Axions, WIMPs and WISPs

Bottum-Up Approach

Markus Ahlers

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5th Patras Workshop
13-17 July 2009, Durham

Motivation I: *What's the problem?*

✘ Standard Model of **particle physics** has some *shortcomings*, notably

- neutrino masses
- stabilization of the weak scale
- flavor structure (mixings and masses)
- unification with gravity
- absence of strong $\mathcal{CP}$ violating terms
- ...

✘ Further *puzzles* from **cosmology**:

- dark matter and dark energy (or alternative 'accelerators')
- baryogenesis, inflation, initial conditions
- ...

✘ More recently, some *new puzzles* from **astrophysics**:

- anomalous contributions of anti-matter and gamma rays
- (*N.B.*: We have still the old problems though!)
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⋆ 'Model-Building' approach

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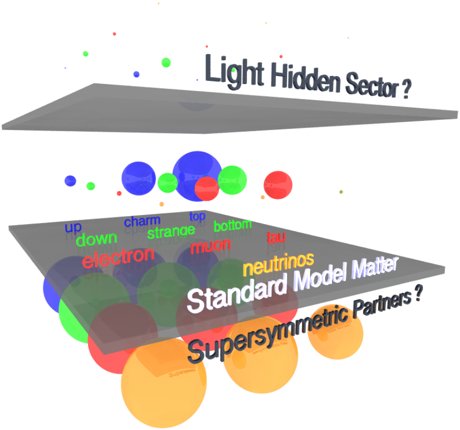
Motivation II: *Testability*

✔ Many solutions to these problems predict a *plethora of additional particles and forces*.

(➜ talks by J. Conlon & M. Goodsell)

➜ 'hidden' by feeble interaction with matter and/or mass thresholds



★ 'Phenomenological' approach:

- interaction guided by gauged and global symmetries
- simple test scenarios from laboratory experiments, astrophysics and cosmology

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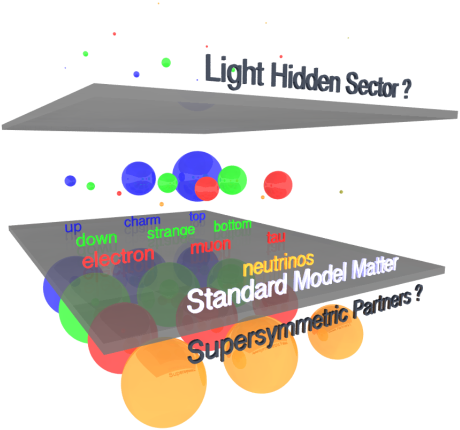

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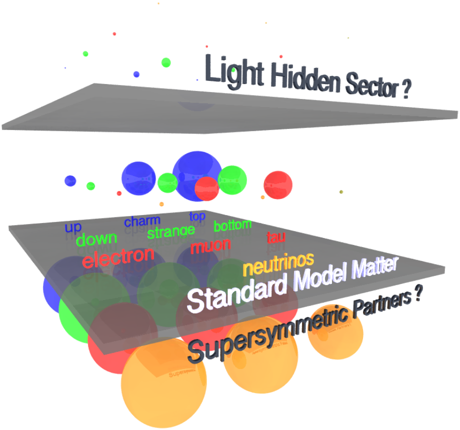
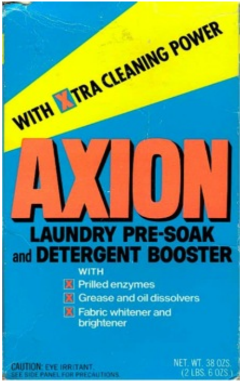


Due to lack of time (and personal bias), I will mainly focus on **Axions** and other **WISPs**.

[WIMPs ➜ talks by L. Covi, A. Jenkins, J. Read & L. Roszkowski]

Axions and their Relatives



Strong $\mathcal{CP}$ Problem

- Instanton action in non-abelian gauge theories: ['t Hooft'76]

$$\int \mathrm{d}^4x\,\mathcal{L}_\theta = \frac{\theta}{16\pi^2}\int \mathrm{d}^4x\,\mathrm{tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu} = \theta\int \mathrm{d}^4x\,\partial_\mu K^\mu = \theta\mathbf{Z}$$

➜ Non-trivial vacuum structure ('θ-vacuum'): [Callan/Dashen/Gross'76;Jackiw/Rebbi'76]

$$|\theta\rangle = \sum_{-\infty}^{\infty}\exp(-i\theta n)|n\rangle \qquad \left(\Delta n = \int \mathrm{d}^3x\,K^0\right)$$

➜ 'θ-vacuum' is not invariant under chiral transformation; invariant quantity:

$$\bar{\theta} = \theta + \arg\det M$$

- $\bar{\theta}$-angle observable; limits from electric dipole moment of the neutron:

$$|d_n| < 2.9\times10^{-26}e\mathrm{cm} \quad \Rightarrow \quad |\bar{\theta}| \lesssim 10^{-11}$$

[Baker et al.'06]

➜ **Why do the contributions in $\bar{\theta}$ cancel to such a precision?**

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Peccei-Quinn Solution (in a nutshell)

- Introduce a **global chiral symmetry** $U(1)_{\rm PQ}$ which is spontaneously broken at the scale f_a. [Peccei/Quinn'77]

$$\Phi \to \frac{f_a + \phi}{\sqrt{2}} e^{ia/f_a}$$

- **Axion** a – the pseudo-Goldstone boson of the broken symmetry – transforms as [Weinberg'78;Wilczek'78]

$$a \to a + \alpha f_a$$

- Effective Lagrangian contains $U(1)_{\rm PQ}$ breaking terms due to QCD and QED chiral anomalies.

$$\mathcal{L}_a = -\frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{\rm int}\left[\frac{\partial_\mu a}{f_a};\psi\right] + \left(\bar\theta + \mathcal{N}\frac{a}{f_a}\right)\frac{\alpha_s}{4\pi}\,{\rm tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + \mathcal{E}\frac{a}{f_a}\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

➜ Elliminate $\bar\theta$-term by a shift $a \to a' \equiv a - \bar\theta f_a/\mathcal{N}$.

