Are There Ultralight Particles in the Hidden Sector?

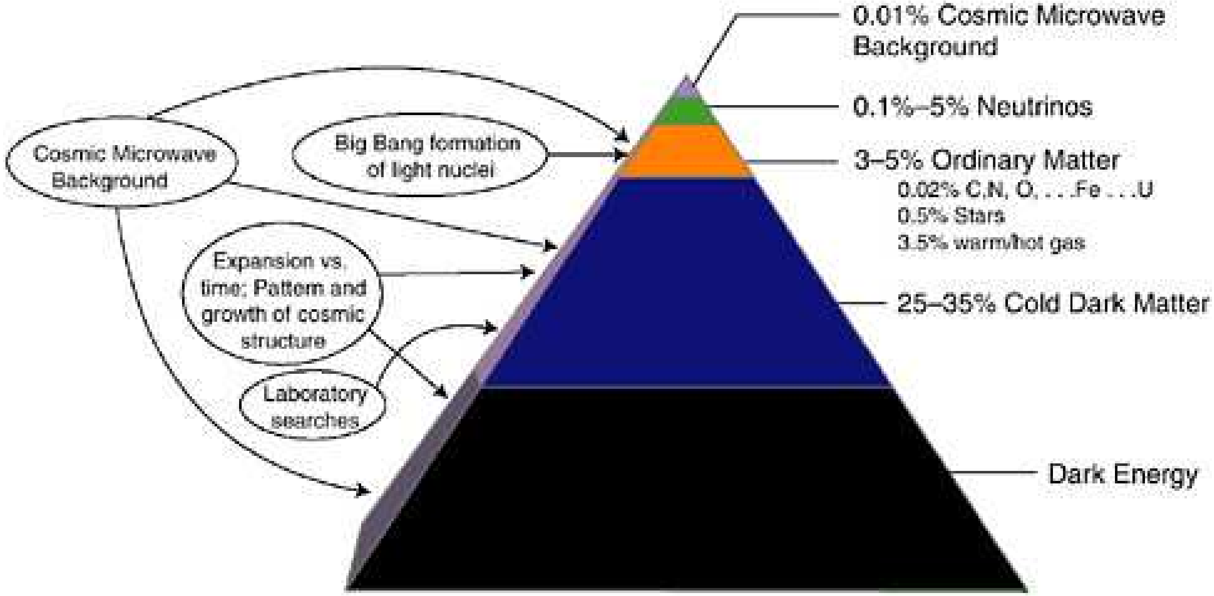
– Particle Physics with Low-Energy Photons –

Andreas Ringwald

TH Colloquium, CERN, 10 June 2009, Geneva, CH

1. Introduction

- Hints for new particles beyond standard model:
  - **Dark matter:** WIMP or WISP?
  - **Dark energy:** ultralight cosmon?



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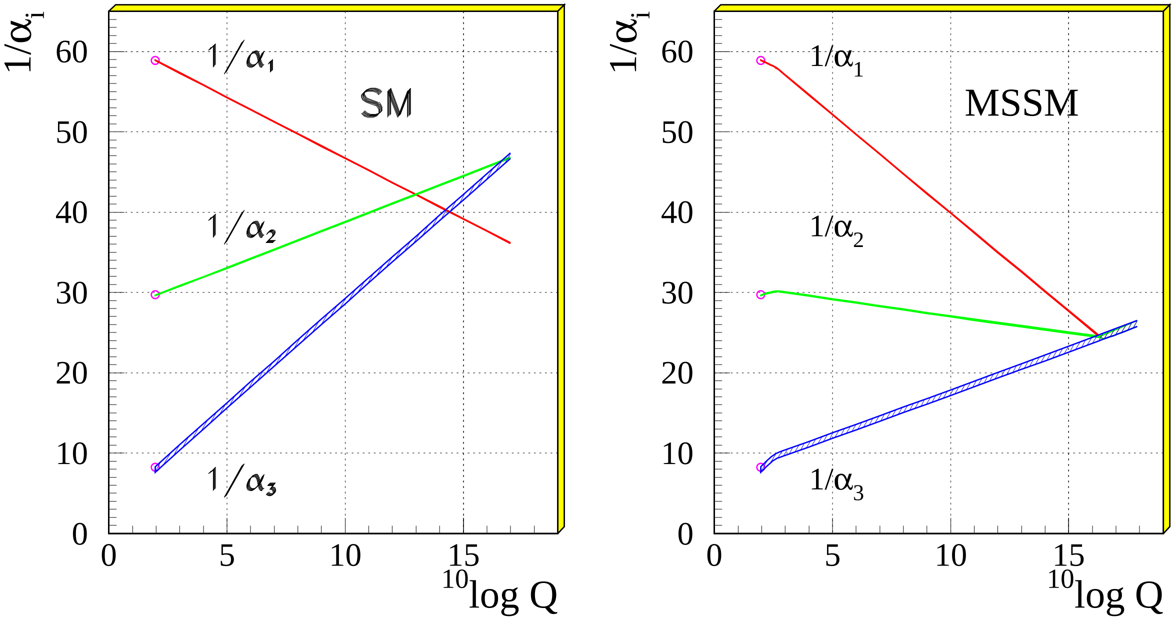
  - **Unification of forces:** heavy superpartners?

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



[Amaldi, de Boer, Fürstenau '91]

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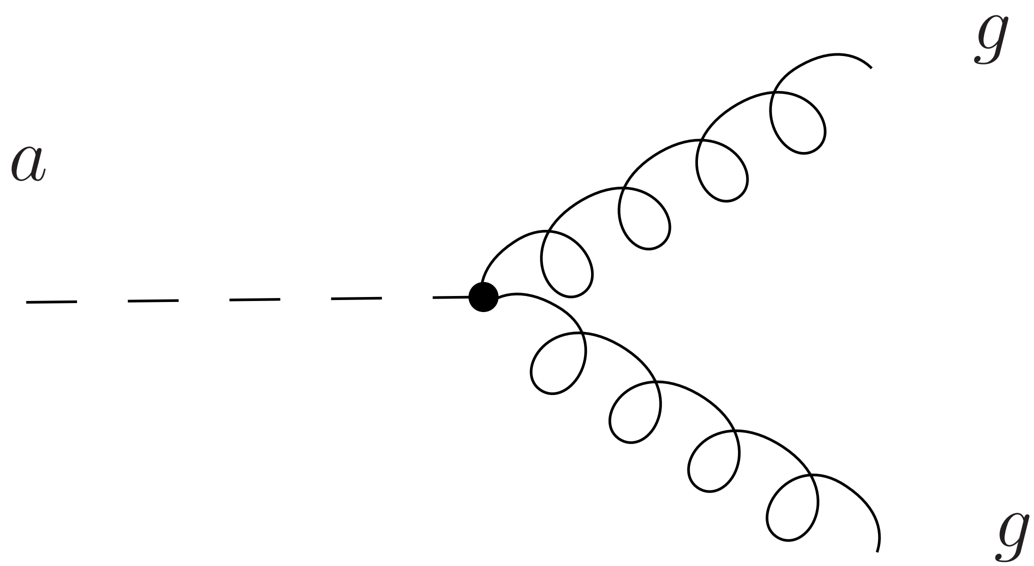
  - **Strong CP problem:** ultralight axion?



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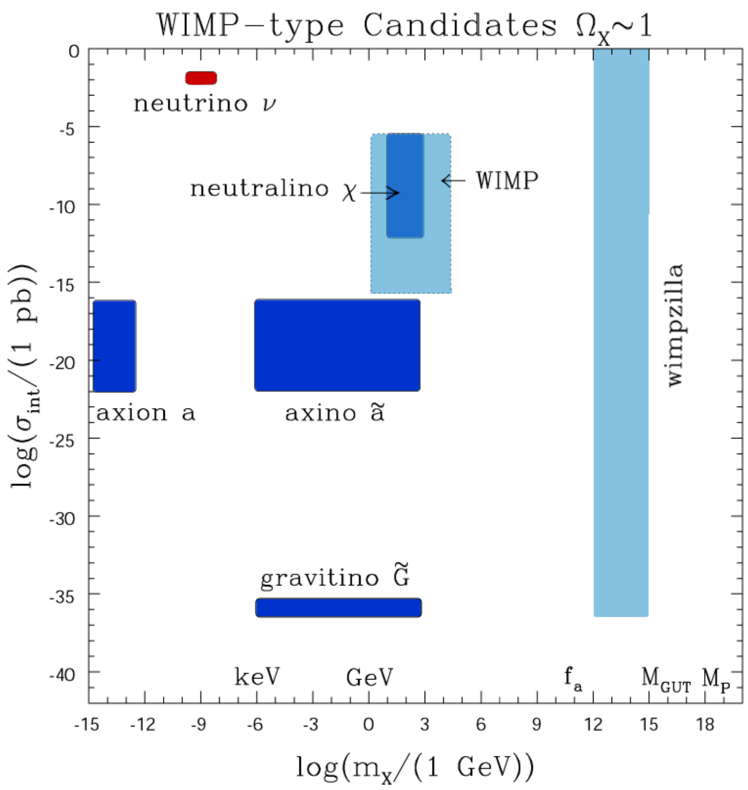
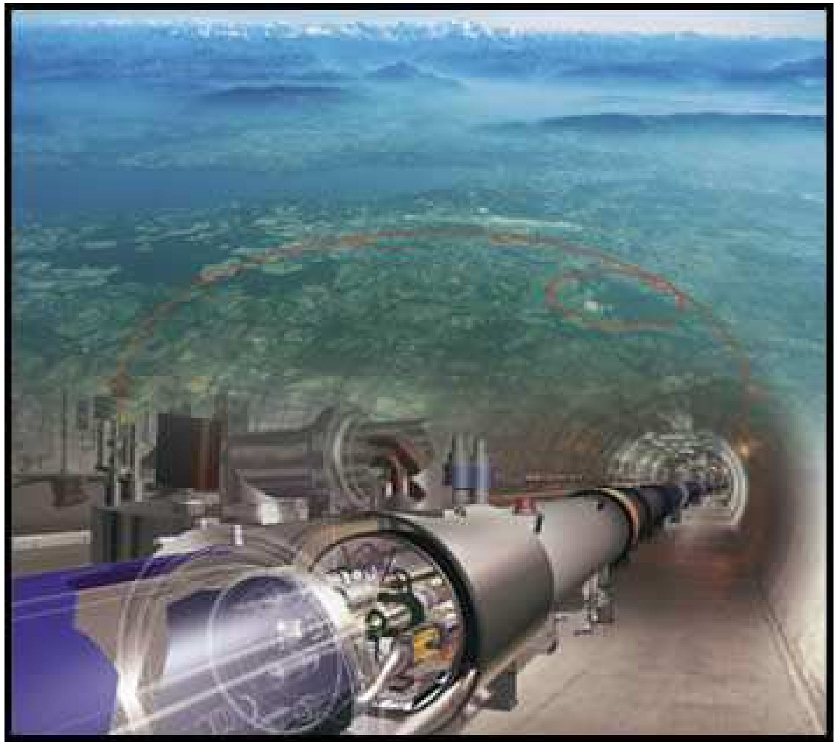


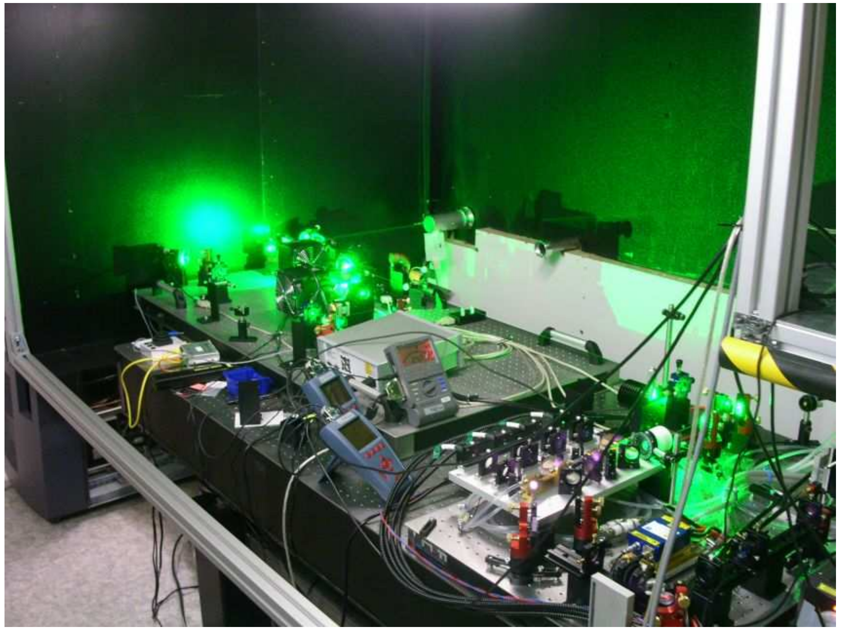
[Roszkowski]

