

Shedding Light on the Hidden Sector

– Particle Physics with Low-Energy Photons –

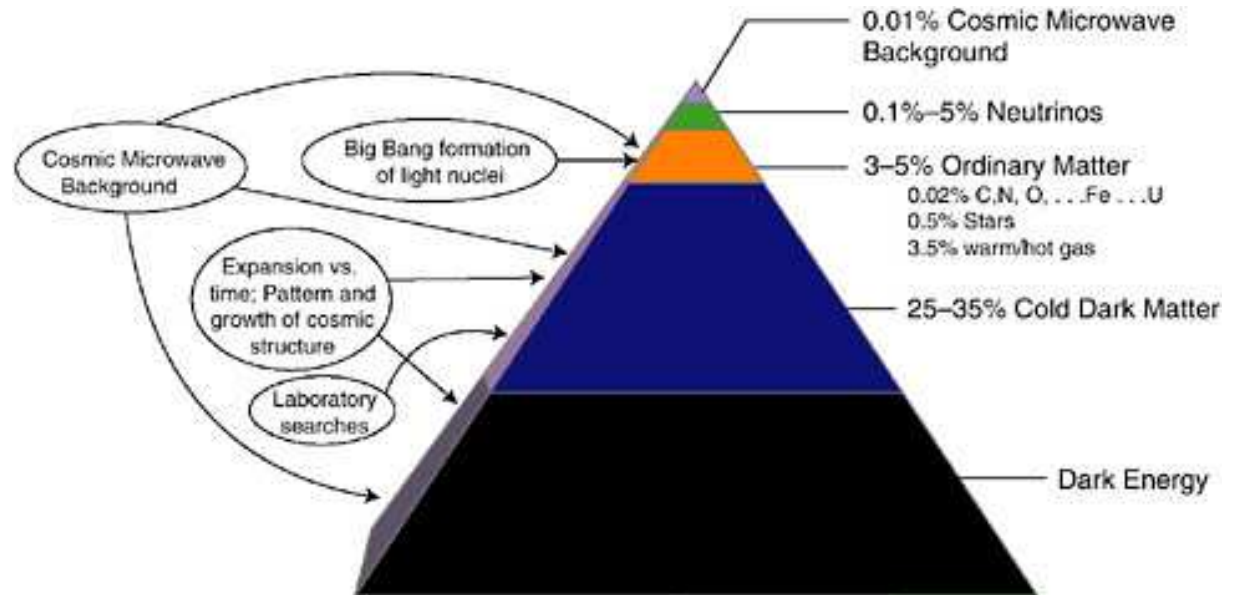
Andreas Ringwald



Theorieseminar, DESY, 25 June 2009, Zeuthen, D

1. Introduction

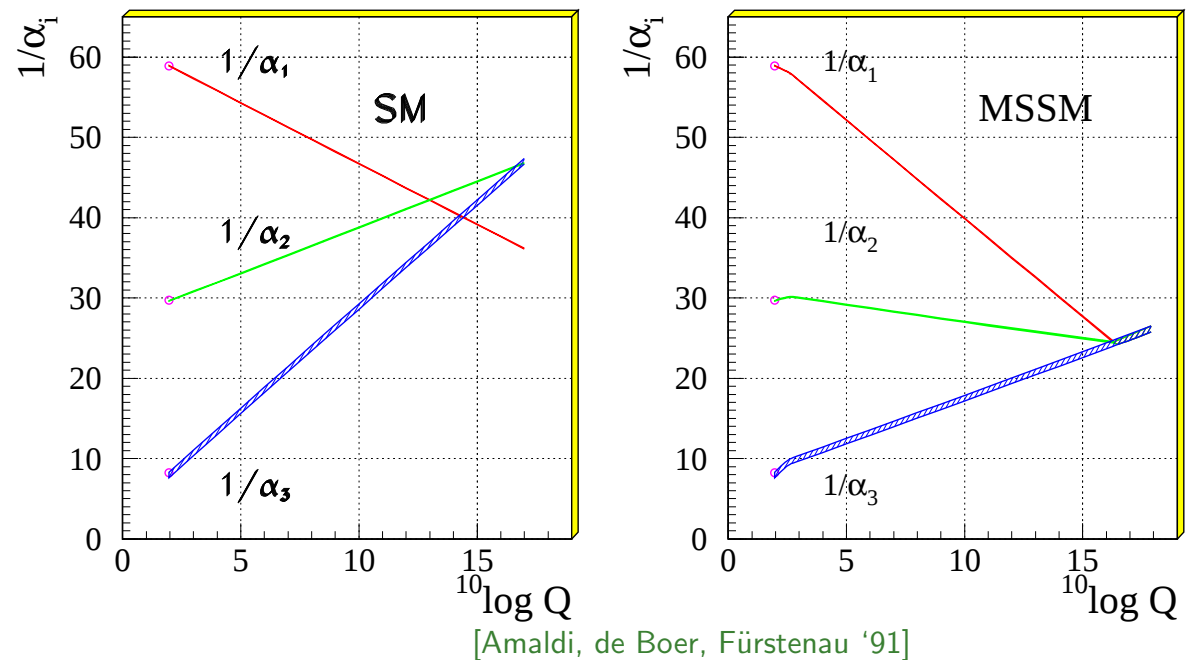
- Hints for new particles beyond standard model:
 - **Dark matter:**
WIMP or WISP?
 - **Dark energy:**
ultralight cosmon?



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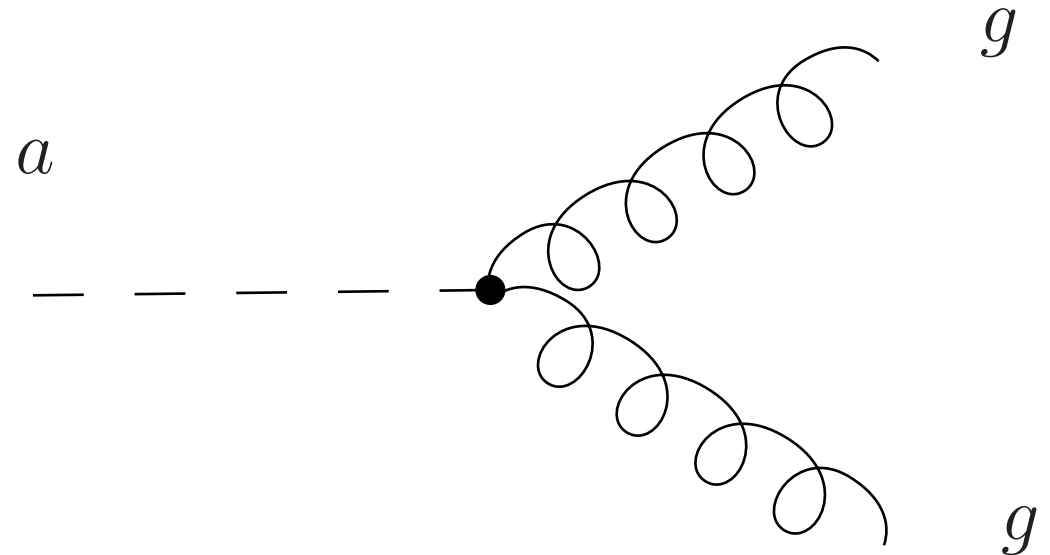
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 - **Unification of forces:**
heavy superpartners?

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



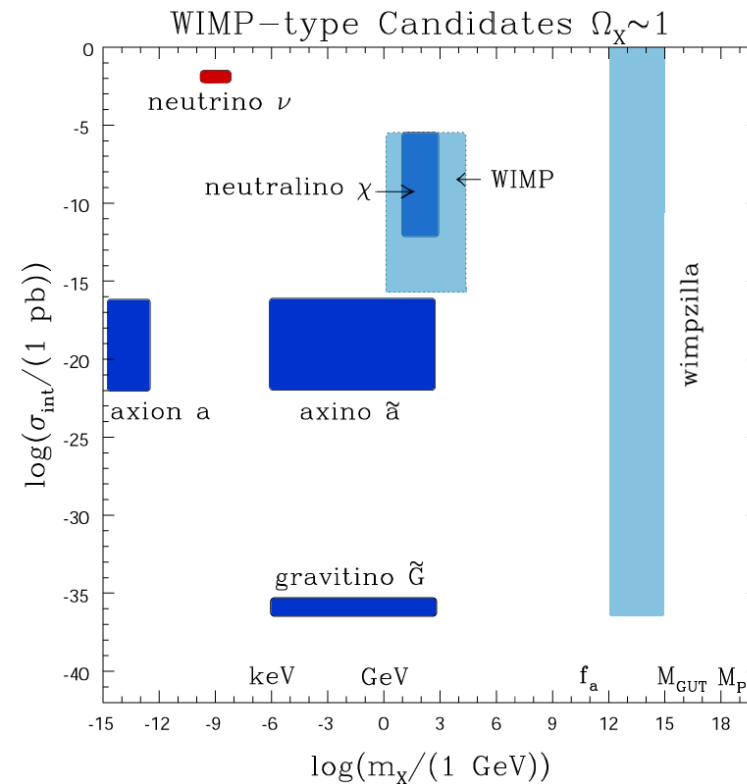
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 - **Strong CP problem:**
ultralight axion?



