Attacking Hidden Forces with Intense Photon- and Electron-Beams

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Outline:

1. Case for Light Particles Beyond the Standard Model

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 Dark Forces Attack with New Fixed-Target Experiments

3. Conclusions

1. Case for Light Particles Beyond the Standard Model

1.1 Axions and Axion-Like Particles

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

$$\mathcal{L}_{\rm CP-viol.} = \frac{\alpha_s}{4\pi}\,\theta\,{\rm tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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

$$|\bar{\theta}| \equiv |\theta + \arg\,\det\,M| \lesssim 10^{-10}$$

  – **Unnaturally small!**

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

  – Introduce axion field a as dynamical θ parameter, which enjoys shift symmetry, $a \to a + \mathrm{const.}$, broken only by anomalous terms

  [Peccei,Quinn '77]

$\Rightarrow$ Low-energy effective Lagrangian:

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

  – θ-term in $\mathcal{L}_{\mathrm{SM}} + \mathcal{L}_a$ can be eliminated by exploiting the shift symmetry, $a \to a - \theta f_a$

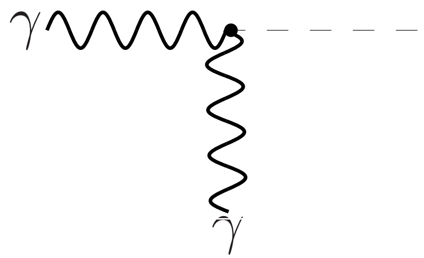
  – Topological charge density $\propto \langle \mathrm{tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}\rangle \neq 0$ provides nontrivial potential for axion field; minimized at $\langle a \rangle = 0 \Rightarrow$ axion is pseudo-Nambu-Goldstone boson with mass [S.Weinberg '78; Wilczek '78]

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

– For large f_a: axion is ultralight and invisible

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

– Phenomenologically very important: axion couples to photons,



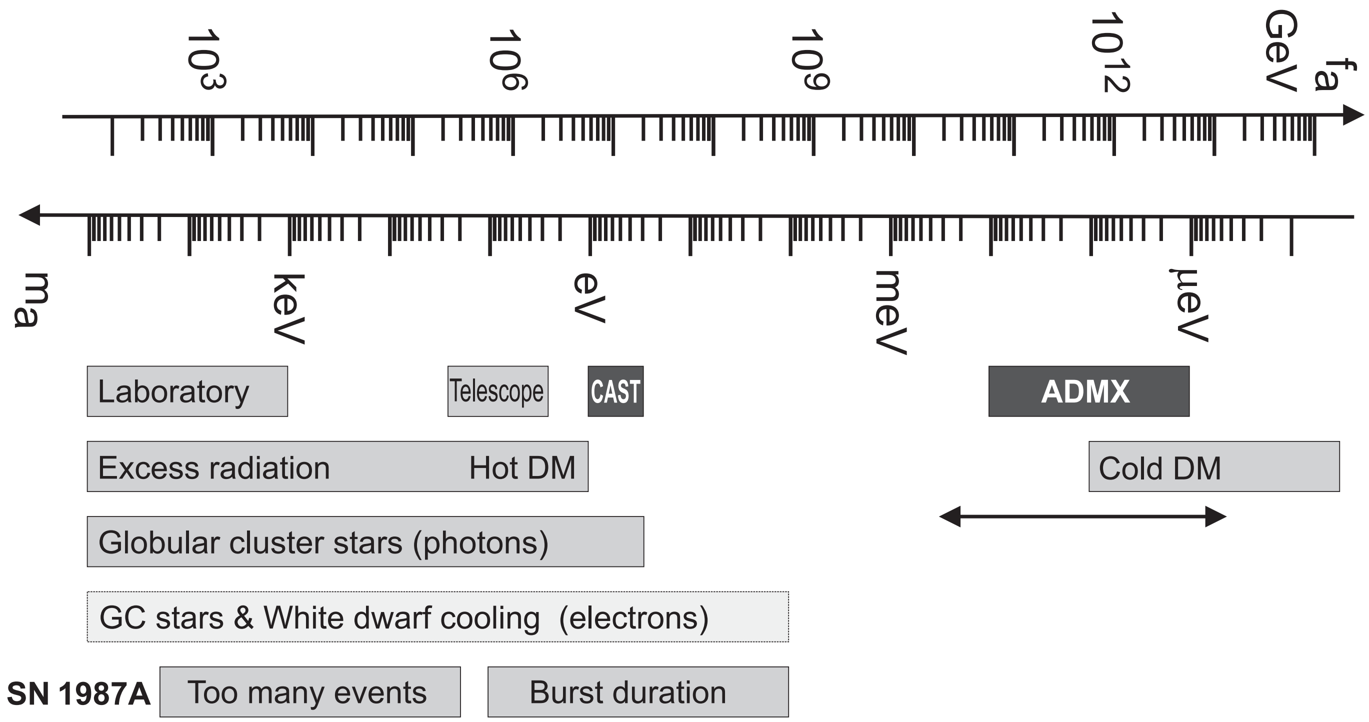
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g\, a\, \vec{E}\cdot\vec{B},$$

with

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

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

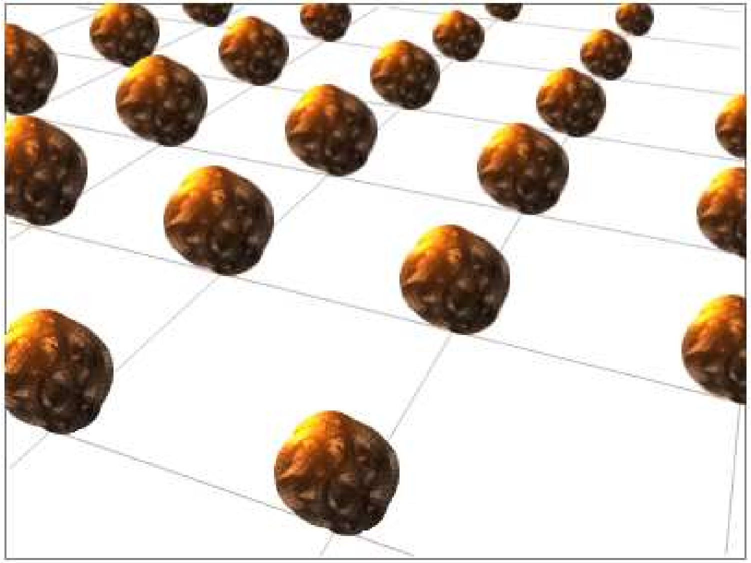
- Observational and experimental exclusion limits on f_a:



[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

- **Axions in string theory:**
  Axions and axion-like fields with global anomalous PQ 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,

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

and, for axion-like particles,

$$
f_\phi \sim f_a, \qquad 0 \leq m_\phi \sim \frac{\Lambda^2}{M_s} \lesssim m_a
$$

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

$$f_a \simeq g_{ea} m_e = 4 \times 10^9 \text{ GeV} \Rightarrow g_{\gamma a} \sim \alpha / f_a \sim 10^{-11} \text{ GeV}^{-1}$$

  - **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. 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 '09]. Additional hint: characteristic scatter observed in AGN luminosity relation [Burrage,Davis,Shaw '09]. Need

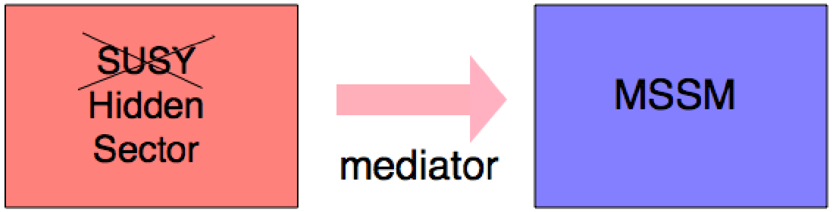
$$g_{\gamma\phi} \sim 10^{-12} \div 10^{-11} \text{ GeV}^{-1}; \qquad m_\phi \ll 10^{-12} \text{ GeV}$$

$\Rightarrow$ Aim for next-generation direct search experiments (see later)

1.2 Hidden-Sector Abelian Gauge Bosons

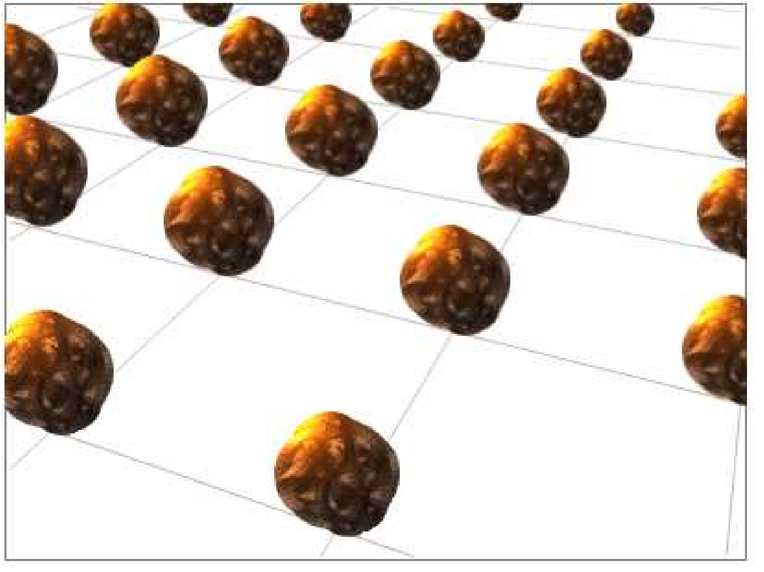
- Extensions of standard model based on supergravity or superstrings rely on "hidden sector" of particles which are very weakly coupled to the "visible sector" standard model particles; cf. "gravity mediation" of SUSY breaking ($\Leftarrow$ condensation of non-Abelian hidden gaugino)

cf. Pran Nath's talk



- Sector "hidden" $\Leftrightarrow$ mediators heavy and/or very weakly coupled
- Possible light hidden particles: hidden sector U(1) gauge bosons ("hidden photons" γ') and hidden sector particles charged under the hidden U(1) ($\Rightarrow$ "mini-charged particles" (MCPs))

