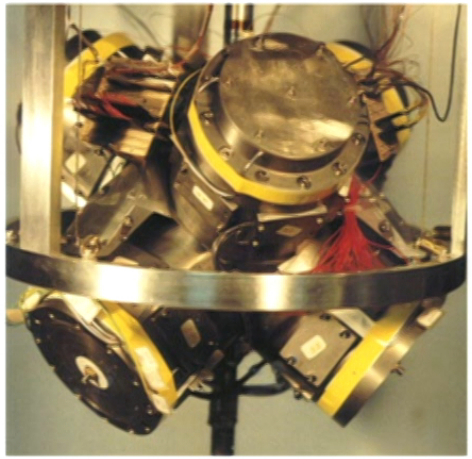
Title: Superconducting accelerometer technology for precision tests of gravitation and search for new interactions

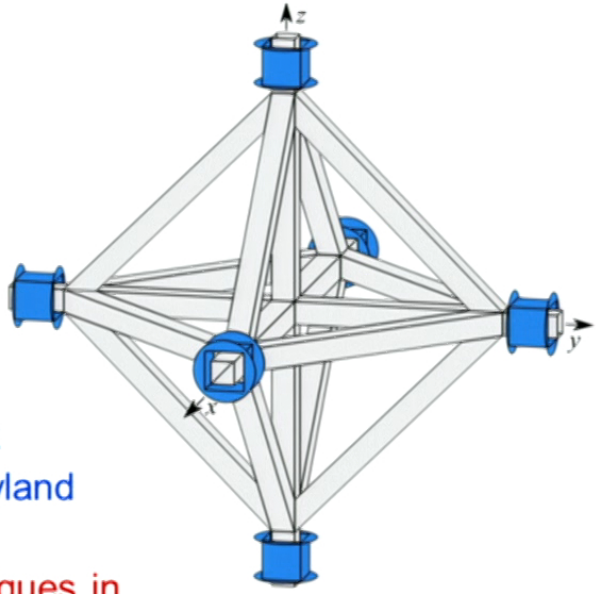
Date: Aug 21, 2017 04:00 PM

URL: http://pirsa.org/17080021

Abstract:

Superconducting Accelerometer Technology for Precision Tests of Gravitation and Search for New Interactions

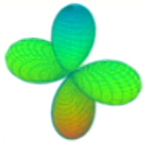




Ho Jung Paik
University of Maryland

Experimental Techniques in
Table-top Fundamental Physics
Waterloo, August 21-25, 2017

Birth of s/c accelerometer



Development of cryogenic GW detector at Stanford (1970)

Motion of 5 ton antenna must be detected to $< 10^{-20}$ m $\mathrm{Hz}^{-1/2}$.

Paik-2

Birth of s/c accelerometer

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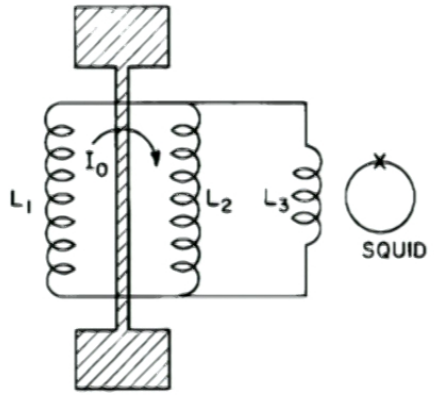
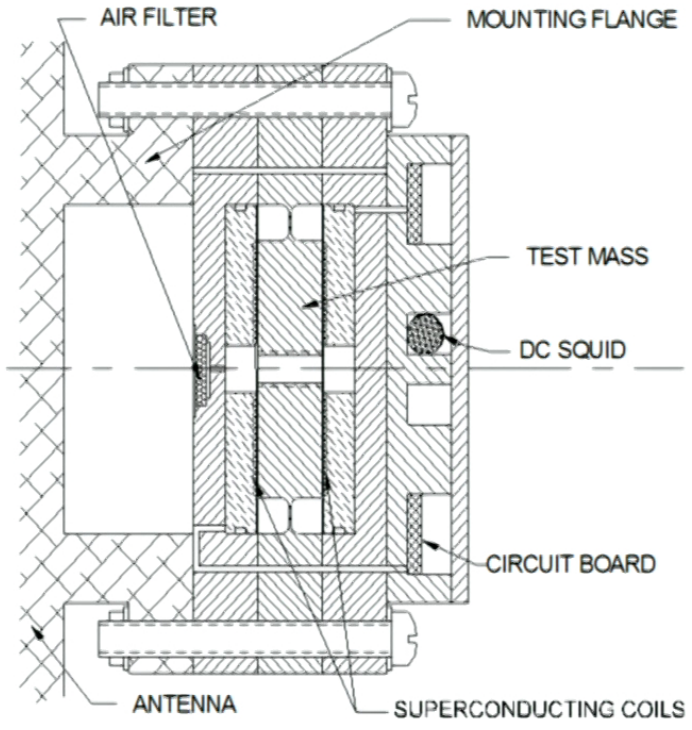
S/C *resonant* transducer (1972)



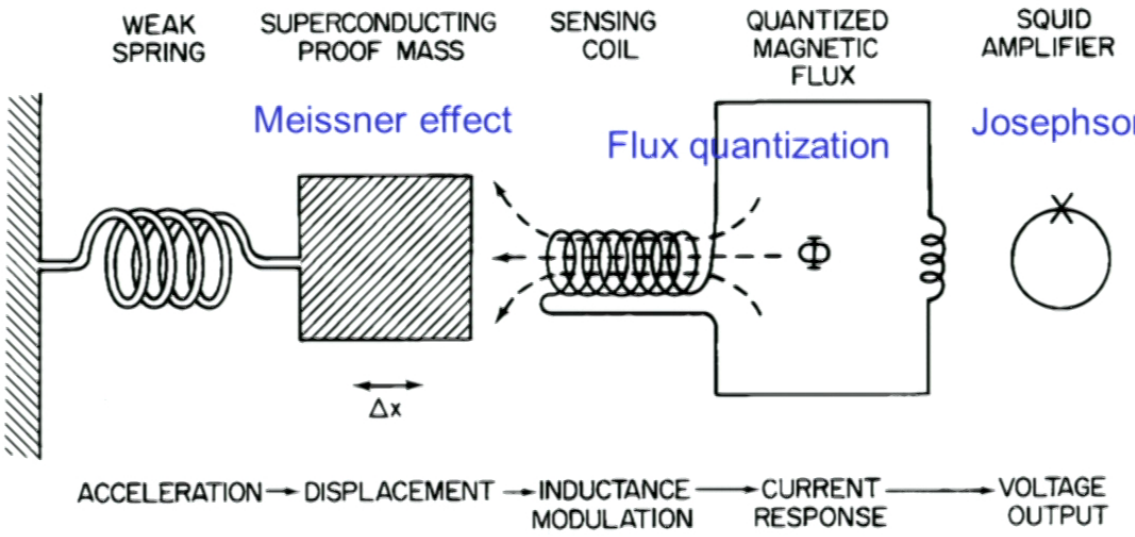
$$\omega_0^2 = \omega_m^2 + \frac{2}{1+\gamma}\frac{B^2 A}{\mu_0 m d}, \quad \gamma \equiv \frac{L_3}{L_p}$$

$$\beta = 1 - \left(\frac{\omega_m}{\omega_0}\right)^2 = \frac{2}{1+\gamma}\frac{B^2 A}{\mu_0 m \omega_0^2 d} \approx \frac{1}{2}$$



Paik-2

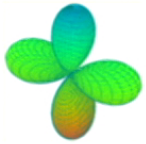
Superconducting accelerometer



- Low noise: $$S_a(f) = \frac{4}{m}\left[k_B T \frac{\omega_0}{Q} + \frac{\omega_0^2}{2\beta\eta} E_A(f)\right]$$
- Extremely stable scale factors ⇒ Sensitive differential measurement possible.

Paik-3

Gravity gradients



- To measure gravity, field on two or more masses must be differenced.
- Gravity gradient Γ_{ij} is a symmetric 3 × 3 tensor:

$$\Gamma_{ij} = -\frac{\partial^2 \phi}{\partial x_i \partial x_j} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{12} & \Gamma_{22} & \Gamma_{23} \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33} \end{pmatrix}.$$

$$\Gamma_{11} + \Gamma_{22} + \Gamma_{33} = -\nabla^2 \phi = 0$$

$\Rightarrow$ 5 independent components

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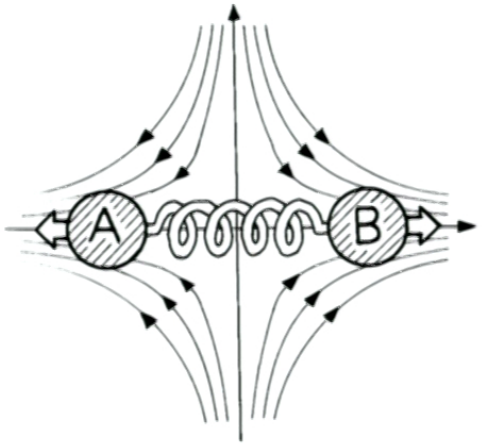
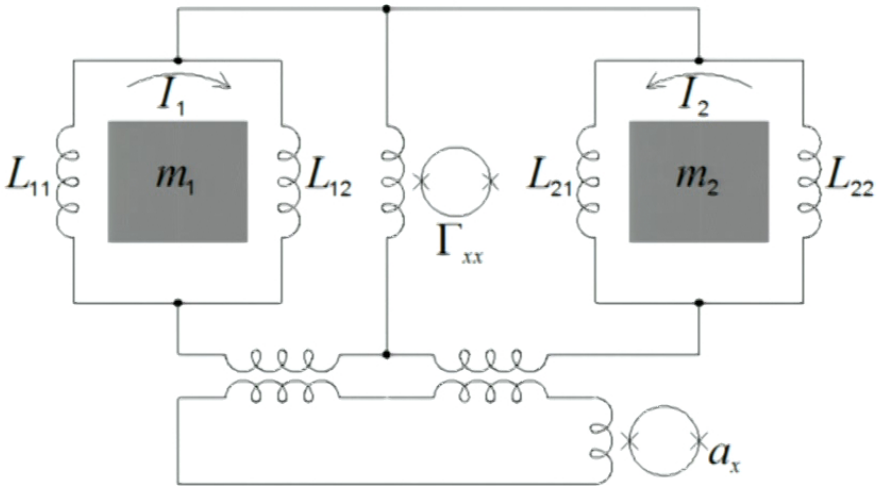
$\Rightarrow$ 5 independent components

Γ_{ii} : "in-line-component" Γ_{ij} ($j \neq i$): "cross-component"



Paik-4

Superconducting gravity gradiometer



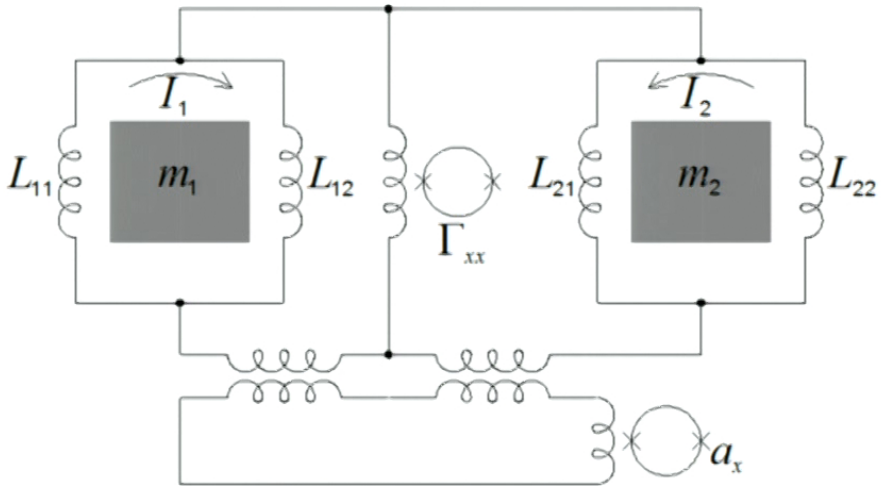
- Low noise: $$S_\Gamma(f) = \frac{8}{m\ell^2}\left[k_B T \frac{\omega_D}{Q} + \frac{\omega_D^2}{2\beta\eta} E_A(f)\right]$$

$$S_\Gamma^{1/2}(f) \approx 2\times10^{-3}\,\mathrm{E\,Hz^{-1/2}}, 1\,\mathrm{E} \equiv 10^{-9}\,\mathrm{s^{-2}} (\Gamma_{zz,\mathrm{Earth}} \approx 3\times10^3\,\mathrm{E})$$

- I_2/I_1 are adjusted to balance out CM. ⇒ Stable CM rejection > 10^7.

