#### Fermilab **BENERGY** Office of Science



#### **GQuEST:** Gravity from the Quantum Entanglement of Space Time

Chris Stoughton INFN Pisa Seminar 15 November 2023

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#### **Quantum Mechanics and General Relativity**



It seems to be inevitable that this length must play some role in any complete interpretation of gravitation...

In recent years great progress has been made in knowledge of the excessively minute;

but until we can appreciate details of structure down to the quadrillionth or quintillionth of a centimetre,

the most sublime of all the forces of Nature remains outside the purview of the theories of physics.

A.S. Eddington, discourse delivered to the Royal Institution, published in Nature 1917 no. 2542 vol 101



#### **Plot of Everything**



### **Theory Motivation**

GQuEST



#### Kathryn Zurek, Caltech

We know that Einstein's General Relativity is incomplete, as gravity must somehow be quantum mechanical.

"The idea that you might be able to look for observable features of quantum gravity is very far from the mainstream, but we'll be lost in the desert if we don't start focusing on ways to link quantum gravity with the natural world that we live in. Having observational signatures to think about tethers us theorists together and helps us make progress on new kinds of questions."



#### Kathryn Zurek's View of the Theoretical Landscape

# One Mountain, Many Faces

# w/He, Sivaramakrishnan, Wilson G. Length Operator

**Equivalent physical descriptions** 

#### A. AdS/CFT w/Verlinde 1911.02018

H. "Pixellon"

KZ 2012.05870 w/Lee,Li,Chen 2209.07543

w/Verlinde, 2208.01059

#### B. Light Ray Operators

F. 2-d Models, e.g. JT gravity w/Gukov, Lee 2205.02233

#### E. Hydrodynamics EFT

w/Zhang 2304.12349

#### D. Shockwaves and Gravitational Memory

w/He, Raclariu 2305.14411

C. Gravitational effective action / saddle point expansion w/Banks, 2108.04806



#### An Observable: GQuEST in One Slide

• The metric of spacetime modifies the metric with a scalar field

$$ds^{2} = -dt^{2} + (1 - \phi)(dr^{2} + r^{2}d\Omega^{2})$$

• This introduces a signal in the sidebands of an interferometer of length L as a PSD with peak level, peak frequency, width:

$$\overline{S}_L^{\phi} = \alpha \frac{l_p L^2}{c 8 \pi^2} \approx \alpha \left( 2.9 \cdot 10^{-22} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \right)^2 \left( \frac{L}{5 \mathrm{m}} \right)^2.$$

$$f_{\rm pk} \approx 15.6 \ \mathrm{MHz} \left( \frac{5 \ \mathrm{m}}{L} \right), \qquad \Delta f \approx 36 \ \mathrm{MHz} \left( \frac{5 \ \mathrm{m}}{L} \right),$$

 We will filter the IFO output, count photons, with S/N=1 in 2.4 hours for each offset frequency. Measure (or exclude) this signal with repeated operations.

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#### Signal/Noise Fringe Readout

Geontropic Signal
$$\overline{S}_L^{\phi} = \alpha \frac{l_p L^2}{c 8 \pi^2} \approx \alpha \Big( 2.9 \cdot 10^{-22} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \Big)^2 \Big( \frac{L}{5 \mathrm{m}} \Big)^2$$
Standard Quantum Noise $\overline{S}_L^q = \frac{\hbar c}{2k P_{\mathrm{BS}}} \approx \Big( 6.2 \cdot 10^{-19} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \Big)^2 \Big( \frac{10 \mathrm{kW}}{P_{\mathrm{BS}}} \Big) \Big( \frac{\lambda}{1.5 \ \mu \mathrm{m}} \Big)$ 

$$\begin{split} \mathrm{SNR}_{\mathrm{fringe}}^2 &= \int_0^T \int_0^\infty \left( \frac{S_L^\phi(f)}{S_L^q(f)} \right)^2 \mathrm{d}f \, \mathrm{d}t \approx T \Delta f \left( \frac{\overline{S}_L^\phi}{S_L^q} \right)^2, \\ &\approx \alpha^2 \left( \frac{T}{160 \mathrm{hr}} \right) \left( \frac{P_{\mathrm{BS}}}{10 \ \mathrm{kW}} \right)^2 \left( \frac{L}{5 \ \mathrm{m}} \right). \end{split}$$

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## A New Way to Operate IFOs

arXiv:2211.04016: Lee McCuller

Single-Photon Signal Sideband Detection For High-Power Michelson Interferometers



Squeezing: 6dB is the seen in real experiments, and would accelerate a Holometer/GQuEST type experiment by ~16x (12db, in time).

