Underground Interferometers in Japan

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Inter-University Corporation,
Institute of Particle and Nuclear Studies (IPNS),
High Energy Accelerator Research Organization (KEK)

LISM, CLIO, LCGT, (TAMA300) Collaboration

LIGO-G050046-00-Z

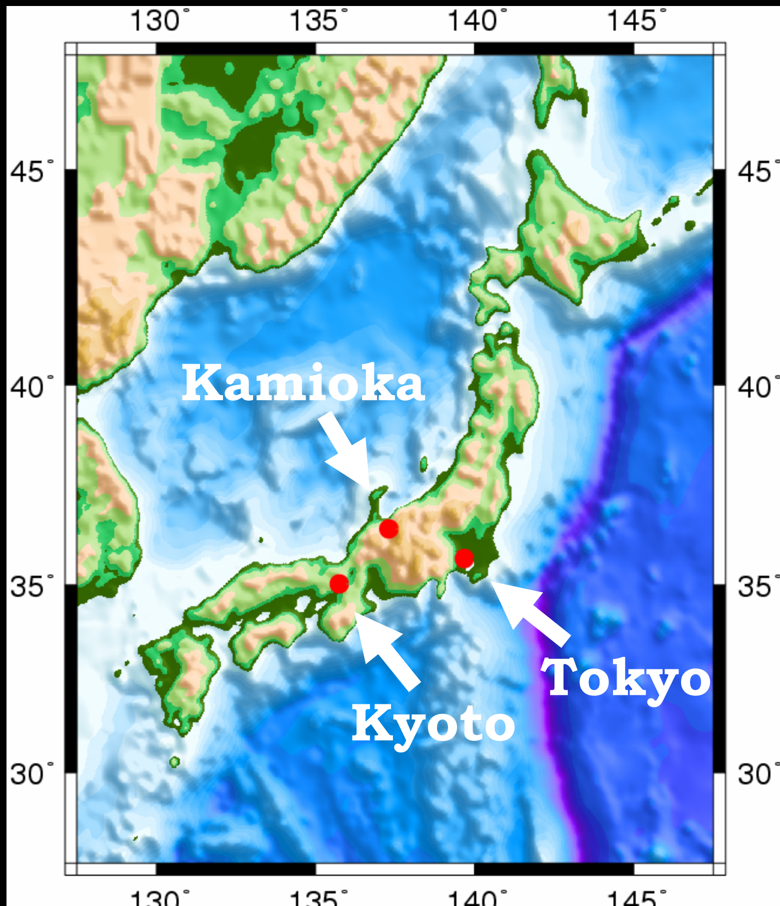
Aspen Winter Conference GWADW Jan.20, 2005

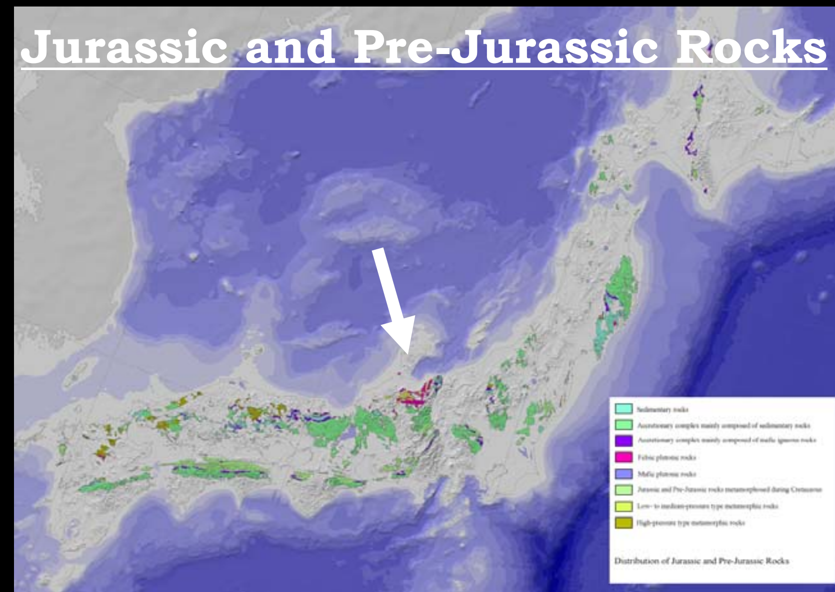
Toward Underground Large-scale Cryogenic Interferometers at KAMIOKA

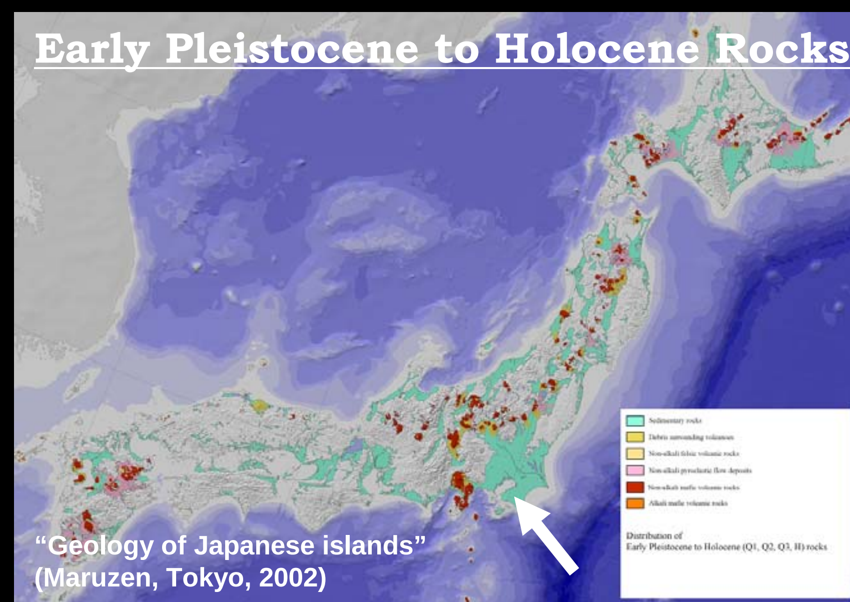
- 1st Generation: LISM (finished)
- 2nd Generation: CLIO (under construction)
- 3rd Generation: LCGT (a future project)

Introduction of KAMIOAKA

Location and Geology of Kamioka and Tokyo



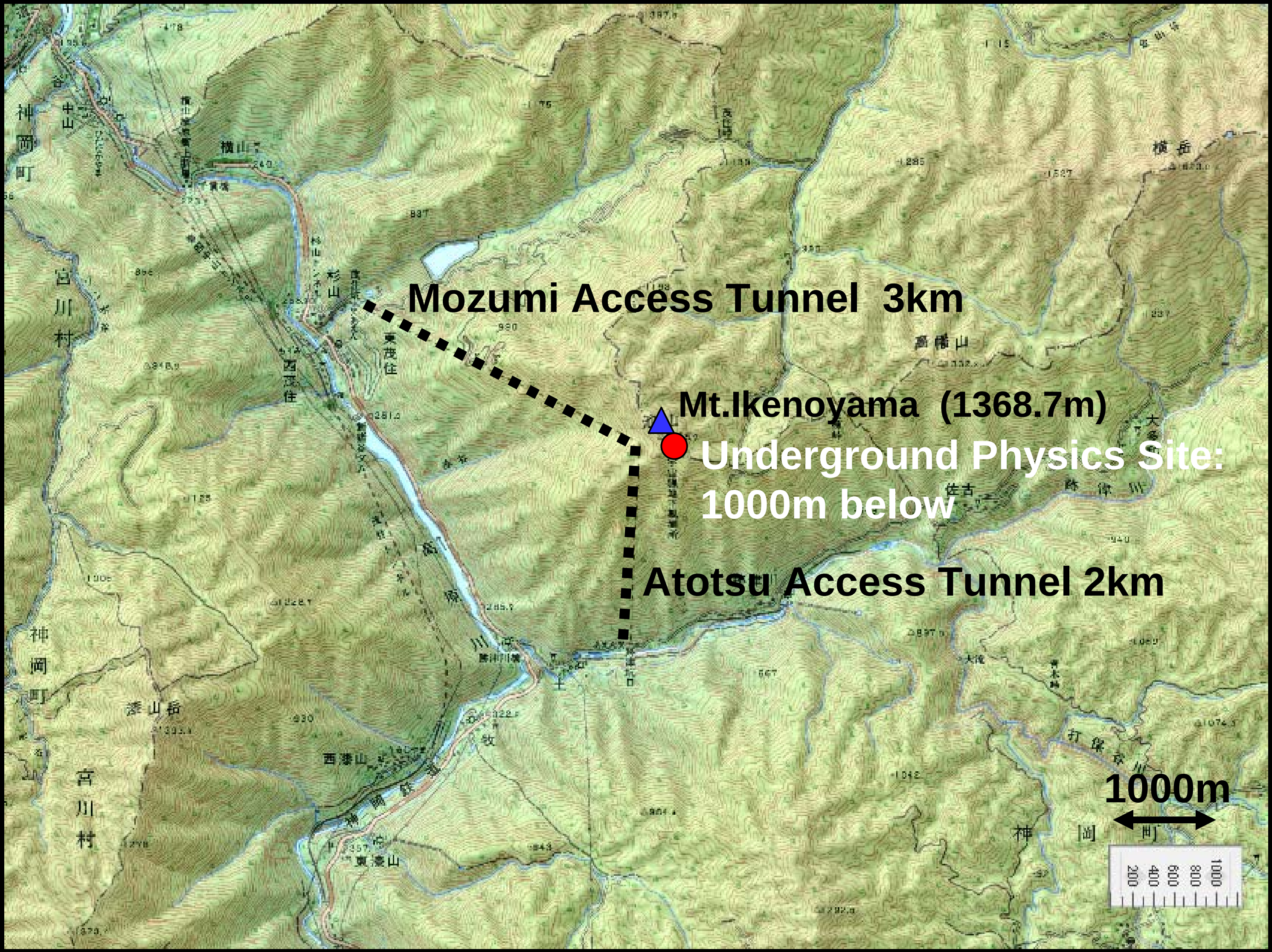




Kamioka Rock: Hida Gneiss (Precamblian?)

Primary wave velocity : 5.5km/s

Kamioka Mine Site

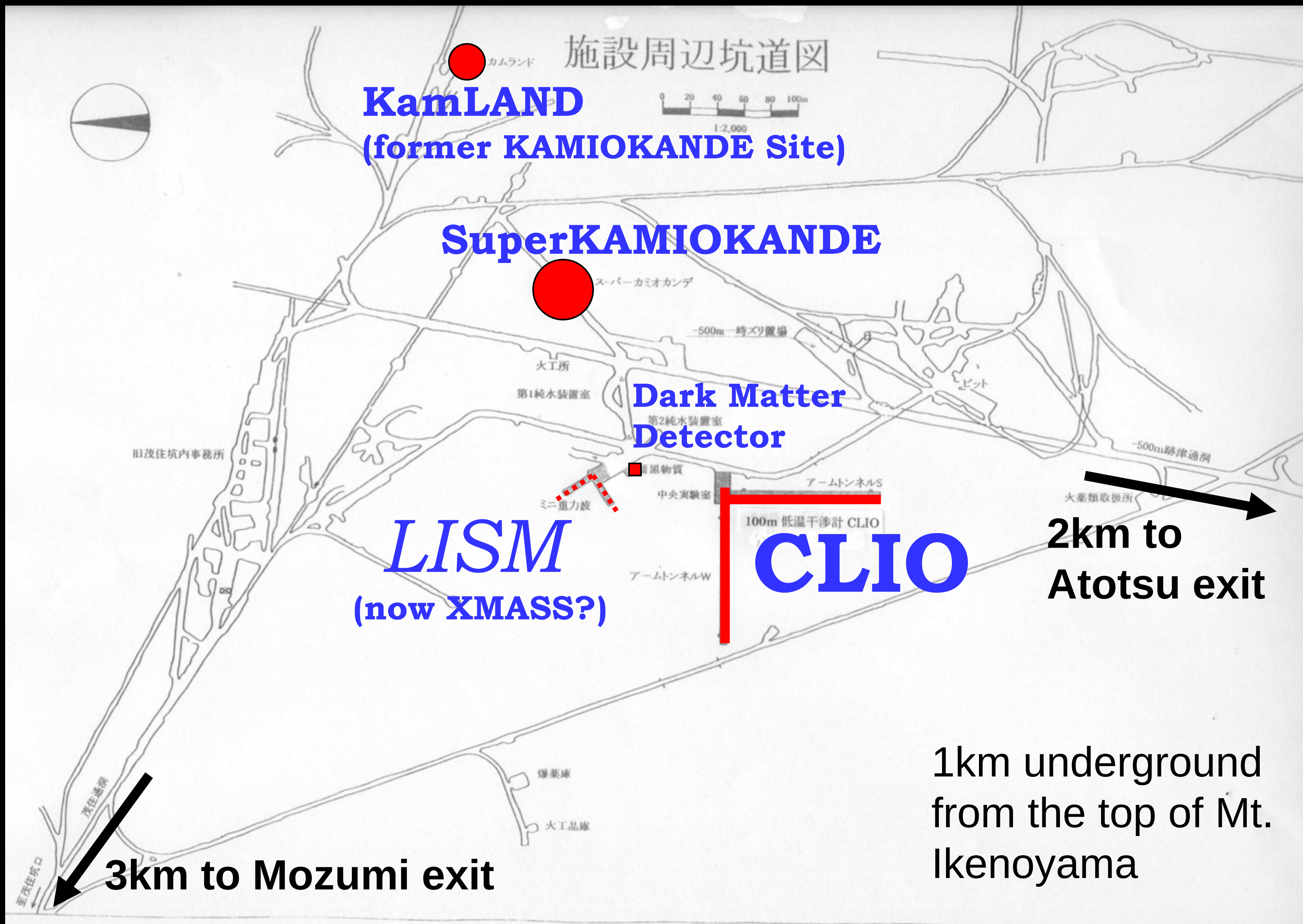


This map is a part of Kamioka mine area.

