Fondamental Physics at Low Energies

Joerg Jaeckel

Institute for Particle Physics Phenomenology
Durham – United Kingdom
Fundamental Physics @ Low Energies

Joerg Jaeckel

IPPP Durham

For a review see, JJ and A. Ringwald 1002.0329
Where we want to go…

The Standard Model
+
Beyond the SM (accessible to colliders)

The Hidden Sector

---

Modified from D. Luest
0707.2305
1. The Physics Case
   (for a low energy frontier of particle physics)
# The Standard Model

| Quarks | Leptons |
|--------|---------|
| **Charge** | **Charge** | **Charge** | **Charge** |
| +2/3 | -1/3 | -1 | 0 |

| 1. Family | 2. Family | 3. Family |
|-----------|-----------|-----------|
| Up | Down | Electron |
| d | u | e |
| Charm | Strange | Myon |
| c | s | μ |
| Top | Bottom | Tau |
| t | b | τ |

**Gravitation** ➔ **graviton**

**Weak forces** ➔ **W- und Z-bosons**

**Electromagnetism** ➔ **photons (γ)**

**Strong forces** ➔ **gluons**
We need...

Physics beyond the Standard Model
Hints for new Physics
Uglyness of old models

• The Standard Model has many free parameters: $O(30)$

• Naturalness problems. Finetuning.

Examples:
Higgs mass, $\theta$-angle (strong CP-problem)
A dirty little secret...

\[ S = \int d^4 x \left[ -\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + \psi D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right] \]

• The $\theta$-term is CP violating!
• Connected to strong interactions!

Measure electric dipole moment of the neutron!
Neutron electric dipole moment

Measure transition frequency.

\[ \hbar \omega = 2 |\vec{d} \cdot \vec{E}| \]
No neutron electric dipole moment...

\[ |\vec{d}| < 3 \times 10^{-26} \text{ e cm} = 3 \times 10^{-13} \text{ e fm} \]

See also https://neutronedm.org
No neutron electric dipole moment...

\[ |d| < 3 \times 10^{-26} \text{ e cm} = 3 \times 10^{-13} \text{ e fm} \]

\[ \frac{1}{16\pi^2} \text{ e fm } \theta \]

Very unnatural!
More precisely

- Detailed calculation gives

\[ |\vec{d}| \sim 1 - 10 \times 10^{-16} \text{ e cm } \theta \]

\[ |\theta| < 3 \times 10^{-10} \]

Extremely unnatural!
Strong CP Problem
Ugliness of old models

• The Standard Model has many free parameters: \( O(30) \)

• Naturalness problems. Finetuning. Examples: Higgs mass, \( \theta \)-angle (strong CP-problem)

• Gravity separate, i.e. not unified.

• (Probably) Breaks down at a finite energy scale
  Landau poles etc.
Unexplained Stuff

- Dark Matter (25%)
  (astrophysical + cosmological observations)
Gravitational lenses

Distortet image (Partial Einstein Ring)

Far away galaxy

Galaxy cluster („Gravitational lense”)

Observer

see
http://ned.ipac.caltech.edu/level5/Tyson2/Tyson2.html
Gravitationslinsen Abell 2218
Unexplained Stuff

• Dark Matter (25%)
  (astrophysical + cosmological observations)

• Dark Energy (70%)
  (astrophysical + cosmological observations)

• Mass Hierarchies
  (colliders, neutrino exp, etc)

• Small parameters (θ-angle, again)
  (neutron electric dipole measurements)
BSM physics @ Work?

- $(g-2)_\mu$ deviations from SM prediction
- DAMA anomaly
- CoGeNT etc.
- PAMELA + Fermi observation
- WMAP observes extra “neutrinos”
- Proton radius in muonic hydrogen
Hints for new Physics

Model Building

Bottom-up (pheno)
- Fix problem `here and now`

Top-down (theory)
- Go back to drawing board `Start from scratch`
The Axion
Commercials
Your CP is violated too strongly?
Use Axion!

New! With special cleaning particles and extra strong photon coupling.
As we have seen...

\[ S = \int d^4x \left[ -\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + i \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right] \]

No electric dipole moment of the neutron!

\[ |\theta| < 3 \times 10^{-10} \]

Need an explanation!
A Dynamical $\theta$

**Idea:**
- Make $\theta$ a dynamical degree of freedom $a$.
- Let $a$ have no tree level potential.
- Let $a$ have only derivative couplings.

**Then:**

$$V[0] \leq V[a] \quad \forall a$$

$a$ will evolve to $a=\theta=0$.

$\rightarrow$ 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

- $a/f_a \in [0, 2\pi]$ since

$$\int d^4x \frac{G_{\mu\nu} \tilde{G}^{\mu\nu}}{32\pi^2} = n \in \mathbb{Z}$$

$a$ is Goldstone boson of a U(1) symmetry

Axion! Peccei-Quinn Symmetry
The mass of the Axion

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

\[ \Rightarrow \quad \text{Goldstone} \quad \Rightarrow \quad \text{Pseudogoldstone} \]

- Dimensional considerations
  - SSB scale
  - Coupling to \( \bar{G}G \):
    \[ \sim \frac{f_X}{a} \frac{G_{\mu\nu}}{f_X} \bar{G}_{\mu\nu} \]
  - Scale of explicit breaking

\[ \sim \frac{1}{f_X} m_{\pi}^2 f_{\pi}^2 \]

\[ \Rightarrow \quad \text{Goldstone mass} \quad m_a^2 \sim \frac{\Lambda^4}{f_X^2} \]
Large scale

Small coupling
The axion couples to two photons

\[ \mathcal{L}_{Int} = -\frac{1}{4} g a F^{\mu \nu} \tilde{F}_{\mu \nu} = -g a E \cdot B \]
Axion coupling to two photons

- Effective higher dimensional coupling

\[ \mathcal{L}_{Int} = -\frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g a E \cdot B \]

Coupling to two photons!

