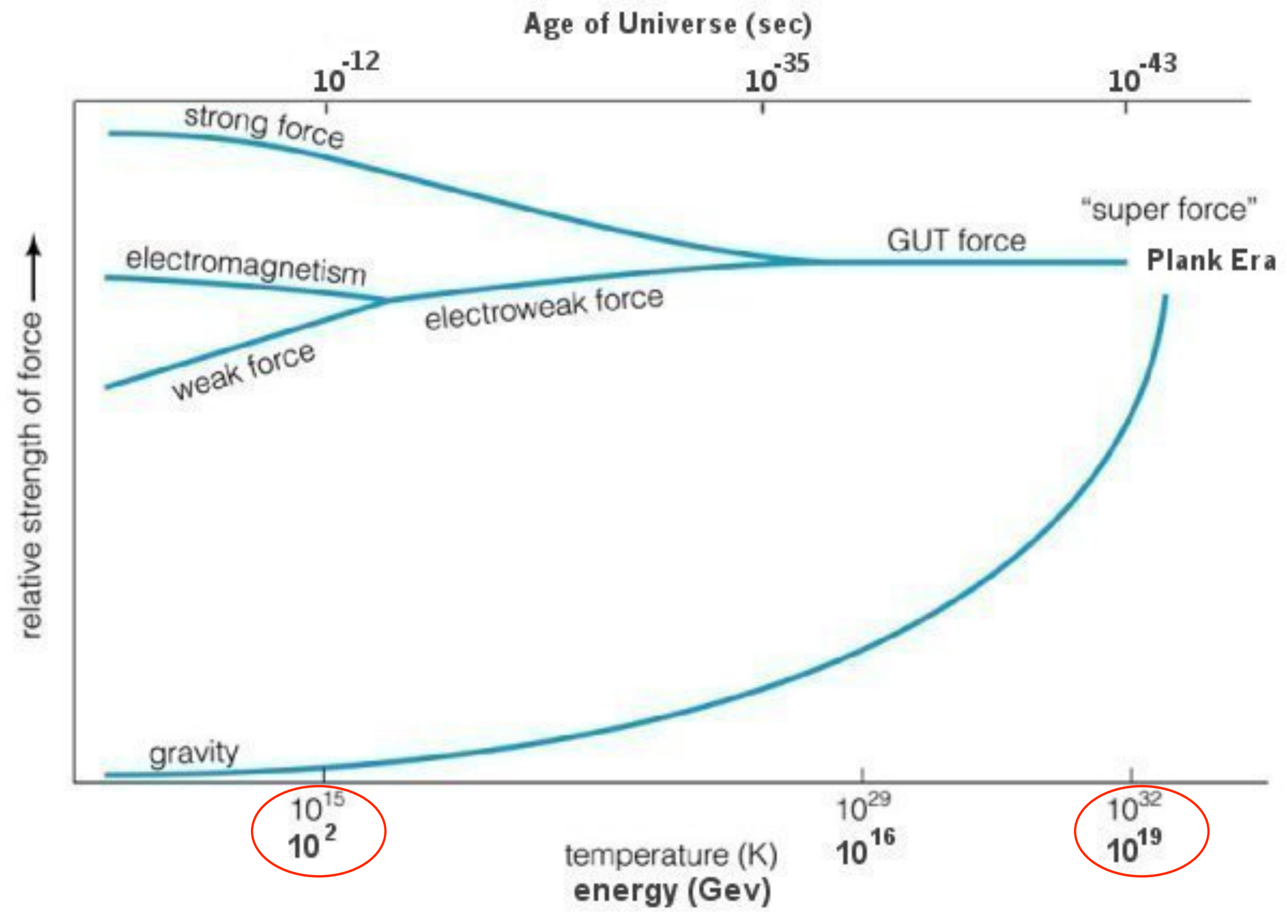
Effective theory for quantum gravity

Xavier Calmet

Physics & Astronomy
University of Sussex

When does quantum gravity matter?



