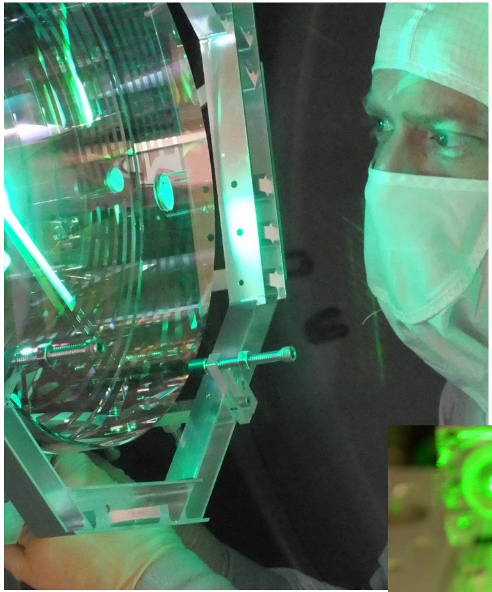
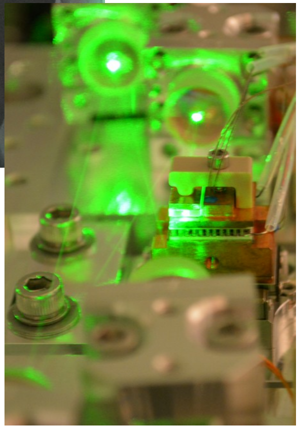
Thinking outside the quadratures for GQuEST



How strongly can we probe mirrors/spacetime?

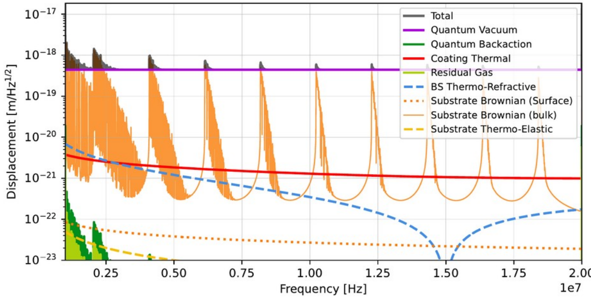
Is squeezed light the best we can do?



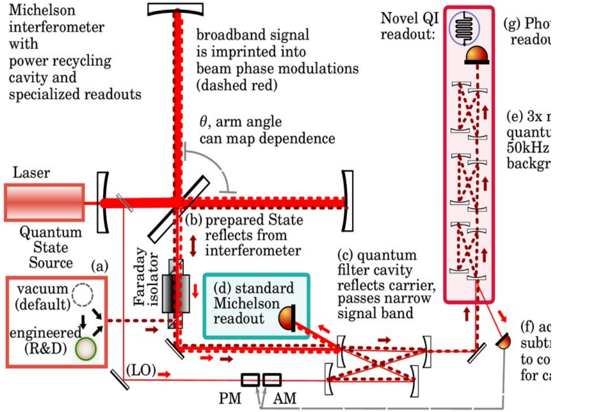
Lee McCuller

Caltech

March LVK 2023



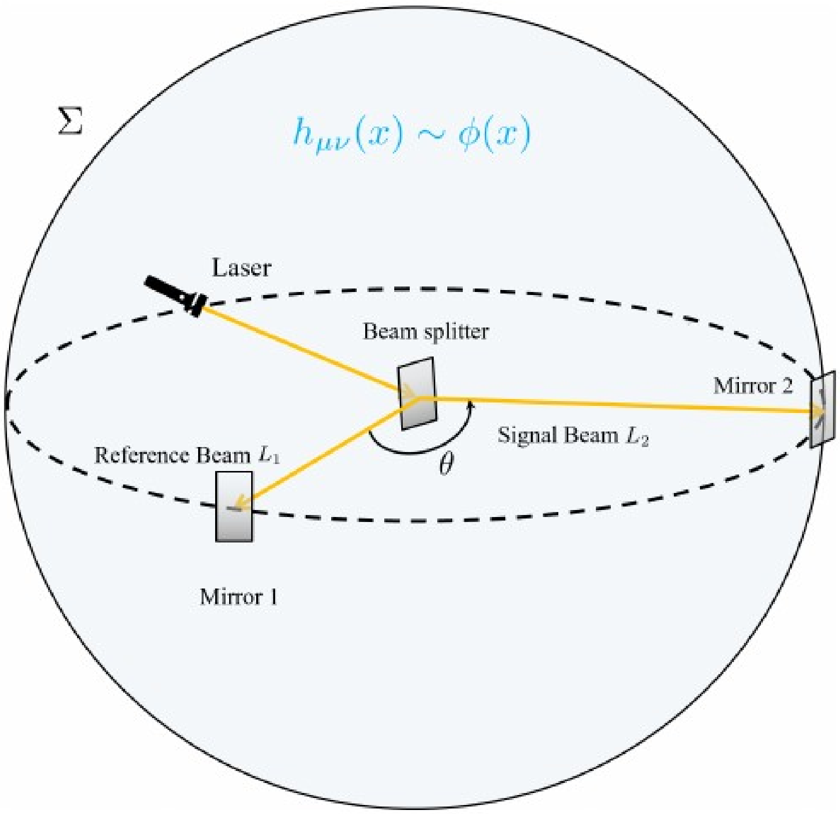
How small can we make classical noise?



Shouldn't we always be rewarded for making a better instrument?

University-Scale Experimentation

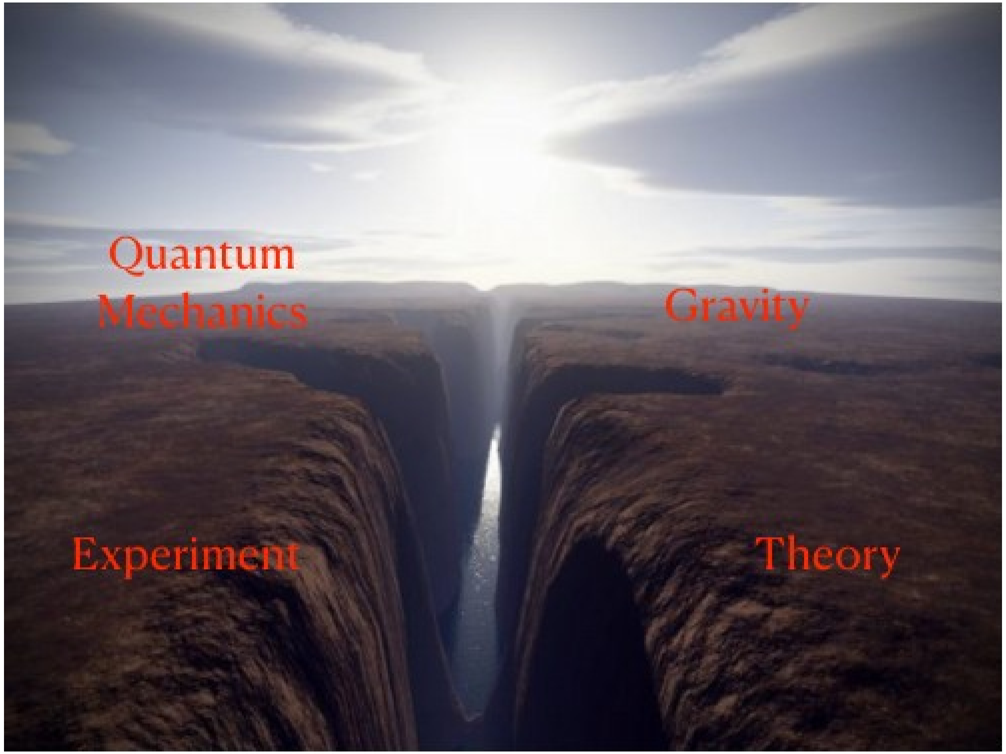
- Achieving quantum-noise limited sensitivity is tough
  - Acoustic isolation takes a lot of engineering
- High Frequency signals are ideal when the physics supports them
  - Many efforts are center on low-mass dark matter
- The best experiments test a model, a theory.
  - Ideally, either test result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

