Is There New Physics at the Milliscale?

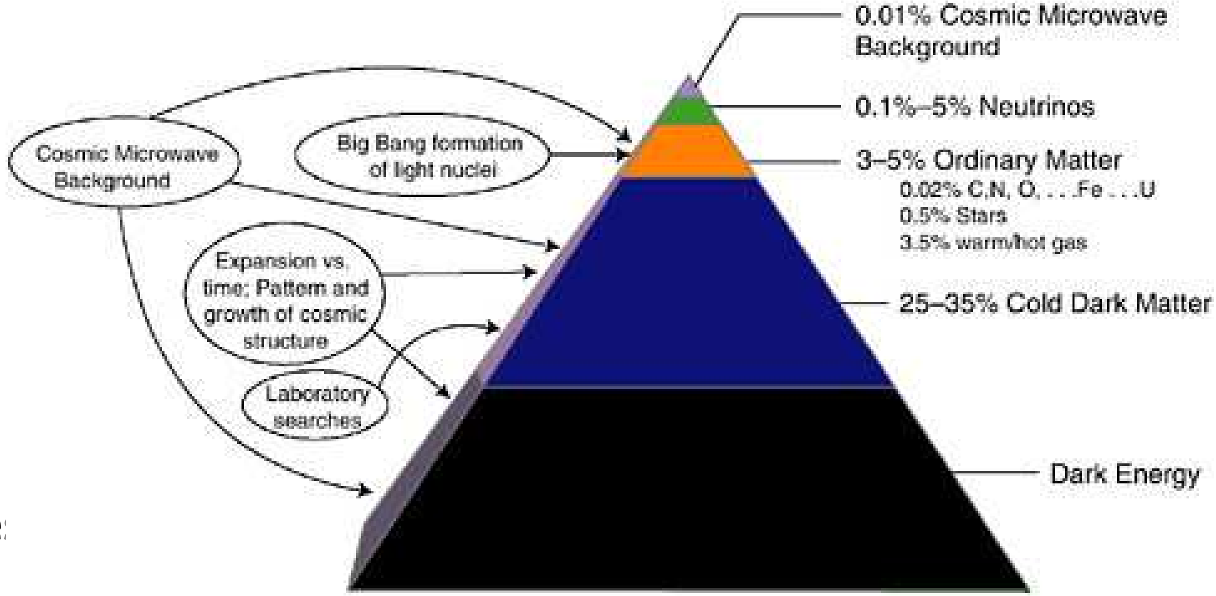
– Particle Physics with Low-Energy Photons –

Andreas Ringwald

Gentner-Kolloquium, MPI für Kernphysik, 27 May 2009,
Heidelberg, D

1. Introduction

- Hints for new particles beyond standard model:
  - **Dark matter:** WIMP or WISP?
  - **Dark energy:** ultralight cosmon?
  - **Unification of forces:** superpartners?
  - **Light neutrino masse[s]:** heavy neutrinos?
  - **Strong CP problem:** ultra-light axion?



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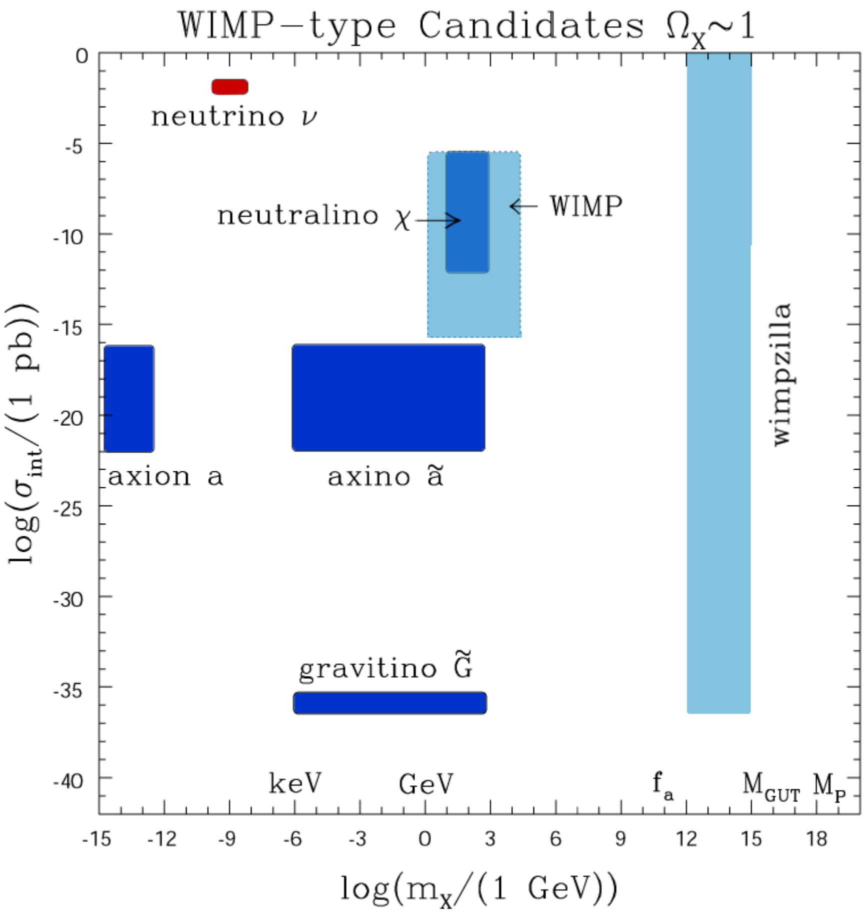

[Roszkowski]

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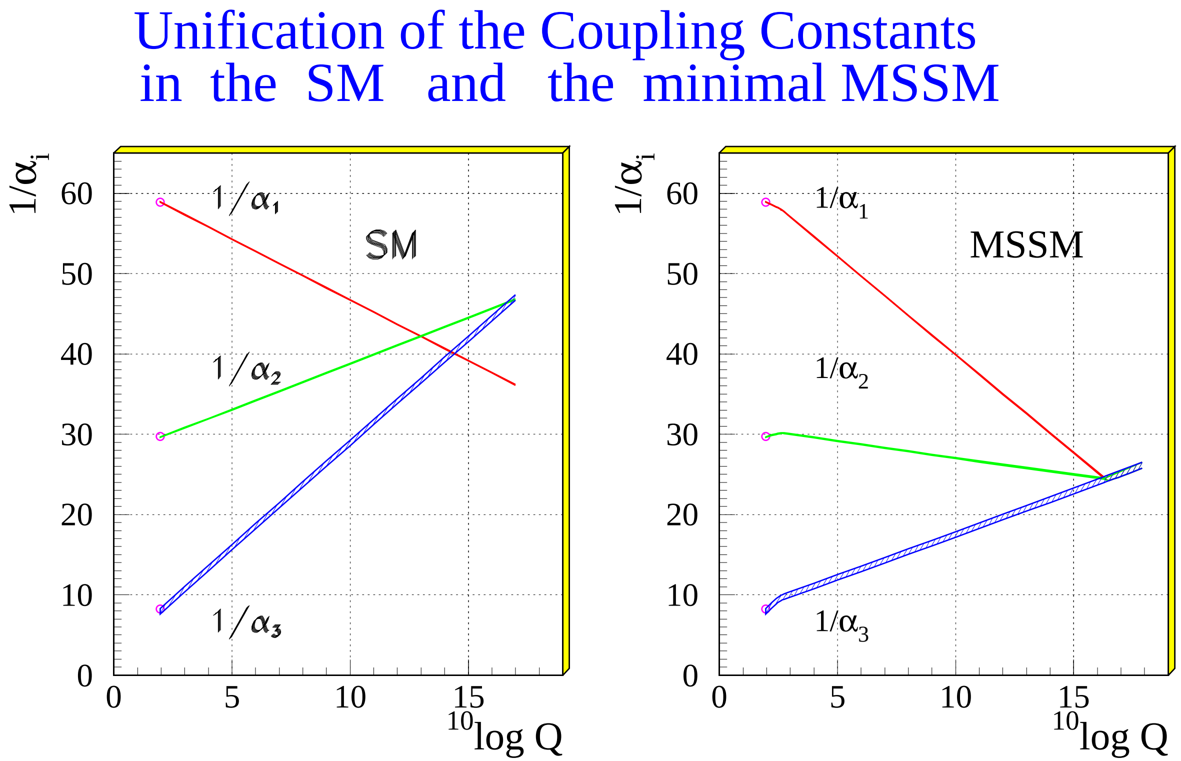

[Amaldi, de Boer, Fürstenau '91]

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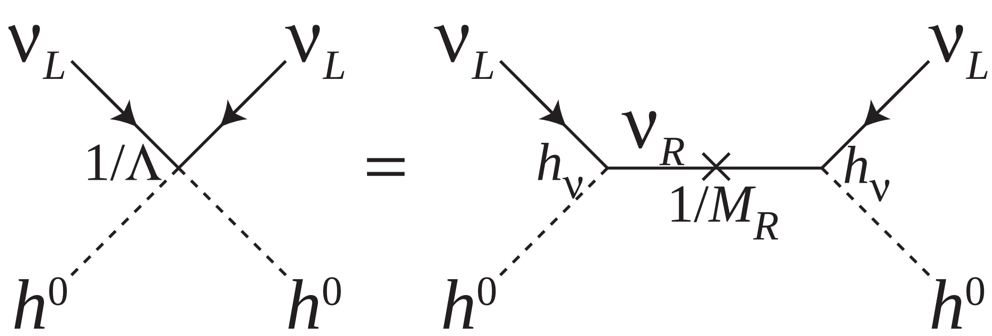