Paik-5

Superconducting gravity gradiometer



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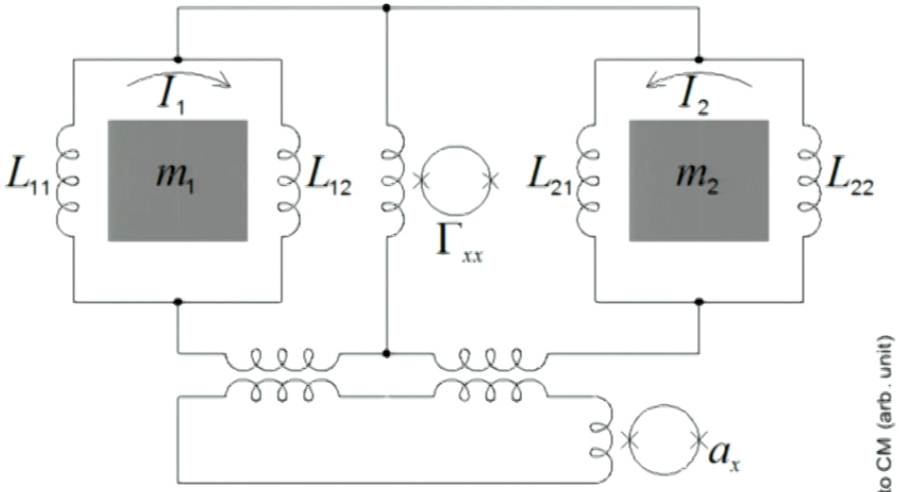

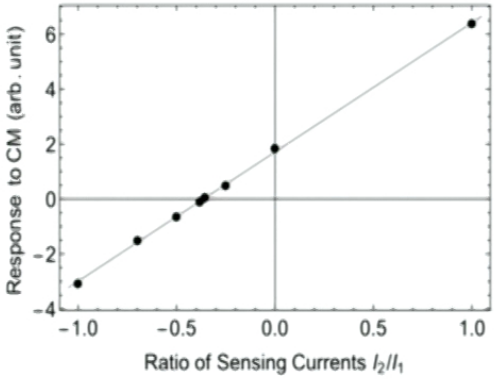

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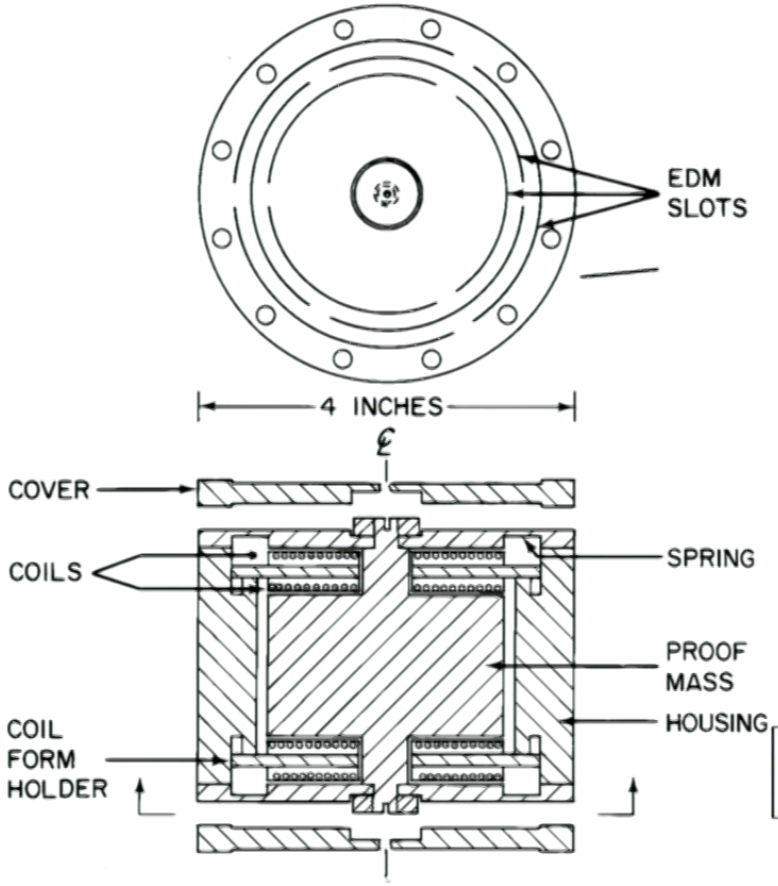
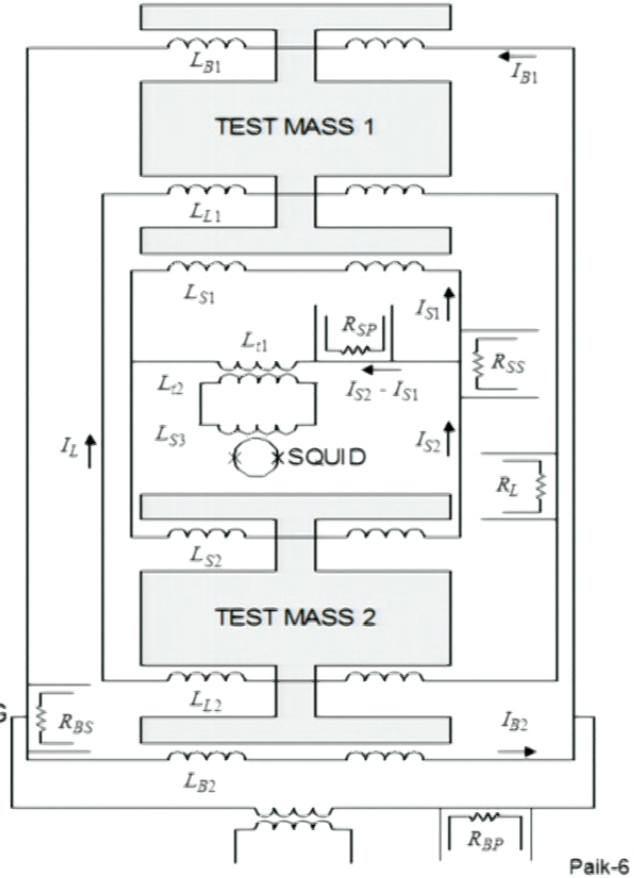
Paik-5

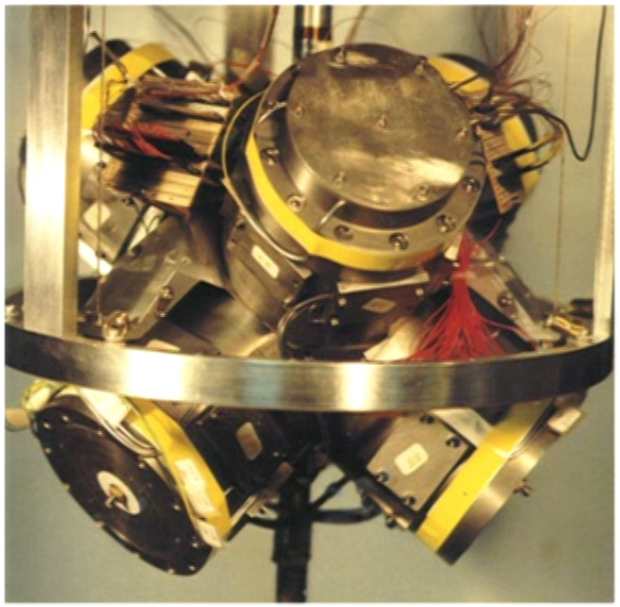
Model II SGG


EDM
SLOTS
4 INCHES
COVER
COILS
SPRING
PROOF
MASS
HOUSING
COIL
FORM
HOLDER

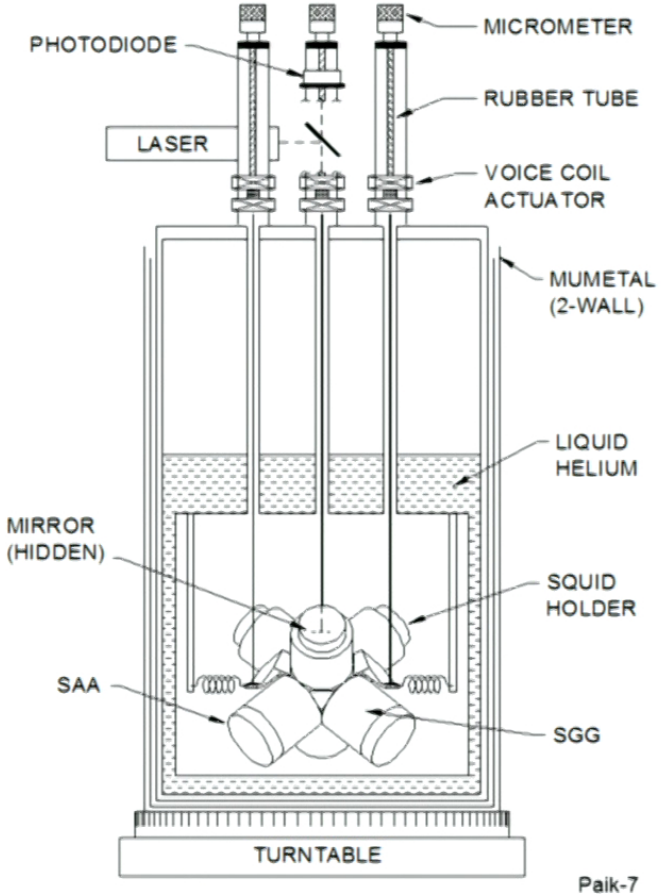

TEST MASS 1
TEST MASS 2
SQUID
Paik-6

SGG in the cryostat

3-axis with mechanical suspension

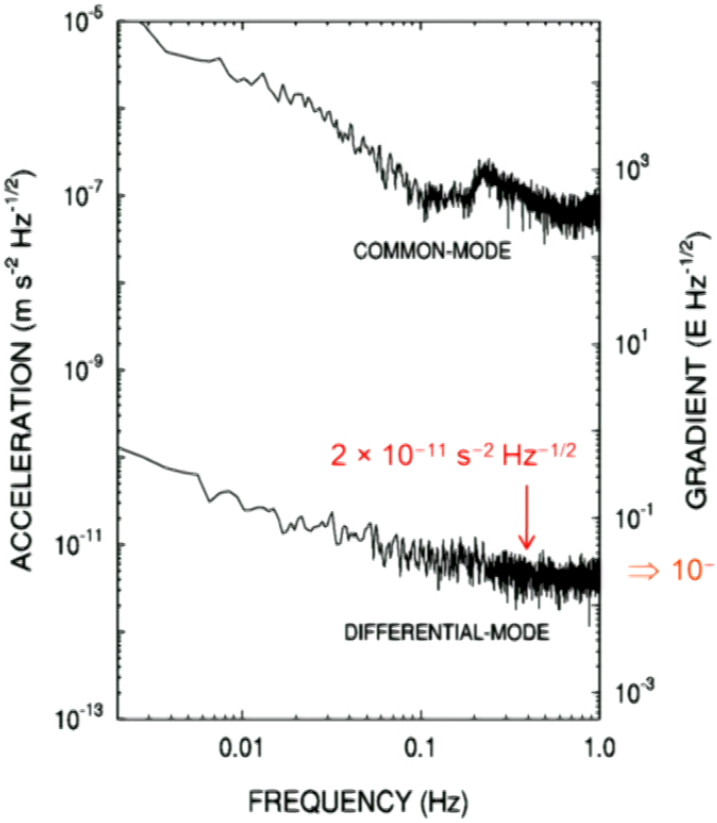


Moody *et al, RSI* 73, 3957 (2002)

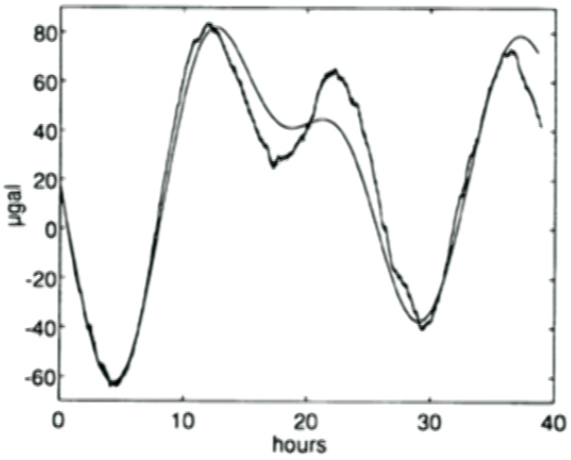


Performance of Model II SGG

Gravity gradient noise PSD



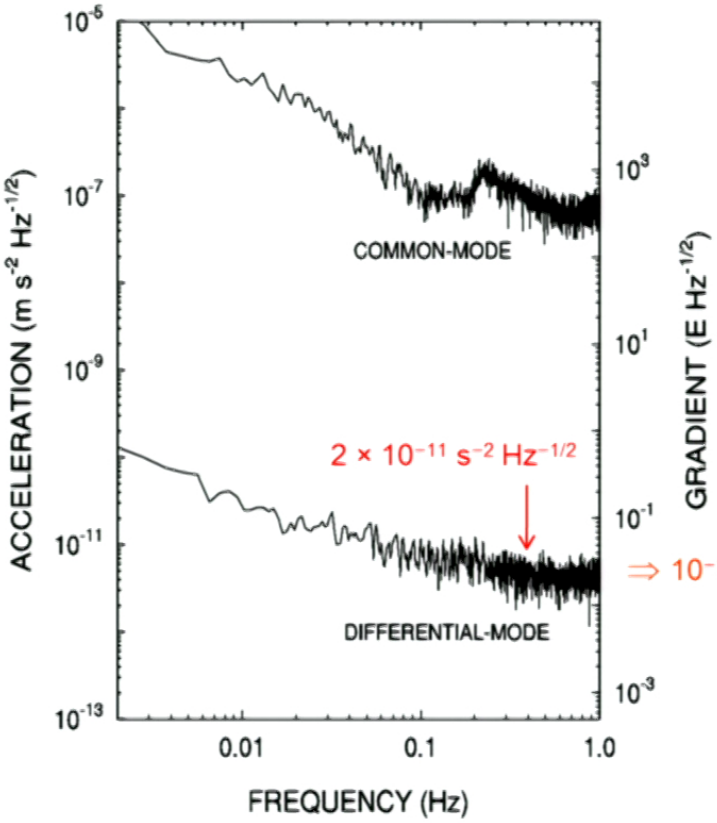
Gravimeter Mode



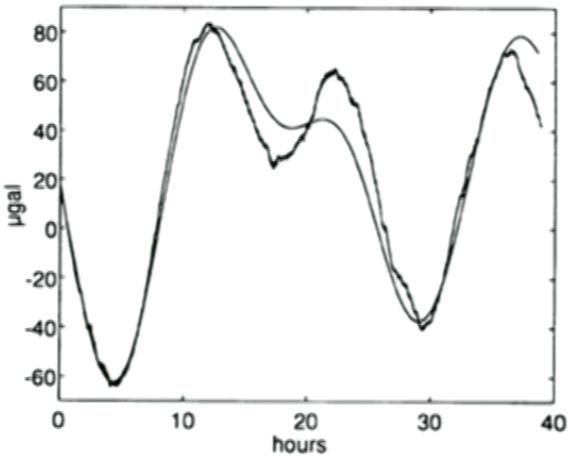
Paik-8

Performance of Model II SGG

Gravity gradient noise PSD



Gravimeter Mode



By early 1990's, SGG achieved sensitivity 10^3 times better than any other gradiometers to date.

Paik-8

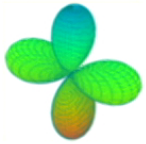
Gauss's law test of the $1/r^2$ law

- Motivation: Many modern theories of gravity predict $\phi(r) = -\frac{GM}{r}\left[1 + \alpha\, e^{-r/R}\right]$

Fifth force?

