Strong Fields as a Probe for Fundamental Physics

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Friedrich-Schiller-Universität Jena

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A view on the quantum vacuum

A view on the quantum vacuum.

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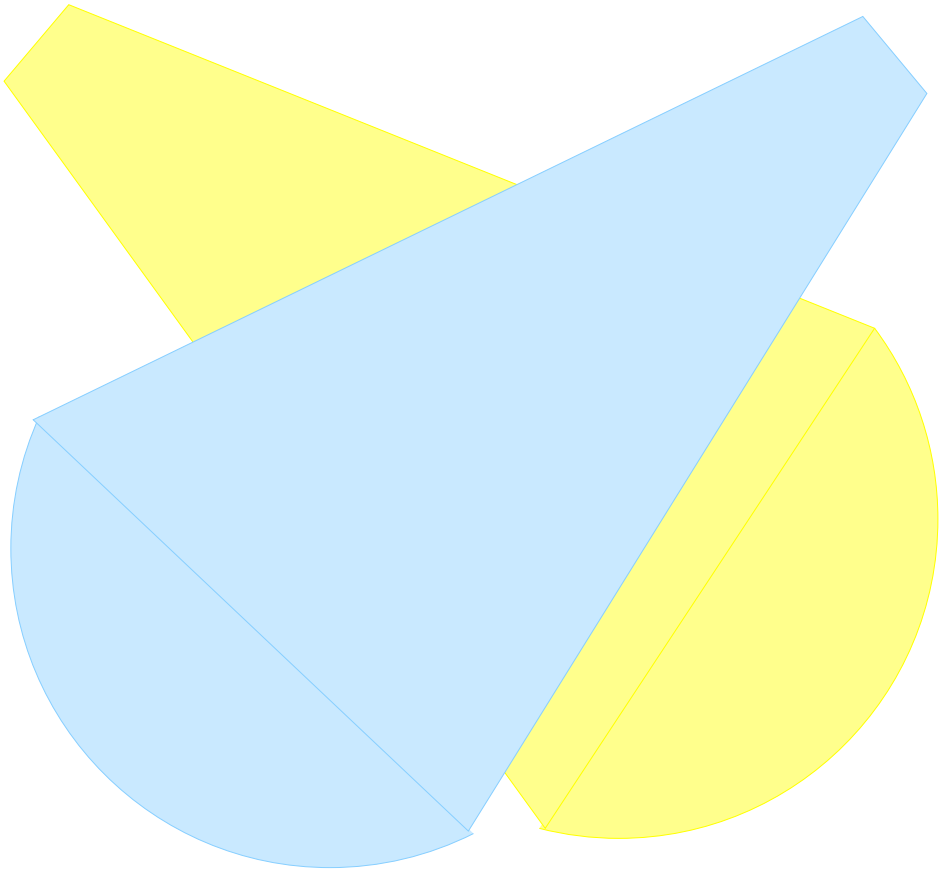

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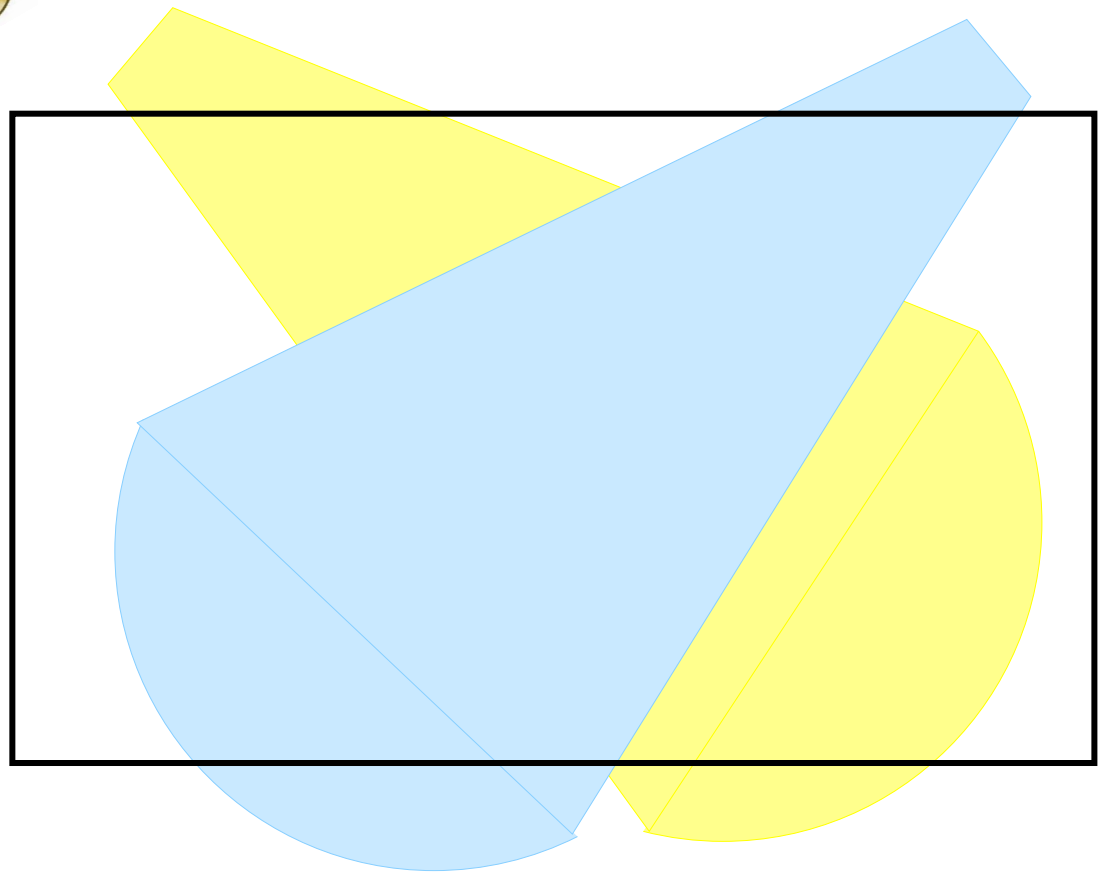

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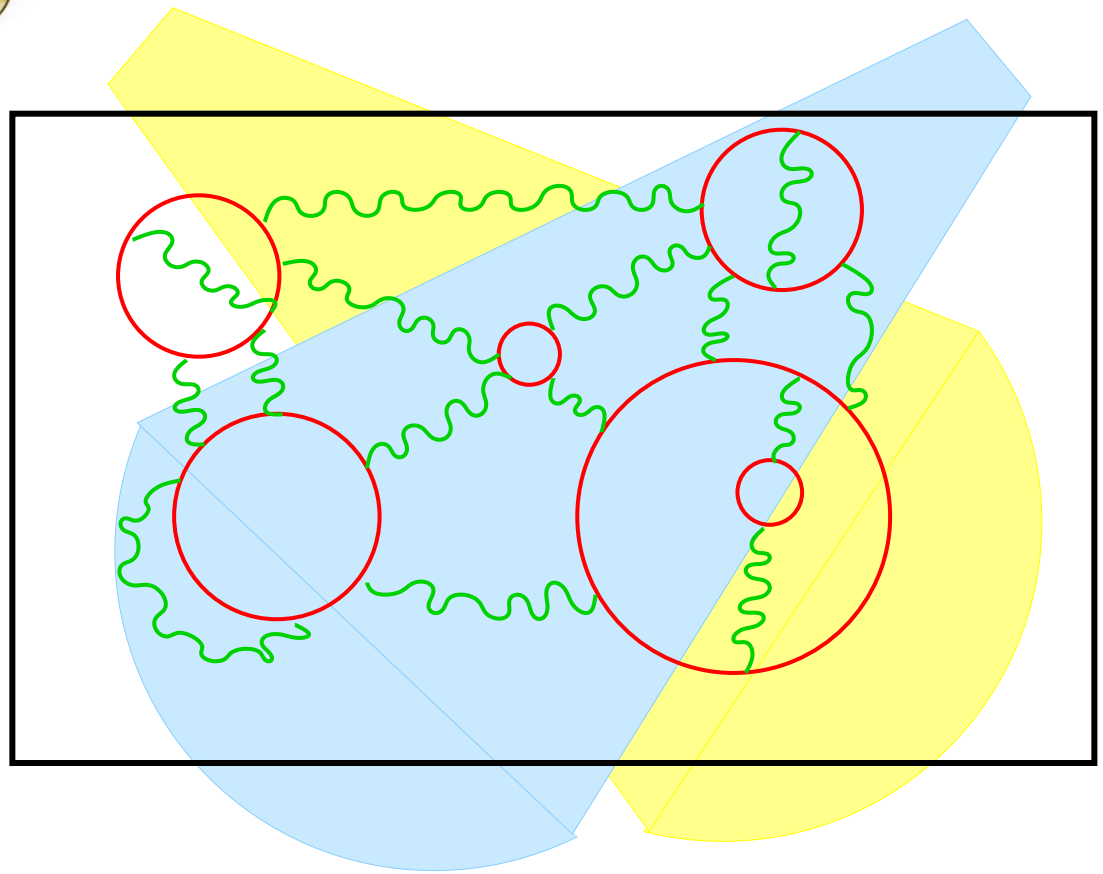

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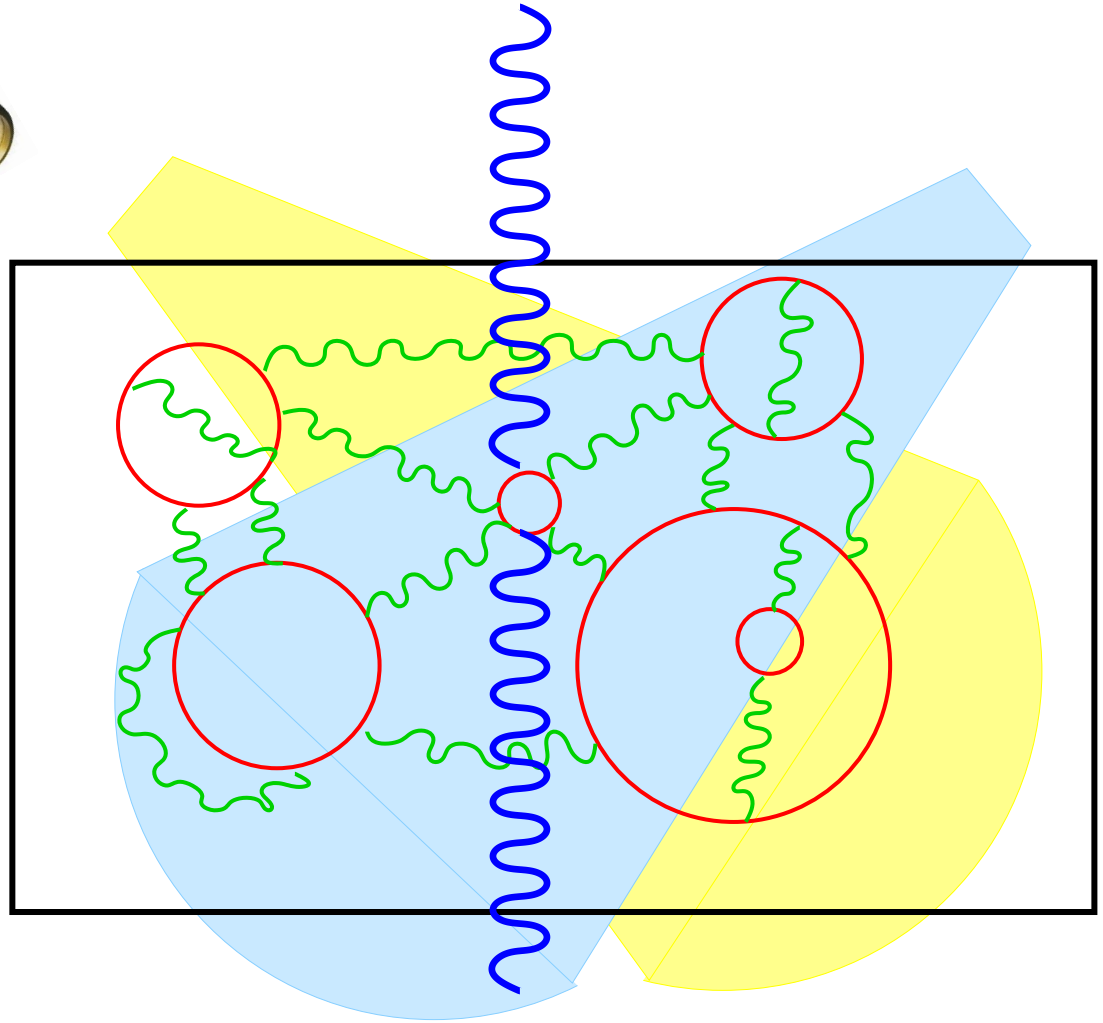

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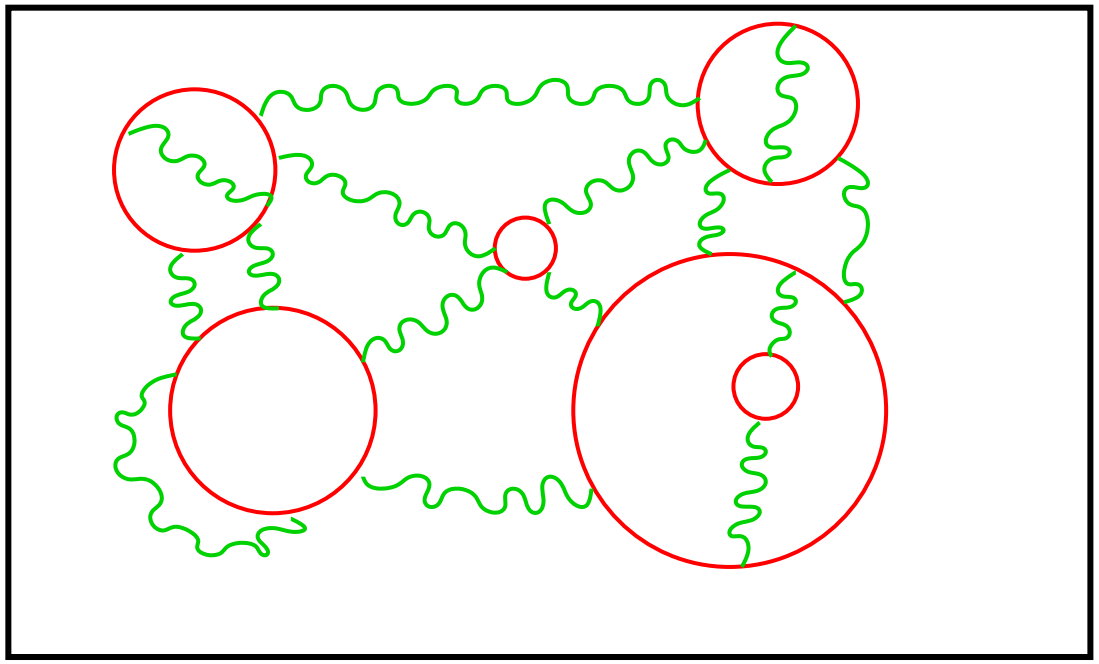
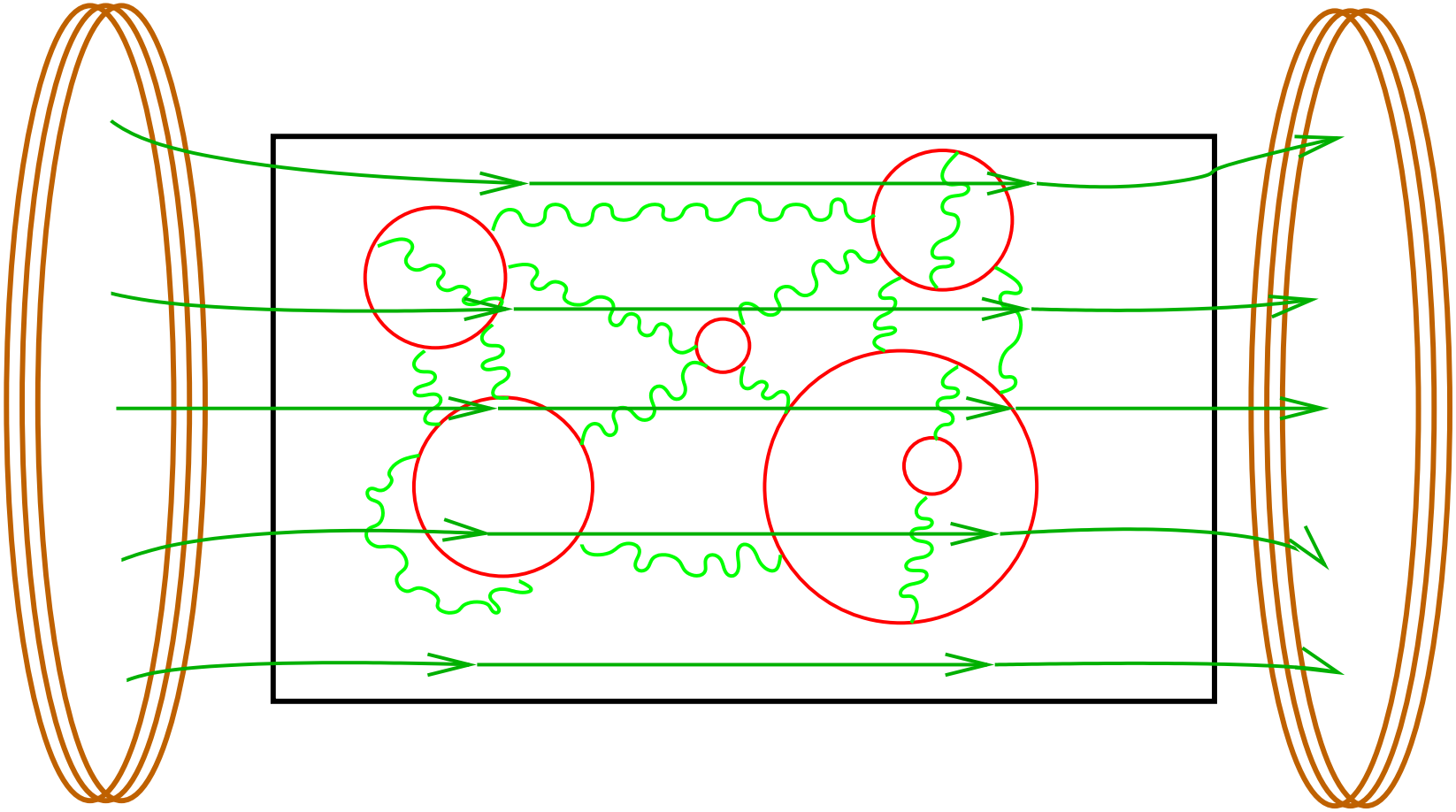


