Ultra-Light Particles Beyond the Standard Model

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[Project C1 in SFB 676]

2nd Bethe Center Workshop: Cosmology meets Particle Physics
4-8 October 2010, Physikzentrum, Bad Honnef, D

Outline:

1. Case for Ultra-Light Particles Beyond the SM

1.1 Axions and Axion-Like Particles
1.2 Hidden-Sector Abelian Gauge Bosons

2. New Experiments at the High-Intensity Frontier

2.1 Photon Regeneration Experiments
2.2 Fixed-Target Experiments

3. Conclusions

1. Case for Ultra-Light Particles Beyond the Standard Model

- Natural very Weakly Interacting Slim Particles (WISPs) candidates:
  - (Pseudo-)Nambu Goldstone bosons $\Leftarrow$ "axions and axion-like particles"
  - Abelian gauge bosons $\Leftarrow$ "hidden photons, dark photons, paraphotons"

1.1 Axions and Axion-Like Particles

- Axionic shift symmetry, $\phi(x) \to \phi(x) + \mathrm{const.}$,

$\Rightarrow$ forbids explicit mass terms, $\propto m_\phi^2 \phi^2$ $\Rightarrow$ ultra-light
$\Rightarrow$ derivative couplings, $\propto \partial\phi/f_\phi$ $\Rightarrow$ very weakly interacting ($f_\phi \gg v_{\mathrm{EW}}$)

• Peccei-Quinn or QCD axion a:

[Peccei,Quinn '77]

– shift symmetry, $a \to a + \mathrm{const.}$, broken only by chiral anomalies,

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

– topological charge density $\propto \langle \mathrm{tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}\rangle \neq 0$ provides nontrivial potential for axion field; minimized at $\langle a \rangle = 0$

$\Rightarrow$ axion solves strong CP problem

$\Rightarrow$ axion is pseudo-NG boson with small mass [S.Weinberg '78; Wilczek '78]

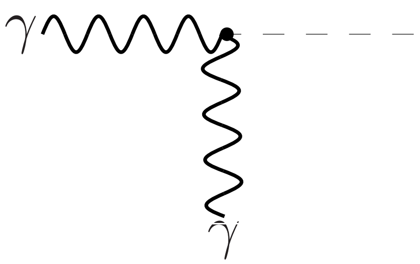
$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

– for $f_a \gg v_{\mathrm{EW}}$: axion is ultra-light and invisible

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

- Axions and axion-like particles (ALPs) have also anomalous couplings to photons,

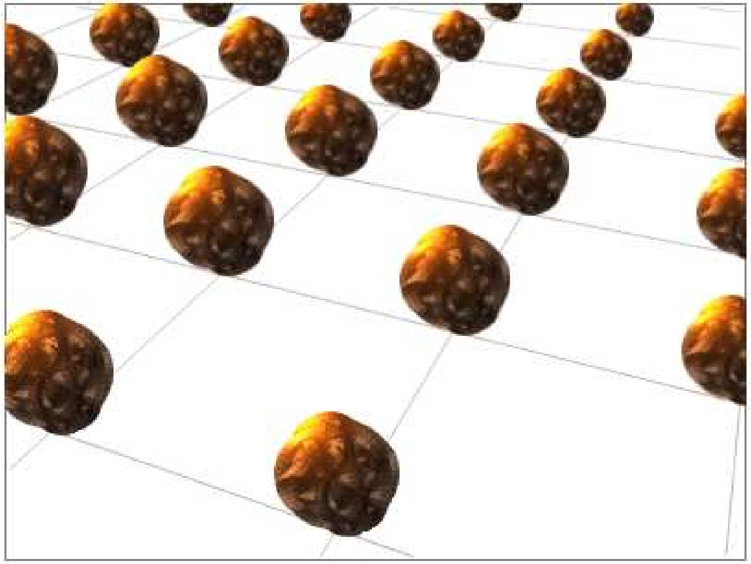
$$\mathcal{L}_{\phi\gamma\gamma} = -\frac{1}{4}\, g\, \phi\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g\, \phi\, \vec{E}\cdot\vec{B},$$



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

$$g \sim \frac{\alpha}{2\pi f_\phi} \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\ \mathrm{GeV}}{f_\phi}\right)$$

- **Axions in string theory:**
  Axions and axion-like fields with global anomalous shift symmetries generic in string compactifications: KK zero modes of form fields [Witten '87; ...; Conlon '06, Svrcek,Witten '06; Arvanitaki *et al.* '09; ...]



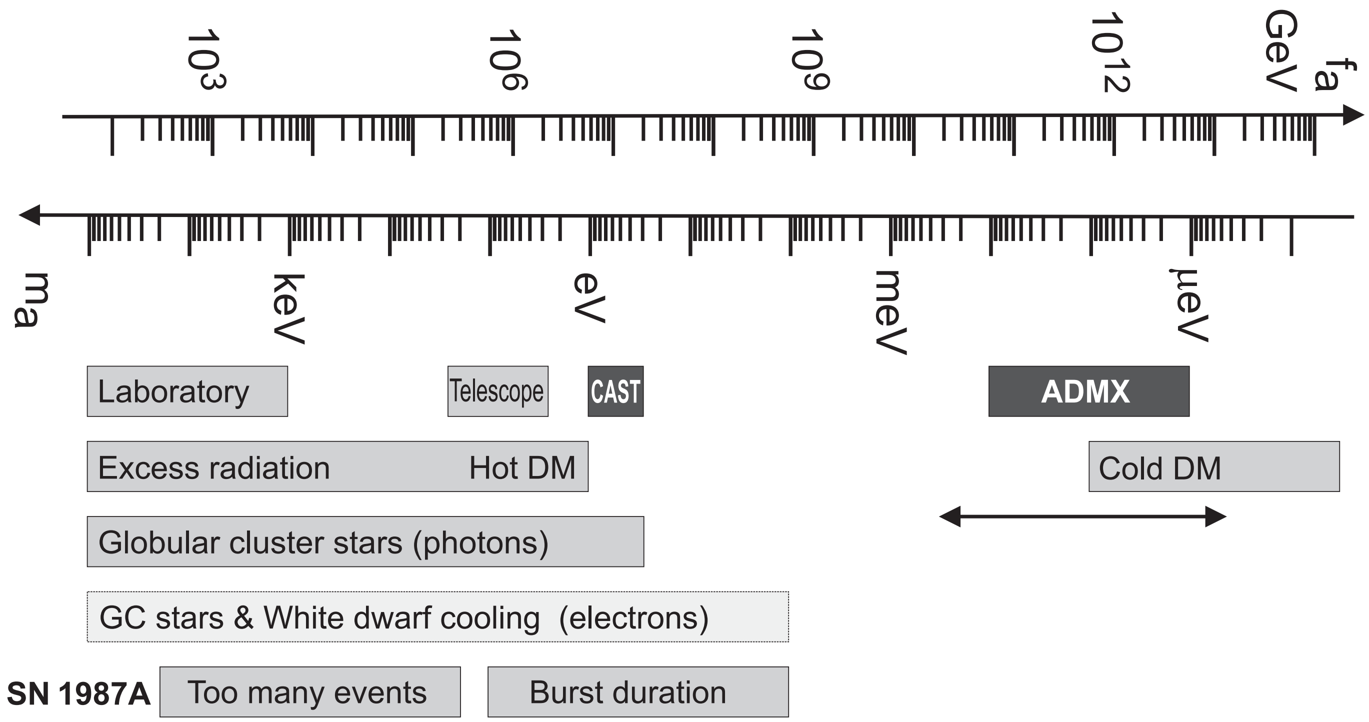
  Typically, for axions,

$$10^9\,\mathrm{GeV} \lesssim \quad f_a \sim M_s \quad \lesssim 10^{16}\,\mathrm{GeV}$$
$$10^{-2}\,\mathrm{eV} \gtrsim \quad m_a \sim \frac{m_\pi f_\pi}{M_s} \quad \gtrsim 10^{-9}\,\mathrm{eV}$$

  and, for axion-like particles,

$$f_\phi \sim f_a, \qquad m_\phi \ll m_a$$

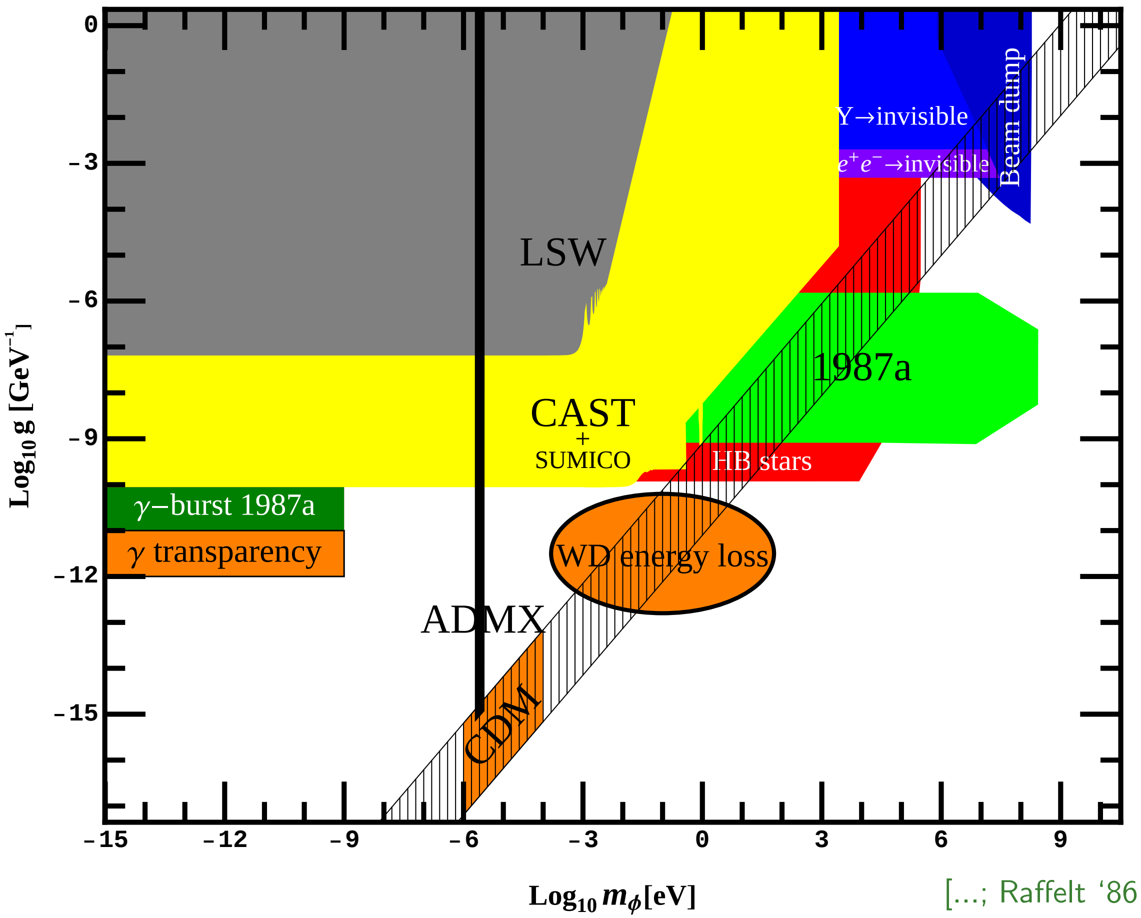
- Observational and experimental exclusion limits on f_a:



[PDG]

  - Solid lower bound, $f_a \gtrsim 10^9$ GeV
  - Overclosure constraint generically $f_a \lesssim 10^{12}$ GeV, but can be postponed to GUT scale, for fine-tuned initial conditions

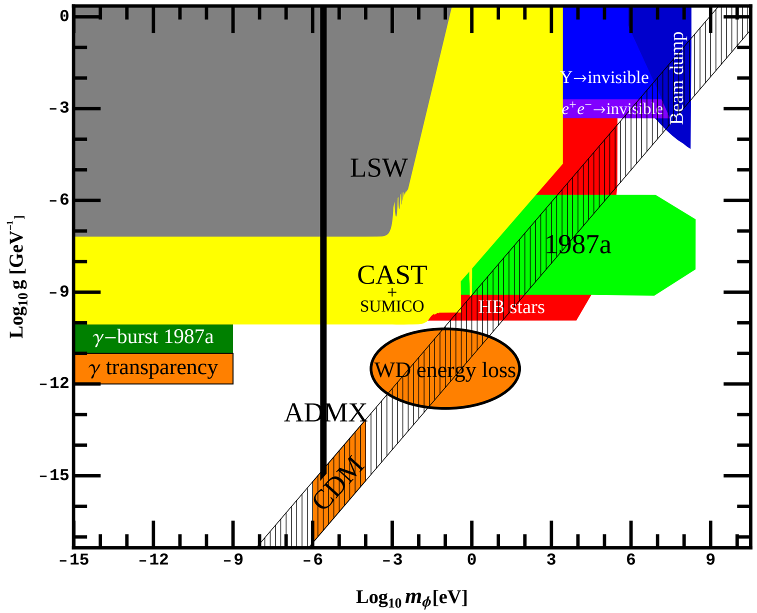
- Observational and experimental exclusion limits on g for axions and ALPs:



[...; Raffelt '86;...; Jaeckel,AR '10]

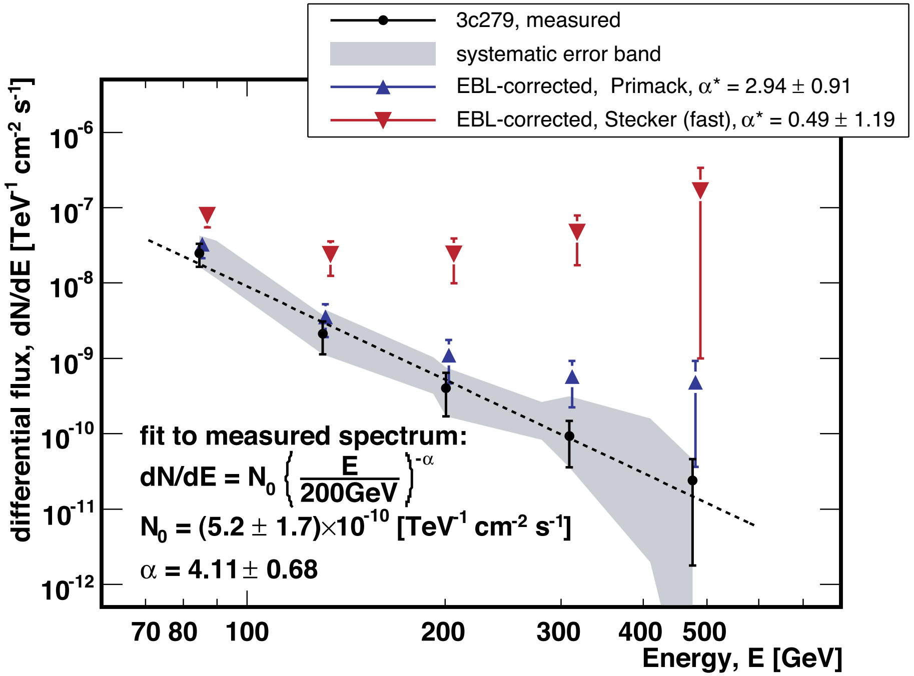
- **Indirect hints for axions and axion-like particles?**
  - **Non-standard energy loss in white dwarfs** recently pointed out, compatible with the existence of axions or ALPs with a coupling to the electron, $g_{e\phi} \simeq 10^{-13}$, suggesting a decay constant [Isern *et al.* '08],

$$f_\phi \simeq g_{e\phi} m_e = 4 \times 10^9 \text{ GeV} \Rightarrow g_{\gamma\phi} \sim \alpha / f_\phi \sim 10^{-11} \text{ GeV}^{-1}$$



[Jaeckel,AR '10]

– **Anomalous transparency of the universe in gamma rays** inferred from observation of distant astrophysical sources in TeV gamma rays, despite expected strong absorption due to e^+e^- pair production on extragalactic background light.

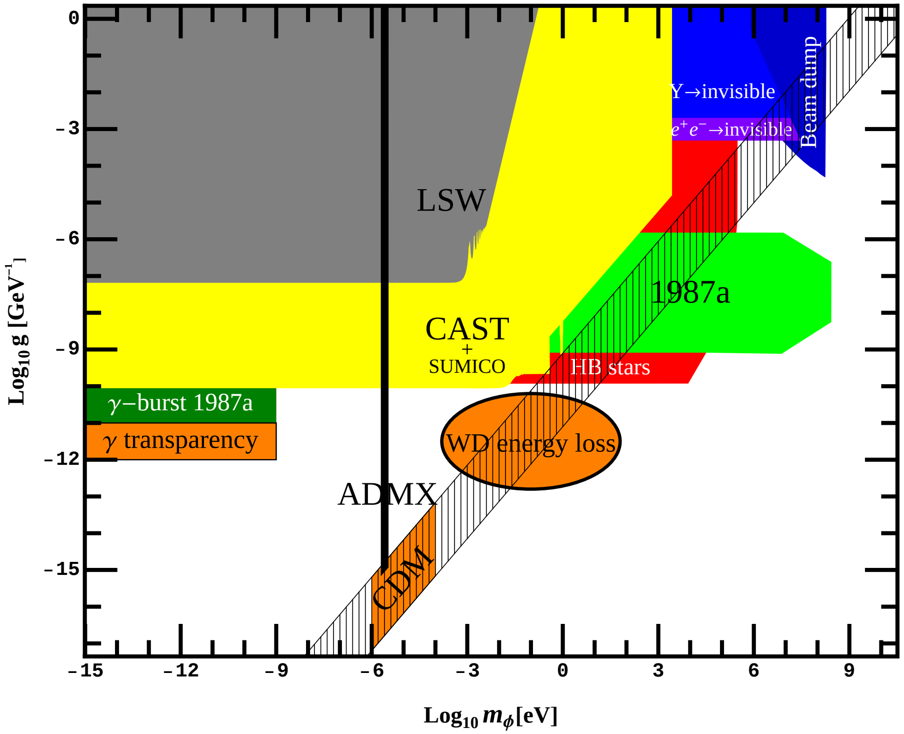


[MAGIC '08]

May be explained by conversion of γs into axion-like particles ϕ in the magnetic fields around the gamma ray sources. These ALPS travel then unimpeded until they reach our galaxy and reconvert into photons in the galactic magnetic fields

[Hochmuth,Sigl '07;Hooper,Serpico '07]. Alternatively, the conversion/reconversion could take place in the intergalactic magnetic fields [De Angelis,Mansutti,Roncadelli '07;..;Mirizzi,Montanino '09]. Need

$$g_{\gamma\phi} \sim 10^{-12} \div 10^{-11}\ \mathrm{GeV}^{-1}; \qquad m_\phi \ll 10^{-9}\ \mathrm{GeV}$$



[Jaeckel,AR '10]

⇒ Aim for next-generation photon regeneration experiments

1.2 Hidden-Sector Abelian Gauge Bosons

- U(1) gauge symmetry:
  - U(1) very naturally "massless"
  - non-zero mass can arise via
    - Higgs mechanism
    - Stückelberg mechanism
    - Kaluza Klein mechanism

- Extra U(1) gauge factors ubiquitous in well motivated extensions of the SM with large rank local gauge group:
  - large gauge symmetries must be broken
  - U(1)s are the lowest-rank local symmetries

- Some of these extra U(1) factors can be hidden (no (MS)SM particles charged under them)