Goal: Demonstrate a signal search accelerated by >100x using a photon-counting Michelson interferometer



### **One Interferometer Designed for GQuEST**





#### **Extreme Filtering of IFO Output**



M1 and M2 have T = 1000 ppm so Finesse=3150
Filter bandwidth is 42 kHz
One cavity suppresses carrier light by ~ 60 dB.
4 cavities in series reduces the output rate from 10^18 Hz to < 10-2 Hz</li>



### **Basic Design Parameters for GQuEST IFOs**

TABLE I. Parameters of the fiducial IFO design. The noise spectral densities are evaluated at 16 MHz

| parameter                           | symbol                  | value  |
|-------------------------------------|-------------------------|--|
| Geontropic fluct. scale parameter   | α                       | $\mathcal{O}(1)$   |
| IFO arm length                      | L                       | 5 m  |
| Power on beamsplitter               | $P_{\rm BS}$            | 10  kW   |
| Laser wavelength                    | $\lambda$               | $1.5~\mu{ m m}$  |
| Laser frequency                     | ν                       | $193.4~\mathrm{THz}$   |
| Nominal filter offset frequency     | $\epsilon_c$            | $15.6 \; \mathrm{MHz}$                                       |
| Filter bandwidth (FWHM)             | $\Delta\epsilon$        | $25~\mathrm{kHz}$  |
| Twin IFO separation                 | S                       | 1.5 m  |
| IFO inter-arm angle                 | Θ                       | $90^{\circ}$   |
| Signal Spectral Density (peak)      | $\overline{S}^{\phi}_L$ | $\left(3 \cdot 10^{-22} \text{ m/}\sqrt{\text{Hz}}\right)^2$ |
| Thermal Noise Spectral Density      | $\overline{S}_{L}^{c}$  | $\left(10^{-21} \text{ m/}\sqrt{\text{Hz}}\right)^2$         |
| Shot Noise Spectral Density         | $S_L^q$                 | $\left(6 \cdot 10^{-19} \text{ m/}\sqrt{\text{Hz}}\right)^2$ |
| Photon Detector Dark Count Rate     | $\dot{N}^d$             | $10^{-3}$ Hz   |
| Observation time for $5\sigma$ test | T                       | $\mathcal{O}(100)$ hours                                     |



## **Signal/Noise for Counting**

Geontropic Signal
$$\overline{S}_{L}^{\phi} = \alpha \frac{l_{p}L^{2}}{c8\pi^{2}} \approx \alpha \left(2.9 \cdot 10^{-22} \frac{m}{\sqrt{Hz}}\right)^{2} \left(\frac{L}{5 m}\right)^{2}$$
Quantum Noise $\overline{S}_{L}^{q} = \frac{\hbar c}{2kP_{BS}} \approx \left(6.2 \cdot 10^{-19} \frac{m}{\sqrt{Hz}}\right)^{2} \left(\frac{10 \text{ kW}}{P_{BS}}\right) \left(\frac{\lambda}{1.5 \ \mu m}\right)$ Coating Noise $\overline{S}_{L}^{c} = \left(10^{-21} \text{ m}/\sqrt{Hz}\right)^{2}$  $\mathrm{SNR}_{\mathrm{counting}}^{2} \approx \frac{T\Delta c}{4} \frac{\left(\overline{S}_{L}^{\phi}\right)^{2}}{S_{L}^{q} \overline{S}_{L}^{c}}$ Noise from C << q $\approx \alpha^{2} \left(\frac{T}{2.4 \text{ hr}}\right) \left(\frac{P_{BS}}{10 \text{ kW}}\right) \left(\frac{L}{5 \text{ m}}\right)^{4} \left(\frac{S_{L}^{c}(f)}{\overline{S}_{L}^{c}}\right)$ 

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## Signal and Noise for a GQuEST IFO



### Photon Counter: Boris Korzh @ JPL/Caltech

#### Superconducting Nanowire Single Photon Detector

- 1. Current-biased superconducting nanowire
- 2. Photon absorption & Hotspot formation
- 3. Suppression of superconductivity
- 4. Normal domain growth *internal gain*

