Strong CP, Peccei-Quinn solution & axions

$$\mathcal{L}_{\rm CP-viol.} = \theta \, \frac{\alpha_s}{16\pi} \, \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

<u>The CP problem</u>: to understand the smallness of $\bar\theta = \theta + {\rm Arg \; Det} \; M_q$

PQ Chiral symmetry allows to rotate away $\bar\theta$

SSB at high scale f_a → Axions

Light particles
Weakly coupled

Light bosons coupled to $\gamma\gamma$

Consider ϕ light PS or S coupled to $\gamma\gamma$

$$\mathcal{L}_{\phi\gamma\gamma} = \tfrac{1}{8}\, g_{\phi\gamma\gamma}\ \phi\ \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = g_{\phi\gamma\gamma}\ \phi\ \vec{E}\vec{B}$$

$$m$$

$$g = M^{-1}$$

$$(= g_{\phi\gamma\gamma}\ \phi\ [|E|^2 - |B|^2]\ )$$

- (Current) axion experiments sensitive to $\gamma\gamma$ coupling
- Other GB or PGB

  Family, Lepton num. sym. ⇨ familons, majorons

  MetaSM theories ⇨ $0^-,\ 0^+$
- Even for the axion, there might be extra contributions to mass, altering relation $m_a \sim f_a^{-1}$
- Interesting implications, cf. SN dimming, ...

Axion Physics
What Is New ?

"Axions"
Axion-like

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with:

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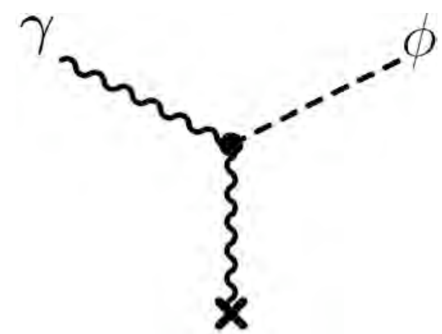
Gabriel Zsembinszki

Consequences of $\phi\gamma\gamma$

- Primakov-like processes

  allows $\gamma \to \phi$ and $\phi \to \gamma$



  (cf. Primakoff process for $\pi^0\gamma\gamma$)

