Hidden Photons in String Theory, in Cosmology, and in the Laboratory

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Theorietreffen,
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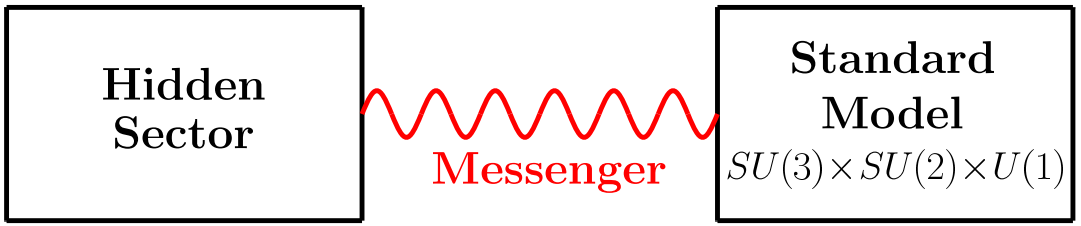
Particle Cosmology in HH DESY T

- **Staff members:** Buchmüller, Lebedev, AR, Westphal, NN
- **Research:**
  - **Early Universe:**
    - inflation
    - leptogenesis
  - **Dark Matter:**
    - WIMPs, superWIMPs, and decaying dark matter:
      top down motivation for gravitinos, hidden gauginos, axinos, ...
      - direct and indirect detection
      - connection to collider searches
    - WISPs:
      top down motivation for axions, hidden U(1)s, ...
      - astrophysical and cosmological probes
      - phenomenology for local experiments

Hidden Sector in String Phenomenology

- 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

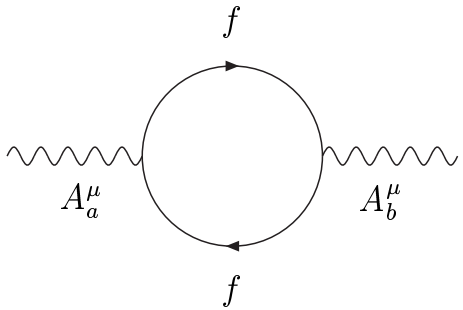
Lagrangian $\Rightarrow$ unsuppressed at low energies [Holdom'85]

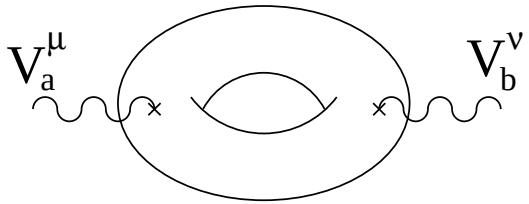
$$\mathcal{L} \supset -\frac{1}{4} F^{(\mathrm{vis})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{vis})} - \frac{1}{4} F^{(\mathrm{hid})}_{\mu\nu} F^{\mu\nu}_{(\mathrm{hid})} + \frac{\chi}{2} F^{(\mathrm{vis})}_{\mu\nu} F^{(\mathrm{hid})\mu\nu} + m^2_{\gamma'} A^{(\mathrm{hid})}_{\mu} A^{(\mathrm{hid})\mu}$$

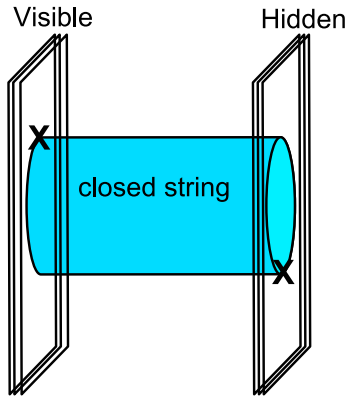
* $\chi \ll 1$ generated at loop level via messenger exchange,

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

* g_h and f depend on the type of messenger:

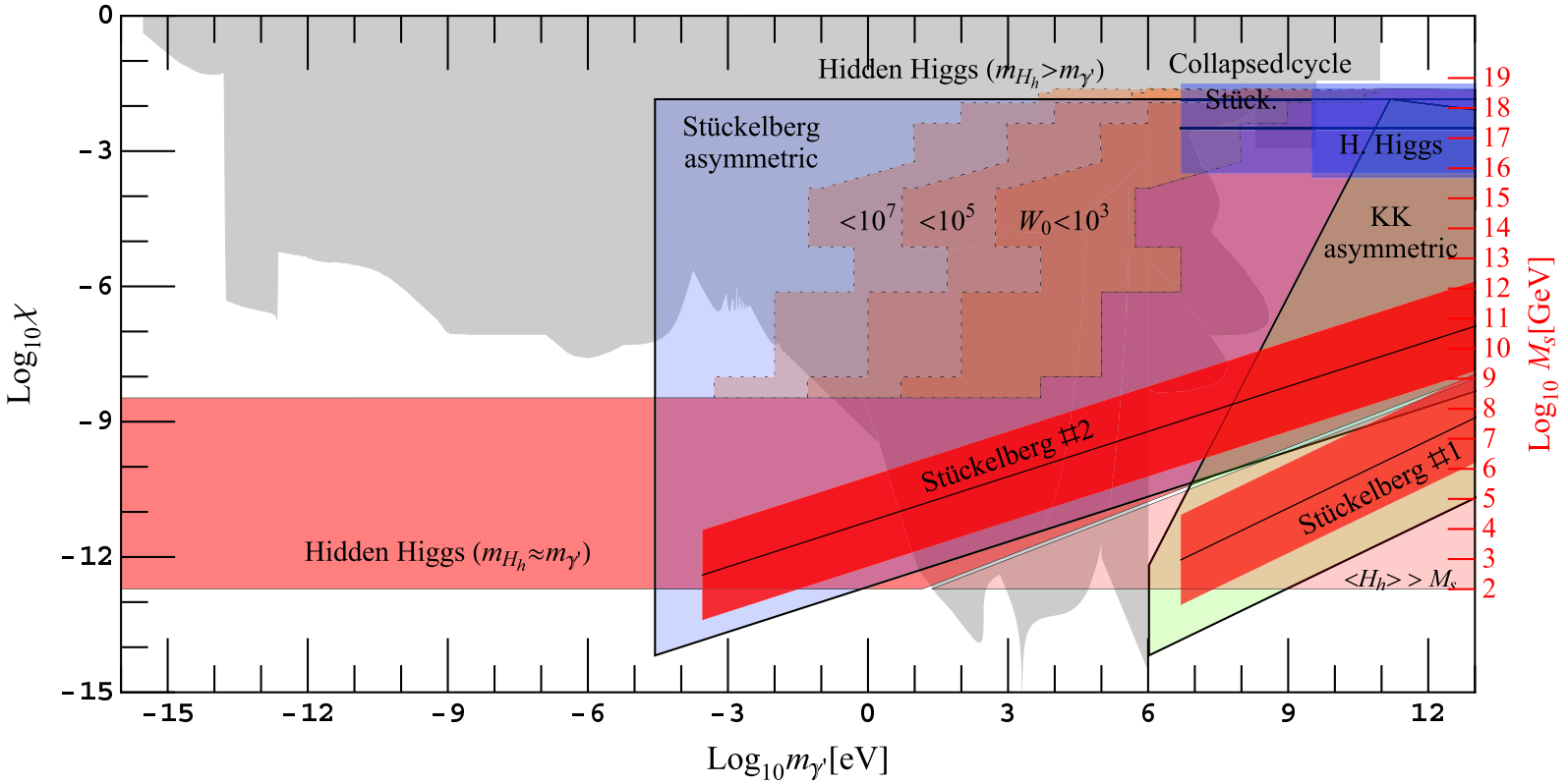






- Predictions of hidden U(1)s from type II string compactifications:

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

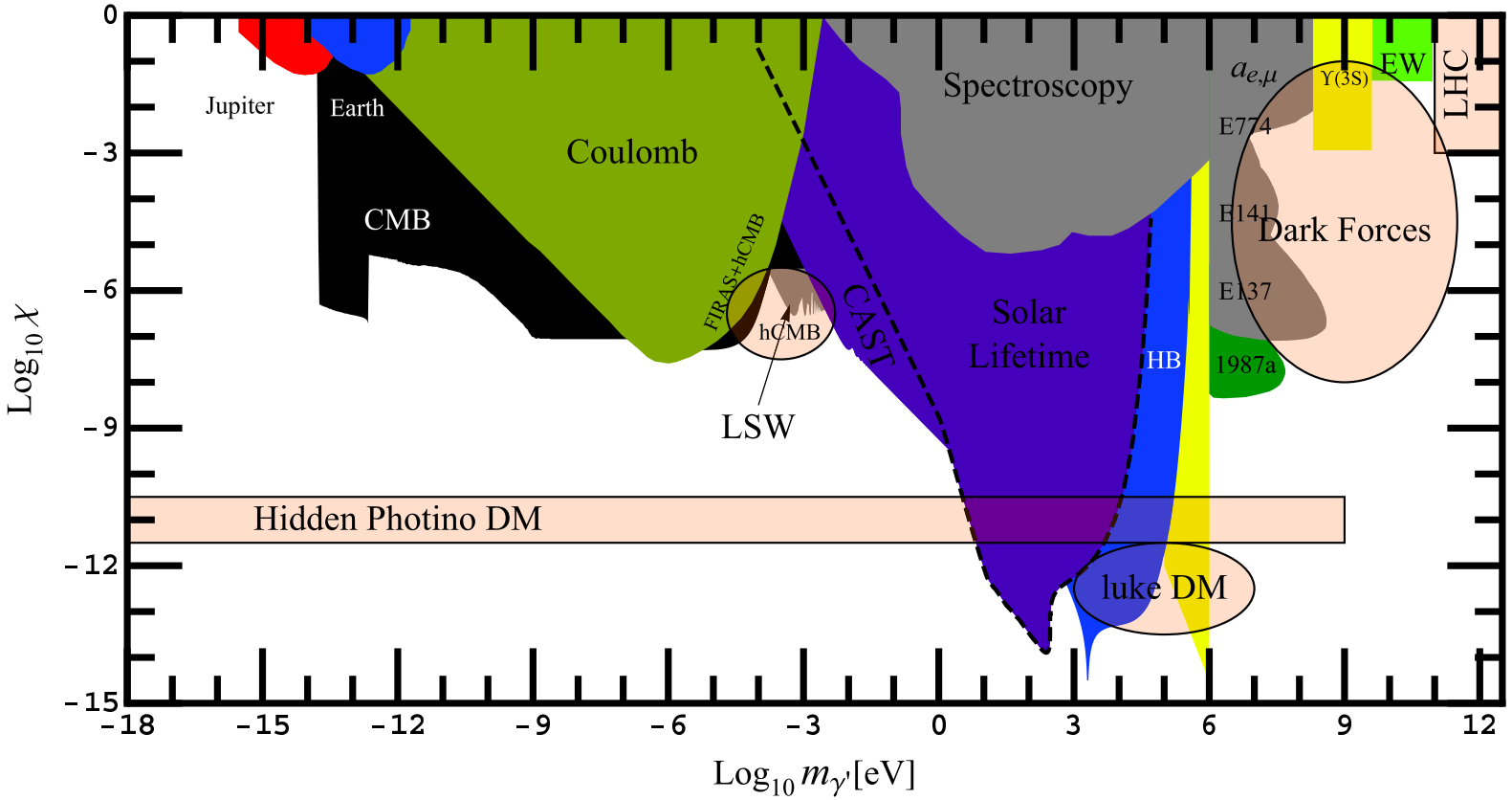


Hidden U(1) string phenomenology in HH DESY T: Cicoli, Goodsell, AR

- 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

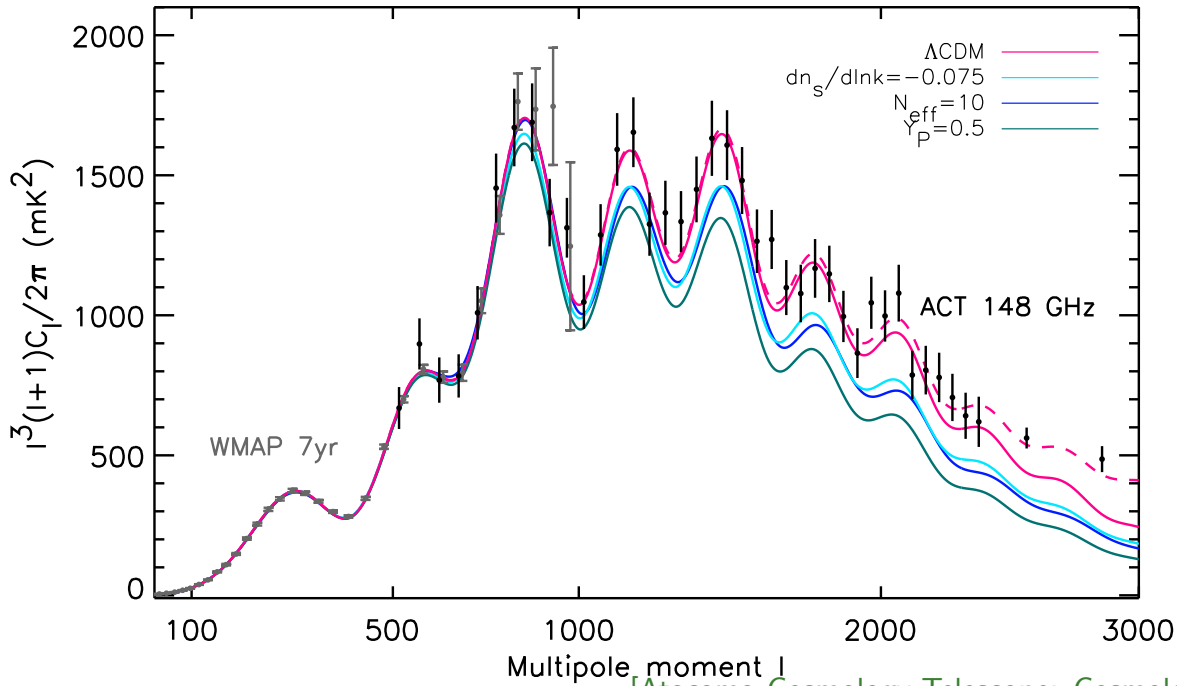
$$x \equiv \rho_{\gamma'}/\rho_\gamma \simeq 3.9 \times 10^{-2}\,(\chi/10^{-6})^2,$$

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

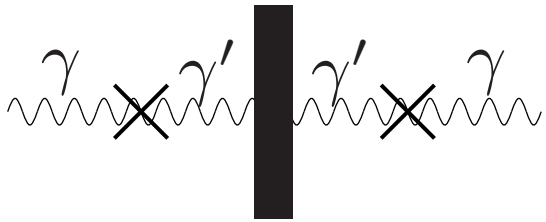
- **Observations seem to favor $N_{\rm eff}^{\nu} > N_{\nu}^{\rm SM} = 3.046$:**
  this may be explained by **meV mass hidden photon with $\chi \sim 10^{-6}$**