- Physics at the Terascale:
  The Large Hadron Collider (LHC) has a huge discovery potential for WIMPs



- Physics at the Terascale:
  The Large Hadron Collider (LHC) has a huge discovery potential for WIMPs

- Physics at the Milliscale:
  Experiments exploiting low-energy photons and/or large electromagnetic fields have considerable discovery potential for WISPs



Outline:

2. **Axions and Axion-Like Particles**
3. **Ultralight Hidden-Sector Particles**
4. **Light Shining Through a Wall**
5. **Microwave Cavity Experiments**
6. **Conclusions**

2. Axions and Axion-Like Particles

- **Strong CP problem:** Due to non-Abelian nature of QCD, additional CP-violating term in the Lagrangian,

$$\mathcal{L}_{\mathrm{CP-viol.}} = \frac{\alpha_s}{4\pi}\,\theta\,\mathrm{tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu} \equiv \frac{\alpha_s}{4\pi}\,\theta\,\frac{1}{2}\,\epsilon^{\mu\nu\alpha\beta}\,\mathrm{tr}\,G_{\mu\nu}G_{\alpha\beta}$$

  – Effective CP-violating parameter in standard model,

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

  – Upper bound on electric dipole moment of neutron $\Rightarrow$

$$|\bar{\theta}| \lesssim 10^{-10}$$

  – **Unnaturally small!**

- **Peccei-Quinn solution to the strong CP problem:**

  – Introduce global anomalous chiral $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry, spontaneously broken by the vev of a complex scalar $\langle\Phi\rangle = f_a e^{ia/f_a}$ [Peccei,Quinn '77]
  – Axion field a shifts under a $\mathrm{U}(1)_{\mathrm{PQ}}$ transformation, $a \to a + \mathrm{const.}$
  ⇒ Low-energy effective Lagrangian:

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_a^{\mathrm{int}}\left[\frac{\partial_\mu a}{f_a};\psi\right] + \frac{r\alpha_s}{4\pi f_a}\, a \,\mathrm{tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{s\alpha}{8\pi f_a}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

  – $\bar\theta$-term in $\mathcal{L}_{\mathrm{SM}}+\mathcal{L}_a$ can be eliminated by exploiting the shift symmetry, $a \to a - \bar\theta f_a/r$
  – Topological charge density $\propto \langle \mathrm{tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}\rangle \neq 0$ provides nontrivial potential for axion field ⇒ axion is pseudo-Nambu-Goldstone boson

[S.Weinberg '78; Wilczek '78]

Mass obtained via chiral perturbation theory: [S.Weinberg '78]

$$m_a = \frac{r\, m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.6\,\mathrm{meV} \times \left(\frac{10^{10}\,\mathrm{GeV}}{f_a/r} \right)$$

– For large f_a: axion is ultralight and invisible:

[J.E. Kim '79; Shifman *et al.* '80; Dine *et al.* '81;...]

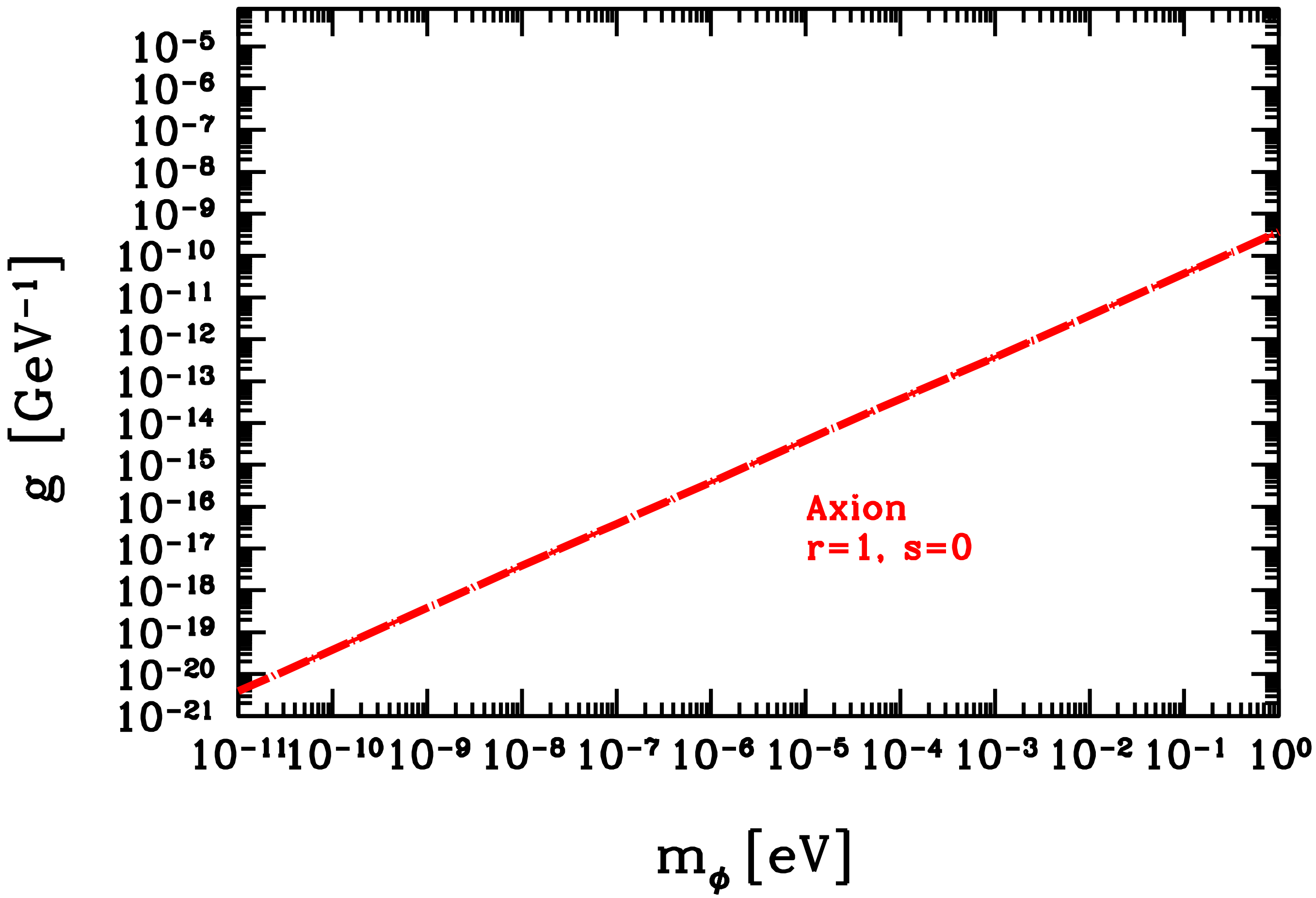
e.g. coupling to photons,

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

with [Bardeen,Tye '78; Kaplan '85; Srednicki '85]

$$g = \frac{r\alpha}{2\pi f_a} \left(\frac{2}{3} \frac{m_u + 4m_d}{m_u + m_d} - \frac{s}{r} \right) \sim 10^{-13}\ \mathrm{GeV}^{-1} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a/r} \right)$$

- Generic prediction for axion:



- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications [Svrcek,Witten '06]

  – Model-independent axion of weakly coupled heterotic string: dual of $B_{\mu\nu}$, with μ and ν tangent to 4d Minkowski spacetime:

$$f_a = \frac{g_s^2}{\sqrt{2\pi V_6 M_s^2}} = \frac{\alpha_C M_P}{2\pi\sqrt{2}}$$

$$\simeq 10^{16}\ \text{GeV}$$

$$m_a \simeq 10^{-9}\ \text{eV}$$

- Heterotic string:

  – 10d low-energy Lagrangian:

$$\mathcal{L}_{10\text{d}} = \frac{2\pi M_s^8}{g_s^2}\sqrt{-g}R - \frac{M_s^6}{2\pi g_s^2}\frac{1}{4}\text{tr}F\wedge\star F - \frac{2\pi M_s^4}{g_s^2}\frac{1}{2}H\wedge\star H + \dots$$

  – Compactify 6 extra dimensions:

$$\mathcal{L}_{4\text{d}} = \frac{M_P^2}{2}\sqrt{-g}R - \frac{1}{4g_{\text{YM}}^2}\sqrt{-g}\text{tr}F_{\mu\nu}F^{\mu\nu} - \frac{1}{f_a^2}\frac{1}{2}H\wedge\star H + \dots$$

$\Rightarrow$ Read off coefficients:

$$M_P^2 = \frac{4\pi}{g_s^2}M_s^8 V_6;\quad g_{\text{YM}}^2 = \frac{4\pi g_s^2}{M_s^6 V_6};\quad f_a^2 = \frac{g_s^2}{2\pi M_s^4 V_6}$$

$\Rightarrow$ Large $M_s = \sqrt{\alpha_{\text{YM}}/(4\pi)}\, M_P$

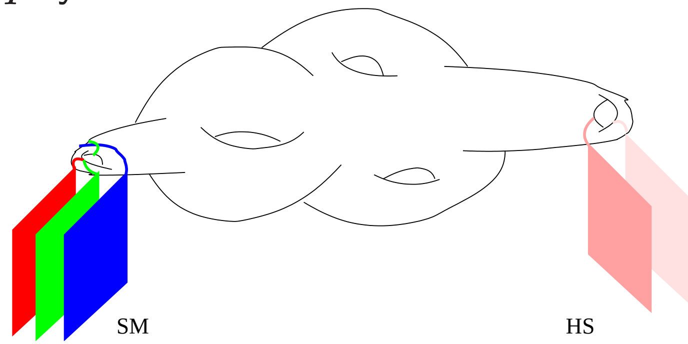
- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications [Svrcek,Witten '06]
  - Axions in intersecting D-brane models in type II string theory come from zero modes of the RR gauge fields C

$$f_a \sim M_s$$

$\Rightarrow$ wider range of possibilities
  - Plenitude of zero modes $\Rightarrow$ axion-like particles
  - Stückelberg axions associated with anomalous U(1)s

[Coriano,Irges,Kiritsis '06]

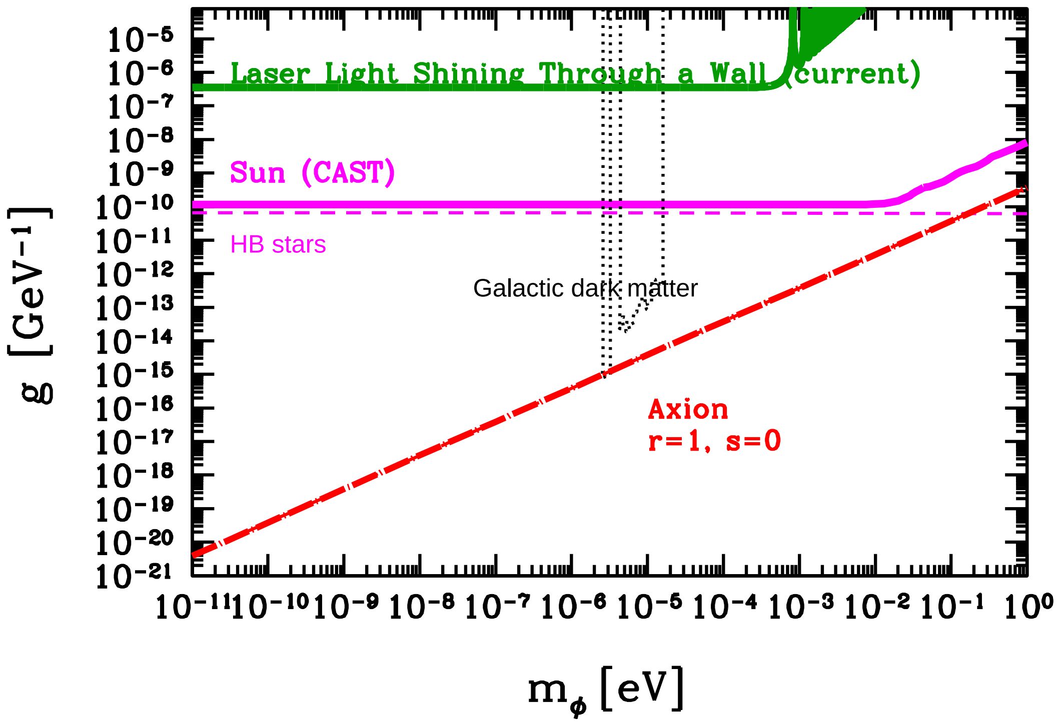
- Intersecting D-brane models:
  - Gauge theory lives on D$(3+q)$-branes, extending along the 4 non-compact dimensions and wrapping a q-cycle in the extra dimensions



  - Gravity lives in all 10 dimensions
  - Smaller string scale because of large volume, $M_s \sim g_s M_P / \sqrt{V_6 M_s^6}$; can be as low as $\sim$TeV

- Constraints on coupling of axion-like particles (ALPs) to photons:

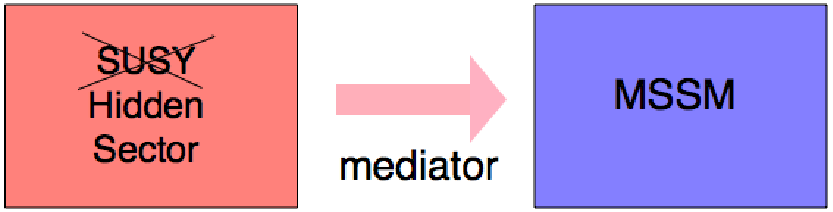
[Raffelt; ...]