- Hidden U(1) gauge factors ubiquitous in string compactifications:
  - heterotic string: arise e.g. in standard embedding,

$$\mathrm{E}_8 \times \mathrm{E}_8 \to \underbrace{\mathrm{E}_6}_{\text{visible}} \times \underbrace{\mathrm{E}_8}_{\text{hidden}} \to \dots,$$

    from breaking of hidden E_8
  - type II/F theory:
    - ∗ KK zero modes of closed string RR form fields
    - ∗ massless excitations of space-time filling D-branes separated in compact space from locus of SM branes

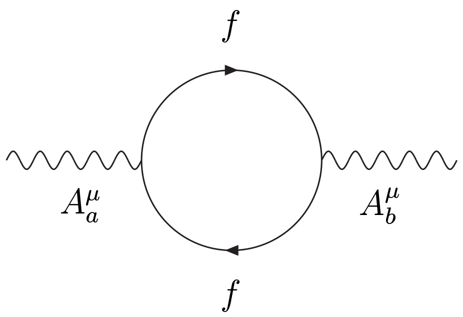
- At low energies, hidden U(1)s interact with U(1)$_Y$ or U(1)$_{\rm em}$ dominantly via kinetic mixing, [Holdom'85]

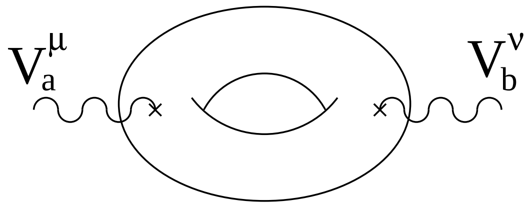
$$\mathcal{L} \supset -\frac{1}{4}F^{(\rm vis)}_{\mu\nu}F^{\mu\nu}_{(\rm vis)} - \frac{1}{4}F^{(\rm hid)}_{\mu\nu}F^{\mu\nu}_{(\rm hid)} + \frac{\chi}{2}F^{(\rm vis)}_{\mu\nu}F^{(\rm hid)\mu\nu} + m^2_{\gamma'}A^{(\rm hid)}_{\mu}A^{(\rm hid)\mu}$$

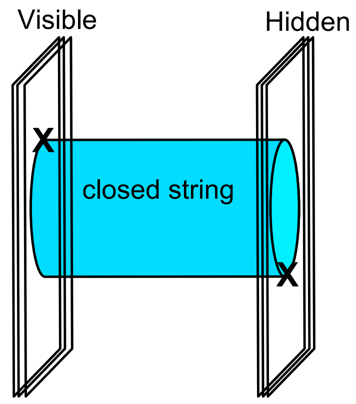
  - $\chi \ll 1$ generated at loop level via messenger exchange,

$$\chi \sim \frac{g_Y g_h}{(16\pi)^2} f$$

  - g_h and f depend on the type of messenger:







– Kinetic mixing in field theory: [Holdom '85; Dienes,Kolda,March-Russell '97]

$$10^{-8} \lesssim \chi \simeq \frac{\alpha}{4\pi} C \log\left(1 + \left(\frac{\Delta m}{m}\right)^q\right) \lesssim 10^{-3},$$

$$\text{for } 1 \lesssim C \lesssim 10;\ \ q = 1, 2;\ \ 10^{-2} \lesssim \frac{\triangle m}{m} \lesssim 1$$

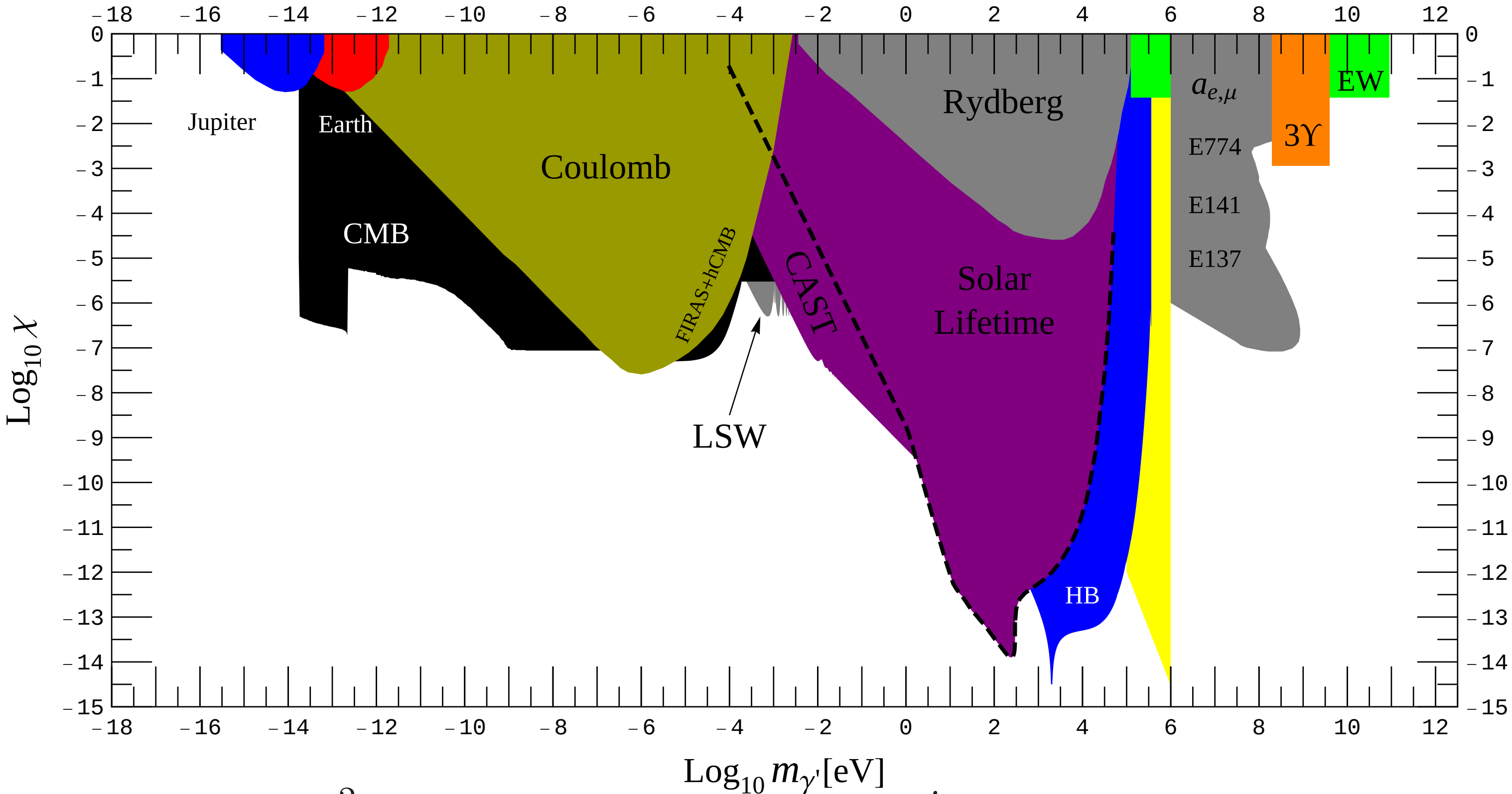
– Kinetic mixing between D-brane localized U(1)s in type II compactifications: [Lüst,Stieberger '03;Abel,Schofield '04;Berg,Haack,Körs '05;..;Goodsell *et al.* '09]

$$10^{-12} \lesssim \chi \sim \frac{g_Y g_h}{16\pi^2} \sim \frac{2\pi g_s}{16\pi^2}\left(\frac{4\pi}{g_s^2}\frac{M_s^2}{M_P^2}\right)^{q/12} \lesssim 10^{-3},$$

$$\text{for } q = 0, 4;\ \ 10^3 \text{ GeV} \lesssim M_s \lesssim 10^{17} \text{ GeV}$$

- Current constraints on hidden U(1)s:

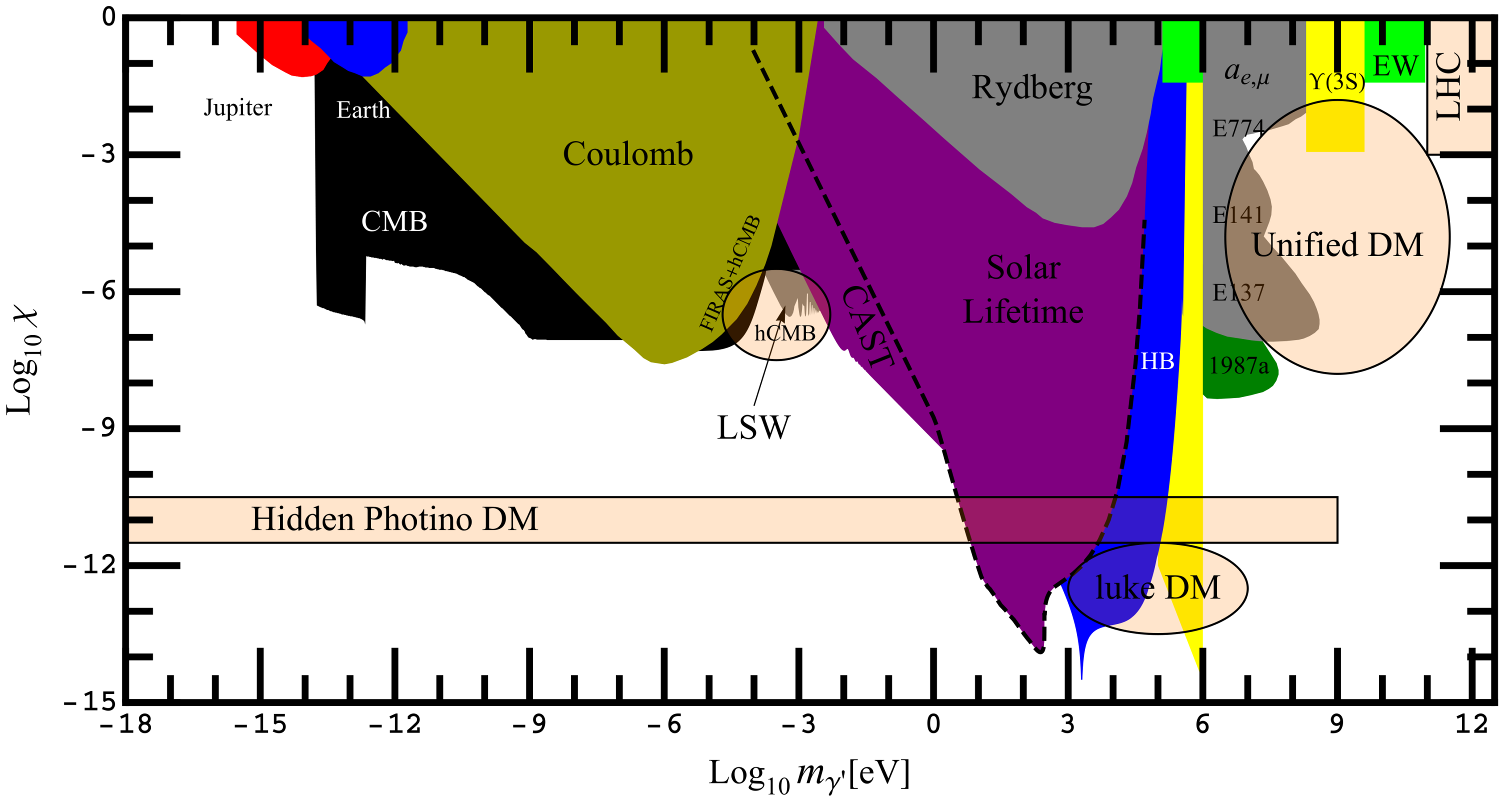
[Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08;Postma,Redondo '08;Bjorken,Essig,Schuster,Toro'09;...]