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

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

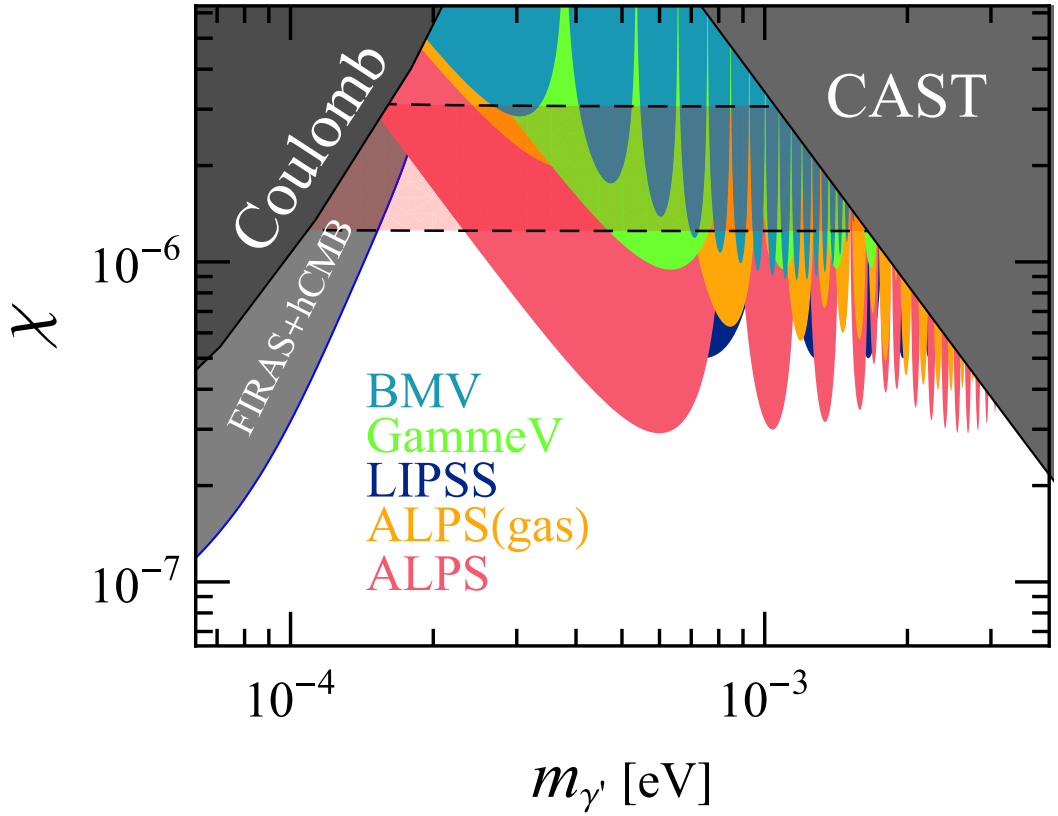
- **meV mass hidden photons** can be searched for in **light-shining-through a wall (LSW) experiment ALPS** (Any Light Particle Search)

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



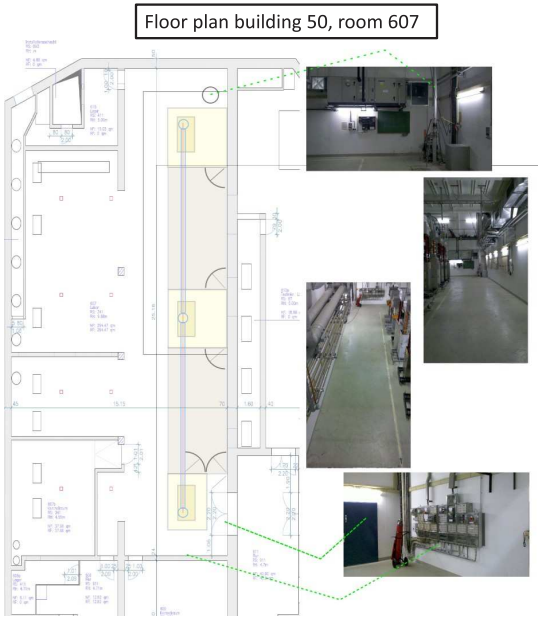
$$P(\gamma \leftrightarrow \gamma') = 4\chi^2 \sin^2\left(\frac{L}{L_{\rm osc}}\right); \qquad L_{\rm osc} = \frac{4\omega}{m^2_{\gamma'}} = 0.79\,{\rm m}\,\left(\frac{\omega}{\rm eV}\right)\left(\frac{\rm meV}{m_{\gamma'}}\right)^2$$

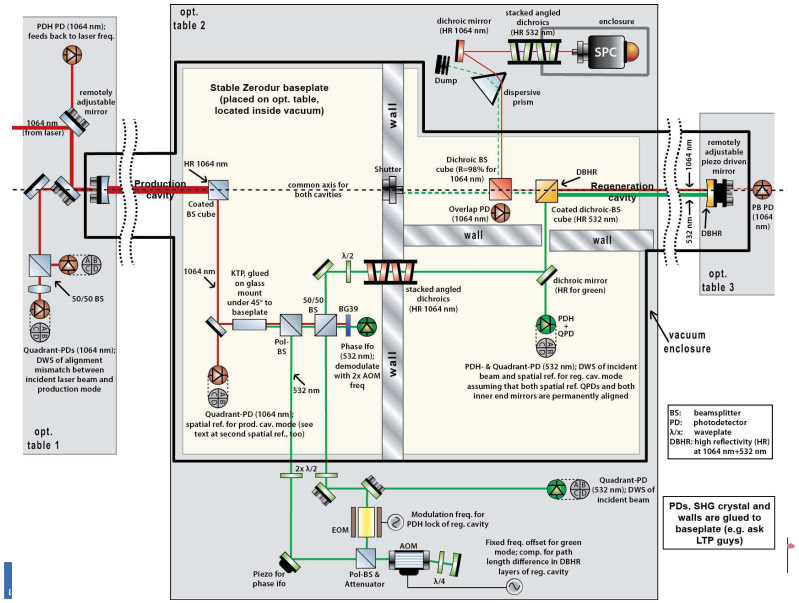
- **Current ALPS** limits on LSW exclude large portion of parameter space compatible with hidden photon explanation of $N_\nu^{\rm eff}$ excess, but there is still room for it:



[ALPS Collaboration '10]

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

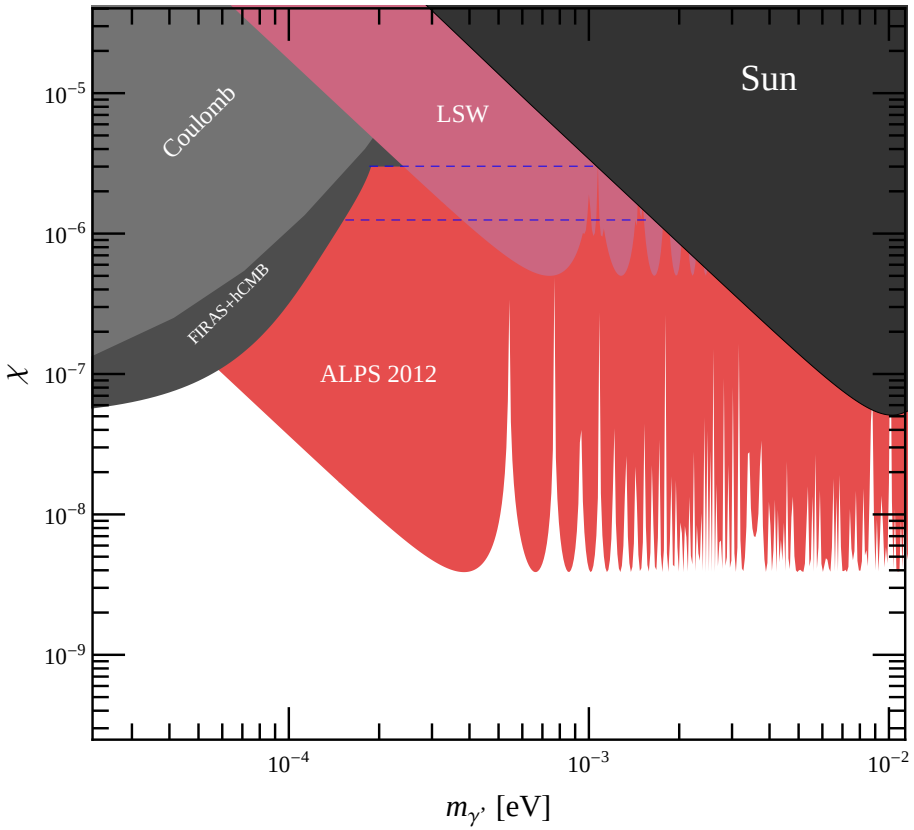




  - higher laser power buildup ($\mathrm{PB_g} \sim 5000$)
  - exploiting also resonant cavity behind the wall ($\mathrm{PB_r} \sim 4 \times 10^4$)
  - better detector
  - prototype for future (> 2014) large scale axion-like particles search experiment exploiting $\geq 6 + 6$ superconducting HERA dipoles

