# Plan of Lectures

**"Introduction to gravitational wave detection experiment and the status of LCGT"**

**Masaki Ando** (Department of Physics, Kyoto University)

⇨ **Lecture (I) Ground-based detector : LCGT**

**Lecture (II) Space-borne detector : DECIGO**

**Lecture (III) Novel type detector : TOBA**

Plan will be changed at your request!

# Ground based detector : LCGT

**Masaki Ando**
(Department of Physics,
Kyoto University)

On behalf of
the LCGT Collaboration

APCTP2011 (August 1, 2011, Pohang, Korea)

1. Introduction
2. Conceptual Design
3. Design
4. R&D, CLIO
5. Schedule
6. Summary

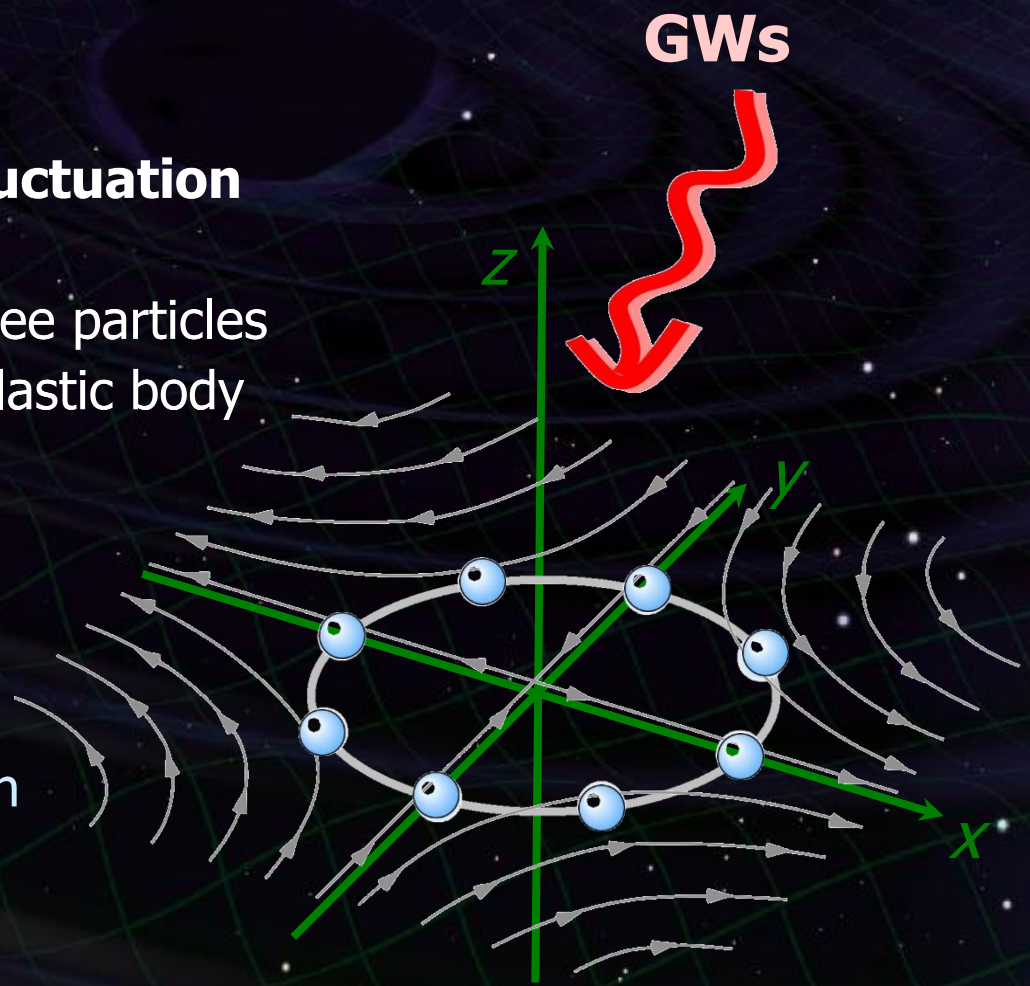
# Introduction

# Effect of gravitational waves

**Effect of GWs : Tidal force fluctuation**

appears as …

- Distance change between free particles
- Tidal forces for finite-sized elastic body




GW amplitude $h$ : strain

$h = 10^{-21}$

→ $10^{-21}$m length fluctuation for 1-m baseline

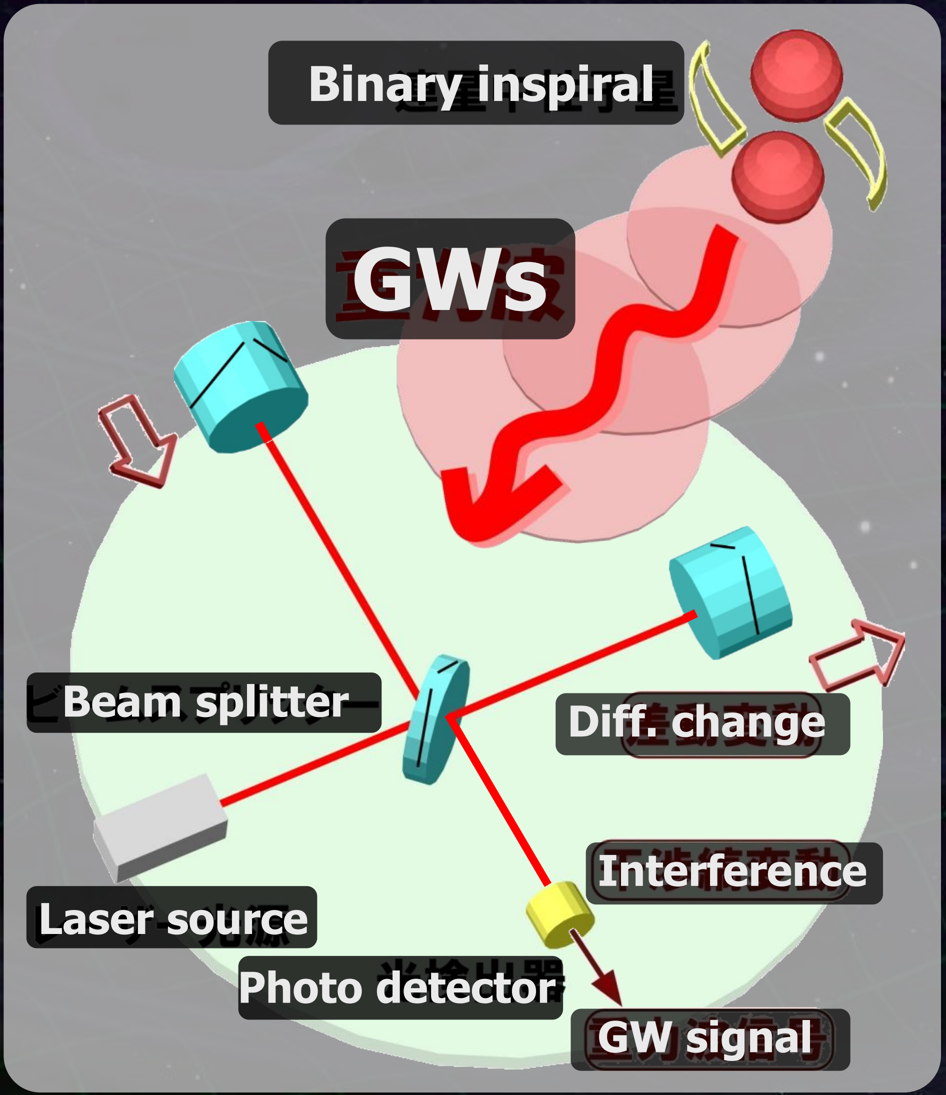
# Laser interferometric detector

**Michelson interferometer**
Separate input beam into two orthogonal direction

Each beam is reflected back by a suspended mirror
→ Interference at beam splitter

**When GW comes…**

Differential length changes are detected at photo detector



# First generation detectors

**Trial for GW detection --- Began in 1960s (Bar detectors)**

→ First-generation large-scale interferometers (1999-)

LIGO (USA), VIRGO, GEO (Europe), TAMA (JPN)


Global observation network

Observation data over 1 year, Scientific outcomes

Neutron-star binary: Observable range ~20Mpc

→ Cover our galaxy and nearby galaxies

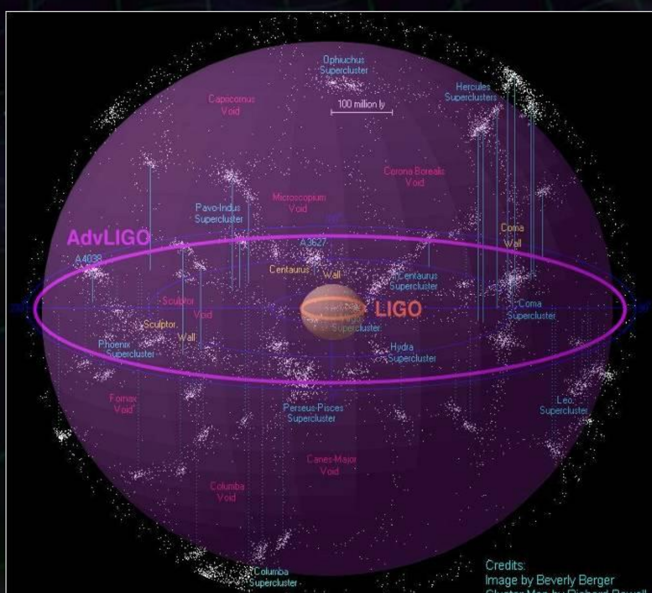
# Expanding the Horizon

**First-gen. GW detectors : ~ 20Mpc obs. range**

However... we can expect only rare events ($10^{-4}$-$10^{-2}$ event/yr)

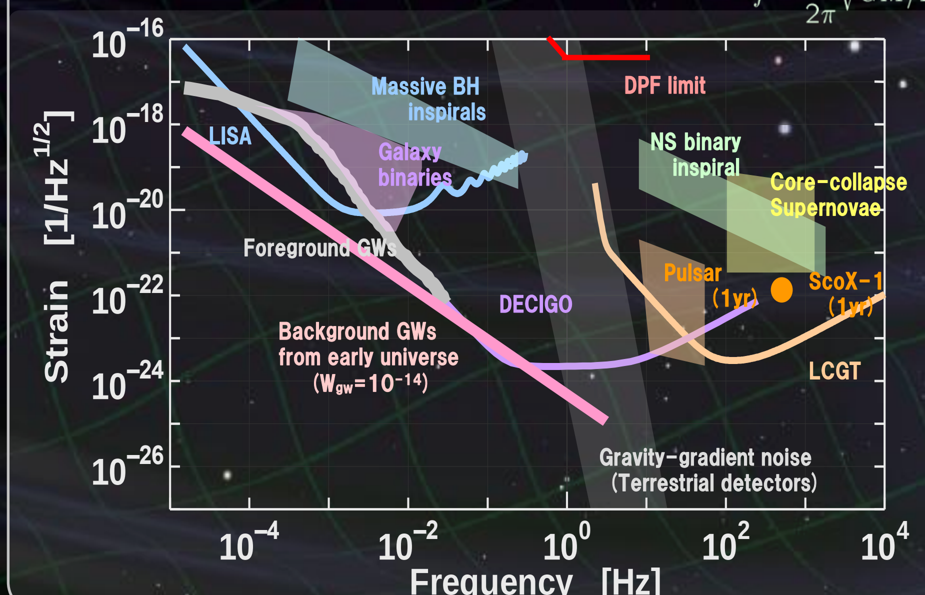
⇨ **Next generation detectors**

Better sensitivity to cover more galaxies




Wider observation band for various sources

$$f \sim \frac{1}{2\pi}\sqrt{GM/R^3}$$



# Improving the sensitivity

**$2^{nd}$-generation detectors --- x10 sensitivity**

GW amplitude $\propto$ 1/(distance)

⇩

Sensitivity x10

→ GW event rate $x10^3$


Expected science

1-year obs. by $1^{st}$-gen. detector

~ 9-hour obs. by $2^{nd}$-gen. detector

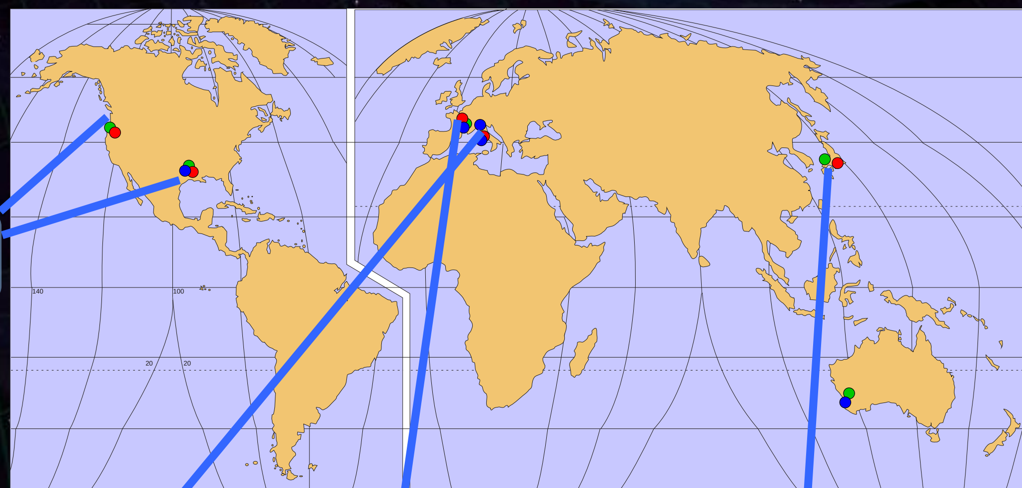
**Event rate > 1 event/year in $2^{nd}$-generation detectors**

# Second generation detectors

**$2^{nd}$-generation detector network** (~5 years from now)

GW astronomy : confident detection, source direction,
scientific information on sources

**aLIGO (USA)**
**4km x 2 (or3)**

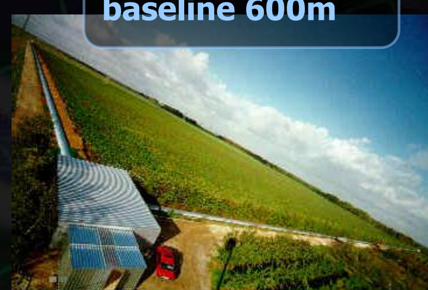


**LIGO-Austreria**
**in proposal**

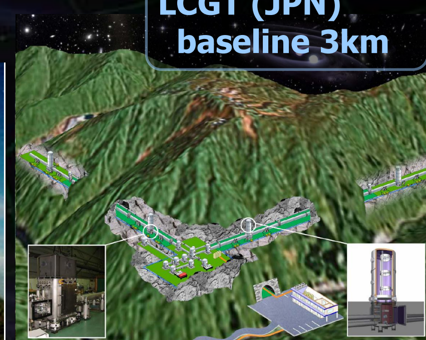
**LIGO-India**
**in proposal**

**Adv.VIRGO (ITA-FRA)**
**baseline 3km**

**GEO-HF (GER-UK)**
**baseline 600m**



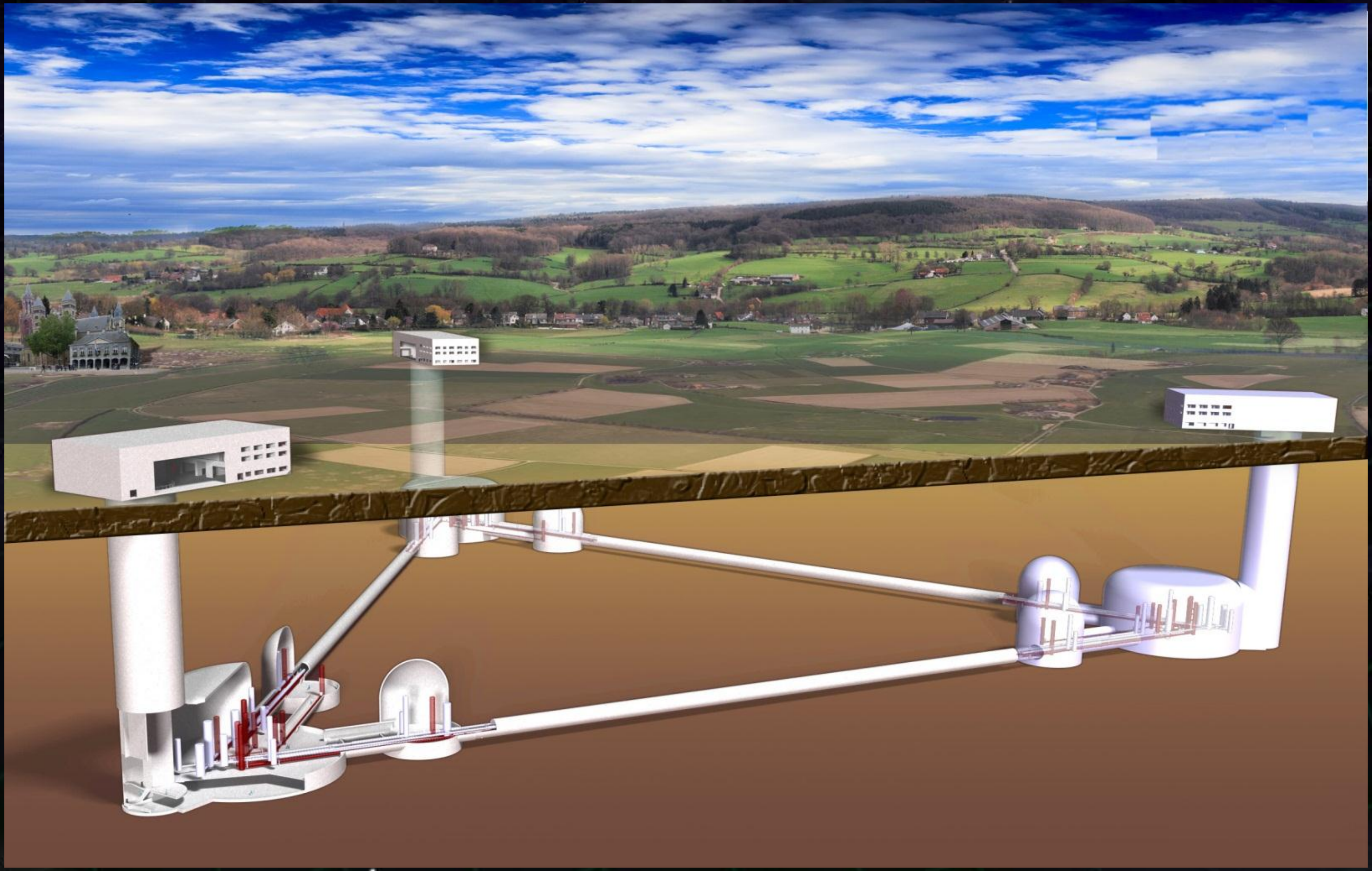
**LCGT (JPN)**
**baseline 3km**



# Third generation detectors

**3rd-generation detector: ET (Einstein Telescope)**

Sensitivity : x 10 improvement
Longer baseline, Underground site, Cryogenic mirrors



# Roadmap of GW detectors

## Ground based detectors

Improved sensitivities (10-1kHz)

LIGO

TAMA CLIO

Virgo/ GEO

2010

Enhanced LIGO

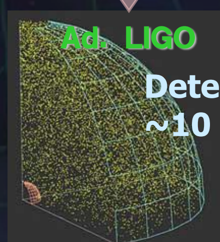
Advanced LIGO

LCGT

Advanced Virgo

GEO-HF

2015




Detection Rate ~10 event/yr


ET

2020


2025

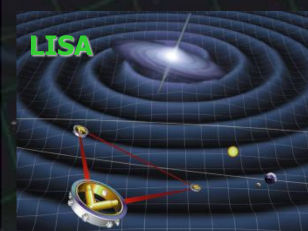
## Space-borne detectors

Low-frequency sources (0.1mHz – 1Hz)


DECIGO

LPF

DPF




Pre-DECIGO

LISA

Guaranteed source 0.1mHz-10mHz

DECIGO

BBO

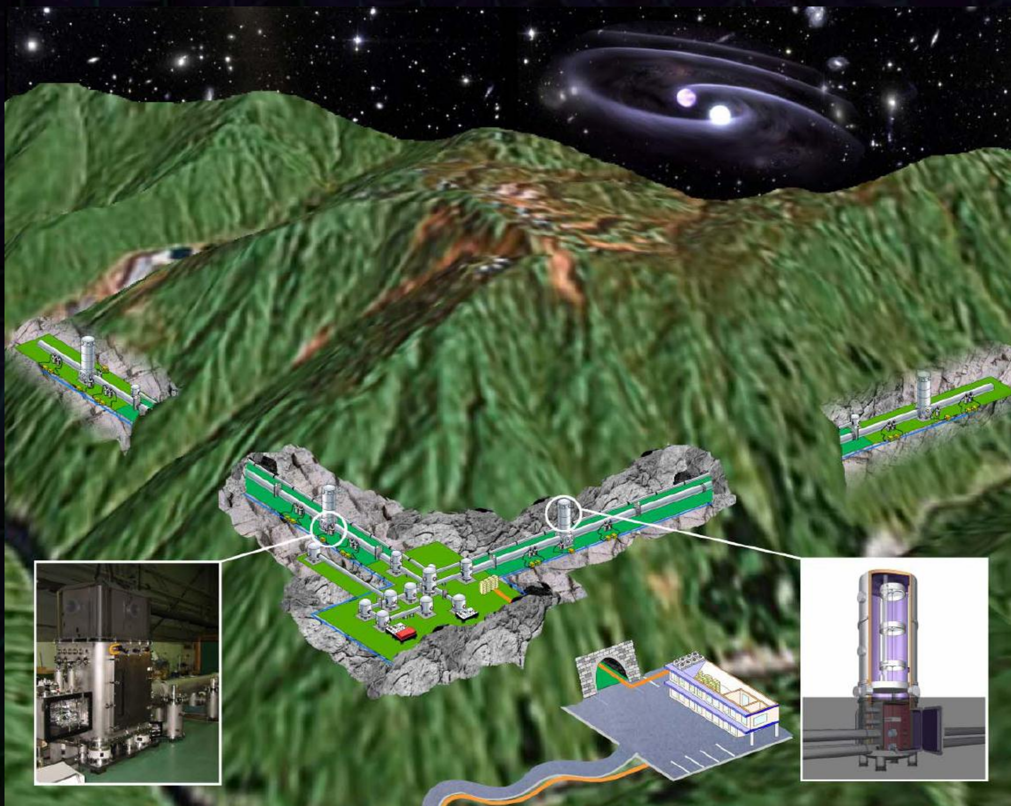
Cosmological GWs around 0.1Hz

# LCGT conceptual design

# LCGT

**LCGT** (Large-scale Cryogenic Gravitational-wave Telescope)

**2nd generation GW detector in Japan**



**Large-scale Detector**

- Baseline length: 3km
- High-power Interferometer

**Cryogenic interferometer**

- Mirror temperature: 20K

**Underground site**

- Kamioka mine,
  1000m underground

# LCGT site

## Kamioka underground site

Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.


Landsat photo data
NASA altitude data
Cashmir 3D

Neutrino
Super Kamiokande, Kamland
Dark matter
XMASS
Gravitational wave
CLIO, LCGT
Geophysics
Strain meter

- 220km away from Tokyo
- 1000m underground from the top of the mountain. (Near Super Kamiokande)
- 360m altitude
- Hard rock of Hida gneiss (5 [km/sec] sound speed)

# Why LCGT?

**One of key observatories in global network**

Increase detection rate and scientific outcomes

**Advanced technologies**

Advanced technologies used for 3$^{rd}$-generation detectors.

Cryogenics, underground site

→ LCGT is considered as a 2.5-generation detector.

# Network Observation

**Network of multiple GW detectors**

- Detection

  Increase : Detection rate, Detection volume, Sky coverage.

  Reduce : Fake events, Event-detection threshold.

- Astrophysics

  Increase : Sky position precision of the source,
  Waveform reconstruction.

**Multi-messenger astrophysics**

GW source can be central engines of high-energy phenomena

Stellar core collapse, compact binary merger, pulsar, ….

→ Coordinated observation with other telescopes

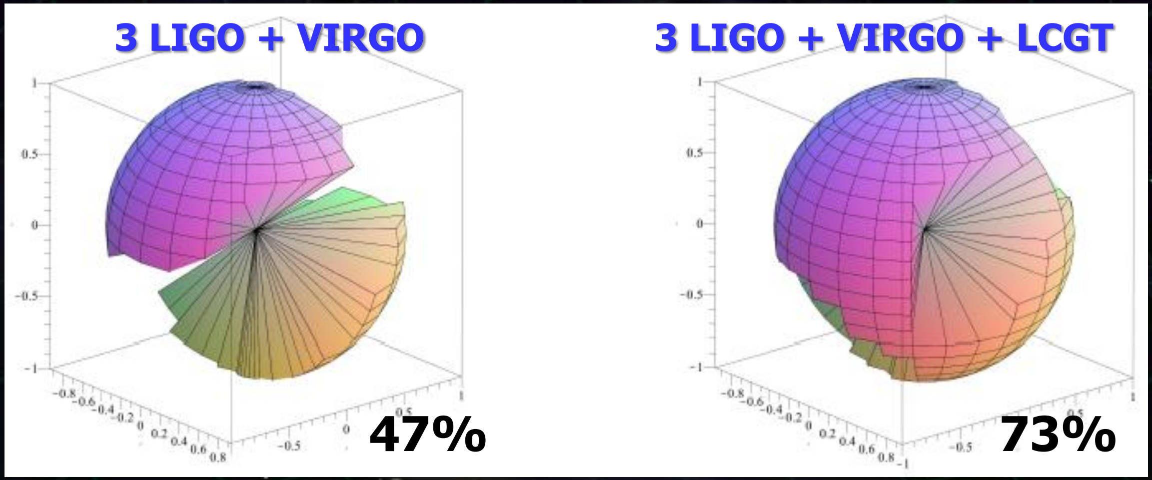
Gamma-ray, X-ray, optical/IR, Radio, Neutrino, ….

