Sub-GeV Scale Dark Forces?!

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Johannes Gutenberg Universität Mainz
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1. Motivation

- Models related to dark matter suggest existence of long-range forces mediated by new gauge bosons with masses in the MeV to GeV range and very weak coupling to ordinary matter:

"Hidden" or "Dark Photons"

- Appear naturally in models descending from strings
- Experimental particle physics community has started to develop strategies and to form collaborations to attack these dark forces

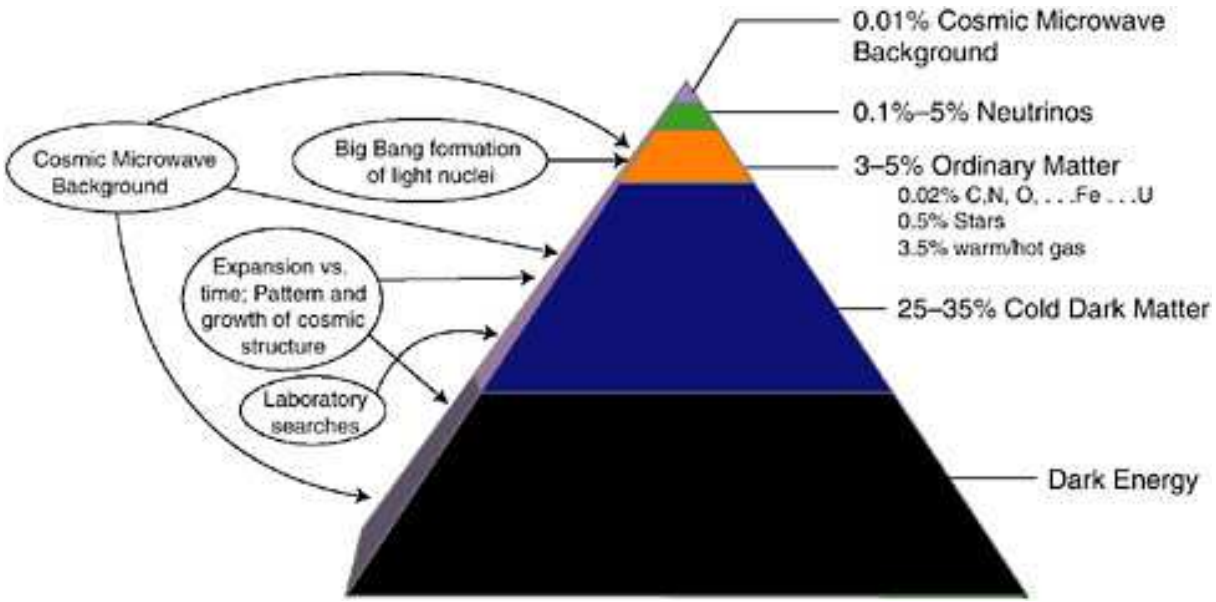
  – Fixed-target experiments exploiting electron beams especially sensitive

  $\Rightarrow$ Opportunity for new experiments at DESY, MAMI, and JLab

Table of Content:

2. Physics Case for Dark Forces

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



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

- Constituents of **dark matter** could be
  - **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, . . .

- **Extra U(1) gauge bosons 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 SM particles charged under them)

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

$$\mathrm{E}_8 \times \mathrm{E}_8 \to \mathrm{E}_6 \times \mathrm{E}_8 \to \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{standard model}} \times \mathrm{U}(1)_{\mathrm{hid}},$$

    from breaking of second 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

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

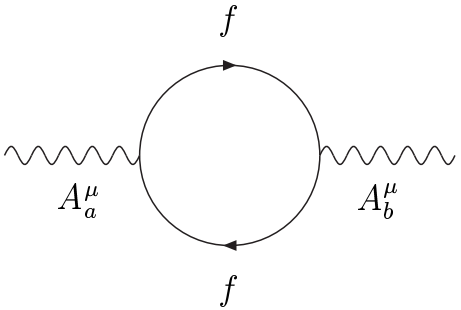
- At low energies, hidden U(1)s interact with the SM dominantly via kinetic mixing with $\mathrm{U}(1)_Y$ or $\mathrm{U}(1)_{\mathrm{em}}$, [Holdom'85]

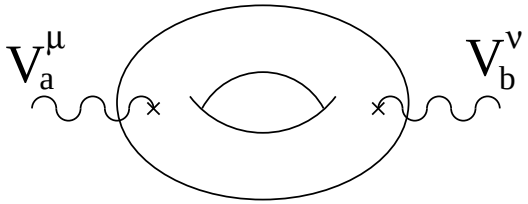
$$\mathcal{L} \supset -\frac{1}{4} F^{(\mathrm{vis})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4} F^{(\mathrm{hid})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2} F^{(\mathrm{vis})}_{\mu\nu} F^{(\mathrm{hid})\mu\nu} + m^2_{\gamma'} A^{(\mathrm{hid})}_{\mu} A^{(\mathrm{hid})\mu}$$

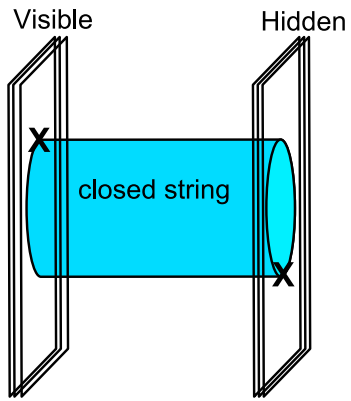
  - $\chi \ll 1$ generated at loop level via messenger exchange,

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

  - g_h and f depend on the type of messenger:







