KAGRA: 2nd GENERATION of GRAVITATIONAL WAVE (GW) EXPERIMENT
&
FIRST UNDERGROUND GW EXPERIMENT

2019/5/19 @INFIERI

ICRR, University of Tokyo

Osamu Miyakawa

GW detection by LIGO!

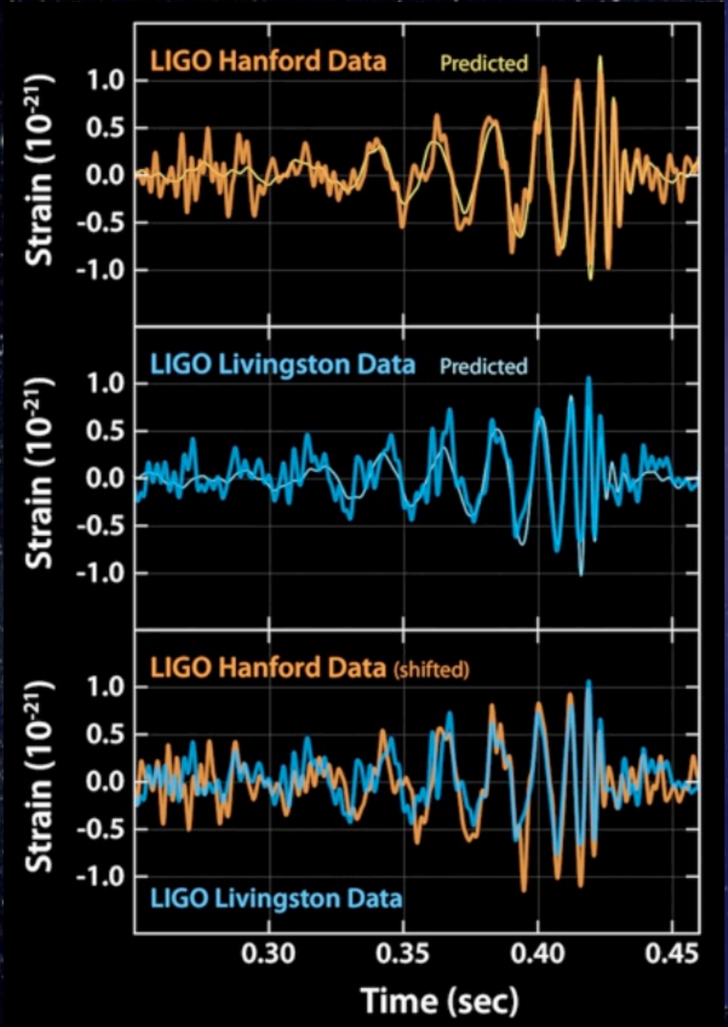
Gravitational wave was detected in 2016.

It was predicted by Einstein’ s General theory of relativity in 1916

Human being took almost 100 years from his prediction.

What was GW signal?

Wave forms measured by two LIGO detectors at very same time in 2015/9/14



- 36 Solar mass BH and 29 Solar mass BH merged into 62 Solar mass BH.
- Energy of 3 Solar mass ($E = m c^2$) was emitted as Gravitational waves !
- GW came from 1.3billion light year away.
- The results show that the general theory of relativity is correct.

Nobel prize for Physics in 2017

The Nobel Prize in Physics 2017

Nobelpriset i fysik 2017

KUNGL.
VETENSKAPS
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Med ena hälften till
With one half to:

och med den andra hälften gemensamt till
and with the other half jointly to:

Rainer Weiss
LIGO/VIRGO Collaboration

Barry C. Barish
LIGO/VIRGO Collaboration

Kip S. Thorne
LIGO/VIRGO Collaboration

"för avgörande bidrag till LIGO-detektorn och observationen av gravitationsvågor"

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

3 October 2017

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- Three LIGO scientists won the Nobel prize by GW detection.
- From left side "Experimentalist", "Project leader", "Theorist"


Drever

LIGO Chronology

idea to realization ~ 15 years


Weiss

Real size R&D for the real detection

Journey for the new astronomy

1970s		Feasibility studies and early work on laser interferometer gravitational-wave detectors
1979		National Science Foundation (NSF) funds Caltech and MIT for laser interferometer R&D
1984		Development of multiple pendulum Advanced LIGO Concept
1989	**December**	**Construction proposal for LIGO submitted to the NSF ($365M as of 2002)**
1990	May	National Science Board approves LIGO construction proposal
1994	July	Groundbreaking at Hanford site
1999		LIGO Scientific Collaboration White Paper on a Advanced LIGO interferometer concept
2000	October	Achieved “first lock” on Hanford 2-km interferometer in power-recycled configuration
2002	August	First scientific operation of all three interferometers in S1 run
2003		**Proposal for Advanced LIGO to the NSF ($205 NSF + $30 UK+Germany)**
2004	October	Approval by NSB of Advanced LIGO
2005	**November**	**Start of initial LIGO Science run, S5, with design sensitivity**
2008	April	Advanced LIGO Project start
2009	July	Science run (“S6”) starts with enhanced initial detectors
2014	May	Advanced LIGO Livingston first two-hour lock
2015	March	Advanced LIGO all interferometers accepted
2015	September	Advanced LIGO observation run 1 and detected GW

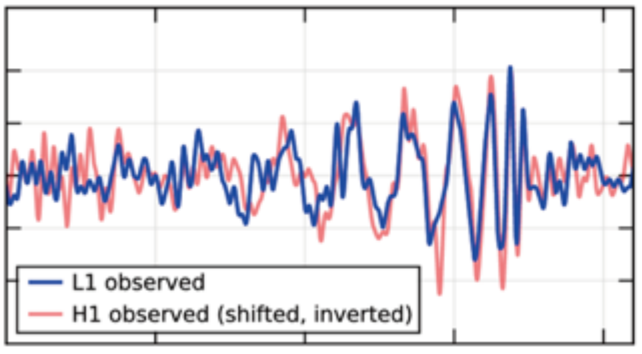

Vogt

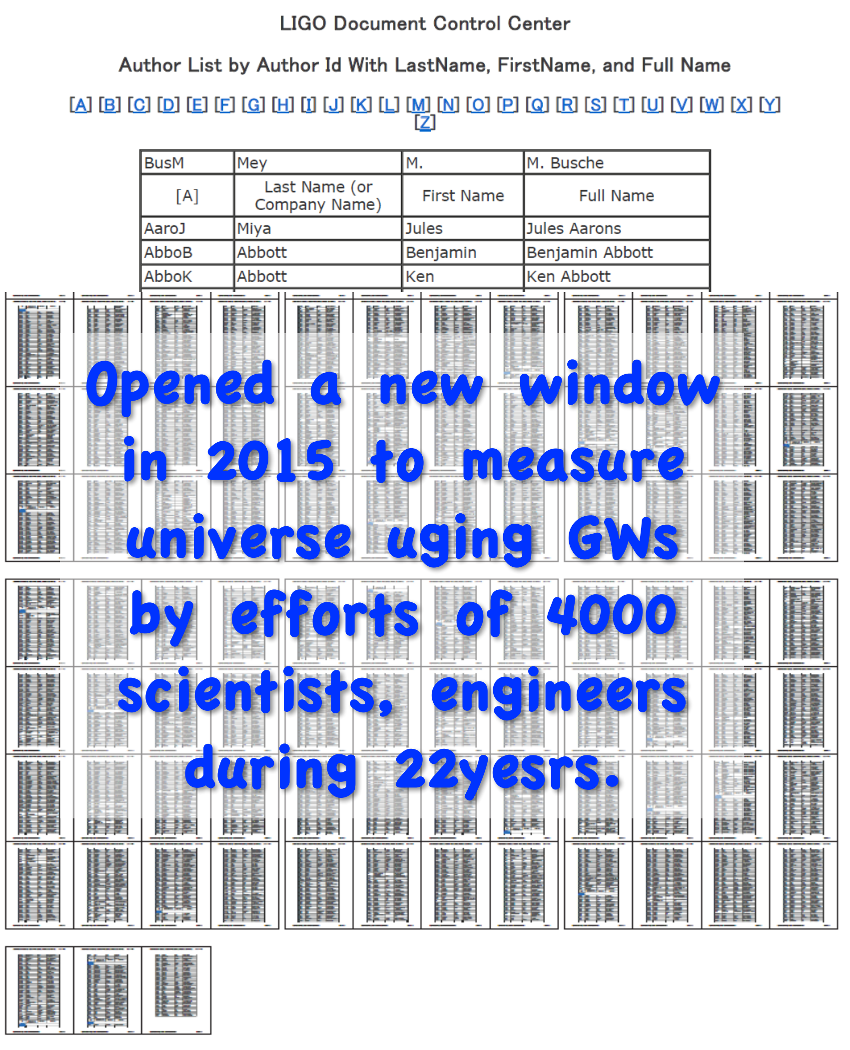

Thorn

Initial LIGO events

Advanced LIGO events

R&D of aLIGO using iLIGO facility





LIGO Document Control Center

Author List by Author Id With LastName, FirstName, and Full Name

[A] [B] [C] [D] [E] [F] [G] [H] [I] [J] [K] [L] [M] [N] [O] [P] [Q] [R] [S] [T] [U] [V] [W] [X] [Y] [Z]

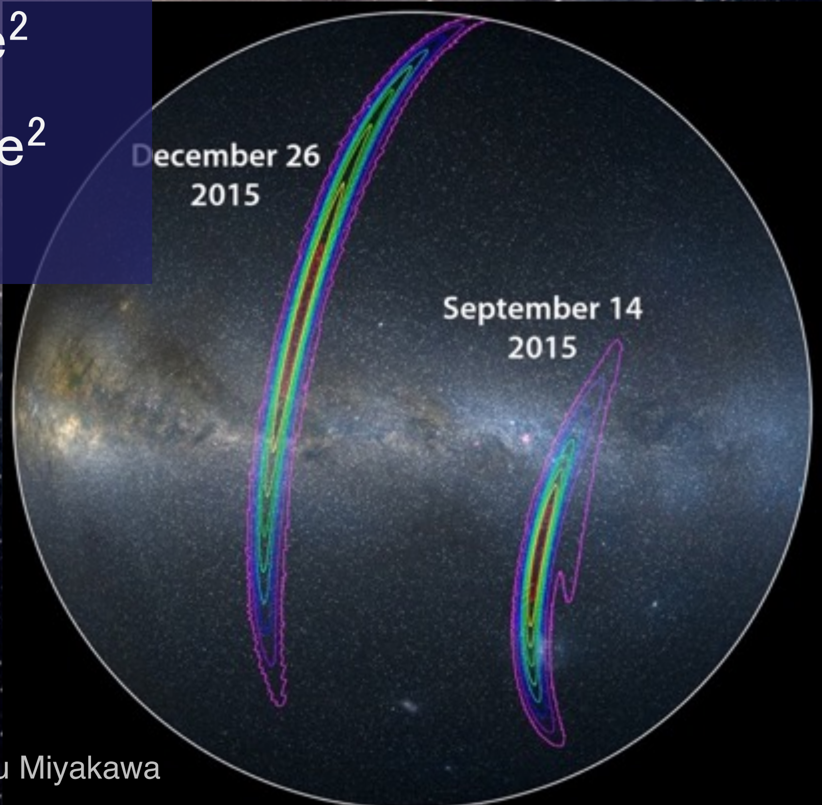
BusM	Mey	M.	M. Busche
[A]	Last Name (or Company Name)	First Name	Full Name
AaroJ	Miya	Jules	Jules Aarons
AbboB	Abbott	Benjamin	Benjamin Abbott
AbboK	Abbott	Ken	Ken Abbott

Opened a new window in 2015 to measure universe uging GWs by efforts of 4000 scientists, engineers during 22yesrs.

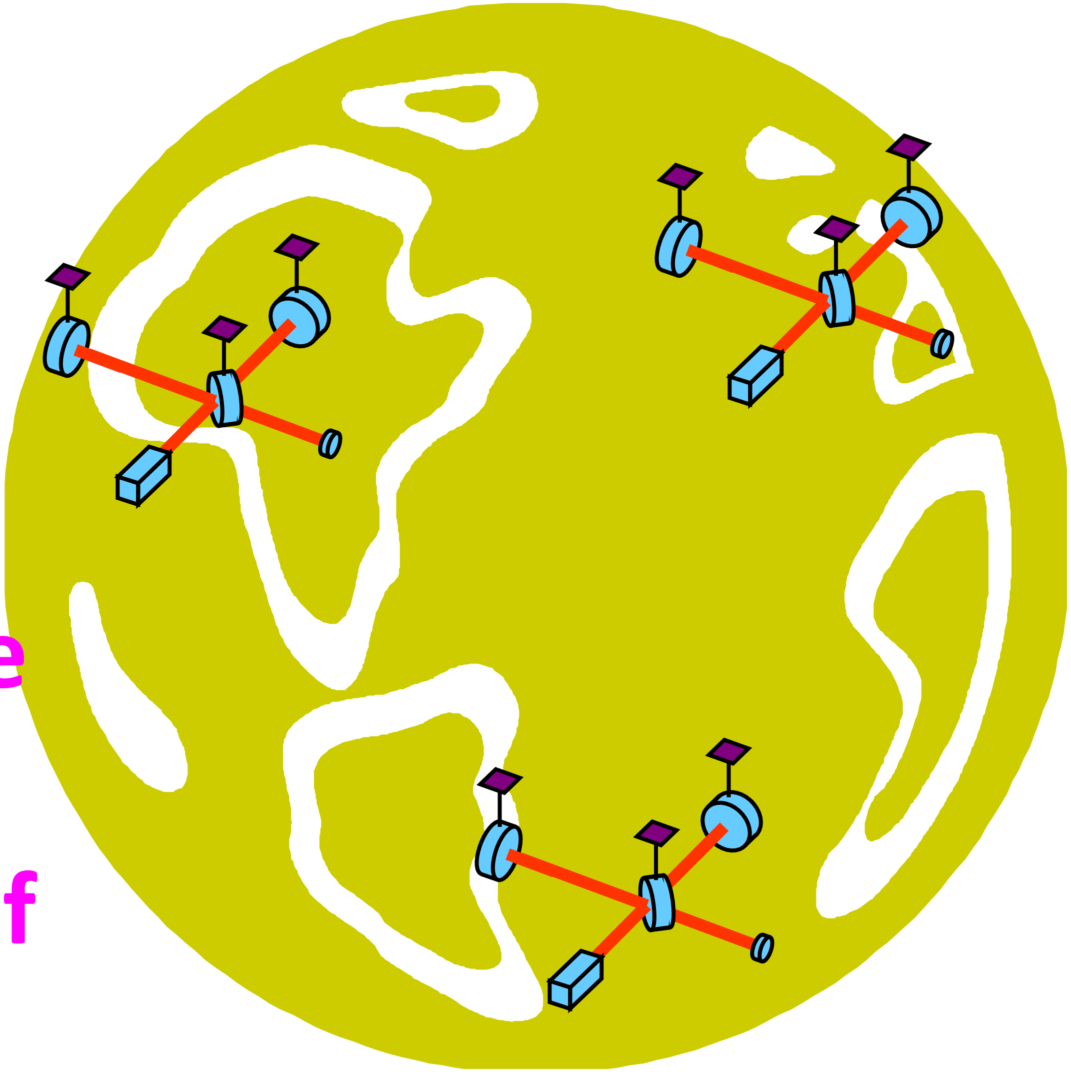
Localization for GW source

- 2 detectors could localize GW source only in very wide range
- 2 LIGO determined ~500degree^2

  ⇒ Too wide to determine where it came from.
- +VIRGO can determine in ~30degree^2
- +KAGRA can determine in ~10degree^2

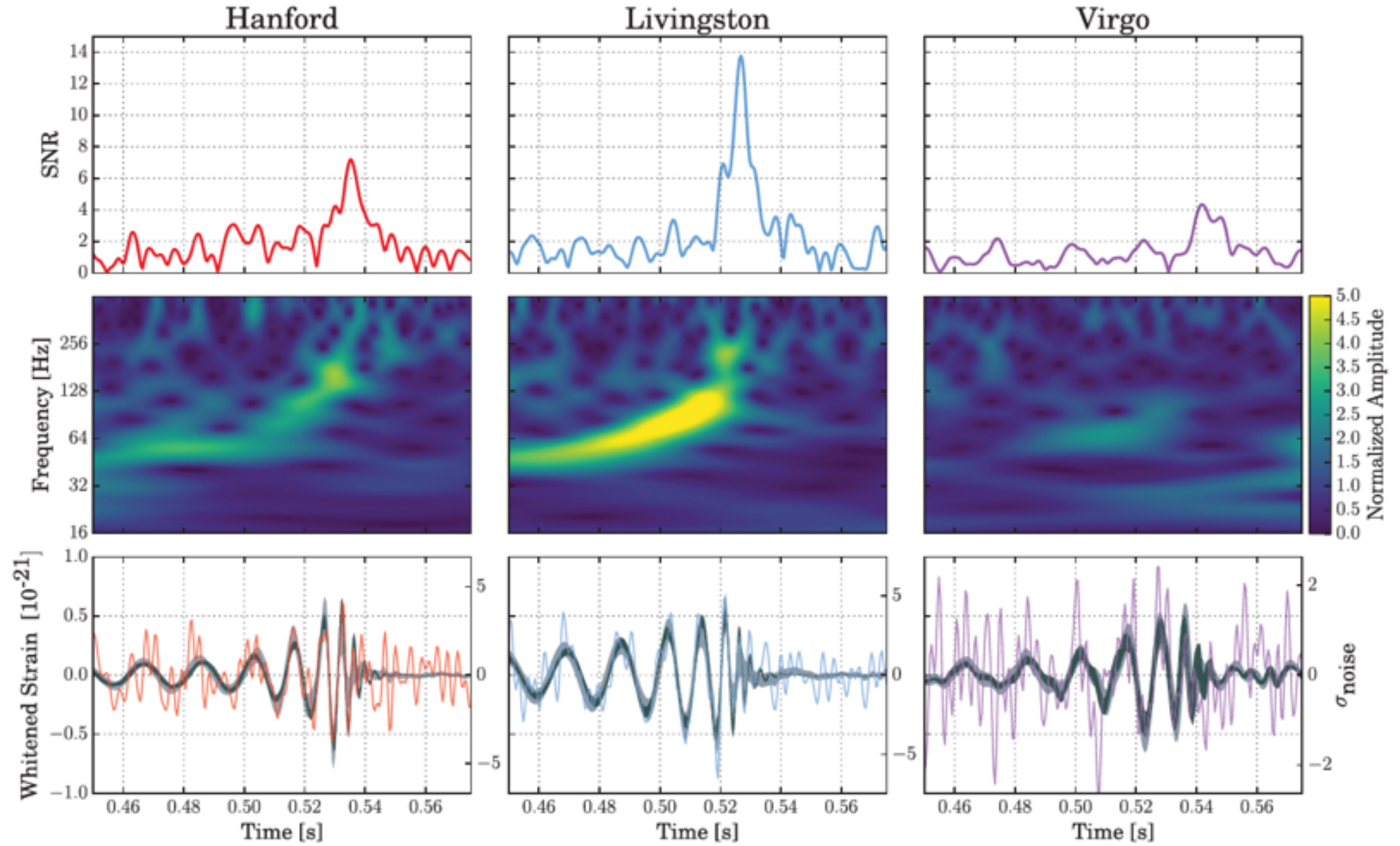


Direction of GW source?



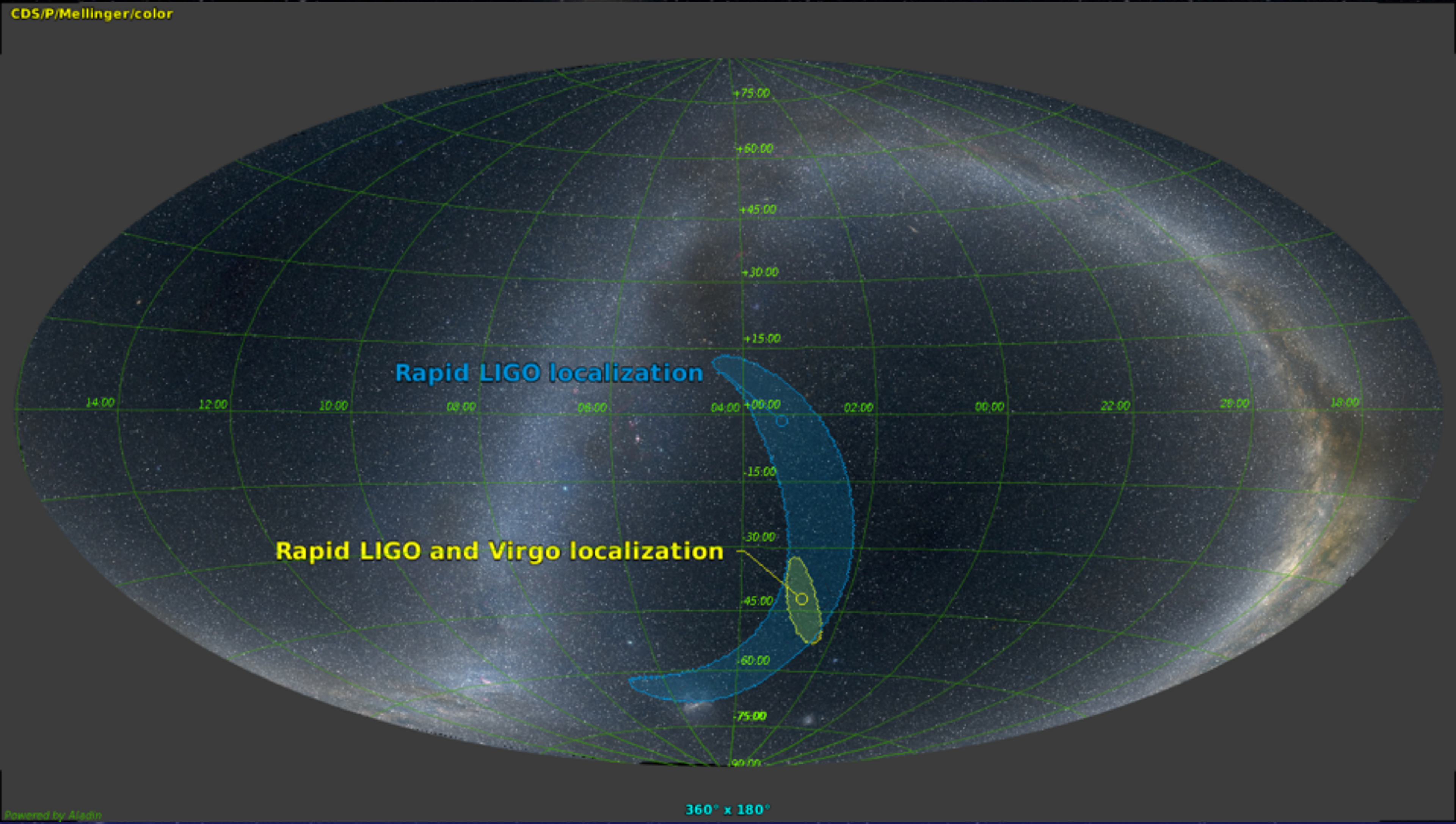
Direction can be extracted from the difference of arrival time ！

2017 August, three detectors measured GW

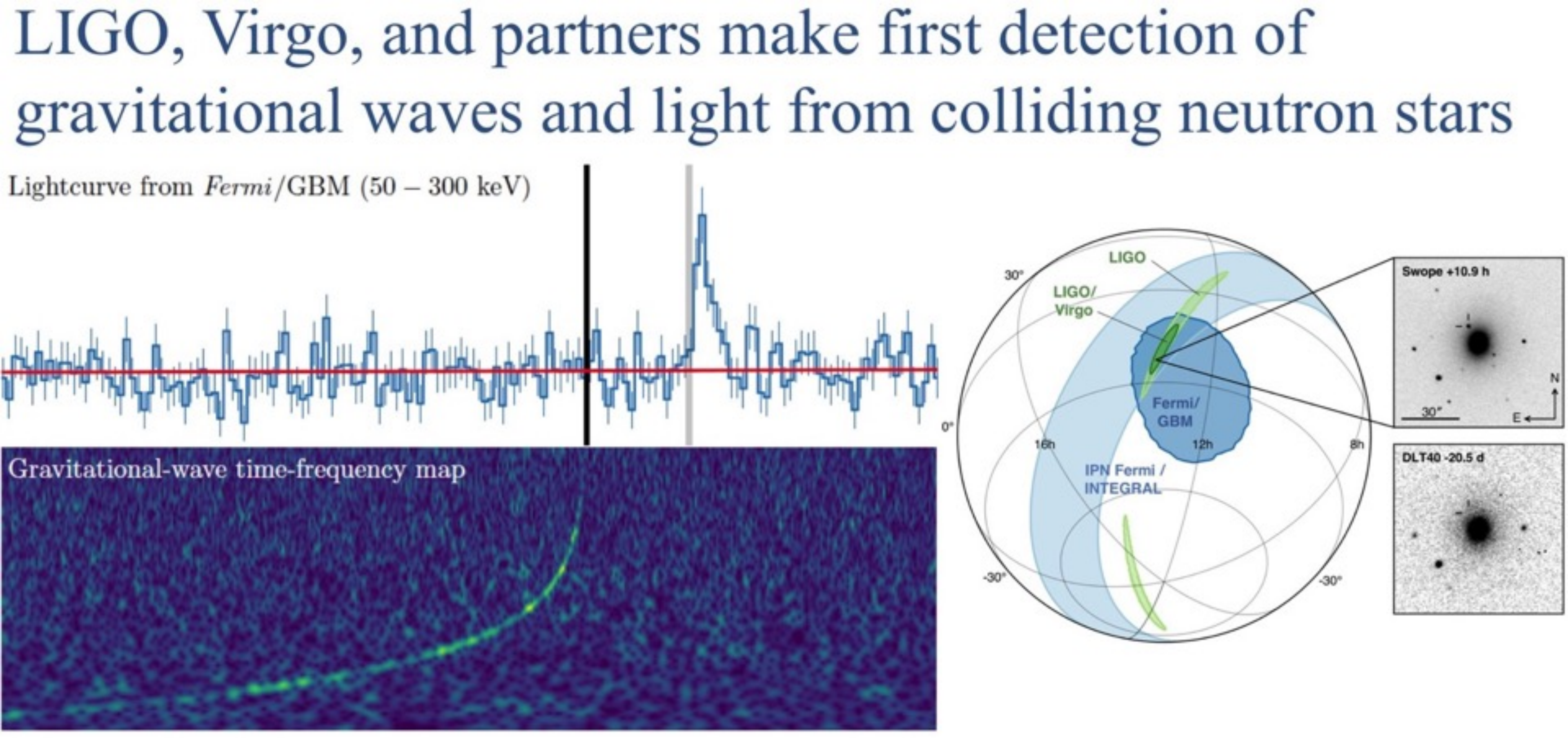


- Two LIGO + Virgo
- Virgo: sensitivity was not enough but contributed for localization.