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Peccei-Quinn Solution (in a nutshell)

- **Axion mass** (determined by current algebra): [Weinberg'78]

$$m_a \simeq \frac{f_\pi m_\pi}{f_a/\mathcal{N}} \frac{\sqrt{z}}{1+z} \simeq 6\,\mathrm{meV}\left(\frac{10^9\,\mathrm{GeV}}{f_a/\mathcal{N}}\right)$$

$$(z \equiv m_u/m_d \simeq 0.56 \quad f_\pi \simeq 93\,\mathrm{MeV} \quad m_\pi \simeq 135\,\mathrm{MeV})$$

- **Coupling to photons**:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a\, F^{\mu\nu}\tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a\, \mathrm{E}\cdot\mathrm{B}$$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a/\mathcal{N}}\left[\frac{2}{3}\frac{4+z}{1+z} - \frac{\mathcal{E}}{\mathcal{N}}\right]$$

➜ effective parameters:

$\mathcal{E}/\mathcal{N}$: ratio of QED and QCD anomalies

$f_a/\mathcal{N}$: effective $U(1)_{\mathrm{PQ}}$ breaking scale

Axion Models

✘ **PQWW** model ($f_a \simeq v \simeq 246$ GeV): [Peccei/Quinn'77;Weinberg'78;Wilczek'78]

SM + second Higgs doublet;
ruled out *e.g.* by kaon and Υ decay ($K^+ \to \pi^+ + a$ & $\Upsilon \to \gamma + a$) [Bardeen et al.'87]

✔ 'Invisible Axion' models ($f_a \gg v$):

- **DFSZ**(-type) models: [Dine/Fisher/Srednicki'81;Zhitnisky'80]

  SM + second Higgs doublet + electroweak scalar;

  $\mathcal{E}/\mathcal{N} = 8/3 \quad \left(= \frac{2}{3}\frac{4Q_{\rm PQ,u}+Q_{\rm PQ,d}+3Q_{\rm PQ,e}}{Q_{\rm PQ,u}+Q_{\rm PQ,d}}\right)$;

- **KSVZ**(-type) models: [Kim'79;Shifman/Vainshtein/Zakharov'80]

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  $\mathcal{E}/\mathcal{N} = 0 \quad (= 6Q^2_{\rm em})$;

- **Composite** models: [Kim'85]

  SM + confining 'axiquarks' in (anti-)fundamental representations of $SU(N)$;

  $\mathcal{E}/\mathcal{N} = 6(Q^2_{Y,\mathbf{3}} - Q^2_{Y,\mathbf{1}})$;

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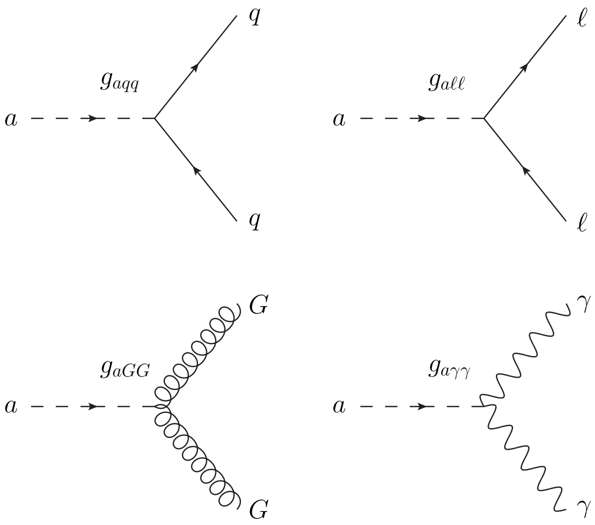
How ‘invisible’ is the Axion?

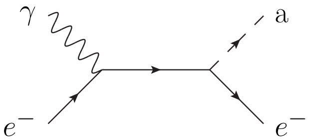
Axion coupling to SM particles:



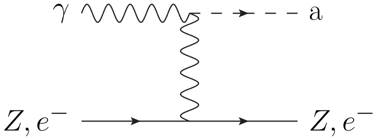
How ‘invisible’ is the Axion?

Important Astrophysical Processes:

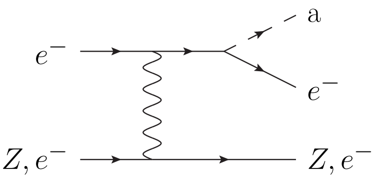
Compton-like Scattering



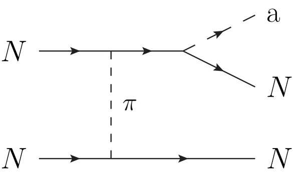
Primakoff Process



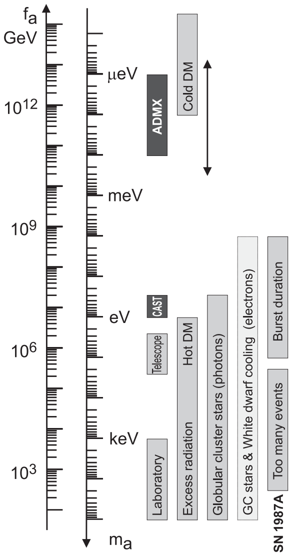
Axion Bremsstrahlung ($g_{a\ell\ell}$)



Axion Bremsstrahlung (g_{aNN})



Direct and Indirect Bounds



[PDG'08]

- Stellar Evolution [e.g. Raffelt'86]
  - Solar Age, Solar Model, Helioseismology [Schlattl&Raffelt'98]
  - White Dwarves (g_{aee}) [Raffelt'86;Isern et al.'08]
  - SN 1987A (g_{aNN}) [Ellis/Olive'87;Turner'88;Raffelt'06]
  - Globular Cluster Stars [Raffelt'86;Raffelt&Dearborn'87]
- Solar Axion Emission
  - Axion Helioscopes [Sikivie'83,'84]
  - Bragg Diffractive Scattering [Buchmüller&Hoogeveen'90]
- Axion Dark Matter
  - Overclosure of Universe
  - Structure Formation [Hannestad&Raffelt'03;Hannestad et al'05]
  - Axion Decay [Bershady et al.'91;Grin et al.'06]
  - Axion Haloscopes [Sikivie'83,'84;Bradley et al.'03]
- Laboratory Experiments
  - Regeneration, Vacuum Birefringence&Dicroism (more on this later)

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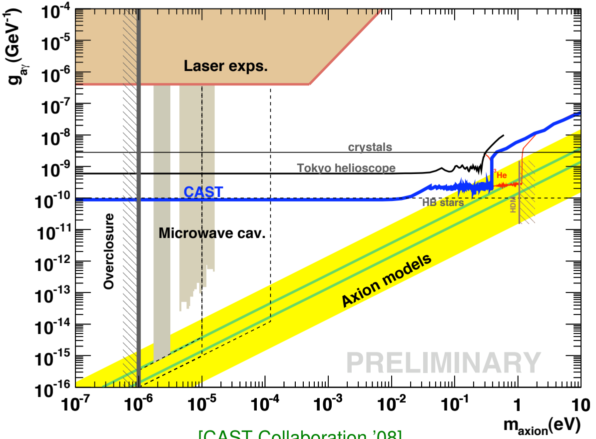
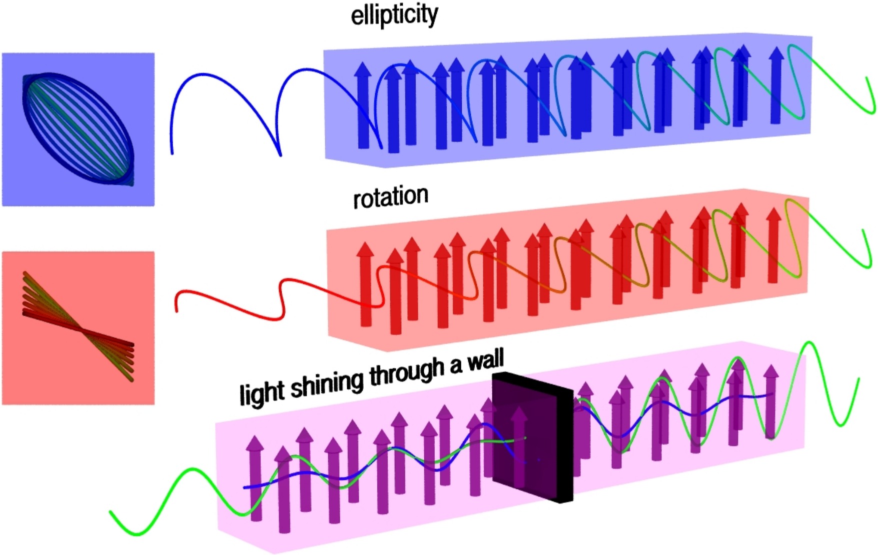


