Large-scale Cryogenic Gravitational wave Telescope: KAGRA

Conference on Laser Energetics 2015,

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High Energy Accelerator Research Organization (KEK)

on behalf of the KAGRA collaboration

Gravitational Wave and Its Detection

淮南子天文訓 ← Ancient Chinese Literature

Universe = 宇宙

「四方上下謂之宇、往古来今謂之宙」

Space *Time*

Language to tell "Universe"

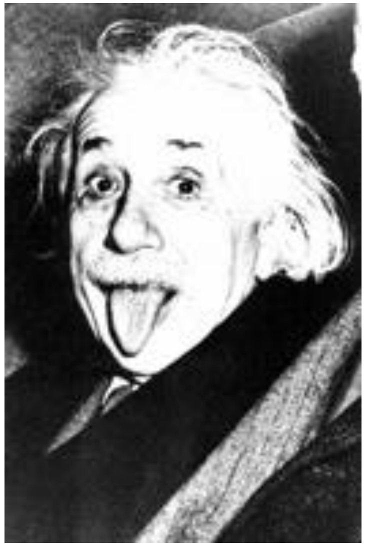
General Relativity

1915-16

100 years anniversary

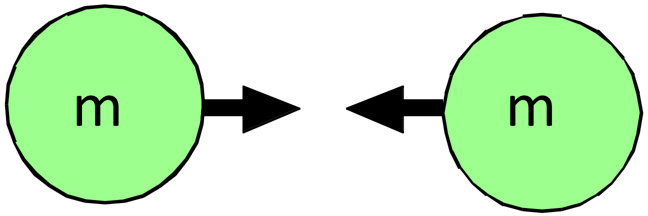
4-dimensional curved space-time theory

= Gravity Theory



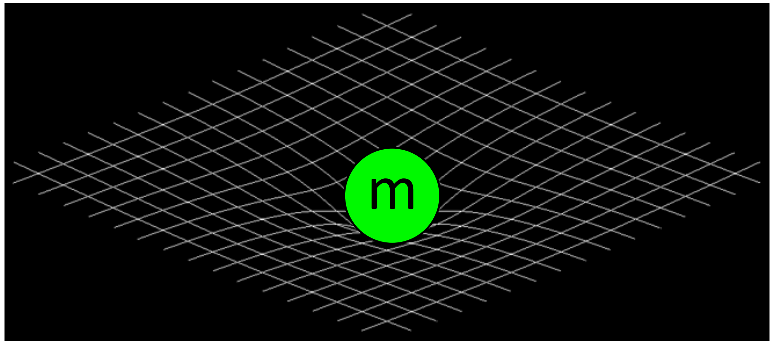
A. Einstein

Newtonian Gravity（1687）



Universal Gravitation（Dynamics）

General Relativity



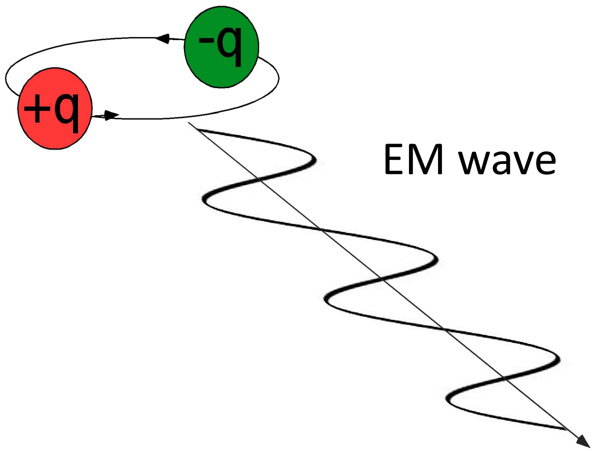
Geometry of Space-Time

Gravitational Wave

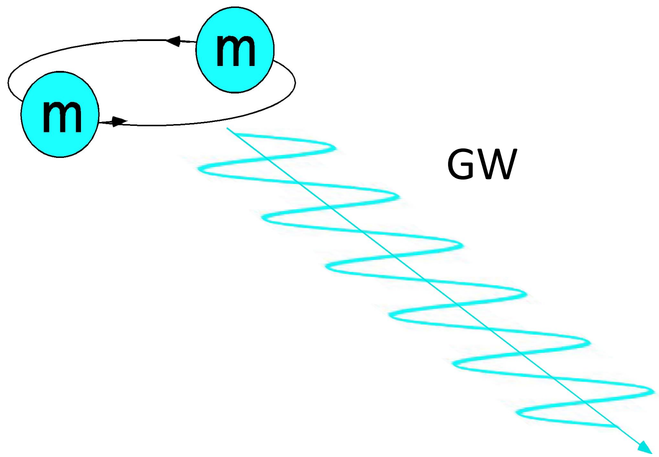
There are many proof of GR.
But it is not still completed.

One of symbolic phenomena in General Relativity

Electromagnetic interaction		**Gravity interaction**
Coulomb's force	⇔	**Universal gravitation**
Electromagnetic wave	⇔	**Gravitational wave**



EM wave



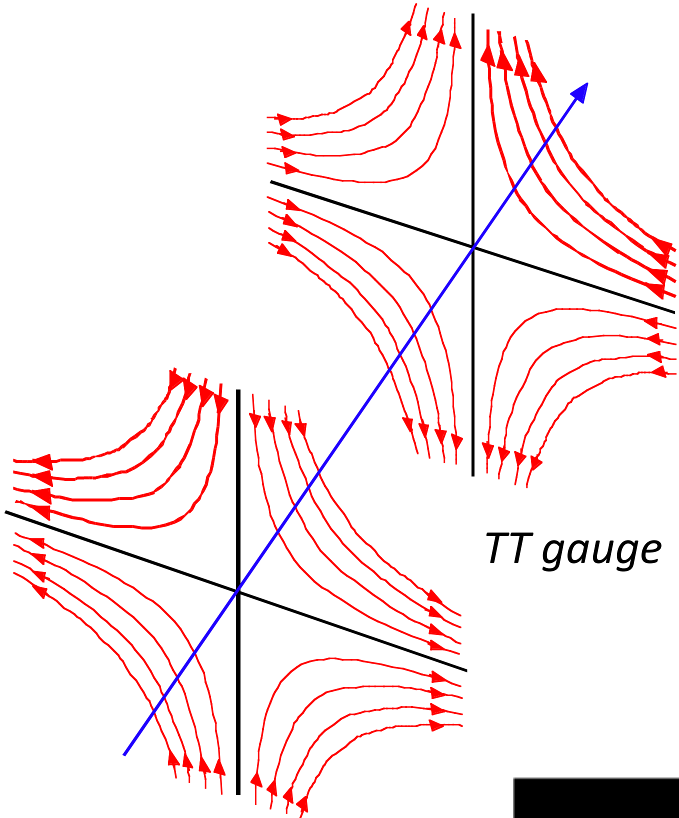
GW

But there are also different natures between both interactions. For an example, the system with + and – charges in EM system is neutral, and it radiates EM wave with same frequency as charge rotation (dipole). But the system with masses can not be neutral, and it radiates GW with twice frequency of the rotation (quadrupole).

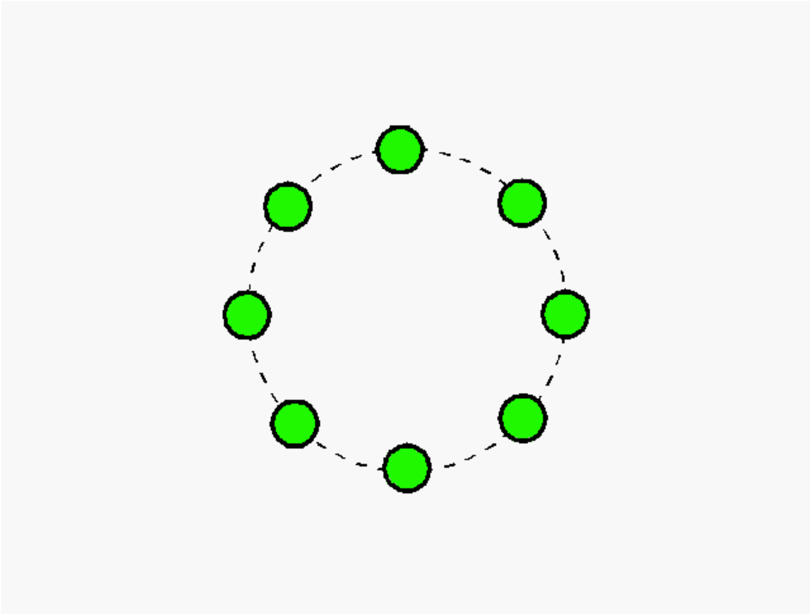
Gravitational Wave :

Propagation of Space-time distortion

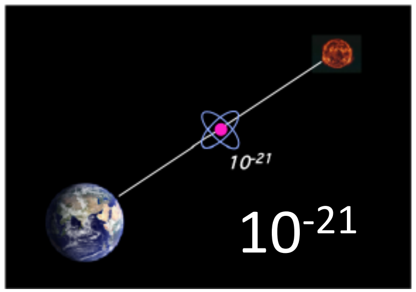
It induces gravity tidal force



Motion of test particles by GW tidal force



But this effect is really small.



