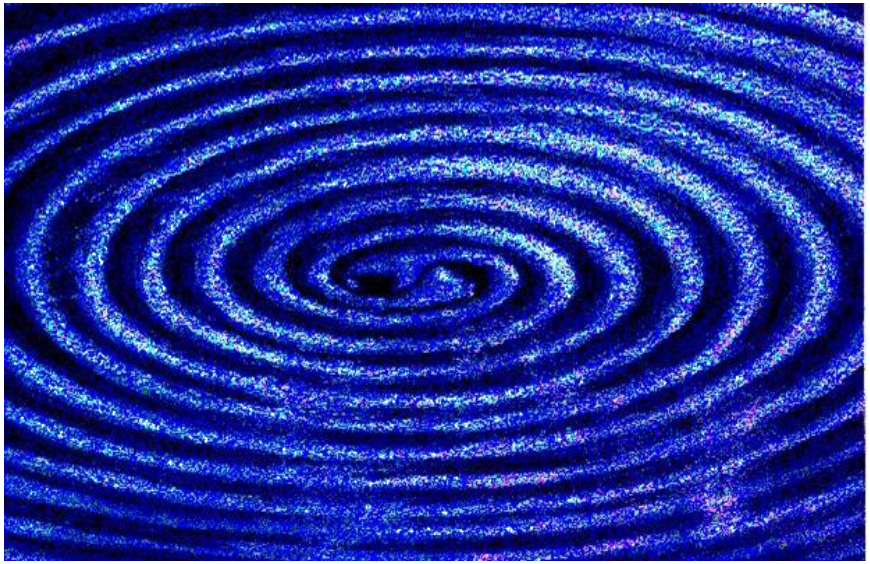
New Low-Frequency GW Detector with Superconducting Instrumentation



Ho Jung Paik
Department of Physics, University of Maryland

GWADW, May 26, 2015

(delivered by Krishna Venkateswara, U Wash)

LIGO-G1500670

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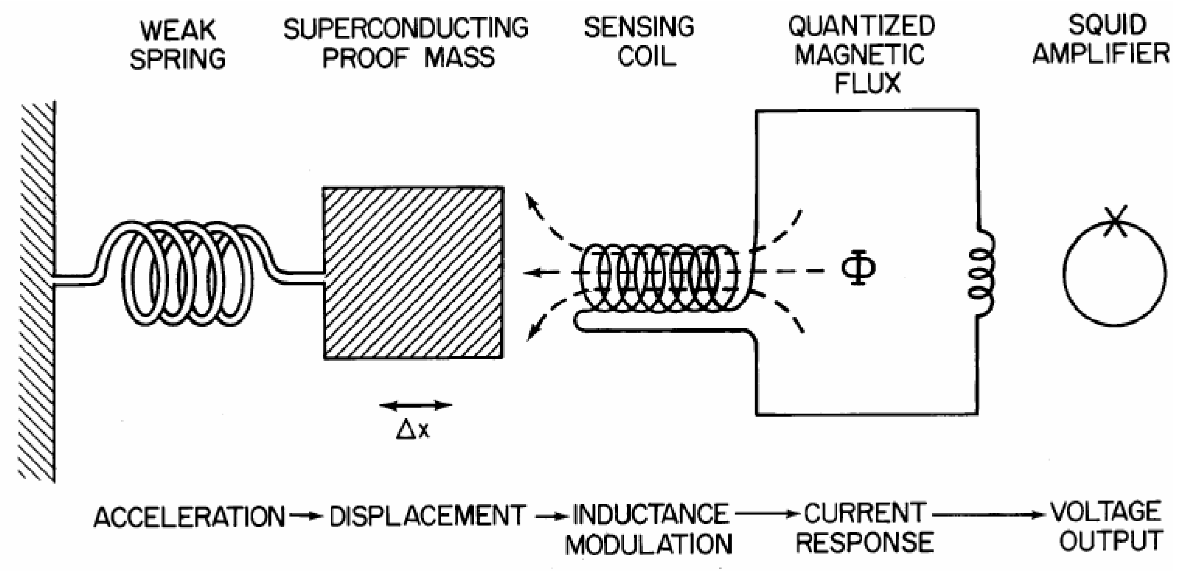
- ❑ SGG as a Gravitational-Wave Detector
- ❑ Current and Future SGGs and Sensitivity
- ❑ SOGRO: Design and Important Noise Sources
- ❑ Sensitivity Goal

Introduction

Introduction to Superconducting Gravity Gradiometer (SGG)



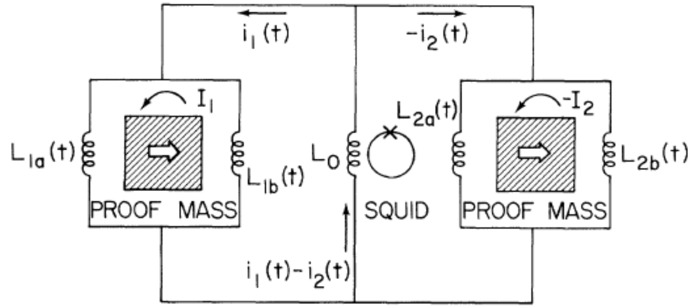


FIG. 1. A schematic of the superconducting gravity gradiometer.

SQUID output is proportional to the difference in displacement of the two masses

Gravity gradient tensor

$$\Gamma_{ij} = -\frac{\partial^2 \phi}{\partial x_i \partial x_j}$$

i=j **: inline-component**

i≠j **: cross-component**

Test of Newton's Inverse-square law using SGG (1993)

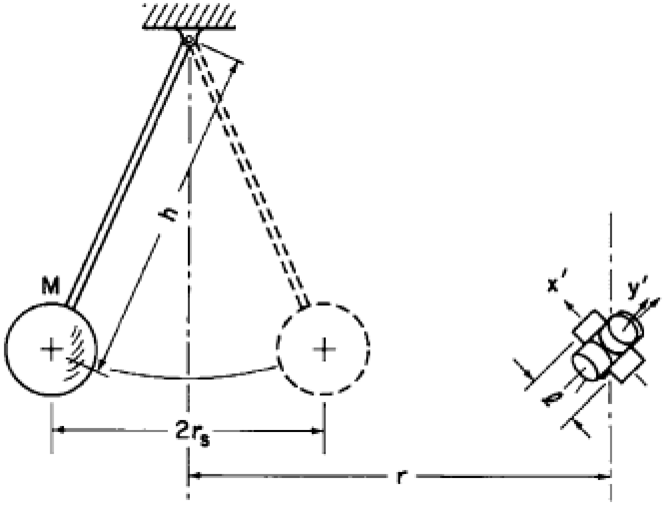
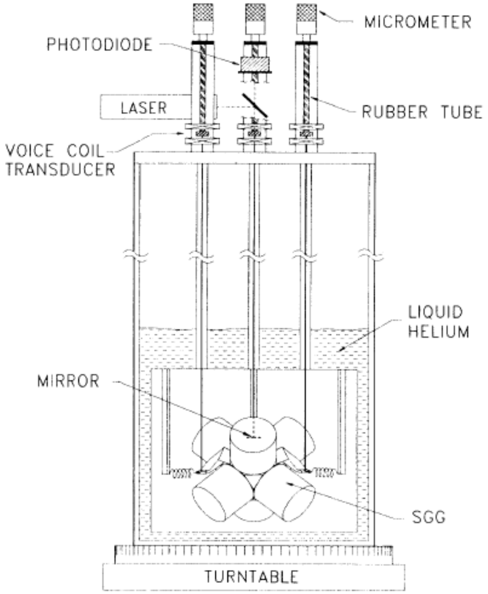
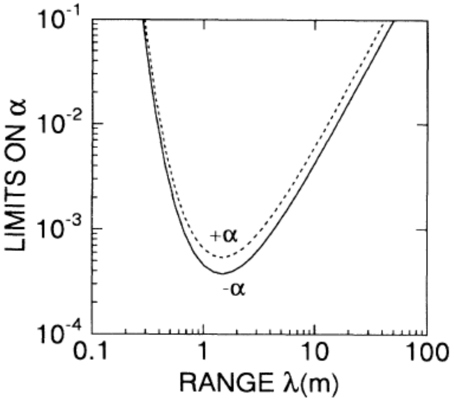