Mining
Started : 720 A.D.?
Stopped: 2001

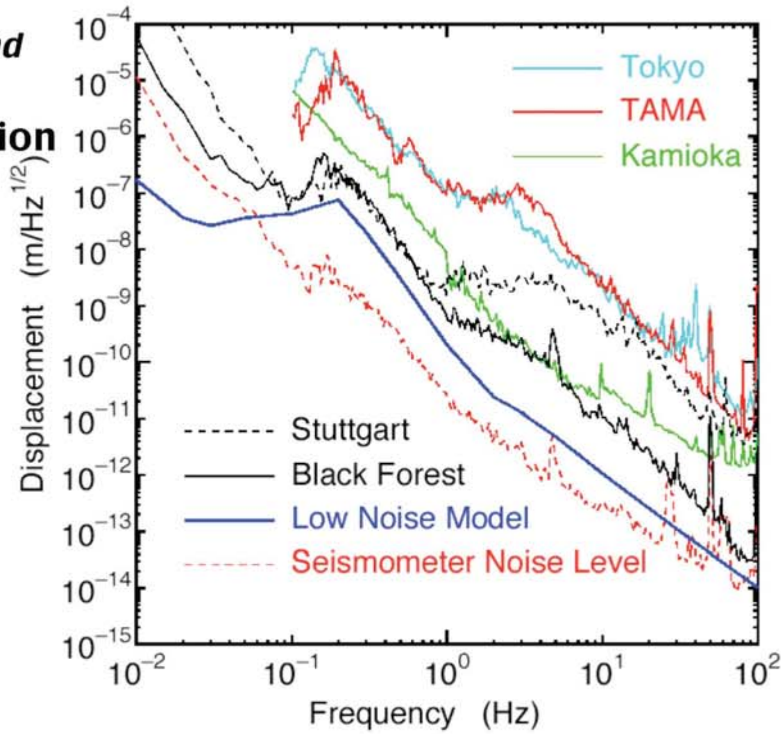
Map from kashmir3d

Tunnels and Detectors



Seismic Vibration at Kamioka, Tokyo, and TAMA Site

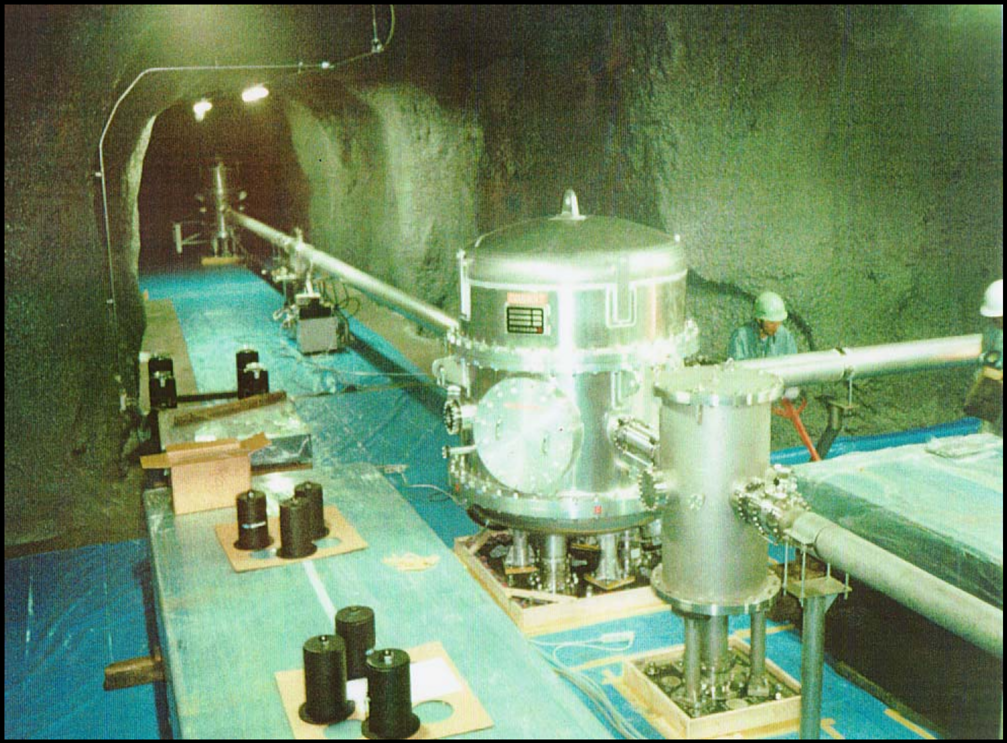
- **Low seismic noise level**
  - ***Great* in lower frequency Region**
  - ***2–3 orders merit@ a few [Hz]***
  - ***Close to Tokyo* in observation band**
- **“Indispensable” for stable operation**



Kamioka: 1000m Undergroud
Tokyo:
TAMA: a suburb of Tokyo (ground base)

GWADW 02/02/2003 Aspen

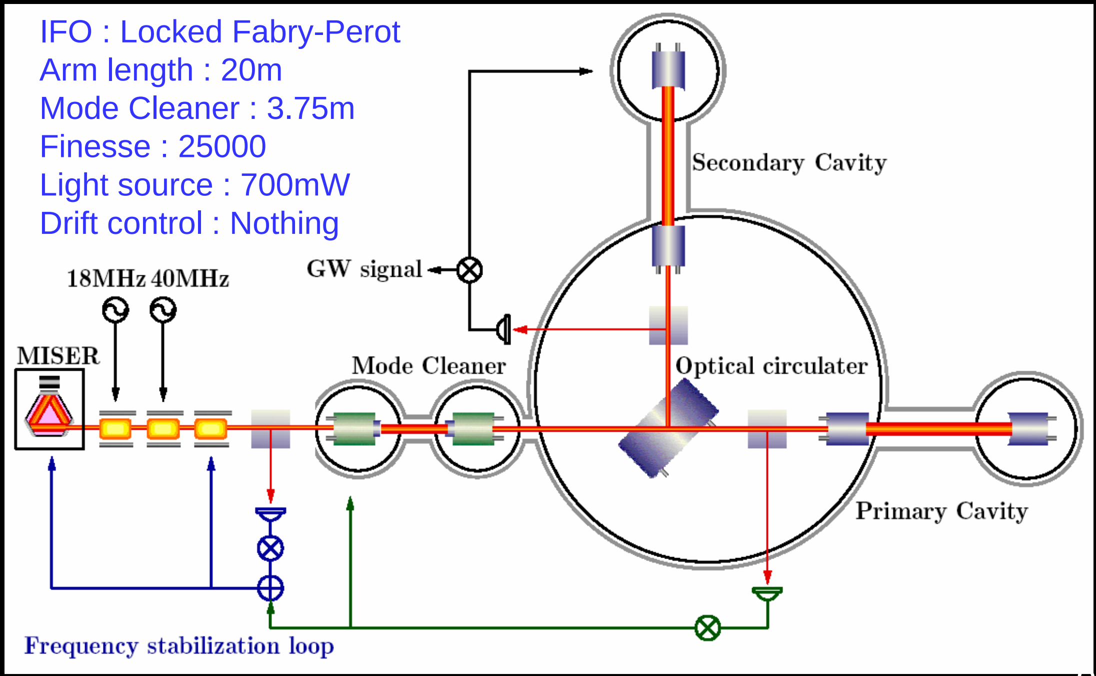
1st Generation: LISM



Laser Interferometer gravitational-wave Small observatory in a Mine

Outline of LISM

- 20m Arm Length
- 1999～2003 (finished and dismantled)
- Confirm underground advantage
- Not Cryogenic



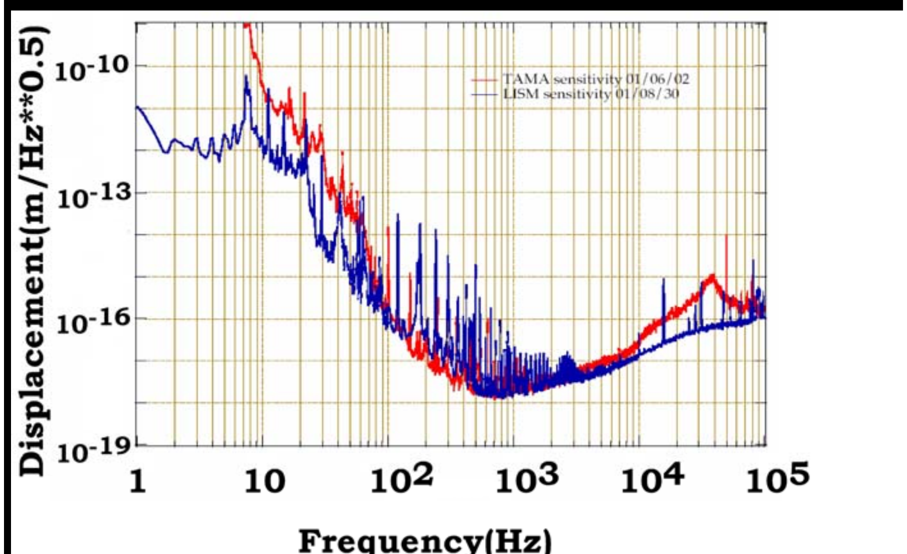
Shuichi Sato et al.
Phys.Rev.D69 (2004) 102005
GWADW 2003 (Aspen)
GWADW 2002 (Elba)

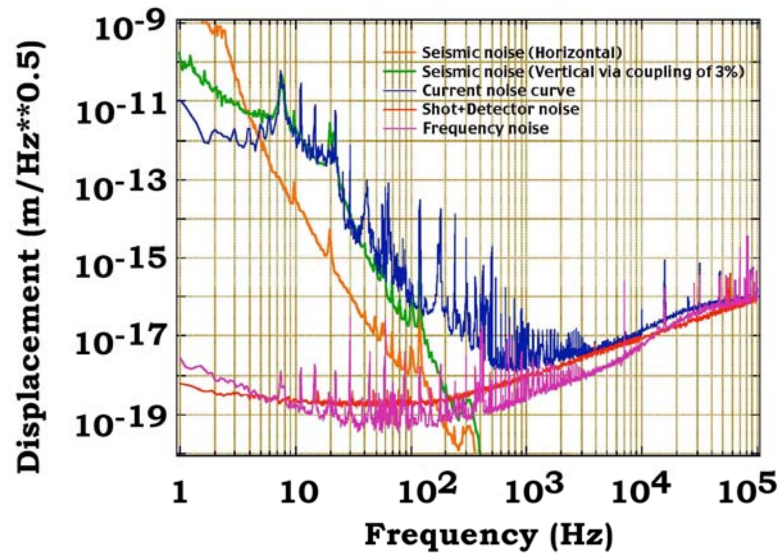
LISM Noise Budget

Horizontal Seismic Noise

3% Coupling
from Vertical Seismic Noise

LISM Noise





TAMA 2001/6/2 5.0×10^{-21}(1/Hz**0.5) @700Hz

LISM 2001/8/30 7.5×10^{-20}(1/Hz**0.5) @700Hz

LISM Summary

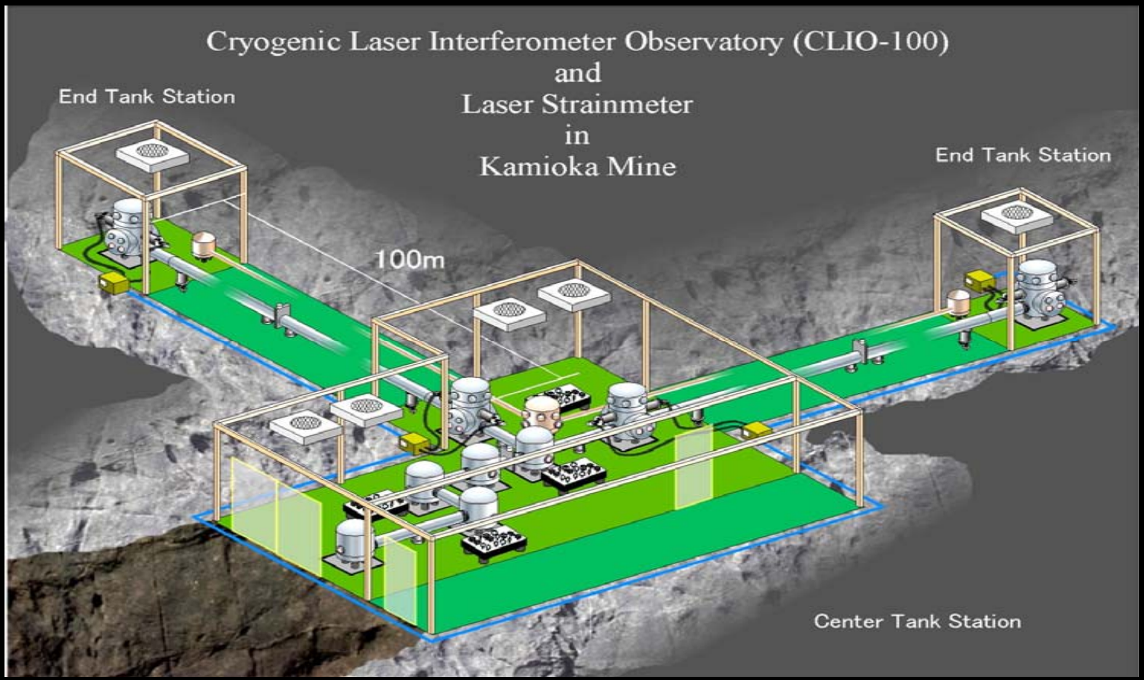
- **Duty Cycle: 99.8%**
  (with more severe condition to lock than TAMA)
- **Continuous Operation Record: 270h**
  (When no blast in the mine.)
- **Temperature variation: 0.01˚C/day**
  (No temperature control system)
- **Humidity variation: 0.08%/day**

