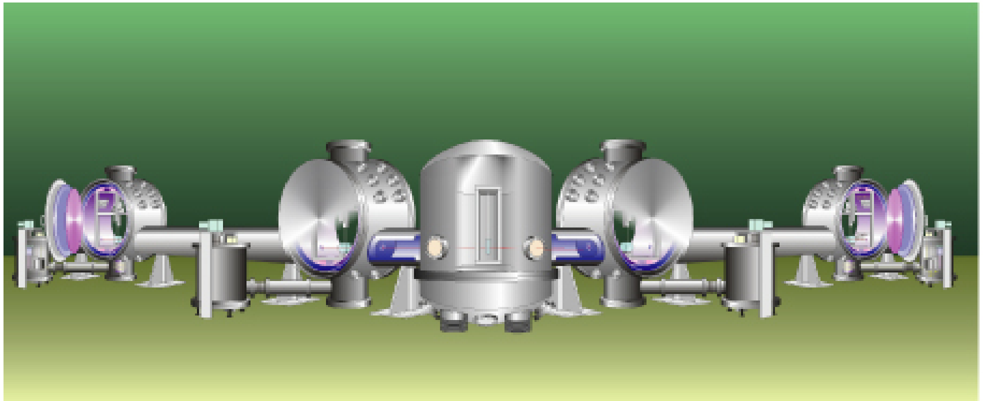
km スケールの低温重力波望遠鏡計画

Large-scale Cryogenic Gravitational wave Telescope

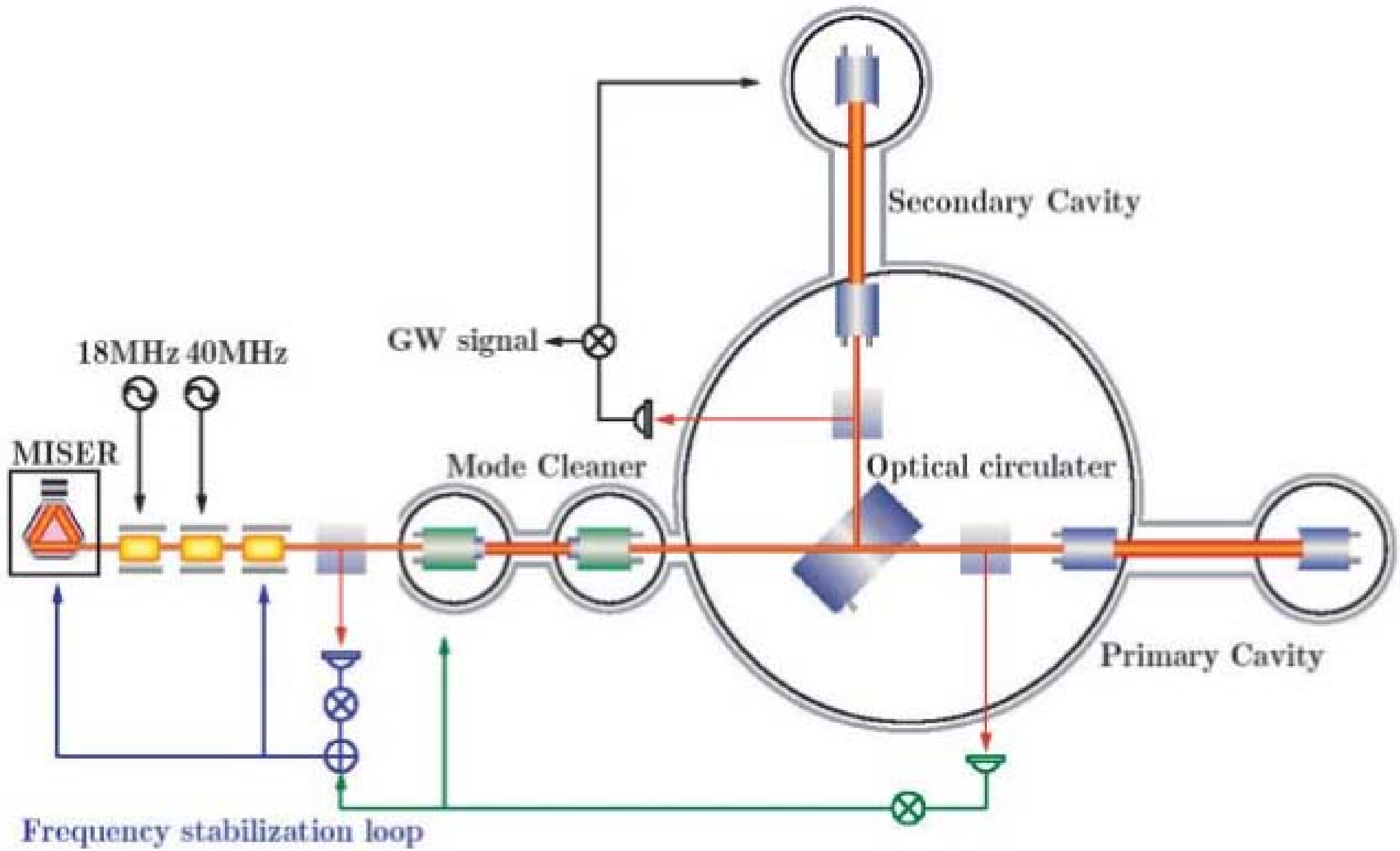


2002.8.31

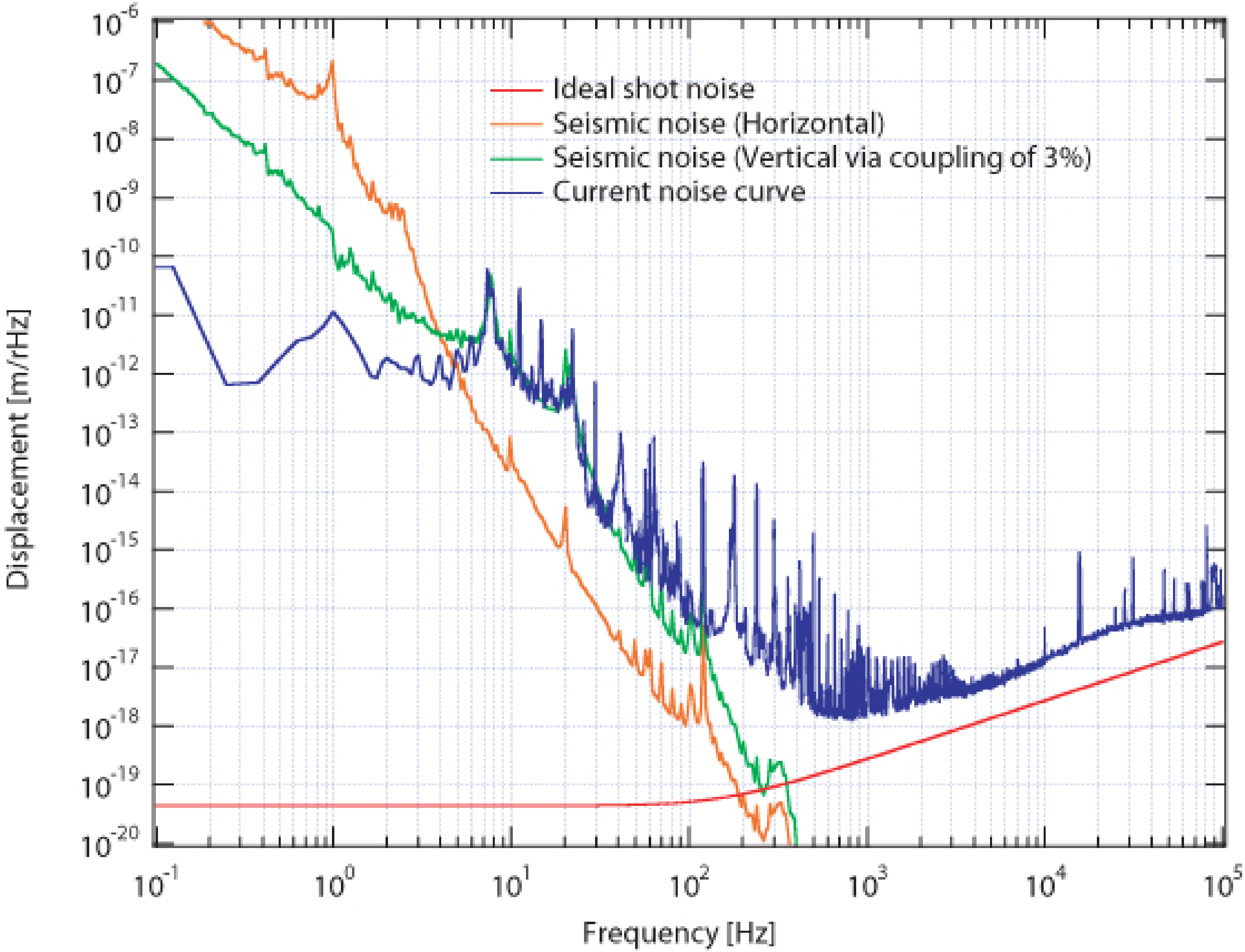
（2002.10.31　revised ）

（2003.1.31　revised ）

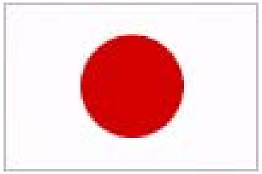
LCGT　Collaboration



Secondary Cavity
GW signal
18MHz 40MHz
MISER
Mode Cleaner
Optical circulater
Primary Cavity
Frequency stabilization loop

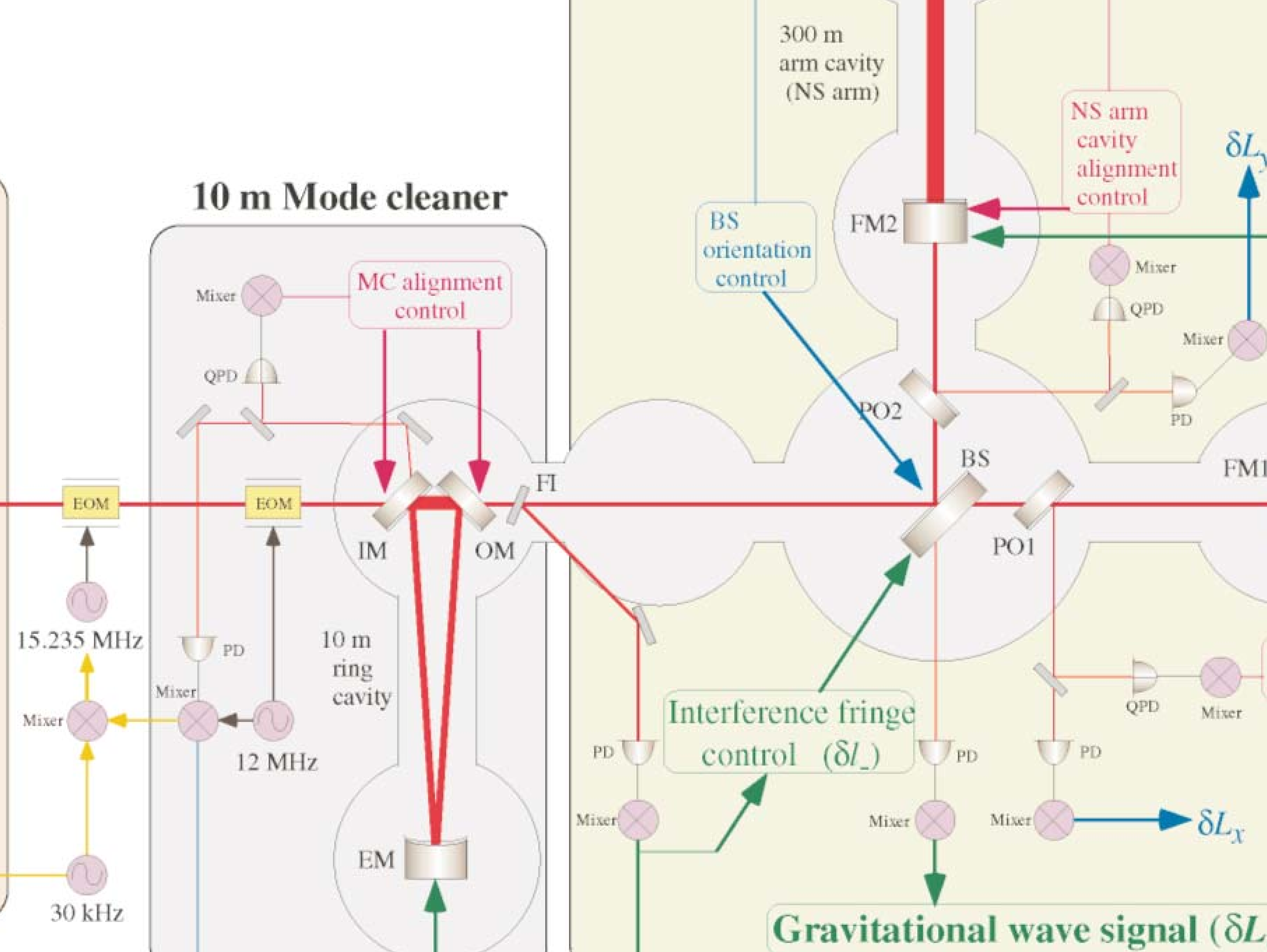

Ideal shot noise
Seismic noise (Horizontal)
Seismic noise (Vertical via coupling of 3%)
Current noise curve
Displacement [m/rHz]
Frequency [Hz]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

TAMA

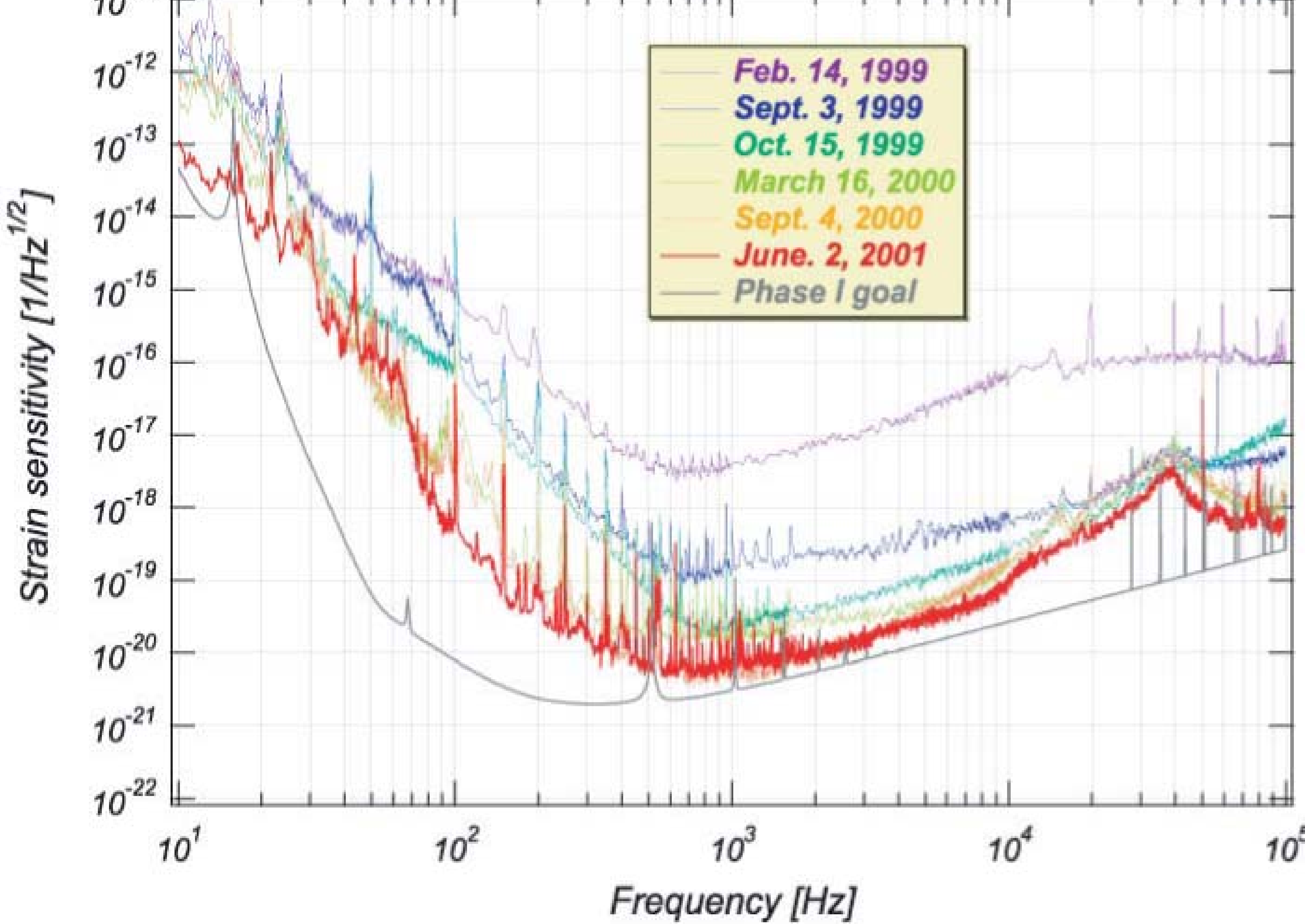


The Objective of TAMA is to develop advanced technologies for km scale interferometer and to observe possibl **GW** events in our Galaxy.

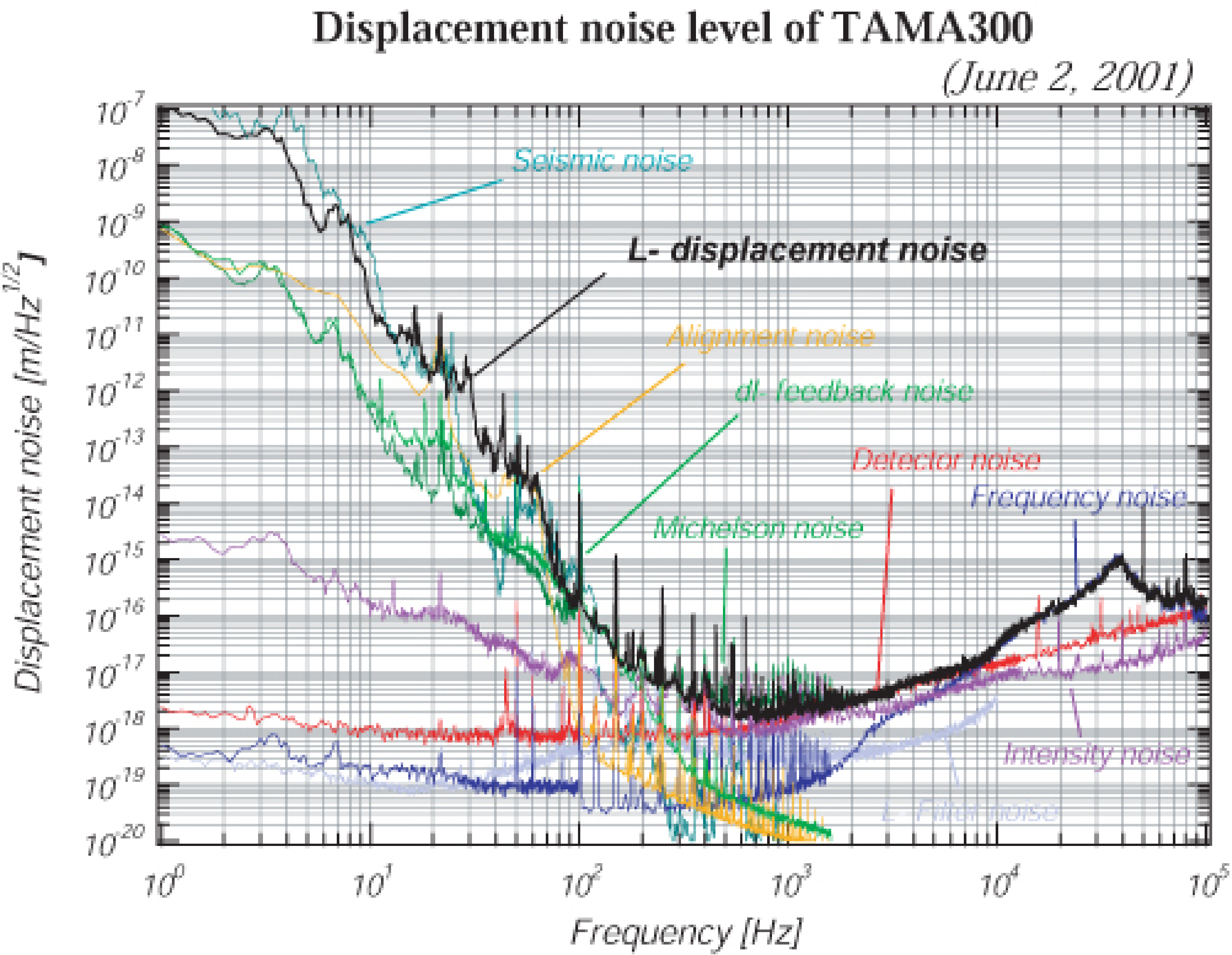
The funding originally covered five years.
We began its construction in April of 1995.It ends in this March after two years extension. Four year research money has been approved from this April.



