Dynamical Relaxation for the Hierarchy Problem and Dark Matter

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Outline

1. Dynamical Relaxation for the Hierarchy Problem

2. Precision Measurement for Dark Matter

Dynamical Relaxation for Fine-Tuning

with

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A New Approach to Fine-Tuning?

current approaches:

Anthropics/Multiverse

- currently lacks mathematical rigor

Dynamics (SUSY, compositeness, …)

- Hierarchy Problem

  lack new physics at weak scale (LHC, direct detection, EDMs,…)

- CC Problem

  probed meV scale a long time ago

- Strong CP Problem

  axion as instructive example?

Dynamical Relaxation

make fundamental constant dynamical

accept large (initial) value, drive parameter small naturally

replaces symmetry with dynamics in time

- shares some elements of axion solution to strong CP (dynamical EDM)
- we present solution to hierarchy problem
- CC?? Abbott (1985)

Hierarchy Problem

Dynamics

- new physics at weak scale, cuts off loops
- theory natural above weak scale

Anthropics/Multiverse

- theory is tuned

New class of solutions to hierarchy problem

- theory natural
- minimal model has no new physics at weak scale
- colliders may see new particles, but Higgs looks tuned

Caveats

- judge models by how much raise cutoff

  $\mu \sim 3 \times 10^4\,\mathrm{GeV} \to 10^8\,\mathrm{GeV}$

- goal: technically natural

- requires large (above cutoff) field excursions

Minimal Model

particle content below cutoff: SM + QCD axion + inflaton

changes to axion:

- softly-broken shift symmetry (via coupling to Higgs)
- large (non-compact) field range

Fuente, Saraswat, Sundrum (2014)
Silverstein, Westphal (2008)

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

g is small, dimensionful parameter ➜ helps set weak scale
technically natural since spurion

this + inflaton solves hierarchy problem

Mechanism

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

What does this model do?

during inflation ϕ slow-rolls: scans Higgs mass

zero is special by dynamics: Higgs gets a VEV

axion potential barriers grow: stops evolution

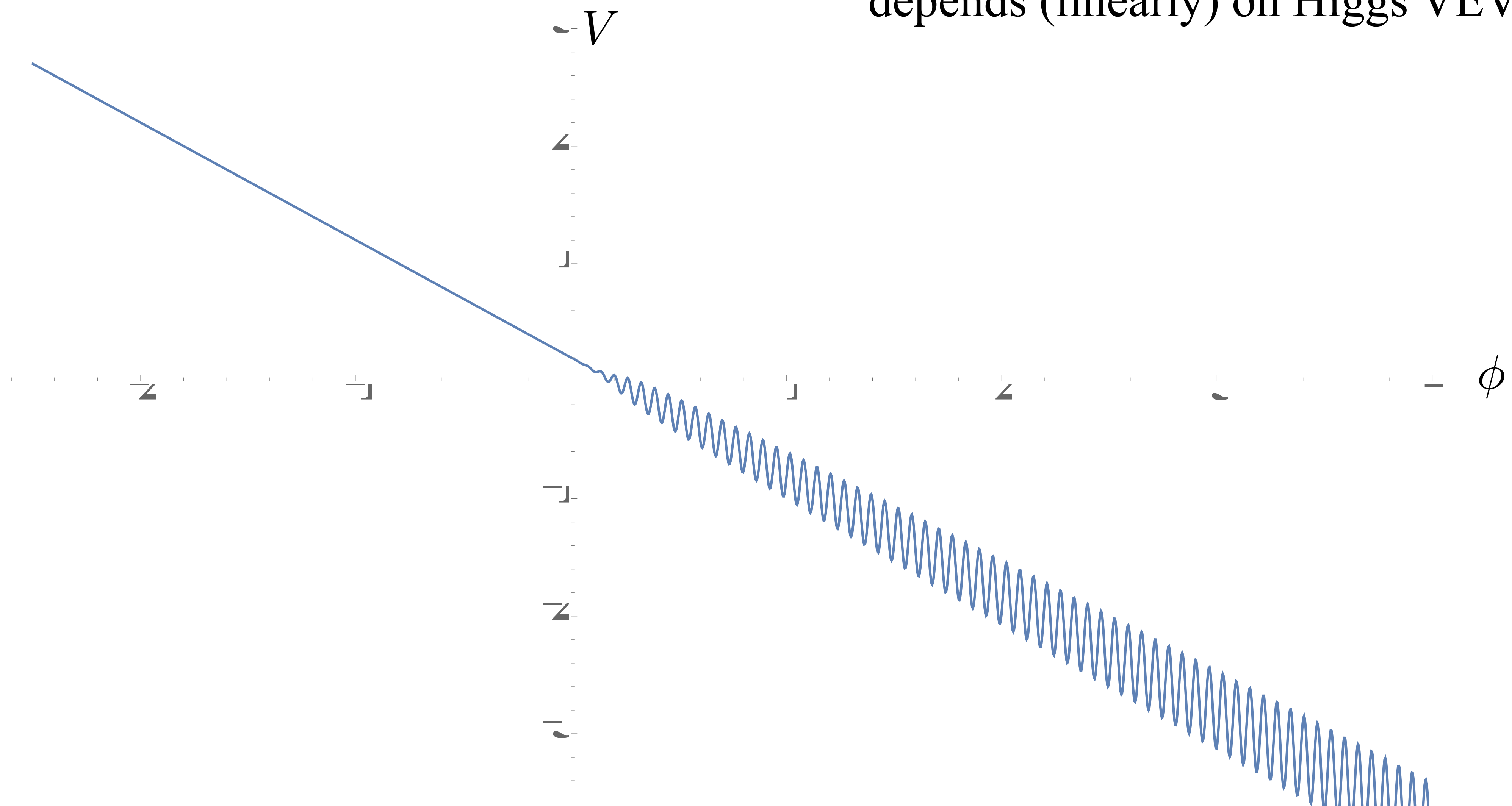
call ϕ the “relaxion”