Localization

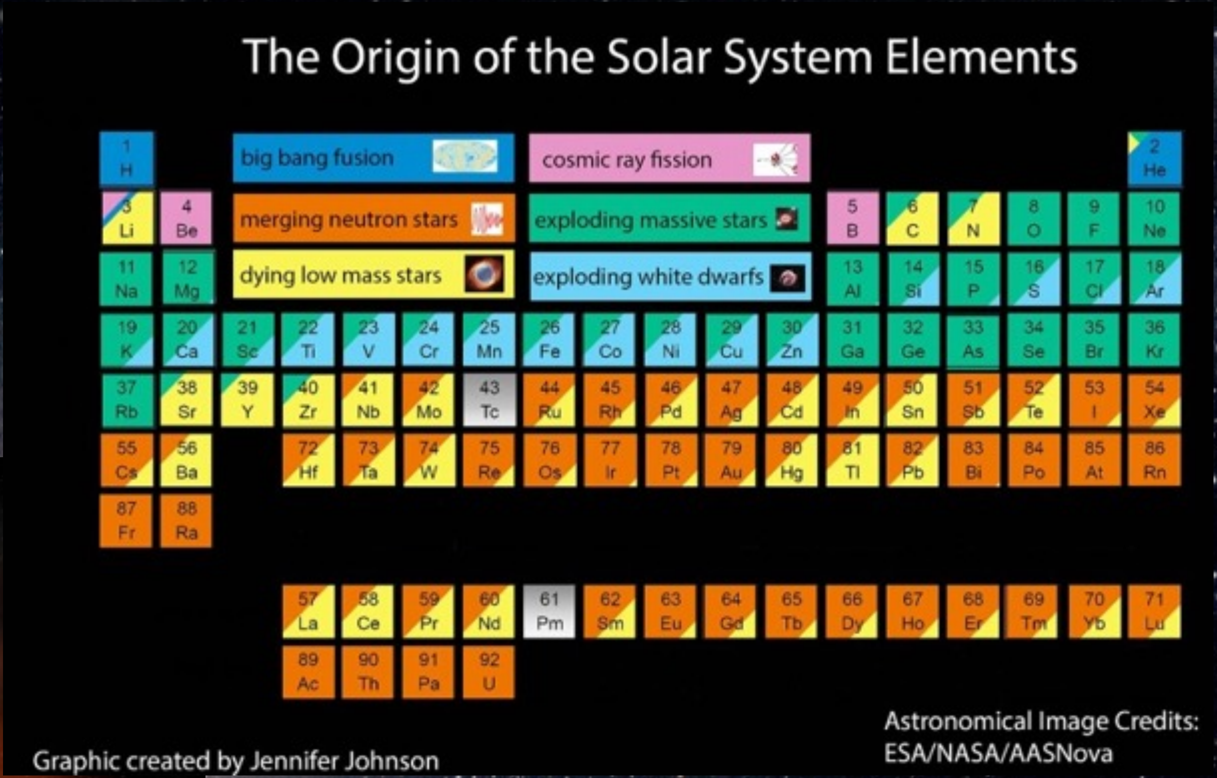


It was also seen in Gamma ray.



LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Periodic table of elements was replaced by merging neutron stars



The Origin of the Solar System Elements

- big bang fusion
- cosmic ray fission
- merging neutron stars
- exploding massive stars
- dying low mass stars
- exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Graphic created by Jennifer Johnson

Astronomical Image Credits:
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- Gold as amount of 10 moons was made in a moment!

100 Years of Detector Development

1916	Einstein predicted gravitational waves
1960s	Weber Bar at U Maryland
1969	Weber claimed detection
1972	Weiss publishes first practical description of laser interferometer detector
1974	Hulse and Taylor discovered a binary neutron star system
1997	Resonant bar detector network begins operation
1999-2007	TAMA (1999) Initial LIGO (2002), GEO (2002), Initial VIRGO (2007) started their observations
2009	LIGO-VIRGO 1 year observation
2010	LIGO & VIRGO started their upgrades
2014	BICEP2 reported evidence for cosmological GWs, but it was foreground dust
2015	LIGO’s first detection (announced in 2016)

Einstein and relativity

Special Relativity (1906):

⇒ 4-dim space-time geometry

⇒ rest mass is a form of energy

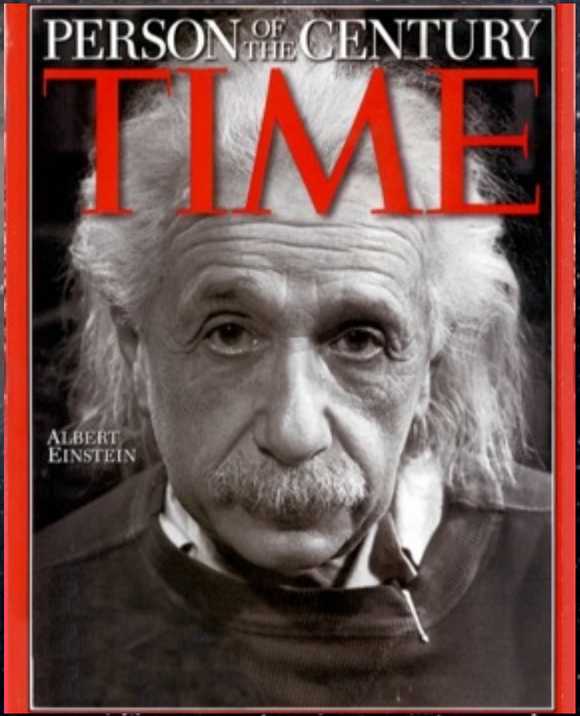
$$E = mc^2$$

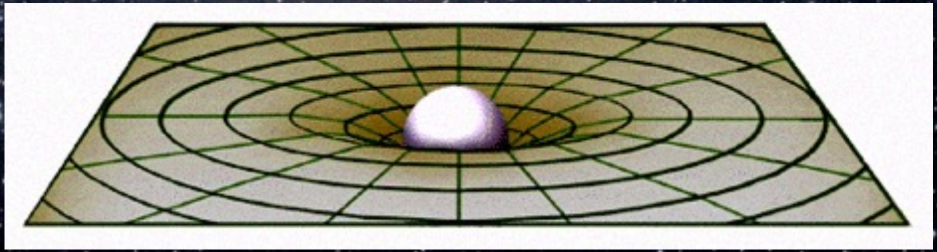
General relativity (1916):

⇒ Einstein's field equation :

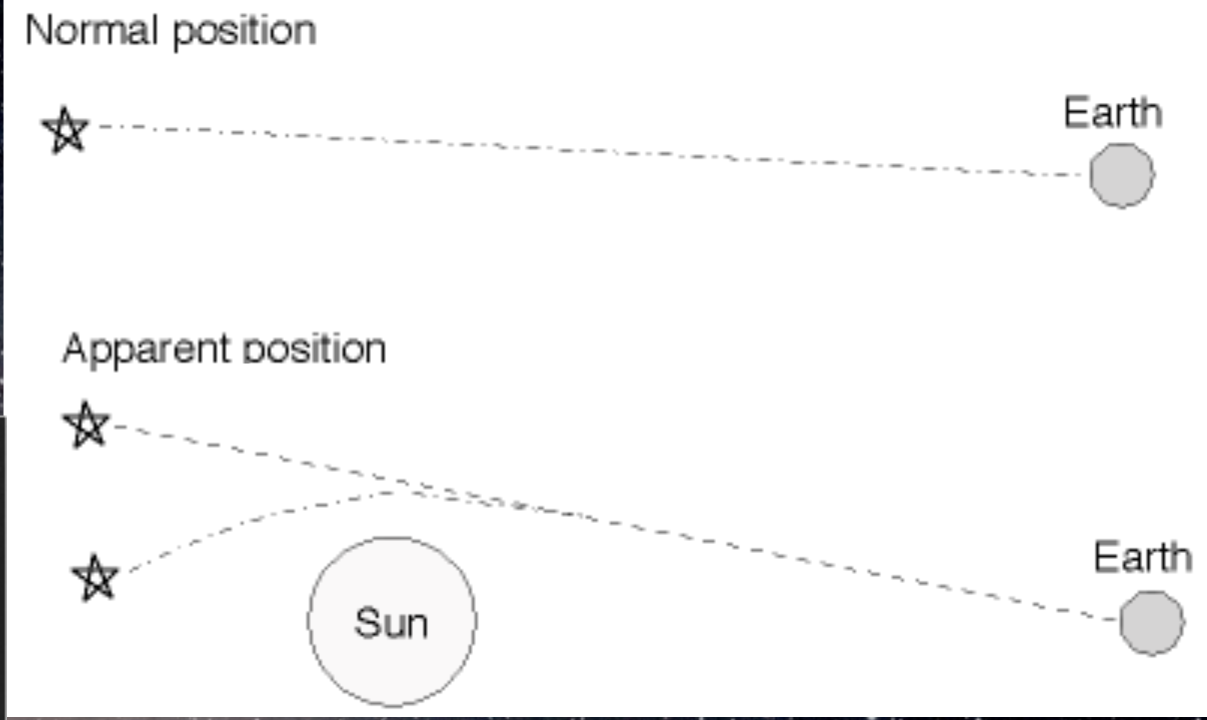
$$G = 8pT$$

spacetime curvature ⇔ matter and energy





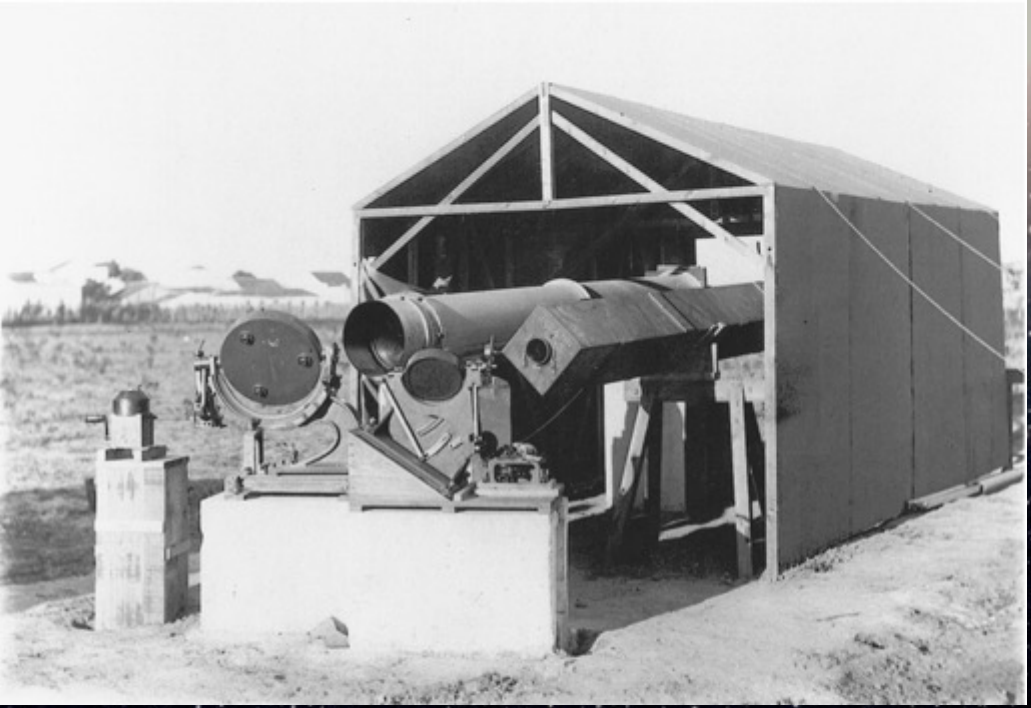
New prediction by Einstein’s theory



- Light can be bent if it goes along heavy mass like the sun.
- **It is observable only in a total solar eclipse.**

Verification of Einstein’s prediction

- May 29, 1919 Arthur Stanley Eddington measured Hyades during total solar eclipse.



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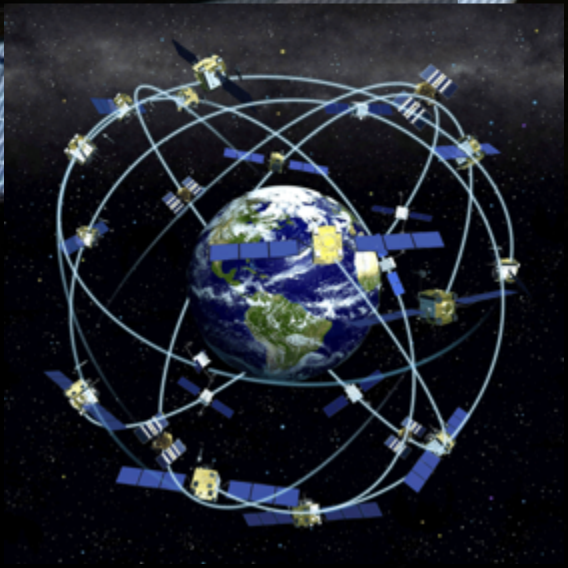
	Measured shift
Newton thery	**0.87arcsec**
Einstein theory	**1.75arcsec**
Island of Príncipe	**1.61 ± 0.30 arcsec**
Sobral	**1.98 ± 0.12 arcsec**

Car navigation system cannot work without Einstein theory



- Satellite moving 20000km above, time goes 0.000286sec per day faster than surface of earth because of smaller gravity.
- Car navigation system has 11km error in a day if no compensation by general relatibity.

Electro Magnetic waves and Gravitational waves

Electromagnetism:

Acceleration of electric charge

↓

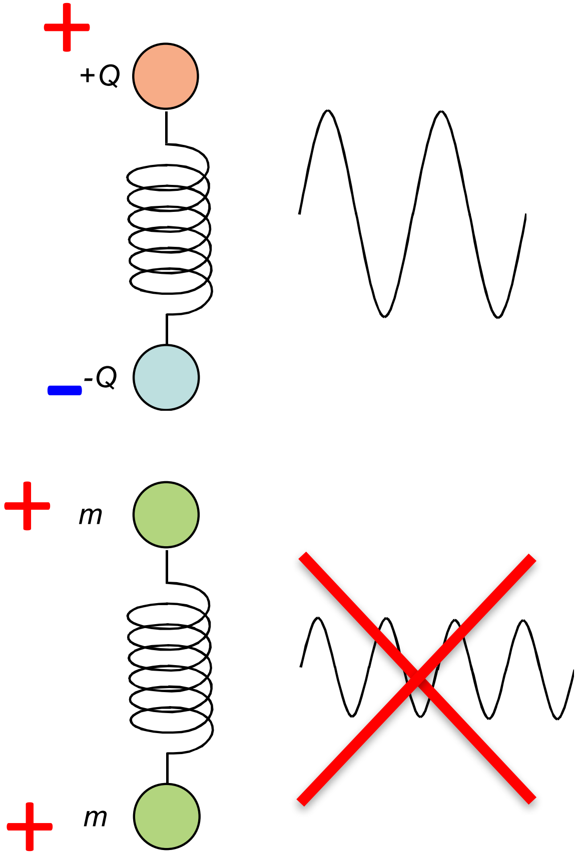
Electromagnetic waves

General relativity:

Acceleration of mass

↓

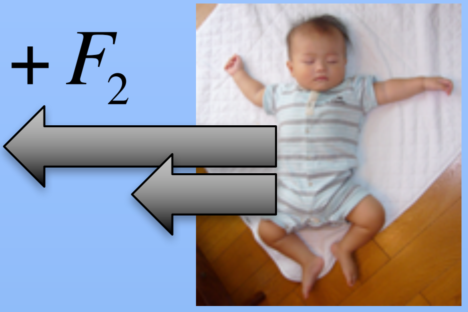
Gravitational waves



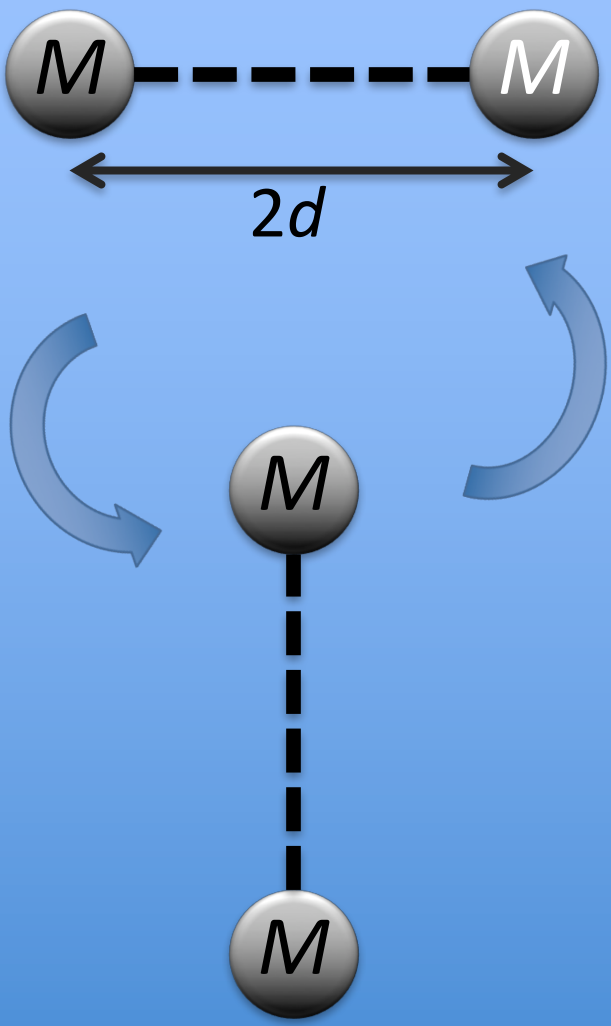
2 masses

Observer

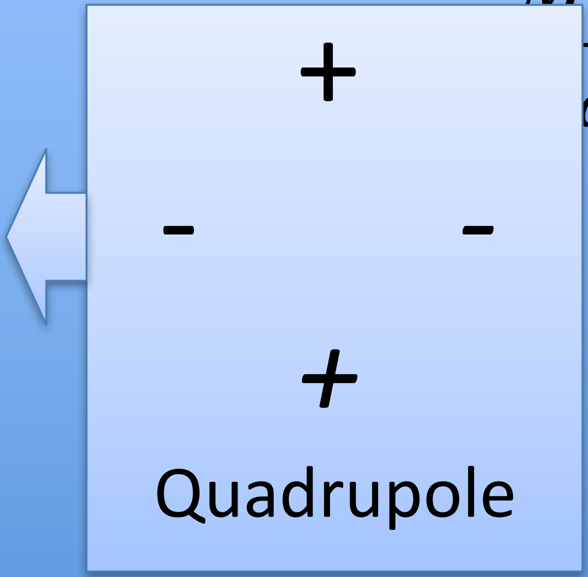
$$F = F_1 + F_2$$



← Distance: *R* →

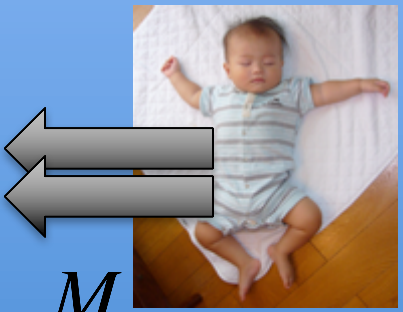


$$\frac{M}{d)^2} + G\frac{M}{(R-d)^2}$$



Quadrupole

Observer

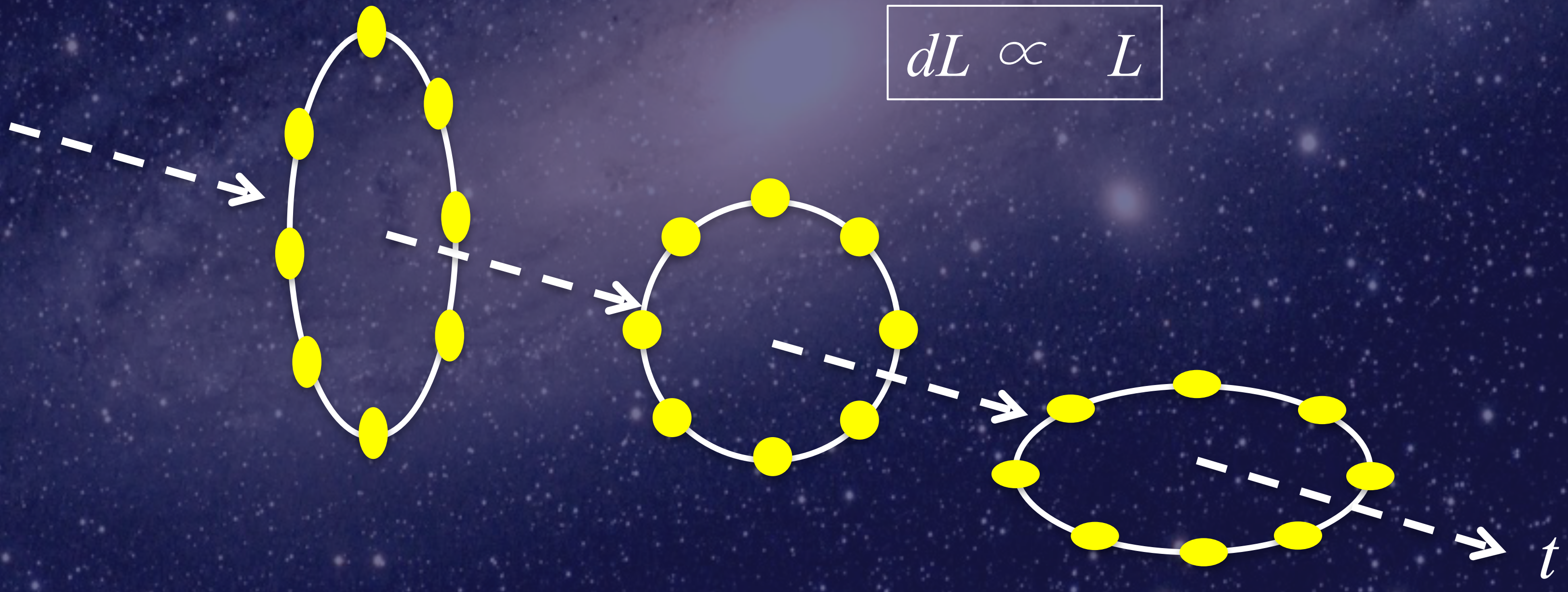


$$F \approx G\frac{M}{R^2} + G\frac{M}{R^2}$$

When GWs come...