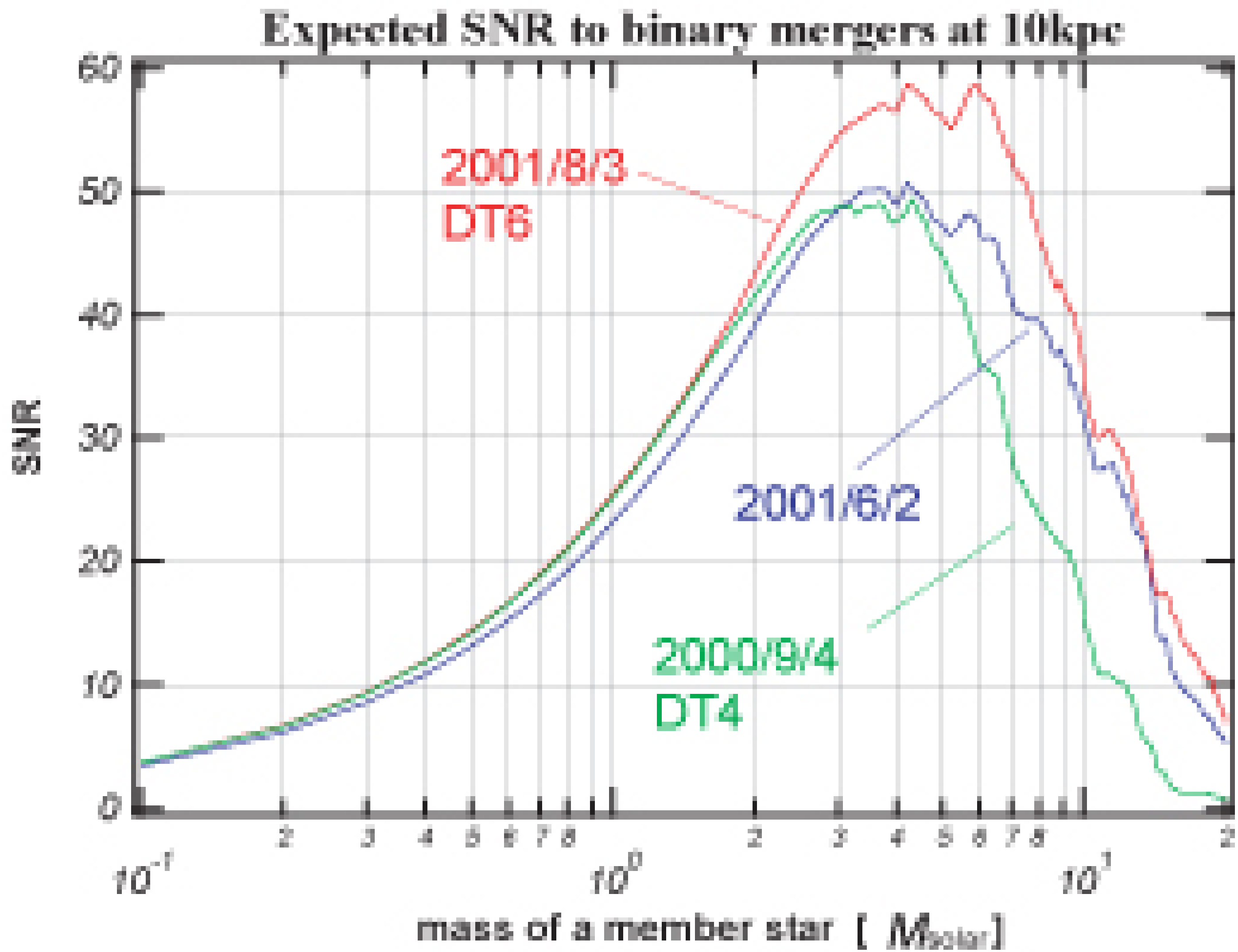
300 m
arm cavity
(NS arm)
NS arm
cavity
alignment
control
10 m Mode cleaner
BS
orientation
control
FM2
MC alignment
control
Mixer
QPD
Mixer
QPD
Mixer
PO2
PD
BS
FM1
EOM
EOM
FI
IM
OM
PO1
15.235 MHz
PD
10 m
ring
cavity
Mixer
Mixer
12 MHz
Interference fringe
control (δl_)
QPD
Mixer
PD
PD
PD
Mixer
Mixer
Mixer
δL_x
EM
30 kHz
Gravitational wave signal (δL



Feb. 14, 1999
Sept. 3, 1999
Oct. 15, 1999
March 16, 2000
Sept. 4, 2000
June. 2, 2001
Phase I goal
Strain sensitivity [1/Hz^1/2]
Frequency [Hz]



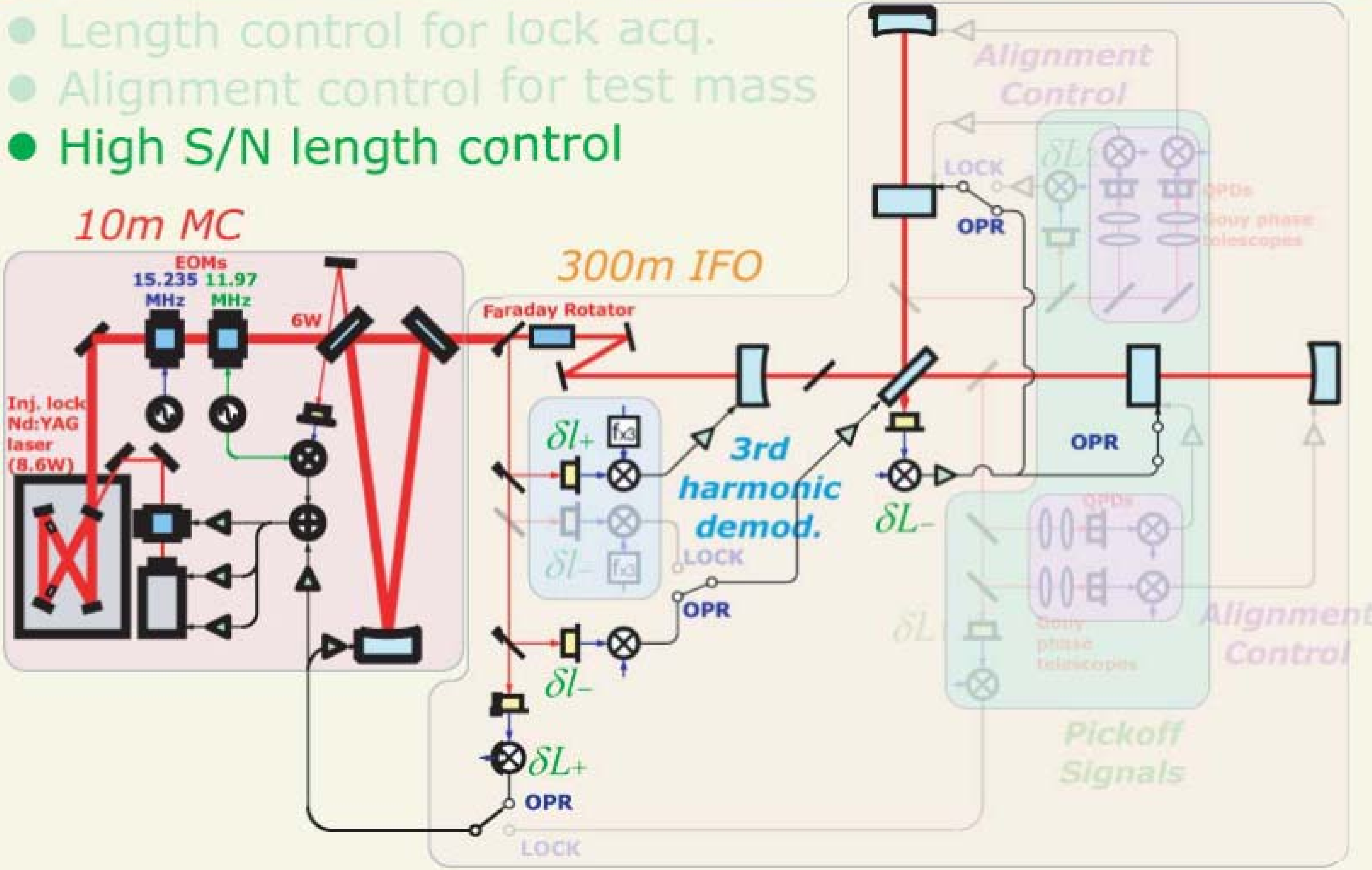
Displacement noise level of TAMA300
(June 2, 2001)
Seismic noise
L- displacement noise
Alignment noise
dl- feedback noise
Detector noise
Frequency noise
Michelson noise
Intensity noise
L- Filter noise
Displacement noise [m/Hz^1/2]
Frequency [Hz]



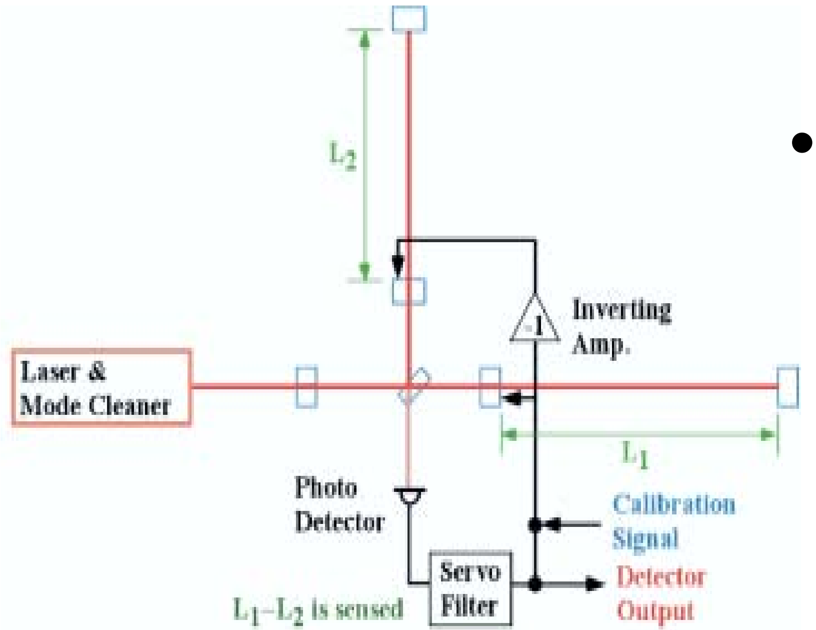
Expected SNR to binary mergers at 10kpc
SNR
60
50
40
30
20
10
0
2001/8/3
DT6
2001/6/2
2000/9/4
DT4
2
3
4
5
6
7
8
10^{-1}
10^{0}
10^{1}
mass of a member star [M_{solar}]

Optical Config. and control system

- Length control for lock acq.
- Alignment control for test mass
- High S/N length control