- Triggered search: Other obs. → GW search
- Follow-up search: GW detection → Other telescopes

# Increase of detection rate

**Increase detection probability**

- Increase of sky and time coverage.
- Decrease of fakes by coincidence analysis.
  → Increase the detection probability




**Sky-coverage pattern (0.707 of max. range)**

**B.Schutz arXiv:1102.5421**

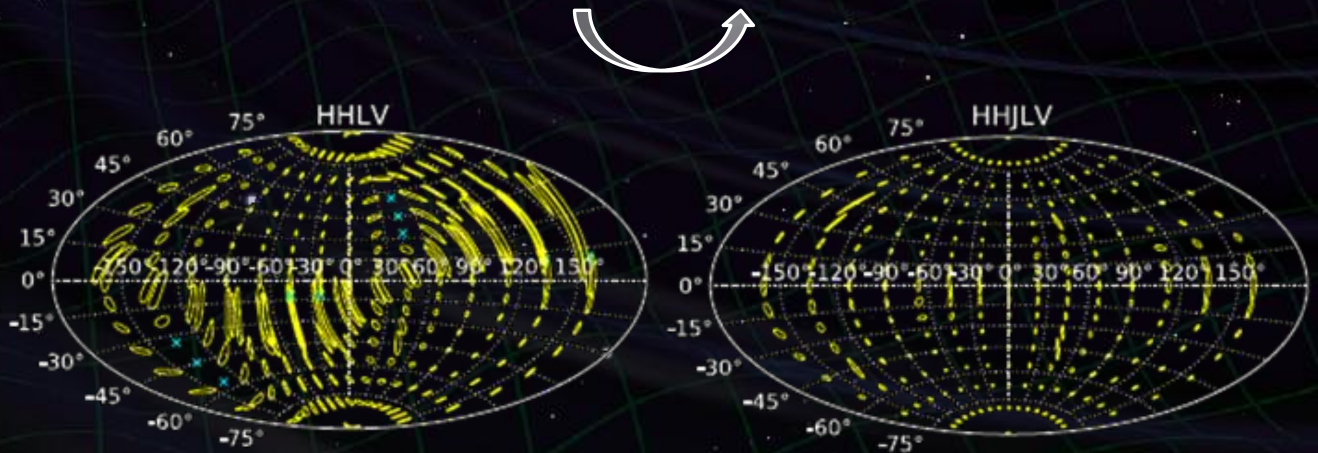
# Parameter estimation

## Angular resolution for the source

By H. Tagoshi

| | LHV | LHVJ | LHVA | LHVJA |
|---|---|---|---|---|
| average of δΩ [Deg²] | 34.4 | 7.26 | 4.20 | 2.78 |
| median of δΩ [Deg²] | 10.8 | 3.54 | 2.20 | 1.46 |

H: LIGO--Hanford
L: LIGO--Livingston
V: Virgo, J: LCGT
A: LIGO--Australia




S.Fairhaurst
CQG 28(2011) 105021

Adding LCGT to (aLIGO + adv. VIRGO) network
→ Factor ~3-4 improvement in sky area

# Start of LCGT project

LCGT project was selected by the
'Facility for the advanced researches'
program of MEXT (June 2010).

Construction cost is partially approved:
9.8 BYen for first 3-year construction.
(Original request: 15.5 BYen for 7 years.)

In addition, request for excavation cost was approved.

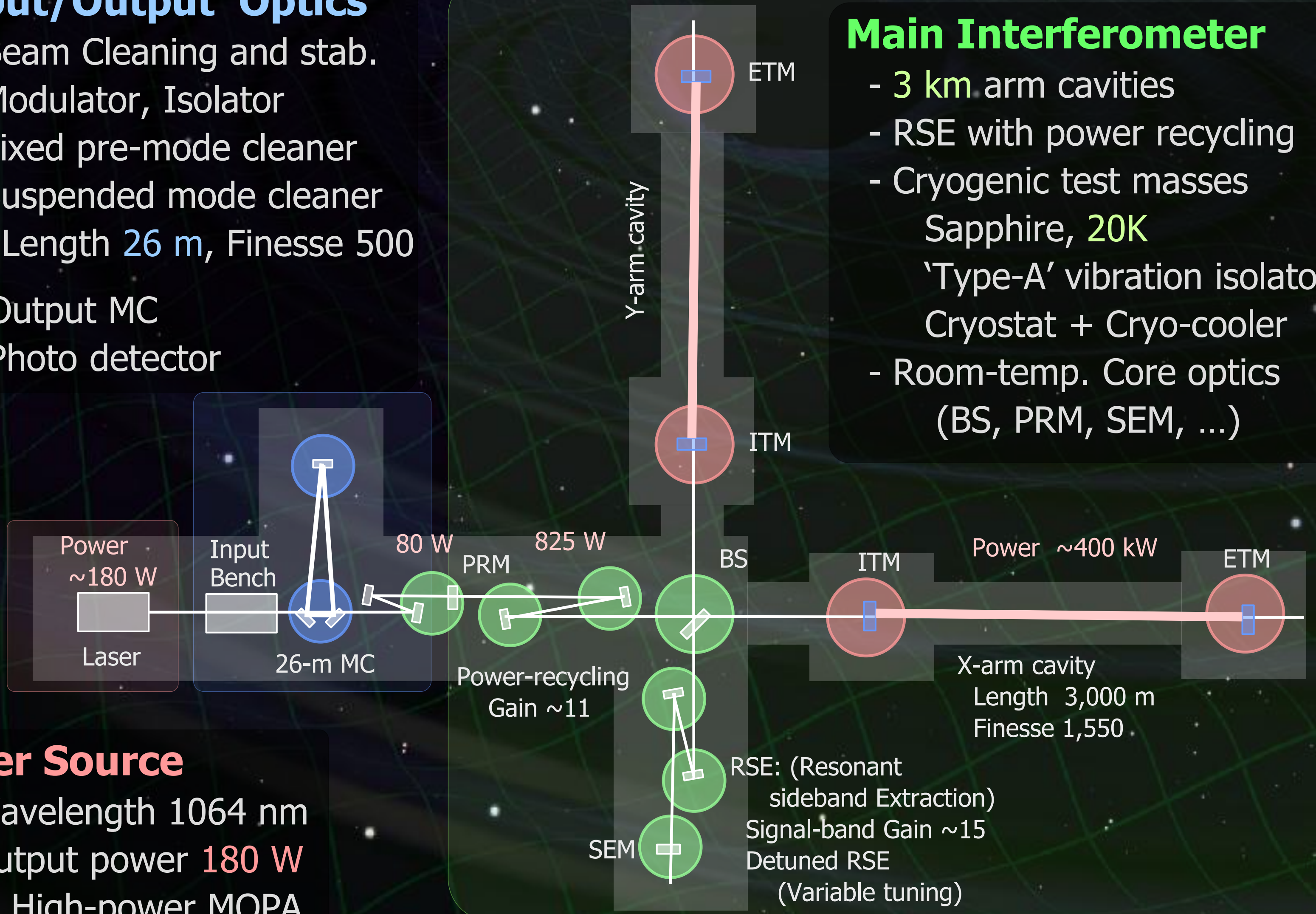
# LCGT configuration

## Input/Output Optics

- Beam Cleaning and stab.
- Modulator, Isolator
- Fixed pre-mode cleaner
- Suspended mode cleaner
  Length 26 m, Finesse 500
- Output MC
- Photo detector

## Main Interferometer

- 3 km arm cavities
- RSE with power recycling
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, ...)



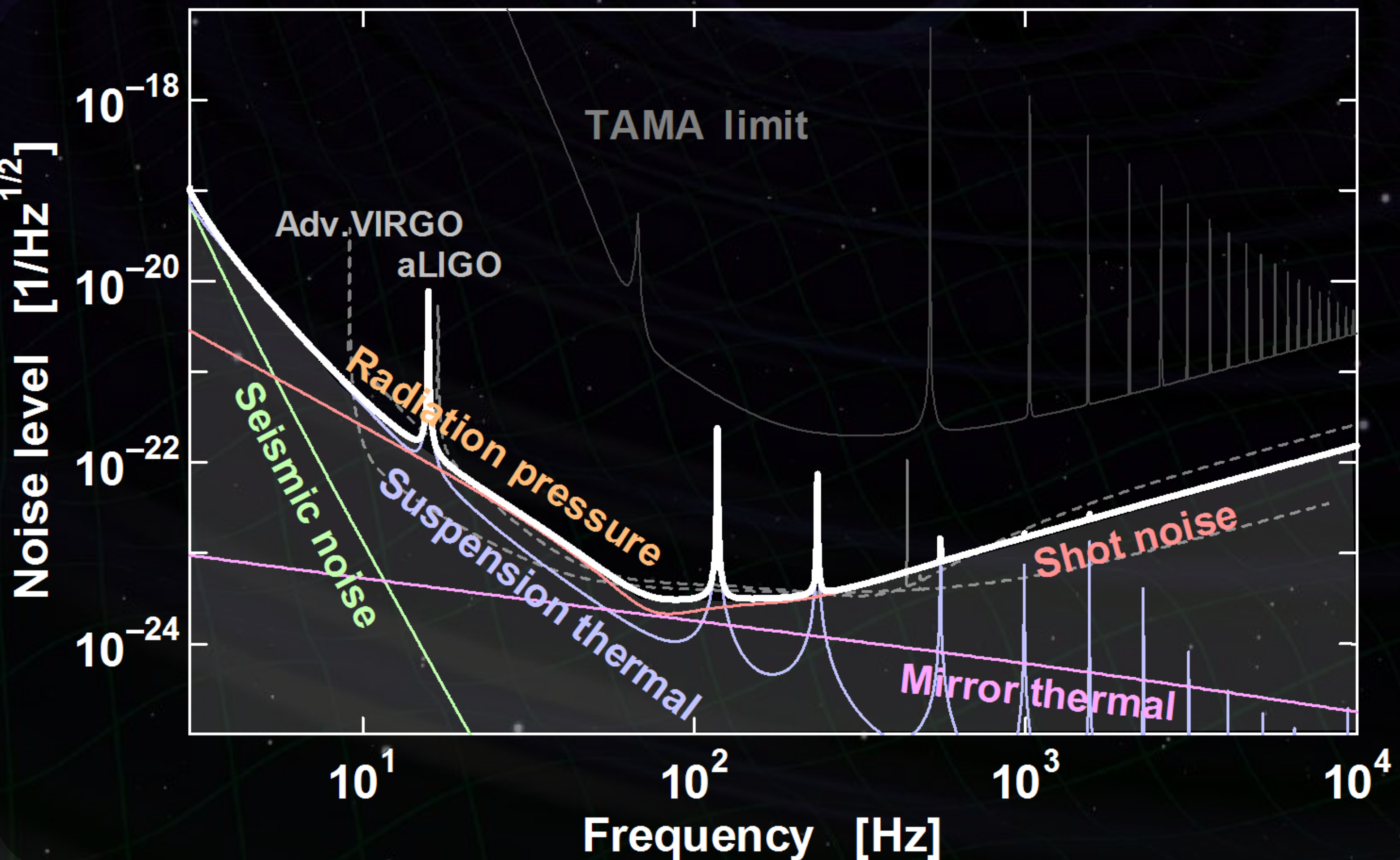

## Laser Source

- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

# Sensitivity Curve

**Comparable with aLIGO Ad.VIRGO**

**→ Global observation network**

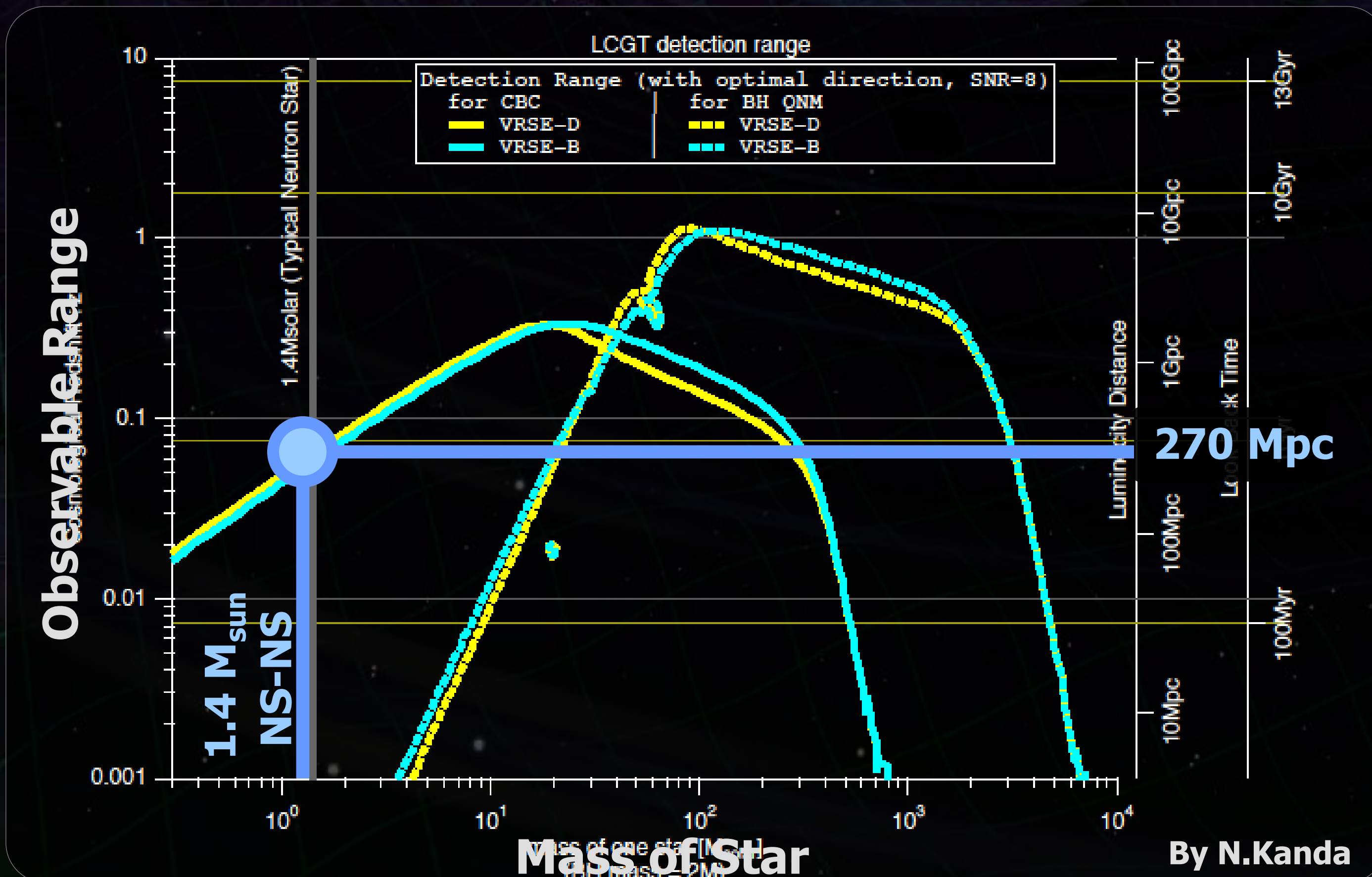


# Observable range

**Primary purpose of LCGT : Detection of GW**

→ **First target : Neutron-star binary inspirals**

⇨ **Obs. Range 270Mpc** (SNR=8, Optimal sky pos. an pol.)



# Detection rate of LCGT

## Neutron-star binary inspirals events

Observable range

sensitivity curve → 270 Mpc

Galaxy number density :

$$\rho = 1.2 \times 10^{-2} \quad [\mathrm{Mpc}^{-3}]$$

**R. K. Kopparapu et.al., ApJ. 675 1459 (2008)**

Event rate :

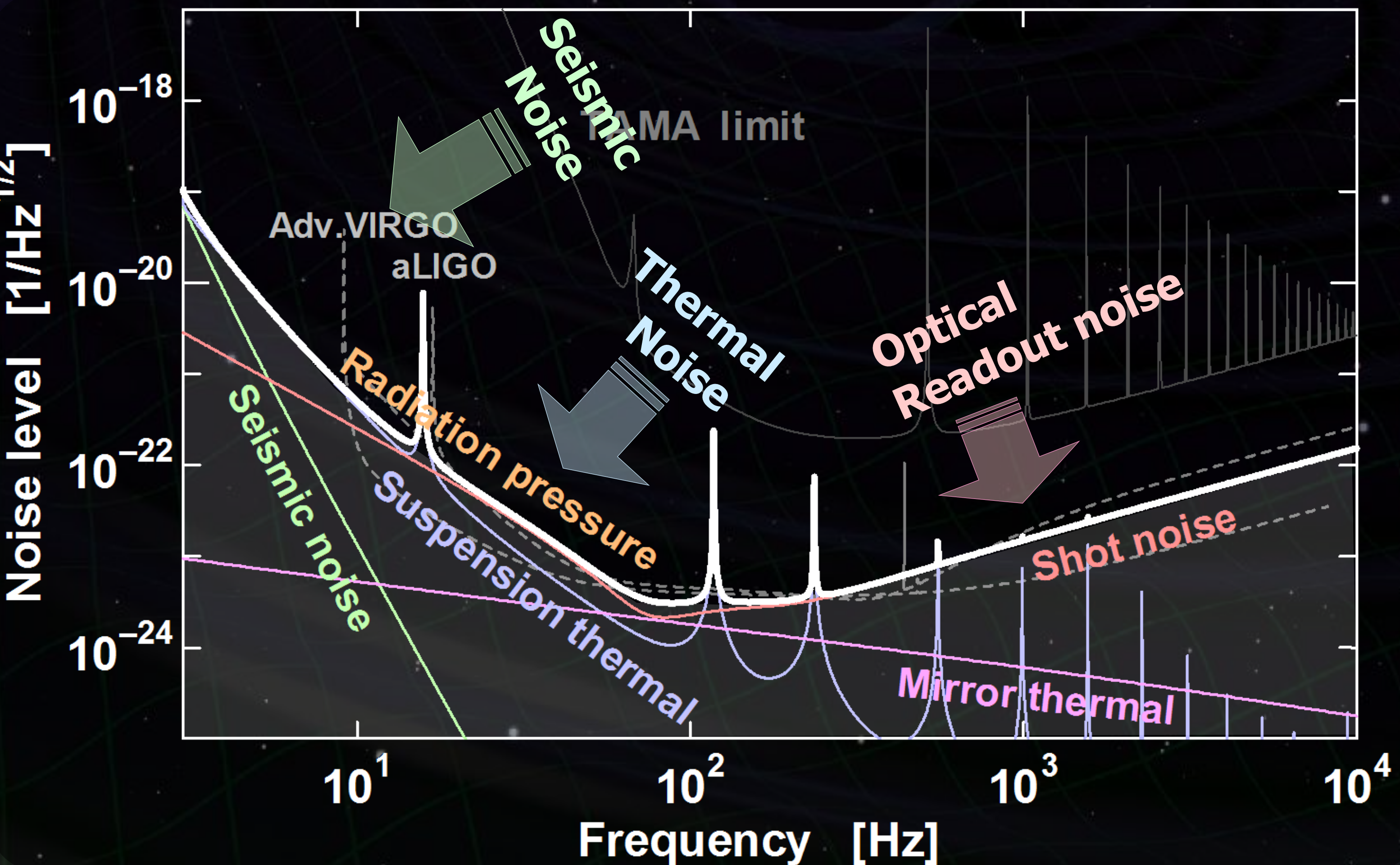
$$\mathcal{R} = 118^{+174}_{-79} [\mathrm{events/Myr}]$$

V. Kalogera et.al., ApJ, 601 L179 (2004)
Kim et al. (2008)

⇨ **LCGT Detection rate 9.8 events/yr**

# Sensitivity Curve

**Improved sensitivity**
**from the first generation detectors**



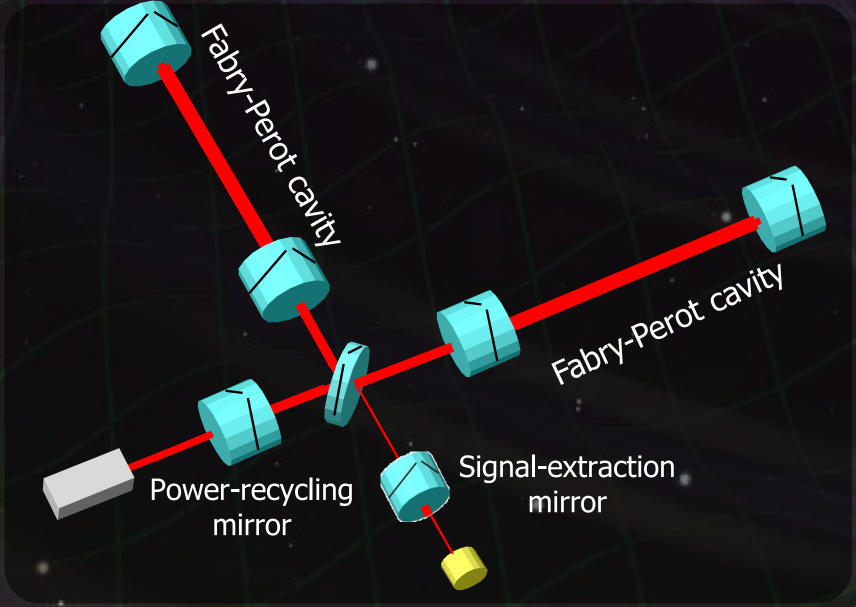
# Readout-noise reduction

**High-freq. (> 100 Hz) improvement**

**Shot noise reduction by high power in arm cavities**

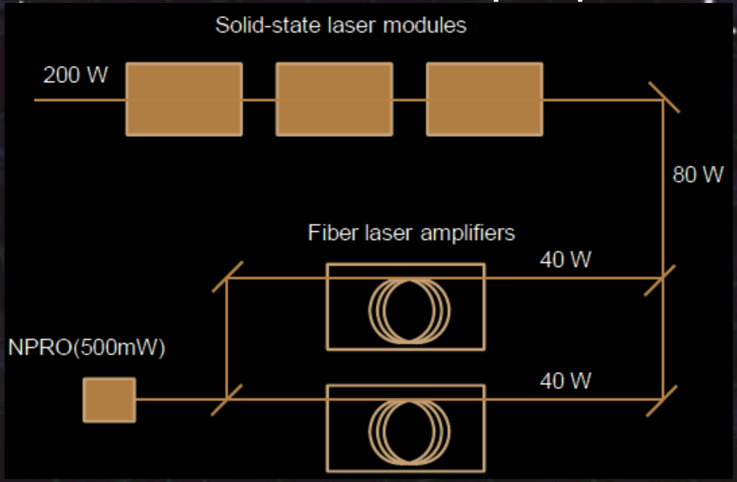
## Optical configuration

Fabry-Perot Michelson interferometer with RSE (Resonant-Sideband Extraction)




## High-power laser source

Nd:YAG laser source with >180W output power




## Low-loss mirror

Optical loss <100ppm (round-trip)
<45ppm in reflection

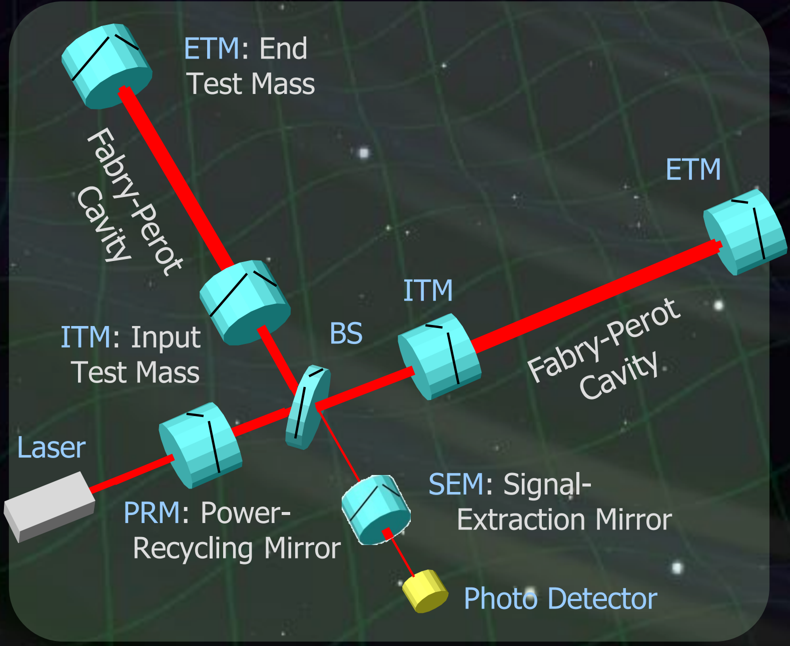
# Interferometer Configuration

**RSE (Resonant-Sideband Extraction) :**

Optical configuration to accumulate high laser power with tunable signal band

(J.Mizuno 1993)

⇨ Additional mirror at output port (SEM: Signal Extraction Mirror)




Arm cavity converts the GW effect to phase change in laser beam
→ Signal ∝ Power and Storage time

High finesse is favorable
(Large bounce number in cavity)

⇕

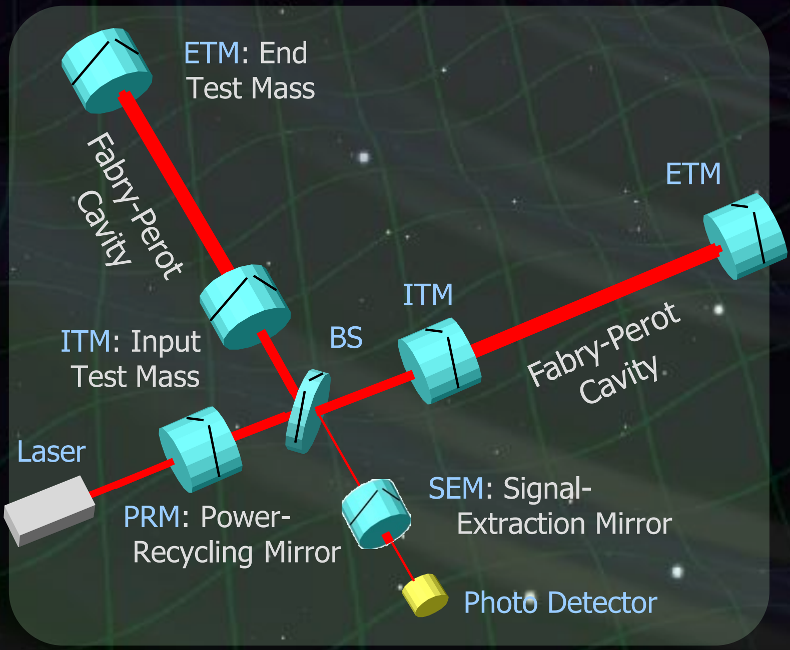
Limited signal band because of signal cancelation in cavity

It is possible to design storage time and signal band independently.