Illustration of Test



Cryostat Schematic



2σ limits on new Yukawa interaction

Poisson's equation $\sum_i \Gamma_{ii} = \nabla^2 \phi = 4\pi G \rho.$

In free space, $\Gamma_{xx} + \Gamma_{yy} + \Gamma_{zz} = 0$

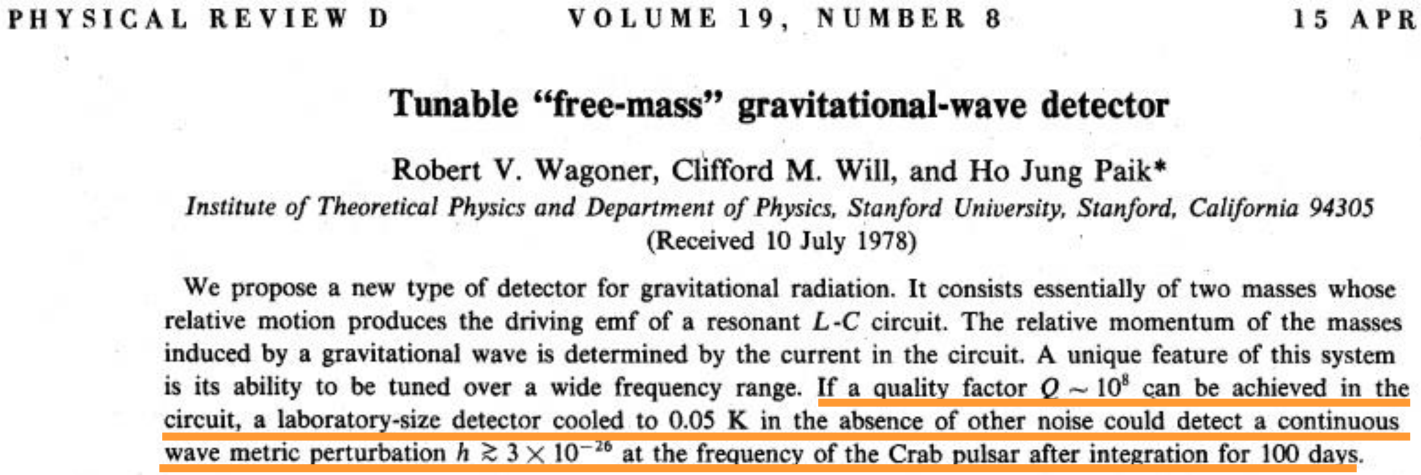
Gravitational Wave Detection

SGG as a Gravitational Wave Detector?

- **In the Newtonian limit, Riemann tensor becomes gravity gradient.**

  ⇒ Gravity gradiometer measures Riemann tensor components.

$$\boxed{R_{0i0j} \rightarrow \Gamma_{ij} = -\partial^2\phi / \partial x_i \partial x_j}$$



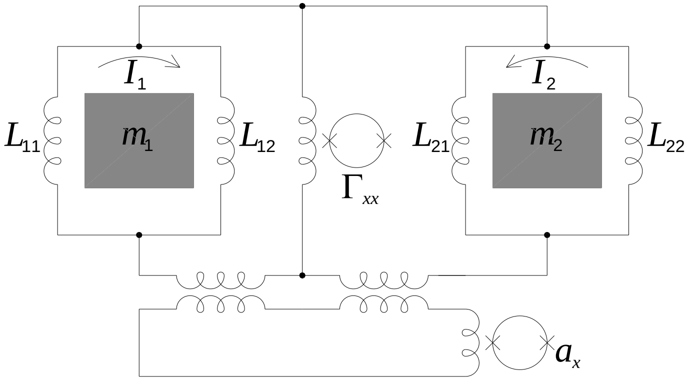
PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Tunable "free-mass" gravitational-wave detector

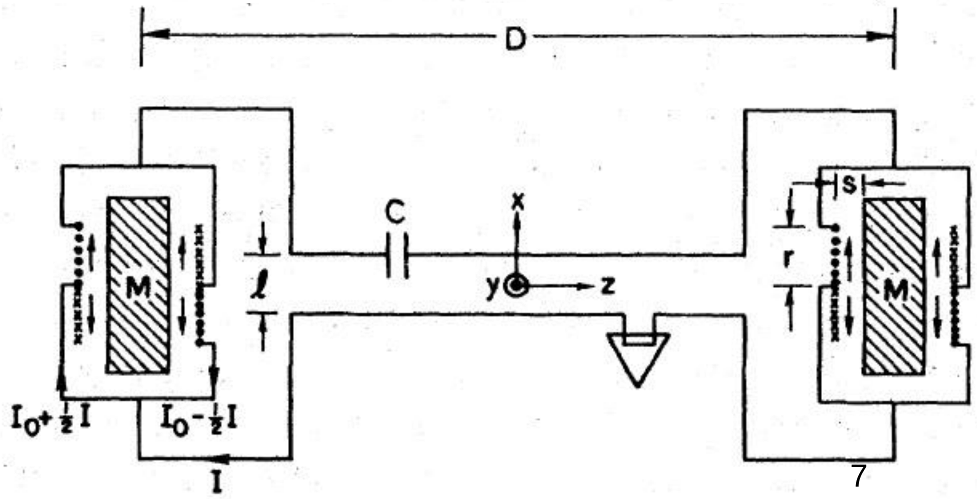
Robert V. Wagoner, Clifford M. Will, and Ho Jung Paik*
Institute of Theoretical Physics and Department of Physics, Stanford University, Stanford, California 94305

(Received 10 July 1978)

We propose a new type of detector for gravitational radiation. It consists essentially of two masses whose relative motion produces the driving emf of a resonant *L*-*C* circuit. The relative momentum of the masses induced by a gravitational wave is determined by the current in the circuit. A unique feature of this system is its ability to be tuned over a wide frequency range. If a quality factor $Q \sim 10^8$ can be achieved in the circuit, a laboratory-size detector cooled to 0.05 K in the absence of other noise could detect a continuous wave metric perturbation $h \gtrsim 3 \times 10^{-26}$ at the frequency of the Crab pulsar after integration for 100 days.

