Weakly Interacting Slim Particles and New Experiments at the Intensity Frontier

Andreas Ringwald

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Message

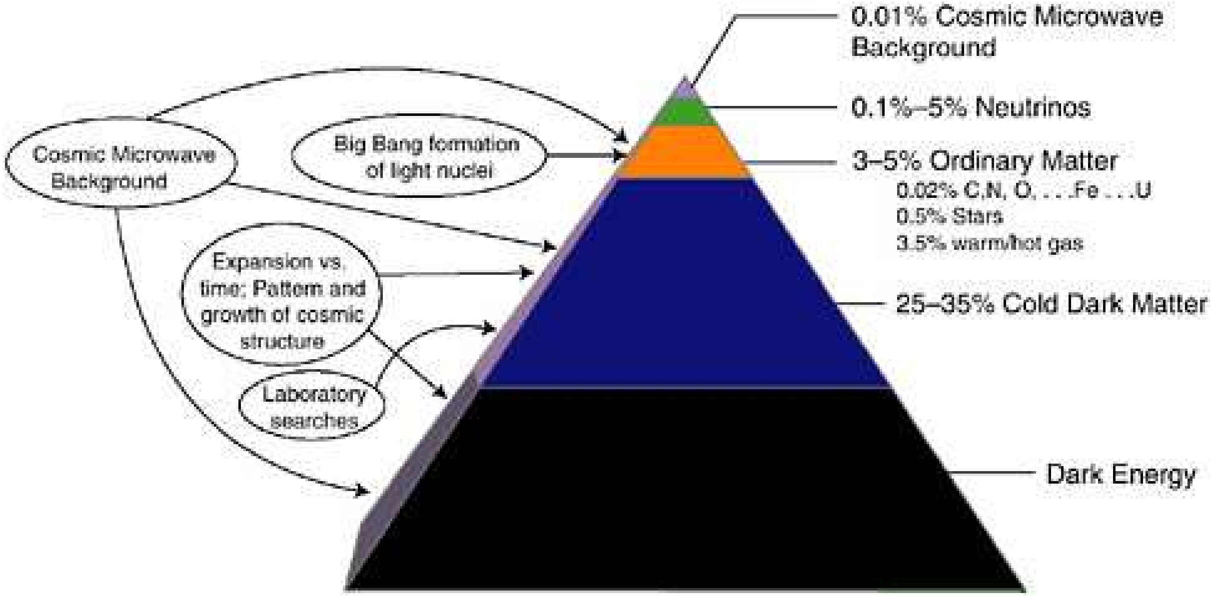
- Axions, Axion-Like Particles (ALPs) and other very Weakly Interacting Slim Particles (WISPs) beyond the Standard Model are strongly motivated from theory, cosmology, and astrophysics

- 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)

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

  $\Rightarrow$ 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 $f_\phi \gg v_{\rm EW}$

- Peccei-Quinn or QCD axion a: [Peccei,Quinn '77]

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

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

  – topological charge density $\propto \langle {\rm tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}\rangle \neq 0$ 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 $f_a \gg v_{\rm EW}$: axion is ultra-light and invisible

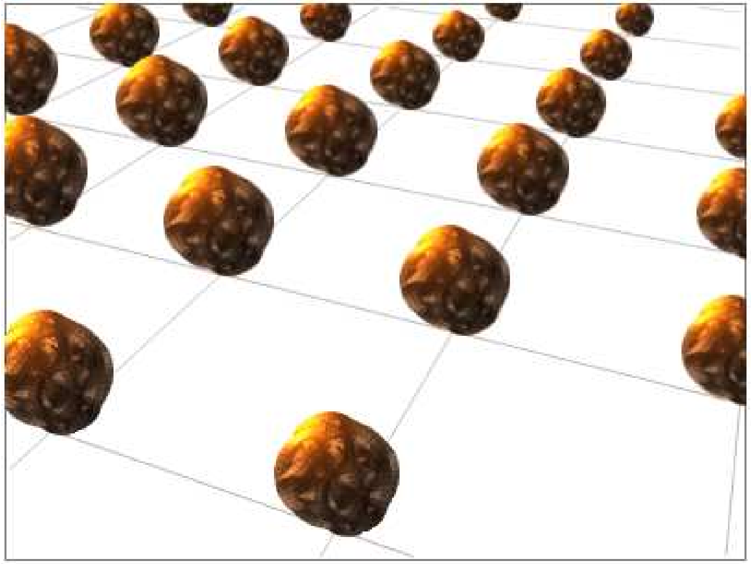
[J.E. Kim '79; Shifman *et al.* '80; Dine *et al.* '81;...]

- Axions and axion-like particles (ALPs) have also anomalous couplings to photons, [Bardeen,Tye '78; Kaplan '85; Srednicki '85]

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

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

- **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,

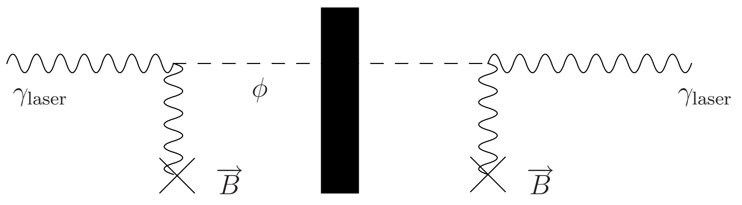
$$f_\phi \sim f_a, \qquad m_\phi \ll m_a$$

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

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

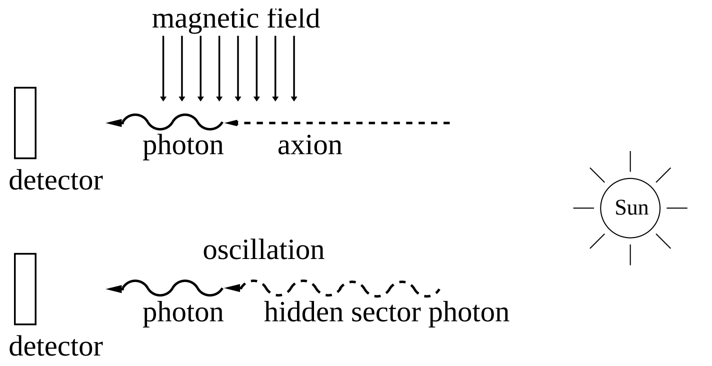
  - **light-shining-through-walls searches** (e.g. ALPS, GammeV, ...)

    [Okun '83;Anselm ; van Bibber]

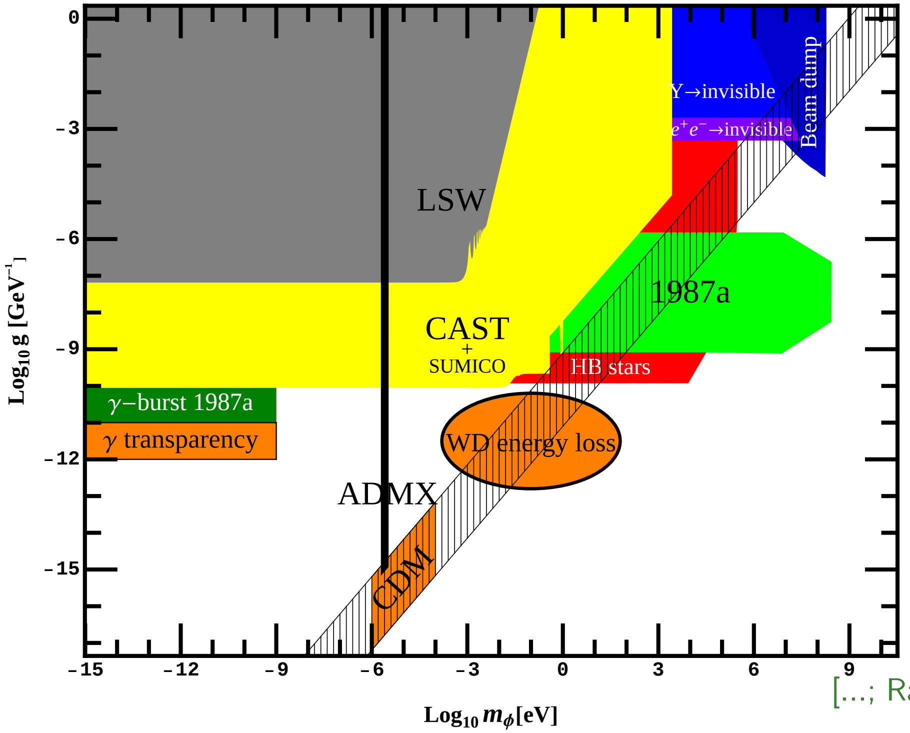


  - **helioscope searches** (e.g. CAST, SUMICO, SHIPS, ...)

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



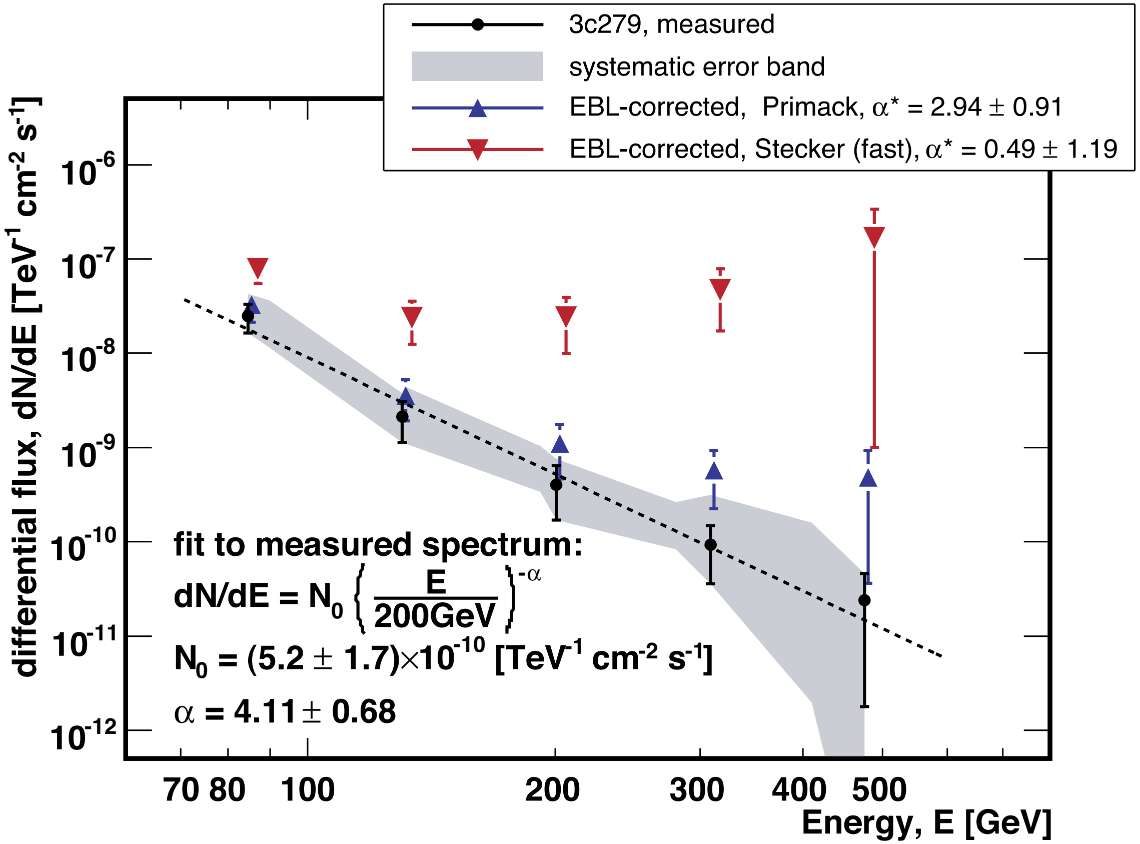
- LSW (helioscopes) probe currently $g \sim 10^{-7}$ GeV^{-1} ($g \sim 10^{-10}$ GeV^{-1}):



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

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

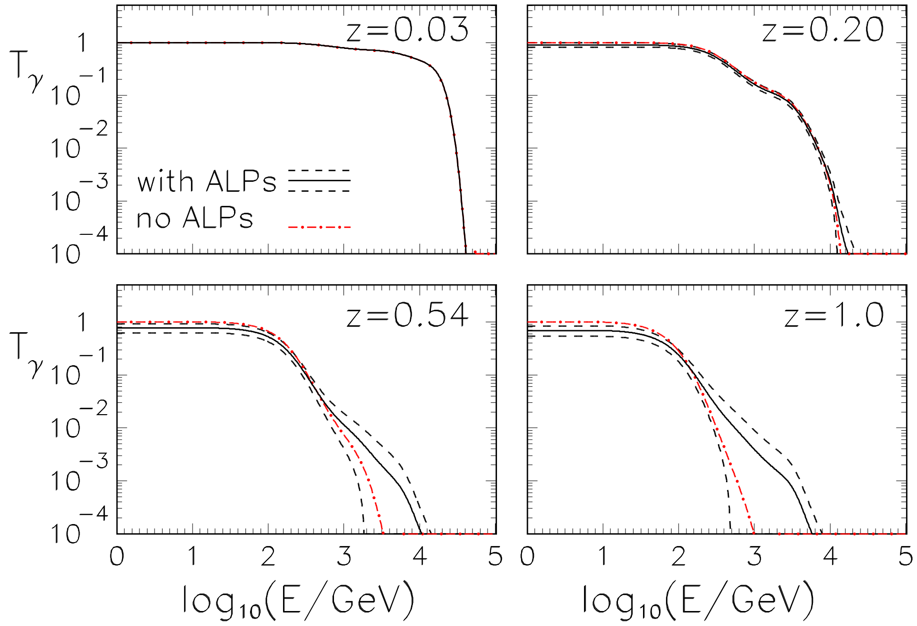
- **TeV γ transparency puzzle:** no cutoff seen in TeV γ spectra of distant sources, despite absorption due to e^+e^- pair production on extragalactic background light



[MAGIC '08]

- **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
  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]

