The dynamical Casimir effect, and the possibility of laser-like generation of gravitational radiation*

Talk at Aerospace Workshop on Advanced Propulsion, by Raymond Chiao

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Our Team:
Collaborators, Postdocs, & Students

- Prof. Jay Sharping,* UC Merced (Experiment)

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- Dr. Luis Martinez, UC Merced
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- Nathan Inan (Theory)
- Al Castelli (Experiment)
- Jacob Pate (Experiment)
- Johnathon Thompson (Both)

- Jacob Parker (Senior)

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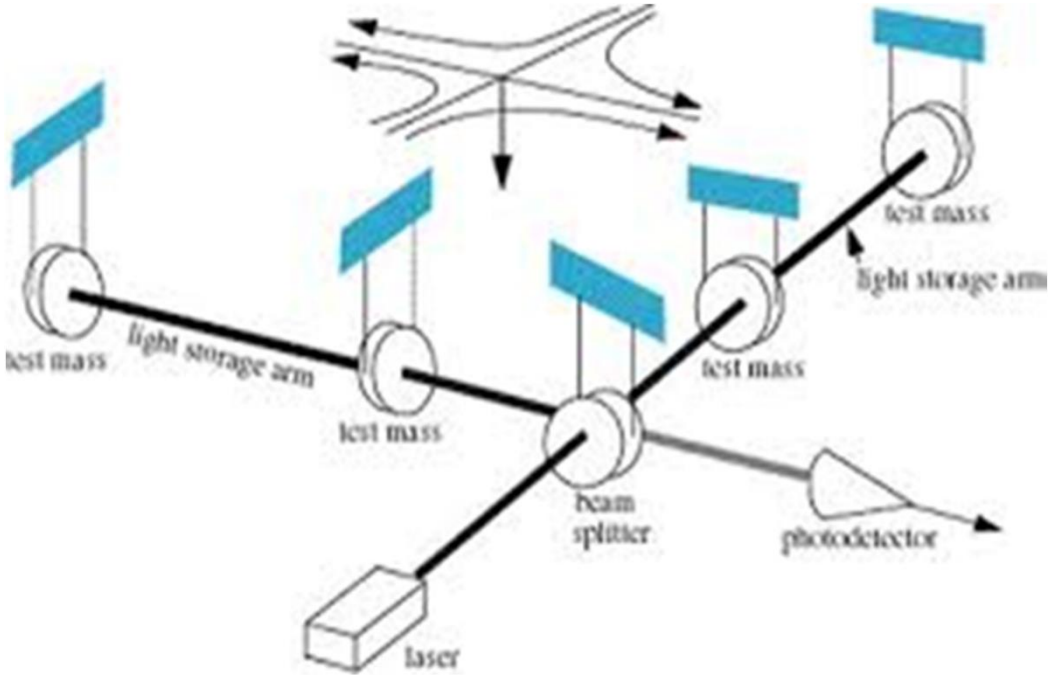
Faculty

Postdocs and Students

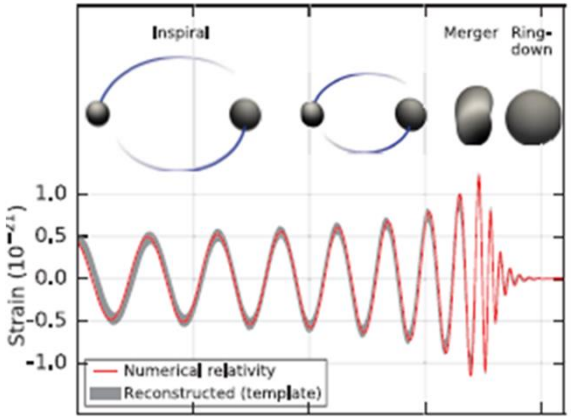
Motivation: Recent LIGO detections of gravitational radiation (GR)

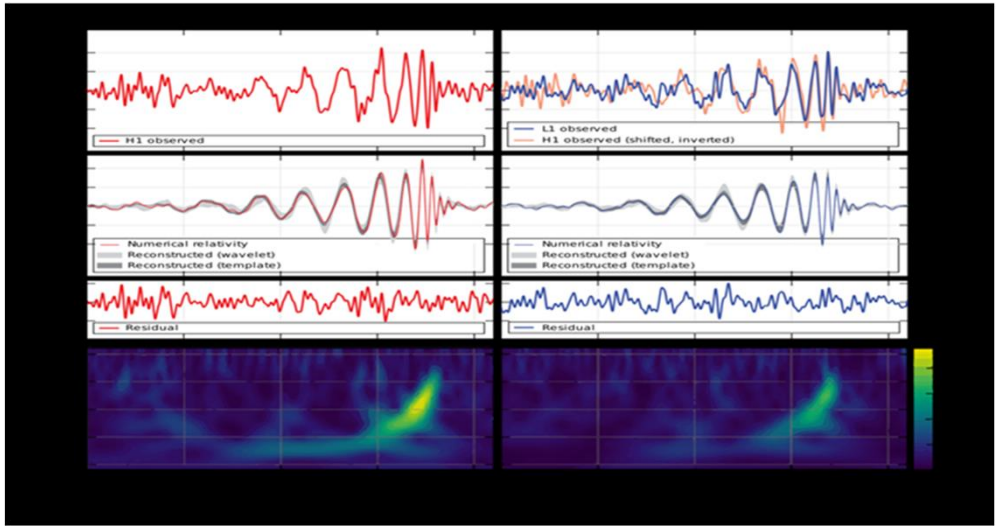
- LIGO (Laser Interferometer Gravitational-Wave Observatory) and VIRGO (European, Italy)



GR Detections by LIGO

- First observation (9.14.2015) PRL 116, 061102 (2016)





- Fourth observation (8.17.2017) PRL 119, 161101 (2017) "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral"

Can GR be generated in the lab?

- Generation of gravitational radiation (GR) in the lab seems impossible.

ñThe construction of a laboratory generator of gravitational radiation is a non attractive enterprise in the absence of new engineering or a new idea or both.ò

(Misner, Thorne, and Wheeler, *Gravitation*, page 979)

GR generation via quantum mechanics

Gravitational Vacuum Fluctuations?

Quantum mechanical sources of GR waves?

In quantum mechanics

- Uncertainty principle

  $\Delta\square\Delta\square\square \ \square/2$

Vacuum fluctuation (zero point energy) for *any* kind of wave, including gravitational waves:

$$E_0 = \tfrac{1}{2}\hbar\omega, \ \omega = \text{wave frequency}$$

INDEPENDENT of G and c

DEPENDENT on $\hbar$

Amplification of gravitational radiation (GR) by the *stimulated emission of radiation*

- *Laser-like* generation of GR should be possible starting from vacuum fluctuations as ñseed radiationò.

- Parametric amplification of vacuum fluctuations via the dynamical Casimir effect may be a practical method to generate GR.