- Small coupling for large axion scale:

\[ g \sim \frac{\alpha}{2\pi f_a} \text{ Small} \quad \text{Large} \]
Large scale

Small mass
Axion See-Saw

- The axion mass is small, too!

\[ m_a \sim \frac{m_\pi f_\pi}{f_a} \]

\[ \sim 0.6 \text{ meV} \left( \frac{10^{10} \text{ GeV}}{f_a} \right) \]

Sub-eV mass

Large scale
Axions live at small mass and coupling

Axion band
The strong CP problem: Axions

• Introduce new Peccei-Quinn symmetry to solve naturalness problem

• Predict as a consequence a new particle: The Axion
  (it’s a Weakly Interacting Sub-eV Particle)

Good motivation for axion/WISP experiments
Axion Dark Matter
Axion production

- $T < f_a$
- Axion potential is flat
- Axion can sit anywhere
- $T < T_{QCD}$
- Potential arises
- $H < m_a$
- Axion starts to oscillate

see S. Hannestad at Patras 2009
Oscillations behave like dark matter

- Initial energy density

\[ \rho_{\text{ini}} = \frac{1}{2} m_a^2 f_a^2 \theta_{\text{ini}}^2 \]

- damped Oscillations

\[ \ddot{\theta} + 3H \dot{\theta} + m_a^2 \theta = 0 \]

Scales like matter

\[ \rho_a(t) \sim \frac{\rho_{\text{ini}}}{a^3(t)} \]
How much?

- Energy density

\[ \Omega_a h^2 = \kappa_a \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{1.175} \theta_{\text{ini}}^2 \]
Too much?

- **Energy density**

\[
\Omega_a h^2 = \kappa_a \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{1.175} \theta_{\text{ini}}^2
\]

For \( f_a \gg 10^{12} \text{ GeV} \) too much DM!
Axion dark matter
How can it be?

- Axions are very light:
- How can they be COLD dark matter?

Non-thermal production!
Supercold?

- At the beginning axion value everywhere the same

- Coherent Oscillations => Supercold!

\[ p_{\text{today}} = p_{\text{ini}} \frac{T_{\text{today}}}{T_{\text{ini}}} \]

\[ \sim H_{\text{ini}} \frac{T_{\text{today}}}{T_{\text{ini}}} \sim 10^{-22} \text{ eV} \ll m_a \]
The strong CP problem: Axions

- Introduce new Peccei-Quinn symmetry to solve naturalness problem

- Predict as a consequence a new particle: The Axion
  (it’s a Weakly Interacting Sub-eV Particle)

Dark matter candidate

Good motivation for axion/WISP experiments
Very cool experiments:

Light shining through walls

A reason for Experimentalists!!!
Light shining through walls

“Light shining through a wall”

Laser

Detector
Light shining through walls

“Light shining through a wall”

- Test \( P_{\gamma \rightarrow X \rightarrow \gamma} \lesssim 10^{-20} \)
- Enormous precision!
- Study extremely weak couplings!
Photons coming through the wall!

- It could be Axion(-like particle)s!

- Coupling to two photons:

\[
\frac{1}{M} a \tilde{F} F \sim \frac{1}{M} a \vec{E} \cdot \vec{B}
\]

\[
P_{\gamma \rightarrow a \rightarrow \gamma} \sim N_{\text{pass}} \left( \frac{B L}{M} \right)^4
\]
Light Shining Through Walls

- A lot of activity
- ALPS
- BMV
- GammeV
- LIPPS
- OSQAR
Small coupling, small mass
Hints for new Physics

Model Building

Bottom-up (pheno)

Top-down (theory)

Go back to drawing board `Start from scratch`
WISPs from String Theory
String theory

• Attempt to unify SM with gravity
• New concept: strings instead of point particles
Axion(-like particles)
String theory: Moduli and Axions

- String theory needs Extra Dimensions
  
  Must compactify

- Shape and size deformations correspond to fields:
  Moduli (WISPs) and Axions
  Connected to the fundamental scale, here string scale

WISP candidates
Axions and Moduli

• Gauge field terms

$$\mathcal{L} = \frac{1}{g^2} F^2 + i \theta F \tilde{F}$$

+ Supersymmetry/supergravity

$$\mathcal{L} = \text{Re}[f(\Phi)] F^2 + \text{Im}[f(\Phi)] F \tilde{F}$$

Scalar ALP/moduli coupling + pseudoscalar ALP coupling

see J. Conlon at Patras 2009
Axions and Moduli

- Gauge couplings always field dependent (no free coupling constants)

- Axions + Moduli always present in String theory
Masses and Couplings

- “Axion scale” related to fundamental scale

\[ f_a \sim \frac{M_P}{\text{Volume}^x} \sim M_s \left( \frac{M_s}{M_P} \right)^y \]

- If QCD axion: \( m_a \) fixed

- However, if not QCD axion

\[ m_{\text{ALP}} \sim \frac{\Lambda^2}{f_a} \]  

(nearly) arbitrary
Axion (like particles): Where are we?
Axion (like particles): Where are we?
Hidden Photons
String theory likes extra gauge groups

Many extra U(1)s!

Candidates for WISPs
How coupled?

