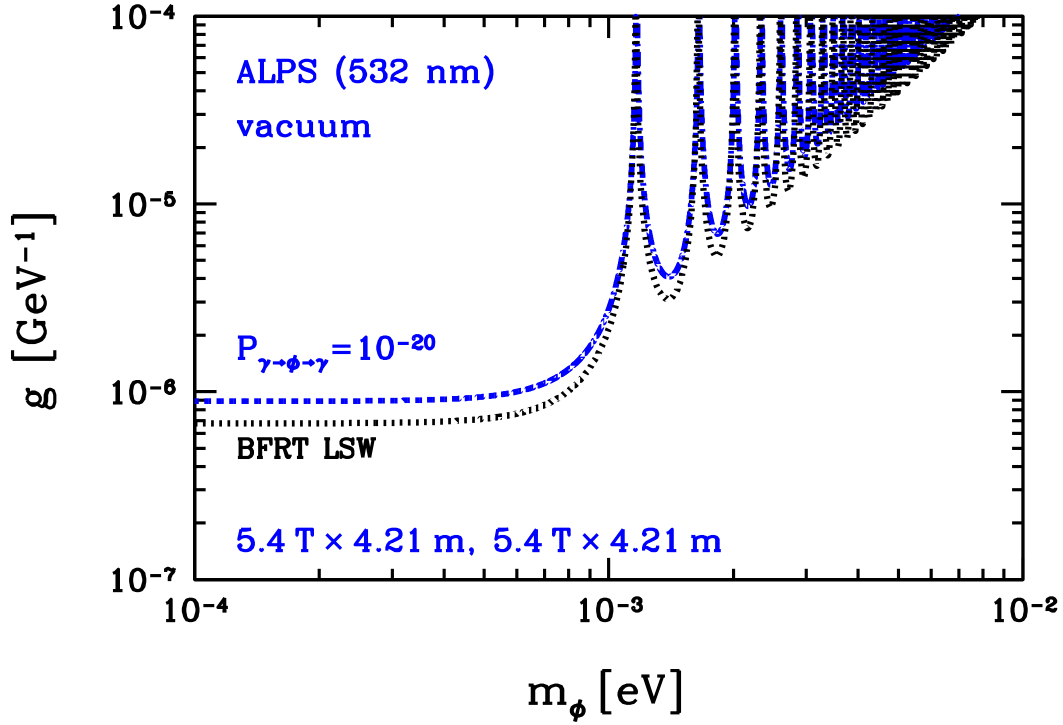
Axion-**L**ike **P**article **S**earch:

[DESY, Laser Zentrum Hannover, Sternwarte Bergedorf]



Phase 0: 3 W laser; preliminary limit $P_{\gamma\to\phi\to\gamma} < 8\times 10^{-21}$

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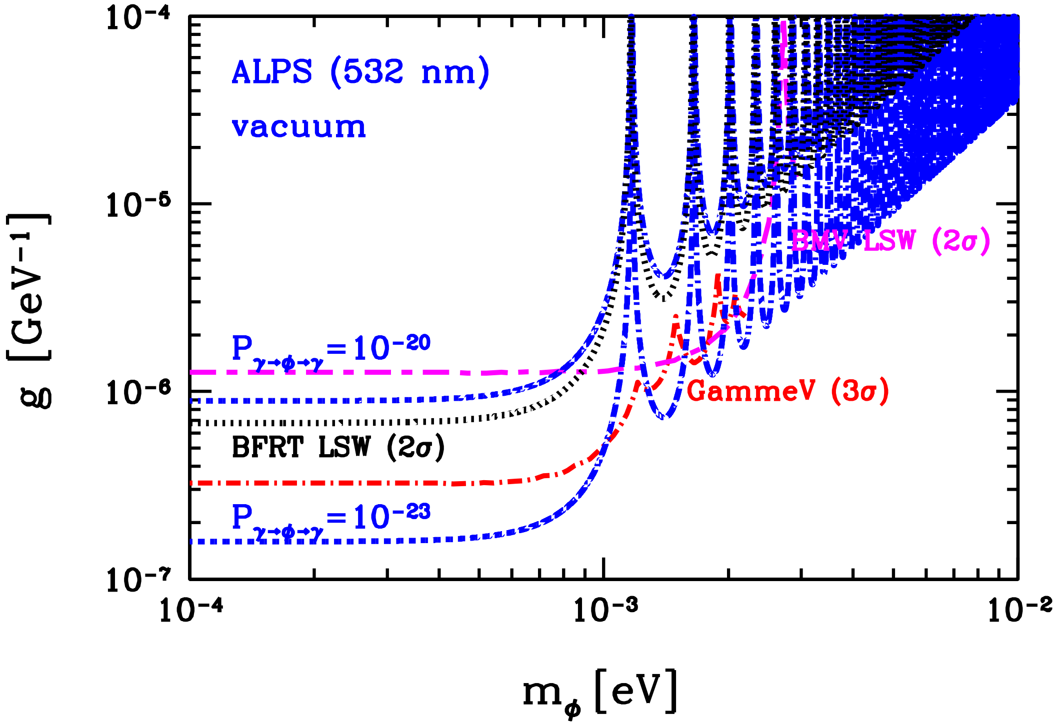