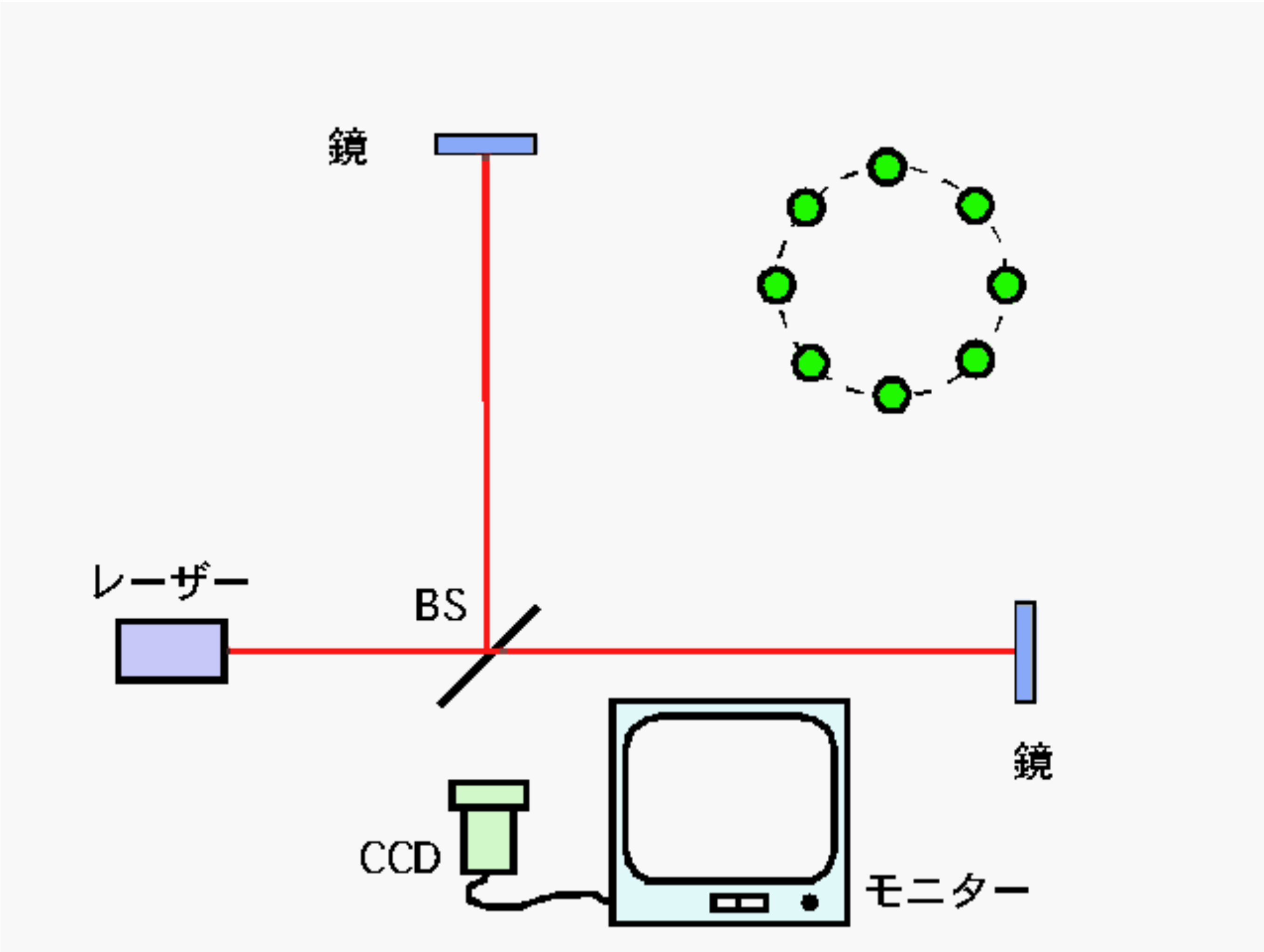
GW detection is figured such as

"Like a search of Hydrogen atom

between the Earth and the Sun."

Principle of GW Measurement by Michelson Interferometer

When length difference between both interferometer arms are occurred by GW, leakage of light will be dropped onto CCD.



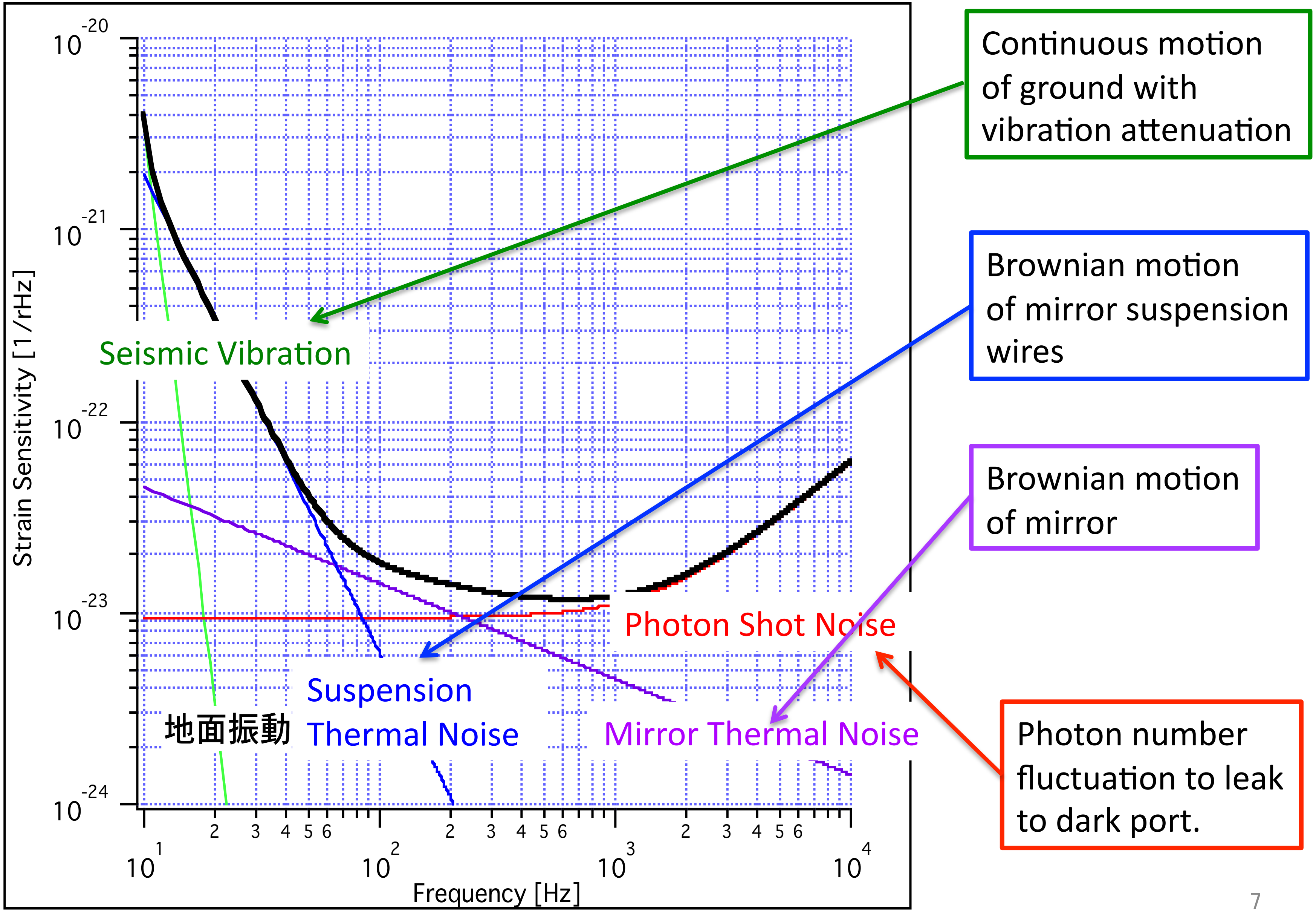
GW causes space -time distortion

Long arm interferometer has advantage.

1kHz GW
= 300km
in wavelength

Longer arm than 75km
cause cancelation
of over 1kHz GW signal.

Sensitivity Limitations of Interferometric GW Detector



A Practical Configuration:
Power Recycled Fabry-Perot Michelson Interferometer

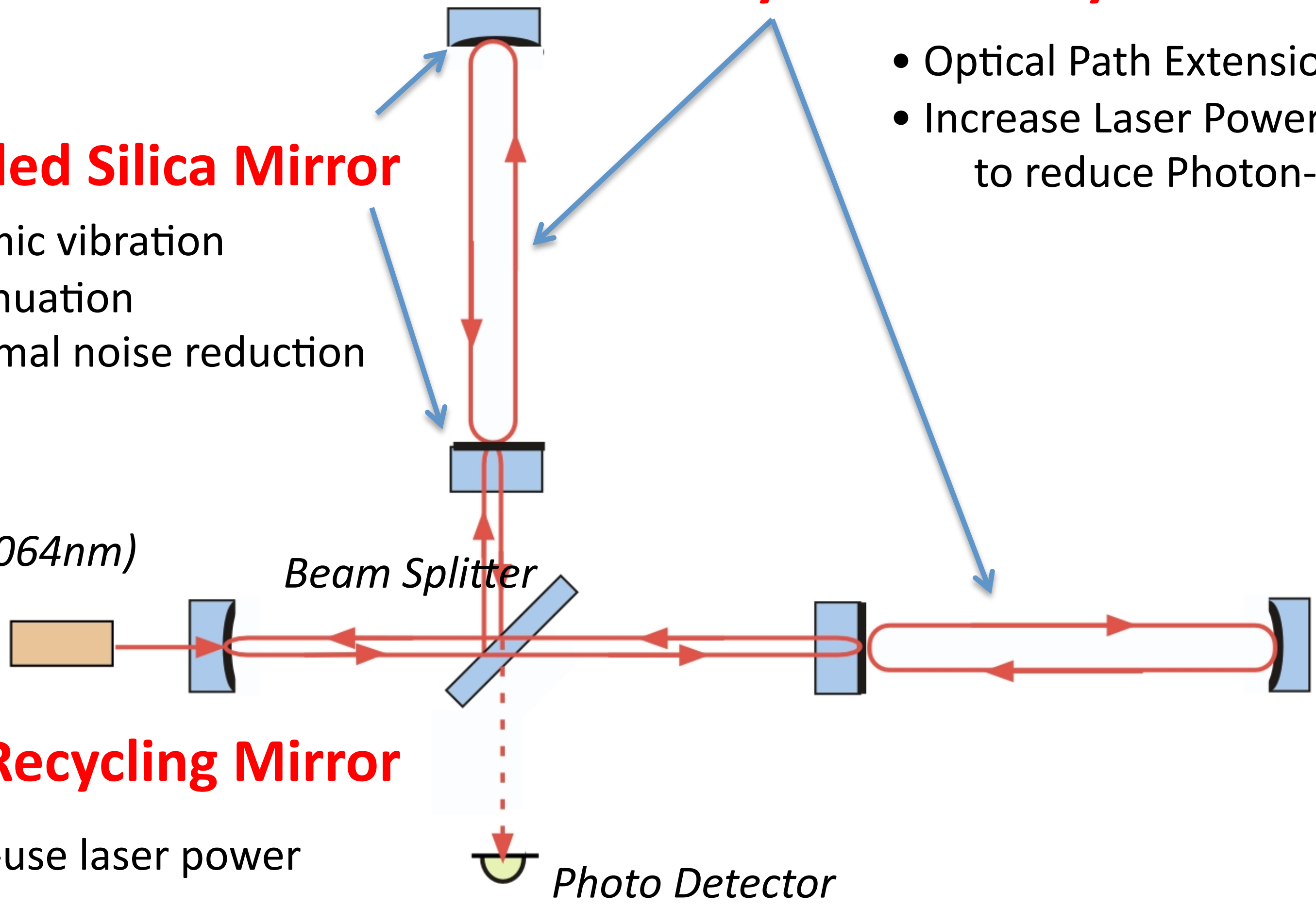
Fabry-Perot Cavity

- Optical Path Extension
- Increase Laser Power
  to reduce Photon-Shot Noise

Suspended Silica Mirror

- Seismic vibration
  attenuation
- Thermal noise reduction

Laser
(Nd: YAG, 1064nm)