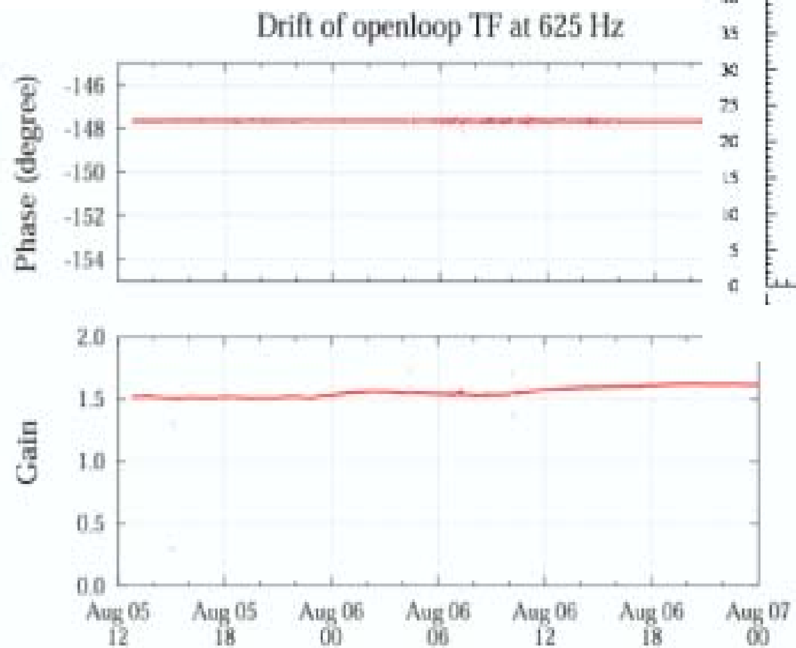


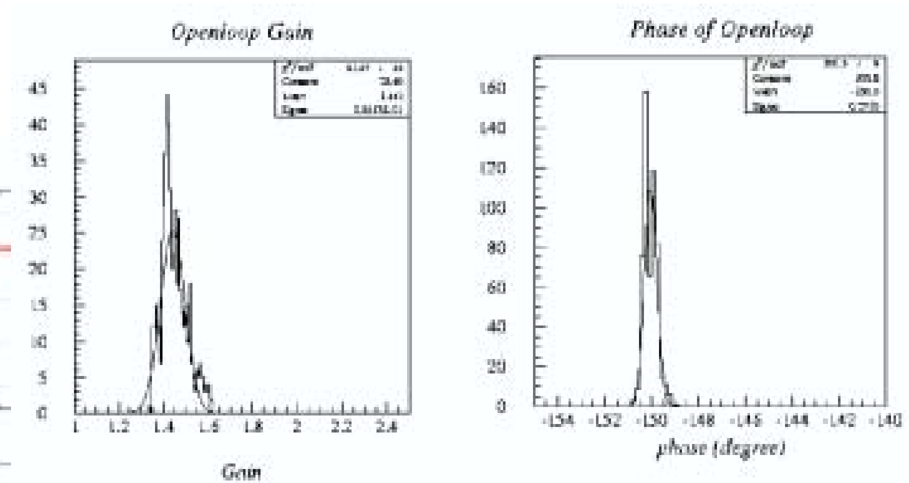
感度の校正



- 振幅の分かっている信号を入力し、振幅と位相を測定
- TAMAでは、周波数を625Hzに固定して測定している。

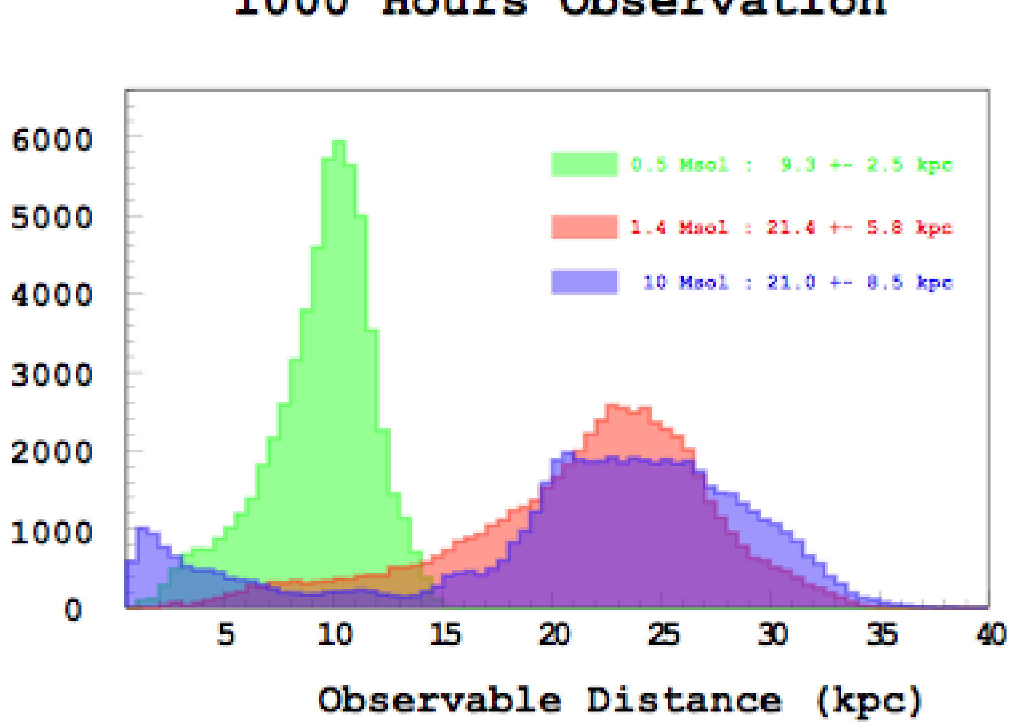
校正結果の変動





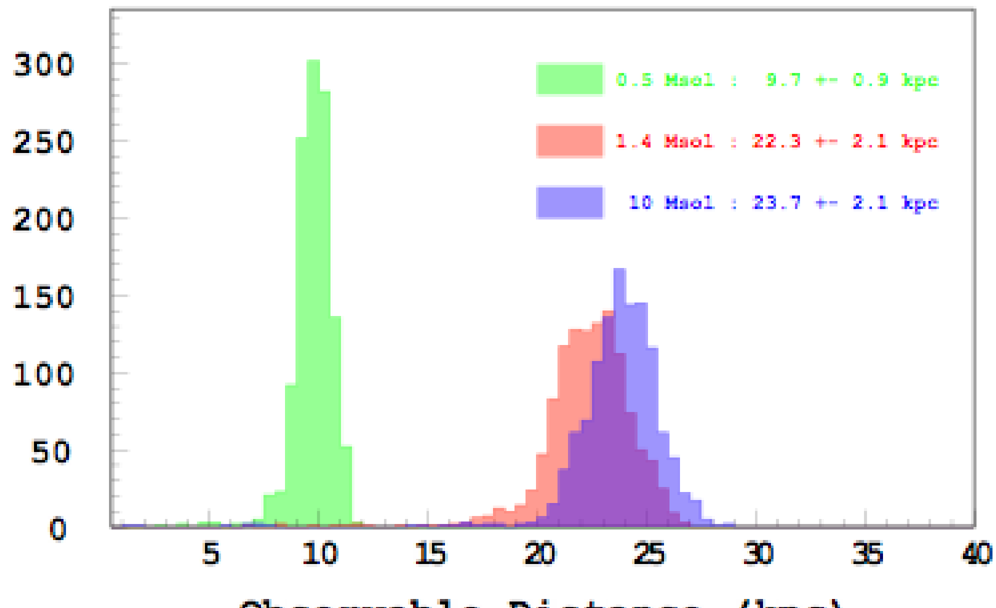
校正の不確かさ:
ゲイン:1%**以下**
位相:0.3**度以下**

- DT6



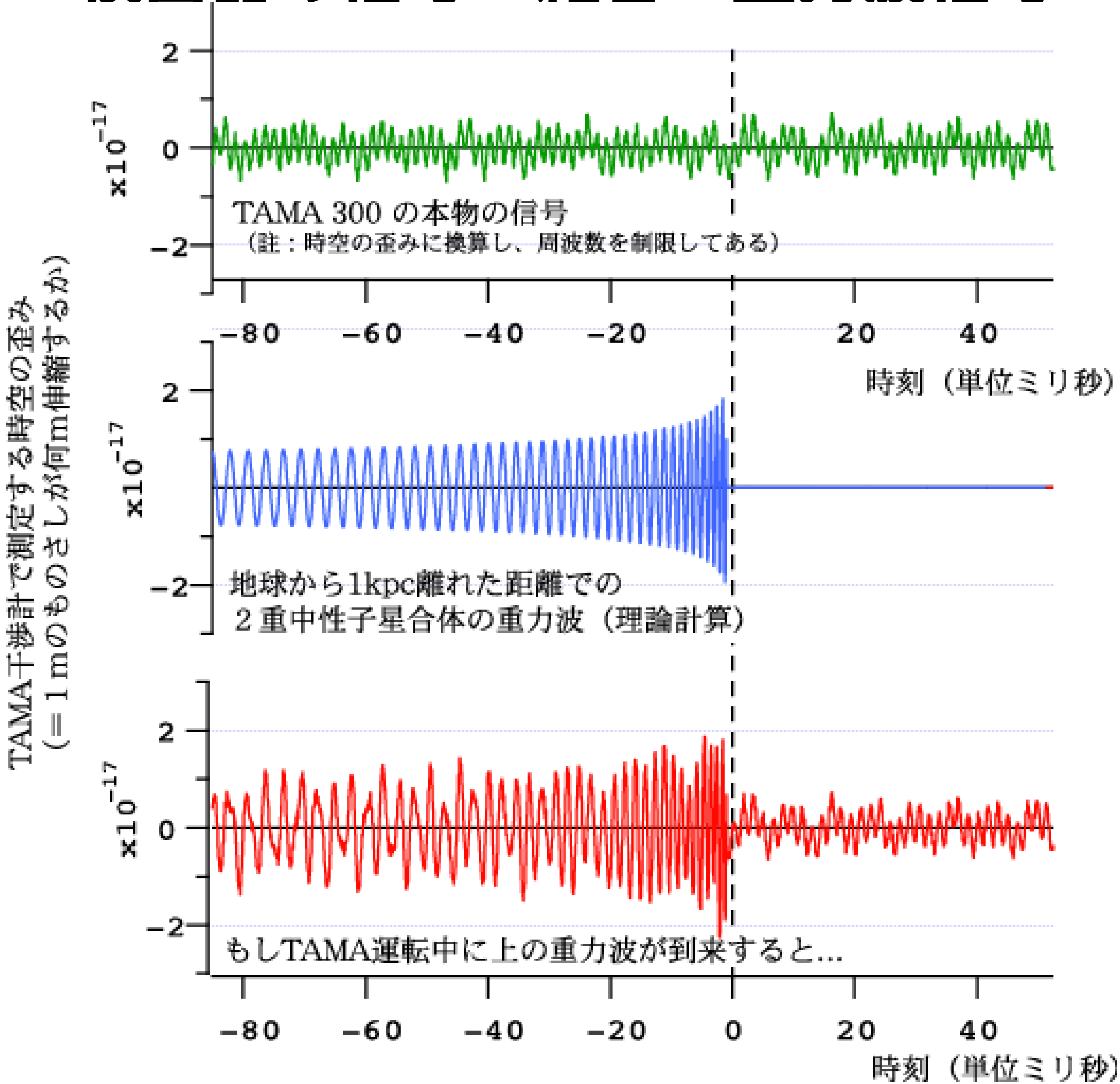
1000 Hours Observation
0.5 Msol : 9.3 +- 2.5 kpc
1.4 Msol : 21.4 +- 5.8 kpc
10 Msol : 21.0 +- 8.5 kpc
6000
5000
4000
3000
2000
1000
0
5
10
15
20
25
30
35
40
Observable Distance (kpc)

- DT7



0.5 Msol : 9.7 +- 0.9 kpc
1.4 Msol : 22.3 +- 2.1 kpc
10 Msol : 23.7 +- 2.1 kpc
300
250
200
150
100
50
0
5
10
15
20
25
30
35
40

検出器の信号＝雑音＋重力波信号



4. 主たる解析手法の実装
(1) Matched Filterによる連星合体サーチ

- Detector outputs: $s(t) = Ah(t) + n(t)$

  $h(t)$: known gravitational waveform (template) → Post-Newtonian approximation

  $n(t)$: noise.

- Outputs of matched filter:

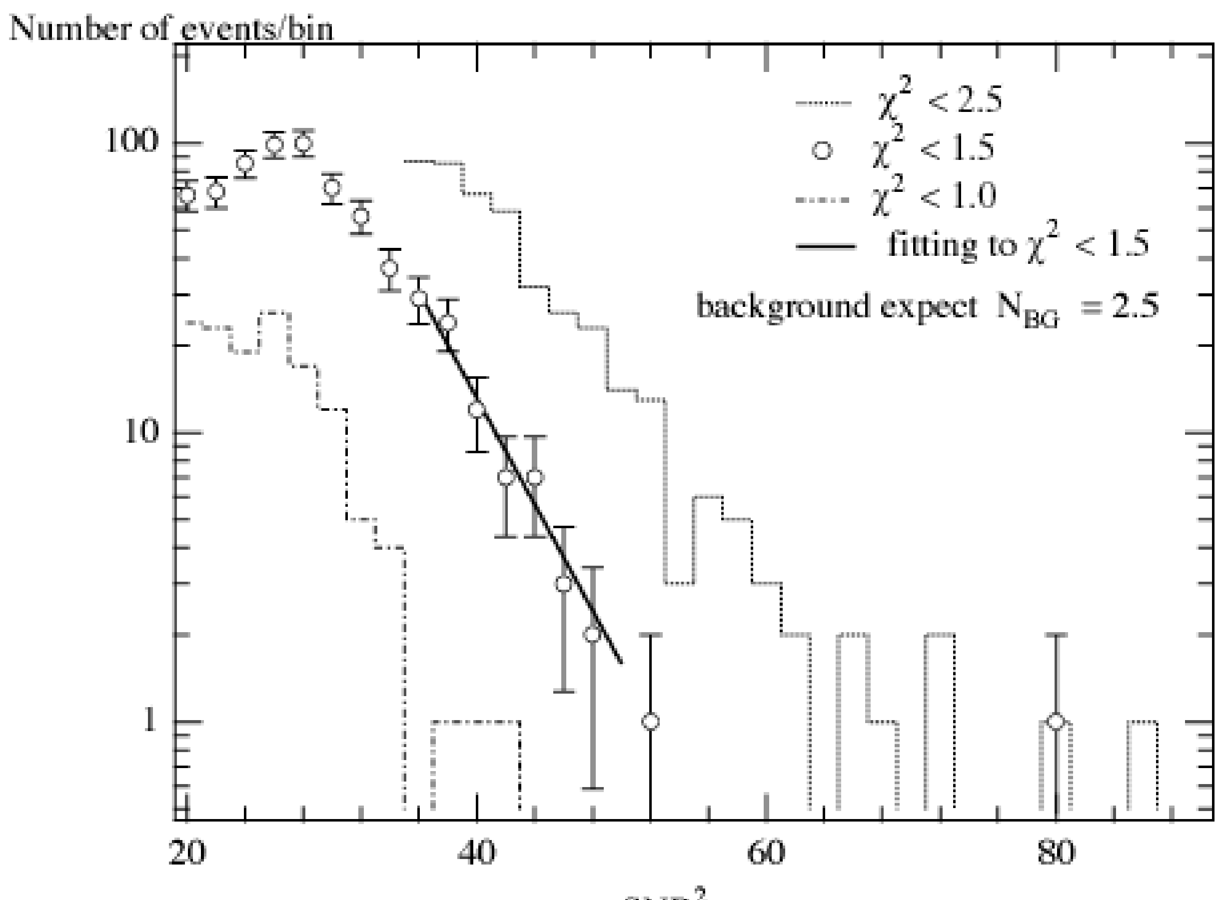
$$\rho(t_c, m_1, m_2, \ldots) = 2\int \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df$$

- $S_n(f)$ noise power spectrum density

- Signal to noise ratio is SNR $= \rho / \sqrt{2}$
- Find the parameter which realize the maximum of ρ for each certain interval of t_c

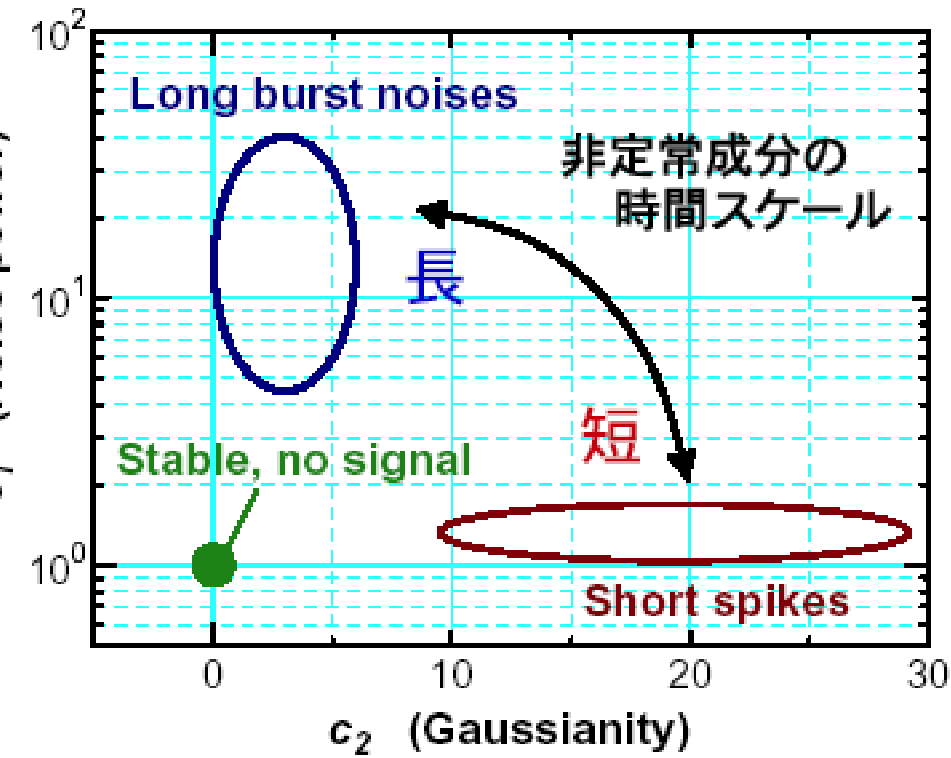
$$\max \rho(t_c, m_1, m_2, \ldots)$$

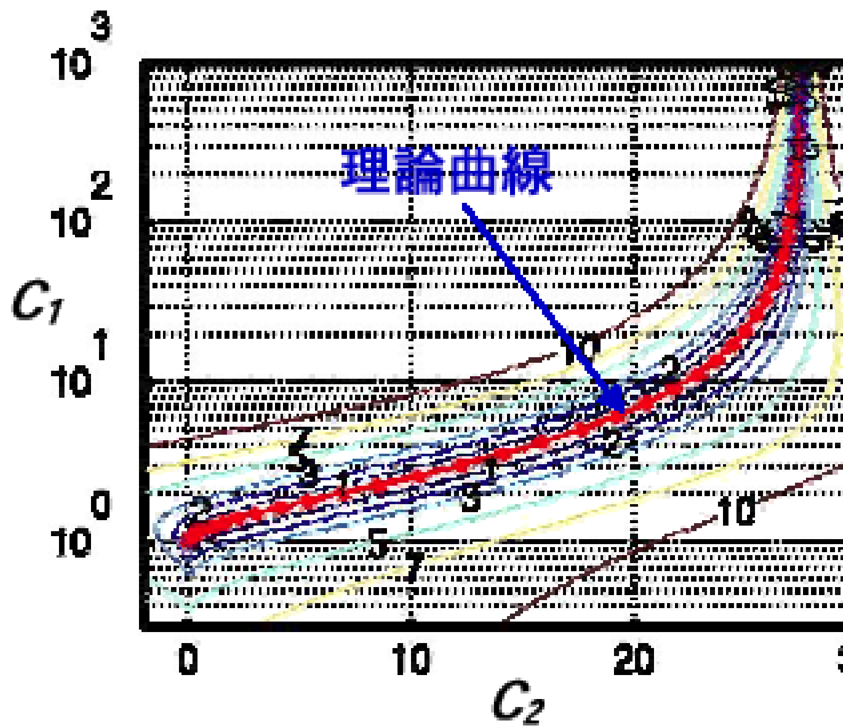
- Result with DT2
  - Survey mass region: 0.3 - 10 Msolar
  - 0.59 event / hour C.L. 90 %
    - Note: **グラフ横軸の**SNR**は雑音で規格化した信号の大きさ、という意味であって**survived event**の**significancy**を示すものではない。**
    - **最終的な選別閾値**(SNR>7.2)**をこえた数**：Nobs = 2
    - **バックグラウンドの期待値**：Nbg = 2.5
    - Poisson**分布と**Bays**統計から導かれるイベント上限値は、**3.7 event (C.L.90%)



4. 主たる解析手法の実装
(2) バースト

- 干渉計診断から発展
- あるtime spanでの信号のパワーとガウス性を比較
  - 超新星バーストについてのいくつかの波形予測は、
  - 典型的な干渉計の雑音と違うsignatute





4. 主たる解析手法の実装
(3) 連続波

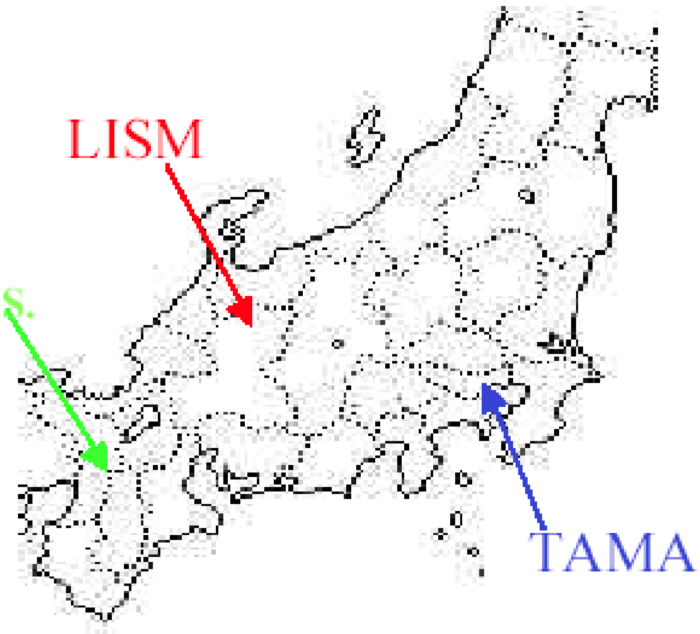
- SN1987A 跡のパルサーを仮定
  - 周波数　$934.9080 \sim 934.9826\,Hz$　をサーチ
  - スピンダウンは 2.5×10^{-10} Hz/s
  - 平均パワー $P_0 = 3.6434\times10^{-40}(1/Hz)$
    ひずみ度にして $h = 9.1\times10^{-24}$
    ・・重力波なし
  - 第一種の誤り $P_1 = 0.026 \rightarrow P_T = 14P_0$
  - 得られた重力波のupper limitは $h_{upper} = 3.4\times10^{-23}$
    $h_{DT4} = 1.1\times10^{-22}$

6. 相関解析
(1) LISM - TAMA

Location of TAMA and LISM

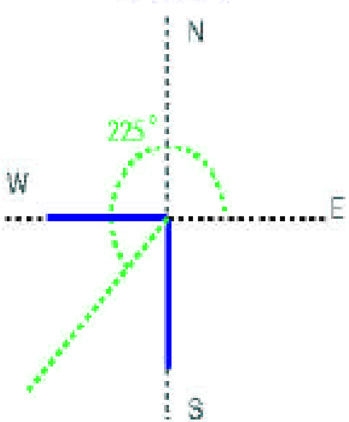
- Location of TAMA and LISM

	orientation	latitude	longitude
TAMA	225°	35.68° N	139.54° E
LISM	165°	36.25° N	137.18° E

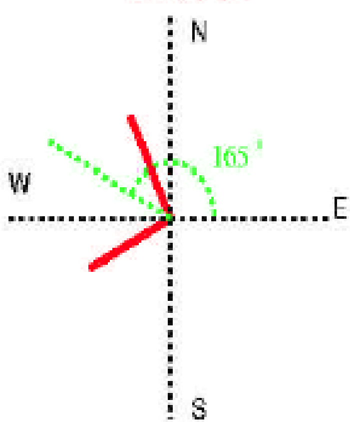


Relation between TAMA and LISM arms direction

TAMA



LISM



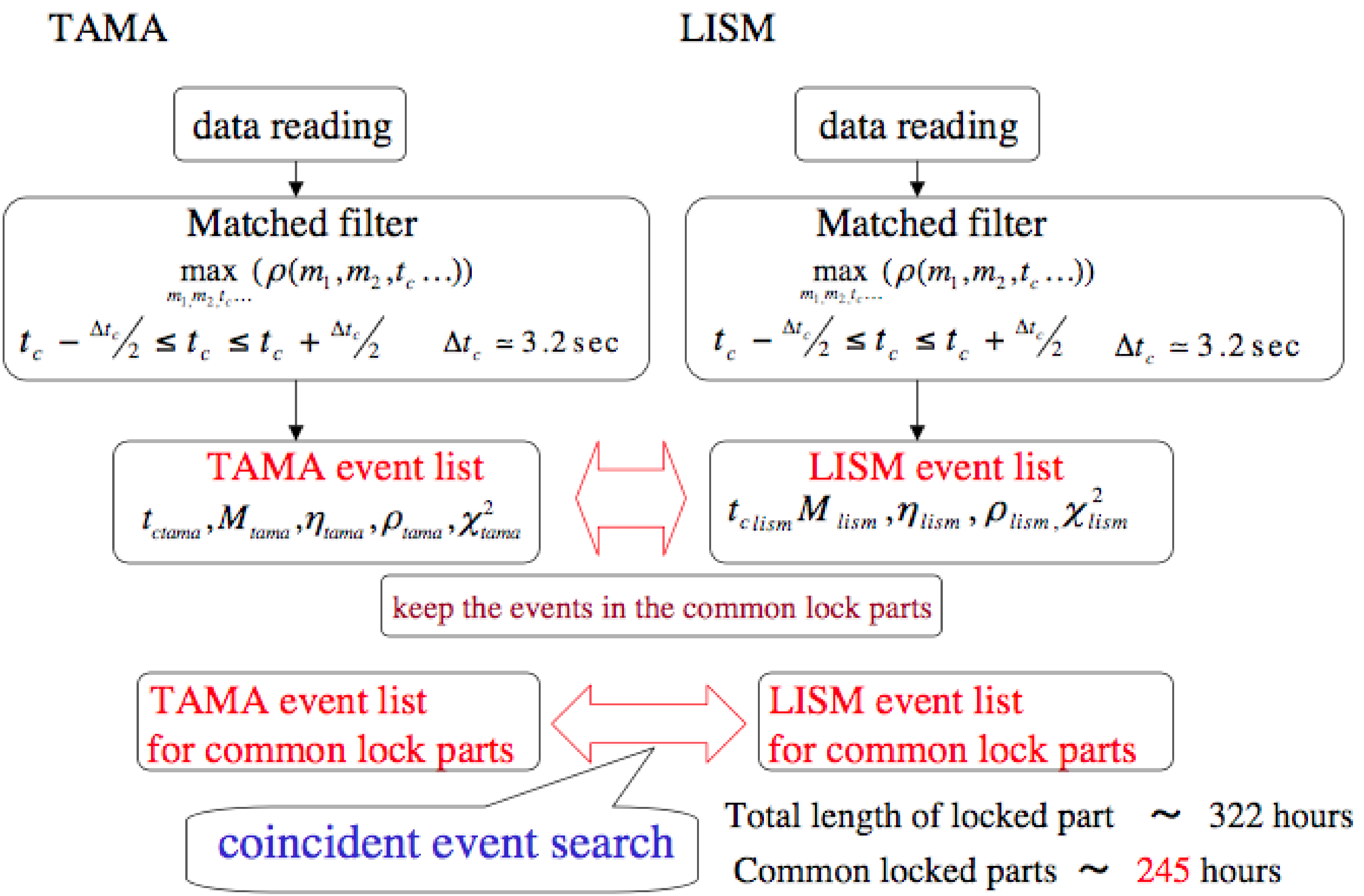
Distance between TAMA and LISM ～220km

Maximum delay of signal arrival time

～ 0.73msec

Difference of zenith direction ～ 1.97 °

TAMA－LISM Analysis Algorithm



Results of coincident event search

Results of onestep search for common lock parts

TAMA	LISM
158437 events	142465 events

After t_c-coincidence — 70 events
accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 70.45 ±8.53

