# LCGT Interferometer


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On behalf of
the LCGT Collaboration

1. Introduction
2. Main interferometer
3. Laser and I/O optics
4. Schedule
5. Summary

# Introduction

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

## Next-generation GW detector in Japan

**Large-scale Detector**
- Baseline length: 3km
- High-power Interferometer

**Cryogenic interferometer**
- Mirror temperature: 20K

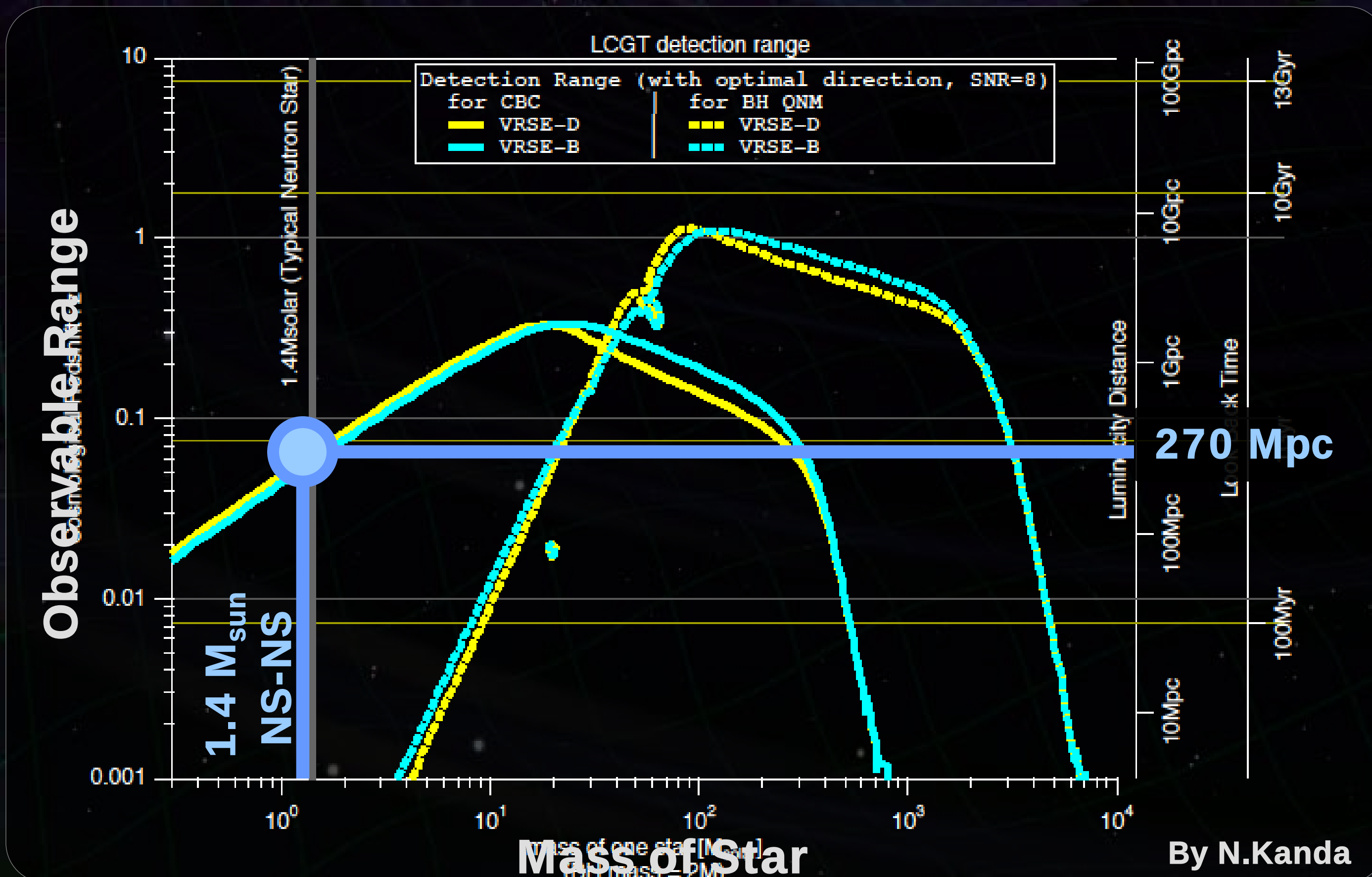
**Underground site**
- Kamioka mine, 1000m underground

# Observable range

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

→ First target : Neutron-star binary inspirals

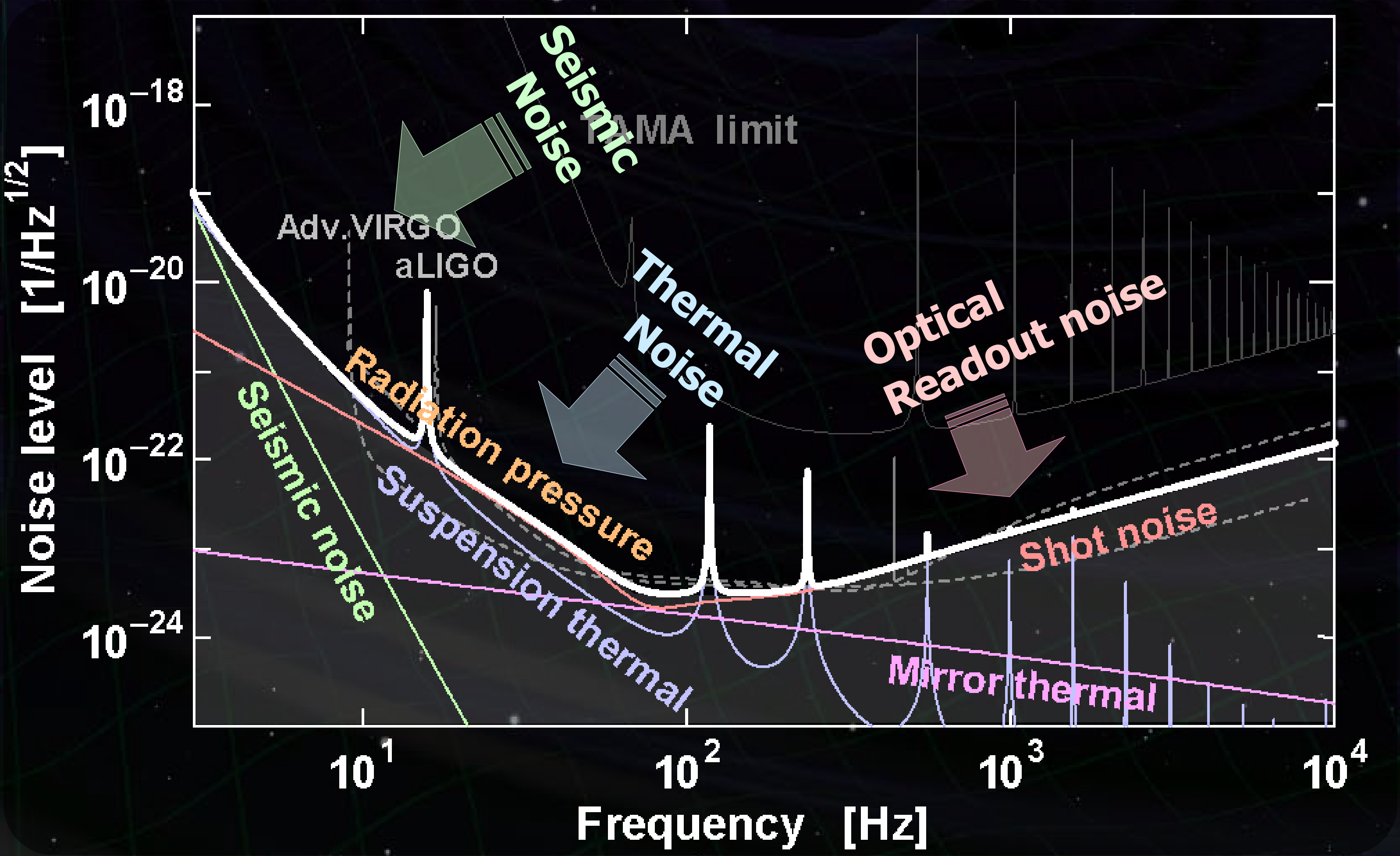
⇨ Obs. Range 270Mpc (SNR=8, Optimal sky pos. an pol.)



# Sensitivity Curve

Comparable with aLIGO Ad.VIRGO

→ Global observation network



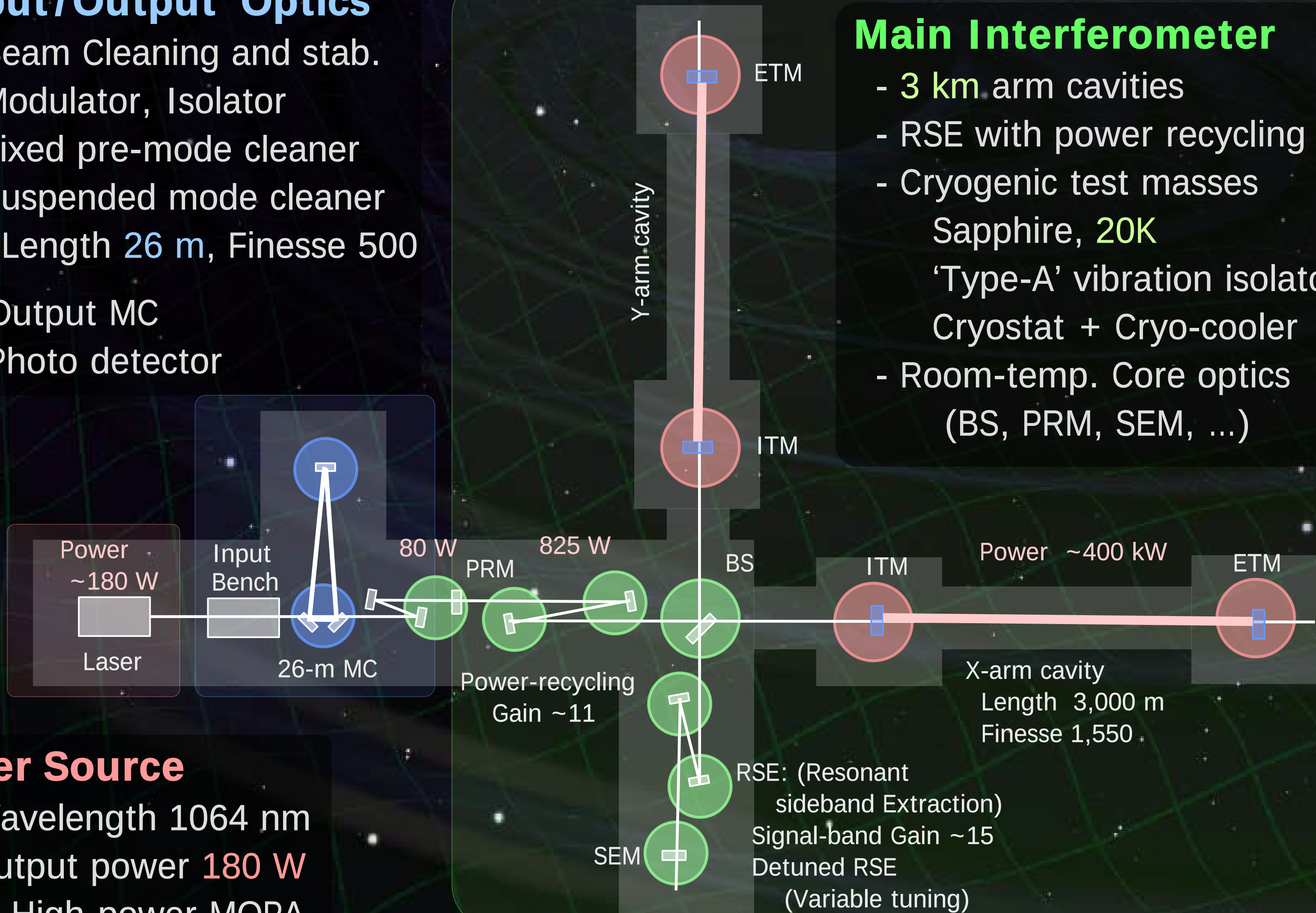
# LCGT configuration

## 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

# Main interferometer

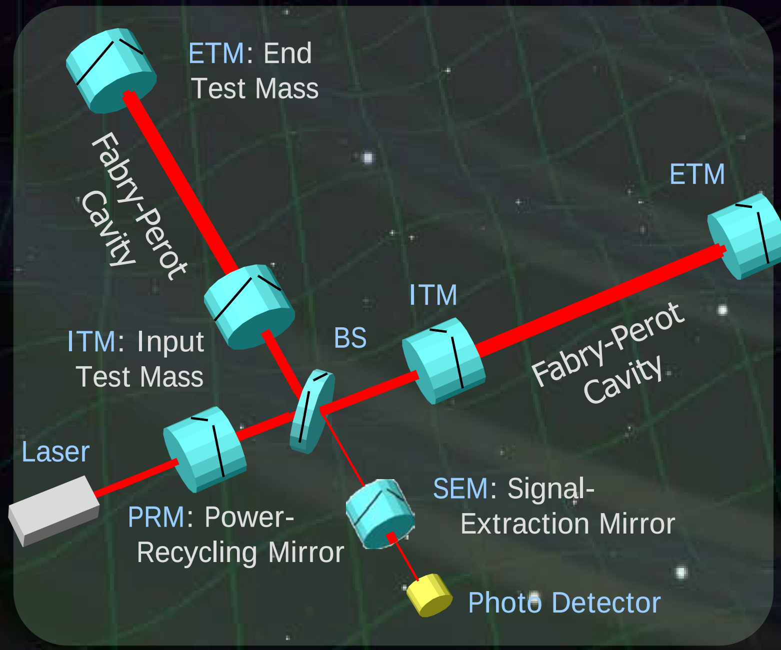
- Optical configuration
- Observation band design
- Length control
- Alignment control
- Lock acquisition
- Optics geometric design
- Research and Developments

# Interferometer Configuration

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

Optical configuration to accumulate high laser power with tunable signal band ⇨ Additional mirror at output port (SEM: Signal Extraction Mirror)

(J.Mizuno 1993)




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

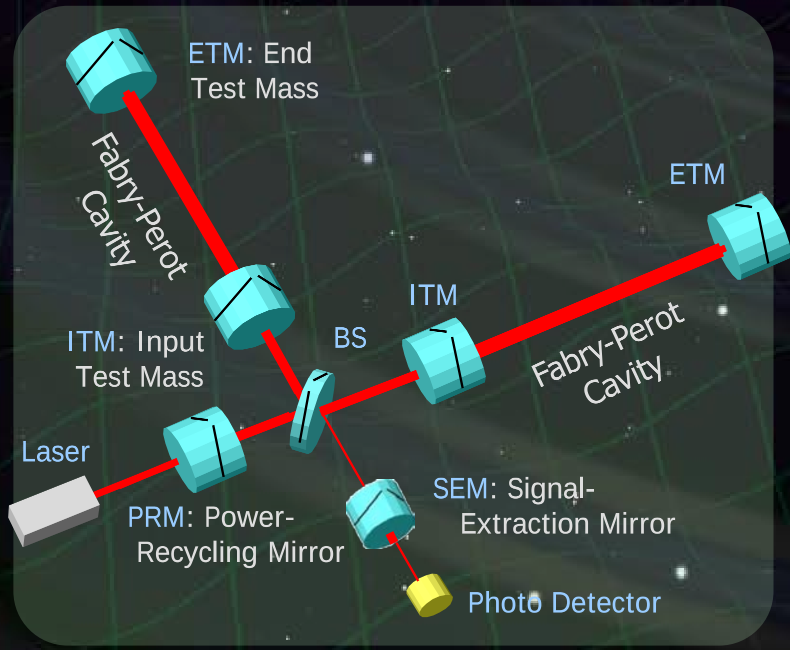
It is possible to design storage time and signal band independently.

# Resonant-Sideband Extraction

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

PRM and ITM : Power in the arm cavities
SEM and ITM : Signal band for GW observation

⇨ 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.

# Observation band

## Design of optical parameters (observation band)

- Scientific outcomes:
  - Obs. range and parameter estimation for binary inspirals
  - Super novae, Pulsars, Stochastic background
- Technical feasibility
  - Detector control, Noise behavior, Robustness

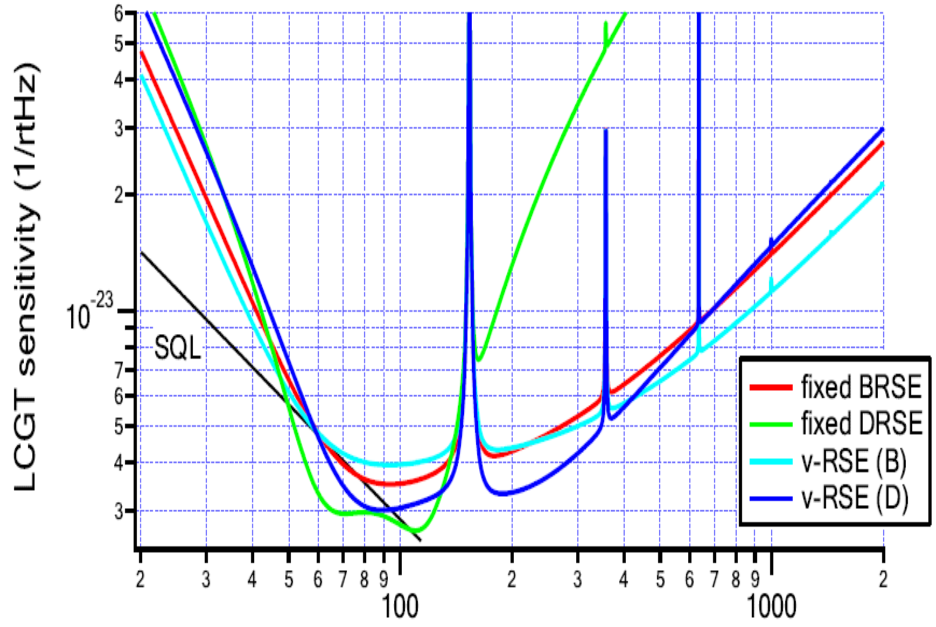



Figure: K.Somiya

**LCGT is designed to be VRSE-D**

**(Variable RSE config. with detuned operational point)**

- Slightly better detection prob.
- Broad-band option for wider scientific outcomes.
- No critical difficulty in the variable configuration.

⇨ **Inspiral Range ~270Mpc**

# Length control

## 5 Length DoF should be controlled

- **Signal extraction**
  - Modulation to input beam
    Phase mod. : 16.875 MHz, 45 MHz
    Optional mod. at 56.3 MHz
  - Demodulation of PD output
    Single demodulation

|  | DARM | CARM | MICH | PRCL | SRCL |
|---|---|---|---|---|---|
| AS_DC | 1 | 4.2e-5 | 1.0e-3 | 4.8e-6 | 4.7e-6 |
| REFL_1I | 5.4e-3 | 1 | 4.3e-5 | 6.5e-3 | 4.3e-3 |
| REFL_1Q | 5.0e-3 | 1.3e-2 | 1 | 1.02 | 0.67 |
| POP_2I | 2.3e-2 | 4.3 | 1.0e-2 | 1 | 2.5e-4 |
| POP_1I | 8.7e-2 | 16.23 | 3.1e-2 | 2.1 | 1 |

- **Control**
  'Loop noise' should should be less than
  1/10 of the LCGT sensitivity.
  - Filter design (DARM UGF ~200Hz)
  - Feed forward gain of 100
  - Use digital control system
  - Dynamic range, U.C. noise → OK

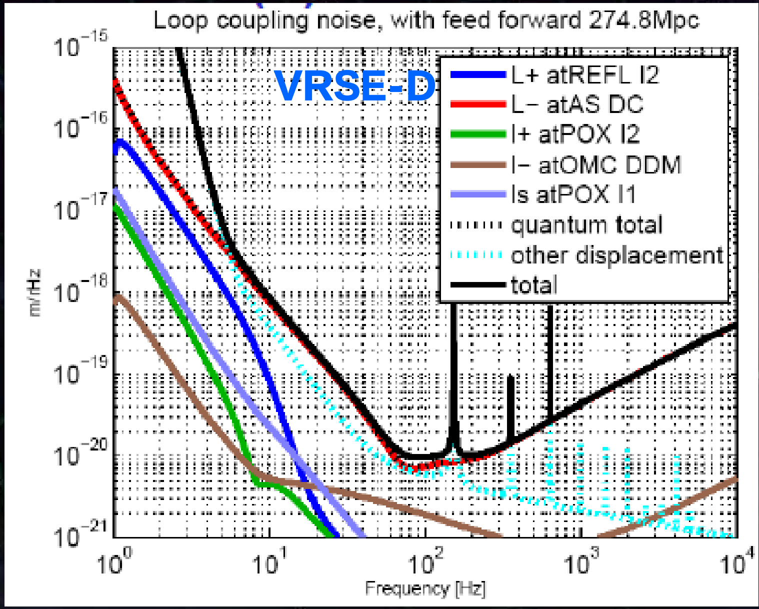



Figure: O. Miyakawa

⇨ **No critical problem is found so far**

# Alignment control

## Suppress angular fluctuation of core optics

- **Sensors**

  Wave-front sensing : Global control -- Reference : the optical axis

  (Folding PRC design for 20deg Gouy phase shift)

  Optical lever : Local control -- Reference : local optical bench

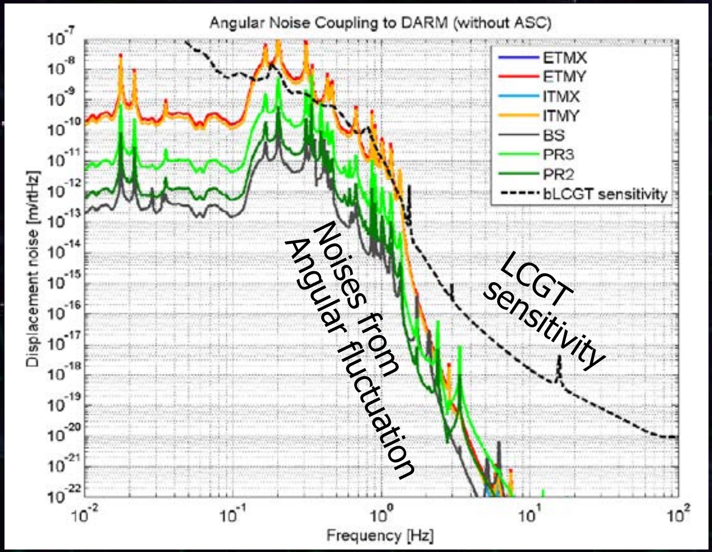
- **Alignment control**

  - No control at observation band
  - Alignment control to suppress RMS, mainly by suspension resonances.

    → Damp at upper stages of suspension.

    WFS will be used only at DC.

⇨ **No Critical problem in design**




Angular optical spring instability is being analyzed.

Detailed modeling and design is underway

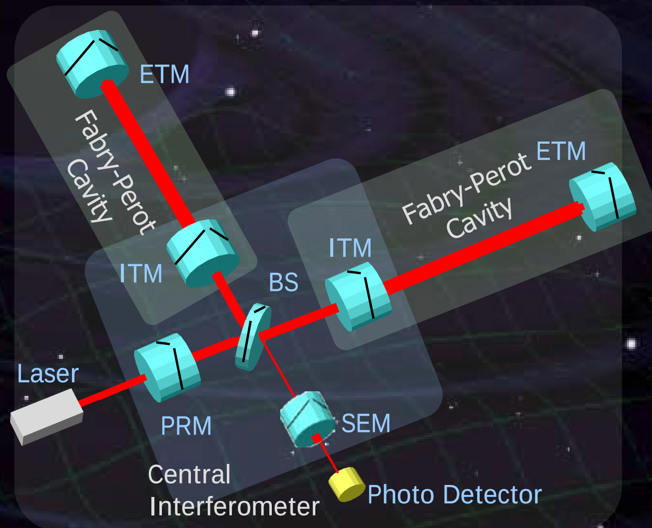
Suspension design, Actuator design, Tolerance for optics

# Lock Acquisition

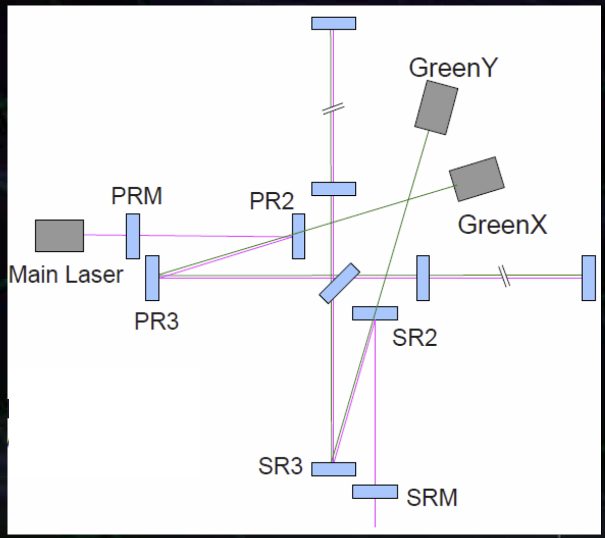
## 'Lock' the interferometer from uncontrolled state

- **Deterministic scheme**
  - (1) Pre-lock the arm cavities at off-resonance by green laser pre-lock.
  - (2) Lock the central interferometer part.
  - (3) Offset the operational point of the arm cavities to resonance.
  - (4) Switch control signals to final ones.

  3rd-harmonics demodulation or Non-resonant sideband as a backup plan.




- **Green laser pre-lock**
  - Green laser beam
    Freq. doubled laser from 1064nm
    Phase-locked to main beam.
  - Two beams for x and y arms.
  - Arm cavity has low finesse, and BS is almost transparent for this wavelength.



# Optics geometric design (1/2)

- **Interferometer length design** (Separation between core optics)
  - Arm cavity : 3 km (LCGT concept)
  - PRC, SEC length : 66 m (Resonant condition of RF sidebands)
  - Asymmetry: 3.3 m (RF sideband reflectivity by MI)

- **Folded recycling cavity**
  - RF-sideband power loss in PRC
    by thermal lens and mirror angular fluctuation.
  - Gouy-phase shift for alignment-signal separation
  - Signal loss in SEC
    → The loss seems to be critical with straight cavity
    in current estimation. Detailed investigation is required.

# Optics geometric design (2/2)

- **Arm cavity g-factor and mirror tolerance**

  Determined by RoC of the main mirrors

  - Spatial mode stability for $TEM_{00}$, higher-mode rejection
  - Beam spot size for low thermal noise
  - Angular radiation pressure instability

    Possible problem in alignment control design.
  - Parametric instability

    Very sensitive to small ROC error.