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

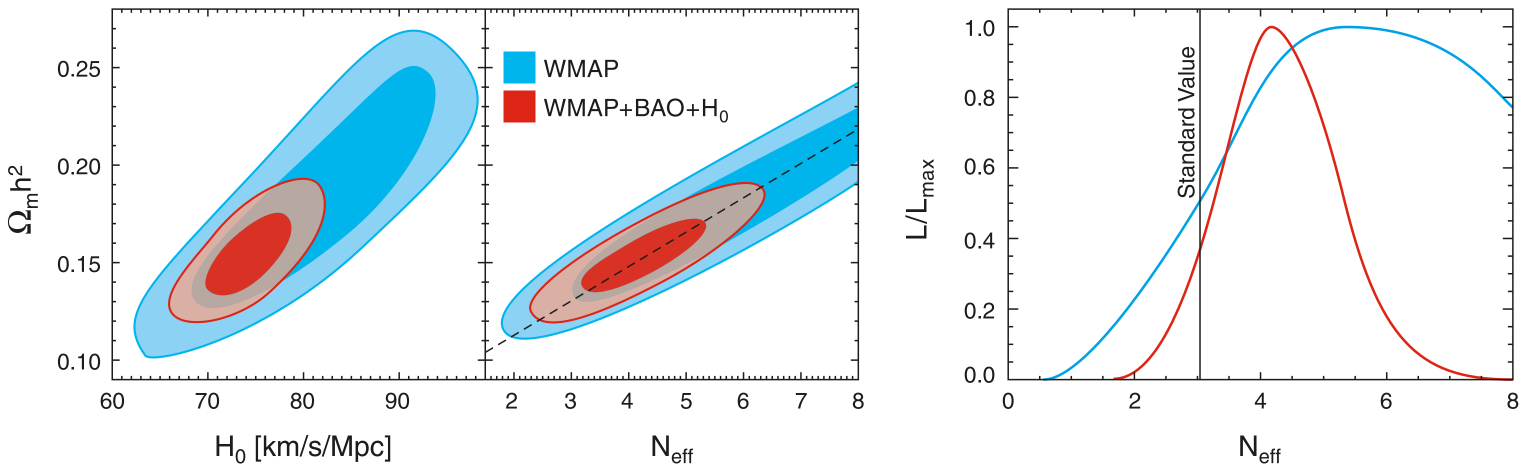
- Phenomenologically interesting hidden U(1) parameter ranges:

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



- meV scale hidden photon results in hidden CMB due to resonant $\gamma \leftrightarrow \gamma'$ oscillations after BBN but before CMB decoupling; may explain $N_\nu^{\rm eff} > 3.04$, as favored from global analyses of CMB + large scale structure data;

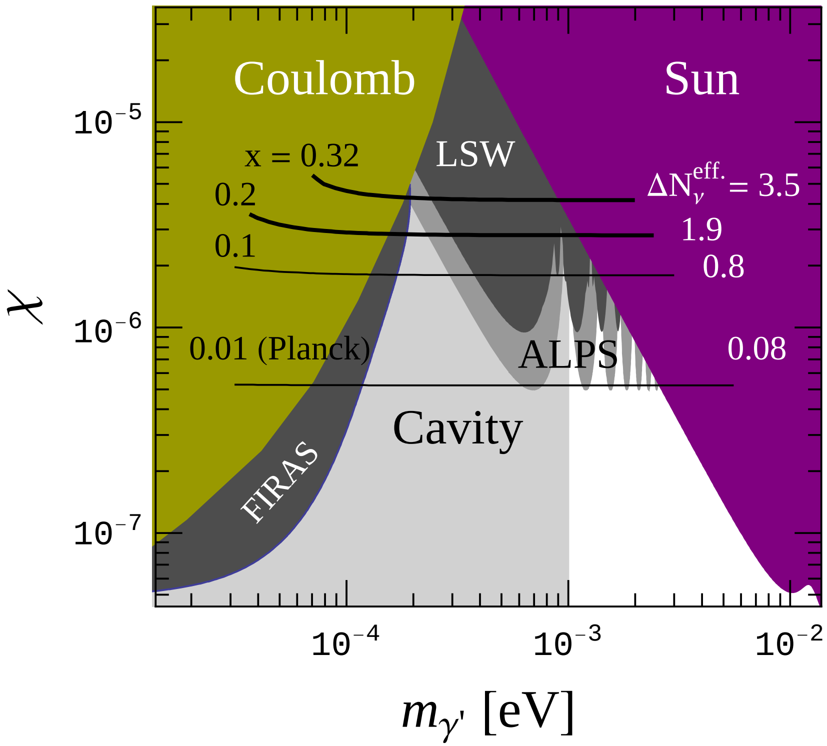
[Jaeckel,Redondo,AR '08]



[WMAP 7-year Cosmological Interpretation]

- meV scale hidden photon results in hidden CMB due to resonant $\gamma \leftrightarrow \gamma'$ oscillations after BBN but before CMB decoupling; may explain $N_\nu^{\rm eff} > 3.04$, as favored from global analyses of CMB + large scale structure data; can be checked in light-shining-through-wall experiments

[Jaeckel,Redondo,AR '08]



- MeV-GeV scale hidden photon

  – may explain $(g-2)_\mu$ anomaly [Pospelov '08]

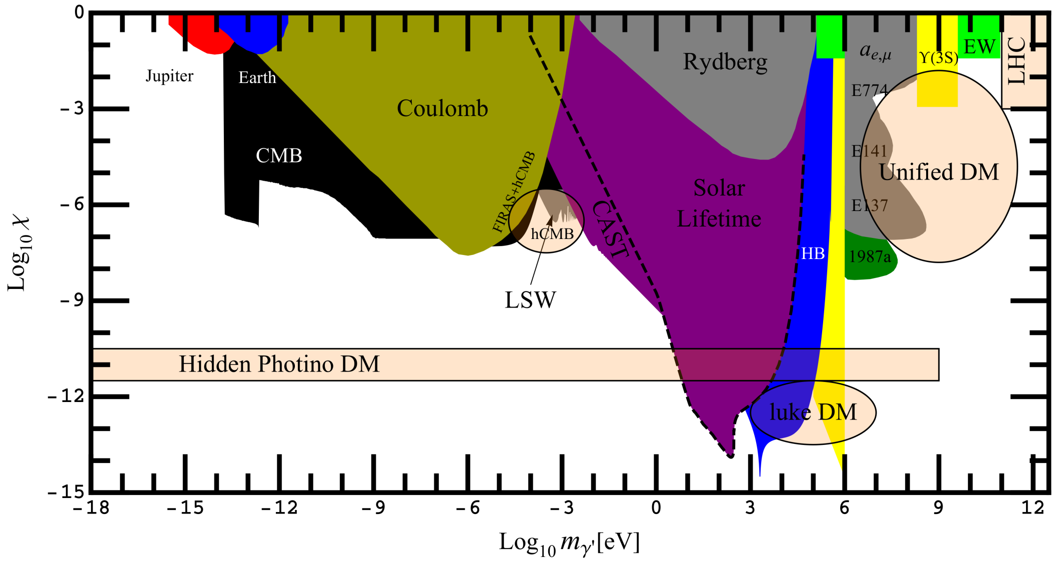
  – may explain [Arkani-Hamed *et al.* '08; Pospelov,Ritz '08;...]