[CAST Collaboration '08]

⋆ ADMX	(➜ talk by G. Rybka)
⋆ Tokio Helioscope	(➜ talk by R. Ohta)
⋆ CAST	(➜ talks by E. Ferrer-Ribas, M. Karuza & K. Jakovcic)

Axion-Like Particles (ALPs) in Laser Experiments



[Okun'82,Sikivie'83,Anselm'85,van Bibber et al.'87,Raffelt&Stodolsky'88]

Axion-Like Particles (ALPs) in Laser Experiments

scalar $\phi^{(+)}$

$$\mathcal{L}_{\rm int}^{(+)} = -\frac{1}{4} g \phi^{(+)} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} g \phi^{(+)} (\vec{E}^2 - \vec{B}^2)$$

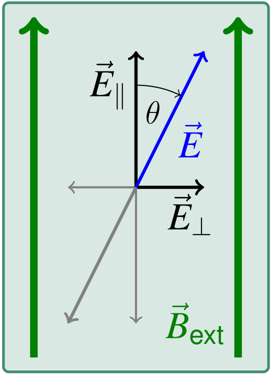
pseudo-scalar $\phi^{(-)}$

$$\mathcal{L}_{\rm int}^{(-)} = -\frac{1}{4} g \phi^{(-)} F_{\mu\nu} \widetilde{F}^{\mu\nu} = g \phi^{(-)} (\vec{E} \cdot \vec{B})$$

parameters:

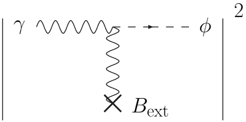
mass m_ϕ

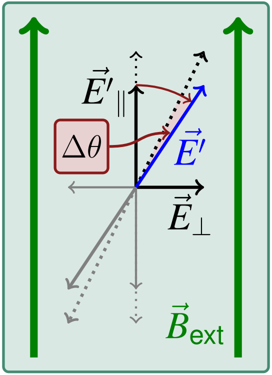
coupling g



Anisotropic light absorption causes a **rotation** $\Delta\theta$ of the polarization plane.

e.g. axion-like particles:





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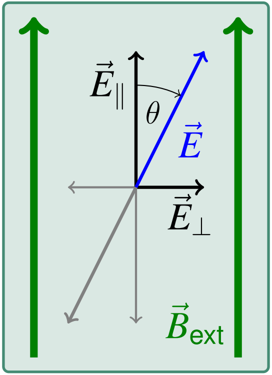

Anisotropic speed of light propagation causes a phase shift and **ellipticity** ψ.

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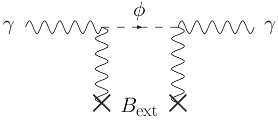

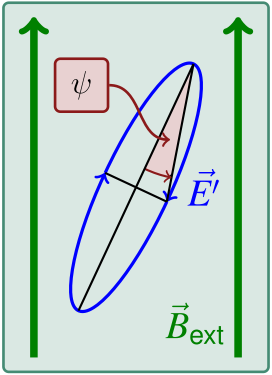

Axion-Like Particles (ALPs) in Laser Experiments

- **ellipticity**:

$$-\psi^{(+)} = \psi^{(-)} = \frac{N_{\text{pass}}}{2}\left(\frac{gB\omega}{m_\phi^2}\right)^2\left(\frac{\ell m_\phi^2}{2\omega} - \sin\left(\frac{\ell m_\phi^2}{2\omega}\right)\right)\sin 2\theta$$

- **rotation**:

$$-\Delta\theta^{(+)} = \Delta\theta^{(-)} = N_{\text{pass}}\left(\frac{gB\omega}{m_\phi^2}\right)^2\sin^2\left(\frac{\ell m_\phi^2}{4\omega}\right)\sin 2\theta$$

- **"light-shining-through-a-wall"** (LSW):

$$\dot{N}^{(-)}_{\gamma\ \text{reg}} = \dot{N}_0\left\lfloor\frac{N_{\text{pass}}+1}{2}\right\rfloor\frac{1}{16}\left(gB\ell\cos\theta\right)^4\left(\frac{\sin\left(\frac{\ell m_\phi^2}{4\omega}\right)}{\frac{\ell m_\phi^2}{4\omega}}\right)^4$$

⋆ typically: $\ell/\omega \simeq \mathrm{m/eV} \simeq (45\mu\mathrm{eV})^2$ and $B\ell \simeq \mathrm{Tesla\,m} \simeq \mathrm{GeV}$ (!)

Laser Experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
ALPS (DESY/D) "**A**xion-**L**ike **P**article **S**earch"	`arXiv:0905.4159`	✘	✘	✔
BFRT (**B**NL-**F**ermilab-**R**ochester-**T**rieste)	Phys.Rev.**D47**(1993)	✔	✔	✔
BMV (LULI/F) "**B**iréfringence **M**agnétique du **V**ide"	Phys.Rev.Lett.**99** (2007) Phys.Rev.D**78** (2009)	✘	✘	✔
GammeV (Fermilab/USA) "**Gam**ma to **meV** particle search"	Phys.Rev.Lett.**100** (2008) Phys.Rev.Lett.**102** (2009)	✘	✘	✔
LIPSS (Jefferson Lab/USA) "**LI**ght **P**seudoscalar or **S**calar particle **S**earch"	Phys.Rev.Lett.**101** (2008) `arXiv:0810.4189`	✘	✘	✔
OSQAR (CERN/CH) "**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration"	Phys.Rev.D**78** (2008)	✘	✘	✔
PVLAS (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
Q&A (Hsinchu/Taiwan) "**Q**ED **&** **A**xion"	Mod.Phys.**A22** (2007)	✔	✘	✘

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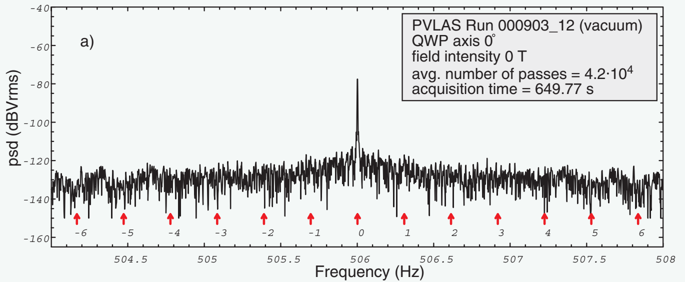
BMV "**Biréfringen**				✔
Gamme "**Gam**ma to				✔
LIPSS "**LI**ght **P**seu				✔
OSQAR "**O**ptical **S**ea gence, **Axio**				✔
PVLAS (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
Q&A (Hsinchu/Taiwan) "**Q**ED **&** **A**xion"	Mod.Phys.**A22** (2007)	✔	✘	✘