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

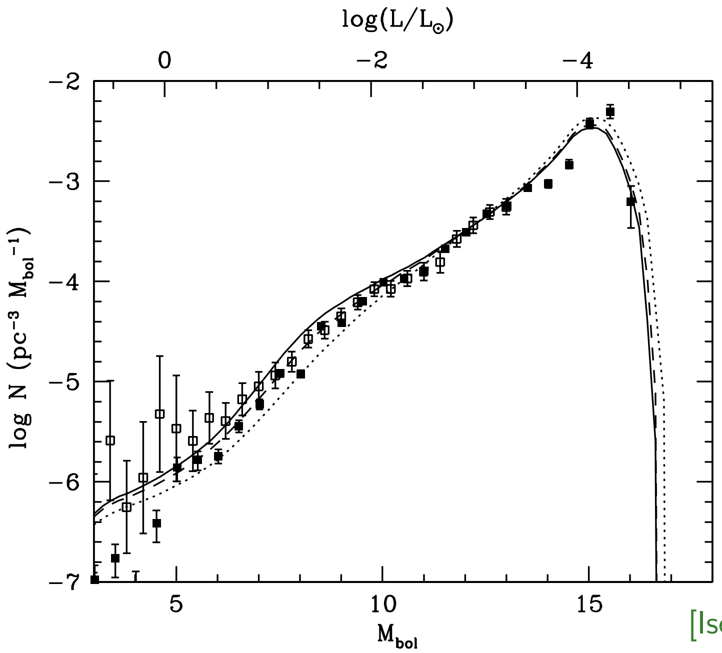


[Mirizzi,Montanino '09]

Seem to arise naturally in string compactifications with $M_s \sim 10^9$ GeV [Cicoli,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, $g_{e\phi} \simeq 1.5^{+0.2}_{-0.9} \times 10^{-13}$, suggesting a decay constant [Isern *et al.* '08; '10]

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



[Isern,Garcia-Berro,Torres,Catalan '08]

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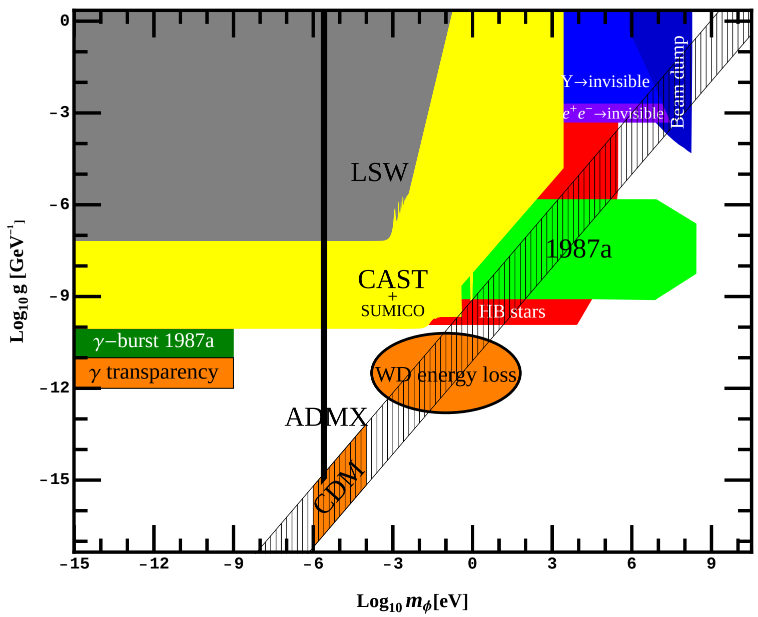


[Jaeckel,AR '10]

- **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)

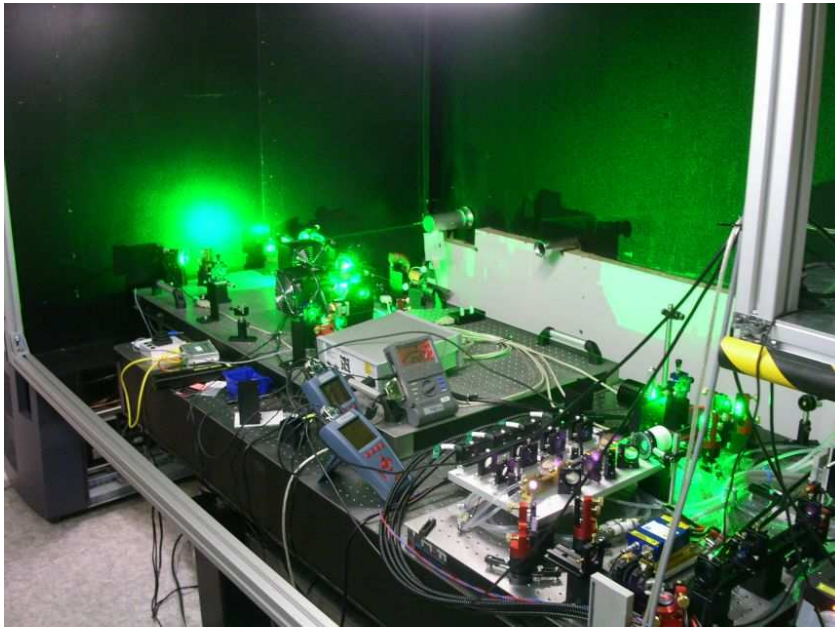
ALPS (Any-Light Particle Search)

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

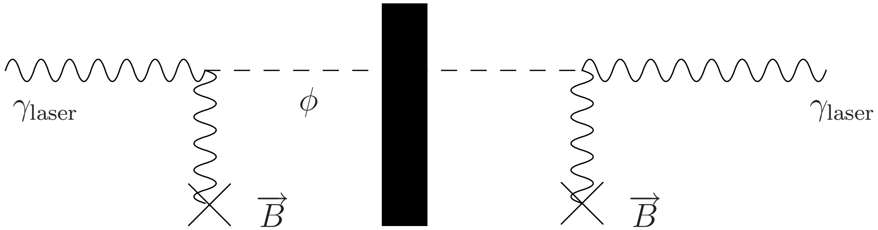
- primary beam: enhanced LIGO laser (1064 nm, 35 W cw)

⇒ frequency doubled to 532 nm

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



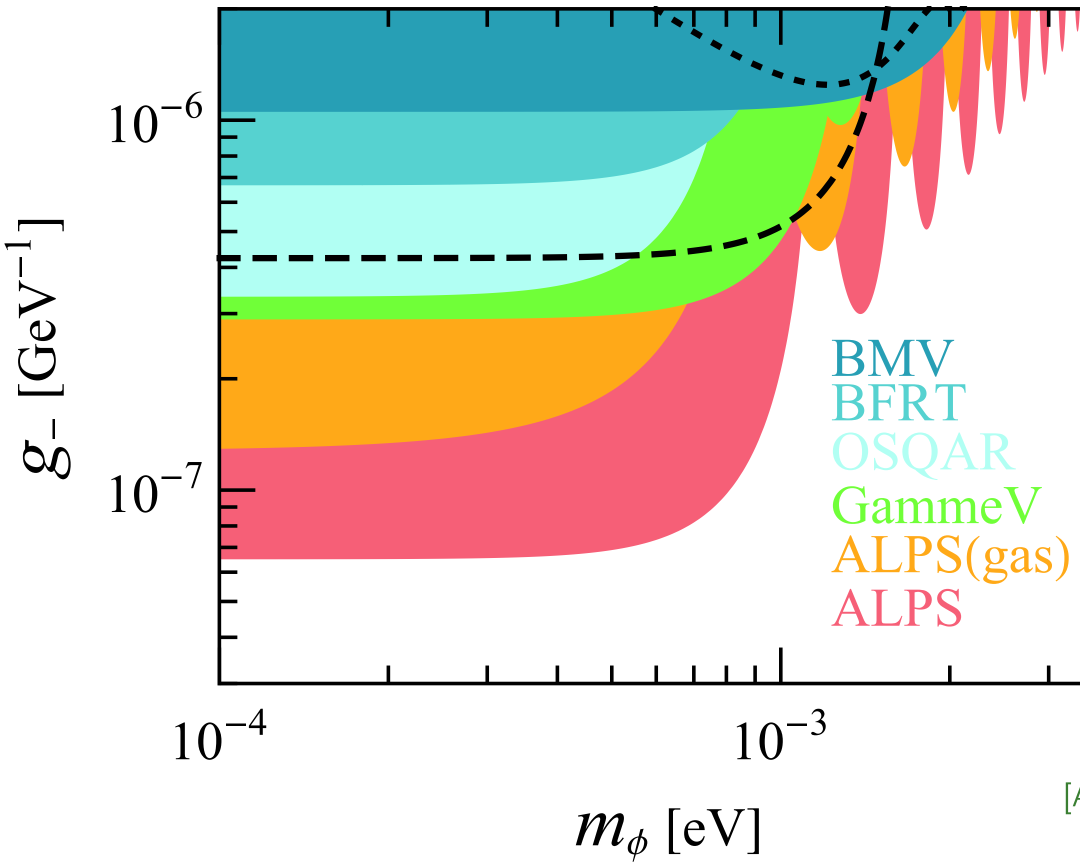
- **ALPS** (Axion-Like Particle Search): [AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]



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

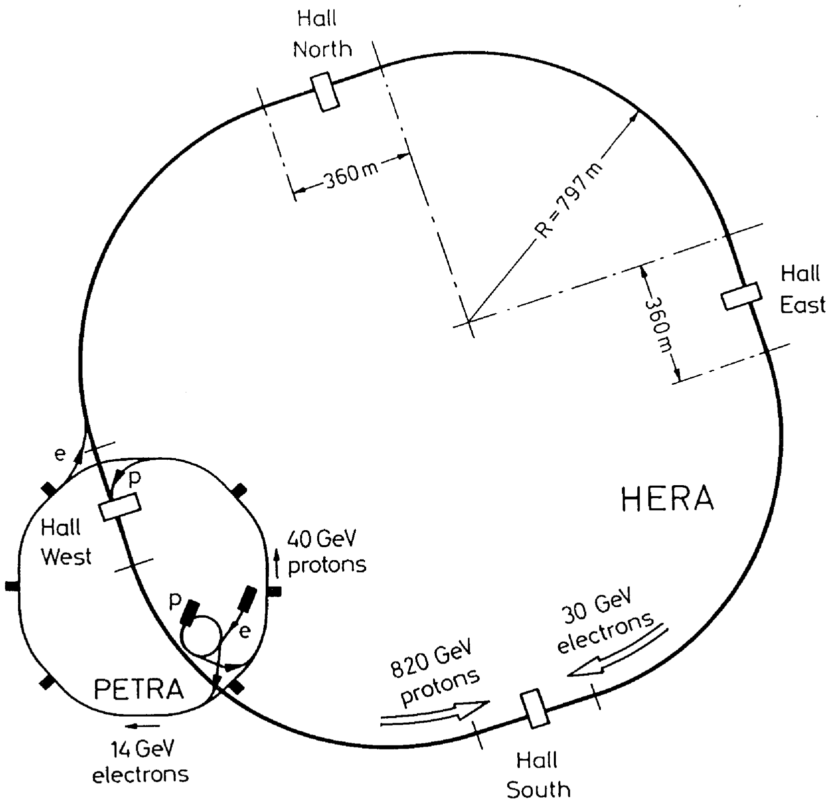
- Last **ALPS** run end of 2009 [Phys. Lett. B 689 (2010) 149-155]

$\Rightarrow$ *"Not a WISP of evidence"* [Nature 465 (2010) 271]

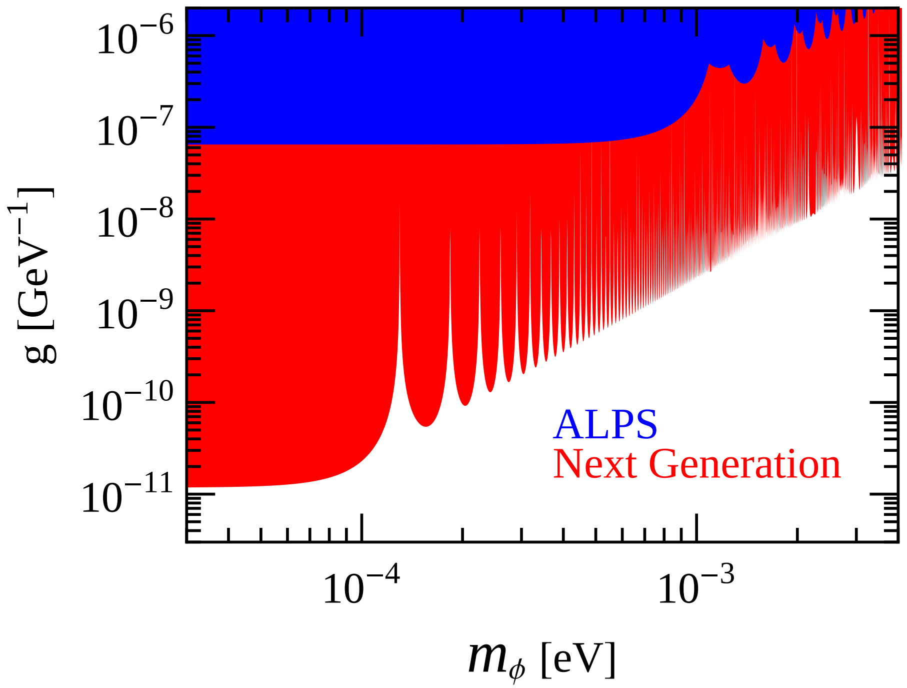


[ALPS Collaboration '10]

- **Upgrade plans** at DESY (similar at Fermilab):
  - exploit more (e.g. 20+20) HERA (Tevatron) magnets (> 2014)



- **Upgrade plans** at DESY (similar at Fermilab):
  - exploit more (e.g. 20+20) HERA (Tevatron) magnets (> 2014)
  - exploit resonant regeneration cavity [Hoogeveen,Ziegenhagen '91;Sikivie,Tanner,van Bibber '07]



