# Particle Physics in Modified Quantum Vacua

## – puzzles from the PVLAS experiment –

Holger Gies

Universität Heidelberg

# A view on the quantum vacuum.

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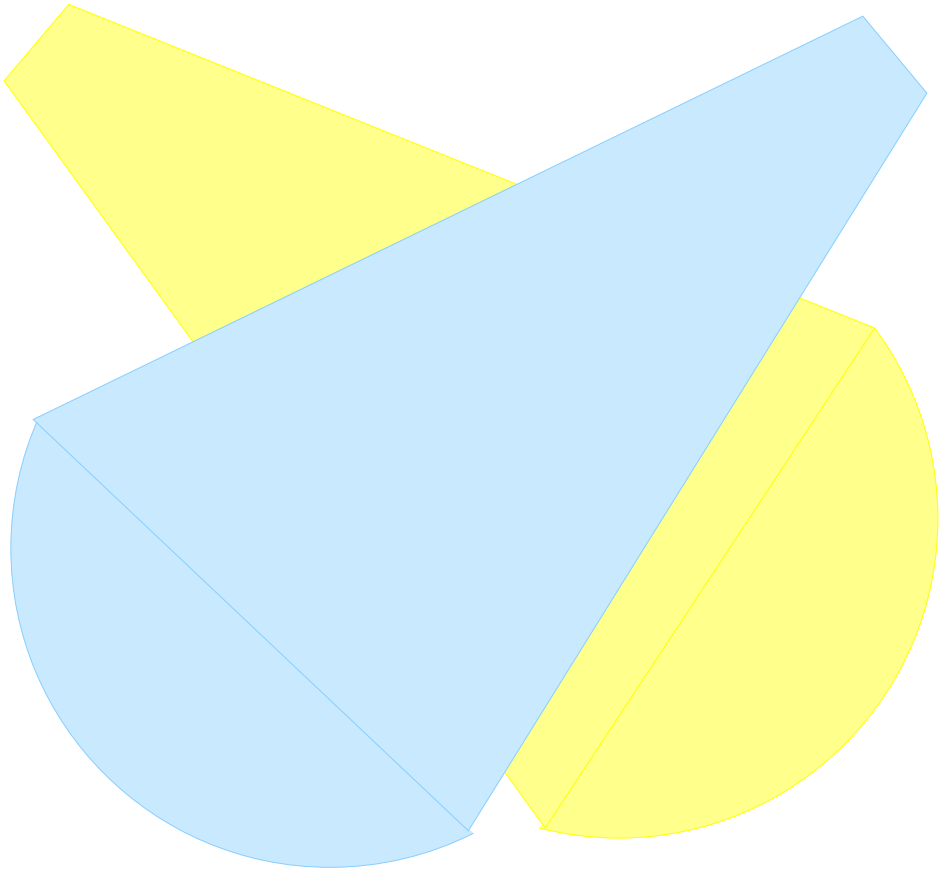

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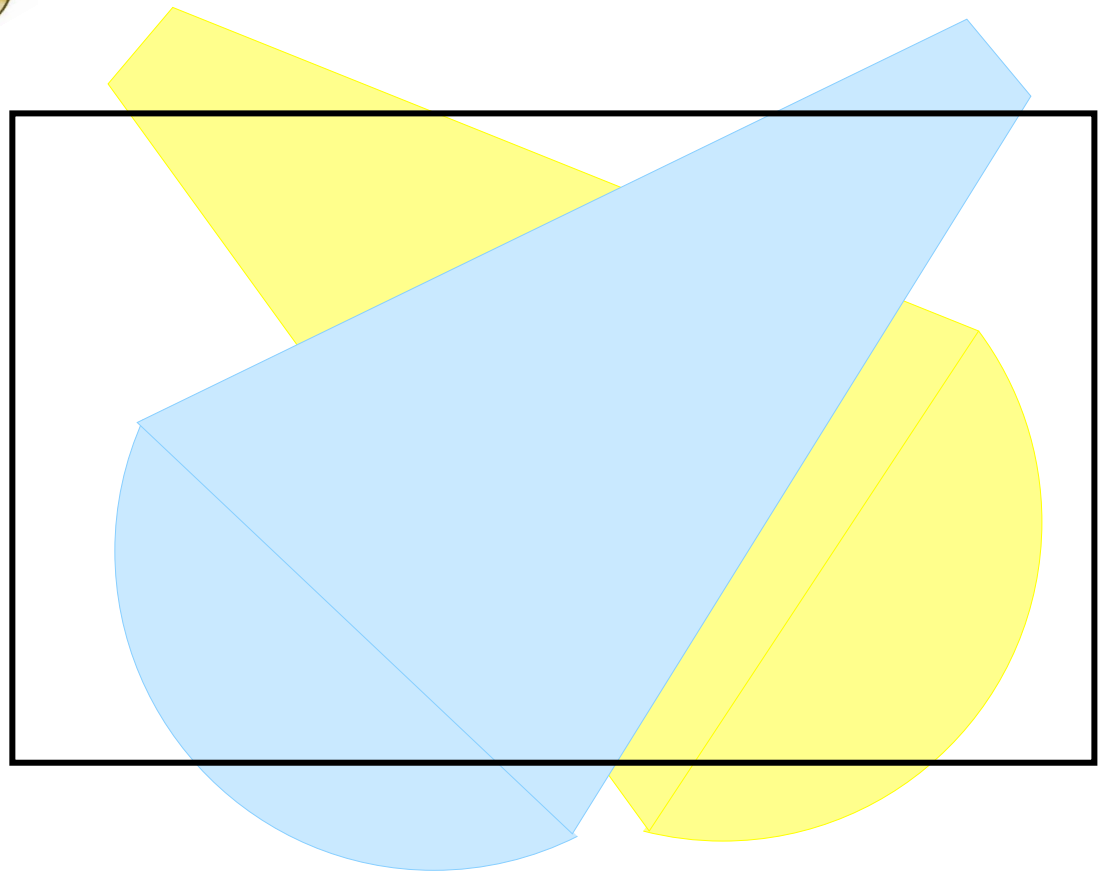

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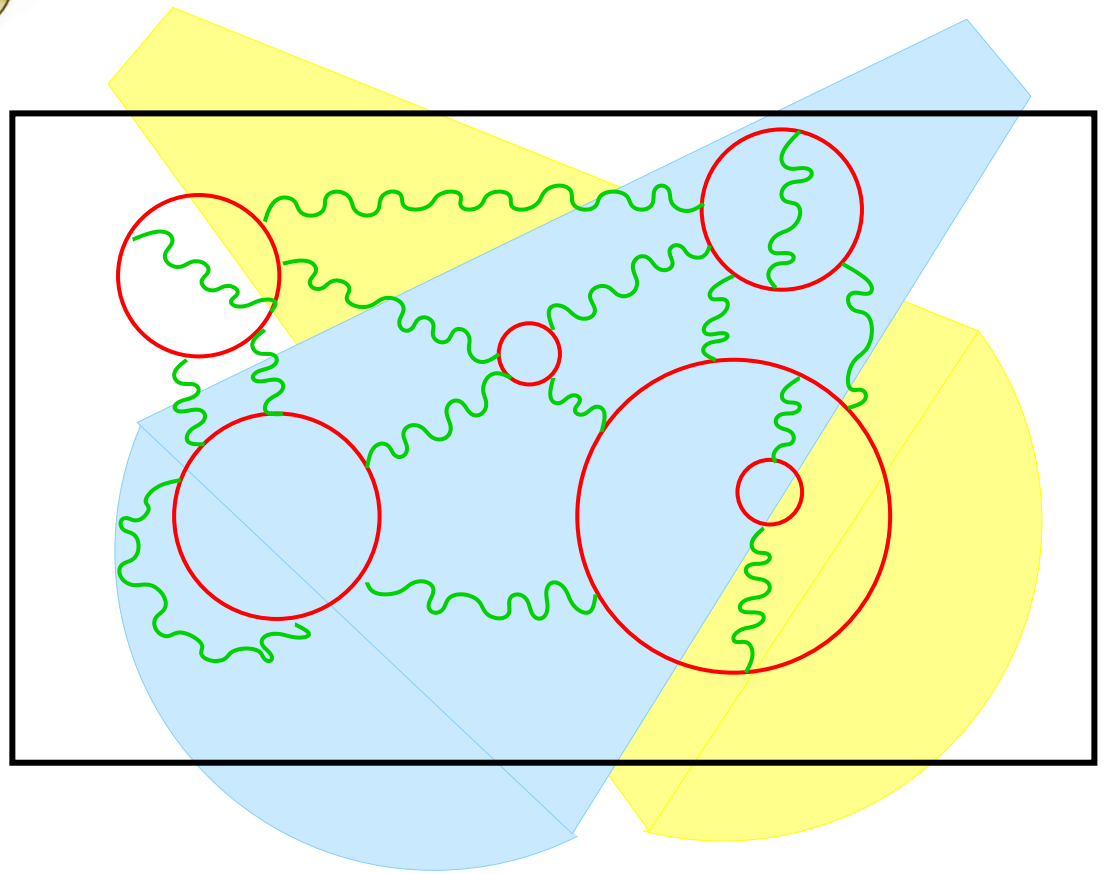

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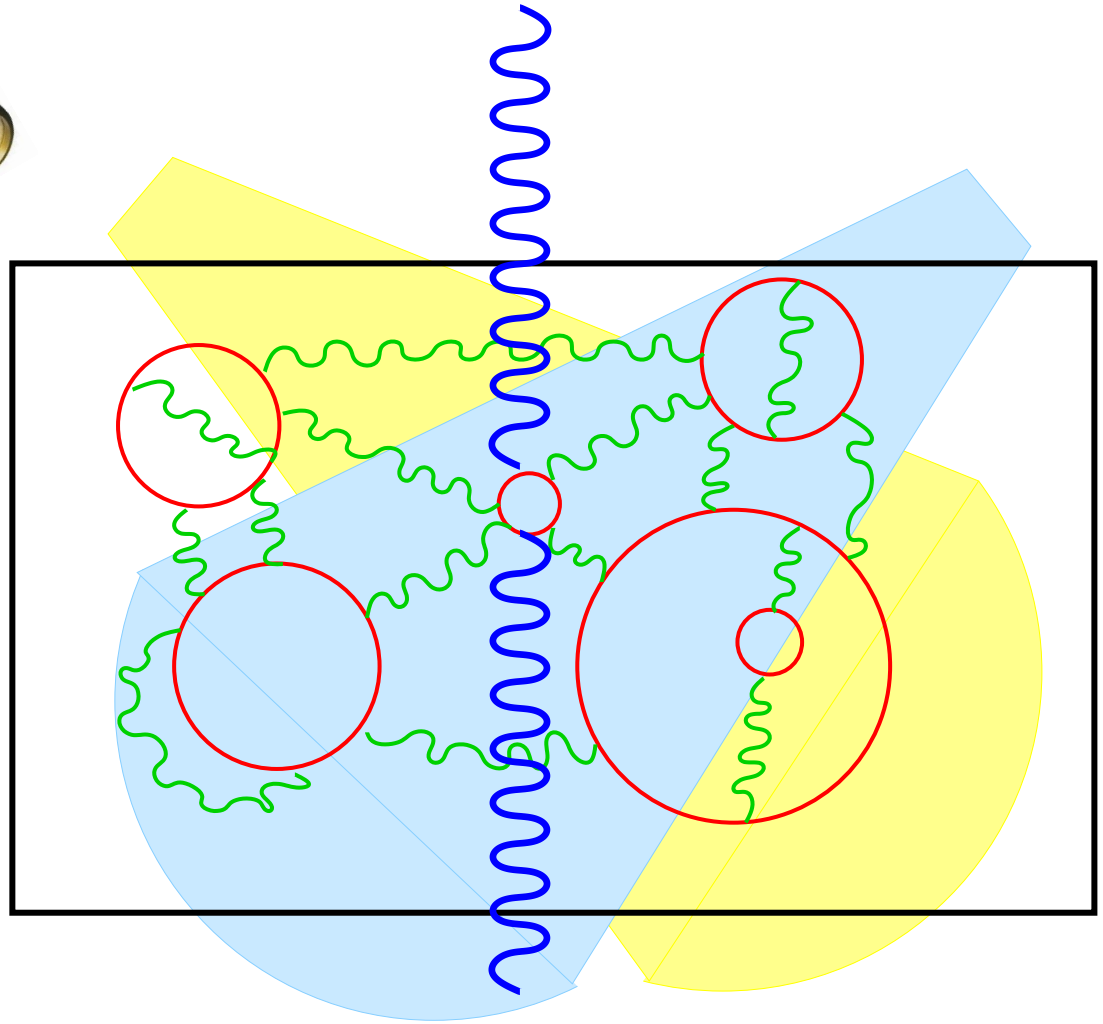

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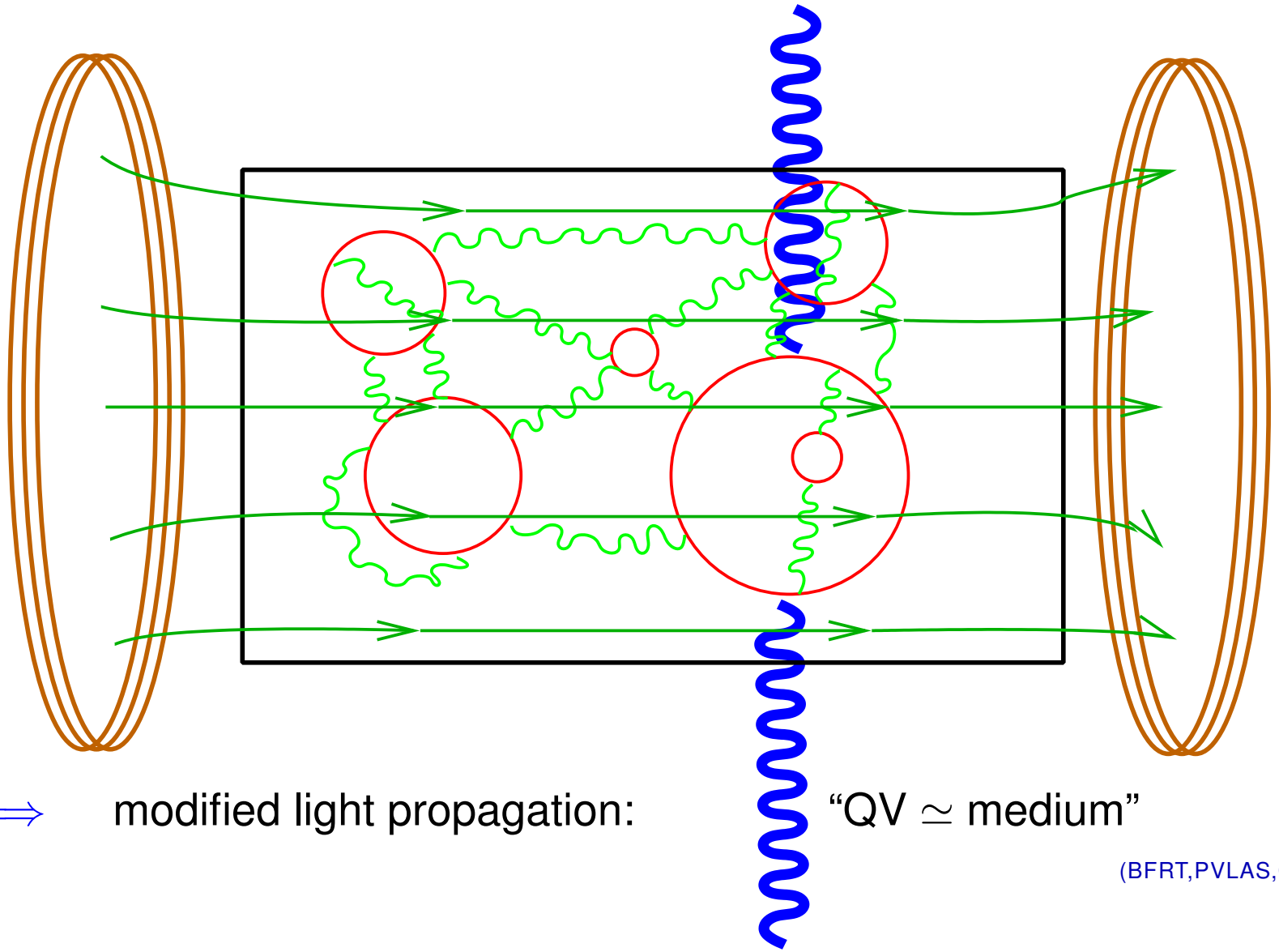

$\Longrightarrow$ modified light propagation: "QV $\simeq$ medium"

(BFRT,PVLAS,Q&A,BMV,...)

