Searching for ALPs and Hidden Photons with Intense Photon- and Electron-Beams

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Message

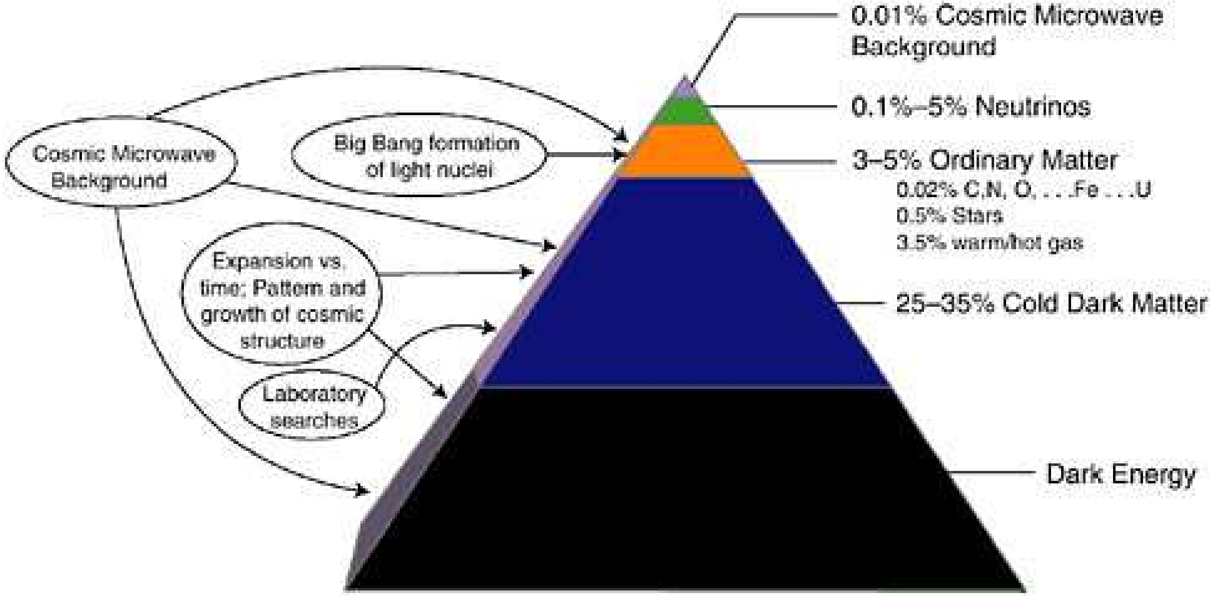
- Axions, Axion-Like Particles (ALPs) and other very Weakly Interacting Slim Particles (WISPs) beyond the Standard Model are strongly motivated from theory, cosmology, and astrophysics

- There are experiments around the globe, notably at accelerator labs, which search for ALPs and other WISPs, exploiting/recycling existing equipment:
  - Light-shining-through-walls experiments exploiting lasers and magnets
  - Beam dump and fixed target experiments exploiting electron beams

$\Rightarrow$ **New intensity frontier, complementary to energy frontier!**

Case for Particles Beyond the Standard Model

- Standard Model (SM) describes only $\sim 5\,\%$ of the universe:



$\Rightarrow$ **There are particles beyond the SM**

Case for Particles Beyond the Standard Model

- Constituents of **dark matter** could be heavy or light:
  - **WIMPs**: Weakly Interacting Massive Particles
  - **Super-WIMPs**: Super-Weakly Interacting Massive Particles
  - **WISPs**: very Weakly Interacting Slim Particles

- Embedding of Standard Model in **supergravity or string theory** $\Rightarrow$ particles beyond the Standard Model, in all three categories:
  - **WIMPs**: neutralinos, sneutrinos, . . .
  - **Super-WIMPs**: gravitinos, axinos, hidden U(1) gauginos, . . .
  - **WISPs**: axions, axion-like particles, hidden U(1) gauge bosons, . . .

Axions and Axion-Like Particles (ALPs)

- solve the strong CP problem [Peccei,Quinn '77; Weinberg '78; Wilczek '78;...]

- enjoy anomalous shift symmetry, $\phi(x) \to \phi(x) + \text{const.}$,

  $\Rightarrow$ explicit mass terms, $\propto m_\phi^2 \phi^2$, forbidden $\Rightarrow$ (ultra-)light

  $\Rightarrow$ derivative coupling to matter, $\propto \partial\phi/f_\phi$, and anomalous coupling $\propto 1/f_\phi$ to gauge fields $\Rightarrow$ very weakly coupled, if $f_\phi \gg v_{\rm EW}$; in particular

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

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

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

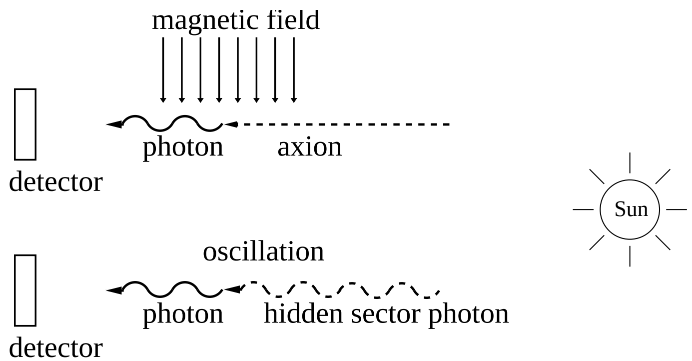
  – for string embeddings, $f_\phi \sim M_s$

- Most sensitive probes for ALPs based on **photon-ALP conversion**:

(for axion and ALP: in presence of (electro-)magnetic field)

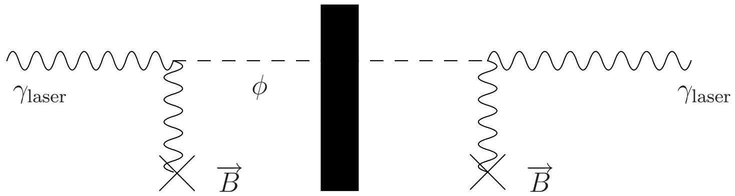
- **helioscope searches** (e.g. CAST, SUMICO, SHIPS, ...)

[Sikivie ‘83;...;Redondo ‘08;...]

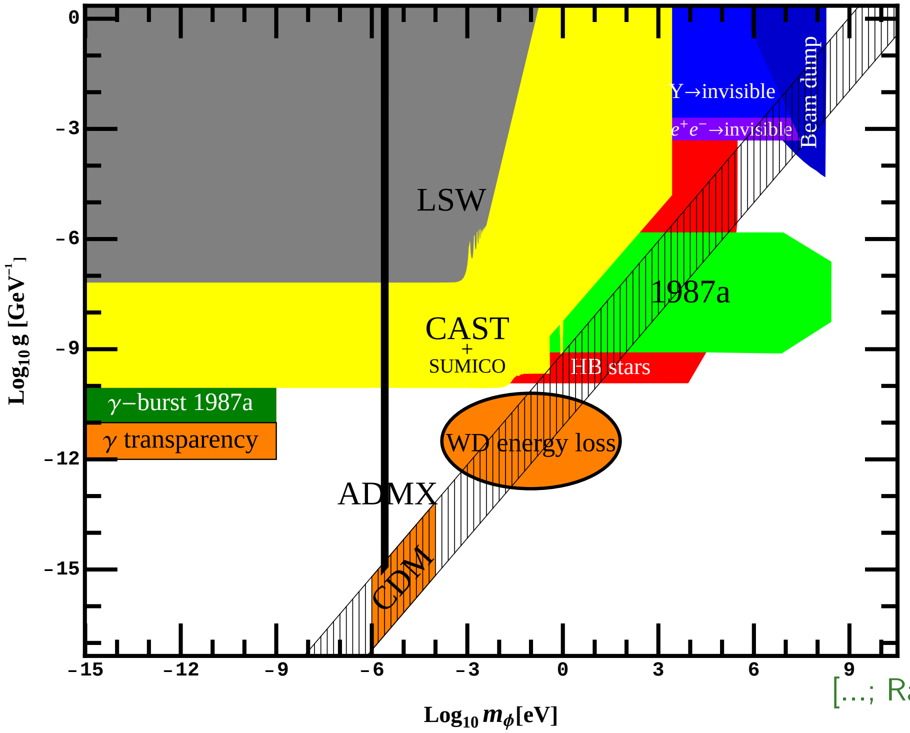


- **light-shining-through-walls searches** (e.g. ALPS, GammeV, ...)

[Okun ‘83;Anselm ; van Bibber]



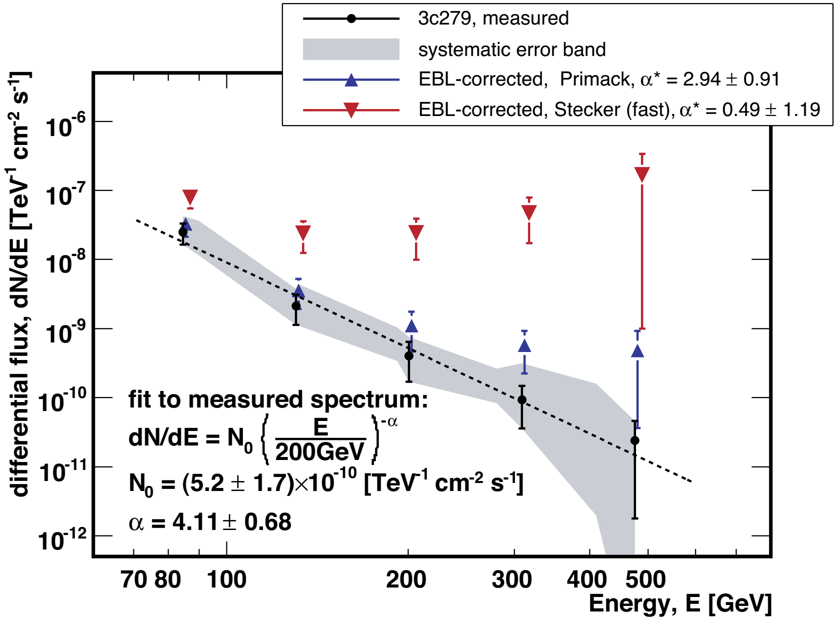
- LSW (helioscopes) probe currently $g \sim 10^{-7}$ GeV^{-1} ($g \sim 10^{-10}$ GeV^{-1}):



