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Effect of energy deposited by cosmic-ray particles on interferometric gravitational wave detectors

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Effect of energy deposited by cosmic-ray particles on interferometric gravitational wave detectors

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We investigated the noise of interferometric gravitational wave detectors due to heat energy deposited by cosmic-ray particles. We derived a general formula that describes the response of a mirror against a cosmic-ray passage. We found that there are differences in the comic-ray responses (the dependence of temperature and cosmic-ray track position) in cases of interferometric and resonant gravitational wave detectors. The power spectral density of vibrations caused by low-energy secondary muons is 100 times smaller than the goal sensitivity of future second-generation interferometer projects, such as LCGT and Advanced LIGO. The arrival frequency of high-energy cosmic-ray muons that generate enough large showers inside mirrors of LCGT and Advanced LIGO is one per a millennium. We also discuss the probability of exotic-particle detection with interferometers.

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0. Abstract

Investigation of the cosmic ray effect on the interferometric gravitational wave detector

(i) Serious noise ?

(ii) Exotic particle search ?

Contents

1. Introduction

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Gravitational wave detector (interferometer and resonator)

: Ultra high sensitive sensor

Many noise sources : Quantum noise
(shot and radiation pressure noise),
Thermal noise, Seismic motion,
Noise from laser source
(frequency, intensity, jitter),
Circuit noise, Electric and Magnetic fields, ...

Cosmic rays ?

Process of cosmic-ray excitation

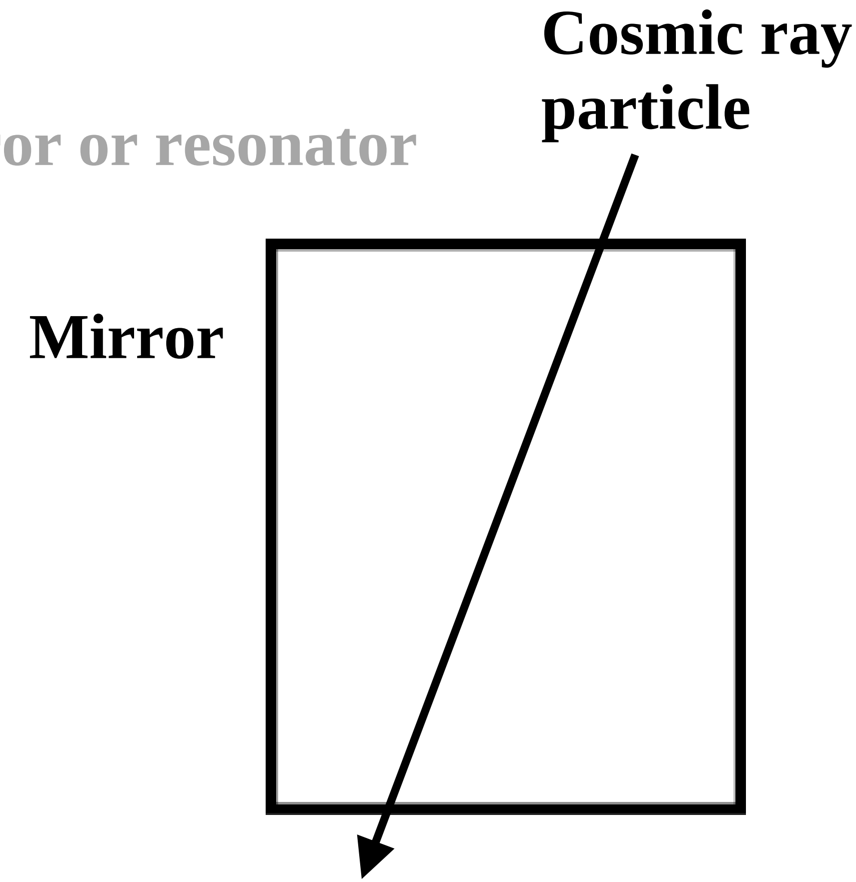
(i) **Passage** of cosmic ray particle in mirror or resonator

(ii) Energy deposition

(iii) Temperature gradient

(iv) Thermal stress

(v) Elastic vibration of mirror or resonator



Process of cosmic-ray excitation

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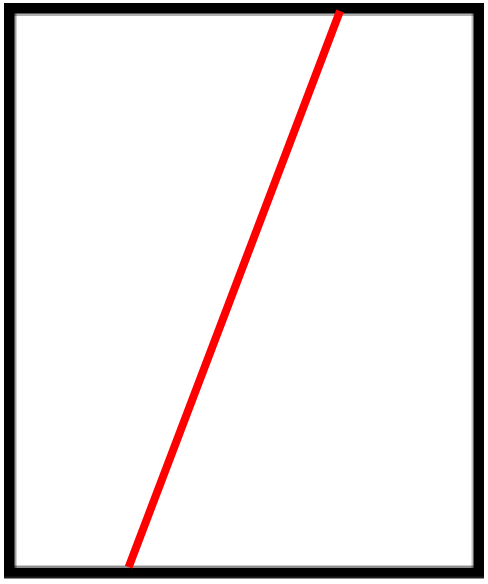
(v) Elastic vibration of mirror or resonator

Mirror



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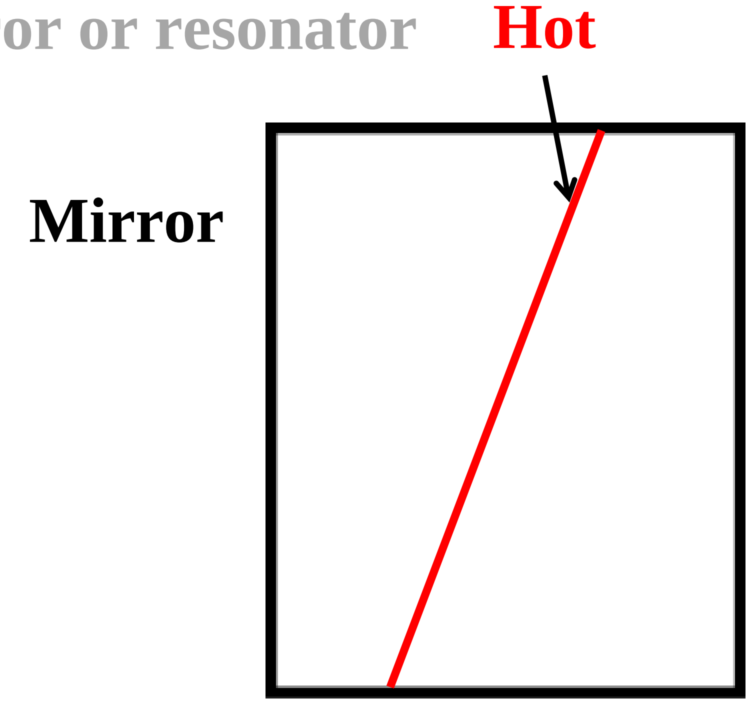

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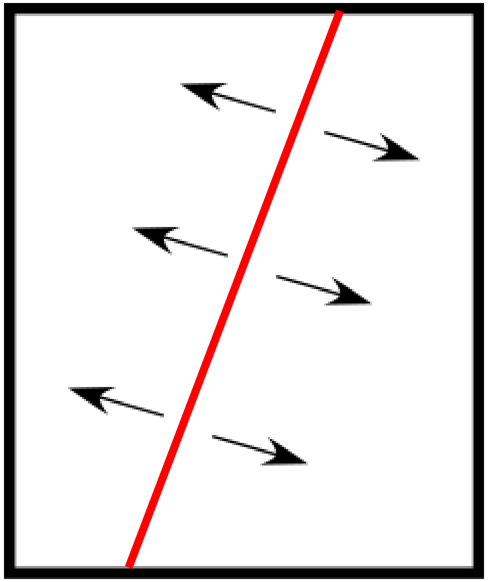