Extreme Physics in "mundane" space

- Mapping black hole quantum gravity to flat spacetime

"

BLACK HOLE – (EMPTY!) CAUSAL DIAMOND DICTIONARY

Black Hole	*Causal Diamond*
➤ Horizon	➤ Horizon Defined by Null Rays
➤ Black Hole Temperature	➤ Size of Causal Diamond $T \sim 1/L$
➤ Black Hole Mass	➤ Modular Fluctuation $M = \frac{1}{2\pi L}\Big(K - \langle K \rangle\Big)$
➤ Entropy	➤ Entanglement Entropy $S = \langle K \rangle = \frac{A}{4G}$

Banks, KZ 2108.04806

"

Extreme Physics in “mundane” space

“

- As long as we are interested in only the part of spacetime inside the causal diamond, the metric in some common spacetimes can be mapped to “topological black hole”

”

$$ds^2 = dudv + dy^2$$

$$ds^2 = -f(R)dT^2 + \frac{dR^2}{f(R)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$f(R) = 1 - \frac{R}{L} + 2\Phi$$

- Schwarzschild metric can describe flat spacetime

E. Verlinde, KZ 1902.08207
E. Verlinde, KZ 1911.02018

Prediction of an 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 <u>stochastic background</u>

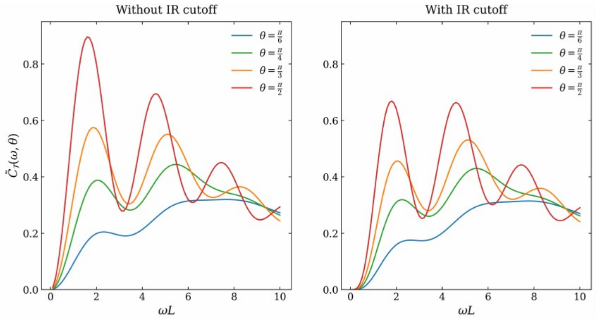
Interferometer Response to Geontropic Fluctuations

Dongjun Li,[1,2,*] Vincent S. H. Lee,[1,†] Yanbei Chen,[2,‡] and Kathryn M. Zurek[1,§]

[1] *Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*

[2] *Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, CA 91125, USA*

(Dated: September 19, 2022)



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

$$\phi(x) = l_p \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{\sqrt{2\omega(\mathbf{p})}} \left(a_{\mathbf{p}} e^{ip\cdot x} + a^\dagger_{\mathbf{p}} e^{-ip\cdot x}\right)\,,$$

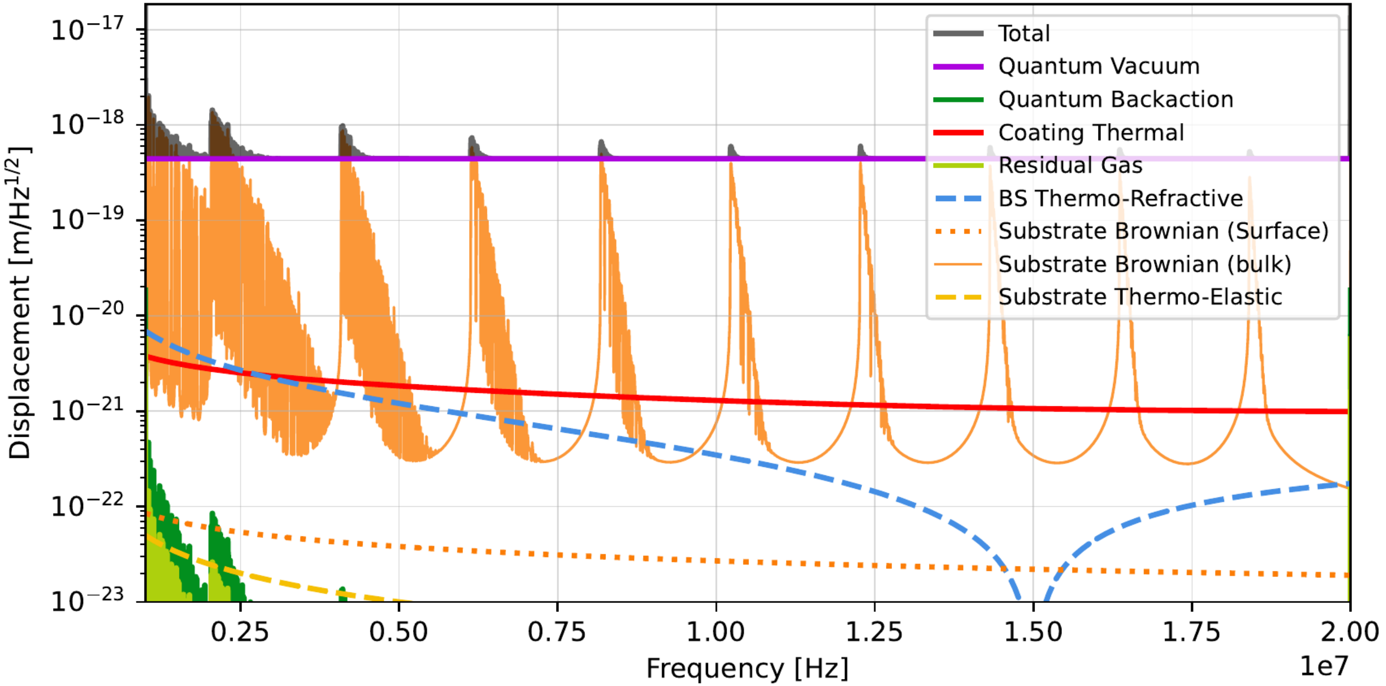
$$\mathrm{Tr}\left(\rho_{\rm pix} a^\dagger_{\mathbf{p}_1} a_{\mathbf{p}_2}\right) = (2\pi)^3 \sigma_{\rm pix}(\mathbf{p}_1)\delta^{(3)}(\mathbf{p}_1 - \mathbf{p}_2)$$

$$\sigma_{\rm pix}(\mathbf{p}) = \frac{a}{l_p \omega(\mathbf{p})}\,,$$

(Minimal set of equations to build the phenomenology)

GQuEST experiment:

Gravity from Quantum Entanglement of Space-Time



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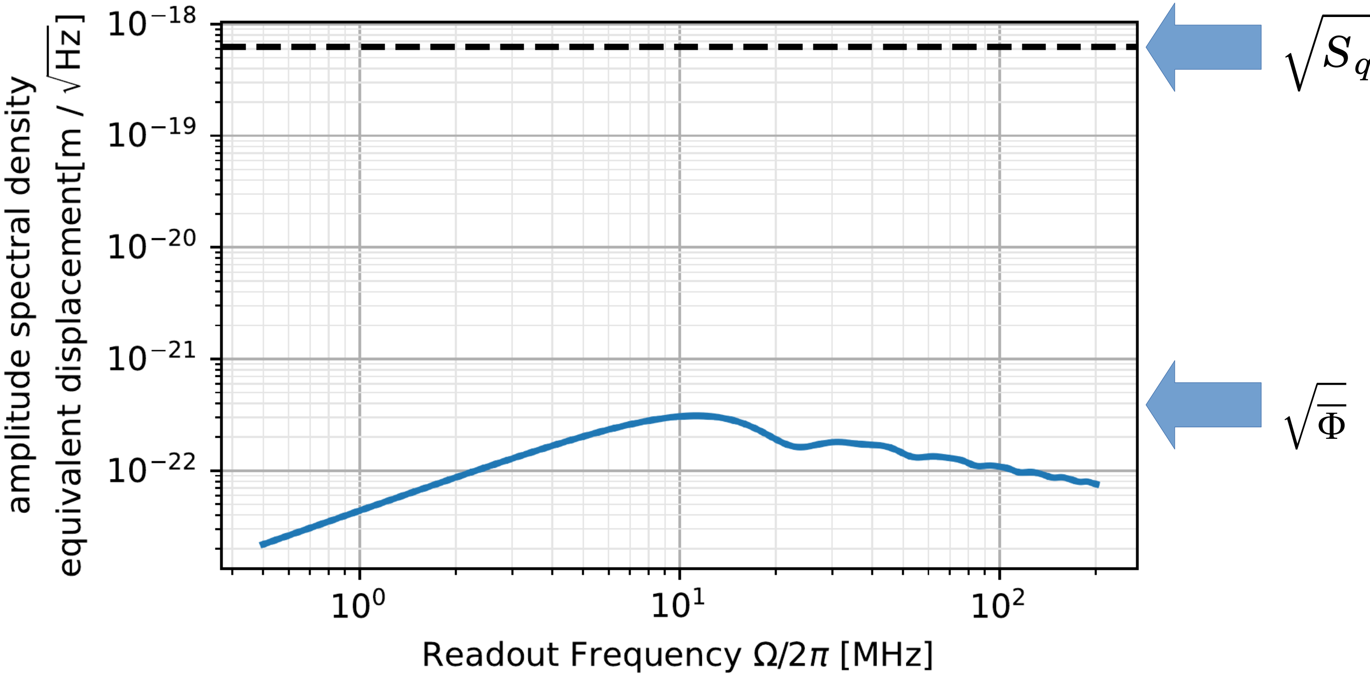
A Tabletop Stochastic Search

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



$$S_\phi \equiv \alpha\Phi(\Omega)$$

$$\overline{\Phi} \equiv \max_{\Omega<\infty} \Phi(\Omega)$$

$$\overline{\Phi} \approx \left(3\cdot 10^{-22}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2\left(\frac{L}{5\mathrm{m}}\right)^2 \qquad S_q \approx \left(5\cdot 10^{-19}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)^2\left(\frac{10\mathrm{kW}}{P_{\mathrm{bs}}}\right) \qquad N = \Delta T\Delta F = \frac{S_q^2}{\alpha^2\overline{\Phi}^2} \approx 10^{13}$$

A Tabletop Stochastic Search

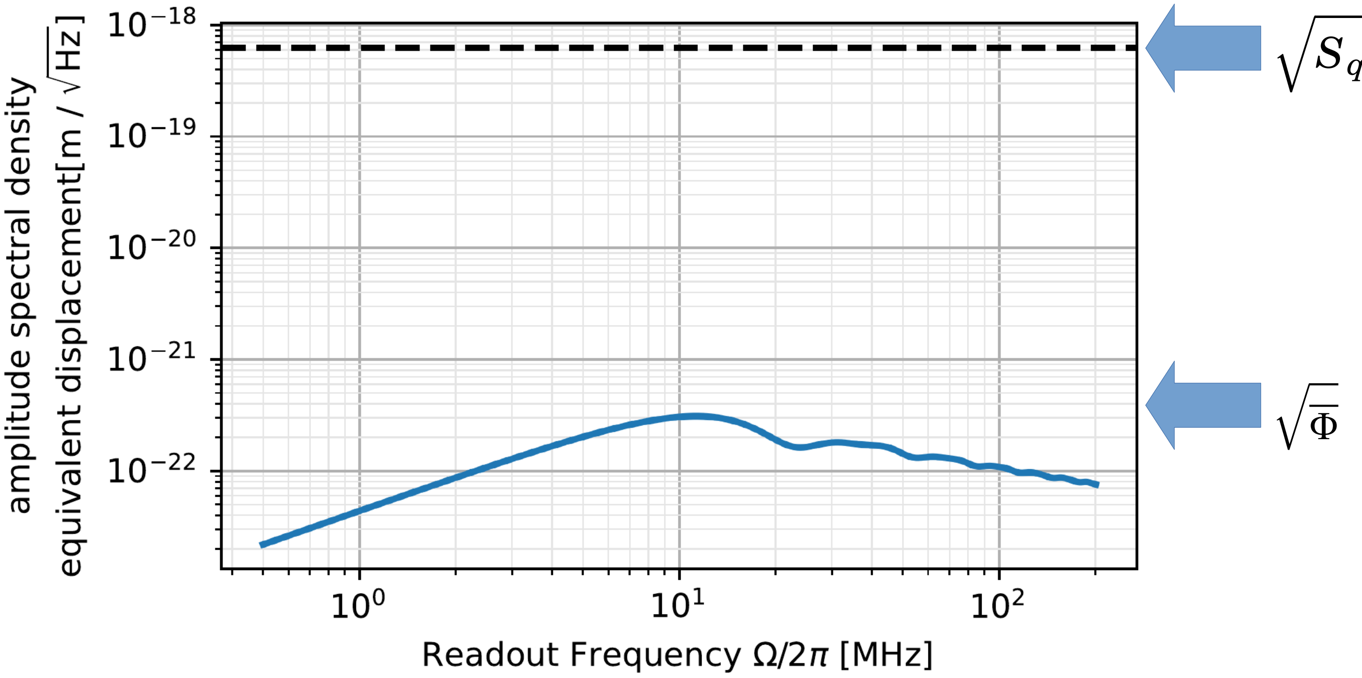
Two Interferometer
Cross Correlation…!

$$N = \Delta T \Delta F = \frac{S_q^2}{\alpha^2 \overline{\Phi}^2} \approx 10^{13}$$

$$\Delta T_{1\sigma} \approx 185\mathrm{Hr}$$

$$S_\phi \equiv \alpha \Phi(\Omega)$$

$$\overline{\Phi} \equiv \max_{\Omega<\infty} \Phi(\Omega)$$



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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)*

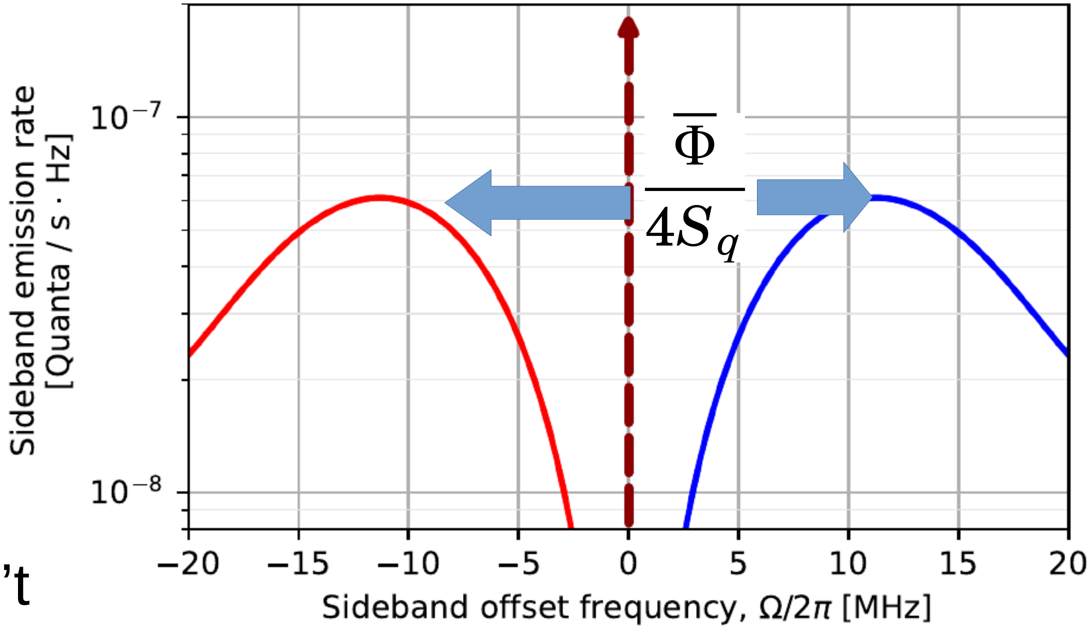
different observable, different statistics