Photon regeneration due to ALP-γ oscillations (light shining through a wall; CERN Axion Solar Telescope (CAST); galactic dark matter search); energy loss (lifetime of Helium Burning (HB) stars)

3. Ultralight Hidden-Sector Particles

- Extensions of standard model based on supergravity or superstrings predict "hidden sector" of particles which are very weakly coupled to the "visible sector" standard model particles; cf. "gravity mediation" of SUSY breaking



- Sector "hidden" $\Leftrightarrow$ mediators heavy and/or very weakly coupled
- Possible WISPs: hidden sector U(1) gauge bosons ("hidden photons" γ') and hidden sector particles charged under the hidden U(1) ($\Rightarrow$ "mini-charged particles" (MCPs))
- More models with ultralight hidden U(1)s: mirror world or extreme, 10^{32} copies of SM [Foot,...;Dvali,...]

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $E_8 \times E_8$ heterotic closed string theory

Orbifold compactifications of heterotic string theory:
e.g. [Buchmüller *et al.* '07;. . .]

$$E_8 \times E_8 \longrightarrow G_{SM} \times U(1)^4 \times \left[SU(4) \times SU(2) \times U(1)^4 \right]$$

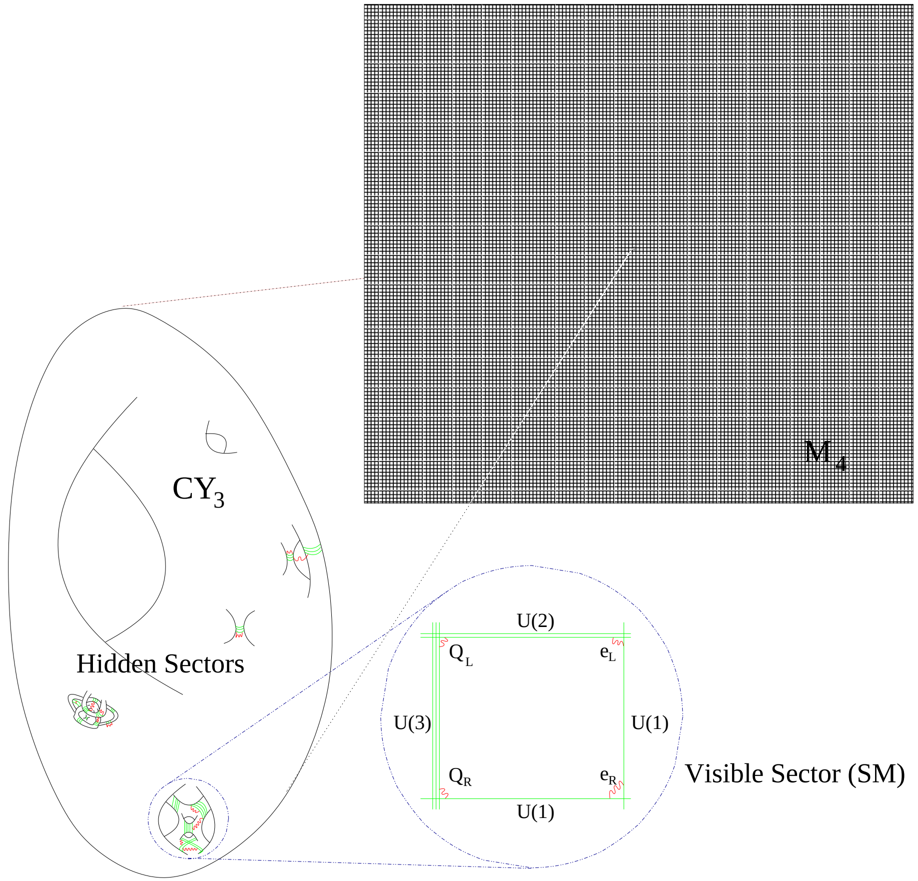
or [Lebedev *et al.* '07]

$$E_8 \times E_8 \longrightarrow G_{SM} \times U(1)^4 \times \left[SO(8) \times SU(2) \times U(1)^3 \right]$$

and many more

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $E_8 \times E_8$ heterotic closed string theory
  - IIA/IIB open string theory with branes

Compactification of type II string theory:



[..,Conlon,Quevedo,..]

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
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  - IIA/IIB open string theory with branes

- Some hidden U(1) gauge bosons and hidden charged fermions may remain massless or light

⇒ Dominant interaction with standard model: gauge kinetic mixing and minicharge (for Chern-Simons like coupling: [Antoniadis,Boyarski,Ruchayski])

- Low-energy effective Lagrangian: [Holdom '85]

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\mathrm{U(1)_v}} \underbrace{-\frac{1}{4}B^{\mu\nu}B_{\mu\nu}}_{\mathrm{U(1)_h}} \underbrace{+\frac{1}{2}\chi\, F^{\mu\nu}B_{\mu\nu}}_{\text{kin mix}}$$
$$\underbrace{+\bar{v}(\mathrm{i}\partial\!\!\!/ + eA\!\!\!/)v}_{\text{v matter}} \underbrace{+\bar{h}(\mathrm{i}\partial\!\!\!/ + e_h B\!\!\!/)h}_{\text{h matter}} + \ldots$$

  - 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 messenger particles generically tends to generate $\chi \neq 0$:
  - Diagonalization of kinetic term, $B^\mu \to \tilde{B}^\mu + \chi A^\mu$;
  - Hidden sector charged particle gets induced electric charge:

$$e_h \bar{h} B\!\!\!/ h \quad \to \quad e_h \bar{h} \tilde{B}\!\!\!/ h + \chi e_h \bar{h} A\!\!\!/ h$$

$$\Rightarrow \quad Q_h^{\mathrm{vis}} \equiv \epsilon e = \chi e_h$$

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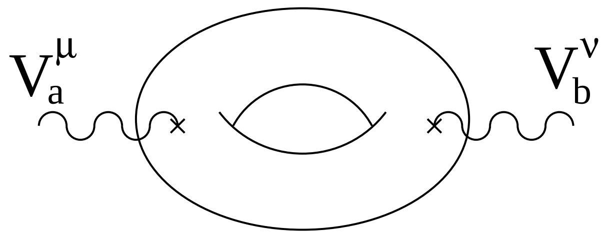
KM in heterotic string models:

[Dienes,Kolda,March-Russell '97]



$$\chi \simeq \frac{e e_h}{16\pi^2} C \frac{\Delta m}{M_P} \gtrsim 10^{-17},$$

for $C \gtrsim 10$, $\triangle m \gtrsim 100$ TeV

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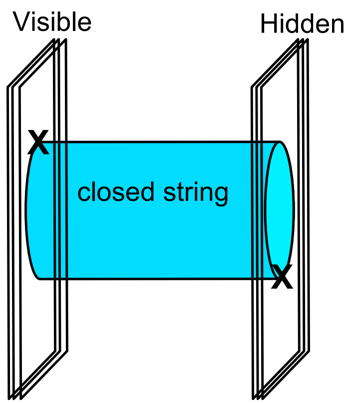
KM in IIA/IIB string models:

[Lüst,Stieberger '03;Abel,Schofield '04;Berg,Haack,Körs '05]



e.g. mixing with U(1) residing on D7 brane wrapping LARGE 4-cycle

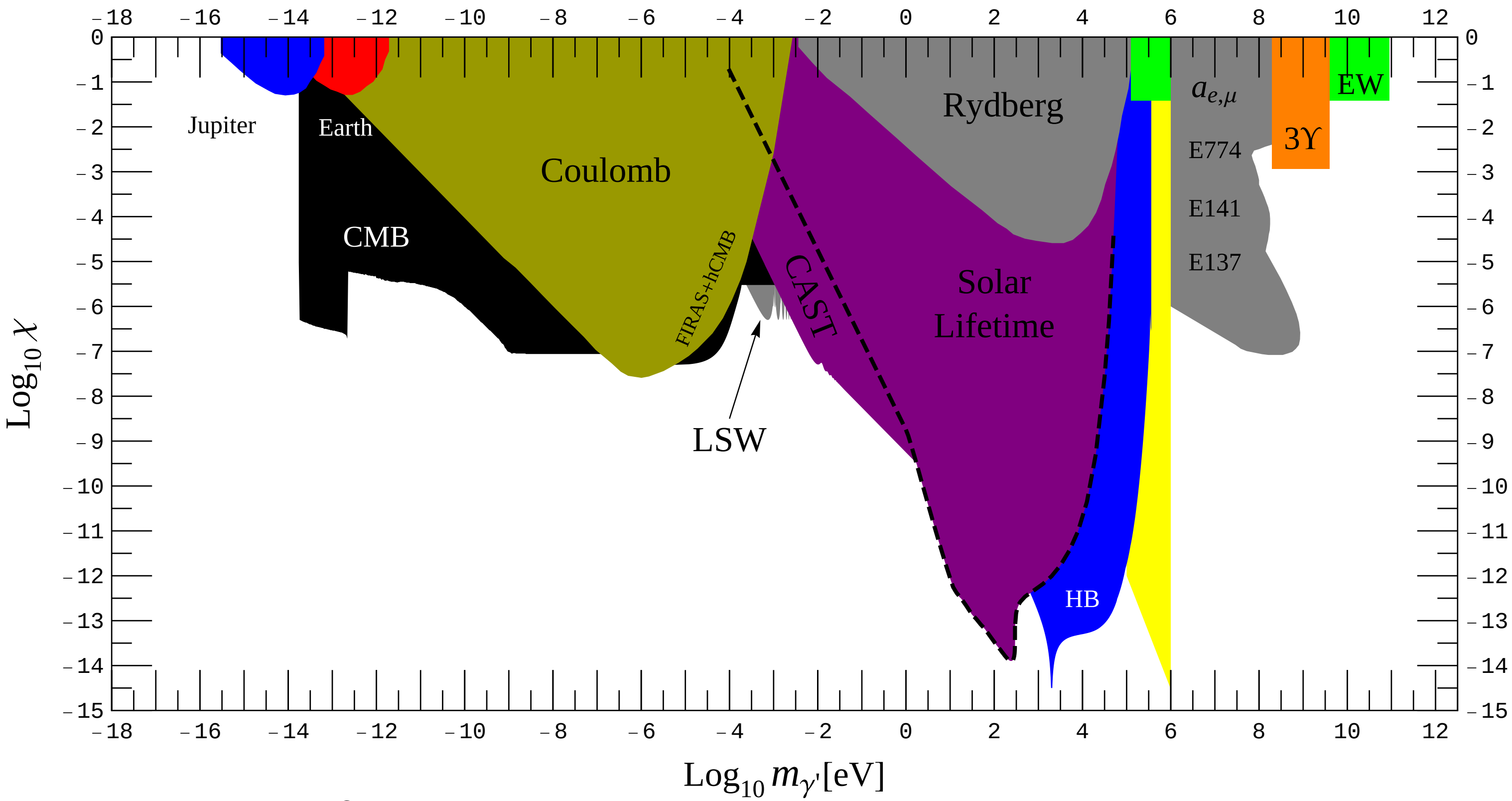
$$\chi \sim \frac{e\, e_h}{16\pi^2} \sim \frac{g_s}{8\pi}(V_6 M_s^6)^{-1/3} \gtrsim 10^{-12},$$

for $V_6 M_s^6 \lesssim 10^{30}$ (i.e. $M_s \gtrsim$ TeV)