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

Projected sensitivity:



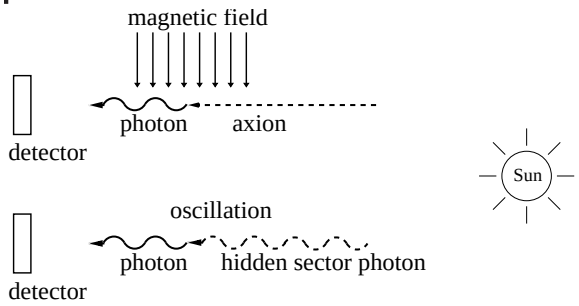
[Arias '11]

Phenomenology for ALPS in HH DESY T: Arias, AR

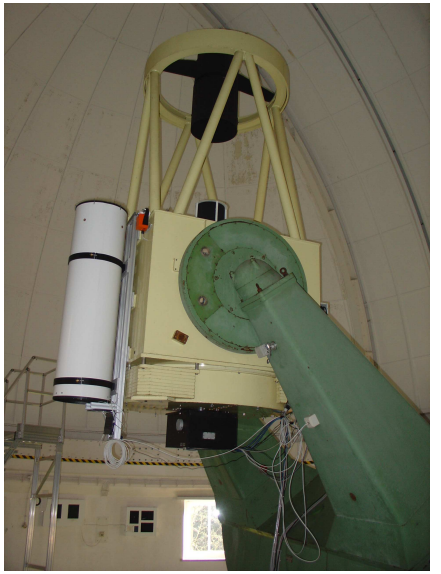
- **SHIPS** (Solar Hidden Photon Search) **may probe hidden CMB parameter space already in 2011:** [Hamburg Observatory, Uni HH, DESY]
  - $\gamma \longrightarrow \gamma'$ oscillations in the solar interior would lead to sizeable flux of solar hidden photons at Earth, [Redondo '08]

$$\frac{d\Phi_{\gamma'}}{d\omega} \gtrsim \frac{4.2 \times 10^5}{\mathrm{cm}^2\,\mathrm{s}\,\mathrm{eV}} \left(\frac{m_{\gamma'}}{0.18\,\mathrm{meV}}\right)^4 \left(\frac{\chi}{2 \times 10^{-6}}\right)^2 ;$$
$$\text{for } \; m_{\gamma'} < 0.1 \text{ eV}, \; \omega = 1 \div 10 \text{ eV}$$

  - 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



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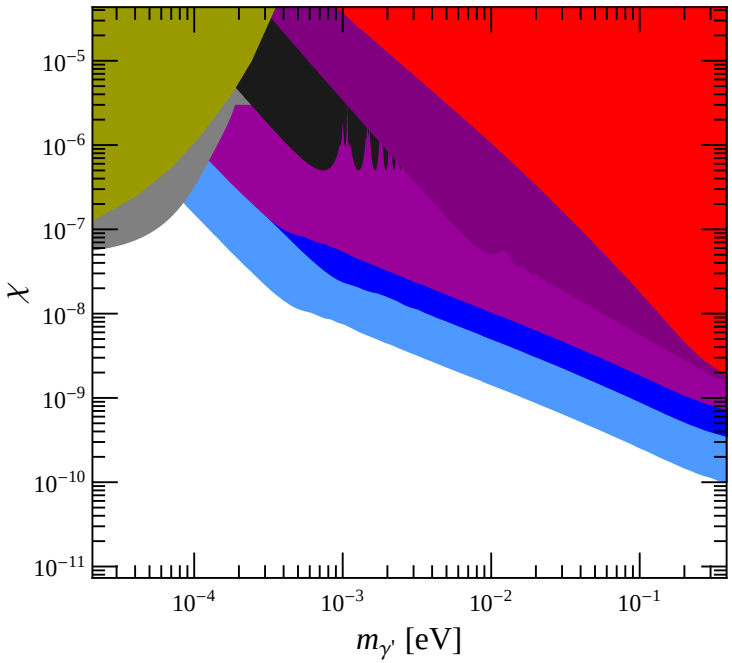
  - projected sensitivities of **toySHIPS** and **CAST:**



[Redondo in prep.]

  - exploit predictions of solar γ' flux also from photosphere

[Cadamuro,Redonde '10 and in prep.]

Phenomenology for SHIPS in HH DESY T: Arias, AR

Sub-GeV Scale Dark Forces?!

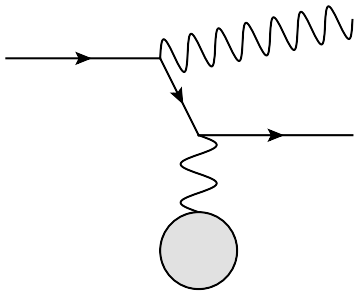
- **MeV-GeV scale hidden photon** (dark force, dark photon, ...)
  - may explain $(g-2)_\mu$ anomaly, if $\chi \sim 10^{-3} \div 10^{-2}$ [Pospelov '08]
  - may explain [Arkani-Hamed *et al.* '08; Pospelov,Ritz '08; Morrissey *et al.* '09;...]
    - terrestrial (DAMA, CoGeNT vs. CDMS, XENON) and
   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

    DM anomalies if DM charged under hidden U(1) and $\chi \gtrsim 10^{-6}$
    - 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**

- **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:



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

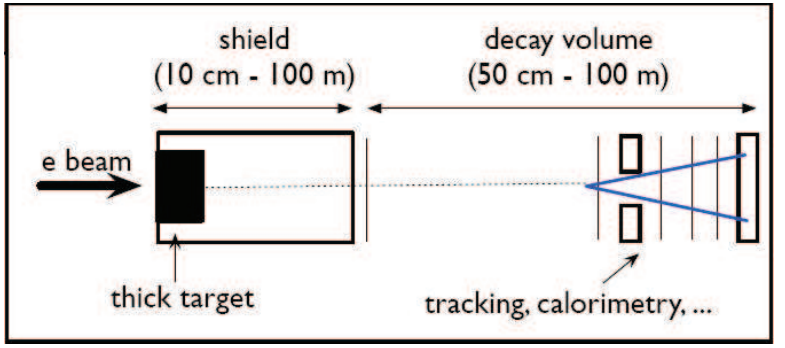
  - Sizeable decay length of $\gamma' \to e^+e^-$,

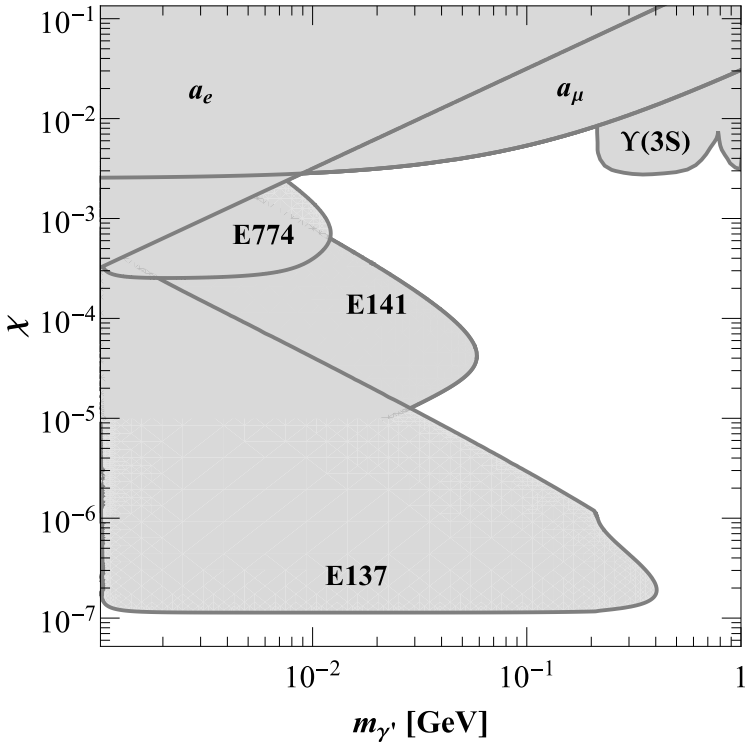
$$\ell_d = \gamma c\tau \sim 8 \text{ cm} \left(\frac{E}{\text{GeV}}\right) \left(\frac{10^{-5}}{\chi}\right)^2 \left(\frac{100 \text{ MeV}}{m_{\gamma'}}\right)^2$$