[Cantatore et al. PRL '06]

Laser Experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
ALPS (DESY/D) "**A**xion-**L**ike **P**article **S**earch"	arXiv:0905.4159	✘	✘	✔
BFRT (**B**NL-**F**ermi				✔
BMV "**B**iréfringen				✔
Gamme "**Gam**ma to				✔
LIPSS "**LI**ght **P**seu				✔
OSQAR "**O**ptical **S**ea gence, **A**xio				✔
PVLAS (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
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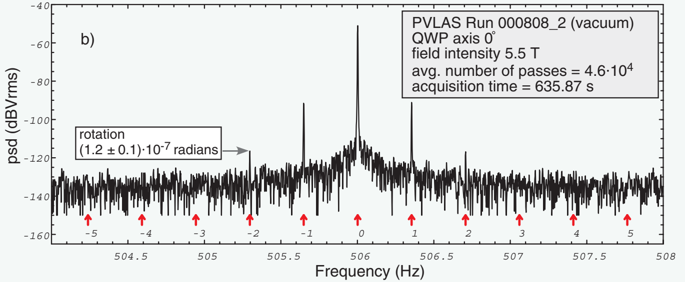

[Cantatore et al. PRL '06]

Laser Experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
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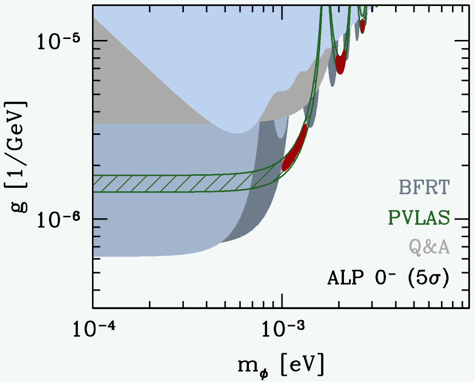
BFRT (**B**NL-**F**ermilab-**R**ochester-**T**ries			✔	✔
BMV "**B**iréfringence **M**agnétique du **V**			✘	✔
GammeV (F "**Gamma** to **meV** particle search			✘	✔
LIPSS (Jeffer "**LI**ght **P**seudoscalar or **S**calar p			✘	✔
OSQAR "**O**ptical **S**earch for **QED** vacuu gence, **A**xions and photon **R**ege			✘	✔
PVLAS "**P**olarizzazione del **V**uoto con **LAS**er"	Erratum ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
Q&A (Hsinchu/Taiwan) "**Q**ED & **A**xion"	Mod.Phys.**A22** (2007)	✔	✘	✘

Axion-like particle (ALP) interpretation:



Laser Experiments: History & Presence

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PVLAS "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.D**77** (2008)	✔	✔	(✔)
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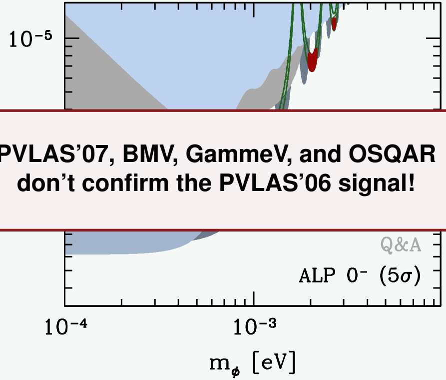

PVLAS'07, BMV, GammeV, and OSQAR don't confirm the PVLAS'06 signal!

Laser Experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
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BFRT (**B**NL-**F**ermilab-**R**ochester-**T**rieste)	Phys.Rev.**D47**(1993)	✔	✔	✔
BMV (LULI/F) "**B**iréfringence **M**agnétique du **V**ide"	Phys.Rev.Lett.**99** (2007) Phys.Rev.D**78** (2009)	✘	✘	✔
GammeV (Fermilab/USA) "**Gam**ma to **meV** particle search"	Phys.Rev.Lett.**100** (2008) Phys.Rev.Lett.**102** (2009)	✘	✘	✔
LIPSS (Jefferson Lab/USA) "**LI**ght **P**seudoscalar or **S**calar particle **S**earch"	Phys.Rev.Lett.**101** (2008) `arXiv:0810.4189`	✘	✘	✔
OSQAR (CERN/CH) "**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration"	Phys.Rev.D**78** (2008)	✘	✘	✔
PVLAS (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
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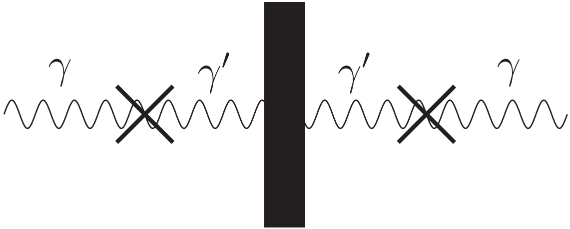
Weakly Interacting Sub-eV Particles



WISPs

- Standard Model may communicate with hidden sectors via **renormalizable operators**, *e.g.*

$$\mathcal{L}_\chi = -\frac{1}{2}\chi F^{\mu\nu}X_{\mu\nu} \quad , \qquad \mathcal{L}_\kappa = -\kappa|\theta|^2|\phi|^2 \quad , \qquad \mathcal{L}_\lambda = \lambda\theta\bar{\psi}\psi \quad , \qquad \ldots$$

- Theoretical motivation:
  Extra $U(1)$s and matter are ubiquitious in string and GUT extensions of the Standard Model.

⋆ Phenomenological approach:
Can there exist very light ($m \ll eV$) hidden sectors with extremely weak interactions ($\chi \ll 1$ and $\kappa \ll 1$)?

⋆ Model-building approach:
Could these particles be responsible for experimental or observational data?