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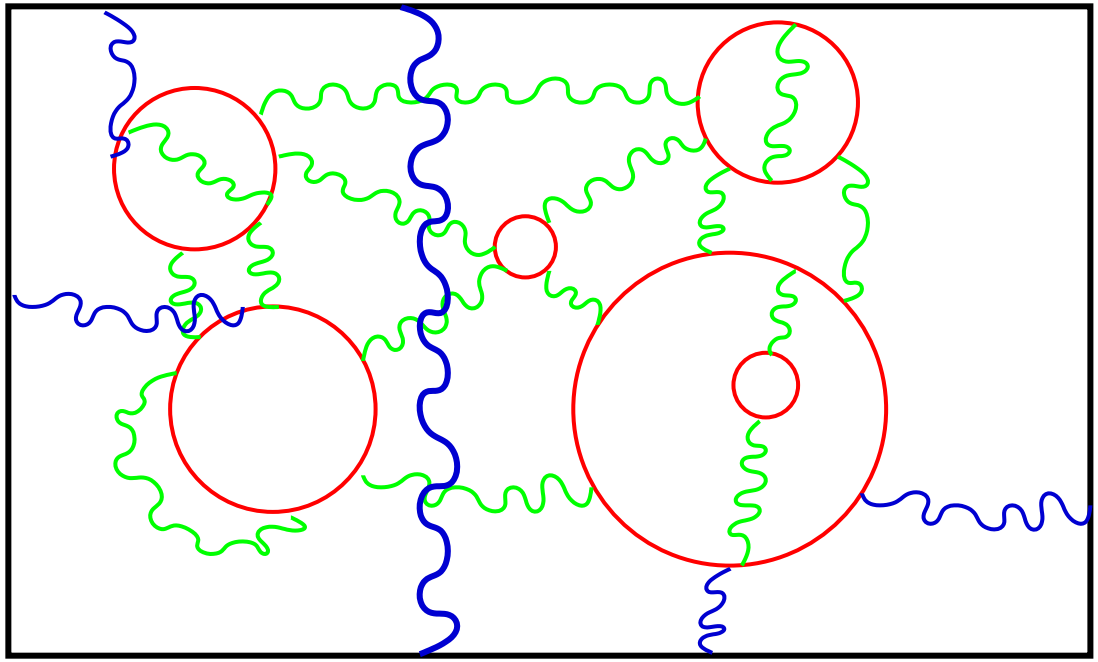

▷ Boundary conditions: Casimir effect

$\Longrightarrow$ probing non-Newtonian gravity

(GR302@DPG: LAUX, WARRING, SCHMIDT, DEKIEVIET)

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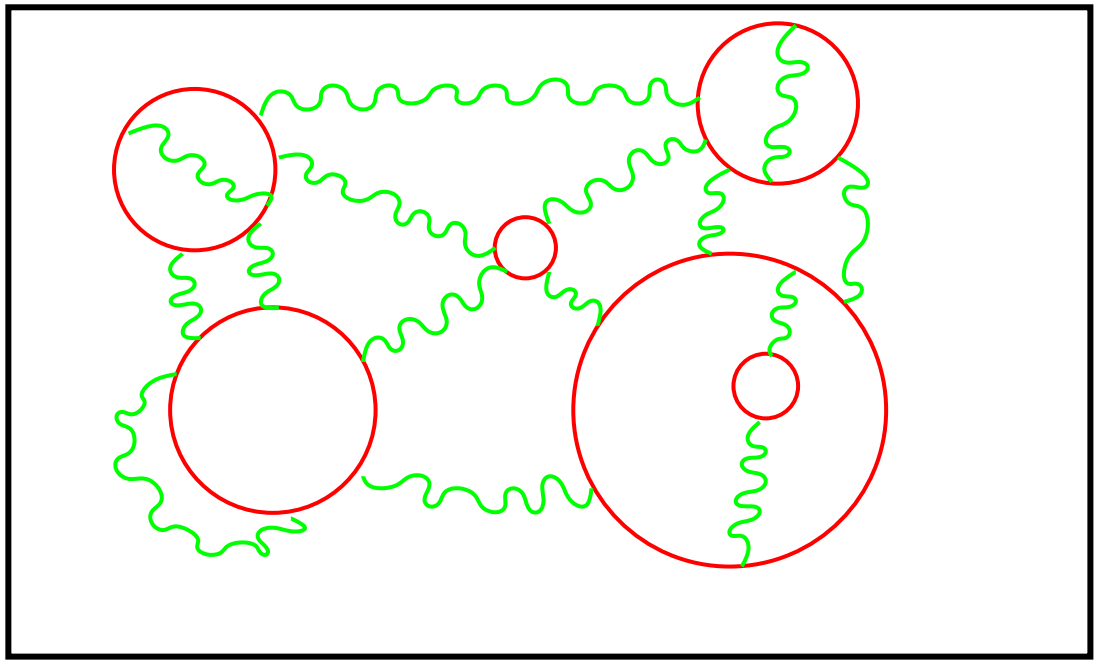
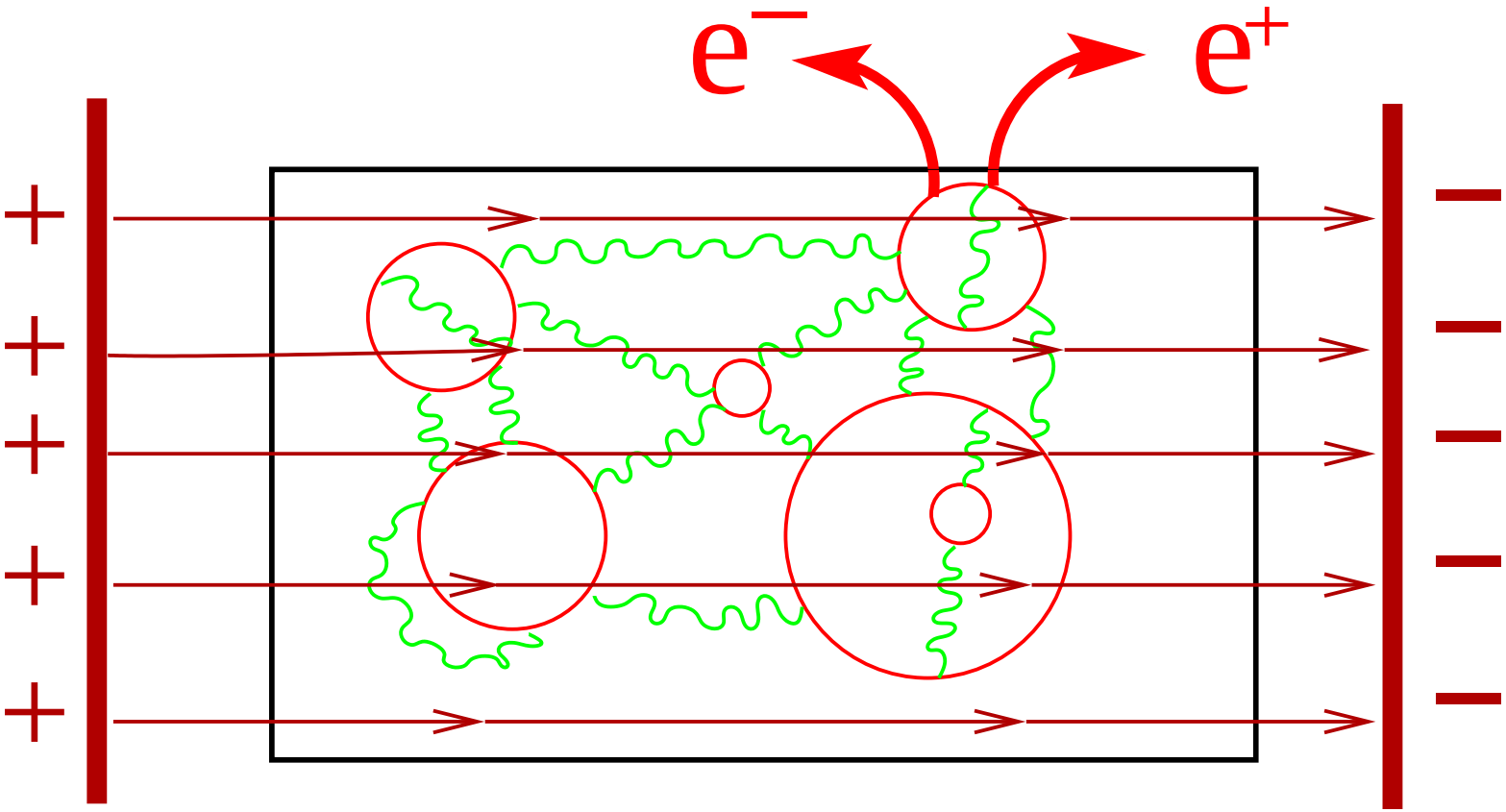


- Heat bath: quantum & thermal fluctuations

# A view on the quantum vacuum.




- electric fields: Schwinger pair production “vacuum decay”

# Light Propagation.

- classical Maxwell equation in vacuo (MAXWELL 1864)

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

- 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.

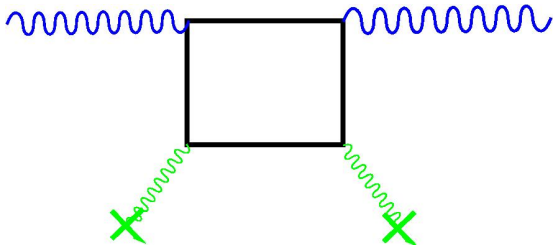
▷ quantum Maxwell equation for a "light probe" $f^{\mu\nu}$

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

## 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)

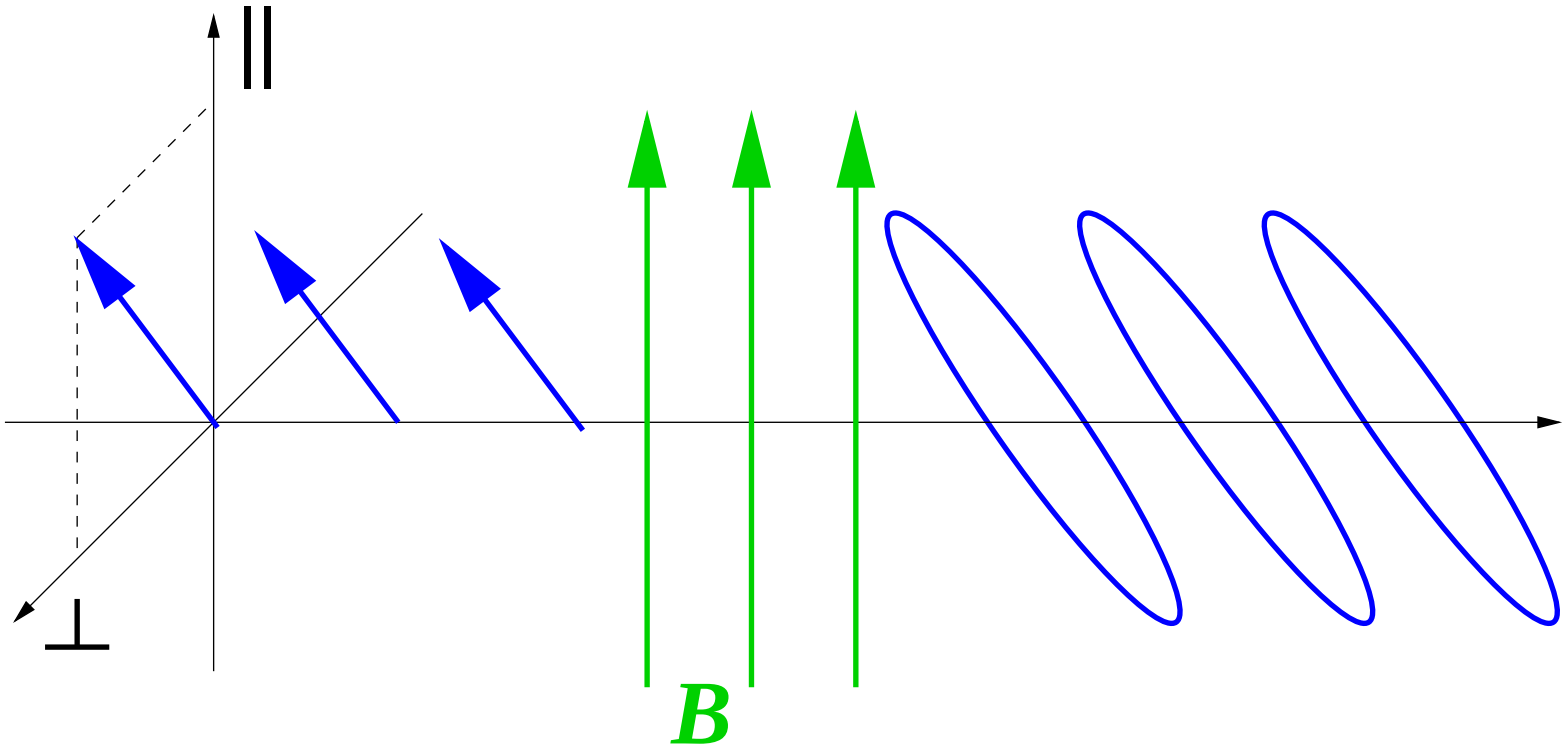
(Adler'71)

