Motivation for WIMPs and WISPs *

I. Antoniadis

CERN

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1. WIMPs
2. WISPs from string compactifications: moduli, axions and ALPs **
3. Extra $U(1)$s and anomaly induced terms
   - new short-range forces and 5th force experiments
   - axion alternatives and optical experiments

*WeaklyInteractingMassiveParticle WeaklyInteractingSub-eVParticle

**AxionLikeParticle

WIMPs: Dark matter candidates

Most plausible characteristics:

- mass: $\mathcal{O}(10^2 - 10^3)$ GeV
- coupling: weak interactions, em neutral
- life-time: cosmologically stable $\Rightarrow$

  need discrete symmetry to protect decay

  e.g. R-parity in SUSY, T-parity in little Higgs models,
  KK-parity in models with extra TeV-dimensions, etc
- spin: fermion or boson

Intensive search in the following years:

direct and indirect detection experiments + particle accelerators

Other cases may also work such as: keV gravitino, axions, etc

see G. Servant's talk

WISPs from BSM models

Examples of WISPs: ALPs, fifth force, . . .

ALPs: mass and decay constant (m_a, f_a): arbitrary parameters

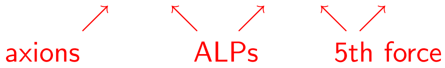
standard Peccei-Quinn axions: $m_a f_a = m_\pi f_\pi$ (strong CP problem)

Generic in string theory compactifications

but varying properties in different classes of models

- supersymmetric compactifications with high string scale
- low string scale and large extra dimensions

$\Rightarrow$ light pseudoscalars, extra $U(1)$s, scalars (+ SUSY partners) : WISPs

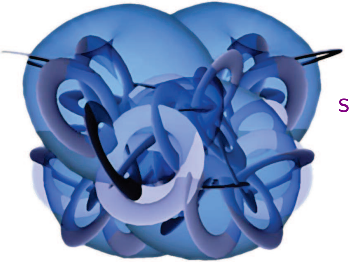


axions ALPs 5th force

String moduli

String compactifications from 10/11 to 4 dims → scalar moduli

arbitrary VEVs: parametrize the compactification manifold



size of cycles, shapes, . . . , string coupling

- $N = 1$ SUSY $\Rightarrow$ complexification: scalar + i pseudoscalar $\equiv \phi_i$
- Low energy couplings: functions of moduli

e.g. gauge couplings: $\frac{1}{g_a^2} F_a^2$ a: gauge group

$N = 1$ SUSY $\Rrightarrow$ holomorphicity: $\frac{1}{g_a^2} = \mathrm{Re}\, f_a(\phi_i)$

SUSY transformation $\Rrightarrow$ moduli-dependent θ-angles:

$$\theta_a F_a \tilde{F}_a \quad \text{with} \quad \theta_a = \mathrm{Im}\, f_a(\phi_i)$$

In superspace: $\int d^2\theta\, f(\phi_i)\, W_a^2 \leftarrow$ gauge field-strength chiral superfield

Moduli stabilization

If moduli massless → inconsistent

long range forces, cosmological production, accelerators

Outstanding problem: moduli stabilization

- avoid experimental conflict
- fix their VEVs ⇛ compute low energy couplings

Generate moduli potential:
- preserving SUSY
- after SUSY breaking

via

• non-perturbative effects or by

• turn-on fluxes: constant field-strengths of generalized gauge potentials

gauge fields: internal magnetic fields

generalization: higher rank antisymmetric tensors

string axions

Pseudoscalars: approximate shift symmetries (PQ type)

$\Rightarrow$ candidates for axions and ALPs

perturbation theory: $a\sum_i c_i F_i \tilde{F}_i \equiv a\sum_i c_i F_i \wedge F_i$

Poincaré duals to 2-index antisymmetric tensors $B_{\mu\nu} \equiv B_2$

$\partial_\mu a = \epsilon_{\mu\nu\lambda\rho}\partial^\nu B^{\lambda\rho}$ also $F \wedge F = \partial_\mu \omega^\mu \leftarrow$ Chern-Simons current

$$\omega_\mu = \epsilon_{\mu\nu\lambda\rho} A^\nu F^{\lambda\rho} \quad \Rightarrow (dB_2)\sum_i c_i (A_i F_i)$$

- Heterotic: universal axion complexified with dilaton (string coupling)
- Other string theories: several

shift symmetries broken by non-perturbative effects

$\rightarrow$ in general (m_a, f_a): independent parameters

Particular values of (m_a, f_a)

m_a: - dynamical scale of new strong interactions

- string scale
- suppressed by compactification volume

  axion in the bulk of large extra dimensions

- related to SUSY breaking:

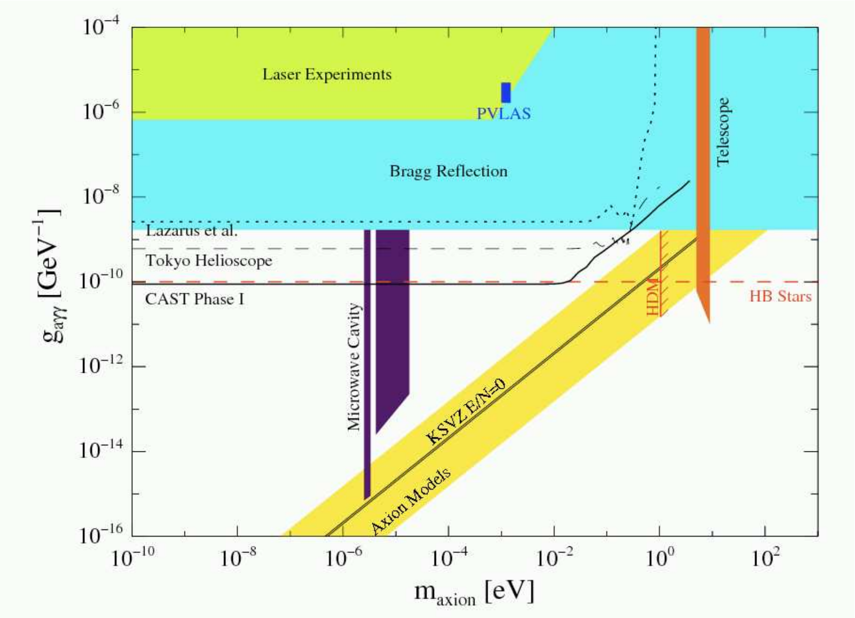
$$m_a \sim \frac{m_s^2}{M_p} \begin{array}{l} \leftarrow \ \text{su}\not{\text{s}}\text{y in SM} \\ \leftarrow \text{Planck mass} \end{array} \sim 10^{-3} \text{ eV}$$

f_a: - Planck scale

- string scale
- suppressed by compactification volume
- VEV of a scalar field

astrophysical constraints $\Rightarrow \ f_a \gtrsim 10^{10}$ GeV

Experimental bounds on Axion Like Particles



Extra $U(1)$'s: present in many SM extensions

- GUTs with rank > 4

- general feature of string compactifications

e.g. in D-brane models: $U(N)$ groups away from orientifolds

Masses and couplings:

- $m_X = g_X v \leftarrow$ VEV of a Higgs field breaking $U(1)_X$

- $m_X = g_X M \leftarrow$ string (or new physics) scale

$\Rightarrow$ small mass from coupling suppression:

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

1. Standard Model fermions charged under $U(1)_X$

   accelerator experimental constraints $\Rightarrow$

   m_X heavy or light with small coupling $m_X/g_X \gtrsim$ TeV

   e.g. $g_X \lesssim 10^{-12}$ if $m_X \sim$ subeV → 5th force experiments

   for instance in models with large extra dimensions

   anomalous $U(1)_X$ with Green-Schwarz anomaly cancellation

2. All Standard Model fermions neutral under X

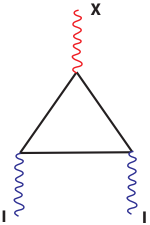
   but possible extra heavy fermions charged under SM and $U(1)_X$

   $\Rightarrow$ interesting effects: - novel anomaly driven signatures [20]

   - small X-photon kinetic mixing →

   'millicharged' fermions originally hidden under SM   see Jaeckel's talk

Green-Schwarz anomaly cancellation



$$= k_I^X \sim \mathrm{Tr}\, Q_X Q_I^2 \; \rightarrow \; \text{axion } \theta : \; \delta X = d\Lambda \quad \delta\theta = -m_X \Lambda$$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + m_X X)^2 + \frac{\theta}{m_X} k_I^X \,\mathrm{Tr}\, F_I \wedge F_I$$