Power Recycling Mirror

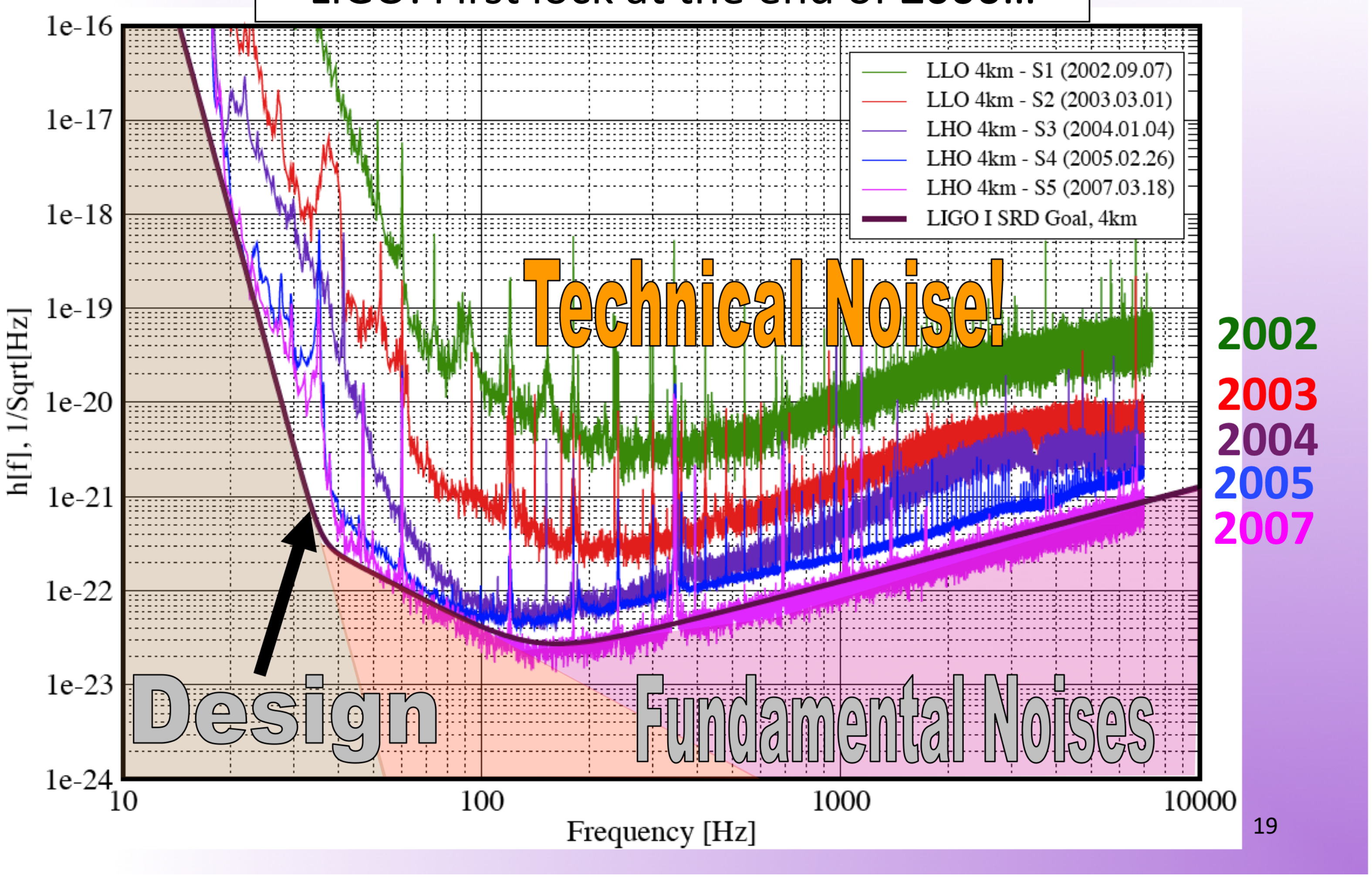
- Re-use laser power

These are 1st generation Technologies.

from Lisa Barsotti (LIGO-MIT)

