GQuEST: Gravity from the Quantum Entanglement of Space Time

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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…

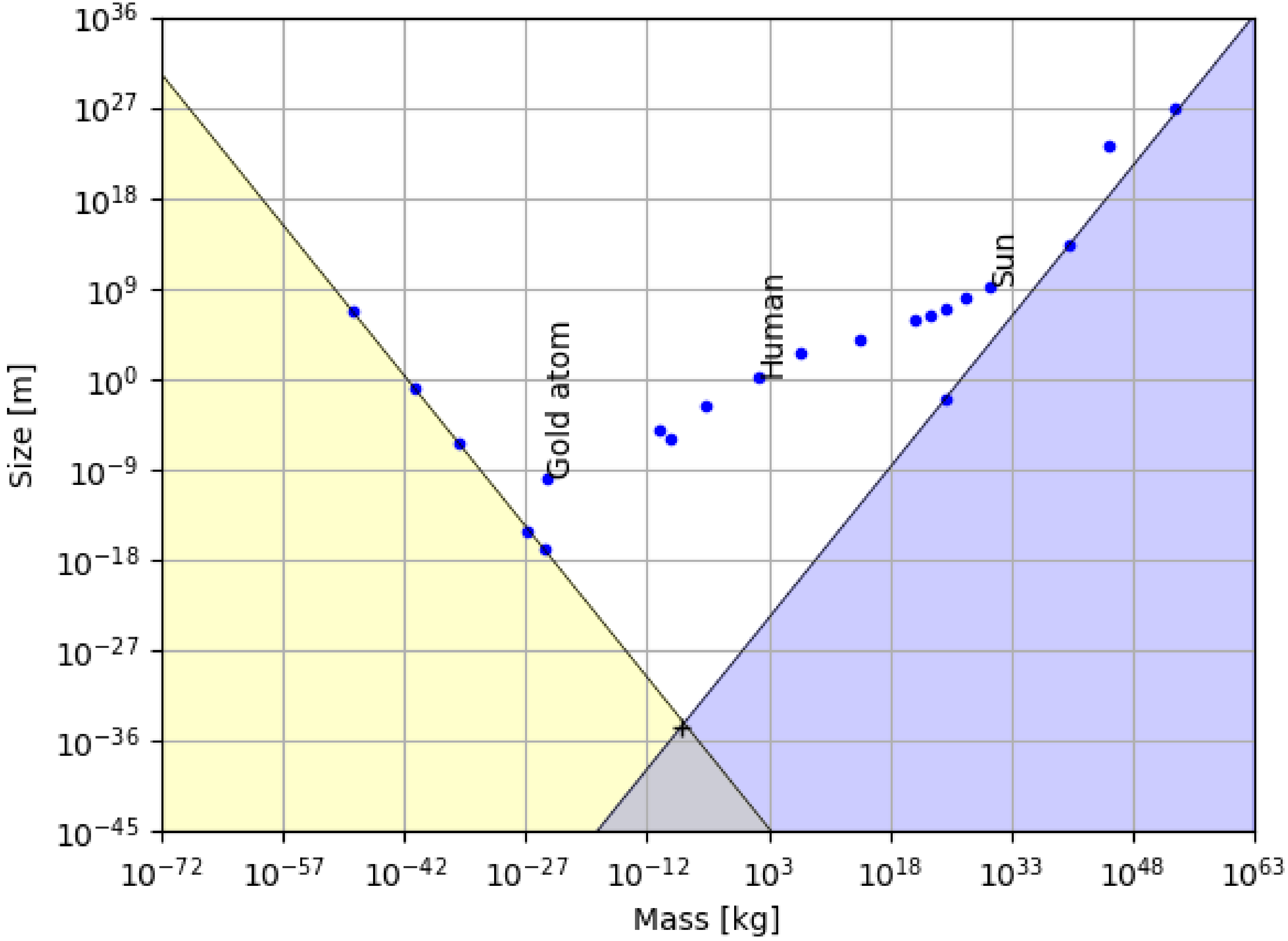
In recent years great progress has been made in knowledge of the excessively minute;

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

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."

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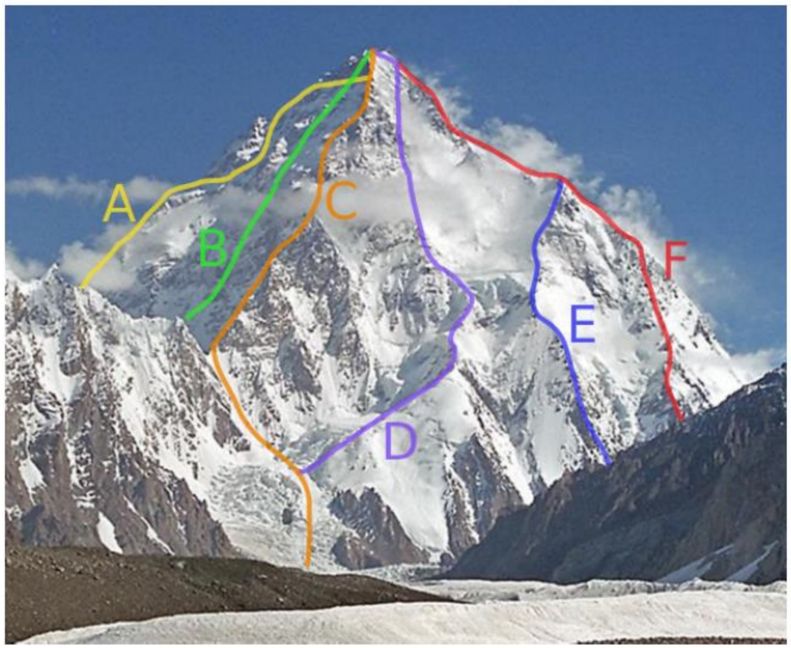
Kathryn Zurek's View of the Theoretical Landscape

