Fundamental Physics at Free Electron Lasers

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Seminar
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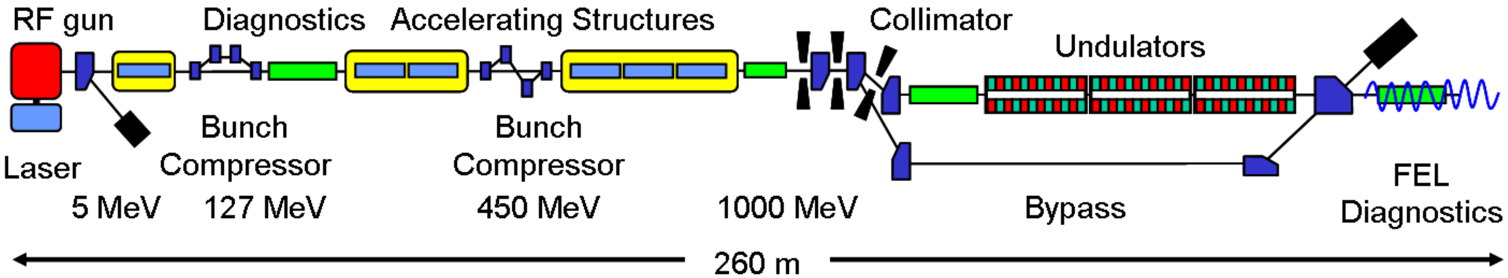
- World-wide a number of

Free Electron Lasers in **VUV to X-Ray Band**

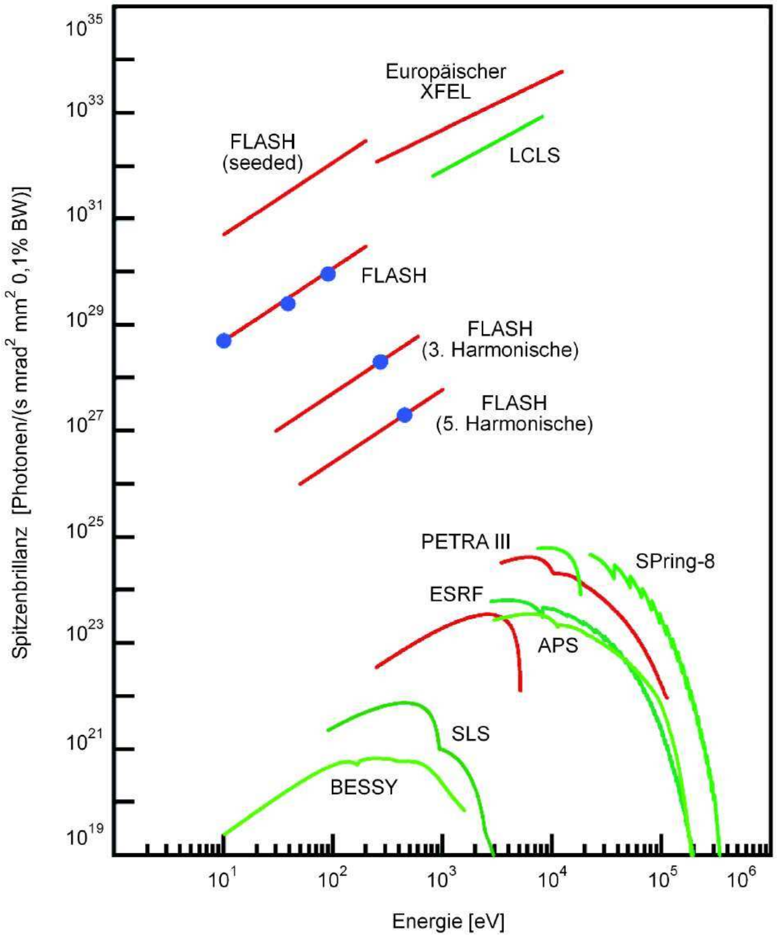
in operation/commissioning/construction/planning, e.g.

- **FLASH: F**ree Electron **LAS**er in **H**amburg at DESY



- **LCLS: L**inac **C**oherent **L**ight **S**ource at SLAC
- **SCSS: S**Pring-8 **C**ompact **S**ASE **S**ource in Japan
- **European XFEL** in Hamburg
- . . .
- **ZFEL** in Groningen

- **Photon beam characteristics**
  - High power
  - Short pulse length
  - Narrow bandwidth
  - Spatial coherence
  - Tunable wavelength



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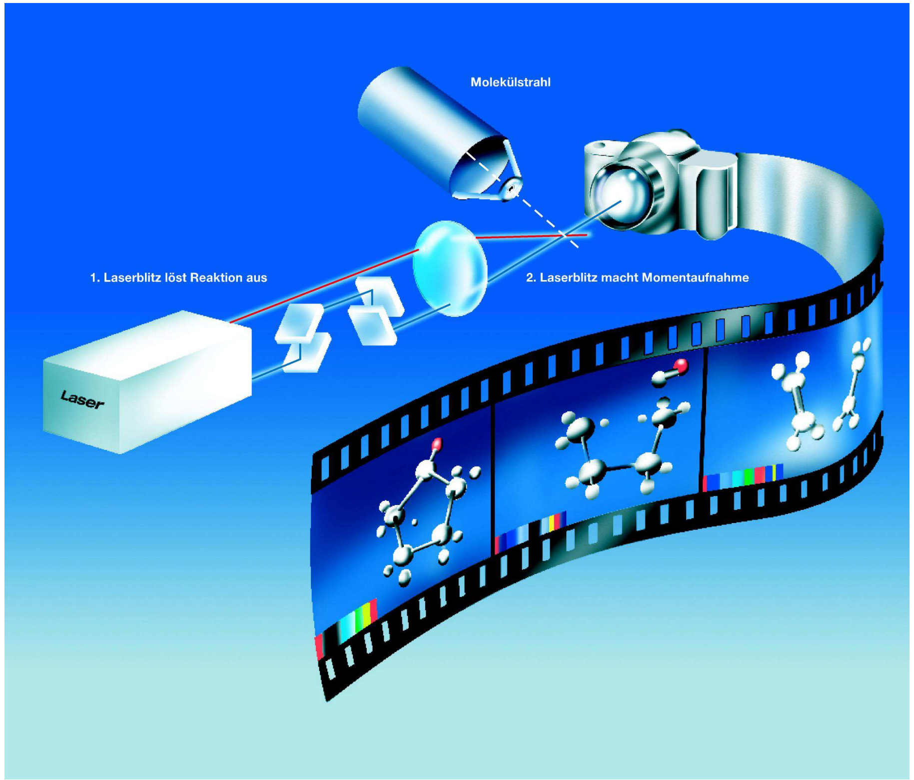

⇒ **Applications**

- Atomic and molecular physics
- Condensed matter physics
- Material science
- Structural biology
- **Chemistry**
- Plasma physics

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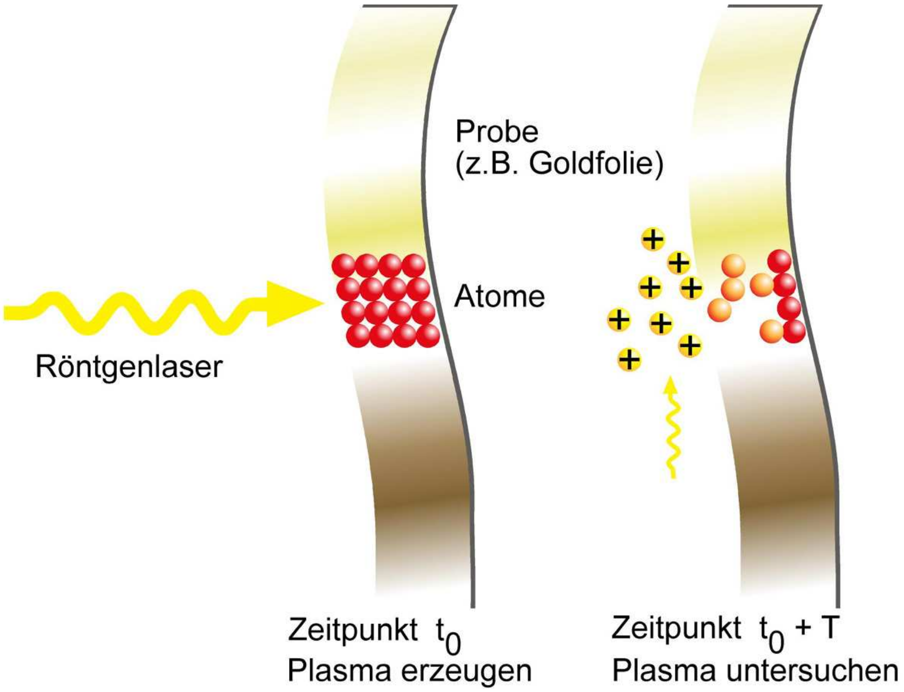
  - Chemistry
  - **Plasma physics**



- **Free electron laser applications in fundamental physics?**
  - **Non-linear and non-perturbative QED**
    - Pair creation in overlap of crossed laser beams
    - Non-linear Compton and pair creation in overlap of electron beam crossed with laser beam
    - Vacuum magnetic birefringence
  - **Searches for very weakly interacting slim particles (WISPs)**
    - Axions and axion-like particles
    - MeV-GeV scale hidden or dark photon γ'

Non-linear and non-perturbative QED

- **Spontaneous pair creation from vacuum**, induced by an **external field**, was first proposed in the context of e^+e^- **pair creation in static, spatially uniform electric field** [Sauter (1931); Heisenberg,Euler (1936); Schwinger (1951); . . .]