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

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

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

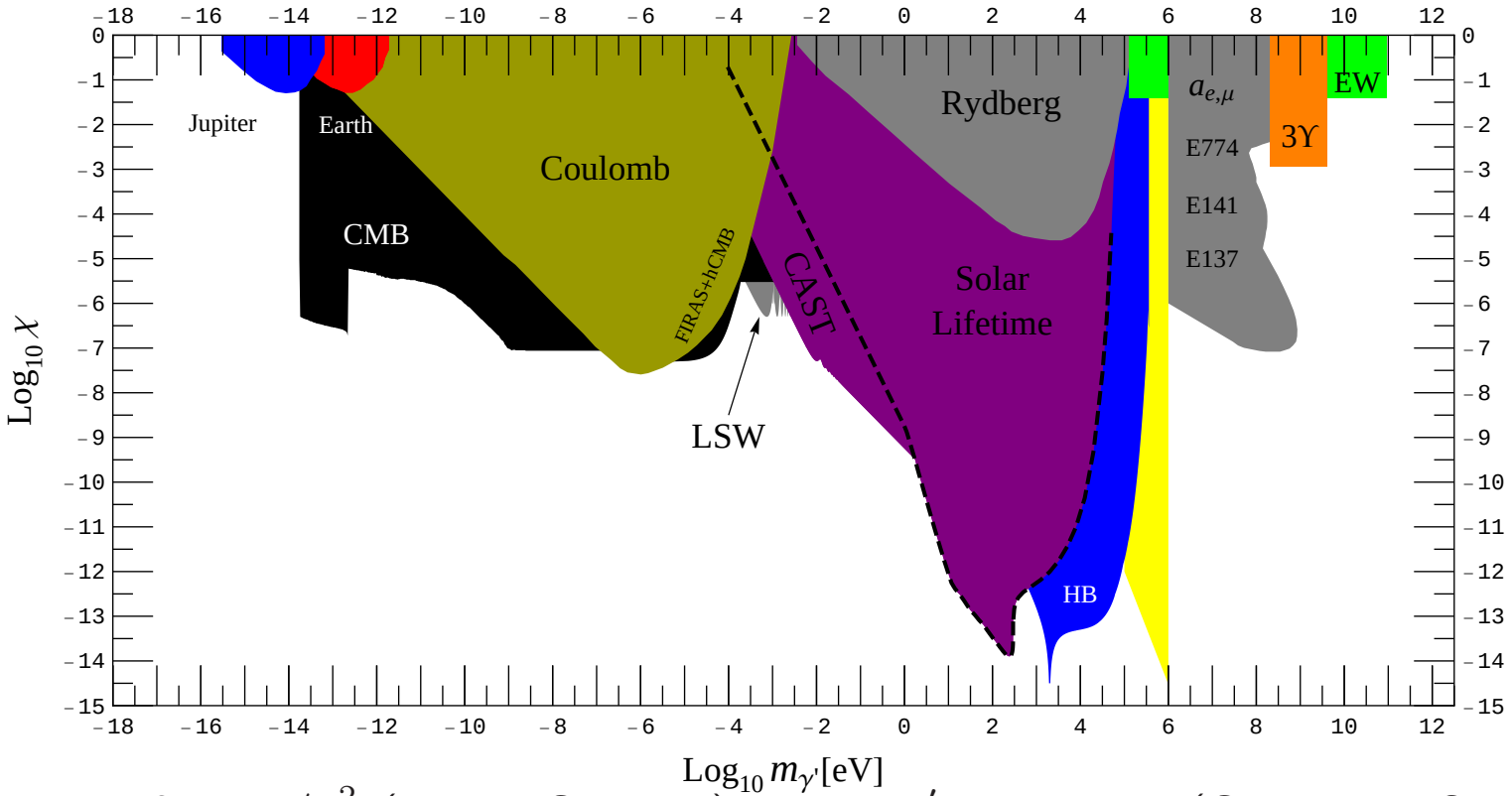
- Kinetic mixing between D-brane localized U(1)s in type II compactifications: [...;Abel,Schofield '04; Abel,Jaeckel,Khoze,AR '06;...;Goodsell *et al.* '09]

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

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

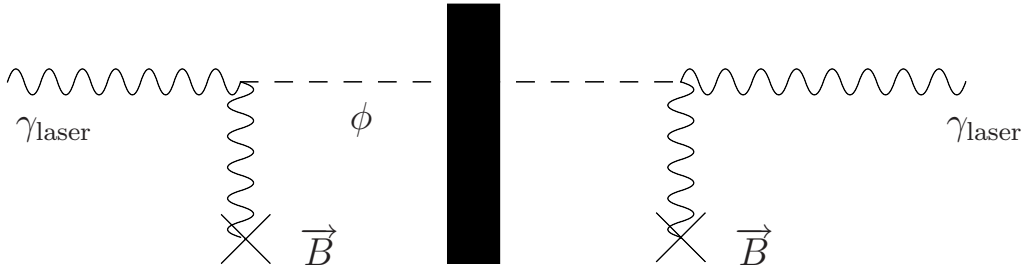
- Current constraints on hidden U(1)s:

[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)

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



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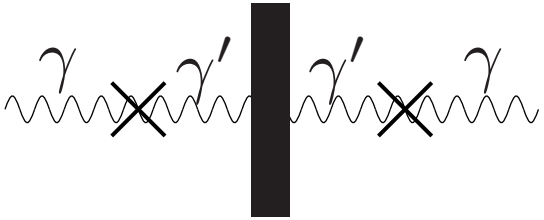
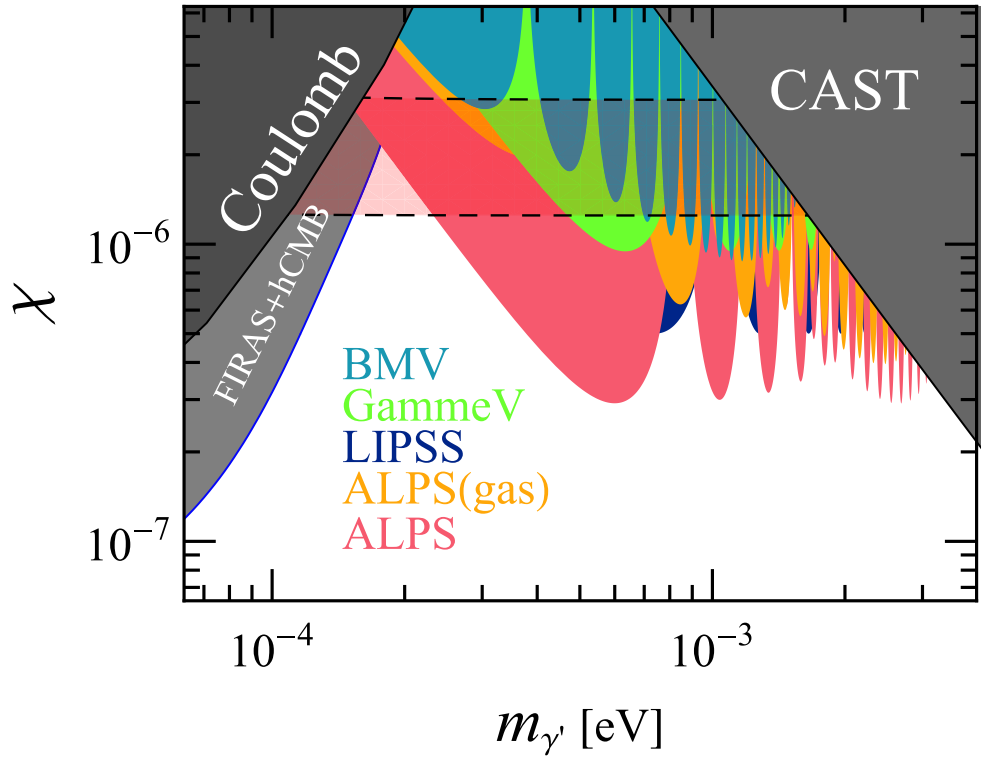


- Last **ALPS** run end of 2009 [Phys. Lett. B 689 (2010) 149-155]