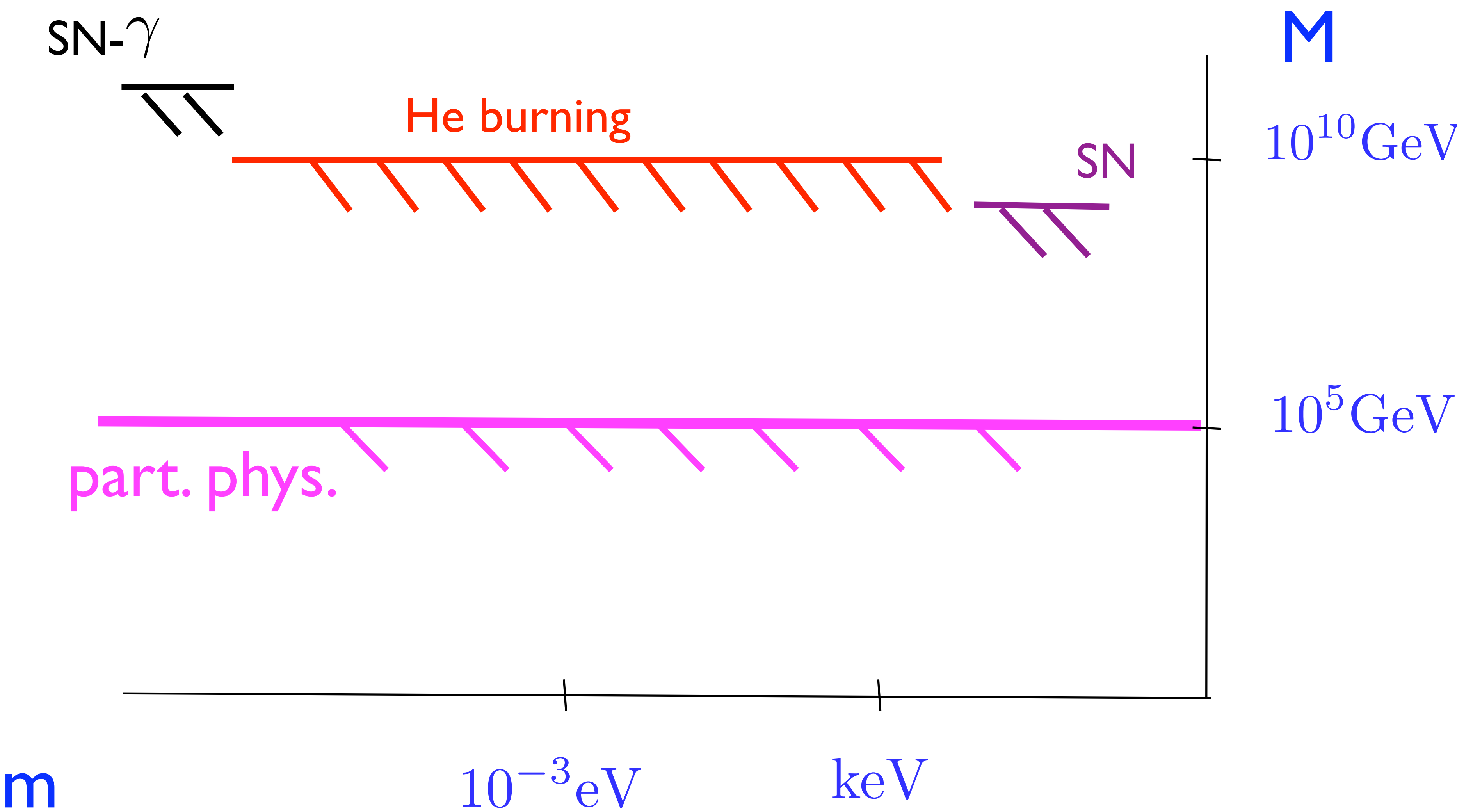
- $\phi\gamma$ mixing in external B-field

$$\mathcal{L}_{\rm int} = \mathcal{L}_{\phi\gamma\gamma} \Rightarrow g_{\phi\gamma\gamma}\ \phi\ \vec{\epsilon}\cdot\vec{B}$$