McCuller, arXiv:2211.04016

A Tabletop Particle Search

So… lets view this
as a particle detector

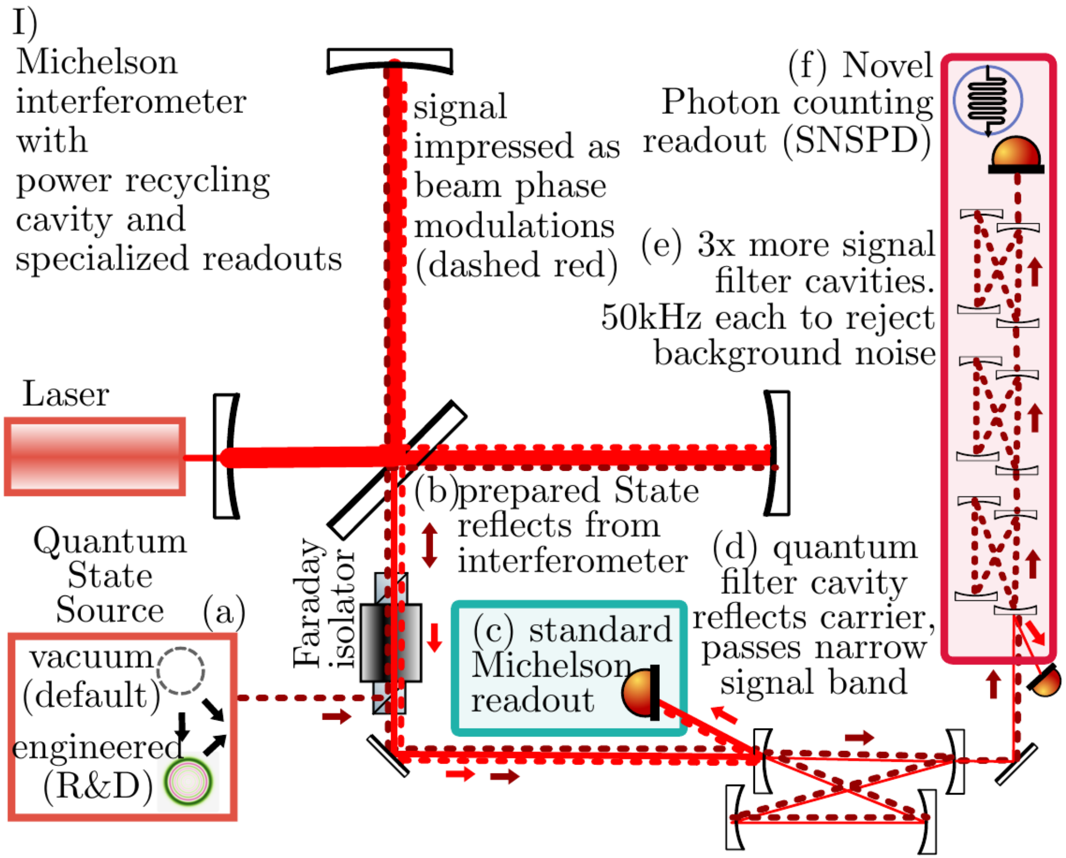
- 1e-7 photons/(s Hz) emitted (spectral flux-density)
- over 10MHz (1e7 Hz) signal bandwidth
- Should take <u>1second</u> for 1σ by Poisson statistics
  - Shot noise quantum limit isn't so fundamental for this search



McCuller, arXiv:2211.04016

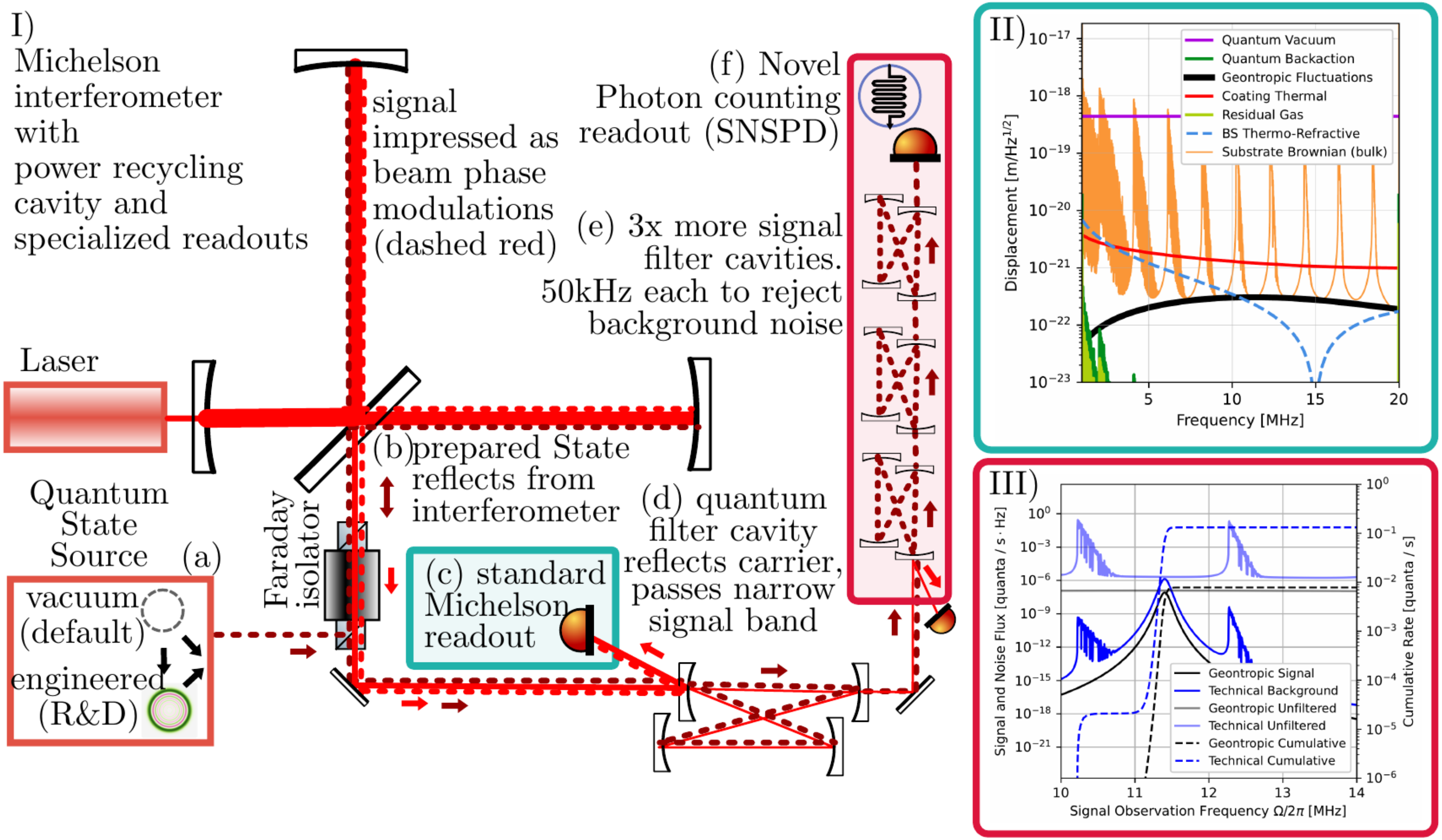
The GQuEST Realization

- 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 ~240db
- New interferometer for Raman/Brillouin spectroscopy of <u>spacetime</u>



