Some Thoughts on the Relaxion

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Outline

1. Raising the cutoff

2. Relaxion inflation

3. Other phenomenology (e.g. DM, 750 GeV)

Raising the cutoff

Reverse Relaxion

Would like to solve hierarchy problem all the way,
raise relaxion cutoff to scales believed to be fundamental

instead of decreasing Higgs mass^2 we can increase it (from -cutoff^2)

already done in some models (e.g. Batell, Giudice, McCullough)

an example (original non-QCD model):

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

take $\tilde{y}$ small and $m_N < m_L$

$$\begin{pmatrix} m_L & yv \\ 0 & m_N \end{pmatrix}$$

➜ seesaw, small eigenvalue is $\sim \dfrac{m_L m_N}{yv}$ when $yv \gg m_L$

$\sim m_N$ when $yv \ll m_L$

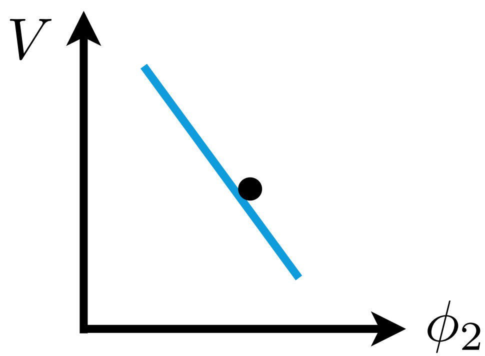
as Higgs vev drops, lightest mass increases ➜ raises barriers, stops vev

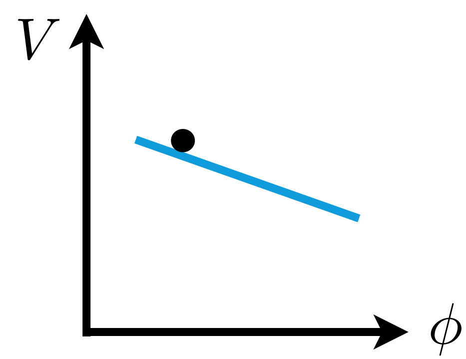
Two Axions

If have two axions coupling to Higgs:

$$\mathcal{L} \supset M^2|h|^2 + g\phi|h|^2 + \Lambda^4\cos(\phi/f) + gM^2\phi + \cdots$$
$$+ g_2\phi_2|h|^2 + \Lambda_2^4\cos(\phi_2/f_2) + g_2M^2\phi_2 + \cdots$$

take scales to be higher for ϕ_2 than ϕ, ($g_2 > g$) then both axions roll from start





but 2 rolls faster, stops first ➜ can think of it in stages (though really happens simultaneously)

ϕ_2 will "go first." Scans Higgs vev until nearer to zero.

ϕ goes next, scans in finer steps, stops when vev even smaller.

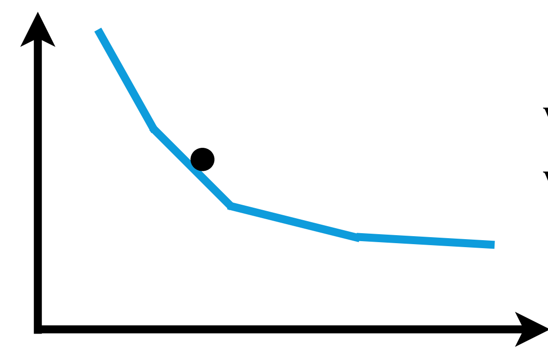
Together do more tuning of Higgs vev than either one alone.

Multiple Axions

If have multiple axions coupling to Higgs:

$$M^2|h|^2 + \sum_i \left(g_i\phi_i|h|^2 + \Lambda_i^4 \cos(\phi_i/f_i) + g_i M^2 \phi_i\right)$$

higher slopes go "first"
(really simultaneous)
➜ effectively like a potential:



weak scale is special location,
would be tuned for single field

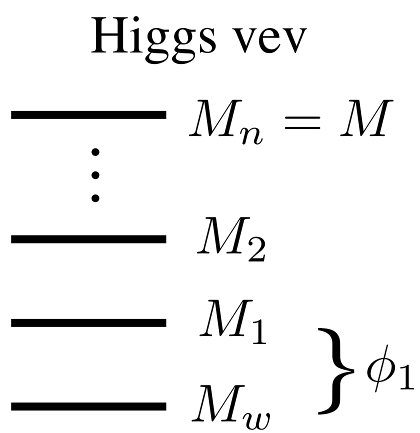
increases cutoff since steepest at start where "eternal inflation" constraint strictest $H^3 < V'$

and shallowest slope at end where barriers must stop it $V'f < \Lambda^4$

works most easily if these are inflation (CC tuned as usual!)