One Mountain, Many Faces

w/He, Sivaramakrishnan, Wilson

G. Length Operator

Equivalent physical descriptions



F. 2-d Models, e.g. JT gravity

w/Gukov, Lee 2205.02233

A. AdS/CFT

w/Verlinde 1911.02018

E. Hydrodynamics EFT

w/Zhang 2304.12349

H. "Pixellon"

KZ 2012.05870

w/Lee, Li, Chen 2209.07543

D. Shockwaves and Gravitational Memory

w/He, Raclariu 2305.14411

w/Verlinde, 2208.01059

B. Light Ray Operators

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

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

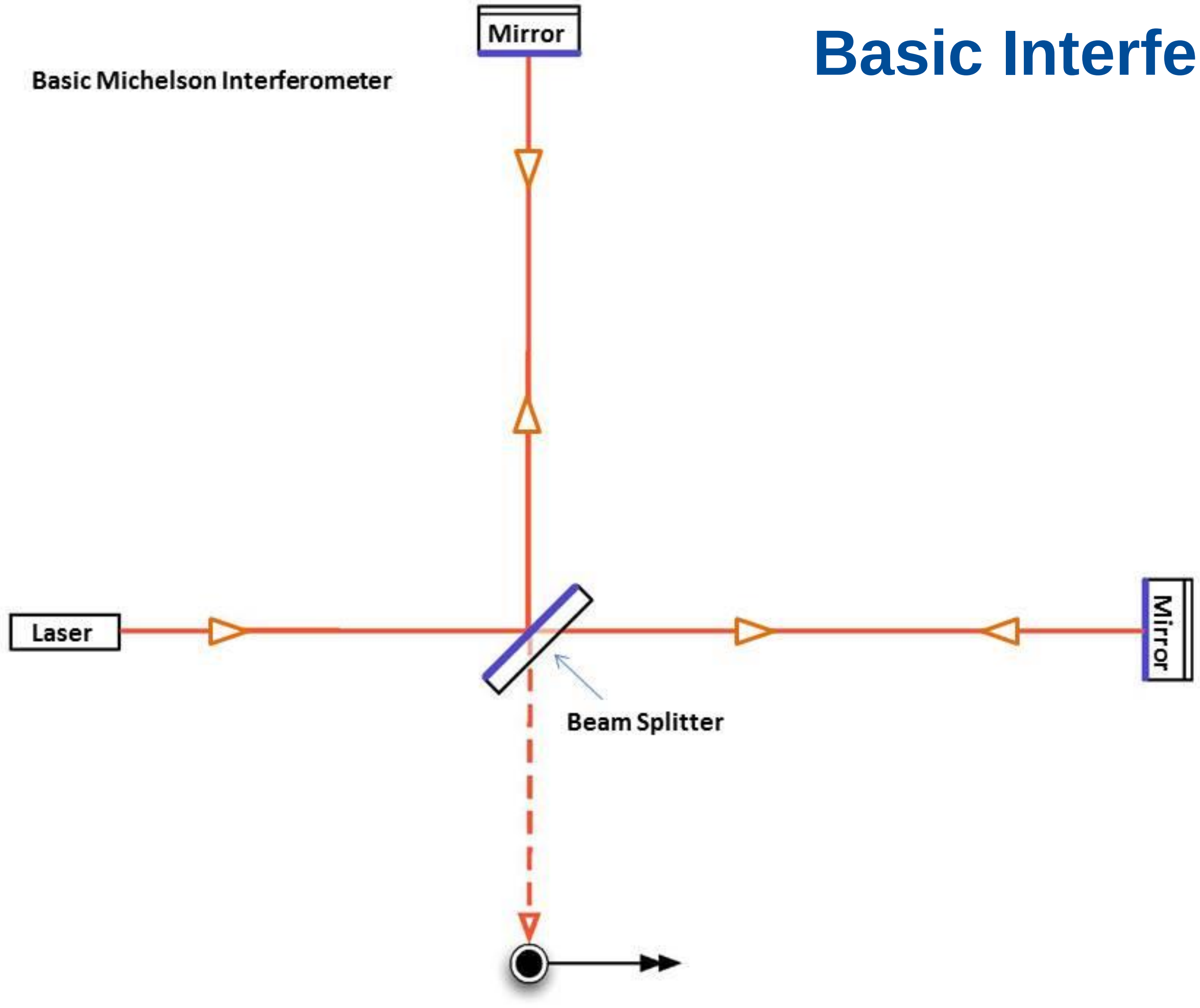
- This introduces a signal in the sidebands of an interferometer of length L as a PSD with peak level, peak frequency, width:

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

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

- 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.