strength of interaction

photon polarization

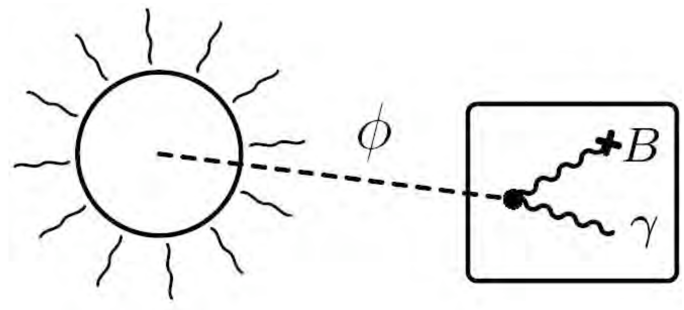
Constraints on $\phi\gamma\gamma$



EM, Toldrà
Klebart, Rabadan

New experimental results

CAST



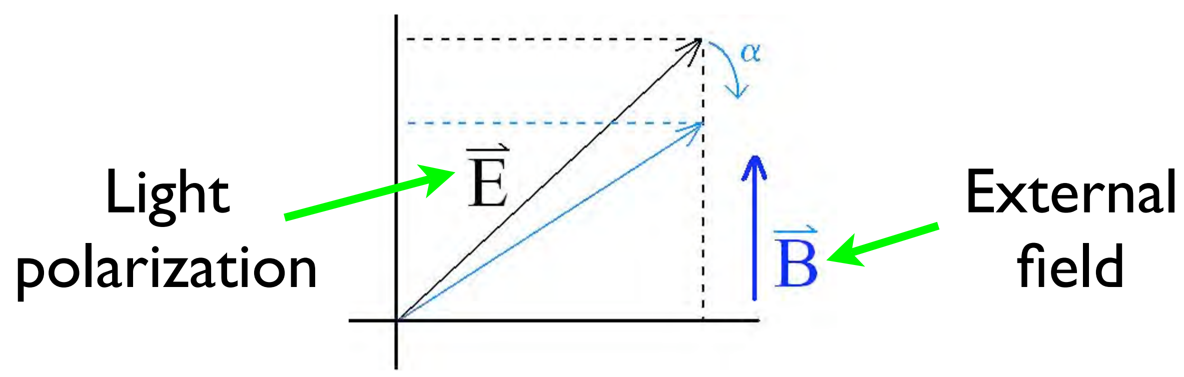
Helioscope

Sikivie

$$M > 0.9 \times 10^{10} \text{ GeV}$$
$$(m < 0.02 \text{ eV})$$

K. Zioutas et al.
PRL (2005)

PVLAS



Observe selective absorption
(dichroism)