- Hidden U(1) gauge factors generic feature of string compactifications

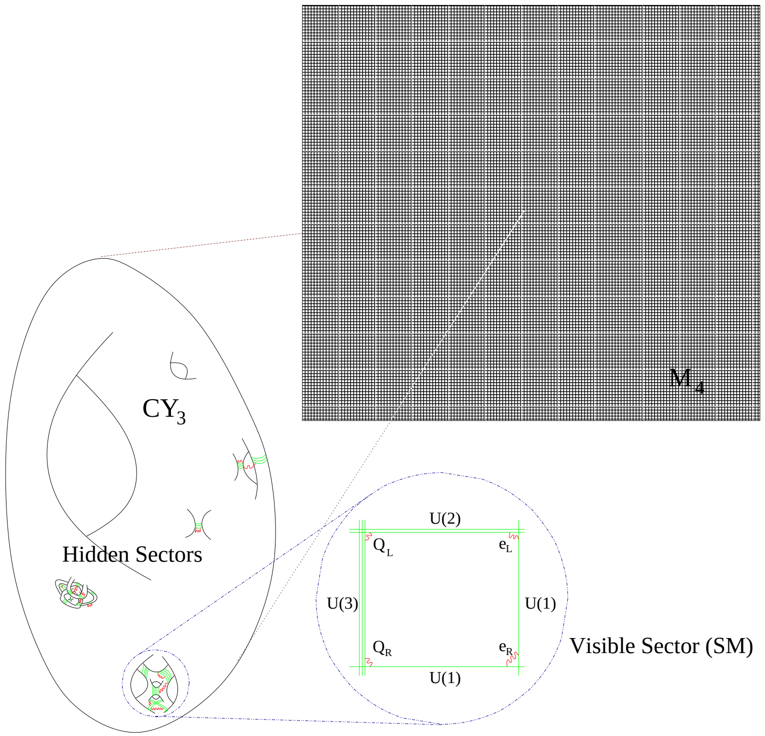


  – both in heterotic compactifications, e.g. [Lebedev,Ramos-Sanchez '09]

$$E_8 \times E_8 \to G_{SM} \times [SU(6) \times U(1)]$$

  – as well as in type II orientifold compactifications with D-branes

* ∗ KK zero modes of form fields
* ∗ Massless excitations of space-time filling D-branes



- Hidden U(1) gauge bosons ("photons") may be light, $m_{\gamma'} \ll$ TeV

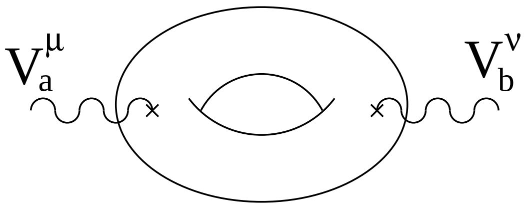
- Dominant interaction with $\mathrm{U}(1)_Y$ or $\mathrm{U}(1)_{\mathrm{em}}$ via kinetic mixing [Holdom'85]

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

$\chi \ll 1$ generated at loop level via messenger exchange $\Rightarrow$ U(1) hidden

– Kinetic mixing in compactification of heterotic string:

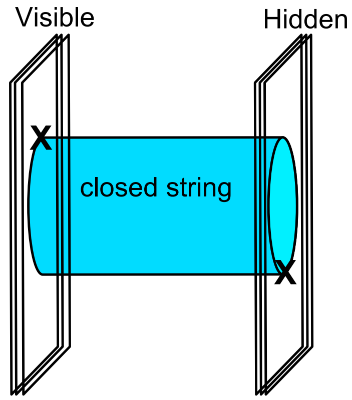
[Dienes,Kolda,March-Russell '97]



$$10^{-17} \lesssim \chi \simeq \frac{e^2}{16\pi^2}\,C\,\frac{\Delta m}{M_P} \lesssim 10^{-5},$$

$$\text{for } C \gtrsim 10;\;\; 10^5\ \mathrm{GeV} \lesssim \Delta m \lesssim 10^{17}\ \mathrm{GeV}$$

– 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]

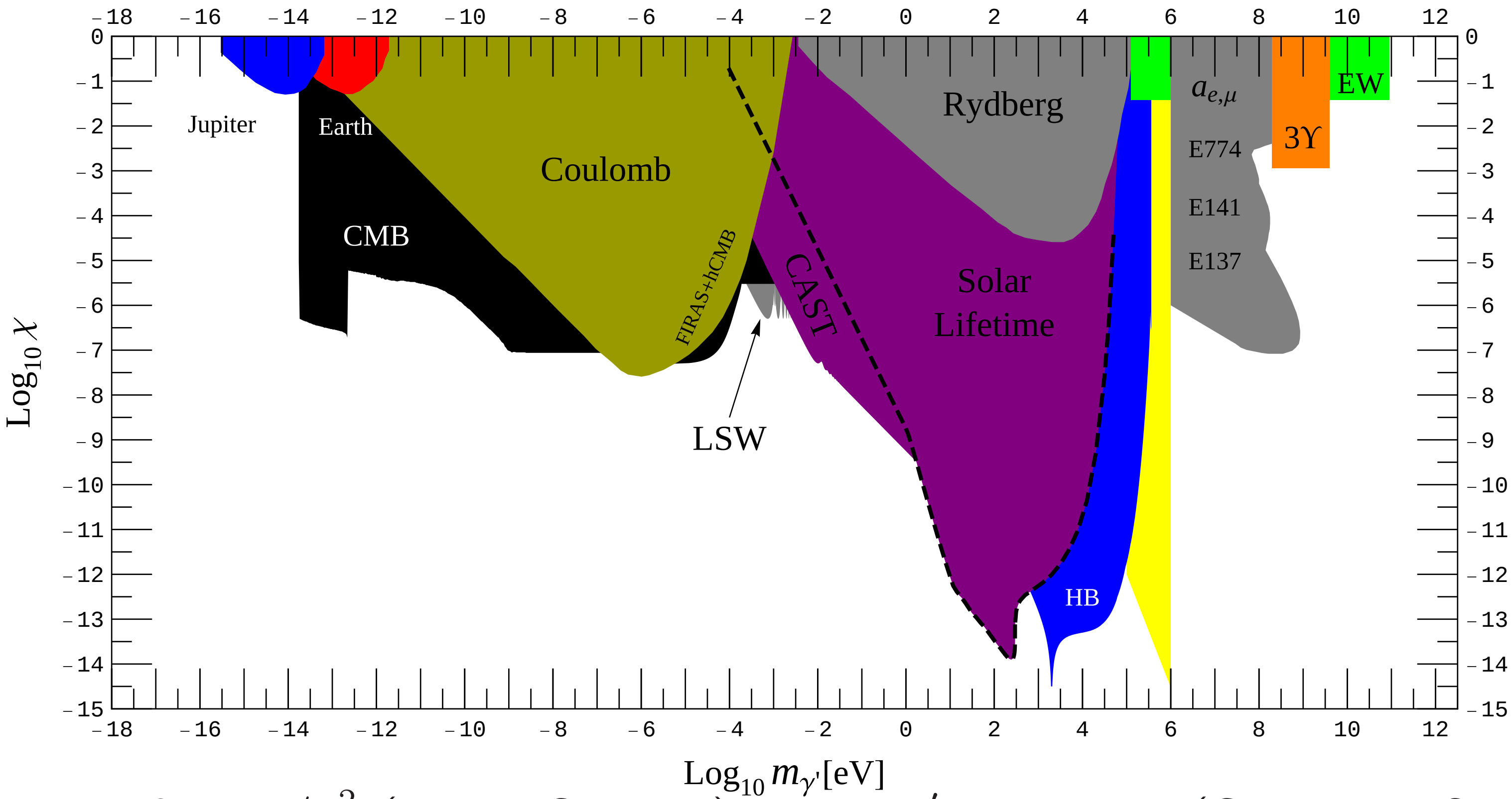


$$10^{-12} \lesssim \chi \sim \frac{e e_h}{16\pi^2} \sim 2\pi g_s \left(\frac{4\pi}{g_s^2}\frac{M_s^2}{M_P^2}\right)^{q/12} \lesssim 10^{-3},$$

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

- Current constraints on hidden U(1)s:

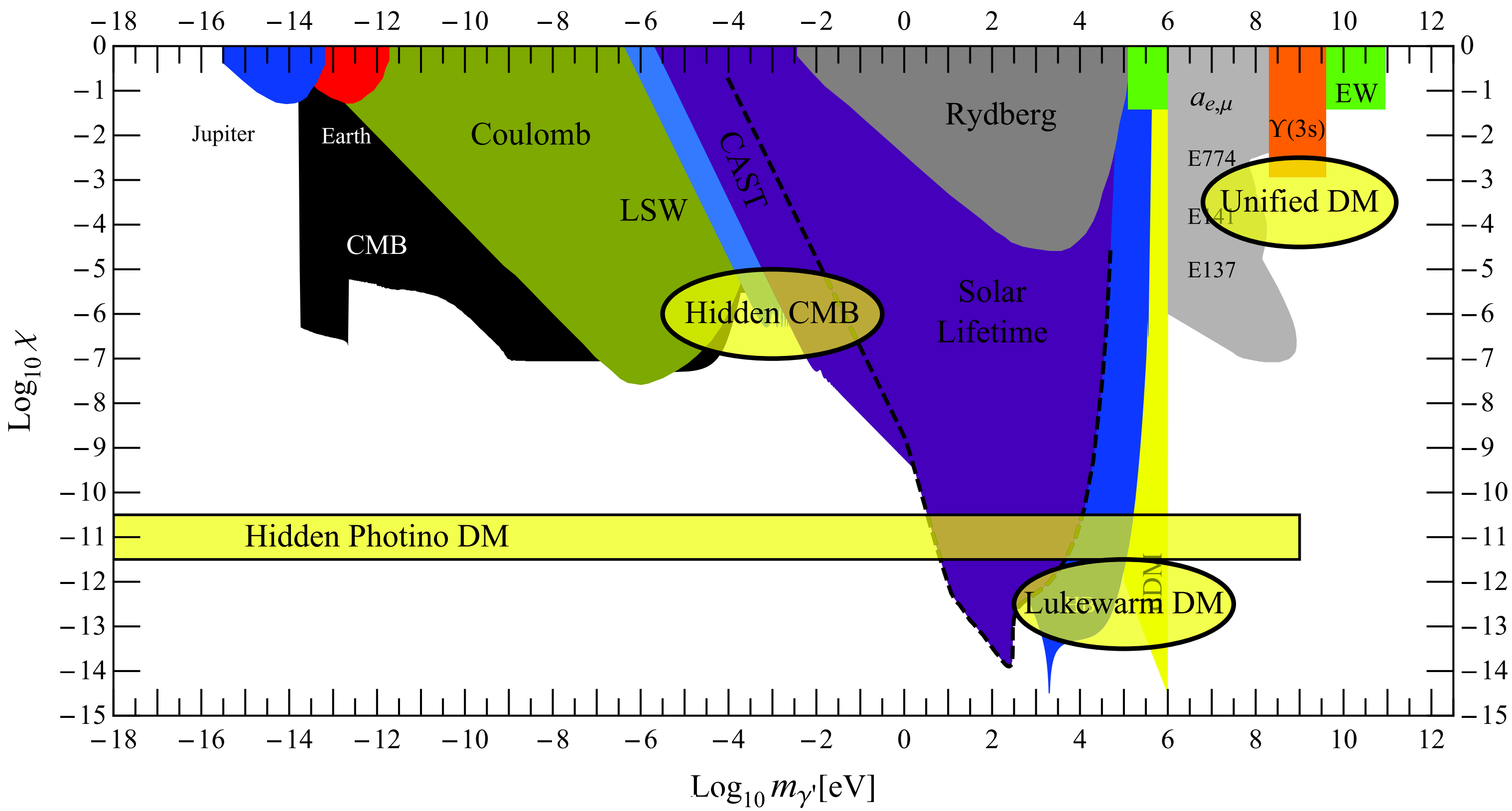
[Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08;Postma,Redondo '08;Bjorken,Essig,Schuster,Toro'09;...]