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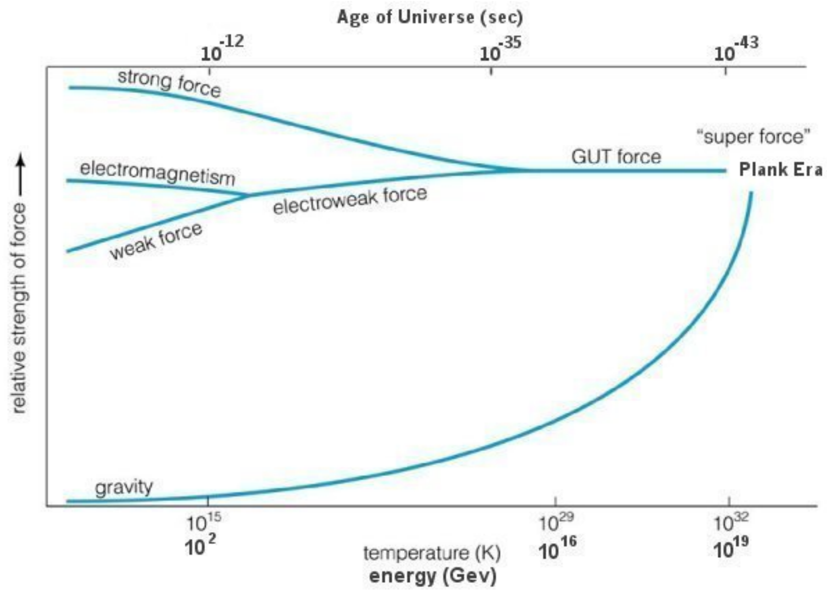
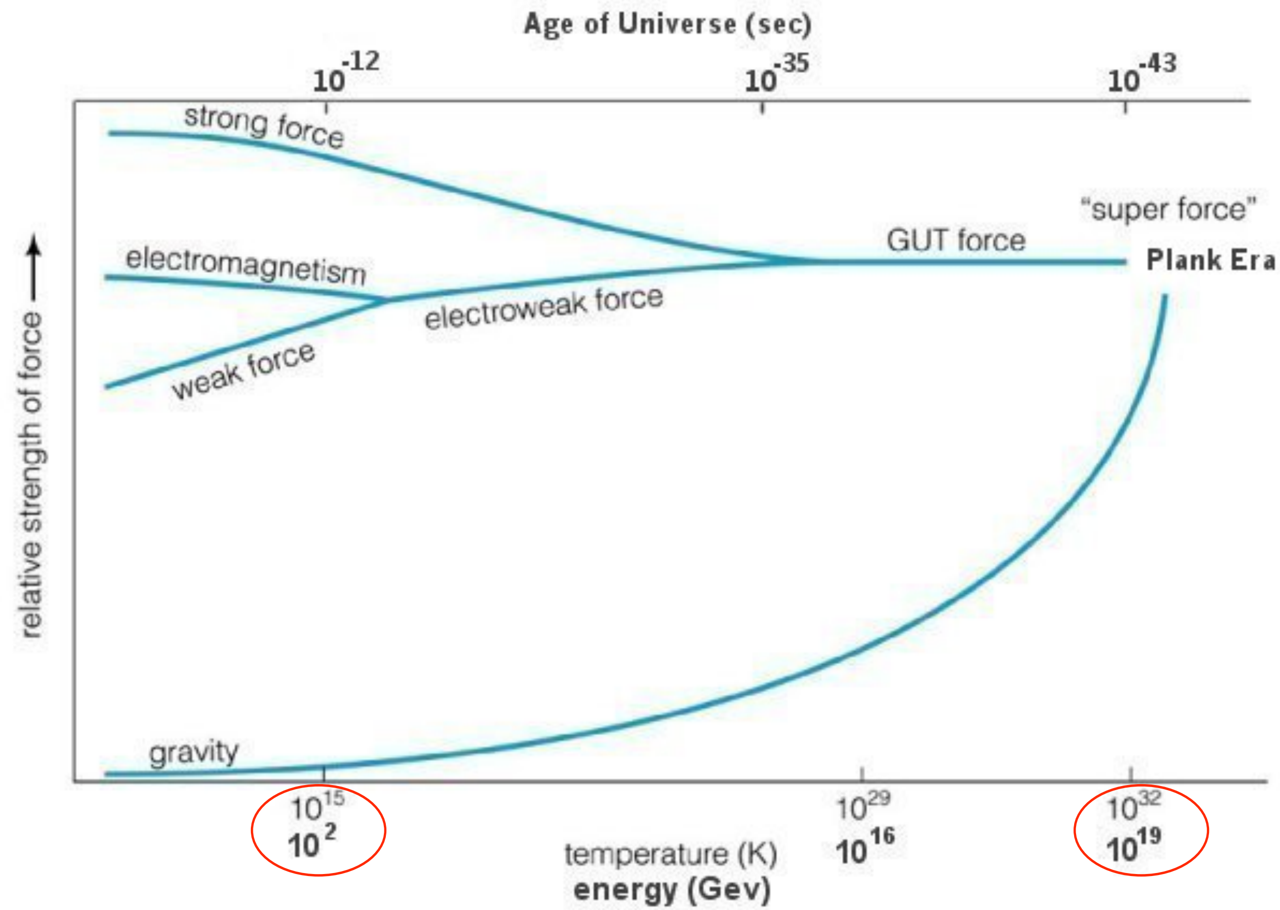