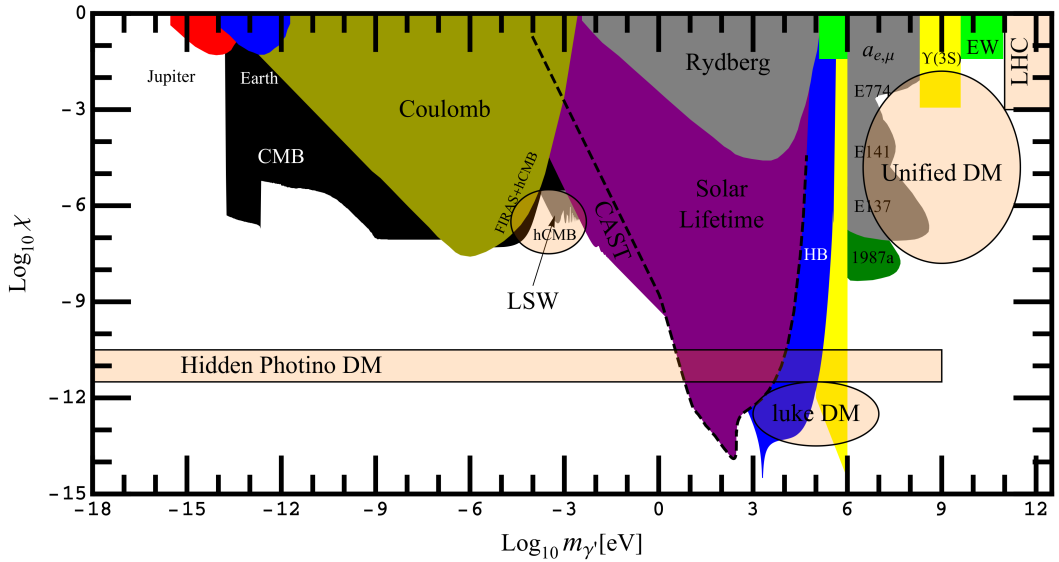
$\Rightarrow$ *"Not a WISP of evidence"* [Nature 465 (2010) 271]



[ALPS Collaboration '10]

- **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)

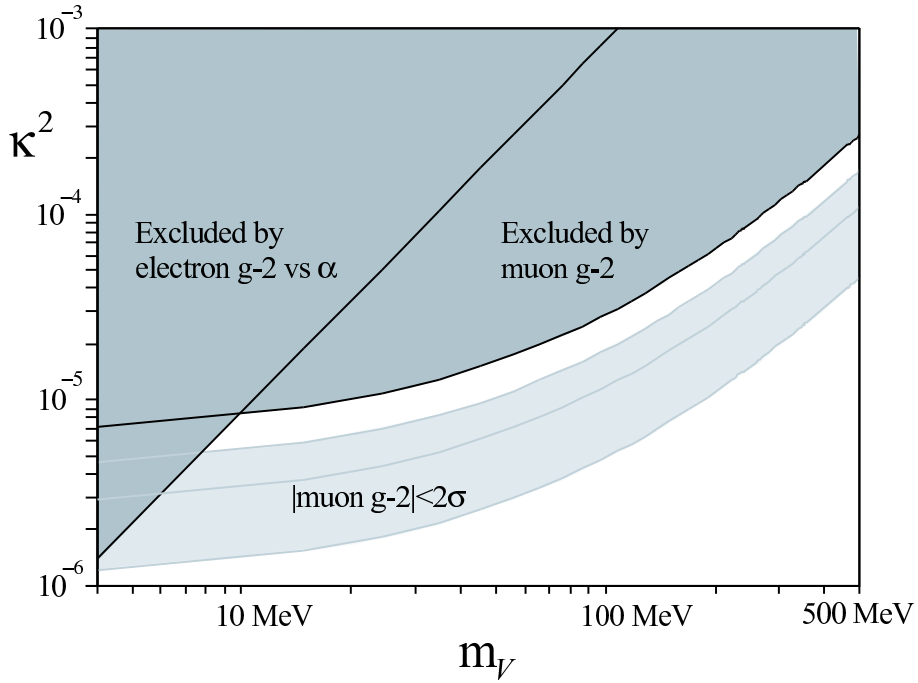
    DM anomalies if DM charged under hidden U(1)
  - can be checked in new fixed-target experiments



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

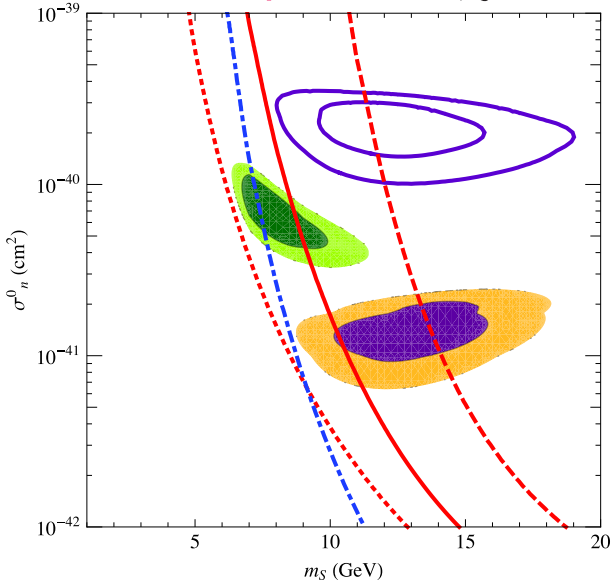
$$a_\ell^{\gamma'} = \frac{\alpha\chi^2}{2\pi} \times \int_0^1 dz \frac{2m_\ell^2 z(1-z)^2}{m_\ell^2(1-z)^2 + m_{\gamma'}^2 z} = \frac{\alpha\chi^2}{2\pi} \times \begin{cases} 1 \text{ for } m_\ell \gg m_{\gamma'}, \\ 2m_\ell^2/(3m_{\gamma'}^2) \text{ for } m_\ell \ll m_{\gamma'}, \end{cases}$$

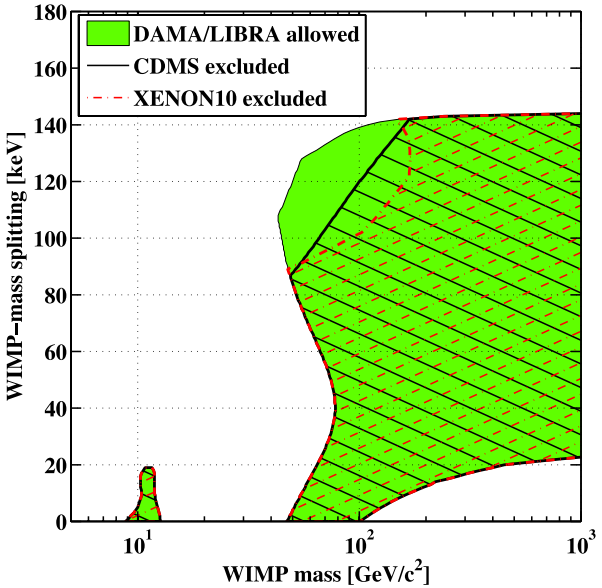
may explain a_μ anomaly: [Pospelov '08]