- **Limits from beam dumps:**

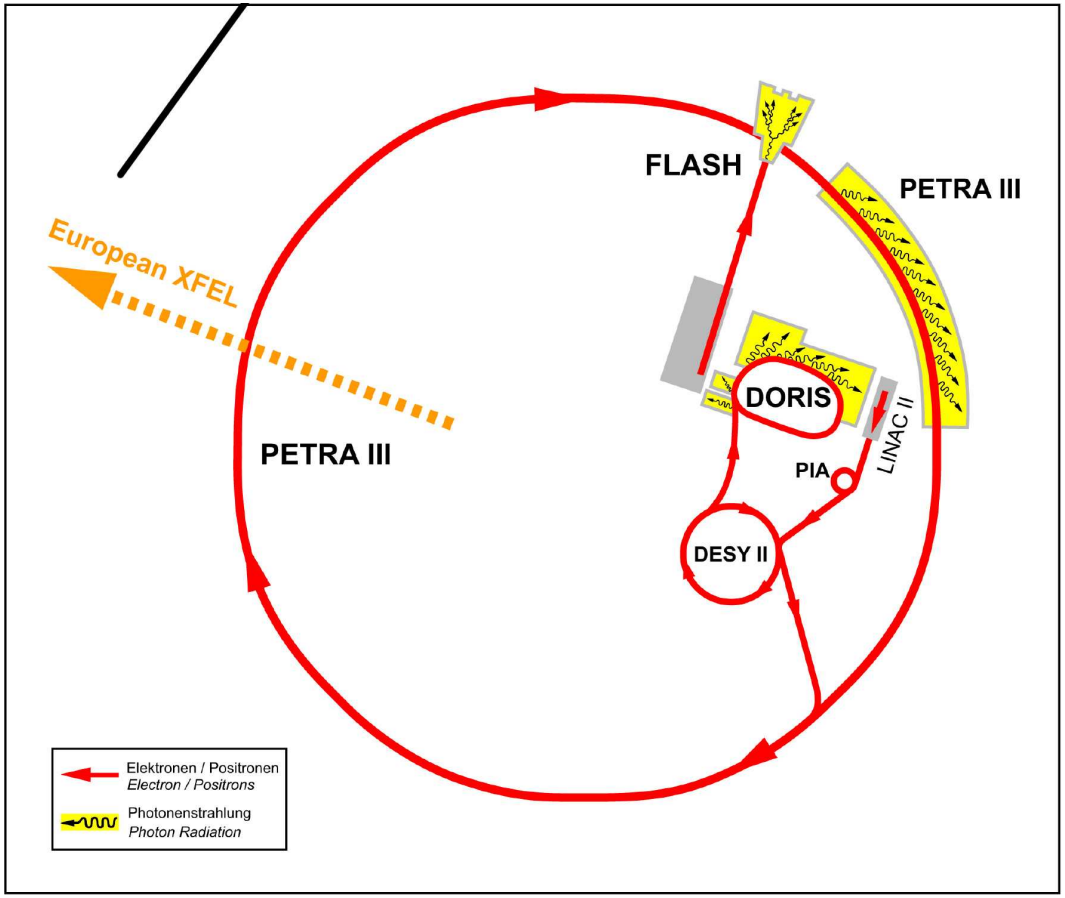
  [Bjorken,Essig,Schuster,Toro '09]

  – 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)

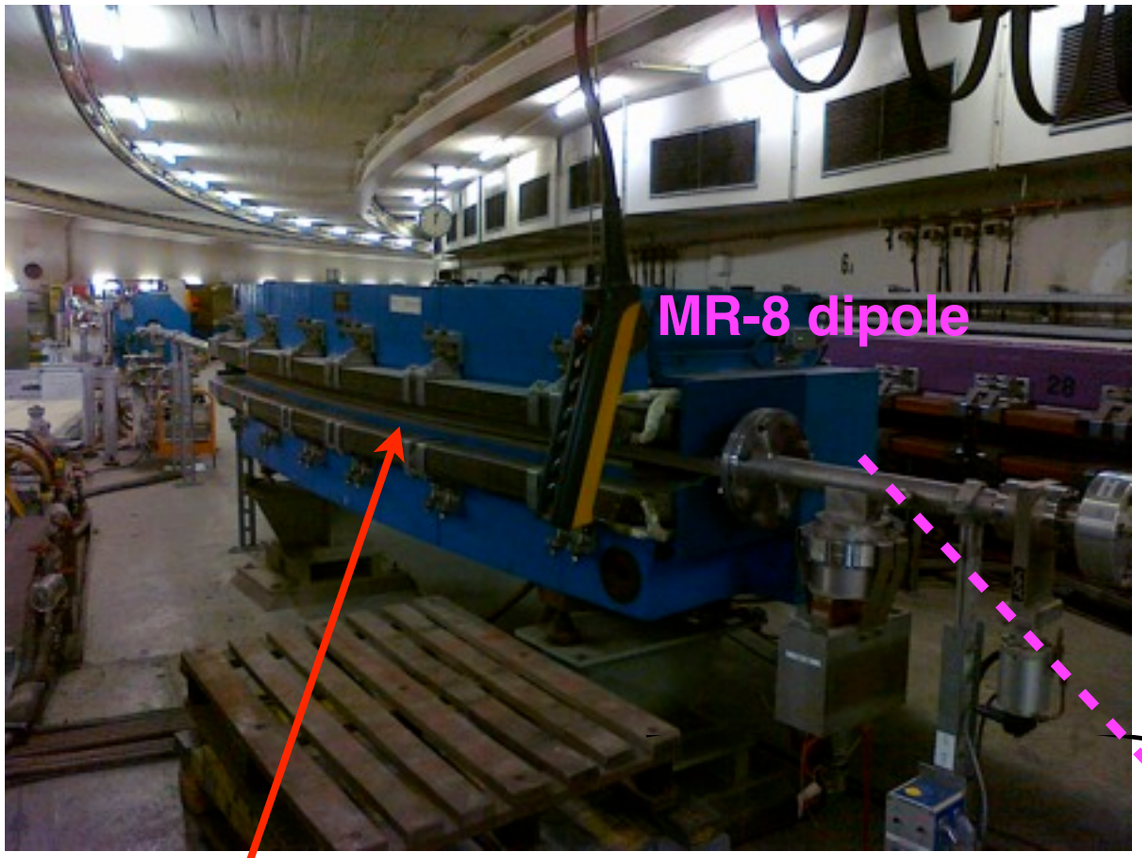


- **HIPS** (HIdden Particle Search): towards a new **beam dump** experiment at DESY II (10 nA, .45–7 GeV)