- QFT: quantum fluctuations

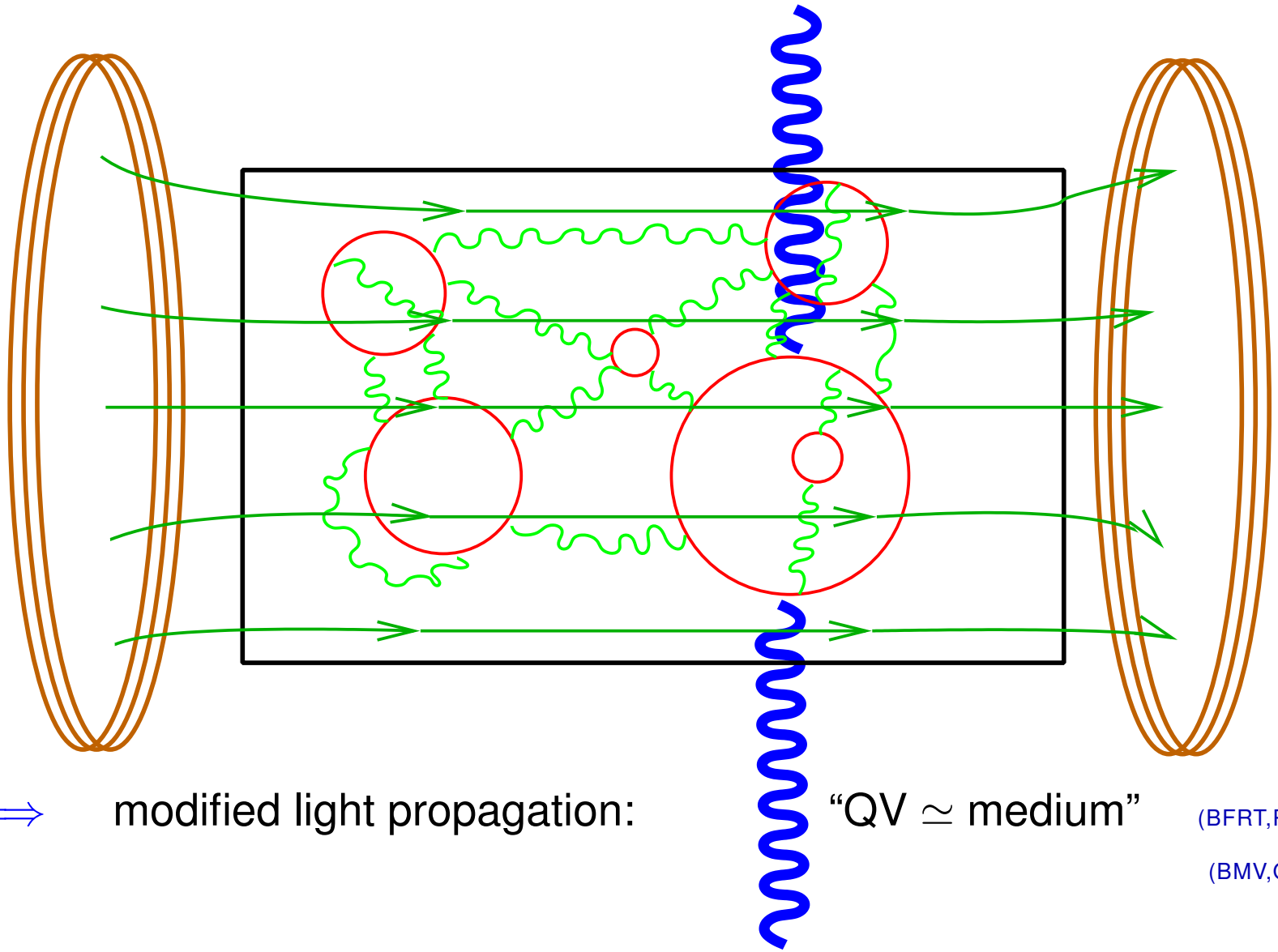
BUT: . . . just a picture !

A view on the quantum vacuum.



- External fields: Heisenberg-Euler effective action

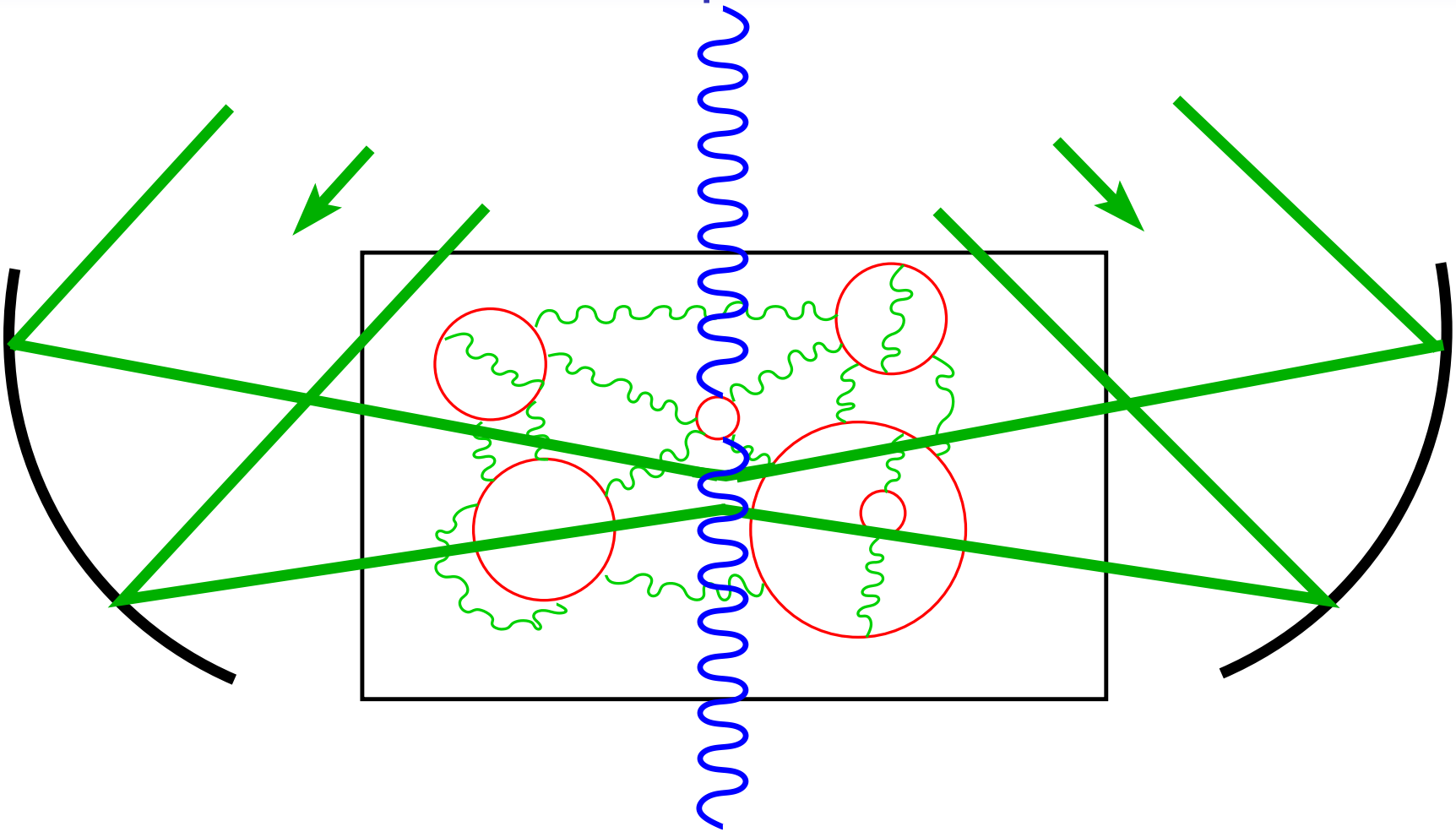
A view on the quantum vacuum.



$\Longrightarrow$ modified light propagation: "QV $\simeq$ medium" (BFRT,PVLAS,Q&A)

(BMV,OSQAR)

A view on the quantum vacuum.



$\Longrightarrow$ modified light propagation: "QV $\simeq$ medium" (POLARIS@JENA)

(HEINZL ET AL.'06)

(B7@SFB-TR18)

Effective action

for the electromagnetized quantum vacuum

Light Propagation

- classical Maxwell equation in vacuo (MAXWELL 1861, 1865)

$$S = -\int d^4x \, \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad \Longrightarrow \quad 0 = \partial_\mu F^{\mu\nu}$$

- velocity of a plane-wave solution:

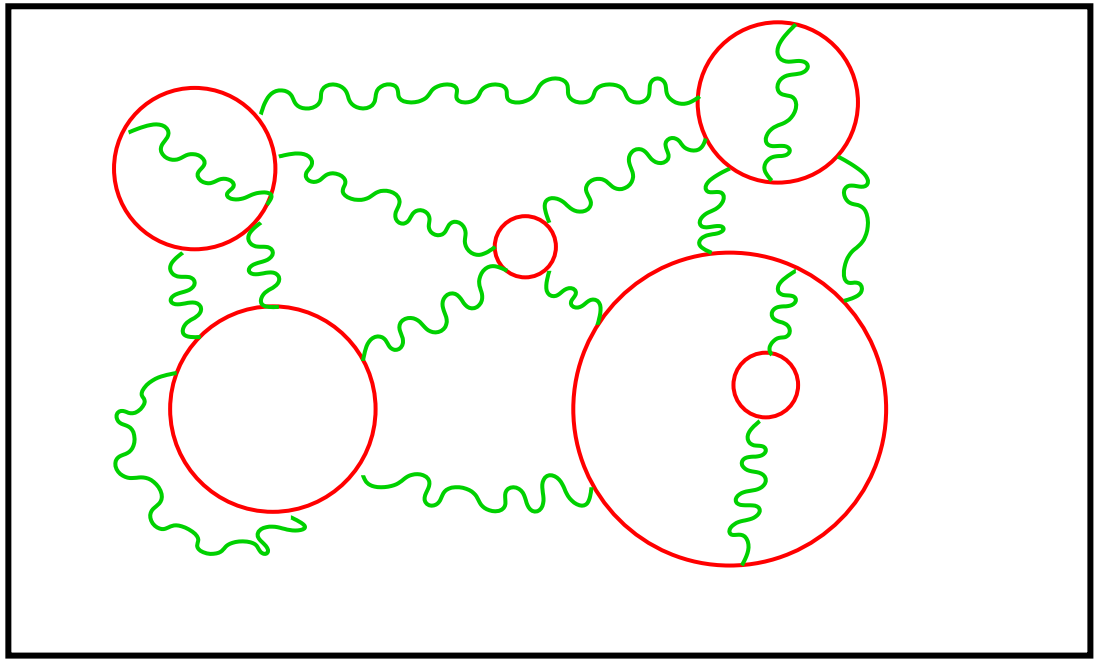
$$v = 1 \quad (= c)$$

- superposition principle

$$F^{\mu\nu} = F_1^{\mu\nu} + F_2^{\mu\nu}$$

$\Longrightarrow$ no self-interactions

Self-interactions from the Quantum Vacuum



Mind the e^+e^- fluctuations

Electron mass scale

▷ the electron . . .

$$m \simeq 511\,\text{keV} \simeq 9 \cdot 10^{-31}\,\text{kg}$$

. . . is very heavy!

▷ $\hbar = 1 = c$

- $E_{\text{cr}} \simeq 4 \cdot 10^{17}$ Volt/m
- $m \simeq 7.6 \cdot 10^{11}$ GHz
- $m \simeq 6 \cdot 10^{9}$ Kelvin
- $m^2 \simeq 1.3 \cdot 10^{9}$ Tesla

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$$I_{\text{cr}} \equiv E_{\text{cr}} \simeq 4.4 \times 10^{29}\,\text{W/cm}^2$$

$\Longrightarrow$ Polaris: $\sim 1\%\, m$

$\Longrightarrow$ ELI: $\sim 25\%\, m$

From QED to Nonlinear ED

▷ mass scale m divides quantum fluctuations in

hard $\lvert p^2 \rvert > m^2$	soft $\lvert p^2 \rvert < m^2$
(photons and electrons)	(only photons =EM fields)

Physics of the soft fields:

average over $\int$ (integrate out) hard modes

$\Longrightarrow$ Heisenberg-Euler effective action Γ

Heisenberg-Euler Effective Action

- vacuum energy

$$E = \frac{1}{2}\hbar\omega$$

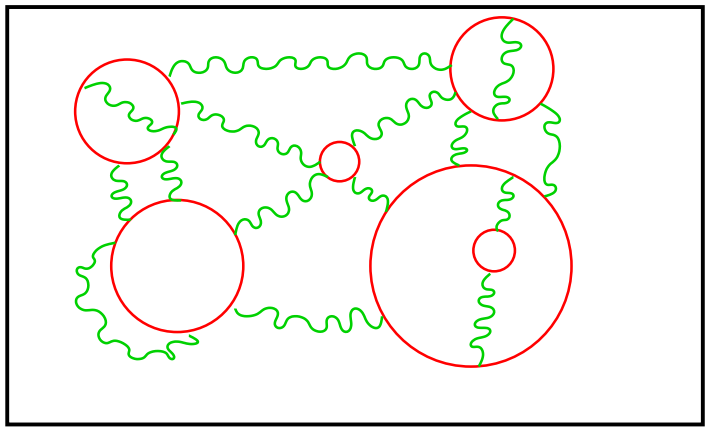
Heisenberg-Euler Effective Action

- vacuum energy

$$E = \frac{1}{2}\hbar \sum_n \omega_n$$

- electron modes

$$\omega_n = \sqrt{\vec{p}^2 + m^2}$$



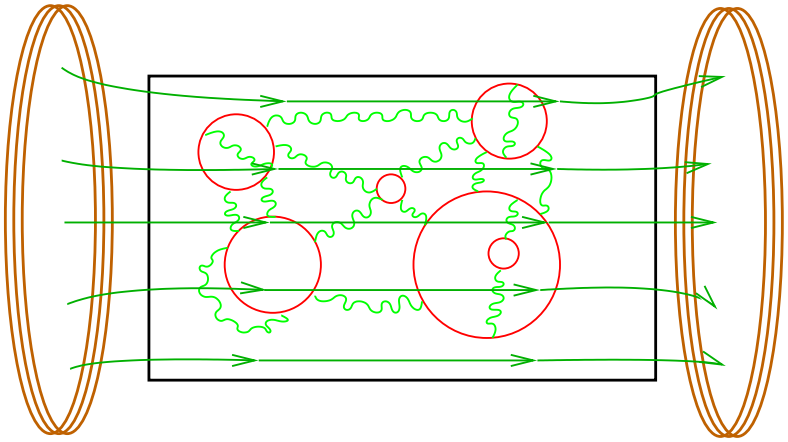
Heisenberg-Euler Effective Action

- vacuum energy

$$E = \frac{1}{2}\hbar \sum_n \omega_n$$

- electron modes

$$\omega_n = \sqrt{p_\parallel^2 + m^2 + eB(2n + 1 \pm 1)}$$



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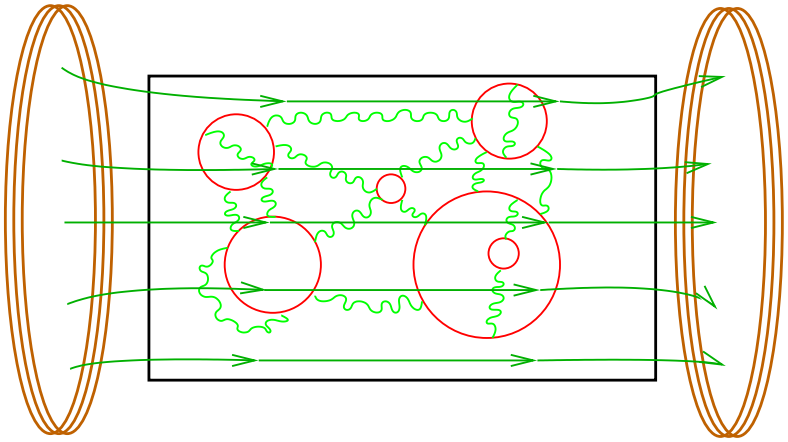


- Heisenberg-Euler effective action Γ (HEISENBERG& EULER'36; WEISSKOPF'36)

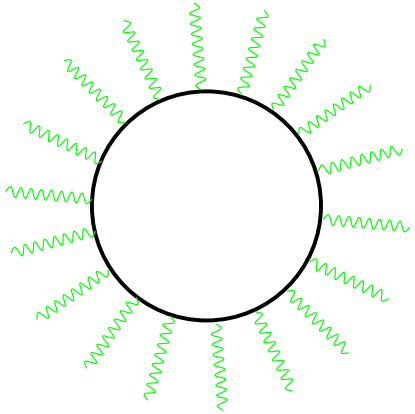
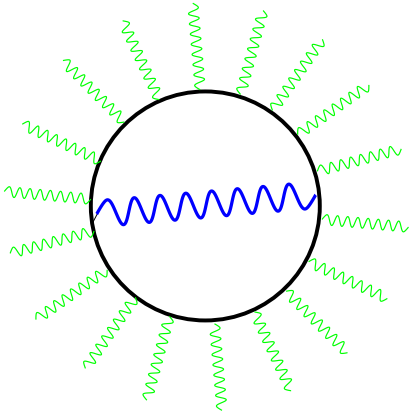
$$\begin{aligned} \frac{\Gamma^1}{L_t} &= -\Delta E(B) = -\frac{1}{2}\hbar \sum_n \left(\omega_n(B) - \omega_n(B=0)\right) \\ &= \frac{1}{8\pi^2} \int_0^\infty \frac{ds}{s^3}\, e^{-m^2 s} \left(\frac{eBs}{\tanh eBs} - 1 \right) \end{aligned}$$

(unrenormalized)

Heisenberg-Euler Effective Action.

(Euler, Kockel'35; Heisenberg, Euler'36; Weisskopf'36; Schwinger'51; Ritus'76)

[Dunne @ ThisWorkshop]

$\Gamma =$  $+$  1% $+$  $+ \dots$

$$= -\int_x \mathcal{F} + \frac{1}{8\pi^2}\int_x \int \frac{ds}{s} e^{-im^2 s}\left[(es)^2|\mathcal{G}|\cot\left(es\sqrt{\sqrt{\mathcal{F}^2+\mathcal{G}^2}+\mathcal{F}}\right)\right.$$
$$\left.\times \coth\left(es\sqrt{\sqrt{\mathcal{F}^2+\mathcal{G}^2}-\mathcal{F}}\right)\right]\dots$$

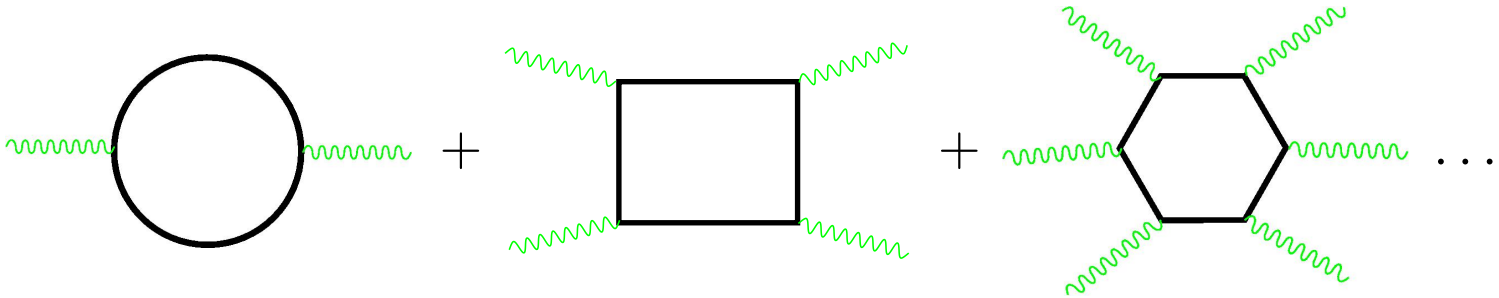
Conventions: $\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}(B^2 - E^2)$, $\mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = -B\cdot E$

Heisenberg-Euler Effective Action.