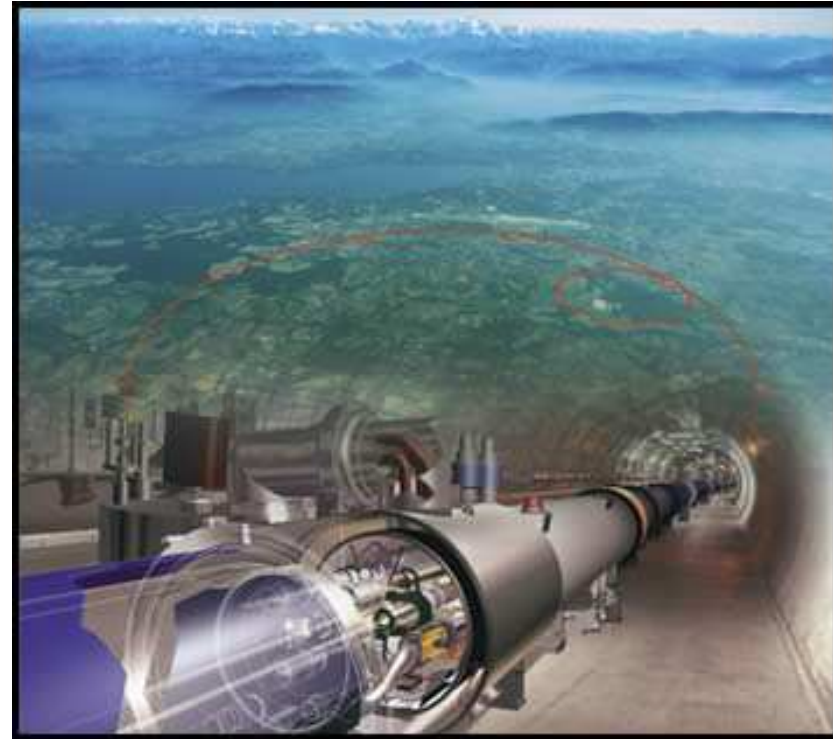
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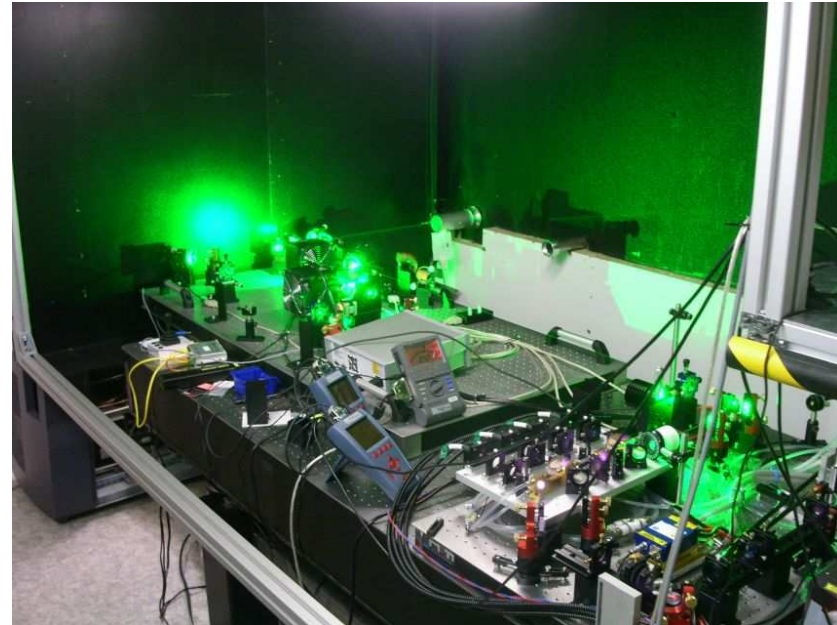


[Roszkowski]

- **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. Conclusions**

2. Axions and Axion-Like Particles

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

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

- Effective CP-violating parameter in standard model,

$$\theta \rightarrow \bar{\theta} = \theta + \arg \det M$$

- 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 $U(1)_{PQ}$ 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 $U(1)_{PQ}$ transformation, $a \rightarrow a + \text{const.}$
- $\Rightarrow$ Low-energy effective Lagrangian:

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

- $\bar{\theta}$ -term in $\mathcal{L}_{\text{SM}} + \mathcal{L}_a$ can be eliminated by exploiting the shift symmetry, $a \rightarrow a - \bar{\theta} f_a / r$
- Topological charge density $\propto \langle \text{tr} G^{\mu\nu} \tilde{G}_{\mu\nu} \rangle \neq 0$ 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]

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

– 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,

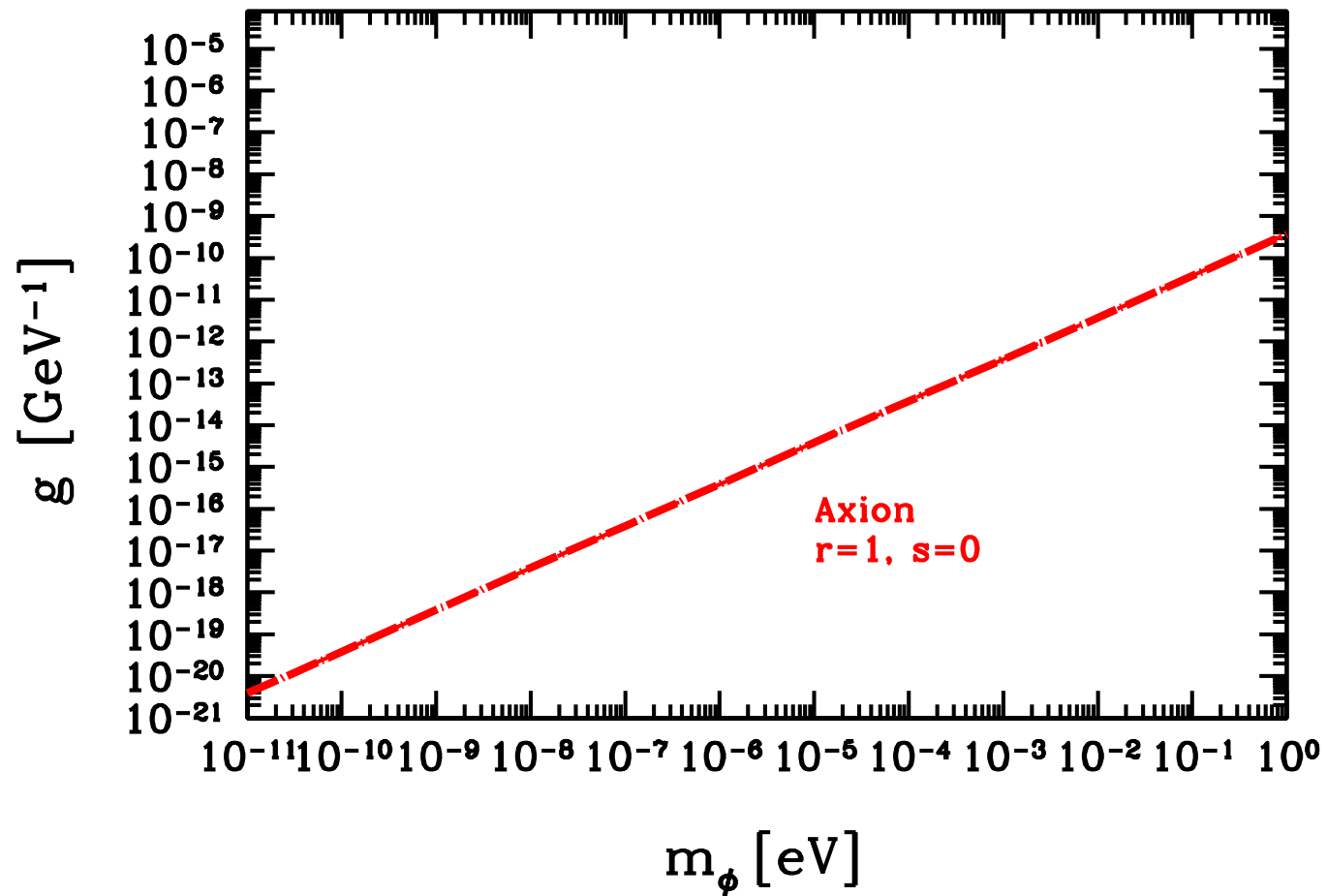
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu} = g a \vec{E} \cdot \vec{B},$$

with

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

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

- 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:

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

- Compactify 6 extra dimensions:

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

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

Zeuthen, June 2009

- **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

$$f_a \sim M_s$$

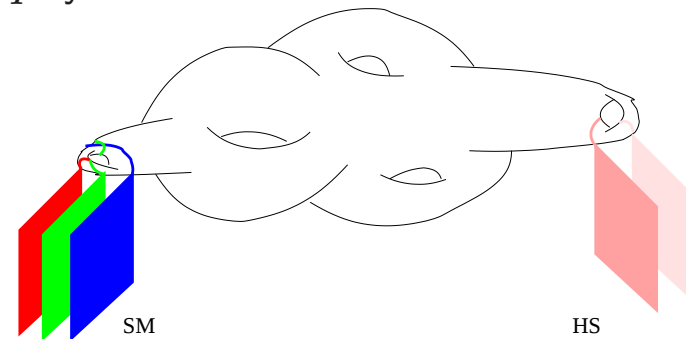
⇒ wider range of possibilities

- Plenitude of zero modes ⇒ **axion-like particles**
- **Stückelberg axions** associated with anomalous U(1)s

[Coriano, Irges, Kiritsis '06]

- **Intersecting D-brane models:**

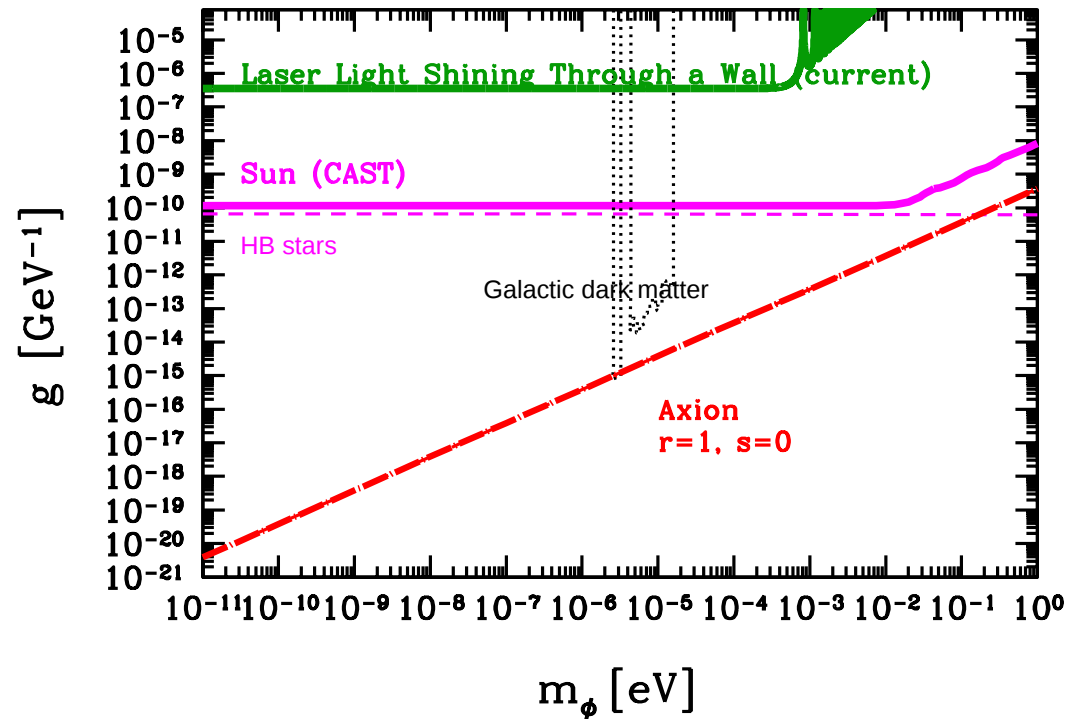
- Gauge theory lives on $D(3 + q)$ -branes, extending along the 4 non-compact dimensions and wrapping a q -cycle in the extra dimensions