Maybe something modifies gravity in such a way that it becomes strong before 10^{19} GeV?

Models with a large extra-dimensional volume can do that.

When does quantum gravity matter?



What if we are not lucky?

Phenomenology of quantum gravity?

- Traditional approach focuses on highly speculative assumptions.
- Probe of violation of Lorentz invariance or other fundamental symmetries.
- Yes we know of some vacua in string theory with broken Lorentz invariance but that is not the norm.
- People build models of space-time discreteness and play with their models.

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- People build models of space-time discreteness and play with their models.

This is highly speculative and poorly motivated!!!

Effective theory approach

- We can describe any theory of quantum gravity below the Planck scale using effective field theory techniques:

$$S = \int d^4x \sqrt{-g} \left[\left(\frac{1}{2} M^2 + \xi H^\dagger H \right) \mathcal{R} - \Lambda_C^4 + c_1 \mathcal{R}^2 + c_2 \mathcal{R}_{\mu\nu} \mathcal{R}^{\mu\nu} + \mathcal{L}_{SM} + \mathcal{O}(M_\star^{-2}) \right]$$

- Electroweak symmetry breaking:

$$(M^2 + \xi v^2) = M_P^2 \qquad M_P = 2.4335 \times 10^{18} \text{ GeV}$$

- Several energy scale:
  - $\Lambda_C \sim 10^{-12}$ GeV cosmological constant
  - M_P or equivalently Newton's constant $G = 1/(8\pi M_P^2)$
  - $M_\star$ energy scale up to which one trusts the effective theory

- Dimensionless coupling constants ξ, c_1, c_2 etc

What values to expect for the coefficients?

- It all depends whether they are truly new fundamental constants or whether the operators are induced by quantum gravitational effects.
  - If fundamental constants, they are arbitrary
  - If induced by quantum gravity we can estimate their magnitude.
- Usually induced dimension four operators are expected to be small

$$\exp\left(-\lambda/\Lambda_{NP}\right)$$

- However, $\xi H^\dagger H \mathcal{R}$ translates into $\xi H^\dagger H h \Box h / M_P^2$ in terms of the graviton h. $\mathcal{R}^2$-type operators lead to $h \Box h h \Box h / M_P^4$
- We thus expect the coefficients of these operators to be $O(1)$.
- Naturalness arguments would imply $M_\star \sim \Lambda_C$. However, there is not sign of new physics at this energy scale.

What do experiments tell us?

- In 1977, Stelle has shown that one obtains a modification of Newton's potential at short distances from R^2 terms

$$\Phi(r) = -\frac{Gm}{r}\left(1 + \frac{1}{3}e^{-m_0 r} - \frac{4}{3}e^{-m_2 r}\right)$$