Initial LIGO Sensitivity improvement

LIGO: First lock at the end of **2000…**

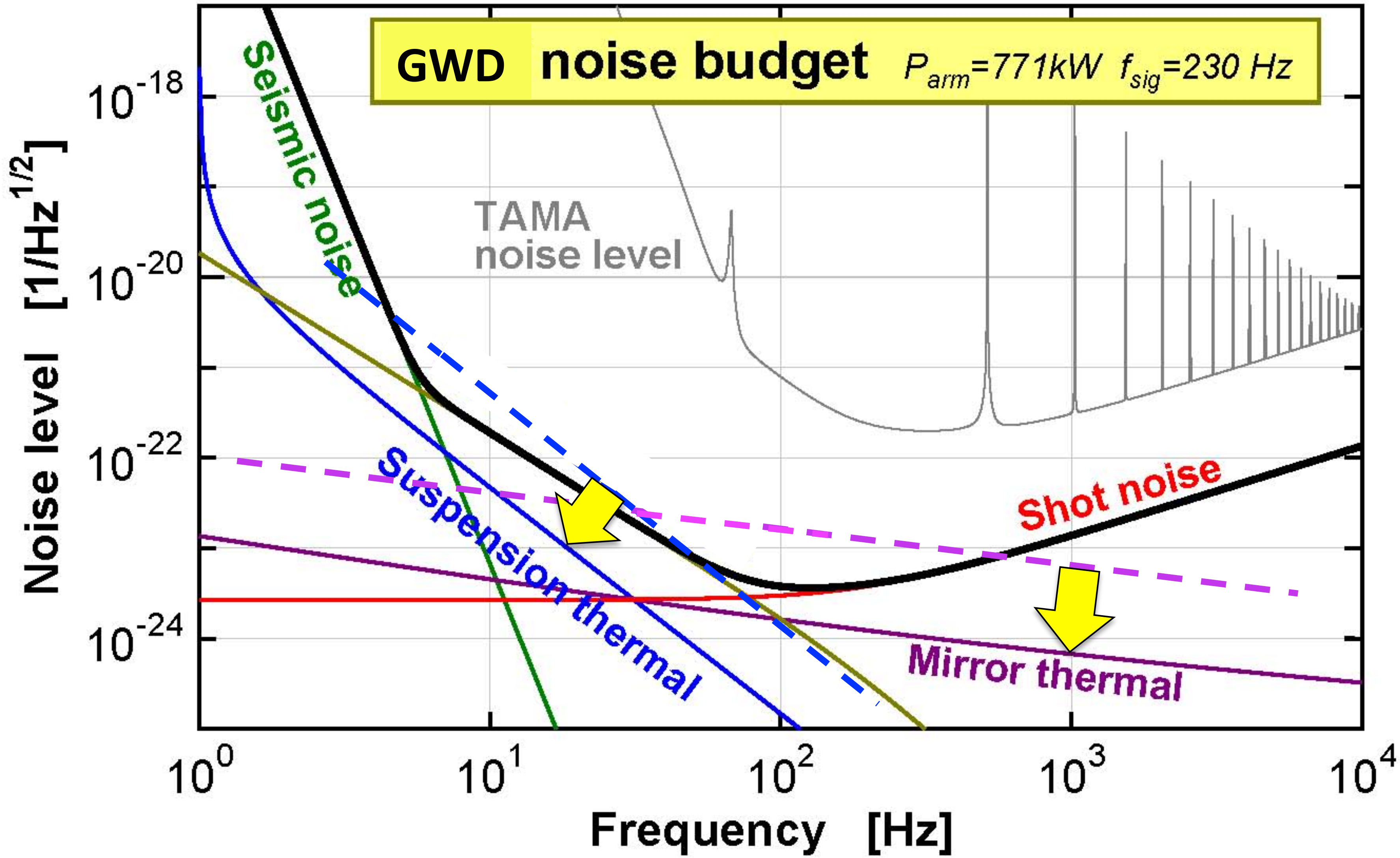


Large-scale Cryogenic Gravitational wave Telescope

-KAGRA-

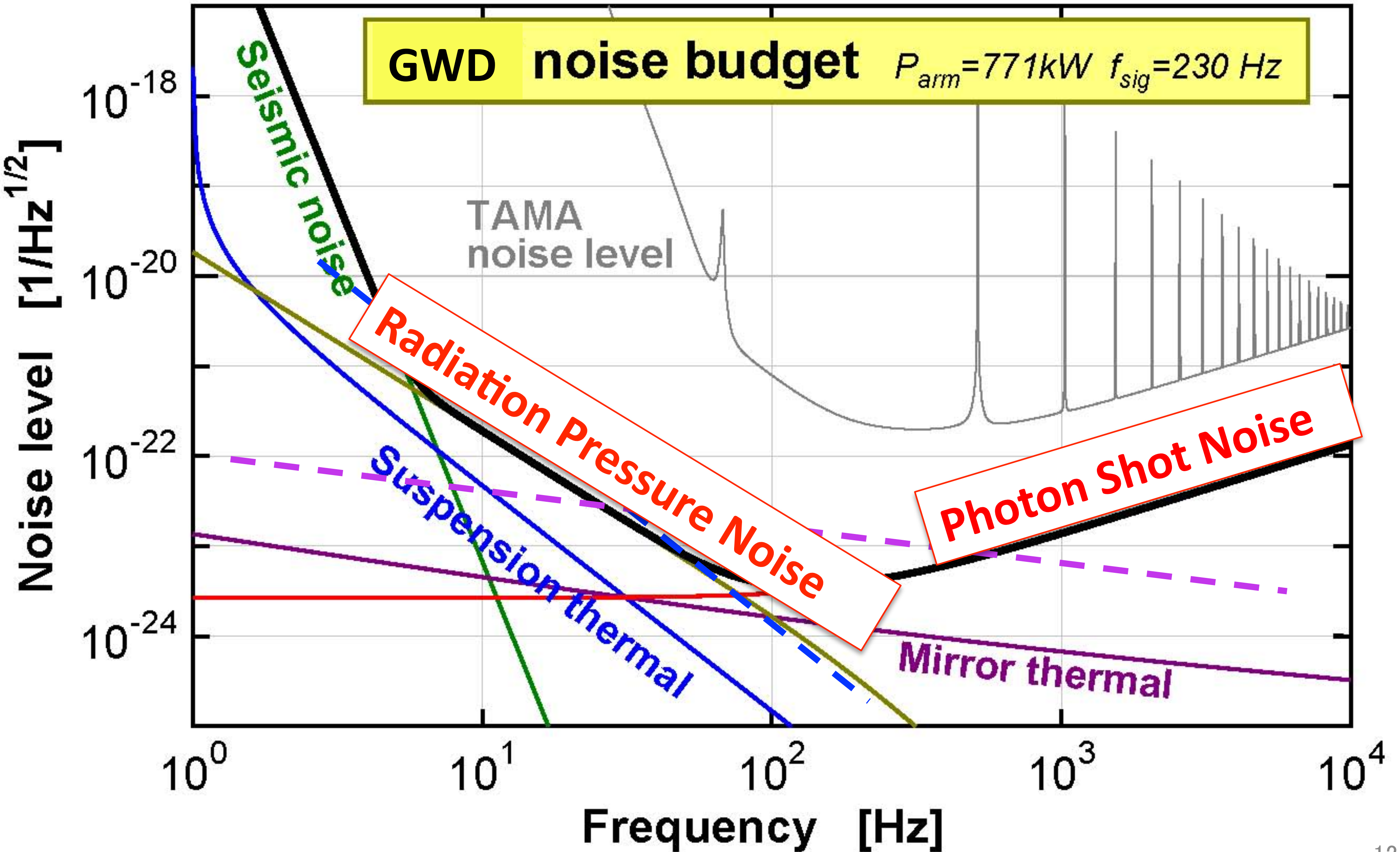
2^{nd} Generation Interferometric GW Detector

Sensitivity Improvement Plan in 2nd Generation GW Detector



A theme in 2nd generation GW detectors is how we can reduce "thermal noises".

Sensitivity Improvement Plan in 2nd Generation GW Detector



The sensitivity of 2nd generation GW detectors will be limited by "quantum noises".


Cryogenic Mirror System
Features in
KAGRA
Underground

KAGRA collaboration

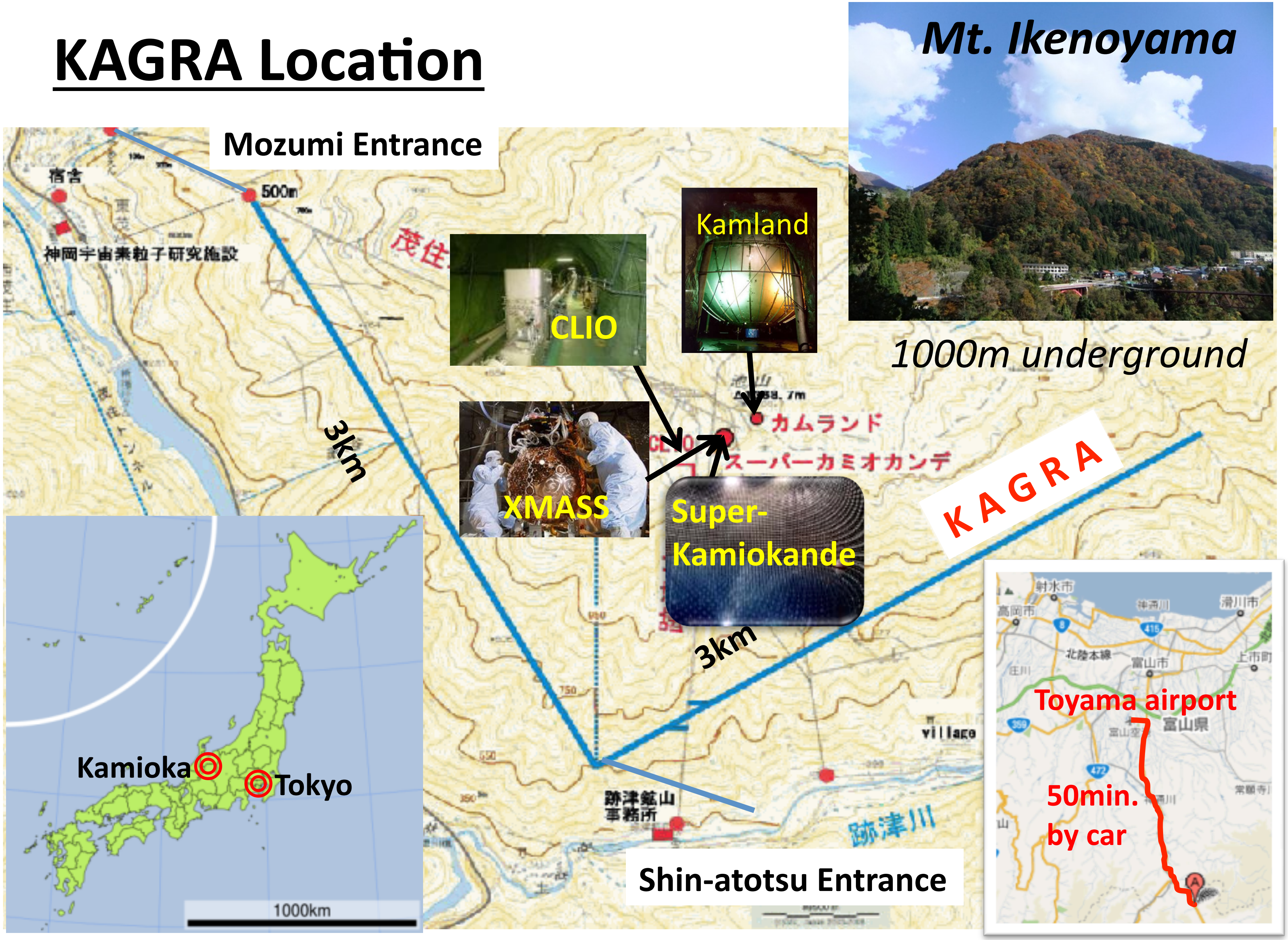
80 international institutions

the University of Tokyo, ICRR
High Energy Accelerator Research Organization (KEK)
National Astronomical Observatory of Japan (NAOJ)
the University of Tokyo, Science
the University of Tokyo, Frontier Science
the University of Tokyo, Engineering
Osaka City University
Kyoto University
University of Electro-Communications
the University of Tokyo, ERI
Hosei University, Science & Engineering
Hosei University, Engineering
National Institute of Advanced Industrial Science and Technology
National Institute of Information and Communications Technology
Osaka University
Kyoto University
Kyushu University
Ochanomizuu University
National Institute for Fusion Science
Nihon University, ARISH
Niigata University, Science
Niigata University, Engineering
Nagaoka University of Technology
Nihon University, CIT
Hirosaki University
Tohoku University

Rikkyo University
Hiroshima University
University of the Ryukyus
Waseda University, ASE
Waseda University, Education
Teikyo University
University of Toyama, Science
University of Toyama, Engineering
University of Toyama, ITC
Yokohama City University
Fukuoka University
Aichi University of Technology
Japan Student Service Organization
Institute for Molecular Science
Kavli Institute for the Physics and Mathematics of the Universe
National Defense Academy of Japan
Max-Planck-Institut
California Inst. Technology
University of Western Australia
Louisiana State University
Beijing Normal University
Inter University Center for Astronomy & Astrophysics
Moscow University
LATMOS, CNRS
University of Science and Technology of China
Tsinghua University
Industrial Technology Research Institute

University of Maryland
Columbia University
University of the West of Scotland
University of Sannio
Rome University
Shanghai Normal University
National Tsing Hua University
Korea University
Inje University
Seoul National University
Myongii National University
Korea Atomic Energy Research Institute
Hanyang University
Pusan National University
Korea Institute of Science and Technology Information
National Institute for Mathematical Sciences
Kyungpook National University
Kunsan National University
Korea Institute for Advanced Study
Sogang University
Chinese Academy of Sciences
The Pennsylvania State University
Montana State University
Indian Institute of Science Education and Research Thiruvananthapuram
National Institute for Subatomic Physics
University of Wisconsin-Milwaukee
Warsaw U of Technology