$\Longrightarrow$ magnetized quantum vacuum induces birefringence

▷ detection schemes: (PVLAS, BMV, Q&A, Heinzl et al.'06, DiPiazza,Hatsagortsyan,Keitel'06)

# Light Propagation in a $B$ field.

▷ observable: birefringence induces ellipticity

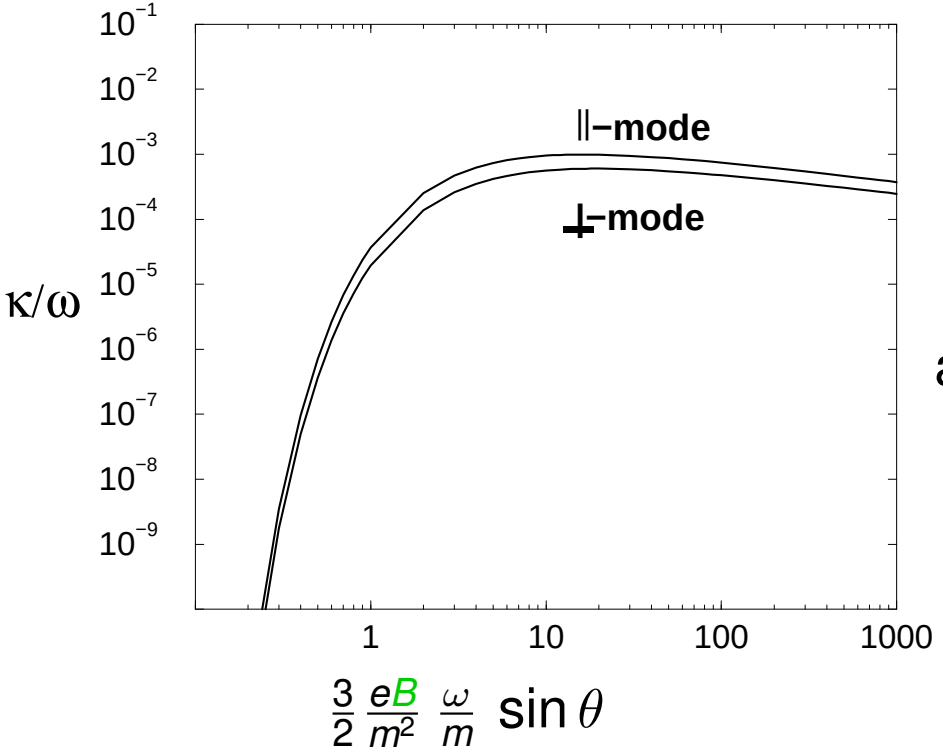



ellipticity: $\psi_{\text{ell}} = \pi \frac{L}{\lambda} \Delta v \sin 2\theta, \quad \Delta v(5.5\text{T}) \simeq 10^{-22}$

# Light Propagation in a $B$ field.

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

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

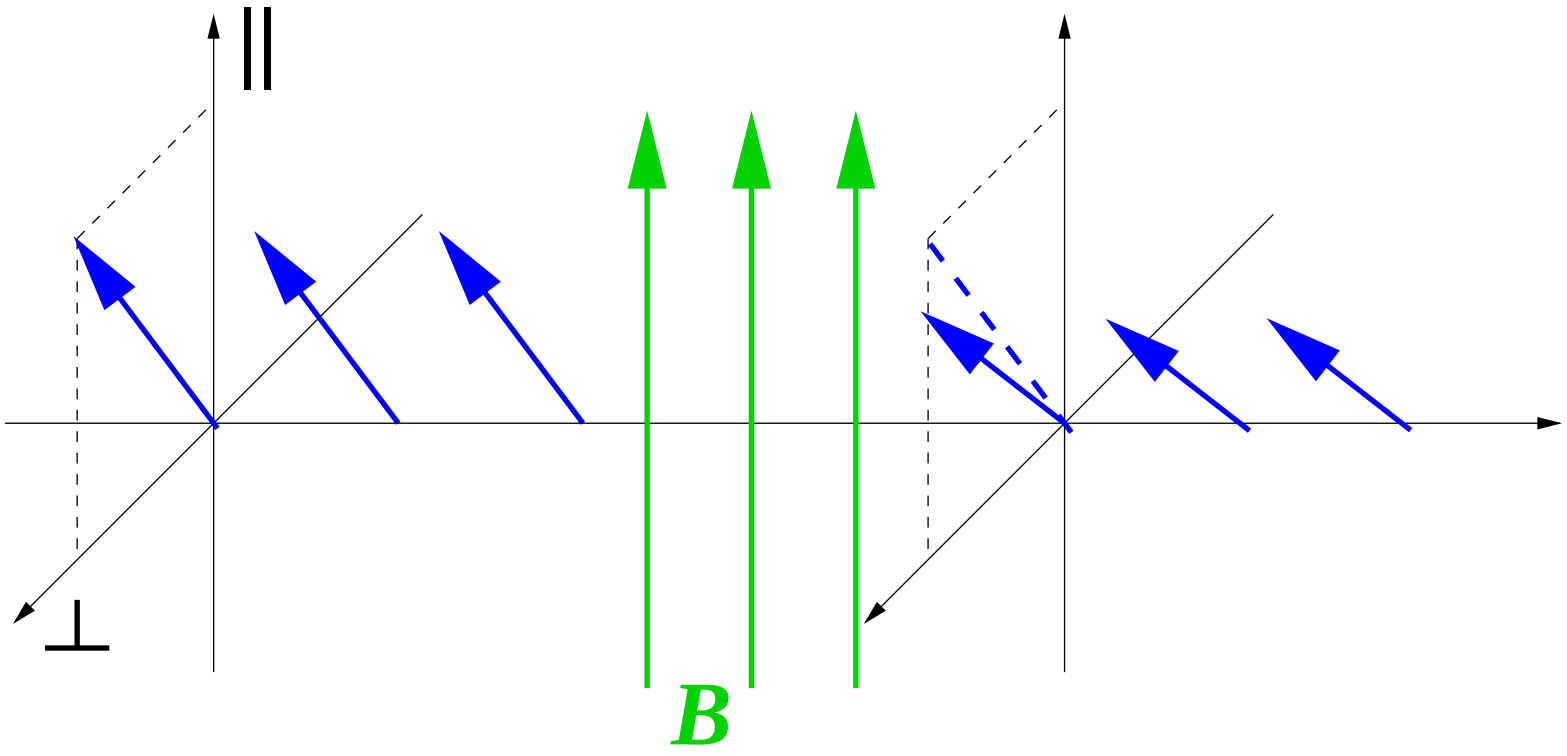



absorption $\Longrightarrow$ dichroism

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

# Light Propagation in a $B$ field.

▷ observable: dichroism induces rotation

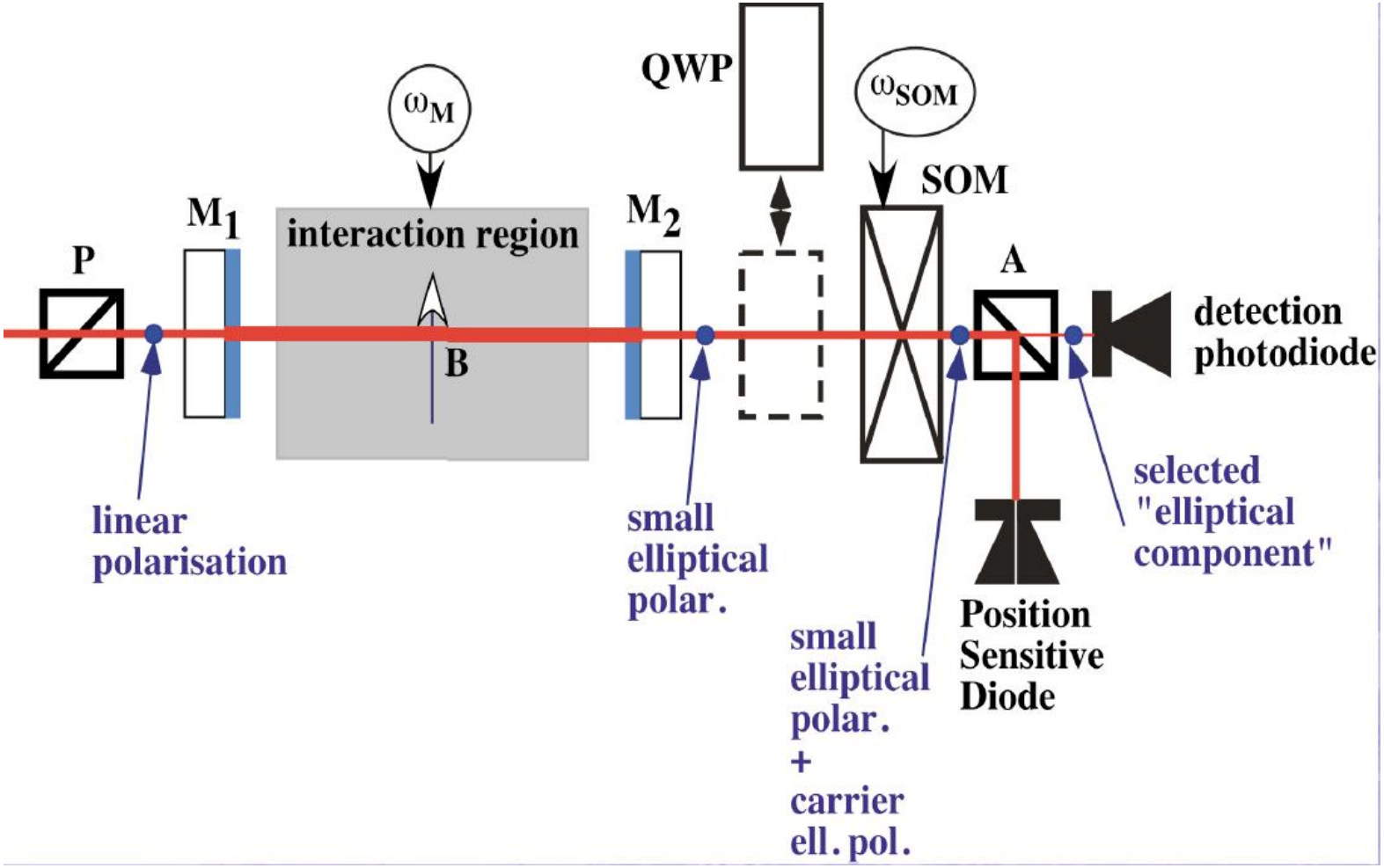



rotation: $|\Delta\theta| \simeq \frac{1}{4}\,\Delta\kappa\ell\,\sin 2\theta$

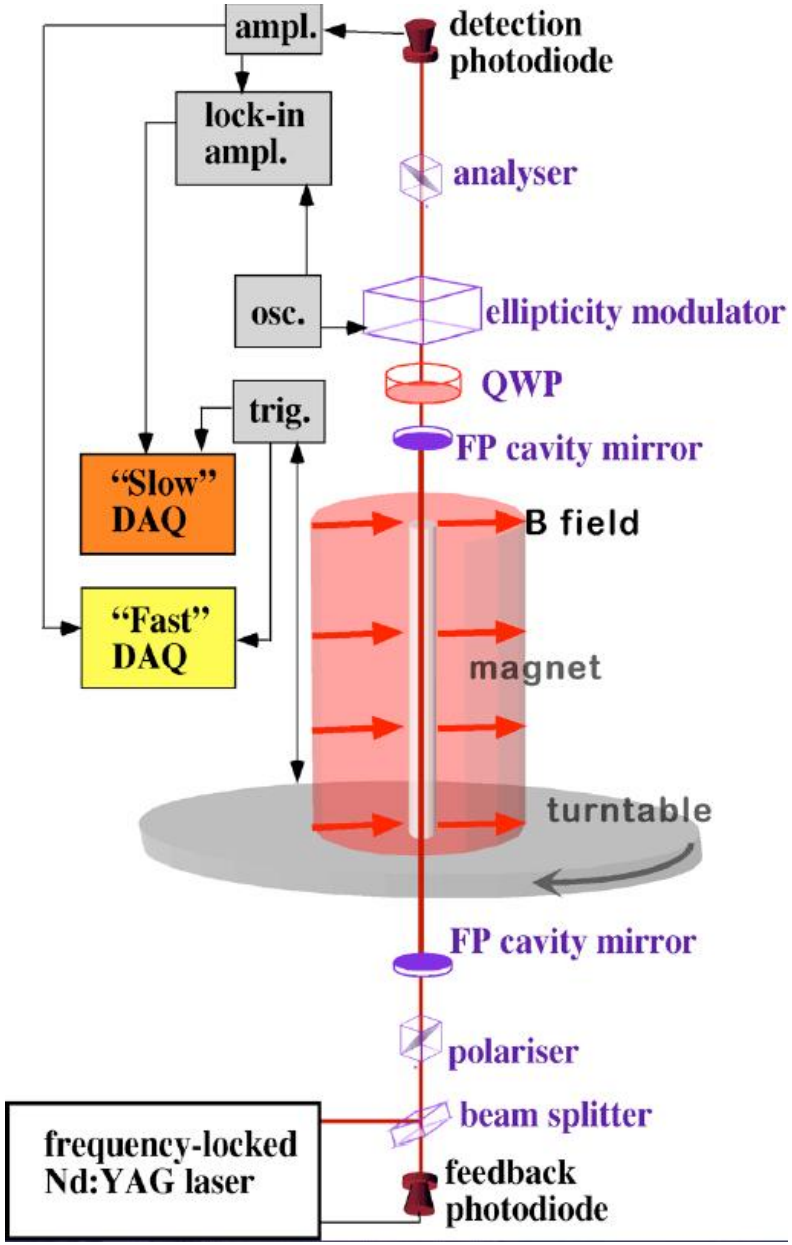
# PVLAS Detection Method.

