How do rotations and local inertial frames emerge from Planck scale quantum geometry?

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KAIST / Fermilab Holometer Collaboration

Simplicity II

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arXiv:1607.03048 [gr-qc] *with C. J. Hogan, J. Richardson*

The Fermilab Holometer Collaboration

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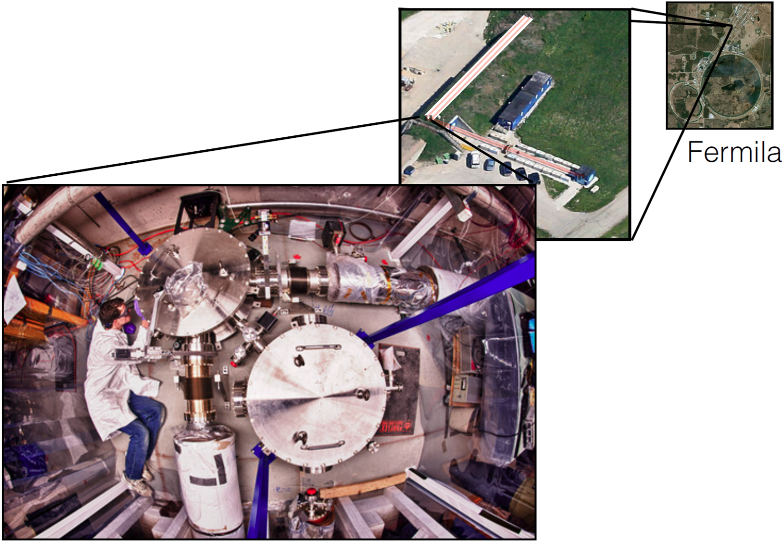
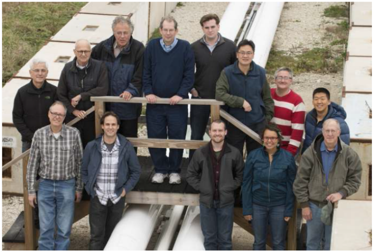
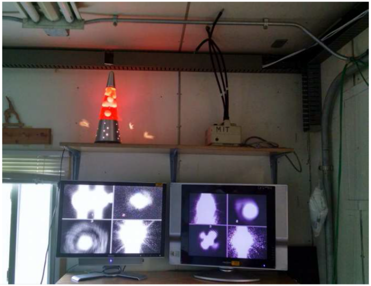
The Fermilab Holometer



Vertex - Looking Down

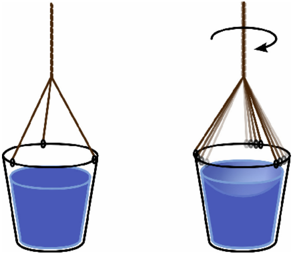
The Fermilab Holometer





Absolute Space and Rotation

- Newton said space is absolute.
- How to measure it?
  - Relative to a distant body.
  - Locally, using a rotating vessel of water.
- Mach asked why local rotation agrees with distant stars.

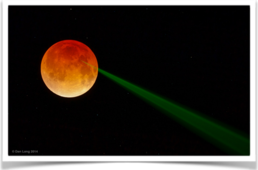


Rotation in General Relativity

- Complete theory of absolute space. Well-defined local inertial frames.
- Local and global frames are connected.

- Frame dragging: Distant matter directly affects local space.
  - Local inertial frame is "dragged" by *dynamical* space-time.
  - Local frame rotates with respect to the distant universe.

- Drag is measured in the solar system.
- Drag becomes extreme in spinning black holes.



Apache Point Observatory lunar laser ranging

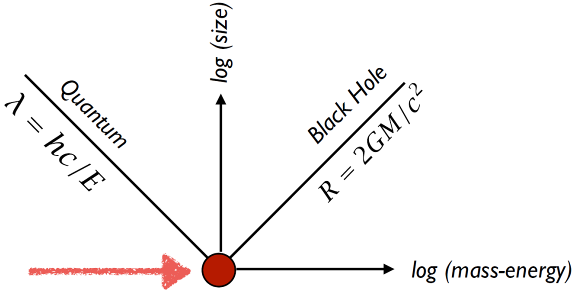
Gravity Probe- B

Rotation in Quantum Mechanics

- Standard elementary particles, or quantum matter, live in classical spacetime— absolute and determinate; not a quantum system.
- Spin is defined with respect to the local inertial frame.
- Rotation is defined even for infinitesimal distances.

Planck Scale: GR meets QM

Geometry has to be fundamentally different at the Planck scale.