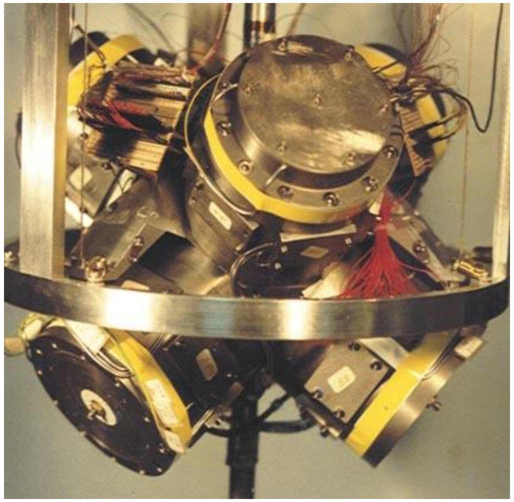


⇨

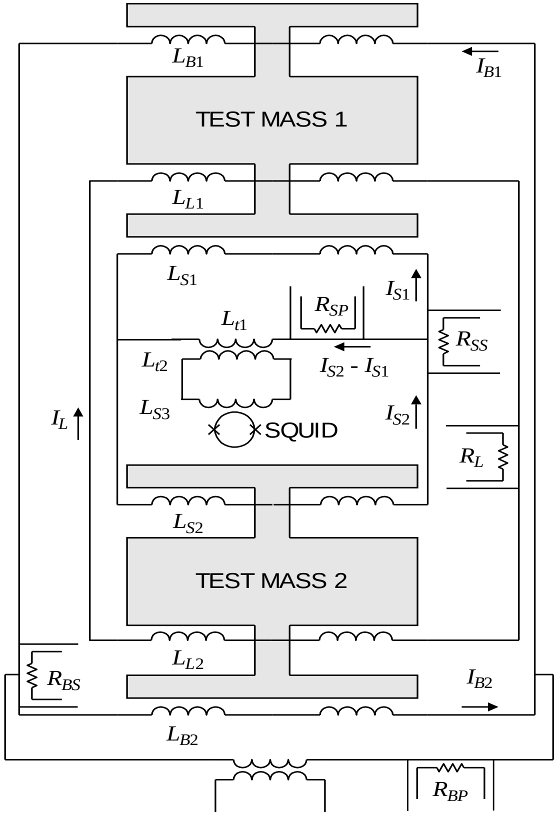


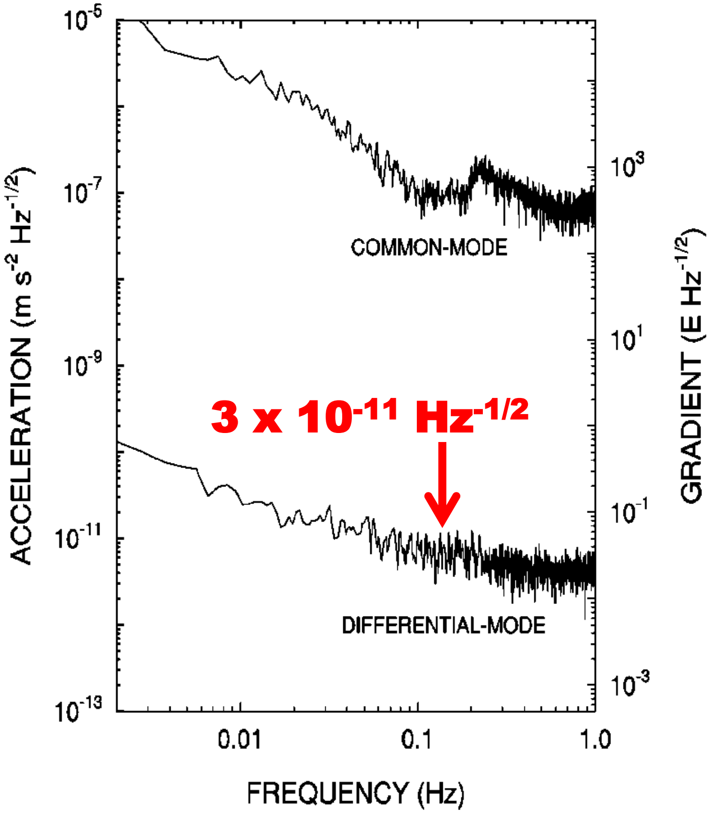
Current and Future SGGs

UM diagonal-component SGG (1993)



(Moody *et al.*, 2002)



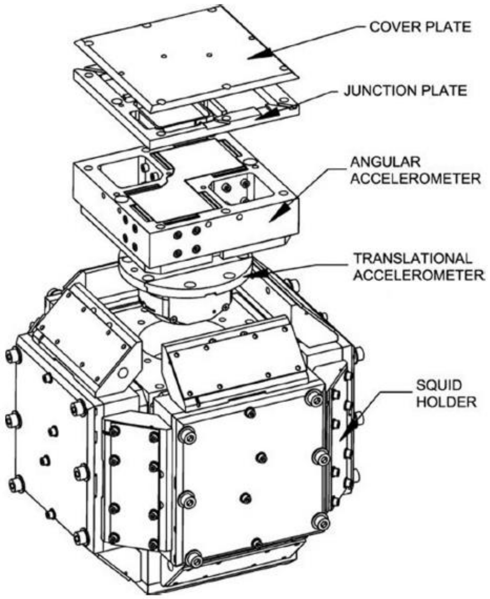


3×10^{-11} Hz$^{-1/2}$

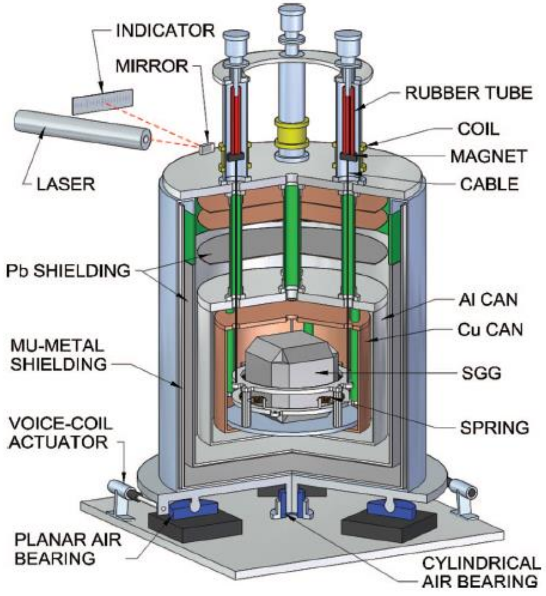
- **Test masses are mechanically suspended (f_{DM} ~ 10 Hz).**
- **Development was completed by early 1990s.**
- **100 times better amplitude sensitivity than TOBA 20 years earlier.**

⟹ 10^4 times better limit than TOBA in GW energy density.

