Evading Astrophysical Bounds on Axion-Like Particles ...in Paraphoton Models

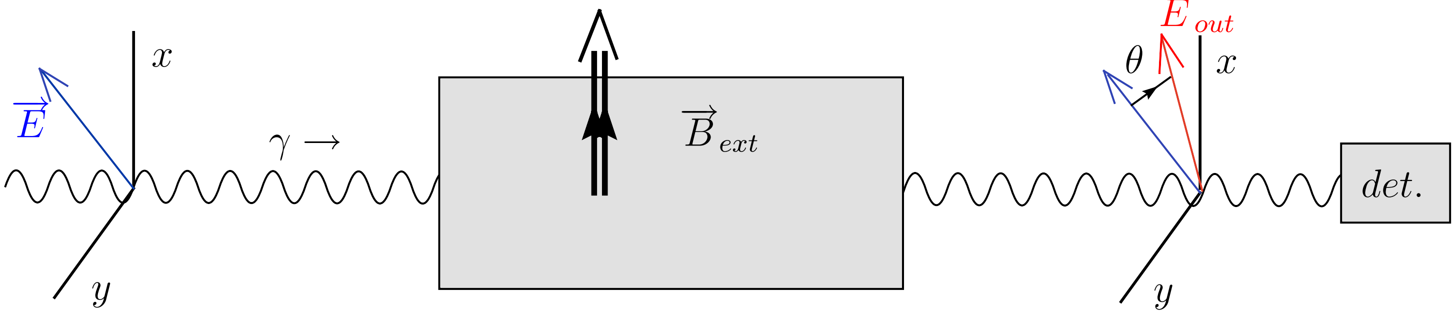
collaboration with C. Biggio, J. Jaeckel, E. Masso, A. Ringwald and F. Takahashi

Javier Redondo

redondo@ifae.es

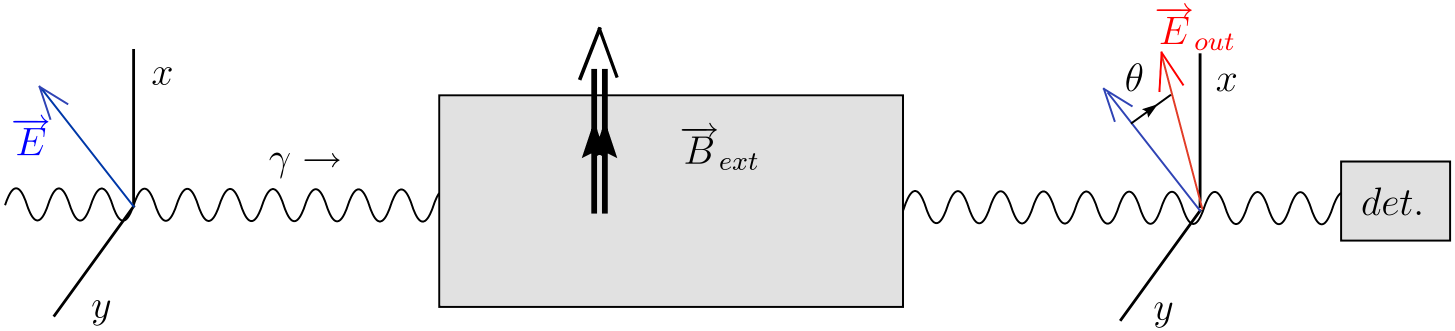
PVLAS experiment

Set up:



$$\theta = 10^{-12} rad/pass!!!$$

PVLAS experiment



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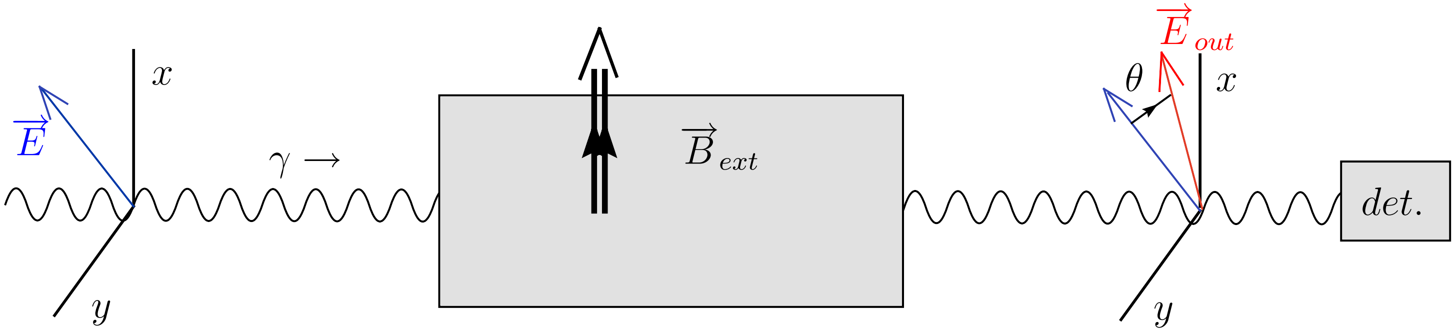
- Vacuum is Dichroic (and Birefringent)

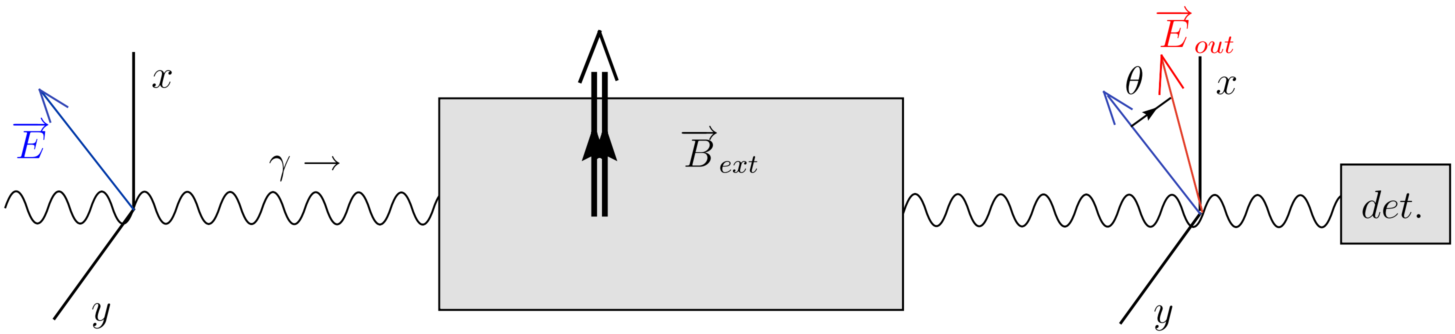
PVLAS experiment



$$\theta = 10^{-12} rad/pass!!!$$

- Vacuum is Dichroic (and Birefringent) (with $\vec{B}$)
- NO explanation between conventional physics!

