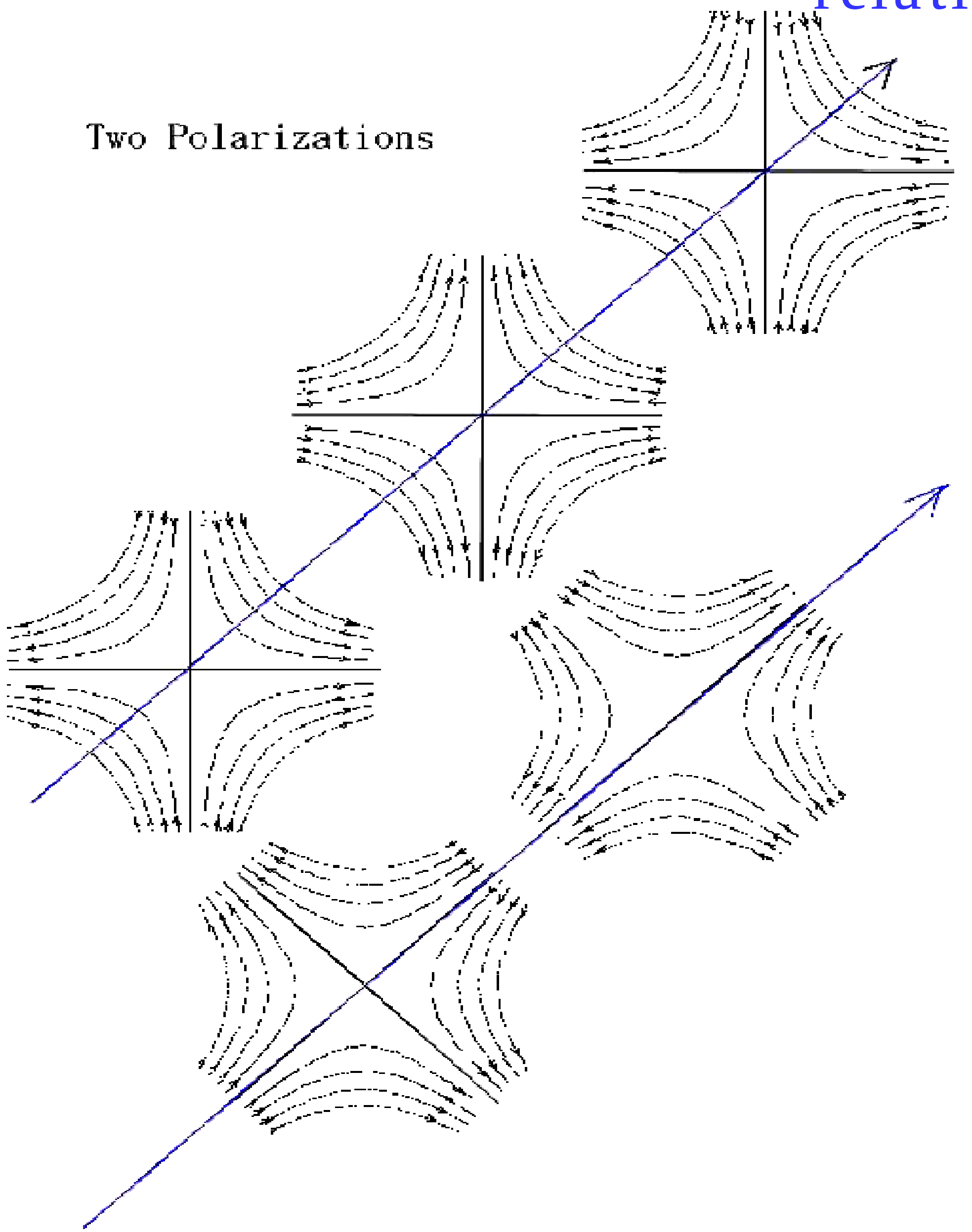

ICRR Review
@Kashiwa
19-20, October 2006
Gravitational wave group
Kazuaki Kuroda
LCGT/CLIO/TAMA Collaboration

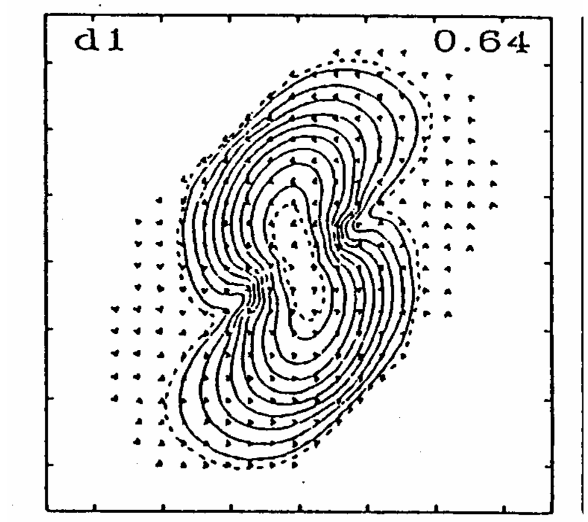
Gravitational wave (GW) is the propagation of spacetime distortion predicted by Einstein's general relativity.

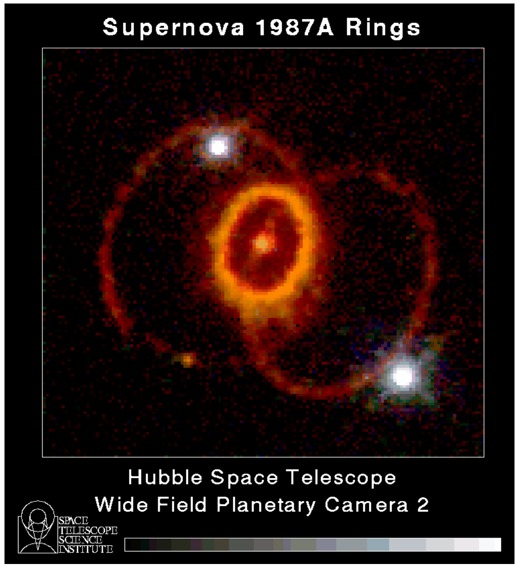


- Hulse & Taylor proved its existence by the observation of PSR 1913+16.
- It propagates as transverse wave with the speed of light
- Theories of gravitation are tested by the detection of GW.
- GW presents new eye to observe the Universe.

Possible sources of GW

- Coalescence of neutron star binary
- Super nova explosion
- Coalescence of blackhole (BH) binary
- Falling stars to BH
- Spinning of a neutron star
- Orbital motion of neutron star binary
- Cosmic back ground radiation
- Vibration of a cosmic string



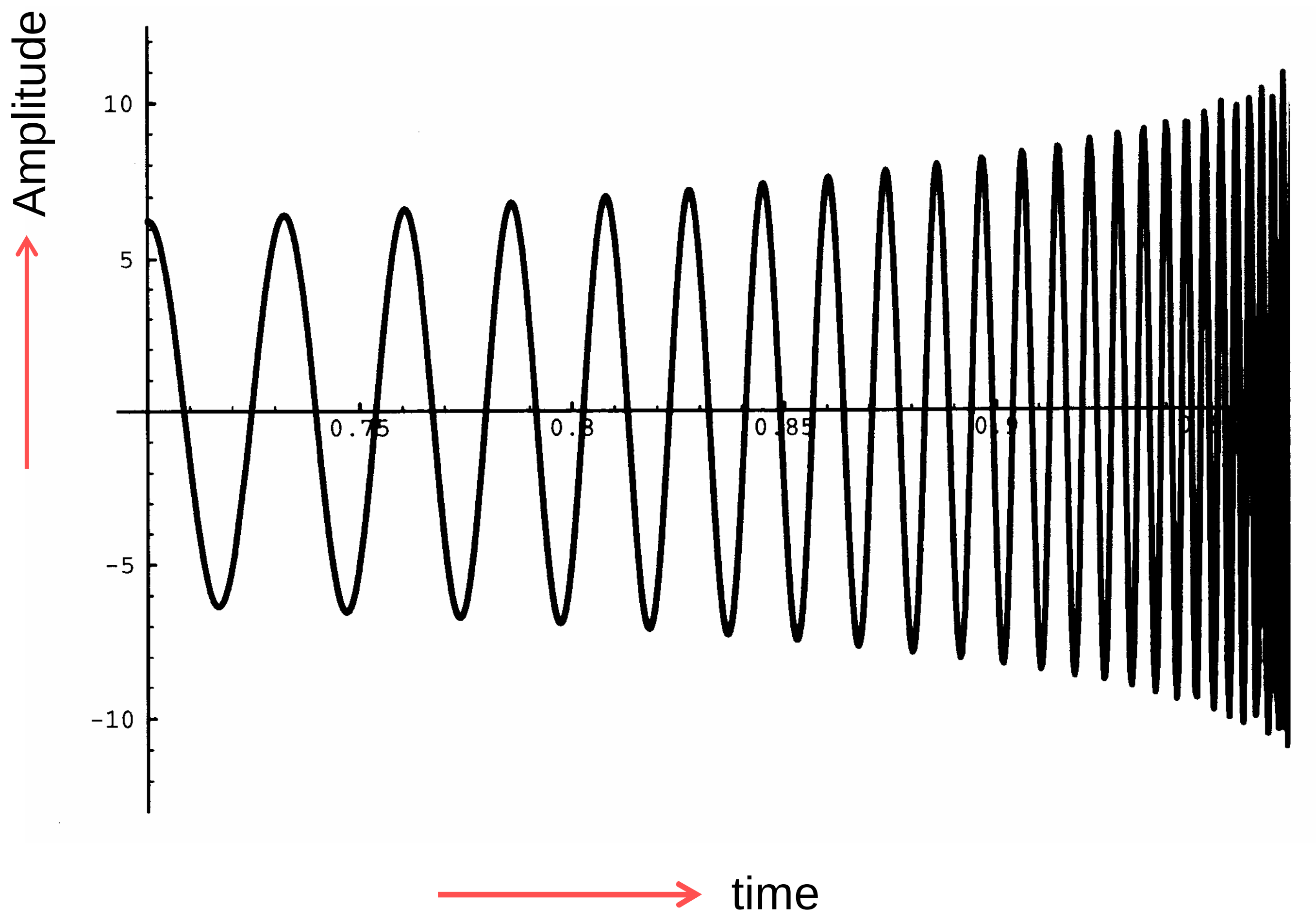


Neutron star binaries detected in our Galaxy

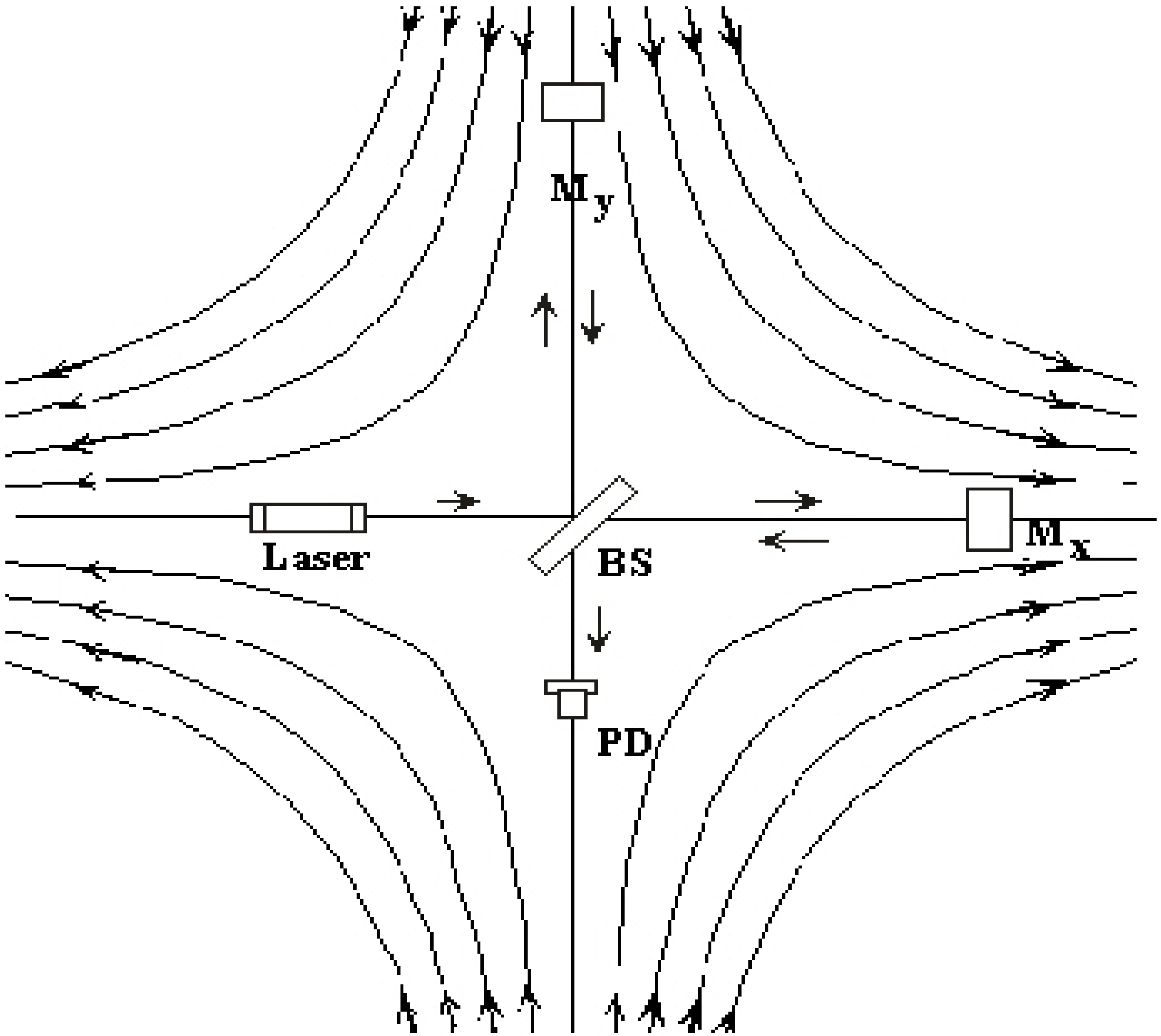
- PSR B1913+16
- PSR B1534+21
- PSR J1141-6545
- PSR J0737-3039
- PSR J1906+0746

Occurrence rate of coalescence is estimated by both the distribution and the life time of binaries, which gives about 10^{-5} per galaxy every year.

