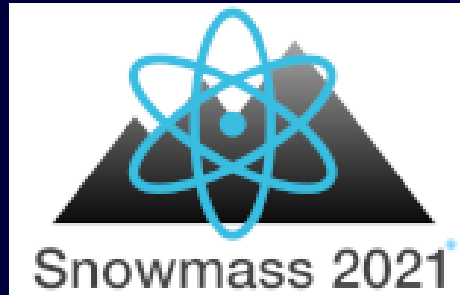


Precision Studies of Spacetime Symmetries And Gravitational Physics



Ralf Lehnert

Indiana University Center for Spacetime Symmetries

White Paper Co-Authors: E. Adelberger, D. Budker, R. Folman,
A. Geraci, J. Harke, D. Kaplan, D. Kimball, D. Moore, G. Morley,
A. Palladino, T. Phillips, G. Piacentino, M. Snow, and V. Sudhir

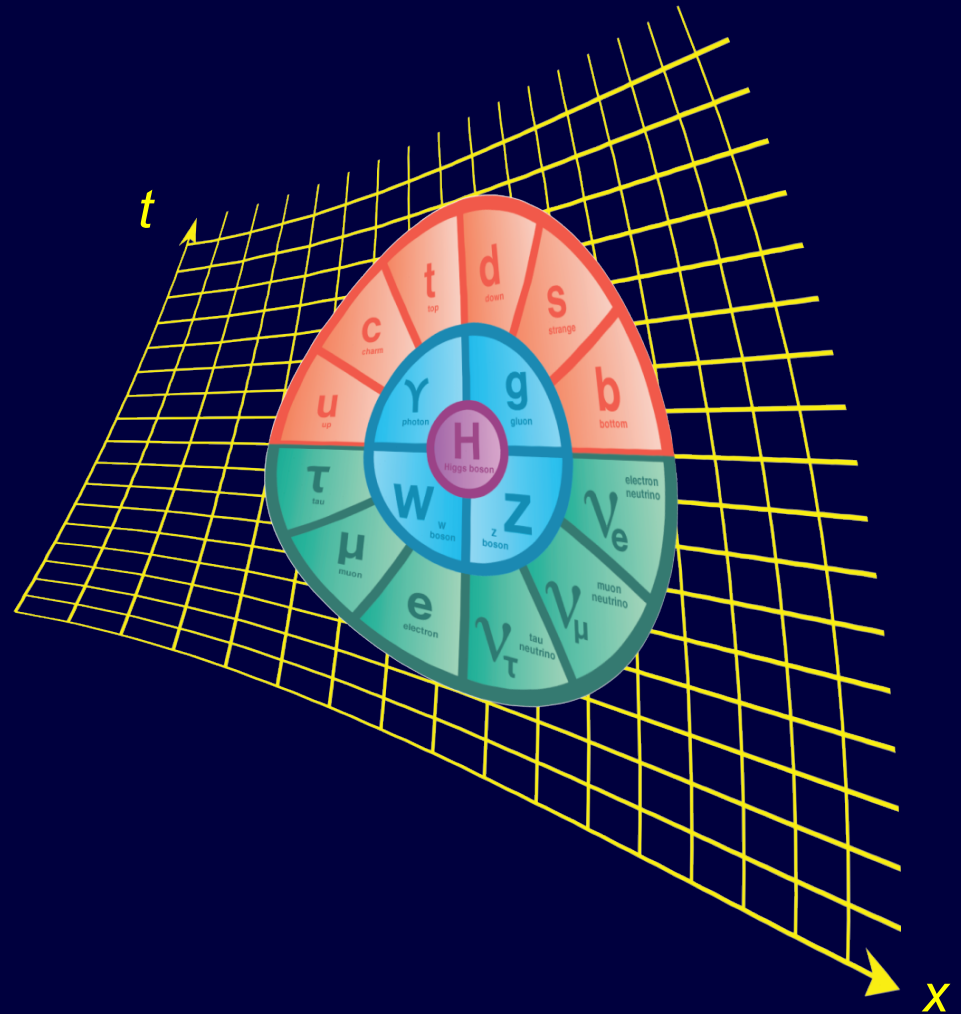


US Department of Energy:

High Energy Physics (HEP) explores **what the world is made of and how it works at the smallest and largest scales, seeking new discoveries from the tiniest particles to the outer reaches of space.** This quest inspires young minds, trains an expert workforce, and drives innovation that improves the nation's health, wealth, and security.