[Pospelov '08]

- **Dark matter interpretation** of annual modulation 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 $\triangle m \approx 100\,\mathrm{keV}$



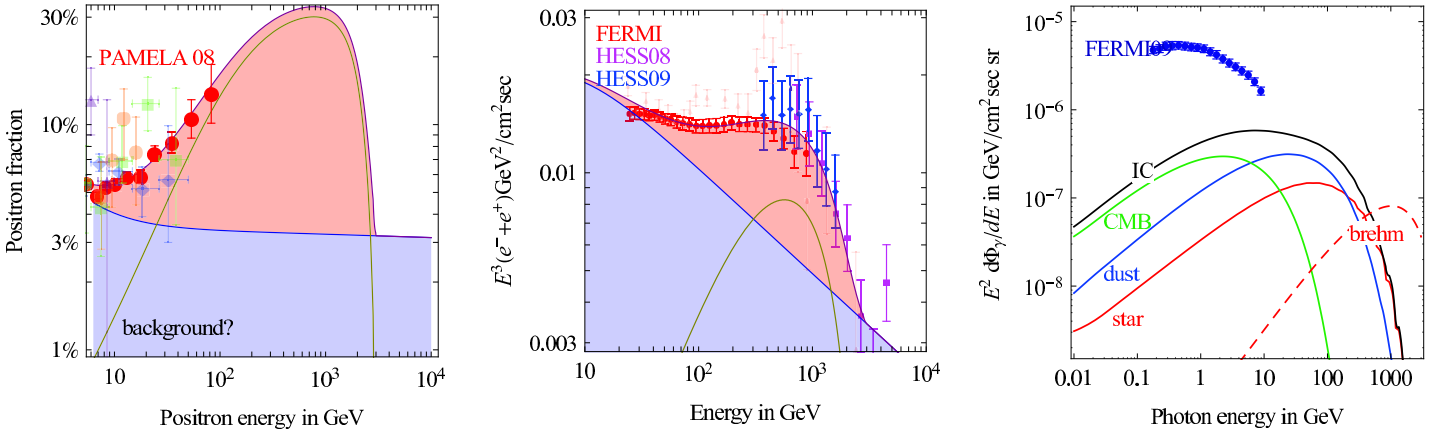


[Andreas *et al.* '10; CDMS II '10]

⇐ **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]

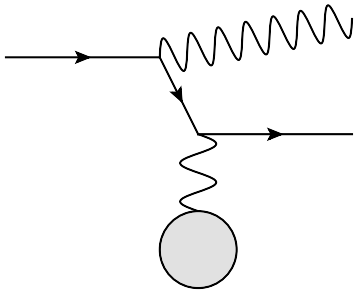
- **Can be achieved via $\chi + \chi \to \gamma' + \gamma'$, if $2\,m_e < m_{\gamma'} \lesssim m_p$**

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

3. Attacking Dark Forces with Fixed-Target Experiments

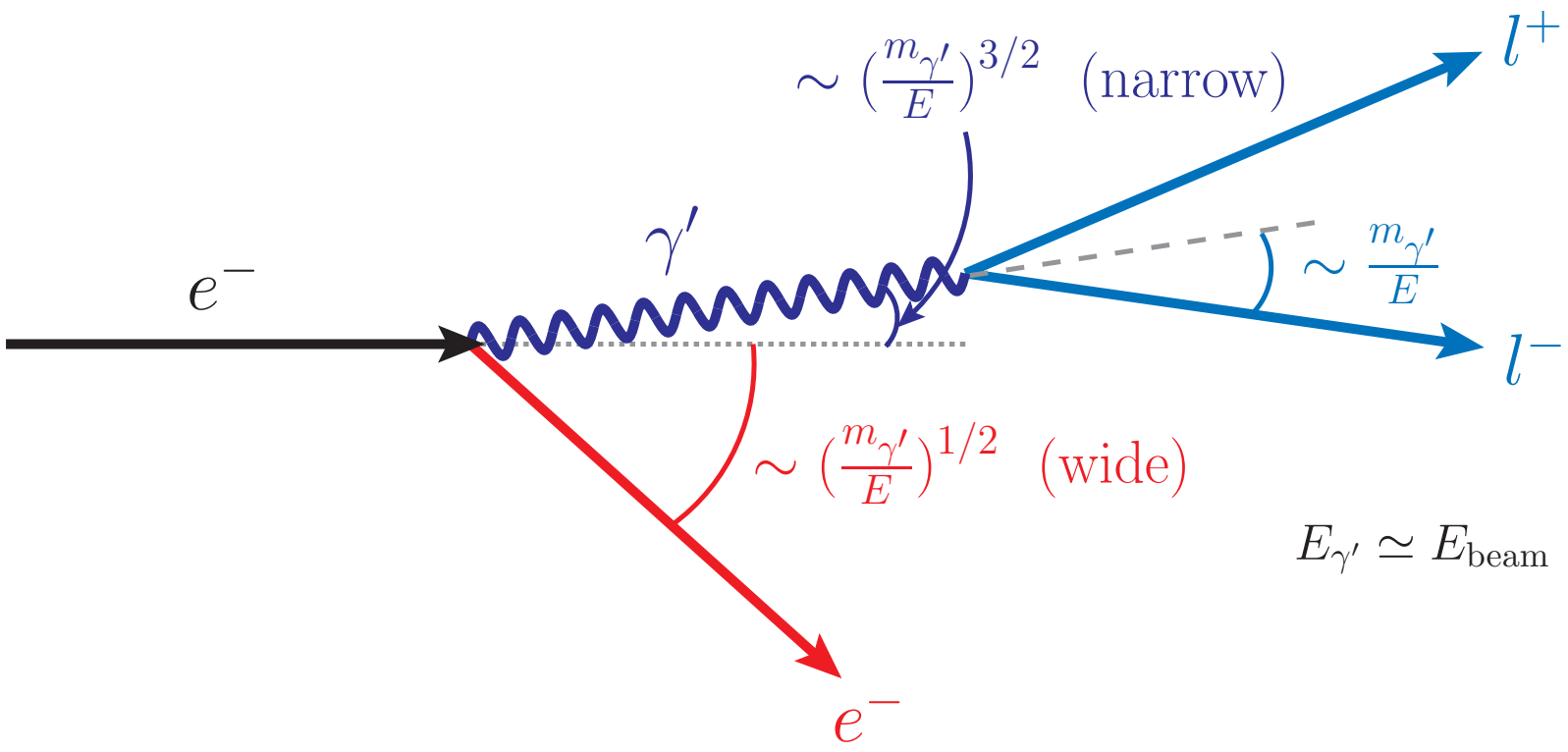
- **Fixed-target experiments with intense electron beams** particularly sensitive to MeV-GeV scale hidden photon [Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09]

