Axions and their Relatives: Theory and Experiment

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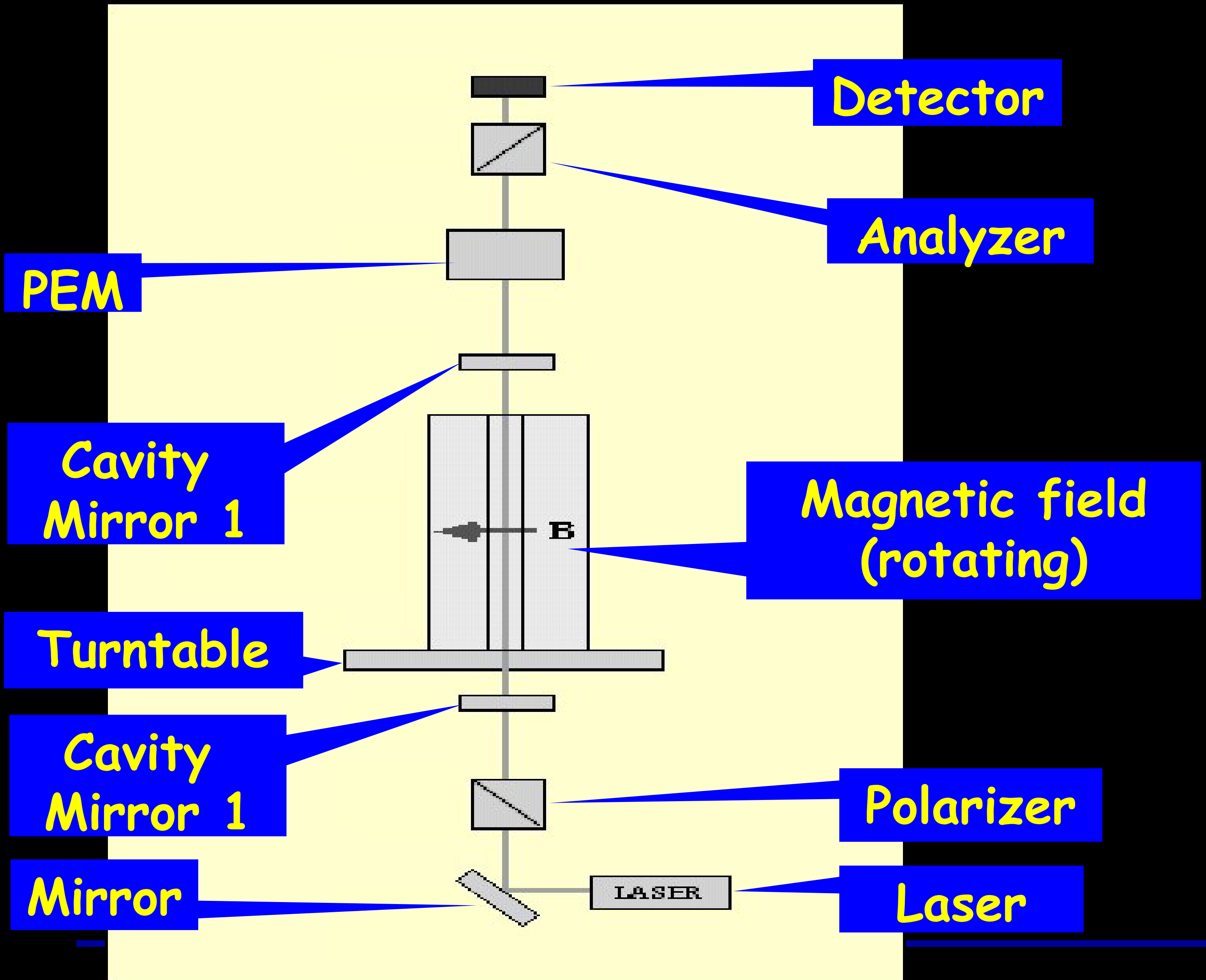
DESY

PVLAS:
An unexpected Result

The Experiment

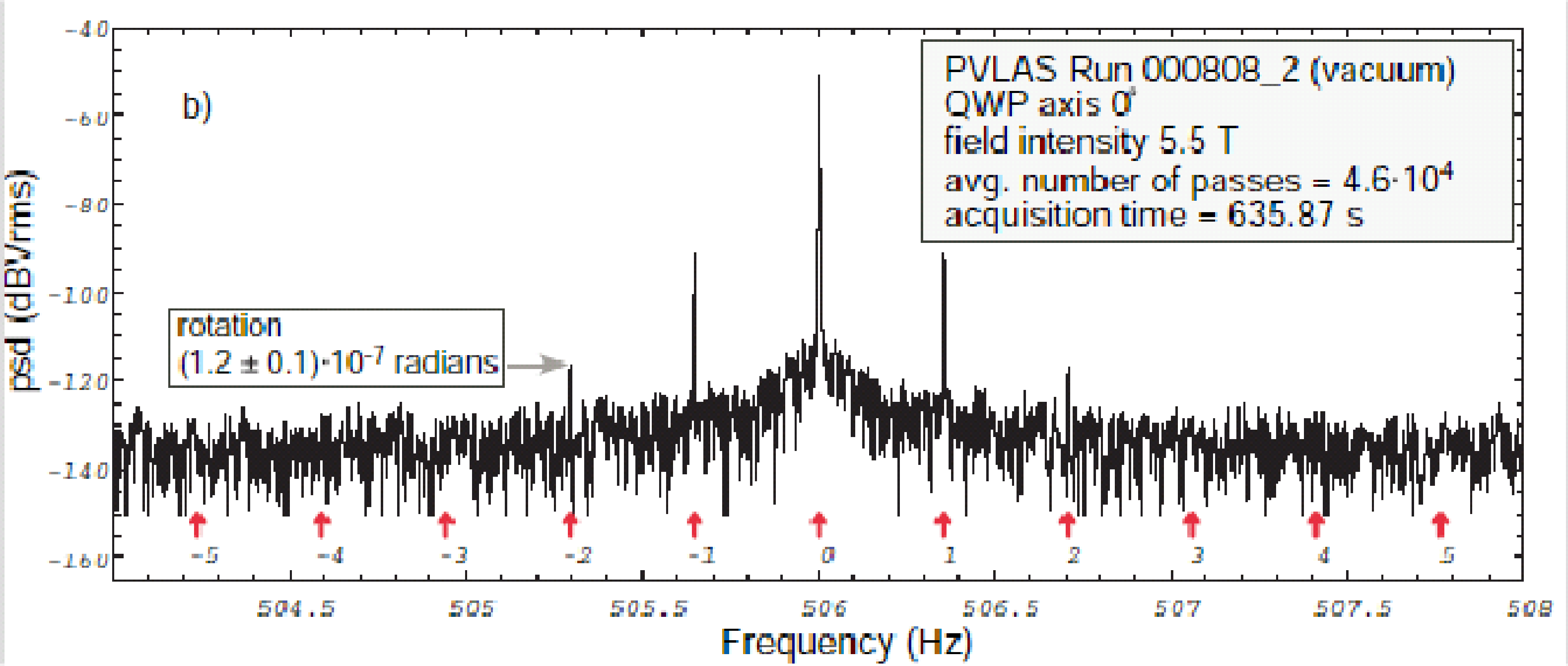


Goal

- Measure the change in polarization when light passes through B-field:
  - Rotation of the polarization
  - Ellipticity (phase shift),

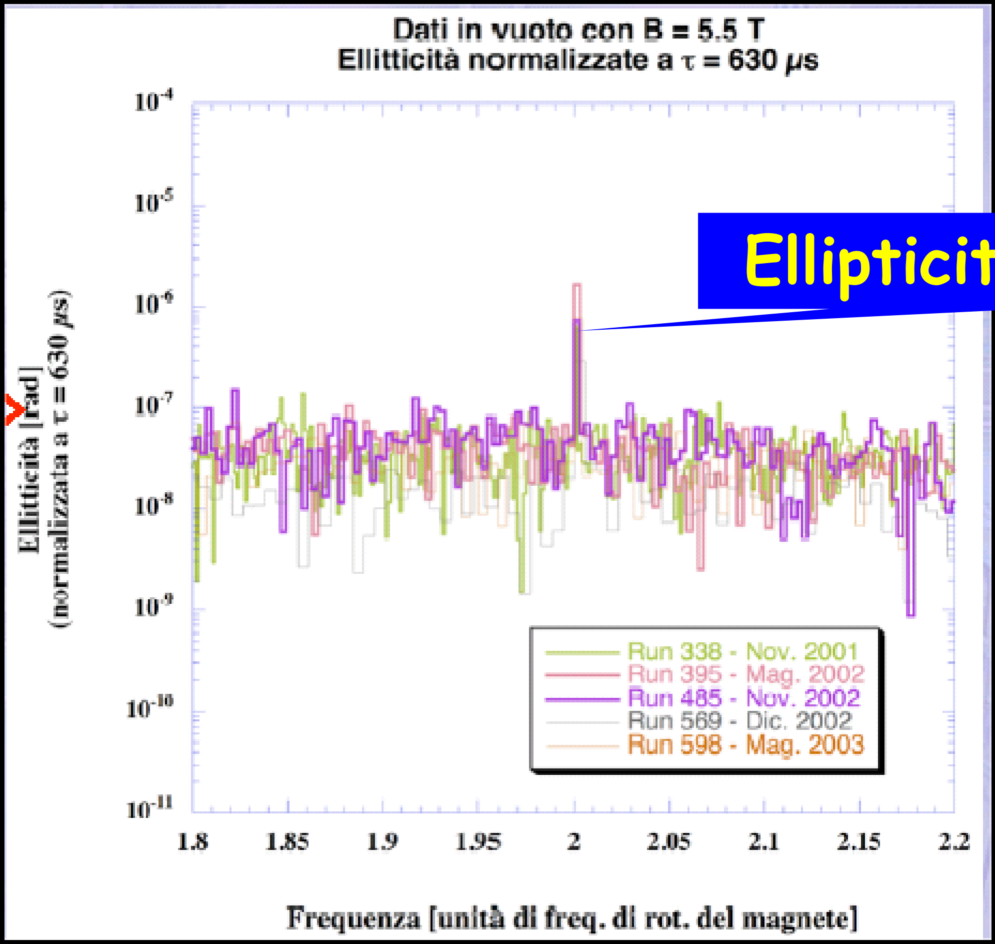
    i.e., linear polarized light is changed into (partly) circular polarized light.