2nd Generation: CLIO

Cryogenic Laser Interferometer Observatory

Practical Cryogenic Interferometer （ＣＬＩＯ project, 2002－2005)

- **2002～ (under construction)**
- **To Confirm Cryogenic Operation　of 100m Underground Interferometer**
- **Reduce Thermal Noise with 20K Sapphire Mirrors Suspended by Sapphire Fibers**
- **Locked Fabry-Perot**



http://www.icrr.u-tokyo.ac.jp/gr/gr.html
GWADW 2004 Kazuaki Kuroda
JGRG14 2004 Nov. (Kyoto) Masaki Ando

Present Status of CLIO

- Mode Cleaner (Installed)
- One Set of Cryostat with 4K and 80K Low Vibration Pulse-Tube Cryocoolers (Confirmed Cooling Specifications at the site)

Parts Carried in the Site in 2004

- Vacuum Chambers of Center Room
- Perpendicular Arm Vacuum Duct

Low Vibration Pulse-Tube Cryo-cooler for Underground Site

Cryogenic Facilities at Underground Site

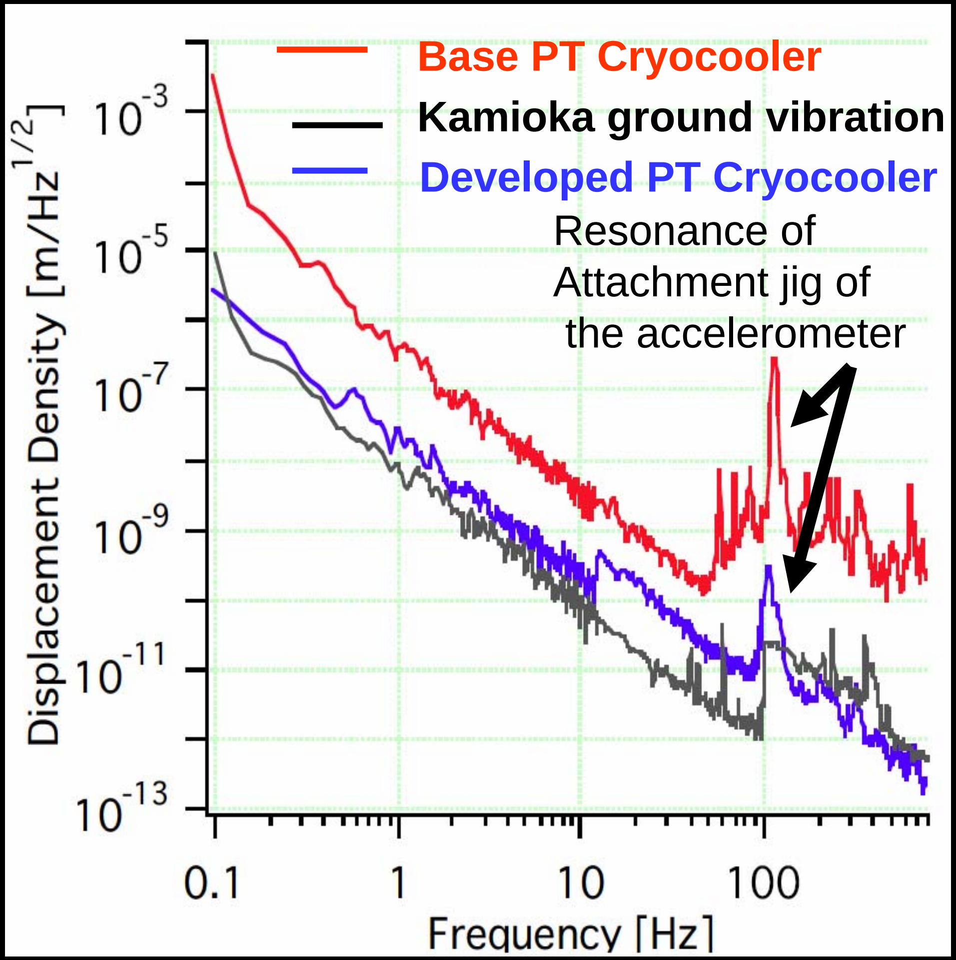
	Liquid Nitrogen Liquid Helium	Pulse-Tube Cryocooler
At Closed Area	×	●
Continuous Operation	×	●
Vibration	●	▲

(1) We chose pulse-tube cryocoolers.

(2) We developed a low vibration pulse-tube cryo-cooler with a vibration of less than 50nm.

Nano-Level Vibration Pulse-Tube Cryocooler

Vibration Measurement at Kamioka



Geophysical Observations at Kamioka

100m Laser Strainmeter for Geophysical Observations

- **Parallel observation with CLIO detector in the same tunnel.**

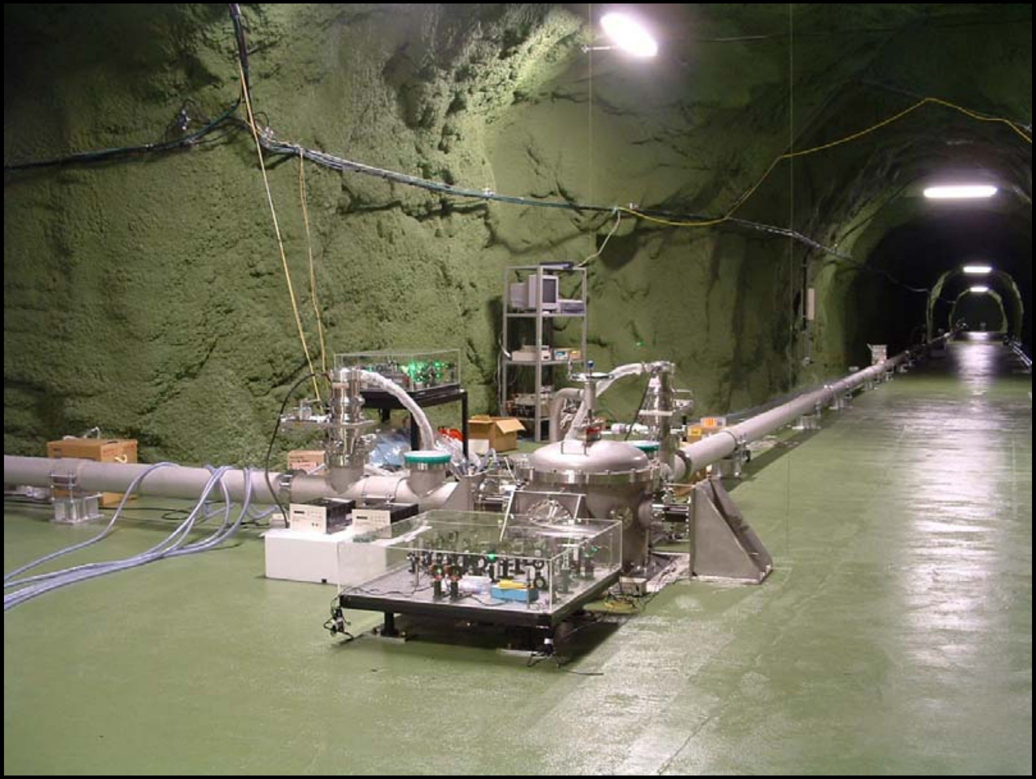


Photo Before CLIO installing

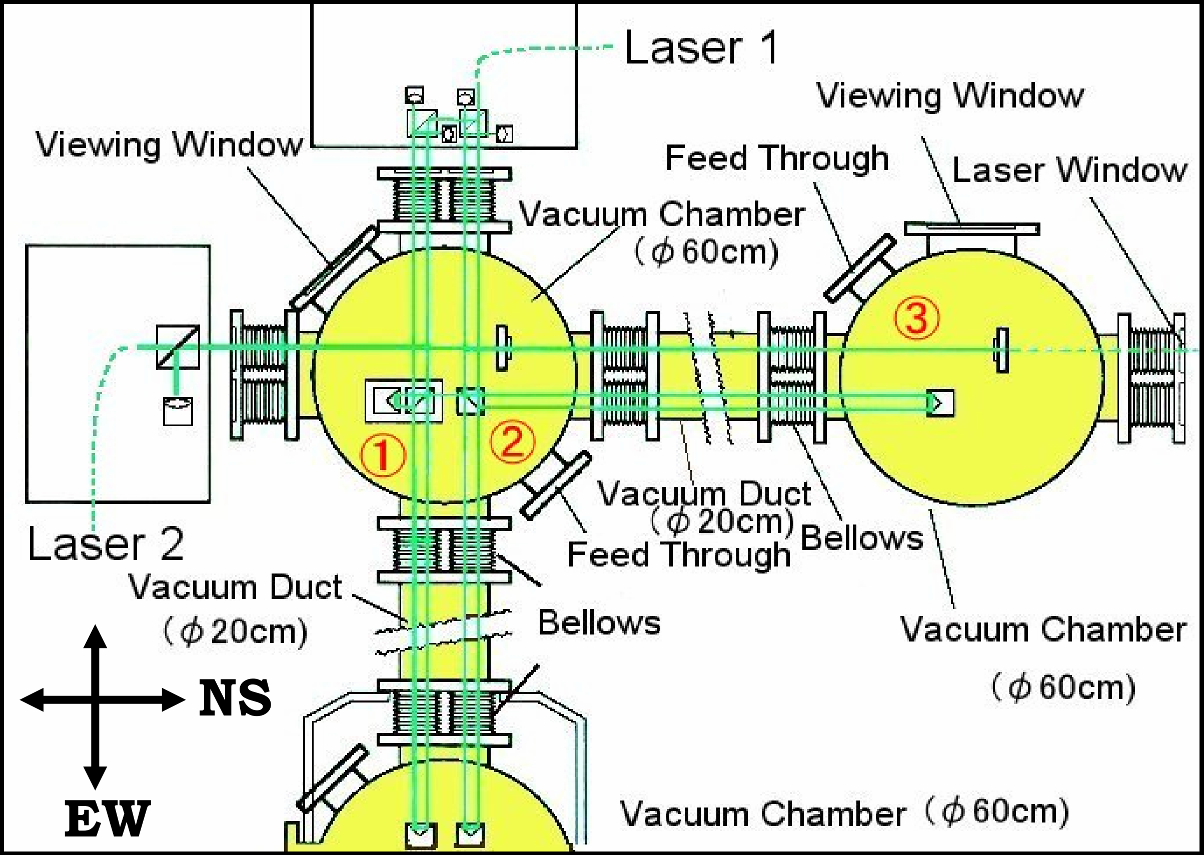
A.Araya (Earthquake Research Institute, Univ. of Tokyo)

Targets of 100m Laser Strainmeter

- Earth’s Free Oscillations (Core Modes etc.)
- Earth Tides
- Fault-motion Monitor
- Metrological Application (Absolute-distance Measurement)

Geophysical Instruments

- **Laser Strainmeter (①Linear and ②Shear, Resolution ~10^{-13})**
- **③ 100m Absolute-length Interferometer (Accuracy ~0.1μm/100m)**
- **Superconducting Gravimeter (Resolution ~10^{-11}m/s^2)**