Local rotation cannot be defined below the Planck length

Planck length ~ 10^{-35} meters

$$l_P \equiv ct_P \equiv \sqrt{\hbar G/c^3}$$

Planck mass ~ 10^{19} proton masses

$$m_P = \sqrt{\hbar c/G}$$

C. J. Hogan, arXiv:1509.07997 [gr-qc]

No Absolute Rotation at the Planck Scale

- Dynamical space-time must be a quantum system.
- Consider Wheeler's spacetime foam with Kerr black holes and Lense–Thirring effect.
- Or, extrapolate Newton's bucket to the Planck scale:
  - Gravity and frame dragging $\sim$ black hole
  - Indeterminacy and spin $\sim$ quantum particle
  - Indeterminate spin gravitationally drags the inertial frame.
  - The local inertial frame is a quantum superposition of spin states.
- *The indeterminate quantum spin of any measurement device is gravitationally inherited by the space-time.*
- No definite local nonrotating frame can be measured or defined.

C. J. Hogan, arXiv:1509.07997 [gr-qc]

Inertial Frames in a Quantum System of Geometry

- The local inertial frame does not exist at small scales.
- Space-time woven together *relationally* from entanglement amongst quantum subsystems.
  - A measurement projects onto a subspace. A measurement of one subsystem projects all the others.
- Rotation and direction emerge statistically— and frames become nearly classical— in larger systems.
- A quantum theory must predict— and only predicts— correlations among observables.
  - In QM, no locality. Nothing "happens" at a definite location or time, but correlations obey causality.
- Small, exotic quantum-gravitational rotational correlations must exist. Radically different from standard theory, which assumes absolute background space-time.

Reasons to Consider Large Scales

- Quantum geometric correlations are confined to the microscopic in standard QFT, as well as UV completions such as string theory.
- Might be because of assumed classical locality, with fixed backgrounds.

Infrared Paradoxes (Cohen Kaplan Nelson 1999)

- A standard QFT in a volume of size R with UV cutoff scale $k = mc/\hbar$ has $(Rk)^3$ independent modes.
- Its general state is a superposition of excitations.
- A state with mean occupation ~ 1 has $(mc/\hbar)^3$ particles per volume.
- Exceeds the gravitational binding energy at idealized Chandrasekhar radius:

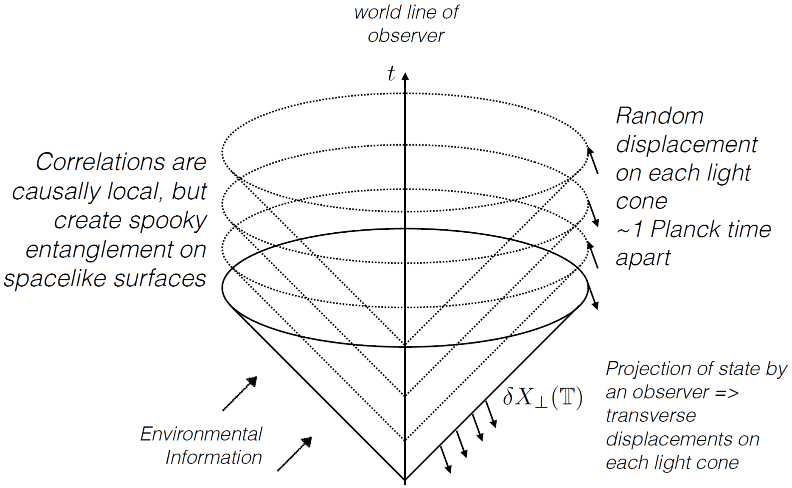
$$R_C/l_P \approx (m/m_P)^{-2}$$

- This field state is incompatible with GR at large R.

- Exotic correlations with geometry on large scales could solve this.
- Directional entanglement reduces independent degrees of freedom.

A Covariant Statistical Model for How Directions in Space-Time Emerge from the Planck Scale — Building a QM of Special Relativity

The statistical covariances follow causal symmetry and Planck coherence scale.

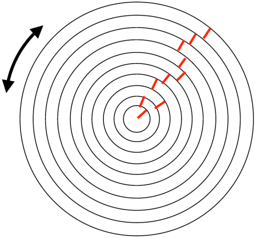


Exotic Rotational Fluctuations on Spacelike Surfaces

- Transverse displacement (from spin algebra) is constant along causal surfaces originating from observer's world-line.
- Random $\sim l_P$ displacement on each light cone $\sim t_P$ apart.

