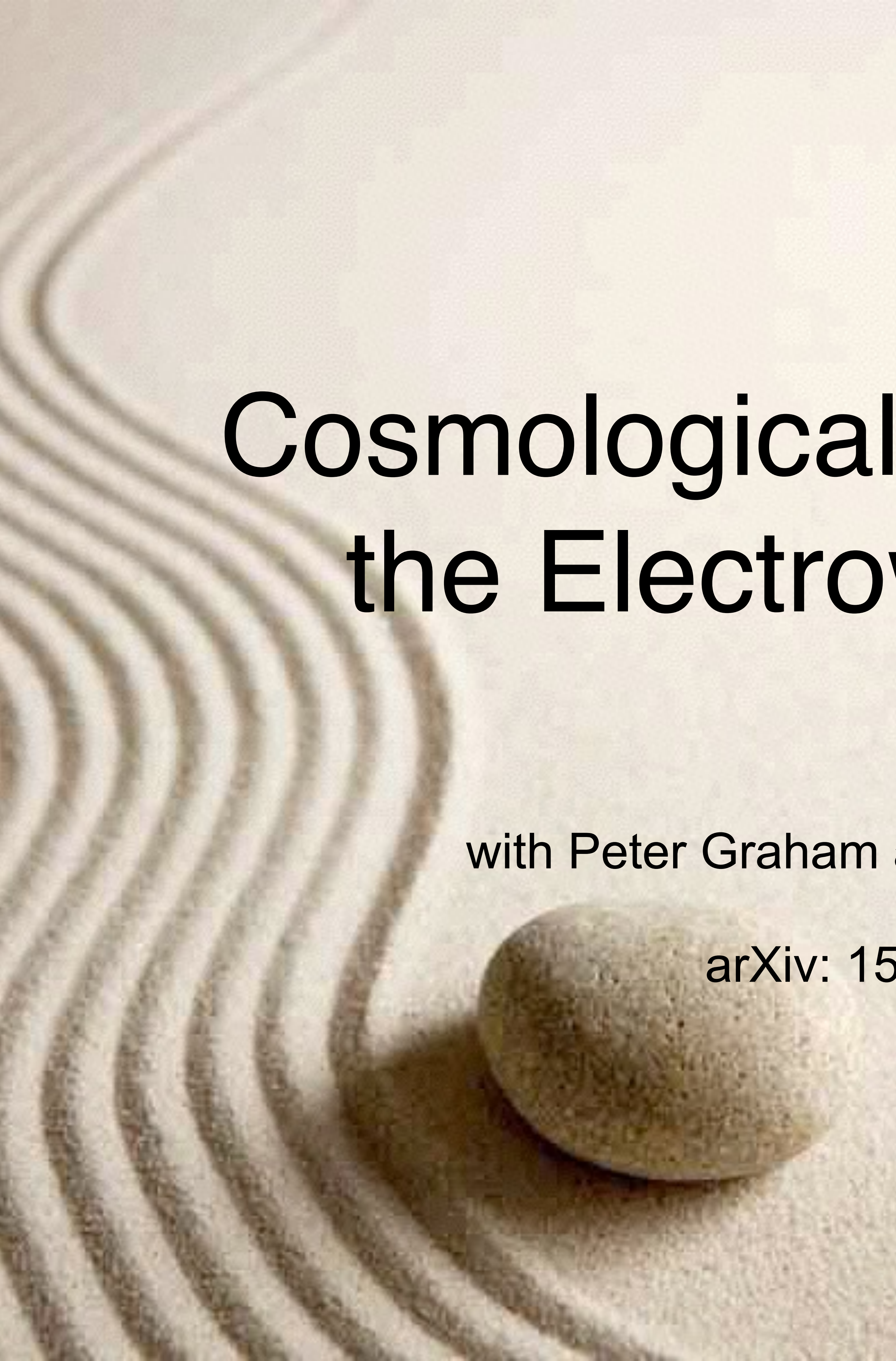

Cosmological Relaxation of the Electroweak Scale

with Peter Graham and David *E.* Kaplan

arXiv: 1504.07551

the Relaxion

The Hierarchy Problem

The Higgs mass in the standard model is sensitive to the ultraviolet.

Gravity << Electromagnetism

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Traditional Approach: new symmetries/dynamics at the weak scale (supersymmetry, composite higgs, extra-dimensions/quantum gravity)

Requires a large number of new particles at the weak scale with standard model charges(super-partners, KK excitations)

New particles can be directly produced in colliders. Or, through loops, lead to signals in precision experiments (electric dipole moment, flavor violation etc.)

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Stringent bounds from ~ 35 years of experiment

The Hierarchy Problem

Weak scale symmetries/ dynamics

Constrained by experiment

Anthropic Explanation for fine tuning (Multiverse).

Hard to constrain

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A Third Possibility: Cosmological Relaxation

Cosmological Relaxation

Time evolution can change our expectations of naturalness

Initial Formation

State after millions of years of erosion

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Relaxion: Could the Higgs mass have evolved from a large natural value to a small “eroded” value?