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

- Bottom-up motivated hidden U(1) parameter ranges:

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



- meV scale hidden photon results in hidden CMB; may explain $N_\nu^{\rm eff} > 3$, as favored from some analyses of CMB + large scale structure if Ly-α data is included; can be checked in light-shining-through-wall experiments

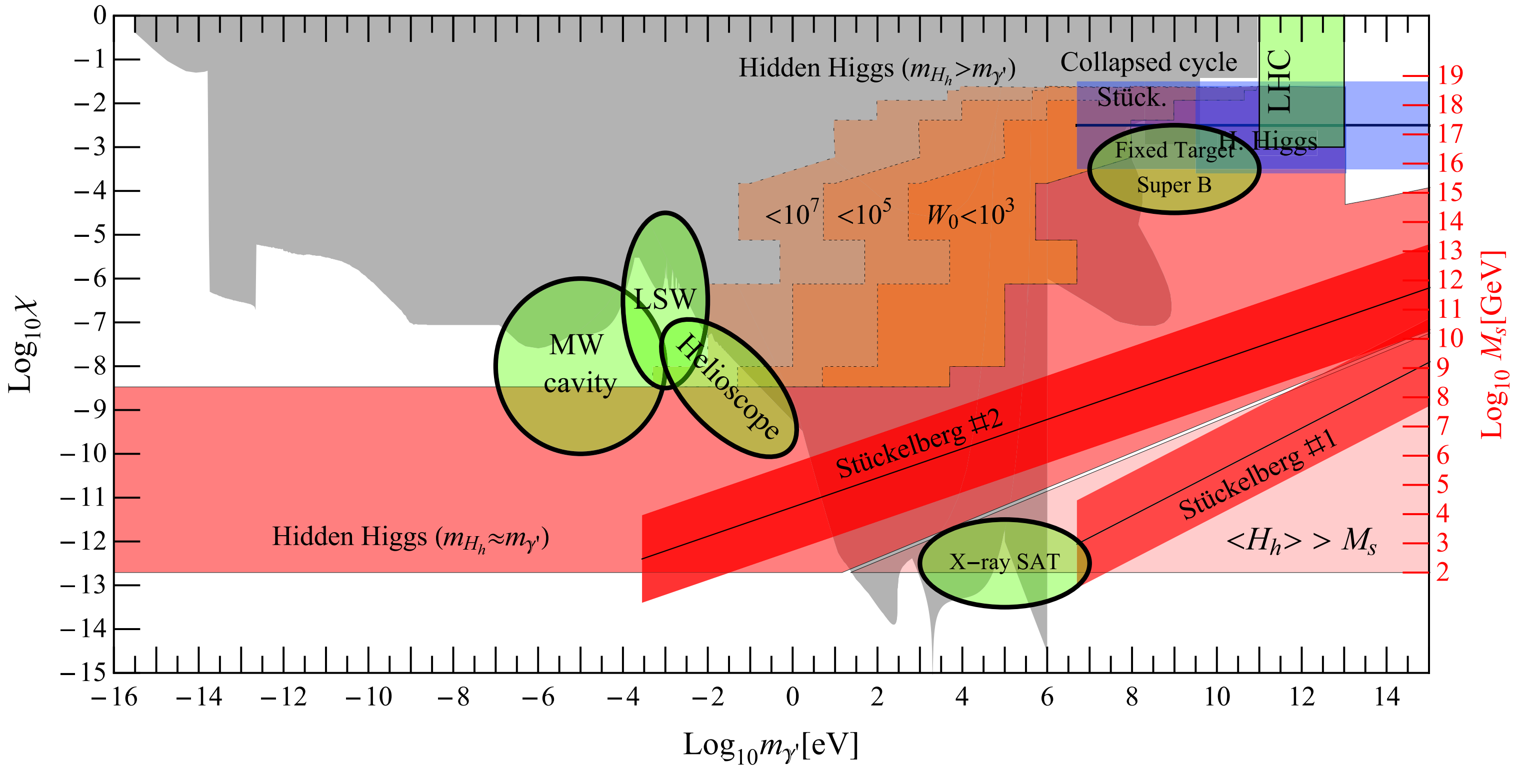
  [Jaeckel,Redondo,AR '08]

- Region $(\chi, m_{\gamma'}) \sim (10^{-4}, {\rm GeV})$ favored by Unified Dark Matter scenario: unified description of PAMELA excess and annual modulation signal seen by direct DM search experiment DAMA ... Hidden sector dark matter; hidden U(1) mediates Dark Force [Arkani-Hamed *et al.* '08;...]; can be checked in new fixed-target experiments

- Larger mixing and mass above Z favored by scenario where PAMELA excess explained by annihilation of hidden sector Dirac fermions close to γ' resonance [Feldman,Liu,Nath '08]; can be checked at LHC $\Rightarrow$ Pran Nath's 2nd talk

- Experimental opportunities for hidden U(1)s:

[Goodsell,Jaeckel,Redondo,AR '09]



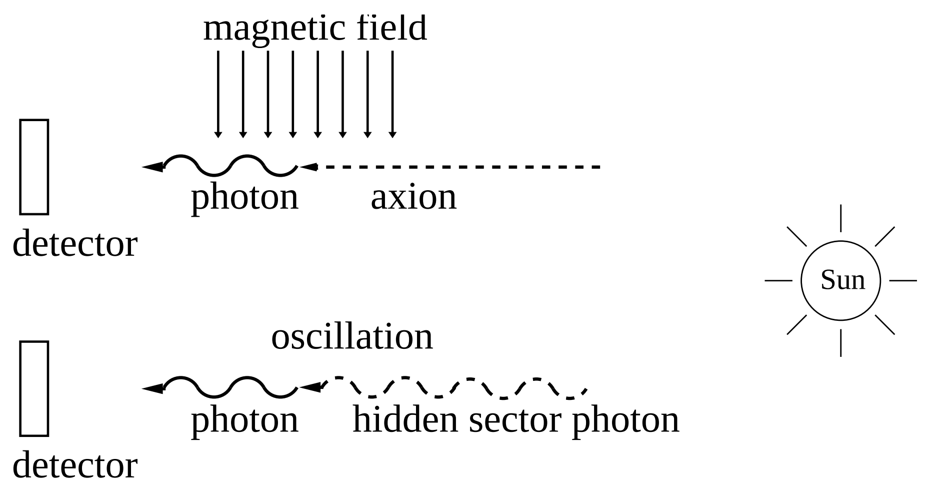
2. New Experiments at the High-Intensity Frontier