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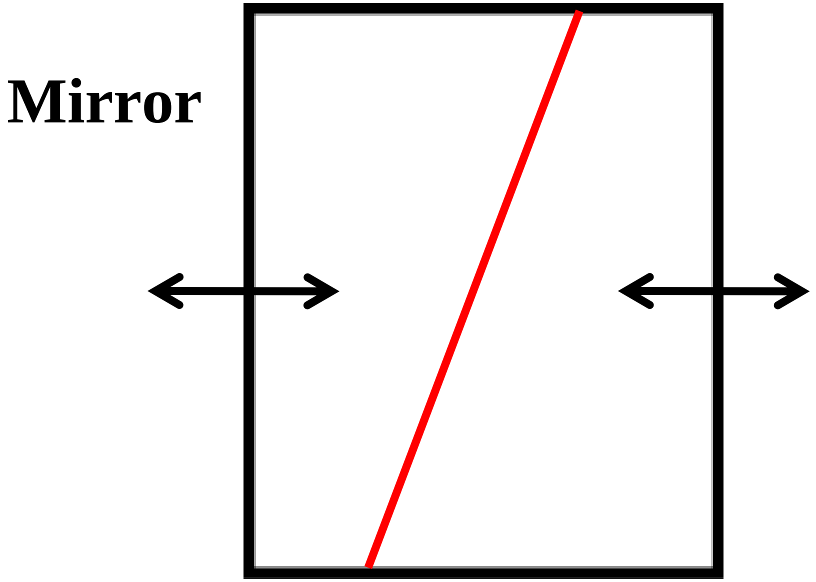

Study of resonator

First paper : B.L. Baron and R. Hofstadter

Physical Review Letters 23 (1969) 184.

First observation : P. Astone et al.,

Physical Review Letters 84 (2000) 14.

Recent hot topic : Exotic events in superconductive resonator

Physics Letters A 373 (2009) 1801.

Study of interferometer

only a few calculations ...

→ Topic in this talk

Study of resonator

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First paper

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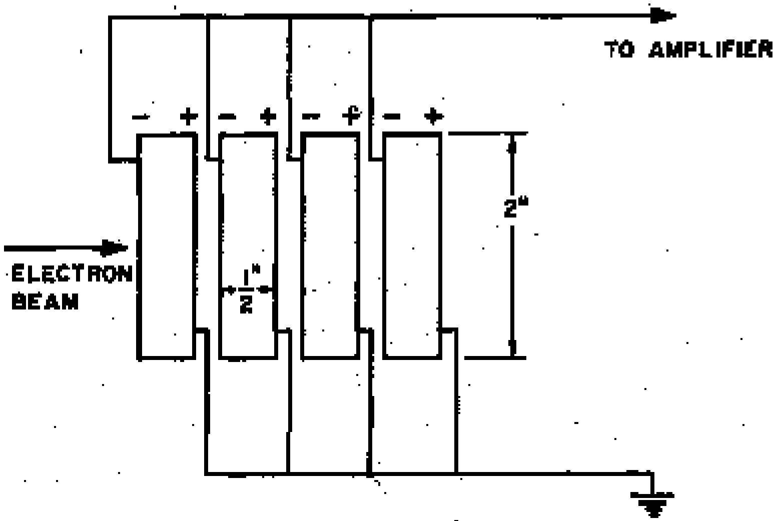

FIG. 1. Schematic diagram of the PZT disk assembly exposed to a high-energy electron beam.

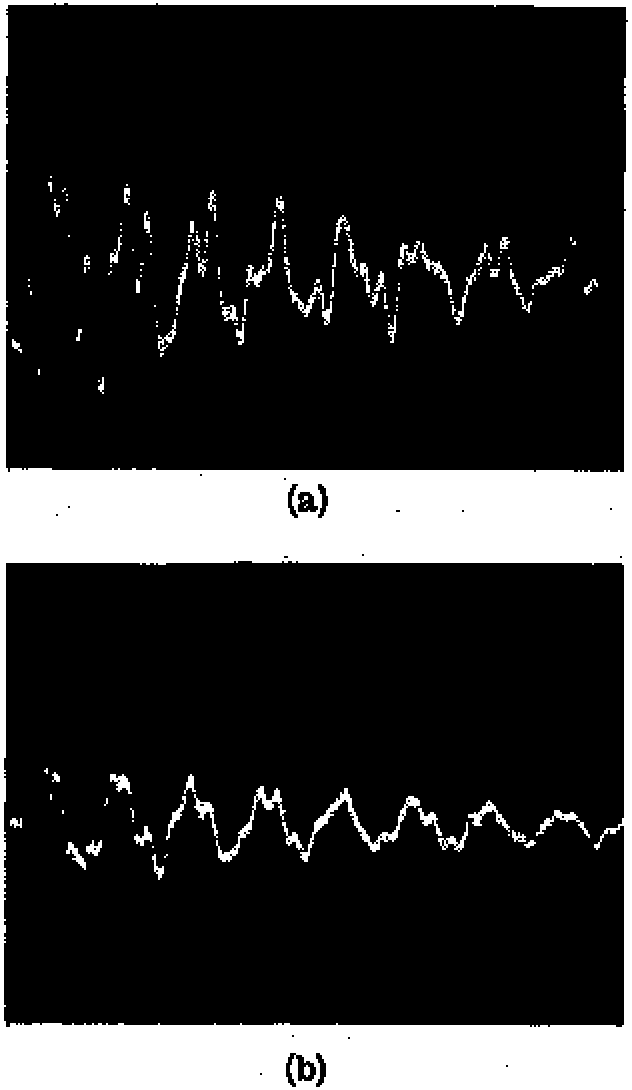

FIG. 2. Oscilloscope photograph of the radial (40-kHz) and compressional (158-kHz) modes of mechanical vibrations induced by a pulse of 1.0-BeV electrons. Case (a) Beam parallel to axis of disks. Case (b) Beam perpendicular to axis of disks. In each case the horizontal scale corresponds to 20 μsec/div.

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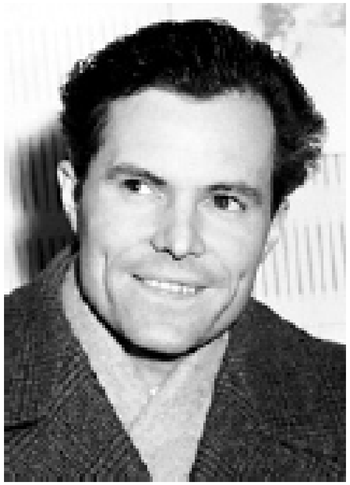
The Nobel Prize in Physics 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"

Robert Hofstadter

1/2 of the prize



Rudolf Ludwig Mössbauer

1/2 of the prize

Web of Nobel Foundation

Study of resonator

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Study of interferometer

only a few calculations ...