- 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 $\sim \text{TeV}$

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

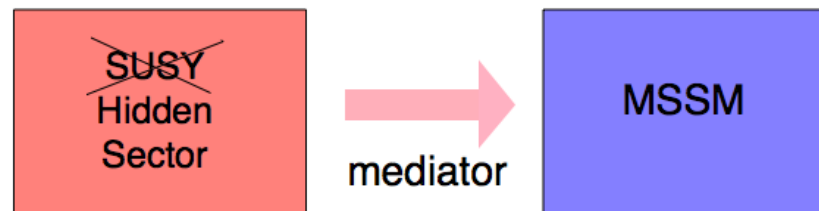
[Raffelt; ...]



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; . . .]

$$E_8 \times E_8 \rightarrow$$

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

or

[Lebedev *et al.* '07]

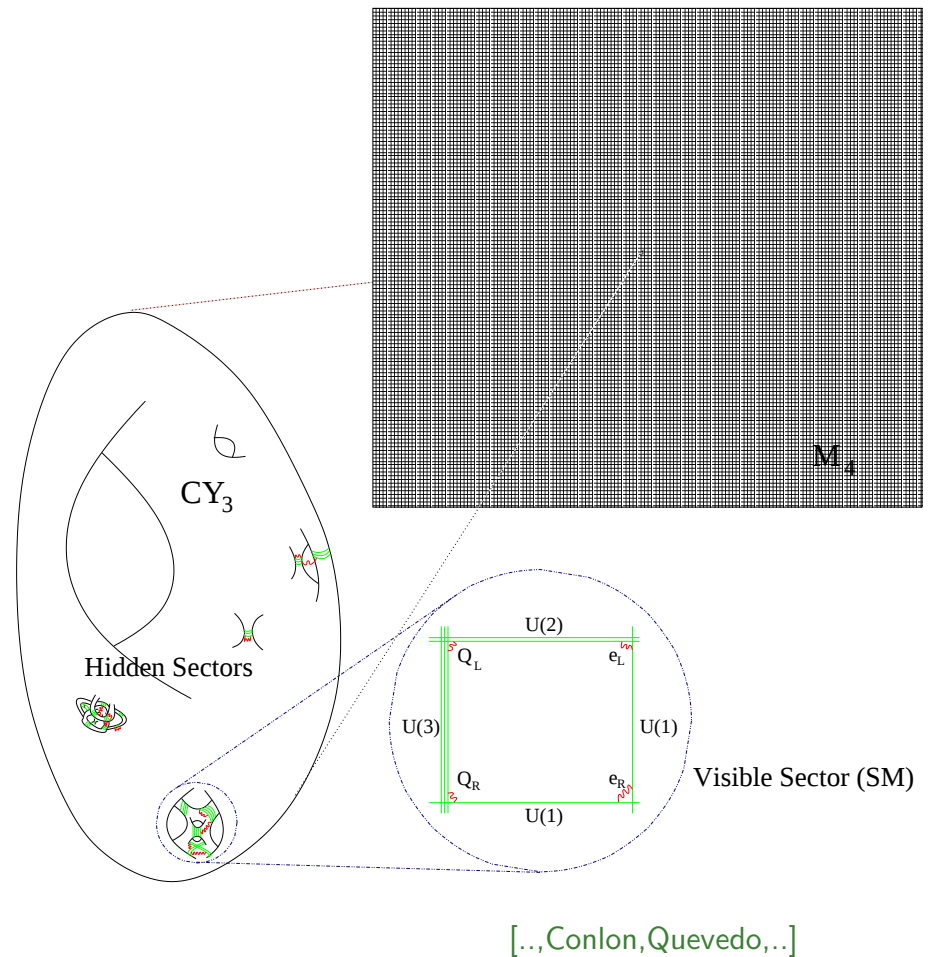
$$E_8 \times E_8 \rightarrow$$

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

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:



- U(1) factors in hidden sectors:
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- 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])
A. Ringwald (DESY)

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

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{U(1)_v} \underbrace{-\frac{1}{4}B^{\mu\nu}B_{\mu\nu}}_{U(1)_h} + \underbrace{\frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu}}_{\text{kin mix}} \\ + \underbrace{\bar{v}(i\not{D} + e\not{A})v}_{v \text{ matter}} + \underbrace{\bar{h}(i\not{D} + e_h\not{B})h}_{h \text{ matter}} + \dots$$

- 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, $B^\mu \rightarrow \tilde{B}^\mu + \chi A^\mu$;
- Hidden sector charged particle gets induced electric
charge:

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

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

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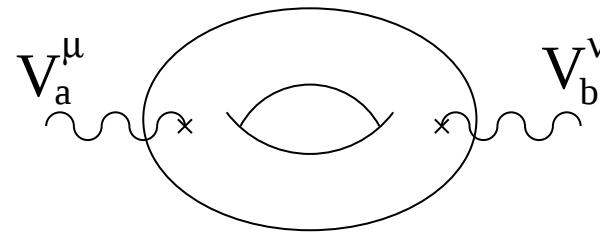
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KM in heterotic string models:

[Dienes, Kolda, March-Russell '97]



$$\chi \simeq \frac{ee_h}{16\pi^2} C \frac{\Delta m}{M_P}$$

$$\gtrsim 10^{-17},$$

$$\text{for } C \gtrsim 10, \Delta m \gtrsim 100 \text{ TeV}$$

- U(1) factors in hidden sectors:
generic prediction of realistic
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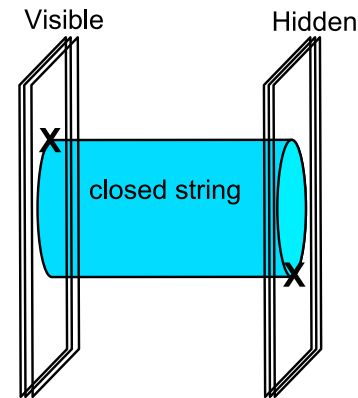
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KM in IIA/IIB string models:

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



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

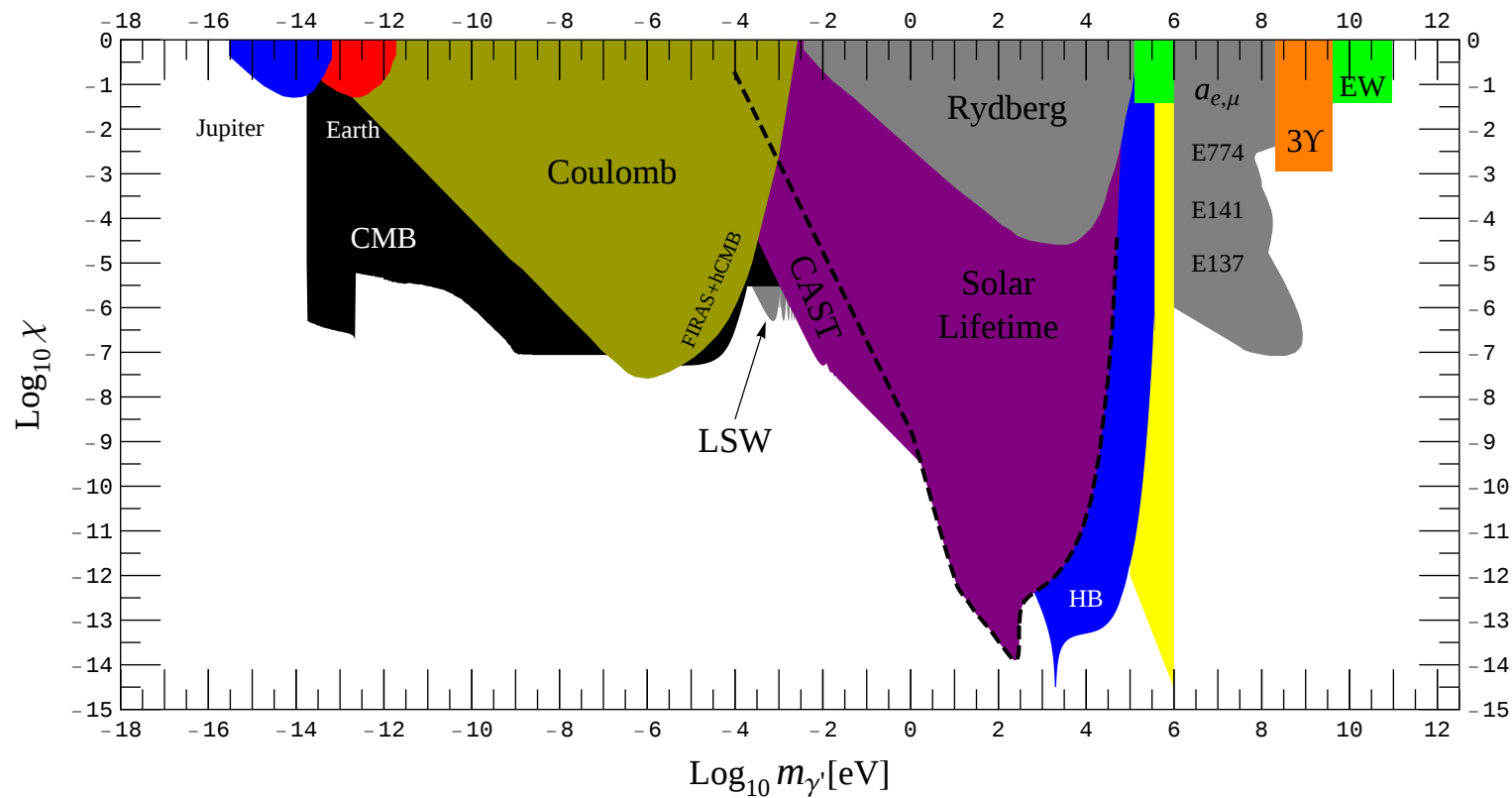
$$\chi \sim \frac{e e_h}{16\pi^2} \sim \frac{g_s}{8\pi} (V_6 M_s^6)^{-1/3} \gtrsim 10^{-12},$$