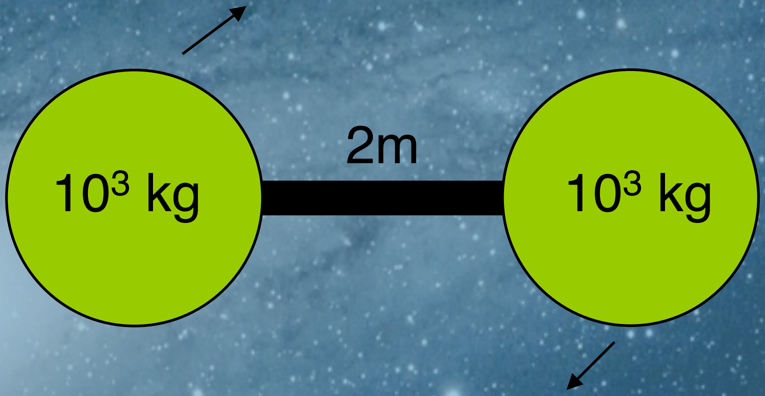
Space-time squeeze and stretch when the GWs pass
→ Distances between free-falling masses change

$$\boxed{dL \propto L}$$



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

$\gg 10^{-36}$!!

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

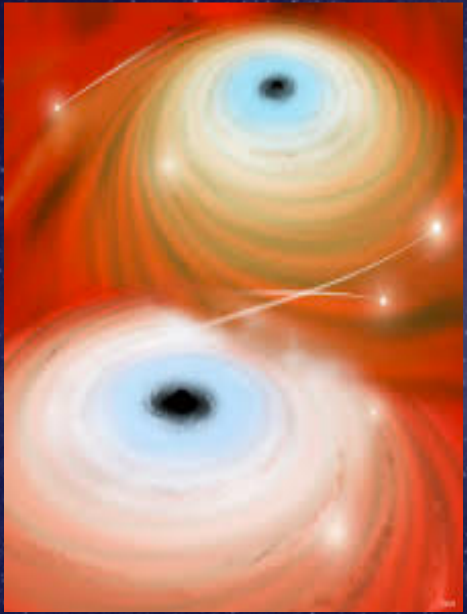
13 orders smaller !!
(detection limit is ~ 10^{-23})

Gravitational Wave Sources

Every object having mass emits GW,

however, observable sources are

→ Drastic Astrophysical Phenomena



Binary Black Hole Merger

Supernova

Binary Neutron Star Merger

Unknown Source

?

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)

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

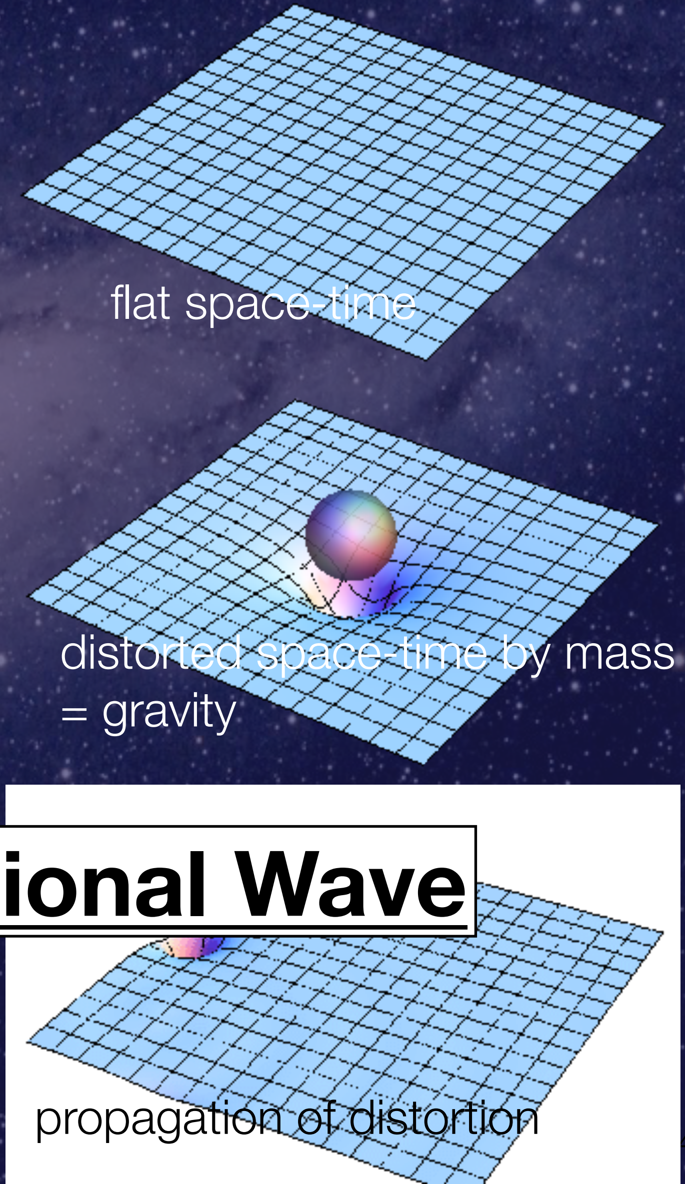
"curved (distorted)" space-time

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

small perturbation 'h' --> Waves

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

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



Gravitational Wave

What is Gravitational Wave ?

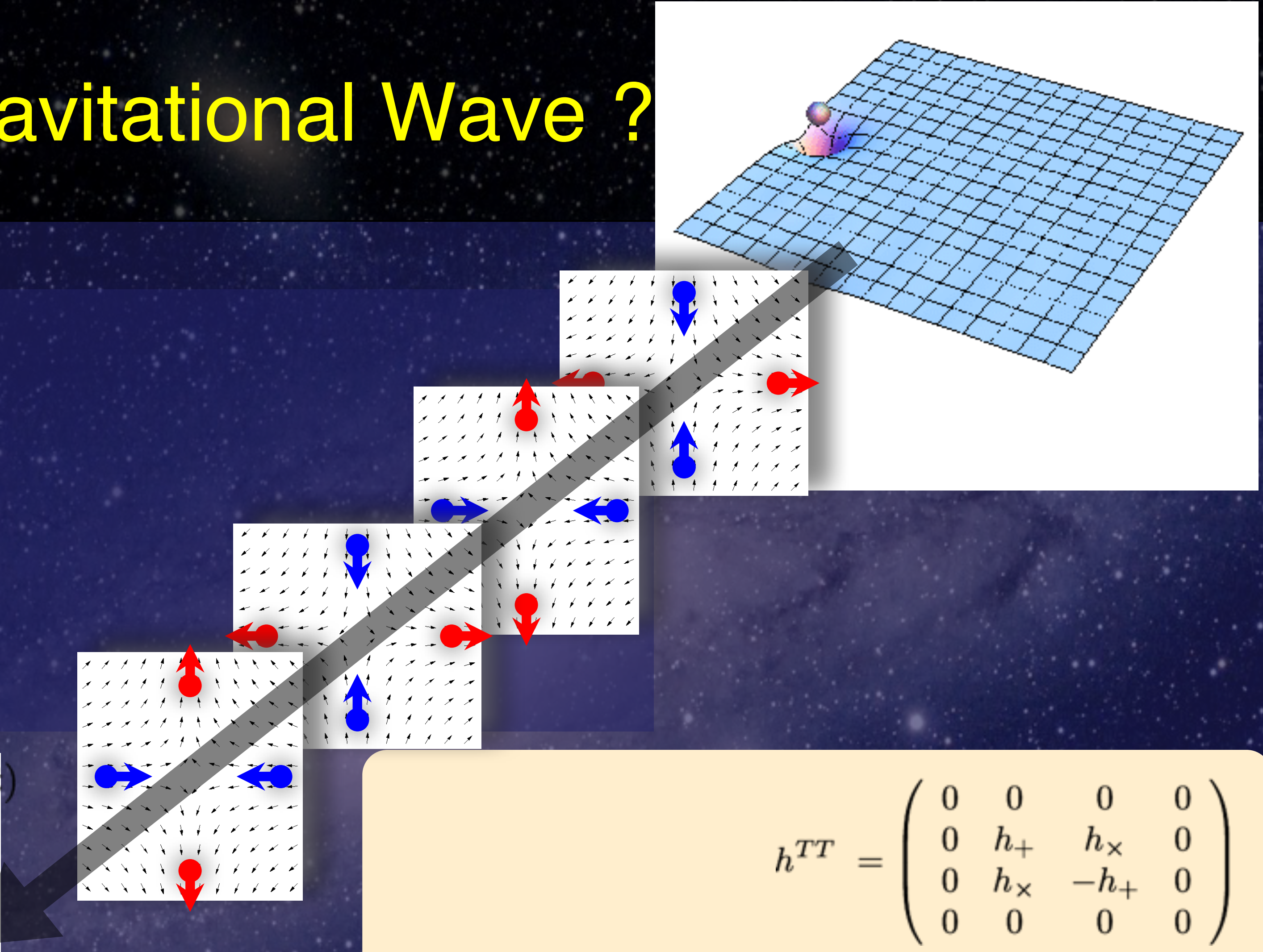
- **Characteristics:**

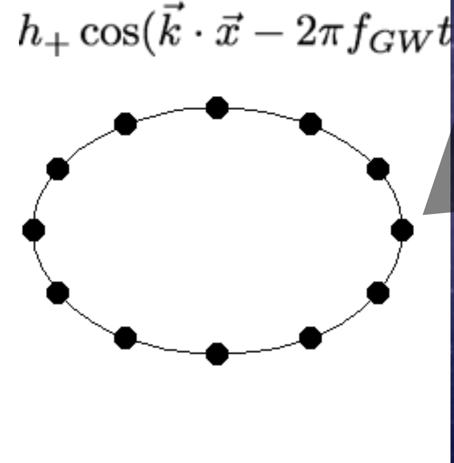
⇒light speed

⇒transverse

⇒quadrupole

⇒(tidal force)





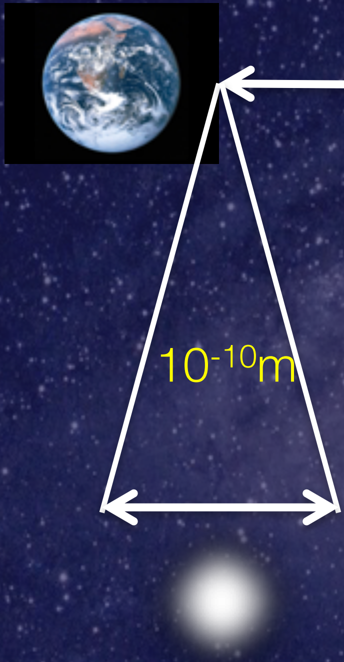
Tidal force on masses will be induced by GW incident.

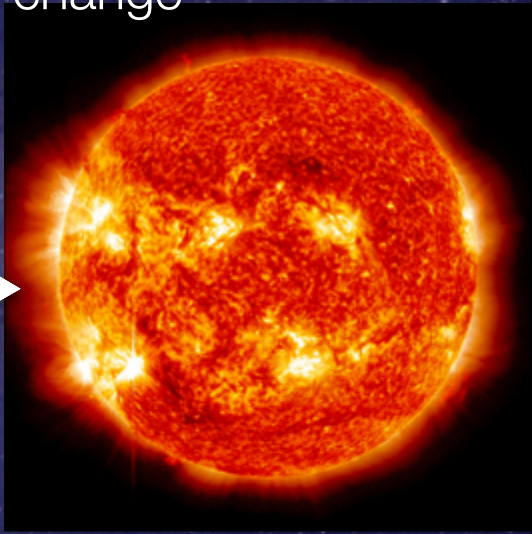
$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

Amplitude of Squeeze & Stretch

A ratio as small as hydrogen atom size length change
for a Sun – Earth distance





150,000,000 km

(1.5×10^{11}m)

Strain (ratio of squeeze and stretch)

$= 10^{-10}\text{m} / 10^{11}\text{m}$

$= 10^{-21}$

Hydrogen atom

GPS: 10000km above, 1cm accuracy

$= 10^{-2}\text{m} / 10^{7}\text{m}$

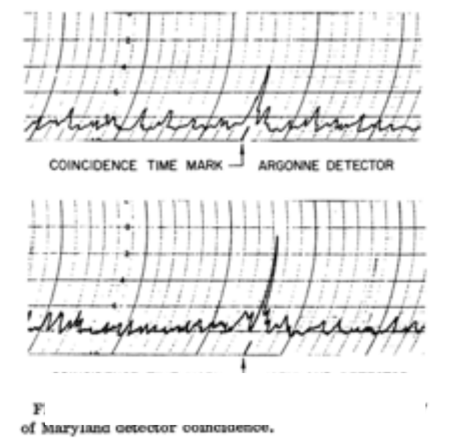
$= 10^{-9}$

Weber’s Bar Detector in 60s

Pioneer work for experimental search

Aluminum alloy
cylinder bar
GWs excite the
mechanical resonance

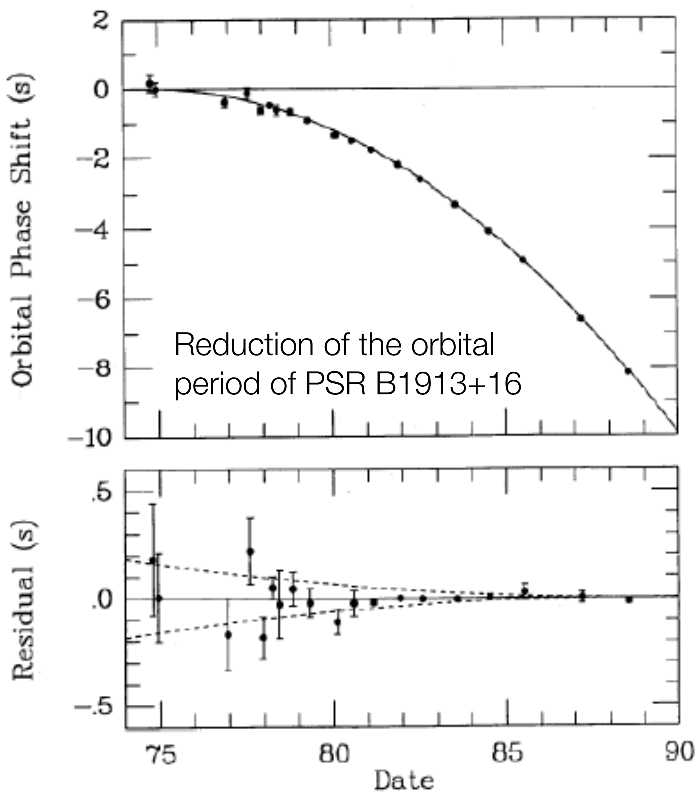
AIP Emilio Segre Visual Archives



He claimed the detection and many groups built bar detectors motivated by his work

His events are considered as noise nowadays, but he triggered the experimental approach to detect GWs

Hulse and Taylor’s Discovery



Reduction of the orbital period of PSR B1913+16

FIG. 5.—*Top:* Cumulative shift of the times of periastron passage relative to a nondissipative model in which the orbital period remains fixed at its 1974.78 value. *Bottom:* Differences between the locally measured periastron times and those expected according to the DD(1) parameter set. Dashed curves illustrate differential trends that would be
if the rate of orbital decay $\dot{P}_b$ were 2% larg

Evidence of gravitational waves!

Nobel Prize

“For the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.” (1993)

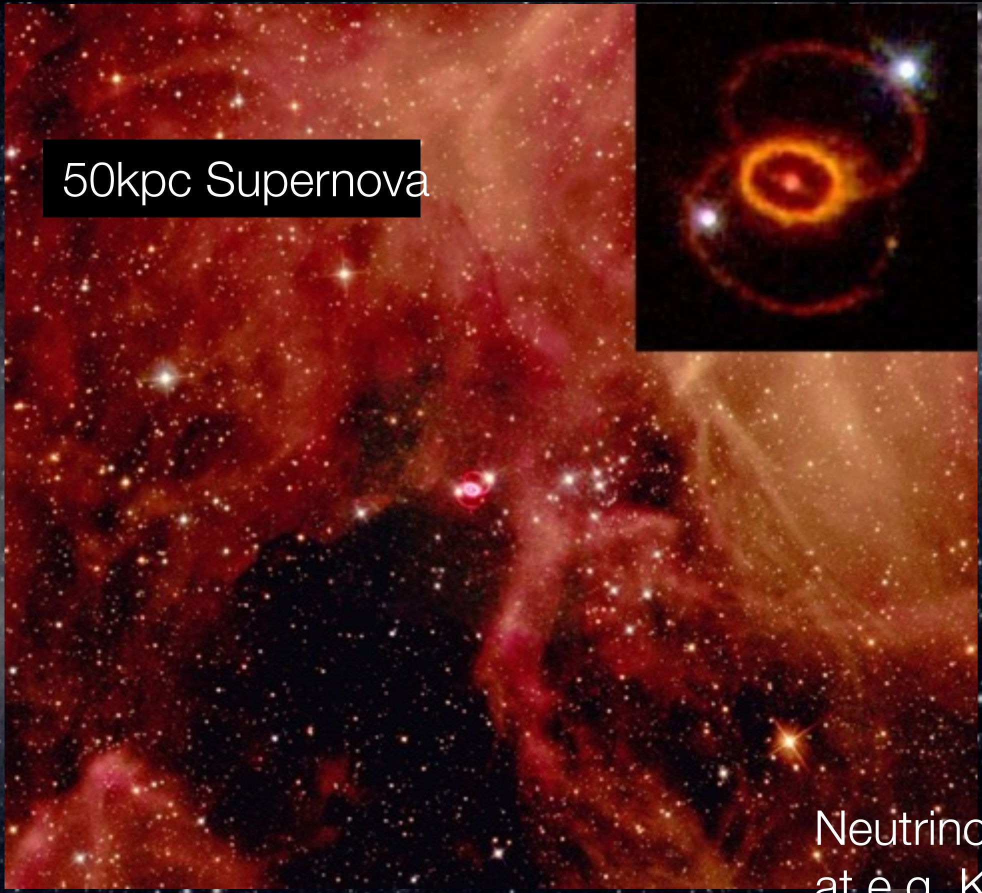
Bar Detectors in 80's

- More sensitive (many were cryogenic, suspended etc) bars were built
- Observation run with three detectors, "triple coincidence," were made in 1986

  ⟹ Allegro (LSU), Explorer (CERN), and Stanford bar detectors

Supernova 1987A

Major bar detectors were down for upgrades!