Stimulated emission of gravitons

- For quantum radiation oscillators from *linearized* GR theory:

$$[a_G, a_G{}^\dagger] = 1 \text{ where}$$

$$a_G = \text{graviton } \textit{annihilation} \text{ operator}$$

$$a_G{}^\dagger = \text{graviton } \textit{creation} \text{ operator}$$

Stimulated emission occurs when

$$a_G{}^\dagger \left| n_G \right\rangle = \sqrt{n_G + 1} \left| n_G + 1 \right\rangle$$

where

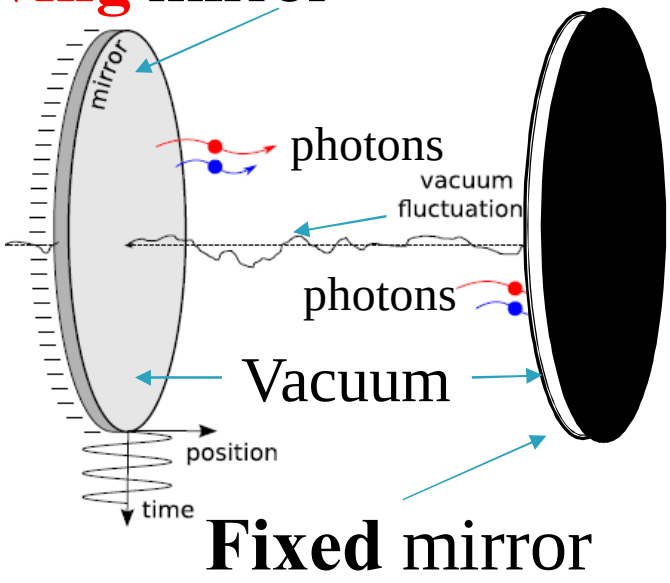
$$\left| n_G \right\rangle = \text{graviton } n_G \text{ number state}$$

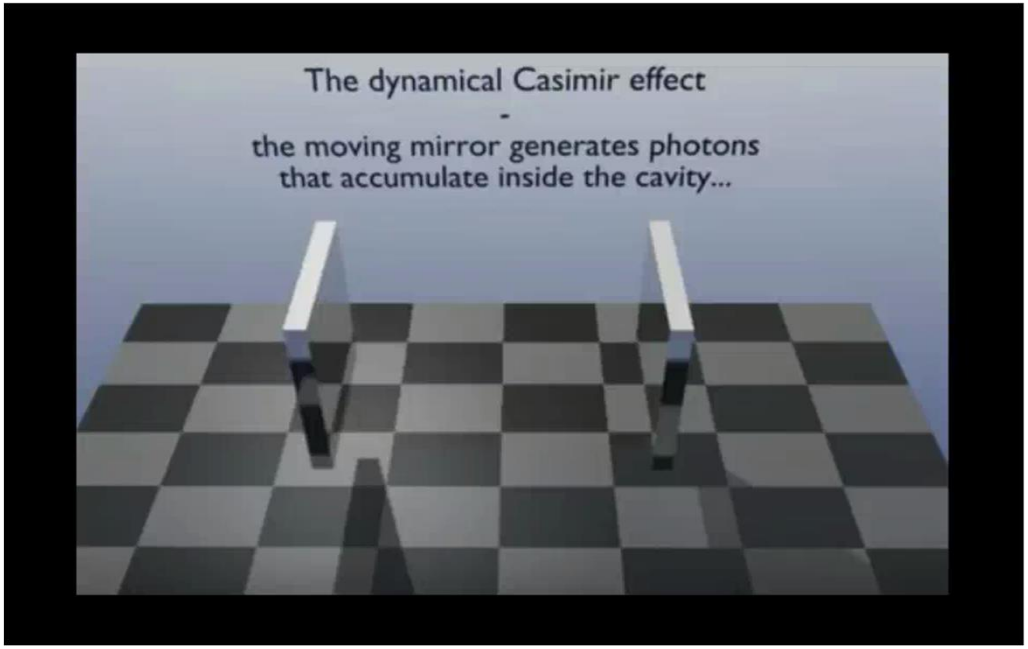
$$\left| n_G + 1 \right\rangle = \text{graviton } n_G + 1 \text{ number state}$$

What is the Dynamical Casimir Effect?

Conversion of vacuum fluctuations into detectable waves (i.e., particles, e.g., photons and gravitons)

- **Moving** mirror

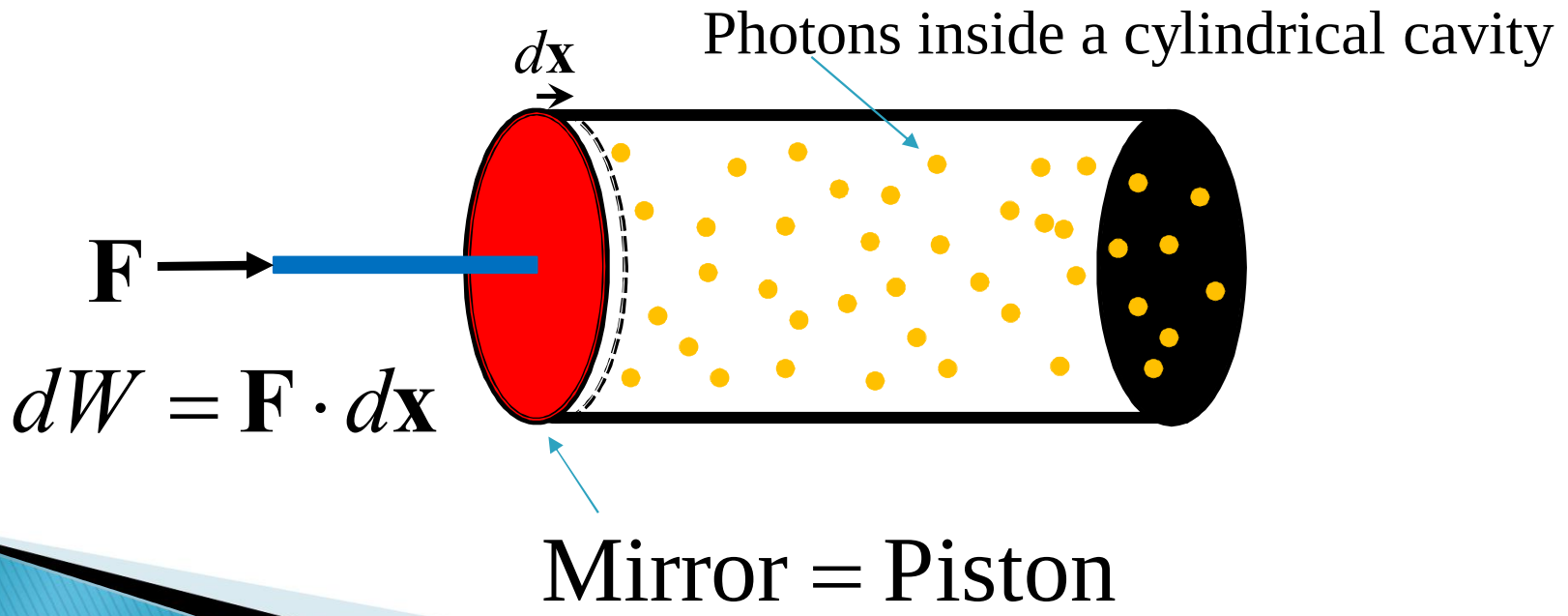




- G.T.Moore, J.Math. Phys.(N.Y.) 11 (1970), 2679
- S.A.Fulling and P.C.W.Davies, Proc.R.Soc. A 348(1976), 393

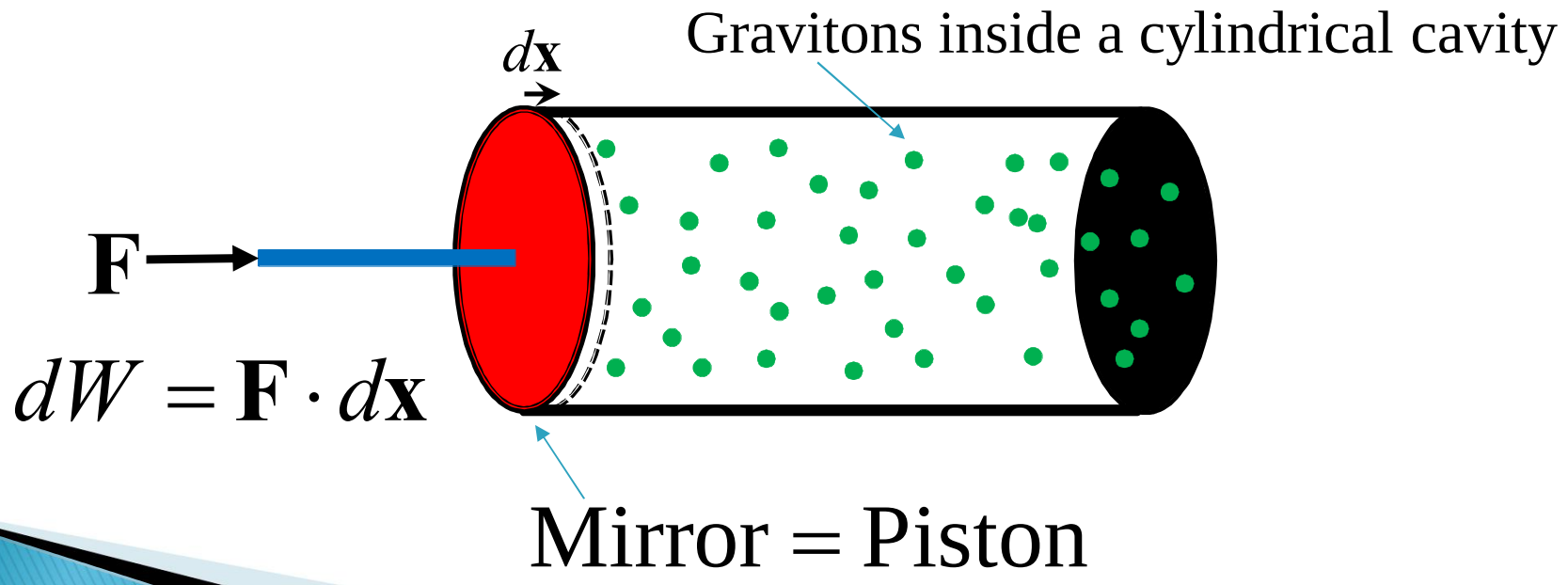
What is the Dynamical Casimir effect?