(➜ talks in session 'Tentative Signals for WISPs')

Gauge Kinetic Mixing I

- Electro-magnetic $U(1)$ may mix with a hidden $U(1)_X$: [Holdom'86,Foot&He'91]

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}X_{\mu\nu}$$

- Gauge kinetic term can be diagonalized by a shift:

$$X_\mu \to X_\mu - \chi A_\mu \qquad \& \qquad e^2 \to \frac{e^2}{1-\chi^2}$$

- Hidden sector matter with a $U(1)_X$ charge:

$$D_\mu = \partial_\mu - iQ_X g_X X_\mu \to \partial_\mu - iQ_X g_X X_\mu + i\chi Q_X g_X A_\mu$$

➜ receives a small EM charge after the shift:

$$Q_{\text{EM,mixing}} = -\chi\left(\frac{g_X}{e}\right)Q_X$$

➜ "**mini-charged particles**" (MCPs) if $\chi \ll 1$ and $(g_X/e)Q_X \lesssim 1$

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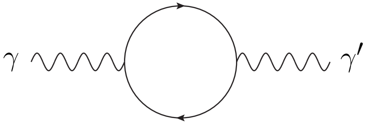
Gauge Kinetic Mixing I

- Kinetic mixing $\chi > 0$ generically arises in field or sting theoretic setups
  [Holdom'86,Dienes/Kolda/March-Russell'96,Foot&Kobakhidze'07]
  [Lüst,Stieberger'03;Abel&Schofield'03;Berg,Haack,Körs'04]

- Two fermions with charges $(1,1)$ and $(1,-1)$ and masses m and m': [Holdom'86]



$$\chi \simeq \frac{eg_X}{16\pi^2}\log\left(\frac{m'}{m}\right) \simeq \frac{eg_X}{16\pi^2}\frac{\Delta m}{m}$$

- candidates of SM extensions cover a wide range [Dienes,Kolda,March-Russell'96]

$$\chi \simeq C\frac{eg_X}{16\pi^2}\frac{\Delta m_{\text{split}}}{M_{\text{Pl}}} \simeq g_X \underbrace{C}_{10\text{–}100}(\underbrace{10^{-16}}_{\text{GMSB}} - \underbrace{10^{-4}}_{\text{GUT}})$$

Mini-Charged Particles (MCPs)

scalar ϕ_ϵ

$$\mathcal{L}^{\rm sc} = -|D_\mu \varphi_\epsilon|^2 - m_\epsilon^2 |\varphi_\epsilon|^2$$

$$D_\mu = \partial_\mu - i\epsilon e A_\mu$$

Dirac spinor ψ_ϵ

$$\mathcal{L}^{\rm Dsp} = \overline{\psi}_\epsilon (i\gamma_\mu D^\mu - m_\epsilon)\psi_\epsilon$$

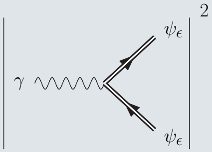
$$D_\mu = \partial_\mu - i\epsilon e A_\mu$$

parameters:

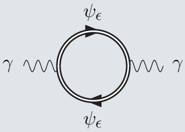
mass m_ϵ

Q-fraction ϵ

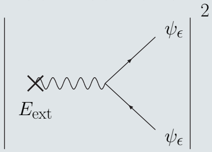
rotation



ellipticity



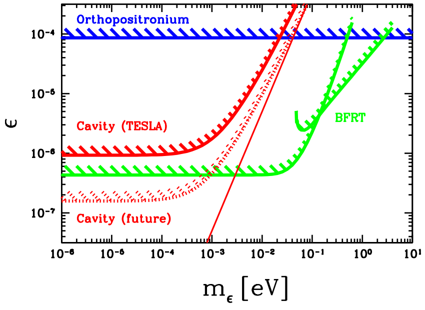
“dark current”



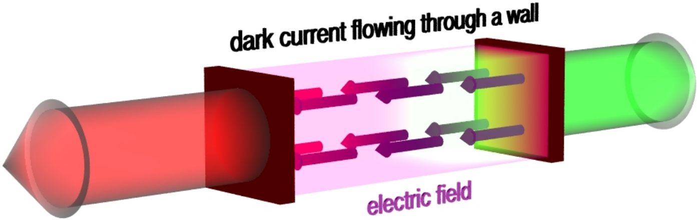
- dressed MCP propagator in external magnetic field depend on field orientation w.r.t. the polarization axis
- “light-shining-through-a-wall” only via hidden photon-photon oscillations
- “dark-current-through-a-wall” originating in strong electric fields

Mini-Charged Particles (MCPs)

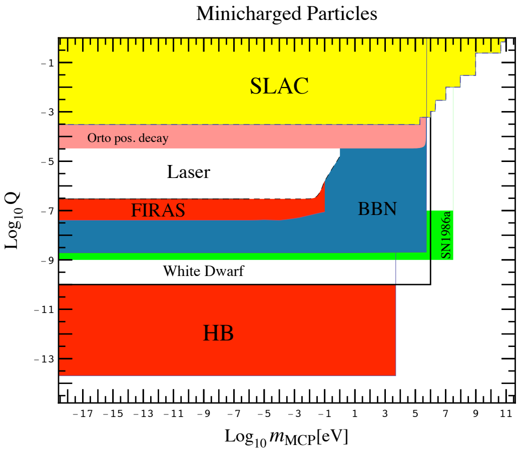
- Schwinger pair production of MCPs reduce the quality factor Q of the cavity.
- TESLA accelerator cavities: $\mathcal{E}_0 = 25$ MV/m with $L_{\text{cav}} = 10$ cm and high quality factor: $Q \sim 10^{10}$
- **AC/DC @ DESY**: MCPs produced in an accelerator cavity (**AC**) and traversing a wall (/) can be detected by their dark current (**DC**).



[Gies/Jäckel/Ringwald '06]



Mini-Charged Particles (MCPs)



[Redondo'08]

- Stellar Evolution
  - SN 1987A [Raffelt'96]
  - Globular Cluster Stars [Raffelt'96]
  - White Dwarves [Dobroliubov&Ignatiev'90]
- Cosmological Bounds
  - BBN [Davidson et al.'00]
  - CMB [Melchiorri et al.'07]
  - SN Dimming [Ahlers'09]
- Laboratory Searches
  - Beam Dump [Prinz'98]
  - Direct Search [Akers'95]
  - Orthopositronium Decay [Dobroliubov&Ignatiev'89] [Badertscher et al. Õ06]
  - Lamb Shift [Hagley&Pipkin'94]

Gauge Kinetic Mixing II

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$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{1}{2}\chi\, F^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m^2_{\gamma'}X_\mu X^\mu$$

- Hidden photon mass $m_{\gamma'}$ may arise due to Higgs or Stückelberg mechanism.

[Stückelberg'38,Ogievetskii&Polubarinov'62]

[Antoniadis,Kiritsis,Rizos'02;Ghilencea et al.'02]

- diagonalization with $X^\mu \to X^\mu - \chi A^\mu$ and $e^2 \to e^2/(1-\chi^2)$:

$$\mathcal{L}_{\text{gauge}} \to -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m^2_{\gamma'}\begin{pmatrix}A_\mu\\X_\mu\end{pmatrix}^T\begin{pmatrix}\chi^2 & -\chi\\-\chi & 1\end{pmatrix}\begin{pmatrix}A^\mu\\X^\mu\end{pmatrix}$$

➜ hidden photon-photon oscillations **without** magnetic field

$$P_{\gamma\to\gamma'} = 4\chi^2\sin^2\left(\frac{m^2_{\gamma'}\ell}{4\omega}\right)$$

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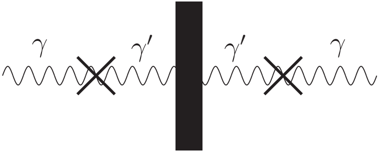
Gauge Kinetic Mixing II

➜ Limits on the hidden sector mixing from LSW experiments via hidden photon-photon oscillations