    Can be suppressed by additional damping mechanism.

⇨ Under discussion

Positive g-factor : Flat – 7km

Negative g-factor : 1.6km – 1.9km

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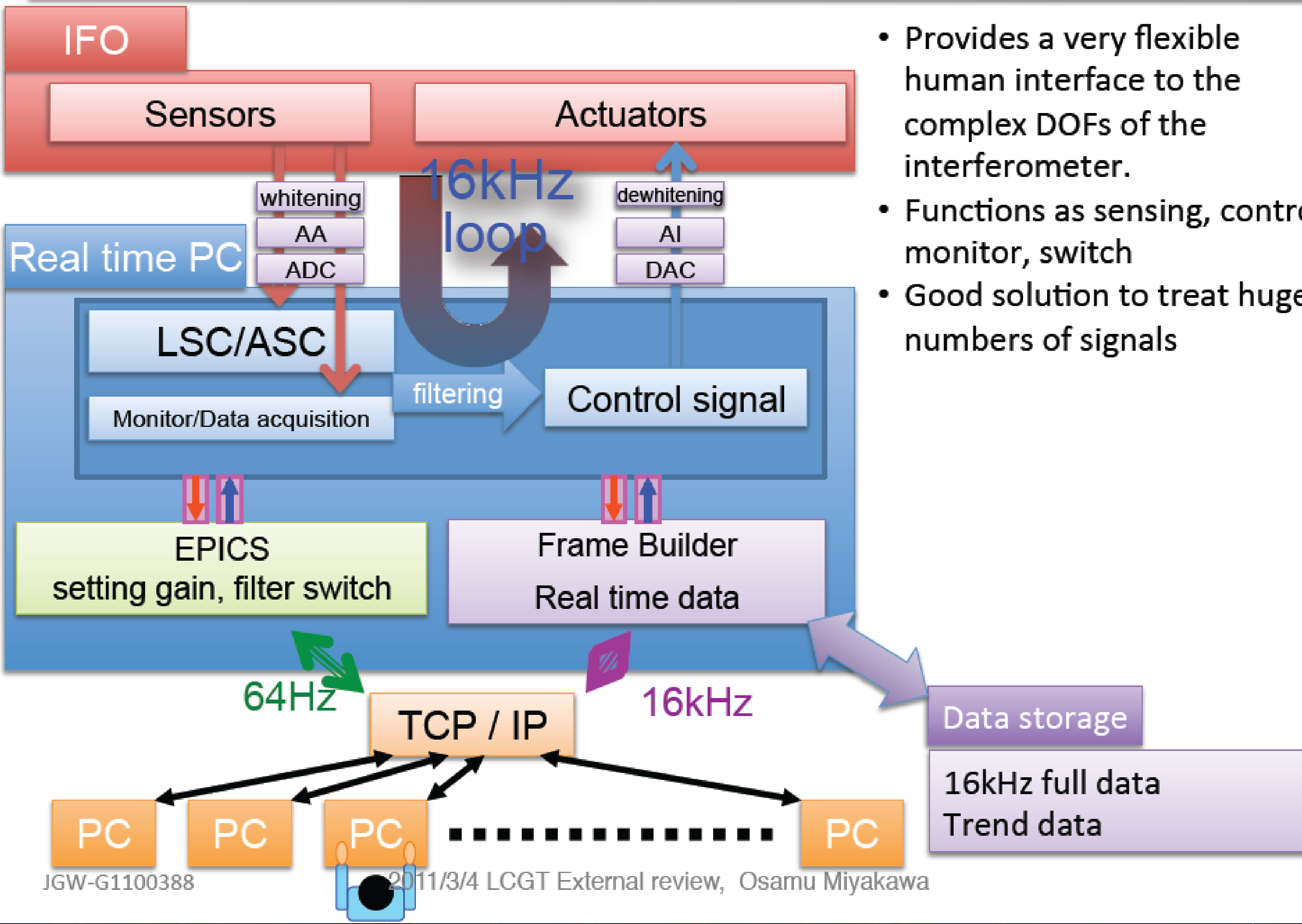
# Digital System




- 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

JGW-G1100388

2011/3/4 LCGT External review, Osamu Miyakawa

# Large-scale interferometer

- **TAMA300**
  - Fabry-Perot Michelson interferometer with power recycling.
  - Baseline length : 300m

  - Observation runs since 1999.
  - World best sensitivity in 2000 – 2002.

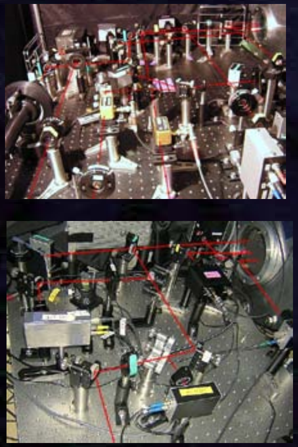

⇨ **Operation and observation with a large interferometer as a full system.**

- Commissioning and noise hunting
- Interferometer operation
- Observation system
- TAMA-SAS installation and test

# RSE demonstration

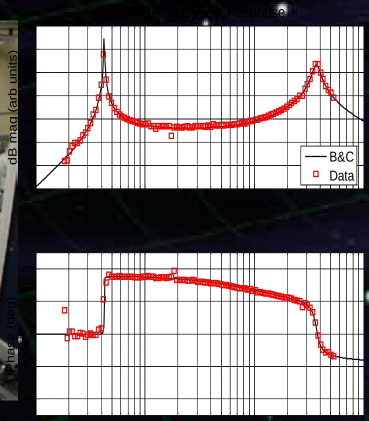
- **4-m prototype interferometer**
  - Prototype for RSE demonstration
  - Built at NAOJ

  - BRSE w/o PR (Miyakawa ~2002)
  - DRSE w/o PR (Somiya ~2004)
  - BRSE + PR (Kawazoe ~2007)



- **40-m prototype interferometer**
  - Prototype for RSE demonstration
  - Built at Caltech

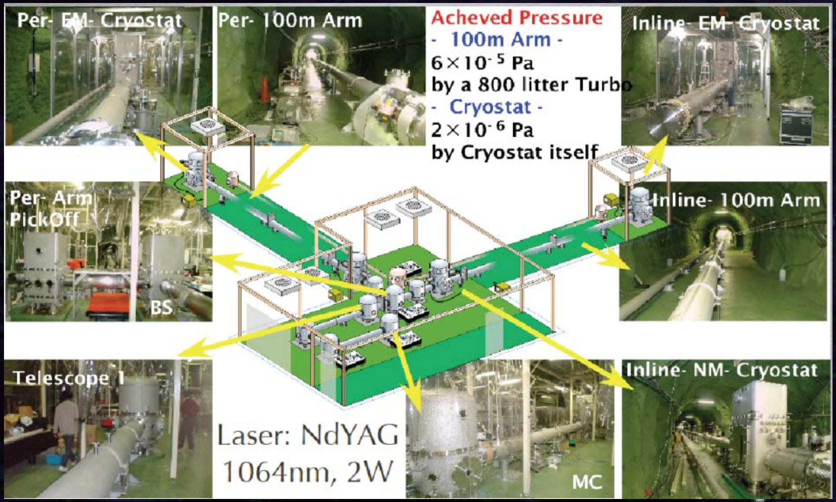
  - BRSE + PR (Miyakawa ~2005)




⇨ **Operation of RSE interferometer with power-recycling.**

# Cryogenics and underground site

- **CLIO**
  - Locked Fabry-Perot interferometer
  - Baseline length : 100m
  - Built at Kamioka underground site
  - Cryogenic test mirrors.
  - Observation runs since 2003.




⇨ **Operation of cryogenic interferometer at underground site.**

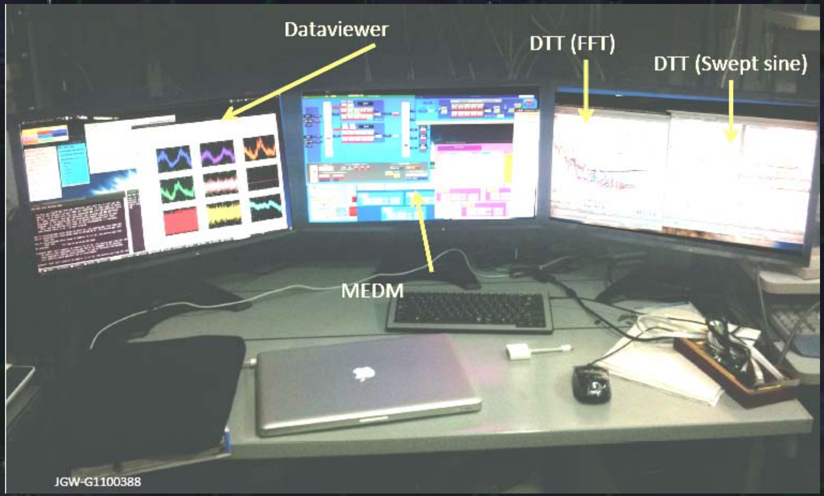
- Long-term stability
- Thermal noise investigation
- Digital control system test

# CLIO digital system

**LCGT will employ LIGO's digital system**

Full-scale test of the control system at CLIO, based on MOU with LIGO laboratory

## Client System




## Main System

**Differential drivers for ADC, DAC, and BO**

**Real time PC**
**4core x 2 Xeon**
**CentOS 5.2 + Real time kernel**
**Anti-aliasing and anti-imaging filters**
**ADC, DAC, and Binary out adapters**

**ADC/DAC In Expansion Chassis**

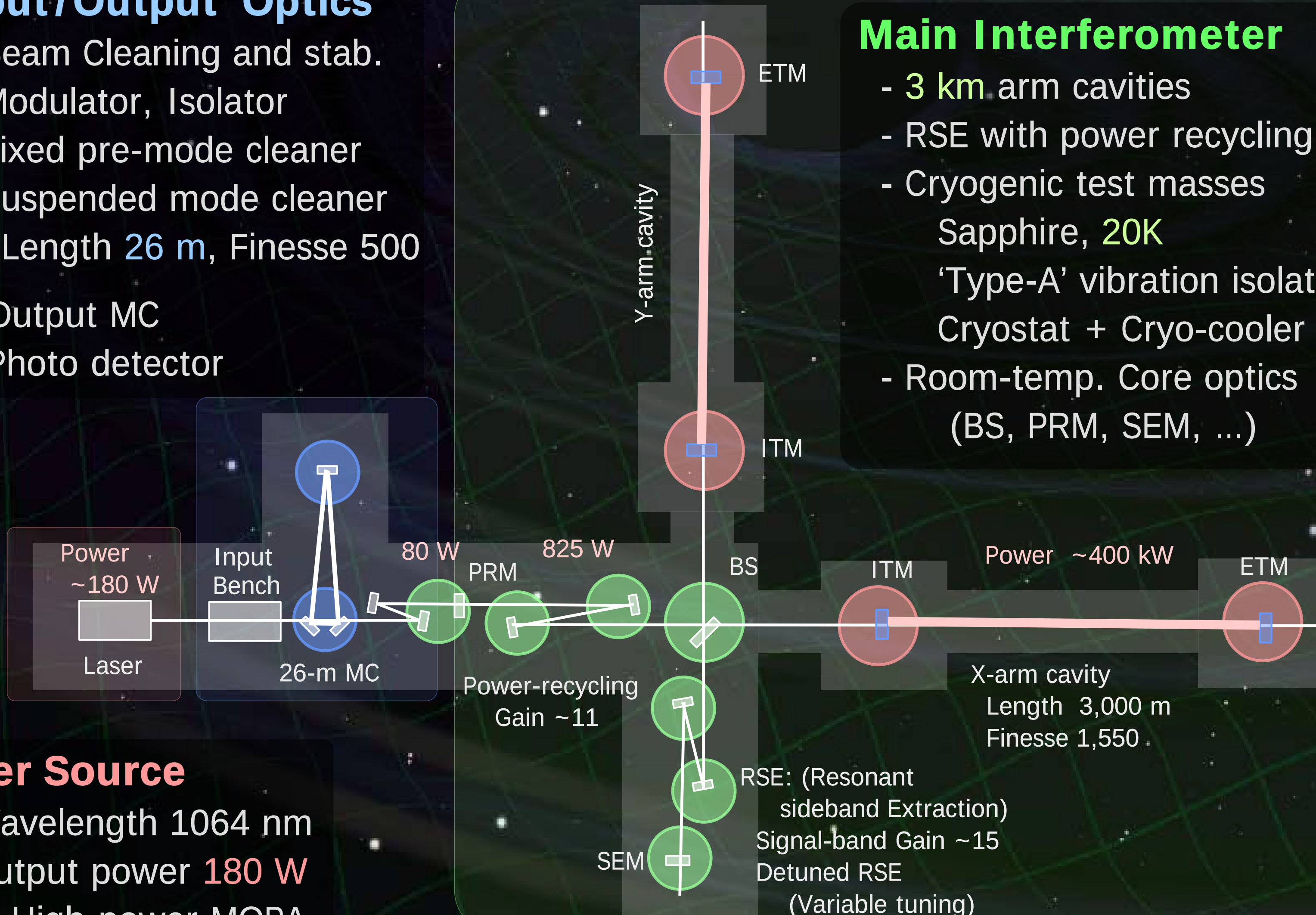
# Laser and I/O optics

- High-power laser source
  - Input/output optics
  - 100W laser prototype
  - Stabilization experiment

# 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

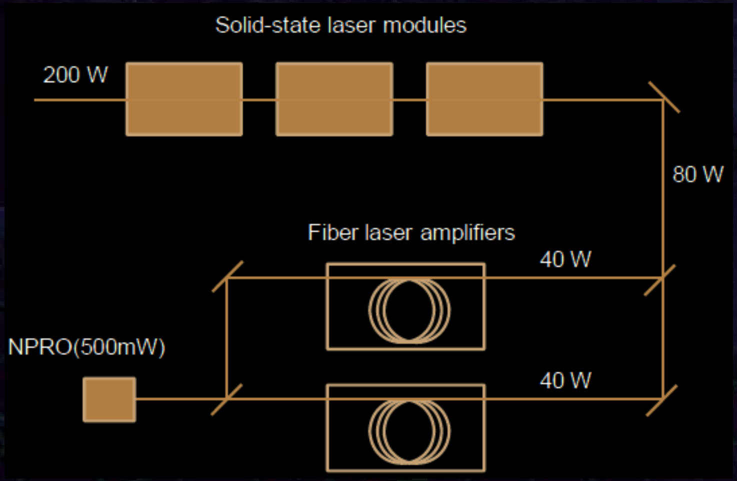
# High-power laser

## High-power and stable laser source

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

# LCGT Laser Source

- **Adopt a MOPA configuration in LCGT**
  - Injection-lock is slightly complex, and requires well-trained operators for best performance.
  - MOPA is easy for assembly and maintenance.




**High-power MOPA laser**
**→ Easy assembly and maintenance**

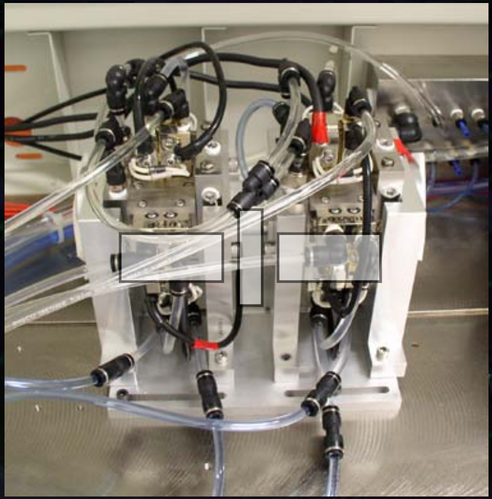
- **Seed laser**
  **NPRO (Nonplanar Ring Oscillators)**
  **Power 500mW**
- **Fiber amplifier**
  **Commercial fiber amp.**
  **NUFERN Single Freq. PM amp.**
  **Output power ~40W**
  **Coherent addition with two units**

- **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**

# Power Amplifier

- **Fiber amplifier**
  - Commercial amplifier platform.
  - 40 W output power
  - Single frequency
  - PM LMA (25/400) fiber.


- **Solid-state laser module**
  - Commercial amplifier by Mitsubishi.
  - 50 W output power.
  - Two lase rods and
    rotator for polarization stability.
  - Side pump + diffusive reflector



Two rods and rotator

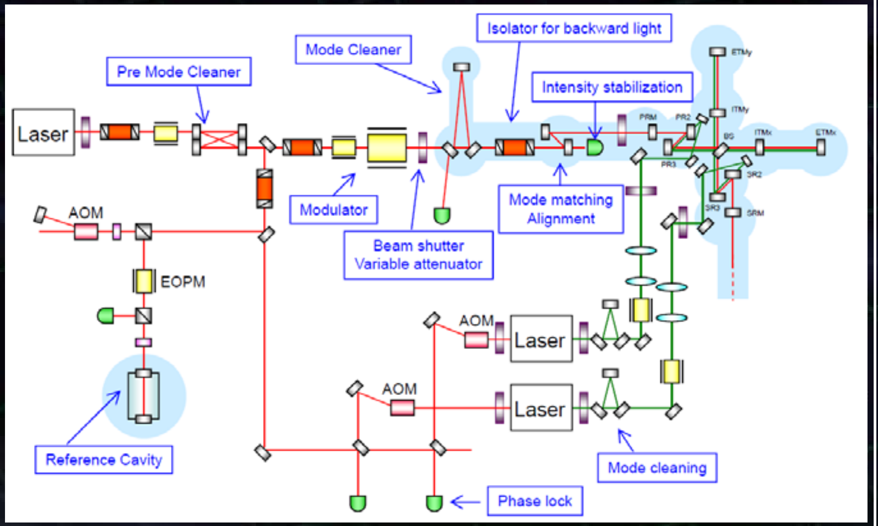
# Input/Output Optics

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

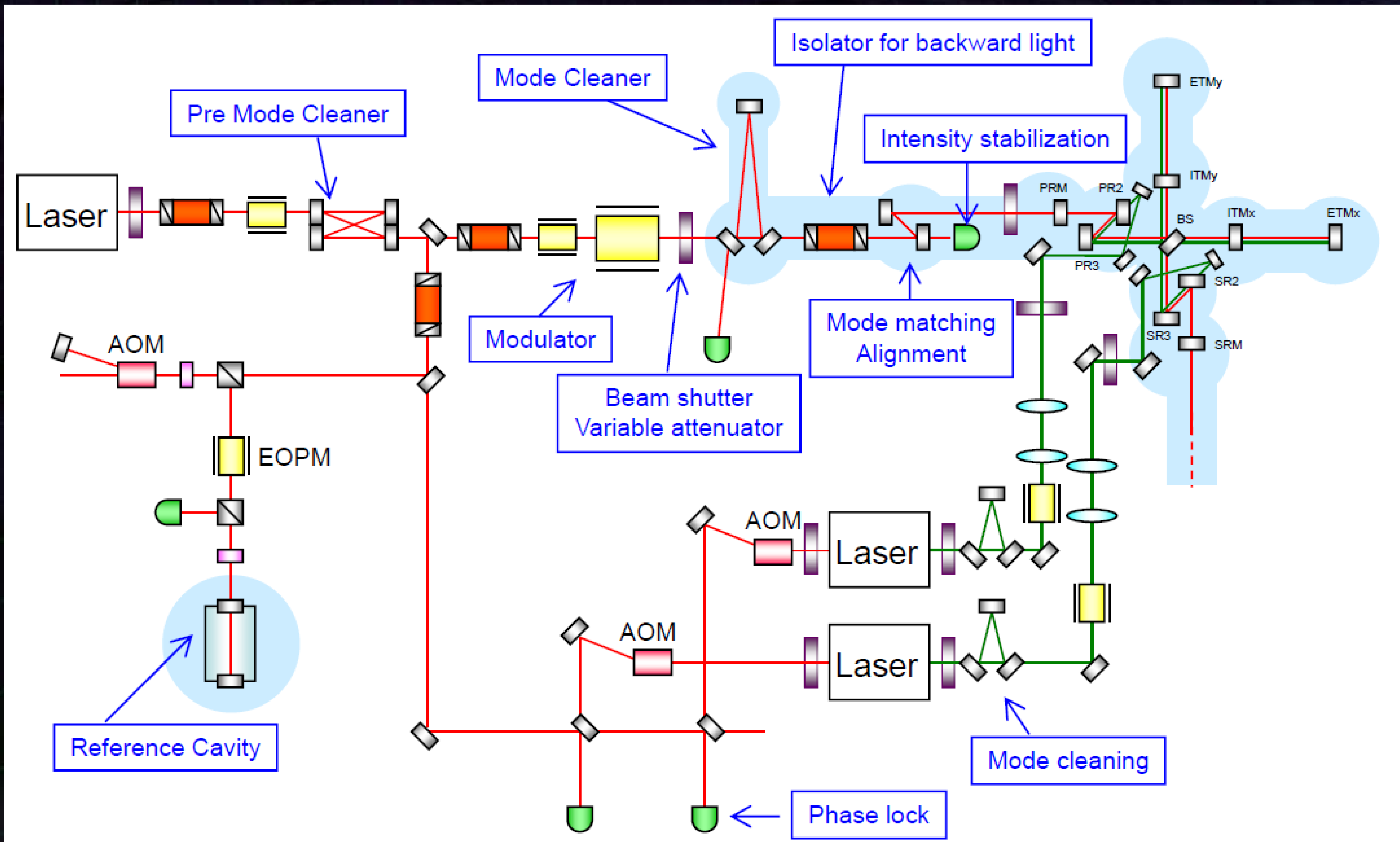
$TEM_{00}$ power throughput $>50$ %
Frequency stability $< 3\times10^{-8}$ Hz/Hz$^{1/2}$
Intensity stability $< 2\times10^{-9}$ Hz$^{-1/2}$
RF intensity noise $< 1\times10^{-9}$ Hz$^{-1/2}$ (>10MHz)
Beam jitter : ---
RF modulation : 16.875 MHz 45 MHz (optional 56.25 MHz)

- **Mode Cleaner**

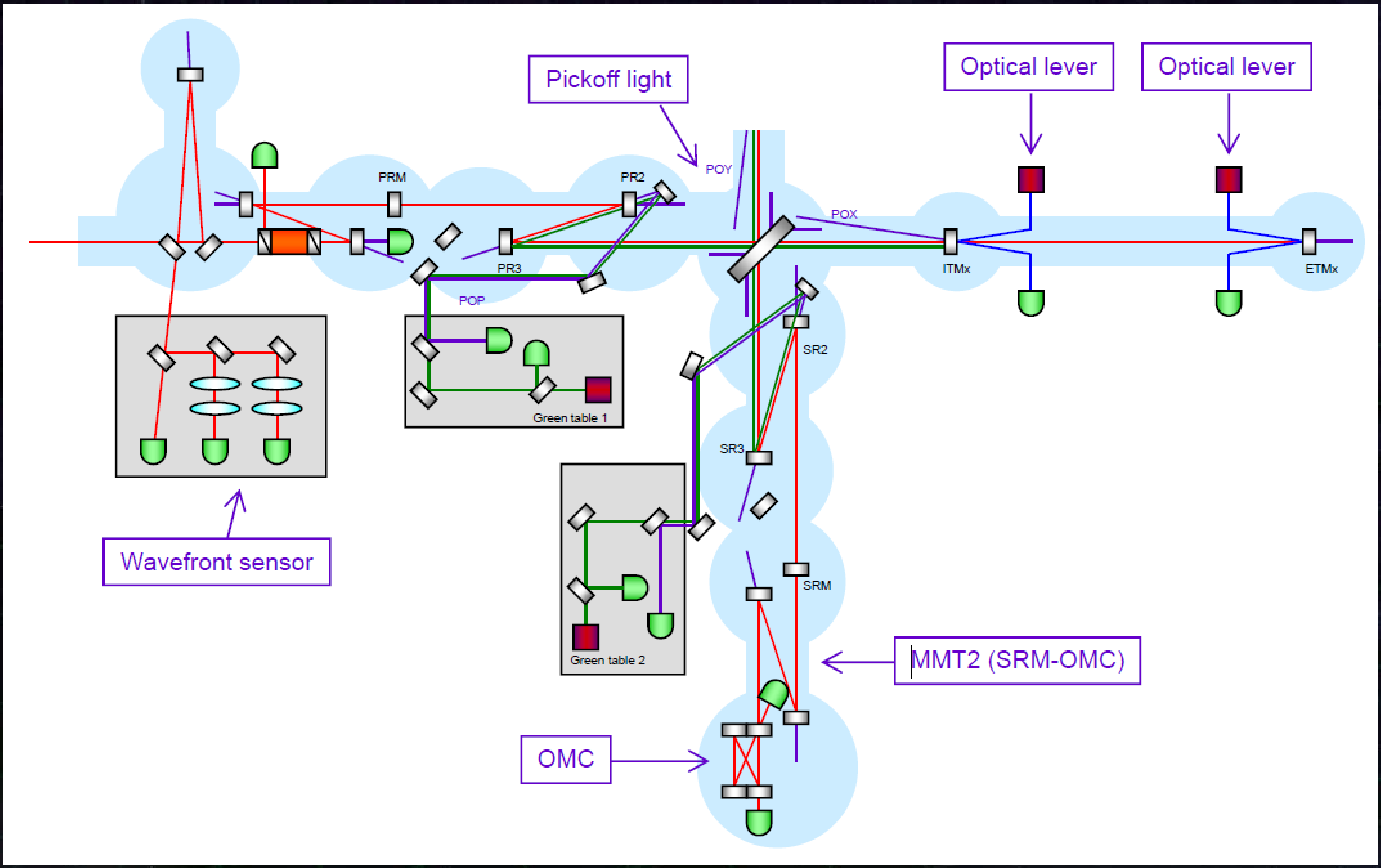
**Suspended triangle cavity**
**for spatial MC, reduction of beam jitter, and freq. stabilization**
**Transmission of RF sidebands for main interferometer control**
**Round-trip length : 53.333 m**
**Finesse : ~500**
**FSR : 5.625 MHz**
**Mirror dimension : ϕ100mm, t30mm**
**ROC : Flat (In and Out)**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



# Input / Output Optics



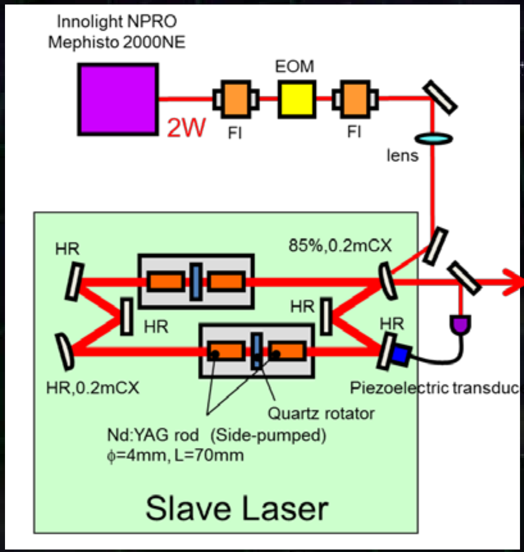
# Output Optics

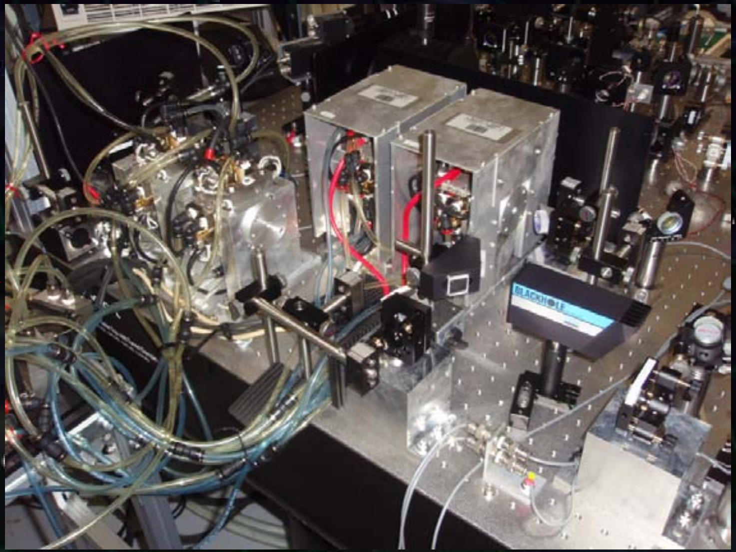


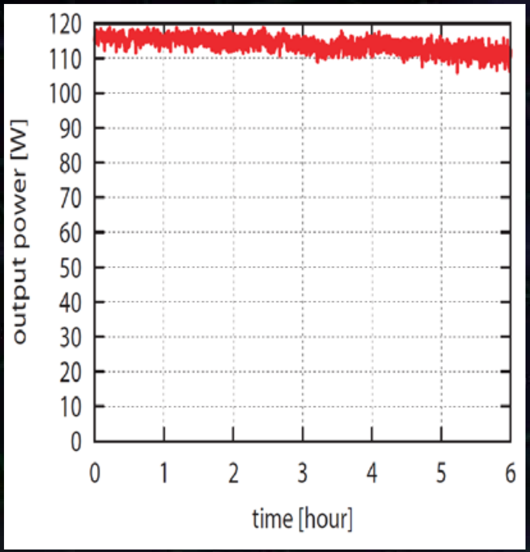
# Prototype Test

- **100-W injection-lock laser**
  - Output power >100 W
    Continuous wave, Single frequency, Linear polarization
  - Linewidth ~ 1kHz, $M^2$ ~ 1.1
  - Two amplifier module in bow-tie cavity.