PVLAS experiment



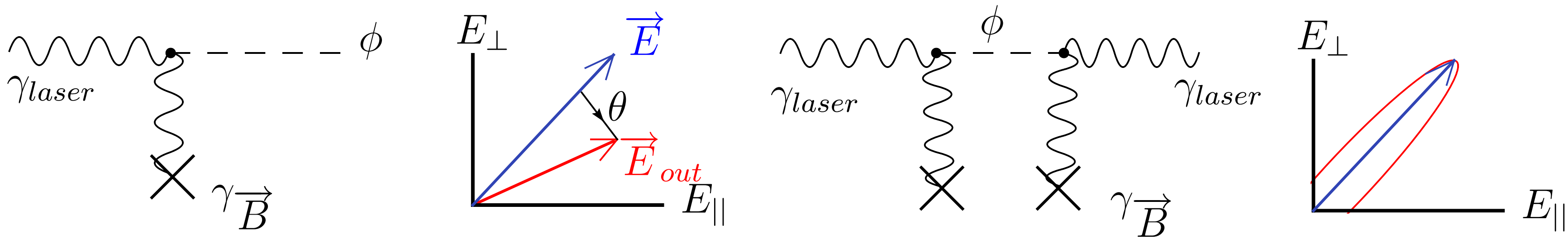
$$\theta = 10^{-12} rad/pass!!!$$

- Vacuum is Dichroic (and Birefringent) (with $\vec{B}$)
- NO explanation between conventional physics...
- What about new physics?

PVLAS and Axion-Like Particles

- Dichroism (Birefr.) from coherent $\gamma - \phi$ oscillations

Maiani, Petronzio, Zavattini, Phys.Lett.B **175** (1986)



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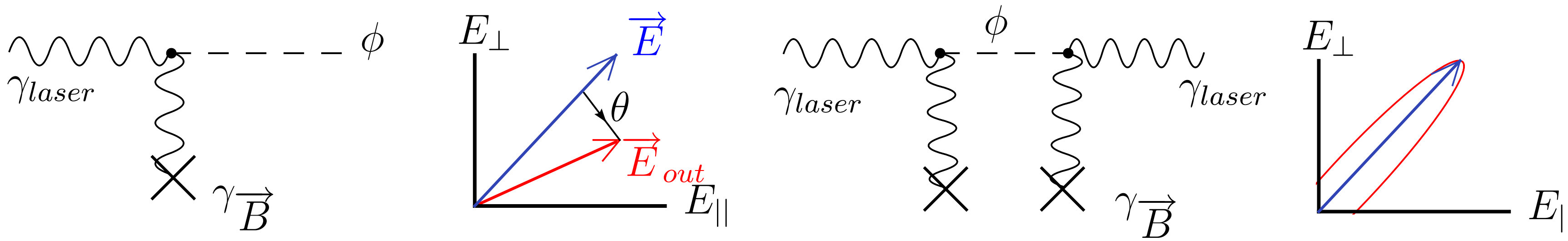

- requirements for ϕ
  - Neutral
  - Integer Spin
  - m_ϕ < Energy of γ_{laser}, otherwise $\theta = 0$

PVLAS and Axion-Like Particles

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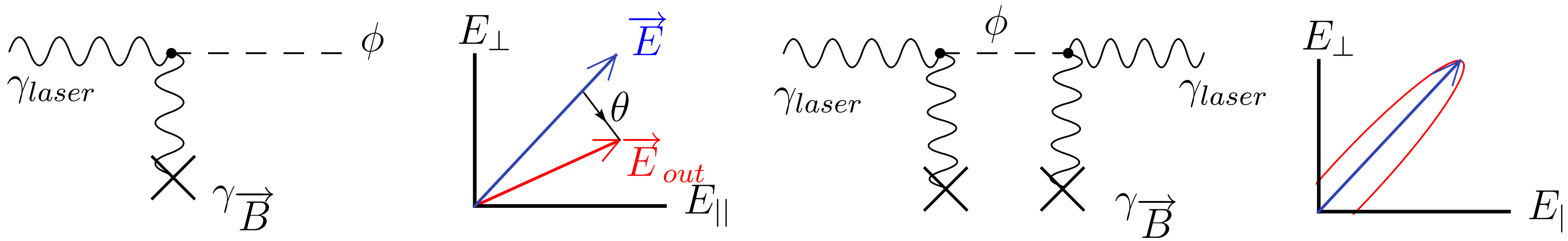

- requirements for ϕ
  - Neutral
  - Boson
  - m_ϕ $<$ Energy of γ_{laser}, otherwise $\theta = 0$
  - Defined Parity (?)
  - CP conserving coupling to $\gamma\gamma$ (?)
- θ largest when $S = 0$ (S=2 in *C. Biggio, E. Massó, JR* [hep-ph/0604062])

PVLAS and Axion-Like Particles

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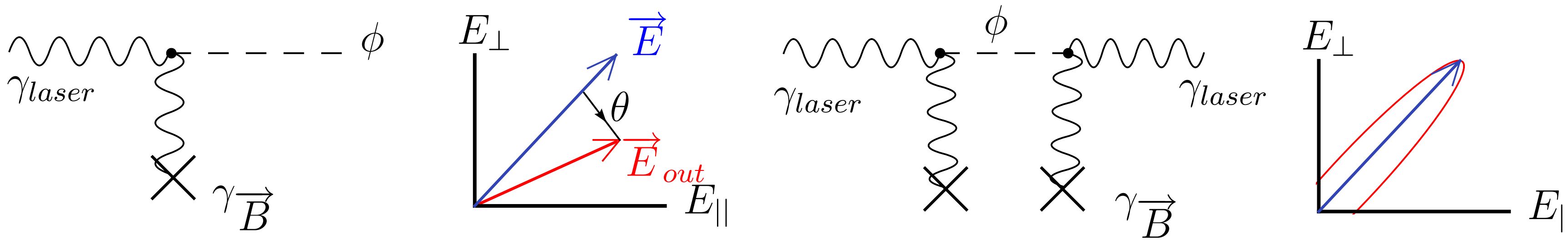