# Resonant-Sideband Extraction

**RSE enables independent design of power and signal band**

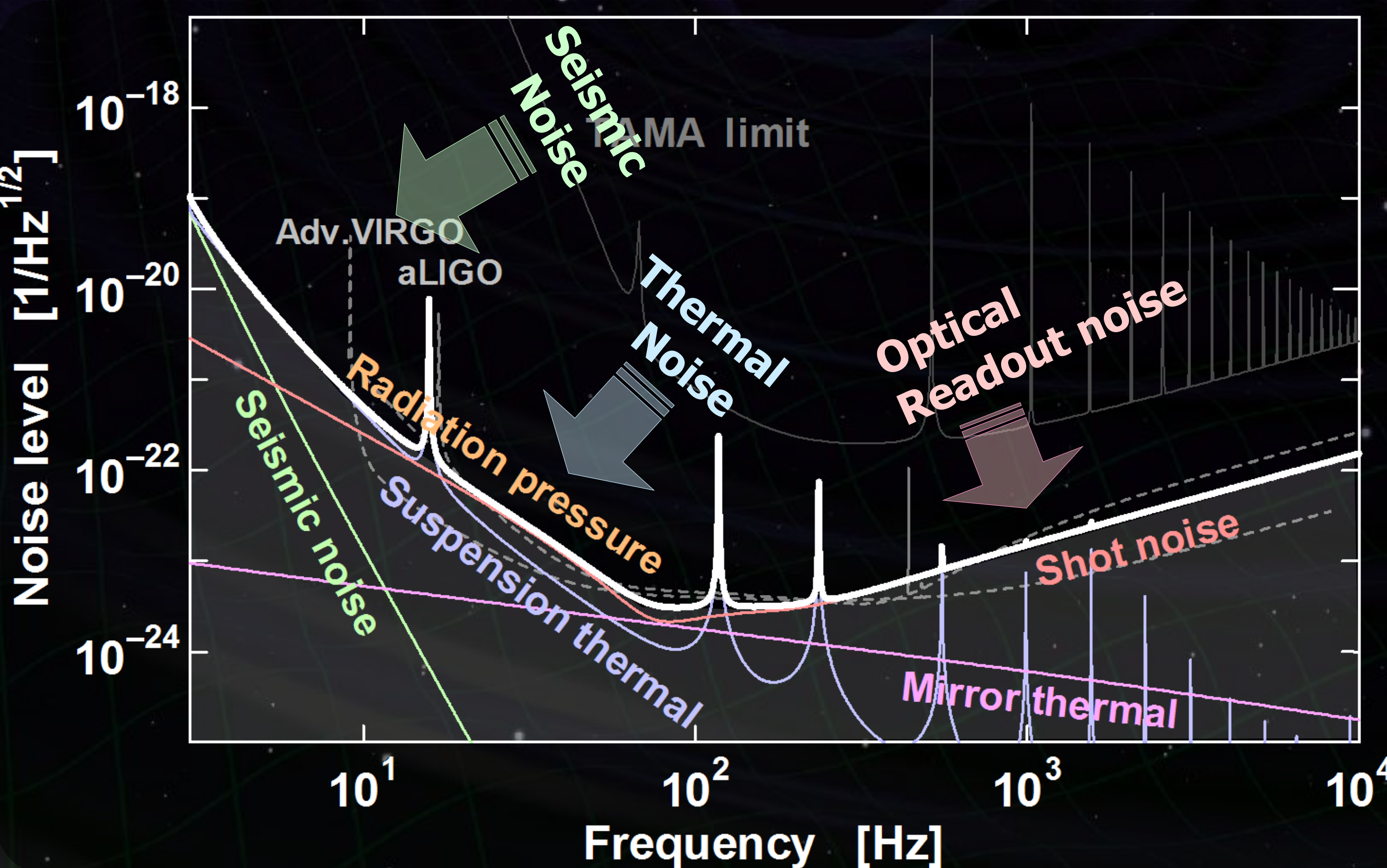
⇨ LCGT design : High finesse arm cavity
Moderate power-recycling and signal-band gains




- **High laser power in the arm cavities**
  Robust against optical losses
  in central interferometer part.
  (Substrate loss, Contrast defect)
- **Low thermal absorption in substrate**
  → Critical to cool ITM (Input Test Mass)
  down to cryogenic temperature.
- **Tunable observation band**
  Detector response (frequency band)
  is optimized for target GW signals.

# Sensitivity Curve

**Improved sensitivity**
**from the first generation detectors**



# Thermal-noise reduction

## Mid.-freq. (around 100 Hz) improvement

### Cryogenics

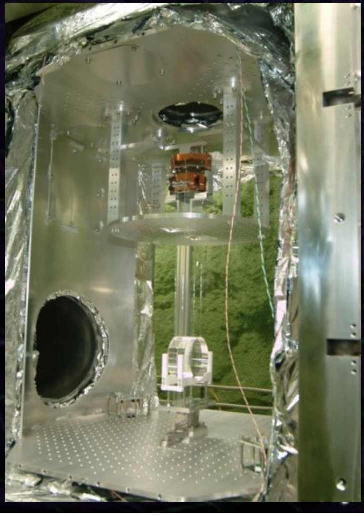
Mirror ~20K
Suspension ~16K

Sapphire mirror
→ High mechanical Q-value at low temperature

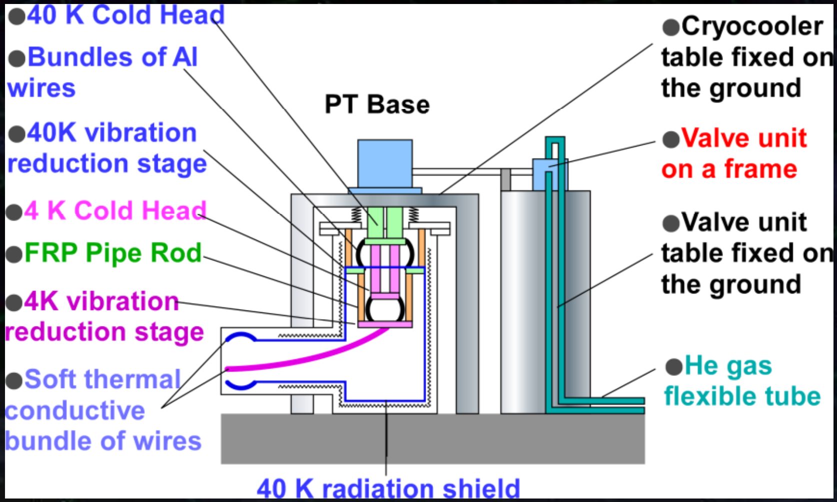
**Thermal noise** $\propto \sqrt{\frac{T}{Q}}$

⇨ Cryogenic is a straight-forward way to reduce thermal noise.

Cryogenic mirror and suspension of CLIO 100-m interferometer

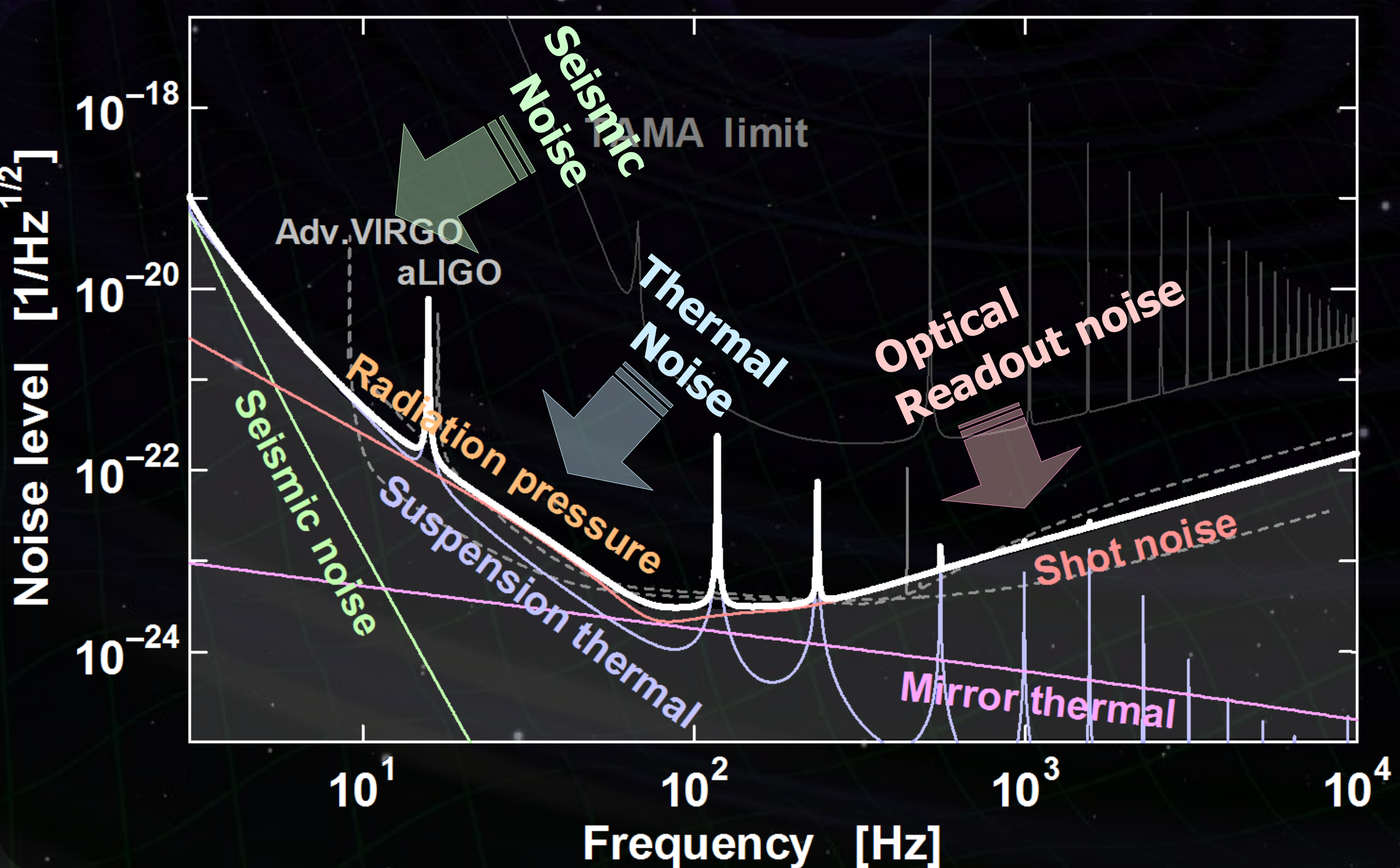


Low-vibration Cryo-cooler design



# Sensitivity Curve

**Improved sensitivity**
**from the first generation detectors**

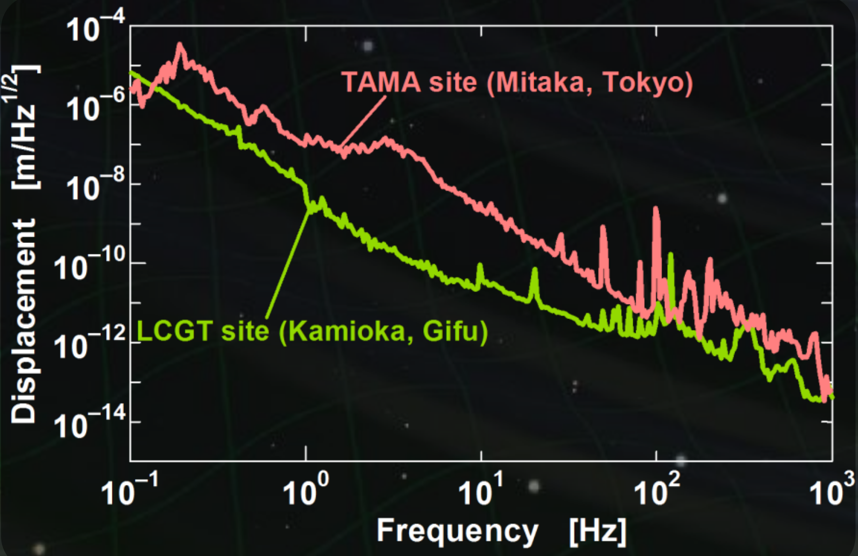


# Seismic-noise reduction

## Low-freq. (< 100 Hz) improvement

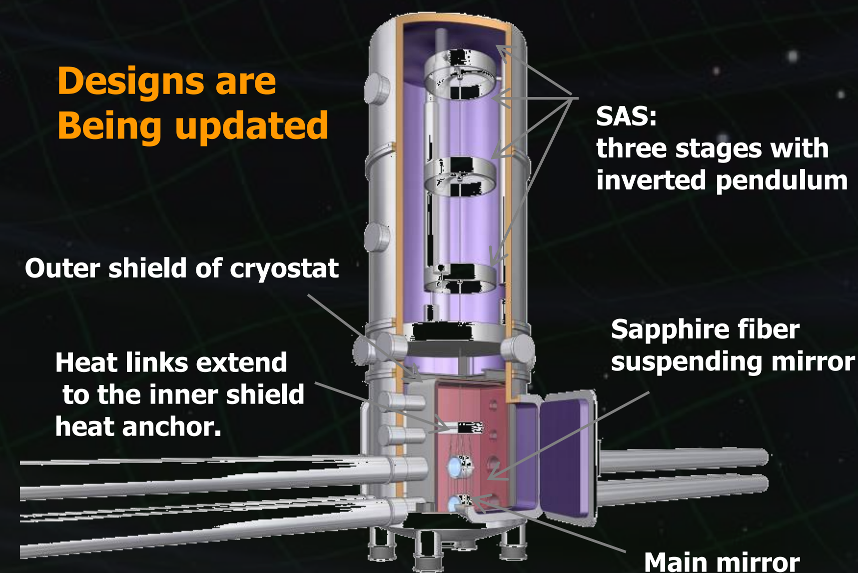
### Quiet site

Kamioka underground site
(~1000km underground)
Lower seismic disturbance
by 2-3 orders




### Better Isolation system

SAS: Multi-stage and Low-freq.
vibration isolation system



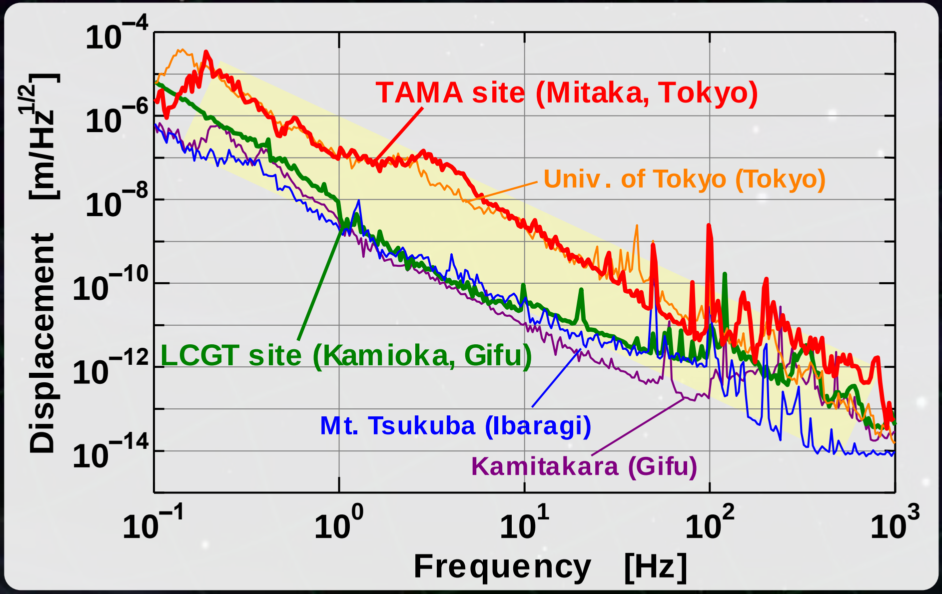
# Seismic fluctuations

**Ground is fluctuating, even without earthquakes**
**~ a few micro-meter (depending on the site)**

**Limit the detector sensitivity at low freq.**

**Spectrum** ~1/f$^2$
(depends on the site)
Obs. band → limit sensitivity
Low freq. → limit stability

**To reduce seismic noises** …
Long baseline length
Select a quiet site
Good seismic attenuator



# Passive seismic attenuator

**Passive isolator**

**(Require no energy supply)**

⇨ Supported by spring or pendulum

Basic unit : single pendulum

Isolation Ratio:

Disp. ratio of mass to platform

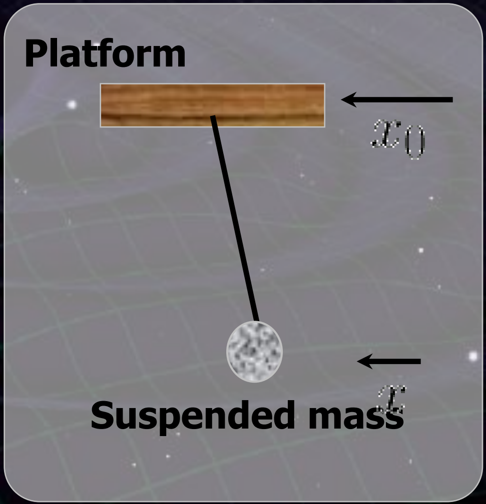
$$\frac{x}{x_0} = \frac{1 + \frac{i}{Q}\frac{f}{f_0}}{1 + \frac{i}{Q}\frac{f}{f_0} - (\frac{f}{f_0})^2}$$

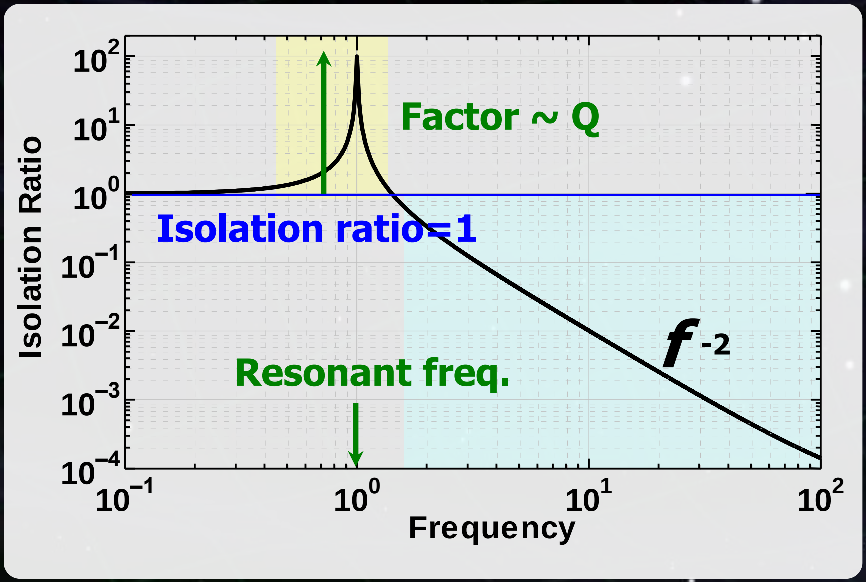
$f$ : Frequency

$f_0$ : Pendulum frequency

$Q$ : Q-value (sharpness of resonance)

**→ Isolation above $f_0$**



# High-performance isolator

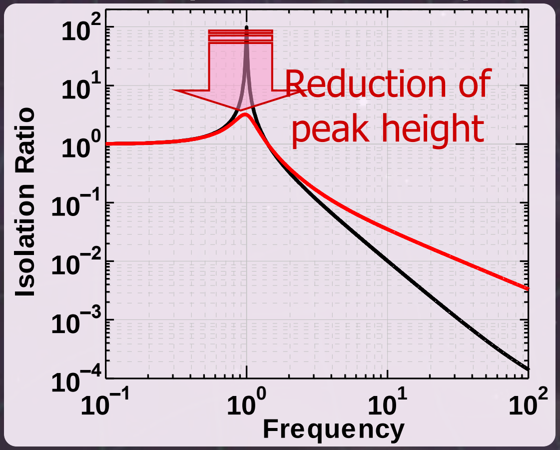
**Better seismic attenuator**

**→ Improve stability and isolation ratio**

**Damping**

Reduce Q-value

→ improve stability

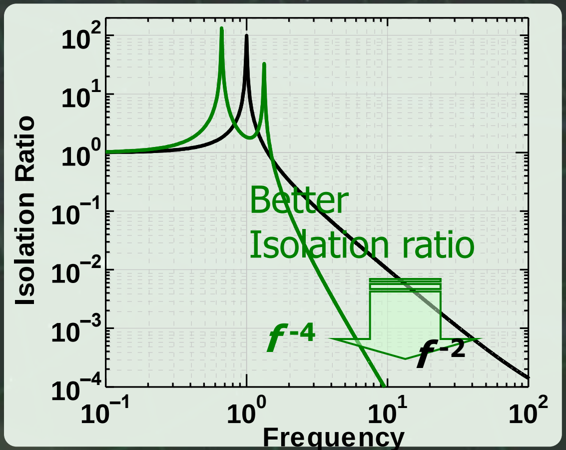



Degraded isolation

**Multi stage**

More steep reduction

→ Better isolation

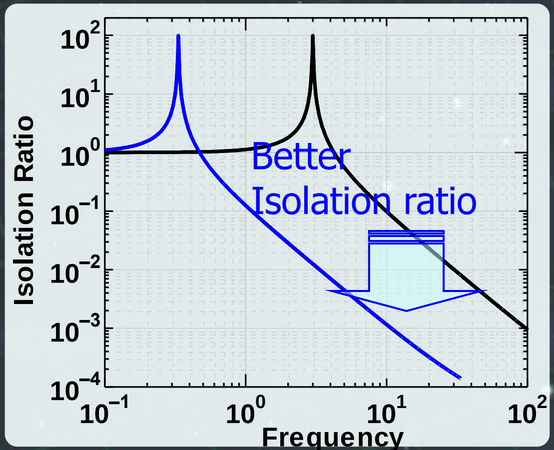



Resonant peaks

**Low reso. freq.**

Low-freq. cut-off

→ Better isolation

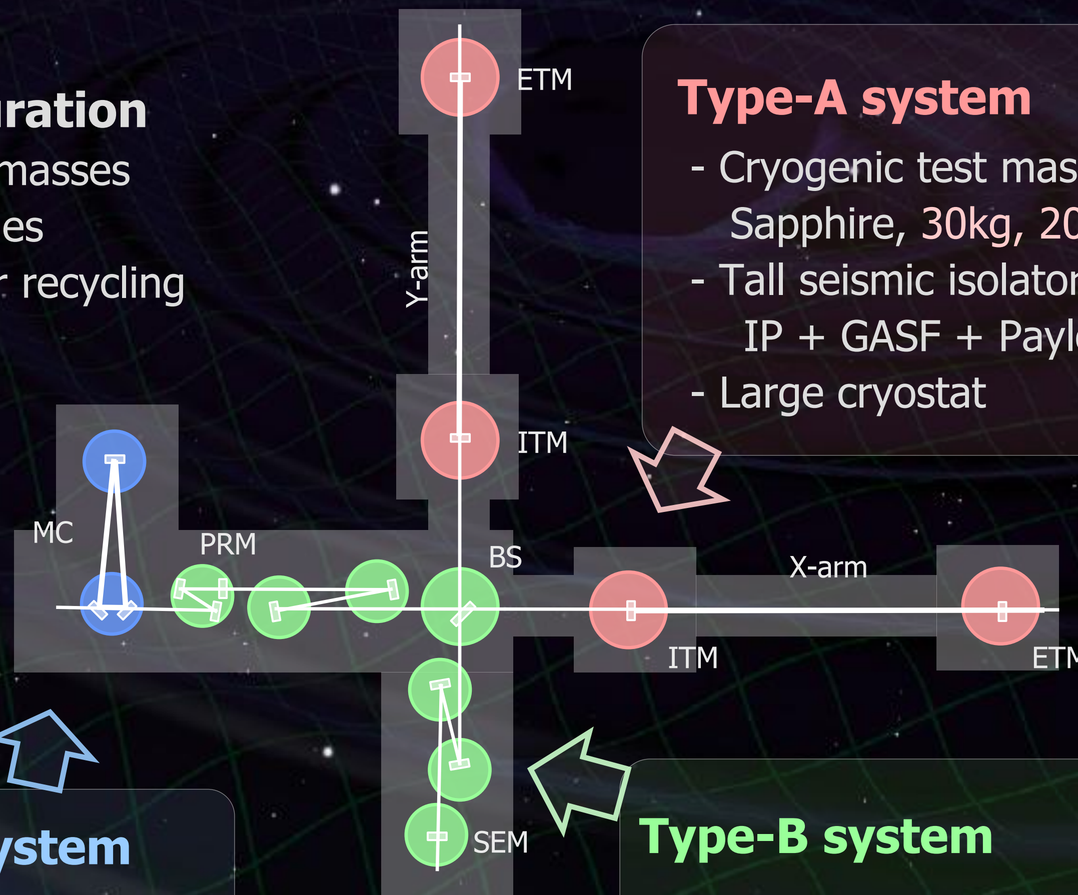



Drift by environment

**Combine them in design of the seismic attenuator**

# bLCGT configuration

## bLCGT configuration
- Cryogenic test masses
- 3 km arm cavities
- RSE with power recycling




## Type-A system
- Cryogenic test mass
  Sapphire, 30kg, 20K
- Tall seismic isolator
  IP + GASF + Payload
- Large cryostat