After $t_c, \mathcal{M}, \eta$ -coincidence — 18 events
accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 17.55 ± 4.08

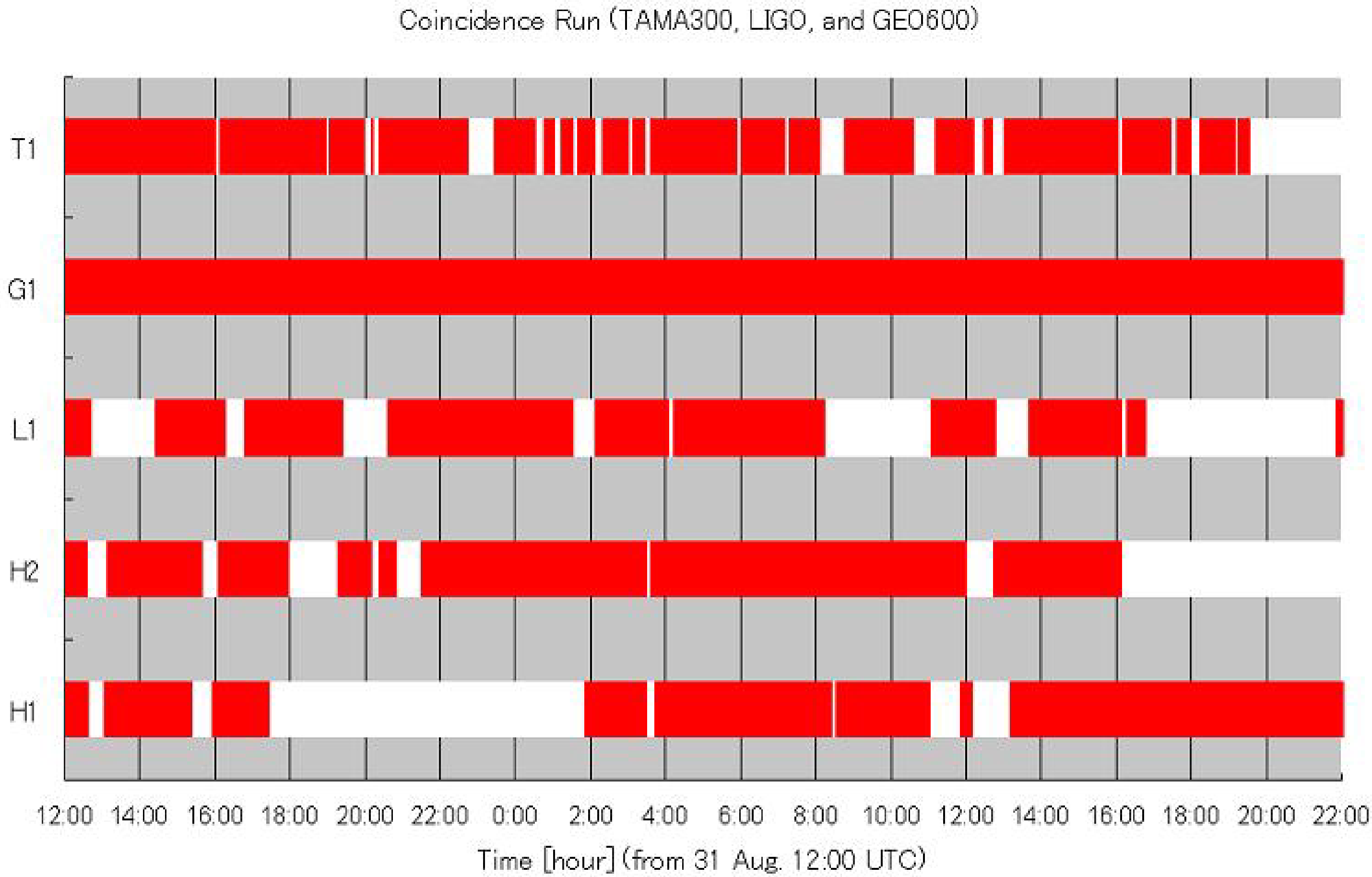
After $t_c, \mathcal{M}, \eta, \rho$ -coincidence — 13 event
accidental coincidence $(\bar{n}_{acc} \pm \sigma_c)$ — 12.76 ±3.51

6. **相関解析**
(2) LIGO - GEO - TAMA

- **利点**
  - **全天にたいする死角がなくなる**
  - **到来方向、偏極が解ける**
  - Fake event**除去に有効**
  - **複数の情報(周波数応答の違い、偏極、時間差の**constraint)**を用いうるので、**Redundancey**が持たせられる。**
  - **解析の国際交流**
- Memorandom of Understanding **は締結**
- **観測予定**
  - DT7 - LIGO S1
    - Five detectors common lock data: 9 hours 50 min
  - DT8 - LIGO S2
    - 2/14 - 4/14/2003

S1 & DT7

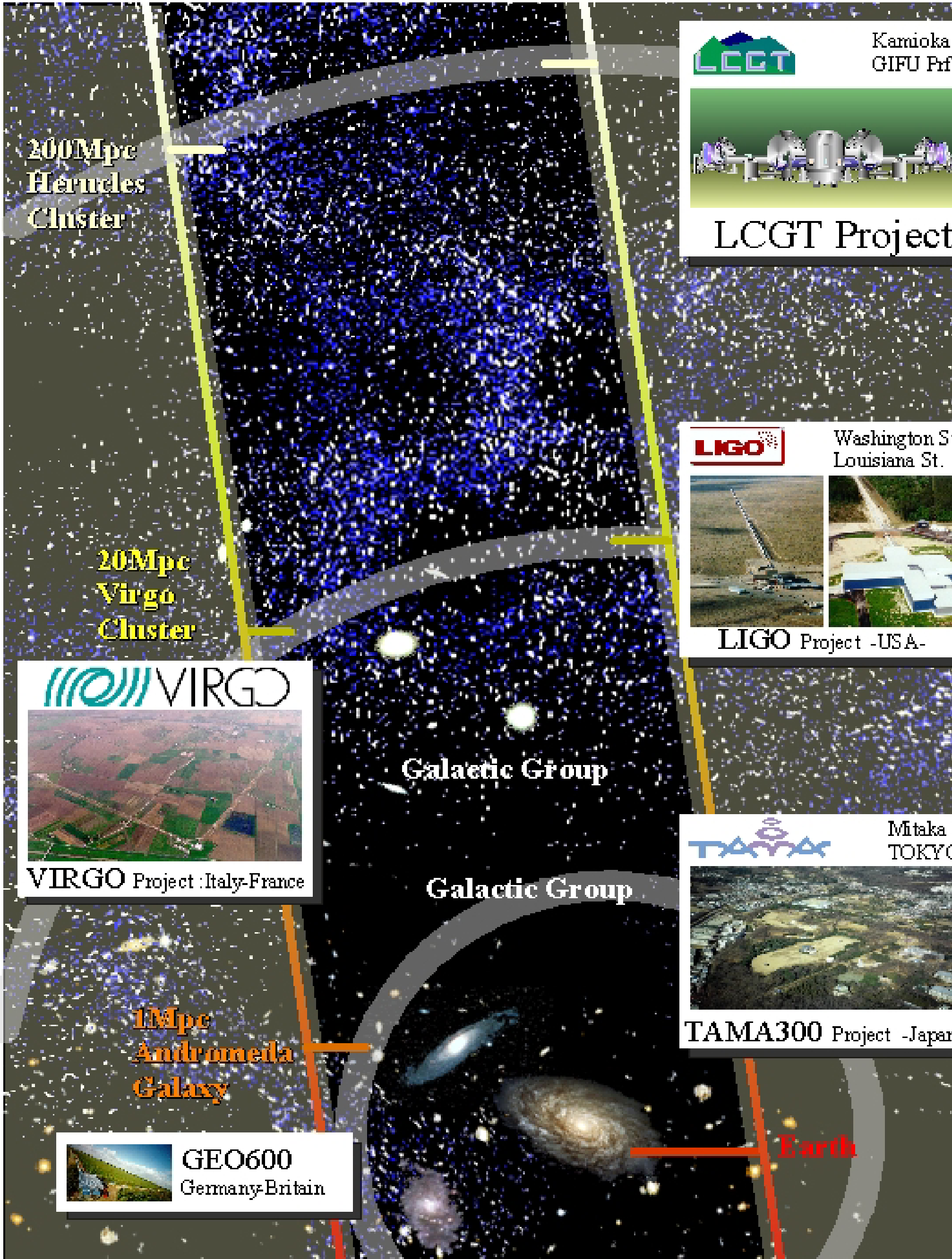
Common Lock: 9hrs 50min
Longest Lock: 2hrs 24min



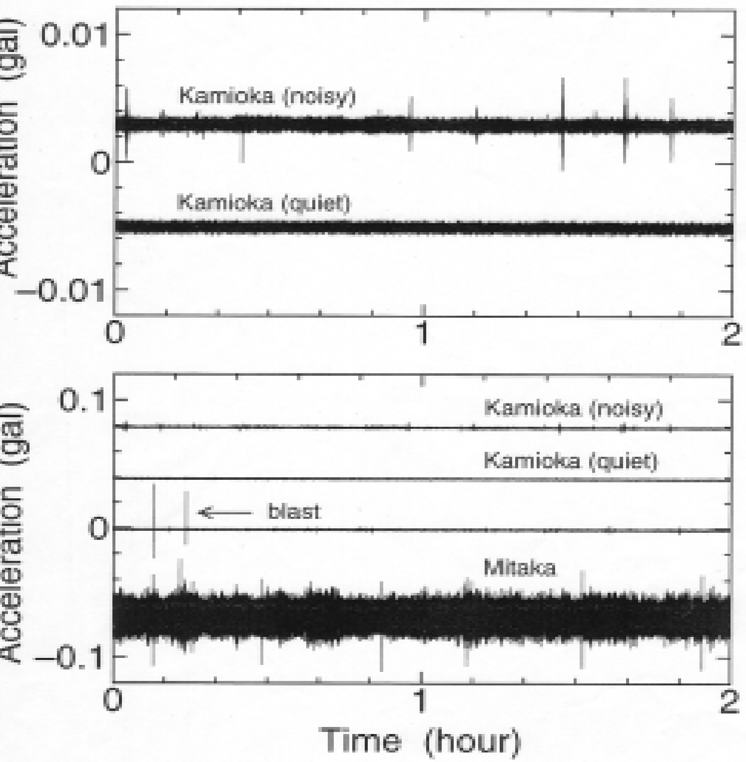
Since BNS exist and the signal of the coalescence is precisely predicted, the event is the most important target of the ground based interferometric detectors.

However, since the event rate is 10^{-6} per year per matured galaxy as ours, we have to wait for 30 years on average by the sensi-tivity to observe the VIRGO cluster (20Mpc). Because there is one galaxy per cubic Mpc on average.

Therefore, it is clear to everyone to develop more sensitive detector to see more remote galaxies. Increasing the sensitivity by ten times, the above waiting time becomes 0.4 months.

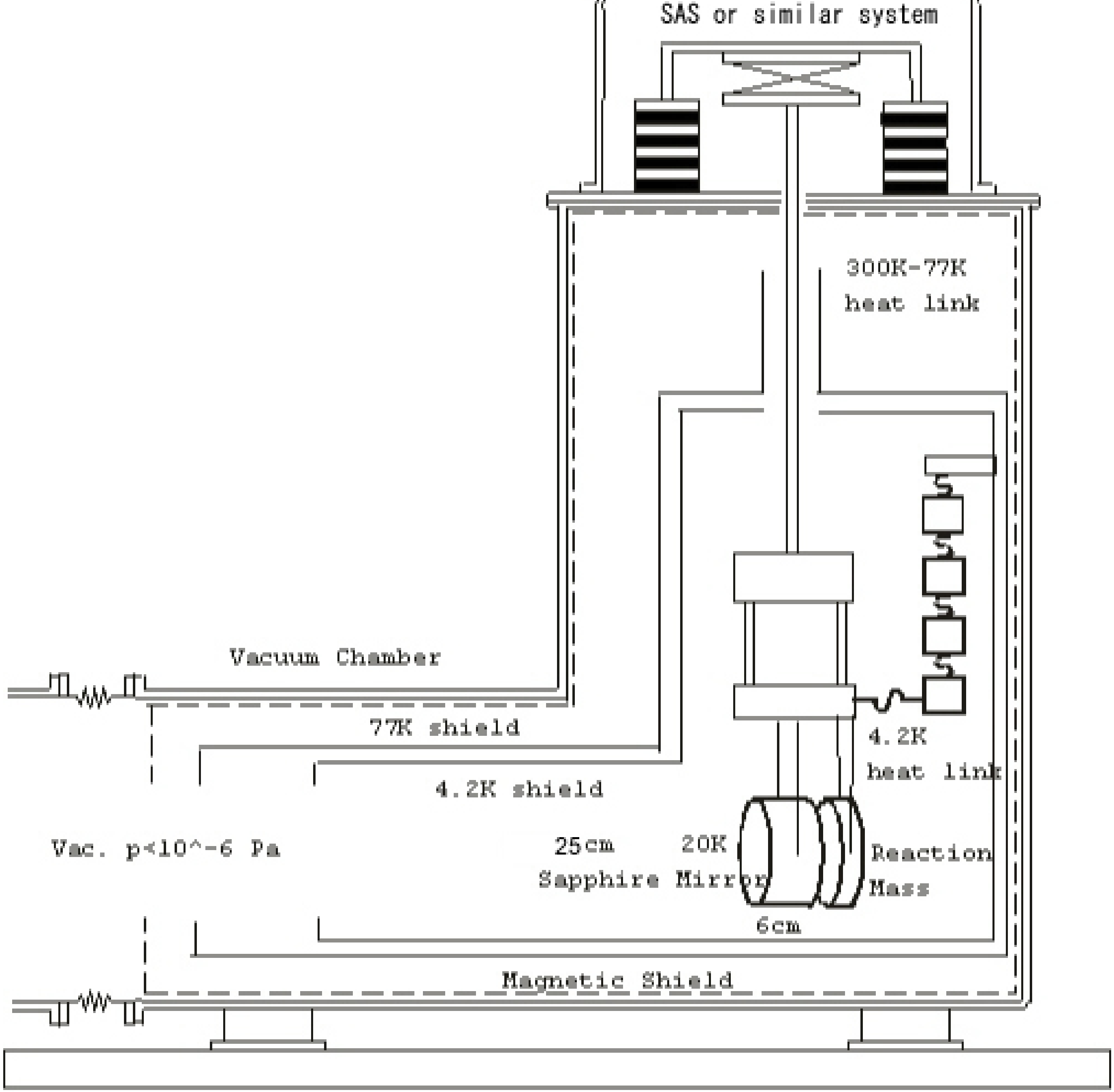


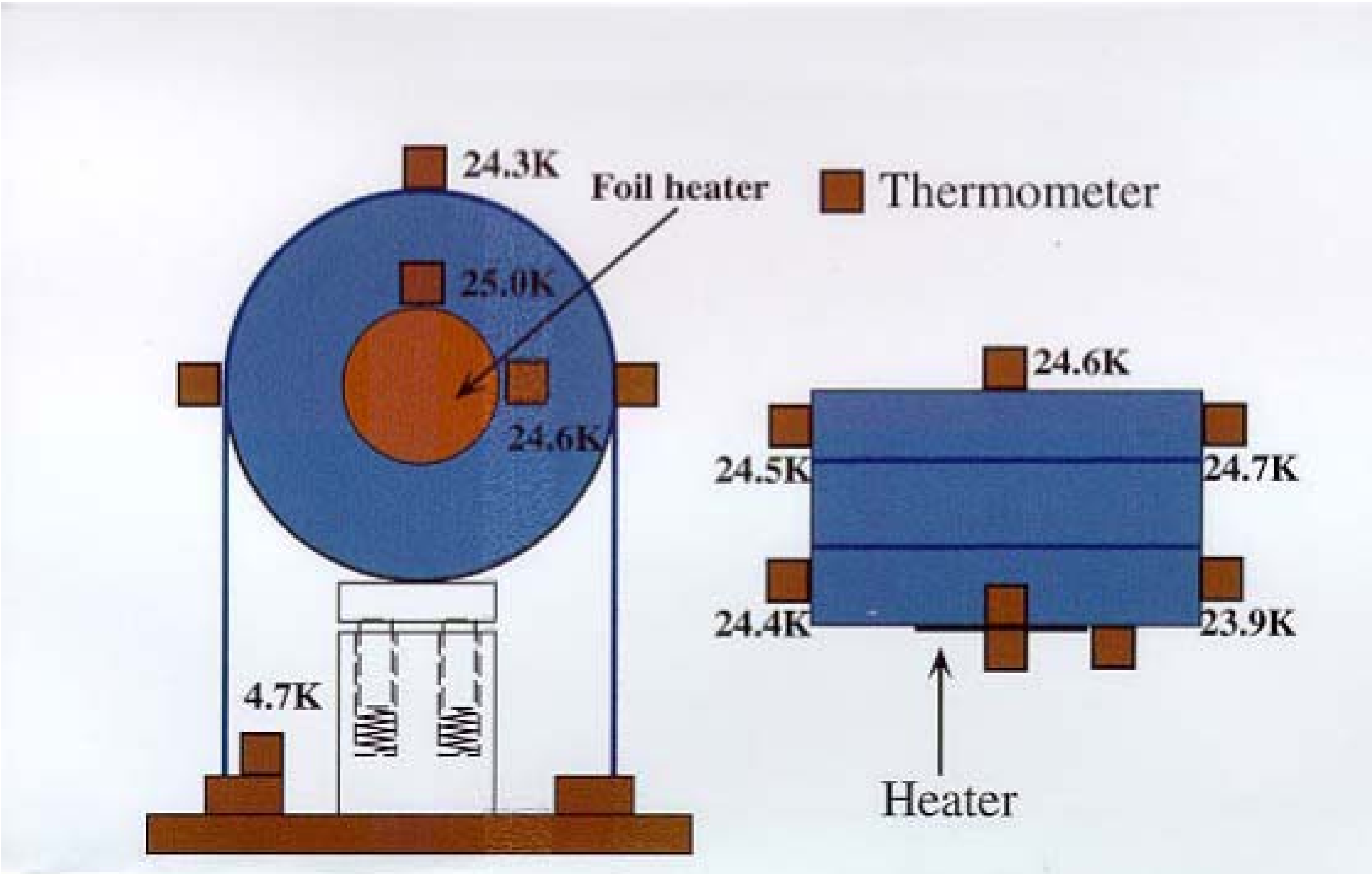
Underground merit is the smaller seismic noise

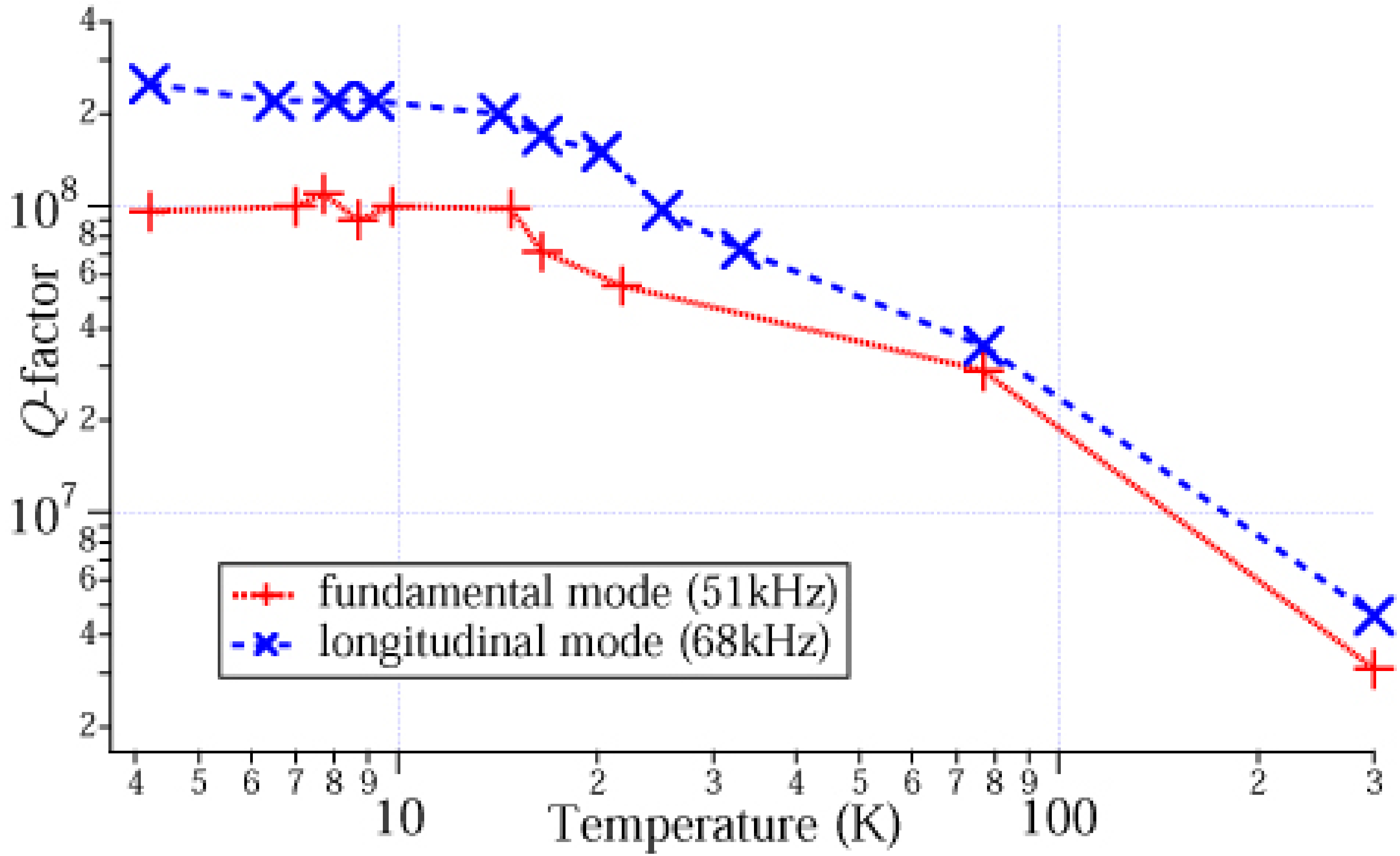


The amplitude is smaller by two orders than that of TAMA site.