Phase 1: 40 W laser; sensit. $P_{\gamma\to\phi\to\gamma} < 10^{-23}$

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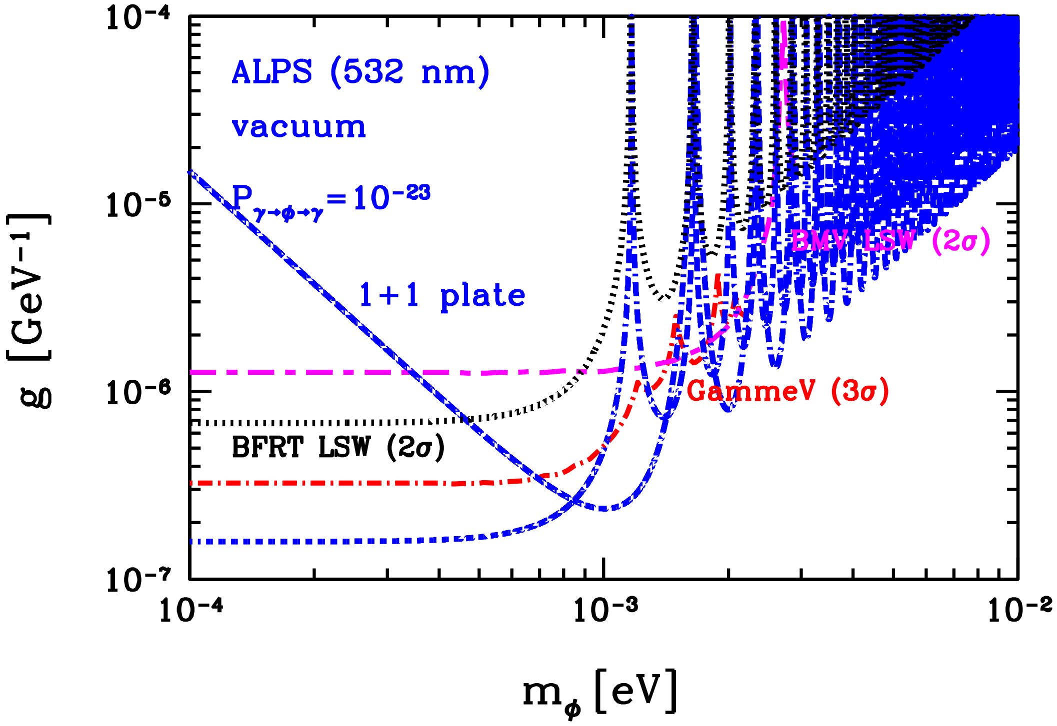

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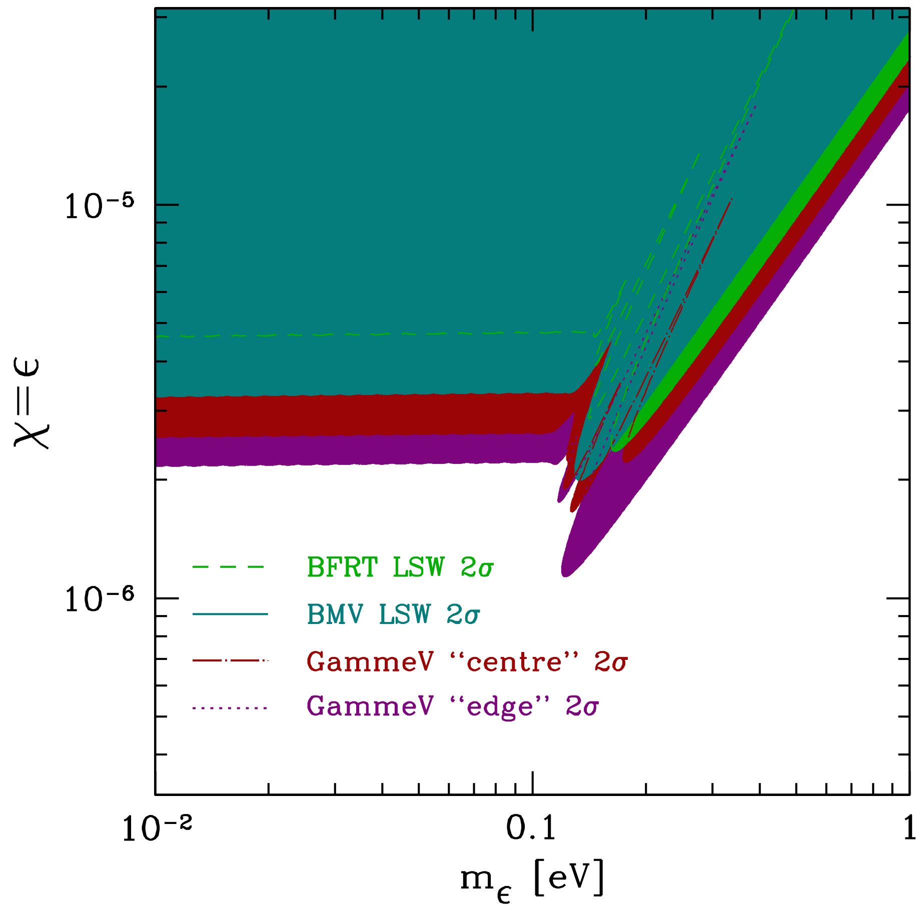
Limit on massless γ' + MCP:



[Ahlers *et al.* '07]