KAGRA Location



Optical Configuration of KAGRA

Dual Recycled Fabry-Perot Michelson Interferometer

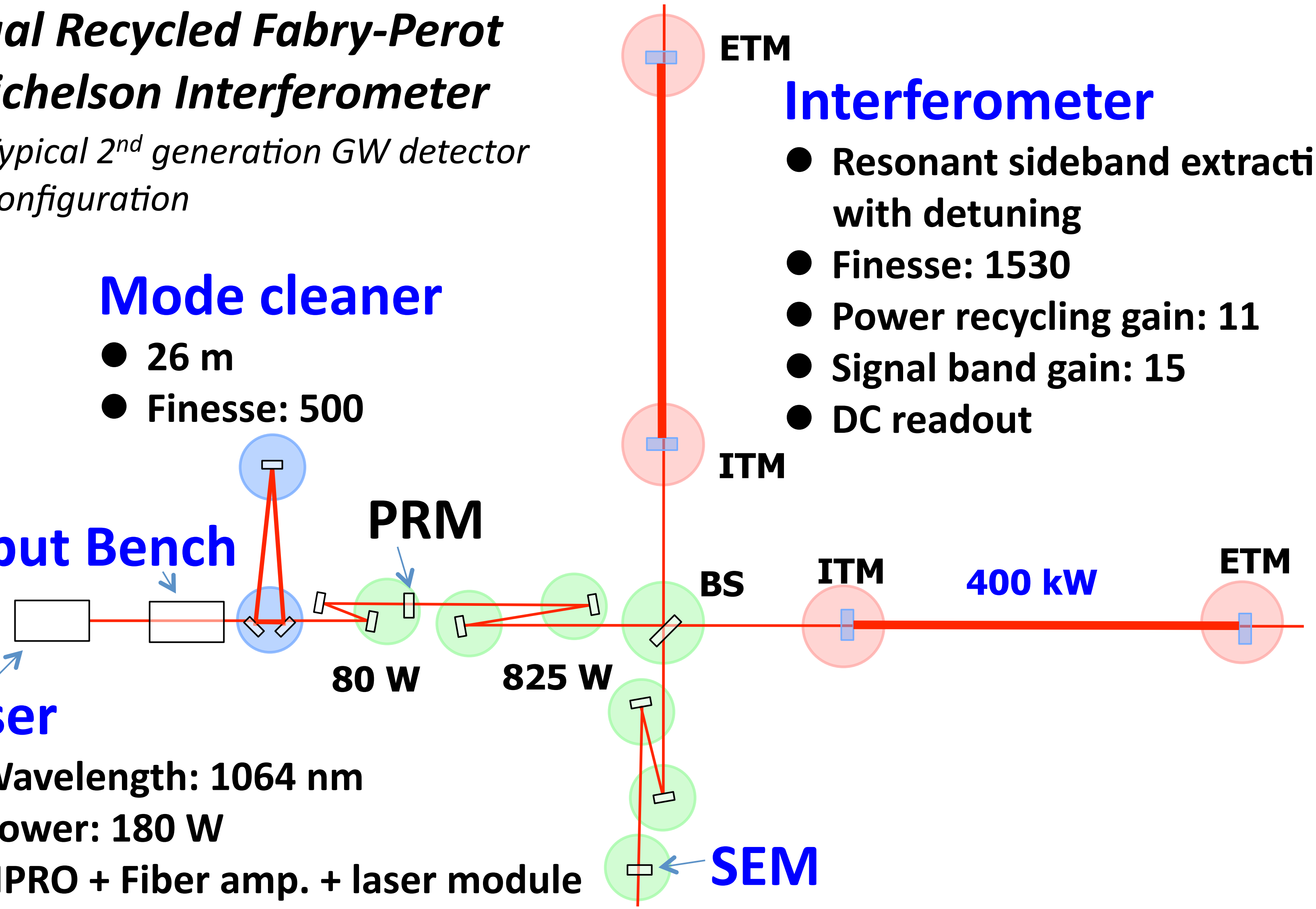
Typical 2nd generation GW detector configuration

Interferometer

- Resonant sideband extraction with detuning
- Finesse: 1530
- Power recycling gain: 11
- Signal band gain: 15
- DC readout

Mode cleaner

- 26 m
- Finesse: 500



Laser

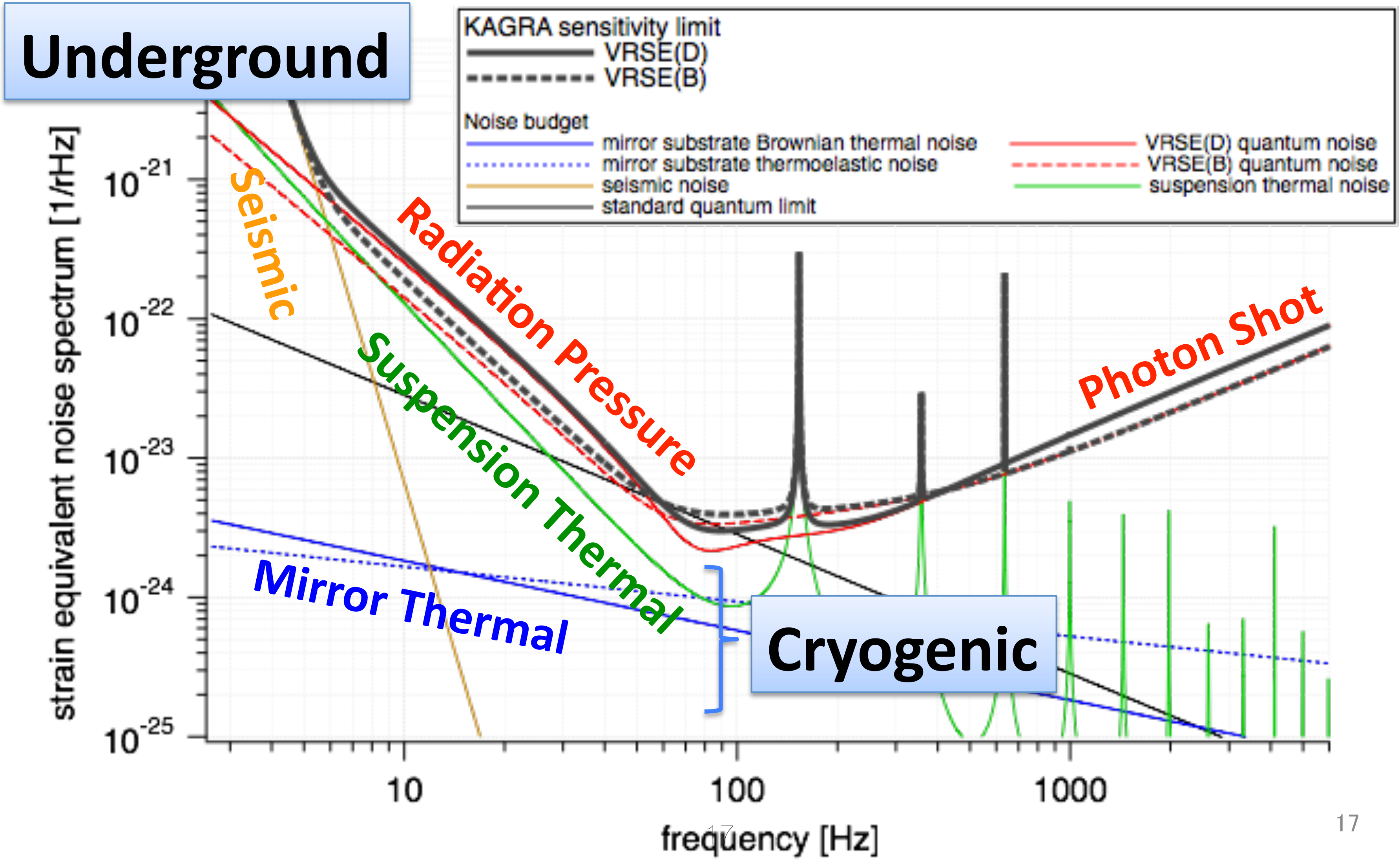
- Wavelength: 1064 nm
- Power: 180 W
- NPRO + Fiber amp. + laser module

Output mode cleaner

Goal Sensitivity of KAGRA

h ~ factor x 10^{-24} [/√Hz]

We expect GW signal of NS-NS binary Coalescence from 280Mpc distance.
Event rate is proportional to volume (cubic sensitivity) → about 10 event/yr.



Advanced Optical Technologies

Ultra-high Precision Core-optics

Specifications of KAGRA core-optics

Arm Cavity Finesse	1530
Optical Loss for End Mirror	< 50ppm
Reflectivity of Input Mirror	99.6%
Reflectivity of Power-Recycling Mirror	90%

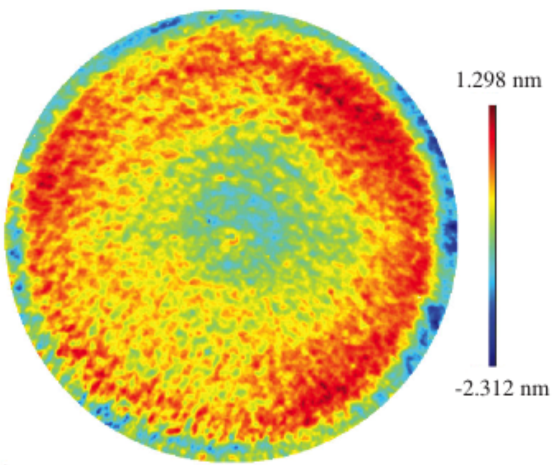
optical power loss on four main mirrors is critical to realize

- high power-recycling gain
- small scattered light noise

Ultra-high quality mirror polishing and reflective/antireflective coating are required.

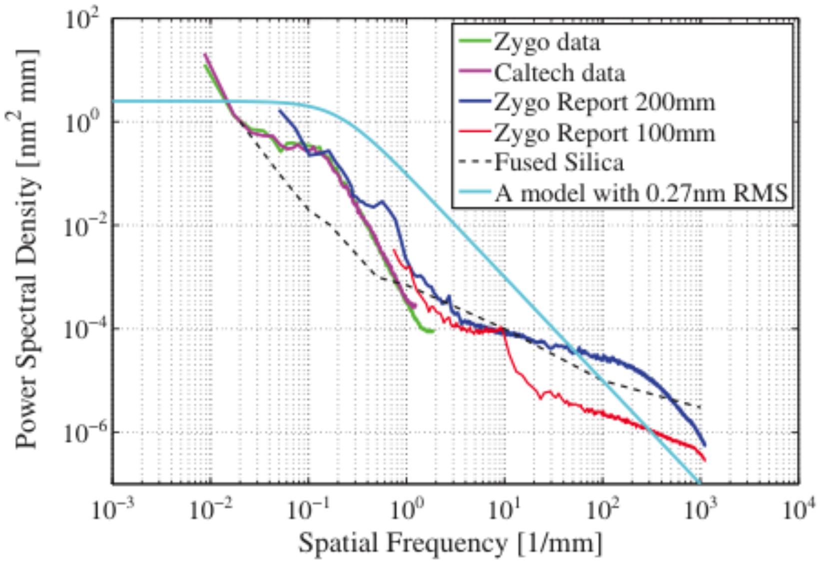
Measurement result of surface polish of ϕ200mm test sapphire substrate

Measured by ZYGO EPO



RMS waviness in ϕ180mm is 0.48nm

Power spectrum density of surface roughness



E. Hirose et al., Phys. Rev. D 89, 062003 (2014)

Cryogenic Sapphire Mirror and Suspension

(1) Thermal noise Reduction

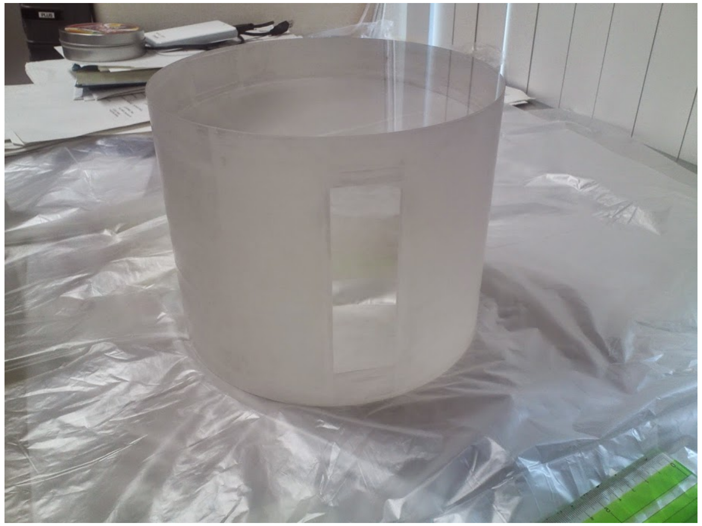
$$\sqrt{x(\omega)^2} \propto \sqrt{T\,\phi}$$

Cryogenic mirror is most straightforward method to reduce thermal noises.