  One of the most intriguing non-linear phenomena in quantum field theory
  - theoretically important: beyond perturbation theory
  - eventual experimental observation: probes theory in domain of very strong fields

- Mechanism applied to many problems in contemporary physics:
  - quantum evaporation of black holes [Hawking (1975); Damour,Ruffini (1976); . . .]
  - e^+e^- creation in vicinity of charged black holes [Damour,Ruffini '75; . . .]
  - particle production in early universe [Parker (1969); . . .]
  - particle production in hadronic collisions [Casher, Neuberger, Nussinov (1979); . . .]

- Vacuum in **QED** unstable in a static, spatially uniform electric background field:

$\Rightarrow$ sparks with spontaneous emission of e^+e^- pairs

– observable rate requires extraordinary strong electric field strength, of order

$$\mathcal{E}_c \equiv \frac{m_e\, c^2}{e\, \lambdabar_e} = \frac{m_e^2\, c^3}{e\, \hbar} = 1.3 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}$$

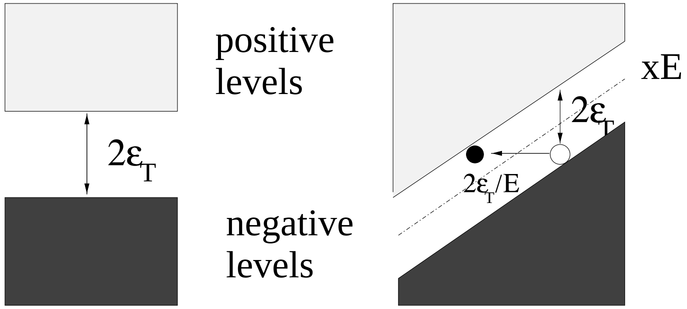
[Sauter (1931); Heisenberg, Euler (1936)]

such that

work of field		**rest energy**
on unit charge e	$\approx$	of e^+e^- pair
over Compton wavelength $\lambdabar_e$		

$$e\, \lambdabar_e\, \mathcal{E}_c \quad = \quad m_e\, c^2$$

- For $\mathcal{E} \ll \mathcal{E}_c$: [Schwinger (1951)]
  - pair creation: **tunneling**
  - rate: **non-perturbative; exponentially suppressed,**



$$w = \frac{d^4 n_{e^+e^-}}{d^3x\,dt} \propto \exp\left[-\pi \frac{\mathcal{E}_c}{\mathcal{E}}\right] = \exp\left[-\pi \frac{m_e^2\, c^3}{\hbar\, e\, \mathcal{E}}\right]$$

- No human-made macroscopic static fields of order $\mathcal{E}_c$ accessible
- Proposals (in early 1970's):
  - critical fields in **nuclear collisions with** $Z_1 + Z_2 \approx 1/\alpha$?

    [Zel'dovich, Popov (1971); Müller, Rafelski, Greiner (1972)]
  - critical fields **at focus**[1] **or at overlap of crossed**[1] **intense lasers**?

    [Bunkin, Tugov (1969); Brezin, Itzykson (1970); Popov (1971);...; Fried *et al.* (2001)]

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[1] No pair creation in plane wave.

Pair creation in overlap of crossed laser beams

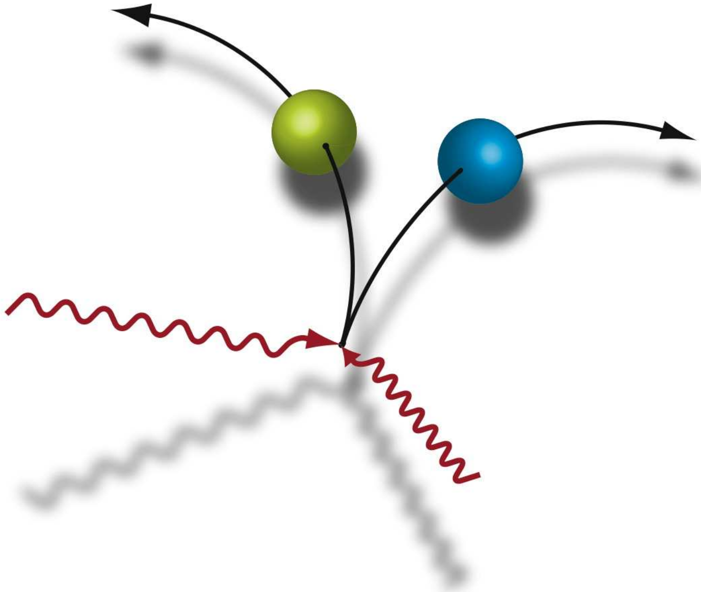


Illustration from [Marklund,Lundin ‘08]

- For realistic lasers,

$$\mathcal{E} \ll \mathcal{E}_c = \frac{m_e^2\, c^3}{e\, \hbar}\,, \qquad\qquad \hbar\omega \ll m_e c^2,$$

rate of spontaneous e^+e^- creation calculable in **semi-classical** manner

[Brezin,Itzykson (1970), Popov (1971)];...]

$$w \equiv \frac{\mathrm{d}^4\, n_{e^+e^-}}{\mathrm{d}^3x\, \mathrm{d}t} \simeq \frac{c}{4\,\pi^3 {\lambda\!\!\!^{-}}_e{}^4} \times$$

$$\times \begin{cases} \frac{\sqrt{2}}{\pi}\left(\frac{\mathcal{E}}{\mathcal{E}_c}\right)^{\frac{5}{2}} \exp\left[-\pi\,\frac{\mathcal{E}_c}{\mathcal{E}}\left(1-\frac{1}{8}\eta^{-2}+\mathcal{O}(\eta^{-4})\right)\right], & : \quad \eta \gg 1\,, \\ \sqrt{\frac{\pi}{2}}\left(\frac{\hbar\,\omega}{m_ec^2}\right)^{\frac{5}{2}} \sum_{n>2\frac{m_ec^2}{\hbar\omega}} \left(\frac{\mathrm{e}\,\eta}{4}\right)^{2n} \mathrm{e}^{-2\left(n-2\frac{m_ec^2}{\hbar\omega}\right)} \mathrm{Erfi}\left(\sqrt{2\left(n-2\frac{m_ec^2}{\hbar\omega}\right)}\right) & : \quad \eta \ll 1\,, \end{cases}$$

- Dimensionless adiabaticity parameter η,

$$\eta \equiv \frac{e\,\mathcal{E}\,{\lambda\!\!\!^{-}}_e}{\hbar\,\omega} = \frac{e\,\mathcal{E}}{m_e c\,\omega}$$

  - **$\eta \gg 1$:** Adiabatic high-field, low-frequency limit agrees with **non-perturbative Schwinger result** for a static, spatially uniform field.
  - **$\eta \ll 1$:** Non-adiabatic low-field, high-frequency limit resembles **perturbative result:** corresponds to $\geq n$-th order perturbation theory, n being the minimum number of quanta required to create an e^+e^- pair: $n \gtrsim 2\, m_e c^2/(\hbar\omega) \gg 1$

- Laser parameters:

Laser parameter				
		Optical	**XFEL**	
		focus: **state-of-art**	design **SASE 5**	focus: **state-of-art**
wavelength	λ	1 μm	0.4 nm	0.4 nm
photon energy	$\hbar\,\omega = \frac{hc}{\lambda}$	1.2 eV	3.1 keV	3.1 keV
max. power	P	1 PW	110 GW	1.1 GW
spot radius (rms)	σ	1 μm	26 μm	21 nm
coherent spike length (rms)	$\triangle t$	500 fs ÷ 20 ps	0.04 fs	0.04 fs
derived quantities				
max. power density	$S = \frac{P}{\pi\sigma^2}$	$3\cdot 10^{22}\ \frac{\rm W}{\rm cm^2}$	$5\cdot 10^{15}\ \frac{\rm W}{\rm cm^2}$	$8\cdot 10^{19}\ \frac{\rm W}{\rm cm^2}$
max. electric field	$\mathcal{E} = \sqrt{\mu_0\, c\, S}$	$4\cdot 10^{14}\ \frac{\rm V}{\rm m}$	$1\cdot 10^{11}\ \frac{\rm V}{\rm m}$	$2\cdot 10^{13}\ \frac{\rm V}{\rm m}$
max. electric field/critical field	$\mathcal{E}/\mathcal{E}_c$	$3\cdot 10^{-4}$	$1\cdot 10^{-7}$	$1\cdot 10^{-5}$
photon energy/e-rest energy	$\frac{\hbar\omega}{m_e c^2}$	$2\cdot 10^{-6}$	0.006	0.006
adiabaticity parameter	$\eta = \frac{e\,\mathcal{E}\,\bar{\lambda}_e}{\hbar\omega}$	$1\cdot 10^{2}$	$2\cdot 10^{-5}$	$2\cdot 10^{-3}$