  ∗ terrestrial (DAMA, CoGeNT vs. CDMS, XENON) and

  ∗ cosmic ray (PAMELA, FERMI)

  DM anomalies if DM charged under hidden U(1)

  – can be checked in new fixed-target experiments

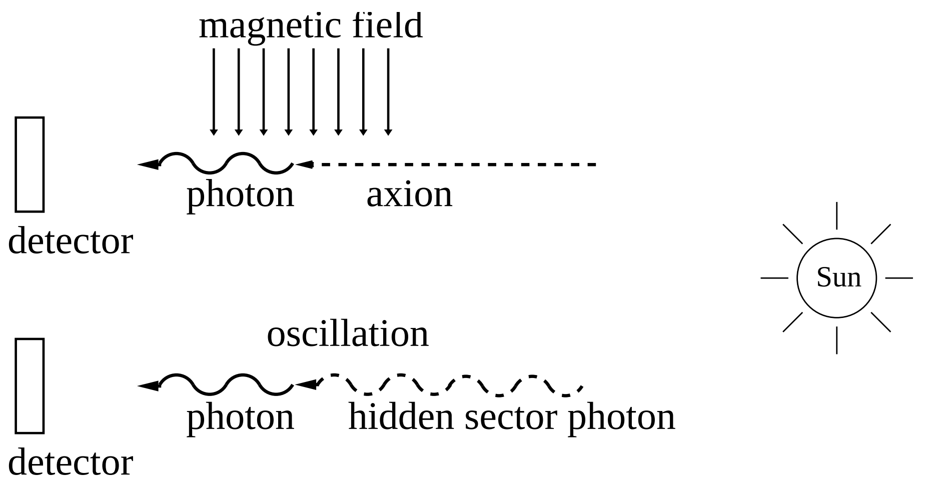


2. New Experiments at the High-Intensity Frontier

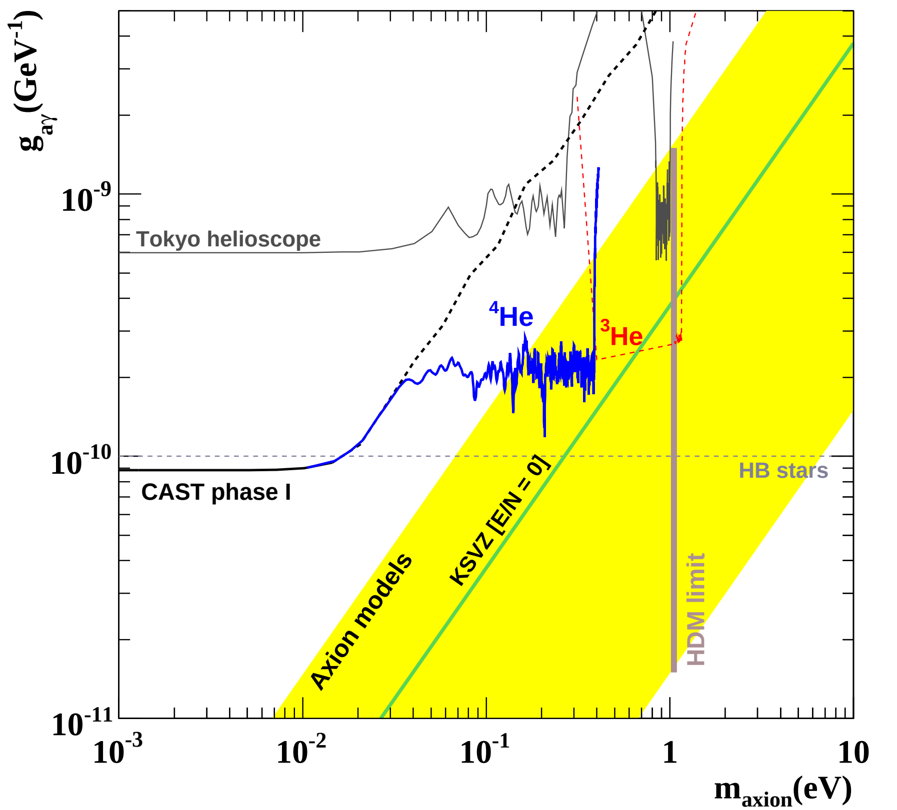
2.1 Photon Regeneration Experiments

- **Helioscope searches** for axions, axion-like particles and hidden photons

[Sikivie '83;...;Redondo '08;...]



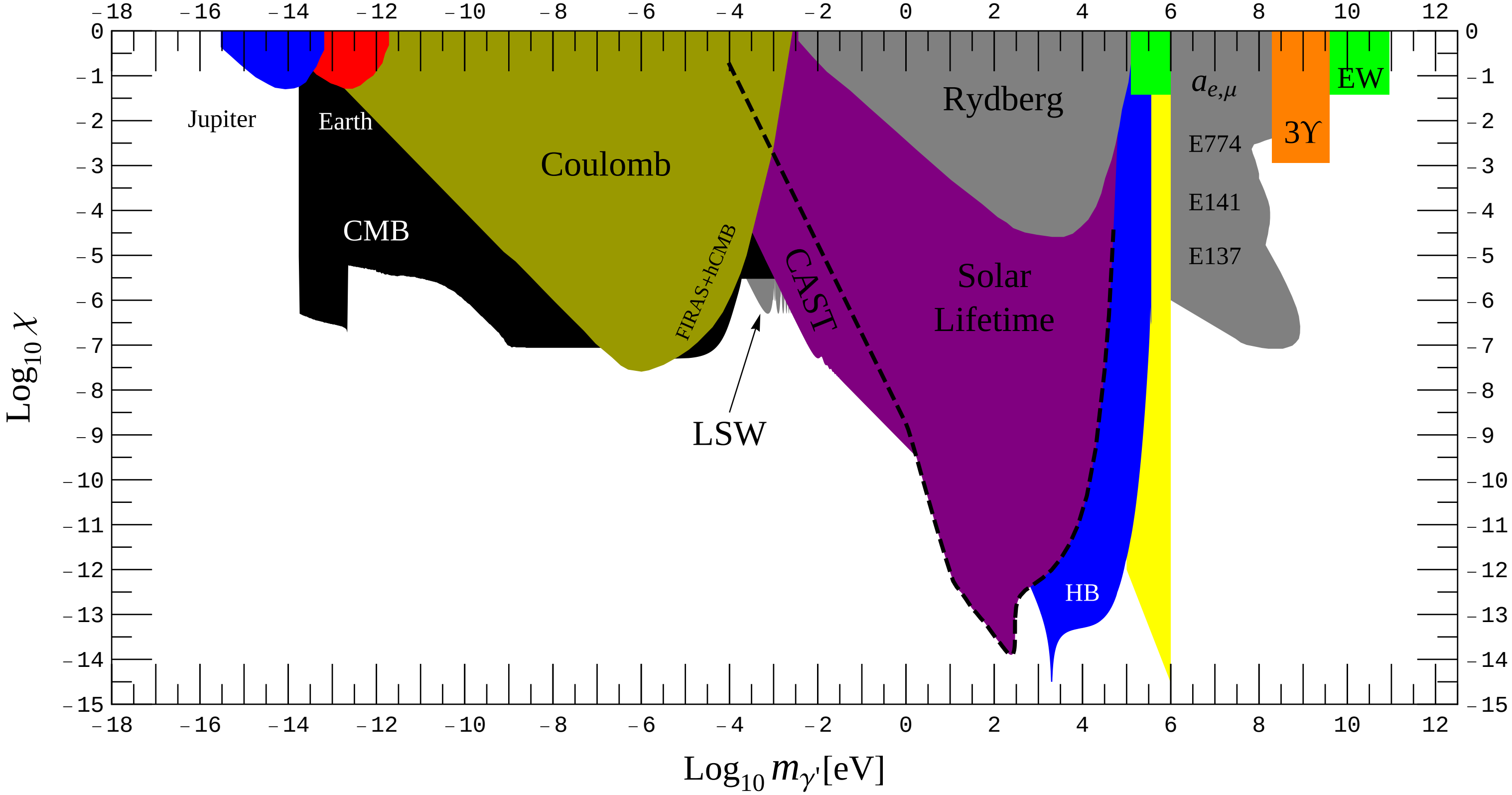
- CAST limits on photon coupling g of axions and axion-like particles:



[CAST Collaboration '09]

- very hard to reach $g \sim 10^{-11}$ GeV^{-1} with helioscope technology

- CAST limits on kinetic mixing χ of hidden photons: [Redondo '08]

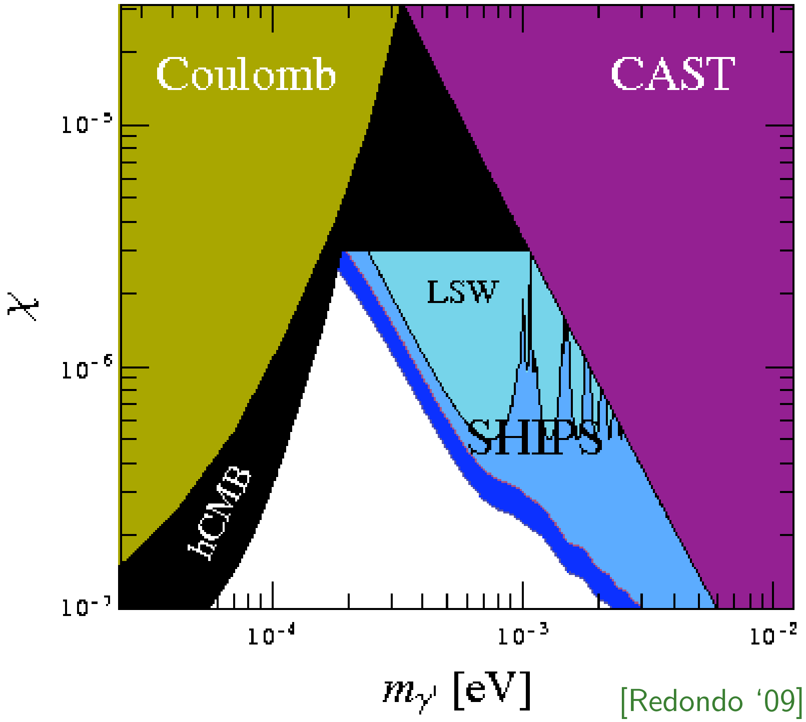


- better sensitivity in meV range possible by increasing helioscope volume

⇒ **SHIPS** (Solar Hidden Photon Search) at Hamburger Sternwarte:

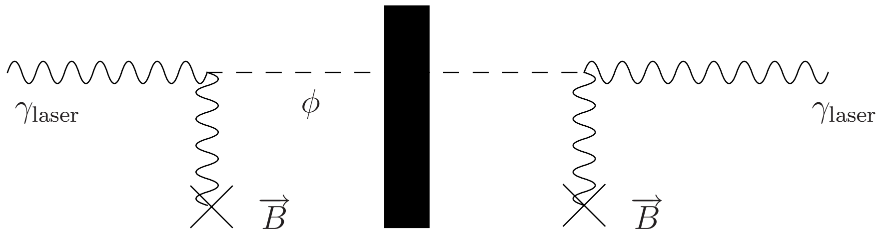
[SFB 676 Project C1: AR, Wiedemann, ...]