⇨ **Test of high-power laser and controllability**



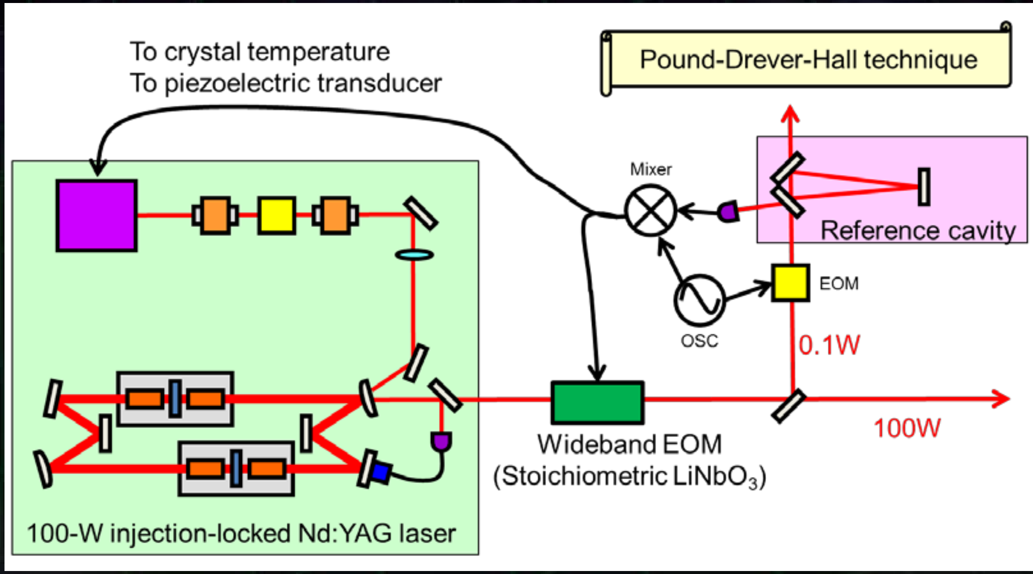



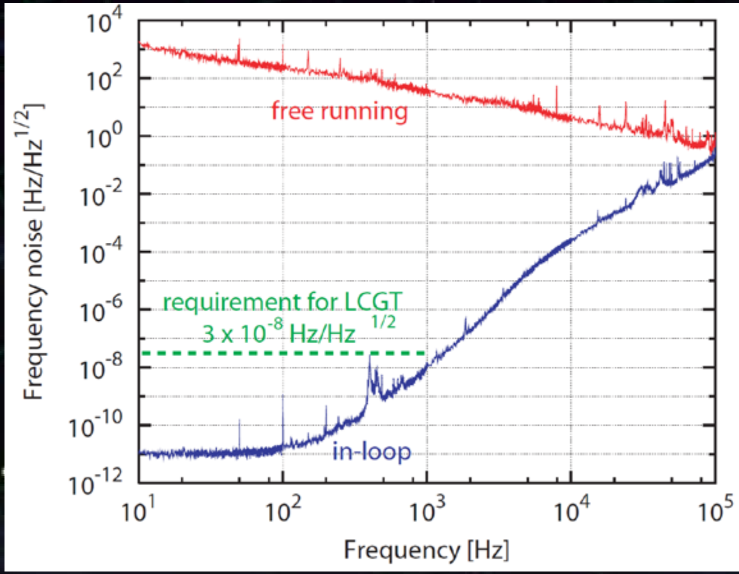


# Frequency Stabilization

- **Frequency stabilization with 100-W laser**
  - Fixed triangle cavity for frequency reference.
  - Fed back to master laser and a wideband EOM.
  - Unity Gain Freq. ~800kHz

⇨ **Satisfy LCGT requirement**

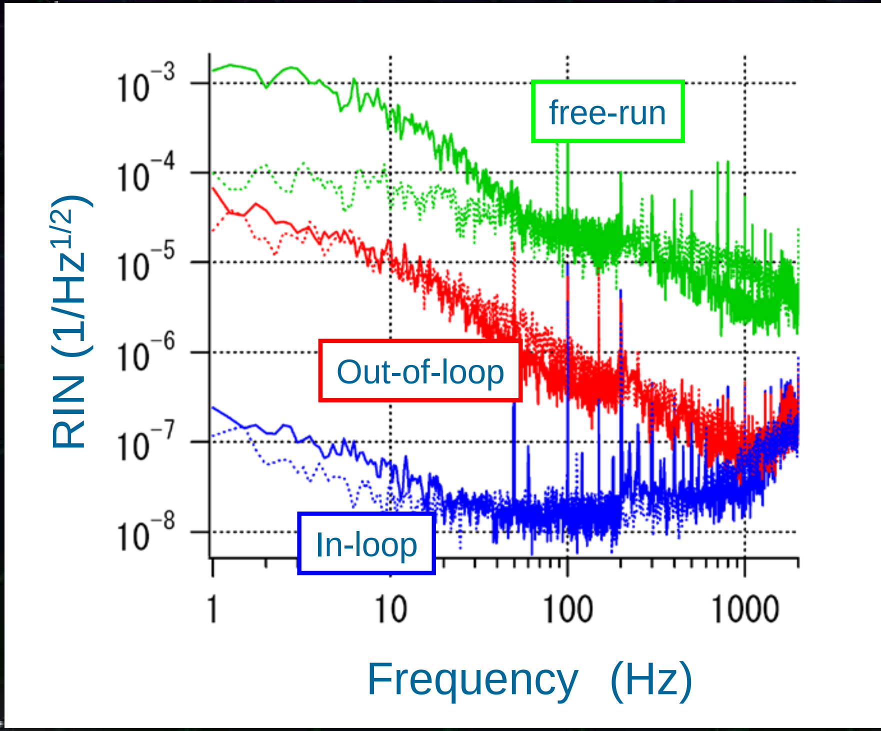


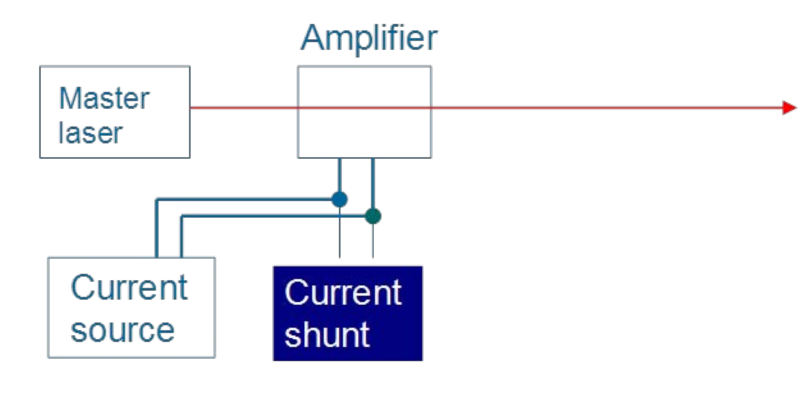



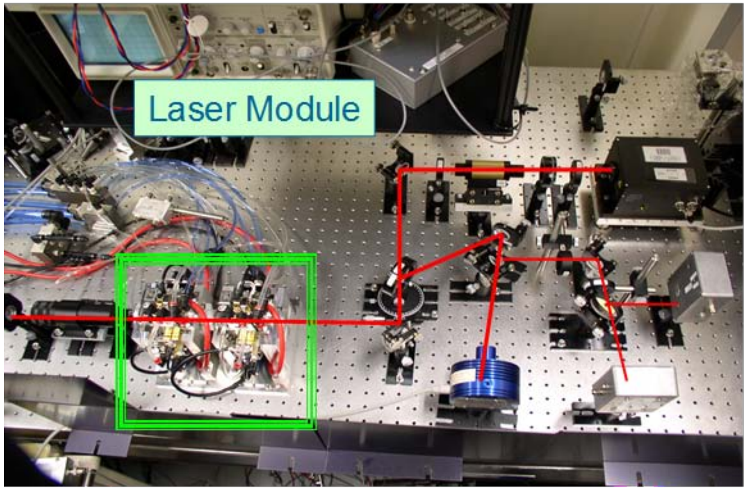
# Intensity Stabilization

- **Intensity stabilization with a power amplifier**
  - Current shunt circuit on the power amplifier.
  - Unity Gain Freq. ~30kHz

⇨ **Check controllability**

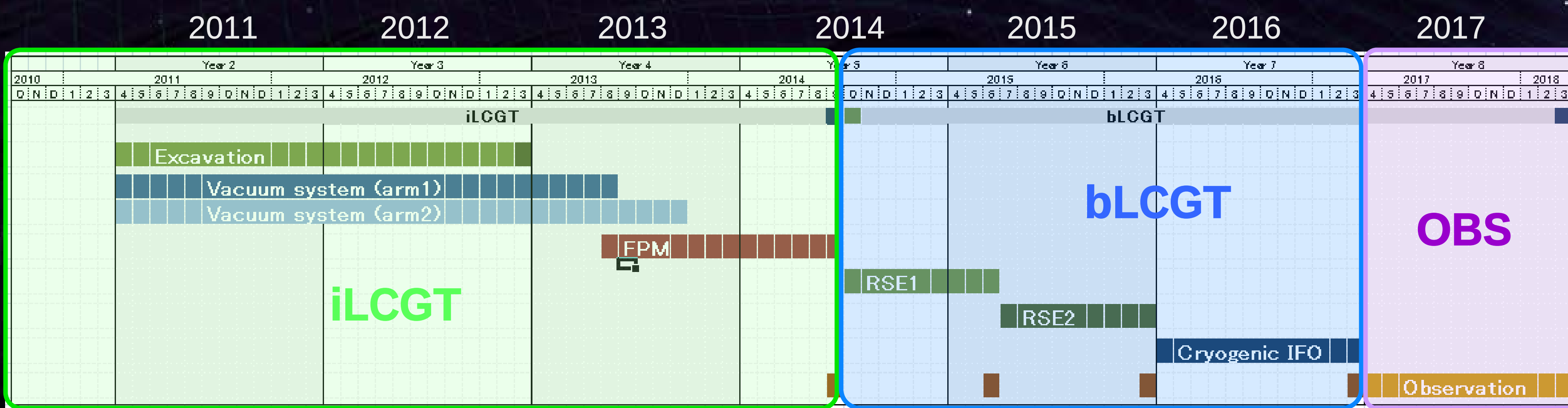


# Schedule

# Schedule




iLCGT laser preparation

Installation and operation

bLCGT laser operation

MC installation

MC operation

Room-temperature IFO commissioning

Half-cryogenic operation

Full-cryogenic operation

Observation and tuning

iLCGT commissioning

RSE implementation

Cryostat + Cryo-payload Prototype test

Cryogenic full system installation and shakedown

# Summary

# Summary

- **LCGT main interferometer**
  - RSE with power recycling, variable observation band.
  - Inspiral range ~ 270Mpc is expected.
  - Detailed design tasks underway.
  - Heritages with TAMA300, CLIO, and prototype interferometers.
    Knowledge from other projects are very helpful!

- **Laser and Input/Output optics**
  - Laser design based on commercial modules.
  - Input/output optics comprised of many components,
    but well-established techniques in GW community.
  - Require high-power handling.
  - Detailed design tasks underway.
  - Prototype test with a 100-W injection-lock laser.

# End

# Backups

# Scientific outcomes

| Scientific outcomes | | BRSE | VRSE-B | VRSE-D | DRSE | |
|---|---|---|---|---|---|---|
| Neutron-star binary | | | | | | 1.4Msolar neutron-star |
| Detection probability | [ % ] | 99.6 | 99.4 | 99.9 | 99.9 | At least one detection with one-year observation |
| Observation time required for the first event detection | [Month] | 5.1 | 5.3 | 4.0 | 3.4 | With 90% probability |
| Observable range | [Mpc] | 114 (259) | 112 (255) | 123 (281) | 132 (299) | SNR 8, sky average<br>SNR 8, maximum direction |
| Detection rate | [/yr] | 5.4 | 5.2 | 6.9 | 8.2 | One-year observation |
| Parameter estimation | | ○ | ○ | ○ | △ | Factor of two difference |
| Error in arrival time | [msec] | 0.254 | 0.220 | 0.255 | 1.08 | 200Mpc events |
| Fake reduction | | ○ | ○ | ○ | △ | |
| Black-hole binary | | | | | | 10Msolar black-hole inspirals |
| Observable range | [Mpc] | 570 | 557 | 615 | 677 | |
| Event rate | [/yr] | 0.07-7 | | | | |
| Black-hole ringdown | | | | | | |
| Observable range | [Gpc] | 2.1 | 2.0 | 2.3 | 3 | |
| Mass range | [Msolar] | 110-910 | 115-760 | 100-490 | 100-450 | Events within 1 Gpc distance |
| Supernova | | | | | | |
| Observation possibility | | ○ | ○ | ○ | △ | |
| Event rate | [/yr] | 0.01 – 0.05 | | | | Events in our Galaxy |
| Pulsar | | | | | | With one-year observation |
| Number of observable pulsars | | 35 | 38 | 35 | 25 | Reach spin-down upper limit |
| Crab upper limits | 1e-27 | 8.5 | 8.5 | 8.3 | 5.9 | 60Hz |
| Vela upper limits | 1e-27 | 6.9 | 6.0 | 9.3 | 1.0 | 22Hz |
| LMXB | 1e-26 | 1.1 | 0.95 | 1.1 | 14 | 600Hz |

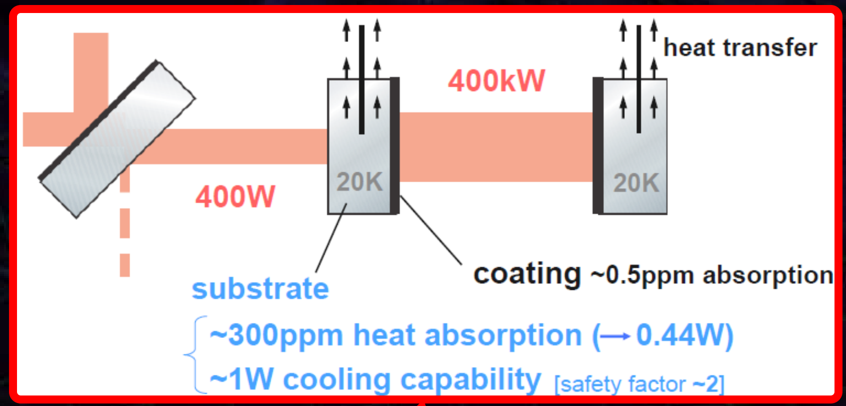
# RSE and cryogenics

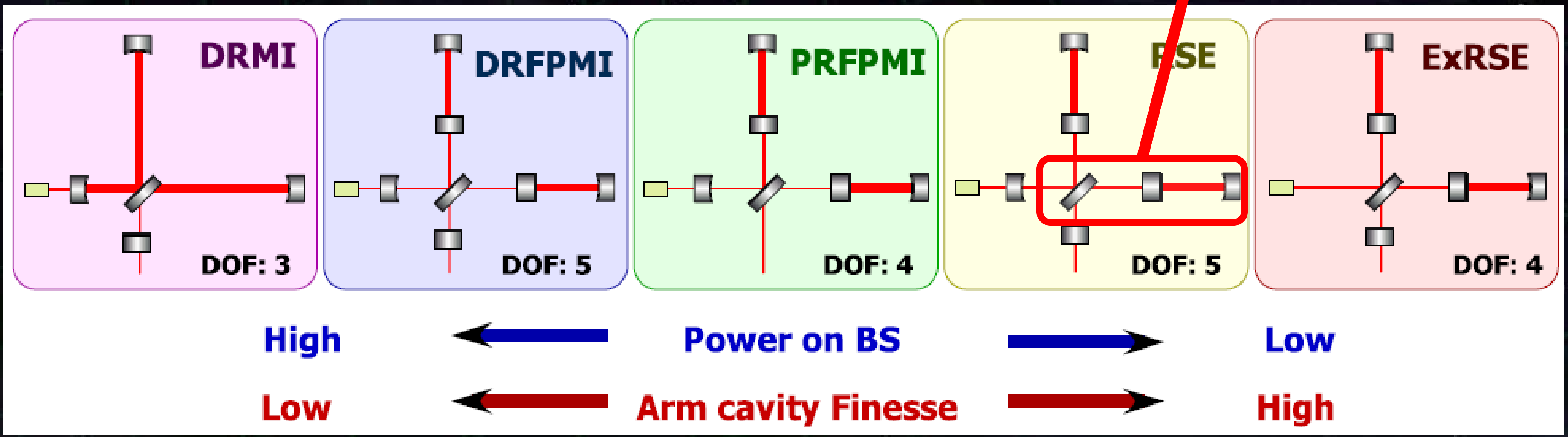
**RSE**

High arm-cavity finesse
moderate Power recycling gain
→ Smaller optical loss and absorption in ITM substrate

⇨ high power and cryogenics

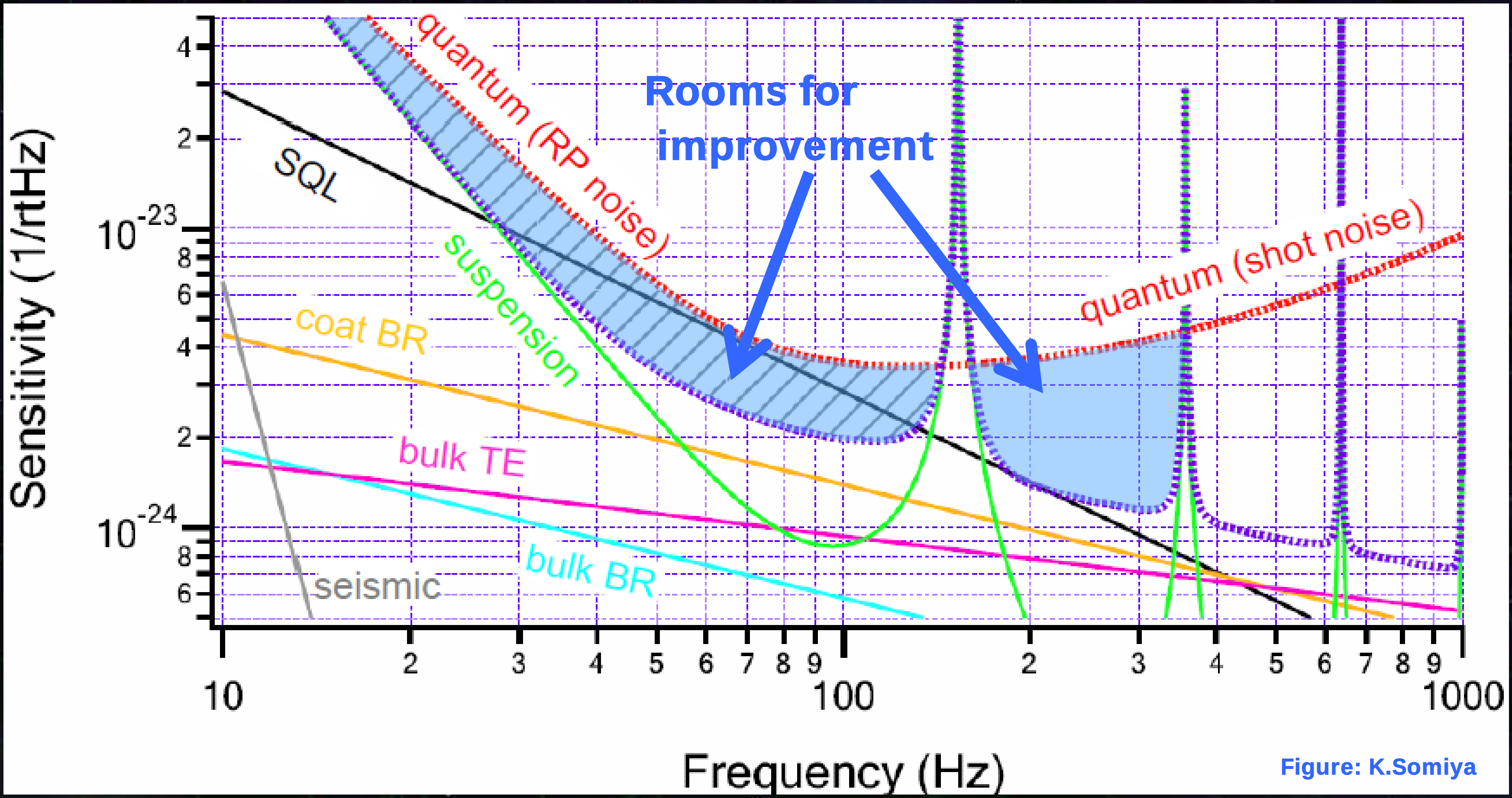
Figure: K.Somiya



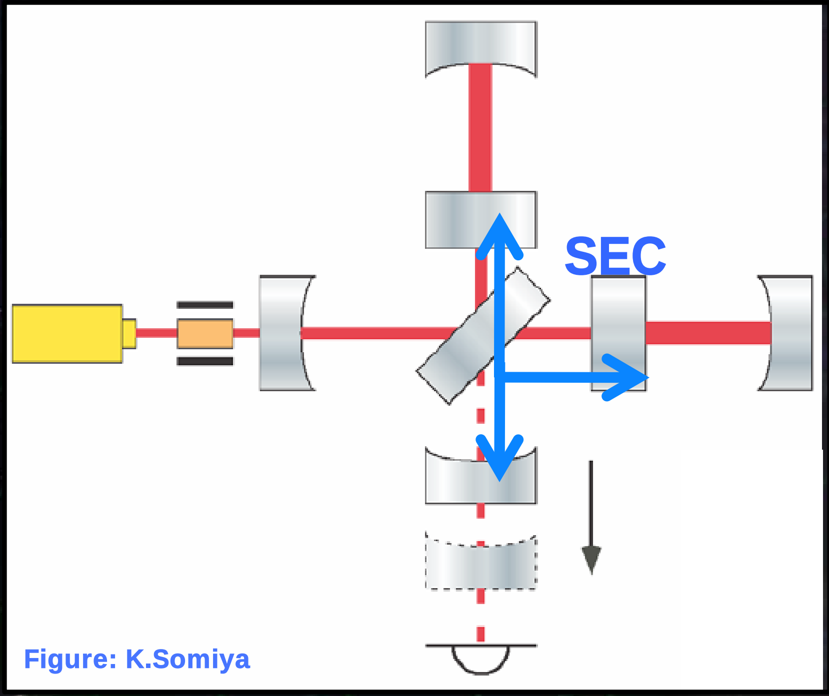
# Quantum and Classical noises

**Quantum noise is dominant**
→ **Optimization of RSE configuration** ⇨ **Tuning of obs. band**
**DC readout**



# Tuning of observation band

Tune the resonance condition of Signal-Extraction Cavity ⇨ Enhance IFO response, Reduce quantum noise at certain frequency band




Optimal reflectivity of mirrors are different in Broadband RSE (BRSE) and Detuned RSE (DRSE) configurations

Variable RSE (VRSE)
Change tuning without replacement of mirrors or changing in macroscopic position