- Kinetic mixing

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(A)} F_{(A)\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(B)} F_{(B)\mu\nu} + \frac{1}{2} \chi F^{\mu\nu}_{(A)} F_{(B)\mu\nu}, \]

"Our" U(1)  "Hidden" U(1)  Mixing

+ Mass

\[ \mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\gamma'}^2 X_{\mu} X_{\mu}, \]

photon - hidden photon oscillations
Light shining through walls
Fixed target signatures
If you don't like string theory...

- Another simple motivation:

  Question: Are there extra gauge groups?

  Testcase: $U(1)$ is the simplest example we can think of!
How to get Kinetic Mixing ...

- Field Theory:

\[ \chi \sim \frac{e_A e_B}{16\pi^2} \log \left( \frac{m_X^2}{\Lambda^2} \right) \]

*UV sensitive since dimension 4 operator.*

*Tests underlying high scale physics!*
How to get Kinetic Mixing ...

• Field Theory:

• String Theory:
Hidden by distance

\[ \chi \sim \frac{g_s}{8\pi} \frac{1}{\text{Volume}^x} \]

\[ g_{\text{hid}} \sim 1 \]
Hidden by weakness

$$\chi \sim \frac{g_{\text{vis}} g_{\text{hid}}}{16\pi^2} \sim \frac{2\pi g_s}{\text{Volume}^{x/2}} \sim \left(\frac{M_s^2}{M_P^2}\right)^{x/2} \ll 1$$

$$g_{\text{hid}}^2 \sim \frac{2\pi g_s}{\text{Volume}^x} \sim \left(\frac{M_s^2}{M_P^2}\right)^x \ll 1$$
Hidden Photons, all over the place
Hidden Photons: Preview for Wednesday...
Hidden Matter
-
Minicharged Particles
Minicharged particles

- Extra $U(1)$ gauge boson, i.e. extra photon
- Normal matter not charged under it

Main interaction:
- Small coupling to photons, related to kinetic mixing

\[ \chi \sim \text{dimensionless} \ll 1 \]
\[ g_h \sim \text{dimensionless} \sim 1 \quad \text{or} \quad \ll 1 \]
How coupled?

• Kinetic mixing

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{\chi}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}, \]

„Our“ U(1)  „Hidden“ U(1)  Mixing

+ Matter

\[ \mathcal{L}_{\text{int}} = g_{\text{hid}} \bar{h} \gamma_\mu X^\mu h \]

Particles with small electric charges

LSW + other experiments
Kinetic Mixing - How to get Minicharges

- Two U(1)'s

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{\mu\nu}^{(A)} F_{\mu\nu}^{(A)} - \frac{1}{4} F_{\mu\nu}^{(B)} F_{\mu\nu}^{(B)} + \frac{\chi}{2} F_{\mu\nu}^{(A)} F_{\mu\nu}^{(B)} , \]

“Our” U(1) \quad “Hidden” U(1) \quad Mixing

\[
\begin{align*}
\Rightarrow A^2 + B^2 - 2\chi AB, \\
= A^2 + (B + \chi A)^2 + O(\chi^2)
\end{align*}
\]

Diagonalization:

\[ B^\mu \rightarrow B^\mu + \chi A^\mu \]
Kinetic Mixing - How to get Minicharges

- Two U(1)'s

$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{\chi}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}$,

"Our" U(1)  "Hidden" U(1)  Mixing

Diagonalization:

$B^\mu \rightarrow B^\mu + \chi A^\mu$

$g_h \bar{h} B^\mu h \rightarrow g_h \bar{h} B^\mu h + \chi g_h \bar{h} A^\mu$

\[ \begin{array}{c}
\hline
\text{carries}
\end{array} \]

\[ \begin{array}{c}
\epsilon = \chi g_h
\end{array} \text{ electric charge!} \]
Necessary ingredients:

- Extra `hidden' U(1) gauge groups!
- Kinetic mixing term!
- Matter charged under hidden U(1)
String theory likes extra matter

Hidden matter

$U(A) \times U(B) \times U(C)$

Hidden sector matter

Appears to be minicharged
Minicharged particles...
Crazy stuff
Summary
Summary

• Good motivation for:
  Axions and other light very weakly coupled
  From Bottom-Up (Strong CP problem, DM)
  Top-down (String theory)
  +++ Cool experiments

• Insight into light particles
  may provide information on hidden sectors and thereby
  into the underlying fundamental theory

• Surprises like Lorentz symmetry violation possible!

explore `The Low Energy Frontier'
2. Light particles in astrophysics and cosmology
Hints for new Physics

Model Building

Bottom-up (pheno)

Top-down (theory)

Observations/Experiments
Warmup
More particles +
Photon-WISP
interactions
Axion(-like particles)
How can we see light particles?

- Example: Axions

\[ \mathcal{L}_a = \partial_\mu a \partial^\mu a - m_a^2 a^2 - \frac{1}{4} g a F^{\mu\nu} \tilde{F}_{\mu\nu} + \ldots \]

Two-photon interaction!
Axion interactions

- Light scalars or pseudoscalars
  - Can also have Yukawa couplings

- Electrons, $e$
- Nucleons, $N$

$k \sim \text{dimensionless} \ll 1$
Axion(-like particle) interactions

• Light scalars or pseudoscalars

Can also have Yukawa couplings

- Electrons, e
- Nucleons, N

$k \sim \text{dimensionless} \ll 1$

For QCD axion:

$k_{e,N} \sim \frac{m_{e,N}}{f_a} \ll 1$
Hidden Photons

\[ U(A) \times U(B) \times U(C) \]
Hidden Photon interactions

- Kinetic mixing

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{\chi}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}, \]