- Production via γ' Bremsstrahlung:



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

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:

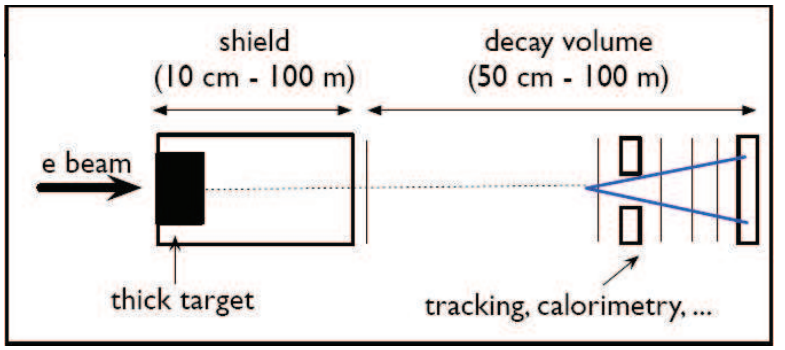
  – $\ell_d \gg$ cm: **beam dump**; low background
  – $\ell_d \sim$ cm: **vertex**; limited by instrumental bkg
  – $\ell_d \ll$ cm: **bump hunt**; fight bkg with high intensity, resolution

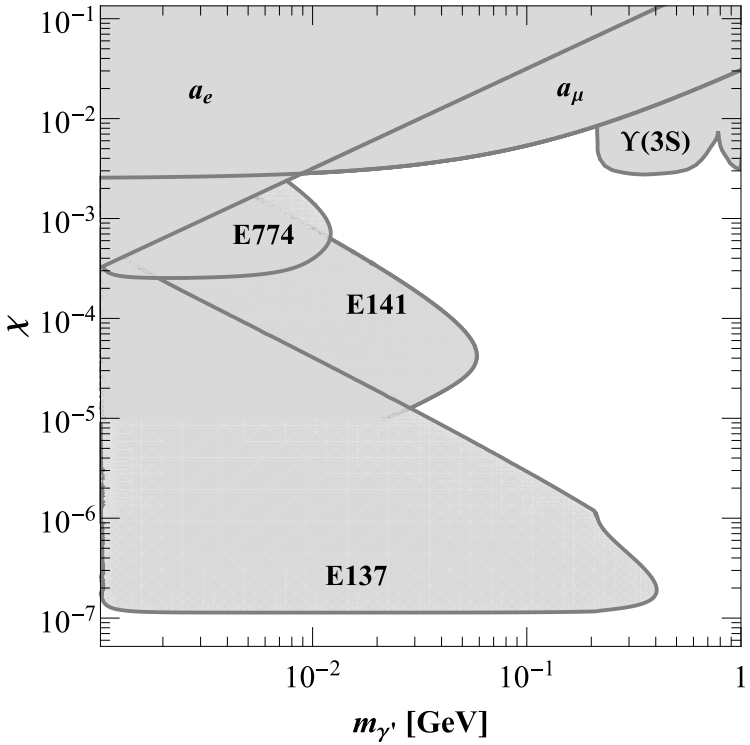
$\Rightarrow$ New experiments funded/proposed/designed/commissioned at DESY (HIPS), MAMI (A1 Collaboration), and JLab (APEX, DarkLight, HPS)

- **Past beam dumps:**

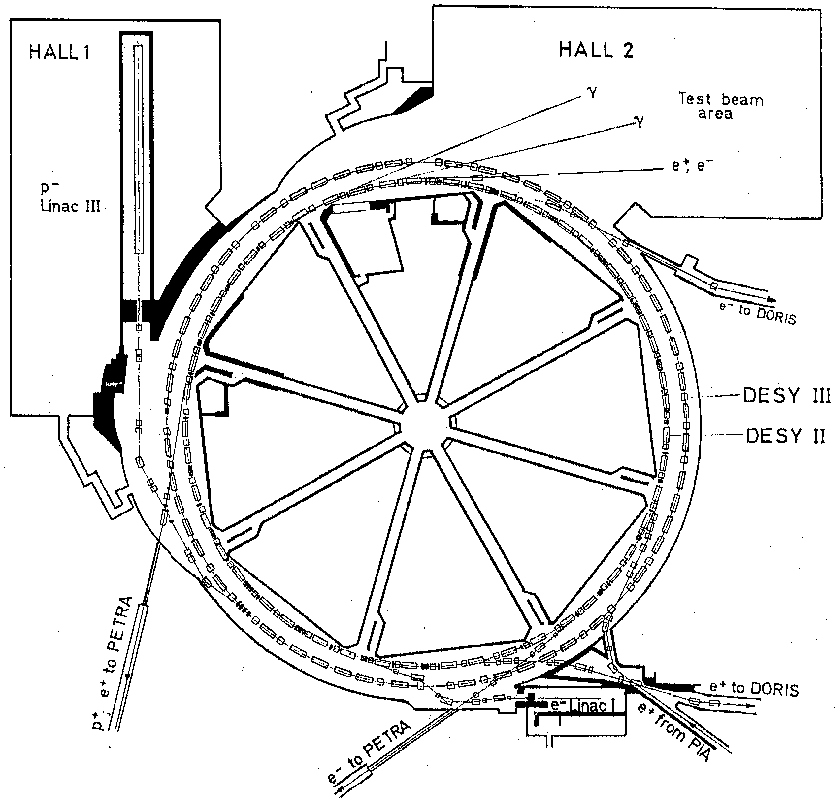
[Bjorken,Essig,Schuster,Toro '09]

  - 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); funded by SFB 676 [Andreas,Bechtle,Ehrlichmann,Garutti,Lindner,Niebuhr,AR,Soloviev]