⇒ see also talk by Andrei Afanasev

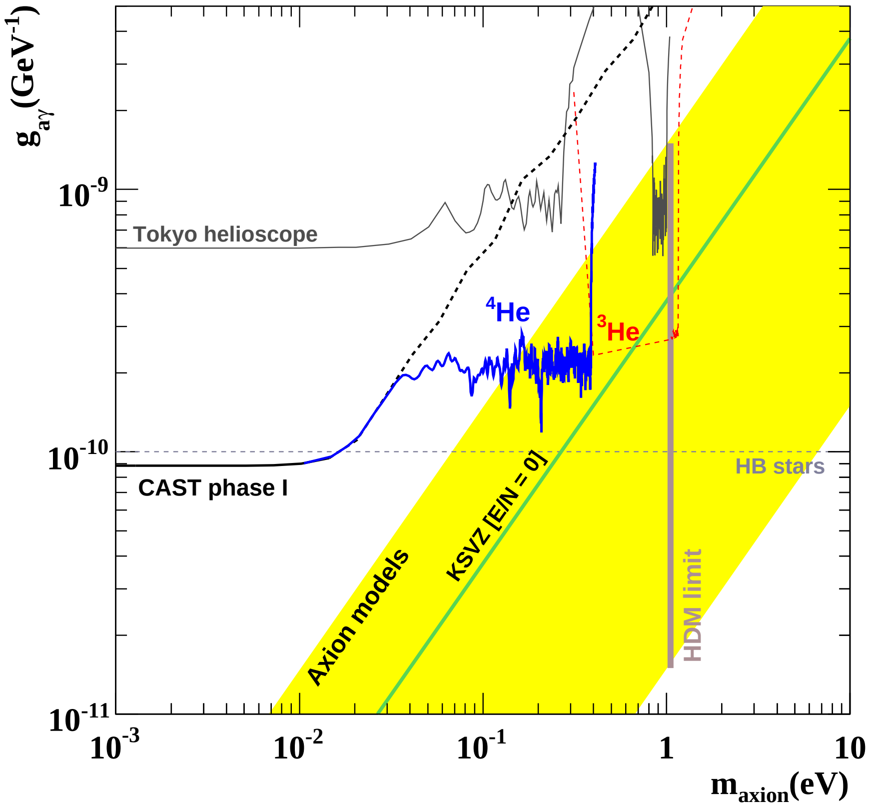
2.1 Photon Regeneration Experiments

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

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

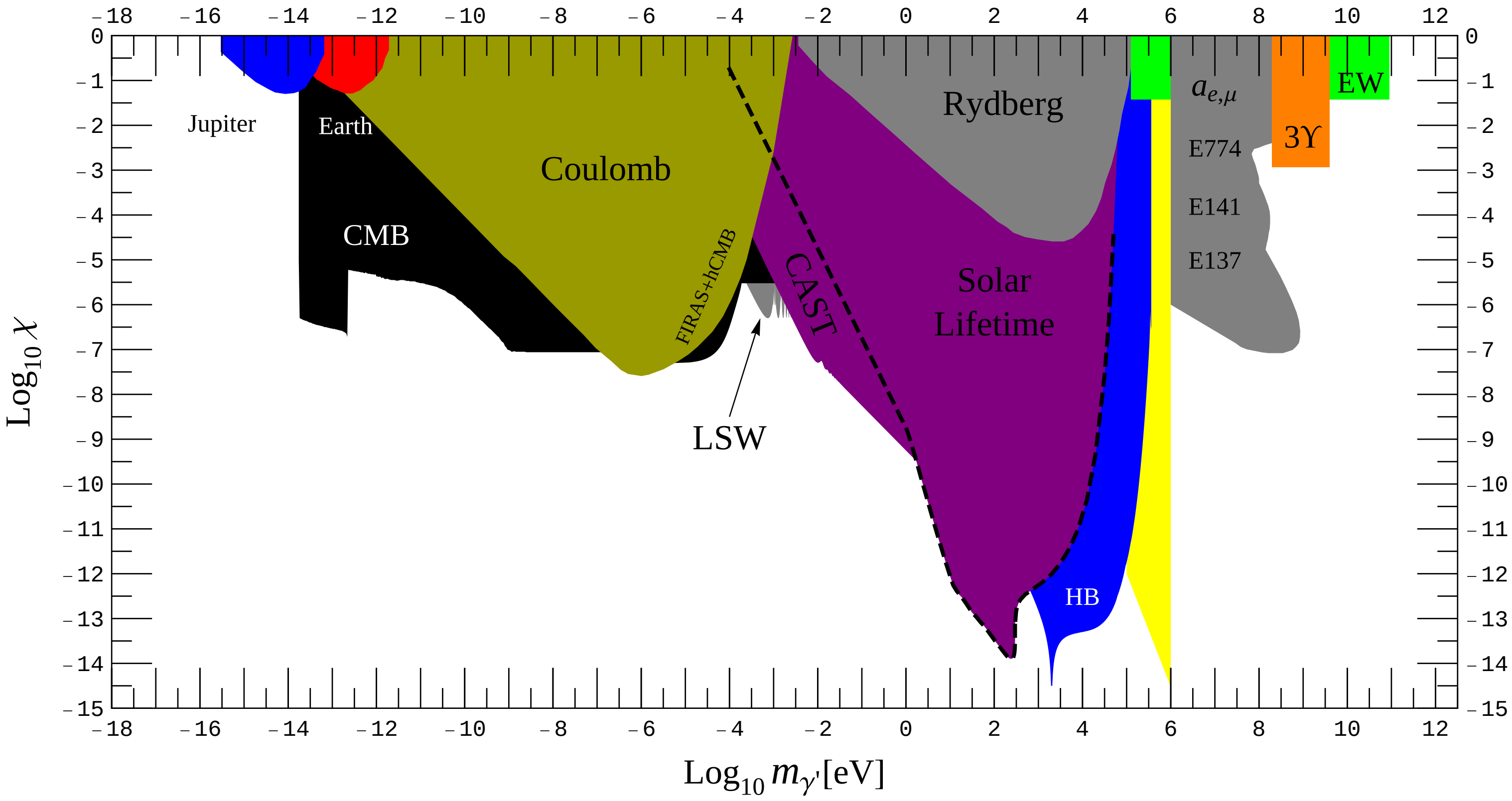


- Limits on photon coupling g of axions and axion-like particles:



[CAST Collaboration '09]

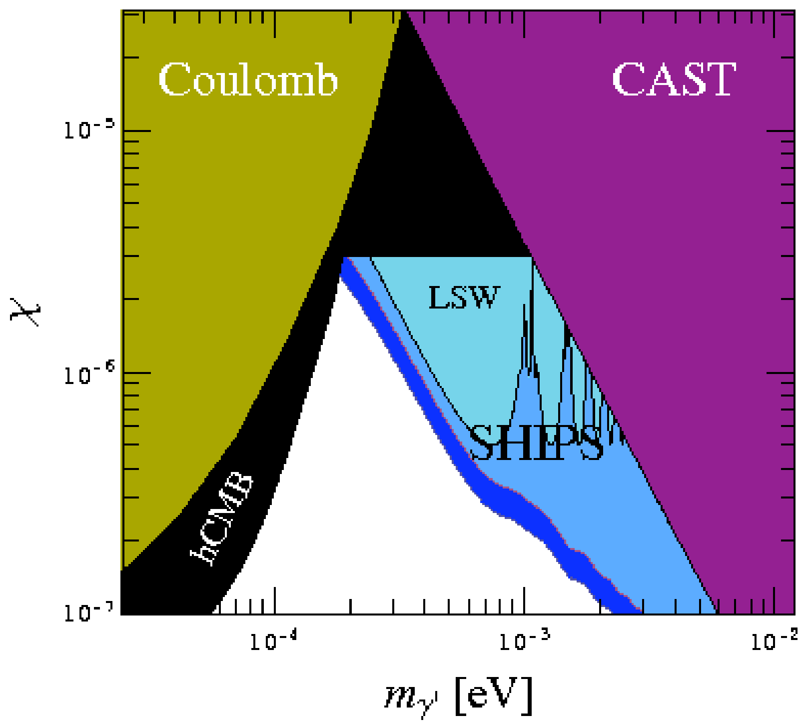
- CAST limits on kinetic mixing χ of hidden photons: [Redondo '08]



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

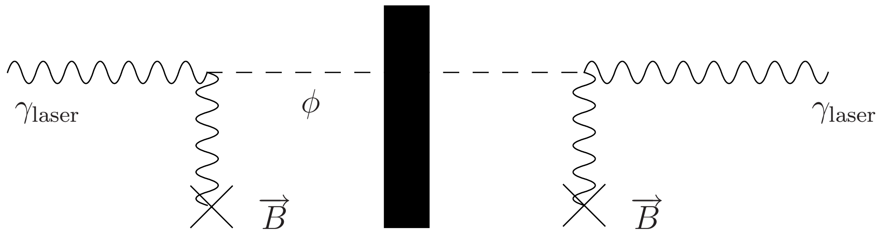
  – Big helioscope will be mounted on 1 m telescope:

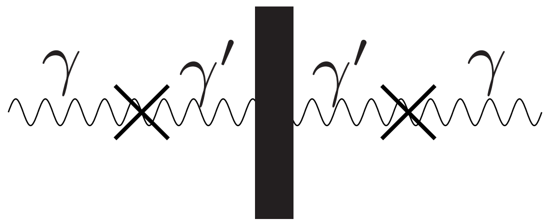
- **SHIPS** (Solar Hidden Photon Search) at Hamburger Sternwarte:
  - Expected sensitivity:



[Redondo '09]

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

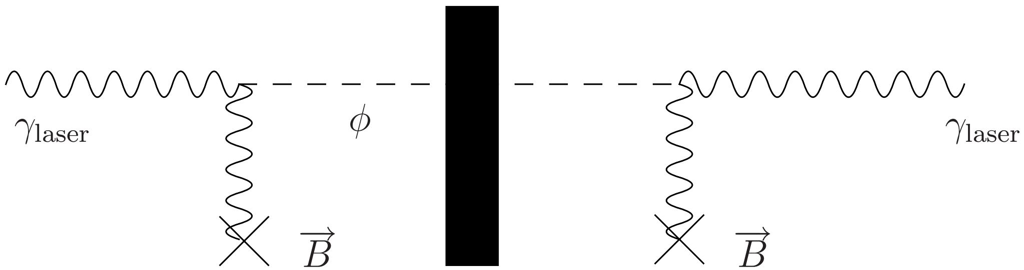




- **Laser-light shining through a wall:**

Experiment	Laser	$< P >$	Magnets
ALPS (DESY)	532 nm; FP	30-1200 W	$\mathrm{B}_1 = \mathrm{B}_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m
BFRT (Brookhaven)	~ 500 nm; DL	100 W	$\mathrm{B}_1 = \mathrm{B}_2 = 3.7$ T $\ell_1 = \ell_2 = 4.4$ m
BMV (LULI)	1064 nm; LULI	8×10^{21} γ/pulse	$\mathrm{B}_1 = \mathrm{B}_2 = 11$ T $\ell_1 = \ell_2 = 0.25$ m
GammeV (Fermilab)	532 nm;	3.2 W	$\mathrm{B}_1 = \mathrm{B}_2 = 5$ T $\ell_1 = \ell_2 = 3$ m
LIPSS (JLab)	900 nm; FEL	$300 - 900$ W	$\mathrm{B}_1 = \mathrm{B}_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m
OSQAR (CERN)	1064 nm; FP	> 1 kW	$\mathrm{B}_1 = \mathrm{B}_2 = 9.5$ T $\ell_1 = \ell_2 = 14$ m