- "Our" U(1)
- "Hidden" U(1)
- Mixing

\[ \mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\gamma'}^2 \, X^\mu X_\mu \]
Hidden Photons

- Extra U(1) gauge boson, i.e. extra photon
- Normal matter not charged under it

- Main interaction: Kinetic mixing

\[ + \frac{\chi}{2} F^{\mu\nu}_{(A)} F_{(B)\mu\nu} , \]

\[ \chi \sim \text{dimensionless} \ll 1 \]

\[ \chi \]

\[ = A \quad \chi \quad \gamma' = B \]
Hidden Photon: Different basis

- Kinetic mixing

\[ \mathcal{L}_\text{gauge} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{x}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}, \]

- Mass

\[ \mathcal{L}_\text{mass} = \frac{1}{2} m_\gamma^2 X^\mu X_\mu, \]

- Interactions with electrons

\[ \mathcal{L}_\text{int} = j^\mu A_\mu. \]
Removing kinetic mixing

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(A)} F_{(A)\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(B)} F_{(B)\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(A)} F_{(B)\mu\nu}, \]

\[ + \quad \mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\gamma'}^2 B^\mu B_\mu, \]

\[= \quad A^2 + B^2 - 2\chi A B, \]

\[= \quad A^2 + (B + \chi A)^2 + \mathcal{O}(\epsilon^2) \]

\[= \quad (A + \chi B)^2 + B^2 + \mathcal{O}(\epsilon^2) \]

\[
\text{Diagonalization:} \quad A^\mu \rightarrow \hat{A}^\mu - \chi B^\mu
\]
Hidden Photon: Different basis

• No Kinetic mixing for $\hat{A}$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} \hat{F}^{\mu \nu} \hat{F}_{(A) \mu \nu} - \frac{1}{4} F^{\mu \nu} F_{(B) \mu \nu}$$

+ Mass

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\gamma'}^2 B^\mu B_\mu$$

+ Interactions with electrons (and other charges)

$$\mathcal{L}_{\text{int}} = j^\mu (\hat{A}_\mu - \chi B_\mu)$$
Minicharged Particles

$U(A) \times U(B) \times U(C)$

SM

HS

$U(A) \times U(B)$

Hidden matter
How coupled?

- Kinetic mixing

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{\chi}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}, \]

„Our“ U(1)  „Hidden“ U(1)  Mixing

\[ \mathcal{L}_{\text{int}} = g_{\text{hid}} \bar{h} \gamma_\mu X^\mu h \]

Particles with small electric charges

LSW + other experiments

+ Matter
Kinetic Mixing - How to get Minicharges

- Two U(1)'s

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu\nu} F_{(A)\mu\nu} - \frac{1}{4} F_{(B)}^{\mu\nu} F_{(B)\mu\nu} + \frac{\chi}{2} F_{(A)}^{\mu\nu} F_{(B)\mu\nu}, \]

- "Our" U(1)
- "Hidden" U(1)
- Mixing

\[
\begin{align*}
\quad &= A^2 + B^2 - 2\chi AB, \\
&= A^2 + (B + \chi A)^2 + \mathcal{O}(\chi^2)
\end{align*}
\]

Diagonalization:

\[ B^\mu \rightarrow B^\mu + \chi A^\mu \]
Kinetic Mixing - How to get Minicharges

- Two U(1)'s

\[ \mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_{(A)}^{\mu \nu} F_{(A)\mu \nu} - \frac{1}{4} F_{(B)}^{\mu \nu} F_{(B)\mu \nu} + \frac{\chi}{2} F_{(A)}^{\mu \nu} F_{(B)\mu \nu}, \]

„Our“ U(1)  „Hidden“ U(1)  Mixing

Diagonalization:

\[ B^\mu \rightarrow B^\mu + \chi A^\mu \]

\[ g_h \bar{h} B^\mu h \rightarrow g_h \bar{h} B^\mu h + \chi g_h \bar{h} A^\mu h \]

\( \bar{h} \) carries \( \epsilon = \chi g_h \) electric charge!
Minicharged particles

- Extra U(1) gauge boson, i.e. extra photon
- Normal matter not charged under it

- **Main interaction:**
  - Small coupling to photons, related to kinetic mixing

\[
\chi \sim \text{dimensionless} \ll 1
\]

\[
g_h \sim \text{dimensionless} \sim 1 \quad \text{or} \quad \ll 1
\]
Energy loss in Stars

See G. Raffelt
"Stars as Laboratories for Fundamental Physics"
Axions

- Primakoff process

\[ p \rightarrow q \rightarrow k \]
Axions

- Primakoff process (in the sun)

Photon (plasma)

ALP (leaving the sun)

Ion or electron
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:
  \[ L_a \approx 1.7 \times 10^9 (g \times 10^4 \text{GeV})^2 L_\gamma \]
- Sun Lifetime with ALPs
  \[ t_{\text{sun}} \sim 10 \text{ years} \times (g \times 10^4 \text{GeV})^{-2} \]
- Pretty sure sun has been around for more than 10 years
  \[ g \leq \frac{1}{10^4 \text{GeV}} \]
Axion-like particles

\[ \text{Log}_{10} g \left( \text{GeV}^{-1} \right) \] 
\[ \text{Log}_{10} m_a [\text{eV}] \] 

- Sun
- γ-burst 1987a
- γ transparency
- SUMICO
- ADMX
- CDM
- WD energy loss
- HB stars
- Beam dump
- e⁺e⁻ → invisible
- Y → invisible

University of Durham
Can do better...

