GRASP: Fundamental Phyiscs with clocks

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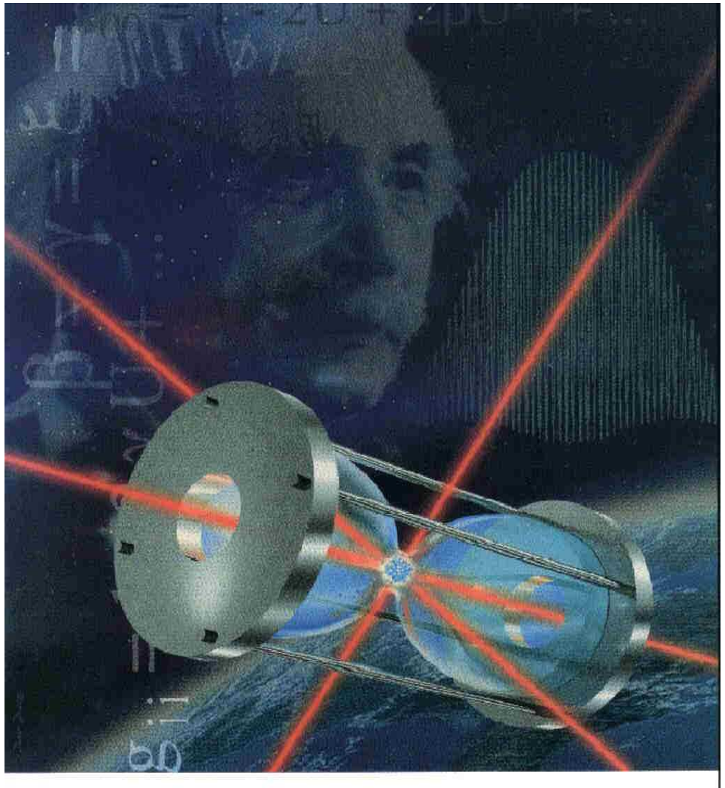

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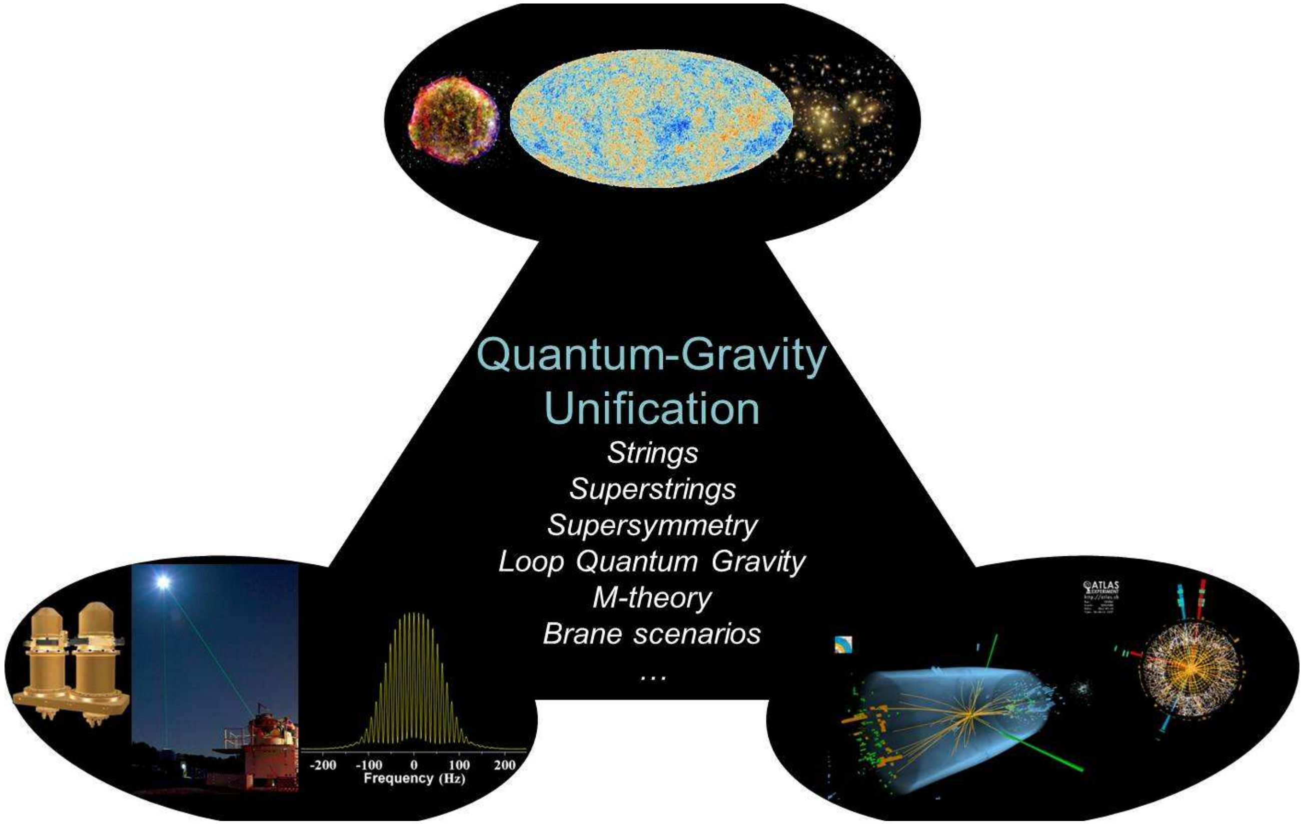
Fundamental Physics: Introduction

- General relativity is a classical theory and difficult to reconcile with quantum mechanics and the standard model of particle physics.
- Most unification models predict modifications of gravitational phenomena at some small (generally unknown) level.
- Dark energy and dark matter can be seen as deviations from our known laws of gravitation. A small (but non-zero) value of the cosmological constant (Λ-CDM model) is incompatible with quantum field theory (vacuum energy ?).
- Many modified gravitational theories and corresponding cosmological models contain long range scalar fields. BEH (Higgs) boson is the first known fundamental scalar field (short range).
- Low energy tests of fundamental gravitational physics can provide pieces of the puzzle that are complementary to cosmological observation or high energy physics in accelerators (LHC).

Fundamental Physics: Scientific Context

Astronomy & Cosmology
(*CMB, Planck, EUCLID*, …)



Low energy
(*LLR, lab-tests, ACES, μ-scope, …*)

High energy
(*CERN-LHC, Fermilab, DESY, …*)

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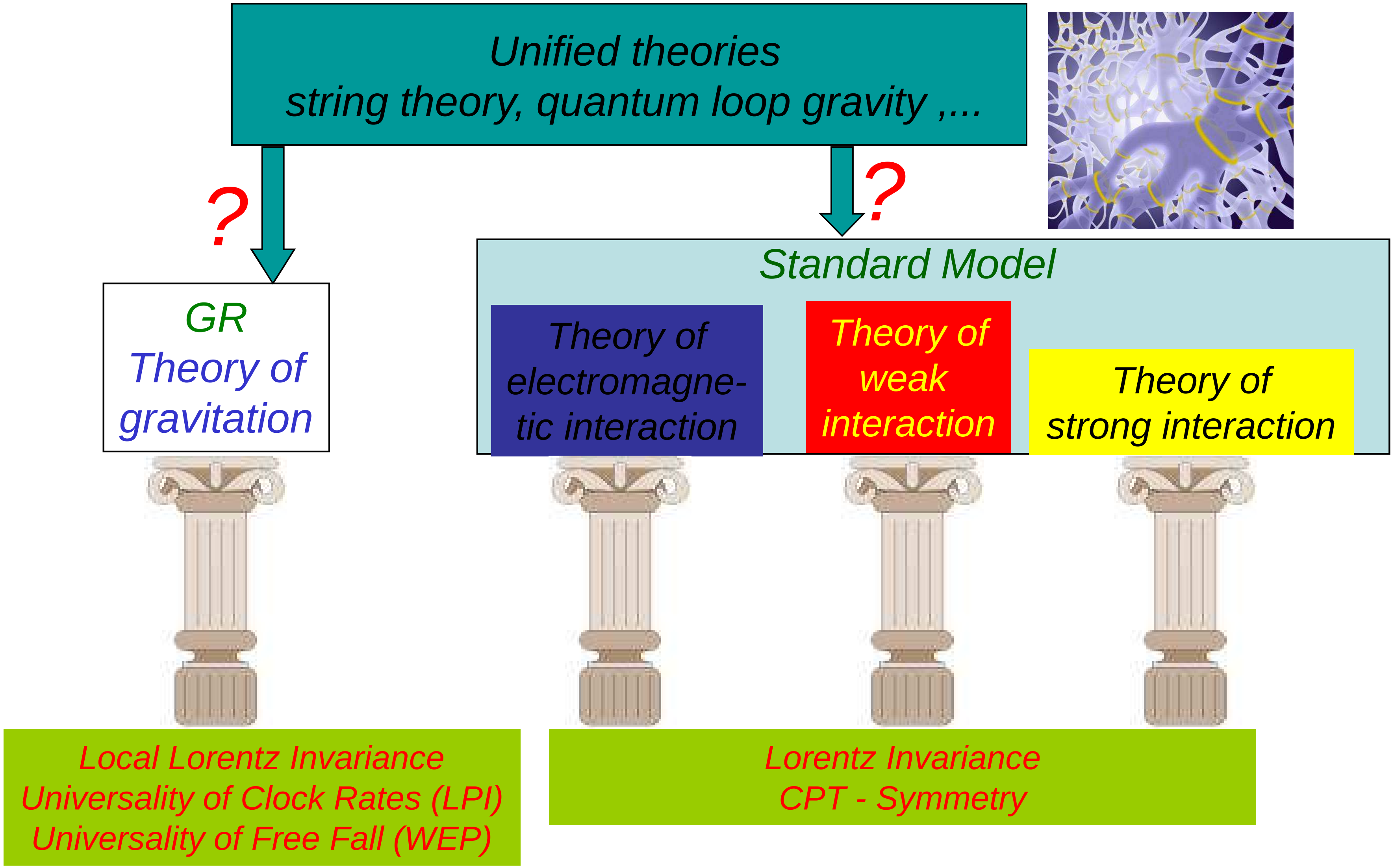
Fundamental Theories



exactly valid?

(courtesy S. Schiller)

GRASP test of UCR/LPI (1)

Violations of UCR/LPI (and UFF/WEP) are generally expected from non-universal couplings of some particle/interaction to gravity eg. due to scalar or tensor fields additional to $g_{\nu\mu}$. This then implies a dependence on the source eg. Sun (p) vs. Earth (p+n).

Test in the field of the Sun (Moon):

- Measure the diurnal frequency variations of two distant Earth clocks using the GRASP link(s). Phenomenological approach (Will 2006):

$$\frac{\Delta\nu}{\nu} = (1+\alpha_{LPI})\frac{U_A - U_B}{c^2} + \frac{v_A^2 - v_B^2}{c^2} + \Delta$$

$\Delta U/c^2$ varies sinusoidally at ≈ diurnal frequency with $A \approx 5\text{x}10^{-13}$ (6.9 ns in phase).

Note that in GR ($\alpha_{LPI} = 0$) the total frequency variation is zero (Equiv. Principle) up to tidal terms.

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GRASP test of UCR/LPI (2)

Assumptions:

- Ground stations at Boulder(USA) and Paris(F), 1 common view > 300 s/day
- Periods of 10 d continuous ground clock operation
- T2L2 GRASP: 3 ps @ 300 s, diurnal systematics < 10 ps
- MWL GRASP: 0.3 ps @ 300 s, diurnal systematics < 3 ps
- TWSTFT, GNSS (Fujieda 2014): diurnal systematics ≈ 50 ps

In all cases, after a few 10 d periods systematics are limiting:

- T2L2 GRASP: $\alpha_{LPI} \leq 1.5 \times 10^{-3}$
- MWL GRASP: $\alpha_{LPI} \leq 4.4 \times 10^{-4}$
- TWSTFT/GNSS: $\alpha_{LPI} \leq 7.2 \times 10^{-3}$
- Solar spectra / Galileo USO: $\alpha_{LPI} \leq 0.01$ [LoPresto 1991, Krisher 1993]

GRASP test of Lorentz Invariance

- Search for a modulation of clock comparison as a function of orientation of the baseline
- Test for general modification of “time” part of Lorentz transformations (e.g. Robertson-Mansouri-Sexl framework: α_{RMS}) $\rightarrow$ “Ives-Stillwell” experiment
- Performance depends on link performance and onboard clock stability and systematics at typically orbital period (7600 s @ 2000 km)
- Assume typical GNSS clock performance ≈ $5\text{x}10^{-14}$ sinusoidal @ orbital period ≈ 25 ps i.e. dominating with respect to link noise

$$\frac{\tau_r + \tau_e}{2} - \tau_s = 2\alpha_{RMS} \frac{\vec{D} \cdot \vec{w}}{c^2} + \Delta$$

- GRASP: $\alpha_{RMS} \leq 1.5\text{x}10^{-6}$ (*D* =4000 km, *w* =377 km/s)
- Li ion spectroscopy: $\alpha_{RMS} \leq 2.0\text{x}10^{-8}$ [Botermann 2014]

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Summary

- Anomalous couplings between Gravitation and standard model fields are expected from unification models and may lead to violations of the Einstein Equivalence Principle.
- GRASP could lead to an improvement by about a factor 10 in tests of UCR/LPI (grav. Redshift) in the field of the Sun/Moon.
- A test of Lorentz Invariance (Ives-Stillwell experiment) using the space clock is possible, but unlikely to lead to improvement on best present knowledge.