(Euler, Kockel'35; Heisenberg, Euler'36; Weisskopf'36; Schwinger'51; Ritus'76)

▷ weak-field expansion

$$\Gamma = \int \left\{ -\mathcal{F} + \frac{8}{45}\frac{\alpha^2}{m^4}\mathcal{F}^2 + \frac{14}{45}\frac{\alpha^2}{m^4}\mathcal{G}^2 + \mathcal{O}(F^6) \right\}$$

$=$ 

[Marklund @ ThisWorkshop]

Conventions: $\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}(B^2 - E^2)$, $\mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = -B \cdot E$

Light Propagation.

- classical Maxwell equation in vacuo (MAXWELL 1861, 1865)

$$0 = \partial_\mu F^{\mu\nu}$$

- velocity of a plane-wave solution:

$$v = 1 \quad (= c)$$

Light Propagation in a B field.

▷ quantum Maxwell equation (HEISENBERG,EULER'36;WEISSKOPF'36)

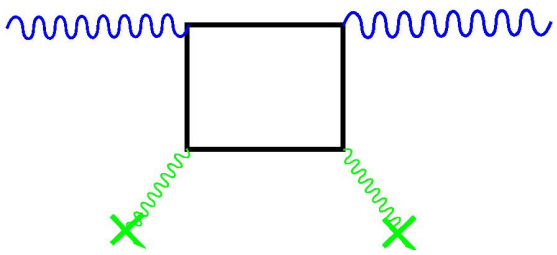
$$0 = \partial_\mu \left(F^{\mu\nu} - \frac{1}{2}\frac{8}{45}\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} - \frac{1}{2}\frac{14}{45}\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} \tilde{F}^{\mu\nu} \right)$$

Light Propagation in a B field.

▷ quantum Maxwell equation for a "light probe" $f^{\mu\nu}$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45}\frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45}\frac{\alpha^2}{m^4} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta}$$

Phase and group velocity



$$v_\parallel \simeq 1 - \frac{14}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

$$v_\perp \simeq 1 - \frac{8}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

(TOLL'54)

(BAIER,BREITENLOHNER'67;NAROZHNIY'69)

(BIALYNICKA-BIRULA,BIALYNICKI-BIRULA'70)

(ADLER'71)

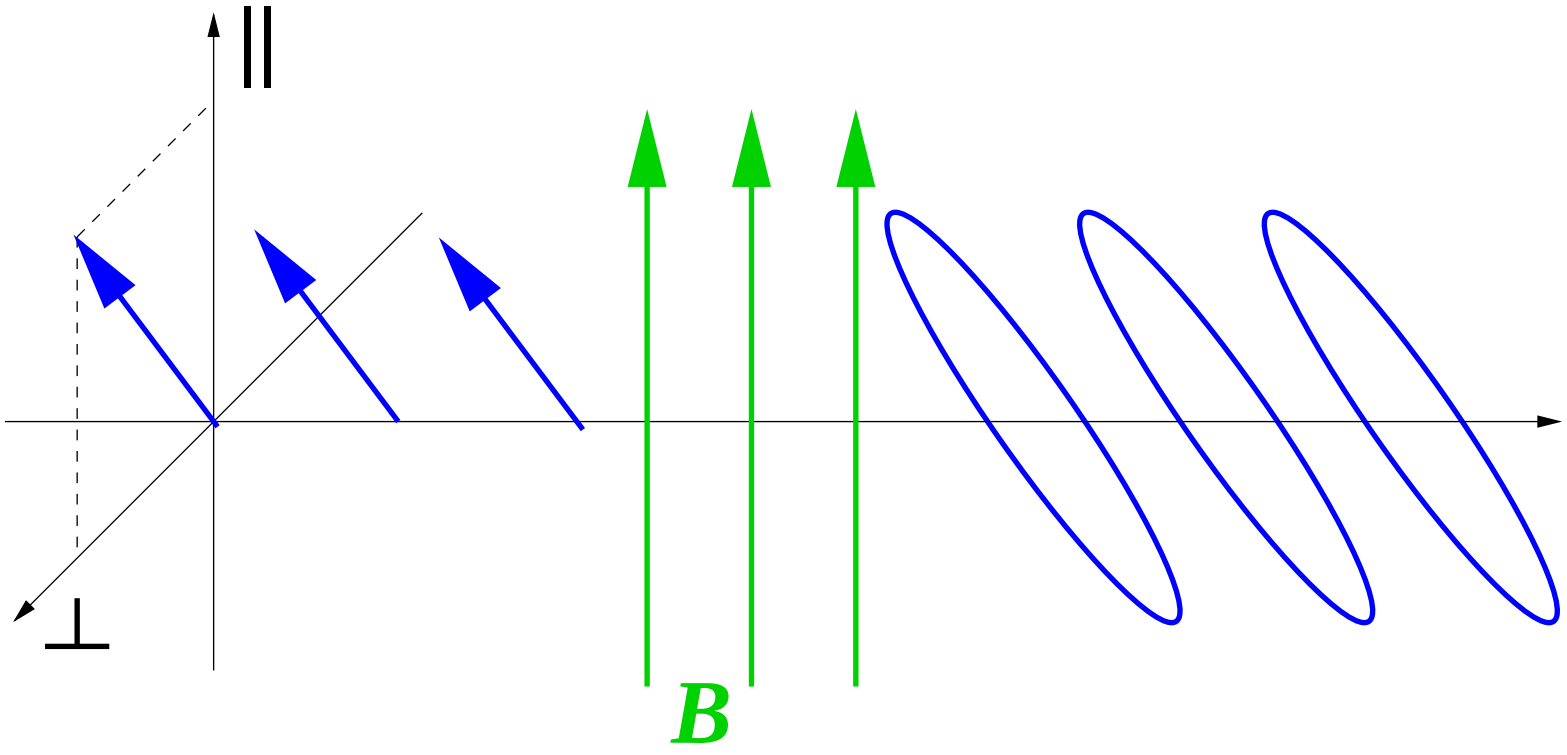
$\Longrightarrow$ magnetized quantum vacuum induces birefringence

[DIPIAZZA @ THISWORKSHOP]

▷ detection schemes: PVLAS, BMV, Q&A, OSQAR, TR18-B7

Light Propagation in a B field.

▷ observable: birefringence induces ellipticity



▷ ellipticity:

$$\Delta\phi = \pi \frac{L}{\lambda} \Delta v \sin 2\theta, \quad \Delta v(5.5\mathrm{T}) \simeq 10^{-22}$$

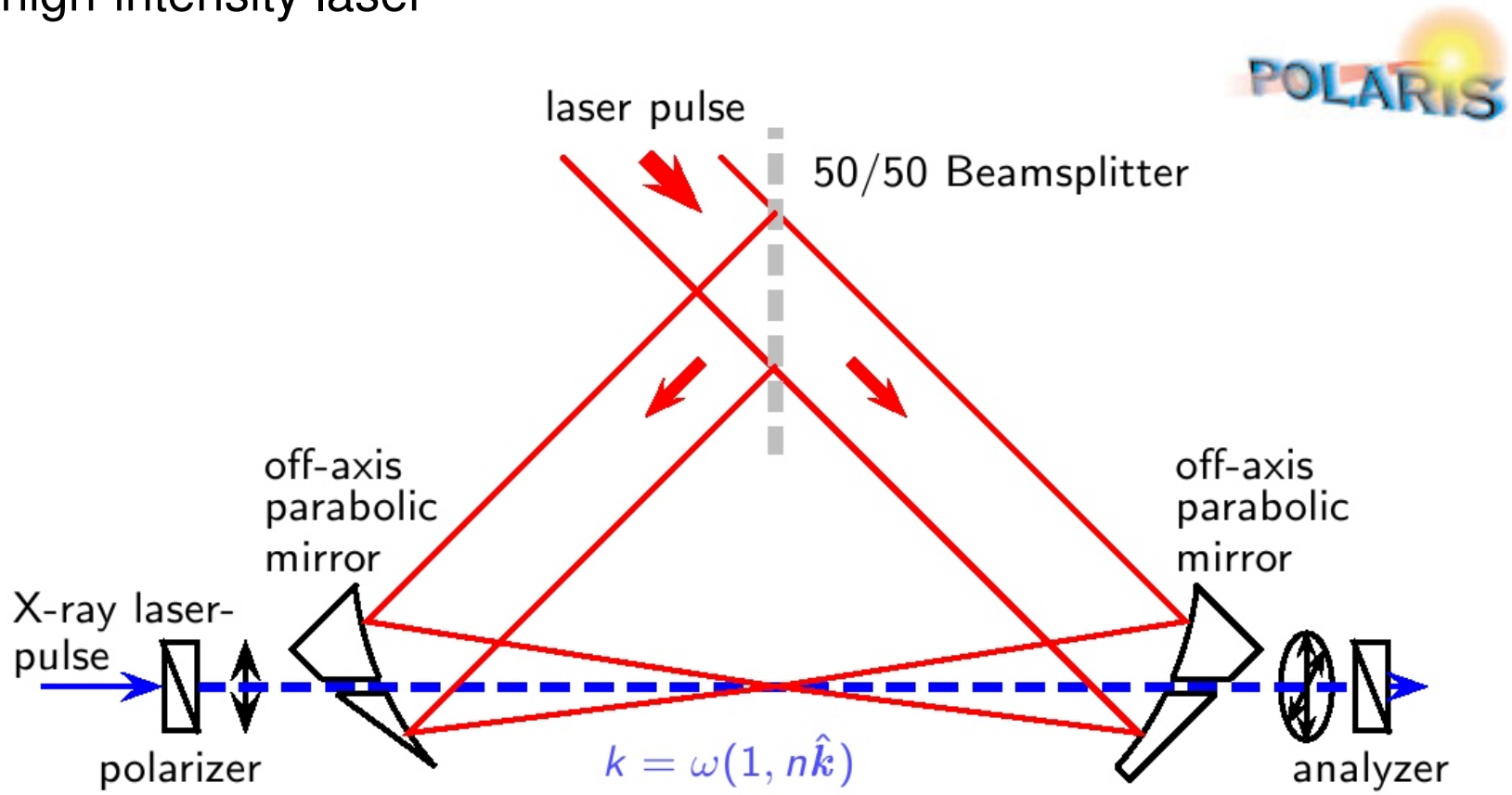
Quantum Vacuum@Jena

- ▷ birefringence at a photon collider (HEINZL,LIESFELD,AMTHOR,SCHWOERER,SAUERBREY,WIPF'06)

  (SFB-TR18-PROPOSAL: HG,KALUZA,WIPF,PAULUS'08)

  [HEINZL @ THISWORKSHOP]

- ▷ high-intensity laser



[WIPF@JENA]

Birefringence@Jena

▷ back-scattered Thomson photons

$$\omega \simeq 2 \times 10^{-3} m$$

▷ intensity (KOCH, HEINZL, WIPF'05)

$$I = 2 \times 10^{-8} I_{cr} \simeq 10^{22} \mathrm{W/cm^2}$$

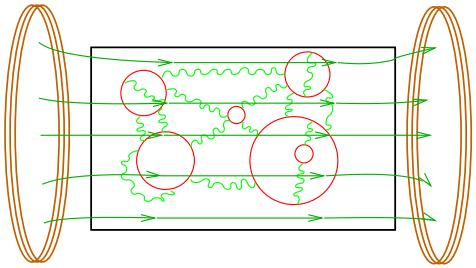
▷ parameters (ω in keV, λ in nm, z_0 in μm)

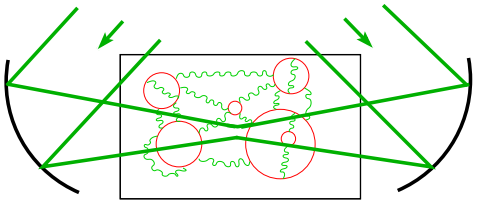
	ω	λ	L	$\Delta\phi$ (rad)
Polaris	1	1.2	10	1.2×10^{-6}
	12	0.1	10	1.4×10^{-5}
XFEL	15	0.08	25	4.4×10^{-5}

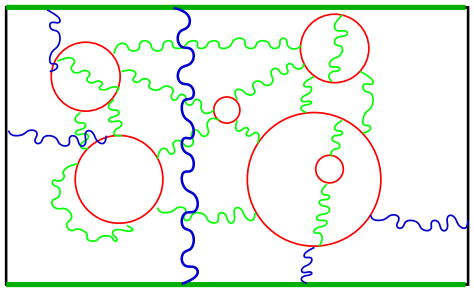
▷ vacuum: pre-pulse?

▷ x-ray optics, in principle $\Delta\phi \simeq 6 \times 10^{-6}$? (ALP ET AL.'00)

Why quantum vacuum physics?

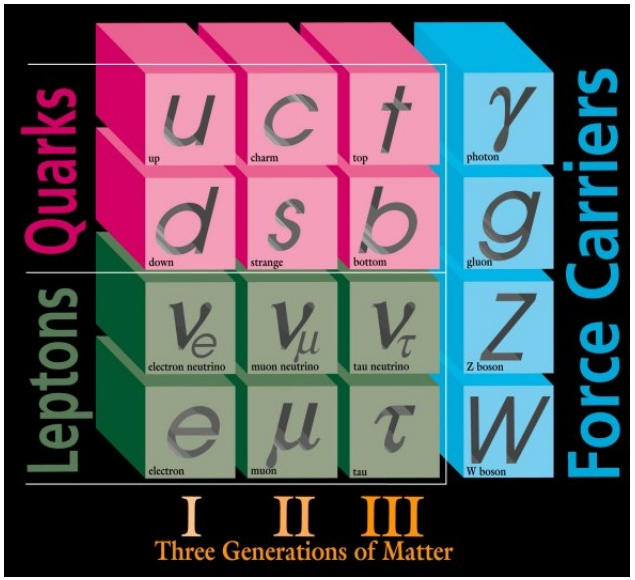






- Heisenberg-Euler/Casimir in mathematical physics
  - QFT in strong fields or with boundaries
  - functional determinants
- applied quantum vacuum physics
  - quantum fluctuations as a building block
  - dispersive forces in micro/nano machinery [DeKieviet @ ThisWorkshop]
- fundamental effect of QFT
  - ($\sim$ Lamb shift, $g-2$, ...)
- fundamental physics
  - search for new physics
  - new particles or forces

Discovery Potential



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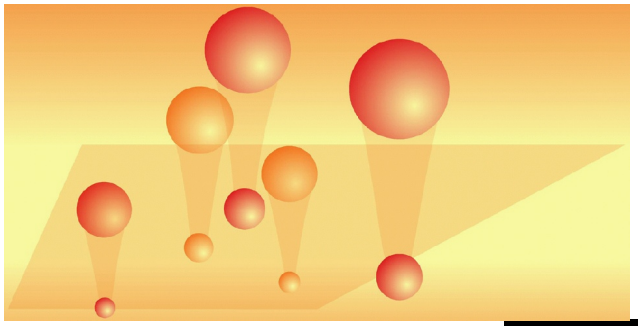
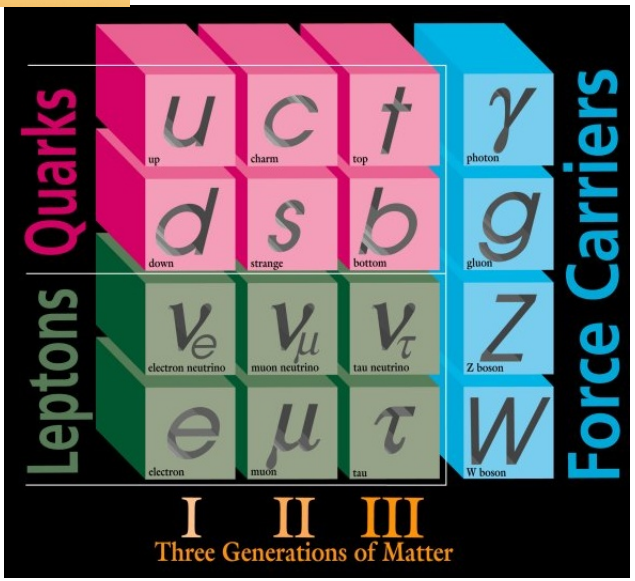
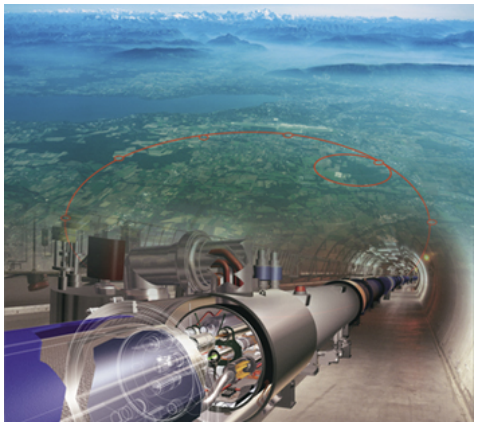


[ZMS.DESY.DE]

beyond SM

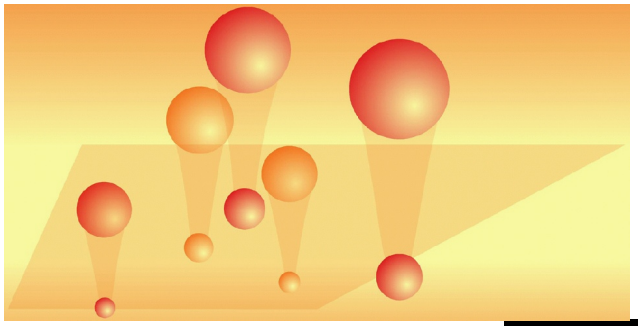
e.g. SUSY (heavy)





[WWW.CERN.DE]