- A moving **mirror** is a moving **piston** that can do **work** on a photon gas e.g. vacuum fluctuations in a SRF cavity, converting them to **detectable** EM waves)

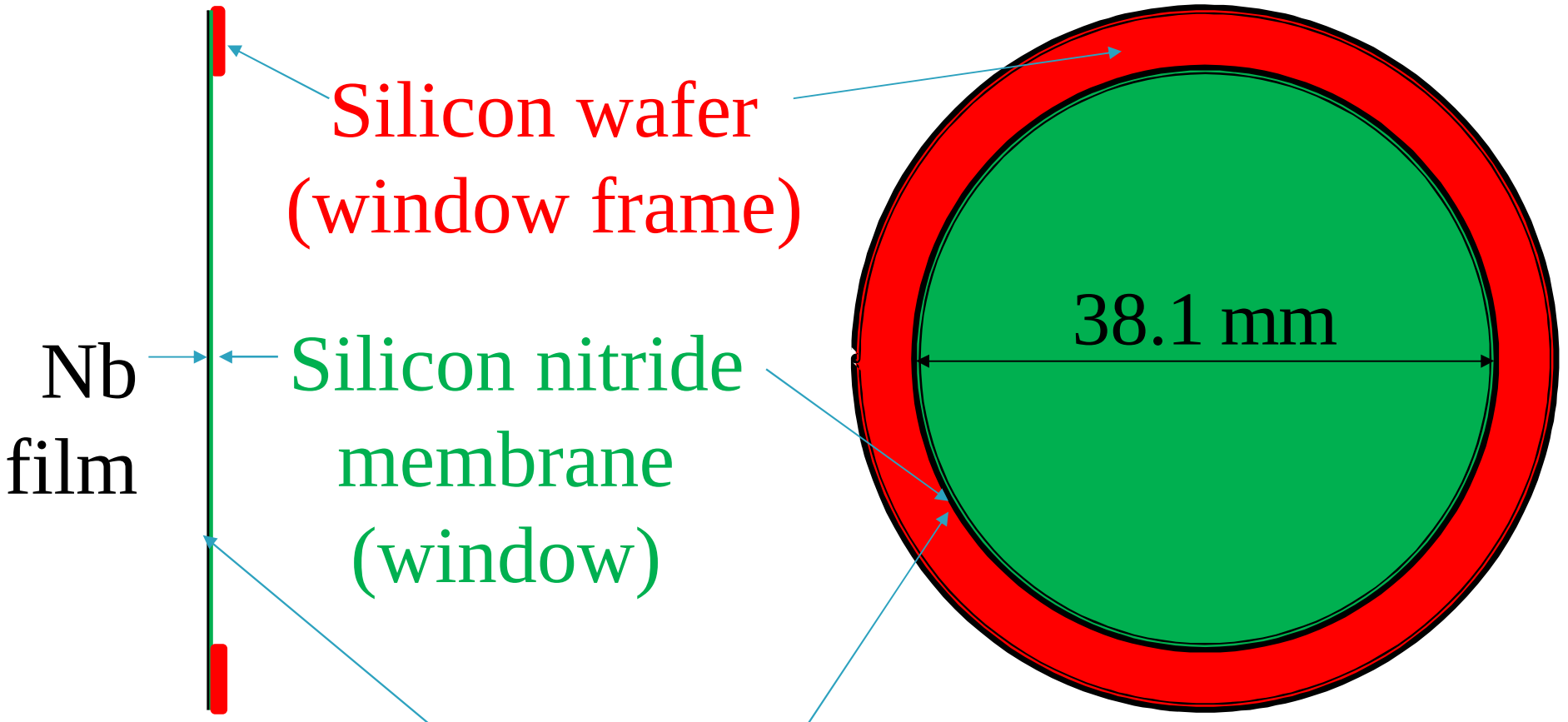


What is gravitational Dynamical Casimir Effect?

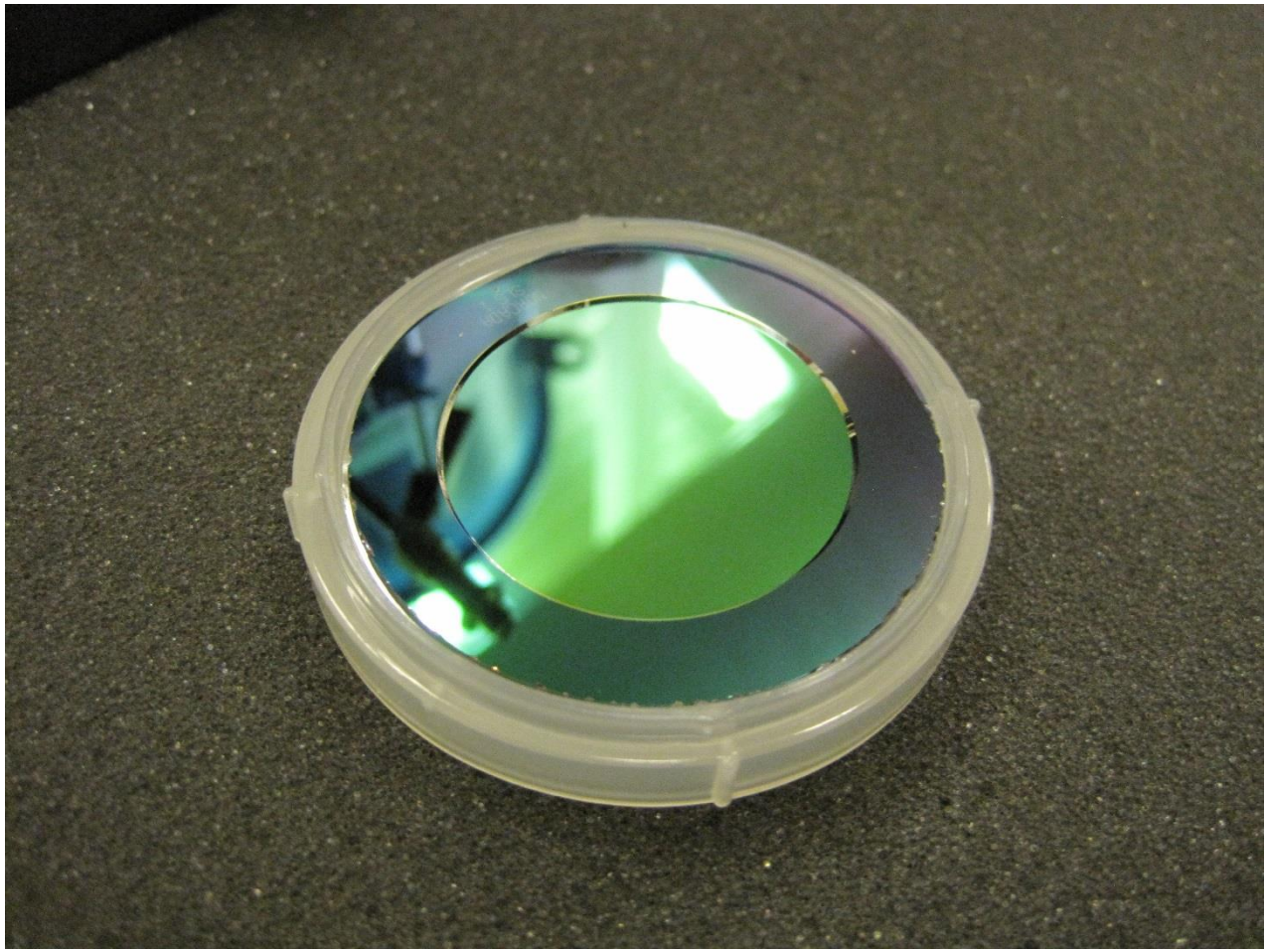
- A moving **mirror** is a moving **piston** that can do **work** on a graviton gas e.g. GR vacuum fluctuations, converting them to **detectable** gravitational waves)