Basic Interferometer



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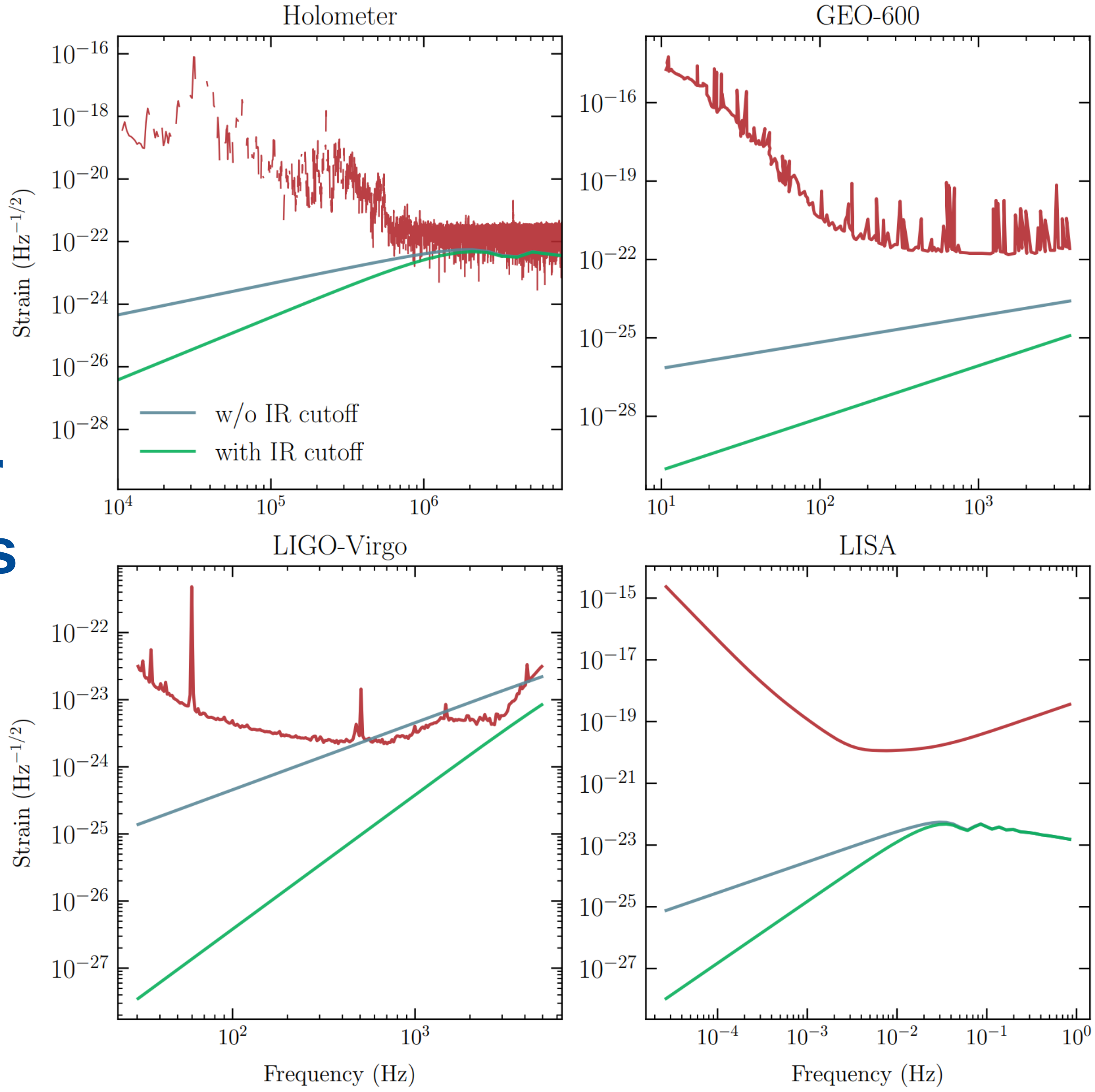
Basic Interferometer Measurements



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Signal/Noise Fringe Readout

Geontropic Signal

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

Standard Quantum Noise

$$\overline{S}_L^{q} = \frac{\hbar c}{2k P_{\mathrm{BS}}} \approx \left(6.2 \cdot 10^{-19} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2 \left(\frac{10\ \mathrm{kW}}{P_{\mathrm{BS}}}\right) \left(\frac{\lambda}{1.5\ \mu\mathrm{m}}\right)$$

$$\mathrm{SNR}^2_{\mathrm{fringe}} = \int_0^T \int_0^\infty \left(\frac{S_L^{\phi}(f)}{S_L^{q}(f)}\right)^2 \mathrm{d}f\,\mathrm{d}t \approx T\Delta f \left(\frac{\overline{S}_L^{\phi}}{\overline{S}_L^{q}}\right)^2 ,$$

$$\approx \alpha^2 \left(\frac{T}{160\mathrm{hr}}\right) \left(\frac{P_{\mathrm{BS}}}{10\ \mathrm{kW}}\right)^2 \left(\frac{L}{5\ \mathrm{m}}\right).$$