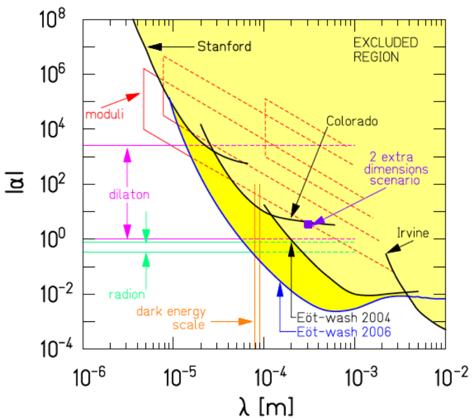
$$m_0^{-1} = \sqrt{32\pi G\,(3c_1 - c_2)}$$

$$m_2^{-1} = \sqrt{16\pi G c_2}$$

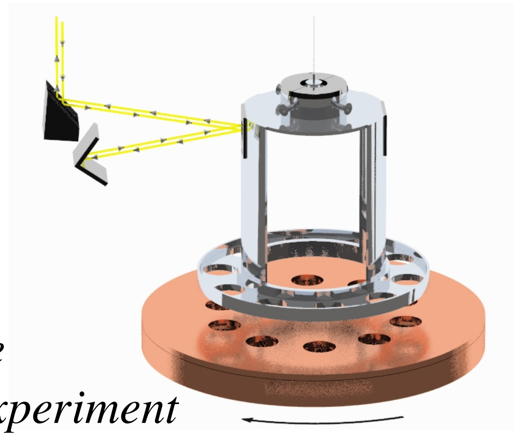
$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 + \alpha \exp\left(-r/\lambda\right)\right]$$

c_1 and c_2 $<10^{61}$

xc, Hsu and Reeb (2008)



NB: Bound has improved by 10 order of magnitude since Stelle's paper!



Schematic drawing of the Eöt-Wash Short-range Experiment

Can better bounds be obtained in astrophysics?

- Bounds on Earth are obtained in weak curvature, binary pulsar systems are probing high curvature regime.

- Approximation: Ricci scalar in the binary system of pulsars by G M/(r^3c^2) where M is the mass of the pulsar and r is the distance to the center of the pulsar.

- But: if the distance is larger than the radius of the pulsar, then the Ricci scalar vanishes. This is a rather crude estimate.

Can better bounds be obtained in astrophysics?

- Let me be optimistic and assume one can probe gravity at the surface of the pulsar. I take r=13.1km and M=2 solar masses.

- I now request that the R^2 term should become comparable to the leading order Einstein-Hilbert term ($1/2\ M_P^2\ R$)

- One could reach bounds of the order of 10^{78} only on c_1 or c_2

- Such limits are obviously much weaker that those obtained on Earth.

Atkins & XC arXiv:1211.0281

Higgs boson has been found

- There is thus one new dimension 4 operator allowed by all the symmetries of the theory

$$S \supset \int d^4x \sqrt{-g}\, \xi H^\dagger H \mathcal{R},$$

- Going to the Einstein frame one see easily that the Higgs field needs to be rescaled by a factor

$$\phi/\sqrt{1+\beta} \text{ where } \beta = 6\xi^2 v^2/M_P^2$$

- Hence all couplings of the Higgs field to the SM are rescaled. The Higgs boson decouples from the SM for

$$\xi \gg M_P/v \simeq 10^{16}$$

- Since the Higgs has been found, a large $\xi > 10^{16}$ is excluded.

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- There is thus one new dimension 4 operator allowed by all the symmetries of the theory

$$S \supset \int d^4x \sqrt{-g}\, \xi H^\dagger H \mathcal{R},$$

- Doing a careful analysis, one finds

$$\xi > 2.6 \times 10^{15} \text{ at the 95\% C.L.}$$

- Future colliders (LHC @ 14 TeV or ILC) will not improve the situation much. At a 500 GeV ILC with an integrated luminosity of 500 fb^{-1}, one could reach:

$$\xi < 4 \times 10^{14}$$

- Probably this is the limit of what can be reached.

Conclusions

- Goal of the program is to find serious ways to constrain models of quantum gravity by finding methods allowing to measure the coefficients of the effective action.

- Clearly this is tough, but one needs to start somewhere.

- In the case of the Higgs boson, if we could measure the properties of the Higgs boson with perfect precision we would be able to measure the non-minimal coupling (but that is utopia!). It would be important for Higgs inflation models which need a non-minimal coupling of the order of 10^4.

- We need to be (very) creative!

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Thanks for your attention!