50kpc Supernova

Neutrino events
at e.g. Kamiokande

Bar Detector Network (90s)

Res.Astron.Astrophys. 11 (2011) 1-42

Allegro (LSU)

Explorer (CERN)

NIOBE (Perth)

NAUTILUS in Italy

http://www.auriga.lnl.infn.it/

AURIGA (Italy)

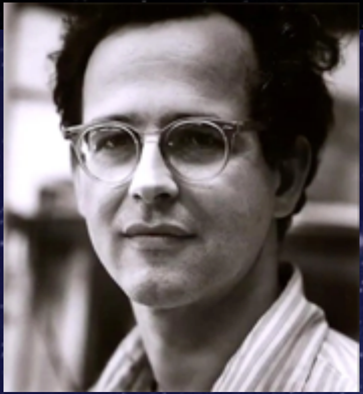
GW International Collaboration was Formed

- In 90s, they decided to share the data to improve the statistical results
- 97-03 triple operation for two years, quadruple operation for four months
- Allegro – iLIGO joint search in 2007

Resonant Bar Detector Params

Project	Location	Features	Sensitivity
Allegro	LSU	2300 kg, AL5056 cylinder, 3 m long, 4.2 K 6K	904Hz 7e-19
Explorer	CERN	AL5056 cylinder, 2270 kg, 3 m long, 2.5 K	3e-21 at 906 and 923 Hz. CQG 19 (2002) 1905-1910
NIOBE	Western Australia	Niobium, 2-5K.	700Hz. Strain sensitivity of 1e-22 can be achieved.
AURIGA	Italy	2300 kg, 3 m long, aluminum cylinder 0.1K	4e-22 at 911, 929 Hz (2Hz BW)
NAUTILOUS	Italy	Al 5056 cylinder, 2350 kg, 0.1K S1 '95-97, S2'98,3 '02	908 and 924 Hz. NAUTILUS has a sensitivity 4e-22. Pulsar in NS 1987A CQG 19 (2002) 1911-1917

First R&Ds for Interferometry (70s - 80s)



Russian scientists proposed in 1962
Weiss independently got the idea and proposed in ‘72

Weiss, Thorne and Drever established the idea to use laser interferometers for the GW detections

Possible noise sources, required size of the detector, and optical technologies were studied

Early Prototypes

- MIT 1.5m prototype delay line
- Munich 3m prototype
- Glasgow 10m prototype

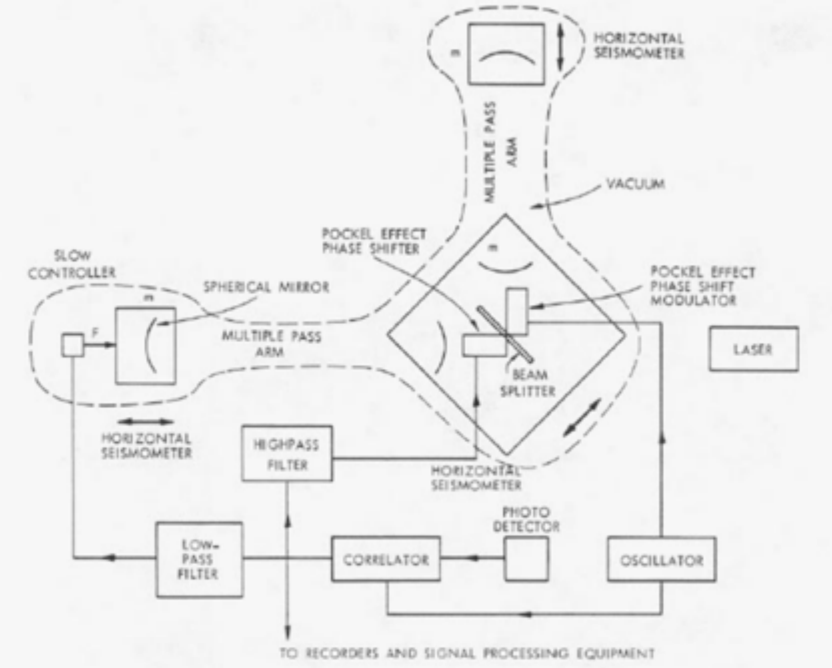
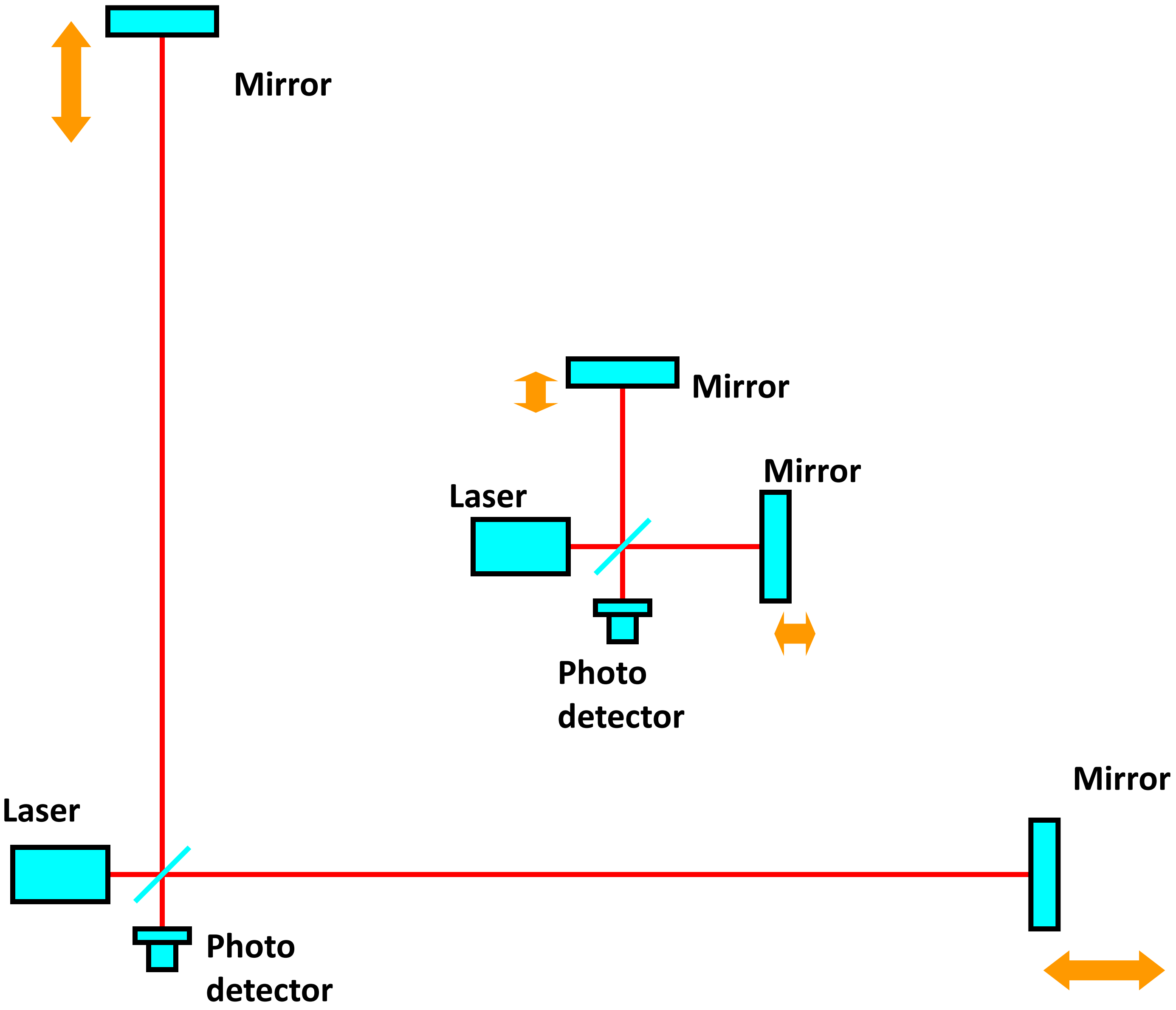


Fig. V-20. Proposed antenna.

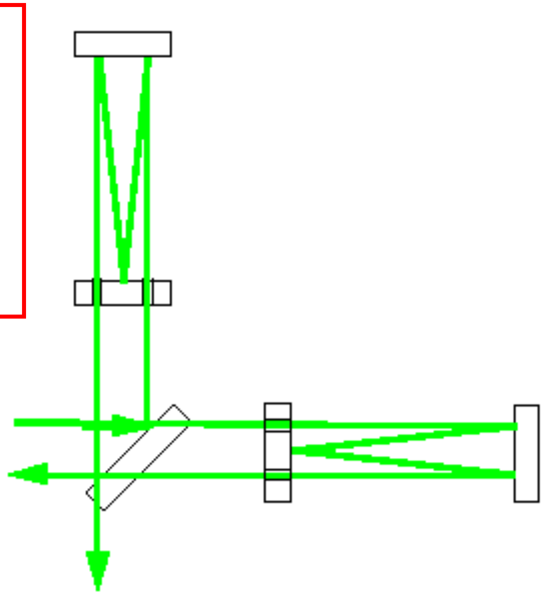
Longer arm length, better sensitivity



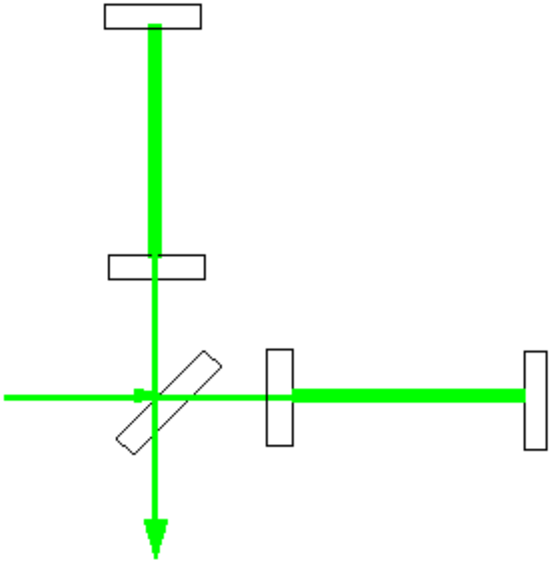
Light storage: folding the arms

How to get long light paths without making *huge* detectors:

Fold the light path!



Delay line interferometer



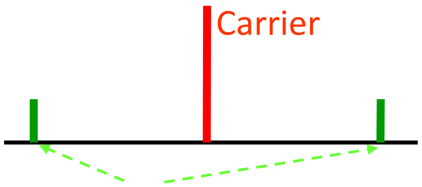
Fabry Perot interferometer

Simple, but requires large mirrors; limited τ_{stor}

(LIGO design) $\tau_{stor} \sim 3$ *msec*

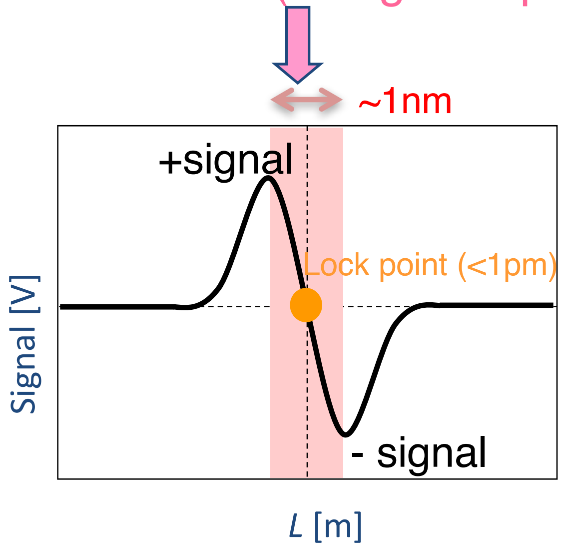
More compact, but harder to control

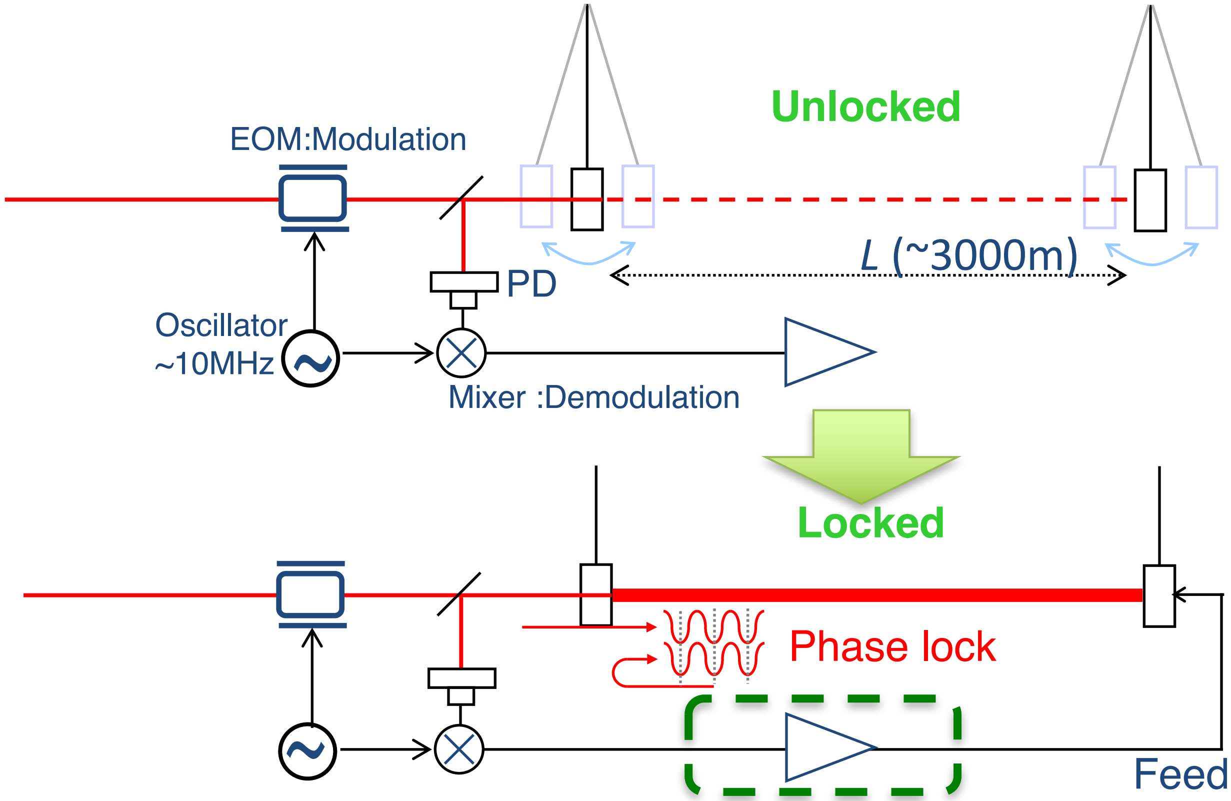
Lock acquisition for interferometer


Carrier

Sidebands **(probes for carrier)**

Resonant area
= Control area
= linear area (straight slope)



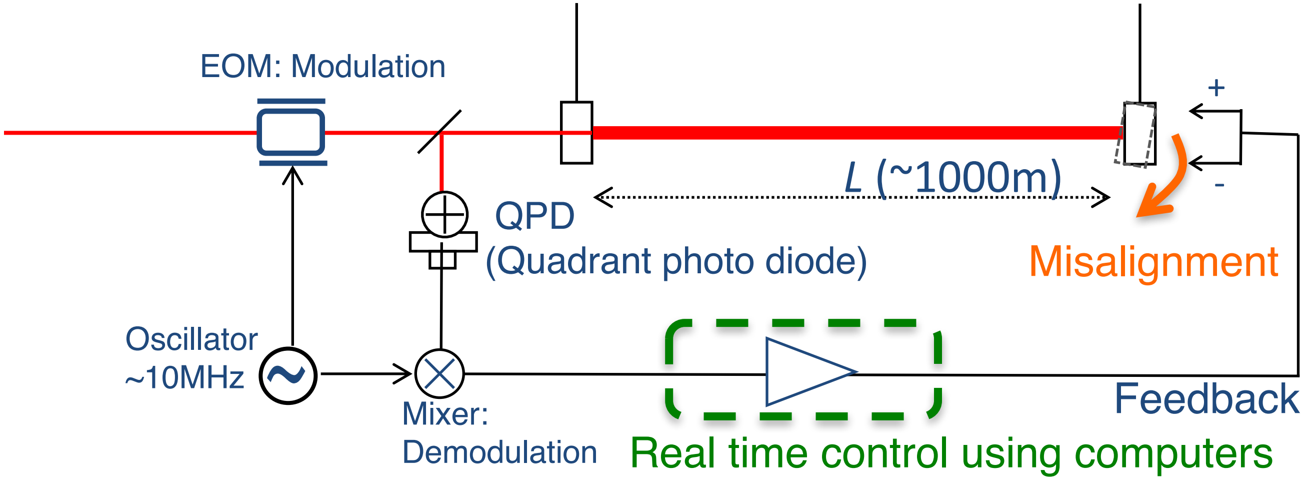


Phase lock

Feedback

Real time control using computers

Alignment control for mirrors



EOM: Modulation

QPD
(Quadrant photo diode)

L (~1000m)

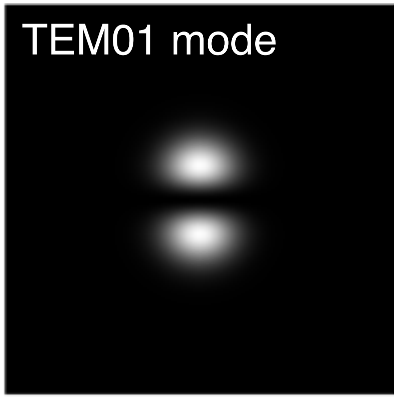
Misalignment

Oscillator
~10MHz

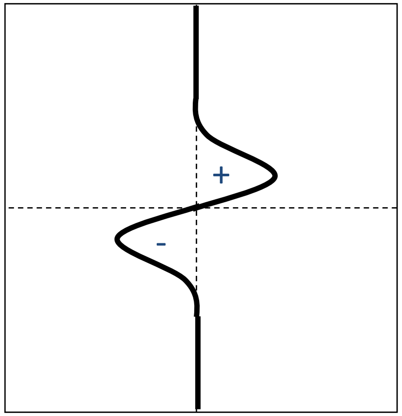
Mixer:
Demodulation

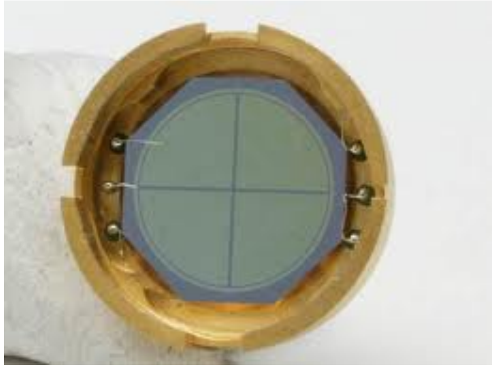
Feedback

Real time control using computers



TEM01 mode





Prototypes in 80s - 90s

Caltech 40m prototype

NAOJ 20m prototype

Many prototypes were built

- Glasgow 10m (FP) prototype
- Caltech 40m
- Max Plank Institute, Garching 30m
- TENKO-10, TENKO-100 (delay line), NAOJ 20m (FP), Hongo 3m, LISM

Large Detectors were funded

NSF approved LIGO funding in 1990
TAMA was approved in 1995
GEO was approved in ~1994
VIRGO was approved in 1993-94

The First Generation Detectors (00s)

LIGO, VIRGO went offline for big upgrades,
KAGRA was funded in 2010

* start years of their first observation

LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

Desert in north west, Washington

LIGO Livingston Observatory (LLO)
L1 : 4 km arms

Swamp in gulf coast, Louisianna

Hanford, WA (LHO)

- **Desert area**
- **25 km from Richland, WA**
- **2 interferomters: 2km & 4km**

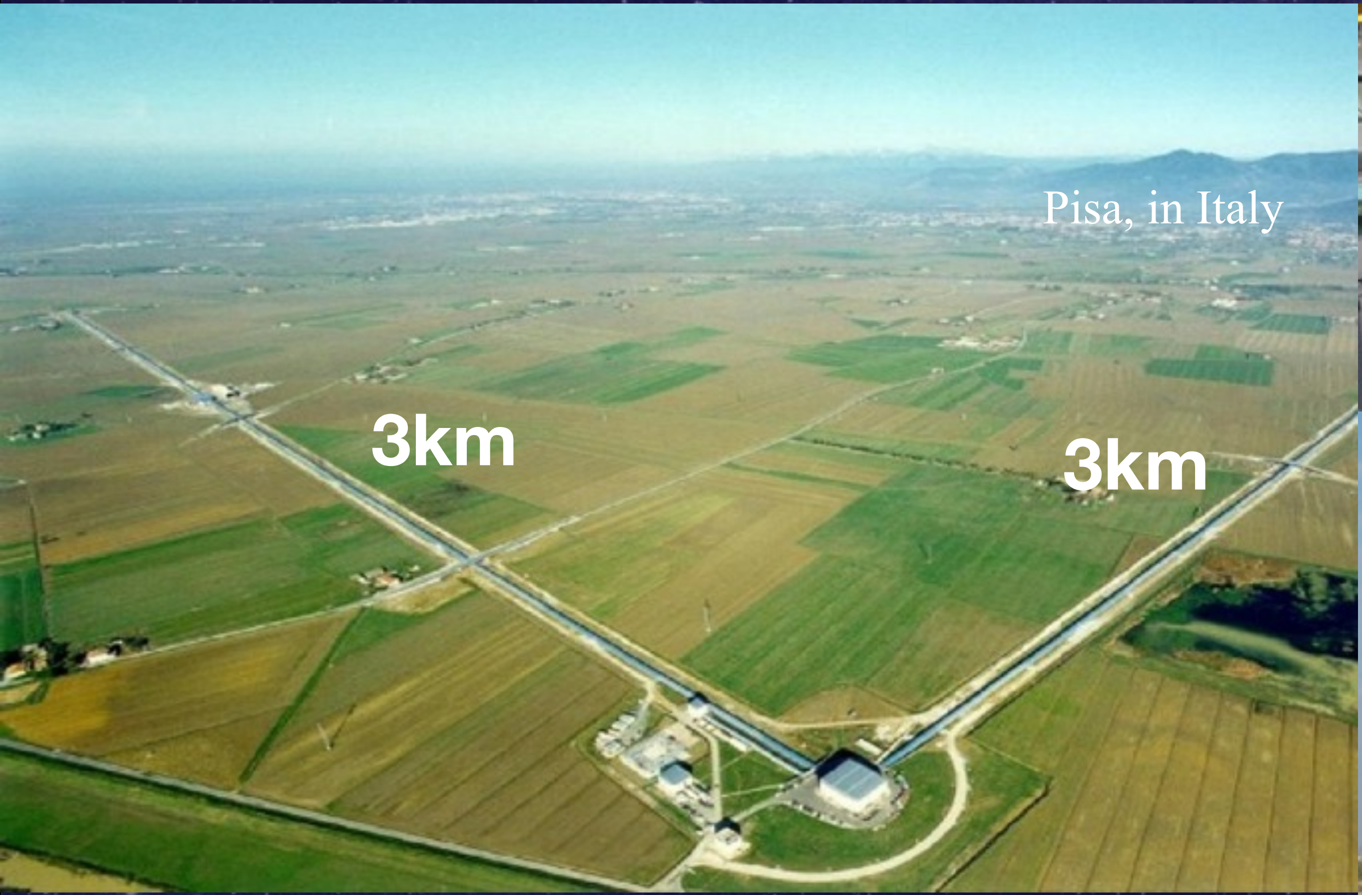
Livingston, LA (LLO)

- **Swamp area**
- **50km from Baton Rouge, LA**
- **1 interferomter: 4km**

- Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at visibleearth.nasa.gov
- NASA Goddard Space Flight Center Image by Reto Stöckli (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).

VIRGO

-Group of French, Italy, Netherland etc.