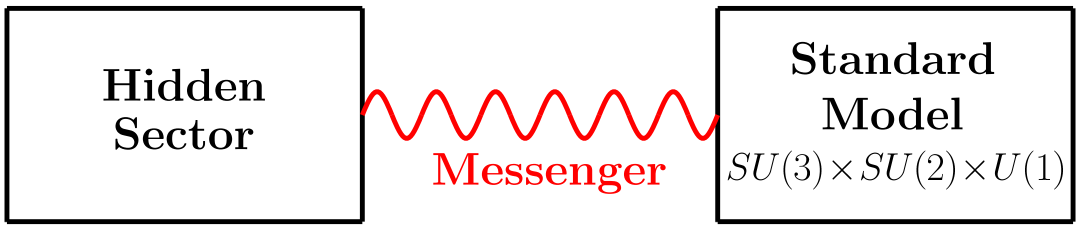
[Redondo,AR '10]

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

Hidden Sector Abelian Gauge Bosons

- In all major attempts to obtain the (Minimal Supersymmetric) Standard Model as a low energy limit of string theory, e.g. from
  - the heterotic string,
  - type II strings with D-branes,
  - F-theory,

  there arises also a hidden sector of gauge bosons (and possibly matter particles) which interact with the visible sector only very weakly because there are no light messenger states charged under both gauge sectors



Hidden-Sector Abelian Gauge Bosons

- Direct effects associated with hidden sector unobservably small at low energies, since interactions between SM and hidden sector particles occur via operators of mass dimension $n > 4$ arising from integrating out messenger fields $\Rightarrow$ suppressed at low energies by powers $\sim (E/M_s)^{n-4}$
- **Notable exception: hidden-sector Abelian gauge bosons**, arising in
  - heterotic string theory from breaking the hidden E_8 gauge factor,
  - type II$/F$ theory as
    - Kaluza-Klein zero modes of closed string form fields
    - excitations of space-time filling D-branes wrapping cycles in the extra dimensions,

  because they can
  - be massless or light (Higgs or Stückelberg mechanism)
  - mix kinetically with the visible sector hypercharge U(1) gauge boson, corresponding to a mass dimension four term in the low energy effective

Lagrangian ⇒ unsuppressed at low energies

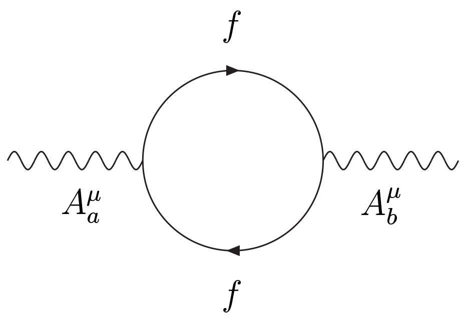
[Holdom'85]

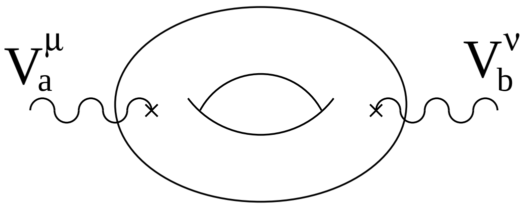
$$\mathcal{L} \supset -\frac{1}{4}F^{(\mathrm{vis})}_{\mu\nu}F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4}F^{(\mathrm{hid})}_{\mu\nu}F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2}F^{(\mathrm{vis})}_{\mu\nu}F^{(\mathrm{hid})\mu\nu} + m^2_{\gamma'}A^{(\mathrm{hid})}_{\mu}A^{(\mathrm{hid})\mu}$$

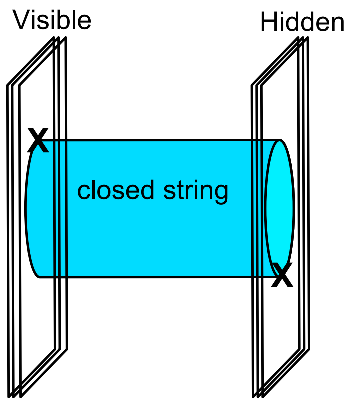
* $\chi \ll 1$ generated at loop level via messenger exchange,

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

* g_h and f depend on the type of messenger:





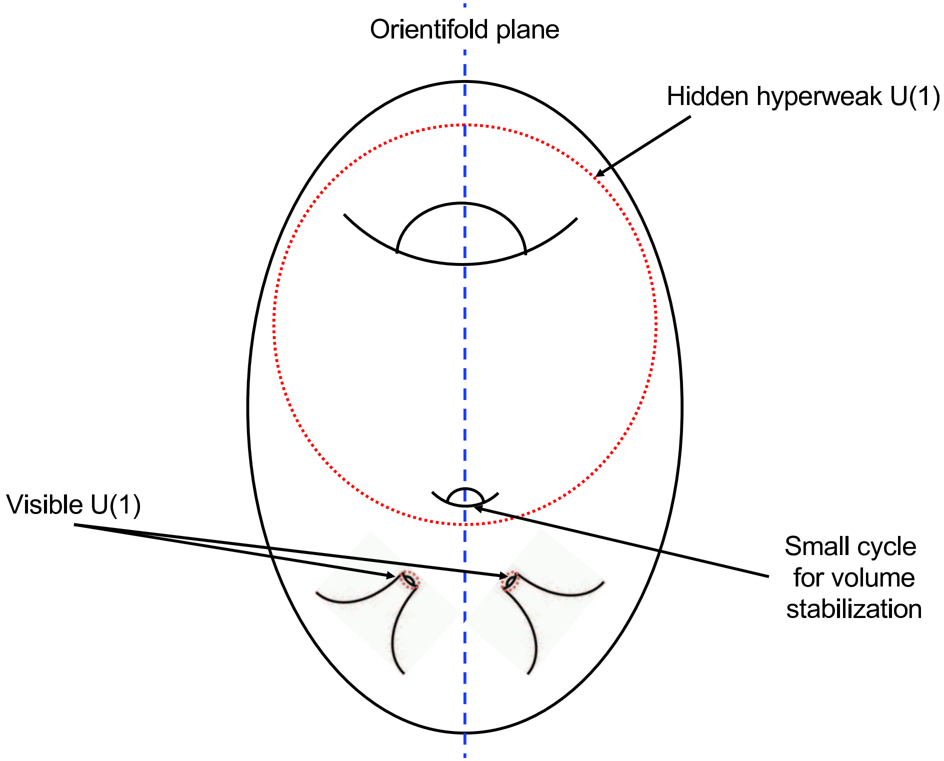


Hidden U(1)s from D7-Branes in IIB Flux Compactifications

LARGE volume compactifications:

[Balasubramanian,Berglund,Conlon,Quevedo '05;...]

- Arise naturally in IIB Calabi-Yau flux compactifications where
  - dilaton and complex structure moduli fixed by background fluxes
  - Kähler moduli fixed by non-perturbative corrections
- visible sector: stack of space-time filling D7-branes wrapping small collapsed 4-cycles
- hidden sector: space-time filling D7-branes wrapping 4-cycles not intersecting visible sector branes



[Goodsell,Jaeckel,Redondo,AR '09]

Hidden U(1)s from D7-Branes in IIB Flux Compactifications

- **Kinetic mixing:** [...; Goodsell,Jaeckel,Redondo,AR '09]
  - kinetic mixing appears as holomorphic quantity in low energy effective field theory:

$$\mathcal{L} \supset \int d^2\theta \left\{ \frac{1}{4(g_a^h)^2} W_a W_a + \frac{1}{4(g_b^h)^2} W_b W_b - \frac{1}{2}\chi_{ab}^h W_a W_b, \right\}$$

    where g_a^h, g_b^h and χ_{ab}^h must run only at one loop
  - in analogy to structure of holomorphic gauge kinetic function,

    cf. e.g. [Akerblom,Blumenhagen,Lüst,Schmidt-Sommerfeldt '07]

$$\chi_{ab}^h(z^k, y_i, T_j) = \chi_{ab}^{1-\mathrm{loop}}(z^k, y_i) + \chi_{ab}^{\mathrm{non-perturbative}}(z^k, y_i, e^{-T_j}),$$

    with complex structure moduli z^k and open string moduli y_i. Kähler moduli T_j, cannot enter at 1-loop, since
    - T_j have shift symmetries $\Rightarrow$ may only appear as exponentials
    - T_j depend on g_s^{-1}

– Therefore, generically,

$$\chi_{ab}^{h} \simeq \chi_{ab}^{1-\mathrm{loop}}(z^k, y_i) \simeq \frac{1}{16\pi^2} \times \mathcal{O}(1),$$

verified in explicit toroidal compactifications

[...; Abel,Goodsell,Jaeckel,Khoze,AR '08; Bullimore,Conlon,Witkowski '10]

– physical and holomorphic kinetic mixing related by

[Benakli,Goodsell '09; Goodsell,Jaeckel,Redondo,AR '09]

$$\frac{\chi_{ab}}{g_a g_b} = \mathrm{Re}(\chi_{ab}^{h}) + \frac{1}{8\pi^2}\mathrm{tr}\Big(Q_a Q_b \log Z\Big) + \frac{1}{16\pi^2}\sum_r n_r Q_a Q_b(r)\frac{K}{M_P^2}$$

⇒ Physical kinetic mixing between hypercharge U(1) and hidden U(1) localized on D7-brane wrapping 4-cycle of volume $\tau_{\rm hid}$ can be much smaller than naive expectation,

$$\chi \simeq \frac{g_Y g_h}{16\pi^2} \times \mathcal{O}(1) \sim \frac{2\times 10^{-3}}{\sqrt{\tau_{\rm hid}}}$$

Hidden U(1)s from D7-Branes in IIB Flux Compactifications

- **Stückelberg masses:** [Buican,Malyshev,Morrison,Verinde,Wijnholt '07; ...]

  – U(1) living on hidden D7$_i$ can become massive by turning on 2-form gauge flux $c_1(\mathcal{L}_i) = f_i^k \hat{D}_k$, in terms of basis $\hat{D}_k$ of (1,1)-forms, on a 2-cycle internal to the 4-cycle wrapped by D7$_i$:

  * non-zero gauge flux induces U(1) charges

$$q_{ij} = \int_{D_i} \hat{D}_j \wedge c_1(\mathcal{L}_i) = f_i^k k_{ijk}$$

for the Kähler moduli $T_i = (\int_{D_i} \sqrt{g}\, d^4y + i \int_{D_i} C_4)\, e^{-\phi} \equiv \tau_i + i b_i$

  * axion b_i gets eaten up by the U(1) gauge boson, resulting in mass matrix

$$m_{ab}^2 = g_a g_b \frac{M_P^2}{4\pi^2} q_{a\alpha} (\mathcal{K}_0)_{\alpha\beta} q_{b\beta},$$

where $g_a = \sqrt{2\pi/\tau_a}$, $(\mathcal{K}_0)_{ij} \equiv \frac{\partial^2}{\partial\tau_i \partial\tau_j} K_0$, $K_0 \equiv -2 \log \mathcal{V}$

- **In isotropic compactifications:** [Goodsell,Jaeckel,Redondo,AR '09]

  Get smallest mass for U(1) living on large 4-cycle, with $\tau_b \sim \mathcal{V}^{2/3}$:

$$m_{\gamma'} \sim f_b \frac{M_P}{\tau_b^{3/2}} \sim f_b \frac{M_P}{\mathcal{V}} \sim f_b \frac{M_s^2}{M_P}; \qquad \chi \sim \frac{2 \times 10^{-3}}{\tau_b^{1/2}} \sim 2 \times 10^{-3} \left(\frac{M_s}{M_P}\right)^{2/3}$$

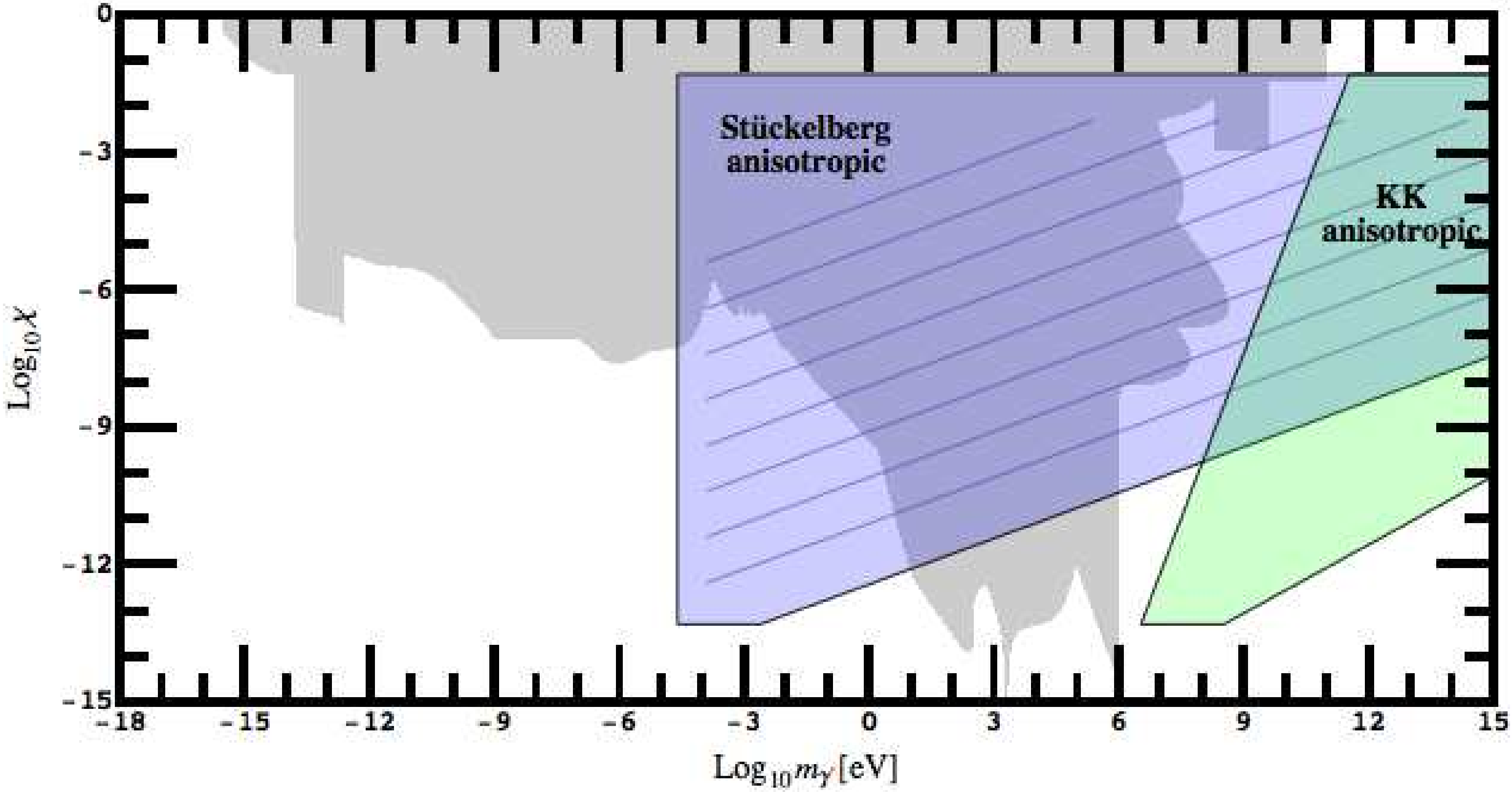
  $\Rightarrow$ strong correlation between size of mass and size of mixing