[Goodsell,Jaeckel,Redondo,AR '09]

- The rich phenomenology of hidden U(1)s:

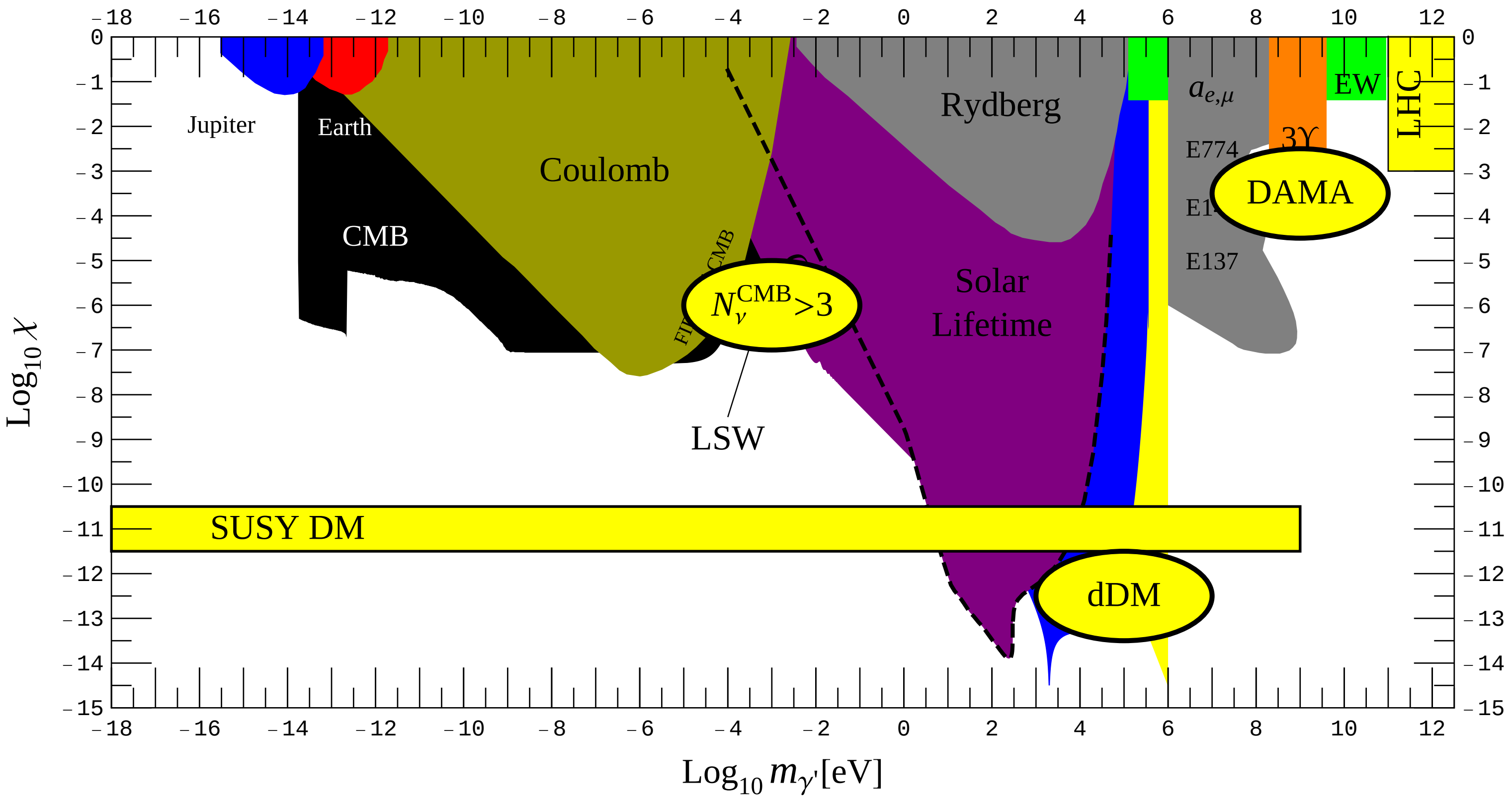
[Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08;...]



Deviations from $1/r^2$ (Jupiter,Coulomb); $\gamma \leftrightarrow \gamma'$ oscillations (CMB,Light Shining through a Wall (LSW); stellar evolution (Sun,HB,dDM); fixed target; e^+e^- (Υ,EW)

- The rich phenomenology of hidden U(1)s:

[Jaeckel,Redondo,AR '08;Postma,Redondo '08;Arkani-Hamed,..'08;Ibarra,AR,Weniger '08;Bjorken,Essig,Schuster,Toro '09;...]



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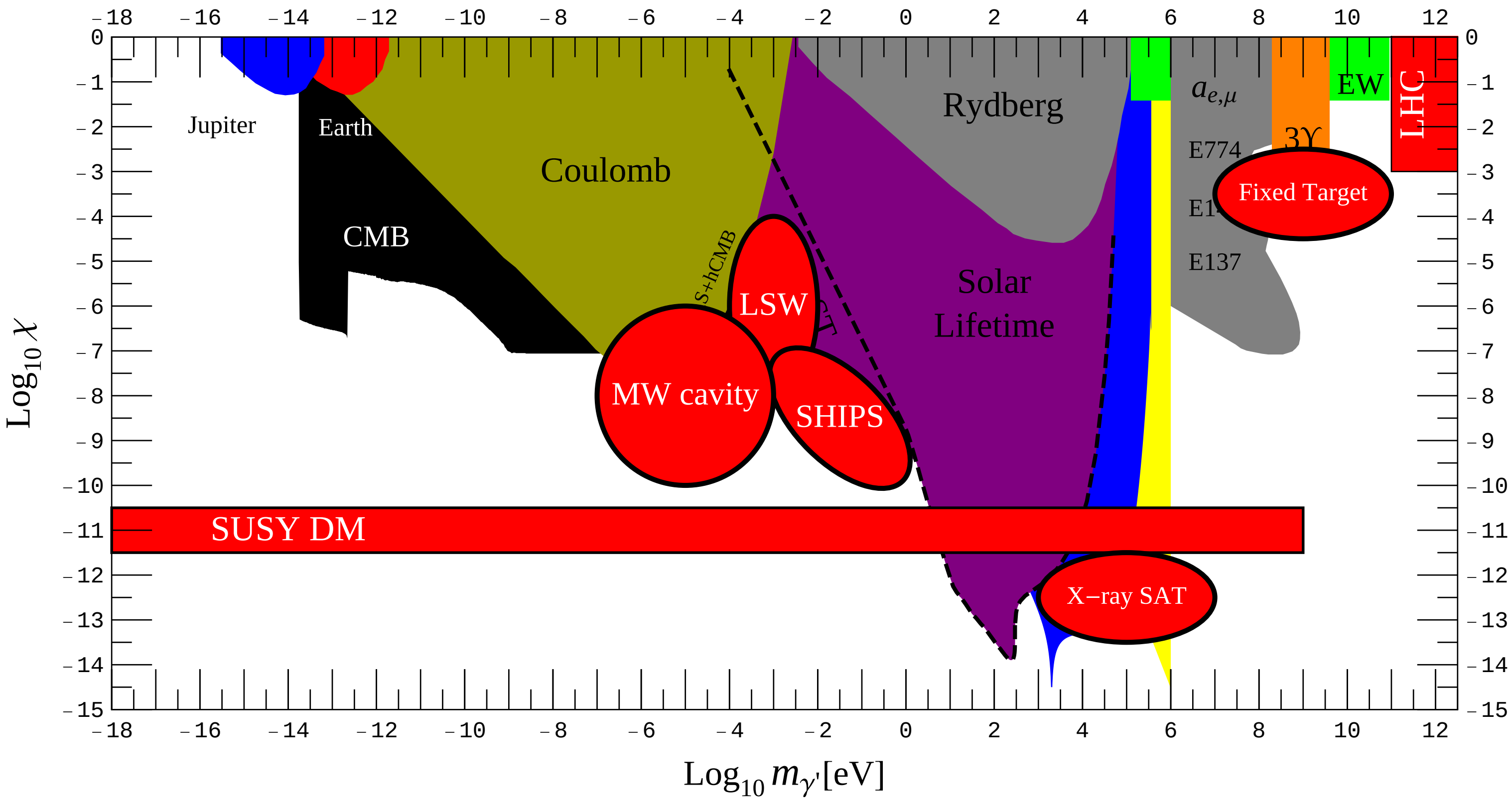
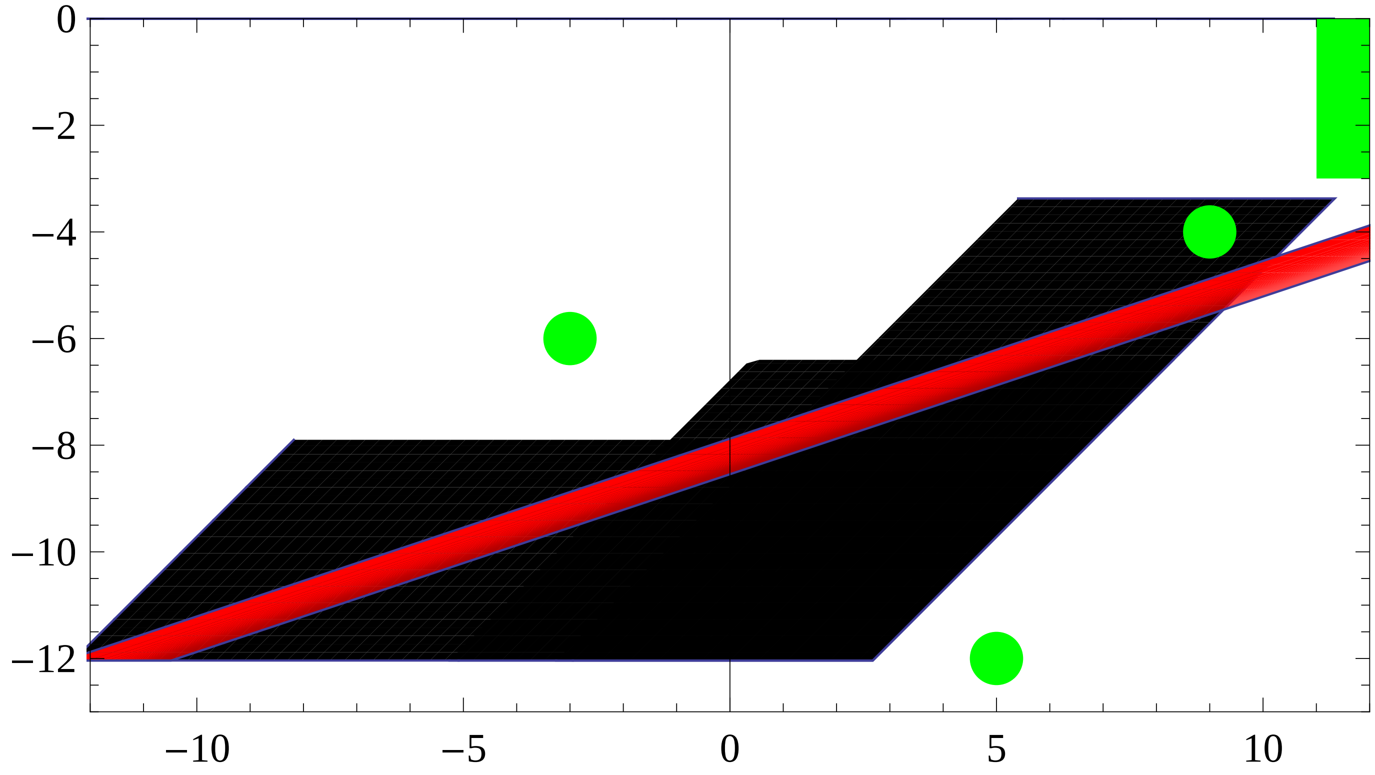
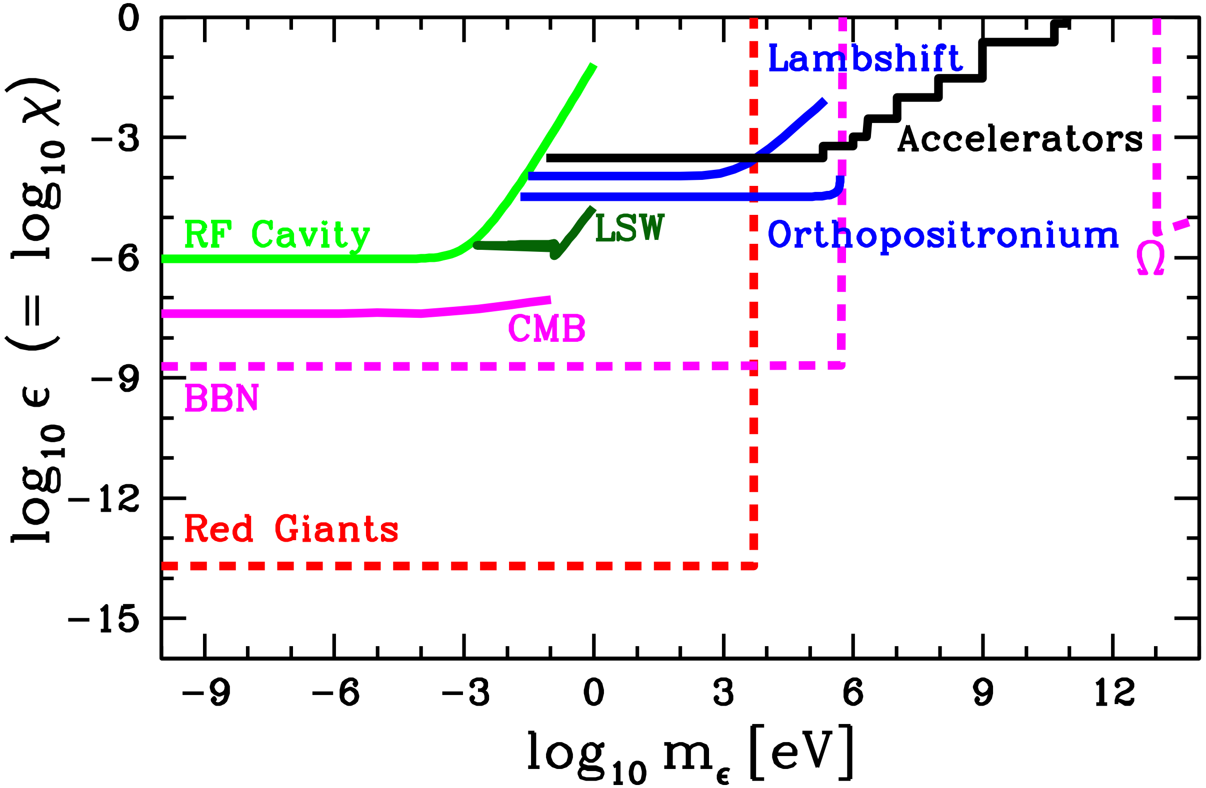