## Polarizzazione del Vuoto con LASer

(Bakalov et al.'94, Cantatore et al.'00, Zavattini et al.'05)



# PVLAS Design.




- magnet: 6T, 4.2K, 1m
- magnet rotation: $\simeq$ 0.3Hz
- laser: $\lambda =$ 1064nm (532nm)
- cavity: high-finesse ($N \sim 10^5$) Fabry-Perot, $\Longrightarrow$ $\ell \simeq$ 60km

# PVLAS @ LNL.

# Vacuum Birefringence?

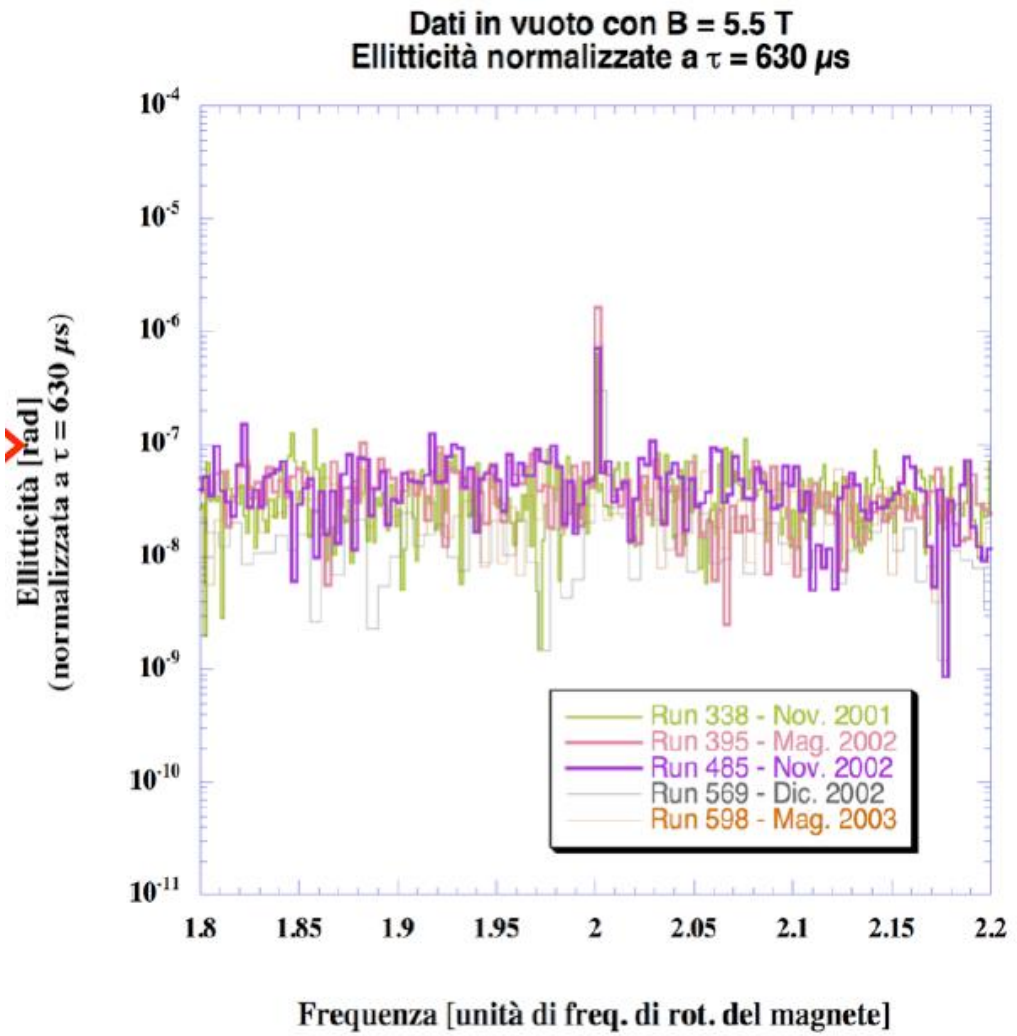
▷ observed ellipticity signal

$$\frac{\psi_{\text{ell}}}{[10^{-12}\text{rad/pass}]} = -3.4 \pm 0.3$$

at $B = 5.5\text{T}$

$$\Longrightarrow \quad \frac{\psi_{\text{exp}}}{\psi_{\text{QED}}} \simeq 10^4$$

**(preliminary)**




(CANTATORE@IDM2004,IDM2006)

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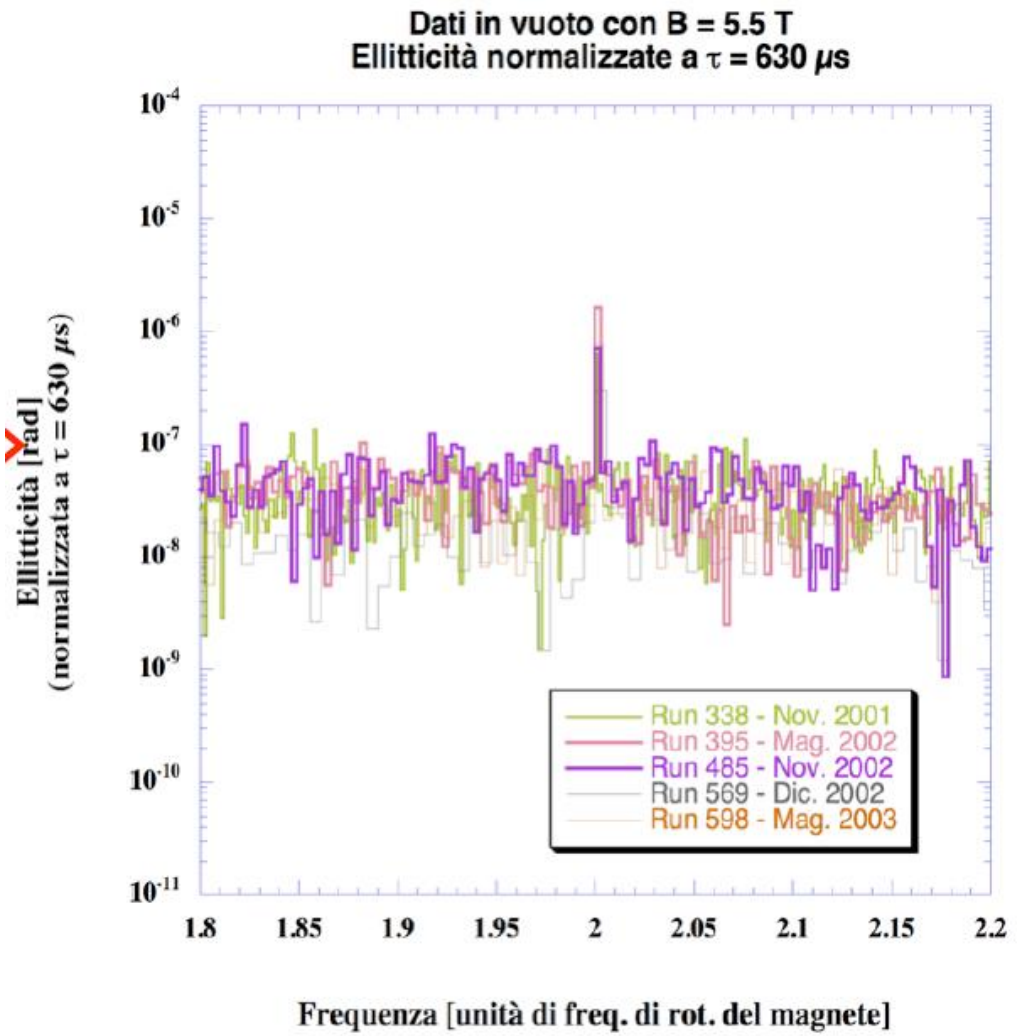
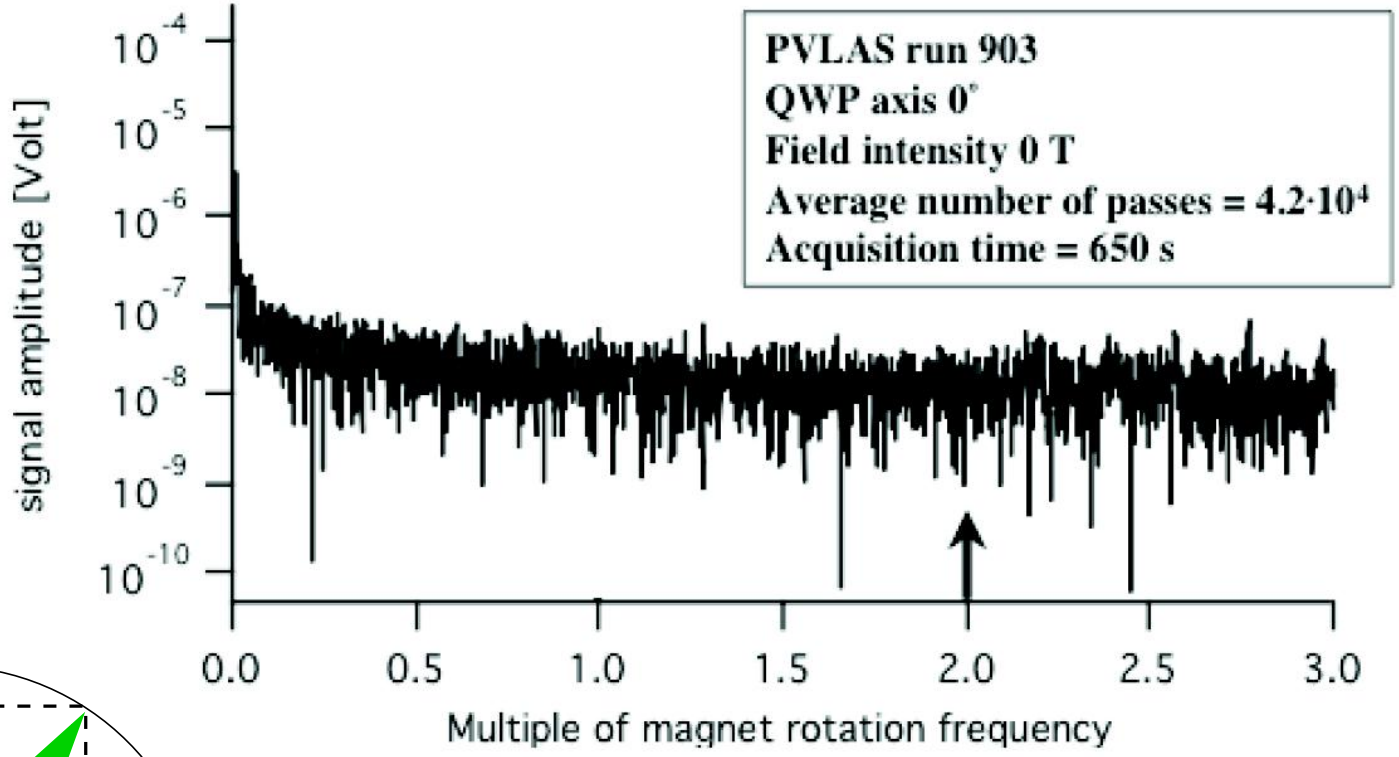


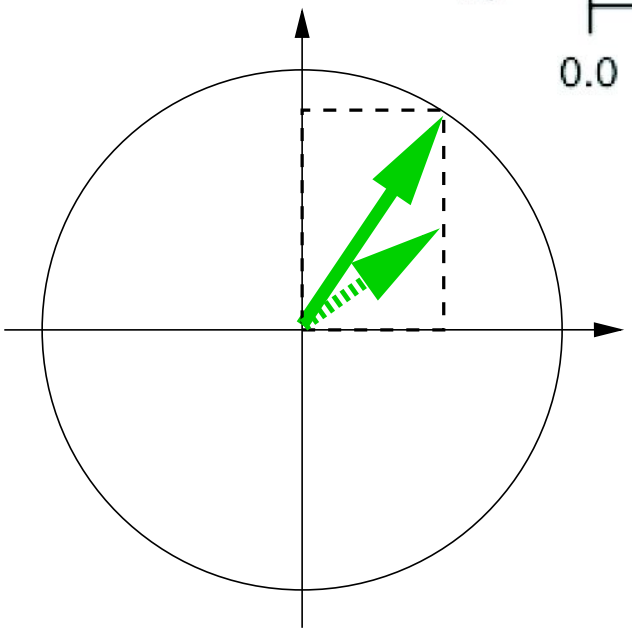

(CANTATORE@IDM2004,IDM2006)

# Vacuum Rotation: loss of photons.

$B = 0\text{T}$




(CANTATORE@CERN-AXION-TRAINING2005)



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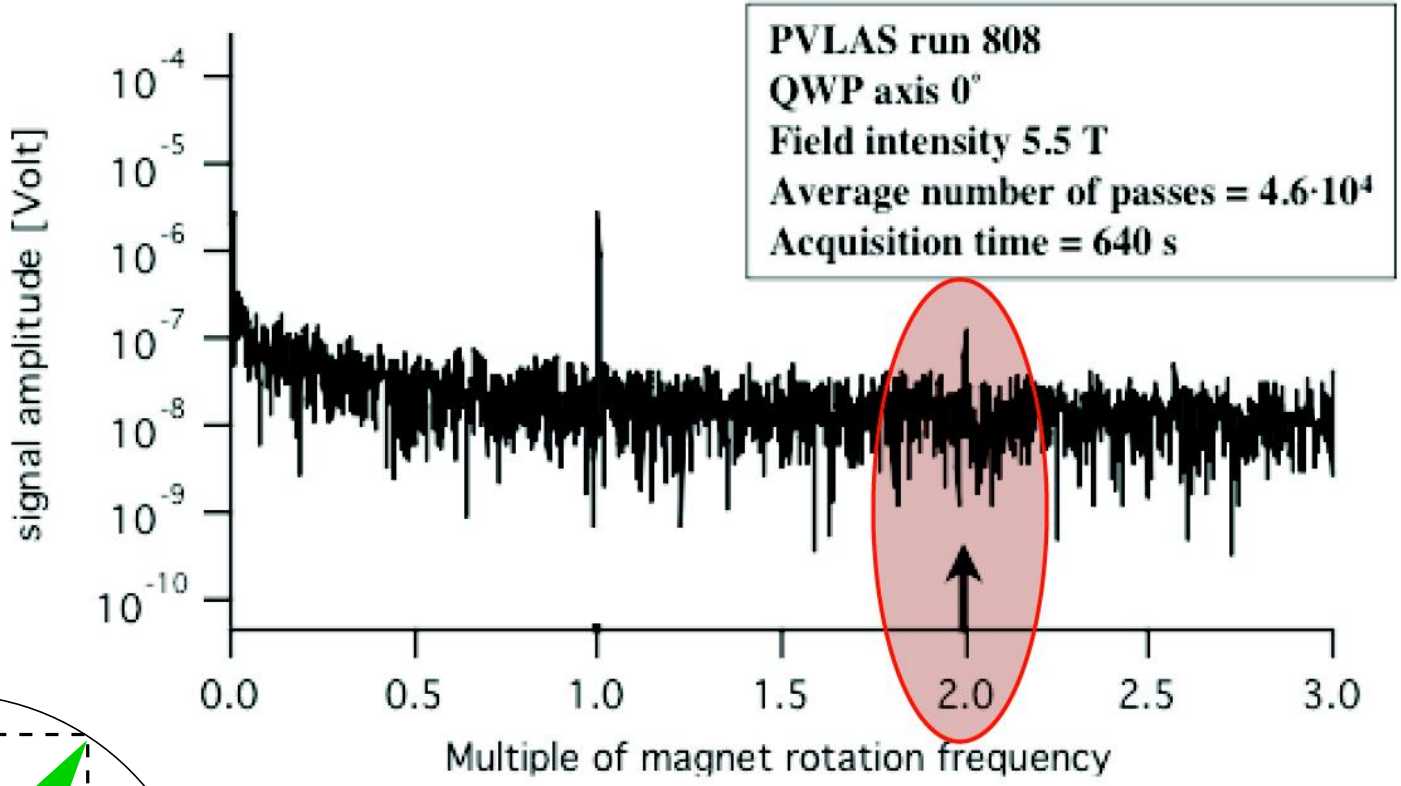