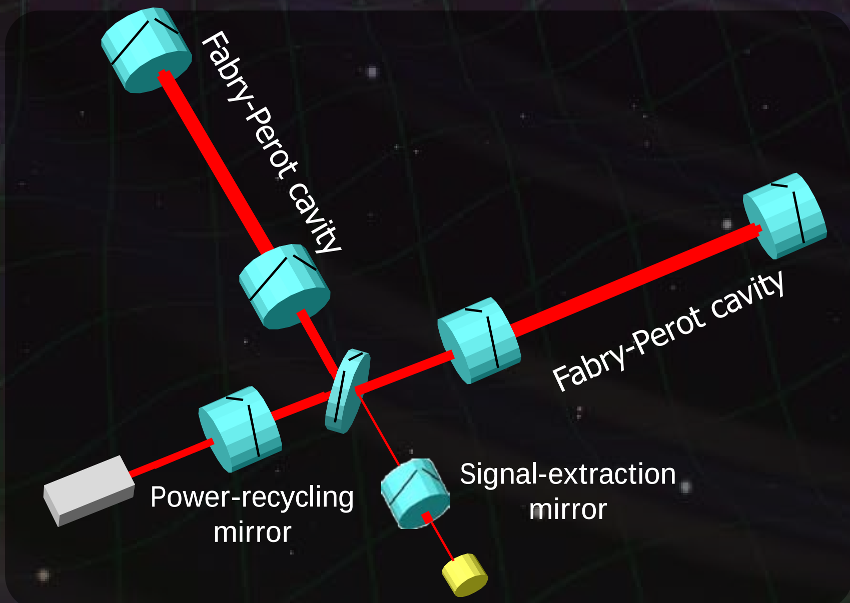
# Readout-noise reduction

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

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

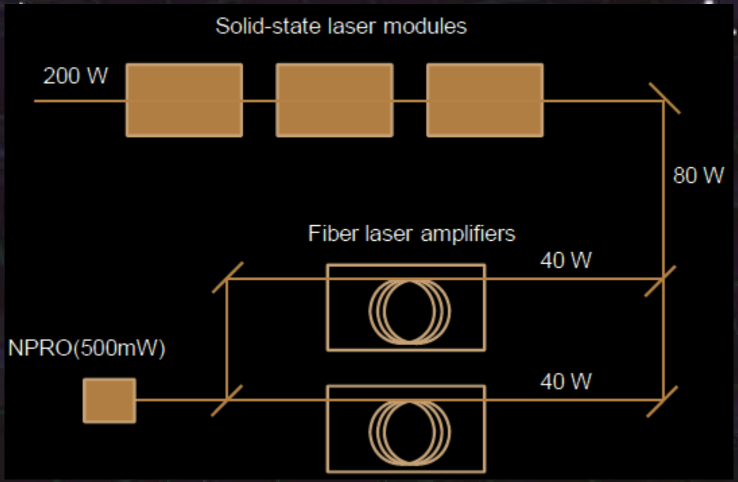
## Optical configuration

**Fabry-Perot Michelson interferometer with RSE (<u>R</u>esonant-<u>S</u>ideband <u>E</u>xtraction)**




## High-power laser source

**Nd:YAG laser source with >180W output power**




## Low-loss mirror

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

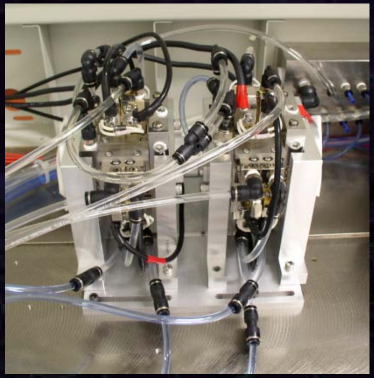
# Developments (Optics)

## High-power laser source

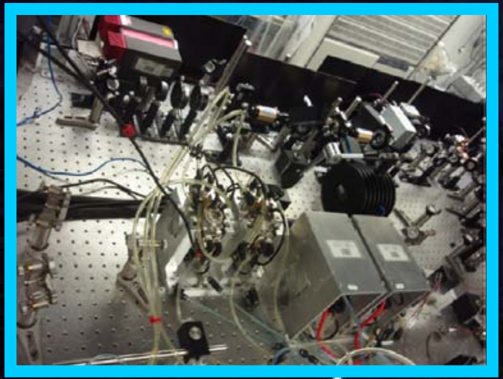
100-W injection-locked laser
→ Test high-power laser module
Freq. and Int. stabilization

⇨ 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

# Thermal-noise reduction

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

### Cryogenics

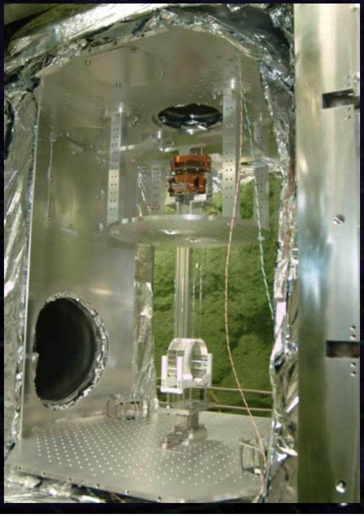
Mirror ~20K
Suspension ~16K

Sapphire mirror
→ High mechanical Q-value at low temperature

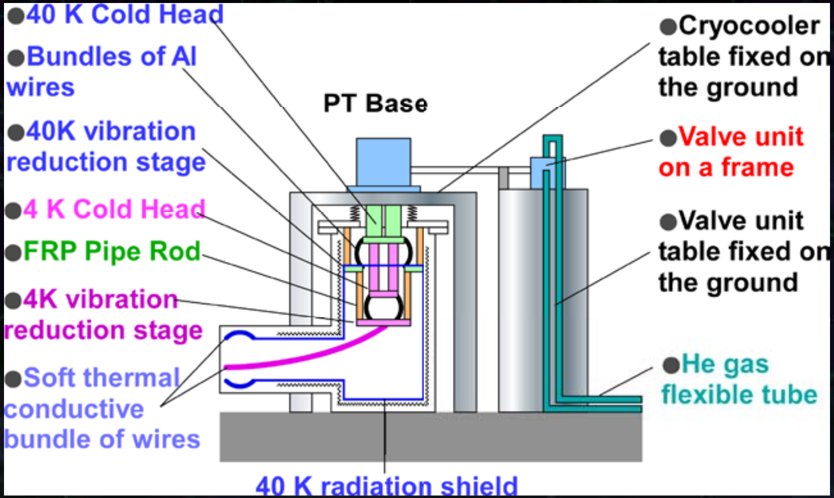
$$\text{Thermal noise} \propto \sqrt{\frac{T}{Q}}$$

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

Cryogenic mirror and suspension of CLIO 100-m interferometer



Low-vibration Cryo-cooler design



# Developments (Cryogenics)

## Cryogenic system

**Heritages by CLIK and CLIO**
- Thermal design
- Cryogenic IFO operation

**Under detailed design**
- Cryostat + Cryocooler + Radiation shield

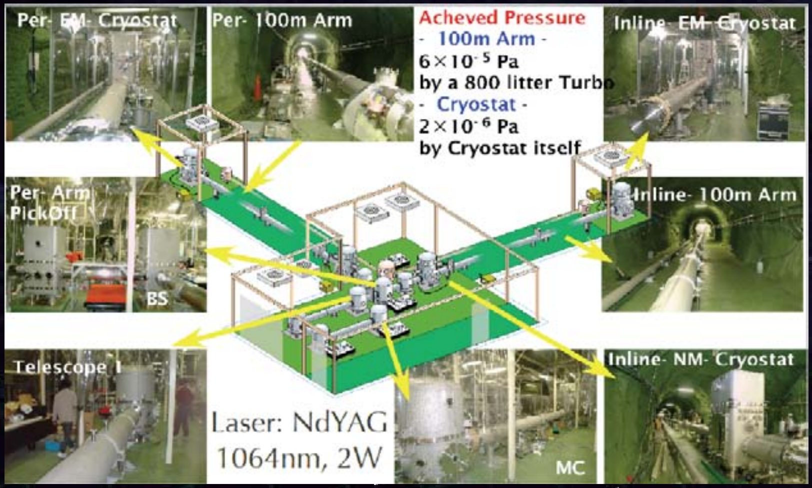
⇩

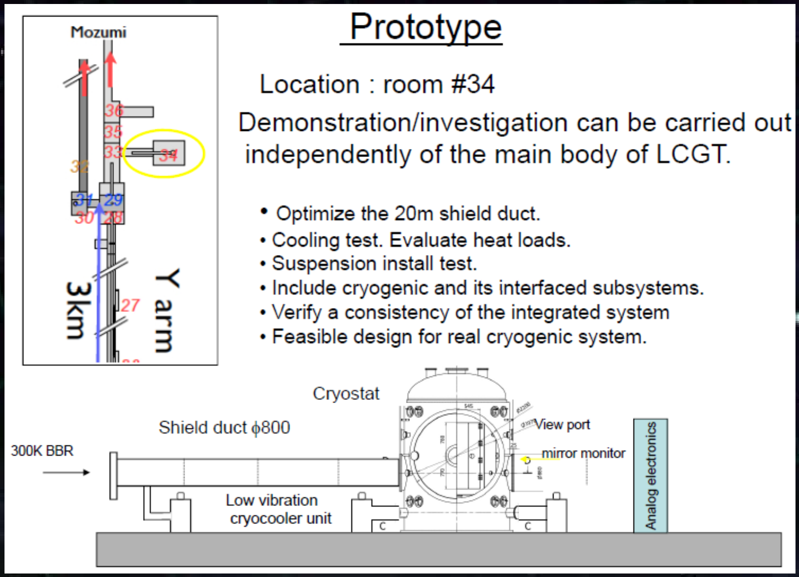
**Planning a full-scale prototype test at Kamioka site**

- Vacuum – Cryostat system
- Radiation shield
- Low-vibration cryocooler
  → Cooling test, Installation test,

**On-site development from 2013**

CLIO : 100-m cryogenic interferometer



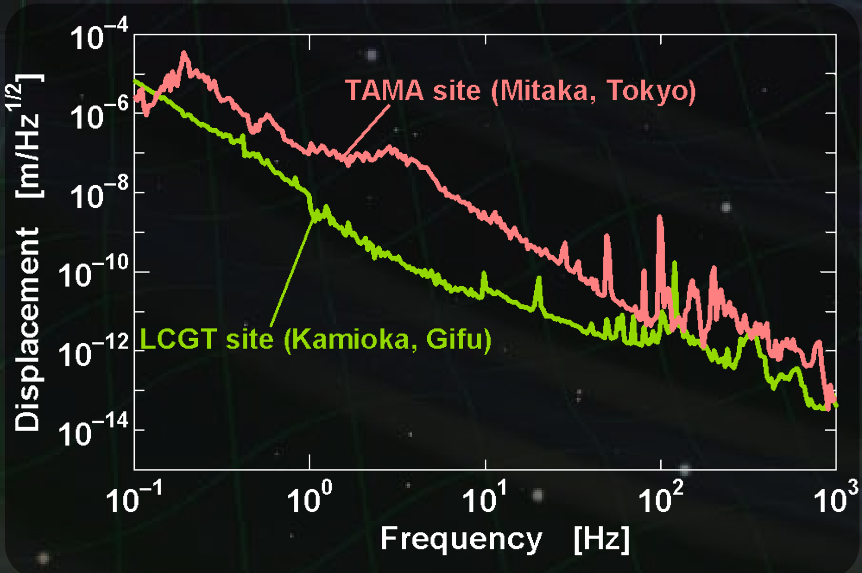
# Seismic-noise reduction

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

### Quiet site

Kamioka underground site
(~1000km underground)

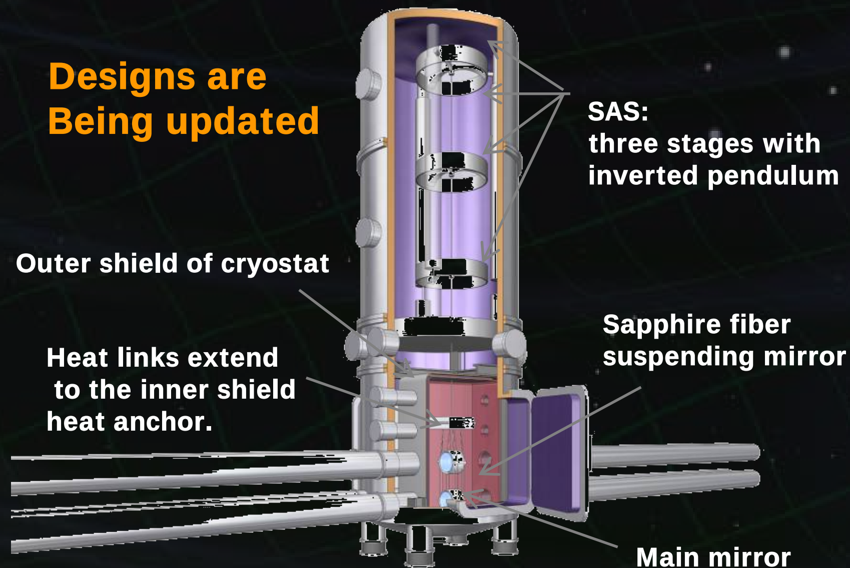
Lower seismic disturbance
by 2-3 orders




### Better Isolation system

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

Designs are
Being updated



# Developments (Seismic noise)

## Underground site

Heritages by

CLIO (100m baseline)

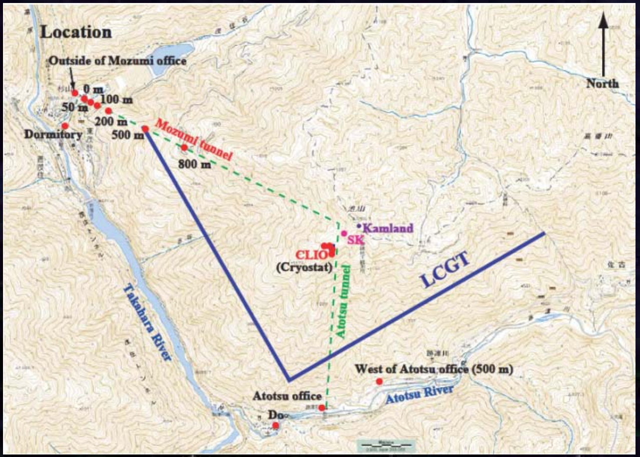
20m prototype moved from NAOJ

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

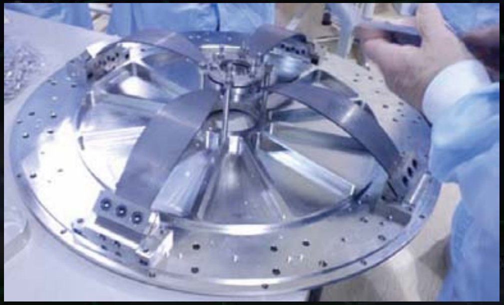
⇨ Detailed design

## 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

## 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

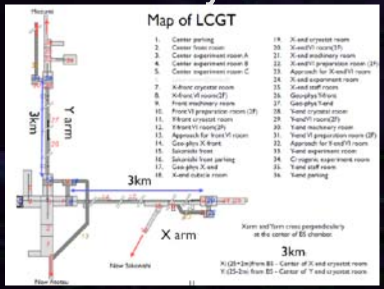
Computing platform, network design

## Analog electronics

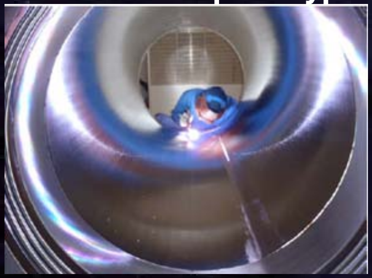
Design policy under discussion

Detailed designs

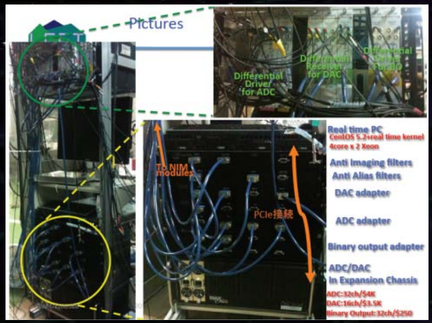
Tunnel layout

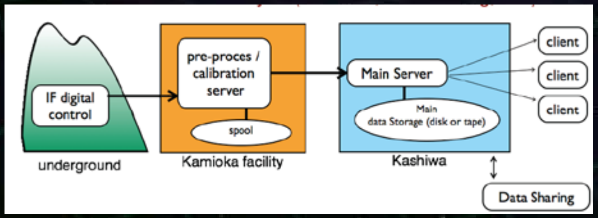



Vacuum tube prototype



Digital system installed to CLIO




Computing platform and Network

# Summary

## LCGT : Project started

- Costs have been partially funded
- Form global network with 2nd generation detectors

⇨ Aim to detect GW, and to open new astronomy

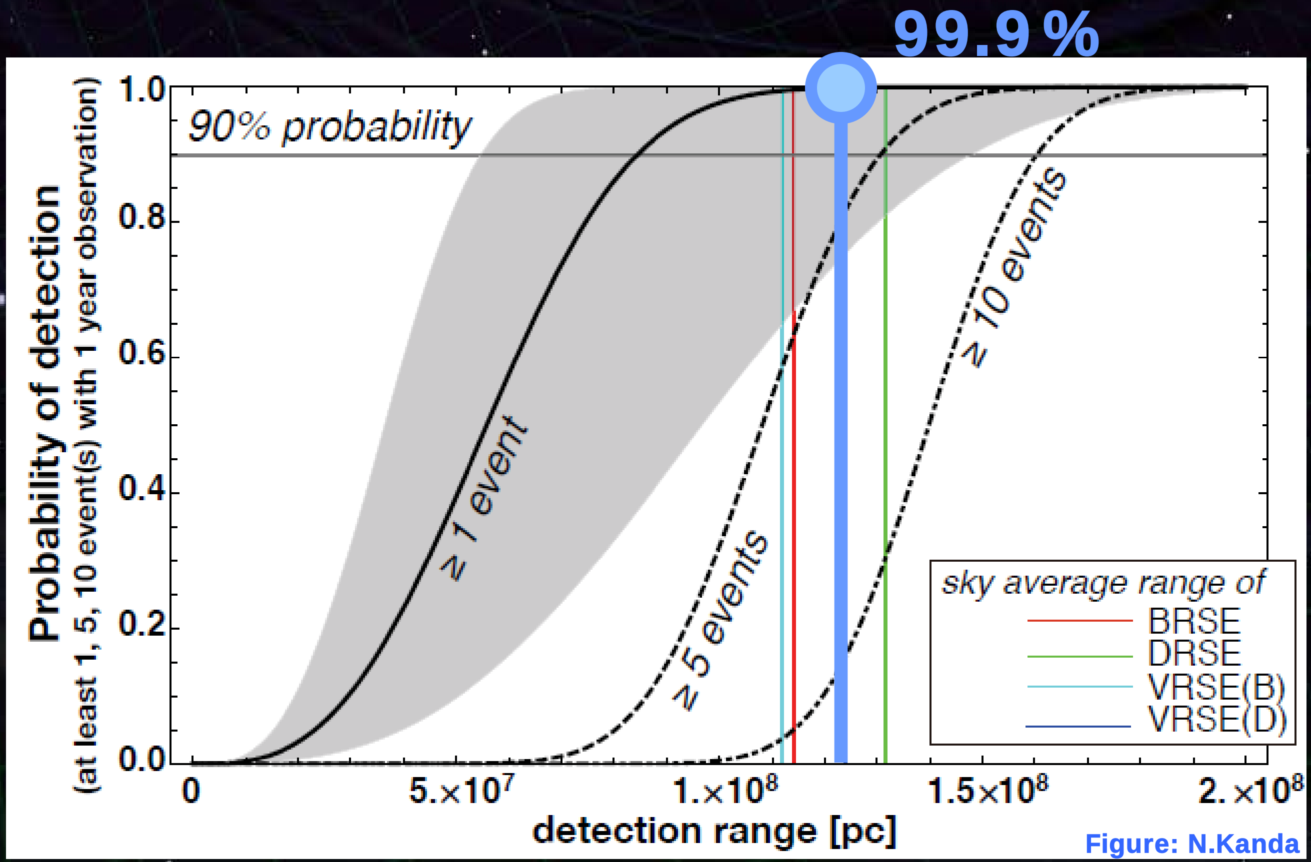
- LCGT will demonstrate 3rd generation detector techniques: cryogenics and underground

## 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

# Detection probability

**Probability to detect at least one event in one-year observation** ⇨ **Success probability of the LCGT project**




Assume
Poisson distribution

# 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 : 15K
  - 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 : < $1 \times 10^{-7}$ Pa ← Ion pump lifetime (5 years)
< $2 \times 10^{-7}$ 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 : $\phi$1.6 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 : $\phi$500 mm, t 10 mm
  - Baffle aperture: $\phi$250 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

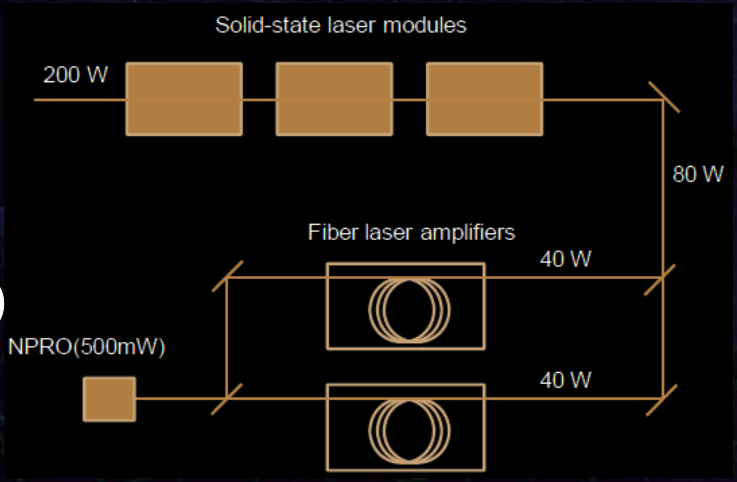
  **Multi-layer stack**

  **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 < $10^{-7}$

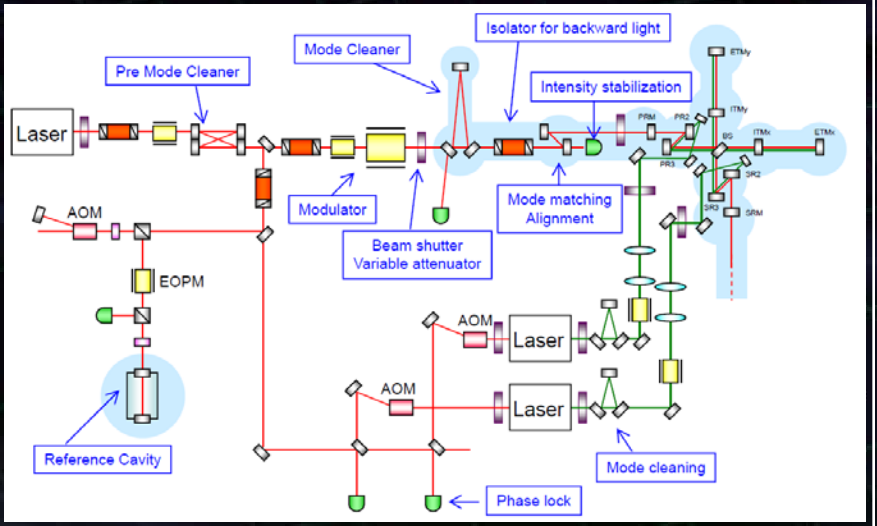
- **Main interferometer** (PRM, SEM, Folding Mirror)
  - Diameter : 25cm
  - Thickness : 10cm
  - Mass : 10 kg
  - *also used for iLCGT test mass
  - AGC or Heraeus (ITM)
  - LIGO TM substrates (other)
- **Beam splitter**
  - Diameter : 38cm
  - Thickness : 12cm
  - Mass : 30 kg
- **Input optics (MC, 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 < $3 \times 10^{-8}$ Hz/Hz$^{1/2}$
Intensity stability < $2 \times 10^{-9}$ Hz$^{-1/2}$
RF intensity noise < $1 \times 10^{-9}$ 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 : $\phi$100mm, 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 μsec

- **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$3 mm
    - Frequency : 16.875MHz, 45 MHz
  - RF-QPD for wave front sensors (WFS)
  - AF-QPD for beam position sensing
  - Optical lever sensors
  - CCD imaging monitors
- **RF system**
  - Low-noise oscillator synchronized to 10MHz standard
  - RF distributor
  - Modulator resonant driver
  - Demodulator
    - Noise level : 1nV/Hz$^{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

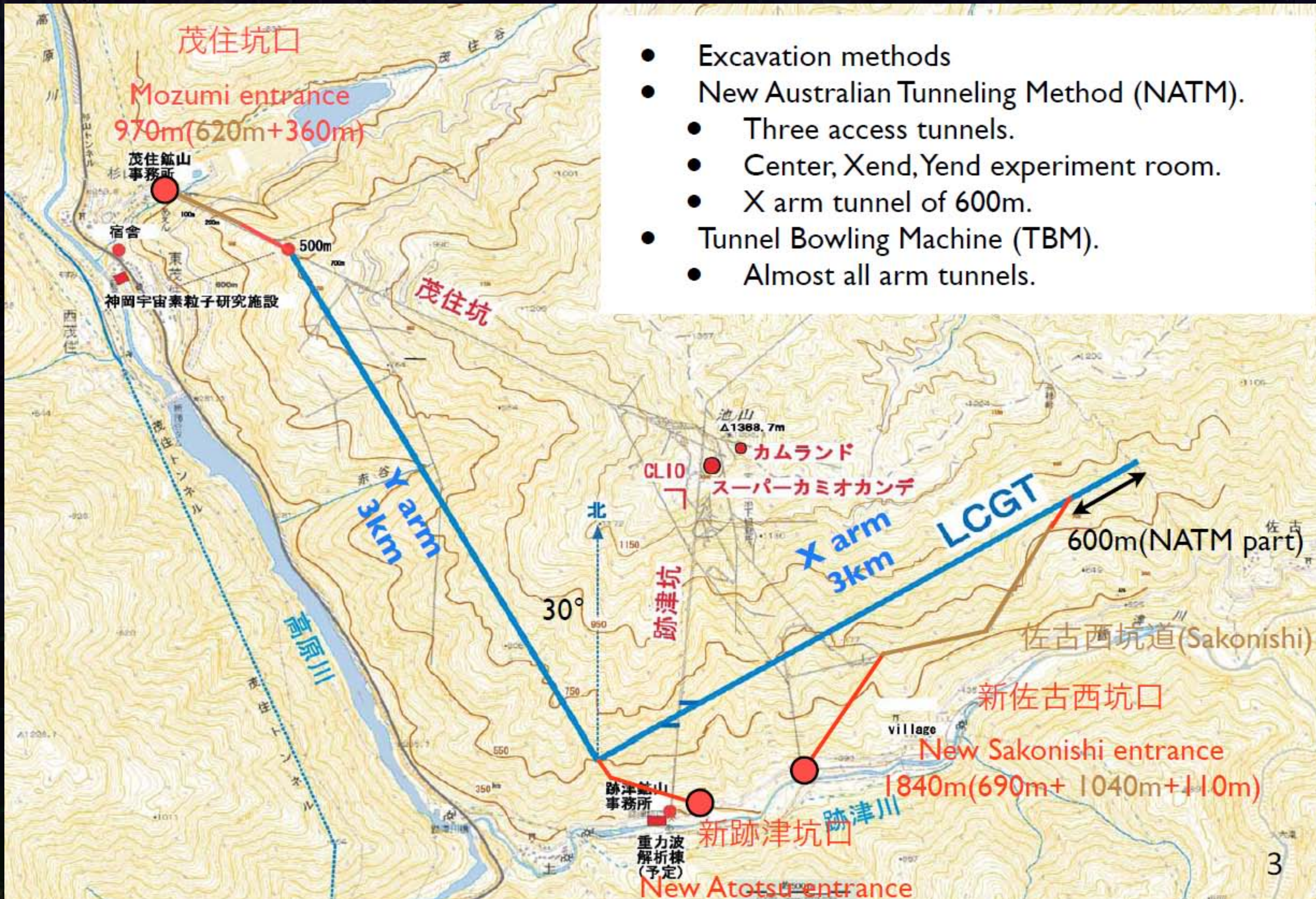
- **Computing platform**
  Main computing platform at Kashiwa
  Computation power > a few TFlops
  Software libraries in cooperation
  with world-wide network
  Distribution of
  data subset to collaborators