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



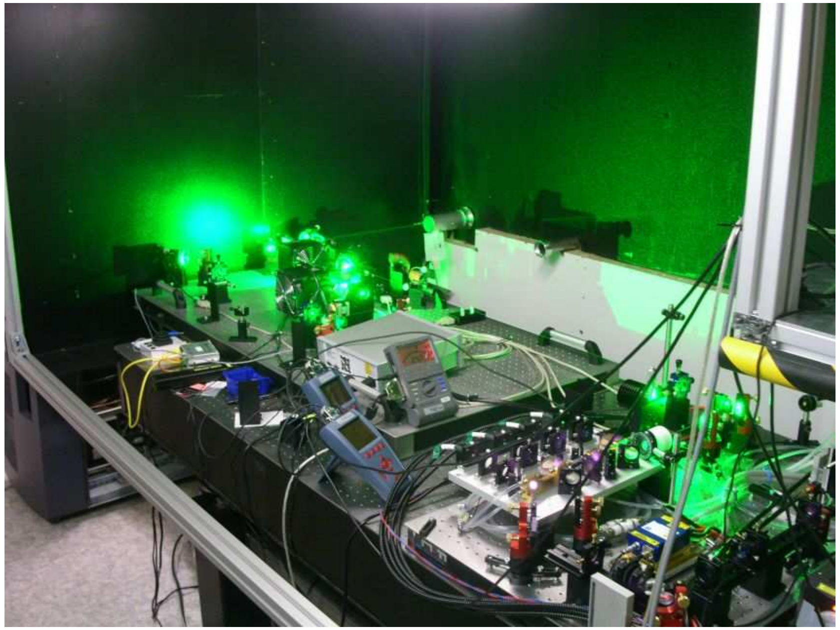
ALPS:

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

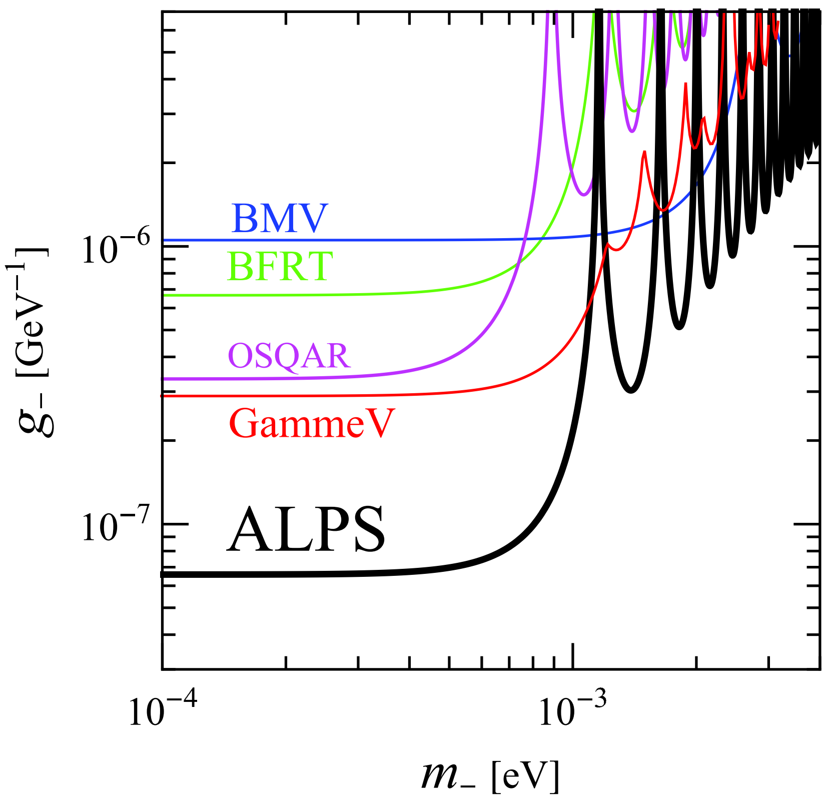
$\Rightarrow$ frequency doubled to 532 nm

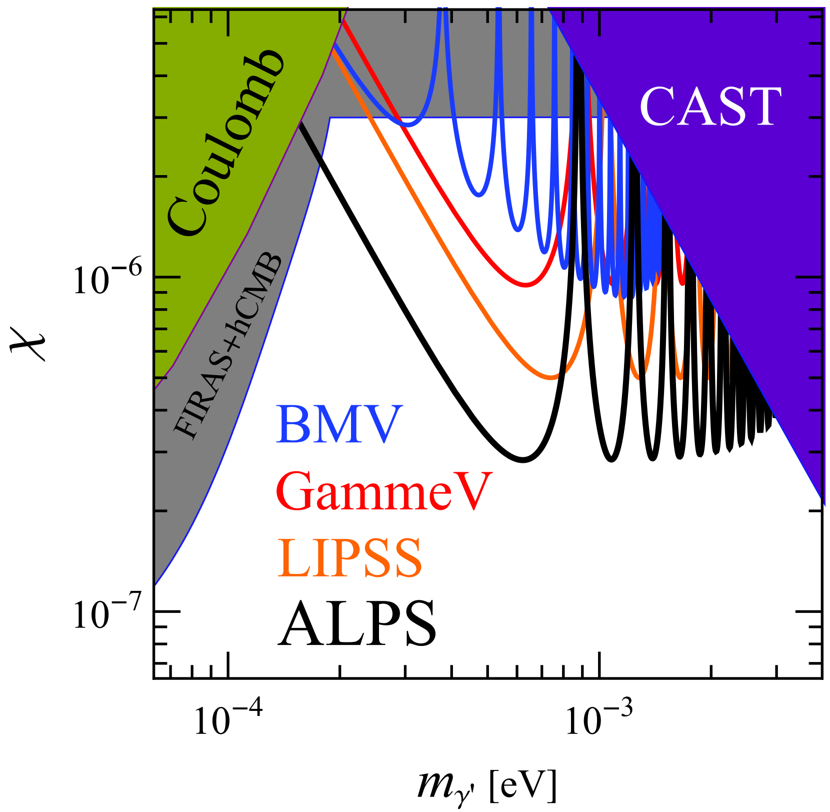
$\Rightarrow$ $\sim\ 100$ fold power build up through resonant optical cavity (Fabry-Perot), $\sim 10\ \mu m$ focus

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



- Preliminary limits from **ALPS** run in 10/2009:

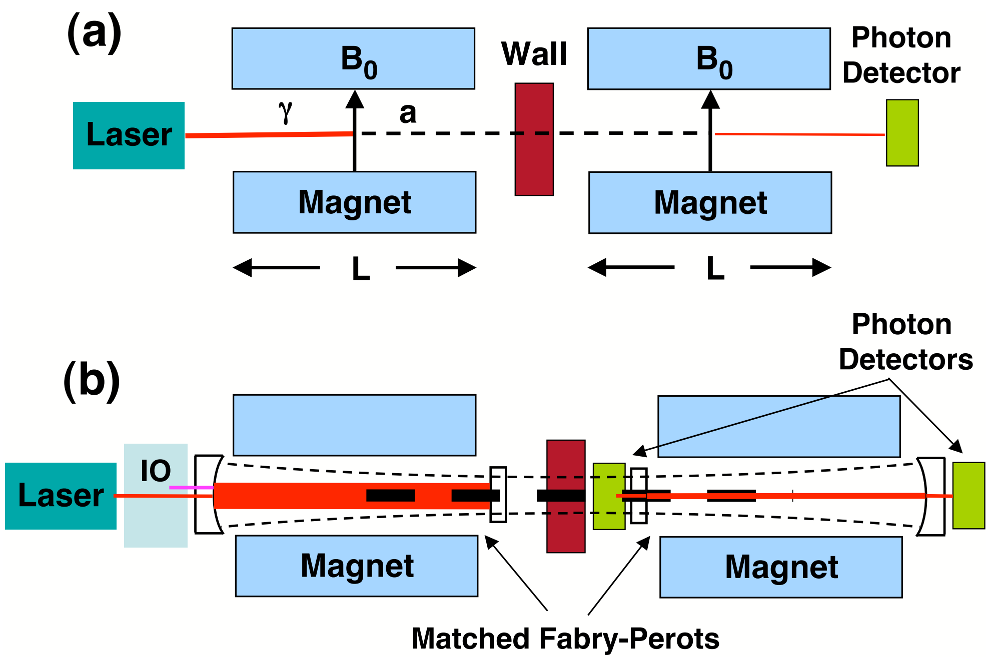




[ALPS Collaboration '09]

- Possible upgrades of ALPS:

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



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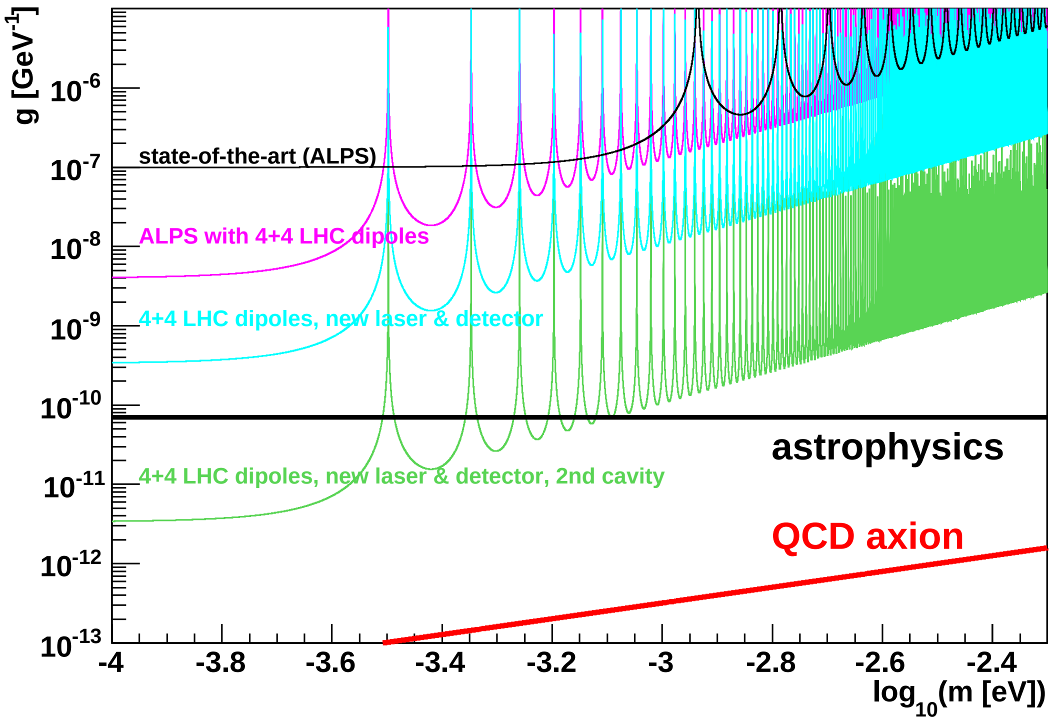


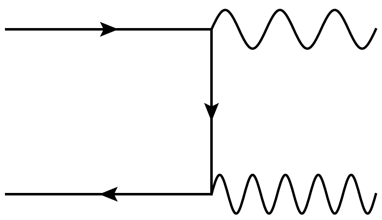
[A. Lindner '09]

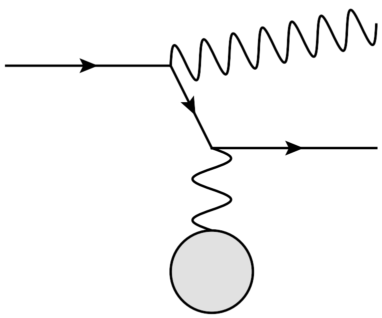
$\Rightarrow$ Astrophysics barrier can be broken! Interesting parameter range in view of white dwarf energy loss and universe's transparency for TeV gamma rays anomaly can be tested!