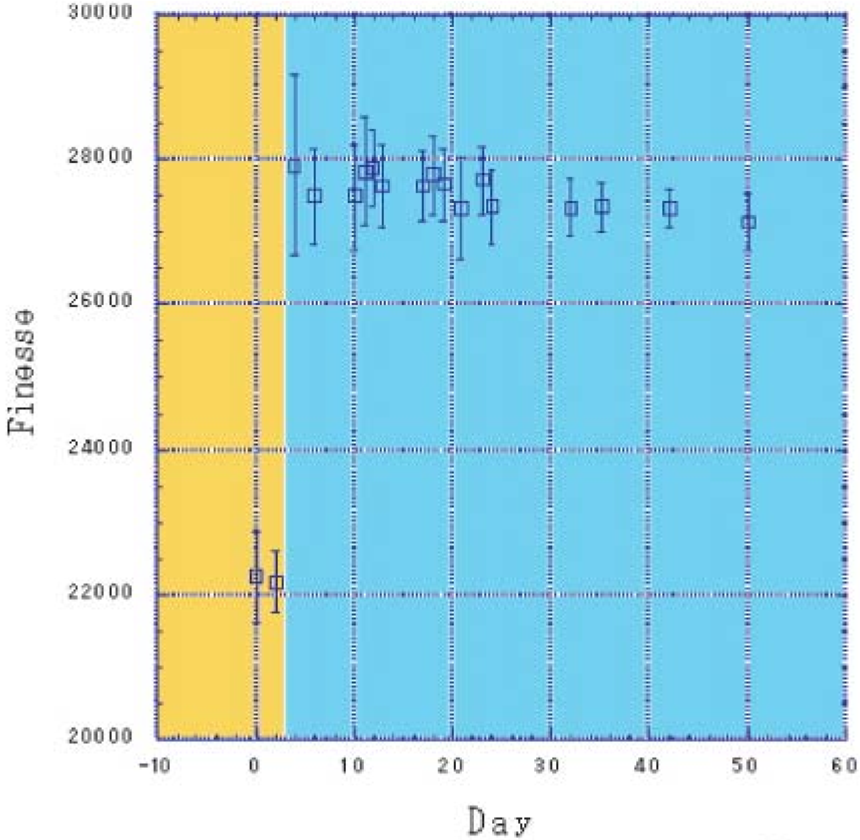
20m prototype interferometer mounted


SAS or similar system
300K-77K
heat link
Vacuum Chamber
77K shield
4.2K
heat link
4.2K shield
Vac. p<10^-6 Pa
25cm
20K
Sapphire Mirror
Reaction
Mass
6cm
Magnetic Shield

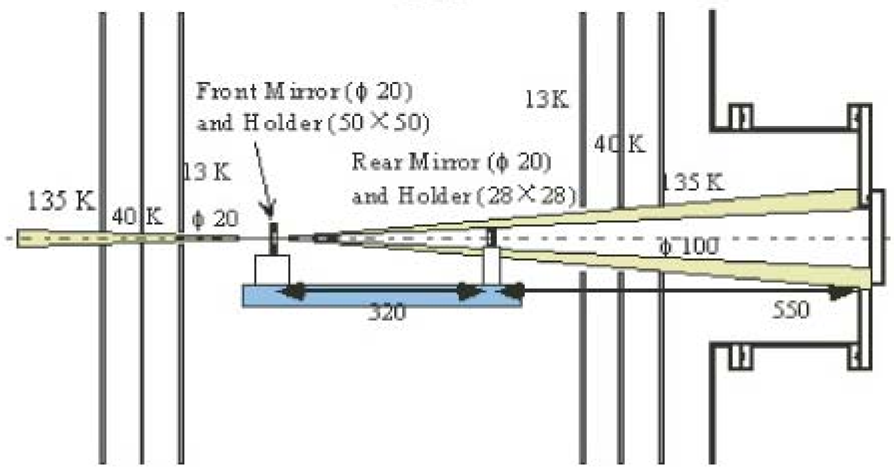

24.3K
Foil heater
Thermometer
25.0K
24.6K
4.7K
24.6K
24.5K
24.7K
24.4K
23.9K
Heater



Q-factor
10^8
10^7
4
2
8
6
4
2
8
6
4
2
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
100
2
3
Temperature (K)
fundamental mode (51kHz)
longitudinal mode (68kHz)

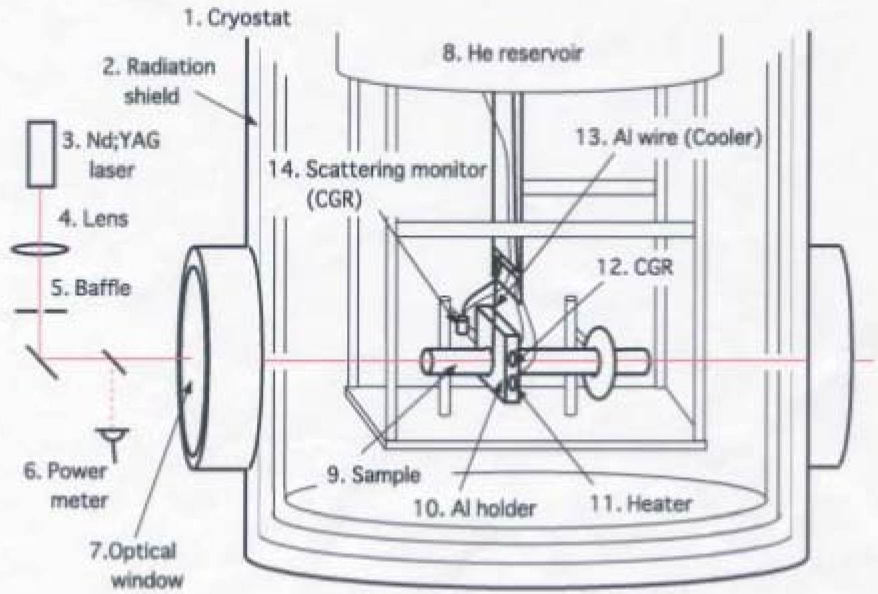


30000
28000
26000
24000
22000
20000
Finesse
-10
0
10
20
30
40
50
60
Day



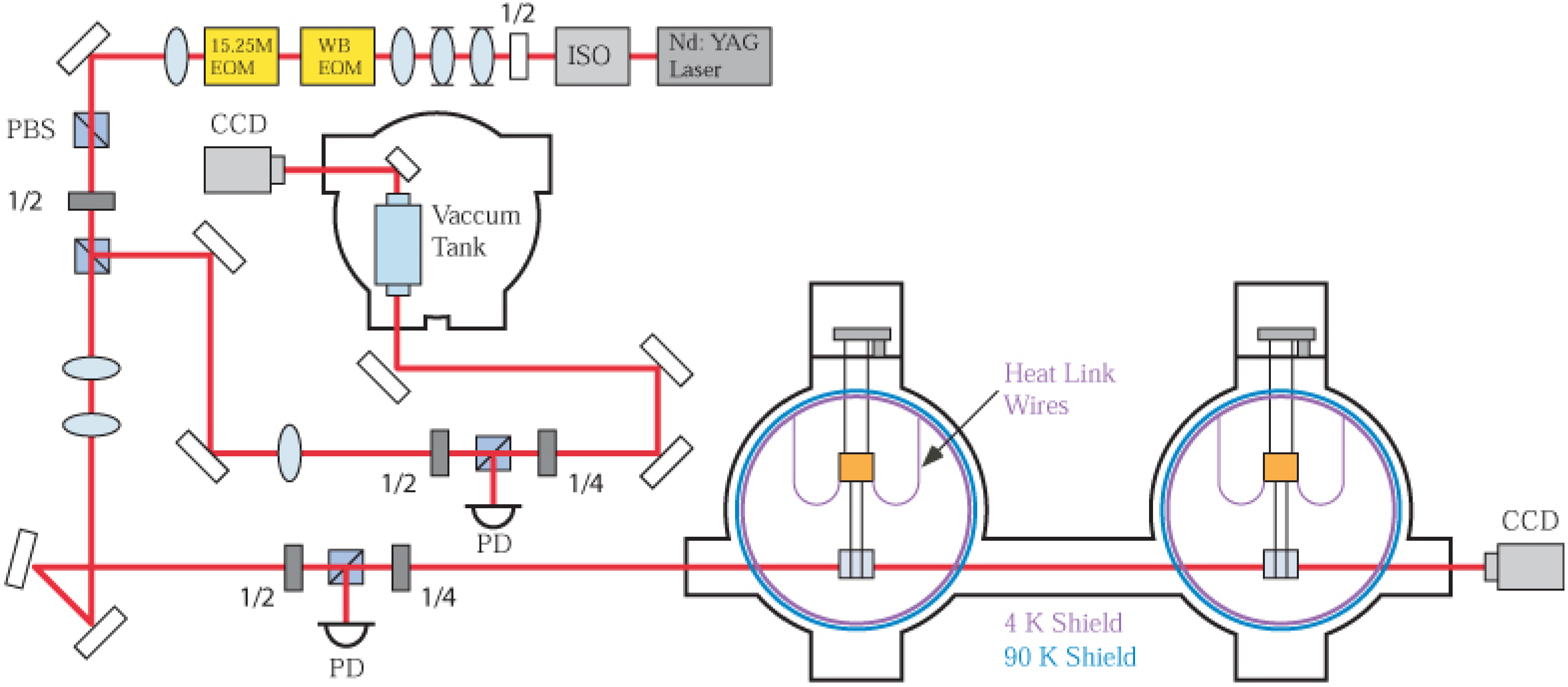
Front Mirror (ϕ 20)
and Holder (50 × 50)
13K
40 K
Rear Mirror (ϕ 20)
and Holder (28 × 28)
13 K
135 K
135 K
40 K
ϕ 20
ϕ 100
320
550

Optical absorption in Sapphire

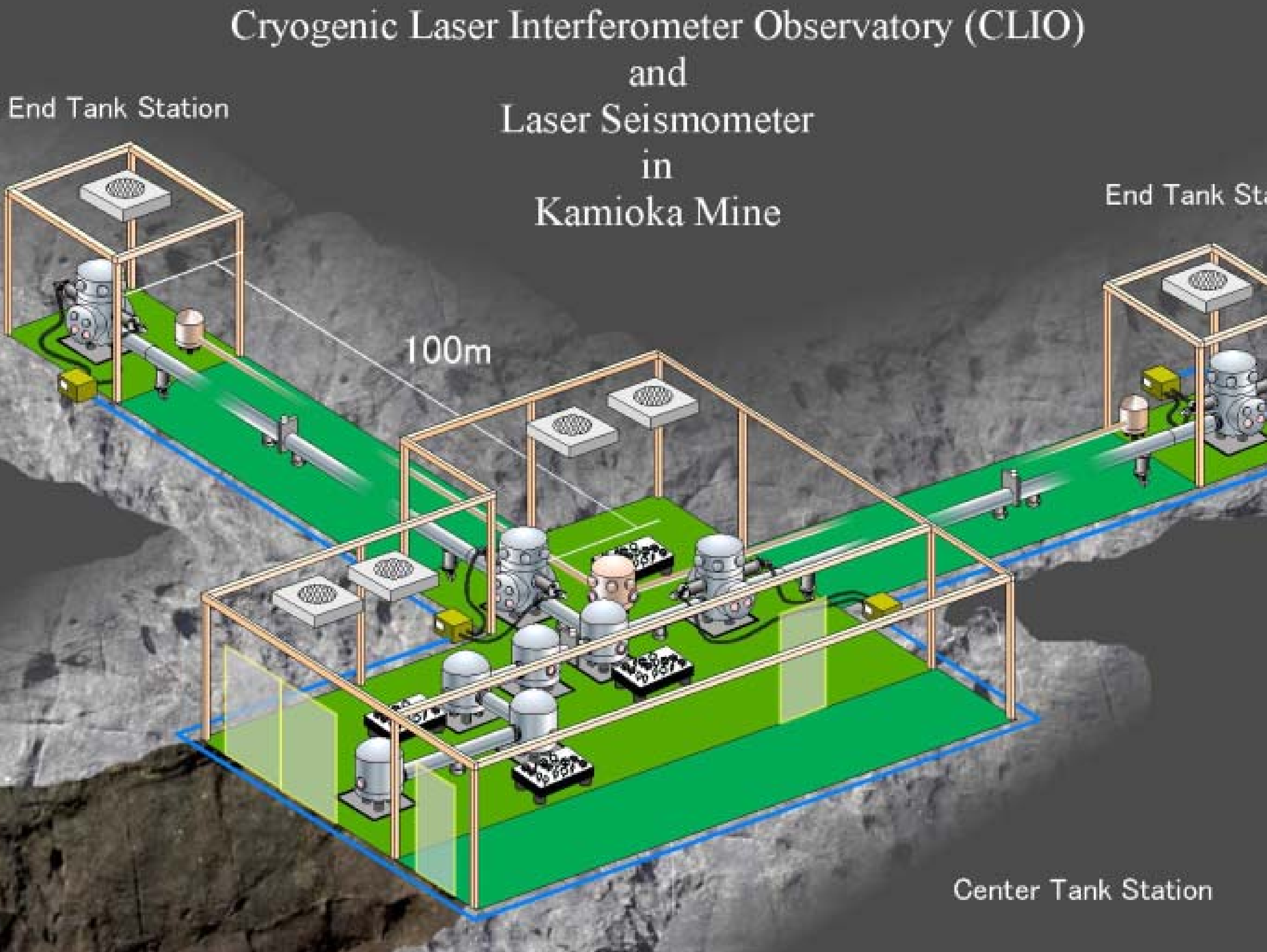


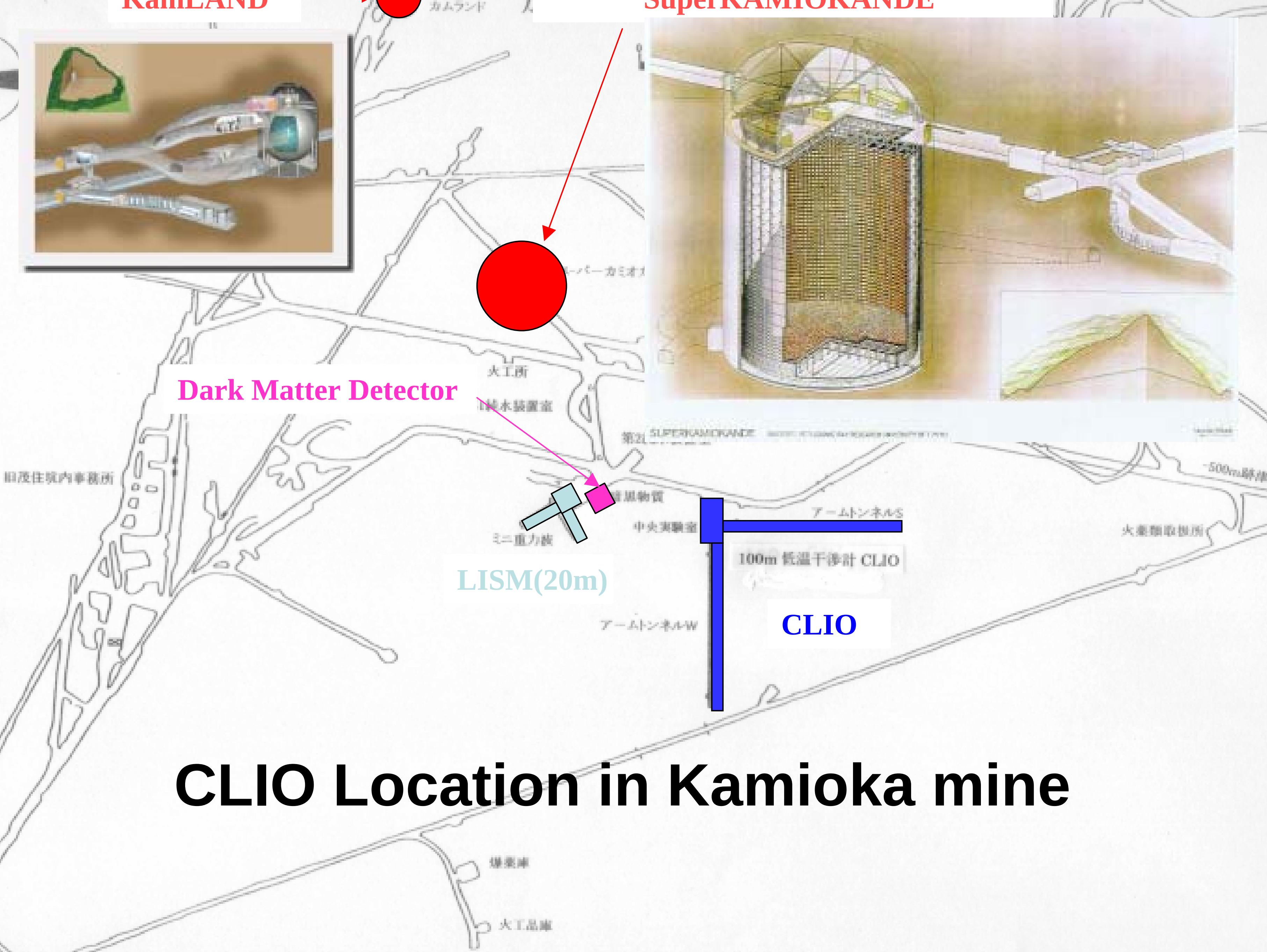
Sample	UWA	Stanford	VIRGO	LCGT (5K)
Hemex	55+-4	140	-	-
Hemlite	-	-	-	90 - 99
CSI White	3.1 - 3.5	120	-	-
CSI White	-	41	-	-
CSI White	-	68	142+-15	-
CSI White	-	58	90+-10	-
CSI White	-	-	-	88 - 93

ppm/cm



1/2
15.25M EOM
WB EOM
ISO
Nd: YAG Laser
PBS
CCD
1/2
Vaccum Tank
1/2
1/4
PD
1/2
1/4
PD
Heat Link Wires
CCD
4 K Shield
90 K Shield