- **In anisotropic compactifications:** [Cicoli,Goodsell,Jaeckel,AR to appear]

  Can have small mass, while still sizeable mixing, e.g., for $\mathcal{V} \sim \tau_1^{1/2} \tau_2$, with $\tau_2 \gg \tau_1$, D7 wrapping D_1, gauge flux on t_2,

$$m_{\gamma'} \sim f_2 \frac{M_P}{\tau_1^{1/2} \tau_2} \sim f_2 \frac{M_P}{\mathcal{V}} \sim f_2 \frac{M_s^2}{M_P}; \qquad \chi \sim \frac{2 \times 10^{-3}}{\tau_1^{1/2}}$$

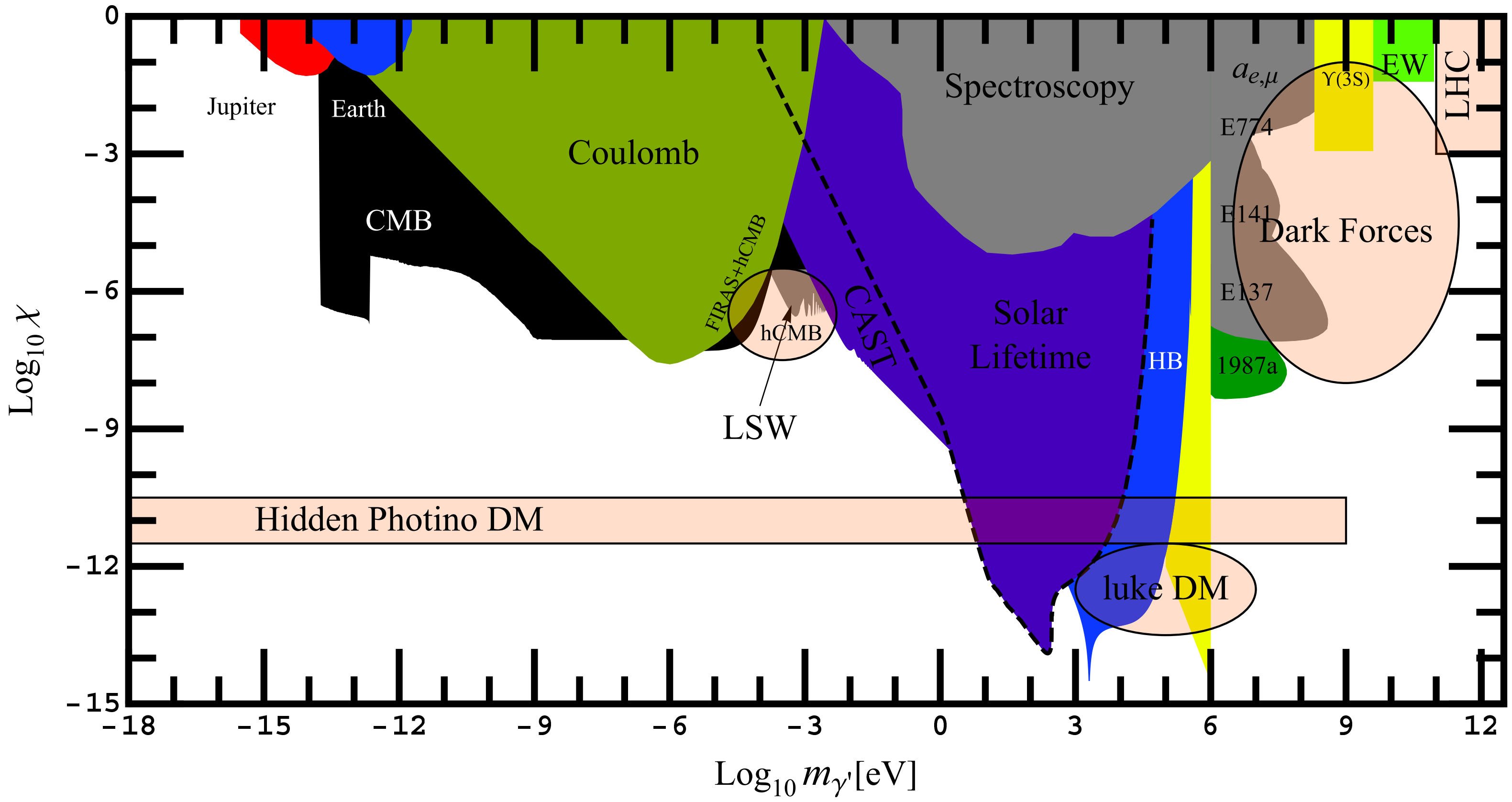
• Hidden U(1)s from D7-branes in anisotropic type IIB string compactifications: [Cicoli,Goodsell,Jaeckel,AR in prep.]



- Current constraints and phenomenologically interesting parameter ranges

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

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



Signatures of a Hidden CMB?!

[Jaeckel,Redondo,AR '08]

- Kinetic mixing of hidden photons with $m_{\gamma'} \neq 0 \Rightarrow \gamma \leftrightarrow \gamma'$ oscillations
- Cosmic plasma induces an anomalous dispersion relation for photons, i.e. they acquire a plasma mass, $\omega_{\rm P}^2 = 4\pi\alpha n_e/m_e$
- **For meV masses**, $\gamma \leftrightarrow \gamma'$ oscillations occur resonantly $(m_{\gamma'} = \omega_{\rm P})$ after BBN but before CMB decoupling, producing a **hidden CMB**, with

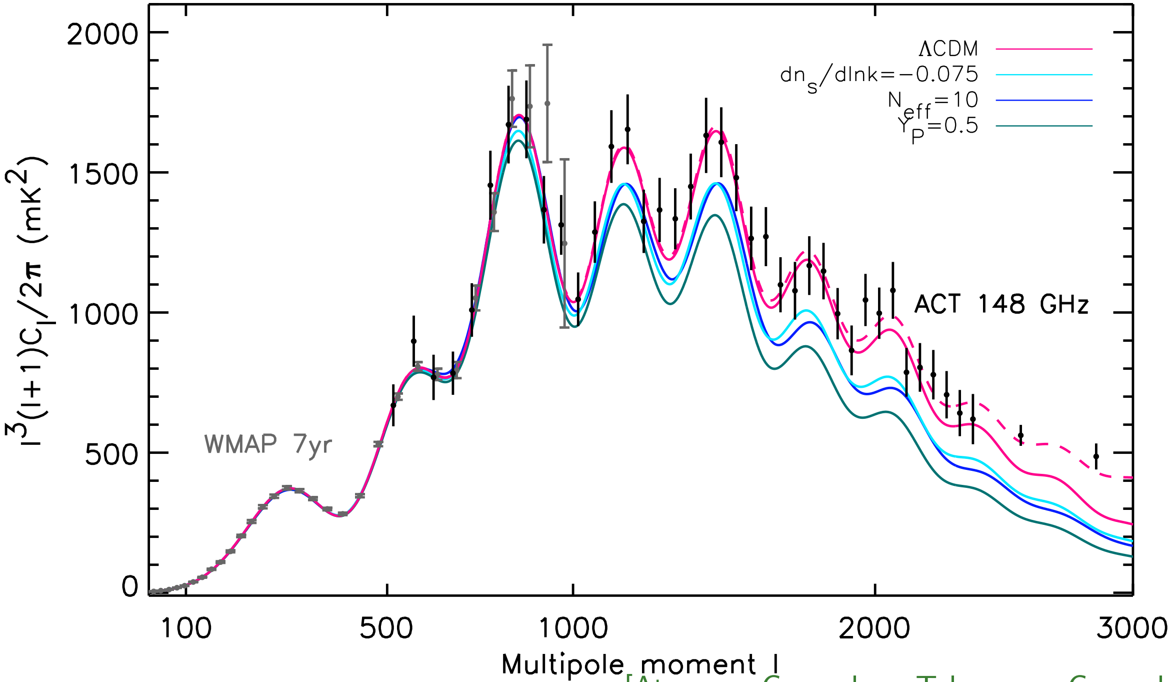
$$\boldsymbol{x \equiv \rho_{\gamma'}/\rho_\gamma \simeq 3.9 \times 10^{-2}\,(\chi/10^{-6})^2,}$$

leading to an increase of the cosmic energy density in invisible radiation at decoupling, often quoted as the effective number of neutrino species,

$$N_{\rm eff}^{\nu} \equiv \frac{\rho_{\rm total}^{\rm rad} - \rho_\gamma}{\rho_\nu} = \frac{N_\nu^{\rm SM}}{1-x} + \frac{x}{1-x}\,\frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\,;\, N_\nu^{\rm SM} = 3.046$$

- Additional relativistic degrees of freedom at decoupling would
  - enhance first two peaks/suppress third and higher acoustic peaks
  - shift peak positions to higher l (smaller angular scales)

  in CMB angular power spectrum



[Atacama Cosmology Telescope: Cosmological Parameters]

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  in CMB angular power spectrum

- $N_{\rm eff}^{\nu}$ can be further constrained by adding constraints from baryon acoustic oscillations (BAO) and the Hubble constant H_0

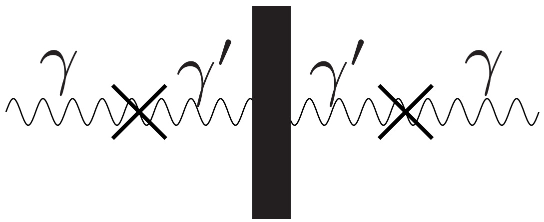
- **Observations seem to favor $N_{\rm eff}^{\nu} > N_{\nu}^{\rm SM} = 3.046$:**
  this may be explained by **meV mass hidden photon with $\chi \sim 10^{-6}$**

Data	$N_{\rm eff}^{\nu}$	x	χ
WMAP+BAO+H_0	$4.34^{+0.86}_{-0.88}$	$0.148^{+0.084}_{-0.086}$	$2.29^{+0.73}_{-1.03} \times 10^{-6}$
ACT+WMAP+BAO+H_0	$4.56^{+0.75}_{-0.75}$	$0.169^{+0.067}_{-0.067}$	$2.51^{+0.65}_{-0.77} \times 10^{-6}$

PLANCK: expect better sensitivity, $\Delta N_{\rm eff}^{\nu} \simeq 0.07 \Rightarrow$ stay tuned!

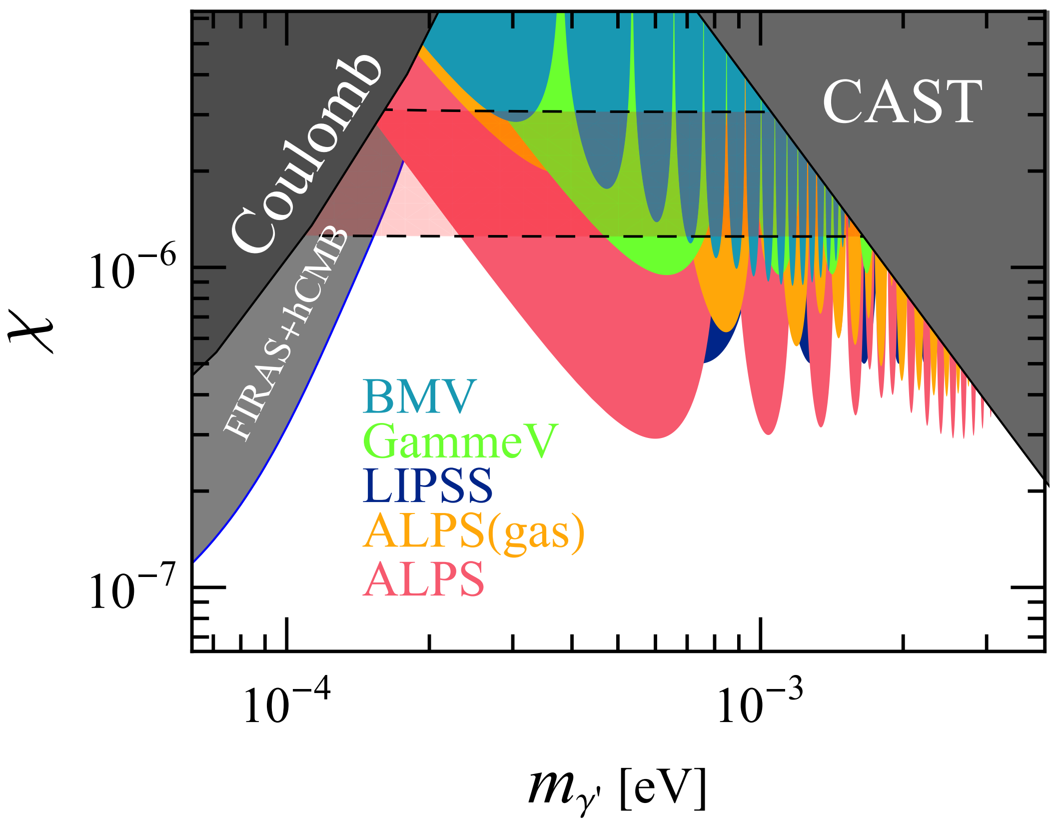
- **meV mass hidden photons** can be searched for in **light-shining-through a wall (LSW) experiment ALPS** (Any Light Particle Search)