Axion Potential

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \Lambda^4 \cos(\phi/f)$$

Axion mass → 0 as quark masses → 0

depends (linearly) on Higgs VEV



Requirements

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \Lambda^4 \cos(\phi/f)$$

field range: $\Delta\phi \sim \mu^2/g$

e-folds required: $N \gtrsim \frac{H_{\rm i}^2}{g^2}$

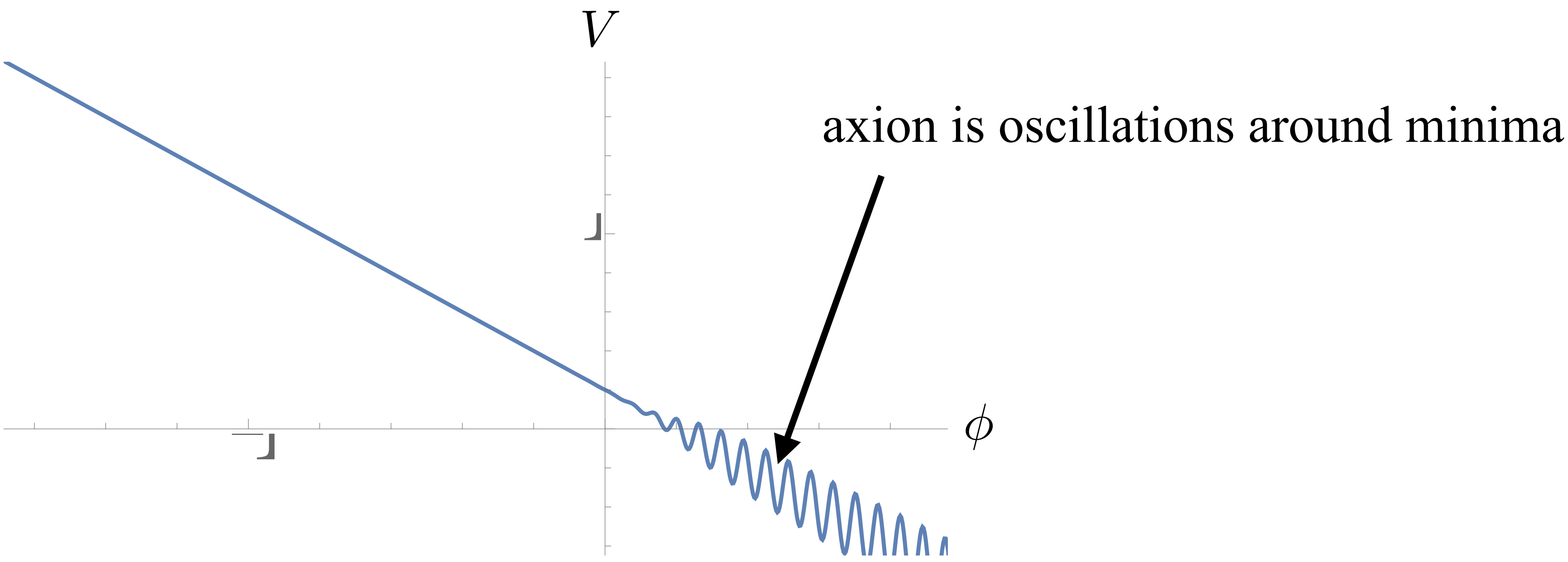
inflaton dominates: $H_{\rm i} > \frac{\mu^2}{M_{\rm pl}}$

classical beats quantum: $H_{\rm i} < (g\mu^2)^{\frac{1}{3}}$

barriers form: $g\mu^2 f \sim \Lambda^4$

interestingly, there is parameter space that works!