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

[Goodsell,Jaeckel,Redondo,AR '09]
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- The rich phenomenology of hidden $U(1)$ s:

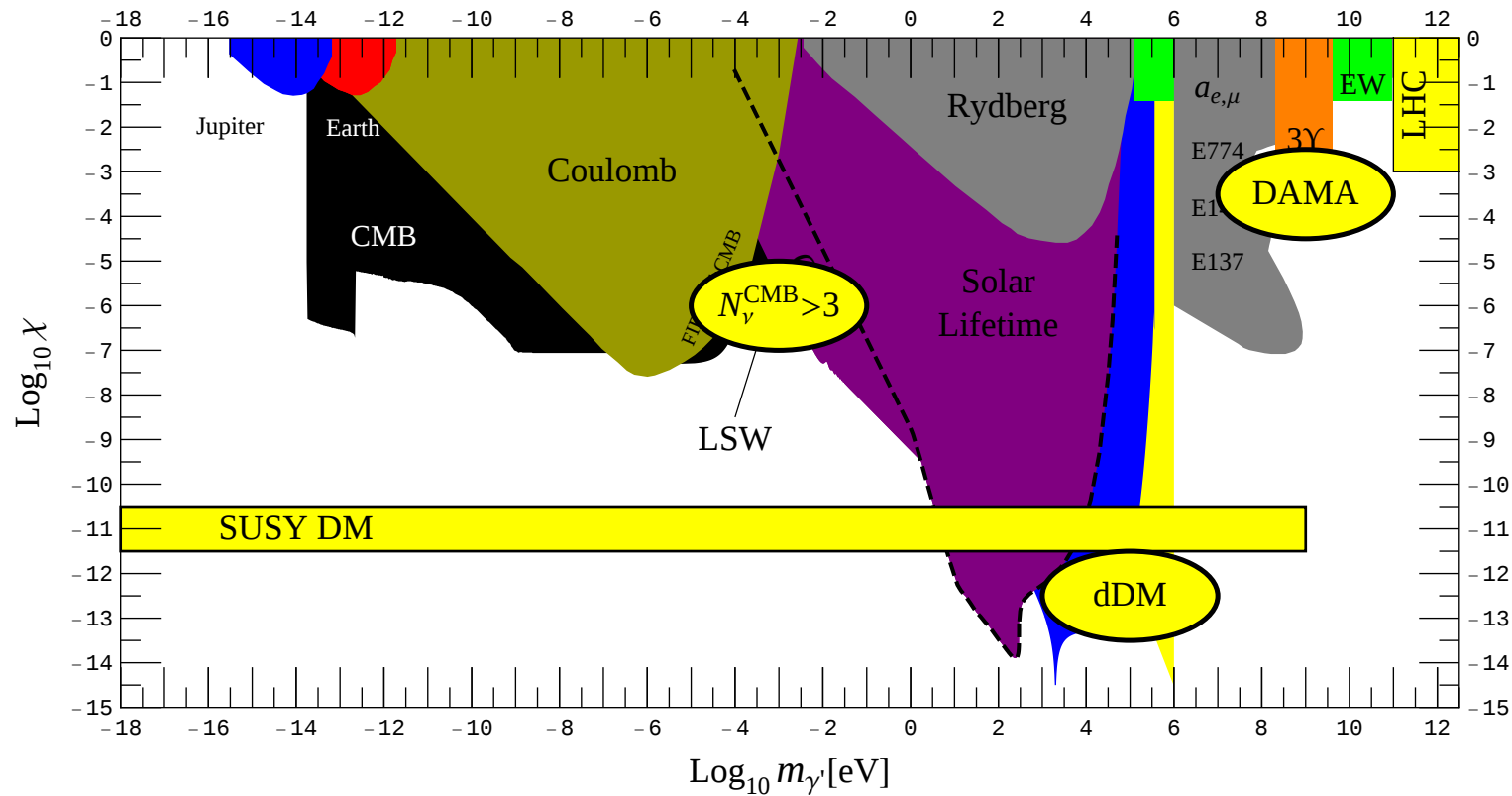
[Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08;Postma,Redondo '08;Bjorken,Essig,Schuster,Toro'09;...]



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)

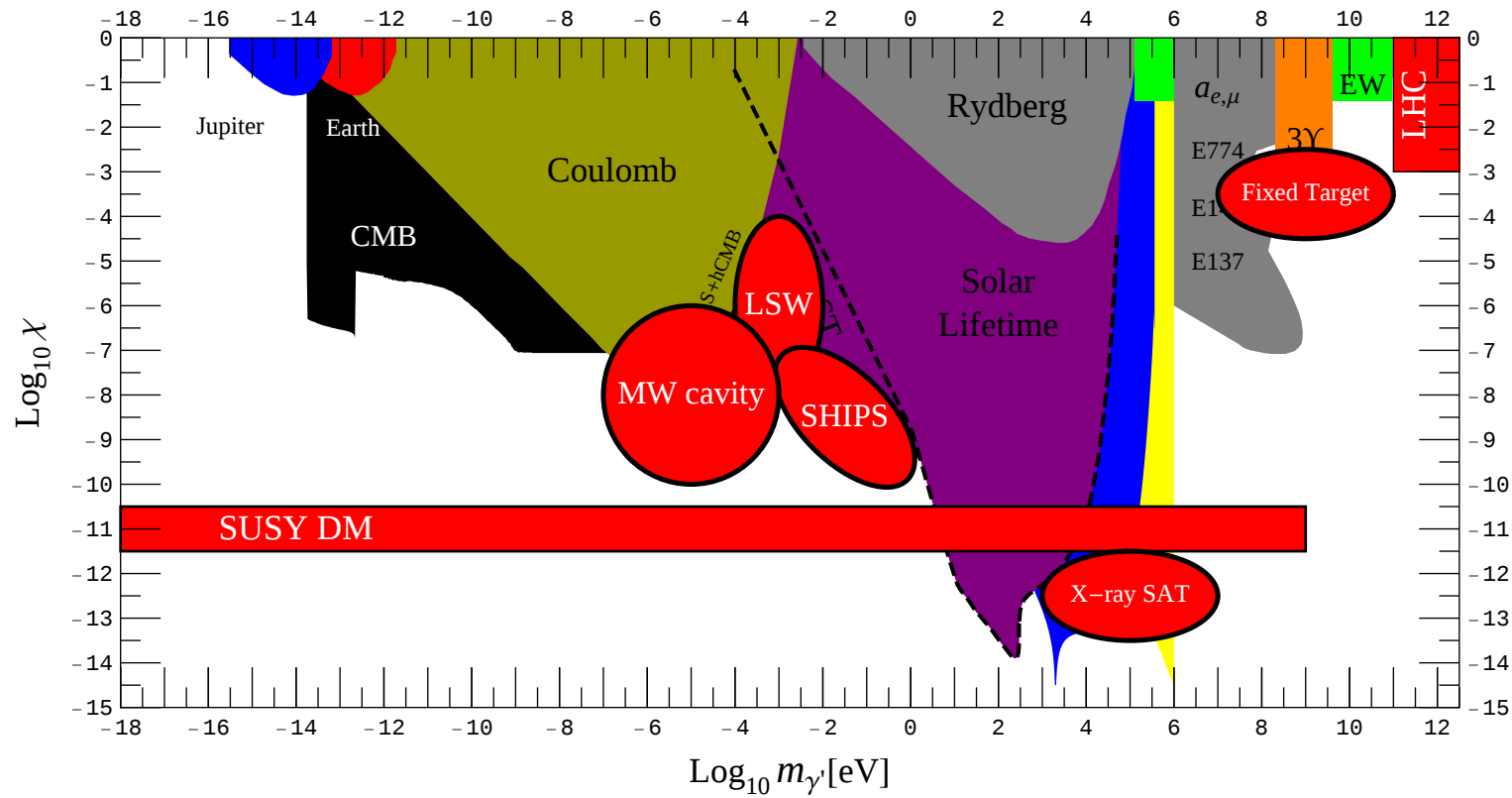
- The rich phenomenology of hidden $U(1)$ s:

[Jaeckel,Redondo,AR '08;Arkani-Hamed,..'08;Ibarra,AR,Weniger '08;...]