GEO

1995 construction started

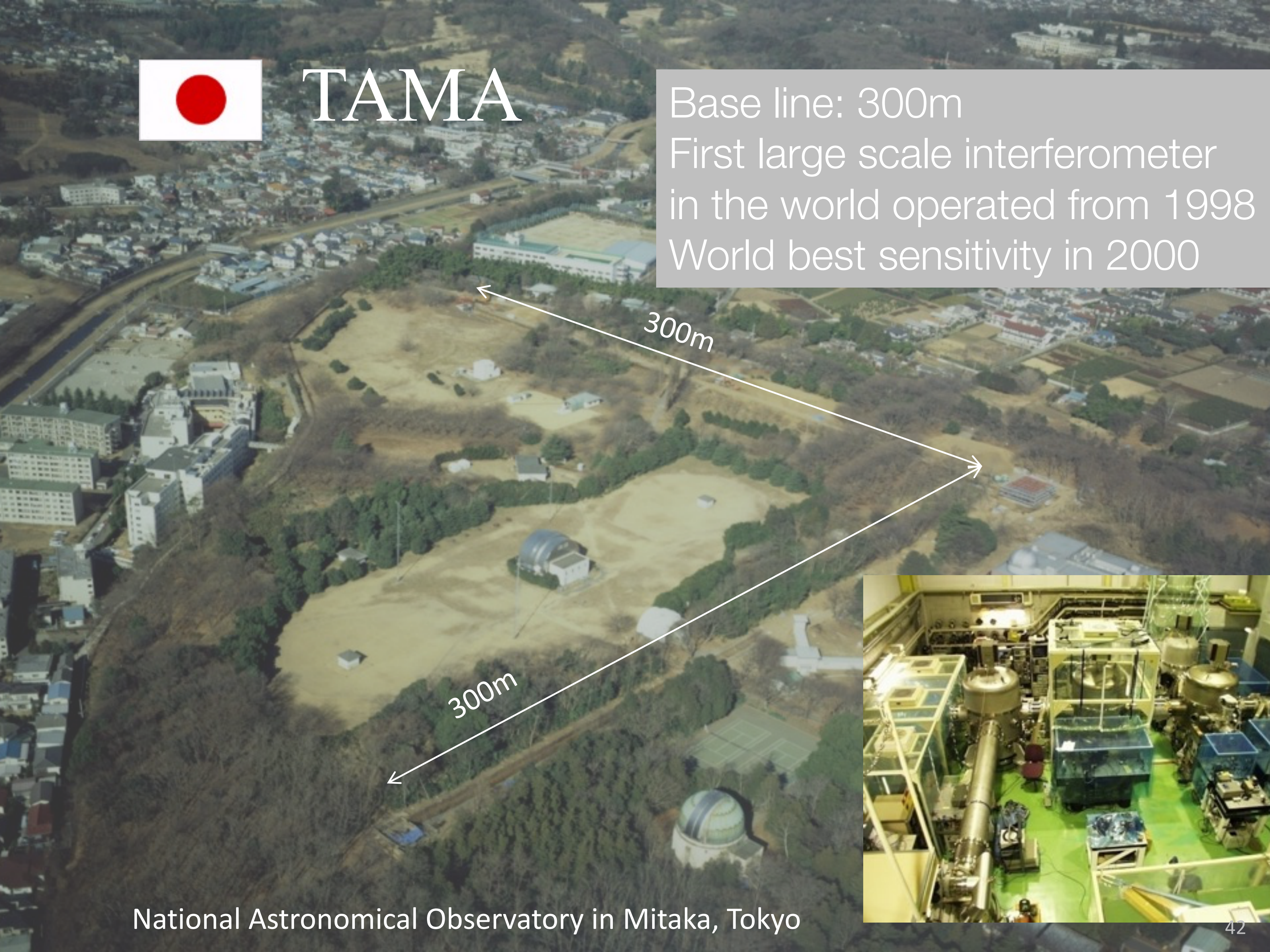
England and Germany

Baseline: 600m

Location: Hanover in Germany

TAMA

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



National Astronomical Observatory in Mitaka, Tokyo

The Second Generation Detectors (10s)

4km Arms
aLIGO
Hanford
2015

aLIGO
Livingston
2015
4km Arms

aVIRGO
2016
3km Arms

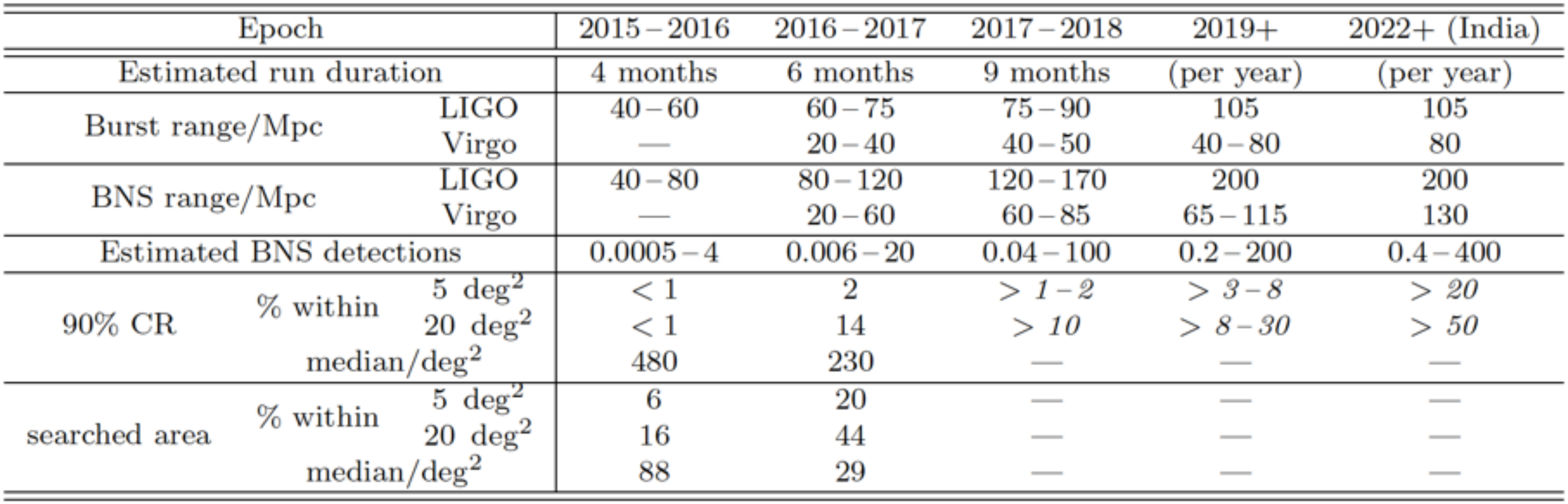
600m Arms
GEO600-HF

KAGRA
2018
3km arms

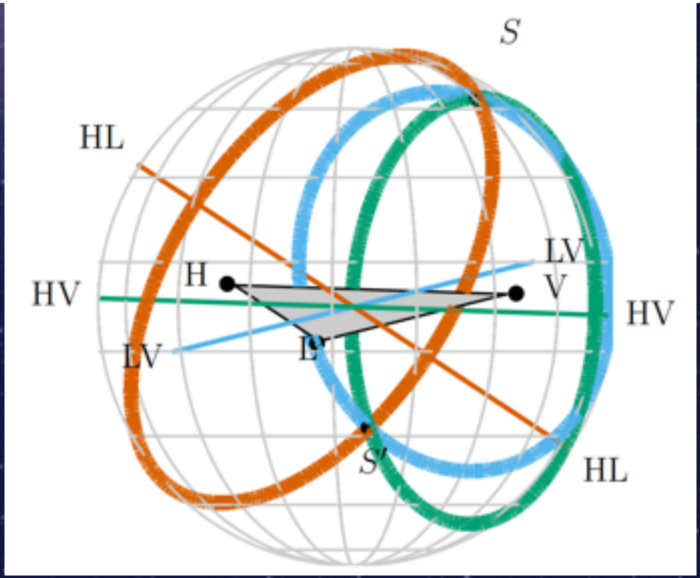
LIGO India
2023
4km Arms

Sky Localization

arXiv 1304.0670



Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—



- KAGRA is located in Kamioka mine underground
  - 220km away from Tokyo
  - 360m altitude
  - Big laboratory area

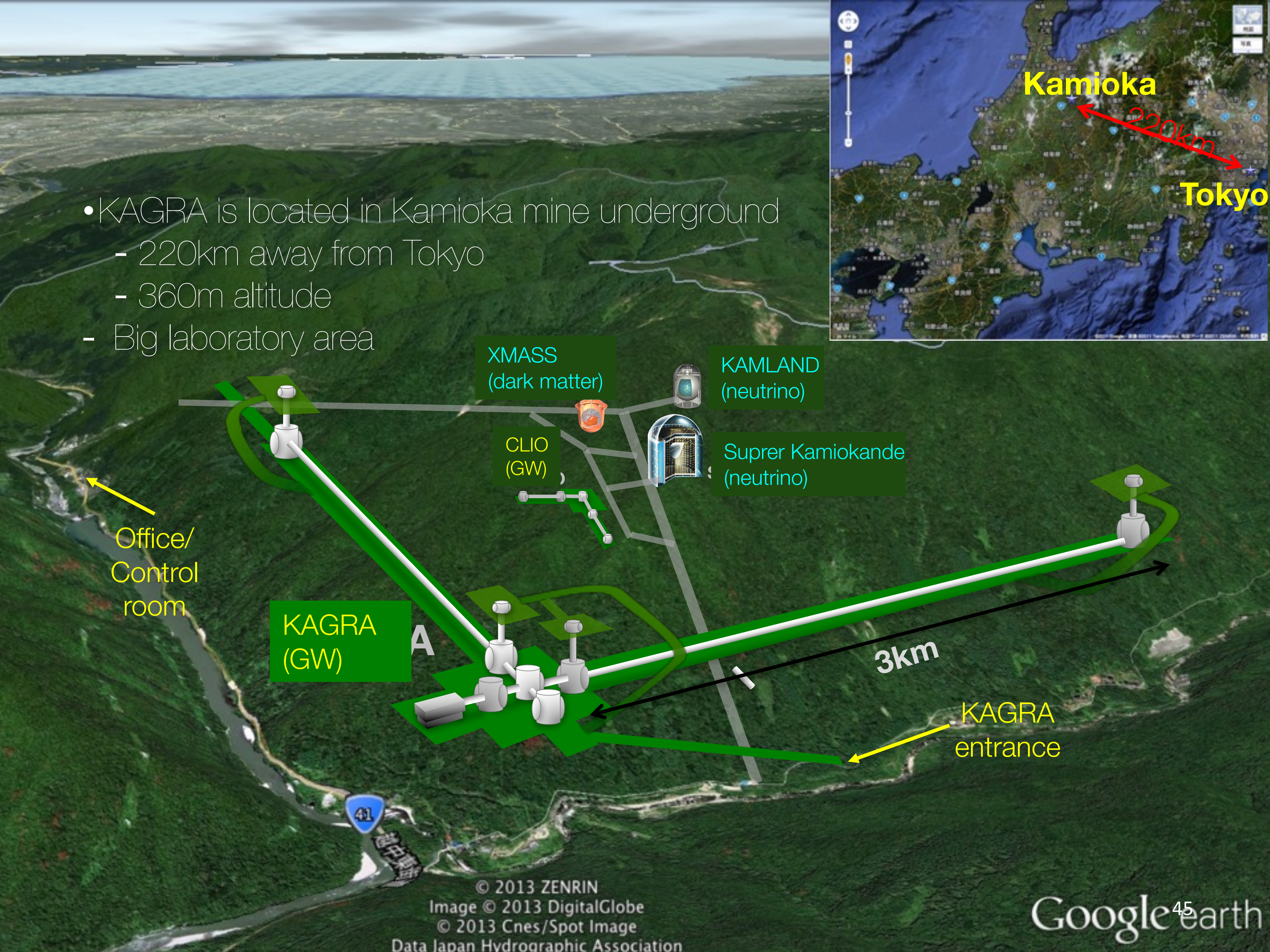


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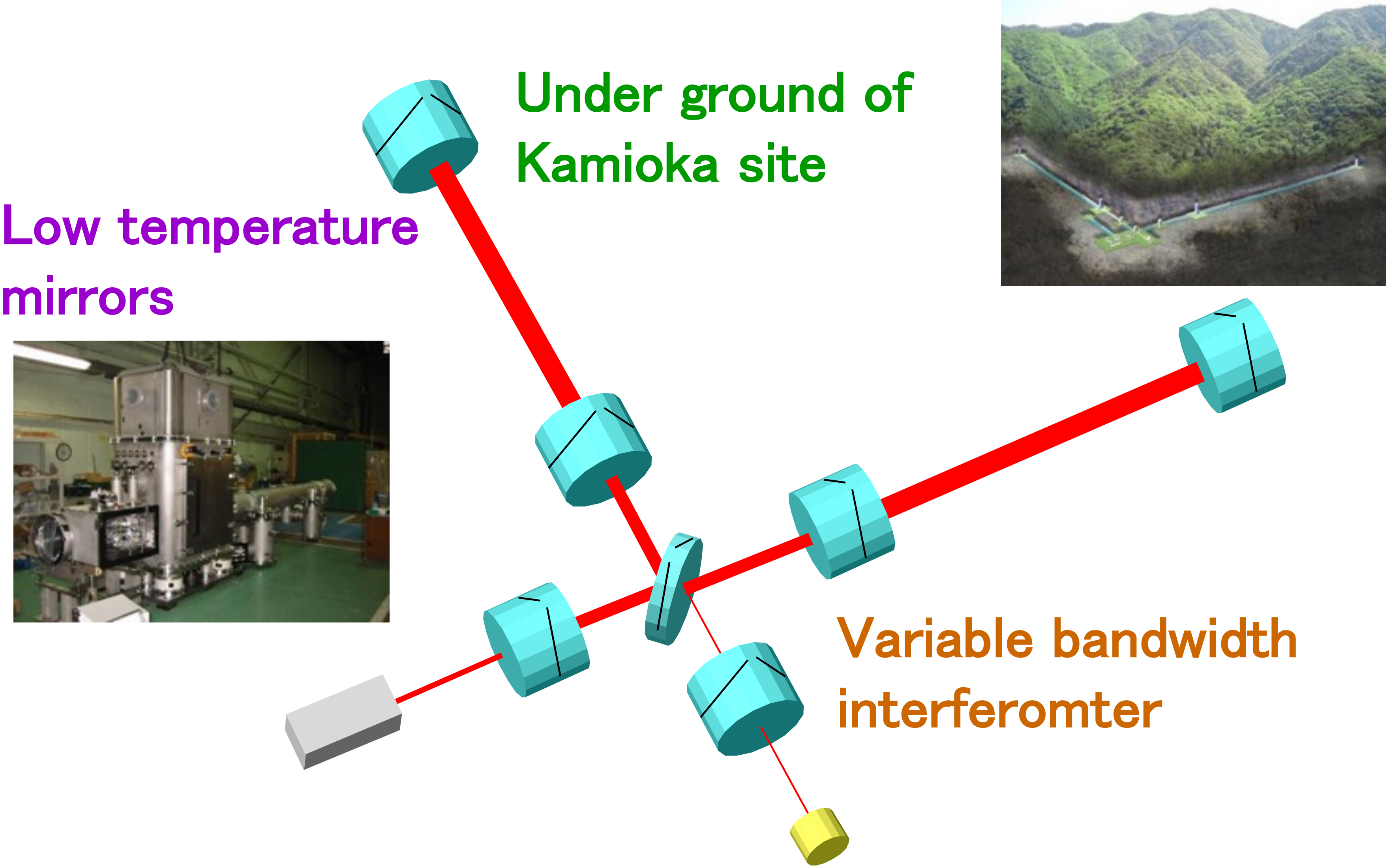
Image © 2013 DigitalGlobe
© 2013 Cnes/Spot Image
Data Japan Hydrographic Association