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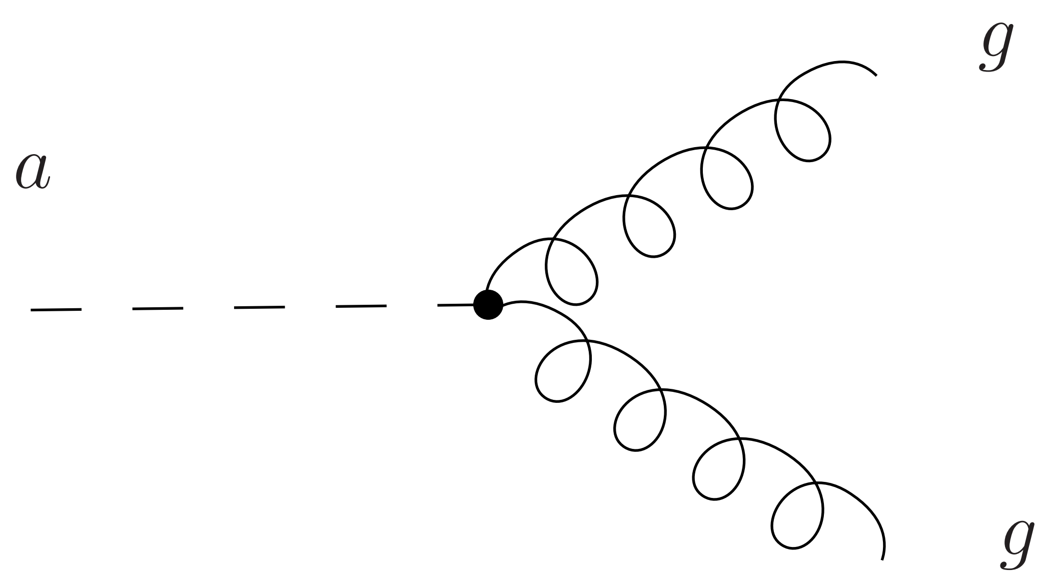
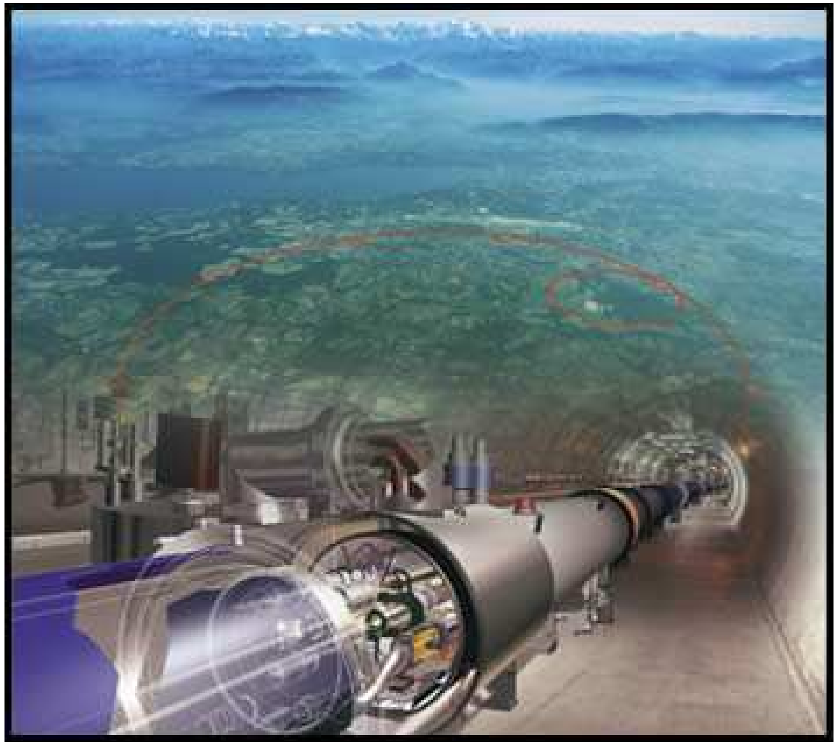


- Heavy superpartners of standard model particles as well as ultralight axion may easily be accommodated in Grand Unified Theories and occur especially naturally in the low-energy description of string theory

- Phenomenologically viable string compactifications potentially predict even more Weakly Interacting Sub-eV Particles (WISPs):

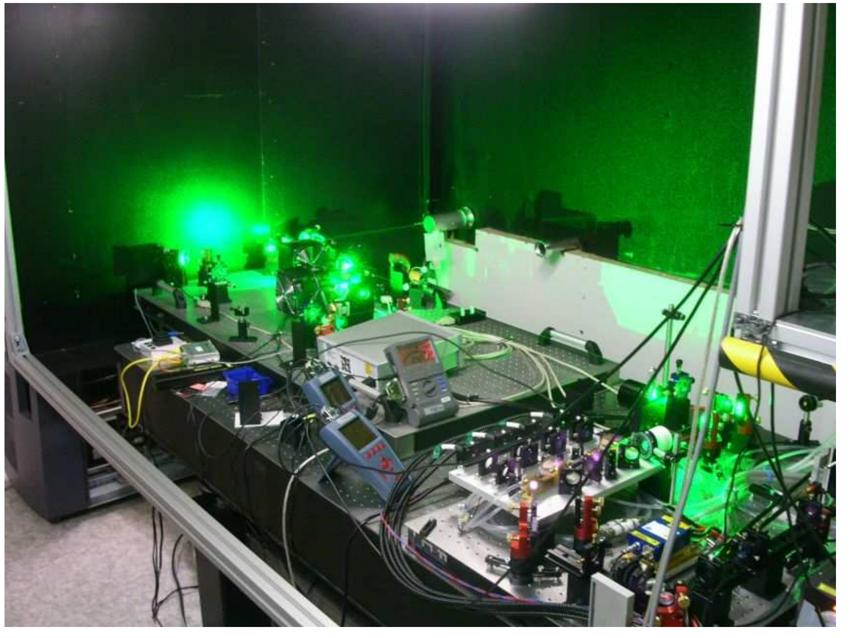
  - Axion-Like Particles (ALPs)
  - hidden-sector U(1) gauge bosons ($\Rightarrow$ hidden photons)
  - hidden-sector U(1) charged fermions ($\Rightarrow$ minicharged particles)

- 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 ⇒

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

  – **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, $a \to a + \mathrm{const.}$
  - Axion field can enter in Lagrangian only through derivative terms and explicit symmetry violating terms originating from chiral anomalies,

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

  - $\bar{\theta}$-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 $\Rightarrow$ 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;...]

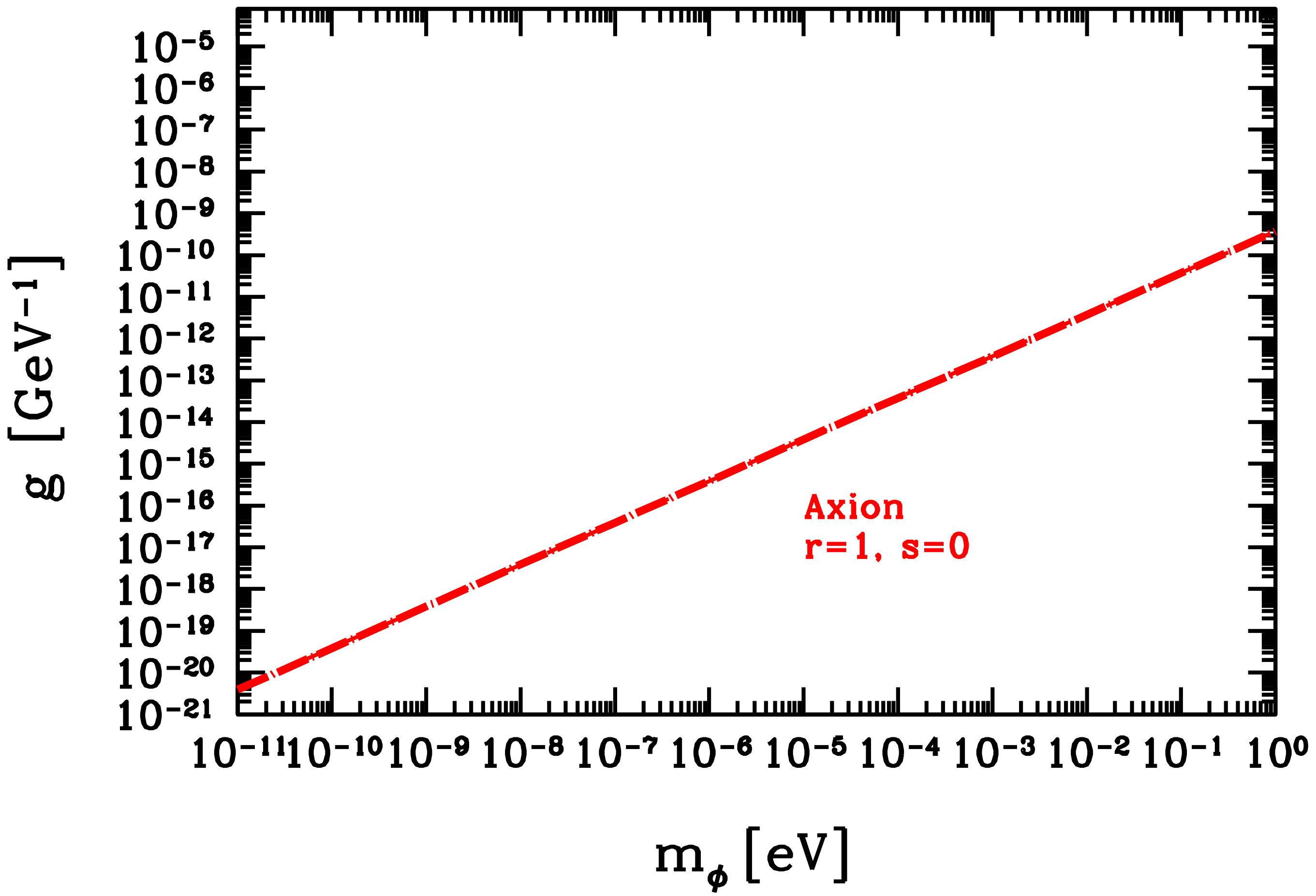
e.g. coupling to photons,

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

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

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

- Generic prediction for axion:



- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications

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

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

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

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

- Heterotic string:

  – 10d low-energy Lagrangian:

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

  – Compactify 6 extra dimensions:

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

$\Rightarrow$ Read off coefficients:

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

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

- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications

  – Axions in intersecting D-brane models in type II string theory come from zero modes of the RR gauge fields C

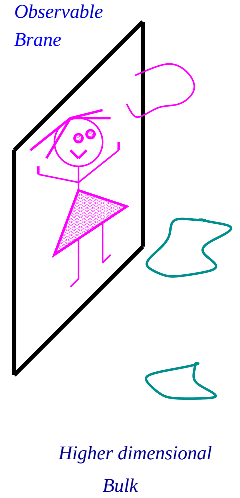
$$f_a \sim M_s$$

$\Rightarrow$ wider range of possibilities; phenomenologically preferred: intermediate scale, $M_s \sim \sqrt{M_{\rm EW} M_P} \sim 10^{11}$ GeV $\Rightarrow m_a \simeq 10^{-4}$ eV

- 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

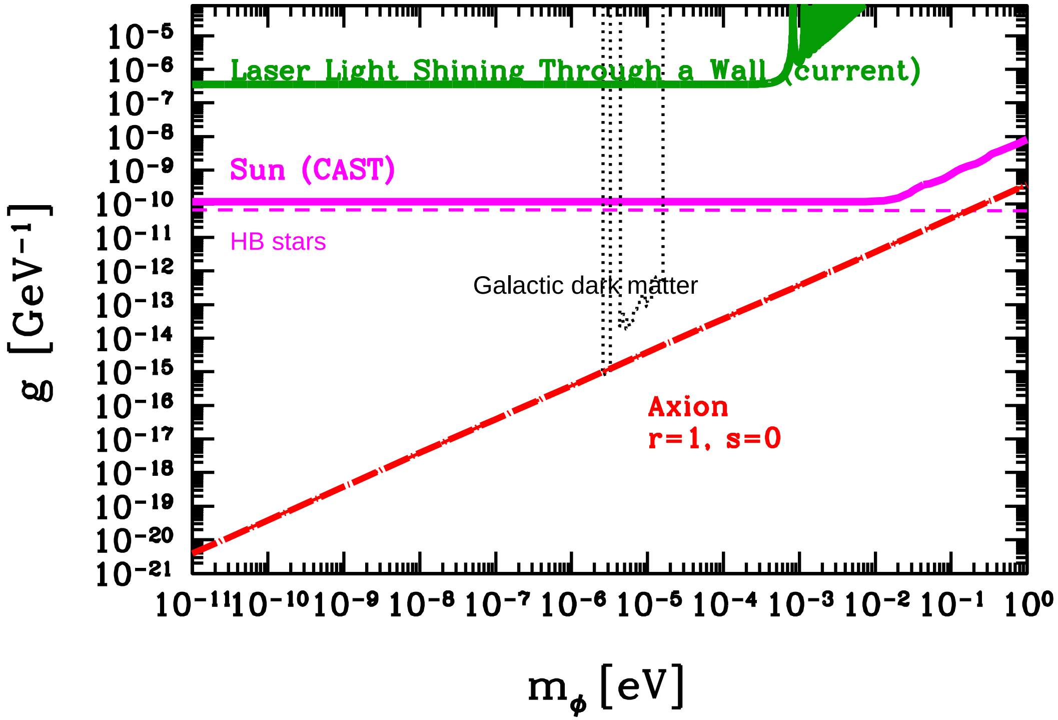
- **Axion-like particles:**
  Other (pseudo-)Nambu-Goldstone bosons associated with breakdown of other continuous global symmetries

  - Familons, associated with global family symmetry [Wilczek '82]
  - Majorons, associated with global $U(1)_{B-L}$ [Chikashige,Mohapatra,Peccei '80]
  - Accelerons: [Friemann,Hill,Stebbins,Waga '95]
    breaking scale $f_\phi \sim M_P$ and explicit symmetry breaking scale $\Lambda \sim m_\nu \sim 10^{-3}$ eV $\Rightarrow m_\phi \sim \Lambda^2/f_\phi \sim 10^{-33}$ eV $\sim H_0$
  - Stückelberg axions: associated with anomalous U(1)s in low-scale string compactifications [Coriano,Irges,Kiritsis '06]
  - . . .

- Not as predictive as axion:

  - explicit symmetry breaking scale?
  - any experimental hint from astrophysics, cosmology, and laboratory experiments very welcome

- Constraints on axion-like particles: [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

- Most 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 from hidden sector to visible sector
- Gauge interactions in hidden sector generically involve U(1) factors. There are also hidden sector matter particles charged under these U(1)s.
  - Usual assumption: hidden sector particles very heavy

    $\Rightarrow$ no constraints from low-energy phenomenology
  - Here: what if hidden sector particles remain massless or light?

    $\Rightarrow$ hidden sector U(1) gauge boson ("hidden photon" γ') interacts with visible photon through gauge kinetic mixing

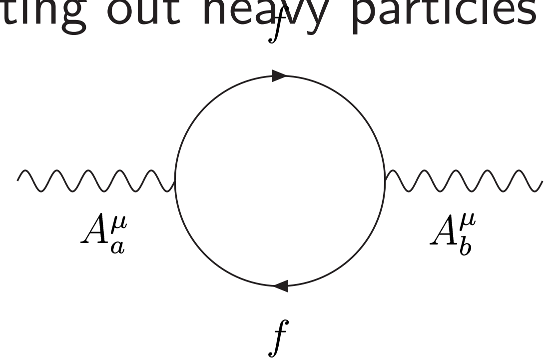
    $\Rightarrow$ hidden sector U(1) charged matter appears to have a small electric charge due to this mixing ("minicharged particle" ϵ)

- Simplest model: [Holdom '85]

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

  – 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 $\chi \neq 0$:



$$\Rightarrow \Delta\chi = \frac{e e_h}{16\pi^2}\log(m^2/\mu^2)$$

– Diagonalization of kinetic term:

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

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

– Hidden sector charged particle gets induced electric charge:

$$e_h \bar{h} \not{B} h \quad \to \quad e_h \bar{h} \tilde{\not{B}} h + \chi e_h \bar{h} \not{A} h$$

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

∗ may be fractional

∗ may be tiny, if $\chi \ll 1$: h is minicharged particle

- Possible parameter ranges in string phenomenology: [Dienes *et al.* '97; Abel *et al.* '08]

$$\chi \sim 10^{-23} \div 10^{-2}; \qquad m_{\gamma'} \sim 0 \div M_s; \qquad m_\epsilon \sim 0 \div M_s$$

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic closed string theory

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

$$\mathrm{E}_8 \times \mathrm{E}_8 \longrightarrow$$
$$\mathrm{G}_{\mathrm{SM}} \times \mathrm{U}(1)^4 \times \left[\mathrm{SU}(4) \times \mathrm{SU}(2) \times \mathrm{U}(1)^4\right]$$

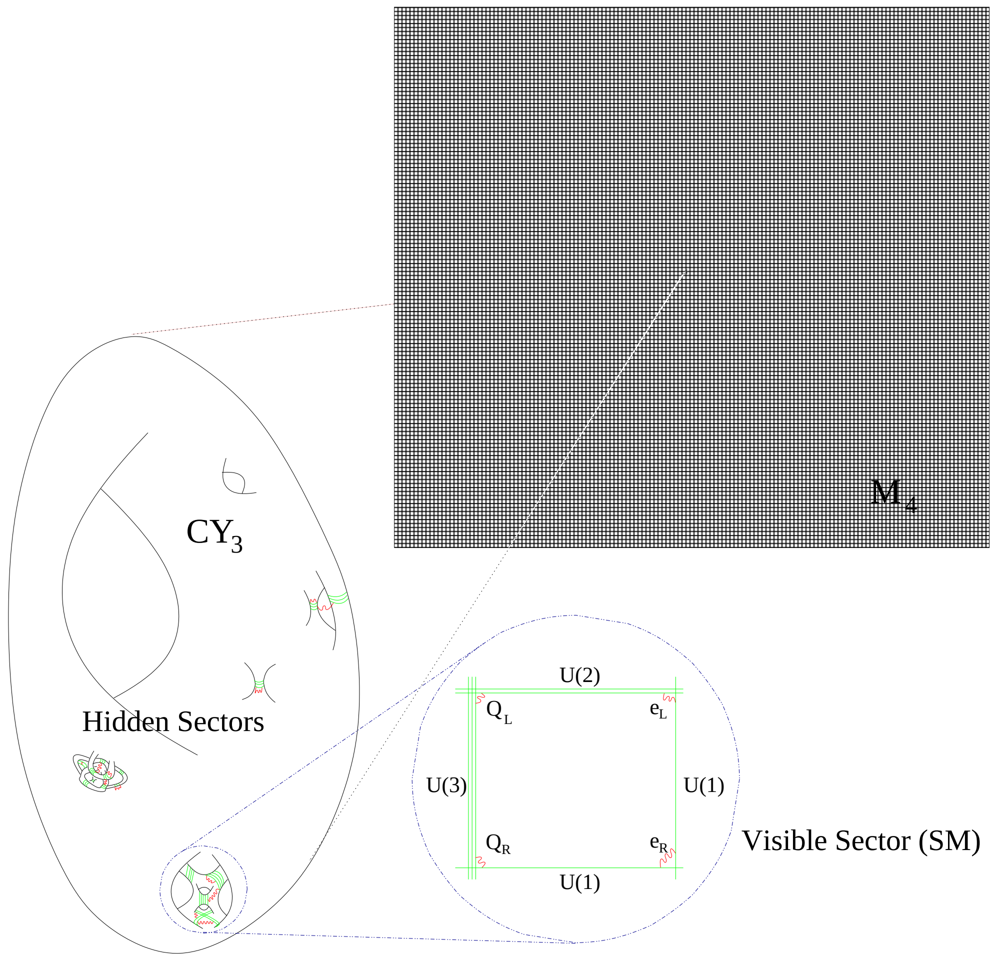
or [Lebedev *et al.* '07]

$$\mathrm{E}_8 \times \mathrm{E}_8 \longrightarrow$$
$$\mathrm{G}_{\mathrm{SM}} \times \mathrm{U}(1)^4 \times \left[\mathrm{SO}(8) \times \mathrm{SU}(2) \times \mathrm{U}(1)^3\right]$$