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

- Astrophysical hints (TeV γ transparency puzzle (H.E.S.S., MAGIC); anomalous energy loss of white dwarfs) point at $g \sim 10^{-12} \div 10^{-11}$ GeV^{-1}, compatible with $M_s \sim f_\phi \sim 10^9$ GeV

- **TeV γ transparency puzzle:** no cutoff seen in TeV γ spectra of distant sources, despite absorption due to e^+e^- pair production on extragalactic background light



[MAGIC '08]

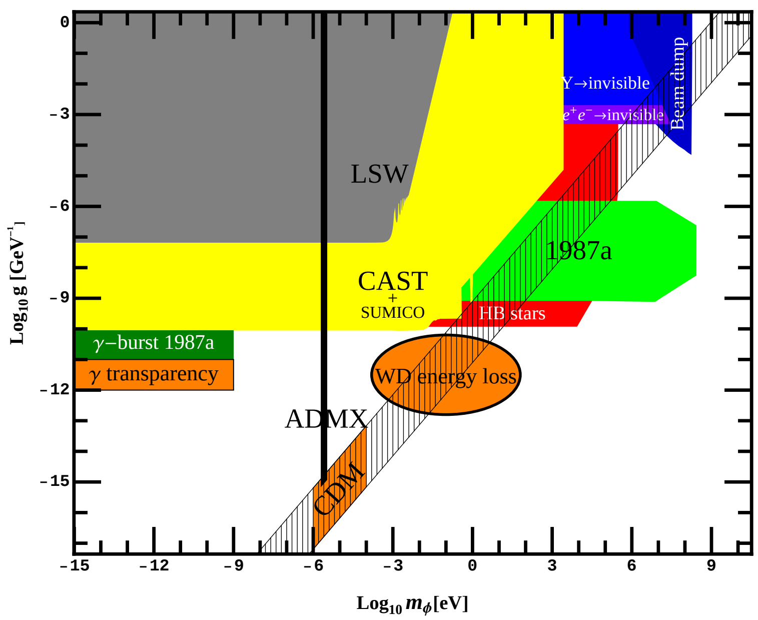
May be explained by conversion and reconversion of γs into axion-like particles ϕ in intergalactic magnetic fields with [De Angelis,Mansutti,Roncadelli '07;..;Mirizzi,Montanino '09]

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

Seem to arise naturally in string compactifications with $M_s \sim 10^9$ GeV [Goodsell,AR]

- **Non-standard energy loss in white dwarfs** recently pointed out, both apparent in their luminosity function as well as in the secular drift of DAV white dwarfs, compatible with an additional sink of energy due to axions or ALPs with a coupling to electrons, $g_{e\phi} \simeq 10^{-13}$, suggesting a decay constant [Isern *et al.* '08; '10]

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



[Jaeckel,AR '10]

- **LSW experiments**
  - worldwide activity at accelerator labs recycling existing dipole magnets

Experiment	ω	$\mathcal{P}_{\rm prim}$	β_g	Magnets
ALPS (DESY)	2.33 eV	4 W	300	$B_g = B_r = 5$ T $L_g = L_r = 4.21$ m
BFRT (Brookhaven)	2.47 eV	3 W	100	$B_g = B_r = 3.7$ T $L_g = L_r = 4.4$ m
BMV (LULI)	1.17 eV	8×10^{21} γs/pulse	14 pulses	$B_g = B_r = 12.3$ T $L_g = L_r = 0.4$ m
GammeV (Fermilab)	2.33 eV	4×10^{17} γs/pulse	3600 pulses	$B_g = B_r = 5$ T $L_g = L_r = 3$ m
LIPSS (JLab)	1.03 eV	180 W	1	$B_g = B_r = 1.7$ T $L_g = L_r = 1$ m
OSQAR (CERN)	2.5 eV	15 W	1	$B_g = B_r = 9$ T $L_g = L_r = 7$ m

  - exploit optical lasers, because they have the highest average photon flux, $\mathcal{P}_{\rm prim}\beta_g/\omega$, up to a few $\times 10^{21}$/s (ALPS)

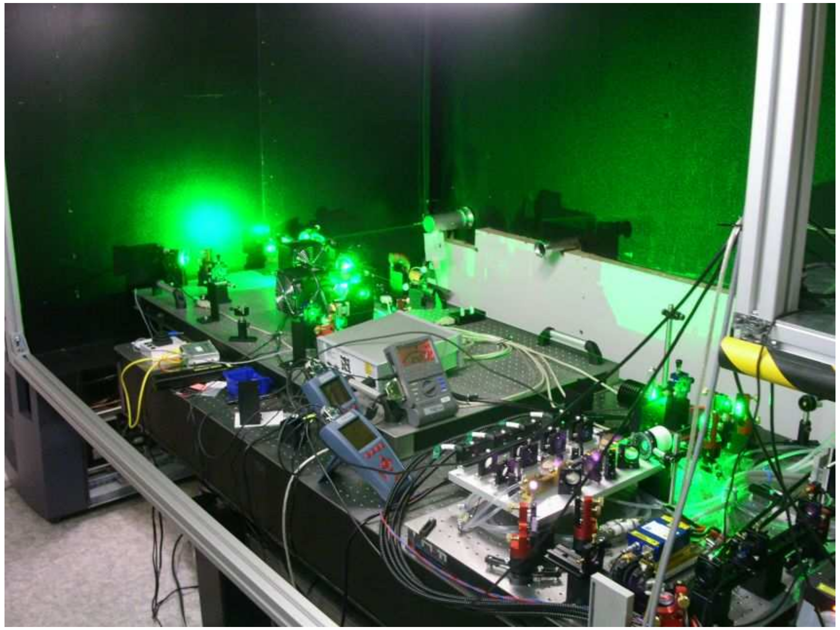
ALPS (Any-Light Particle Search)

[Albert Einstein Institute Hannover, DESY Hamburg, Hamburger Sternwarte, Laser Zentrum Hannover]

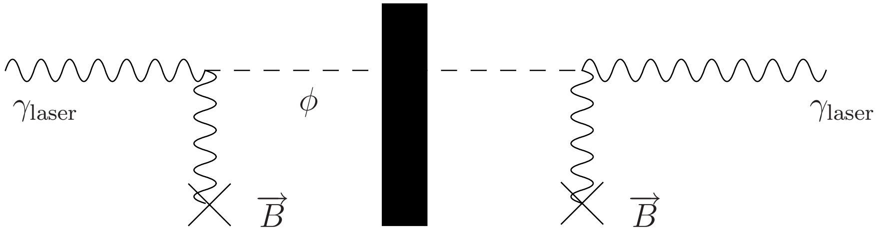
- primary beam: enhanced LIGO laser (1064 nm, 35 W cw)

⇒ frequency doubled to 532 nm

⇒ $\sim$ 300 fold power build up through resonant optical cavity (Fabry-Perot)



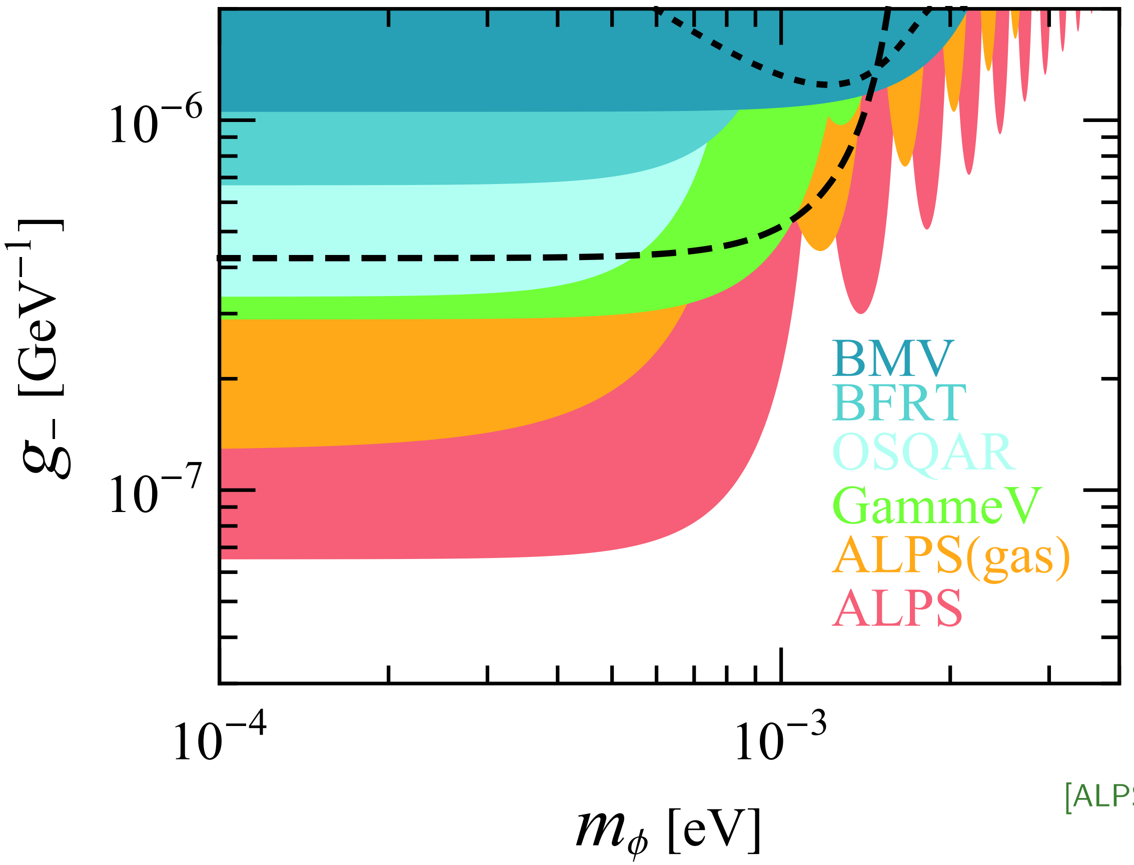
- **ALPS** (Axion-Like Particle Search): [AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]



$$P(\gamma \to \phi) = P(\phi \to \gamma) = 4\frac{(g\omega B)^2}{m_\phi^4}\sin^2\left(\frac{m_\phi^2}{4\omega}L_B\right)$$

