Detection of gravitational waves from underground in Kamioka-mine

GCOE seminar @Nagoya University
2011/9/27

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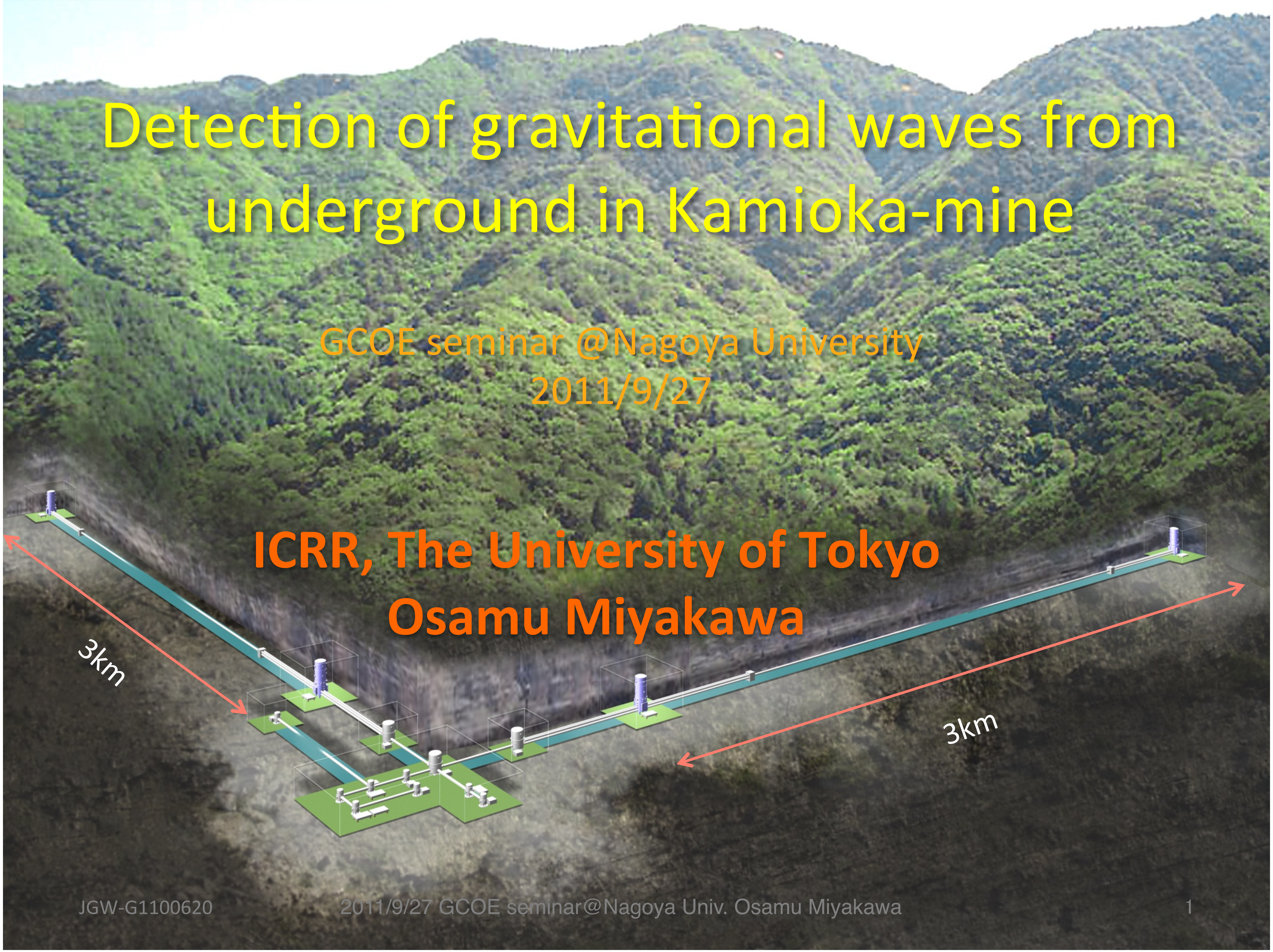


Today's talk

1. What is Gravitational Wave?

   ⟹ Basics of Ground-based Detectors

2. CLIO (Cryogenic Laser Interferometric observatory

   `100m, underground, cryogenic`

3. LCGT (Large-scale Cryogenic Gravitatoonal wave Telescope

   `3km, construction started in 2010`

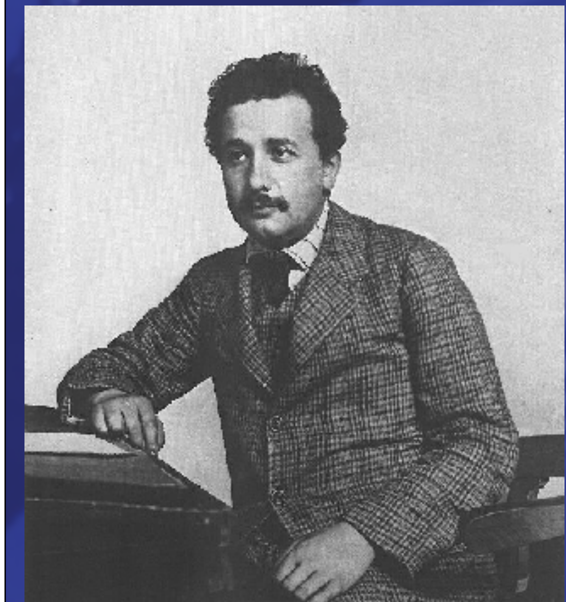
4. Global Network of GW Detectors

   ⟹ in World-wide

Sources of Gravitational waves

Einstein's Theory: ***information carried by gravitational radiation at the speed of light***

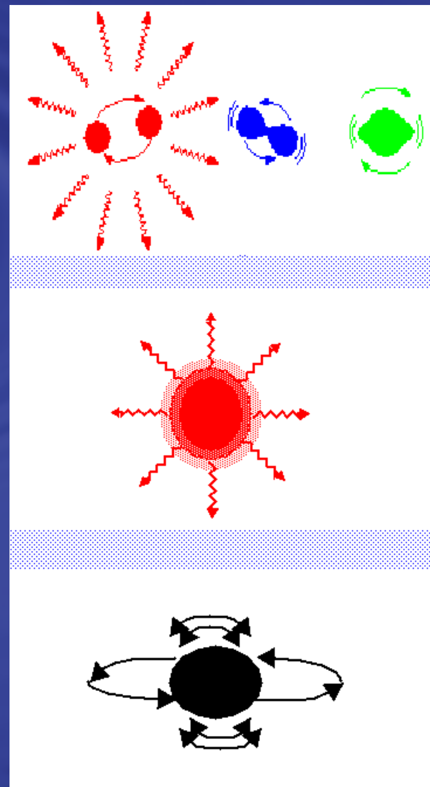
→ Gravitational waves!



Coalescing compact binaries
(neutron stars, black holes)

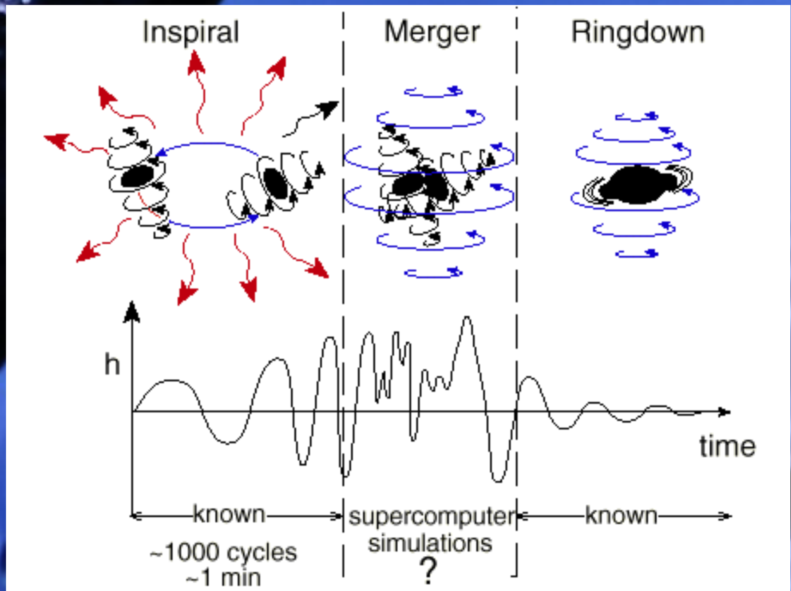
Non-axi-symmetric
supernova collapse

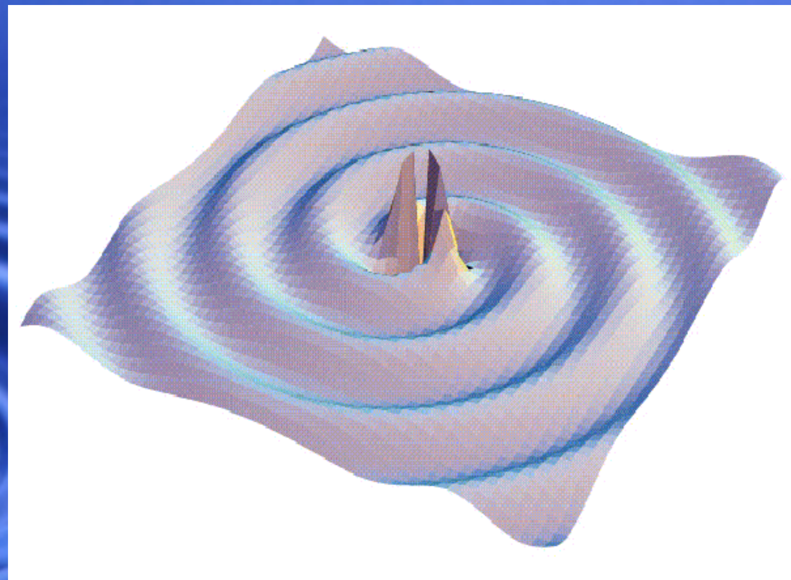
Non-axi-symmetric pulsar
(rotating, beaming neutron star)



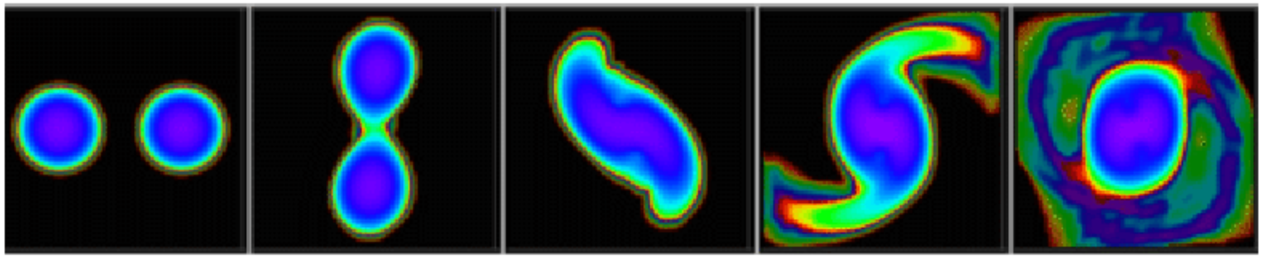
Compact binary mergers

Amplitude of GW waves





- Neutron star – neutron star (Centrella et al.)



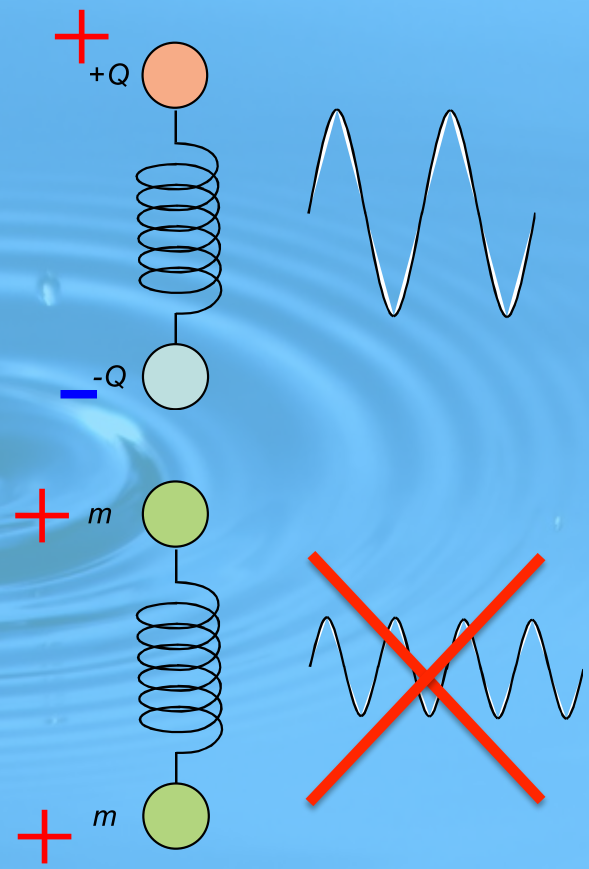
Electro Magnetic waves and Gravitational waves

Electromagnetism:

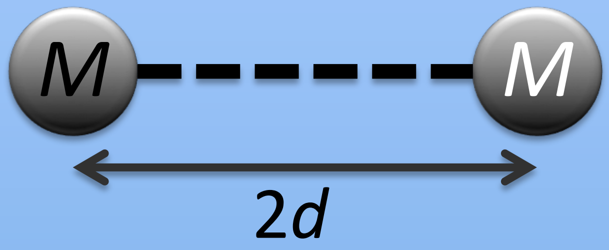
Acceleration of electric charge
↓
Electromagnetic waves

General relativity:

Acceleration of mass
↓
Gravitational waves



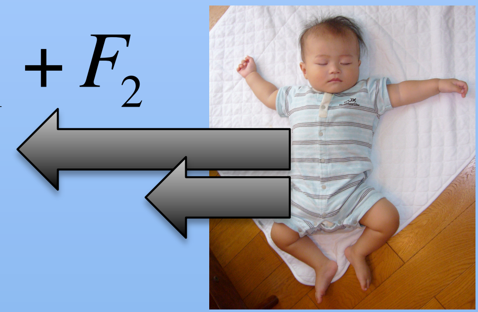
2 masses



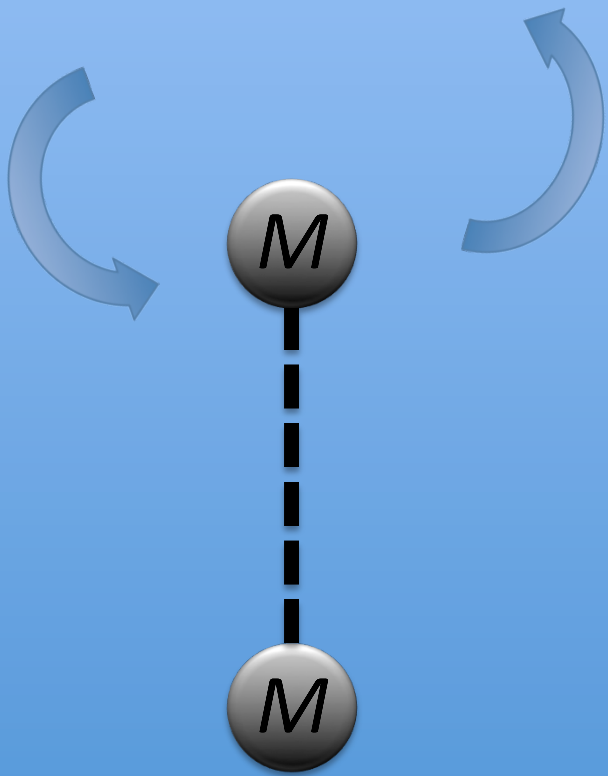
← Distance: R →

Observer

$$F = F_1 + F_2$$



$$\cdots \frac{M}{\cdots d)^2} + G\frac{M}{(R-d)^2}$$



+

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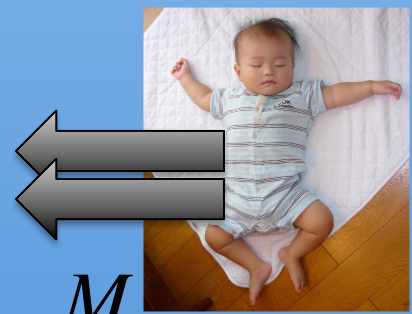
+

Quadrupole

Observer



$$F \approx G\frac{M}{R^2} + G\frac{M}{R^2}$$

What is Gravitational Wave ?

Einstein Eq.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa\, T_{\mu\nu}$$

metric tensor

“flat” space-time (Minkowski)

$$g_{\mu\nu} = \eta_{\mu\nu} = \begin{array}{cc} & \begin{array}{cccc} ct & x & y & z \end{array} \\ \begin{array}{c} ct \\ x \\ y \\ z \end{array} & \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array}$$

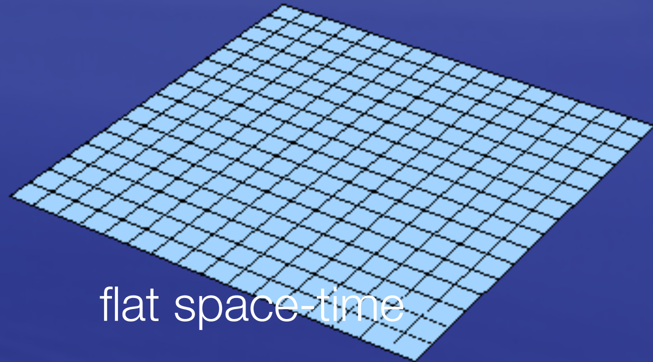
“curved (distorted)” space-time

$$g_{\mu\nu} \neq \eta_{\mu\nu}$$

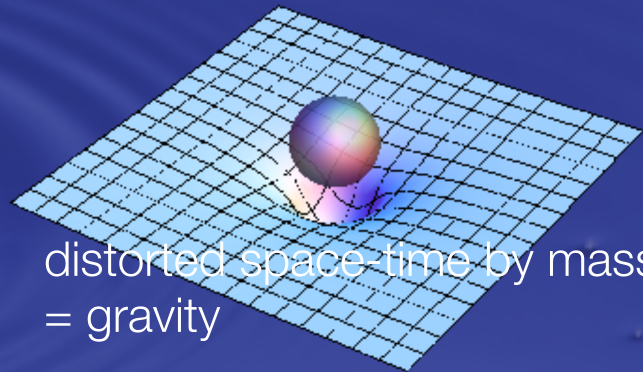
small perturbation ‘h’ --> Waves

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

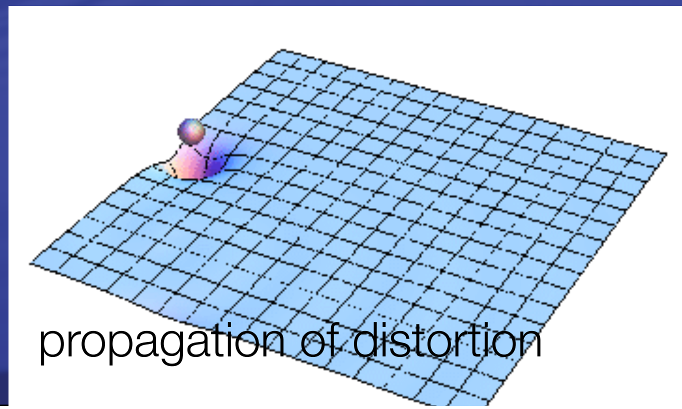
$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$



flat space-time



distorted space-time by mass
= gravity



propagation of distortion

What is Gravitational Wave ?