[AEI Hannover, DESY, Hamburg Observatory, Laser Zentrum Hannover, Uni HH]



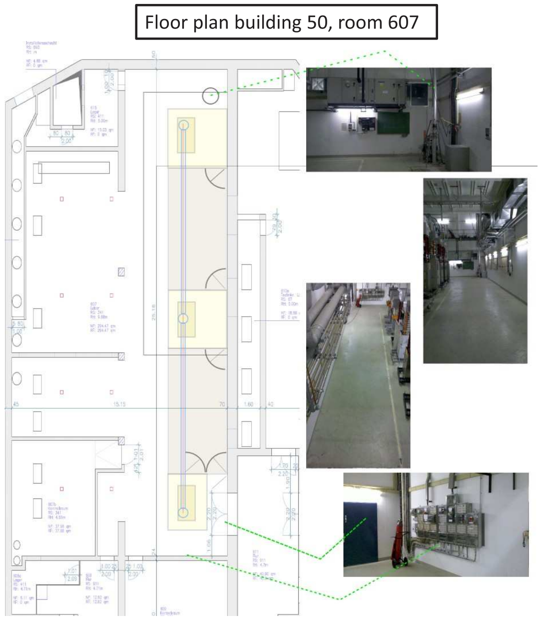
$$P(\gamma \leftrightarrow \gamma') = 4\chi^2 \sin^2\left(\frac{L}{L_{\rm osc}}\right) ; \qquad L_{\rm osc} = \frac{4\omega}{m_{\gamma'}^2} = 0.79\,{\rm m}\left(\frac{\omega}{\rm eV}\right)\left(\frac{\rm meV}{m_{\gamma'}}\right)^2$$

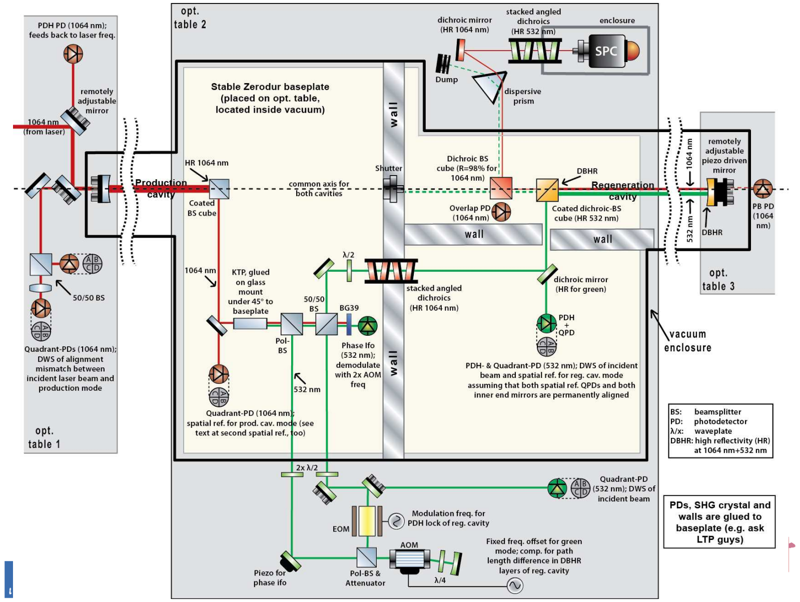
- **Current** **ALPS** limits on LSW exclude large portion of parameter space compatible with hidden photon explanation of $N_\nu^{\rm eff}$ excess, but there is still room for it:



[ALPS Collaboration '10]

- **ALPS upgrade:** dedicated γ' search in 2012 in HERA Hall West

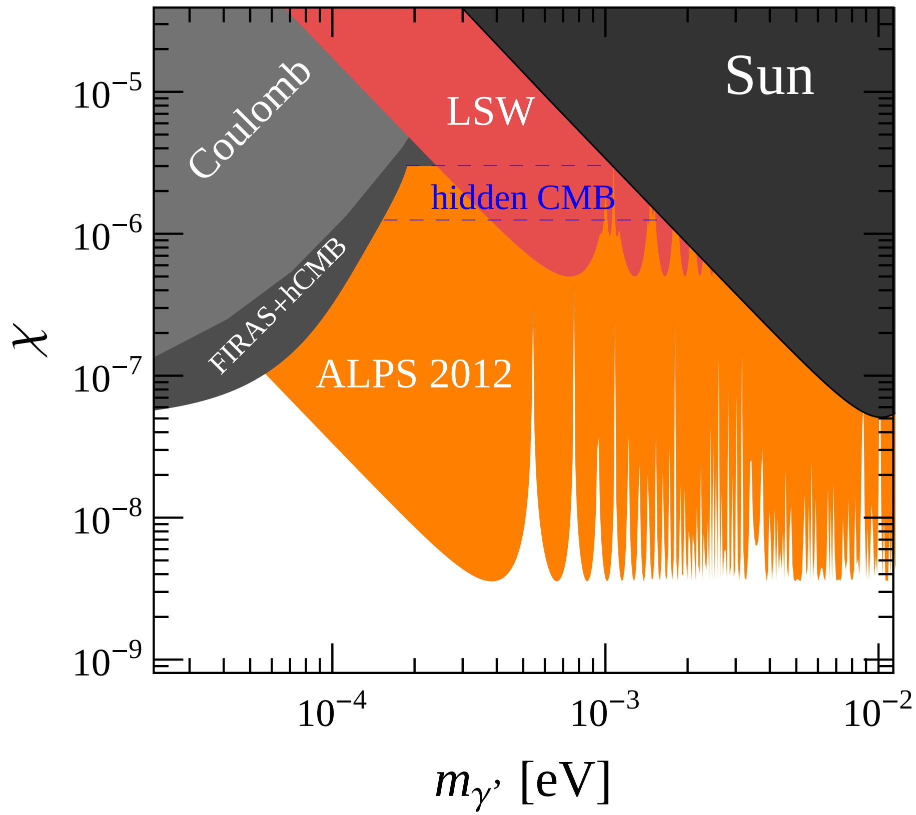




  - higher laser power buildup ($\mathrm{PB_g} \sim 5000$)
  - exploiting also resonant cavity behind the wall ($\mathrm{PB_r} \sim 4 \times 10^4$)
  - better detector
  - prototype for future (> 2014) large scale axion-like particles search experiment exploiting $\geq 6 + 6$ superconducting HERA dipoles

- **ALPS upgrade:** dedicated γ' search in 2012 in HERA Hall West

Projected sensitivity:



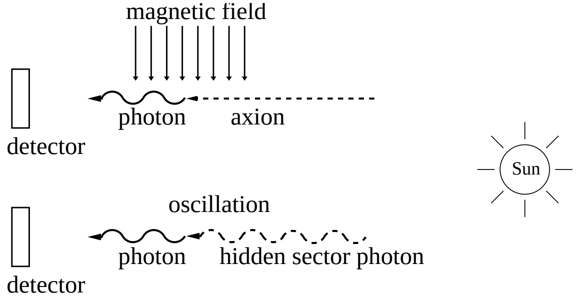
[Arias '11]

- **SHIPS** (Solar Hidden Photon Search) **may probe hidden CMB parameter space already in 2011:** [Hamburg Observatory, Uni HH, DESY]
  - $\gamma \to \gamma'$ oscillations in the solar interior would lead to sizeable flux of solar hidden photons at Earth, [Redondo '08]

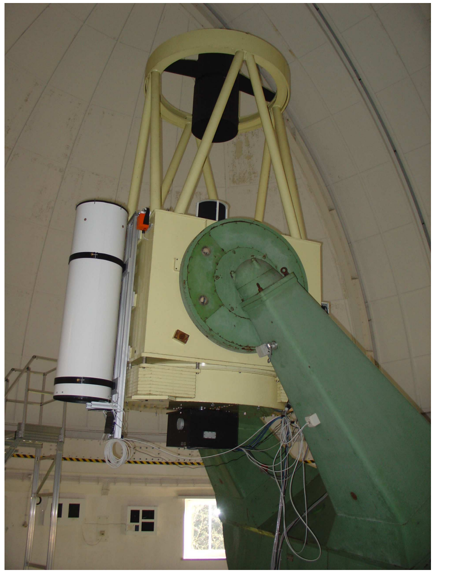
$$\frac{d\Phi_{\gamma'}}{d\omega} \gtrsim \frac{4.2\times 10^5}{\mathrm{cm}^2\,\mathrm{s}\,\mathrm{eV}}\left(\frac{m_{\gamma'}}{0.18\,\mathrm{meV}}\right)^4\left(\frac{\chi}{2\times 10^{-6}}\right)^2 ;$$

$$\text{for}\ \ m_{\gamma'} < 0.1\ \mathrm{eV},\ \ \omega = 1 \div 10\ \mathrm{eV}$$

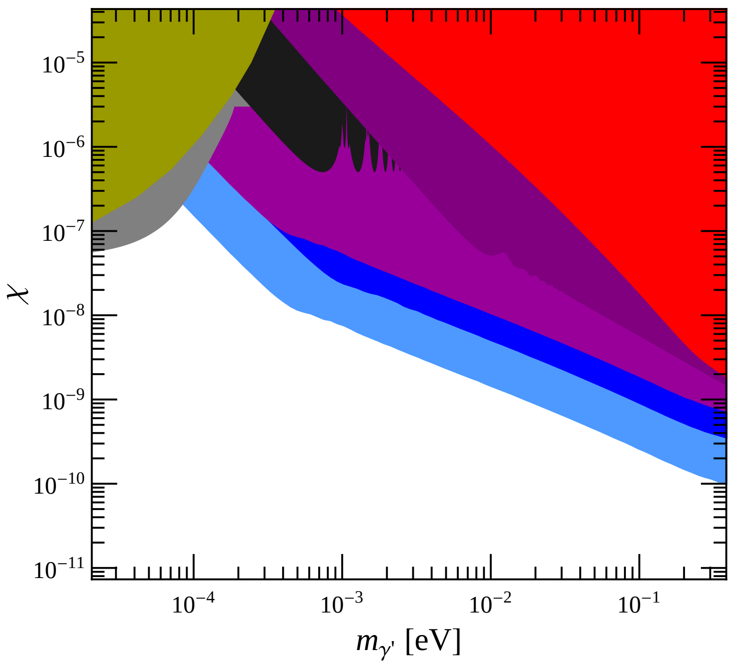
  - these solar hidden photons may be detected by their oscillation into photons inside a light-tight and evacuated tube, exploiting collecting optics and a sensitive photodetector



- **SHIPS** (Solar Hidden Photon Search) **may probe hidden CMB parameter space already in 2011:** [Hamburg Observatory, Uni HH, DESY]
  - toySHIPS presently being assembled and soon to be mounted on Oskar Lühning Telescope at Hamburg Observatory
    * vacuum tube (2 m length, 26 cm diameter)
    * 2 Fresnel lenses
    * 2 photomultipliers



- **SHIPS** (Solar Hidden Photon Search) **may probe hidden CMB parameter space already in 2011:** [Hamburg Observatory, Uni HH, DESY]
  - projected sensitivities of **toySHIPS** and **CAST:**



[Redondo in prep.]

  - exploit predictions of solar γ' flux also from photosphere

[Cadamuro,Redonde '10 and in prep.]

Sub-GeV Scale Dark Forces?!

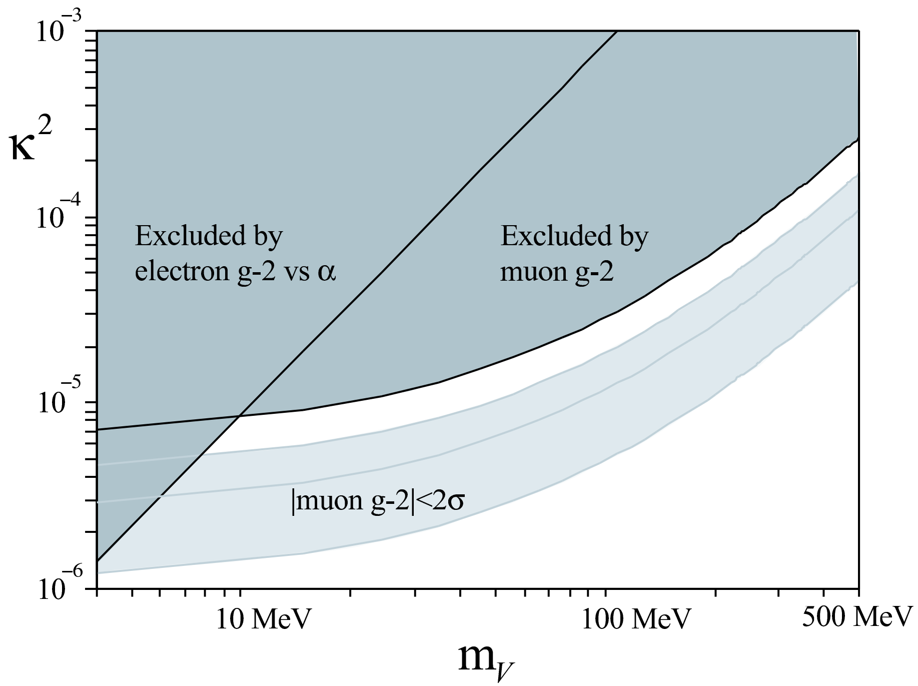
- **MeV-GeV scale hidden photon** (dark force, dark photon, ...)
  - may explain $(g-2)_\mu$ anomaly, if $\boldsymbol{\chi \sim 10^{-3} \div 10^{-2}}$ [Pospelov '08]
  - may explain [Arkani-Hamed *et al.* '08; Pospelov,Ritz '08; Morrissey *et al.* '09;...]
    - ∗ terrestrial (DAMA, CoGeNT vs. CDMS, XENON) and
    - ∗ cosmic ray (PAMELA, FERMI)

    DM anomalies if DM charged under hidden U(1) and $\boldsymbol{\chi \gtrsim 10^{-6}}$
    - ∗ DM-nucleus scattering dominated by exchange of γ'
    - ∗ DM annihiliation dominated by DM $+$ DM $\to \gamma' + \gamma'$
  - can be searched for in **new fixed-target experiments**

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

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

may explain a_μ anomaly: [Pospelov '08]