Discovery Potential



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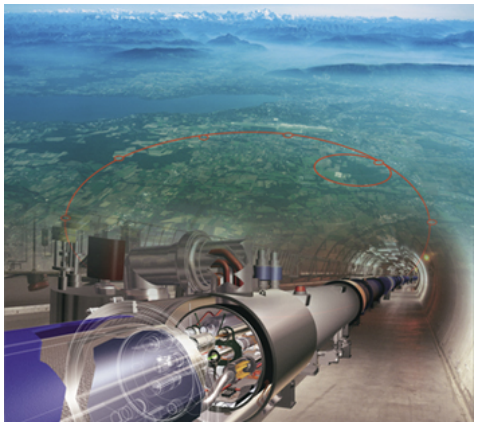

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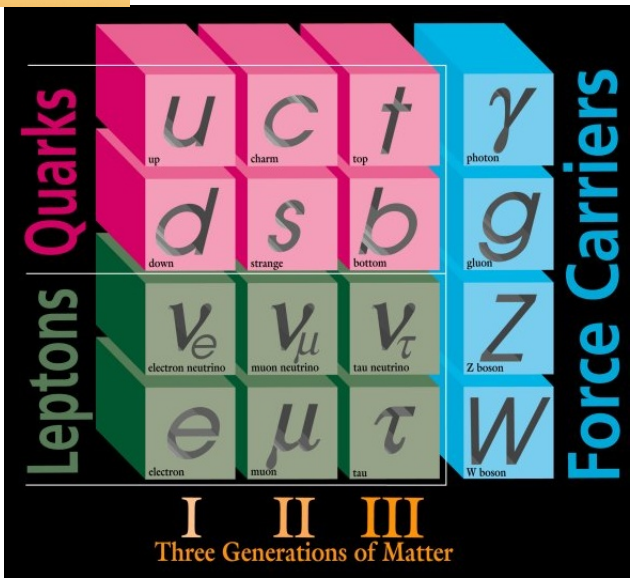
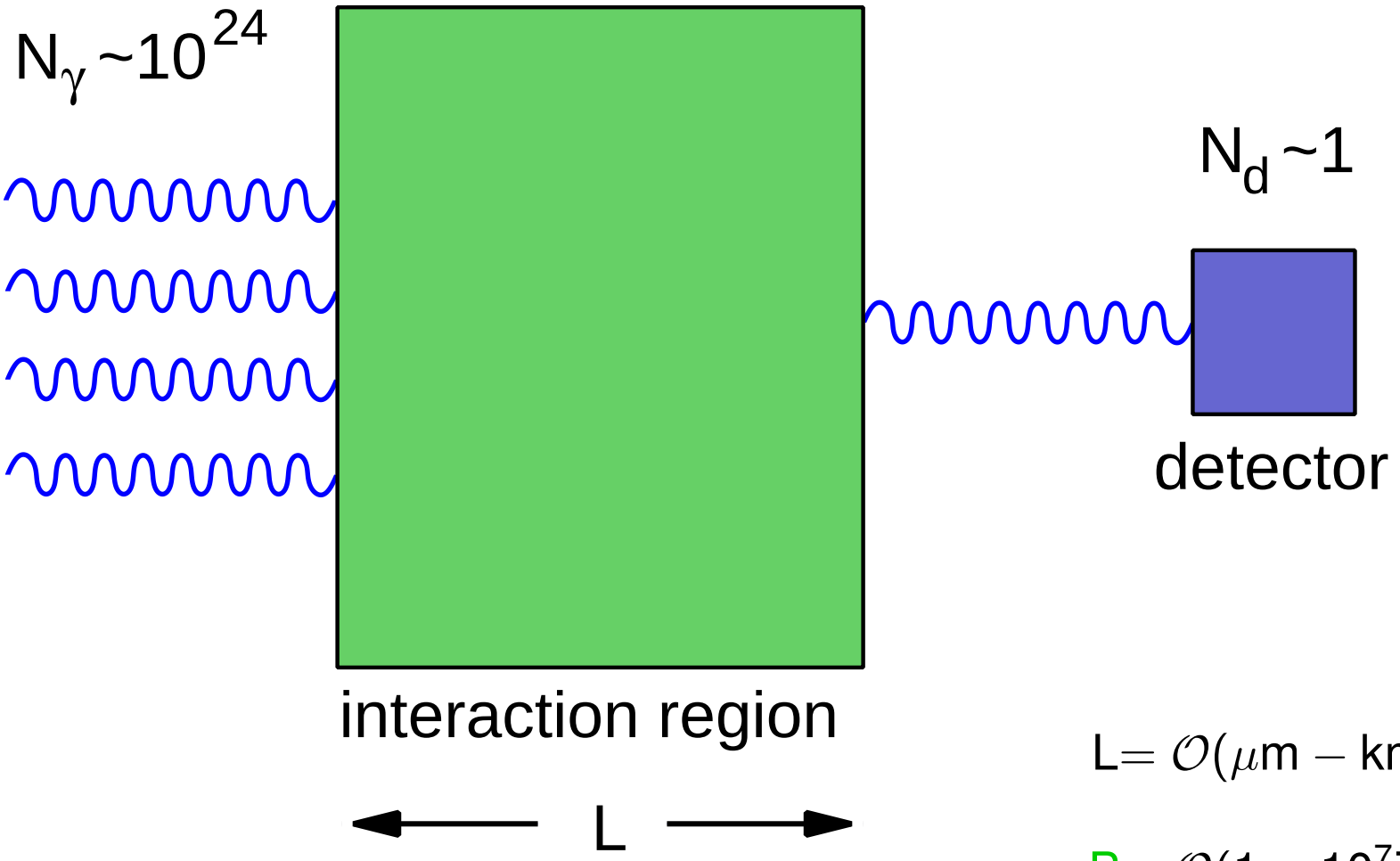


[AHLERS@DESY]

Hidden Sector (weakly coupled & light)

$\Longrightarrow$ Optical Experiments

Optical Experiments



L$= \mathcal{O}(\mu\text{m} - \text{km})$

B$= \mathcal{O}(1 - 10^7\text{T})$

Low-Energy Effective Theories

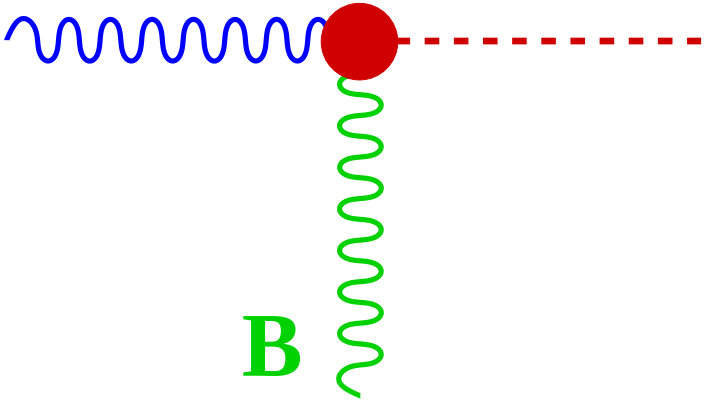
Low-Energy Effective Theories?

▷ Axion-Like Particle (PECCEI,QUINN'77; WEINBERG'78; WILCZEK'78)

$$\mathcal{L}_{\text{ALP}} = \frac{g}{4}\phi F^{\mu\nu} \overset{(\sim)}{F}_{\mu\nu} - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}{m_\phi}^2\phi^2$$

▷ 2 parameters:

- ALP mass: m_ϕ (potentially very light)
- ALP-γ coupling: $g = \frac{1}{M}$ (weak, e.g., M=10^X GeV)



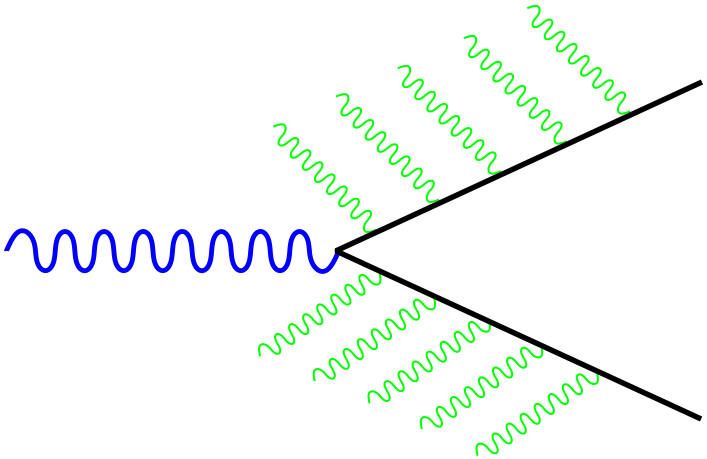
Low-Energy Effective Theories?

▷ **M**ini-**C**harged **P**article (OKUN'82; HOLDOM'85)

$$\mathcal{L}_{\text{MCP}} = -\bar{\psi}(i\partial\!\!\!/ + \epsilon e A\!\!\!/)\psi + m_\epsilon \bar{\psi}\psi$$

▷ 2 parameters:

- MCP mass: m_ϵ (potentially very light)
- MCP-γ coupling: ϵ (weak, e.g., ϵ=10^{-X})

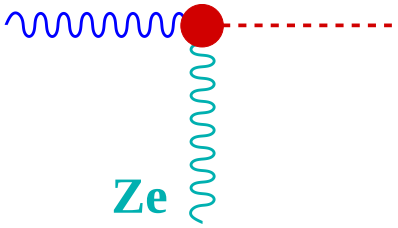


Bounds on m_ϕ, g, ϵ, m_ϵ, χ, μ, . . . ?

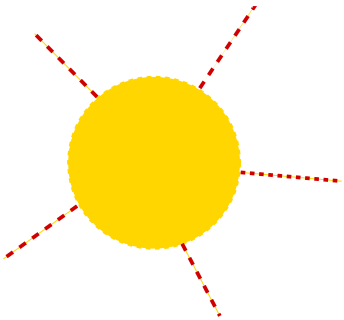
Astrophysical Bounds from Stellar Energy Loss

▷ ALP production:

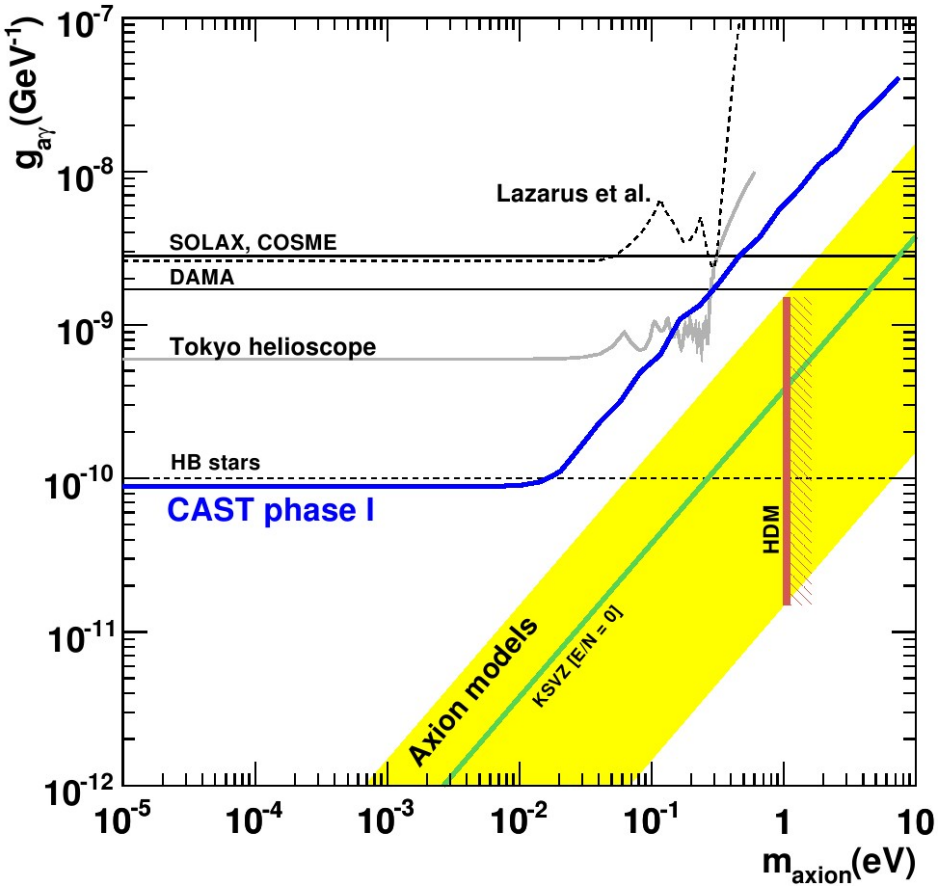
Primakov process



▷ ALP emission



(VAN BIBBER ET AL.'89)



$$\frac{1}{g} = M \gtrsim 10^{10}\text{GeV}$$

(CAST COLLABORATION 2007)

Astrophysical Bounds from Stellar Energy Loss

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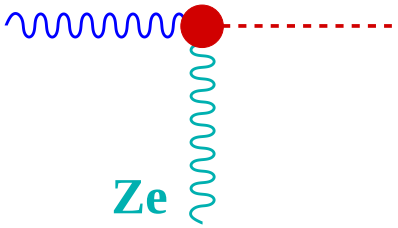
Primakov process



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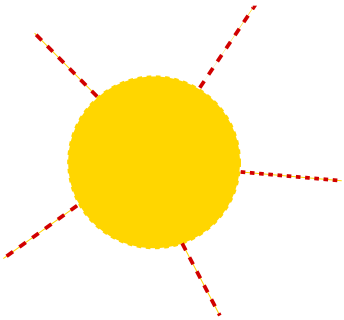
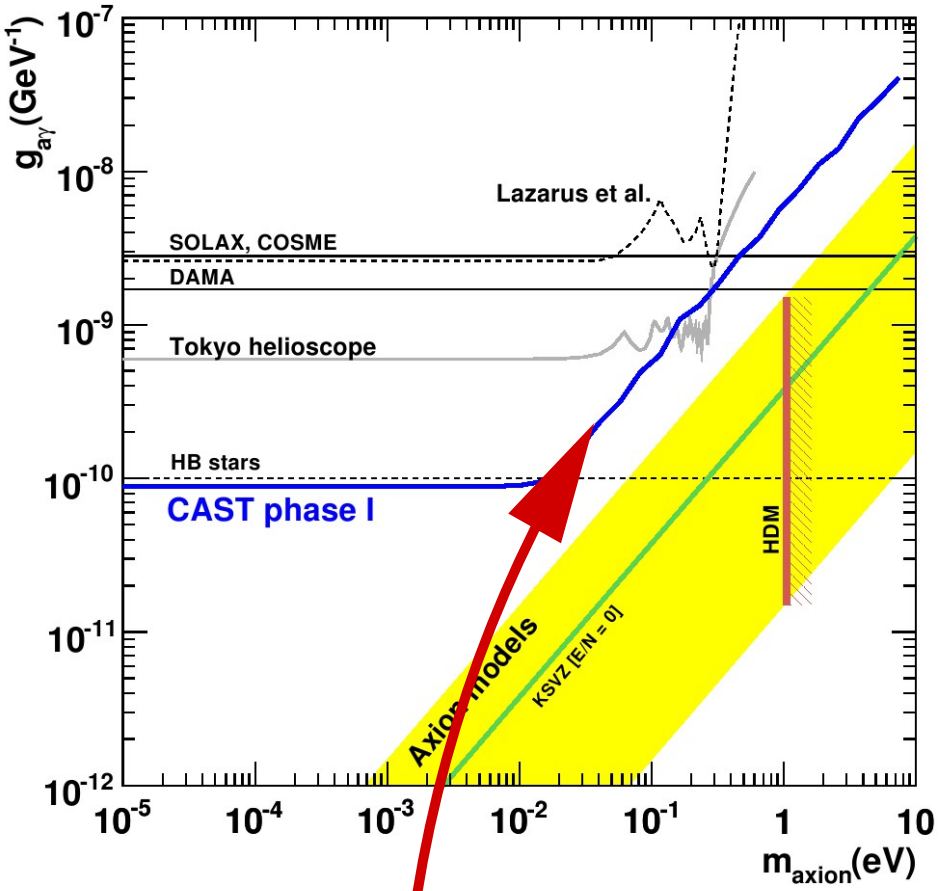


(VAN BIBBER ET AL.'89)



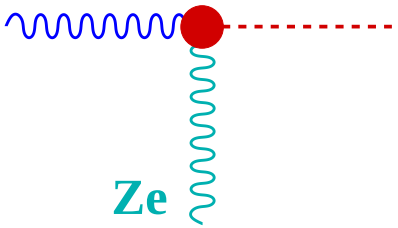
$|q| \sim$ keV

laboratory: $|q| \sim$ micro eV

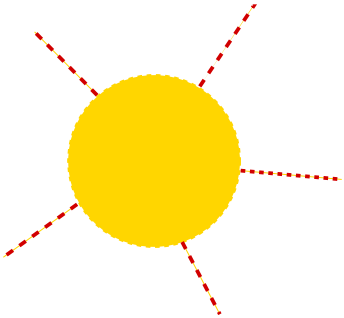
Astrophysical Bounds from Stellar Energy Loss

▷ ALP production:

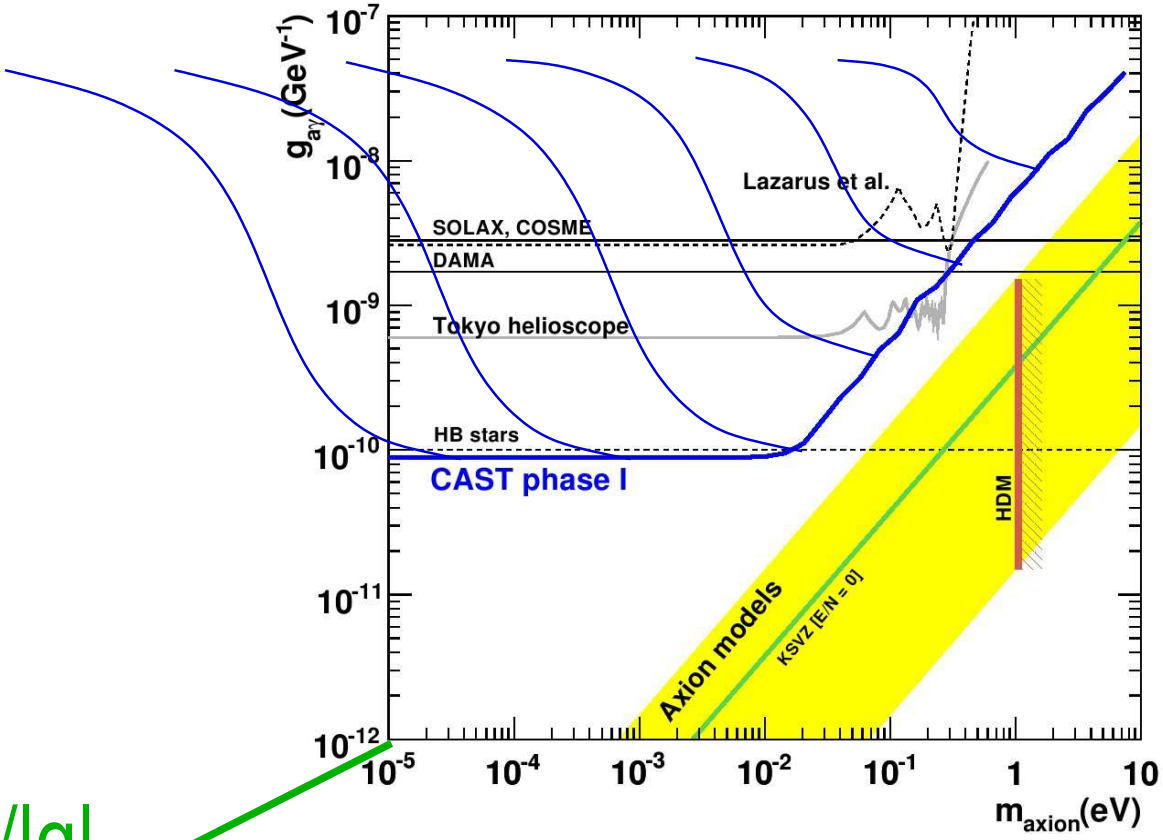
Primakov process



▷ ALP emission



1/|q|



(VAN BIBBER ET AL.'89)

(JAECKEL,MASSO,REDONDO,RINGWALD,TAKAHASHI'06)

Physics at the Milliscale?