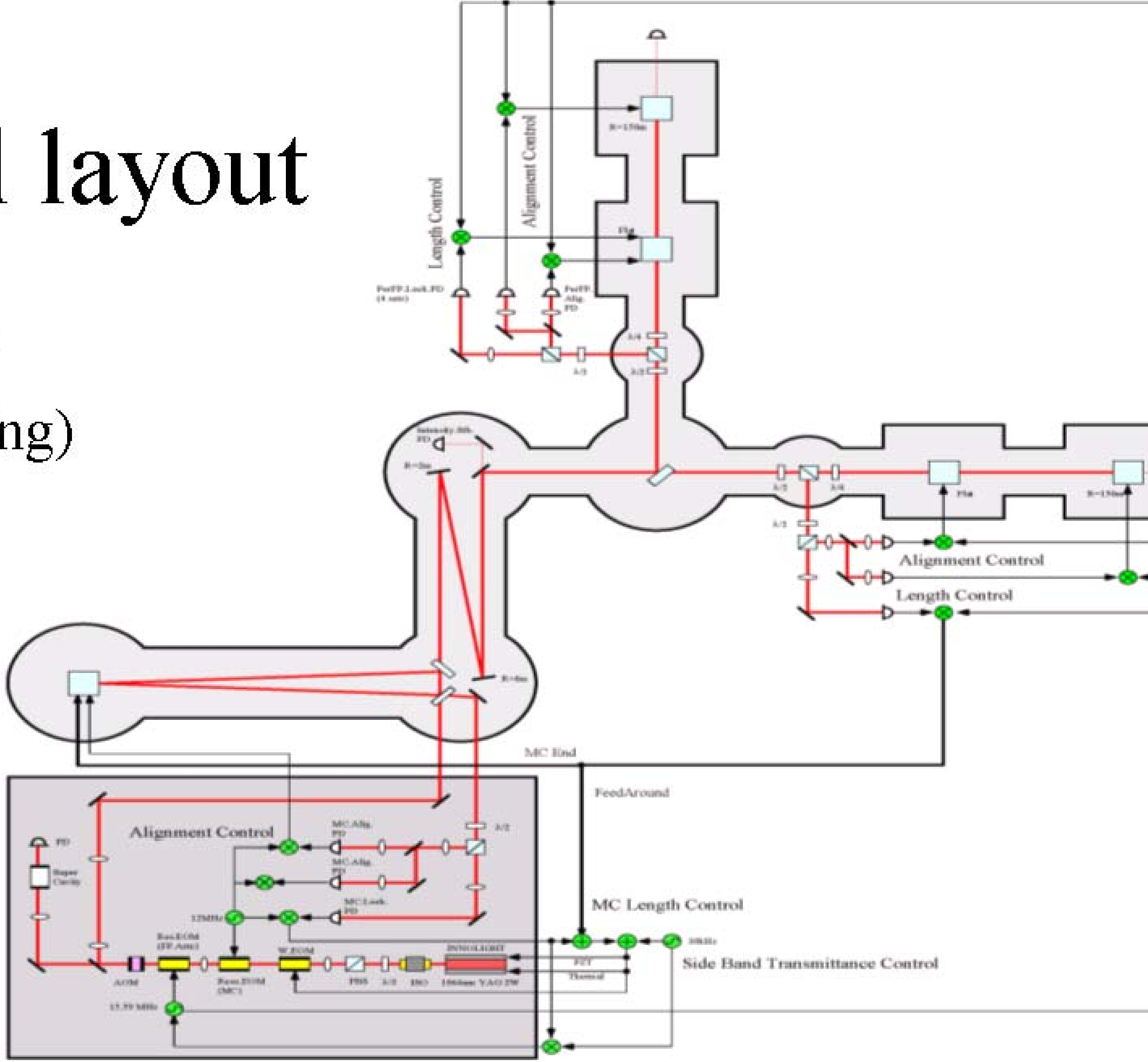

Cryogenic Laser Interferometer Observatory (CLIO)
and
Laser Seismometer
in
Kamioka Mine
End Tank Station
End Tank Sta
100m
Center Tank Station



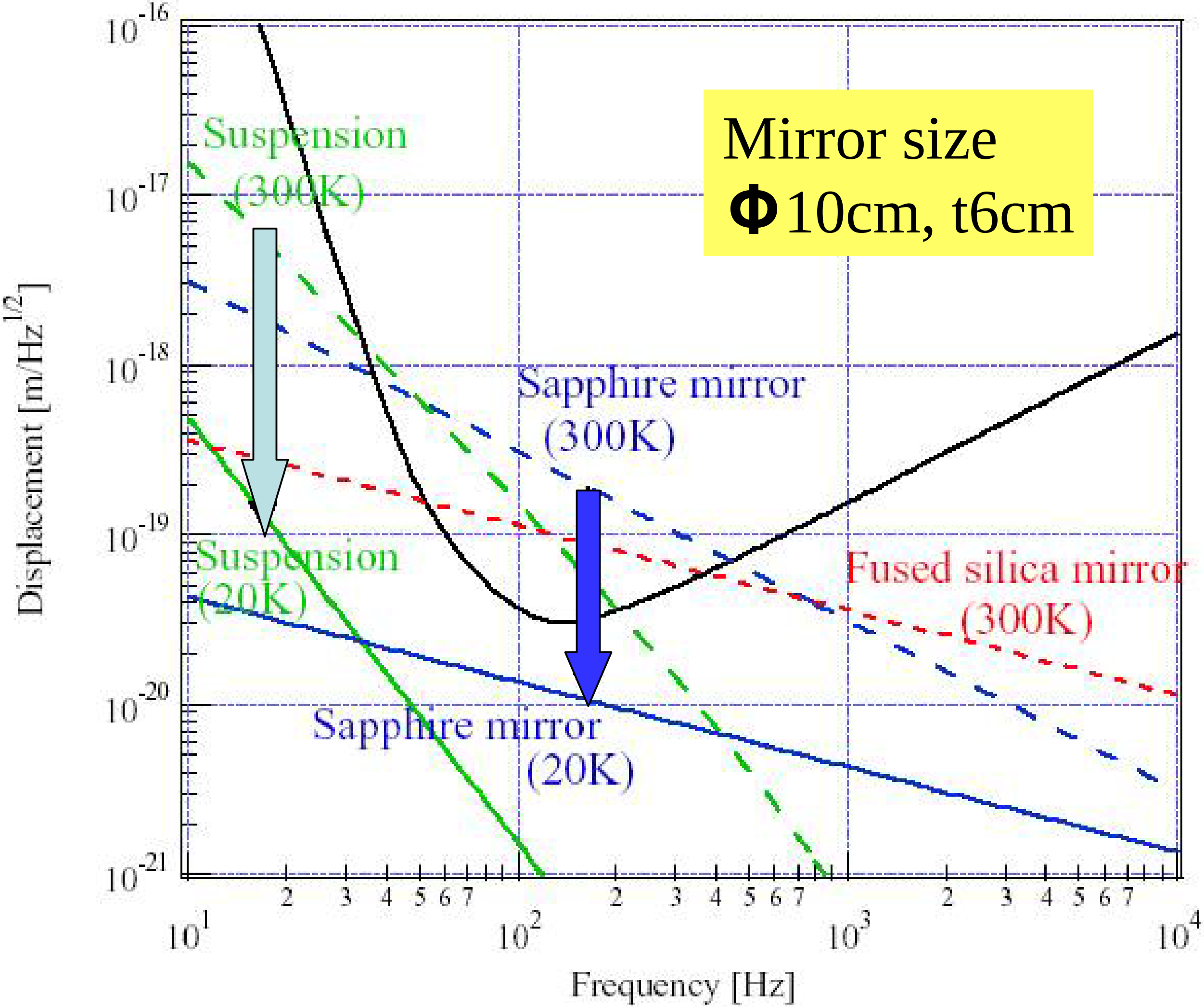
CLIO Location in Kamioka mine

Optical layout

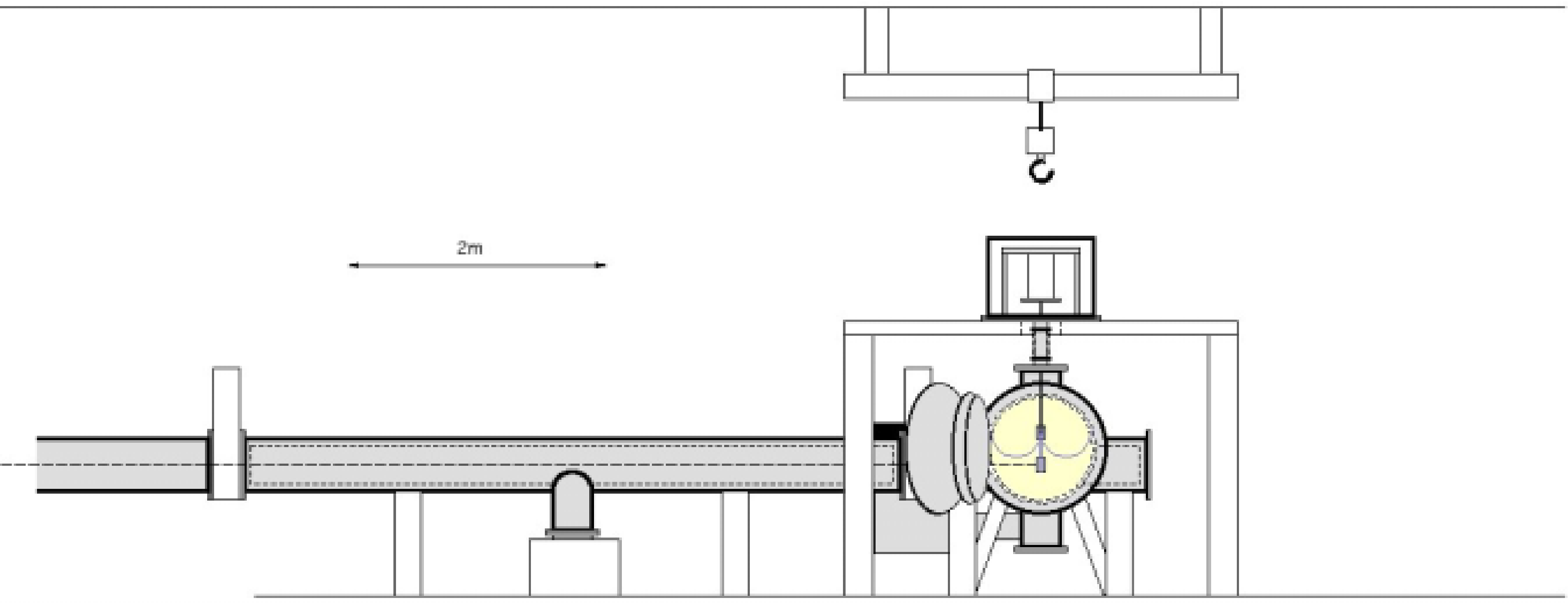
Locked FP
(no recycling)

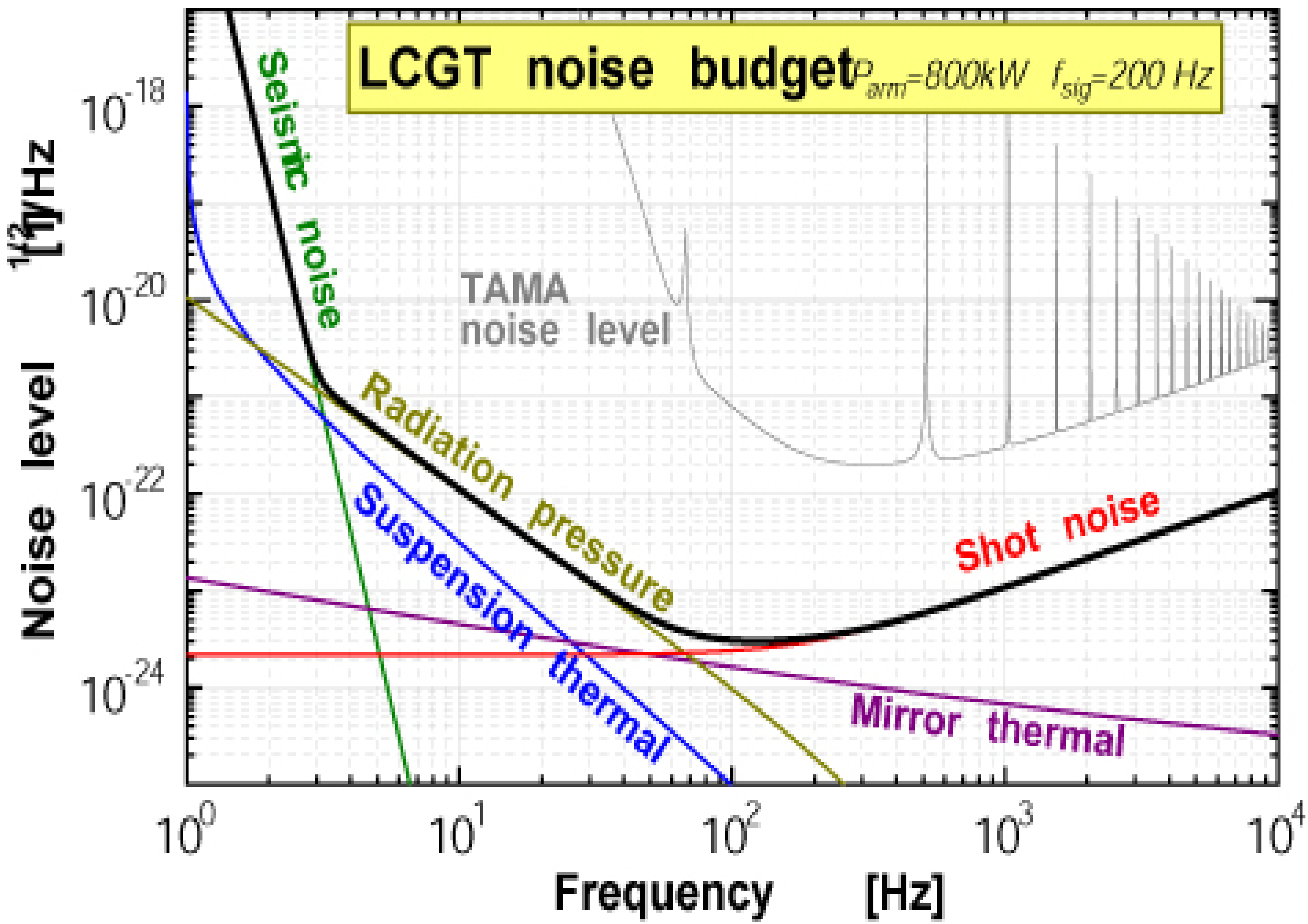


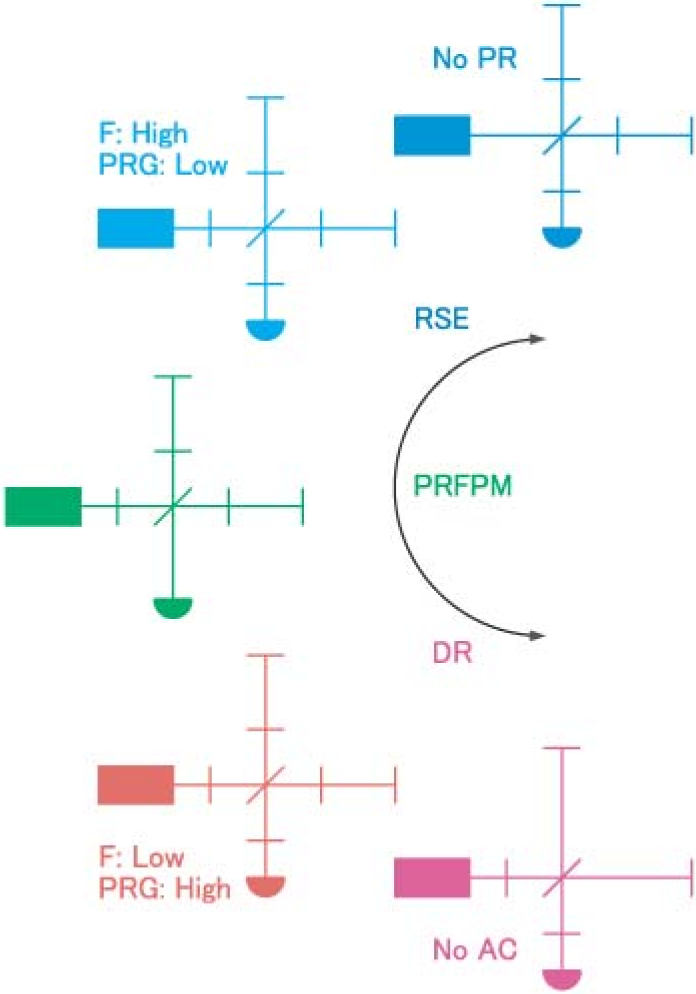
Thermal noise (300K – 20K)

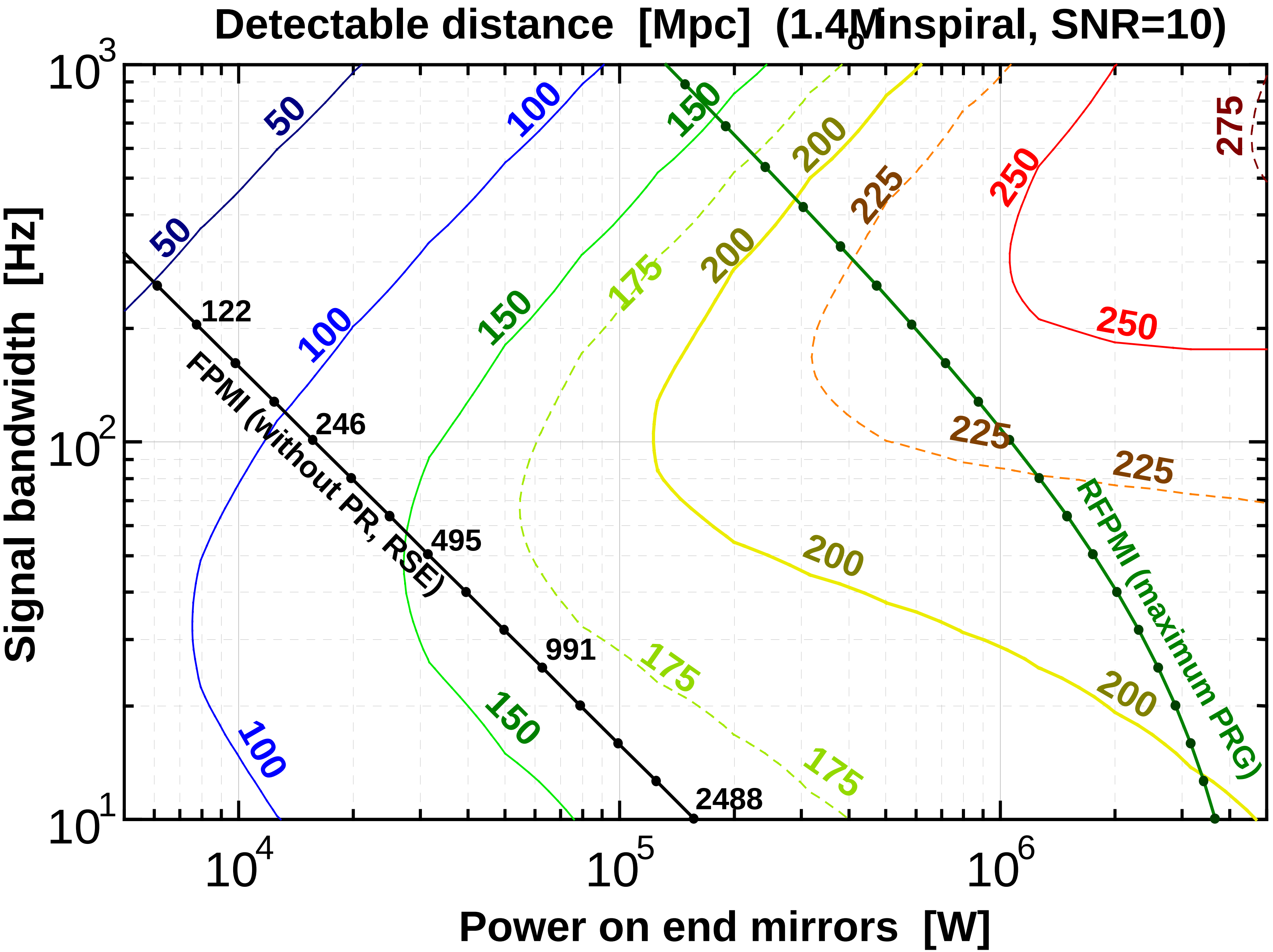


クライオスタット模式図




LCGT noise budget
P_arm=800kW f_sig=200 Hz
Seismic noise
TAMA noise level
Radiation pressure
Suspension thermal
Shot noise
Mirror thermal
Noise level [1/Hz^1/2]
Frequency [Hz]
10^-18
10^-20
10^-22
10^-24
10^0
10^1
10^2
10^3
10^4