cancel the anomaly

D-brane models: $U(1)_X$ gauge boson acquires a mass

but global symmetry remains in perturbation theory

5th force and microgravity experiments

$m_X = g_X M \Rrightarrow$ small mass from coupling suppression

e.g. in models with large extra dims if X propagates in (part of) the bulk

but localized mass from anomalies induced by localized chiral states

I.A.-Arkani-Hamed-Dimopoulos-Dvali '98, I.A.-Benakli-Maillard-Laugier '02

$g_X \sim 1/\sqrt{V_X}$ (volume suppressed) $\gtrsim M_s/M_P \sim 10^{-16}$ $\qquad M_s \sim$ TeV

$$\Rrightarrow \quad m_X \gtrsim M_s^2/M_P \simeq 10^{-4}\,\mathrm{eV}$$ → submm range

can be experimentally tested for any number of extra dimensions

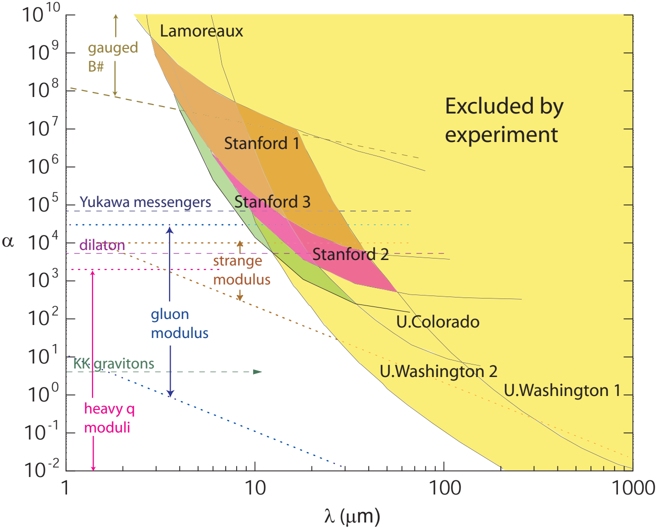
Light $U(1)$ gauge bosons: no derivative couplings

