Experimental Search for Quantum Gravity

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Plan

- **Motivation:** Why do we need quantum gravity? Why is it difficult to quantize gravity? What can we do about it? What is a phenomenological model and what is it good for?
- **Introduction:** How do phenomenological models work? Why is it so difficult to see quantum gravitational effects? Can we directly detect gravitons? Have we already indirectly detetected gravitons?
- **Models I:** Models with a lowered Planck scale and recent contraints. Lorentz invariance violation and constraints. Deformations of special relativity and constraints.
- **Discussion**
- **Models II:** What is cool about neutral Kaons and what do they have to do with quantum gravity? The Holometer, Bekenstein's table-top experiment, and space-time defects
- **Summary:** Where are we and what is next?
- **Discussion**

$c = \hbar = 1$, so $m_{\rm p} = 1/l_{\rm p}$, $G = 1/m_{\rm p}^2$, key references in handout.

Why do we need quantum gravity?

Because

- We don't know what is the gravitational field of a quantum superposition.
- Black holes seem to destroy information, and we don't know how that is compatible with quantum mechanics.
- General relativity predicts its own breakdown: Singularities.
- It is esthetically unpleasing to have it stand out.
- We hope it will help with other unsolved problems like the cosmological constant or dark matter.

In the following I'll refer as 'quantum gravity' to any attempted solution of these problems.

This does not mean that one necessarily obtains quantum gravity by quantizing gravity.

What you need to know about GR in the following

- GR describes the relation between the curvature of space-time and the matter in it.
- $g_{\nu\kappa}$ is a (Lorentzian) metric on the manifold and dimensionless
- $\Gamma^{\alpha}{}_{\nu\kappa}$ is the connection and contains ∂g's, i.e. it has dimension of an energy.
- $R^{\mu}{}_{\nu\kappa\alpha}$ and contractions $R_{\nu\kappa}$ and $\mathcal{R}$ describe the curvature. The R family contains $\partial\partial g$ and $(\partial g)^2$ and has dimension of energy^2
- The action of GR coupled to matter in 3+1 dimensions is

$$S = \int d^4x \sqrt{-g} \left(\frac{m_{\rm p}^2}{16\pi} \mathcal{R} + \mathcal{L}_M \right)$$

- For the dimensions to match, the coupling constant $m_{\rm p}^2$ has to be dimensionful.
- Variation leads to Einstein's field equations

$$m_{\rm p}^2 \left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \right) = 8\pi T_{\mu\nu} \quad \text{with} \quad T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta \sqrt{-g} \mathcal{L}_M}{\delta g_{\mu\nu}}$$

What is so difficult about quantizing gravity?

It's not difficult to quantize. It's just that the result of the 'easy' quantization is not a meaningful fundamental theory.

- First, look at small perturbations around flat background and define $g_{\alpha\nu} = \eta_{\alpha\nu} + h_{\alpha\nu}/(4\sqrt{\pi} m_{\rm p})$. (Factor added for convenience).
- Linearization of action leads to

$$S = \int d^4x (h_{\alpha\mu} D^{\alpha\mu\kappa\gamma} h_{\kappa\gamma} + \frac{1}{4\sqrt{\pi} m_{\rm p}} h_{\alpha\kappa} T^{\alpha\kappa})$$

  D is a 2nd order differential operator and gauge dependent. With redefinition $\bar{h}_{\nu\kappa} = h_{\nu\kappa} - \eta_{\nu\kappa} h/2$ fulfills the usual wave equation.
- Now quantize. Make fourier expansion of h and replace coefficients with operators to get $\hat{h}$. Watch after gauge, and read off Feynman rules.
- Fourier trafo of $D^{\alpha\mu\kappa\gamma}$ gives propagator and $h_{\alpha\kappa} T^{\alpha\kappa}$ the graviton-matter vertices, $1/m_{\rm p}$ is the coupling constant.
- Note that $\hat{h}$ couples universally to the energy momentum tensor.

A dimensionful coupling ruins the game

- Graviton couples to derivatives of the fields (and to itself) $h_{\nu\kappa} T^{\nu\kappa}$ e.g.

$$T_{\mu\nu} = F_{\mu}{}^{\alpha} F_{\alpha\nu} + \frac{1}{4} g_{\mu\nu} F^2 \ , \ \ T_{\mu\nu} = \nabla_\nu \Psi \nabla_\mu \Psi^\dagger$$

- Calculate quantum corrections, for example graviton contribution to propagator is of the form

$$\Pi(p) = \frac{1}{m_{\rm p}^2} \int d^4 k \frac{kk}{(k^2)(k-p)^2}$$

- The result is divergent and cannot have the same form as the original terms in the action. For dimensional reasons it must have different powers of momentum.
- To cancel this quantum correction, one needs to introduce a new term which has an arbitrary finite part. It causes another term, which needs another counterterm and so on[1]
- The so quantized theory is perturbatively non-renormalizable.

[1] Pure gravity is fine till 2 loops.

Divergence at high energies

Another way to see this

- Graviton-graviton scattering, tree level[2]

$$A(++,--) \sim \mathrm{i}\frac{1}{m_{\mathrm{p}}^2}\frac{s^3}{tu}$$

  Power counting E^2/m_{p}^2

- Graviton-graviton scattering, 1 loop amplitude

$$\begin{aligned} A(++,--) &\sim \mathrm{i}\frac{1}{m_{\mathrm{p}}^4}(s^2+t^2+u^2) \\ A(++,+-) &\sim A(++,--) \end{aligned}$$

  Power counting E^4/m_{p}^4

- Divergence at high energies

[2] See e.g. Anber and Donoghue, arXiv:1111.2875

So, that is difficult about quantizing gravity

- Naively quantized gravity is perturbatively non-renormalizable
- Its perturbative expansion breaks down when energies reach $m_{\rm p}$
- Or distances reach $l_{\rm p}$.
- This is the so-called Planck scale

What is the Planck scale?

- The Planck mass, m_{p}, is the energy at which a particle causes a significant perturbation of the metric in a volume given by its own Compton wavelength $l_{\mathrm{p}} = 1/m_{\mathrm{p}}$
- An energy E in a volume Δx^3, where $\Delta x \sim 1/E$ causes a curvature perturbation

$$\frac{\delta g}{\Delta x^2} \sim \frac{1}{m_{\mathrm{p}}^2} \frac{E}{\Delta x^3} \Rightarrow \delta g \sim \frac{E^2}{m_{\mathrm{p}}^2}$$

- $\delta g \approx 1$ for

$$\begin{aligned} m_{\mathrm{p}} &= \sqrt{\frac{\hbar c}{G}} \approx 10^{16}\mathrm{TeV} \\ l_{\mathrm{p}} &= \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-20}\mathrm{fm} \\ t_{\mathrm{p}} &= \sqrt{\frac{\hbar G}{c^5}} \approx 10^{-43}\mathrm{s} \end{aligned}$$

History: The Planck Scale

Max Planck,

Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin (1899), p. 479

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Ausdruck (41) der Strahlungsentropie auftretenden Constanten a und b die Möglichkeit gegeben ist, Einheiten für Länge, Masse, Zeit und Temperatur aufzustellen, welche, unabhängig von speciellen Körpern oder Substanzen, ihre Bedeutung für alle Zeiten und für alle, auch ausserirdische und aussermenschliche Culturen nothwendig behalten und welche daher als »natürliche Maasseinheiten« bezeichnet werden können.

It is interesting to note that with the help of the [above constants] it is possible to introduce units [...] which [...] remain meaningful for all times and also for extraterrestial and non-human cultures, and therefore can be understood as 'natural units'.

Can we just leave gravity classical?

Hannah and Eppley's thought experiment: Use classical gravitational wave with small momentum and small wavelength ($k \neq \hbar p!$) and try to measure position of quantum particle

- If the gravitational wave collapses the wavefunction, then the measurement
  - either violates the uncertainty principle of the quantum theory
  - or energy conservaton
- If it doesn't, the measurement can be used for superluminal signalling with suitably prepared states

Either way, something isn't working.

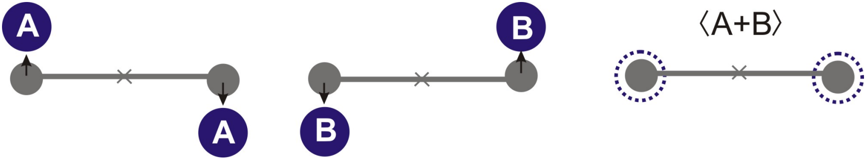
Can we just leave gravity classical?

- Semi-classical gravity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G \langle T_{\mu\nu} \rangle$$

cannot be interpreted as a fundamental theory. Besides the problem of renormalization (::) and interpretation (what about the collapse??), this appraoch does not make sense when superpositions carry large amounts of energy.

- Example: Page and Geilker. The gravitational field is not determined by the expectation value of the position of two masses. The realization of this experiment however doesn't make much sense.



Schrödinger-Newton equation

$$\mathrm{i}\partial_t \psi(t,\vec{x}) = \left(-\frac{\Delta}{2m} - \phi(t,\vec{x})\right)\psi(t,\vec{x}) \quad \text{with} \quad \Delta\phi(t,\vec{x}) = \frac{4\pi m}{m_{\mathrm{Pl}}^2}|\psi(t,\vec{x})|^2$$

- Wave-function in gravitational potential generated by its own *expectation value*
- Potential acts against dispersion. For masses larger than some critical value (depending on width), a Gaussian wave-packet will remain localized.
- Due to nonlinearity, studies are mostly numerical.
- Observable in molecule interference, but 5 orders of magnitude off today's experimental possibilities.
- van Meter arXiv:1105.1579 [quant-ph], Giulini and Großardt arXiv:1105.1921 [gr-qc]

Now what?

So naive quantization fails, and we cannot leave it classical either. We have to try to find different, more suitable, fundamental degrees of freedom. Some approaches

- String theory
- Loop Quantum Gravity
- Causal Dynamical Triangulations
- Causal Sets
- Asymptotically safe gravity
- ...

But progress is slow and despite decades of effort, it is still not clear which approach is the right one

- Instead of looking for fundamental theory, try to use phenomenological models as guides.

What is a phenomenological model?

A phenomenological model

- is an extension of a known theory that allows one to compute effects of specific additional features
- bridges the gap between theory and experiment
- is not itself a fundamental theory and therefore not entirely self-contained. It leaves open questions and may work only in some limits

There is no way around phenomenology one way or the other!

What is the relevance of the Planck scale?

- The Planck scale sets the scale at which quantum gravitational effects are expected to become important.
- It should be the only additional dimensionful scale of the model. Dimensionless parameters should be of order one.
- One does not need to detect single gravitons to find evidence for quantum gravity for the same reason one doesn't need to detect single photons to find evidence for quantum electrodynamics. That atoms are stable and atomic spectra quantized is ample experimental evidence.
- We should therefore more generally look for 'Planck scale effects' that could carry information about the quantum theory without directly probing the regime where quantum effects are strong. Think of Brownian motion carrying information about atoms without the need to actually resolve an atom.
- The craziness factor: $\mathbf{X} \in [0, 1]$.

A well known example of a phenomenological model

- The anomalous Zeeman effect puzzled physicists in the 1920s.
- Gouldsmit and Uhlenbeck proposed 1925 to treat the electron as a spinning charge and coupled it to the background field. The result was wrong by a factor of 2 but otherwise worked well.
- In 1927 Pauli formulated the Pauli-equation to deal with that

$$i\partial_t \psi = \frac{1}{2m}\left(\vec{p} - q\vec{A}\right)^2 \psi - \frac{q}{2m}\vec{\sigma}\cdot\vec{B}\psi$$

- In 1928, Dirac formulated the relativistically invariant equation for spin 1/2 particles. Later, Schrödinger derived the Pauli equation in the non-relativistic limit of the Dirac equation coupled to electrodynamics.
- Gouldsmit and Uhlenbeck's phenomenologically motivated ad hoc model lead the way.

Simplify the Complicated

Top-down

Top-down inspired bottom-up approaches

. . . Extra Dimensions. . . Minimal Length . . .

. . . DSR . . . Holographic Principle . . .

Bottom-up

An example: Generalized Uncertainty

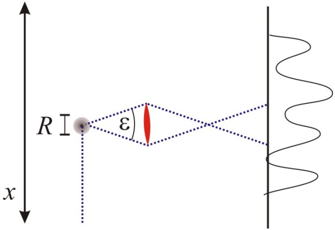
- Classical optics, wavelength $1/\omega$ of photon sets limit to possible resolution

$$\Delta x \gtrsim \frac{1}{\omega \sin \epsilon}$$

- Photon recoil transfers a momentum to the particle. Since the direction of the photon is uncertain to ϵ, one gets an uncertainty for the momentum of the particle

$$\Delta p_x \gtrsim \omega \sin \epsilon \quad .$$

- Taken together one obtains Heisenberg's uncertainty



$$\Delta x \Delta p_x \gtrsim 1$$

An example: Generalized Uncertainty

- Now with gravity, time between interaction and measurement has to be at least of the order of the time, τ, the photon needs to travel the distance R, so that $\tau \gtrsim R$.
- During that time, the gravitational acceleration acting on the particle is at least of the order

$$a \approx \frac{\omega}{m_{\rm p}^2 R^2}$$

- Assuming the particle is non-relativistic, it gains $v \approx aR \approx l_{\rm p}^2 \omega / R$
- And in the time R, the aquired velocity allows the particle to travels a distance of $L \approx l_{\rm p}^2 \omega$
- Since the direction of the photon was unknown however to within the angle ϵ, the direction of the acceleration and the motion of the is also unknown. Projection on the x-axis then yields the additional uncertainty of

$$\Delta x \gtrsim l_{\rm p}^2 \omega \sin \epsilon$$

An example: Generalized Uncertainty

- Combining the additional with the usual uncertainty

$$\Delta x \gtrsim \frac{1}{\omega \sin \epsilon} \quad , \quad \Delta x \gtrsim l_{\rm p}^2 \omega \sin \epsilon$$

  One obtains $\Delta x^2 \gtrsim l_{\rm p}^2$
- The Planck length appears as a smallest possible resolution!
- Adding that the particle's momentum uncertainty Δp should be of the order of the photon's momentum ω

$$\Delta x \gtrsim l_{\rm p}^2 \Delta p$$

  One obtains the generalized uncertainty principle

$$\Delta x \gtrsim \frac{1}{\Delta p} + l_{\rm p}^2 \Delta p$$

Pessimists and Optimists

"We shall have the basic framework of the quantum theory of gravity by 2010, 2015 at the outside."

Lee Smolin,Three Roads to Quantum Gravity (2001), p-211.

"I propose as a hypothesis... that single gravitons may be unobservable by any conceivable apparatus. If this hypothesis were true, it would imply that theories of quantum gravity are untestable and scientifically meaningless. The classical universe and the quantum universe could then live together in peaceful coexistence. No incompatibility between the two pictures could ever be demonstrated. Both pictures of the universe could be true, and the search for a unified theory could turn out to be an illusion."

Freeman Dyson, The Edge Annual Question 2012, www.edge.org

Why is Dyson so pessimistic?

Let us estimate if gravitons can be detected (think of photoelectric effect) to show quantization of gravity. Hint: the answer is no. Therefore we won't bother too much with factors and details[3]

- For one graviton, the mean free path λ in a detector medium with number density $n_{\rm d}$ and cross-section $\sigma_{\rm d}$ is

$$\sigma_{\rm d} n_{\rm d} = \frac{1}{\lambda}$$

- For successful detection, λ should be smaller than the size of the detector $L_{\rm d}$, or

$$\sigma_{\rm d} n_{\rm d} L_{\rm d} \gtrsim 1.$$

- For N gravitons

$$\sigma_{\rm d} n_{\rm d} L_{\rm d} N \gtrsim 1.$$

[3] Details: T. Rothman, S. Boughn, Found. Phys. **36**, 1801 (2006) [gr-qc/0601043].

Can we detect single gravitons?

- For simplicity, let us use a detector of atomic hydrogen, so $n_{\rm d} = M_{\rm d}/(m_{\rm prot} L_{\rm d}^3)$, where $M_{\rm d}$ is the mass of the detector. The detector should not collapse to larger densities, so the maximal mass is approx

$$M_{\rm d} \sim \left(\frac{e^2 m_{\rm p}^2}{m_{\rm prot}^2} \right)^{3/2} = e^3 \left(\frac{m_{\rm p}^2}{m_{\rm prot}} \right)^3 m_{\rm prot}$$

  That's about $10^{-3} M_\odot$ or the mass of Jupiter (!).

- So the requirement of successful detection becomes

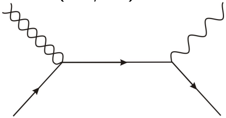
$$\sigma_{\rm d} n_{\rm d} L_{\rm d} N = \sigma_{\rm d} e^3 \left(\frac{m_{\rm p}}{m_{\rm prot}} \right)^3 \frac{N}{L_{\rm d}^2} \gtrsim 1$$

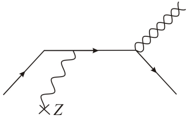
Can we detect single gravitons?

- For detection, we consider a graviton-Compton scattering, for which $\sigma_{\rm d} \approx e^2/m_{\rm p}^2$.
- For production, we consider electron-graviton Bremsstrahlung, and estimate cross-section also with $\sigma_{\rm p} \approx e^2/m_{\rm p}^2$. (That is not actually correct since the cross-sections are energy-dependent. It will however give us a rough idea of how the constants come in.)
- Source be a white dwarf with $N_{\rm e} \approx 10^{56}$ and $R \approx 10^4$km.
- The production rate per volume per time is $(N_{\rm e}/{\rm Vol})^2 \sigma_{\rm p} v$. Setting $v \approx 1$, the rate per time is

$$\#\text{Gravitons/time} \approx \frac{N_{\rm e}^2}{R^3}\frac{e^2}{m_{\rm p}^2}$$

- In a distance D from the white dwarf, the detector gets a ratio $(L_{\rm d}/D)^2$ of that flux.





Can we detect single gravitons?

- Now put everything together. For a running time τ, the requirement for detection becomes

$$\sigma_{\rm d} n_{\rm d} L_{\rm d} N = e^7 \frac{1}{m_{\rm p}} \frac{1}{m_{\rm prot}^3} N_{\rm e}^2 \frac{1}{R^3 D^2} \tau \gtrsim 1$$

- Sticking with extremes, we put the detector in orbit around the white dwarf at 1 AU $\approx 10^8$km, then

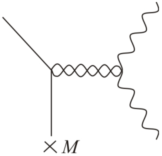
$$\tau \gtrsim 10^8 {\rm s}$$

- In summary: if we'd manage to build a detector the size of Jupiter and put it in orbit around a neutron star, then we'd be just about the brink of detection, with a gravitons every few years (1 year $= 3 \times 10^7$s).

Two recent papers defying conventional wisdom

- Neutrino decoherence: Miller and Pasechnik 1305.4430 [hep-ph]. Bremsstrahlung with *black hole* as source, ultra-relativistic. Replace $Z \to ME/m_{\rm p}^2$, estimate $\sigma \sim (ME)^2/m_{\rm p}^6$. That can potentially be fairly large?!
- Problems: Scattering approximation bad because wavelength of neutrinos too small, only good approximation when $E \sim 1/R_H \sim m_{\rm p}^2/M$. Possible with radio sources, but then no amplification. Also need take into account flux: no medium, just one 'atom'. Absorption cross-section $\sim R_H^2$, bremsstrahlung suppressed by factor $E^2/m_{\rm p}^2$
- Decoherence of Planck mass objects: Riedel arXiv:1310.6347 [quant-ph]. Non-relativistc 'particle' of about Planck mass interact via gravitational bremsstrahlung with source. Non-coherent exchange spoils interference.
- Problem: Need (neutral) Planck mass object in superpositions!

$\longrightarrow$ Both not very promising



I will not talk about cosmology...

Well, maybe I will. Distinguish between:

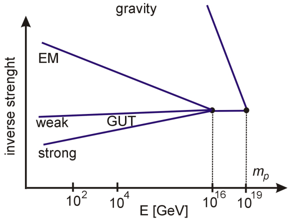
- **Evidence for perturbative quantization of gravity.**
  Is used in cosmology. Sufficient or actually necessary? Need analog of Bell's theorem from cosmological perturbation. Very few people doubt this. What we are actually looking for is
- **Evidence for type of UV completion.**
  String cosmology → CMB tensor modes, non-gaussianities
  - String gas/brane gas cosmolgy
  - Ekpyrotic/cyclic
  - Brane-Antibrane inflationary
  - Pre big-bang

  Cosmic superstrings → gravitational waves, lensing, CMB
  Loop quantum cosmology → CMB tensor modes
- BICEP2: The jury's still out. These are exciting times.

From graviton detection to Planck scale effects

- So let's forget trying to detect quantization of gravity directly as we did with light
- We'll have to find a way to be sensitive to Planck-scale effects by their influence on well-tested standard model predictions
- In the following we will see some examples where experimental tests are not impossible
- But note that this way we can test only specific manifestations of quantum gravity
- First, note that I've been cheating on the estimate with the Planck scale...

Extrapolation over 16 orders of Magnitude



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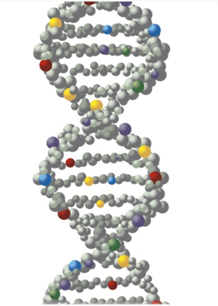

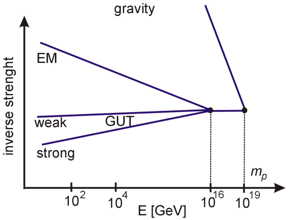

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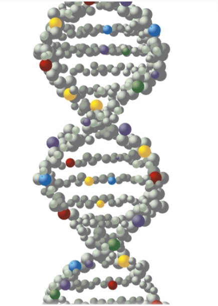
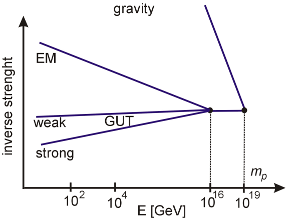




If the Planck scale is much lower than naively expected, the following questions become interesting:

- How does particle physics look like in the Planckian regime? Can we produce and observe gravitons?
- Can we produce black holes?
- What mechanicsm can lead to the apparent weakness of gravity?

Lowered Planck Scale

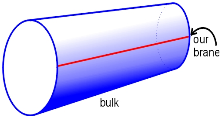
- SM unitarity violated at $\sim$2 TeV (without Higgs)
- Hierarchy problem: Why is gravity so weak?
- Maybe it isn't! What if 'true' Planck scale at $\sim$TeV?

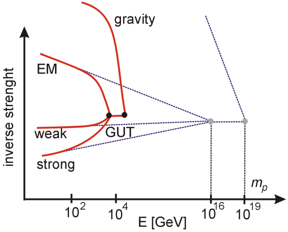
$\longrightarrow$ Quantum gravitational effects would become important already at the lowered Planck scale

- Concrete scenarios to lower Planck scale: Extra dimensions
- Inspired by string theory, but the existence of additional dimensions is of general interest

Models with Extra Dimensions, Overview

- ADD-model: Arkani-Hamed, Dimopolous, Dvali ['98], 'large' flat additional dimensions. Standard Model particles are bound to brane. The simplest case, more now
- RS-model (I and II): Randall-Sundrum ['99], extra dimension is curved, Standard Model particles (partly) localized at brane, in brief later
- UXD: 'small' TeV-scale dimensions, Standard Model particles free. Not actually quantum gravity, but accellerated unification of coupling constants, not here





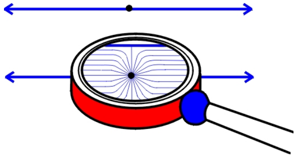
ADD: How does it work?

Gravity is strong at short distances, but appears weak on larger distances because it dilutes into the additional dimensions

$$V \sim \frac{1}{m_{\rm p}^2}\frac{1}{r}$$

$$V \sim \frac{1}{M_{\rm f}^{d+2}}\frac{1}{r^{d+1}} \to \frac{1}{M_{\rm f}^{d+2}}\frac{1}{R^d}\frac{1}{r}$$

So we find the relation $M_{\rm f}^{d+2} R^d = m_{\rm p}^2$.



ADD: How 'large' is 'large'?

With $M_{\rm f} \approx$2 TeV

- $d = 1 : 1/R \approx 10^{-32}$TeV, $R \approx 10^{13}$m
- $d = 2 : 1/R \approx 10^{-15}$TeV, $R \approx \frac{1}{2}$mm
- ..
- $d = 6 : 1/R \approx 10$MeV, $R \approx 10^{-13}$m

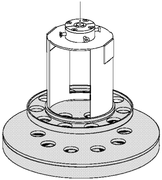
Note that $1/R \ll M_{\rm f}$. R is not a 'natural' scale. So ADD is not actually a solution to the hierarchy problem, but a geometrical reformulation.

ADD: Deviations from Newton's Law

- Direct tests of deviations from Newton's law are possible if the extra dimensions are in the mm to μm range.
- Tests are performed by Cavendish-like experiments that are very sensitive to gravitational acceleration

Chiaverini *et al*, Phys. Rev. Lett. **90**, 151101 (2003)
Long and Price, Comptes Rendus Physique **4**, 337 (2003)

Kapner *et al*, Phys. Rev. Lett **98**, 021101 (2007)



- Best current constraint: $R < 30\mu$m
- This means for ADD the case $d = 2$ is pretty much off the table for interesting values of $M_{\rm f}$.

General Relativity in Higher Dimensions

With d extra dimensions:

$$\begin{aligned} R_{IJ} - \frac{1}{2} g_{IJ} \mathcal{R} &= 16\pi G_d T_{IJ} \\ \left[\frac{1}{\mathrm{Length}^2} \right] &= G_d \left[\frac{\mathrm{Energy}}{\mathrm{Length}^{3+d}} \right] \end{aligned}$$

- IJ run from 0 to $d+3$. G_d has dimension of $\mathrm{Length}^{1+d}/\mathrm{Energy}$ or, with $\hbar = 1$, it has dimension Energy^{-2-d}.
- We will therefore write the coupling as the $d+2$nd power of a higher-dimensional Planck mass , which is the new fundamental scale M_f, such that $1/G_d = M_\mathrm{f}^{d+2}$

ADD: Linearized higher-dimensional gravity

- GR action in 3+d+1 dimensions where y are the d extra dimensions

$$S = M_f^{d+2} \int \mathrm{d}^4x \mathrm{d}^d y \sqrt{-g} \mathcal{R}$$

- Linear approximation $g_{IJ} = \eta_{IJ} + M_{\mathrm{f}}^{-1-d/2} \Psi_{IJ}$, factor added for convenience as previously
- Decompose into tensor, vector and scalar fields

$$\Psi_{IJ} = \left(\begin{array}{cc} h_{\mu\nu} & V_{\mu\ i} \\ V_{\nu\ j} & \phi_{ij} \end{array} \right)$$

- Standard model fields live on submanifold, thus

$$T_{IJ} = T_{\mu\nu}(x) \eta^\mu{}_I \eta^\nu{}_J \delta(y) \ .$$

- Note that there is no $d+3+1$ dimensional Poincaré invariance. Thus, momentum into the y-directions is not conserved.

ADD: Linearized higher-dimensional gravity

- Lagrangian of higher-dimensional gravity in linear approximation

$$
\begin{aligned}
\mathcal{L} = \quad & - \quad \frac{1}{2} h^{\mu\nu} \Box h_{\mu\nu} - V^{\mu i} \Box V_{\mu i} - \frac{1}{2} \phi^{ij} \Box \phi_{ij} \\
& - \quad h^{\mu\nu} \partial_\mu \partial_\nu \phi - V^{i\mu} \partial_i \partial_\mu \phi - \phi^{ij} \partial_i \partial_j \phi \\
& + \quad \frac{1}{2} T \phi - M_{\mathrm{f}}^{-1-d/2} h^{\mu\nu} T_{\mu\nu}
\end{aligned}
$$

- Only the gravitons couple to the energy momentum tensor
- Can now read off propagator and vertices as before
- Still non-renormalizable, divergences worse!
- Need dimensionful cut-off for loop contributions

ADD: Towers of Massive Gravitons

- Now use periodicity of extra dimensions and expand fields as

$$h_{\mu\nu} = \sum_{\vec{n}} \frac{h^{\vec{n}}_{\mu\nu}}{(2\pi R)^{d/2}} \exp\left(\mathrm{i}\frac{2\pi\vec{n}\cdot\vec{y}}{R}\right)$$

  where $\vec{n} = (n_1, ...n_d)$.

- Note normalization factor. Each single mode couples with $1/m_{\mathrm{p}}$, but lots of them.
- Leads to graviton excitations with an apparent mass of n/R because

$$\Box h_{\mu\nu} = \left(\partial_\alpha\partial^\alpha - \sum_{i=1}^{d} \frac{n_i^2}{R^2}\right) h_{\mu\nu}$$

- Since $1/R \ll M_{\mathrm{f}}$ also $\ll$ than typical collider energies. Therefore, it is often useful to treat the discrete sum as an approximate integral

ADD: Example for Graviton Cross-section

- Let us estimate relevance of graviton emission in $e^+e^- \to \gamma + G$

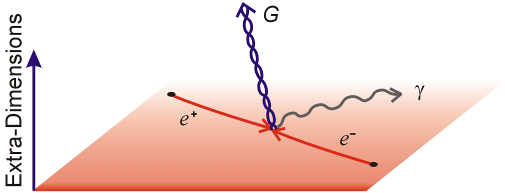
$$\sigma(e^+e^- \to \gamma + G) \approx \frac{1}{(2\pi R)^d} \frac{\alpha}{M_{\rm f}^{2+d}} N(E) \approx \frac{\alpha}{m_p^2} N(E)$$

  where $N(E)$ is the phase-space volume of outgoing graviton

- $N(E)$ is the sum over all possible $\vec{n}$ that belong to excitations with a total mass smaller than E, i.e. $\sum_i (n_i/R)^2 \leq E^2$. In continuum approximation, this $N(E) \sim (ER)^d$. Thus

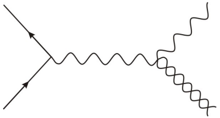
$$\sigma(e^+e^- \to \gamma + G) \propto \frac{\alpha}{E^2} \left(\frac{E}{M_{\rm f}} \right)^{d+2}$$

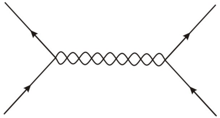
- Becomes comparable to QED cross-sections at $E \sim M_{\rm f}$.



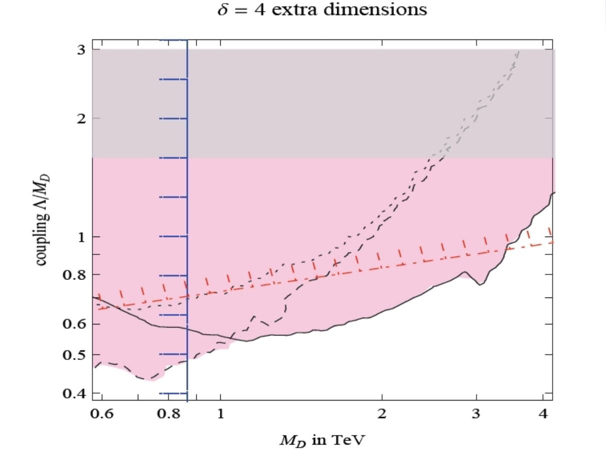
ADD: Graviton Phenomenology

- Production of (apparently massive) gravitons becomes important around lowered Planck scale
- Modification of Standard Model cross-section due to virtual graviton exchange
- Black hole production becomes possible at lowered density
- Constraints from astrophysics
  - Cooling of supernovae by emission of massive gravitons
  - Radiative decay of gravitons causes diffuse cosmic γ-ray background
  - Gravitationally trapped massive gravitons can result in a re-heating of supernovae remnants and neutron-stars
  - For $d < 4$, the lowered Planck scale is not in LHC range
  - Details: Particle Data Book





Constraints on virtual graviton exchange from LHC



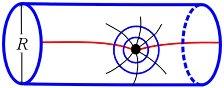
The shaded area is the bound from virtual graviton exchange at CMS (continuous line, preliminary data after 36/pb), ATLAS (dashed line, data after 3.1/pb; the dotted line shows the fit of the simplified F-variable). Vertical blue line: bound from graviton emission. Red line: Naive Dimensional Analysis estimate of LEP bound from loop graviton exchange. Upper shading: NDA estimate of the non-perturbative region.

Franceschini *et al*, arXiv:1101.4919 [hep-ph]

ADD: Extra-dimensional Black Holes

In large extra dimensions (ADD)

- Gravity stronger at small distances $\Rightarrow$ horizon radius R_H larger
- For $M \sim 1$ TeV , R_H increases from $\sim 10^{-38}$ fm to 10^{-4} fm!
- For these black holes it is $R_H \ll R$ and they have approx higher dimensional spherical symmetry



- Myers-Perry metric

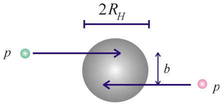
$$\mathrm{d}s^2 = \gamma(r)\mathrm{d}t^2 + \frac{1}{\gamma(r)}\mathrm{d}r^2 + r^2 d\Omega_{d+3} \ , \ \gamma(r) = 1 - \frac{2}{d+1}\frac{1}{M_{\mathrm{f}}^{d+2}}\frac{1}{r^{d+1}}$$

where

$$R_H^{d+1} = \frac{2}{d+1}\left(\frac{1}{M_{\mathrm{f}}}\right)^{d+1}\frac{M}{M_{\mathrm{f}}}$$

ADD: Production of Black holes at LHC

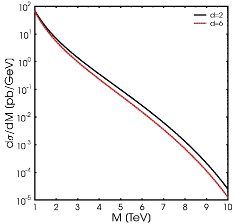
- Since gravity is now much stronger at $\sim$TeV, at the LHC partons can come closer than their Schwarzschild horizon and a black hole can be created



- Semi-classical cross-section $\sigma(M,d) \sim \pi R_H^2$ with threshold at $M \sim M_{\rm f}$
- Has to be integrated over parton distribution functions

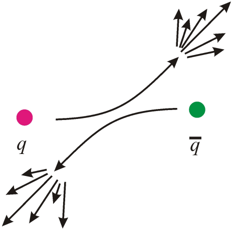
$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} = \sigma(M,d) \sum_{A,B} \int_0^1 \mathrm{d}x \frac{2\sqrt{\hat{s}}}{xs} f_A(x,\hat{s}) f_B(\hat{s}/(sx),\hat{s})$$

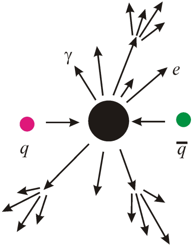
- Almost all black holes are created at threshold



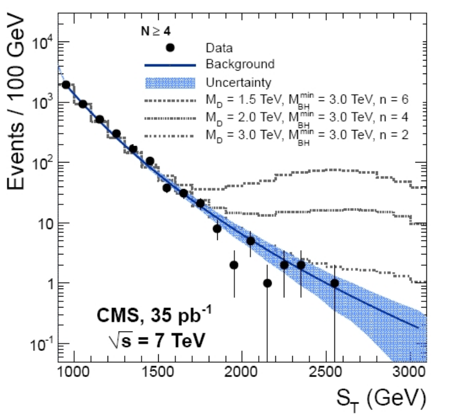
ADD: Evaporation of LHC Black Holes

- Once produced, TeV-scale black holes decay rapidly via Hawking radiation
- Use black hole thermodynamics: $T = \kappa/2\pi$ and $dS/dM = 1/T$
- $T \sim 200$GeV, lifetime is some fm/c
- Decay looks like multijet
- Numerical tools have to be used (Blackmax, Catfish, etc)
- For the final phase QG is important. But: Most of the black holes *only* make the final decay!





ADD: Black holes at LHC?



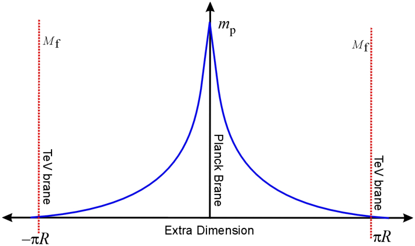
- CMS collaboration, arXiv:1012.3375 [hep-ex], excludes production of black holes with minimum mass of 3.5 - 4.5 TeV at 95% CL.
- But: Park, Phys. Lett. **B** 701:587-590 (2011).

The Randall-Sundrum Model in brief

- ADD model: flat extra-dimensions, needs to introduce new 'large' scale $R \ll 1/M_{\rm f}$.
- RS model: one additional dimension, compactified on radius R, with standard model fields on a submanifold (TeV-brane) and a second brane (Planck-brane).
- Assume homogeneous energy distribution (cosmological constant) on both branes $\Rightarrow$ the additional dimension is not flat, but curved with line element

$$\mathrm{d}s^2 = e^{-2k|y|}\eta_{\mu\nu}\mathrm{d}x^\nu \mathrm{d}x^\mu + \mathrm{d}y^2$$

where $y = \in [-\pi R, \pi R]$ parameterizes position into the additional dimension, and k the curvature of the additional dimension.



RS: Suppression of masses

- The wave equation (similarly, gravitons) in that background takes the form

$$\partial_I \sqrt{-g} g^{IJ} \partial_J \psi = e^{-2k|y|} \eta^{\mu\nu} \partial_\nu \partial_\mu \psi - \partial_y \left(e^{-4k|y|} \partial_y \psi \right) = 0 \quad .$$

- With separation of variables $\psi(x^\alpha, y)_n = \phi_n(x^\alpha)\chi_n(y)$, the ϕ_n's obey the normal wave-equation on the TeV-brane, with masses $m_n = x_n k \exp(-\pi k R)$, where x_n are the zeros of the 1st Bessel-function.
- The masses are discrete in steps of $\approx k$, but not equally spaced
- Assuming that the lowest lying mass is of order TeV and $k \sim m_{\rm p}$, $R \approx 12 l_{\rm p}$ will suppress the masses sufficiently.
- It is not necessary to introduce another hierarchy, the exponential factor does it for you.
- This model has a phenomenology very distinct from the ADD model.
- Ayazi and Mohammadi-Najafabadi, JHEP **1201**, 111 (2012) [arXiv:1110.6163 [hep-ph]]: $t\bar{t}$ spin assymmetry, nothing found at LHC (CMS data), parameter space constrained.

Forget all about lowering of the Planck scale now

Deviations from Lorentz Invariance

- Violations of Lorentz-invariance: Preferred frame, usually a time-like vector field n_α
- Very general feature of 'emergent gravity' because one needs something to emerge with: a time or temperature for example that constitutes a preferred slicing with fundamental significance
- A regular lattice cannot be Lorentz-invariant, it has the desired regularity only in a particular frame
- Lorentz-invariance violation can be constrained by looking for phenomenology of that fundamental timelike vector field n_α, coupled to the Standard Model
- Standard Model extension with higher order operators: Very strongly constrained, more about that now
- Deformation of Lorentz-invariance: No preferred frame, we will come to that later

LIV: Parameterization

- The best tested and best testable sector of the standard model is QED.
- Dimension 5 operators that break Lorentz-invariance can be put in the following form (Myers and Pospelov)

$$-\frac{\xi}{2m_{\rm p}} n^\alpha F_{\alpha\beta}(n\cdot\partial)(n_\kappa \tilde{F}^{\kappa\beta}) + \frac{1}{2m_{\rm p}} n^\alpha \overline{\Psi}\gamma_\alpha(\xi_1 + \xi_2\gamma_5)(n\cdot\partial)^2\Psi$$

  where n^α is the symmetry-breaking vector field with $n\cdot n = 1$. In some frame $n^\alpha = (1,0,0,0)$. We'll work with this frame.
- ξ, ξ_1, ξ_2 should be of order one for quantum gravitational effects.
- A generic consequence of LIV are modifications of the dispersion relation.

LIV: Modified dispersion relations

- Eom of a plane wave with $\omega, \vec{k}$. For photon field A_α with $\partial \cdot A = 0$

$$\Box A_\alpha = -\frac{\xi}{m_{\rm p}} \epsilon_{\alpha\beta\gamma\kappa} n^\beta (n \cdot \partial)^2 F^{\gamma\kappa}$$

$$\Rightarrow (\omega^2 - k^2 \pm \frac{2\xi}{m_{\rm p}} \omega^3)(\varepsilon_x \pm {\rm i}\varepsilon_y) = 0$$

  Thus, to that order the photons have dispersion relation $\omega^2 - k^2 \pm 2\xi/m_{\rm p} k^3 = 0$ (sign depends on polarization).

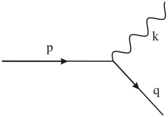
- For electrons with $(E, \vec{p})$ and mass m one finds similarly in the ultrarelativistic limit (sign depends on chirality):

$$E^2 - p^2 - m^2 - \frac{2}{m_{\rm p}} (\xi_1 \pm \xi_2) p^3 = 0.$$

- One important constraint on this type of models comes from vacuum birefringence, but we'll look at something else.

Example for LIV constraints: Vacuum Cherenkov Radiation

- Cherenkov radiation in vacuum is normally impossible because of momentum conservation. From $(\mathbf{p}-\mathbf{k})^2 = \mathbf{q}^2$ one finds



$$E_p^2 - p^2 + \omega^2 - k^2 - 2(E_p\omega - \vec{p}\cdot\vec{k}) = E_q^2 - q^2$$

- But with modified dispersion relation now

$$m^2 + \frac{\xi_1}{m_{\rm p}}p^3 + \frac{\xi}{m_{\rm p}}k^3 - 2(E_p\omega - \vec{p}\cdot\vec{k}) = m^2 + \frac{\xi_1}{m_{\rm p}}q^3$$
$$\Leftrightarrow \frac{1}{m_{\rm p}}\left(\xi_1 p^3 + \xi k^3 - \eta q^3\right) = 2pk\left(\frac{E_p\omega}{pk} - \cos\theta\right)$$

- In the approximation of a low energy photon $\mathbf{q} \approx \mathbf{p}$, also ultrarelativistic $p^2 \gg m^2$, this simplifies to $2\xi_1 p^3 = m^2 m_{\rm p}$.
- Above this threshold electrons basically stop to propagate. The requirement that this threshold lies outside current observational limit $p \approx 80$TeV, leads to $\xi_1 \lesssim 10^{-3}$. This already rules out such Planck scale effects.
- Other bounds on ξ, ξ_1, ξ_2 are even tighter.

Deformed Special Relativity

- Motivation: want transformations that keeps c and $m_{\rm p}$ invariant
- (Homework: Is that a justified expectation?)
- Λ keeps ∞ invariant. Define $p = f(k)$ with $m_{\rm p} = f(\infty)$ and k normal Lorentz-vector ("pseudo-momentum"), ie $k' = \Lambda k$.
- Then $p' = f(k') = f(\Lambda k) = f(\Lambda f^{-1}(p))$.
- Example for boost[4] with $p_\nu = k_\nu/(1 + k_0/m_{\rm p})$

$$p'_0 = \frac{\gamma(p_0 - vp_z)}{1 + (\gamma - 1)p_0/m_{\rm p} - \gamma v p_z/m_{\rm p}}$$
$$p'_z = \frac{\gamma(p_z - vp_0)}{1 + (\gamma - 1)p_0/m_{\rm p} - \gamma v p_z/m_{\rm p}}$$

which transforms $(m_{\rm p}, m_{\rm p}) \to (m_{\rm p}, m_{\rm p})$

- Leads to: generalized uncertainty, curved momentum space, modified dispersion relation possibly with an energy-dependent speed of light

[4] Magueijo and Smolin, Phys. Rev. Lett. **88**, 190403 (2002)

Generalized Uncertainty Principle

- This is an interesting model because it reproduces the earlier discussed generalized uncertainty
- With $p = f(k)$

$$[x_i, k^j] = \delta_i^j \quad \Rightarrow [x_i, p^j] = \frac{\partial p^j}{\partial k^i}$$

- For $\vec{p} \approx \vec{k}(1 + \alpha k^2/m_{\rm p}^2)$ one finds to 2nd order

$$[x_i, k^j] = \delta_{ij}\left(1 + \frac{p^2}{m_p^2}\right) + 2\frac{p_i p_j}{m_p^2}$$

$$\Delta x_i \Delta p_i \geq \frac{1}{2}\left(1 + 3\alpha\frac{\Delta p_i^2}{m_p^2}\right) \quad ,$$

- Also: modified dispersion relation possibly with an energy-dependent speed of light because $E/p \neq$ constant.
- In expansion $c(E) = 1 + \alpha E/m_{\rm p} + \beta(E/m_{\rm p})^2 ...$

DSR: Example for Phenomenology

- Modified dispersion relation for *free* particles

$$m^2 \approx E^2 - \vec{p}^2 + \alpha \left(\frac{E}{m_{\rm p}} \right) E^2$$

where α should be of order 1 for quantum gravitational effects.

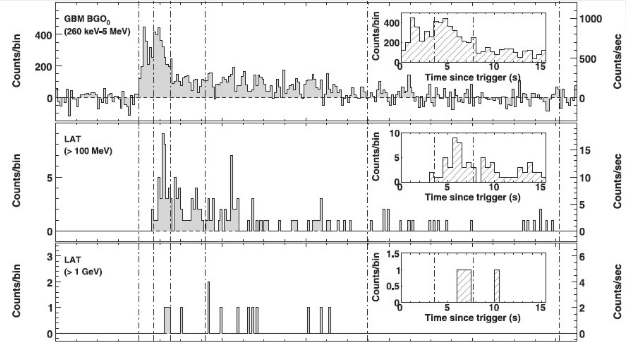
- Consider 2 photons ($m = 0$) with energy E and $E' \ll E$. Difference in arrival time after distance L is

$$\Delta t = t_1 - t_2 = (c(E) - c(E'))\, L \approx (1 + \alpha \frac{E}{m_{\rm p}} - 1)L = \alpha \frac{E}{m_{\rm p}} L$$

- Insert $L \approx$ Gpc and $E \approx$ GeV, and find

$$\Delta t \approx 1{\rm s}$$

Time Delay In GRBs



- Figure: Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C (Science 27 March 2009, Vol. 323, pp. 1688 - 1693)
- $z \approx 4.35$, highest energetic photon $\approx$ 13 GeV, arriving $\approx$ 16.5 seconds after the onset of the burst
- Lower limit from GRB090510 $M_{QG} > 1.2 \times m_{\rm p}$ GeV.
- Nemiroff et a arXiv:1109.5191, $M_{QG} > 3060 \times m_{\rm p}$. But...
- Presently very much under discussion.

Do Modified Commutators affect Quantum Oscillators?

- Deforming Special Relativity leads to a modified commutation relation and a generalized uncertainty principle. (Minimal length!)
- Details depend on $k(p)$, one example is

$$[x, p] = i\sqrt{1 + \alpha(p^2 + m^2)/m_{\rm p}^2}$$

- Note: If Lorentz-transformations act non-linearly on momentum space, momenta cannot add linearly and still respect observer independence. The addition of momenta must be suitably modified to allow momenta of composits to exceed $m_{\rm p}$. "Soccer-ball-problem"
- *If you ignore this*, effects get stronger with the mass of the system. Then one can test them eg with quantum oscillators. Pikovski et al, Nature Physics 8, 393-397 (2012), arXiv:1111.1979 [quant-ph].

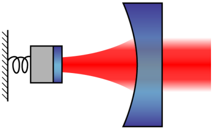
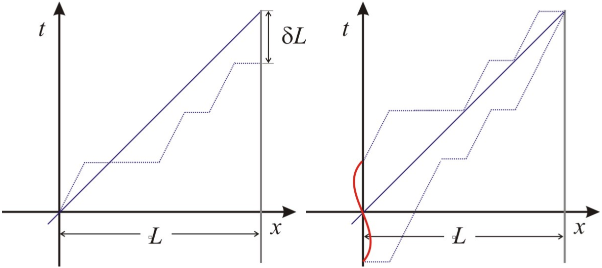


Image: Wikipedia

$\mathbf{X} = 0.99$

A terrible model for effects of space-time fuzz

- Imagine space-time fuzz causes random walk[5] for particle with $\delta t = \pm\alpha t_{\rm p}$ for each step of $l_{\rm p}$. Expect $\alpha \sim 1$. Over a distance L with $L/l_{\rm p} = N$ steps, the average deviation is $\delta L = \alpha l_{\rm p}\sqrt{N}$.
- This leads to a phase blur of $\delta\phi \sim \omega\delta L \sim \alpha\omega l_{\rm p}(L/l_{\rm p})^{1/2}$
- If the phase blur becomes ~ 1, then interference patterns (Airy rings) of distant stars should vanish. From observations of such rings at distances of Gpc, $\alpha < 10^{-12}$.
- So that model is ruled out which is however not a big loss.



[5] Amelino-Camelia 2000, Ng and van Dam 2000

Space-time fuzzlies

- Small fluctuations in background can be treated with linearized gravity. Effects are similar to gravitational wave background. In particular they are very weak for fluctuations that started out after reheating at or close by the Planck-scale.
- Direct detection: Far below today's experimental possibilities, also difficult to distinguish classical stochastic distortion from quantum effects
- Estimate a signal traveling over distance L is stochastically delayed (or advanced) by

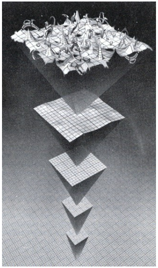
$$\Delta T \sim \sqrt{\langle h^2 \rangle} L$$

- Nucleosynthesis gives the bound $\langle h^2 \rangle \lesssim 10^{-43}/(f\,\mathrm{s})^2$. For fluctuations that started out at Planck scale (are in chance of being quantum)

$$\Delta T \lesssim 10^{-30} L$$

Space-time fuzz

- So forget about the small fluctuations, be daring and make big fluctuations.
- The idea is that big fluctuations may act similar to tiny black holes that immediately decay
- This can ruin quantum mechanic's unitary evolution and lead to decoherence: pure states may evolve into mixed states by interaction with the space-time fuzz
- We also have no reason to expect fundamendal Lorentz-invariance, so the CPT theorem does not apply



Pure and mixed states, terminology, reminder of

- To deal with pure and mixed states, talk about density matrix instead of states. It is

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| \quad , \quad \mathrm{Tr}(\rho) = 1 \quad .$$

- A state is pure iff $\mathrm{Tr}(\rho^2) = \mathrm{Tr}(\rho)$. Otherwise, $\mathrm{Tr}(\rho^2) < \mathrm{Tr}(\rho)$, it is mixed.
- Time evolution takes the form

$$\frac{d}{dt}\rho = \mathrm{i}[\rho, H] \quad .$$

- Under unitary time-evolution (hermitian Hamiltonian), a pure state remains pure.

Introducing Fundamental Decoherence

- Change evolution equation to

$$\frac{d}{dt}\rho = \mathrm{i}[\rho, H] + \delta\not{h}\rho \quad .$$

- Where $\delta\not{h}$ parameterizes the non-hermitian part. For a 2-dimensional system in the basis of σ_i, Id it can be parameterized as

$$\rho = \frac{1}{2}\rho_\alpha\sigma_\alpha \ , \ H = \frac{1}{2}h_\beta\sigma_\beta \ , \ \delta\not{h}\rho = \frac{1}{2}\not{h}_{\alpha\beta}\rho_\alpha\sigma_\beta$$

$$\delta\not{h} = -2\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha & \beta \\ 0 & 0 & \beta & \gamma \end{pmatrix}$$

- For quantum gravitational effects, we expect α, β, γ to be approx E^2/m_{p} or m^2/m_{p}
- Are there experiments sensitive to such small terms?

What experiment may be very sensitive to decoherence?

- Decoherence is the loss of phase information (coherence).
- Quantum mechanical oscillation between two eigenvectors of the Hamiltonian is sensitive to loss of coherence
- A system that oscillates between two Hamiltonian eigenvectors and can be easily studied will be useful
- Problem with neutrinos: oscillation length at typical energies very long, also interaction very weak
- Preferably use something more massive, enter the Kaons

What is cool about neutral Kaons?

- Kaons are mesons. There are 4 of them, we'll only be interested in the two neutral ones.
- The K^0 is $d\bar{s}$ and the $\overline{K}^0$ which is $s\bar{d}$, masses are $\approx$ 500MeV.
- They are neutral, but not their own antiparticles!
- Produced in collisions are K^0 and $\overline{K}^0$, but these are not eigenstates of the Hamiltonian. Thus, the time evolution mixes them.
- CP-eigenstates are

$$
\begin{aligned}
CP+1 \quad &: \quad |K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right) \\
CP-1 \quad &: \quad |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right)
\end{aligned}
$$

- If CP conserved, K_1, K_2 should be eigenstates of the Hamiltonian (weak interaction, s not conserved!)

CP violation in neutral Kaon oscillations

- Know experimentally: There is a long and a short-lived mass eigenstate for neutral Kaons, K_L and K_S with $\tau_S \approx 10^{-9}$s, $\tau_L \approx 5 \times 10^{-8}$s.
- The decay into $\pi^+\pi^-$ has CP $+1$, the decay into $\pi\pi\pi$ has CP -1. The first goes faster because the phase-space is smaller.
- So: Produce K^0, wait for the short-lived part to decay into $\pi\pi$, and show that the long-lived part can *still* decay into $\pi\pi$.
- Follow that CP eigenstate is not mass eigenstate: indirect CP violation.

$$
\begin{aligned}
|K_L\rangle &= \frac{1}{\sqrt{1+\epsilon^2}} \left(|K_1\rangle + \epsilon |K_2\rangle \right) \quad , \\
|K_S\rangle &= \frac{1}{\sqrt{1+\epsilon^2}} \left(\epsilon |K_1\rangle + |K_2\rangle \right) .
\end{aligned}
$$

- Win Nobelprize: 1980, Christenson, Cronin, Fitch and Turlay

Decoherence in neutral Kaon oscillations

- One can determine ϵ in τ_L limit from

$$\frac{\text{Rate of}(K_L \to \pi^+\pi^-)}{\text{Rate of}(K_S \to \pi^+\pi^-)} = \epsilon^2 \approx 2 \times 10^{-3}$$

- With decoherence (simplified $\beta = 0$)

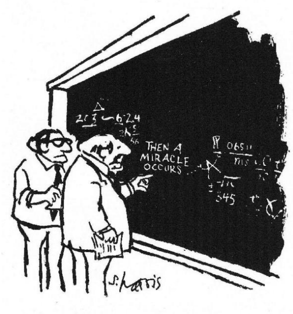
$$\frac{\text{Rate of}(K_L \to \pi^+\pi^-)}{\text{Rate of}(K_S \to \pi^+\pi^-)} = \epsilon^2 + \frac{\gamma}{|\Gamma_L - \Gamma_S|}$$

  where $|\Gamma_L - \Gamma_S| \approx 10^{-14}$GeV.

- So one becomes sensitive to γ when $\epsilon^2|\Gamma_L - \Gamma_S| \approx \gamma$ or $\gamma \approx 4 \times 10^{-20}$GeV.
- Compare to $M^2/m_{\rm p} \approx 3 \times 10^{-20}$GeV!
- Current constraint: $\gamma \lesssim 5 \times 10^{-21}$GeV. But constraints on α, β weaker. Experiments running.

Holographic Noise

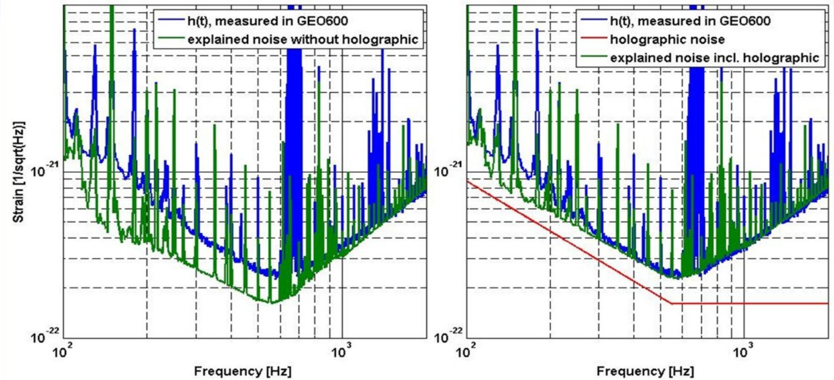
- Holography: Degrees of freedom inside a volume are encoded in degrees of freedom on the boundary.
- Idea: Test reduction of degrees of freedom by searching for correlations in space-time fluctuations (normally too small to be measureable), Craig Hogan arXiv:1002.4880v27 [gr-qc]
- Problem: Lorentz-invariance. New attempt $[x_\mu, x_\nu] = i l_{\rm p} x^\kappa U^\lambda \epsilon_{\kappa\lambda\mu\nu}$ The x are positions of a *macroscopic body* (the mirrors), ‘assumed to be massive enough that we ignore the conventional position commutators’ arXiv:1204.5948v8 [gr-qc]



"I think you should be more explicit here in step two."

$$\mathbf{X} = i\sqrt{2}$$

GEO600 Mystery Noise

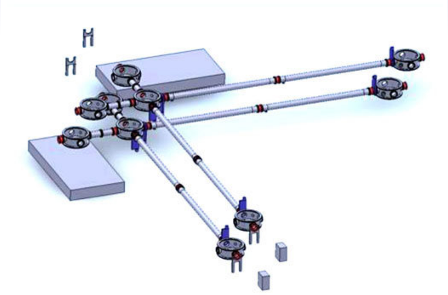


GEO600 noise with and without holographic noise as in Hogan, arXiv:0806.0665

Plot: Stefan Hild

- A mystery? With different readout method most of the noise could be explained.

The Holometer!



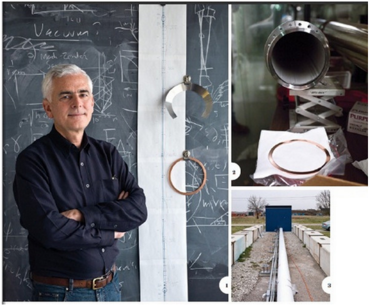


Image: Scientific American

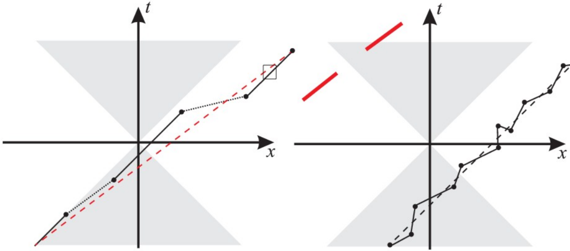
- “It’s a slight cheat because I don’t have a theory.” –Craig Hogan
- `holometer.fnal.gov`
- This is the first ever experiment especially designed to test for quantum gravity phenomenology.

Space-time Defects

- If space-time has a fundamentally non-geometric origin, eg networks, then it approximates today to excellent precision a smooth manifold of dimension four.
- But one expects this approximation to be imperfect: It should have defects.
- Defects will affect the propagation of particles and may have observable consequences.

Space-time defects: Example for Phenomenology

- Space-time defects do not have worldlines.
- They come in two types: Local defects that change a particle's momentum. And non-local effects that dislocate a particle.
- Example for effects on propagation from non-local defects



- Density smaller than $1/\text{fm}^4$.
- Effects stronger for *smaller* energies and scale with the world-volume.
- Phys. Rev. D 88, 124030 and 124031 (2013), arXiv:1309.0311 and arXiv:1309.0314

Bekenstein's Table-top Experiment

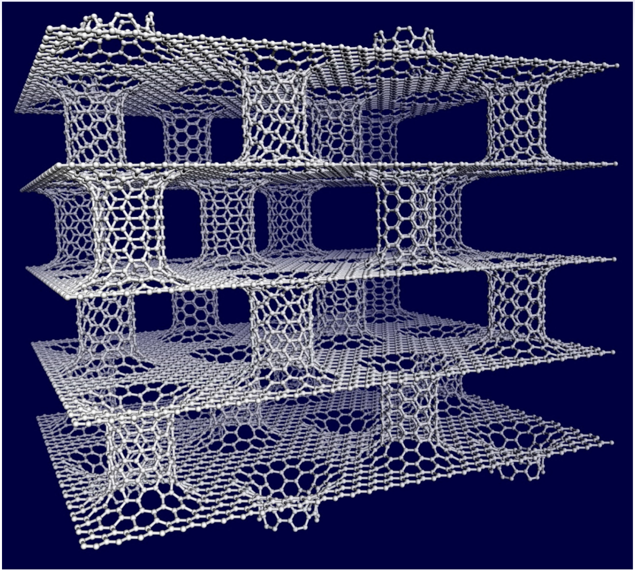
- Phys. Rev. D 86, 124040 (2012), arXiv:1211.3816 [gr-qc]
- Let photon propagate through block of crystal. Upon impact, the photon is absorbed and its momentum redistributed *on the whole crystal*, moving the crystal's center-of-mass oh-so-slightly.
- *If the crystal reacts as one* (think Mösbauer), this moves each single atom by an amount suppressed by the number of atoms, which can be below the Planck length.
- Bekenstein argues that this should be forbidden by some quantum gravity models (I don't know which).
- If that was so, the photon sometimes can't trespass the crystal and is reflected, which is measureable.
- Problem: The effective description of phonons on an atomic lattice isn't at all sensitive to Planck length shifts; the crystal just isn't rigid to a Planckian precision.

Evolving Dimensions

- Dimensionality depends on distance scale
- Short distances, lower dimension
- Space is
  - 1-d on scales $L \ll L_2$
  - 2-d on scales $L_2 \ll L \ll L_3$
  - 3-d on scales $L_3 \ll L \ll L_4$
  - ...
- L_4 ∼Gpc? L_3 ∼1/TeV?
- Improves renormalizability

Anchordoqui *et al*, arXiv:1003.5914, arXiv:1012.1870

Evolving Dimensions - Example



Picture credits: Dimitrakakis, Tylianakis and Froudakis, Nano Lett., 2008, 8 (10), pp 3166-3170

Predictions of evolving dimensions

- 4-jet events at LHC: planar alignment (arXiv: 1012.1870)
- Gravitational wave cutoff: no dof's in lower-d gravity (arXiv:1102.3434)

Open questions:

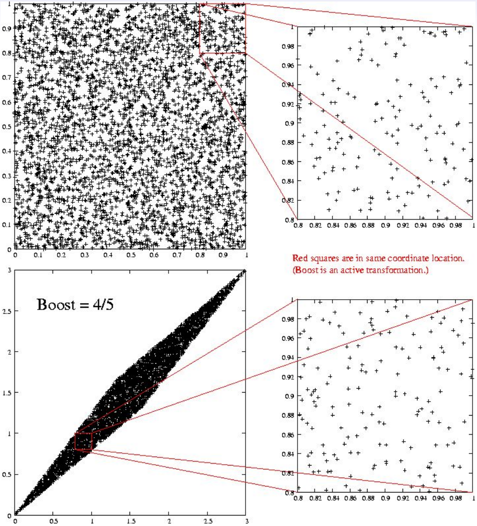
- What is the space-time picture? How does dynamics work?
- Lorentz-invariance??

Causal Sets

Set-up

- Locally finite partially ordered set
- Sprinkling of elements is approximation to manifold
- Discrete *and* Lorentz-invariant (on average)
- Geodesics are approximated by chains
- Leads to: Random fluctuations in particle's momentum

Causal Sets: Sprinkling



Picture credits: David Rideout www.phy.syr.edu/řideout/

Causal Sets: Observable Consequences

Consequences

- Diffusion in momentum space → CMB Polarization (Dowker, Philpott and Sorkin, Phys. Rev. D79:124047 (2009) arXiv: 0810.5591)

$$\frac{\partial \rho_t}{\partial t} = -i\frac{p_i}{m\gamma}\partial_i \rho_t + k\partial_a\left(g^{ab}\sqrt{g}\partial_a\left(\frac{\rho_t}{\gamma\sqrt{g}}\right)\right)$$
$$\frac{\partial \rho_\lambda}{\partial \lambda} = -p_\mu\frac{\partial \rho_\lambda}{\partial x_\mu} + k_1\frac{\partial}{\partial E}\left(E^3\frac{\partial}{\partial E}\left(\frac{\rho_\lambda}{E}\right)\right) - k_2\frac{\partial}{\partial_E}\left(E\rho_\lambda\right)$$

- Becomes observable for $k_i \sim 10^{-92} m_{\rm p}^2$. Note that the Hubble radius brings in a dimensionful scale.
- Modification of $1/r^2$ potential (too small to be observable)
- Presently very active research area.

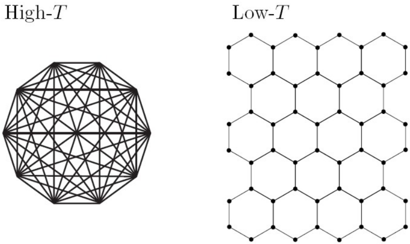
$\mathbf{X} = 0.0$

Naked Singularities

- Cosmic censorship is a hypothesis – unproved.
- Recent numerical evidence shows that naked singularities can form from physically realistic initial conditions, arXiv:1201.3660 [gr-qc]
- Naked singularities allow us, in principle, to look right onto regions of strong curvature.
- Problem: It's hard already to observationally distinguish between naked singularities and black holes, arXiv:1401.4227 [gr-qc]
- Hard doesn't mean impossible: Expect more to happen in this area.

Geometrogenesis

- If space-time is not fundamental, then the early phases of the universe might not be describable by a geometry at all. Konopka, Markopoulou, Severini, Phys. Rev. D **77**, 104029 (2008)
- Phase transition can have consequences for CMB/structure formation. Magueijo, Smolin, Contaldi, Class. Quant. Grav. **24**, 3691 (2007), Olaf Dreyer arXiv:1307.6169 [gr-qc] ,
- Remaining distortions of locality constitute deviations from QFT and be responsible for the cosmological constant Prescod-Weinstein, Smolin [arXiv:0903.5303]
- Not much going on in this area.



Postdictions

- We have presently unexplained data: Dark matter, dark energy, parameters in SM...
- Are any of these unrecognized signatures of quantum gravity?
- Models that post-dict Λ, ν-masses or DM are abundant

What you should have learned in this lecture

- The phenomenology of quantum gravity is a lively research area at the interface of theoretical and experimental phyiscs
- It brings together many different areas of physics (astro, particle, neutrino, cosmology, etc)
- Various effective models that incorporate quantum gravitational features, some of which make predictions that have been ruled out or will be testable soon.
- The connection between these models and a possibly underlying fundamental theory of quantum gravity is currently weak.
- More: "Experimental Search for Quantum Gravity," arXiv:1010.3420 [gr-qc], backreaction.blogspot.com
- Next conference on 'Experimental Search for Quantum Gravity', SISSA, September 1-5, 2014
- Questions to: hossi@nordita.org