→ **Topic in this talk**

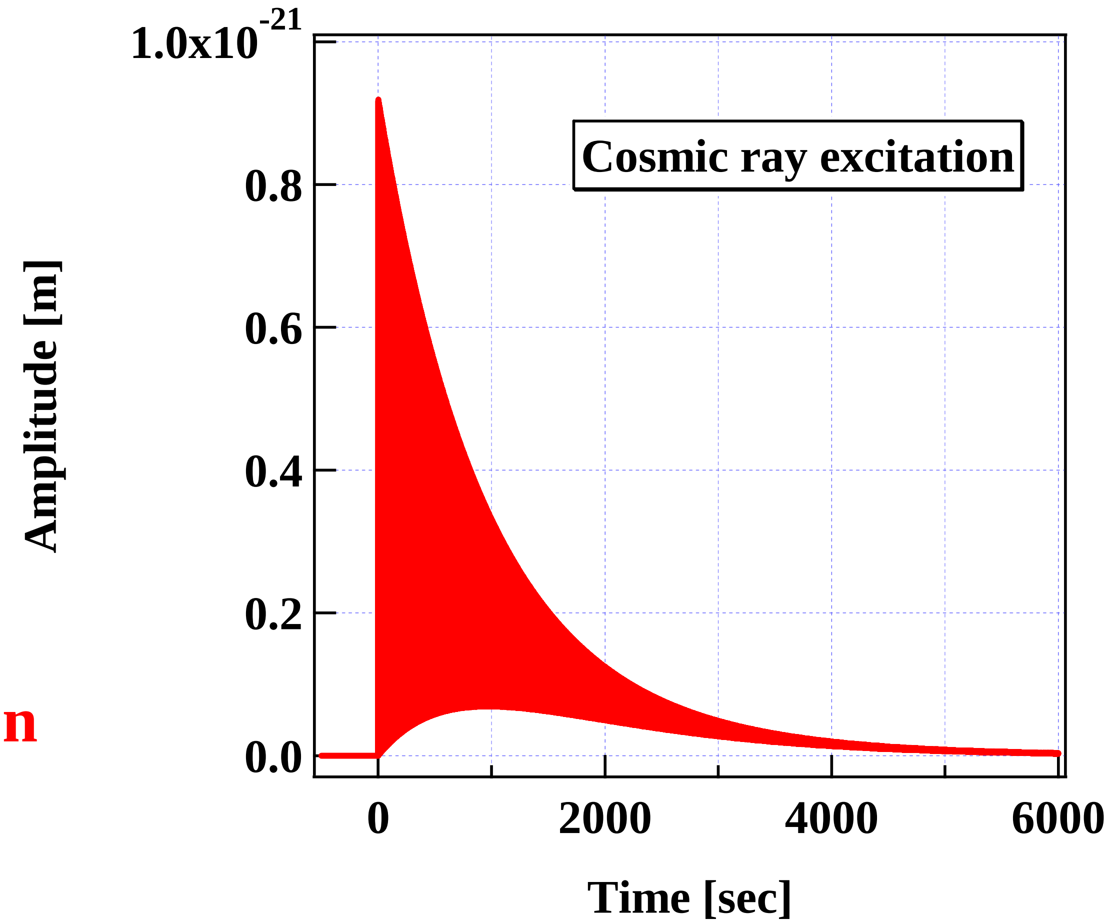
2. Difference between interferometer and resonator

Two components

(1) Excitation and decay of resonant motion

(2) Motion of center of resonant motion

(Excitation and relaxation of thermal stress)



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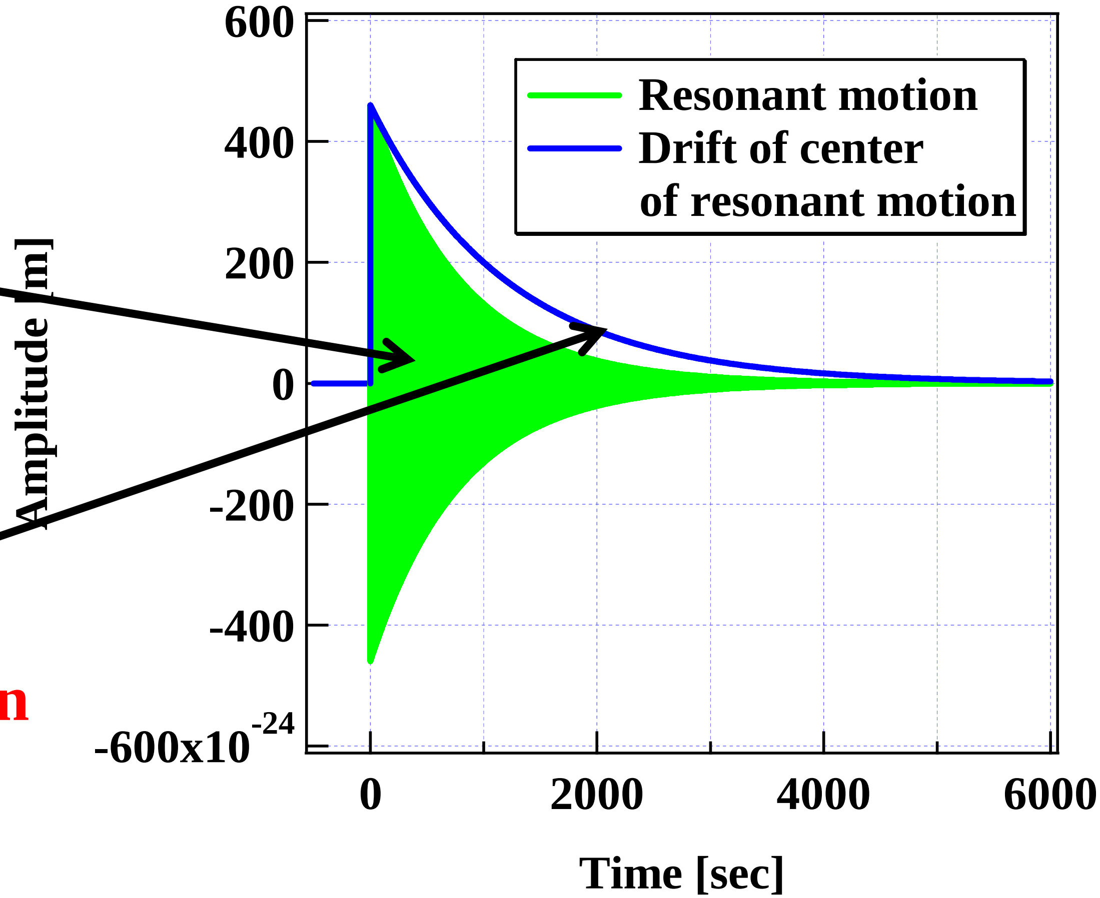