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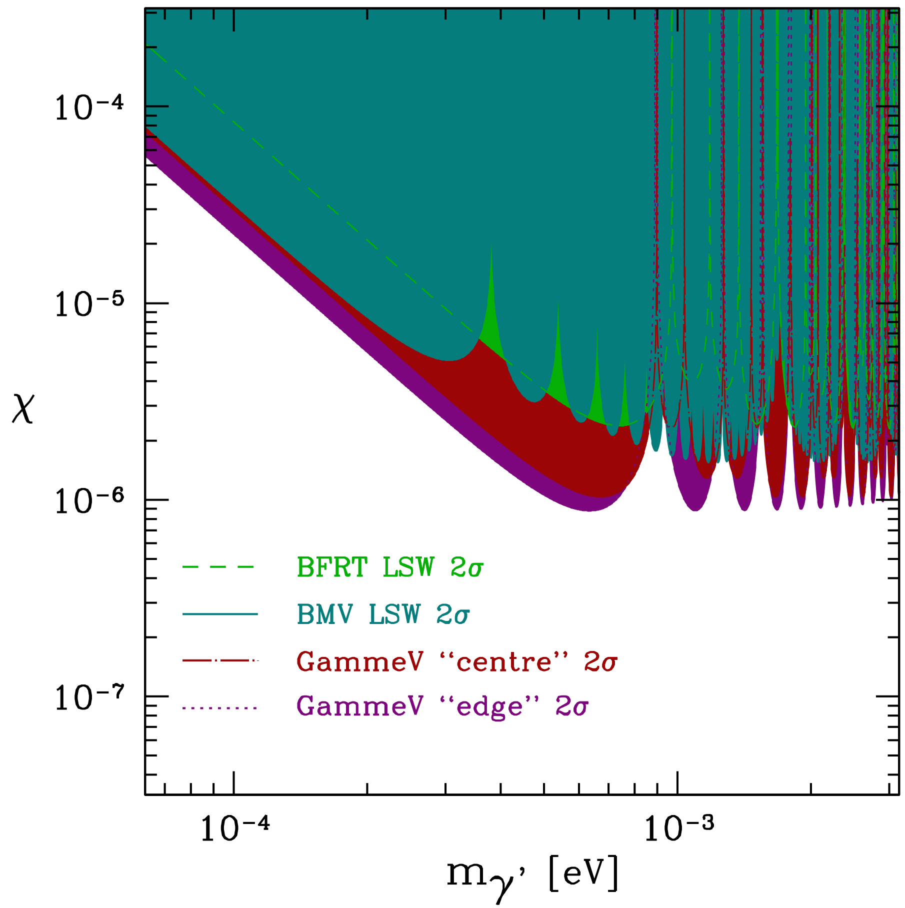
Vacuum PR: Limit on massive γ'



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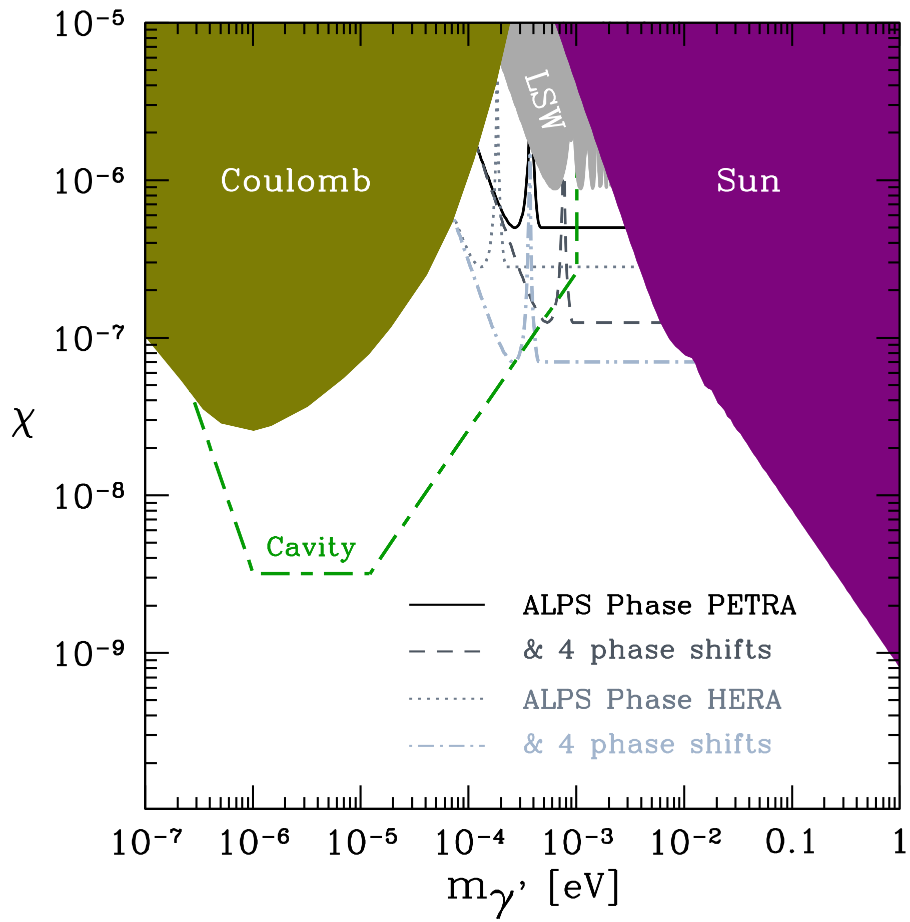
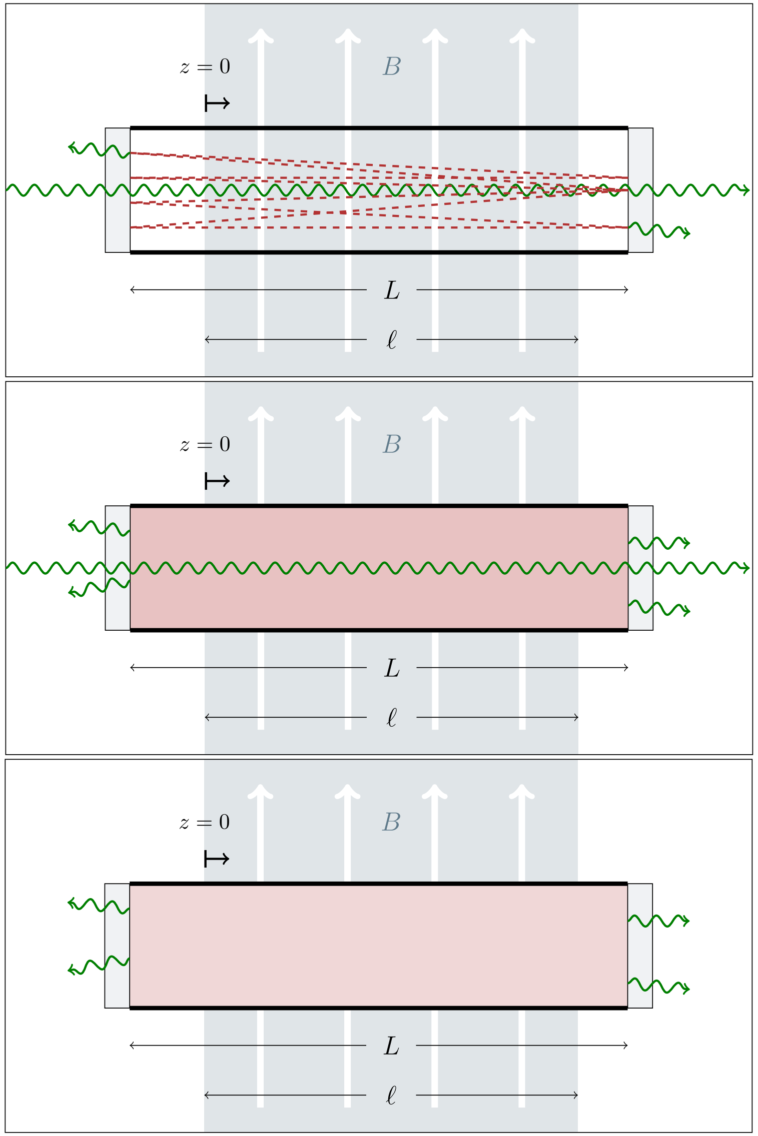