Chirping wave form produced at the coalescence of binary neutron star



How to detect GW?



- Suspended mass (Mx) and suspended beam splitter (BS) behave as two test masses.
- Michelson interferometer measures the difference of displacements of two arms; M_x-BS and M_y-BS
- Typical displacement triggered by an event of VIRGO cluster is 10^{-14} rad (10^{-18} m) for 1km arm length.
- To enhance the sensitivity, optical paths are folded by many times. There are Delay-Line, Fabry-Perot and so on.

Existing observatories

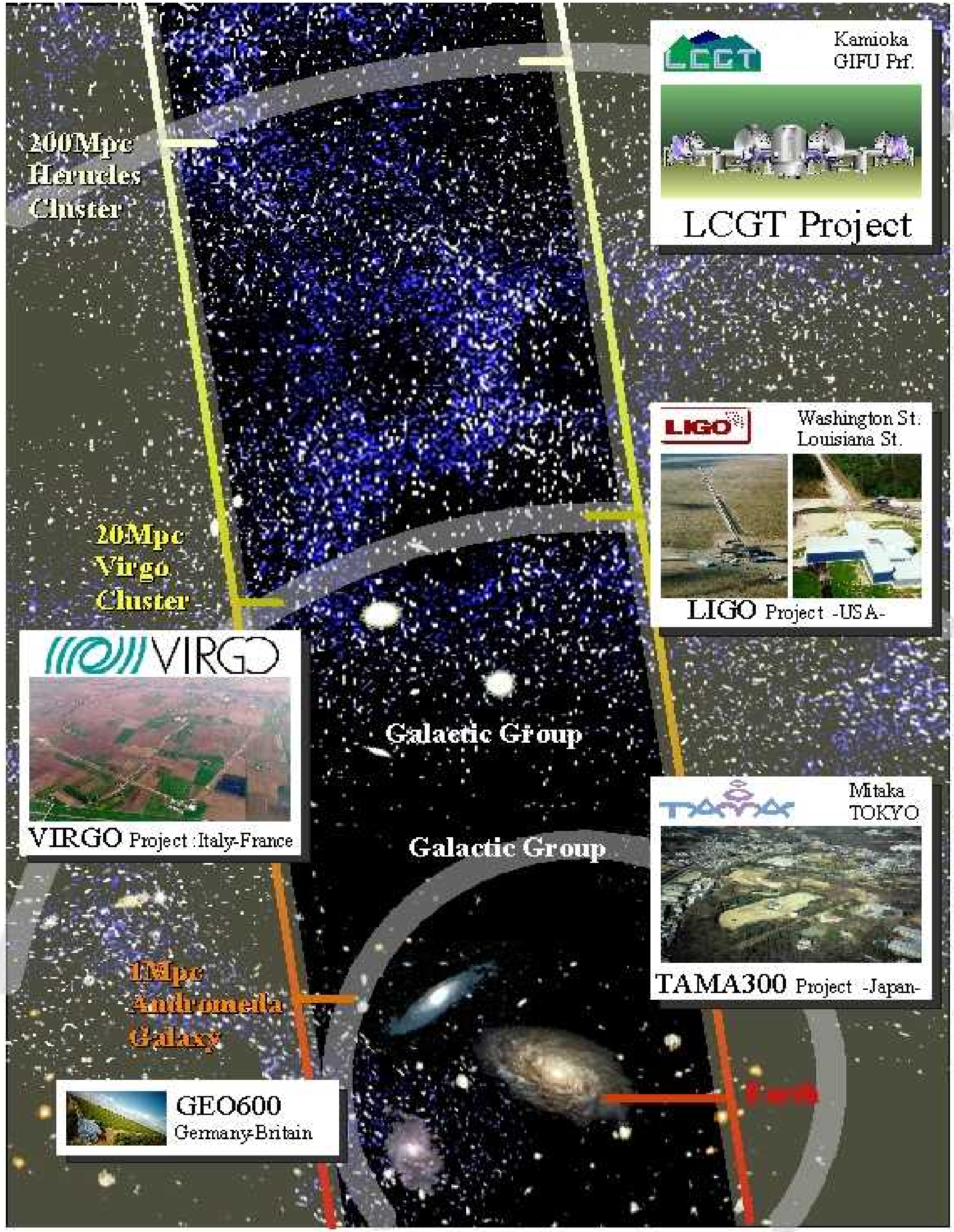
There are LIGO (USA), VIRGO (French-Italian), GEO (Germany-England), TAMA (Japan).

The frequency is about 10^{-5} for one year for matured galaxy as ours. The detector covering the Virgo cluster (20Mpc) needs many years of observation.

For this reason, we need more sensitive detector to cover more remote galaxies. LCGT can observe events by neutron star binaries coalescing at 260Mpc at the maximum, rating from 1 to 28 for year on average.

1pc=3.3 ly

View Ranges of Gravitational Wave Detectors

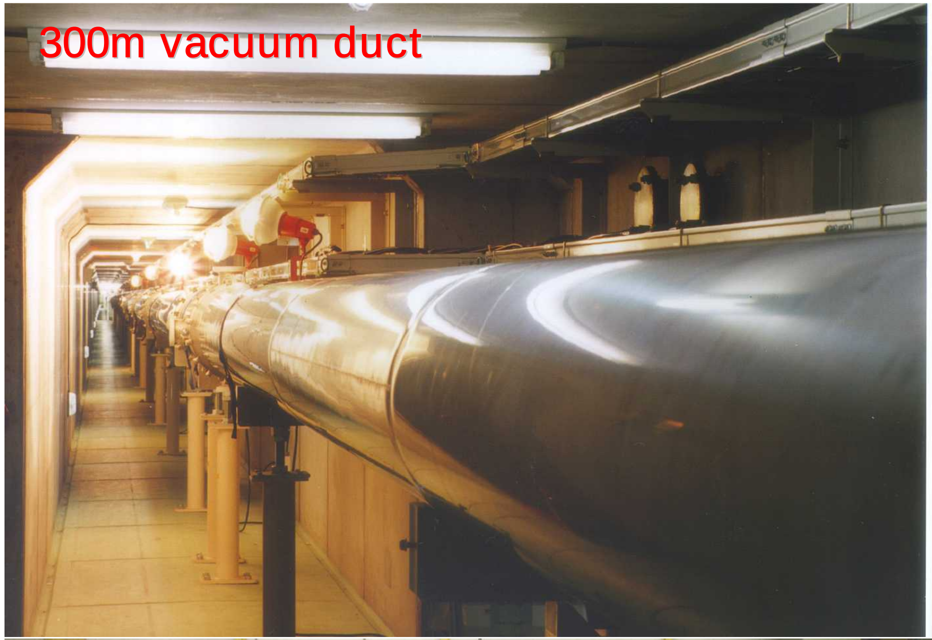


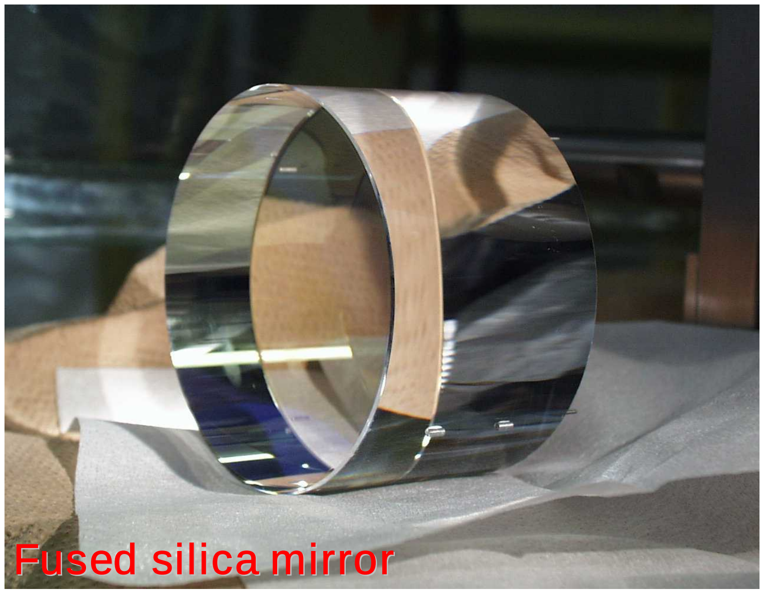
History of Interferometer in Japan

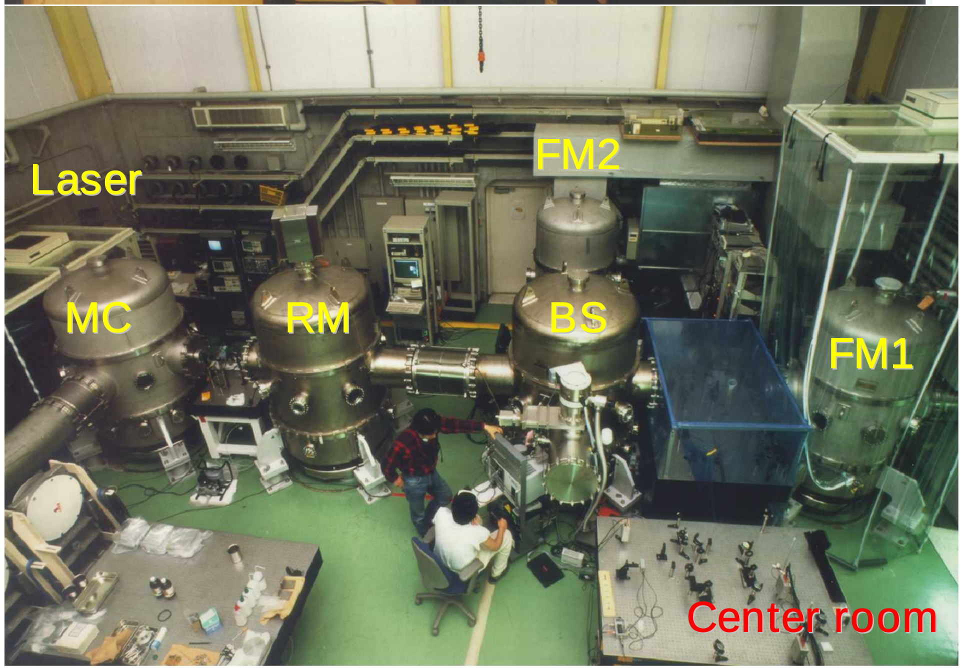
• TENKO-100	1991-1994	ISAS
• 20m prototype	1991-1994	NAOJ
• TAMA	1995-2001	NAOJ
• LISM	2000-2002	Kamioka
• CLIO	2003-2006	Kamioka
• LCGT	…….	Kamioka

TAMA interferometer with baseline of 300m is placed at Mitaka campus, NAOJ, in a suburb of Tokyo.

Technical achievements by TAMA







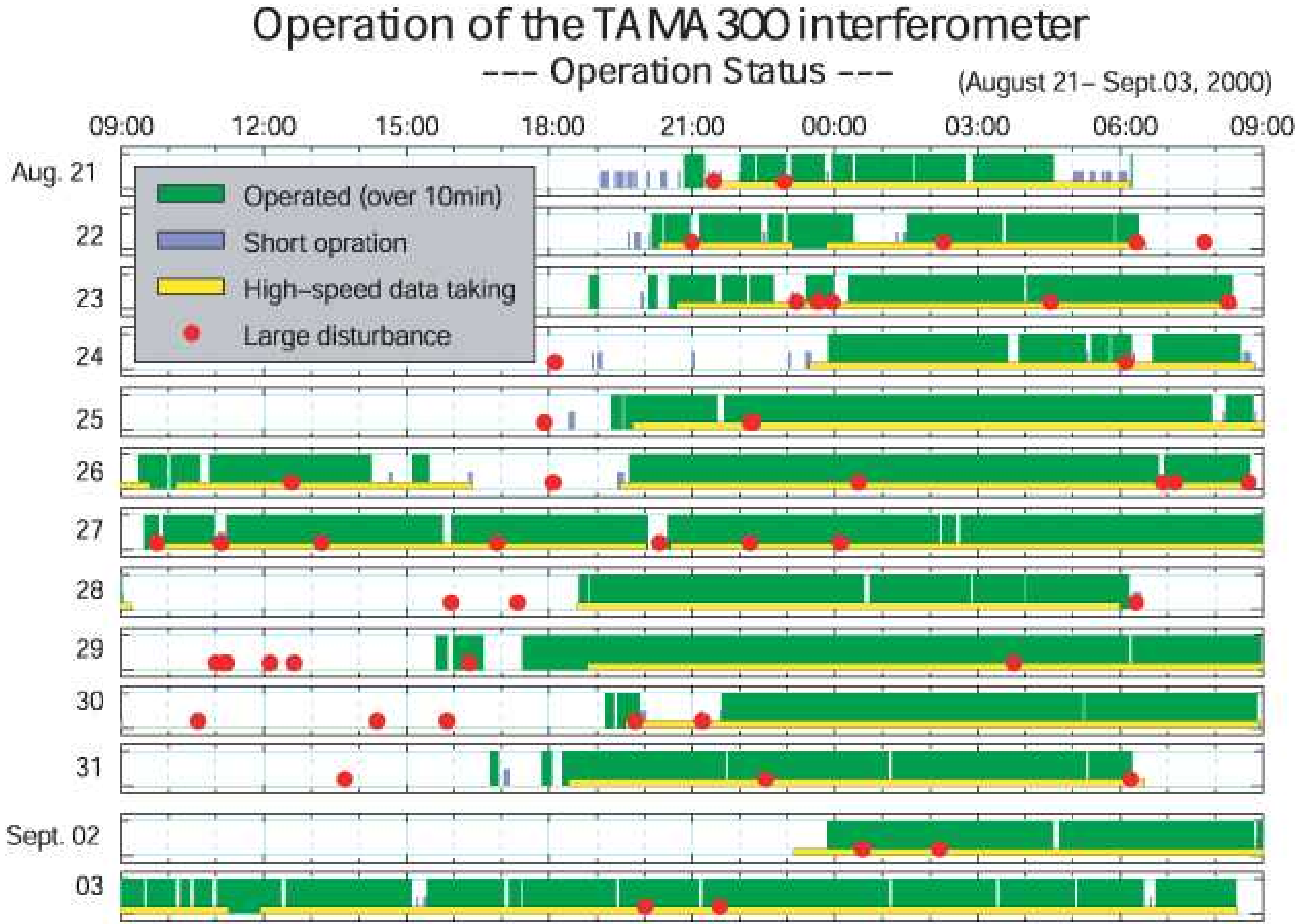
Observation by TAMA

TAMA data-taking runs including long-term observations

Run	Term	Year	Live Time (Hour)
DT1	6-Aug → 7-Aug	1999	7
DT2	17-Sept → 20-Sept	1999	31
DT3	20-Apr → 23-Apr	2000	13
DT4	21-Aug → 4-Sept	2000	161
DT5	2-Mar → 8-Mar	2001	111
DT6	15-Aug → 20-Sept	2001	1038
DT7	31-Aug → 2-Sept	2002	25
DT8	14-Feb → 14-Apr	2003	1158
DT9	28-Nov → 10-Jan	2004	558