Chronology

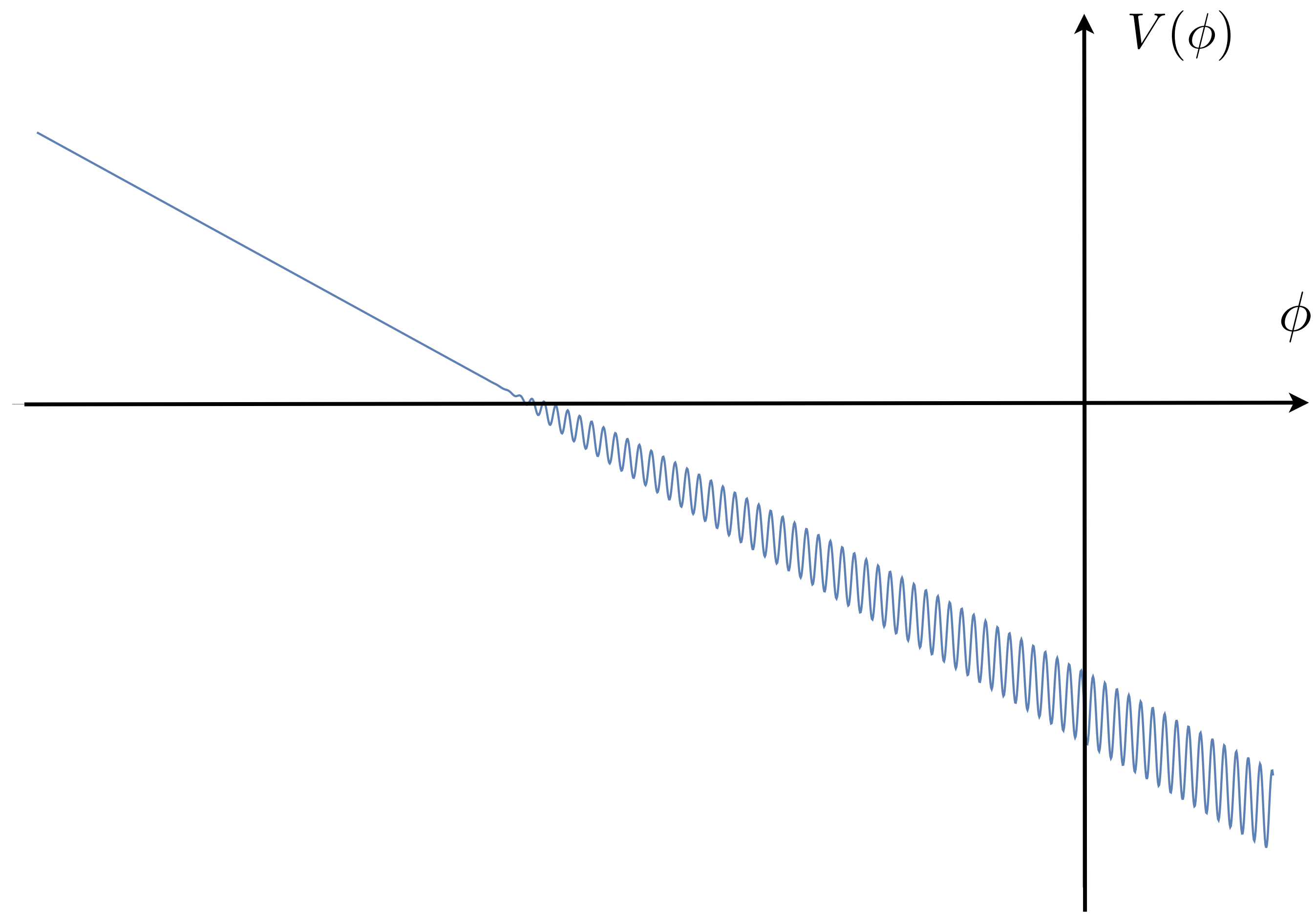
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe.
- The mass-squared relaxes to a small negative value.
- The electroweak symmetry breaking stops the time-dependence.
- The small electroweak scale is fixed until today.

Chronology

QCD Axion + Inflation solves the Hierarchy Problem

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

- Take initial ϕ value such that $m_h^2 > 0$
- During inflation, ϕ slow-rolls, scanning physical Higgs mass.
- ϕ hits value where ~ m_h^2 crosses zero.
- Barriers grow until rolling has stopped.



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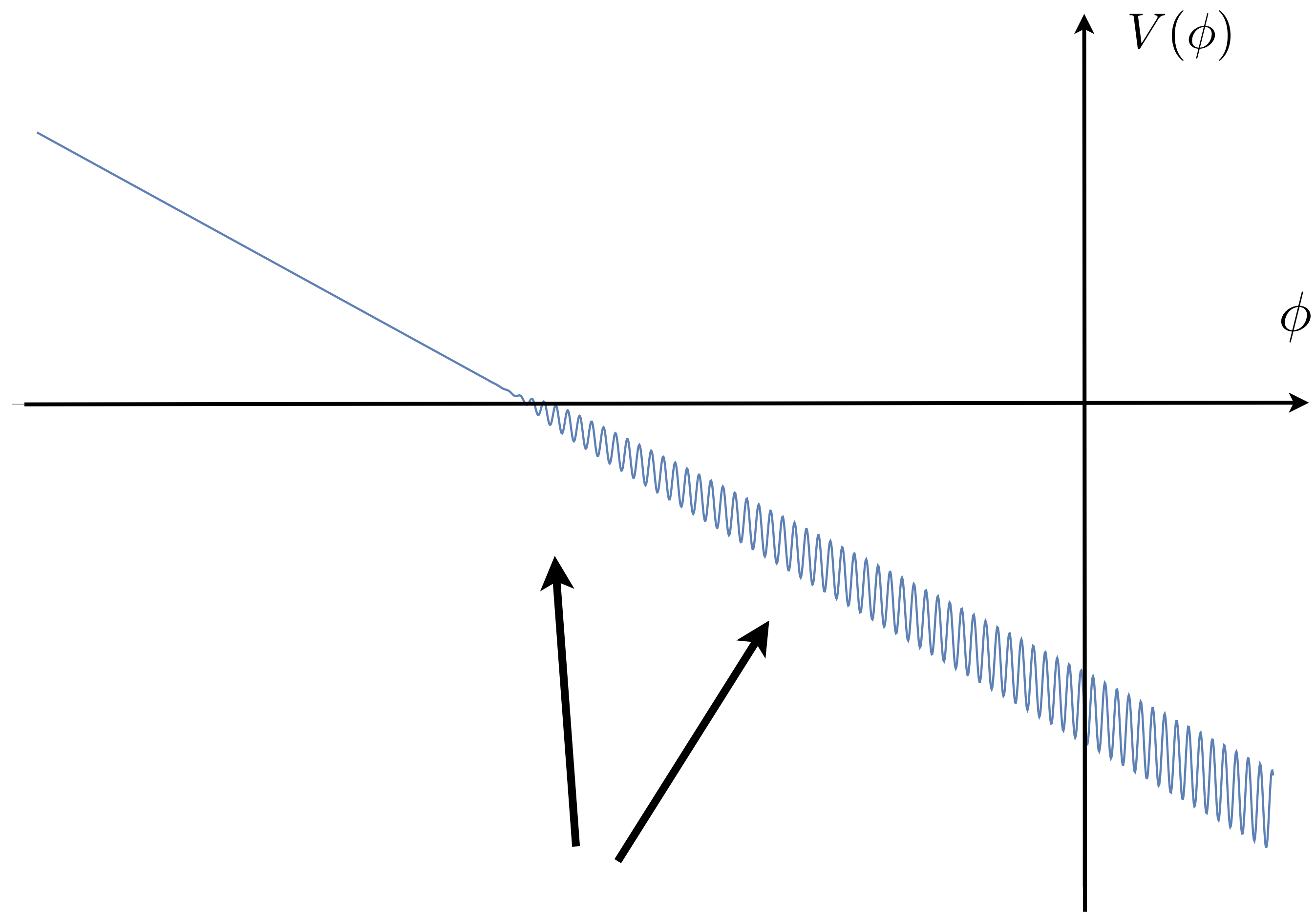

Key: Barriers grow because they depend on the Higgs vev.