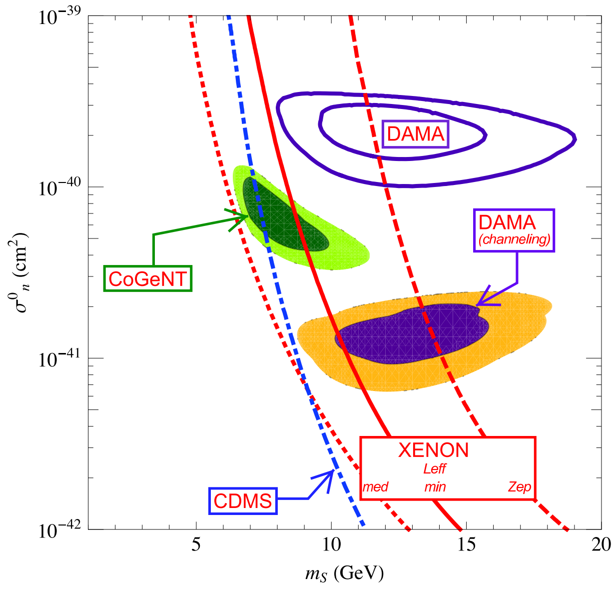


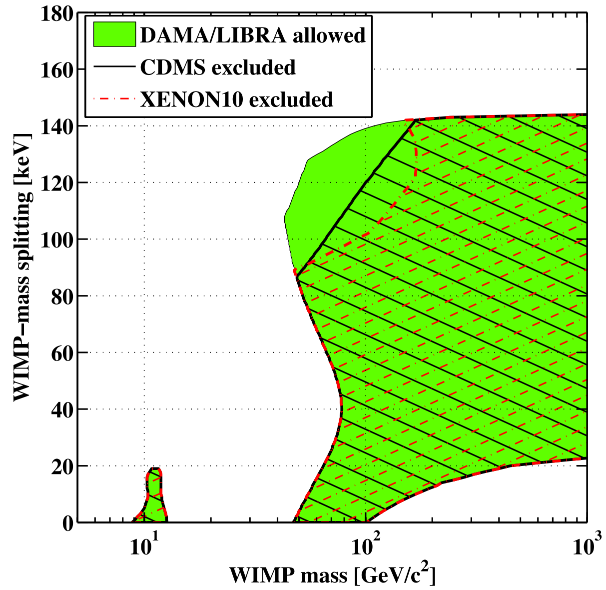
[Pospelov '08]

- **Dark matter interpretation** of annual modulation observed by DAMA and of excess of low energy events in CoGeNT not in conflict with null results of CDMS and XENON if DM-nucleus scattering dominated by

[Tucker-Smith,Weiner '01;...;Arkani-Hamed *et al.* '08;...;Morrissey,Poland,Zurek '09;...; Mambrini '10]

  – elastic process, $\mathrm{DM}+N \to \mathrm{DM}+N$, with low mass $m_{\mathrm{DM}} \sim 5-10$ GeV
  – inelastic process, $\mathrm{DM}+N \to \mathrm{DM}^* + N$, with $\triangle m_{\mathrm{DM}} \approx 100$ keV





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

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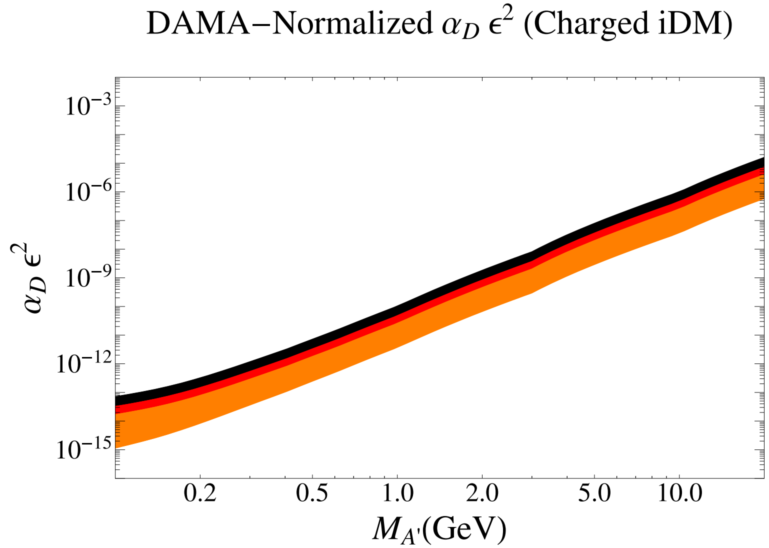
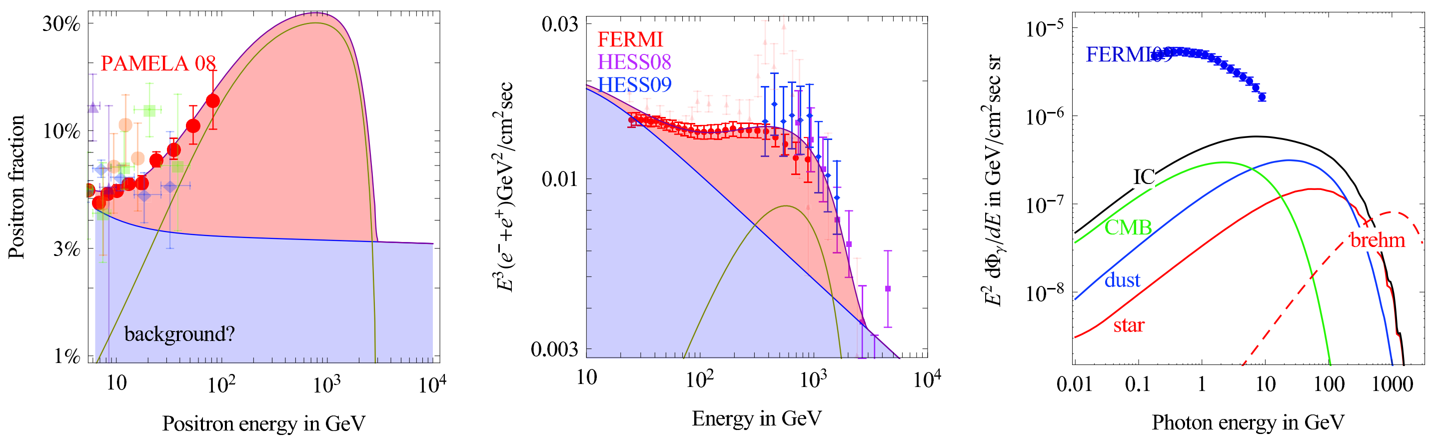
- **can be mediated by kinetically mixed sub-GeV scale γ'**



[Essig,Schuster,Toro '09]

- **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]

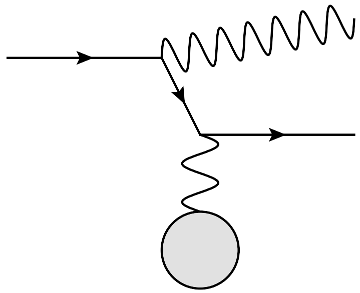
$\Leftarrow$ **can be achieved via** $\mathrm{DM} + \mathrm{DM} \to \gamma' + \gamma'$**, if** $2\, m_e < m_{\gamma'} \lesssim m_p$

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

- **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]

  – Sizeable cross section of γ' Bremsstrahlung:



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

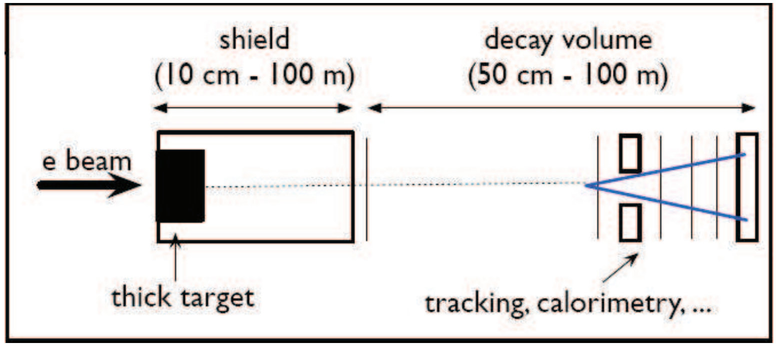
  – Sizeable decay length of $\gamma' \to e^+e^-$,

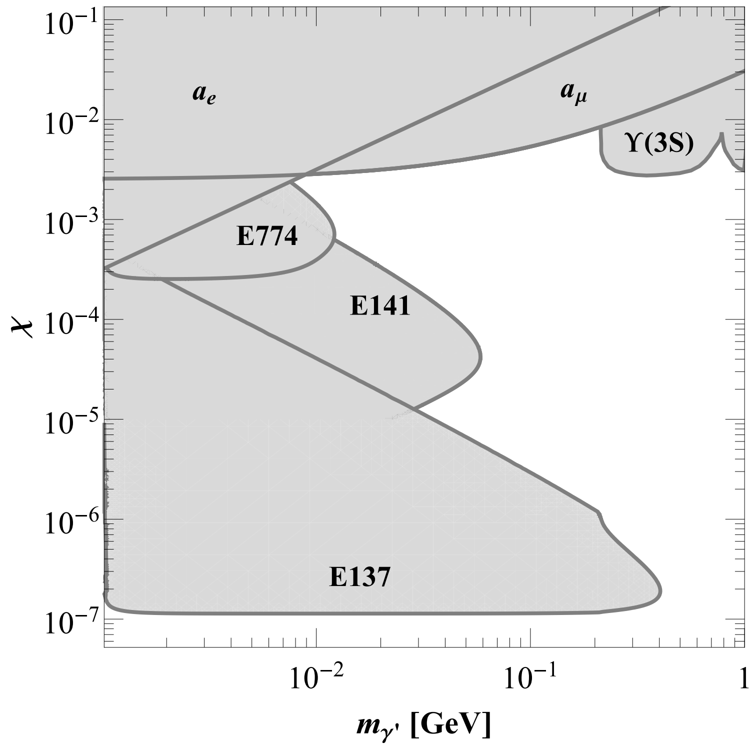
$$\ell_d = \gamma c \tau \sim 8 \text{ cm} \left(\frac{E}{\text{GeV}}\right) \left(\frac{10^{-5}}{\chi}\right)^2 \left(\frac{100 \text{ MeV}}{m_{\gamma'}}\right)^2$$

- **Limits from beam dumps:**

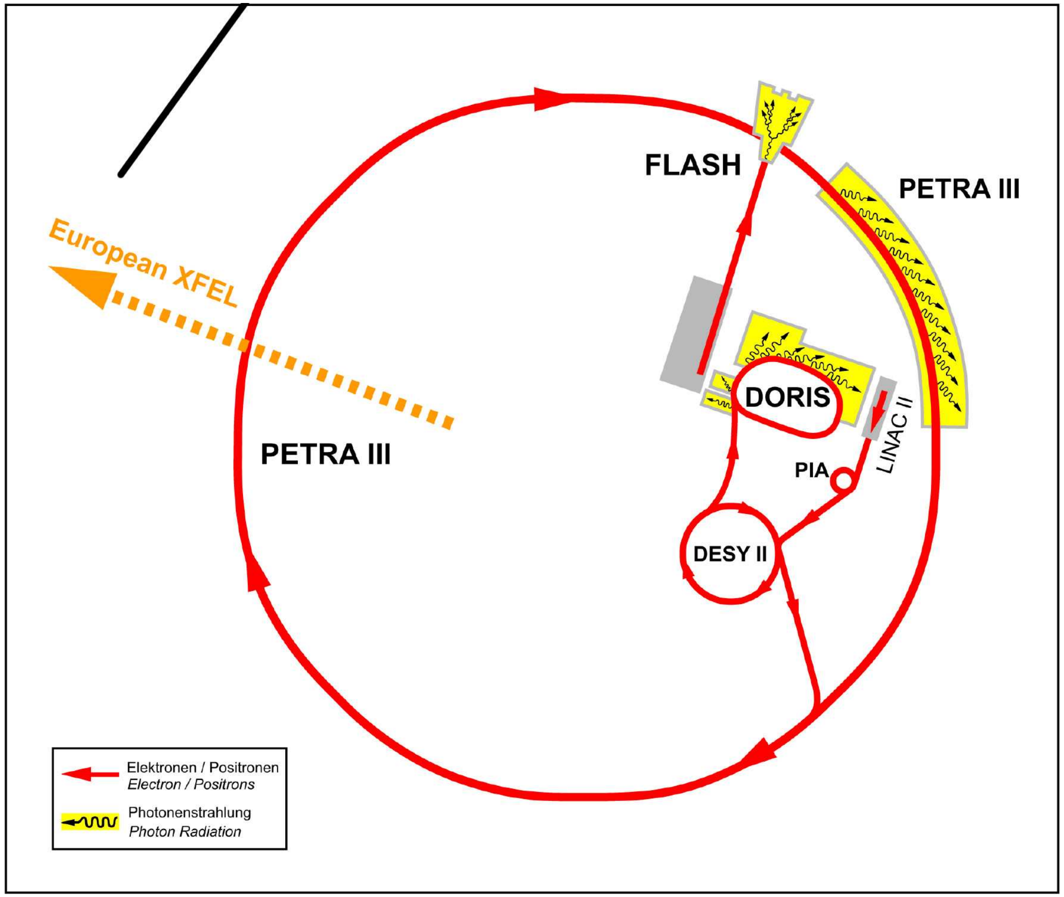
[Bjorken,Essig,Schuster,Toro '09]

  – 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): towards a new **beam dump** experiment at DESY II (10 nA, .45–7 GeV)