What is our *moving* mirror?



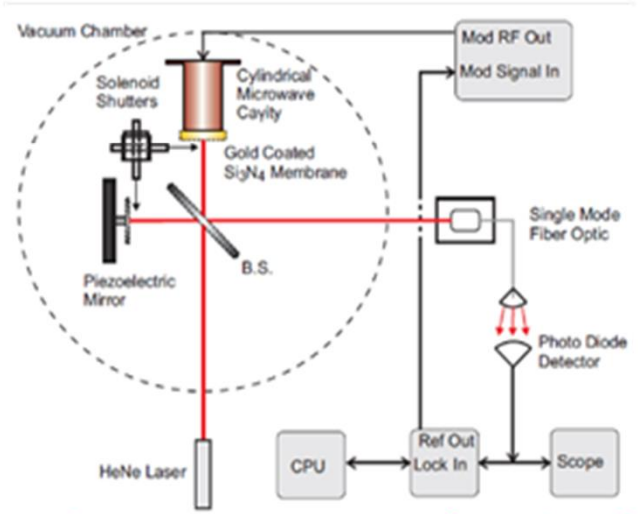
Our Nb-coated SiN membrane sample

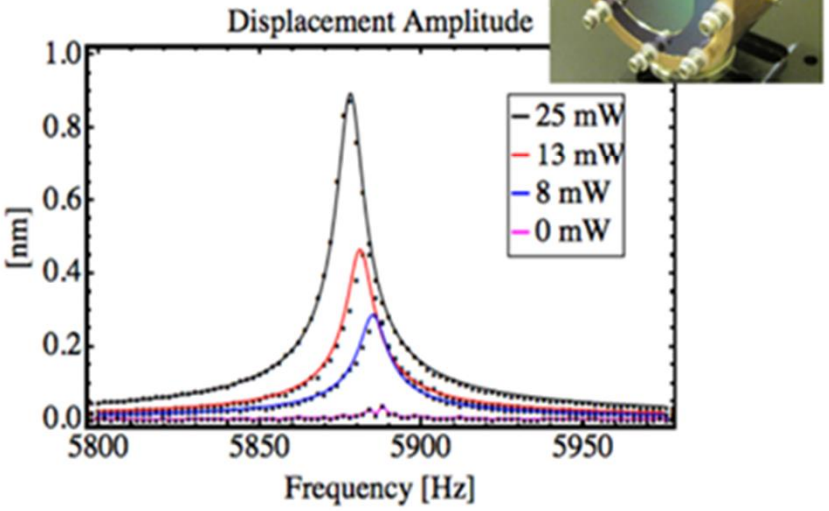


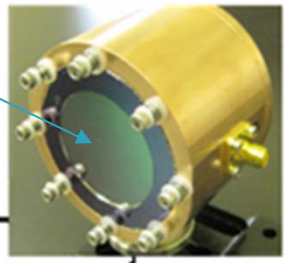
50 mm

Silicon nitride membranes coated with SC niobium will serve as the moving mirrors

- Experiment has observed acoustical oscillations of inch-diameter silicon nitride membranes coated with niobium