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:

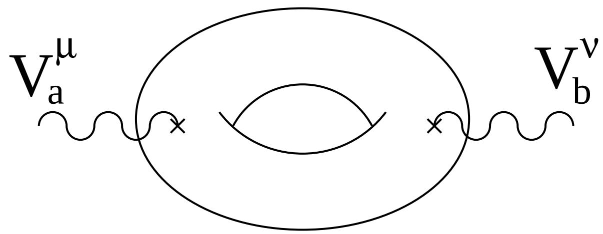


- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $E_8 \times E_8$ heterotic closed string theory
  - IIA/IIB open string theory with branes
- Some hidden U(1) gauge bosons and hidden charged fermions may remain massless or light

$\Rightarrow$ Dominant interaction with standard model: gauge kinetic mixing and minicharge

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

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $E_8 \times E_8$ heterotic closed string theory
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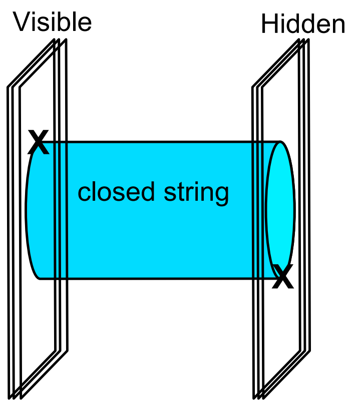
⇒ Dominant interaction with standard model: gauge kinetic mixing and minicharge

KM in IIA/IIB string models:

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

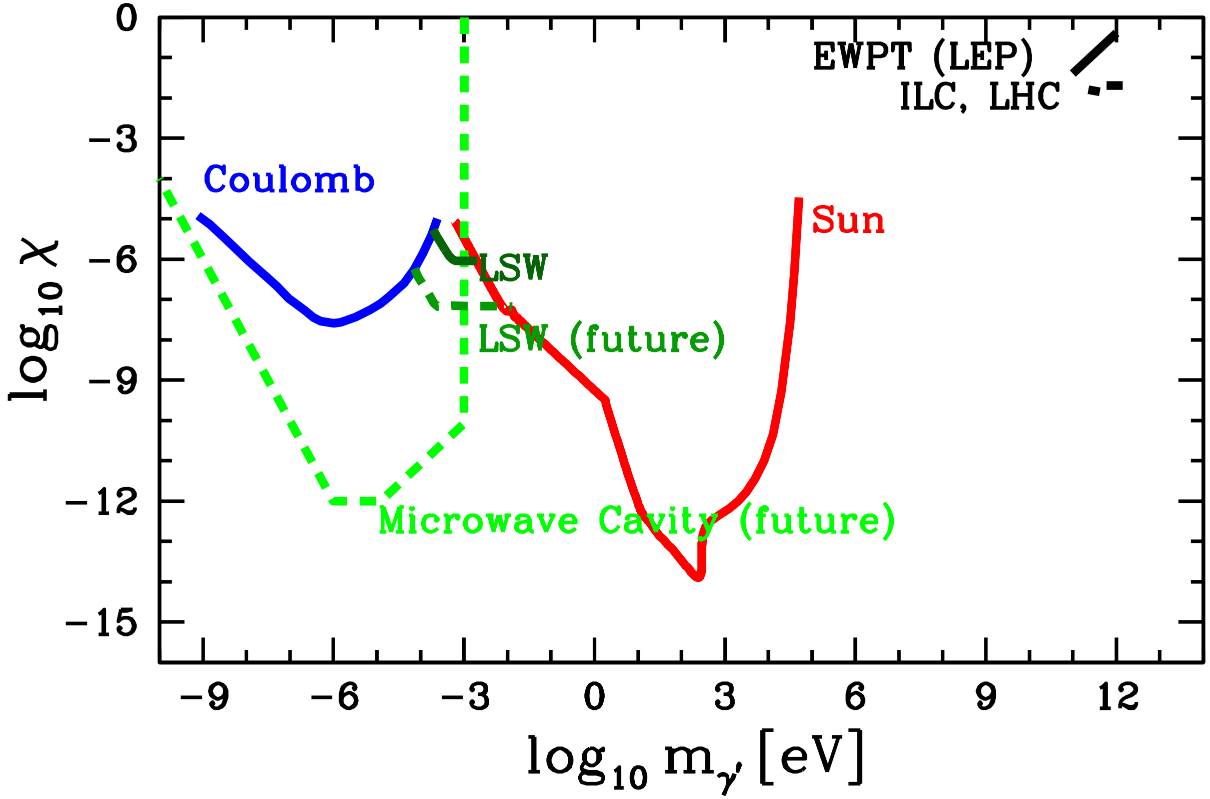


$$\chi \sim \frac{e\, e_h}{16\pi^2} \sim \frac{g_s}{8\pi}(V_6 M_s^6)^{-1/3} \gtrsim 10^{-12},$$

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

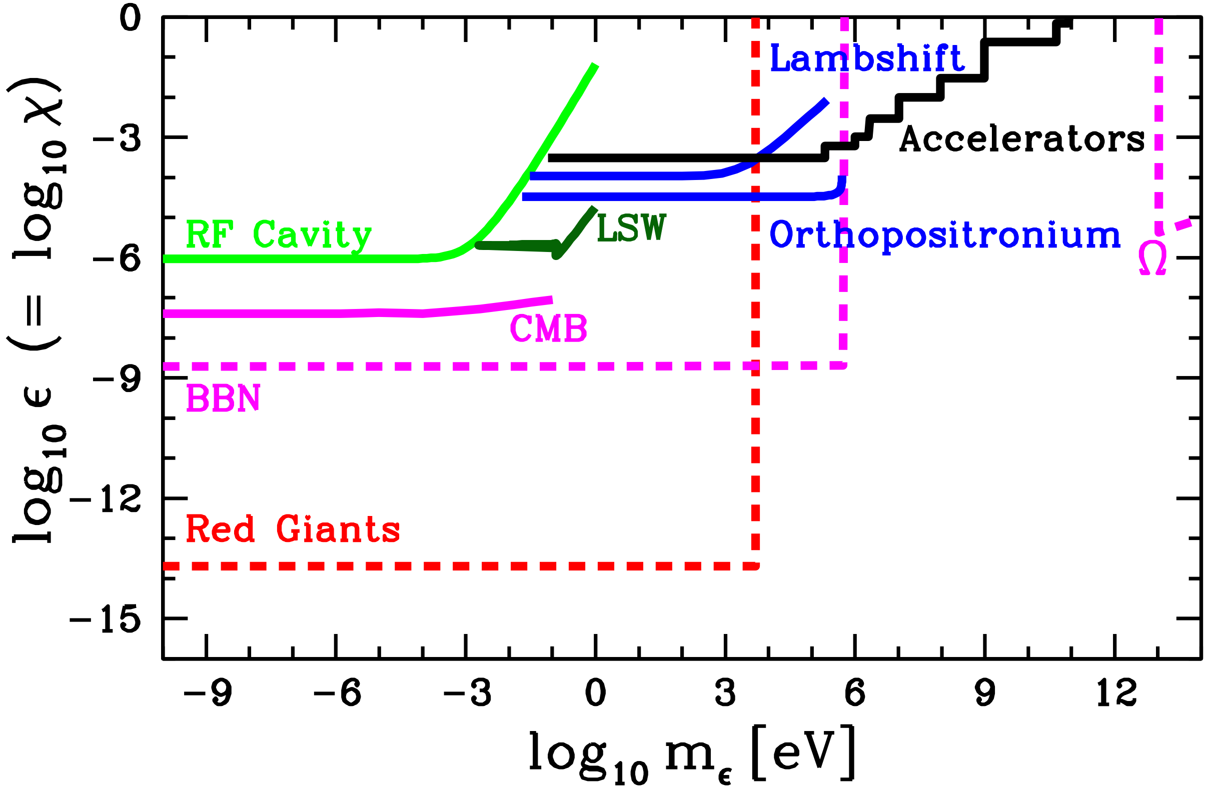
[Goodsell,Jaeckel,Redondo,AR '09]

- Constraints on hidden photons: [Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08]



Deviations from $1/r^2$ (Coulomb); $\gamma \leftrightarrow \gamma'$ oscillations (Cavity, Light Shining through a Wall (LSW), Sun); $Z \leftrightarrow \gamma'$ mixing (LEP, LHC, ILC)

- Constraints on 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

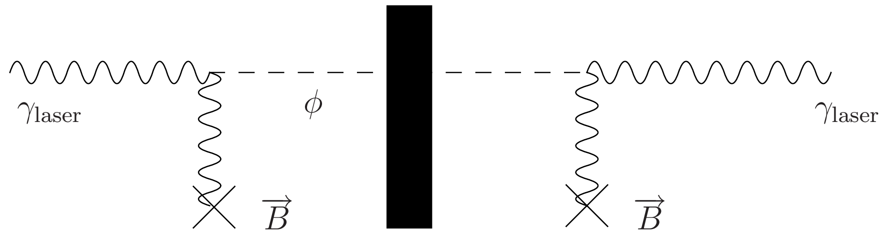
- Place wall in beam pipe:

  – 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

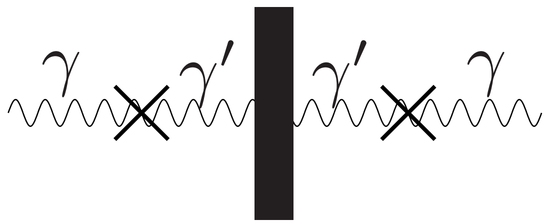
[Okun '82;Sikivie '83;Anselm '85;..]

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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[Okun ‘82;Sikivie ‘83;Anselm ‘85;..]