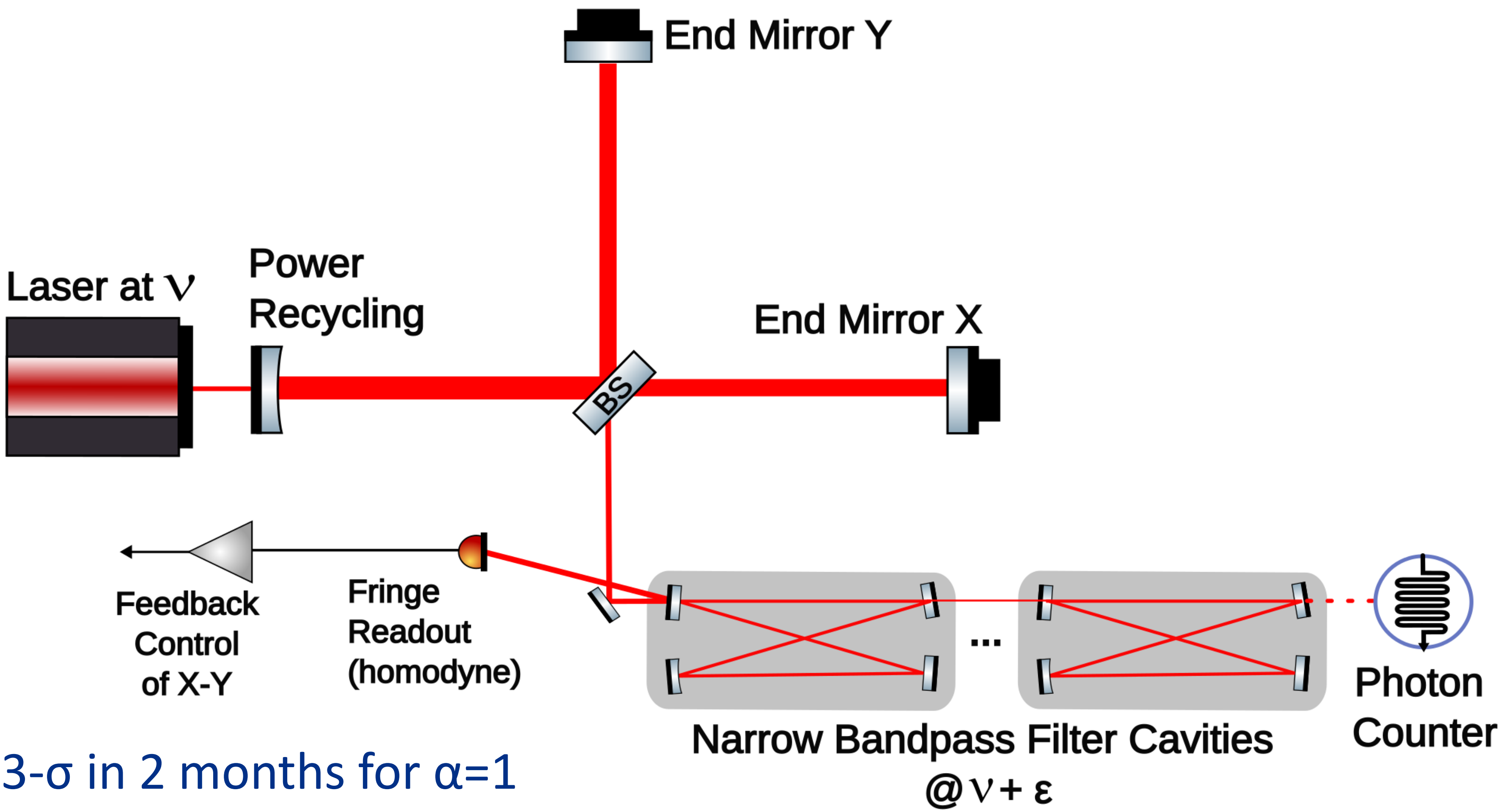
A New Way to Operate IFOs

arXiv:2211.04016: Lee McCuller

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

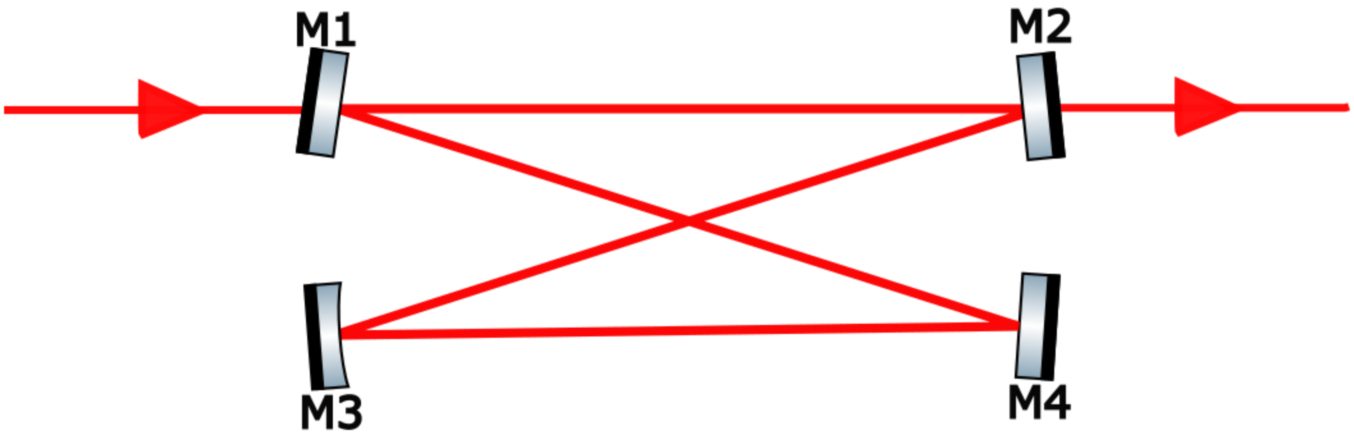
Squeezing: 6dB is the seen in real experiments,
and would accelerate a Holometer/GQuEST type experiment by ~16x (12db, in time).
Goal: Demonstrate a signal search accelerated by >100x using a photon-counting Michelson interferometer

One Interferometer Designed for GQuEST



3-σ in 2 months for α=1

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

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_{BS}	10 kW
Laser wavelength	λ	1.5 μm
Laser frequency	ν	193.4 THz
Nominal filter offset frequency	ϵ_c	15.6 MHz
Filter bandwidth (FWHM)	$\Delta\epsilon$	25 kHz
Twin IFO separation	s	1.5 m
IFO inter-arm angle	Θ	90°
Signal Spectral Density (peak)	$\overline{S}_L^{\phi}$	$\left(3\cdot 10^{-22}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Thermal Noise Spectral Density	$\overline{S}_L^{c}$	$\left(10^{-21}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Shot Noise Spectral Density	S_L^{q}	$\left(6\cdot 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$
Photon Detector Dark Count Rate	$\dot{N}^d$	10^{-3} Hz
Observation time for 5σ test	T	$\mathcal{O}(100)$ hours

Signal/Noise for Counting

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

Quantum Noise → $\overline{S}_L^{q} = \frac{\hbar c}{2kP_{\text{BS}}} \approx \left(6.2\cdot 10^{-19}\ \frac{\text{m}}{\sqrt{\text{Hz}}}\right)^2 \left(\frac{10\ \text{kW}}{P_{\text{BS}}}\right)\left(\frac{\lambda}{1.5\ \mu\text{m}}\right)$