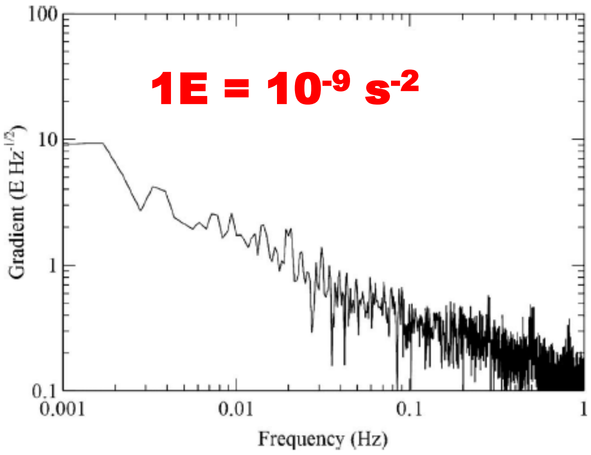
Cross-component SGG (2011)



3-axis Cross-component SGG

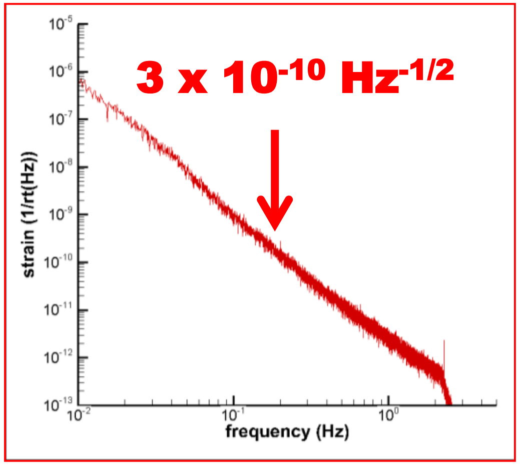


Cryostat Schematic



1E = 10^{-9} s^{-2}

Gravity gradient sensitivity



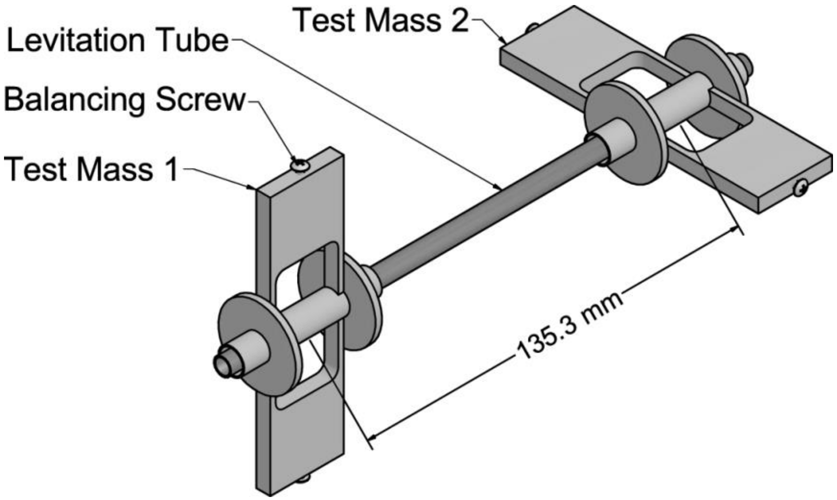
3 x 10^{-10} $Hz^{-1/2}$

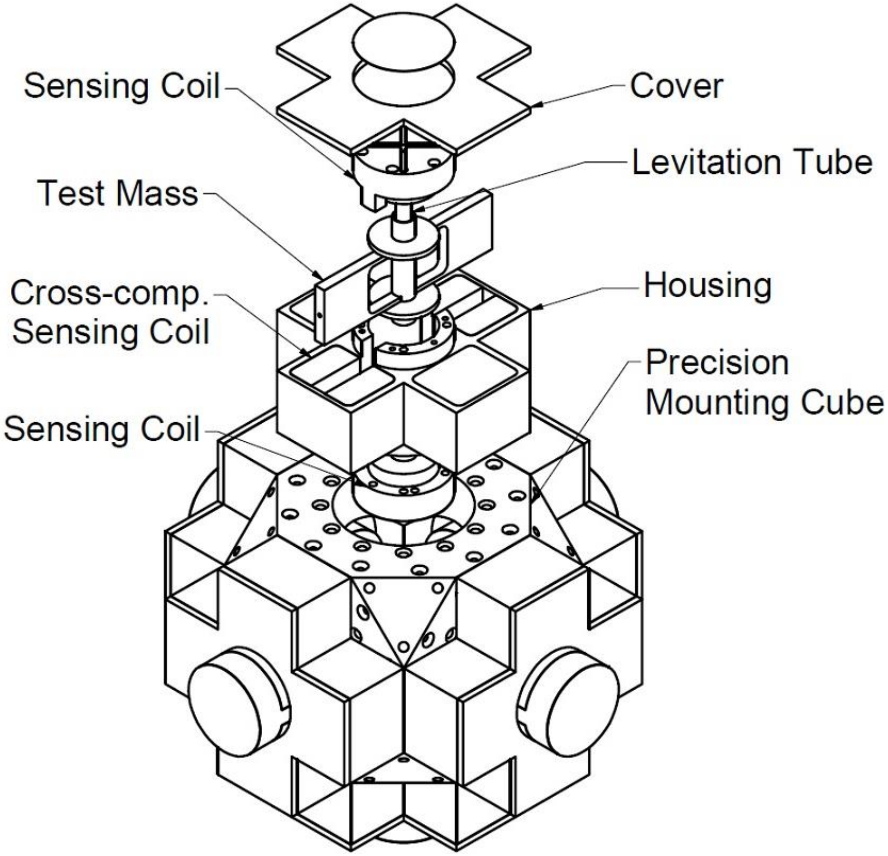
GW strain sensitivity

New Superconducting tensor gravity gradiometer

- **More sensitive SGG is under development with NASA support.**
- **Test masses are magnetically suspend (f_{DM} ~ 0.01 Hz).**