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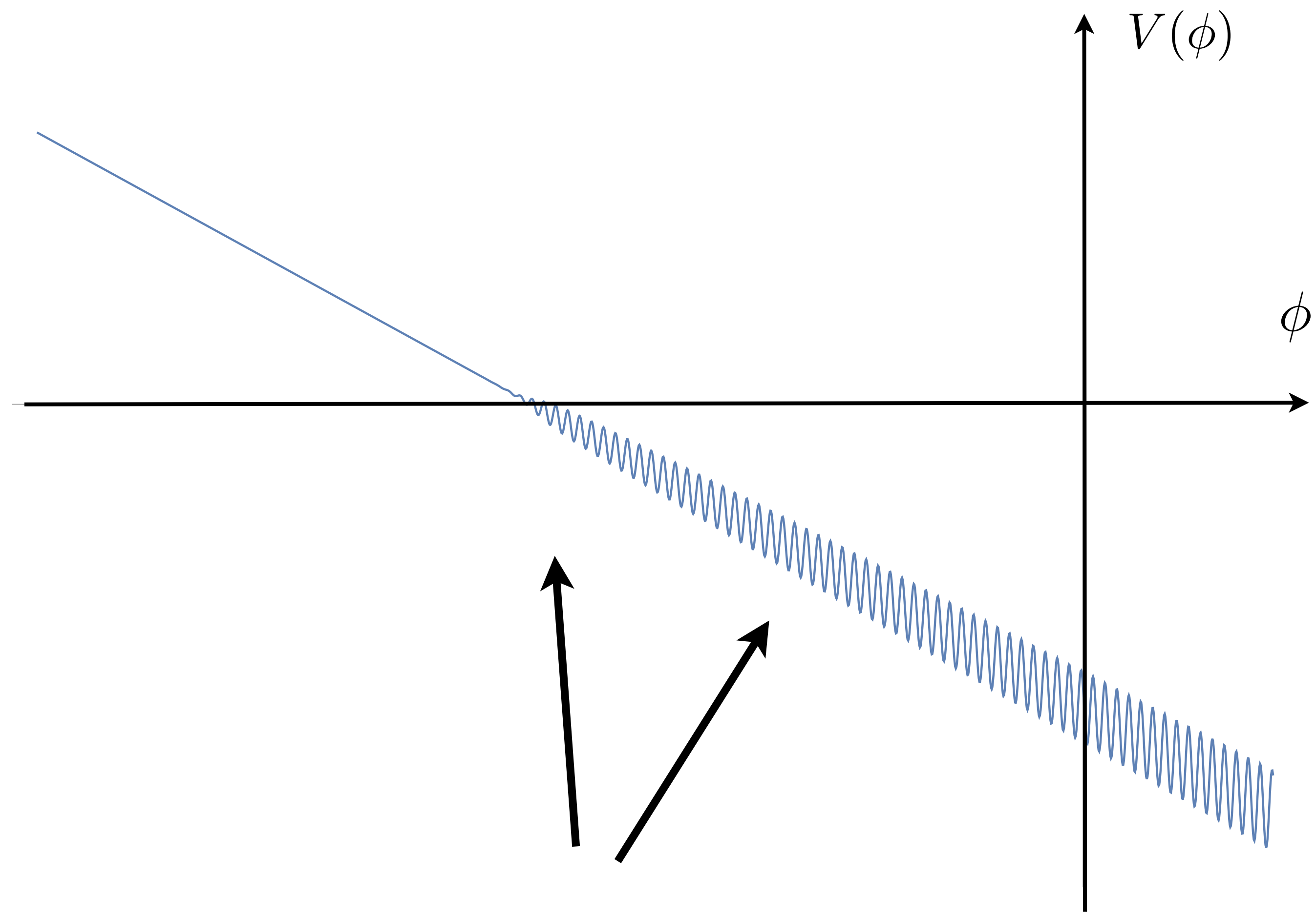

Can solve Hierarchy Problem up to M ~ 100 TeV

Key: Barriers grow because they depend on the Higgs vev.

Another Possibility

Use a different strong group and couple ϕ to $G'^{\mu\nu}\tilde{G}'_{\mu\nu}$.

The Higgs must change the barrier heights: Add fermions

	$SU(3)$
L, N	$\square$
L^c, N^c	$\bar{\square}$

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

Require Higgs vev to be dominant contribution to m_N

Radiative naturalness => $m_L < 900$ GeV
$m_L > 250$ GeV from LHC

For naturalness, new gauge group confines ~ TeV

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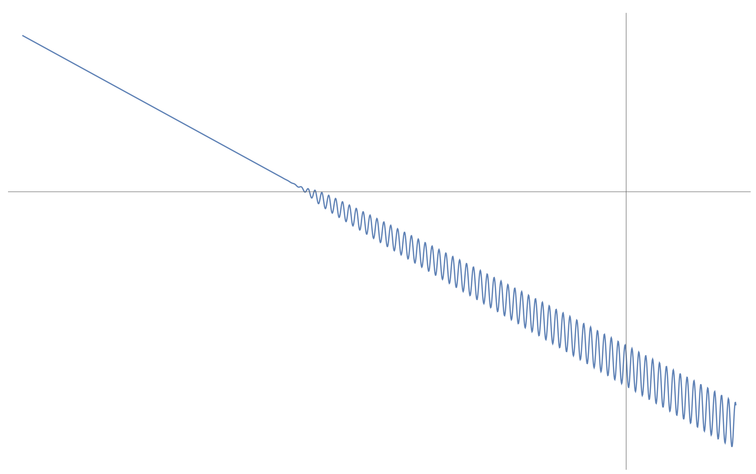
Can solve Hierarchy Problem up to M ~ 10^5 TeV

Relaxion Conditions

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

Self-organized criticality?

- Dissipation - Dynamical evolution of Higgs mass (field) must stop. **Hubble friction**.
- Self-similarity - Cutoff-dependent quantum corrections will choose an arbitrary point where the Higgs mass is cancelled. **Periodic axion**.