- Sensitivity improvement
- Automatic operation system for reliability
- Continuous observation more than 1000 hr with the highest sensitivity.
- Introduction of power recyl
- LIGO overtook TAMA

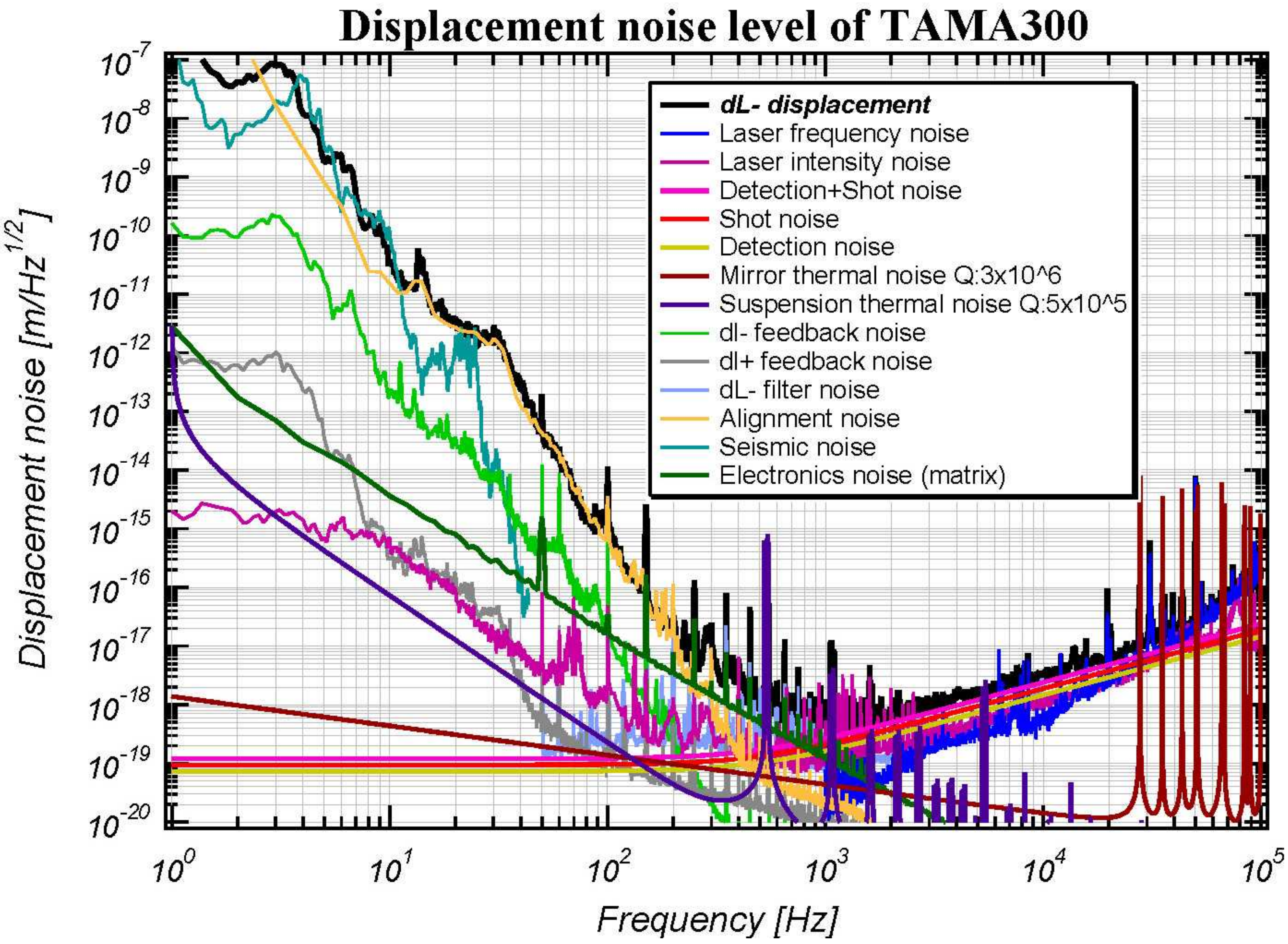
Some parts of DT7-9 are overlapped with the science runs of LIGO (GEO) and cooperative two papers have been published to limit the birth rates of both coalescence and supernova in our Galaxy.



Large seismic disturbances tend to cause the loose lock. By this data we installed extra anti-vibration systems under the vacuum chambers and improved the suspension system.

Current sensitivity of TAMA

---all noise sources are identified within an error of factor 2---



TAMA Achievement

1. Optical interferometer system (power recycling, Fabry-Perot Michelson, control system) was successfully completed.
2. Nine observation runs accumulated data exceeding 3000 hours. →Nine papers published
3. The sensitivity of TAMA in 2000 was the best in the world and achieved a stable long term operation for the first time.

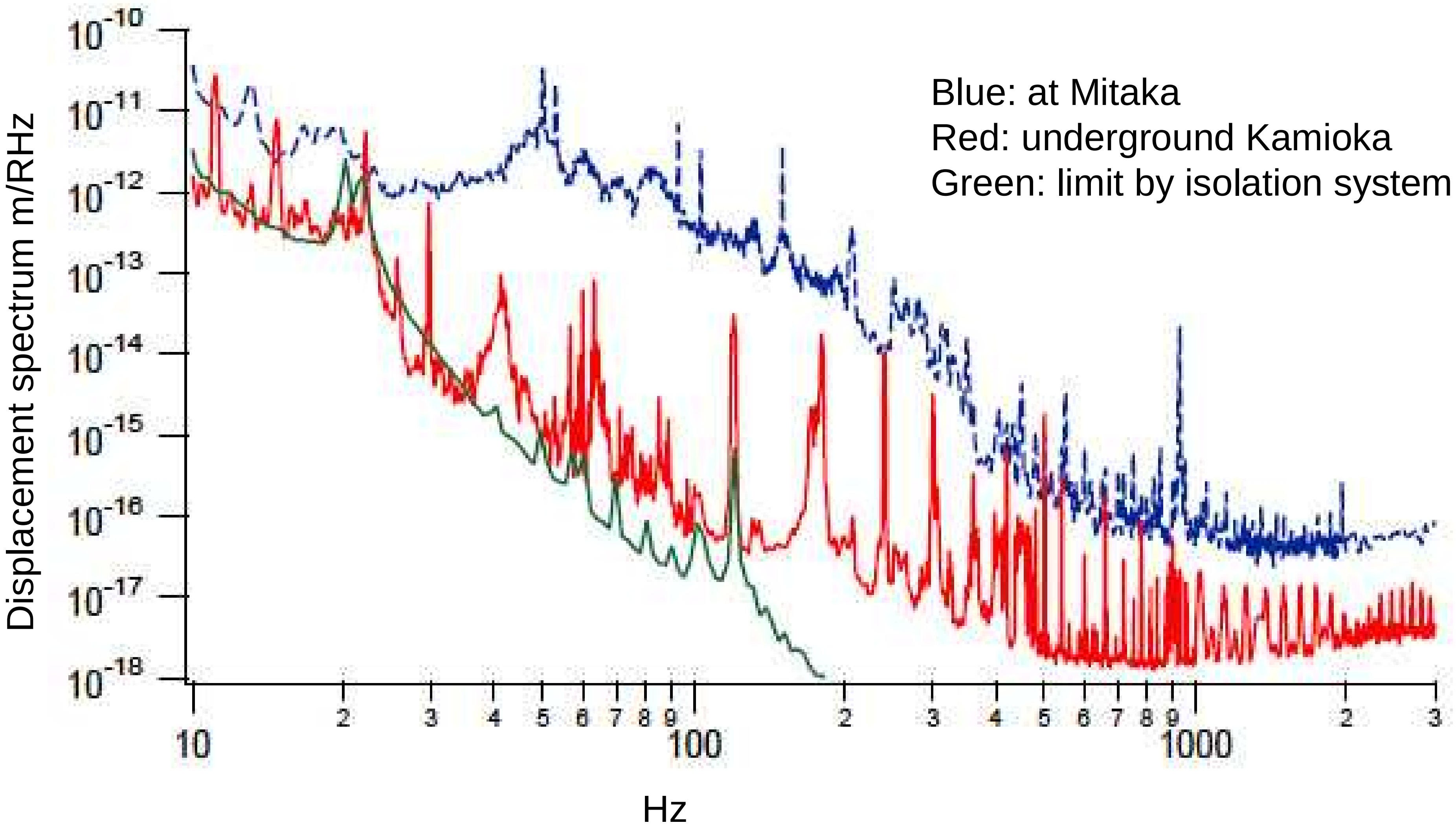
Current status

１. Observation runs have not been done after DT9 ended in January, 2004.
２. Installation of a low frequency anti-vibration system (SAS) is ongoing.

LISM

We had been heavily bothered by seismic noise in the operation of both a 20m prototype and TAMA. LISM is the 20m prototype moved from Mitaka campus of NAOJ to Kamioka mine. This prototype confirmed the quietness of the underground and guaranteed a stable operation of the interferometer. The 20m prototype at Mitaka was a Fabry-Perot Michelson interferometer but it was changed to a locked Fabry-Perot one at Kamioka.

When the 20m interferometer was moved from Mitaka to Kamioka mine, the noise at 100Hz was decreased by 4 orders and the spectrum limit by the anti-vibration system was achieved at frequencies less than 100Hz.



CLIO

- CLIO is a 100 m locked Fabry-Perot interferometer with cryogenic mirrors
- Construction was started in 2002 and finished early in 2006.
- Commissioning is underway.
- CLIO will demonstrate the effectiveness of cryogenic mirror.

Thermal noise

- Amplitude of thermal noise $\propto \{T\Phi\}^{1/2}$
  - T: temperature, Φ: mechanical loss angle
- Pendulum mode thermal noise
  - amplitude $\propto \{1/f\}^{1/2}$ $(f<f_0)$ f_0: pendulum resonance
  - amplitude $\propto \{1/f\}^{5/2}$ $(f>f_0)$
- Substrate and Coating thermal noise

(consisting of Brownian noise and thermo-elastic one)

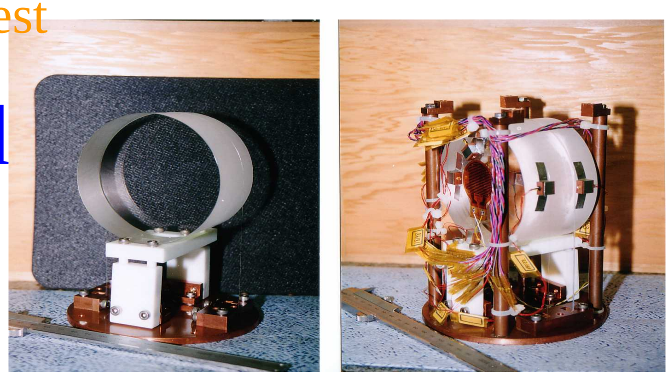
- amplitude $\propto \{T\Phi_{eff} / r\}^{1/2}\Lambda$, r: beam radius, Λ:

  Brownian noise changes $\propto \{1/f\}^{1/2}$

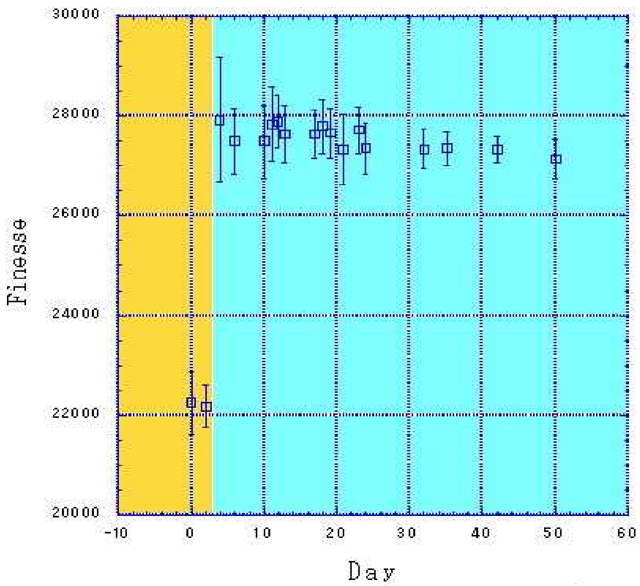
  thermo-elastic noise $\propto \{1/f\}$

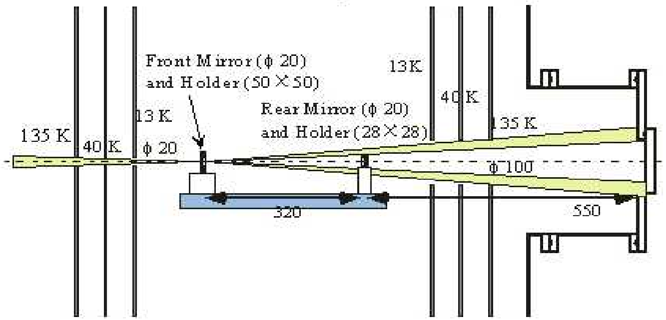
Cryogenic mirror was established by several basic experiments.