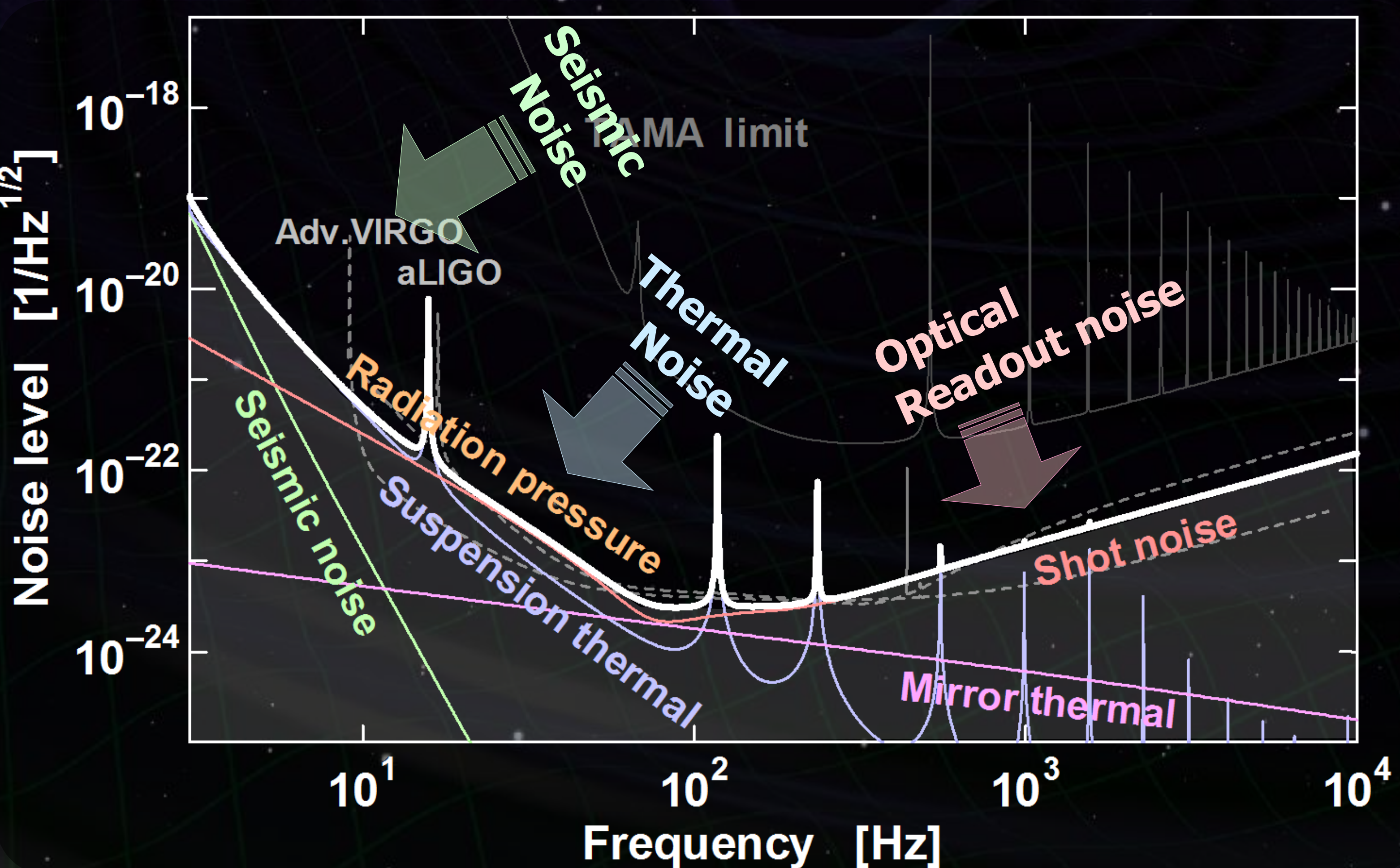
## Type-C system

- Mode cleaner
  Silica, 1kg, 290K
- Stack + Payload

## Type-B system
- Core optics (BS, RM ,...)
  Silica, 10kg, 290K
- IP + GASF + Payload
- Stack for aux. optics

# Sensitivity Curve

**Improved sensitivity from the first generation detectors**



# Developments for LCGT

# TAMA300 and CLIO

## TAMA300 (1995~)

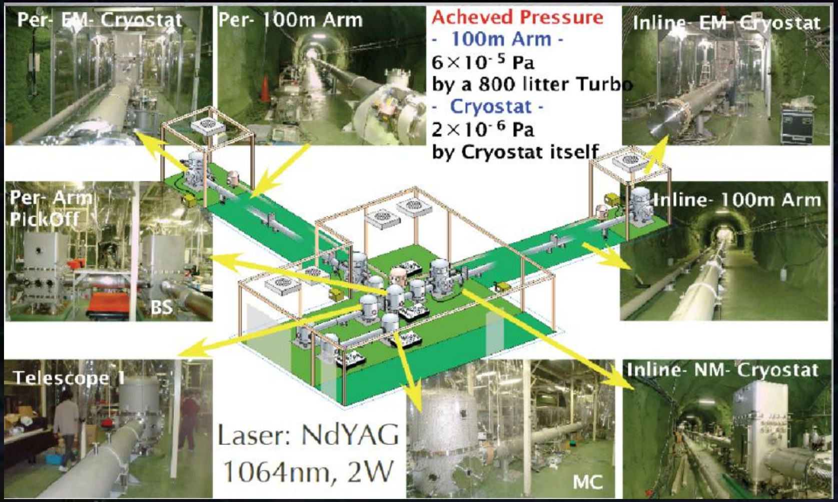
GW detector with a baseline of 300m

Sensitivity to cover our galaxy
(World best in 2000-2002)
Earlier observation runs
(Obs. data over 3000hours)


## CLIO (2002~)

Cryogenic interferometer (Kamioka)
with 100m baseline length

Stable operation taking
advantage of underground site
Cryogenic operation below 20K
→ Improved sensitivity



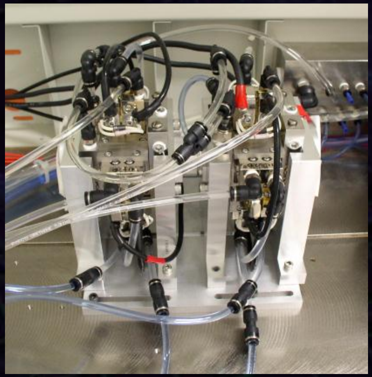
# Developments (Optics)

## High-power laser source

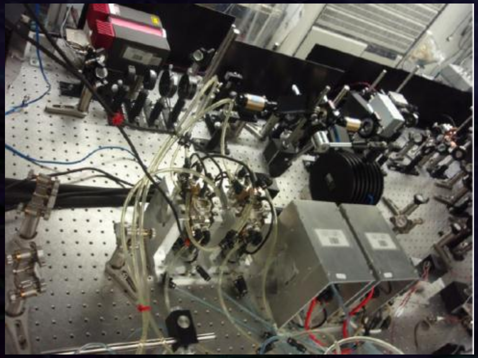
100-W injection-locked laser
→ Test high-power laser module
Freq. and Int. stabilization

⇨ **Sufficient stability**

Laser module (Mitsubishi)



100W Inj.-locked Laser



## Interferometer + I/O optics

TAMA300 operation (PRFPMI)
NAOJ 4m, Caltech 40m experience
→ RSE prototype test

⇨ **Fundamentals are established**

4m RSE prototype at NAOJ

TAMA300

## Mirror

Cryogenic mirror test
in CLIO (Low-noise cryogenic operation, Contamination)
Sapphire substrate
→ Require measurements and developments

# Developments (Cryogenics)

## Cryogenic system

Heritages by CLIK and CLIO

Thermal design

Cryogenic IFO operation

Under detailed design

Cryostat + Cryocooler

+ Radiation shield

⇩

Planning a full-scale prototype test at Kamioka site

Vacuum – Cryostat system

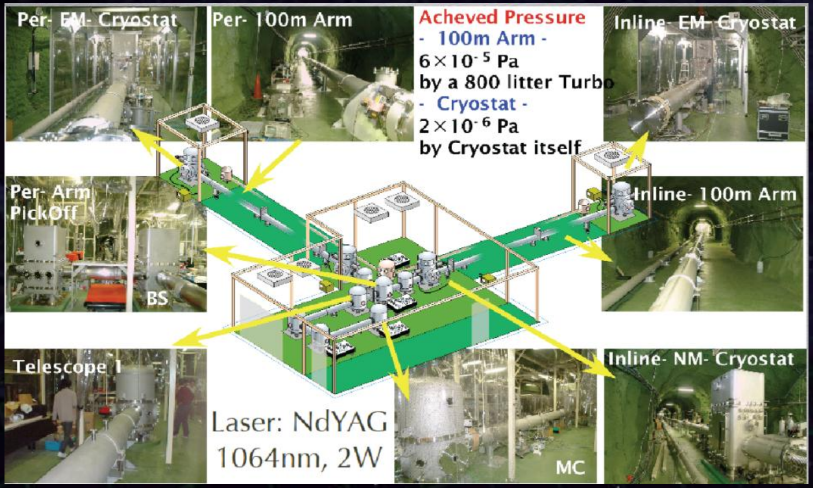
Radiation shield

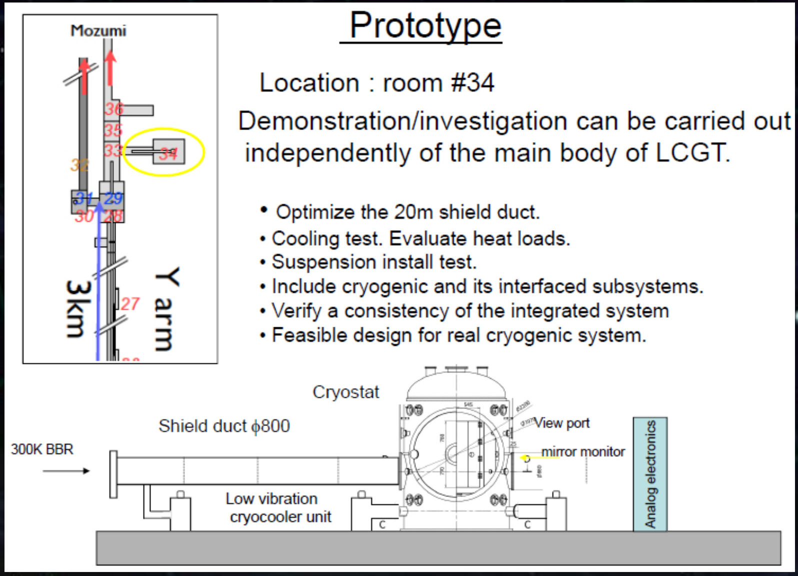
Low-vibration cryocooler

→ Cooling test, Installation test,

On-site development from 2013

CLIO : 100-m cryogenic interferometer



# Developments (Seismic noise)

## Underground site

Heritages by

CLIO (100m baseline)

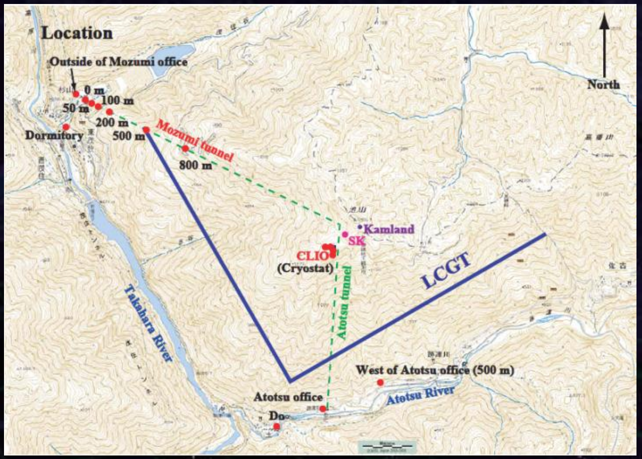
20m prototype moved from NAOJ

Measurements at several points

→ Sufficiently quiet with

>50m from ground level

Seismic noise measurement at Kamioka




## Isolation system

Heritages by

3m prototype FP test

TAMA-SAS

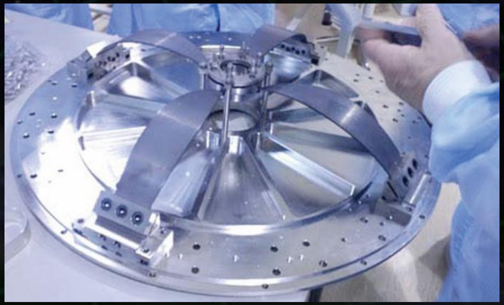
⇨ Detailed design

Pre-commissioning test

plan at TAMA site

SAS test with 3m prototype


First prototype for LCGT GASF



# Developments (Others)

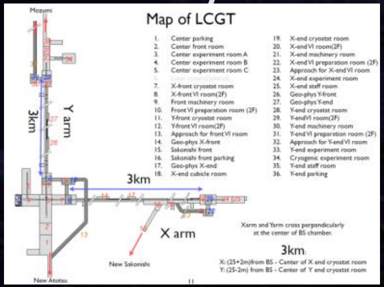
## Tunnel + Facility

Detailed design

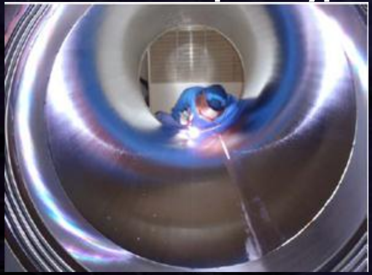
→ Begin excavation April 2011

will be finished April 2013

Tunnel layout




Vacuum tube prototype



## Vacuum system

Detailed design

→ Fabrication test of short tube

Fabrication, Storage, Installation plans

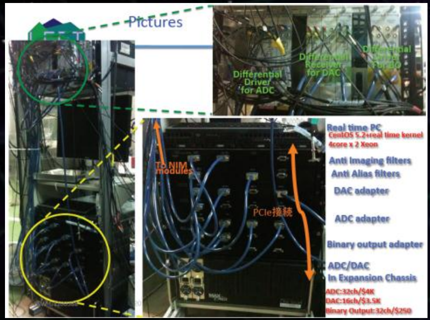
## Digital system + Data processing

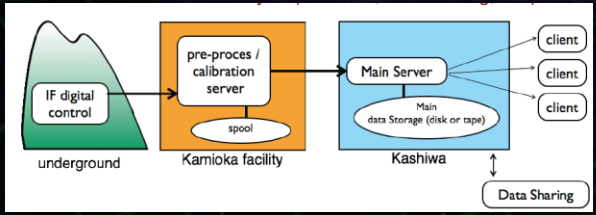
Real-time system development

based on MOU attachment with LIGO

Computing platform, network design

Digital system installed to CLIO






Computing platform and Network

## Analog electronics

Design policy under discussion

Detailed designs

# CLIO

(Cryogenic Laser Interferometer Observatory)

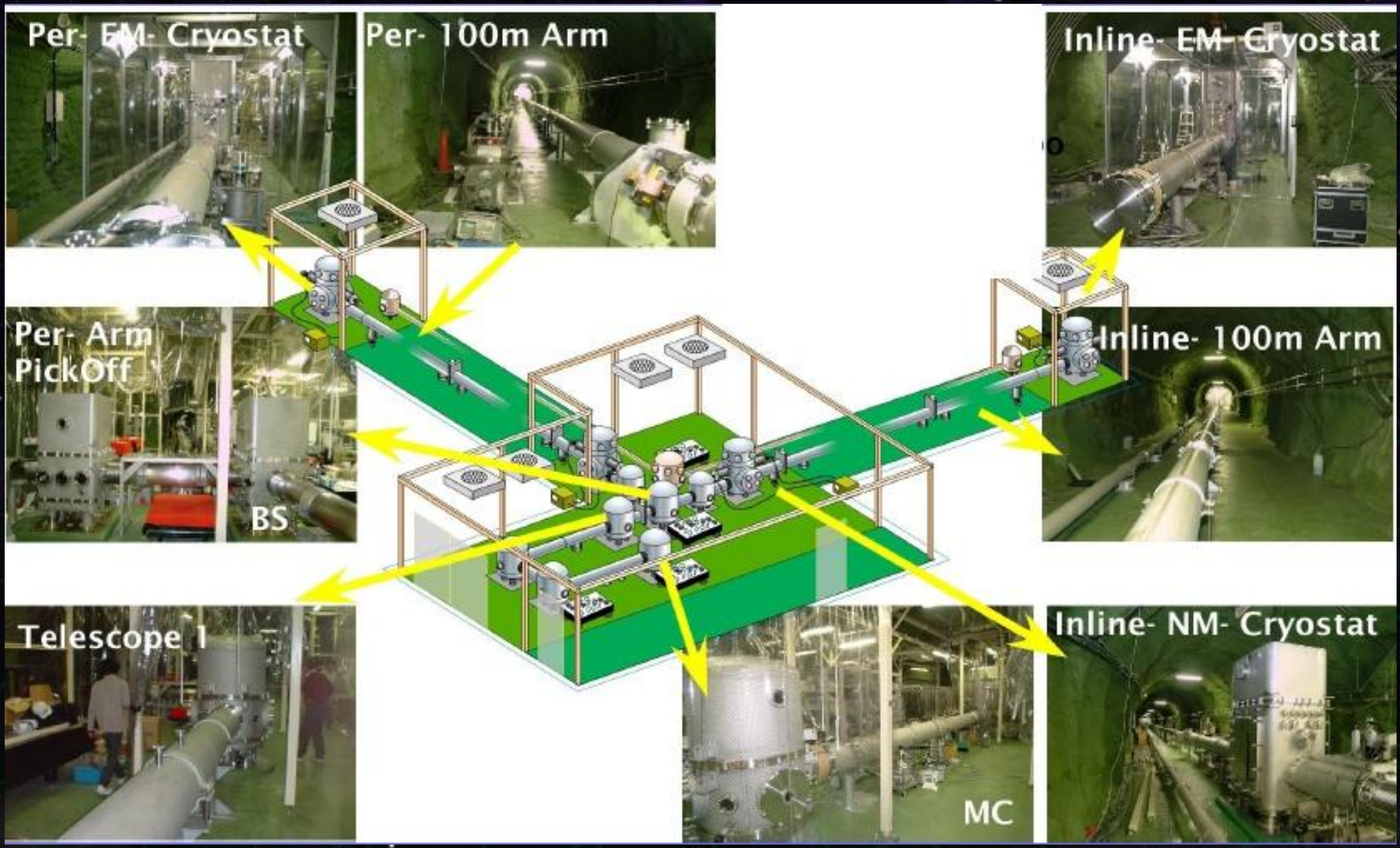
※ Most of the materials were prepared by …

S. Miyoki,  T. Uchiyama,  O.Miyakawa

# CLIO

**Locked-Fabry-Perot interferometer**

**Cryogenic Sapphire TM , underground ,baseline length of 100m**



# CLIO site

## Same site as LCGT: Kamioka underground site


Landsat photo data
NASA altitude data
Cashmir 3D

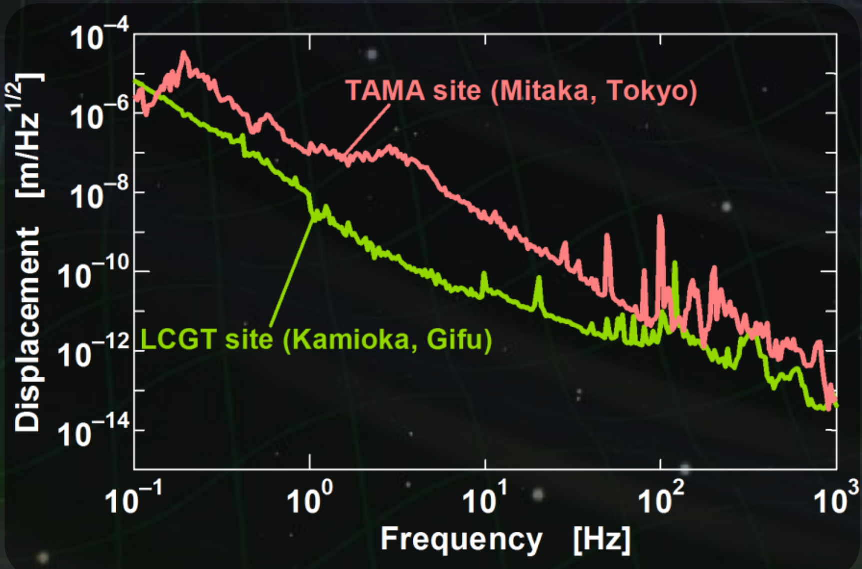
- 220km away from Tokyo
- 1000m underground from the top of the mountain. (Near Super Kamiokande)
- 360m altitude
- Hard rock of Hida gneiss (5 [km/sec] sound speed)

# CLIO environment (1/2)

**Stable environment for long-term operation**
**Small seismic disturbance for low-freq. sensitivity**

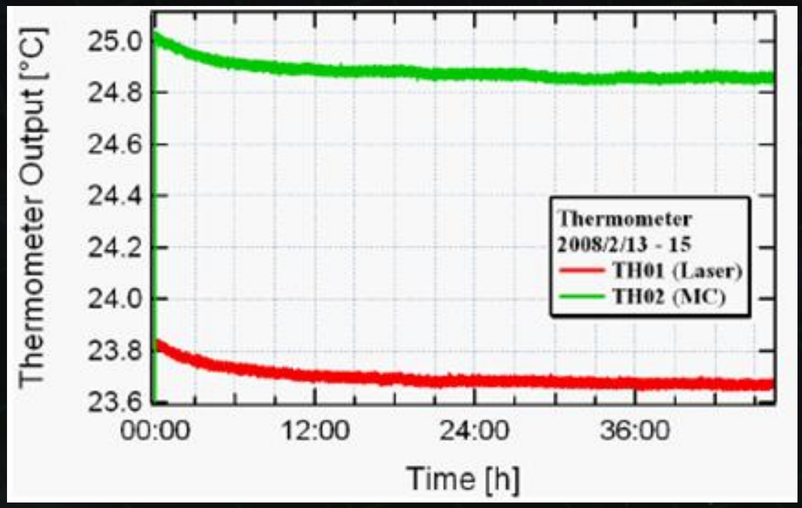
## Seismic disturbance

Kamioka underground site
(~1000km underground)
Lower than TAMA300 site
by 2-3 orders




## Temperature

Temp. fluctuation < 0.2 degree
for about 2 days



# CLIO environment (2/2)

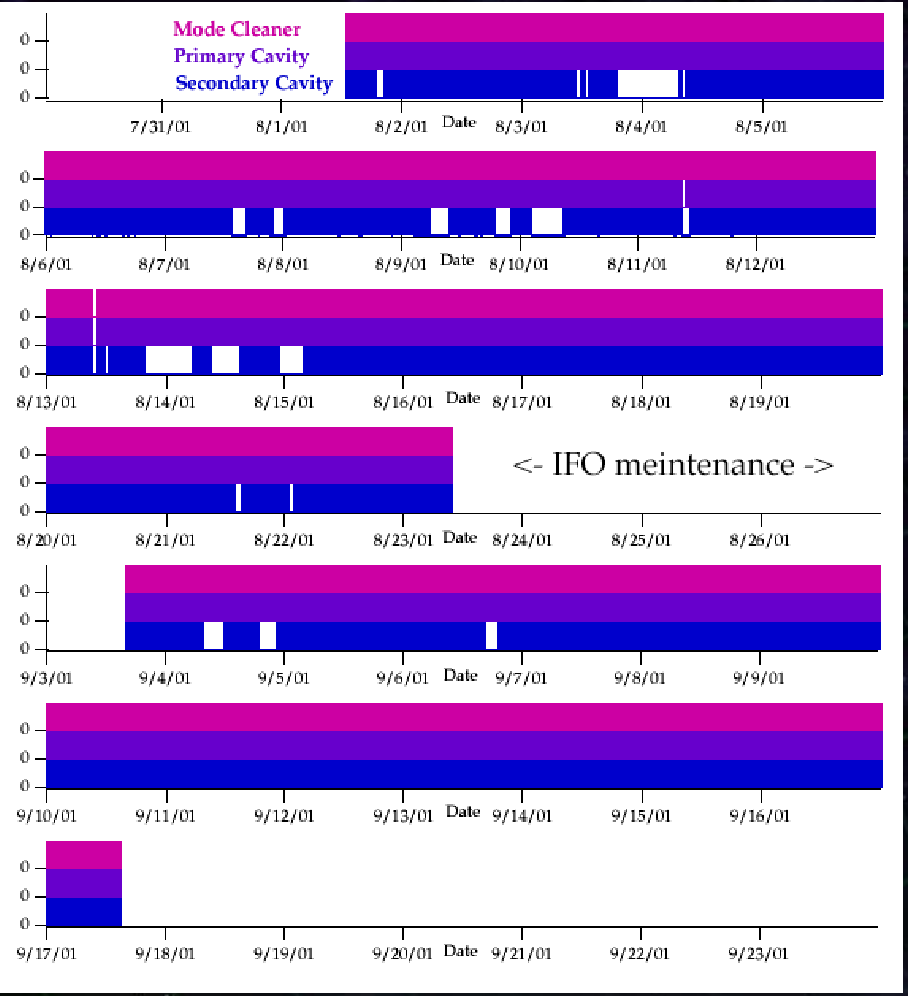
## Long-term run at Kamioka site

**LISM interferometer**

Baseline : 20m
Suspended test masses
Locked-FP config.
No global alignment ctrl.