Multiple Axions

$$M^2|h|^2 + \sum_i \left(g_i\phi_i|h|^2 + \Lambda_i^4 \cos(\phi_i/f_i) + g_i M^2 \phi_i\right)$$



each field will roll over $\Delta\phi_i \sim \frac{M_i^2}{g_i}$ before stopping

trade Lagrangian parameters for top and bottom of vev ranges:

no eternal inflation: $H_i^3 < g_i M^2$

barriers form: $g_i M^2 f_i < \Lambda_i^4 \; (\sim M_{i-1}^4)$

$\Longrightarrow$

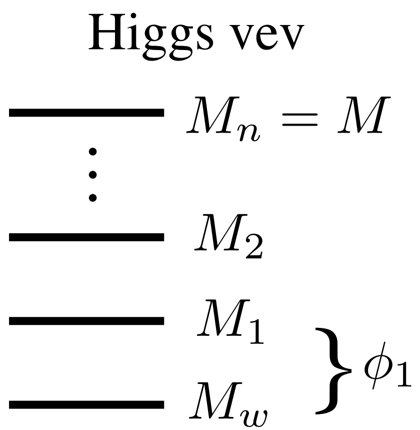
bound on "cutoff" of stage M_i

$$M_i^3 M^4 < M_{i-1}^4 M_{\rm pl}^3$$

was M_i was M_w

so $\{M_i\}$ a series of geometric means

Increased Cutoff



rearranging ➜ size of each step: $\left(\frac{M_{i-1}}{M_i}\right)^4 > \frac{M^4}{M_i M_{\rm pl}^3}$

can keep lowering vev until this = 1

so setting $M_i = M_w$ find cutoff: $M^4 \sim M_w M_{\rm pl}^3$

check classical rolling and quantum fluctuations during any upper stage don't move lower axions too far. Turns out automatically satisfied (weaker than above constraint).

3 axions give cutoff $\sim 10^{14}$ GeV

asymptotically cutoff $\sim 10^{16}$ GeV

Inflation

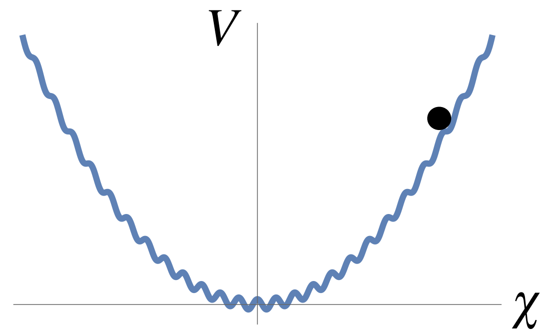
Two-field Model

new relaxion model:

$$\mathcal{L} \supset \left(-M^2 + g_S S\right) h^2 + g_S M^2 S + \Lambda_S^4 \cos\left(\frac{S}{f_S}\right) + kS^2\chi^2 + \Lambda_\chi^4 \cos\left(\frac{\chi}{f_\chi}\right)$$

$\propto \langle h \rangle$

S scans Higgs vev
χ released at M_w ➜ drops S slope, stops S



} can be >> M_w

main new constraint: slope drop fast enough

changes relaxion rules

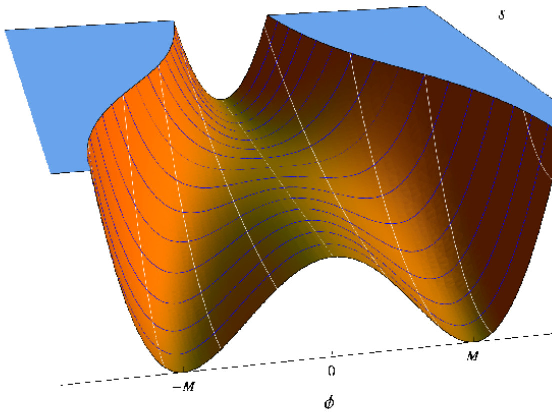
h vev steps can be weak scale size

stops in unique vacuum

χ carries large energy density

χ can fast roll (satisfies new constraint)