Paik-10

Gauss's law test of the $1/r^2$ law



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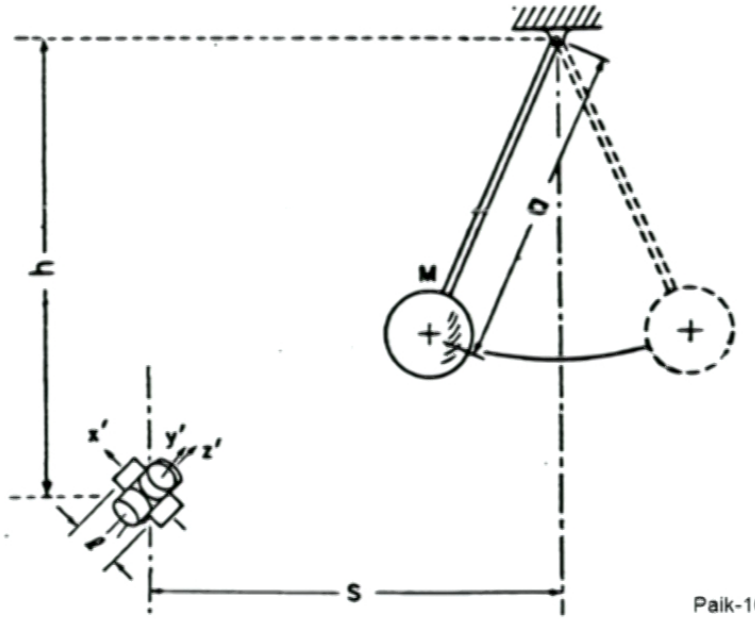
- Detector: 3-axis SGG

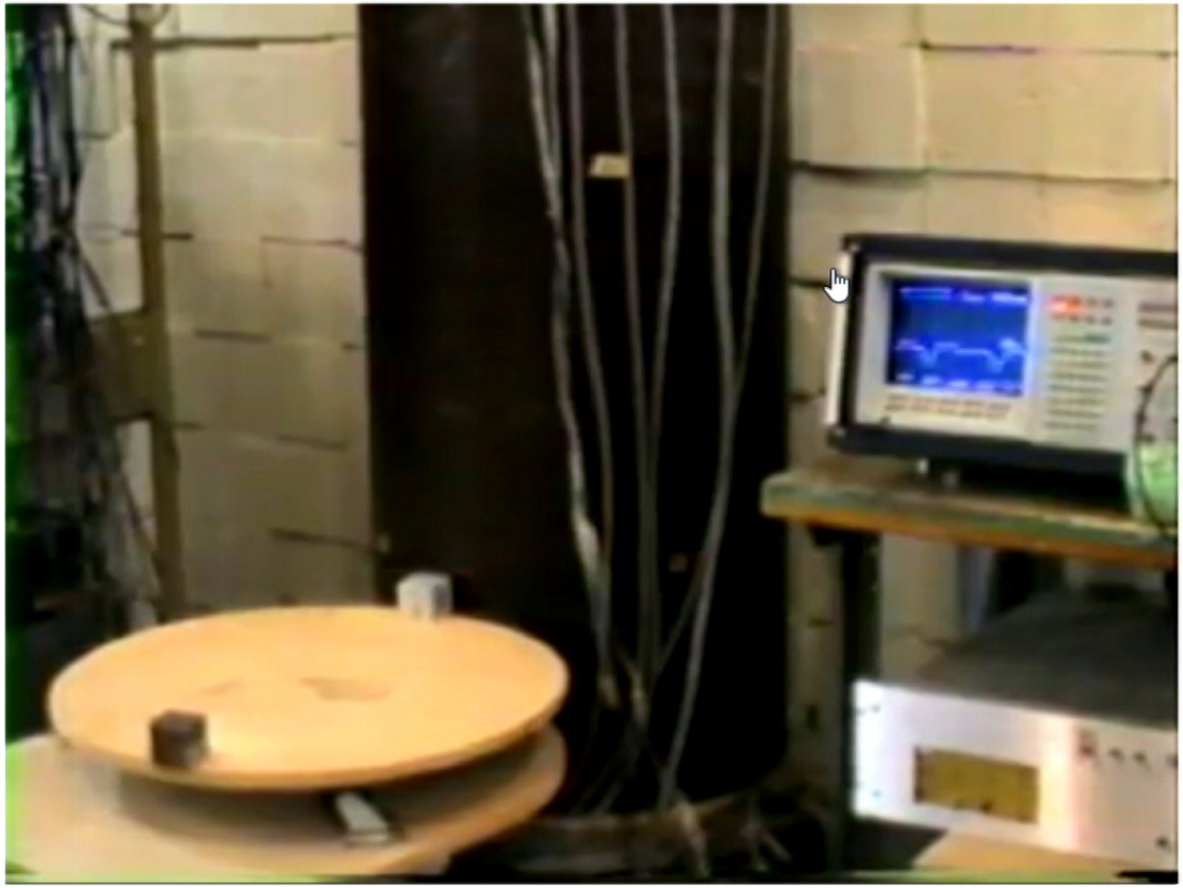
$\nabla \cdot \mathbf{g} = 0\,?$



Paik-10

Demonstration of Model 2 SGG

www.physics.umd.edu/GRE/SGG_video.htm



Paik-9

Demonstration of Model 2 SGG

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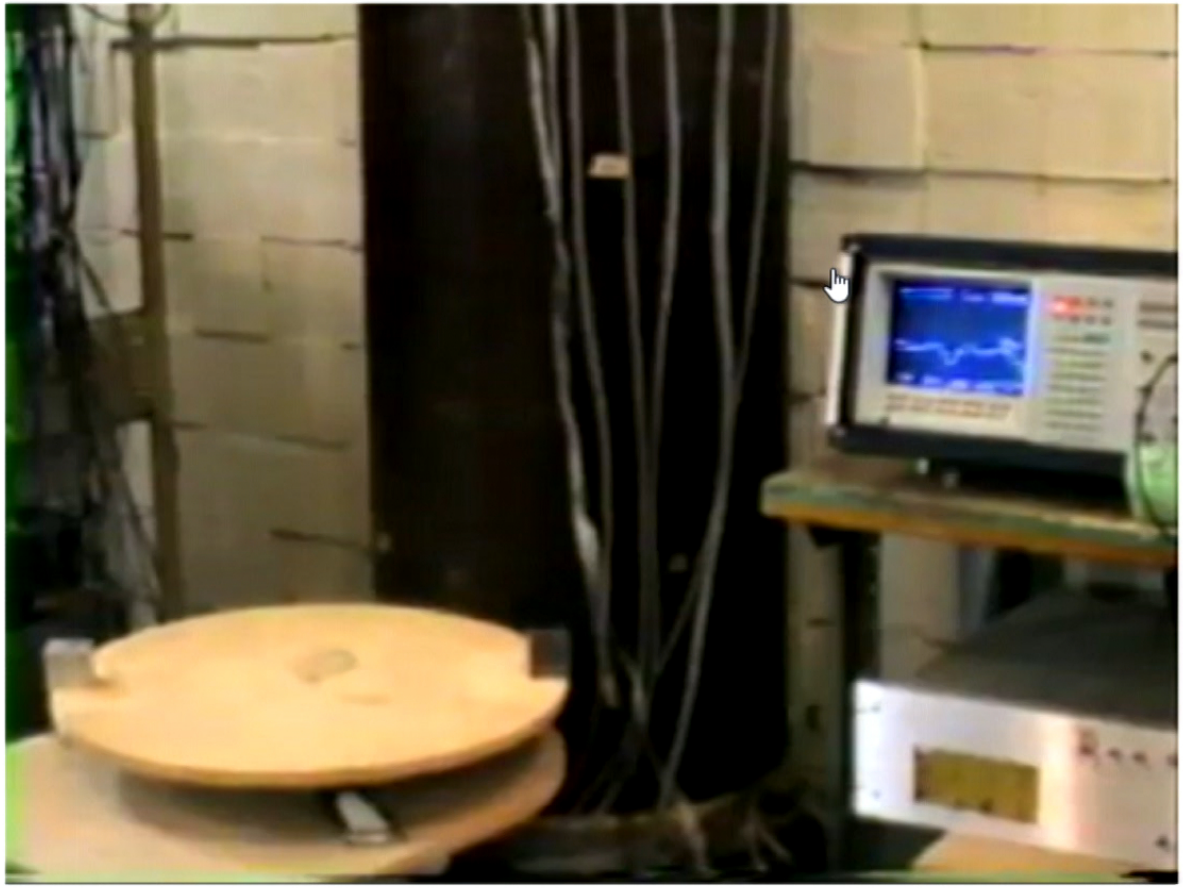

Paik-9

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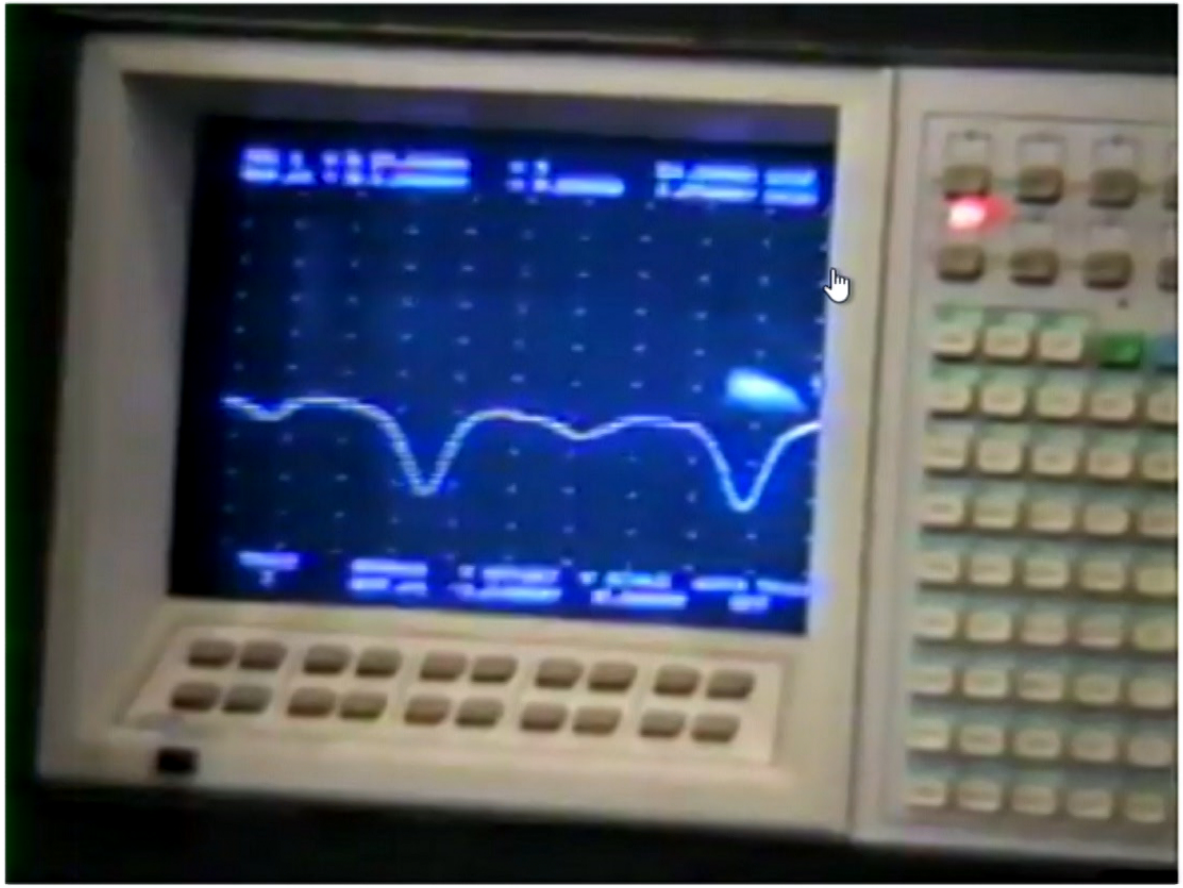
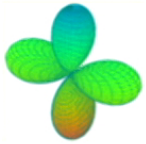