$$\alpha = (3.9 \pm 0.5)\ 10^{-12} \text{ rad/pass}$$

E. Zavattini et al.
PRL (2005)

Particle interpretation

photons decay into light particles

Scale: $1\ 10^5 < M < 6\ 10^5$ GeV $\quad M = g_{\phi\gamma\gamma}^{-1}$

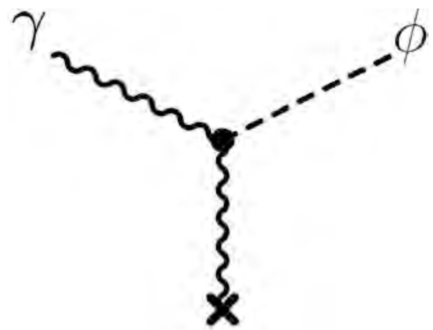
Mass: $0.7 < m < 2$ meV

the particle

is NOT be the standard axion

Spin two

Biggio, EM, Redondo



Spin-two particle

2^- $$\mathcal{L} = g\ \chi^{\mu\nu} F_{\mu\rho} \widetilde{F}_{\nu}{}^{\rho}$$

It vanishes
Need higher-order terms

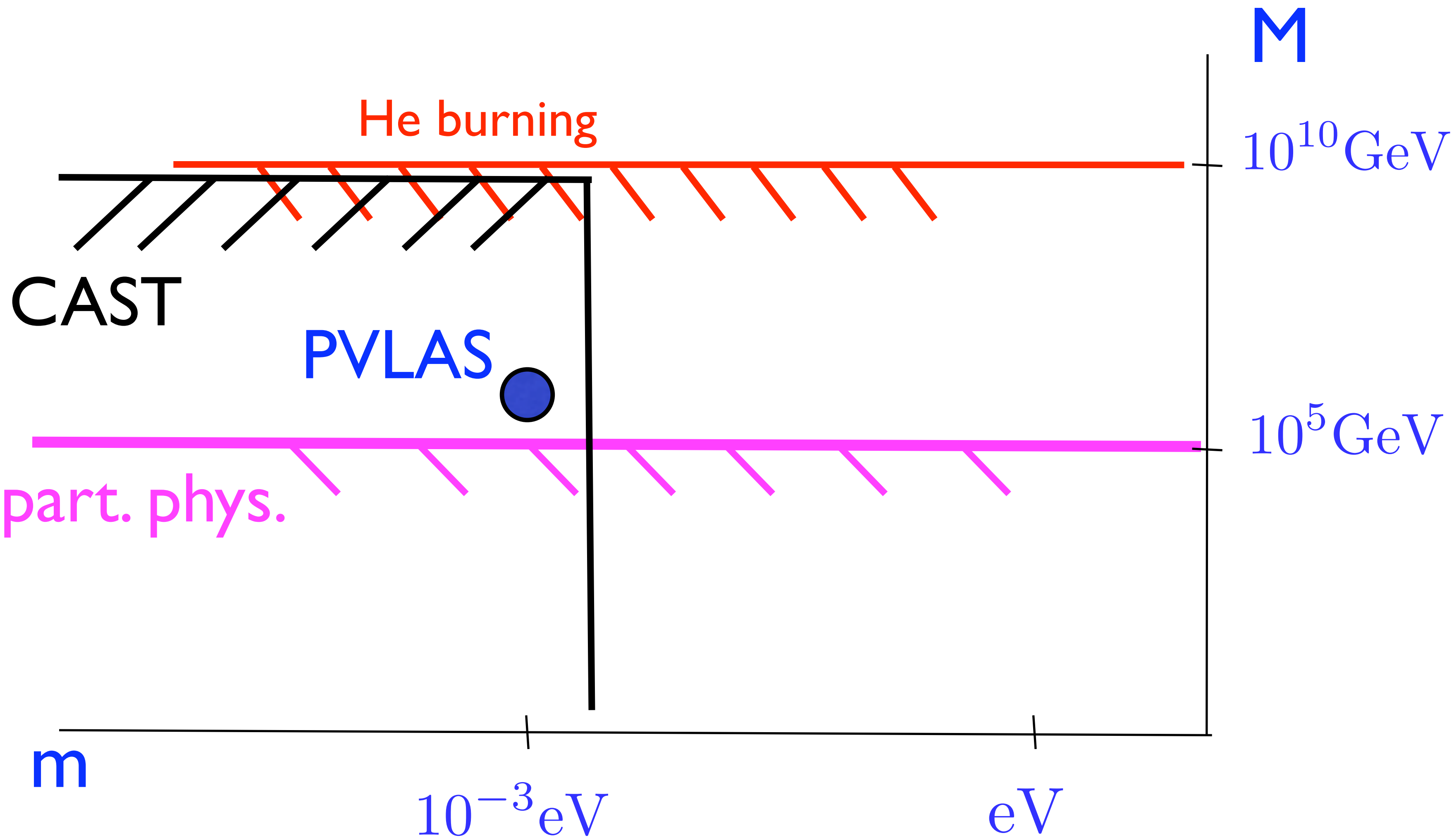
2^+ $$\mathcal{L} = g\ \chi^{\mu\nu}\ F_{\mu\rho} F_{\nu}{}^{\rho}$$

Rotation effects $(m/E)^2$

⇒ If particle interpretation OK, spinless option favoured

PVLAS, CAST & the STARS

Obvious and dramatic conflict !



PVLAS strength of interaction leads to $\mathcal{L}_{exotic} \sim 10^6 \ \mathcal{L}_\odot$