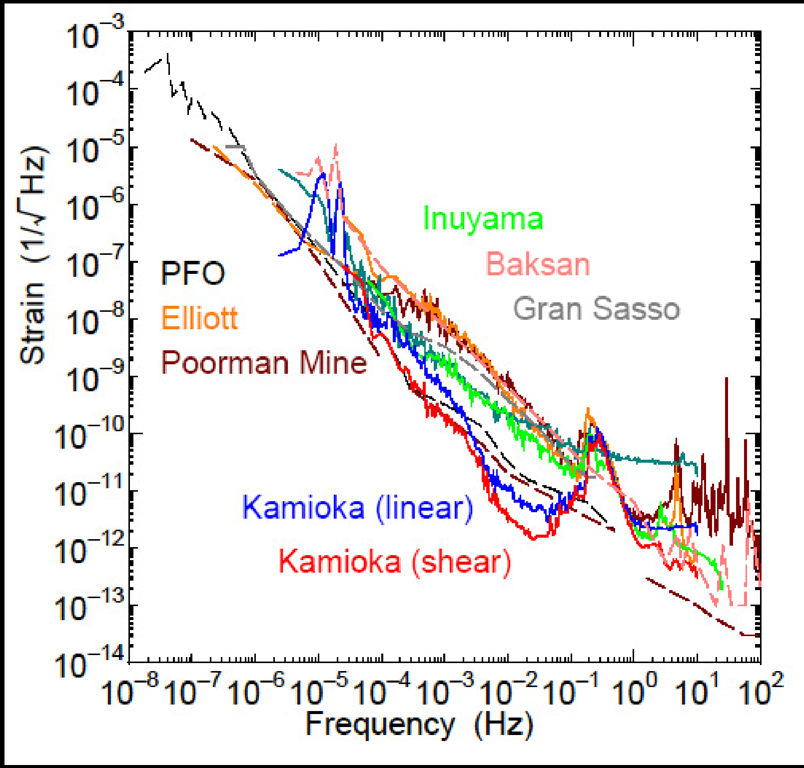


Laser Strainmeters

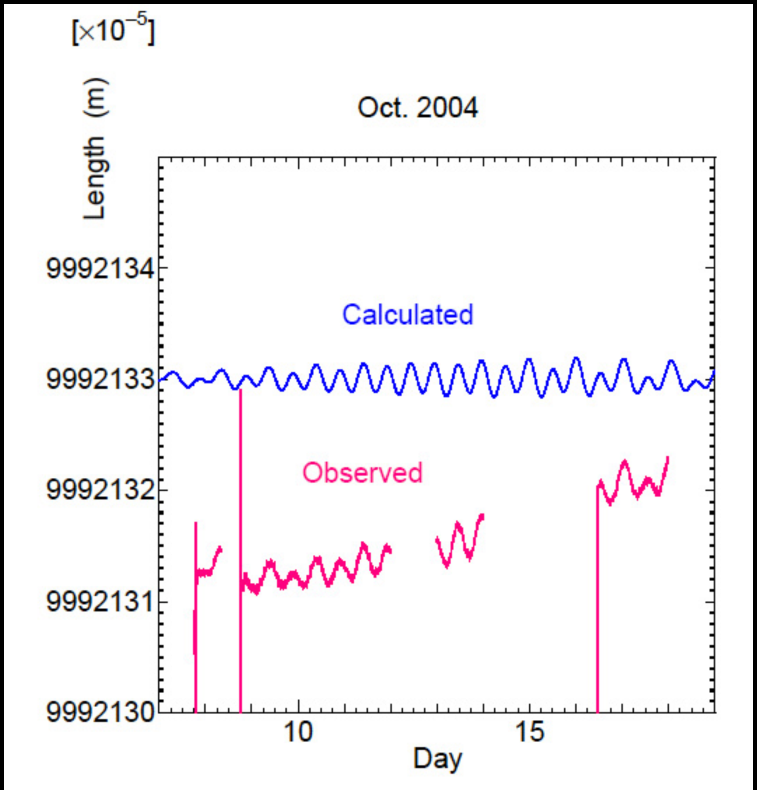
Superconducting Gravimeter

100m Laser Strainmeter Achievements at present

- Most sensitive strain observation at 1-100mHz with an iodine-stabilized 532nm laser (freq. stability of 10^{-13})
- Earth tides and Earth's fundamental free oscillations have been clearly observed.



Background Noise Level



Earth Tides observed by Absolute-length Interferometer

Recent Study of Kamioka Geophysical Instruments

- **M9.0 Sumatra Earthquake (2004 Dec.26)**

100m Laser Strainmeter:

First few hours after the earthquake: Continuous Data taken

After the first few hours: Sporadic Data taken

Superconducting Gravimeter:

All the time after the earthquake: Data taken

Now under analyses

3rd Generation: LCGT

Large-scale Cryogenic Gravitational-wave Telescope

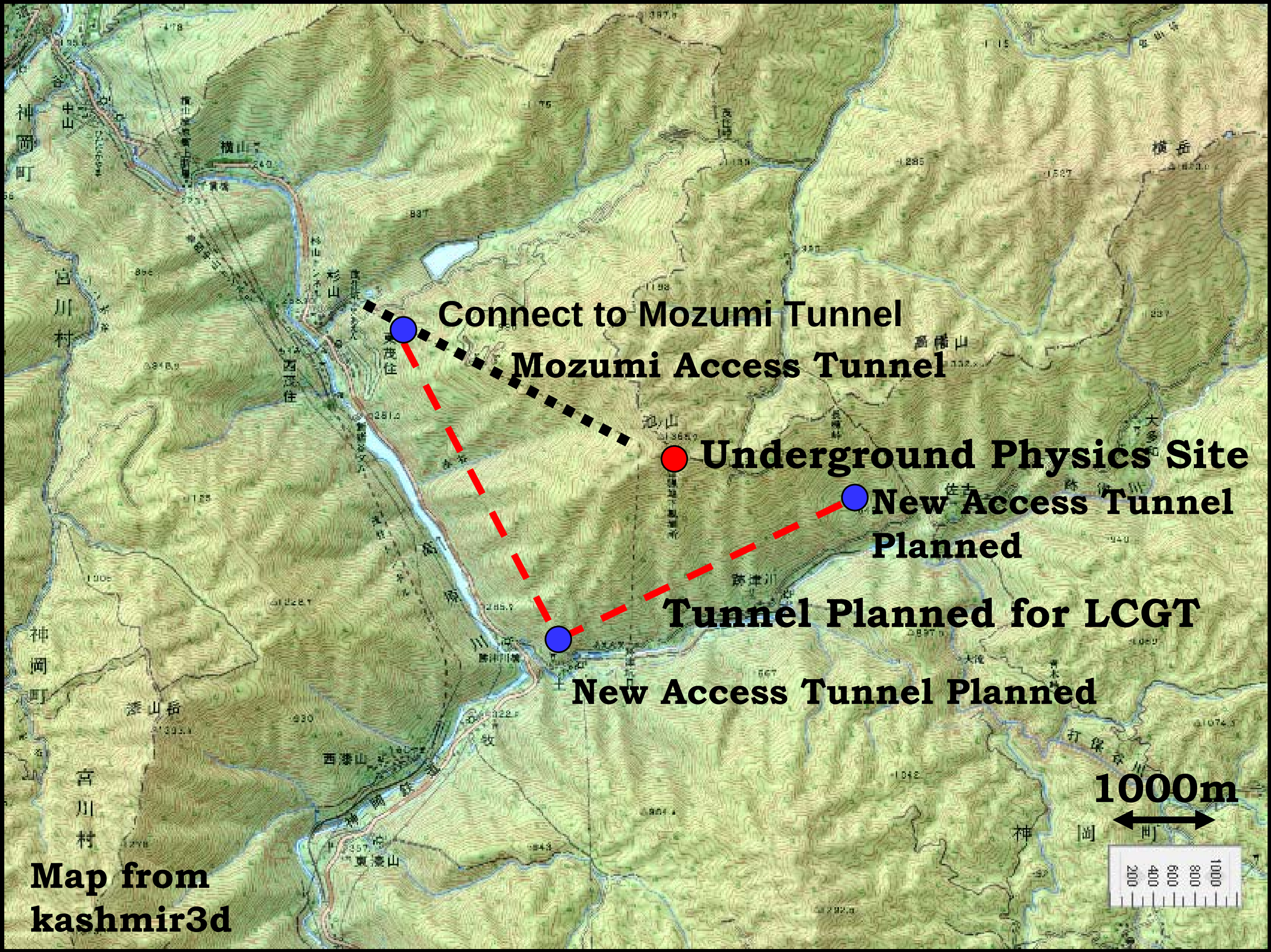
Near Future project from 1997

Status of LCGT

- **Submitted the budget request last month (2006~2012)**

http://www.icrr.u-tokyo.ac.jp/gr/gr.html
GWADW 2004 (Aspen) Kazuaki Kuroda
JGRG14 2004 Nov. (Kyoto) Masaki Ando

LCGT Site Planned

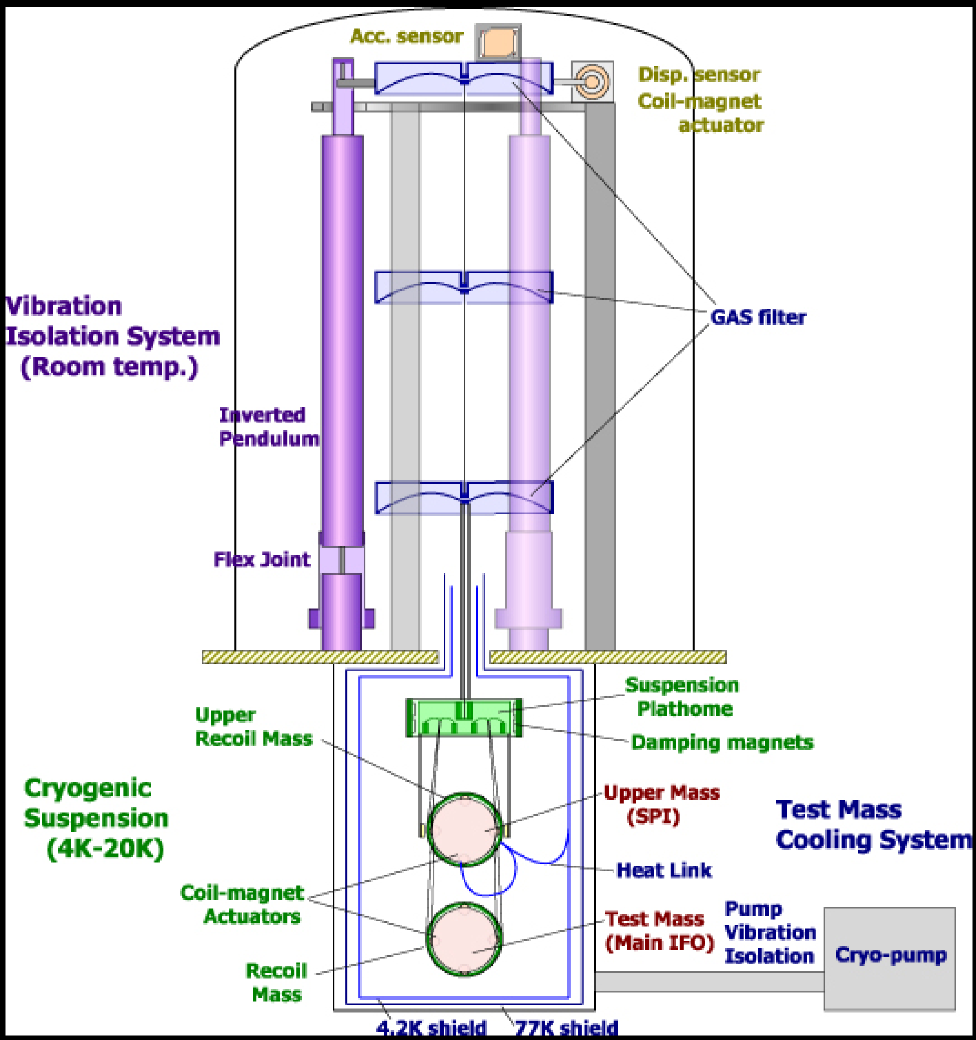


Characteristics and Parameters of LCGT

- Interferometer Configuration: Broad Band Resonant Sideband Extraction
- 2 Parallel Interferometers in the Same Vacuum Duct
- Suspension Point Interferometers

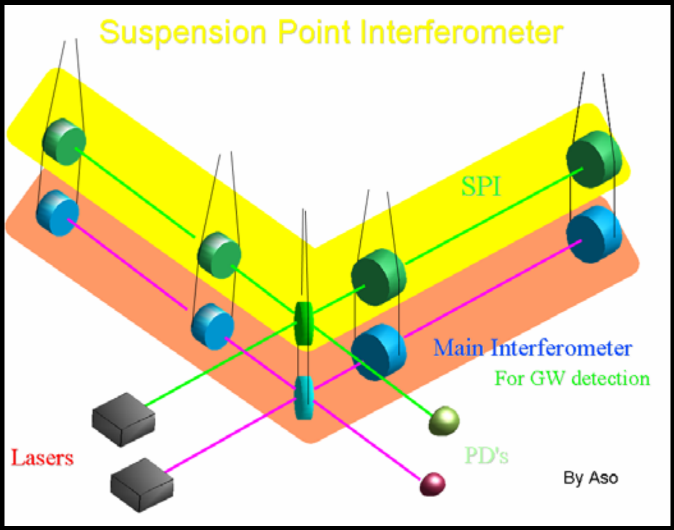
- **Baseline Length: 3km**
- **Mirror Substrate: ϕ25cm, 30kg, Sapphire**
- **Temperature of Mirror: 20K**
- **Laser Power: 150W**
- **Stored Power: 780kW**
- **Observational Band Width: 30~1000Hz**
- **Maximum Sensitivity: $3 \times 10^{-24}/\mathrm{Hz}^{1/2}$**
- **Observable Distance: 174Mpc (Average)**