"Twists" of Inertial Frame

- On a constant-time hypersurface, each "shell" jitters relative to the ones adjacent to it— relational space-time from Planck scale elements.
- *Planckian random walk* in transverse position.
  - Mean rotation vanishes, mean square does not.



Planck Diffraction Scale: Inertial Frames and Directional Resolution

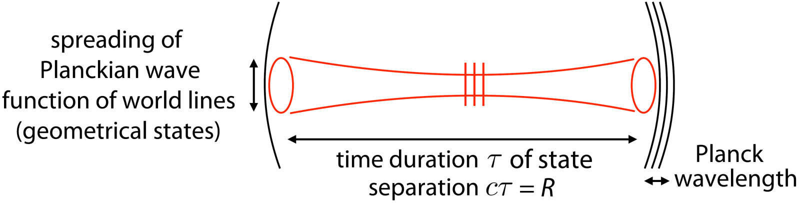
- Directional fluctuations on large scales get smaller:

$$\left\langle X_\perp^2 \right\rangle_R = \ell_P R \qquad \left\langle \Delta\theta^2 \right\rangle_R \approx \left\langle X_\perp^2 \right\rangle_R / R^2 = \ell_P / R$$

- Rotational fluctuations on large scales get slower:

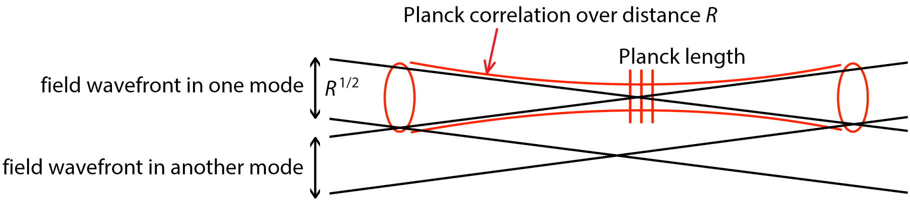
$$\left\langle \omega^2 \right\rangle_R \approx c^2 \ell_P / R^3$$

- A "paraxial" solution for the Wheeler-De Witt equation for a pendulum in the low-frequency nearly-free limit, with Planck mass cutoff.
  - The world line "diffracts" at the de Broglie wavelength of the body.
  - Like normal modes of light in a laser cavity, with Planck wavelength.



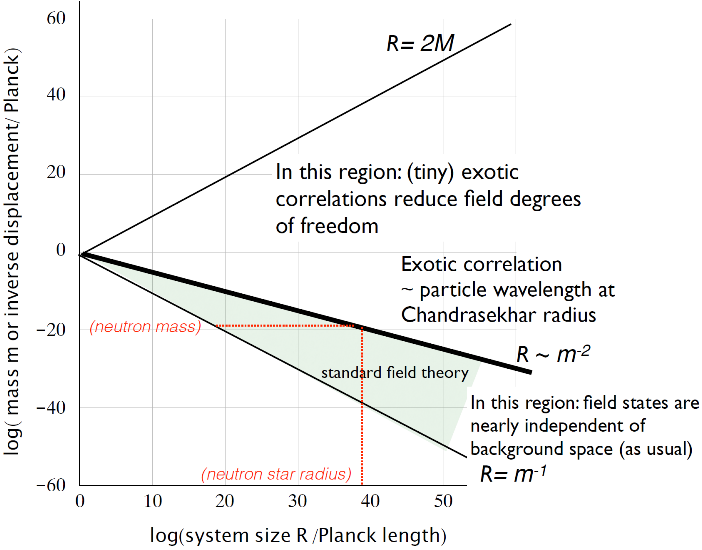
Quantum Geometry Entangles Field States on Large Scales

- Geometrical correlations at the Planck diffraction scale.
- Field phase is affected by geometrical phase.
- Extended field states become less distinct from each other at large R, reducing number of independent modes from standard theory.
  - Exotic correlation length $R^{1/2} \approx$ Inverse particle mass m^{-1}



C. J. Hogan, arXiv:1509.07997 [gr-qc]

The Right Amount of Exotic Correlation...