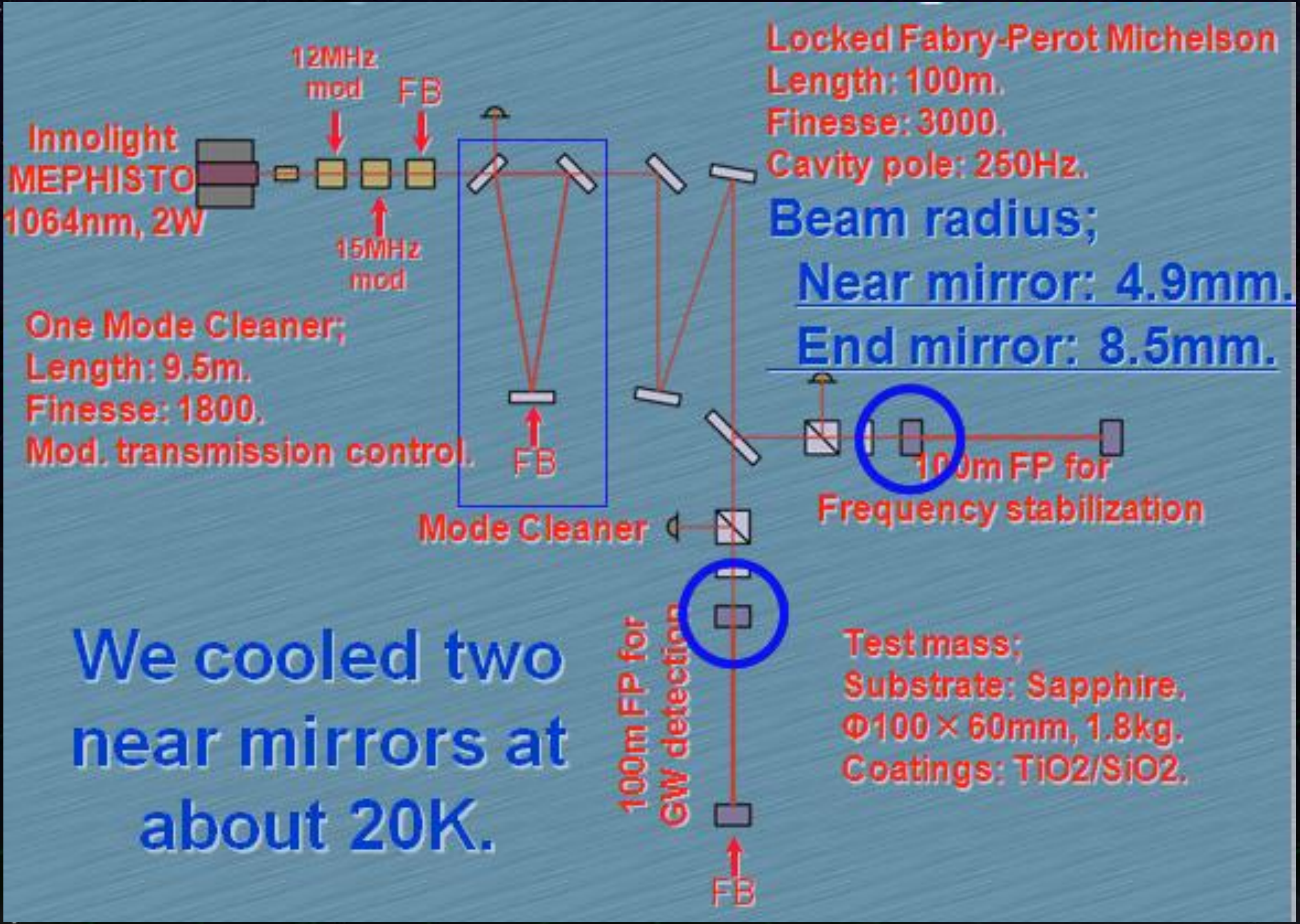
- Observation period : 8/1-8/23, 9/3-9/17 (2002)
- Total observation time : 862h
- Total lock : 786h
- Longest stretch of lock : 72h

**Live rate : 91%**
**(99.8% for last 1week)**



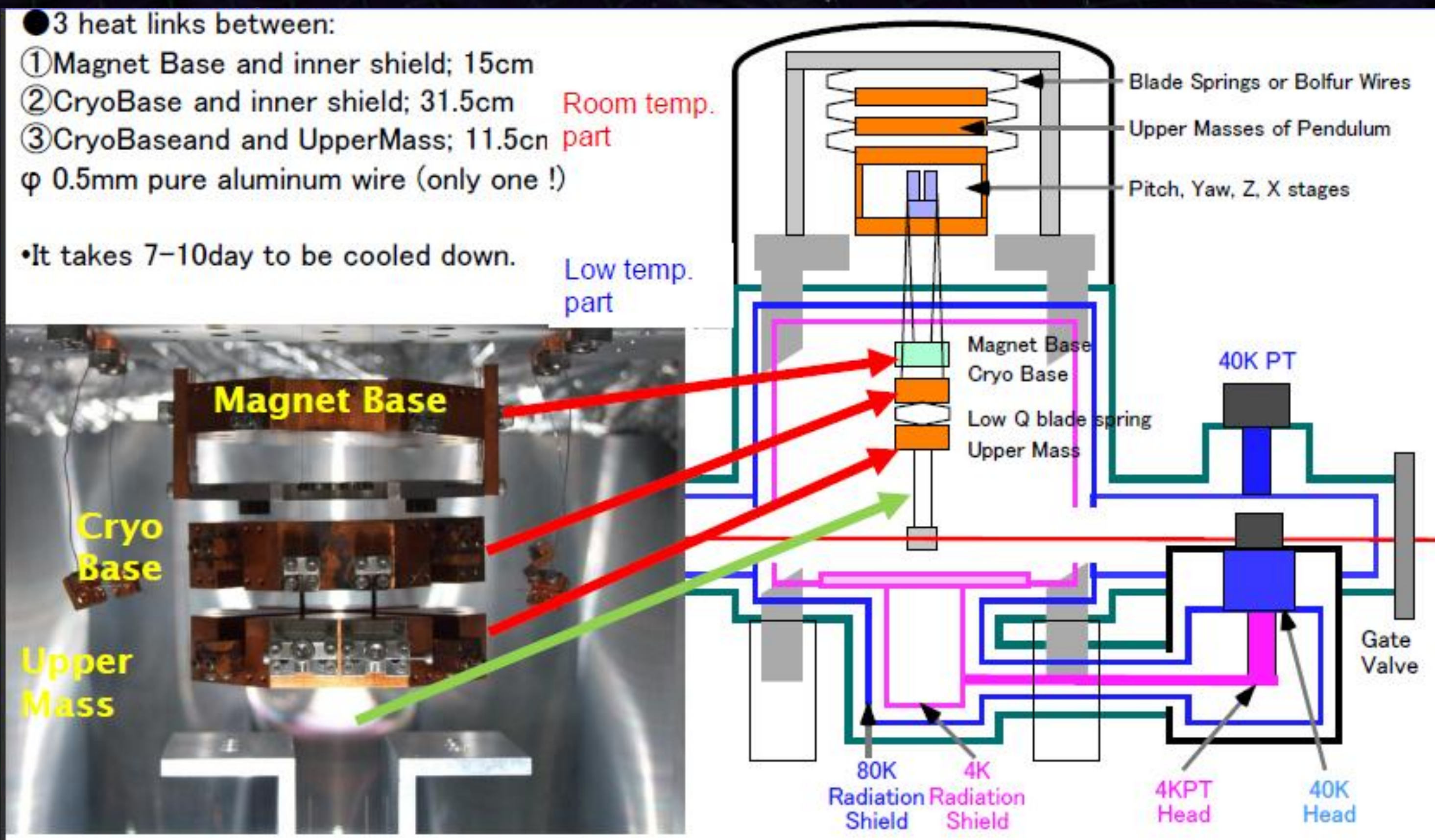
# CLIO Configuration

## Two input test masses were cooled down



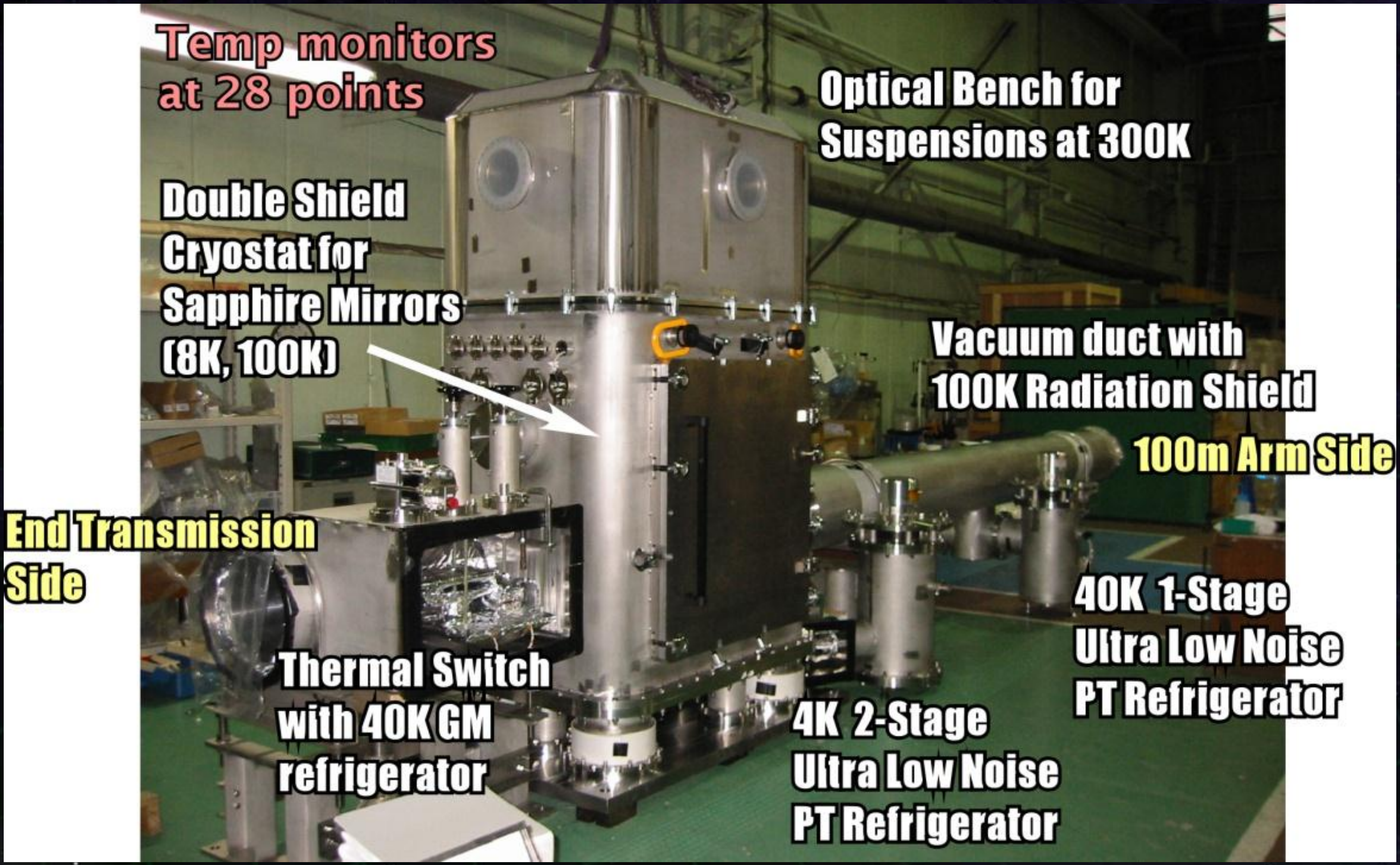
# Cryogenic Test-Mass

Test mass: Sapphire 2 kg, $\phi$100 x t60 mm
Suspension: 3 stages at room-temp, 3 stages in cryostat
Heat links for conductive cooling
Low-vibration pulse-tube cryo-cooler



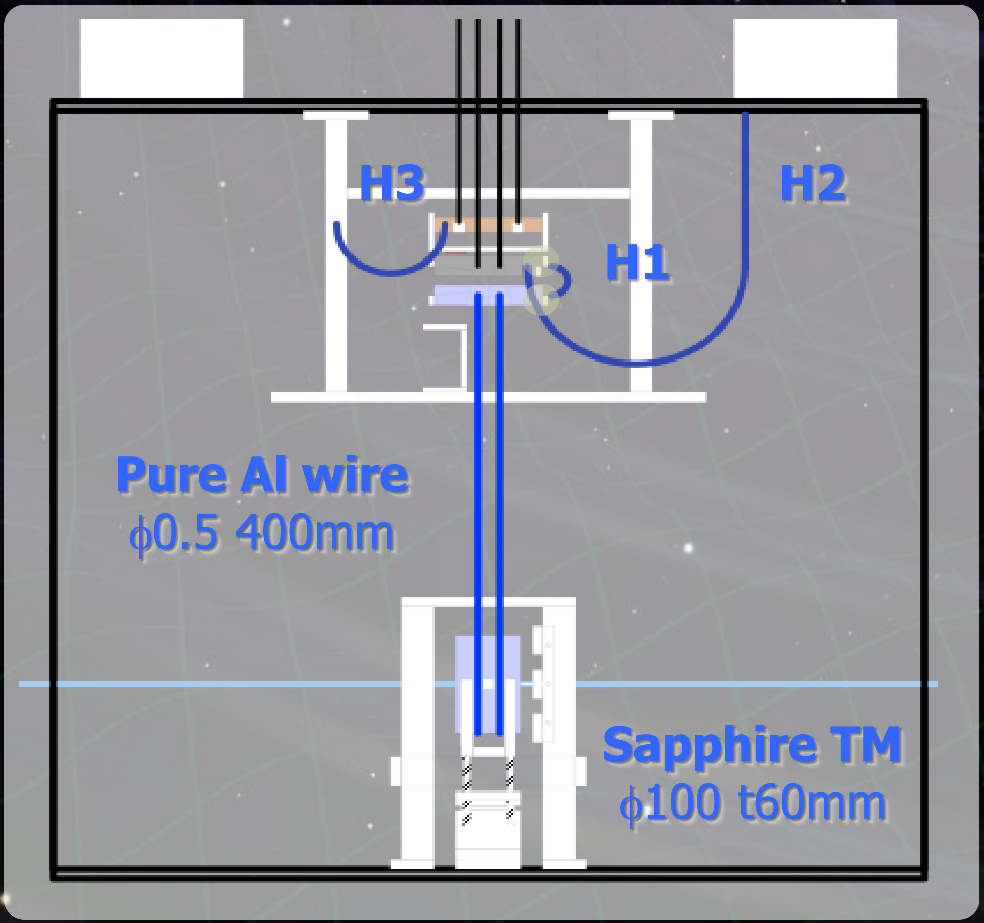
# CLIO Cryogenic system

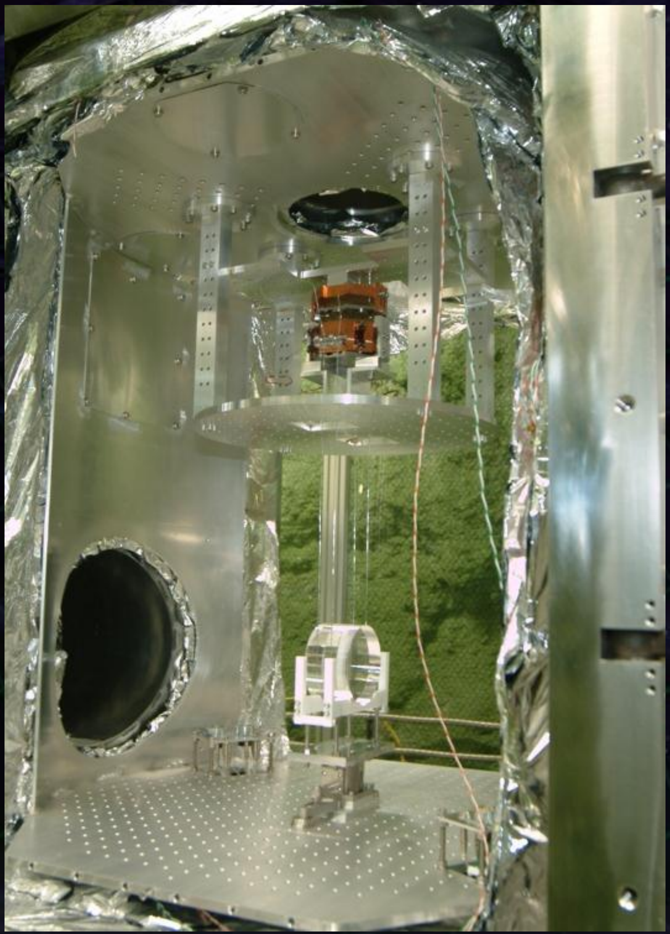
## Cryostat, cryo-cooler and radiation shield



# CLIO Cryogenic Suspension

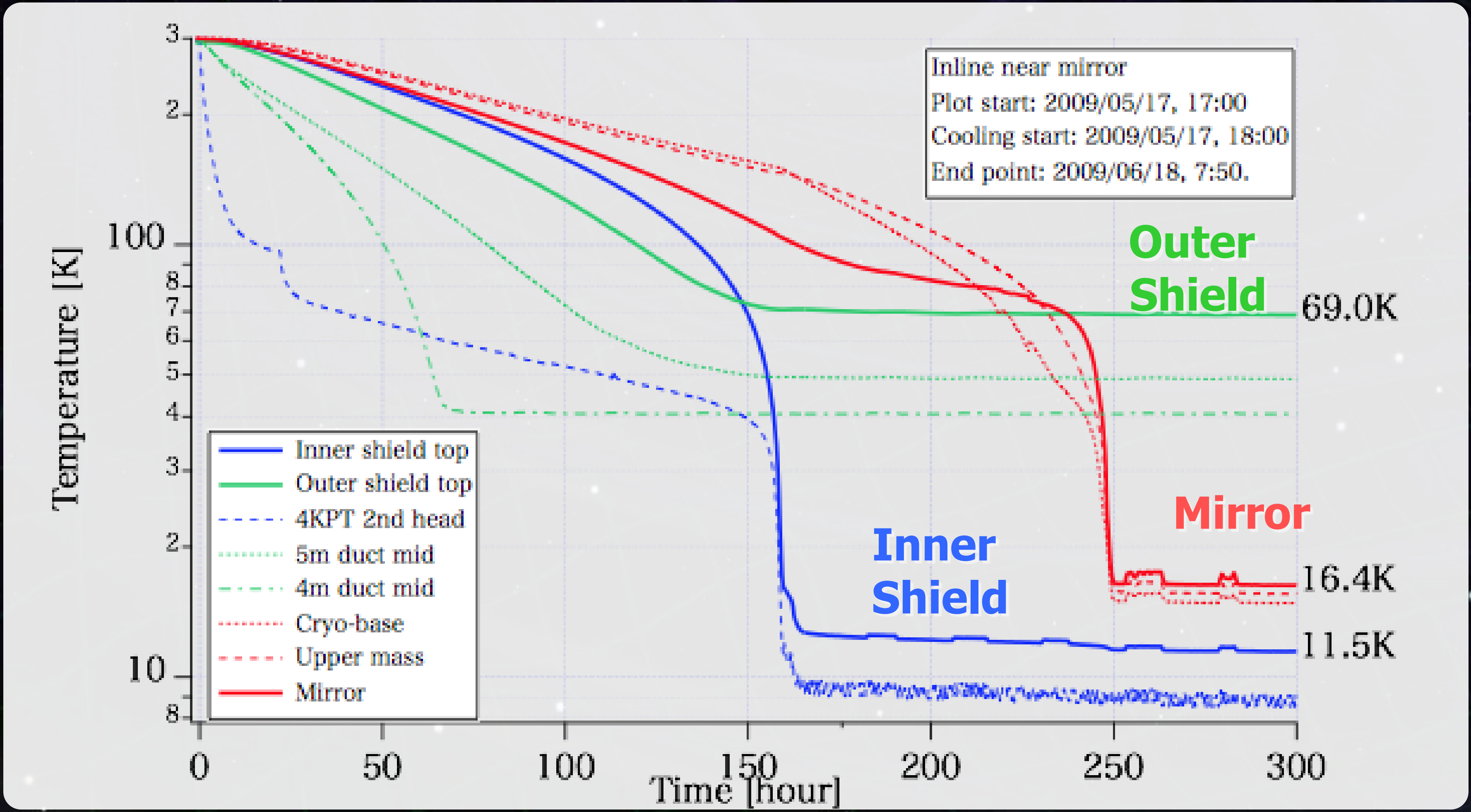
**Triple pendulum in cryostat**
**Sapphire test mass: 2 kg, ϕ100 x t60 mm**



# CLIO Test-Mass Cooling

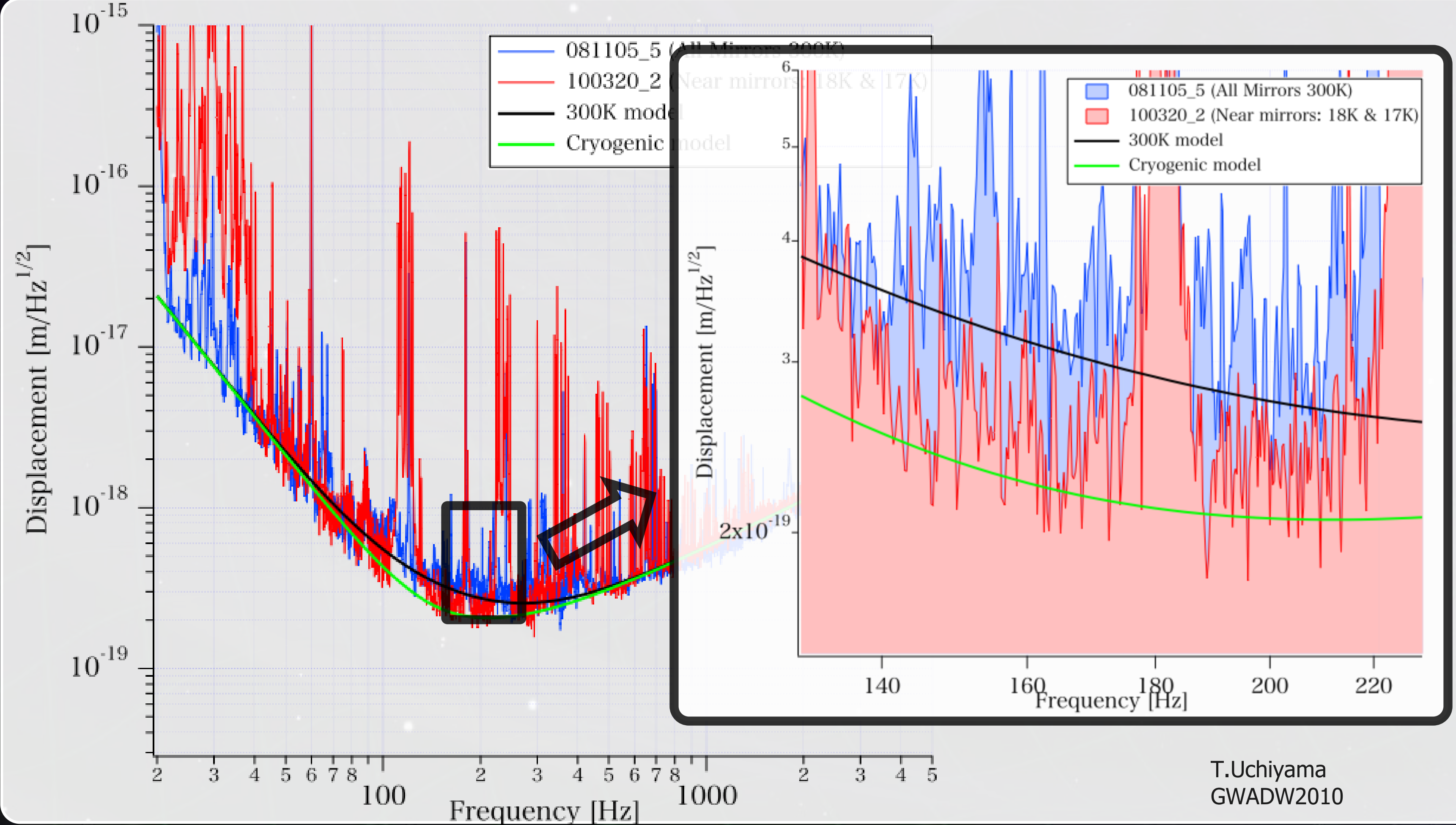
Cooling time: 250 hours for the test-mass mirror.
→ Cooled down to 16.4K



# CLIO sensitivity

**Sensitivity improvement with cryogenic operation**

**→ Seems to be Sapphire mirror thermo-elastic noise**




T.Uchiyama
GWADW2010

# Schedule

# LCGT schedule

- **We will have an initial-phase operation (iLCGT) as the first 3-year program**

  3km FPM interferometer at room temperature,
  with simplified vibration isolation system (TBD)
  ~1 month (TBD) engineering run in 2014.

- **Start observation in 2017 with the baseline design (bLCGT).**

  Cryogenic RSE interferometer
  with originally-designed vibration isolation system.

**Note: Details under discussion**

# Master Schedule

- 3 Major stages

  iLCGT (- 2014.9) Stable operation on large-scale IFO

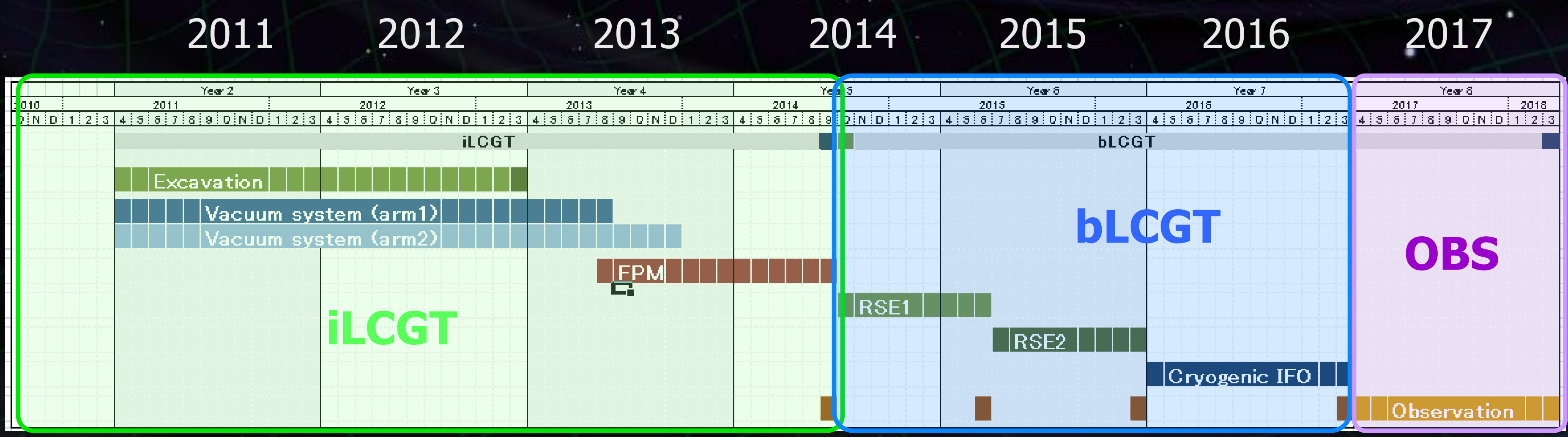
  → 3km FPM interferometer at room temperature,
  with simplified vibration isolation system

  ~1 month (TBD) engineering run

  bLCGT (2014.10 – 2017.3) Observation run with final configuration

  → RSE, upgraded VIS, cryogenic operation

  OBS (2017.4 -) Long-term observation and detector tuning



# Summary

# Summary

## LCGT : Project started

- Costs have been partially funded
- Form global network as one of the 2nd generation detectors

⇨ Aim to detect GW, and to open new astronomy

- LCGT will demonstrate 3rd generation detector techniques: cryogenics and underground

## Design and R&D

- Detailed design underway : internal and external reviews
- TAMA and CLIO experiences
  TAMA : GW observatory, TAMA-SAS
  CLIO : Cryogenic interferometer, underground site
- Prototype developments : SAS, Digital system, Cryostat

# By the way…

**LCGT will have a new Nickname soon…**

- Invite candidates from the public
  → over 600 applications.
- Naming committee with 6 peoples.
  Chair: Y. Ogawa (Novelist)
  → Has been decided in June 2011.

- Will be announced in a few month (?)

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- M.Ohashi, Class. Quantum Grav. 20 (2003) S599.
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- K.Agatsuma, Class. Quantum Grav. 27 (2010) 084022.