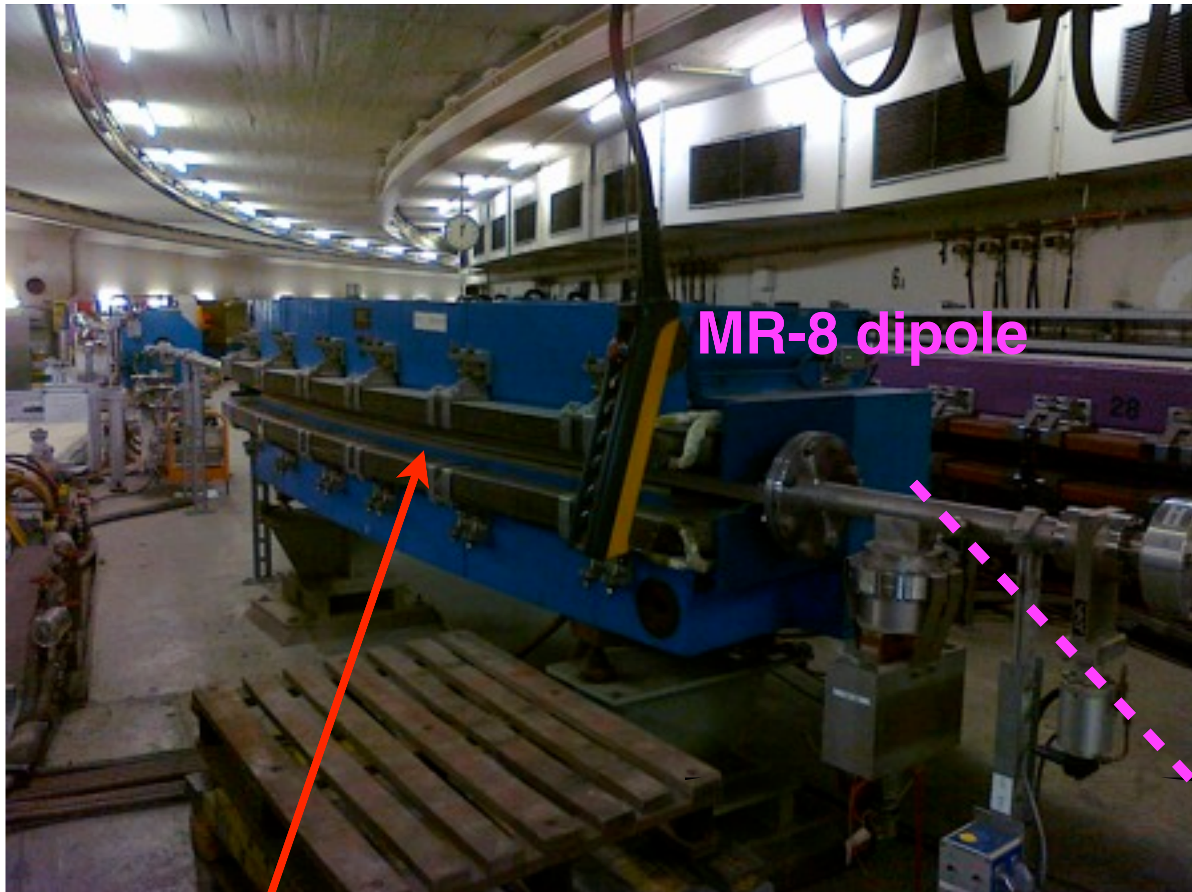


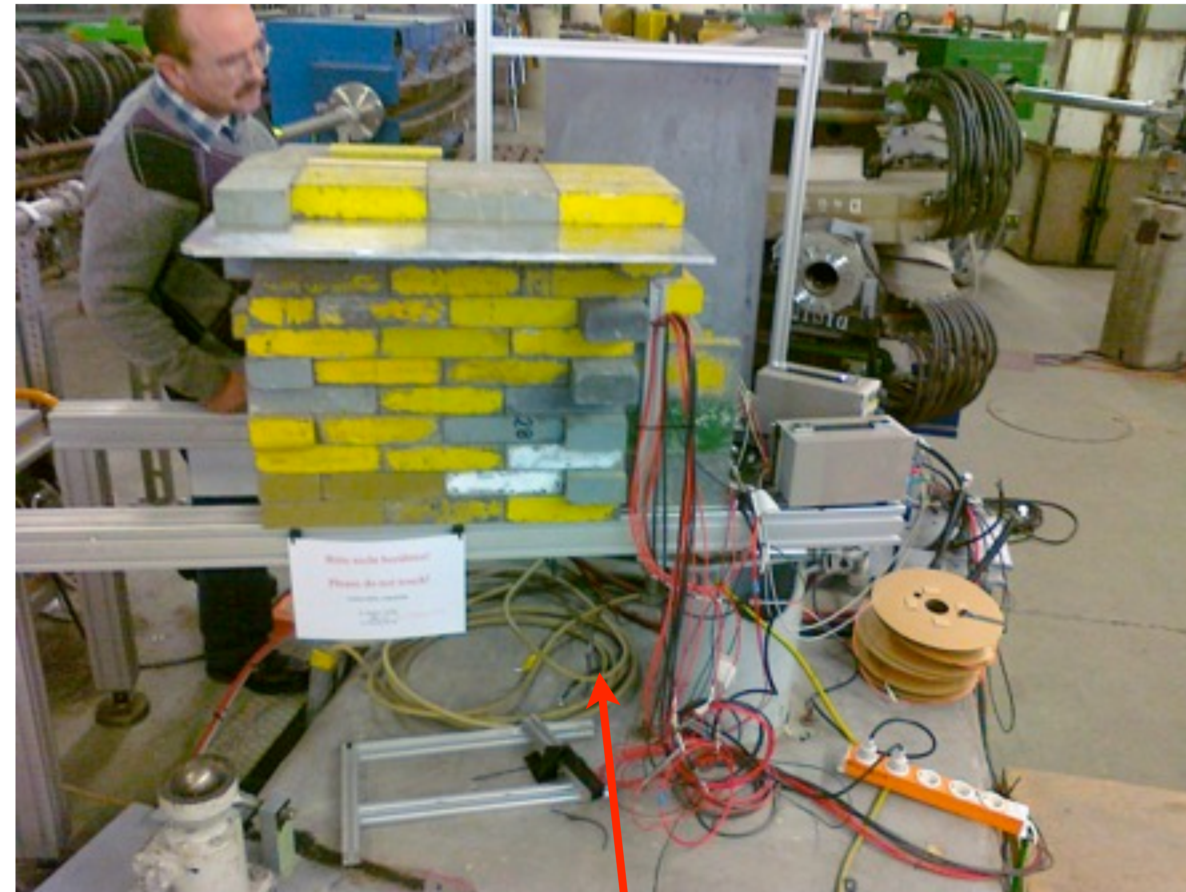
- **HIPS** (HIdden Particle Search): towards a new **beam dump** experiment at DESY II (10 nA, .45–7 GeV)

  Current status:

  – HIPS beam extraction chamber installed in Winter shutdown
  – first measurements with scintillators beyond pure Pb beam dump two weeks ago; proper development of beam dump (target + shielding) started
  – currently different options for detectors explored
    * tracking: ZEUS MVD module (alternatives: SiLC module; MediTPC)
    * calorimetry: H1 Spacal super module or available Cherenkov detector

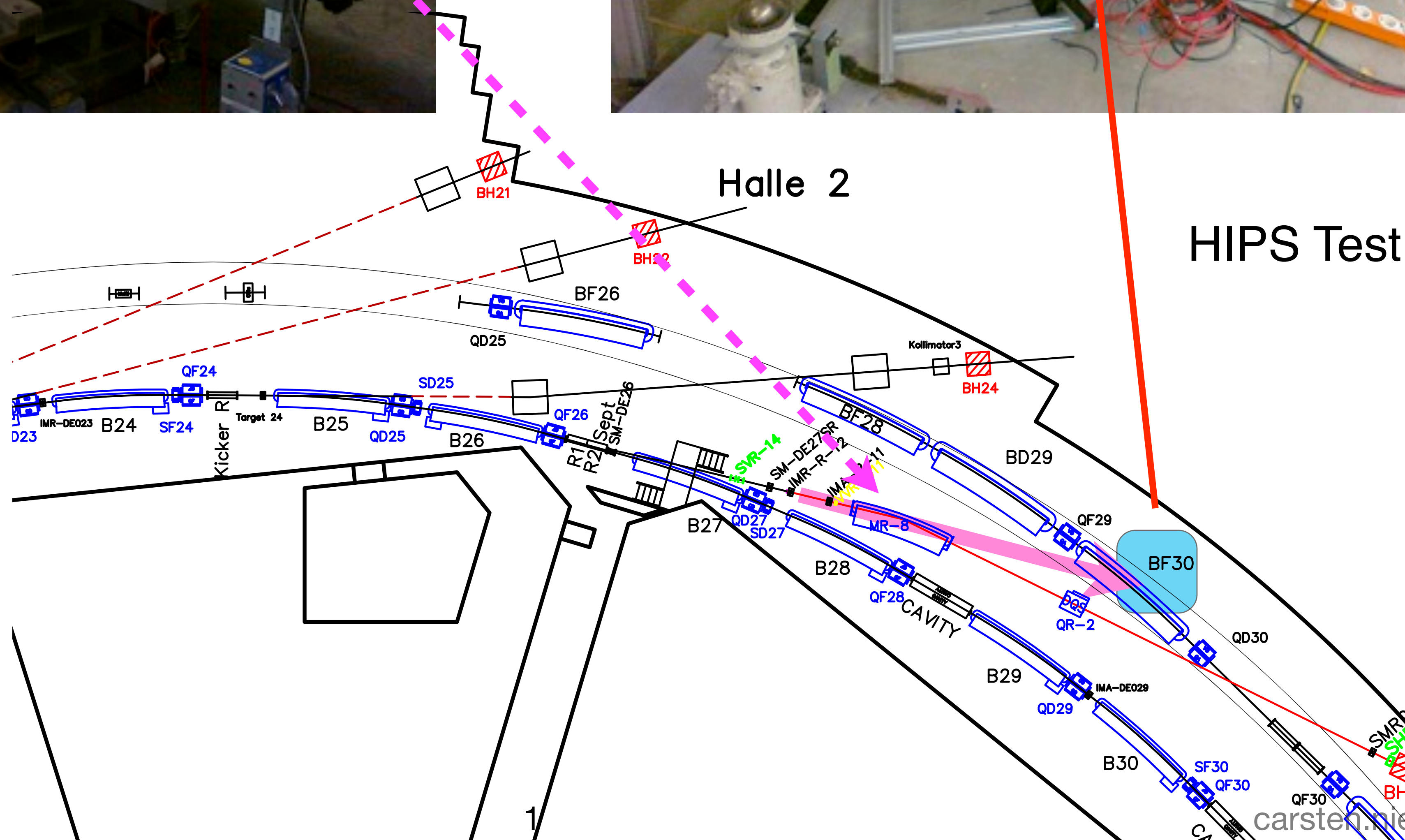
HIPS at DESY II





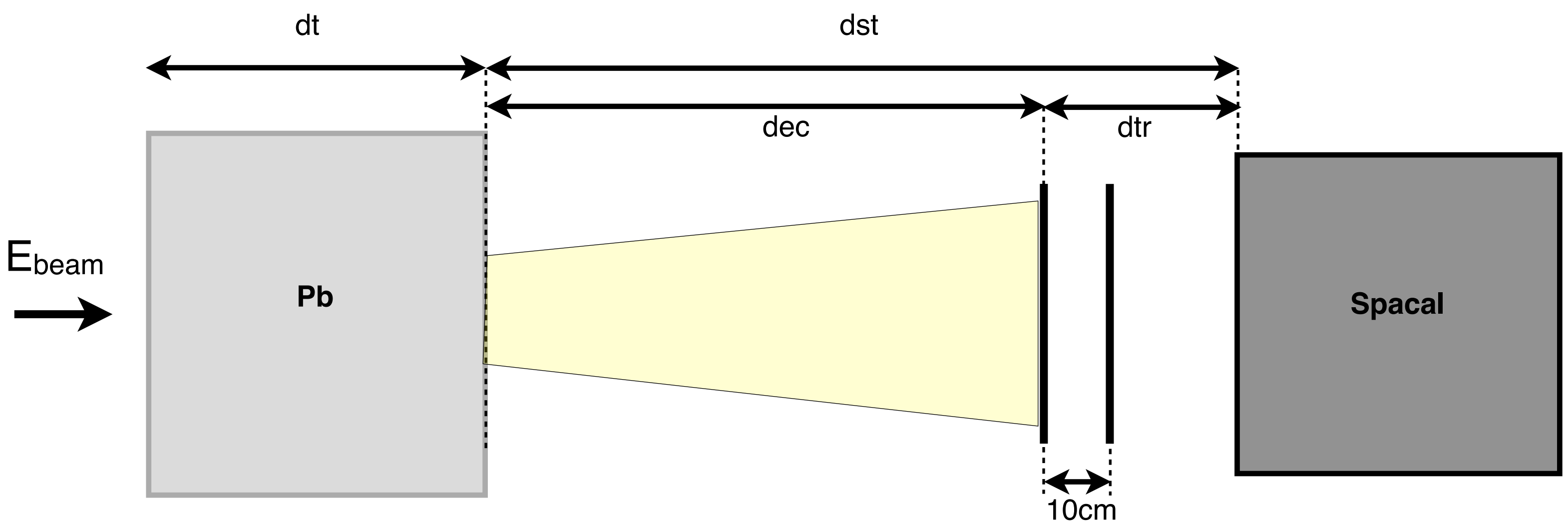
HIPS beam extraction chamber replaced in DESY Winter shutdown