Cooling test

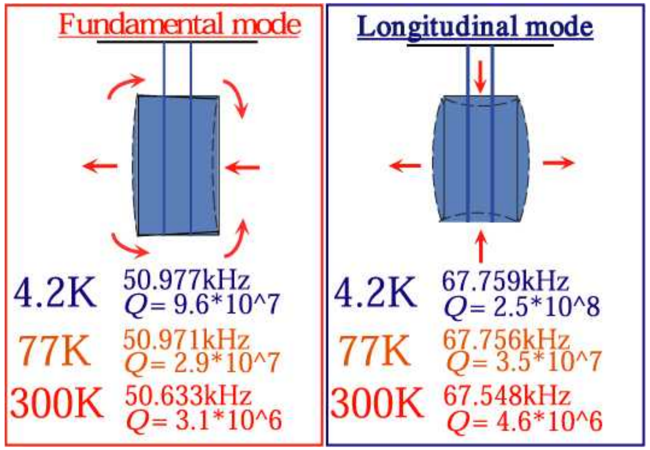


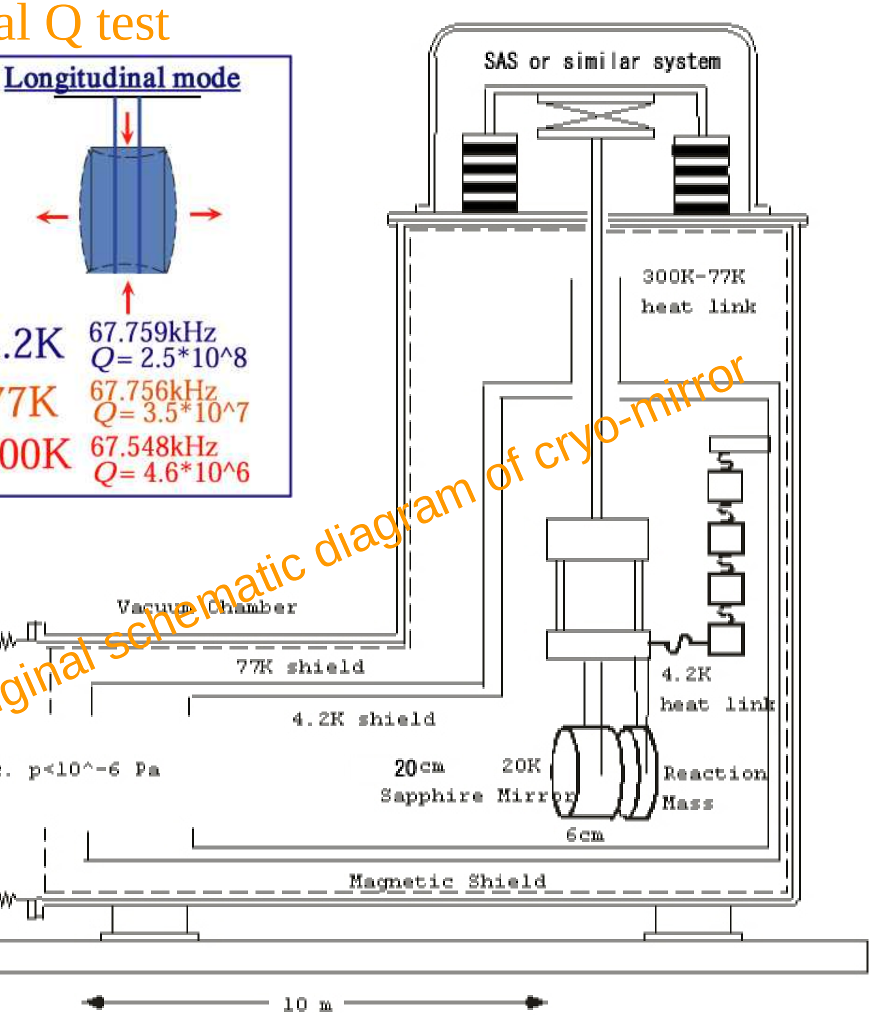
Contamination test





Mechanical Q test

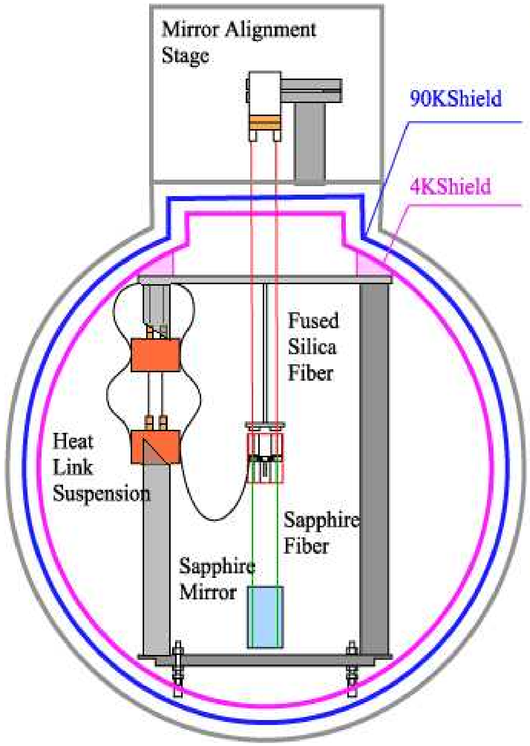


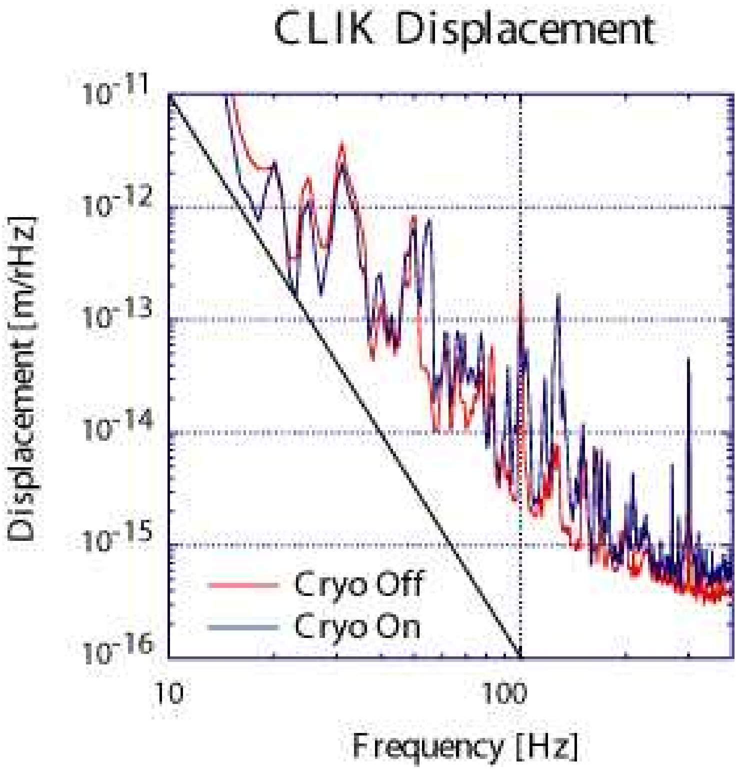


Original schematic diagram of cryo-mirror

Suspension prototype was tested in Kashiwa campus in ICRR, in 2001.

Fabry-Perot cavity was locked at cryogenic temperature and requirements on refrigerator were studied.





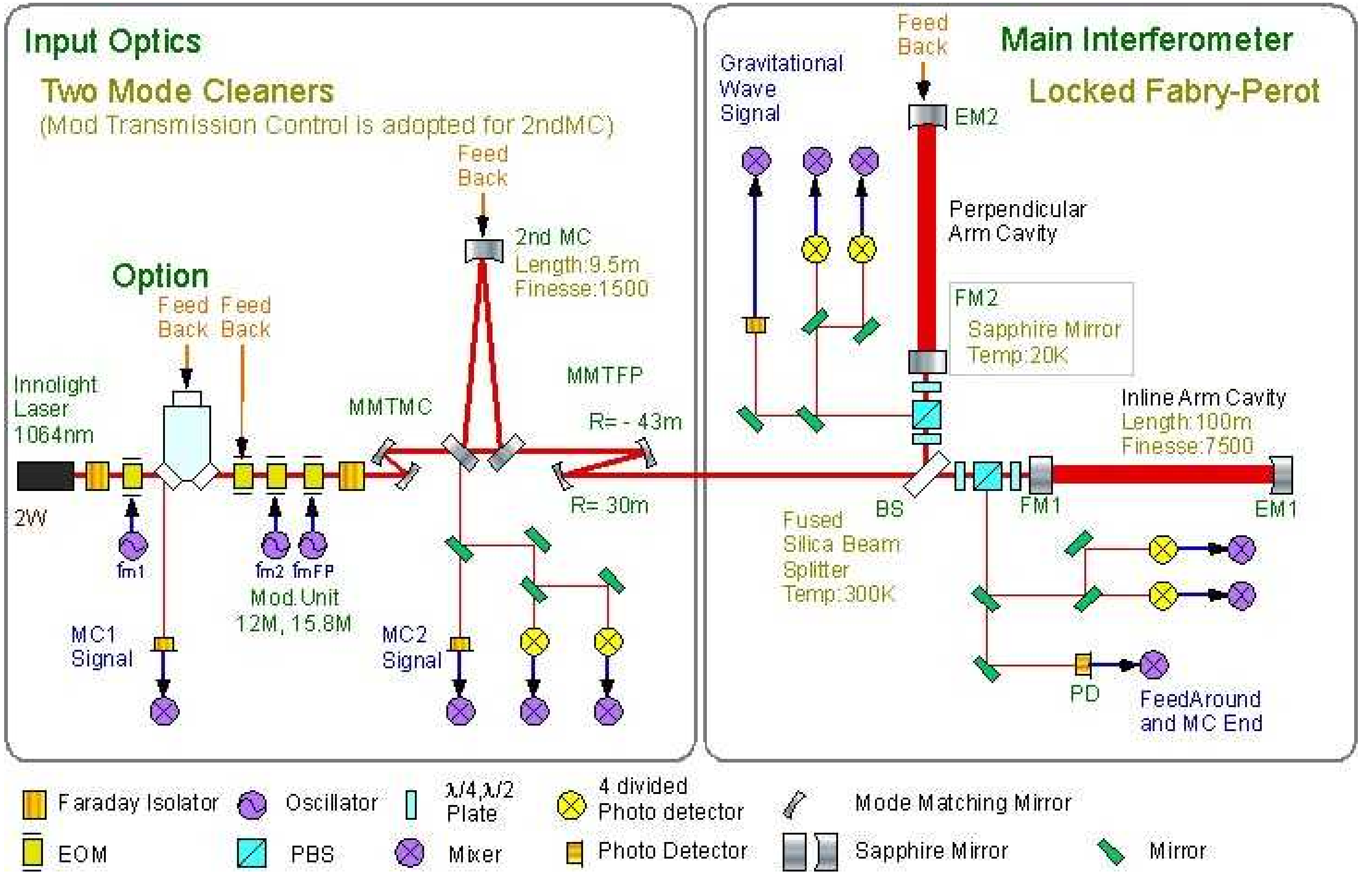
This result makes us to develop quieter refrigerator and softer heat link design.

Parameters of CLIO

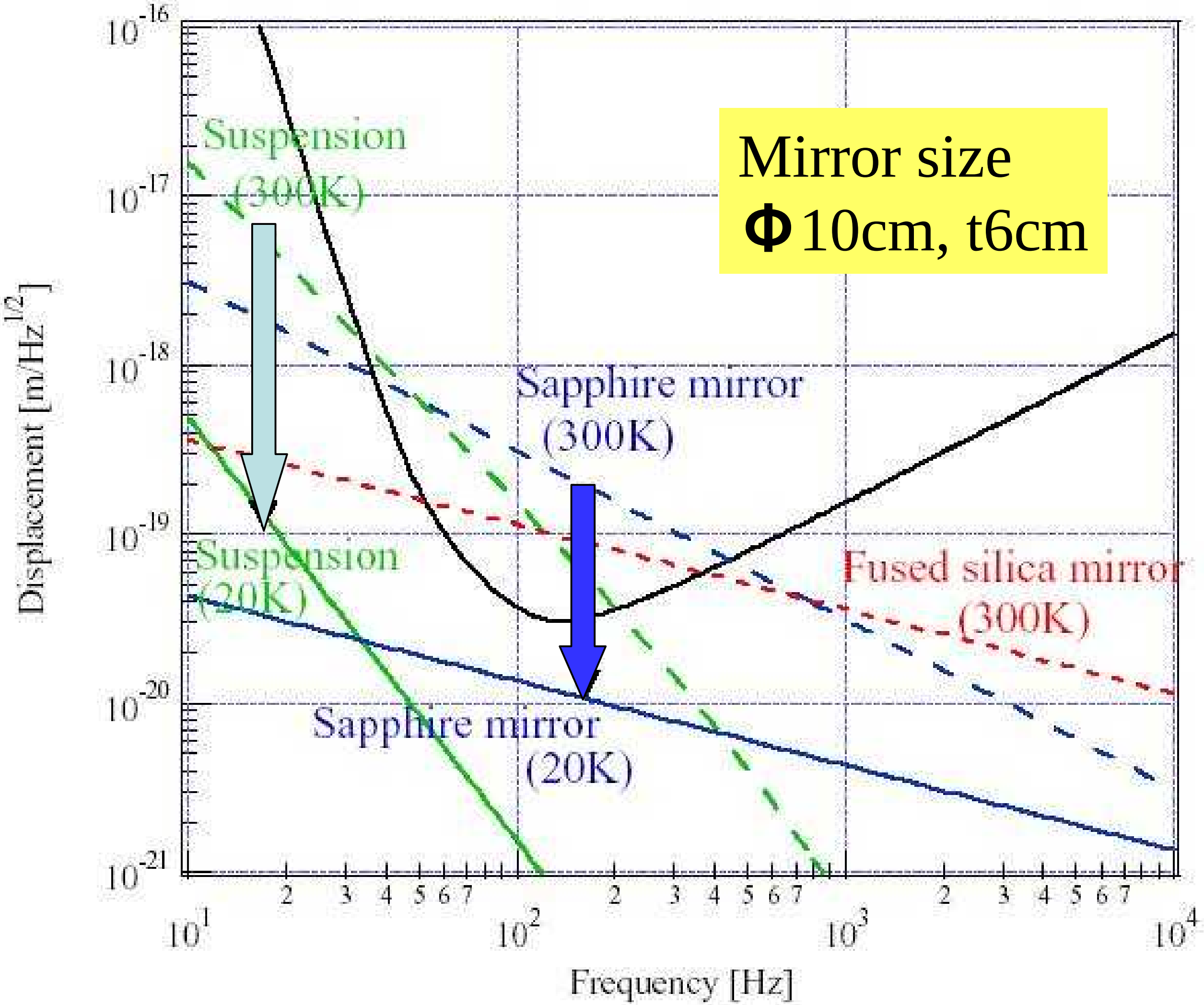
- Practical prototype of cryogenic interferometer
- Baseline length: 100m
- Interferometer: Locked FP
- Laser source: 2W NPRO (1064nm)
- Finesse: 7500
- Main mirrors: 20K sapphire (TAMA size, Φ10cm)
- Refrigerators: Pulse Tube type with flexible heat links