Result (rotation)



$$\frac{\text{rotation}}{\text{pass}} = \frac{\epsilon}{N} \sim 2.6\,10^{-12} rad$$

Result (ellipticity)



B=5.5T
N≈97000

Ellipticity≈ 6 10^{-7} rad

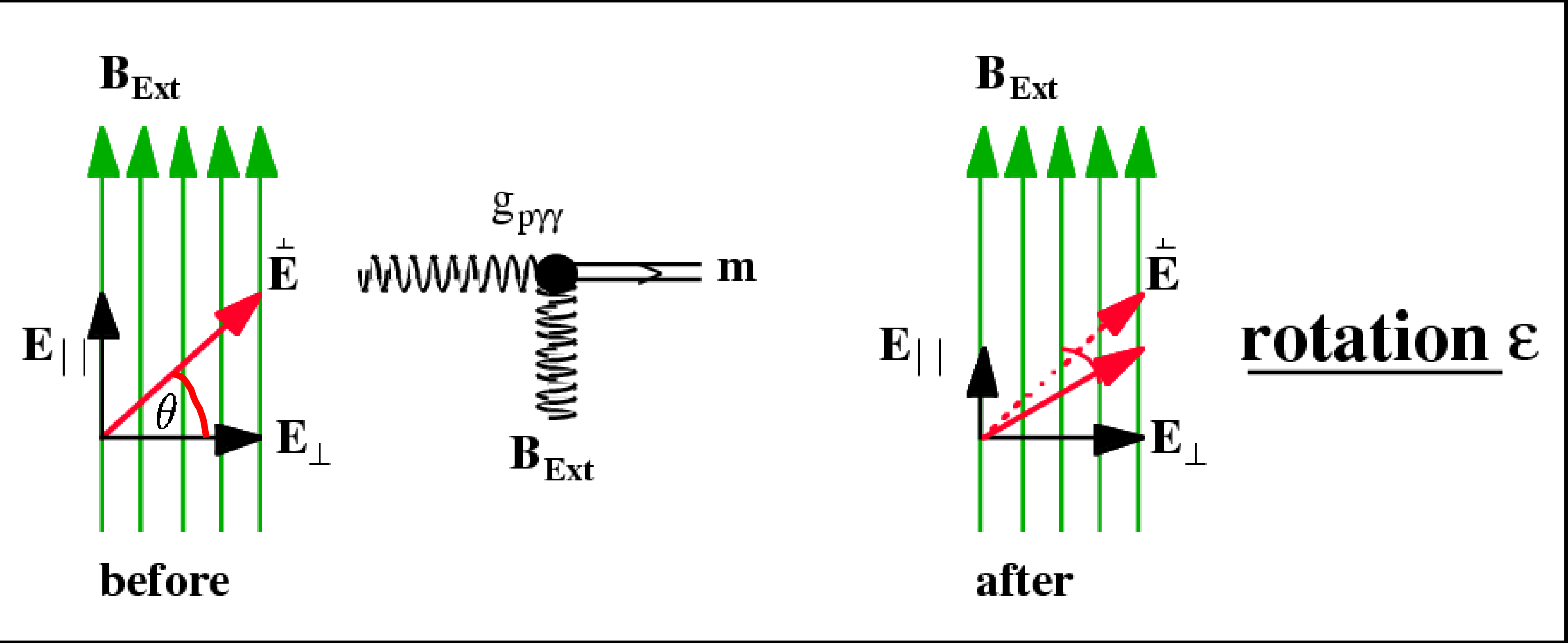
$$\frac{\text{ellipticity}}{\text{pass}} = \frac{\psi}{N} \sim 6\,10^{-12} rad$$

A possible Interpretation

- Photons are converted into light (pseudo-)scalars

Dichroism (Rotation)

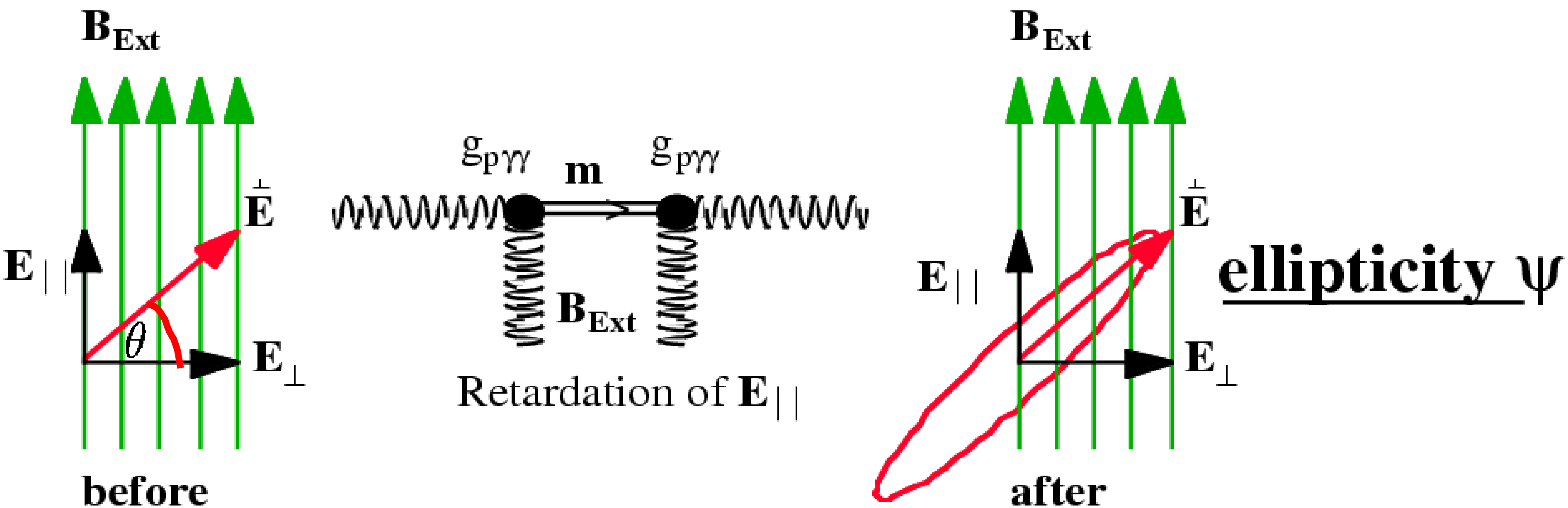
- **Coupling** $\mathcal{L} \sim g a\, F^{\mu\nu} \tilde{F}_{\mu\nu} \sim g a \vec{E} \cdot \vec{B}$



$$\Rightarrow \epsilon \approx -N \left(\frac{gBL}{4} \right)^2 \sin(2\theta)$$

Ellipticity

Virtual ALP production leads to Birefringence



$$\psi \approx \frac{N}{6}\left(\frac{gBL}{4}\right)^2 \frac{m_a^2 L}{\omega}\sin(2\theta)$$

A possible Interpretation

- Photons are converted into light (pseudo-)scalars

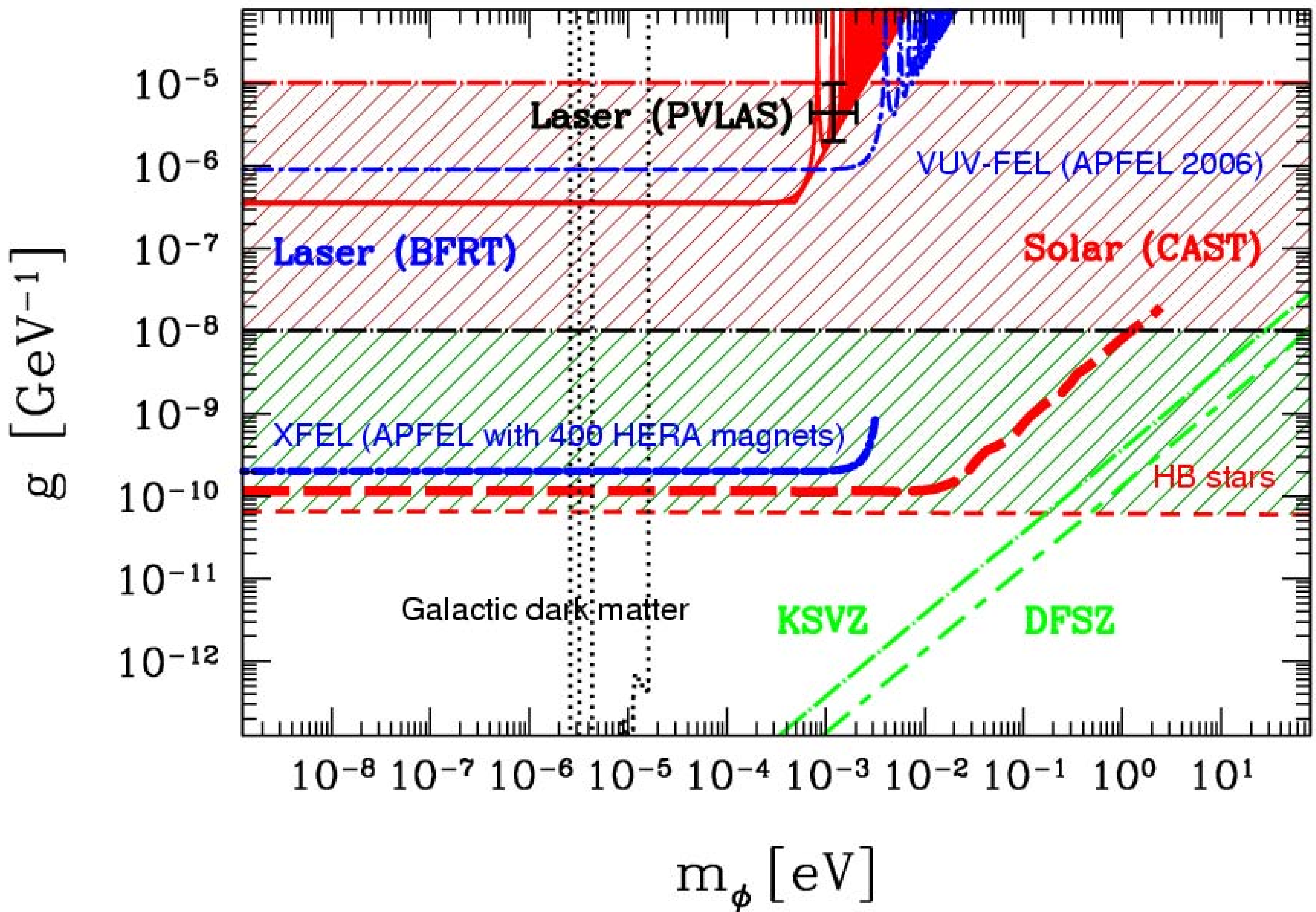
- With mass $m = (1 - 1.5)\,\mathrm{meV}$

$$g = (1.7 - 5) \times 10^{-6}\,\mathrm{GeV}^{-1}$$

0. Overview

- 1. Axions and their Relatives
- 2. Astrophysical Bounds
- 3. PVLAS again
- 4. Evading Astrophysical Bounds
- 5. The future: Light shining through walls
- 6. Conclusions