Experimental future

Ringwald et al

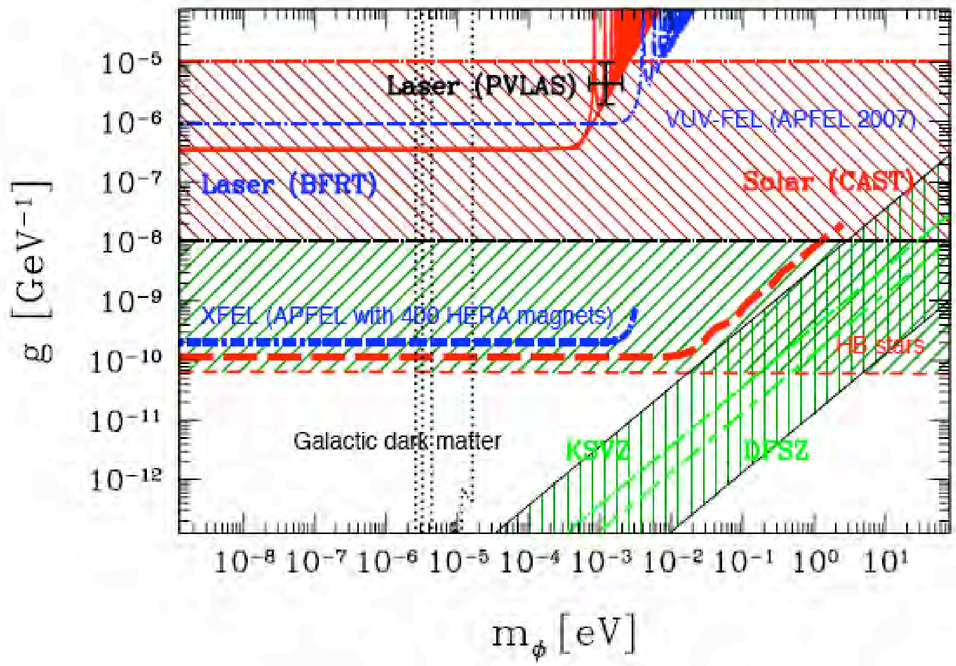


Figure 1: Various bounds on the coupling g and mass m_ϕ of a (light) boson coupled to two photons (areas above single lines are excluded). The green vertically shaded strip gives the range of all reasonable axion models. The two lines within its boundaries give a typical KSVZ and DFSZ model. The green and red diagonally shaded areas give the additional area allowed when we suppress the production of ALP's in the sun (the green smaller one is a little bit more conservative).

PVLAS, CAST & the STARS

EM, Redondo

A way out of the puzzle is to have a model where the Sun emits much less axion-like particles than expected

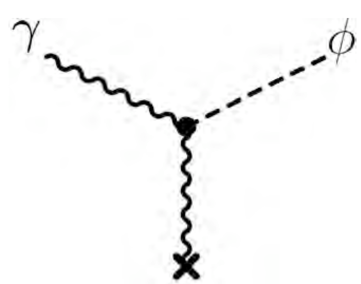
➡ There would be less energy loss and thus stellar limit are avoided

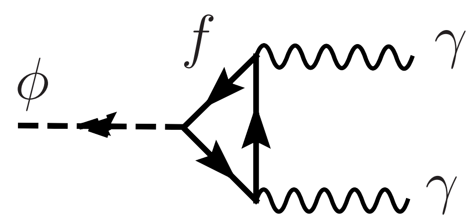
➡ CAST limit not valid because it assumes "solar- standard" ϕ - flux

PVLAS & the STARS

Suppression of production in the stars

- Neutral particle coupled to 2 photons
  Triangle diagram of charged particle





ϕ composite $\bar{f}f$

ϕ coupled to f

Amplitude $\sim 1/\Lambda$

Λ = mass scale

cf. pion

cf. Higgs, standard axion

- Coupling is weak
  - mass scale Λ is large — Problem: no running with energy
  - q_f small ... models ?

Paraphoton model

Okun
Holdom

- QED $\mathcal{L} = -\frac{1}{4}F^2 + e\ j \cdot A$ Photons, charged particles
- Extend QED: $U(1) \times U(1)'$

Paraphotons,
Paracharged particles
+ ultramassive fermions with charge and paracharge

$$\mathcal{L} = -\frac{1}{4}(1+\eta)F^2 - \frac{1}{4}(1+\eta')F'^2$$

$$+ \frac{1}{2}\ \varepsilon\ F \cdot F' \ + \ \frac{1}{2}\mu^2\ A'^2$$

$$+ e\ j \cdot A \ + \ e'\ j' \cdot A'$$

mixing (small) → $\frac{1}{2}\varepsilon F \cdot F'$

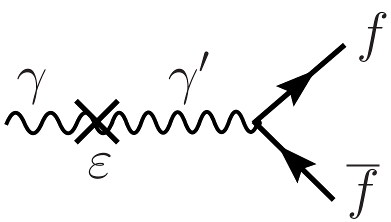
paraphoton mass → $\frac{1}{2}\mu^2 A'^2$

low energy fermions → $e'\ j' \cdot A'$

Paraphoton model

- A' (massive) paraphoton

- particles with paracharge e'
  adquire small electric charge



$\varepsilon\ e'$ charged particles

- others

Reconciling PVLAS with the stars

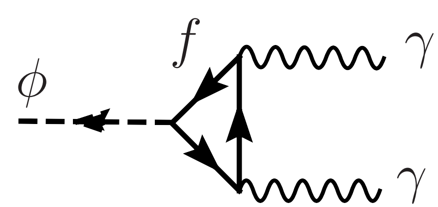
charge T-dependent q(T)