CLIO Optical design

Locked FP
(no recycling)



Expected reduction of thermal noise by CLIO (300K – 20K)



Construction of CLIO

Acheved Pressure

- 100m Arm -

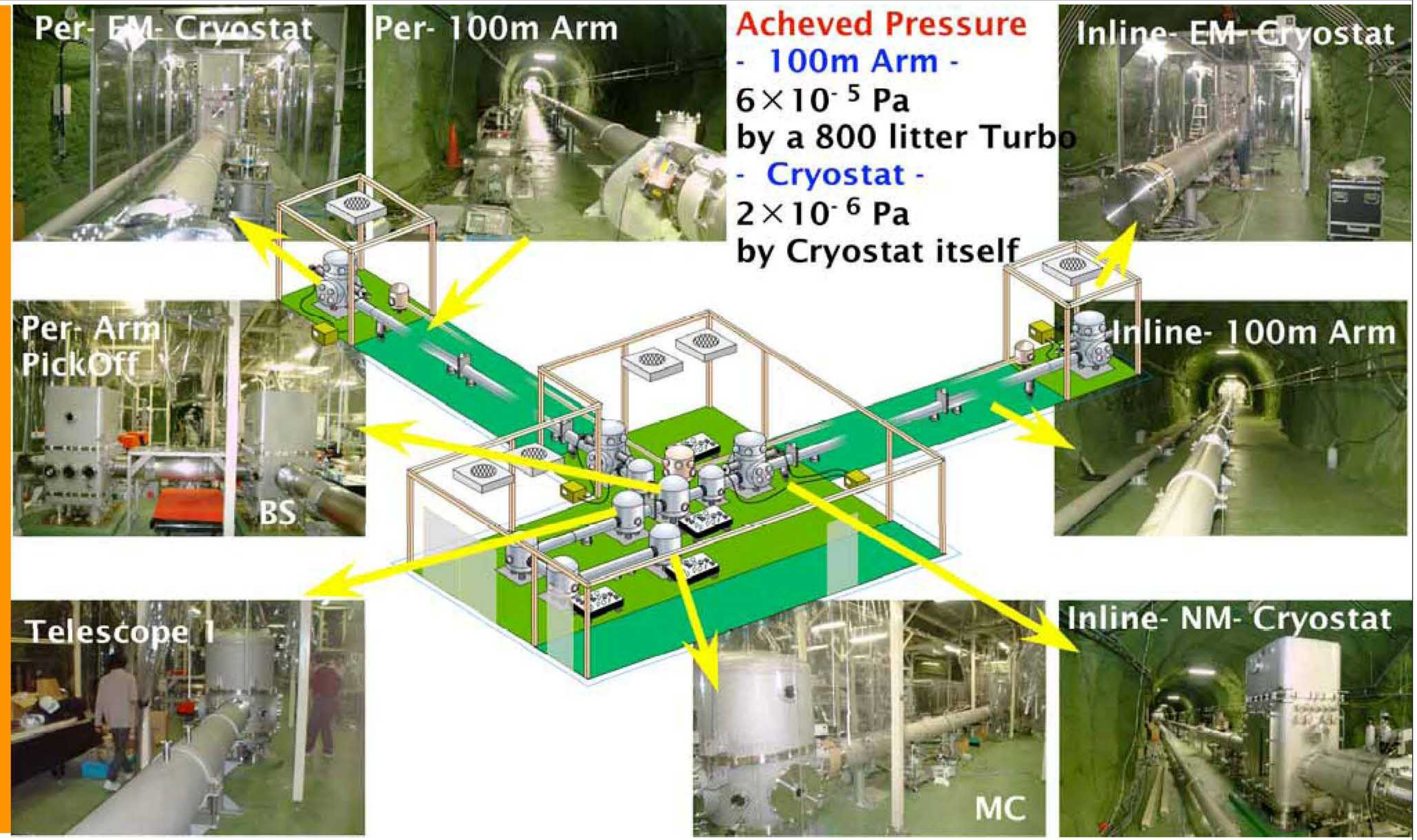
6×10^{-5} Pa

by a 800 litter Turbo

- Cryostat -

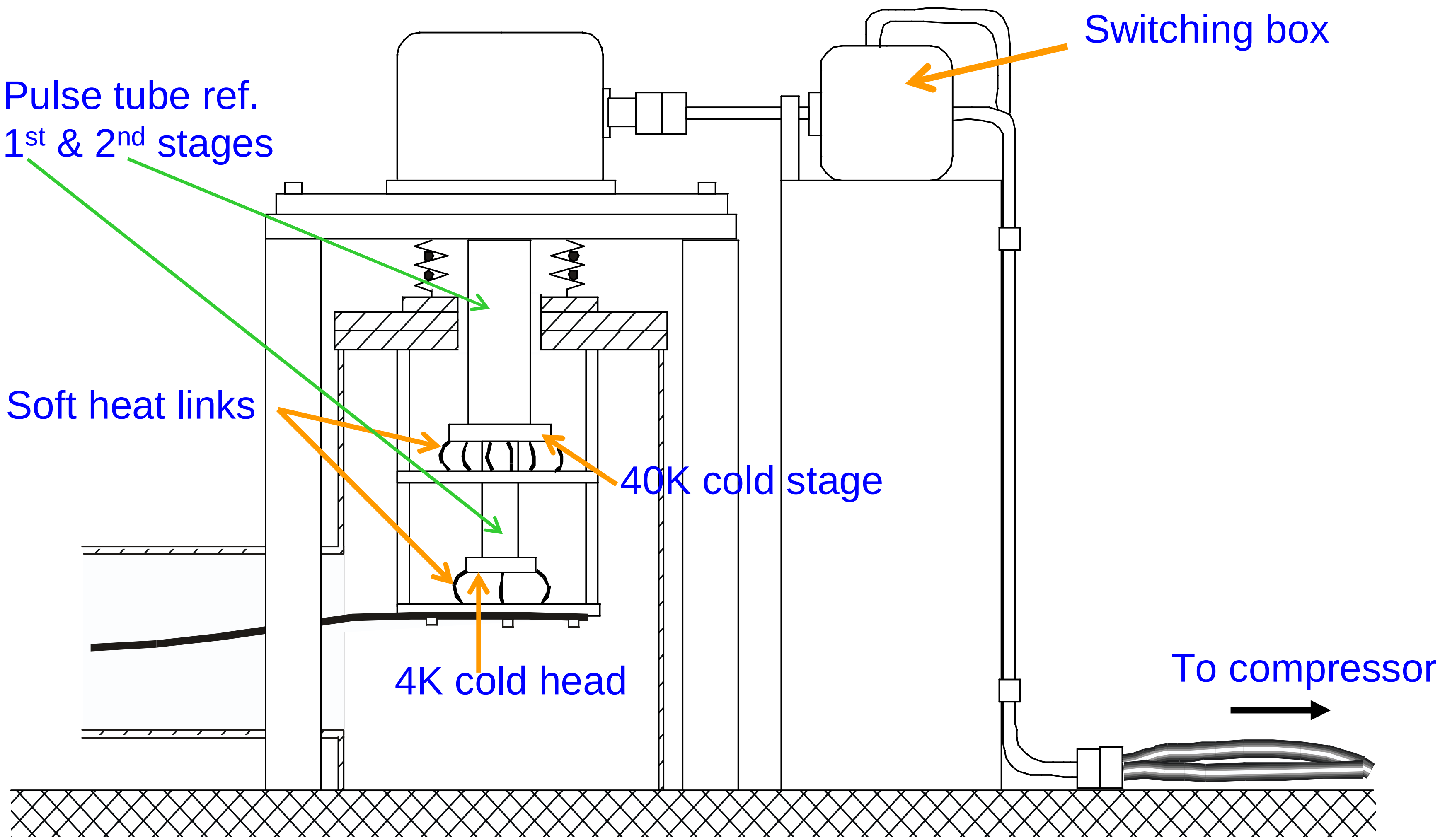
2×10^{-6} Pa

by Cryostat itself

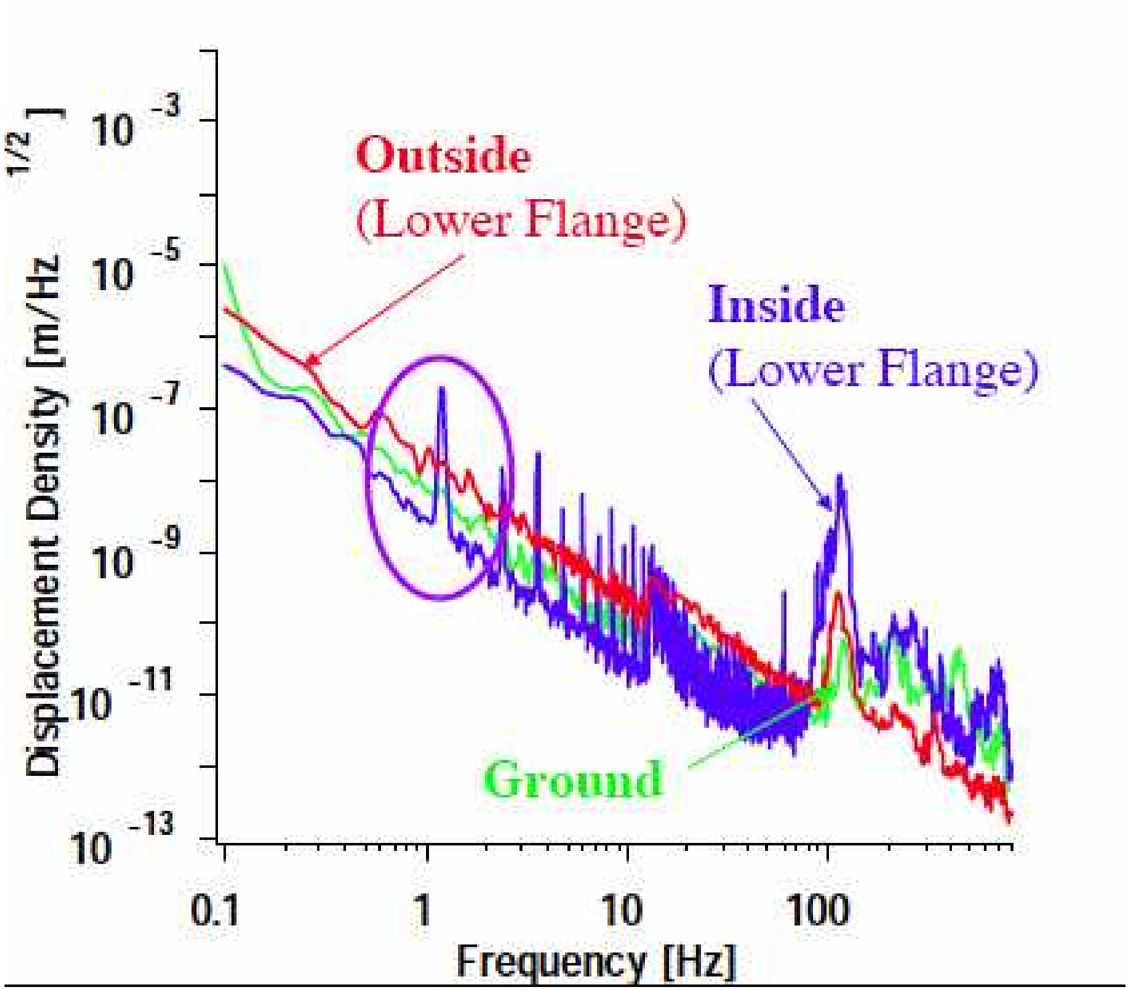


Quiet refrigerator was developed (design in 2003)

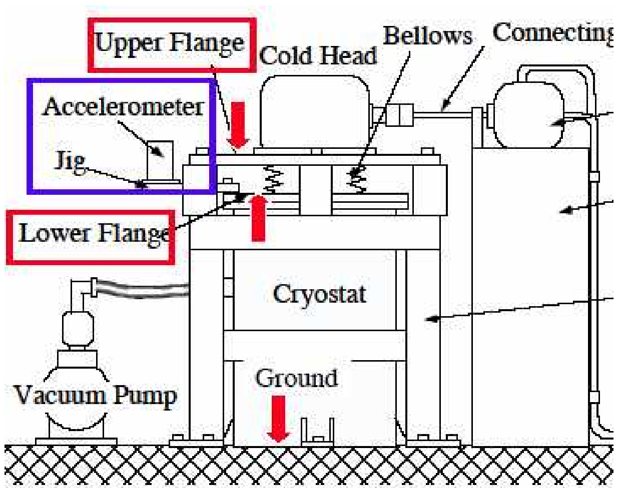
F-6: Class. Quantum Grav. (Accepted), Pr-1: Proc. 28th ICRC (2003),
patent: Pa-3 Tomaru et al., 2003; Suzuki et al., 2003.