Overview Picture



1. Axions and their Relatives

The QCD Action

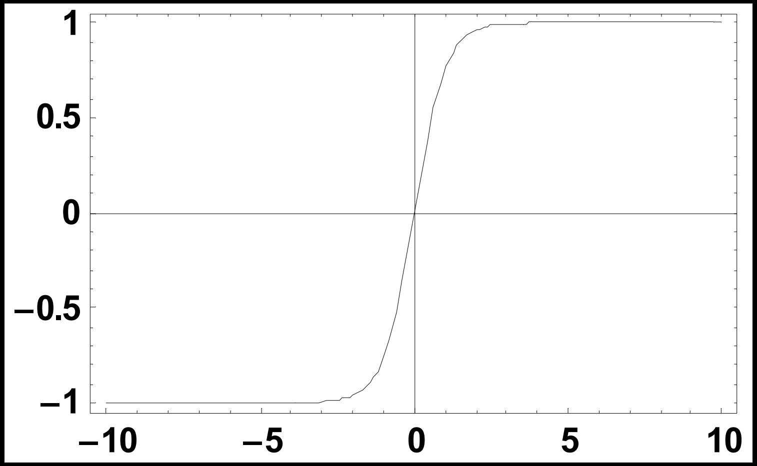
$$S = \int d^4x \Big[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{\theta}{4} F^{\mu\nu} \tilde{F}_{\mu\nu} + \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \Big]$$

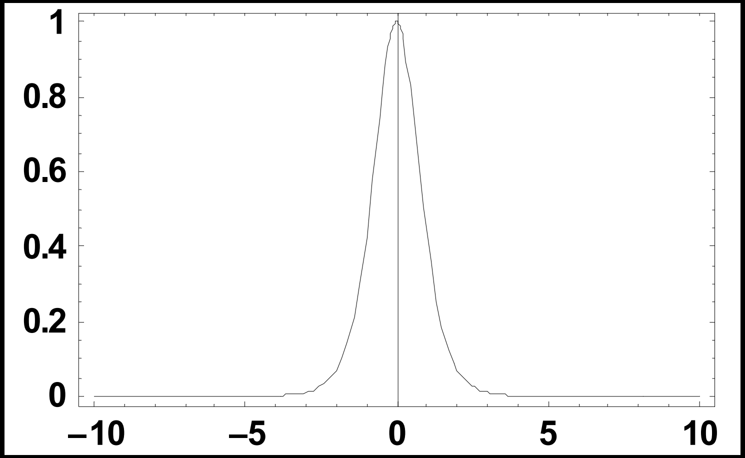
- The θ-term is a total divergence!
- That does not mean it can be neglected!

⇒ θ has observable consequences!

Boundaries matter! - An analogy

$$\tanh(x) \qquad\qquad \frac{d}{dx}\tanh(x)$$





$$\int_{-\infty}^{\infty} dx \frac{d}{dx}\tanh(x) = 2 \neq 0$$

Boundary terms can not always be neglected!

It's CP violating

- The θ-term violates CP:

$$F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \vec{E}\cdot\vec{B}$$

$$\vec{E} \xrightarrow{P} -\vec{E} \xrightarrow{C} \vec{E} \qquad \vec{B} \xrightarrow{P} \vec{B} \xrightarrow{C} -\vec{B}$$

$$\vec{E} \xrightarrow{CP} \vec{E} \qquad \vec{B} \xrightarrow{CP} -\vec{B}$$

$$\Rightarrow \quad \vec{E}\cdot\vec{B} \xrightarrow{CP} -\vec{E}\cdot\vec{B}$$

θ can be measured

- θ-term is a color singlet!

➡ Search for CP violation in hadrons!

- Electric dipole moment is CP violating!

$$H \sim \vec{d} \cdot \vec{E} \sim q\vec{S} \cdot \vec{E}$$

➡ **Measure EDM of the neutron!**

One finds...nothing

- **Calculation:** $|\vec{d}| \sim 1 - 10 \times 10^{-16} e\, cm\, \theta$
- **Measurement:** $|\vec{d}| < 3\, 10^{-26} e\, cm$

⇒ $|\theta| < 3\, 10^{-10}$

⇒ **Extremely unnatural!**

⇒ **Strong CP Problem!**

The Axion Solution

A Dynamical θ

- **Idea:**
  - Make θ a dynamical degree of freedom a
  - Let a have no tree level potential
  - Let a have only derivative couplings
- **Then:**

$$
\begin{aligned}
\exp\left(-\int_x V(a)\right) &= \left|\int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-\imath \frac{a}{32\pi^2}\int_x F^{\mu\nu}\tilde{F}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \left|\exp\left(-S_{eff}[\phi, A^\mu]\right) \exp\left(-\imath \frac{a}{32\pi^2}\int_x F^{\mu\nu}\tilde{F}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \exp\left(-S_{eff}[\phi, A^\mu]\right) \\
&\leq \exp\left(-\int_x V[0]\right)
\end{aligned}
$$

A Dynamical θ

- Idea:
  - Make θ a dynamical degree of freedom.
  - Let θ have no tree level potential
  - Let θ have only derivative couplings
- Then:

⇒ $V[0] \leq V[a] \;\; \forall a$

⇒ a will evolve to a=θ=0

⇒ CP is conserved

What is a?

- Properties:
  - Let a be a dynamical degree of freedom.
  - Let a have no tree level potential
  - Let a have only derivative couplings

  - $a \in [0, 2\pi]$ since $$\int d^4x \frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{32\pi^2} = n \in \mathbb{Z}$$

⇒ a is Goldstone boson of a U(1) symmetry ⇒ Axion!

Peccei-Quinn Symmetry

- **Toy model:**

$$\mathcal{L} = -\frac{1}{4}F^2 + \imath\bar{\psi}D_\mu\gamma^\mu\psi - |\partial_\mu\phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4$$
$$+\bar{\psi}\left(G\phi\frac{1+\gamma_5}{2} + G^\star\phi^\star\frac{1-\gamma_5}{2}\right)\psi$$

- **U(1):**

$$\phi \to \exp(i\alpha)\phi$$
$$\psi \to \exp\left(-i\frac{\alpha}{2}\gamma_5\right)\psi$$

- **If $\mu^2<0$ we have SSB**

➡ **Phase is Goldstone** ➡ **Use it as Axion**

The Coupling to $F\tilde{F}$

- **Adler-Bell-Jackiw anomaly**

$$\partial_\mu j^\mu = \frac{g^2}{16\pi^2} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

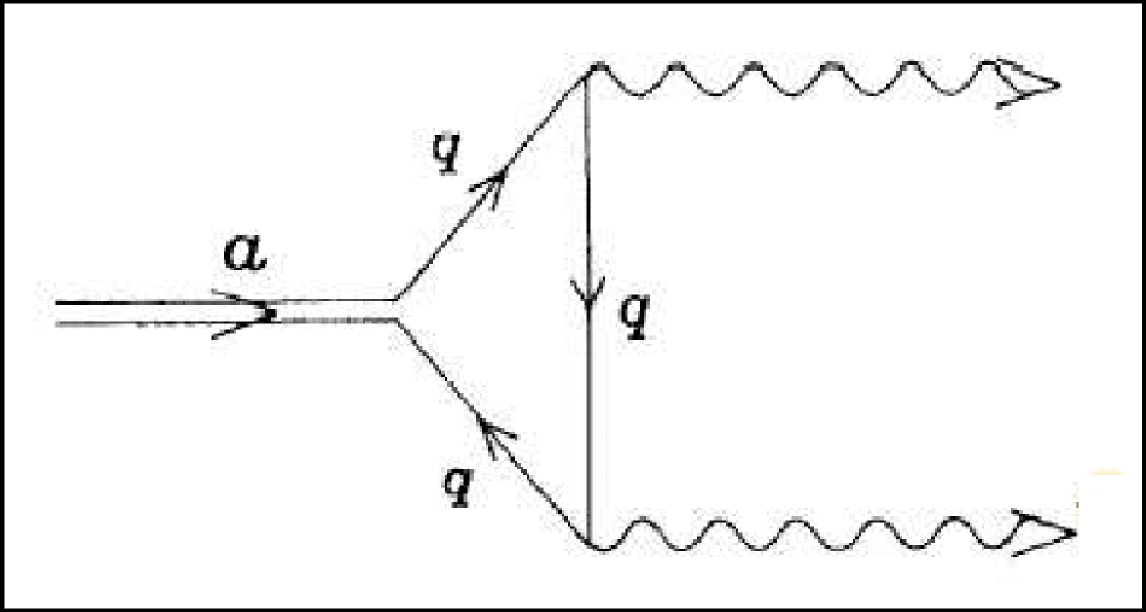
- **Chiral rotations not a good symmetry: it is anomalous**

$$d\mu' = \mathcal{D}\psi'\mathcal{D}\bar{\psi}' = d\mu \exp\left(-1\int_x \frac{\alpha}{2}\frac{1}{8\pi^2} Tr F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$$

$$\psi' = \exp\left(-i\frac{\alpha}{2}\gamma_5\right)\psi$$

The Coupling to $F\tilde{F}$

- A diagram



The mass of the Axion

- $U(1)_{PQ}$ is not exact

⇒ Goldstone → Pseudogoldstone

- Dimensional considerations
  - SSB scale $\sim f_X$
  - Coupling to $F\tilde{F}$: $\sim \frac{a}{f_X} F^{\mu\nu}\tilde{F}_{\mu\nu}$
  - Scale of explicit breaking $\frac{1}{f_X}\langle F^{\mu\nu}\tilde{F}_{\mu\nu}\rangle \sim \frac{\Lambda^4}{f_X}$

⇒ Goldstone mass $m_a^2 \sim \frac{\Lambda^4}{f_X^2}$

The Coupling to $F_{em}\tilde{F}_{em}$

- Analog to F_{strong} coupling (anomaly)
- Differs by a factor of roughly α
- More precisely, with