Strong CP Problem



slope shifts minima ➜ strong CP problem!

QCD Axion

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \Lambda^4 \cos(\phi/f)$$

Two solutions:

1. decrease slope dynamically after inflation: e.g. $g^2 \to k\sigma^2\phi^2$

σ is inflaton

result:

$$\mu < \left(\frac{\Lambda^4 M_{\rm pl}^3}{f}\right)^{\frac{1}{6}} \theta^{\frac{1}{4}} \sim 3 \times 10^4\,\mathrm{GeV} \times \left(\frac{10^9\,\mathrm{GeV}}{f}\right)^{\frac{1}{6}} \left(\frac{\theta}{10^{-10}}\right)^{\frac{1}{4}}$$

(or ~ 10^6 GeV if loosen eternal inflation constraint)

solves hierarchy, strong CP, and can give DM

Non-QCD Axion

2. non-QCD axion: same constraints, now Λ up to ~ 100 GeV

$$V \ni (-\mu^2 + g\phi)|h|^2 + g^2\phi^2 + \Lambda^4 \cos(\phi/f)$$

add new weak scale fermions charged under new strong group

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y h L N^c + \tilde{y} h^\dagger L^c N$$

$$\mu < \left(\frac{\Lambda^4 M_{\rm pl}^3}{f}\right)^{\frac{1}{6}} \sim 10^8\,\text{GeV} \times \left(\frac{\Lambda}{10\,\text{GeV}}\right)^{\frac{2}{3}} \left(\frac{10^9\text{GeV}}{f}\right)^{\frac{1}{6}}$$

rich phenomenology of new bound states

Predictions

Dynamics (SUSY, extra dimensions…) ➜ weak-scale particles (e.g. WIMP)

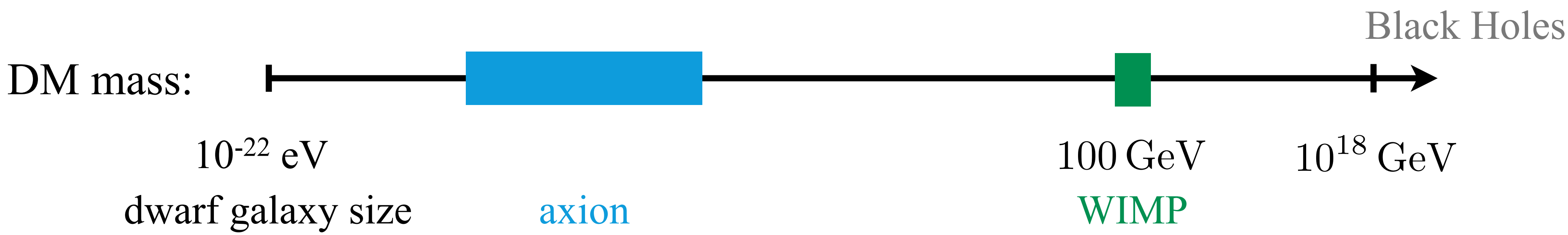
Dynamical Relaxation ➜ light particles (e.g. axion)

- changed predictions for axion DM
- axion DM fluctuates Higgs VEV ➜ oscillates all scales (electron mass…) potentially observable (at low cutoff), would be true proof of mechanism

Precision Measurement for Dark Matter

Dark Matter Candidates

What do we know about dark matter?



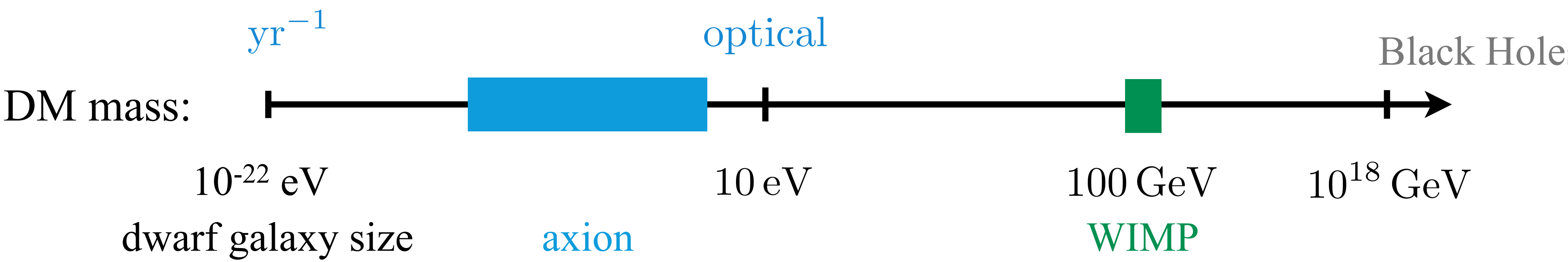
WIMP is well-motivated, significant direct detection effort focused on WIMPs,

Axion is other best-motivated candidate, only a small fraction of parameter space covered

Huge DM parameter space currently unexplored!