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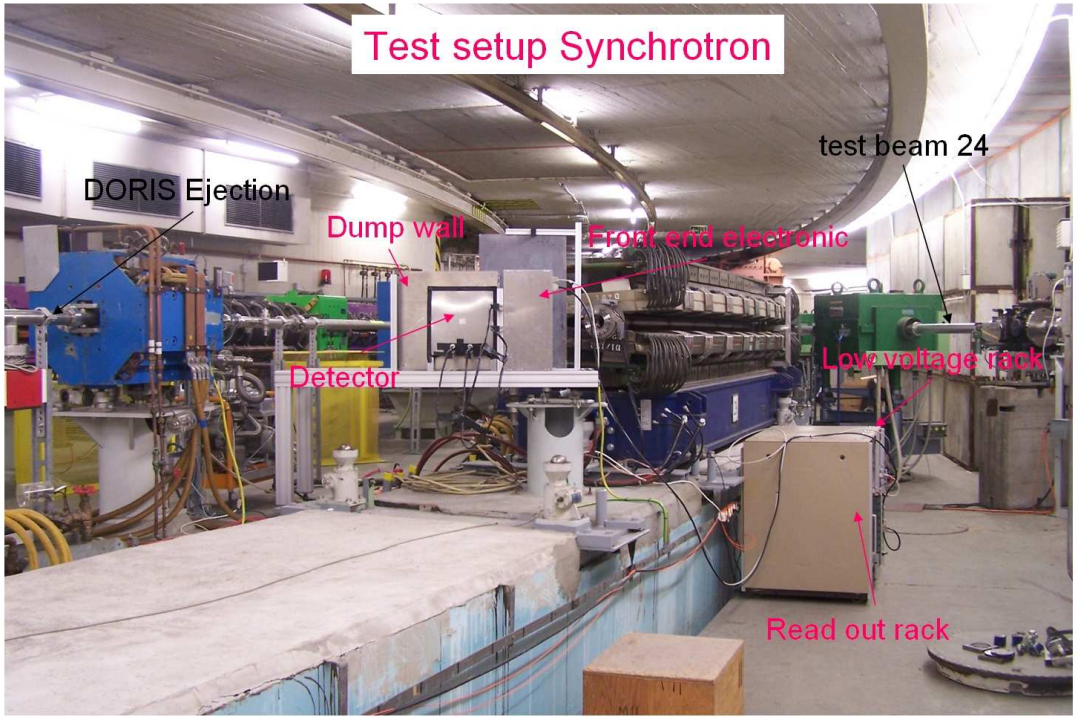

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  Current situation:

  – detector parts (H1 electron tagger) 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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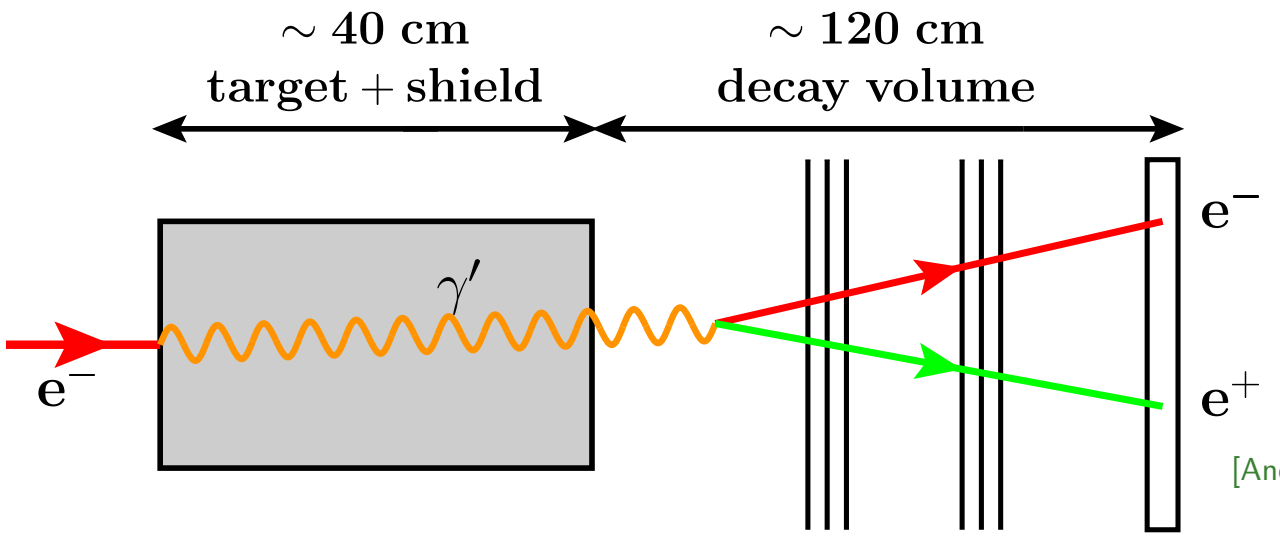

[Andreas,AR '10]

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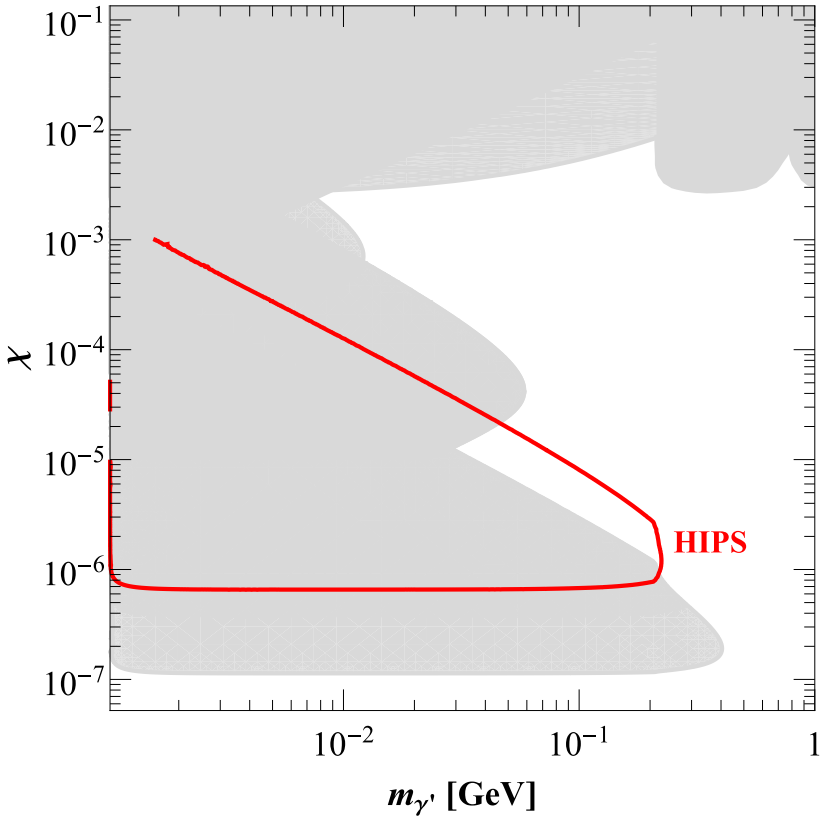
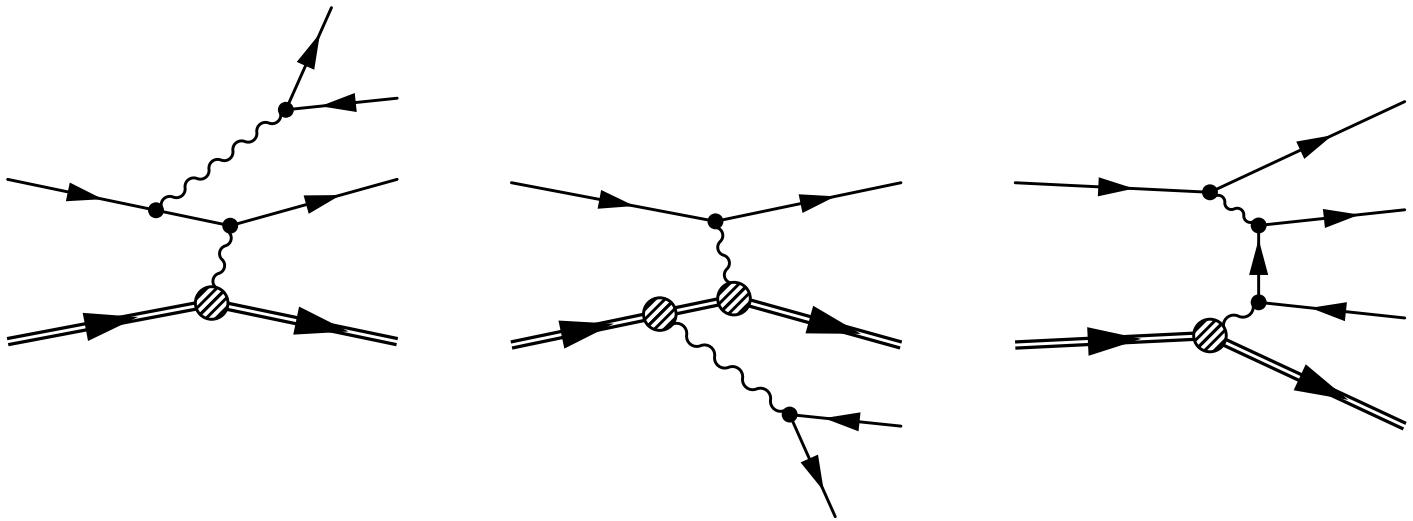