2.2 Dark Forces Attack with New Fixed-Target Experiments

- High intensity frontier to search for MeV ÷ GeV-scale γ':
  - low-energy e^+e^- collider

    talk of Bertrand Echenard
    - $\mathcal{O}$(few) ab^{-1} per decade
    - $\sigma \sim \frac{\alpha^2\chi^2}{s}$
  - fixed-target experiments
    - $\mathcal{O}$(few) ab^{-1} per day
    - $\sigma \sim \frac{\alpha^3 Z^2 \chi^2}{m_{\gamma'}^2}$





⇒ Beam dump and fixed-target experiments especially sensitive!

[Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09; Batell,Pospelov,Ritz '09]

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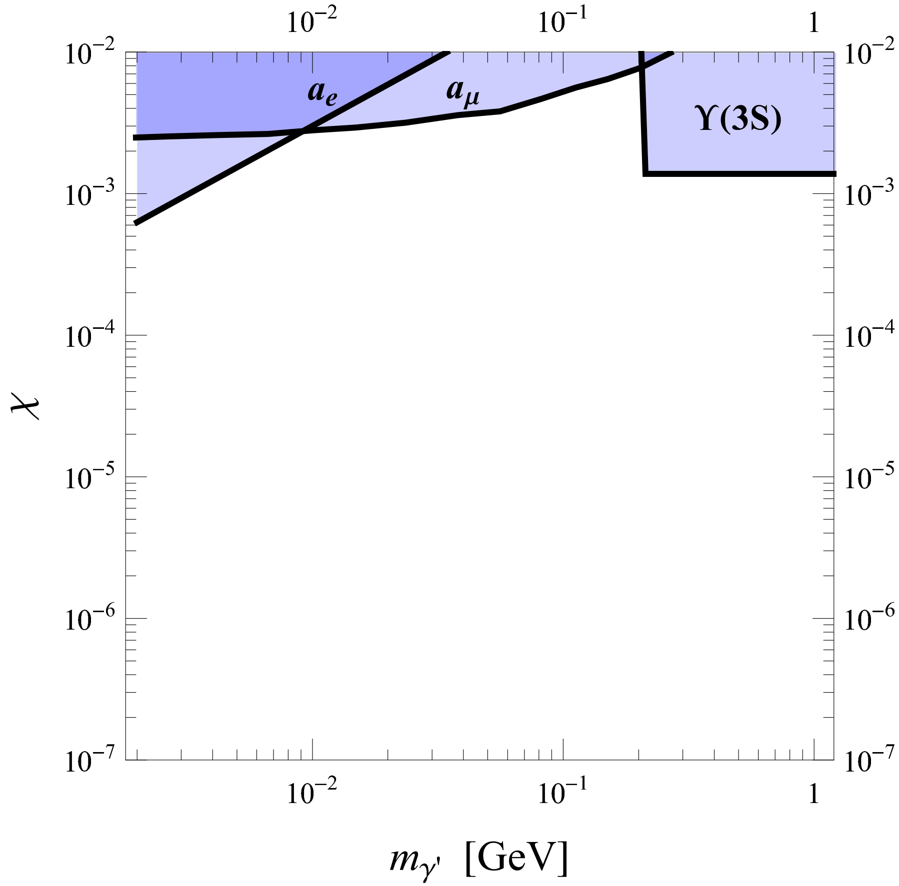

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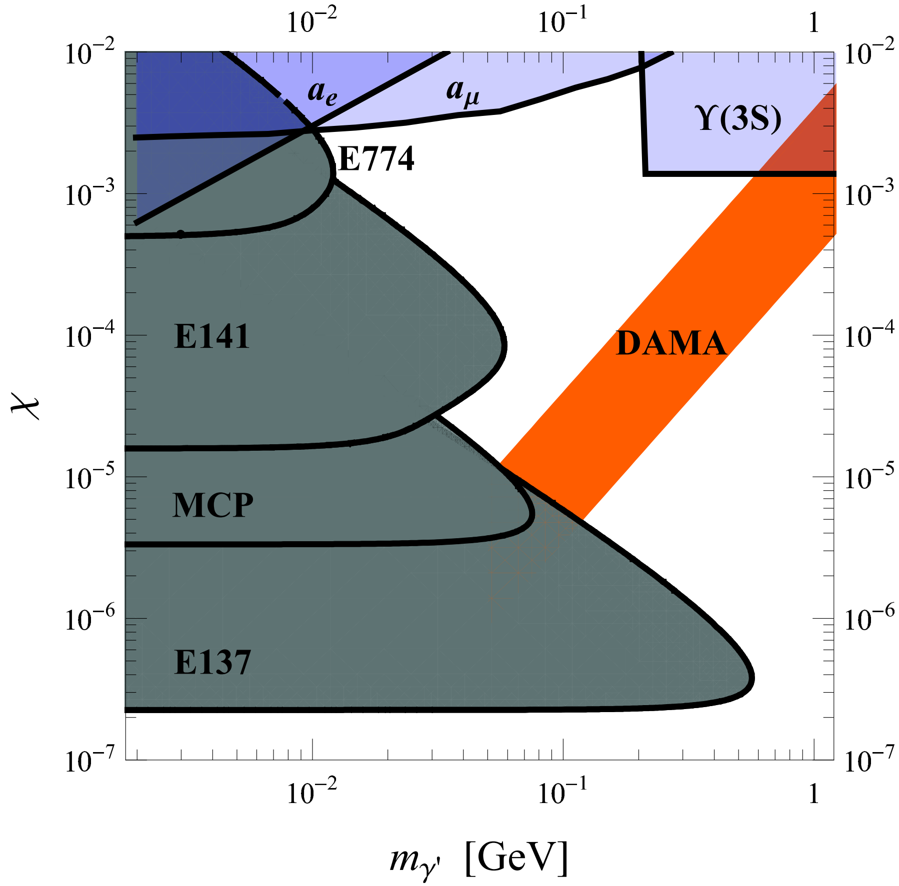

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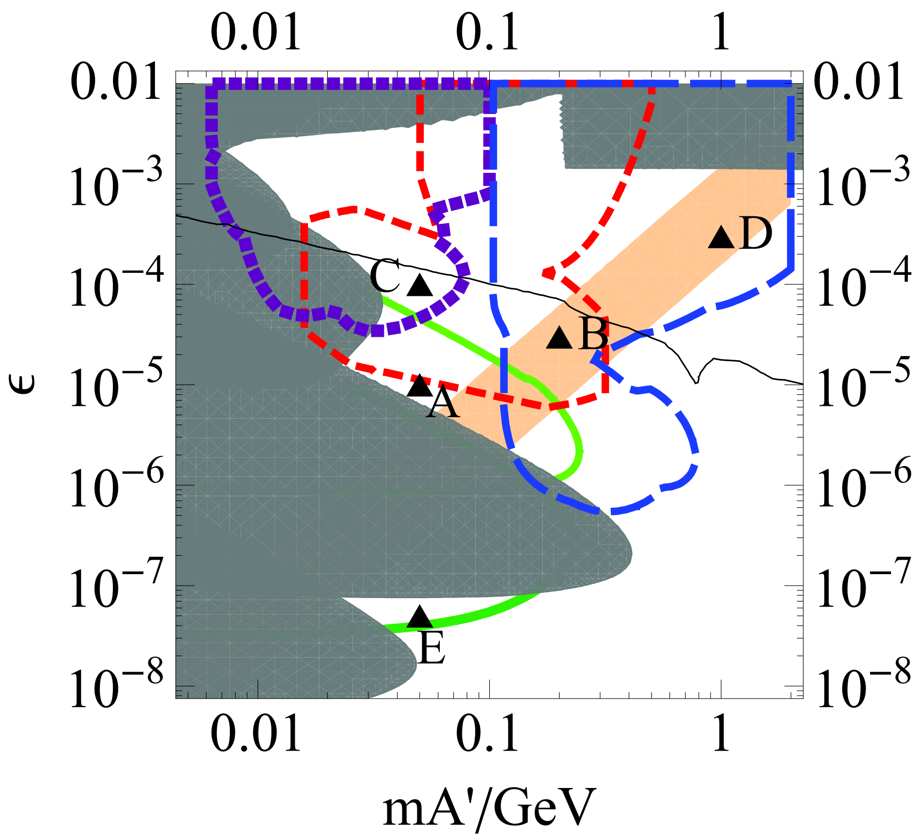


[Bjorken,Essig,Schuster,Toro '09]

⇒ Opportunities at DESY, ELSA, JLab, MAMI?