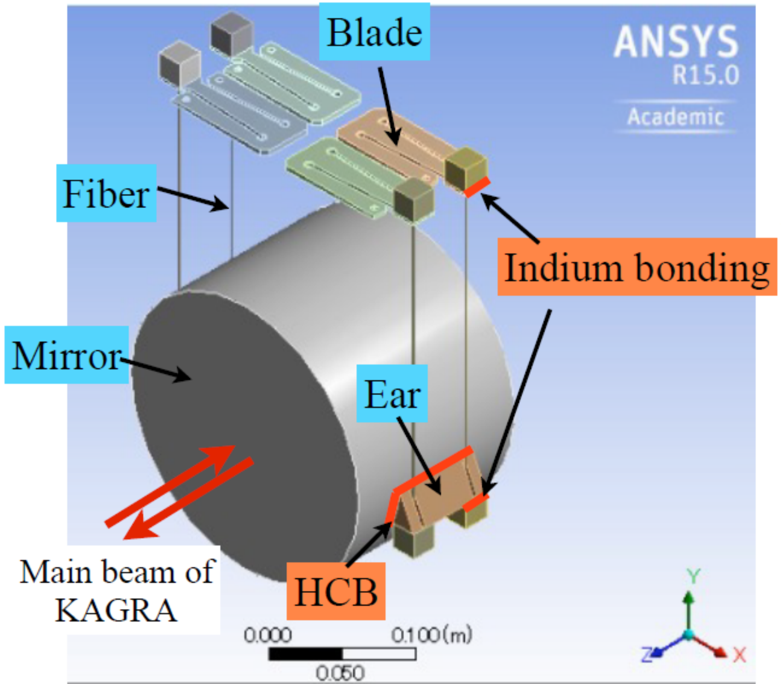
Moreover **Sapphire @ 20K**

$$\phi = 5 \times 10^{-9} \quad \text{(bulk)}$$
$$\phi = 1 \times 10^{-7} \quad \text{(fiber)}$$

Typical Φ of sapphire at room temperature is ~10^{-6}



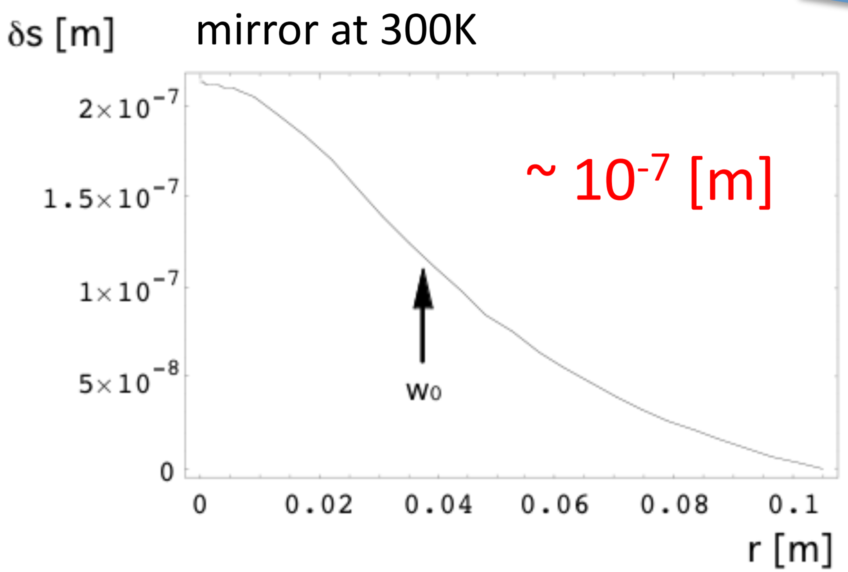
Sapphire substrate



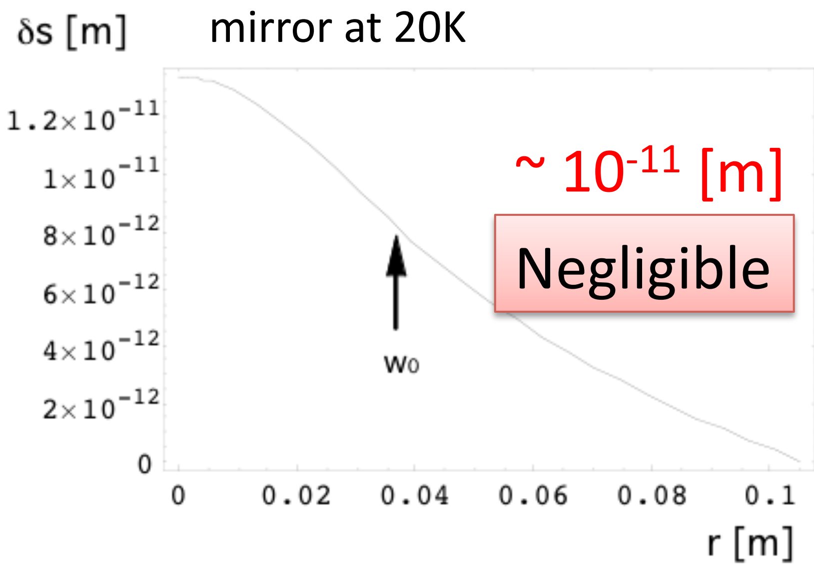
(2) Thermal Lensing

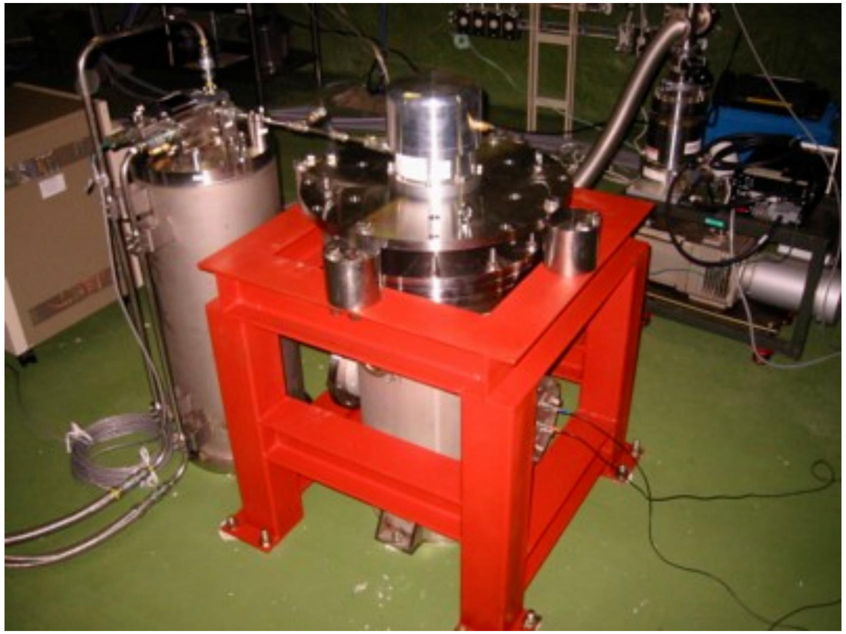
	Fused Silica (300K)	Fused Silica (20K)	Sapphire (300K)	Sapphire (20K)
α [ppm/cm]	2 - 20	2 - 20?	40 -140	20 - 90?
κ [W/m•K]	1.4	0.15	46	4.3×10^{3}
dn/dT [K^{-1}]	1.4×10^{-5}	1.4×10^{-5}	1.3×10^{-5}	$< \lvert 9 \times 10^{-8} \rvert$
α (dn/dT)/κ x 10^{-11}	2 - 20	20 - 200	1.1	$< \lvert 0.4 - 2 \times 10^{-4} \rvert$

Wave-front distortion at input mirror at 300K



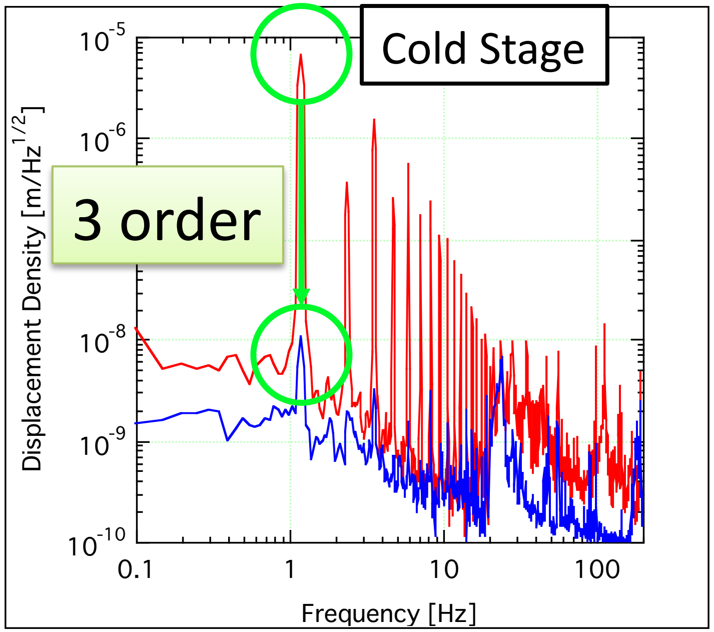
Wave-front distortion at input mirror at 20K