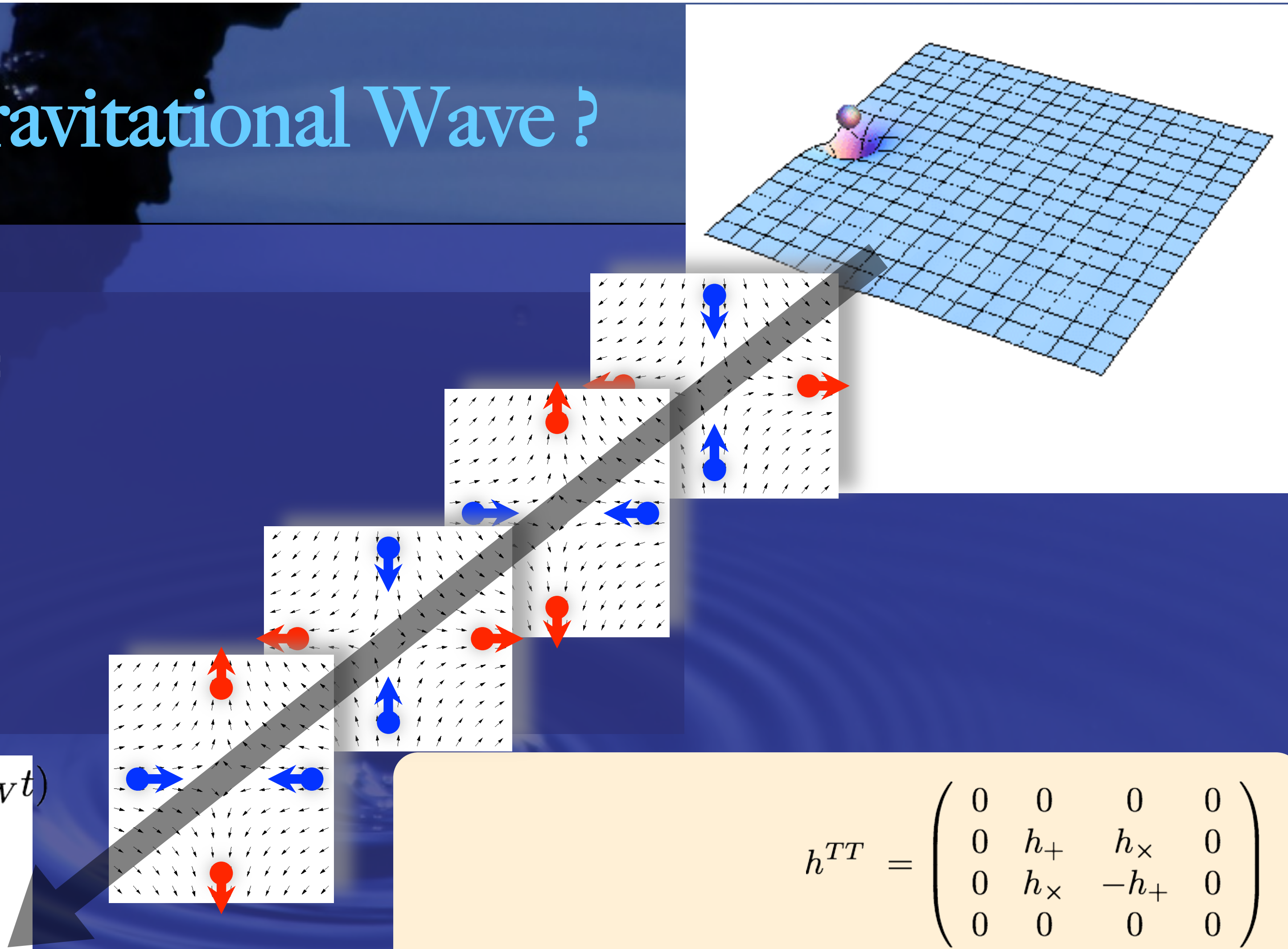
- **Characteristics:**

⇒light speed

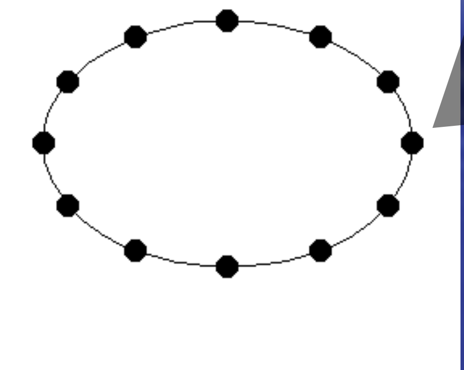
⇒transverse

⇒quadrupole

⇒(tidal force)



$h_+ \cos(\vec{k}\cdot\vec{x} - 2\pi f_{GW} t)$

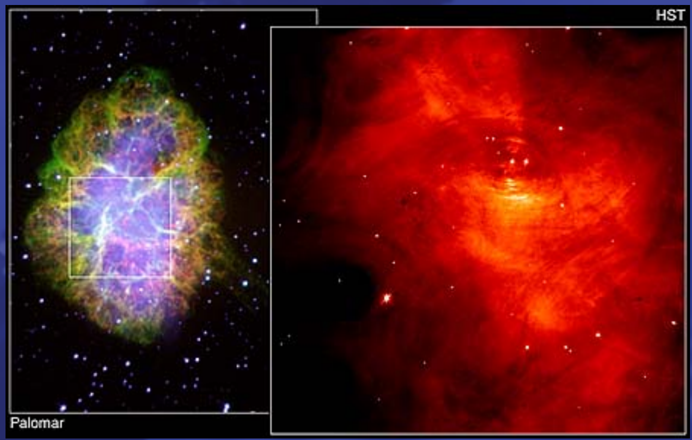


Tidal force on masses will be induced by GW incident.

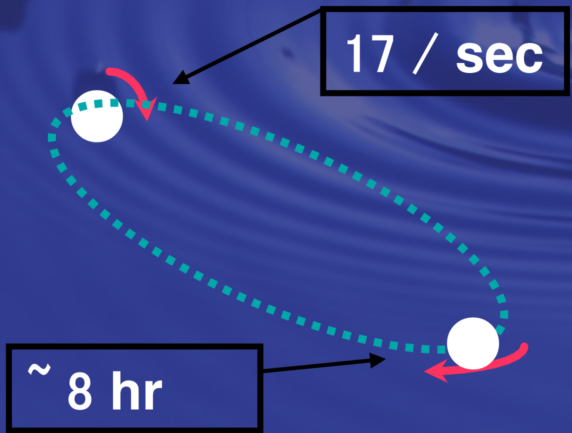
$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \hat{h}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

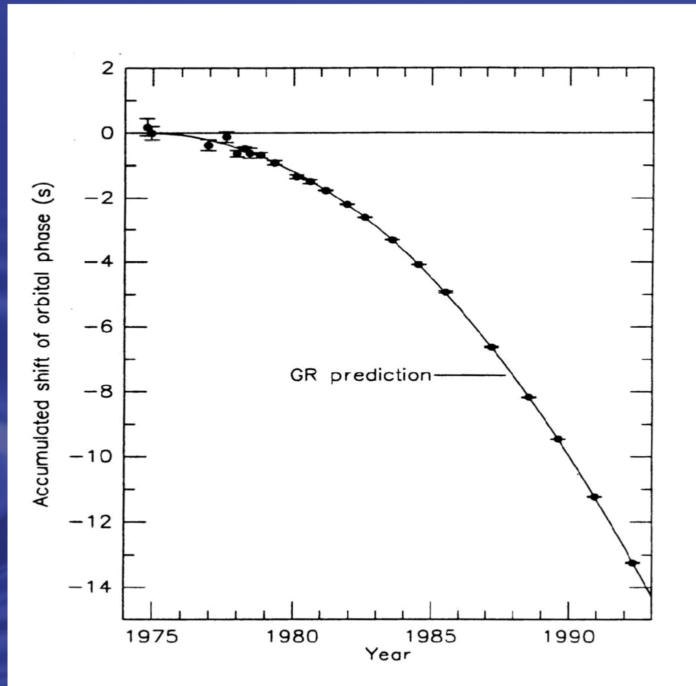
GWs really exist?



Neutron binary systems
PSR 1913 + 16 -- Timing of pulsars



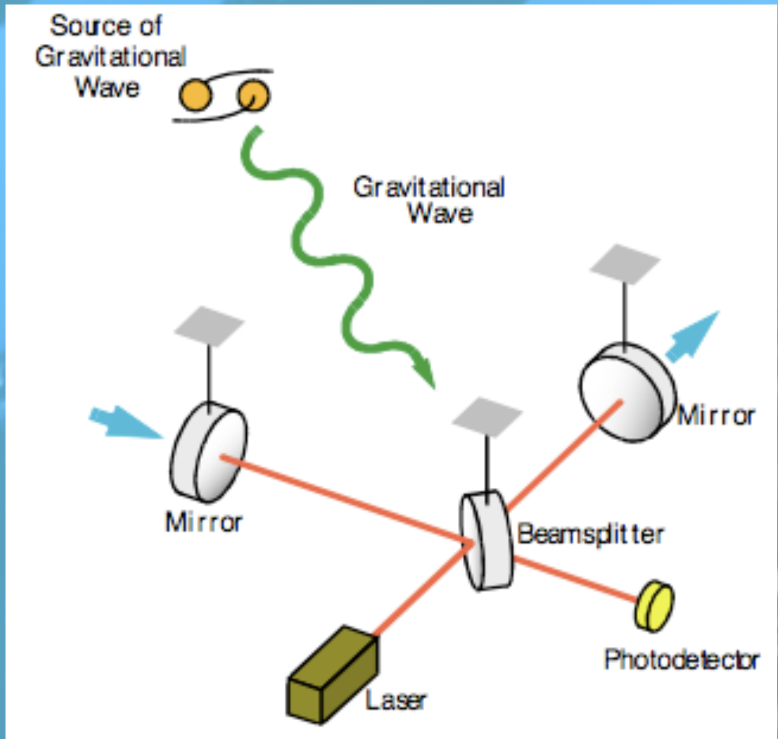
• Found in 1975, and the orbital period was observed for 25 years.

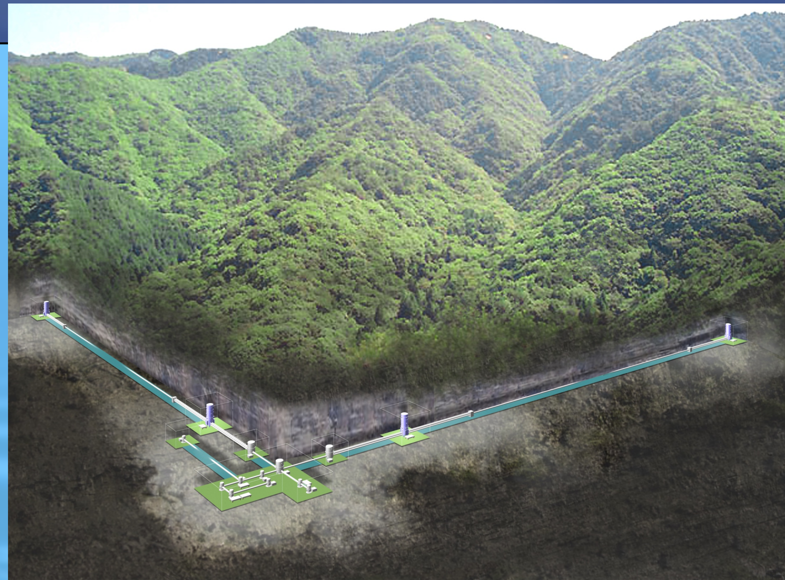


- The period changed 14seconnd between 1975 and 1994.
- It agreed with the GW emission within 1% accuracy.
- Hulse and Taylor won Novel prize in 1993

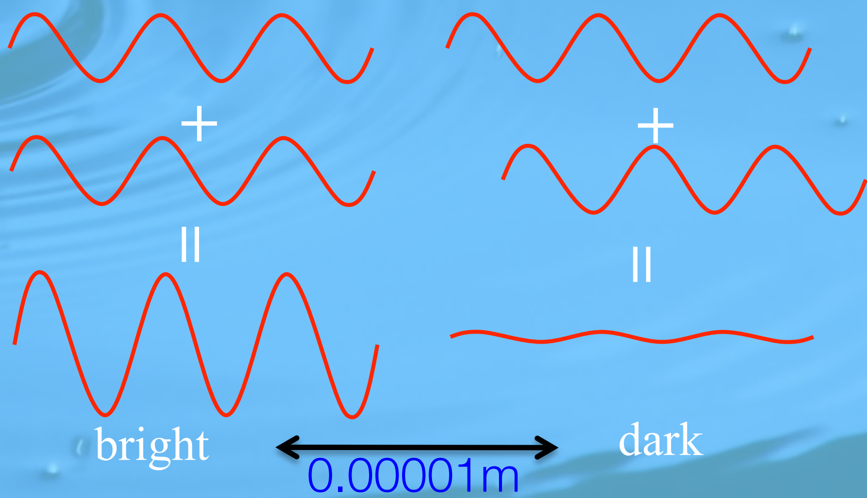
Still Not a direct measurement of GWs

Detection of gravitational wave using laser interferometer





Superimpose of light (interference)

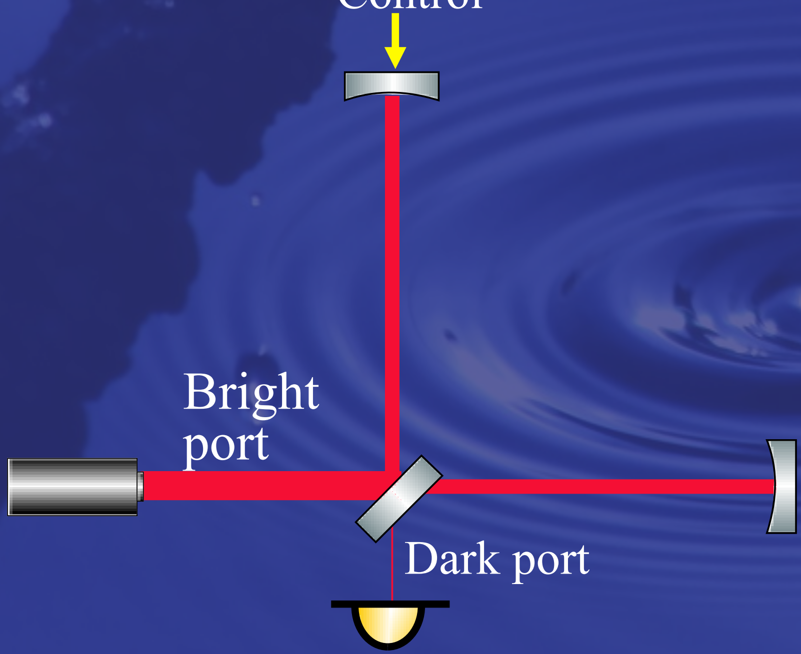


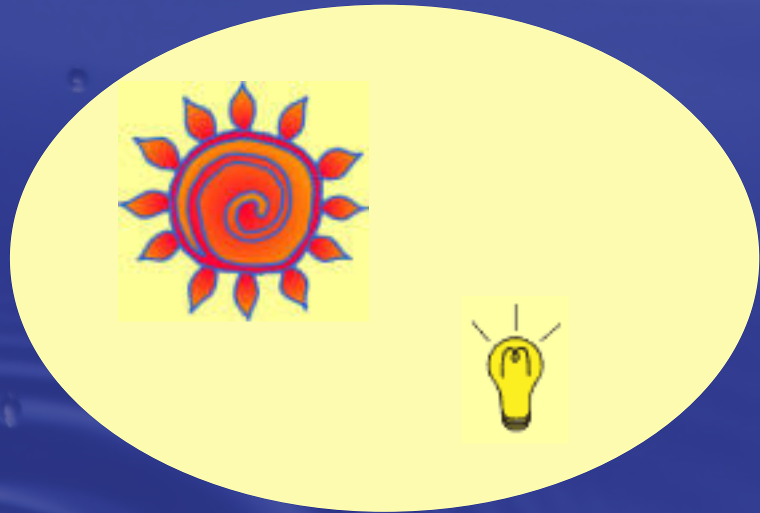
GWs move mirrors differentially.
We measure the distance between mirrors using fringe of light.

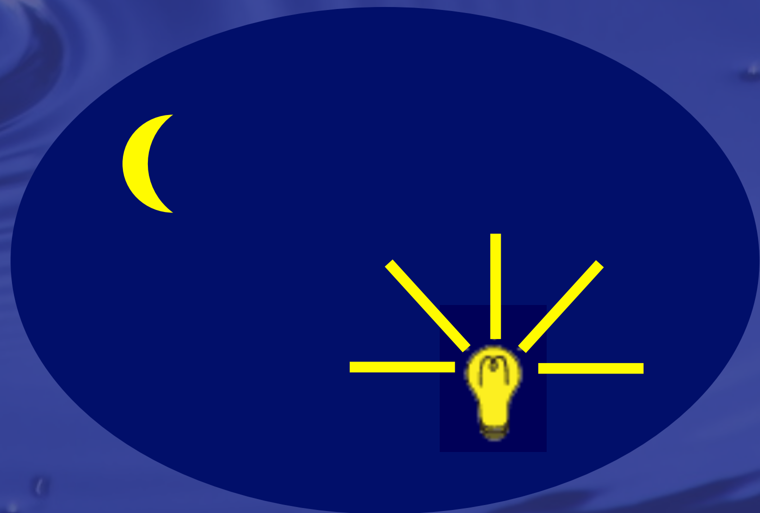
Expected length change by GW :
~1×10^{-19}m

How to get More sensitivity with control?

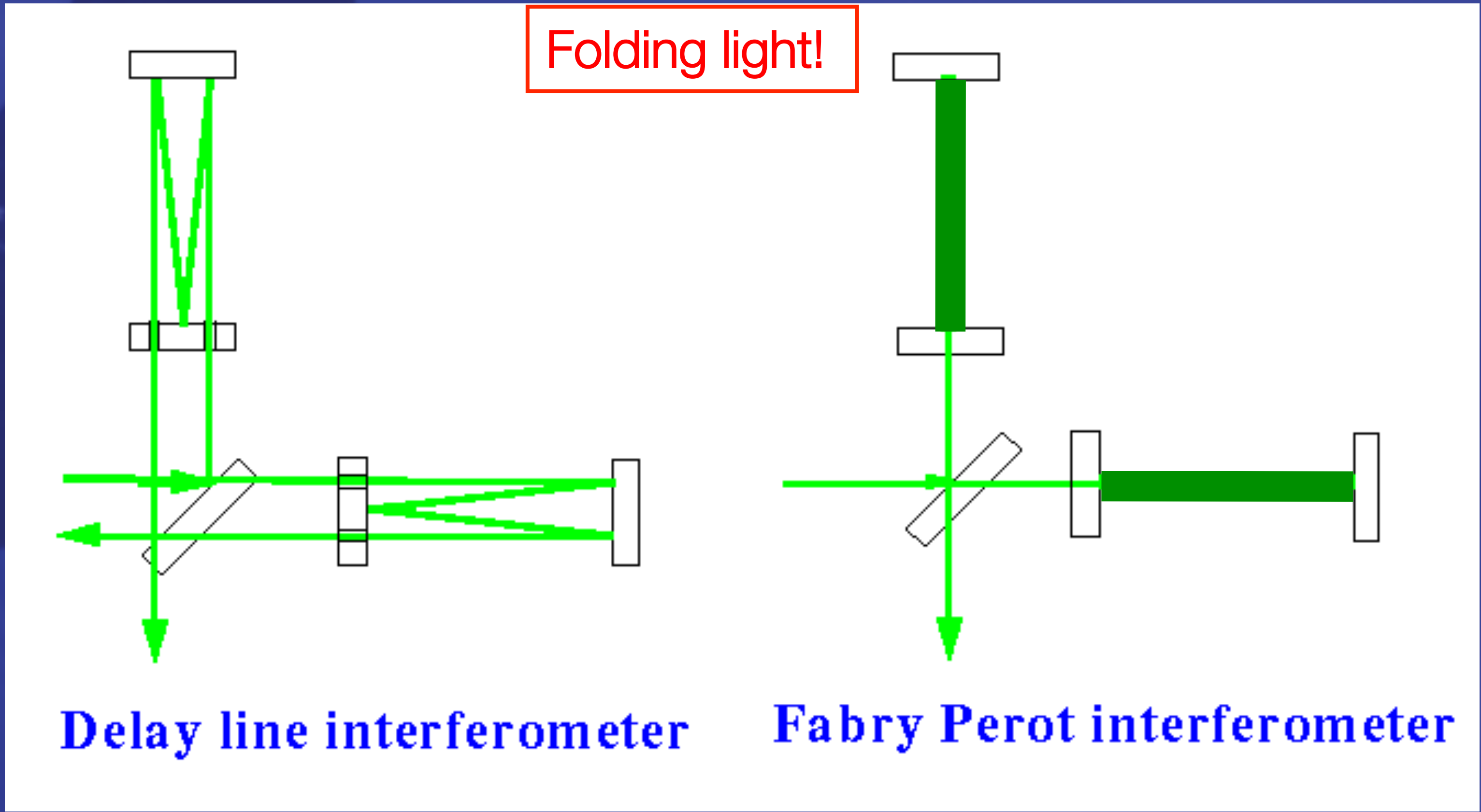
One of the mirror is **controlled to keep dark** at detection port (Dark fringe locking)







Longer arms



Simple, but large mirror required

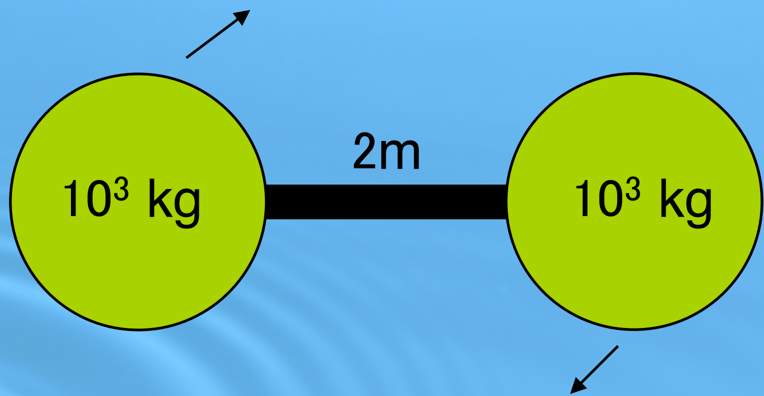
Scattering light is a serious issue.

Parallel mirrors make light round trip.

Small mirrors, but difficult to control.

Generating gravitational waves on the earth

- Let's rotate 1000kg masses separated by 2m for 100 times per second.
- Measure gravitational waves at 1m away.
- How much GWs can you detect?



$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

$M = 10^3$ kg $R = 1$ m

$F = 100$ Hz $r = 1$ m

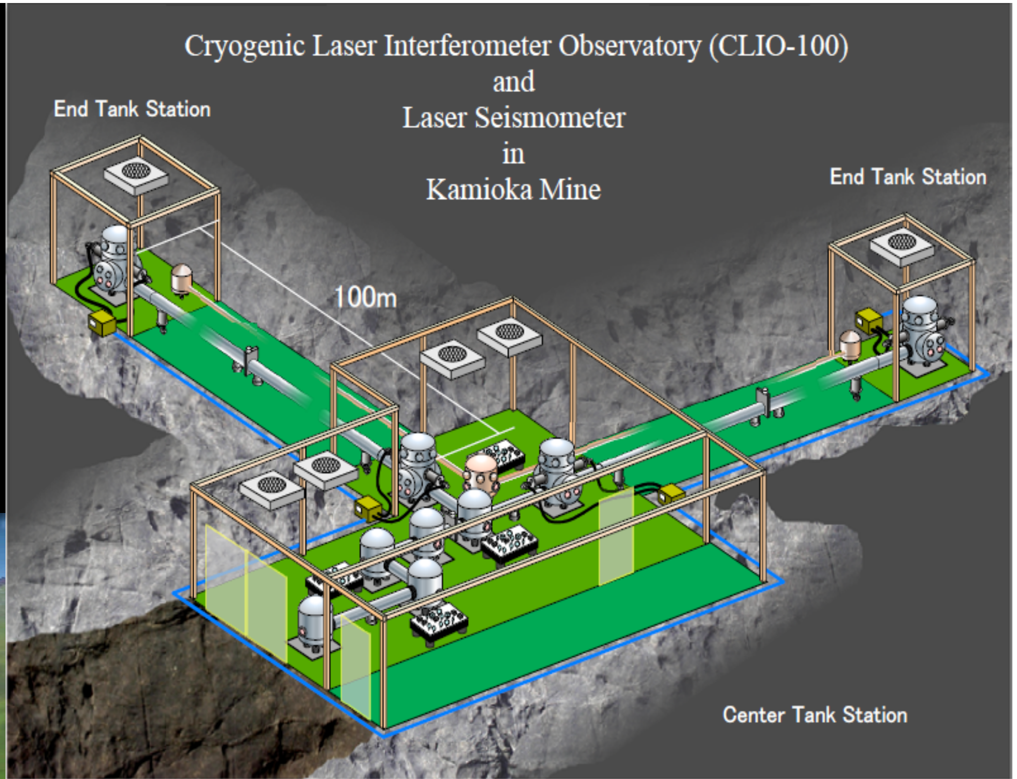
»10^{-36} !!