Vibration test in the Kamioka mine

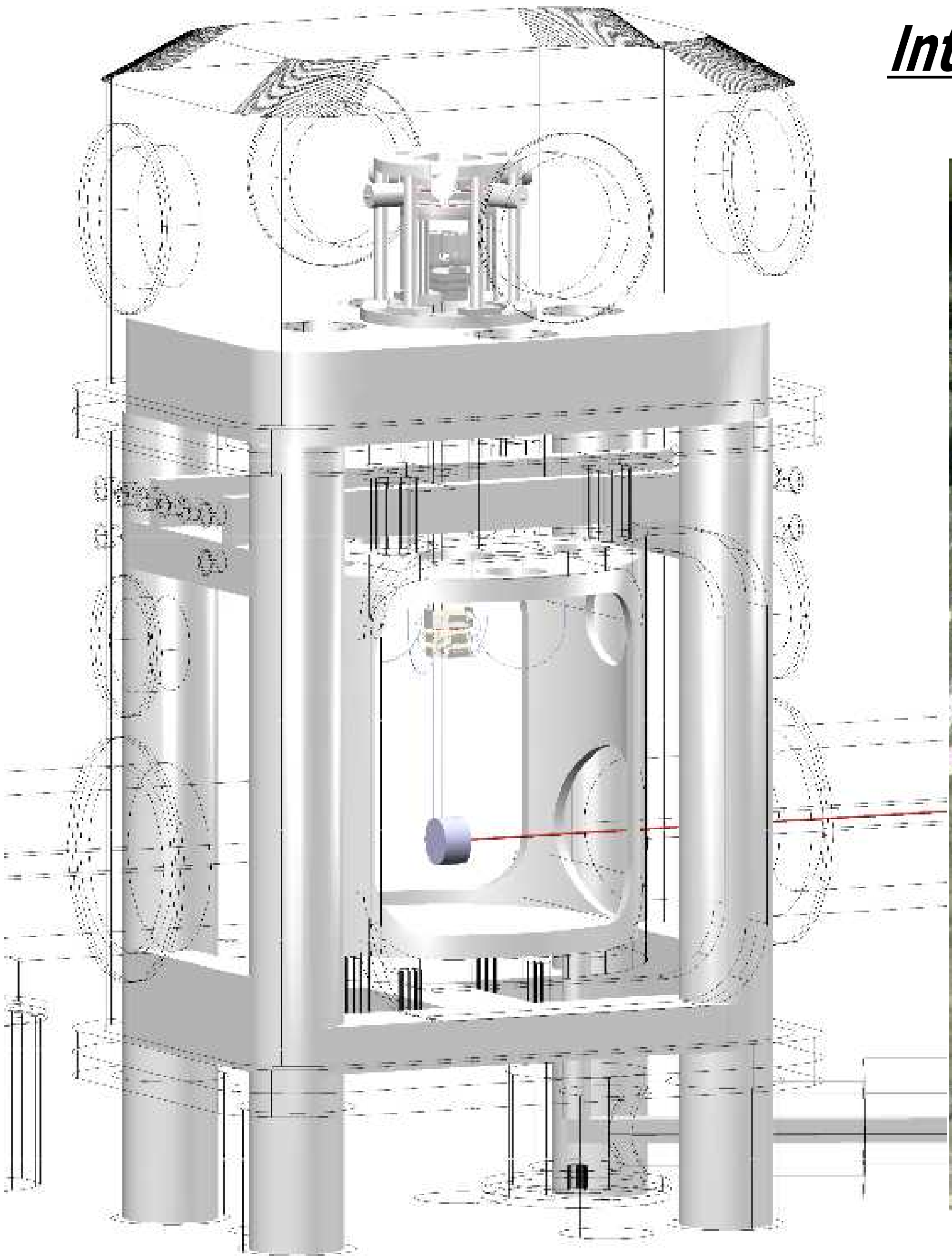


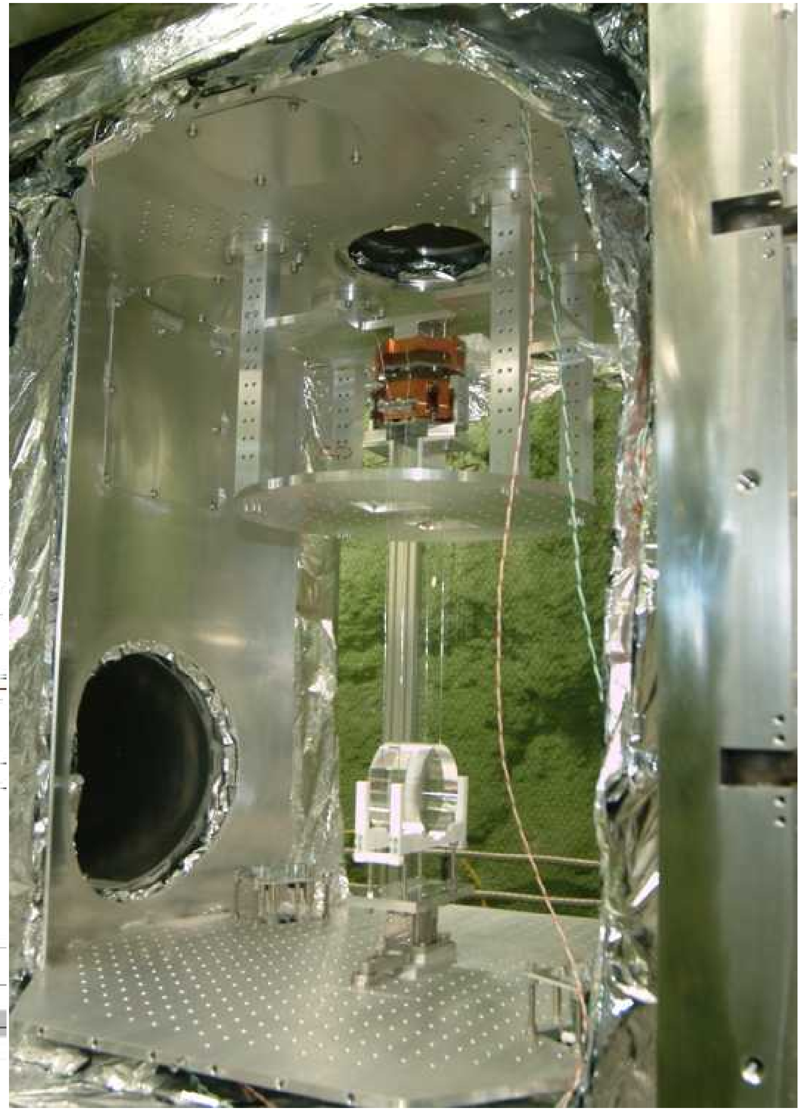
Compressor inside



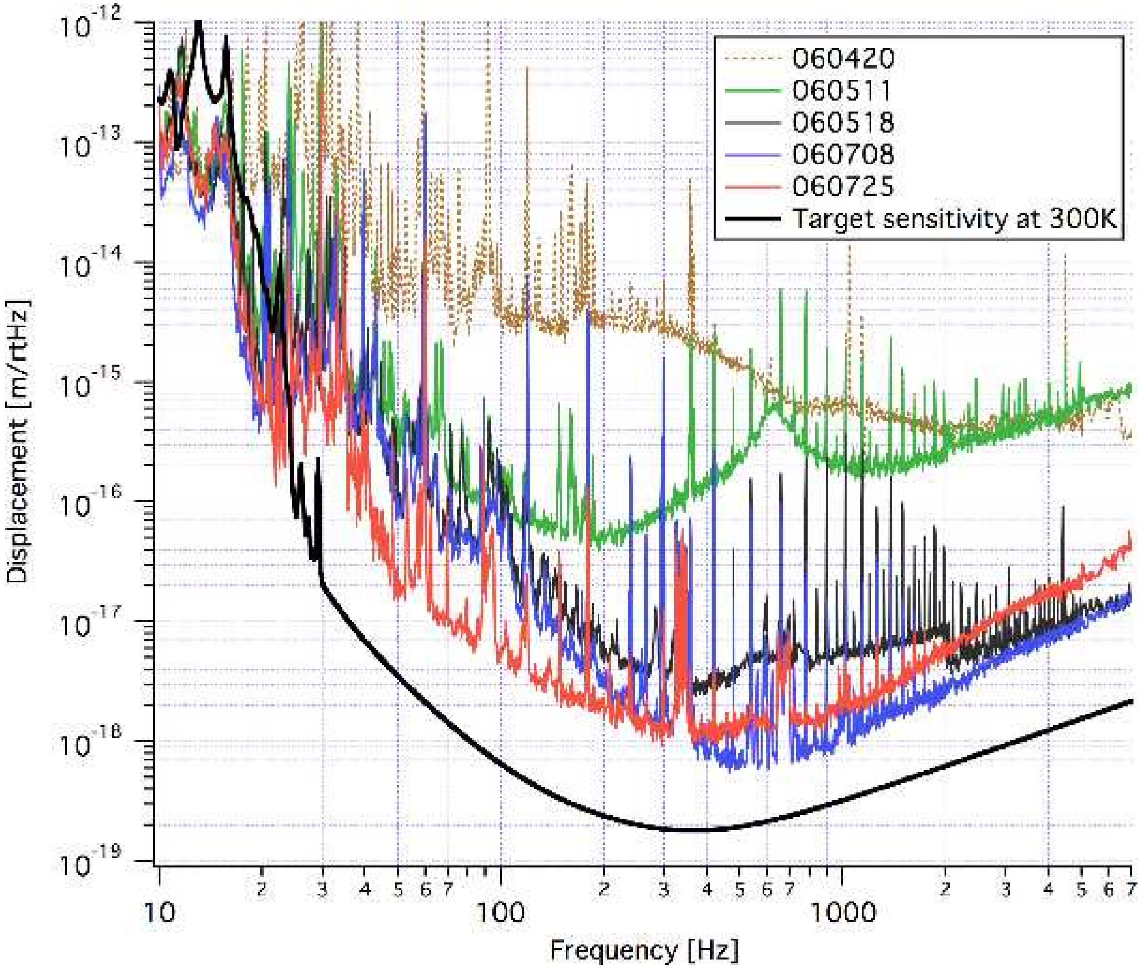
●Equivalent to the seismic noise has been achieved.

Internal view of mirror suspension





Sensitivity improvement of CLIO at 300K



Current status of CLIO

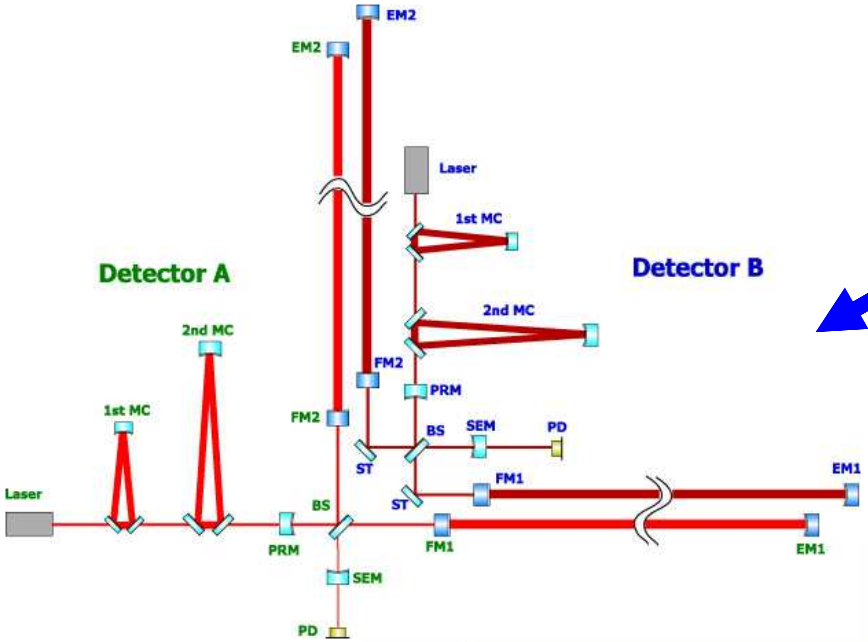
- We have finished its hardware in this March and have succeeded to lock Fabry-Perot cavities at cryogenic temperature.
- We are now in commissioning phase of the interferometer.
- During this phase, we found out that the radiation shields extending to both sides introduced more heat than expected, which was quantitatively measured and radiation baffles were designed.

LCGT

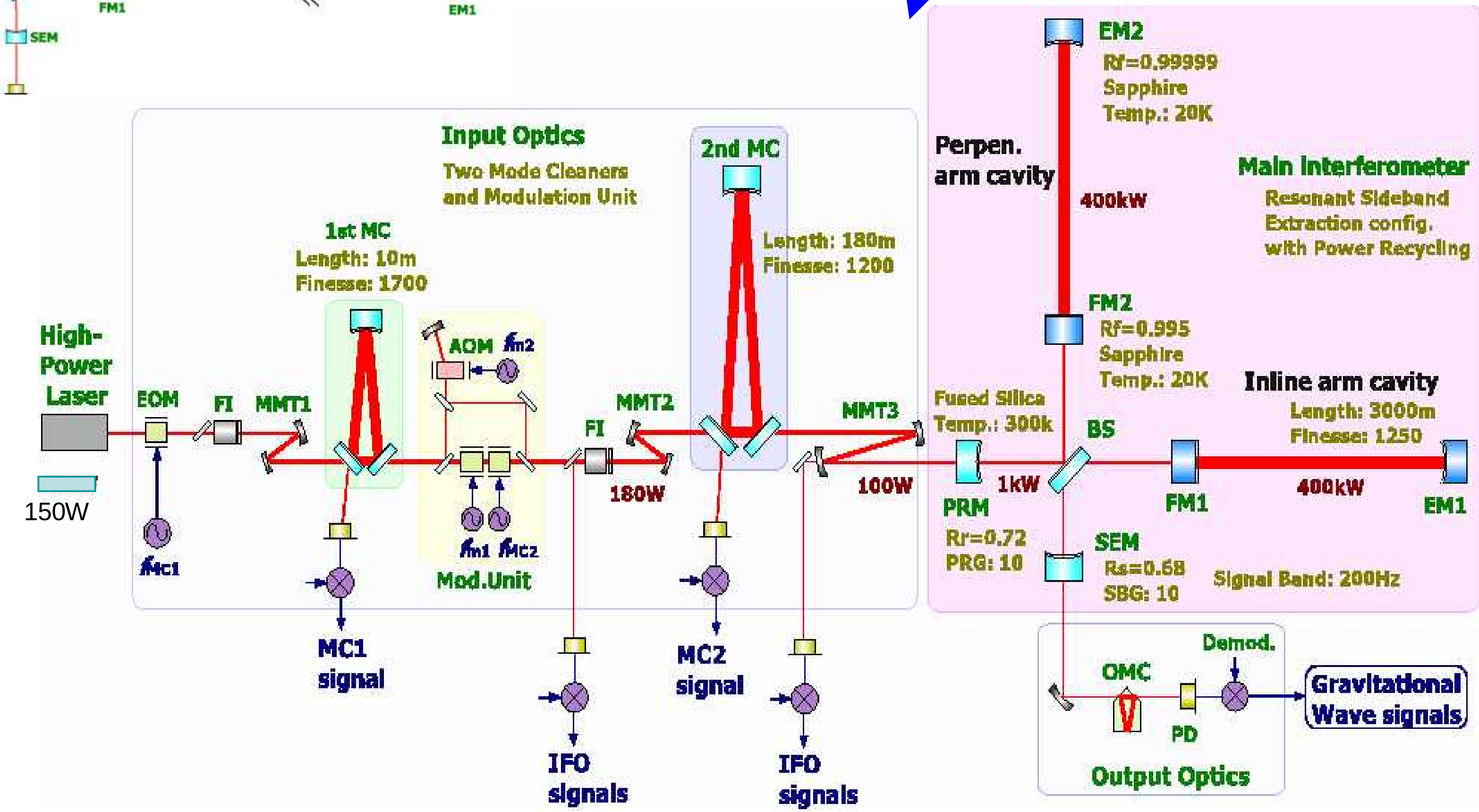
- LCGT is characterized by ‘cryogenics’, ‘underground’, and ‘3 km’.
- Budget request for FY 2007 in vain.
- LCGT collaboration requests to repeat the trial for FY 2008.
- LCGT has a potential to be the final detector on the Earth.
- Standard GW detector in the future international network to detect GW.