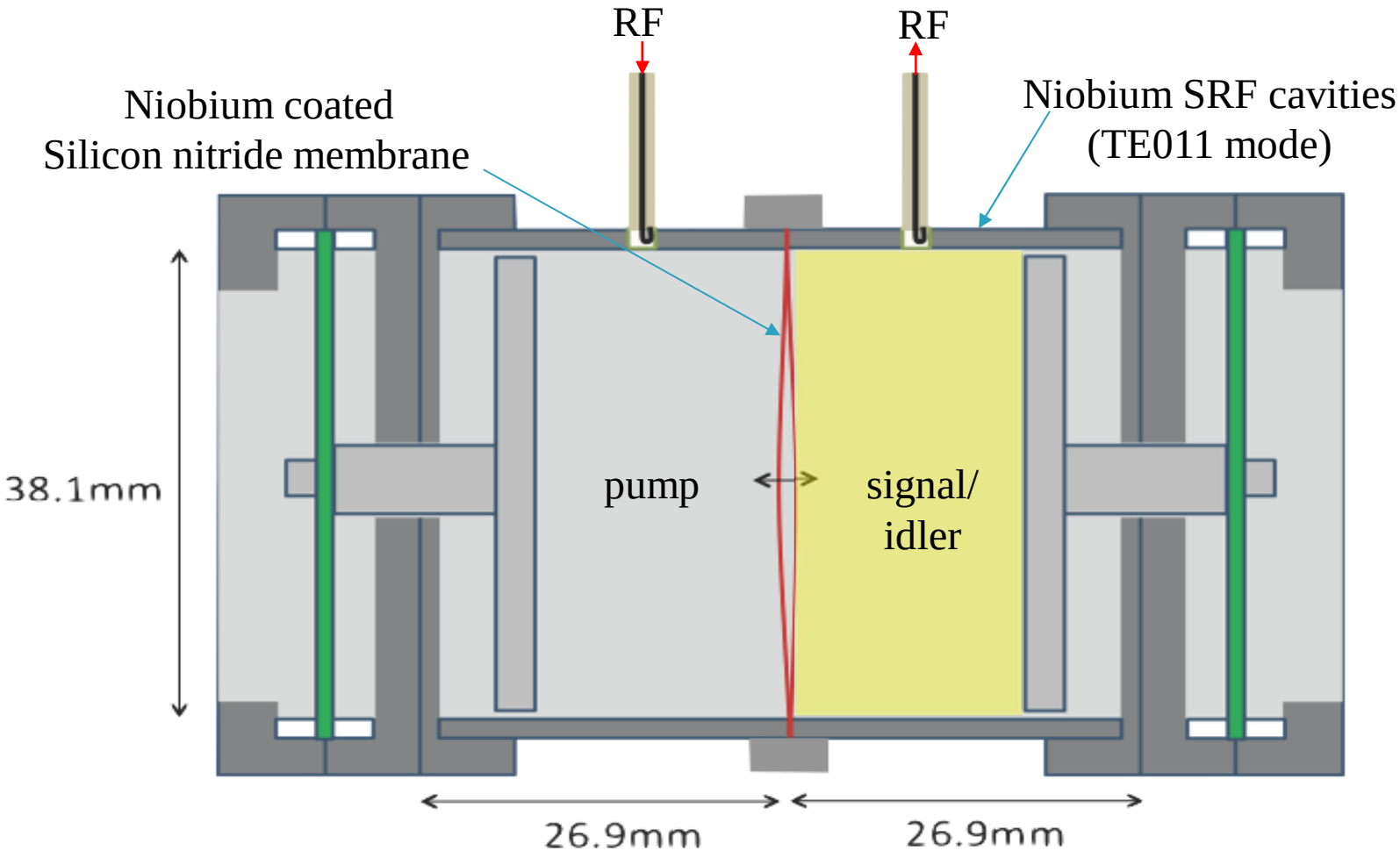






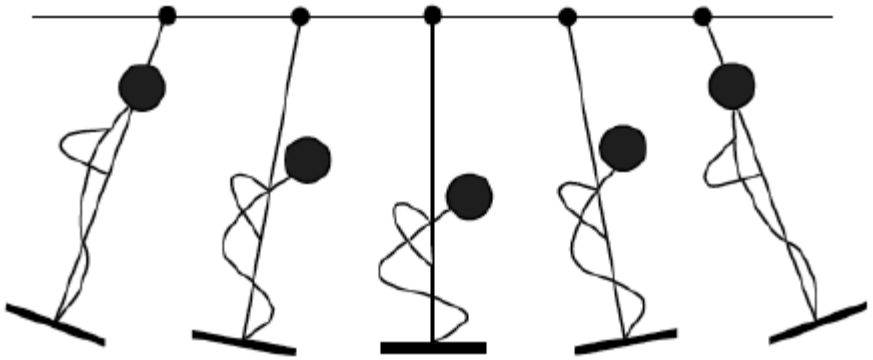
Room temperature confirmation of MST driving

Twin SRF cavities for observing the Dynamical Casimir Effect



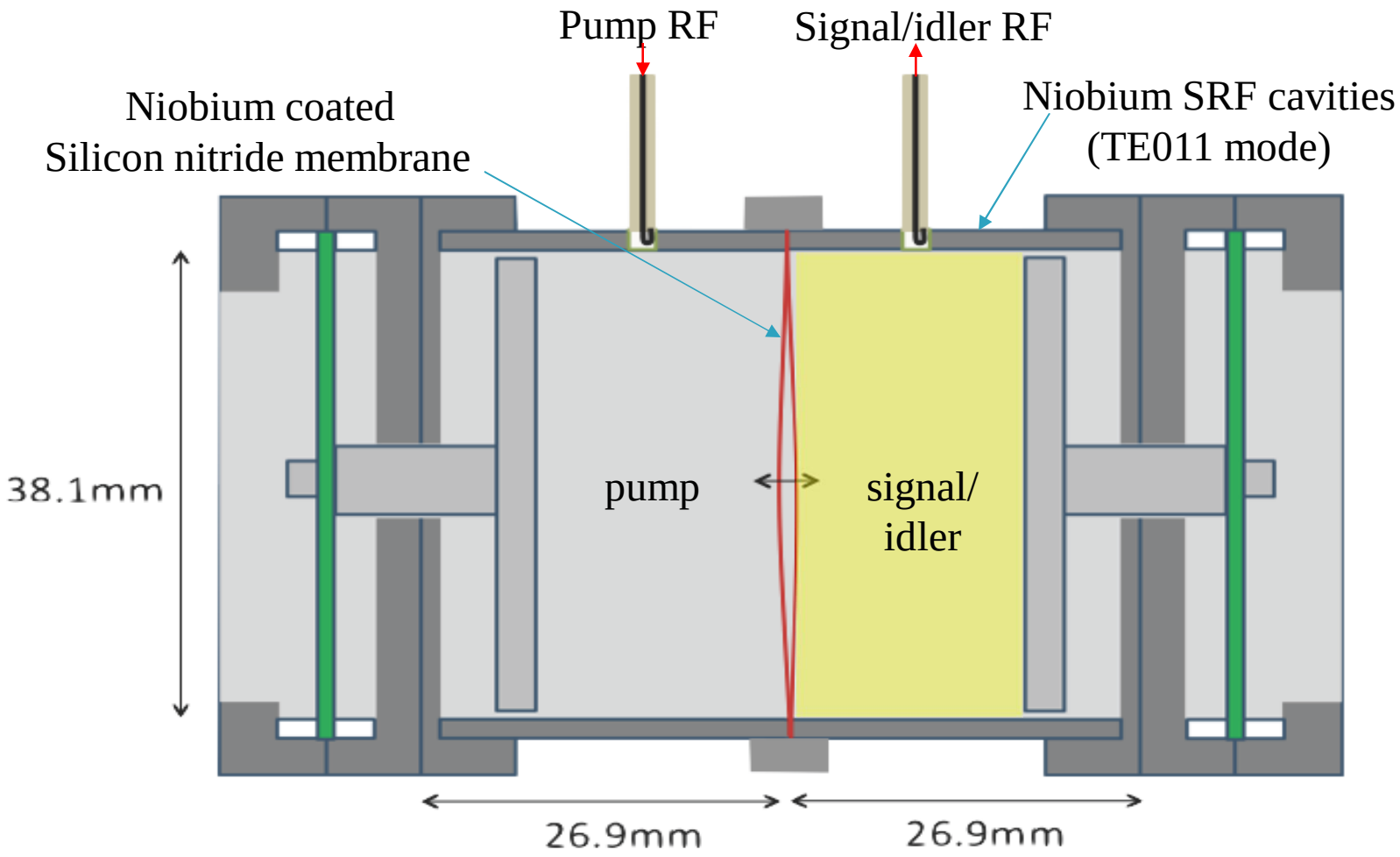
Radiation generation via parametric amplification of radiation