Google earth

Features of KAGRA



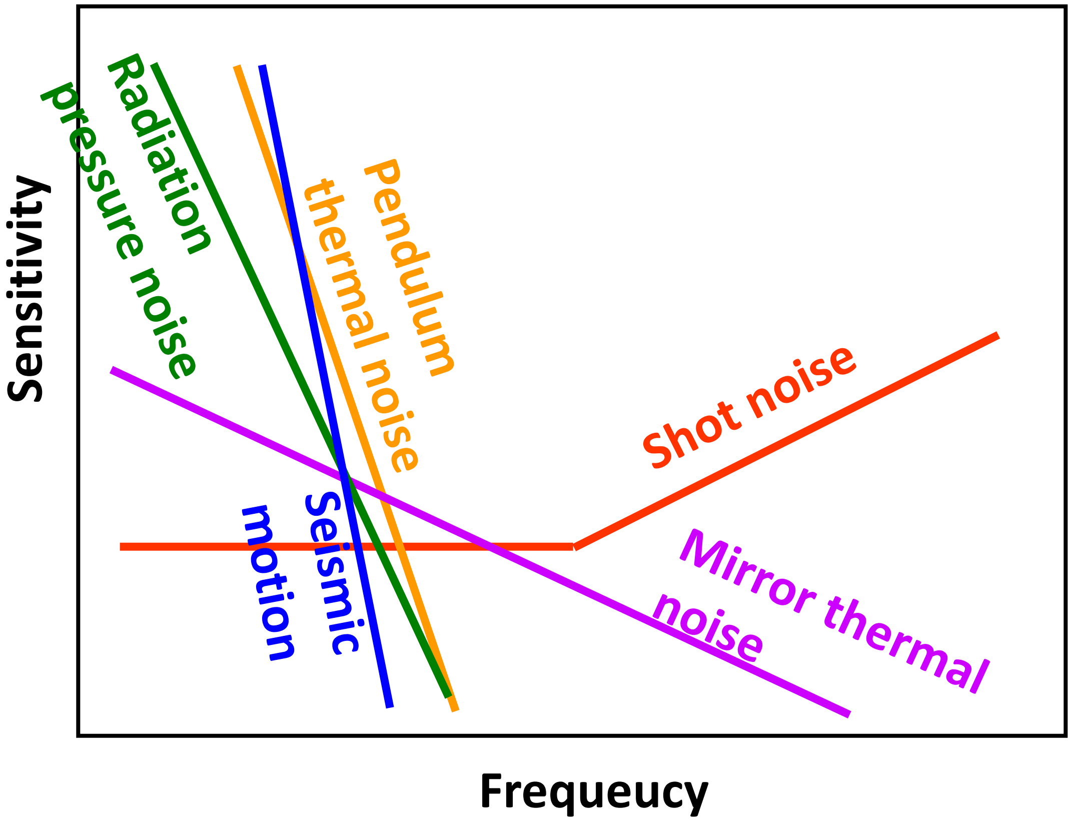
Under ground of Kamioka site

Low temperature mirrors

Variable bandwidth interferomter

Noise sources

Sensitivity = Noise / Response of interferometer

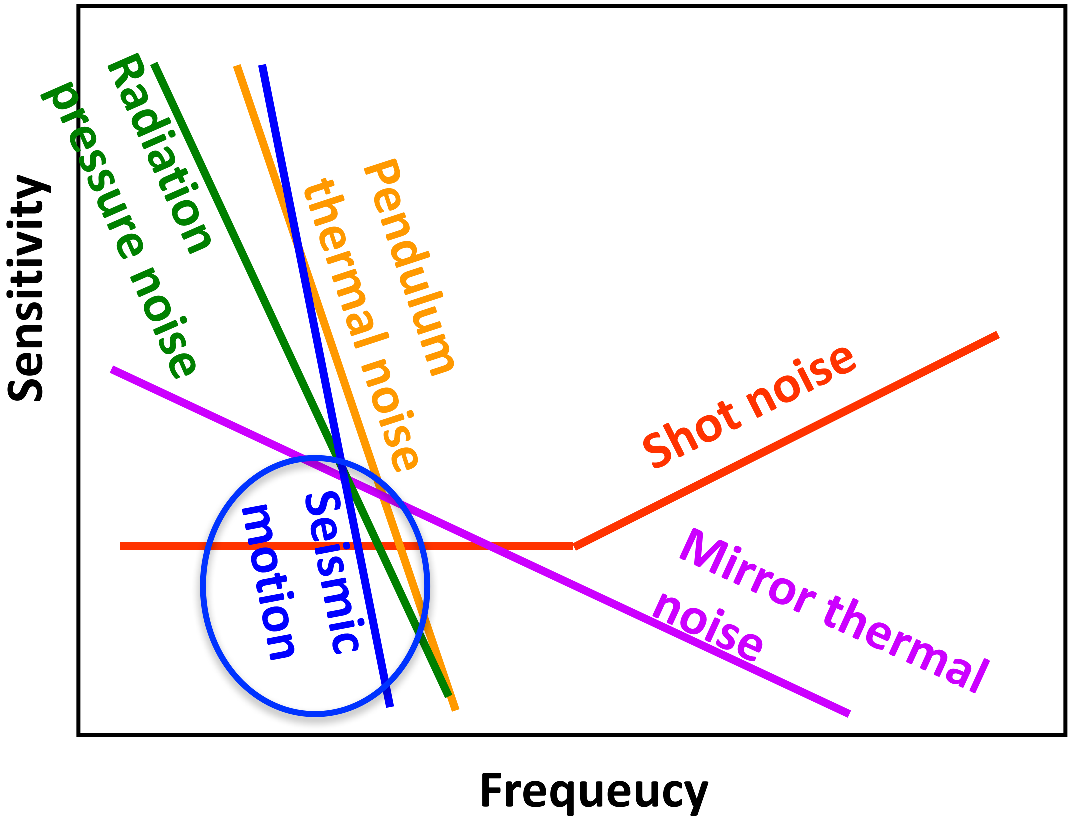


For better sensitivity

1. Reducing noise
2. Higher response for interferometer

Noise sources

Sensitivity = Noise / Response of interferometer

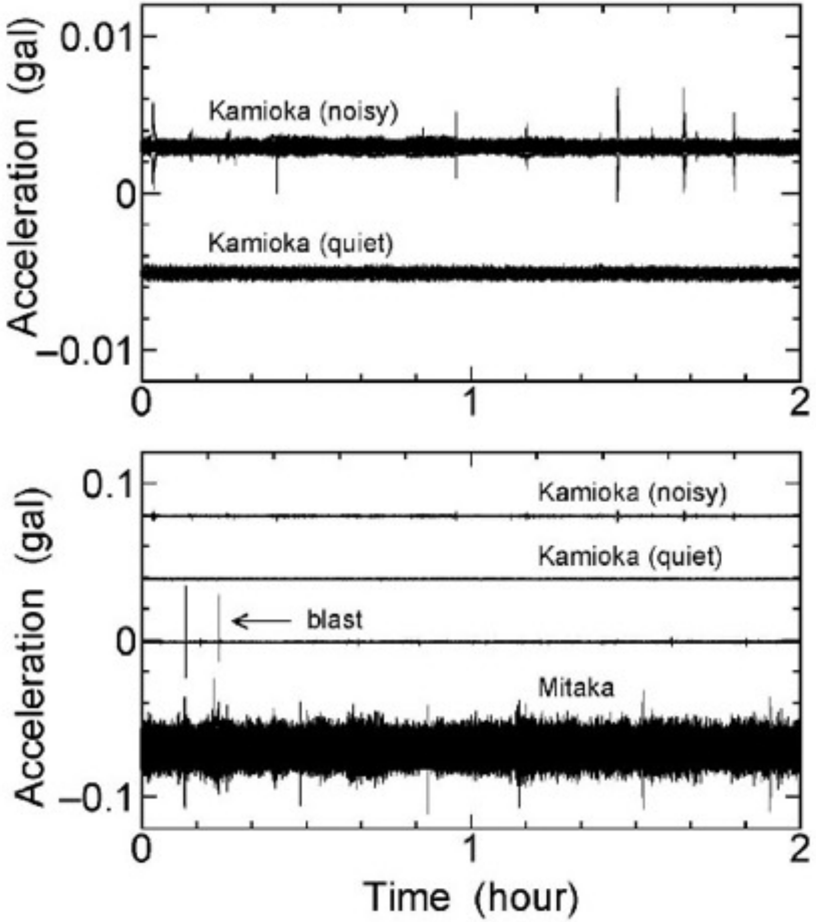


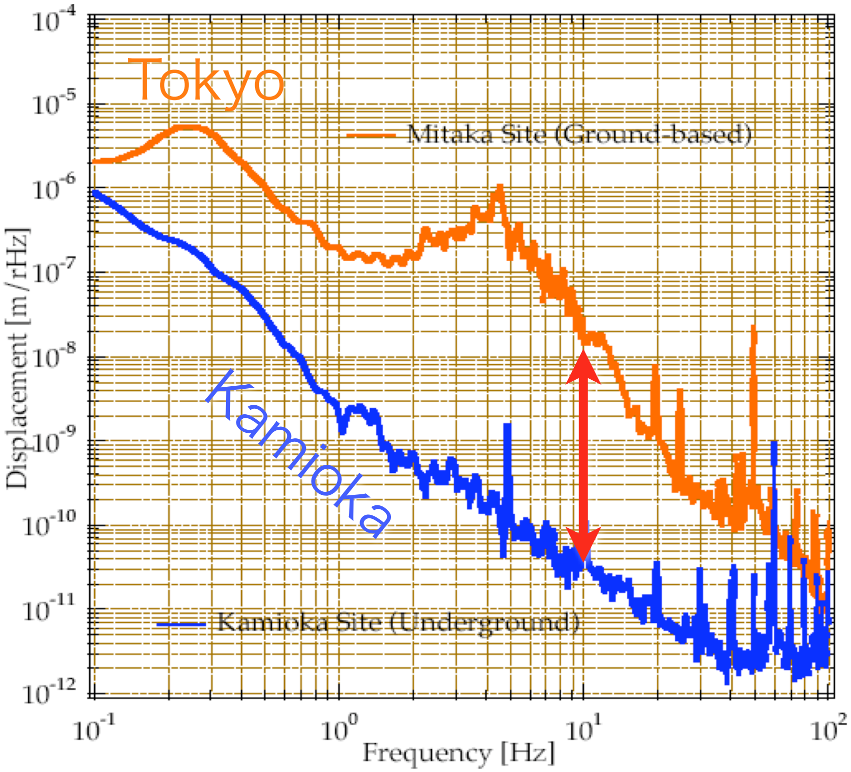
For better sensitivity

1. Reducing noise
2. Higher response for interferometer

KAGRA

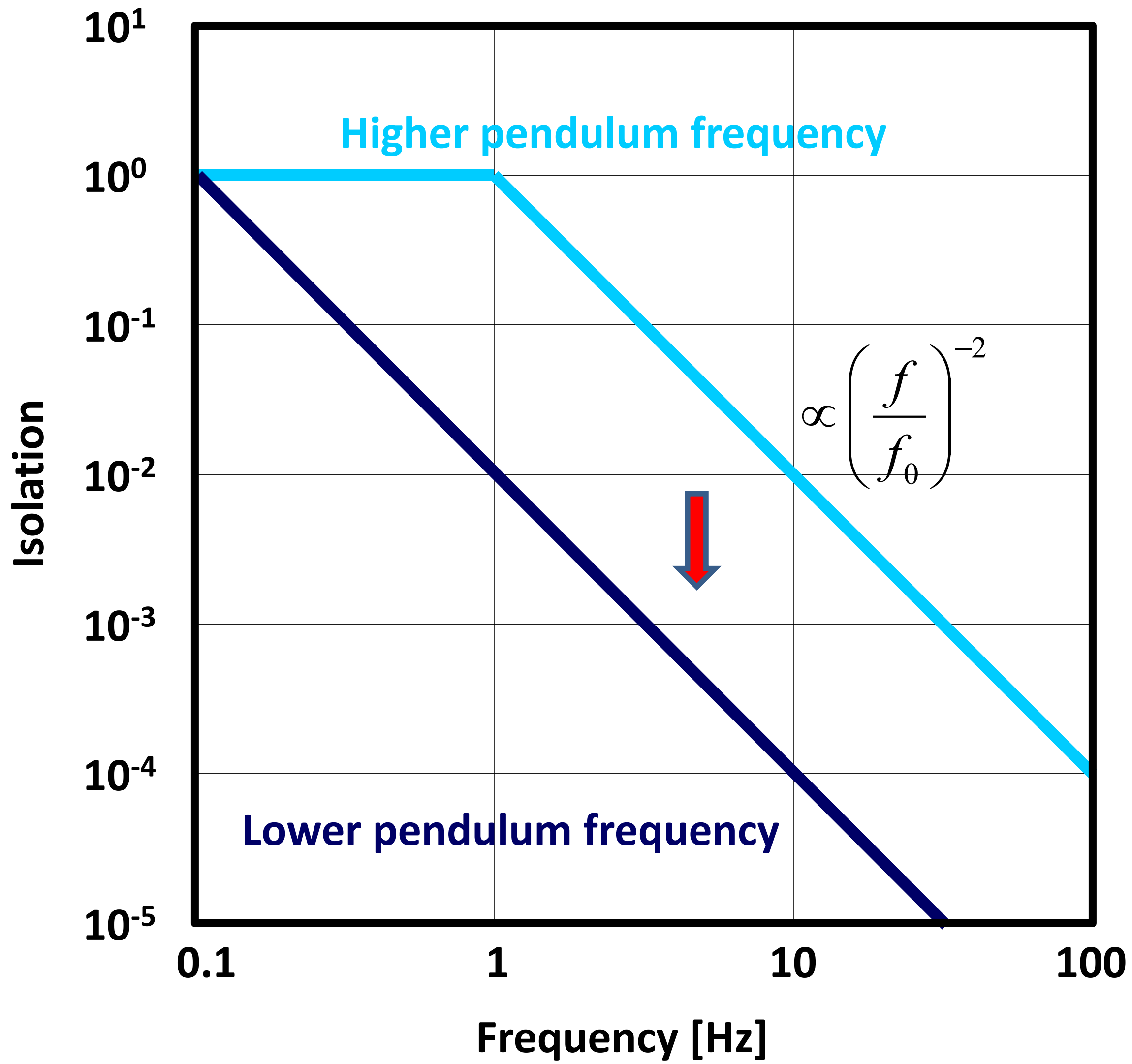
Underground site is QUIET

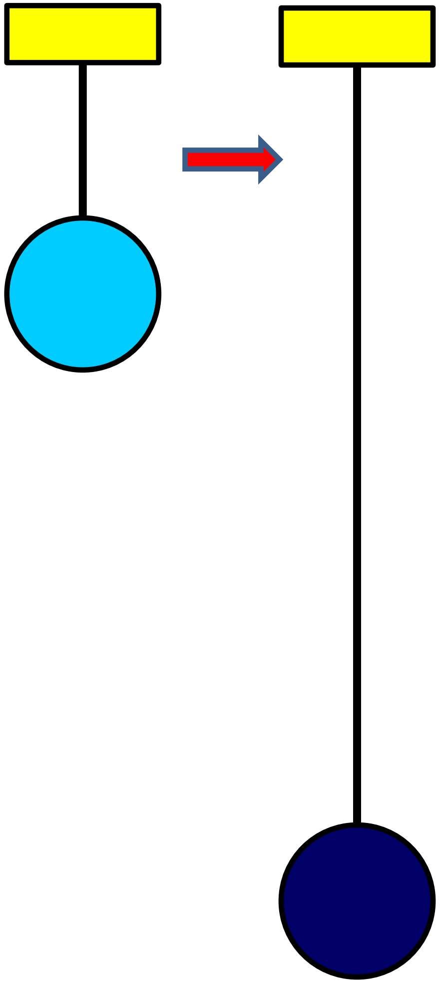




Amplitude of seismic motion

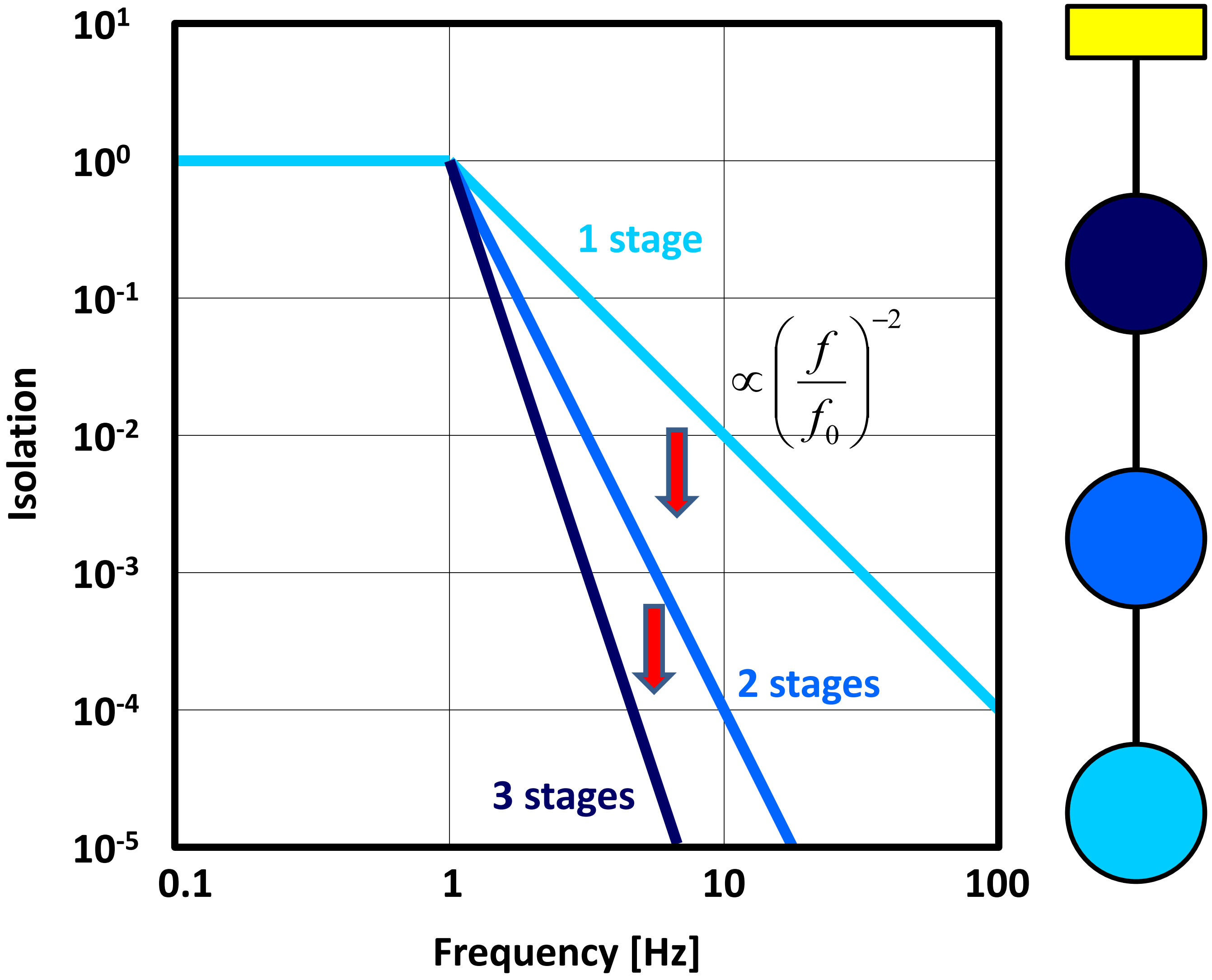
Vibration isolation (1)



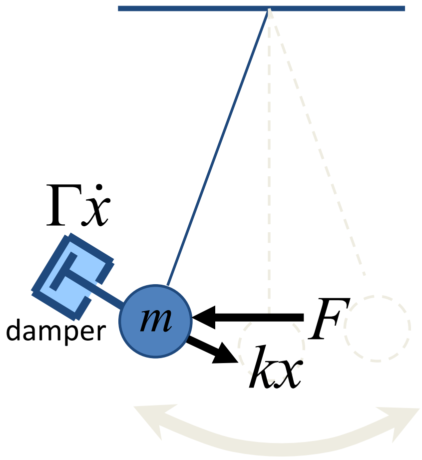


Vibration isolation (2)

Seismic motion ×



Pendulum in Physics



$$F = m\frac{d^2x}{dt^2} + \Gamma\frac{dx}{dt} + kx$$

$x = Ae^{i\omega t}$: complex number

$|\mathrm{x}| = A$: amplitude

$\mathrm{Arg(x)} = \omega t = 2\pi ft$: angle

$$\frac{dx}{dt} = i\omega x$$

$$\frac{d^2x}{dt^2} = -\omega^2 x$$

Laplace transform $\bar{f}(s) = L[f(t)] \equiv \int_0^\infty f(t)e^{-st}dt$

$$L[F] = m\times L\left[\frac{d^2x}{dt^2}\right] + \Gamma\times L\left[\frac{dx}{dt}\right] + k\times L[x]$$

$$\bar{F} = ms^2\bar{x} + \Gamma s\bar{x} + k\bar{x}$$

$$\frac{\bar{x}}{\bar{F}} = \frac{1}{ms^2 + \Gamma s + k} = \frac{1}{(s - (\frac{-\Gamma-\sqrt{\Gamma^2-4mk}}{2m}))(s - (\frac{-\Gamma+\sqrt{\Gamma^2-4mk}}{2m}))}\text{; 2 poles}$$

$$s \equiv i\omega$$

$$\bar{F} = -m\omega^2\bar{x} + i\Gamma\omega\bar{x} + k\bar{x}$$

$$\frac{\bar{x}}{\bar{F}} = \frac{1}{-m\omega^2 + i\Gamma\omega + k}$$

Interpretation in Physics

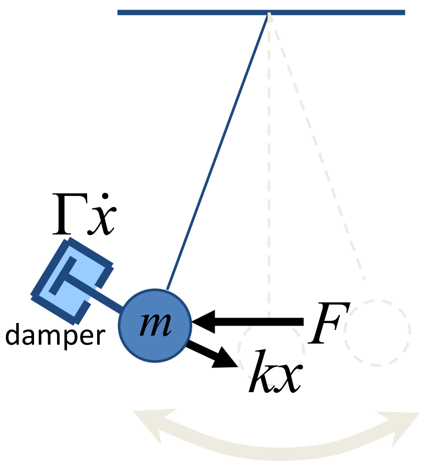
resonant anglar frequency: $\omega_0 = 2\pi f_0 = \sqrt{k/m}$

quality factor $Q \Rightarrow$ 1/energy loss: $Q = m\omega_0/\Gamma$

Transfer function from force to position:

$$\frac{\bar{x}}{\bar{F}/m} = \frac{1}{-\omega^2 + i\omega\omega_0/Q + \omega_0^2}$$

Bode plot : frequency vs. gain, phase



$$\frac{\bar{x}}{\bar{F}/m} = \frac{1}{-\omega^2 + i\omega\omega_0/Q + \omega_0^2}$$

$$\text{if } \omega << \omega_0 \Rightarrow \frac{\bar{x}}{\bar{F}/m} \rightarrow \frac{1}{\omega_0^{\ 2}} \ :\text{constant}$$

$$\text{if } \omega >> \omega_0 \Rightarrow \frac{\bar{x}}{\bar{F}/m} \rightarrow \frac{1}{-\omega^2} \ : f^{-2} \text{ slope}$$

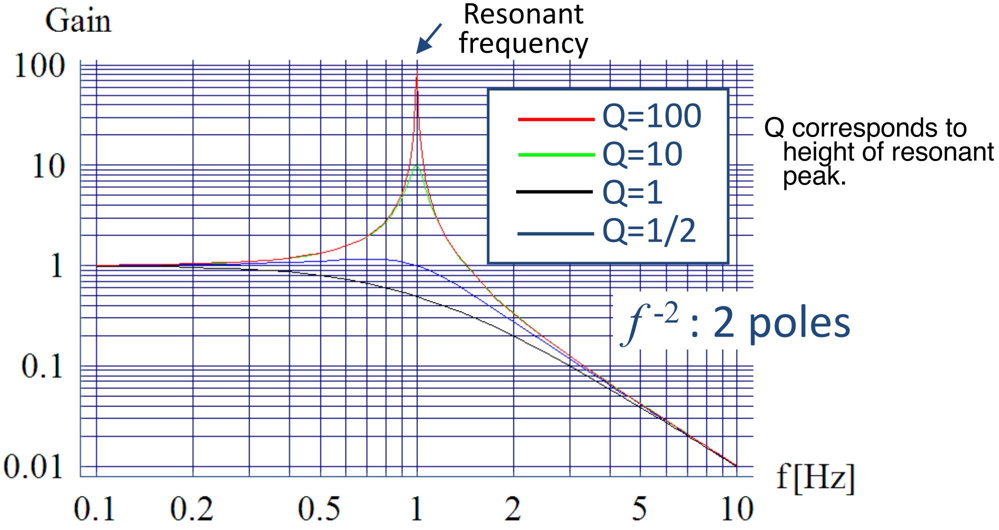
$$\text{if } \omega = \omega_0 \Rightarrow \frac{\bar{x}}{\bar{F}/m} \rightarrow \frac{Q}{i\omega_0^{\ 2}} \ :\text{resonance}$$

$$\text{if } \omega = \omega_0, \mathrm{Q} \rightarrow \infty \Rightarrow \frac{\bar{x}}{\bar{F}/m} \rightarrow \infty$$

$$:\text{resonance, no damp}$$

$$\text{if Q} = 1/2 \ \Rightarrow \text{cretical damping}$$

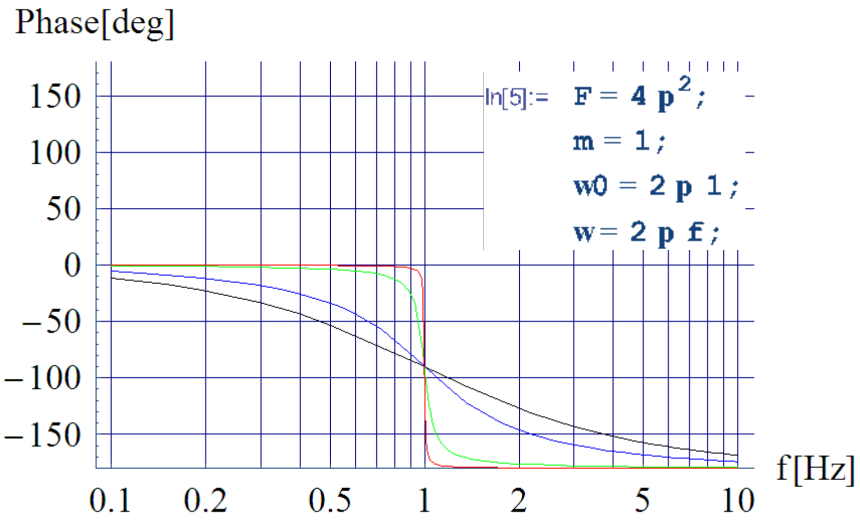
$$\text{if Q} < 1/2 \ \Rightarrow \text{over damping}$$



Resonant frequency

Q corresponds to height of resonant peak.

f^{-2} : 2 poles

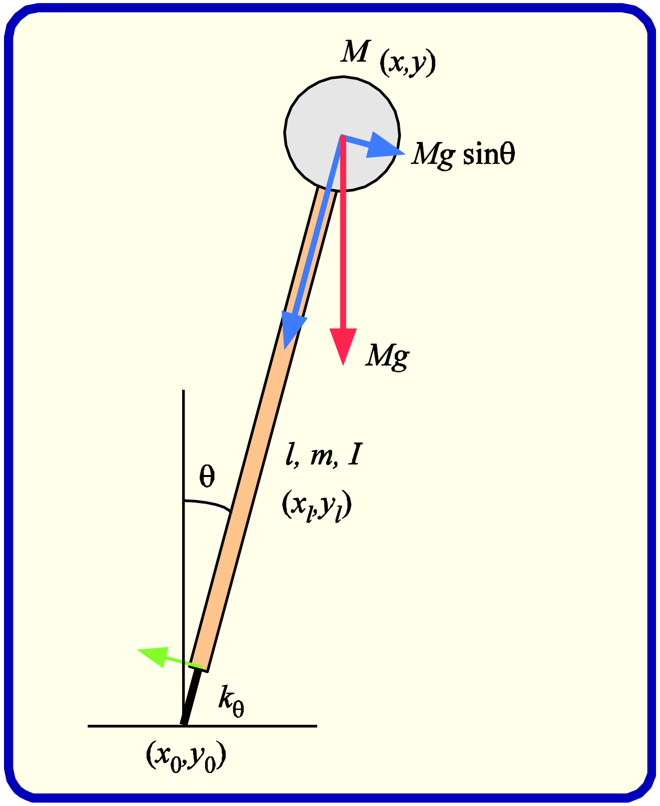


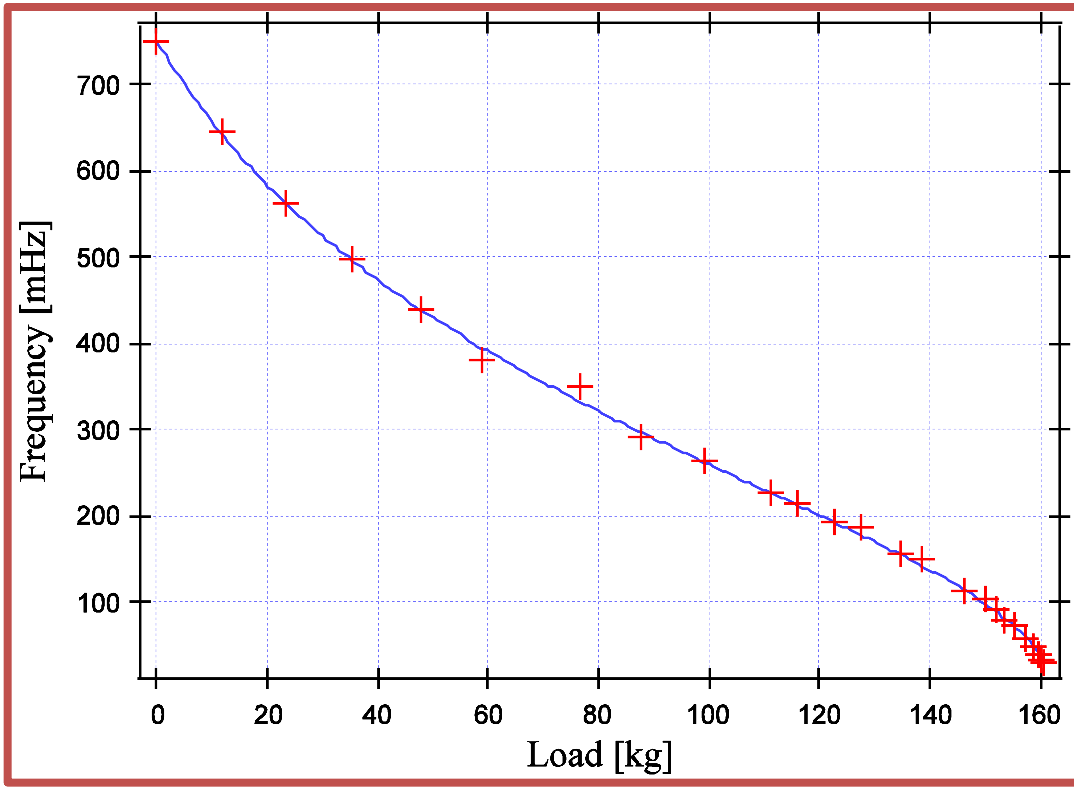
```
In[5]:=  F = 4 p^2;
         m = 1;
         w0 = 2 p 1;
         w= 2 p f;
```

Inverted pendulum

Recovering force = Spring force of metal + Anti spring force by gravity

⇒ Lower resonant frequency





Isolation for vertical motion

Coupling between vertical motion and beam direction exists

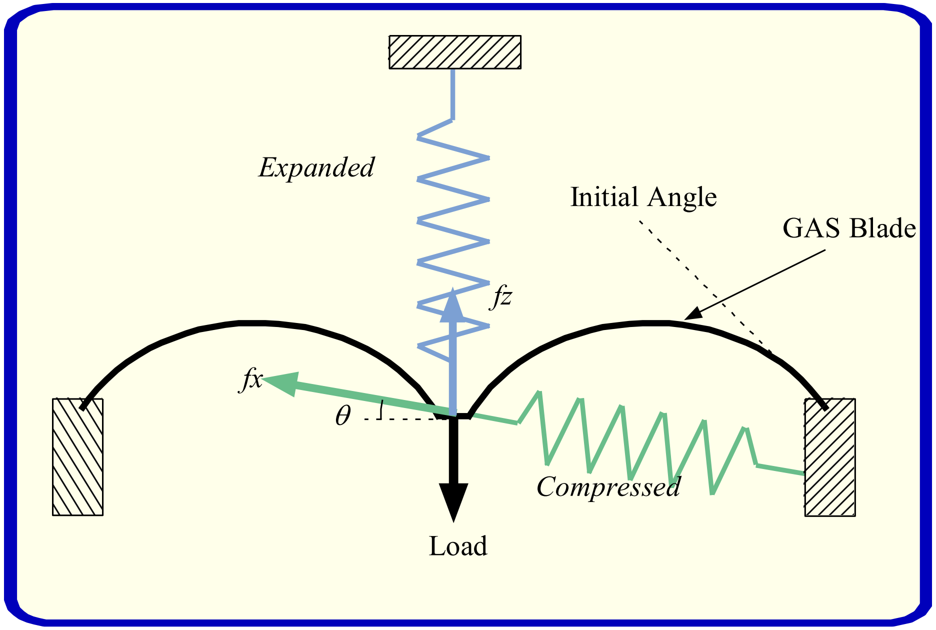
- by curvature of Earth
- Mechanical asymmetry
- Slope of tunnel (for draining water)