  ⇨ **Very high sensitivity**



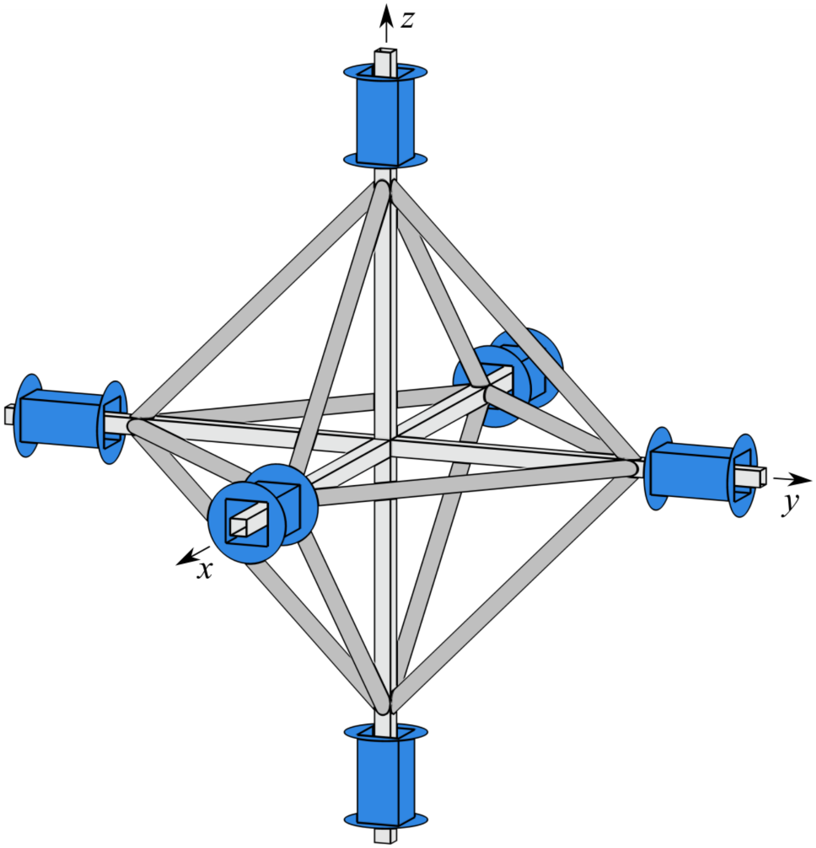


Test masses are levitated by a current induced along a tube.

Six test masses mounted a cube form a *tensor* gradiometer.

SOGRO:
Superconducting Omni-directional Gravitational Radiation Observatory

Superconducting tensor gravitational wave detector



SOGRO

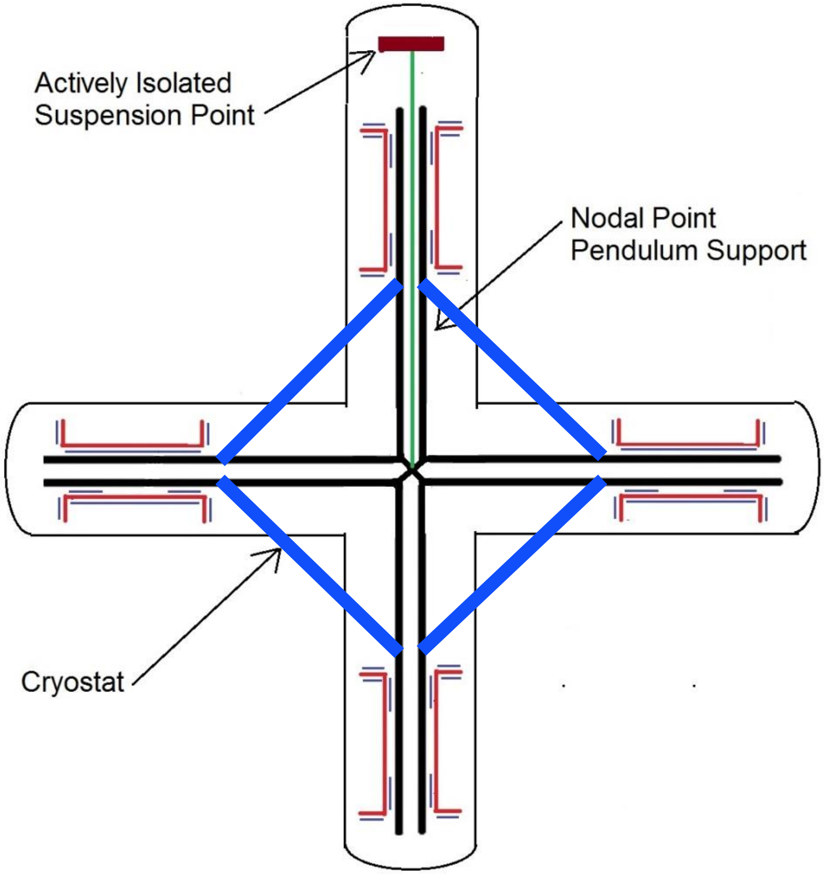
(Superconducting Omni-directional Gravitational Radiation Observatory)

- **Each test mass has three degrees of freedom.**
- **Combining six test masses, a tensor GW detector is formed.**

By detecting all six components of the Riemann tensor, the source direction (θ, ϕ) and wave polarization (h_+, $h_\times$) can be determined by a single detector. ⟹ "Spherical" Antenna

Suspension of SOGRO

- **Go underground** to reduce seismic and gravity gradient noise, as well as to be far away from moving objects.



- **Nodal support** prevents odd harmonics from being excited.
- **Cable suspension** gives $f_r < 10^{-3}$ Hz for three angular modes.

  ⇒ Active isolation unnecessary.
- **25-m pendulum** gives $f_p = 0.1$ Hz for two horizontal modes.

  ⇒ Provide passive isolation for high frequencies.
- Problem: Platform is **not rigid enough**.

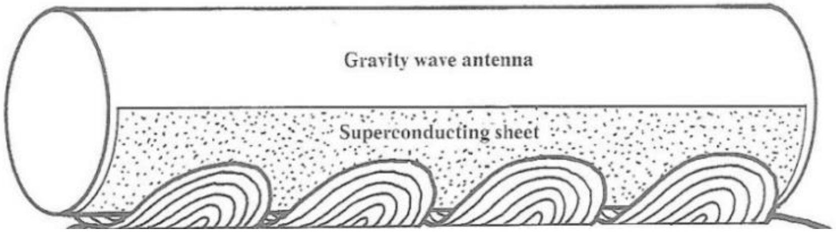
  ⇒ **Triangulate** with struts.

Alternative suspension: Optical rigid body
⇒ **Simpler cryogenics, larger baseline (up to 3 km?)**

Magnetic levitation

Stanford (1976)

1 ton Al antenna wrapped with Nb-Ti sheet was levitated magnetically.



- **Field required to levitate 5-ton mass:**

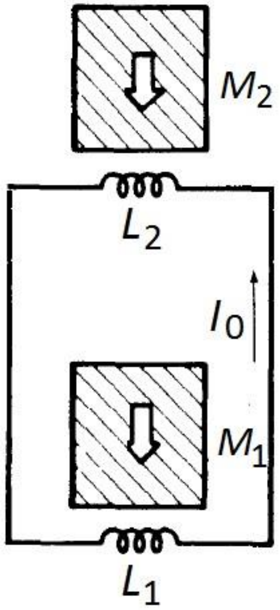
$$\frac{B^2}{2\mu_0}A = Mg,\ B = \left(\frac{2\mu_0 Mg}{A}\right)^{1/2} = \left(\frac{2\times 4\pi\times 10^{-7}\times 5\times 10^{3}\times 9.8}{10}\right)^{1/2}$$

$$= 0.11\,\mathrm{T} < H_{c1} = 0.16\,\mathrm{T}\ (\mathrm{Nb\ at}\ T = 4\,\mathrm{K}).$$

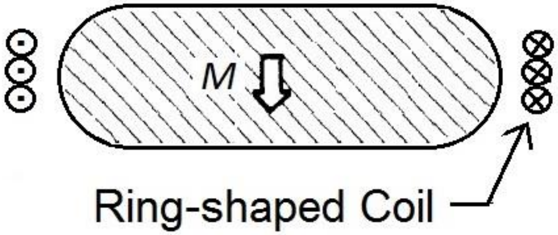
- **The biggest challenge:**

  To obtain symmetry, vertical DM resonance frequencies must also reduced to 0.01 Hz.