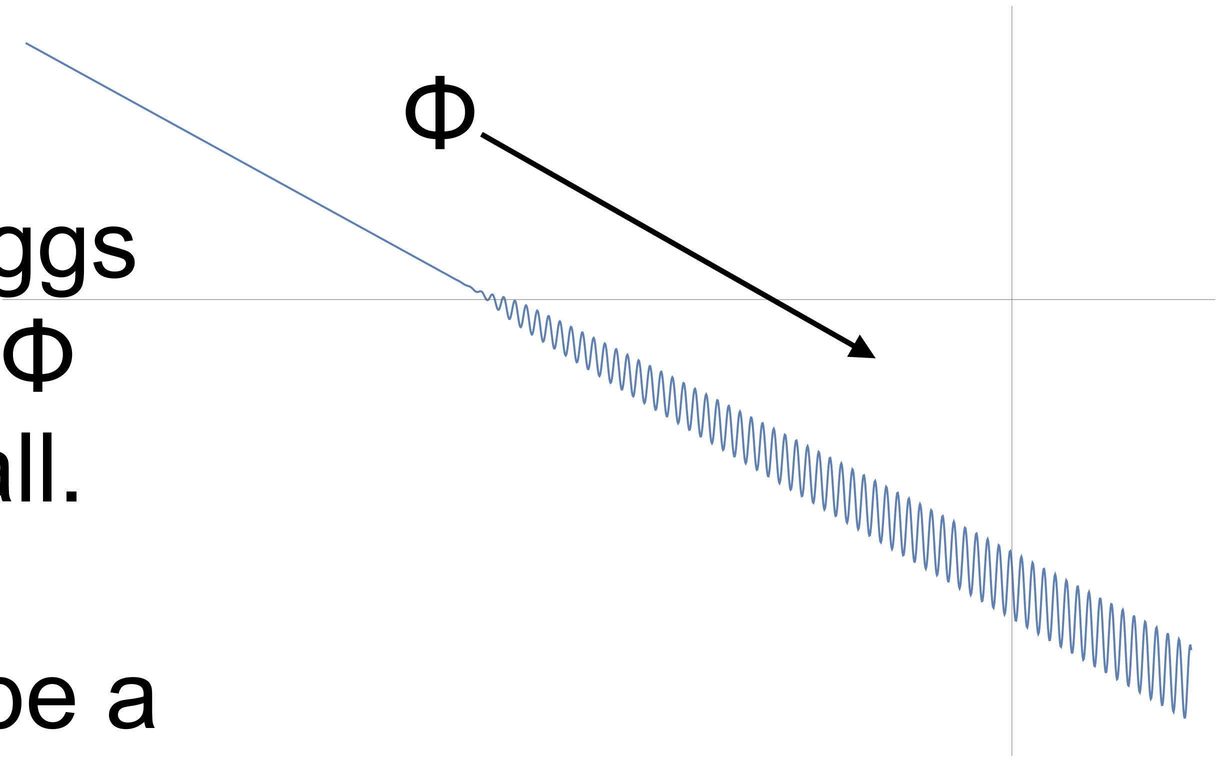


- Higgs back-reaction - EWSB must stop the evolution at the appropriate value. **Yukawa couplings**.
- Long time period - There must be a sufficiently long time period during the early universe for scanning. **Inflation**.

The Axion

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

The axion is central.



Quantum corrections to the Higgs will pick an arbitrary value of Φ where the Higgs mass is small.

This arbitrary value of Φ must be a minimum of Φ - else, Φ cannot stop there

Hence Φ needs to have a large number of minima where it can easily get stuck, solving hierarchy problem

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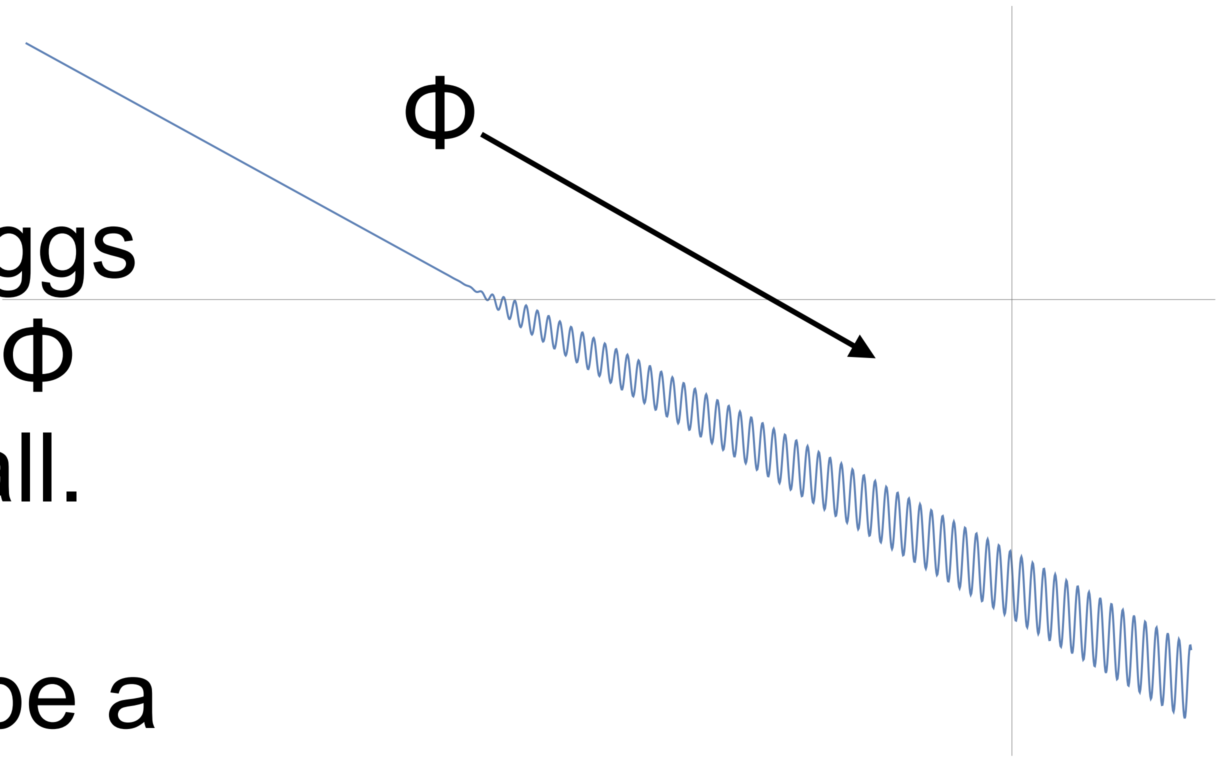

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Axion + Strong Dynamics is a natural way to accomplish this!

Relaxion Essentials

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

Axion Φ couples to Higgs boson. Associated with a group that gets strong at the weak scale (either QCD or a new gauge group)

Need back-reaction to stop Φ. So there must be fermions that carry electroweak quantum numbers, allowing them to mix with higgs.

$$\mathcal{L}_{\mathcal{SM}} \supset y_u hQU, \mathcal{L} \supset yhLN^c + \ldots$$

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No obvious connection to hierarchy problem. S(750)?

The Relaxion and S(750?)

Ask colleague for 750 GeV model, check if model works consistent with relaxion requirements

The Relaxion and S(750?)

Ask colleague for 750 GeV model, check if model works consistent with relaxion requirements

(1) Naturalness requires f_π < 250 GeV => confinement scale Λ ~ 1.5 - 2 TeV

(2) Need two fermions with that carry electroweak quantum numbers allowing them to mix with the Higgs

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

(3) One of these fermions must get a mass dominantly from the Higgs e.g. m_N ~ 0.

(4) Check rate, constraints on spectrum

Relaxion Phenomenology

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

Require fermions that couple to the Higgs - hence there must be kaons that can mix with the Higgs

One fermion (e.g. m_N) needs to dominantly get a mass from the Higgs i.e. $m_N \sim 0$. Infer mass of m_N from the corresponding baryon!

Relaxion dynamics typically leads to O(1) $\theta' \sim \frac{\pi}{2}$

Should lead to CP violating observables - yukawa suppressed, but may be visible

Relaxion Phenomenology

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

- Relaxion could be dark matter - phenomenology similar to that of axion dark matter. Oscillating field associated with relaxion dark matter: $\Phi = \Phi_0 \cos(m_\Phi t + m_\Phi v x)$
- **Coupling to the Higgs**: (tiny)
  - New force experiments
  - Background oscillations of SM mass scales (if DM)

Low energy precision measurements to test this solution to the hierarchy problem!