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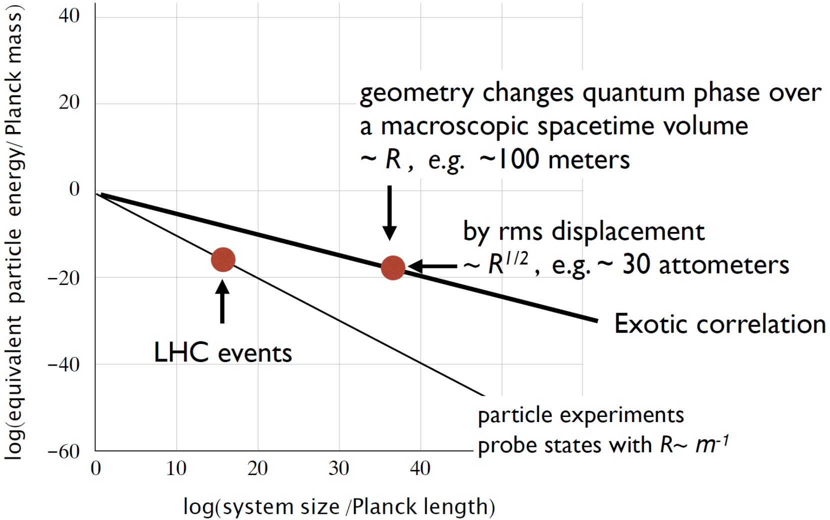
Consistent with Experimental Bounds and Detectable!



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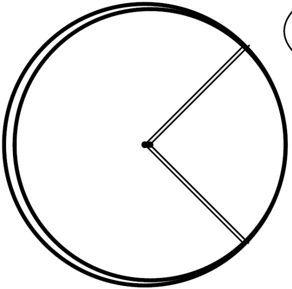
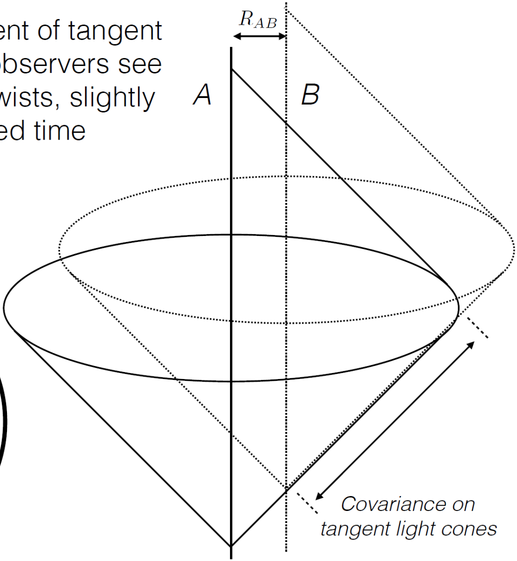
How Do Planck Subsystems Collapse Consistently?

"spooky" entanglement of tangent light cones: nearby observers see the same rotational twists, slightly displaced in measured time





Let's Calculate Some Statistical Signatures!

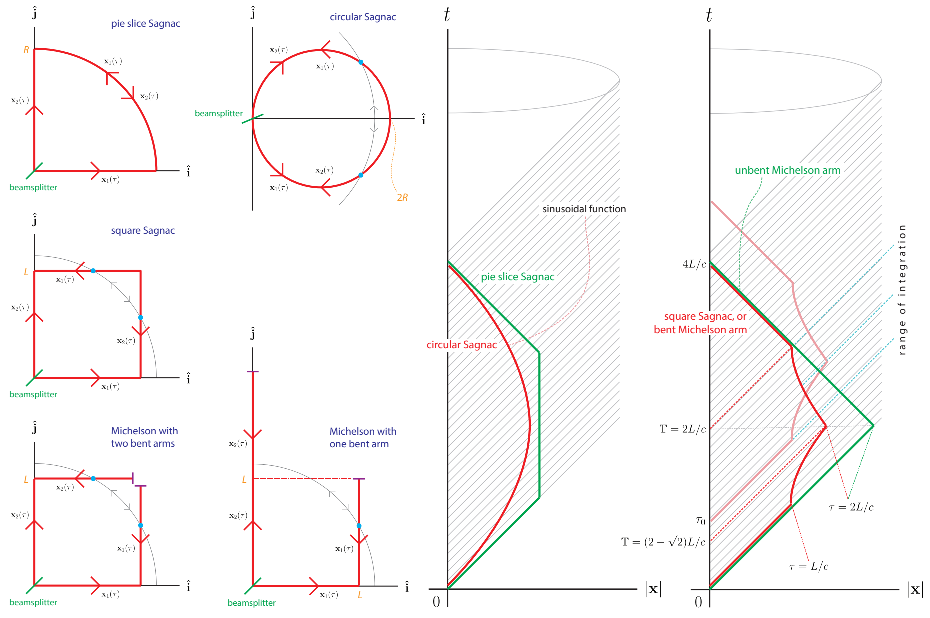
- In an interferometer, the extended nonlocal photon states collapse upon measurement at the beamsplitter.
- Projection onto future light cone time, with respect to the observer:

$$\mathbb{T} \equiv t - \frac{|\mathbf{x}|}{c}$$

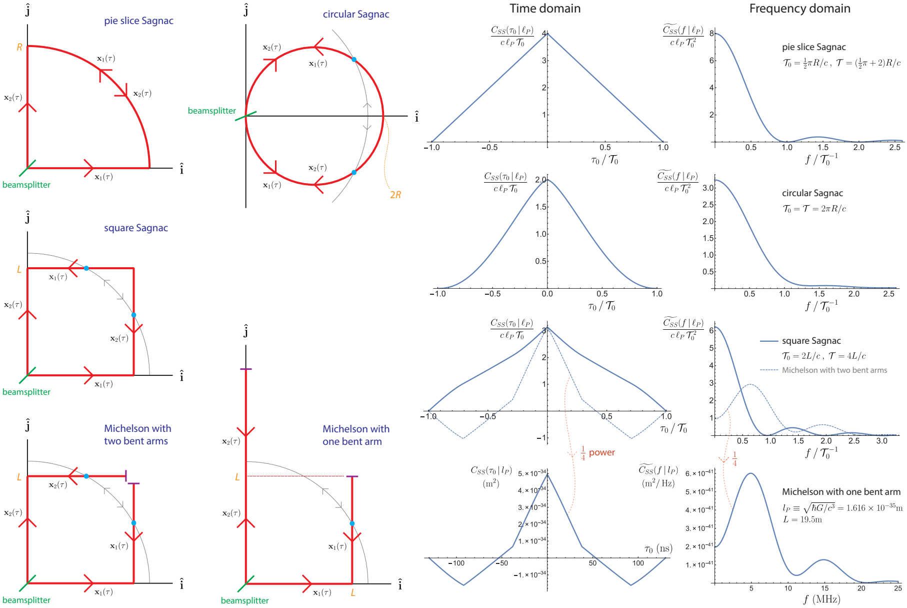
- The covariance structure:

$$\mathrm{cov}\left(\frac{dX_\perp}{d\mathbb{T}}(\mathbb{T}'),\, \frac{dX_\perp}{d\mathbb{T}}(\mathbb{T}'')\right) = \begin{cases} \left(\frac{\ell_P}{t_P}\right)^2, & |\mathbb{T}' - \mathbb{T}''| < \frac{1}{2} t_P \\ 0\,, & \text{otherwise} \end{cases}$$