Optical design of LCGT

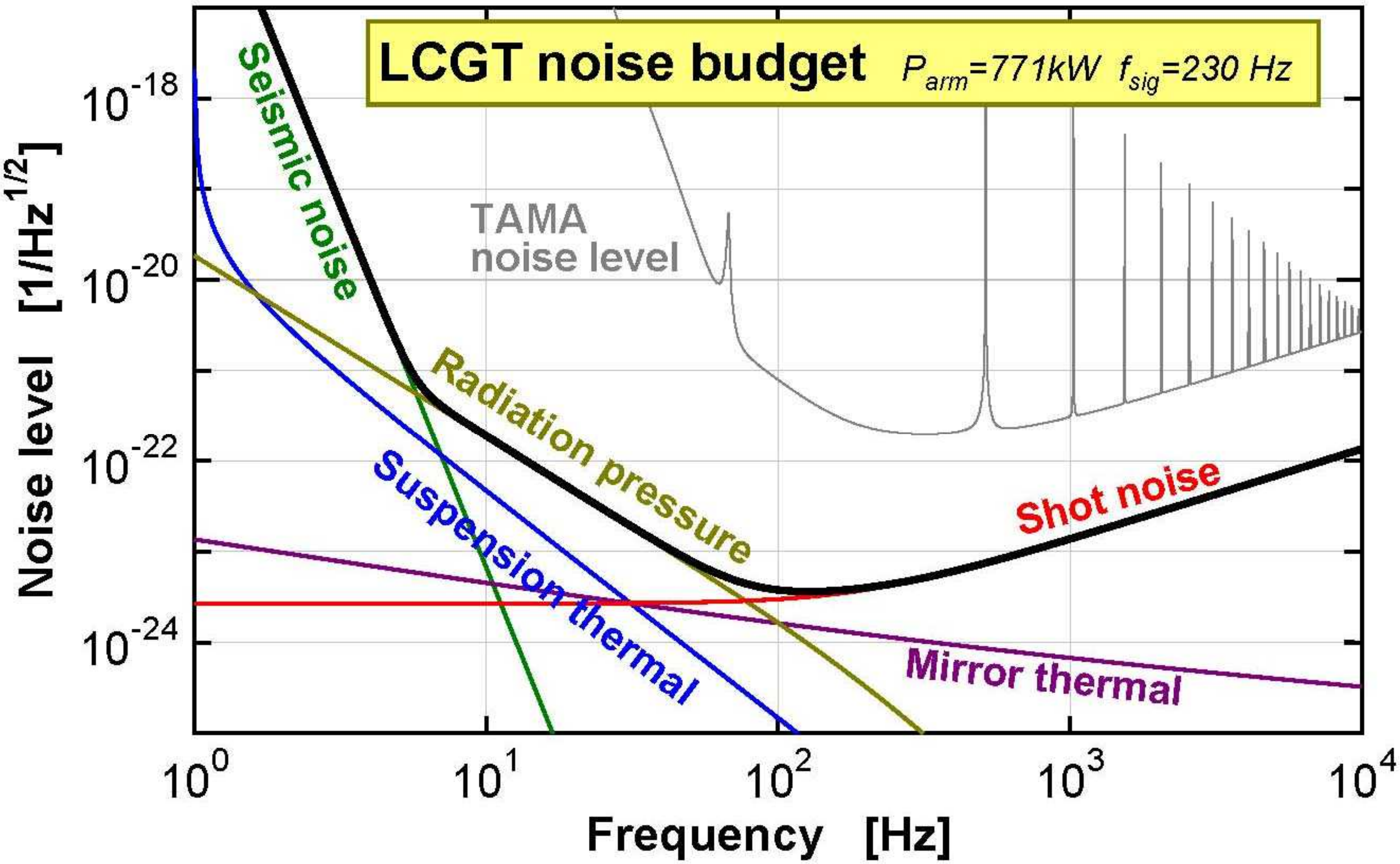
Two interferometers are arranged not to interfere in the same vacuum system.

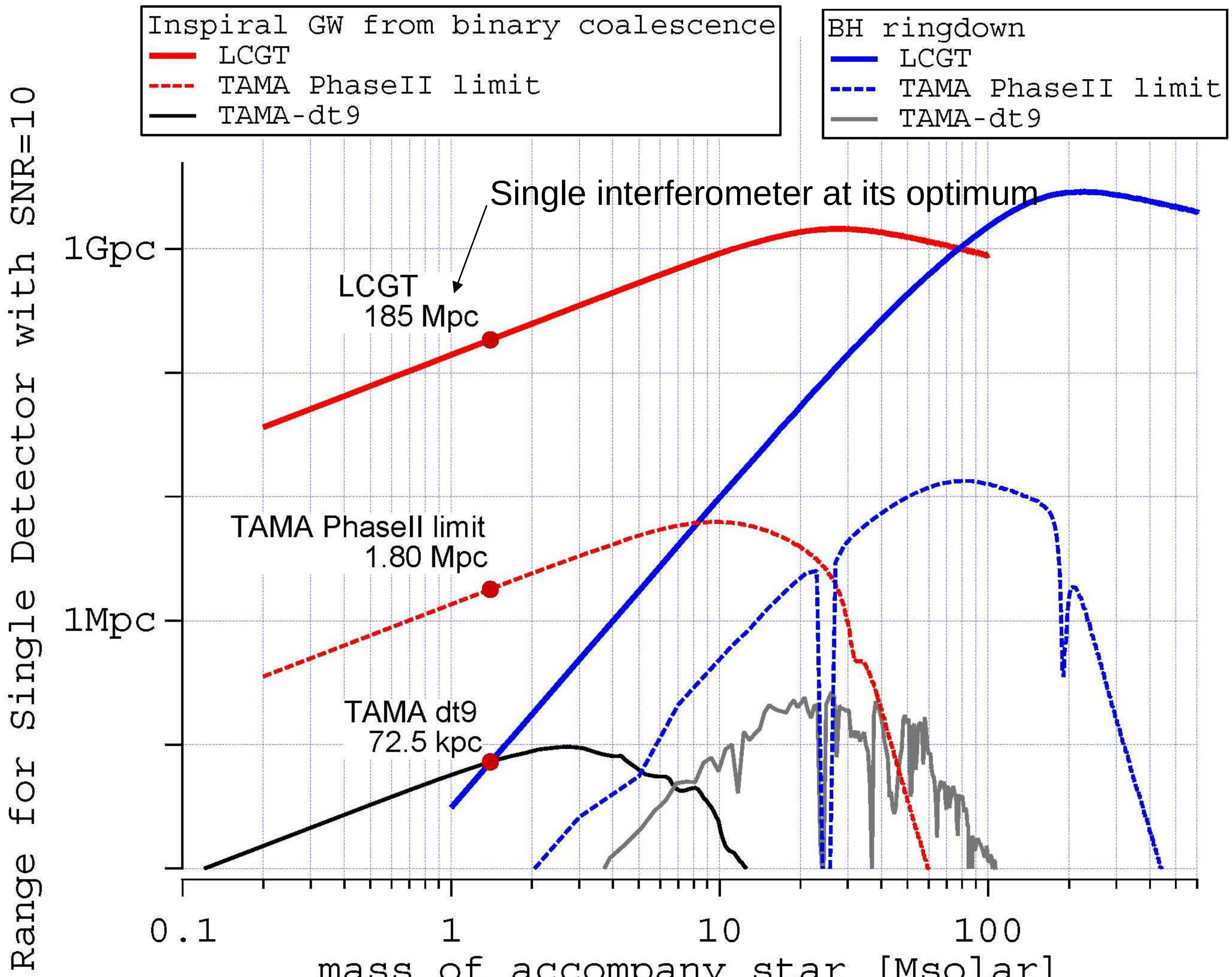


Optical design of the basic interferometer



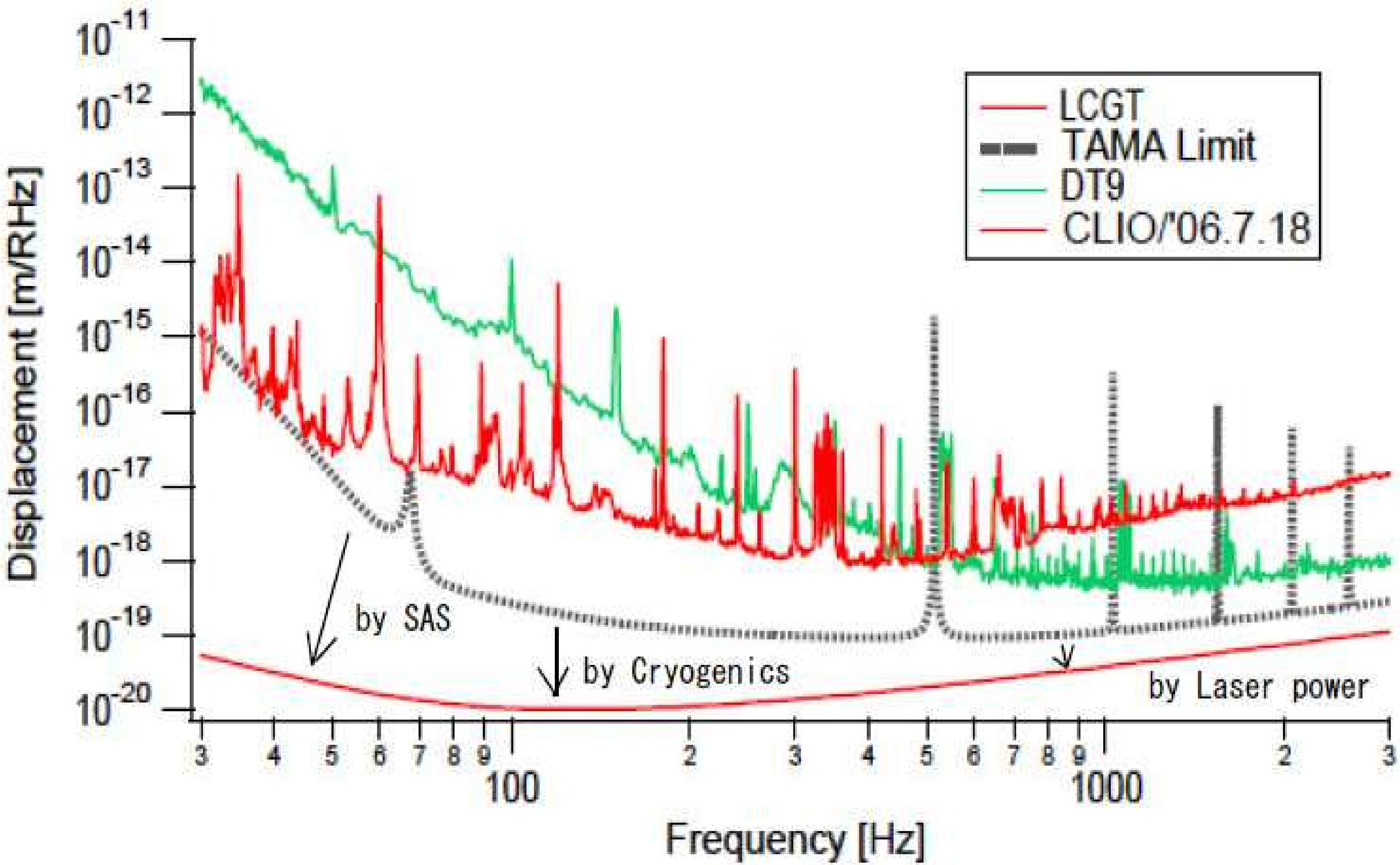
Sensitivity is limited only by quantum noises around at observational frequency band.