- Swing as an example of a parametric amplifier



- Center of mass is being pumped at 2^{nd} harmonic of swing

Pumping membrane is like pumping swing



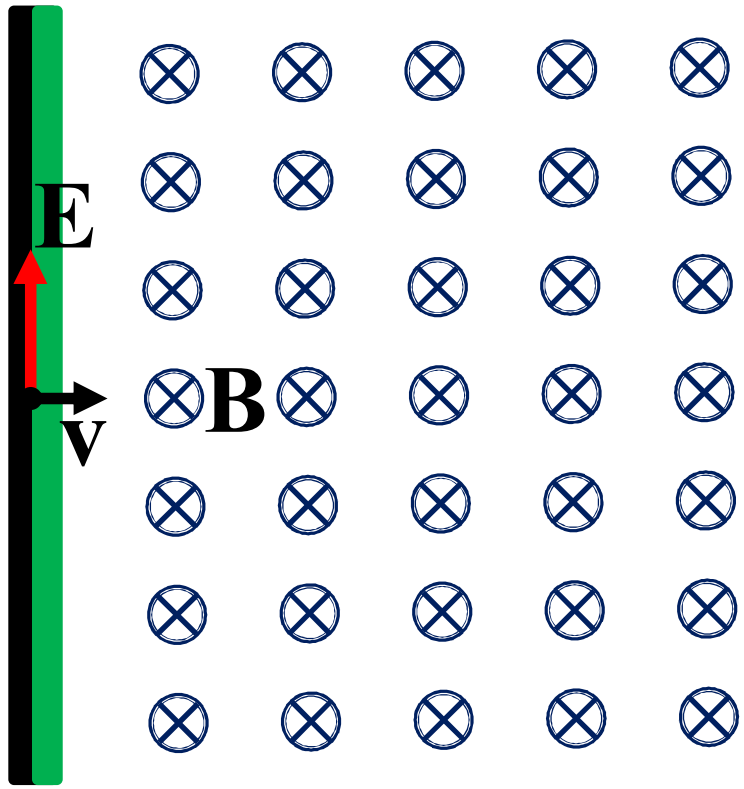
Motional EMF can generate radiation

Motional EMF: $\mathbf{E} = \mathbf{v} \times \mathbf{B}$

Radiation pressure from pump wave leads to

$\mathbf{F}_{pump}$

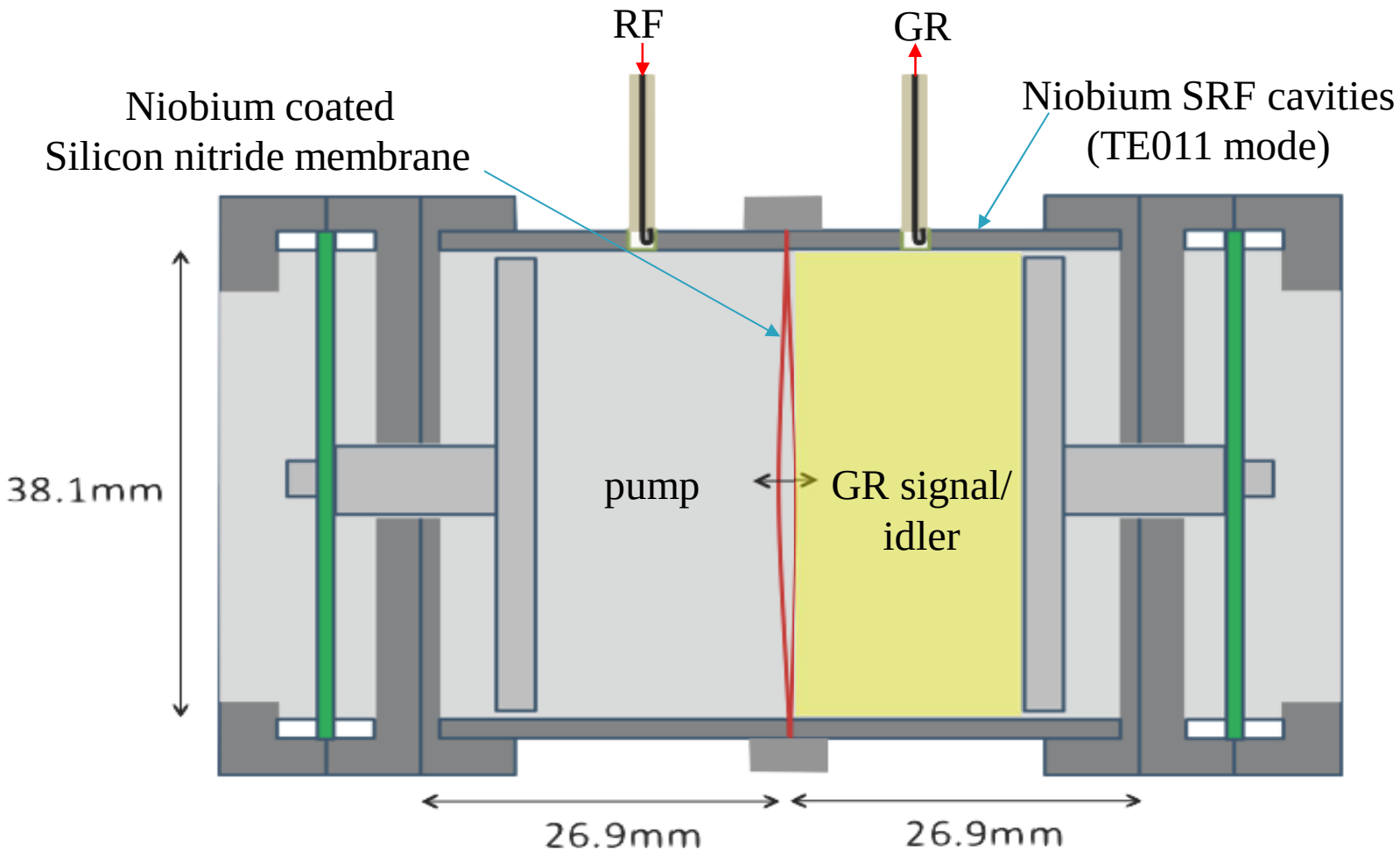
which causes SC membrane to *move*.



Time-varying EMF: $\mathbf{E}(t) = \mathbf{v}(t) \times \mathbf{B}(t)$

leads to parametric amplification of *subharmonic*

A parametric oscillator to generate GR



Threshold for parametric oscillation

$$P_{pump} = \frac{m\omega_p\omega_i\omega_s L_{cavity}^2}{4Q_pQ_iQ_s} = 0.17 \text{ milliwatts}$$

For

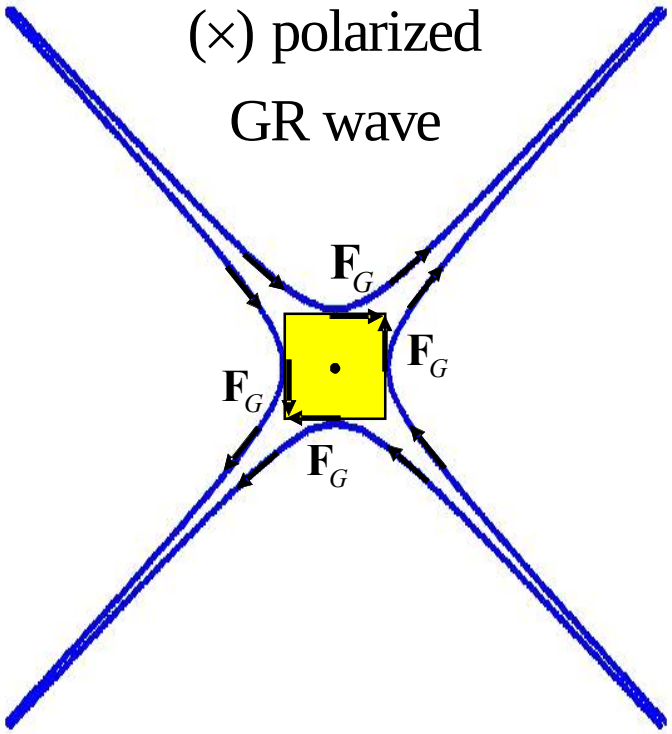
$m = 3$ milligrams

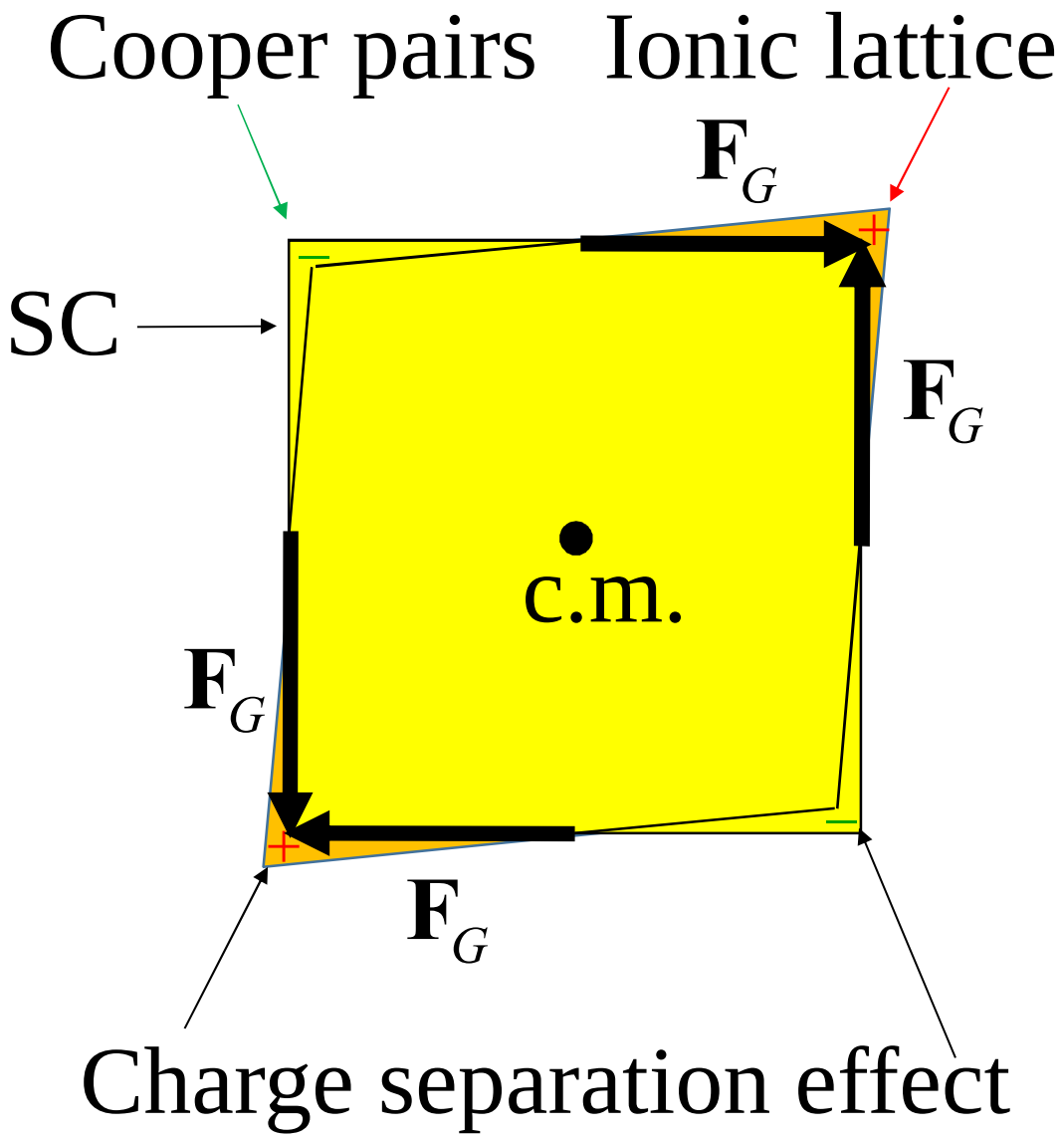
$\omega_p = \omega_i = \omega_s = 2\pi \times 10$ GHz