Interferometer Light Paths in 2D and 1+1D

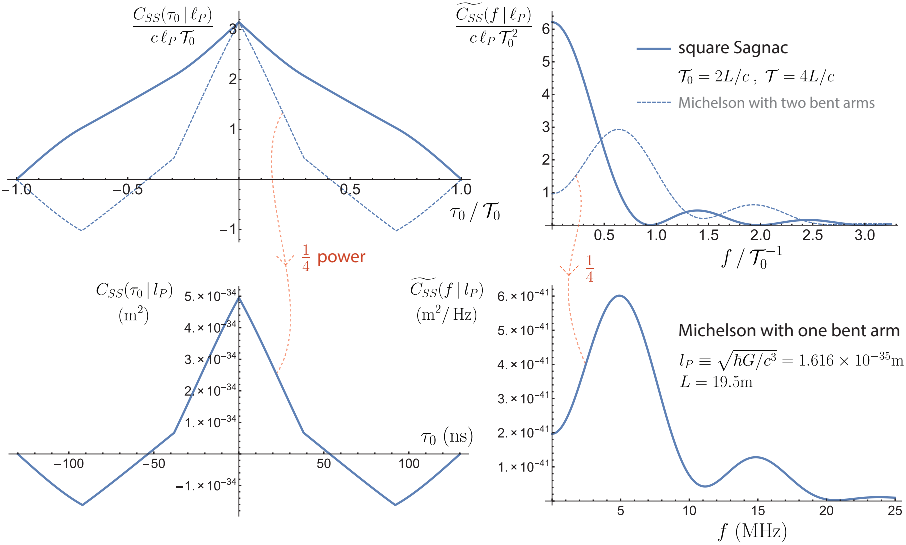


Examples of Predicted Spectra



The Bent Michelson Design

Time domain | Frequency domain



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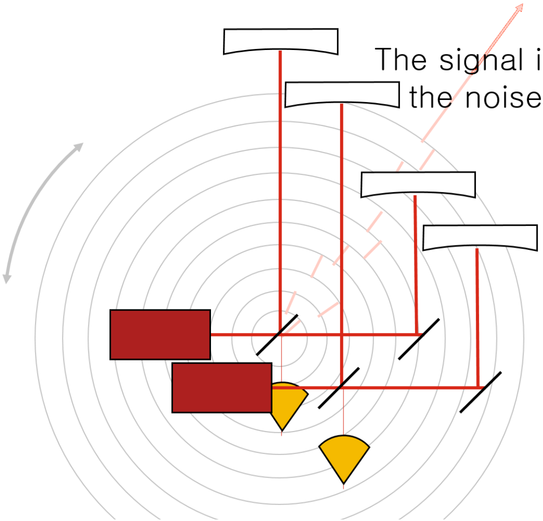
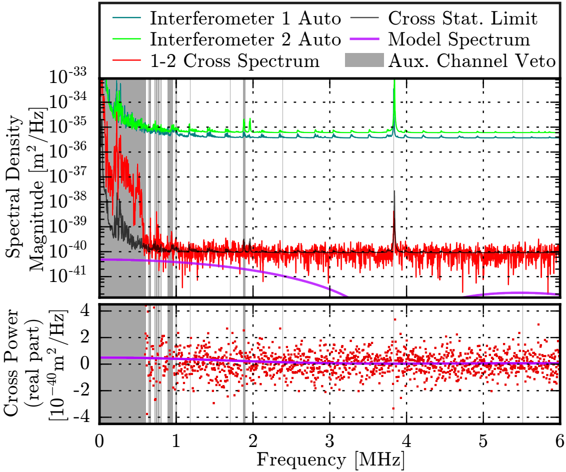


Two co-located interferometers.

The signal is correlated and the noise is uncorrelated.

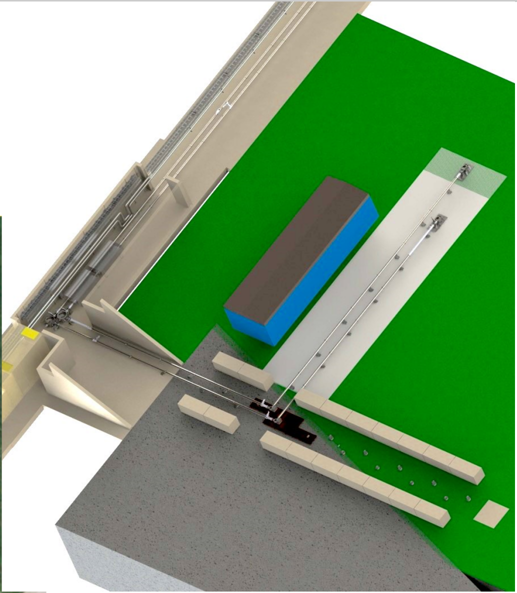
Sensitivity Proven in Simple Michelson Configuration

- Designed to test an earlier naive model of transverse uncertainty (correlations related by shear transformations).
- 145 hours of data, 3.8 kHz resolution (arXiv:1512.01216 [gr-qc], PRL):



Reconfiguration from Simple Michelson (Null Configuration)

Bent arm configuration
in construction.
Hope to run in the fall.



Construction in Progress

A Possible Explanation for the Cosmological Constant?

- "Centrifugal acceleration" from rotational fluctuations statistically mimics cosmic acceleration at the scale where:

$$\left\langle \omega^2 \right\rangle_{R_\Lambda} \approx c^2 l_P / R_\Lambda^3 \approx H_\Lambda^2 = \Lambda/3$$

$$m_\Lambda / m_P \approx (R_\Lambda / l_P)^{-1/2} \approx (H_\Lambda t_P)^{1/3}$$

$\sim$ strong interaction scale: $m_\Lambda \sim 200$ MeV, $R_\Lambda \sim 60$ km.

  - Coincidence of scales pointed out by Zeldovich 1968, Bjorken 2003, etc.
  - Of course, there is no physical movement or energy involved here—the phenomena is understood as phase shifts in quantum geometry.

- "Twists" of the strong interaction vacuum "shake space apart" below confinement scale.
- Cosmic acceleration timescale is set by $\sim$ the same combination of constants that determine a stellar lifetime.

C. J. Hogan, arXiv:1509.07997 [gr-qc]

Thank you!

Tour today! Meet in front of Wilson Hall by 5:30pm.