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

# Materials

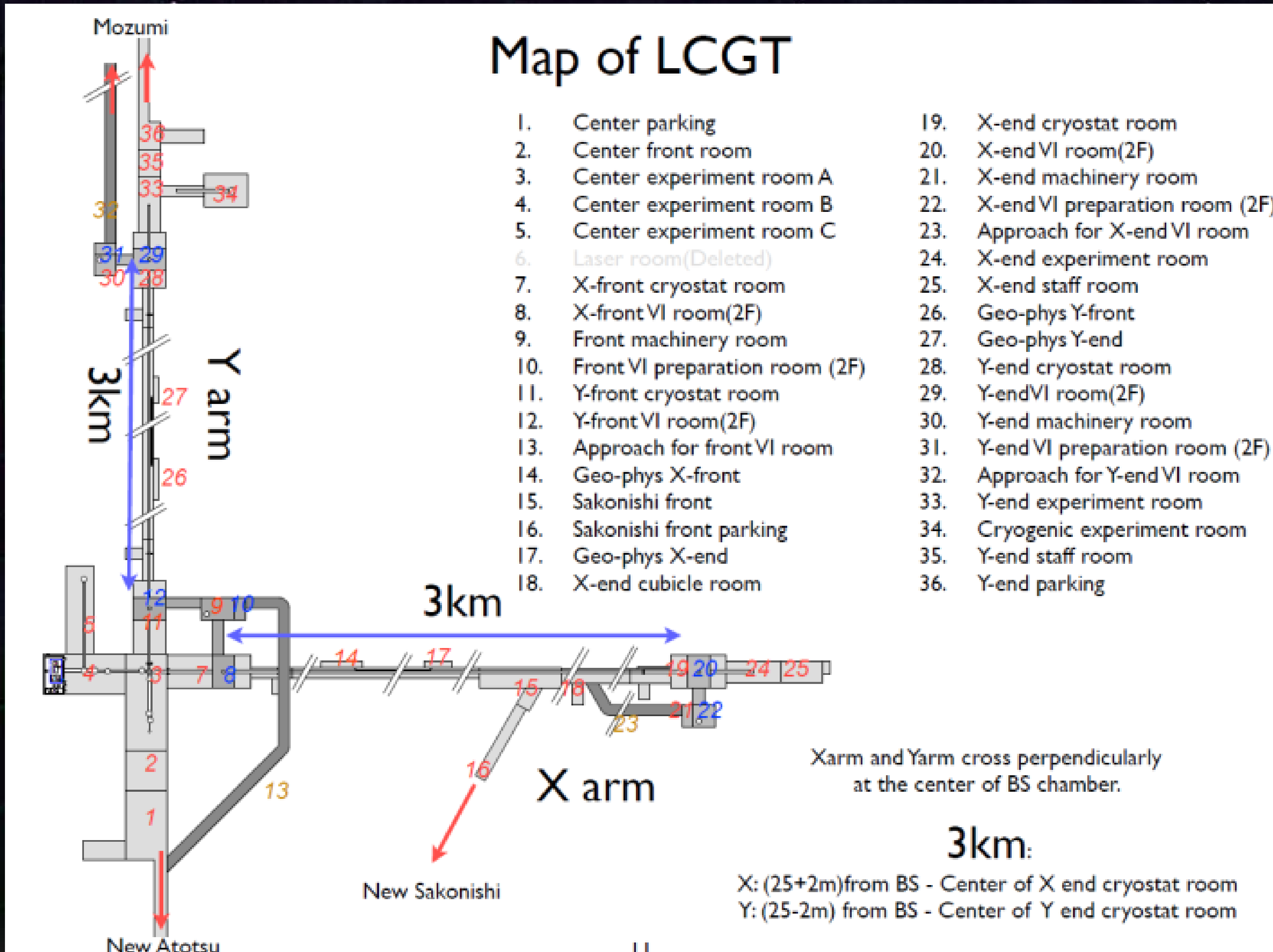
# Tunnel

- 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.



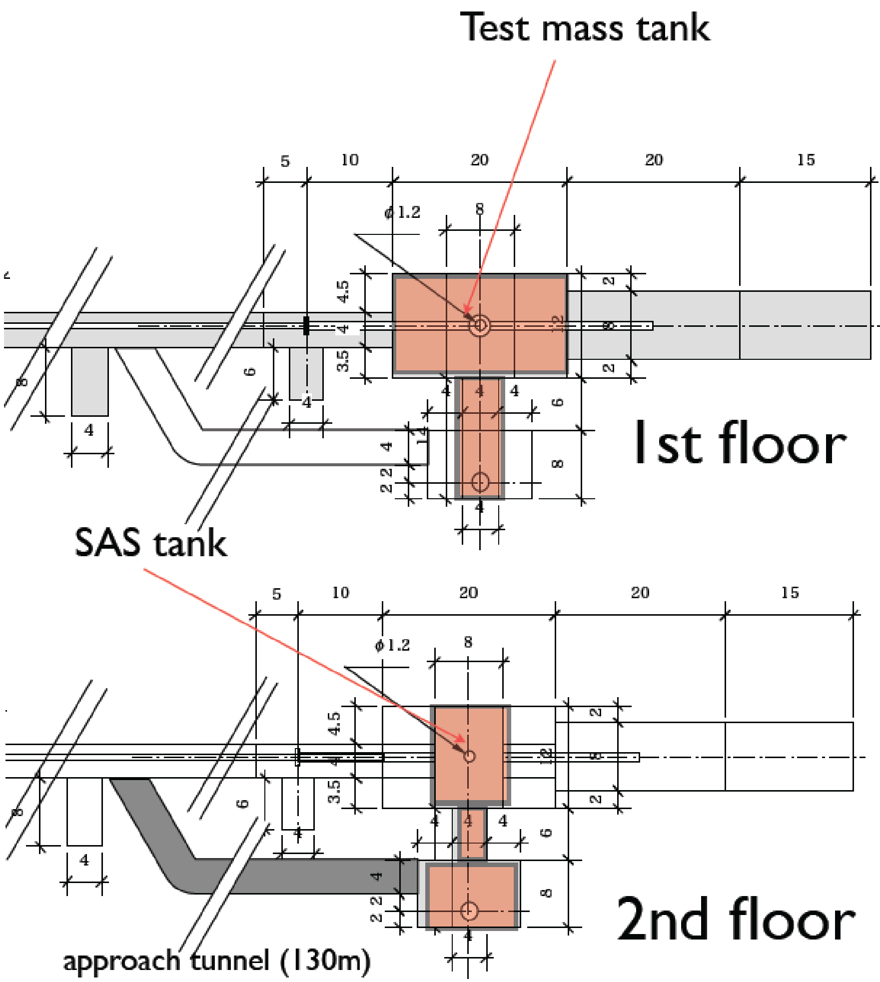

9

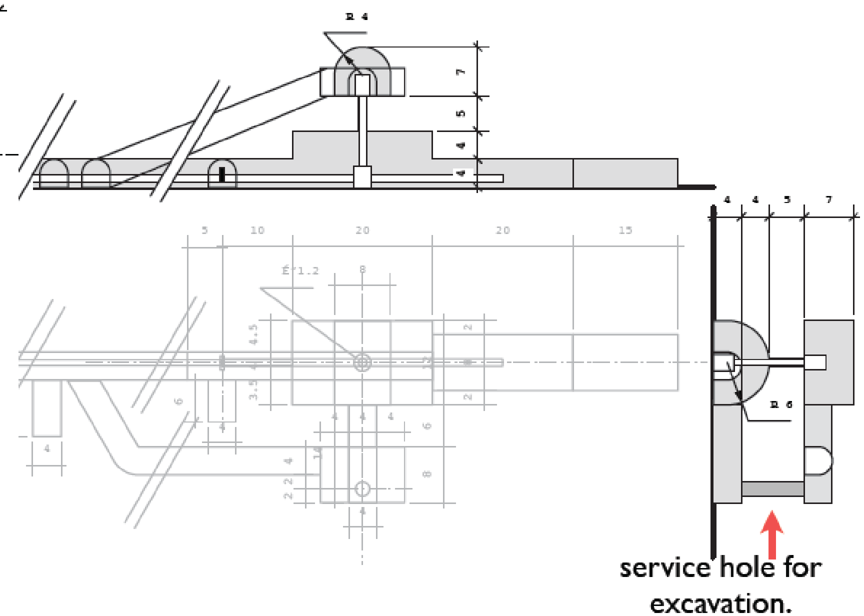
# Tunnel


Map of LCGT
Mozumi
Y arm
3km
3km
X arm
New Sakonishi
New Atotsu
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
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 : $400m^2 \rightarrow 512m^2$

Volume : $5140m^3 \rightarrow 2860m^3$

Approach tunnel(130m) : $1860m^3$.

Vertical hole: about 2,500,000Yen.

# Vacuum system

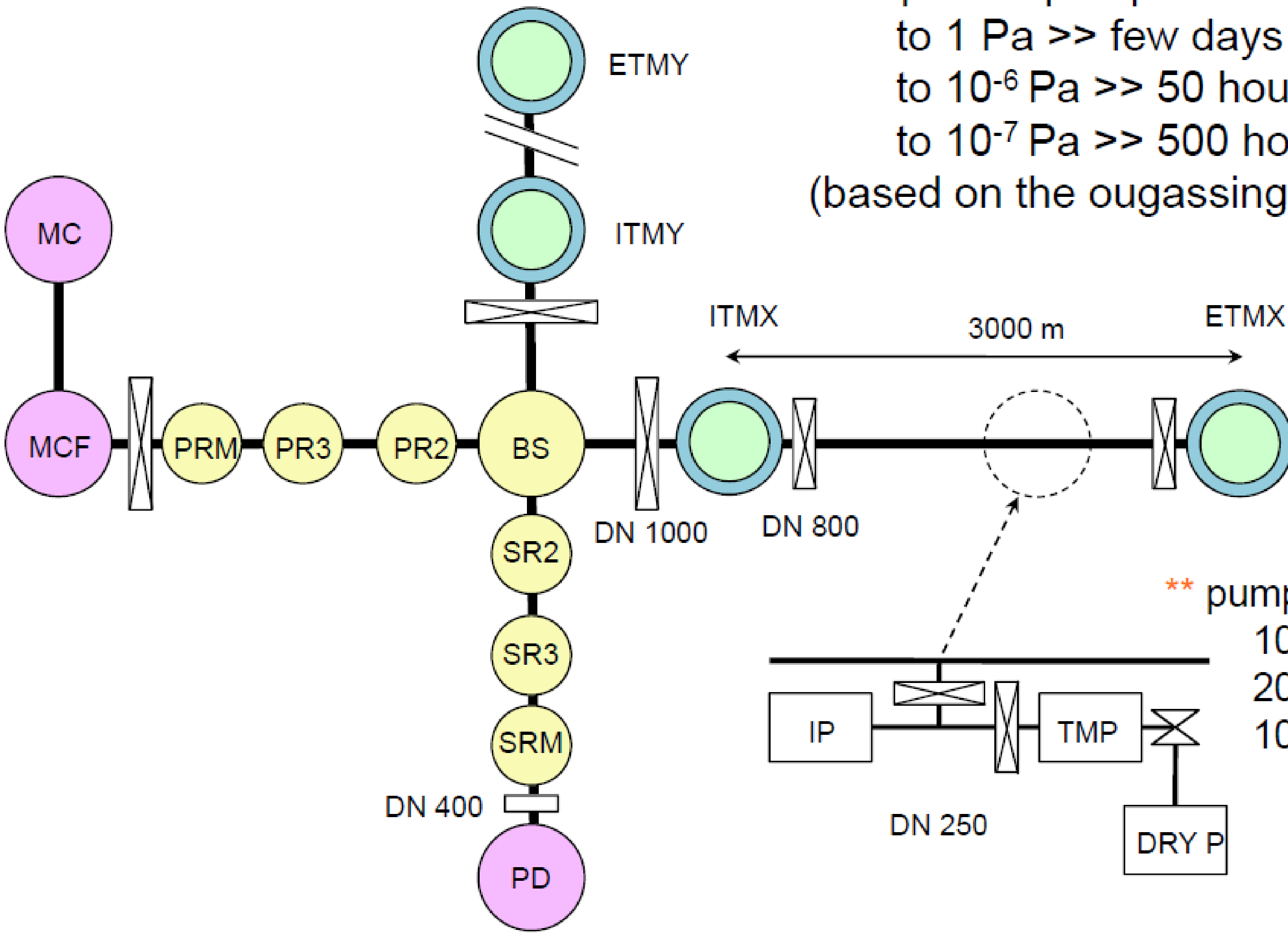
** expected pump-down scheme

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

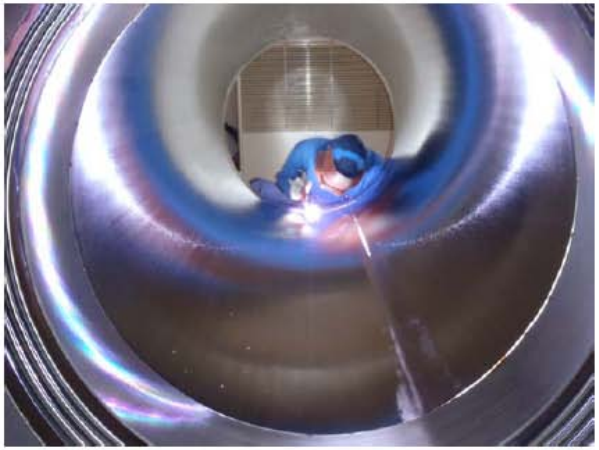
110302 VAC (YS)

## LCGT Vacuum System

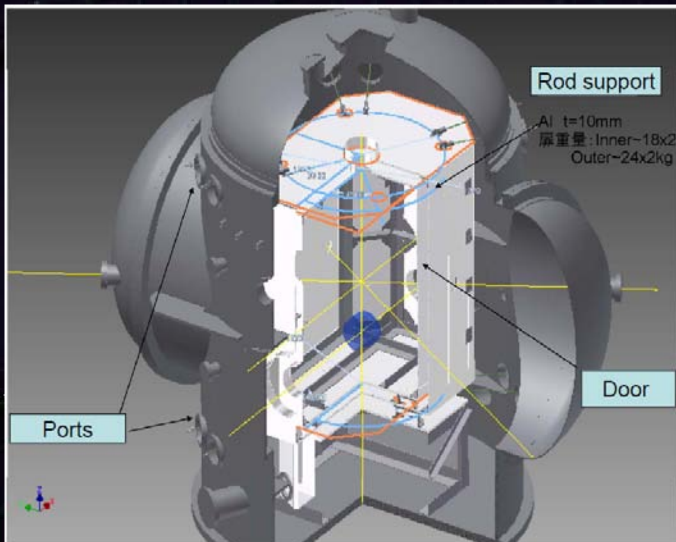
** test product of the tube

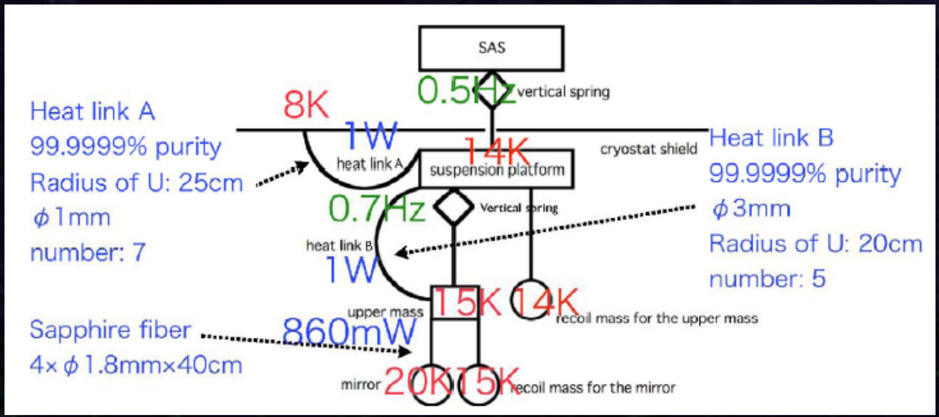
* A 4-m long tube was manufactured and a half of the inner surface was electro polished.

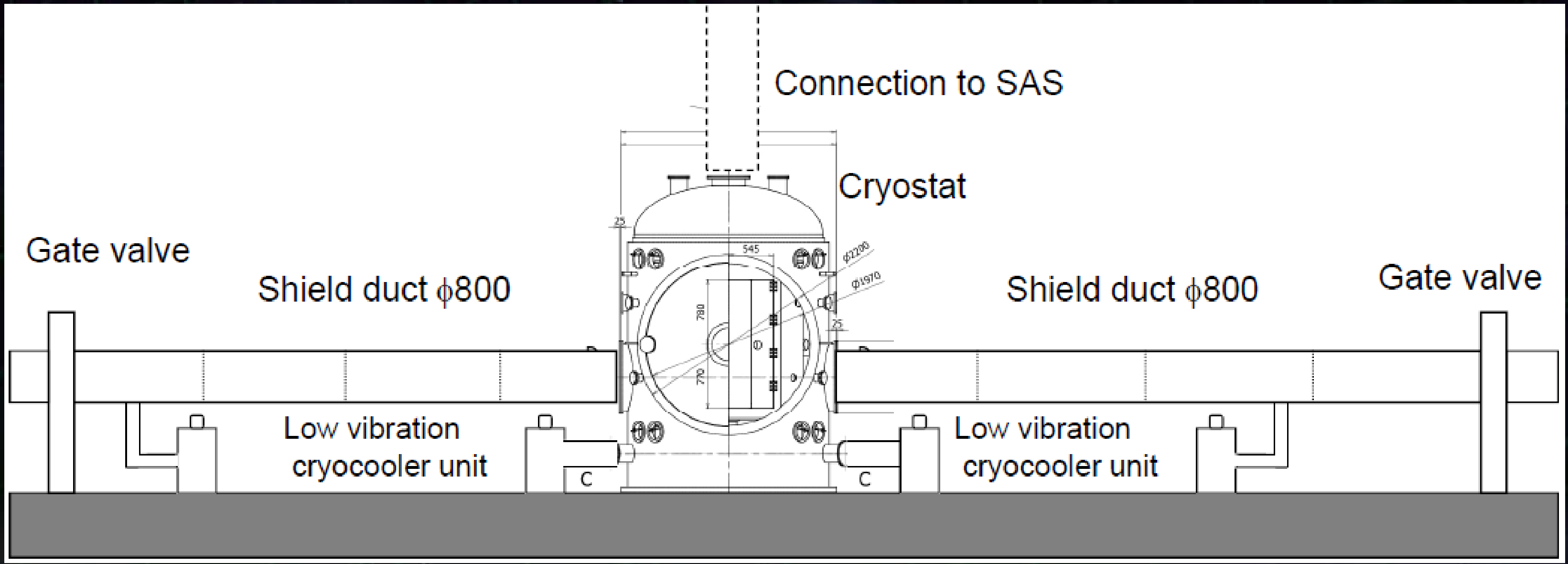
* A flange with a bellows (one convolution) was manufactured.



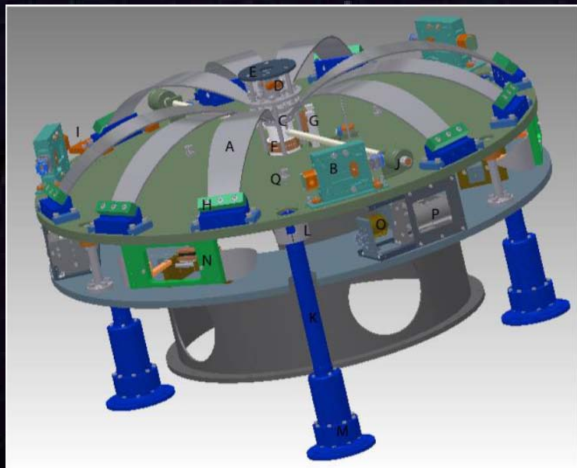
# Cryogenics

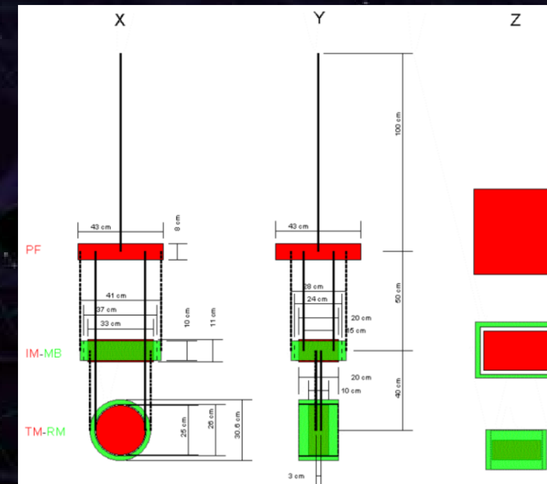

Rod support
Al t=10mm
Outer~24x2kg
Door
Ports


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

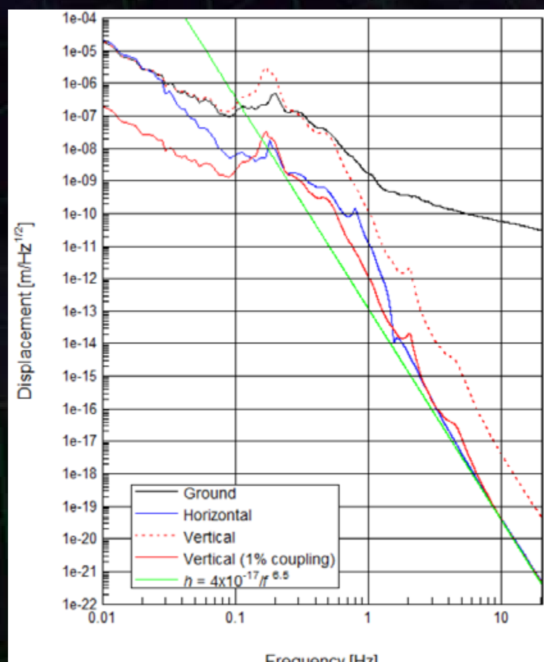

Connection to SAS
Cryostat
Gate valve
Shield duct ϕ800
Shield duct ϕ800
Gate valve
Low vibration
cryocooler unit
Low vibration
cryocooler unit