Relaxion Dark Matter

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

ϕ is a light scalar coupled to higgs with small coupling g

$$\implies \frac{g\phi}{v} m_q \bar{q} q$$

$$\text{Dark matter } \phi \implies \phi = \phi_0 \cos\left(m_\phi \left(t - \vec{\mathrm{v}}.\vec{x}\right)\right)$$

Time variation of masses of fundamental particles

$$\implies \text{force on atoms } \frac{g\nabla\phi}{v} m_q \sim \frac{g m_\phi \vec{\mathrm{v}}}{v} m_q$$

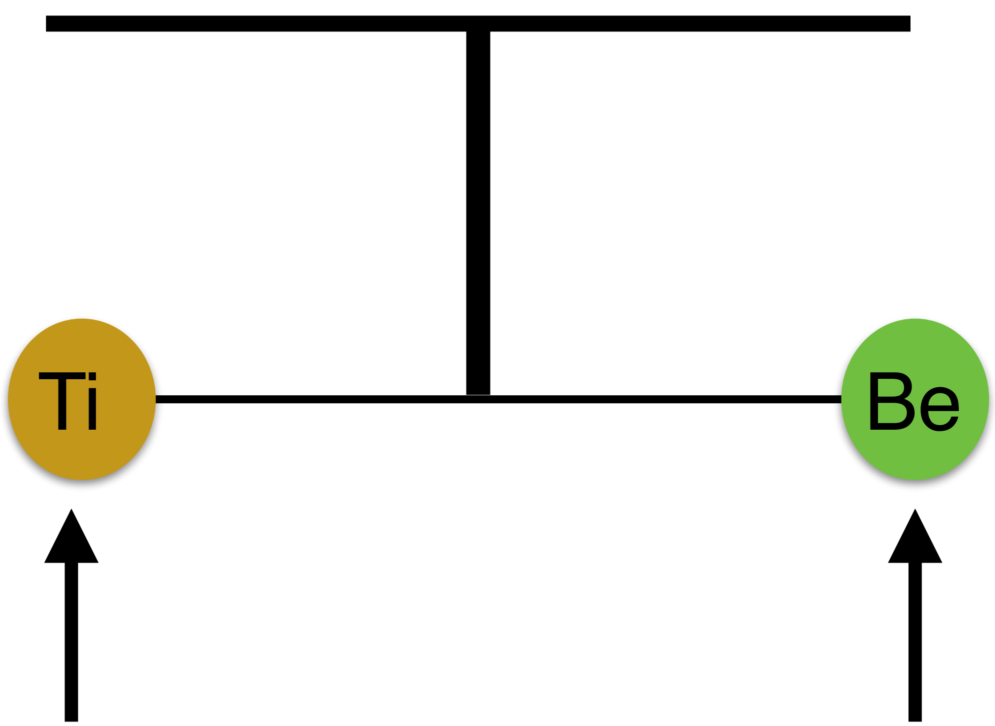
Force violates equivalence principle. Time dependent equivalence principle violation!

Detection Options

Measure relative acceleration between different elements/isotopes.

Leverage existing EP violation searches and work done for gravitational wave detection

Torsion Balance

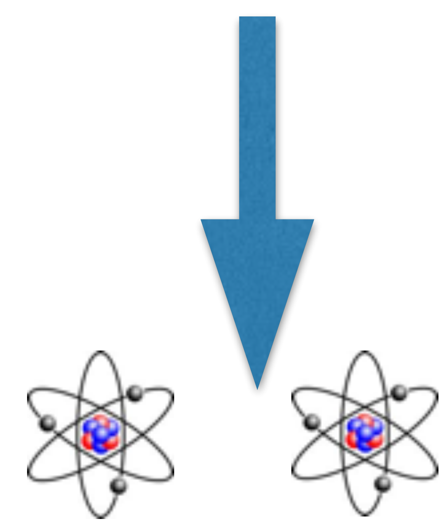


Force from dark matter causes torsion balance to rotate

Measure angle, optical lever arm enhancement

Atom Interferometer

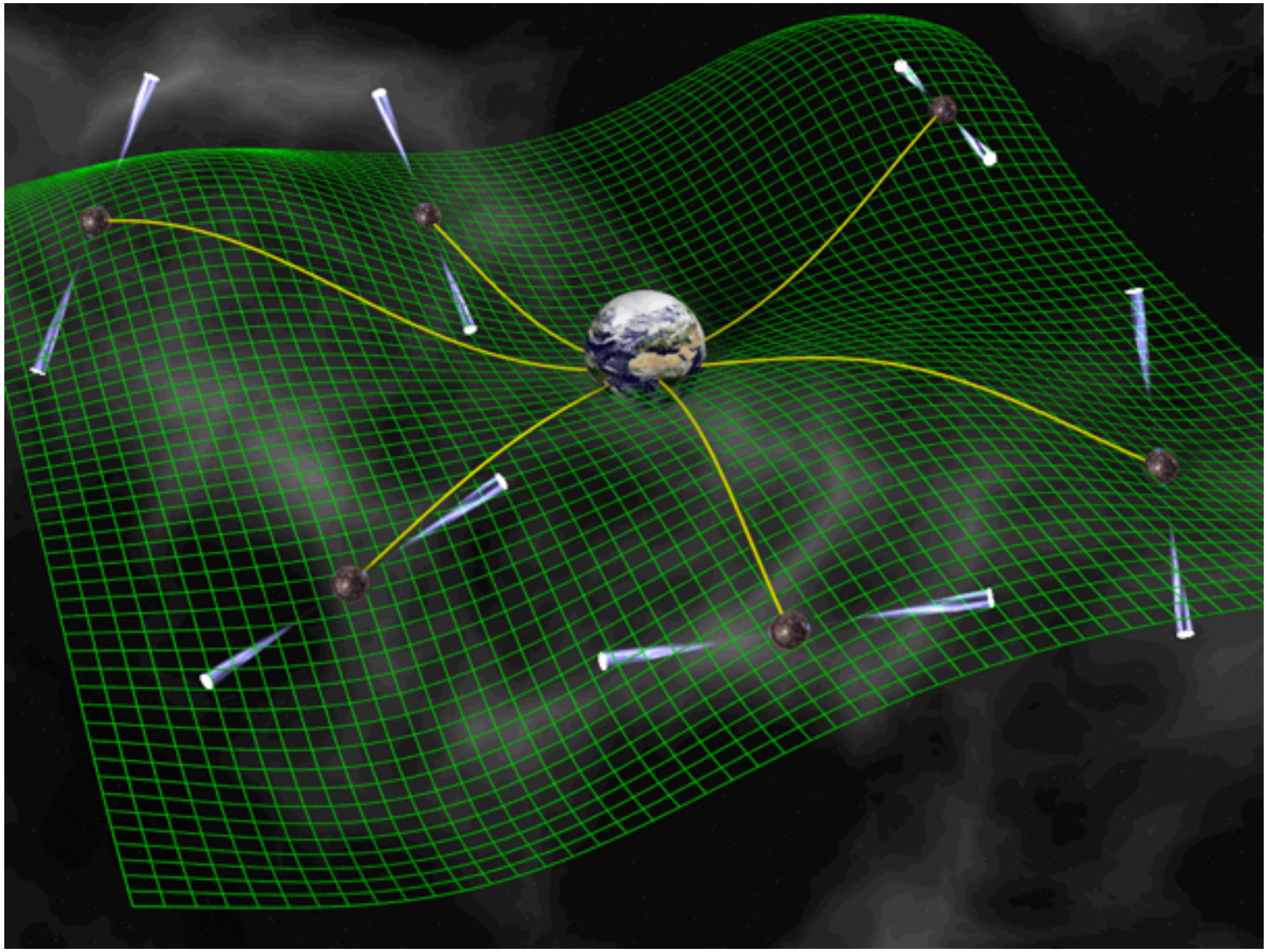
Dark Matter



Differential free fall acceleration

Stanford Facility

Pulsar Timing Arrays



Pulsars are known to have stable rotation - can be used as clocks

Presently used to search for low frequency (100 nHz) gravitational waves.