**GQuEST** 

5. Recovery



G. Goltsman, et al., APL 79, 705 (2001)

- J.P. Allmaras, A.G. Kozorezov, B.A. Korzh, K.K. Berggren, and M.D. Shaw, PRApplied 11 034062 (2019)
- J.P. Allmaras, Modeling and Development of Superconducting Nanowire Single-Photon Detectors. Ph.D. Dissertation, Caltech (2020)



### **Dark Count Rates of SNSPDs**



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## **Optically Filter Thermal Photons on SNSPDs**



#### **SNSPD Dewar Design and Fabrication @ FNAL**



### **Full GQuEST Configuration**



## **Experimental Risks and Opportunities**

- 1. Carrier-power Isolation
- 2. Laser noise
- 3. Black-body Radiation on SNSPDs
- 4. Isolate SNSPDs from noise
- 5. High power operation
- 6. Thermal Distortion of Mirrors
- 7. Coating Thermal Noise
- 8. Bulk-mode Thermal noise
- 9. RFI: RF coupling
- 10. Characterize Backgrounds,
- 11. Subtraction or Correlation

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Red- Unexplored risks of new photon counting technique

Orange- Known risks made somewhat More challenging from photon counting needs

Yellow-standard experimental needs, Requires full setup and time



#### **Optics**

| end mirror beam size                               | w                       | $2\mathrm{mm}$                                  |
|--|-------------------------|---|
| end mirror diameter                                | d                       | 25.4mm  |
| end mirror thickness                               | h                       | $2\mathrm{mm}$                                  |
| end mirror mass                                    | m                       | $24\mathrm{g}$                                  |
| end mirror temperature                             | T                       | $294\mathrm{K}$                                 |
| end mirror bulk Q                                  | Q                       | $10^6 \cdot \frac{\Omega/2\pi}{10^7 \text{Hz}}$ |
| end mirror substrate material                      | c-Si                    | crystalline Si                                  |
| beamspitter beam size                              | w                       | $2\mathrm{mm}$                                  |
| beamspitter diameter                               | $d_{ m BS}$             | 38.1mm  |
| beamspitter thickness                              | h                       | $2\mathrm{mm}$                                  |
| beamspitter mass                                   | $m_{ m BS}$             | $53\mathrm{g}$                                  |
| beamspitter temperature                            | $T_{ m BS}$             | $123\mathrm{K}$                                 |
| beamspitter bulk Q                                 | $\mathbf{Q}$            | $10^6 \cdot \frac{\Omega/2\pi}{10^7 \text{Hz}}$ |
| beamsplitter substrate material                    | c-Si                    | crystaline Si                                   |
| c-Si density                                       | ho                      | $2329 \text{ kg/m}^3$                           |
| c-Si thermal conductivity                          | κ                       | 739 W/m/K                                       |
| c-Si index of refraction at $\lambda$              | n                       | 3.48  |
| c-Si $\partial n/\partial T$ at 123K and $\lambda$ | eta                     | $10^{-4}$ /K                                    |
| c-Si Young's modulus                               | Y                       | $156\mathrm{GPa}$                               |
| c-Si Shear modulus                                 | G                       | 61 GPa  |
| c-Si Coef Thermal Expansion at 123K                | α                       | 0 /K  |
| c-Si Coef Thermal Expansion at 294K                | α                       | $2.5 \cdot 10^{-6}$ /K                          |
| c-Si Poisson ratio                                 | $v_s$                   | 0.265   |
| c-Si Specific Heat                                 | C                       | 710  J/kg/K                                     |
| c-Si Fractional Power Absorption at $\lambda$      | $\Lambda_{SI}$          | $2\cdot 10^{-4}$ /m                             |
| Fractional BS Coating Power Absorption             | $\Lambda_{ m Coatings}$ | 3 ppm   |
| Fractional BS Bulk Power Absorption                | $\Lambda_{ m Bulk}$     | 0.4 ppm   |
| Coating Material                                   | Ti:TaO2                 | ?   |
| Coating Thickness                                  | $t_c$                   | [SV: CHECK] 40 $\mu$ m                          |
| Coating Stress                                     | $\sigma$                | 0.5 GPa   |
|  |                         | 🛟 🛟 🕹 🕹 🕹                                       |

### This year: build a Technology Demonstrator

- For the demonstrator, focus on the red risks
- Currently, squeezing speeds up direct readout by 16x
- Our goal is to accelerate > 100x speedup using photon counting
- 1 Watt on beam splitter, locked to 1 mW output fringe
- Couple output to bowtie cavities with 57 db each
- Read with SNSPDs with 1e-2 Hz (or better) dark count rates.

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