Direct Detection

How can we detect DM?



$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4$ ➔ high phase space density if $m \lesssim 10\,{\rm eV}$

field-like (e.g. axion)
new detectors required

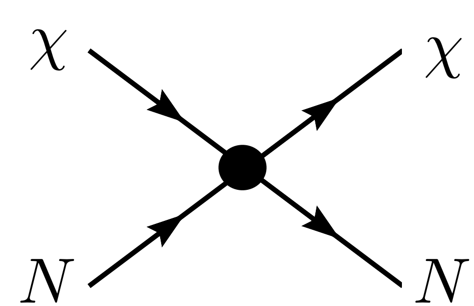
Described as classical field *a(t,x)*

Detect coherent effects of entire field,
not single particle scatterings

Frequency range accessible!

particle-like (e.g. WIMP)
particle detectors best

Search for single, hard particle scattering



Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities (symmetry, effective field theory):

scalar	pseudo-scalar (axion)	$a\,F\tilde{F}$	E&M
		$a\,G\tilde{G}$	QCD
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	matter (spin)
	scalar	$\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$	SM properties (electron mass)
vector	vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	charged
		$F'_{\mu\nu}F^{\mu\nu}$	DM-photon mixing
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	dipole moment
	axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	spin

current searches (e.g ADMX)

use other couplings

e.g. can reach axion parameter space considered impossible

Can cover all these possibilities!

arXiv:1512.06165

Cosmic Axion Spin Precession Experiment (CASPEr)

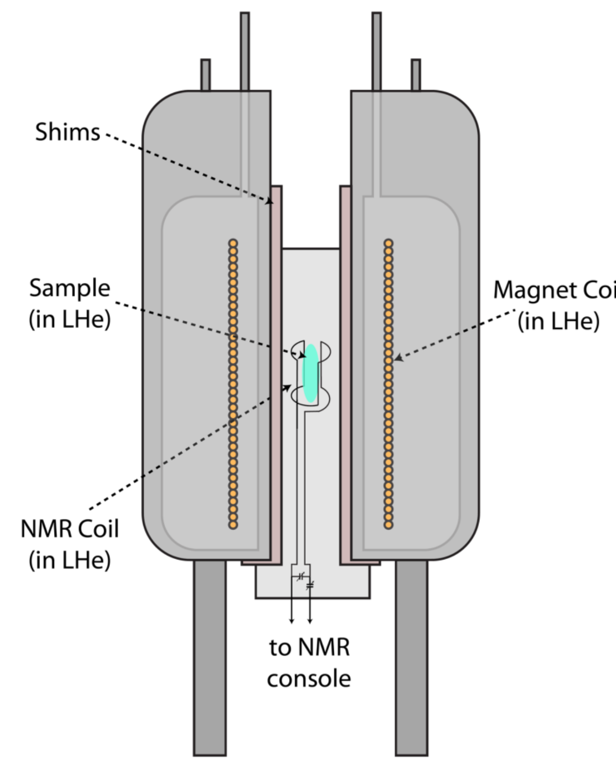
Detect axion with NMR and high-precision magnetometry

New field of axion direct detection, similar to early stages of WIMP direct detection

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies

Construction beginning at Mainz and BU



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Possibilities for Light Dark Matter

All UV theories summarized by only a few possibilities (symmetry, effective field theory):

- scalar
  - pseudo-scalar (axion)
    - $a\,F\tilde{F}$ — E&M — current searches (e.g ADMX)
    - $a\,G\tilde{G}$ — QCD — CASPEr
    - $(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$ — matter (spin) — CASPEr
  - scalar
    - $\phi\,h^\dagger h,\ \phi\,\mathcal{O}_{\rm SM}$ — SM properties (electron mass) — accelerometers
- vector
  - vector
    - $A'_\mu\bar{\psi}\gamma^\mu\psi$ — charged — accelerometers
    - $F'_{\mu\nu}F^{\mu\nu}$ — DM-photon mixing — DM Radio (in construction at SLAC)
    - $F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$ — dipole moment — CASPEr
  - axial-vector
    - $A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$ — spin — CASPEr

Can cover all these possibilities!