- Look at variety of stars
- Best are horizontal branch stars.
Works also for hidden photons...
...and minicharged particles
Not only bounds but also a new hint!!!

- White Dwarfs seem to lose a bit more energy than expected.
- This could be explained by an Axion(-like particle) coupled to electrons.
- The corresponding two-photon coupling
Extra degrees of freedom at BBN

See, e.g., E. Kolb and M. Turner, "The Early Universe". Also S. Hannestad 2010
Basic facts of Big Bang Nucleosynthesis

- After the quark-hadron transition
  - $T \sim$ few 100 MeV, $t \sim 10^{-6}$ s
  - Most hadrons are Pions.
Basic facts of Big Bang Nucleosynthesis

- Later when $T < < 100 \text{ MeV} \sim m_\pi$
  - pions decay away
- Mostly neutrons and protons (+ electrons)

In equilibrium:

\[
\frac{n_n}{n_p} = \exp \left( - \frac{\delta m}{k_B T} \right)
\]

\[
\delta m = m_n - m_p = 1.293 \text{ MeV}
\]
Are we in equilibrium?

- **n-p changing interactions**
  
  \[
  \begin{align*}
  \nu_e + n & \leftrightarrow e^- + p \\
  e^+ + n & \leftrightarrow \bar{\nu}_e + p \\
  n & \leftrightarrow e^- + p + \bar{\nu}_e
  \end{align*}
  \]

- **Rate**
  
  \[
  \Gamma_{n-p} = n \langle \sigma v \rangle \sim T^3 G^2_F T^2
  \]

- **Hubble**
  
  \[
  H = \sqrt{\frac{8\pi}{3}} \frac{\rho}{m^2_{Pl}} \sim 1.66 \sqrt{g_*} \frac{T^2}{m_{Pl}}
  \]

- **Freeze out:**
  
  \[
  \Gamma_{n-p} < H \Rightarrow T_{freeze} \sim 1 \text{ MeV}.
  \]
Are we in equilibrium?

- Freeze out:

\[ \Gamma_{n-p} < H \Rightarrow T_{\text{freeze}} \sim 1 \text{ MeV}. \]

- At this point in time

\[ \frac{n_n}{n_p} \sim \exp\left( -\frac{m_n - m_p}{T_{\text{freeze}}} \right) \frac{1}{6} \]

- From then on: Neutrons decay with \( \tau_n = 886 \text{ s} \)
Nucleosynthesis...

- The first process is

\[ p + n \leftrightarrow D + \gamma \]

- Naively it should start when

\[ T < m_D - m_p - m_n \sim 2.2 \text{ MeV} \]

- However much much more \( \gamma \) than \( p, n \)!!!

\[ \eta = \frac{n_B}{n_\gamma} \sim 10^{-10} \]

Need:

\[ \Gamma_{\text{production}}(D) = \Gamma_{\text{destruction}}(D) \]
Nucleosynthesis...

\[ \Gamma_{\text{production}} \approx n_B \langle \sigma v \rangle \]
\[ \Gamma_{\text{destruction}} \approx n_\gamma \langle \sigma v \rangle e^{-E_b/T} \]
\[ \Rightarrow T_{BBN} \approx -\frac{E_b}{\ln(\eta)} \approx 0.2 \text{ MeV} \]

\[ t_{BBN} \sim 50 \text{ s} \]

- At this point in time

\[ \frac{n_n}{n_p} \sim \frac{1}{7} \]
Nucleosynthesis...

• After formation of deuterium everything goes quickly

• Nearly all neutrons end in helium.

\[ Y_{He} = \frac{4n_{He}}{n_{nucleon}} = \frac{4}{16} = 0.25 \]

• This is roughly what is observed!
Extra species...

- Extra light particles in equilibrium increase the Hubble constant

⇒ (Smallish) changes in $t_{freeze}, t_{BBN}$

⇒ Changes $Y_{He}$ (and other element abundances)
Extra species...

$N_{\nu} = 4$

$N_{\nu} = 3$

$N_{\nu} = 2$
Measured abundancies...
Extra species...

- Extra light particles in equilibrium increase the Hubble constant

→ (Smallish) changes in

\[ t_{\text{freeze}}, t_{\text{BBN}} \]

→ Changes \( Y_{\text{He}} \) (and other element abundances)

We can constrain (or have a hint ;-)):

\[ n_{\text{light species}} \sim 1 \pm 2 \]
Example of constraint: Minicharges

Not in equilibrium

Not enough energy
Axion-like particles

- Not my favourite bound: only 1 extra degree of freedom.
- Need to use one of the optimistic error estimate
Intermezzo

Photon-WISP oscillations
Coherent evolution...

• In many situations we have coherent interactions over long distances.

• Multiple interactions...

• All tree-level

Use classical equations of motion!
Equations of motion...

\[ \left[ \omega^2 1 + \partial^2_{\tau} 1 - \mathcal{M}^X \right] \begin{pmatrix} A \\ X \end{pmatrix} = 0, \]

- Axion-like particles

\[ \mathcal{M}^{a-}_{||} = \begin{pmatrix} 0 & -gB\omega \\ -gB\omega & m^2_a \end{pmatrix} \]
Equations of motion...

\[
\left[ \omega^2 1 + \partial_z^2 1 - \mathcal{M}^X \right] \begin{pmatrix} A \\ X \end{pmatrix} = 0,
\]

- Hidden photons

\[
\mathcal{M}' = m_{\gamma'}^2 \begin{pmatrix} \chi^2 & -\chi \\ -\chi & 1 \end{pmatrix}
\]
Solutions...