- **Employ "push-pull levitation" plus negative spring.**



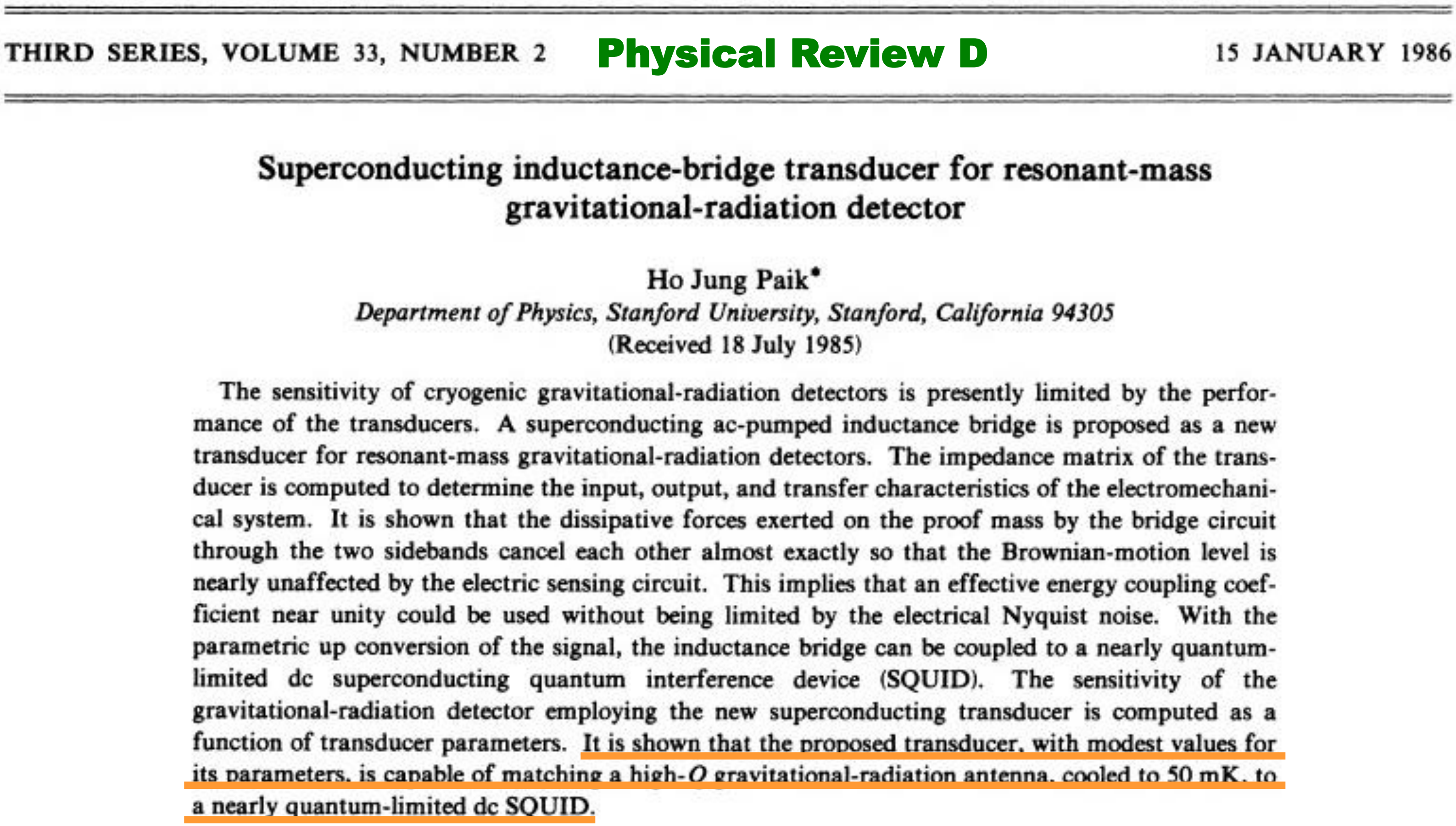
Push-pull levitation



Superconducting negative spring

Parametric transducer

- Near quantum-limited SQUIDs have 1/f noise below 100 kHz.
- Signal needs to be upconverted to f_p = 100 kHz by pumping at f_p by using a **parametric transducer**.
- An **inductance bridge** can be coupled naturally to a SQUID.



THIRD SERIES, VOLUME 33, NUMBER 2 **Physical Review D** 15 JANUARY 1986

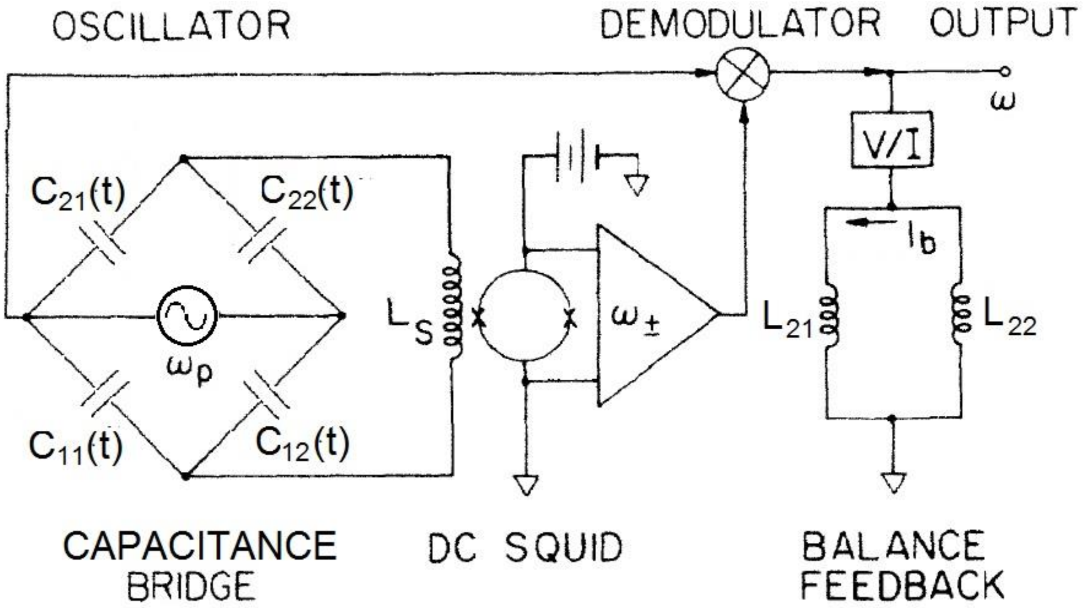
Superconducting inductance-bridge transducer for resonant-mass gravitational-radiation detector