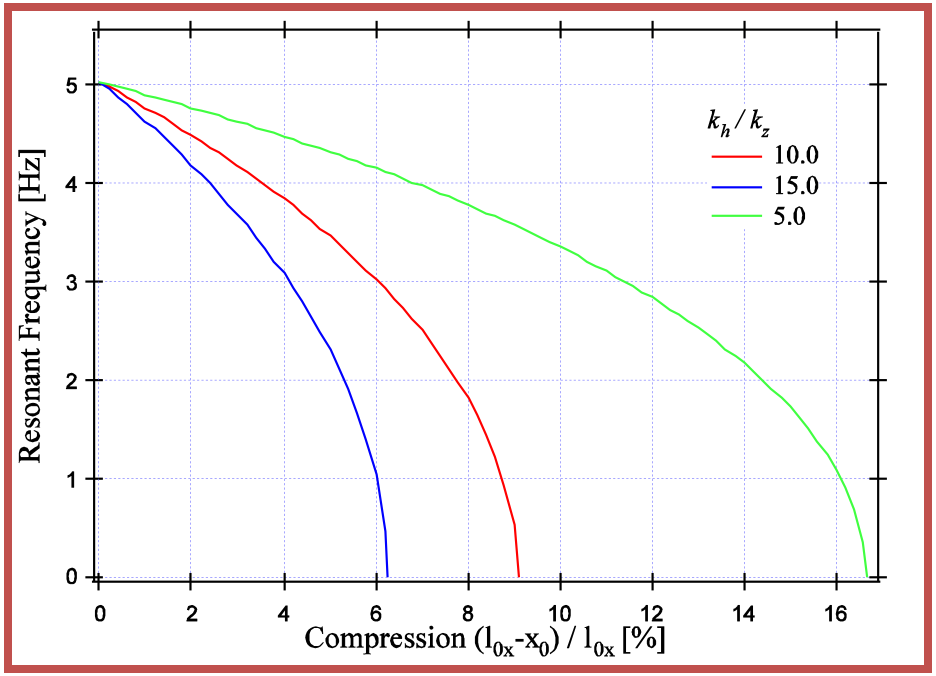
→ Needs isolation for vertical ground motion

Geometric Anti-Spring (GAS) Filter

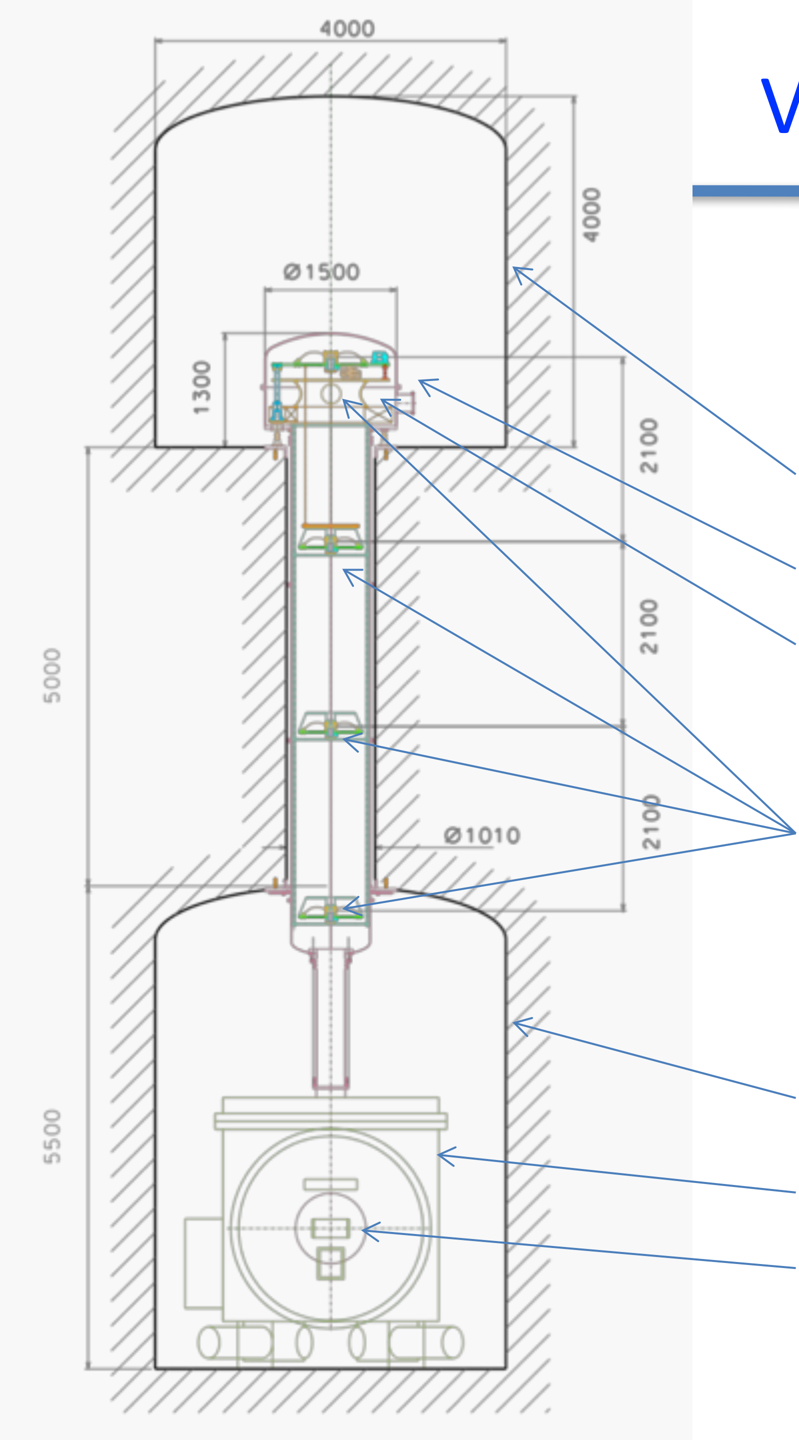
Recovering force = Spring force of blade + Anti spring force by pushing from sides

⇒ Lower resonant frequency





Vibration isolation system



Tunnel (2nd floor)

Chamber

Inverted pendulum

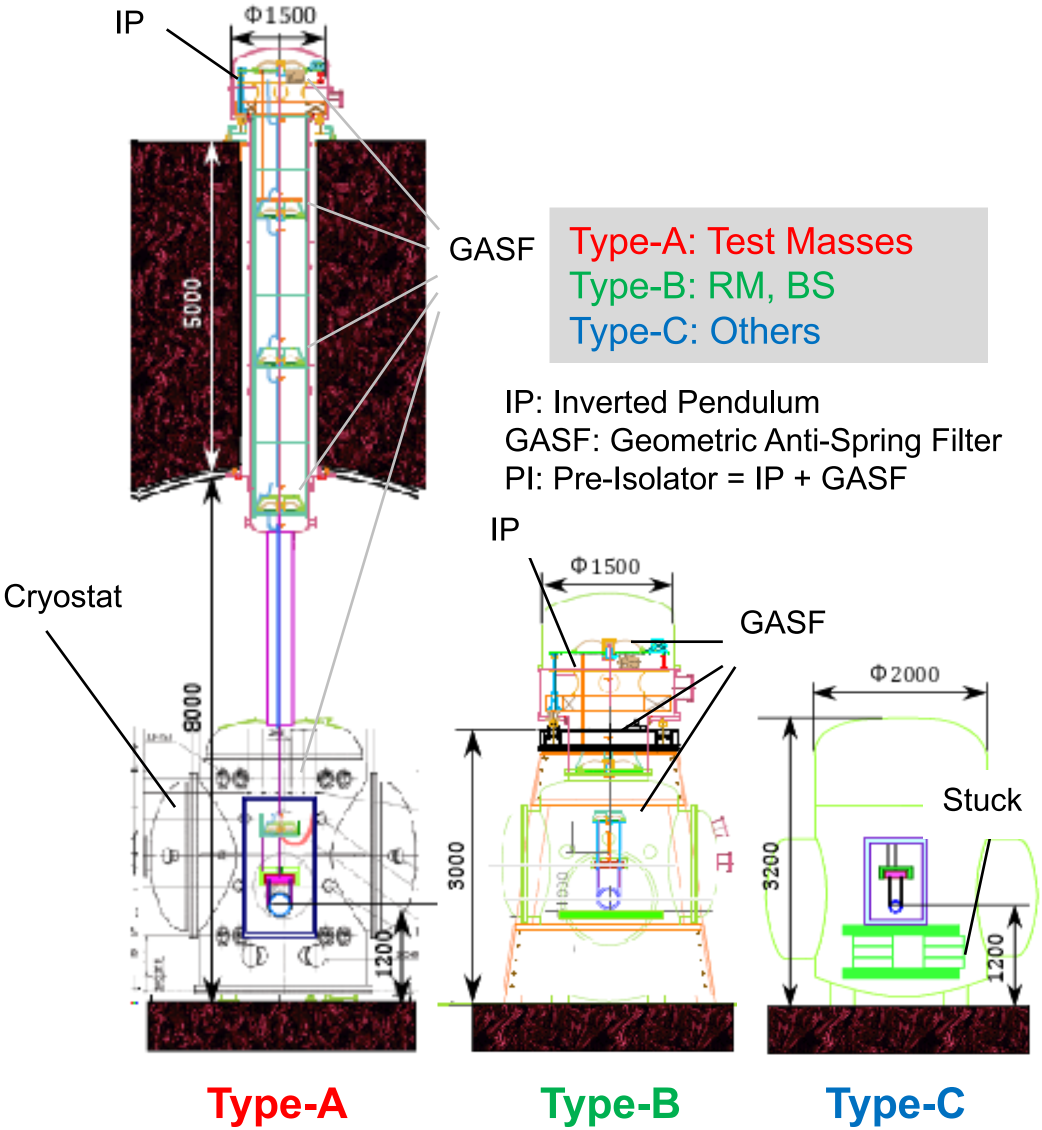
GAS filters

Tunnel (1st floor)

Chamber

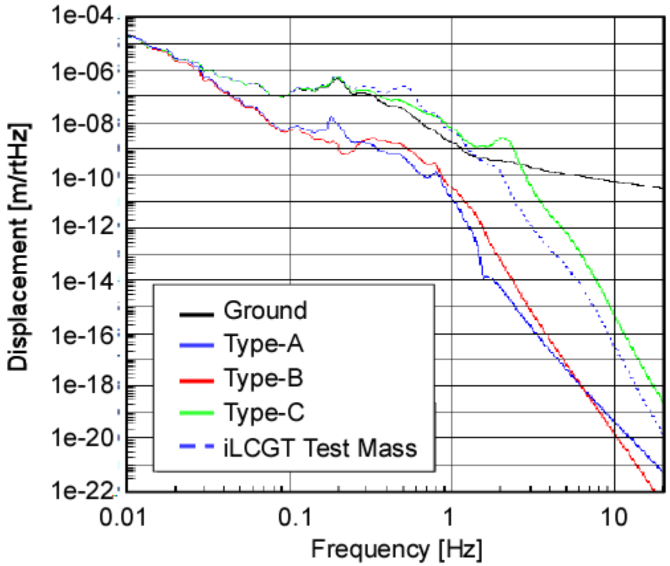
Mirror

Vibration Isolation System



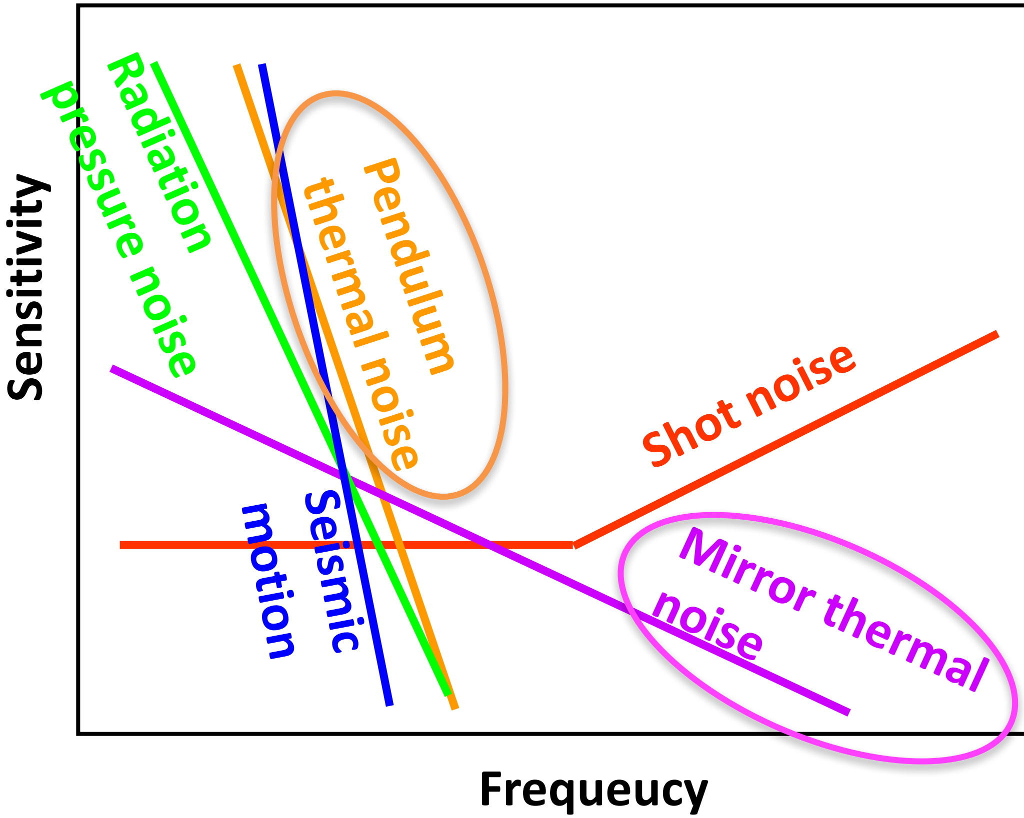
Type-A: Test Masses
Type-B: RM, BS
Type-C: Others

IP: Inverted Pendulum
GASF: Geometric Anti-Spring Filter
PI: Pre-Isolator = IP + GASF



Noise sources

Sensitivity = Noise / Response of interferometer



For better sensitivity

1. Reducing noise
2. Higher response for interferometer

Thermal-noise reduction

Mid.-freq. (around 100 Hz) improveme

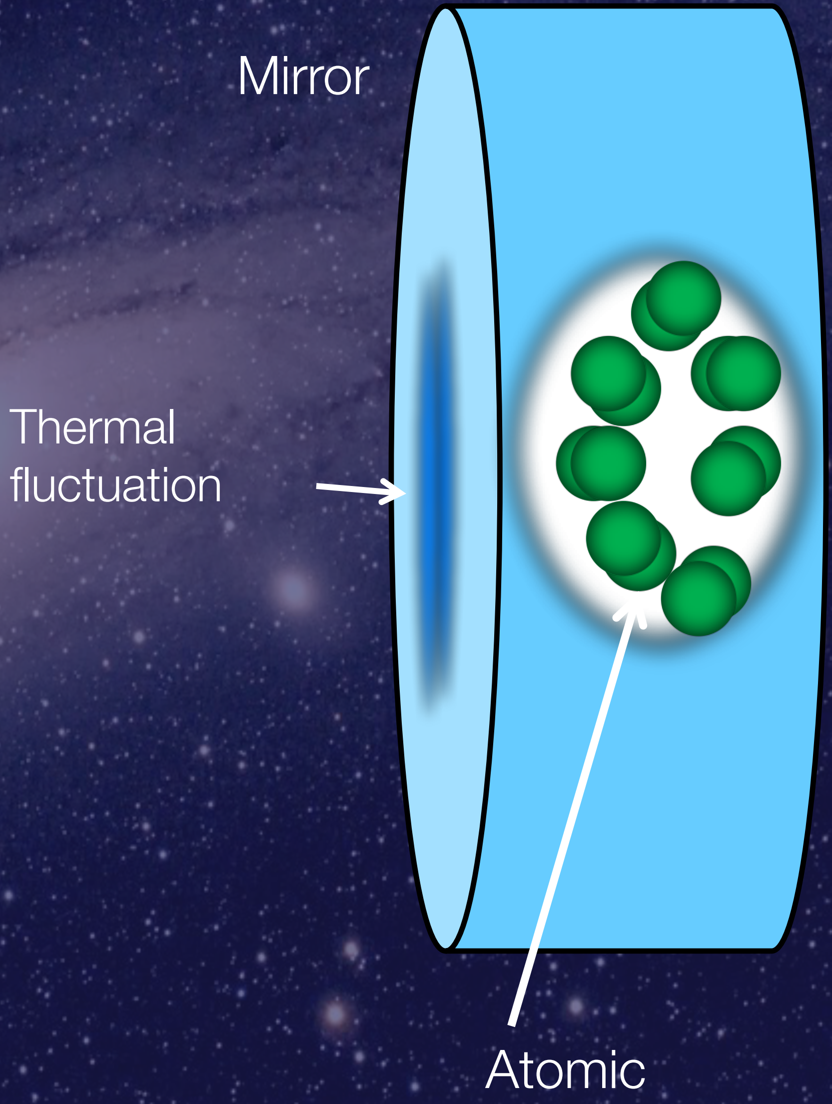
Cryogenics

Mirror ~20K
Suspension ~16K

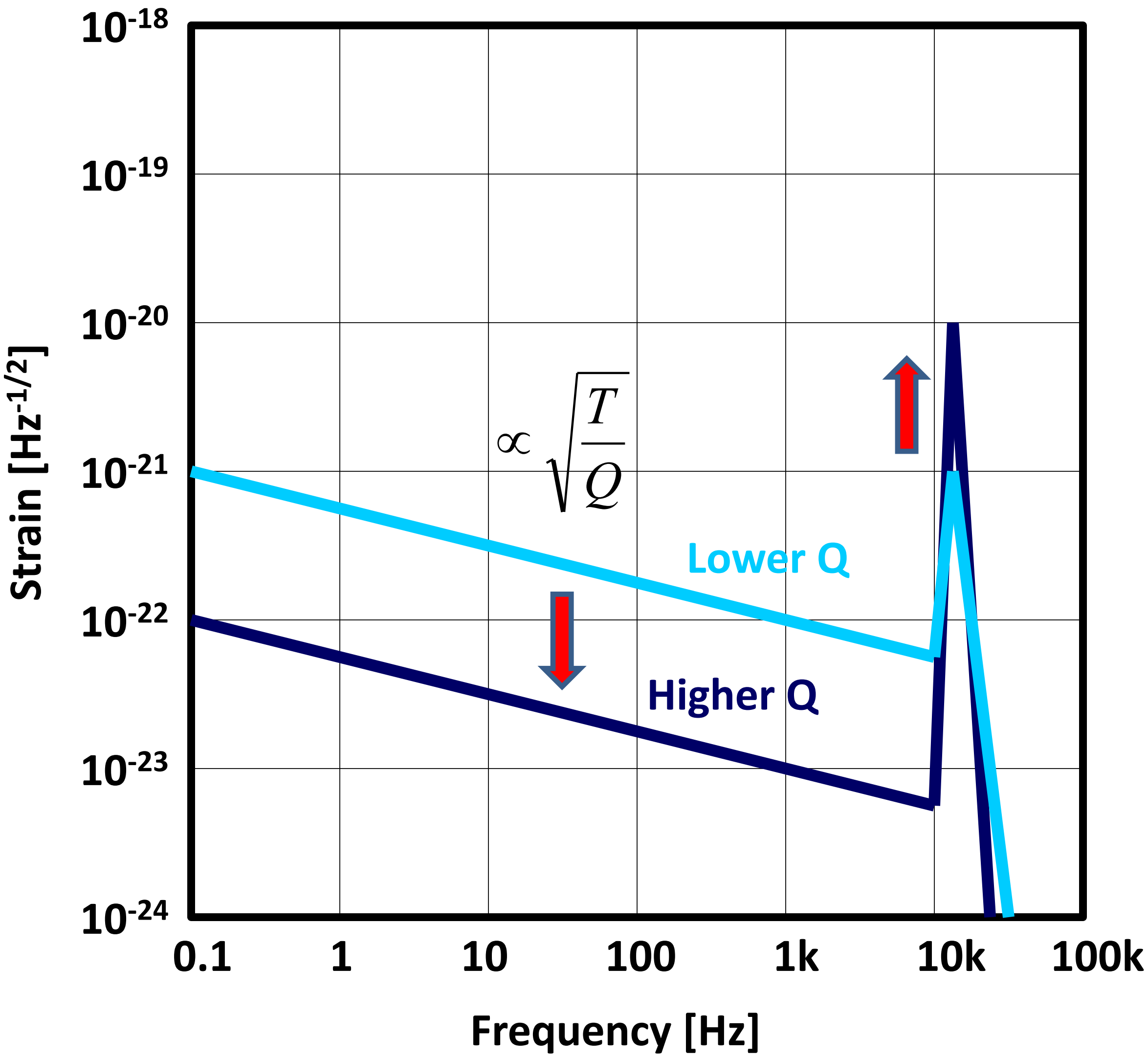
Sapphire mirror
→ High mechanical Q-value at low temperature

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

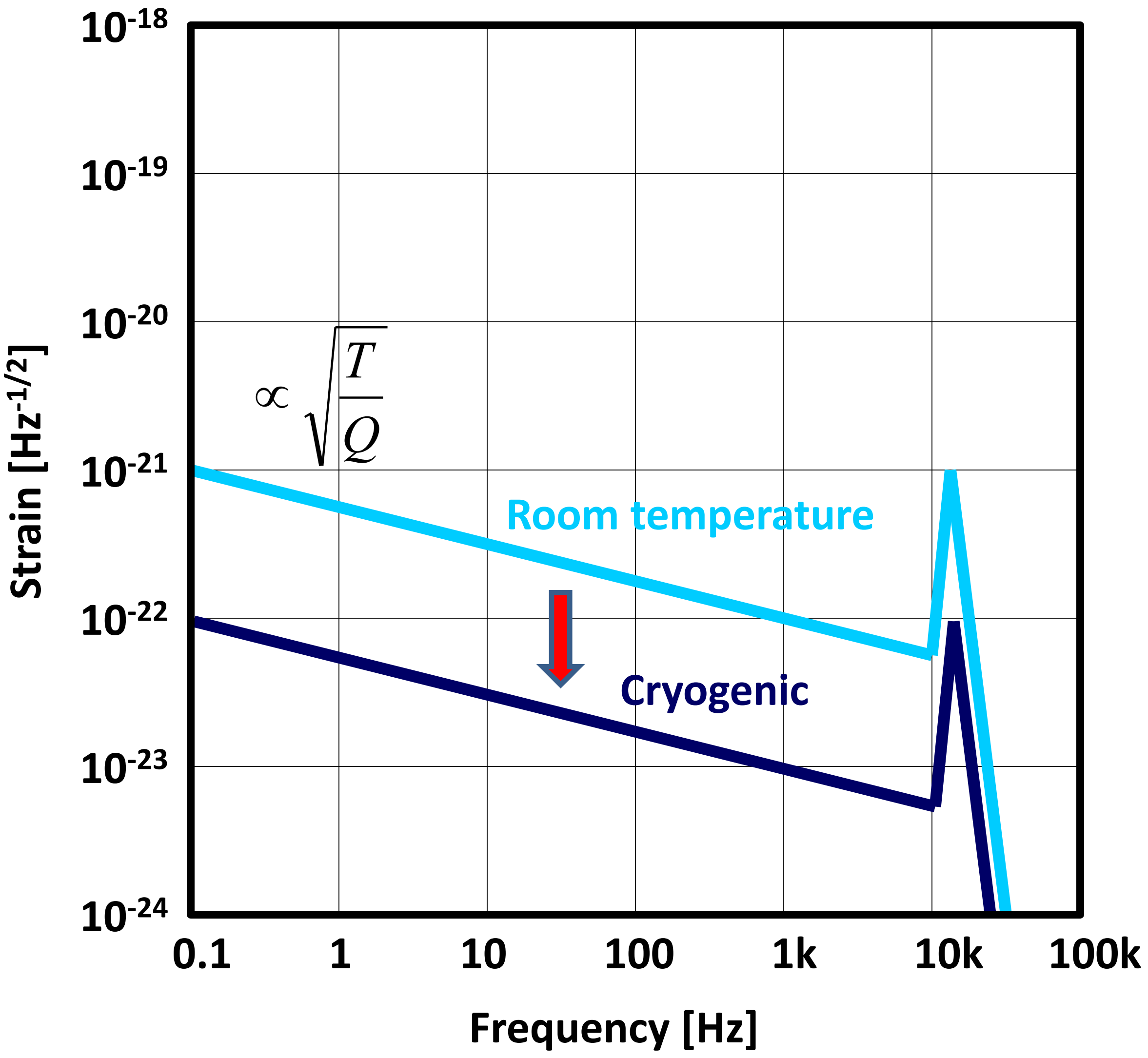
⇨ Cryogenic is a straight-forward way to reduce thermal noise.