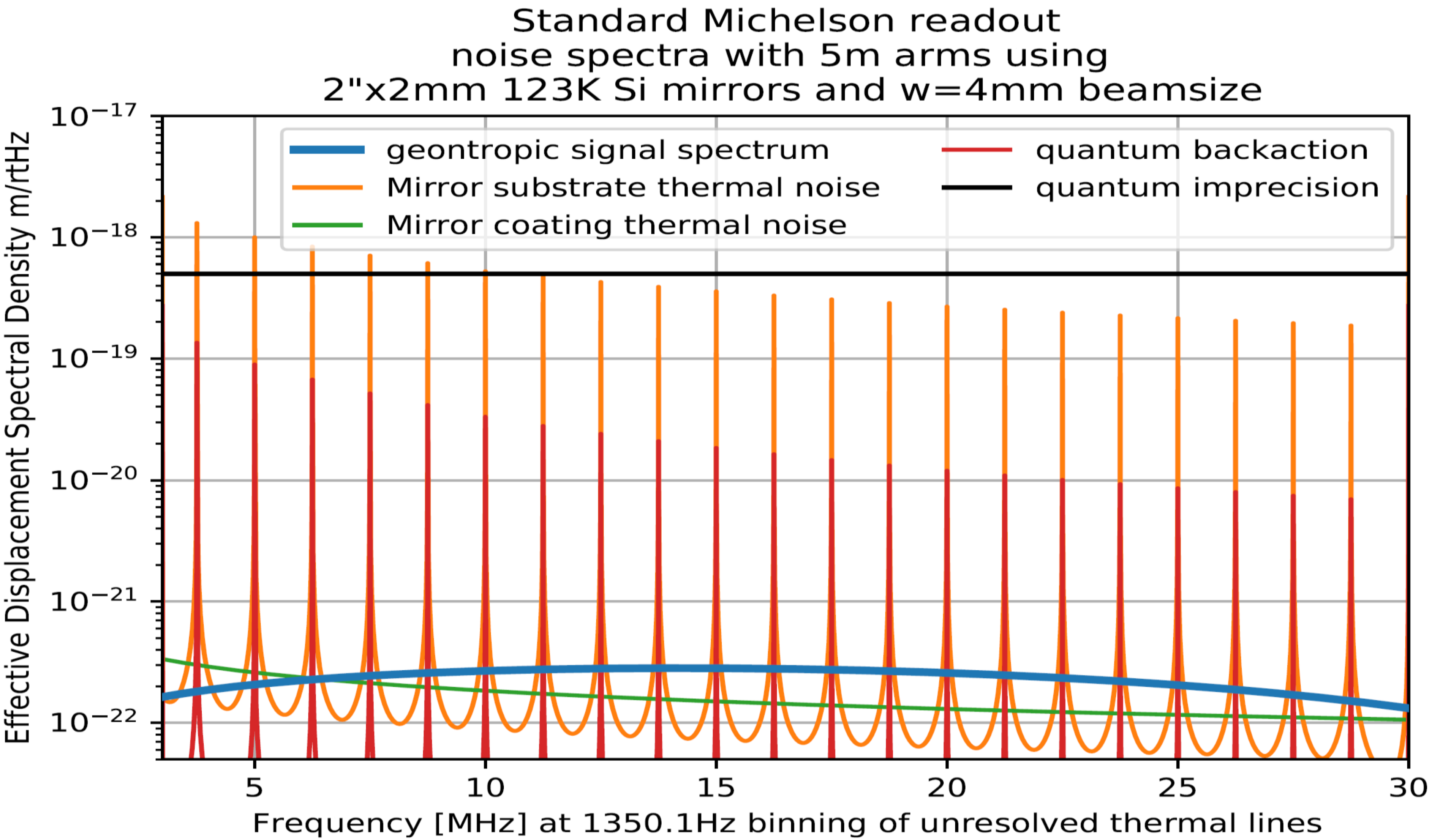
Coating Noise → $\overline{S}_L^{c} = \left(10^{-21}\ \text{m}/\sqrt{\text{Hz}}\right)^2$

$$\text{SNR}^2_{\text{counting}} \approx \frac{T\Delta\epsilon}{4} \frac{\left(\overline{S}_L^{\phi}\right)^2}{S_L^q \overline{S}_L^c}$$

← Noise from c << q

$$\approx \alpha^2 \left(\frac{T}{2.4\ \text{hr}}\right)\left(\frac{P_{\text{BS}}}{10\text{kW}}\right)\left(\frac{L}{5\ \text{m}}\right)^4 \left(\frac{S_L^c(f)}{\overline{S}_L^c}\right)$$