[Andreas,AR '10]

- **APEX** at JLab and dark photon search by the A1 collaboration (MAMI): **bump hunts** exploiting large data samples (due to currents in 100 μA range) taken by high resolution spectrometers to search for a peak in the e^+e^- invariant mass distribution (pilot runs already took place)

  Backgrounds to fight with:



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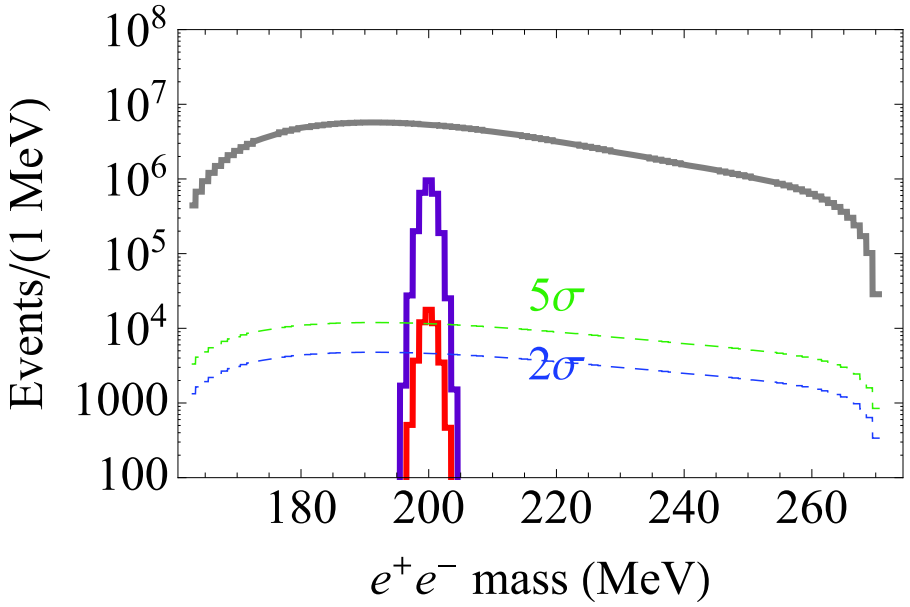
  Raw rates:



[Essig *et sl.* '10]

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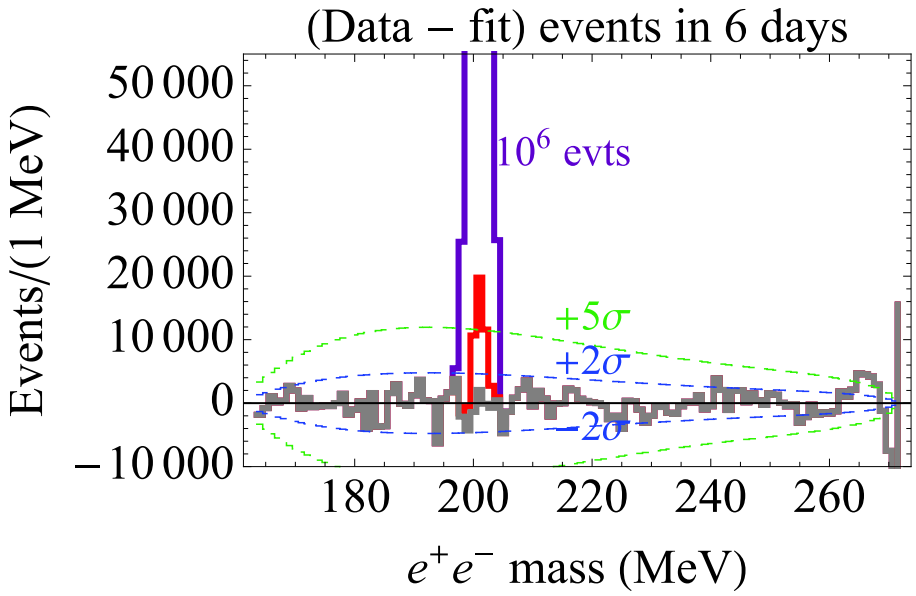
  After cuts:



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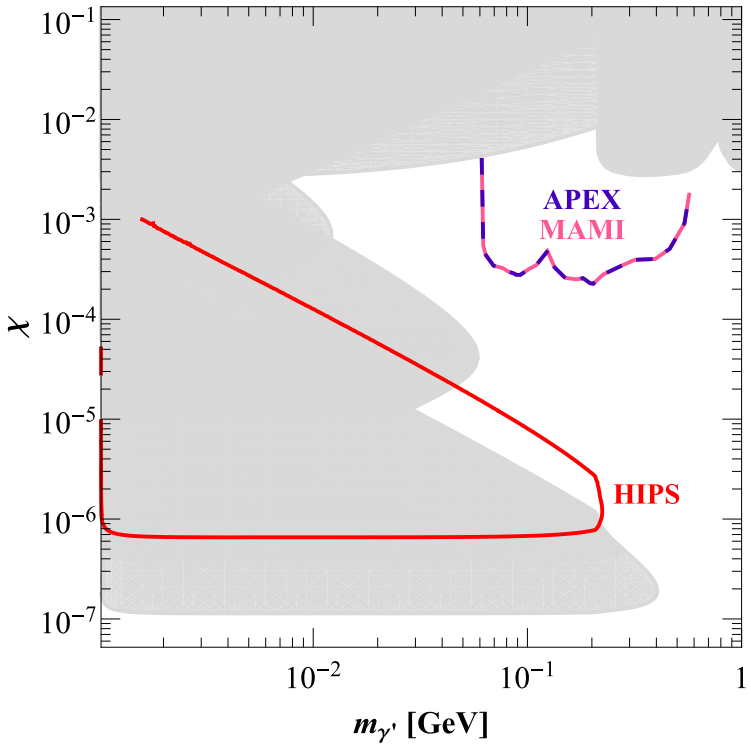
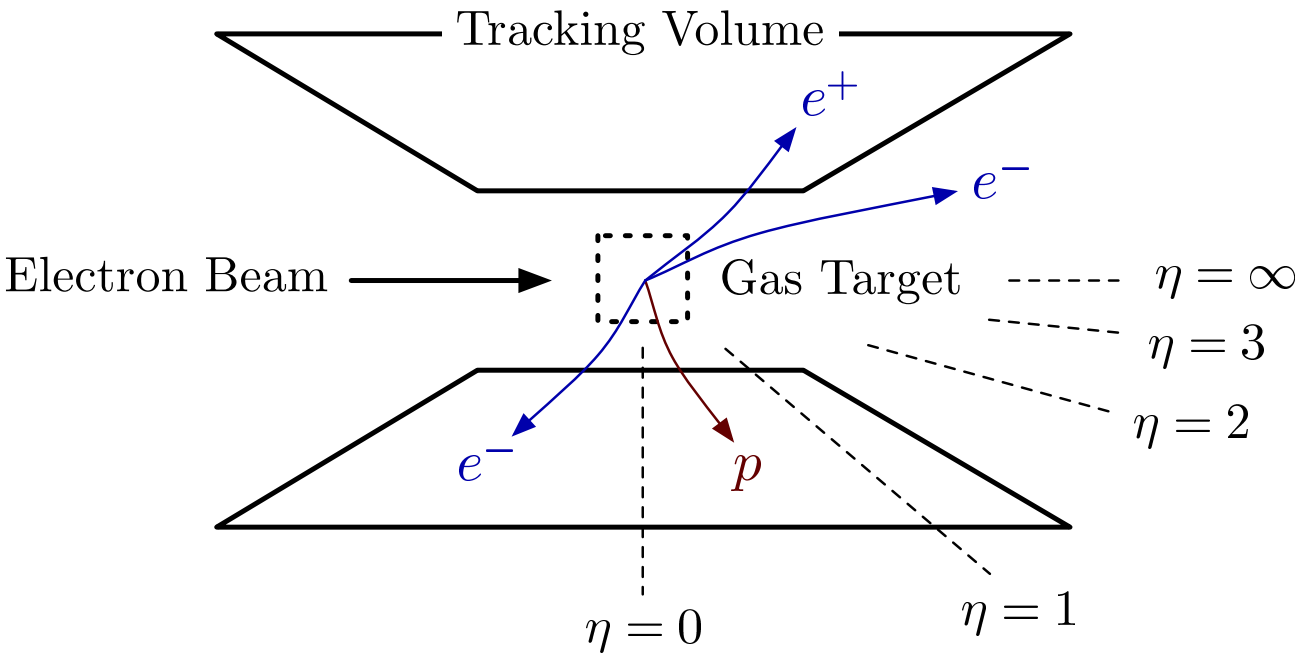


[Andreas,AR '10]

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



[Freytsis, Ovanesyan, Thaler '09]

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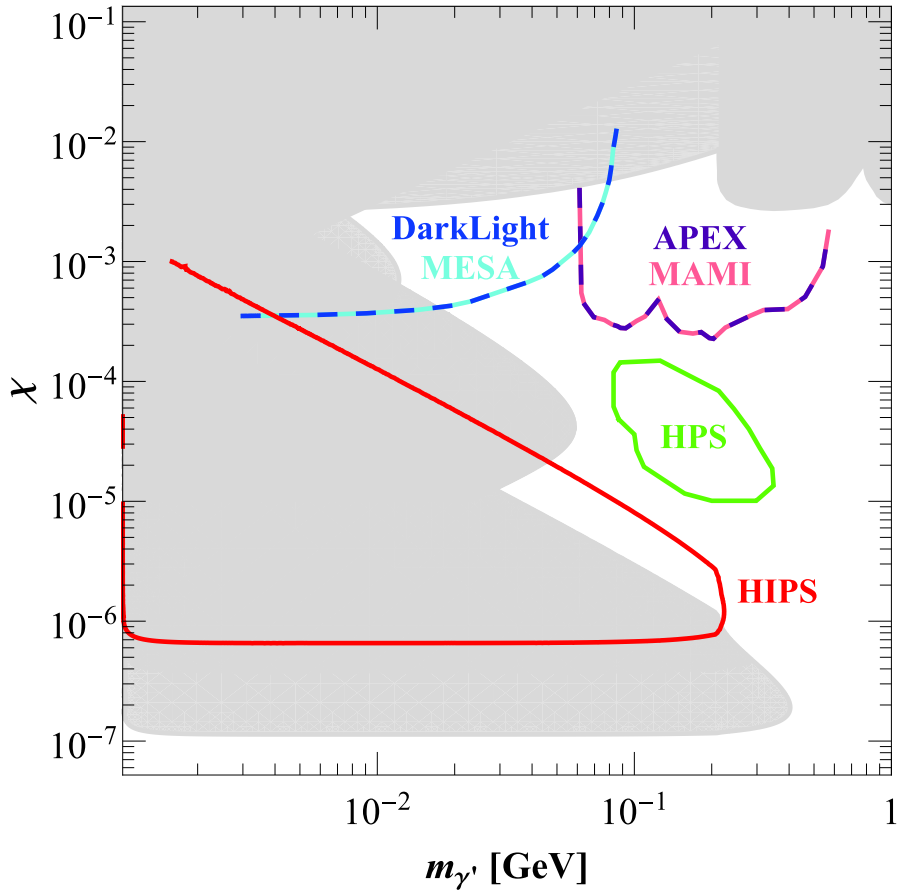

[Andreas,AR '10]

4. Conclusions

- Strong physics motivation for the possible existence of GeV-scale hidden/dark photons:
  - top down: many extra U(1)s in string compactifications
  - bottom up: anomalies associated with dark matter and $(g-2)_\mu$
- Fixed-target experiments well suited to attack dark forces
- Large parameter space requires multiple search strategies and experiments
  - low coupling/mass: new beam dump experiments
  - intermediate region: new forward-geometry experiments
  - high coupling/mass: standard wide-angle spectrometers

$\Rightarrow$ Great opportunities for new particle physics experiments at intensity frontier at DESY, MAMI, and JLab!