[Ahlers *et al.* '07]

4. Photon Regeneration Experiments

- Chameleon ALPs: [Khoury,Weltman '04]
  - Scalar particles with density dependent mass arising from conformal coupling to matter and electromagnetism
  - For suitable self-interaction potential, candidate for dark energy
- Signature: [Chou et al.;Ahlers et al.;Gies et al.] ALPenglow from magnetically induced conversion of trapped chameleons into photons
- May probe so far unaccessible region of parameter space



[Ahlers,Lindner,AR,Schrempp,Weniger '07]

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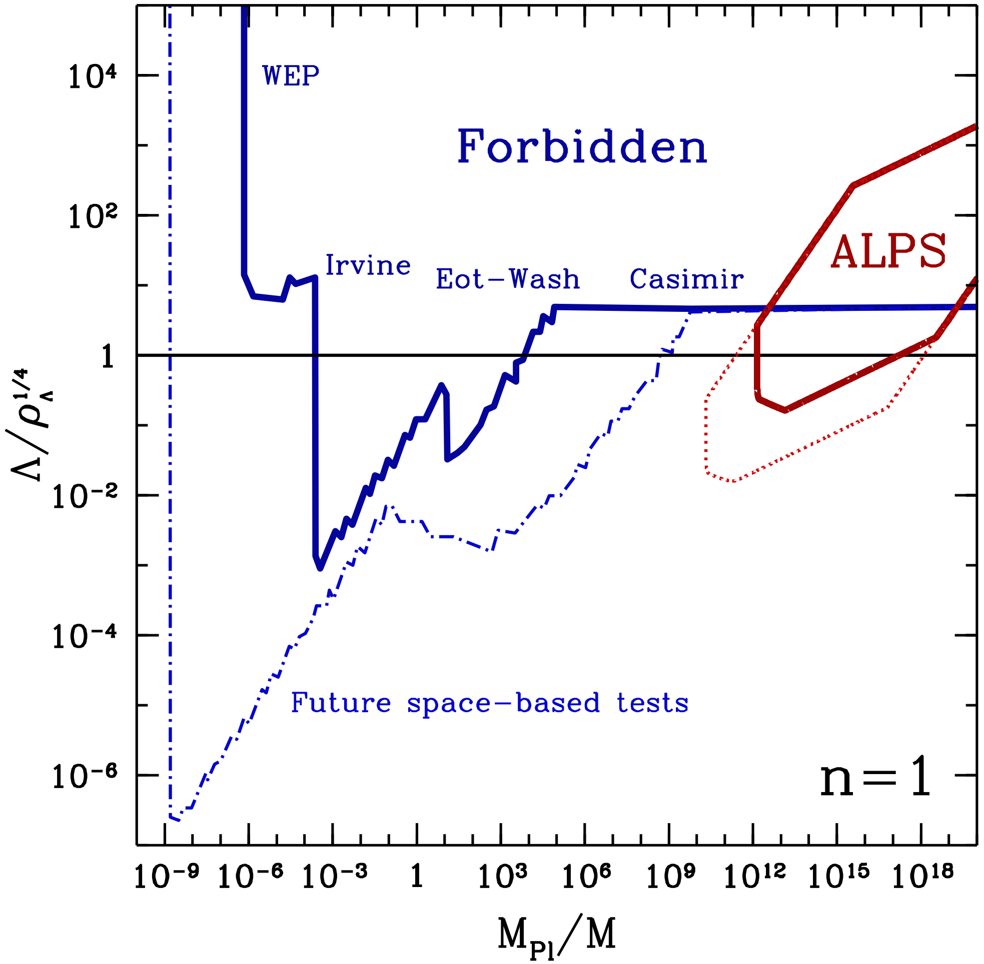