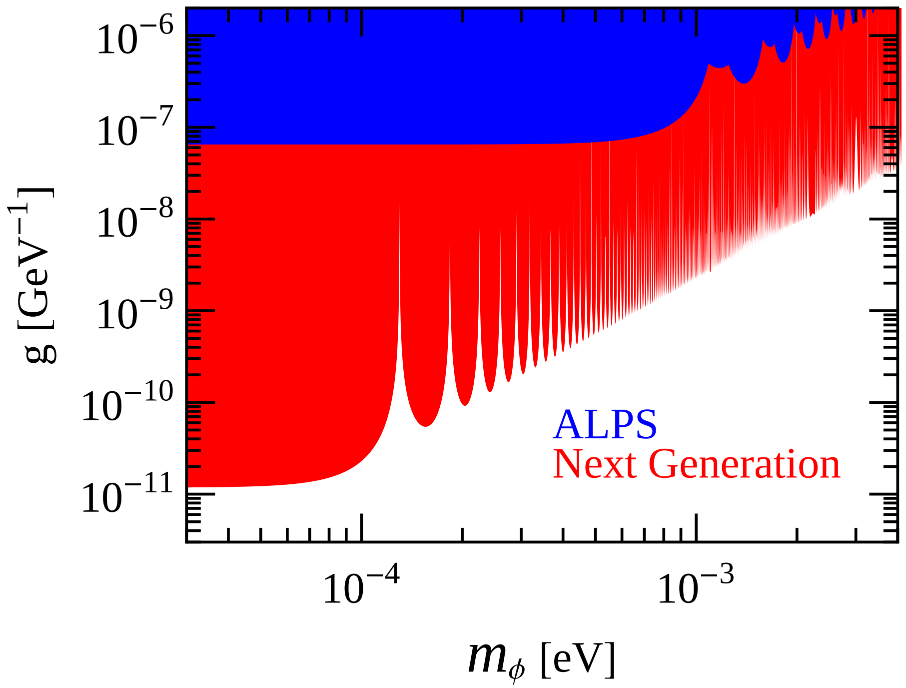
- Last **ALPS** run end of 2009 [Phys. Lett. B 689 (2010) 149-155]

⇒ *"Not a WISP of evidence"* [Nature 465 (2010) 271]



[ALPS Collaboration '10]

- **Upgrade plans** at DESY (similar at Fermilab):
  - exploit more (e.g. 20+20) HERA (Tevatron) magnets
  - exploit resonant regeneration cavity [Hoogeveen,Ziegenhagen '91;Sikivie,Tanner,van Bibber '07]



[Redondo,AR '10]

$\Rightarrow$ Next generation LSW ready to probe ALP coupling of great interest in context of intermediate string scale scenarios and astro/cosmo hints

Hidden-Sector Abelian Gauge Bosons

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

- Extra U(1) gauge factors ubiquitous in well motivated extensions of the SM with large rank local gauge group

- 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

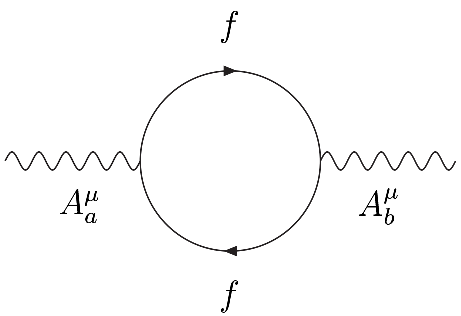
- At low energies, hidden U(1)s interact with $\mathrm{U}(1)_Y$ or $\mathrm{U}(1)_{\mathrm{em}}$ dominantly via kinetic mixing, [Holdom'85]

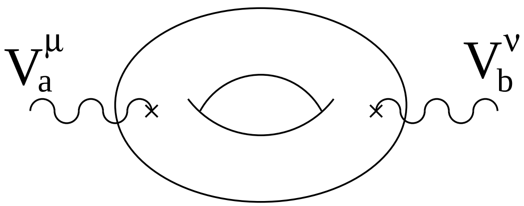
$$\mathcal{L} \supset -\frac{1}{4} F^{(\mathrm{vis})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4} F^{(\mathrm{hid})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2} F^{(\mathrm{vis})}_{\mu\nu} F^{(\mathrm{hid})\mu\nu} + m^2_{\gamma'} A^{(\mathrm{hid})}_{\mu} A^{(\mathrm{hid})\mu}$$

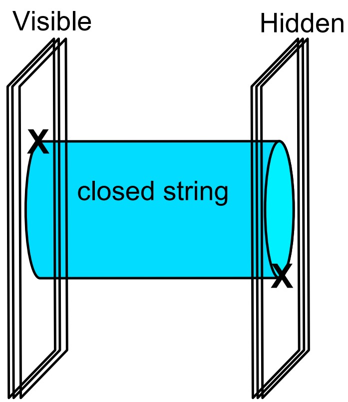
  – $\chi \ll 1$ generated at loop level via messenger exchange,

$$10^{-12} \lesssim \chi \sim \frac{g_Y g_h}{(16\pi)^2} f \lesssim 10^{-3}$$

  – g_h and f depend on the type of messenger:

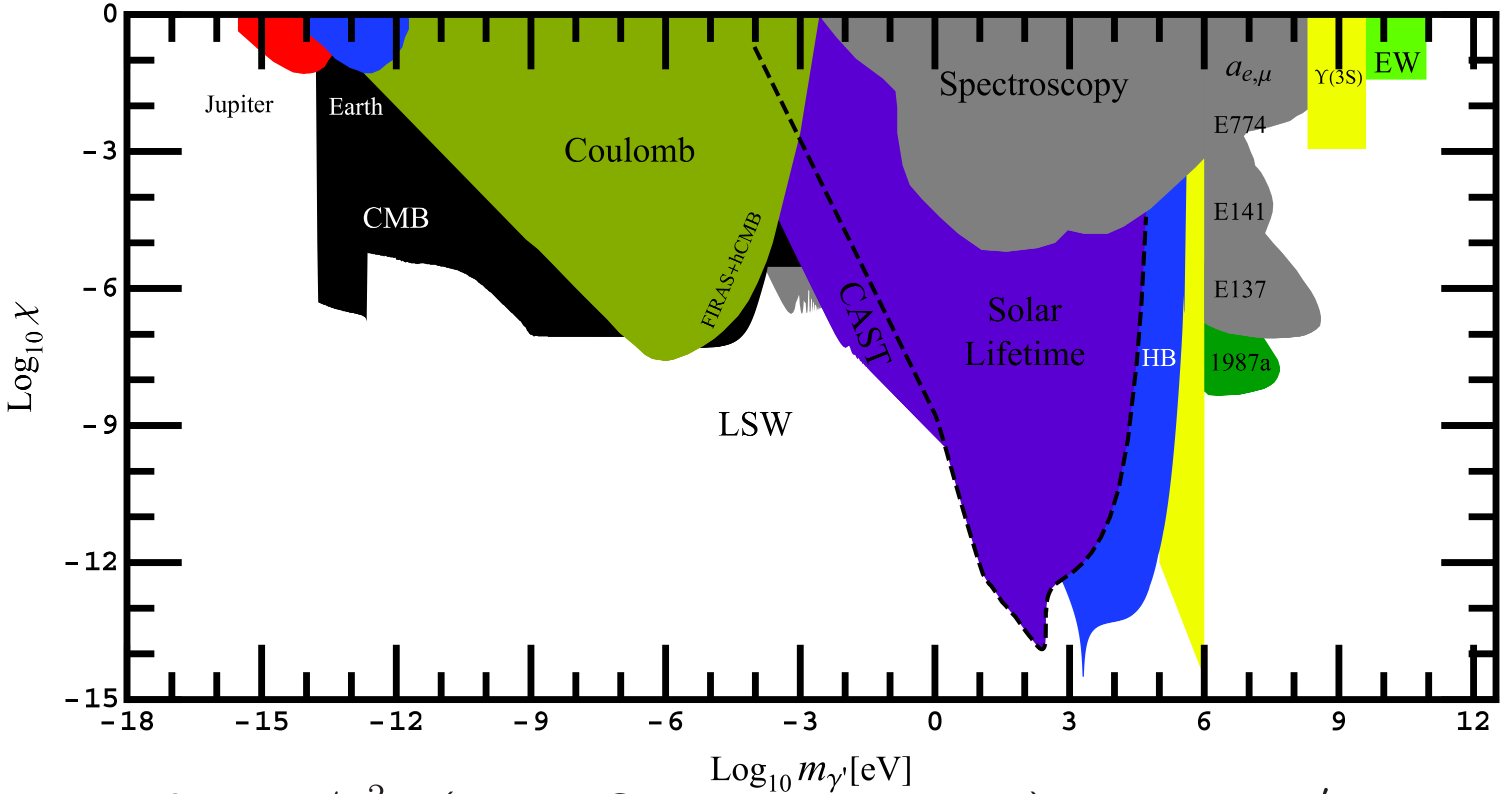






- Current constraints on hidden U(1)s:

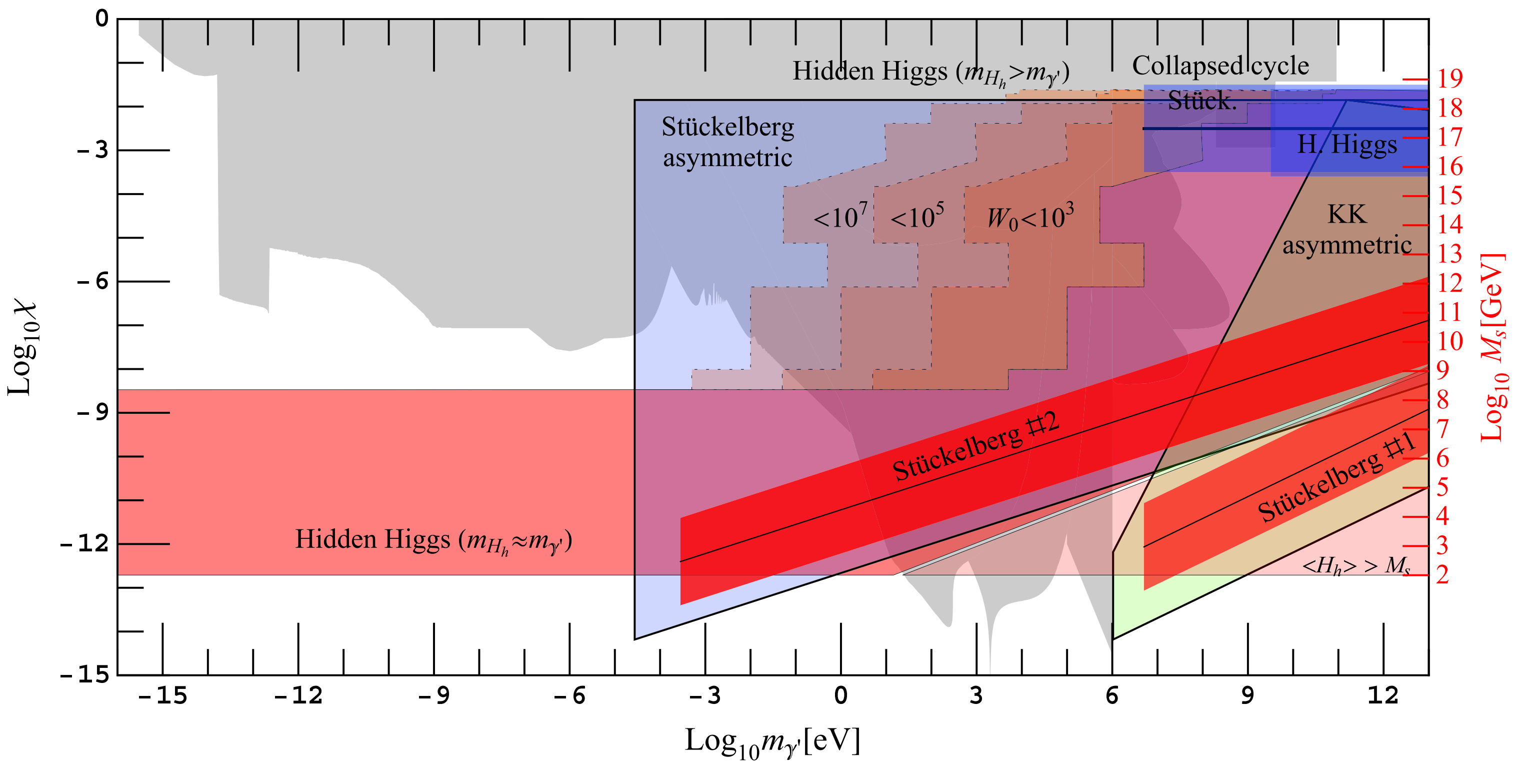
[Bartlett,..‘88; Kumar,..‘06; Ahlers,..‘07;...;Redondo,..‘08;Pospelov ‘08;Bjorken,Essig,Schuster,Toro‘09;Jaeckel,..‘10;...]



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

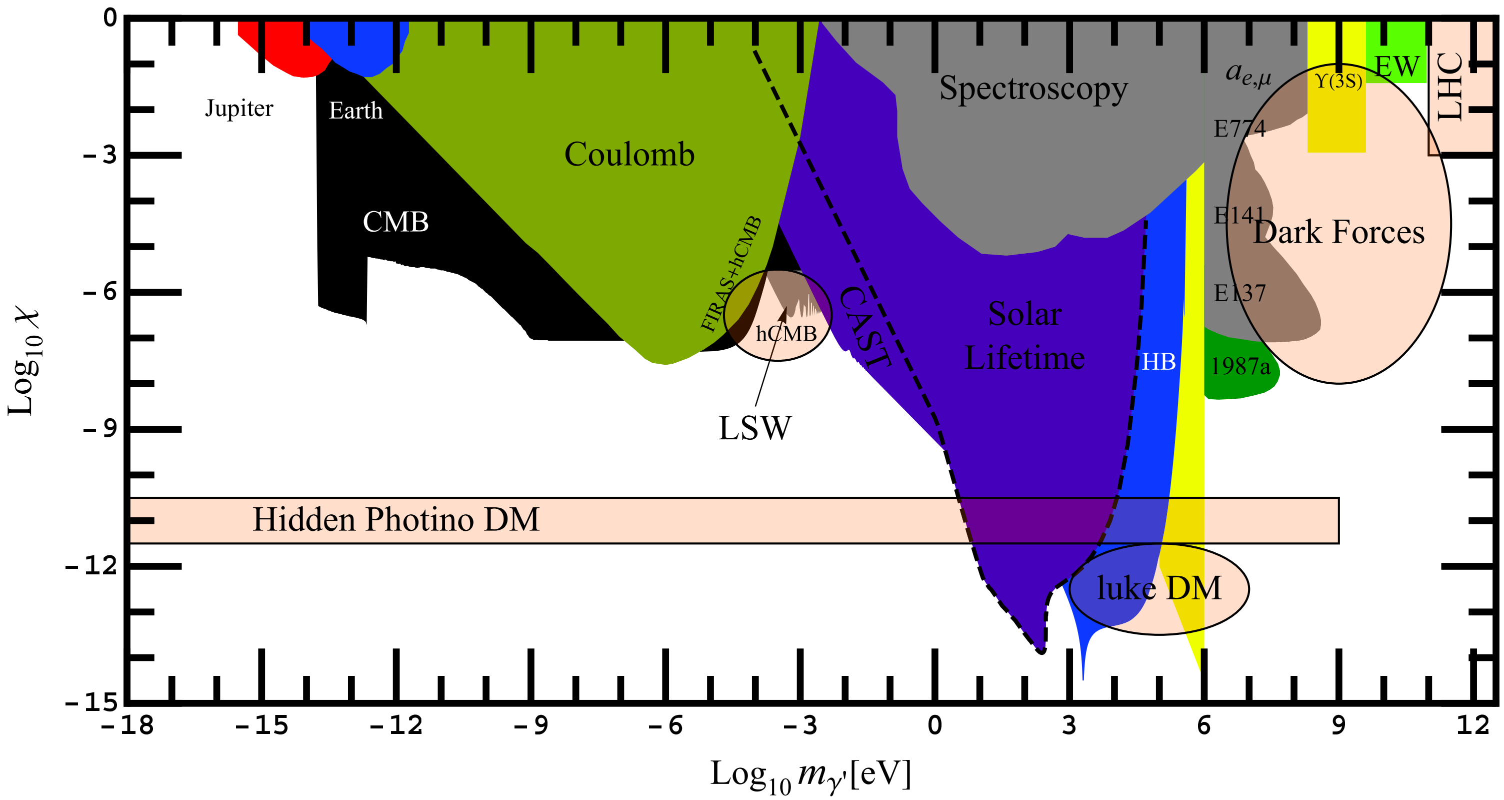
- Predictions of hidden U(1)s from string compactifications:

[Abel,Goodsell,Jaeckel,AR '08; Goodsell,Jaeckel,Redondo,AR '09; Goodsell,Jaeckel,AR in prep.]

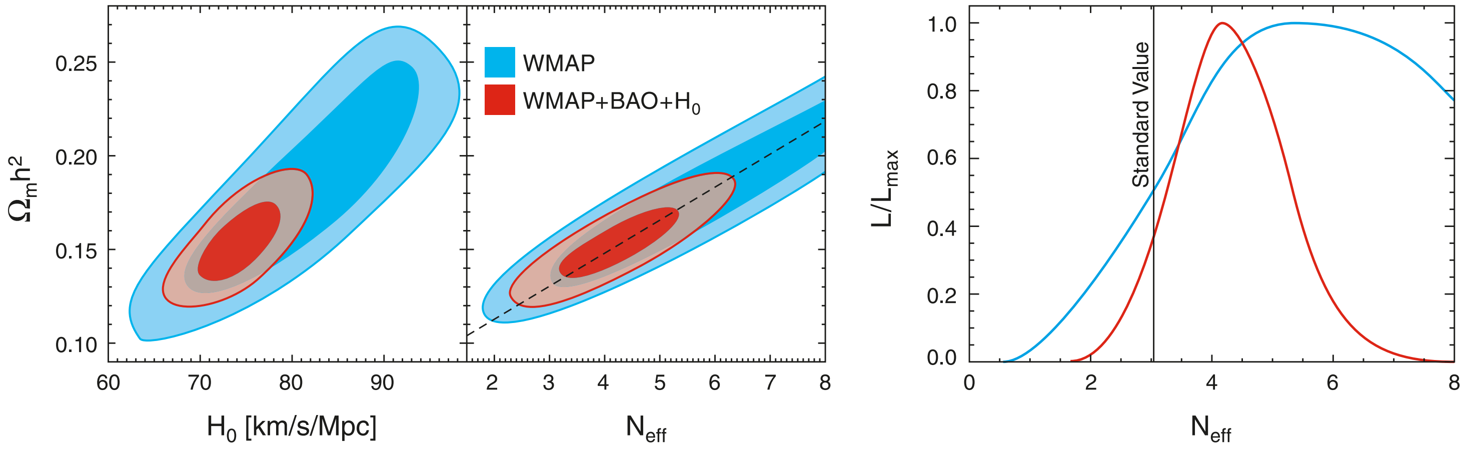


- Phenomenologically interesting hidden U(1) parameter ranges:

[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]

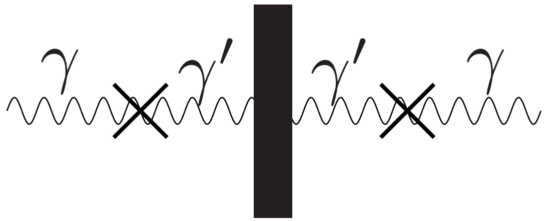


[WMAP 7-year Cosmological Interpretation]