Inflation



can reheat with energy in χ ➜ like hybrid inflation (χ waterfall)

can solve hierarchy problem and do inflation

to reheat (i.e. fast roll): $\chi < M_{\rm pl}$ ➜ cutoff ~ 100 TeV

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if barriers unrelated to M_w then can increase cutoff

if change h to new "Higgs" H_S

$$\mathcal{L} \supset \left(-M^2 + g_S S\right)|H_S|^2 + g_S M^2 S + \Lambda_S^4 \cos\left(\frac{S}{f_S}\right) + kS^2\chi^2 + \Lambda_\chi^4 \cos\left(\frac{\chi}{f_\chi}\right)$$

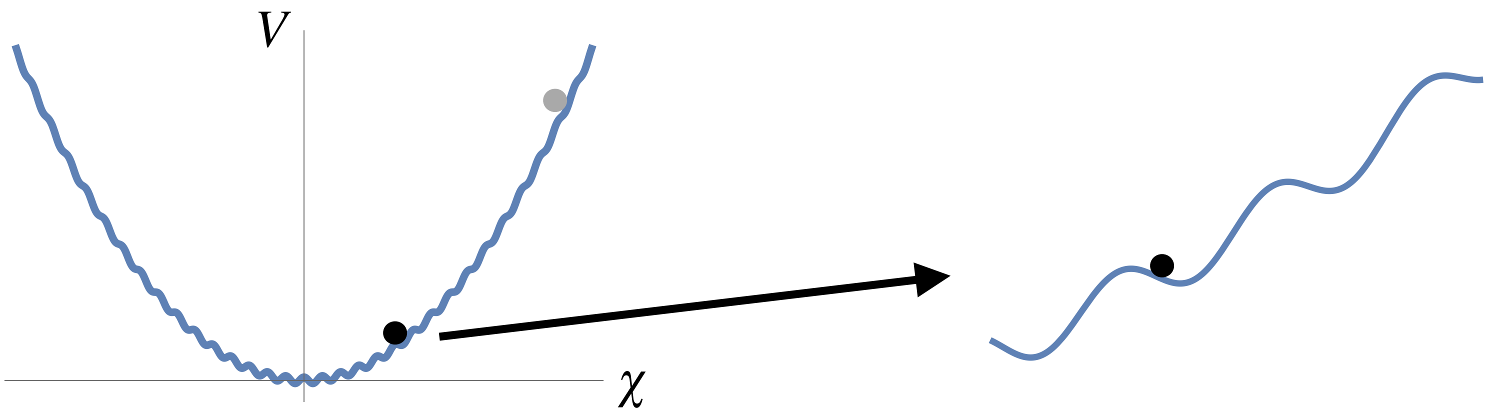
changes relaxion parameters: e.g. $\Lambda_\chi \to M$ instead of M_w

gives natural inflation model with 10^{42} e-folds and cutoff at ~ 10^9 GeV

➜ can be inflation model for original relaxion

Reheating

χ energy redshifts with expansion of universe by O(1), turnaround within barriers



greatly increases effective mass of χ $\quad m_\chi \sim \frac{M^2}{M_{\rm pl}} \to \frac{M^2}{f_\chi}$

rapid decays to SM through $\frac{\chi}{f_\chi} F\tilde{F}$ ➜ can reheat to high scale

can it be end stage of inflation for multiple axions?

Other phenomenology

Relaxion Baryogenesis?

Can the axion cause baryogenesis?

during electroweak phase transition, axion couples to baryon number current

Servant (2014), …

sphalerons violate B, axion violates CP

breaking of shift symmetry ➔ relaxion is rolling
➔ non-zero chemical potential for B

➔ Baryon number generated in equilibrium (spontaneous baryogenesis)

goal: single field does hierarchy, strong CP, baryogenesis, and DM

requires some model-building for large enough B

Summary

Cutoff can go up to ~ 10^{16} GeV with multiple axions coupled to Higgs

Demonstrated inflation models for relaxion

Can we put these two together?

Interesting phenomenology

- 750 GeV
- dark matter predictions?
- baryogenesis?

A new friction mechanism besides Hubble?