# Vibration Isolation

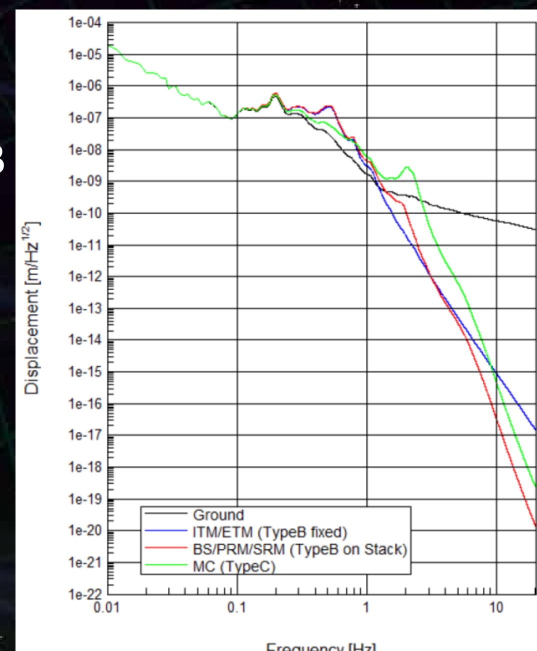




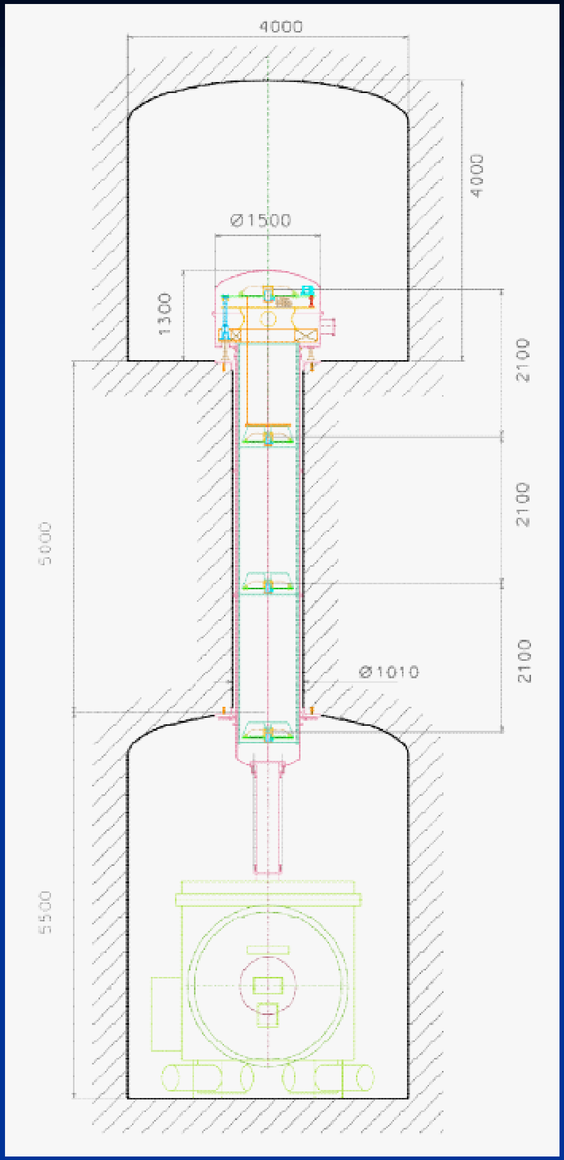

**Type-A**




**Type-B**



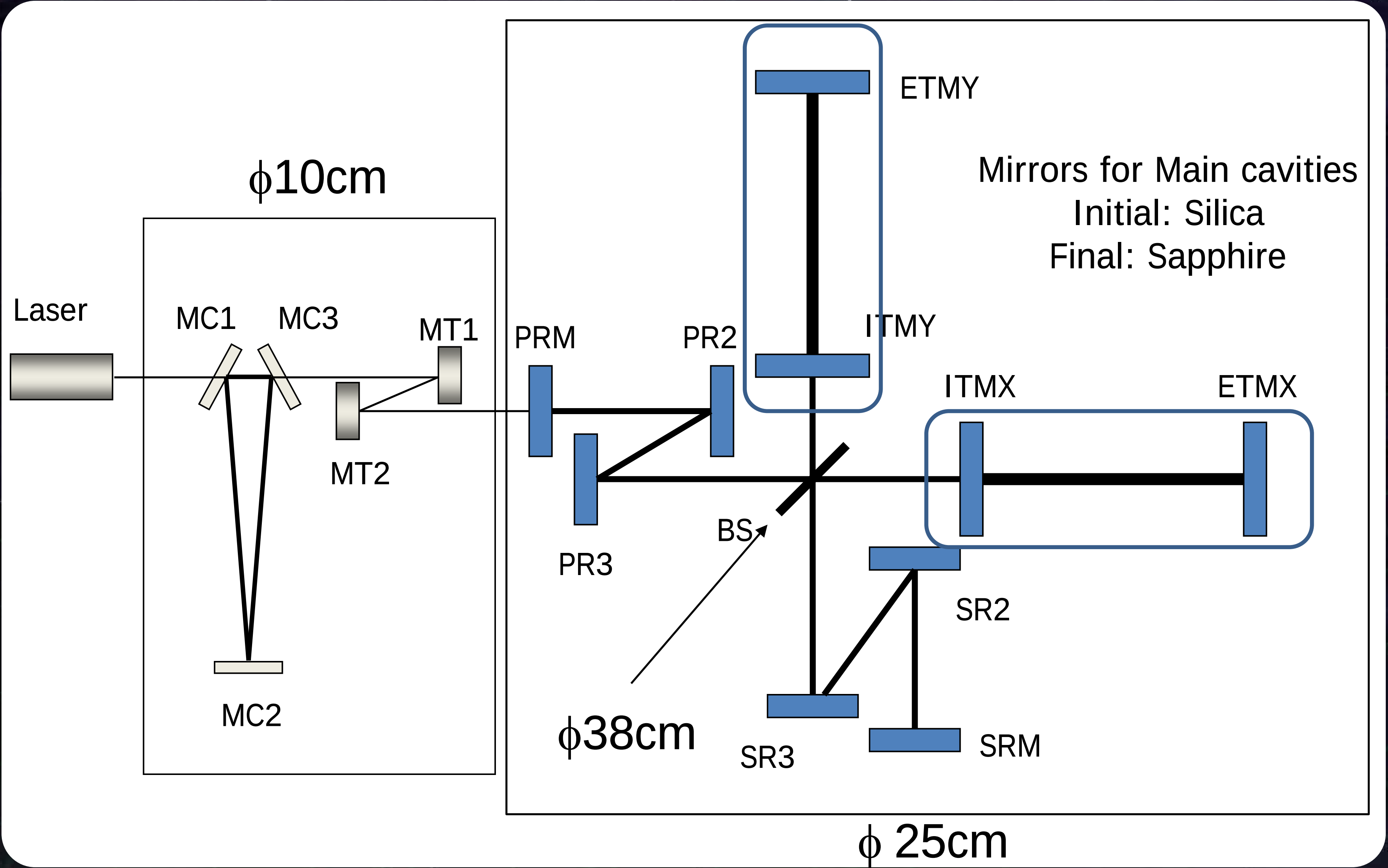
# Vibration Isolation



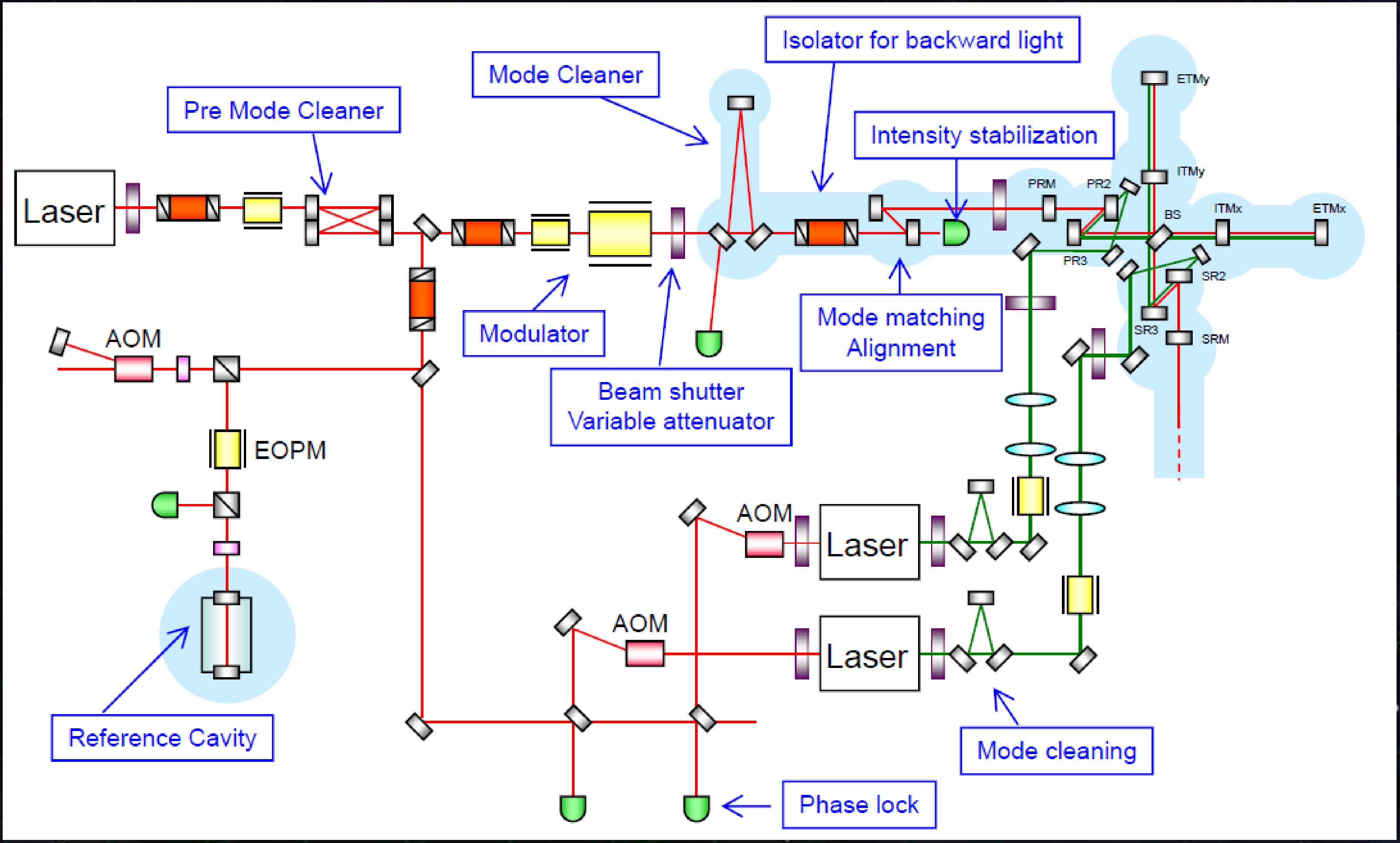

## Type-A (2-layer structure)

- 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

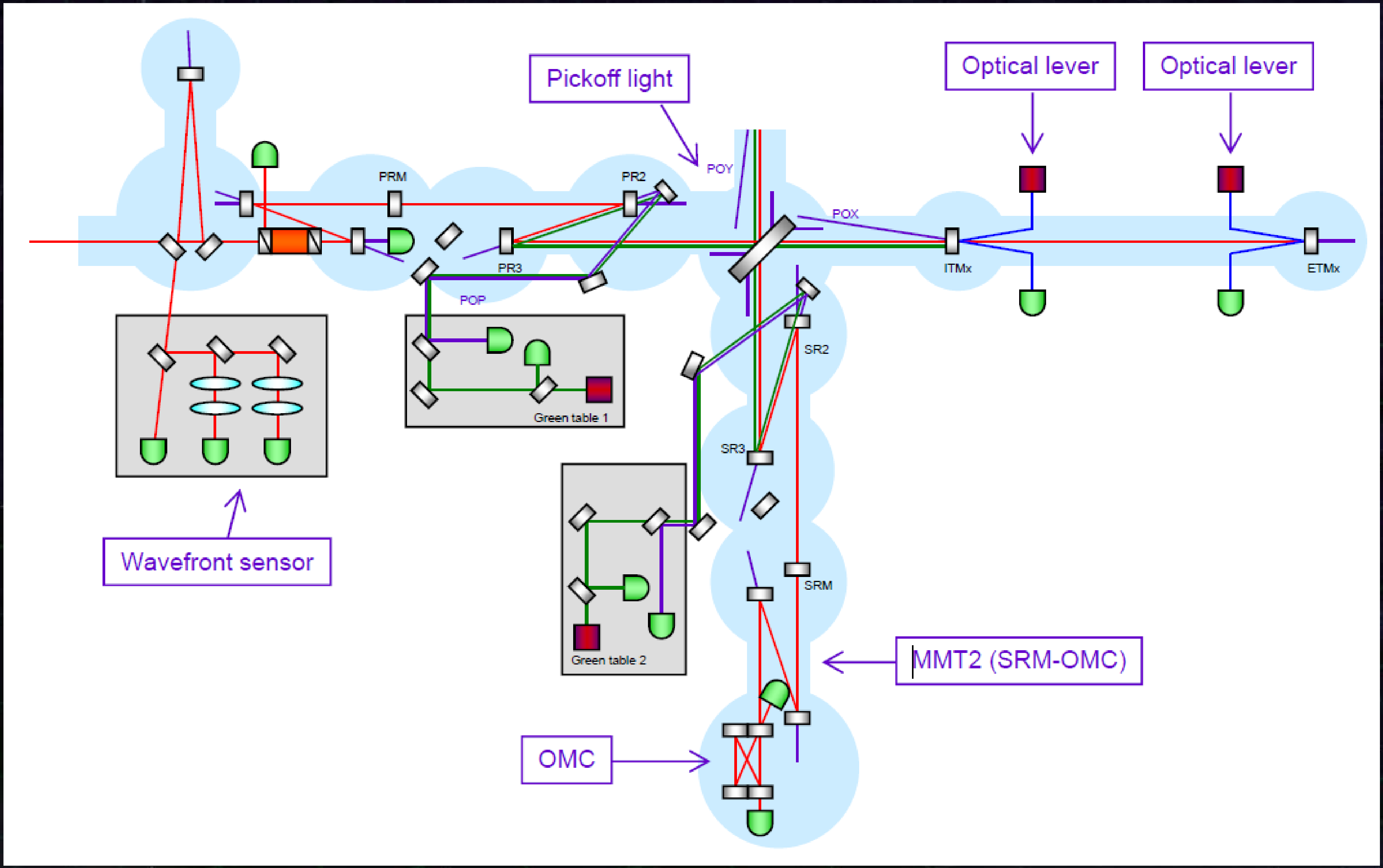
# Core Optics


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

# Input/Output Optics

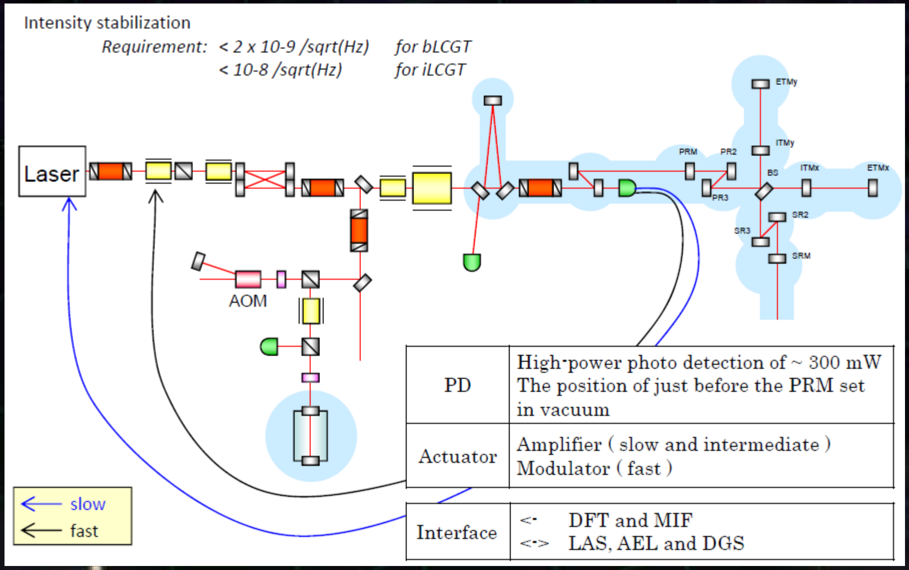


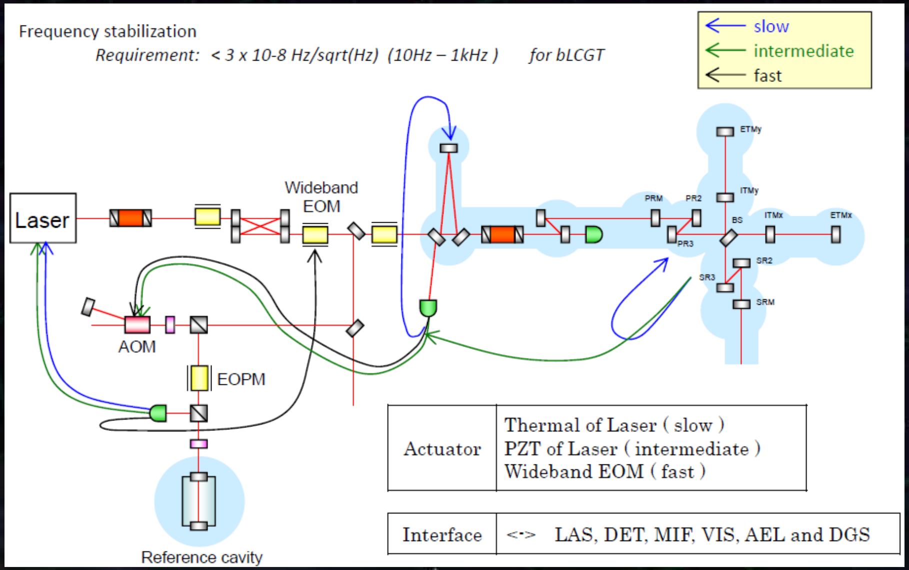
# Output Optics



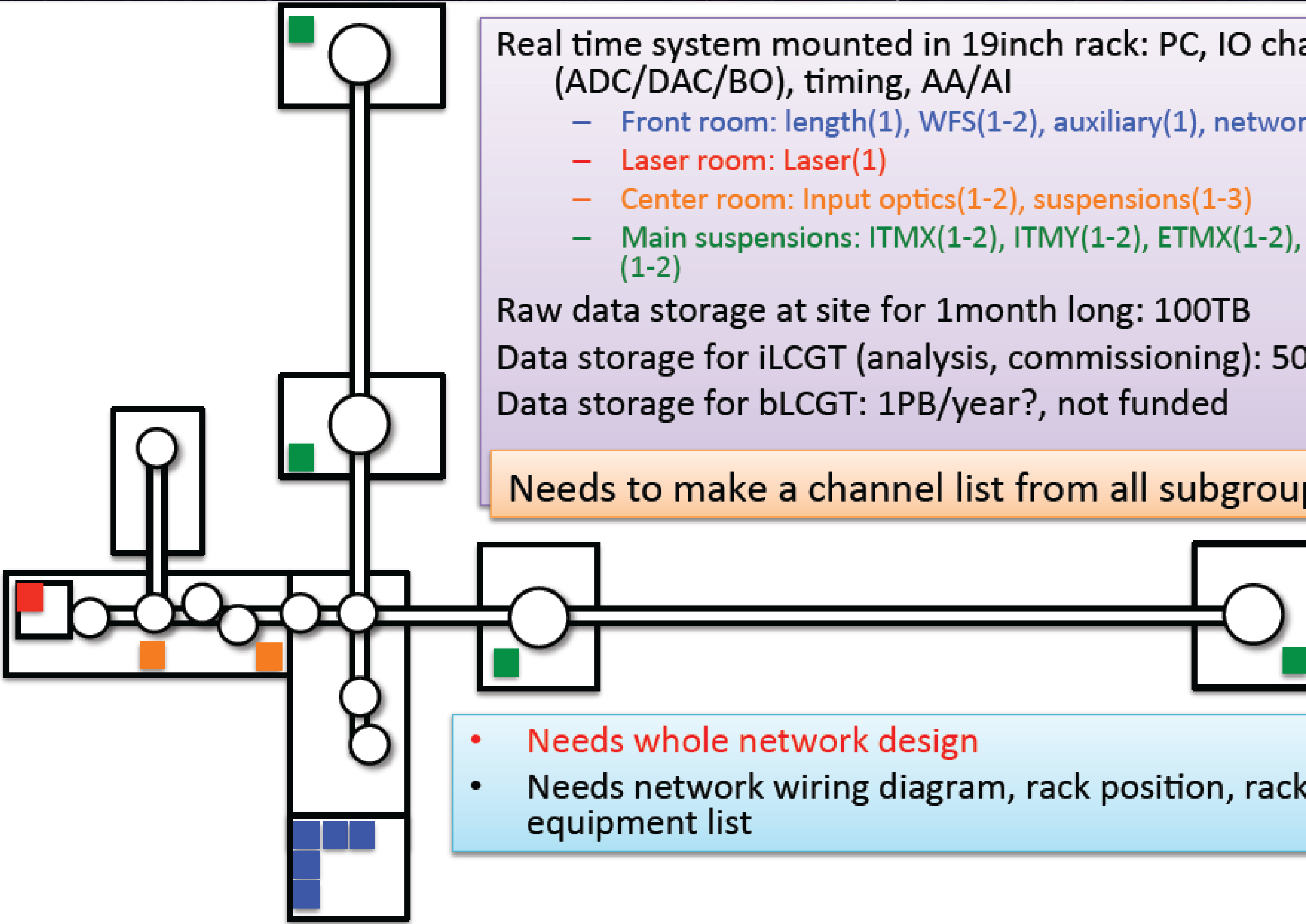
# Freq. and Int. stabilization

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



# 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

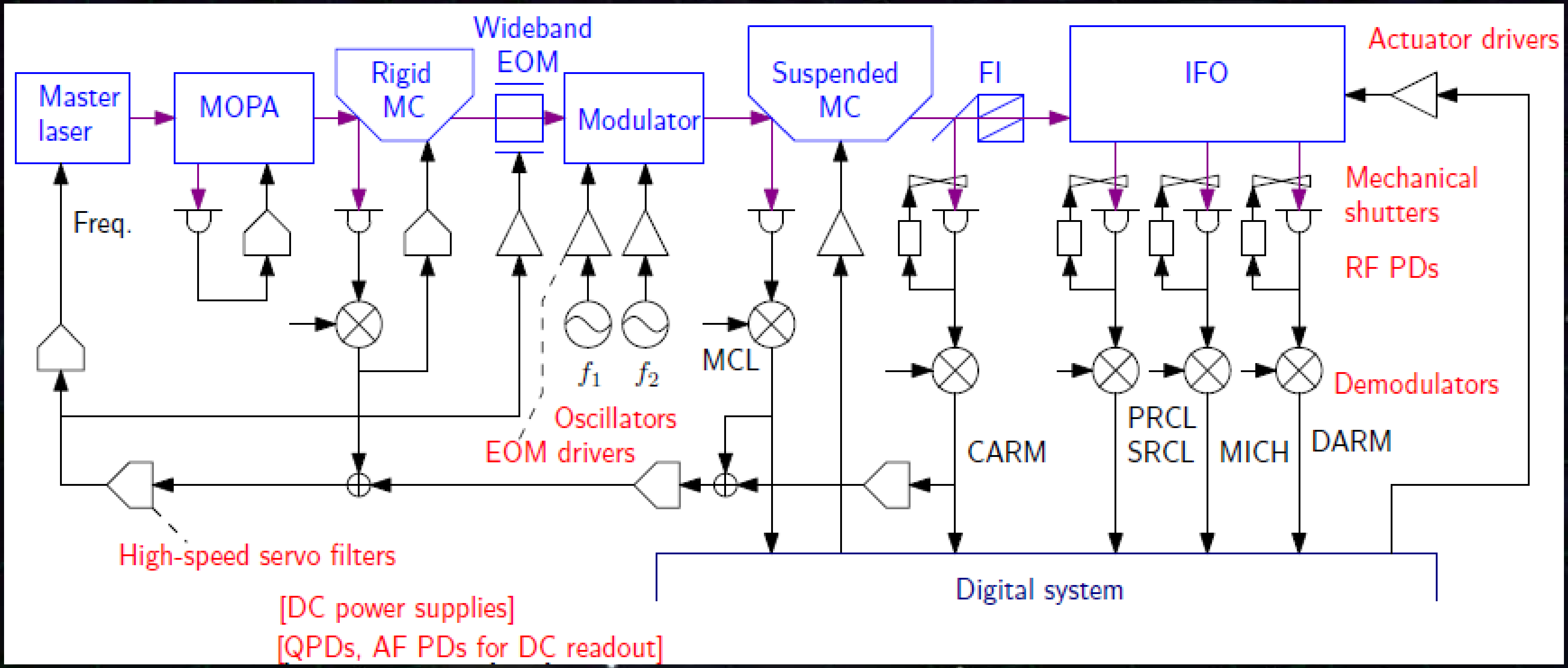
Data storage for iLCGT (analysis, commissioning): 500TB

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

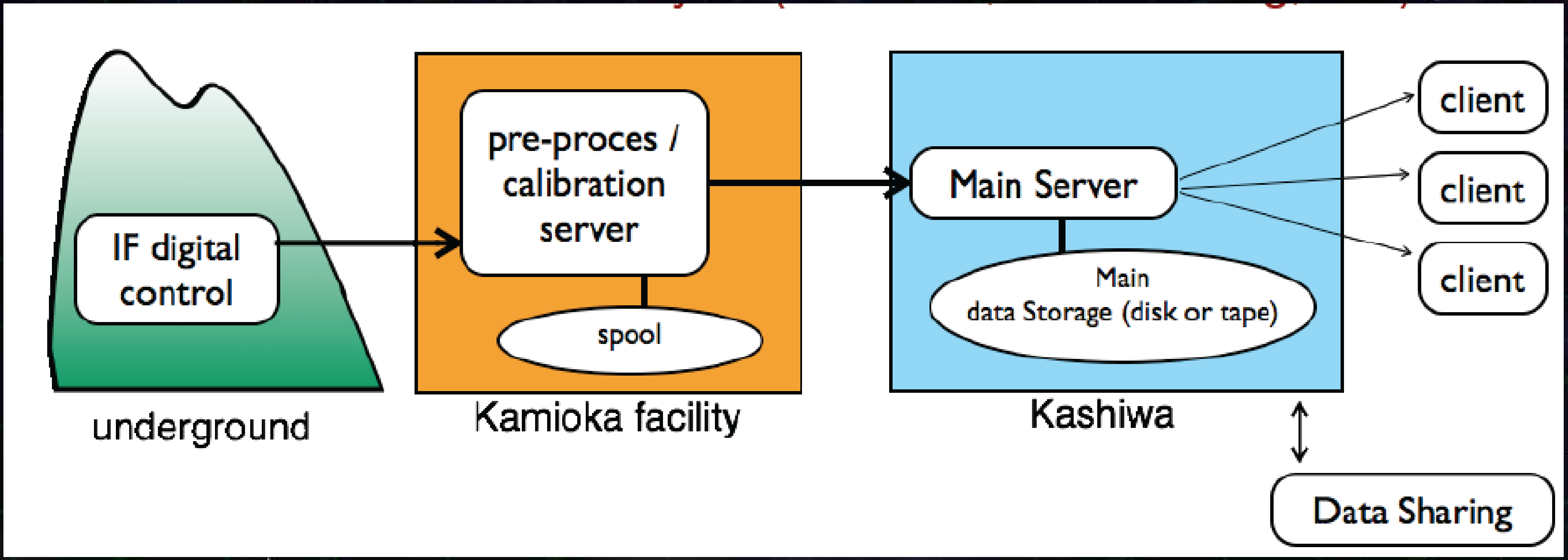
Needs to make a channel list from all subgroups