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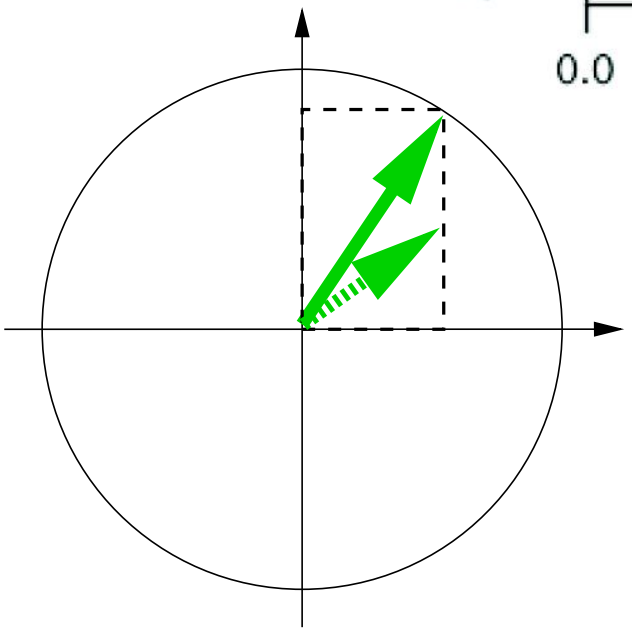

observed rotation

$$|\Delta\theta| \simeq 3.9 \pm 0.2 \cdot 10^{-12}\text{rad/pass}$$

(ZAVATTINI ET AL., HEP-EX/0507107, PRL'06)

# Options: Error or Physical Signal?

(CANTATORE@IAS-AXION-WORKSHOP'06)

| Candidate | Test/Cure | Comment |
|---|---|---|
| residual gas | pressure measurement | excluded |
| mirror coating birefringence/ rotation | direct measurement | excluded |
| electrical pick-up | measurement without the cavity | excluded |
| diffusion from magnetised surfaces | pinhole insertion | excluded |
| polarizer/QWP movement | measurement without the cavity | excluded |
| residual Faraday rotation (static and modulated) | study freq. locking offset<br>eliminate fringe fields | possible source of birefr/ rotation at $\Omega_{mag}$ |
| yet uknown magnet-polarisation coupling | study freq. locking offset<br>eliminate fringe fields | possible source of birefr/ rotation at $\Omega_{mag}$ |
| beam pointing instability | correlation with measured position signal<br>eliminate fringe fields | possible source of birefringence at $\Omega_{mag}$ |

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"The possibility that this effect is due to an unknown, albeit very subtle, instrumental artifact has been investigated at length without success." (HEP-EX/0507107, PRL'05)

# Standard (Model) Explanations ?

- Quantum light cone deformations . . . ?

  $\sim \frac{\pi^2 T^4}{15}, \quad -\frac{\pi^2}{720 a^4}, \ldots$ too small!

  (LATORRE,PASCUAL,TARRACH'95; SHORE'96; DITTRICH, HG'98)

- Photon Splitting . . . ? (ADLER'71)

  PVLAS mean free path $1/\kappa \sim\simeq 3 \cdot 10^{57} \times$ SoU

  also experimentally ruled out by PVLAS (CANTATORE@IAS-AXION-WORKSHOP'06 )

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

  too small!

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- QED effect due to magnet rotation . . . ? (MENDONCA ET AL'06)

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  (HG'06; ADLER'06; BISWAS,MELNIKOV'06)

ruled out !

# Low-Energy Effective Theories?

**A**xion-**L**ike **P**article

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

scalar or pseudo-scalar

neutral

**M**illi-**C**harged **P**article

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

scalar of fermion

charged

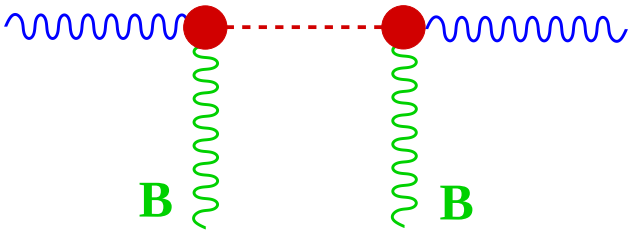
2 parameters

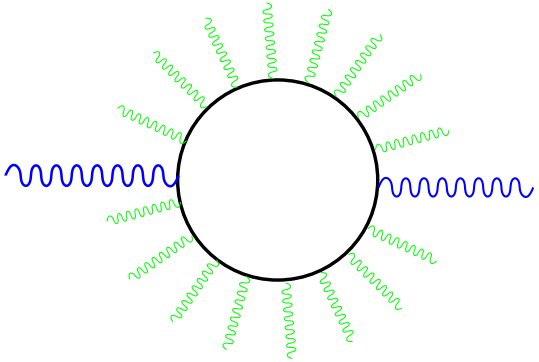
# Low-Energy Effective Theories?

**A**xion-**L**ike **P**article

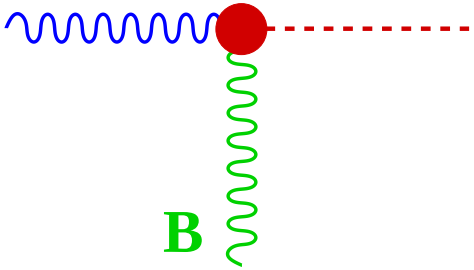
**M**illi-**C**harged **P**article

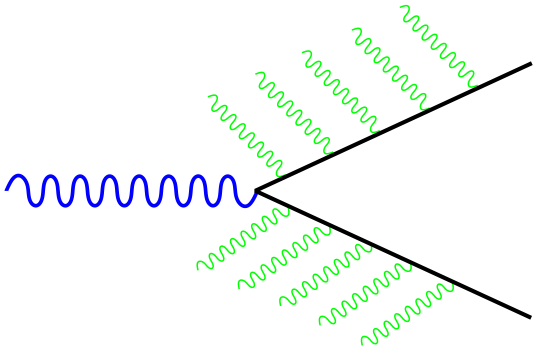
birefringence induced ellipticity:



dichroism induced rotation:



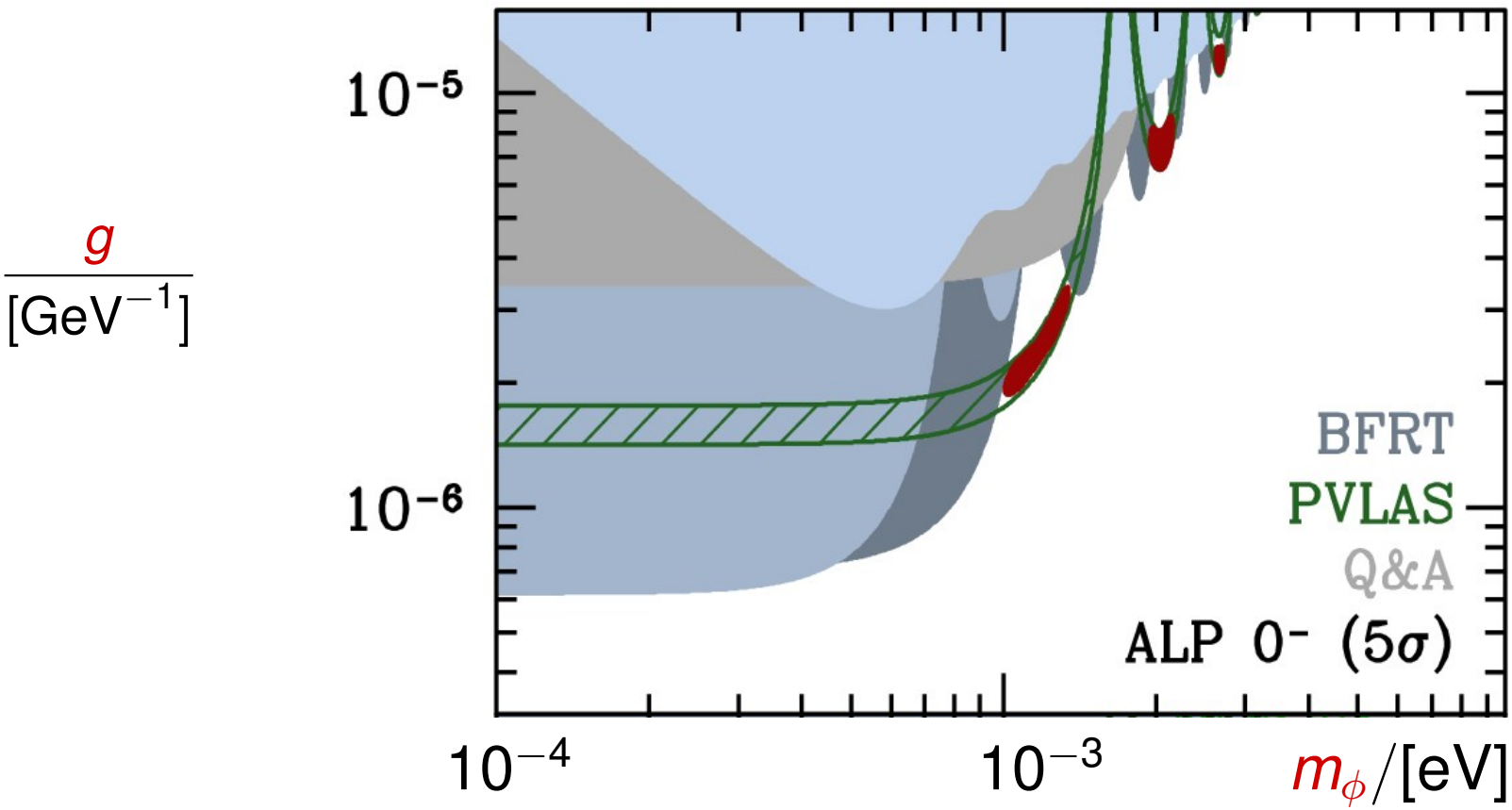
(MAIANI,PETRONZIO,ZAVATTINI'86; RAFFELT,STODOLSKY'88)

(ADLER'71; TSAI,ERBER'74)

(HG,JAECKEL,RINGWALD'06)

# ALP Global Fit.

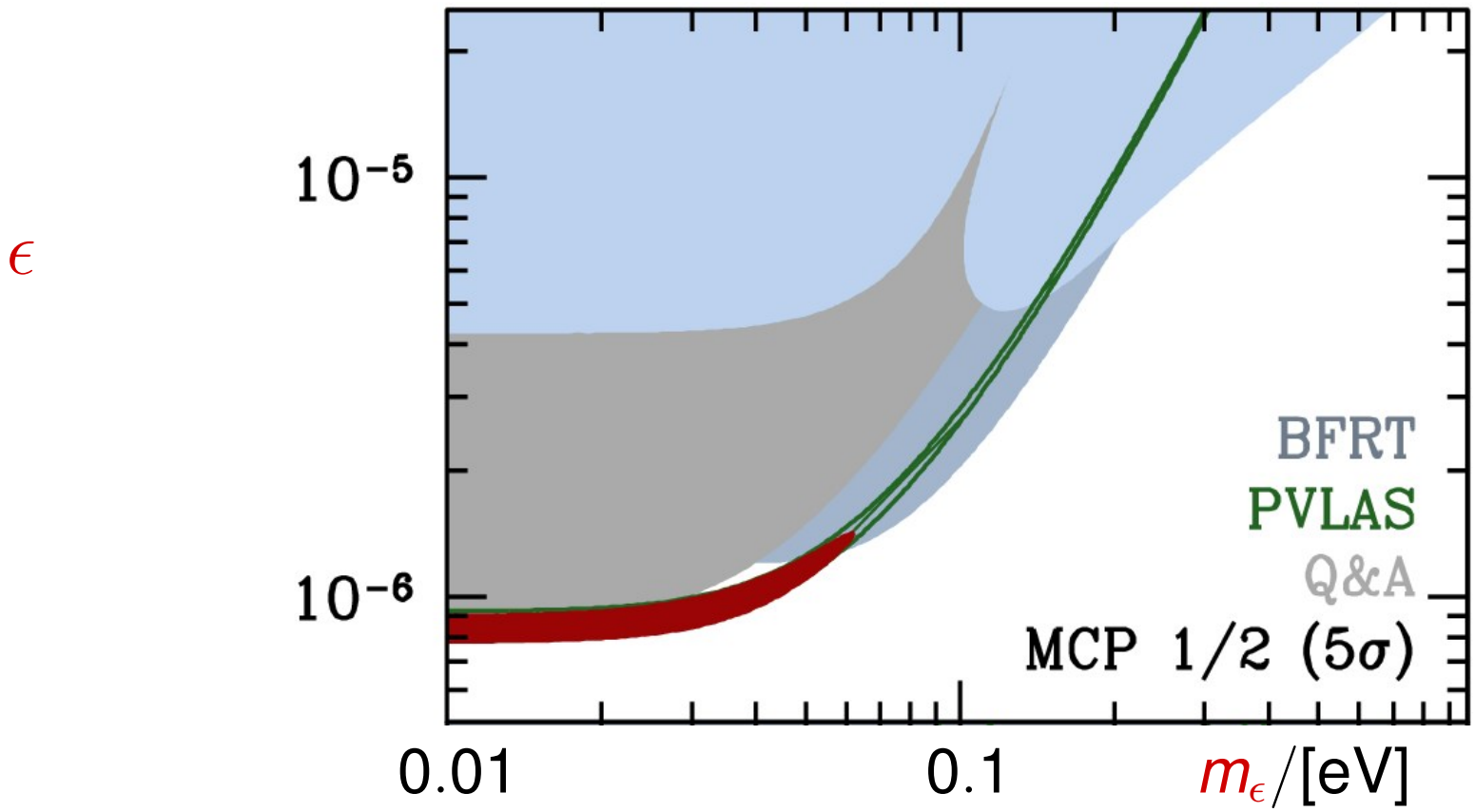
▷ pseudoscalar ALP, fit to all published data (AHLERS,HG,JAECKEL,RINGWALD'06)




e.g., $m_\phi \simeq 1.5 \cdot 10^{-3}\mathrm{eV}$, $\frac{1}{g} \simeq 4 \cdot 10^5 \mathrm{GeV}$ (ZAVATTINI'05)

# MCP Global Fit.

▷ fermionic MCP, fit to all published data (AHLERS,HG,JAECKEL,RINGWALD'06)



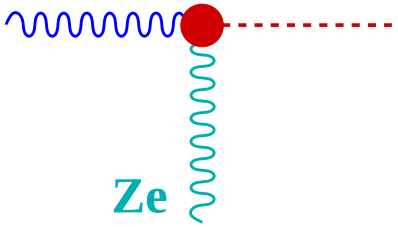

$$m_\epsilon \lesssim 0.1\text{eV}, \quad \epsilon \simeq 10^{-6}$$

(HG,JAECKEL,RINGWALD'06)