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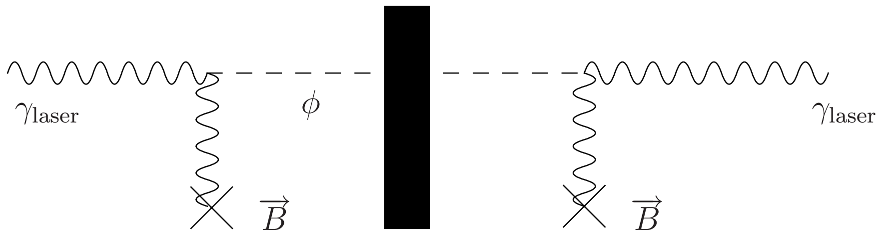
ALPS (Any-Light Particle Search):

[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)

⇒ frequency doubled to 532 nm

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

⇒ CCD camera: expect regenerated photons in signal region of a few pixel

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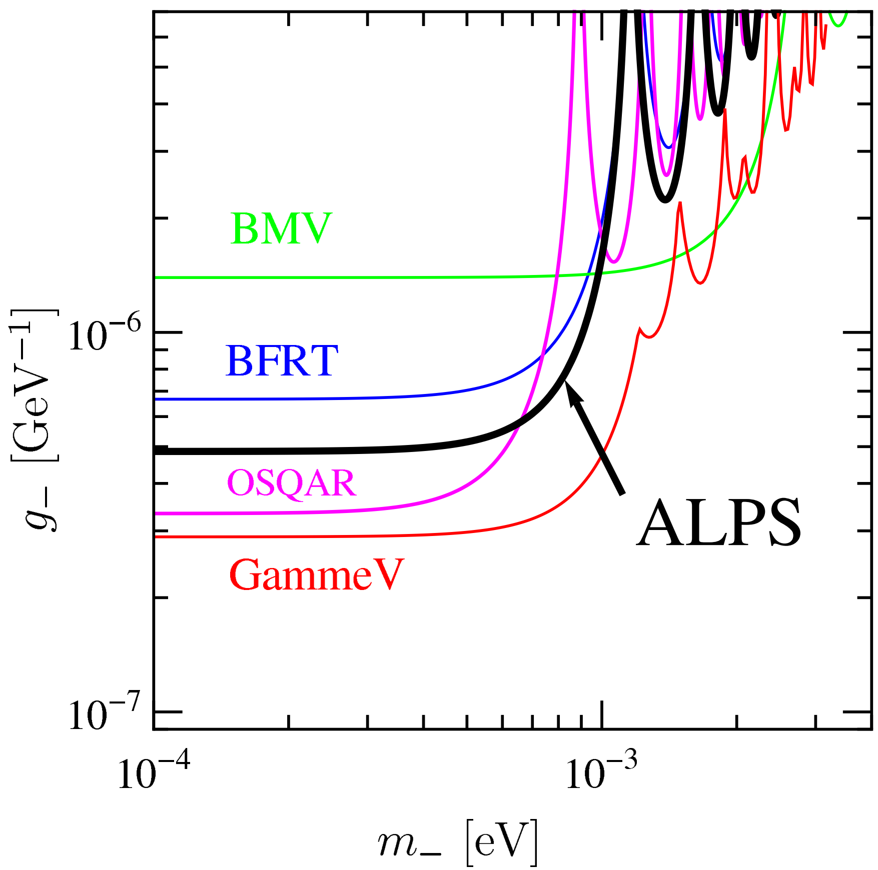
Limits from **ALPS** run in December 2008 (0.03 kW at 532 nm):



[ALPS Collaboration '09]

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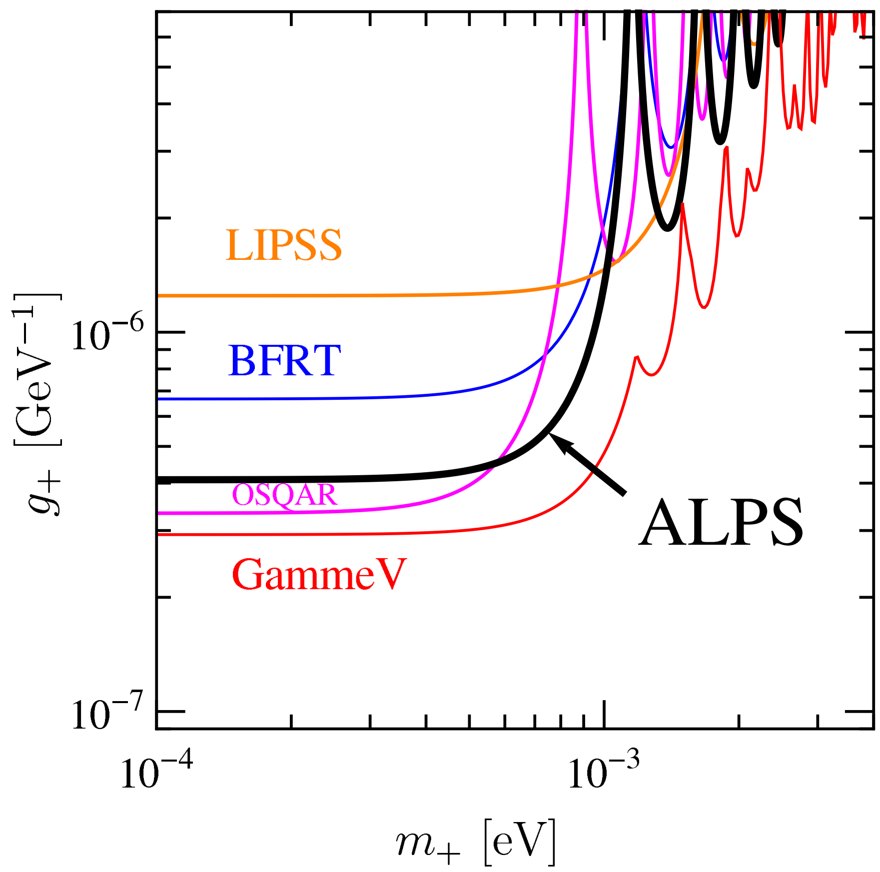

[ALPS Collaboration '09]

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 (γ', ALP) fly through wall and
  - reconvert on other side of wall into photons, which can be detected

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

- Pioneering experiment: BFRT

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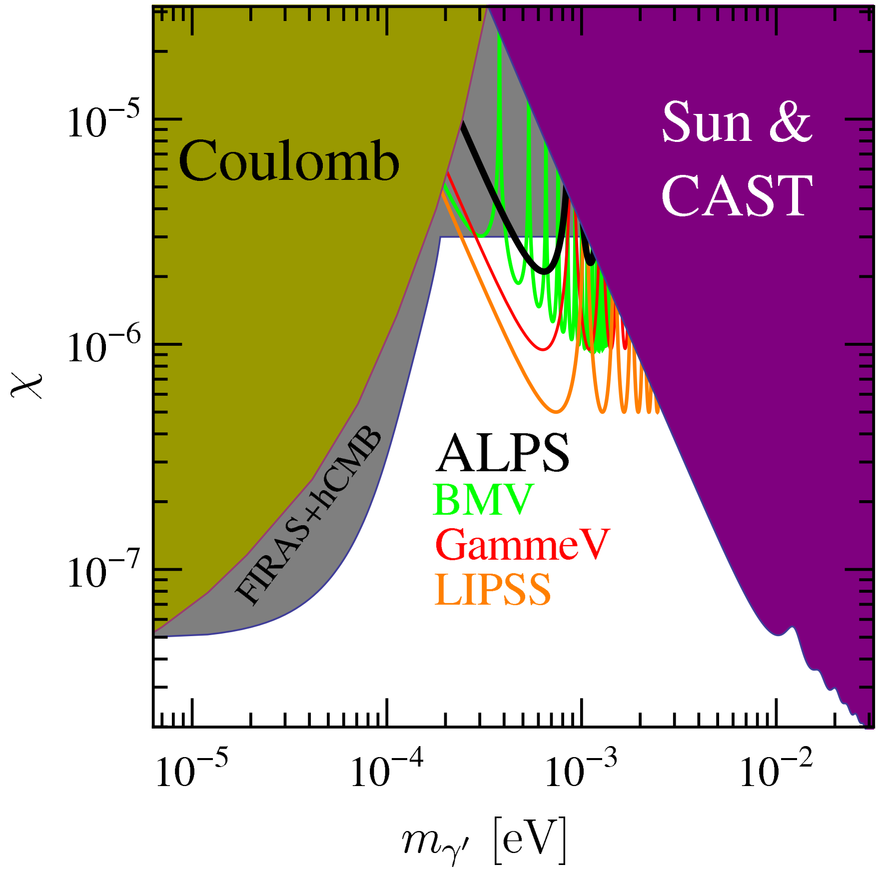