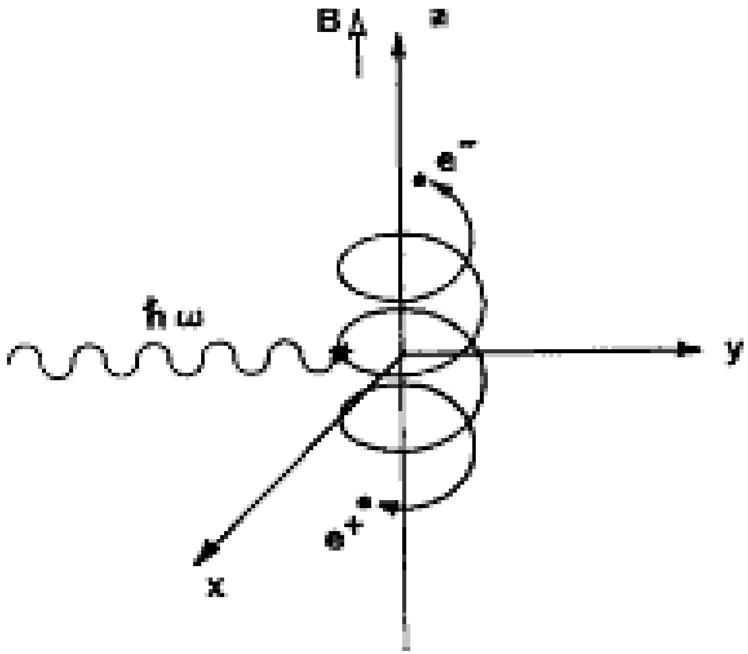
[Ahlers,Lindner,AR,Schrempp,Weniger '07]

5. Microwave Cavity Experiments

- Minicharged particles don't meet again behind the wall ⇒ no light shining through the wall

- Current-Through-a-Wall:
  - In strong electric field of accelerator cavity, minicharged particles may be produced in pairs and accelerated along the beam axis
  - MCP beam leaves cavity and is flowing through thick wall
  - Corresponding electrical current can be measured directly via its induced magnetic field

[Gies,Jaeckel,AR '06]



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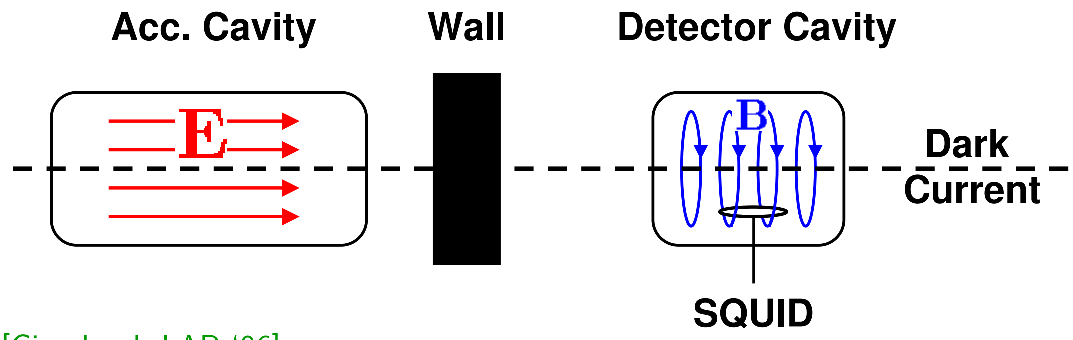

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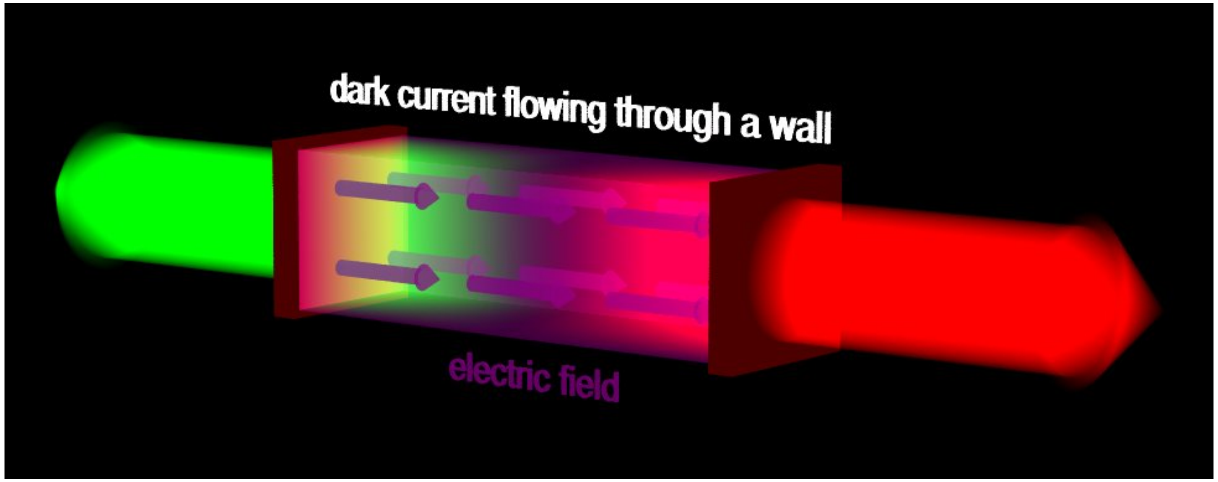