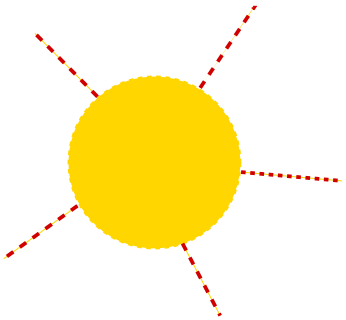
# Astrophysical Bounds: ALPs

▷ Axion production:

Primakov process

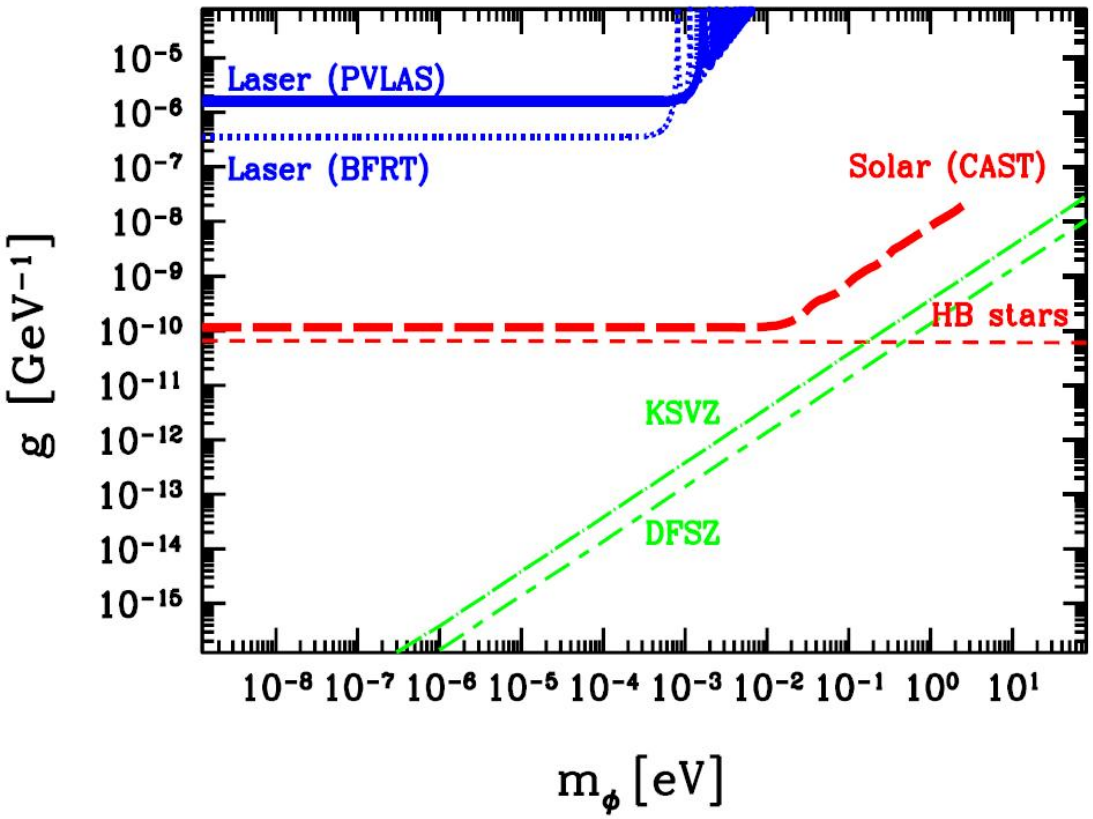



▷ Axion emission



$$\mathcal{L}_\phi \simeq 10^6\, \mathcal{L}_\gamma$$

(VAN BIBBER ET AL.'89)




CAST: (T316@DPG07: KUSTER, NORDT, HOFFMANN)

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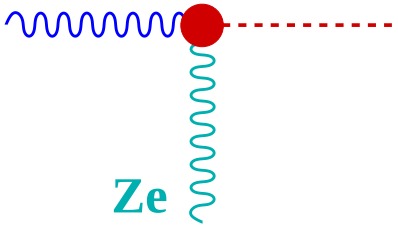


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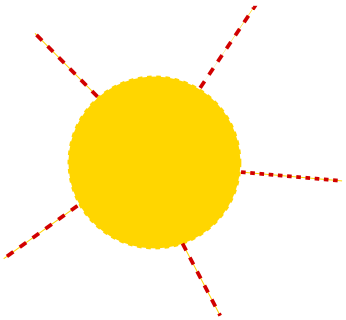

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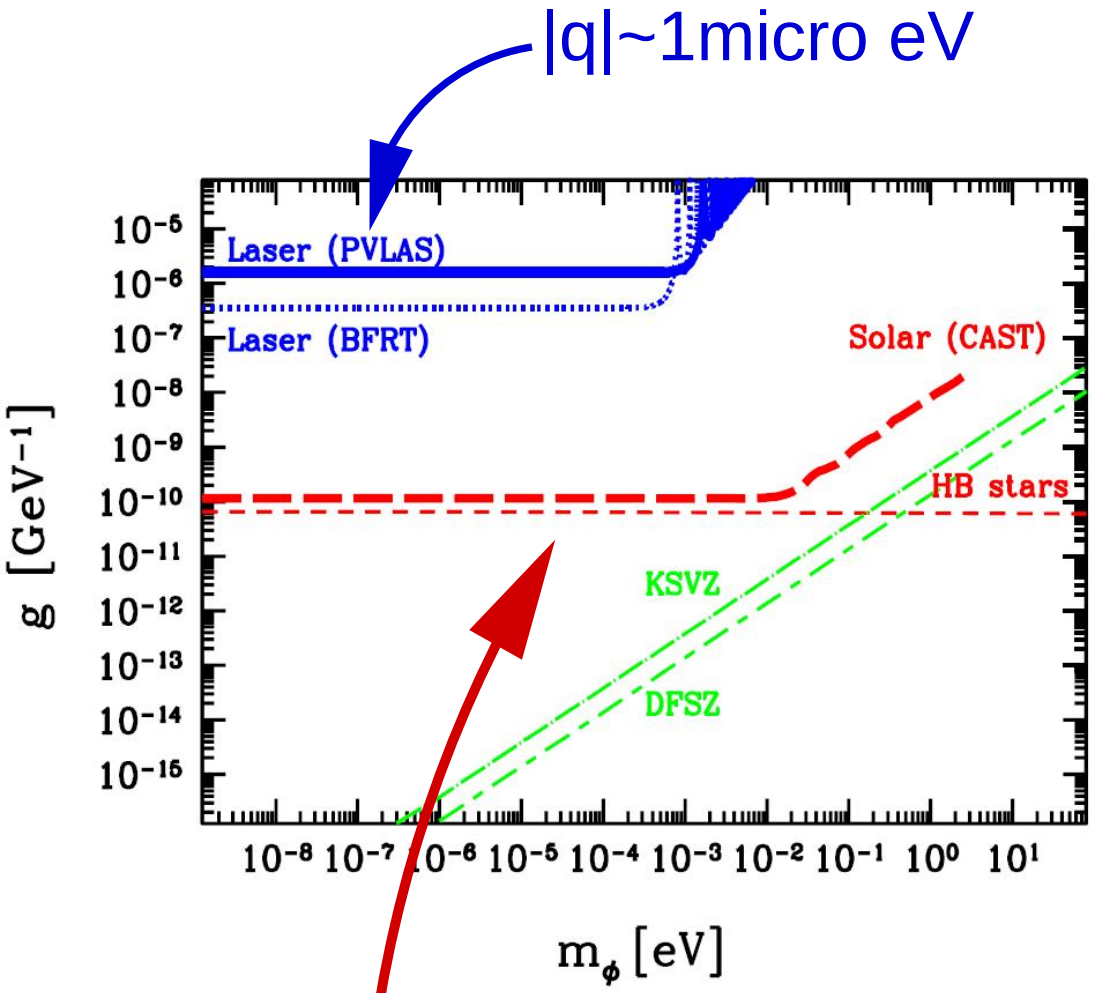



CAST: (T316@DPG07: KUSTER, NORDT, HOFFMANN)

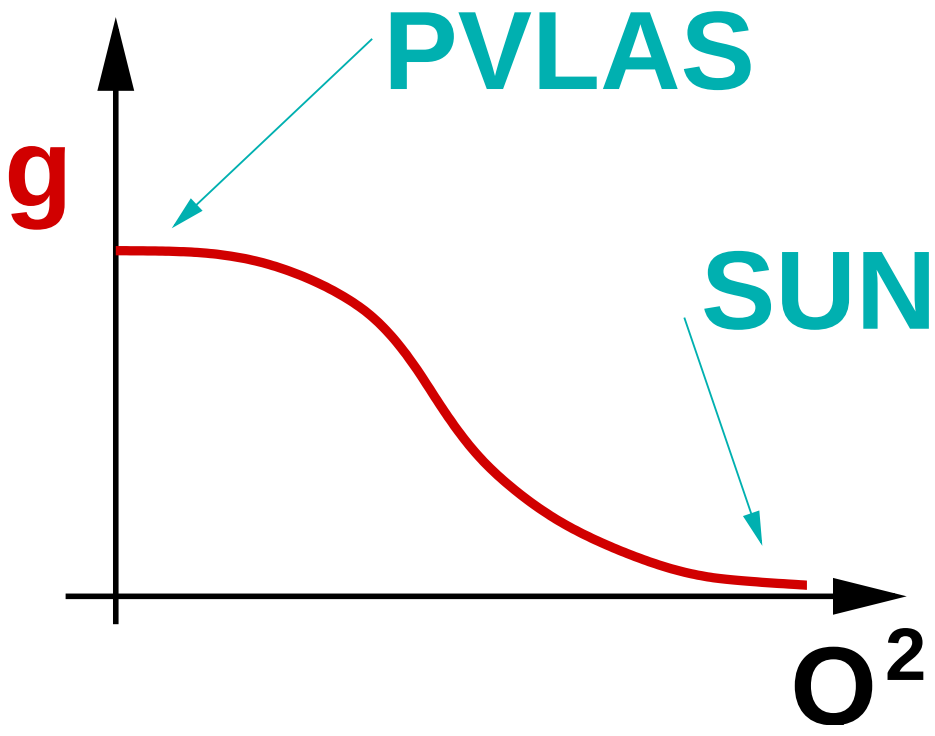
# Resolving the CAST-PVLAS puzzle.

▷ suppress solar ALP production: (JÄCKEL, MASSO, REDONDO, RINGWALD, TAKAHASHI'06)

$$g = f(T, n, B, Q^2 \ldots)$$

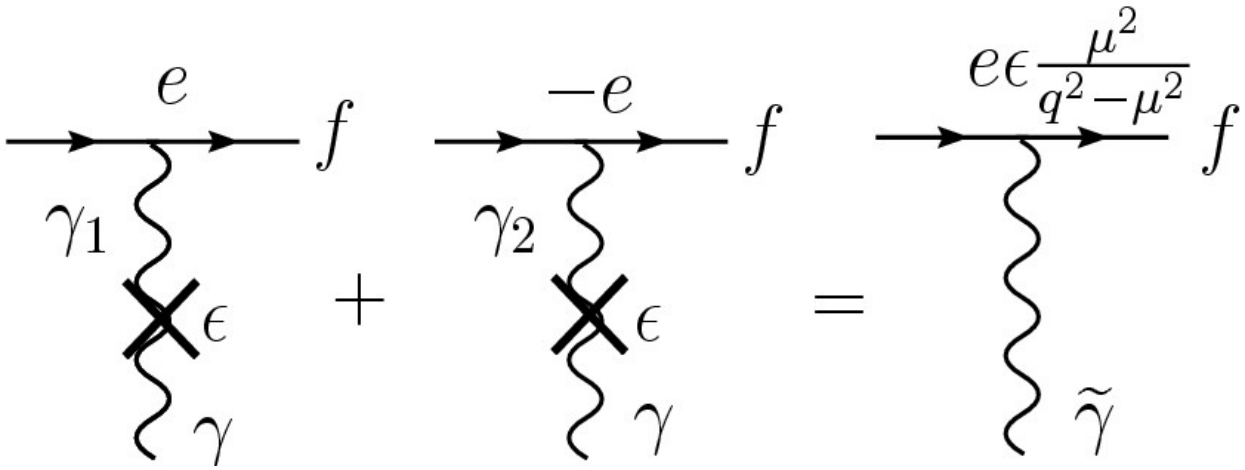
▷ e.g., momentum suppression:

$$Q^2_{\text{Sun}} \sim \text{keV}^2$$
$$Q^2_{\text{PVLAS}} \sim 7 \cdot 10^{-13}\text{eV}^2$$



# Resolving the CAST-PVLAS puzzle.

▷ e.g., U(1)×U(1)×U(1) paraphoton model (MASSO,REDONDO'06)



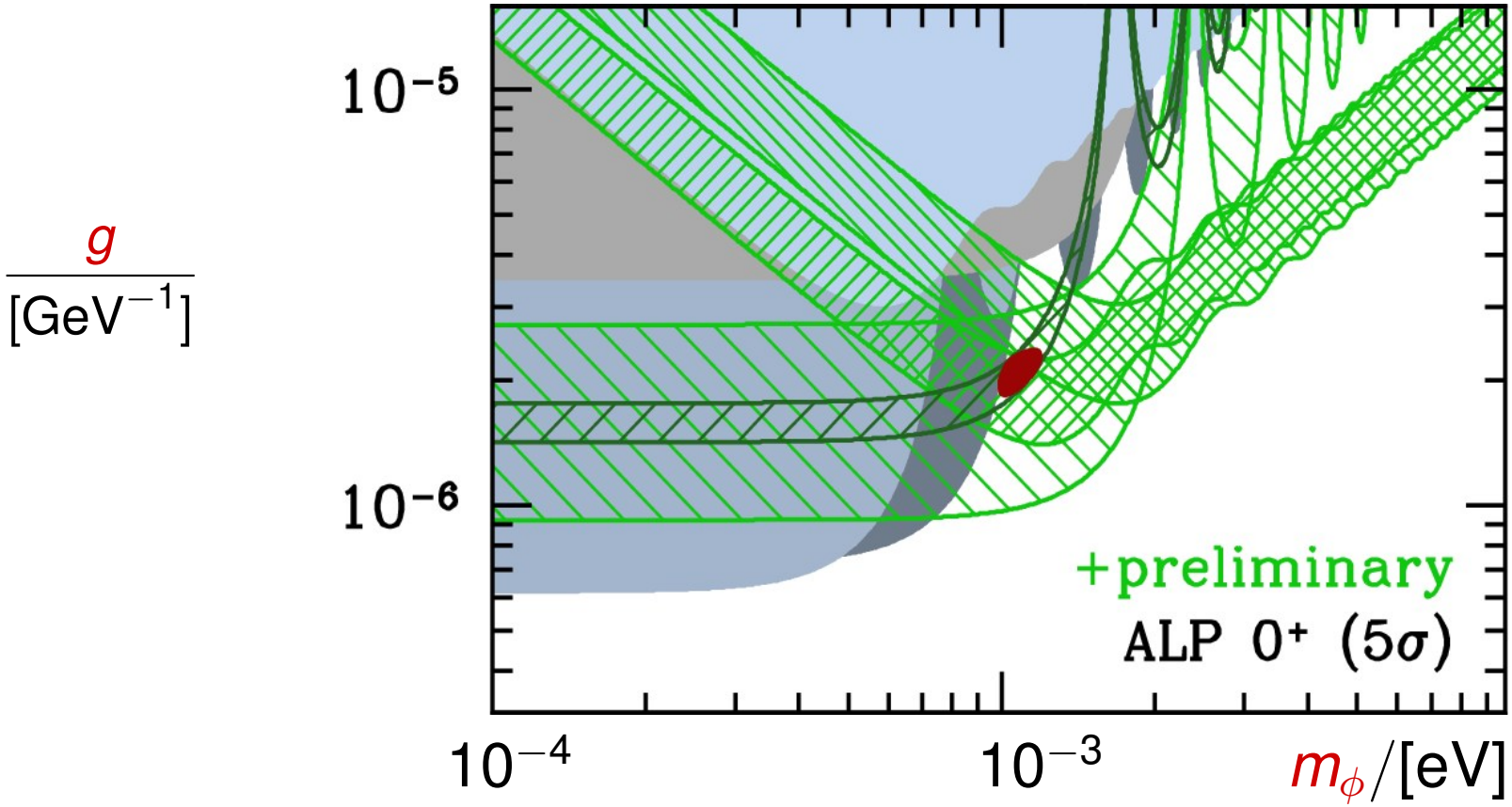

⟹ can naturally be embedded in string theory (ABEL,JAECKEL,KHOZE,RINGWALD'06)