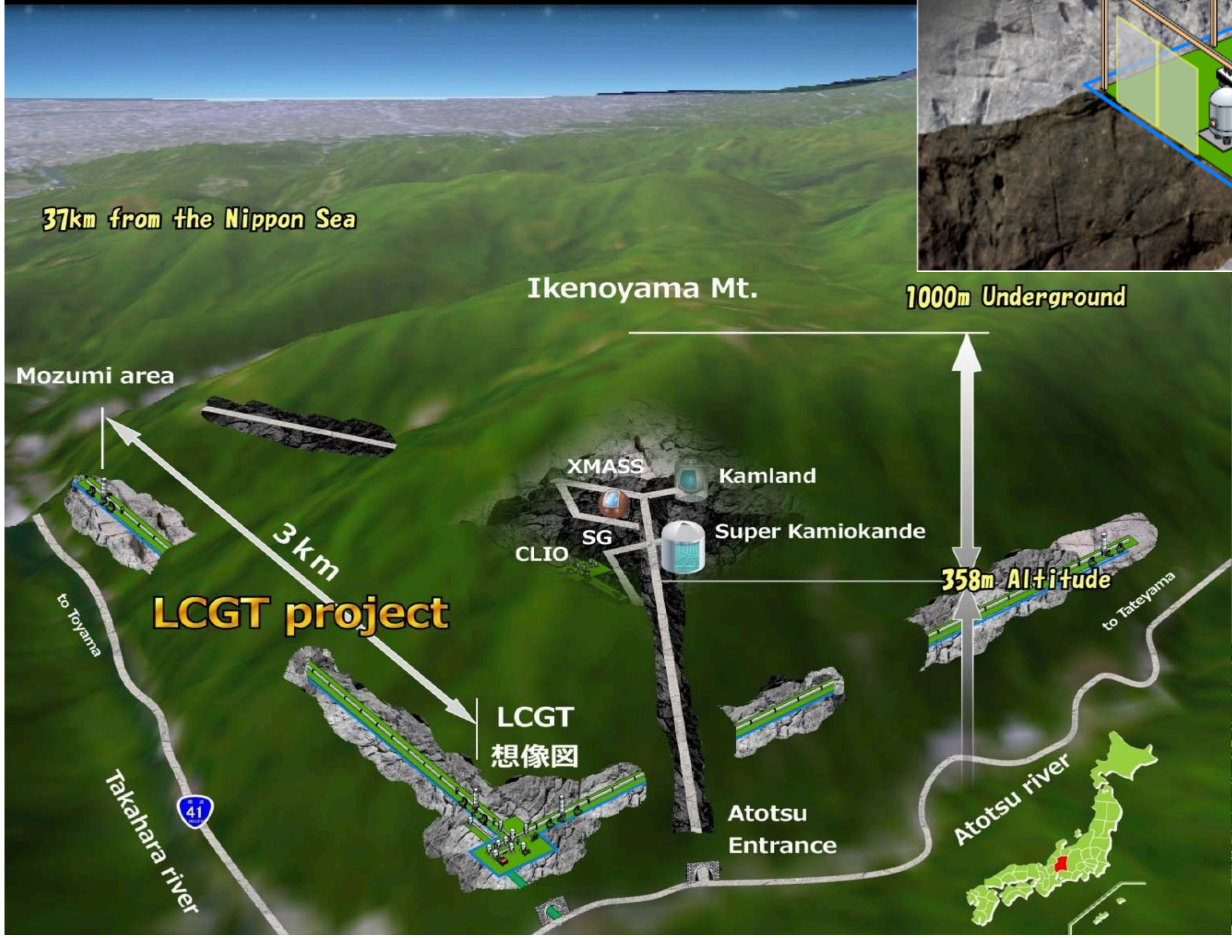
13 orders smaller !!
(detection limit is ~ 10^{-23})

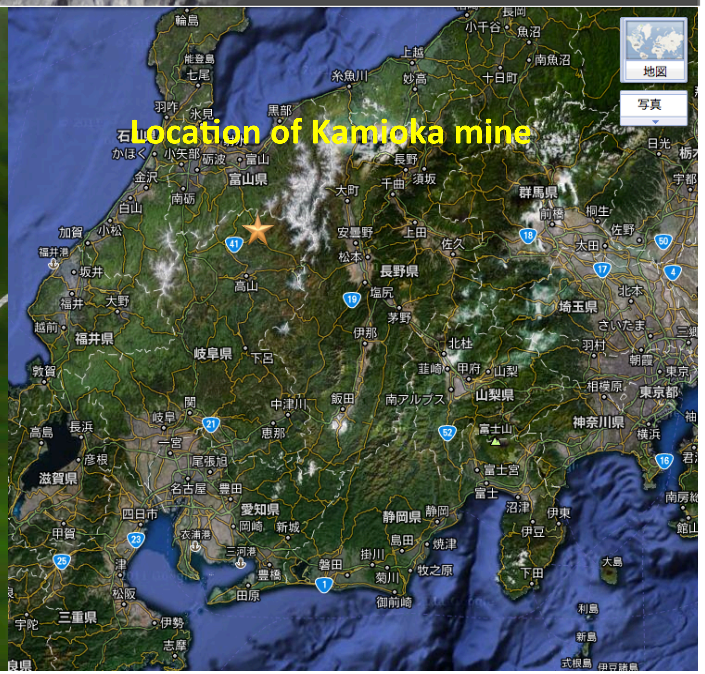
- GW on the earth is too small.
- Needs massive astronomical events even very far.

CLIO 100m prototype

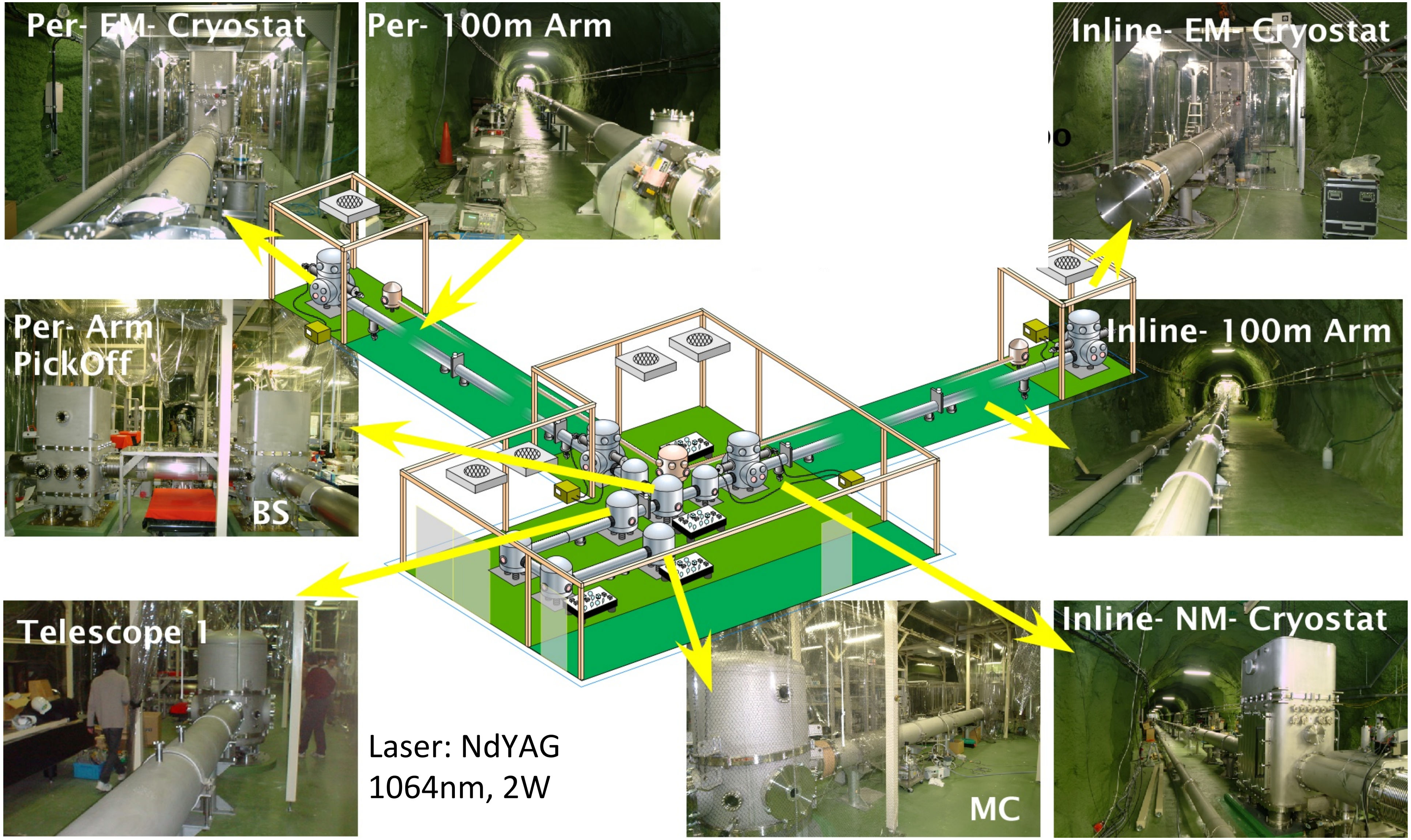
- Located in Kamioka mine underground
- Prototype of 3km LCGT
- Baseline: 100m, Locked Fabry-Perot type
- Low temperature mirror to improve thermal noise
- Low seismic environment
- Constructed in the same location as LCGT

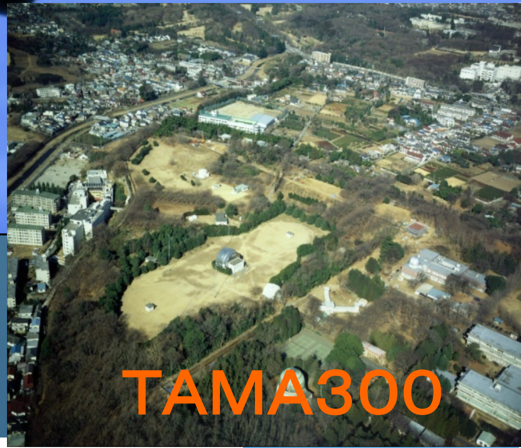


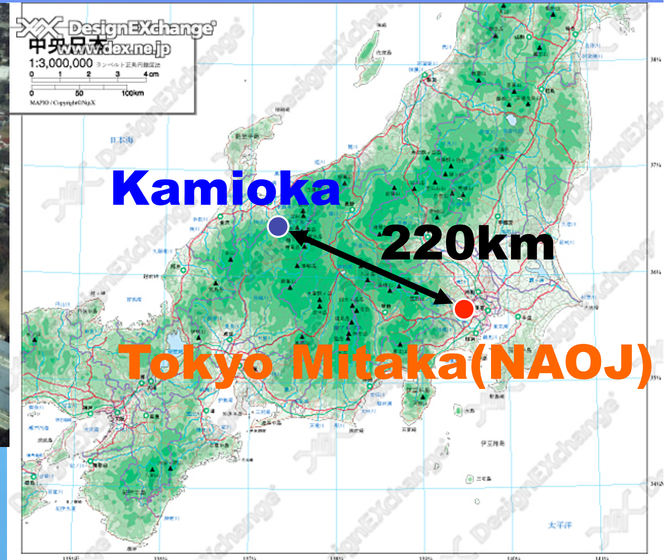


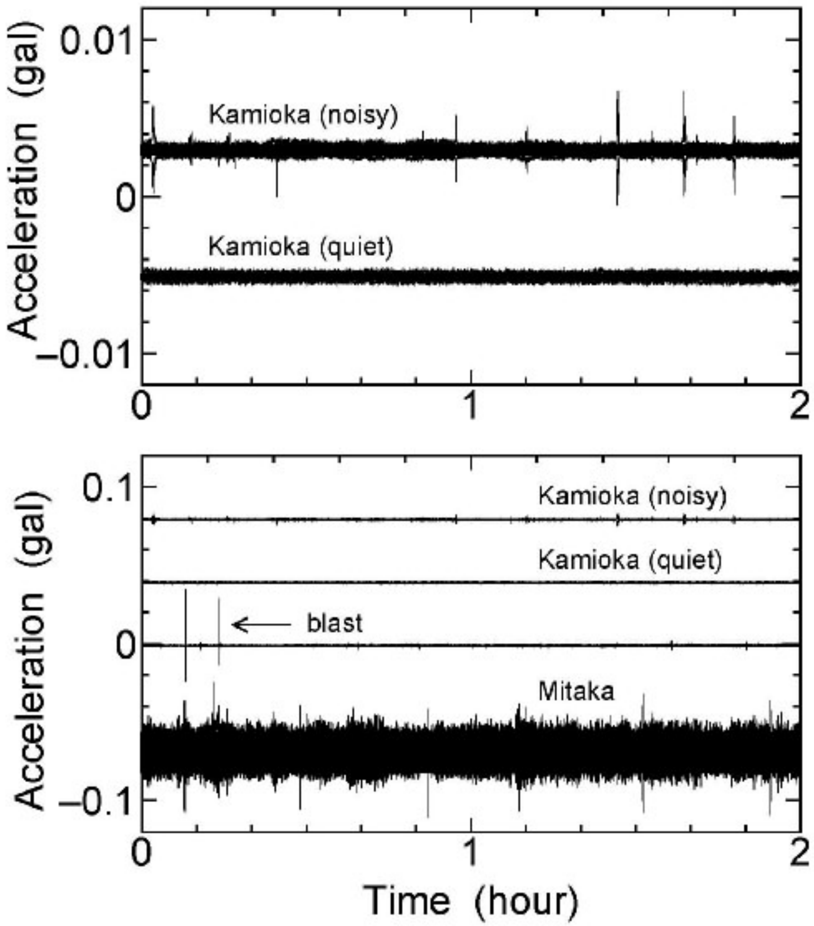


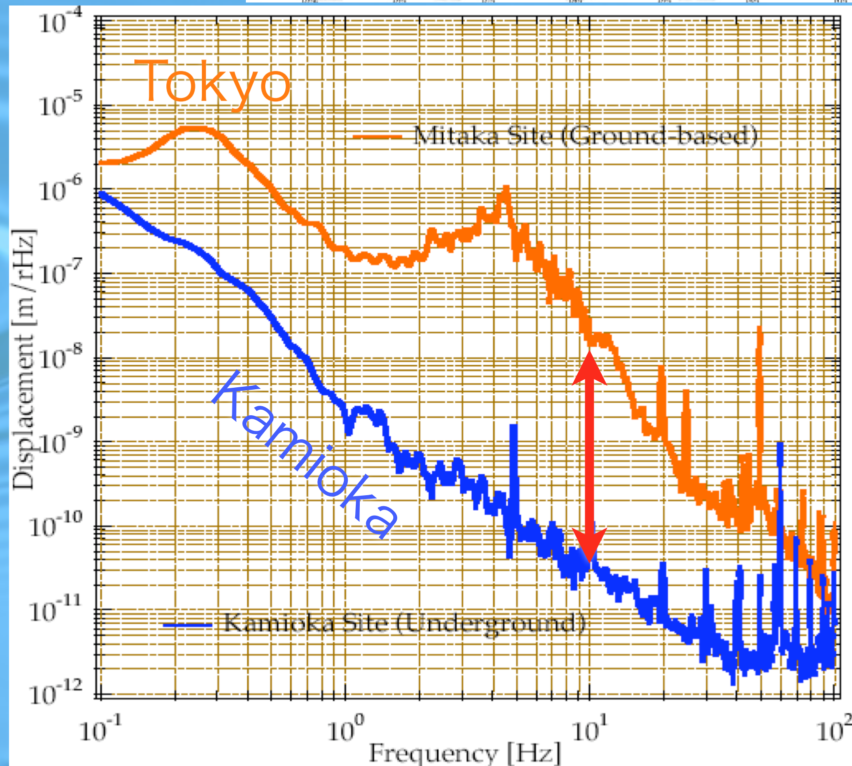
CLIO: Cryogenic Laser Interferometer Observatory











Amplitude of seismic motion

Thermal-noise reduction

Mid.-freq. (around 100 Hz) improvement

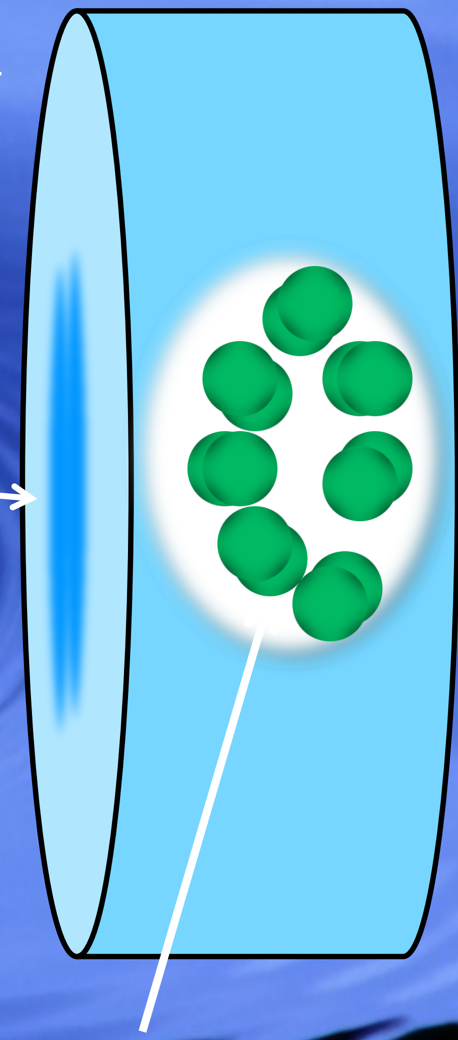
Cryogenics

Mirror ~20K
Suspension ~16K

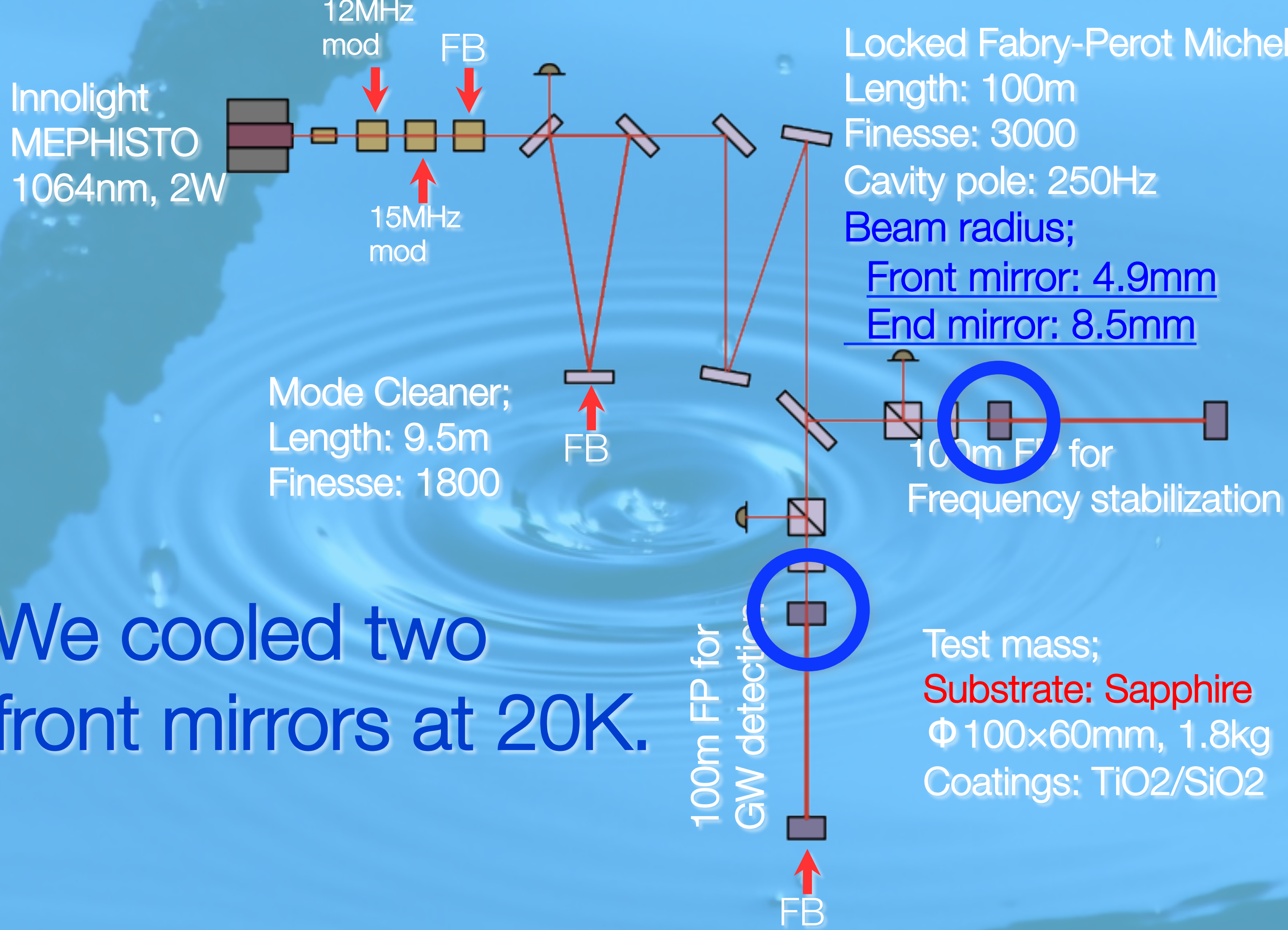
Sapphire mirror
→ High mechanical Q-value at low temperature

