Title: Planck Meets Hubble and Boltzmann: Holographic Quantum Foam and Cosmology

Date: Nov 05, 2007 11:15 AM

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Abstract: Quantum fluctuations of spacetime give rise to quantum foam, and black hole physics dictates that the foam is of holographic type. One way to detect quantum foam is to exploit the fact that an electromagnetic wavefront will acquire uncertainties in direction as well as phase as it propagates through spacetime. These uncertainties can show up in interferometric observations of distant quasars as a decreased fringe visibility. The Very Large Telescope interferometer may be on the verge of probing spacetime fluctuations which, we argue, have repercussions for cosmology, requiring the existence of dark energy/matter, critical cosmic energy density, and accelerating cosmic expansion in the present era. We speculate that, in the framework of holographic quantum foam, the dark energy is composed of an enormous number of inert ``particles\'\' of extremely long wavelength. These ``particles\' necessarily obey infinite statistics (quantum Boltzmann statistics) in which all representations of the particle permutation group can occur. For every boson or fermion in the present observable universe there could be ~ 1031 such ``particles\'.

CONTENTS

Quantum fluctuations of spacetime

- gedankan expt; holographic principle; ... skip
- [loop quantum gravity (Gambini & Pullin)]
- mapping the geometry of spacetime ⇐
- cumulative effects

Probing spacetime foam with

- Gamma ray bursts? Laser-based interferometry? (skip? / skip)
- VLT interferometers
- [Bose-Einstein condensate (Gambini & Pullin)] skip

STF ⇒ Holographic Foam Cosmology

- Existence of dark energy/matter
- DE/DM and infinite statistics
- [DE, ∞ stat. & M-theory (Jejjala,Kavic,Minic)]

Summary and speculations

Notation: subscript P = Planck units

Planck length: $l_P \equiv \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-33}$ cm etc

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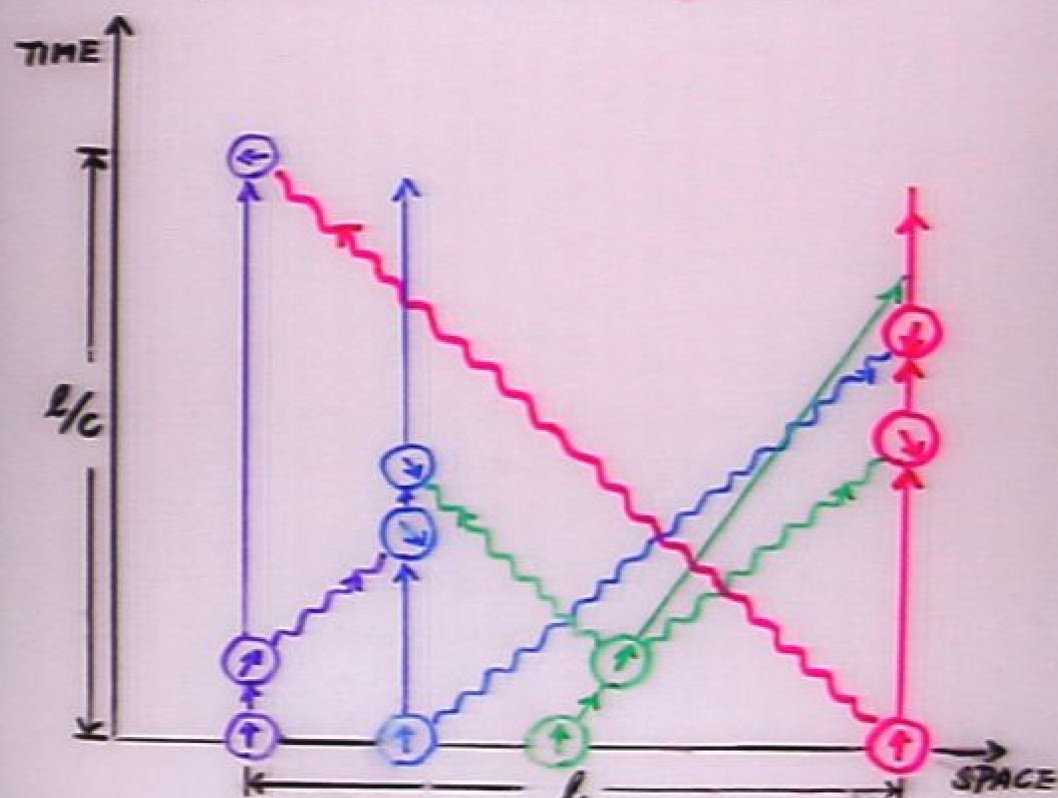
Method 2: Mapping the geometry of spacetime

(using a global positioning system) [Giovannetti et al.] '04 [Lloyd & Ng]

Fill space with a swarm of clocks, exchanging signals with the other clocks and measuring the signals' time of arrival

How accurately can these clocks (of mass M) map out a volume of space-time with radius l over time l/c?