▷ other options:

- $T$ suppression (MOHAPATRA,NASRI'06)
- trapping (JAIN ET AL'05'06)
- (GABRIELLI&GIOVANNINI'07; BESWICK&RIZZO'07; FOOT&KOBAKHIDZE'07; HU&LIAO'07; KRUGLOV'07; CHEUNG&YUAN'07; GAETE&SCHMIDT'06; FLACKE&MAYBURY'06; KASTRUP'06; RODRIGUES'06; FAIRBAIN&RASHBA&TROITSKY'06 . . . )

# “Near-Future” Data.

- ▷ pseudoscalar ALP strongly disfavored: $\psi_{\text{ell}} < 0$ (CANTATORE@IDM2006)
- ▷ scalar ALP, including preliminary PVLAS data (AHLERS,HG,JAECKEL,RINGWALD’06)

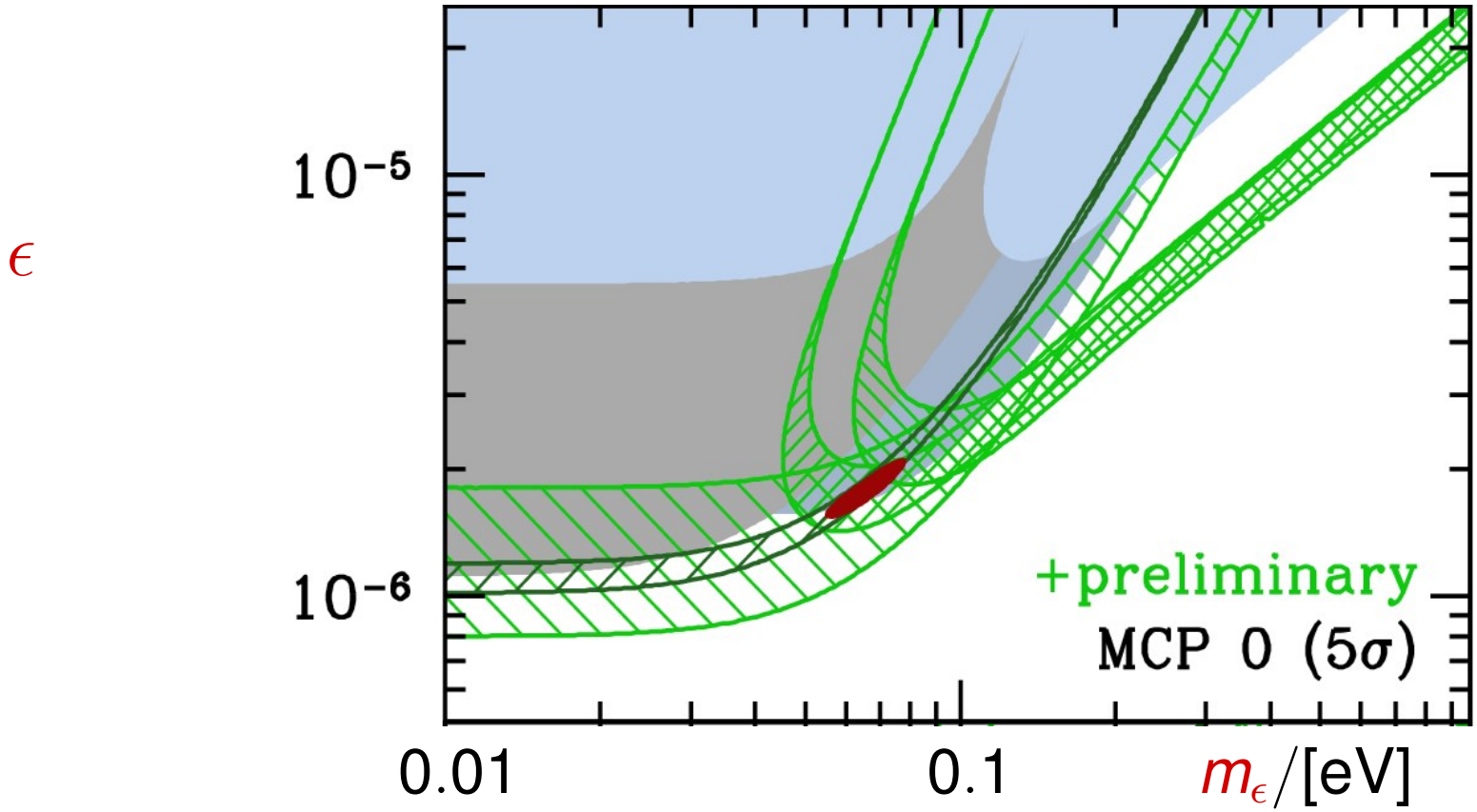



$$m_\phi \simeq 1 \cdot 10^{-3}\text{eV}, \quad \frac{1}{g} \simeq 2 \cdot 10^5\text{GeV}$$

# “Near-Future” Data.

▷ scalar MCP, fit including preliminary PVLAS data (CANTATORE@IDM2006)

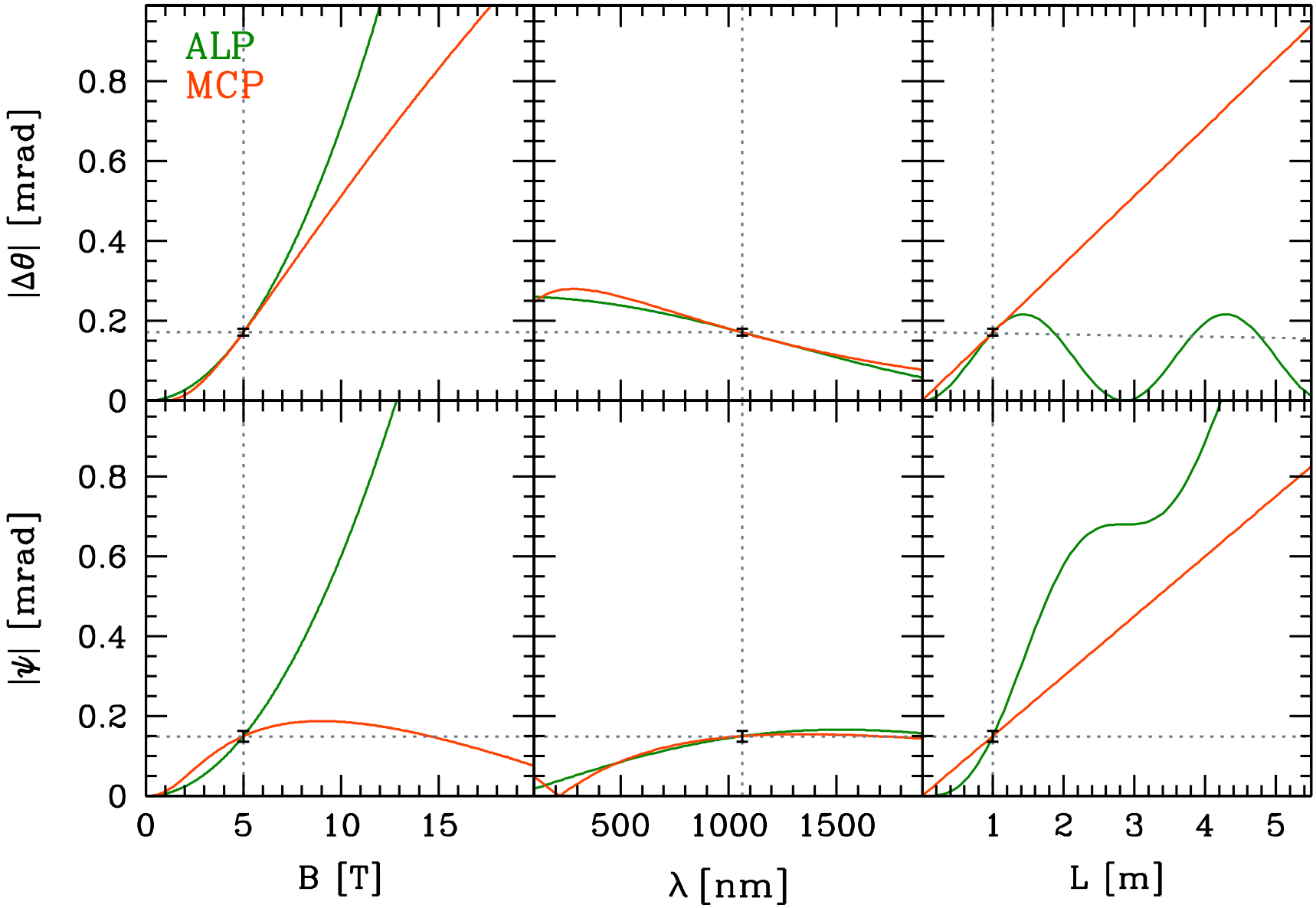
(AHLERS,HG,JAECKEL,RINGWALD’06)




$$m_\epsilon \lesssim 0.07\text{eV}, \quad \epsilon \simeq 2 \cdot 10^{-6}$$

# ALPs vs. MCPs

(AHLERS,HG,JAECKEL,RINGWALD'06)



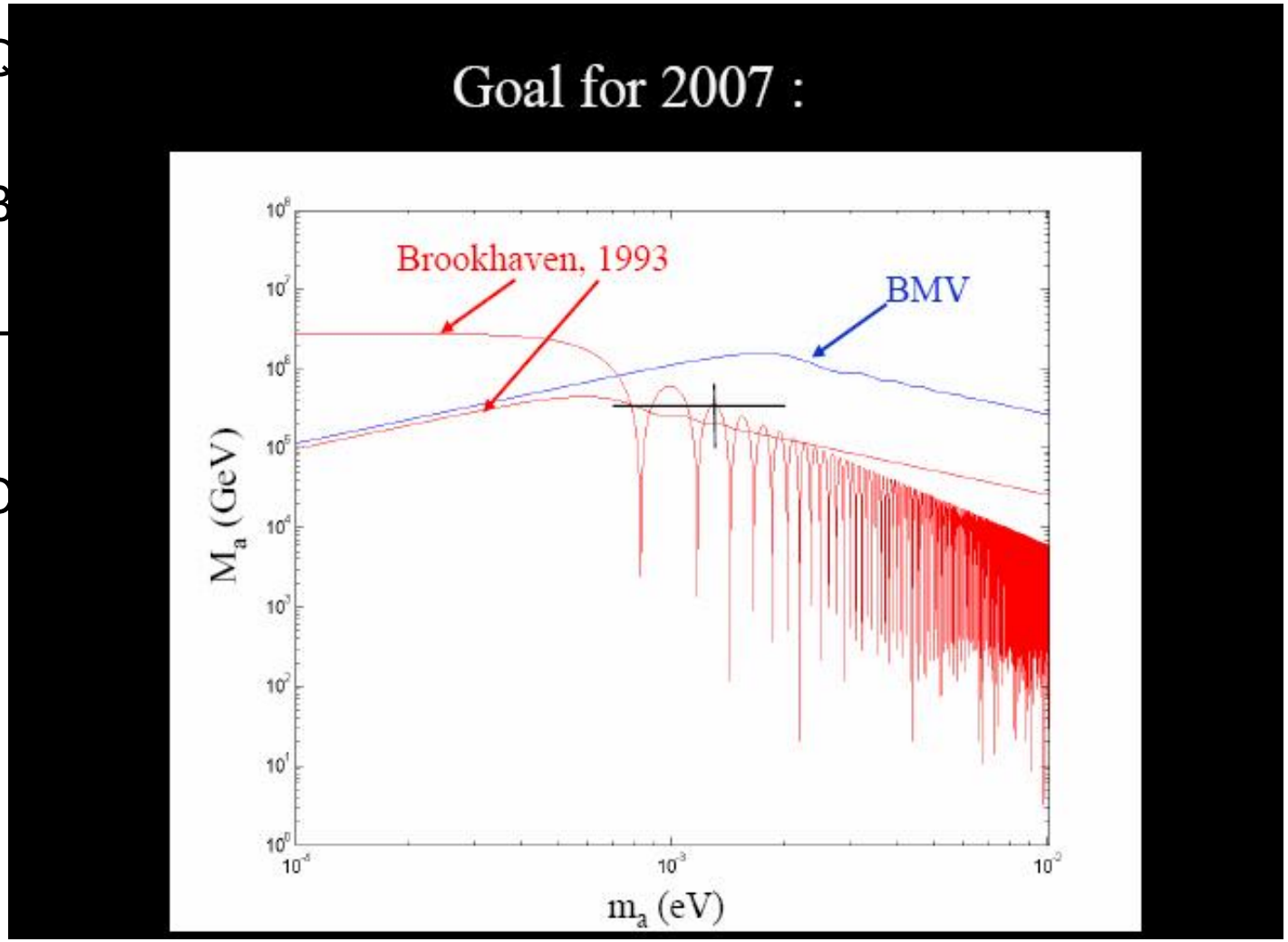
# Future Experiments.