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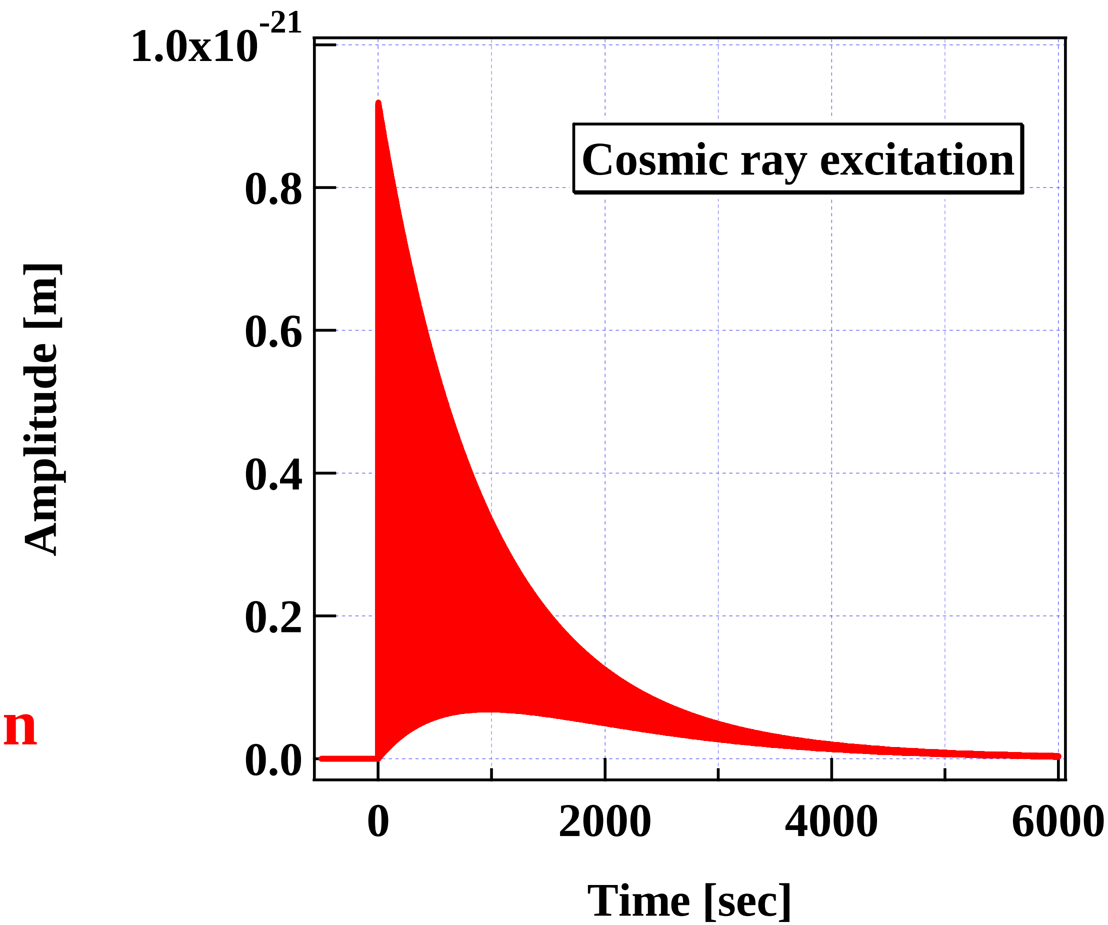

Resonator

Observation band : Near resonant frequency (about 1 kHz)

→ **Excitation of resonant motion**

Interferometer

Observation band : Below resonant frequencies (10 Hz - 10 kHz)

→ **Motion of center of resonant motion**

Difference of cosmic ray effect at cryogenic temperature

Room and cryogenic temperature (resonator)

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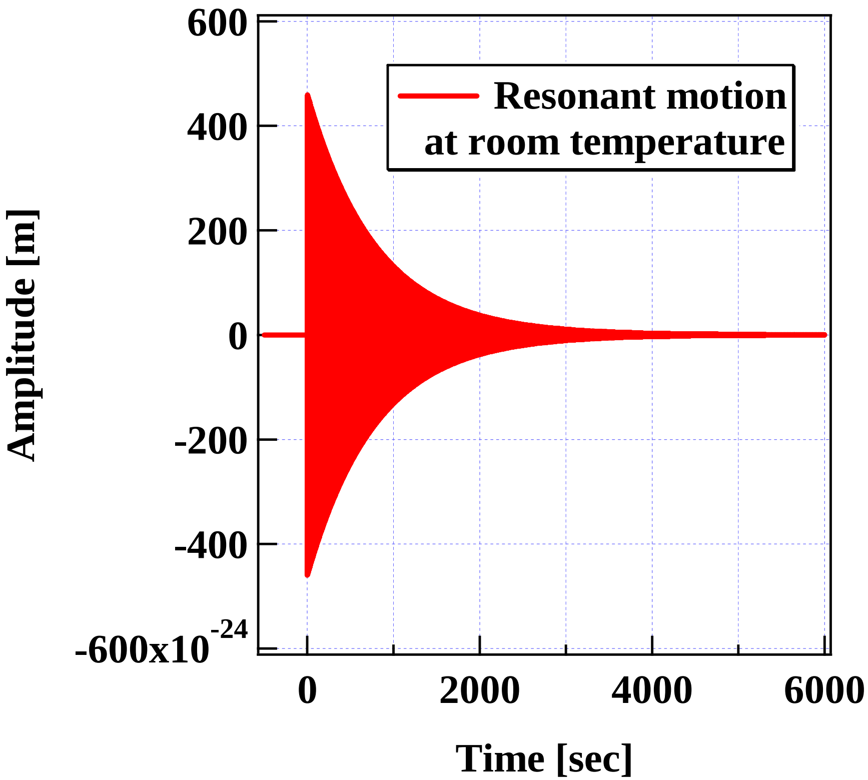
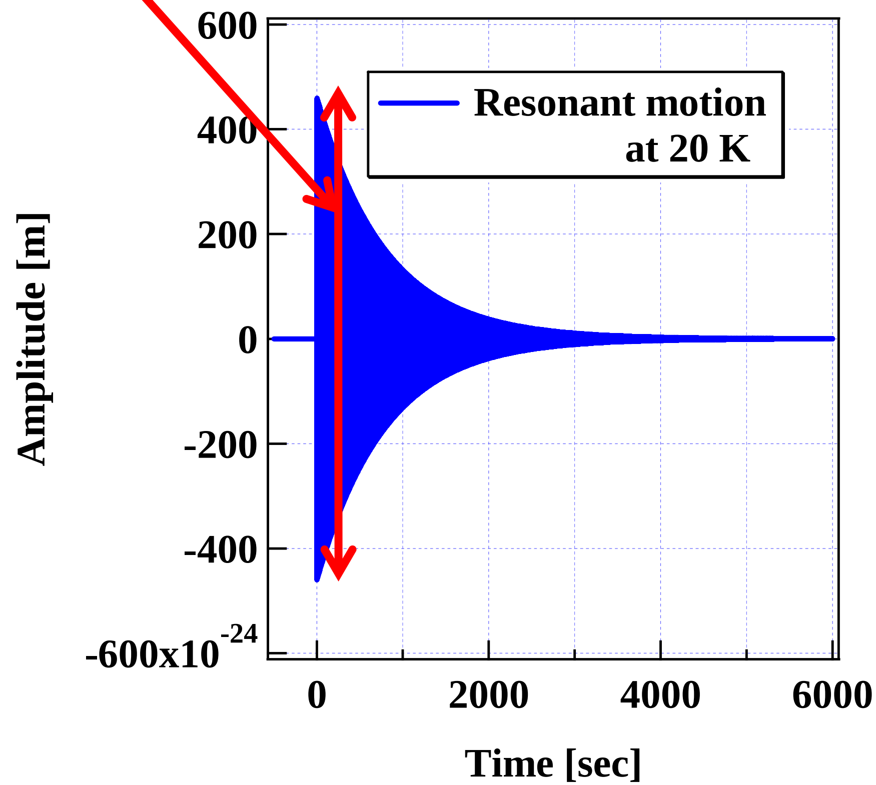
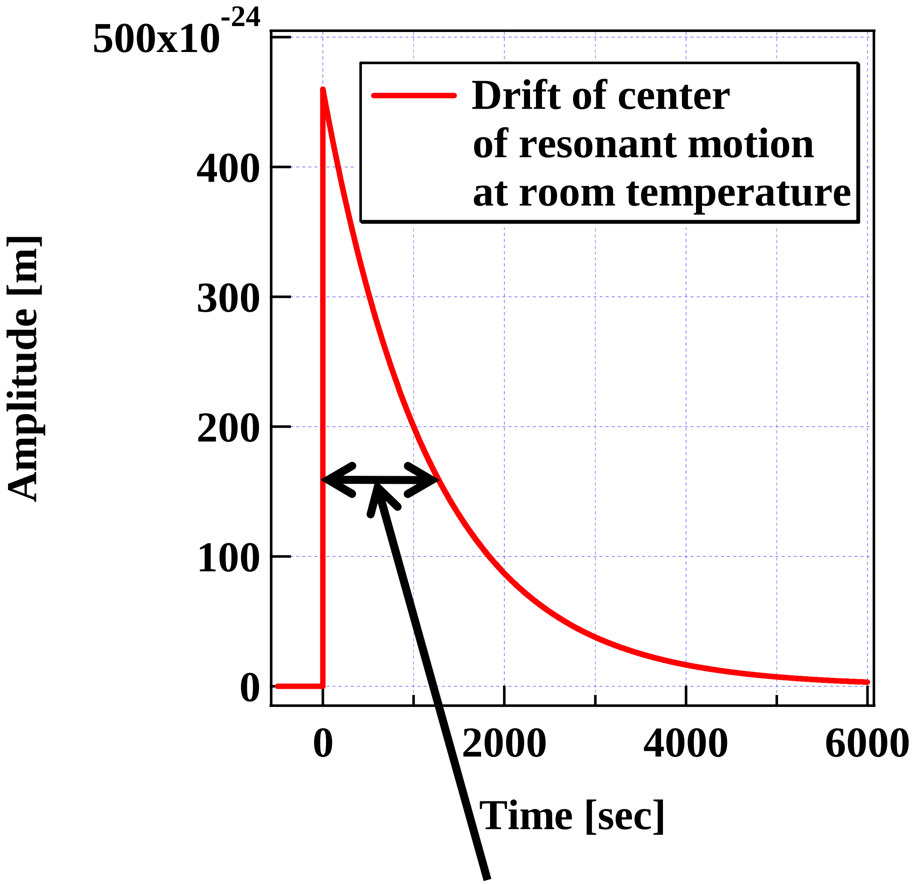
(thermal expansion)/(specific heat)