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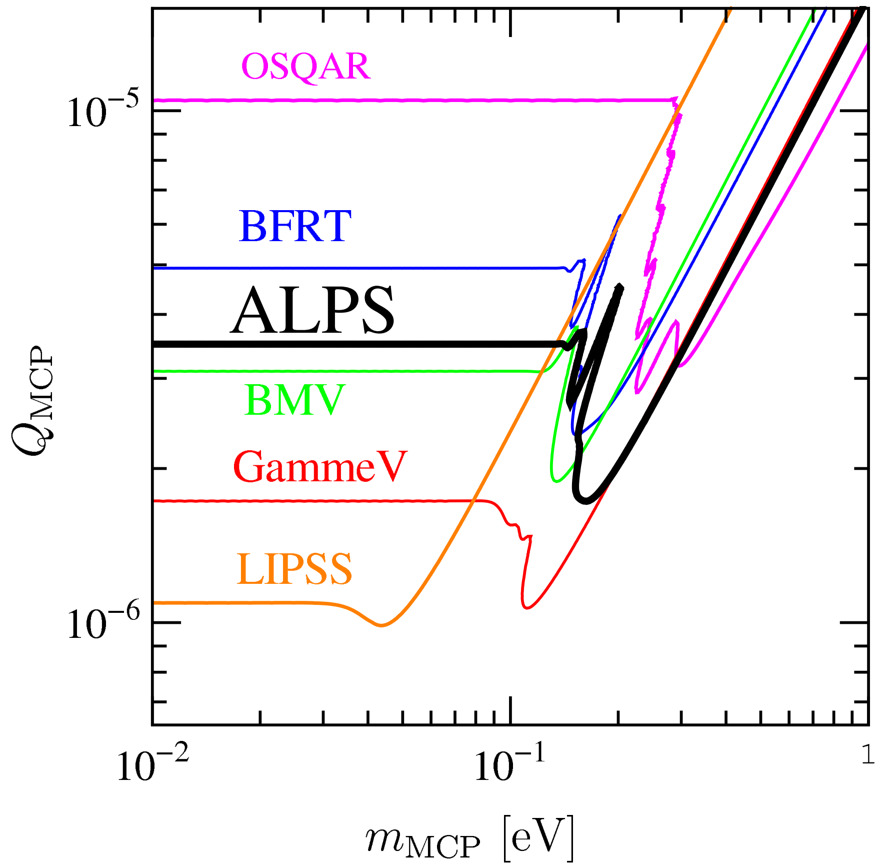

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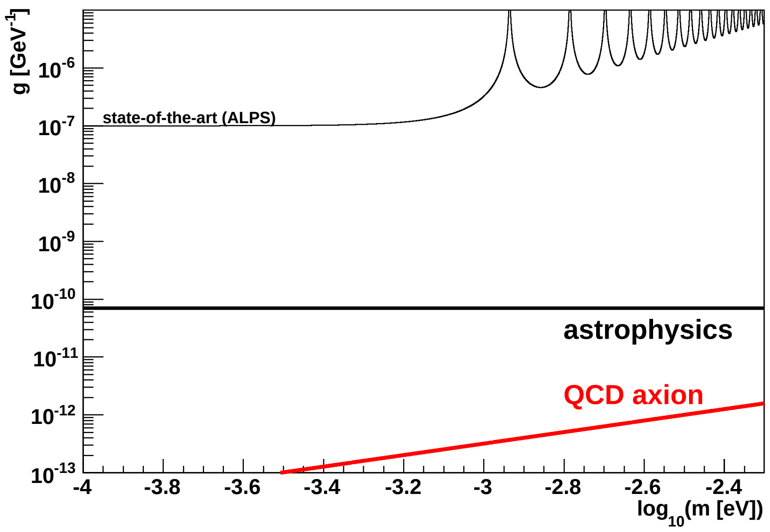
Roadmap of ALP search with LSW:



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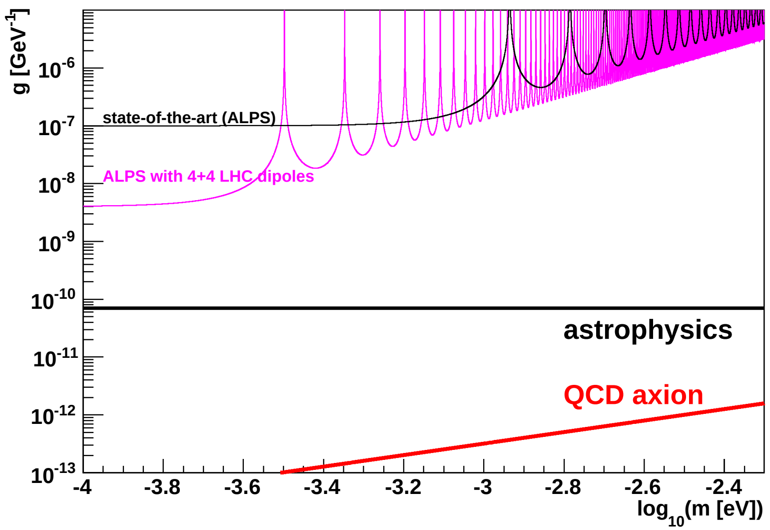

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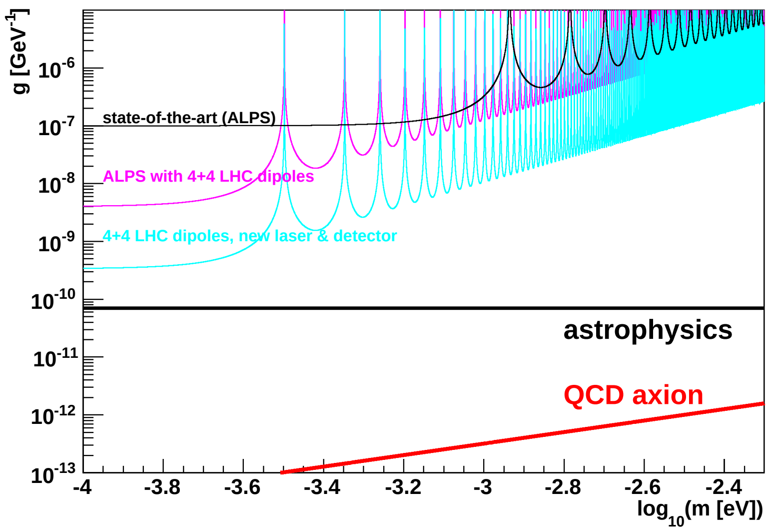

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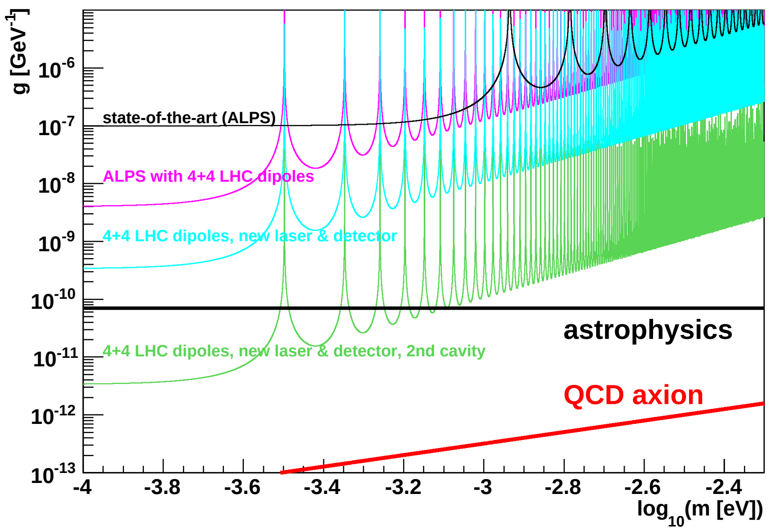

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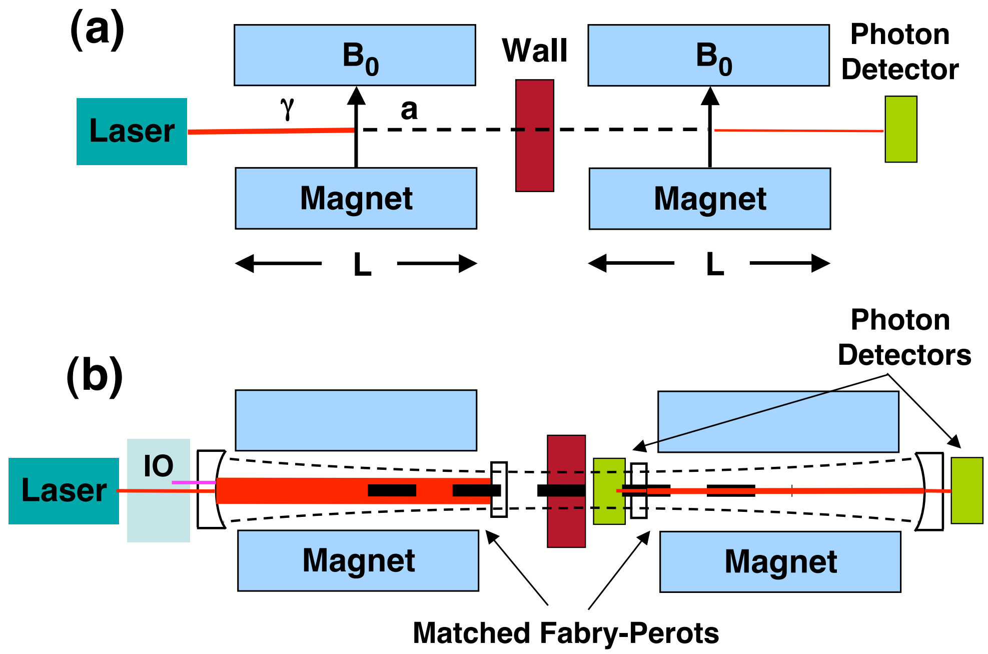
Second Fabry-Perot Cavity:

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



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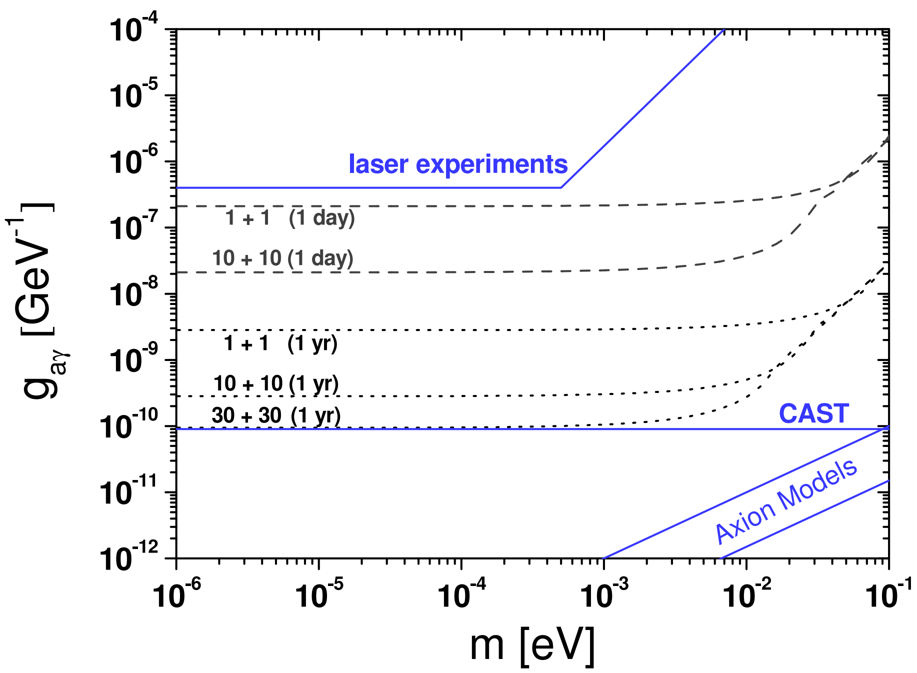
XFEL or synchrotron light through wall suffers from "low" photon flux