Ho Jung Paik*
Department of Physics, Stanford University, Stanford, California 94305

(Received 18 July 1985)

The sensitivity of cryogenic gravitational-radiation detectors is presently limited by the performance of the transducers. A superconducting ac-pumped inductance bridge is proposed as a new transducer for resonant-mass gravitational-radiation detectors. The impedance matrix of the transducer is computed to determine the input, output, and transfer characteristics of the electromechanical system. It is shown that the dissipative forces exerted on the proof mass by the bridge circuit through the two sidebands cancel each other almost exactly so that the Brownian-motion level is nearly unaffected by the electric sensing circuit. This implies that an effective energy coupling coefficient near unity could be used without being limited by the electrical Nyquist noise. With the parametric up conversion of the signal, the inductance bridge can be coupled to a nearly quantum-limited dc superconducting quantum interference device (SQUID). The sensitivity of the gravitational-radiation detector employing the new superconducting transducer is computed as a function of transducer parameters. It is shown that the proposed transducer, with modest values for its parameters, is capable of matching a high-Q gravitational-radiation antenna, cooled to 50 mK, to a nearly quantum-limited dc SQUID.

Tuned capacitor-bridge transducer



- **Capacitor bridge coupled to a near quantum-limited SQUID thru S/C transformer.**
- **LC resonance increases energy coupling β by Q_p.**
- **Oscillator noise is rejected by the bridge balance.**

⇨ **Maintain precise bridge balance by feedback.**

Parametric gain: $G_p^{\pm} = \left| Z_{\pm 1} / Z_{1\pm} \right| = \omega_{\pm} / \omega_m \approx \omega_p / \omega_m$

Energy coupling constant: $\beta_{\pm} \approx \dfrac{C E_p^2 Q_p}{M \omega^2}$

$$E_N(f) = \frac{k_B T \omega_D}{Q_D} + \frac{\left|\omega^2 - \omega_D^2\right|}{\omega_p} \left(1 + \frac{1}{\beta^2}\right)^{1/2} k_B T_N$$

Achievable detector noise

- **For CW signal with impedance-matched bridge transducer,**

$$S_h(f)=\frac{8}{ML^2\omega^4}\left\{\frac{k_BT\omega_D}{Q_D}+\frac{\left|\omega^2-\omega_D^2\right|}{\omega_p}\left(1+\frac{1}{\beta^2}\right)^{1/2}k_BT_N\right\},\ k_BT_N=n\hbar\omega_p$$

Parameter	**SOGRO 1**	**SOGRO 2**	**Method Employed (SOGRO 1 /2)**
Each mass *M*	5 ton	5 ton	Nb square tube
Separation *L*	30 m	100 m	Over “rigid” mounting platform
Antenna temp *T*	1.5 K	0.1 K	Superfluid He / dilution refrigerator
DM frequency f_D	0.01 Hz	0.01 Hz	Magnetic levitation w/ negative spring
DM quality factor Q_D	10^8	10^9	Surface polished pure Nb
Signal frequency *f*	0.1-10 Hz	0.1-10 Hz	Detector noise computed at 1 Hz
Pump frequency f_p	50 kHz	50 kHz	Tuned capacitor bridge transducer
Amplifier noise no. *n*	200	10	Near-quantum-limited SQUID
Detector noise $S_h^{1/2}(f)$	2×10^{-20} Hz$^{-1/2}$	2×10^{-21} Hz$^{-1/2}$	Two phase development

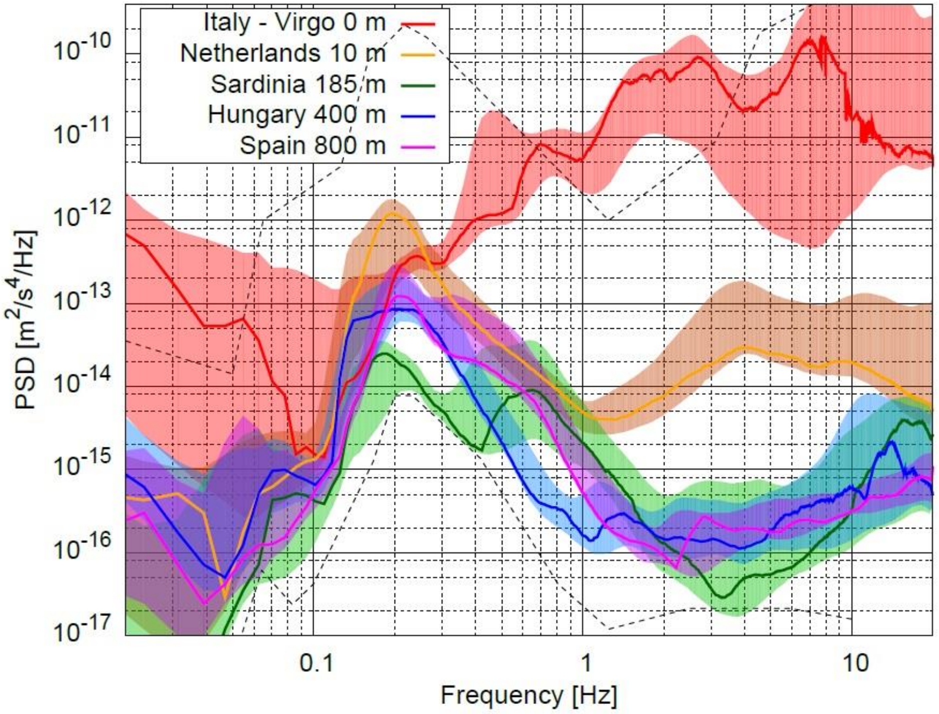
- **SOGRO can also be operated as tunable *resonant* detector.**