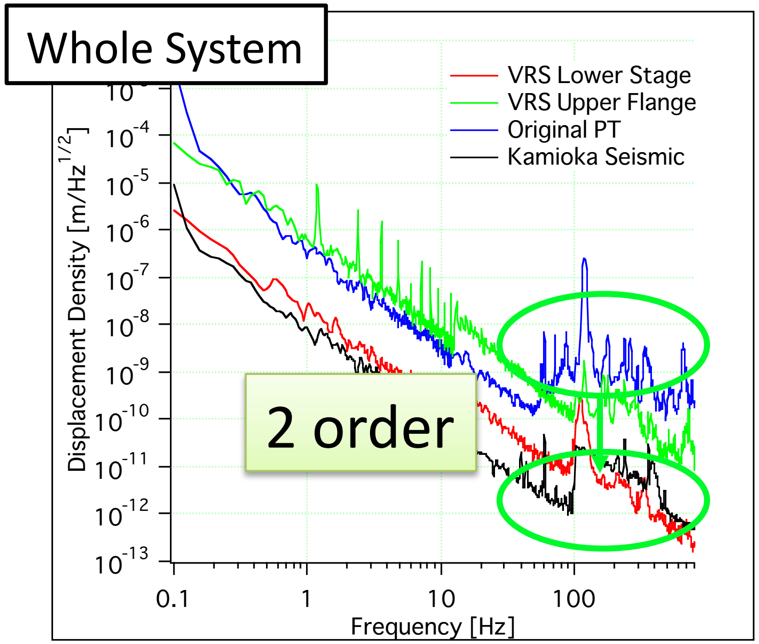




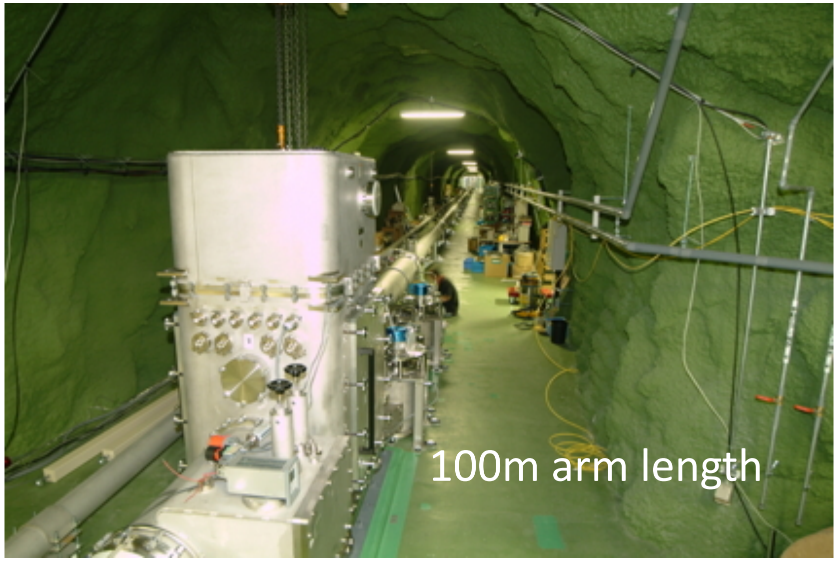
(3) Vibration-Free cryocooler system to realize cryogenic sapphire mirror

- **nm vibration** at cold stage
- comparable vibration level of whole system with Kamioka seismic vibration



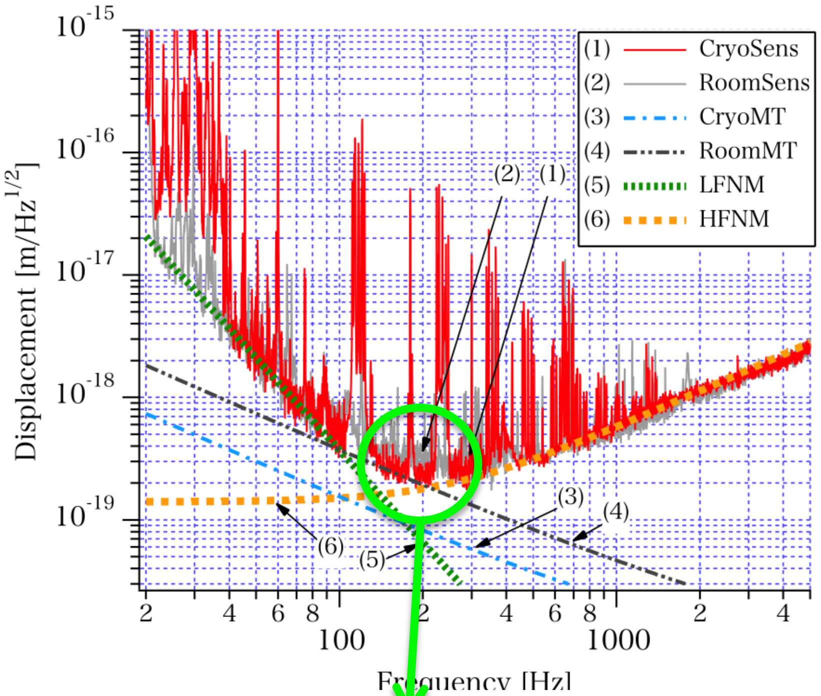


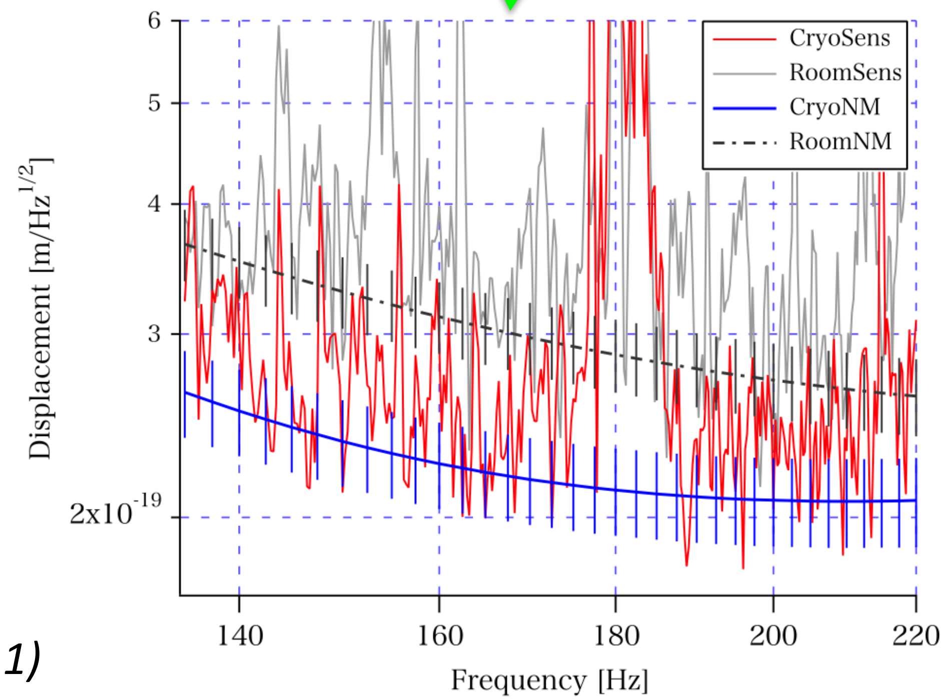
Demonstration Experiment in Cryogenic Interferometer Prototype (CLIO)



Reduction of sapphire mirror thermal noise at room temperature by cooling to 17K was demonstrated.