Vibration Isolation

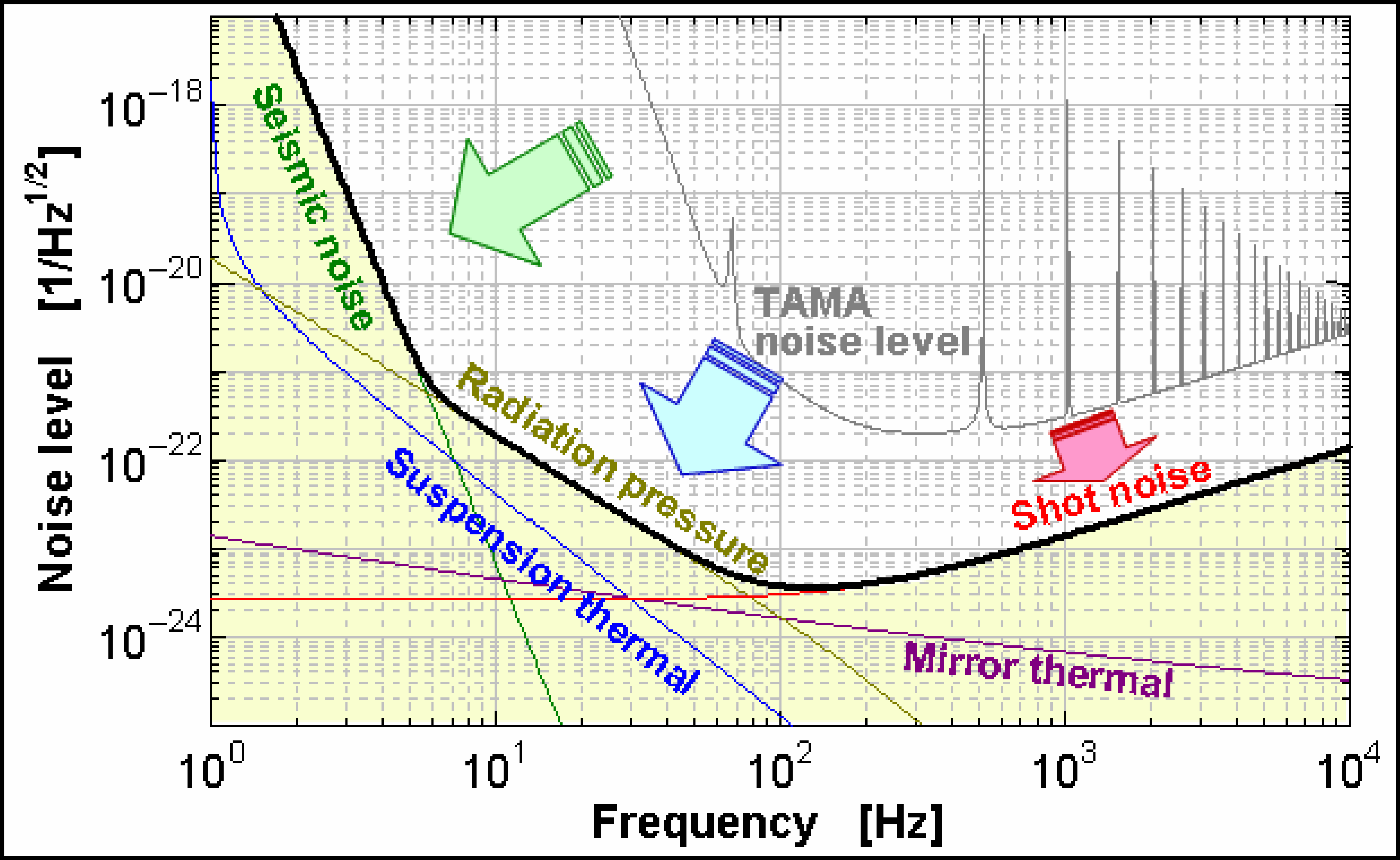


Test mass of LCGT is connected to a cooling system by a heat link that introduces mechanical noise.

A suspension point interferometer is Introduced to maintain high attenuation of seismic and mechanical noise without degrading high heat conductivity.



LCGT Sensitivity

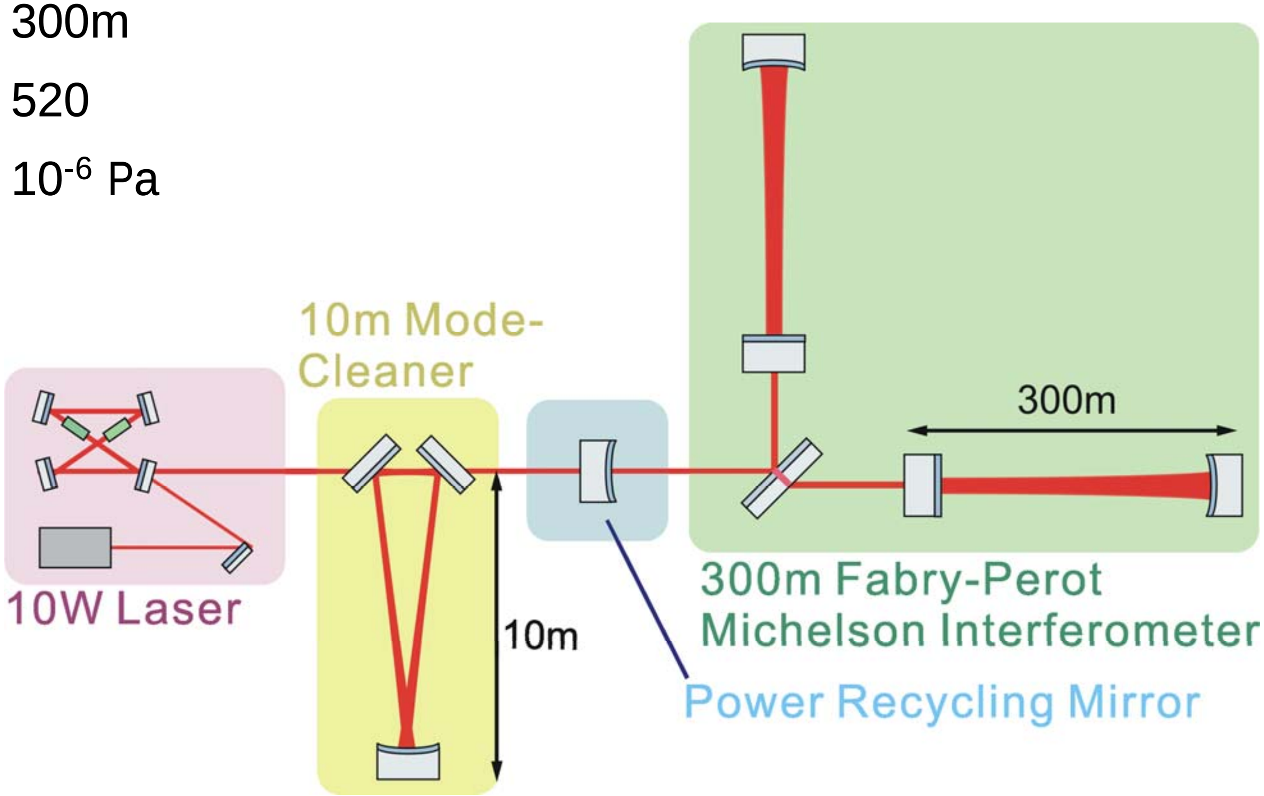


R&D (1)

Status of TAMA 300

Specification

Location	Mitaka campus of NAO (E139.32.21 N35.40.25)
Aimed sensitivity	h=3x10^{-21} @300Hz (BW 300Hz)
Type	Recycled Fabry-Perot Michelson Interferometer
Laser	Injection-lock Nd:YAG (λ=1062nm), 10W
Baseline length	300m
Finesse of cavity	520
Vacuum	10^{-6} Pa



Past data taking (DT)

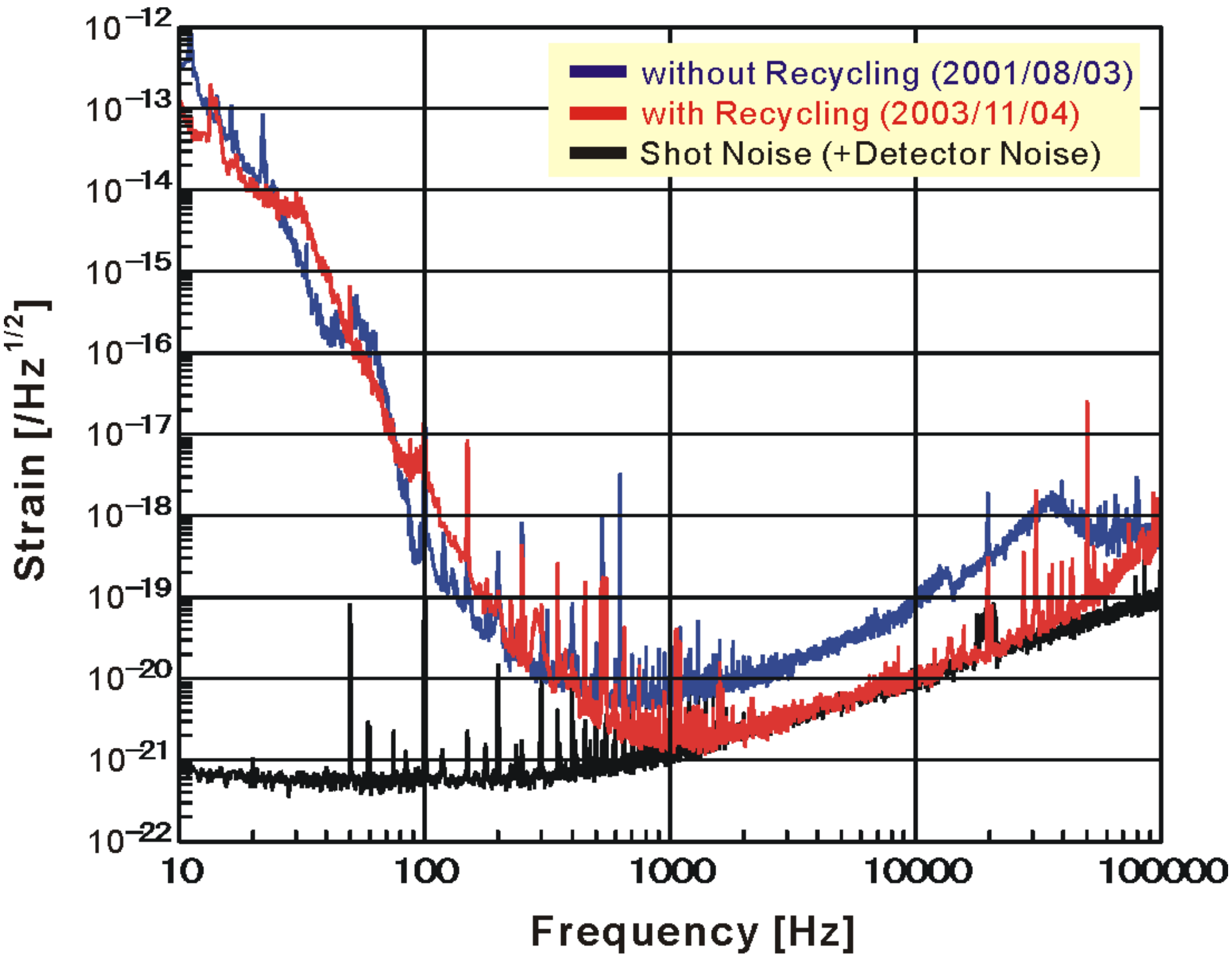
	Period	Obs. Time	Main Target
DT1	1999 8/6〜8/7	11h	Establishment of calibration
DT2	1999 9/17〜9/20	31h	First event search
DT3	2000 4/20~4/23	13h	Improved sensitivity
DT4	2000 8/21~9/4	167h	100-h data
DT5	2001 3/2~3/10	111h	24-h full-time observation
DT6	2001 8/1~9/20	1038h	1000-h data
DT7	2002 8/31~9/2	25h	Recycling
DT8	2003 2/14~4/15	1158h	International coincidence run
DT9	2003/4 11/28~1/10	557h	Automatic operation