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

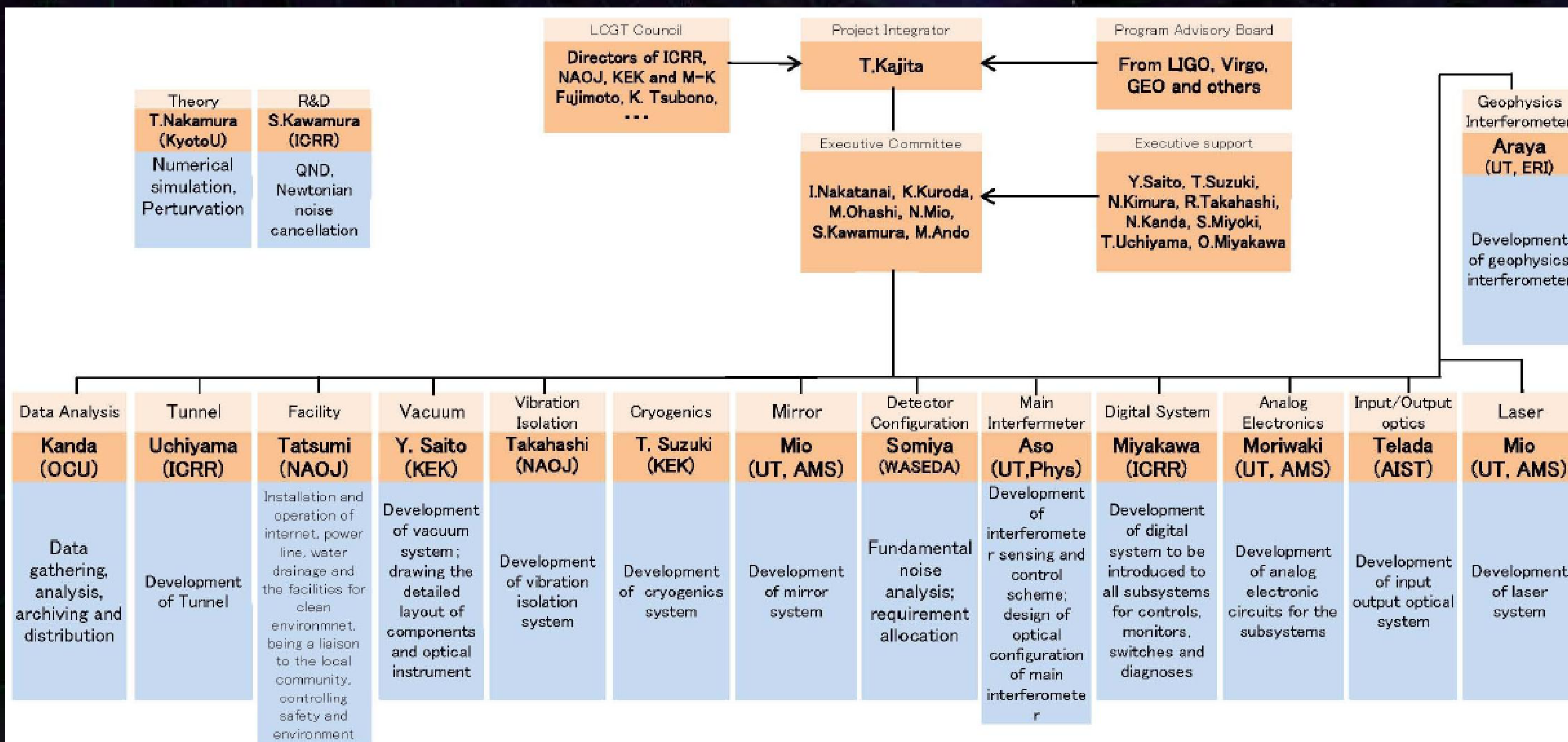
# Analog electronics



# Data Analysis



# Organization



# LCGTとAd. LIGO

| LCGT (JPN) | | Advanced LIGO (USA) |
|---|---|---|
| 1 detector (3km) | Scale | 3 detectors (4km) (2 close, 1 separated) |
| Long baseline<br>Better seismic attenuation system<br>Underground site | Seismic noise reduction | Long baseline<br>Better seismic attenuation system<br>Suburban site |
| Low-mechanical-loss mirrors and suspensions<br>Cryogenic (20k) | Thermal noise reduction | Low-mechanical-loss mirrors and suspensions<br>Large beam size |
| High-power laser source<br>Low-loss optics<br>Variable RSE config. | Quantum noise reduction | High-power laser source<br>Low-loss optics<br>Detuned RSE config. |

# Roadmap of GW detectors

## Ground based detectors

Improved sensitivities (10-1kHz)

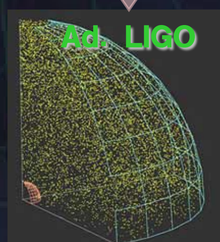
LIGO
Enhanced LIGO
Advanced LIGO

TAMA CLIO
LCGT

Virgo / GEO
Advanced Virgo

ET

2010
2015
2020
2025



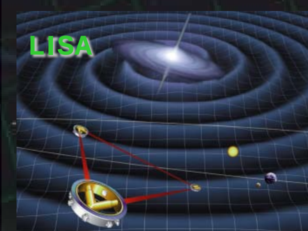


Detection Rate
~10 event/yr


## Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)

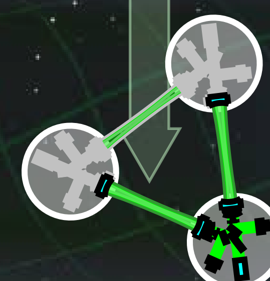

DECIGO
LPF
DPF




LISA
Pre-DECIGO

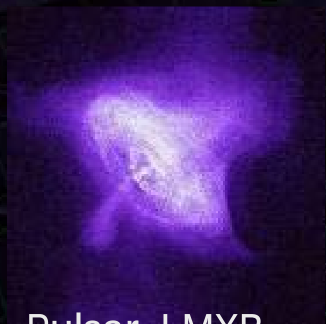
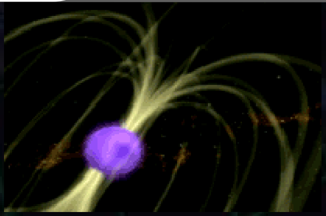
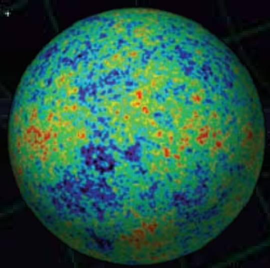
Guaranteed source
0.1mHz-10mHz

DECIGO
BBO



Cosmological GWs
around 0.1Hz

# GW targets and data analysis

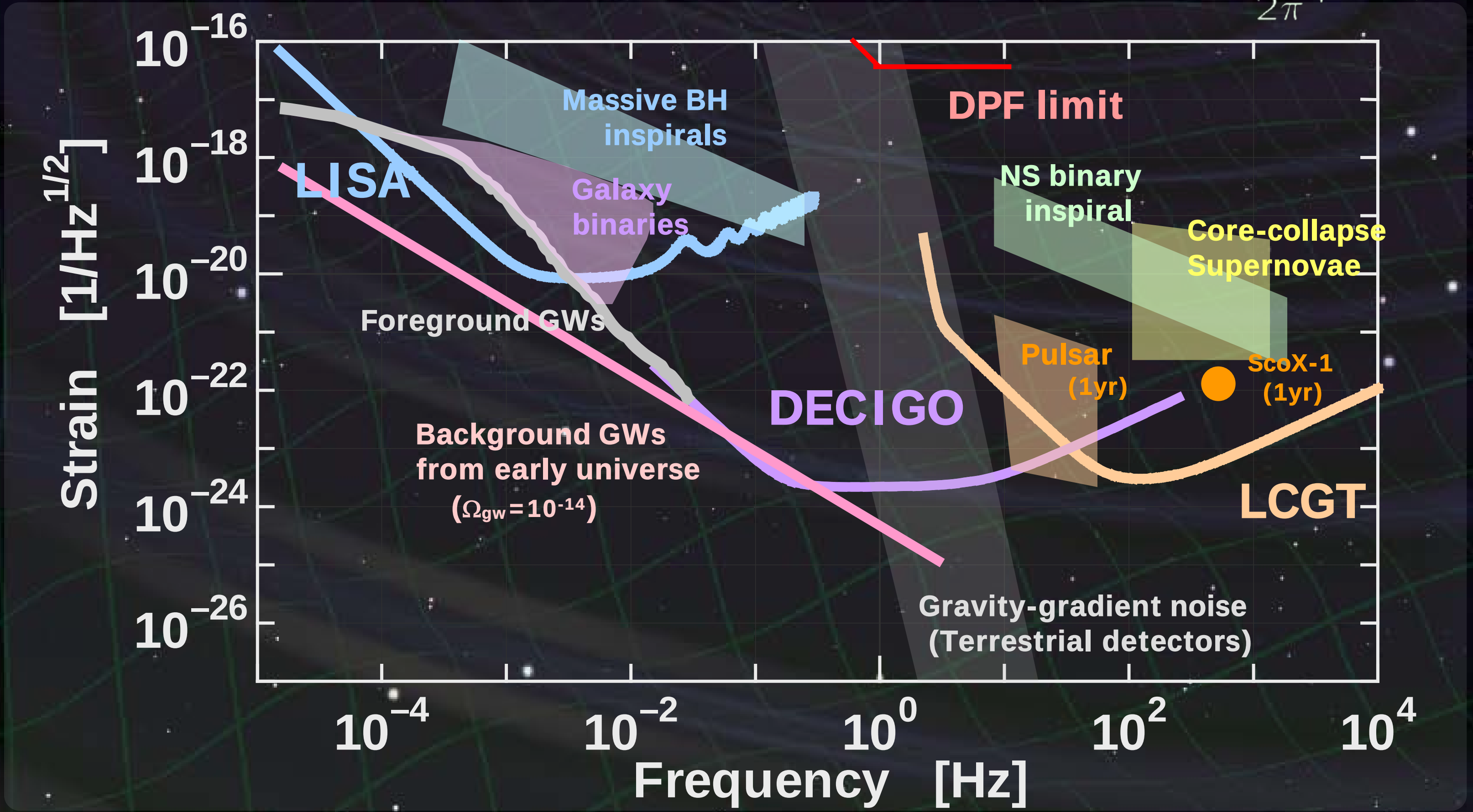
| | | Signal duration | |
|---|---|---|---|
| | | Short (bursts) | Long (stationary) |
| Waveform | Known |  Binary merger → Chirp wave, Ringdown wave<br>Gamma-ray bursts |  Pulsar, LMXB → Continuous |
| | Unknown |  Stellar core collapse → burst wave<br> Soft gamma-ray repeater |  Stochastic background → Random wave |

# DPF sensitivity

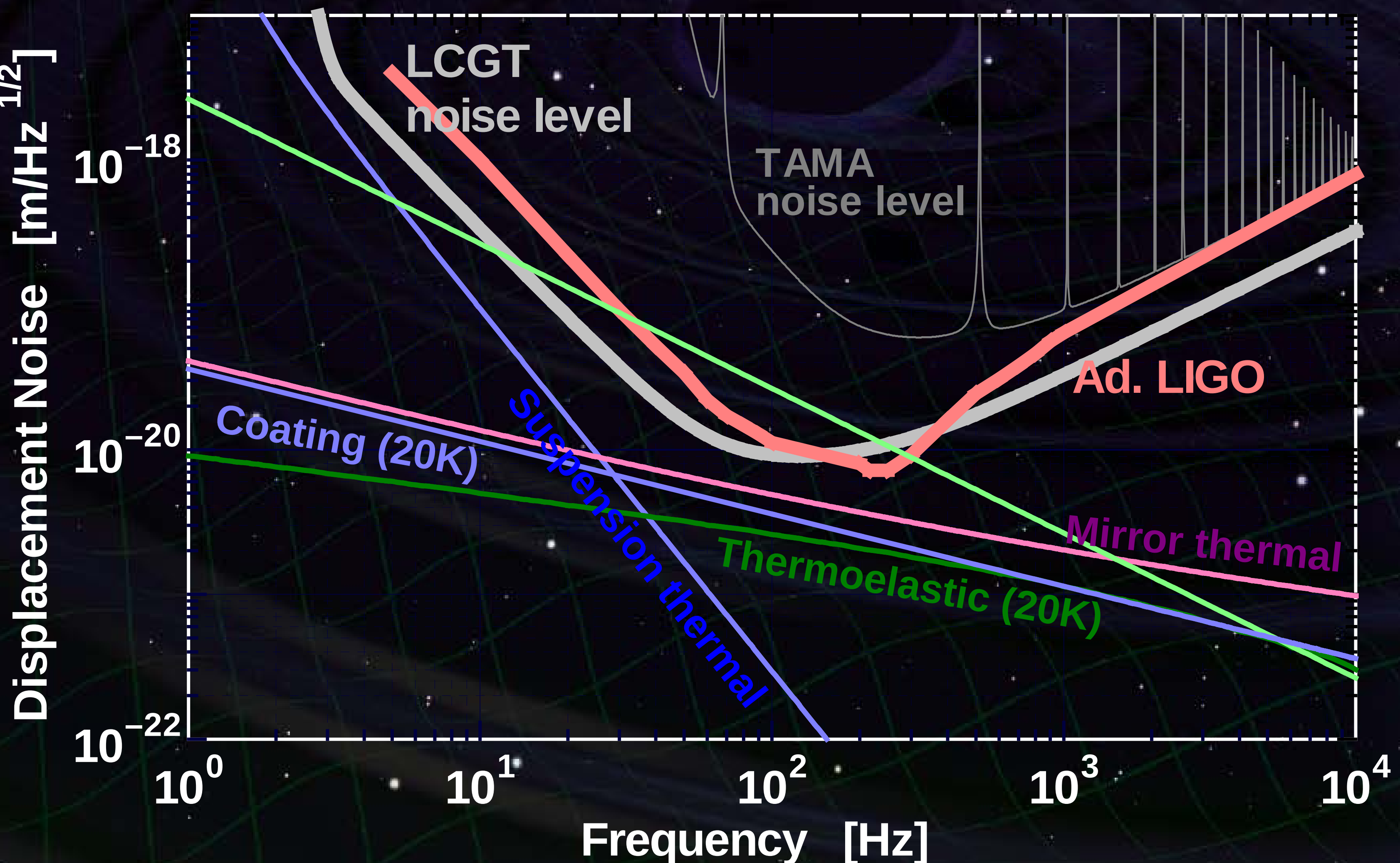
DPF sensitivity $h \sim 2\mathrm{x}10^{-15}\ \mathrm{Hz}^{1/2}$

(x10 of quantum noises)

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



# LCGTとAd. LIGO



# LCGT and DECIGO

**LCGT (~2017)**

Terrestrial Detector

→ High frequency events

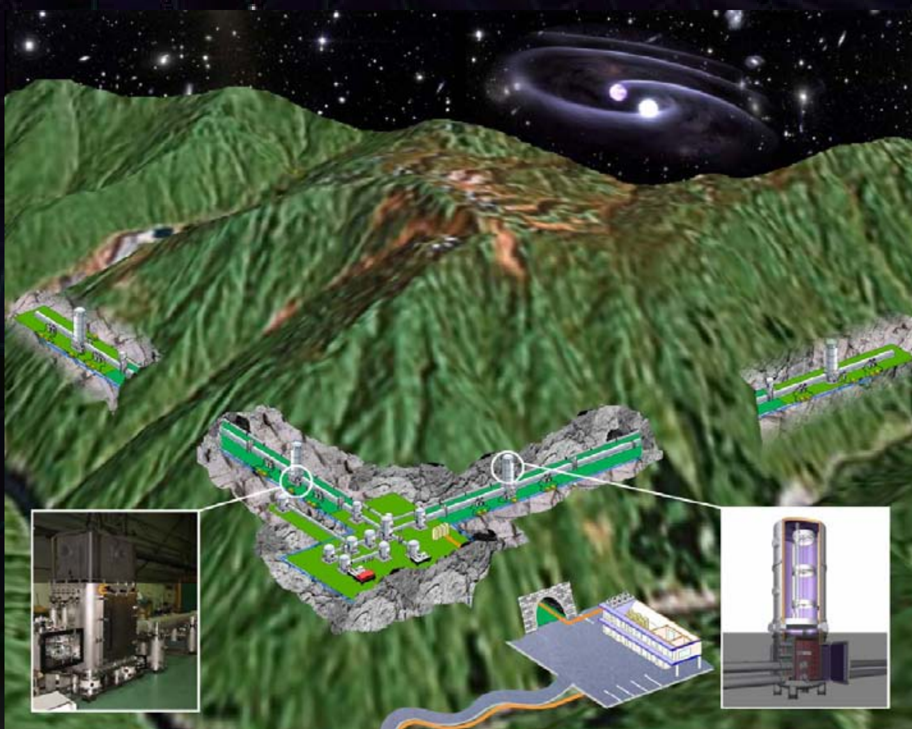
Target: GW detection

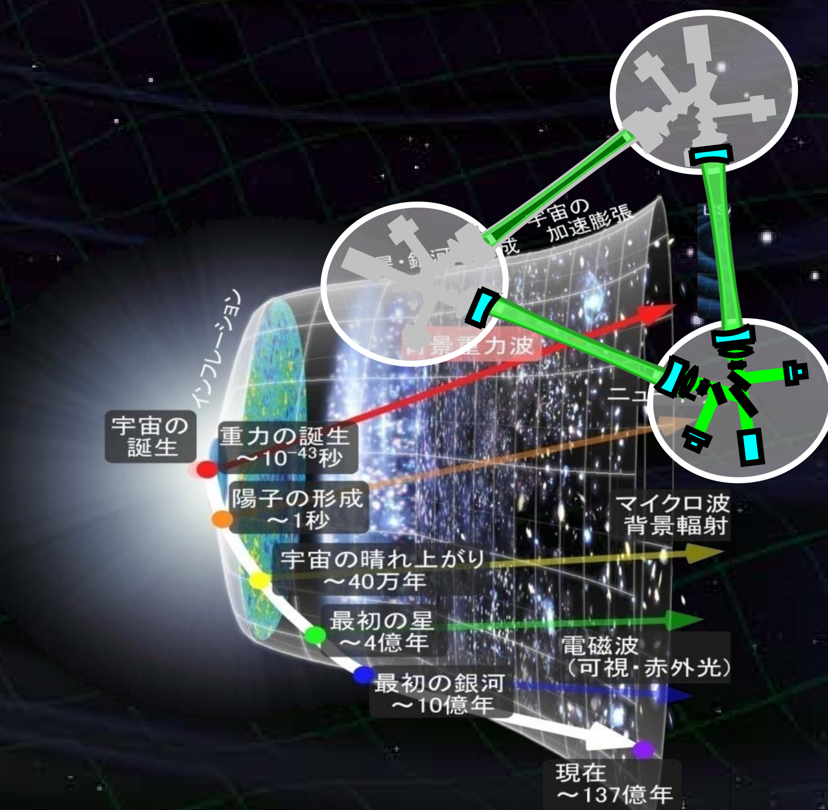
**DECIGO (~2027)**

Space observatory

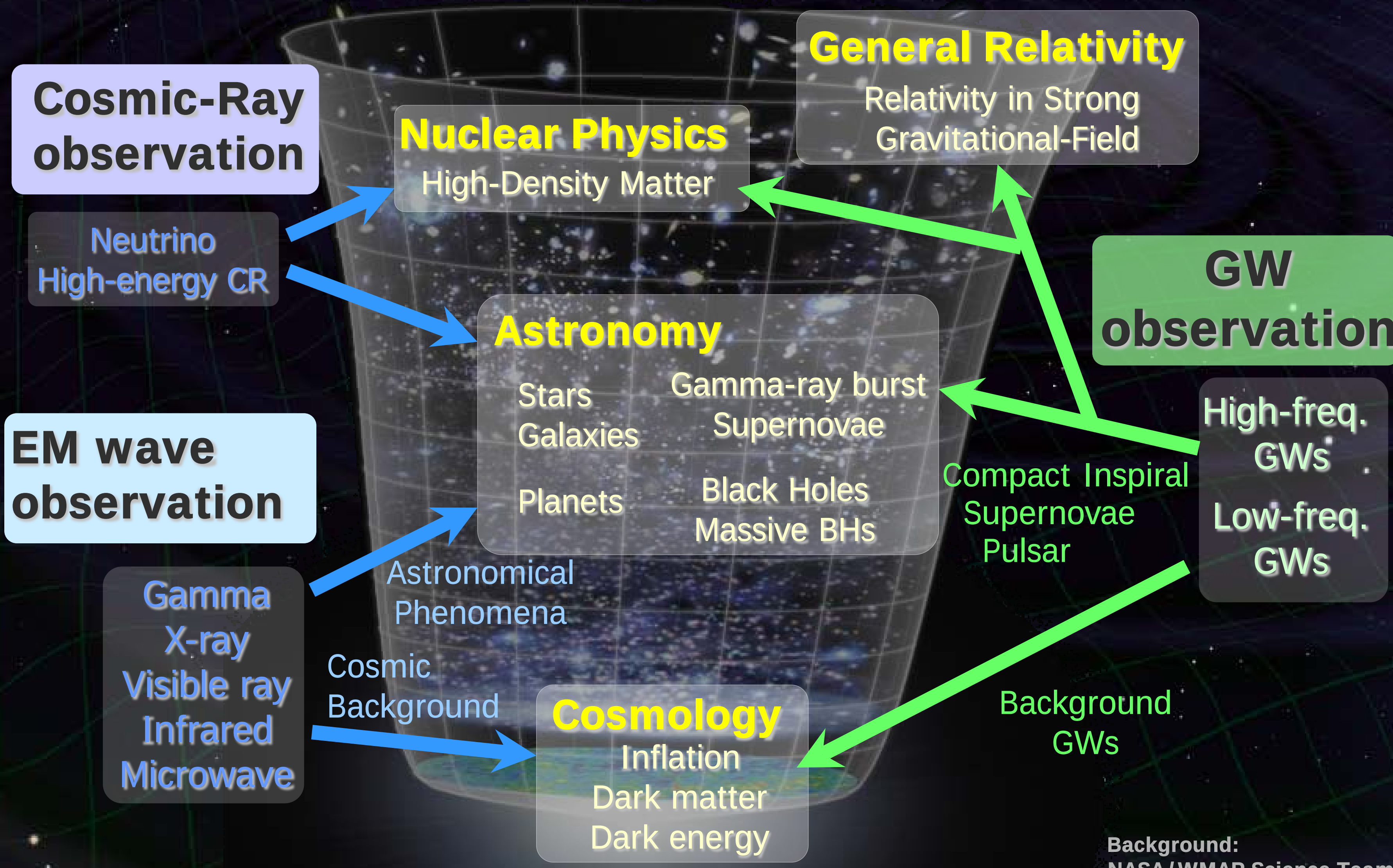
→ Low frequency sources

Target: GW astronomy





# Observation of the Universe




Background:
NASA / WMAP Science Team

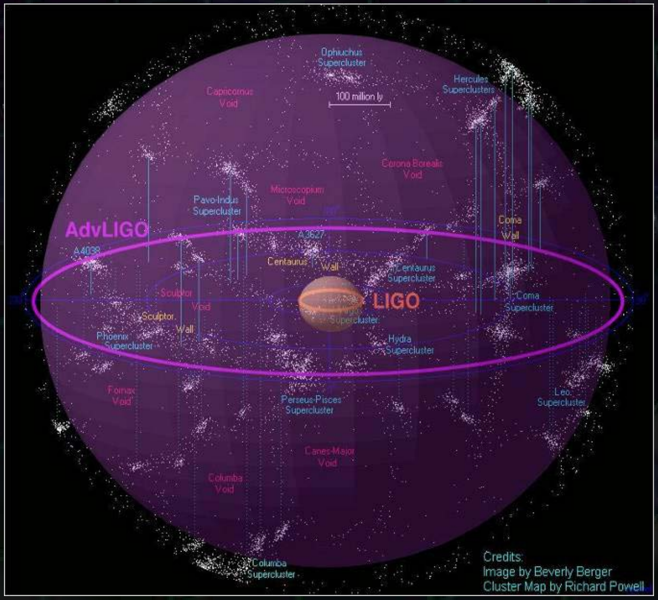
# Expanding the Horizon

**Current GW detectors : <20Mpc obs. range**

**However... we can expect only rare events ($10^{-5}$-$10^{-3}$ event/yr)**

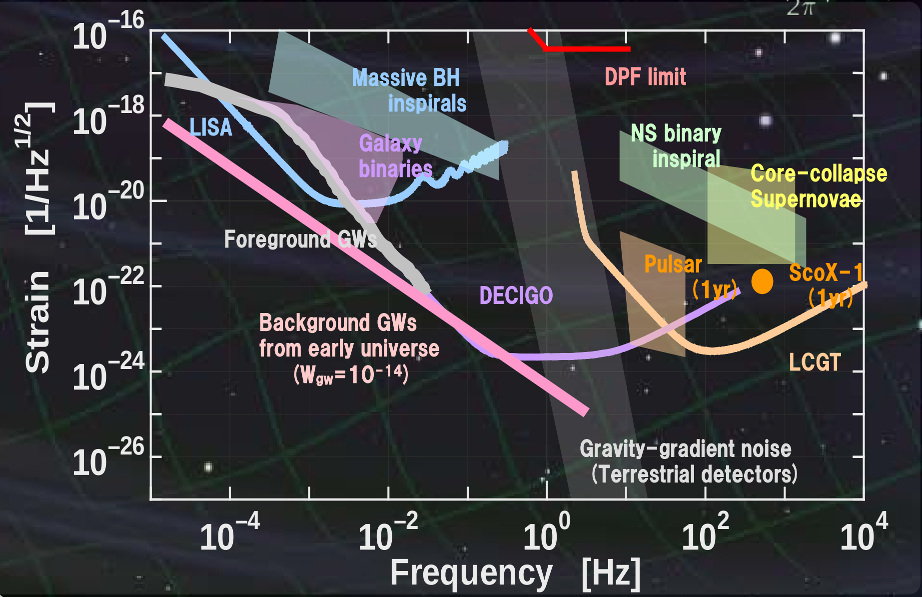
⇨ **Next generation detectors**

## Better sensitivity to cover more galaxies

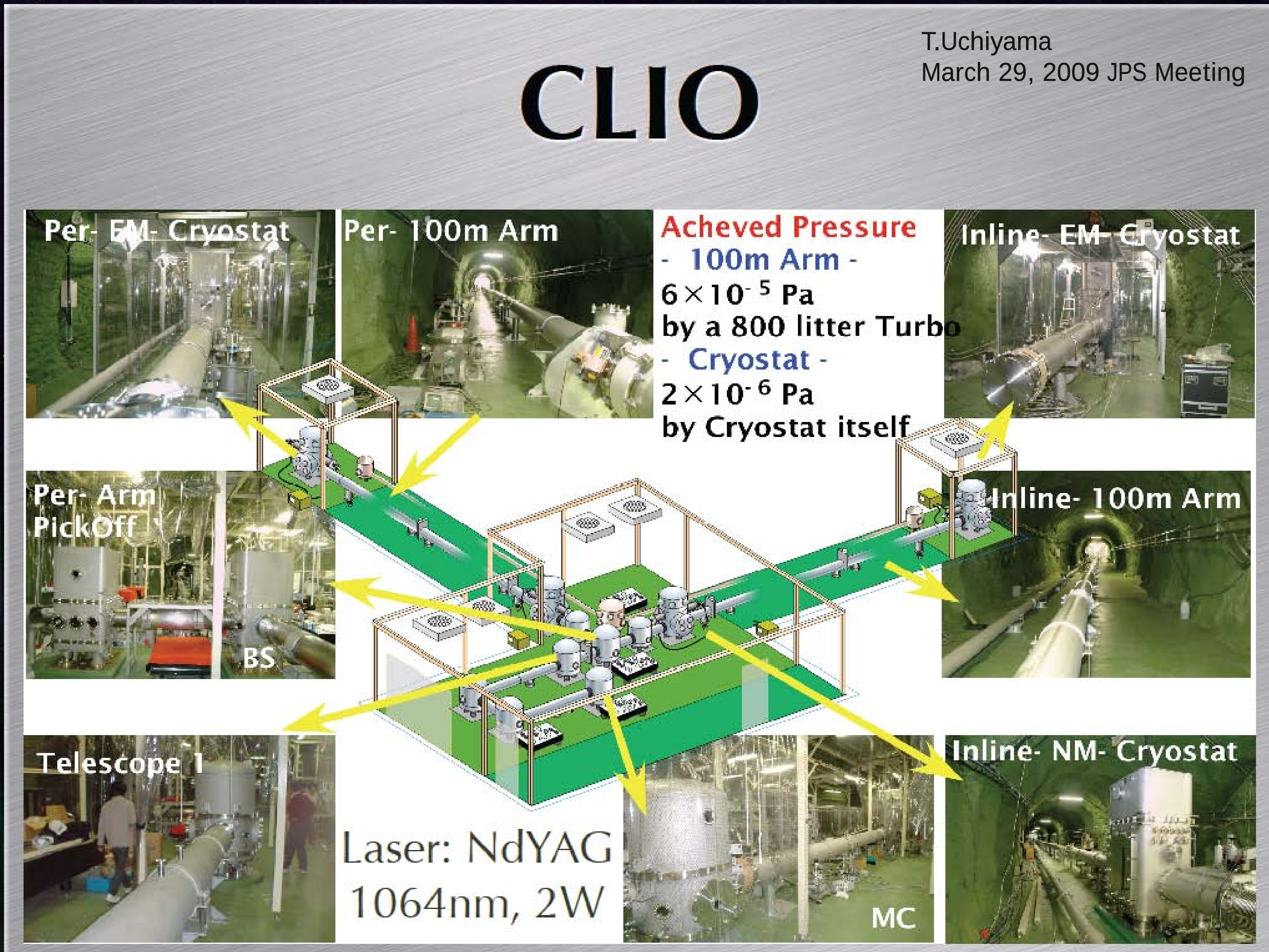



## Wider observation band for various sources

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

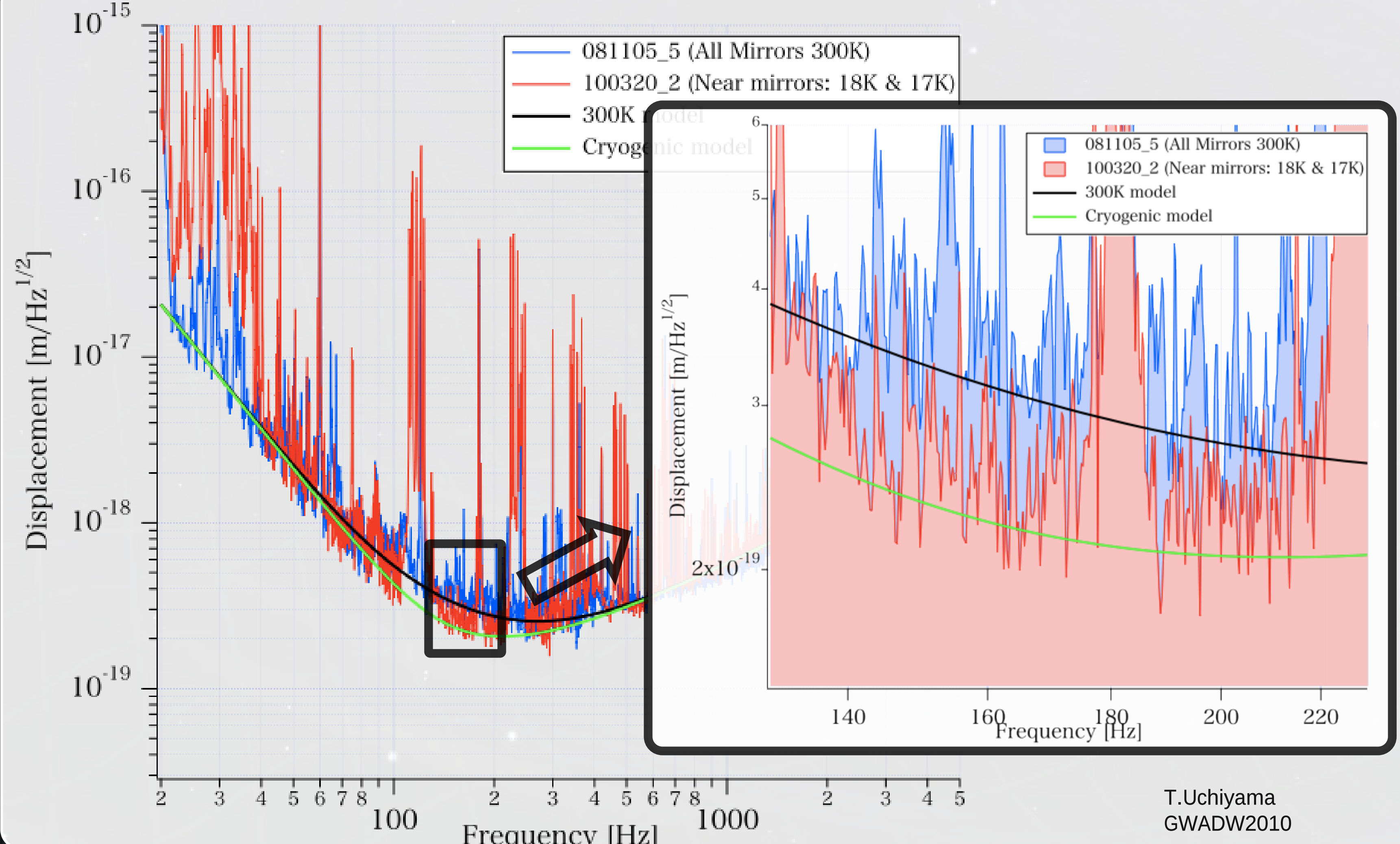


# CLIO


T.Uchiyama
March 29, 2009 JPS Meeting
CLIO
Per- EM- Cryostat
Per- 100m Arm
Acheved Pressure
- 100m Arm -
6×10^-5 Pa
by a 800 litter Turbo
- Cryostat -
2×10^-6 Pa
by Cryostat itself
Inline- EM- Cryostat
Per- Arm PickOff
BS
Inline- 100m Arm
Telescope 1
Laser: NdYAG
1064nm, 2W
MC
Inline- NM- Cryostat

# CLIO sensitivity

## Sensitivity improvement with cryogenic operation




T.Uchiyama
GWADW2010

# Interferometer setup

**LCGT baseline design**

- Arm length of 3km, Underground site of Kamioka
- Cryogenic mirror and suspension

## High-power RSE interferometer with cryogenic mirrors

**Resonant-Sideband Extraction**

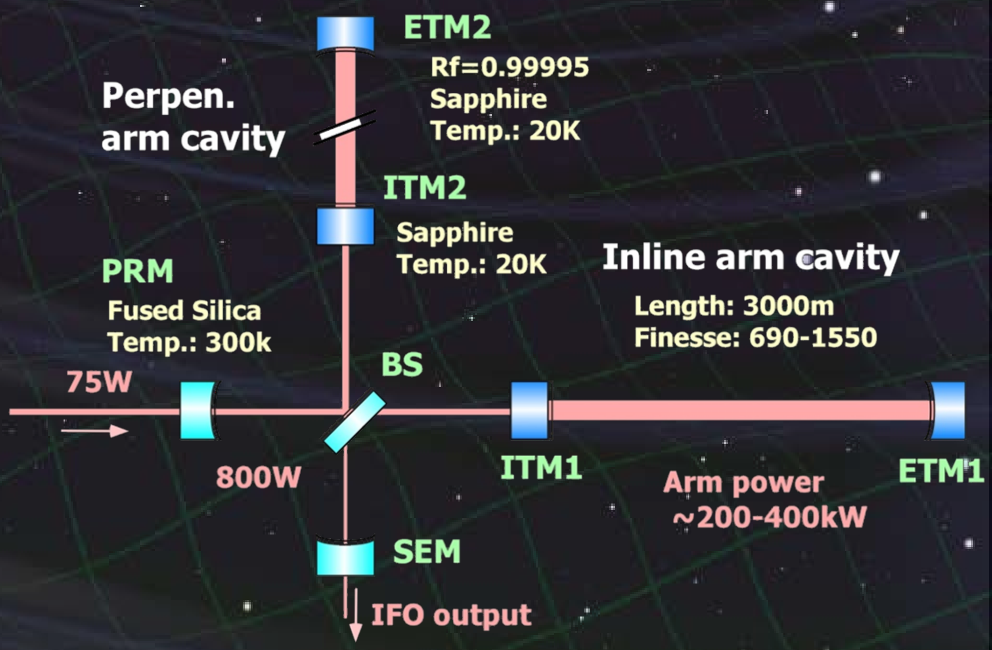
- Input carrier power : 75W
- DC readout

**Main IFO mirror**

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

**Suspension**

- Sapphire fiber 16K
- Mech. Loss : $2 \times 10^{-8}$



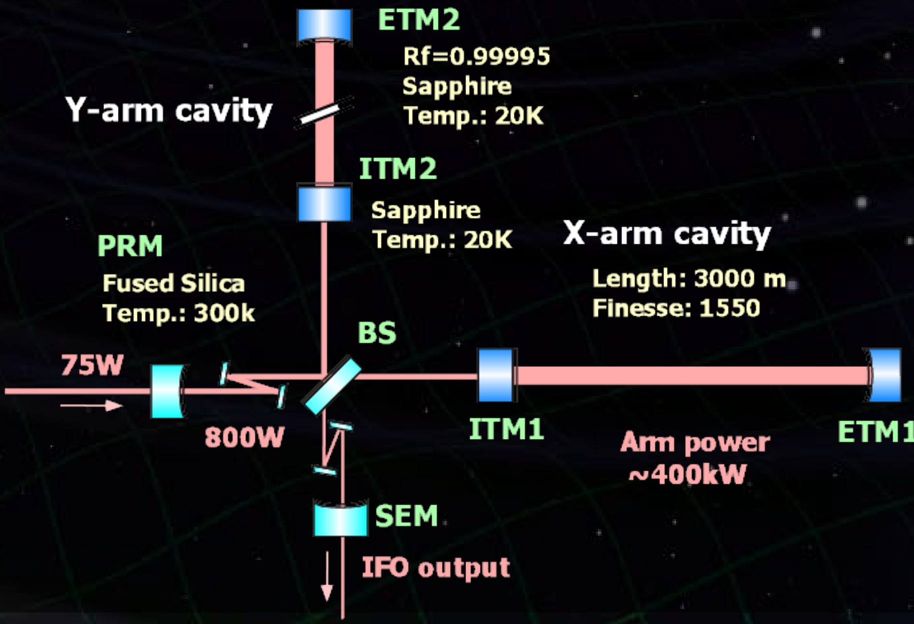
# LCGT interferometer

## 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 15K
- Mech. Loss : $2\times10^{-7}$



# TAMA300 and CLIO

## TAMA300 (1995~)

GW detector with a baseline of 300m

Sensitivity to cover our galaxy
(World best in 2000-2002)

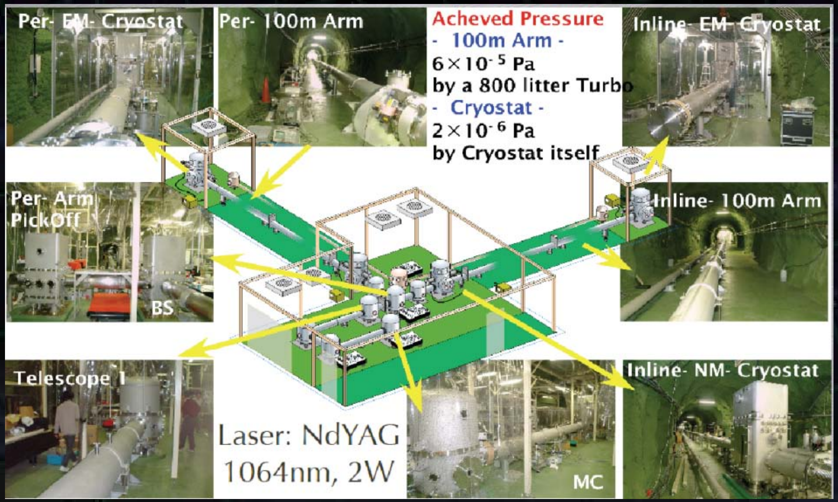
Earlier observation runs
(Obs. data over 3000hours)


## CLIO (2002~)

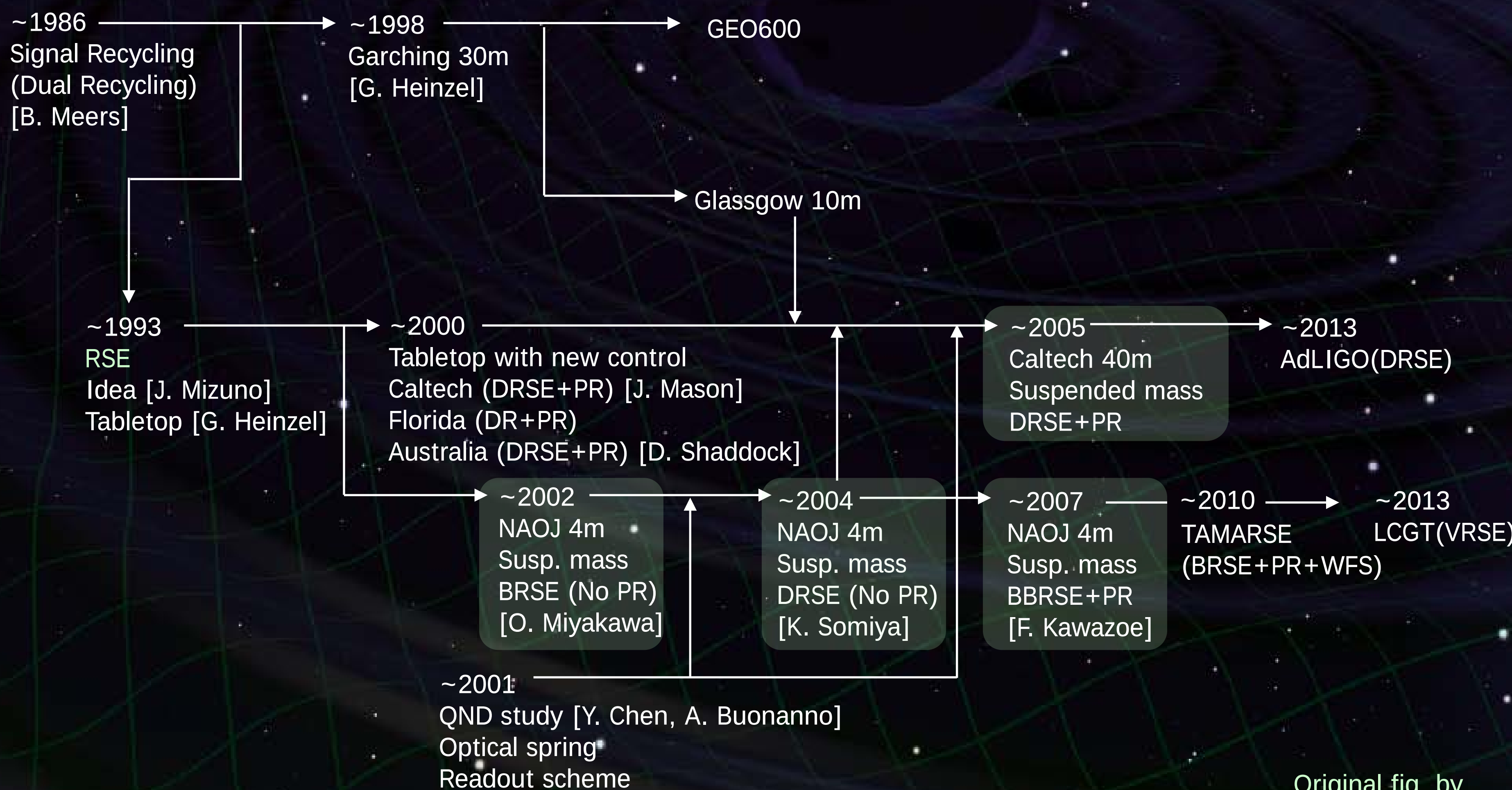
Cryogenic interferometer (Kamioka)
with 100m baseline length

Stable operation taking
advantage of underground site

Cryogenic operation below 20K
→ Improved sensitivity



# RSE / SRプロトタイプ試験




Original fig. by
O.Miyakawa

# (1) 到達目標設定 – 達成技術

何を持ってRSE 技術が完成した、と言えるのか?

⇨ プロトタイプ干渉計において
- RSE干渉計を安定に動作させること.
- 重力波に対する応答(伝達関数)がRSEによって向上すること.

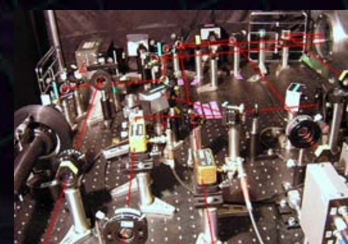
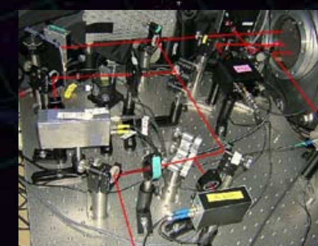
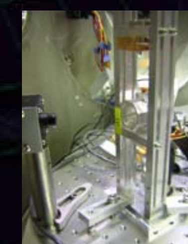
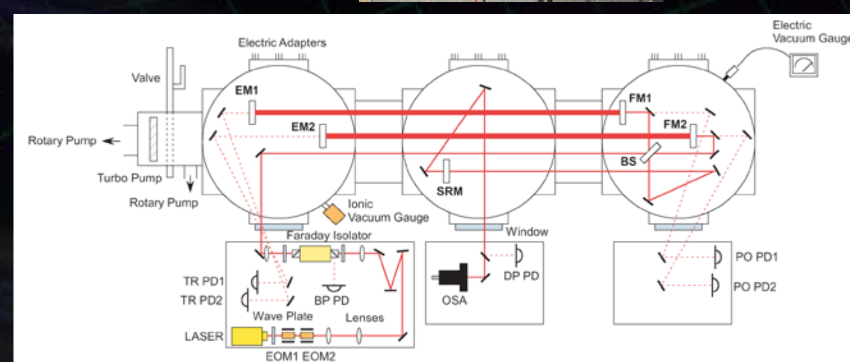
- RSE導入によって, 光量子雑音レベルの低減を確認することが望ましいが、実機に匹敵する労力を要し、困難.
- RSEの効果は伝達関数に集約されている.

(・RSEは低温化のための技術であり, 感度は問わない.)

# NAOJ 4m プロトタイプ

RSE開発のために製作された、
懸架された鏡によるプロトタイプ干渉計

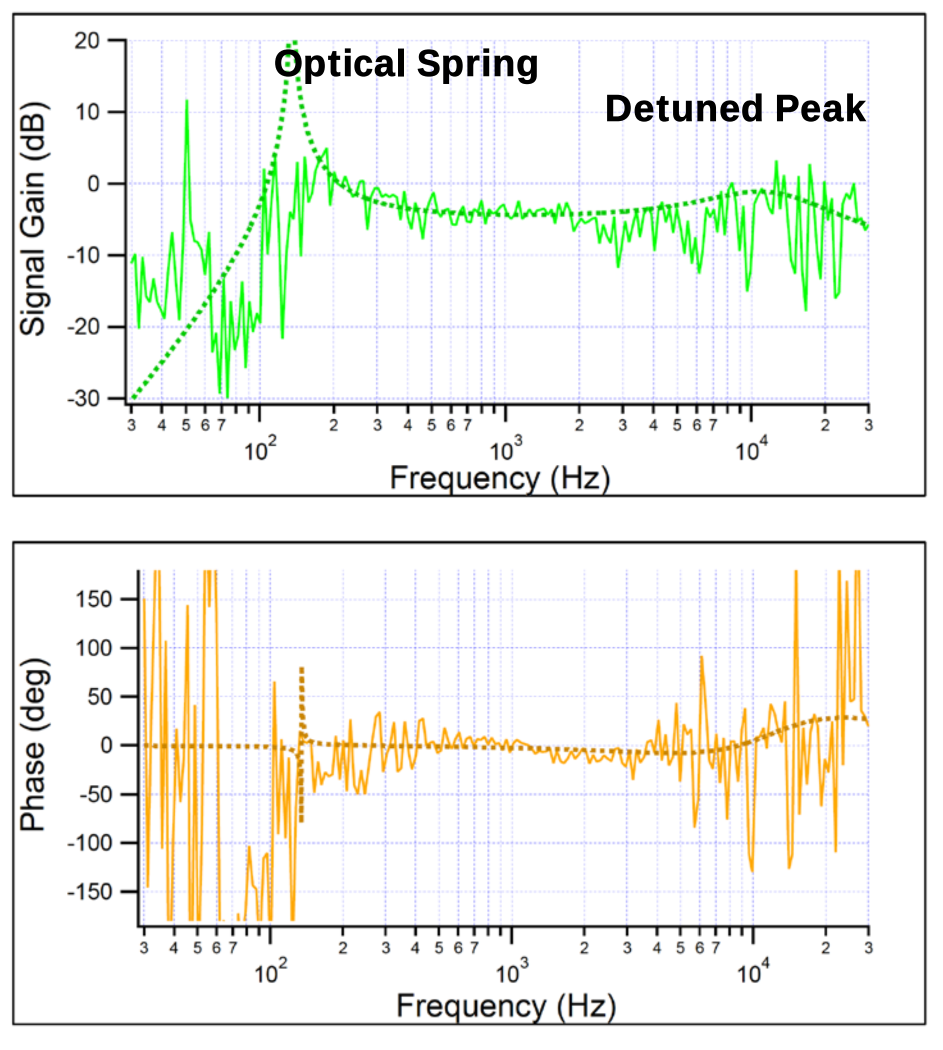
~2002 BRSE w/o PR (宮川ら)　干渉計動作, 応答関数
~2004 DRSE w/o PR (宗宮ら)　干渉計動作, 応答関数 (Two bumps)
~2007 BRSE + PR (川添ら)　干渉計動作, 制御信号分離度測定

# DRSE 干渉計応答関数 (NAOJ 4m IFO)

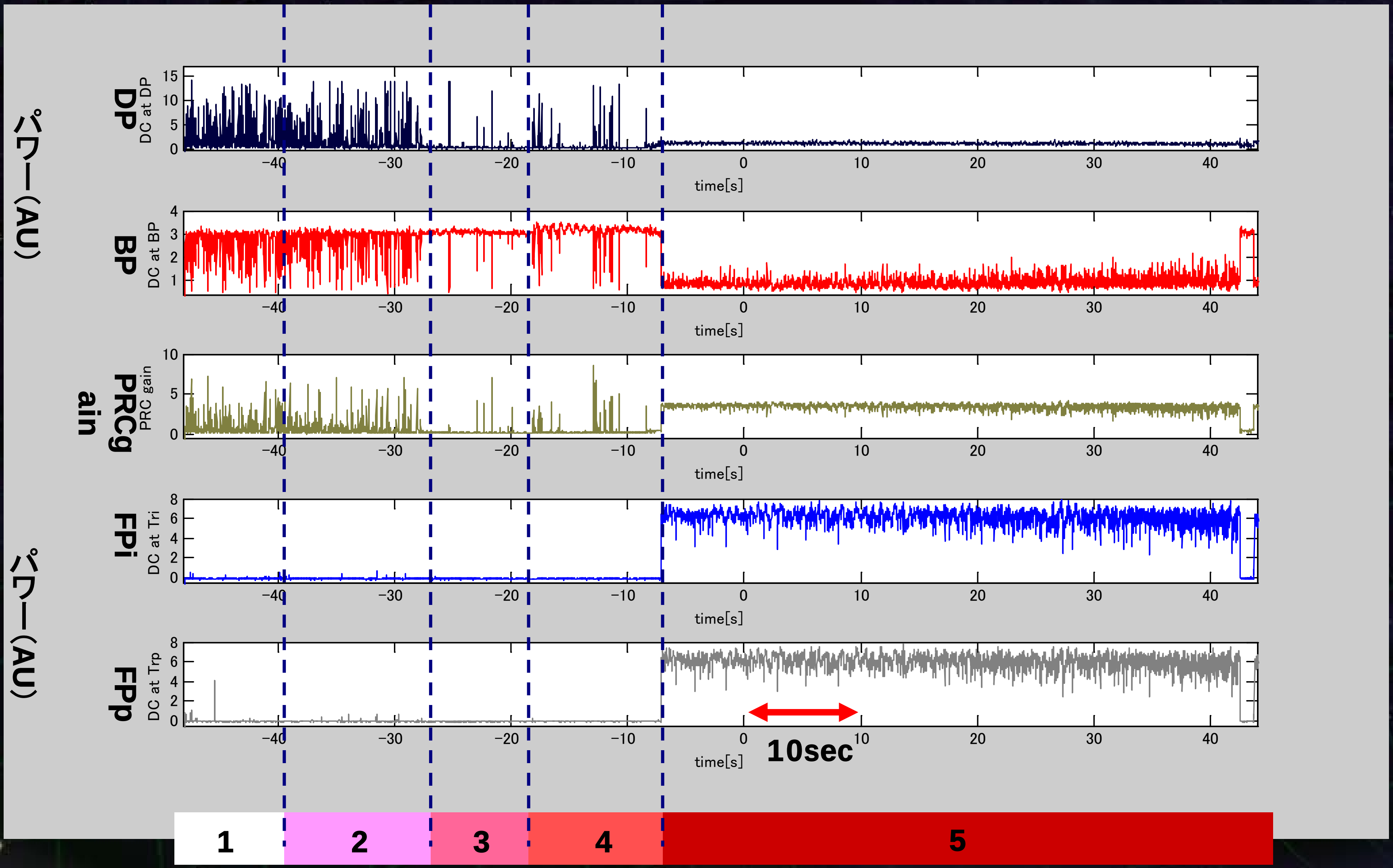
DRSE実験 (2004 宗宮ら)

- 干渉計の動作
- Detuningの効果の確認
- Optical Springの世界初観測



# RSE 干渉計の動作 (NAOJ 4m IFO)

PR-BRSE実験 (2007 川添ら)




1: 無制御 2: MI 3:PRMI 4:CIFO 5:RSE

# PR-RSE 干渉計の動作 (Caltech 40m IFO)

PR-DRSE実験（2005 宮川ら)

- 干渉計動作
- 応答関数測定