T. Uchiyama et al., PRL 108, 141101 (2011)

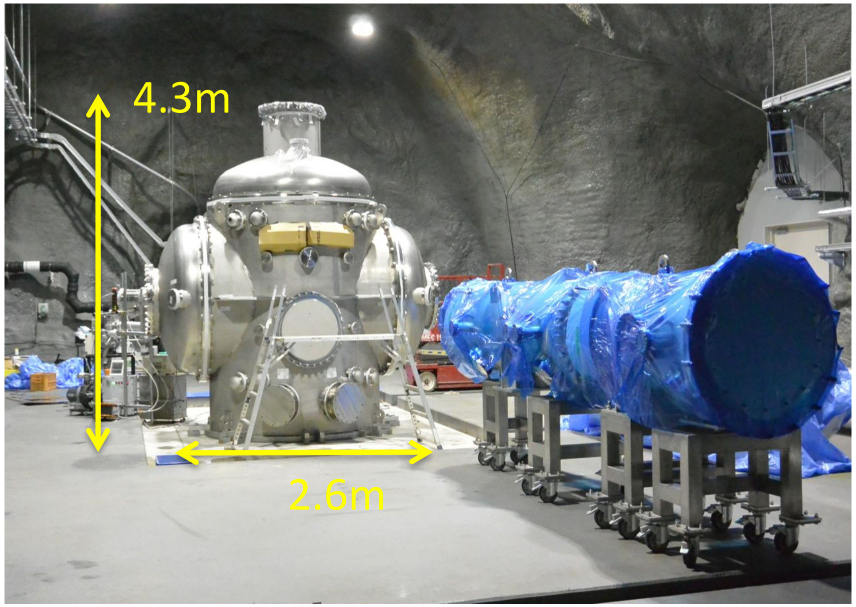




Present Status of KAGRA

Tunnel excavation was done at Mar. 2014

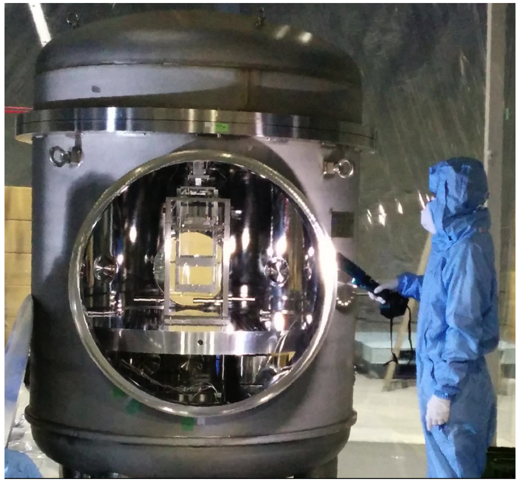
Cryostat Installation



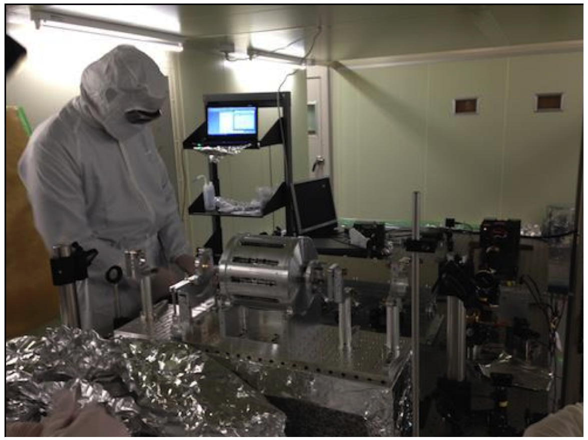
Vacuum Tubes Installation

Clean Booth Construction

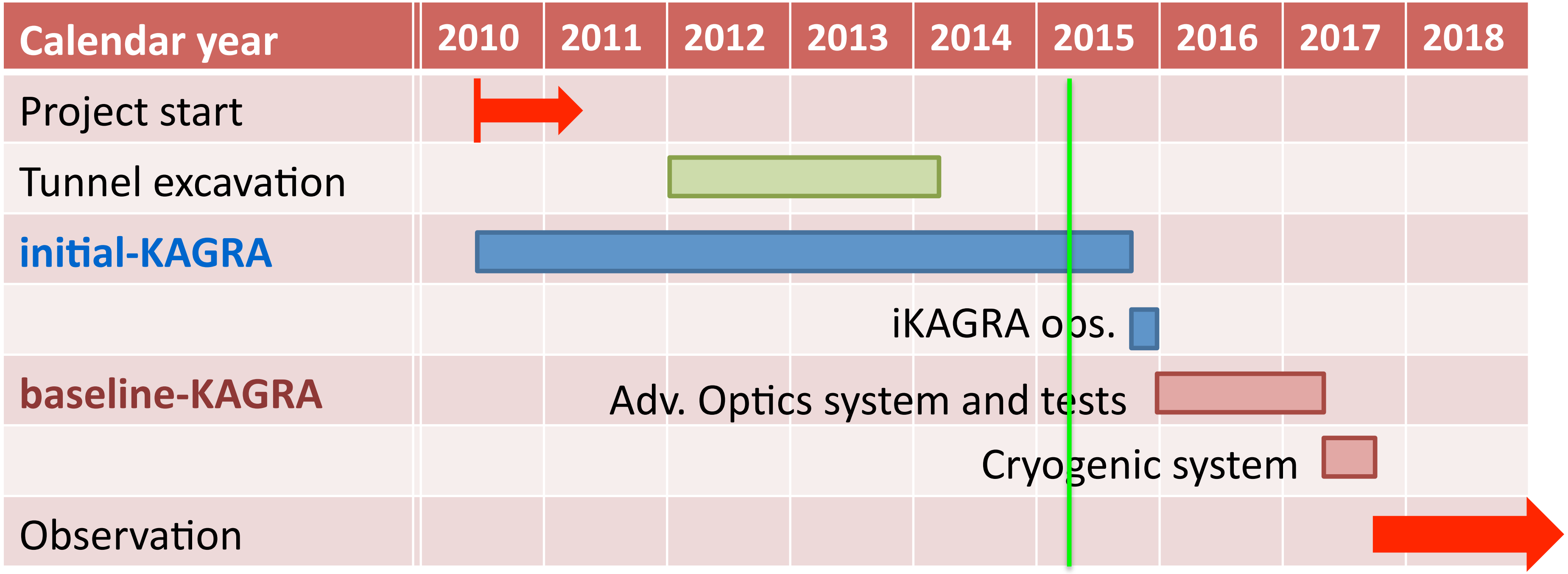
Mode-cleaner Mirror Installation



Input-optics Installation

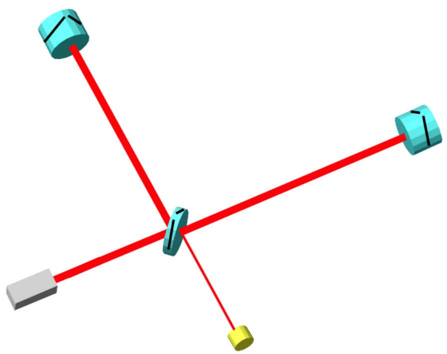


Schedule of KAGRA



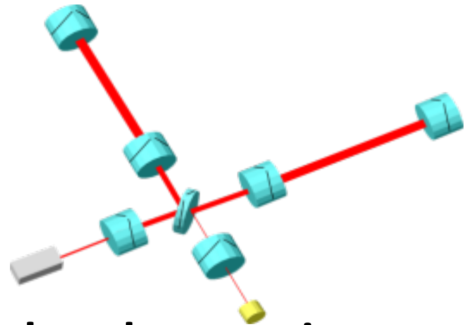
iKAGRA

basic operation test



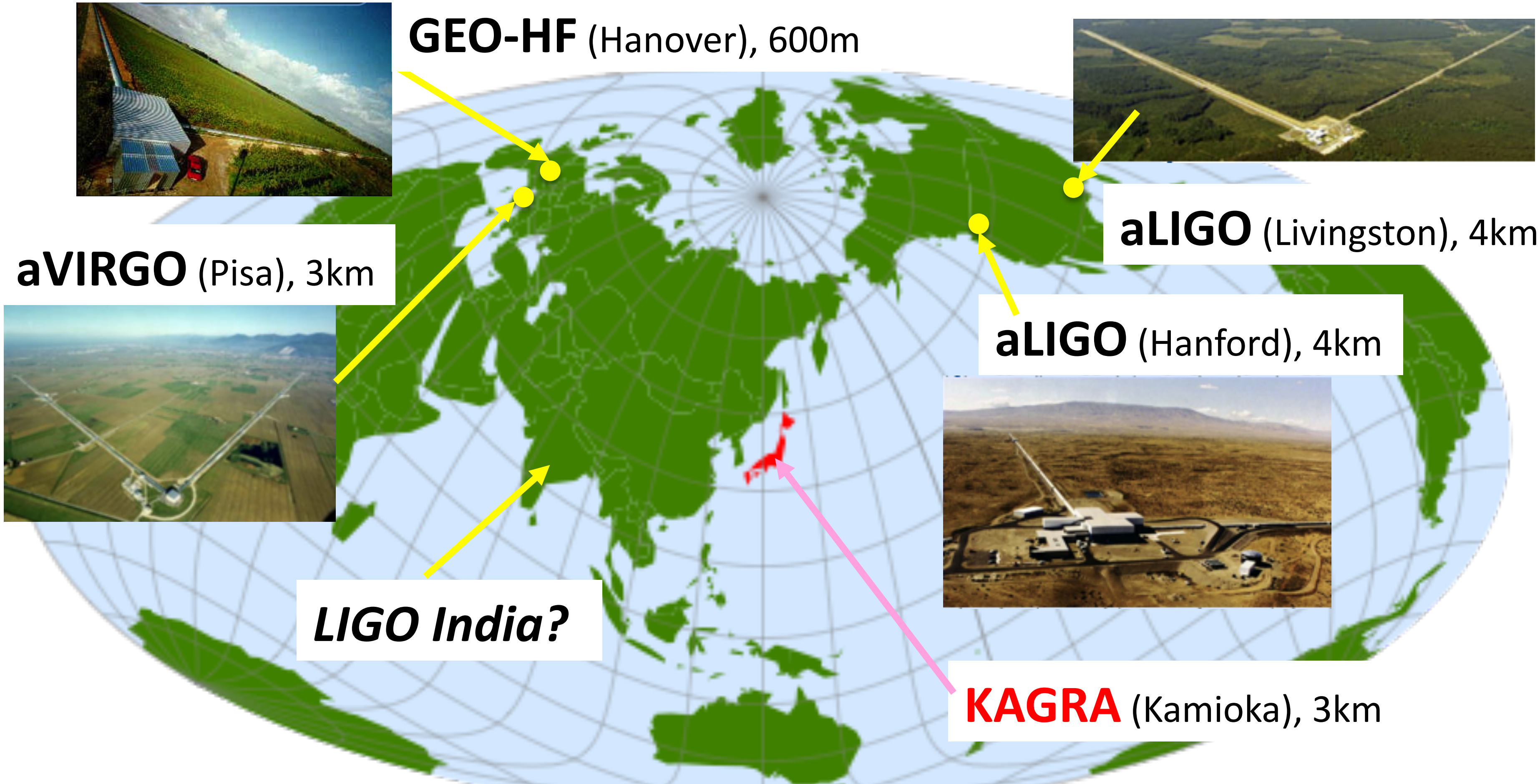
- Michelson
- Room temperature
- Simple seismic isolation system
- Low power Laser

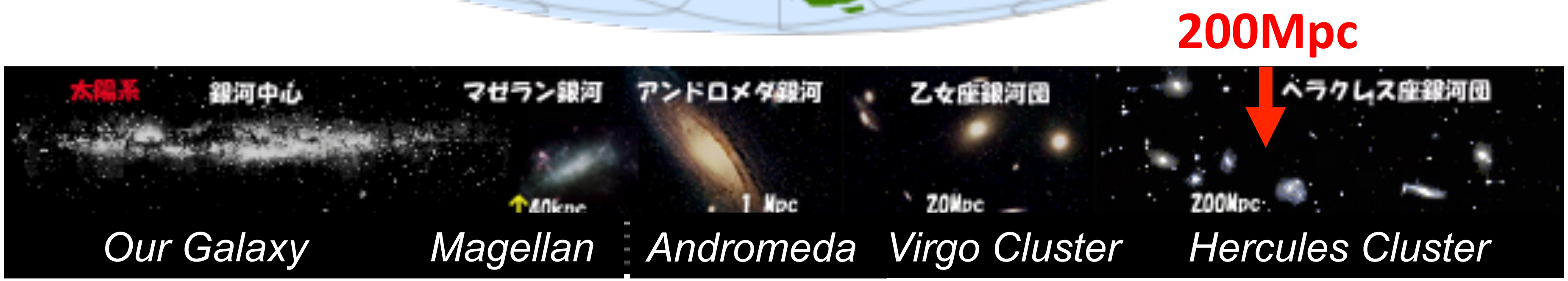
bKAGRA



- Resonant sideband extraction
- Cryogenic Sapphire Mirror
- Advanced seismic isolation system
- High power laser

2nd Generation GW Observation Network





We will start new gravitational wave astronomy soon.