Quantum Control Platforms for Gravitational Physics in GQuEST

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How strongly can we probe mirror displacement for gravitational physics?
Is squeezed light the best we can do?

How small can we make classical noise?

Shouldn’t we always be rewarded for making a better instrument?
GQuEST experiment:
Gravity from Quantum Entanglement of Space-Time
University-Scale Experimentation

- Achieving quantum-noise limited sensitivity is tough
  - Acoustic isolation takes a lot of engineering
- High Frequency signals are ideal when the physics supports them
  - Many efforts are center on low-mass dark matter
- The best experiments test a model, a theory.
  - Ideally, either test result is significant
- New theory predicting observable signatures of quantum gravity checks these boxes:

Li et al, arXiv:2209.07543 [gr-qc]
Extreme Physics in “mundane” space

Quantum Gravity entails spacetime fluctuations from entanglement entropy

- Kathryn Zurek @ Caltech
- Systematically bridging the divide, theory side
Prediction of interferometer response

- Fluctuations of Newtonian potential on micro/local scales
- Looks like a field that causes isotropic dilations of the metric
- Thermal population
- Behaves much like a stochastic background

\[
ds^2 = -dt^2 + (1 - \phi)\left(dr^2 + r^2 d\Omega^2\right). \\
\phi(x) = l_p \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2\omega(p)}} \left(a_p e^{ip \cdot x} + a_p^\dagger e^{-ip \cdot x}\right), \\
\text{Tr} \left(\rho_{\text{pix}} a_{\textbf{p}_1}^\dagger a_{\textbf{p}_2}\right) = (2\pi)^3 \sigma_{\text{pix}}(\textbf{p}_1) \delta^{(3)}(\textbf{p}_1 - \textbf{p}_2) \\
\sigma_{\text{pix}}(\textbf{p}) = \frac{a}{l_p \omega(\textbf{p})}, \quad (\text{Minimal set of equations to build the phenomenology})
\]
A Tabletop Stochastic Search

- Michelson Interferometer
- 10kW+
- 1550nm
- Broadband signal
- Will need cryogenic Si

\[ S_\phi \equiv \alpha \Phi(\Omega) \]

\[ \Phi \equiv \max_{\Omega<\infty} \Phi(\Omega) \]

\[ \Phi \approx \left(3 \cdot 10^{-22} \frac{m}{\sqrt{\text{Hz}}} \right)^2 \left( \frac{L}{5\text{m}} \right)^2 \]

\[ S_q \approx \left(5 \cdot 10^{-19} \frac{m}{\sqrt{\text{Hz}}} \right)^2 \left( \frac{10\text{kW}}{P_{bs}} \right) \]

\[ N = \Delta T \Delta F = \frac{S_q^2}{\alpha^2 \Phi^2} \approx 10^{13} \]
A Tabletop Stochastic Search

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\[ \Delta T_{1\sigma} \approx 185\text{Hr} \]

\[ S_\phi = \alpha \Phi(\Omega) \]

\[ \Phi \equiv \max_{\Omega<\infty} \Phi(\Omega) \]

\[ \bar{\Phi} \approx \left( 3 \cdot 10^{-22} \frac{\text{m}}{\sqrt{\text{Hz}}} \right)^2 \left( \frac{L}{5\text{m}} \right)^2 \]

\[ S_q \approx \left( 5 \cdot 10^{-19} \frac{\text{m}}{\sqrt{\text{Hz}}} \right)^2 \left( \frac{10\text{kW}}{P_{bs}} \right) \]
Blame the time-series

Here is where it gets interesting:

The background noise-power is from observing vacuum fluctuations of the optical light

- Michelson interferometers observe the vacuum due to their Fringe light. Which makes them measure the optical signal field vs. time

- Is this necessary? If there is no signal power then why can I not test observing something vs. observing nothing