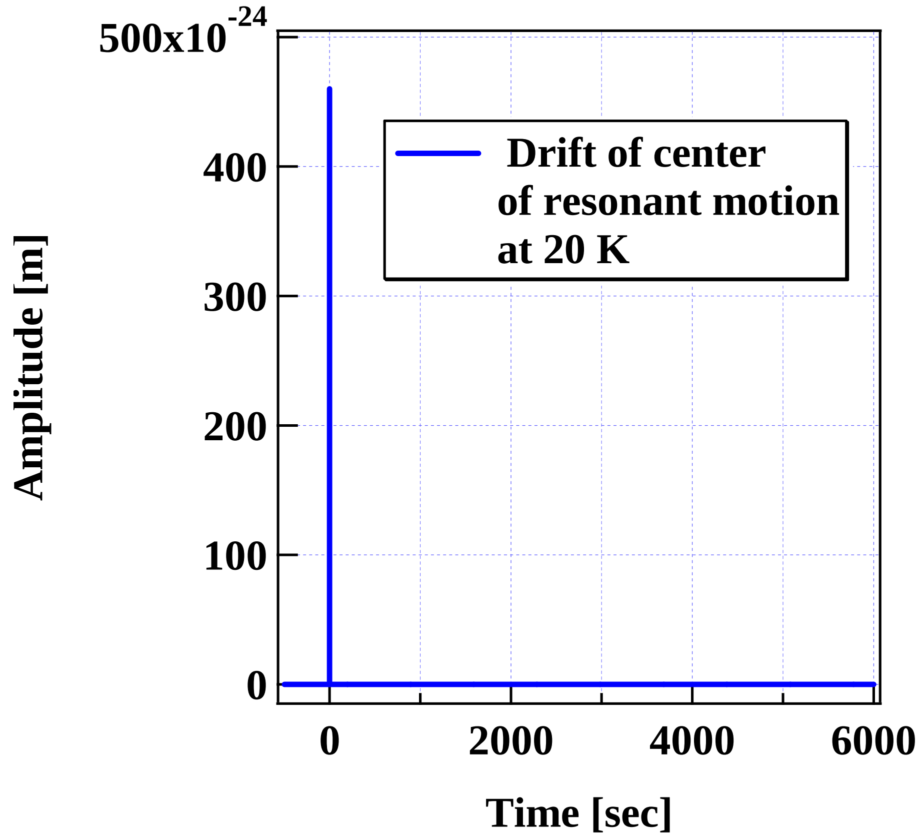




Temperature independent (Grueneisen relation)

Room and cryogenic temperature (interferometer)





(specific heat)/(thermal conductivity)

Smaller cosmic ray effect at cryogenic temperature

3. Effects on interferometers

(i) Low energy cosmic rays

(ii) Shower

(iii) Exotic particle search

3-1. Low energy cosmic rays

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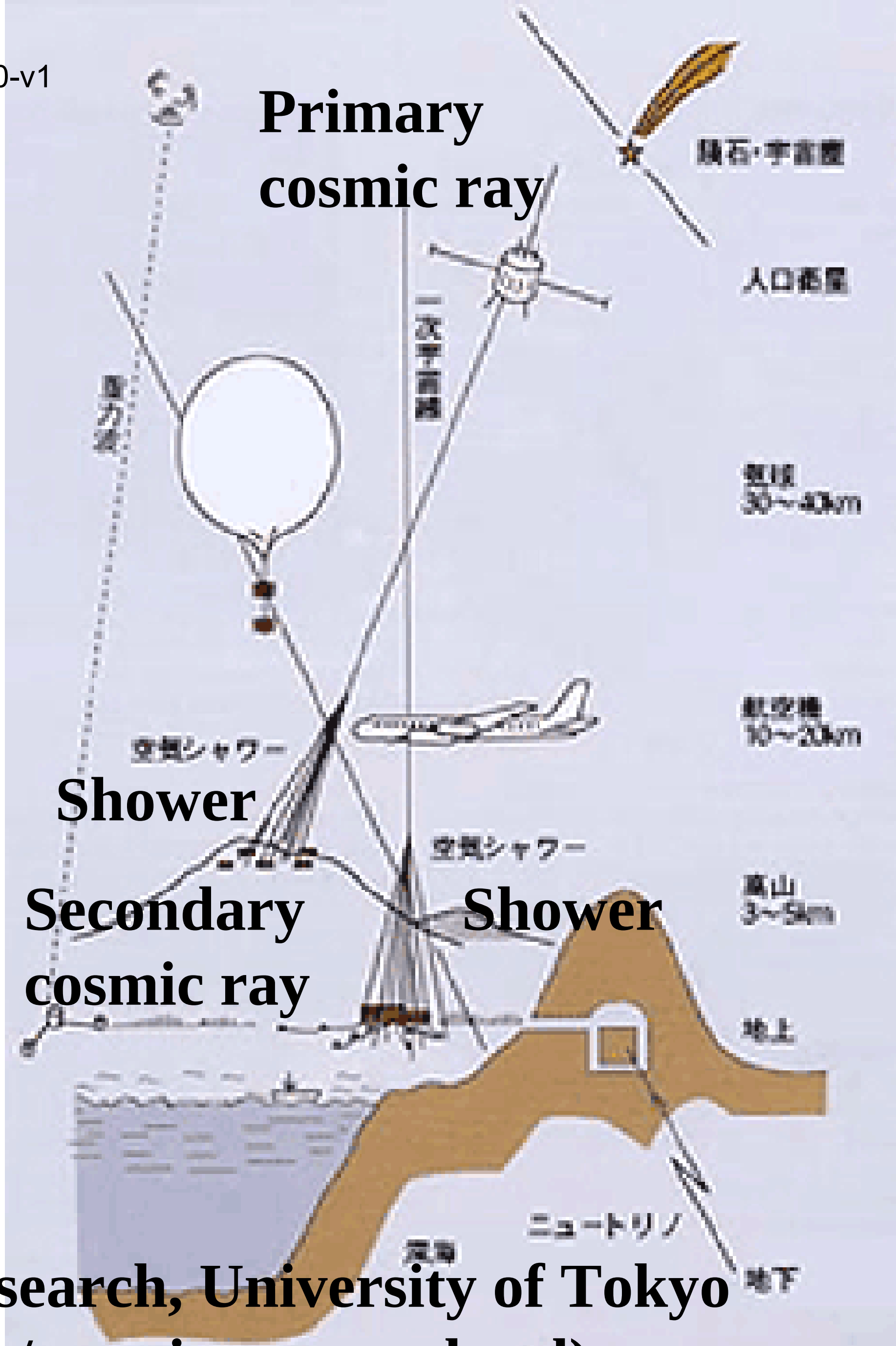
Primary particles (from Universe)

Secondary particles
: Shower caused
by primary particles

Secondary particles are different from primary particles.

