Probing Fundamental Physics including Planck Scale Physics and Equivalence Principle using Matter Wave Interferometry

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Probing Fundamental Physics Using Matter Wave Interferometry

- Exploring quantum spacetime fluctuations (Wang et al 2006)
- Testing Equivalence Principle (Dimopoulous et al 2006)
- Verifying Newtonian Gravity and $1/r^2$,also *G* (Dimopoulous et al 2003)
- Detection of extra dimensions (Dimopoulous et al 2003)
- Precision measurement of Casimir effect
- …

Atom interferometers and quantum gravity

- Grand unification theory (GUT) predict that the four forces of nature unify close to the Planck scale.
- Spacetime is smooth on the normal scales but granulated due to quantum gravity on the Planck scale.

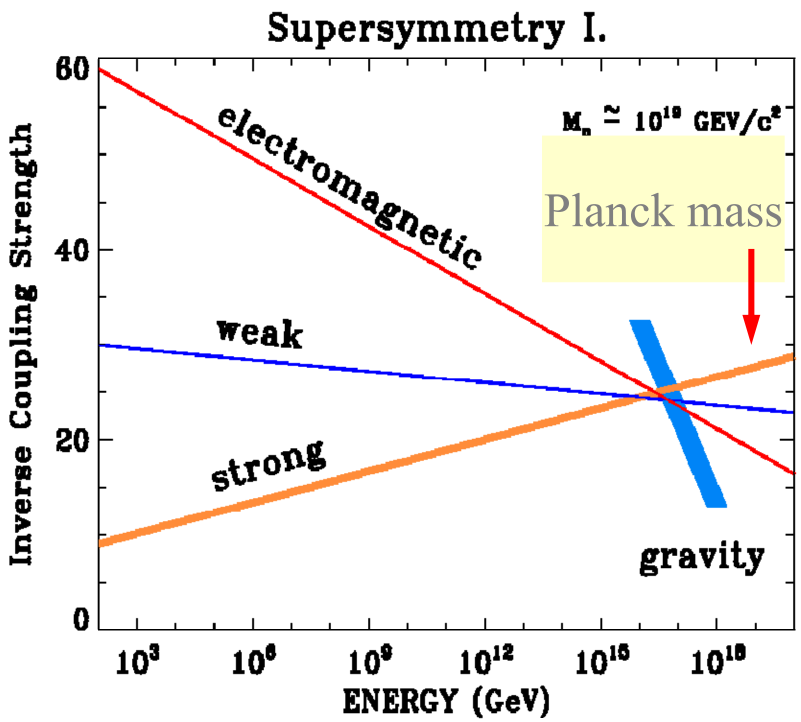
Planck time $T_{\text{planck}} = (\hbar G\, c^{-5}) \approx 10^{-43}$s

Planck length $c\,T_{\text{planck}} = (G\hbar\, c^{-2}) \approx 10^{-35}$ m

Planck mass $M_{\text{planck}} = (\hbar c/G) \approx 10^{-8}$ kg

Planck energy $\approx 10^{19}$ GeV

GUT scale $\approx 10^{16}$ GeV

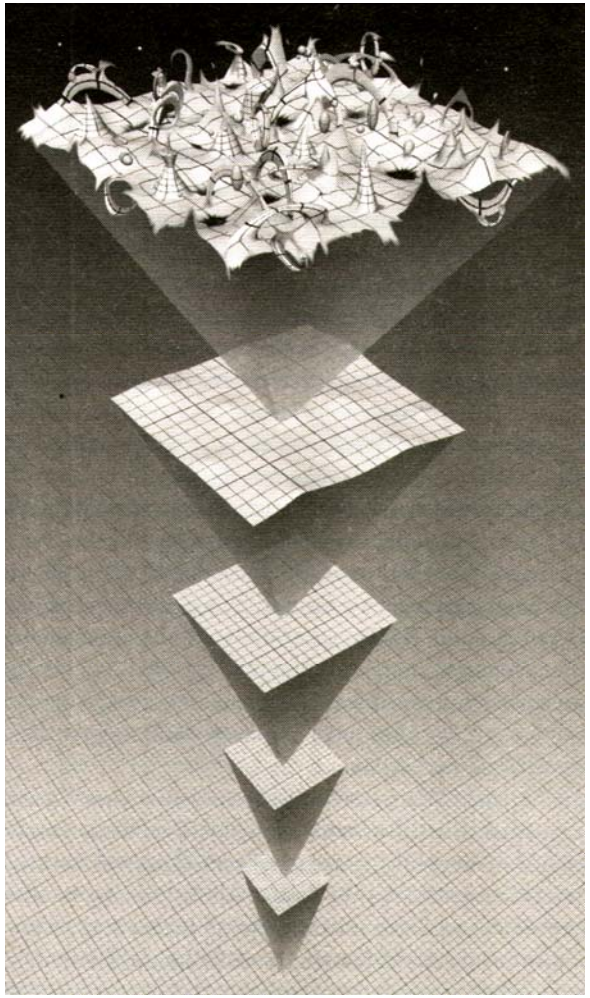


Quantum foam of spacetime

- Spacetime at the Planck scale could be topologically nontrivial, manifesting a granulated structure $\Rightarrow$ Quantum Foam

- Quantum decoherence puts limits on spacetime fluctuations at the Planck scale.

- Semi-classical and Superstring theory support the idea of loss of quantum coherence.

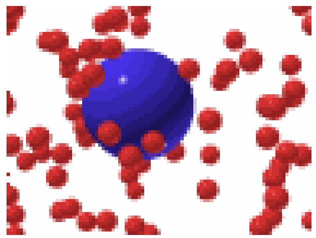


Atom interferometers and quantum gravity

- How can an atom interferometer measure physics on the Planck scale?
- Hard to find gravitational analogue of Casimir effect due to weakness of coupling
- Einstein's (1905) Brownian motion work of inferred properties of atoms by observing stochastic motion of macrostructure's
- Space time fluctuations on the Planck scale produce stochastic phase shifts.

$\Rightarrow$ Diffusion of the wave function

Produces decoherence in an atom interferometer



Random walk of a Brownian particle (blue) due to stochastic interactions with molecules (red).

Q: Without full quantum gravity, is there any tractable approach?

Physics of decoherence

- Interaction with environment • Collisions with ambient particles • Black body radiation
- Interaction with its own components • Natural vibrations of the system
- Quantum spacetime fluctuations:

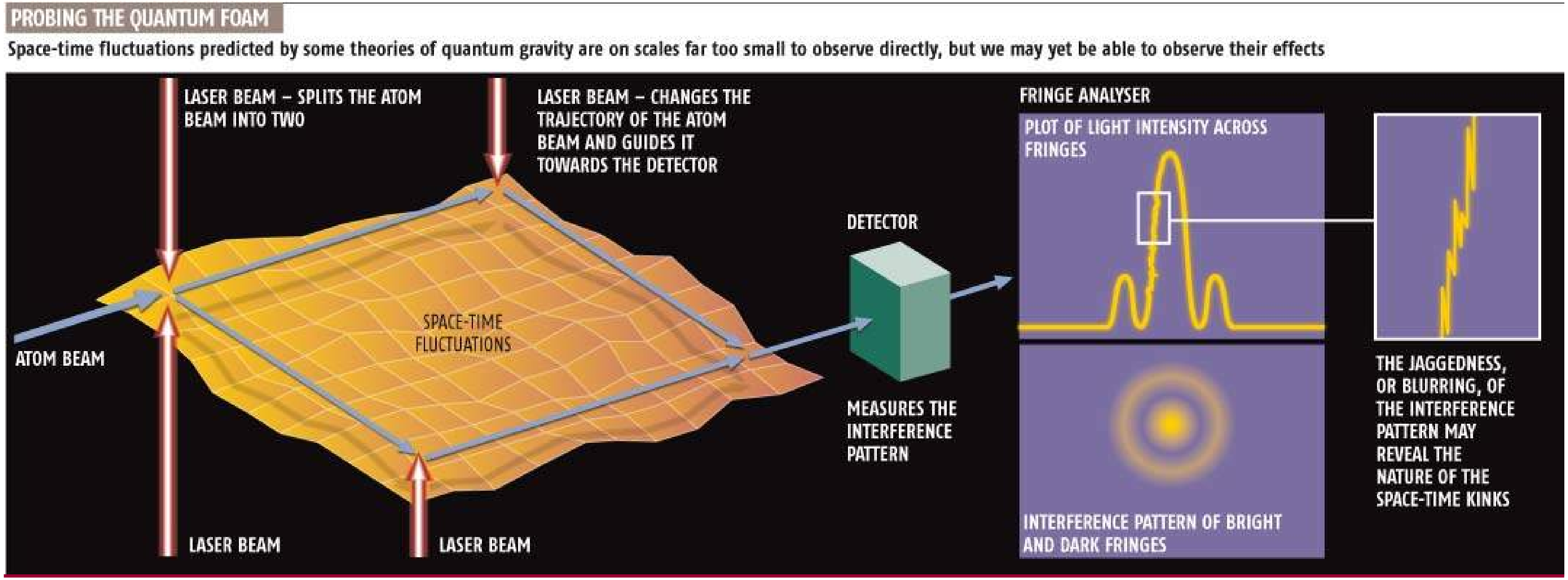
  Granulation of spacetime - extra dimensions may be required. e.g. Superstring theories ≥ 10 dimensions.

  Introduce a phenomenological correlation length scale below which granulation is important:

$$\ell_0 = \lambda \ell_{Planck}$$

  From theoretical considerations: $\lambda > 10^2$

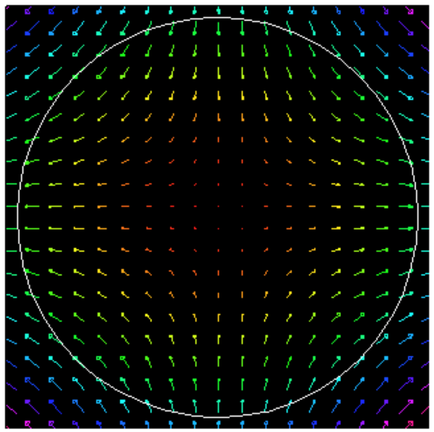
(New Scientist 2 Sept 2006)



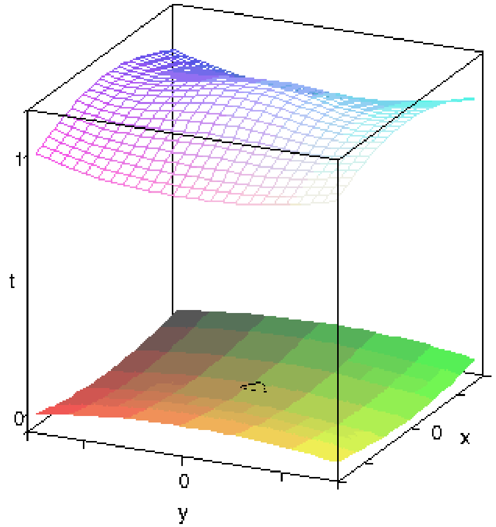
Conformal structure in general relativity

- Similar decoherence ideas using neutrons was proposed by Ellis *et al.* (1984). The possibility of detecting spacetime fluctuations using modern matter wave interferometers was outlined by Percival *et al.* Proc. R. Soc. (2000). However, these models are too crude to make predictions.

- Recent developments of conformal decomposition (Wang 2005, PRD 71,124026) in canonical gravity provides theoretical tools for estimating quantum gravitational decoherence without freezing any degrees of freedom of general relativity.



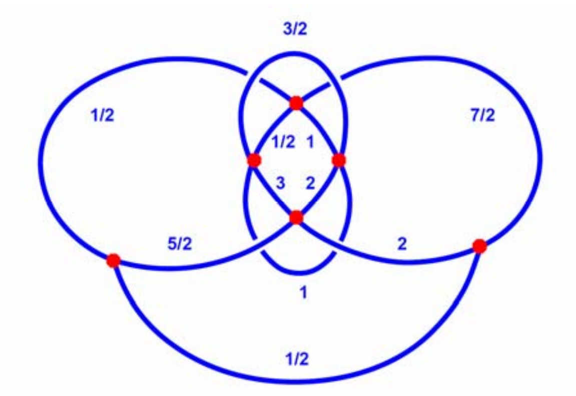
The shearing nature
of gravitational waves



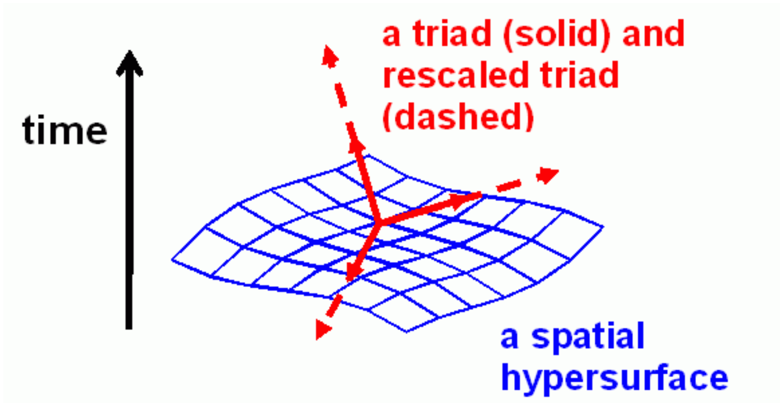
Spacetime evolution with
diffeomorphism, spin &
conformal invariance

Conformal structure in general relativity

The conformal decomposition of gravity also has important implications for loop quantum gravity ,e.g. Wang 2005 PRD 72, 087501; 2006 Phil. Trans. R. Soc. A)



Spin network states based on the present form of loop quantum gravity are ‘too discrete’ to yield classical limits (Smolin 1996).



Conformal equivalence classes of triads are used to reformulate loop quantum gravity to be free from the Barbero-Immirzi ambiguity.

Conformal decomposition of canonical gravity

The essential requirement for the theoretical framework in which the conformal field interacts with GWs at zero point energy is a conformally decomposed Hamiltonian formulation of GR. Such a theoretical framework has been established in recent papers (Wang 2005: PRD 71, 124026 & PRD 72, 087501). It allows us to consider a general spacetime metric of the form

$$g_{\alpha\beta} = (1 + A)^2 \gamma_{\alpha\beta}$$

in terms of the conformal field A and the rescaled metric $\gamma_{\alpha\beta}$. We shall work in a standard laboratory frame where the direction of time is perpendicular to space. Accordingly, we set $\gamma_{00} = -1$ and $\gamma_{0a} = 0$ (using $a, b = 1, 2, 3$ as spatial coordinate indices.) The spatial part of the metric $\gamma_{\alpha\beta}$ is denoted by γ_{ab} and is normalized using $\det(\gamma_{ab}) = 1$. Hence, γ_{ab} will be referred to as the 'conformal metric' as it specifies the conformal geometry of space. Its inverse is denoted by γ_{ab}. The spacetime metric above therefore accommodates both the conformal field and in addition the spin-2 GWs encoded in the deviation of the conformal metric γ_{ab} from the Euclidean metric δ_{ab}.

Conformal decomposition of canonical gravity

The canonical theory of general relativity has been constructed in terms of the conformal classes of spatial metrics by extending the ADM phase space consisting of the spatial metric g_{ab} and its momentum p^{ab}, (a, b = 1, 2, 3). The canonical transformation (g_{ab}, p^{ab}) $\rightarrow$ (γ_{ab}, π^{ab}; τ,μ) is performed using a conformally transformed spatialmetric γ_{ab}, its momentum π^{ab}, the scale factor $\mu = \sqrt{(\det g_{ab})}$ and York's mean extrinsic curvature variable τ. We then perform the canonical transformation (γ_{ab}, π^{ab}; τ,μ) $\rightarrow$ (γ_{ab}, π^{ab}; A, P), where P is the momentum of A.

In terms of these variables, the gravitational Hamiltonian density becomes

$$\mathcal{H} = \mathcal{H}^{(CF)} + \mathcal{H}^{(GW)}$$

where

$$\mathcal{H}^{(GW)} = (1 + A)^{-2}\pi_{ab}\pi^{ab} - (1 + A)^{2} R\gamma$$

is the Hamiltonian density for the GWs, where $R\gamma$ is the Ricci scalar curvature of γab, and

$$\mathcal{H}^{(CF)} = -{}^{1}/_{24}\, P^{2} - 6\, \gamma^{ab} A_{,a} A_{,b}$$

is the Hamiltonian density for the conformal field. This Hamiltonian density has a remarkable feature of being similar to that of a massless scalar field but with a 'wrong sign', i.e. negative energy density, which has important physical consequences.

(Full GR used without linearization)

Quantum gravitational decoherence of matter waves

- We have decomposed the gravitational Hamiltonian density into

$$\mathcal{H} = \mathcal{H}^{(CF)} + \mathcal{H}^{(GW)}$$

where $\mathcal{H}^{(CF)}$ is the *negative* Hamiltonian of the conformal factor and $\mathcal{H}^{(GW)}$ is the *positive* Hamiltonian of the gravitational wave, so that the Hamiltonian constraint $\mathcal{H} = 0$ is satisfied. This yield the estimated ground state conformal fluctuation spectrum up to the cut-off value given by $1/\tau_0$:

$$< A(\omega)^2 >= {}^2/_{3\pi}\, T_{\text{Planck}}{}^2\, \omega$$

- Decoherence can be measured by the loss of contrast of the matter wave denoted by Δ. For massive matter waves, fluctuations of the conformal factor, rather than GWs, contribute to decoherence

$$\Delta = \sqrt{\frac{\pi}{2}}\frac{M^2 c^4 T A_0^4 \tau_0}{\hbar^2}$$

through a stochastic Newtonian potential ~ $-g_{00}/2 = (1+A)^2/2$, where M is the mass of the quantum particle; T is the separation time before two wavepackets recombine; $\tau_0 = \lambda T_{\text{Planck}}$ is the correlation time and A_0 is the amplitude of the fluctuating conformal factor due to zero point energy.

- The amplitude A_0 can be estimated by integrating the above CF states. This leads to the formula (Wang, Bingham & Mendonca CQG **23** L59, 2006):

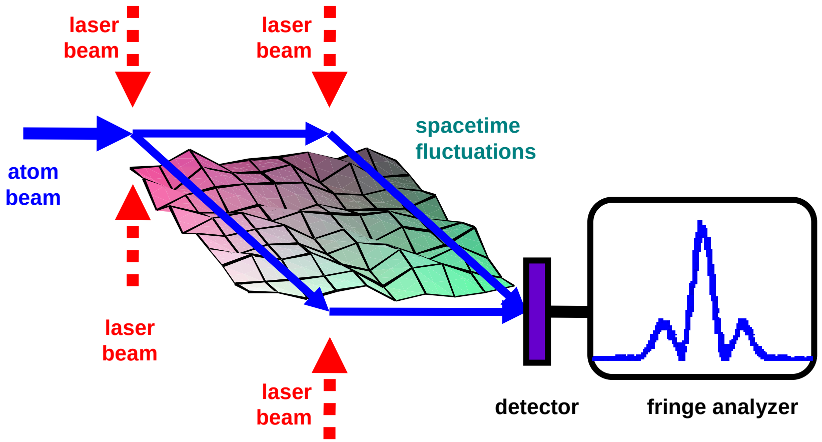
$$\lambda \sim \left(\frac{M^2 c^4 T_{Planck} T}{\hbar^2 \Delta}\right)^{\frac{1}{3}}$$

The precise form factor depends on possible contributions from the ground states of matter fields as well as the spectral distribution of the conformal factor states.

Atom optics & quantum spacetime fluctuations

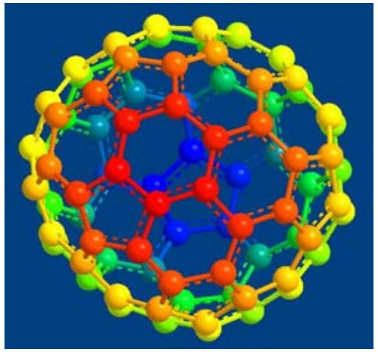
The basic scenario is that gravitons constantly modulate the conformal factor of spacetime, a bit like the way in which pollen grains have a random Brownian motion as they are buffeted by much smaller molecules.

By observing these tiny distortions in an atom interferometer, it is possible to extract information on the gravitons and understand their underlying physics.

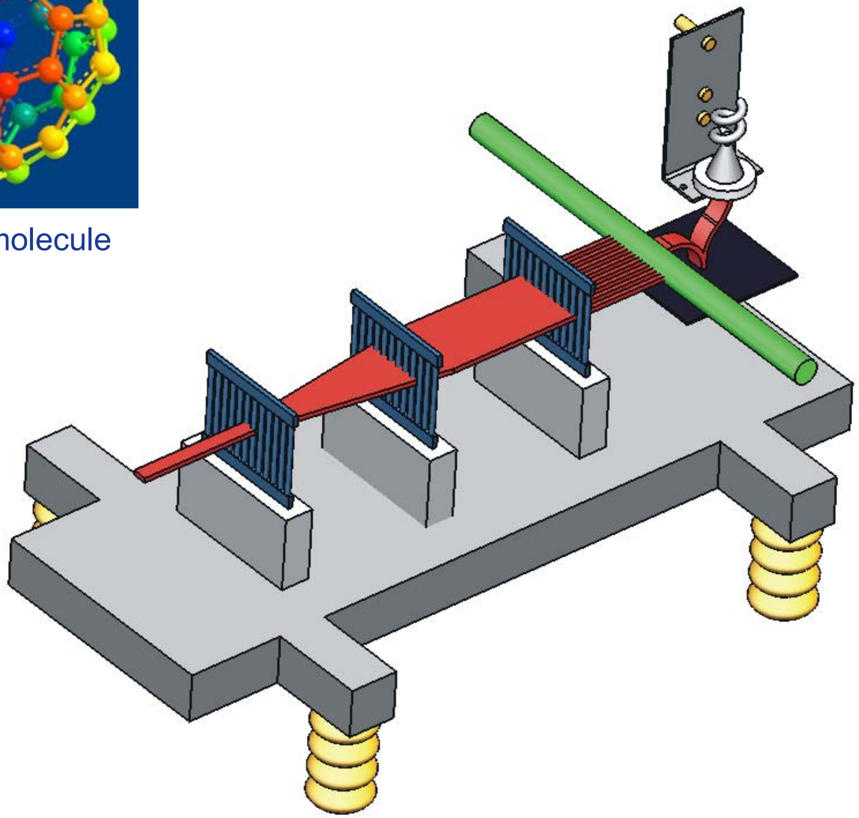


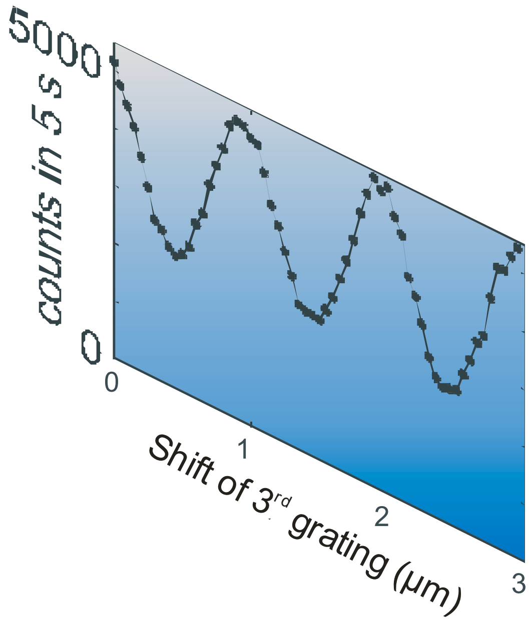
An atom interferometer sends beams of ultracold atoms down two identical arms. Fluctuations in space-time caused by the gravitons will randomly modulate the time it takes for the beams to travel down the arms. This will then create a slight fuzziness in the fringe patterns that are created when the beams interfere.
(Physics World 6 Sept. 2006)

Matter wave interferometry using large molecules



C_{70} fullerene molecule





Visibility:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Arndt *et al.* Phys. Rev. Lett. **88**, 100404 (2002); Hornberger, Arndt *et al.* Nature **427**, 711 (2004)

Experimental bounds on quantum gravitational decoherence of matter waves

- The formula

$$\lambda \sim \left(\frac{M^2 c^4 T_{Planck} T}{\hbar^2 \Delta} \right)^{\frac{1}{3}}$$

  implies that experiments using caesium atom interferometers by Peters & Chu *et al* (1997 Phil. Trans. R. Soc. A) and fullerene C_{70} molecule interferometer by Hornberger & Arndt *et al* (2004 Nature) set a lower bound of λ to be of order 10^4, consistent with theoretical expectations. (Wang, Bingham & Mendonca CQG **23** L59, 2006)*

- This lower bound corresponds to the scale ~ 10^{15} GeV, close to the GUT scale ~10^{16} GeV.

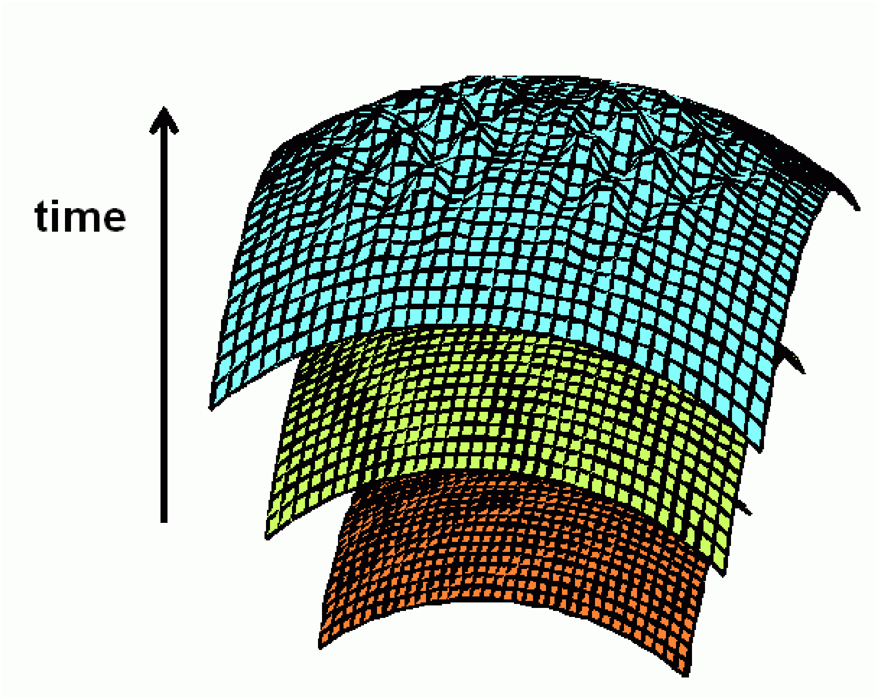
- Improvements on experimental sensitivity can raise this value. Further improved measurement may decrease the upper bound of decoherence resulting in an increased λ.

- A space mission flying an atom wave interferometer can provide such improvements.

- Meanwhile, tests from advanced ground based interferometers are welcome, e.g. Drop Tower …

*Free online; ~300 downloads in first month of pub. 18/08/2006

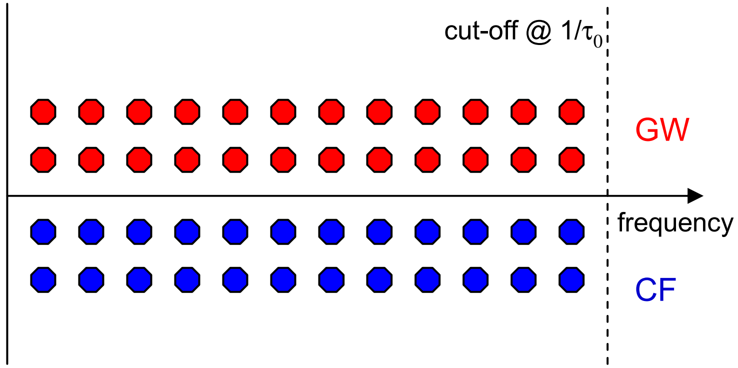
The effects of overall and local activities of the conformal factor on the Universe



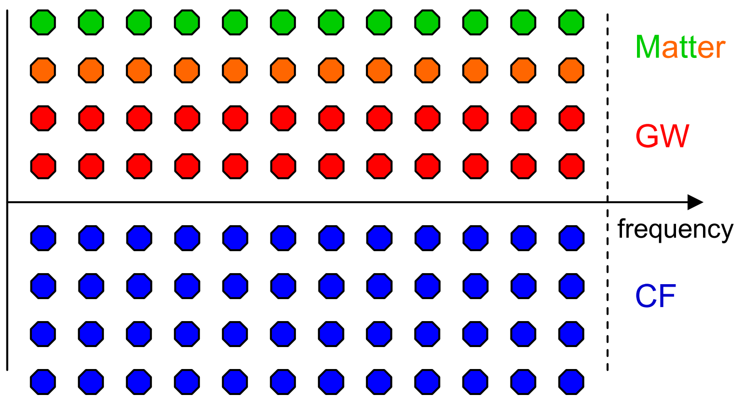
Expansion of the universe with local in inhomogeneity and anisotropy.

The spectral property of the conformal factor, inclusion of matter and the expansion of the Universe

Higher entropy occupations of the conformal factor quanta (Late Universe)



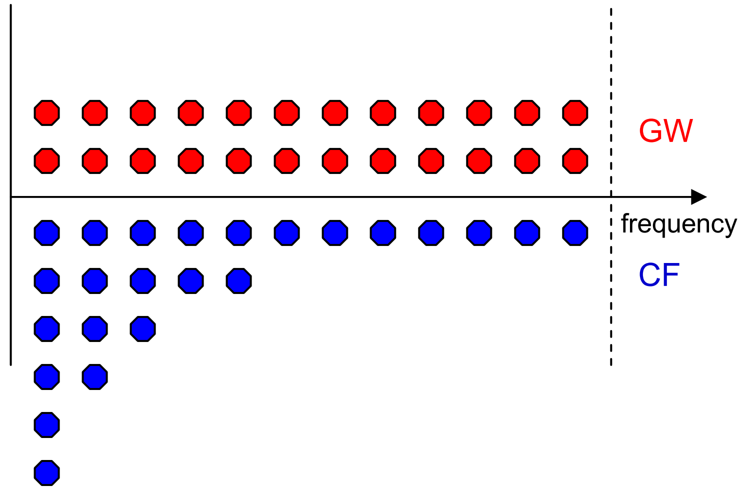
Higher entropy occupations of the conformal factor quanta with matter fields (Late Universe)



While the high frequency modes of the conformal factor is relevant for the decoherence of matter waves, the lower frequency modes are responsible for cosmic acceleration.

The formula of λ relating the measured decoherence of matter waves to space-time fluctuations, is "minimum" in the sense that ground-state matter fields have not been taken on board. Their inclusion may further increase the estimated conformal fluctuations and result in a refined form factor.

Lower entropy occupations of the conformal factor quanta (Early Universe)



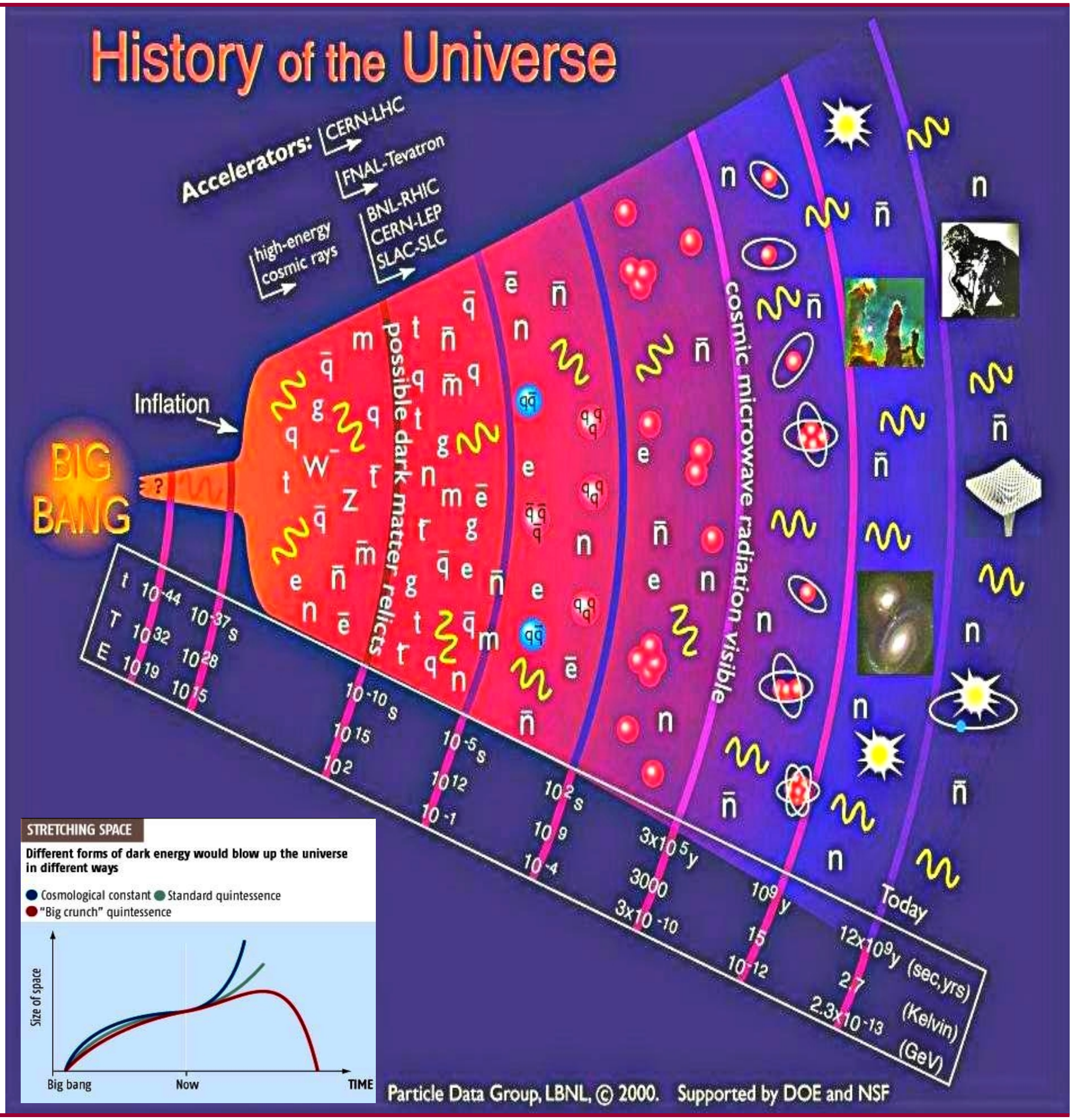
Implications on the very small as well as the very large

As well as causing quantum matter waves to lose coherence at small scales, the conformal gravitational field is responsible for cosmic acceleration linked to inflation and the problem of the cosmological constant.

The formula for λ relating the measured decoherence of matter waves to spacetime fluctuations, is "minimum" in the sense that ground-state matter fields have not been taken on board.

Their inclusion will further increase the estimated conformal fluctuations. In this sense, the implications go beyond quantum gravity to more generic physics at the Planck scale.

It opens up new perspectives of the interplay between the conformal dynamics of spacetime and vacuum energy due to gravitons, as well as elementary particles. These have important consequences on cosmological problems such as inflation and dark energy. (Bingham, Mendonca & Wang, CERN Courier October 2006).



Conclusions

- Theories of quantum gravity support the idea of loss of coherence in matter interferometers.
- Advanced matter interferometers will put upper limits to the measurement of decoherence providing tests for the various theories of quantum gravity.
- In matter interferometers it is difficult to avoid interactions with the environment. The challenge is to detect the spacetime fluctuations unambiguously.
- However, the work presented here suggests that investigating Planck scale physics using advanced matter interferometry is becoming a reality.
- The final value of the correlation parameter λ will be a compelling evidence for the quantum behaviour of spacetime and set a stringent benchmark in the search for quantum gravity.
- The experimental determination of λ will unveil new physics at the Planck as well as cosmological scales through its undetermined theoretical role on vacuum energy.
- The proposed decoherence experiments can be performed in a space mission flying a matter wave interferometers, where other aspects of fundamental physics are also tested, e.g. equivalence principle, Casimir effect, fundamental constants,
- More from the GAUGE proposal …