Ticks & clicks of clocks in spacetime volume l^4/c

The process of mapping the geometry of spacetime is a kind of computational operation

- Margolus-Levitin theorem (rate of operations $\leq E/\hbar$; essentially energy-time Heisenberg uncertainty)

$$\Rightarrow \# \text{ operations} < (E/\hbar)\times \text{ time} = \frac{Mc^2}{\hbar}\frac{l}{c}$$

- To prevent black-hole formation $\Rightarrow M \lesssim \frac{lc^2}{G}$ $\left(\rho \lesssim \frac{1}{l^2 l_P^2}\right)$

$$\Downarrow$$

$$\# \text{ ops or events (i.e., } \# \text{ spacetime "cells")} < l^2 \frac{c^3}{\hbar G} = \frac{l^2}{l_P^2}$$

For max. spatial resolution, each clock ticks only ONCE

$\Rightarrow$ Each "cell" occupies spatial vol. $\frac{l^3}{l^2/l_P^2} = l l_P^2$

$\Rightarrow$ Average spatial separation of "cells" $\simeq l^{1/3} l_P^{2/3}$

- Consistent with the holographic principle
- Interpretation: $\delta l \gtrsim l^{1/3} l_P^{2/3}$, holographic model

[Karolyhazy; Ng + van Dam]

Maximum spatial resolution

- requires max. energy density $\rho \sim (l l_P)^{-2}$
- yields # bits $\sim l^2/l_P^2$

Holography in spherically symmetric loop quantum gravity

Rodolfo Gambini[1], Jorge Pullin[2]
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2. *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803-4001*

We show that holography arises naturally in the context of spherically symmetric loop quantum gravity. The result is not dependent on detailed assumptions about the dynamics of the theory being considered. It ties strongly the amount of information contained in a region of space to the tight mathematical underpinnings of loop quantum geometry, at least in this particular context.

arXiv : 0708.0250

ysical principles usually represent facts partially collected by observation that end up guiding the development of
cal theories. When the underlying theories are completely understood in detail, the principles can be explained
nsequences of the theory they guided to create. The holographic principle has guided the construction of some
leading physical theories of space time in the last few years. In a nutshell, holography establishes a limit to the
nt of information contained in a space-time region [1]. In its simplest form, for spherical symmetry and weak
y the principle establishes that the entropy of a region of space is limited by the area surrounding it and was
ormulated by t'Hooft and Susskind [2]. Any successful theory of quantum gravity that incorporates holography
d be able to derive it as a consequence of its framework. We would like to argue that holography does indeed
from the framework of loop quantum gravity in spherical symmetry and that the result is robust: it does not
nd on the details of the dynamics of the theory nor the type of matter included but rather on its kinematical
ture and elementary dynamical considerations independent of the details of the Hamiltonian or its potential
rization ambiguities. In a nutshell, holography follows from the dependence of the volume operator in spherical
quantum gravity on the radial distance, yielding an uncertainty in the determination of volumes that grows
lly. Such a dependence for the uncertainty of spatial measurements had already been postulated in heuristic
ments relating limitations of space-time measurements to holography by Ng [3] and with alternative reasonings
and Lloyd [4]). In this article we show that such a dependence can be derived from the kinematical structure of
ical loop quantum gravity. That holography in its simple and straightforward *spatial* form is materialized in the
ical case is appropriate, since it is known that in non-spherical cases more care is needed (in particular involving
temporal regions) in its definition in order not to run into counterexamples (see [1] for details).
op quantum gravity is emerging as a viable candidate for a theory of quantum gravity. Recent general discussions
approach can be found in [5]. The kinematical setting for loop quantum gravity in spherically symmetric
tions is well established and was discussed in detail by Bojowald and Swiderski [6]. There is only one non-
l spatial direction (the radial) which we call x since it is not necessarily parameterized by the usual radial

But IF (not arguing that is the case)

Spread spacetime "cells" uniformly in both space and time:

temporal resolution $\sim$ spatial resolution (here use $c = 1$)

Av. spatial separation of "cells" $\sim \left(\frac{l^4}{(l/l_P)^2}\right)^{1/4} = (l l_P)^{1/2}$

time sep. of successive ticks of each clock is $(l l_P)^{1/2}$

- Interpretation: $\delta l \gtrsim l^{1/2} l_P^{1/2}$, random-walk model

[Amelino-Camelia]

Time bet. ticks = time to communicate w. neighboring cells

Random Walk model

- predicts a coarser spatial resolution (larger fluctuations) than HM
- yields smaller bound on information content:

$$\frac{(l/l_P)^2}{(l/l_P)^{1/2}} = (l/l_P)^{3/2} = (l^2/l_P^2)^{3/4}$$

- does NOT require maximum energy density

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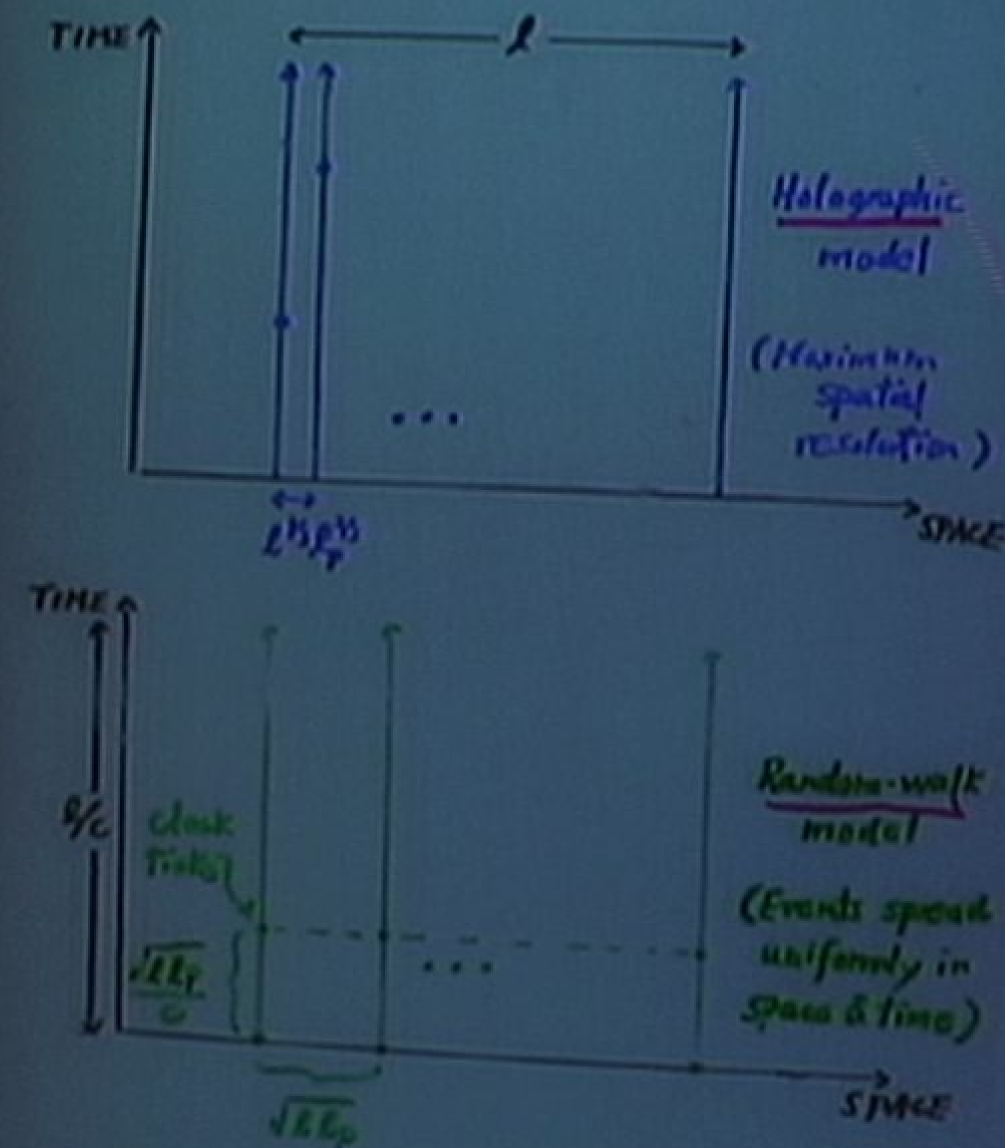

For $\ell \sim 10^{28}$ cm $\sim R_H$, $\frac{\sqrt{\ell \ell_P}}{c} \sim 10^{-14}$ sec

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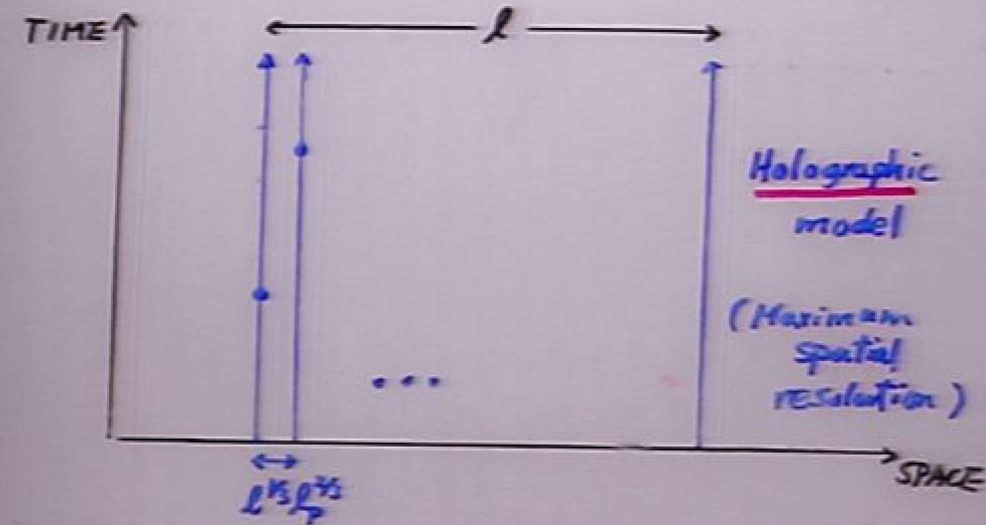