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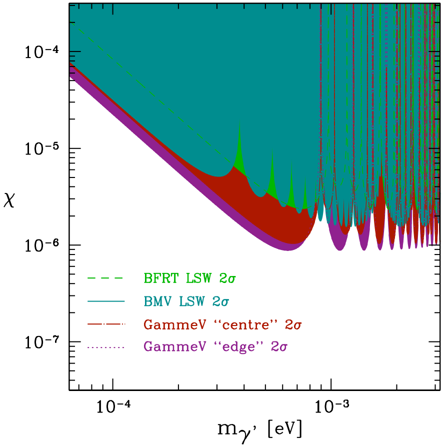
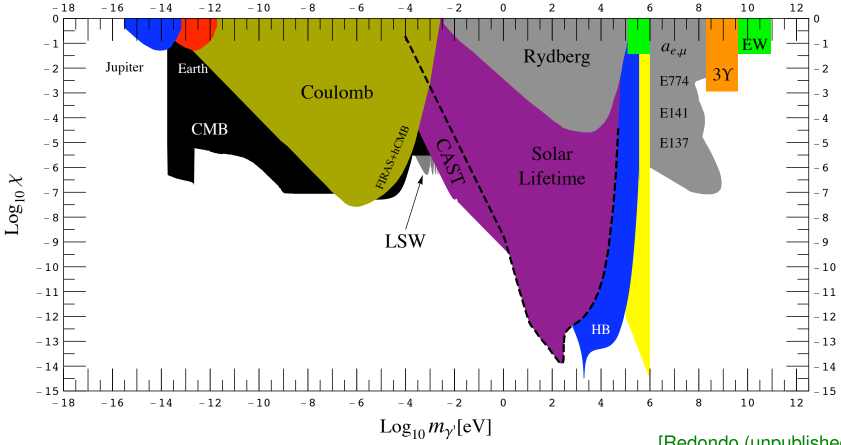


Gauge Kinetic Mixing II

➜ Limits on kinetic mixing with massive hidden photons.



[Redondo (unpublished)]

Summary

- The dynamical solution of the strong $\mathcal{CP}$ problem predicts the axion, a pseudo-Goldstone boson of the spontaneously broken Peccei-Quinn symmetry.
- Many direct and indirect signals of the axion from astrophysics, cosmology and laboratory experiments.
- In general, low energy hidden sectors of ALPs and other WISPs have a rich phenomenology.
- Many further ideas that I haven't covered:
  - 'Enviromental' WISPs
  - Chameleons (➜ talk by P. Brax)
  - Hidden Higgs
  - Hidden Monopoles and Magnetic Mixing (➜ talk by F. Brümmer)
  - ...

➜ Thank you for your attention!

Appendix

MCPs in Laser Experiments

- In general, birefringence and dichroism show up in a (complex) refractive index:

$$\Delta N^{\parallel,\perp} = \Delta n^{\parallel,\perp} + \frac{i}{2\omega}\kappa^{\parallel,\perp}$$

- Absorption coefficient κ and (real) refractive index $1 + \Delta n$ can be inferred from the Heisenberg-Euler effective action. [Adler '71;Tsai&Erber'74]

- **ellipticity**:

$$\psi = \frac{1}{2}[\mathrm{Arg}(A^{\parallel}_{\gamma\to\gamma}) - \mathrm{Arg}(A^{\perp}_{\gamma\to\gamma})]\sin(2\theta) \approx \frac{1}{2}\omega Q^2_{\mathrm{MCP}} e^2(\Delta n^{\parallel} - \Delta n^{\perp})\ell\sin(2\theta)$$

- **rotation**:

$$\Delta\theta = \frac{1}{2}(|A^{\perp}_{\gamma\to\gamma}| - |A^{\parallel}_{\gamma\to\gamma}|)\sin(2\theta)$$
$$\approx \left[\frac{1}{4}Q^2_{\mathrm{MCP}}e^2(\kappa^{\parallel} - \kappa^{\perp})\ell + \frac{1}{4}\chi^2\omega^2[(g_X^2\Delta n^{\parallel})^2 - (g_X^2\Delta n^{\perp})^2]\ell^2\right]\sin(2\theta)$$

- **LSW** via MCP loops in electro-magnetic fields:

$$P_{\gamma\to\gamma'} = \chi^2\left[1 + \exp\left(-\frac{g_X^2\kappa\ell}{\chi^2}\right) - 2\exp\left(-\frac{g_X^2\kappa\ell}{2\chi^2}\right)\cos\left(g_X^2\frac{\Delta n\omega\ell}{\chi^2}\right)\right]$$

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Hidden Higgs Potential

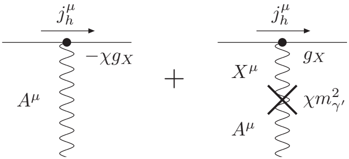
- Hidden $\mathrm{U}(1)$ can be broken by a hidden-Higgs potential:

$$V_{\text{Higgs}} = -\mu_\theta^2 |\theta|^2 + \lambda_\theta |\theta|^4 \qquad \langle\theta\rangle = \frac{v_\theta}{\sqrt{2}} = \frac{1}{\sqrt{2}}\sqrt{\frac{\mu_\theta^2}{\lambda_\theta}}$$

- **symmetric phase ($v_\theta = 0$):** Higgs is scalar MCP with charge $q_\theta = -\chi\,(g_X/e)\,q_X$.
- **broken phase ($v_\theta \neq 0$):** hidden photon mass term

$$\mathcal{L}_{\text{mass}} = \frac{v_\theta^2}{2} q_X^2 g_X^2 X^\mu X_\mu \xrightarrow{\text{shift}} \frac{v_\theta^2}{2} q_X^2 g_X^2 (X^\mu X_\mu - 2\chi X^\mu A_\mu + \chi^2 A^\mu A_\mu)$$

- Higgs coupling to photons



$$\sim -\chi g_X \frac{q^2}{q^2 - m_{\gamma'}^2} = \begin{cases} 0 & \text{for} \quad q^2 = 0 \\ -\chi g_X & \text{for} \quad |q^2| \gg m_{\gamma'}^2 \end{cases}$$

➜ Hidden-Higgs acts like a scalar MCP for large photon virtualities.