- Production cross-section and decay length of γ',

$$\sigma_{\gamma'} \sim 100\ \mathrm{pb} \left(\frac{\chi}{10^{-4}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)^2$$

$$\ell_d = \gamma c \tau \sim 1\ \mathrm{mm} \left(\frac{\gamma}{10}\right) \left(\frac{\chi}{10^{-4}}\right)^{-2} \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)$$

- Vary over many orders of magnitude in interesting parameter range

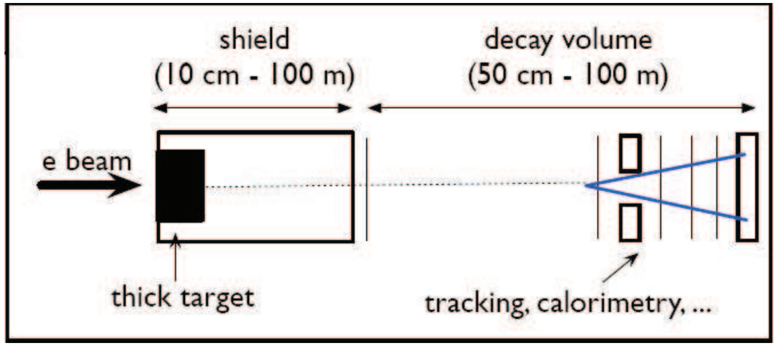
⇒ Multiple experimental approaches, with different strategies for fighting backgrounds

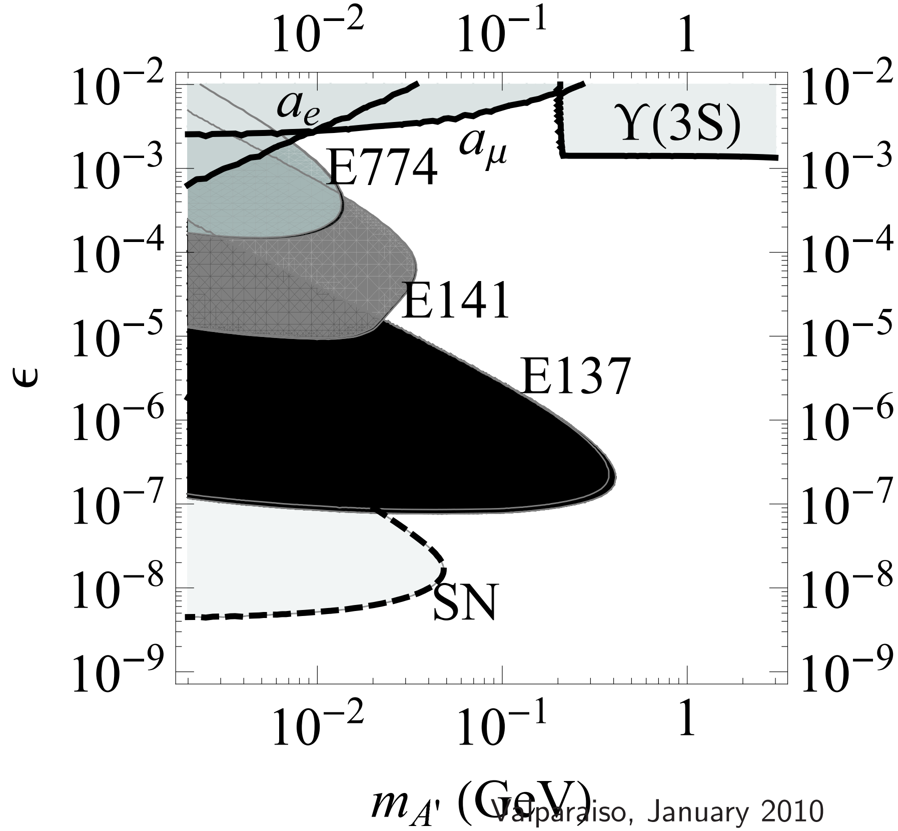
  – $\ell_d \gg$ cm: beam dump; low background
  – $\ell_d \sim$ cm: vertex; limited by instrumental bkg
  – $\ell_d \ll$ cm: bump hunt; fight bkg with high intensity, resolution

- **Past beam dumps:**

[Bjorken,Essig,Schuster,Toro '09]

  - SLAC E137:
    30 C, 20 GeV, 200 m, 200 m
  - SLAC E141:
    .3 mC, 9 GeV, 10 cm, 35 m
  - Fermilab E774:
    .8 nC, 275 GeV, 30 cm, 7 m





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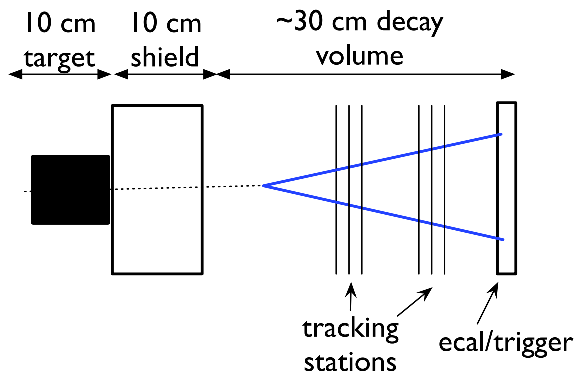
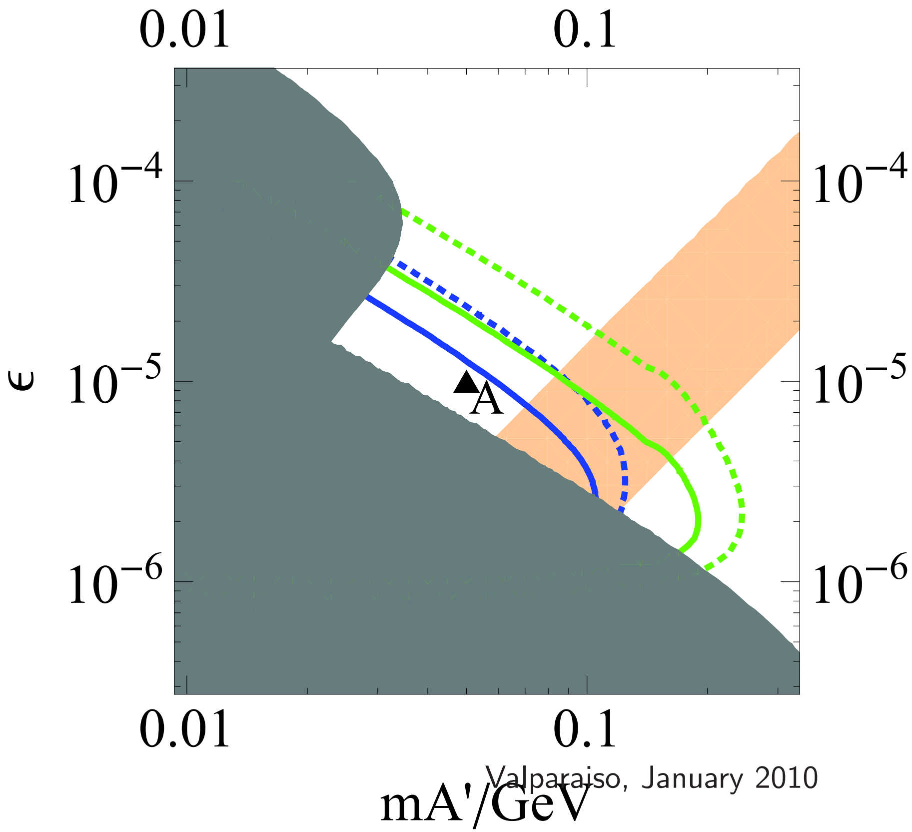
- **New beam dump suggested:**

  [Bjorken,Essig,Schuster,Toro '09]

  – Low power W beam dump
  .3 C, 200 MeV, 20 cm, 50 cm
  .1 C, 6 GeV, 3.9 m, 7 m





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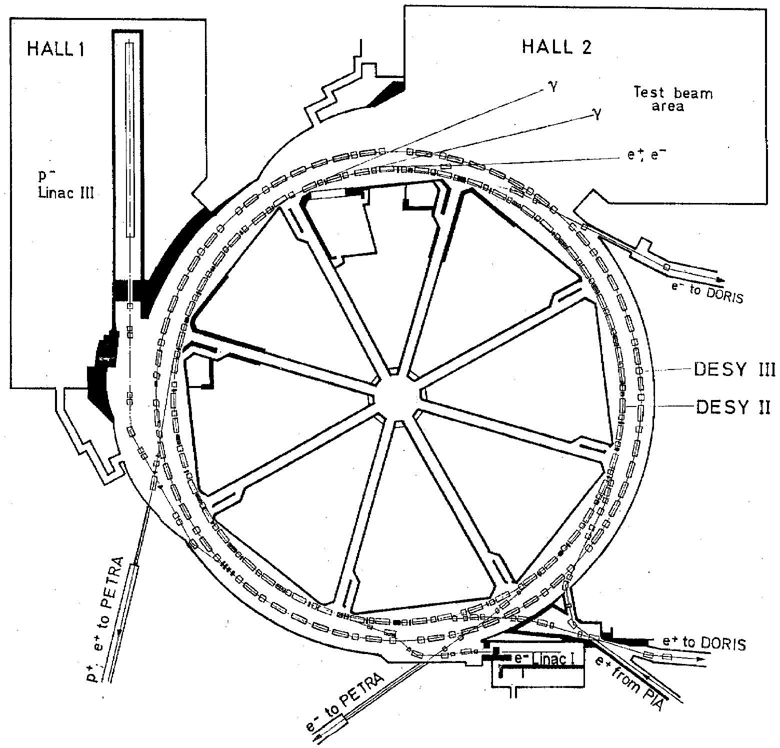
  - **DarkDESY** at DESY II

    [Andreas,Bechtle,Ehrlichmann,Garutti,Gregor,Lindner,Meyners,Redondo,AR]

    * $\sim$ 10 nA with 0.45 - 7 GeV



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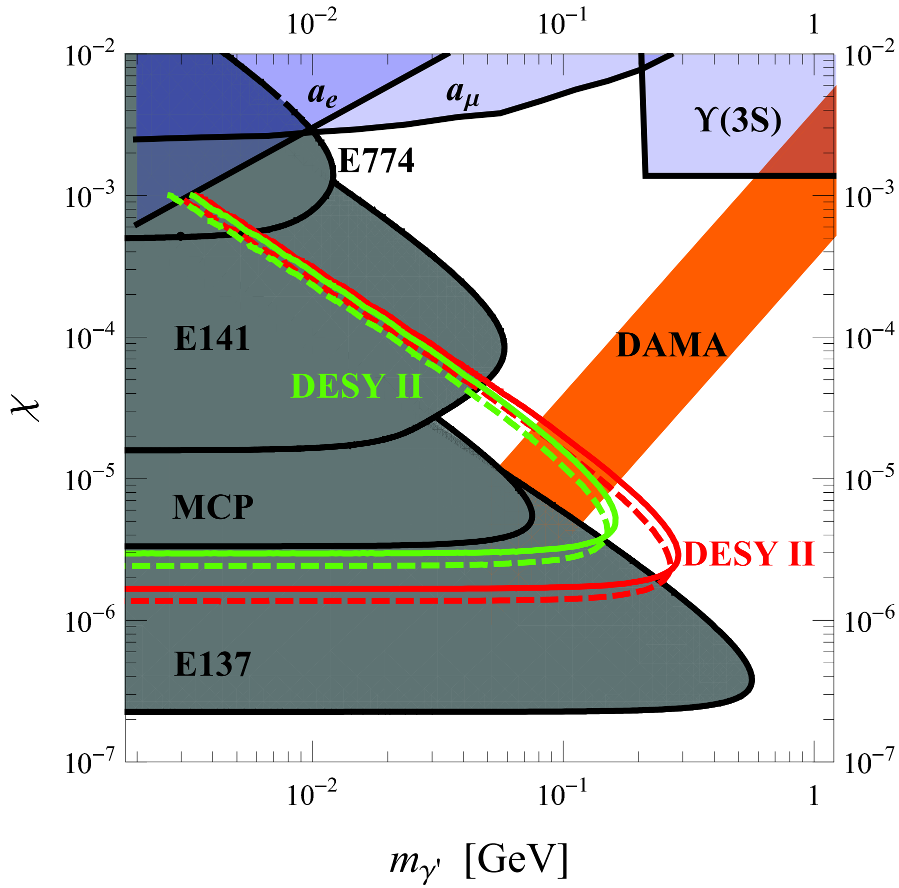
    * $\sim$ 10 nA with 0.45 - 7 GeV
    * first estimates of beam dump sensitivity
    * detector (spare parts of HERA experiments) will be installed this month
    * if background handable, full proposal in spring; experiment could be done in 2010