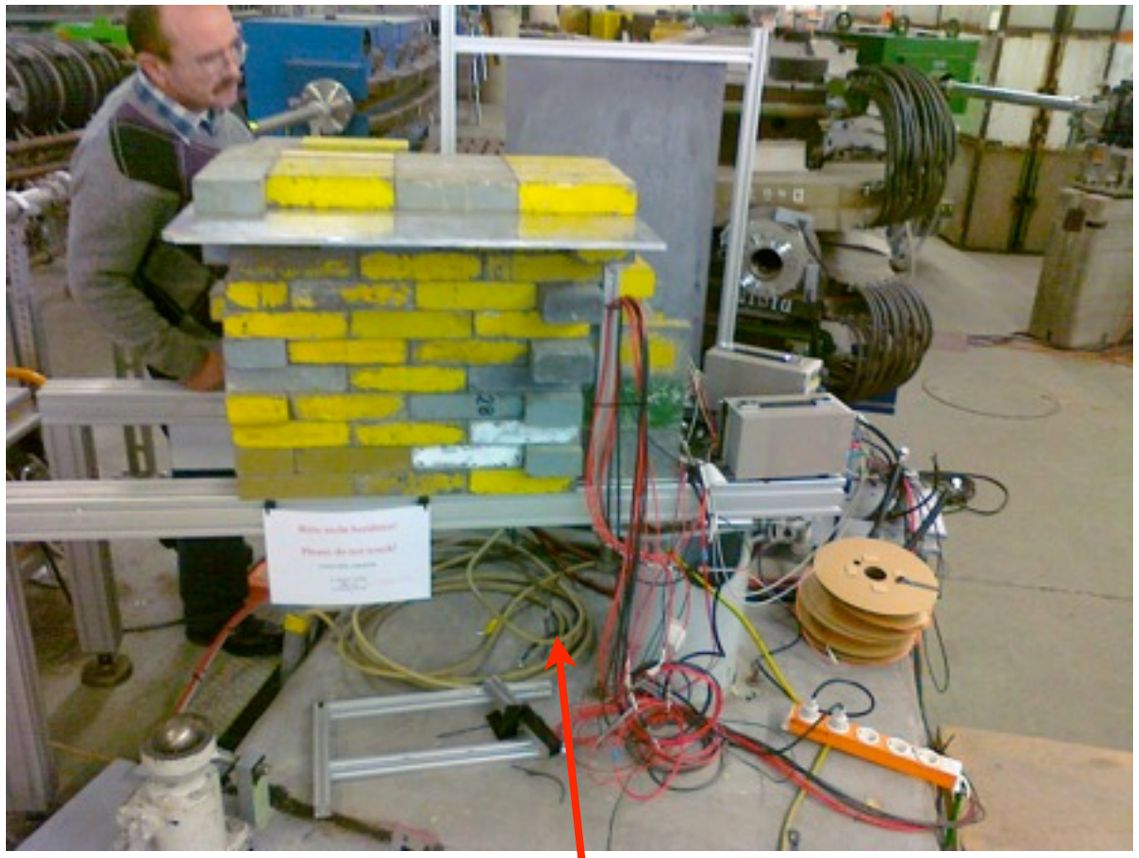
  Current status:

  – HIPS beam extraction chamber installed in Winter shutdown
  – first measurements with scintillators beyond pure Pb beam dump last week; proper development of beam dump (target + shielding) started
  – currently exploring if we can use
    * H1 Spacal super module for calorimetry
    * ZEUS MVD module for tracking (alternatives: SiLC module; MediTPC)