Can be checked in

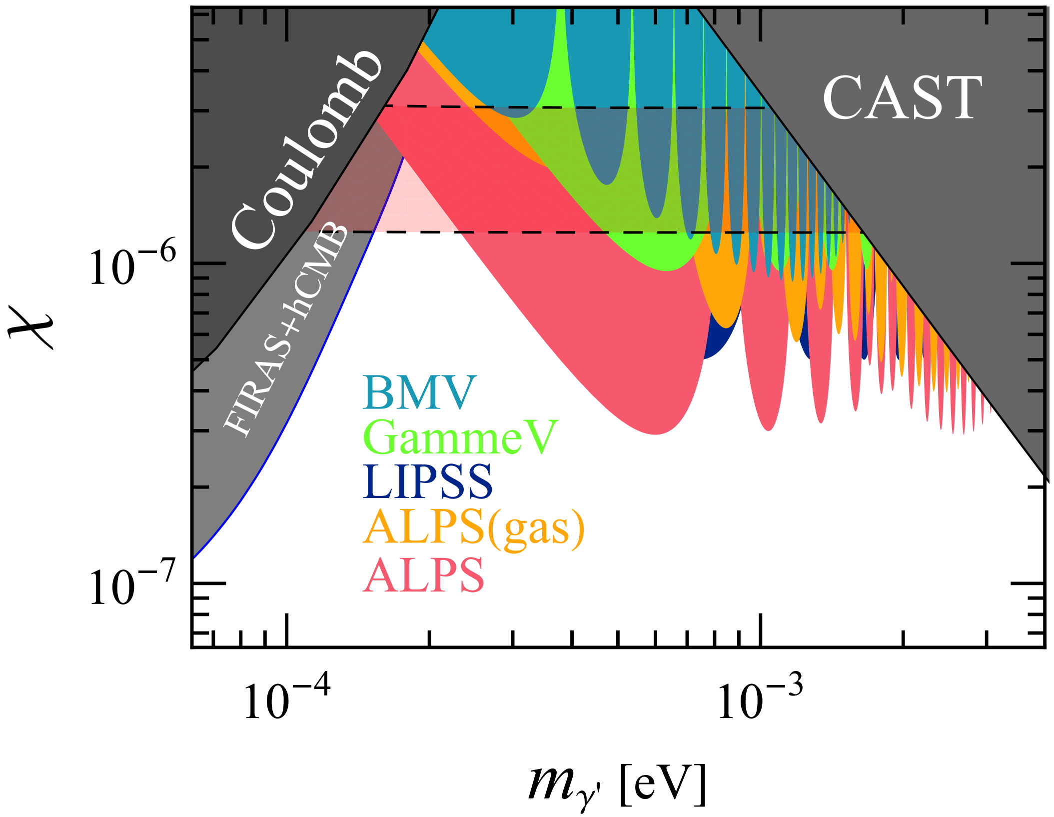
– light-shining-through-walls experiments [Okun '82; ...]
– helioscopes [...; Redondo '08;...]
– microwave cavity experiments [Jaeckel,AR '07;...]

- **meV scale hidden photons** also lead to **light-shining-through-walls** (no B needed!): [Okun '82; ...]



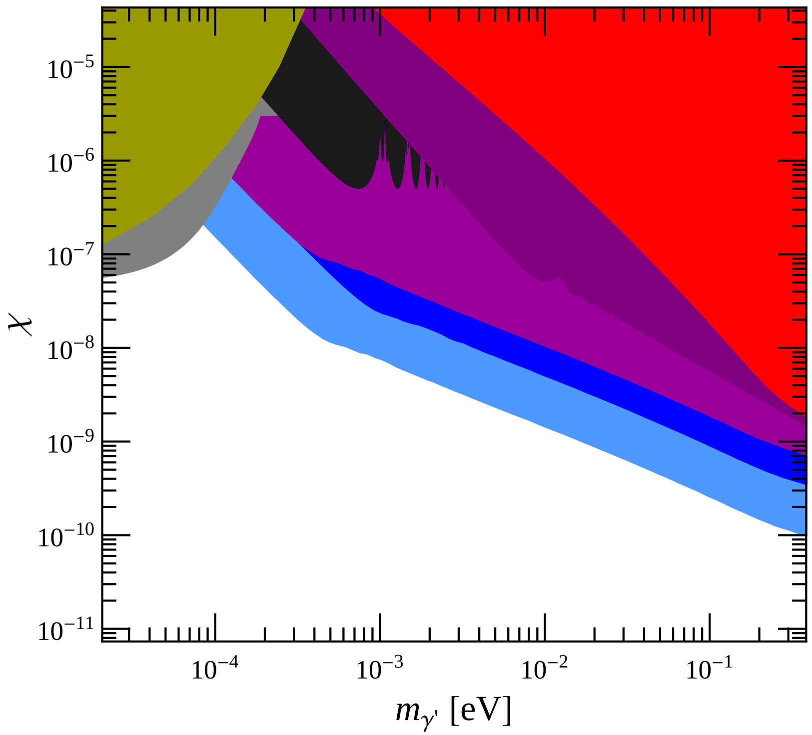
$$P(\gamma \to \phi) = P(\phi \to \gamma) = 4\chi^2 \sin^2 \left(\frac{m_{\gamma'}^2}{4\omega} L \right)$$

- Last **ALPS** limits on LSW excludes large portion of parameter space compatible with hCMB explanation of WMAP N_ν^{eff} excess:



[ALPS Collaboration '10]

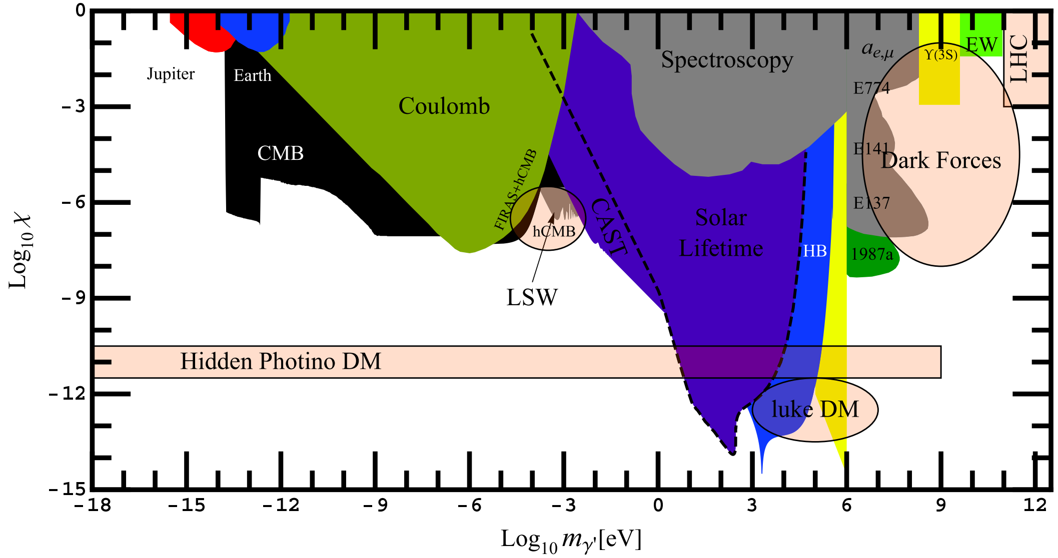
- Helioscopes **CAST** and **SHIPS** (Solar Hidden Photon Search) may probe remaining parameter space very soon: [DESY, Hamburger Sternwarte]



[Redondo in prep.]

- **MeV-GeV scale hidden photon** (dark force, dark 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)

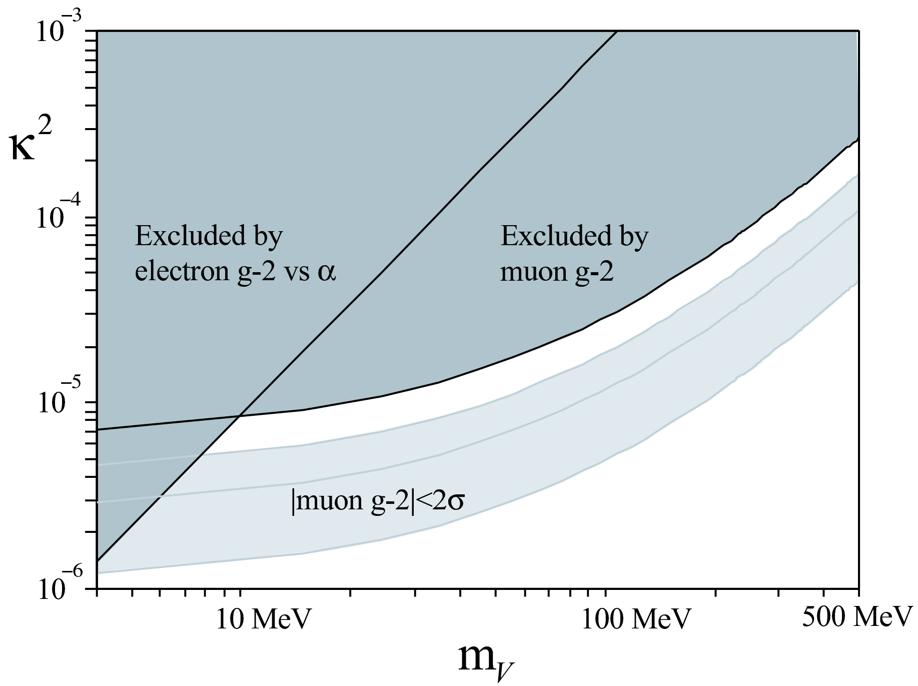
    DM anomalies if DM charged under hidden U(1)
  - can be checked in new fixed-target experiments



- **Contribution of sub-GeV scale γ' to anomalous magnetic moment,**

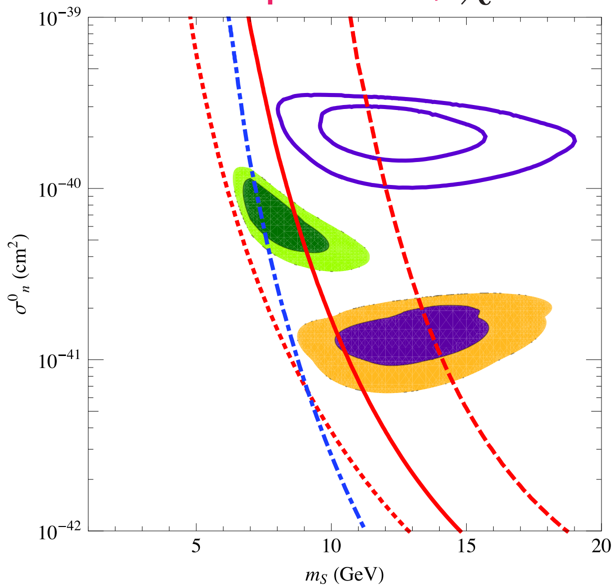
$$a_\ell^{\gamma'} = \frac{\alpha\chi^2}{2\pi} \times \int_0^1 dz \frac{2m_\ell^2 z(1-z)^2}{m_\ell^2(1-z)^2 + m_{\gamma'}^2 z} = \frac{\alpha\chi^2}{2\pi} \times \begin{cases} 1 \quad \text{for} \quad m_\ell \gg m_{\gamma'}, \\ 2m_\ell^2/(3m_{\gamma'}^2) \quad \text{for} \quad m_\ell \ll m_{\gamma'}, \end{cases}$$