- milliscale observations
  - neutrino masses:
    - $\sum m_i < 0.7\,\mathrm{eV}$,
    - $|\Delta m_{21}| \simeq 9\,\mathrm{meV}$,
    - $|\Delta m_{23}| \simeq 56\,\mathrm{meV}$
  - cosmological constant:
    - $\Lambda \sim (2\,\mathrm{meV})^4$

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- physicist's imperative:

Do experiments!

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Ask for experiments!

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  - cosmological constant:
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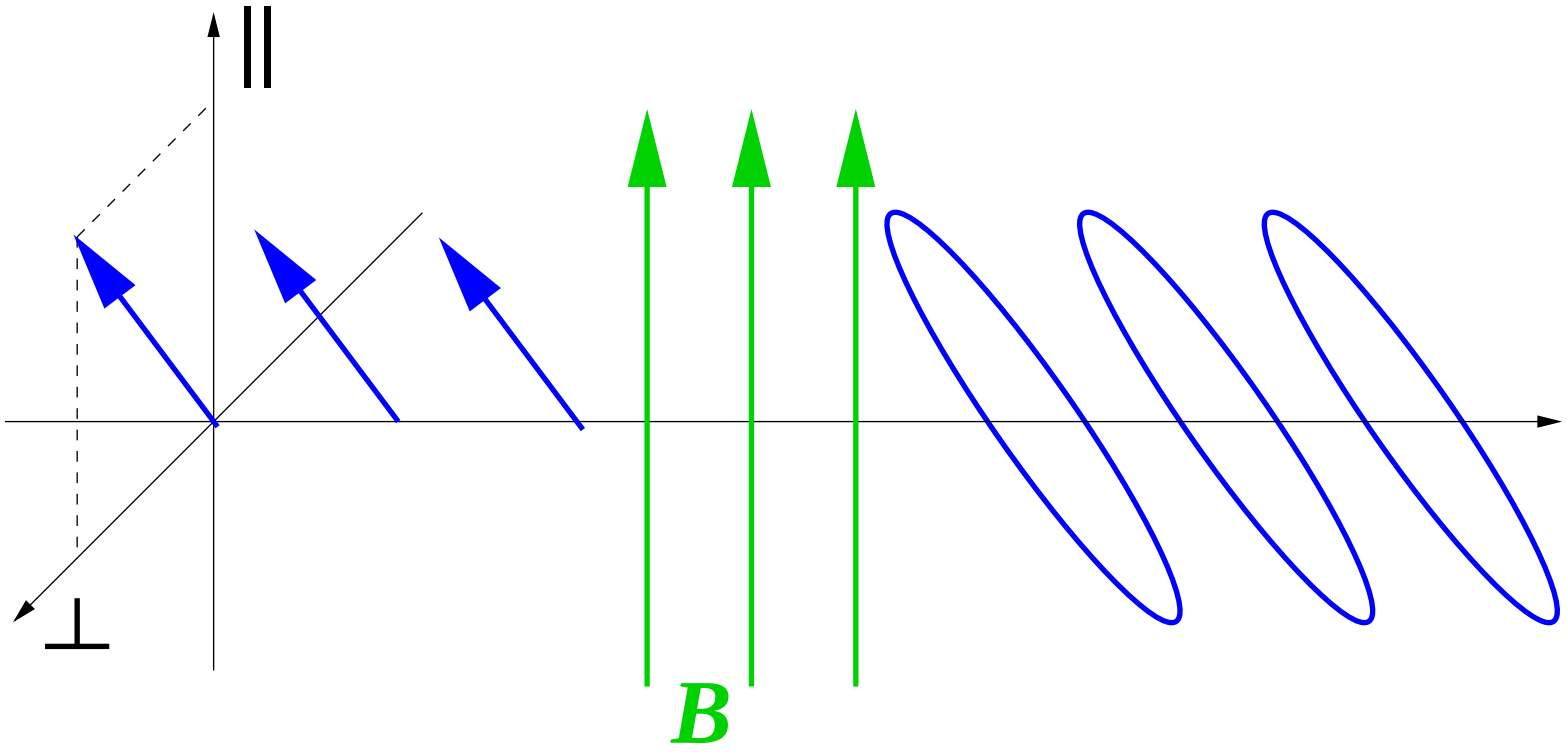
- theorist's categoric imperative:

Ask only for those experiments
for which you are willing to do calculations.

Optical Signatures

Light Propagation in a B field.

▷ observable: birefringence induces ellipticity



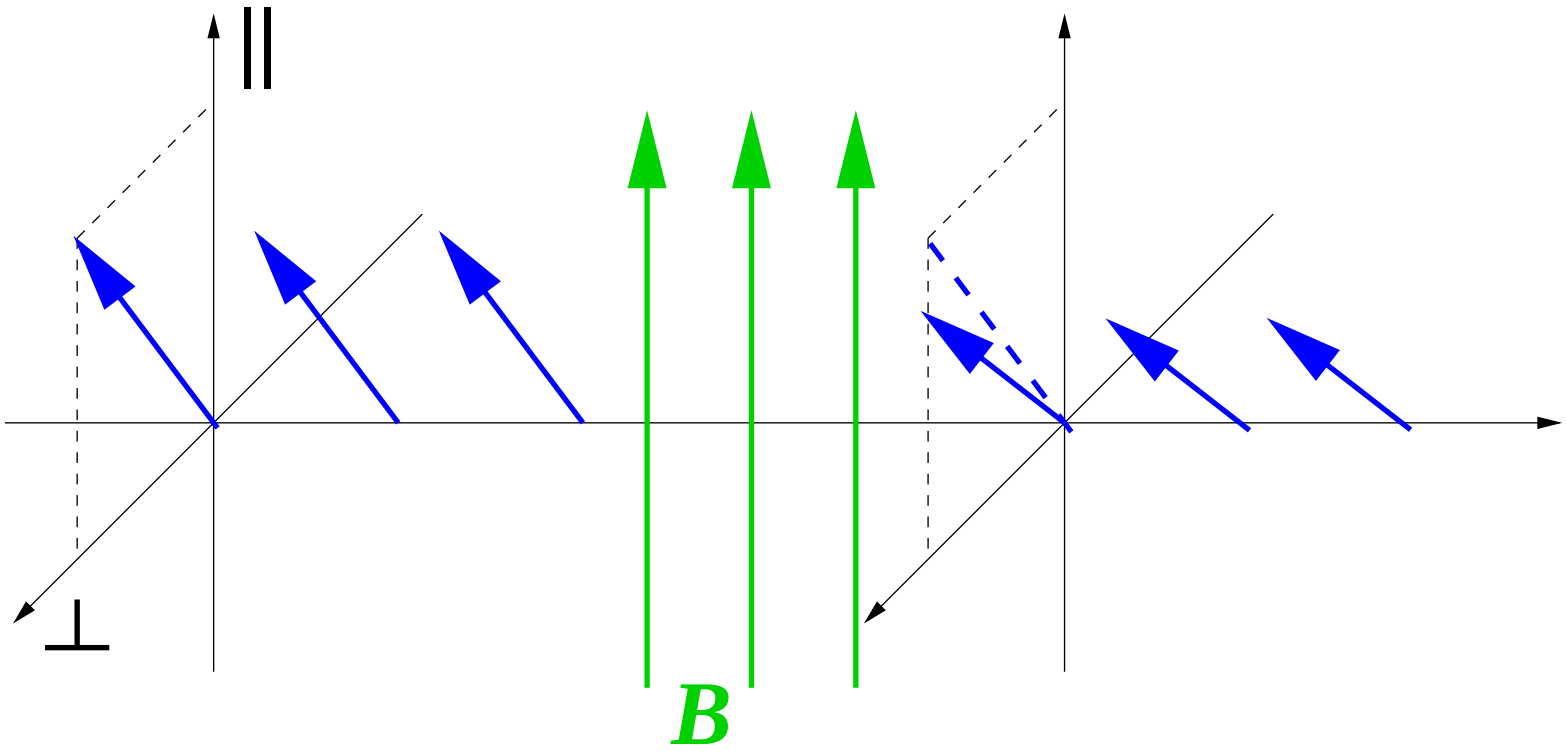
▷ ellipticity:

$$\psi_{\text{ell}} = \pi \frac{L}{\lambda} \Delta v \sin 2\theta$$

Light Propagation in a B field.

▷ observable:

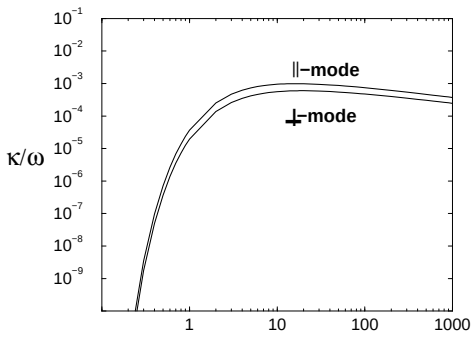
dichroism (polarization-dependent absorption) induces rotation



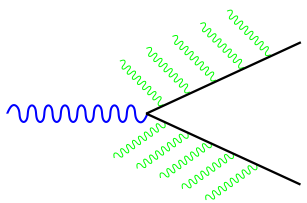
rotation: $|\Delta\theta| \simeq \frac{1}{4}\,\Delta\kappa L \sin 2\theta$, κ: absorption coefficient

Light Propagation in a B field.

▷ absorption: in QED only above pair-production threshold $\omega > 2m$



$$\kappa_{\parallel,\perp} = -\frac{1}{\omega}\,\mathrm{Im}\,\Pi_{\parallel,\perp}$$



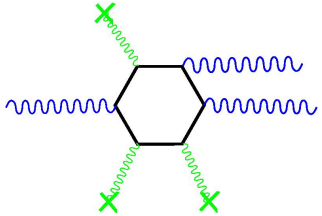
absorption $\Longrightarrow$ dichroism

(TSAI&ERBER'74,DITTRICH&HG'00)

$$\frac{3}{2}\,\frac{eB}{m^2}\,\frac{\omega}{m}\,\sin\theta$$

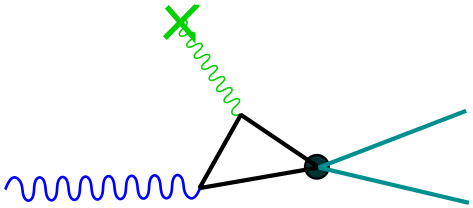
▷ photon splitting

(ADLER'71)



lab mean free path $1/\kappa|_{\mathrm{PVLAS}} \sim 3\cdot 10^{57}\times$ SoU

- neutrino $\bar{\nu}\nu$ pair emission in EM fields . . . ?



too small!

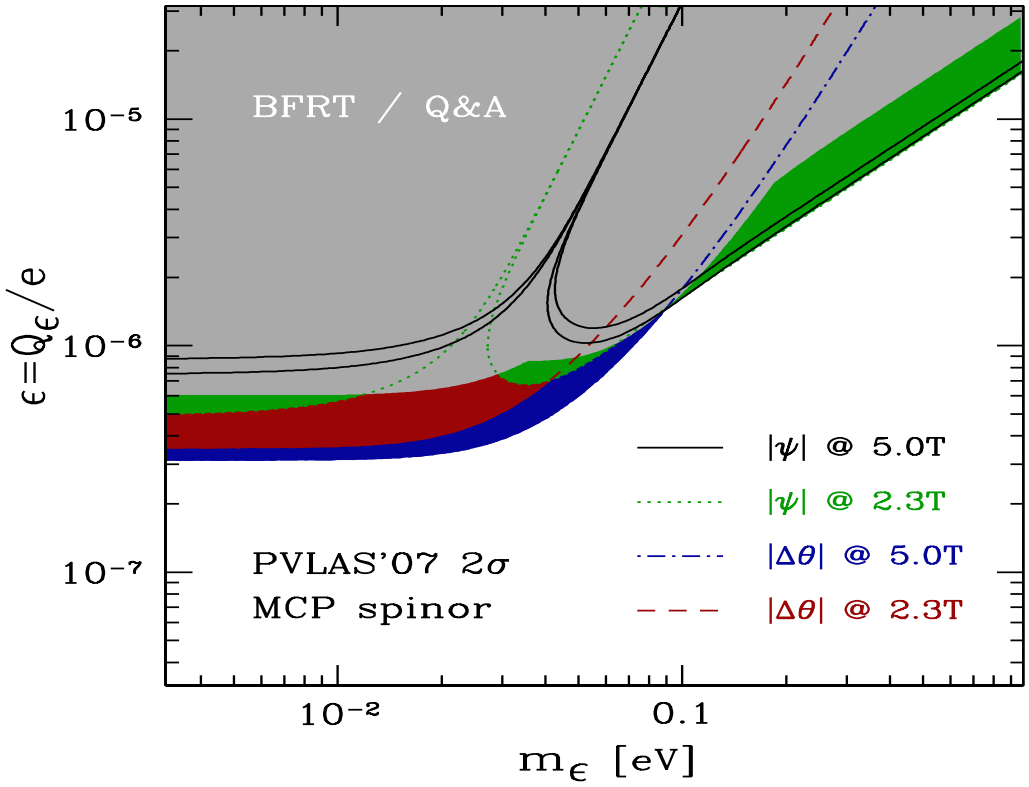
(HG,SHAISULTANOV'00)

MCP Results from Birefringence& Rotation Data

▷ PVLAS'07: (ZAVATTINI ET AL.'07) (cf. BFRT (CAMERON'93), Q&A (CHEN'06))

birefringence: $\Delta v \leq 1.1 \times 10^{-19}$/pass at $B = 2.3$T

dicroism: $\Delta \kappa \leq 5.4 \times 10^{-15}$cm^{-1} at $B = 5.5$T



(HG,JAECKEL,RINGWALD'06; AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)

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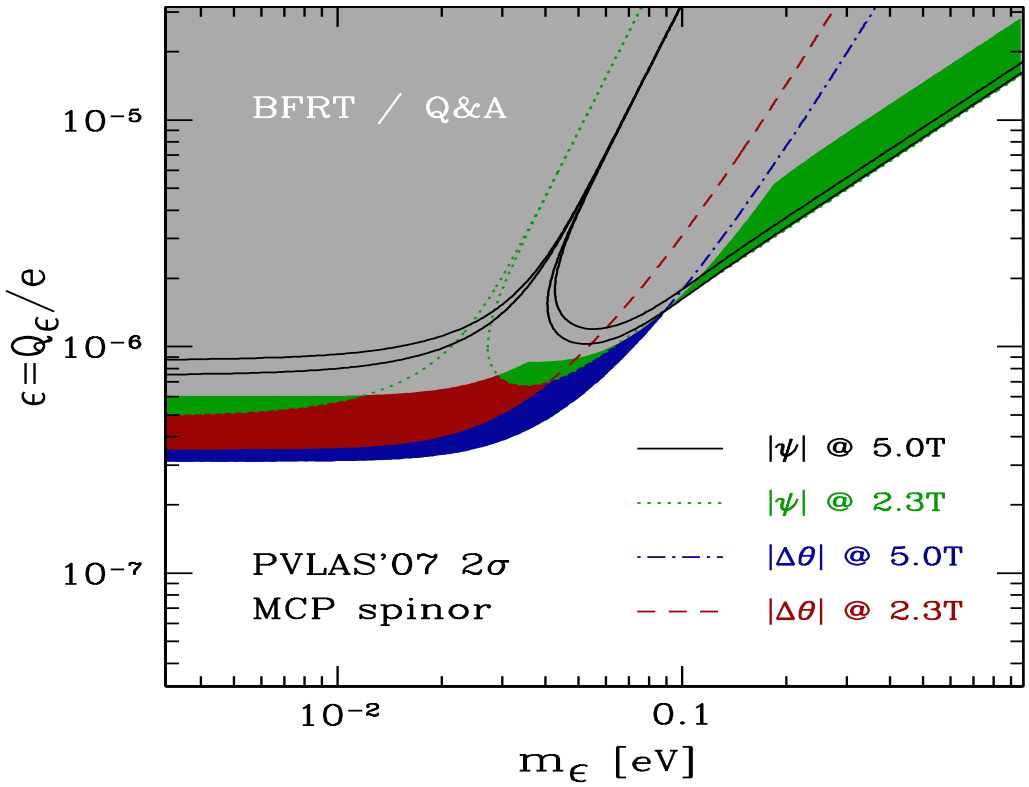
Orthopositronium Lamb shift

(MITSUI'93)

(DAVIDSON ET AL.'00)



(HG,JAECKEL,RINGWALD'06; AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)

$\sim$ new CMB bounds

(MELCHIORRI ET AL.'07)

model-dependent astro-bounds $\Downarrow$

MCP Results from Birefringence& Rotation Data

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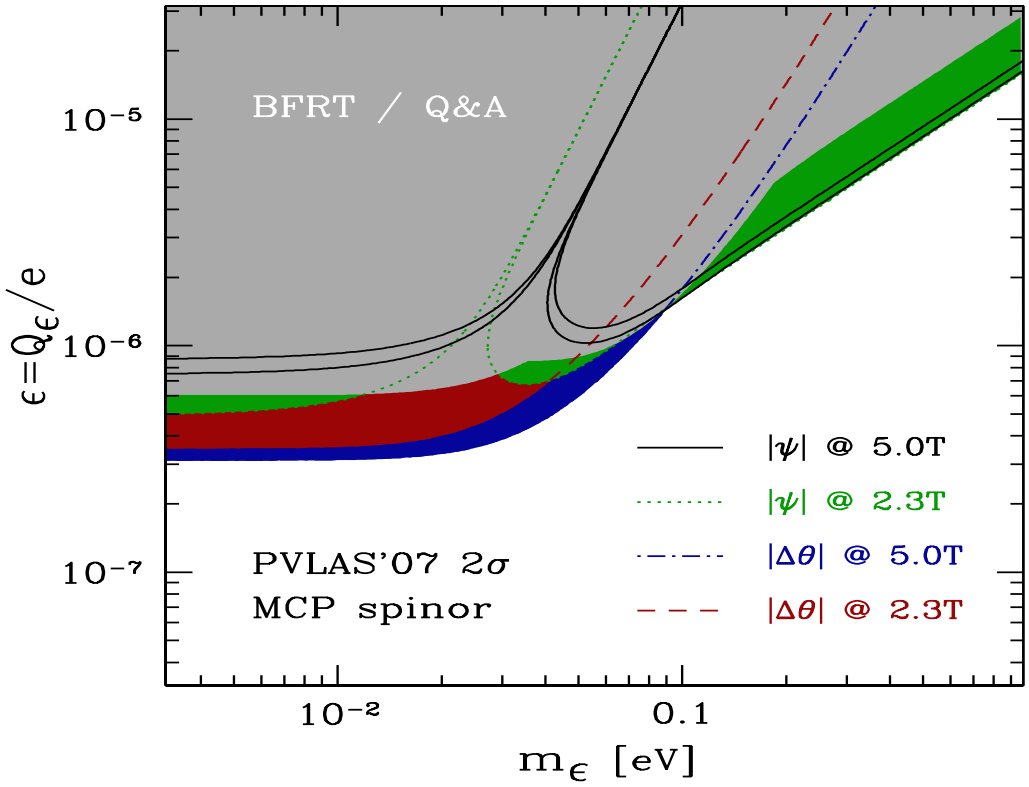


ELI: $\epsilon \gtrsim 10^{-7}$

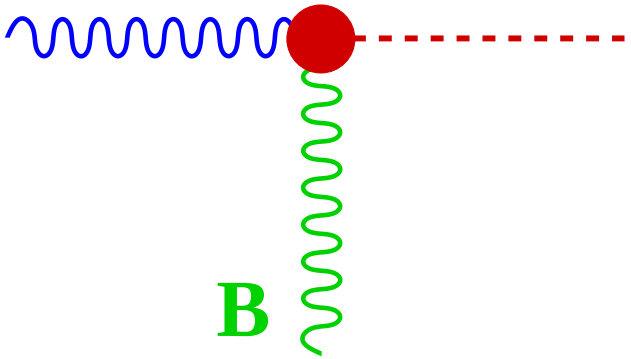
(HG,JAECKEL,RINGWALD'06; AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)

ALP Effects.