$\Rrightarrow$ for the same mass much stronger than gravity: $\gtrsim 10^6$

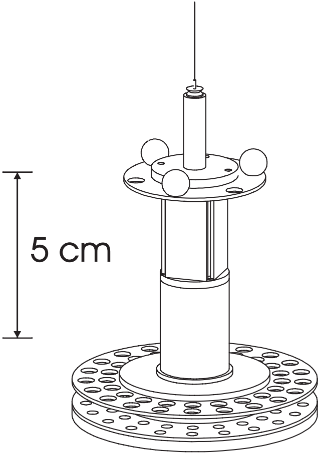
→ see Hoedl's talk

Experimental limits on short distance forces

$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Adelberger et al. '06

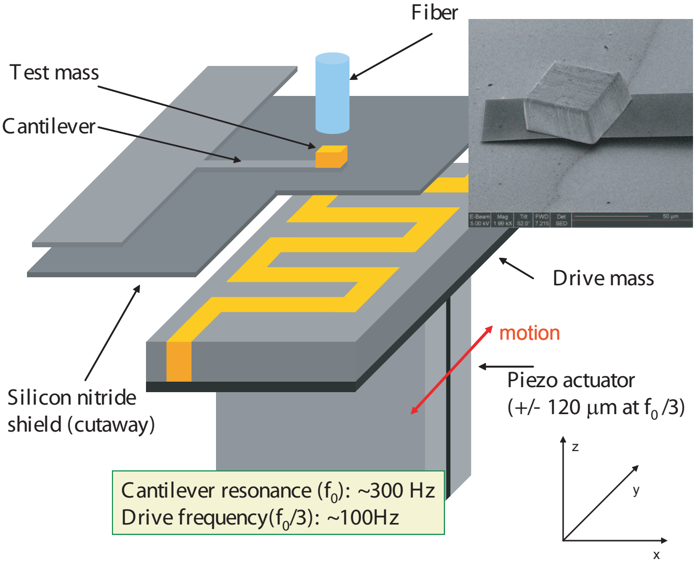


$\lambda \sim 55\ \mu$m

- dark-energy length scale $\approx 85\mu$m

improved bounds in the range 5-15 μm

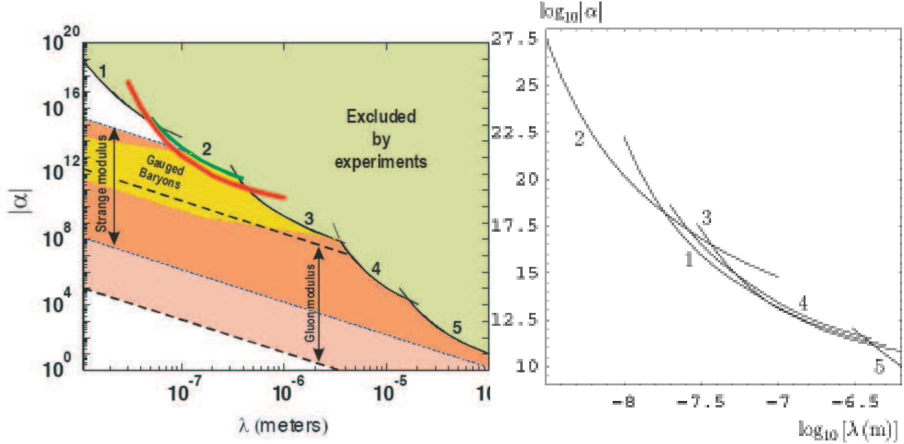
Geraci-Smullin-Weld-Chiaverini-Kapitulnik '08



Cantilever resonance (f_0): ~300 Hz
Drive frequency($f_0/3$): ~100Hz

improved bounds from Casimir effect in the nm range

Decca-Fischbach et al '07, '08



5: Colorado   4: Stanford

3: Lamoureaux   1: Mohideen et al.

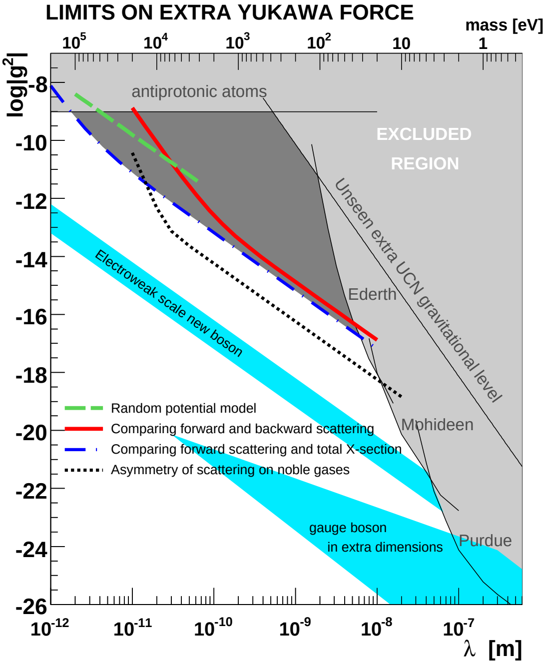
Neutron scattering:

bounds in the range

$\sim$ 1pm - 1nm [11]

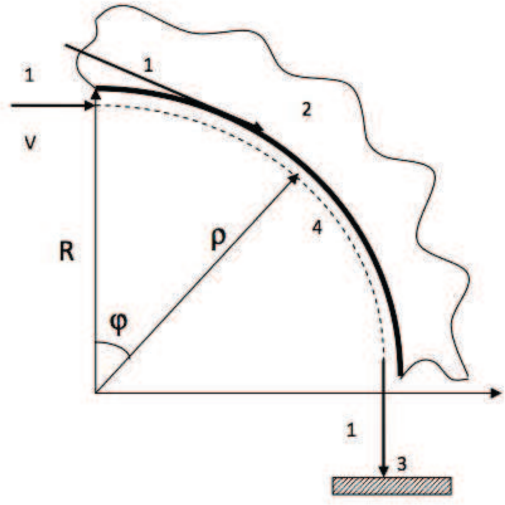
GRANIT:

Nesvizhevsky-Pignol-Protasov '07



Neutron whispering gallery

Centrifugal quantum states of neutrons

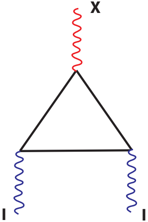


challenging case: all new fermions charged under SM and X unobservable

either heavier than LHC energy or very weakly coupled

naive expectation from decoupling $\Rightarrow$

at low energies double suppression: coupling + mass



e.g. X coupling to SM gauge bosons:

loop factor $\times$ E^2/M_f^2

dim-6 effective operator $F_X F_I F_I$

exception: mixed $U(1)$ anomalies

- Non trivial anomaly cancellation → new dimensionless coupling

  $\Rightarrow$ $U(1)_X$ may couple to SM gauge bosons with no mass suppression

$U(1)_X \times U(1)_A$ example and Chern-Simons terms

X anomalous, A anomaly free : cancel mixed anomalies

$\Rightarrow$ also possible Chern-Simons terms: I.A.-Kiritsis-Tomaras '00

Coriano-Irges-Kiritsis '05, Anastasopoulos-Bianchi-Dudas-Kiritsis '06

$$\mathcal{L} = -\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{1}{2}(D\theta_X)^2 - \frac{\kappa}{m_X}\, D\theta_X \wedge A \wedge F_A + \dots \qquad D = d + m_X X$$