- Minimum necessary peak power for observable effect: [AR (2001)]

	λ	σ	$\triangle t$	$P_{\rm min}$	$S_{\rm min}$	$\mathcal{E}_{\rm min}$
Focused XFEL:	0.1 nm	0.1 nm	0.1 ps	2.5 TW	$7.8 \cdot 10^{27}$ W/cm^2	$1.7 \cdot 10^{17}$ V/m
(≈ “aim”)	0.1 nm	0.1 nm	0.1 fs	4.5 TW	$1.4 \cdot 10^{28}$ W/cm^2	$2.3 \cdot 10^{17}$ V/m
Focused XFEL:	0.1 nm	20 nm	0.1 ps	38 PW	$3.0 \cdot 10^{27}$ W/cm^2	$1.1 \cdot 10^{17}$ V/m
(≈ “state-of-art”)	0.1 nm	20 nm	0.1 fs	55 PW	$4.3 \cdot 10^{27}$ W/cm^2	$1.3 \cdot 10^{17}$ V/m
Focused optical laser:	1 μm	1 μm	10 ps	49 EW	$1.6 \cdot 10^{27}$ W/cm^2	$7.7 \cdot 10^{16}$ V/m
diffraction limit	1 μm	1 μm	100 fs	58 EW	$1.8 \cdot 10^{27}$ W/cm^2	$8.3 \cdot 10^{16}$ V/m

⇒ Need **tens of EW optical laser** or **TW X-ray FEL**

⇐ Power densities and electric fiels that can be reached with presently available techniques far too small for observable effect (cf. extra table)

- Conceivable **improvements** in **XFEL** technology:
  - X-ray optics, in order to approach diffraction limit $\sigma \gtrsim \lambda$
  - energy extraction, in order to increase power
- Hard to predict whether this goal will be reached before the commissioning of EW-ZW optical lasers ($\gtrsim 2020$?).

Pair creation in overlap of electron beam crossed with laser beam

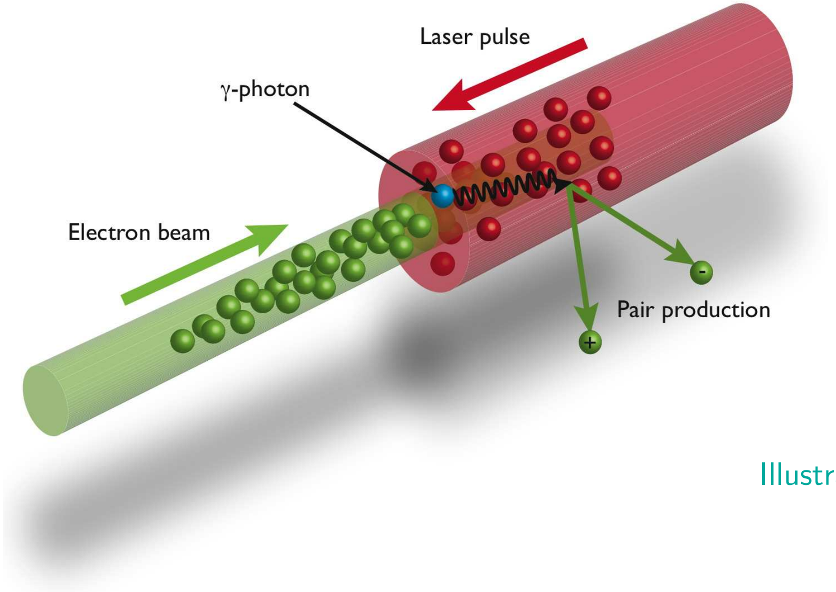
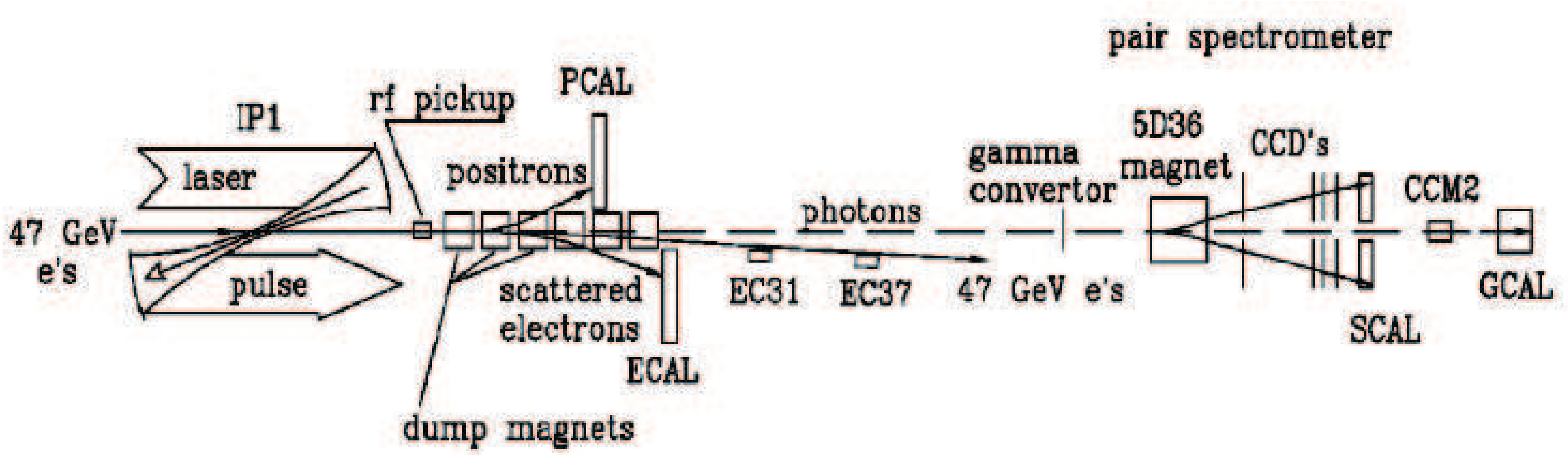


Illustration from [Marklund,Lundin '08]

- Two stage process:
  - non-linear Compton process, $e + n\,\gamma_{\rm L} \to e + \gamma$, followed by
  - stimulated, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$, or spontaneous pair production

- **SLAC E144** studied **non-linear Compton and stimulated pair production** in the collision of a **46.6 GeV electron beam** (the Final Focus Test Beam) with **terawatt photon pulses** of 1053 nm and 527 nm

[Bula et al., PRL 76 (1996) 3116; Burke et al., PRL 79 (1997) 1626; Bamber et al., PRD 60 (1999) 092004]



- **Non-linear QED in $e\gamma_{\rm L}$ coll.:**
  adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$

  - **Non-linear Compton**
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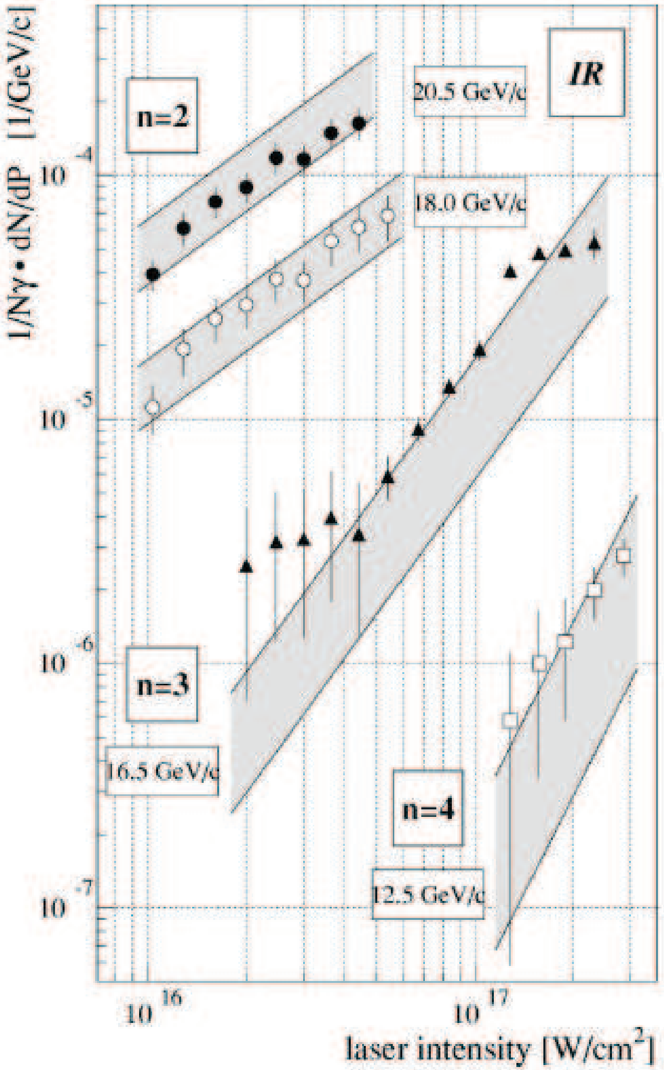
    Electron yield,
    $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$



[SLAC E144]