Secondary particles
Three quarters : Muon(μ)
One quarter : Electron
(Electron easily stop in wall etc.)



Web of Institute for Cosmic Ray Research, University of Tokyo
(http://www.icrr.u-tokyo.ac.jp/about/cosmicray_eng.html)

Flux of low energy cosmic rays (μ) at sea-level

$2*10^{-2}$ /cm^2/sec

Typical mirror size : 25 cm in diameter
15 cm in thickness

km-scale interferometer

Average arrival interval : ~ 0.1 sec
Decay time of resonant motion : ~ 1000 sec

Mirrors always vibrate owing to low energy μ.

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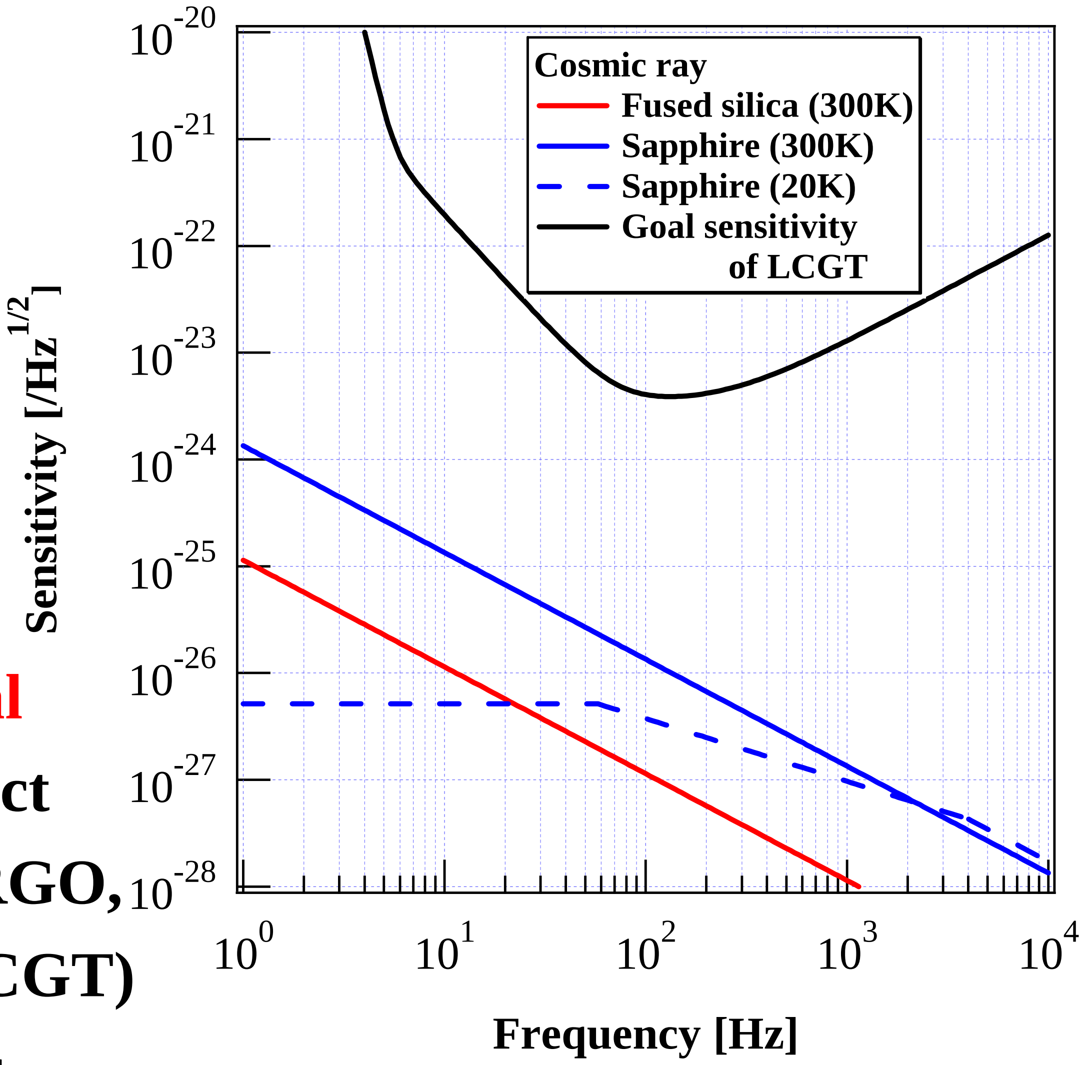
Power spectrum density of cosmic-ray vibration



100 times smaller than goal of second generation project (Advanced LIGO and VIRGO, LCGT)

not serious problems

3-2. Shower

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Shower : Many particles generated

by high energy cosmic-ray particle

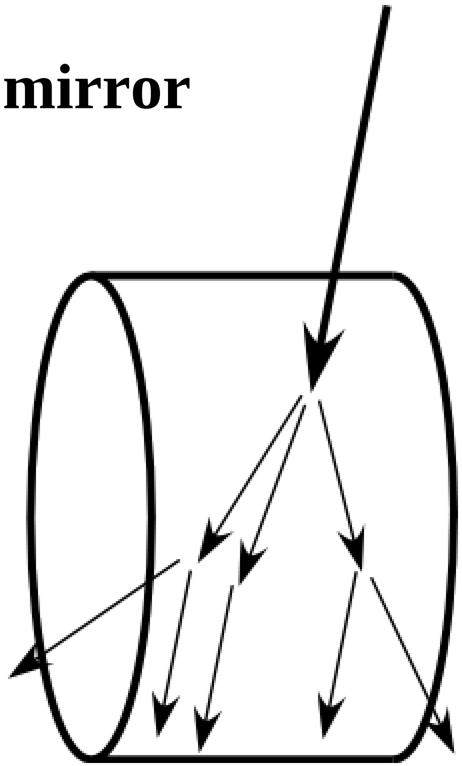
Burst like fake signal

In second generation interferometers,

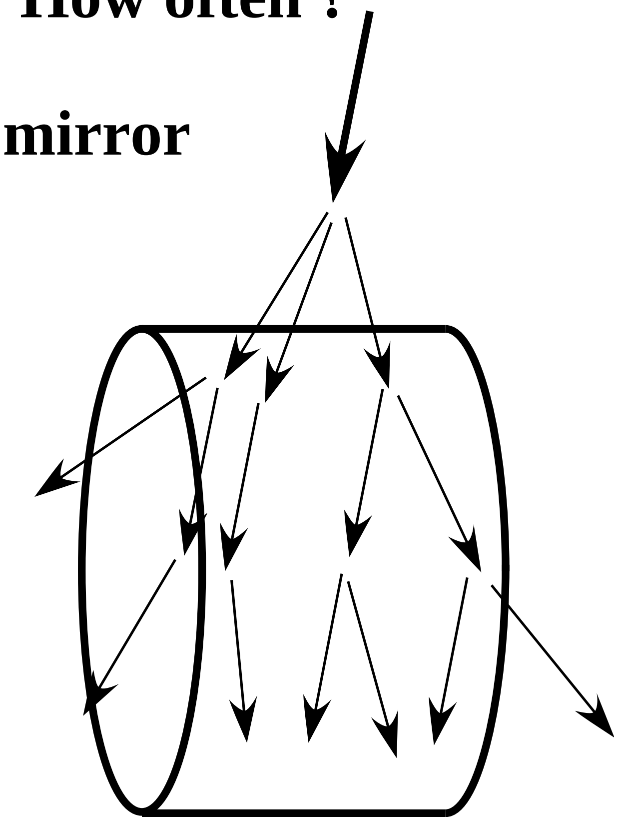
1000 particles shower makes sufficiently large fake signal.