No PR
F: High
PRG: Low
RSE
PRFPM
DR
F: Low
PRG: High
No AC

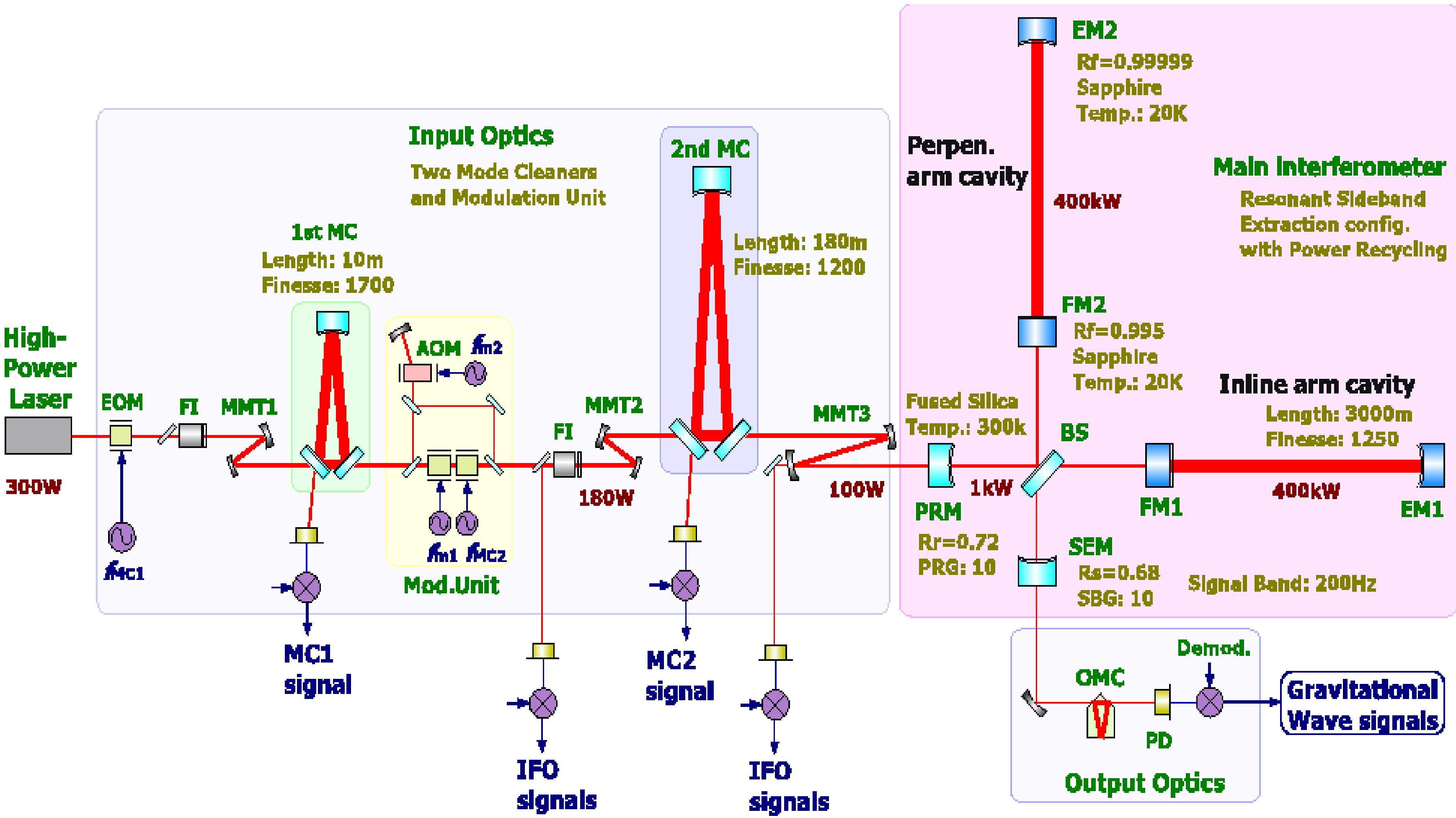


Detectable distance [Mpc] (1.4Mo inspiral, SNR=10)
Signal bandwidth [Hz]
Power on end mirrors [W]
10^3
10^2
10^1
10^4
10^5
10^6
50
50
100
100
100
100
150
150
150
150
175
175
175
200
200
200
200
200
225
225
225
250
250
275
122
246
495
991
2488
FPMI (without PR, RSE)
RFPMI (maximum PRG)

Design detail

- Suspension point interferometer
- Vacuum system
- Suspension system
- Refrigerator system
- Heat link system
- Data acquisition system
- Others

An Optical Design of LCGT interferometer



Optical Design Parameters

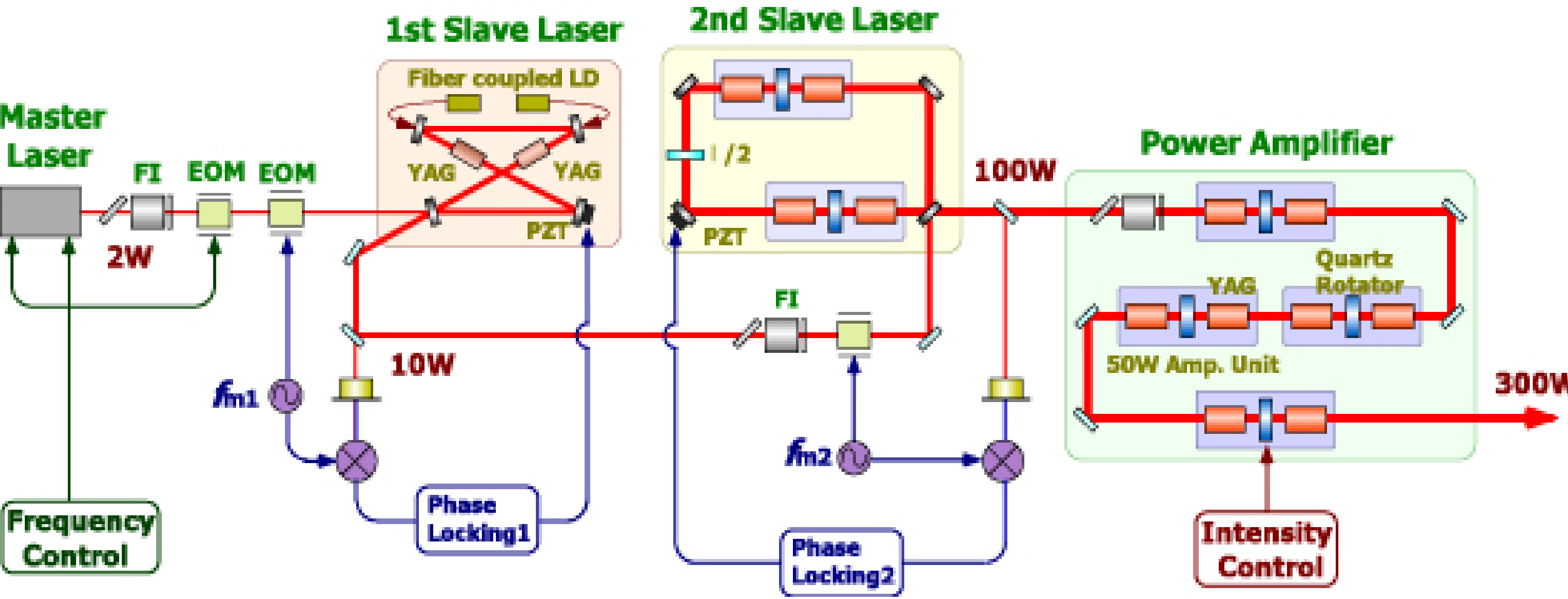
- Main Interferometer
  - Resonant Sideband Extraction
    with power recycling, broad band configuration
  - Arm cavity length 3000 m
  - Power in arm cavities 800 kW
  - Signal bandwidth 200 Hz
  - Arm cavity finesse 1250
  - Power recycling gain 10
  - Signal band gain 10

- Laser source
  - Output power 300W
  - Wavelength 1064nm

- Input optics
  - Power transmittance 33.3%
  - Modulation sidebands 15 MHz, 50 MHz
    1st Mode cleaner 10m Triangle ring cavity, 4.5kHz, FSR 15 MHz
    2nd Mode cleaner 180m Triangle ring cavity, 350Hz, FSR833kHz
- Core optics
  - Main Mirror: sapphire, 20K, 30cm, 18cm, 50kg
  - Substrate optical loss 500ppm/18cm; heat absorption 20ppm/cm

- PRM, SEM, BS, MC mirrors: Fused silica

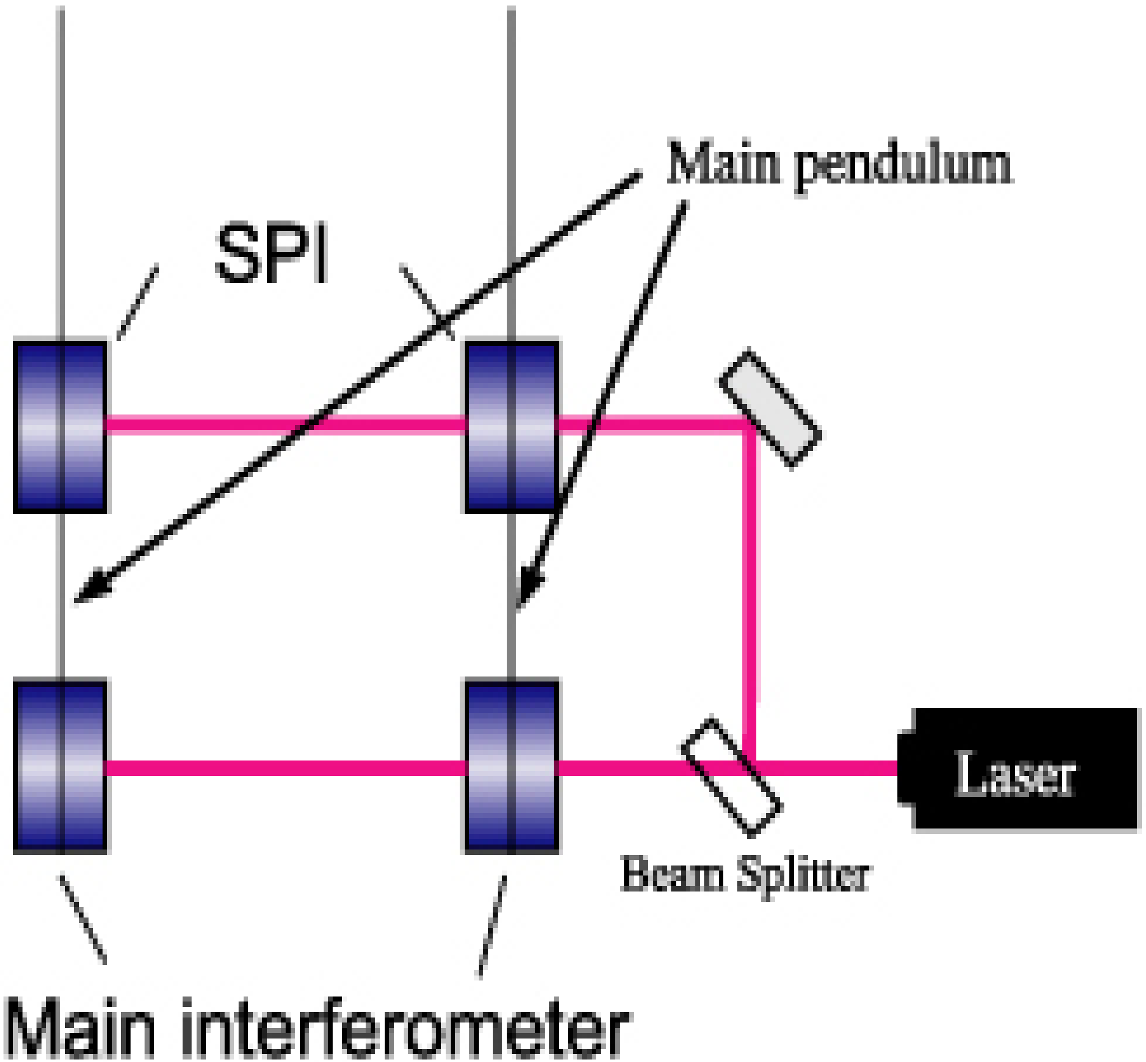
LCGT Laser (300W)

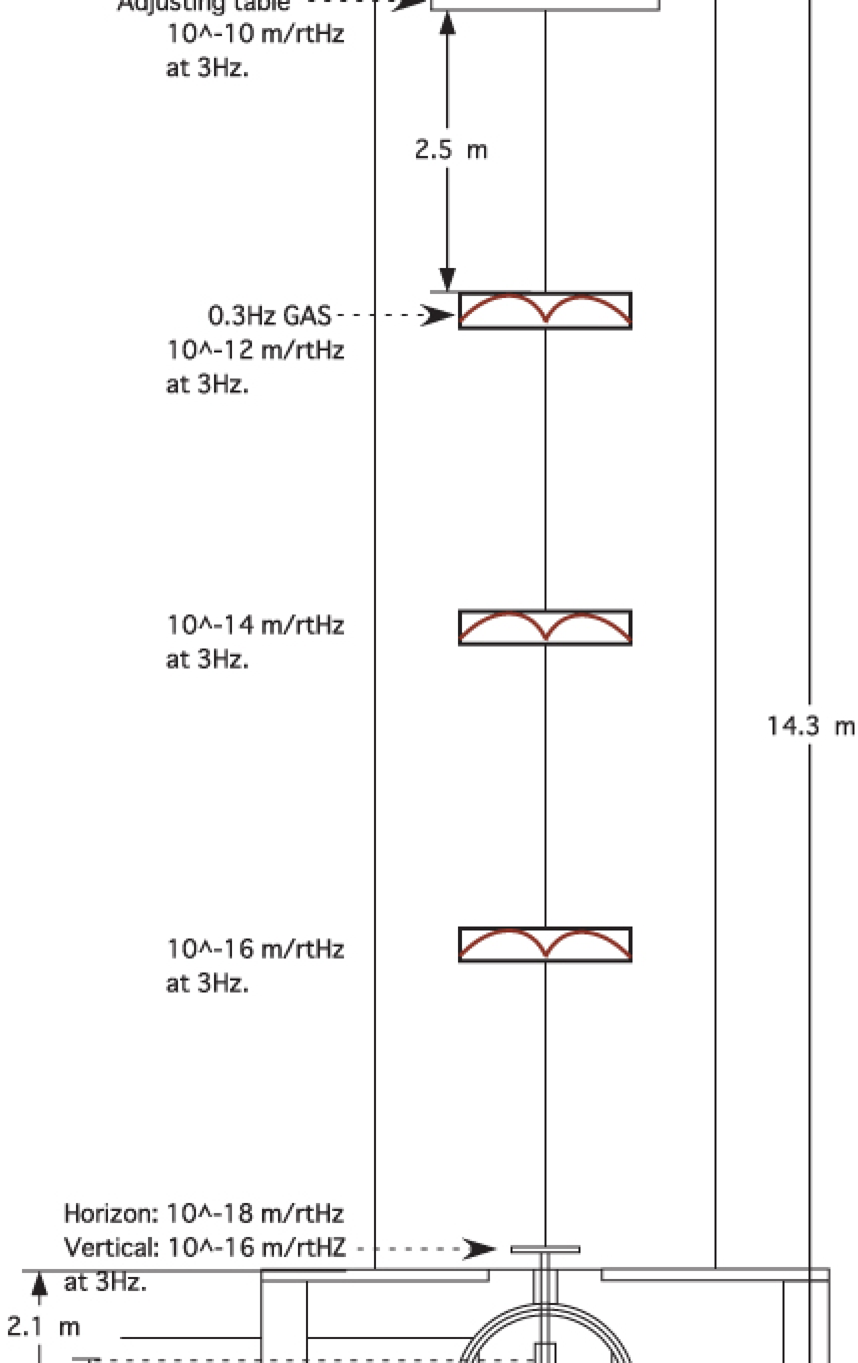


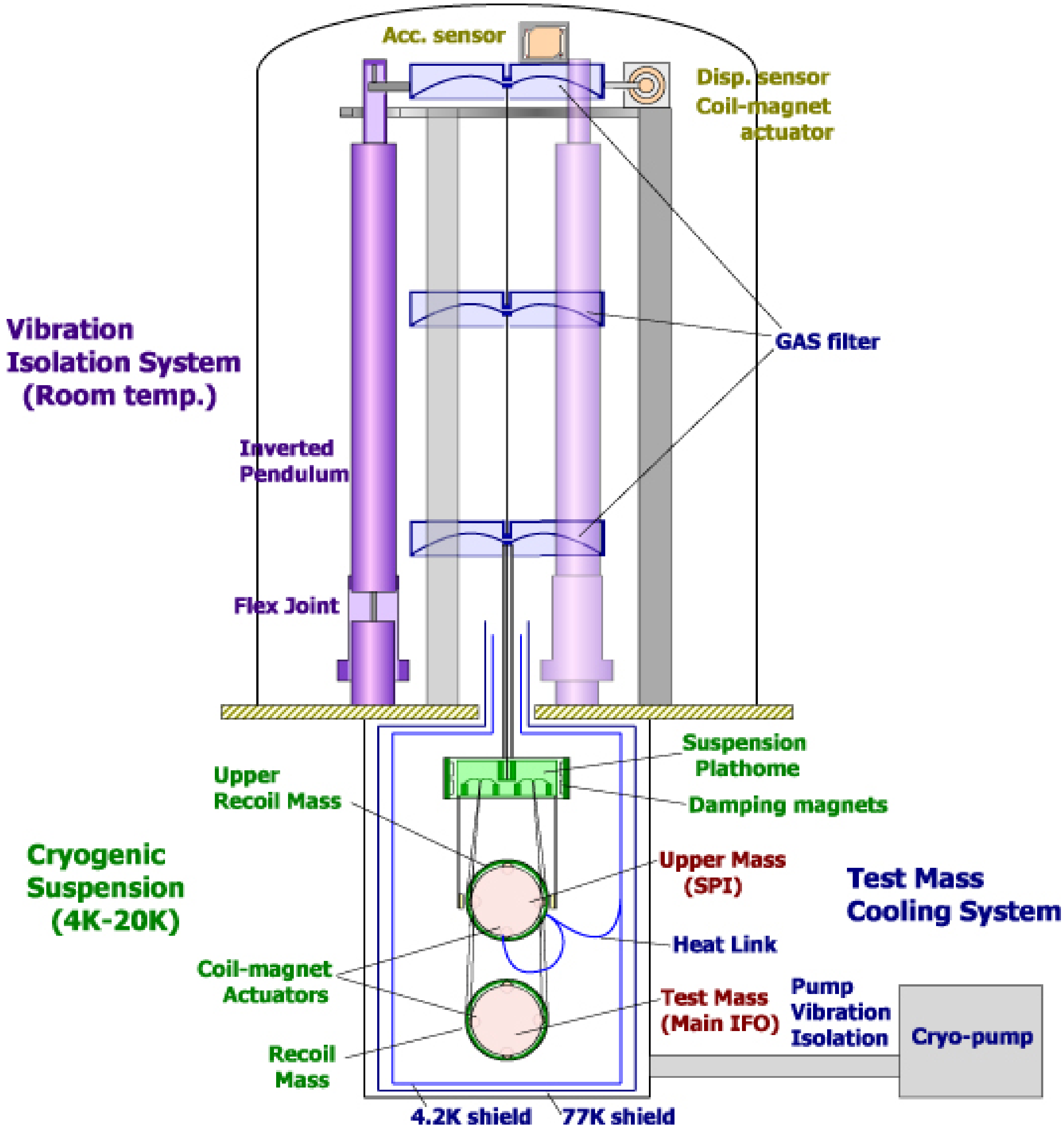
Vacuum System

- Pressure
  - $2X10^{-7}$ Pa
- Ducts
  - Total length 3km
  - 1.2m Diameter
  - 11m Unit
  - Titanium or Stainless steel
- Pumps
  - 10 Root pumps
  - 30 Turbo molecular pumps or 10 Cryopumps
  - 30 Ion pumps
- Optical Buffles
  - 10cm Height
  - Made by M2052
  - DLC (diamond likecarbon)
  - 80 pieces