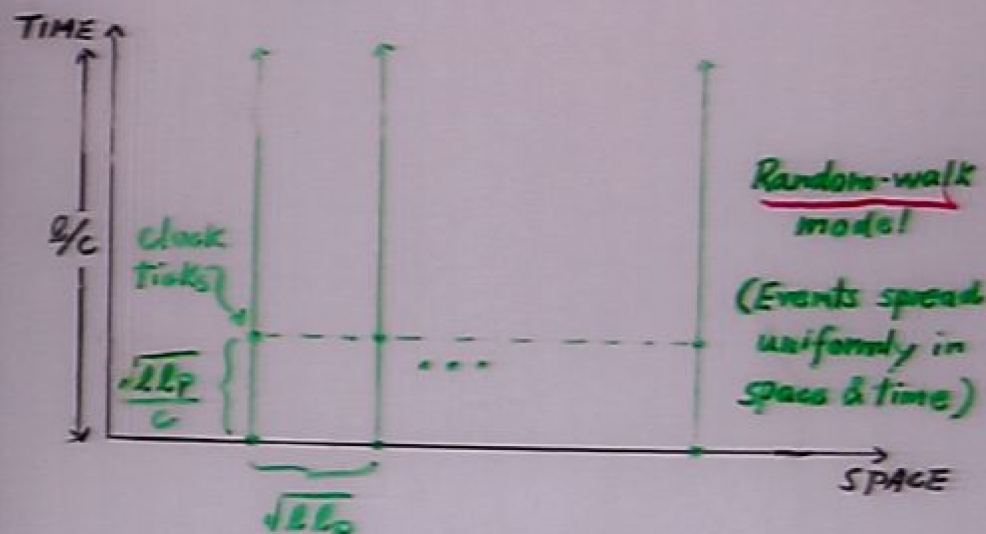

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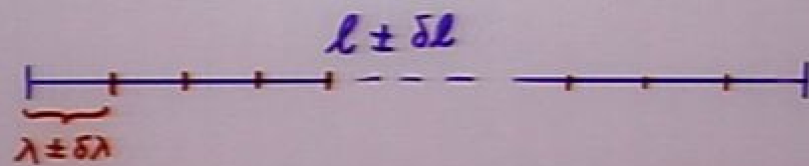
Cumulative effects of spacetime fluctuations

Divide distance l into l/λ equal parts each of length λ (for any $l_p \leq \lambda \leq l$)



Question: Starting with $\delta\lambda$ from each part, how do the l/λ parts add up to δl for the whole distance l?

I.e., find the cumulative factor $\mathcal{C}$ in $\delta l = \mathcal{C}\,\delta\lambda$

$$\delta l \sim l^{1/3} l_P^{2/3}; \quad \delta\lambda \sim \lambda^{1/3} l_P^{2/3}$$

$$\Downarrow$$

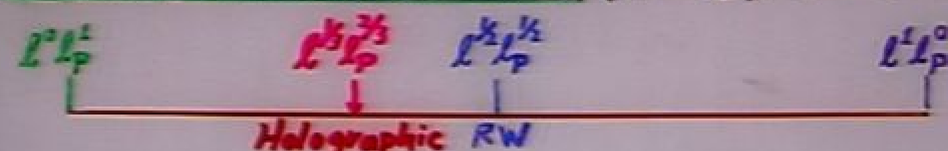
$$\mathcal{C} = \left(\frac{l}{\lambda}\right)^{1/3}$$

Cumulative Factor $= (\#intervals)^{1/3}$

($\sim$ Brownian motion with self-similarity parameter 1/3)

Random walk model ($\delta l \sim l^{1/2} l_P^{1/2}$): $\mathcal{C} = (l/\lambda)^{1/2}$

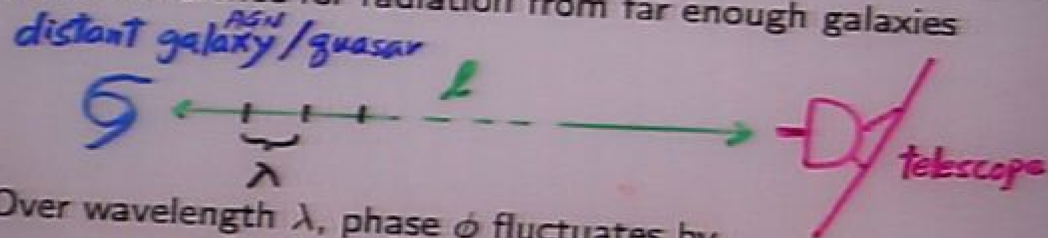
Completely anti-correlation model ($\delta l \sim l_P$): $\mathcal{C} = 1$



δl (anti-correlation $\Longleftarrow$; correlation $\Longrightarrow$)

Phase incoherence of γs from distant galaxies

Idea: Spacetime fluctuations can cumulatively lead to loss of phase coherence for radiation from far enough galaxies



Over wavelength λ, phase ϕ fluctuates by

$$\delta\phi = 2\pi \frac{\delta\lambda}{\lambda} \sim \pm 2\pi (\lambda^{1/3} l_P^{2/3})/\lambda = \pm 2\pi \left(\frac{l_P}{\lambda}\right)^{2/3}.$$

Intuitively, over distance l, the cumulative phase dispersion is $\Delta\phi = \delta\phi \times \frac{l}{\lambda}$. [Lieu & Hillman; Ragazzoni et al.]

Factor $\frac{l}{\lambda}$ is enormously huge so that $\Delta\phi \gg 2\pi$

$\Rightarrow$ Distant compact radiation sources should not produce normal interference patterns. But ... Wrong!

$\delta\phi$'s fluctuate $\pm$ "randomly", do not add coherently
Cumulative factor is $\left(\frac{l}{\lambda}\right)^{1/3} \ll \frac{l}{\lambda}$:

$$\Delta\phi \sim 2\pi \left(\frac{l_P}{\lambda}\right)^{2/3} \left(\frac{l}{\lambda}\right)^{1/3} = 2\pi \frac{l_P^{2/3} l^{1/3}}{\lambda}$$

For PKS1413+135, $\Delta\phi \sim 10^{-9} \times 2\pi \ll 2\pi$ for holographic model
[Ng, Christiansen, & van Dam]

- $\Delta\phi \sim 10 \times 2\pi$ for random walk model, ruled out (?)