# End

# Detailed Specifications

# Main parameters

## Detector parameters

**Laser**
- Nd:YAG laser (1064nm)
- Master Laser + Power Amplifier
  - Power : 180 W

**Main Interferometer**
- Broad band RSE configuration
  - Baseline length : 3km
  - Beam Radius : 3-5cm
  - Arm cavity Finesse : 1550
  - Power Recycling Gain : 11
  - Signal Band Gain : 15
  - Stored Power : 771kW
  - Signal band : 230Hz

**Vacuum system**
- Beam duct diameter : 80cm
- Pressure : $10^{-7}$ Pa

**Mirror**
- Sapphire substrate + mirror coating
  - Diameter : 25cm
  - Thickness : 15cm
  - 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 : 30cm
  - Fiber diameter : 1.6mm
  - Temperature : 16K
  - Q of final suspension : $10^8$

# Main Interferometer (1/2)

## LCGT Main interferometer

- Sufficient sensitivity and stability to detect GWs
  - Inspiral range >250Mpc (Optimal direction and polarization, SNR>8)
  - Duty cycle > 90%

- **Optical design**
  - Dual-recycled Fabry-Perot-Michelson interferometer in RSE mode
  - Variable RSE between Detuned and Broadband operation
  - Inspiral range : 275Mpc
- **Arm cavity**
  - Baseline length : 3000 m
  - Sapphire test masses at cryogenic temperature of 20K
  - Finesse : 1546
  - ITM reflectivity : 99.6%
  - Round-trip loss < 100ppm
  - Accumulated power: ~400kW/arm
  - ROC : Flat (ITM), 7km (ETM)
  - g-factor : $g_1=1$ , $g_2=0.572$
  - Beam size : 3.43cm (ITM), 4.53cm (ETM)

- **Central interferometer**
  - Power recycling gain : ~11
  - Signal band gain : ~15
  - PRM, SEM ROC : 300m
  - Folded cavities for stability
    - Length : 66.62m
    - ROC : -3.251m, 27.26m
    - Gouy phase shift : 20deg
  - MI Asymmetry : 3.33 m
  - RF sideband condition
    - f1 (PM 16.875 MHz)
      - Resonant with PRC-SRC
    - f2 (PM 45 MHz)
      - Resonant with PRC
      - Full reflectivity by MI part
    - f3 (AM 56.25MHz)
      - Non-resonant to PRC

# Main Interferometer (2/2)

- **Length signal sensing and control**
  - Frontal modulation
    - for 5 length DoF for MIF control

| | Signal port | UGF |
|---|---|---|
| DARM | ASDC | 200 Hz |
| CARM | REFL 1I | 10 kHz |
| MICH | REFL 1Q | 10 Hz |
| PRCL | POP 2I | 50 Hz |
| SRCL | POP 1I | 50 Hz |

Feed forward gain : 100
Non-linear factor : $10^9$ $m^{-1}$
PD dynamic range : 160dB
Variable RSE by SRC tuning :
Offset addition to control signal

- **Alignment signal sensing and control**
  - Wave front sensing and optical lever
  - Details : TBD

- **Lock acquisition**
  - Pre-lock of arm cavities with auxiliary green laser beams
    - Beam injection from folding mirrors in PRC and SEC
    - Arm finesse to green beam : ~10

Third-harmonic demodulation
(Beat between 2*f1 and f1)

Non-resonant sideband

# Tunnel

**LCGT underground site**

Ikenoyama mountain >200m from the ground level
Tunnel tilt : 1/300 for natural water drain
(Experimental rooms : leveled)

- Location
  Latitude 36 deg N , Longitude 137 deg E
  Height : 372 m above the sea level
  Arm direction: X-arm 300 deg, Y-arm 30 deg (from North)
  → height difference of 20m between X and Y end rooms
- 3 access tunnels from the ground level
- 2 water drain points
- Arm tunnels
  Excavation by TBM
  (Tunnel Bowling Machine)
  Tunnel Width 4m, Height 3.8m
- Experimental rooms
  Center and end rooms
  Excavation by NATM
  (New Australian Tunneling Method)
  Height : 4.2 m
- Test mass area
  20m x 12 m room
  2 layer structure
  1st floor height 8m
  2nd floor height 7m
  5m bedrock between them
  130m approach tunnel for 2nd floor

# Vacuum

## LCGT vacuum system

Vacuum pressure : < $1\times10^{-7}$ Pa ← Ion pump lifetime (5 years)
< $2\times10^{-7}$ Pa ← Residual gas noise (safety margin 10)

Scattered light suppression

- **Beam tube** for two 3km arms
  - Diameter : 0.8 m
  - Material : Stainless steel
  - Outgas rate : $10^{-8}$ Pa•m/s
  - Inner surface : Electro polishing
  - Pre-baking and dry-air seal before installation
  - Flange Connection of 500 tubes with 12-m length
- **Optical baffle**
  - 500 optical baffles at every 12-m inside the vacuum tube
  - Diamond-like Carbon (DLC) coating
  - Height : 40 mm (Saw-tooth edge, 45deg. tilted)
- **Chamber** (14 chambers)
  - 4 chambers with cryogenic system
    - Diameter : 2.4 m
    - Type-A vibration isolation for test mass
    - Aluminum-coated PET (polyethylene terephtalate) for thermal insulation
  - 7 chambers (BS, PRM, SEM, folding)
    - Diameter : 1.5 m (2 m for BS)
    - Type-B vibration isolation
  - 3 chambers (MC, PD)
    - Diameter : 2 m
    - Type-C vibration isolation
- **Pumping system**
  - Every 100m along the tube
  - Pumping unit with dry-pump + TMP + ion-pump

# Cryogenics

## Cryogenic System for test-mass mirror

Temperature of test mass : 20 K
Avoid excess vibration and mirror contamination

- **Test-mass suspension**
  - Cool mirror by thermal conduction
  - Sapphire suspension from upper mass
    - Cooling power : 1 W
    - 4 sapphire fibers
    - Diameter : ϕ1.6 mm
    - Length : 300 mm
  - Heat link : pure Aluminum (6N) wires (Upper Mass – CM – Cryo-shield)
- **Cryostat**
  - Vacuum chamber with cryo-shield (radiation shield)
  - Access to inside from both sides
  - Mechanical resonance >30 Hz
  - Inner shield : 10 K, 2W
  - Outer shield : 80 K, 90W
    - Insulator: Low-outgas MLI (or SI)
    - Size : 1990 x 1220 x 1500? mm
    - Mechanical resonance > 22 Hz
- **Low-vibration cryocooler**
  - Pulse-tube cryocooler
    - Cold head temperature : 4 K
  - Vibration isolated cold head
    - Separated valve unit
    - Flexible link to heat bath
    - Rigid frame for supporting stage
  - Acoustic shield
    - Compressor placed in a separated room with acoustic shield
- **Shield duct**
  - to avoid incoming residual gas and thermal radiation
  - Length : 20 m (TBD)
  - Diameter : ϕ500 mm, t 10 mm
  - Baffle aperture: ϕ250 mm
  - Temperature : 65 - 77 K
  - Cryocooler : 50K, 150W

# Vibration Isolation (1/2)

## Vibration isolation system

- Reduce the seismic noise level below optical-readout noise at 10 Hz
  - Displacement noise < $4 \times 10^{-20}$ m/Hz$^{1/2}$ at 10Hz,
  - Residual RMS fluctuation < 0.1μm, < 0.1 μm/s

- **Type-A system for cryogenic test mass**
  Low-frequency, multi-stage vibration-isolation system with cryogenic compatibility

### Room-temperature isolator part

**Pre-Isolator**

- Inverted Pendulum (IP) and GASF
- IP Length : 50 cm
- Resonant frequency : 30mHz
- Sensor : 4 Geophones (L4-C), 4 LVDTs
- Actuator : Magnet-coil
  Stepping motor, Pico motor

**GAS (Geometric Anti-Spring) filter**

- 3-stage filters suspended by a single wire
- Resonant frequency : ~ 350 mHz
- Yaw-mode damping onto the first stage

### Cryogenic Payload

3-stage suspension (PF-IM-TM)

**Test mass (TM)**

- Sapphire mirror, Temp: 20K
- Weight : 30kg
- Recoil mass (RM) for actuation

**Intermediate mass (IM)**

- Suspend TM with sapphire fibers
- Damping from Magnet Box (MB)

**Platform (PF)**

- Suspended from room-temp. part by a single wire with low-thermal conductivity
- Actuated from CB (Control box)

**Heat link**

- Pure Aluminum wire
- Link between IM-PF and PF-Radiation shield

# Vibration Isolation (2/2)

- **Type-B system for room-temp. optics**

  Low-frequency, multi-stage
  vibration-isolation system
  Used for BS, PRM, SEM, Folding mirrors
  Based on TAMA-SAS

  **Pre-Isolator**
  Inverted Pendulum (IP) and GASF
  IP Length : 50 cm
  Resonant frequency : 30mHz
  Sensor : 4 Geophones (L4-C), 4 LVDTs
  Actuator : Magnet-coil
  Stepping motor, Pico motor

  **GAS (Geometric Anti-Spring) filter**
  Vertical filter
  suspended by a single wire
  Resonant frequency : ~ 350 mHz
  Yaw-mode damping

  **Payload**
  3-stage suspension (PF-IM-TM)
  Test-mass weight : 10kg

- **Type-C system**

  Double pendulum on
  Multi-layer stacks
  Used for MC, PD
  Based on original TAMA isolation
  Suspended optics : 1kg

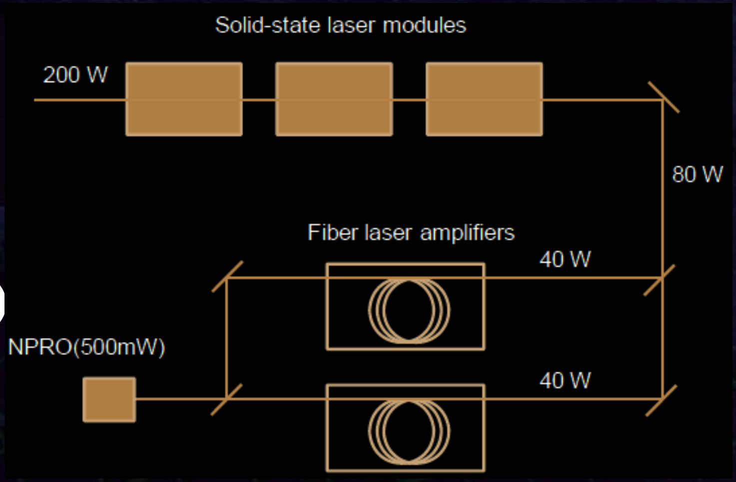
  **Multi-layer stack**

  **Double pendulum**

# Laser

## High-power and stable laser source

Wavelength : 1064nm
Output Power 180 W
Single mode, Linear polarization
Line width < a few kHz
Frequency noise $< 100\ Hz/Hz^{1/2}$ (100Hz)
Freq. Control band ~ 1 MHz
Intensity noise $< 10^{-4}\ Hz^{-1/2}$ (100Hz)
Int. control band > 100 kHz




## High-power MOPA laser

→ Easy assembly and maintenance

- Seed laser
  NPRO (Nonplanar Ring Oscillators)
  Power 500mW
- Fiber amplifier
  Commercial fiber amp.
  NUFERN Single Freq. PM amp.
  Output power ~40W
  Coherent addition with two units
- Solid-state laser module
  Side pump + diffusive reflector
  Laser module by Mitsubishi
- Frequency stabilization
  PZT of the master laser
  External wideband EOM
  Stoichiometric $LiNbO_3$
- Intensity stabilization
  Current shunt control
  on power amplifier

# Core Optics

**Cryogenic test mass --- Sapphire**

Temperature : 20 K
Absorption Loss < 20ppm/cm
Optical loss < 45ppm
Mechanical loss < $10^{-8}$

- **Substrate**
  - Diameter : 25cm
  - Thickness : 15cm
  - Mass : 30 kg
  - ITM: c-axis, ETM: a-plane (TBD)
  - Heat Exchange Method (HEM) by Crystal Systems Inc.
- **Polish**
  - ROC ITM: Flat, ETM: 7km
  - ROC Error : 100m (Error $\lambda/40$)
  - Scattering < 30ppm
- **Coating**
  - Absorption < 0.5ppm
  - Mechanical Loss < $10^{-4}$
  - Moderate reflectivity for green beam

**Room-temp. optics --- Fused Silica**

Temperature : 290 K
Absorption Loss < 1ppm/cm
Homogeneity < $10^{-7}$

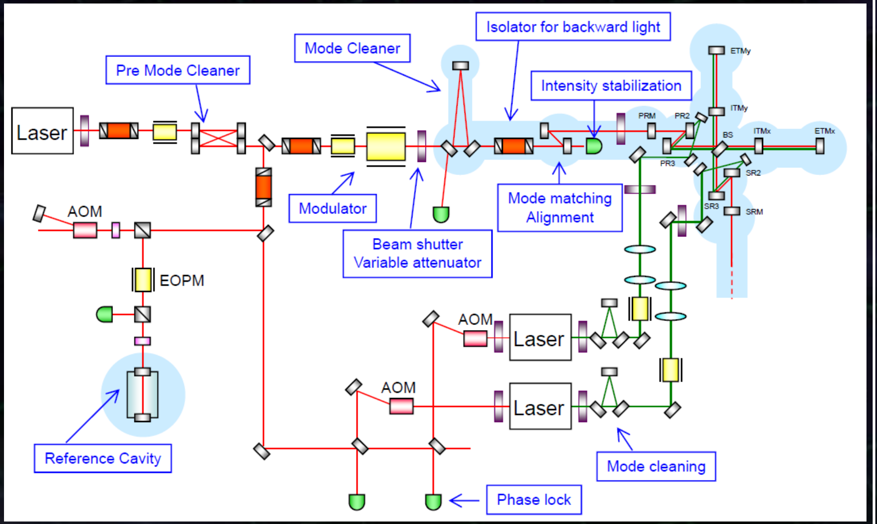
- **Main interferometer** (PRM, SEM, Folding Mirror)
  - Diameter : 25cm
  - Thickness : 10cm
  - Mass : 10 kg
  - *also used for iLCGT test mass
  - AGC or Heraeus (ITM)
  - LIGO TM substrates (other)
- **Beam splitter**
  - Diameter : 38cm
  - Thickness : 12cm
  - Mass : 30 kg
- **Input optics (MC, MMT)**
  - Diameter : 10 cm
  - Thickness : 3 cm
  - Mass : 0.5 kg

# Input/Output Optics (1/3)

## Input Optics between the laser source and the main interferometer

Frequency stability < $3\times10^{-8}$ Hz/Hz$^{1/2}$
Intensity stability < $2\times10^{-9}$ Hz$^{-1/2}$
RF intensity noise < $1\times10^{-9}$ Hz$^{-1/2}$ (>10MHz)
Beam jitter : ---
RF modulation : 16.875 MHz 45 MHz (optional 56.25 MHz)
$TEM_{00}$ power throughput >50 % (?)

- **Mode Cleaner**
  Suspended triangle cavity
  for spatial MC, reduction of beam jitter, and freq. stabilization
  Transmission of RF sidebands for main interferometer control
  Round-trip length : 53.333 m
  Finesse : ~500
  FSR : 5.625 MHz
  Mirror dimension : φ100mm, t30mm
  ROC : Flat (In and Out)
  40 m (End)
  Beam radius : ~2.5mm at waist



# Input/Output Optics (2/3)

**Input Optics** between the laser source and the main interferometer

- **Pre Mode Cleaner (PMC)**
  - 2 or 3 PMCs in series for
    RF noise reduction and spatial MC
  - Monolithic 4-mirror bow-tie cavity
  - Roundtrip length : 1.95 m
  - Finesse : 155
  - Cutoff freq. : 154 MHz
  - Length control :
    PZT (<1kHz) and heat expansion
  - Spacer material : Aluminum
  - Placed in air-enclosed case

- **Reference cavity**
  - Low-frequency reference at DC - 10Hz
  - Linear cavity in vacuum,
    supported by a vibration isolator
  - Length : 15cm
  - Finesse : $10^5$
  - Cutoff freq. : 50kHz
  - Spacer material : ULE or Silica

- **Modulator**
  - RF sidebands for MIF control
    16.875 MHz (PM), 45 MHz (PM)
    56.25 MHz (AM optional)
  - Mach-Zender IFO for 2 PMs
  - EOM : RTP or MgO-doped $LiNbO_3$
    4x4 (or 5x5) $mm^2$ for PM
    2x2 $mm^2$ for ~1MHz control
    4x4 $mm^2$ for >100kHz control
    Crystal length : 20 – 40 mm

- **Isolator**
  - Suspended Faraday isolator
    between MC and MIF
  - Details : TBD

- **Mode-matching telescope**
  - Suspended folded telescope
    between MC and MIF
  - Length : ~5.6 m
  - Mirror size : $\phi$100mm, t30mm
  - ROC : ~20.6m, 26.1 m

# Input/Output Optics (3/3)

## Output Optics

between the main interferometer and analog electronics

OMC throughput : TBD
Photo detection power : ~100mW

- **Output Mode Cleaner**
  - 4-mirror bow-tie cavity for beam cleaning at dark port
  - Round-trip length : 1.52 m (TBD)
  - Finesse : 1000 (TBD)
  - Cutoff freq. : 98 kHz
  - Spacer material : TBD
  - Actuator and control : TBD

- **Output Telescope**

- **Photo Detection**
  - Main PD in vacuum tank
  - DC/RF PD
  - Wave Front Sensor
  - Beam Shutter

## Others

- **Green beam** injection for lock-acquisition of MIF
  - Phase-locked to the main beam
  - Injected to MIF from PRC and SEC folding mirror

- **Optical lever** for test masses
  - Details TBD

- **Laser room facility**
  - for optical benches of laser source and input optics
  - Clean room : Class TBD
  - Temp. control : +/- 1K
  - Acoustic shield

# Digital System

**LCGT digital observation system**

Data acquisition and control system

Observation bandwidth >5 kHz, Dynamic range >120 dB

Control bandwidth > 200 Hz, Signal number > 1024 channels

Observation system

Human interface , Observatory monitor, Detector diagnosis

- **Control system**

  Network of ~12 real-time systems and client workstations

  Sampling rate : 16,384 Hz

  ADC resolution : 16 bit

  Input

  ADC range : +/- 15 V

  Signal number : 2048 ch

  Output

  DAC range : +/- 10 V

  Signal number : 512 ch

  Binary Output : 2048 ch

  DAC/DAC noise : $<3\ \mu V/Hz^{1/2}$

  Delay $< 100\ \mu sec$

- **Timing system**

  GPS-based timing distribution system

  Ground-level GPS antenna

  → Timing master in the center room

  Real-time modules are synchronized using 1 PPS signal

  Recorded with data as IRIG-B format

  Timing accuracy : ???

- **Environment monitor**

  RT system or

  EPICS-based system (TBD)

- **Data Storage**

  Recorded in frame format

  300 TByte/year

  (16kHz : 64ch, 2kHz : 512ch, 64Hz : 1024ch, 16 Hz : 10000ch)

# Analog electronics

## Analog electronics

- **DC power supply**
  - Low-voltage power supply
    - Bipolar : 24V
    - Distributed by D-Sub 3W3
    - 24-to-15 V series regulator
  - High-voltage power supply
    - Bias voltage for QPD : 180 V
    - Power supply for
      - Coil driver, PZT actuator,
      - LD driver, TEC driver
- **Conditioning filter** for digital system
  - Anti-aliasing and Whitening filter for ADCs
  - Anti-imaging and de-whitening filter for DACs
- **High-speed controls**
  - High-speed servo, Feedaround,
  - Threshold detector for digital I/F
- **Actuator drivers**
- **Photo detector**
  - Quantum efficiency > 0.9
  - DC photo detector for MIF DC readout
    - Input power : 100 mW
    - PD diameter : $\phi$3 mm
  - RF photo detector
    - Input power : 100 mW
    - PD diameter : $\phi$3 mm
    - Frequency : 16.875MHz, 45 MHz
  - RF-QPD for wave front sensors (WFS)
  - AF-QPD for beam position sensing
  - Optical lever sensors
  - CCD imaging monitors
- **RF system**
  - Low-noise oscillator synchronized to 10MHz standard
  - RF distributor
  - Modulator resonant driver
  - Demodulator
    - Noise level : $1\text{nV/Hz}^{1/2}$
    - Range : 100 mV

# Data Analysis

**Data analysis**

- DAQ
  - Data acquisition, low-latency transfer
  - Data storage
  - Data characterization
- Analysis
  - Search for GW signals, and extract scientific outcomes
  - Cooperate with other GW experiments

- **Data acquisition and storage** (by digital subsystem)
  - Raw-data rate : 70 GByte/hour
  - Data spool storage at Kamioka > 500 TByte

- **Calibration and data characterization**
  - Pre-processing for calibrated data
  - Data and detector characterization
  - Recorded in frame format at the ICRR Kashiwa site
  - Total storage : 30 PByte

- **Computing platform**
  - Main computing platform at Kashiwa
  - Computation power > a few TFlops
  - Software libraries in cooperation with world-wide network
  - Distribution of data subset to collaborators

- **Network observation**
  - Low-latency data processing for follow-up observations
  - GW observatories
  - Counterpart observations
    - X-ray, Gamma-ray, Radio afterglow
    - Neutrino

# Materials

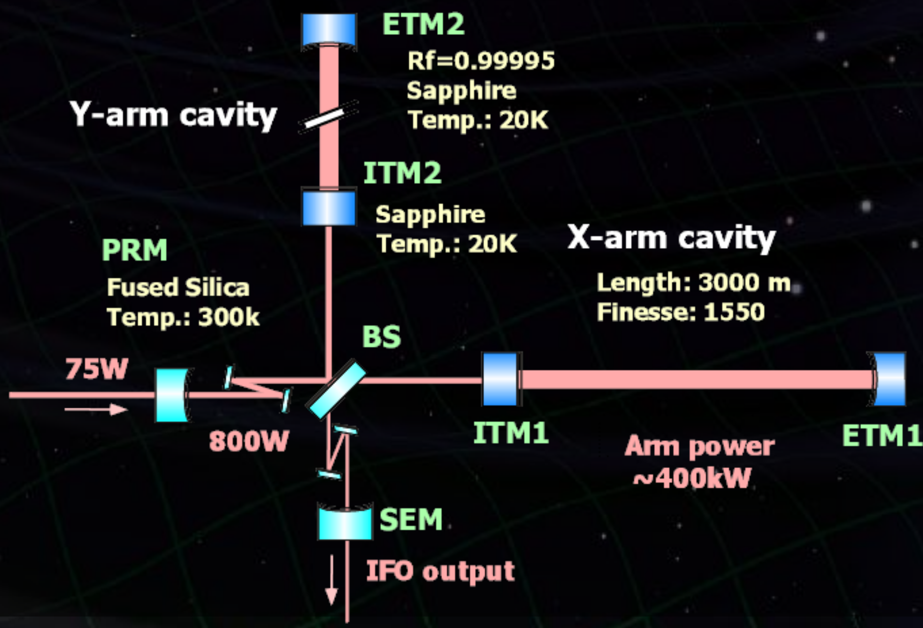
# LCGT interferometer

## High-power RSE interferometer with cryogenic mirrors

**Resonant-Sideband Extraction**
- Input carrier power : >85W
- DC readout
- PRC, SEC :Folded for stability

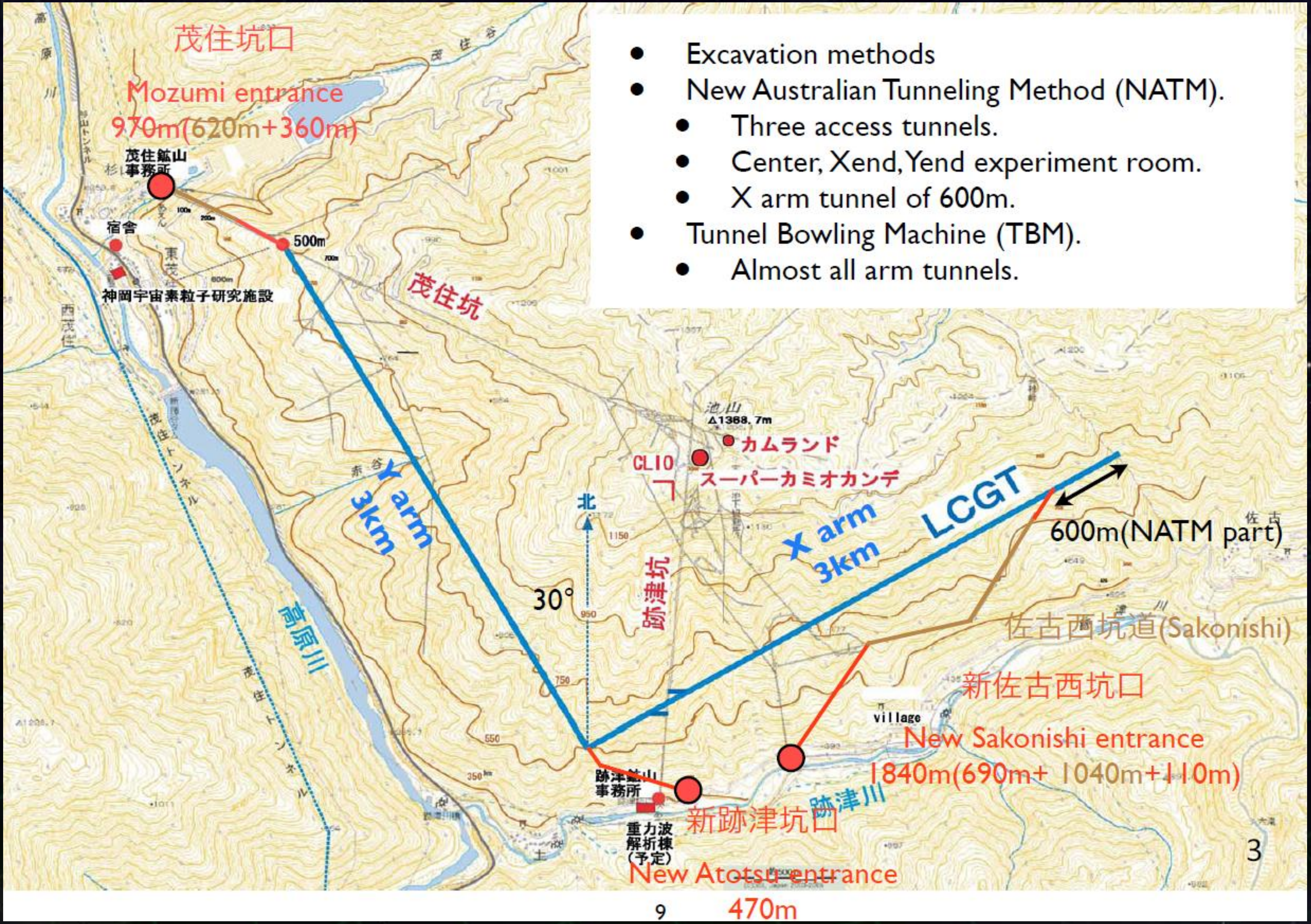
**Main IFO mirror**
- 20K, 30kg (Φ250mm, t150mm)
- Mech. Loss : $10^{-8}$
- Opt. Absorption 20ppm/cm

**Suspension**
- Sapphire fiber 16K
- Mech. Loss : $2x10^{-7}$

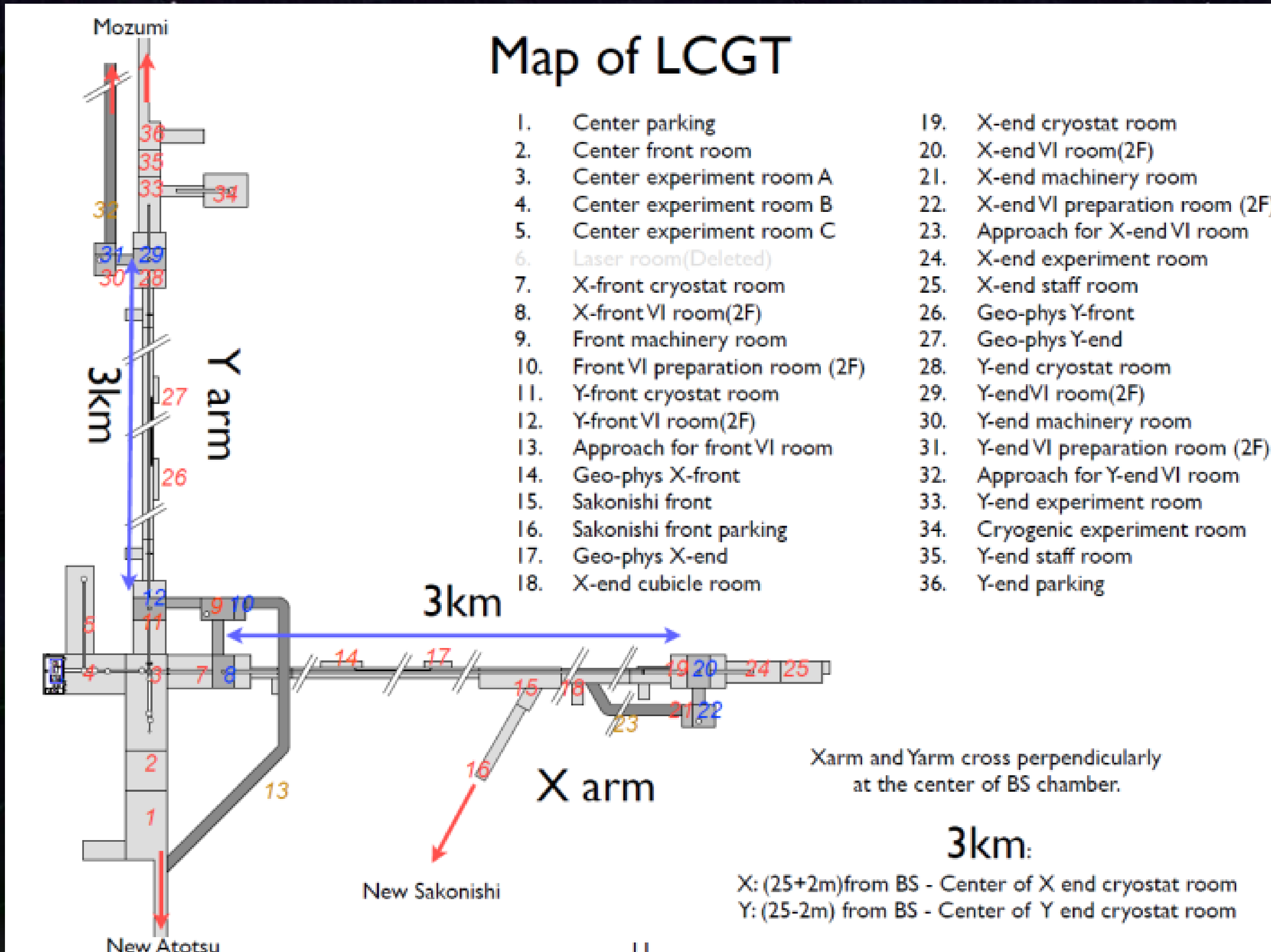


# Tunnel

- Excavation methods
- New Australian Tunneling Method (NATM).
  - Three access tunnels.
  - Center, Xend, Yend experiment room.
  - X arm tunnel of 600m.
- Tunnel Bowling Machine (TBM).
  - Almost all arm tunnels.