➜ Strong astrophysical and cosmological bounds on MCPs translate into bounds on the kinetic mixing parameter. [Melchiori et al.'07]

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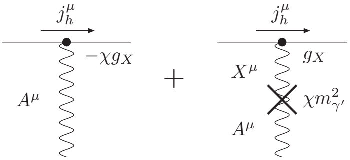

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Hidden-Higgs in External Magnetic Field

- hidden-Higgs in external magnetic field:

$$\left[\partial^\mu - \mathrm{i}q_X g_X (X^\mu - \chi A^\mu_{\mathrm{B}})\right]^2 \theta + V'(\theta) = 0 \quad \text{with} \quad \mathbf{A}_B = \frac{1}{2}\mathbf{B}\times\mathbf{r} = \frac{1}{2}(0, -zB, yB)$$

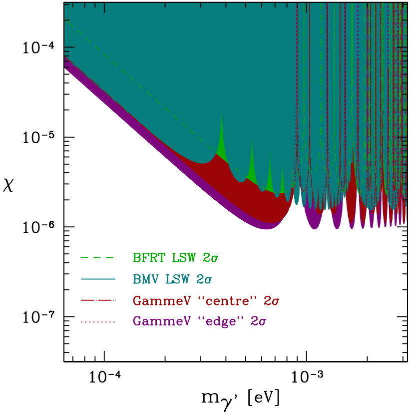
➜ **Landau levels** ($n = 0, 1, 2, \ldots$):

$$\omega_n^2 = -\mu_\theta^2 + p_x^2 + 2|eq_\theta B|\left(n + \frac{1}{2}\right)$$
$$\geq -\mu_\theta^2 + |eq_\theta B|$$

➜ **broken** hidden $U(1)_X$: $|q_\theta e B| \ll \mu_\theta^2$

- massive γ' with $m^2_{\gamma'} \approx q_X^2 g_X^2 v_\theta^2$
- photon–hidden-photon oscillations:

$$P_{\gamma\to\gamma'} = 4\chi^2 \sin^2\left(\frac{m^2_{\gamma'} z}{4\omega}\right)$$



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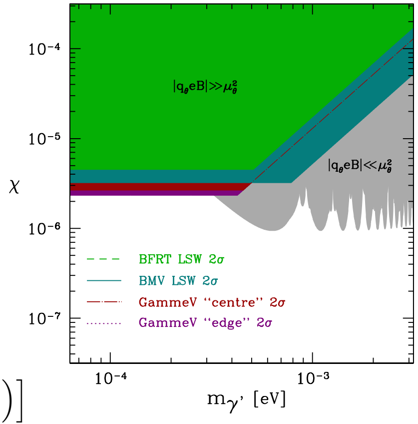
➜ **unbroken** hidden $U(1)_X$: $|q_\theta eB| \gg \mu_\theta^2$

- *would-be* Higgs acts as a scalar MCP
- MCP induces a refractive index Δn and absorption coefficient κ depending on polarization.



$$P_{\gamma\to\gamma'} = \chi^2\left[1 + e^{-\frac{\kappa z}{\chi^2}} - 2e^{-\frac{\kappa z}{2\chi^2}}\cos\left(\frac{\Delta n \omega z}{\chi^2}\right)\right]$$

Higgs Portal Mixing

- most general gauge-invariant and renormalizable Higgs potential ($\lambda_{\phi/\theta} > 0$ and $4\lambda_\phi\lambda_\theta > \kappa^2$):

$$V_{\text{Higgs}} = \underbrace{-\mu_\phi^2|\phi|^2 + \lambda_\phi|\phi|^4}_{\text{SM Higgs potential}} \underbrace{-\mu_\theta^2|\theta|^2 + \lambda_\theta|\theta|^4}_{\text{hidden-Higgs potential}} \underbrace{+\kappa|\phi|^2|\theta|^2}_{\text{“Portal term”}}$$

- symmetry breaking in unitary gauge:

$$\theta \to \frac{1}{\sqrt{2}}\left(v_\theta + \theta\right) , \qquad \phi \to \frac{1}{\sqrt{2}}\left(0, v_\phi + \phi\right)$$

- Higgs mass matrix:

$$\mathcal{L}_{\text{Higgs mass}} = -\frac{1}{2}\left(\theta \;\; \phi\right)\begin{pmatrix} 2\lambda_\theta v_\theta^2 & \kappa v_\phi v_\theta \\ \kappa v_\phi v_\theta & 2\lambda_\phi v_\phi^2 \end{pmatrix}\begin{pmatrix} \theta \\ \phi \end{pmatrix}$$

- mass eigenstates, h and H, after rotation ($\rho = \frac{v_\theta}{v_\phi} \ll 1$):

$$m_H^2 \approx 2v_\phi^2\lambda_\phi , \qquad m_h^2 \approx m_H^2 \sin^2\alpha\left(\frac{4\lambda_\theta\lambda_\phi}{\kappa^2} - 1\right) , \qquad \sin\alpha \approx \frac{\kappa\rho}{2\lambda_\phi} .$$

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Non-Newtonian Forces

- Higgs–matter coupling with Higgs mixing:

$$\frac{m_f}{v_\phi} H \rightarrow \frac{m_f}{v_\phi} (\cos\alpha\, H - \sin\alpha\, h)$$

- effective Higgs–nucleon coupling: [Gunion et al.'89]

$$\mathcal{L} = -g_{HNN}\, H\, \overline{\psi}_N \psi_N \qquad g_{HNN} = \frac{m_N}{v_\phi} \frac{2 n_H}{3\left(11 - \frac{2}{3} n_L\right)}$$

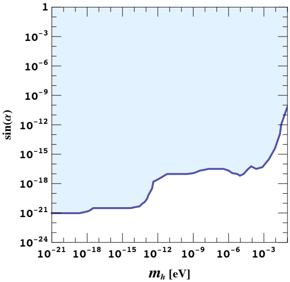
n_H = #(heavy quarks) / n_L = #(light quarks)

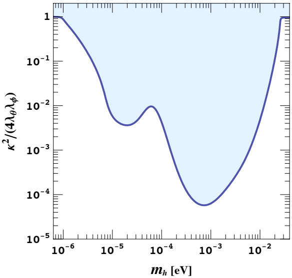
➜ "Portal term" provides a non-Newtonian contribution to the gravitational force.

$$V(r) \approx G \frac{m_1 m_2}{r} + \frac{1}{4\pi} g_{HNN}^2 \sin^2\alpha \frac{n_1 n_2}{r} e^{-m_h r}$$

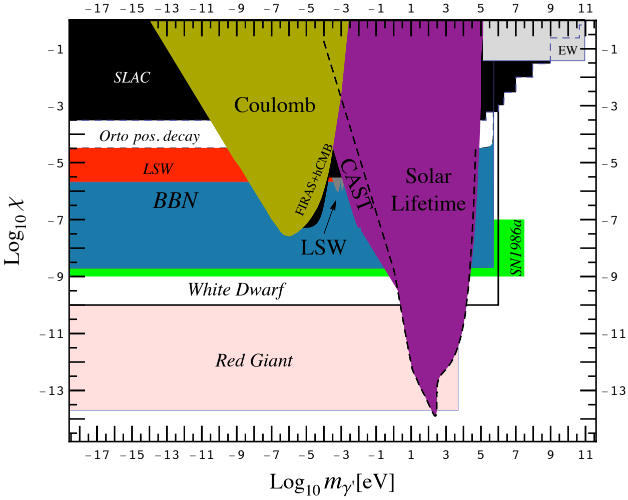
- Hidden-Higgs mass and mixing is related via:

$$m_h^2 \approx m_H^2 \sin^2\alpha \left(\frac{4\lambda_\theta \lambda_\phi}{\kappa^2} - 1 \right)$$





Summary: Bounds on Kinetic Mixing



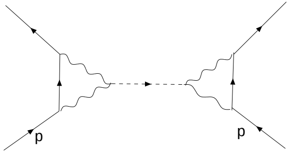
(Regions labeled in *italic* are bounds that apply if the hidden-photon receives its mass via a Higgs mechanism.)