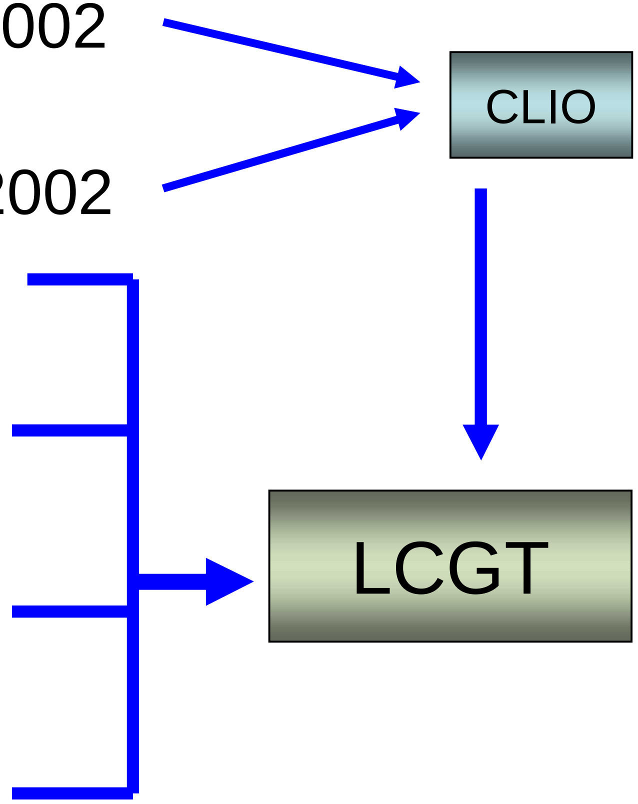
Inspiral GW from binary coalescence
LCGT
TAMA PhaseII limit
TAMA-dt9
BH ringdown
LCGT
TAMA PhaseII limit
TAMA-dt9
Single interferometer at its optimum
LCGT
185 Mpc
TAMA PhaseII limit
1.80 Mpc
TAMA dt9
72.5 kpc
1Gpc
1Mpc
Range for Single Detector with SNR=10
0.1
1
10
100
mass of accompany star [Msolar]

Displacement Sensitivities of interferometers



Technical foundation of LCGT is established by a prototype and intermediate size interferometers with challenging techniques

- 20m interferometer
  - Kamioka mine 1999-2002
- Cryogenic experiments
  - KEK-ICRR 1997-2002
- TAMA advancement
  - NAO 1995-
- RSE adoption
  - NAO 1998-
- SPI installation
  - Phys. Dept. UT 1999-
- SAS
  - Phys. Dept. & NAO 1998-
    (CALTECH)

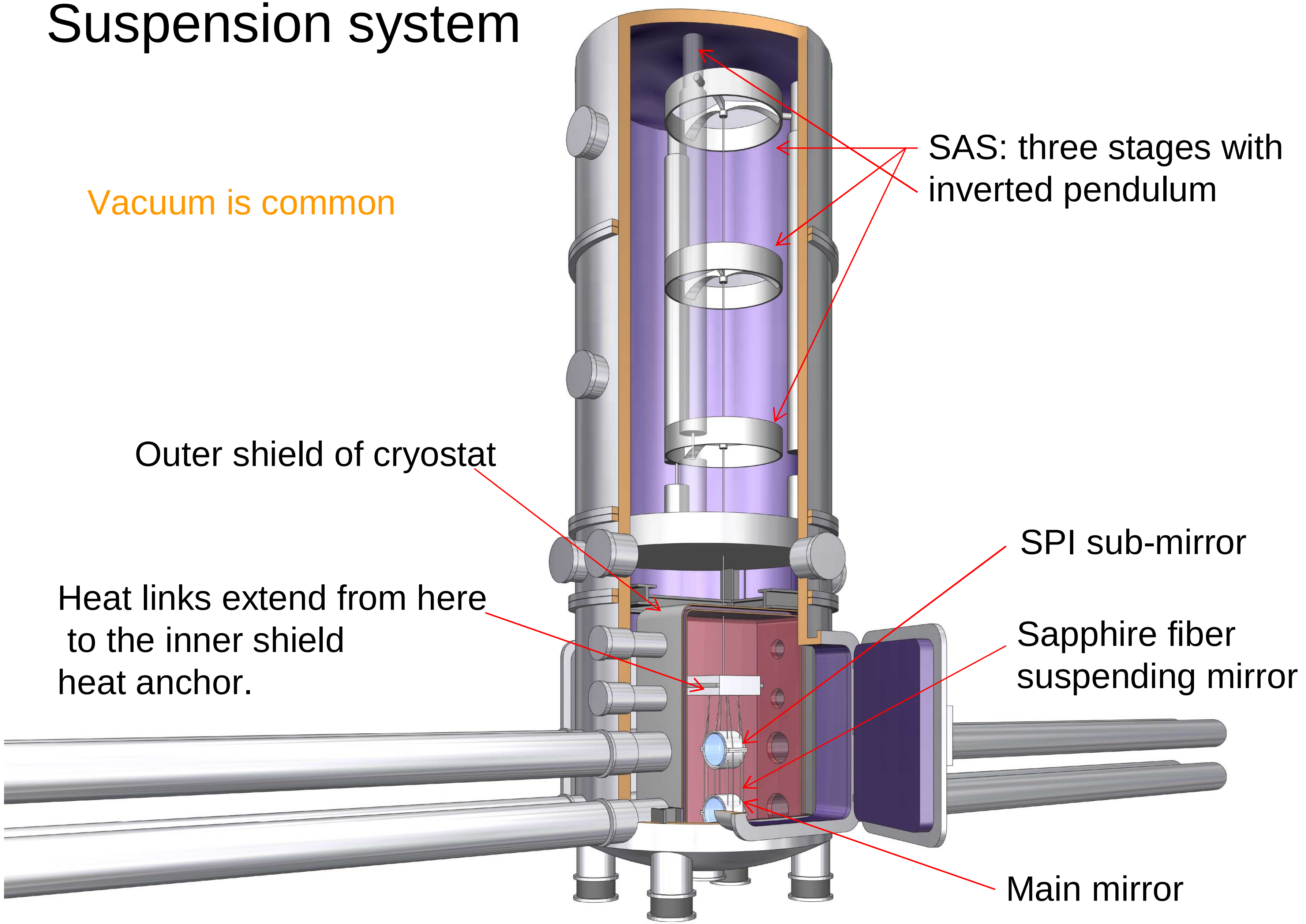


Sapphire cryogenic mirror produces valuable merits

- No thermal lens effect
  - due to high thermal conductivity and low thermal expansion rate (sapphire)
- Avoidable optical spring parametric instabilities
  - due to higher elastic wave speed (sapphire) and small beam size (cryogenic)
- Free from large optical coating loss
  - due to low temperature

Suspension system

Vacuum is common

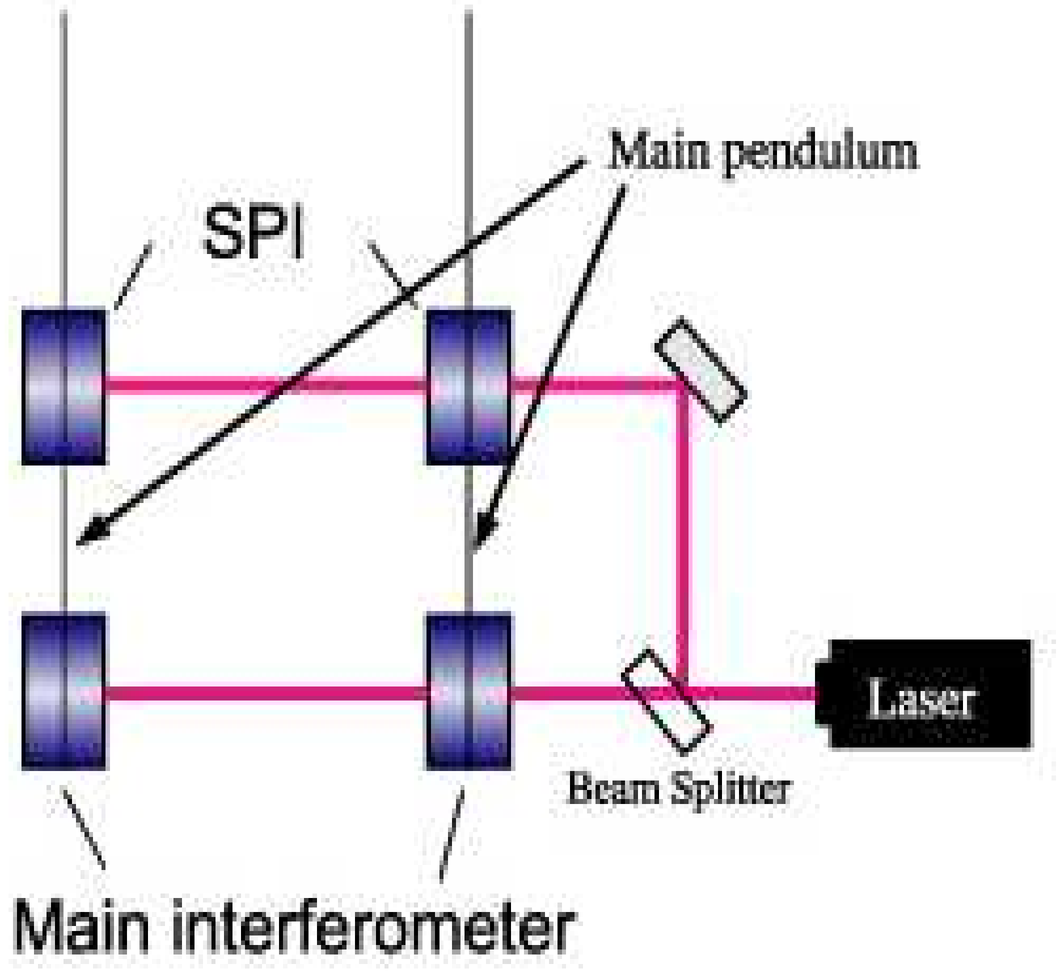


Large heat production is avoided by RSE

- Broad band RSE (Resonant Side band Extraction method) is applied.
- Power recycling gain is set 11.
- Finesse of the cavity is 1550, which means that observational band becomes to be lower than required.
- RSE keeps the observation frequency band unchanged.

Refrigerator noise is avoided by SPI

Test mass of LCGT is connected to a cooling system by a heat link that possibly introduces mechanical noise. A suspension point interferometer (SPI) is introduced to maintain high attenuation of seismic and mechanical noise without degrading high heat conductivity.



Schedule in the budget request for FY2008

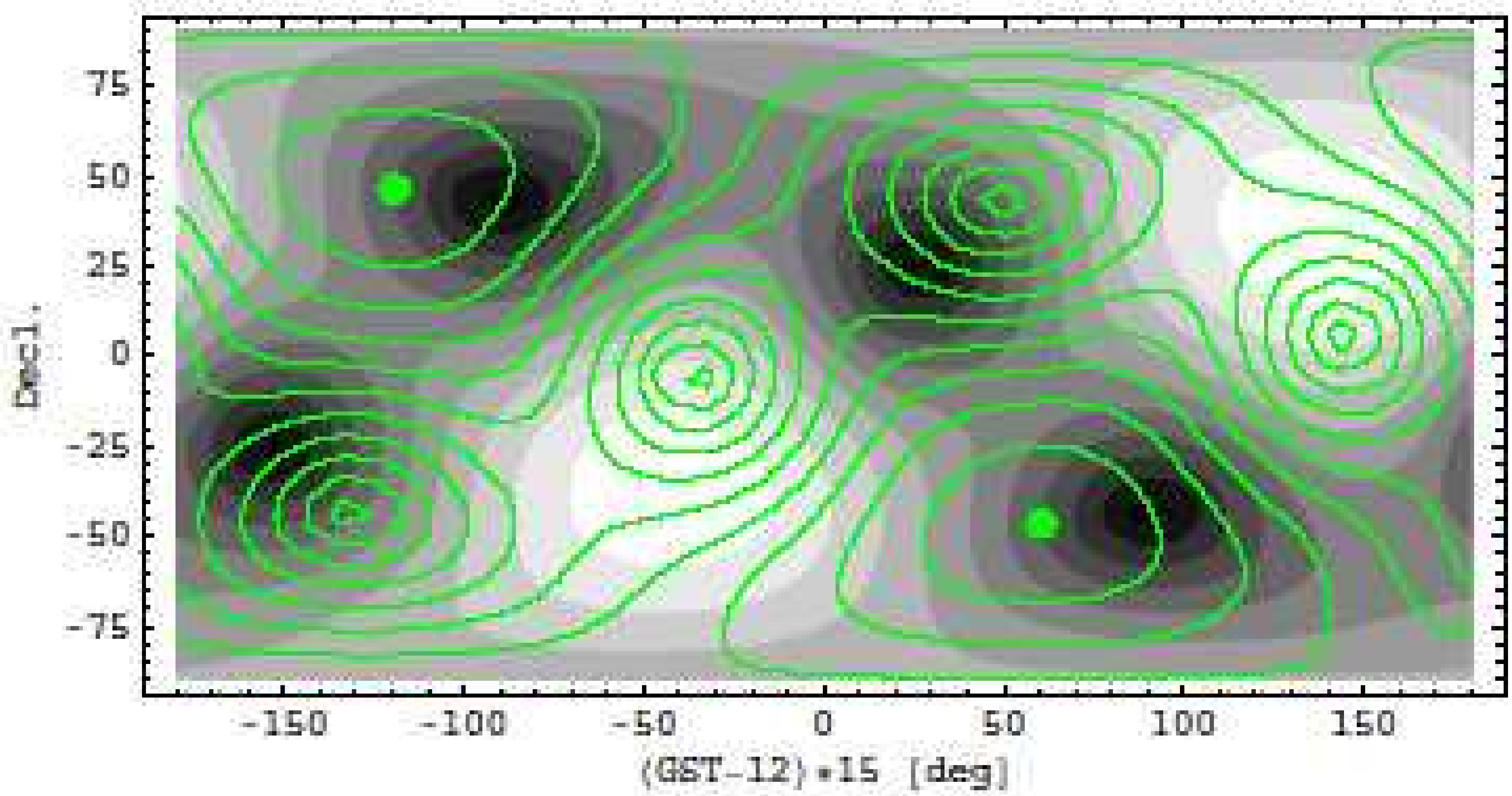
110 JpnYen=1 US$

Item	Financial Year								Cost
	2008	2009	2010	2011	2012	2013	2014	After 2015	(thousand yen)
Tunnel construction									3586000
Building construction									210000
Making Vacuum Parts									3308000
Vacuum system Install									2205000
Optical System									902716
Optics Install									98784
Laser source									793210
Laser Install									9040
Cryogenic Suspension									2615720
Suspension Install									17430
SAS Isolator									229400
SAS Installation									12600
Main mirror									312900
Mirror Installation									2100
Data-taking system									315000
Data Analysis									21000
PD Salary									200000
Commissioning									
Observation									
Total	413500	3407320	4147240	4078080	3772760				14838900

US$ 135M

It does not include salaries & maintenances of facilities.

LCGT contributes the international observation by the coverage of a complimentary sky to other detectors:
LCGT, grey scale, LIGO (Hanford), green contour curves.



Summary of LCGT

- It is a 3km Fabry-Perot MI with a power recycling scheme and equipped with a broadband RSE. The laser power is 150W
- Main mirrors made of sapphire are cooled at 20K. A SPI impedes the refrigerator- vibration.
- Underground usage guarantees stable operation
- Two independent interferometers are installed in the vacuum system.
- The main target is detecting the coalescence of BNS, which can be detected 1.2-27.8 events per year at confidence level of 95% for mass 1.4Msun and S/N=10.
- Possible standard interferometer in the future international network

International Collaboration (as a dream)

- GW observation on the Earth needs an international network consisting of detectors with similar sensitivity and reliable operation
- Positioning LCGT as the standard interferometer on the Earth
- Every observatory hopefully constructs LCGT in the future
- An international organization is needed to help the hardware construction in each observatory
- We will contribute to establish such organization by obtaining each governmental fund

Summary

- We have acquired interferometer techniques (power recycling, Fabry-Perot Michelson, control system) by TAMA.
- LISM confirmed underground significance.
- CLIO proves the feasibility of cryogenic mirror, soon.
- LCGT as the final and standard interferometer on the Earth reliably detects gravitational wave events.