Sensitivity in DT9

Recycling gain: 4.5

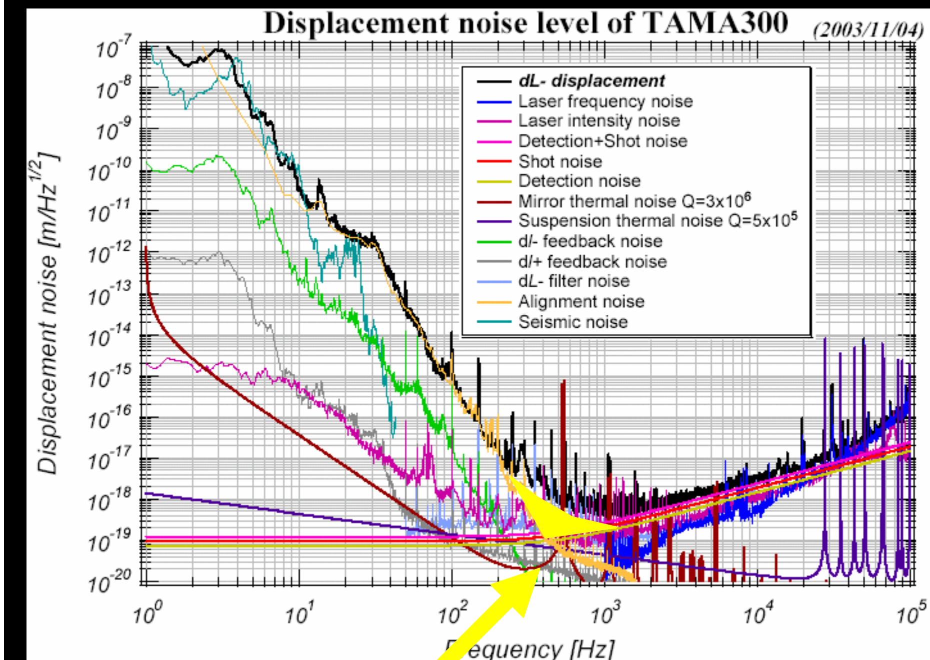
Extended control band width for the laser frequency

Improved strain sensitivity: h=1.7x10^{-21} /Hz$^{1/2}$ @1kHz

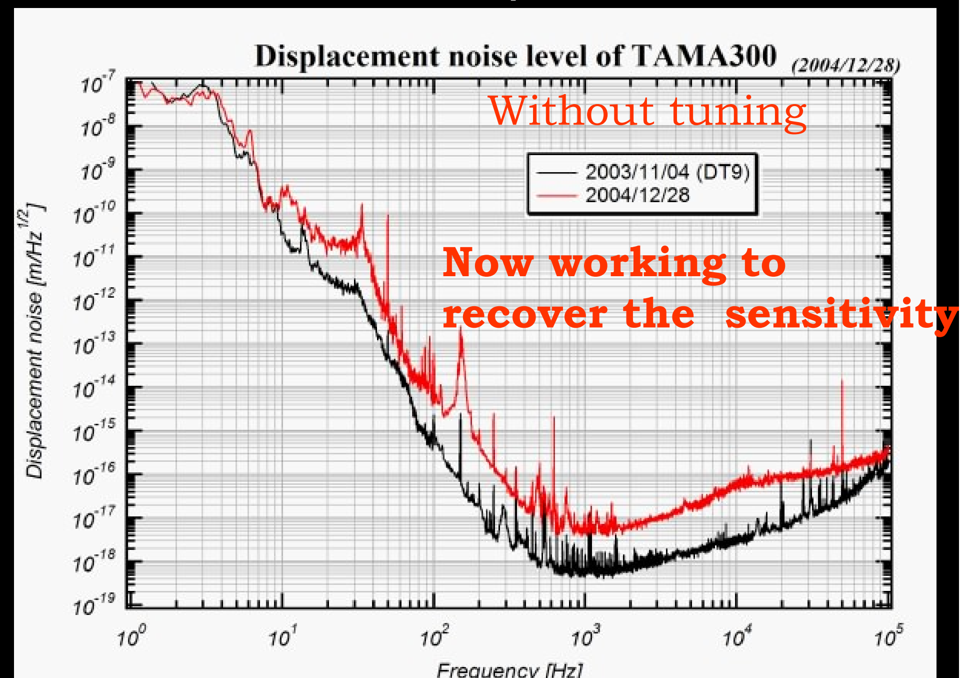


Recent TAMA300 Displacement

Nov. 04, 2003 **RFPMI**



Dec. 28, 2004 **RFPMI**



Unidentified Noise

RFPMI ➔ RMI

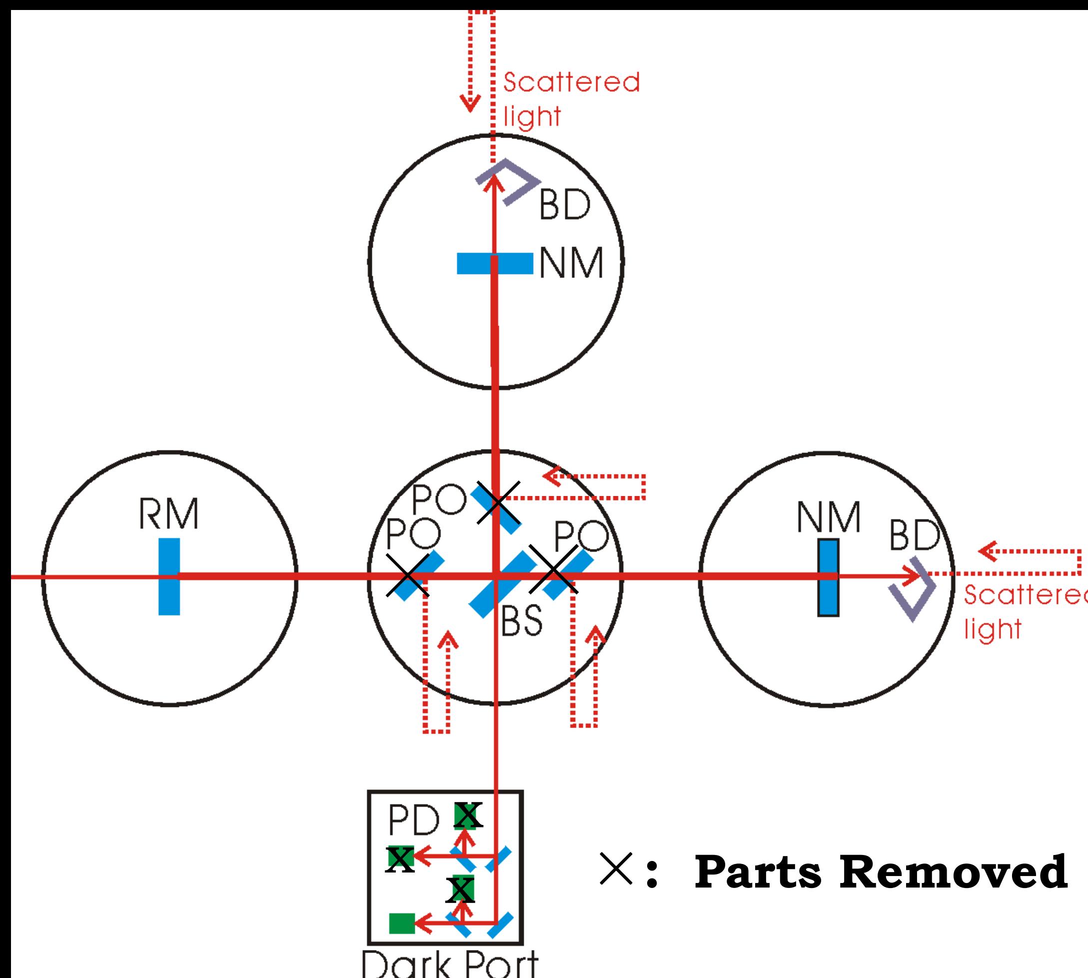
Noise Hunting for scattered light with Power Recycled Michelson Interferometer

RMI ➔ RFPMI

Noise Hunting in the Michelson Part

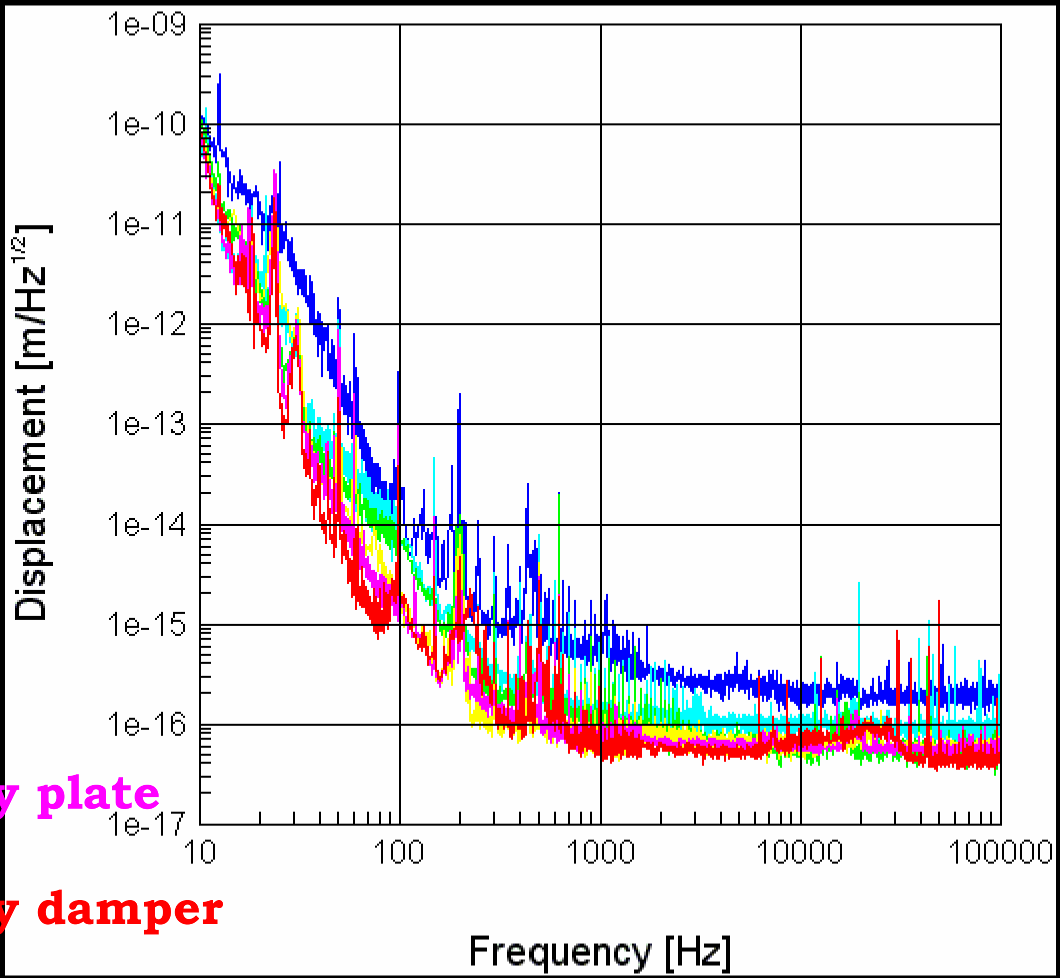
Noise source

- **Electronics:**
  PD, Servo filter
- **Scattered light:**
  PO, End chamber



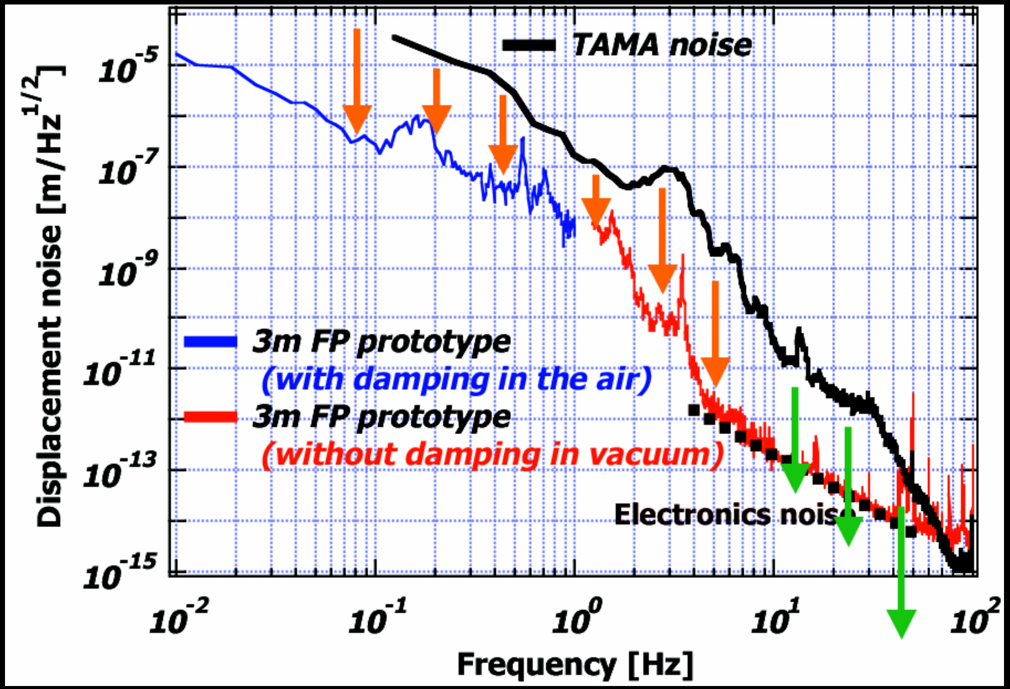
Improvement in the Michelson part

2004/1/15
Just after DT9
2004/1/29
PO removal,
Dark WFS
2004/2/05
4PD→1PD,
servo filter improved
2004/2/12
PD modified
2004/2/28
Scattered light rejection by plate
2004/4/23
Scattered light rejection by damper



Status of TAMA300, (II) Seismic Attenuation System (SAS)

Now assembling at NAOJ **(SAS will be installed in 2005.)**



Expected Isolation @4Hz 10^{-8}m/Hz$^{1/2}$ → 10^{-11}m/Hz$^{1/2}$

Expected RMS velocity 3.7μm/s → 0.3μm/s

Assembling is being delayed.