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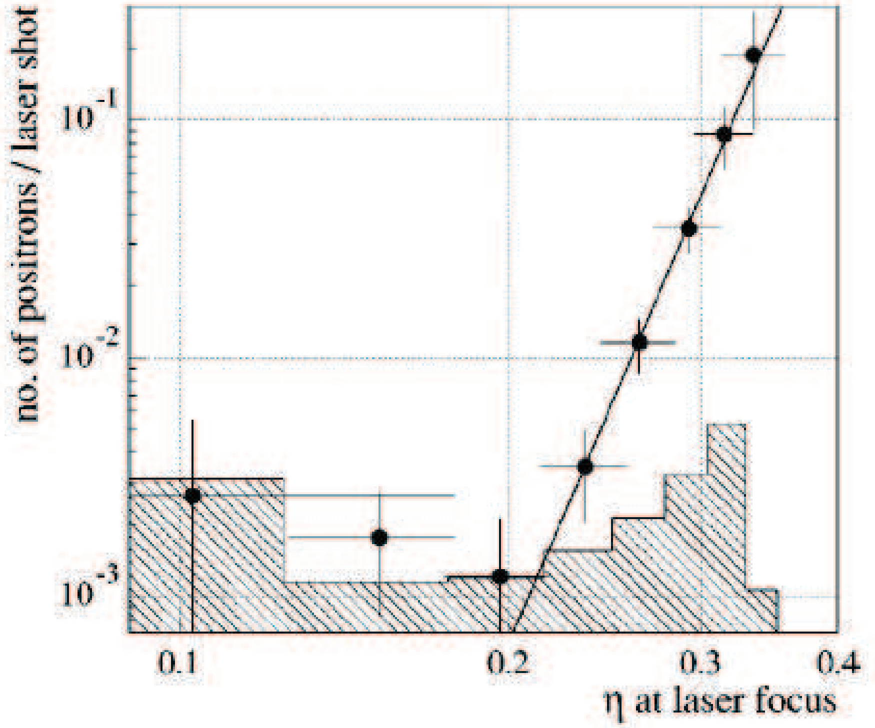
    $e + n\,\gamma_{\rm L} \to e + \gamma$
    Electron yield,
    $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$
  - **Pair production:**
    - **$\eta \ll 1$:** stimulated process, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$, positron rate, $R_{e^+} \propto \eta^{2n} \propto I^n$
    - **$\eta \gg 1$:** non-perturbative, spontaneous tunneling process, $R_{e^+} \propto \exp(-8/3\kappa)$, where $\kappa = 2\frac{\omega'}{m_e}\frac{\mathcal{E}}{\mathcal{E}_c}$, not observed yet:
      SLAC E144: $\eta \ll 1$, $\kappa \ll 1$



[SLAC E144]

Improvements over SLAC 144: petawatt laser pulses to probe $\eta \gg 1$, $\kappa \lesssim 1$:

$$\eta = 7.6 \left[\frac{I}{10^{21}\ \mathrm{W/cm^2}}\right]^{1/2} \left[\frac{\lambda_{\mathrm{L}}}{0.4\ \mu\mathrm{m}}\right]$$

LASER	SLAC 144	Required e.g.
Wavelength	527-1064 nm	800 nm
Intensity on target	10^{18} W/cm^2	10^{21} W/cm^2
η (maximum)	0.32	15.38

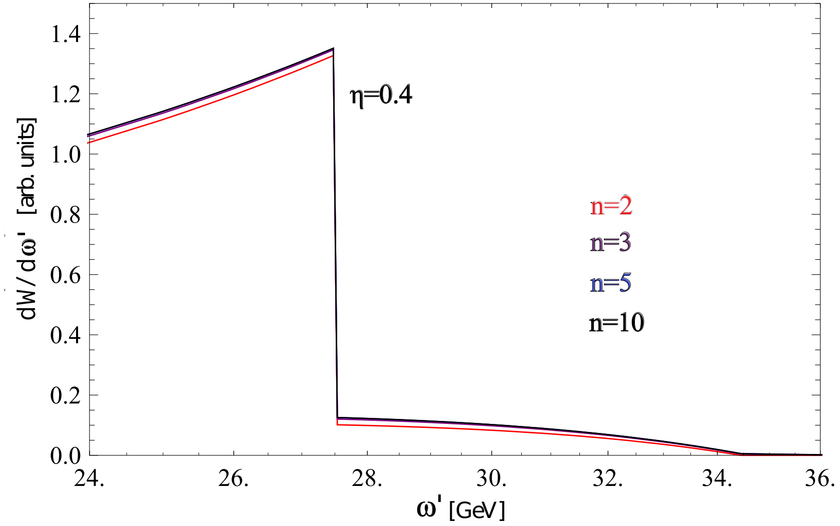
$$\kappa = 0.94 \left[\frac{I}{10^{21}\mathrm{W/cm}^2}\right]^{1/2} \left[\frac{\omega'}{5\ \mathrm{GeV}}\right]$$

Experiment	ω' [GeV]	I [W/cm^2]	κ
SLAC	29	10^{18}	0.17
FLASH	0.2	10^{21}	0.03
XFEL	5	10^{21}	0.94

⇒ **Crossing FEL electron beam pulses with intense laser pulses allows**

- **unprecedented studies of non-linear Compton scattering**
- **the first experimental observation of non-perturbative, spontaneous pair production**

SLAC:



[Arias,Redondo,AR]

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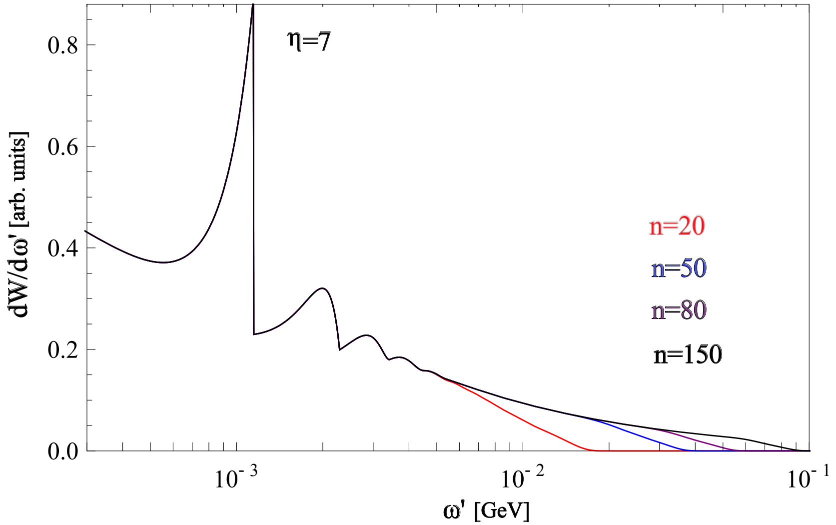

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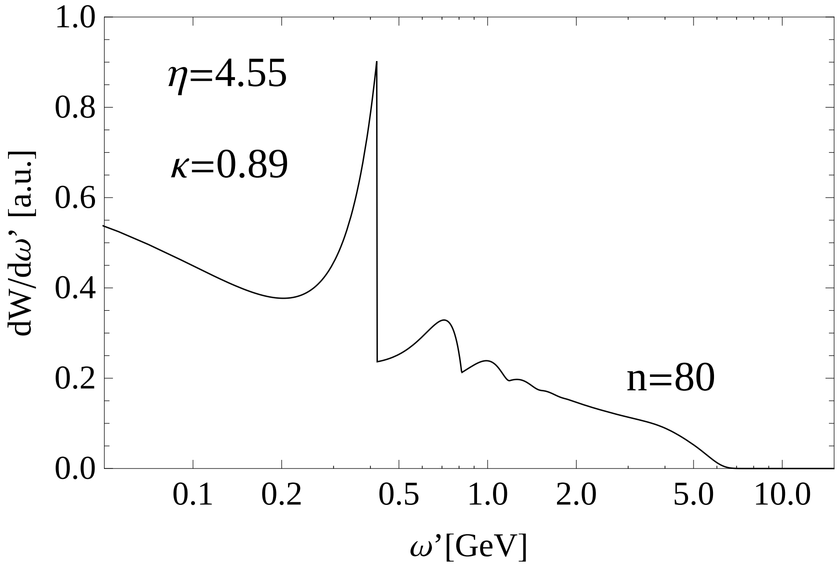
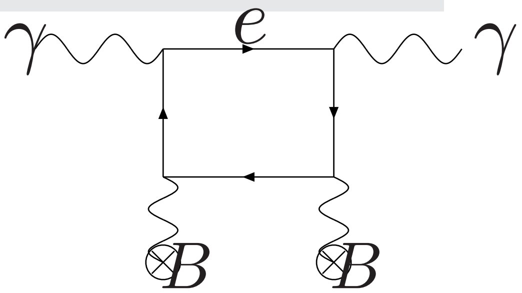
European XFEL:



[Arias,Redondo,AR]