For $S = 0$ they find:

- $\mathcal{L} = \mathcal{L}_{KG} + \frac{1}{4M}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$
- 1 meV $\lesssim \; m_\phi \; \lesssim 1.5$ meV
- 2×10^5 GeV $\lesssim \; M \; \lesssim 6 \times 10^5$ GeV

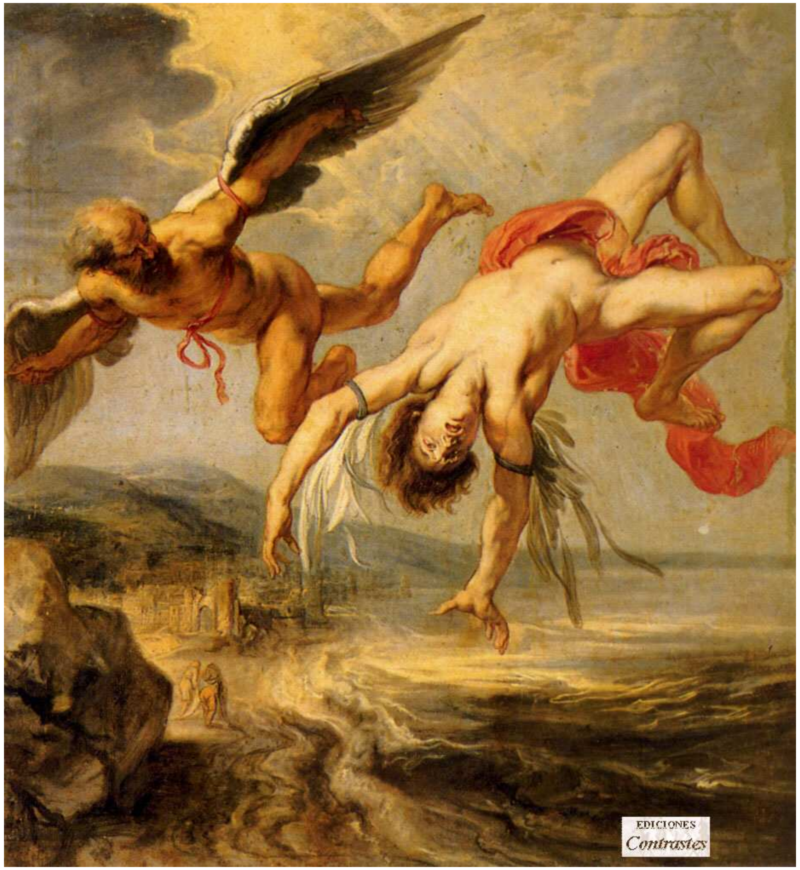
question...

How far can we go with the ALP interpretation?

- Earth-Ground laboratory experiments are consistent
  (*M. Kleban, R. Rabadan,* [hep-ph/0510183])

answer...

We cannot even touch the sun!



CAST and Astrophysical

- Solar Lifetime
  $M \sim 10^5$ GeV $\rightarrow\ L_\odot^\phi \sim 10^6 L_\odot^{std} \rightarrow\ \tau_\odot \sim 10^3$ years!

CAST and Astrophysical

- Solar Lifetime ($M > 0.24\ 10^9$ GeV)