Our research is inspired by some of the biggest questions about our universe. **What is it made of? What forces govern it? How did become the way it is today?** Finding these answers requires the combined efforts some of the largest scientific collaborations in the world, using some of the most sensitive detectors in the world, at some of the largest scientific machines in the world.

Spacetime



- Foundational
- Small-scale structure unknown
- Theory ideas: dynamics, dimensionality, symmetries, ... can be affected

This talk: spacetime studies

symmetries

intersection

dynamics
(GR)

- P, T, CP, CPT, ...
- Translations
- Rotations
- Boosts

- gravitational interaction of antimatter
- gravitational interaction of quantum spins
- ...

- corrections to r^{-2}
- gravitational quantum-entanglement properties
- precision GR tests
- gravitational-wave detection

...



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Effective field theory:

$$\text{effect} \sim \lambda \frac{E^k}{M^l}$$

- high E for larger effects
- high statistics **or ultra-high precision**
- high E and/or accumulation of effects over long d

Snowmass21:

Rare Frontier for Rare Processes and **Precision Measurements**



**Particle Physics, but also AMO Physics, Mechanics,
Nanophysics, Nuclear Physics, ...**

Long history:

- photoelectric effects (1905)
- Stern-Gerlach (1922)
- hyperfine structure (1935)
- Lamb shift (1947)
- electron $g-2$ (1948)
- Casimir effect (1948,1997)

- various DM searches (ongoing)
- EDMs (ongoing)
- proton radius (ongoing)
- quantum sensors for HEP (ongoing)

Bright future:

Snowmass21 Frontier: Rare Processes and Precision Measurements

Topical group: Fundamental Physics in Small Experiments

Axion Dark Matter
(arXiv:2203.14923)

Directional Detection of Dark Matter Using Solid-State Quantum Sensing
(arXiv:2203.06037)

EDMs and the search for new physics
(arXiv:2203.08103)

Quantum Sensors for HEP Science - Interferometers, Mechanics, Traps, and Clocks
(arXiv:2203.07250)

Future GW Detector Facilities
(arXiv:2203.08228)

New Horizons: Scalar and Vector Ultralight Dark Matter
(arXiv:2203.14915)

Quantum Sensors for High Precision Measurements of Spin-Dependent Interactions
(arXiv:2203.09488)

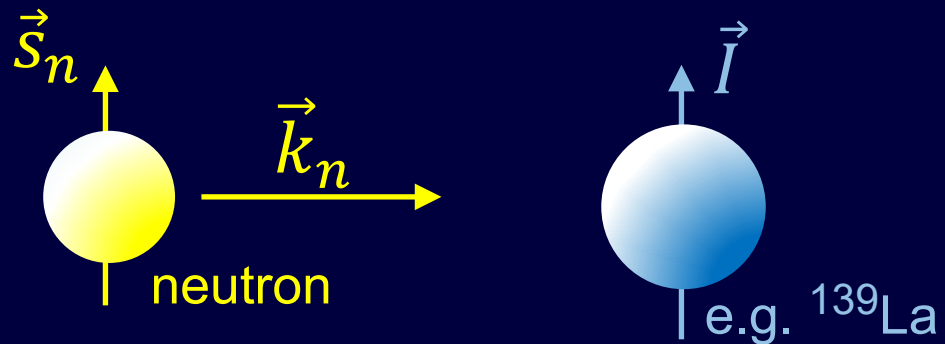
Tabletop Experiments for Infrared Quantum Gravity
(arXiv:2203.11846)

Light DM Direct Detection at the Interface With CM Physics
(arXiv:2203.07492)

(A) Search for new sources of T violation with NOPTREX

Motivation: - origin of observed matter-antimatter asymmetry
- sensitivity to BSM T violation and eV-MeV axion-like particles

Method: - nuclear physics



$$\text{amplitude} \supset \vec{s}_n \cdot (\vec{k}_n \times \vec{I})$$

Prospective Insight:

- **1 order of magnitude** improvement on P- & T-odd n-N interactions (10^7 s with ^{139}La at MW-class pulsed neutron spallation source)
- **2 orders of magnitude** (ongoing R&D with supermirror neutron optics)
- **competitive** with current nEDM searches

(B) Studies of Lorentz and CPT symmetry

Motivation: - origin of observed matter-antimatter asymmetry
- noncommutative field theory
- string theory
- other theoretical approaches to quantum gravity

Method: - AMO physics, storage rings, cavities, mechanics
- matter-antimatter comparisons ($\overline{H}, \overline{p}$)
- clock comparisons
- cold neutrons
- matter-wave interferometry
- muon physics (muonium spectroscopy and free fall, $g-2$)
- resonant cavities
- short-range interaction studies

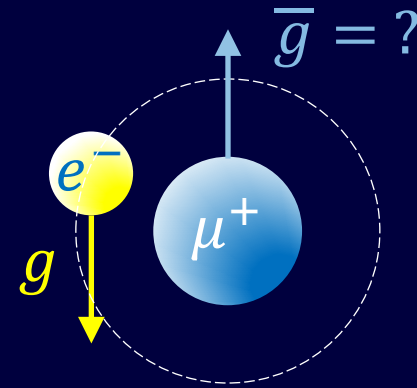
Prospective Insight:

- insight into spacetime structure at Planck sensitivity
- potential source of matter-antimatter asymmetry
- constraints on various approaches to quantum gravity

(C) Muonium Antimatter Gravity Experiment (MAGE)

Motivation: - direct gravitational interaction of antimatter
- antigravity scenario, Lorentz and CPT symmetry test

Method: - particle and atomic physics
- precision interferometer feasible
- prospective muonium beam:
PIP-II and Booster upgrades
→ **Fermilab world's best venue**



Prospective Insight:

- **first-ever** direct measurement of \bar{g} possible
- **first-ever** direct measurement of \bar{g} for second generation likely
- %-level sensitivity **on par** with current first-generation efforts (\bar{H} , Ps)
- but Mu measurement nevertheless **independent** \bar{H} & Ps results
- **more Mu physics**: HF & 1S-2S spectroscopy, $\text{Mu} - \bar{\text{Mu}}$ oscillations, ...

(D) Gravitational interaction of the $K_0 - \bar{K}_0$ system

Motivation:

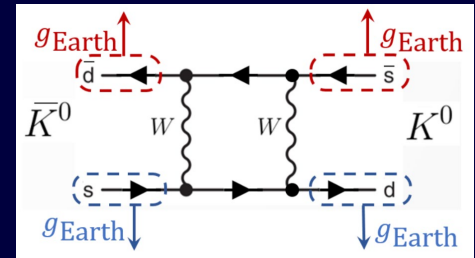
- gravitational interaction of antimatter
- antigravity scenario, baryon asymmetry
- CPT symmetry test

Method:

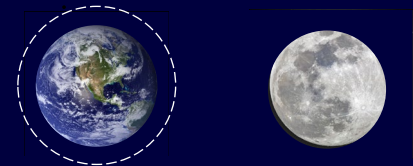
- particle- and astrophysics
- measure CP-violating $\epsilon(g)$
- low-Earth orbit (ISS?) or moon
- K_L generation via cosmic p flux feasible

Prospective Insight:

- $\mathcal{O}(\text{days})$ for 3σ and $\mathcal{O}(\text{tens of days})$ for 5σ measurement
- on moon: nontrivial $\epsilon(g) \rightarrow$ only background in first $\mathcal{O}(\text{tens of days})$



$$\frac{K_L \rightarrow \pi^+ \pi^-}{K_L \rightarrow \pi^+ \pi^- \pi^0}$$

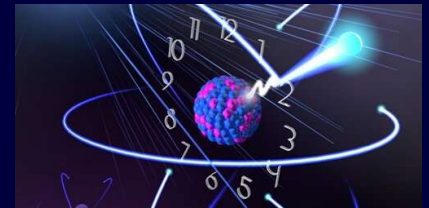


(E) Thorium Clock

Motivation: various fundamental precision measurements including: new f/t standard, GR experiments, $\dot{\alpha}$ (translation invariance), as well as qbit applications, ...)

Method:

- AMO physics, nuclear physics
- nuclear transition between $^{229}_{90}\text{Th}$ and $^{229}_{90}\text{Th}^*$
- 1st step: determination of transition frequency
- then: basis for ultraprecise clock



<https://phys.org/news/2020-10-nucleus-thorium-scientists-closer-nuclear.html>

Prospective Insight:

- **100-1000 fold improvement** of over current 10^{-18} clock accuracy
- $\dot{\alpha}$ improvement by up to **4 orders of magnitude**
- host of other applications for unprecedented **GR measurements**

(F) Mechanical tests of gravity-quantum interface & gravity-spin interaction

Motivation: determination of certain **quantum aspects of gravity**

Method:

- opto-mechanics, nanophysics, AMO physics
- interferometry with **levitated nanoparticles**
- **massive oscillators** (non-interferometric)
- **levitated quantum spins**

Prospective Insight:

- gravity's ability to produce quantum entanglement
→ falsify gravitational models incapable of generating entanglement
- gravitational interaction of quantum spins

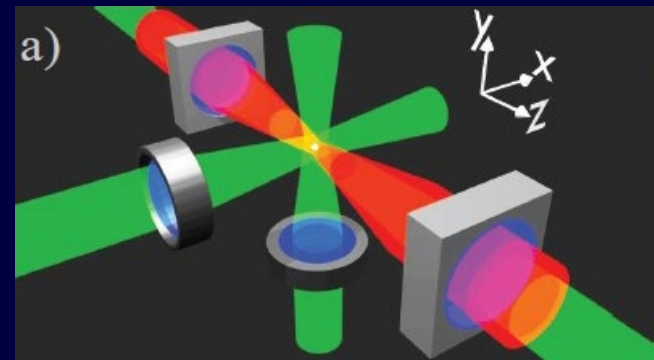
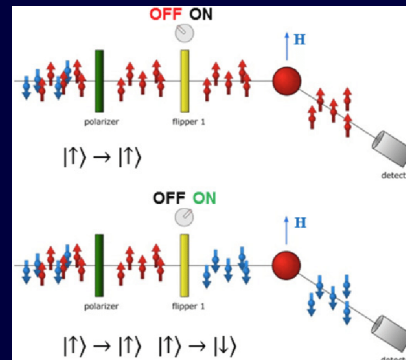
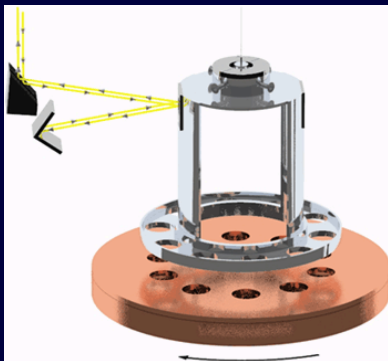
(G) Short-range corrections to gravity, 5th-force interactions + more

Motivation:

- solutions to the **hierarchy problem**
- **novel weak forces** (chameleon dark-energy, light Z' bosons, torsion, nonmetricity, axion-like particles, exotic P-odd interaction, etc.)

Methods: - mechanics, nuclear physics, nanophysics, opto-mechanics

- **torsion pendulum** (down to $50\text{ }\mu\text{m}$)
- **polarized neutron scattering** ($10^{-7}\text{m} - 10^{-11}\text{m}$)
- optically **levitated sensors** (10^{-21}N)
- dedicated **underground facility** desirable



Prospective Insights:

- existence of extra dimensions
- other corrections to the gravitational force (e.g., Yukawa-type)
- existence of new spin-dependent weakly coupled forces
- testing the role of gravity in quantum entanglement
- testing the foundations of quantum mechanics
- quantum behavior in vibrational of modes of mechanical systems
- searches for millicharged particles
- gravitational-wave detection (gravitons from axion annihilation)
- DM searches

Summary:

Precision studies involving aspects of spacetime (its dynamics and its symmetries) and related effects:

- drive our understanding of established fundamental physics
- harbor great potential to uncover underlying physics
- are an integral part of HEP/particle physics

Such precision studies often also use methods from other fields:

- AMO physics
- mechanics
- nanophysics
- nuclear physics
- opto-mechanics

but nevertheless their natural “funding home” lies in HEP/particle physics

Many thanks to Peter and Tom for their management of this Topical Group!