Paik-9

Gauss's law test of the $1/r^2$ law



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Paik-10

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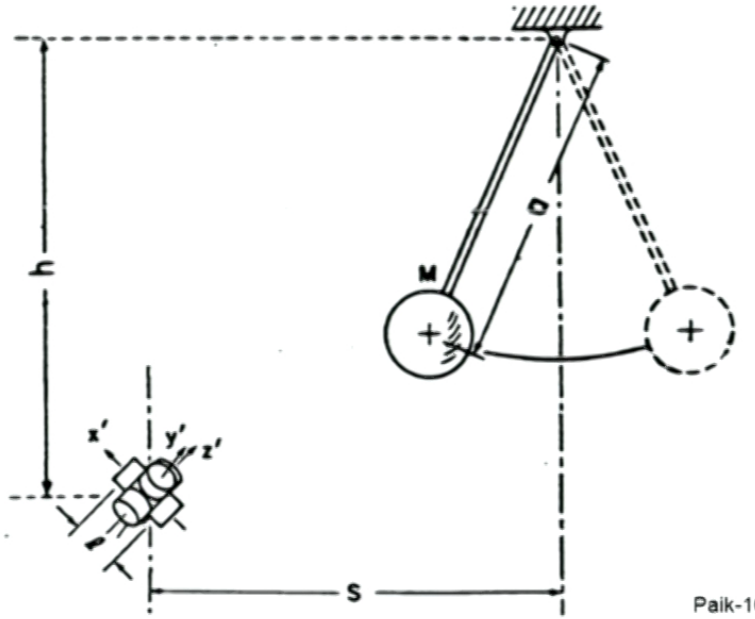
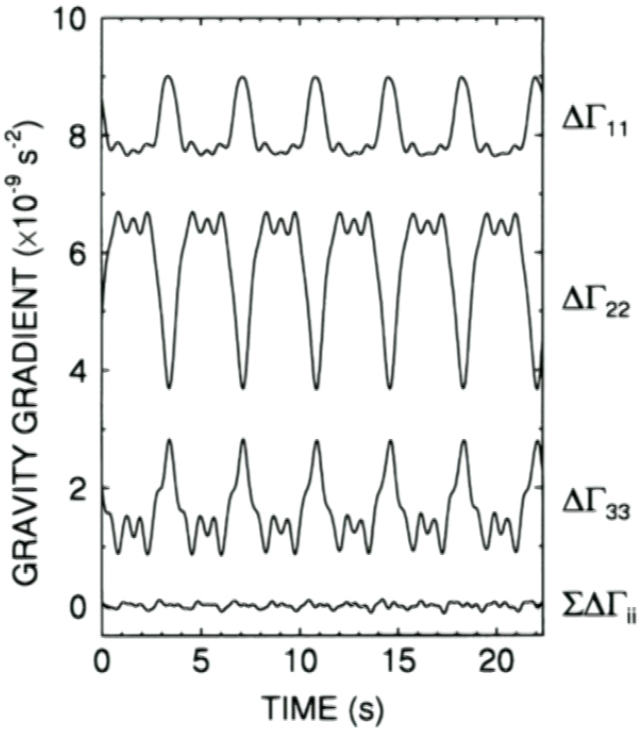
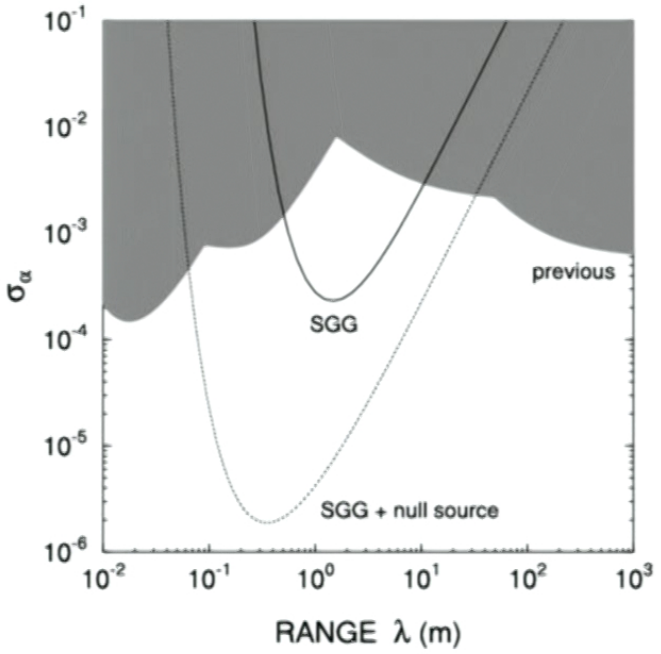


Paik-10

Experimental result

Inverse-square law data





$\alpha = (0.9 \pm 4.6) \times 10^{-4}$ at $\lambda = 1.5\,\mathrm{m}$

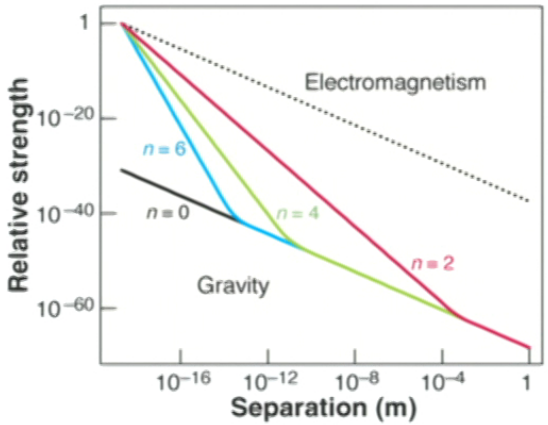
Moody & Paik, *PRL* 70, 1195 (1993)

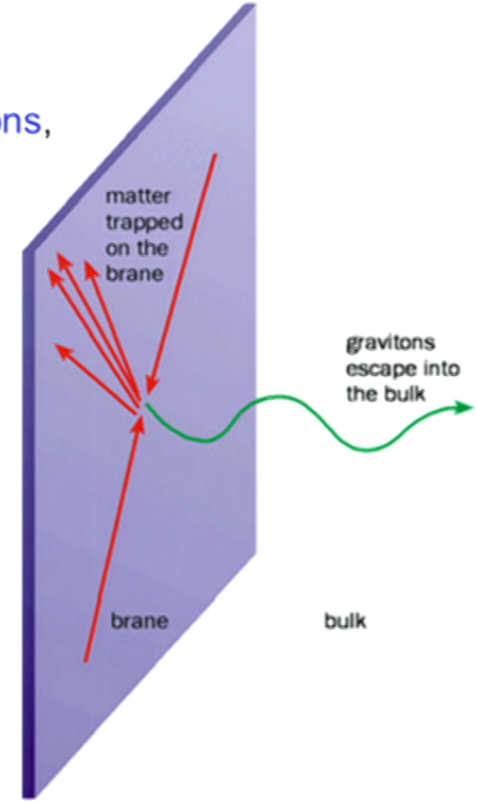
Paik-11

Gravity-only extra dimensions?

Hierarchy problem in the field theory

- Why is gravity 10^{40} times weaker than EM?
- Gravity may escape into *n* gravity-only extra dimensions, (Arkani-Hamed, Dimopoulos and Dvali, 1998).





- For $r > R$, $\phi(r) = -\frac{GM}{r}\left[1 + \alpha\, e^{-r/R}\right]$

  ⇒ For two large dimensions of similar size,

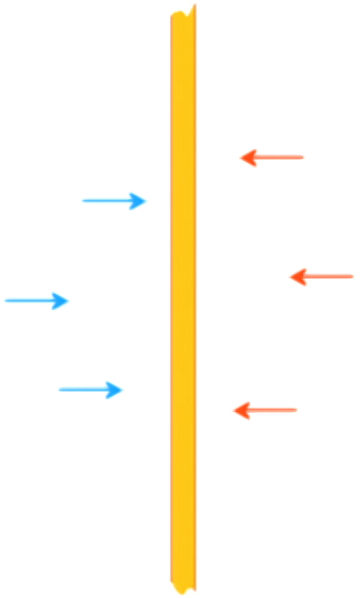
  $\alpha = 4$, $R_1 \approx R_2 \approx 1$ mm (Arkani-Hamed *et al.*, 1999).

Paik-12

UM experiment

- Principle: $\nabla\phi_N$ is constant in position on either side of an infinite plane slab.
- Source: Ta (ρ = 16.6 g cm^{-3}) disk of large diameter-to-thickness (null source).
- Detector: Differential accelerometer formed by two thin Nb disks, located at ~200 μm from source.

  ⇒ Seismic noise rejected by CMRR = 10^3.



Paik-13

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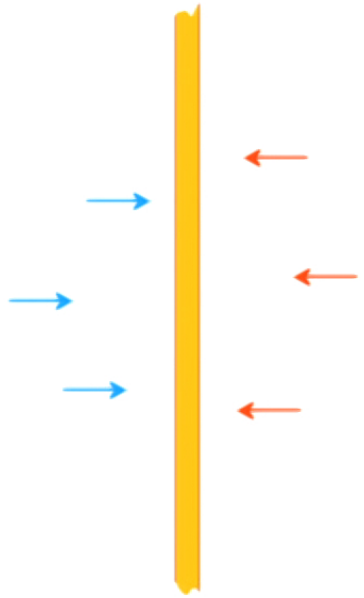
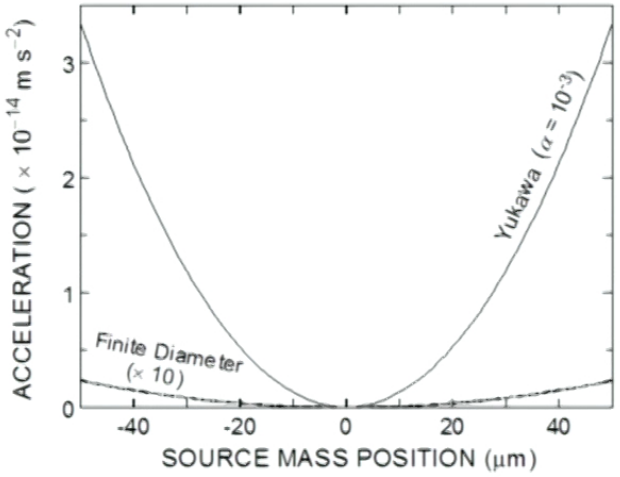


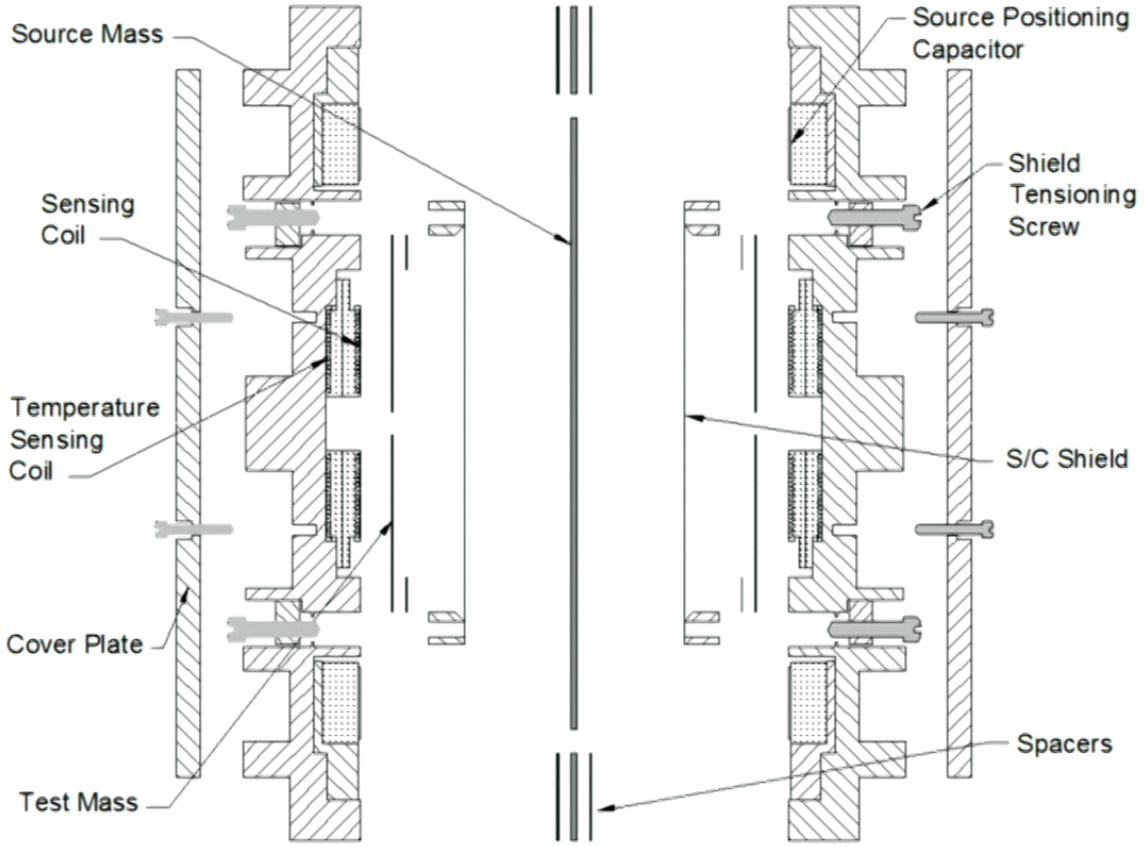


As the source is driven at *f*, the differential signal appears at 2*f*.

⇒ This reduces mechanical and magnetic cross-talk.

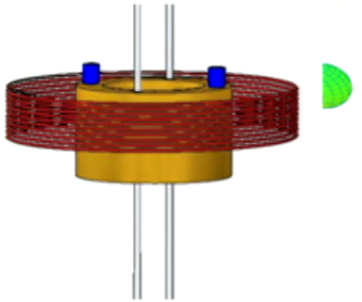
Paik-13

Exploded view of the experiment



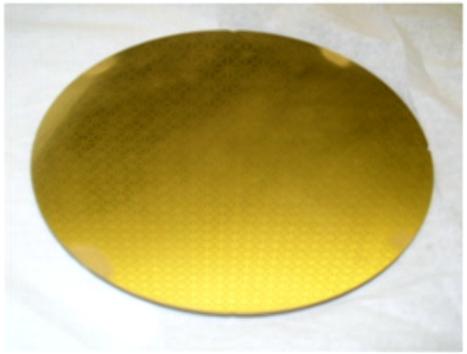
Paik-14

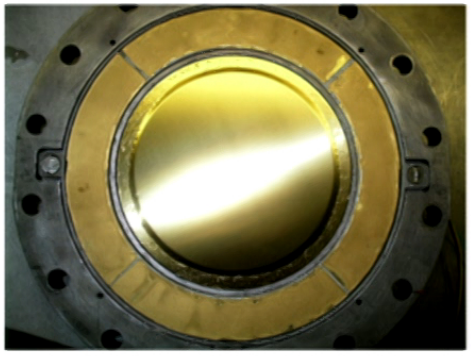
Apparatus

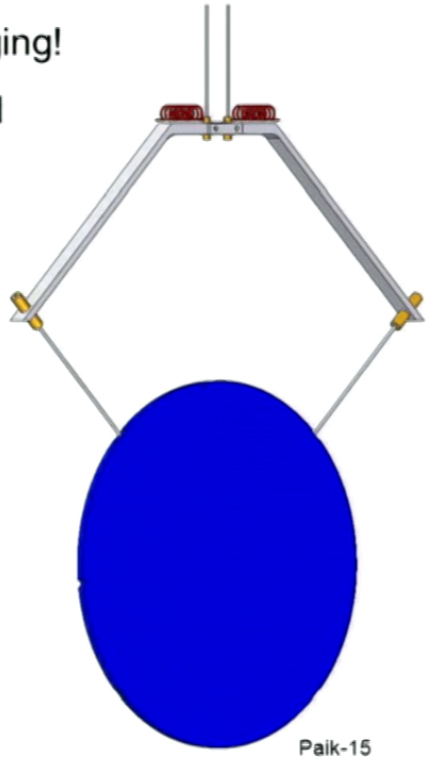


- To decouple source motion from the detector and make it purely sinusoidal, the source is driven from the top of the cryostat.
- Disadvantage: source-detector alignment is very challenging!
- To reduce the patch field potential, the mating source and detector surfaces are coated with gold.