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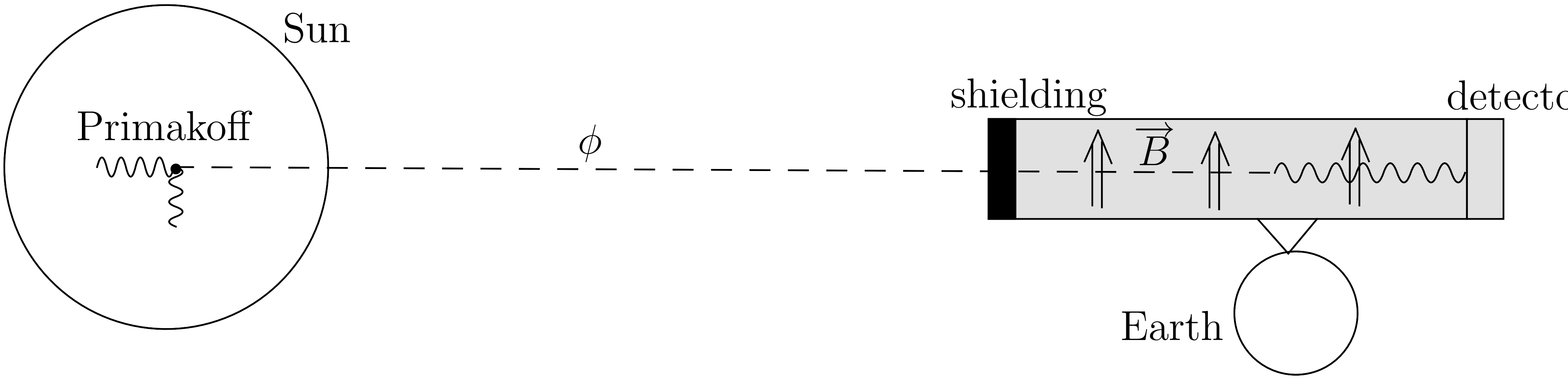
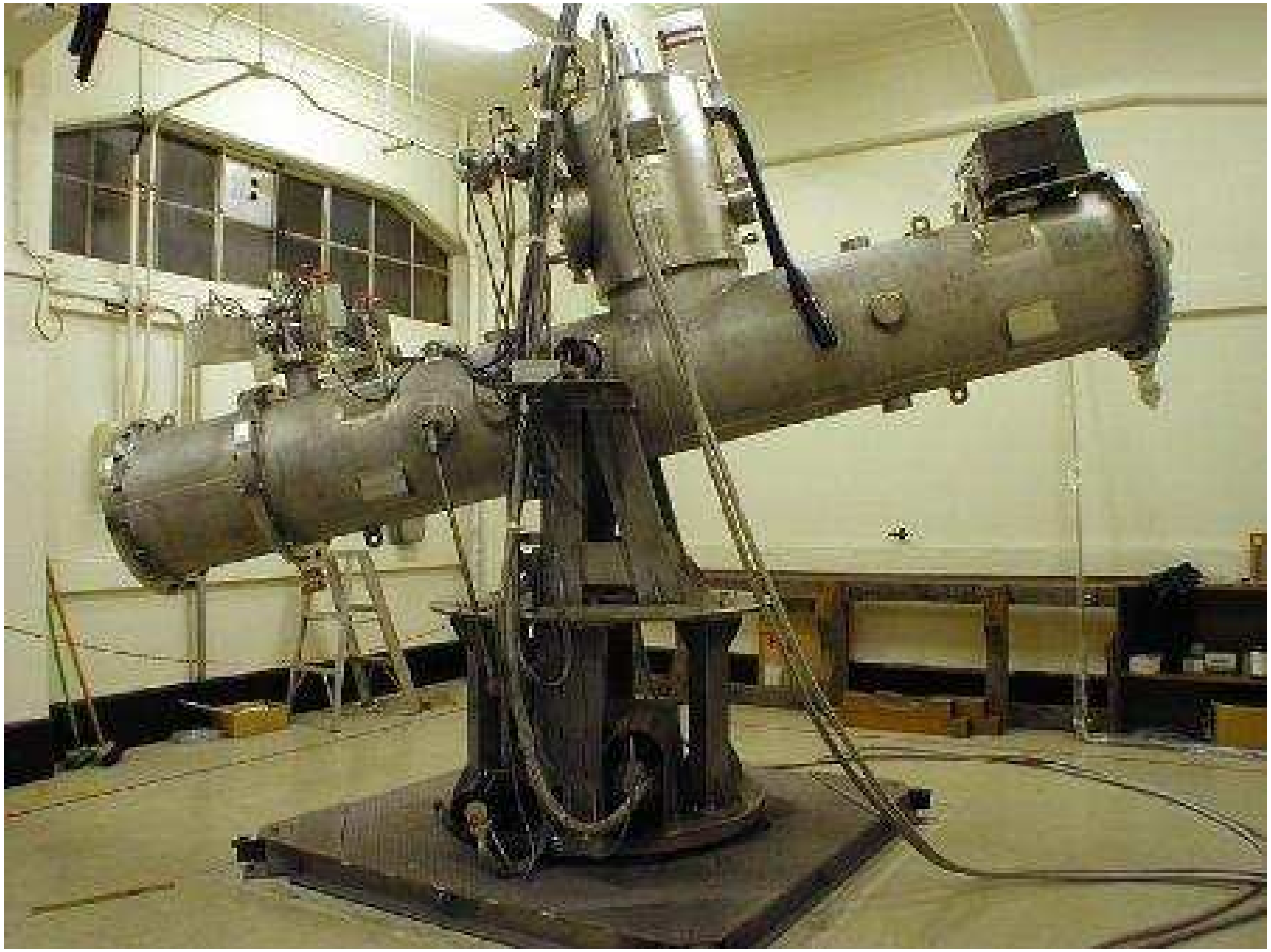
And the Helioscope Idea... (*P. Sikivie, Phys. Rev. Lett.* **51** (1983))



Tokyo Helioscope



CERN Helioscope: CAST

$$M > 0.87\,10^{10}\ \text{GeV}$$

CAST the Astrophysical

- Solar Lifetime ($M > 0.24\ 10^9$ GeV)
- Helium Burning stars in GC ($M > 1.7\ 10^{10}$ GeV)
- CAST Helioscope ($M > 0.87\ 10^{10}$ GeV)

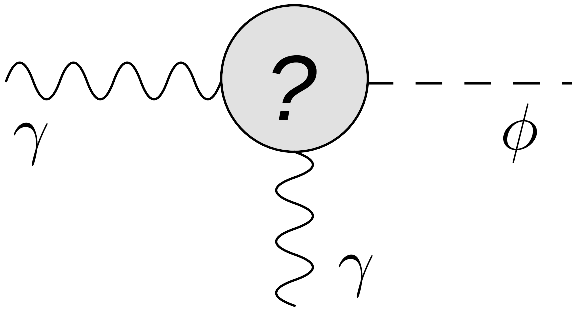
$$M_{PVLAS} \sim 4\ 10^5 \text{ GeV}$$


GAME OVER


GAME OVER ??

PVLAS & Stars: different environment

Introduce New Physics (very) sensible to environment in the $\phi\gamma\gamma$ vertex



	Solar Plasma	HB plasma	PVLAS
T(keV)	1.3	8.6	~ 0
q^2(keV)	~ 1	~ 1	$\sim 10^{-9}$
ω_P(keV)	0.3	2	0
$\rho(gcm^{-3})$	$1.5\ 10^2$	10^4	$< 10^{-5}$
...	...	...	...

PVLAS & Stars: different environment

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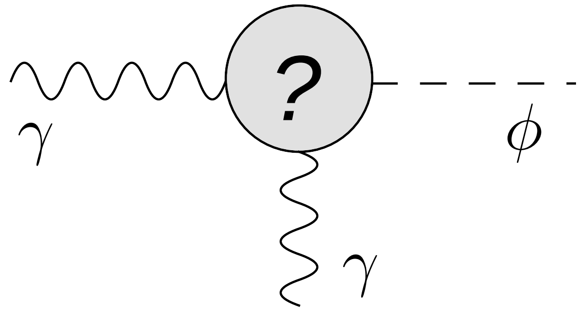

Parameterize this dependence with $M = M(T, \rho, \omega_P, ...)$ and/or $m = m(T, \rho, \omega_P, ...)$ and re-calculate Astrophysical and CAST bounds

(*J. Jaeckel, E. Masso, J. Redondo, A. Ringwald, F. Takahashi* [hep-ph/0605313]).