HIPS Test Setup



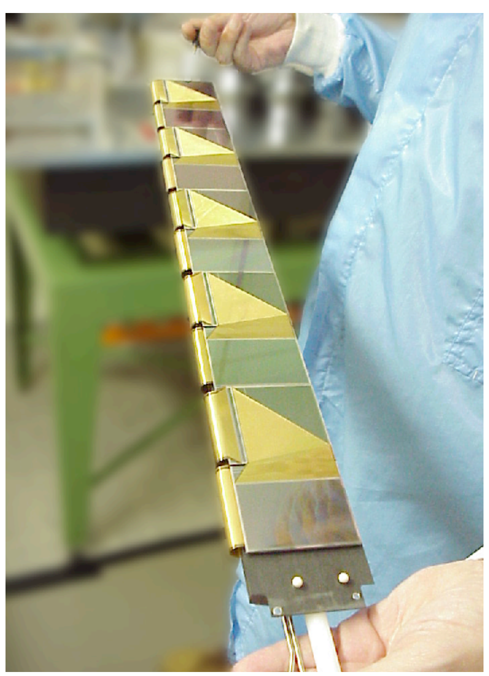
HIPS Detector Considerations

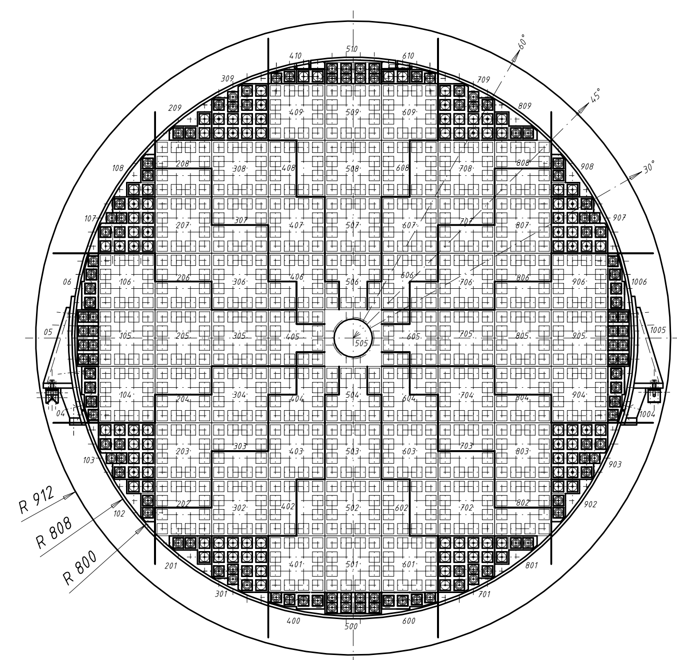
Principle Setup

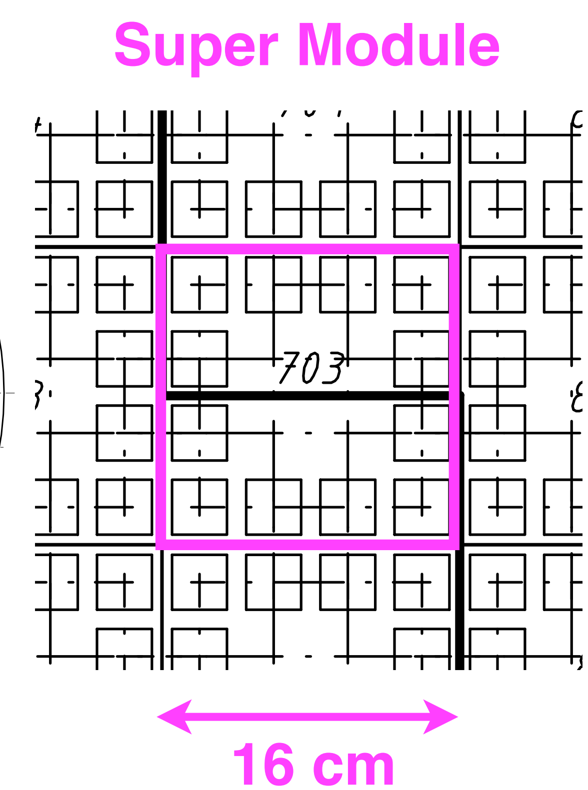


ZEUS MVD module for tracking

H1 Spacal Super Module for calorimetry

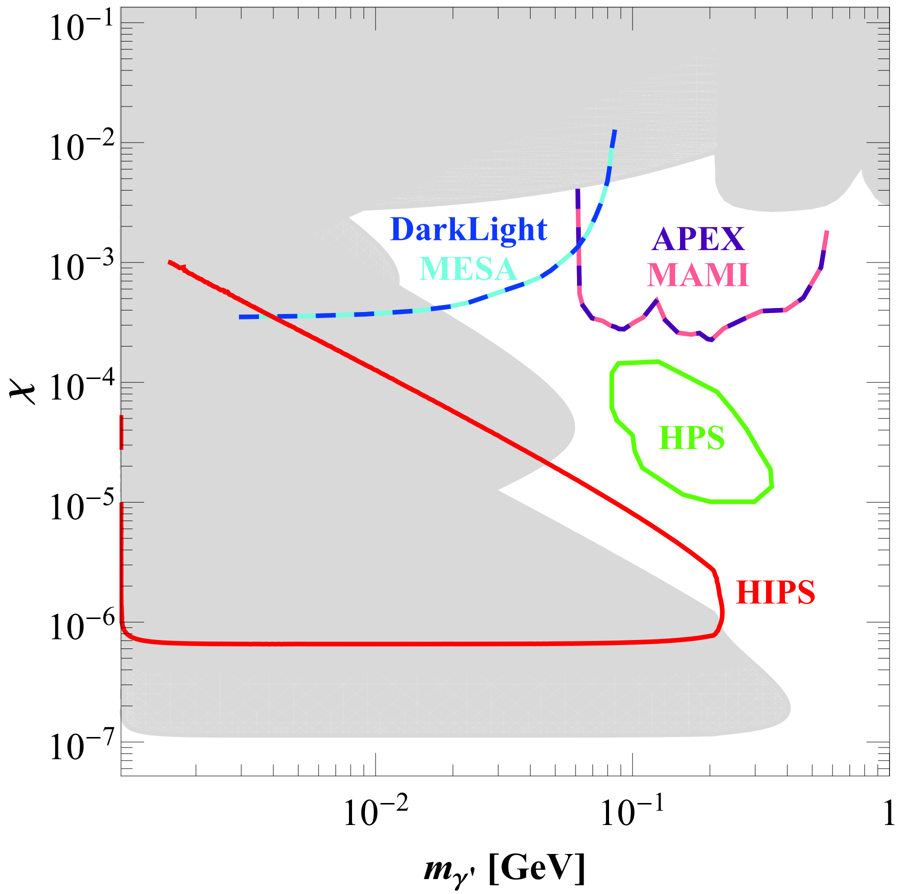






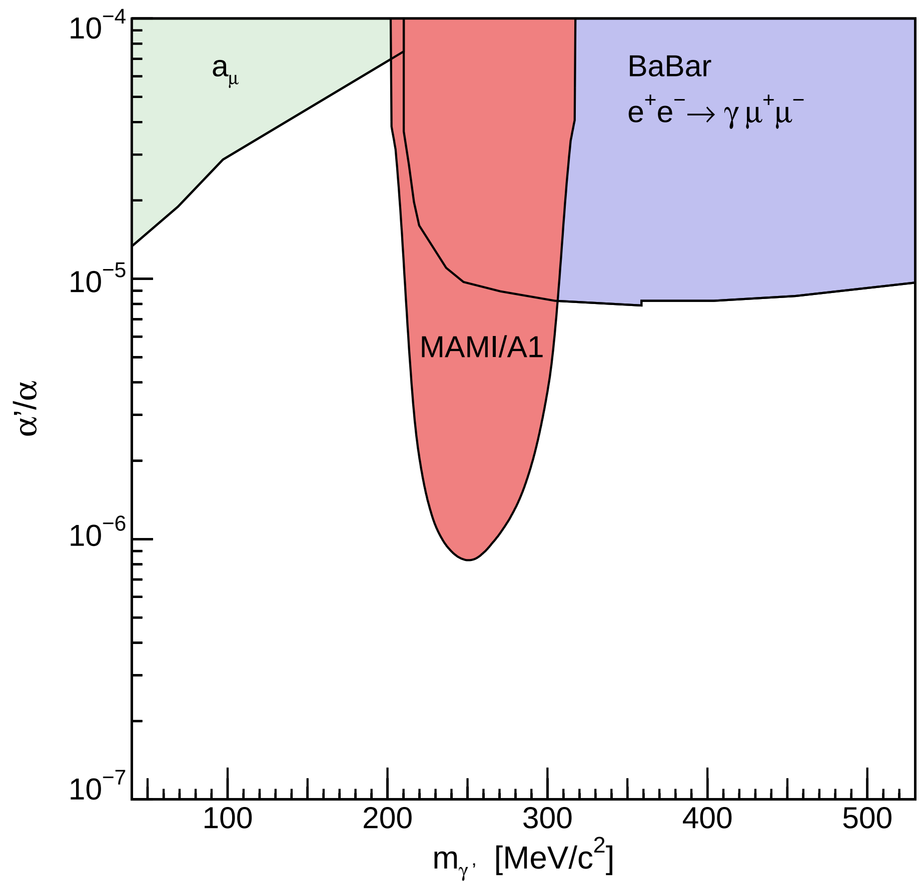
Alternatives: SiLC Module or MediTPC ?

- **HIPS** and planned dark forces attacks of our allies at JLab and MAMI:



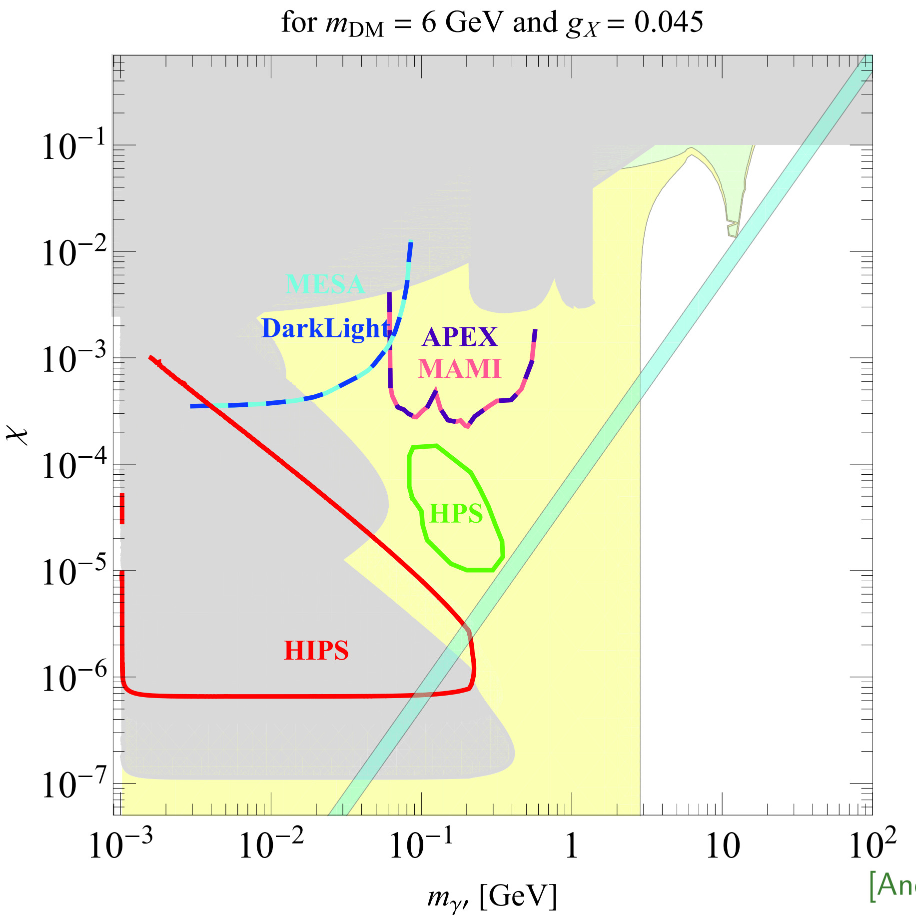
[Andreas,AR '10]

- A1 collaboration at MAMI (Mainz) has published first limits:



[A1 Collaboration '11]

- If all new fixed target experiments are realized, parameter space for hidden photon relevance for dark matter seriously tested:



[Andreas,Goodsell,AR in prep.]

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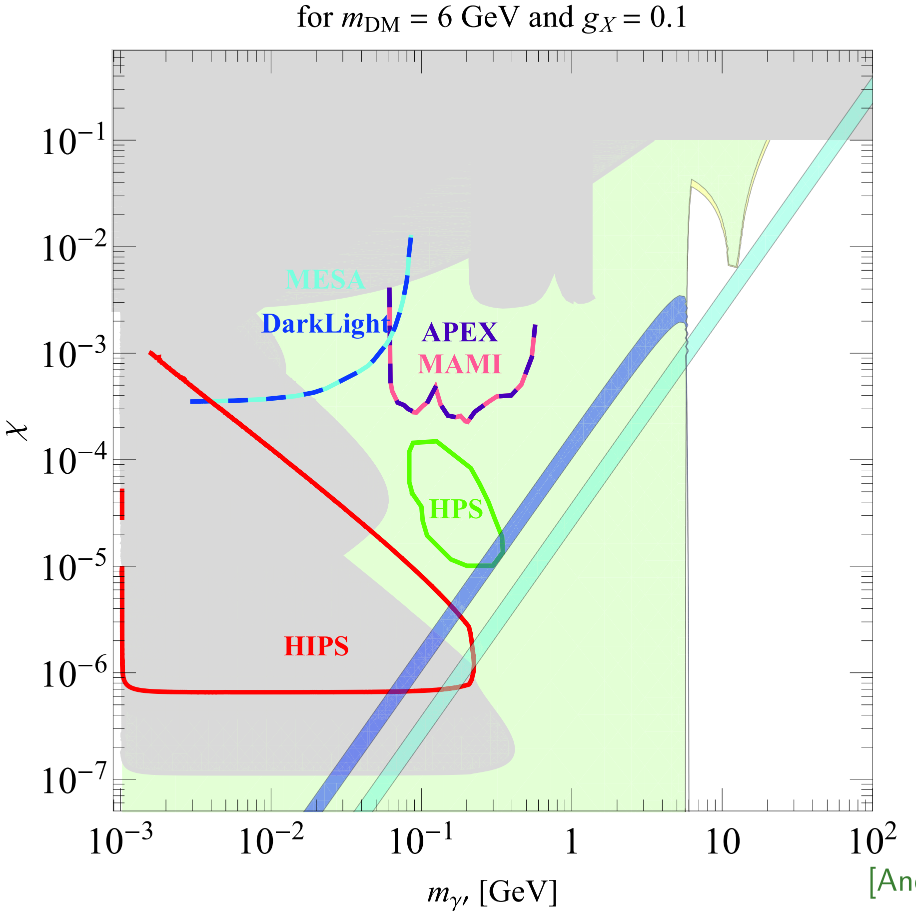

[Andreas,Goodsell,AR in prep.]

Conclusions

- 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!