$\rightarrow$ unitary gauge: $-\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{m_X^2}{2}X^2 - \kappa\, X \wedge A \wedge F_A + \dots$

- $A \equiv \gamma \Rightarrow$ effects in optical experiments

  I.A.-Boyarsky-Ruchayskiy '06, '07
- $A \equiv Z, W \Rightarrow$ LHC physics

  I.A.-Boyarsky-Espahbodi-Ruchayskiy-Wells '09

$A = \gamma \Rightarrow$ axion alternatives **I.A.-Boyarsky-Ruchayskiy '06, '07**

$X \wedge A \wedge F_A \Rightarrow XA$ mixing in the presence of magnetic field $F_A \neq 0$

linearly polarized photon gets a mass ⇒ axion behavior, interesting effects

2 parameters: mass m_X, C-S coupling $\kappa \leftarrow$ dimensionless

$X_\mu \leftrightarrow$ axion: $a \equiv \theta_X$ with mass $m_a = m_X$ and decay constant $f_a \equiv \frac{m_X}{\kappa}$

however without axion constraint $m_a f_a = m_\pi f_\pi$

astrophysical constraints $\Rightarrow m_X/\kappa \gtrsim 10^{10}$ GeV $\Rightarrow \kappa \lesssim 10^{-19} m_X/\mathrm{eV}$

can be evaded if X-current conserved at stellar energies

Idea from QED with photon mass: em current conservation ⇒

high energy longitudinal γ emission suppressed by m_γ/E

Evading the astrophysics bounds

X-current is not conserved: $j_X^\mu = \kappa \epsilon^{\mu\nu\lambda\rho} A_\nu F^A_{\lambda\rho} \Rightarrow \partial_\mu j_X^\mu = \kappa F_A \wedge F_A$

However $\mathcal{L}$ effective up to a scale $\Lambda \lesssim m_X/\kappa$ (unitarity bound)

Idea: modify the theory at Λ so that j_X^μ becomes conserved

e.g. integrate massive fermions f of mass $m_f \Rightarrow$

$$\delta\mathcal{L} = \kappa\, A \wedge X \wedge F_A + \kappa\theta_X \frac{m_f^2}{\Box + m_f^2} F_A \wedge F_A - \kappa(\partial_\mu X^\mu) \frac{1}{\Box + m_f^2} F_A \wedge F_A$$

$E << m_f$: $\kappa\, A \wedge X \wedge F_A + \kappa\theta_X F_A \wedge F_A = \kappa A \wedge D\theta_X \wedge F_A$ as before

$E >> m_f$: $\kappa\, A \wedge X \wedge F_A + \kappa(\partial_\mu X^\mu)\frac{1}{\Box} F_A \wedge F_A$

X-current becomes at high energies:

$$j_X^\mu = \kappa\epsilon^{\mu\nu\lambda\rho} A_\nu F^A_{\lambda\rho} - \kappa\frac{\partial^\mu}{\Box} F_A \tilde{F}_A \;\Rightarrow\; \partial_\mu j_X^\mu = 0$$

longitudinal X production is then suppressed by $(m_X/E)^2$

avoid astrophysical bounds $\Rightarrow$ $m_f \lesssim$ keV $\leftarrow$ stellar energies

$$\Rightarrow\; \kappa m_X \lesssim 10^{-10}\ \text{eV}$$

- gauging axion shift $\Rightarrow$ no $f_a \leftrightarrow m_a$ relation
- conserved current in star emission $\Rightarrow$ weakened bound on f_a

\- can accommodate PVLAS type data

\- $m_X \sim 1 - 10^{-3}$ eV : need $\kappa \sim 10^{-9} - 10^{-6}$

small values of κ may also be obtained from millicharged keV fermions f

Conclusions

- WISPs: light moduli, axions, ALPs, extra U(1)s

  generic appearance from string compactifications

  in particular ALPs with no mass-coupling relation

- New short range forces within the reach of microgravity experiments

- Extra $U(1)$s: novel anomaly induced effects

  new dimensionless coupling to SM gauge bosons

  $\Rightarrow$ gauged PQ symmetries and axion alternatives

  avoiding mass/coupling relation and strong astrophysical bounds

- Non-accelerator experiments: another window to BSM physics