Non-Newtonian Forces

- **non-Newtonian forces** of scalar ALPs from induced Yukawa couplings:

$$\mathcal{L}_{\phi pp} = y_p\, \phi\, \bar{\psi}_p\, \psi_p \qquad y_p \sim \frac{3}{2}\frac{\alpha}{\pi} g m_p \ln \frac{\Lambda}{m_p}$$

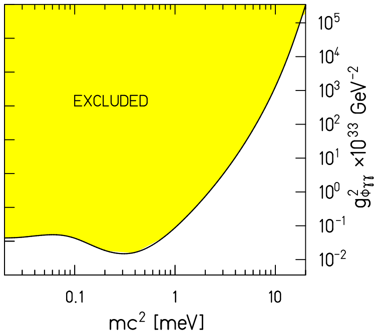
$$V(r) = G\frac{m_1 m_2}{r} + \frac{y_p^2}{4\pi}\frac{n_1 n_2}{r} e^{-m_\phi r}$$



[Adelberger et al. '06]

$g \lesssim 4 \times 10^{-17}$ GeV^{-1}
for $m_\phi = 1$ meV and $\Lambda \gg m_p$

Scalar Axion-Like Particles



[Adelberger et al. '06]

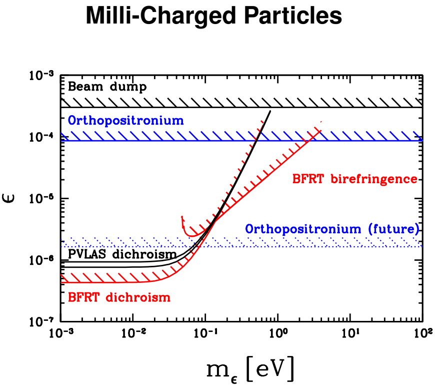
$m_\phi \sim (1.0 - 1.5)$ meV
$g \sim (1.7 - 5.0) \times 10^{-6}$ GeV^{-1}

MCP: Reactor Neutrino Experiments

- Gamma rays produced in nuclear power reactors may convert into $\epsilon^+\epsilon^-$ pairs.
- Experimental signature of $\epsilon - e^-$ scattering is identical to magnetic $\bar{\nu} - e^-$ scattering!
- $\Rightarrow$ Reactor experiments looking for the neutrino magnetic moment are also sensitive to MCPs!
- The TEXONO experiment (Taiwan) probing $\mu_{\bar{\nu}_e}$ gives a bound on the MCP fractional charge of $\epsilon < 10^{-5}$ for $m_\epsilon < 1$ keV. [TEXONO Coll. '03]
- May be improved in near future with massive liquid argon detectors. [Gninenko/Krasnikov/Rubbia '06]

MCP: Invisible Orthopositronium Decay

- milli-charged particles contribute to the branching ratio of invisible orthopositronium (OP) decay
  [Dobroliubov/Ignatiev '89]
- Br(OP $\rightarrow \psi_\epsilon^+ \psi_\epsilon^-) \sim \frac{3\pi\epsilon^2}{4\alpha(\pi^2-9)} \sim 371\epsilon^2$
  [Dobroliubov/Ignatiev '90]
- Br(OP $\rightarrow$ invisible) $\lesssim 4.2 \times 10^{-7}$
  [Mitsui et al. '93,Badertscher et al. '06]
- future experiments (ETH-Zurich, INR-Moscow, NNLN-Berkeley) may reach a sensitivity of Br(OP $\rightarrow$ invisible) $\sim 10^{-9}$
  [e.g. Rubbia '06]



[Gies/Jäckel/Ringwald '06]

Evading Astrophysical Bounds: Examples

Solution: environment-dependent axion couplings and milli-charges?

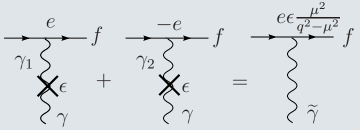
- hidden sector particles may pick up a fractional charge by gauge kinetic mixing [Holdom '86]
- e.g. paraphoton models $\mathrm{U}(1)^3$ with gauge kinetic mixing [Massó/Redondo '06]

$$\mathcal{L} = -\tfrac{1}{4}\, F^T \mathcal{K}_F\, F + \tfrac{1}{2}\, A^T \mathcal{M}_A^2\, A + e \textstyle\sum_i j_i A_i$$

with $\mathcal{K}_F = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 0 \\ \epsilon & 0 & 1 \end{pmatrix}$

and $\mathcal{M}_A^2 = \mathrm{Diag}\,\{m_\gamma^2, \mu^2, 0\}$

"hidden" fermions f with charge $(0, 1, -1)$



induced electric charge:

$$q_f(k^2 \simeq \omega_P^2) \;\simeq\; \frac{\mu^2}{\omega_P^2}\, q_f(k^2 \simeq 0)$$

typical plasma frequencies in stellar environments: $\omega_P = \mathcal{O}(\text{keV})$
$\Rightarrow$ Astrophysical bounds apply for MCPs with $\epsilon \times (\mu/\omega_P)^2 \ll \epsilon$ for $\mu \ll \Omega_P$.

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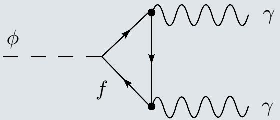
non-minimal model: $\Delta\mathcal{L} = y_f\, \phi \bar{f} f$



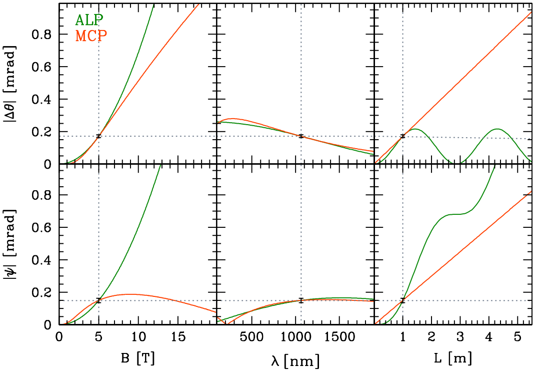
$$g \sim \frac{\alpha}{2\pi} \epsilon^2(q^2)\, \frac{y_f}{m_f}$$

$\Rightarrow$ Astrophysical bounds on ALPs may be evaded as well! [Massó et al. '06]

ALP vs. MCP: Parameter Variation

Scenarios may be further distinguished in future polarization experiments with variations in **magnetic field** B and **cavity length** L
e.g. Q&A (Taiwan), BMV (Toulouse), laser background experiments (Jena), . . .

	$\Delta\theta > 0$ $(\theta = \pi/4)$	$\Delta\theta < 0$ $(\theta = \pi/4)$
$\psi > 0$ $(\theta = \pi/4)$	ALP 0^- or MCP $\frac{1}{2}$ (large m_ϵ)	MCP $\frac{1}{2}$ (small m_ϵ)
$\psi < 0$ $(\theta = \pi/4)$	MCP 0 (small m_ϵ)	ALP 0^+ or MCP 0 (large m_ϵ)



[Ahlers/Gies/Jäckel/Ringwald ’06]