$$F_p(d) = -\frac{\varepsilon_0 v^2}{2d^2}\ ,\ v_{Nb} \approx 1\ \text{V},\ v_{Au} \approx 0.16\ \text{V}$$

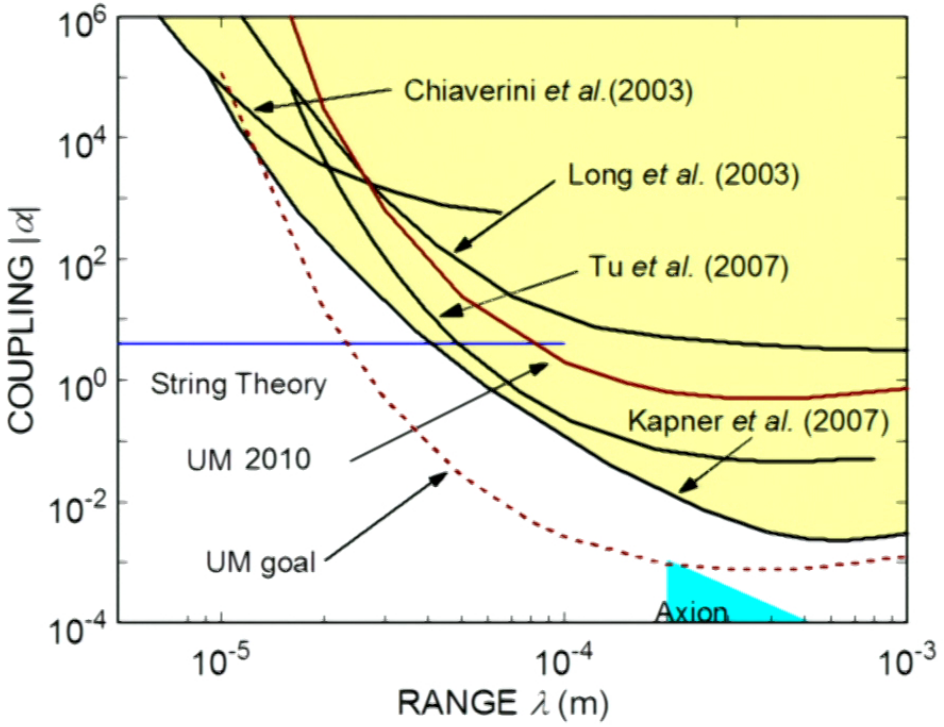






Paik-15

Experimental result



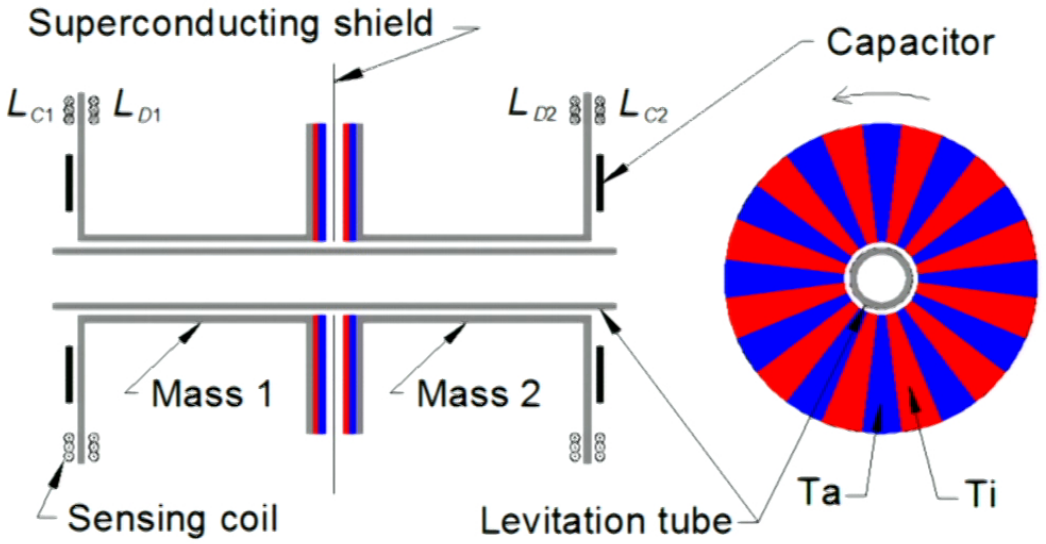
$$\alpha = 0.9 \pm 1.0 \text{ at } \lambda = 100\ \mu\text{m}$$

No extra dimensions were found (95% CL) down to λ = 78 μm.

Paik-16

UM2 with density-modulated source

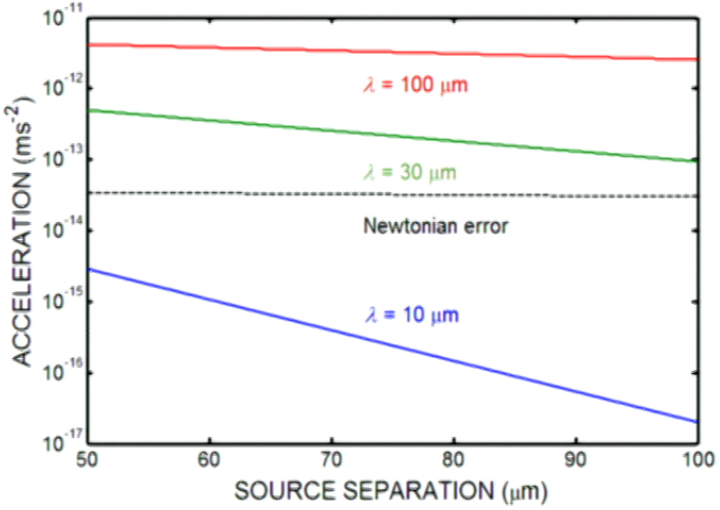
- $1/r^2$ law test using a distance-modulated source becomes increasingly difficult as λ decreases because the source modulates parasitic forces from patch fields, Casimir effect, and residual pressure.
- By using a density-modulated source moving laterally, it may be possible to extend the search for extra dimensions to $\lambda \sim 10\ \mu m$.

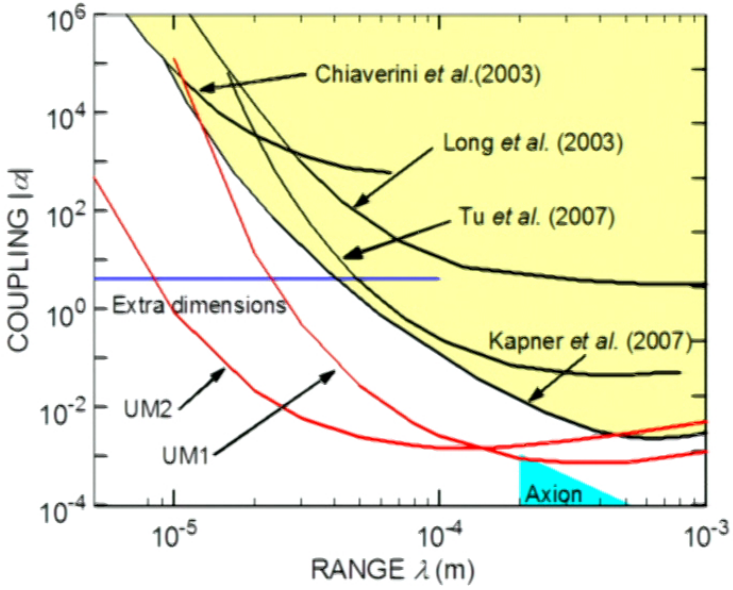


Paik-17

Potential sensitivity of UM2

- Yukawa signal is sensitive to separation d, especially for $\lambda \leq 30$ μm, whereas Newtonian signal varies by only 2% as d varies from 50 to 100 μm.
- By repeating test at d = 50 and 100 μm and subtracting the two results, 98% of metrology error is removed while Yukawa signal remains almost unchanged.

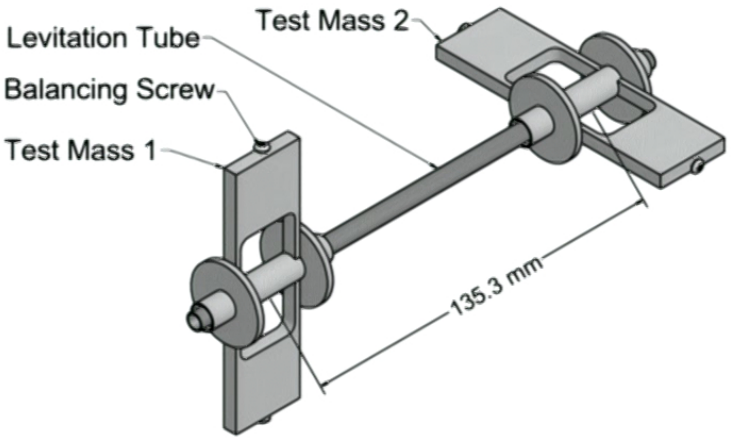




Paik-19

SGG with levitated masses

- New levitated SGG is under development with NASA support.
- A pair of test masses with orthogonal moment arms are levitated by a current on a single levitation tube.



Paik-20

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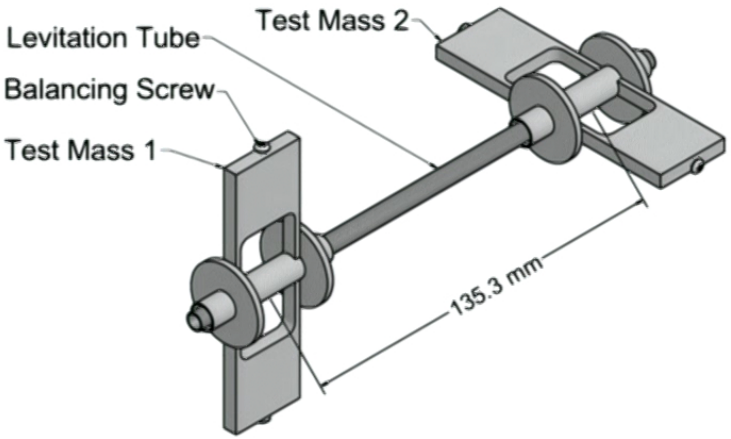
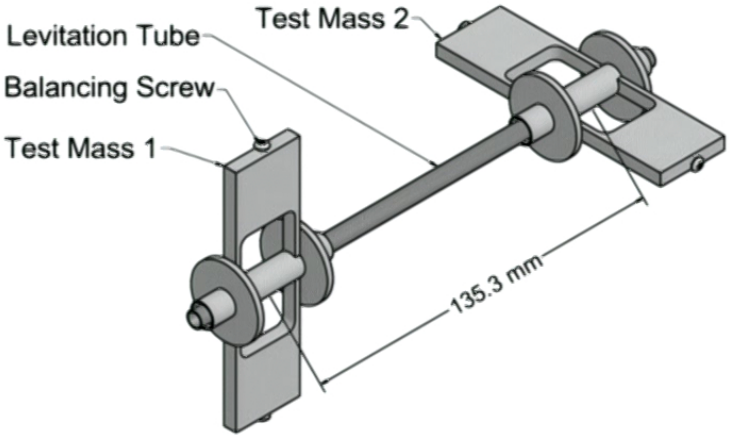
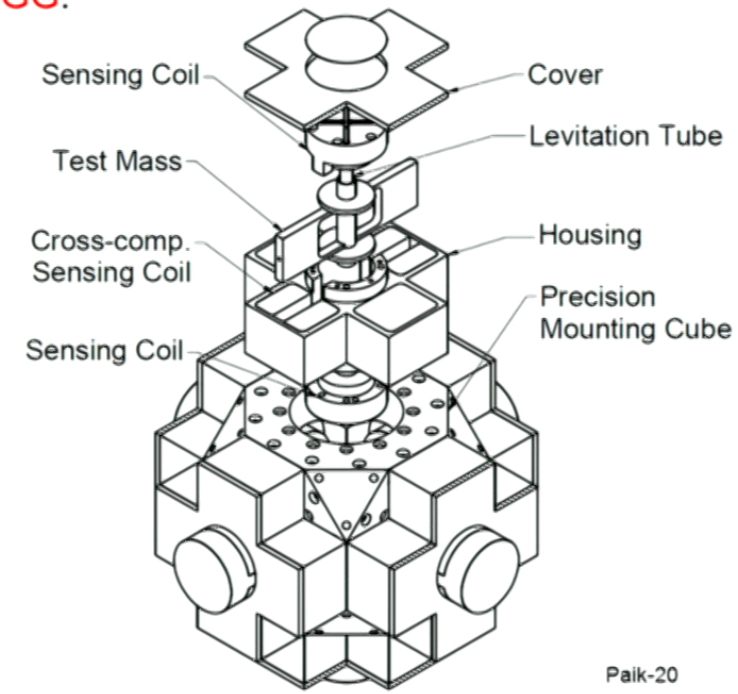


Paik-20

SGG with levitated masses

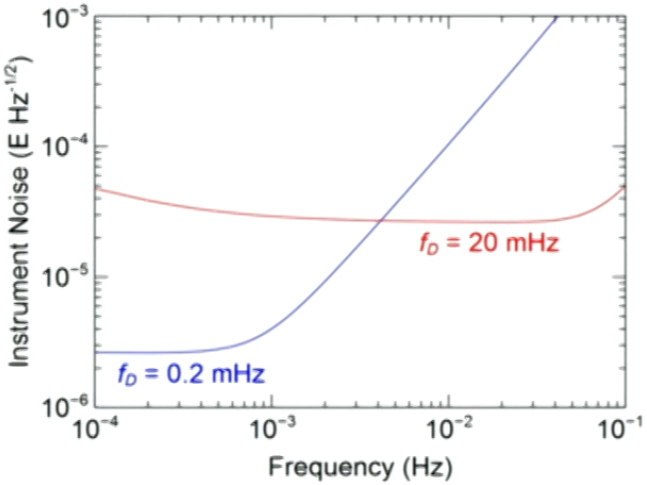
- New levitated SGG is under development with NASA support.
- A pair of test masses with orthogonal moment arms are levitated by a current on a single levitation tube.
- Three orthogonal pairs form a tensor SGG.