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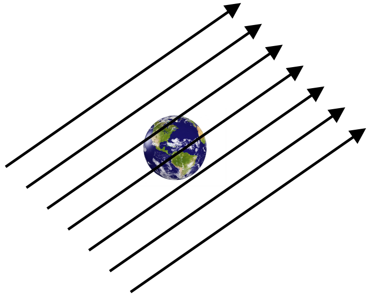
Force from Dark Matter

with couplings $\phi h^\dagger h$, $\phi \mathcal{O}_{\rm SM}$, $A'_\mu \bar{\psi}\gamma^\mu\psi$ DM acts as a field

exerts force on matter: $F \propto g\sqrt{\rho_{\rm DM}}\cos(m_{\rm DM}t)$

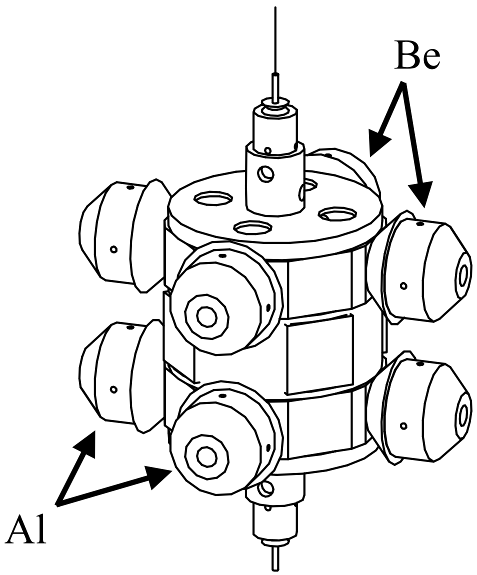


Force is oscillatory and equivalence-principle violating

scalar DM would also cause oscillation of "constants" e.g. electron mass

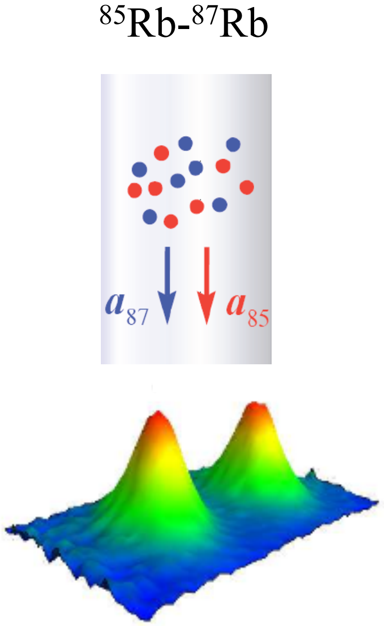
New Direct Detection Experiments:

Torsion Balances



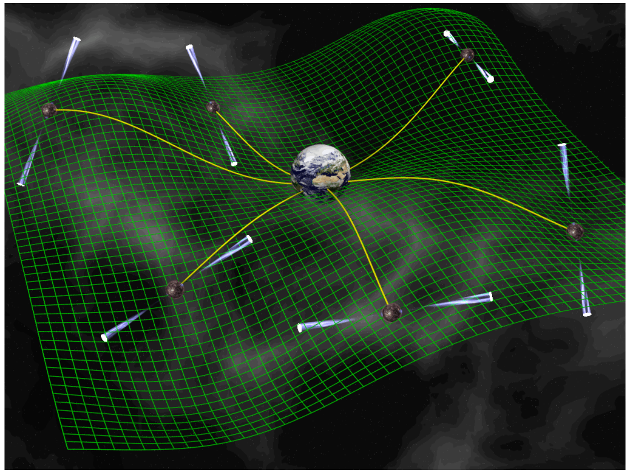
Eot-Wash analysis underway

Atom Interferometers



In construction Kasevich/Hogan groups

Pulsar Timing Arrays



Can probe orders of magnitude past current limits

arXiv:1512.06165

Summary

Dynamical relaxation provides new class of solutions to hierarchy problem

physics at weak scale not required

SUSY motivates WIMPs

dynamical relaxation motivates lighter (axion) DM

Precision measurement is a powerful tool for such light fields

new technologies for particle physics beyond traditional particle detectors

1. Cosmic Axion Spin Precession Experiment (CASPEr) - in construction at BU and Mainz
2. Accelerometers for DM direct detection - searches by Eot-Wash and Stanford groups
3. DM Radio - in construction at Stanford
4. Atom Interferometry for gravitational wave detection

Many more possibilities…