- Instead, measure the optical signal power (vs. time)

  different observable, different statistics
A Tabletop Particle Search

So... let's view this as a particle detector

- $1 \times 10^{-7}$ photons/(s Hz) emitted (spectral flux-density)
- over 10MHz (1e7 Hz) signal bandwidth
- Should take $1$ second for $1\sigma$ by Poisson statistics
  - Shot noise quantum limit isn't so fundamental for this search

McCuller, FNAL QICK, Jan 2023
The GQuEST Realization

- Metric fluctuation signal modulates Stokes, anti-Stokes photon side-bands
- Use a series of optical filters to select photon sidebands
- Requires extreme sideband/carrier contrast \( \sim 240 \text{db} \)
- New interferometer for Raman/Brillouin spectroscopy of spacetime

[Diagram showing the GQuEST setup with labels and arrows indicating laser, quantum state source, and various optical components for signal processing and readout.]

arXiv:2211.04016
50kHz Photopower Integration

I) Michelson interferometer with power recycling cavity and specialized readouts

(a) prepared State reflects from interferometer

(b) standard Michelson readout

(c) quantum filter cavity reflects carrier, passes narrow signal band

(d) quantum filter cavities impress modulations (dashed red)

(e) 3x more signal filter cavities, 50kHz each to reject background noise

(f) Novel Photon counting readout (SNSPD)

II) Data

III) Data

arXiv:2211.04016
Sensing and Control Needs

- Good active and tons of passive isolation of laser noise
- Feedback control of interferometer and cavities
- Many VCO sources and demodulators
High Speed Servo Board

- The LIGO “Common Mode” board is a generic 2-channel in, 2-channel out servo in analog
- Implements 8 custom, toggle-able Sallen-Key filters
  - equiv, digital biquad filter (i.e. SoS)
  - Much more aggressive loop shapes than PID. Are conditionally stable!
- Offsets added at appropriate points
- Along with testpoint/excitation for loop measurements
- Demodulation, mixing done externally with low noise demod boards.
- Requires ~40 binary controls and many analog readbacks ($$, annoying for univ. labs)

The schematics and design are public - on generation 7: https://dcc.ligo.org/LIGO-D040180

Generally, we need the full dynamic range of op-amps (~1e-10/rtHz), which means a 16 bit ADC at 4GHz with “whitened” front-end noise shaping
"TTFSS"

- **Table-top frequency stabilization servo.**
  - Actuates with laser temp, laser PZT, EOM.
  - EOM path is in a short 10ns round-trip for highest bandwidth.
  - Locks two lasers to shot noise of the beatnote to 100kHz or so.
    - Ends up limited by fiber or acoustic pickup between the lasers.
  - Basically makes a secondary laser equivalent to a primary
  - The VCO on the secondary allows one to then modulate the secondary substantially faster than an AOM for single-sideband modulation
  - This is a principle of operation for the LIGO in-vacuum squeezed light source and its coherent control system.

The schematics and design are public - on generation 4: https://dcc.ligo.org/D1700077
Cross Correlating Spectrum Analyzer

- Also equipped with a “standard Michelson” readout.
- Like Holometer, needs multi channel ~100MHz time-averaged cross correlations to dig in to noise
  - Gives Resolution that photon counting doesn’t
GQuEST experiment: Gravity from Quantum Entanglement of Space-Time

- Intends to test quantum gravity fluctuation signals
- Intends to demonstrate the utility of photon counting for interferometers
  - This makes them much more like other HEP rare-process detectors
- I do anticipate counting to be useful in the future of GW astronomy
- Squeezing doesn’t improve quantum performance
  - new platform to explore non-Gaussian quantum improvements
The A+ Upgrade

- 6db of frequency-dependent squeezing
  - Early install, aiming at 4.5db in Run 4
  - Sub-SQL during observations!

- 2x improved coating thermal noise
  - Still researching, but good leads

- Active wavefront control
  - Lowers squeezing loss

- Balanced homodyne readout
  - Multiple benefits

- Bigger Beamsplitter
Filter Cavity Hardware

Drawings: Wenxuan Jia and Dhruva Ganapathy

Ultralow-loss Faraday isolators (UF/Montclair)
Filter Cavity Installation