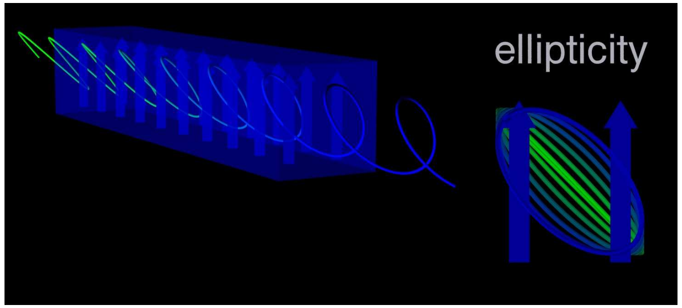
Vacuum magnetic birefringence in QED



⇒ Refractive index in a magnetic field B depends on polarization,

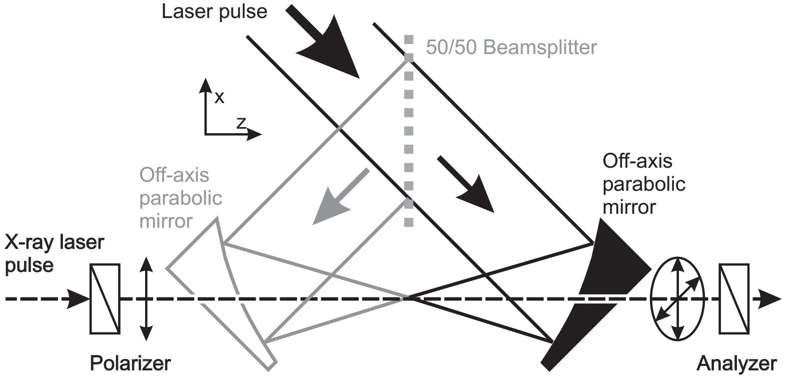
$$\Delta n_{\parallel,\perp} = \left[(7)_{\parallel}\,,(4)_{\perp}\right]\frac{\alpha}{90\pi}\left(\frac{B}{B_{\rm cr}}\right)^2 \; ; \qquad B_{\rm cr} = \frac{m_e^2}{e} \simeq 4\times 10^9 \ {\rm T}$$

⇒ A linear polarized laser beam entering the magnetic field at an angle θ will turn into a beam with elliptical polarization:



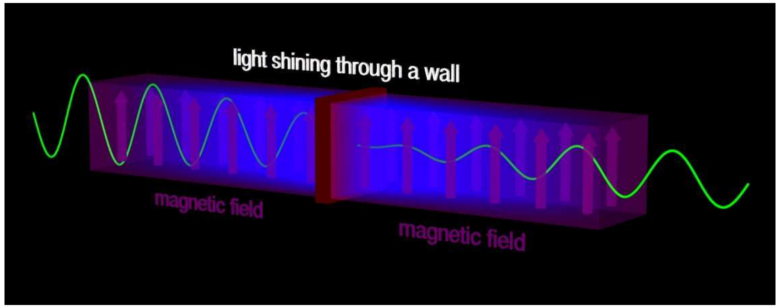
$$\psi_{\rm QED} = 1.0 \times 10^{-17} \left(\frac{\omega}{\rm eV}\right) \left(\frac{\ell}{\rm m}\right) \left(\frac{B}{\rm T}\right)^2 N_{\rm pass} \sin(2\theta)$$

- Experimental possibilities:
  - Optical (eV) laser cavity ($N_{\rm pass} \sim 10^5$) plus macroscopic magnet ($B \sim$ T, $\ell \sim$ m): BMV (Toulouse), OSQAR (CERN), Q&A (Taiwan)
  - X-ray (multi keV) laser ($N_{\rm pass} = 1$) plus
    - macroscopic magnet ($B \sim$ T, $\ell \sim$ m) or [Cantatore *et al.* '91]
    - magnetic field in focal region of crossed petawatt optical laser pulses ($B \sim 10^5$ T, $\ell \sim 10$ μm) [Heinzl *et al.* '06]

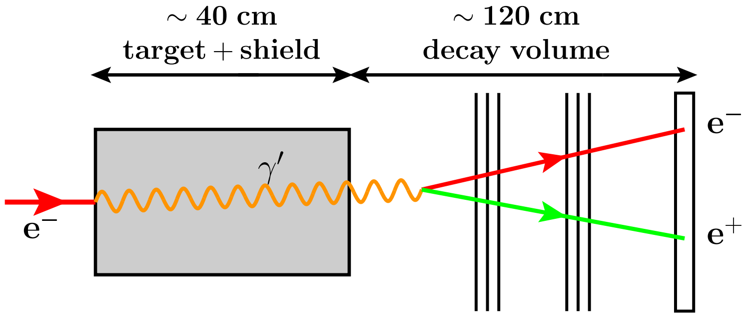


Searches for very weakly interacting slim particles (WISPs)

- **Axions- and axion-like particles** ⇒ laser-light shining through a wall experiments



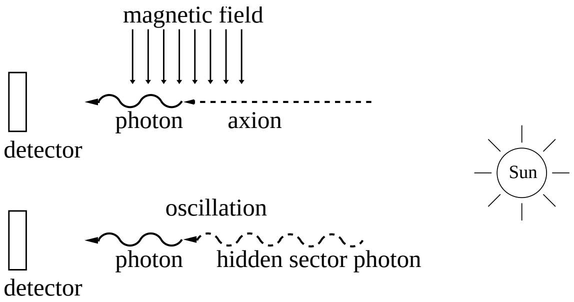
- **Hidden or dark photons** ⇒ electron fixed target experiments



Axions and axion-like particles

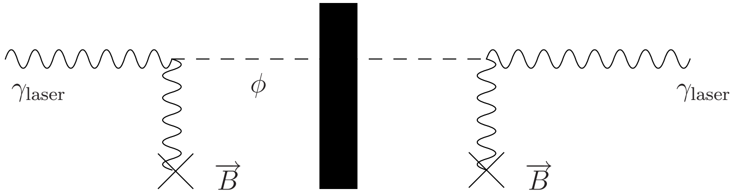
[Peccei,Quinn ‘77; Weinberg ‘78; Wilczek ‘78]

- Axions and axion-like particles (ALPs) occur in many extensions of the standard model and are viable dark matter candidates
- Most sensitive probes of light ALPs based on photon-ALP conversion:
  - helioscope searches (e.g. CAST, SUMICO, SHIPS, ...)



[Sikivie ‘83;...;Redondo ‘08;...]

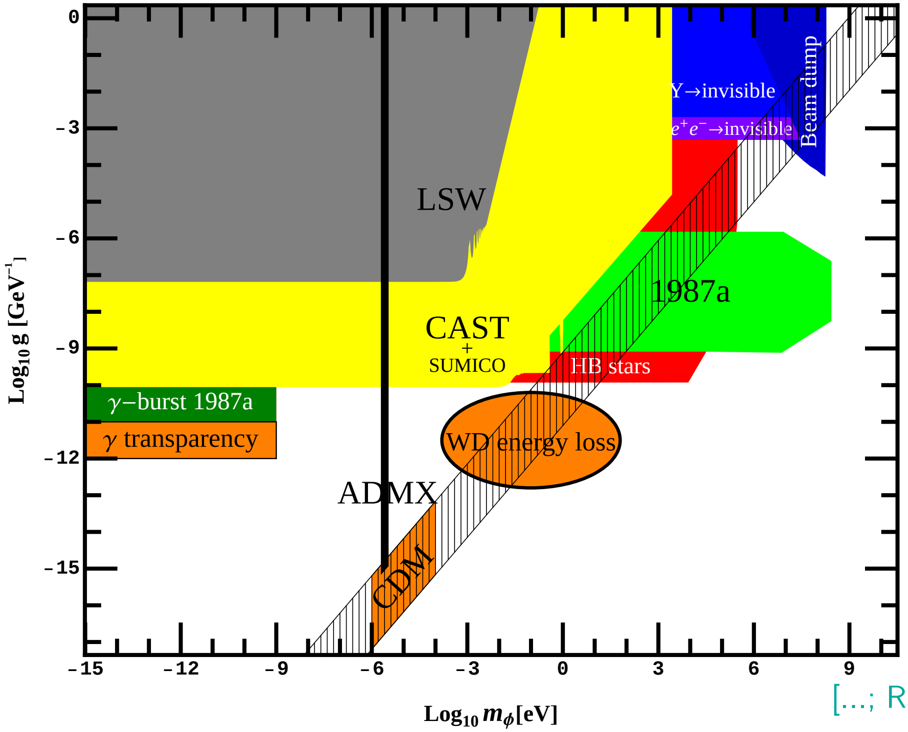
  - light shining through a wall searches (e.g. ALPS, GammeV, ...)