PVLAS & Stars: different environment

- Introduce New Physics (very) sensible to environment in the $\phi\gamma\gamma$ vertex
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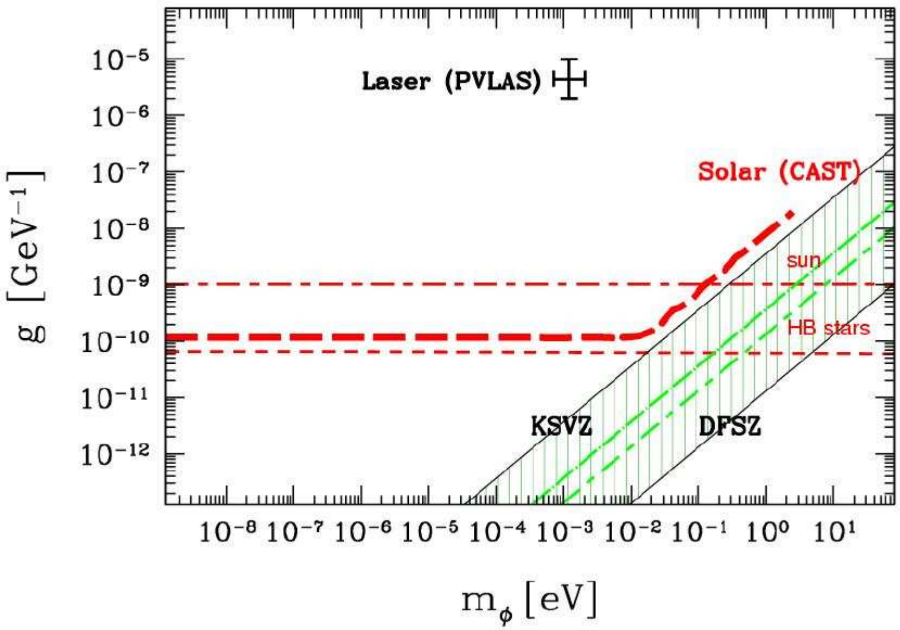
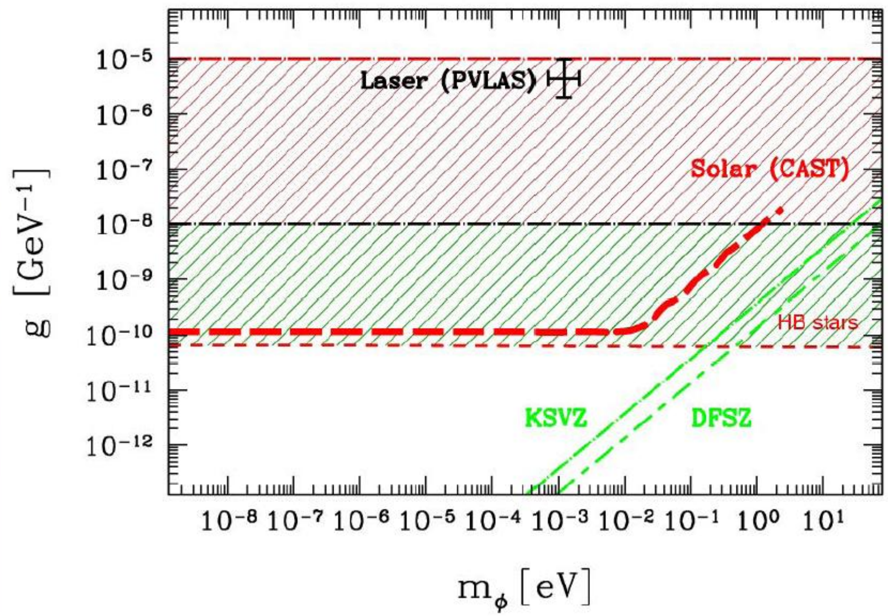
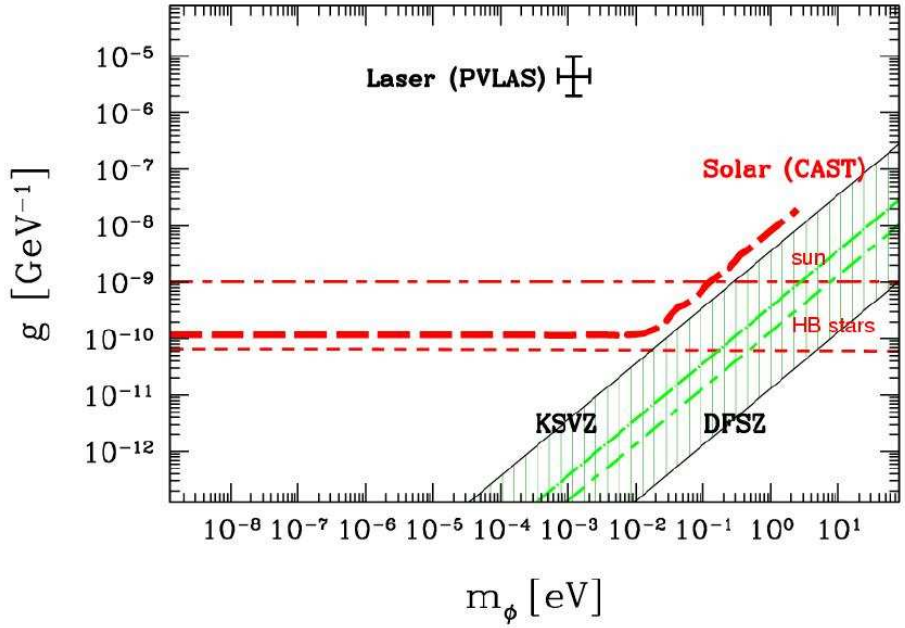