- **Complementary region** can be probed by thin target bump hunt experiment:
  need very high integrated luminosity and high resolution (trident) spectrometer

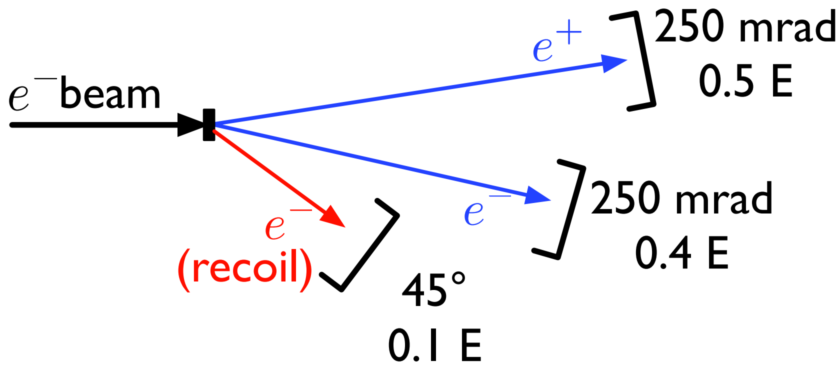
  [Bjorken,Essig,Schuster,Toro '09]

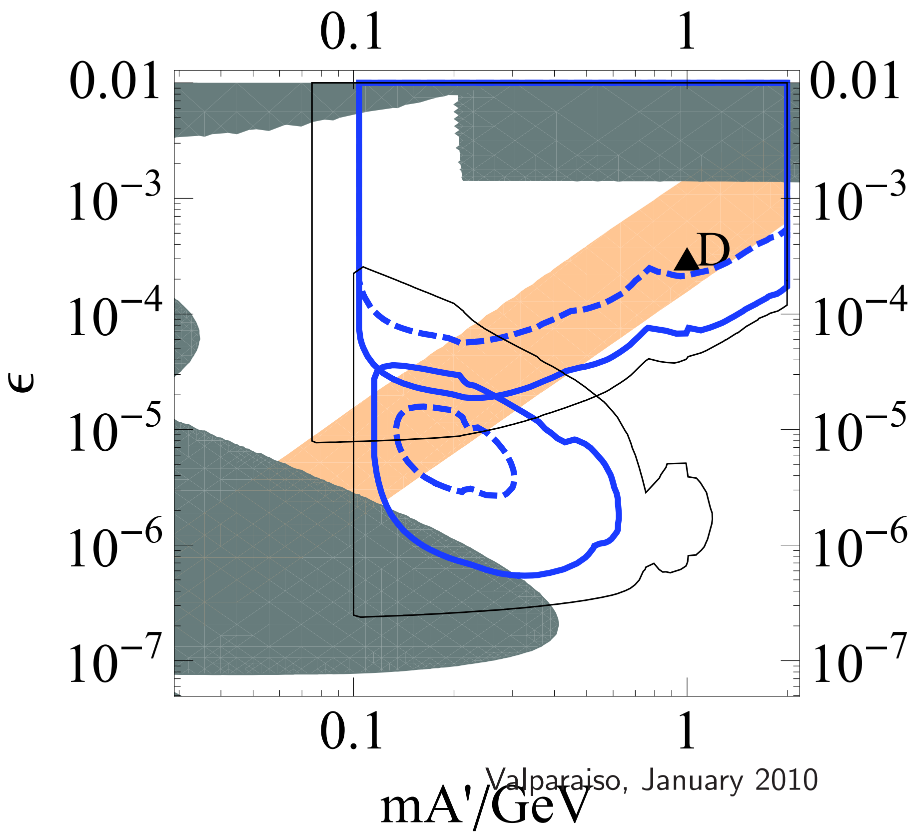
$\Rightarrow$ **New experiment at JLab?**

- **Fixed-target experiment in CEBAF Hall A**

  [Hall A Collaboration]

  * 80 μA at $2 \div 4$ GeV
  * proposed for period after CEBAF upgrade, but could also be done earlier: only target needed





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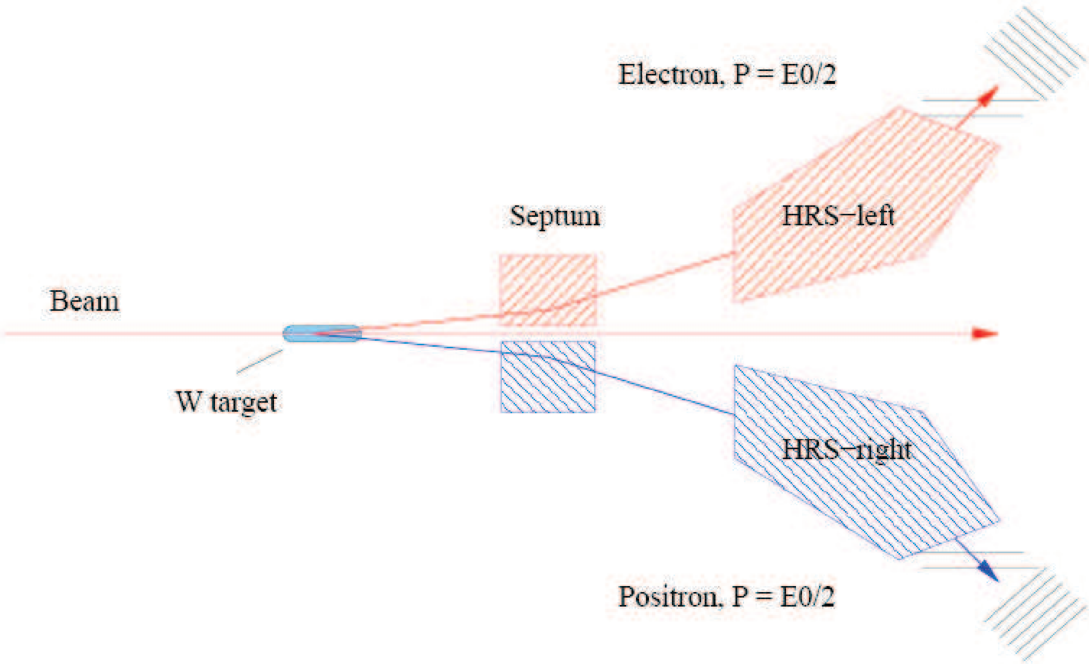

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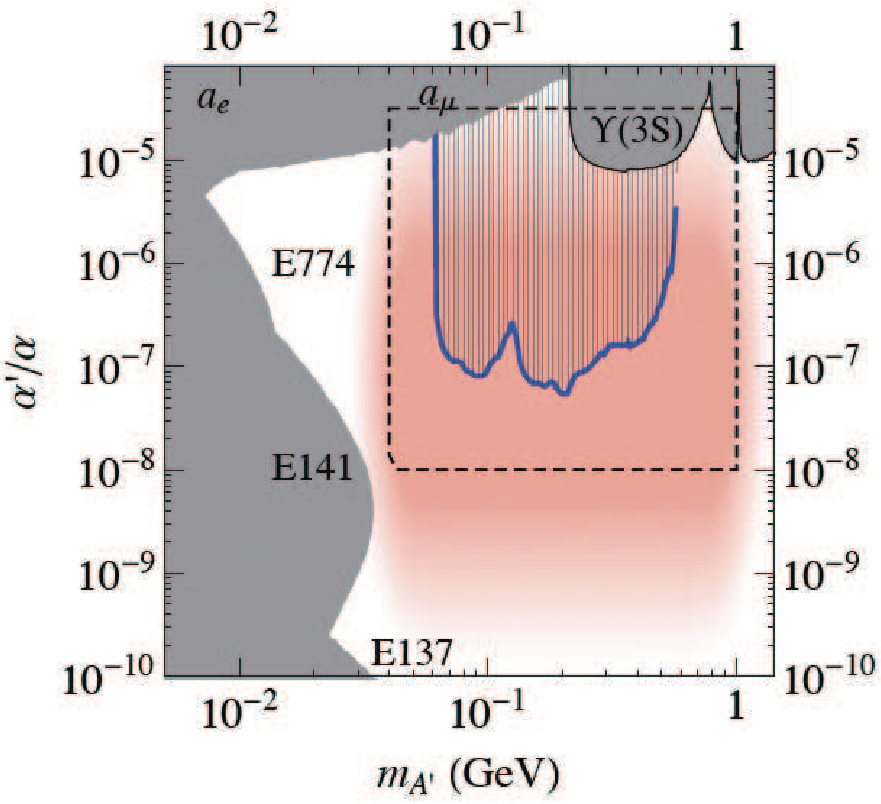

3. Conclusions

- A low-energy, high intentity frontier is forming worldwide:

  Searching for physics beyond the standard model with intense photon and electron beams

- These laboratory experiments have considerable discovery potential for light particles beyond the standard model, for which there is a strong physics case both from theoretical as well as from phenomenological considerations:

  – axions
  – axion-like particles
  – hidden-sector U(1) gauge bosons

- 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!