(MAIANI,PETRONZIO,ZAVATTINI'86; RAFFELT,STODOLSKY'88)

▷ dicroism / rotation:

$$\Delta\theta = -N\left(g\frac{BL}{4}\right)^2\left[\frac{\sin\left(\frac{{m_\phi}^2 L}{4\omega}\right)}{\left(\frac{{m_\phi}^2 L}{4\omega}\right)}\right]^2$$



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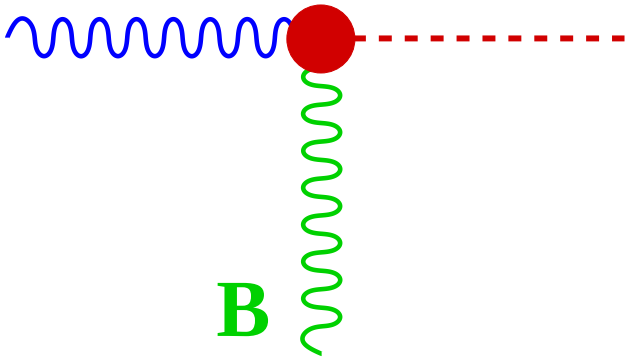
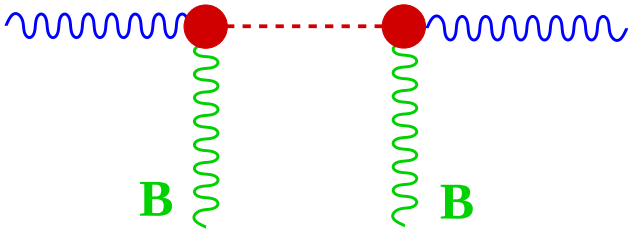


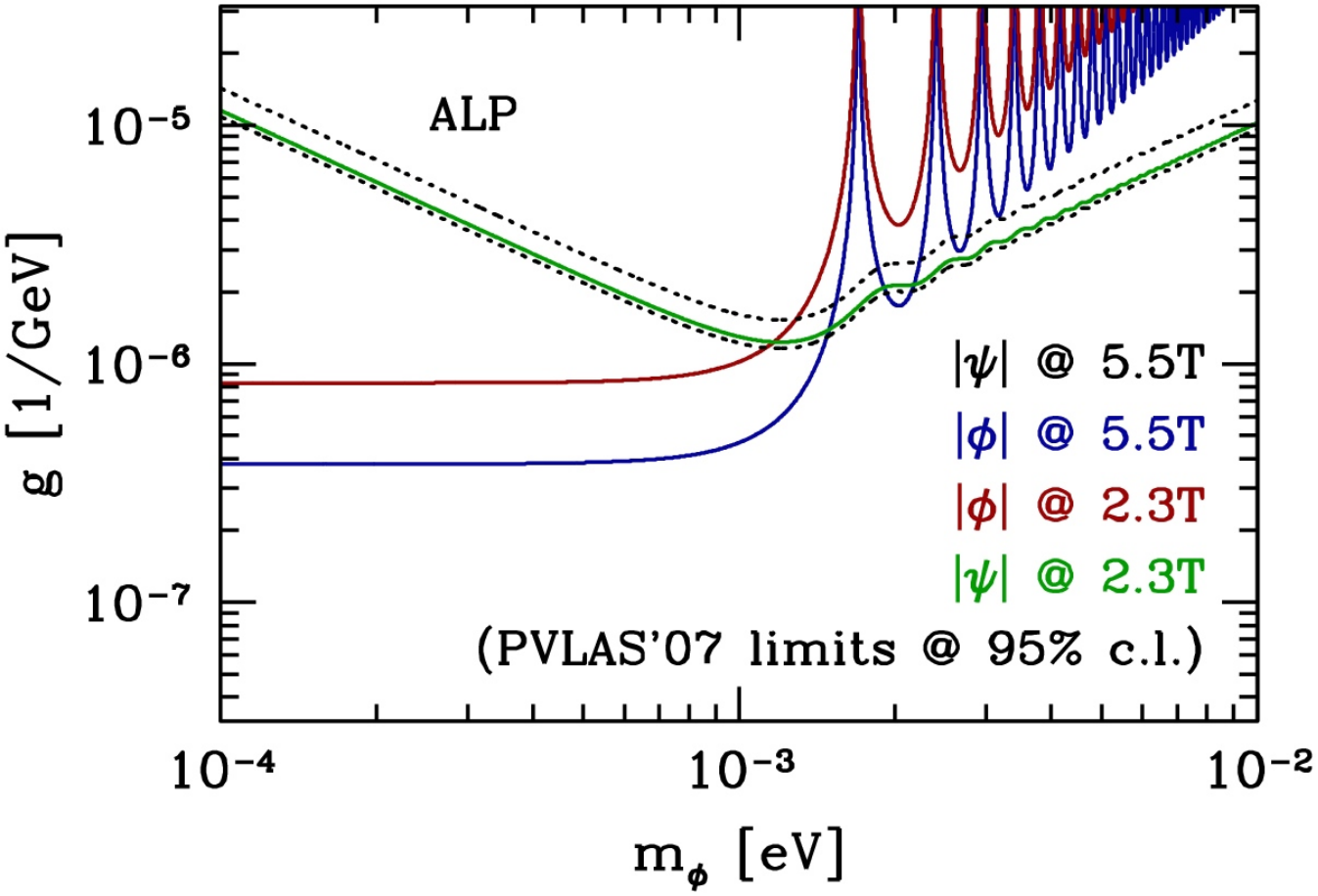
▷ birefringence / ellipticity:

$$\Delta\phi = -N\frac{g^2B^2\,\omega L}{2m_\phi^2}\left[1-\frac{\sin\left(\frac{m_\phi{}^2 L}{4\omega}\right)}{\left(\frac{m_\phi{}^2 L}{4\omega}\right)}\right]$$



ALP Results from PVLAS

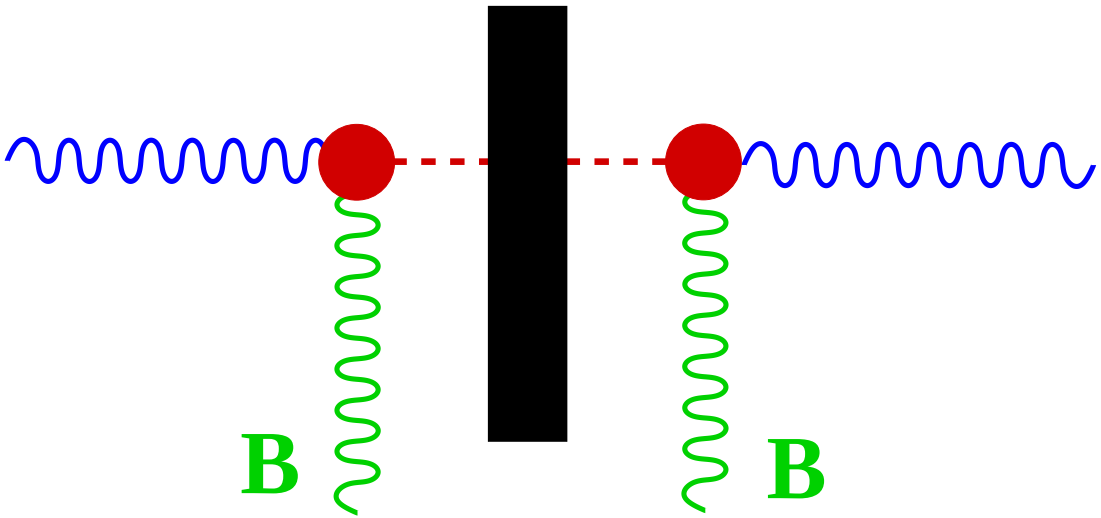
▷ PVLAS'07: (ZAVATTINI ET AL.'07) (AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)



$\Longrightarrow$ Sensitivity scale: $\frac{1}{g} \lesssim 10^7$GeV

ALP: Light-Shining-Through-Walls Experiments

(SIKIVIE'83; ANSELM'85; GASPERINI'87; VAN BIBBER ET AL.'87)



▷ photon regeneration:

$$n_{\text{out}} = n_{\text{in}} \left\lfloor \frac{N_{\text{pass}} + 1}{2} \right\rfloor \frac{1}{16} \left(gBL\cos\theta\right)^4 \left(\frac{\sin(\frac{Lm_\phi^2}{4\omega})}{\frac{Lm_\phi^2}{4\omega}} \right)^4$$

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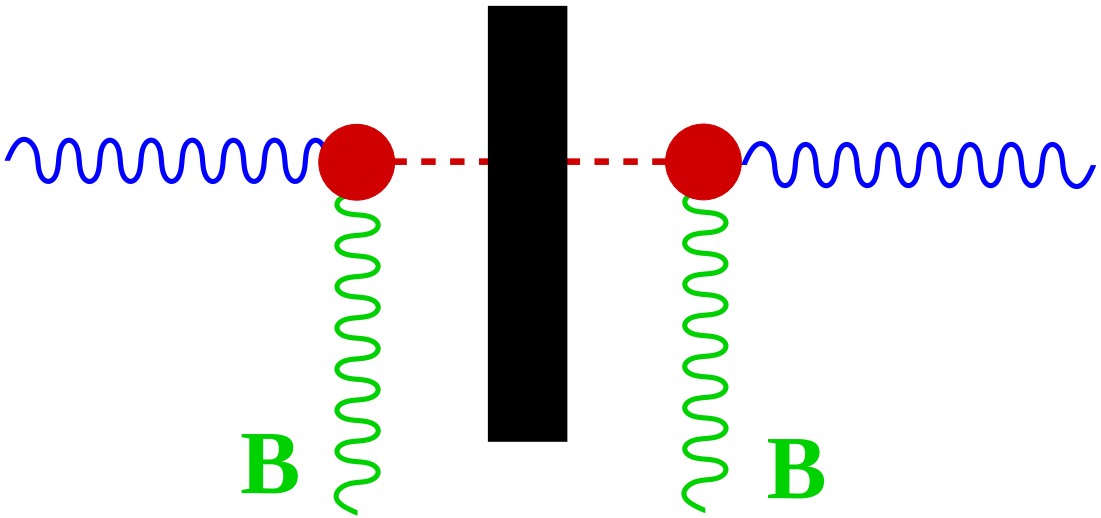
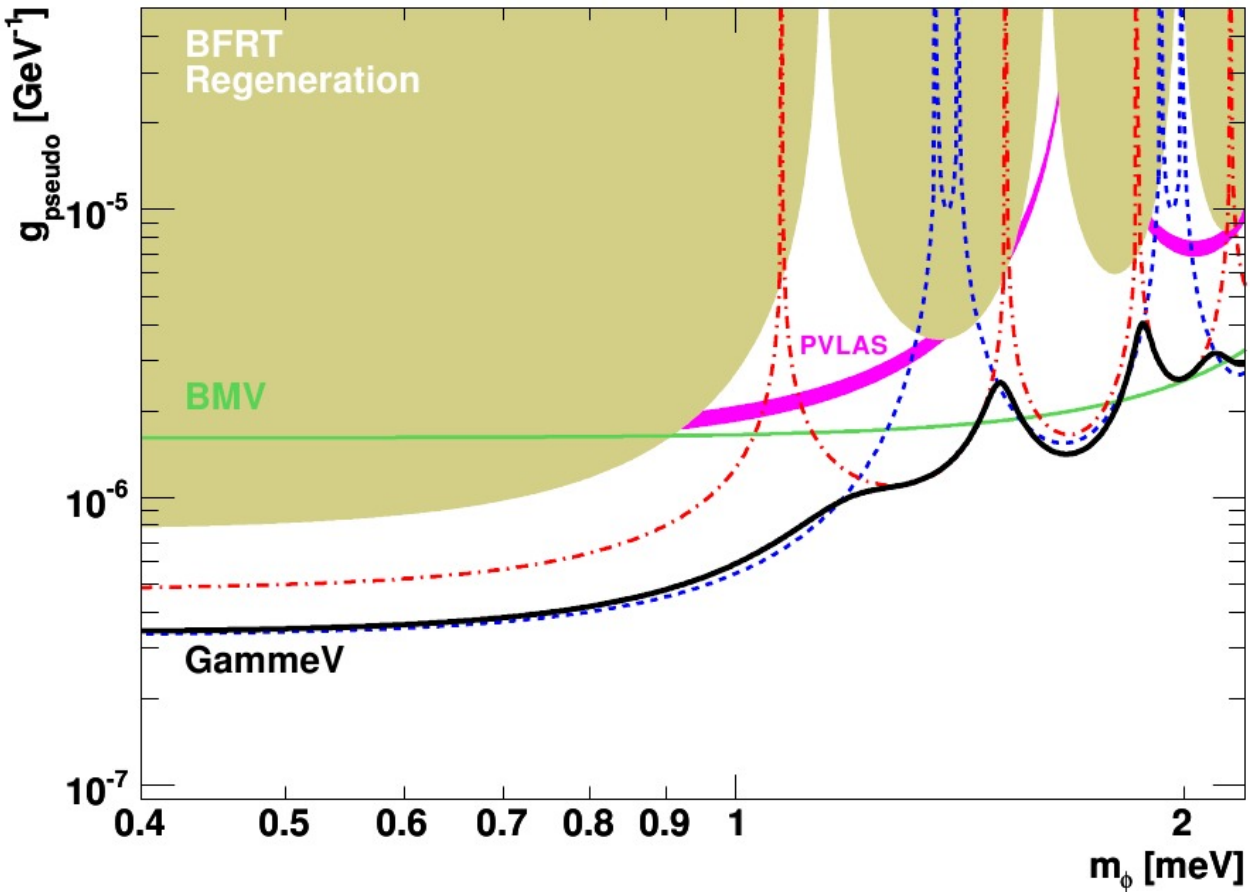


- BMV (Toulouse) — 1st run: 2006; 1st data: Oct 2007
- LIPSS (JLAB) — 1st run: Mar 2007; 1st data: Apr 2008
- OSQAR (CERN) — 1st run: Jun 2007; 1st data: Nov 2007
- GammeV (Fermilab) — 1st run: Jul 2007; 1st data: Jan 2008
- ALPS (DESY) — 1st run: Sep 2007; 1st data: soon

ALP Results from LSTW

▷ GammeV: Light-Shining-Through-Wall (CHOU ET AL.'08)



ELI potential for LSTW

▷ photon regeneration:

$$n_{\text{out}} = n_{\text{in}} \left\lfloor \frac{N_{\text{pass}} + 1}{2} \right\rfloor \frac{1}{16} (gBL\cos\theta)^4 \left(\frac{\sin(\frac{Lm_\phi^2}{4\omega})}{\frac{Lm_\phi^2}{4\omega}} \right)^4$$

▷ PVLAS:

$$(gBL)\Big|_{\text{PVLAS}} \simeq 5 \times \left[\frac{g}{\text{GeV}^{-1}} \right]$$

$\Longrightarrow$ sensitivity scale:

$$g \gtrsim 5 \times 10^{-7} \text{GeV}^{-1}$$

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▷ ELI:

$$(gBL)\Big|_{\text{ELI}} \simeq 3.3 \times 10^3 \left[\frac{g}{\text{GeV}^{-1}} \right] \left[\frac{L}{50\mu\text{m}} \right]$$

$\Longrightarrow$ sensitivity scale:

$$g \gtrsim 3 \times 10^{-9}\text{GeV}^{-1}$$

Strong Fields and Cosmology?

- Dark Energy?

  . . . cosmological constant, quintessence, . . .

- matter couplings?