[Okun ‘83;Anselm ; van Bibber]

⇒ two photon coupling g

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



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

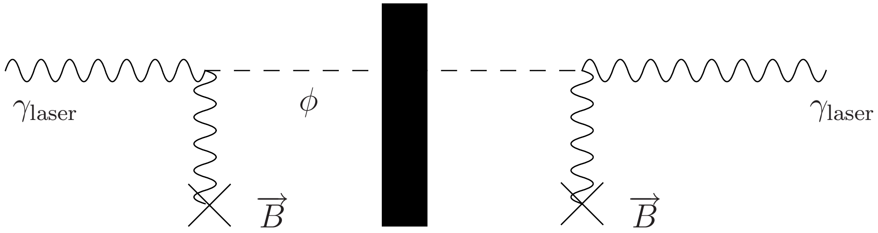
- Astrophysical hints (TeV γ transparency puzzle (H.E.S.S., MAGIC); anomalous energy loss of white dwarfs) point at $g \sim 10^{-12} \div 10^{-11}$ GeV^{-1}

- **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	$\mathrm{B}_g = \mathrm{B}_r = 5$ T $L_g = L_r = 4.21$ m
BFRT (Brookhaven)	2.47 eV	3 W	100	$\mathrm{B}_g = \mathrm{B}_r = 3.7$ T $L_g = L_r = 4.4$ m
BMV (LULI)	1.17 eV	8×10^{21} γs/pulse	14 pulses	$\mathrm{B}_g = \mathrm{B}_r = 12.3$ T $L_g = L_r = 0.4$ m
GammeV (Fermilab)	2.33 eV	4×10^{17} γs/pulse	3600 pulses	$\mathrm{B}_g = \mathrm{B}_r = 5$ T $L_g = L_r = 3$ m
LIPSS (JLab)	1.03 eV	180 W	1	$\mathrm{B}_g = \mathrm{B}_r = 1.7$ T $L_g = L_r = 1$ m
OSQAR (CERN)	2.5 eV	15 W	1	$\mathrm{B}_g = \mathrm{B}_r = 9$ 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)

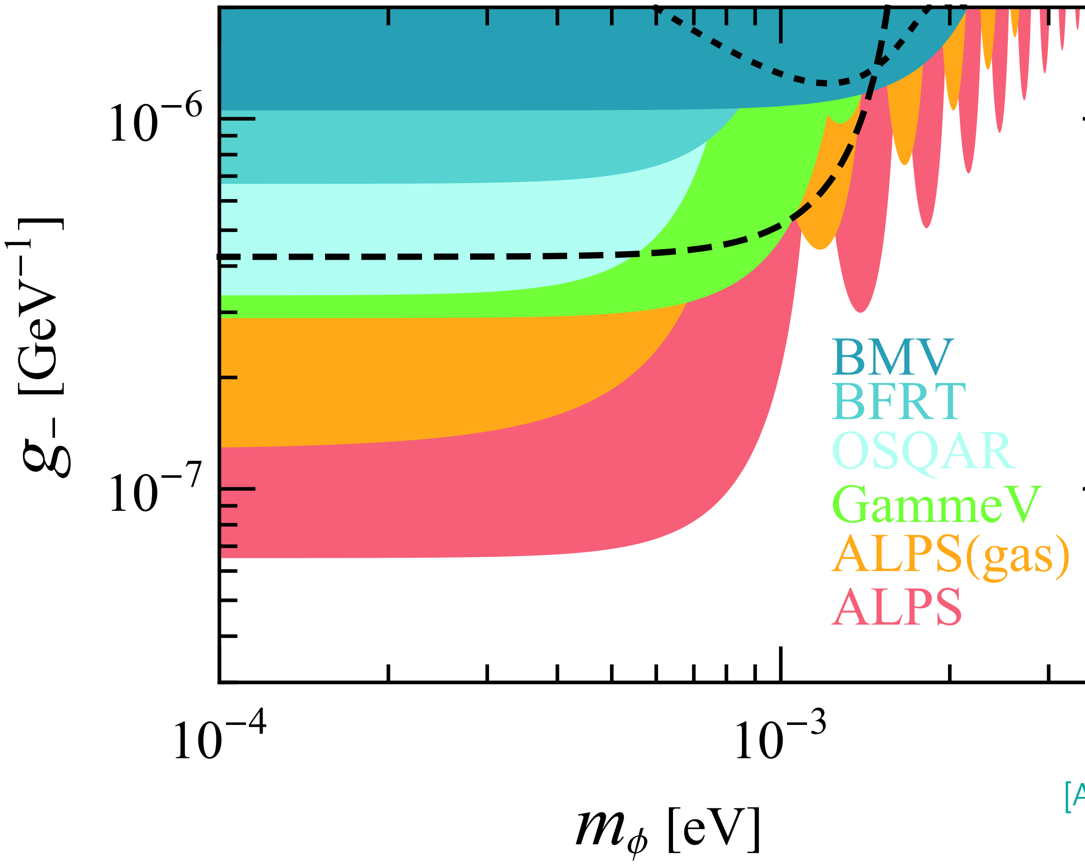
- **ALPS** (Any-Light Particle Search): [AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]



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

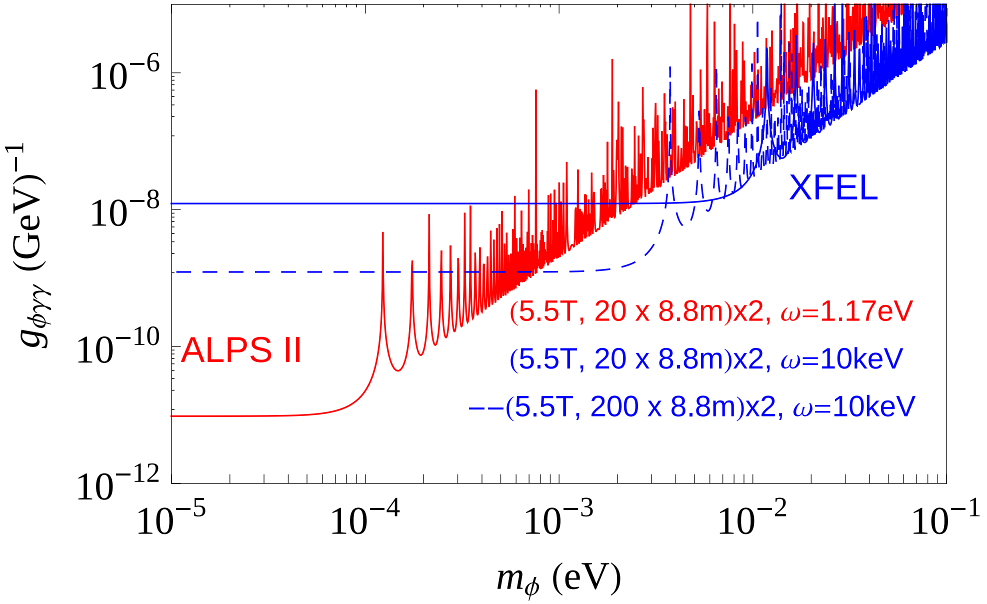
- Last **ALPS** run end of 2009 [Phys. Lett. B 689 (2010) 149-155]

⇒ *“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]



[Arias,AR '10]

⇒ **Exploiting XFEL photon beam will extend sensitivity to larger masses, but will be less sensitive at small masses (average flux $\gamma \sim 10^{18}$/s)**

MeV-GeV scale hidden or dark photon γ':

- Occurs in well-motivated extensions of standard model, e.g. in SUSY

- May explain
  - $(g-2)_\mu$ anomaly [Pospelov '08]
  - DM anomalies [Arkani-Hamed *et al.* '08; Pospelov,Ritz '08;...]
    - $\ast$ in direct detection (DAMA, CoGeNT vs. CDMS, XENON) and
    - $\ast$ cosmic rays (PAMELA, FERMI)

    if DM charged under hidden U(1)

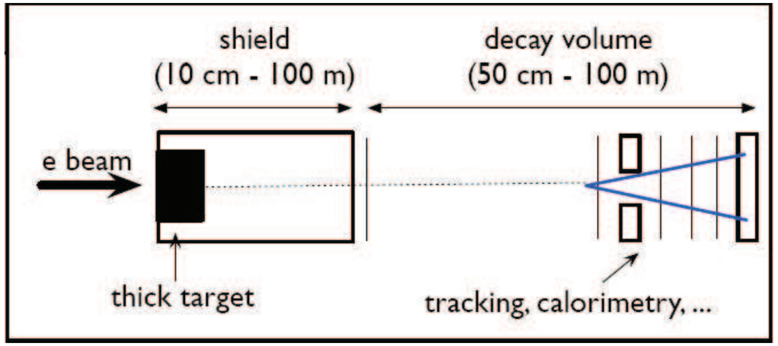
- Can be checked in beam dump and other fixed-target experiments with intense electron beams [Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09]

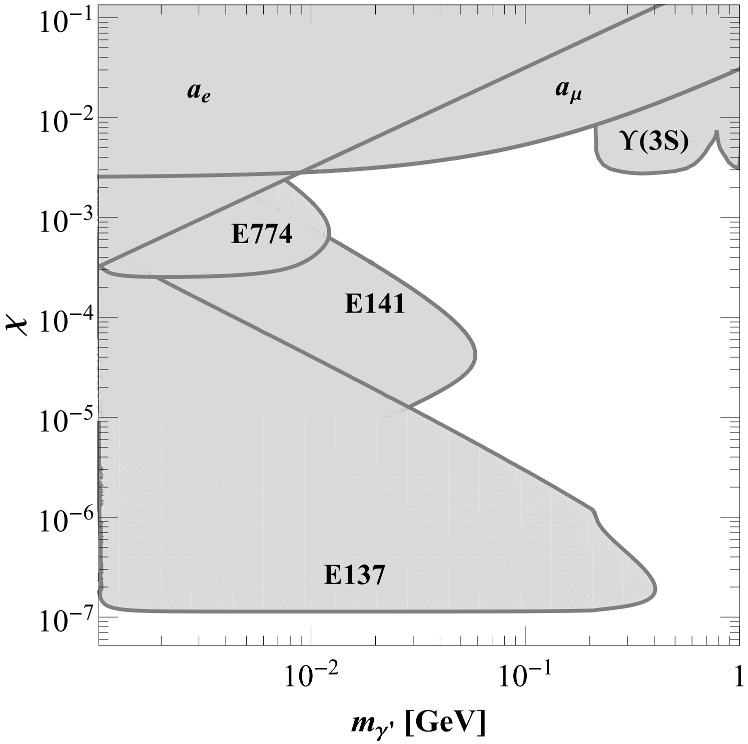
⇒ New experiments commissioned/funded/proposed/designed at DESY (HIPS), MAMI (A1 Collaboration), and JLab (APEX, DarkLight, HPS)