$L_{cavity} = 30$ millimeters

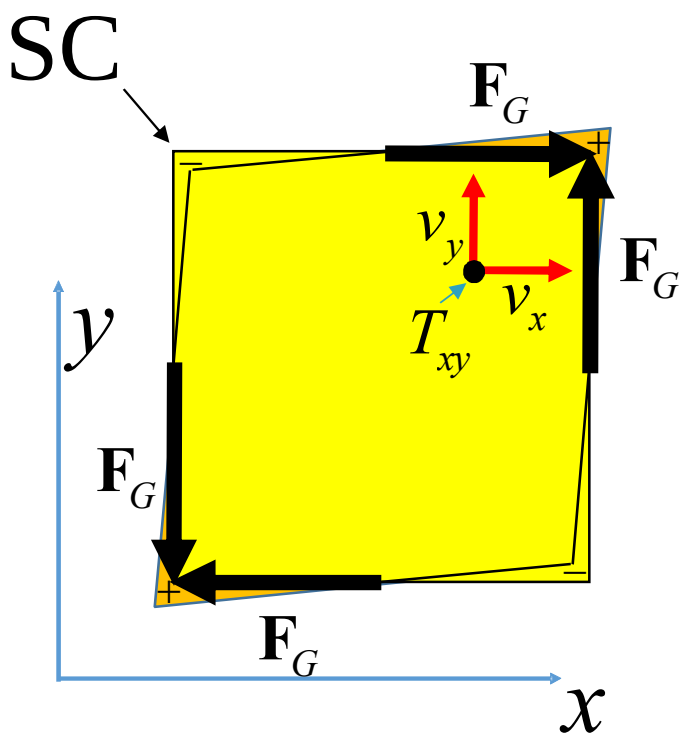
$Q_p = Q_i = Q_s = 10^9$

Why are SC's *mirrors* for GR?





Gravitational Meissner effect



Stress tensor is a **tensor product** of two vectors

$T_{xy} \propto v_x v_y$ where

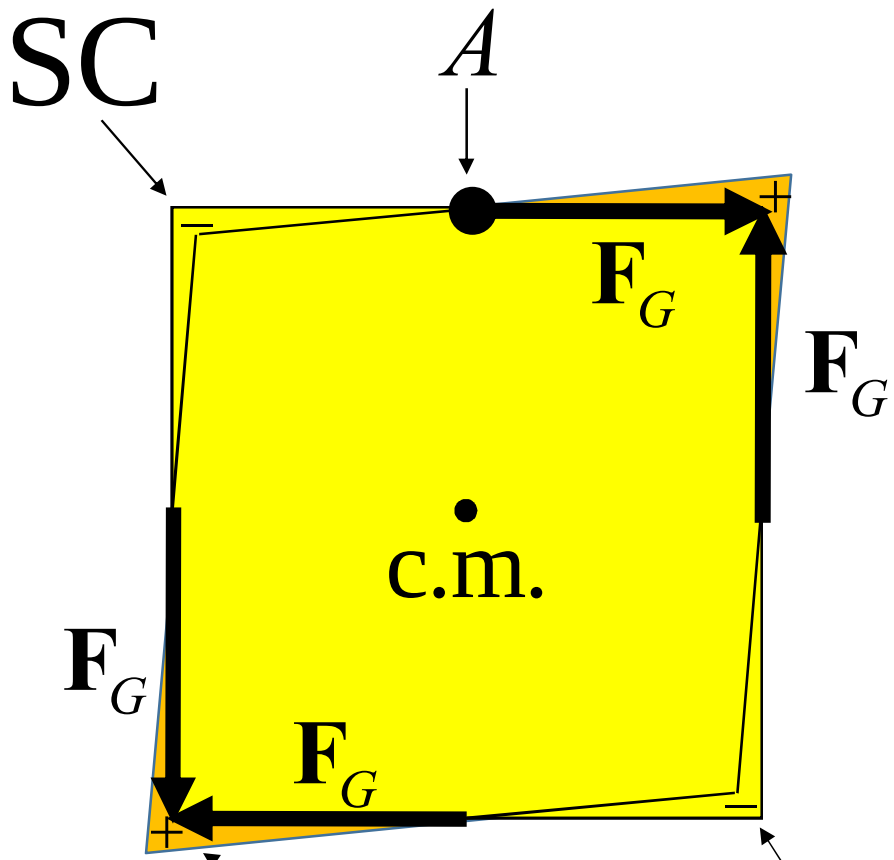
$v_x \propto e^{-\frac{z}{\lambda_L}}$ and $v_y \propto e^{-\frac{z}{\lambda_L}}$

$\therefore T_{xy} \propto e^{-\frac{2z}{\lambda_L}} = e^{-\frac{z}{\lambda_L/2}}$

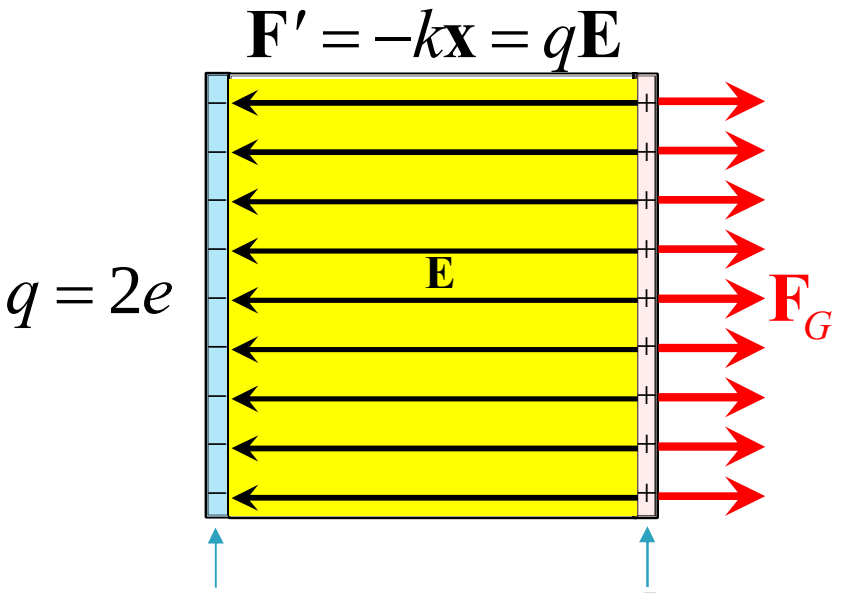
GR penetration **depth** is **half** of EM penetration depth