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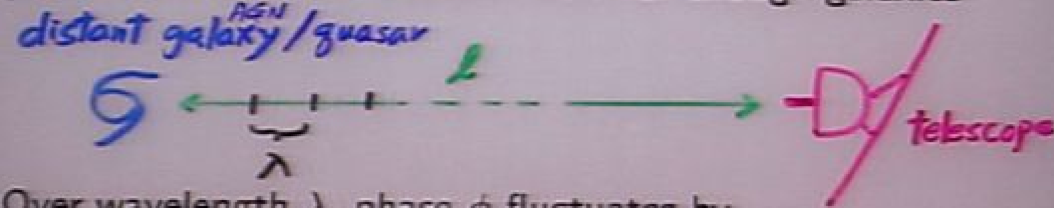

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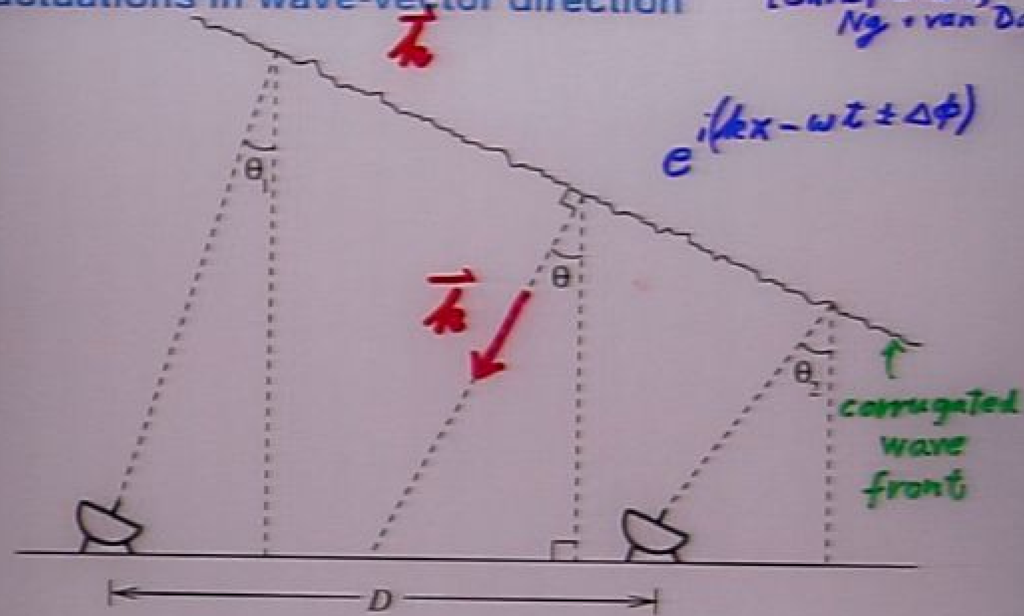
Fluctuations in wave-vector direction

[Christianson, Ng + van Dam]



Spacetime foam-induced fluctuations in wave-vector direction $\sim \Delta\phi/2\pi$

Correlated electric field $|E| \sim \left|\cos\left(\frac{\pi}{2}[2\theta - \Delta\phi/2\pi]\frac{D}{\lambda}\right)\right|$

- For $\Delta\phi = 0$, 1st null at $2\theta = \lambda/D$
- For $\Delta\phi \neq 0$, 1st null for halo at $2\theta - \Delta\phi/2\pi \sim \lambda/D$

$\Rightarrow$ halo appearance w. half-width $\sim \Delta\phi/2\pi$.

In effect, spacetime foam creates a "seeing disk" whose angular diameter is $\sim \Delta\phi/2\pi$.

Shows up in interferometer fringe pattern as decreasing fringe visibility as soon as ...

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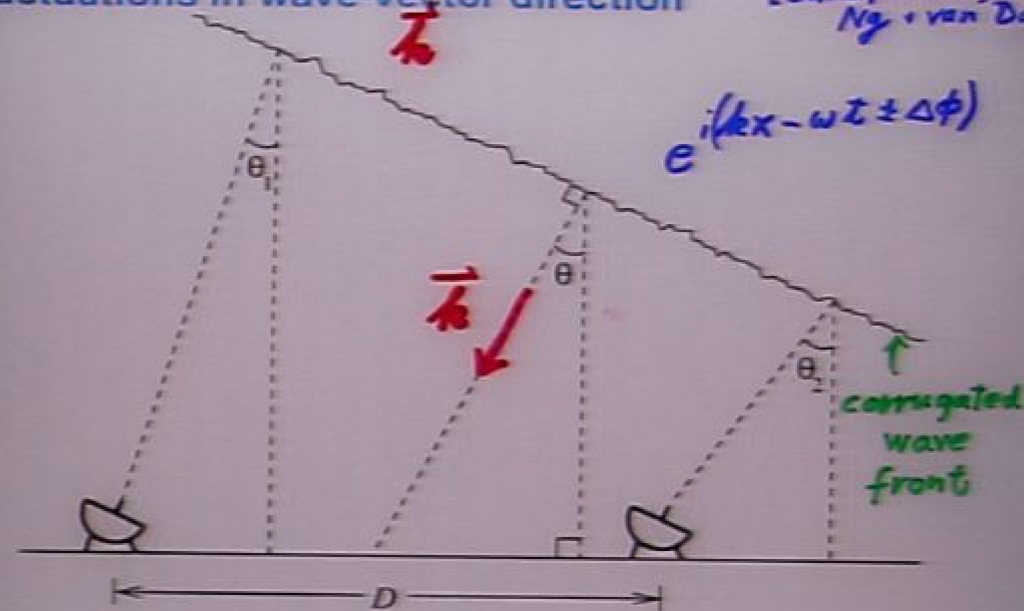

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Shows up in interferometer fringe pattern as decreasing fringe visibility as soon as $\Delta\phi \sim 2\pi\lambda/D \ll 1$

For the PKS1413+135 image at HST (with $D \simeq 2.4$m), expect halos at $\Delta\phi \sim 10^{-6} \times 2\pi$.