Generic signatures? Other (many) light scalars?

Backup

Predictions

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

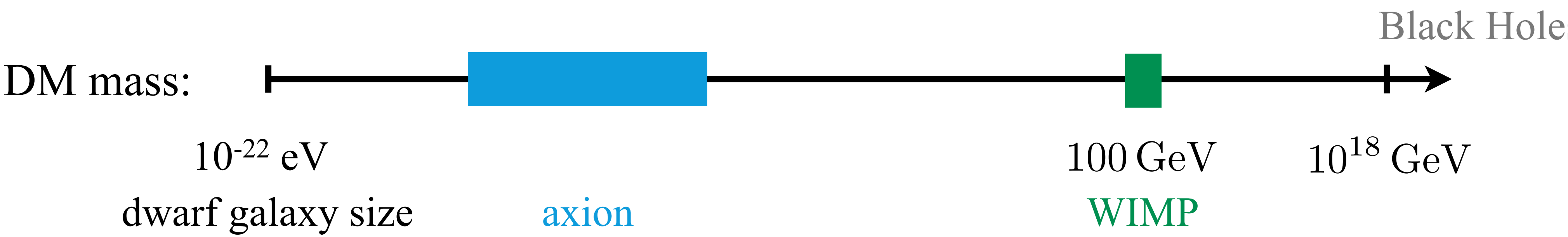
Dynamical Relaxation ➜ light particles (e.g. axion)

- 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?



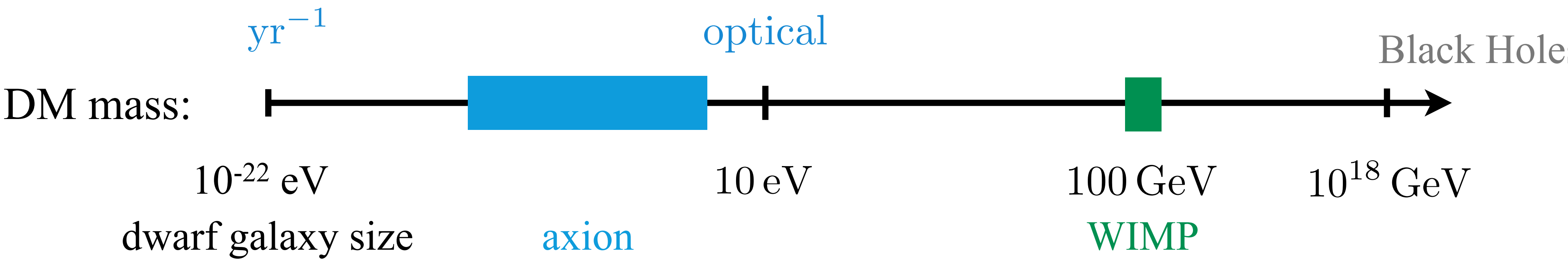
WIMP is well-motivated, significant direct detection effort focused on WIMPs,

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?



$$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$$

➔ high phase space density if $m \lesssim 10\,\mathrm{eV}$

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

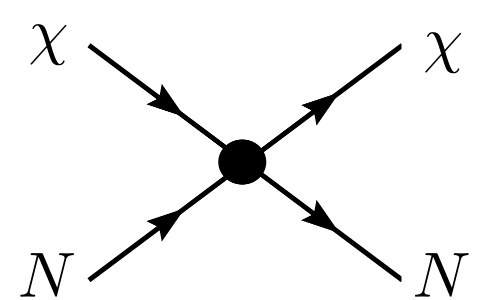
Described as classical field *a(t,x)*

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):