- New polarization experiments:
  - Q&A (Taiwan) (Chen,Mei,Ni'06)
  - BMV (Toulouse)
  - TW or PW standing-wave laser fields (Jena) (Heinzl et al'06)
  - Double-pulsar observations J0737-3039 (Dupays&Roncadelli'06)

# Future Experiments.

▷ New polarization experiments:

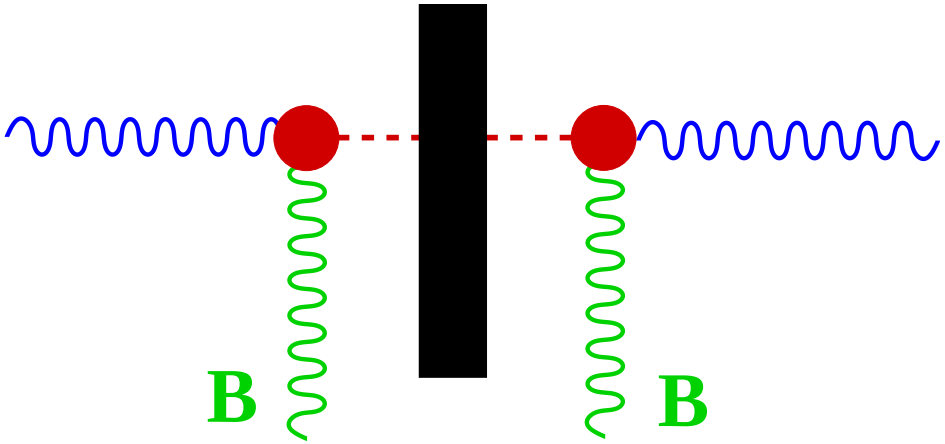
- G
- B
- T
- D




(RIZZO@CERN-AXION-TRAINING2005)

# Future Experiments: ALPs

▷ "light-shining-through-walls" experiments:




- PVLAS upgrade
- ALPS (DESY)
- APFEL (DESY) (VUV-FEL at TTF)
- LIPSS (JLAB)
- ??? (CERN)

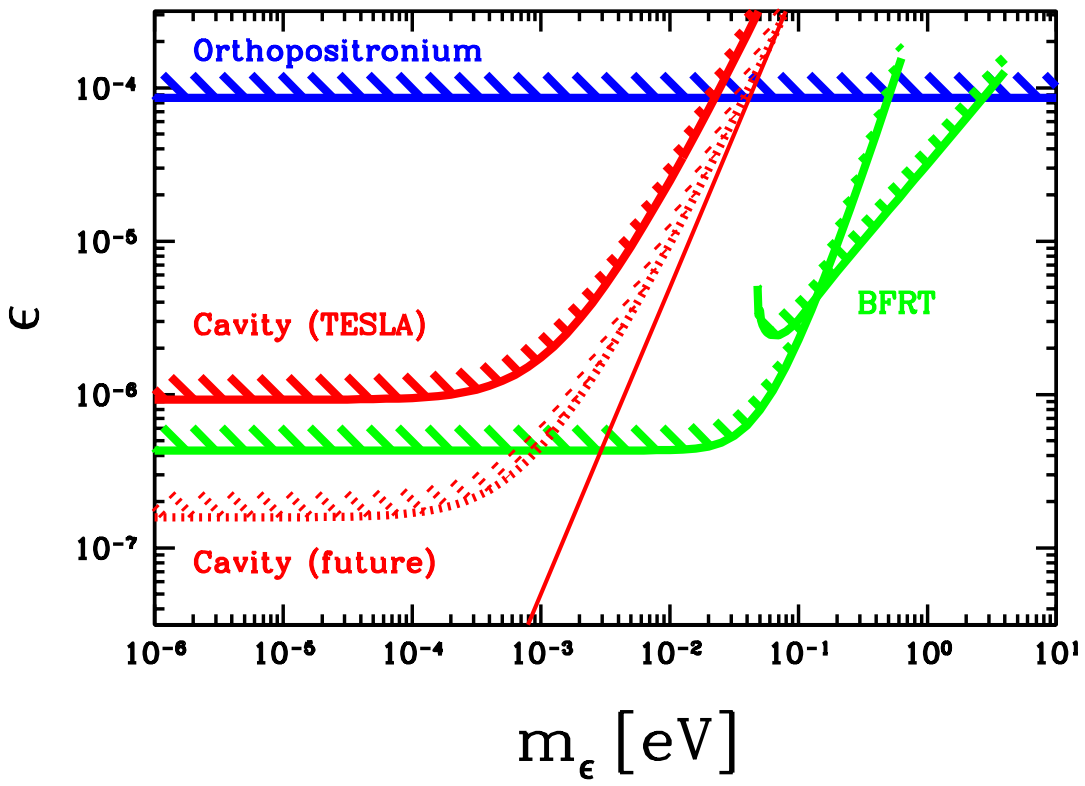
(T316@DPG07: MEYER)

# Future Experiments: ALPs

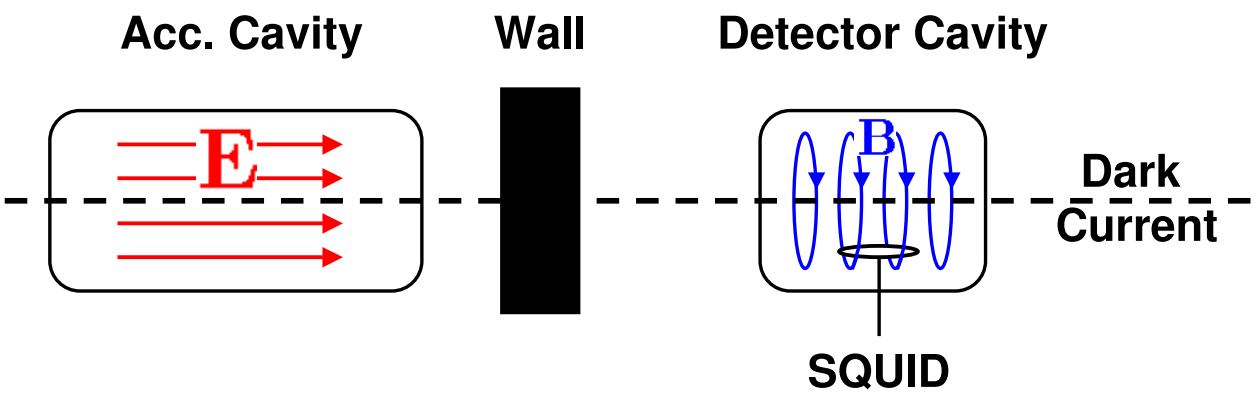
▷ e.g., ALPS @ DESY (A.LINDNER'06)

# Future Experiments: MCPs

- MCP pair production in strong electric fields:




(HG, JAECKEL, RINGWALD'06)



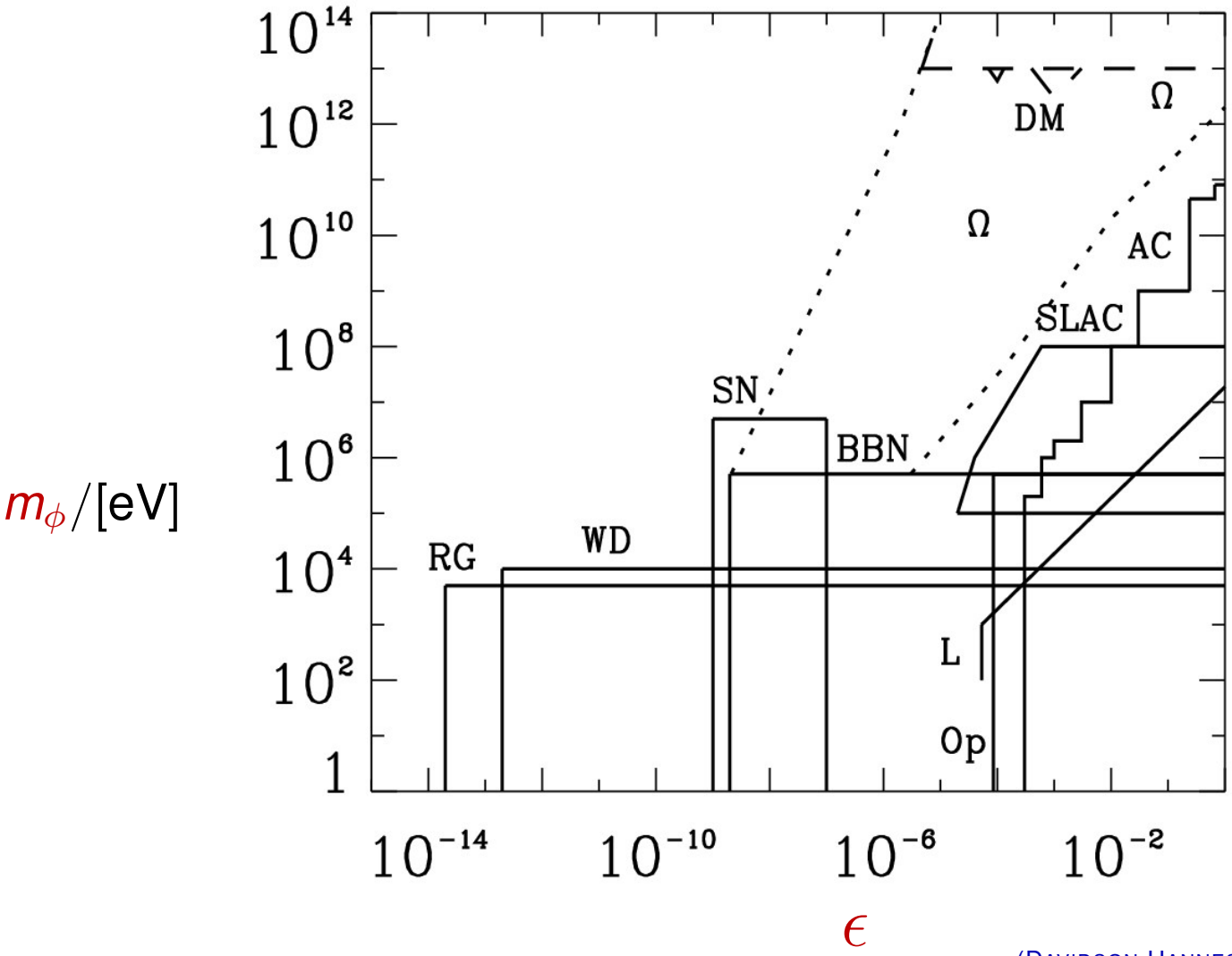
# Conclusions

▷ Why quantum-vacuum physics . . . ?

- " . . . exploring some issues of fundamental physics that have eluded man's probing so far" (TAJIMA'01)
- QFT: high energy (momentum) vs. high amplitude
- "new physics" discovery potential:
  - hypothetical NG bosons (axion, majoron, familon, etc.)
  - millicharged particles
  - sub-millimeter forces
  - . . .

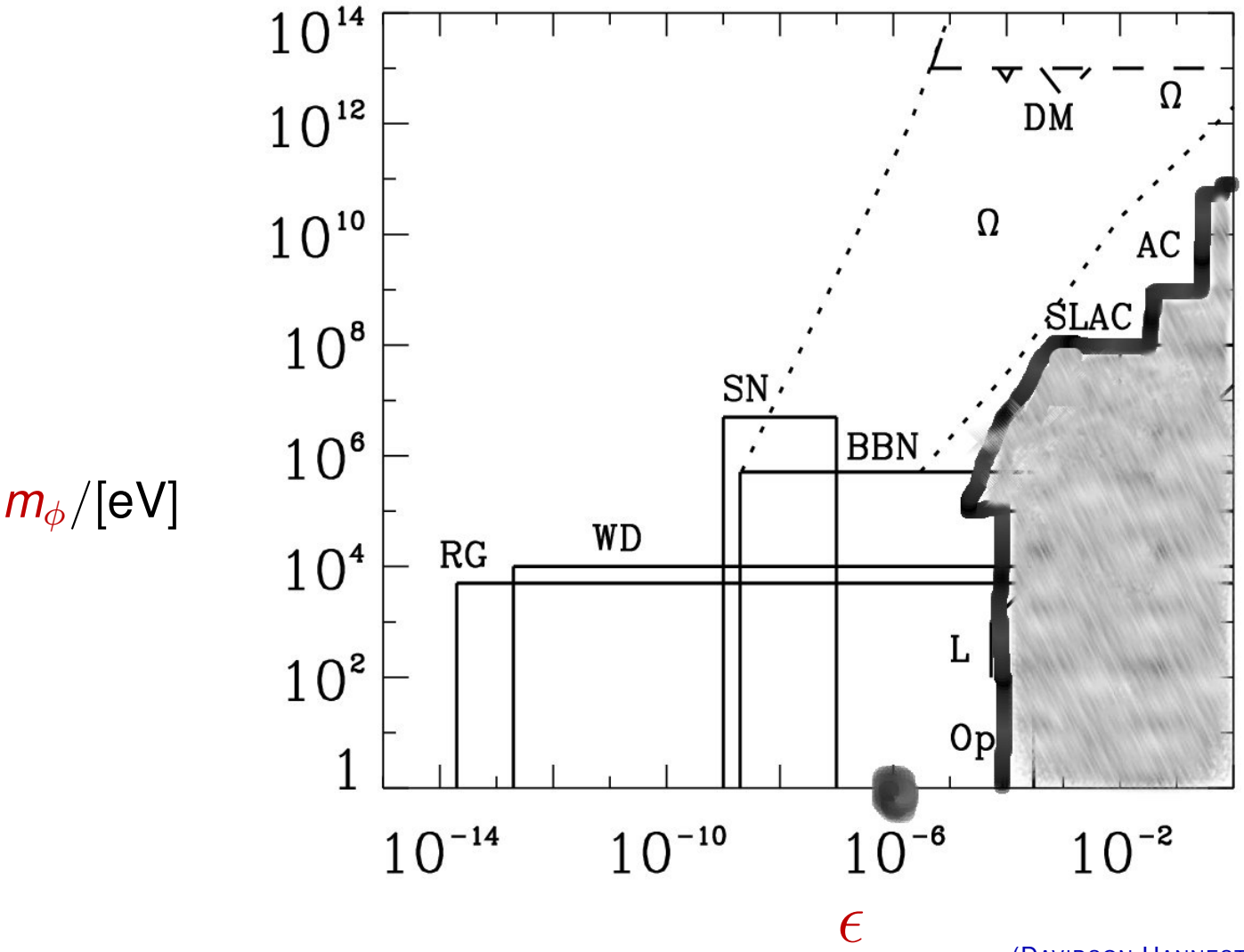
# Bonus Material

# Astrophysical Bounds: MCPs




(DAVIDSON, HANNESTAD, RAFFELT'00)

# Astrophysical Bounds: MCPs




(DAVIDSON, HANNESTAD, RAFFELT'00)

# PVLAS Puzzles

- Does PVLAS observe a signal of unconventional/new physics ?
- Is there a (particle-physics) low-energy effective description of the PVLAS signal ?
- Is there a valid microscopic foundation of such an effective description ?