- Expectations in LARGE volume string compactifications (D7 brane wrapping LARGE 4-cycle): [Goodsell,Jaeckel,Redondo,AR in prep.]



- The rich phenomenology of minicharged particles: [Davidson,..'90;Gies,..'06;Ahlers,..'07;Melchiorri,..'07]



Energy loss (Red Giants, RF Cavity); cosmic expansion rate (BBN); deviations of black body spectrum (CMB); $\gamma \leftrightarrow \gamma'$ oscillations (LSW); ...

4. Light Shining through a Wall

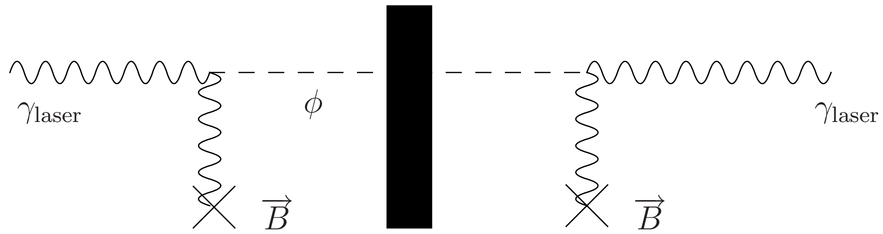
- Linearly polarized laser beam in vacuum or along a transverse magnetic field

- Place wall in beam pipe:
  - laser beam will be absorbed
  - neutral WISPs (ALP, γ') fly through wall and
  - reconvert on other side of wall into photons, which can be detected

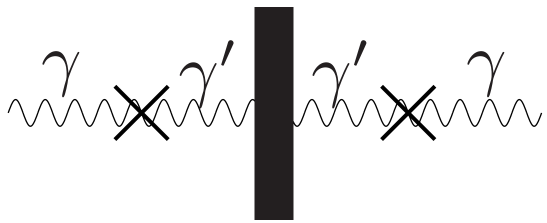
[Okun '82;Sikivie '83;Anselm '85;..]

LSW via

- photon-ALP oscillations:



- γ-γ' oscillations:



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Photon-WISP evolution along distance L:

$$i\frac{d}{dL}\begin{pmatrix} |\gamma\rangle \\ |\phi\rangle \end{pmatrix} = \frac{1}{2\omega}\begin{pmatrix} 0 & \delta \\ \delta & m_\phi^2 \end{pmatrix}\begin{pmatrix} |\gamma\rangle \\ |\phi\rangle \end{pmatrix}$$

[Okun '82;Stodolsky,Raffelt '87;Ahlers,Gies,Jaeckel,Redondo,AR '07]

WISP	$\delta_{\|\|}$	$\delta_\perp$	m_ϕ^2
ALP (0^-)	$g_- B^{\rm ext}\omega$	0	$m_{\phi_-}^2$
ALP (0^+)	0	$g_+ B^{\rm ext}\omega$	$m_{\phi_+}^2$
HP	$\chi m_{\gamma'}^2$	$\chi m_{\gamma'}^2$	$m_{\gamma'}^2$
MCP+HP	$-2\chi\omega^2\Delta N_{\|\|}$	$-2\chi\omega^2\Delta N_\perp$	$-2\omega^2\Delta N_{\|\|,\perp}$

Transition probability:

$$P(\gamma\to\phi) \simeq \frac{4\delta^2}{m_\phi^4}\sin^2\frac{m_\phi^2 L}{4\omega}$$

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

Experiment	Laser	$< P >$	Magnets
ALPS	532 nm; FP	30-300 W	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m
BFRT	~ 500 nm; DL	100 W	$B_1 = B_2 = 3.7$ T $\ell_1 = \ell_2 = 4.4$ m
BMV	1064 nm; LULI	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; FEL	300 W	$B_1 = B_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m
OSQAR	1064 nm; FP	> 1 kW	$B_1 = B_2 = 9.5$ T $\ell_1 = \ell_2 = 14$ m

- Pioneering experiment: BFRT

- Several ongoing experiments

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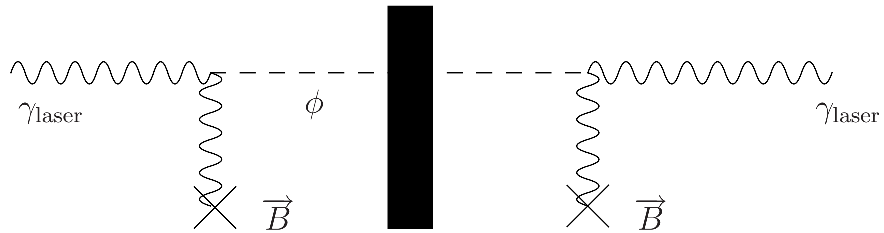
ALPS (Any-Light Particle Search):

[AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]



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

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ALPS (Any-Light Particle Search):

[AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]

- Primary beam: enhanced LIGO laser (1064 nm, 35 W cw)

$\Rightarrow$ frequency doubled to 532 nm

$\Rightarrow$ $\sim$ 100 fold power build up through resonant optical cavity (Fabry-Perot), $\sim 10\ \mu m$ focus

$\Rightarrow$ CCD camera: expect regenerated photons in signal region of a few pixel

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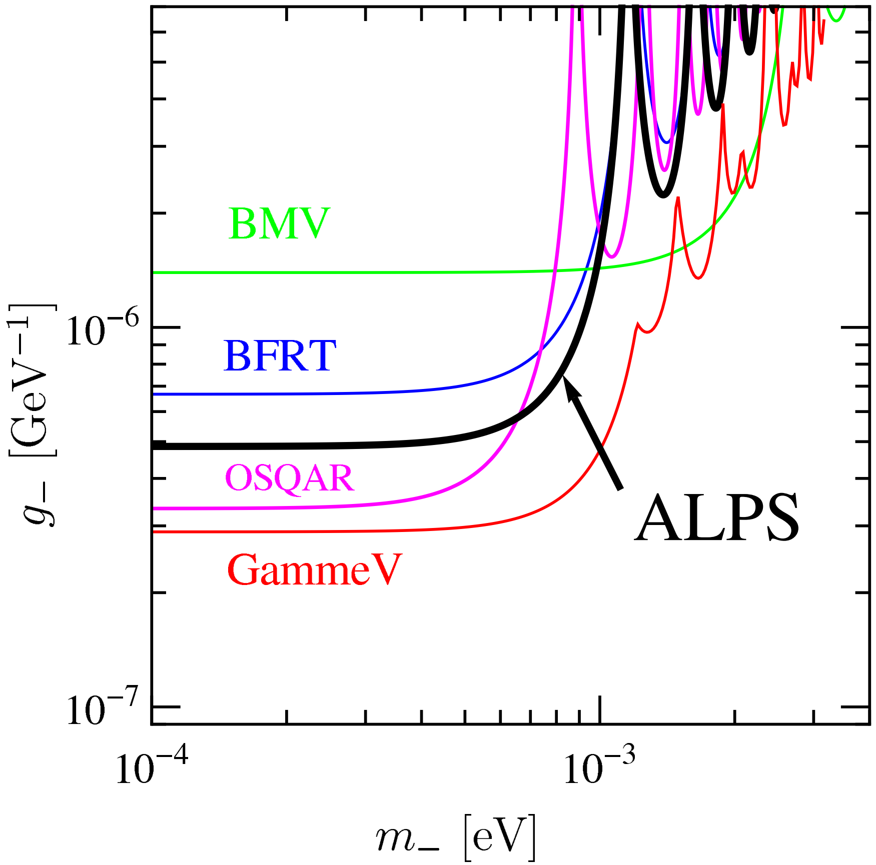
Limits from **ALPS** run in December 2008 (0.03 kW at 532 nm):



[ALPS Collaboration '09]