  . . . “5th-force problem”

Chameleon Dark Energy

▷ density-dependent couplings: (KHOURY,WELTMAN'04)

$$\mathcal{L} = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) - \frac{e^{\frac{\phi}{M}}}{4}F^2 + S_m(e^{\frac{\phi}{M_m}}g_{\mu\nu}, \psi_m)\right)$$

$$\Longrightarrow \; m_\phi = m_\phi(\rho_m)$$

▷ ALP bounds: density suppression in the sun

(BRAX,VAN DE BRUCK,DAVIS,MOTA,SHAW'07)

▷ in vacuo: chameleon-photon coupling $\sim$ ALP

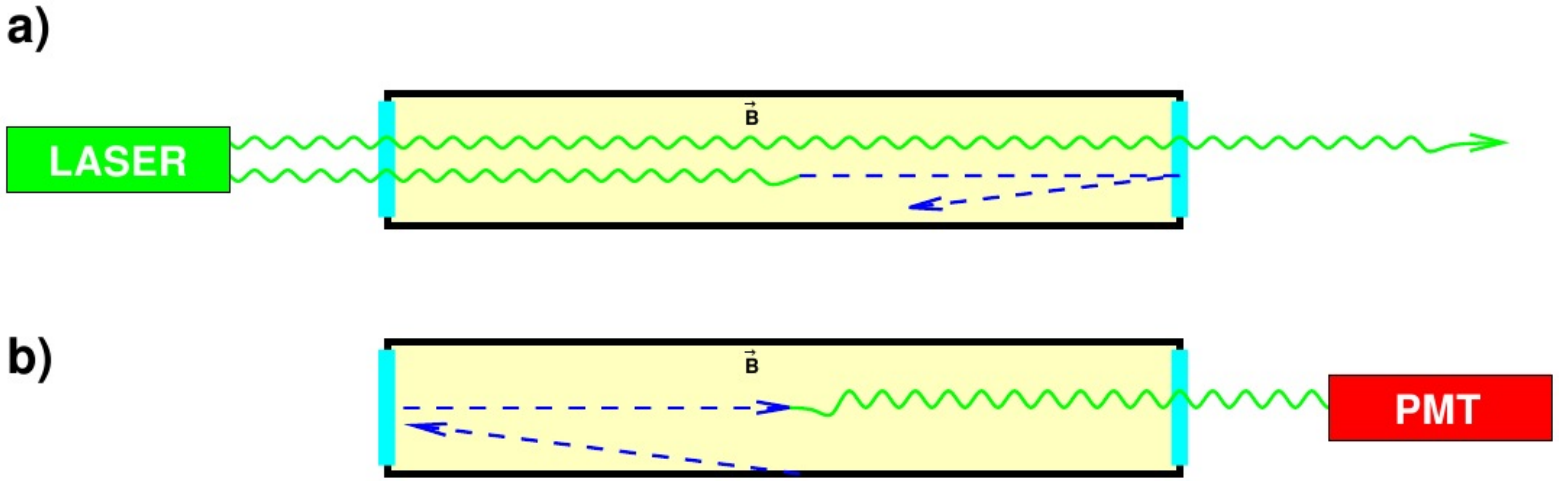
$$\mathcal{L}_{\text{int}} \simeq -\frac{1}{4}\, g\, \phi F_{\mu\nu}F^{\mu\nu}, \quad g = \frac{1}{M}$$

Chameleonic Afterglow

(HG,MOTA,SHAW'07)

(AHLERS,LINDNER,RINGWALD,SCHREMPP,WENINGER'07)

(GAMMEV COLLARBORATION'07)



[A.WELTMAN@0809.4293]

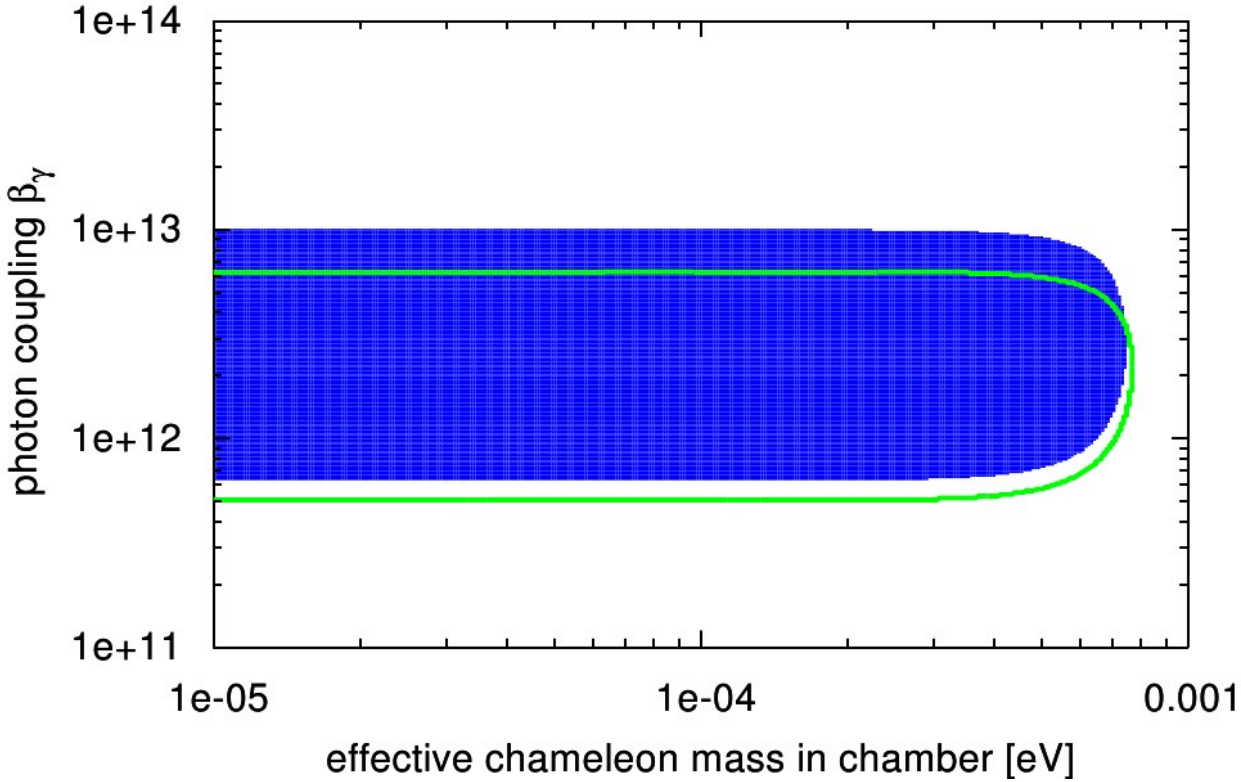
▷ afterglow rate:

$$n_{\text{out}} = n_{\text{in}} \frac{1}{16} (gBL\cos\theta)^4 \left(\frac{\sin(\frac{Lm_\phi^2}{4\omega})}{\frac{Lm_\phi^2}{4\omega}} \right)^4$$

Chameleonic ALP Results

▷ GammeV:

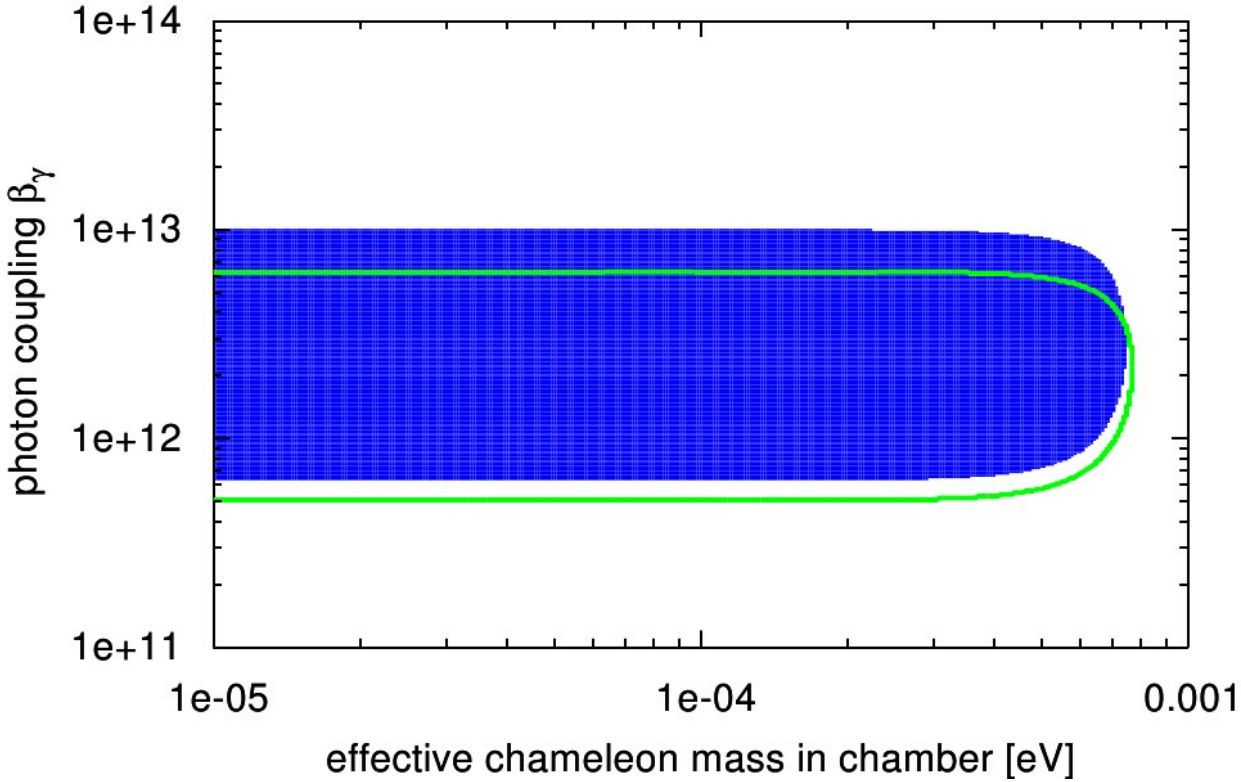
(CHOU ET AL.'08)



$$\Longrightarrow \; g \gtrsim 2.5 \times 10^{-7} \mathrm{GeV}^{-1}$$

Chameleonic ALP Results

▷ GammeV: (CHOU ET AL.'08)



▷ ELI potential:

$$g \gtrsim 3 \times 10^{-9} \mathrm{GeV}^{-1}$$

Conclusions

▷ Why strong-field physics . . . ?

- " . . . exploring some issues of fundamental physics that have eluded man's probing so far" (TAJIMA'01)

- QFT: high energy (momentum) vs. high amplitude

- "Fundamental-Physics" discovery potential:
  - ALPs: hypothetical NG bosons (axion, majoron, familon, etc.)
  - MCPs: minicharged particles
  - paraphotons
  - sub-millimeter forces
  - . . .

- high physics/costs ratio

LHC

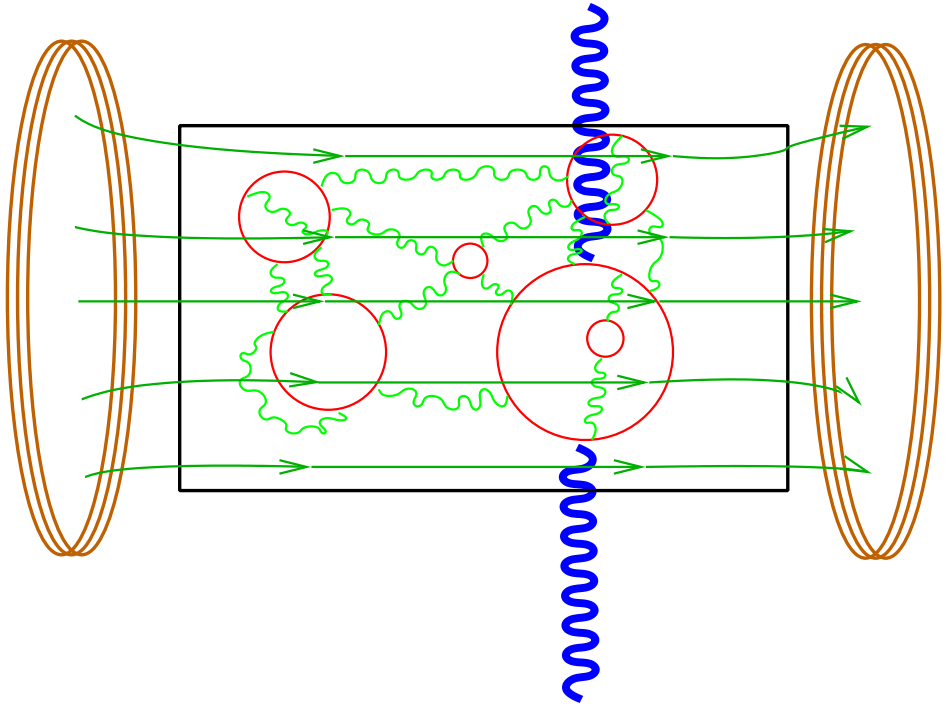
Physics at the Milliscale

[A.LINDNER @ DESY]

Fundamental Physics

▷ Heisenberg-Euler:

e.g., light propagation in strong fields



▷ scale of sensitivity:

magnet: $B = \mathcal{O}(1 - 10\text{T}), \quad \lambda \simeq 1\mu\text{m}, \quad L = \mathcal{O}(1\text{m} - 100\text{km})$

laser: $B = \mathcal{O}(10^4 - 10^7\text{T}), \quad \lambda \simeq 1\text{nm}, \quad L = \mathcal{O}(10 - 100\mu\text{m})$

$$\Longrightarrow \qquad \mu \leq \mathcal{O}(10\text{keV})$$

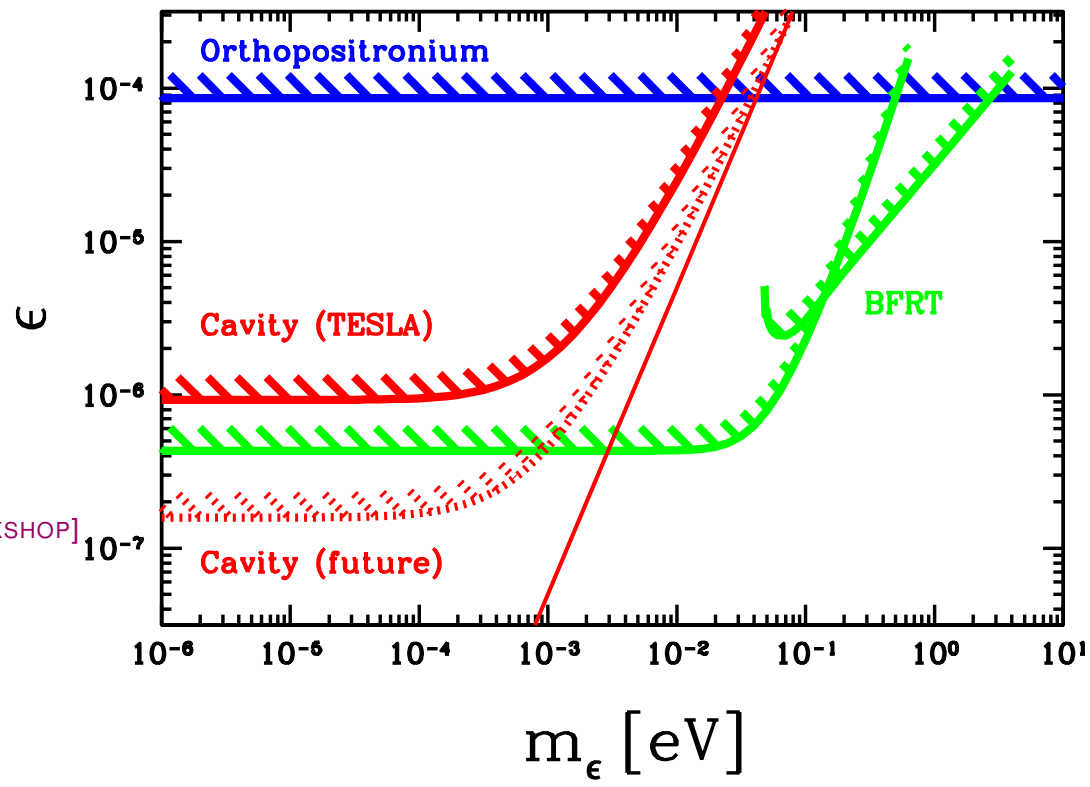
Future Experiments

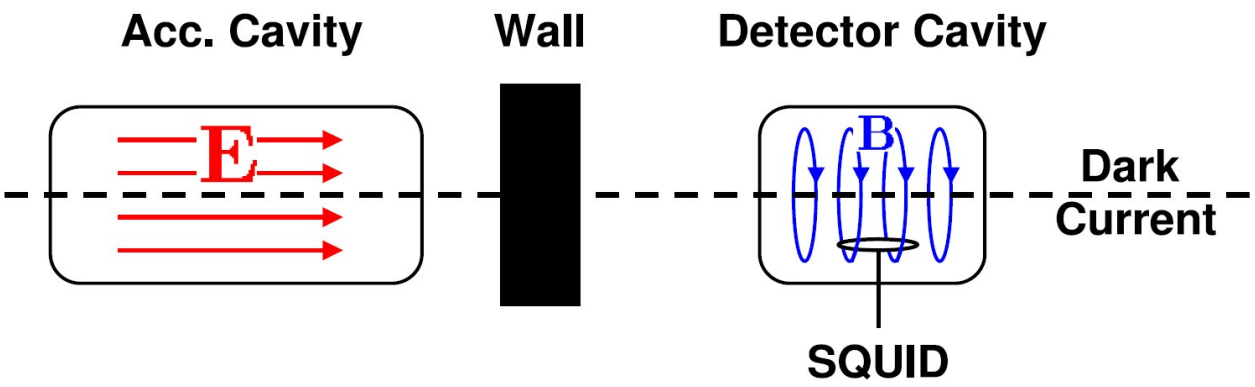
Future Experiments: MCPs

- ▷ MCP pair production in strong electric fields:

  (Schwinger mechanism)

[DUNNE; HEBENSTREIT; SCHÜTZHOLD; BLASCHKE @ THISWORKSHOP]

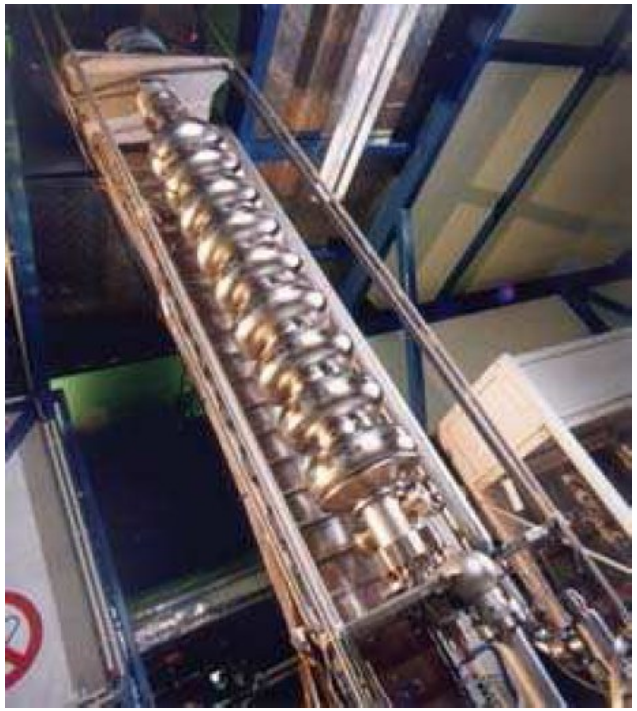


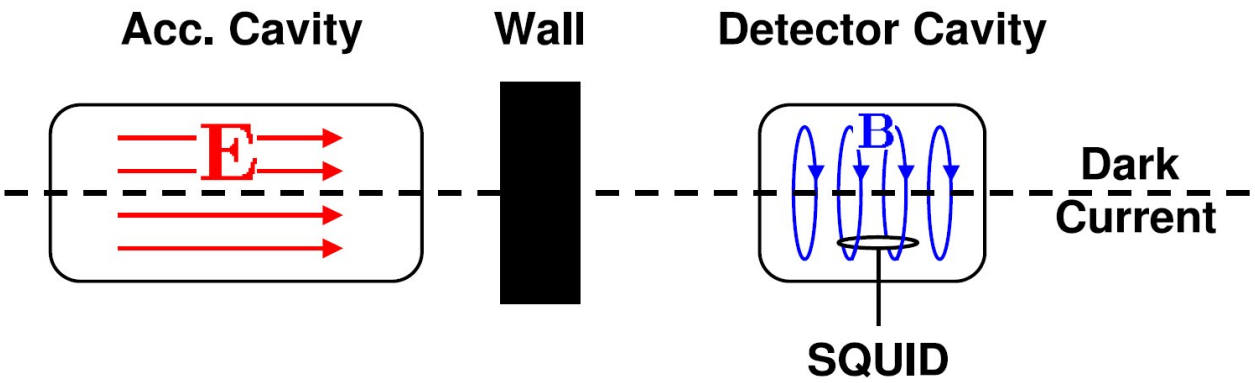


(HG, JAECKEL, RINGWALD'06)