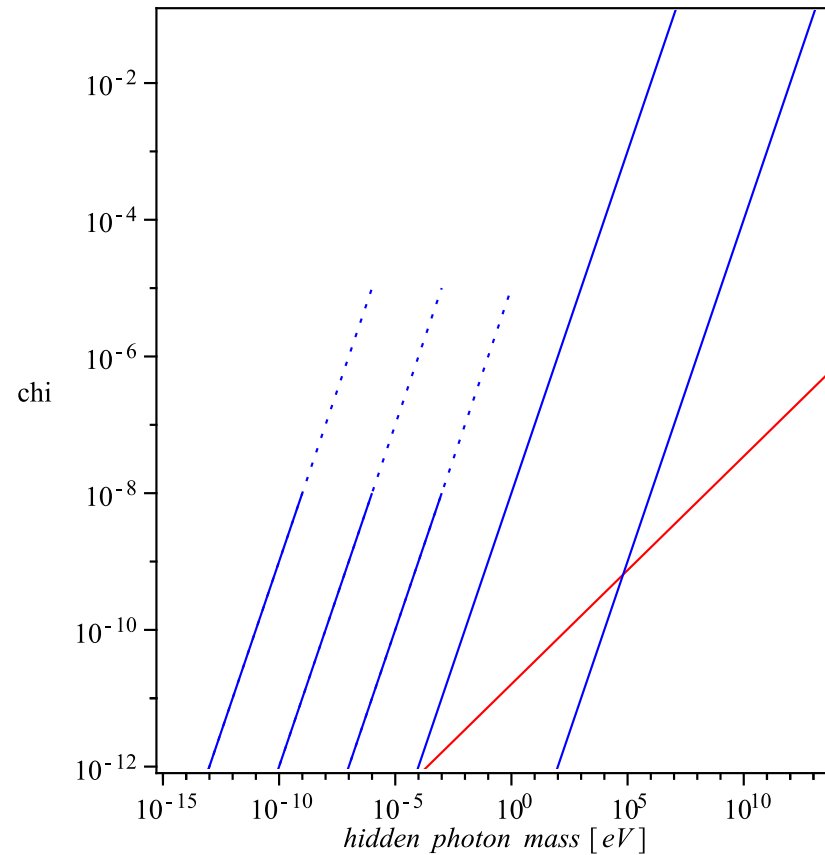
- The rich phenomenology of hidden $U(1)$ s:

[Ahlers,.. '07; Jaeckel, AR '07; Gninenko, Redondo '08; ...]

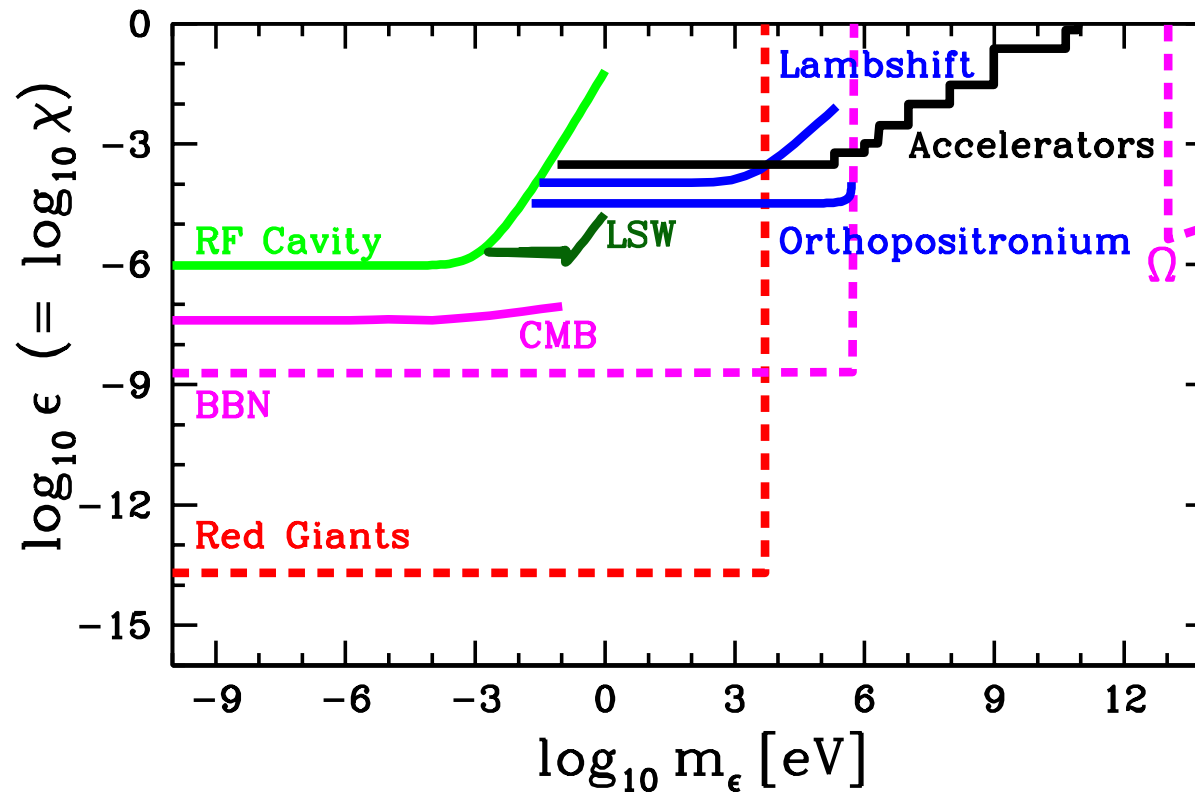


- Expectations in LARGE volume string compactifications (D7 brane wrapping LARGE 4-cycle):

[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); ...

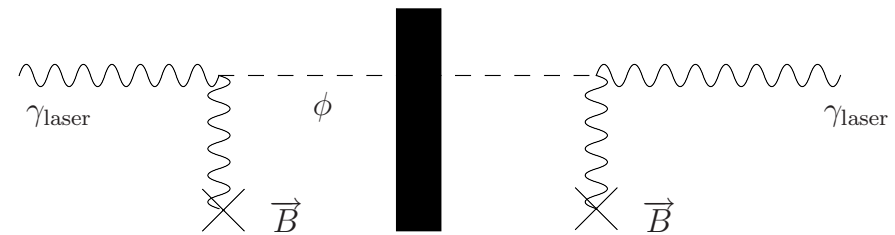
4. Light Shining through a Wall

- 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

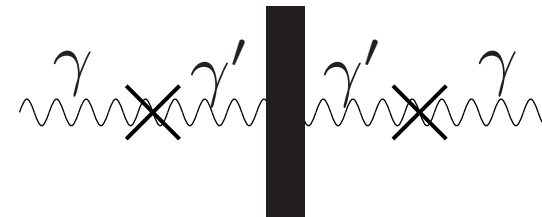
[Okun '82; Sikivie '83; Anselm '85;..]

LSW via

- photon-ALP oscillations:



- γ - γ' oscillations:



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

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^-)	$g_- B^{\text{ext}} \omega$	0	$m_{\phi-}^2$
ALP (0^+)	0	$g_+ B^{\text{ext}} \omega$	$m_{\phi+}^2$
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:

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

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

Experiment	Laser	$\langle P \rangle$	Magnets
ALPS	532 nm; FP	30-300 W	$B_1 = B_2 = 5 \text{ T}$ $\ell_1 = \ell_2 = 4.21 \text{ m}$
BFRT	$\sim 500 \text{ nm}$; DL	100 W	$B_1 = B_2 = 3.7 \text{ T}$ $\ell_1 = \ell_2 = 4.4 \text{ m}$
BMV	1064 nm; LULI	$8 \times 10^{21} \gamma/\text{pulse}$	$B_1 = B_2 = 11 \text{ T}$ $\ell_1 = \ell_2 = 0.25 \text{ m}$
GammeV	532 nm;	3.2 W	$B_1 = B_2 = 5 \text{ T}$ $\ell_1 = \ell_2 = 3 \text{ m}$
LIPSS	900 nm; FEL	300 W	$B_1 = B_2 = 1.7 \text{ T}$ $\ell_1 = \ell_2 = 1 \text{ m}$
OSQAR	1064 nm; FP	$> 1 \text{ kW}$	$B_1 = B_2 = 9.5 \text{ T}$ $\ell_1 = \ell_2 = 14 \text{ m}$

- Pioneering experiment: BFRT
- Several ongoing experiments

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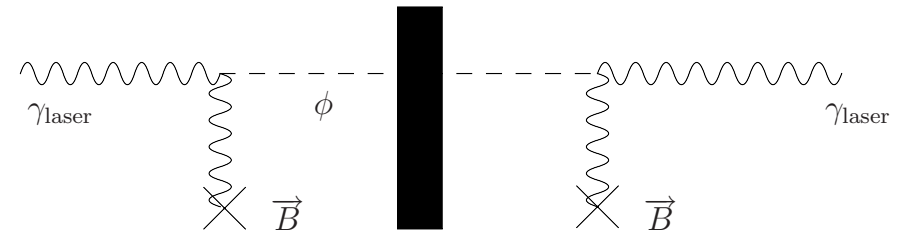
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A. Ringwald (DESY)

ALPS (Any-Light Particle Search):

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



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ALPS (Any-Light Particle Search):

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- Primary beam: enhanced LIGO laser (1064 nm, 35 W cw)
 - ⇒ frequency doubled to 532 nm
 - ⇒ ~ 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

4. Light Shining through a Wall

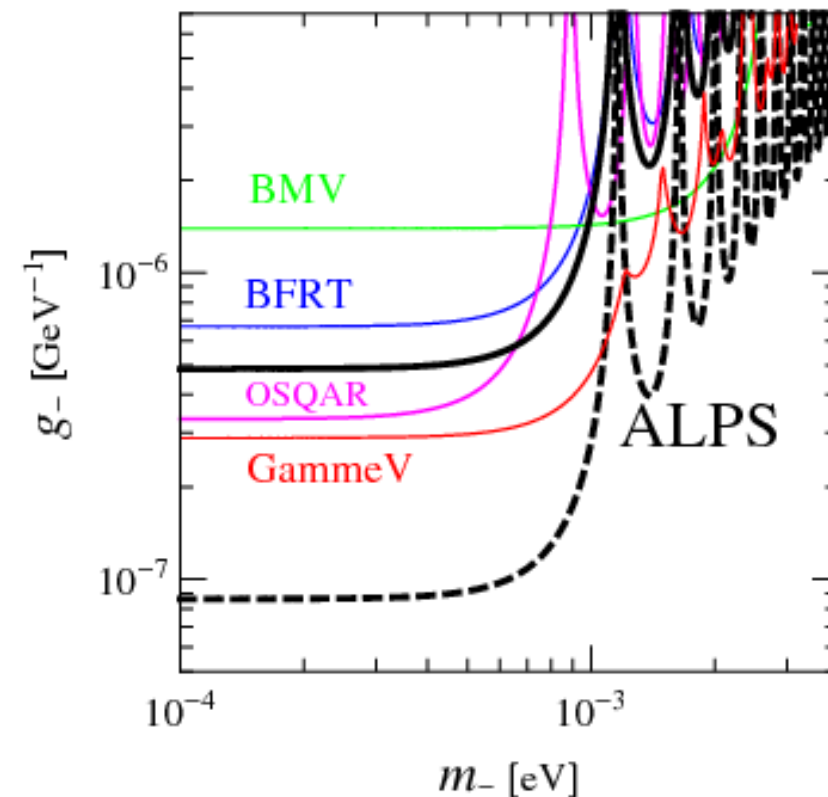
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A. Ringwald (DESY)