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ACDC (Accelerator Cavity Dark Current):

- Cavity available

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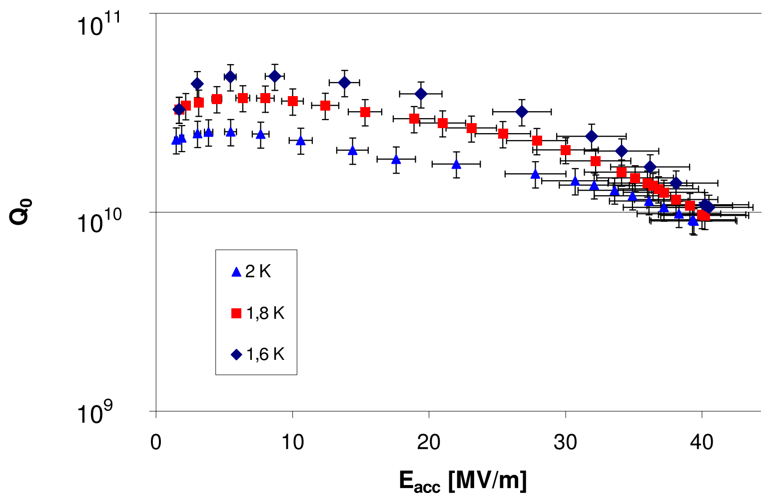

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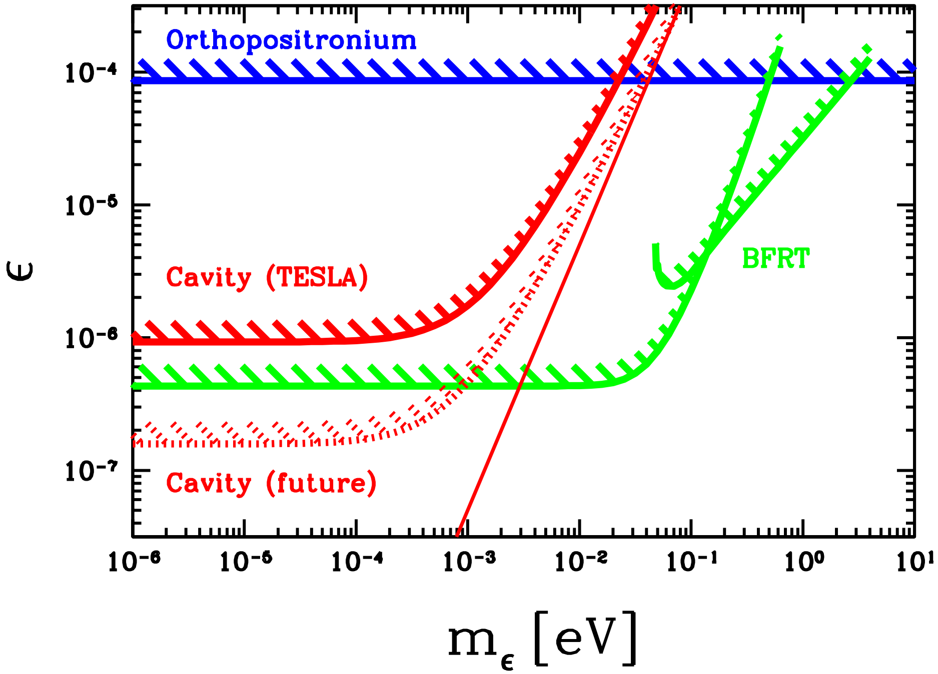

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[Gies,Jaeckel,AR '06]

ACDC (Accelerator Cavity Dark Current):

- Cavity and wall available
- Measurement device available

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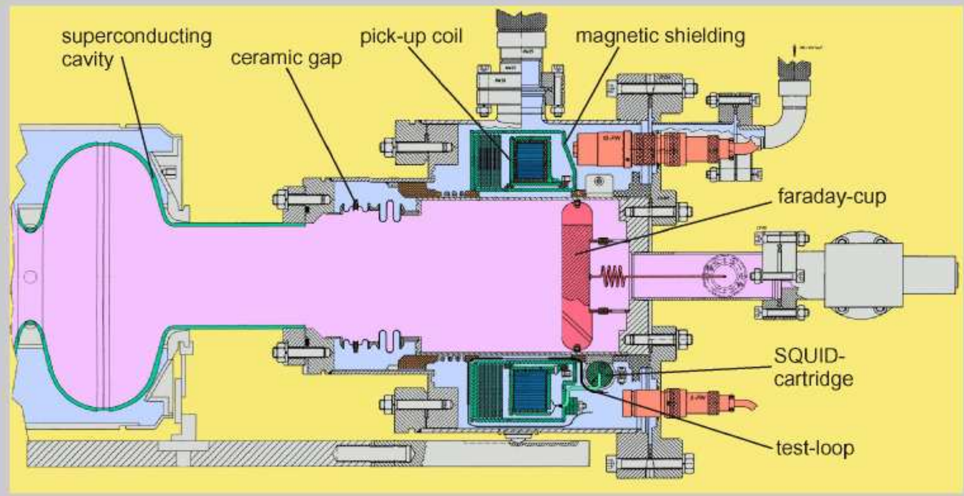