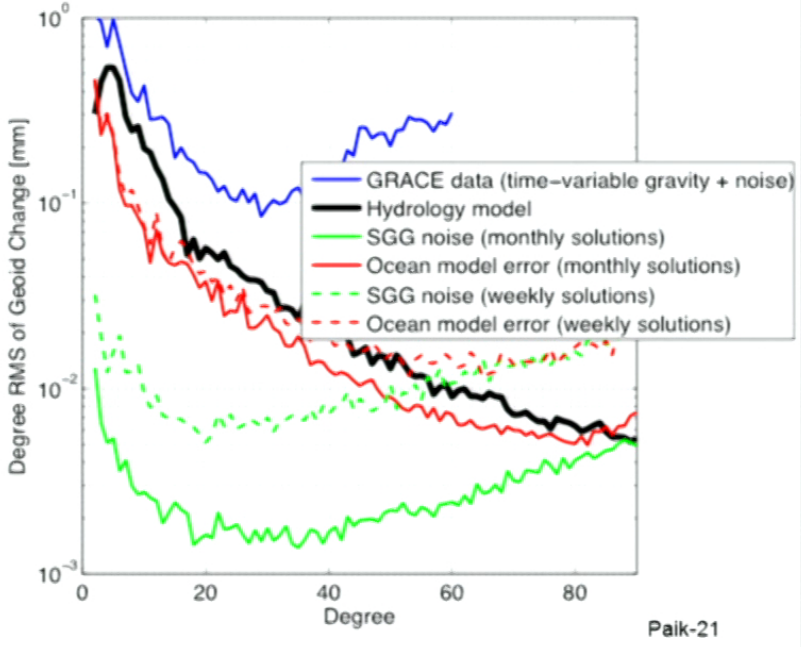


SGG Earth science mission

- Tensor SGG with m = 1 kg, ℓ = 0.2 m, $S_{\Gamma}^{1/2}(f)$ = 3 x10^{-5} E Hz$^{-1/2}$ over 0.5~50 mHz.
- SGG could be *tuned* during the mission to yield higher sensitivity at high f for high spatial resolution or low f for time-variable gravity signals.
- Cryocooler will permit 5-10 year mission lifetime.



Instrument noise spectral density



Paik-21

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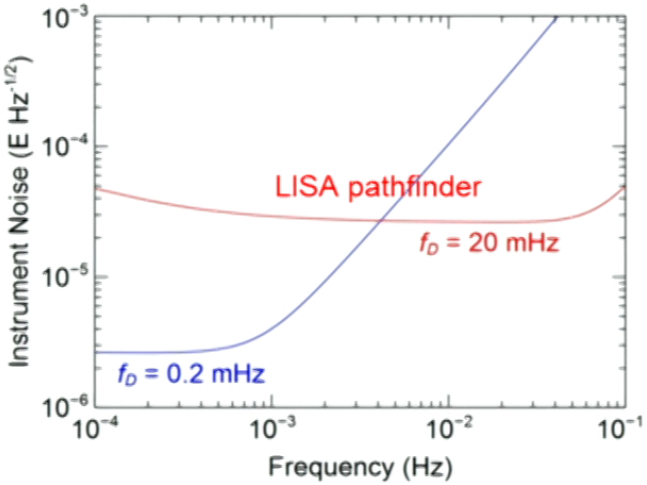
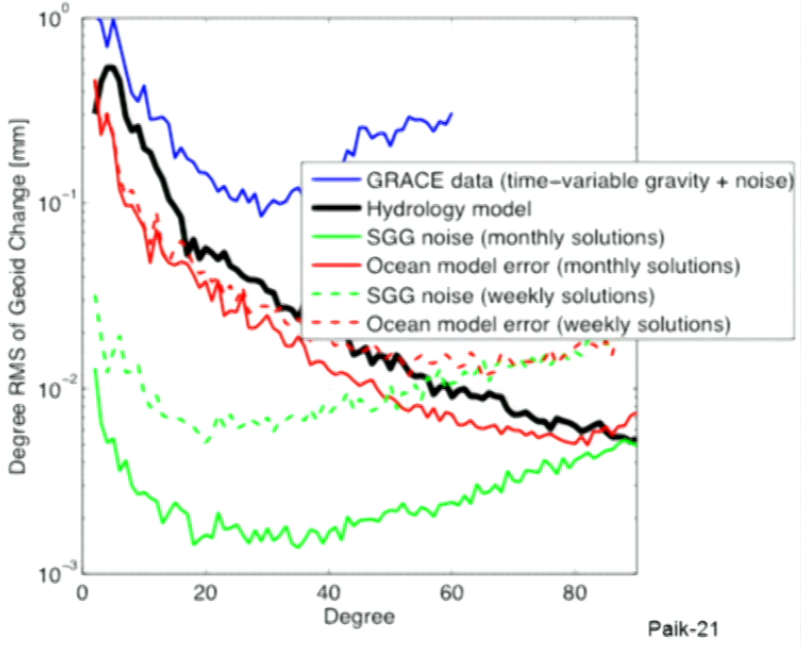
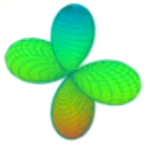


Instrument noise spectral density



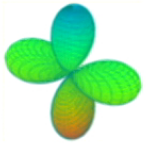
Electrostatic patch fields



- Electrostatic patch fields and trapped magnetic flux limited the performance of GP-B superconducting gyros.
- Parasitic stiffness due to patch fields: $\frac{\partial F}{\partial x} \cong 1.8 \frac{\varepsilon_0 A v^2}{d^3}$ (Speake, 96)

Paik-22

Electrostatic patch fields



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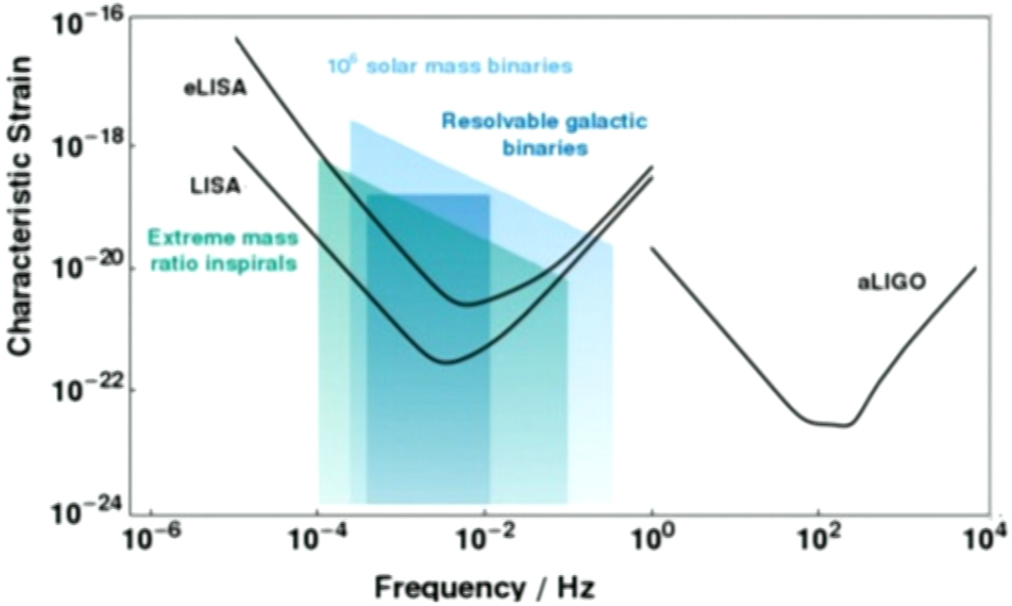
- Parasitic stiffness due to patch fields: $\frac{\partial F}{\partial x} \cong 1.8 \frac{\varepsilon_0 A v^2}{d^3}$ (Speake, 96)
- For high-purity Nb, v = 0.36 V. With design parameters A = 4 cm^2 and d = 0.2 mm, the patch fields affect the spring constant of the SGG as

$$k = m\omega_c^2 - \frac{\partial F}{\partial x} = \left(1.58 - 1.0 \times 10^{-4}\right) \mathrm{N/m}$$

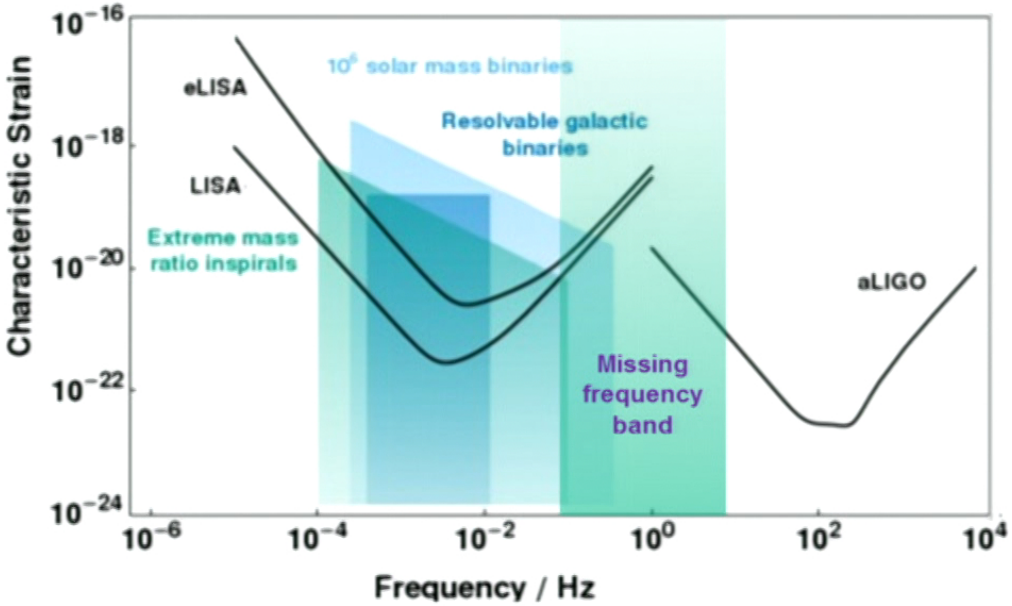
- In high vacuum and temperature controlled environment, the patch fields should remain stationary in time.
- Parasitic stiffness due to patch fields (and trapped flux) modifies the CM stiffness only by one part in 10^4 and is nulled in the process of axis alignment and CM balance (10^9).

GW detector bandwidths



Paik-23

GW detector bandwidths



- Merger of IMBHs and inspiraling stellar mass BHs are expected to produce signals at 0.1 to 10 Hz bandwidth.
- Could a terrestrial antenna be built to fill this missing band?

Paik-23

Long-baseline resonant-mass detector

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.

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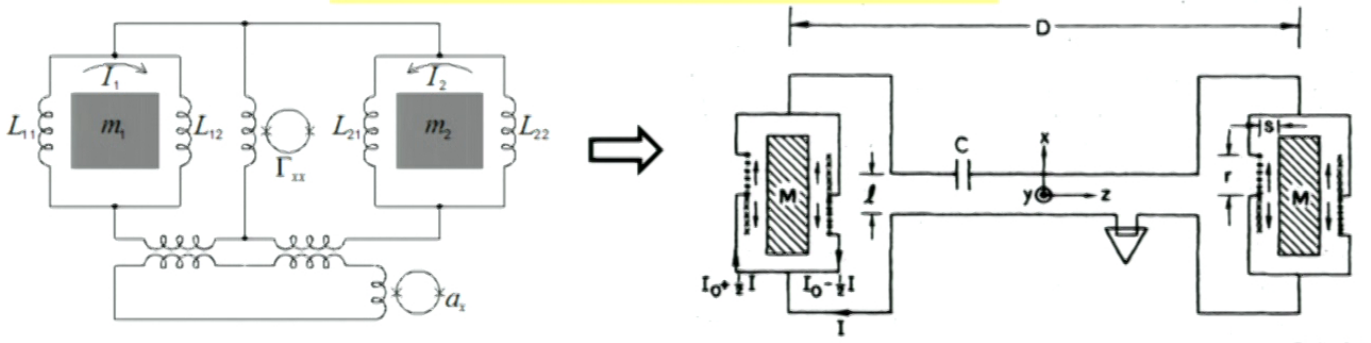
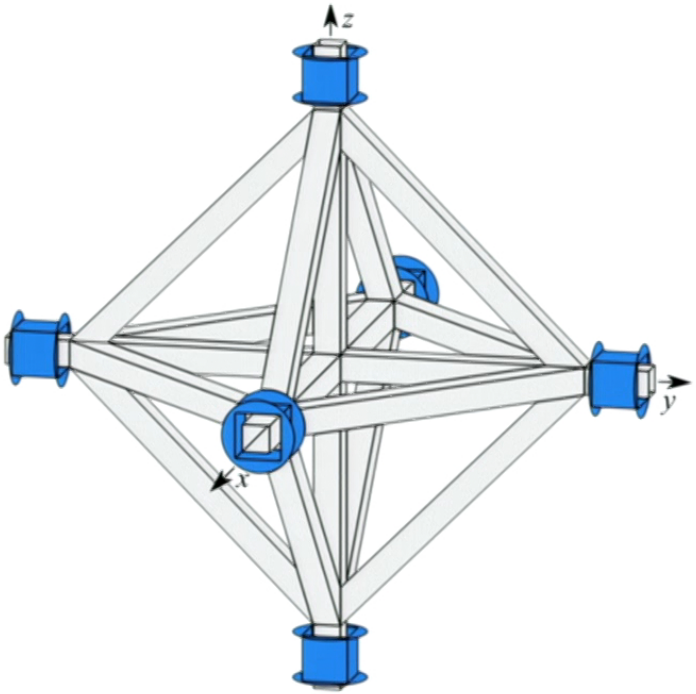
- Gravity gradients are Riemann tensor components.

$$R_{0i0j} \rightarrow \Gamma_{ij} = -\partial^2\phi / \partial x_i \partial x_j \quad \text{in Newtonian limit.}$$



Paik-24

SOGRO (Superconducting Omni-directional Gravitational Radiation Observatory)