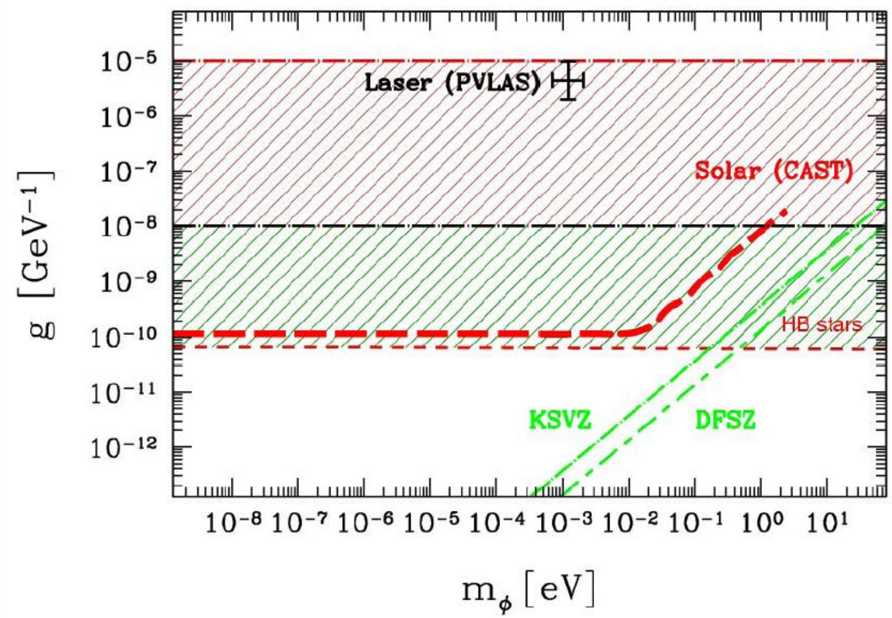


(conservative)(less conservative)

PVLAS & Stars: different environment

- Introduce New Physics in the $\phi\gamma\gamma$ vertex
- $M = M(T, \rho, \omega_P, ...)$; $m = m(T, \rho, \omega_P, ...)$

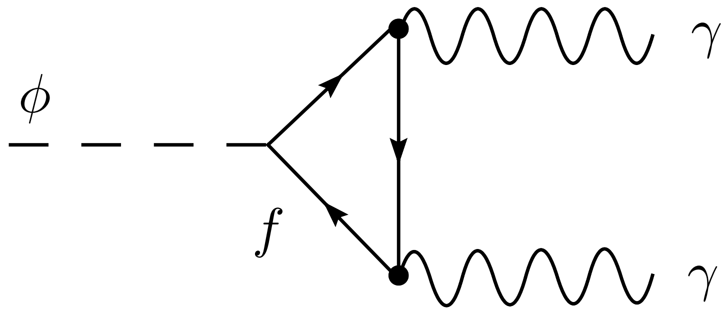




CONCLUSION: LOW ENERGY PHYSICS!
CONCLUSION: We need lab experiments!

A Model with Paraphotons E. Masso& JR [hep-ph/0606163]

Let this structure be a *triangle loop* with a *new fermion* f.



$$\frac{1}{M} = \frac{g \ \alpha \ Q_f^2}{\pi v}$$

v (very) small $\longrightarrow$ Q_f (very) small

Paraphoton Models $\longrightarrow$ Q_f small too

Paraphoton Models *(B. Holdom, L. Okun* (80's))

- Generallization of QED $U(1)_{EM} \rightarrow U(1)_1 \times U(1)_2$

$$-\frac{1}{4}(F_{\mu\nu})^2 + e j^\mu A_\mu$$

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$$-\frac{1}{4}(F_{\mu\nu})^2 + ej^{\mu}A_{\mu} - \frac{1}{4}(F_{\mu\nu})^2 + ej^{\mu}A_{\mu}$$

$$-\frac{\epsilon}{2}F_{\mu\nu}F^{\mu\nu}$$

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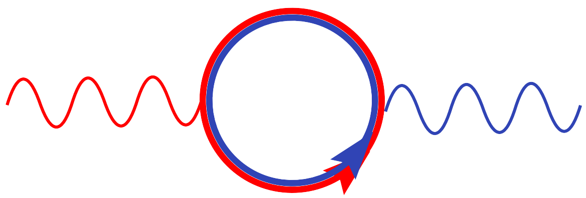
$$-\frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu}$$

ϵ can be very small if comes from



Paraphoton Models (B. Holdom, L. Okun (80's))

- Generallization of QED $U(1)_{EM} \rightarrow U(1)_1 \times U(1)_2$
- $U(1)_1 \times U(1)_2 \xrightarrow{diag.} U(1)_{EM} \times U(1)'$

$$[K] = \begin{pmatrix} 1 & \epsilon \\ \epsilon & 1 \end{pmatrix} \xrightarrow{rot.} \begin{pmatrix} \sqrt{1+\epsilon} & 0 \\ 0 & \sqrt{1-\epsilon} \end{pmatrix} \xrightarrow{ren.} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \xrightarrow{rot.} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

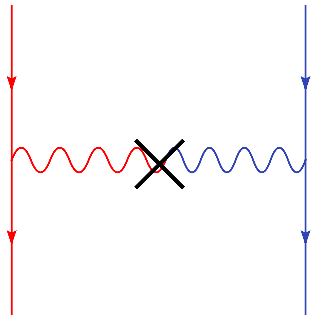
$$[I] = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \xrightarrow{rot.} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \xrightarrow{ren.} \begin{pmatrix} \frac{1}{\sqrt{1+\epsilon}} & \frac{-1}{\sqrt{1-\epsilon}} \\ \frac{1}{\sqrt{1+\epsilon}} & \frac{1}{\sqrt{1-\epsilon}} \end{pmatrix} \xrightarrow{rot.} \begin{pmatrix} 1 & 0 \\ -\epsilon & 1 \end{pmatrix}$$

- define photon as the state coupling with j^μ_{SM}
- THEN j^μ_{NP} **acquires an electric charge** $Q_f = -\epsilon$

$$-\frac{1}{4}(F_{\mu\nu})^2 - \frac{1}{4}(F_{\mu\nu})^2 + e j^\mu_{SM} A_\mu + e j^\mu_f (A'_\mu - \epsilon A_\mu)$$

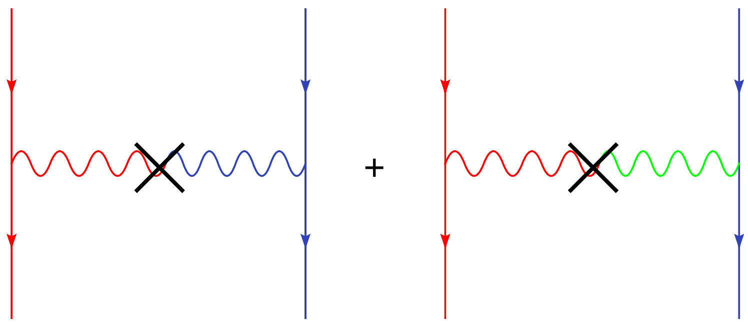
Paraphoton Models

Understanding this charge is easy



$$= -ej^\mu \frac{1}{q^2} q^2 \epsilon \frac{1}{q^2} e j_\mu = -ej^\mu \frac{\epsilon}{q^2} e j_\mu = -ej^\mu \frac{\epsilon}{q^2} e j_\mu$$