Construction details of the CCC dark current hardware

- Cavity and wall available
- Measurement device available

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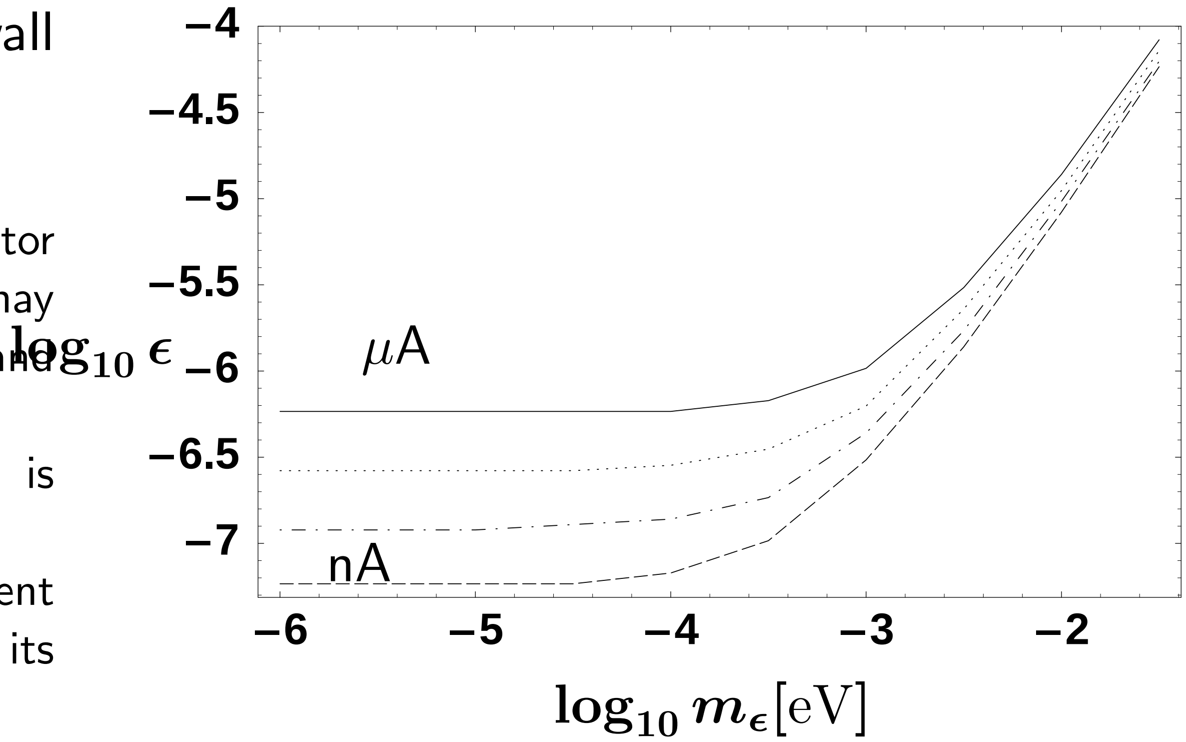


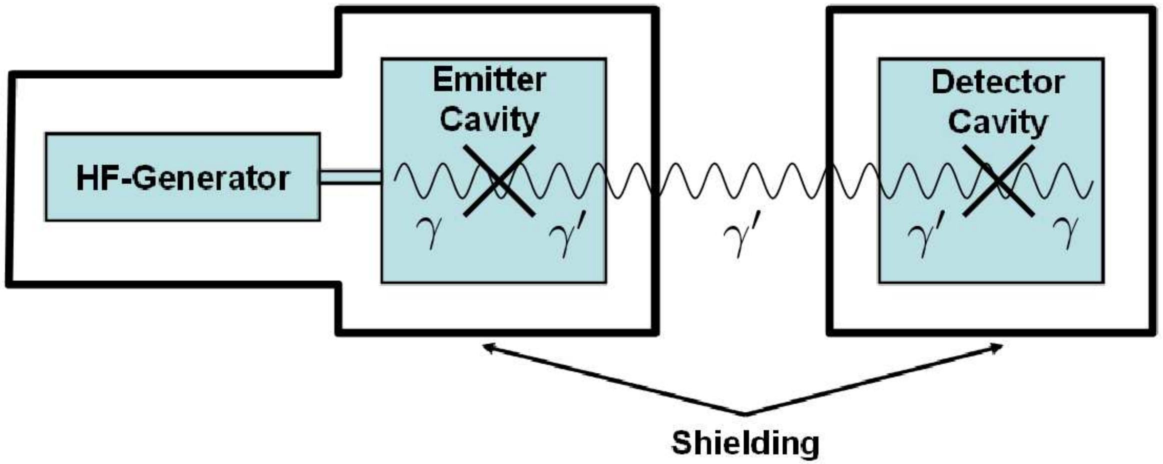
[Ahlers,Gies,Jaeckel,AR in prep.]