Limits from **ALPS** run in 12/2008 and prospects for 7/2009:



[ALPS Collaboration '09]

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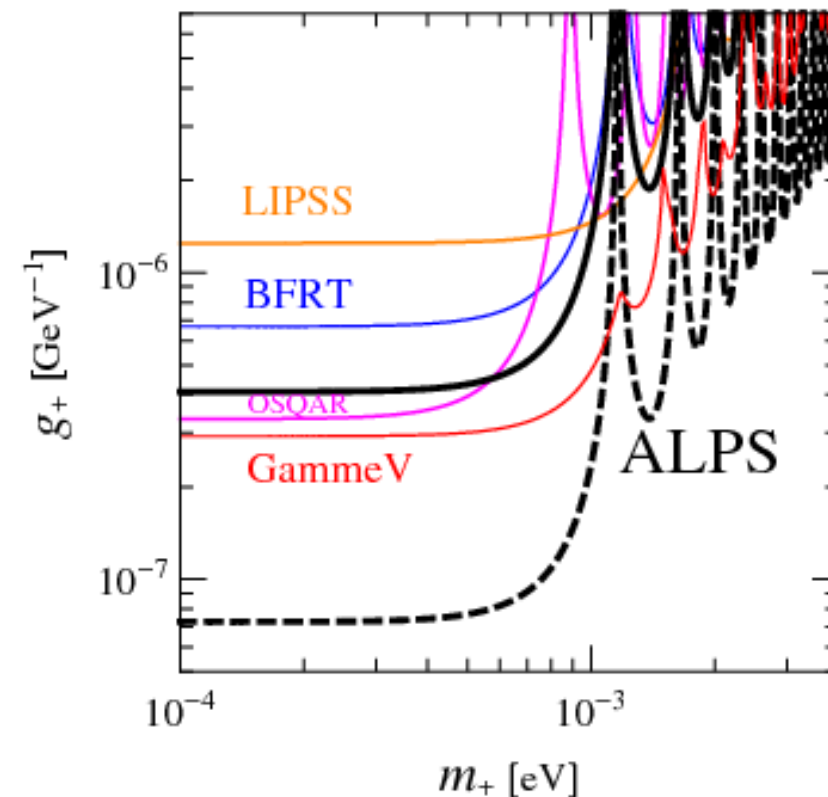
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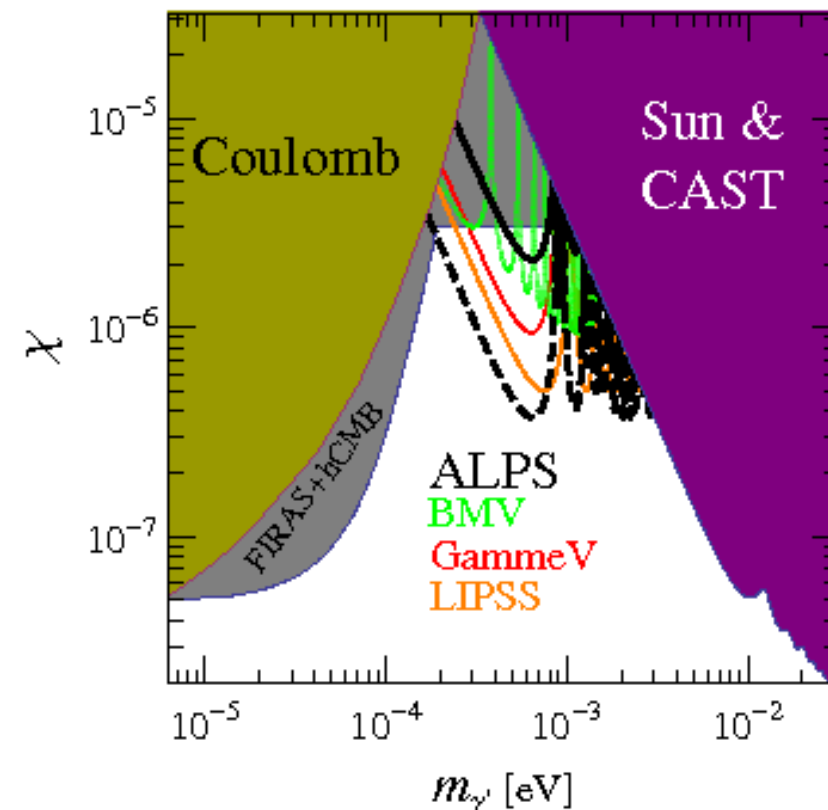
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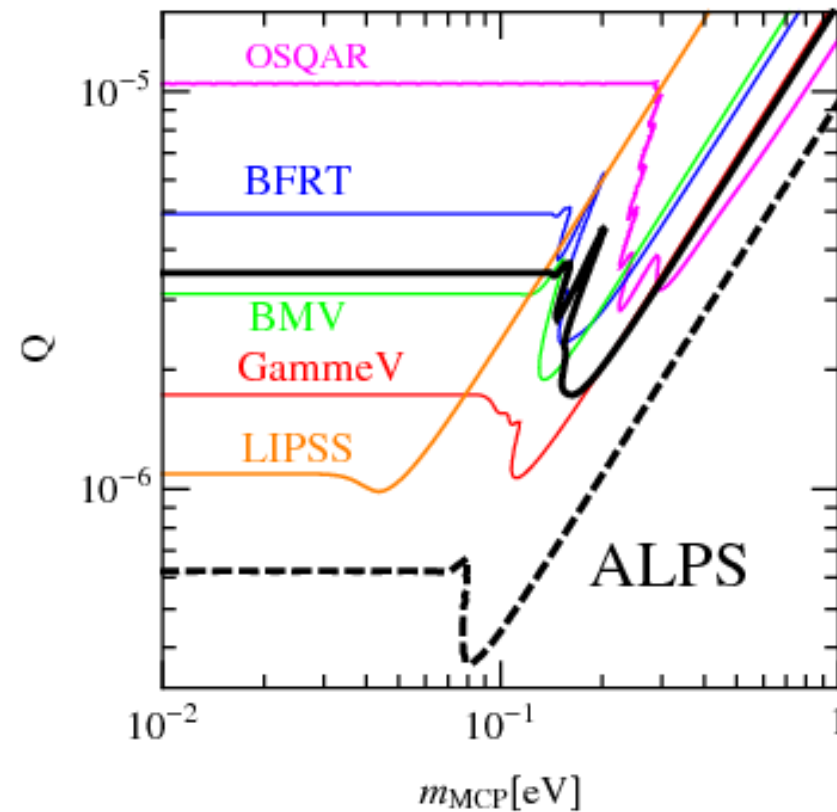
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[Okun '82; Sikivie '83; Anselm '85;...]

- Pioneering experiment: BFRT
- Several ongoing experiments

A. Ringwald (DESY)

Limits from **ALPS** run in 12/2008 and prospects for 7/2009:



[ALPS Collaboration '09]

Zeuthen, June 2009

4. Light Shining through a Wall

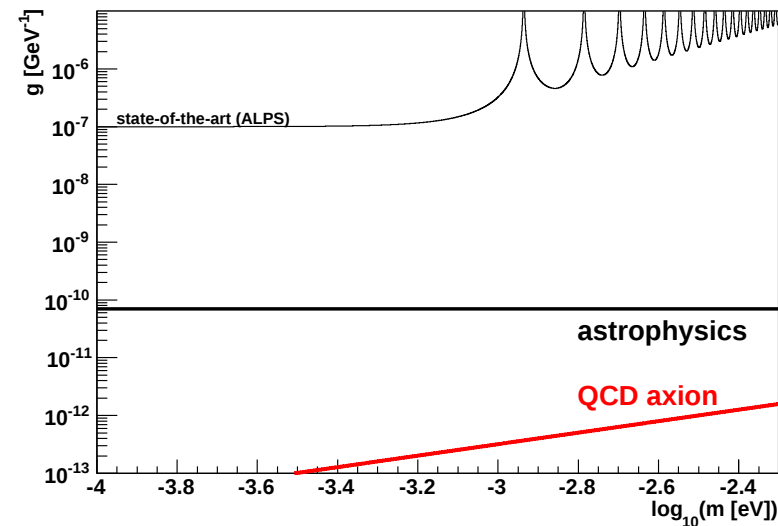
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Roadmap of ALP search with LSW:



[A. Lindner '09]