\[ v_1 = \exp(-i(\omega t - k_1 z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-i(\omega t - k_2 z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix} \]

- Propagation eigenstates
  \[ \neq \] interaction eigenstates
- Photons mix with new particles!!
- Analog of neutrino oscillations!
Solutions... Details

\[ v_1 = \exp(-i(\omega t - k_1 z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-i(\omega t - k_2 z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix} \]

In general:

\[ \tan(2 \delta) = 2 \frac{M_{12}^X}{M_{11}^X - M_{22}^X}, \]

\[ k_1^2 = \omega^2 - M_{11}^X, \quad k_2^2 = \omega^2 - M_{22}^X. \]
Solutions...  Details

\[ v_1 = \exp(-i(\omega t - k_1z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-i(\omega t - k_2z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix} \]

For hidden photons:

\[ \delta \approx \chi \]

\[ k_1 = \omega, \quad k_2 \approx \omega - \frac{m^2}{2\omega} \]
And finally oscillations

\[ A(\gamma \rightarrow \gamma') = \chi \left[ \exp(ik_1x) - \exp(ik_2x) \right] \]

\[ = \chi \exp(i\omega x) \left[ 1 - \exp \left( \frac{m^2_{\gamma'}}{2\omega} x \right) \right] \]

\[ P(\gamma \rightarrow \gamma') = 4\chi^2 \sin^2 \left( \frac{m^2_{\gamma'}}{4\omega} x \right) \]

Exactly the same structure as neutrino oscillations!!!
Modifications of the CMB
In the early Universe...

- We can have photon – hidden photon (WISP) oscillations!

- Small complication: Plasma photon plasma mass!

\[ \tan(2\,\delta) = 2 \frac{\mathcal{M}_{12}^X}{\mathcal{M}_{11}^X - \mathcal{M}_{22}^X} , \]
In the early Universe...

- We can have photon – hidden photon (WISP) oscillations!
- Small complication: Plasma mass!

\[
\tan(2\delta) = 2 \frac{\mathcal{M}_{12}^X}{\mathcal{M}_{11}^X - \mathcal{M}_{22}^X},
\]

Hidden photon mass
In the early Universe...

- We can have photon – hidden photon (WISP) oscillations!

- Small complication: Plasma photon plasma mass! Can be equal Resonance! Hidden photon mass Big effect!
Is observable...

- It transfers energy from Photons to hidden photons

\[ \Delta n_{\text{light species}} \]

- It is energy dependent!

\[ P(\gamma \rightarrow \gamma') = 4\chi^2 \sin^2 \left( \frac{m_{\gamma'}^2}{4\omega} \right) \]

- Can distort the CMB blackbody spectrum!!!
Powerful bounds... and a hint!

WMAP observes $\Delta n_{\text{light species}} \sim 2$
More Hints...

Transparency of the Universe

See M. Fairbairn at Patras 2009
The Universe should be quite opaque...

- ... for high energy photons

\[ \gamma + \gamma_{EBL} \rightarrow e^+ + e^- \]

\[ \gamma + \gamma_{CMB} \rightarrow e^+ + e^- \]
From far away $\gamma$-ray source

- Expect fewer high energy events!!
- Example 3C279

Different models for extragalactic background light
Observed...

• No such strong energy dependence!
Axion-like particles can help!

- Photon oscillates into ALP

![Diagram of photon oscillating into ALP]

Intergalactic magnetic field $\sim 10^{-13}$ T

- ALP doesn't see other photons

- Not absorbed

- Greater Transparency!!
ALPs help!

- Example 3C279

Different models
For extragalactic background light
Where are they???
Summary
Summary

- Astrophysics and Cosmology are a powerful probe of new light particles.

- Can test incredibly tiny interactions!!!

\[
\chi \sim 10^{-8} - 10^{-14}, \quad \epsilon \sim 10^{-14}, \quad g \sim \frac{1}{10^{10} \text{GeV}}
\]

- Interesting hints for new particles!

- Not always perfectly understood!

Beware of uncertainties!
3. Searching light particles in the Lab
Hints for new Physics

Model Building

Bottom-up (pheno)

Observations/Experiments

Top-down (theory)
Exploring fundamental high energy physics...

- The direct approach: MORE POWER
  LHC, Tevatron + ILC, CLIC

- Detects most things within energy range
- E.g. may find SUSY particles, WIMPs etc.
But...

- May miss very weakly interacting matter (Axions, WIMPs, WISPs...)
- Current maximal energy few TeV
Recycling... Complementary approaches
Light shining through walls
Light shining through walls

“Light shining through a wall”

Laser → [experiments] → Detector
Light shining through walls

“Light shining through a wall”

- Test $P_{\gamma \rightarrow X \rightarrow \gamma} \lesssim 10^{-20}$

- Enormous precision!

- Study extremely weak couplings!
Photons coming through the wall!

- It could be Axion(-like particle)s!

- Coupling to two photons:

$$\frac{1}{M} a \tilde{F} F \sim \frac{1}{M} a \vec{E} \cdot \vec{B}$$

$$P_{\gamma \rightarrow a \rightarrow \gamma} \sim N_{\text{pass}} \left( \frac{BL}{M} \right)^4$$
Light Shining Through Walls

- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR
Small coupling, small mass
WISPS = Weakly interacting sub-eV particles

- **Axions**

- **Massive hidden photons** (without B-field) = analog $\nu$-oscillations

- **Hidden photon + minicharged particle (MCP)**
Hidden Photons

LSW already competitive + testing interesting area
Coincidences?