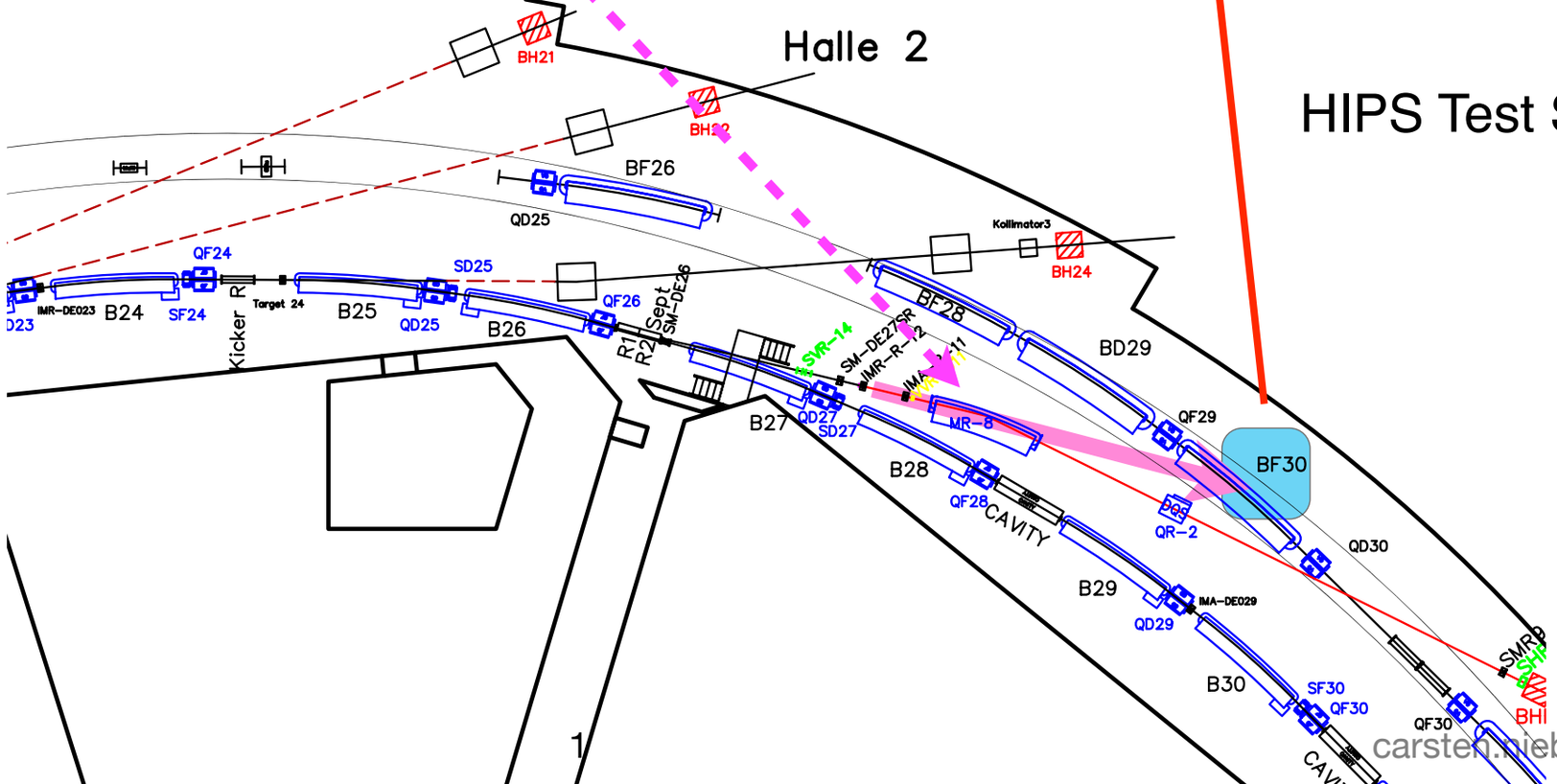
HIPS at DESY II



HIPS beam extraction chamber replaced in DESY Winter shutdown



HIPS Test Setup



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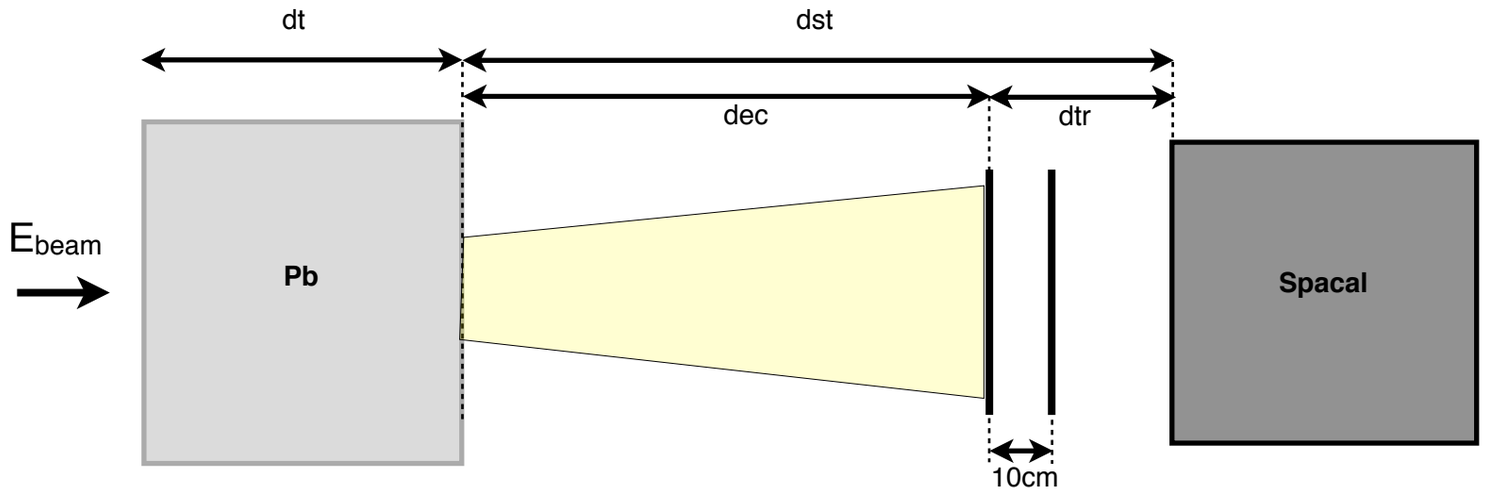
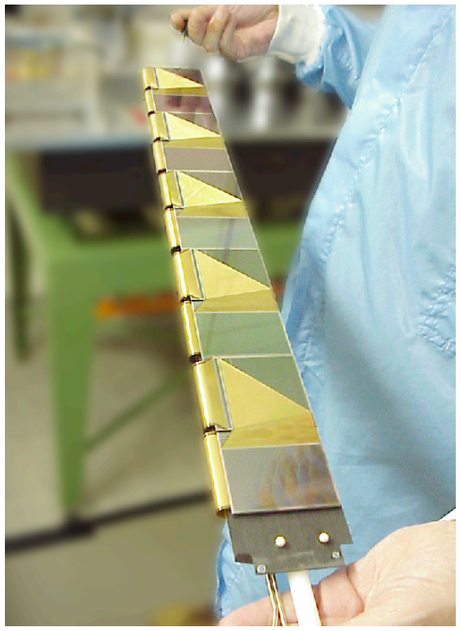
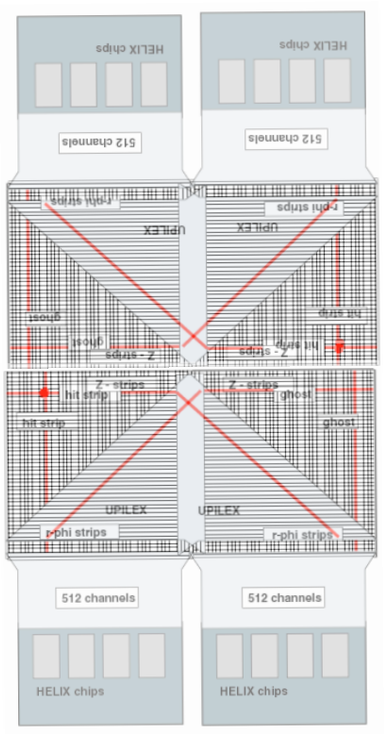
HIPS Detector Considerations