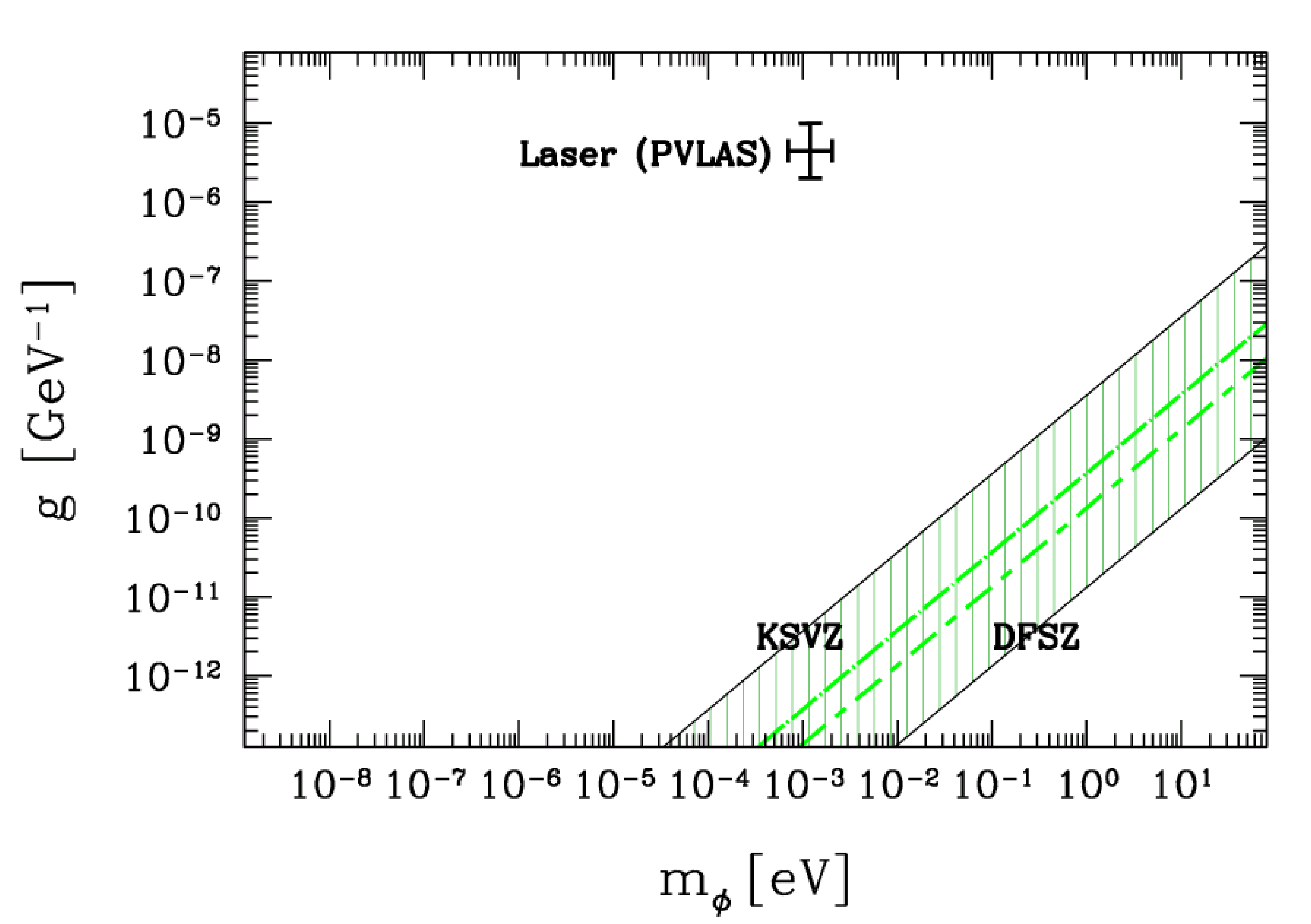
$$\mathcal{L}_F = gaF^{\mu\nu}\tilde{F}_{\mu\nu}$$

- Relation between M and m_a:

$$m_a g^{-1} = \mathcal{O}(1)\frac{\pi}{\alpha}m_\pi f_\pi \frac{\sqrt{m_u m_d}}{m_u + m_d}$$

(model dependent)

The Coupling to $F_{em}\tilde{F}_{em}$



The Relatives: ALPs

- Pseudoscalars: not very creative...

  ...Simply throw away m-g-relation

- Scalars: as above but with coupling to F_{em}^2 instead of $F_{em}\tilde{F}_{em}$

Commercials

Your CP is violated to strongly?

An electric dipole moment is generated by messy θ-term effects?

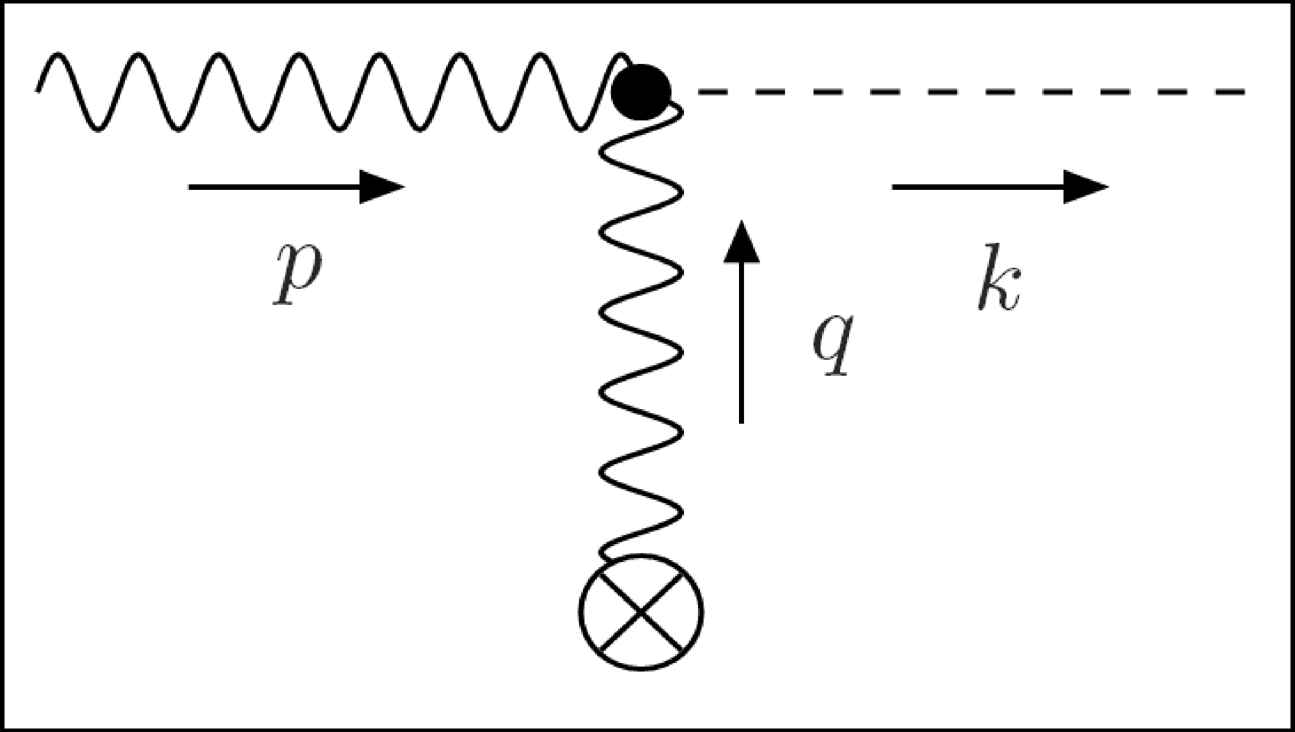
Use Axion!

New! With special cleaning particles and extra strong photon coupling.

2. Astrophysical Bounds

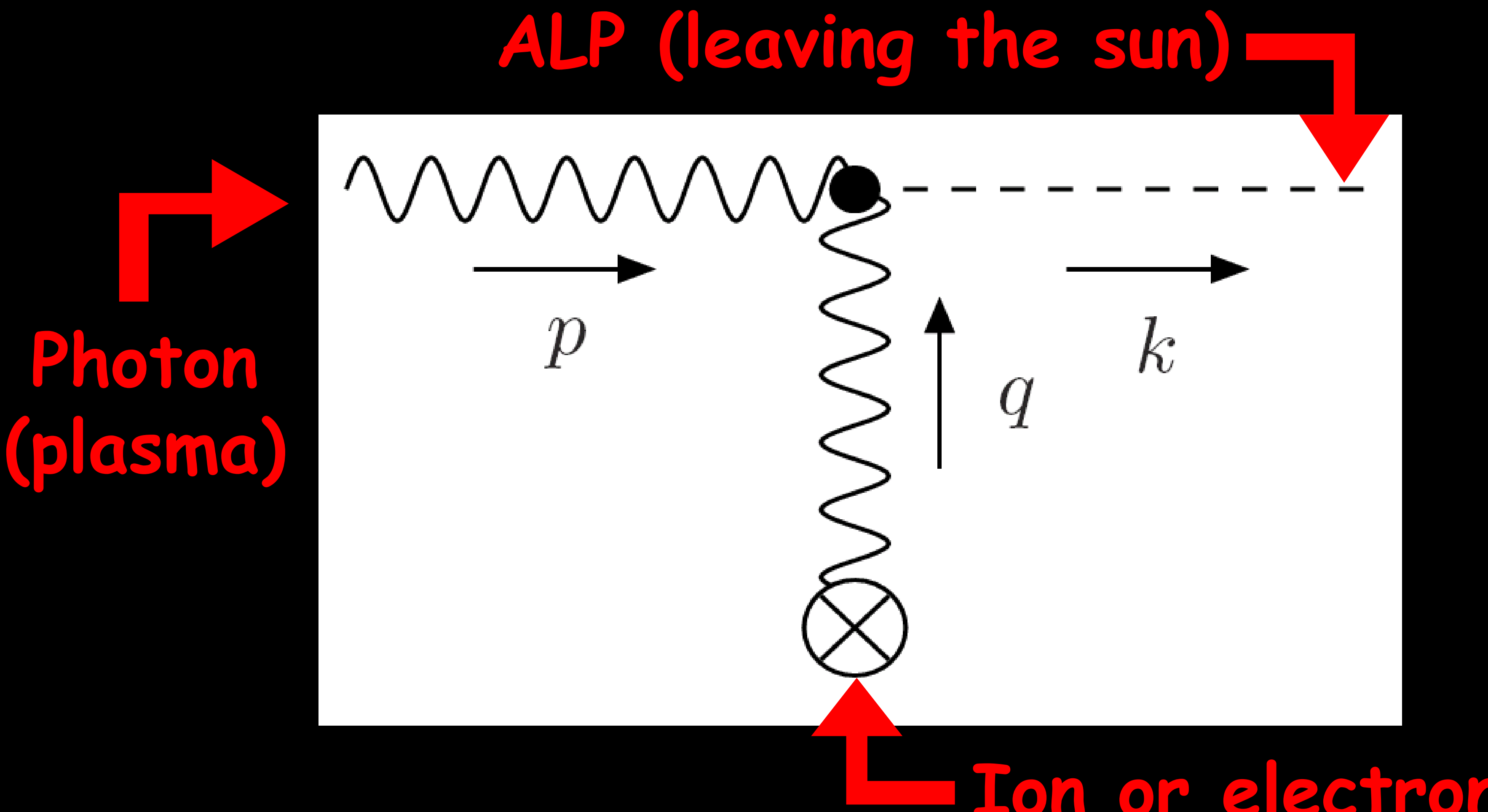
Tests are based on $F_{em}\tilde{F}_{em}$ coupling

- Primakoff proces



Tests are based on $F_{em}\tilde{F}_{em}$ coupling

- Primakoff process (in the sun)



We would freeze...

- If the coupling g is too large the sun would have died long ago.
- Why?