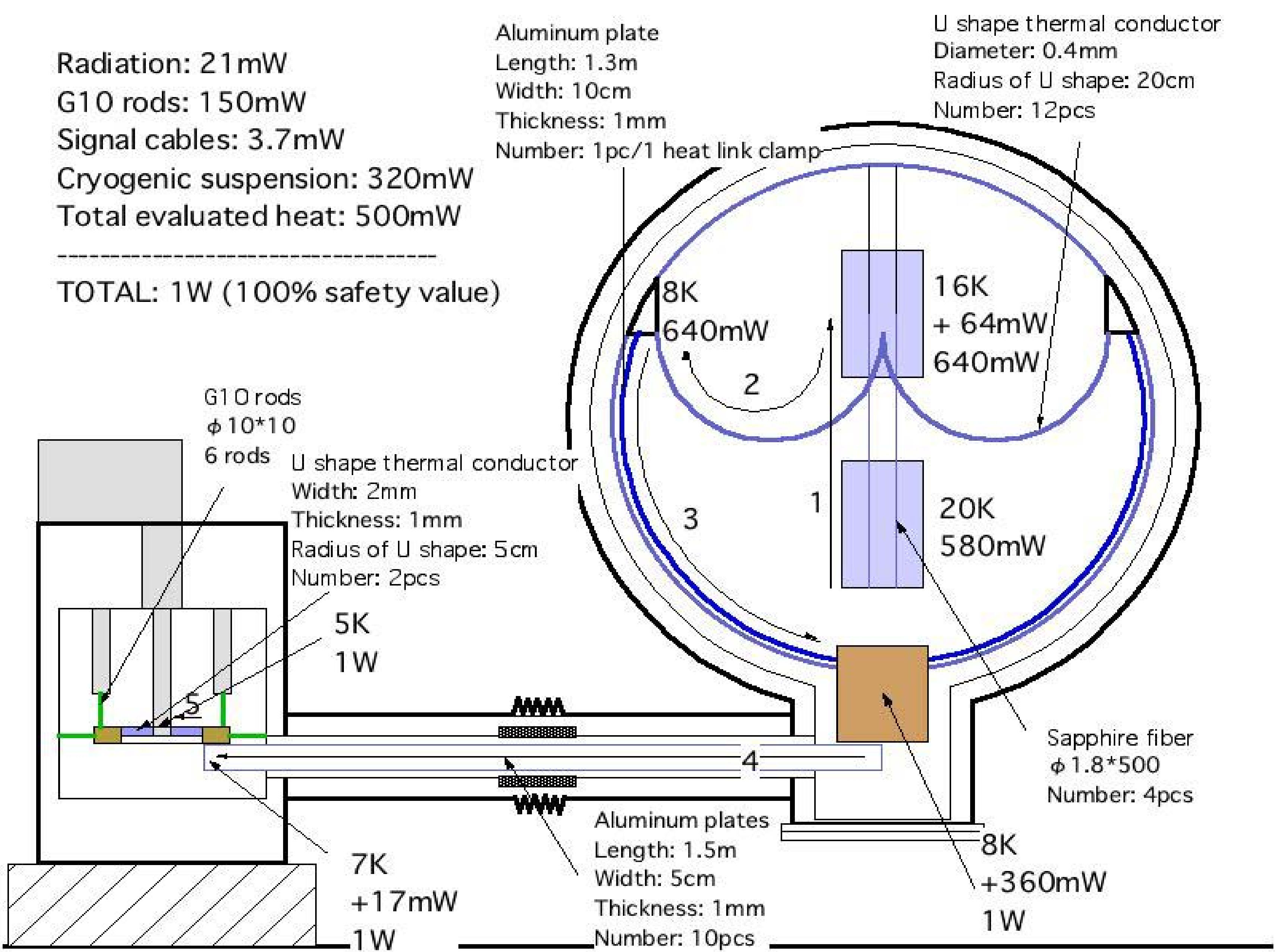
Test mass of LCGT is connected to a cooling system by a heat link that introduces mechanical noise. A suspension point interferometer is introduced to maintain high attenuation of seismic and mechanical noise without degrading high heat conductivity.



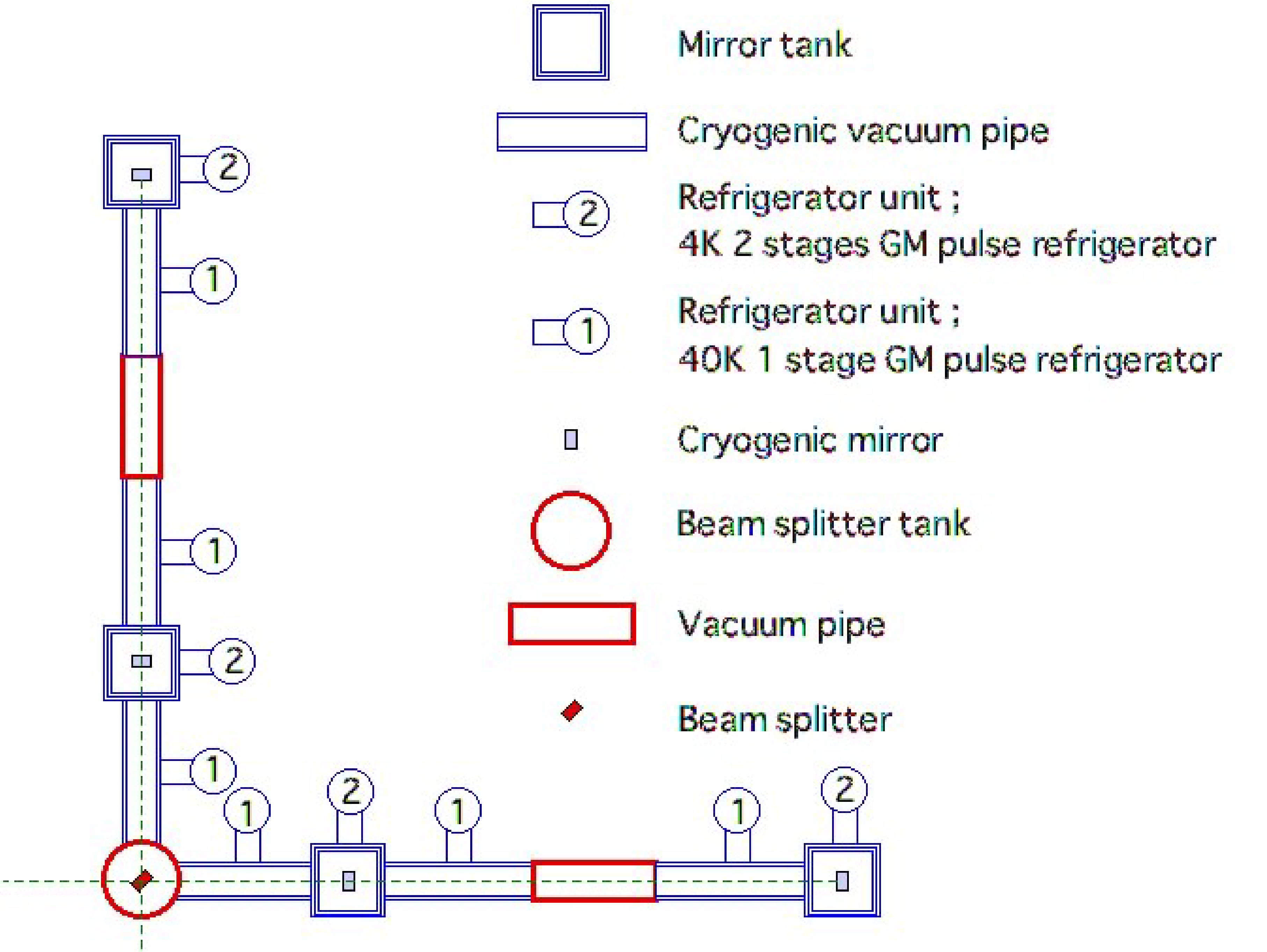

Adjusting table
10^-10 m/rtHz
at 3Hz.
2.5 m
0.3Hz GAS
10^-12 m/rtHz
at 3Hz.
10^-14 m/rtHz
at 3Hz.
14.3 m
10^-16 m/rtHz
at 3Hz.
Horizon: 10^-18 m/rtHz
Vertical: 10^-16 m/rtHZ
at 3Hz.
2.1 m



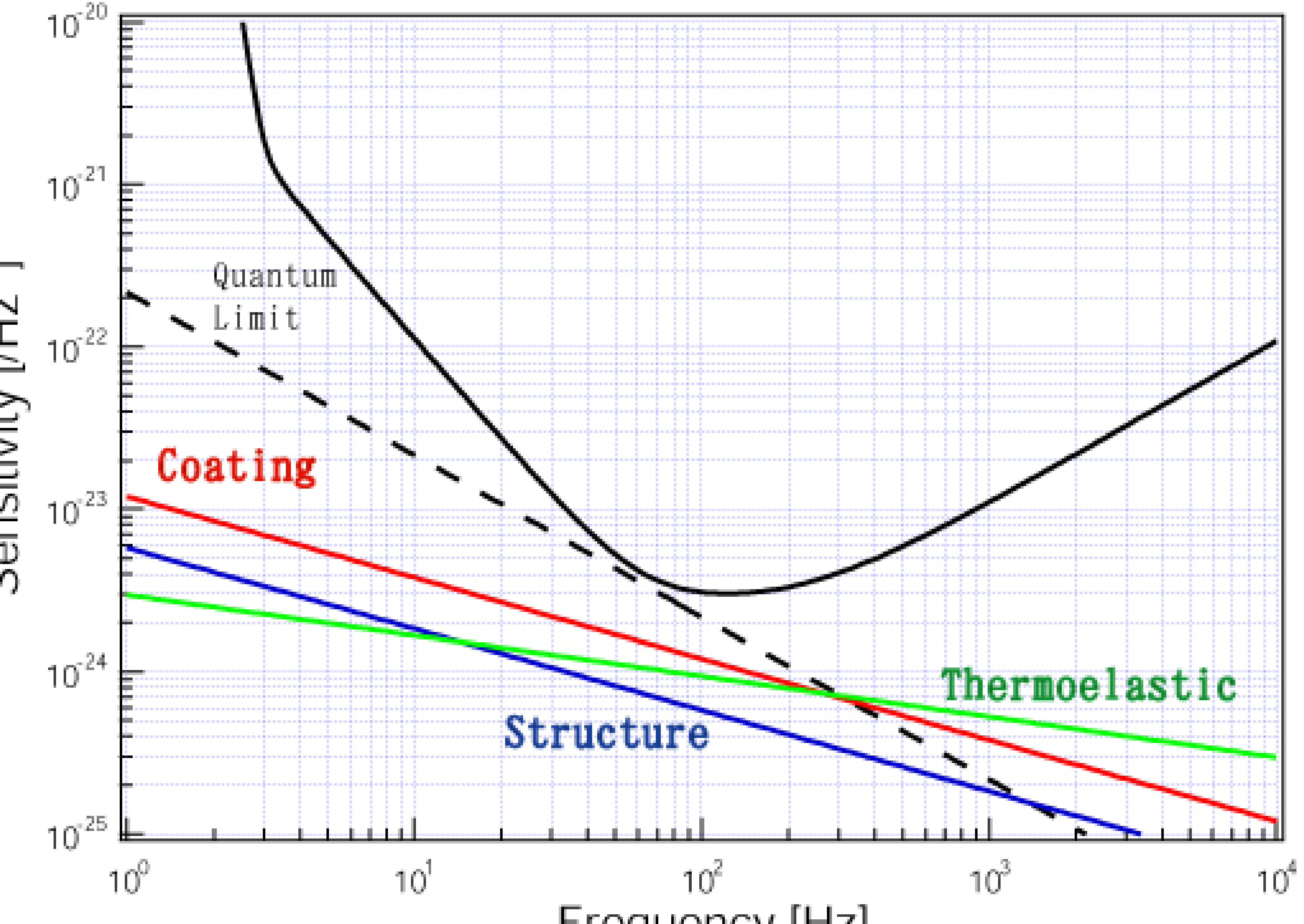
Acc. sensor
Disp. sensor
Coil-magnet actuator
GAS filter
Vibration Isolation System (Room temp.)
Inverted Pendulum
Flex Joint
Suspension Plathome
Damping magnets
Upper Recoil Mass
Cryogenic Suspension (4K-20K)
Upper Mass (SPI)
Test Mass Cooling System
Heat Link
Coil-magnet Actuators
Test Mass (Main IFO)
Pump Vibration Isolation
Cryo-pump
Recoil Mass
4.2K shield
77K shield



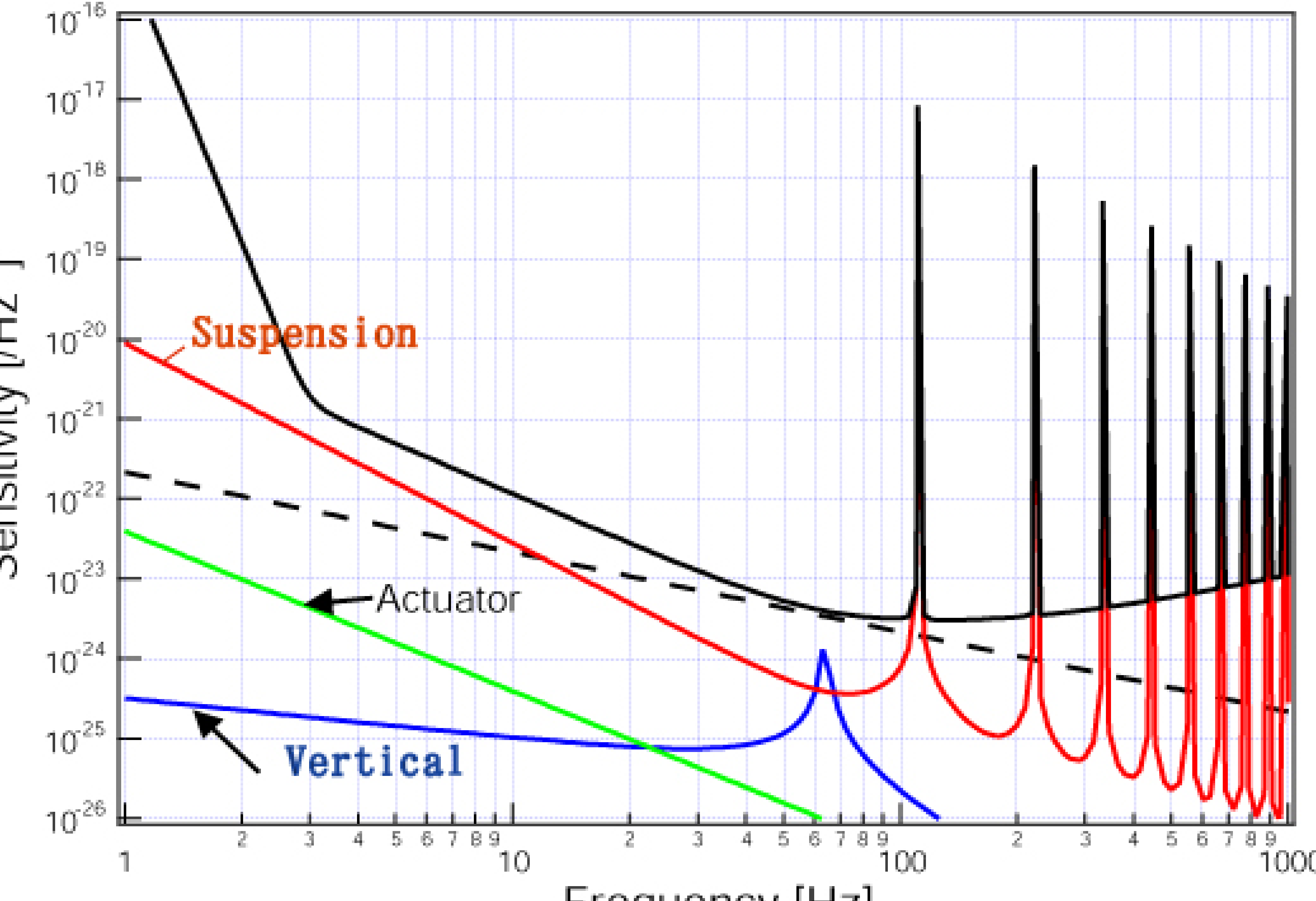
Radiation: 21mW
G10 rods: 150mW
Signal cables: 3.7mW
Cryogenic suspension: 320mW
Total evaluated heat: 500mW
TOTAL: 1W (100% safety value)
Aluminum plate
Length: 1.3m
Width: 10cm
Thickness: 1mm
Number: 1pc/1 heat link clamp
U shape thermal conductor
Diameter: 0.4mm
Radius of U shape: 20cm
Number: 12pcs
8K
640mW
16K
+ 64mW
640mW
2
G10 rods
ϕ10*10
6 rods
U shape thermal conductor
Width: 2mm
Thickness: 1mm
Radius of U shape: 5cm
Number: 2pcs
3
1
20K
580mW
5K
1W
5
4
Sapphire fiber
ϕ1.8*500
Number: 4pcs
Aluminum plates
Length: 1.5m
Width: 5cm
Thickness: 1mm
Number: 10pcs
7K
+17mW
1W
8K
+360mW
1W


Mirror tank
Cryogenic vacuum pipe
Refrigerator unit ;
4K 2 stages GM pulse refrigerator
Refrigerator unit ;
40K 1 stage GM pulse refrigerator
Cryogenic mirror
Beam splitter tank
Vacuum pipe
Beam splitter
1
2

Thermal noise of mirror (LCGT)



Thermal Noise of Suspension (LCGT)



Fake elimination using parallel Interferometers

- Assumption of the TAMA fake event << 1 / 1hour
- Coincidence analysis of two identical interferometer placed side by side
- Probability detecting noise within ±Δt is p^2 Δt
- Δt〜0.5ms×3
- Expected rate of the signal event is assumed as 1event/year ->3×10^{-8} /s
- p^2 Δt < 0.27% × {8×10^{-8}}= 8×10^{-11} / s = 2.7×10^{-3} / year
- p< 2.3×10^{-4} = 1 / (1.2 hour)

LCGT Man Power

• ICRR	5 +3
• NAO	8 +1
• KEK	9 +0
• Physics Dept, UT	2 +5
• Material science Dept, UT	2 +2
• ILS, UEC	2 +0
• ERI	1
• Kyoto University	2
• Osaka University	1
• Osaka City University	1 + **α**
• Niigata University	1+1
	34 +11 + **α**

Estimated budget (to be revised)

• Tunnel Construction	3400	M JpnYen
• Vacuum system	12100	
• Cryogenics	400	
• Optics	800	
• Suspension system	260	
• Laser system	400	
• Control system	100	
• Computer	200	
• Others	340	
Total	18000	

Summary

- Steady R&D for LCGT
- Practical test of cryogenic technique by CLIO
- Result of TAMA
  - World record of sensitivity & observation time
  - Successful collaboration of different organization
- Plural interferometers to assure the detection of GW