Quantum Behavior of Geometry in Large Systems

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Problems at the Planck scale are well known.

Where are quantum-classical boundaries in large systems?

\[ R = \frac{2GM}{c^2} \]

\[ \lambda = \frac{hc}{E} \]
Quantum matter and quantum geometry

Matter is a quantum system (e.g., field theory)

Geometry is dynamical but classical (general relativity)

Standard approximations: ignore geometrical dynamics in small systems, or ignore quantum behavior in large systems

Whole quantum system actually includes matter and geometry

Matter and geometry are “emergent” subsystems

Their degrees of freedom are entangled, beyond standard theory

*Entanglement can have observable consequences on large scales*
Standard quantum position uncertainty in macroscopic systems with gravity

Standard quantum kinematic uncertainty: wave function of position compared at two times increases with time interval,

\[ \Delta x_q(\tau)^2 \equiv \langle (\hat{x}(t) - \hat{x}(t + \tau))^2 \rangle \bigg|_t > 2\hbar\tau/M \]

Gravity also relates mass, size and duration

Quantum-classical boundary is macroscopic at low mass

Gravitational atom: two bodies bound only by gravity

Cosmic Expansion: minimum scale of classical metric
- Log of particle or system mass/Planck mass
- Log of radius or wavelength/Planck length

- Black hole
- Nanoscale system (~10^{-7} meters)
- Gravitational atom ground state wave function
- Quantum position uncertainty in orbital time (~ hours)
- Quantum
log(particle or system mass/Planck mass) vs log(radius or wavelength/Planck length)

- Black hole
- Density = $H_0^2$
- Quantum-classical boundary for cosmic expansion: ~60 meters
- Quantum position uncertainty over $t=1/H_0$
\[
\log\left(\frac{\text{particle or system mass}}{\text{Planck mass}}\right) - 60
\]

\[
\log\left(\frac{\text{radius or wavelength}}{\text{Planck length}}\right)
\]

\[
M = L = H_0^{-1}
\]

black hole

density = \(H_0^2\)

quantum position uncertainty over \(t = 1/H_0\)

directly measure cosmic acceleration in \(\sim 1\) year

\(\sim 10^8\) meters, \(\sim 10\) g,

precision \(\sim 10^{-12}\) meters
Directional Entanglement of Quantum Fields with Quantum Geometry

Energy density of quantum field states is given by the UV cutoff of the theory to the fourth power, independent of volume.

In a sufficiently large volume, these states are unphysical because they exceed the mass of a black hole of the same size.

(Extreme version of this, with Planck cutoff and Hubble volume, is the classic, factor of $\sim 10^{122}$ dark energy problem.)

One proposed solution (Cohen, Kaplan, Nelson): there is a maximum extent of field states (IR cutoff), which depends on UV cutoff.

Can be explained by directional entanglement of fields with emergent geometry: angular resolution is limited by Planck diffraction (CJH).
Field theory is significantly entangled with geometry, reducing degrees of freedom.

Standard field theory is valid here.
Information budget suggests that emergent cosmic acceleration rate could be set by the QCD scale

Entanglement connects micro scale of fields to macro scale of geometry

Density of holographic cosmic information \(\sim\) density of QCD field information

Standard position uncertainty of pion over a Hubble time \(\sim\) extent of QCD field states in entangled scenario (about 100 km)

Dark energy in a volume of this size \(\sim\) 1 Planck mass; amount of expansion in this time \(\sim\) directional uncertainty \(\sim\) QCD scale; effect of acceleration in this time \(\sim\) 1 Planck length difference

Equipartition of information could explain well known coincidence between QCD scale and Hubble scale, in Planck units (e.g., Zeldovich, Bjorken):

\[
m_\pi \approx H_\Lambda^{1/3}
\]
$M = L = H_0^{-1}$

QCD scale sets information density of cosmic system?
Experimental probe of Planckian directional entanglement

Direct laboratory measurement of gravitational indeterminacy or cosmic acceleration is impractical

But interferometers may be able to measure noise from Planckian directional entanglement on lab scale

An operating experiment, the Fermilab Holometer, is designed to measure or rule out this effect

It has recently achieved near-Planck sensitivity

Stay tuned for results in the next year
Holometer (E-990) Operations Status:

- Beginning 1-year operations phase July, 2014
  - Interferometers running stably and high quality data being taken at near full power
  - Uncorrelated shot noise is integrating away nicely

- Operations phase tasks
  - Develop in situ signal calibration schemes
  - Investigate and mitigate any sources of MHz frequency noise which may be uncovered by increased sensitivity levels

- Seismic/acoustic stability is still an issue
  - One of the interferometers still leaks 30% more power than the detectors can handle.
  - Investigating electronic and mechanical fixes (alignment control, tethering hut down)

Photocurrent cross-correlation averaged down over ~1M samples reveals clean, uncorrelated spectrum