Axions can leave the sun without further interaction (in contrast to photons)

➡ Large energy loss from axion emission

➡ Sun burns fuel faster

➡ Sun would have died long ago

A (Very) Moderate Bound

- Without ALPs sun has fuel for about 10^{10} years
- Energy loss via Alps:

$$L_a \approx 1.7\,10^9 (g\,10^4 \mathrm{GeV})^2 L_\gamma$$

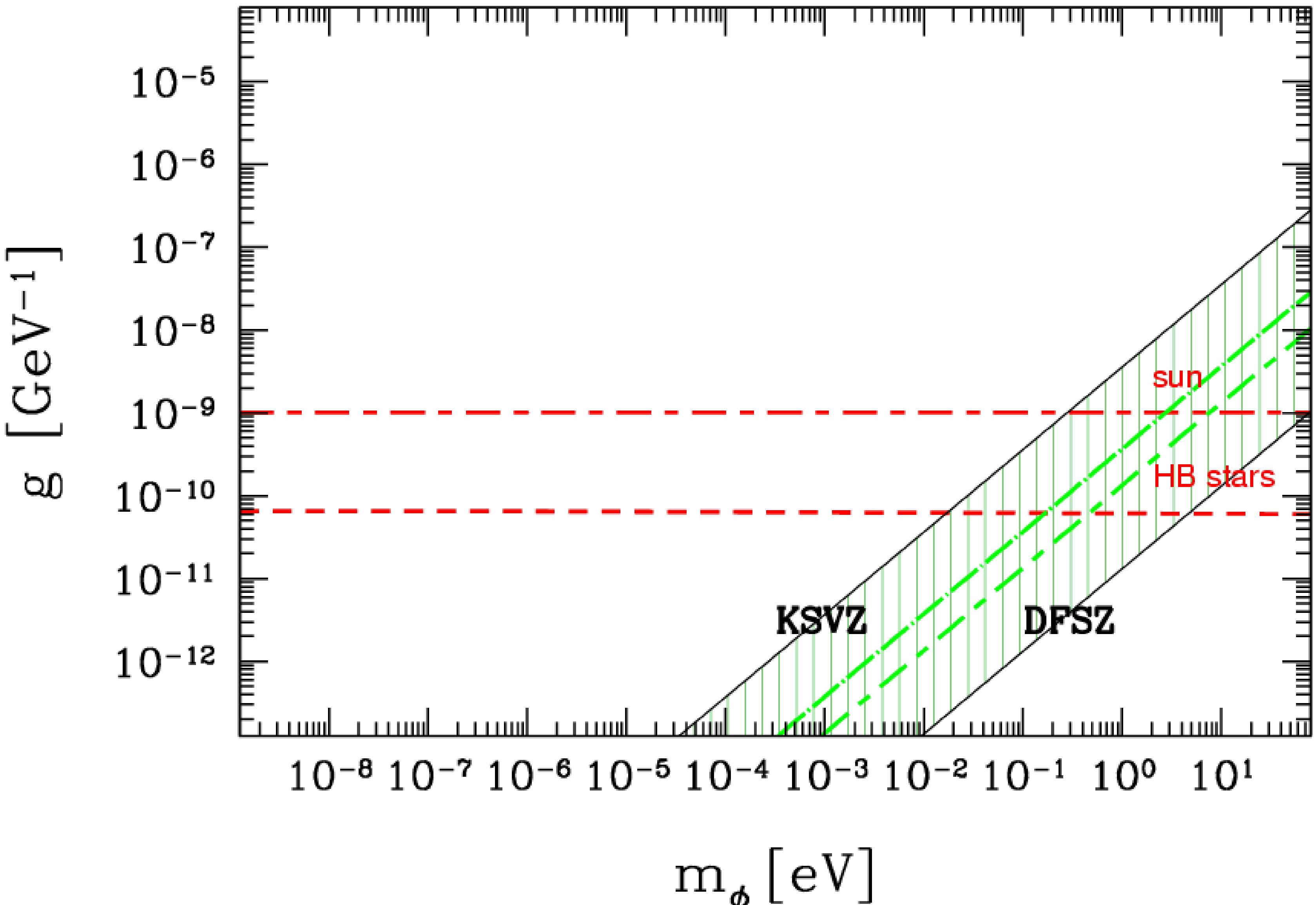
- Sun Lifetime with ALPs

$$t_{sun} \sim \frac{10\,years}{(g\,10^4\,\mathrm{GeV})^2}$$

- Pretty sure sun has been around for more than 10 years

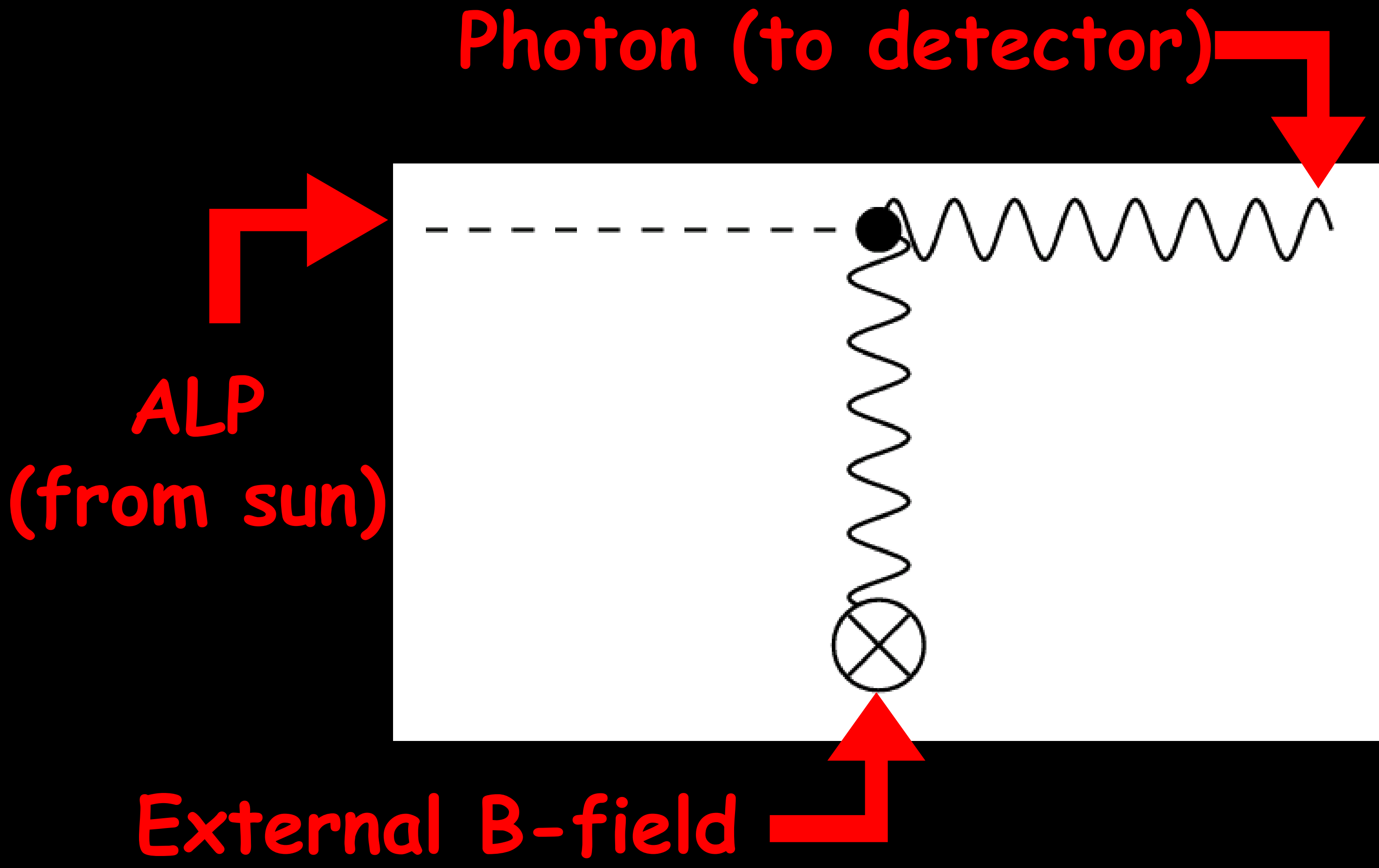
$$\Rightarrow \quad g \leq 10^{-4}\,\mathrm{GeV}^{-1}$$