Rare event : How often ?

(a) In mirror



(b) Near mirror



(a) In mirror

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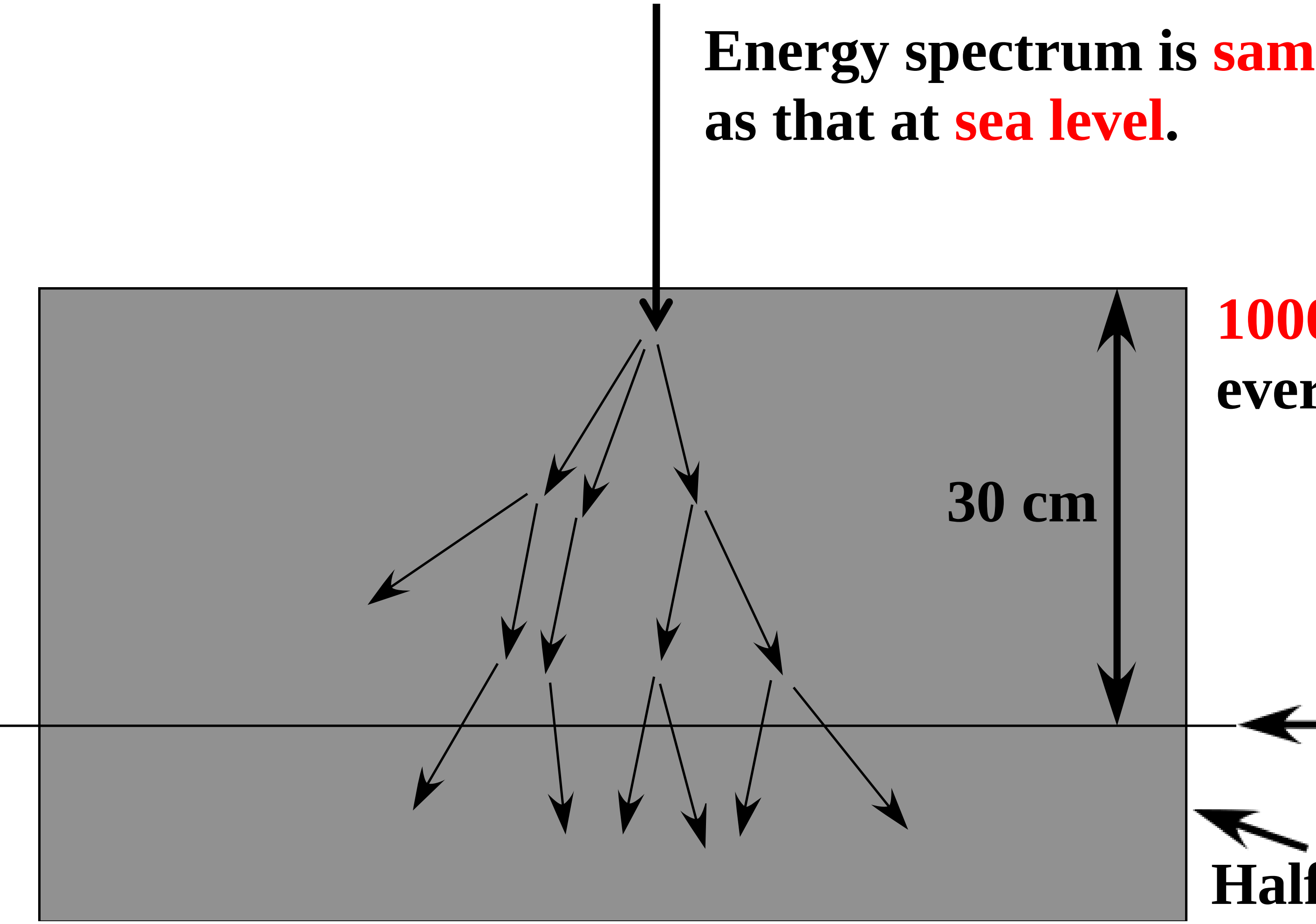
Monte Carlo simulation (by Atsushi Okada)

high energy muon (μ)

Energy spectrum is same as that at sea level.



1000 particles shower every 1000 years !

No problem !

More than 1000 particles ?

Half infinite sapphire

(b) Near mirror

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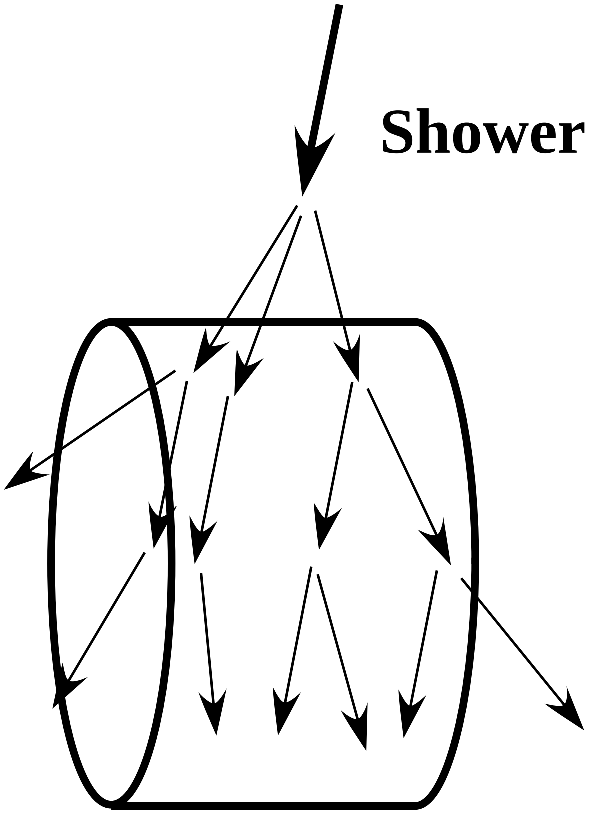

Shower strongly depends on structure around mirror.

↓

Future work

Energy of original particle : 1 TeV ⟶ 1000 particles shower

How many do particles go into mirror ?
How often does such a event occur ?

3-3. Exotic particle search

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Not noise, but signal !

→ **Exotic particle search**

Candidate particles : Large dissipation in material

Magnetic monopole
Nuclearite (up, down, strange quarks nugget predicted by QCD)
Mirror dust particles ...