(1) Some of the Main Parts are not yet arrived.

(2) Some problem of vertical isolation parts: MGAS.

R&D (2)

“Making a Data Analysis Processor with Field Programmable Gate Array (FPGA)”

ECRS 2004 (Florence) SATO Nobuaki et al.
(Submitted to Int’l. J. of Mod. Phys. A)

A Current Computer System for Gravitational wave Event Search

PC Cluster of other group at KEK

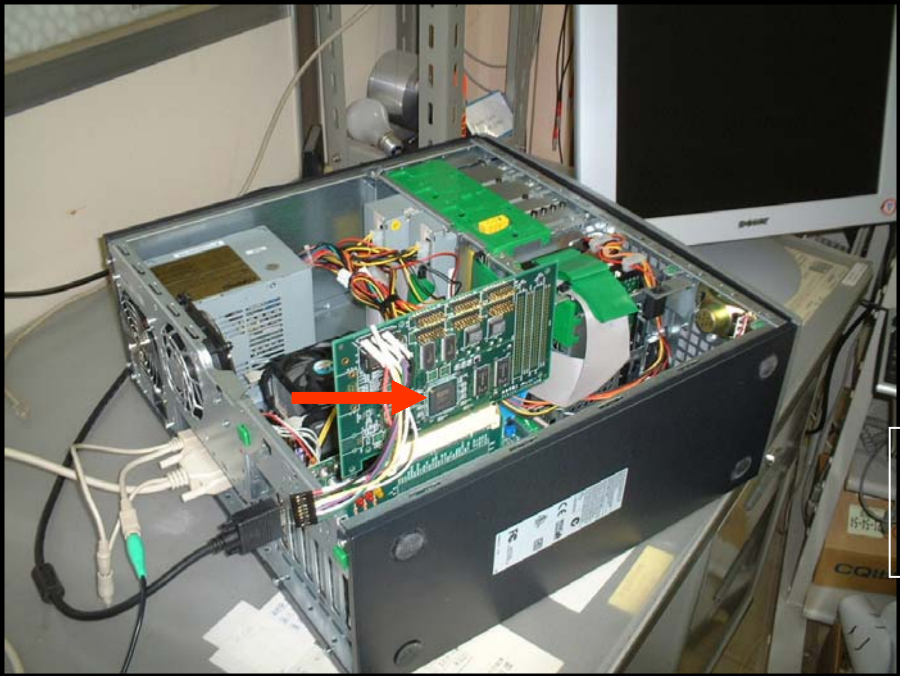
- More than 16 PCs are connected.
- Parallel Computing Library: (for example) MPI.

- If we do not have a PC cluster, how do we analyze data?
- Some analysis consumes most of CPU time for FFT calculations or …….

▼

Special Purpose Hardware connected to one PC for personal use.

Data Analysis Processor:
Special Purpose Hardware with FPGA



One PC + **PCI Board with FPGA**

Calculations by Hardware Logic (For Example, FFT)

Remained part of a analysis program except FFT or other hardware logic.

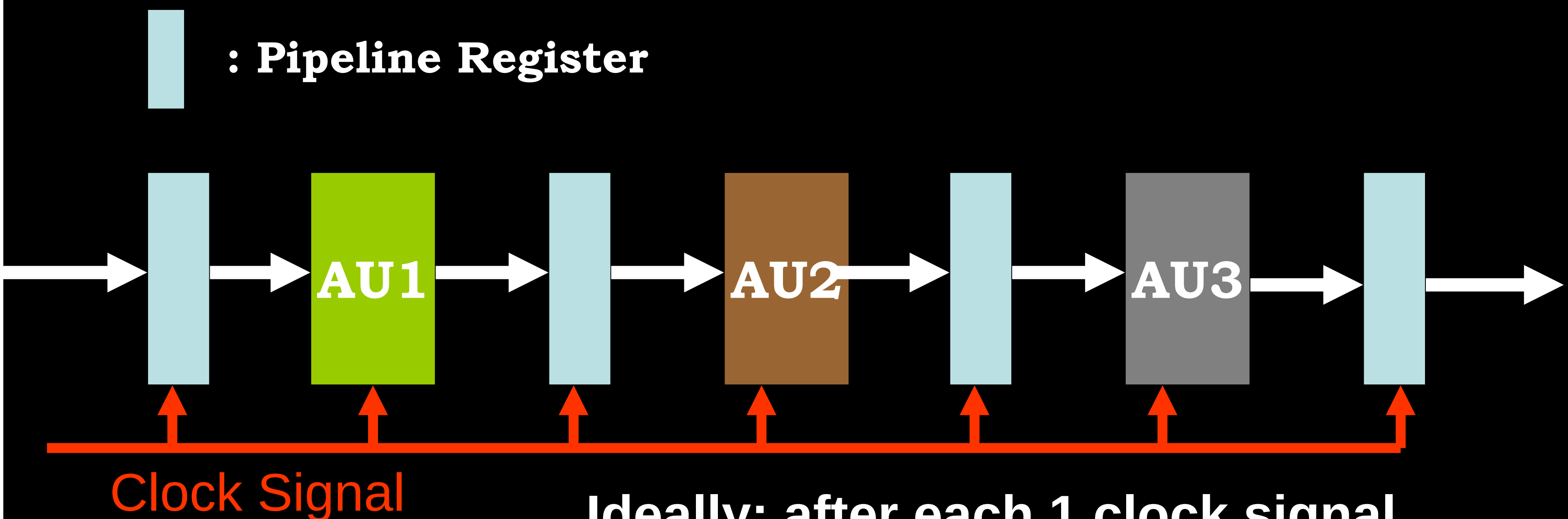
Logic Circuit : into FPGA by software
Data Communication through PCI

Design: Hardware Description Language
Implement: Design Software
(of each FPGA Manufacturer)

several x $100 for FPGA with million logic gates equivalent

FPGA: rewritable ------- useful for making a prototype with try and error

To Speed up: Pipeline, and Stack Pipelines



Ideally: after each 1 clock signal, output 1 processed data

FPGA: (X) MHz operation
Needed # of floating point calculations with a usual computer #: N
Pipeline#: Np

(X・Np・N) MFlops

Other Applications of Data Analysis Processor

- On-line analyses
- Optics simulations for interferometers with 2 dim FFT
- Special purpose hardware besides FFT for offline analyses

Summary

- **LISM :** Confirmed advantage of underground site for stable operation
- **CLIO :** Under Construction
- (Geophysical 100m Laser Strainmeter System: continuous data taking)
- **LCGT :** Submitted the Budget Request of 2006

- **R&D(1) :** TAMA (1) SAS now assembling
  (2) Noise hunting of scattered light with RMI configuration was finished.
- **R&D(2) :** Pipelined data analysis processor with FPGA

Thank you for your attention of Kamioka underground interferometers.

In the list of participants of this workshop,
My affiliation and e-mail address are mistaken.

Error:

Sato, Nobuaki NAOJ sato@gravity.mtk.nao.ac.jp

Correct:

Sato, Nobuaki KEK saton@post.kek.jp

(Among 40 Japanese, one person can be Sato.)

Seismic Noise at Experimental Site

(1) Global, Regional Background

Microseismic (ocean origin 0.2Hz), less than 0.2Hz

Several km tunnel cannot escape

(2) Wave excited near the surface

(3) Noise near the experimental site

Sound from the experimental system
Wind in the tunnels
above several 10Hz
(Sensor in the soundproof room)

Main Parameters of LCGT

Laser

Nd:YAG laser (1064nm)
Injection lock + MOPA
Power : 150 W

Main Interferometer

Broad band RSE configuration
Baseline length : 3km
Beam Radius : 3-5cm
Arm cavity Finesse : 1500
Power Recycling Gain : 12
Signal Sideband Gain : 15
Stored Power : 0.78MW
Signal band : 200Hz

Vacuum system

Beam duct diameter : 90cm
Pressure : 10^{-9} Torr

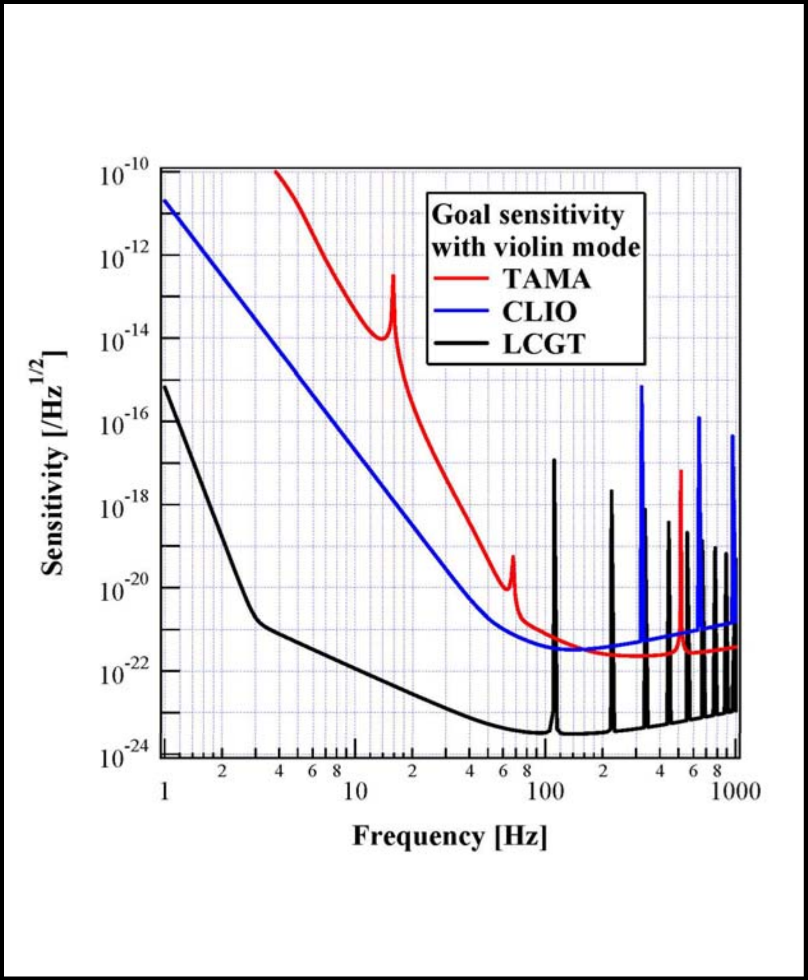
Mirror

Sapphire substrate
+ mirror coating
Diameter : 25cm
Thickness : 18cm
Mass : 30 kg
Absorption Loss : 20ppm/cm
Temperature : 20 K
Q = 10^8
Loss of coating : 10^{-4}

Final Suspension

Suspension (heat link)
with 4 Sapphire fibers
Suspension length : 40cm
Fiber diameter : 1.5mm
Temperature : 16K
Q of final suspension : 10^8

Goal Sensitivity of TAMA, CLIO, and LCGT



CLIO: Suspension
40cm, ϕ150μm

LCGT: Old Parameter
Mirror: 50kg
Laser Power 75W

K.Yamamoto
(ICRR, Univ.of Tokyo)