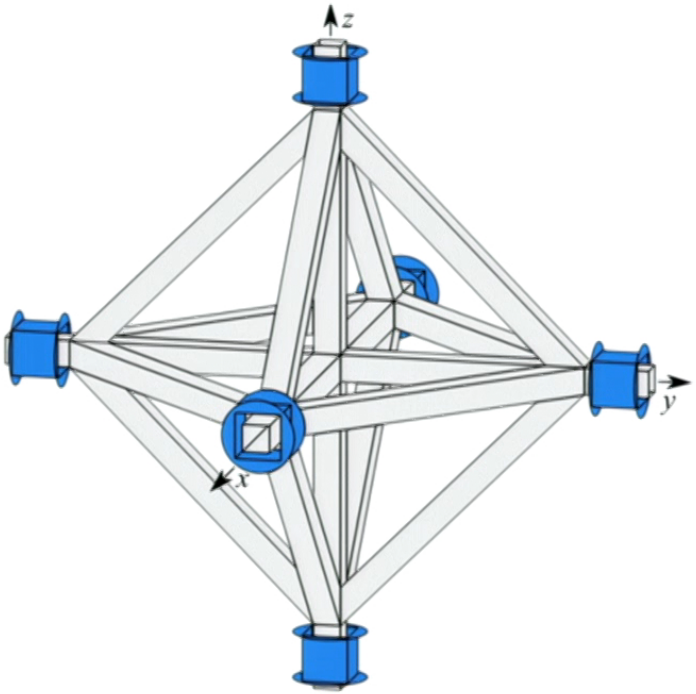
- Each test mass has 3 DOF.
- Combining six test masses, tensor GW detector is formed.

$$h_{ii}(t) = \frac{2}{L}\left[x_{+ii}(t) - x_{-ii}(t)\right]$$

$$h_{ij}(t) = \frac{1}{L}\left\{\left[x_{+ij}(t) - x_{-ij}(t)\right] - \left[x_{-ji}(t) - x_{+ji}(t)\right]\right\}, i \neq j$$

Paik-25

SOGRO (Superconducting Omni-directional Gravitational Radiation Observatory)



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- Source direction (θ, ϕ) and polarization ($h+$, $h\times$) can be determined by a single antenna. ⇨"Spherical" Antenna

+ polarization **x polarization**

Paik-25

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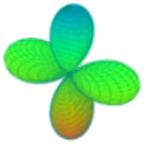

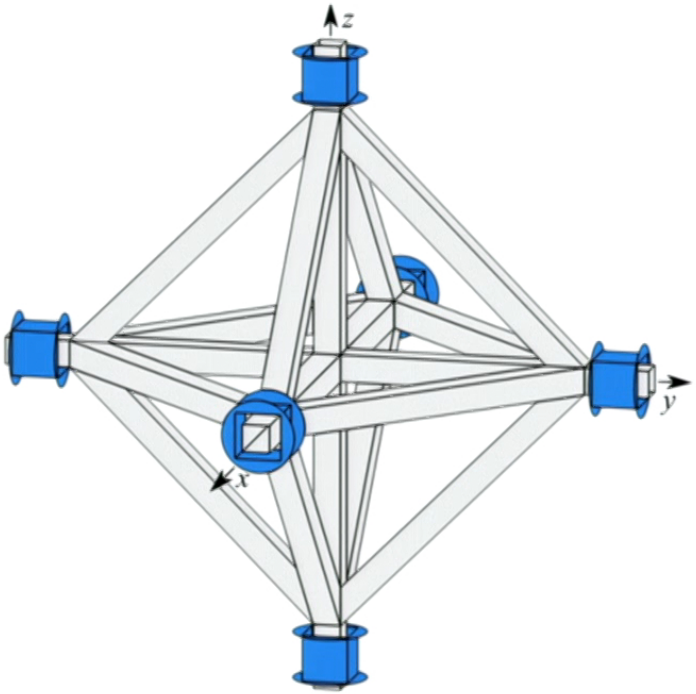

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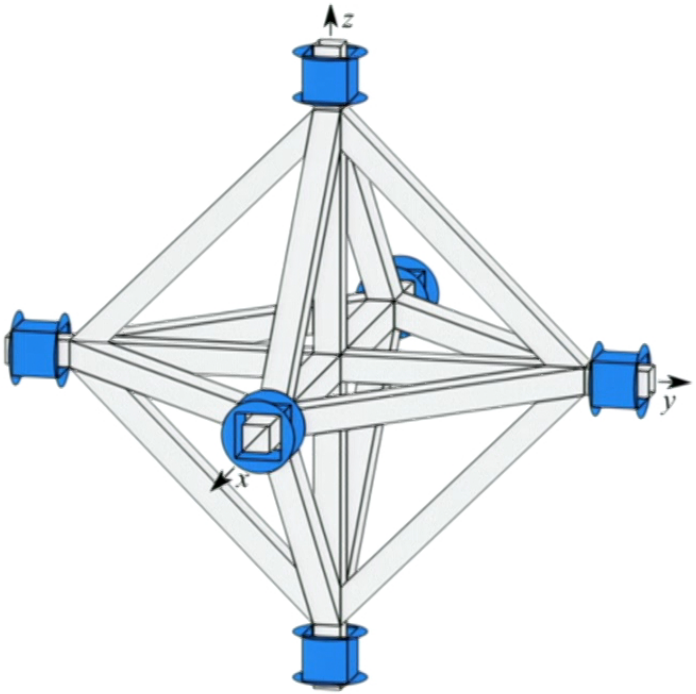

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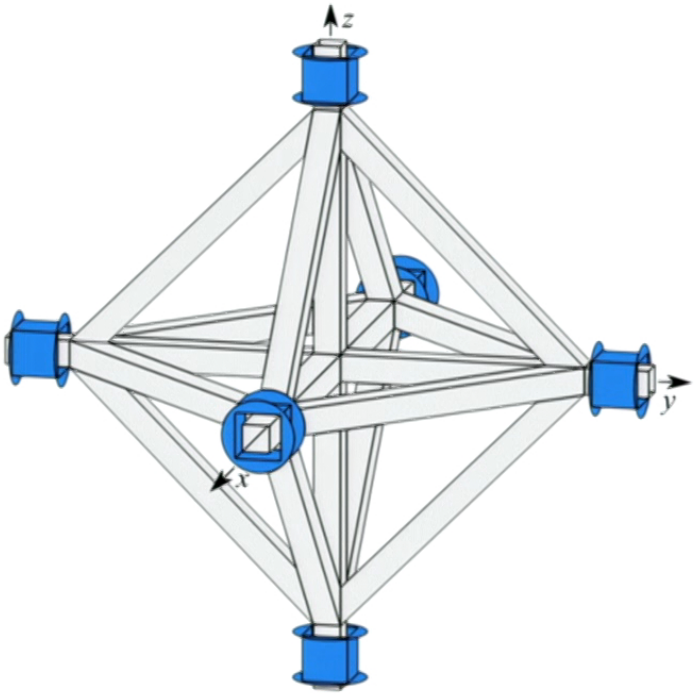

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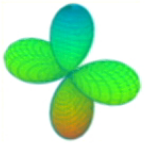

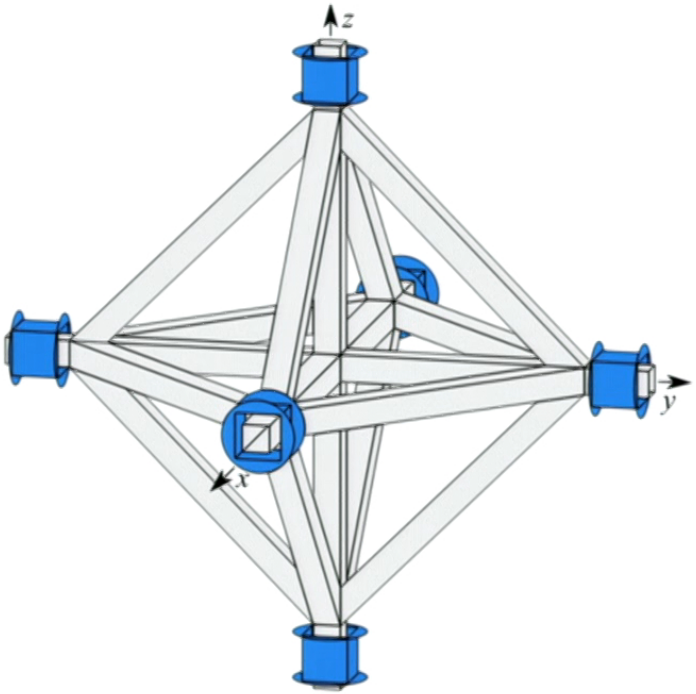

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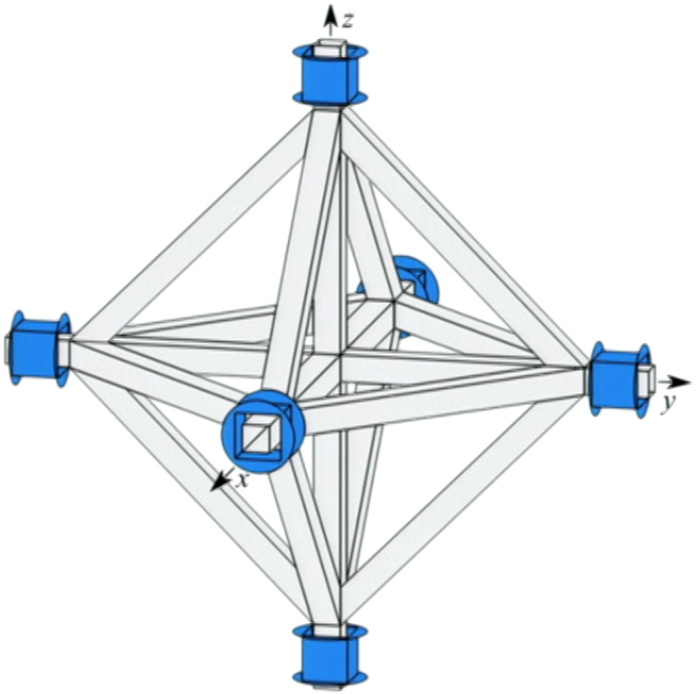

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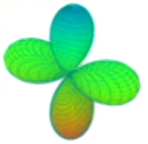

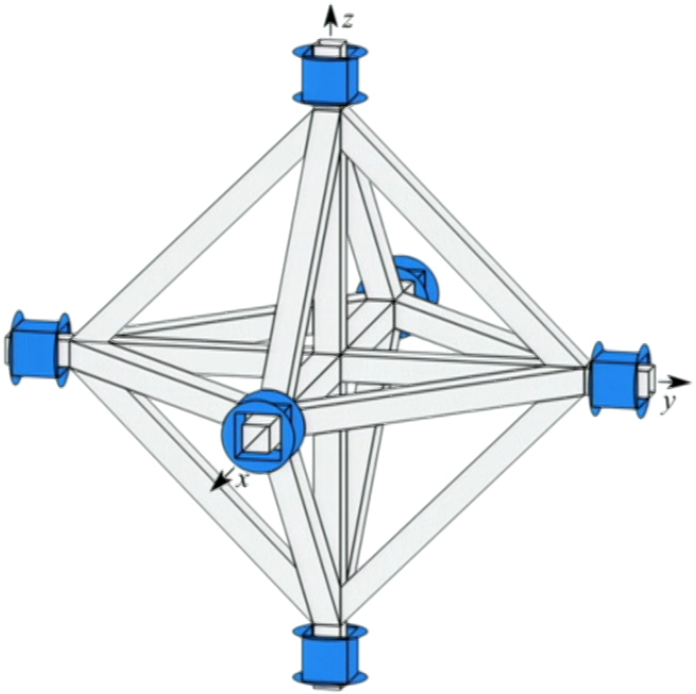

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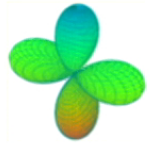
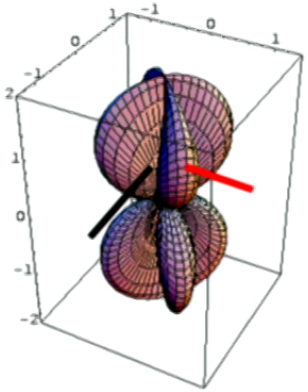
Paik-25

Antenna pattern

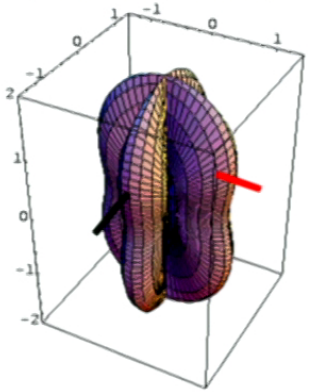


LIGO

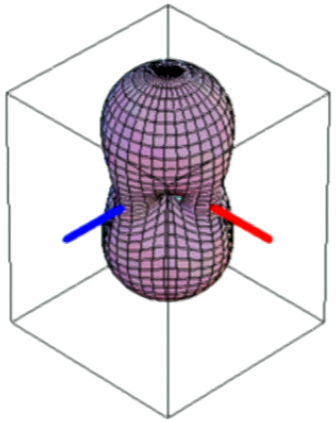
× polarization



+ polarization



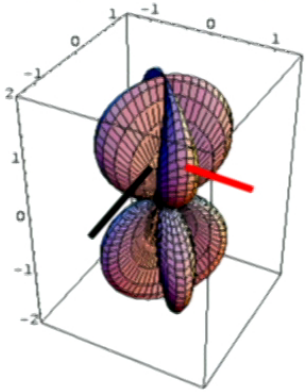
rms sensitivity



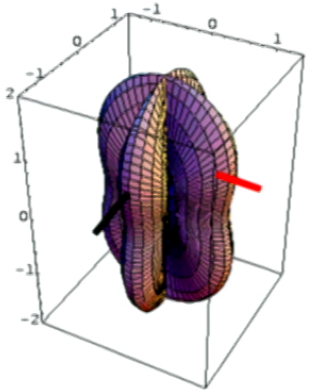
Antenna pattern

LIGO

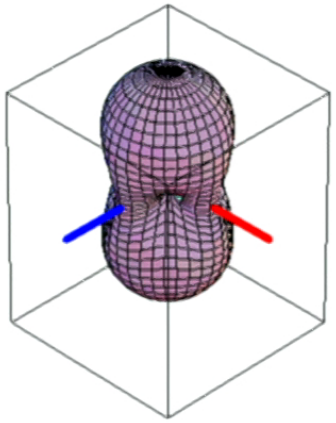
× polarization



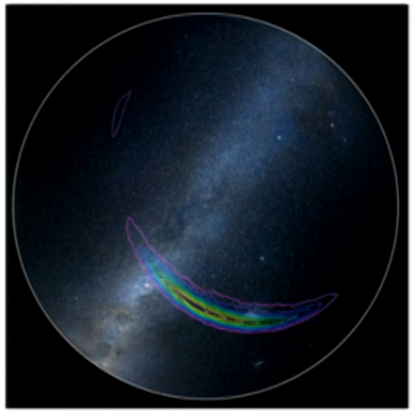
+ polarization



rms sensitivity



Sky location of GW150914



Design philosophy of SOGRO

$$\ddot{h}_{ij} = 2\Gamma_{ij} \rightarrow h_{GW}(f) > h_N(f) = \frac{2}{\omega^2}\Gamma_N(f)$$

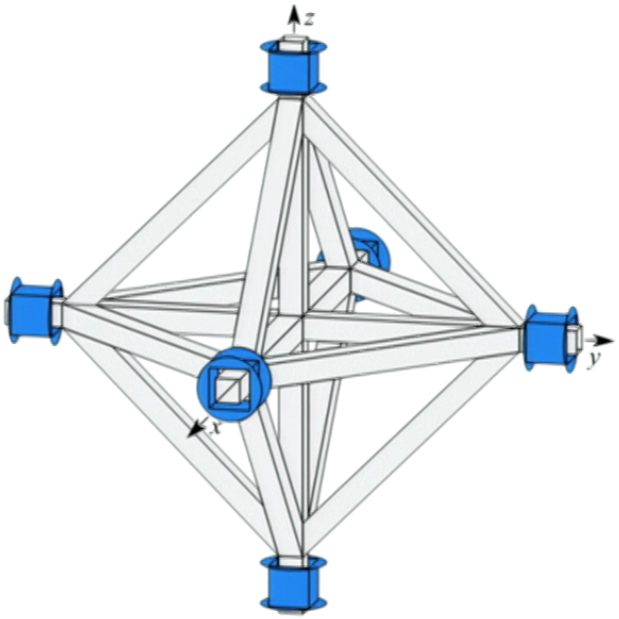
As f is lowered from 100 Hz to 1 Hz, $\Gamma_N(f)$ must be lowered by 10^4 for the same $h_{GW}(f)$.