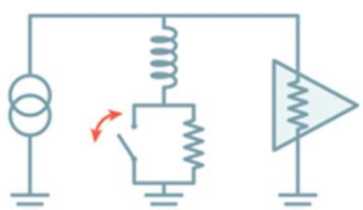
Signal and Noise for a GQuEST IFO

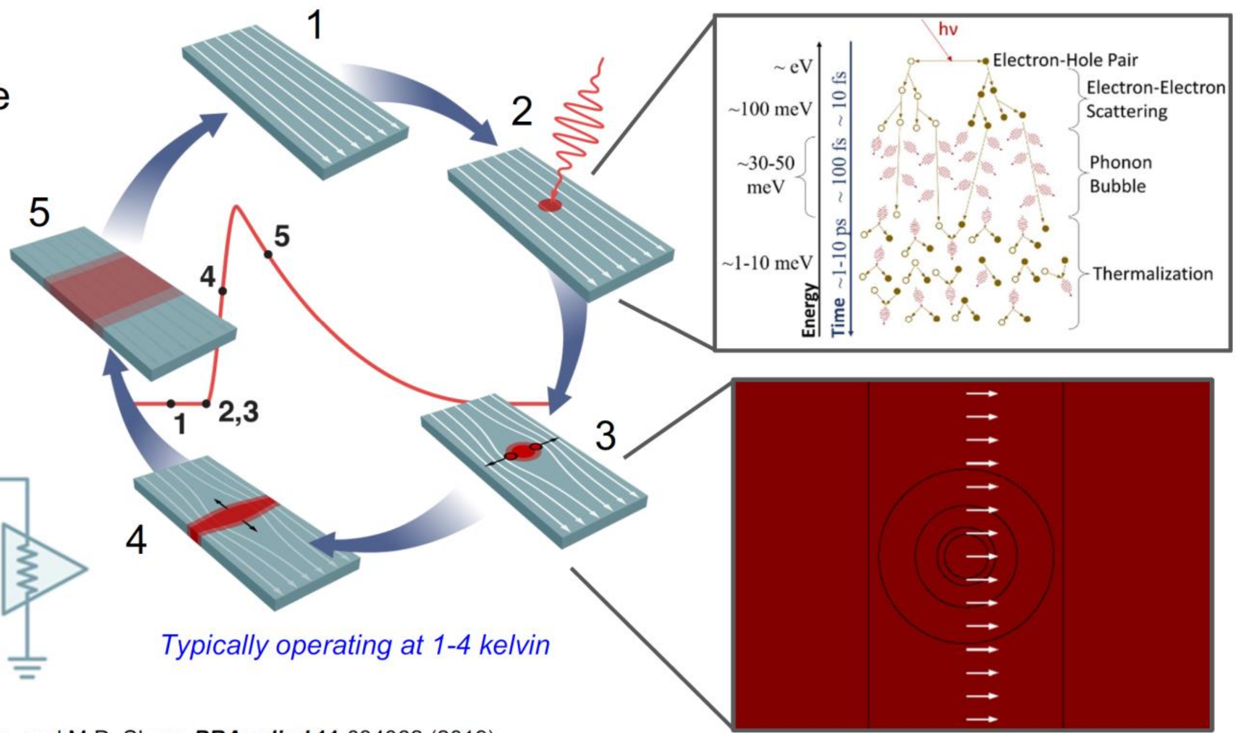


Photon Counter: Boris Korzh @ JPL/Caltech

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***