- Absence of halo rules out convincingly random-walk model ($\Delta\phi \sim 10 \times 2\pi$) .
- Fails to test the holographic model ($\Delta\phi \sim 10^{-9} \times 2\pi$) only by 3 orders of magnitude .

Exciting news: the full Very Large Telescope interferometer (comprising four 8.2 m telescopes with baselines up to $\sim$ 200 m) can reach an angular resolution of 1 - 2 milliarcsec ($\sim 5 - 10 \times 10^{-9}$ radians) w. sensitivity $\sim$ 50 mJy in near IR $\Longrightarrow$ Can potentially detect spacetime foam(!?)

- No need for extra telescope time; can use archived data!

- Next generation of more powerful telescopes: ELT, OWL...
- Alternatives to IR Interometry?

Very Long Baseline Array would require a resolution ~ 4 orders of magnitude finer at radio wavelengths.

Chandra X-ray Observartory, at $\lambda \sim 10^{-8}$cm, might make up for lack of angular resolution ($\sim$ 1 arcsec)?

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From spacetime foam to cosmology

Universe as a computer: (R_H=Hubble radius; T=temp.)

- Known $R_H \Rightarrow$ # operations $\lesssim (R_H/l_P)^2 \sim 10^{123}$
- Stat. mech.: Energy density $\sim T^4$, entropy density $\sim T^3$

$\Rightarrow$ # bits I (on conventional matter) $\sim (\#op)^{3/4} \lesssim 10^{92}$

- Known I & $R_H \Rightarrow$ distance between neighboring bits $\sim 10^{-3}$cm and so takes $\sim 10^{-14}$sec to communicate
- Known density & R_H, via ML, $\Rightarrow$ Op rate $\lesssim 10^{106}$/sec
- Known I & op rate $\Rightarrow$ bit flips once every 10^{-14}sec

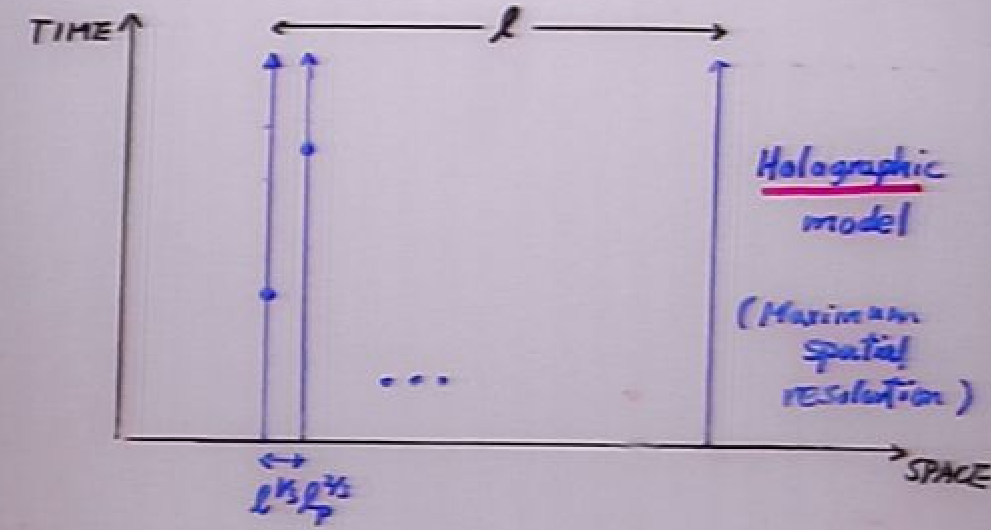
$\Rightarrow$ Storing bits in ordinary matter corresponds to a distribution of events in which each bit flips in the same amout of time it takes to communicate w. a neighboring bit

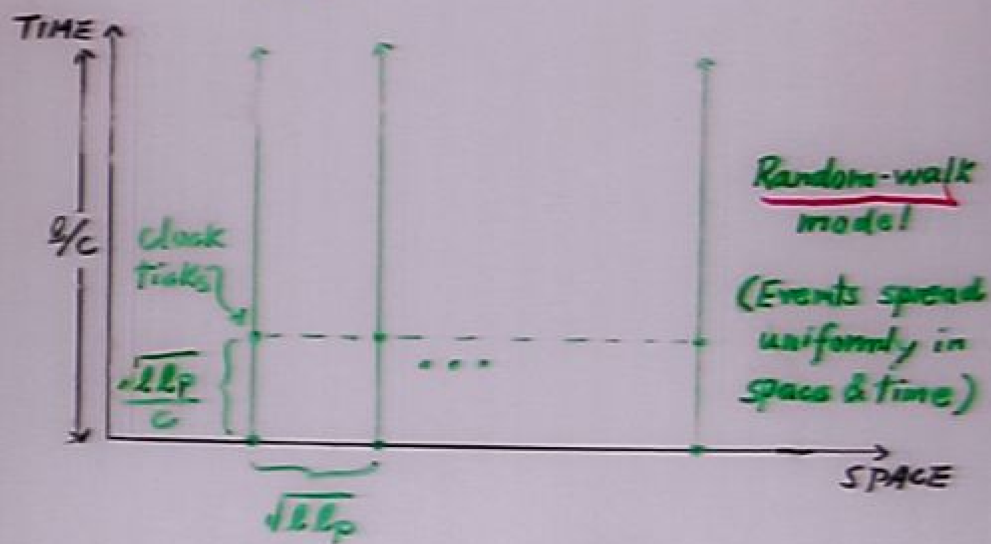
$\Rightarrow$ The accuracy to which ordinary matter maps out spacetime corresponds to the case of events spread out uniformly in spacetime, i.e., to random-walk model