Pulsar signal modulates due to gravitational wave passing between earth and the pulsar

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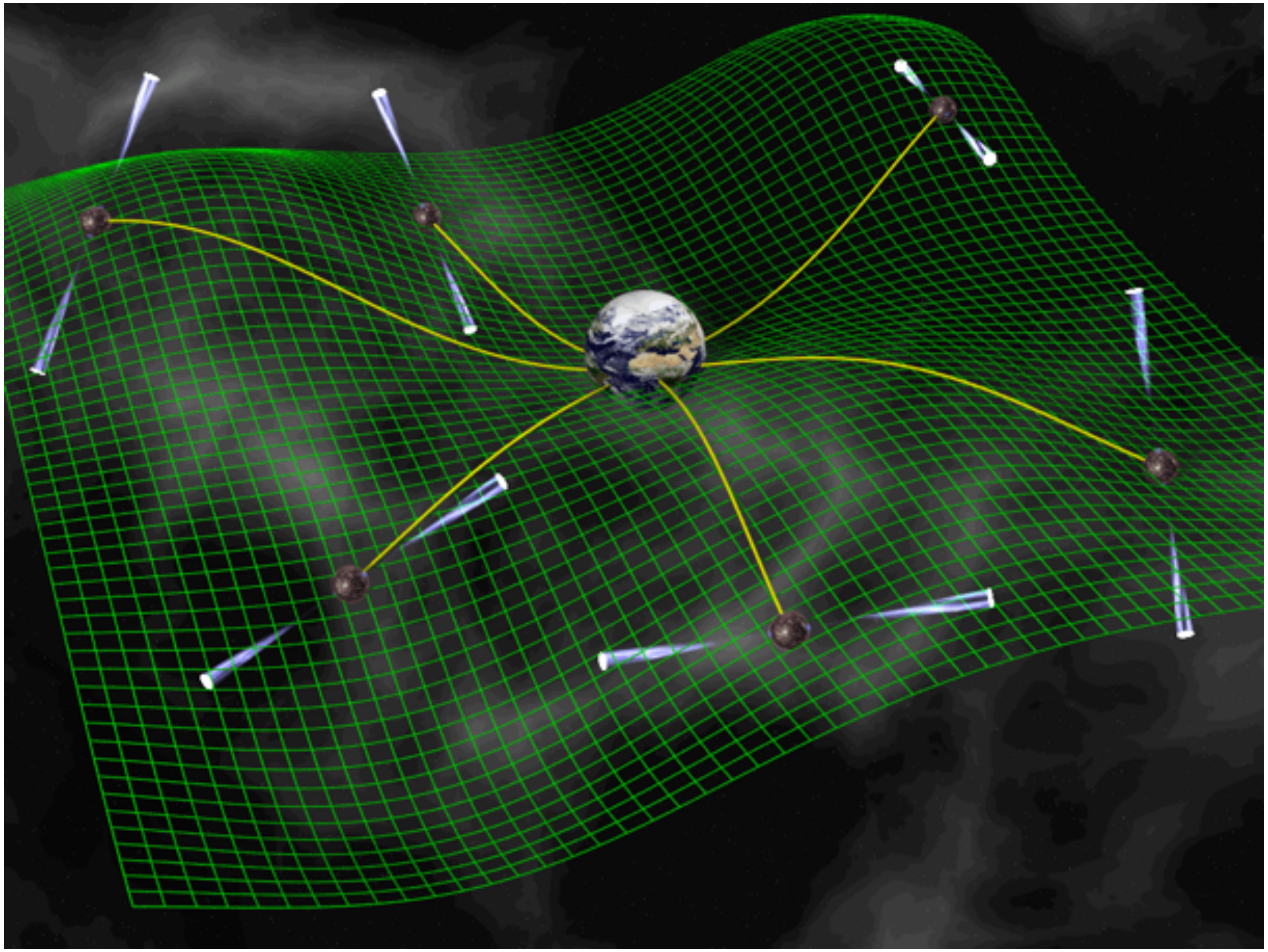

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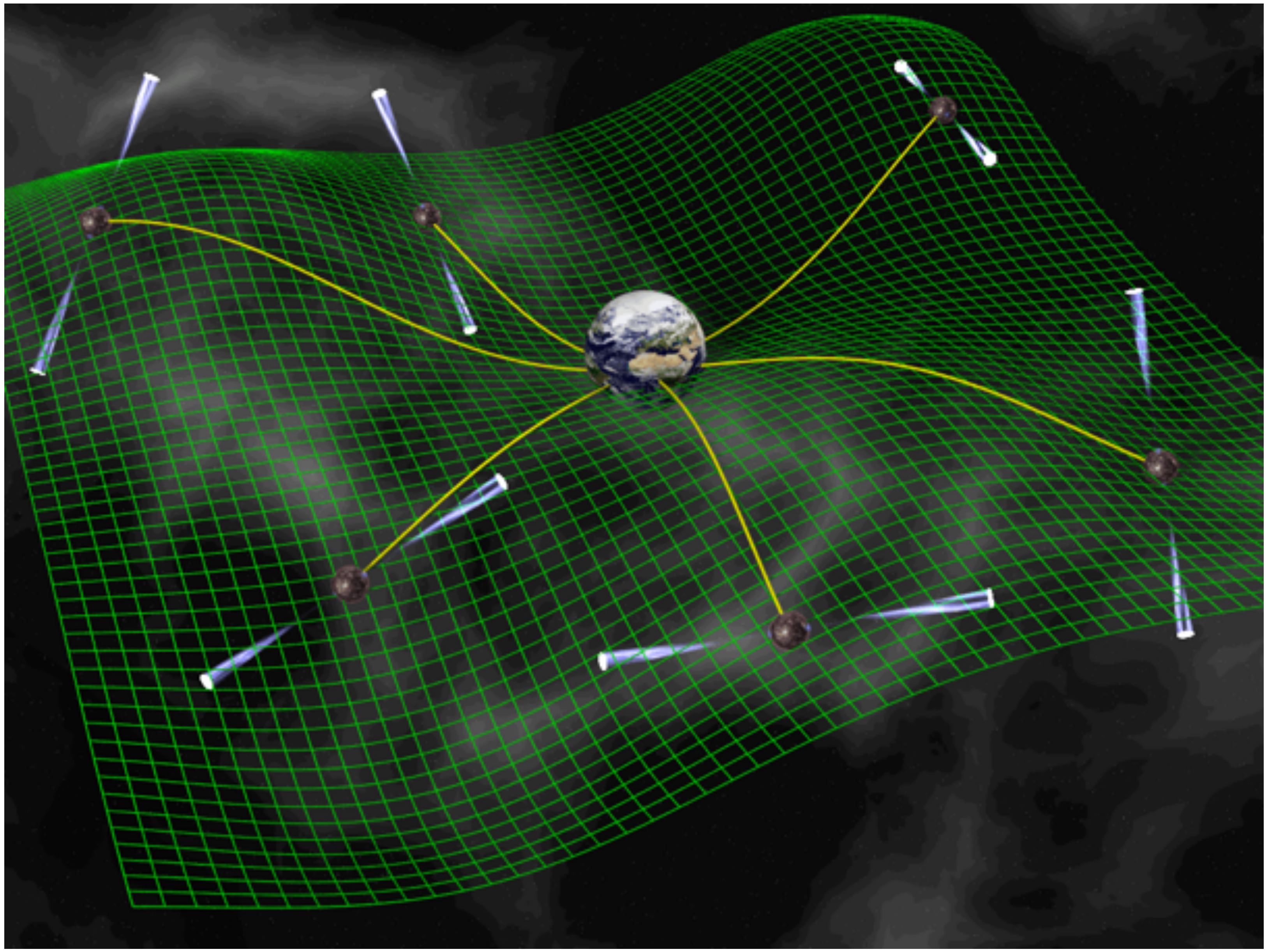