Future Experiments: MCPs

Accelerator
Cavity
Dark
Current





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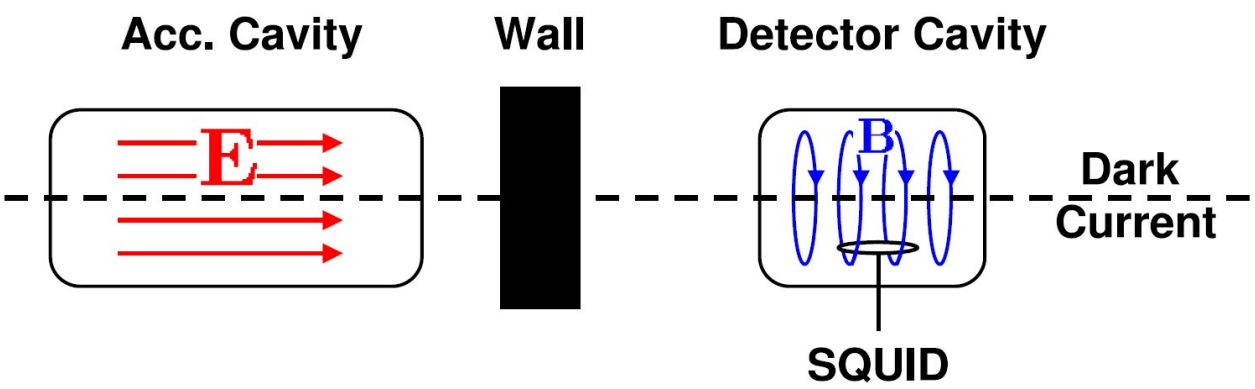
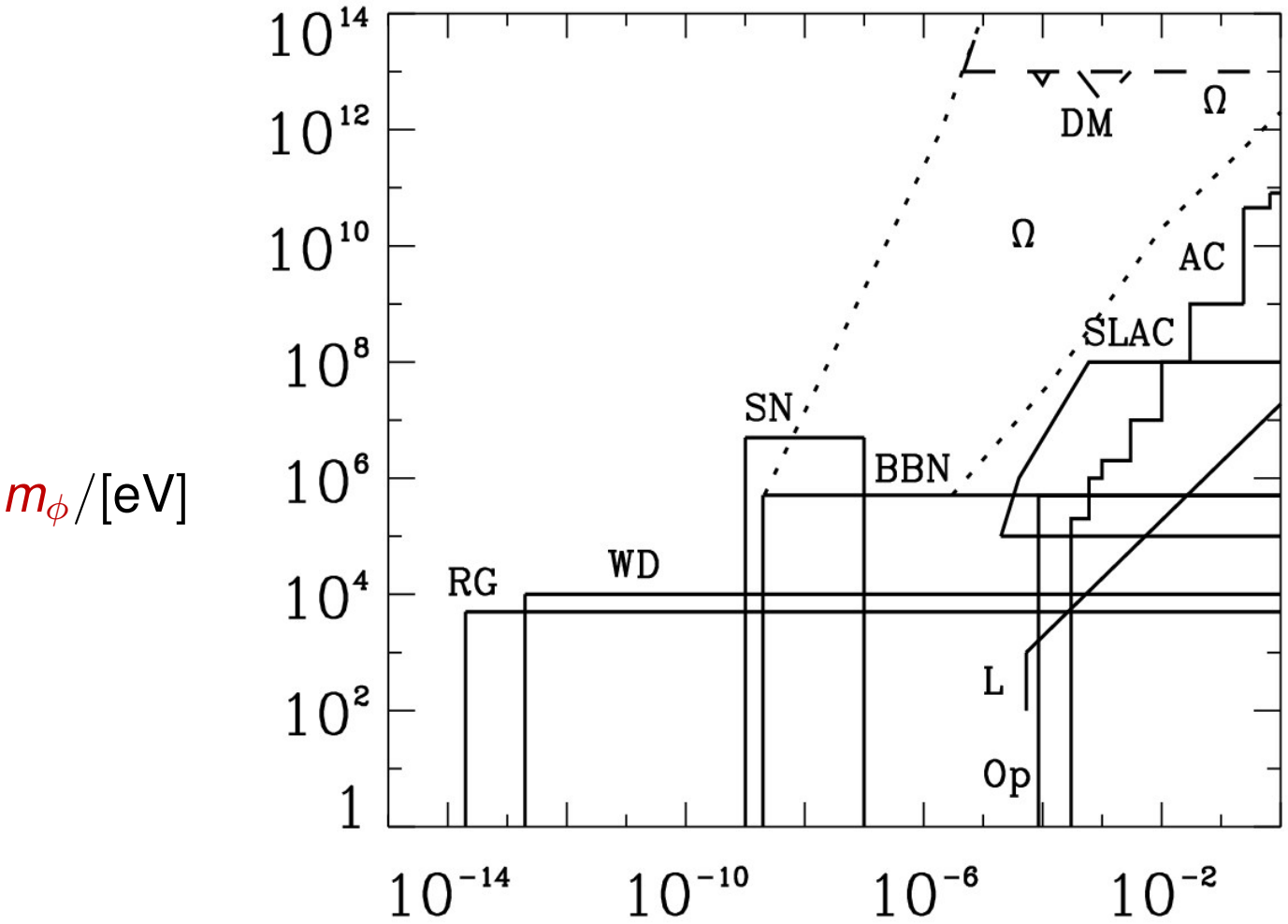


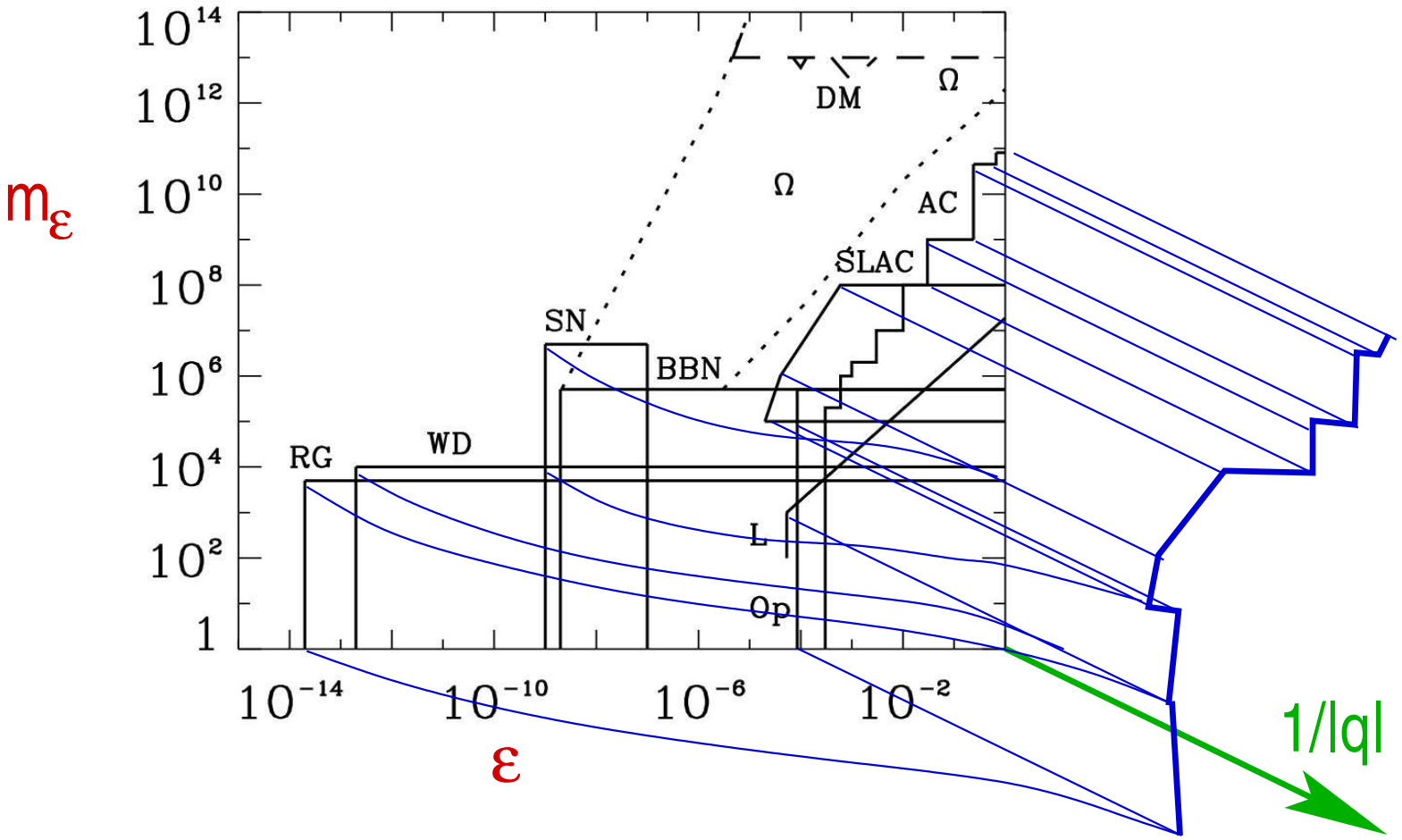
(HG, JAECKEL, RINGWALD'06)

Astrophysical Bounds: MCPs



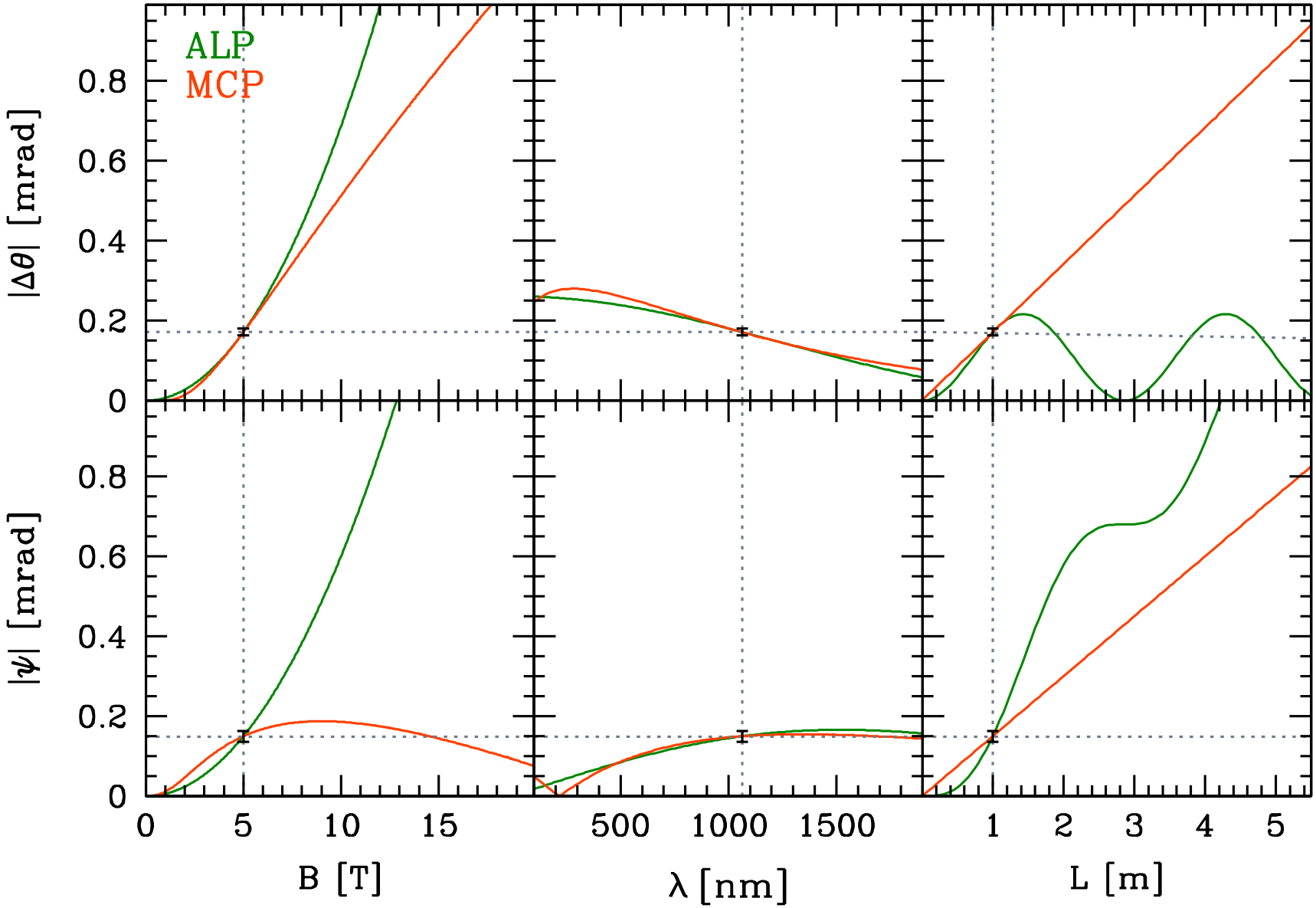
(DAVIDSON, HANNESTAD, RAFFELT'00)

Astrophysical Bounds: MCPs



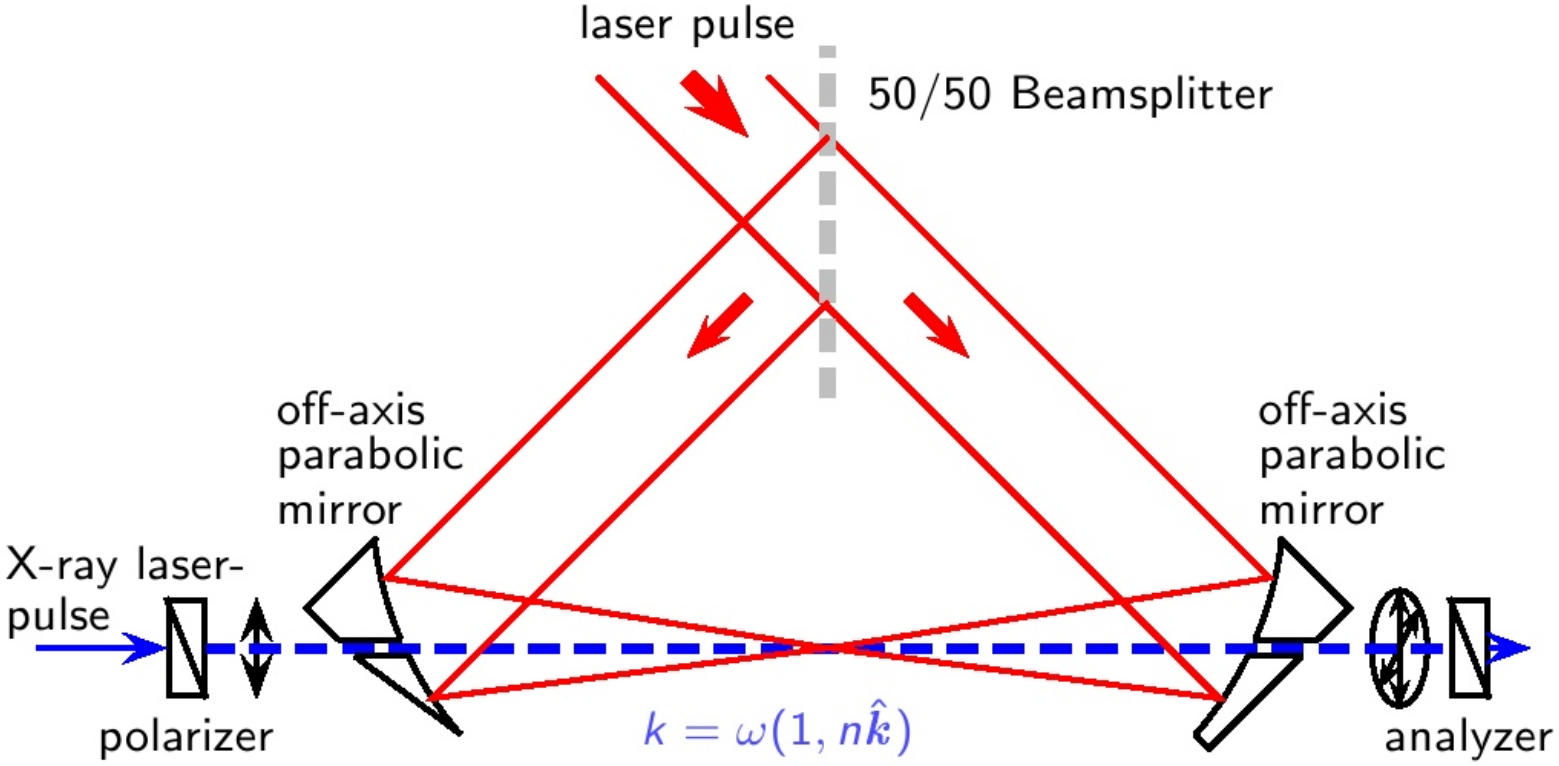
ALPs vs. MCPs

(AHLERS,HG,JAECKEL,RINGWALD'06)



Polaris@Jena

- ▷ birefringence at a photon collider (HEINZL,LIESFELD,AMTHOR,SCHWOERER,SAUERBREY,WIPF'06)
- ▷ high-intensity laser



[WIPF@JENA]

Low-Energy Effective Theories?

▷ Paraphotons γ': gauge-kinetic mixing with further U(1)'s (OKUN'82)

$$\mathcal{L}_{\gamma\gamma'} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\chi\, F^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}\mu A'_{\mu}A'^{\mu}$$

▷ 2 parameters:

- γ' mass: μ (potentially very light)
- γ'-γ coupling: χ (weak, e.g., χ=10^{-X})