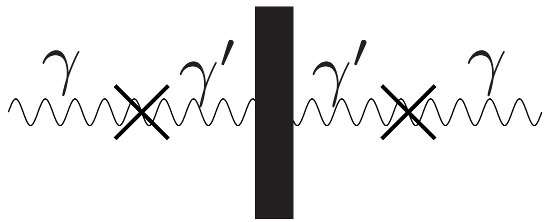
– Big helioscope ($L = 8$ m, $A = 1$ m^2) will be mounted on 1 m telescope:



[Redondo '09]

- **Laser-light shining through a wall:** [Okun '82;Anselm '85; van Bibber *et al.* '87]

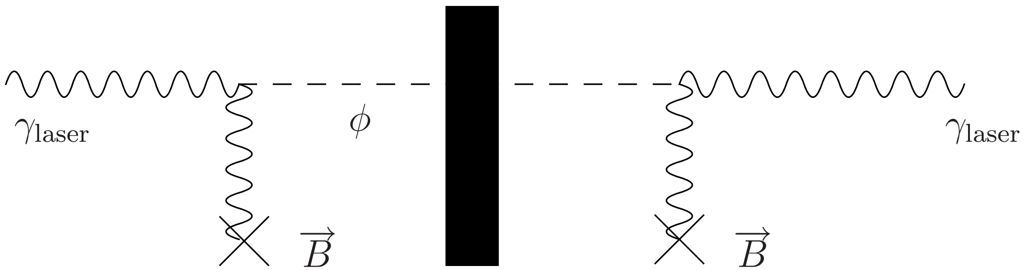




- **Laser-light shining through a wall:**

Experiment	ω	$\mathcal{P}_{\rm prim}$	β_g	Magnets
ALPS (DESY)	2.33 eV	4 W	300	$\text{B}_g = \text{B}_r = 5$ T $L_g = L_r = 4.21$ m
BFRT (Brookhaven)	2.47 eV	3 W	100	$\text{B}_g = \text{B}_r = 3.7$ T $L_g = L_r = 4.4$ m
BMV (LULI)	1.17 eV	8×10^{21} γs/pulse	14 pulses	$\text{B}_g = \text{B}_r = 12.3$ T $L_g = L_r = 0.4$ m
GammeV (Fermilab)	2.33 eV	3.2 W	1	$\text{B}_g = \text{B}_r = 5$ T $L_g = L_r = 3$ m
LIPSS (JLab)	1.03 eV	180 W	1	$\text{B}_g = \text{B}_r = 1.7$ T $L_g = L_r = 1$ m
OSQAR (CERN)	2.5 eV	15 W	1	$\text{B}_g = \text{B}_r = 9$ T $L_g = L_r = 7$ m

- **ALPS** (Any-Light Particle Search): [AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]



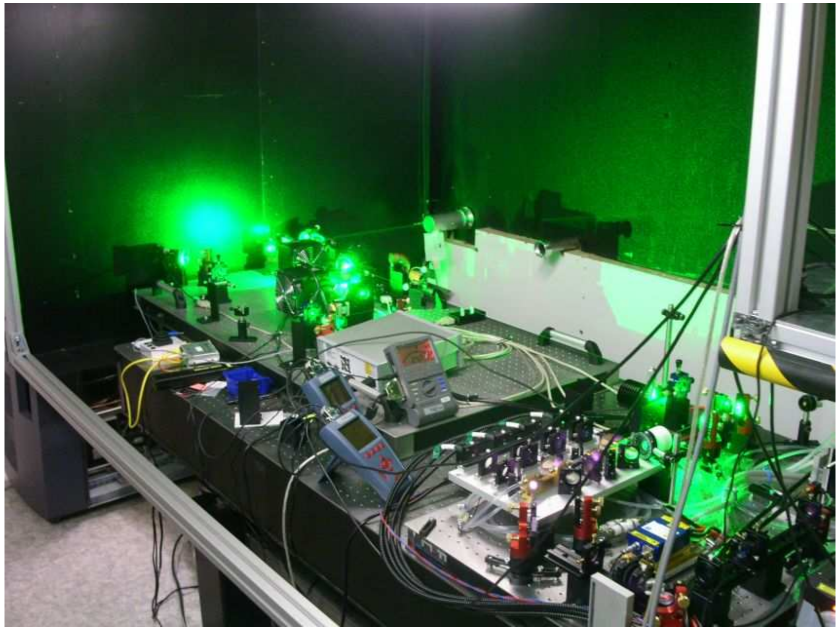
ALPS:

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

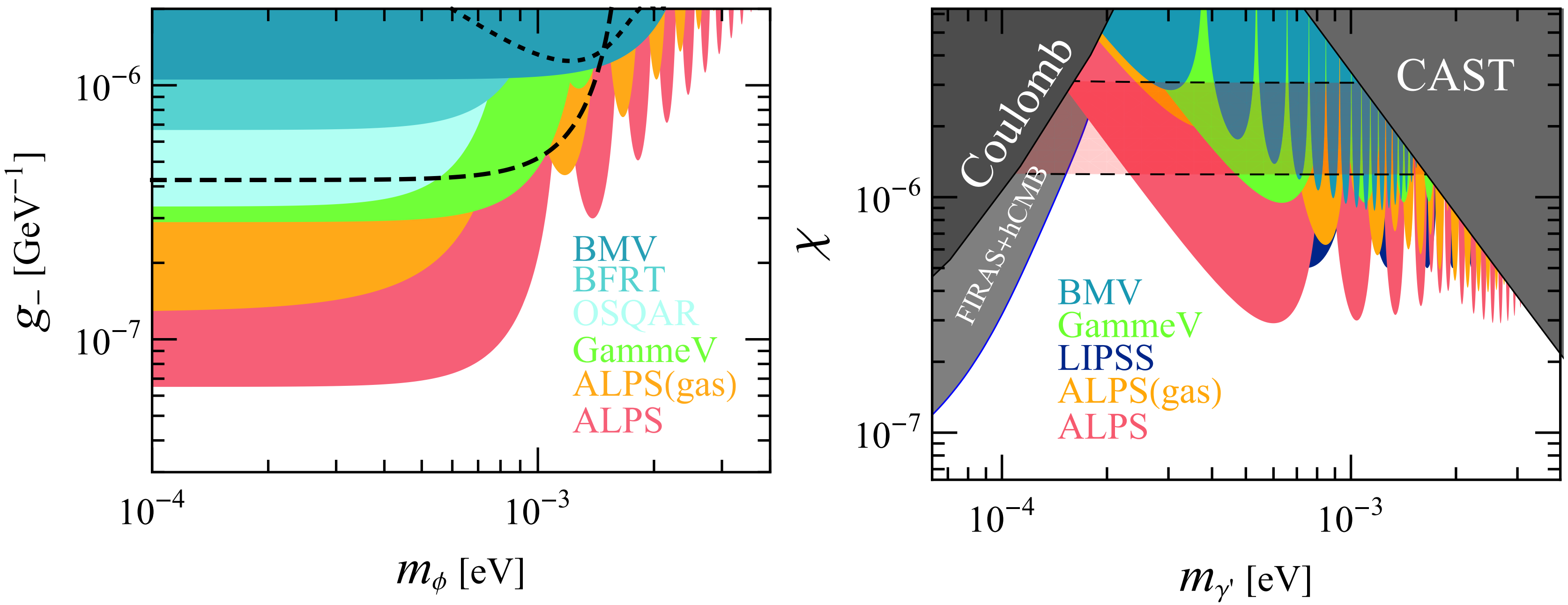
⇒ frequency doubled to 532 nm

⇒ $\sim\ 300$ 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



- Limits from **ALPS** run end of 2009:



[ALPS Collaboration '10]

 - ALPs: still about 2.5 orders of magnitude worse than CAST
 - HPs: hCMB still a possibility; will be probed by SHIPS

- Upgrade plans at DESY and at Fermilab
  - exploit more magnets (e.g. 6+6 HERA)

$6+6$ HERA magnets ($\ell = 8.8$ m)	$L = 52.8$ m
Magnetic field	$B = 5.5$ T
Primary laser power	$\mathcal{P}_{\rm prim} = 3$ W
Power build-up	$\beta_g = \beta_r = 10^5$
Laser frequency	$\omega = 1.17$ eV
Overlap between WISP mode and electric field mode	$\eta = 0.95$
Detection time	$\tau = 100$ h
Dark count rate	$n_b = 10^{-4}$ Hz

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  - exploit second Fabry-Perot cavity: [Hoogeveen,Ziegenhagen '91;Sikivie,Tanner,van Bibber '07]