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

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



CLIO optical configuration



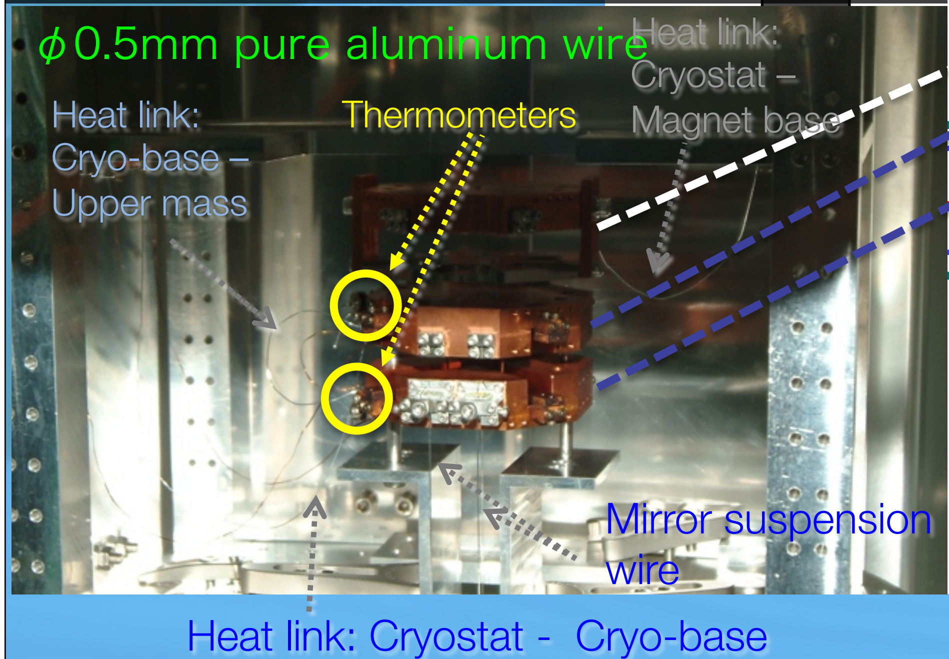
Locked Fabry-Perot Michelson
Length: 100m
Finesse: 3000
Cavity pole: 250Hz
Beam radius;
 Front mirror: 4.9mm
 End mirror: 8.5mm

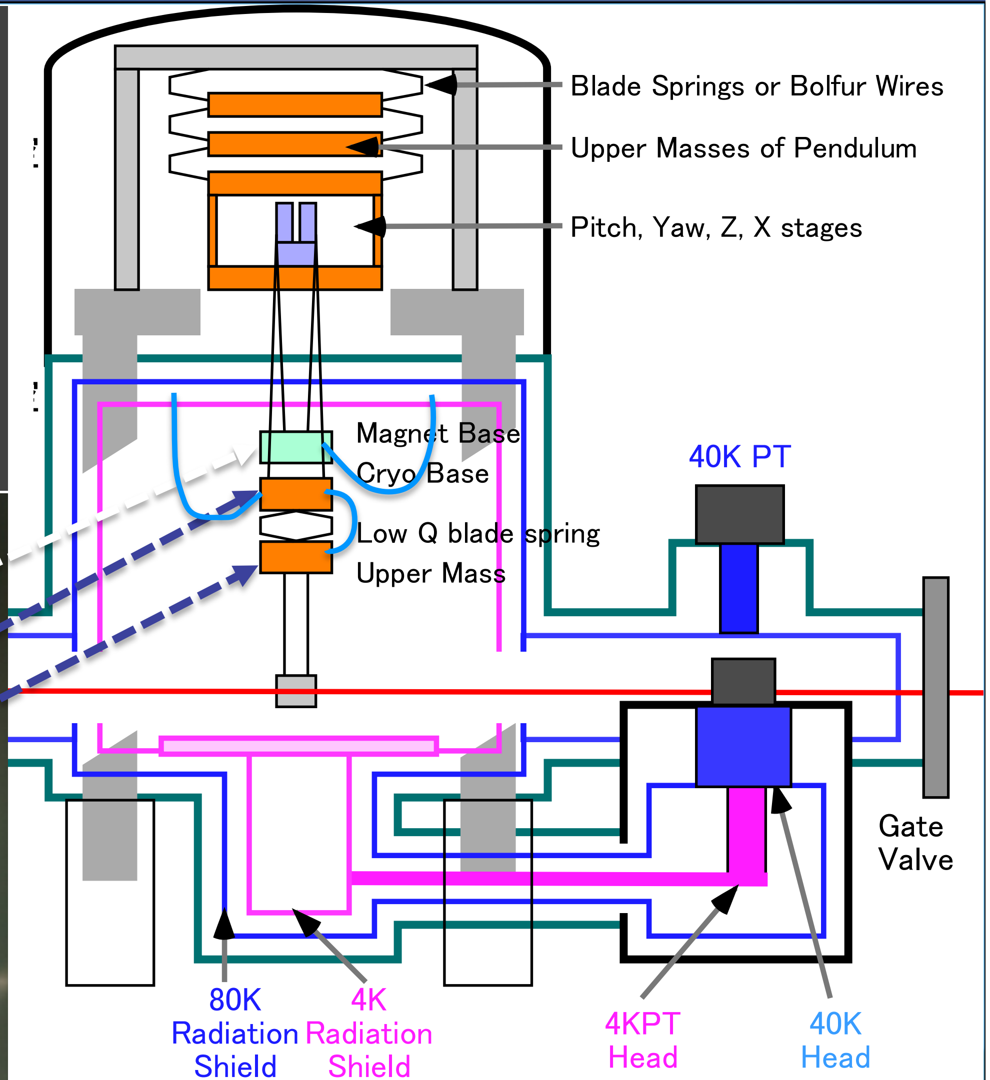
Test mass;
Substrate: Sapphire
 Φ100×60mm, 1.8kg
Coatings: TiO2/SiO2

We cooled two front mirrors at 20K.

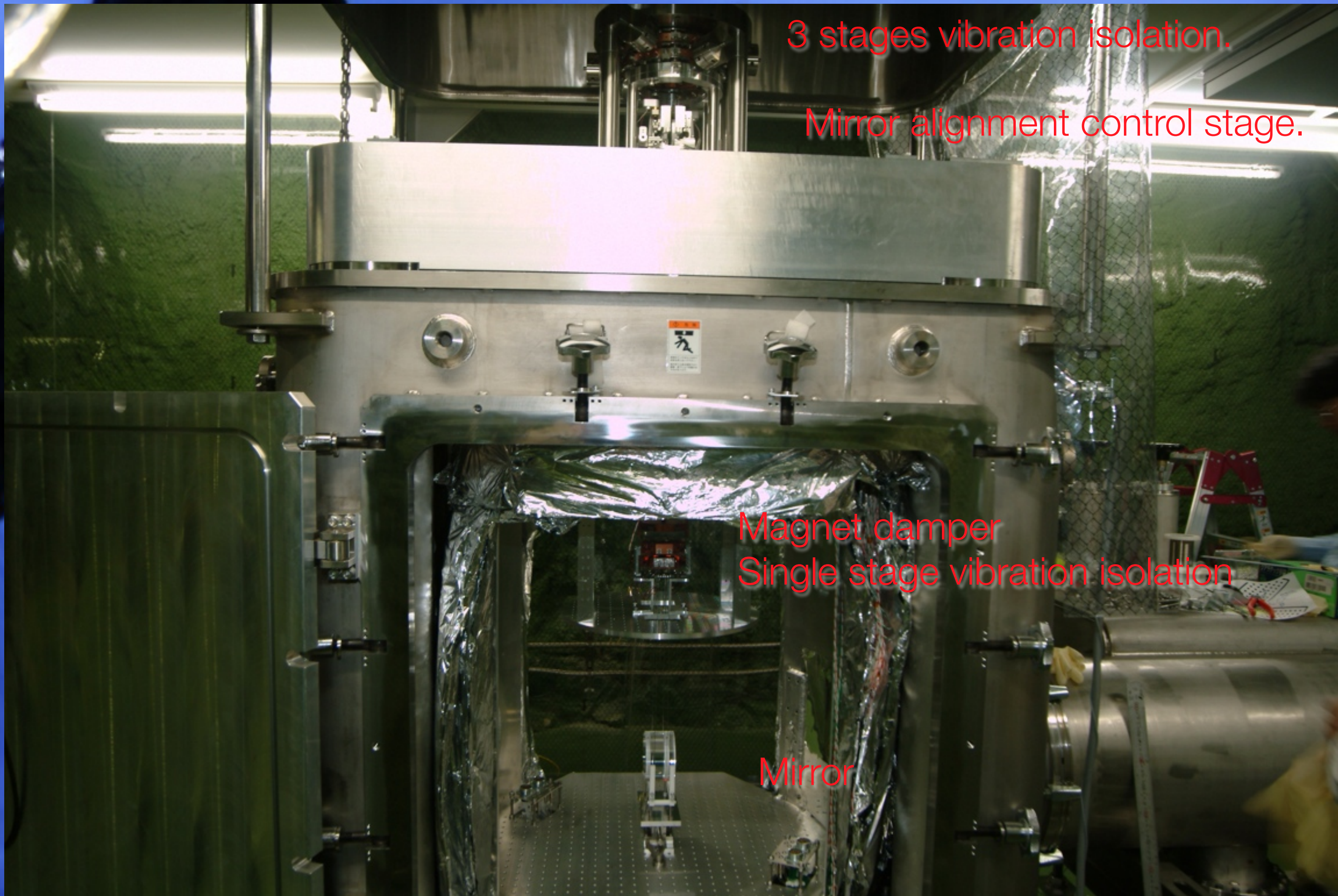
How to cool mirrors

- Mirror is always heated by laser.
- Mirrors are in high vacuum (10^{-5}Pa), so no convection or no radiation works for cooling.
- Heat on mirror is sucked through wire's conduction.
- Vibration from pulse tube coolers, mirror contamination by cooling.

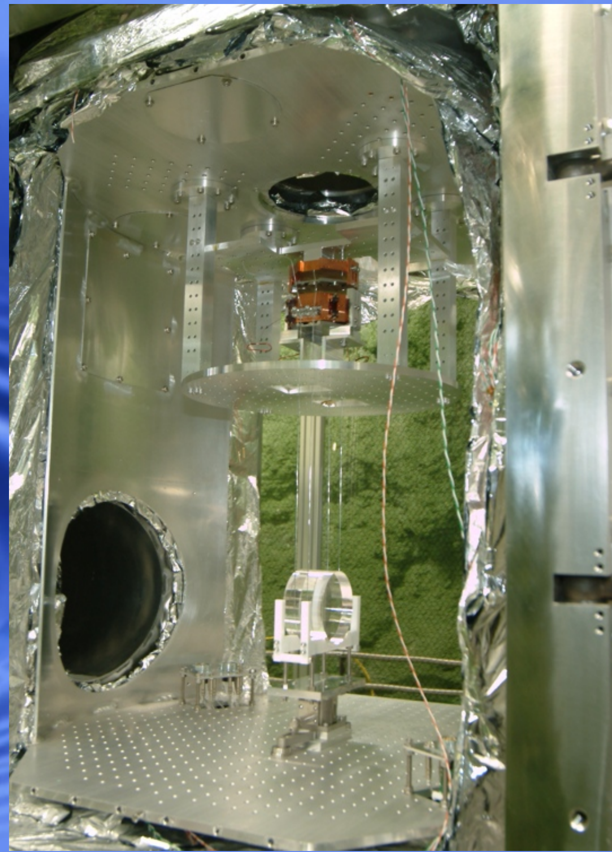




Cryostat and Suspension

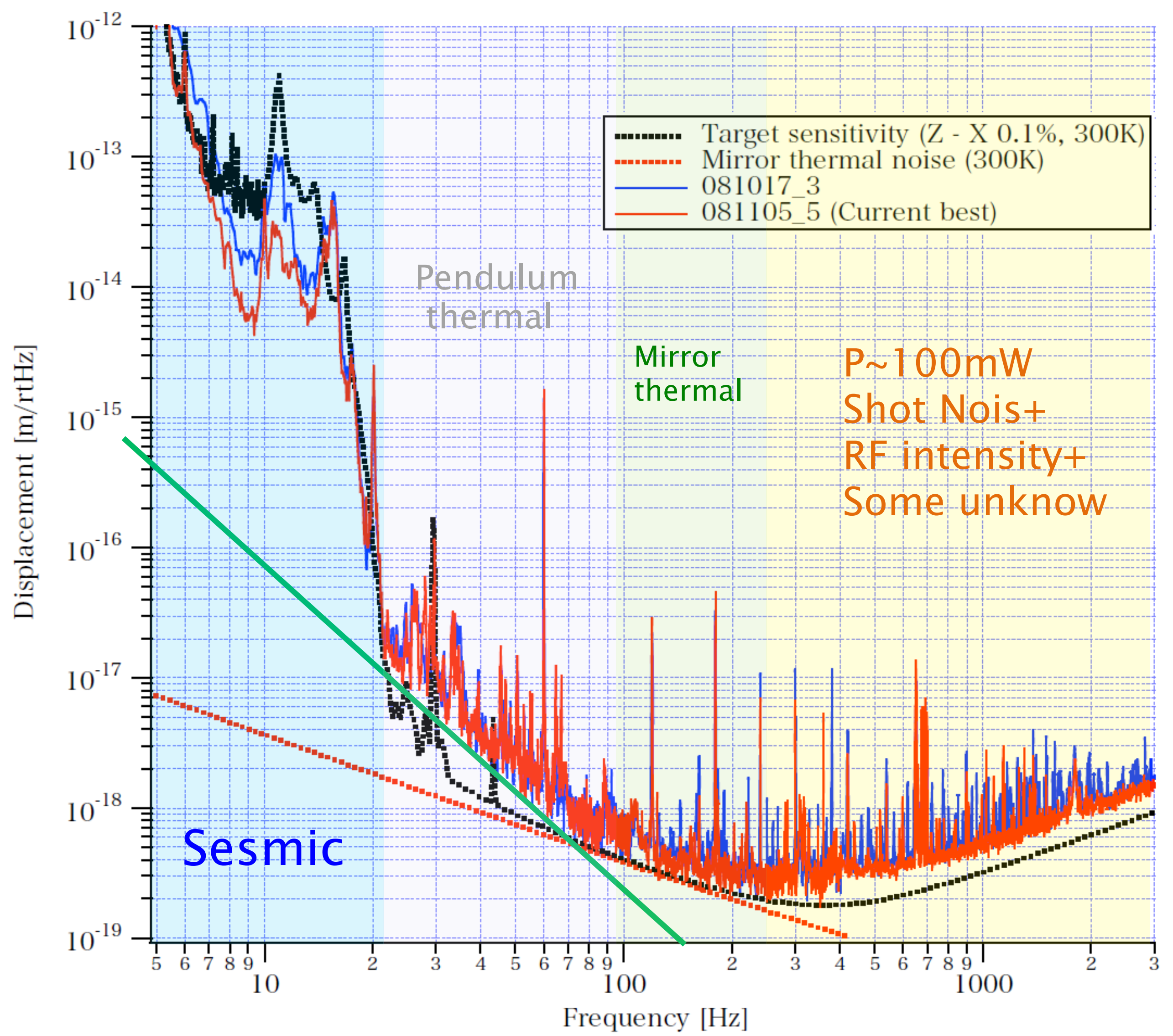


Suspension



Sapphire mirror
Φ100×60

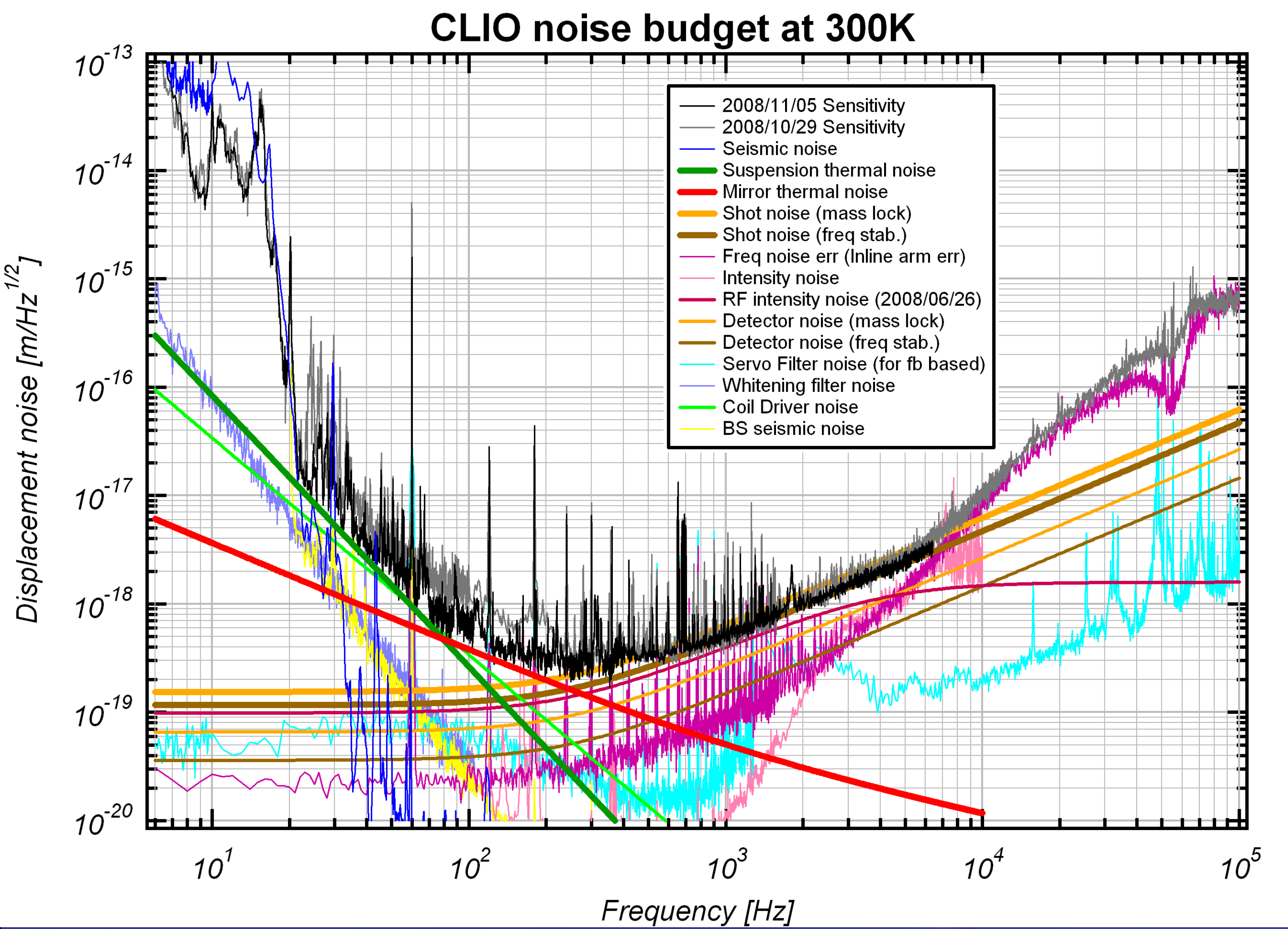
Principle noises in the interferometer



GW detection is a fight against noises.

- Low frequency is limited by seismic motion with 6 stage seismic attenuators.
- Middle frequency is limited by suspension and mirror thermal noise in the room temperature.
- Hi frequency is limited by shot noise which comes from statistical fluctuation of the photon number into the photo detector.