Bound from Star Lifetimes



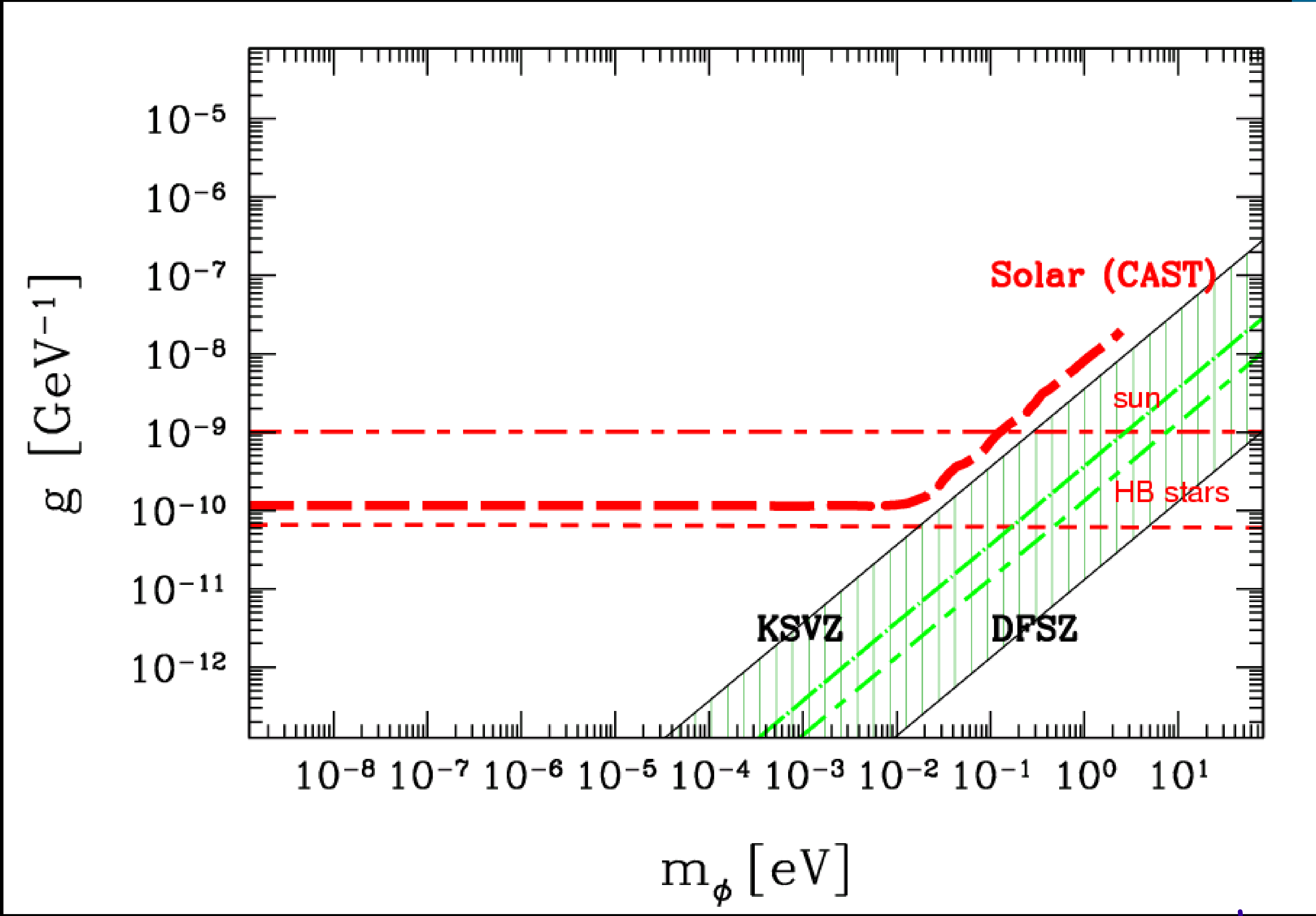
Regeneration

- Primakoff goes the other way around



CAST

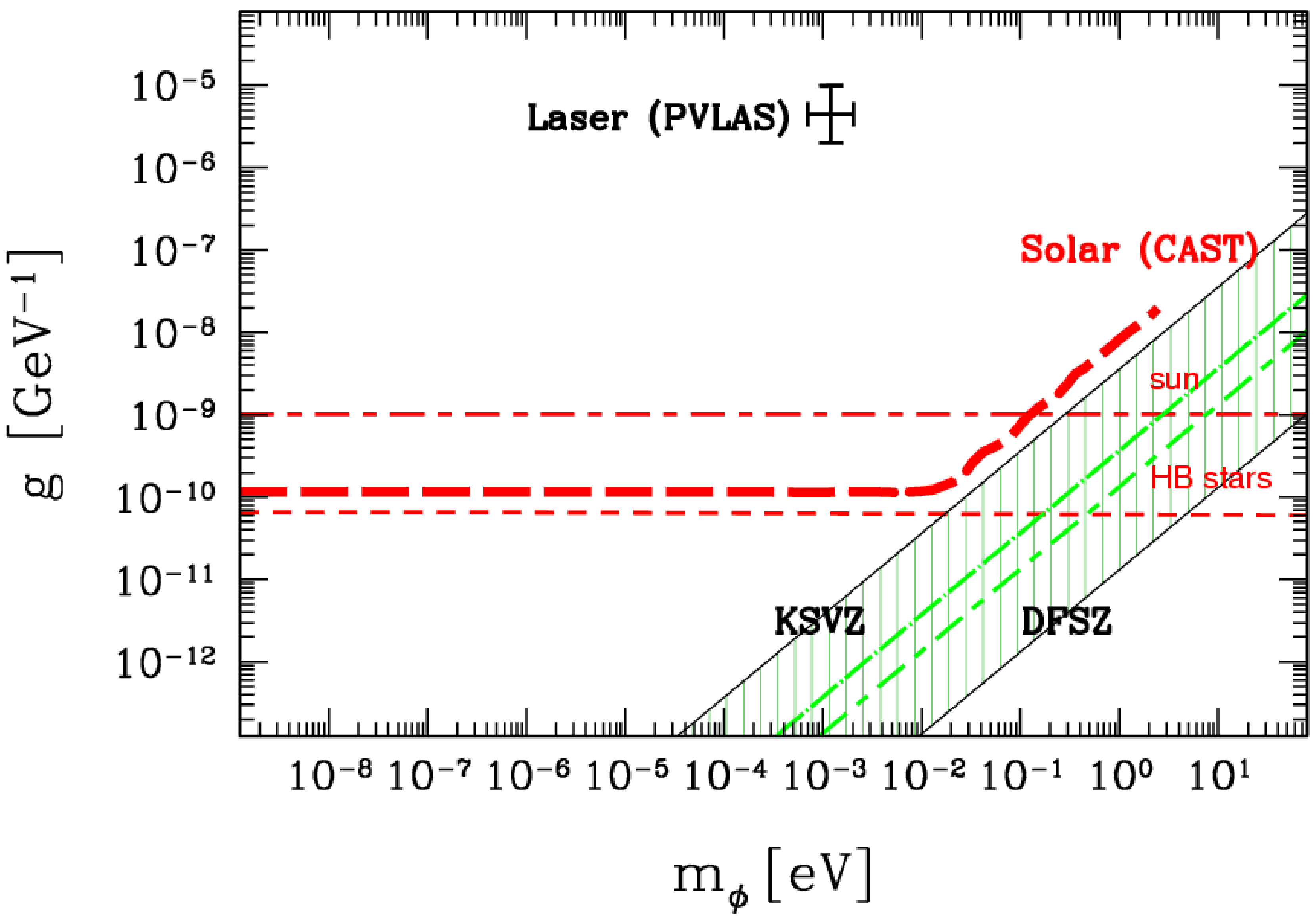
CAST bound



Solar (CAST)
sun
HB stars
KSVZ
DFSZ
g [GeV⁻¹]
m_φ [eV]
10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹

3. PVLAS

PVLAS Result



Problem

- ALP interpretation of PVLAS in severe conflict with astrophysical bounds

Can we reconcile these results?

4. Evading Astrophysical bounds

Be careful: Highly Speculative!

Two Basic Ideas

- 1. Trap the ALPs in the sun (like γ's) (ALPs interact many times before leaving the sun)
  - Prevents excessive energy loss
  - Prevents detection via CAST
    - Smaller number of ALPs emitted
    - Emmitted ALPs have lower energy
- 2. Suppress production in the sun

Suppress Production

- Idea: In the center of the sun the environment is different from a lab environment.
  - High temperature
  - Large virtuality q^2
  - High density (compared to vacuum)
  - Large $F^{\mu\nu}$ in Primakoff prozess
  - High neutrino flux

Phenomenological Approach

- Simplest phenomenological approach: Make ALP-parameters environment dependent

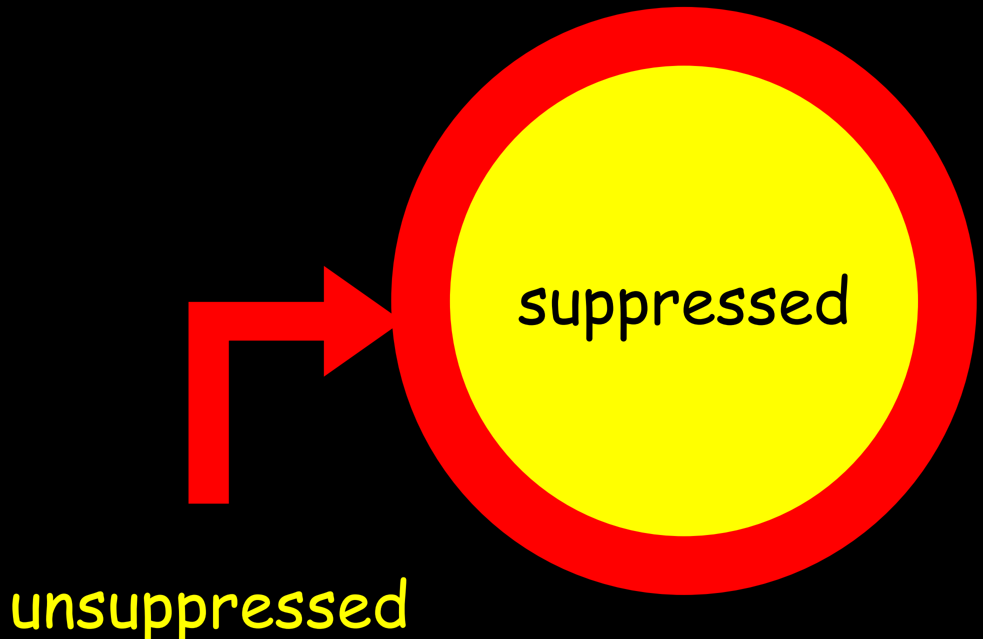
$$m_a \to m_a(\text{environment}), \quad g \to g(\text{environment})$$

$m_a > T$ forbids production kinematically

g small suppresses production via the coupling

Radial suppression

- Since $\rho, T, \langle F \rangle, j_\nu$ depend only on the radius this suppresses production up to a certain radius



X

How much suppression needed?

- The coupling compatible with PVLAS is $g^{-1}_{\mathrm{PVLAS}} \sim 10^5\,\mathrm{GeV}$

- Lifetime argument: $g^{-1}_{\mathrm{life}} \sim 10^{10}\,\mathrm{GeV}$

$$\mathrm{Production} \sim g^2 \quad \Rightarrow \quad S \sim \frac{g^2_{\mathrm{life}}}{g^2_{\mathrm{PVLAS}}} \sim 10^{-10}$$

- CAST: $g^{-1}_{\mathrm{CAST}} \sim 10^{10}\,\mathrm{GeV}$

$$\mathrm{Production} \times \mathrm{Regeneration} \sim g^4$$

$$\Rightarrow \quad S \sim \frac{g^4_{\mathrm{life}}}{g^4_{\mathrm{PVLAS}}} \sim 10^{-20}$$

Is the Sun Extreme?

- At 0% Radius: $T \sim 1.5\ 10^7 K \approx 1200 eV$

  $\rho \sim 150\ g/cm^3$

  $\langle|q|\rangle \gtrsim 290 eV$

  At 79% Radius: $T \sim 1.4\ 10^6 K \approx 117 eV$

  $$S \sim 10^{-4}$$

  $\rho \sim 9.8\ 10^{-2} g/cm^3$

  $\langle|q|\rangle \gtrsim 9 eV$

  At 97% Radius: $T \sim 1.5\ 10^5 K \approx 12.5 eV$

  $$S \sim 10^{-20}$$

  $\rho \sim 3\ 10^{-3} g/cm^3$

  $\langle|q|\rangle \gtrsim 1.4 eV$

➡ The absolute values for T, ρ in the sun are far from extreme!