Principle Setup



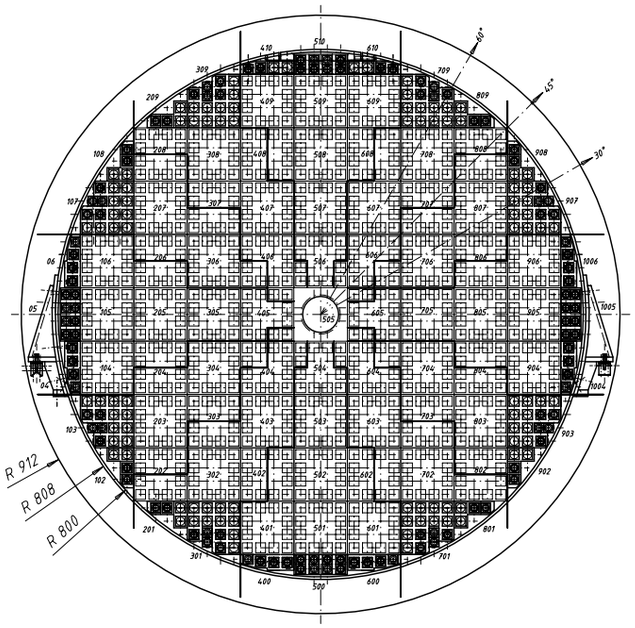
ZEUS MVD module for tracking

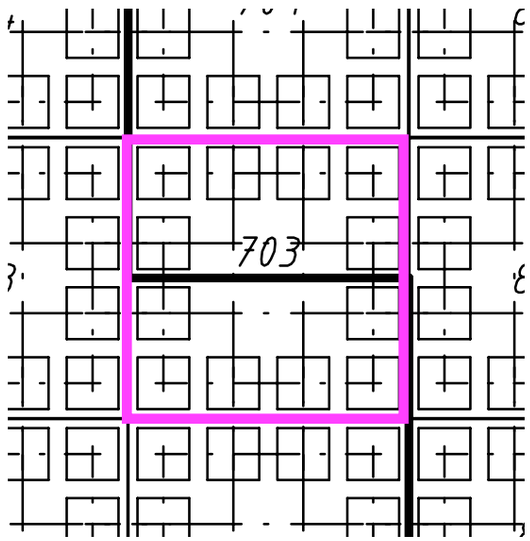




12.4 cm

H1 Spacal Super Module for calorimetry



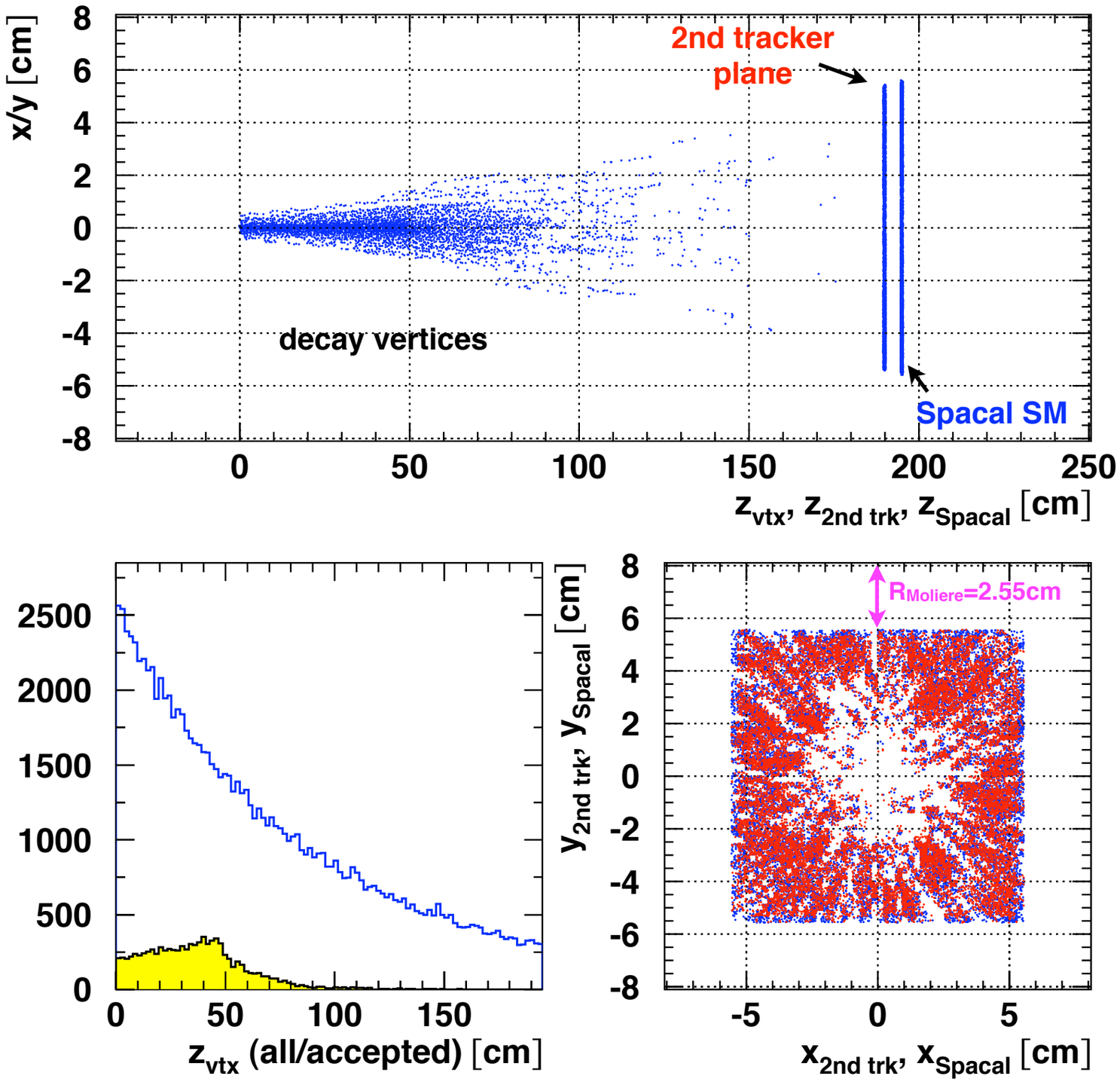


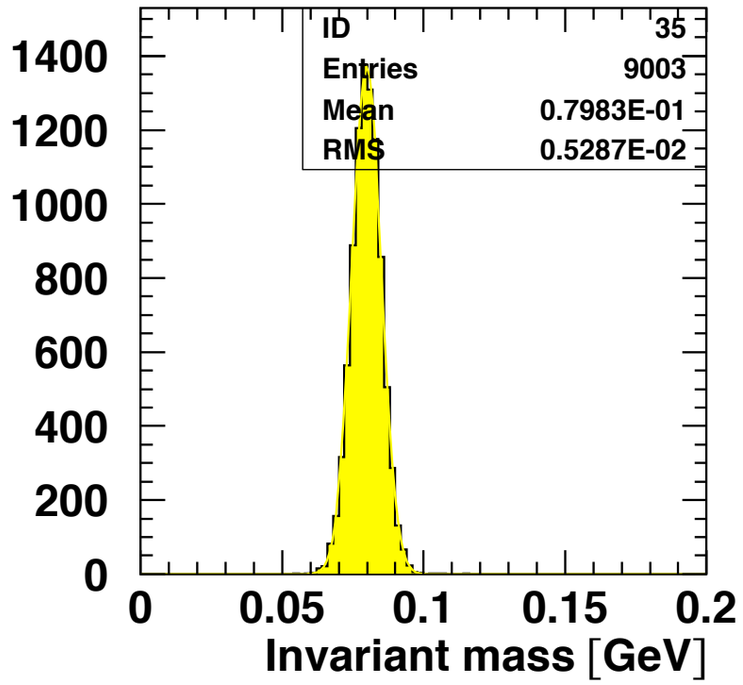
16 cm

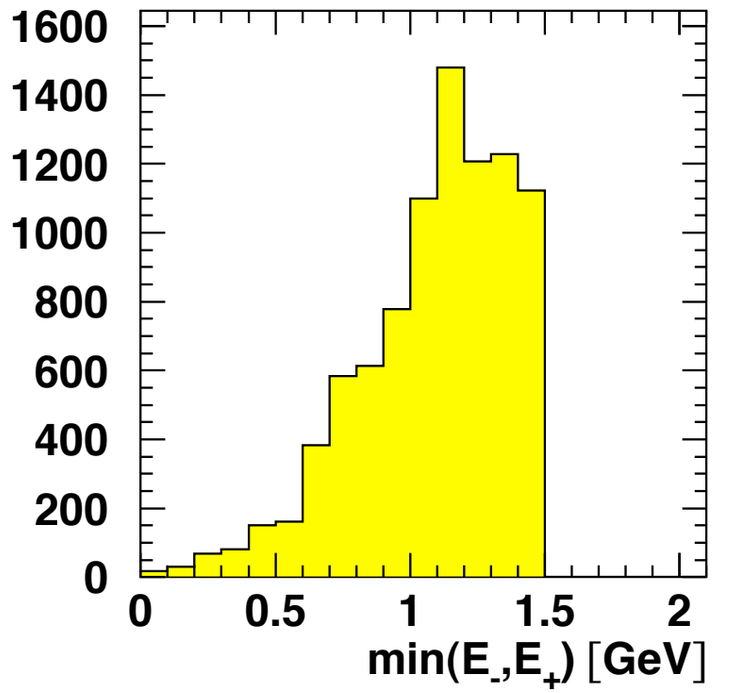
Alternatives: SiLC Module or MediTPC ?

Example for E_{beam}=3GeV and MVD Module

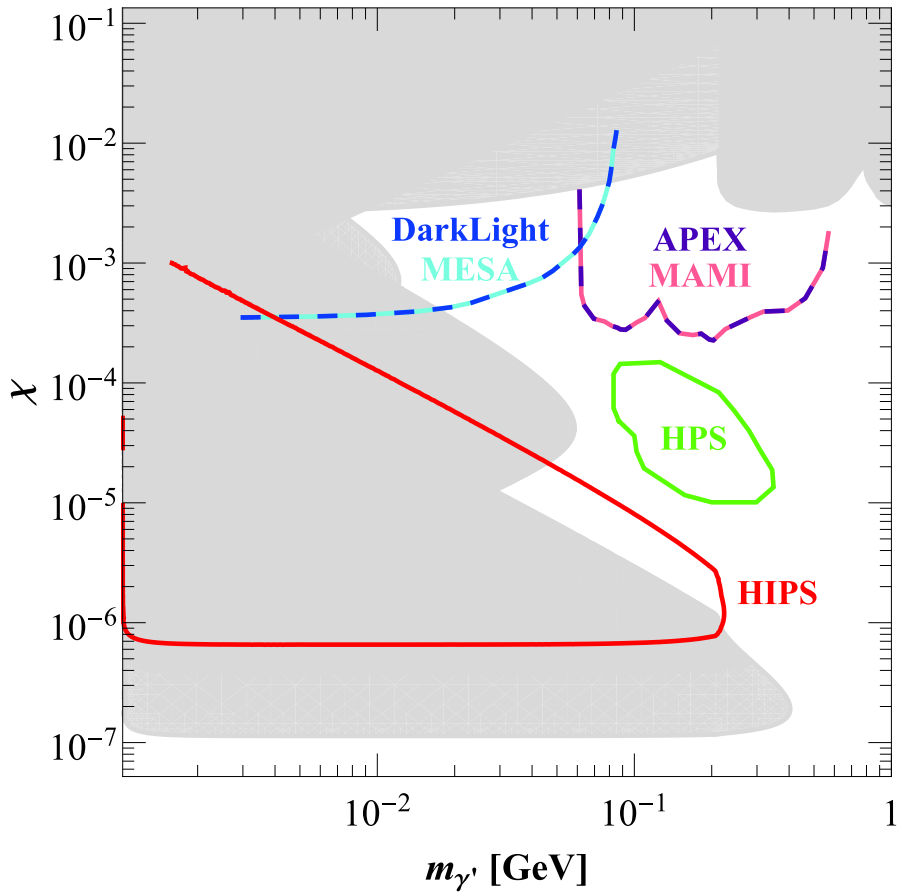
E=3. dt=36.4 N=1 dxt=6.2 drc=8 dec=180 dst=195 A=9







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



[Andreas,AR '10]

Phenomenology for HIPS in HH DESY T: Andreas, Plätzer, AR

Conclusions

- **Hidden photons** are strongly motivated from particle theory, particle phenomenology, particle cosmology, and astroparticle physics, e.g.
  - theory: hidden sectors from string compactifications, ...
  - phenomenology: $(g-2)_\mu$, ...
  - cosmology: hidden CMB, ...
  - astroparticle physics: dark forces in direct and indirect DM searches, ...
- Local low-energy particle physics experiments (ALPS, SHIPS, HIPS) have a large discovery potential for **hidden photons**
- Currently, **DESY** is on the **WISP** forefront both in theory and experiment
- Competitors (CERN, FNAL, MAMI, JLab, ...) do not sleep: have to work hard in order to stay at forefront!