McCuller, arXiv:2211.04016

50kHz Photopower Integration



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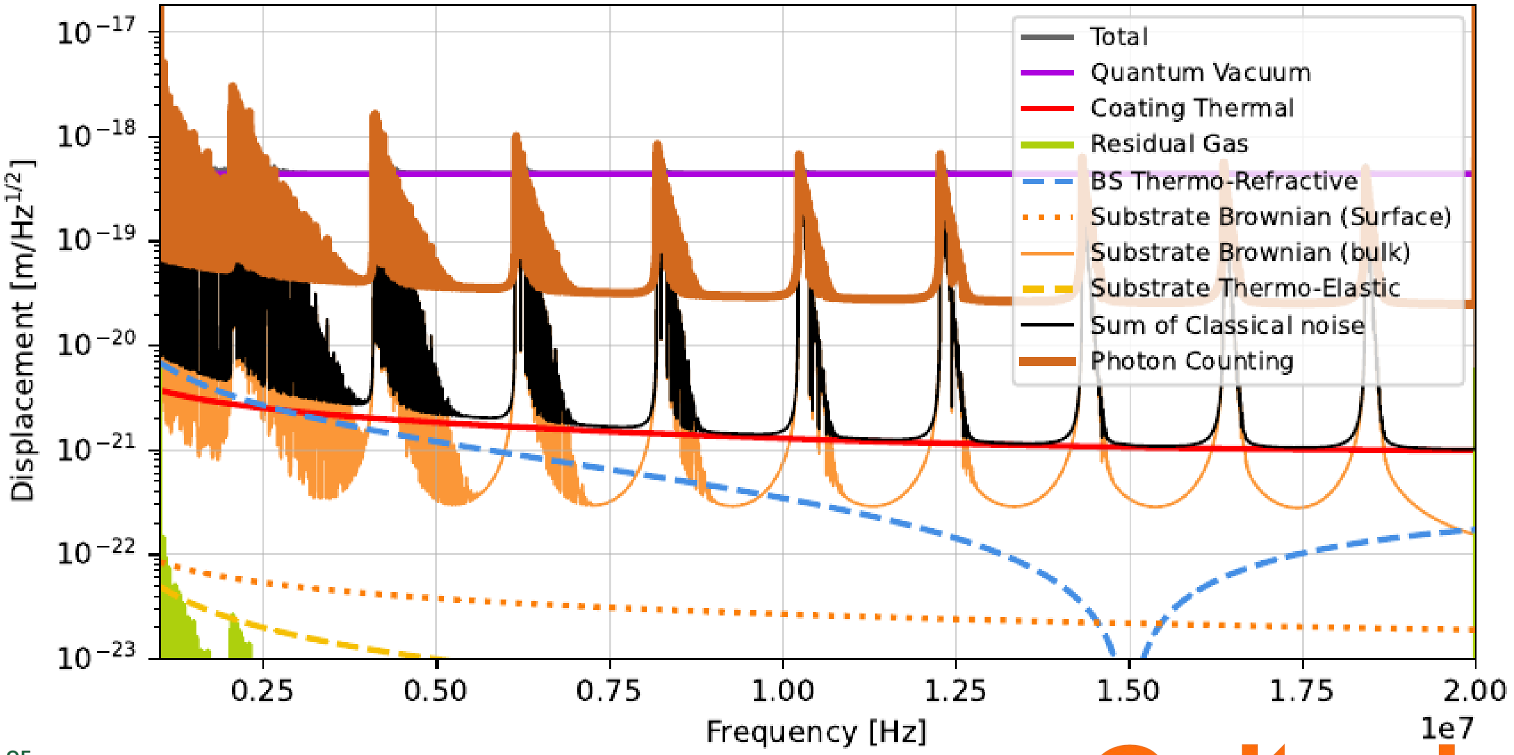

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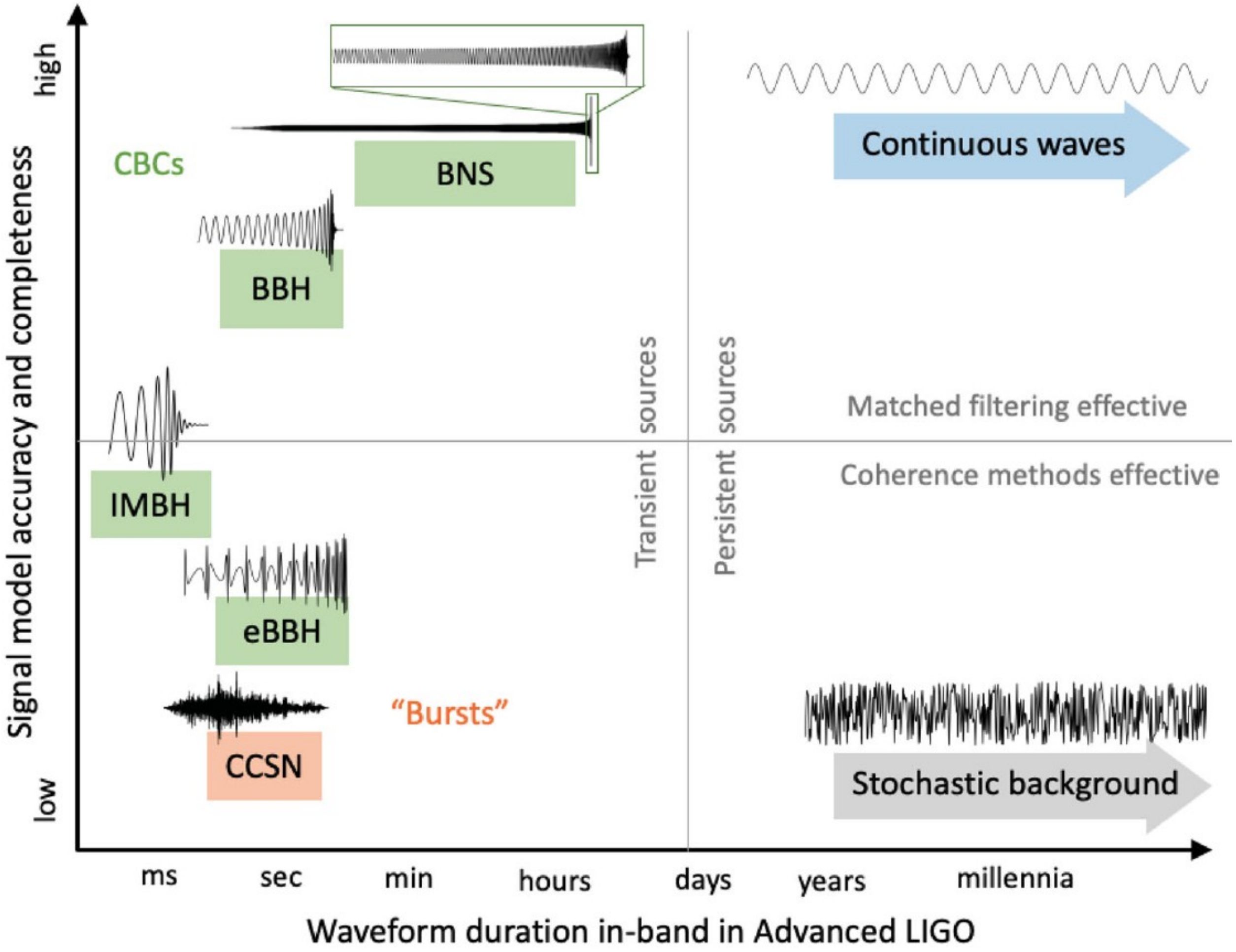
Waveforms and tunings

J. McIver and D. H. Shoemaker,
“Discovering gravitational waves with Advanced LIGO,”
Contemporary Physics, vol. 61, no. 4, pp. 229–255, Oct. 2020,
doi: 10.1080/00107514.2021.1946264.