Upper limit of flux of nuclearite (resonator)

G. Liu and B. Barish, Physical Review Letters 61 (1988) 271.
P. Astone et al., Physical Review D 47 (1993) 4770.

Comparison between interferometer (second generation, 300 K) and resonator (bar)

(i) Cross section

Bar : 2 m^2 (0.6 m in diameter, 3 m in length)

Interferometer : 0.2 m^2

(0.25 m in diameter, 0.15 m in thickness, 4 mirrors)

Bar : 10 times larger

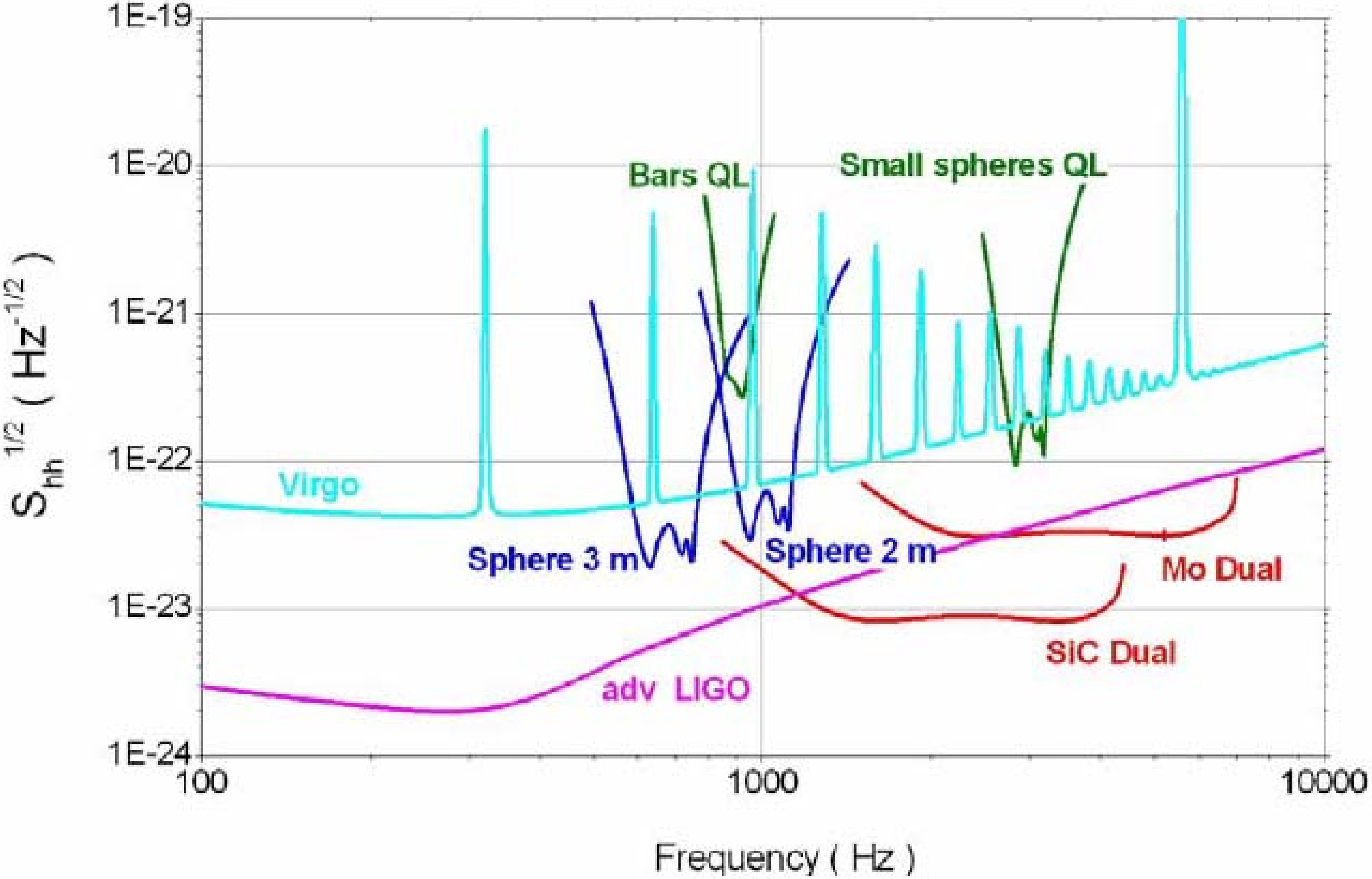
(ii) Sensitivity

Signal to Noise Ratio (output of matched filter)

Bar : (30-300) times larger

sensitivities in the 2006 - 2012 prospective

by M. Cerdonio(Amaldi6,2005 June 20)



(1)Detector size

Gravitational wave detector : Strain sensor

Particle detector : Displacement sensor

If strain sensitivity is same,

smaller detector is better displacement sensor.

↓

Difference of size (Interferometer : 3 km, Bar : 3 m) cancels the advantage of interferometer

(high sensitivity and wide band).

(2) Mechanical response

Bar : 10 times larger

(3) Coefficient of thermal expansion

fused silica : $5.5 * 10^{-7}$ /K

sapphire : $5.0 * 10^{-6}$ /K

Al 5056(bar) : $2.4 * 10^{-5}$ /K

Bar : (4-40) times larger

Total

Bar : (30-300) times larger

4. Summary

(1) Calculation of cosmic-ray effect on interferometer

Resonator : Excitation of resonant motion

Cosmic ray effect : Temperature independent

Interferometer : Motion of center of resonant motion

Smaller cosmic ray effect at cryogenic temperature

(2) Low energy cosmic rays :

Not serious problems in second generation interferometers

(3) Shower generated in mirror :

Not serious problems in second generation interferometers

(4) Exotic particle search :

Bar resonator has larger cross section and higher sensitivity.

(5) Future work

Simulation for shower generated near mirror

Study of interferometer

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A. Giazotto, Phys. Lett. A 128 (1988) 241.

→ No term for drift of center of resonant motion

R.W. Clay *et al.*, Publ. Astron. Soc. Aust. 14 (1997) 195.

→ It is the same as Giazotto's paper.

V.B. Braginsky *et al.*, Phys. Lett. A 350 (2006) 1.

→ Shower (Burst)
Only room temperature
Time domain

V.B. Braginsky *et al.*, Phys. Lett. A 359 (2006) 86.

→ Low energy particles (Power spectrum)
Some comments about cryogenic temperature

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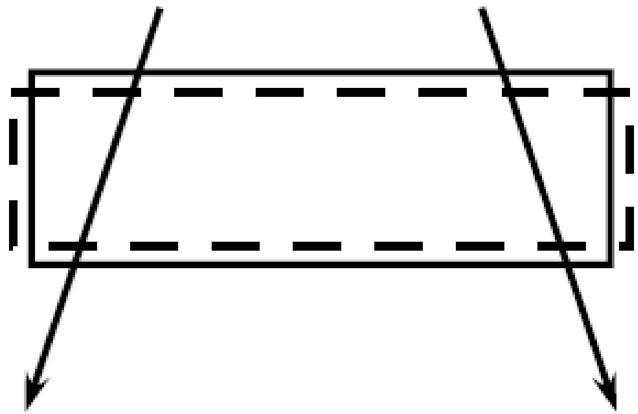
Resonator

Observation band : Near resonant frequency (about 1 kHz)

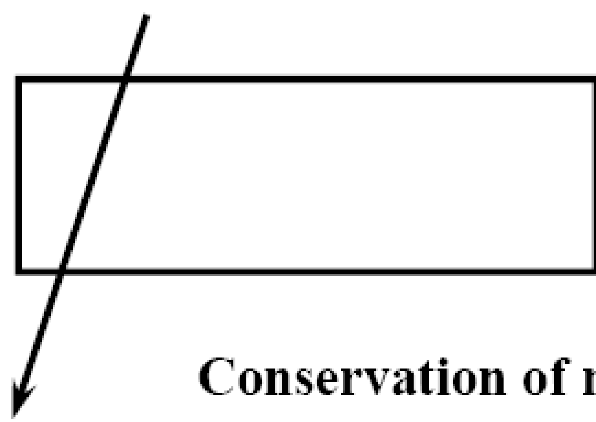


Interferometer

Observation band : Below resonant frequencies (10 Hz - 10 kHz)

Rigid!

Larger motion



Smaller motion

Conservation of momentum