5. Microwave Cavity Experiments

- High quality cavities can also be exploited to search for

  [Jaeckel,AR '07]

  – γ's



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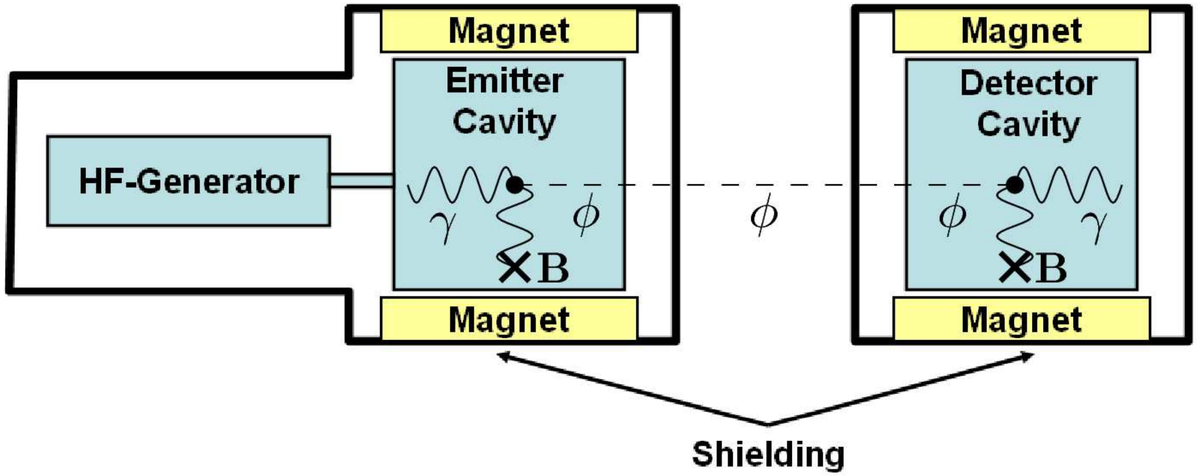


[Jaeckel,AR '07]

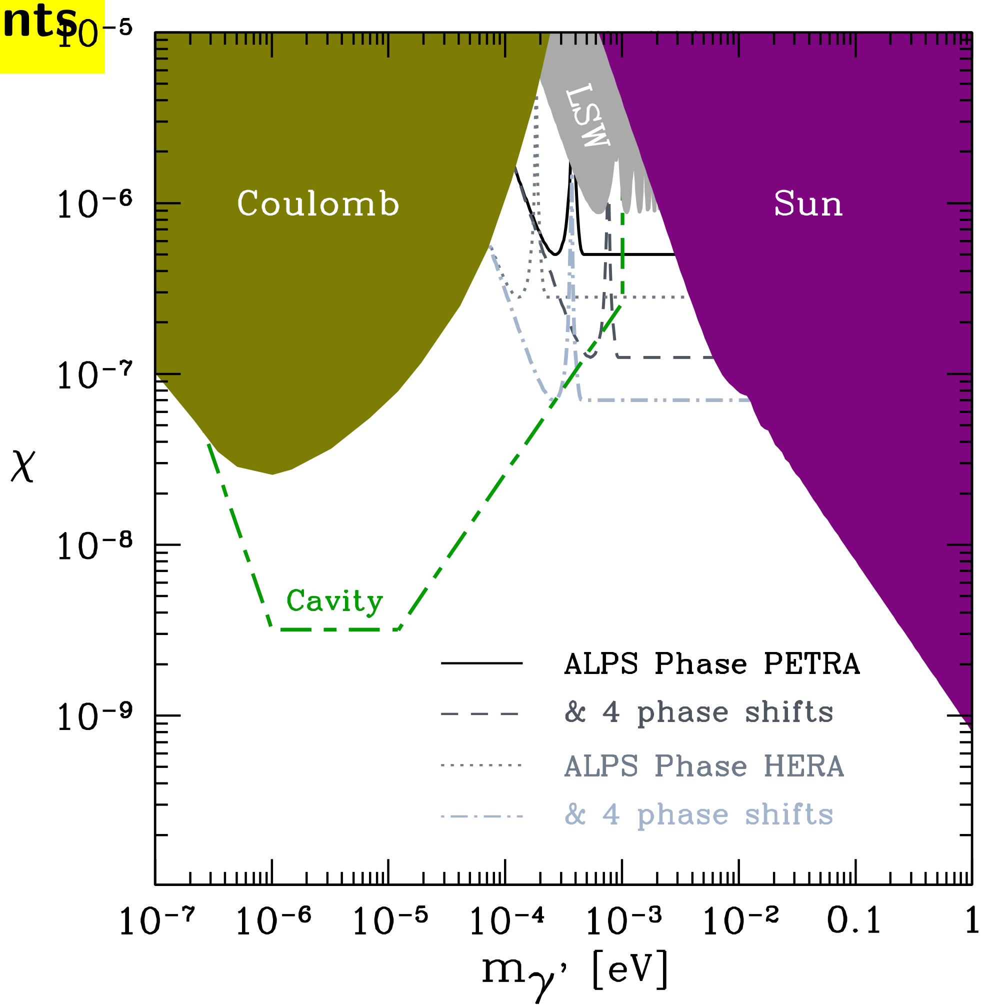
5. Microwave Cavity Experiments

- High quality cavities can also be exploited to search for

[Jaeckel,AR '07]

  - γ's
  - ALPs

- Microwaves permeating through a shielding:
  - substantial reach in parameter space for γ's
  - may reach CAST's ALPs sensitivity with presently available technology



[Ahlers *et al* '07]

6. Conclusions

- A low-energy frontier is forming worldwide:

  Fundamental physics with low energy photons and spare parts from high-energy frontier accelerators

- Unlike for terascale accelerators (LHC, ILC), there is no “no-loose theorem”:

  Perhaps there is no new physics at the milliscale

- However, if a WISP is found, it may have immediate applications ...