- **Past beam dumps:**

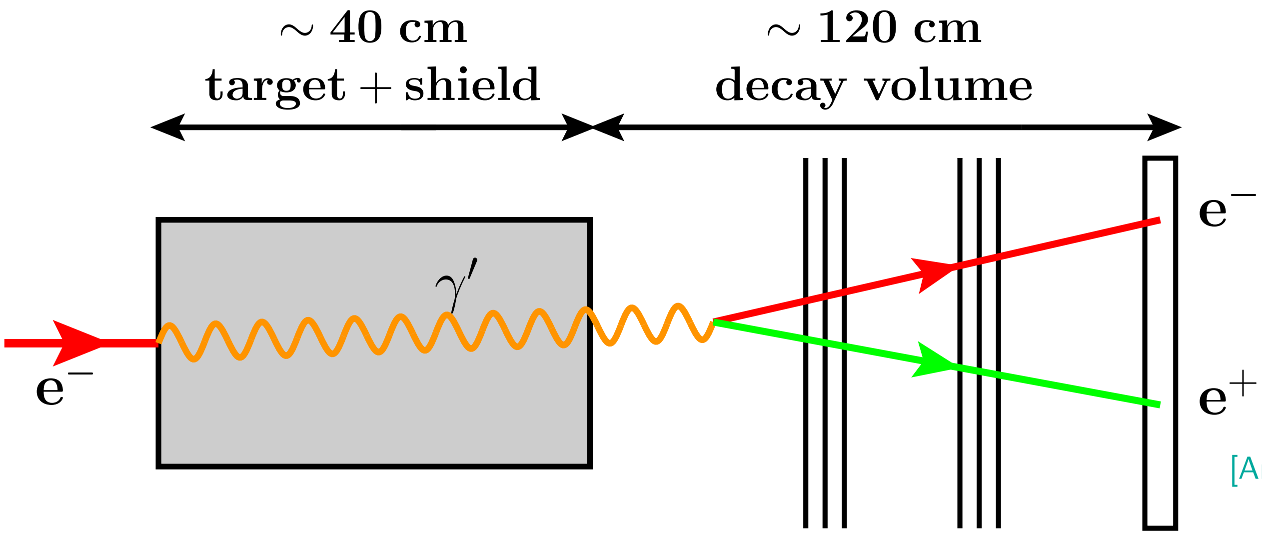
  [Bjorken,Essig,Schuster,Toro '09]

  - 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 LEXI and SFB 676 [Andreas,Bechtle,Ehrlichmann,Garutti,Lindner,Niebuhr,AR,Soloviev]



[Andreas,AR '10]

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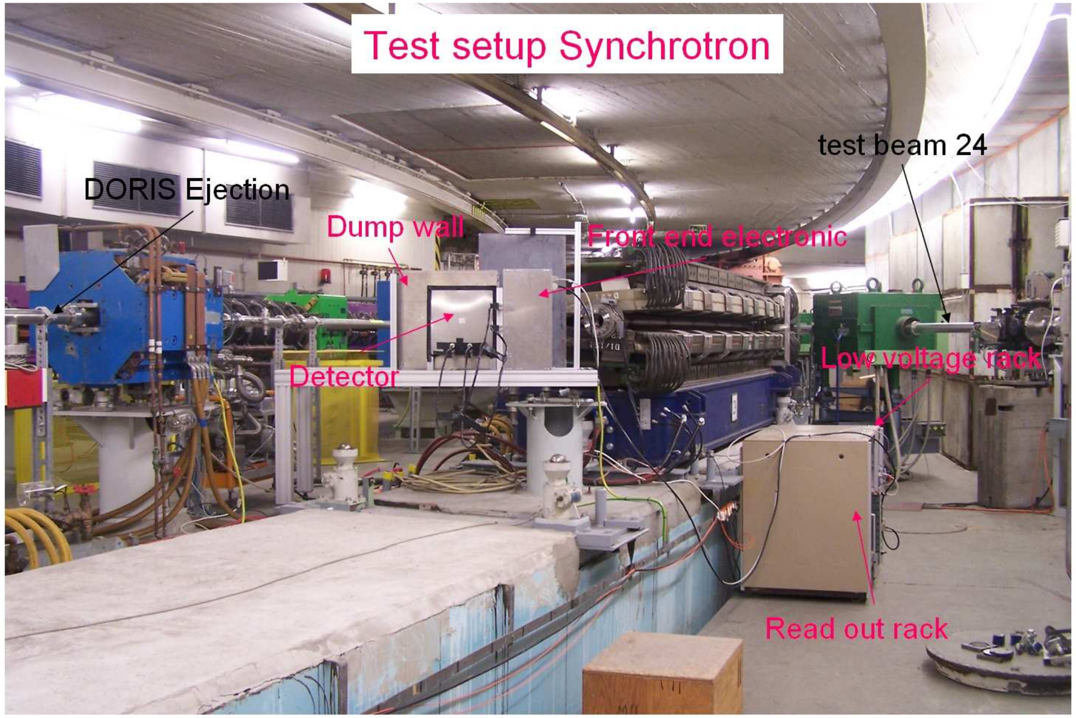

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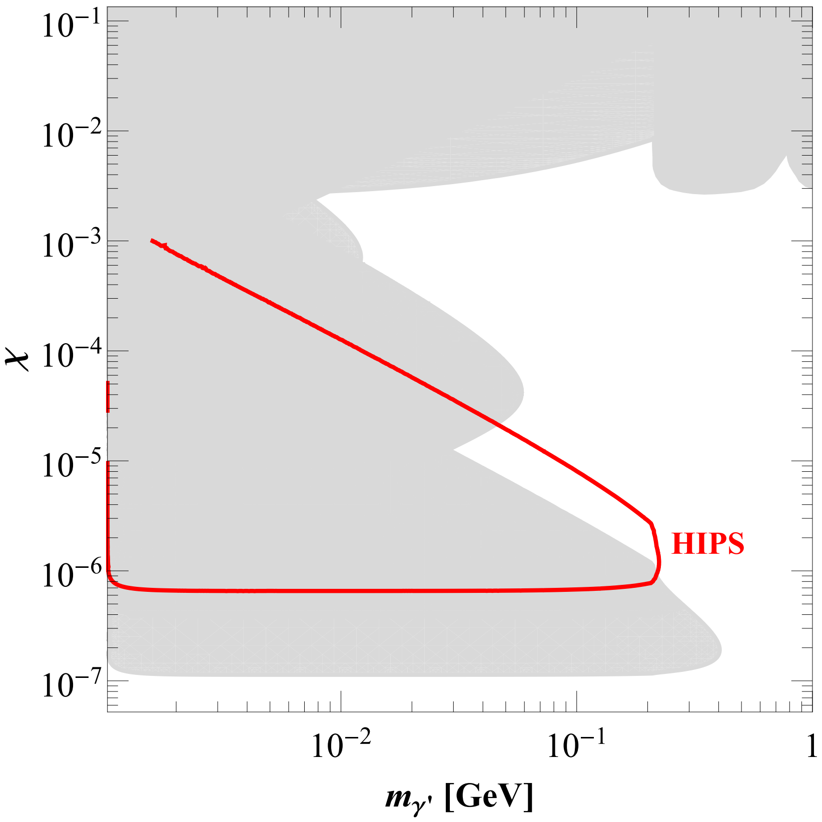
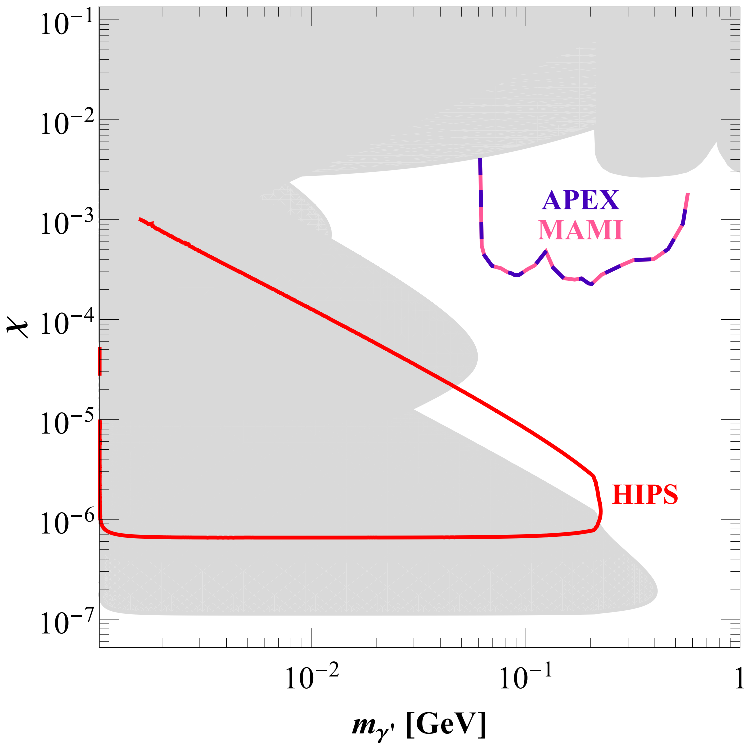