Random-walk model is ruled out $\Rightarrow$ ST can be mapped to a finer accuracy than that provided by using ordinary matter

$\Rightarrow \exists$ unconventional (read dark) matter/energy with which the universe can map out its own spacetime geometry

- Observed critical cosmic ρ supports holographic model (?)





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STF ⇒ HOLOGRAPHIC FOAM COSMOLOGY

2 main features: (H, R_H = Hubble parameter, radius)

- critical cosmic energy $\rho \sim (H/l_P)^2 \sim (R_H l_P)^{-2}$
- Universe contains $I = (R_H/l_P)^2$ bits of info

Average energy carried by each bit is $\rho R_H^3/I \sim R_H^{-1}$

Such long-wavelength bits carry neglible kinetic energy

KE $\sim 0 \Rightarrow P \sim -\rho \Rightarrow$ acceleration, like quintessence?

For $\rho \sim H^2/G$, Friedmann Eq. yields ($a(t)$ = scale factor)

$$H \propto 1/a, \; a \propto t, \text{ and } P = -\rho/3$$

Whether expansion accel or decel depends on interactions between DE and DM (can accommodate both) [Zimdahl]

Each unconventional bit flips once in time $I/\nu \sim R_H$: inert

With $\lambda \sim R_H$, unconventional bits sit on top of one another

⇒ uniform distribution of energy density

⇒ effective cosmological "constant" $\Lambda \sim R_H^{-2}$ (for $P \sim -\rho$)

A LOGICAL SPECULATION

Assume DE is composed of long wavelength "particles"

How different are these "particles"?

Consider $N \sim (R_H/l_P)^2$ such "particles" obeying Boltzmann statistics in volume $V \sim R_H^3$ at $T \sim R_H^{-1}$

The partition function $Z_N = (N!)^{-1}(V/\lambda^3)^N \Rightarrow$ Entropy of the system is $S = N[ln(V/N\lambda^3) + 5/2]$ with $\lambda \sim T^{-1}$

But $V \sim \lambda^3$, so S becomes negative unless $N \sim 1$ which is equally nonsensical

Solution: The N inside the log in S, i.e, the Gibbs factor $(N!)^{-1}$ in Z_N, must be absent $\Rightarrow$ the N "particles" are distinguishable!

Then $S = N[ln(V/\lambda^3) + 3/2]$, + ve $S \sim N$

The only known consistent statistics in greater than 2 space dimensions without the Gibbs factor is the quantum Boltzmann statistics, aka infinite statistics

A logical speculation: The "particles" constituting dark energy obey infinite statistics, rather than the familiar Fermi or Bose statistics. This is the overrideing difference between DE and conventional matter.

In the framework of M theory

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In the framework of M-theory, V. Jejjala, M. Kavic and D. Minic [hep-th:0705.4581] have made a similar suggestion

hep-th/0705.4
DCPT-07
VPI-IPNAS-07

Fine Structure of Dark Energy and New Physics

Vishnu Jejjala,[1*] Michael Kavic,[2†] and Djordje Minic[2‡]

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Abstract

Following our recent work on the cosmological constant problem, in this letter we make a specific proposal regarding the fine structure (*i.e.*, the spectrum) of dark energy. The proposal is motivated by a deep analogy between the blackbody radiation problem, which led to the development of quantum theory, and the cosmological constant problem, which we have recently argued calls for a conceptual extension of the quantum theory. We argue that the fine structure of dark energy is governed by a Wien distribution, indicating its dual quantum and classical nature. We discuss observational consequences of such a picture of dark energy and constrain the distribution function.

DCPT-07
VPI-IPNAS-07

Fine Structure of Dark Energy and New Physics

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Abstract

Following our recent work on the cosmological constant problem, in this letter we make a specific proposal regarding the fine structure (*i.e.*, the spectrum) of dark energy. The proposal is motivated by a deep analogy between the blackbody radiation problem, which led to the development of quantum theory, and the cosmological constant problem, which we have recently argued calls for a conceptual extension of the quantum theory. We argue that the fine structure of dark energy is governed by a Wien distribution, indicating its dual quantum and classical nature. We discuss observational consequences of such a picture of dark energy and constrain the distribution function.

$$N_i = a_i^\dagger a_i + \sum_m a_m^\dagger a_i^\dagger a_i a_m + \sum_{m_1,m_2} a_{m_1}^\dagger a_{m_2}^\dagger a_i^\dagger a_i a_{m_2} a_{m_1} + \dots \quad .$$

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If we consider the various instances in which infinite statistics play a role (*i.e.* physics, Matrix theory, holographic spacetime foam, as well as our formulation of a independent Matrix theory), we note a common feature. In each of these the principle [22] is central. Holographic theories possess a manifestly non-local quality internal degrees of freedom must know something about the boundary. Thus the present in systems obeying infinite statistics and the non-locality present in holograp may be related. (This was also argued in [21].) Perhaps the presence of infinite s quantum gravitational systems is indicative of a holographic view of spacetime.