- Neutrino masses:
  \[ m_\nu \sim \text{meV} \]

- Scale of dark energy:
  \[ \rho_\Lambda \sim (\text{meV})^4 \]

- Energy density of the Universe:
  \[ \rho_{\text{today}} \sim (\text{meV})^4 \]
Hidden Photons

LSW already competitive + testing interesting area

Dark energy scale
Something to hide?
Something to hide?

Use Hidden Photons© to communicate!
Practical applications ;-) 

- Communicating through the Earth
Practical applications ;-)
A cavity experiment
It's a Light shining through walls clone

“Light shining through a wall”

- Microwaves instead of laser

Emitter cavity

Detector cavity
Setup

- HF-Generator
- Emitter Cavity
- Detector Cavity
- Shielding
Advantages

- Resonant cavity setup: Cavity in production and regeneration region
  \[ \text{signal} \sim Q_1 \times Q_2 \]

- Microwave cavities can have very high Q-factors\(\sim 10^{11}\)!

- Sensitive to masses in the interesting \(\mu\text{eV}-\text{meV}\) range
Sensitive to variety of WISPs

- **Axions**
  \[ \frac{1}{M} \alpha \tilde{F} F \]

- **Massive hidden photons (without B-field)**
  = analog $\nu$-oscillations

- **Hidden photon + minicharged particle (MCP)**
Impressive sensitivity/discovery potential

**Hidden photons**

**Axion (-like particle)**s

![Graph showing the sensitivity and discovery potential of different particles and experiments.](image-url)
Impressive sensitivity/discovery potential

Hidden photons

Axion (-like particle)s

Experiments are underway:
@ UWA Perth
@ Yale
An aside:
Sub-Quantum interference
Resonant regeneration

signal $\sim Q_1 \times Q_2$

detector cavity

- The detector acts as high quality oscillator driven by (small) external force (ALPs, HPs...)
- Amplification because the photon amplitude adds up in each pass
Less than one photon inside cavity...

- Already at relevant power levels

\[ P_{\text{out}} \sim P_{\text{loss}} = \omega \frac{E_{\text{stored}}}{Q} = \omega \frac{\hbar \omega}{Q} \]

\[ \sim 2.6 \times 10^{-19} \text{ W} \left( \frac{f}{\text{GHz}} \right)^2 \left( \frac{10^5}{Q} \right) \gg 10^{-23} \text{ W} \]

- Even more relevant for optical experiments (higher frequency)

Is there amplification in this “sub-quantum” regime?
A test/demonstration setup...

- Do we see the (fractional) photon interfering with itself? (i.e. amplitudes adding up)

Look at resonance curve
A true measurement...(preliminary!!)

Interference works!
Laser Polarization Experiments
Dichroism (Rotation)

- Coupling

\[ \mathcal{L} \sim g a F^{\mu \nu} \tilde{F}_{\mu \nu} \sim g a \vec{E} \cdot \vec{B} \]

Before

\[ E_L \quad E_\perp \]

\[ B_{\text{Ext}} \]

Rotation \( \varepsilon \)

After

\[ E_L \quad E_\perp \]

\[ B_{\text{Ext}} \]

\[ \varepsilon \approx -N \left( g B L / 4 \right)^2 \sin(2\theta) \]
Virtual ALP production leads to Birefringence

\[ \psi \approx \frac{N}{6} \left( \frac{g B L}{4} \right)^2 \frac{m_a^2 L}{\omega} \sin(2\theta) \]
Bounds on ALPs

K. Ehret et al. 1004.1313
Pair production with a Laser

Laserphoton

(Milli-)charged Particles

External B-Feld
Pairproduction with a Laser

Laserphoton

(Milli-)charged Particles

External B-Feld

Non-perturbative: Why? -> Homework
Dichroism (Rotation)

- Pairproduction leads to an "absorption" of Laser light
- Pairproduction depends on relative orientation of Laser polarization and B-field

\[ \text{rotation } \varepsilon \]

H. Gies, JJ and A. Ringwald
hep-ph/0607118
\[ \tan(\theta - \Delta \theta) = \frac{E_{||}}{E_{\perp}} = \frac{E_{||}^0}{E_{\perp}^0} \exp \left( -\frac{1}{2} (\kappa_{||} - \kappa_{\perp}) \ell \right) \]

\[ \Delta \theta \approx \frac{1}{4} (\kappa_{||} - \kappa_{\perp}) \ell \sin(2\theta) \]
Minicharges

One of the best laboratory bounds!
Helioscopes
Helioscopes

CAST@CERN
SUMICO@Tokyo

“Light shining through a wall”
Perfect for astronomy in Durham ;-)

This isn't Dark matter, I just forgot to take off the lens cap.
Sensitivity

Axion band
Searching light
Dark Matter
- Haloscopes

See, e.g.
G. Rybka at Patras 2009
Axions: Two photon coupling

- Photon generation from axions!

Axion (dark matter) - Photon (amplified in cavity) - External B-field
Electricity from Dark Matter ;-).