Zeuthen, June 2009

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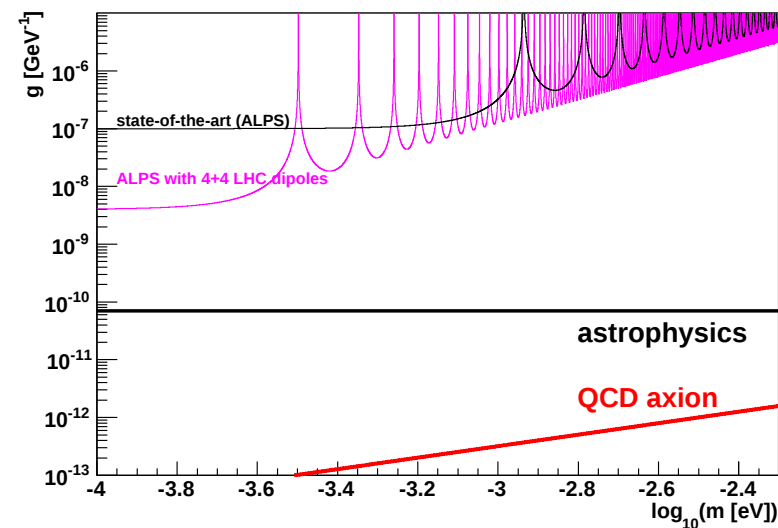
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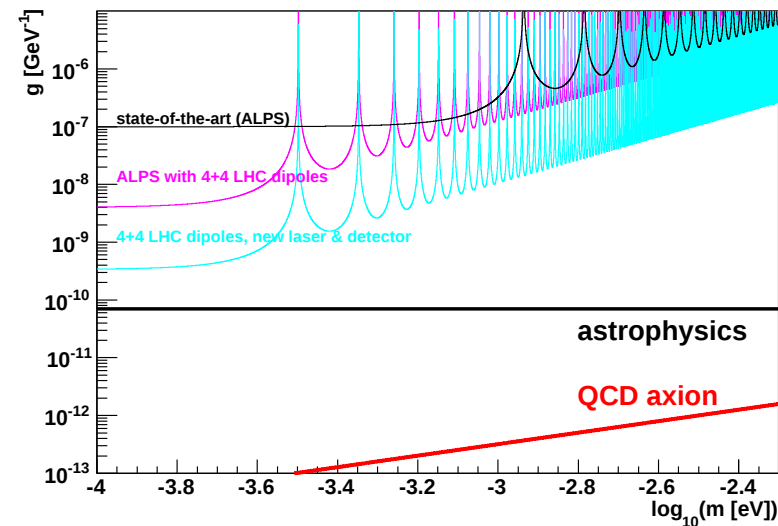
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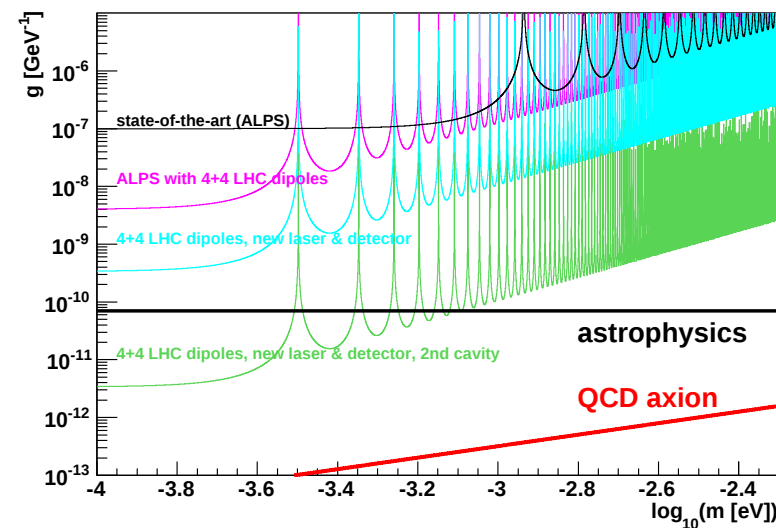
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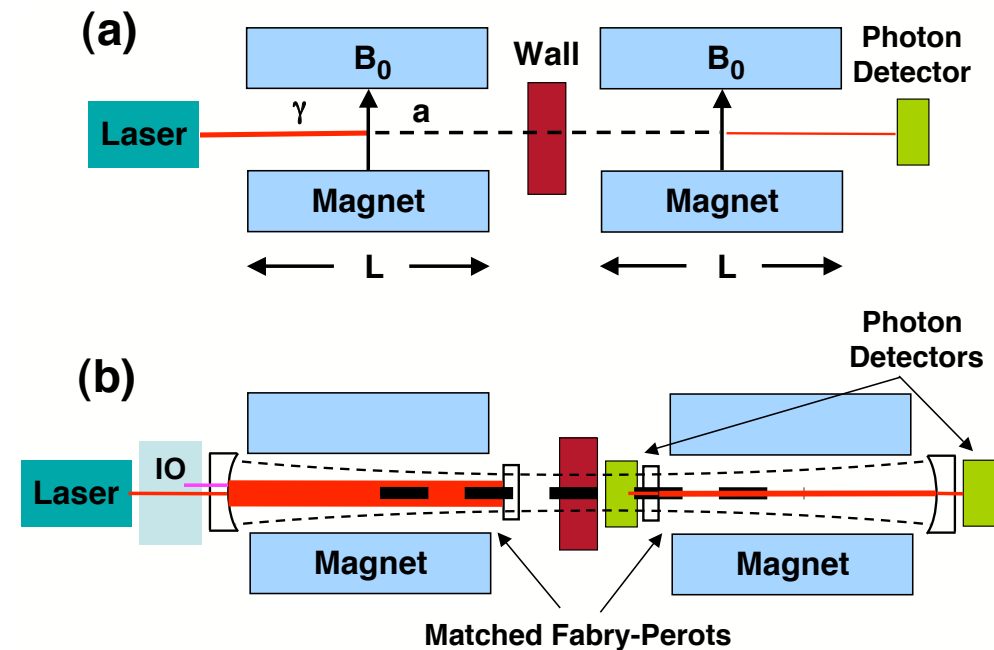
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Second Fabry-Perot Cavity:

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



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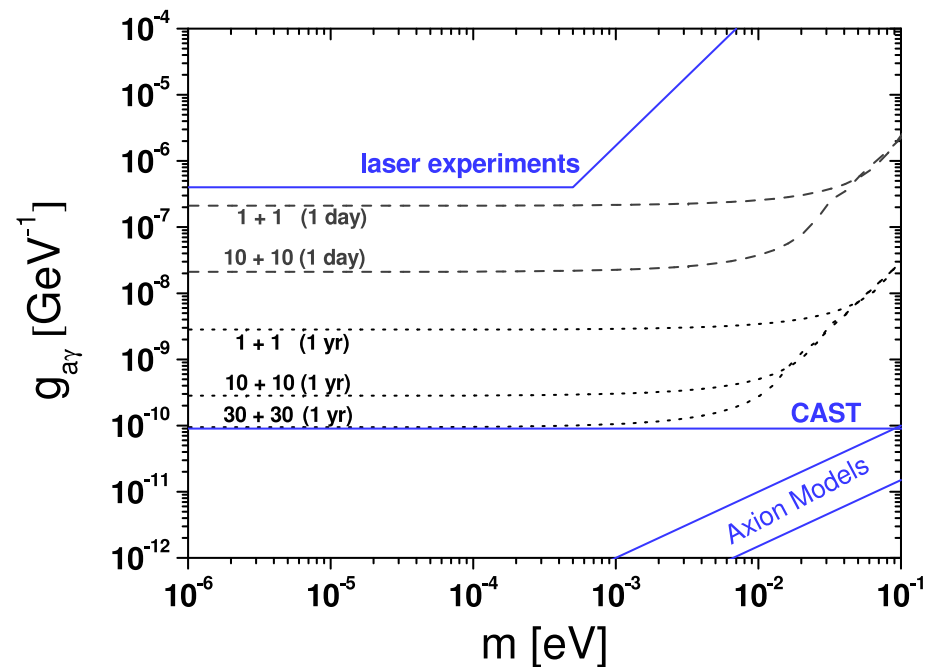
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XFEL or synchrotron light through wall suffers from “low” photon flux

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



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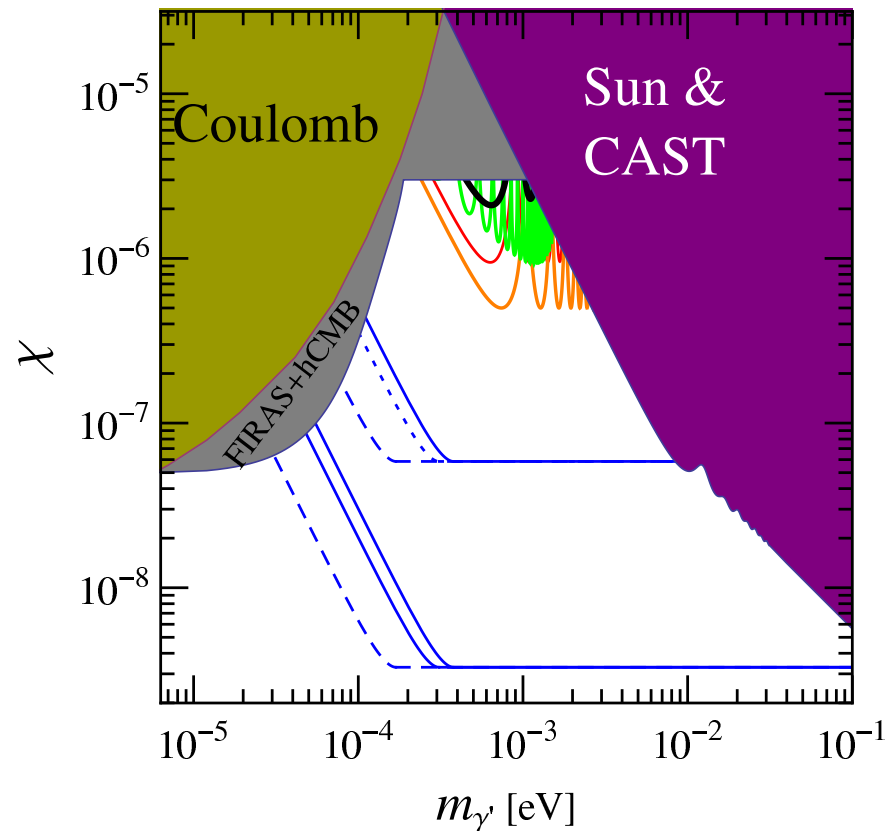
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A. Ringwald (DESY)

Roadmap of HP search with LSW:



[Redondo '09]

Zeuthen, June 2009

Helioscope Search for Hidden Photons

[Redondo '08; Gninenko, Redondo '08; ...]