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[Doplicher, Haag, & Roberts; Govorkov; Greenberg]

- q-deformation of the Heisenberg algebra $(-1 \leq q \leq 1)$

$$a_k a_l^\dagger - q a_l^\dagger a_k = \delta_{kl}; \quad a_i|0\rangle = 0$$

($q = \pm 1$ corresponds to bosons/fermions)

- Inner product of two N-particle states is

$$\langle 0| a_{i_N} \cdots a_{i_1} a_{j_1}^\dagger \cdots a_{j_N}^\dagger |0\rangle = \delta_{i_1 j_1} \cdots \delta_{i_N j_N}$$

2 states obtained from acting with the same a and $a^\dagger$ in a different order are mutually orthogonal: the states may be in any representation of the permutation group

- The partition function is

$$Z = \Sigma e^{-\beta H}, \text{ NO Gibbs factor}$$

- $\sim$ statistics of identical particles with an ∞ of internal degrees of freedom $[SU(\infty)] \Longleftrightarrow$ statistics of nonidentical particles (distinguishable by their internal states)

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Theories of particles obeying ∞ statistics are non-local

[Fredenhagen; Greenberg]

Number operator, Hamiltonian, etc., are both nonlocal and nonpolynomial in the field operators:

$$N_i = a_i^\dagger a_i + \sum_m a_m^\dagger a_i^\dagger a_i a_m + \sum_{m,n} a_m^\dagger a_n^\dagger a_i^\dagger a_i a_n a_m + \dots$$

- difficult to formulate a relativistic verion of the theory,i.e., $\nexists$ consistent 2nd quantized local field theory; but a non-relativistic theory can be developed.

Nonlocality in ∞ statistics can be a virtue

- may be related to nonlocality in holographic principle

Examples:

- charged extremal black holes [Strominger];
- holographic quantum foam; • M-theory

Holographic principle is a crucial ingredient of quantum gravity $\Longrightarrow$ QG and ∞ stat fit together nicely

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SUMMARY

- Spacetime undergoes quantum fluctuations ⇒ uncertainties in spacetime measurements.
- Spacetime fluctuations scale as the cube root of distances. (Supported by an argument in loop QG approach)
- Discussion only depends on the quantum characteristics of spacetime measurements, and NOT on any particular theory.
- Detecting the tiny effects of spacetime fluctuations is difficult, but not impossible. May be within striking distance of detecting spacetime foam when the Very Large Telescope interferometer reaches its design performance. (Indirect detection: Use of Bose-Einstein condensates)
- Spacetime foam ⇒ cosmology: ∃ Dark energy/matter
- Holographic Foam Cosmology: critical cosmic energy density: flatness problem ✓ $P \sim -\rho/3$: accelerating or decelerating expansion depends on interactions with matter (flexible?)
- Speculation: "particles" constituting DE obey ∞ statistics (Supported by an argument in M-theory approach) QG and ∞ statistics appear to fit nicely together Conjecture: QG is unitary but non-local
- Phenomenology of HFC yet to be studied ...

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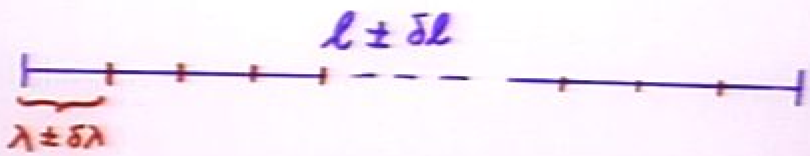
Cumulative effects of spacetime fluctuations

Divide distance l into l/λ equal parts each of length λ (for any $l_p \leq \lambda \leq l$)



Question: Starting with $\delta\lambda$ from each part, how do the l/λ parts add up to δl for the whole distance l?

I.e., find the cumulative factor $\mathcal{C}$ in $\delta l = \mathcal{C}\, \delta\lambda$

$$\delta l \sim l^{1/3} l_P^{2/3}; \quad \delta\lambda \sim \lambda^{1/3} l_P^{2/3}$$

$$\Downarrow$$

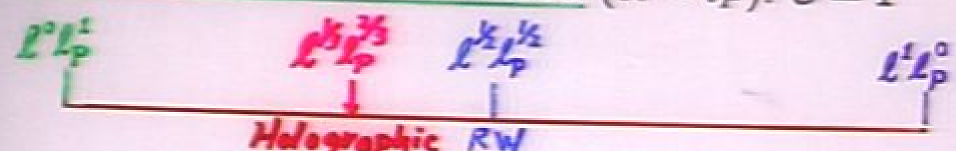
$$\mathcal{C} = \left(\tfrac{l}{\lambda}\right)^{1/3}$$

Cumulative Factor = $(\#intervals)^{1/3}$

(~ Brownian motion with self-similarity parameter 1/3)

Random walk model ($\delta l \sim l^{1/2} l_P^{1/2}$): $\mathcal{C} = (l/\lambda)^{1/2}$

Completely anti-correlation model ($\delta l \sim l_P$): $\mathcal{C} = 1$



δl (anti-correlation $\Longleftarrow$; correlation $\Longrightarrow$)