Noise sources

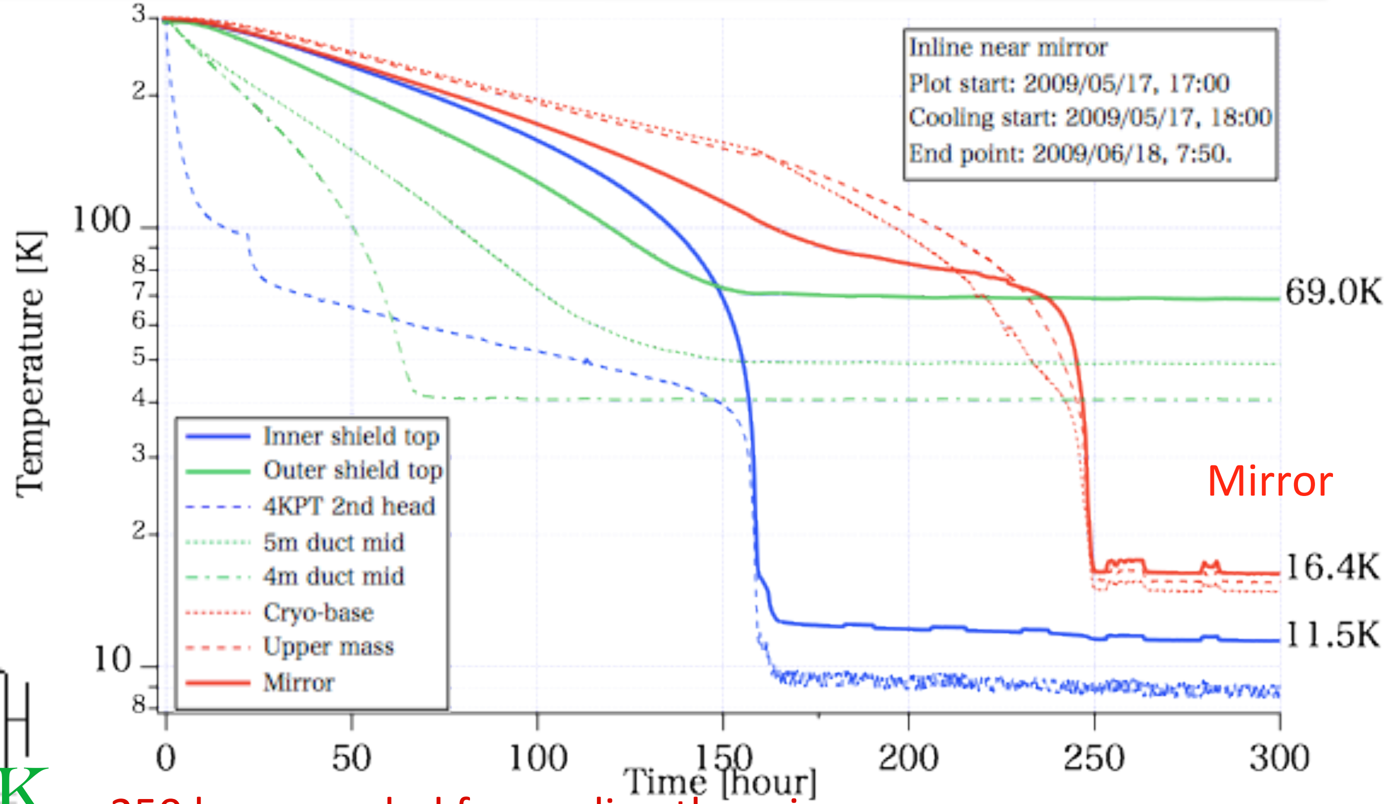


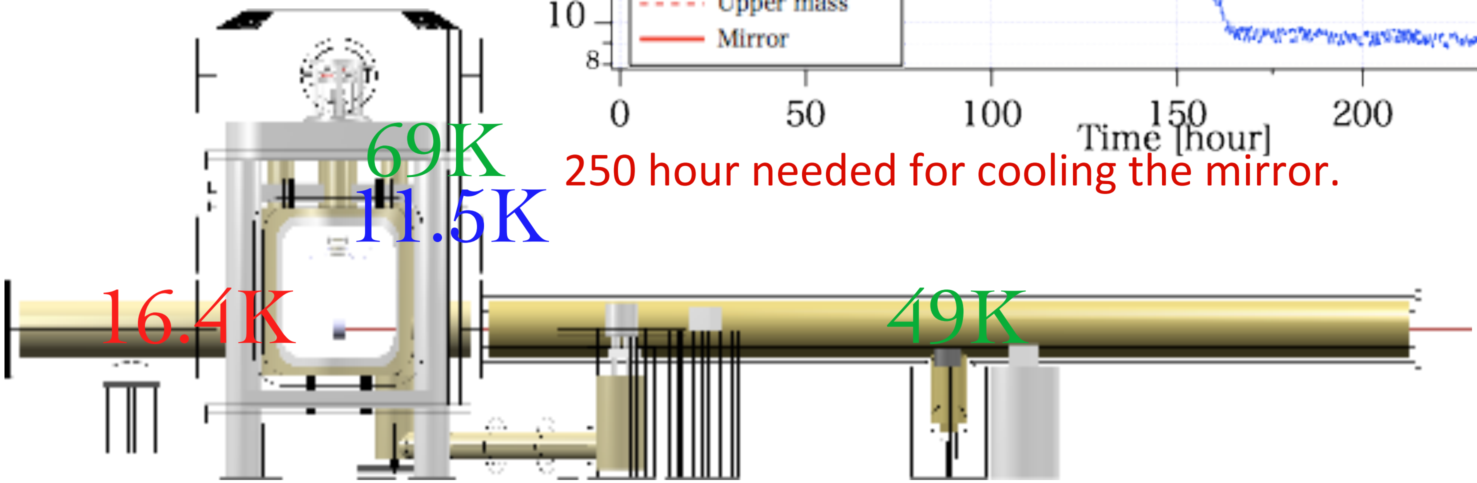
After noise hunting for many things, we see GWs

Seismic noise
Pendulum thermal
Mirror thermal
Shot noise
Laser frequency noise
Laser intensity noise
RF intensty noise
Detector noise
Servo filter noise
Whitening filter noise
Coil driver noise

Others
Radiation pressure noise
Angle fluctuation
Oscillator phase noise
Vacuum fluctuation
Etc.

Cooling example





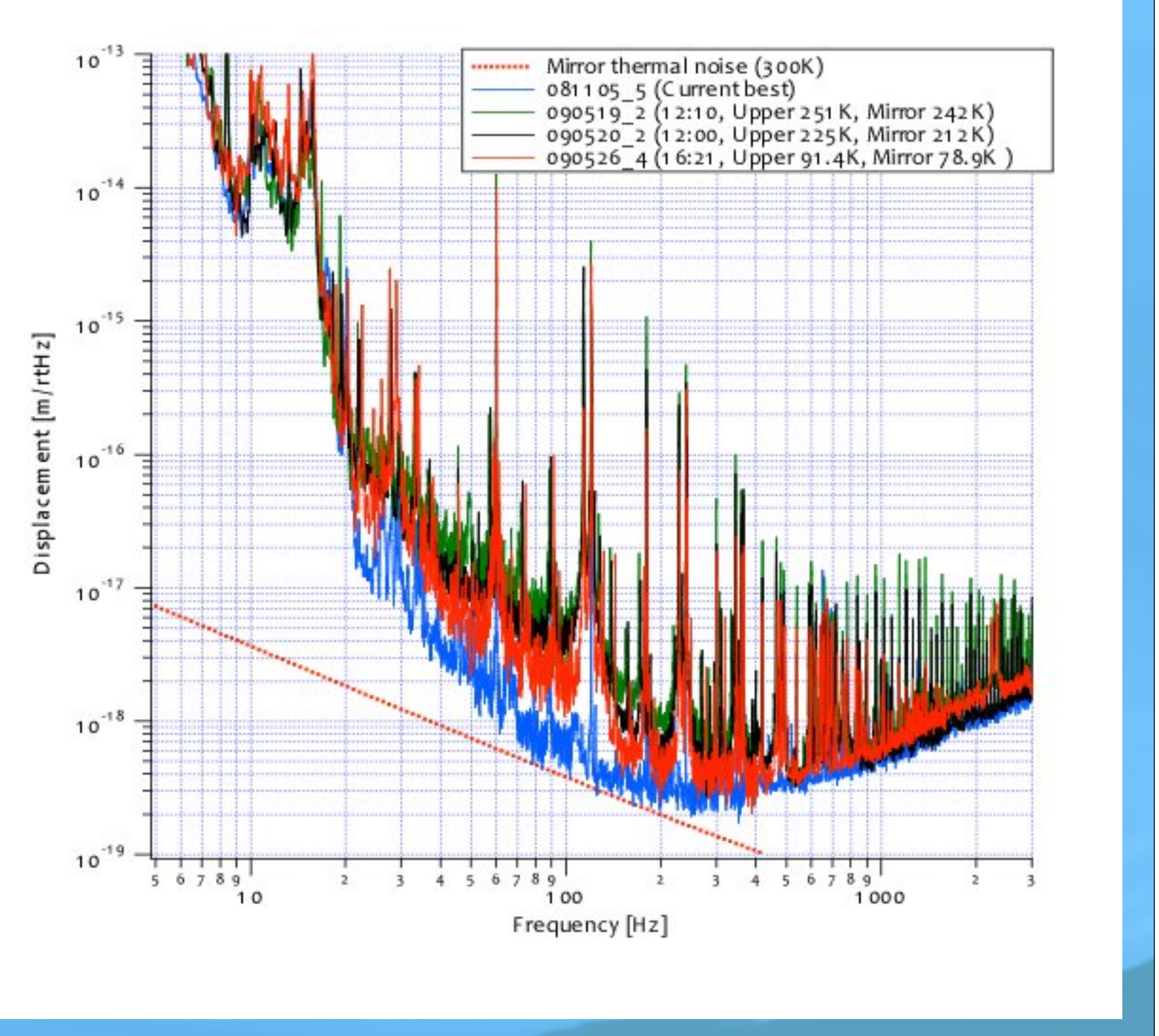
250 hour needed for cooling the mirror.

Low temperature experiment

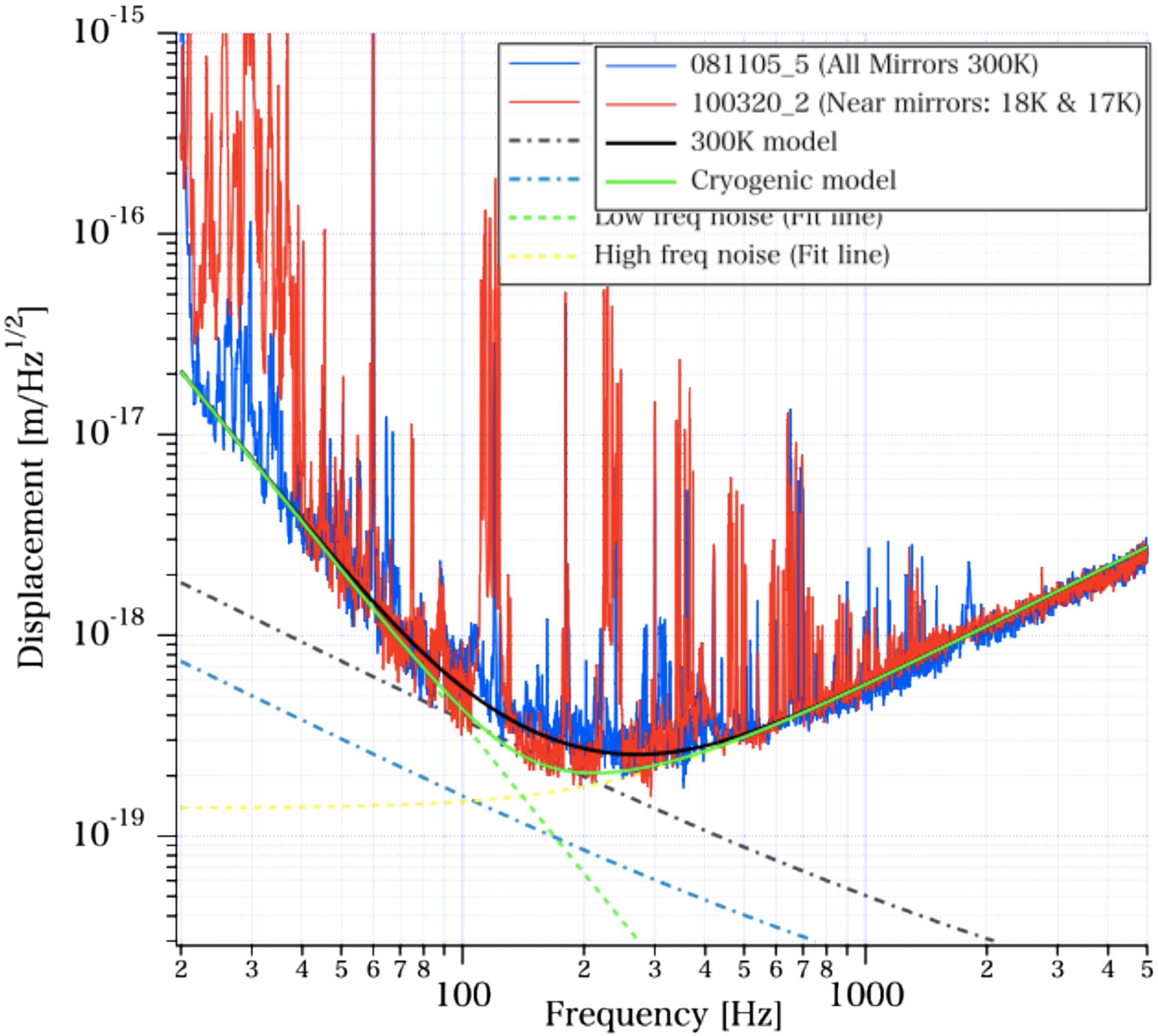
•Suspension thermal noise was reduced, as the aluminum wires were cooled;

1. 242K 5/19/2009
2. 212K 5/20/2009
3. 79K 5/26/2009

•A big jump from 212K to 79K, because of too much creaks when structures were shrinking to measure noise or to keep lock. Creaks vanished below 100K.

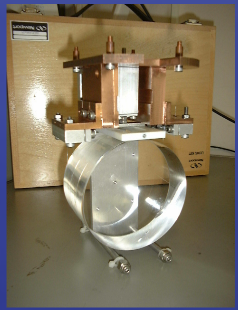


Thermal noise reduction



- Is this sensitivity improvement consistent with the mirror thermal noise reduction?
- Consider 3 noise floors.
- **Low freq noise: $f^{-2.5}$**
  - Suspension thermal noise
- **High freq noise: cavity pole 250Hz.**
  - Shot noise
  - (RF intensity)
- **Mirror thermal noise.**
  - all mirrors at 300K
  - only near mirrors at 20K.

History of cryogenic mirrors Japan original!!



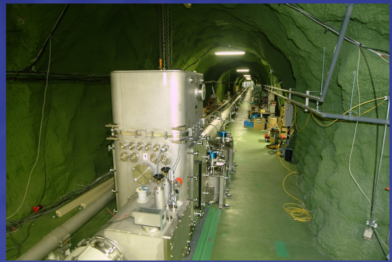
1997 Starting of feasibility study at KEK.
Sapphire mirror & fiber suspension.

10cm

2001 CLIK: Control of cryogenic Fabry-Perot cavity
Kashiwa.

7m

2002~ CLIO: Sensitivity of cryogenic GW detector.



100m

2011: We are here now!!

201? LCGT: Detection of Gravitational wave.

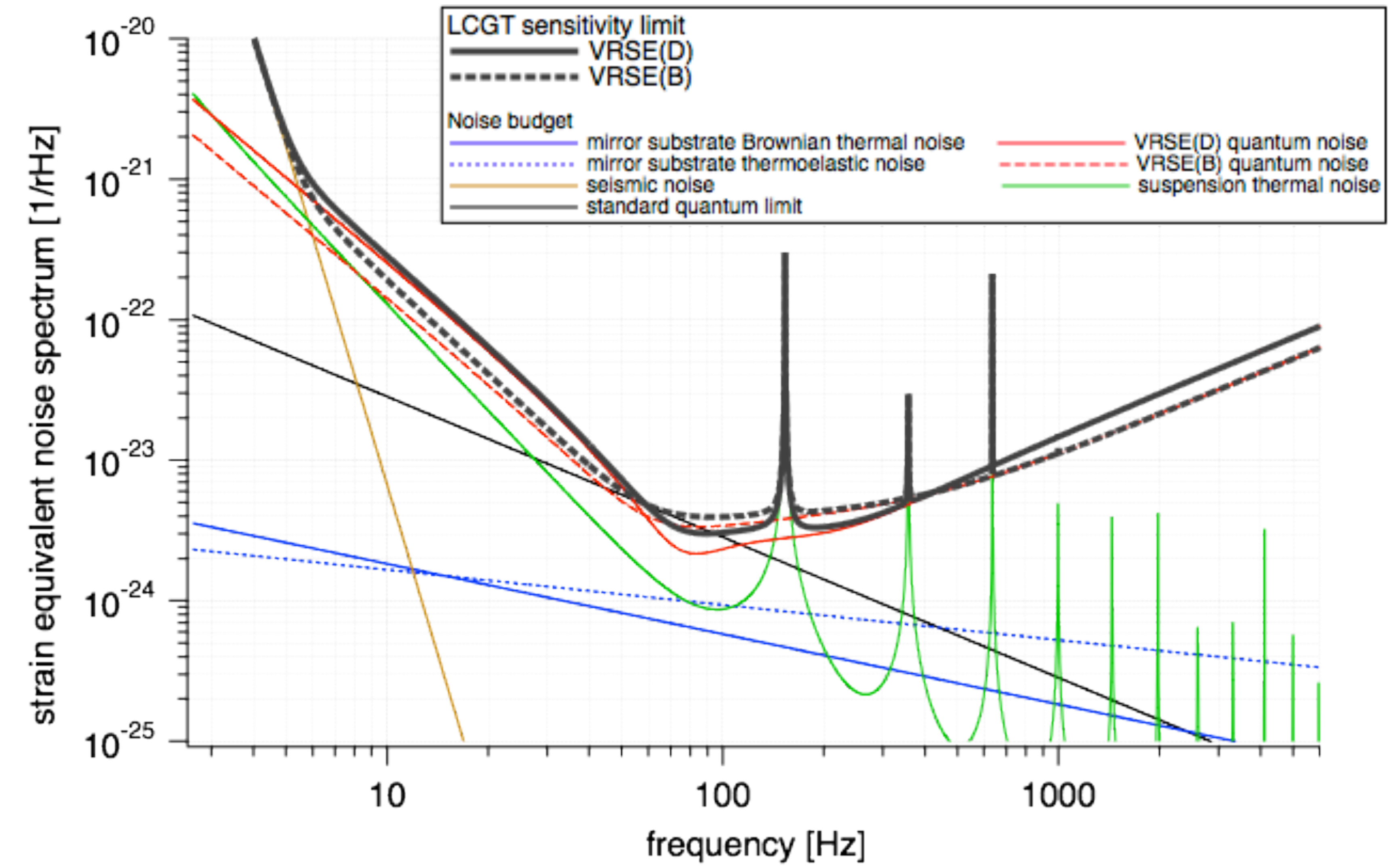
3000m

Location of LCGT

LCGT is planed to be built underground at Kamioka, where the prototype CLIO detector is placed.

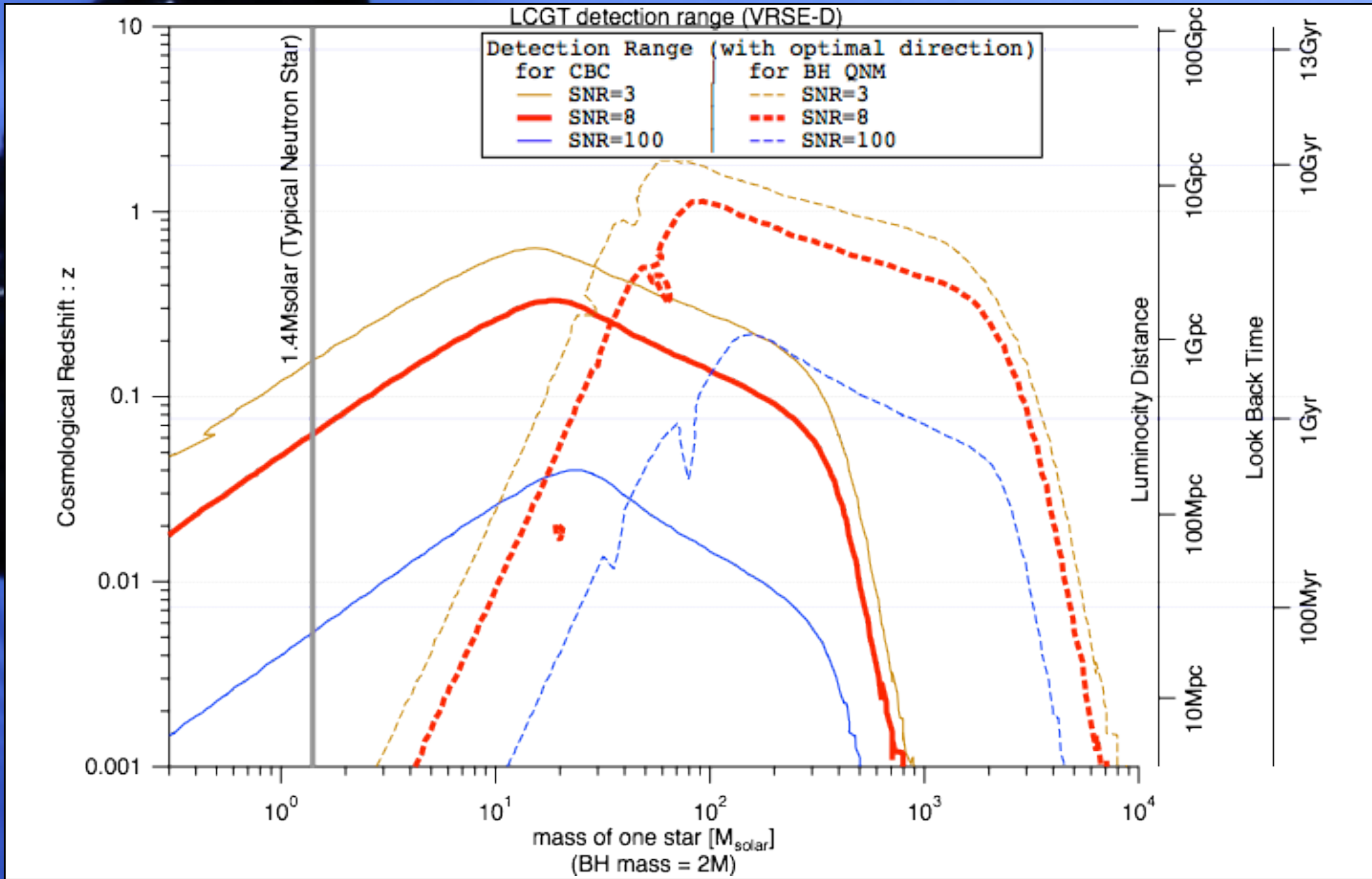
Sensitivity Limit of LCGT

h ~ factor x 10^{-24} [/√Hz]
for observation band



Detection Range

- Compact Binary
- Blackhole QNM



NS-NS Detection Range (sky average) 123 Mpc

(optimal direction) 281 Mpc

NS-NS merger rate

Galactic merger rate: $118^{+174}_{-79}\ \mathrm{Myr}^{-1}$

Current standard LCGT design (VRSE-D) gives horizon distance (@ ρ =8) = 282Mpc (z=0.065)

Event rate for LCGT : $9.8^{+14}_{-6.6}\ \mathrm{yr}^{-1}$

However, systematic errors which are not included in this evaluation may be large.