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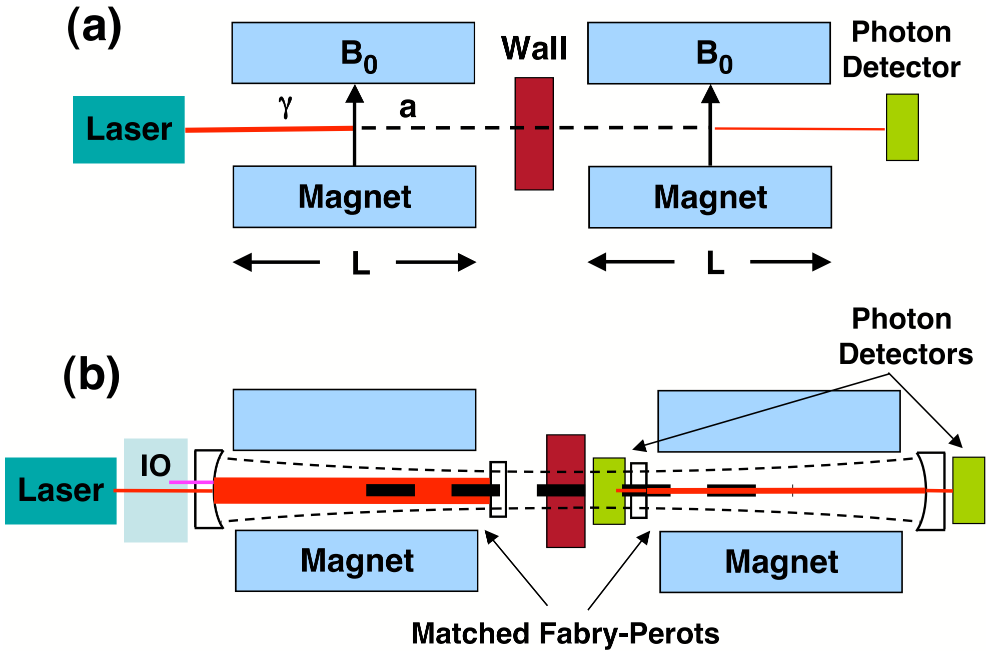

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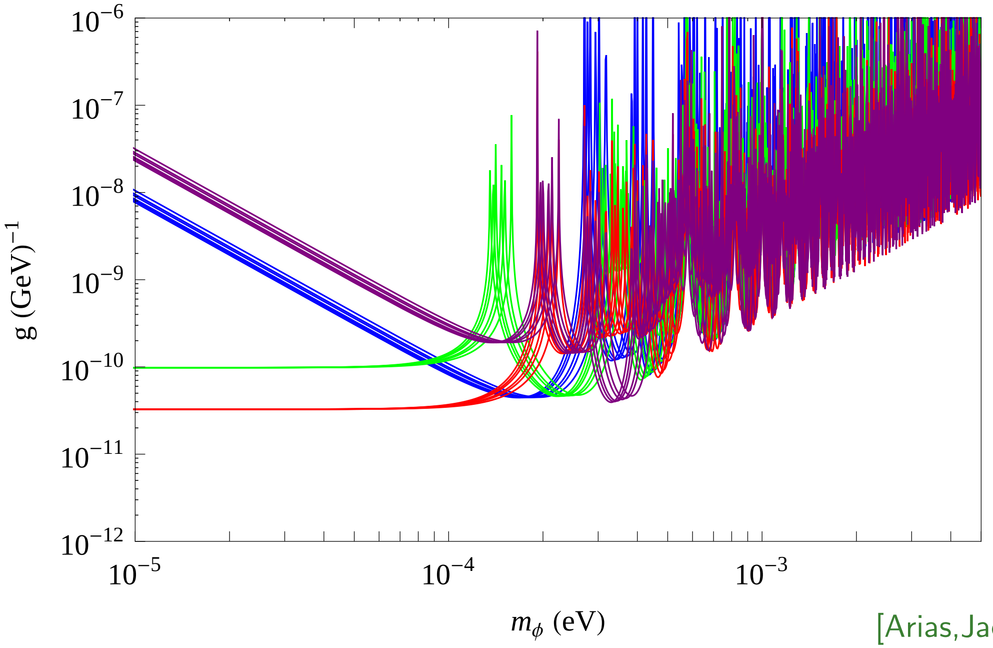

[Arias,Jaeckel,Redondo,AR '10]

  - LSW ready to probe previously unconstrained ALP parameters

- Upgrade plans at DESY and at Fermilab
  - exploit more magnets (opt. 18+18 Tevatron, 20+20 HERA, 12+12 LHC)
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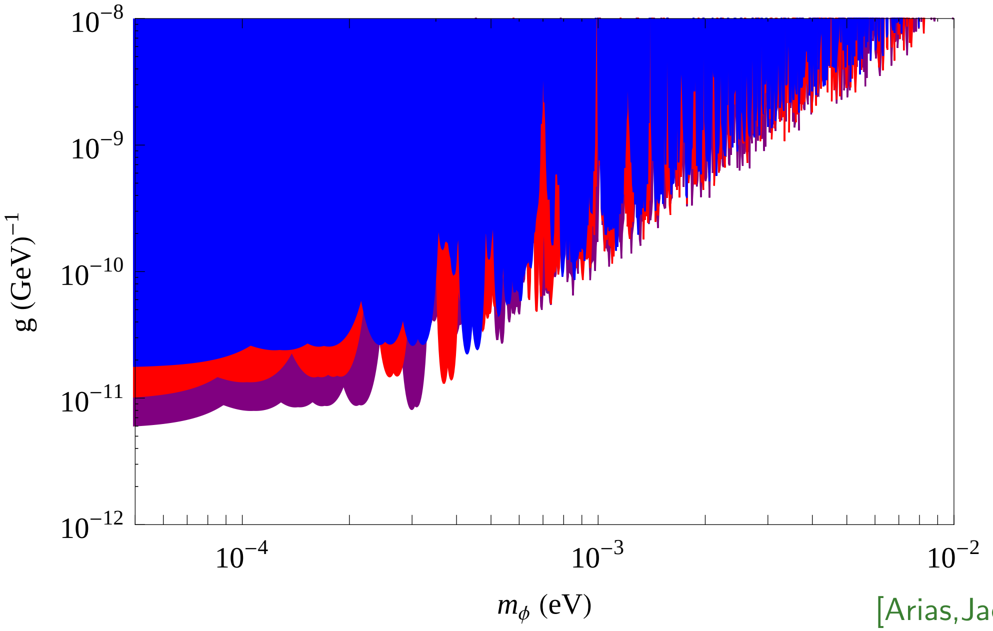

[Arias,Jaeckel,Redondo,AR '10]

  - Next generation LSW ready to probe ALP coupling interesting in context of intermediate string scale scenarios and astro/cosmo hints

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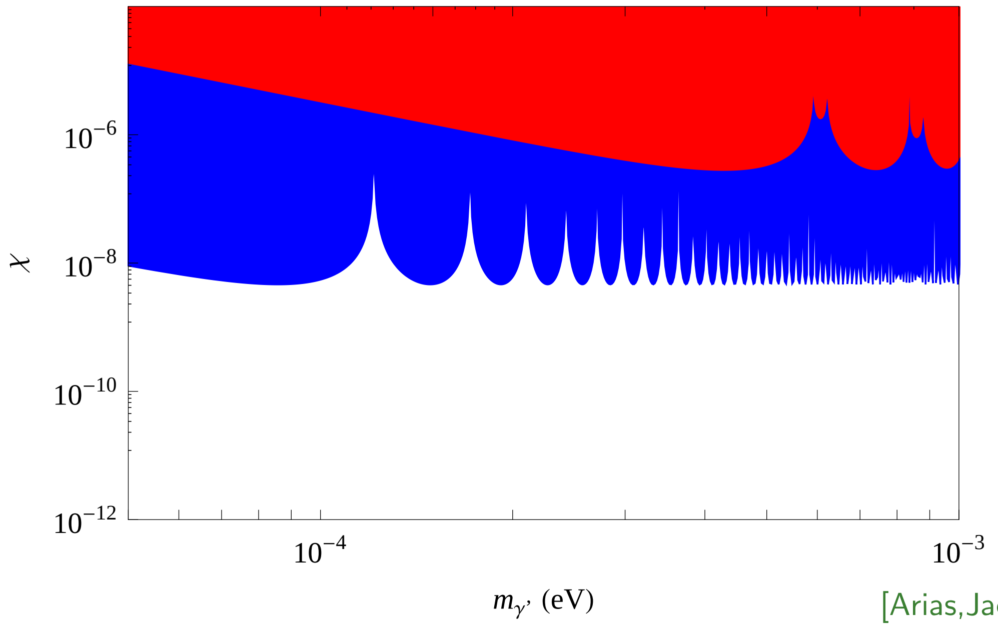


[Arias,Jaeckel,Redondo,AR '10]

  - Next generation LSW ready to probe ALP coupling interesting in context of intermediate string scale scenarios and astro/cosmo hints

2.2 Fixed-Target Experiments

- Fixed-target experiments with intense electron beams particularly sensitive to MeV-GeV scale hidden photon [Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09]

$\Rightarrow$ New experiments proposed/designed/commissioned at DESY (HIPS), MAMI, and JLab (APEX, DarkLight, HPS)

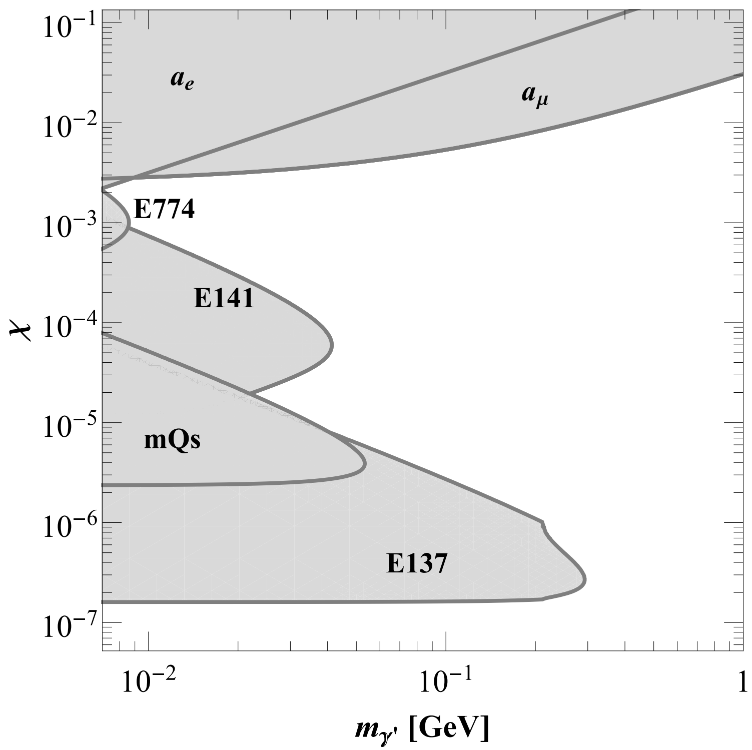
- Production cross-section and decay length of $\gamma' \to e^+e^-$,

$$\sigma_{eN\to eN\gamma'} \sim 1\ \mathrm{pb} \left(\frac{\chi}{10^{-5}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)^2$$

$$\ell_d = \gamma c\tau \sim 8\ \mathrm{cm} \left(\frac{E}{\mathrm{GeV}}\right) \left(\frac{10^{-5}}{\chi}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)^2$$

vary alot in parameter range or interest

$\Rightarrow$ Several experiments, with different strategies for fighting backgrounds:
– $\ell_d \gg$ cm: beam dump; low background