Making it q^2 dependent also, add other intermediate state



$$= -ej^\mu \frac{1}{q^2} q^2 \left(\frac{Q_1 \epsilon_1}{q^2 - m_1^2} + \frac{Q_2 \epsilon_2}{q^2 - m_2^2} \right) e j_\mu$$

Make the amplitudes cancel at high q^2 : $\quad Q_1 \epsilon_1 = -Q_2 \epsilon_2$

$Q_f(q^2)$ Paraphoton Model (*E. Masso, JR* [hep-ph/0606163])

Our Choice $Q_1 = -Q_2 = 1$, $\epsilon_1 = \epsilon_2 = \epsilon$, $m_1 = 0$, $m_2 = \mu \neq 0$.

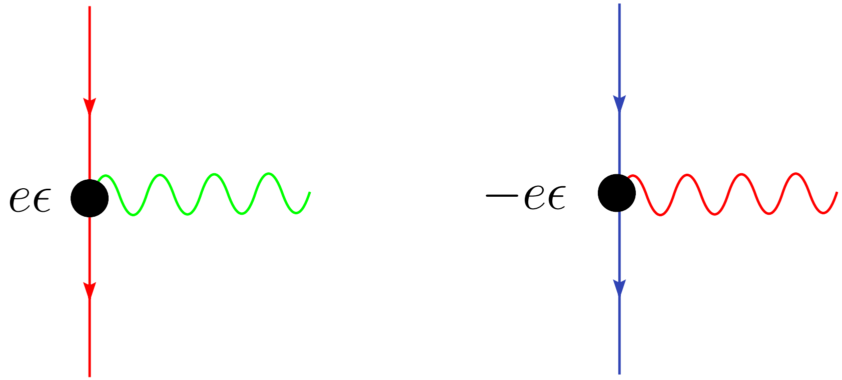
$$e j^\mu \frac{1}{q^2} \left(\frac{\epsilon \mu^2}{q^2 - \mu^2} \right) e j_\mu$$

We got the desired suppression at high q^2!

$$Q_f = Q_f(q^2) = \epsilon \frac{\mu^2}{q^2 - \mu^2}$$

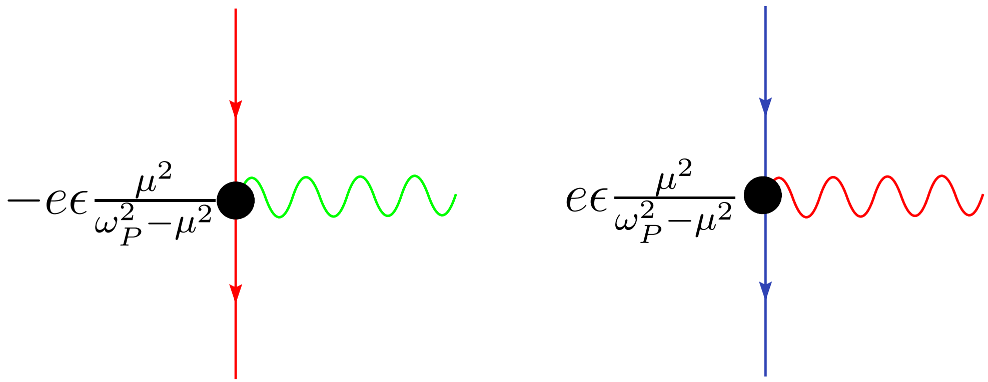
$Q_f(q^2)$ Paraphoton Model (*E. Masso, JR* [hep-ph/0606163])

Polology $\leftrightarrow$ Diagonalization "a la Holdom"



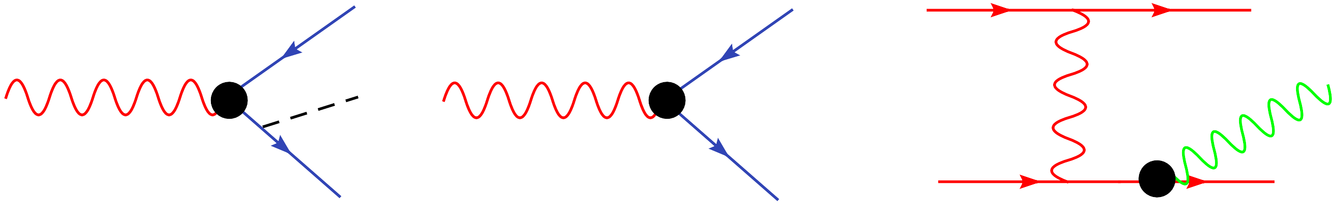
But In a plasma γ has a mass $= \omega_P$

$$ej^\mu \frac{1}{q^2-\omega_P^2}\left(\frac{\epsilon\mu^2}{q^2-\mu^2}\right) ej_\mu$$



$Q_f(q^2)$ Paraphoton Model Constraints

- PVLAS ALP interpretation consistent
  $\epsilon^2 = 10^{-12}\frac{v}{eV} \qquad \mu, v > 10^{-6}$ eV
- Revisit Astrophysical Bounds
  - Energy Loss of $\phi \quad \rightarrow \quad$ of $\phi,\ f$'s and γ's



$\epsilon\frac{\mu^2}{eV^2} < 4\ 10^{-8}$; $\epsilon\frac{\mu^2}{eV^2} < 1.2\ 10^{-7}$

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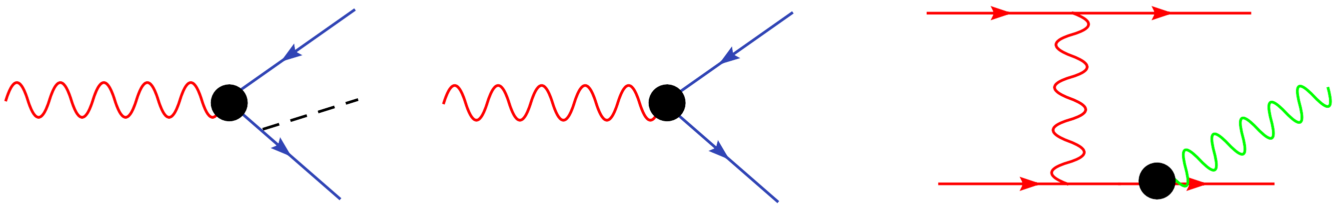

$$\epsilon\frac{\mu^2}{eV^2} < 4\ 10^{-8} \qquad ; \qquad \epsilon\frac{\mu^2}{eV^2} < 1.2\ 10^{-7}$$

  - CAST bounds?
    - ϕ flux very suppressed (μ^4/ω_P^4)
    - ϕ's from Bremsstrahlung! ($E_\phi^{Bremm} \ll E_\phi^{Prim}$) and (CAST $1-15$ keV)
    - Nature of ϕ can play a role ($\bar{f}f$ bound state?)