- Extremely low detector noise is required.
  - ⇨ *Low T, high Q, nearly quantum-limited* amplifier.
- Test mass suspension frequency should be lowered to below signal bandwidth.
  - ⇨ *Almost free* test masses by magnetic levitation.
- Seismic noise is very difficult to isolate at low frequencies.
  - ⇨ High *CM rejection* in a superconducting differential accelerometer.
- Newtonian noise increases sharply below 10 Hz and *cannot* be shielded.
  - ⇨ *Tensor* detector can help mitigate the NN.

H. J. Paik, C. E. Griggs, M. V. Moody, K. Venkateswara, H. M. Lee, A. B. Nielsen, E. Majorana and J. Harms, *Class. Quantum Grav.* **33,** 075003 (2016)

Suspension of SOGRO platform

- Go underground (> 500 m) to reduce the seismic and Newtonian noise, as well as to be far away from moving objects.
- Infrasound is attenuated to 0.15 at 0.2 Hz and to 10^{-8} at 1 Hz.



- Platform needs to be rigid with all DM modes > 10 Hz and Q > 10^6.

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Paik-28

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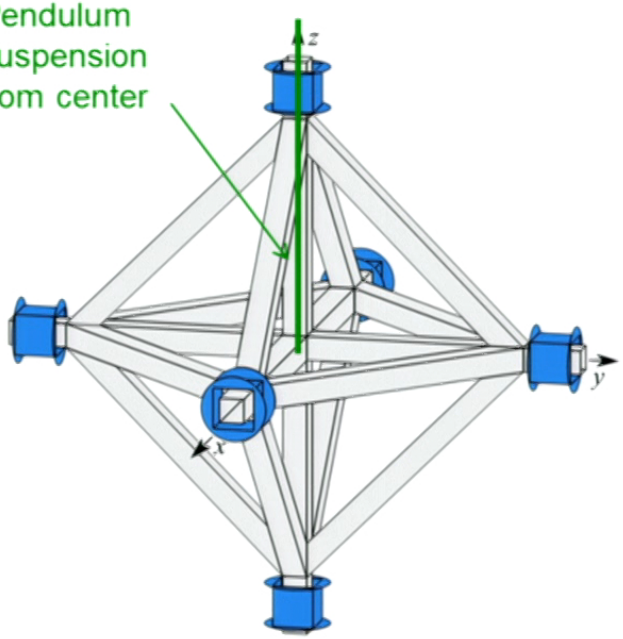
Pendulum suspension from center



- Platform needs to be rigid with all DM modes > 10 Hz and Q > 10^6.
  ⇨ Careful engineering design required.
- Nodal support prevents odd harmonics from being excited.
- 50-m pendulum: f_p = 0.07 Hz for pendulum modes and $f_\phi < 10^{-2}$ Hz for torsional mode.
  ⇨ Completely decouples ground tilt and provides > 40 dB isolation at 1 Hz for horizontal and torsional modes.

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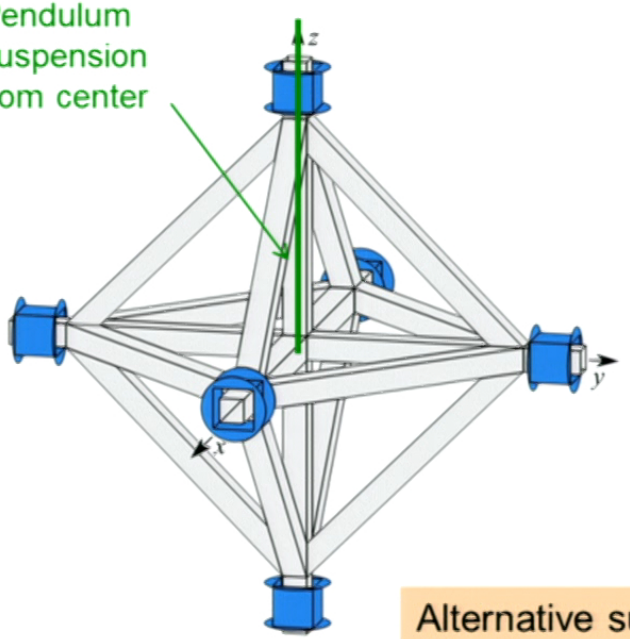

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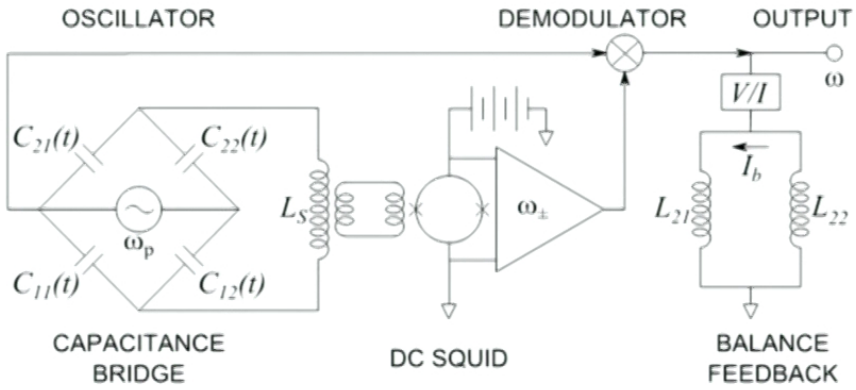
Alternative suspension: Optical rigid body
Simpler cryogenics, larger baseline (≥ 1 km?)

Paik-28

Tuned capacitor-bridge transducer

- Near quantum-limited SQUIDs have 1/f noise below 10 kHz.
- Signal needs to be upconverted to ≥ 10 kHz by using an active transducer.
- Capacitor bridge coupled to nearly quantum-limited SQUID.



Cinquegrana *et al.*, PRD 48, 448 (1993)

- Bridge is driven at *LC* resonance frequency ω_p .
- Energy coupling:

$$\beta \approx \frac{2CE_p^2 Q_p}{M\left|\omega^2 - \omega_D^2\right|} > 1$$

- Oscillator noise is rejected by the bridge balance.

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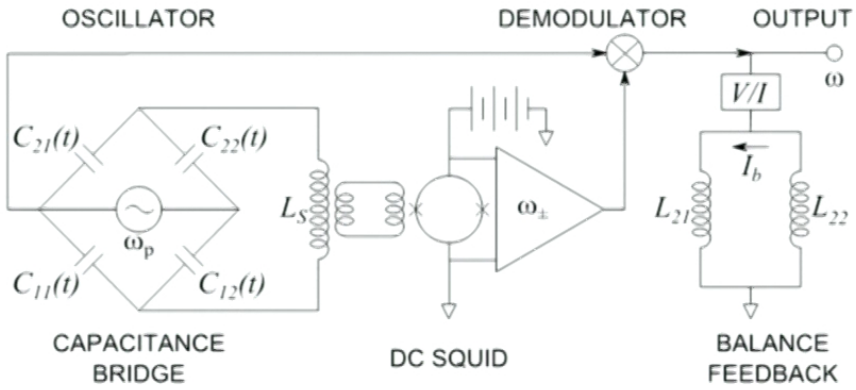

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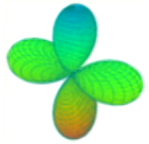
$$S_h(f) = \frac{16}{ML^2\omega^4}\left\{\frac{k_B T \omega_D}{Q_D} + \frac{\left|\omega^2 - \omega_D^2\right|}{2\omega_p}\left(1 + \frac{1}{\beta^2}\right)^{1/2} k_B T_N\right\},\ k_B T_N = n\hbar\omega_p$$

Paik-29

Astrophysics with SOGRO



Parameter	SOGRO	aSOGRO
Each test mass M	5 ton	5 ton
Arm-length L	50 m	50 m
Antenna temp T	4.2 K	0.1 K
Platform temp T_{pl}	4.2 K	4.2 K
DM frequency f_D	0.01 Hz	0.01 Hz
DM Q factor Q_D	10^7	10^8
Platform Q factor Q_{pl}	10^6	10^7
Pump frequency f_p	50 kHz	50 kHz
Amplifier noise no. n	20	5
Detector noise $S_h^{1/2}(f)$	3×10^{-20} Hz$^{-1/2}$	5×10^{-21} Hz$^{-1/2}$

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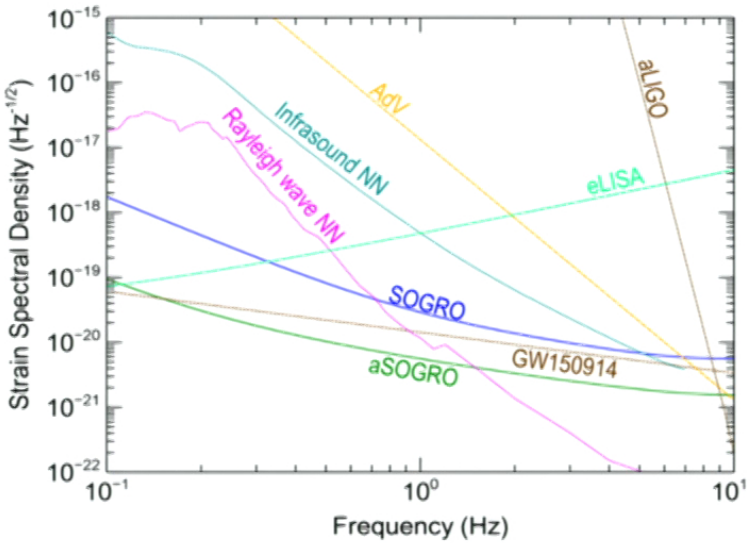

- aSOGRO could detect IMBH binaries with 10^4-$10^5 M_\odot$ at a few billion light years away, and WD binaries within the Local Group.
- aSOGRO could detect BH binaries like GW150914 with SNR ~ 5.

  ⇨ Alert interferometers days before merger.

Paik-30

Astrophysics with SOGRO

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Arm-length L	50 m	50 m
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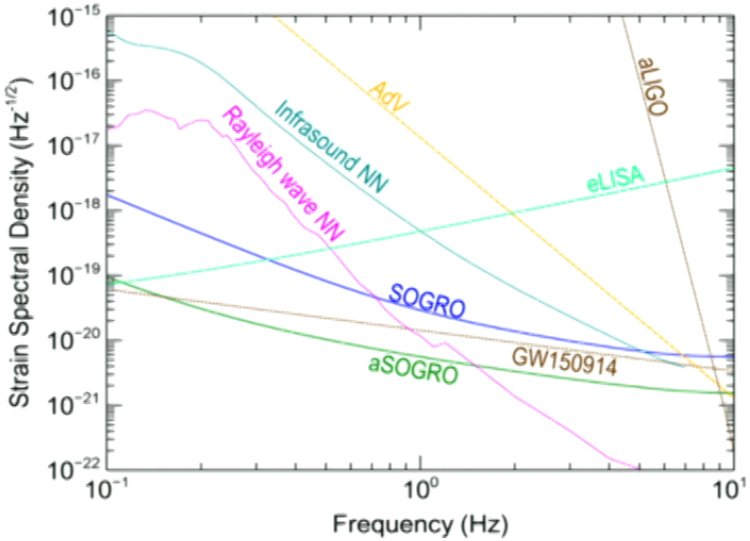

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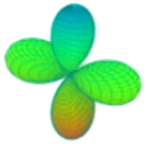
SOGRO is being studied by a consortium of research institutions in Korea.

Paik-30

Electrostatic patch fields



- Electrostatic patch fields and trapped magnetic flux limited the performance of GP-B superconducting gyros.
- Parasitic stiffness due to patch fields: $\frac{\partial F}{\partial x} \cong 1.8 \frac{\varepsilon_0 A v^2}{d^3}$ (Speake, 96)
- For high-purity Nb, v = 0.36 V. With design parameters A = 4 cm^2 and d = 0.2 mm, the patch fields affect the spring constant of the SGG as

$$k = m\omega_c^2 - \frac{\partial F}{\partial x} = \left(1.58 - 1.0 \times 10^{-4}\right) \mathrm{N/m}$$

- In high vacuum and temperature controlled environment, the patch fields should remain stationary in time.
- Parasitic stiffness due to patch fields (and trapped flux) modifies the CM stiffness only by one part in 10^4 and is nulled in the process of axis alignment and CM balance (10^9).