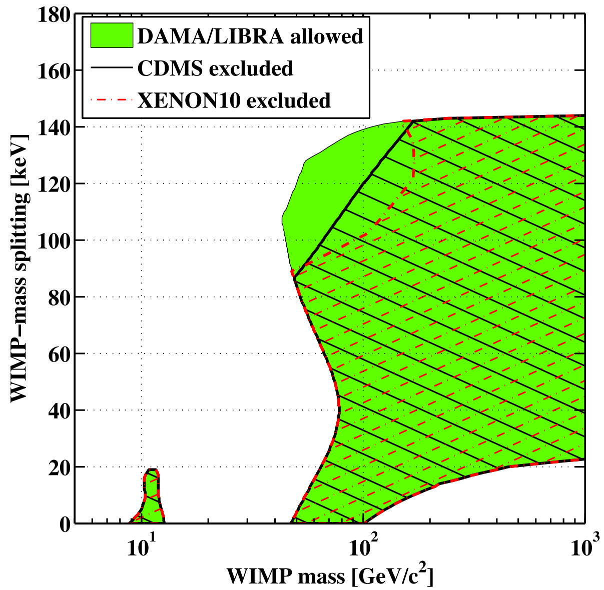
may explain a_μ anomaly: [Pospelov '08]



[Pospelov '08]

- **Dark matter interpretation** of annual modulation signal observed by DAMA and of excess of low energy events in CoGeNT not in conflict with null results of CDMS and XENON if χ-nucleus scattering dominated by
  - elastic process, $\chi + N \to \chi + N$, with low mass $m_\chi \sim 5 - 10$ GeV
  - inelastic process, $\chi + N \to \chi^* + N$, with mass splitting $\triangle m \approx 100\,\mathrm{keV}$



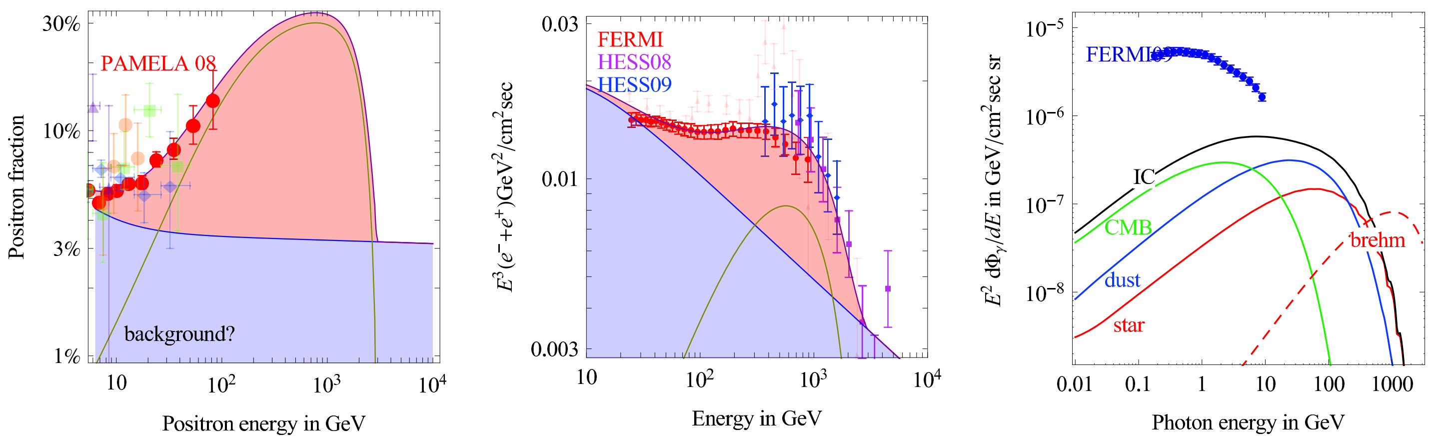


[Andreas *et al.* '10; CDMS II '10]

$\Leftarrow$ **can be mediated by kinetically mixed sub-GeV scale γ'**

- **Explanation of electron and/or positron excesses** by PAMELA, FERMI, ... in terms of thermal relic dark matter annihilation requires
  - enhanced annihilation cross-section (boost factor)
  - leptophilic final state

DM with $M = 3.$ TeV that annihilates into 4μ with $\sigma v = 8.8 \times 10^{-23}$ cm^3/s



[Meade,Papucci,Strumia,Volansky '09]

$\Leftarrow$ **can be achieved via** $\chi + \chi \rightarrow \gamma' + \gamma'$, **if** $2\, m_e < m_{\gamma'} \lesssim m_p$

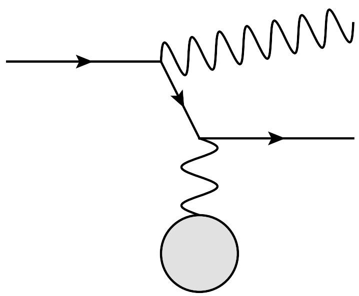
[Arkani-Hamed,Finkbeiner,Slatyer,Weiner '08; Batell,Pospelov,Ritz '09;...]

A new low-energy, high intensity frontier

- **Fixed-target experiments with intense electron beams** particularly sensitive to MeV-GeV scale hidden photon

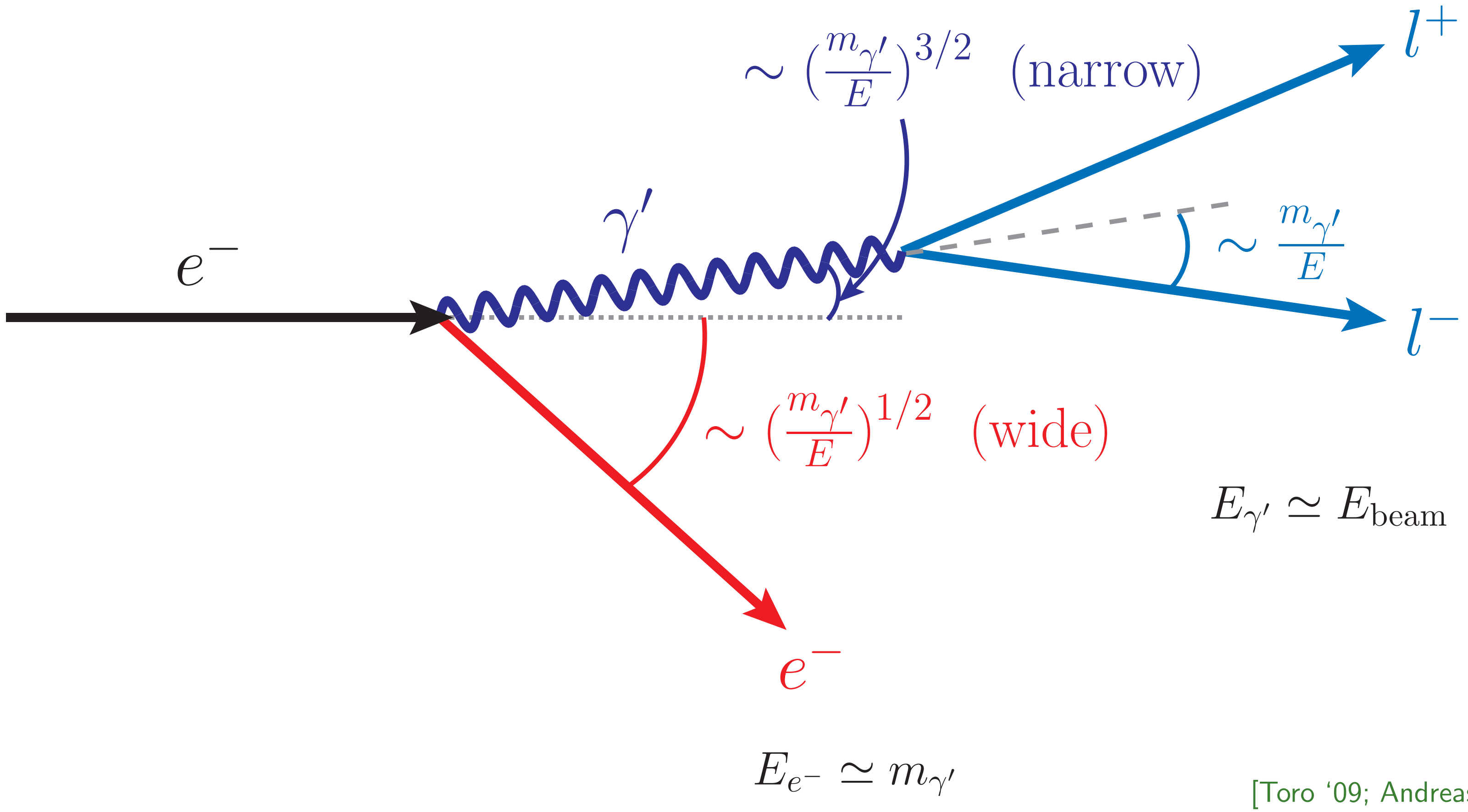
[Heinemeyer,Kahn,Schmitt,Velasco '07; Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09]

- Production via γ' Bremsstrahlung:



$$\sigma_{eN\to eN\gamma'} \sim \frac{\alpha^3 Z^2 \chi^2}{m_{\gamma'}^2} \sim 1\ \mathrm{pb} \left(\frac{\chi}{10^{-5}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\gamma'}}\right)^2$$

Kinematics and geometry:



[Toro '09; Andreas '10]

- Decay length of $\gamma' \to e^+e^-$,

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

varies a lot in parameter range or interest

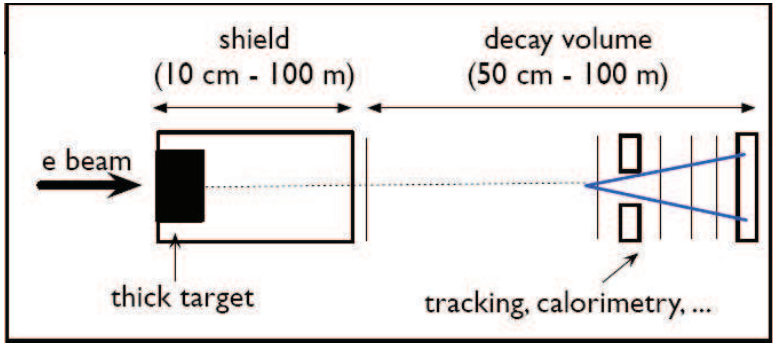
$\Rightarrow$ Multiple experimental approaches, with different strategies for fighting backgrounds:

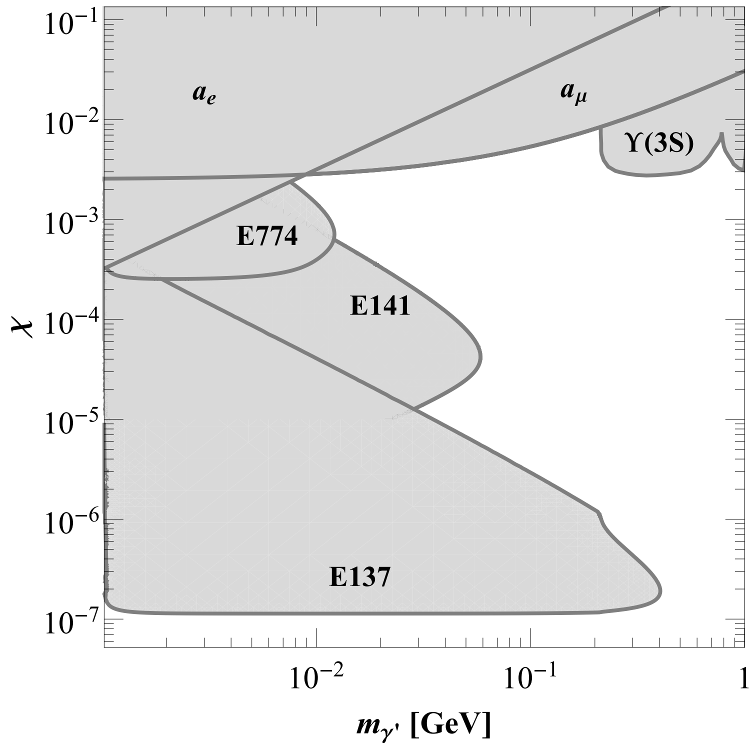
- $\ell_d \gg$ cm: **beam dump**; low background
- $\ell_d \sim$ cm: **vertex**; limited by instrumental bkg
- $\ell_d \ll$ cm: **bump hunt**; fight bkg with high intensity, resolution

- **Past beam dumps:**

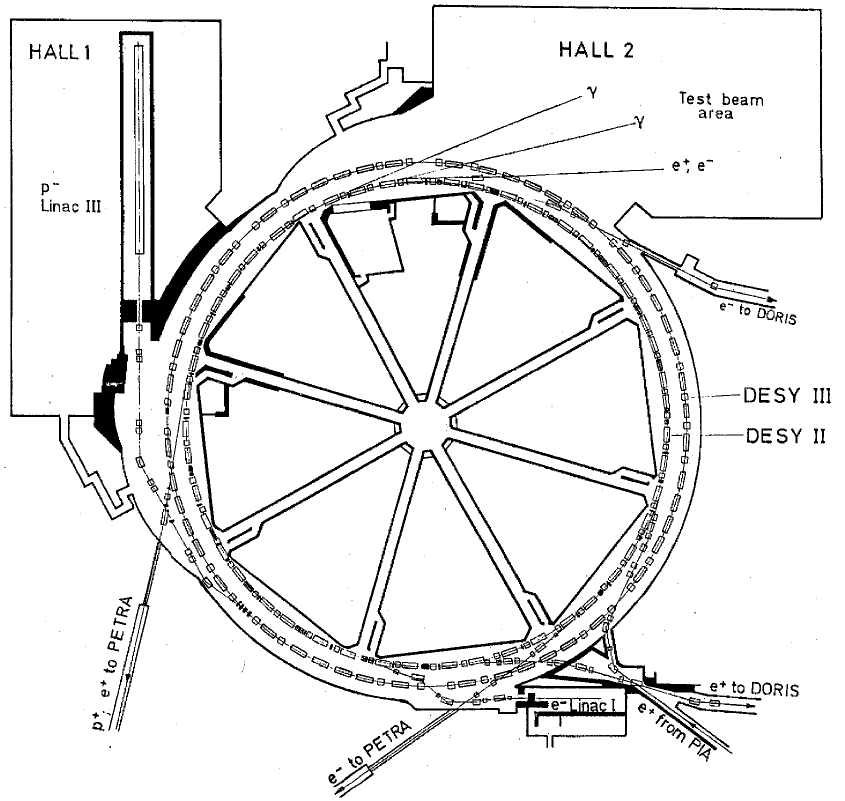
  [Bjorken,Essig,Schuster,Toro '09]

  - 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 (p), 30 cm, 7 m





- **HIPS** (HIdden Particle Search): a new **beam dump** experiment at DESY II (10 nA, .45–7 GeV) [Andreas,Bechtle,Ehrlichmann,Garutti,Lindner,Niebuhr,AR,Soloviev]



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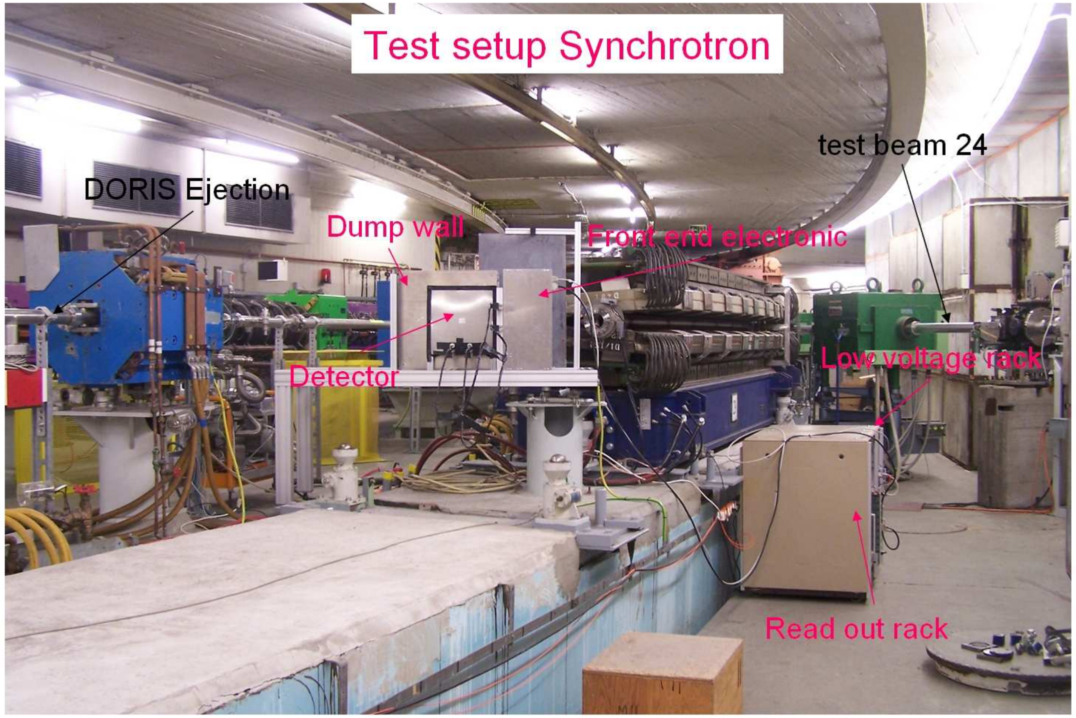

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  Current situation:

  – several scintillator counters installed for background studies
  – simulations for background, signal and sensitivity ongoing
  – plans for 2011:
    * install beam line in January
    * install ZEUS MVX detector and CALICE ECAL
    * take data

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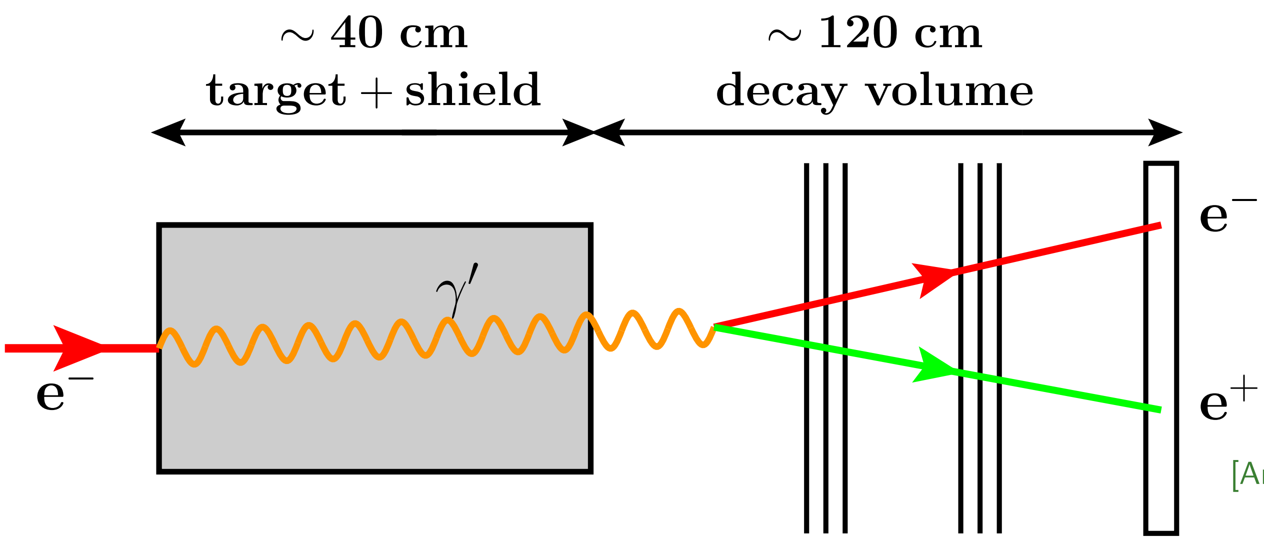
Planned setup:



[Andreas,AR '10]