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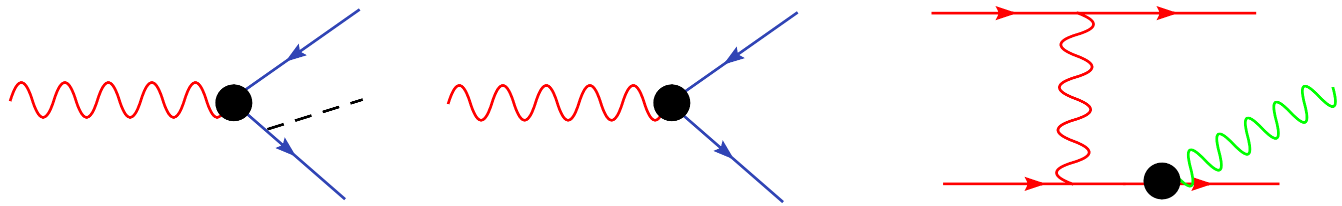
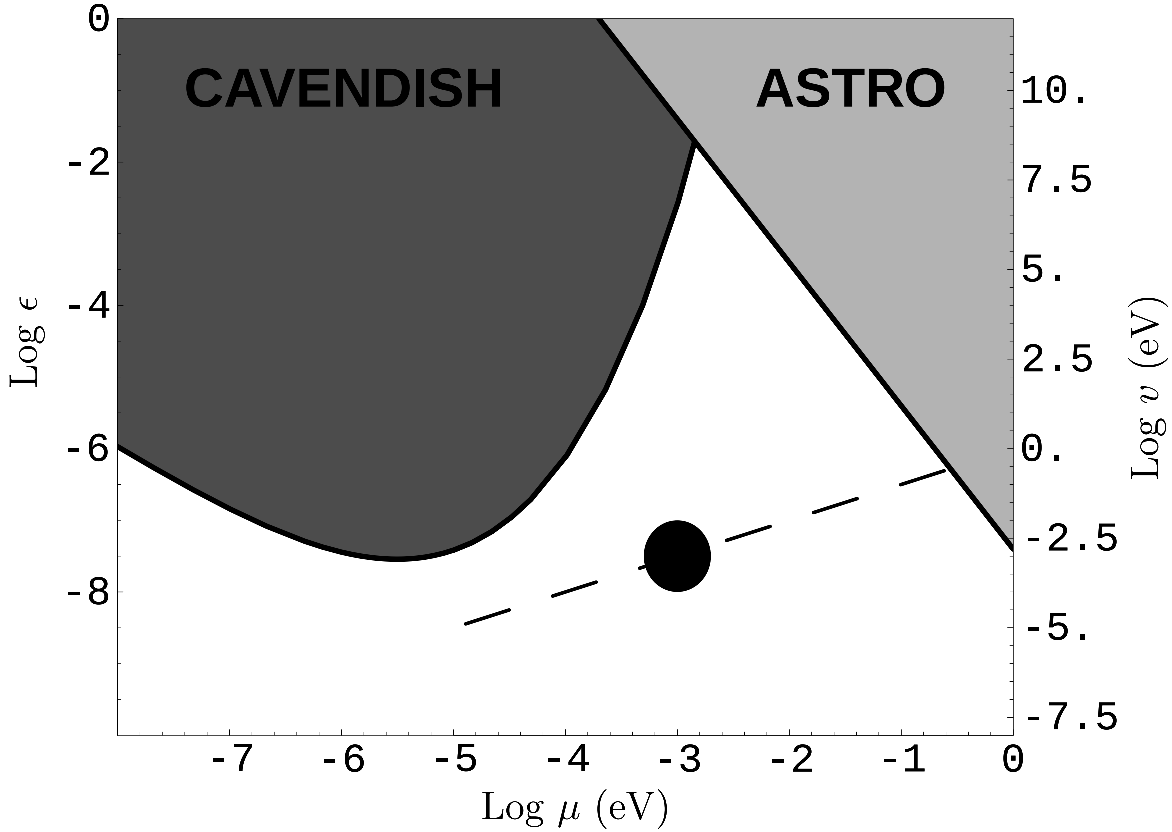


$\epsilon\frac{\mu^2}{eV^2} < 4\ 10^{-8}$; $\epsilon\frac{\mu^2}{eV^2} < 1.2\ 10^{-7}$

  - CAST bounds evaded
- 5^{th} force constraints on $-\epsilon e j^{\mu} A_{\mu}$

$Q_f(q^2)$ Paraphoton Model Constraints

Astrophysical and 5^{th} force limits in our model



Preferred value $v \sim \mu \sim m_\phi \sim 1$ meV; $\epsilon \sim 10^{-8}$

Conclusions

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  - $\phi, f, \gamma_1, \gamma_2$ at a only LOW ENERGY SCALE ($\sim$ meV)
  - $Q_f = Q_f(q^2) = \epsilon \frac{\mu^2}{q^2-\mu^2}$ suppressed in stellar plasmas
  - Allowed by Laboratory and Astrophysical Limits
- ALP interpretation of PVLAS $\checkmark$
- We need Laboratory experiments!
- Many Test of PVLAS proposed

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- We need Laboratory experiments!
- Many Test of PVLAS proposed
  - PVLAS regeneration (2006-7)
  - APFEL (DESY) (2007?)
  - BMV (Toulouse) (2007)
  - JFEL (Jefferson Lab) (2007-8?)
  - CERN regeneration (?)