- Science Cases optimize over both instrumentation and data analysis
- “Coherence methods” search for signal power, rather than phase-coherent templates
- Parameter estimation and tests of new physics search for template-deviations



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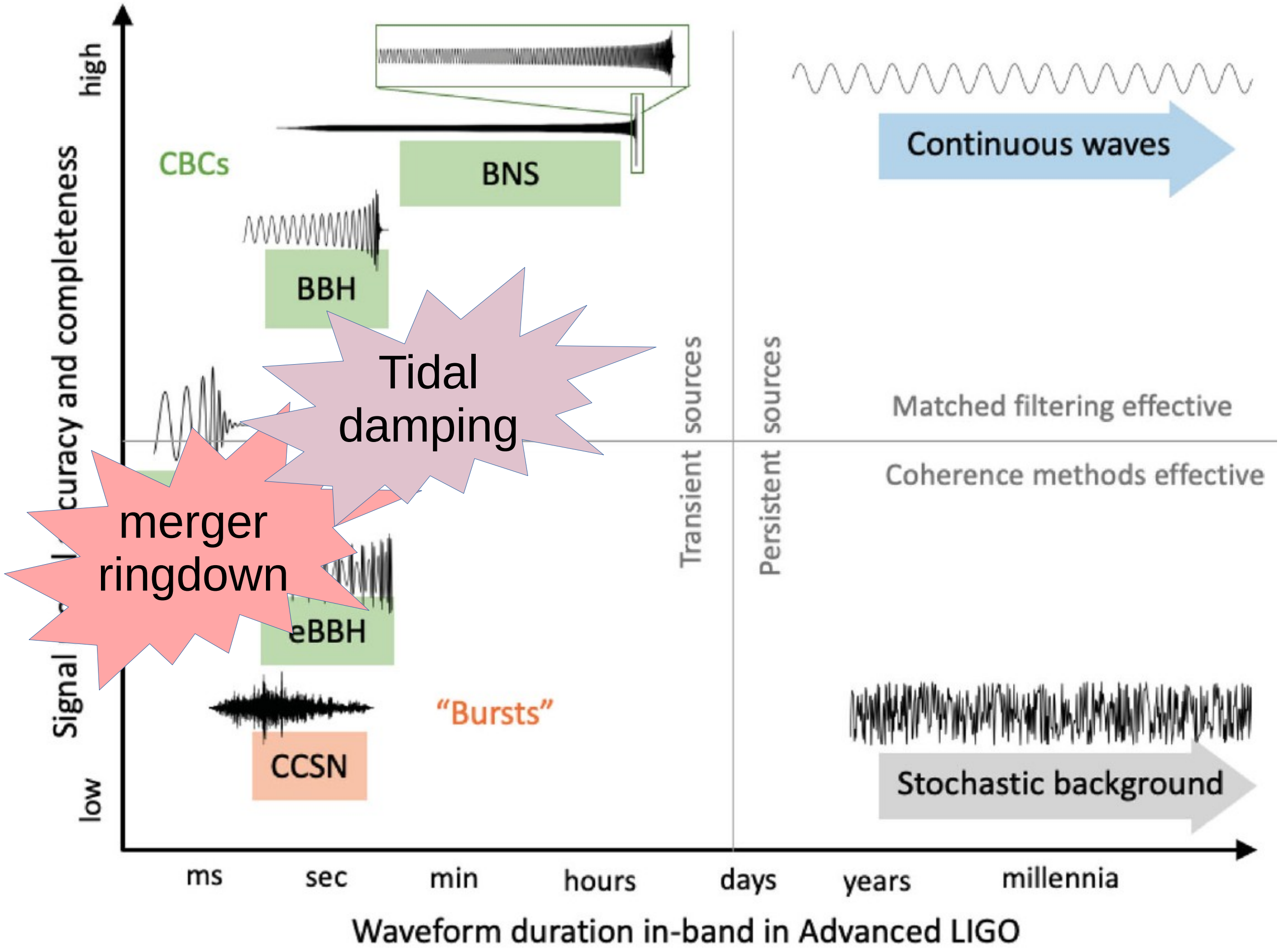

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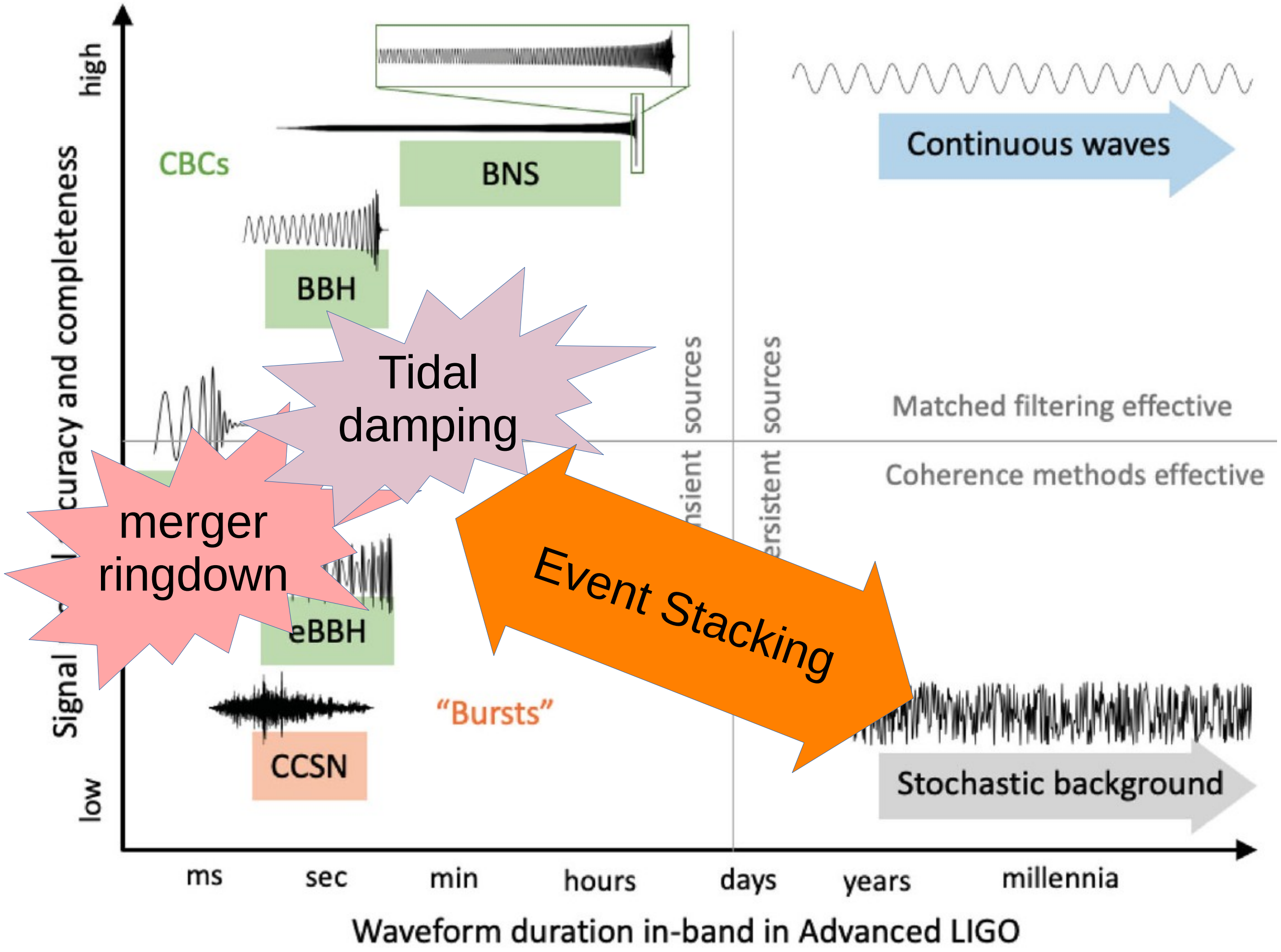
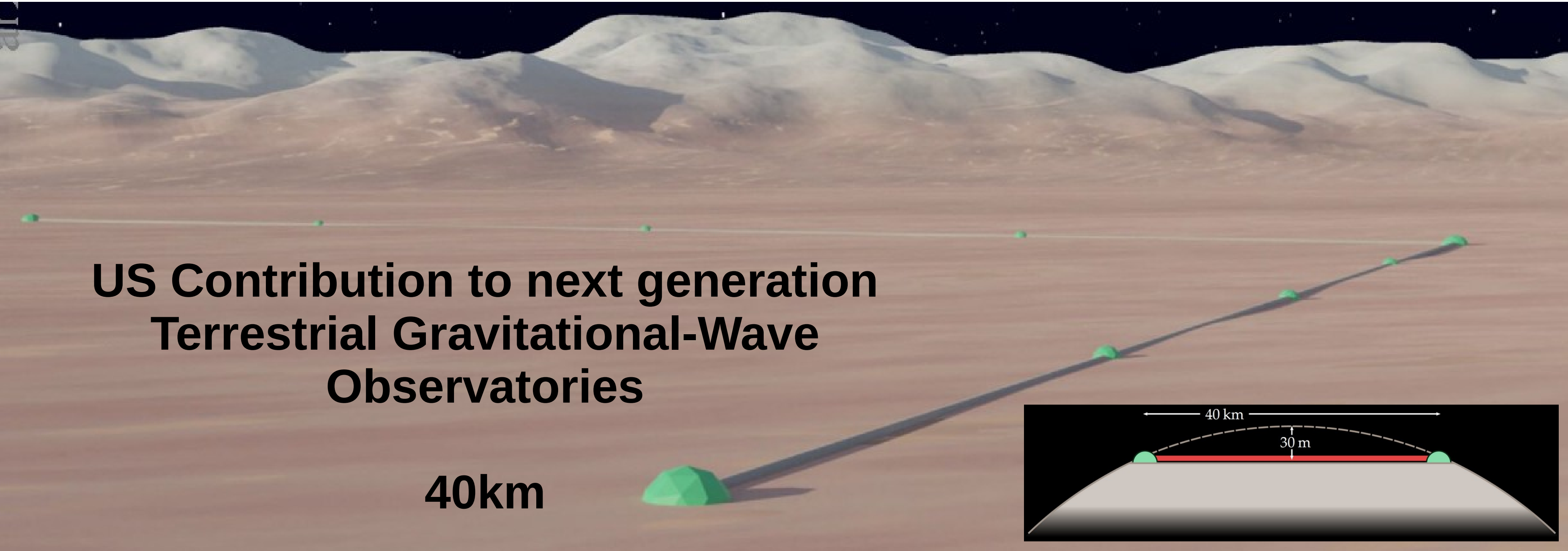