Detection probability

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

99.9%

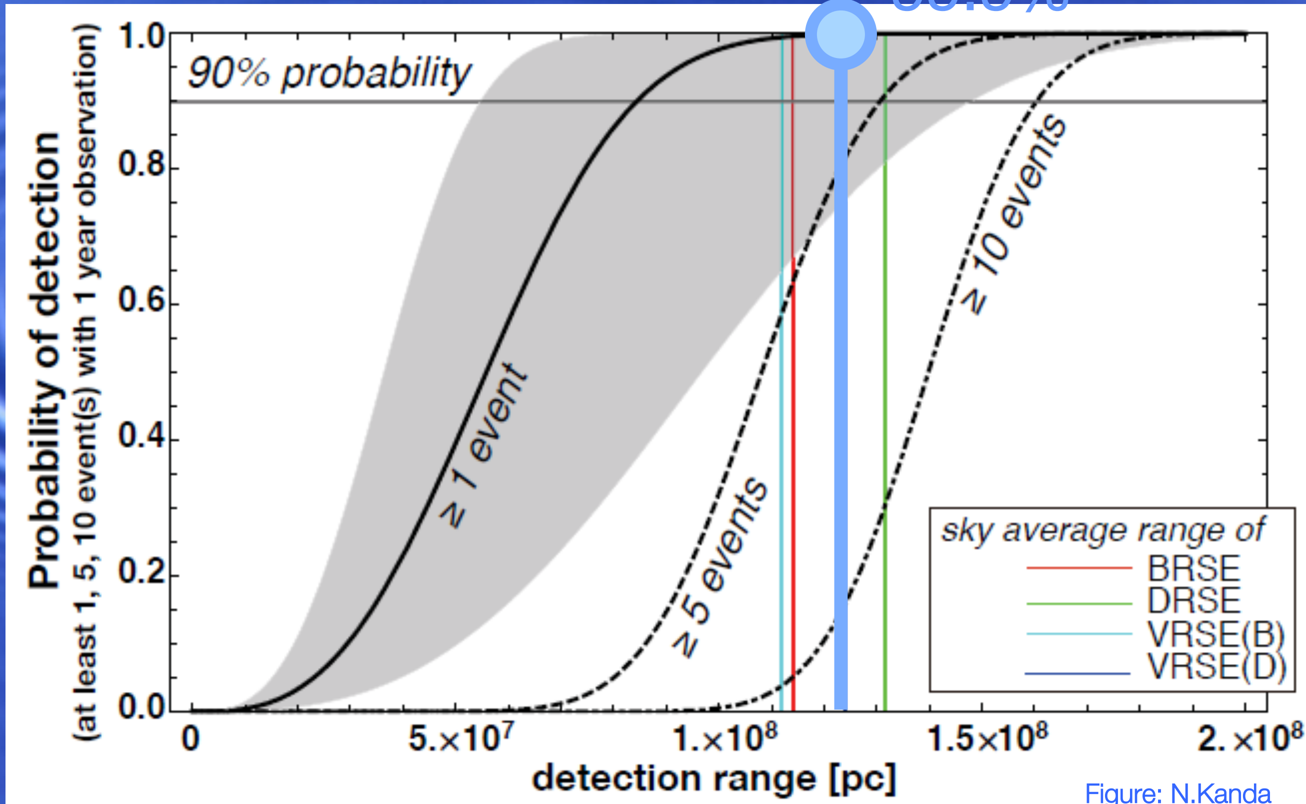


Figure: N.Kanda

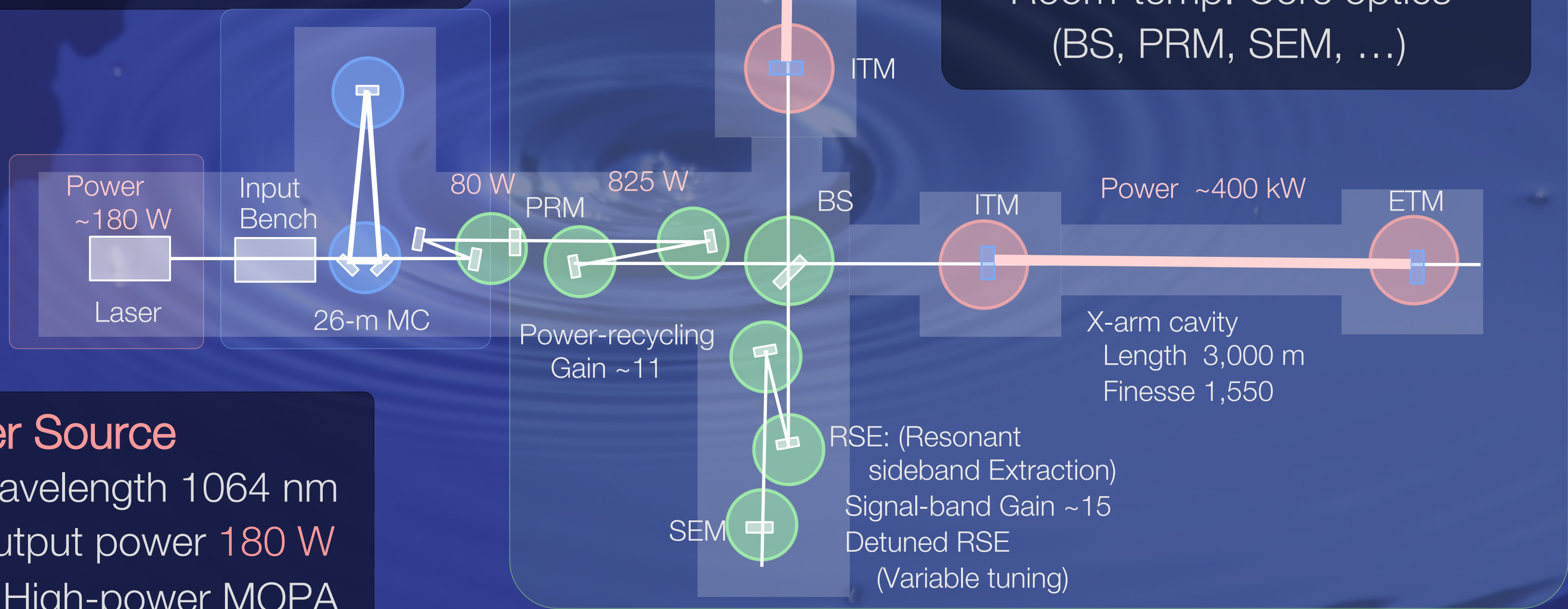
LCGT configuration

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, …)

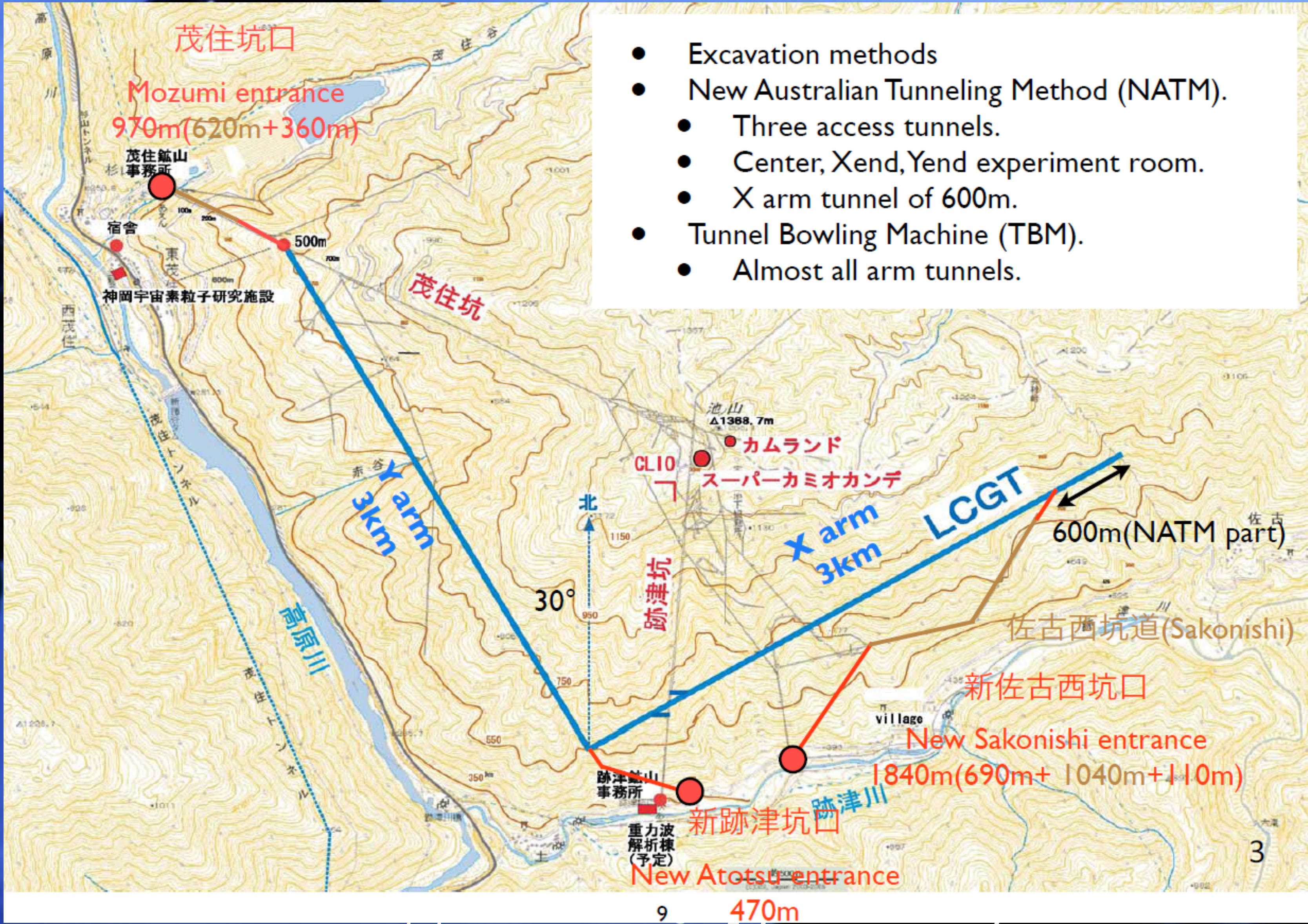


Laser Source

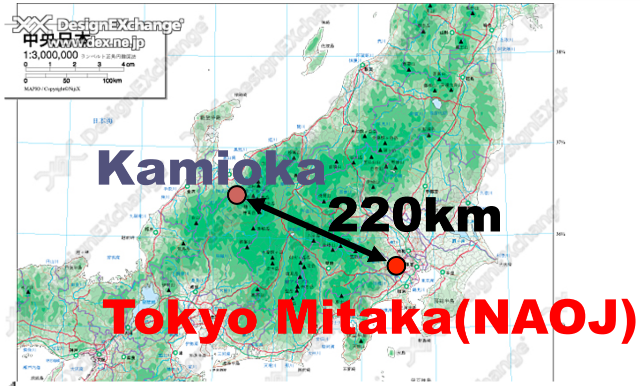
- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

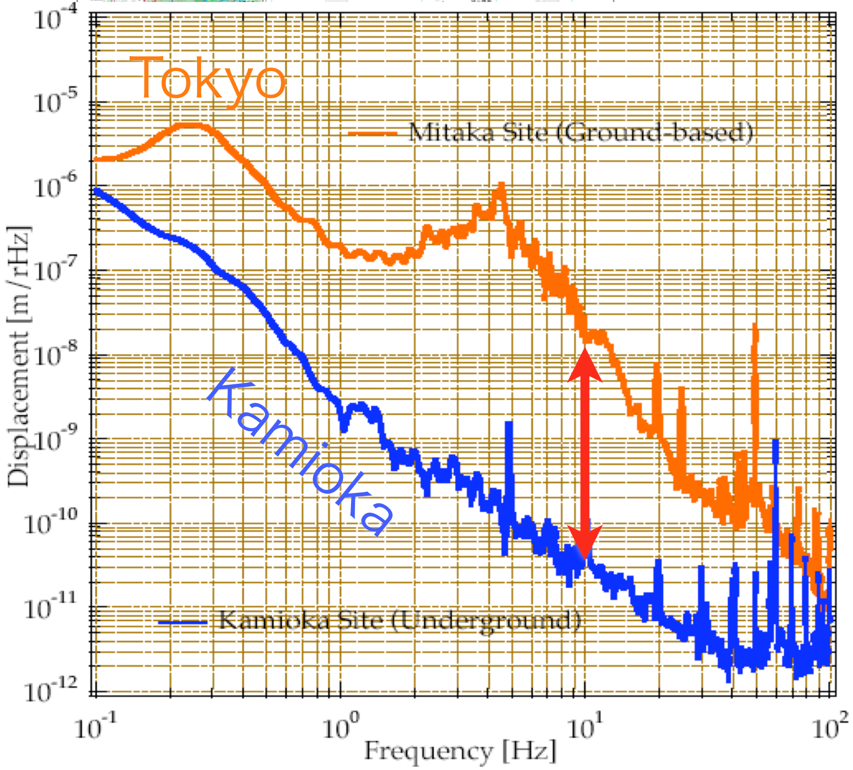
Tunnel

- 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.

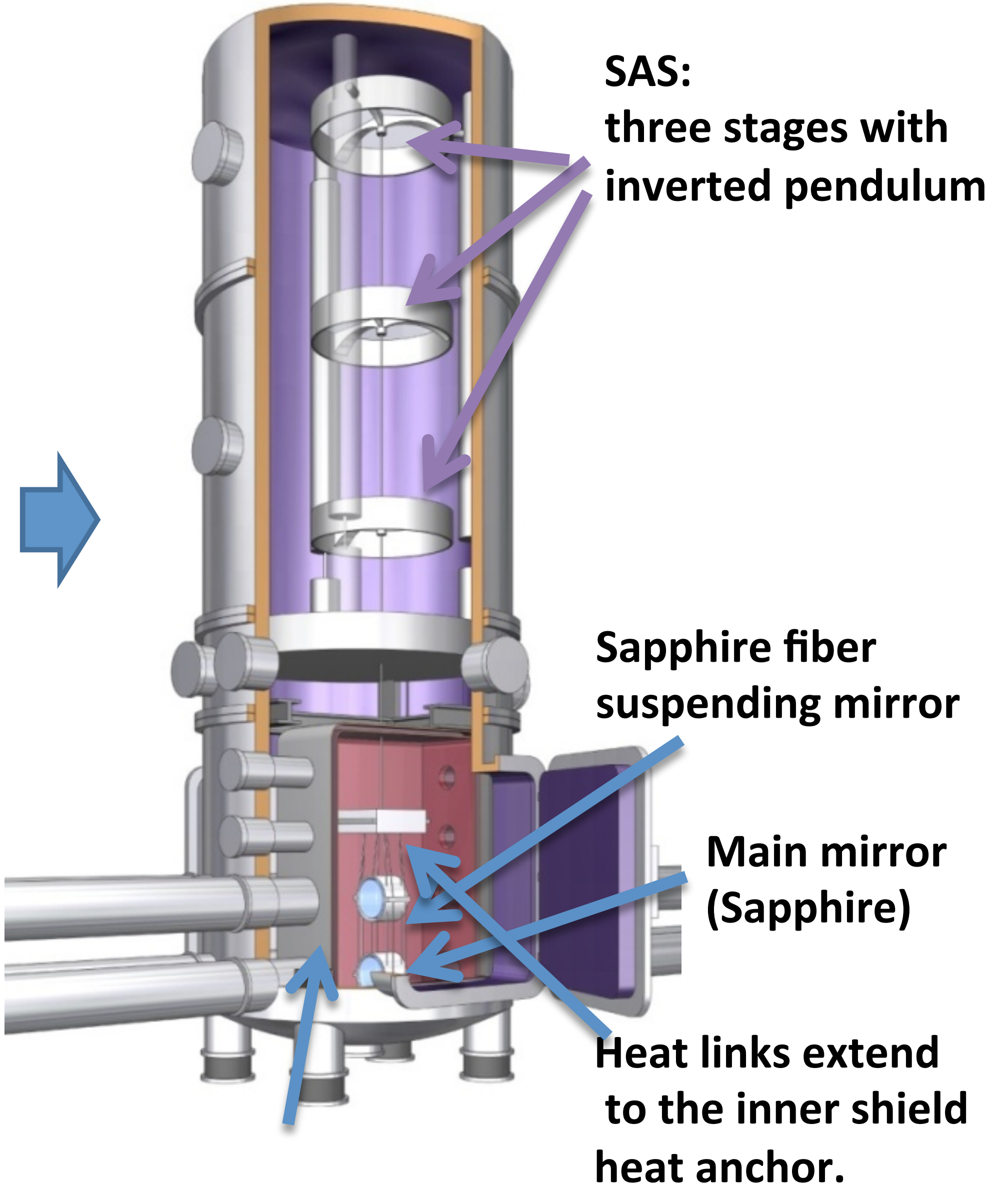


Seismic attenuation system

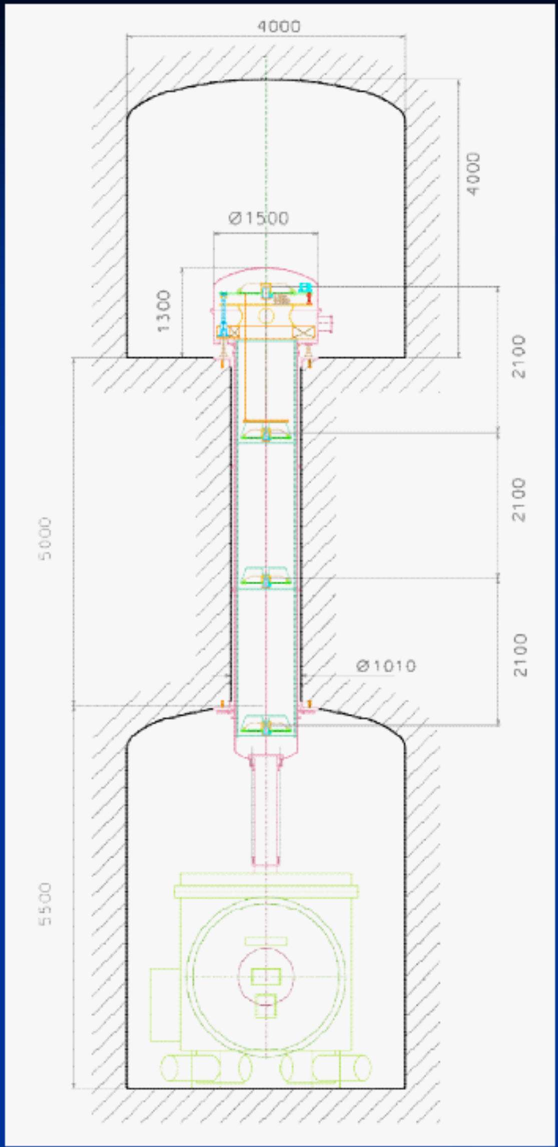




Amplitude of seismic motion



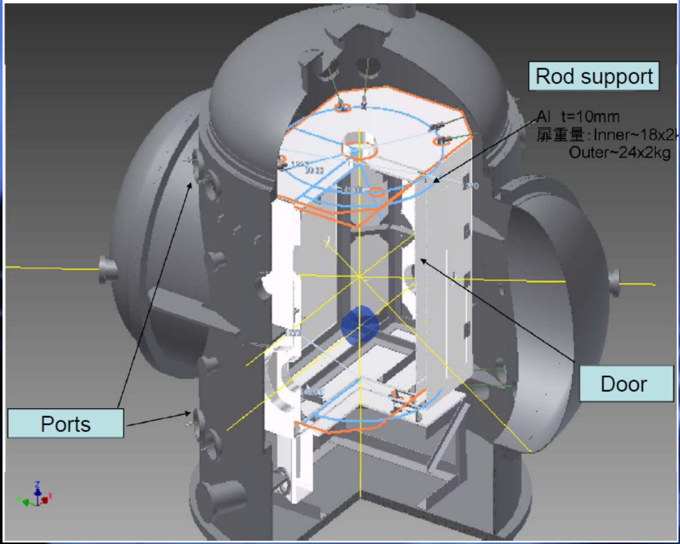
Vibration Isolation



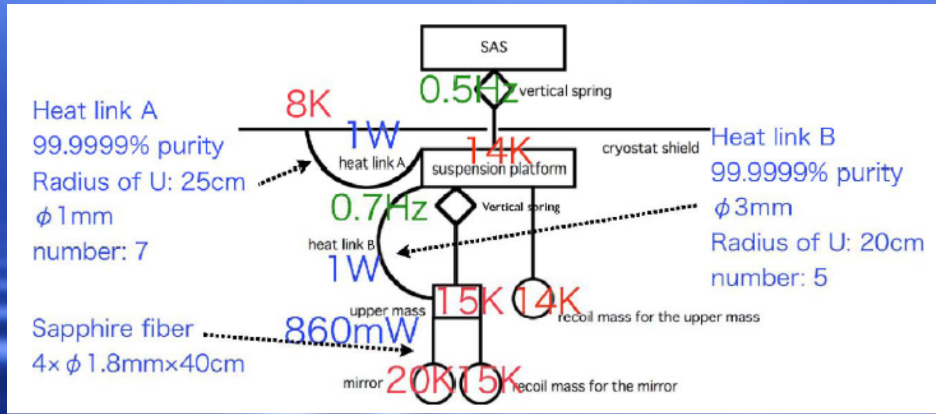
Type-A (2-layer structure)