Status of TAMA
(I) Noise Hunting in the Michelson Part

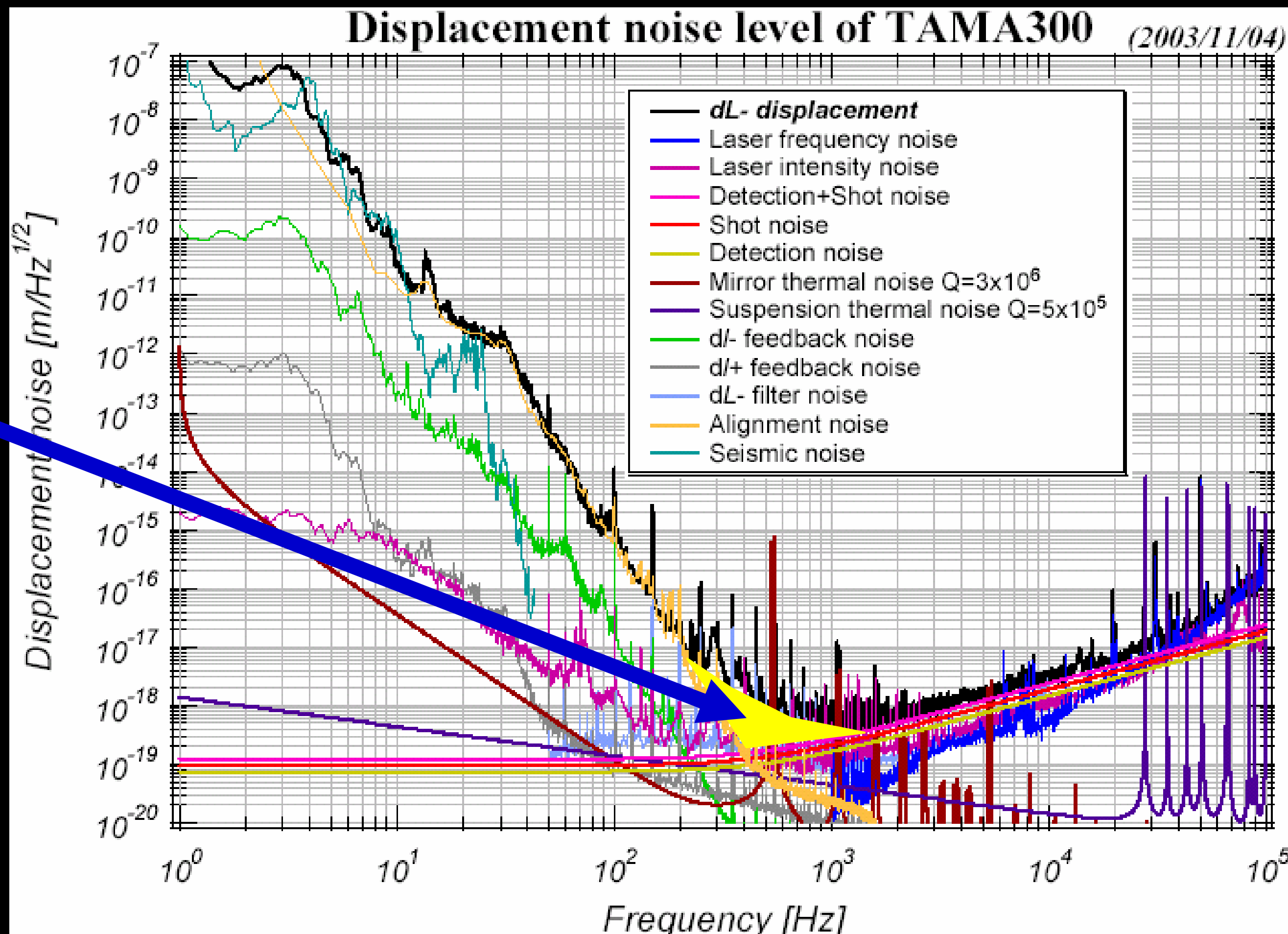
DT9 noise level

- Seismic noise
- Alignment noise
- Shot noise

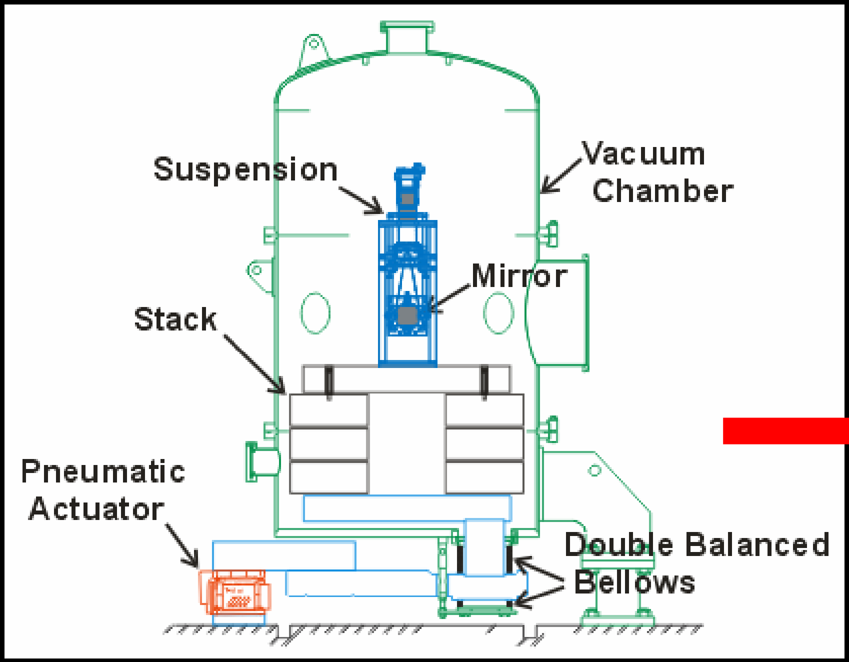
Unidentified Noise

Scattered light ?
Beam jitter ?
Laser source ?
RF detection?
Electronics?

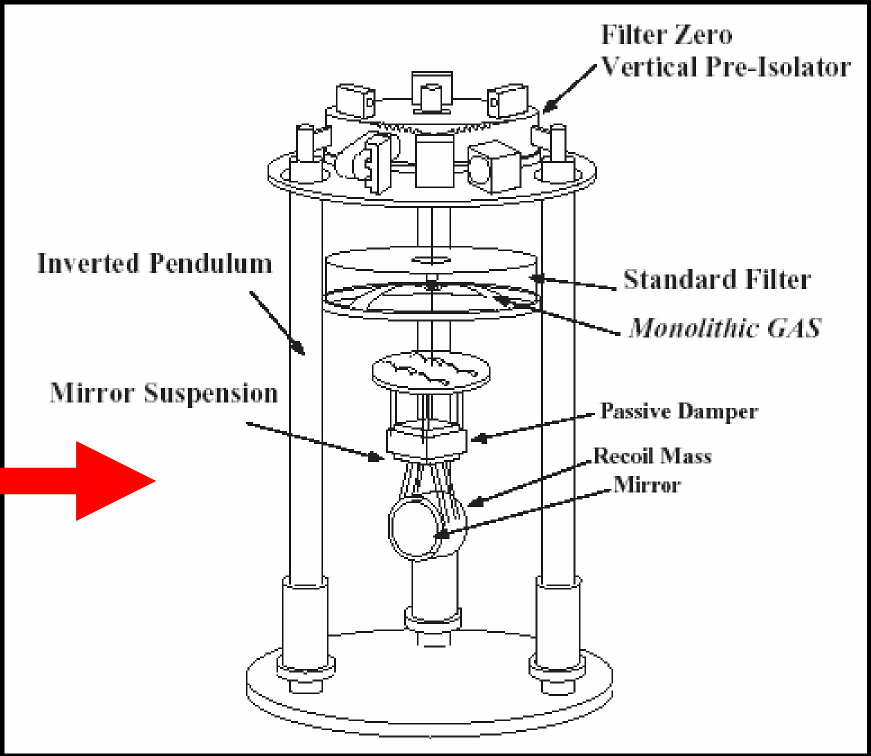
Noise Hunting



To TAMA-SAS

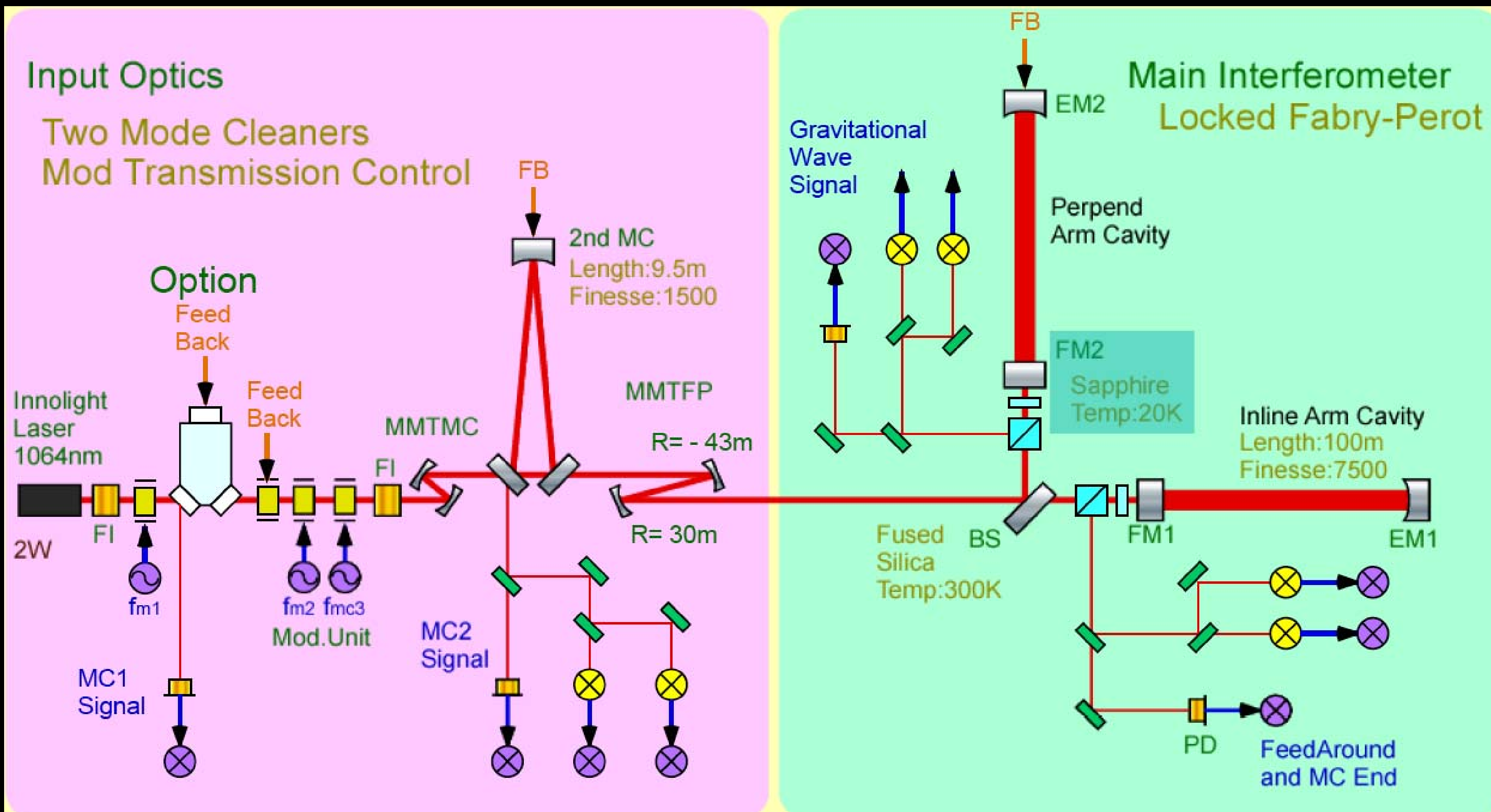


Present System



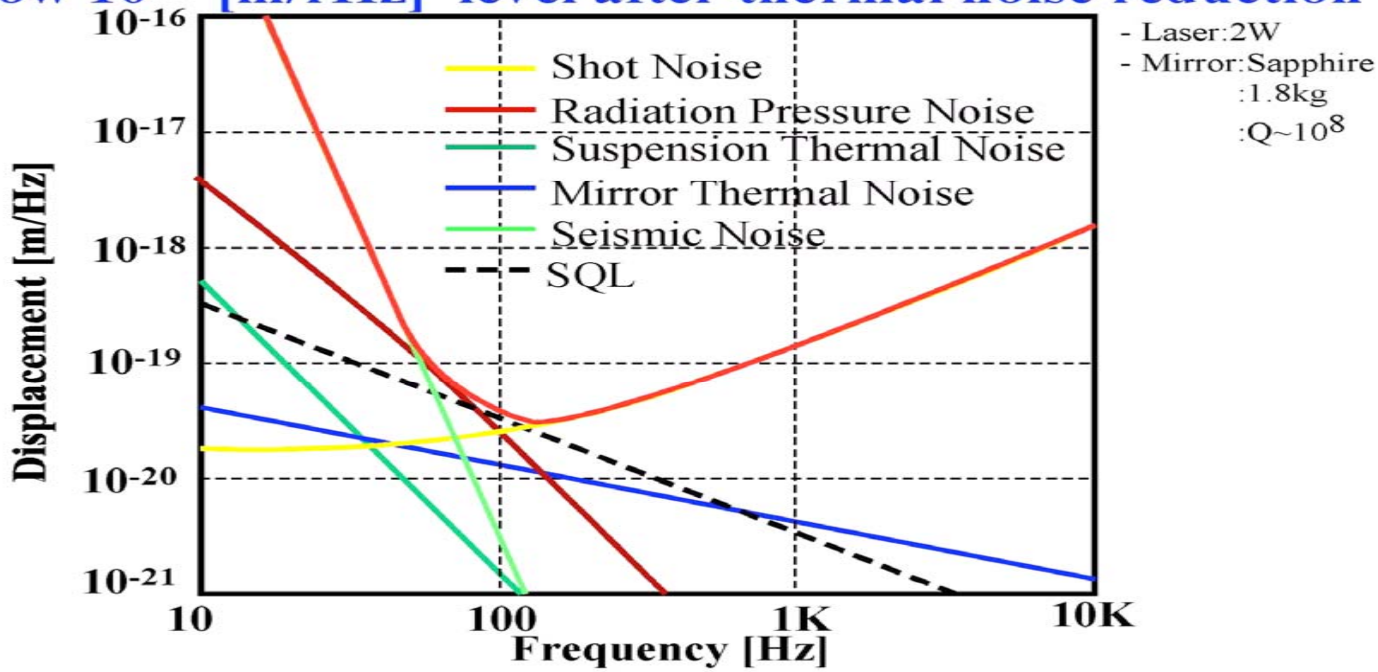
TAMA-SAS

CLIO--- a Locked Fabry-Perot Interferometer



Displacement of CLIO

- Below 10^{-19} [m/rHz] level after thermal noise reduction



LCGT-- Optical configuration

(one of the two interferometers)

- Detector configuration