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



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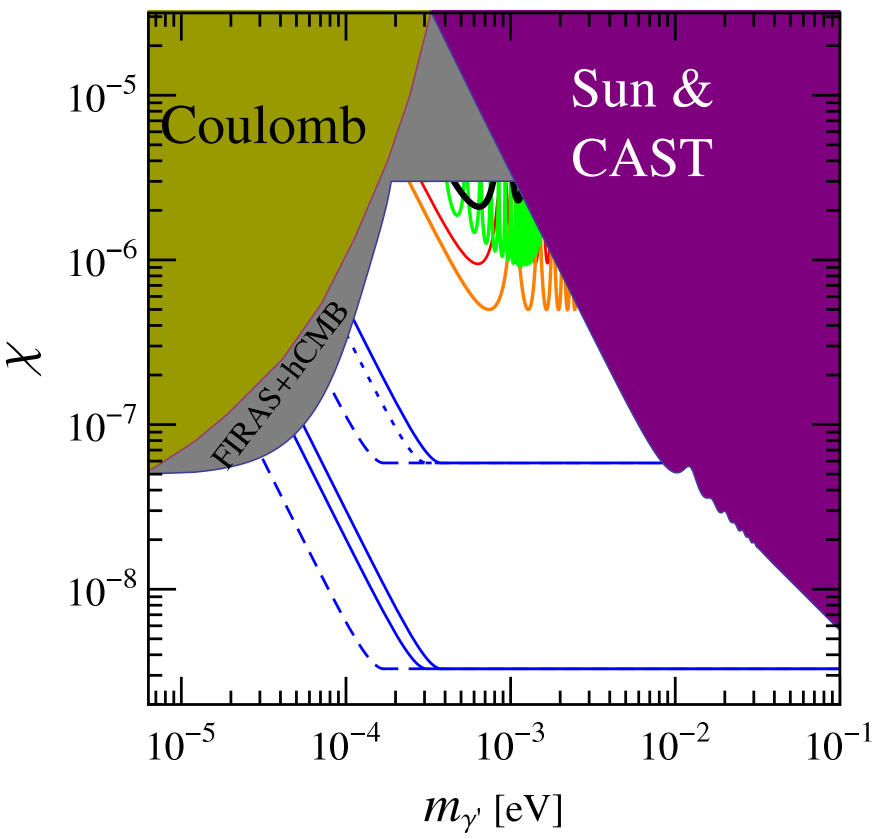


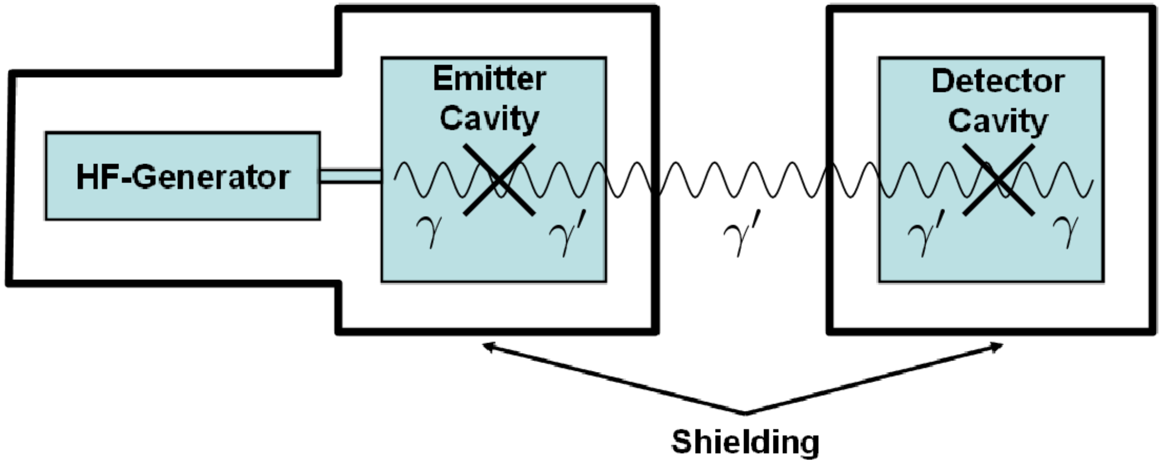
[Redondo '09]

5. Microwave Cavity Experiments

- High quality cavities can be exploited to search for

[Jaeckel,AR '07;Caspers,Jaeckel,AR '09]

  – γ'



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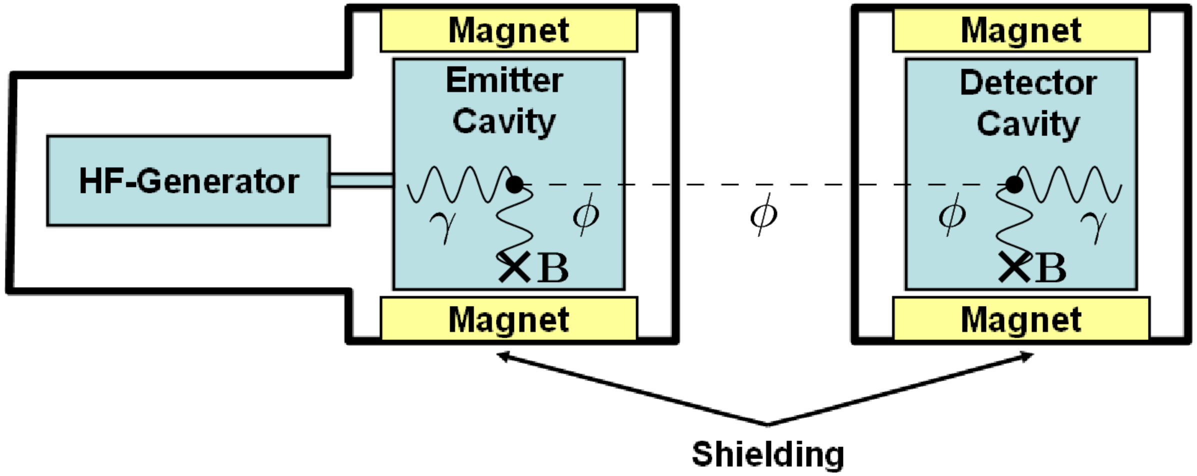
  - γ'
  - ALPs [Hoogeveen '92]



[Jaeckel,AR '07]

5. Microwave Cavity Experiments

- High quality cavities can be exploited to search for

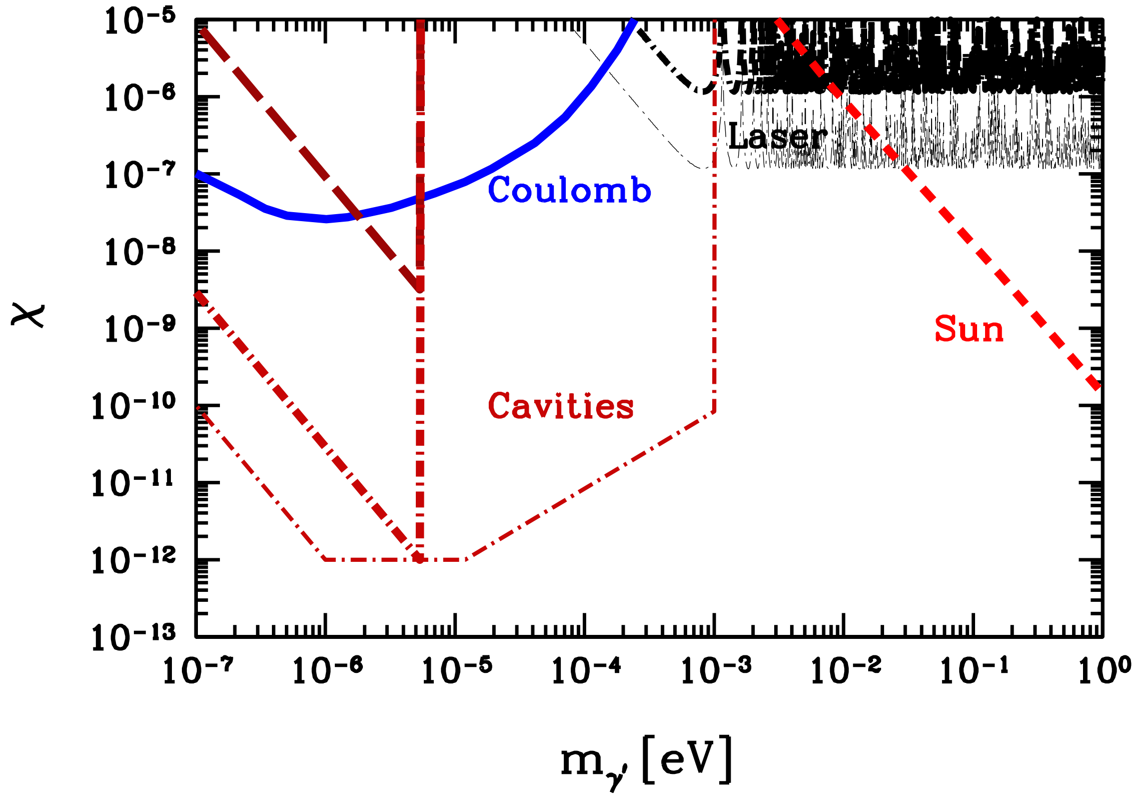
  [Jaeckel,AR '07;Caspers,Jaeckel,AR '09]