$\therefore h_{xy} \propto T_{xy} \propto e^{-\frac{z}{\lambda_L/2}}$

Coulomb force is the origin of hard-wall boundary conditions at surface of SC

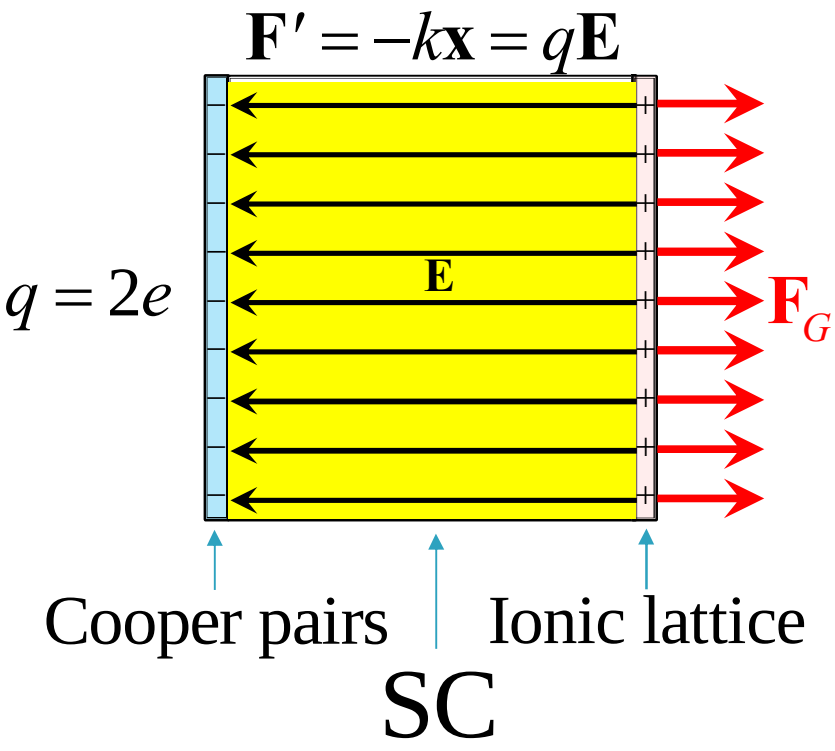


Magnified view of point *A*



Charge separation (ñHeisenberg-Coulomb effectò)

Charge separation leads to a huge SC plasma frequency



$$E = \frac{\sigma}{\varepsilon_0} \text{ where } \sigma = nqx$$

$$F' = qE = \frac{nq^2}{\varepsilon_0} x$$

$$\mathbf{F}' = -k\mathbf{x} \text{ where } k = \frac{nq^2}{\varepsilon_0}$$

$$\mathbf{F}' = m_q \frac{d^2\mathbf{x}}{dt^2} = -k\mathbf{x} \text{ has solution}$$

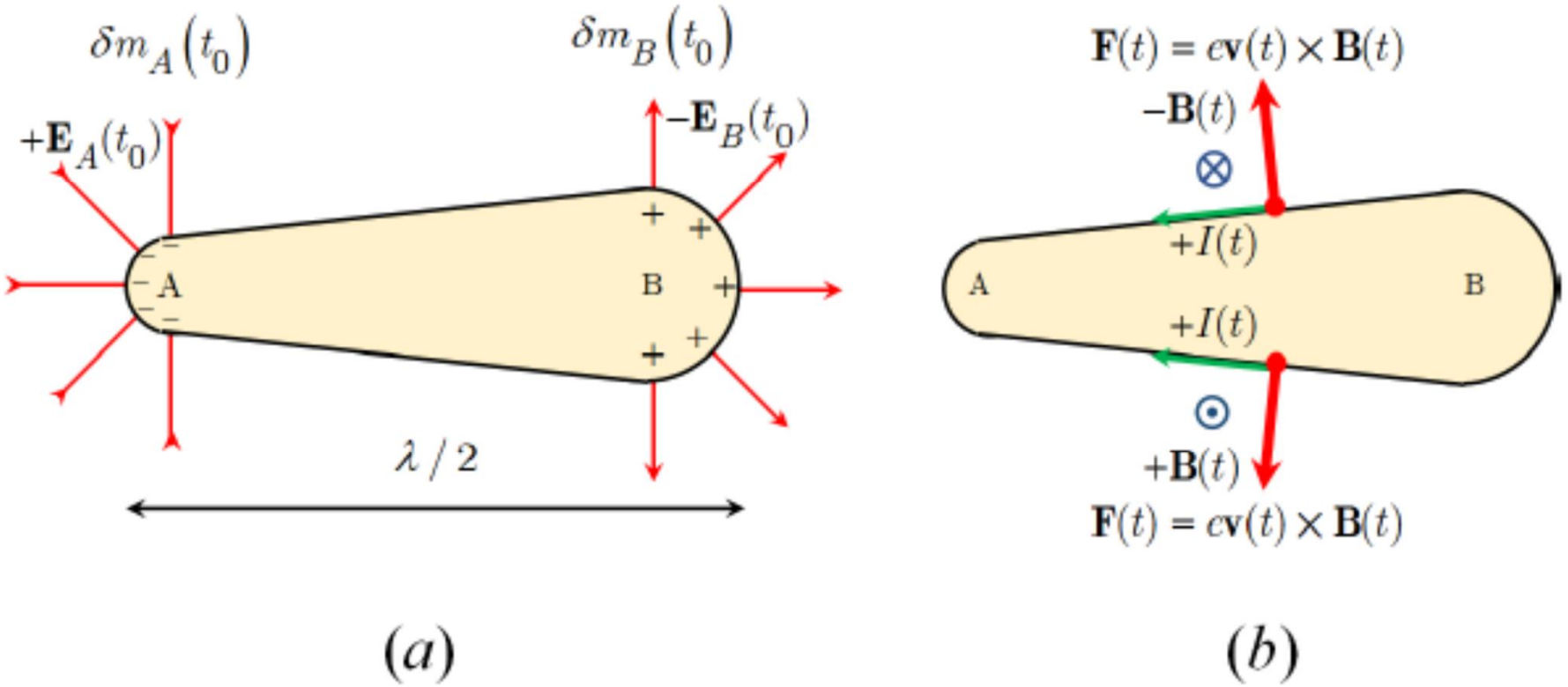
$$\mathbf{x}(t) = \mathbf{x}_0 \sin \omega_p t \text{ where } \omega_p = \sqrt{\frac{nq^2}{m_q \varepsilon_0}} \simeq 10^{16} \text{ s}^{-1}$$

Therefore microwave frequency GR waves will undergo plasma-like reflection from SC surface. SC is a mirror.

Conclusions

- SCôs are mirrors for microwave-frequency GR.
- Moving SC-coated membranes act like moving mirrors or pistons that can do work on vacuum fluctuations.
- EM and GR vacuum fluctuations can be amplified to become detectable EM and GR waves.
- Parametric oscillation can be achieved in SRF cavities with Qôs on the order of a billion with pump powers on the order of milliwatts.
- Thus laser-like generation of microwave-frequency gravitational radiation should be possible in the lab.

“Teardrop” optical Resonator



(a) (b)

Optical Woodward Effect in a "teardrop" optical resonator

$$\left\langle F_{\text{thrust}}^{\text{optical}} \right\rangle = \frac{128}{2\pi^3} \frac{1}{\rho_0 c^4} \frac{a^2 b^2 (b^2 - a^2)}{(a+b)^4 (b-a)^4} (P_{in} Q)^2$$

With
ə=532 nm
a=ə/4=6.65E-8 m
b= ə/8=1.33E-7 m

c=3E8 m/s
ɟ $_0$=19320 Kg/m^3
P_{in}=100 W
Q=10

The net thrust of the "teardrop" cavity is

$$\left\langle F_{\text{thrust}}^{\text{optical}} \right\rangle = 4.42 \times 10^{-19} \text{ N} \sim \ 44\text{aN}$$