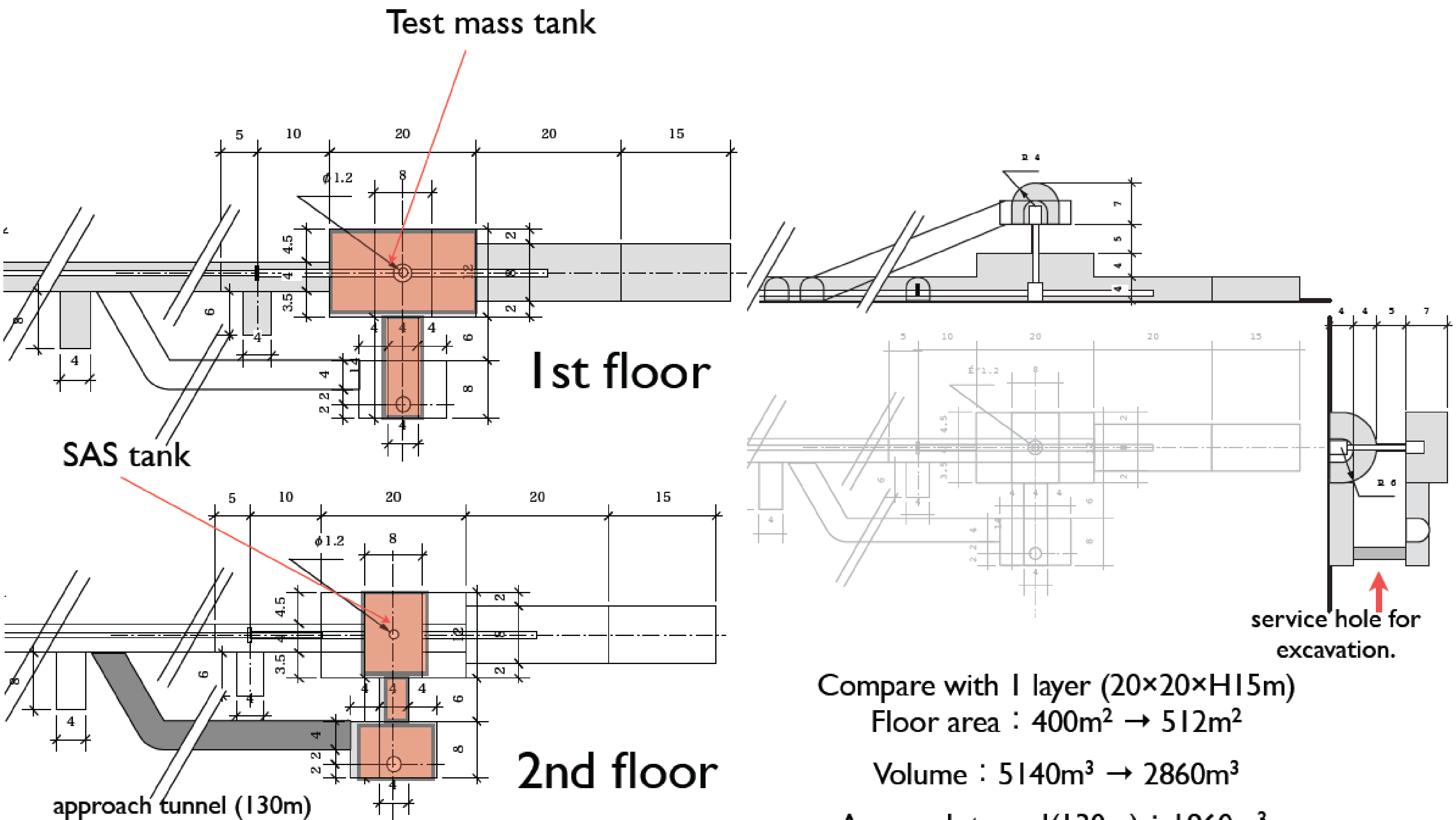


# Tunnel


Map of LCGT
1. Center parking
2. Center front room
3. Center experiment room A
4. Center experiment room B
5. Center experiment room C
6. Laser room(Deleted)
7. X-front cryostat room
8. X-front VI room(2F)
9. Front machinery room
10. Front VI preparation room (2F)
11. Y-front cryostat room
12. Y-front VI room(2F)
13. Approach for front VI room
14. Geo-phys X-front
15. Sakonishi front
16. Sakonishi front parking
17. Geo-phys X-end
18. X-end cubicle room
19. X-end cryostat room
20. X-end VI room(2F)
21. X-end machinery room
22. X-end VI preparation room (2F)
23. Approach for X-end VI room
24. X-end experiment room
25. X-end staff room
26. Geo-phys Y-front
27. Geo-phys Y-end
28. Y-end cryostat room
29. Y-endVI room(2F)
30. Y-end machinery room
31. Y-end VI preparation room (2F)
32. Approach for Y-end VI room
33. Y-end experiment room
34. Cryogenic experiment room
35. Y-end staff room
36. Y-end parking
Mozumi
Y arm
3km
3km
X arm
New Sakonishi
New Atotsu
Xarm and Yarm cross perpendicularly at the center of BS chamber.
3km:
X: (25+2m)from BS - Center of X end cryostat room
Y: (25-2m) from BS - Center of Y end cryostat room
11

# Tunnel

## X end (2layer)




Compare with 1 layer (20×20×H15m)

Floor area：400m$^2$ → 512m$^2$

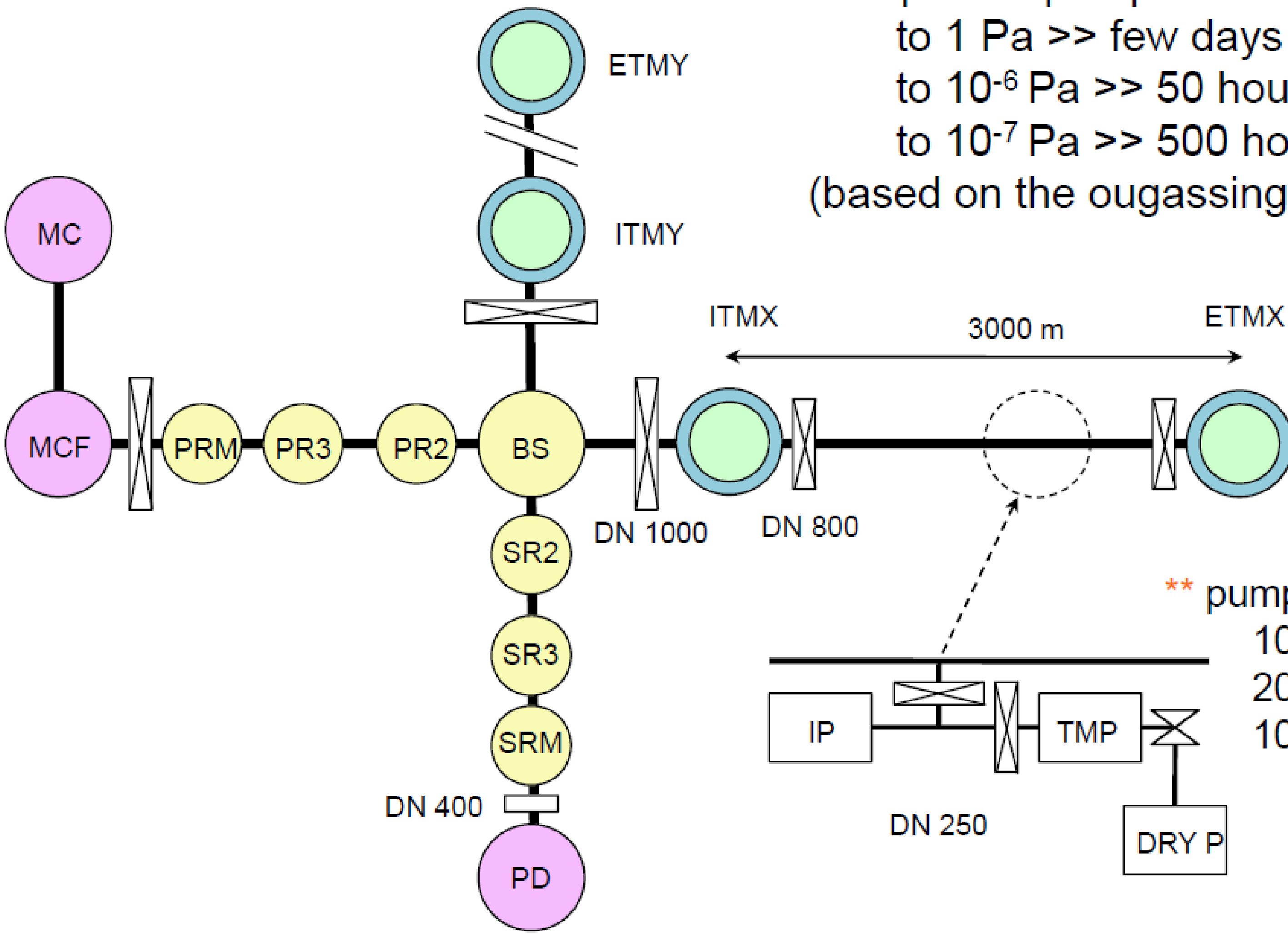
Volume：5140m$^3$ → 2860m$^3$

Approach tunnel(130m)：1860m$^3$.

Vertical hole: about 2,500,000Yen.

# Vacuum system

** expected pump-down scheme
to 1 Pa >> few days by dry-pump
to $10^{-6}$ Pa >> 50 hours by TMP
to $10^{-7}$ Pa >> 500 hours by IP
(based on the ougassing rate in test tube)




** pumping speed of the unit
100 $m^3/h$ >> dry-pump
2000 L/s >> TMP
1000 L/s >> IP

# Vacuum system

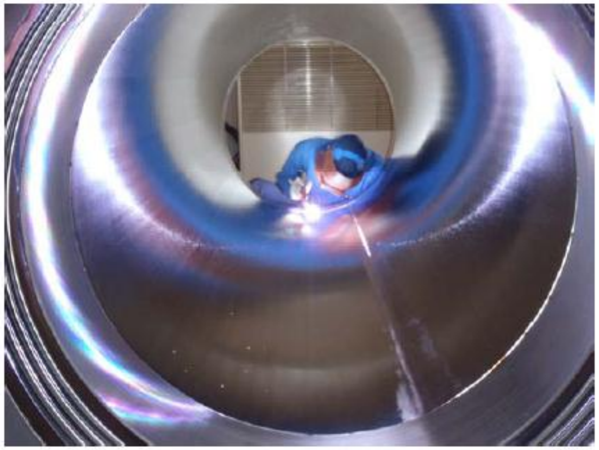
110302 VAC (YS)

## LCGT Vacuum System

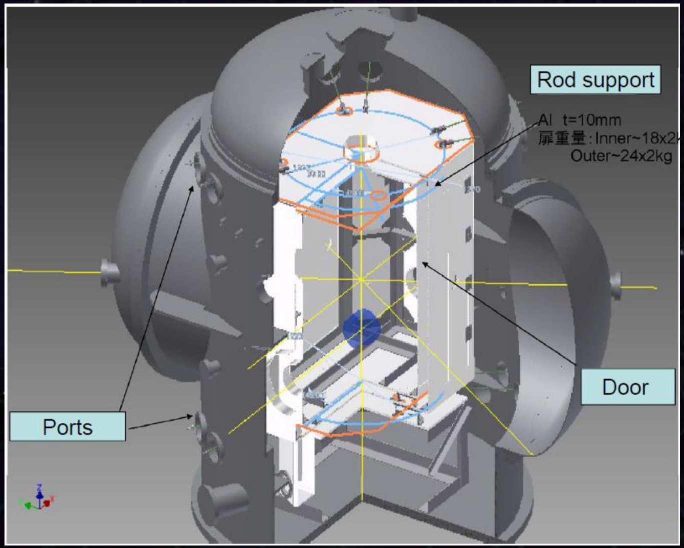
** test product of the tube

* A 4-m long tube was manufactured and a half of the inner surface was electro polished.

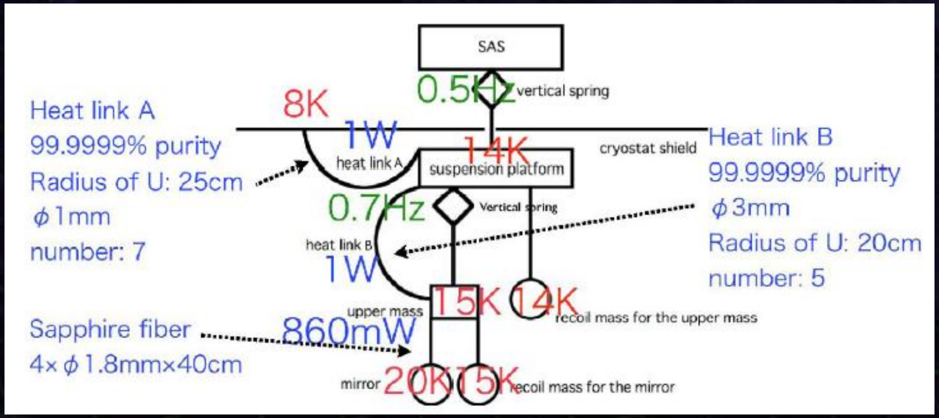
* A flange with a bellows (one convolution) was manufactured.



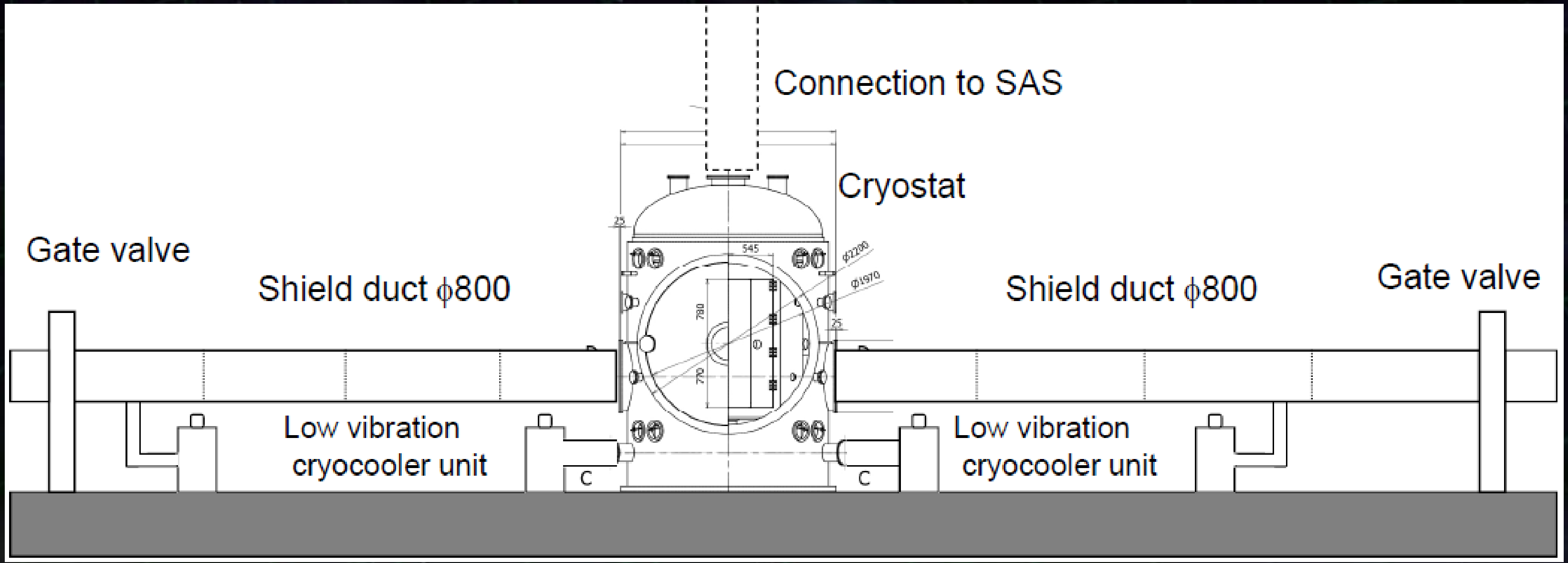
# Cryogenics



Rod support
Al t=10mm
扉重量:Inner~18x2
Outer~24x2kg
Door
Ports

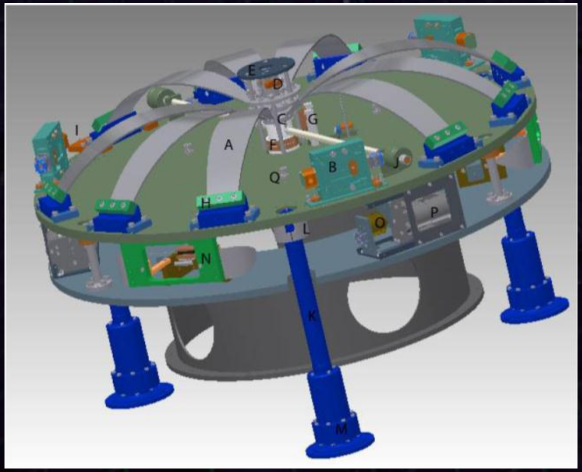



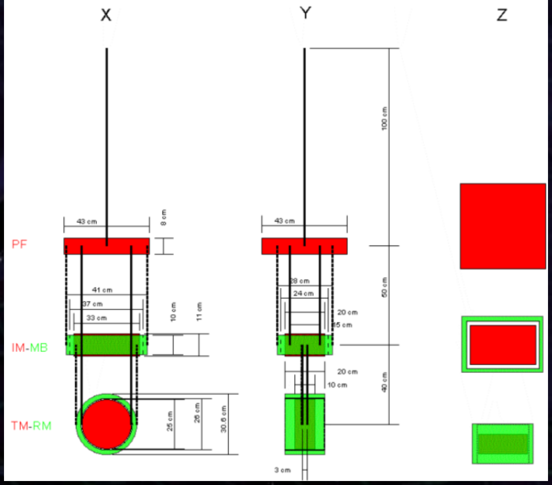
SAS
0.5Hz
vertical spring
Heat link A
99.9999% purity
Radius of U: 25cm
ϕ1mm
number: 7
8K
1W
heat link A
14K
suspension platform
cryostat shield
Heat link B
99.9999% purity
ϕ3mm
Radius of U: 20cm
number: 5
0.7Hz
Vertical spring
heat link B
1W
upper mass
15K
14K
recoil mass for the upper mass
Sapphire fiber
4×ϕ1.8mm×40cm
860mW
mirror
20K
15K
recoil mass for the mirror

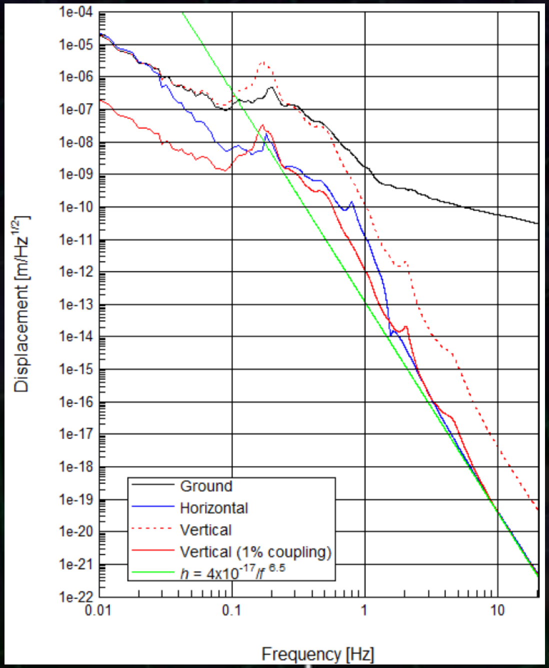
Connection to SAS
Cryostat
Gate valve
Shield duct ϕ800
Shield duct ϕ800
Gate valve
Low vibration cryocooler unit
Low vibration cryocooler unit