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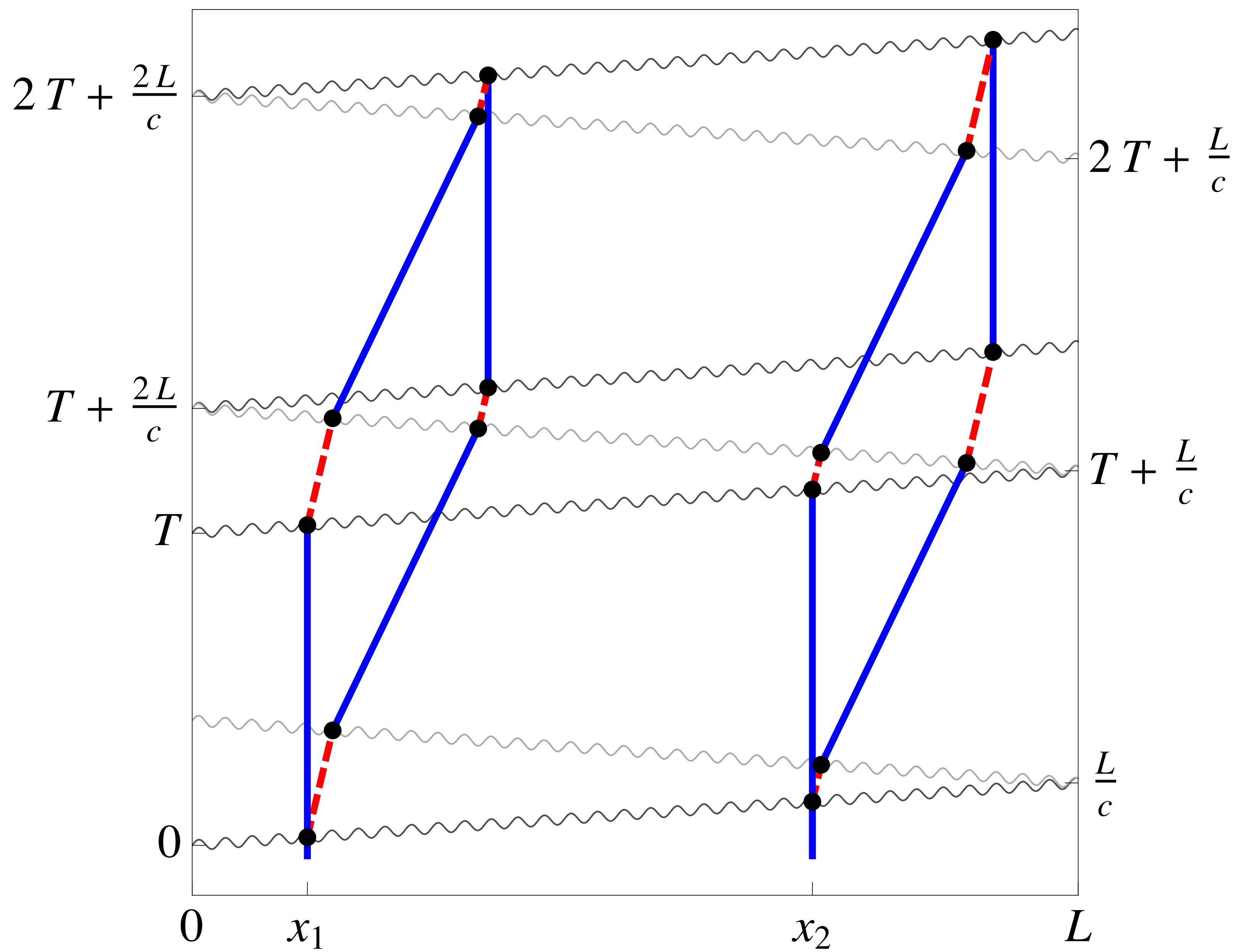
Relaxion changes electron mass at location of Earth - changes clock comparison

Single Baseline Gravitational Wave Detector



Comparison of two distant atomic clocks - for relaxion dark matter, electron mass changes by m_Φ L. Laser noise cancelled upto velocity corrections.

This is a scalar mode - in LIGO, signal is the same in both arms. Leading order term cancelled in differential measurement