- Photon Regeneration

Axion (dark matter) → Photon (amplified in resonator) → external B-field

$10^{-23}$W!
Axions in Cavity

Superconducting magnet

Ultra-low noise microwave receiver

High-Q microwave cavity

$B_0$

Single real photon

Virtual photon
Signal: Total energy of Axion

\[ h \nu = m_a c^2 \left[ 1 + O(\beta^2 \sim 10^{-6}) \right] \]

Virial velocity in galaxy halo!
Optimizing

\[ P \sim 10^{-22} \, W \frac{Vol}{10l} \left( \frac{B}{6T} \right)^2 \min \left( 1, Q \frac{\Delta \nu}{\nu} \right) \]

\[ s/n = \frac{\text{signal}}{\text{noise}} \sim \frac{P}{kT} \sqrt{\frac{t}{\Delta \nu}} \]
## How it looks I

### Magnet with Insert (side view)

- **Stepping motors**
- **Liquid helium**
- **Amplifier, refrigerator, Tuner, Tuning rods, Superconducting magnet 8T, 6 tons**

| Pumped LHe | T ~ 1.5 k |
|------------|-----------|

### Magnet (Wang NMR Inc.)

- **8 T, 1 m x 60 cm Ø**
How it looks II

High-Q Cavity (~200,000)

Experimental Insert
Results
Exciting times!!!

Axion band
Works for general WISP Dark Matter

Nelson and J. Scholtz 1105.2812
P. Arias, D. Cadamuro, M. Goodsell, JJ, J. Redondo A. Ringwald 1201.5902
ALPs

\[ \log_{10} g [\text{GeV}^{-1}] \]

\[ \log_{10} m_{\phi} [\text{eV}] \]

-5
-8
-11
-14
-17
-20
-9
-6
-3
0
3
6

ALPS

CAST+Sumico

EBL

Axion models

HB

\[ \tau_{\text{ALP}} < 10^{17} \text{s} \]

Standard ALP CDM \( (m_1 = m_0) \)

\[ m_1 > 3H(T_{eq}) \]

\[ \frac{m_1}{m_0} = (\Lambda/T)^{\beta} \]
Measuring structure (formation)

See, e.g. S. Asztalos at Patras 2007
Example: infall of matter

Features in the velocity/energy spectrum of dark matter
Detect these features in ADMX

Integration:
Resolution:

FFT

Maxwellian

Fine-Structure

ΔE/E ~ 10^{-17}

ΔE/E ~ 10^{-6}

M_{axion}
Frequency (energy)
Searching WISPishs*

*Weakly interacting sub-TeV particles
Why?

- Lots of interest from astrophysics
- Pamela, DAMA, CoGent...
and \((g-2)_\mu\)

- \(2.3 \sigma\) deviation from SM observed

- Hidden photon could account for this!

\[
\Delta(g - 2)_\mu = \frac{\alpha}{4\pi} f \left( \frac{m_{\gamma'}}{m_\mu} \right)
\]
Fixed targets

Displaced Vertex

\[ E_{\gamma'} \approx E_{\text{beam}} \]

\[ E_{e^-} \approx m_{\gamma'} \]

[Toro '09; Andreas '10]

Detector
Medium energy, high current

- Medium energies of beam 100 MeV–50 GeV
- BUT: High current $\sim mA \sim 10^{16} e^-/s$

Test weak interactions!!
Many beams, many chances...

- DESY
- Jefferson Lab
- Mainz Microtron (MaMi)
- ...
Current state

Cf. S. Andreas, M. Goodsell, A. Ringwald 1109.2869
Near future
Even More Hints...

**Muonic Hydrogen**

R. Pohl et al. Nature 466, 213, 2010
JJ and S. Roy 1008.3536
The Lamb shift a test of new and old physics

- In ordinary QM $2s_{1/2}$ and $2p_{1/2}$ level degenerate

- This is a very peculiar feature of Coulomb's law,

\[ F(r) \sim \frac{1}{r^2} \]

Deviations from Coulomb's law split $2s_{1/2}$ and $2p_{1/2}$

Measuring the Lamb shift is a precise test of Coulomb's law!
Known contributions...

• Finite size of proton:

• QED effects:

\[ \delta V(r) \sim \delta(r) \]
Test for hidden photons and MCPs

- WISPs modify Coulomb's law

- Hidden photons:

\[ \delta V \sim \alpha q^2 \chi^2 \frac{\exp(-m \gamma' r)}{r} \]

- Minicharged particles

\[ \delta V(r) \approx \frac{Q \alpha}{r} \left[ \frac{\alpha e^2}{4 \sqrt{\pi}} \frac{\exp(-2mr)}{(mr)^{3/2}} \right] \]
New bounds...
A puzzling measurement

• Use muonic hydrogen, i.e.

\[ e^- \rightarrow \mu^- \]

• Recently measured

\[ \Delta E_{s_F=1, p_{3/2}} = -206.295000(3) \text{meV} \]

• Compared to expected

\[ \Delta E_{s_F=1, p_{3/2}} = -205.984(062) \text{meV} \]

5 \( \sigma \) deviation!!!
Can it be hidden photons???

- No!
- Wrong sign; hydrogen would be more strongly affected!

\[ e^- \rightarrow \mu^- \]

Need more creative solution!
Can it be hidden photons???

- No!
- Wrong sign; hydrogen would be more strongly affected!

\[ e^- \rightarrow \mu^- \]

Need more creative solution!

Homework ;-)
Experimental Homework.

- WISPs may be visible in deviations of Coulomb’s law

Something to Revive?
Tests of Coulomb’s law
Cavendish Experiments

Charged with Q

uncharged

Measure Voltage
= 0 for exact Coulomb
Quite sensitive

- Best experiment 40 years old!!!!

E. Williams, J. Faller and H. Hill PRL 26, 721, 1971
cm-scale Cavendish test with precision ~ few $10^{-15}$
Conclusions
Conclusions

• Good Physics Case for Axions, WIMPs and WISPs

explore `The Low Energy Frontier`

• Low energy experiments/observations test energy scales much higher than accelerators

Complementary!

• May provide information on hidden sectors and thereby into the underlying fundamental theory

• Surprises (like Lorentz symmetry violation) possible!