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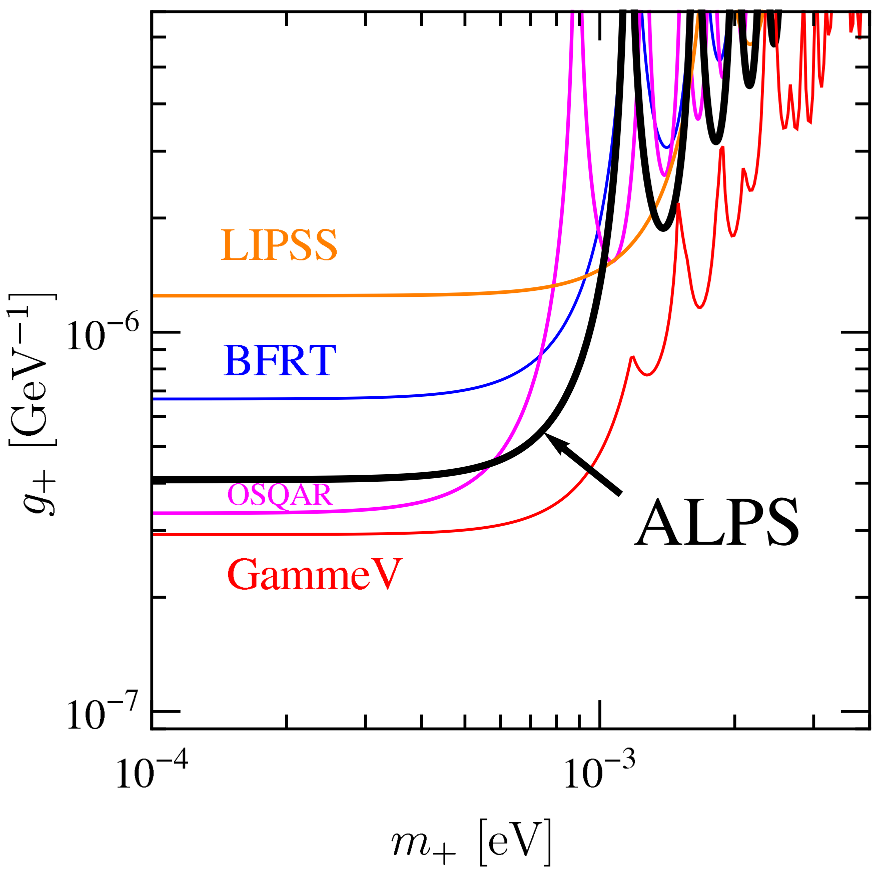

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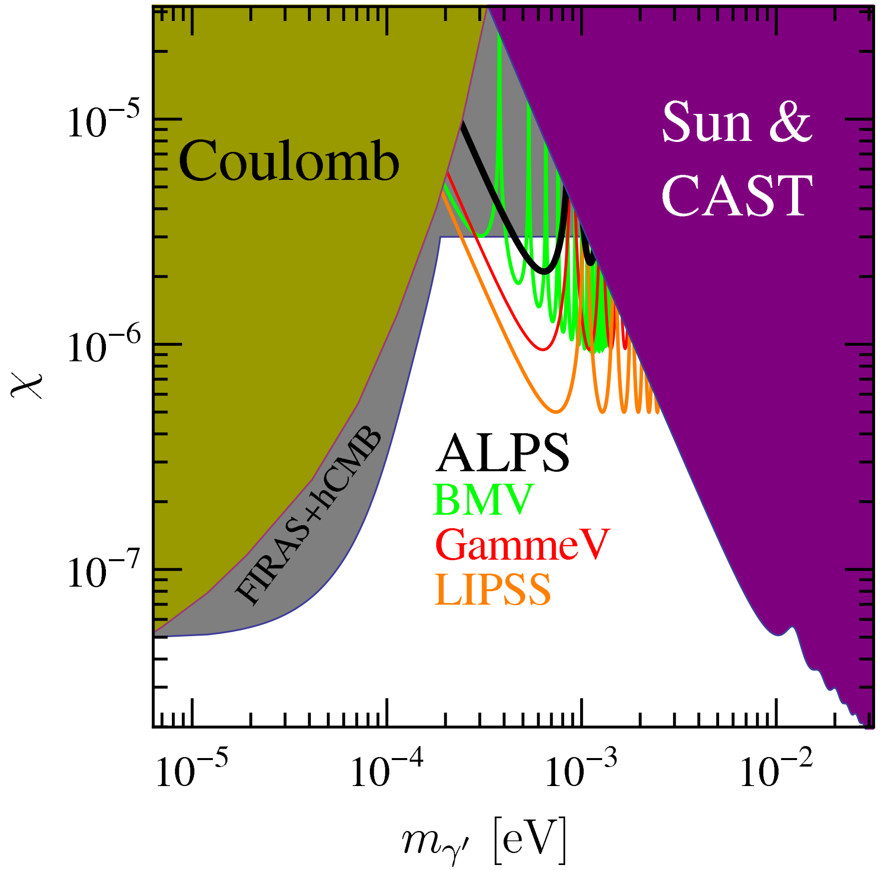
- Pioneering experiment: BFRT

- Several ongoing experiments

Limits from **ALPS** run in December 2008 (0.03 kW at 532 nm):



[ALPS Collaboration '09]

4. Light Shining through a Wall

- Linearly polarized laser beam in vacuum or along a transverse magnetic field

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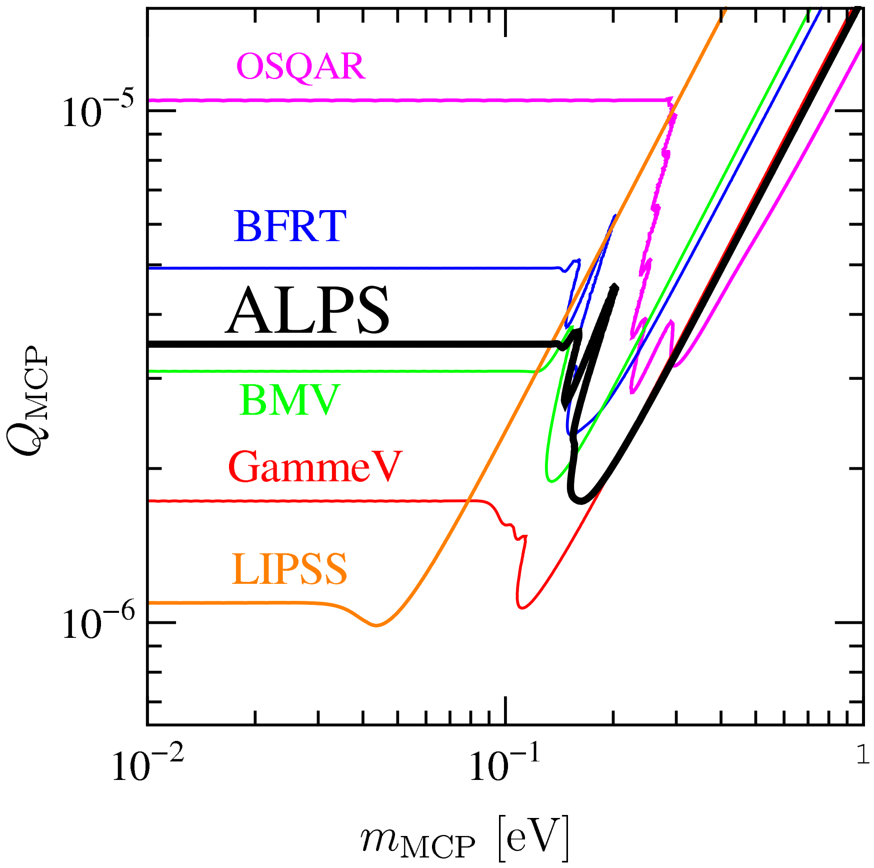

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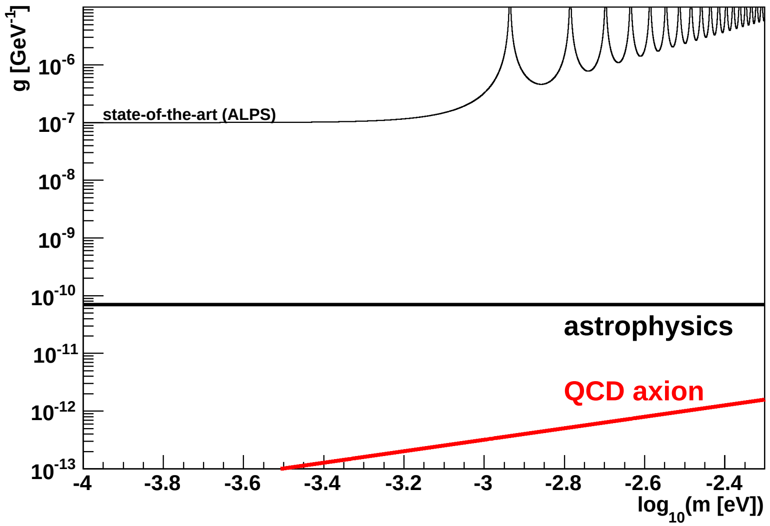
Roadmap of ALP search with LSW:



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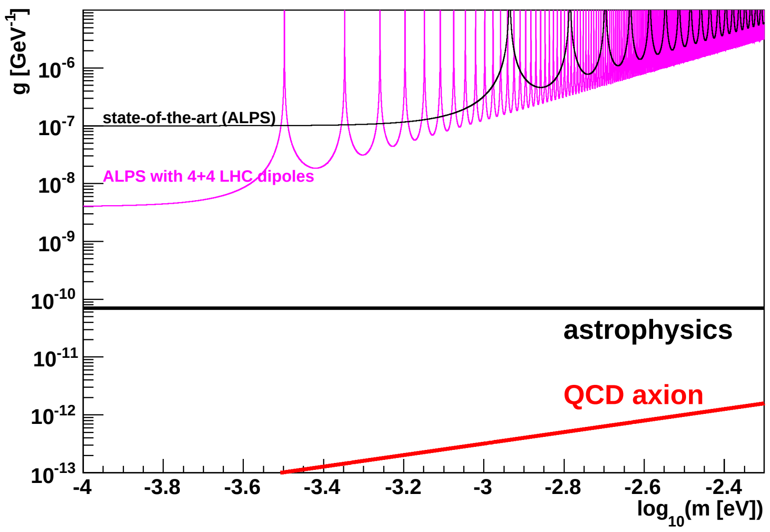

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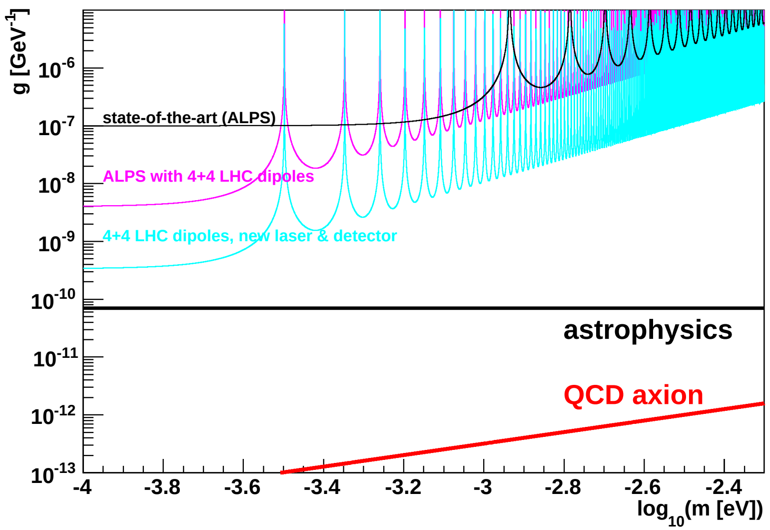

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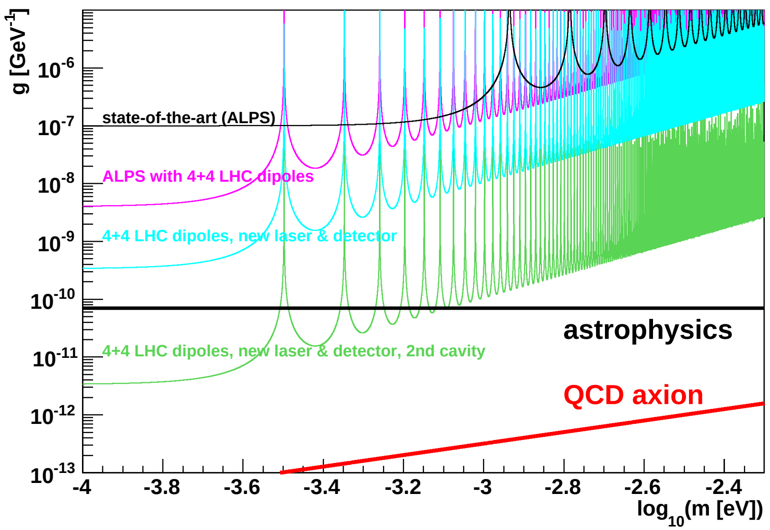