Cosmic Explorer

as a Quantum Frontier Experiment



US Contribution to next generation Terrestrial Gravitational-Wave Observatories

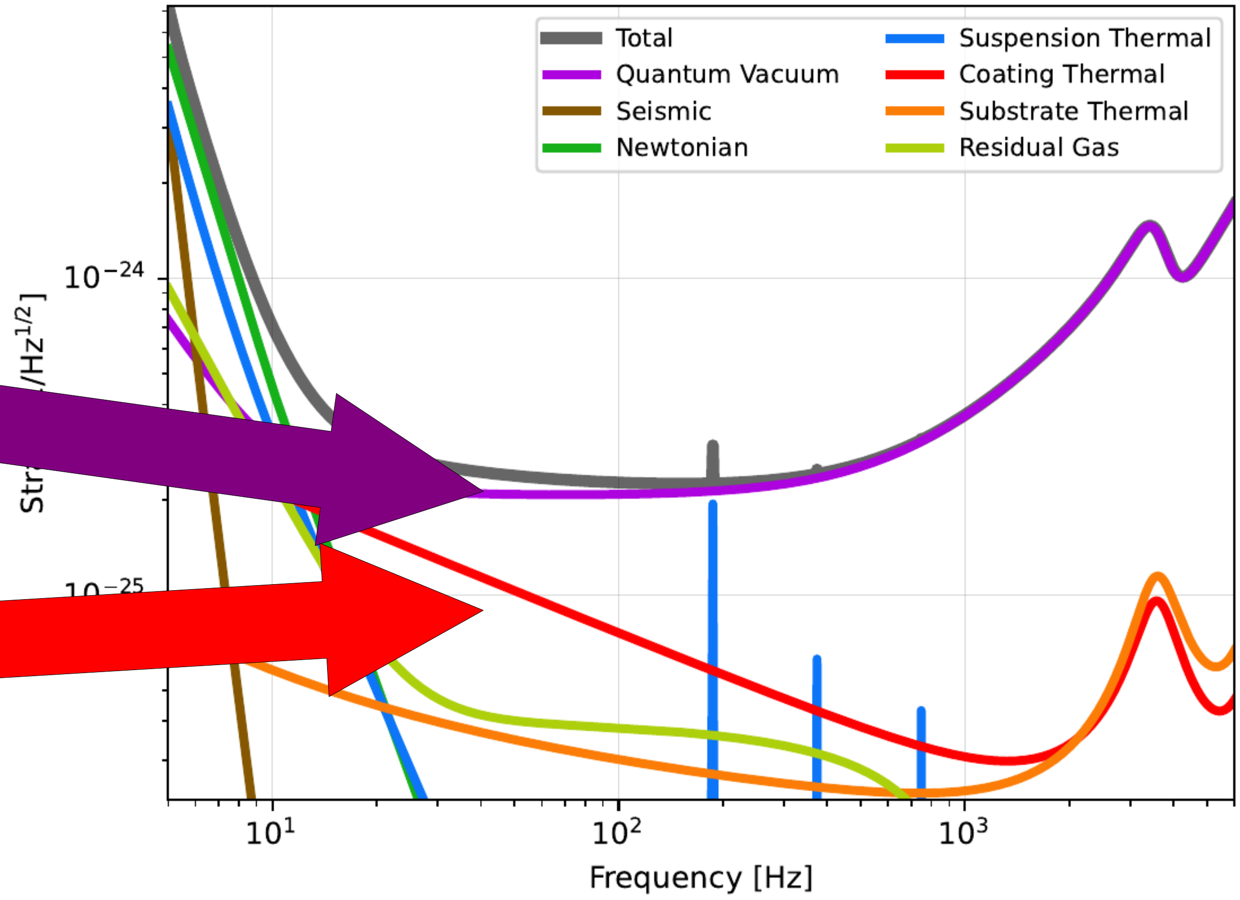
40km

Quantum Noise

Optical gain/bandwidth limit

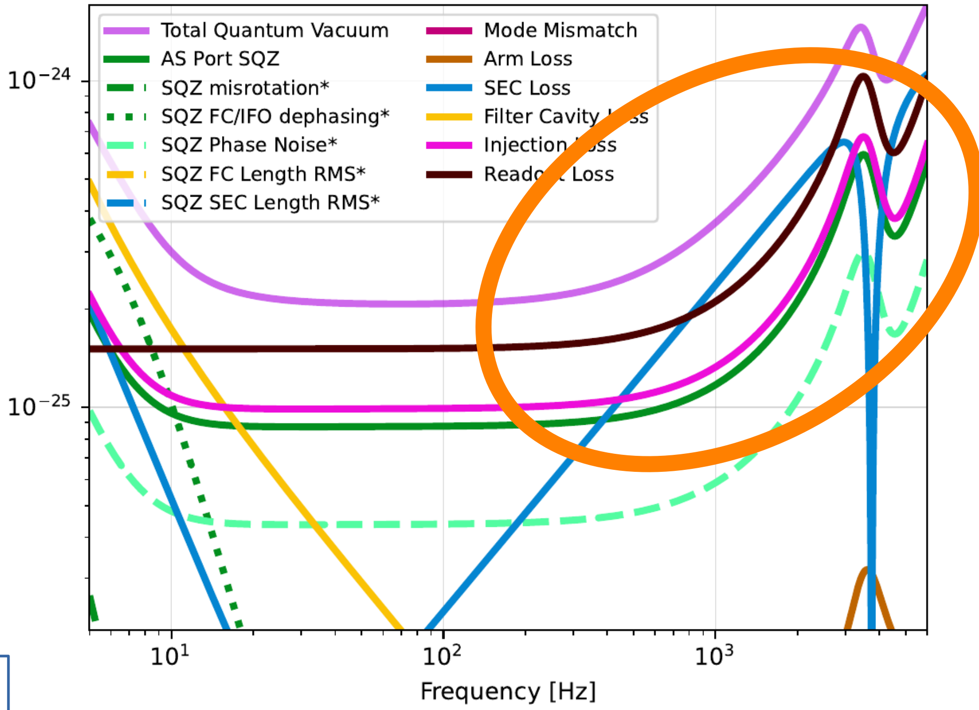
$\propto {}^{1}\!/\!{\sqrt{L}}$

$\propto {}^{1}\!/\!{L^{1.5}}$

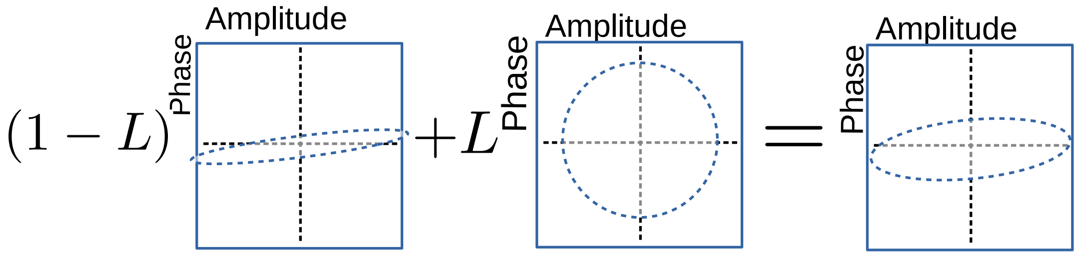


Squeezing Limits

- Lower optical gain is “compensated” by assuming 10db squeezing
- Will be very difficult!
- Intracavity losses causes high-frequency quantum noise

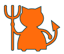


Cosmic-Explorer Quantum Noise budget

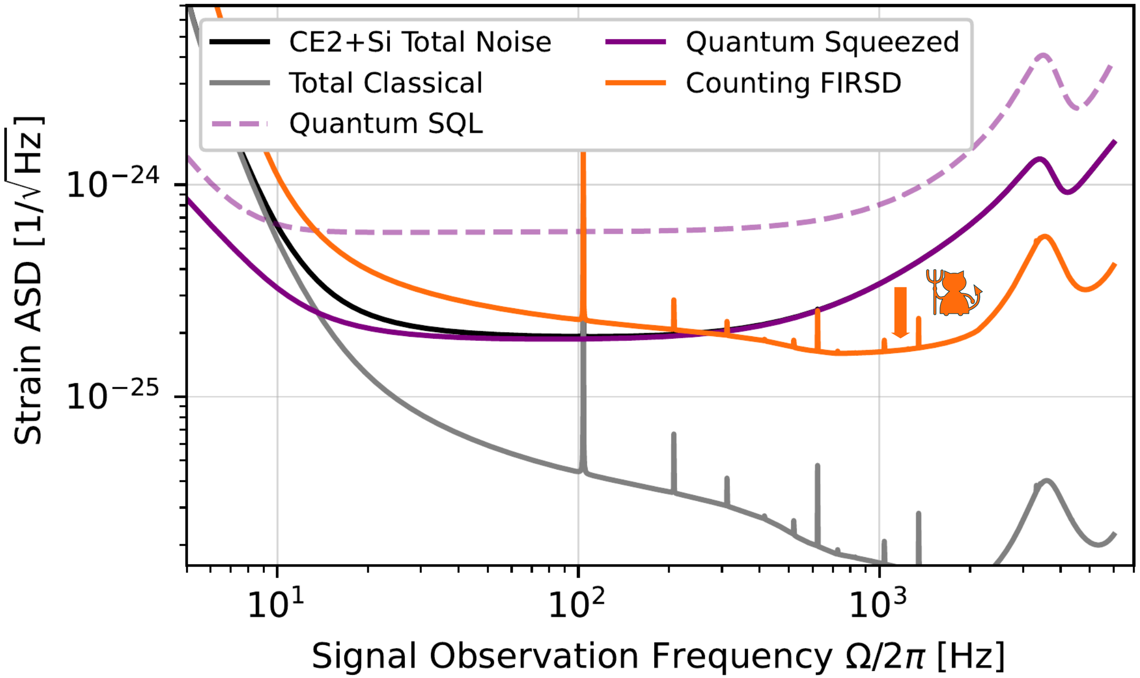


$$(1-L)\begin{bmatrix} e^{-2r} & 0 \\ 0 & e^{2r} \end{bmatrix}\frac{\hbar\omega}{2} + L\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\frac{\hbar\omega}{2} \xrightarrow{r=\infty} \begin{bmatrix} L & 0 \\ 0 & e^{2r} \end{bmatrix}\frac{\hbar\omega}{2}$$

Cosmic Explorer, Photon Counting

- Can create a "*Fisher Information equivalent Power Spectrum*"
- Photon counting is like chi-square tests
  - Must develop optical template matching technology
  - Needs AMO, quantum memories
- Definite caveats! 