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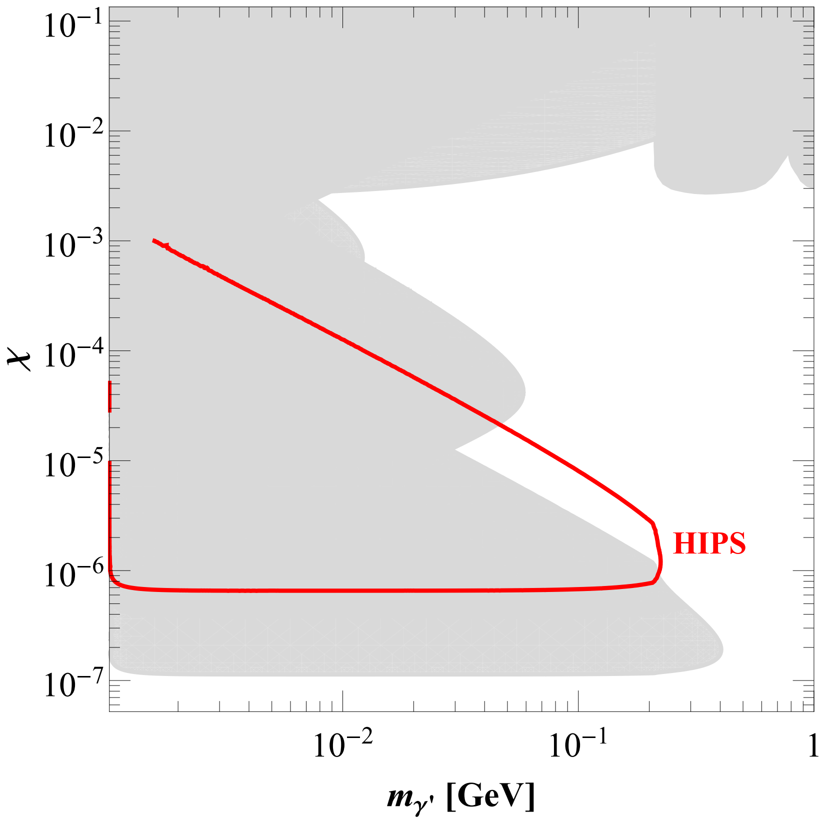
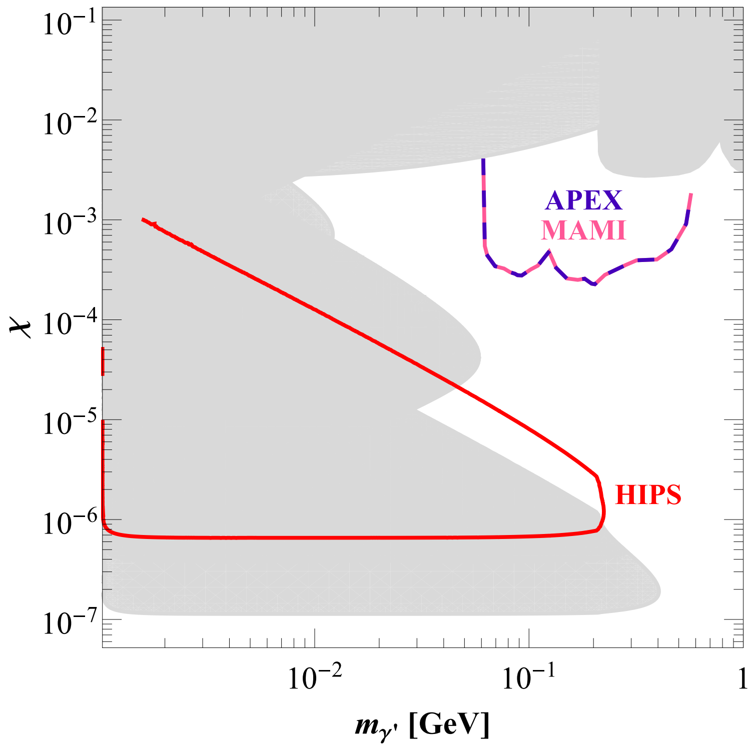
  Projected sensitivitv:



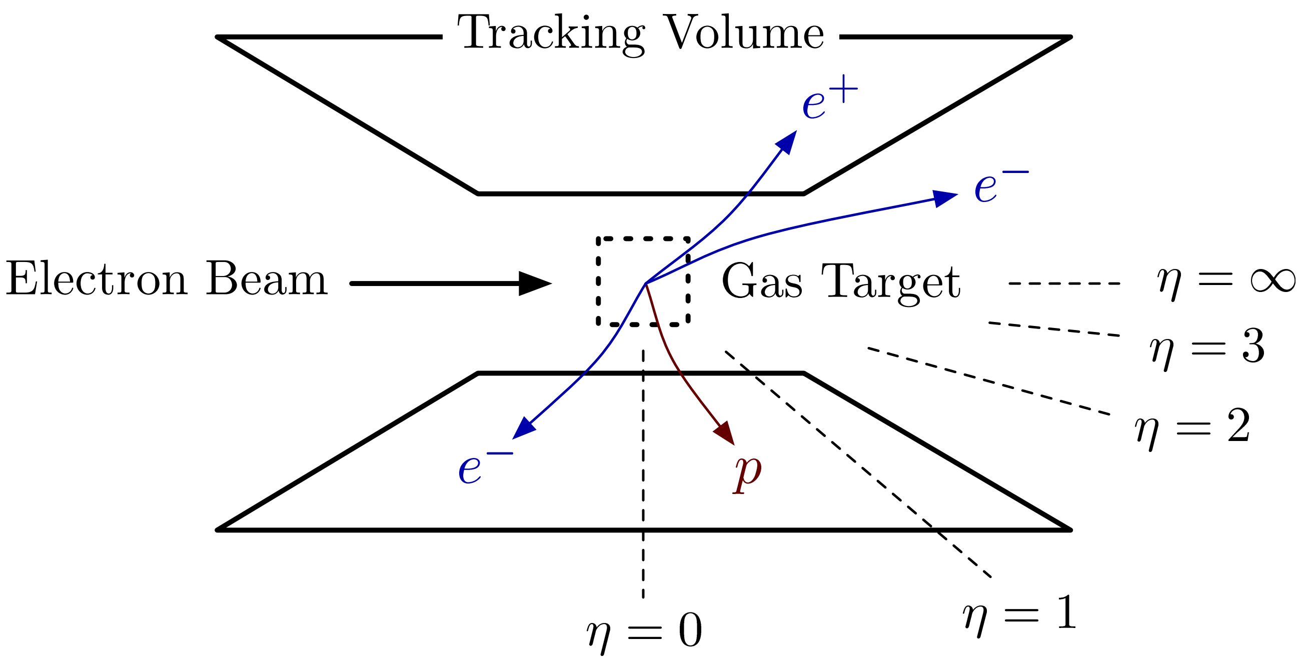
[Andreas,AR '10]

- **APEX** at JLab and dark photon search by the A1 collaboration (MAMI): **bump hunts** exploiting currents in $100\ \mu$A, (multi-)GeV range and high resolution spectrometers to search for a peak in the e^+e^- invariant mass distribution (pilot runs already took place); **projected sensitivities:**



[Andreas,AR '10]

- **Proposals:** JLab: HPS at CEBAF; DarkLight at FEL (10 mA; $E_{\rm max} = 140$ MeV); Mainz internal gas experiment at proposed MESA facility



[Freytsis, Ovanesyan, Thaler '09]

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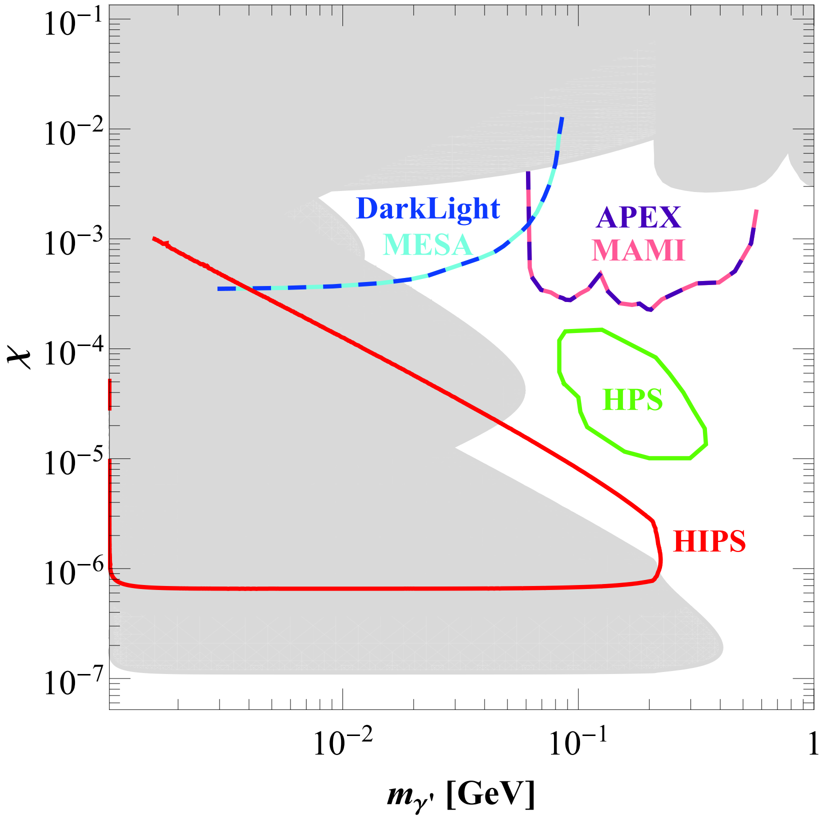

[Andreas,AR '10]

- An opportunity also for the ELBE (200 μA, 40 MeV) facility at HZDR?

Message

- Axion-Like Particles (ALPs) and other very Weakly Interacting Slim Particles (WISPs) beyond the Standard Model are strongly motivated from theory, cosmology, and astrophysics
  - theory: axions, axion-like particles, hidden U(1) gauge bosons, ...,
  - cosmology: axion CDM, hidden photon hDM, hidden photon wDM, ...
  - astrophysics: TeV γ transparency, WD energy loss, ...
- There are experiments around the globe, notably at accelerator labs (CERN, DESY, FNAL, JLab, ...), which search for ALPs and other WISPs, exploiting/recycling existing equipment:
  - Light-shining-through-walls experiments exploiting lasers and magnets
  - Beam dump and fixed target experiments exploiting electron beams

New intensity frontier, complementary to energy frontier!