		Operator	Coupling
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

Boston University
Alexander Sushkov

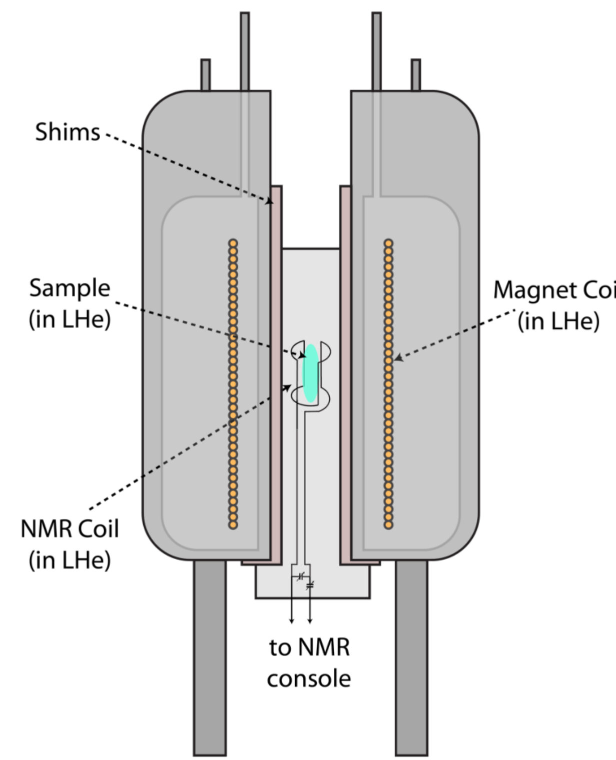
Cal State
Derek J. Kimball

JGU Mainz
Dmitry Budker
Peter Blümler
Arne Wickenbrock

Helmholtz Institute Mainz
John Blanchard
Nathan Leefer

Stanford
Peter W. Graham

UC Berkeley
Dmitry Budker
Surjeet Rajendran



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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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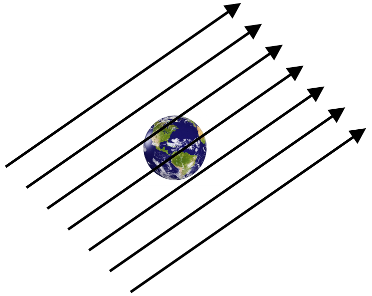
Force from Dark Matter

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

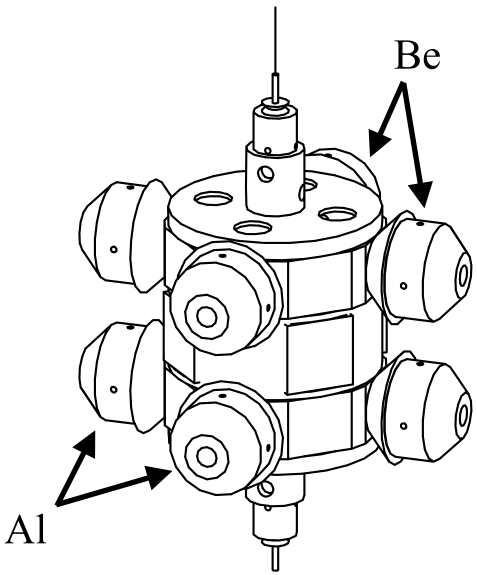


Force is oscillatory and equivalence-principle violating

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

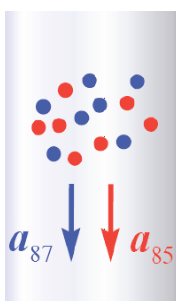
New Direct Detection Experiments:

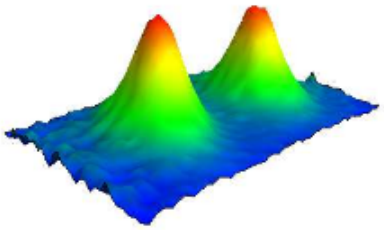
Torsion Balances



Eot-Wash analysis underway

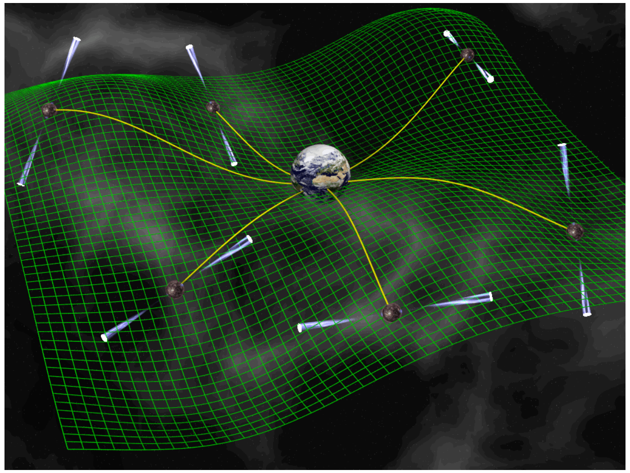
Atom Interferometers





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…