  - Faustian bargain with Maxwell's demon (works primarily with "stacked detections")
  - Must further develop science case
- Beats Squeezing
  - does not care about losses.
  - Further quantum enhancement *is yet possible*

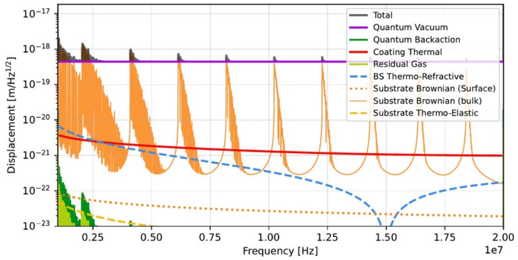
CE2, 2um Voyager Tech. W/ Photon counting



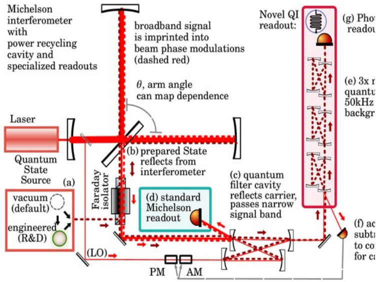
arXiv:2211.04016

Thank You

- We hope to strongly test a model of quantum gravity at Caltech
- GQuEST will change our understanding of the Michelson Interferometer
  - Wave-like detector gains the advantages of HEP particle detectors
  - Spectroscopy of spacetime
  - Yes, it does work with:
    - Signal recycling
    - Cross correlation (of a sort)
    - Quantum enhancement (~4db loss-limit penalty)
- Event search counting hopefully allows further use of the bounty of many at/near threshold GW detections.
  - Develop science case of technique
  - Show feasibility in high power detector



How small can we make classical noise?
Profoundly Small



Shouldn't we always be rewarded for making a better instrument?
Yes, if we try new things

Is squeezed light the best we can do?
We can (in some cases) do better