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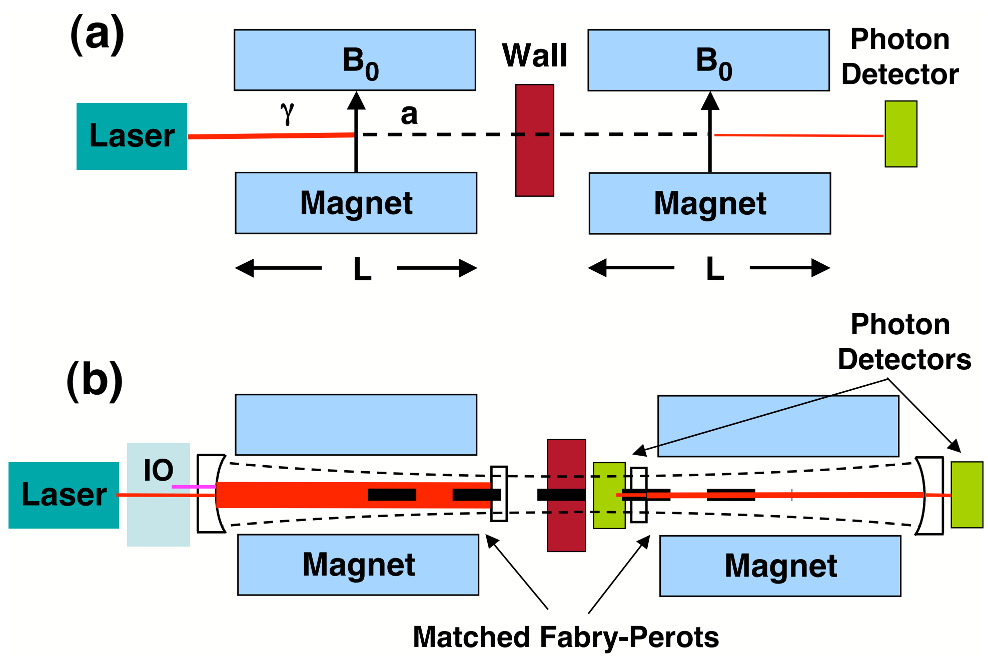
Second Fabry-Perot Cavity:

[Hoogeveen,Ziegenhagen '91;Sikivie,Tanner,van Bibber '07]



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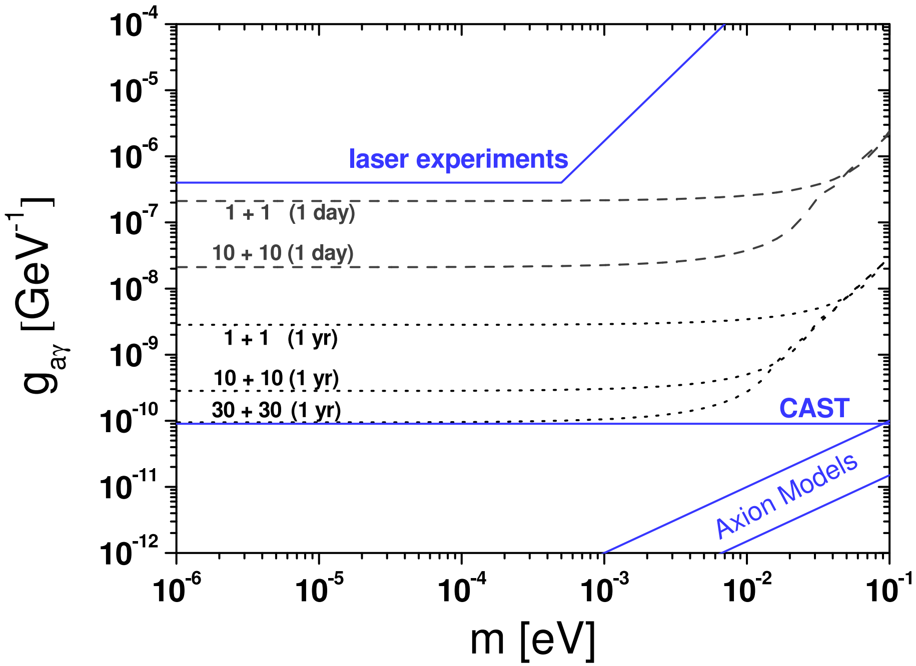
XFEL or synchrotron light through wall suffers from "low" photon flux

[Rabadan,AR,Sigurdson '06;Dias,Lugones '09]



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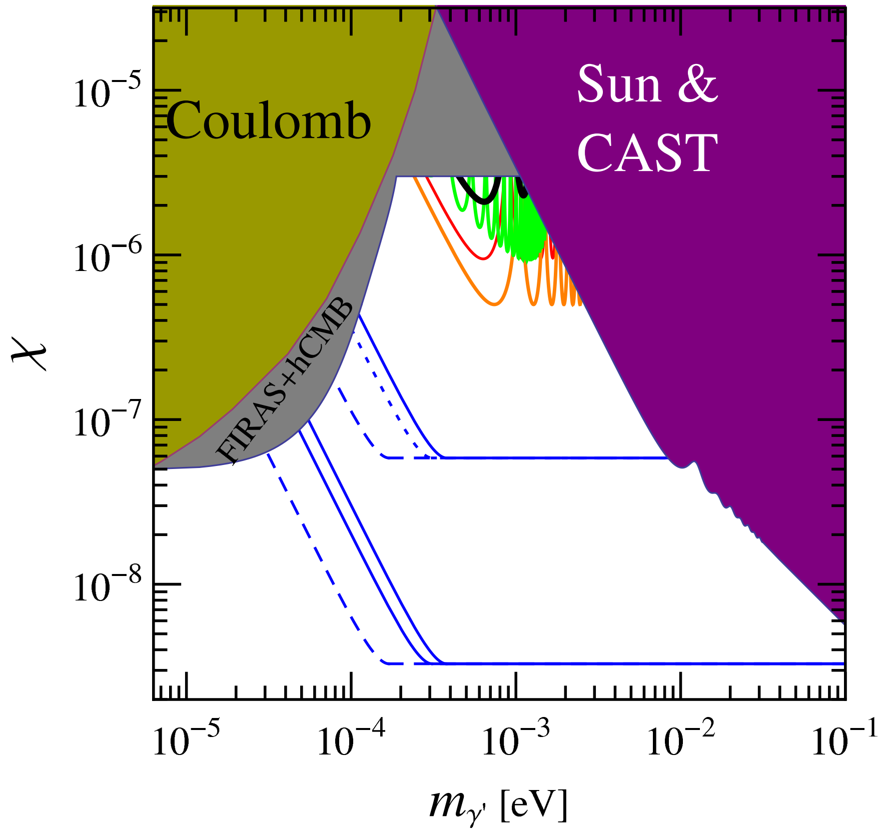


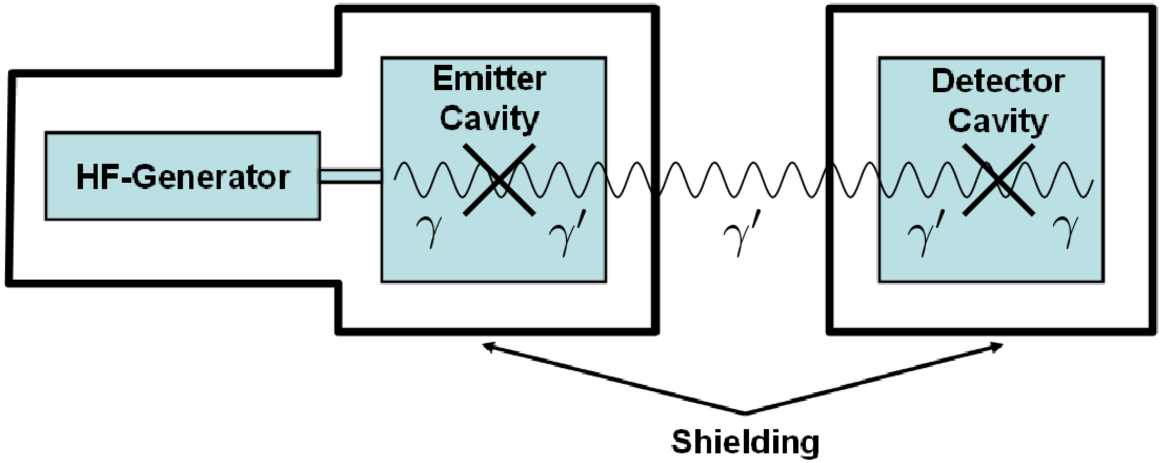
[Redondo '09]

5. Microwave Cavity Experiments

- High quality cavities can be exploited to search for

[Jaeckel,AR '07;Caspers,Jaeckel,AR in prep.]

  - γ'



[Jaeckel,AR '07]

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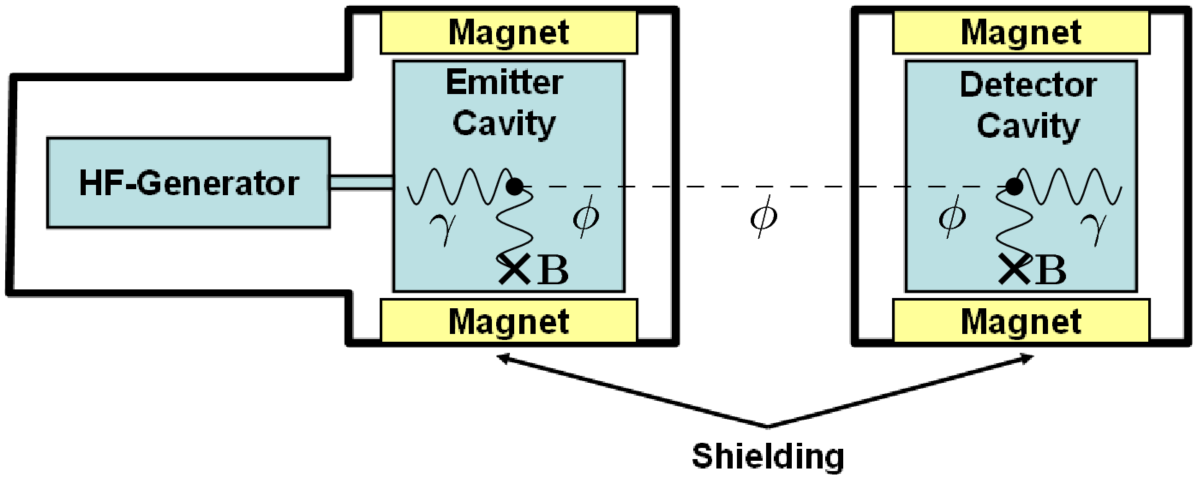
  [Jaeckel,AR '07;Caspers,Jaeckel,AR in prep.]

  – γ'
  – ALPs [Hoogeveen '92]



[Jaeckel,AR '07]

5. Microwave Cavity Experiments

- High quality cavities can be exploited to search for

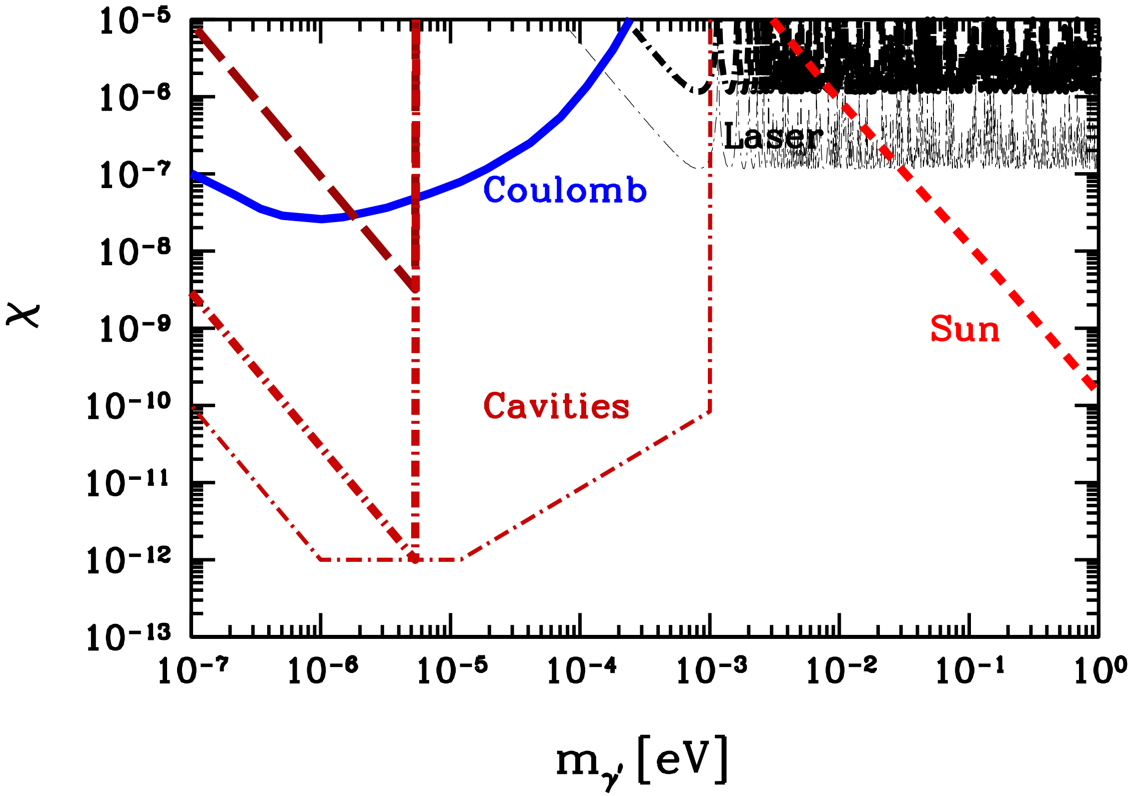
  [Jaeckel,AR '07;Caspers,Jaeckel,AR in prep.]