5. Recovery

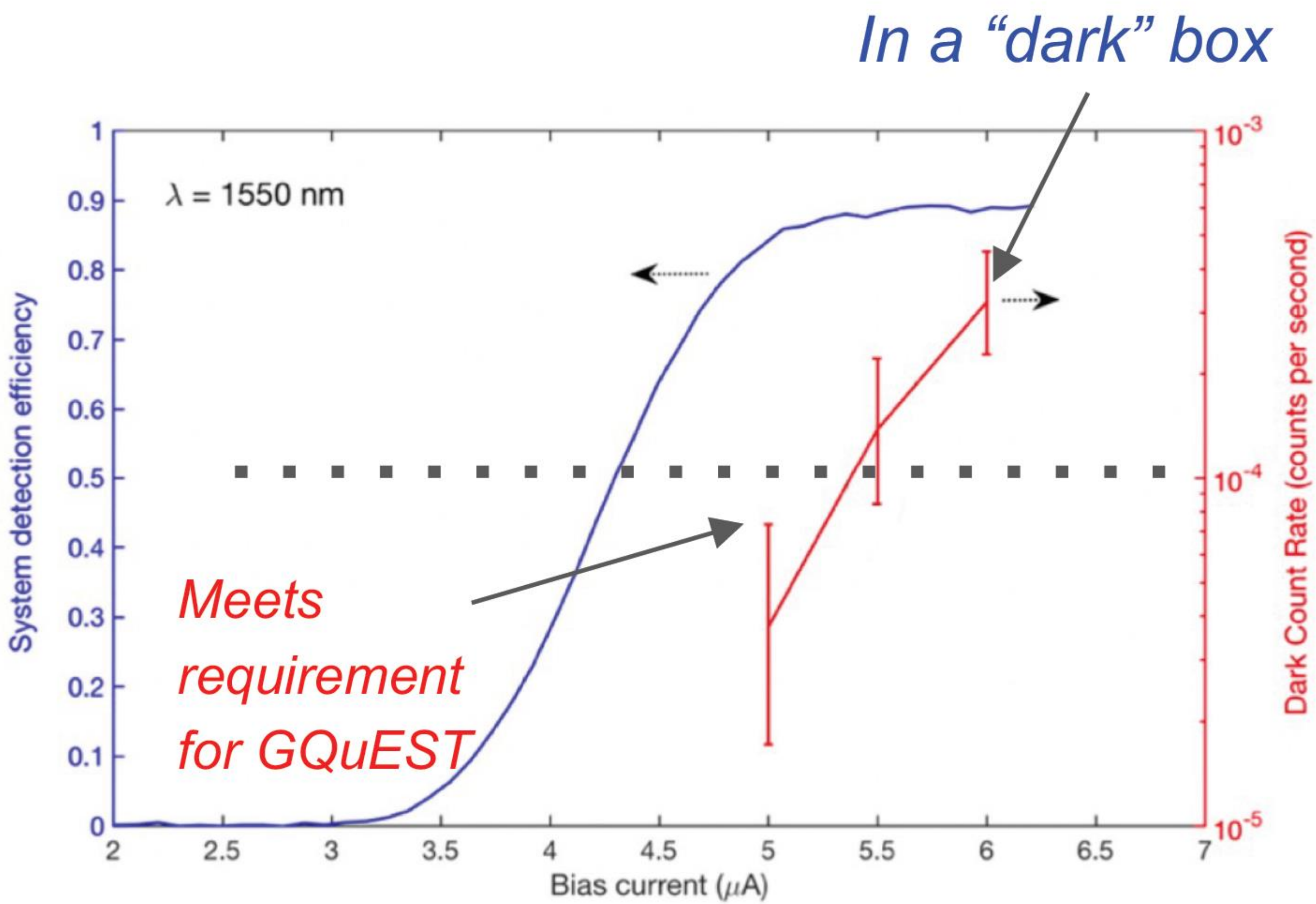




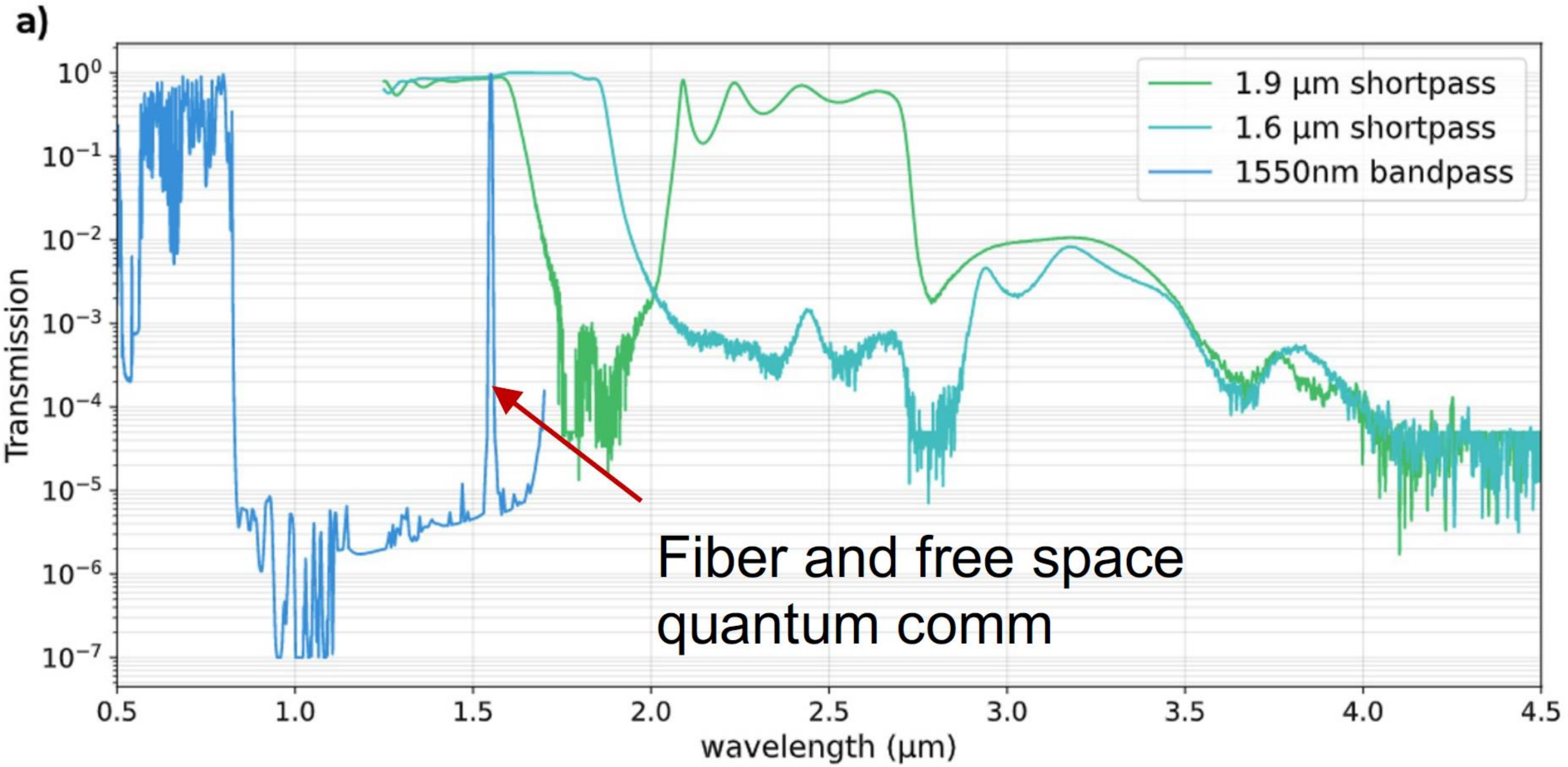
Typically operating at 1-4 kelvin

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)