# Vibration Isolation

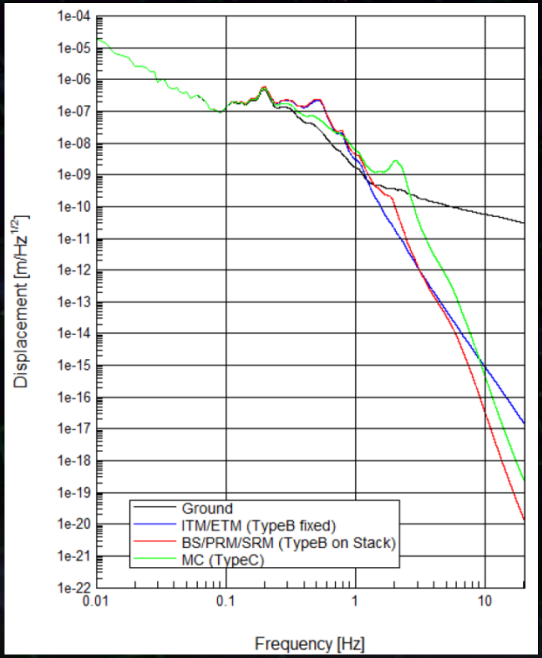


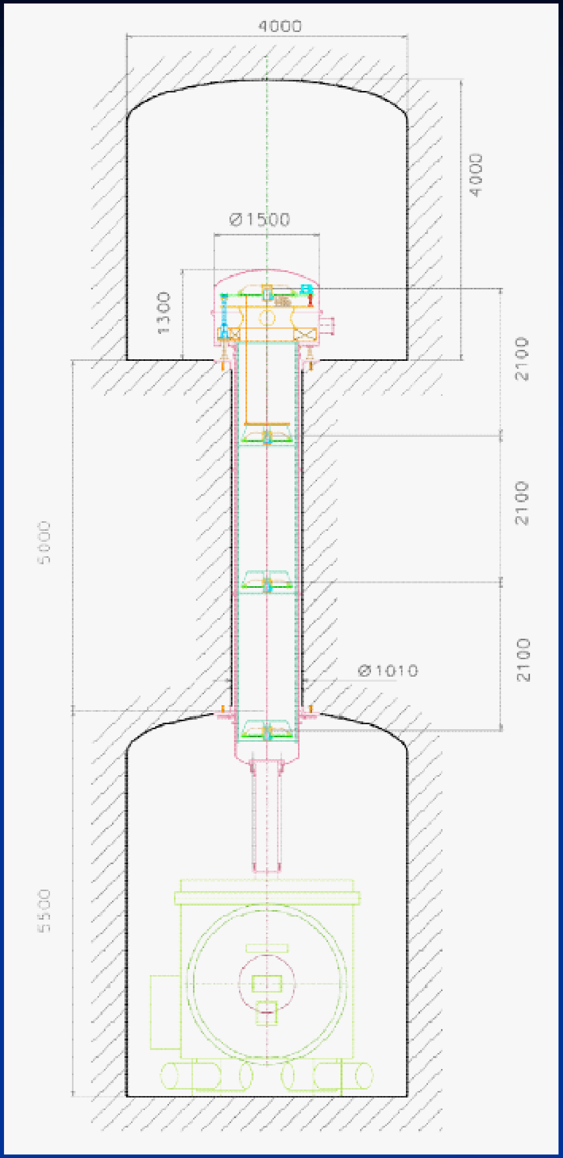

**Type-A**




**Type-B**



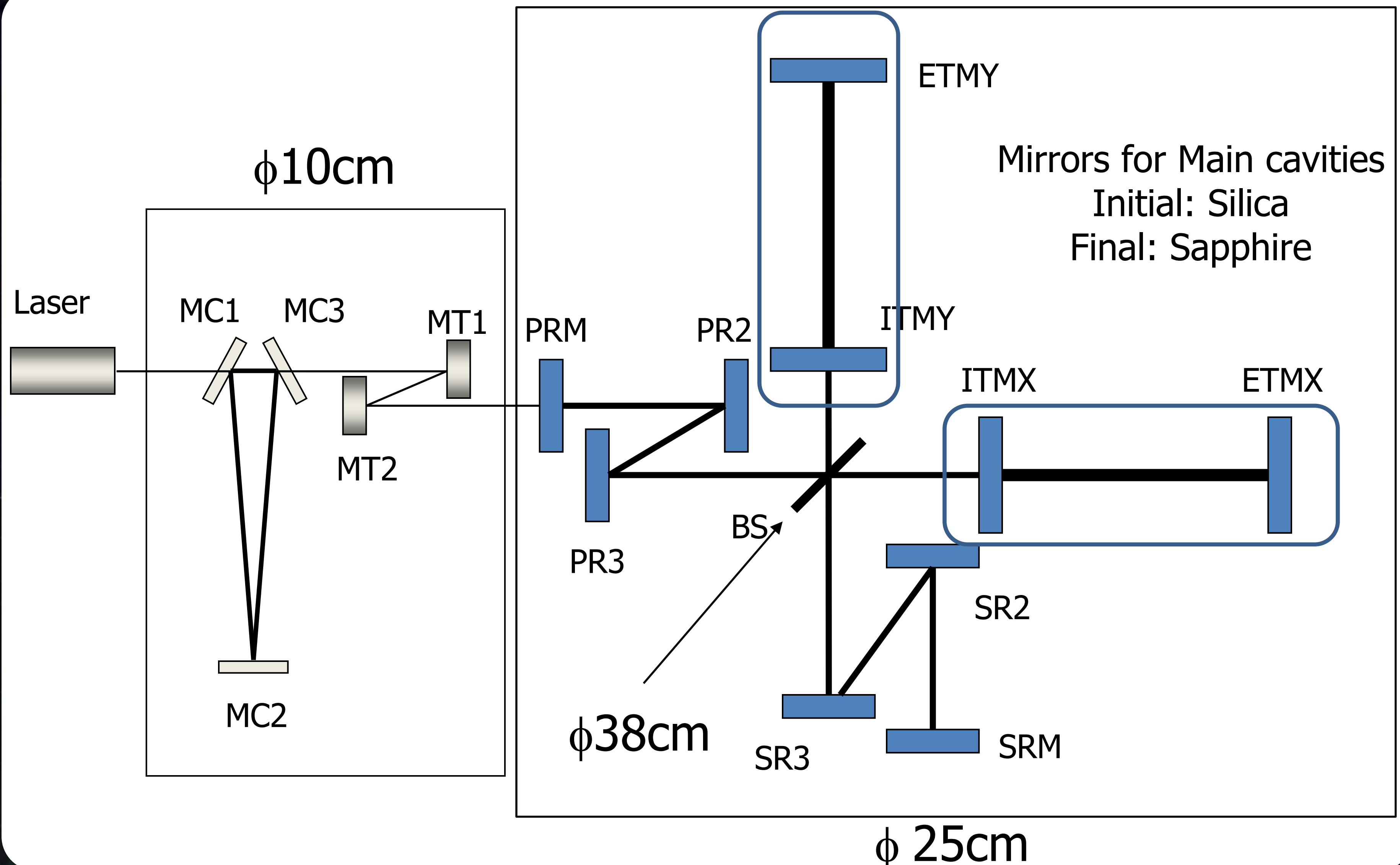
# Vibration Isolation




## Type-A (2-layer structure)

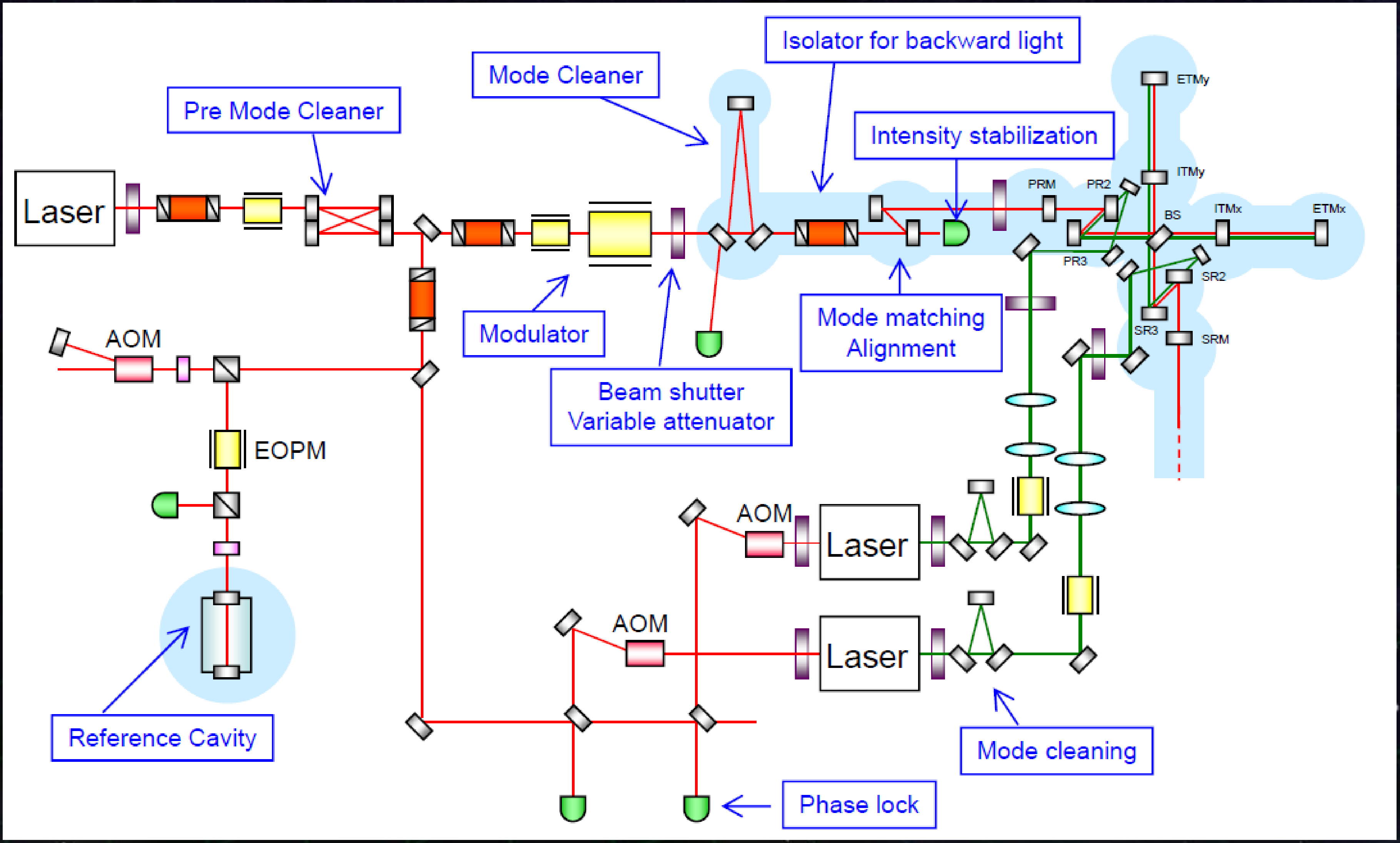
- Upper tunnel containing pre-attenuator (short IP and top filter)
- 1.2m diameter 5m tall borehole containing standard filter chain
- Lower tunnel containing cryostat and payload

# Core Optics

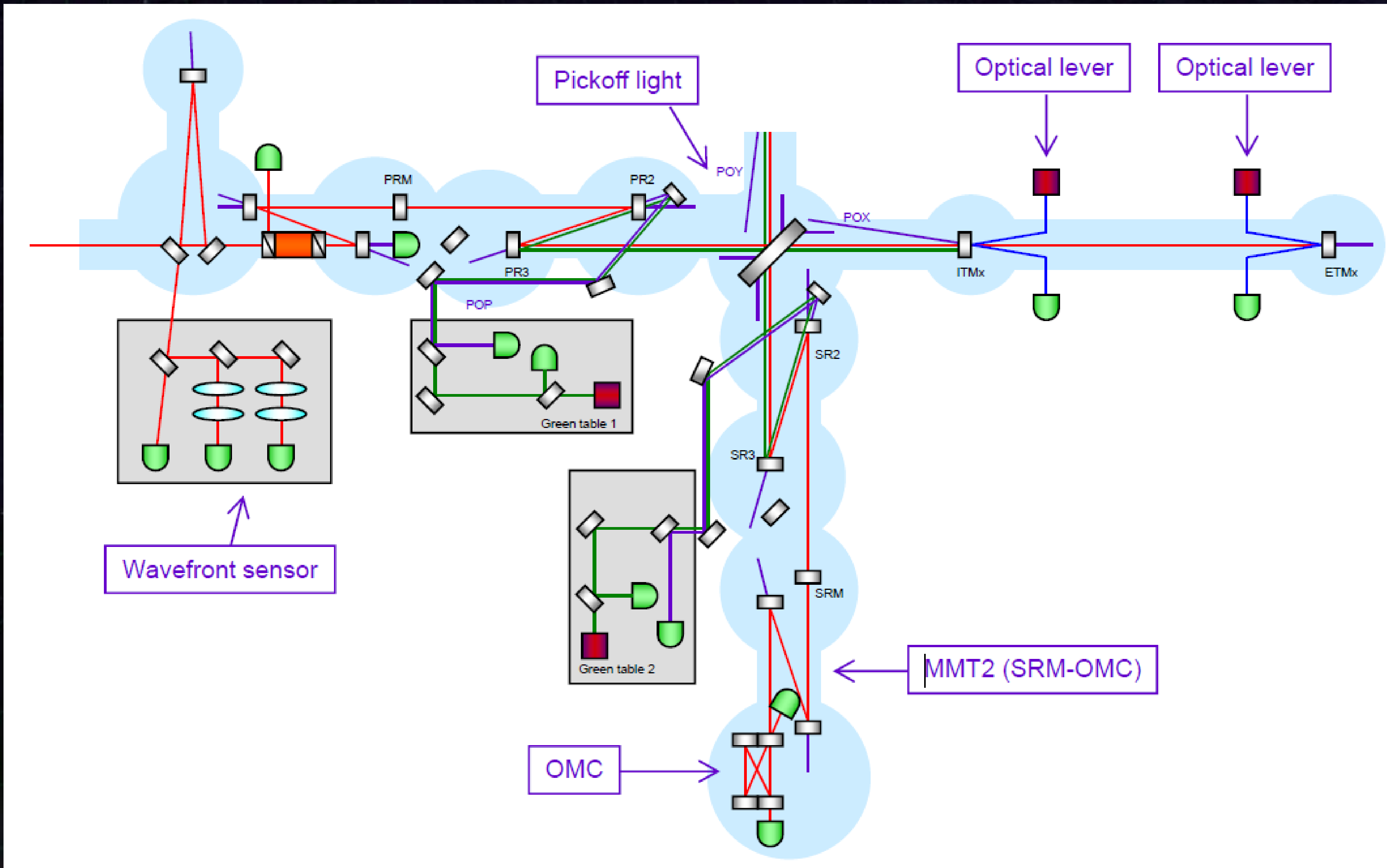


ϕ10cm
Laser
MC1
MC3
MT1
MT2
MC2
PRM
PR2
PR3
BS
ϕ38cm
ETMY
ITMY
ITMX
ETMX
SR2
SR3
SRM
Mirrors for Main cavities
Initial: Silica
Final: Sapphire
ϕ 25cm

# Input/Output Optics

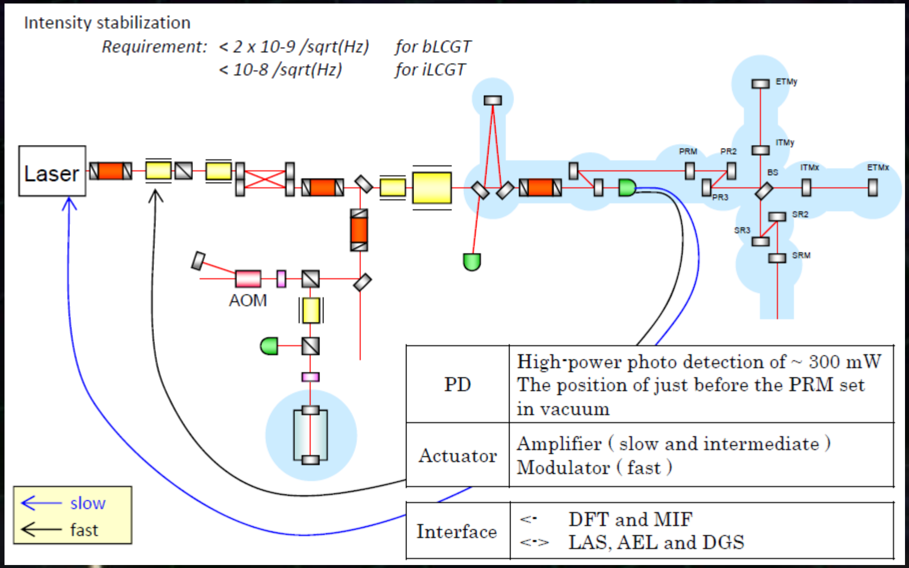


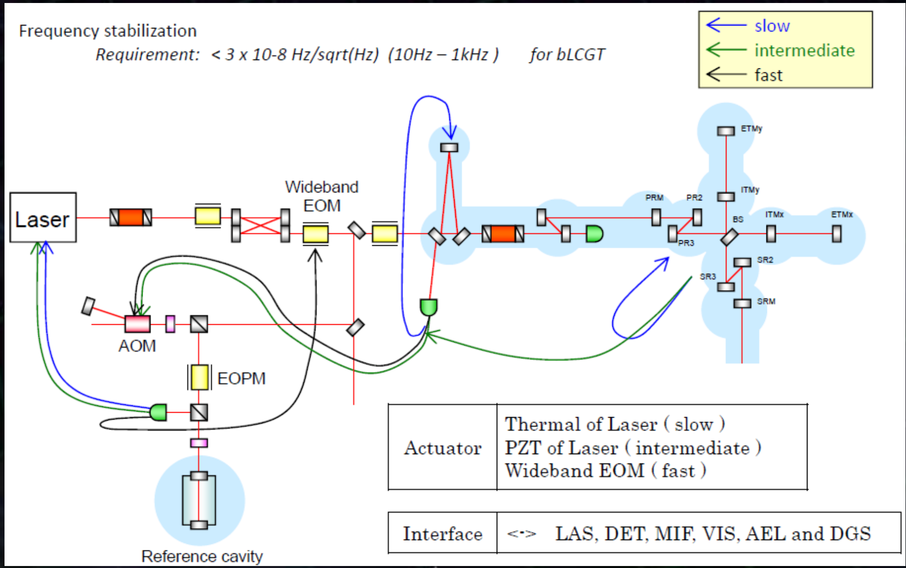
# Output Optics



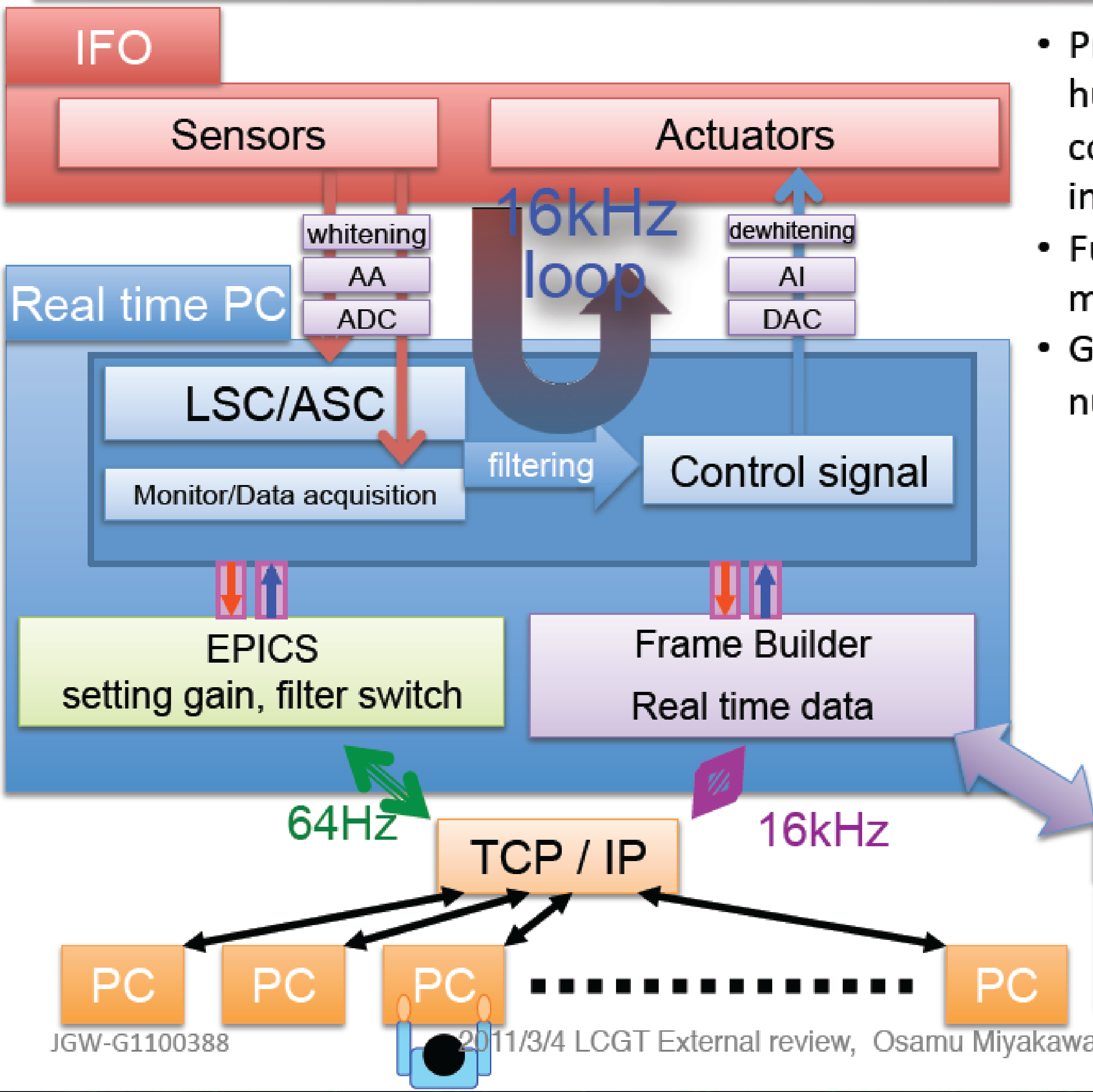
# Freq. and Int. stabilization

- **Intensity stabilization**
- **Frequency stabilization**



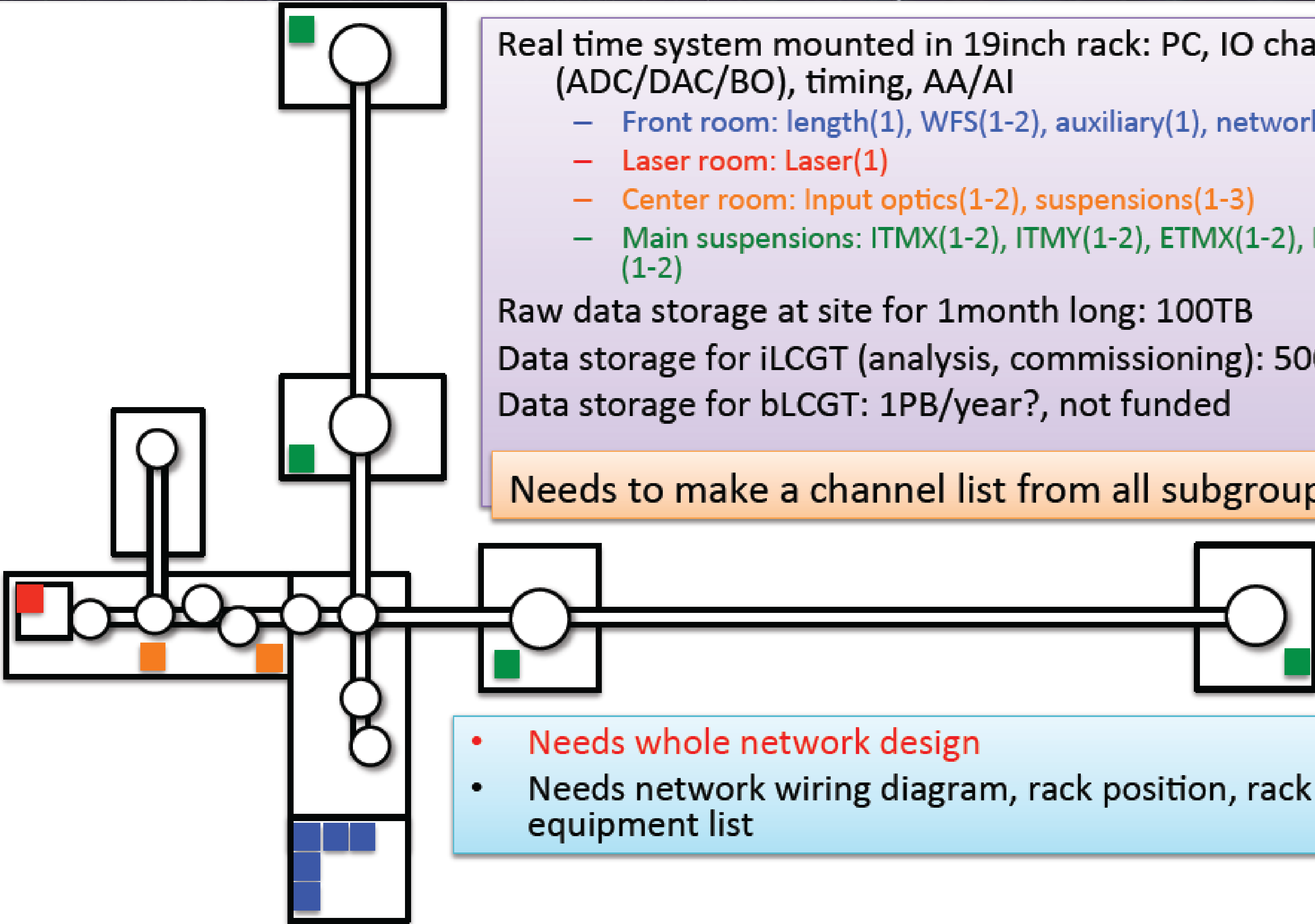
# Digital System




- Provides a very flexible human interface to the complex DOFs of the interferometer.
- Functions as sensing, control, monitor, switch
- Good solution to treat huge numbers of signals

16kHz full data
Trend data

# Digital System



Real time system mounted in 19inch rack: PC, IO chassis (ADC/DAC/BO), timing, AA/AI

- Front room: length(1), WFS(1-2), auxiliary(1), network(1-2)
- Laser room: Laser(1)
- Center room: Input optics(1-2), suspensions(1-3)
- Main suspensions: ITMX(1-2), ITMY(1-2), ETMX(1-2), ETMY (1-2)

Raw data storage at site for 1month long: 100TB

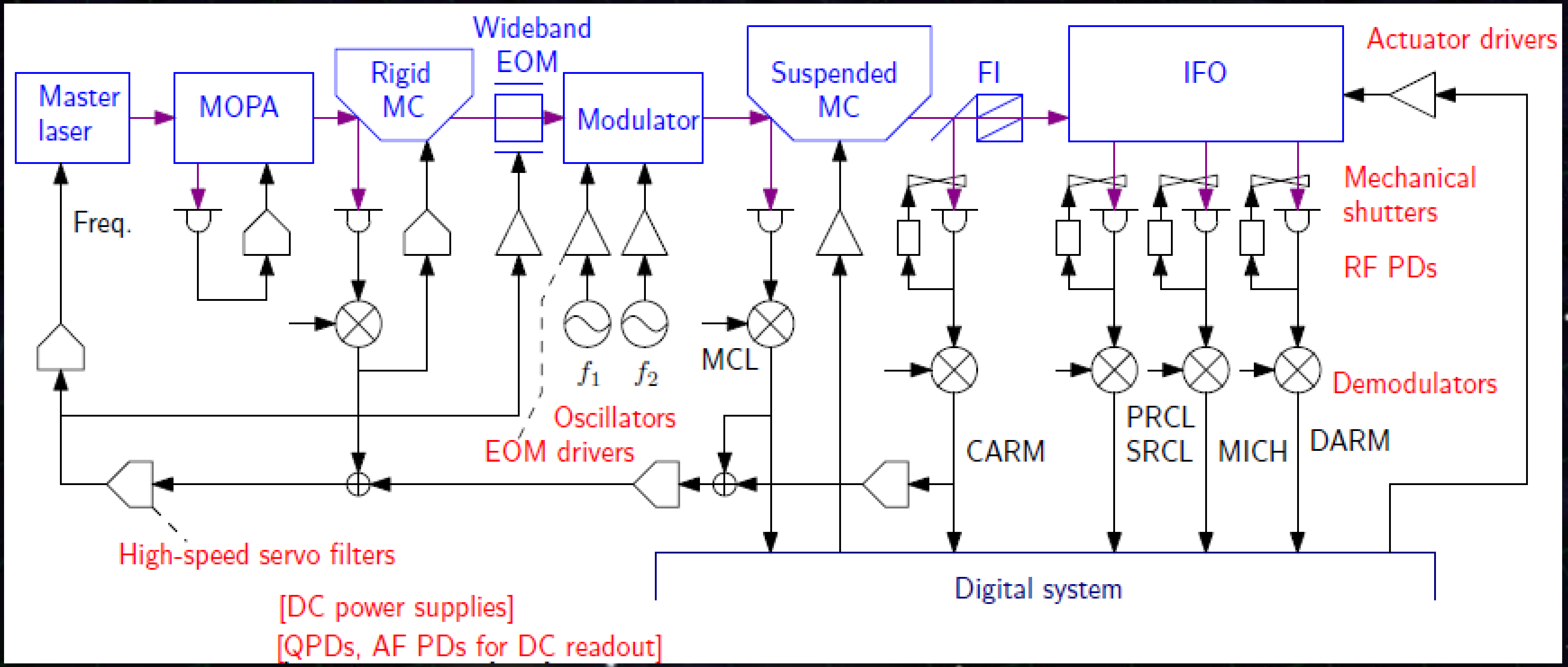
Data storage for iLCGT (analysis, commissioning): 500TB

Data storage for bLCGT: 1PB/year?, not funded

Needs to make a channel list from all subgroups

- Needs whole network design
- Needs network wiring diagram, rack position, rack equipment list

# Analog electronics



# Data Analysis