Compared to PVLAS

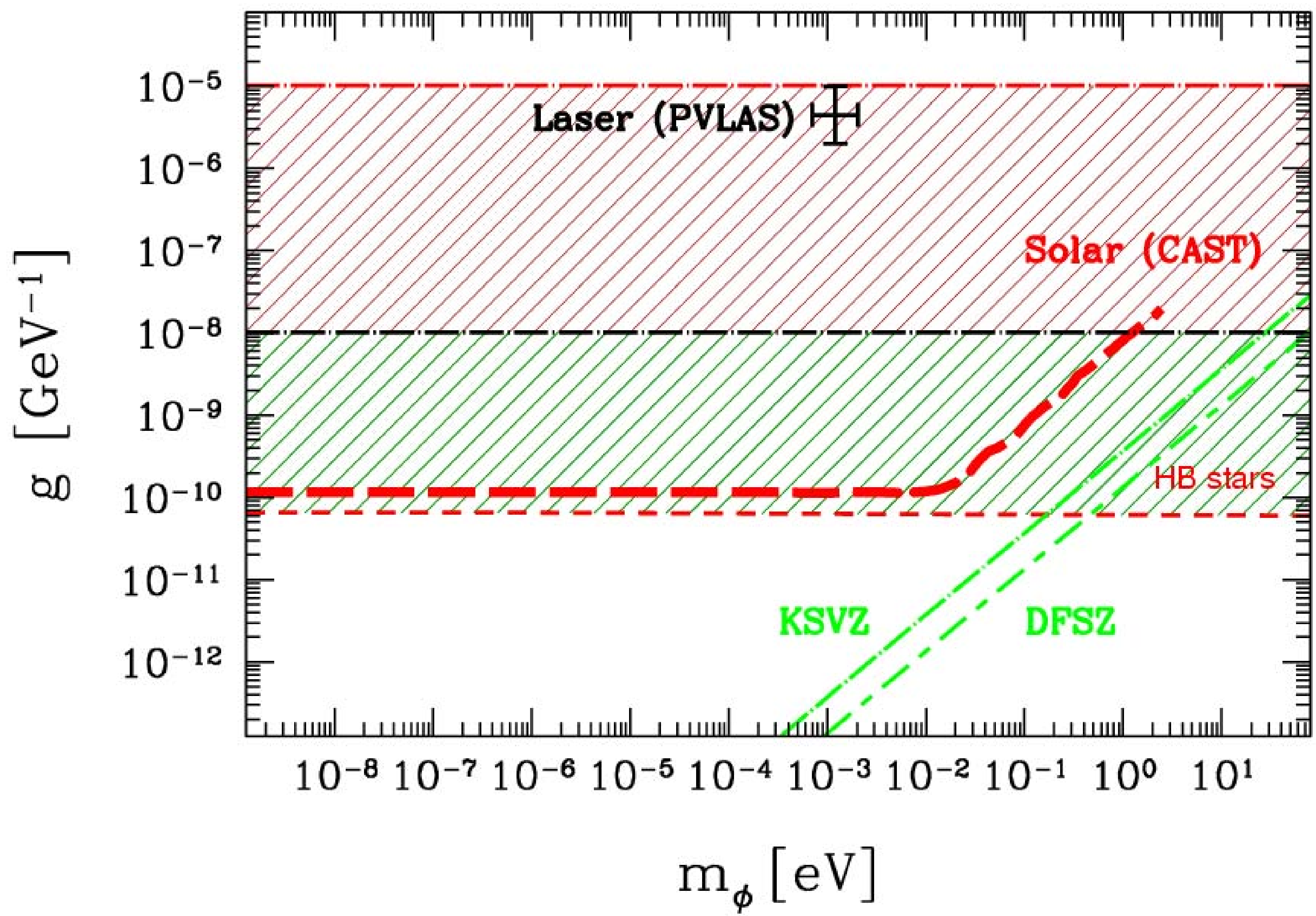
- Density up to $\lesssim$ 2 10^{-5}g/cm^3
- Temperature T$\lesssim$ 300K$\sim$ 0.025eV
- $|q| \sim 10^{-6}$eV

⇒ Compared to the environment of PVLAS:
The sun is hot and dense!
And the average |q| is high.

⇒ Room for exotic possibilities!!!

X

Wiggling Room



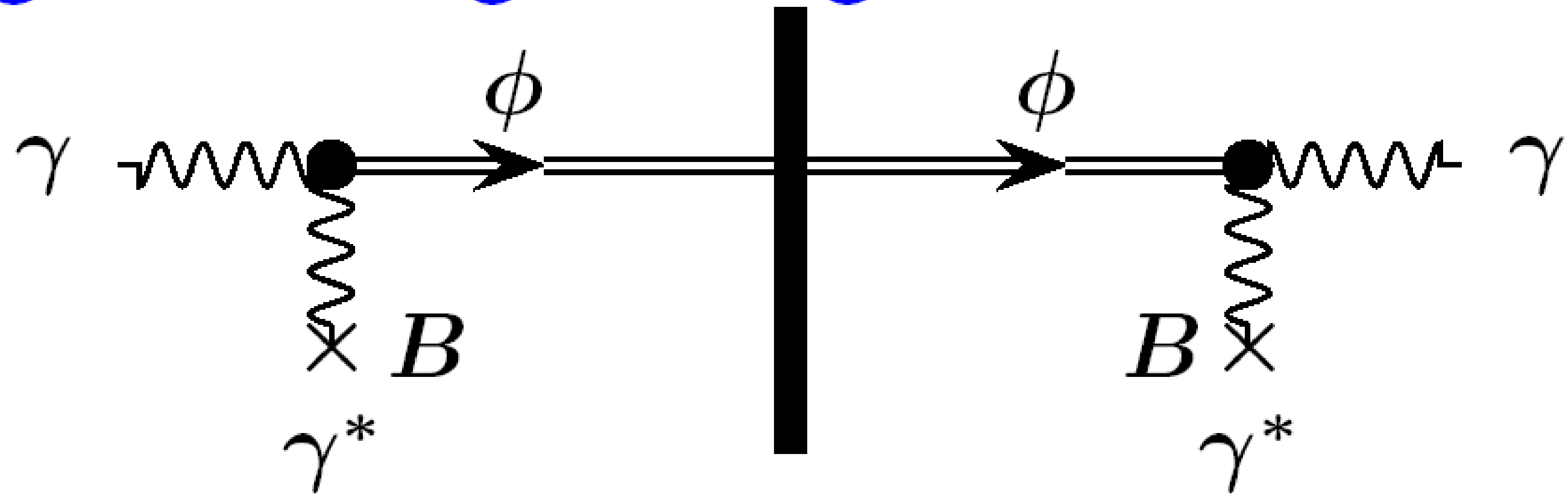
We need

Lab Experiments

5. The Future: Light Shining through Walls

Light shining through walls

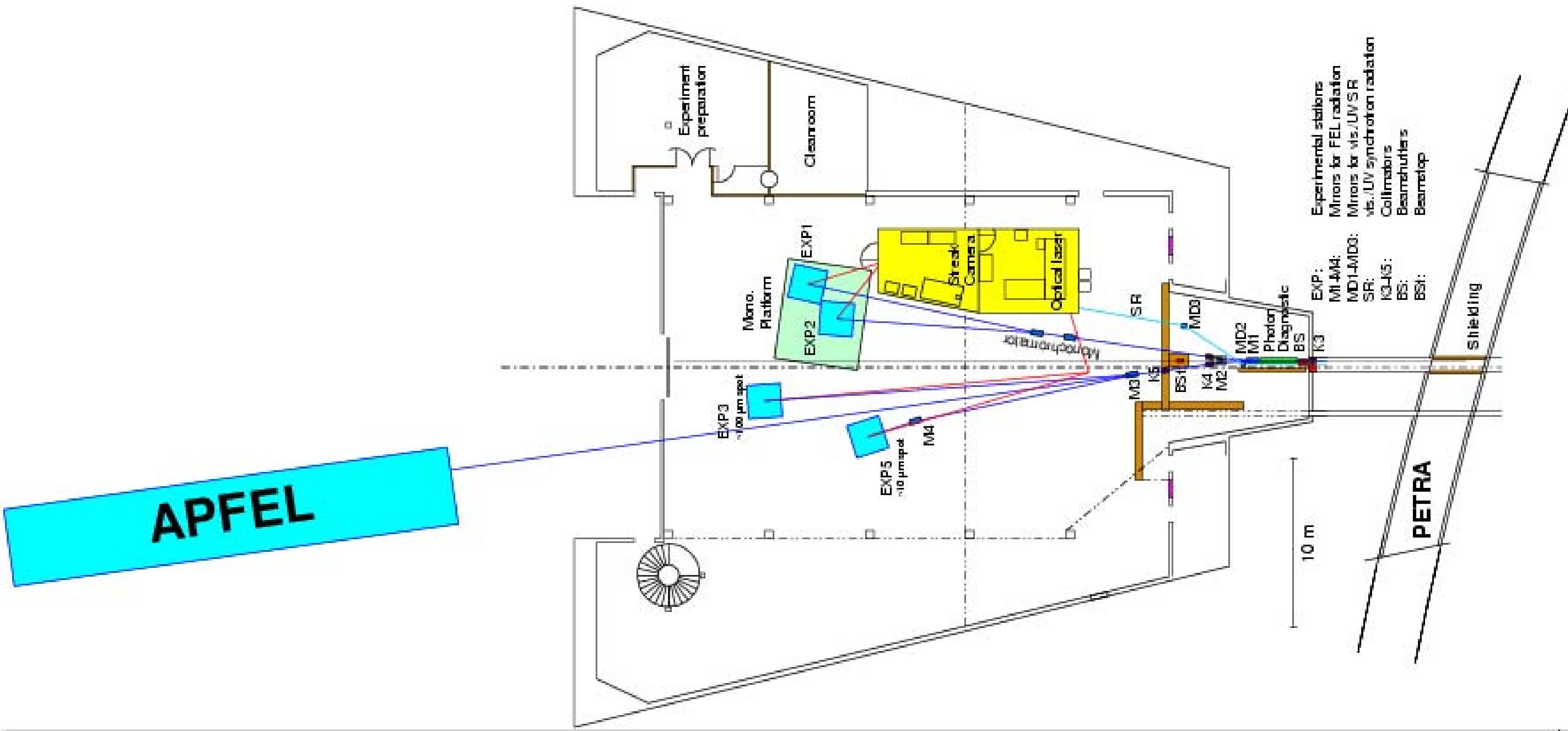
"Light shining through a wall"



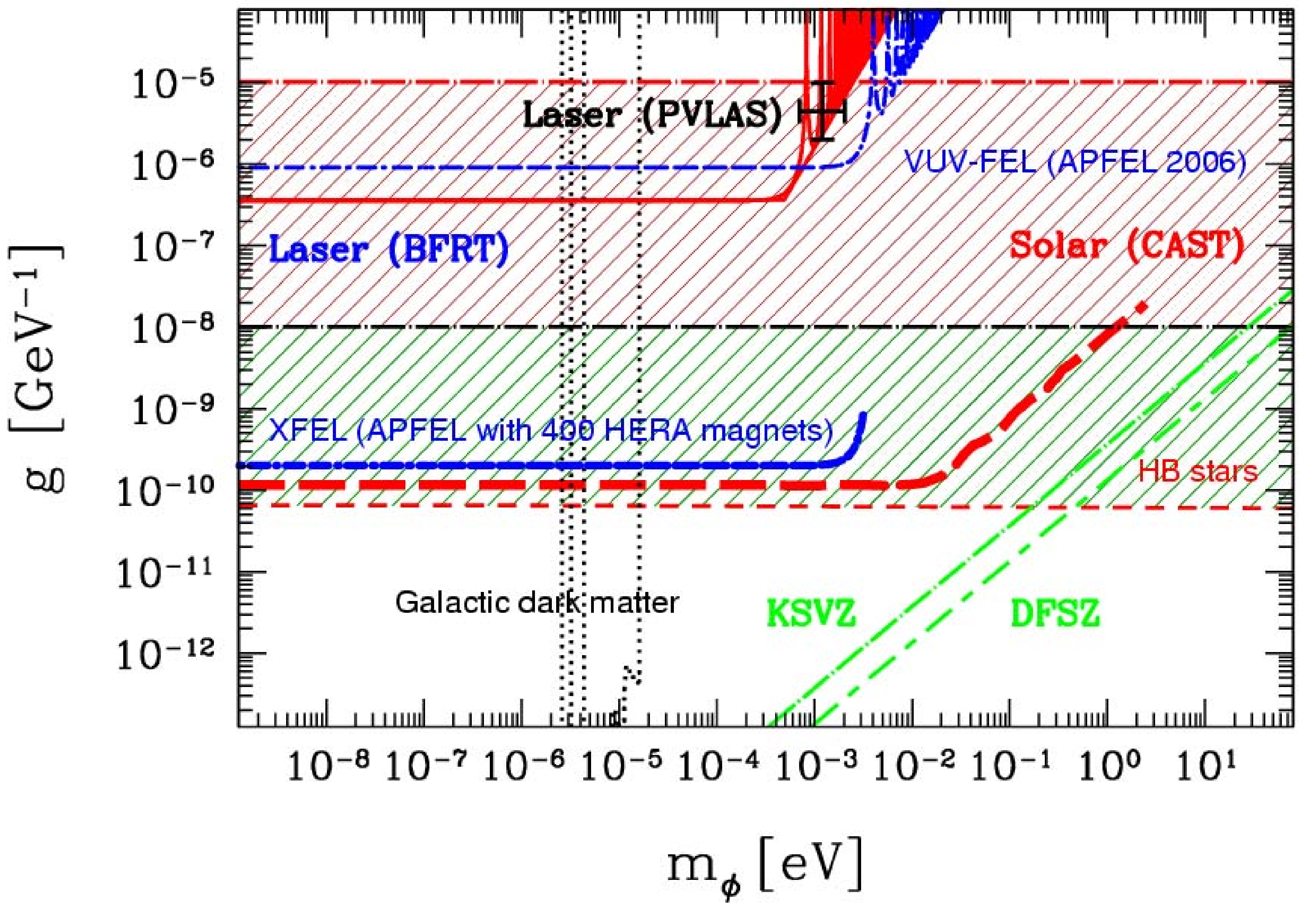
- VUV-FEL + Accelerator Magnets
- XFEL + Hera Magnets