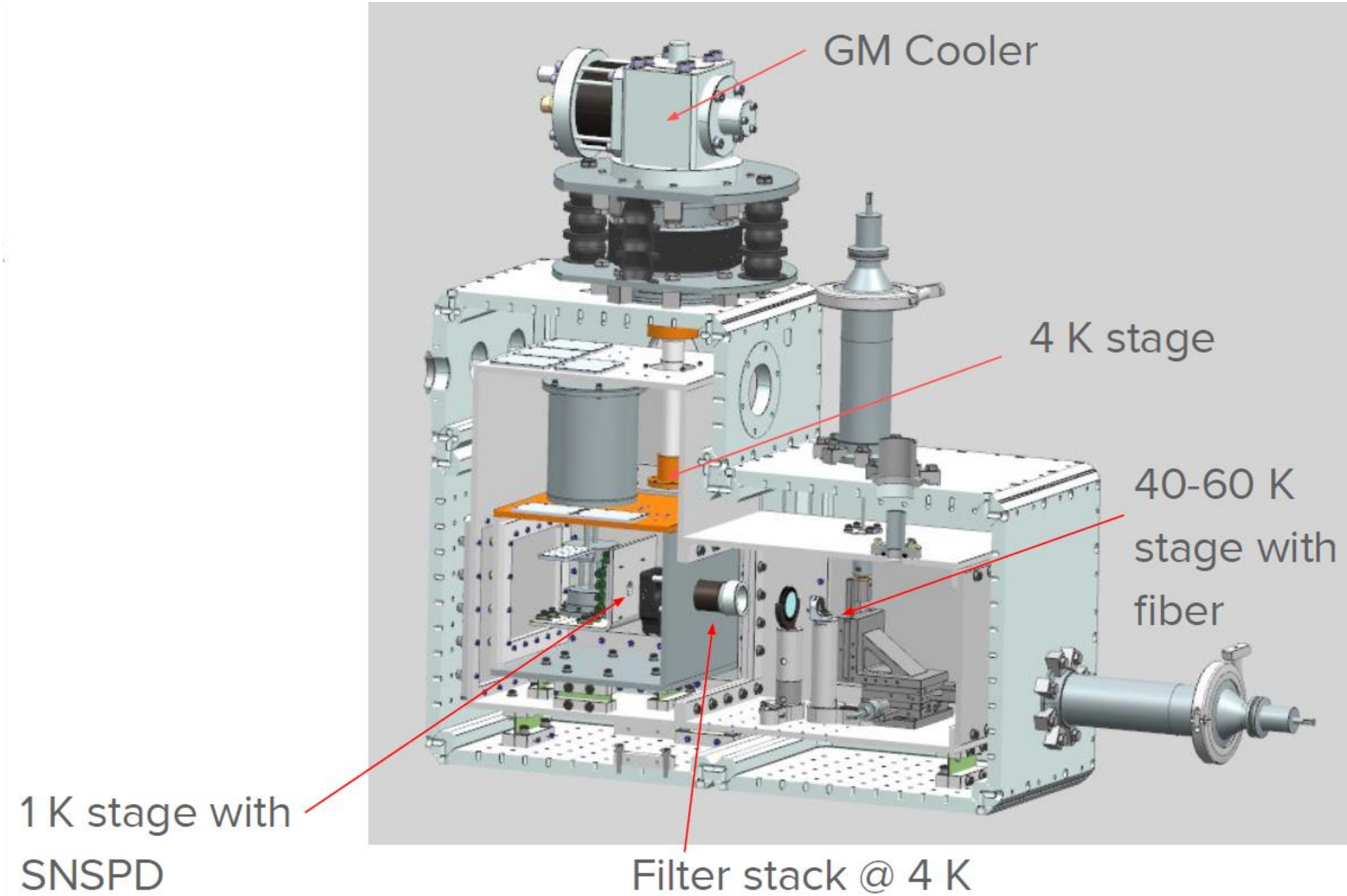
Dark Count Rates of SNSPDs



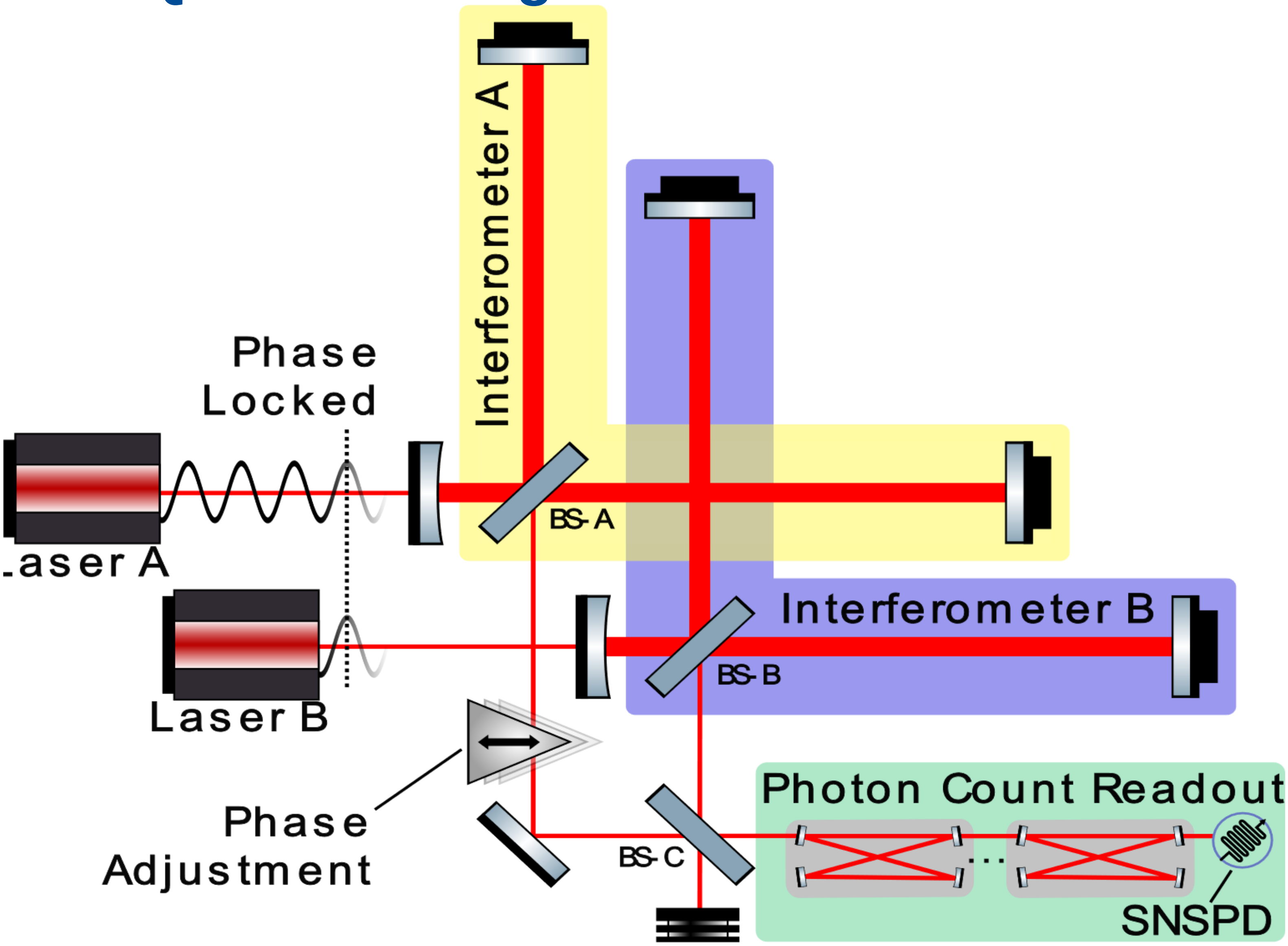
Optically Filter Thermal Photons on SNSPDs



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

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 mm
end mirror diameter	d	25.4mm
end mirror thickness	h	2 mm
end mirror mass	m	24 g
end mirror temperature	T	294 K
end mirror bulk Q	Q	$10^6 \cdot \frac{\Omega/2\pi}{10^7\mathrm{Hz}}$
end mirror substrate material	c-Si	crystalline Si
beamspitter beam size	w	2 mm
beamspitter diameter	d_{BS}	38.1mm
beamspitter thickness	h	2 mm
beamspitter mass	m_{BS}	53 g
beamspitter temperature	T_{BS}	123 K
beamspitter bulk Q	Q	$10^6 \cdot \frac{\Omega/2\pi}{10^7\mathrm{Hz}}$
beamsplitter substrate material	c-Si	crystaline Si
c-Si density	ρ	2329 kg/m^3
c-Si thermal conductivity	κ	739 W/m/K
c-Si index of refraction at λ	n	3.48
c-Si $\partial n/\partial T$ at 123K and λ	β	10^{-4} /K
c-Si Young's modulus	Y	156 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 λ	Λ_{SI}	$2 \cdot 10^{-4}$ /m
Fractional BS Coating Power Absorption	$\Lambda_{\mathrm{Coatings}}$	3 ppm
Fractional BS Bulk Power Absorption	Λ_{Bulk}	0.4 ppm
Coating Material	Ti:TaO2	?
Coating Thickness	t_c	[SV: CHECK] 40 μm
Coating Stress	σ	0.5 GPa

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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.

GQuEST