[Andreas,AR '10]

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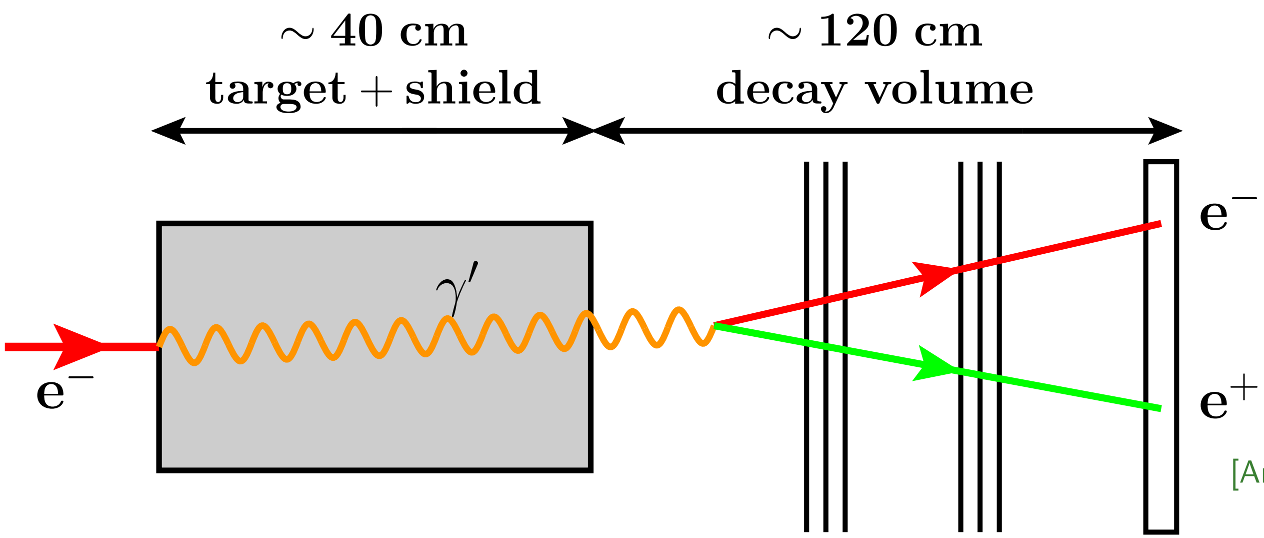

[Andreas,AR '10]

- HIPS: a new beamdump experiment at DESY II; funded by SFB 676

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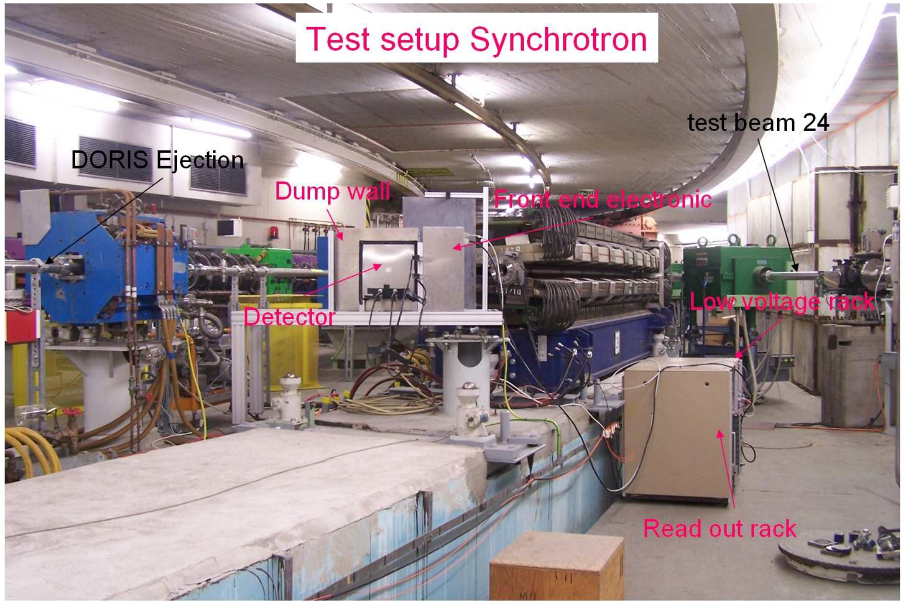

[Garutti '10]

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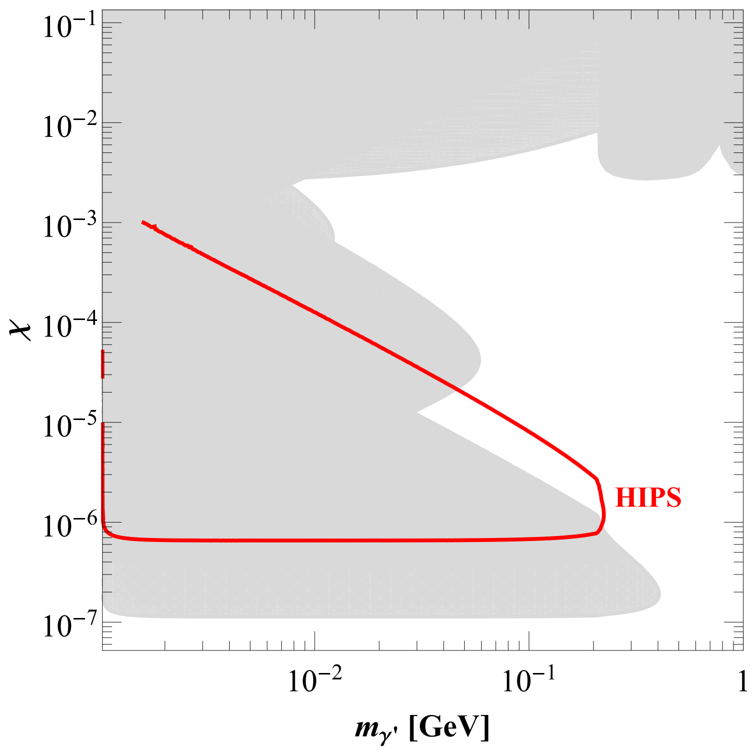


[Andreas,AR '10]

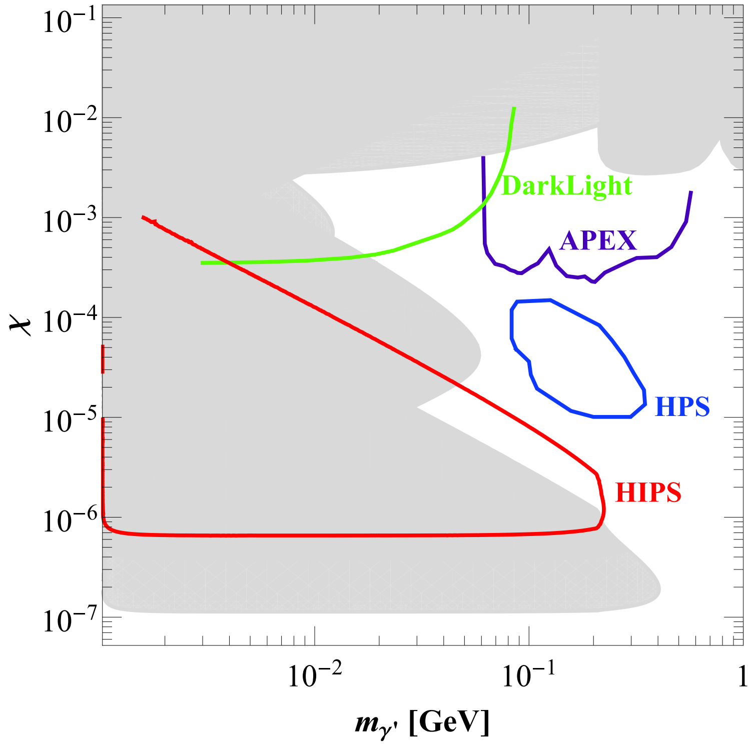
- HIPS: a new beamdump experiment at DESY II; funded by SFB 676

$\Rightarrow$ Several experiments, with different strategies for fighting backgrounds:

– $\ell_d \gg$ cm: beam dump; low background

– $\ell_d \sim$ cm: displaced vertex; limited by instrumental bkg

– $\ell_d \ll$ cm: bump hunt: fight bkg with high intensity, resolution



[Andreas,AR '10]

- FT experiments ready to probe region of interest for $g-2$ and DM

3. Conclusions

- There is a strong physics case both from theoretical as well as from phenomenological considerations for (ultra-)light particles beyond the standard model:
  - axions and axion-like particles
  - hidden-sector U(1) gauge bosons
- Intense photon and electron beams seem to be ideal laboratory tools to hunt for them
- Huge range of masses and couplings to be explored $\Rightarrow$ need to attack the dark forces with various "weapons", ranging from lasers to the LHC!