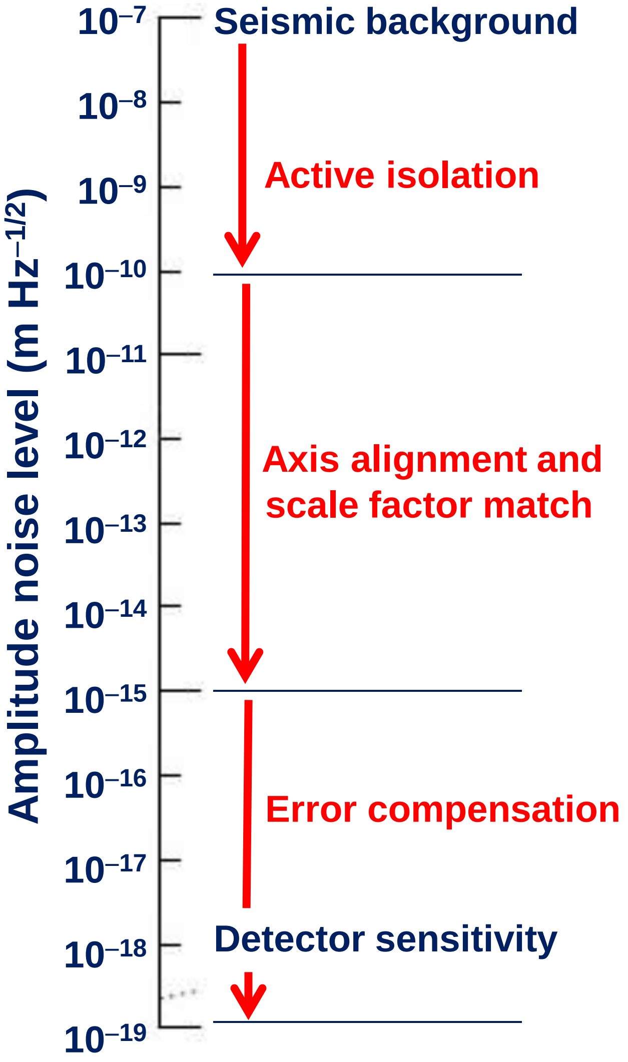
$$S_h(f)=\frac{8}{ML^2\omega_D^3}\left[\frac{k_BT}{Q_D}+\frac{k_BT_N}{Q_D}\left(\frac{\omega_D}{\omega_p}\right)\right]\approx\frac{8}{ML^2\omega_D^3}\frac{k_BT}{Q_D}$$

Seismic noise

- **Seismic noise of bedrock: 10^{-7} m Hz $^{-1/2}$**
- **Could be reduced to the required level by combining active isolation with CM rejection of the detector.**
- **20-m pendulum with nodal support $\Rightarrow$ Passive isolation for $f > 0.1$ Hz.**

Seismic noise of underground sites





Seismic background

Active isolation

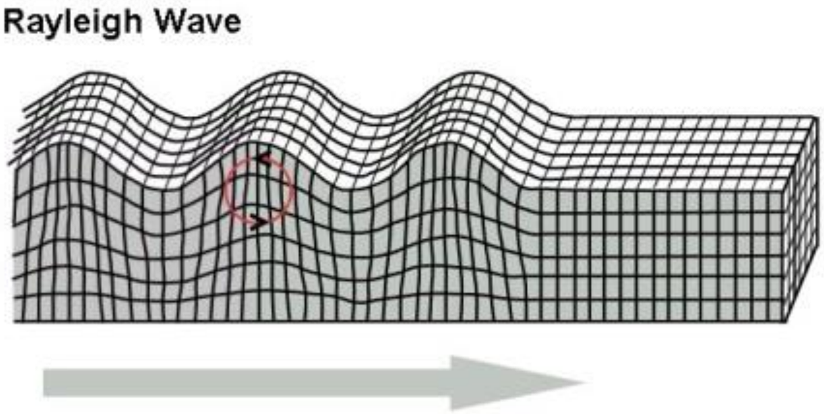
Axis alignment and scale factor match

Error compensation

Detector sensitivity

Newtonian gradient noise

- **The Newtonian noise from seismic and atmospheric density fluctuations cannot be shielded.**



- **GWs are transverse and cannot have longitudinal components whereas the Newtonian gradient does.**

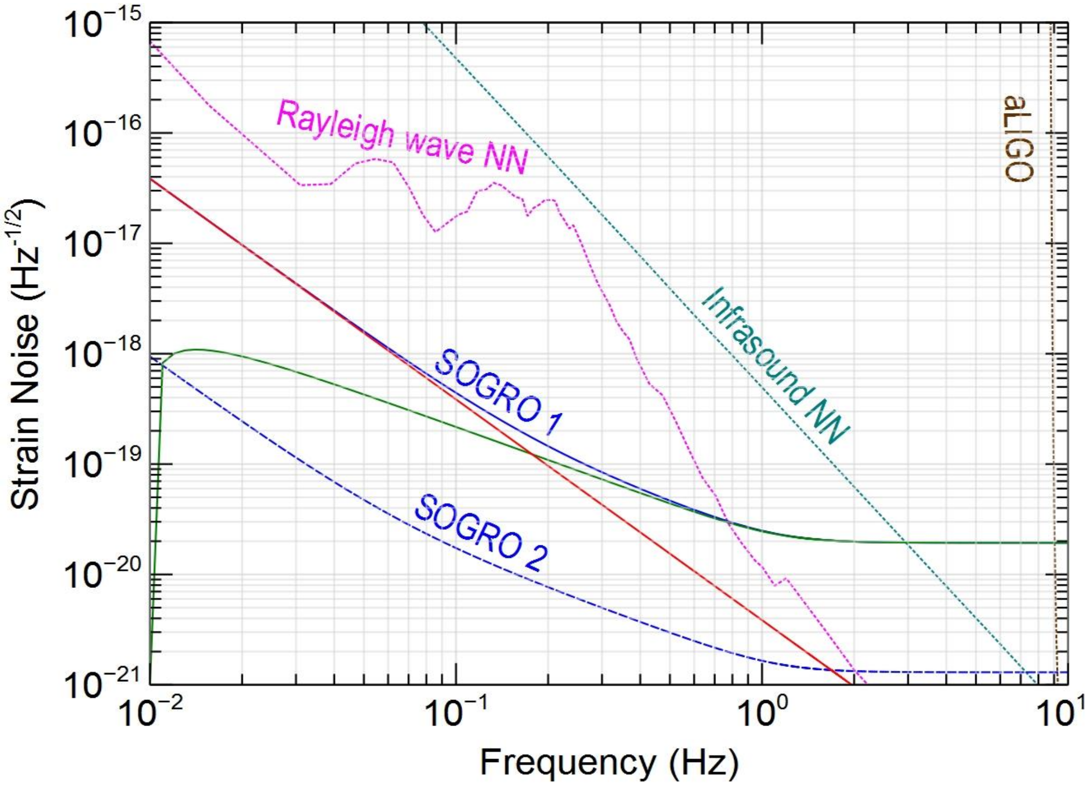
$$h_{GW}(t) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & h_+(t) & h_\times(t) \\ 0 & h_\times(t) & -h_+(t) \end{pmatrix}, \; h_{NG}(t) = \begin{pmatrix} h_{11}(t) & h_{12}(t) & h_{13}(t) \\ h_{12}(t) & h_{22}(t) & h_{23}(t) \\ h_{13}(t) & h_{23}(t) & h_{33}(t) \end{pmatrix}.$$

$\Rightarrow$ **Could be distinguished *in principle* from near-field Newtonian gradients.**

Sensitivity Goal

Sensitivity goals of SOGRO

SOGRO 1: T = 1.5 K, SOGRO 2: T = 0.1 K



- **Detector cooled to 1.5 K or 0.1 K and integrated with near-quantum-limited amplifiers.**
- **Seismic noise rejected by 10^{12} by combining CMRR, passive & active isolation.**
- **Newtonian noise rejected by 10^2~10^4 using tensor nature of the detector and external sensors.**

Major challenges:

- **Large-scale cryogenics.**
- **Mitigation of Newtonian noise.**

Thank you!