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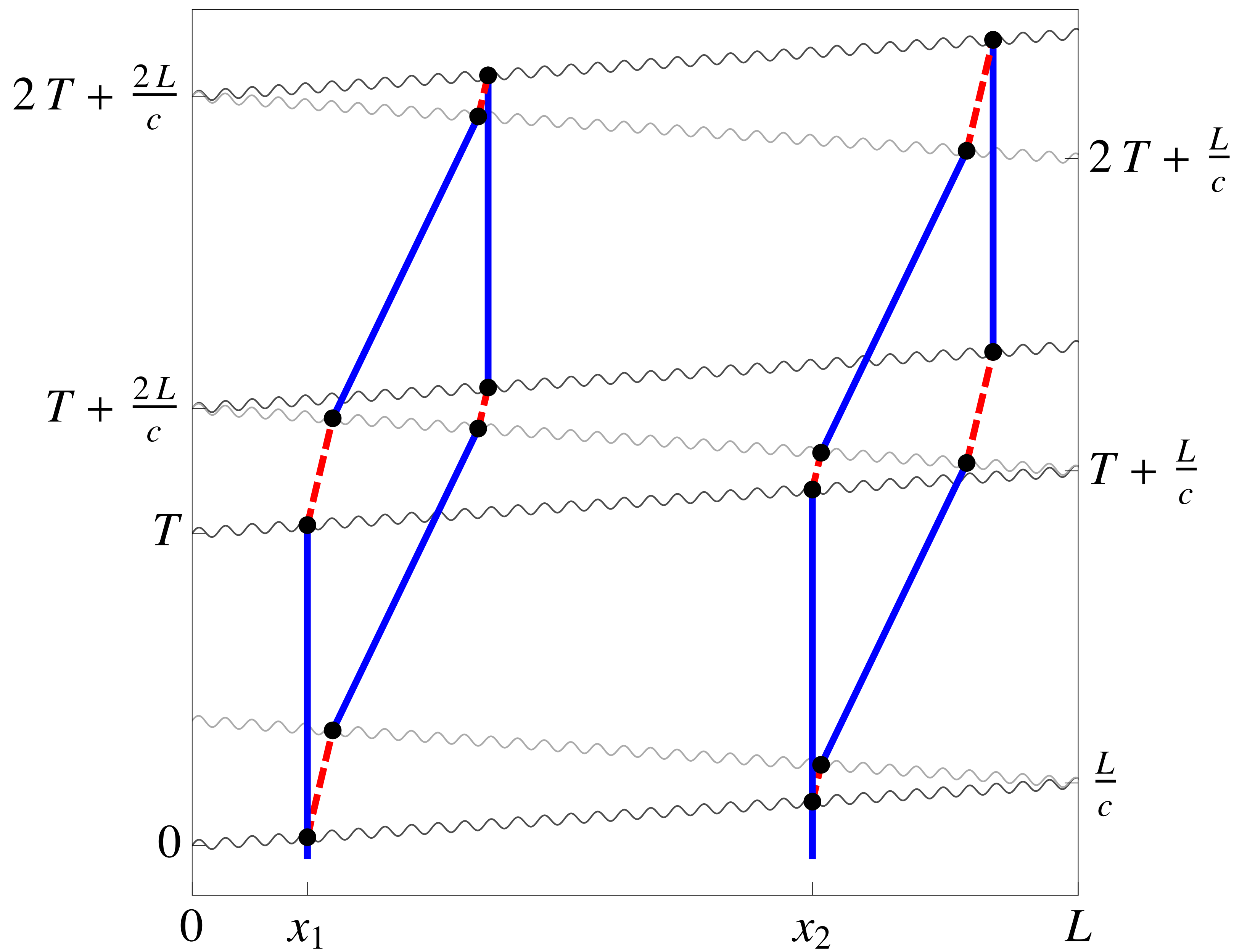

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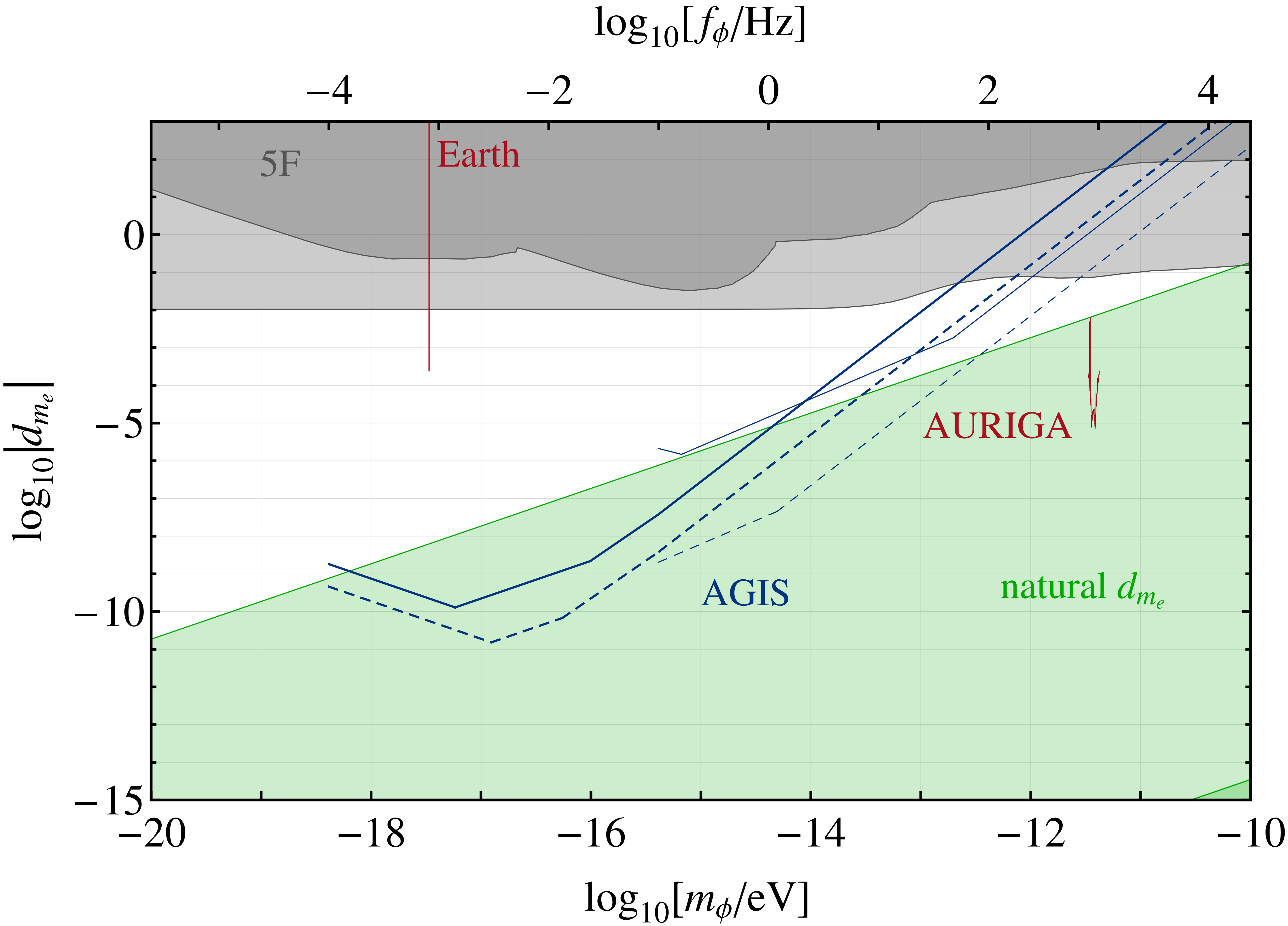
Leading effect retained in optical clock comparison

Projected Sensitivity for AGIS



Conclusions

Traditional View: Hierarchy Problem solved by strongly coupled physics at high energy

Relaxion: Concrete Example where puzzle solved by ultra-weakly coupled, light degree of freedom. Axion essential.

Connection to other hierarchy problems like the cosmological constant?

New Experimental Opportunities?