  – γ'
  – ALPs

- Discovery potential:

  – substantial reach in parameter space for γ'
  – may reach $g \sim 10^{-10}$ GeV^{-1} with presently available technology

- Yale: Experiment in progress



[Jaeckel,AR '07]

5. Microwave Cavity Experiments

- Current-Through-a-Wall:
  - In strong electric field of accelerator cavity, minicharged particles may be produced in pairs and accelerated along the beam axis

$$E^{e}_{\rm crit} = \frac{m_e^2}{e} \simeq 10^{18}\ \frac{\rm V}{\rm m}$$

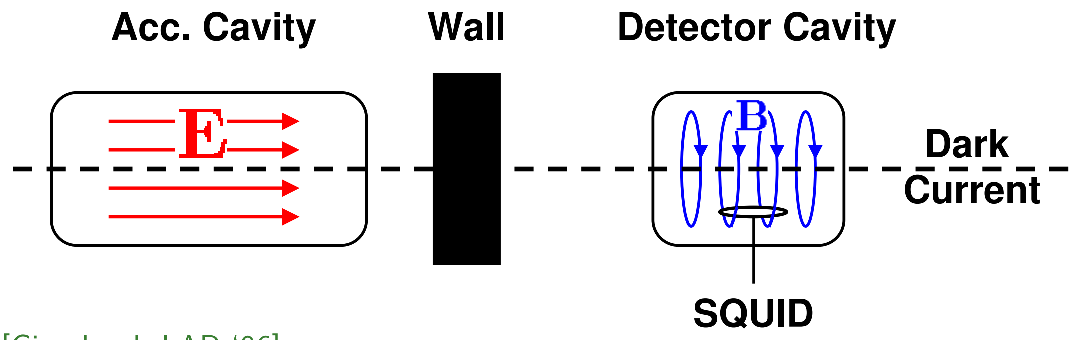
$$E^{\epsilon}_{\rm crit} = \frac{m_\epsilon^2}{\epsilon e} \simeq 5\ \frac{\rm MV}{\rm m}\ \frac{10^{-6}}{\epsilon}\left(\frac{m_\epsilon}{\rm meV}\right)^2$$

Accelerator cavity: few $\times 10$ MV/m
Focus of PW laser: few $\times 10^{14}$ V/m

5. Microwave Cavity Experiments

- 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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ACDC (Accelerator Cavity Dark Current):

- Cavity available

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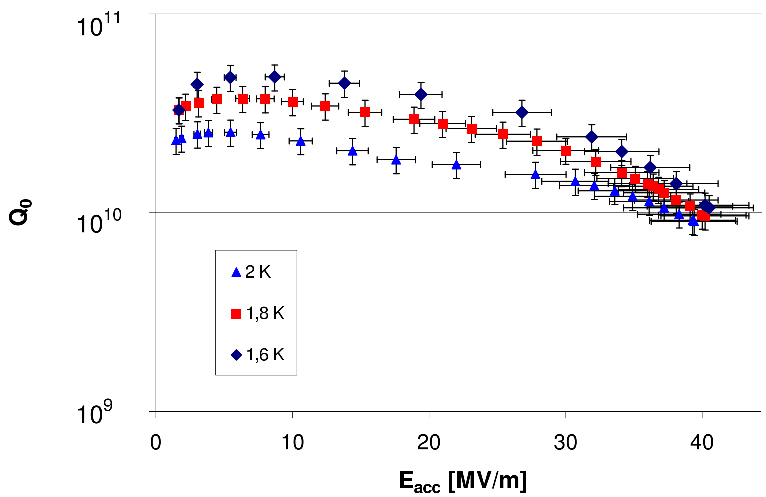

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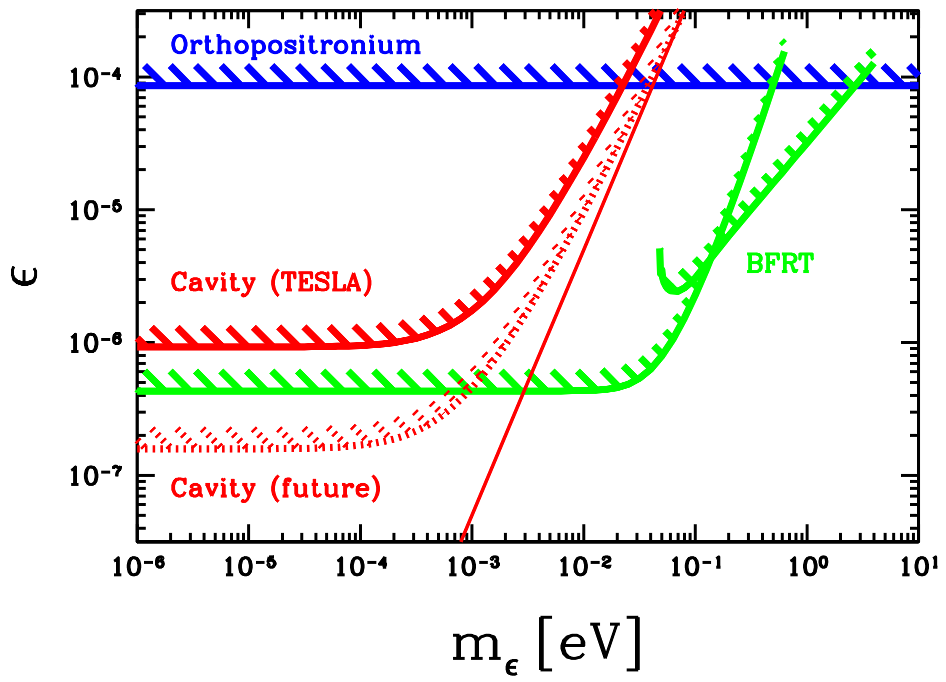

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[Gies,Jaeckel,AR '06]

ACDC (Accelerator Cavity Dark Current):

- Cavity and wall available

5. Microwave Cavity Experiments

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[Gies,Jaeckel,AR '06]

ACDC (Accelerator Cavity Dark Current):

- Cavity and wall available
- Measurement device available (in princ.)

5. Microwave Cavity Experiments

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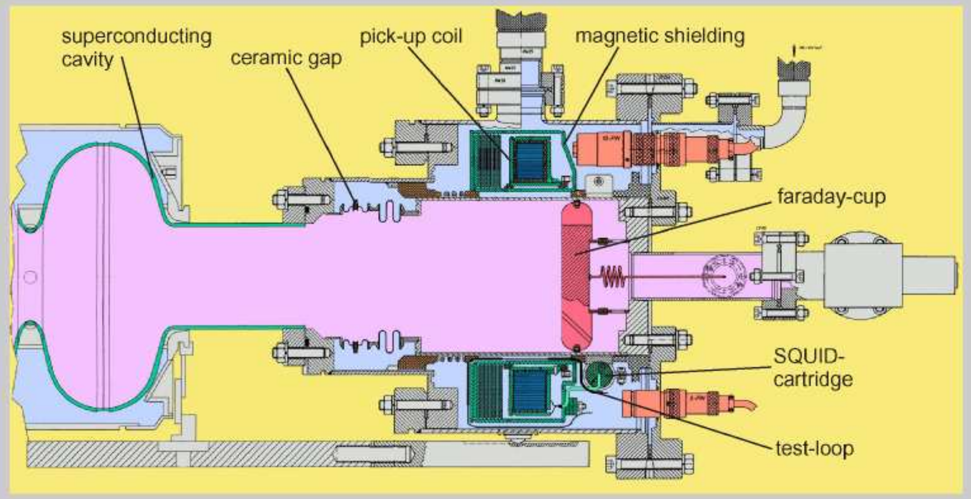

Construction details of the CCC dark current hardware

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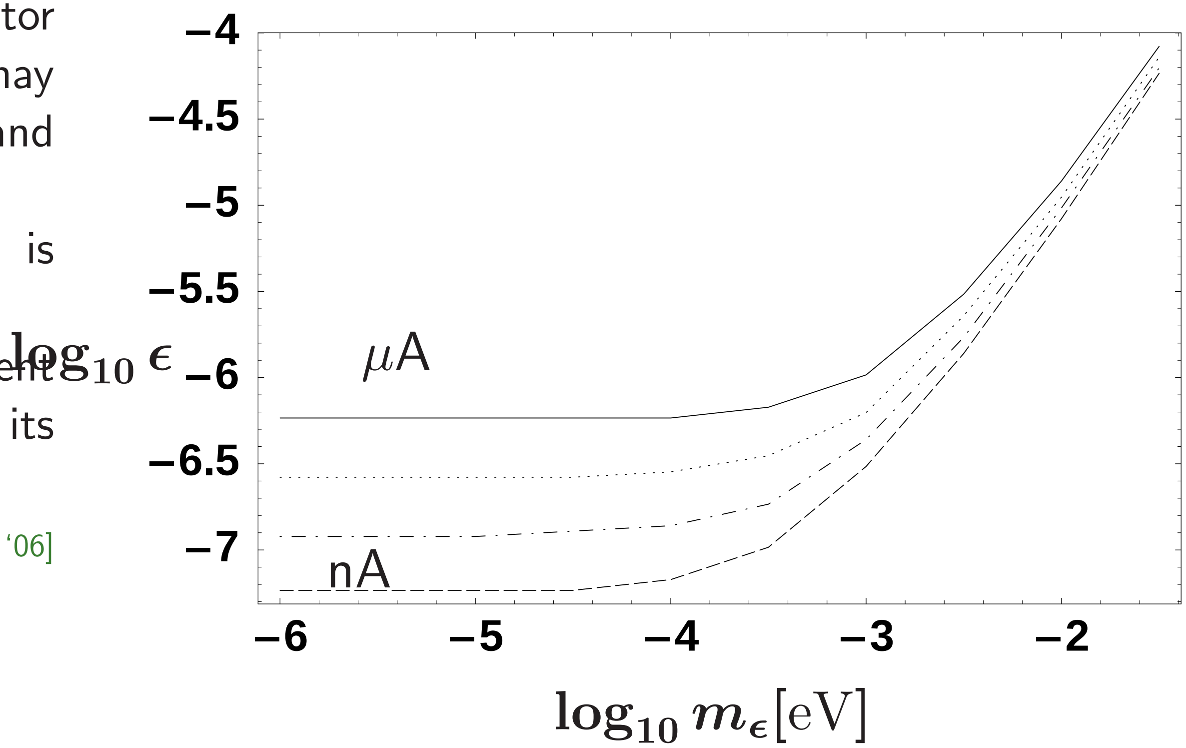

[Ahlers,Gies,Jaeckel,AR in prep.]

6. Conclusions

- A low-energy frontier is forming worldwide:

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

- These laboratory experiments have considerable discovery potential for ultralight particles beyond the standard model, which appear quite naturally in realistic string compactifications:
  - axion-like particles
  - hidden-sector U(1) gauge bosons
  - hidden-sector fermions charged under these extra U(1)s

- Theoretical predictions of masses and couplings very uncertain $\Rightarrow$ any experimental hint or constraint extremely welcome!

- In contrast to a WIMP: If a WISP is found, it may have immediate applications $\Rightarrow$ **Hidden Laser Communications!**

[Jaeckel,Redondo,AR '09]