- 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

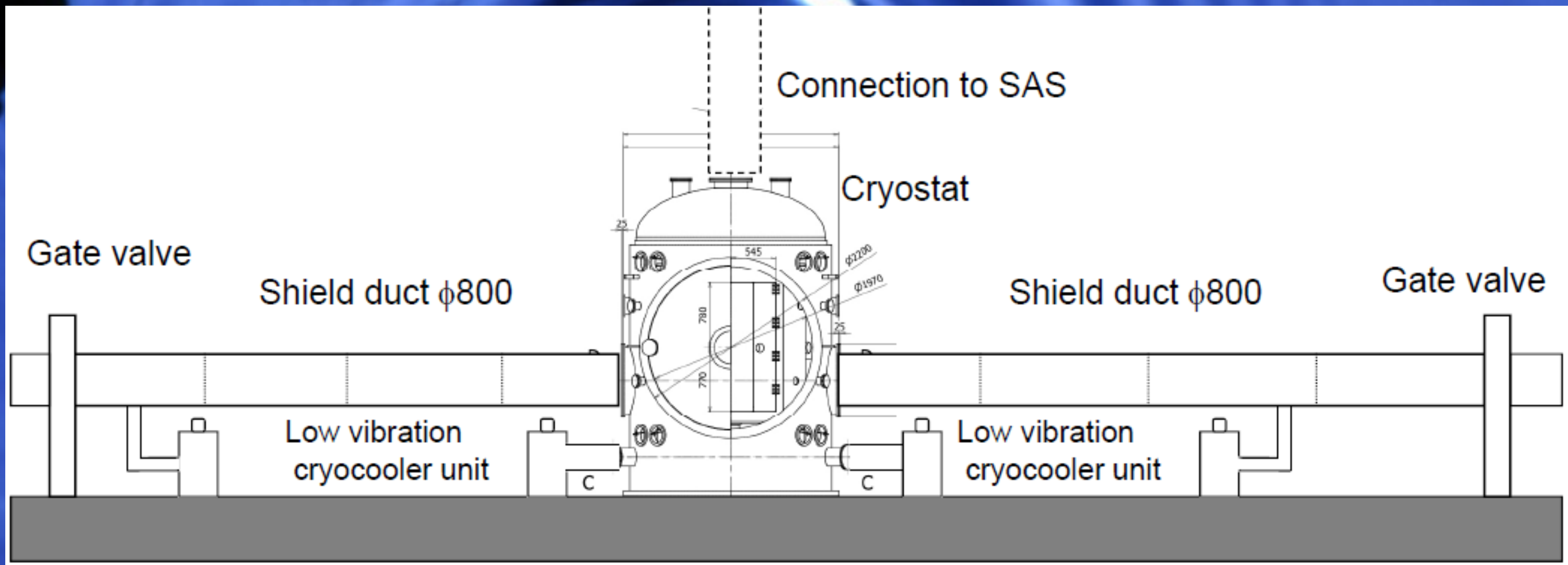
Cryogenics



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

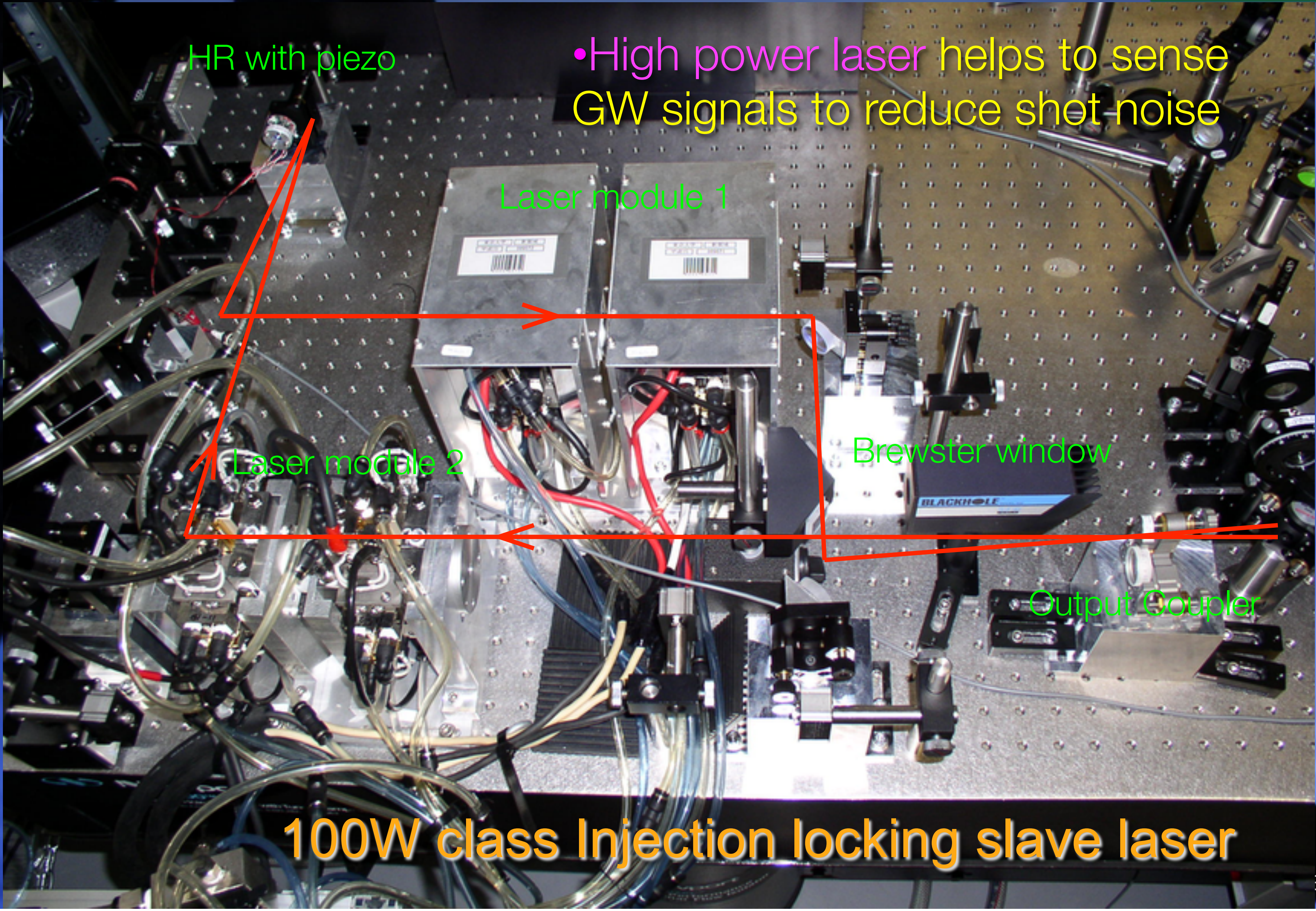


SAS
0.5Hz
vertical spring
8K
1W
14K
cryostat shield
heat link A
suspension platform
Heat link A
99.9999% purity
Radius of U: 25cm
ϕ1mm
number: 7
0.7Hz
Vertical spring
heat link B
1W
Heat link B
99.9999% purity
ϕ3mm
Radius of U: 20cm
number: 5
upper mass
15K
14K
recoil mass for the upper mass
Sapphire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



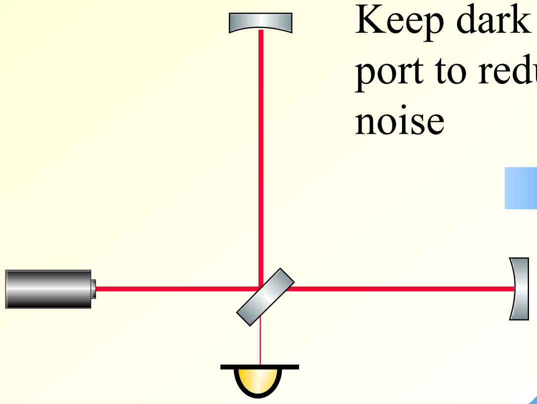
Connection to SAS
Cryostat
Gate valve
Shield duct ϕ800
Shield duct ϕ800
Gate valve
Low vibration cryocooler unit
Low vibration cryocooler unit

High power laser



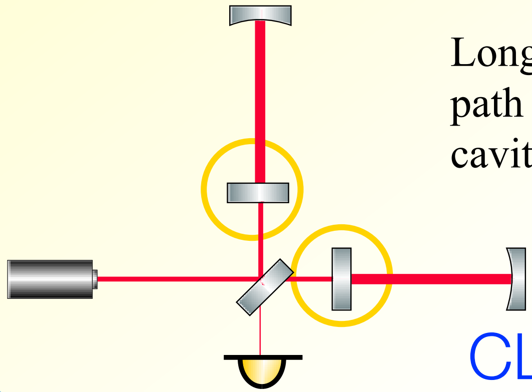
Development of optical configurations

Michelson interferometer (MI)



Keep dark at detection port to reduce shot noise

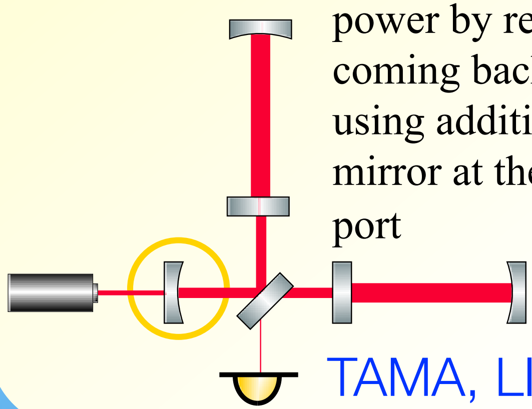
Fabry-Perot MI (FPMI)



Longer folding light path using Fabry-Perot cavity

CLIO

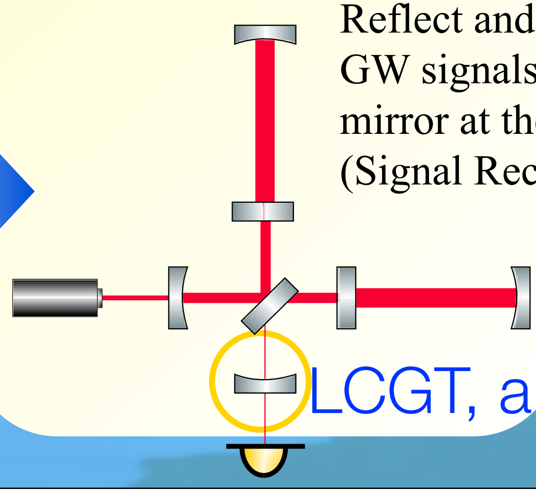
Power recycling (PRFPMI)



Enhance inside laser power by reflecting coming back light using additional mirror at the laser port

TAMA, LIGO , VIRGO

Dual recycling (DR)



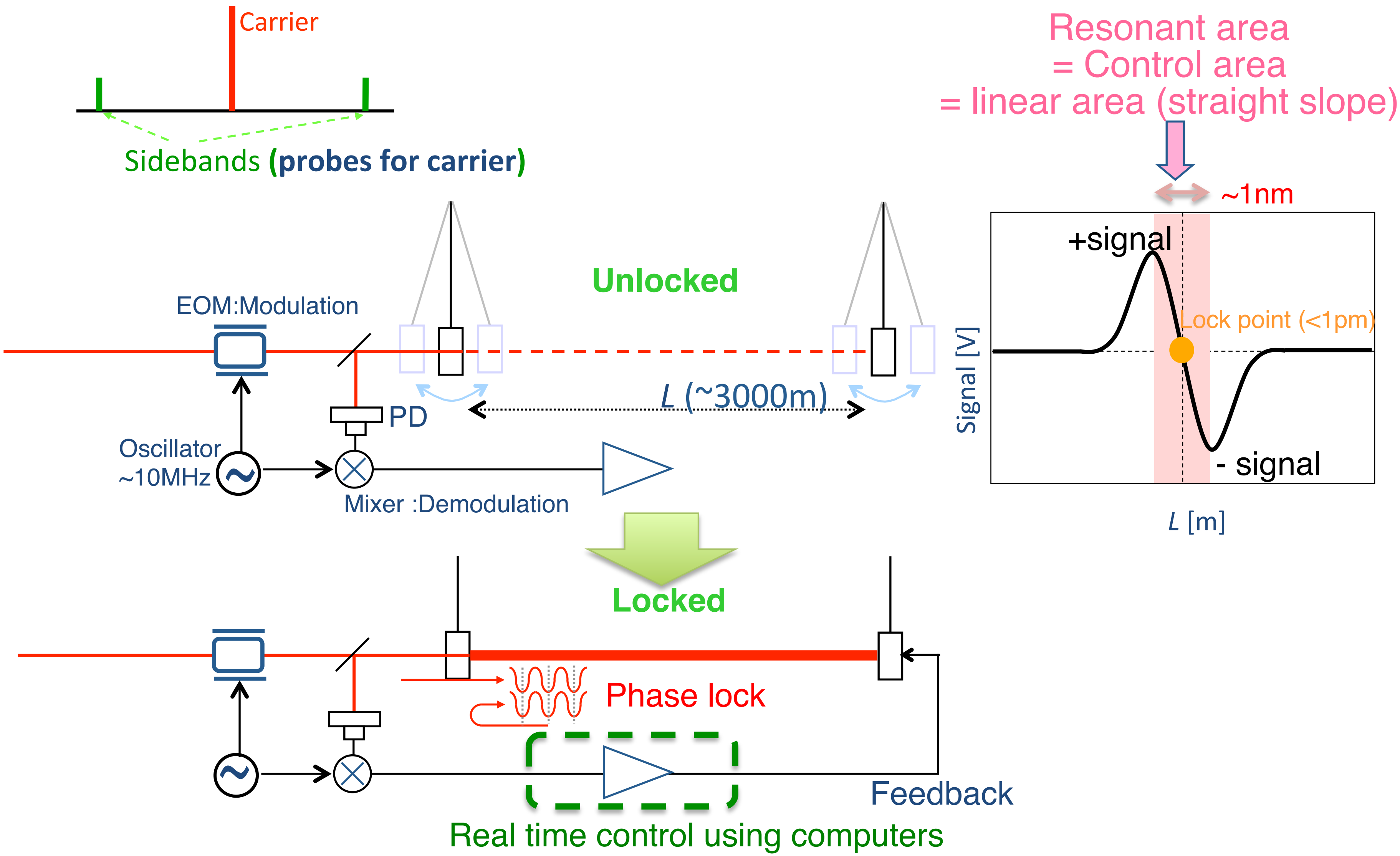
Reflect and enhance the GW signals by additional mirror at the dark port (Signal Recycling, RSE)

LCGT, aLIGO, aVIRGO

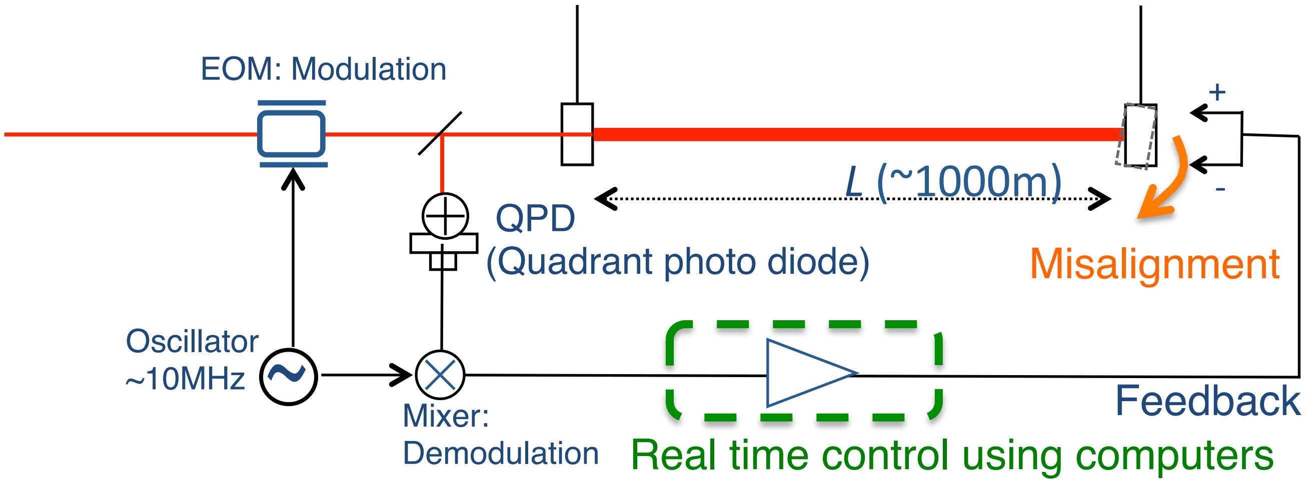
Real time control for interferometer using computers

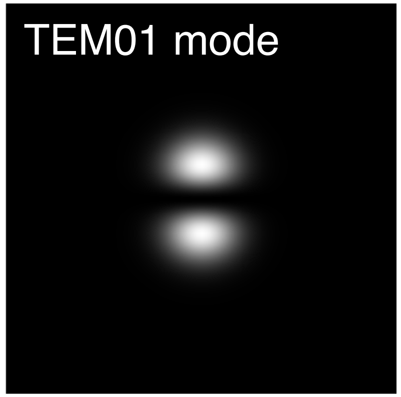
- Recent GW detector allow us to control, measure and tune the interferometer on the PC screen in control room
  - » Importatnt to avoid human noise
- Good software makes a big advance for sensitivity improvement

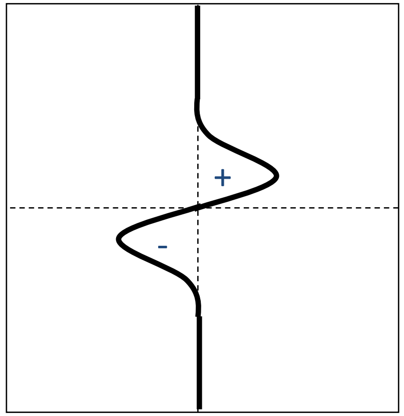
Lock acquisition for interferometer

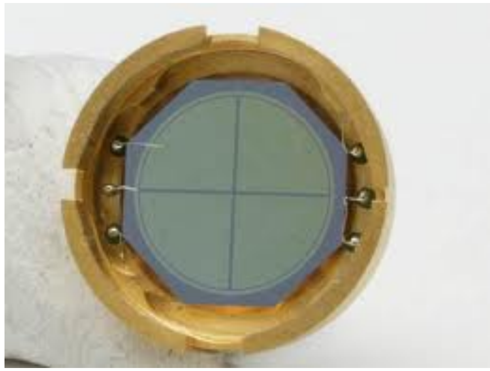


Alignment control for mirrors



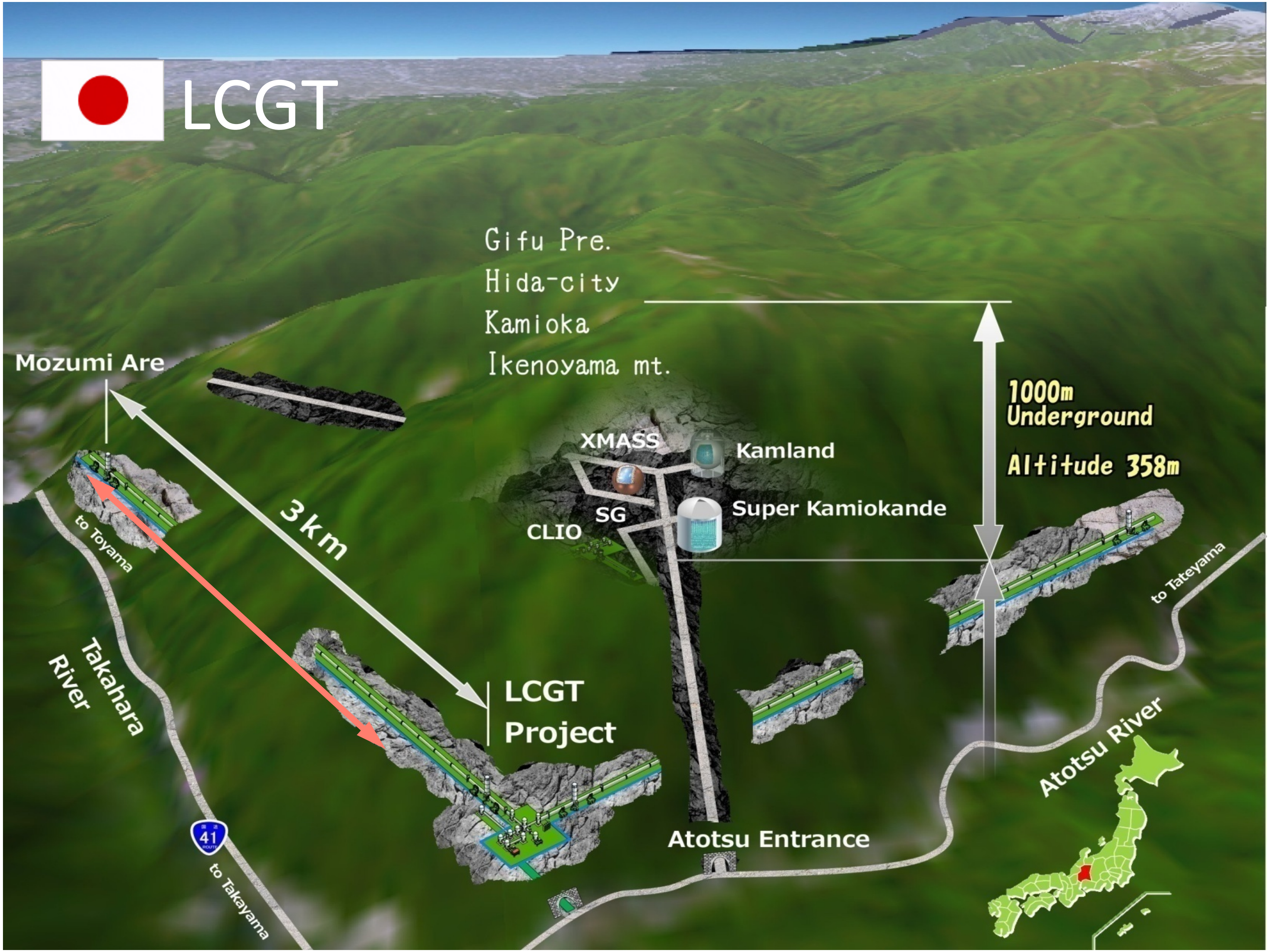







TAMA
Base line: 300m
First large scale interferometer in the world operated from 1998
World best sensitivity in 2000
300m
300m
Ceneral roor