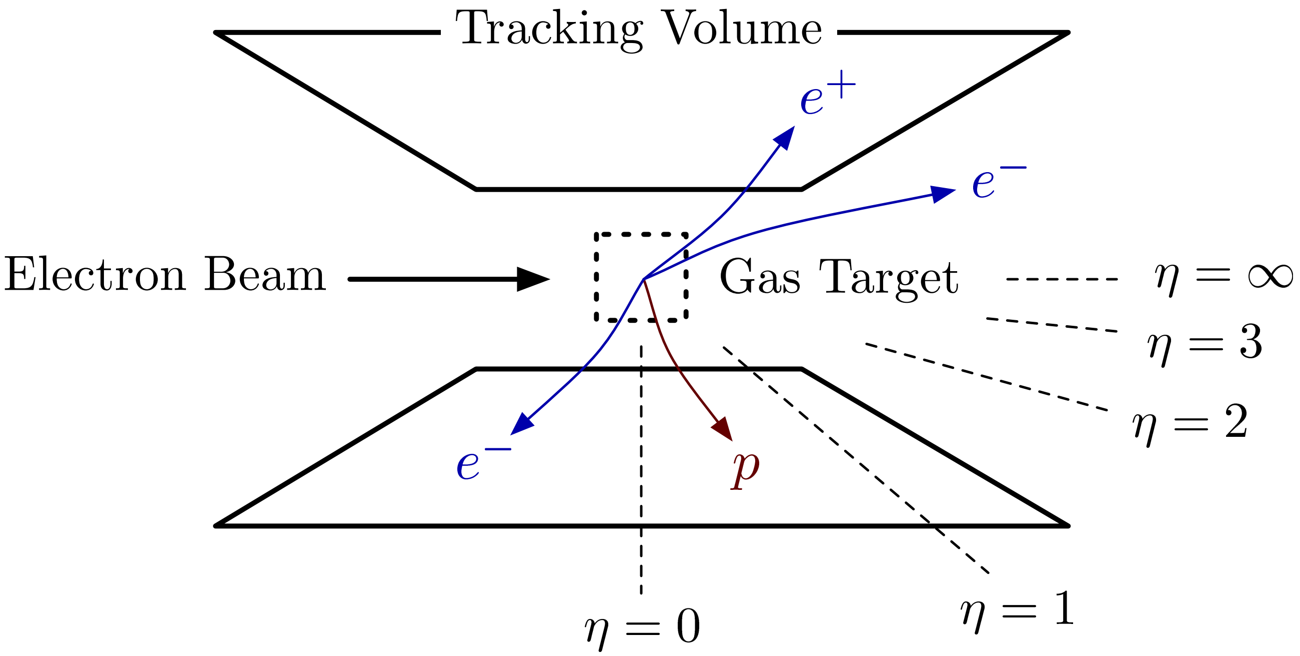
[Andreas,AR '10]

- **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)



[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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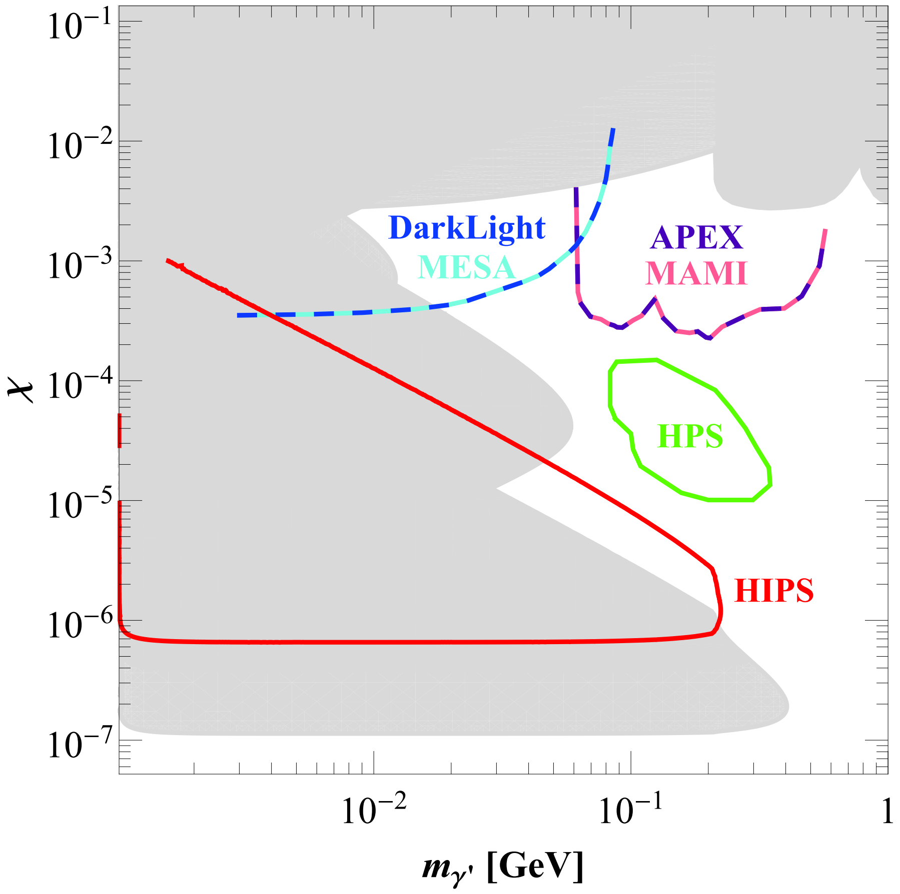
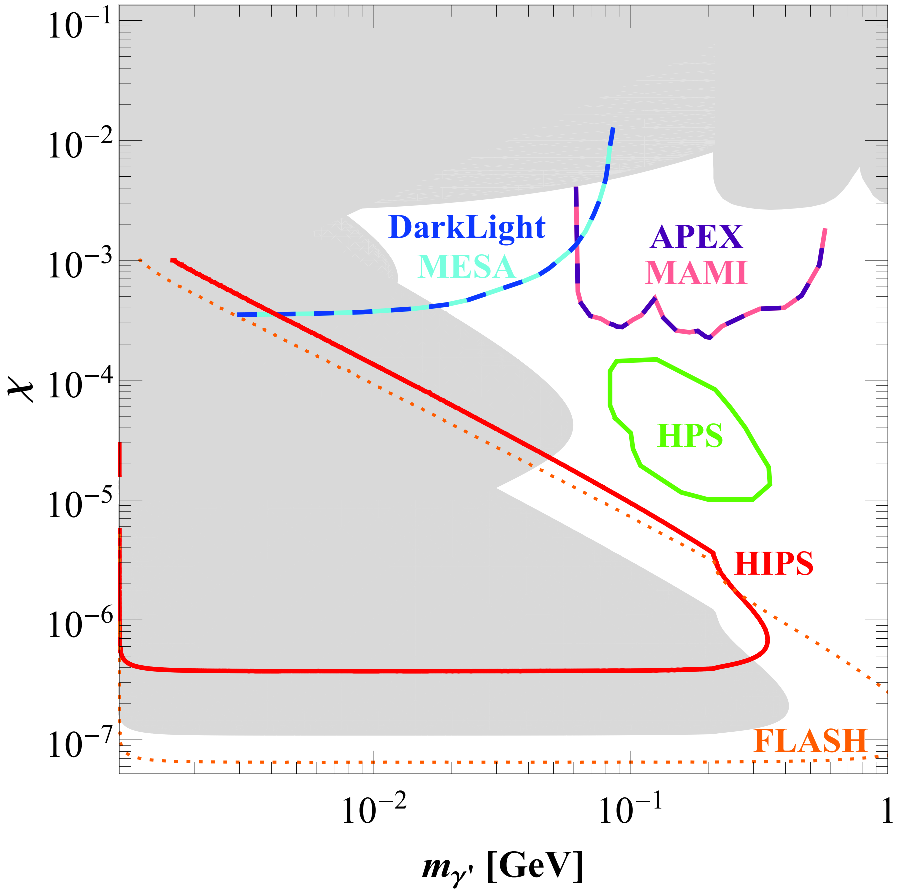


[Andreas,AR '10]

- **Parasitic beam dump experiment** exploiting **FLASH** e-beam (30 μA; 1.2 GeV) enlarges discovery potential (not foreseen at JLab; in Mainz)



[Andreas,AR '10]

Conclusions

- X-ray FELs can be used to study fundamental physics; most promising
  - non-linear and non-perturbative QED processes in crossed electron and high intensity optical laser beams
  - searches for sub-GeV scale hidden particles in electron beam dumps

⇒ Should foresee
  - to install also an intense optical laser
  - to install also a bypass for the electron beam
  - to make also the spent electron beam accessible, in particular not to dump it right after last undulator, cf. FLASH or European XFEL: