Current Status of LCGT

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On behalf of
the LCGT Collaboration

LSC-VIRGO March 2011 Meeting (March 14 2011, Arcadia, USA)

- There was a huge earthquake (M9.0) 130km east of Tohoku area on last friday.
- Several cities along eastern coast of Japan experienced catastrophic damages.
- Many people still have troubles in their lives and lifelines.
- Under this situation, the LCGT plan may be changed.

•CLIO (Kamioka, Gifu ~500km away from epicenter)

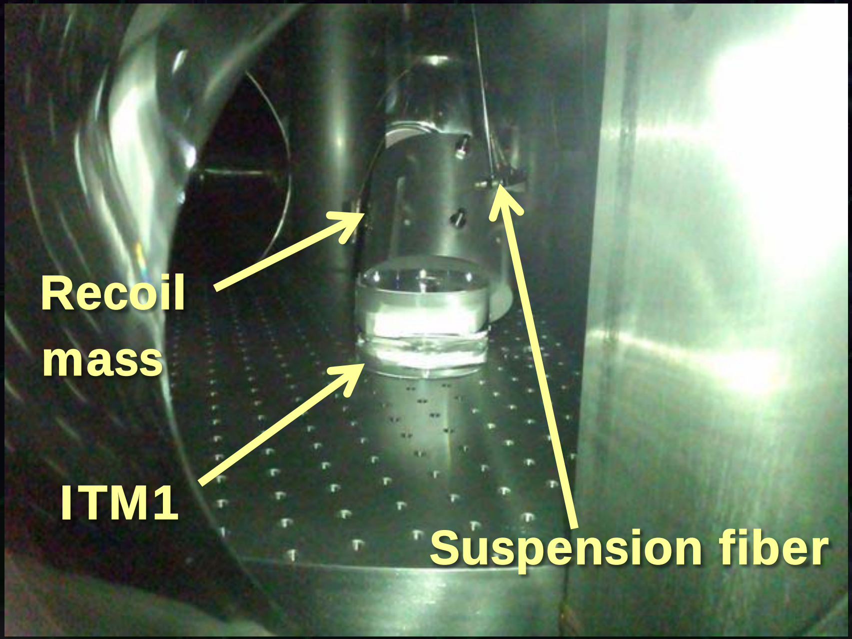
- Two people (Miyakawa, Saito) were working at CLIO site.
  → did not noticed the shake.
- MC couldn't be kept locked more than a few seconds. This condition continues >1 hour.

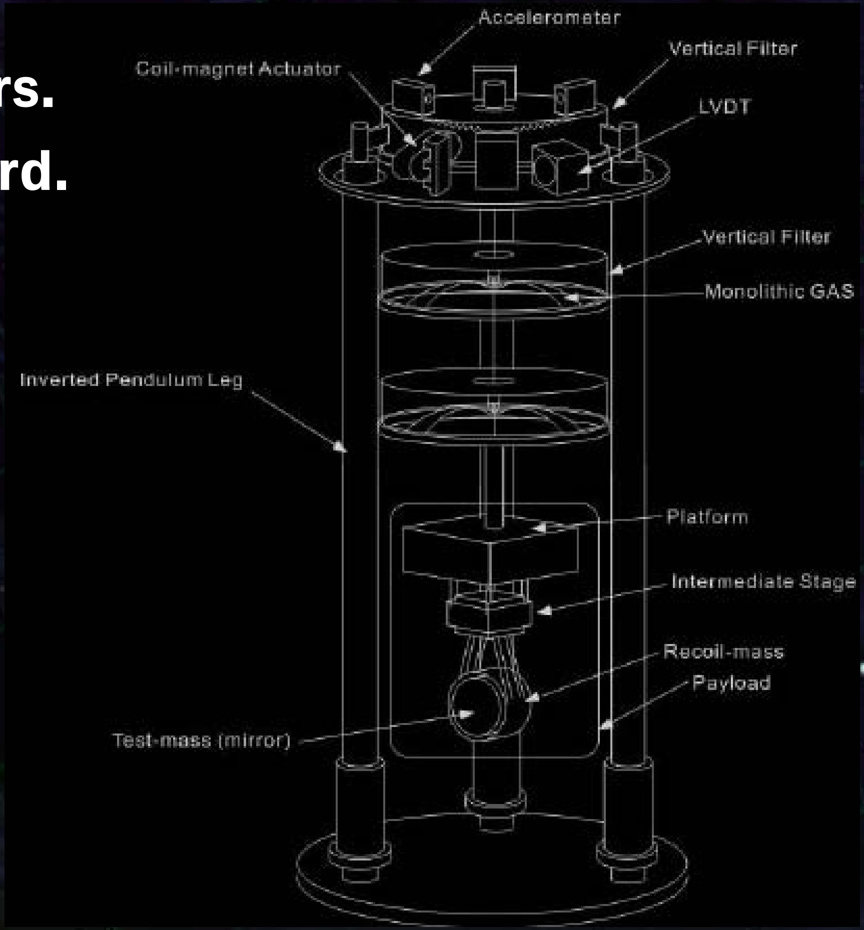
- No serious damages:
  mirror, suspension,
  cryostat system, vacuum system.
- Small misalignment in suspended optics.

- **TAMA** (NAOJ, Tokyo ~400km away from epicenter)

Serious damages in suspensions and mirrors.

Three TMs fell onto breadboard.





1. Introduction
2. Sensitivity
3. Design and R&D
4. Schedule
5. Summary

Introduction

LCGT

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

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 almost approved.

Baseline design is not changed:
Requesting the additional cost for
full construction of LCGT.

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

LCGT sensitivity

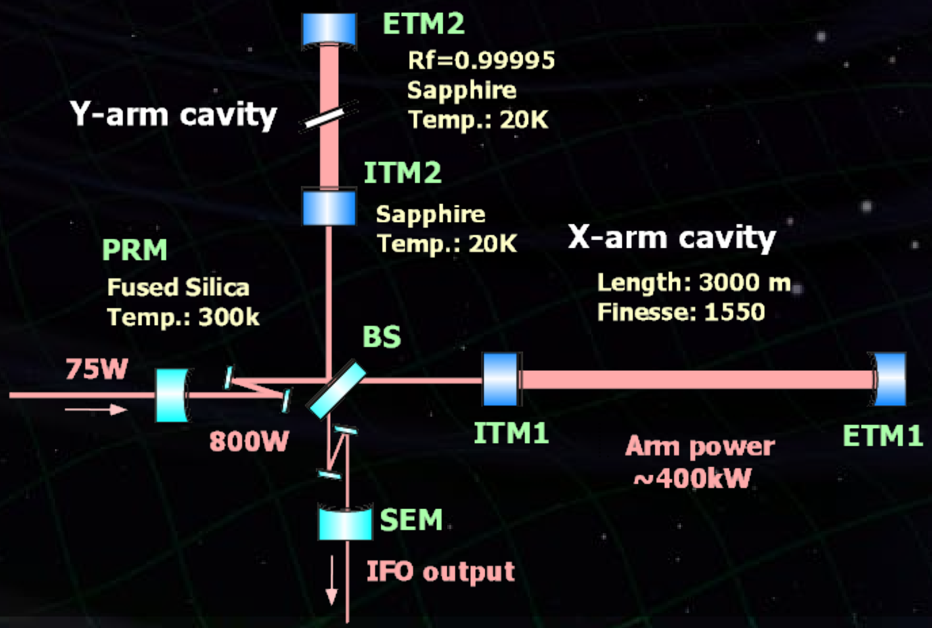
LCGT interferometer

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

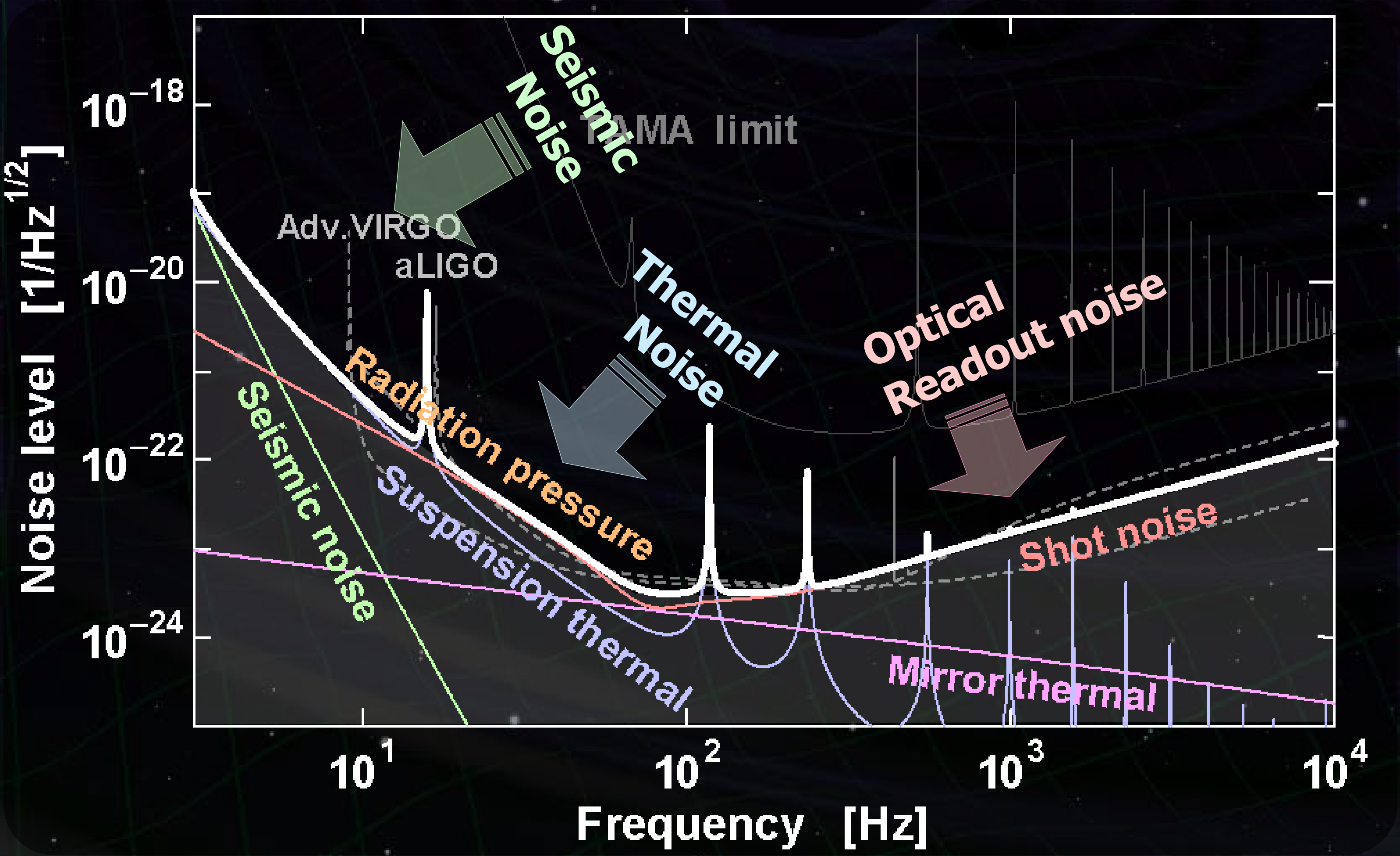
Suspension
- Sapphire fiber 16K
- Mech. Loss : 2×10^{-7}



Sensitivity Curve

Comparable with aLIGO Ad.VIRGO

→ Global observation network

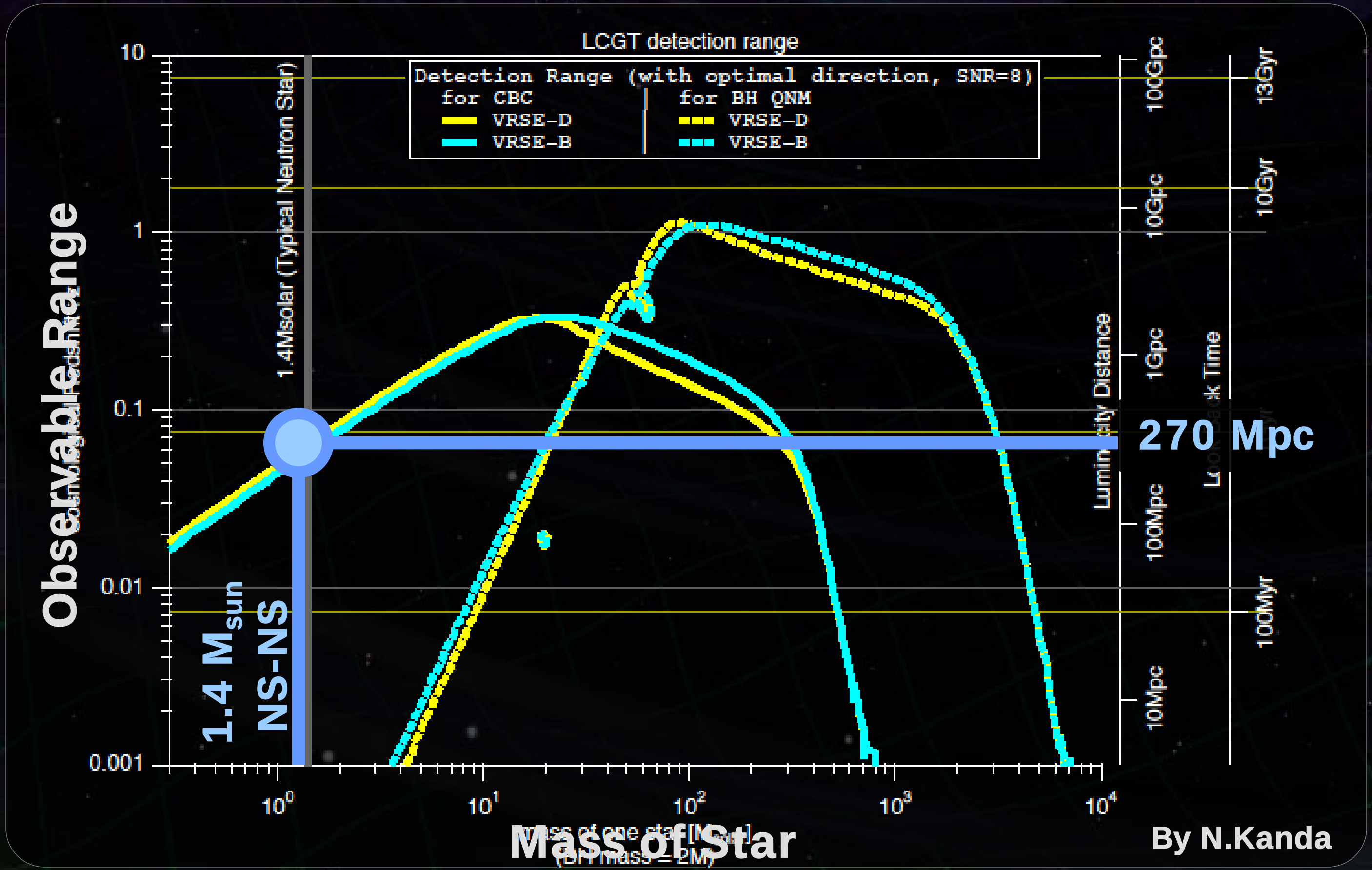


Observable range

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 :

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

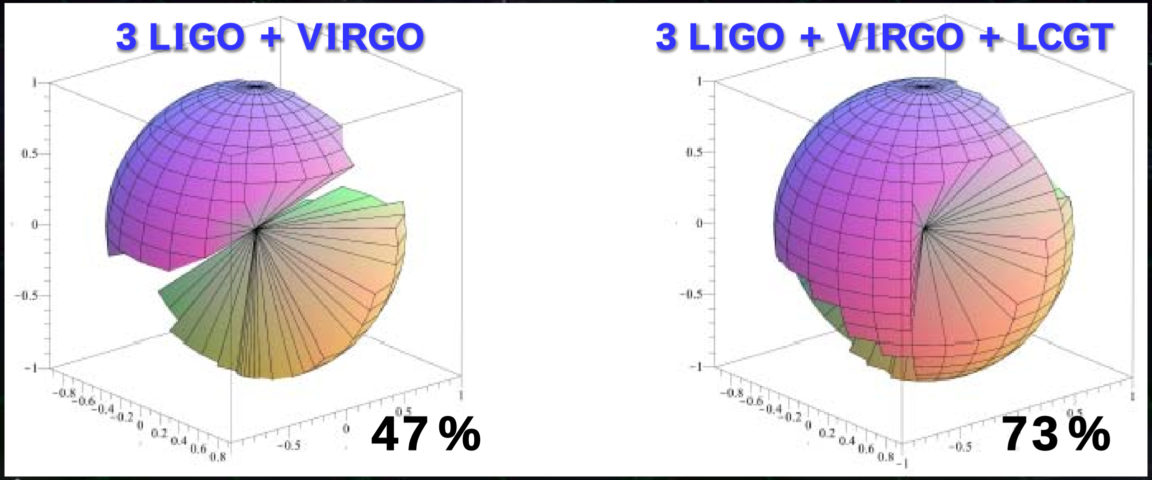
V. Kalogera et.al., ApJ, 601 L179 (2004)
Kim et al. (2008)

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

Network Observation

LCGT will be one of key stations in the world-wide observation network

- Detection
  Increase : Triple-detection rate, Detection volume.
  Reduce : Fake events, Event-detection threshold.
- Astrophysics
  Increase : Sky coverage, Directional precision.
  Waveform reconstruction.



Sky-coverage pattern
(0.707 of max. range)

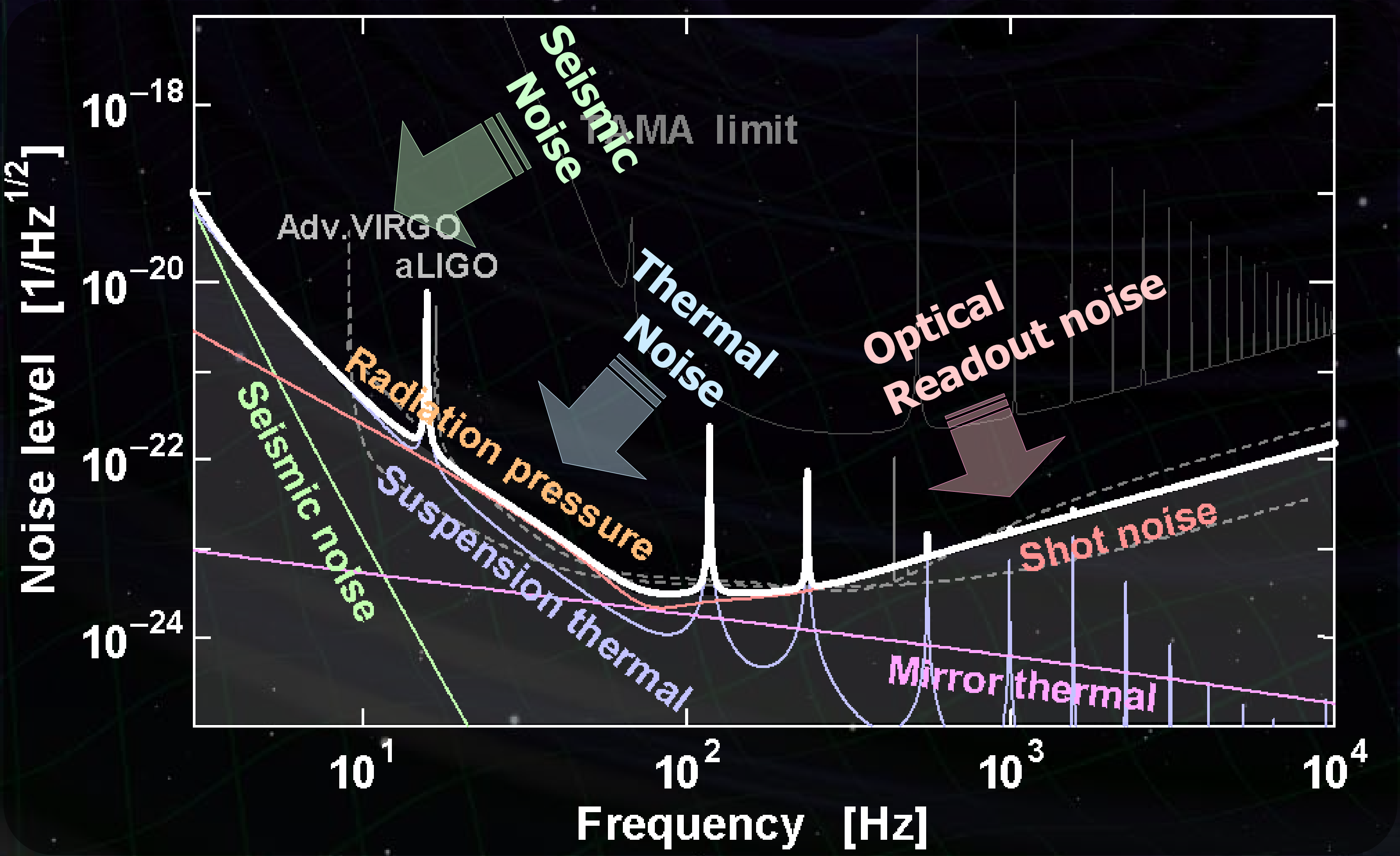
B.Schutz
arXiv:1102.5421

Design and
Developments

Sensitivity Curve

Comparable with aLIGO Ad.VIRGO

→ Global observation network



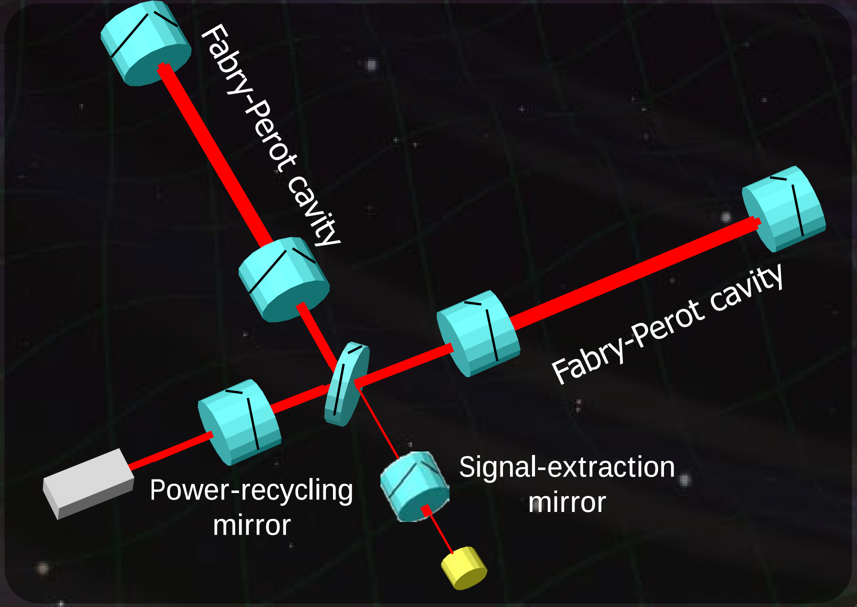
Readout-noise reduction

High-freq. (> 100 Hz) improvement

Shot noise reduction by high power in arm cavities

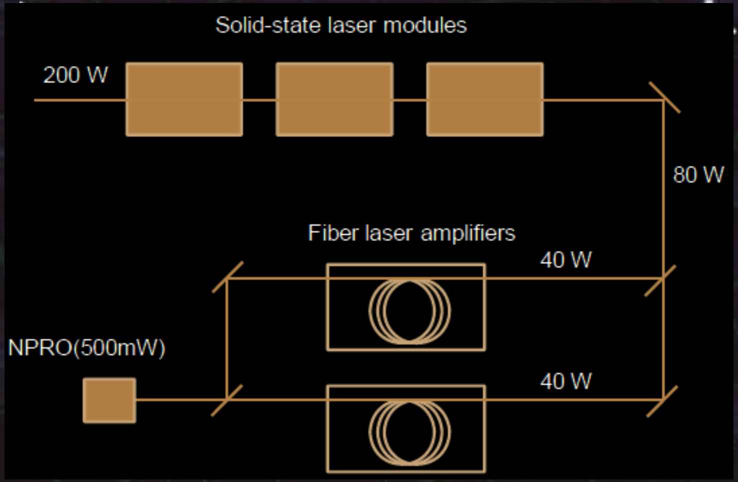
Optical configuration

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

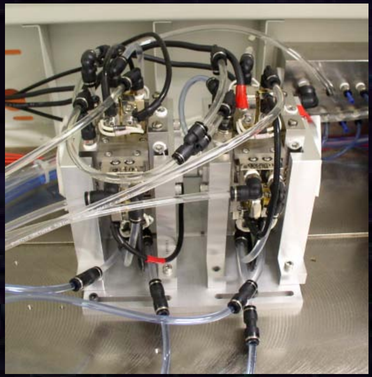
Developments (Optics)

High-power laser source

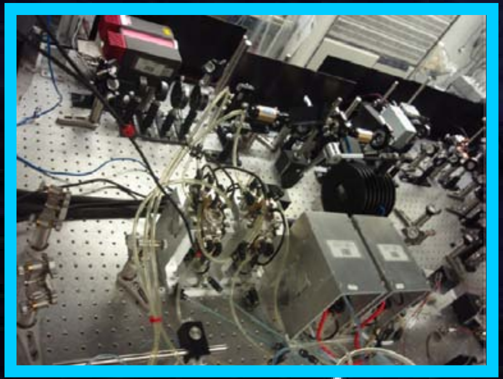
100-W injection-locked laser
→ Test high-power laser module
Freq. and Int. stabilization

⇨ 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

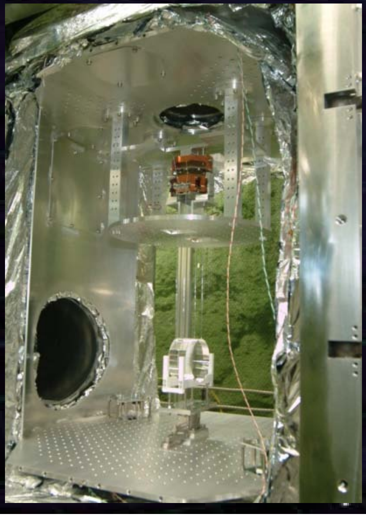
Mirror ~20K
Suspension ~16K

Sapphire mirror
→ High mechanical Q-value at low temperature

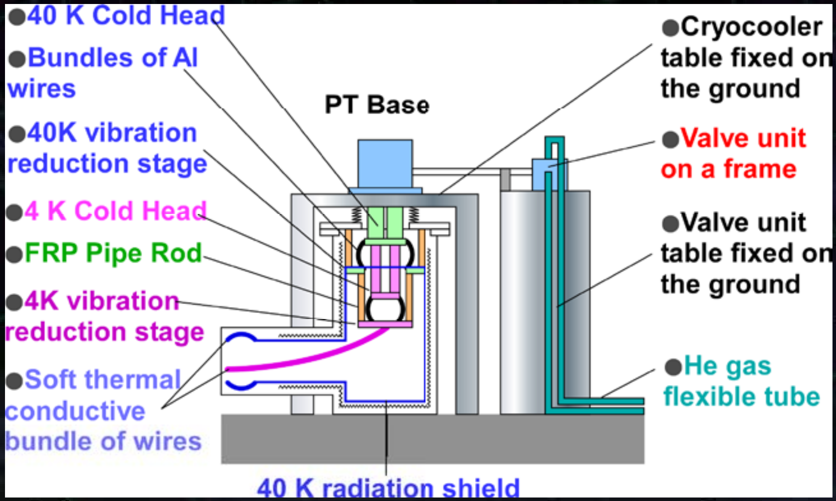
Thermal noise $\propto \sqrt{\frac{T}{Q}}$

⇨ 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

⇩

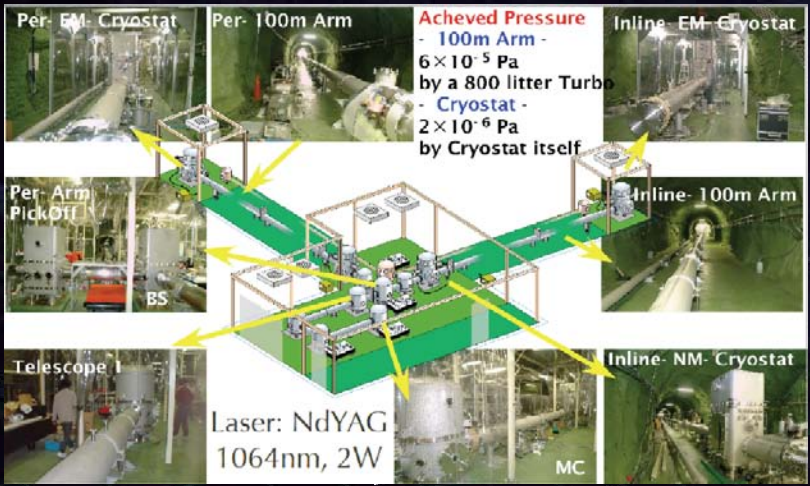
Planning a full-scale prototype test at Kamioka site

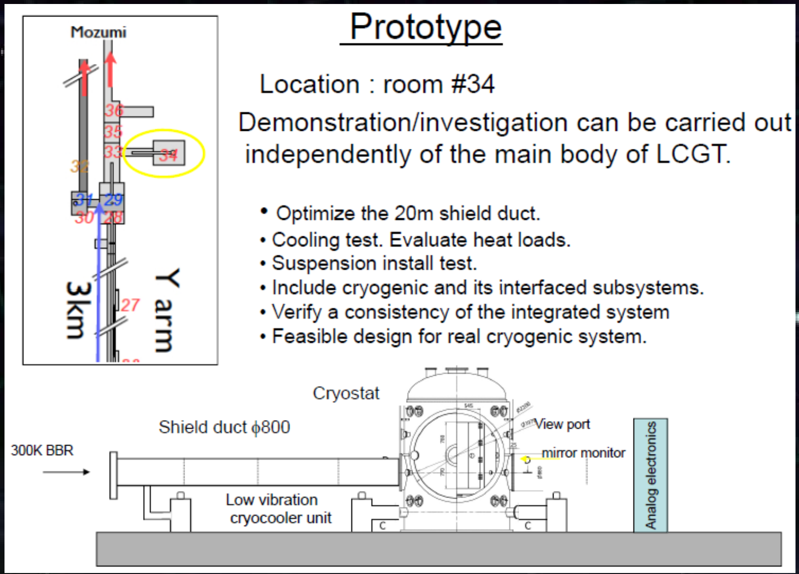
- Vacuum – Cryostat system
- Radiation shield
- Low-vibration cryocooler

→ Cooling test, Installation test,

On-site development from 2013

CLIO : 100-m cryogenic interferometer



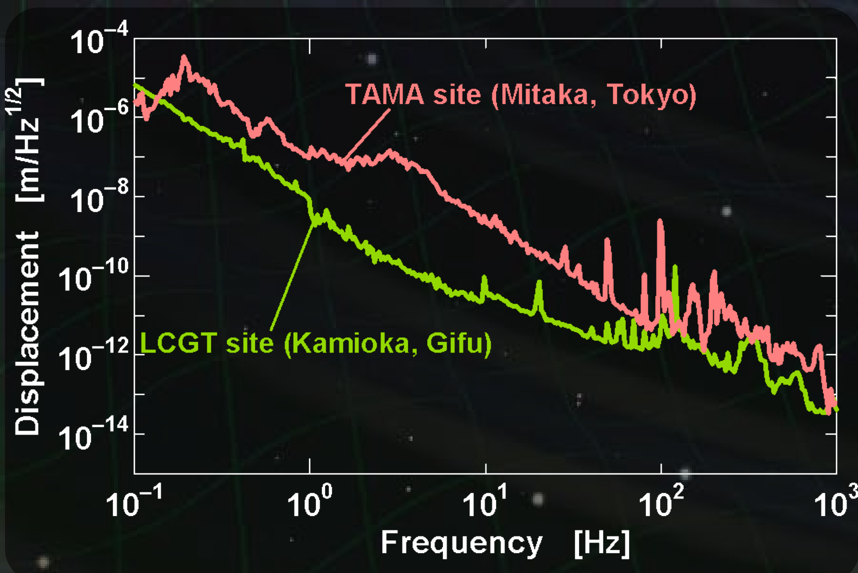


Seismic-noise reduction

Low-freq. (< 100 Hz) improvement

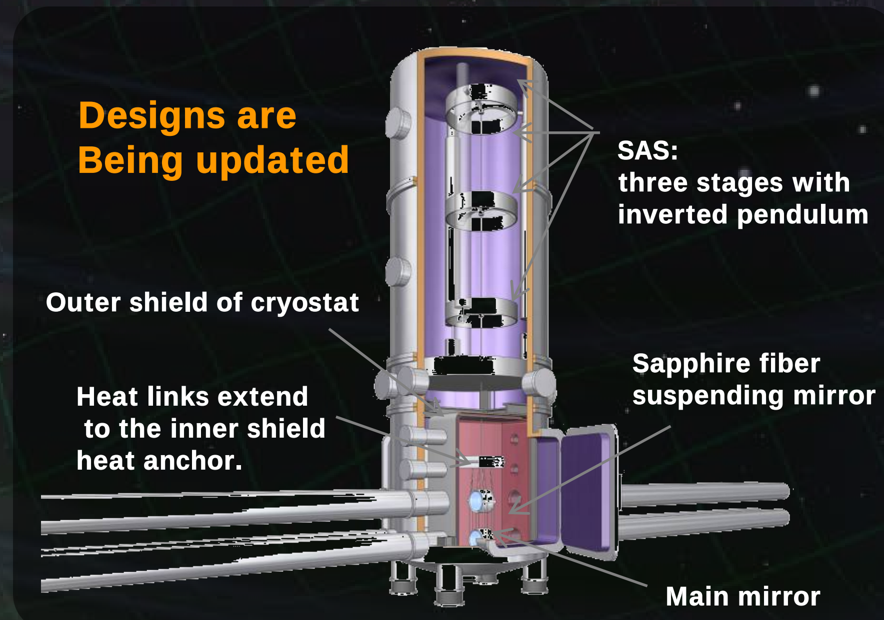
Quiet site

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



Better Isolation system

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



Developments (Seismic noise)

Underground site

Heritages by

CLIO (100m baseline)

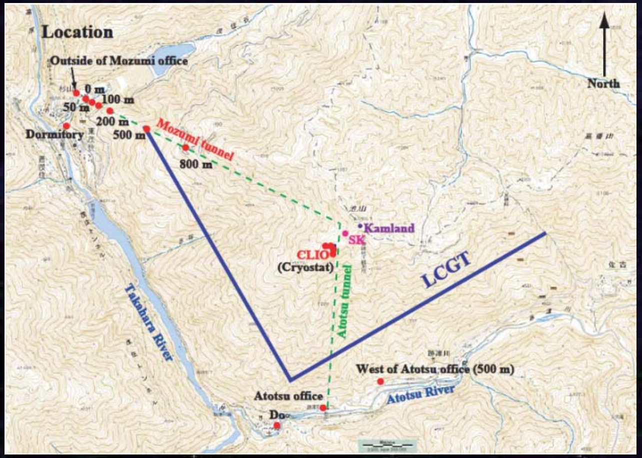
20m prototype moved from NAOJ

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

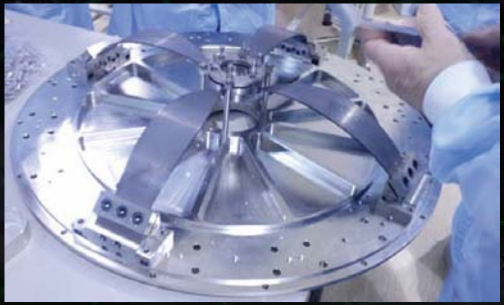
⇨ Detailed design

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

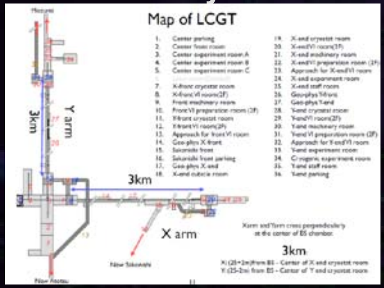
Computing platform, network design

Analog electronics

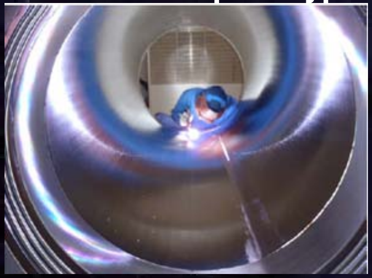
Design policy under discussion

Detailed designs

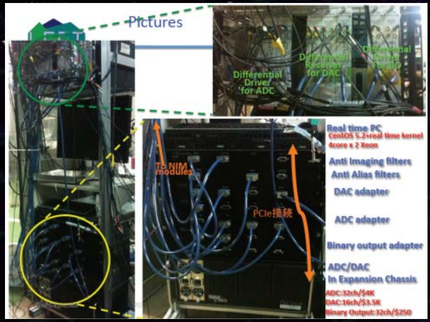
Tunnel layout

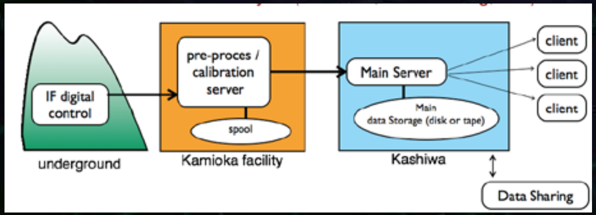


Vacuum tube prototype



Digital system installed to CLIO





Computing platform and Network

Main Concerns

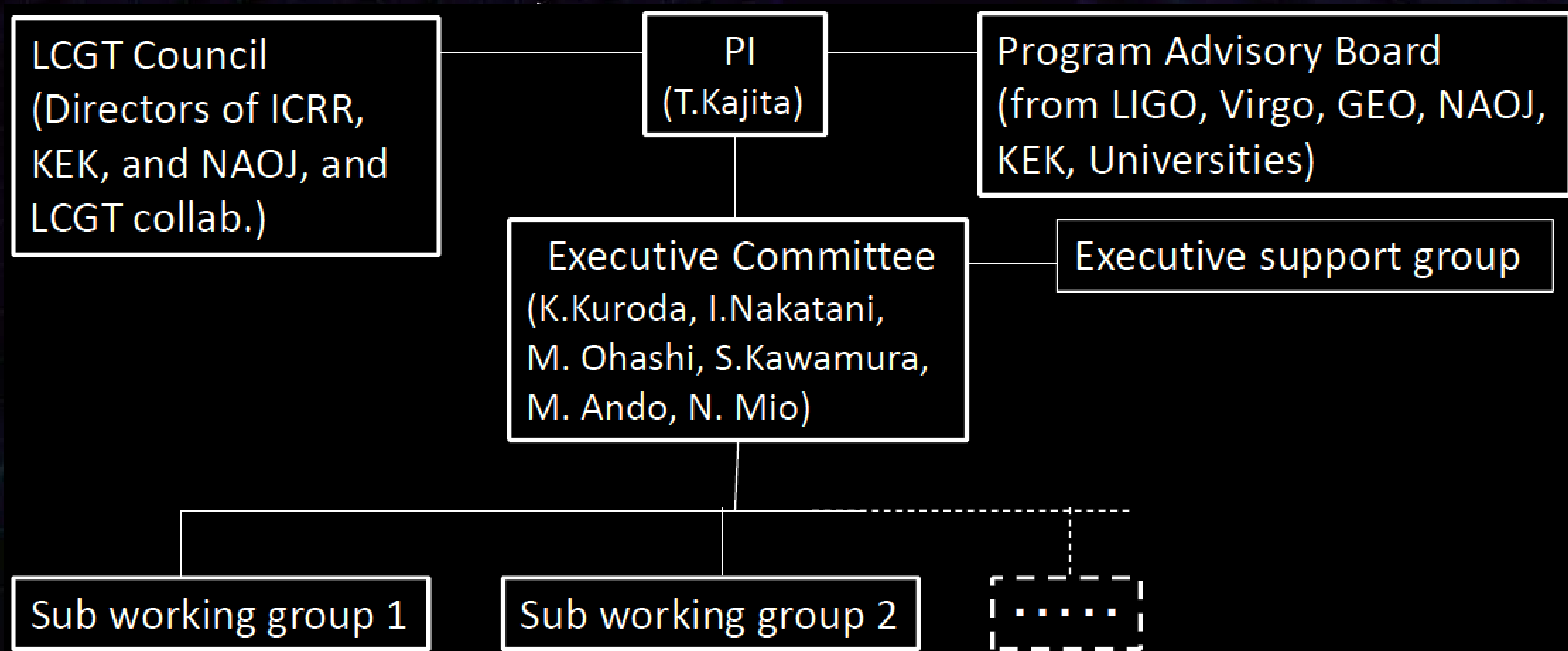
Personal point of view

- Tight schedule, under-estimated cost
  - Excavation takes ~2 years
  - Short commissioning period for iLCGT
- Vibration isolation tuning
  - 14 isolators needed in early period
- Cryogenic suspension
  - Coupling from vertical DoF
- Sapphire substrate
  - with good optical properties
- Thermal noise of mirror coating

Organization and Schedule

Organization

Organization of LCGT during construction



14 subsystems

Tunnel, Facility, Vacuum, Vibration Isolation, Cryogenics, Main interferometer, Input/Output optics, Laser, Mirror, Data analysis, Digital system, Analog electronics, Detector configuration, Geophysics interferometer

Master Schedule

- 3 Major stages

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

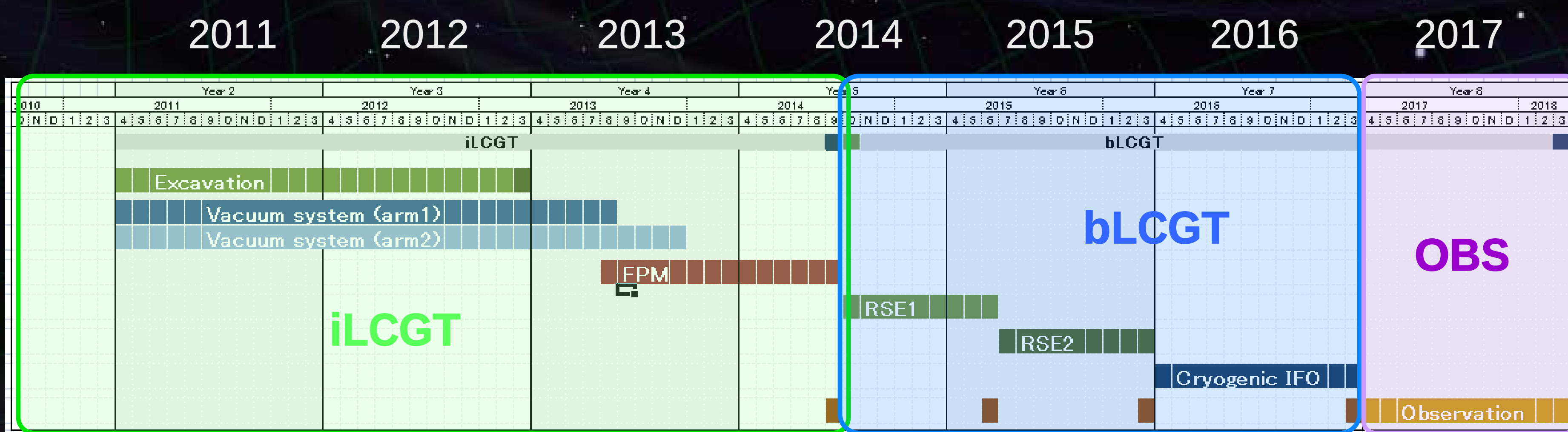
→ 3km FPM interferometer at room temperature, with simplified vibration isolation system

~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



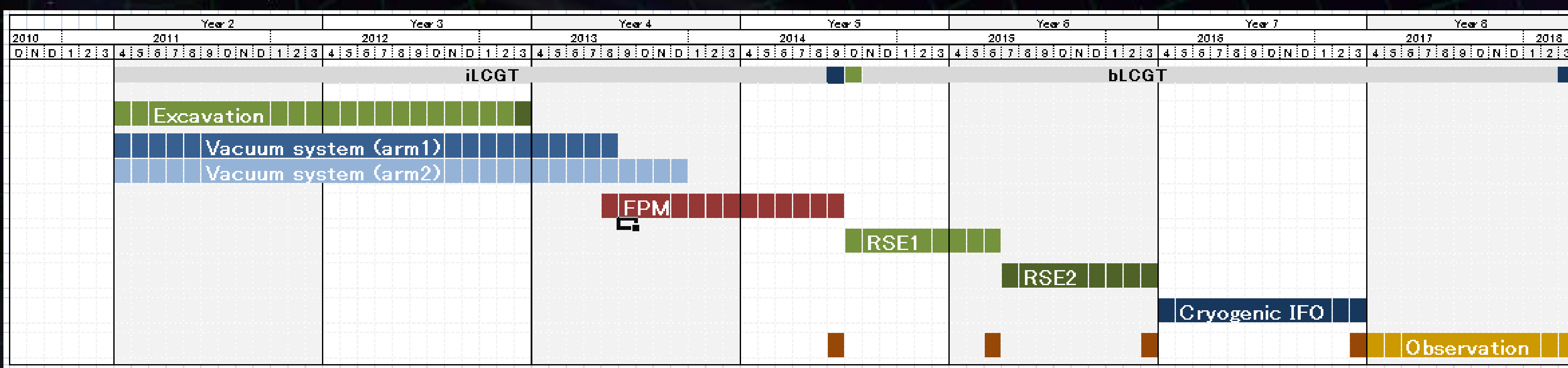
Master Schedule

Draft for discussion

- 6 Milestones

Stage	Phase	Name	Period	Scope
iLCGT	0	EAF	2011.4 - 2013.3	Excavation and Facility
	1	FPM	2013.4 - 2014.9	Operation of FPM IFO
bLCGT	2	RSE1	2014.10 - 2015.6	RSE operation
	3	RSE2	2015.7 - 2016.3	Upgrade of VIS
	4	CRSE	2016.4 – 2017.3	Cryogenic system
OBS	5	OBS	2017.4 –	Observation and tuning

2011 2012 2013 2014 2015 2016 2017



Design Reviews

- **Internal review**
  - Review design, schedule, etc. of each subsystem by the subsystem leaders, Ando, and Kawamura
  - We had 15 internal reviews for the last three months
- **External review** ← 2/28 - 3/4, summary report 3/12
  - Review design, schedule, etc. of each subsystem by external experts in the GW field
  - The most important review for the technical aspects of LCGT

    Special thanks to Reviewers:

    M.Zucker (chair), S.Ballmer, A.Bertolini, R.Flaminio, A.Freise, W.Johnson D.Ottaway, B.Willke
- **Program advisory board**
  - Review management, progress, design, etc. of LCGT by senior (management) people in the GW and neighboring fields
  - The first PAB will be held in June

International Collaborations

- with LIGO laboratory
  Attachment agreed under existing MOU between ICRR (represents LCGT Collaboration) and LIGO laboratory.
  → Manpower, software & technique exchanged, Mirror
- with VIRGO
  MOU with Attachment between VIRGO (EGO + Virgo Collaboration) and ICRR was signed.
- with GEO
  MOU between ICRR and GEO people is also conceived.
- with ET
  Collaboration with ET → Cooperative research on cryogenics and vibration isolation.
- with SUCA (China)
  MOU between ICRR and Shanghai Normal University, SUCA is on the process of agreement.
- with Korea
  Collaboration with Korean researchers is conceived.

Summary

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

By the way…

LCGT will have a new Nickname soon…

- Invite candidates from the public
  → over 600 applications (already closed)
- Naming committee with 6 peoples
  Chair: Y. Ogawa (Novelist)
- Will be announced in a few month (?)

Conclusion

LCGT project has started. But we have serious problems in our country.

We will do our best for life of people and science.

We already receive kind supports.
We greatly appreciate them!

End

Backups

TAMA300 and CLIO

TAMA300 (1995~)

GW detector with a baseline of 300m

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

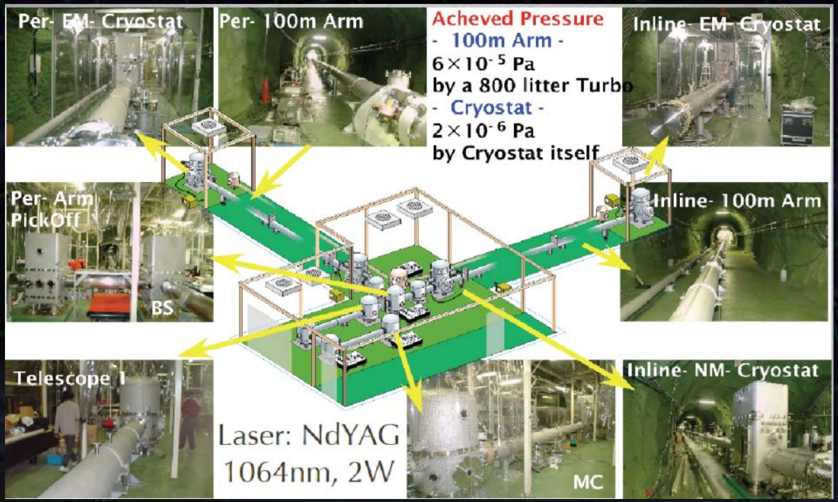
Earlier observation runs
(Obs. data over 3000hours)

CLIO (2002~)

Cryogenic interferometer (Kamioka) with 100m baseline length

Stable operation taking advantage of underground site

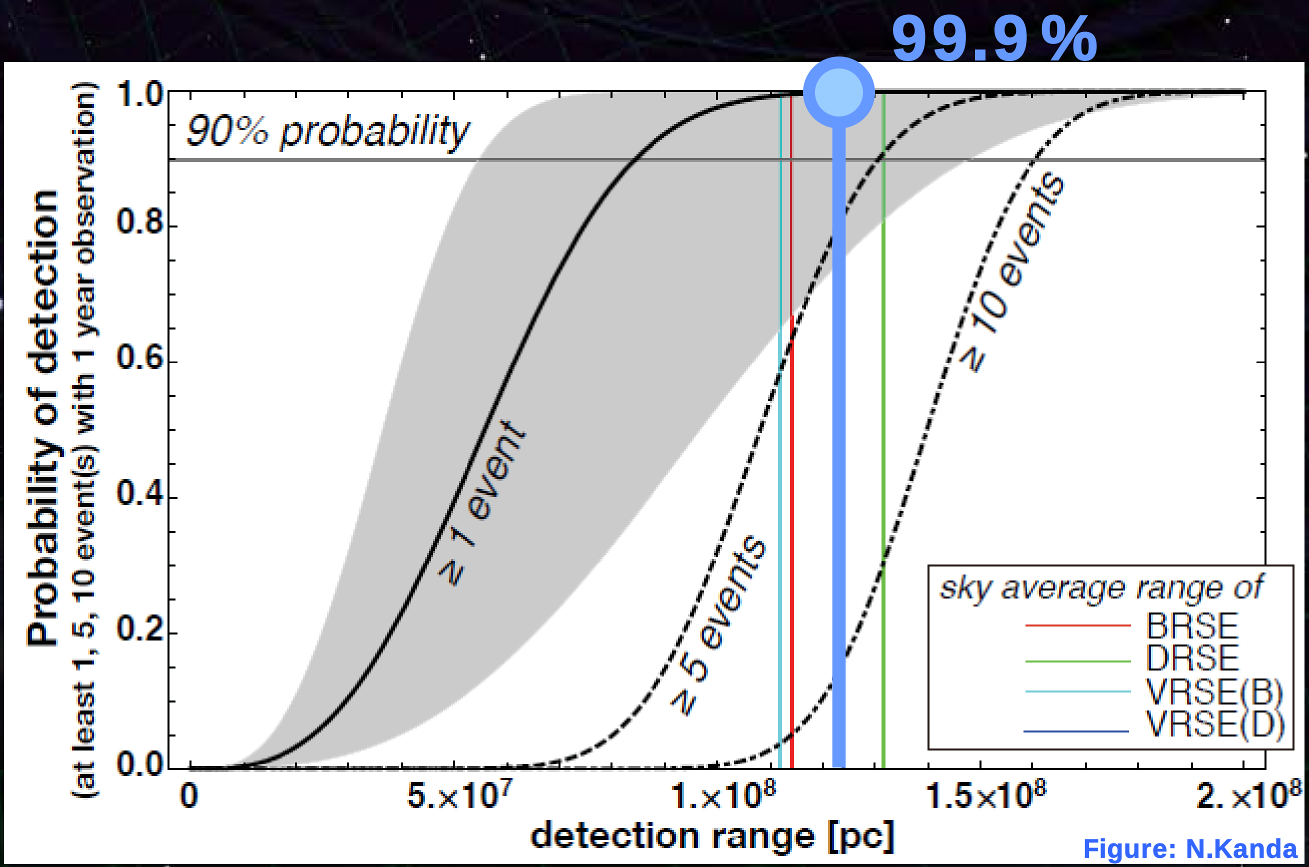
Cryogenic operation below 20K
→ Improved sensitivity



Detection probability

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

99.9 %



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 : 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 : < 1×10^{-7} Pa ← Ion pump lifetime (5 years)
< 2×10^{-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 : 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 < 4×10^{-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

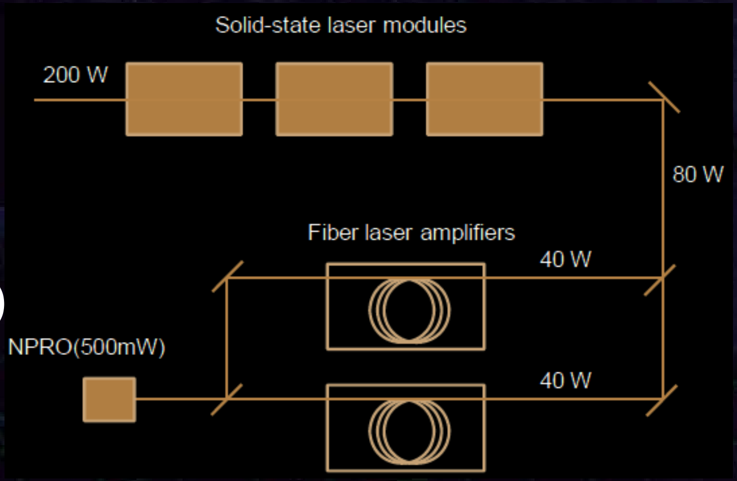
Multi-layer stack

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}

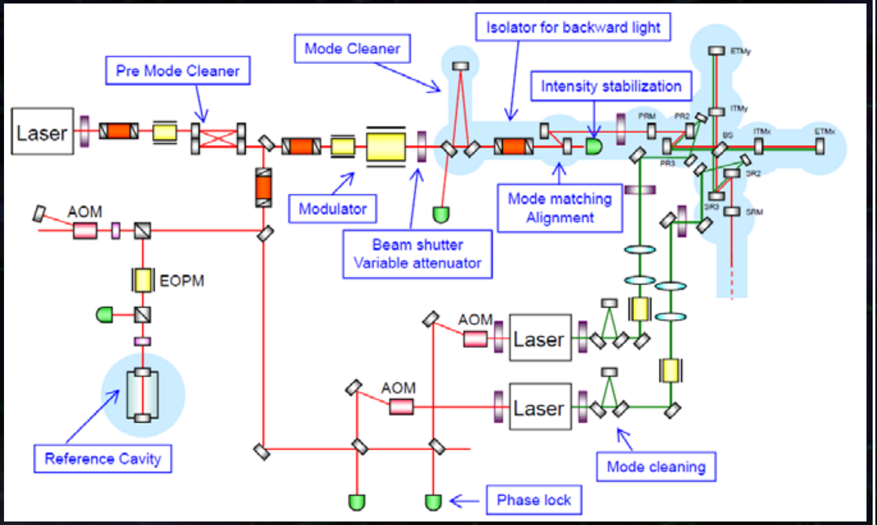
- **Main interferometer** (PRM, SEM, Folding Mirror)
  - Diameter : 25cm
  - Thickness : 10cm
  - Mass : 10 kg
  - *also used for iLCGT test mass
  - AGC or Heraeus (ITM)
  - LIGO TM substrates (other)
- **Beam splitter**
  - Diameter : 38cm
  - Thickness : 12cm
  - Mass : 30 kg
- **Input optics (MC, 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 : ϕ100mm, 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 : ϕ3 mm
  - RF photo detector
    - Input power : 100 mW
    - PD diameter : ϕ3 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

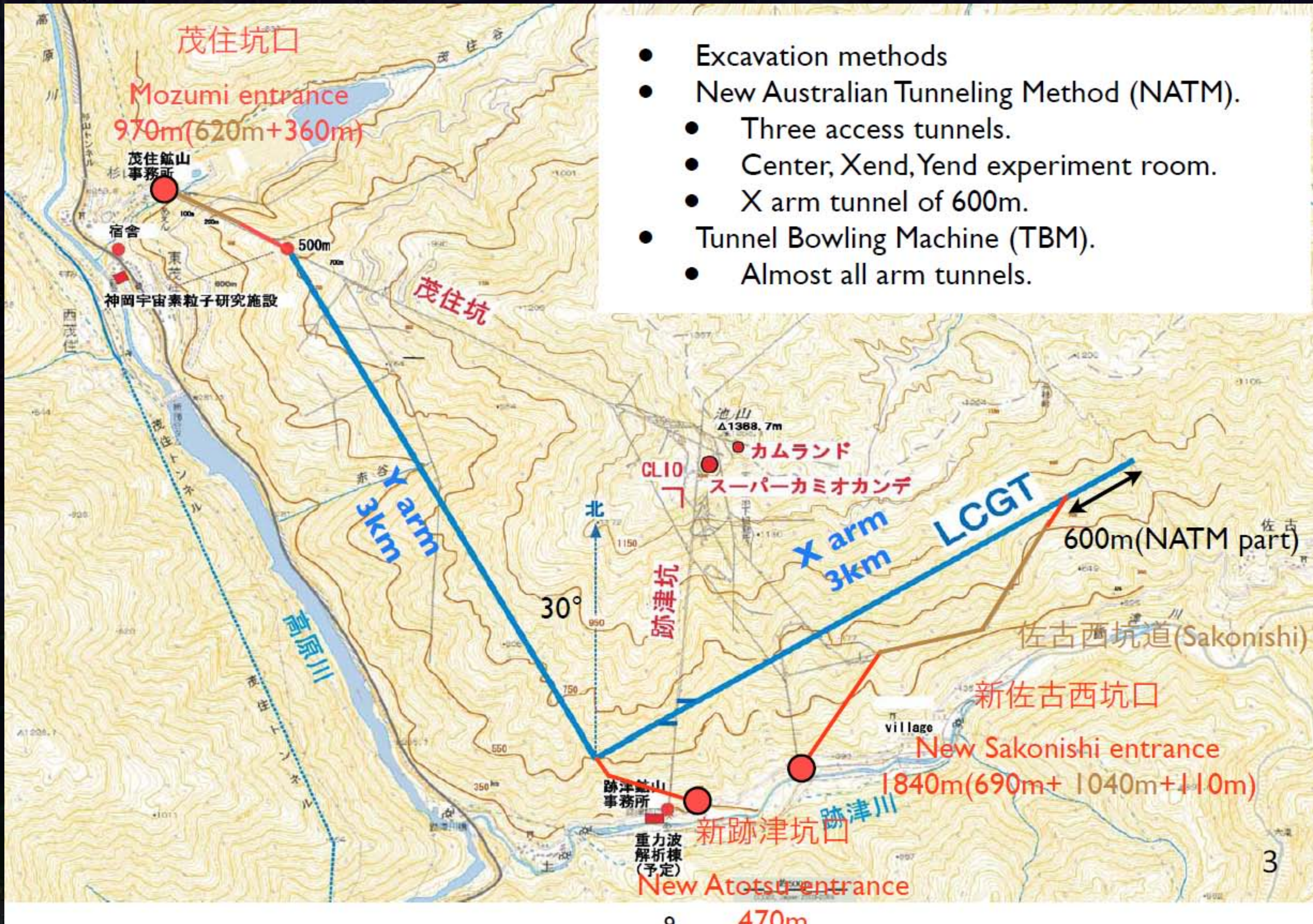
- DAQ
  - Data acquisition, low-latency transfer
  - Data storage
  - Data characterization
- Analysis
  - Search for GW signals, and extract scientific outcomes
  - Cooperate with other GW experiments

- **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

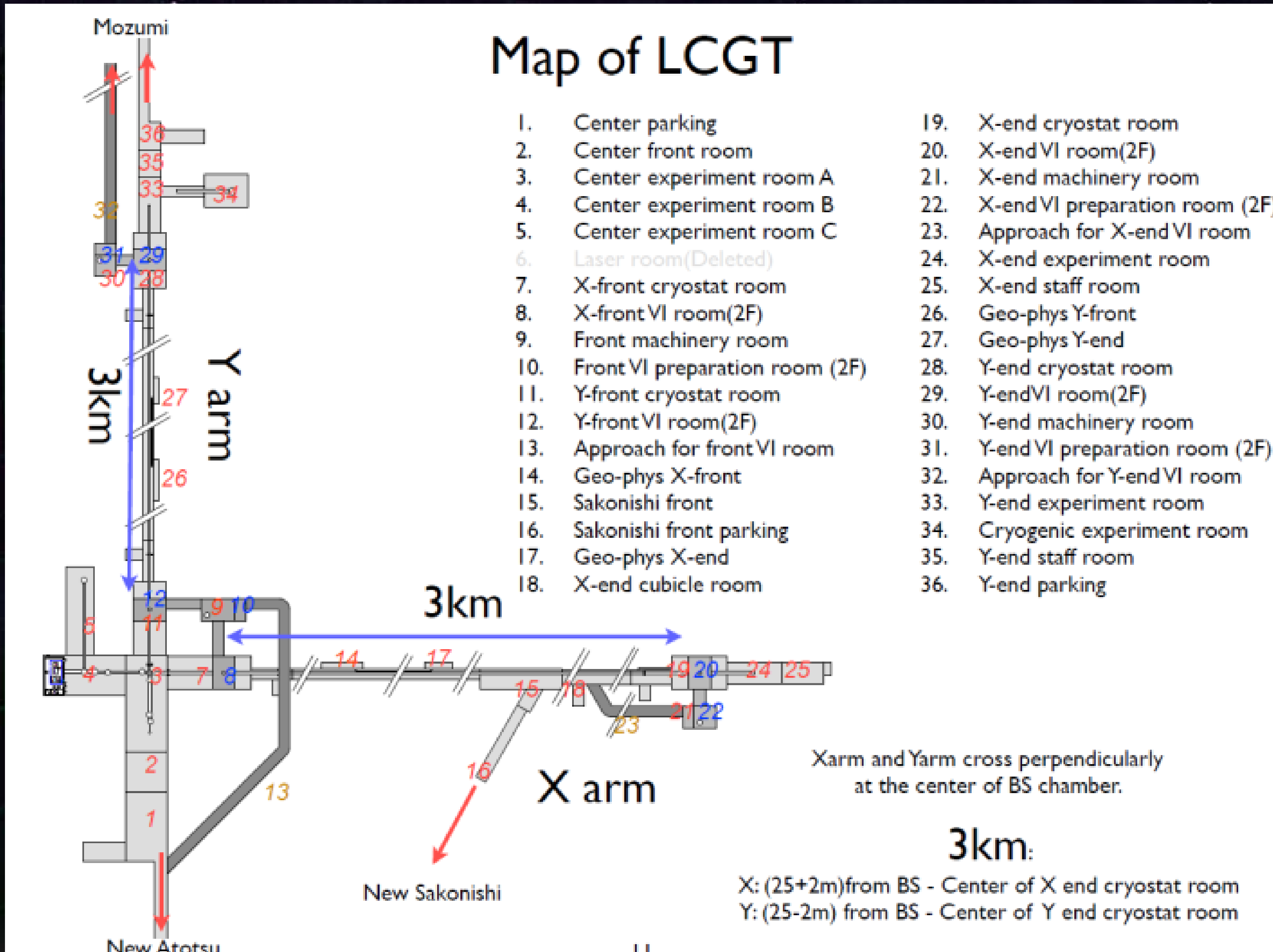
Materials

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.



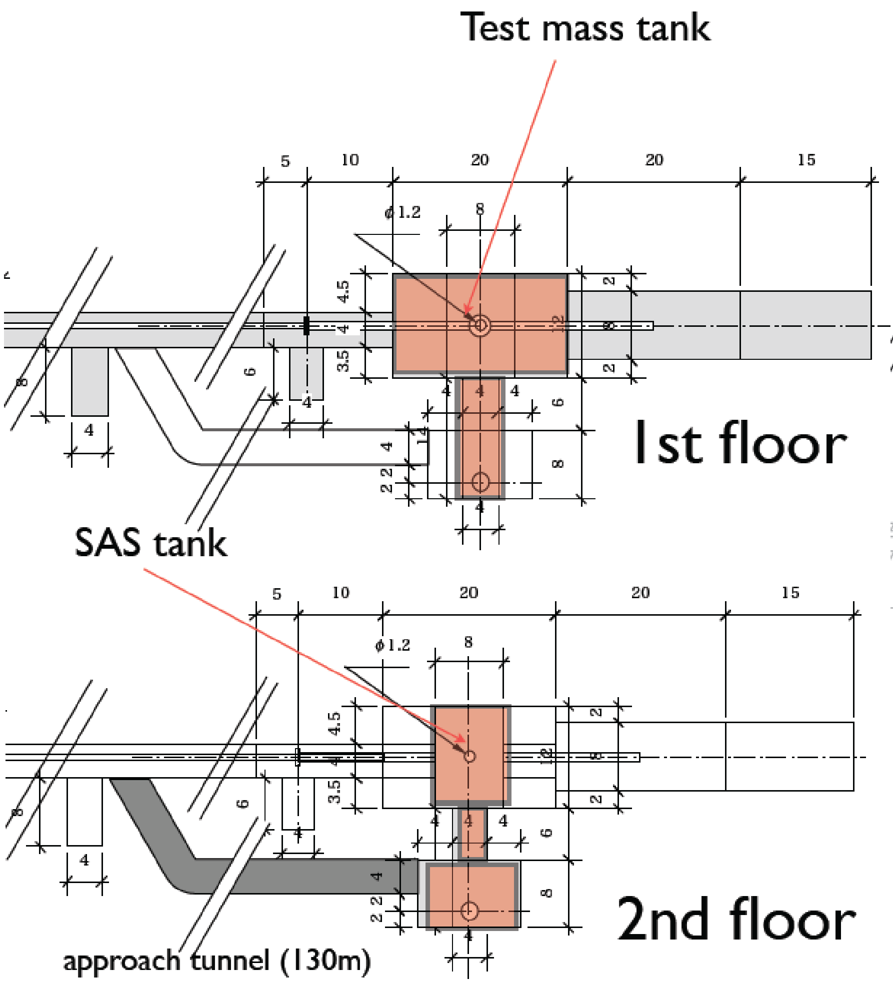
Tunnel

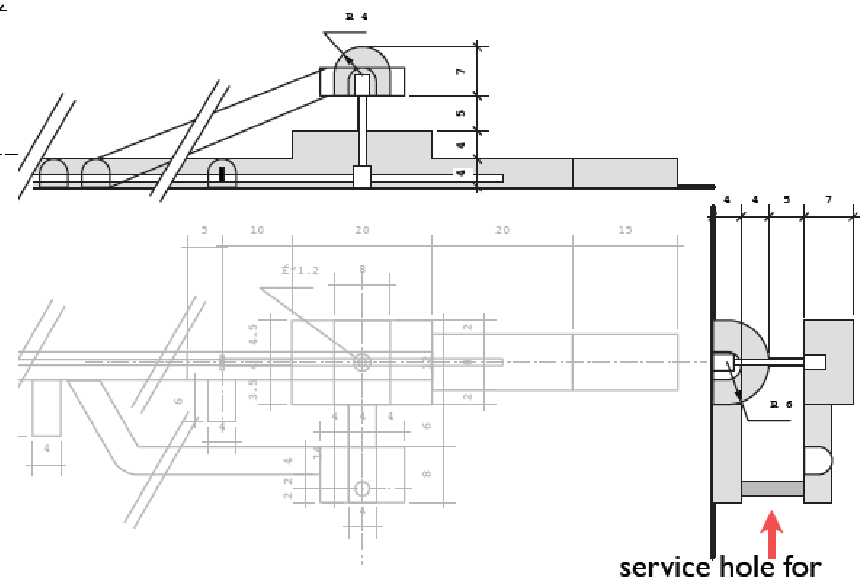


Map of LCGT
Mozumi
3km
Y arm
3km
X arm
New Sakonishi
New Atotsu
1. Center parking
2. Center front room
3. Center experiment room A
4. Center experiment room B
5. Center experiment room C
6. Laser room(Deleted)
7. X-front cryostat room
8. X-front VI room(2F)
9. Front machinery room
10. Front VI preparation 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 → 512m^2

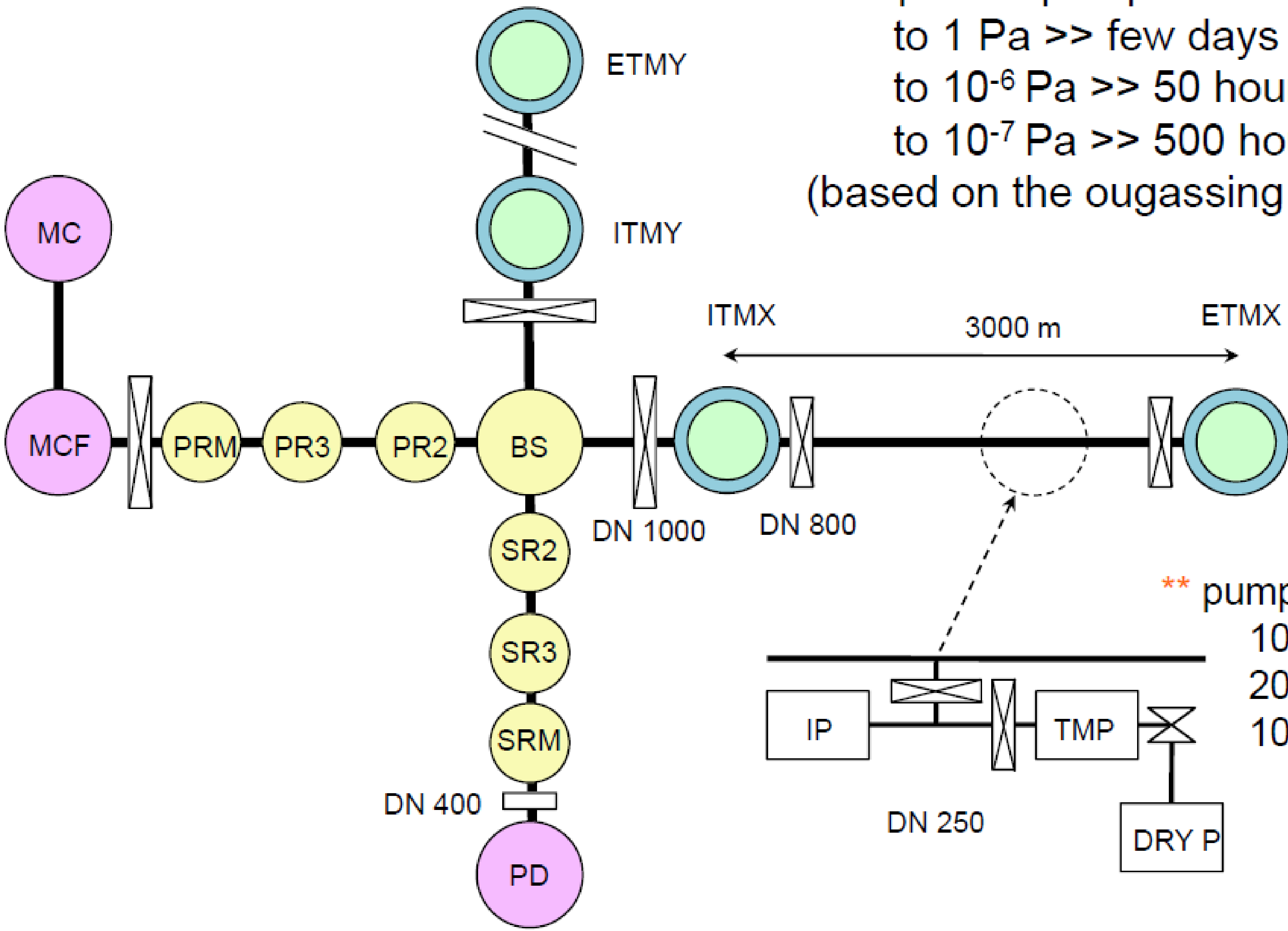
Volume : 5140m^3 → 2860m^3

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

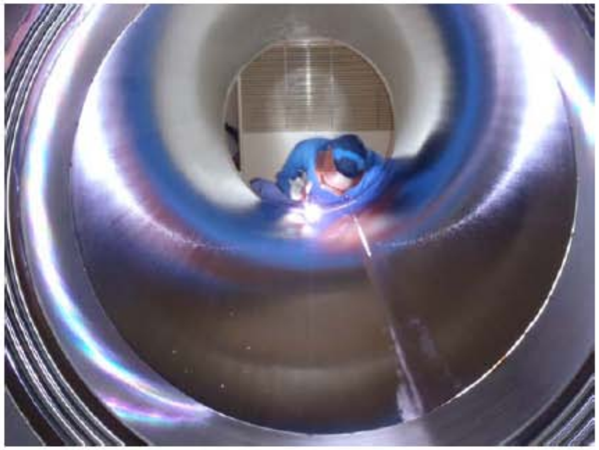
110302 VAC (YS)

LCGT Vacuum System

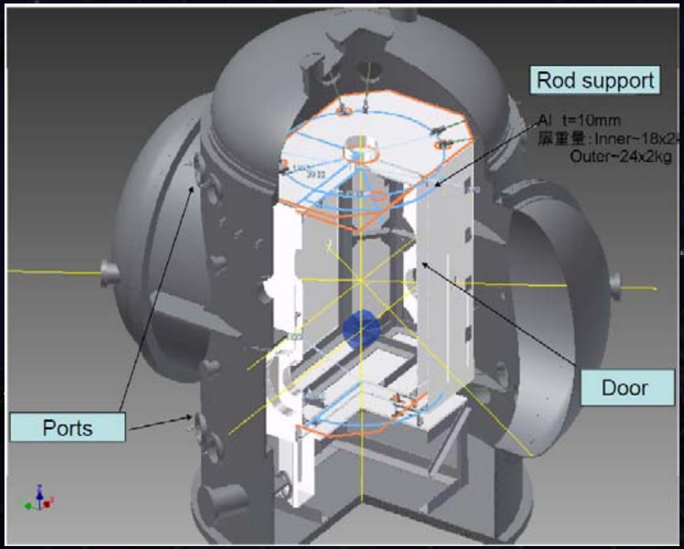
** test product of the tube

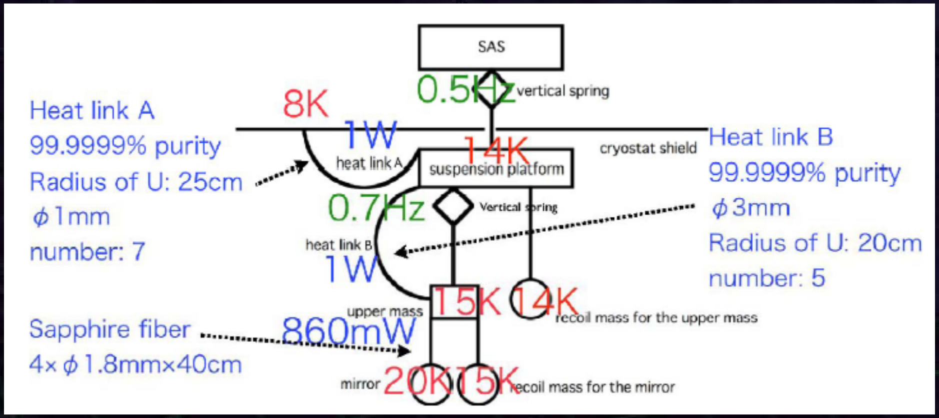
* A 4-m long tube was manufactured and a half of the inner surface was electro polished.

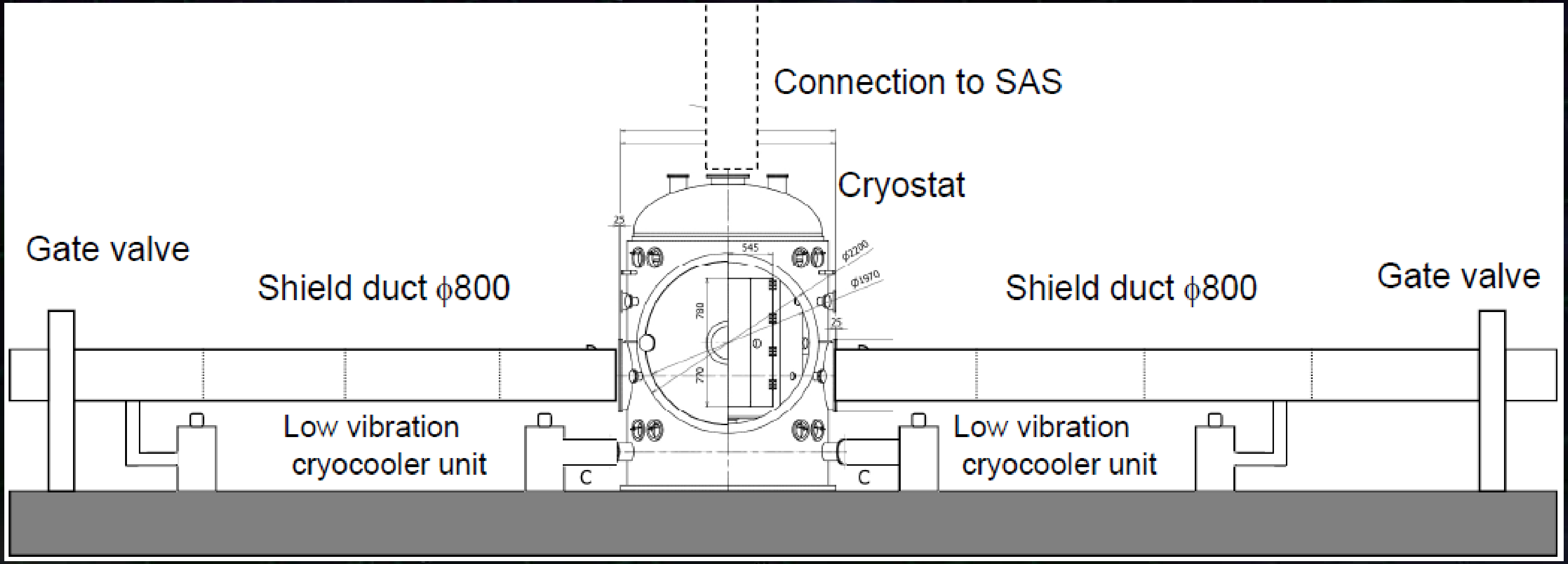
* A flange with a bellows (one convolution) was manufactured.



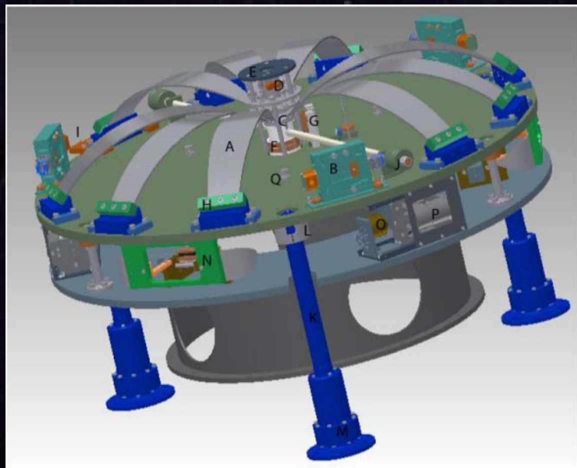
Cryogenics

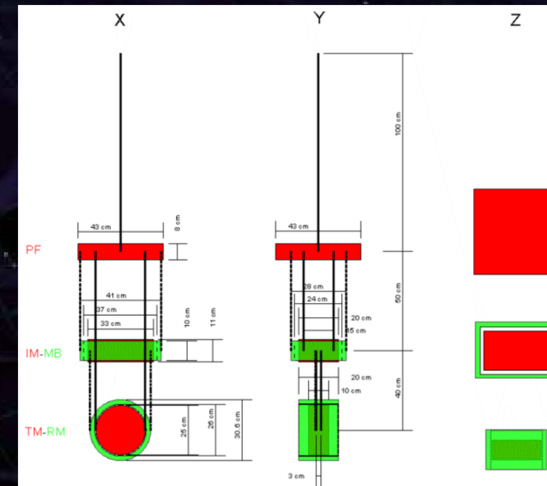

Rod support
Al t=10mm
Ports
Door


SAS
0.5Hz
vertical spring
8K
Heat link A
99.9999% purity
Radius of U: 25cm
ϕ1mm
number: 7
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

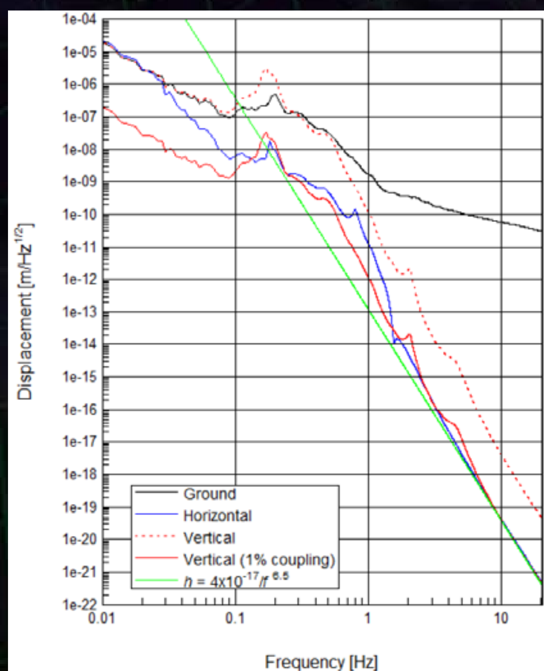

Connection to SAS
Cryostat
Gate valve
Shield duct ϕ800
Shield duct ϕ800
Gate valve
Low vibration cryocooler unit
Low vibration cryocooler unit

Vibration Isolation

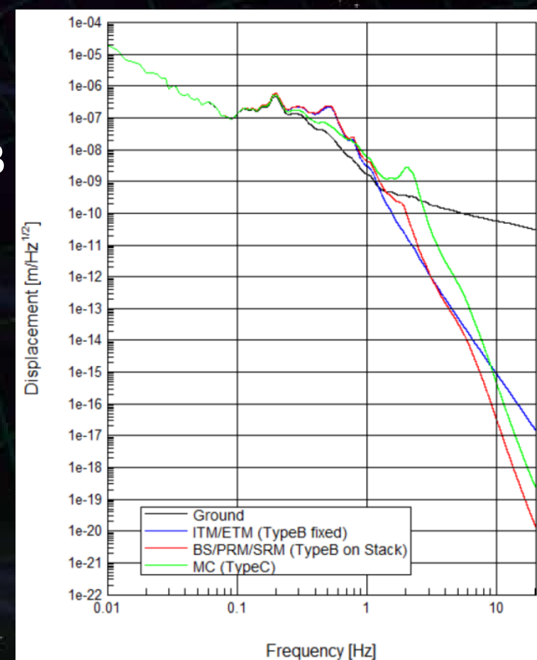




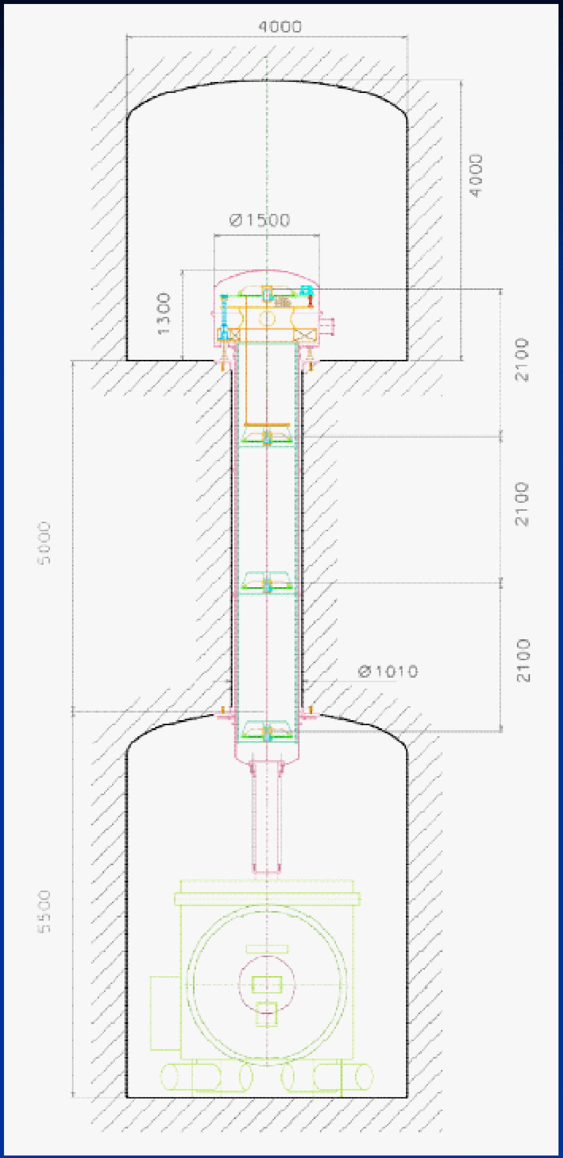
Type-A



Type-B



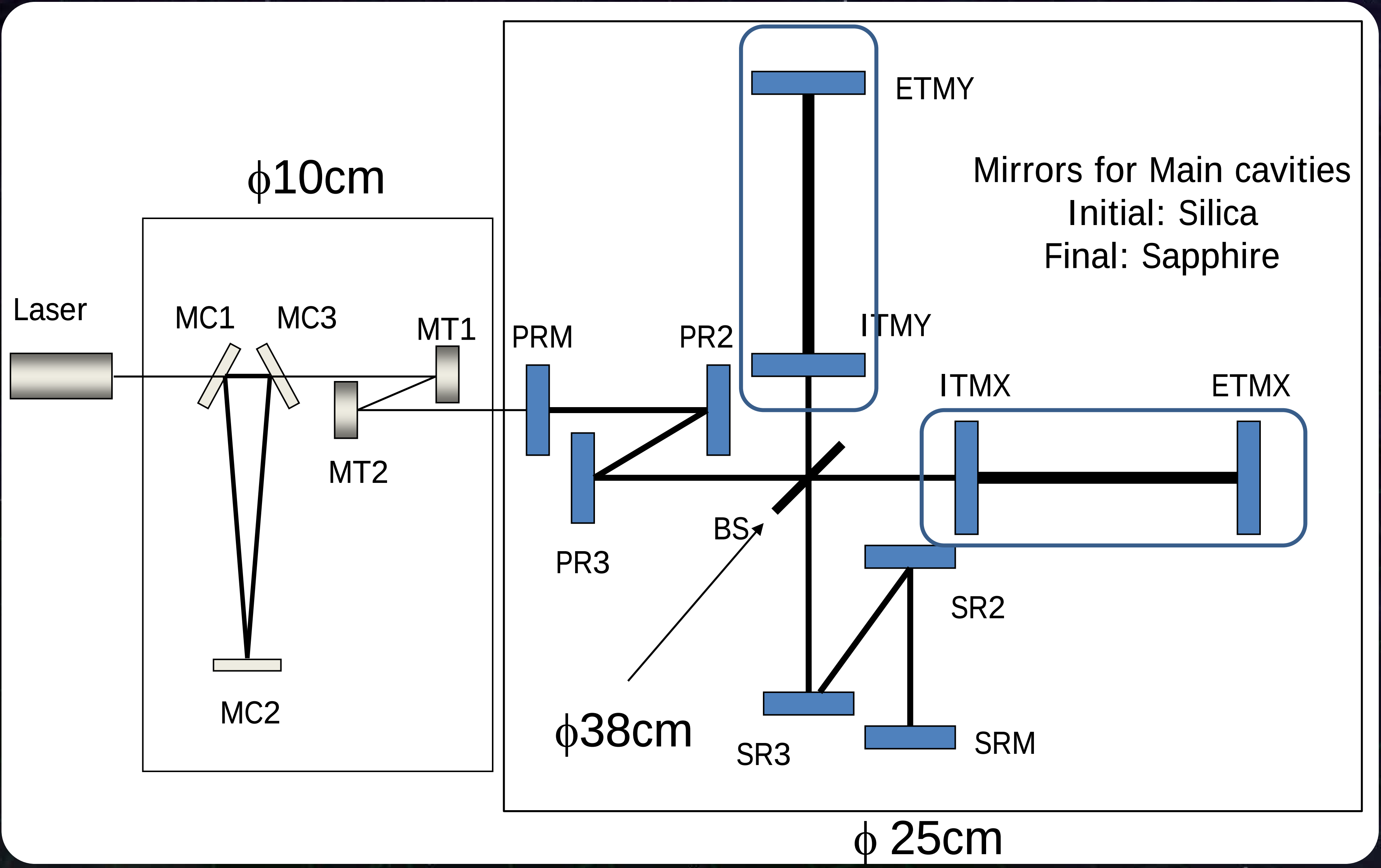
Vibration Isolation



Type-A (2-layer structure)

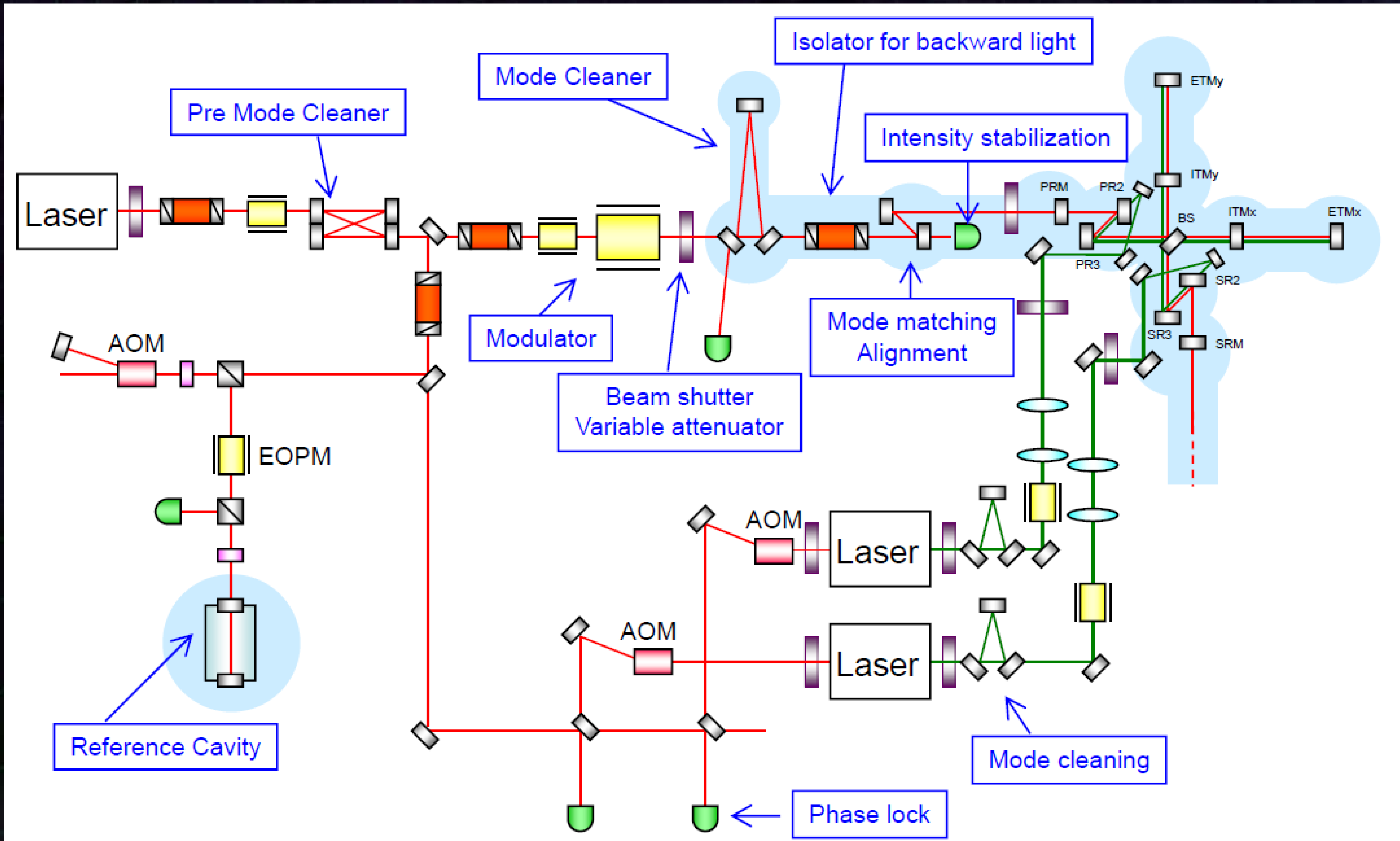
- Upper tunnel containing pre-attenuator (short IP and top filter)
- 1.2m diameter 5m tall borehole containing standard filter chain
- Lower tunnel containing cryostat and payload

Core Optics

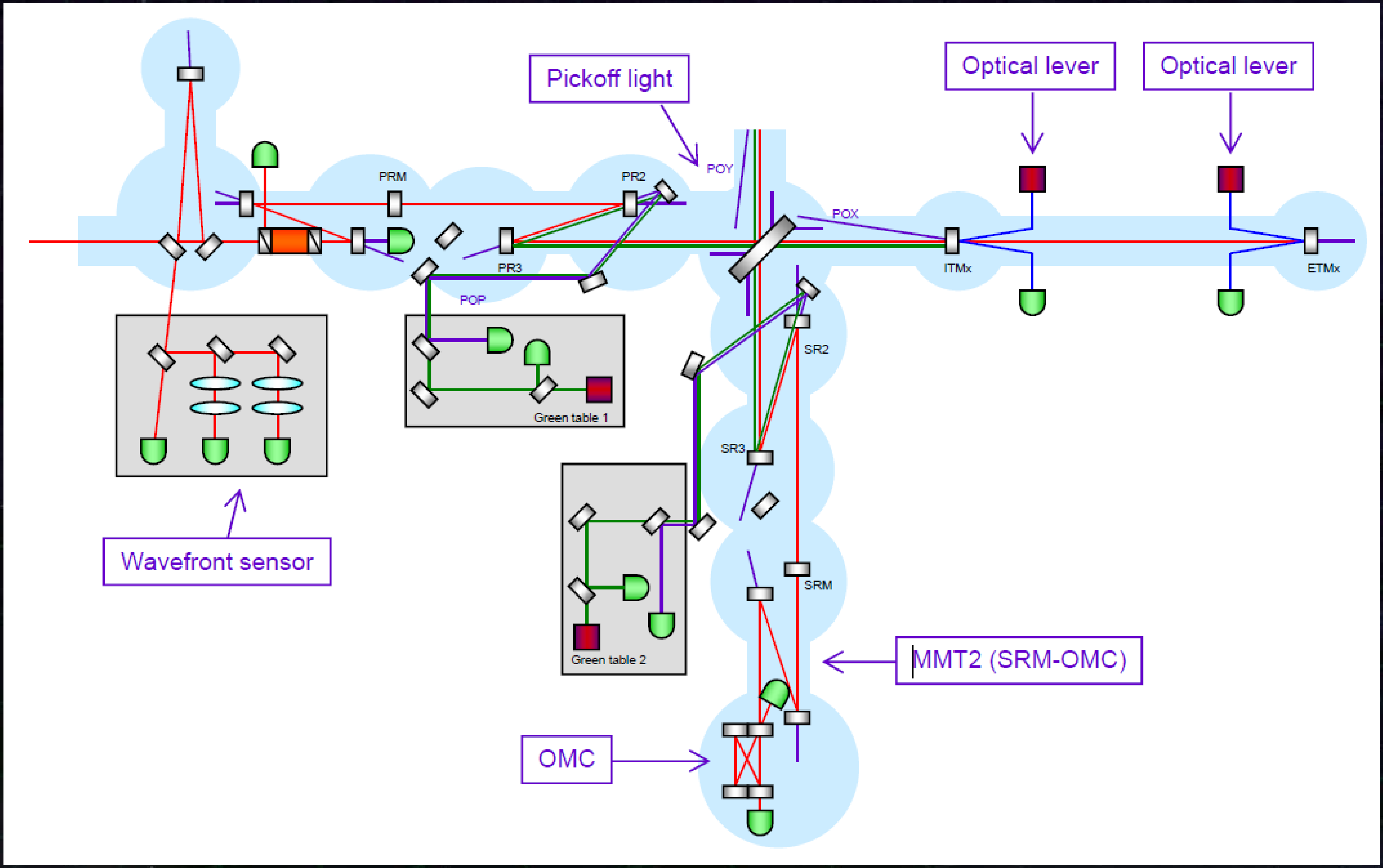


ϕ10cm
Laser
MC1
MC3
MT1
MT2
MC2
PRM
PR2
PR3
BS
ϕ38cm
ETMY
ITMY
ITMX
ETMX
SR2
SR3
SRM
Mirrors for Main cavities
Initial: Silica
Final: Sapphire
ϕ 25cm

Input/Output Optics

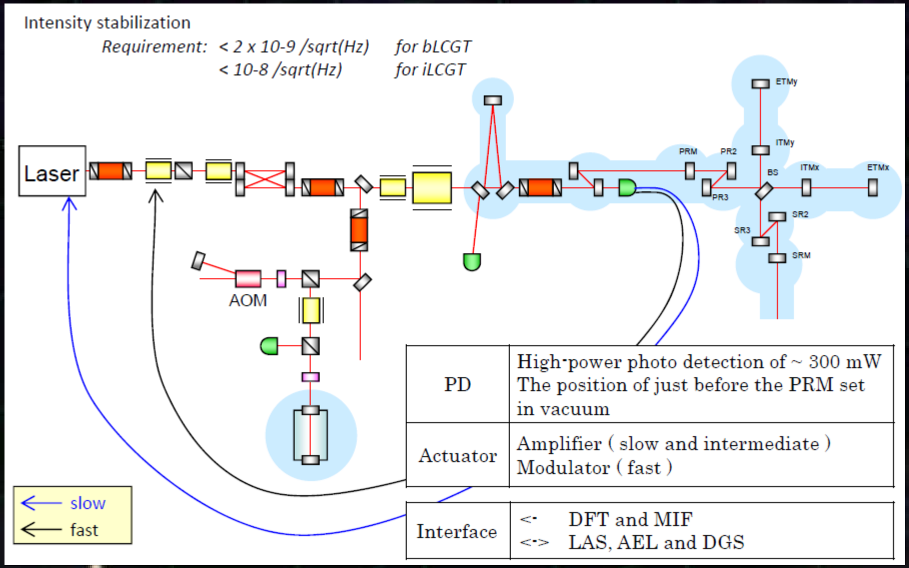


Output Optics



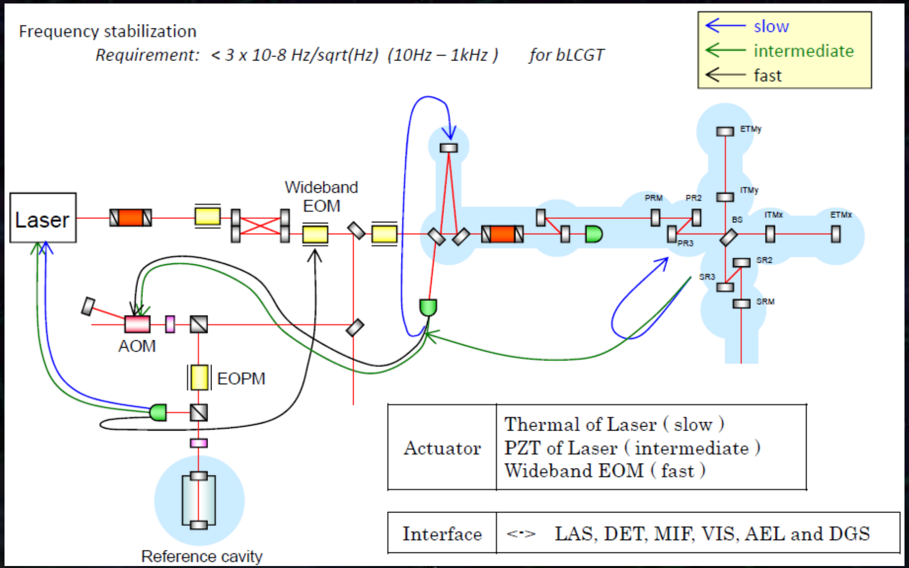
Freq. and Int. stabilization

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



PD	High-power photo detection of ~ 300 mW The position of just before the PRM set in vacuum
Actuator	Amplifier (slow and intermediate) Modulator (fast)

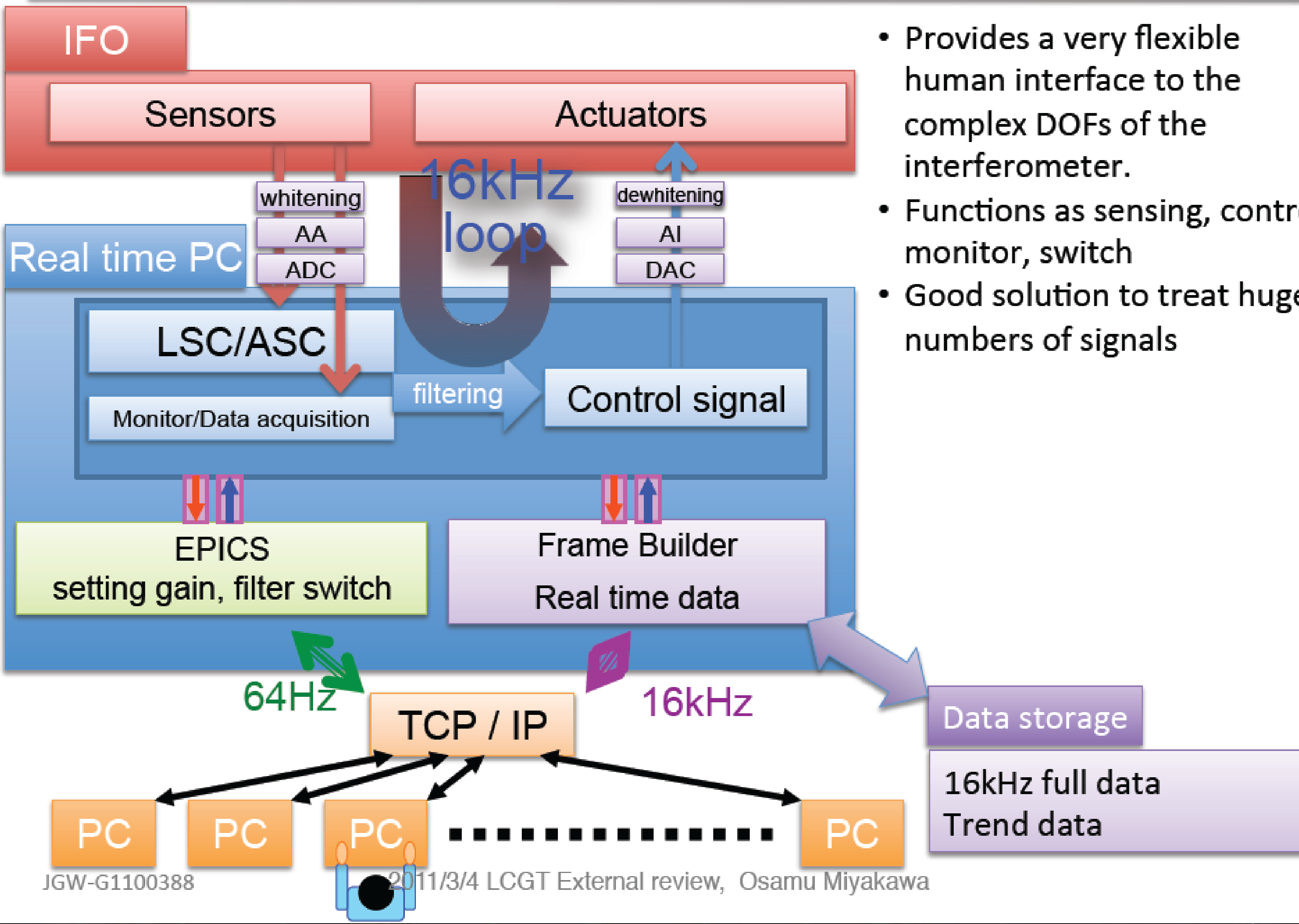
Interface	<-	DFT and MIF
	<->	LAS, AEL and DGS



Actuator	Thermal of Laser (slow) PZT of Laser (intermediate) Wideband EOM (fast)

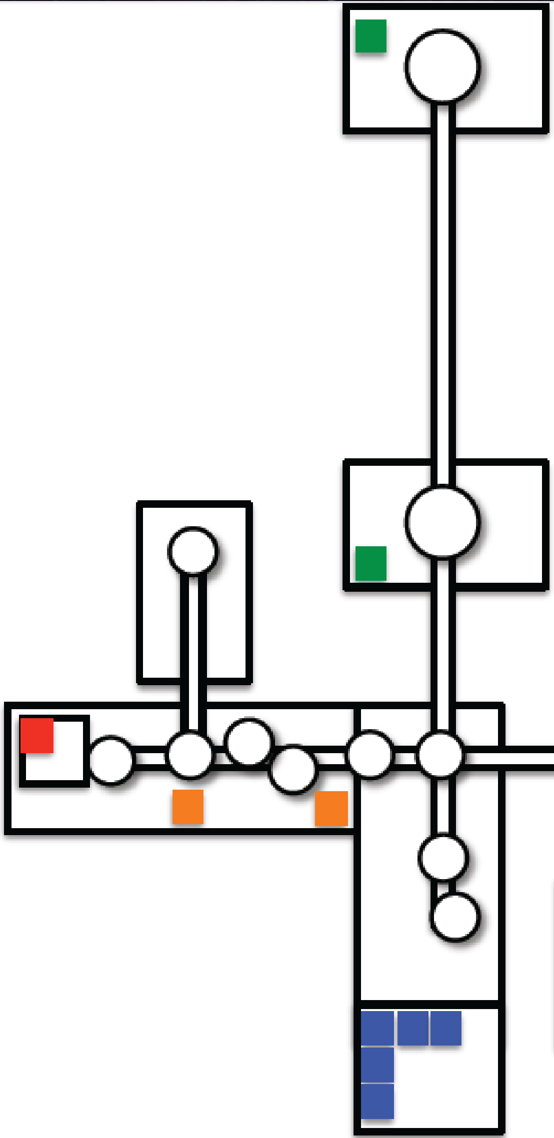
Interface	<-> LAS, DET, MIF, VIS, AEL and DGS

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

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

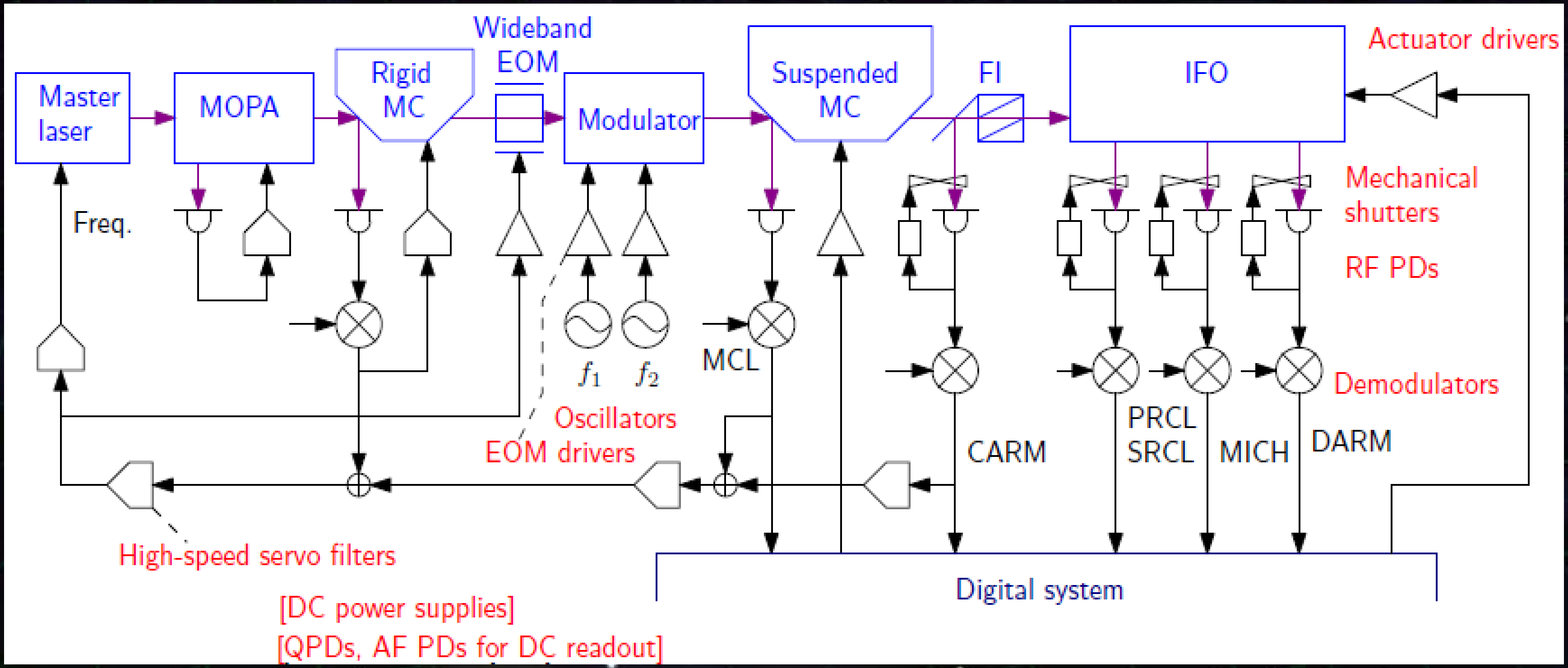
Data storage for iLCGT (analysis, commissioning): 500TB

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

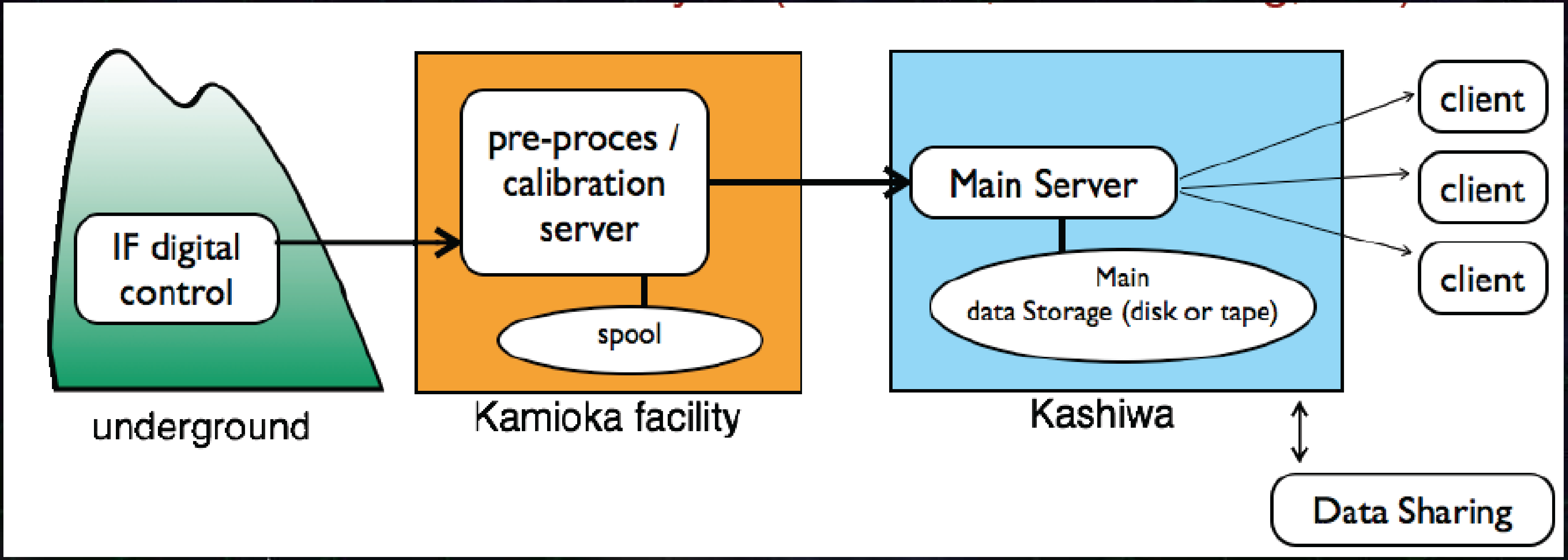
Needs to make a channel list from all subgroups

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

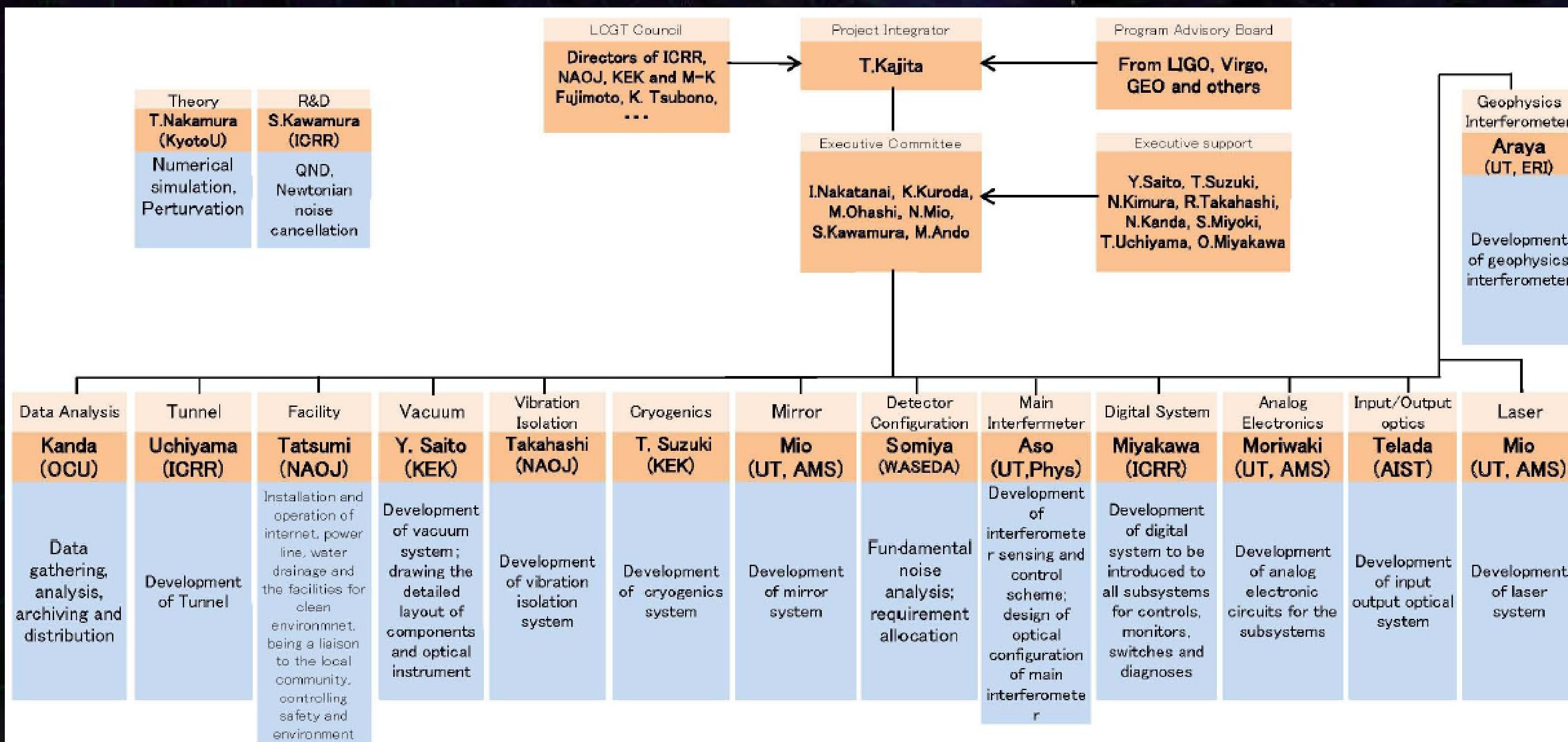
Analog electronics



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 Better seismic attenuation system Underground site	Seismic noise reduction	Long baseline Better seismic attenuation system Suburban site
Low-mechanical-loss mirrors and suspensions Cryogenic (20k)	Thermal noise reduction	Low-mechanical-loss mirrors and suspensions Large beam size
High-power laser source Low-loss optics Variable RSE config.	Quantum noise reduction	High-power laser source Low-loss optics 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

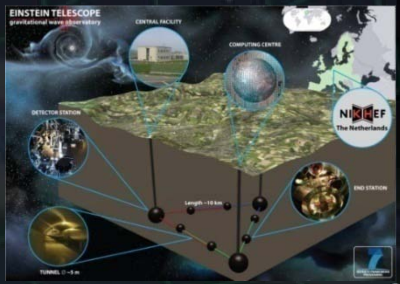
2010

2015

2020

2025

Detection Rate
~10 event / yr



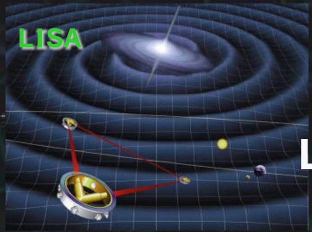
Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)

DECIGO

LPF

DPF



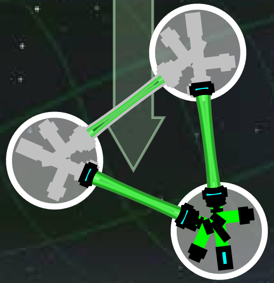
LISA

Pre-DECIGO

Guaranteed source
0.1mHz-10mHz

DECIGO

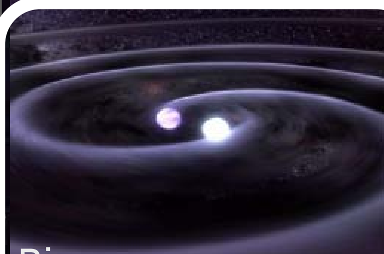
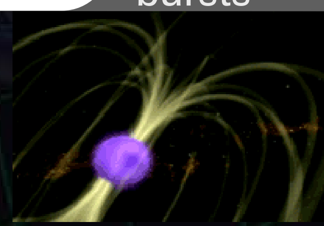
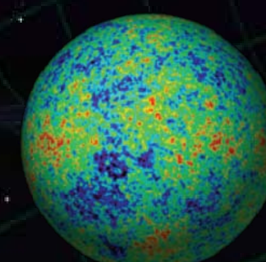
BBO



Cosmological GWs
around 0.1Hz

GW targets and data analysis

Signal duration

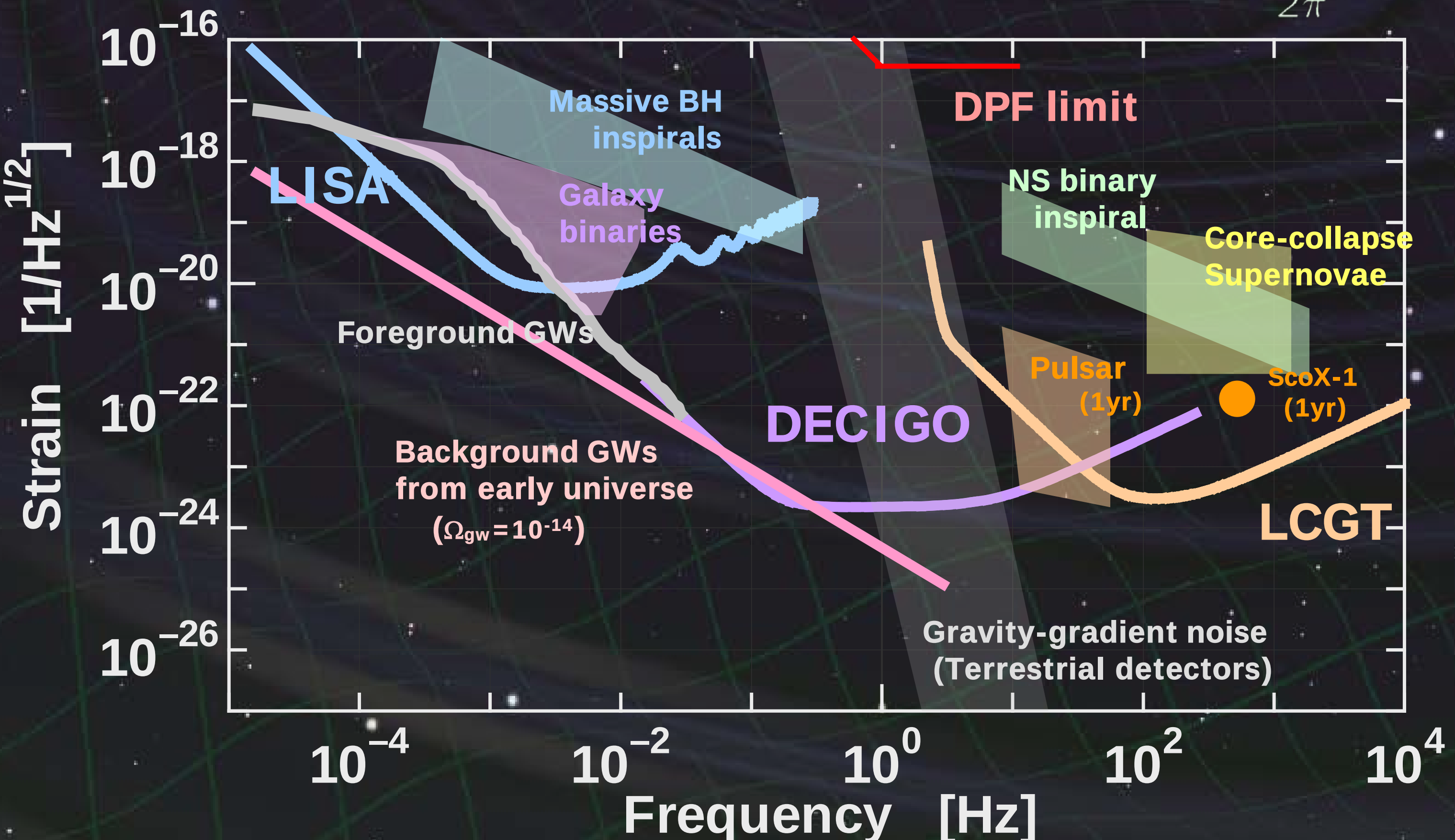
Waveform	Short (bursts)		Long (stationary)
Known	 Binary merger → Chirp wave, Ringdown wave	Gamma-ray bursts	 Pulsar, LMXB → Continuous
Unknown	 Stellar core collapse → burst wave	 Soft gamma-ray repeater	 Stochastic background → Random wave

DPF sensitivity

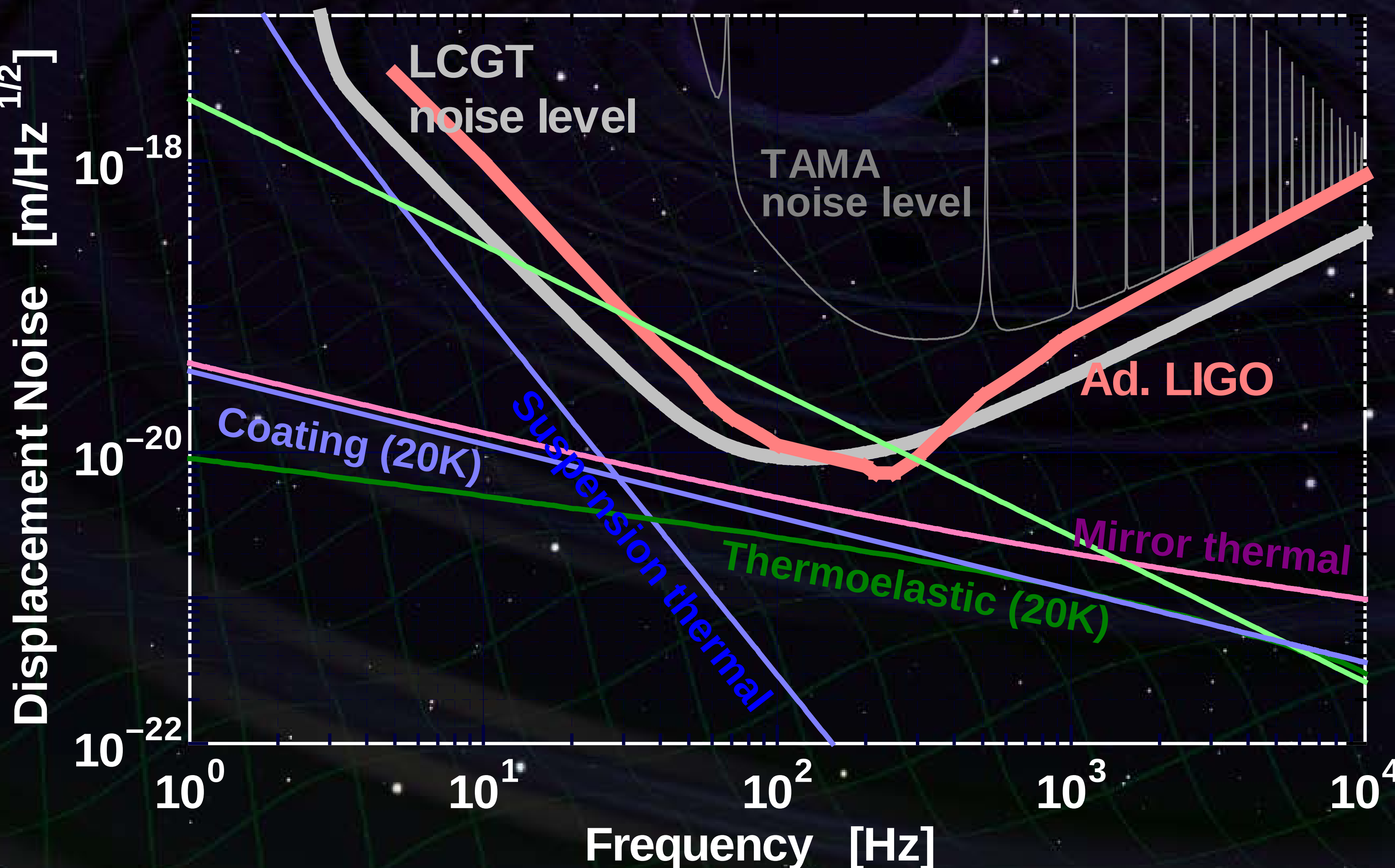
DPF sensitivity *h* ~ 2×10^{-15} $Hz^{1/2}$

(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

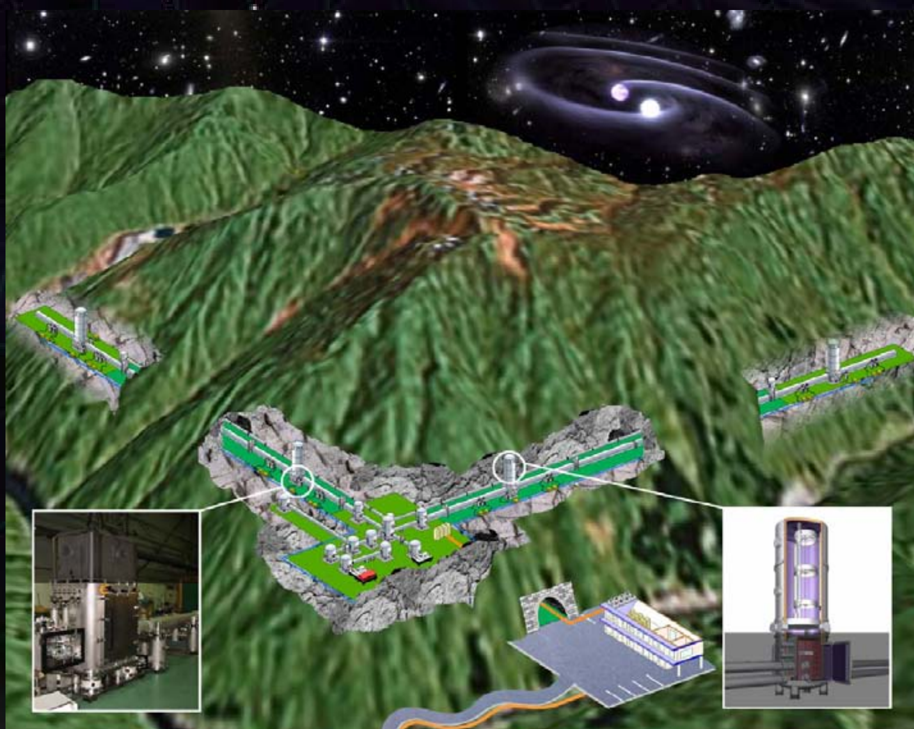
Target: GW detection

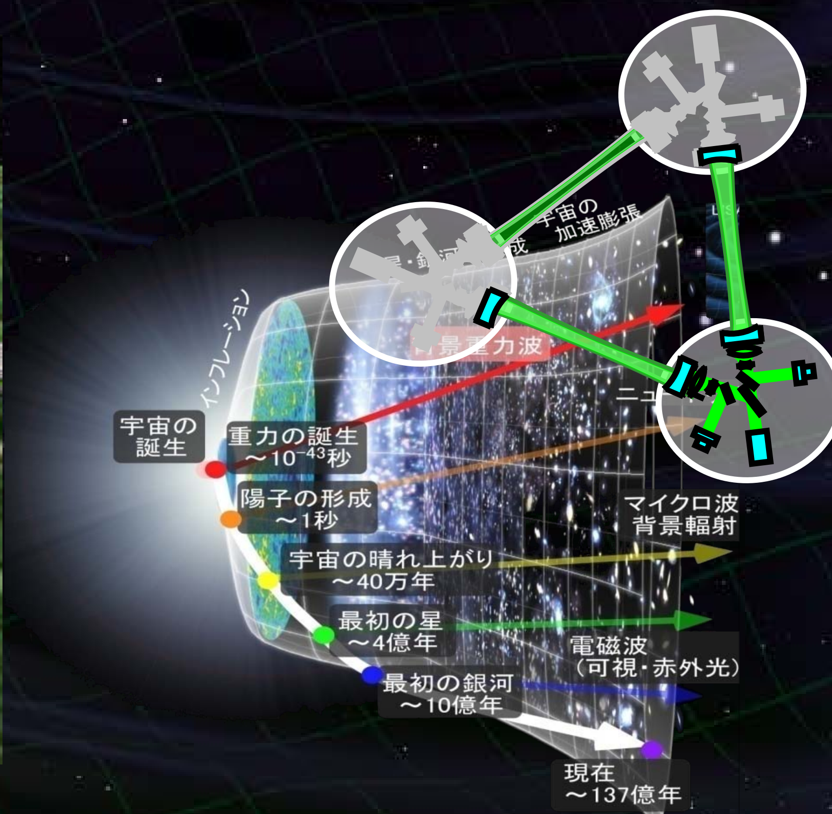
DECIGO (~2027)

Space observatory

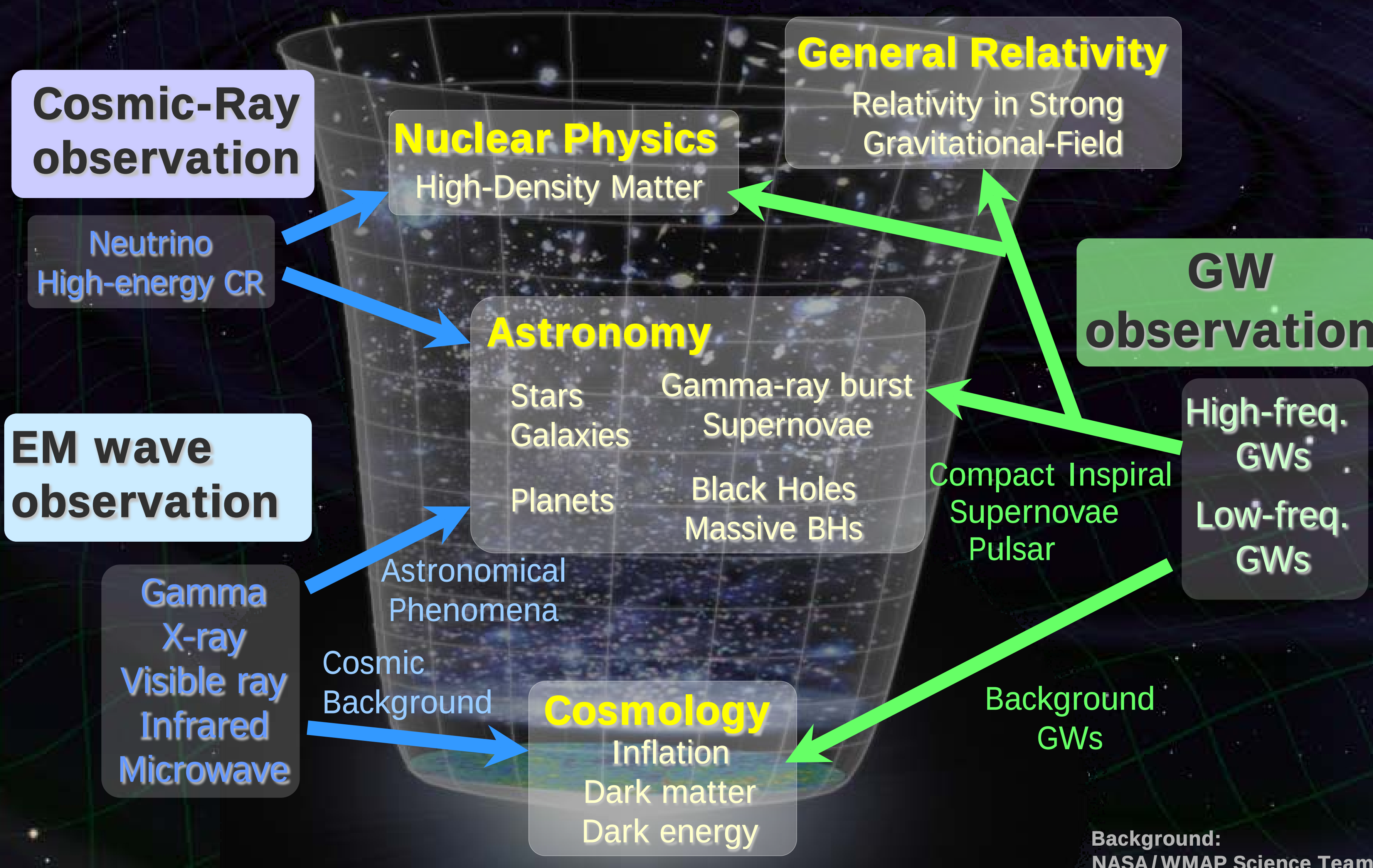
→ Low frequency sources

Target: GW astronomy





Observation of the Universe



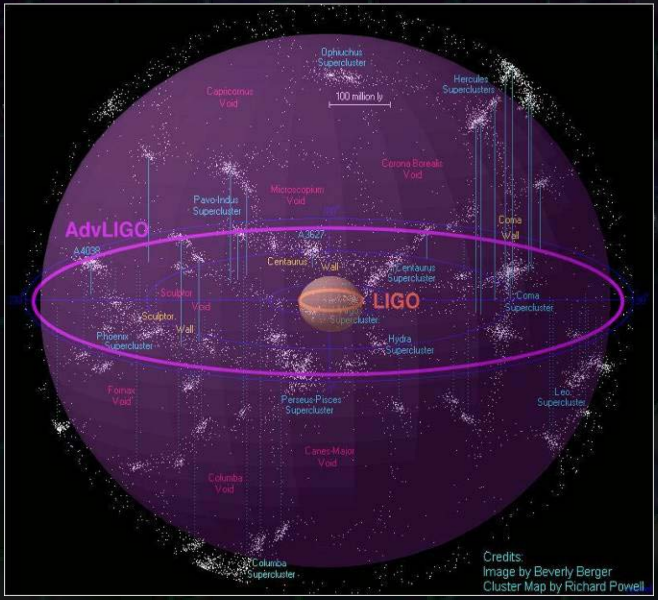
Expanding the Horizon

Current GW detectors : <20Mpc obs. range

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

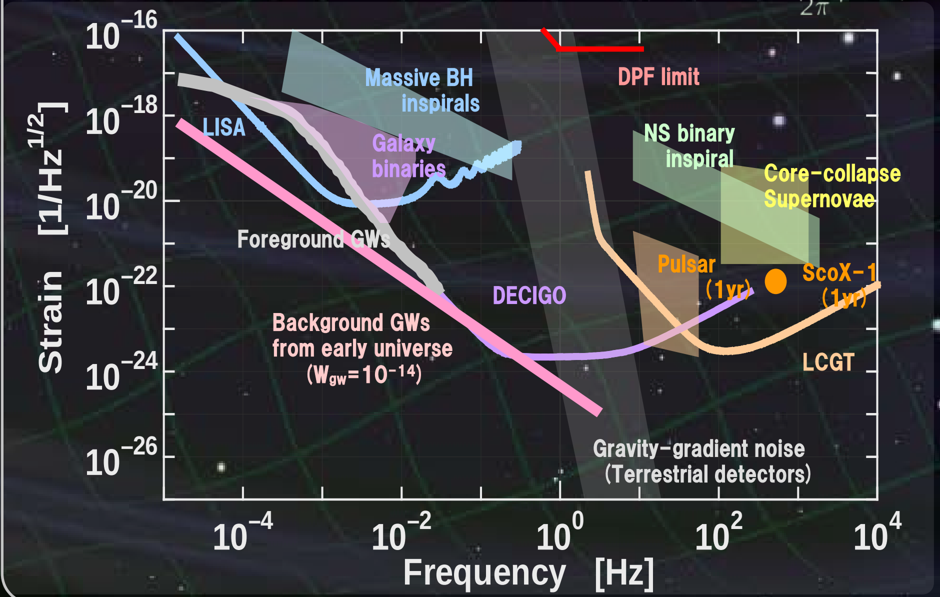
⇨ **Next generation detectors**

Better sensitivity to cover more galaxies



Wider observation band for various sources

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

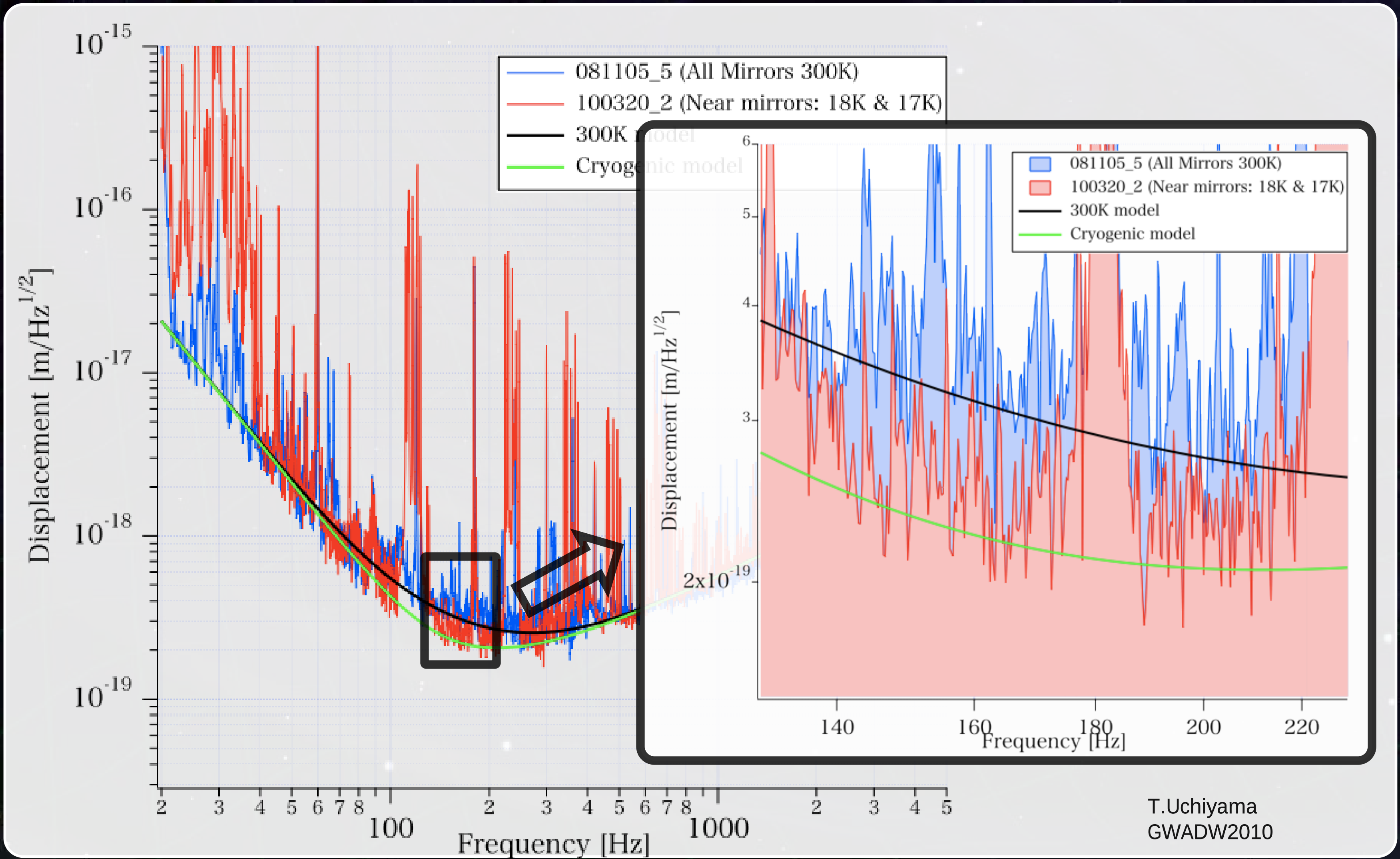


CLIO


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