  – 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

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

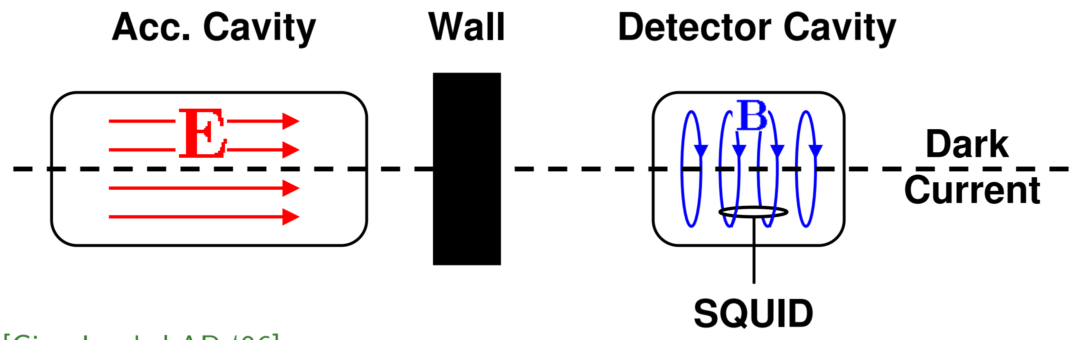
$$E^{\epsilon}_{\rm crit} = \frac{m_\epsilon^2}{\epsilon e} \simeq 5\,\frac{\rm MV}{\rm m}\,\frac{10^{-6}}{\epsilon}\left(\frac{m_\epsilon}{\rm meV}\right)^2$$

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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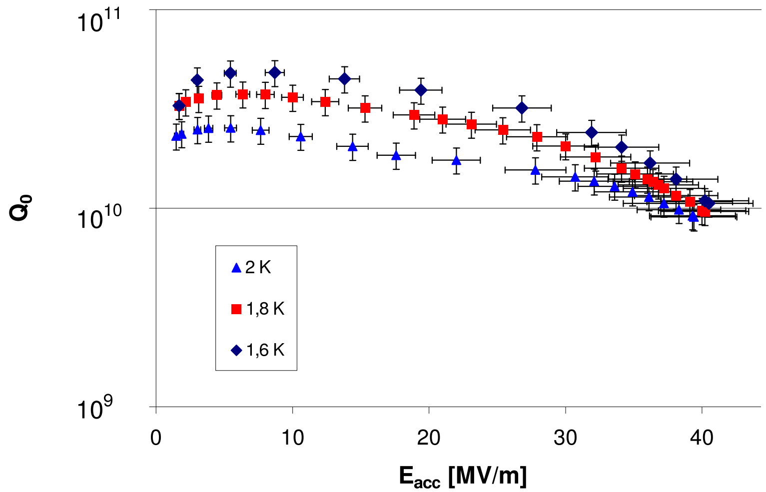

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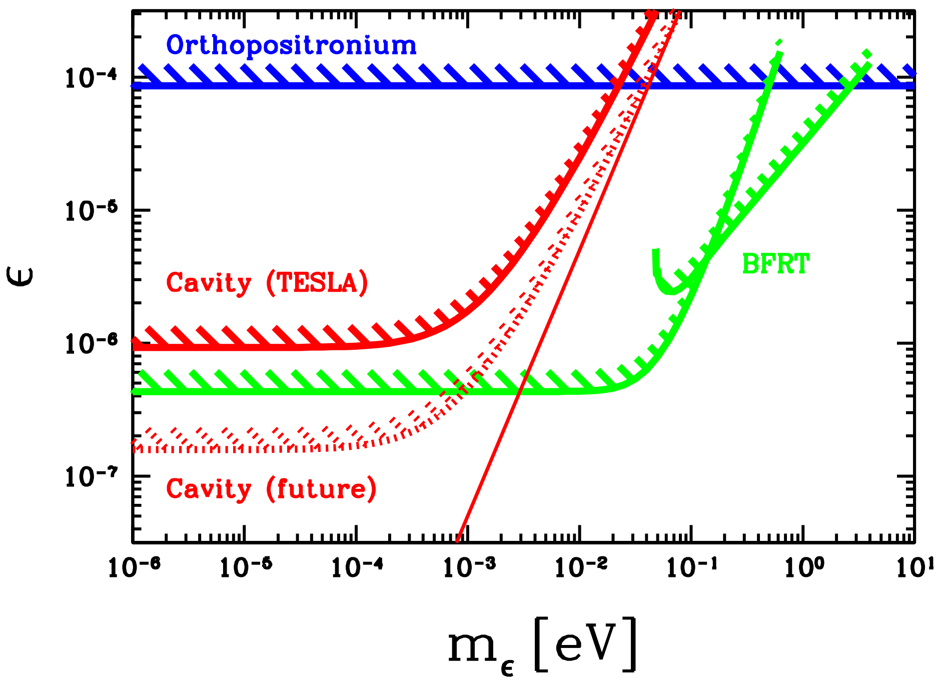

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[Gies,Jaeckel,AR '06]

ACDC (Accelerator Cavity Dark Current):

- Cavity and wall available

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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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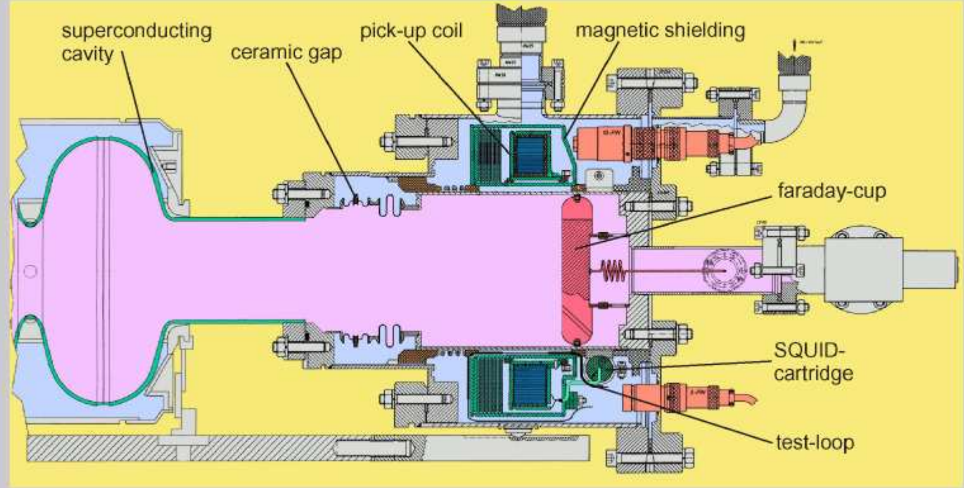

Construction details of the CCC dark current hardware

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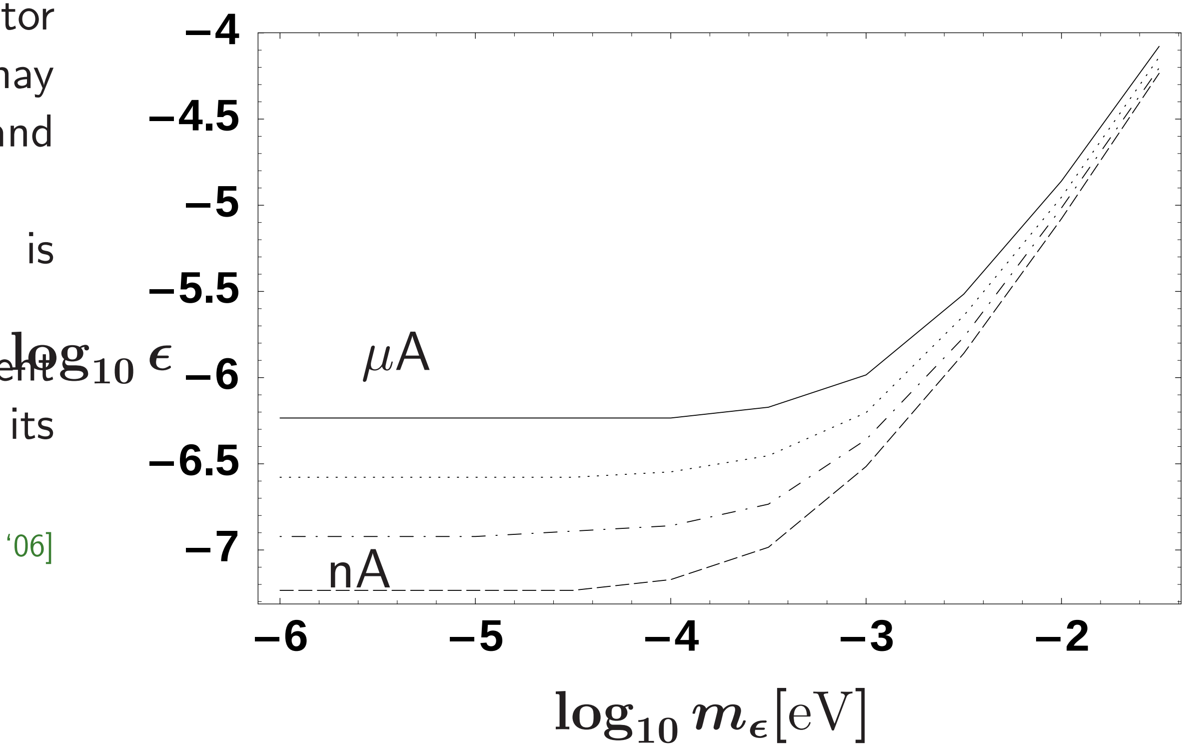

[Ahlers,Gies,Jaeckel,AR in prep.]

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 ⇒ **Hidden Laser Communications!**

[Jaeckel,Redondo,AR '09]