CLIO
Underground in Kamioka mine
Cryogenic mirrors
Baseline: 100m

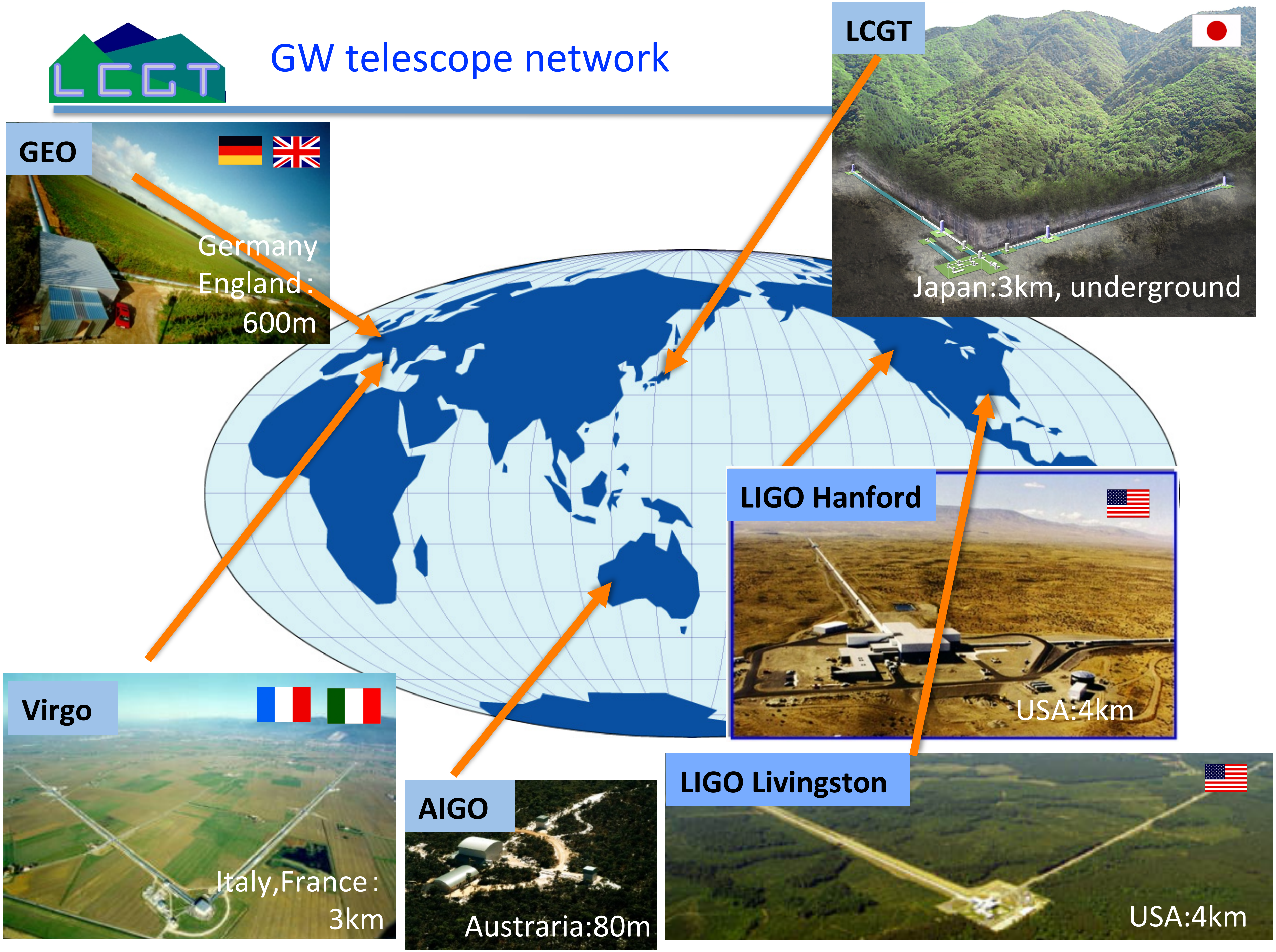

LCGT
Gifu Pre.
Hida-city
Kamioka
Ikenoyama mt.
Mozumi Are
3 km
XMASS
Kamland
SG
CLIO
Super Kamiokande
1000m
Underground
Altitude 358m
to Toyama
Takahara
River
LCGT
Project
to Tateyama
Atotsu River
41
to Takayama
Atotsu Entrance


GEO
1995 construction started
England and Germany
Baseline: 600m
Location: Hanover in Germany


VIRGO
1996 construction
2005 First observation
2008 observation with LIGO
Baseline: 3km
France and Italy
Location: Pisa in Italy

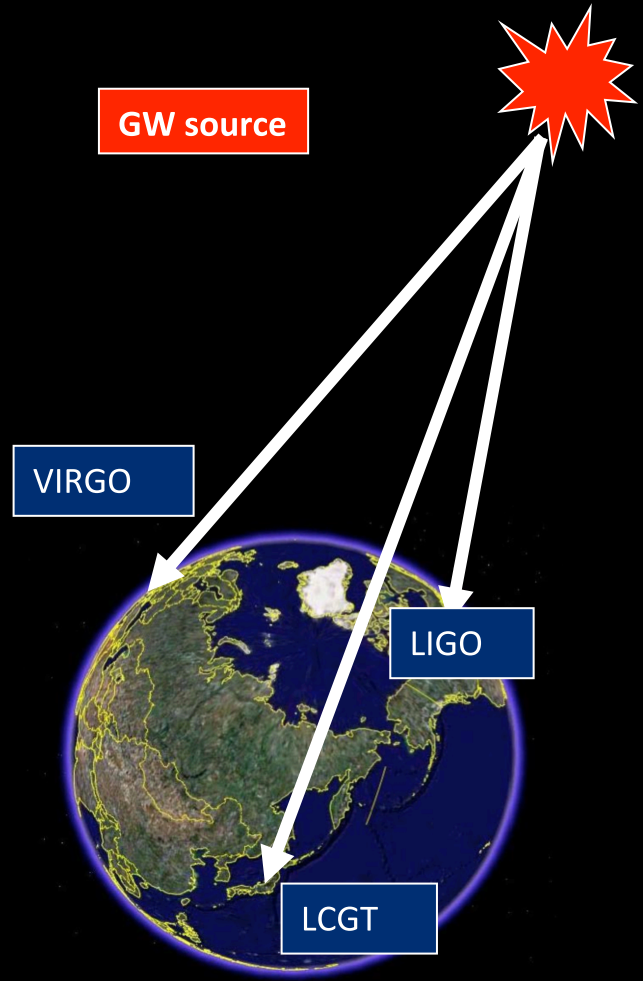

LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
Desert in north west, Washington
3000km, 10 ms
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
Swamp in gulf coast, Louisianna
●Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at visibleearth.nasa.gov
●NASA Goddard Space Flight Center Image by Reto Stxckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

GW telescope network

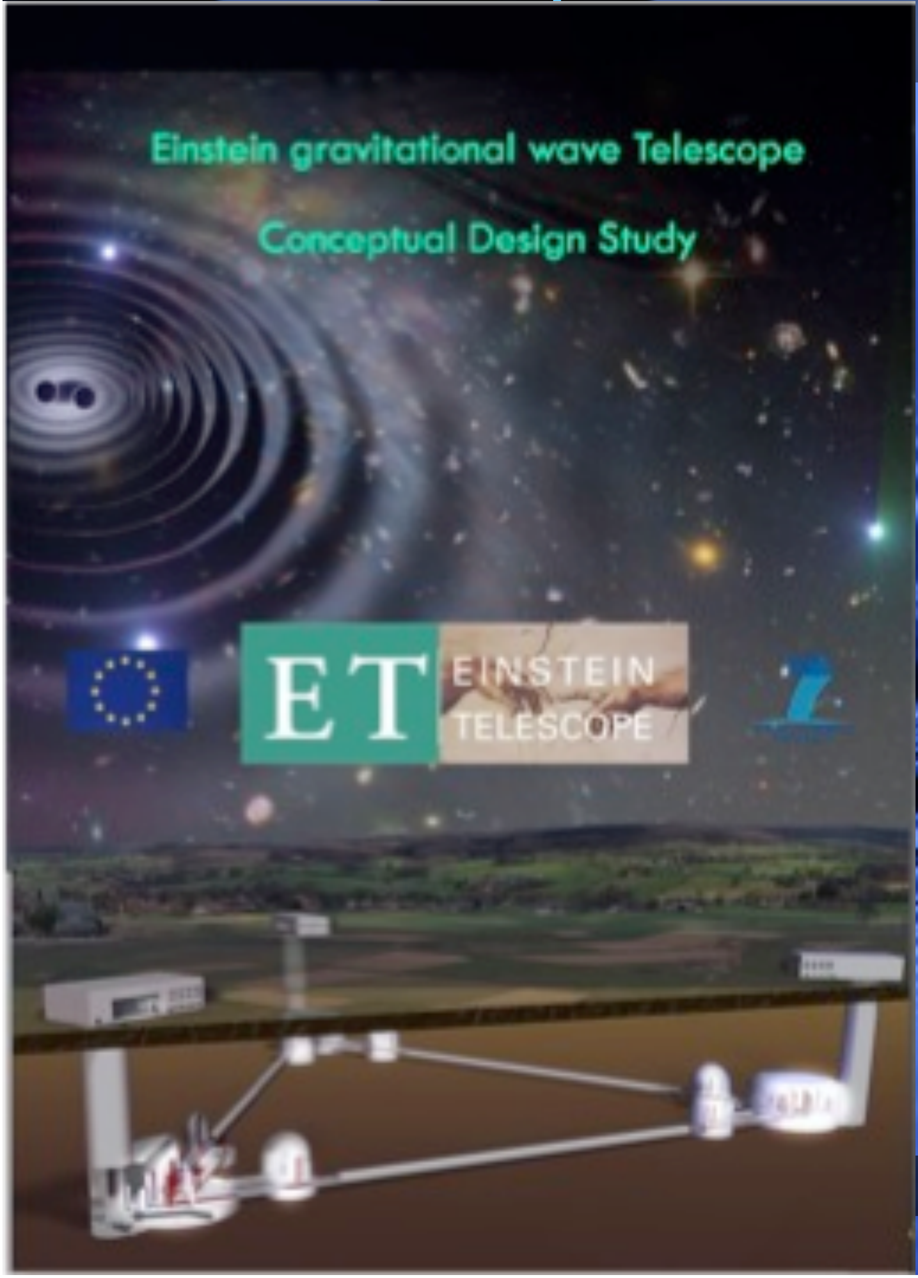


GW network

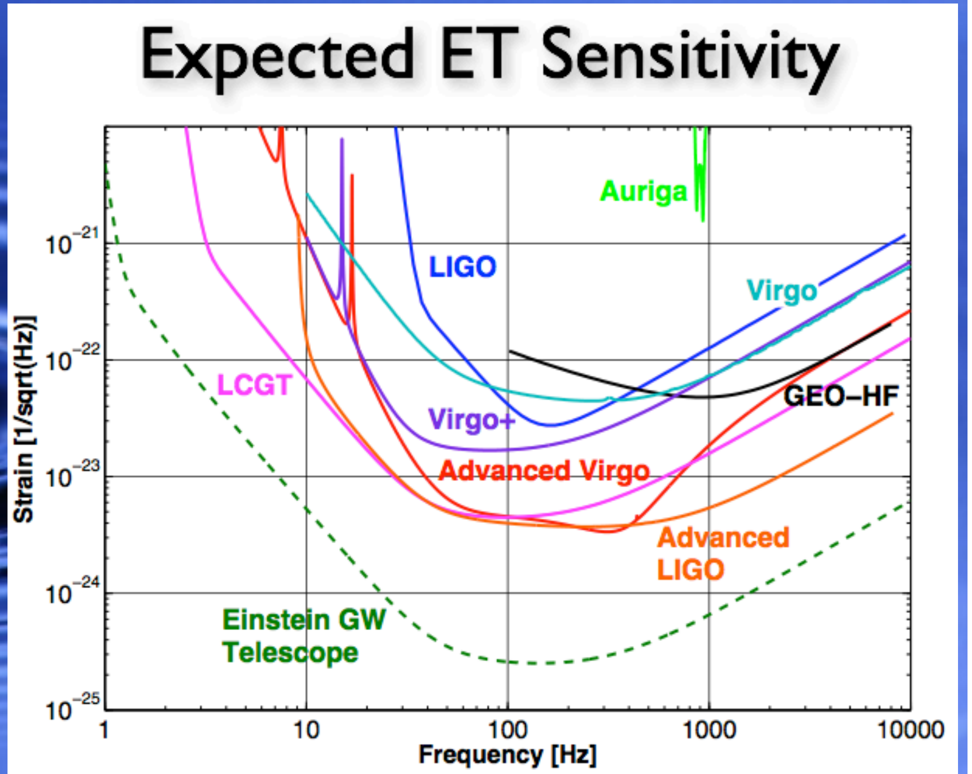
- At least 3 GW detectors which have the same sensitivity are needed to determine the location of GW source
  - Using difference of arrival time at each detector
  - International collaboration



Einstein Telescope (Future Plan)



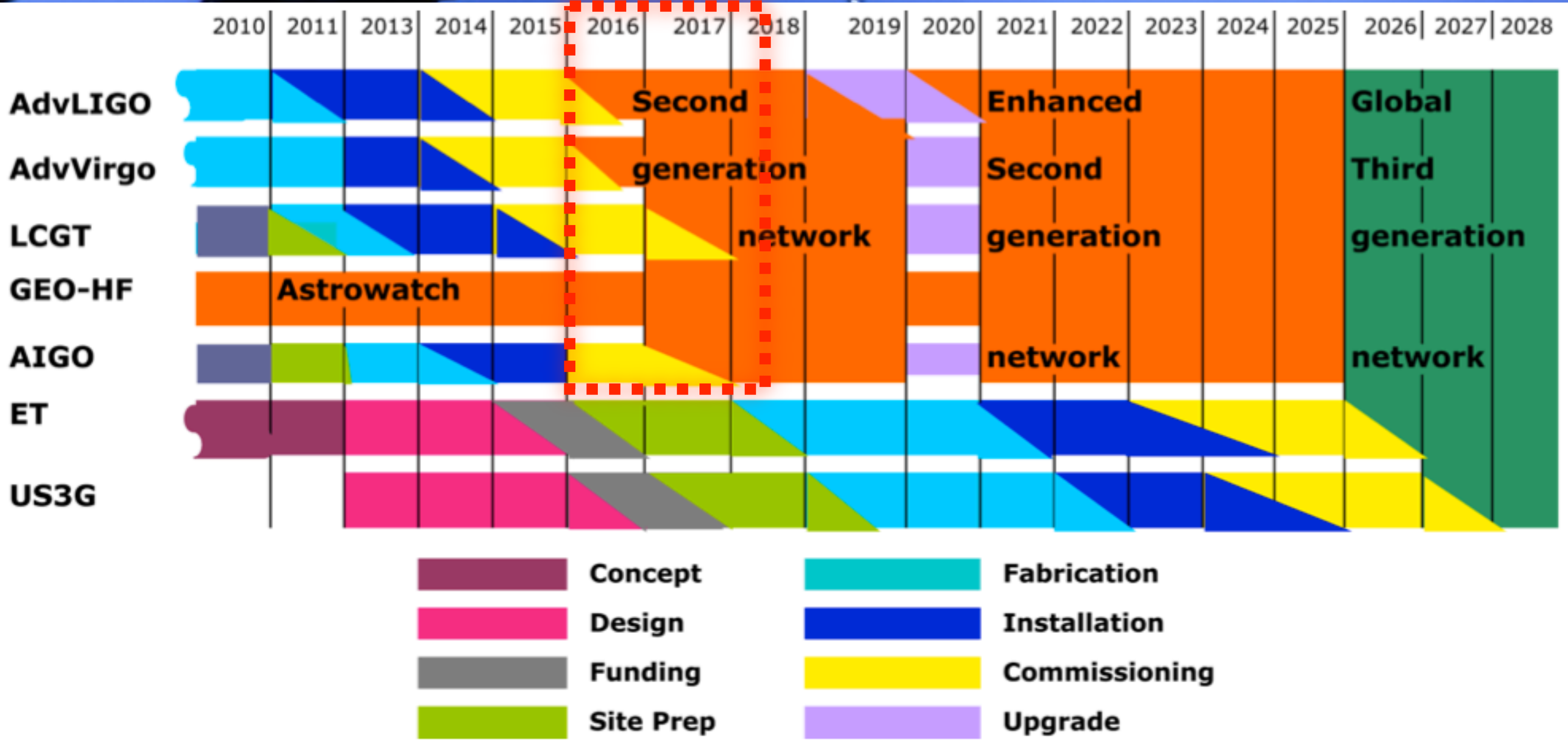
Future European project with 10 times better sensitivity than aLIGO/aVirgo/LCGT.



viewgraph by B.S. Sathyaprakash

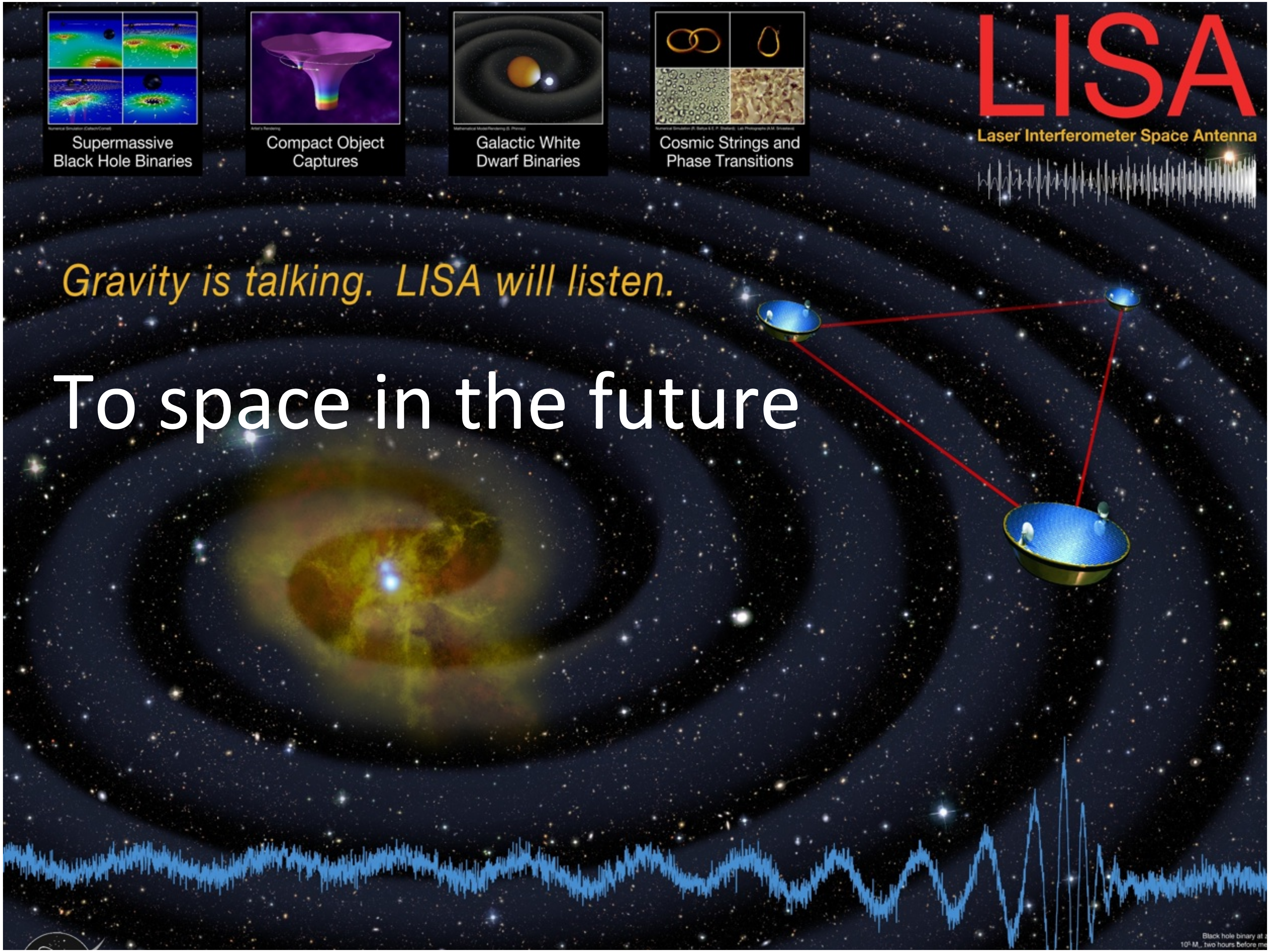
GWIC (Gravitational Wave International Committee) RoadMap

We expect first detection of GW !



https://gwic.ligo.org/
https://gwic.ligo.org/roadmap/Roadmap_100814.pdf

To space in the future



Einstein's Symphony

Fin