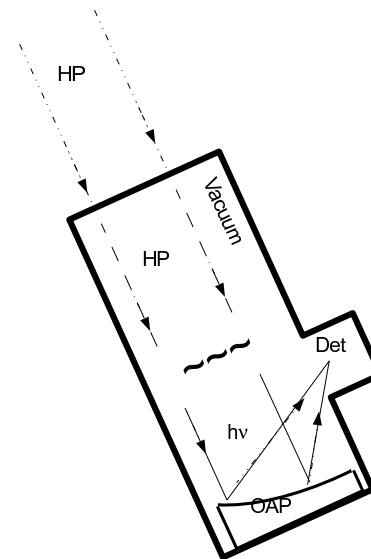
- Sun produces huge flux of hidden photons,

$$10^{32} \chi^2 \left(\frac{m_{\gamma'}}{\text{eV}} \right)^4 \frac{1}{\text{cm}^2 \text{s eV}}$$

- Hidden photons oscillate into real optical photons inside light-tight and evacuated tube, mounted on astronomical telescope to follow the sun
- Photons are collected by mirror onto sensitive photo-detector

A. Ringwald (DESY)

SHIPS (Solar Hidden Photon Search) at Hamburger Sternwarte:



[Wiedemann '09]

Zeuthen, June 2009

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[AR '09]

Zeuthen, June 2009

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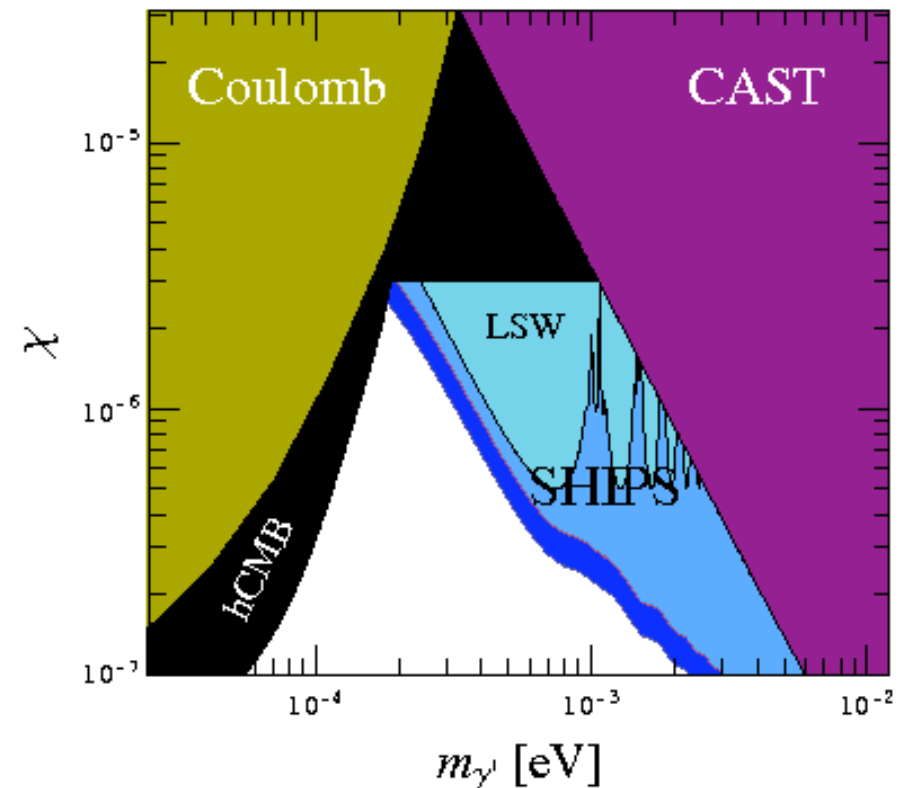
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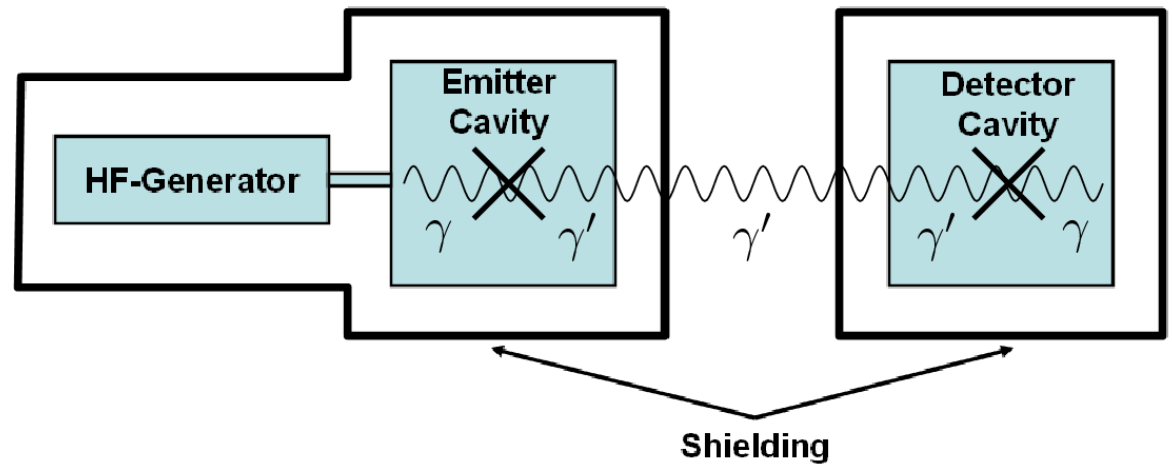
Zeuthen, June 2009

Microwave Cavity Experiments

- High quality cavities can be exploited to search for

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

– γ'



[Jaeckel,AR '07]

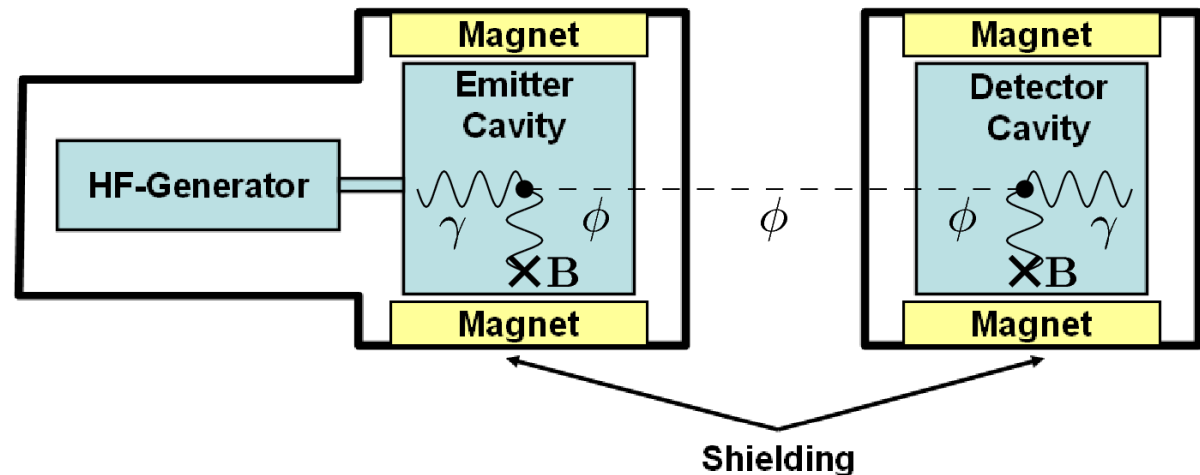
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- γ'
- ALPs

[Hoogeveen '92]



[Jaeckel,AR '07]

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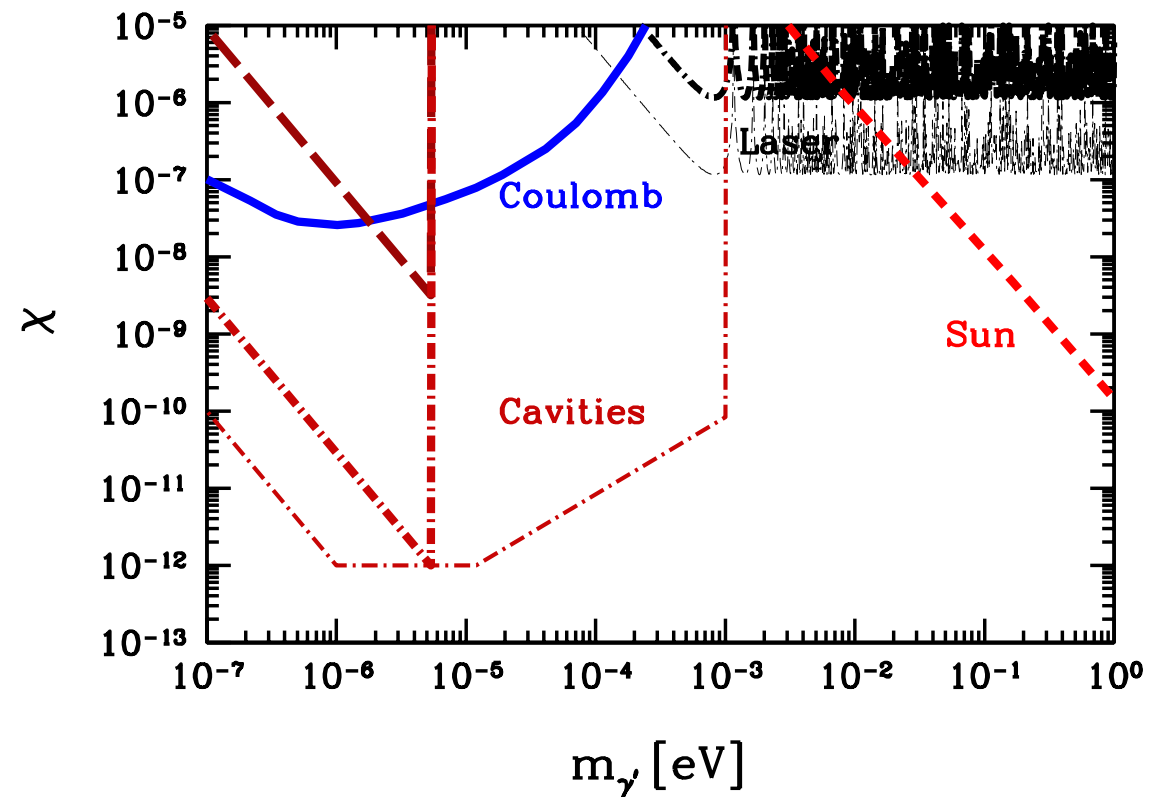
- γ'
- ALPs

- Discovery potential:

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

- Yale: Experiment in progress

A. Ringwald (DESY)



[Jaeckel,AR '07]

5. 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]