$$q(T_{\rm stellar} \sim {\rm keV}) \ll q(T_{\rm pvlas} \sim 0)$$

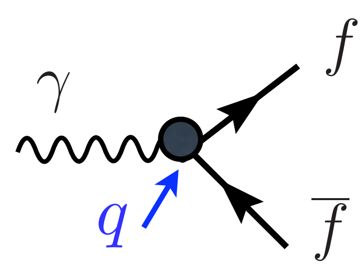
- PVLAS works at T=0

charge eq

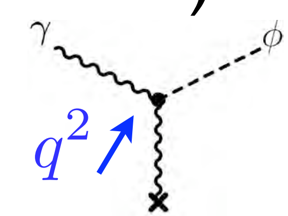
$$\frac{1}{\Lambda}\,\frac{\alpha_{\rm em}}{\pi}\,q(0)^2 = \frac{1}{4\times 10^5\ {\rm GeV}}$$



- Stellar energy loss now dominated by



(No longer by Primakoff effect)



$q \leq 10^{-15}$ (RG)

Davidson
Campbell, Bailey, Peskin
Hannestad, Raffelt

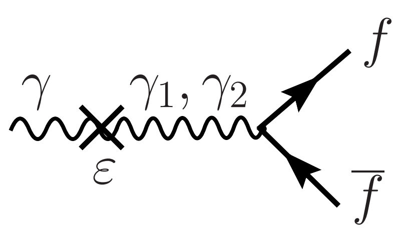
Two-Paraphoton model

EM, Redondo

Charge suppression at keV energies ?

May be obtained within a
two-paraphoton model with partial cancellation

Introduce γ_1, γ_2



$\varepsilon_1 = \varepsilon_2$ high-energy structure

$e'_1 = -e'_2$ (para)charge assignments

$\mu_1 \neq \mu_2$ scalar sector

$$q(T) \simeq \frac{\mu^2}{T^2}\, q(0)$$

$\mu \ll T$

To simplify

$e_1 = e, e_2 = -e$

$\mu_2 = 0, \;\; \mu_1 \equiv \mu \neq 0$

Low-energy scale

Cannot univocally determine parameters $\Lambda, \mu, q(0)$

$$q(T = 10\,\text{keV}) \simeq \frac{\mu^2}{(10\,\text{keV})^2}\, q(0) \;\; \leq 10^{-15}$$

$$\frac{1}{\Lambda}\, \frac{\alpha_{\text{em}}}{\pi}\, q(0)^2 = \frac{1}{4\times 10^5\,\text{GeV}}$$

$$\Rightarrow \quad \Lambda\ \mu^4 \ \leq \ 10^{-2}\ \text{eV}^5$$

- If assume $\Lambda \sim \mu$
  - Bound on new scale

    $$\Lambda \sim \mu \leq 0.4\ \text{eV}$$

  - Consistent with all masses of same order

    $$\Lambda \sim \mu \sim m_\phi \simeq 10^{-3}\ \text{eV}$$

    (e-units)

    $$\Rightarrow \quad q(0) = 10^{-7}$$

Looking for ALPS

Jäckel, EM, Redondo
Ringwald, Takahashi

- Axion Like Particles (ALPs)
  that explain PVLAS result
  and not contradict CAST
  neither astrophysical constraints

  perhaps indicate a dependence
  of ALPS properties
  on the environment (density, temperature, ...)

- (Low-energy) laboratory searches
  important

Hermes (Messenger's God) of Praxiteles

MESSAGE

Evasion of astrophysical bounds
difficult = possible in sophisticated models

If PVLAS confirmed
not many new-physics models
do the job

CONCLUSIONS

If PVLAS signal confirmed, and it is due a new particle coupled to photons, we need a model to explain why astrophysical bound are not valid.

+ PVLAS + Astrophysical constraints

NEW
LOW ENERGY
SCALE