An Accelerator Magnet

APFEL@DESY

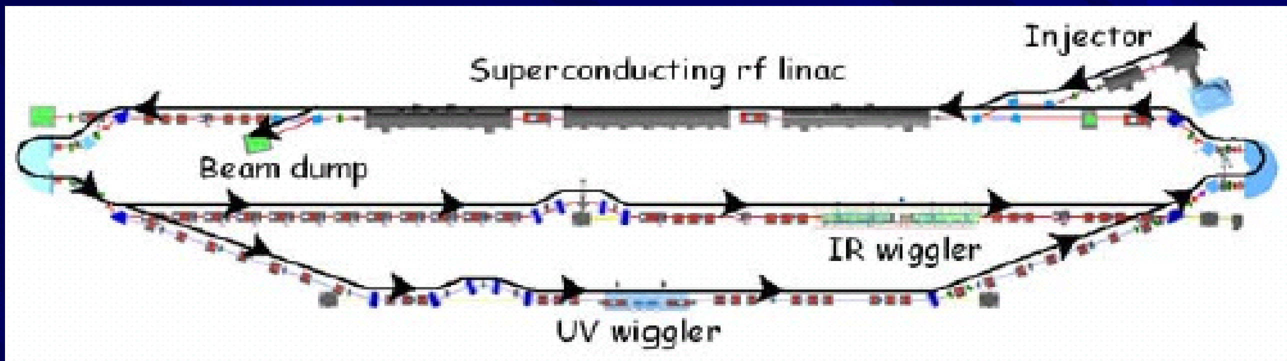

APFEL
PETRA
10 m
Shielding
Experiment preparation
Cleanroom
Optical laser
Streak Camera
Mono. Platform
EXP1
EXP2
EXP3
EXP5
M4
Monochromator
SR
MD3
MD2
M1
M3
K5
BS1
K4
M2
K3
BS
Photon Diagnostic
EXP: Experimental stations
M1-M4: Mirrors for FEL radiation
MD1-MD3: Mirrors for vis./UV SR
SR: vis./UV synchrotron radiation
K3-K5: Collimators
BS: Beamshutters
BSt: Beamstop

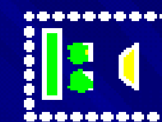
Can Test PVLAS



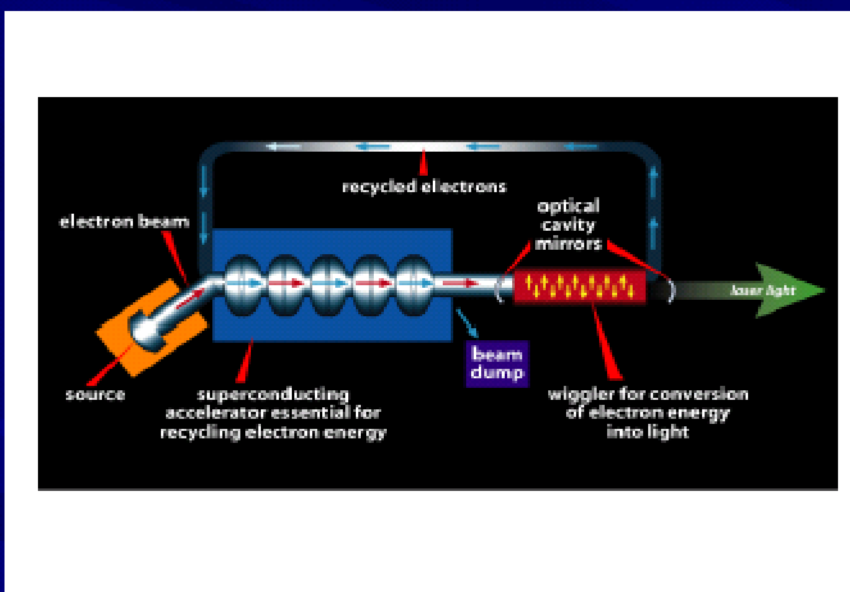
The competition is'nt sleeping...

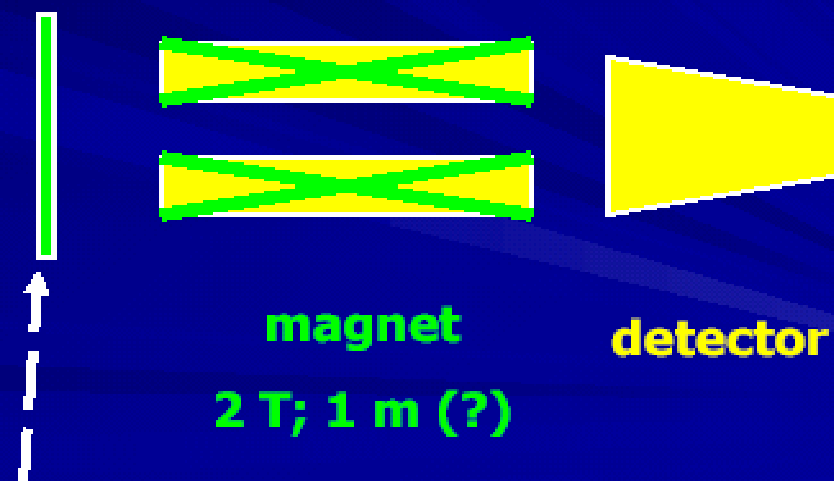
JLAB FEL setup I: regeneration experiment





"parasitic "

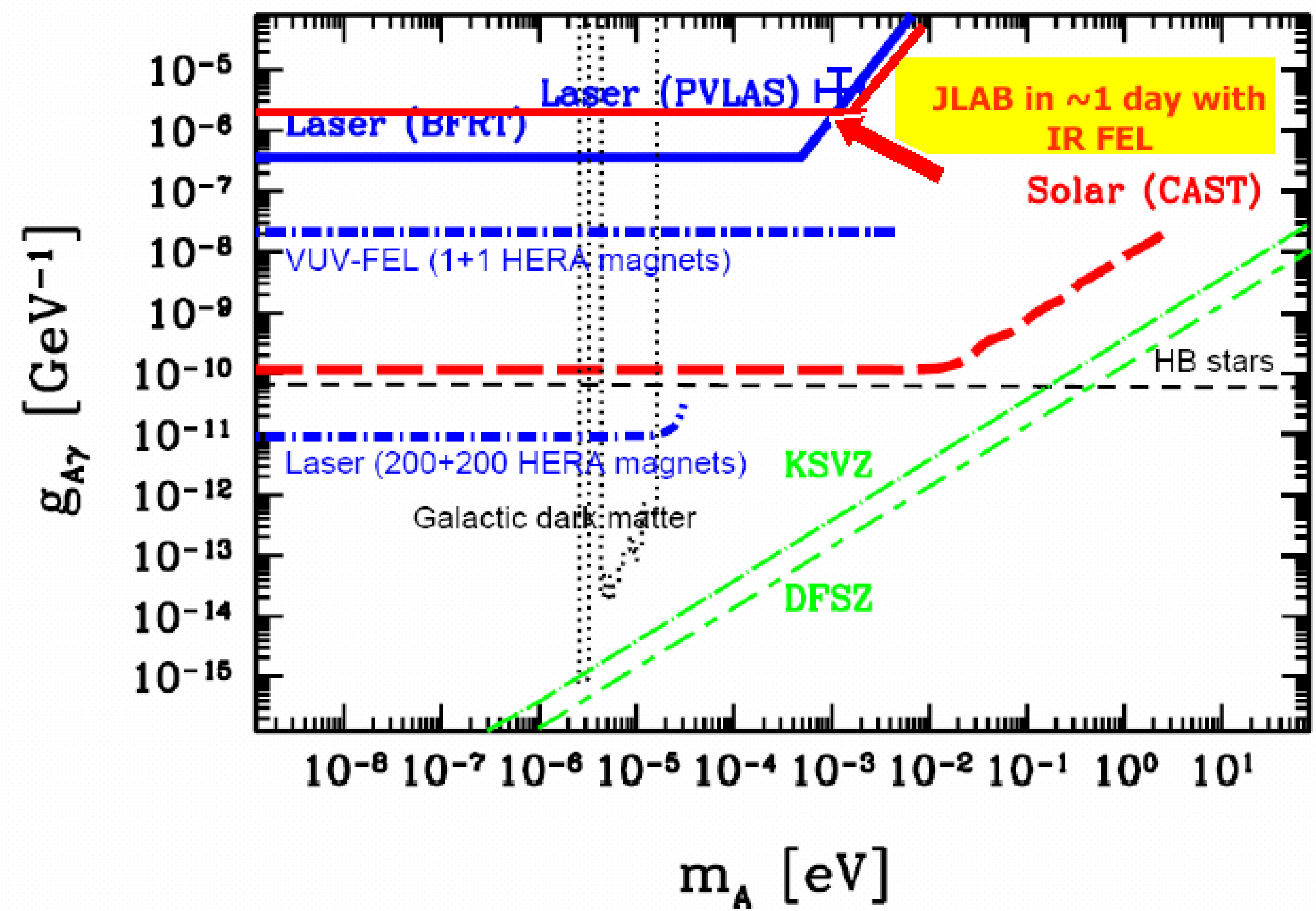




ϕ's produced at JLAB FEL

light shield

Their sensitivity...



6. Conclusions

Conclusions

- Axions are a good solution to the strong CP problem
- Astrophysics provide strong bounds on light bosons coupled to two photons
- PVLAS may have detected an ALP but is in conflict with astrophysics
- Might be possible to evade astrophysical bounds

Near future lab experiments are able to test interesting regions for ALPs

In motion everything is...
Difficult to see is the future...
Uncertain it is...

...exciting it is.