Thermal noise (1)

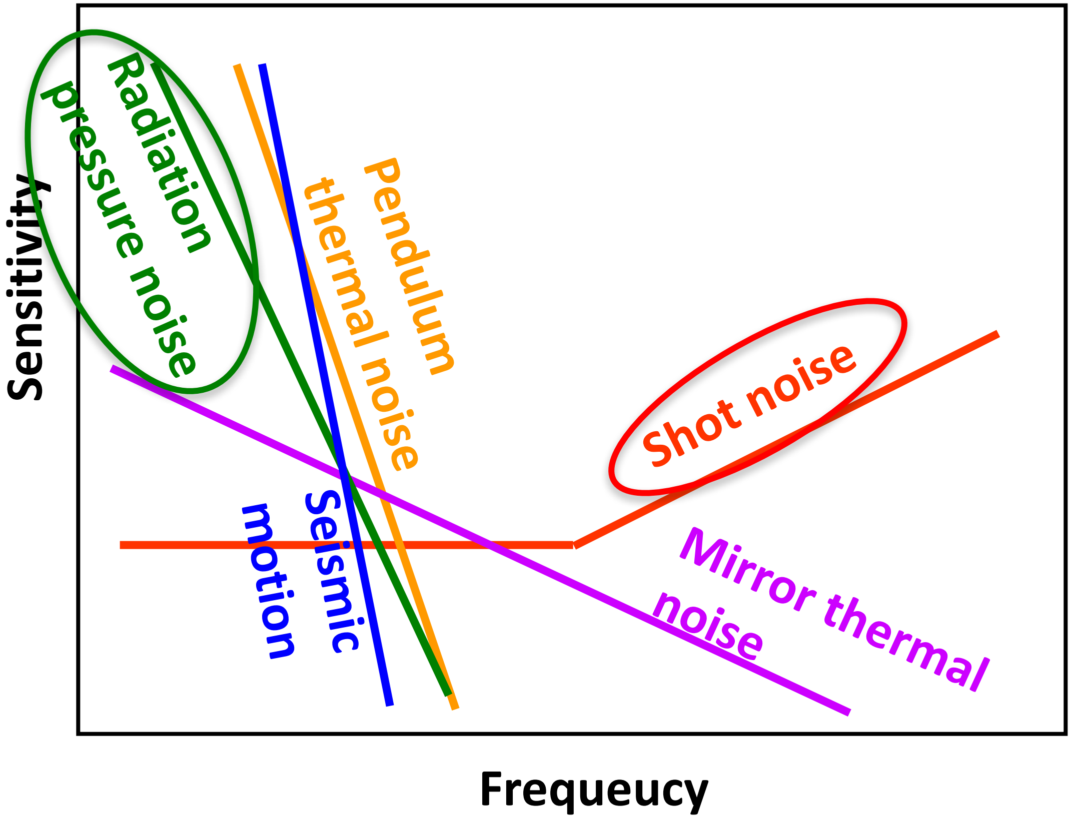


Thermal noise (2)



Noise sources

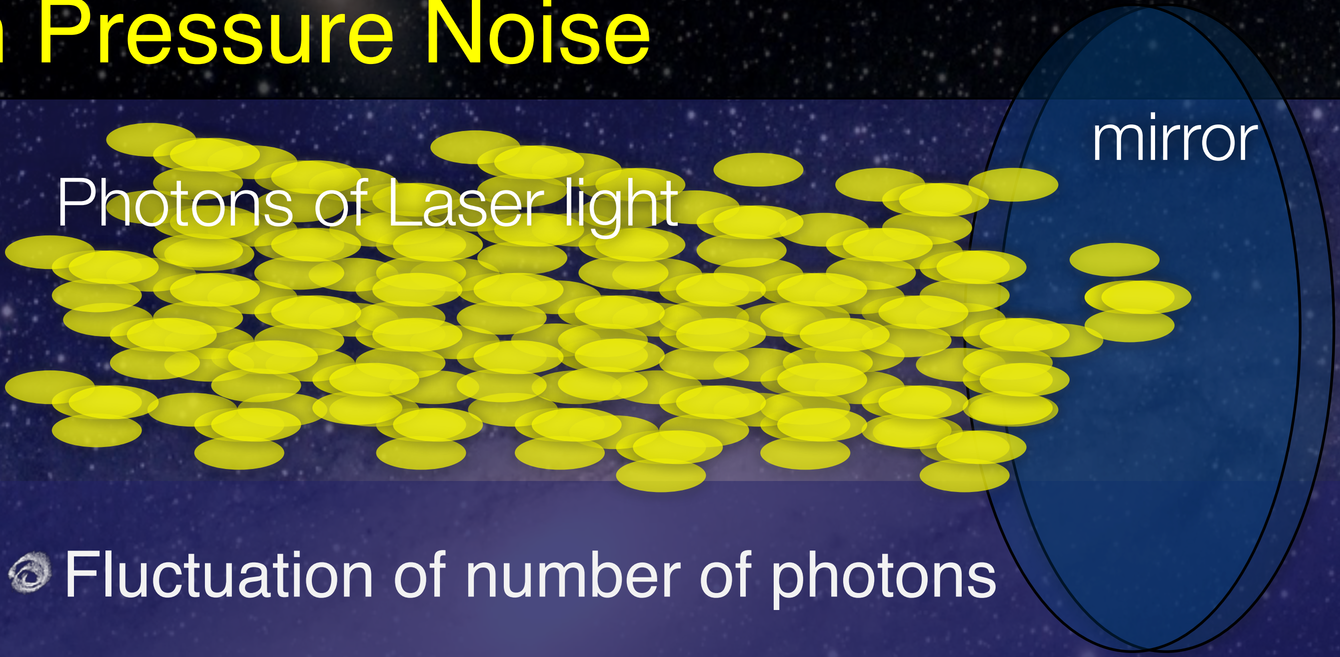
Sensitivity = Noise / Response of interferometer



For better sensitivity

1. Reducing noise
2. Higher response for interferometer

Shot Noise
Radiation Pressure Noise



- Fluctuation of number of photons

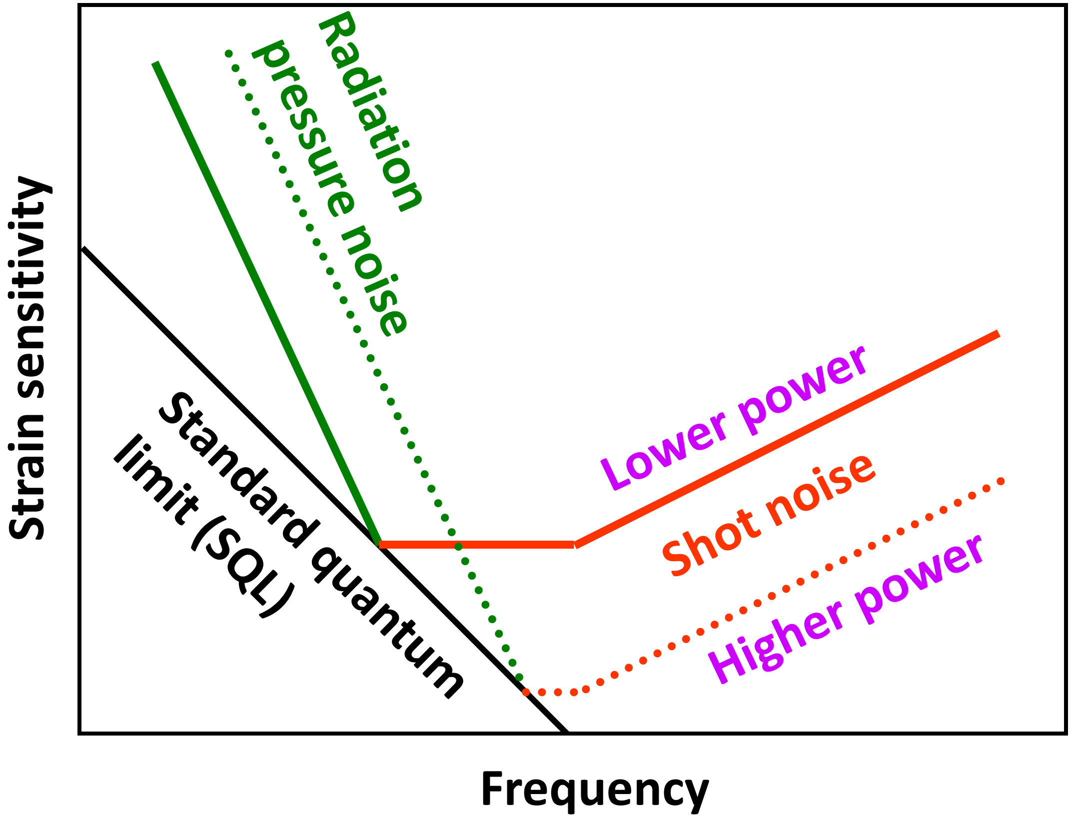
Shot Noise $$x_{shot}(f) \propto \sqrt{\frac{\hbar c \lambda}{P}}$$

Radiation Pressure Noise $$x_{rp}(f) \propto \frac{1}{mf^2}\sqrt{\frac{\hbar P}{c\lambda}}$$

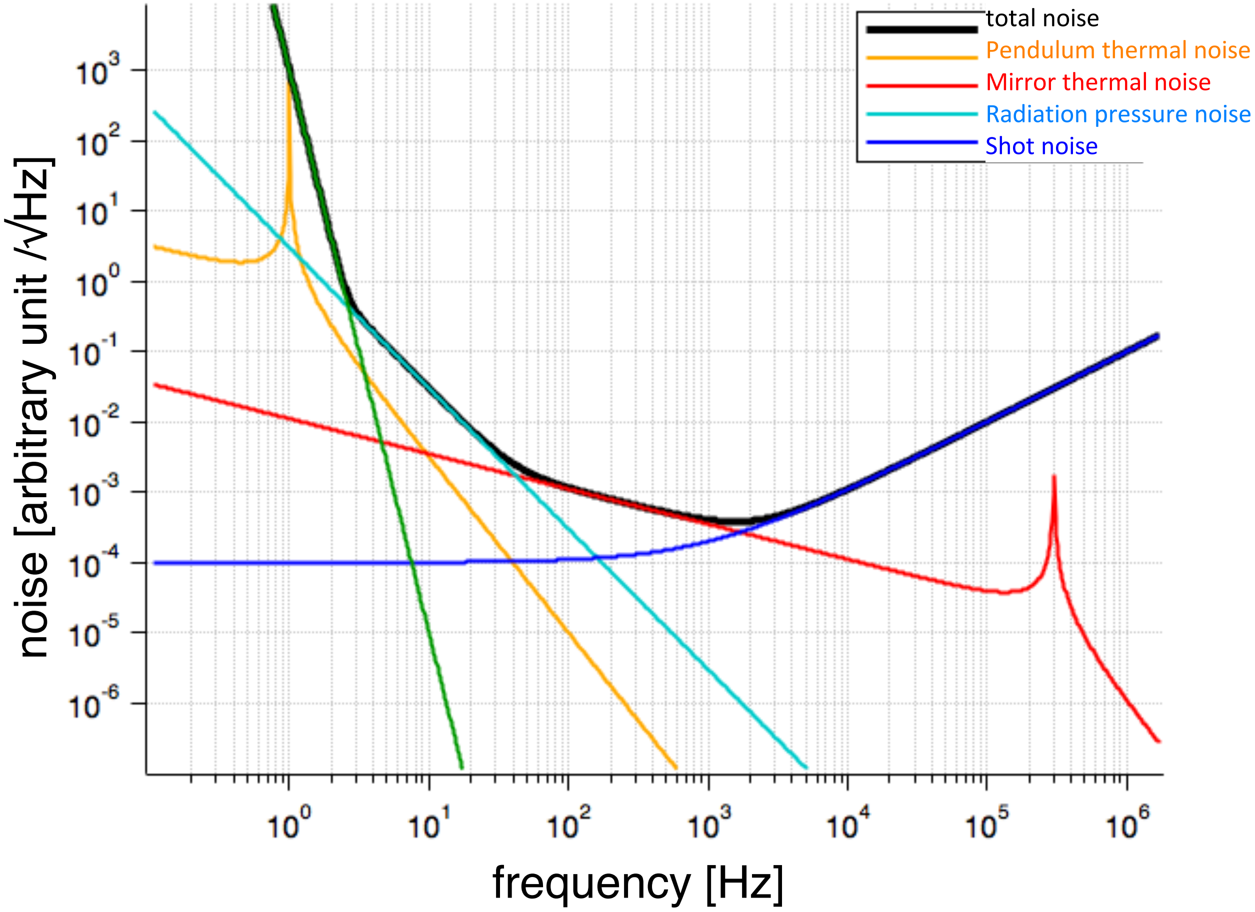
High Power ? or Low Power ?

To reduce quantum noise?

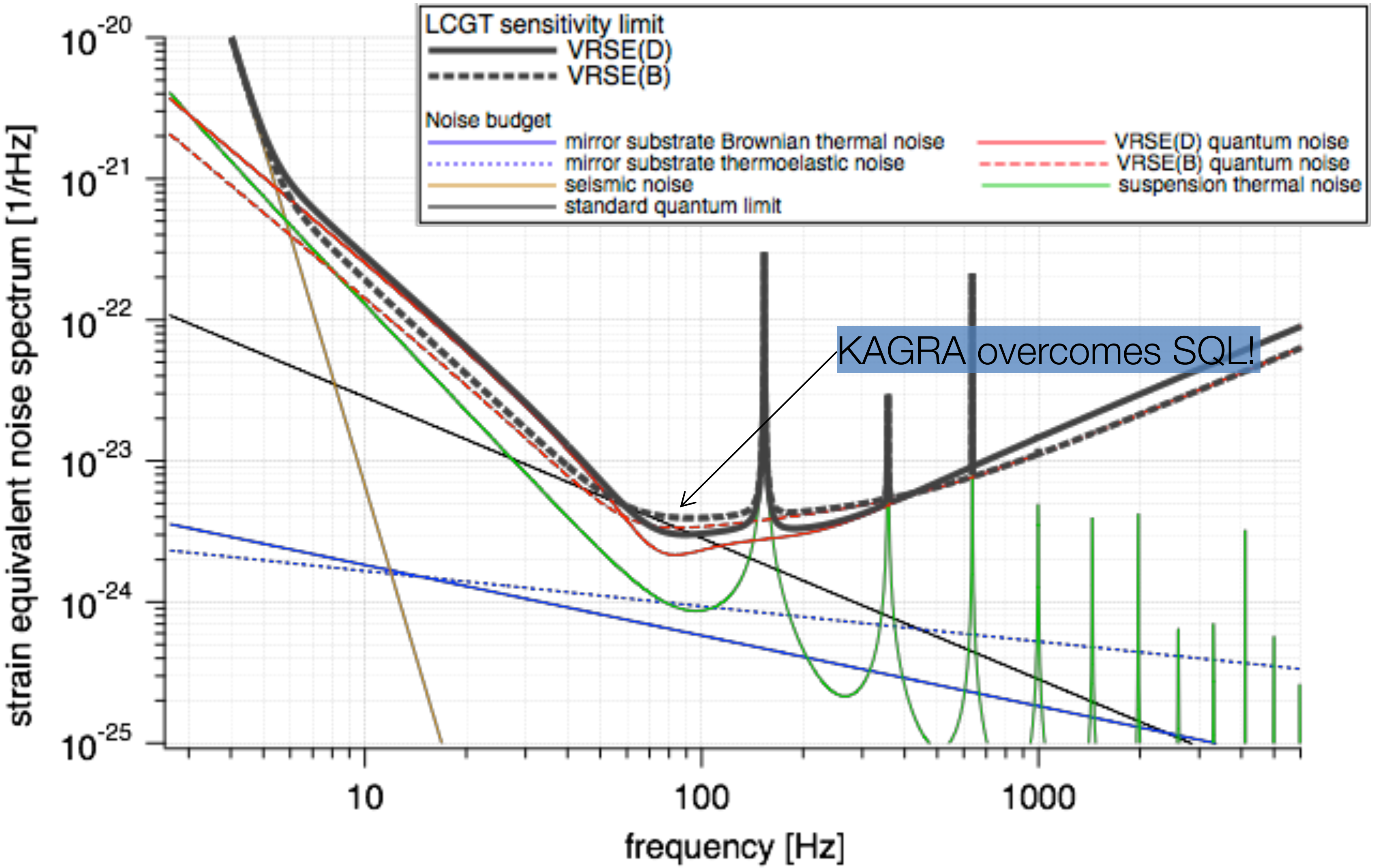
Reducing laser power reduces the shotnoise and increases the radiation pressure noise.



Noises !


total noise
Pendulum thermal noise
Mirror thermal noise
Radiation pressure noise
Shot noise
noise [arbitrary unit /√Hz]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
frequency [Hz]

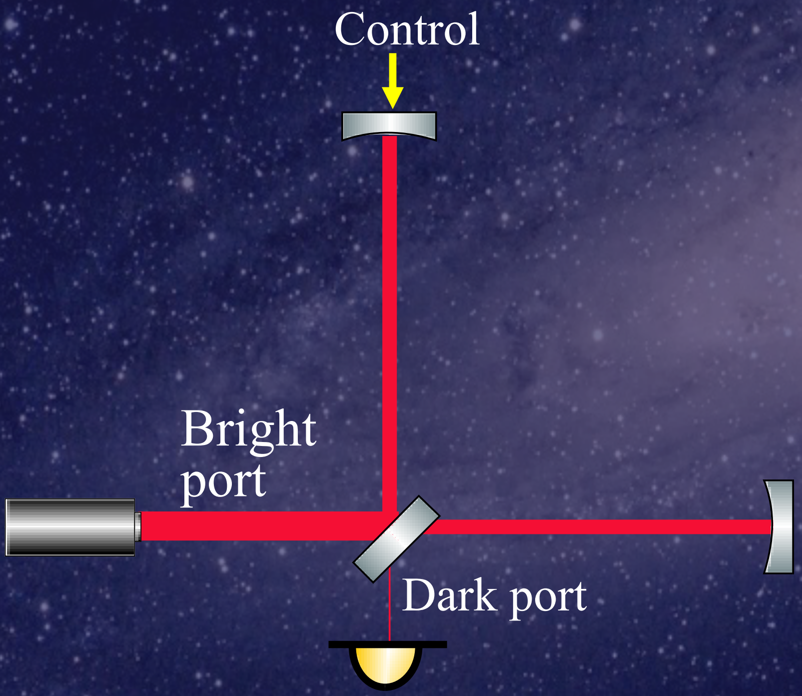
Sensitivity of KAGRA

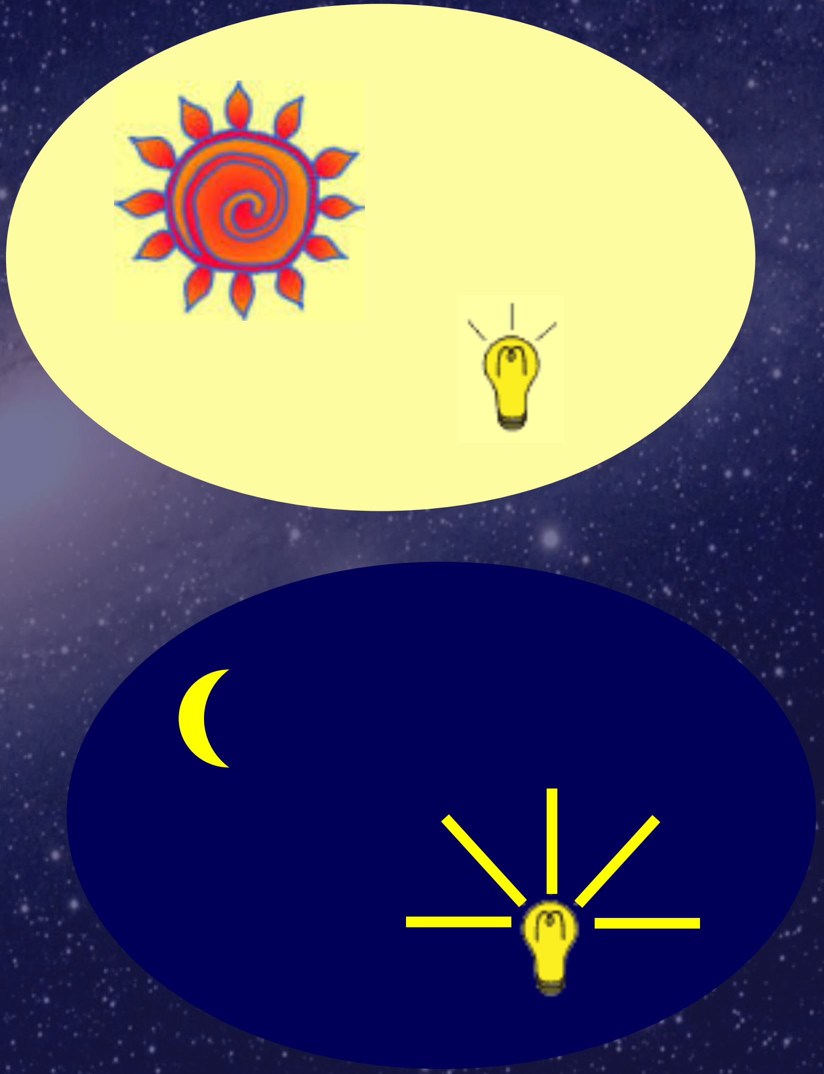


KAGRA overcomes SQL!

How to get More sensitivity with control?

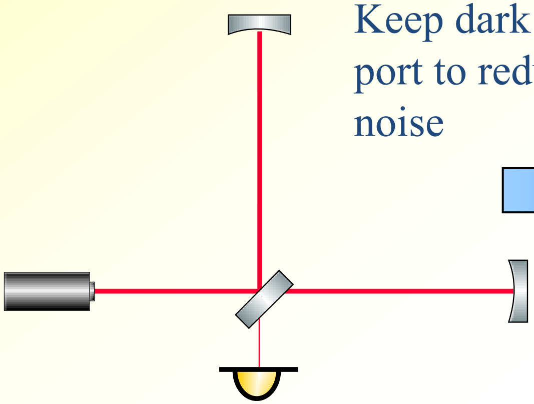
One of the mirror is controlled to keep dark at detection port (Dark fringe locking)





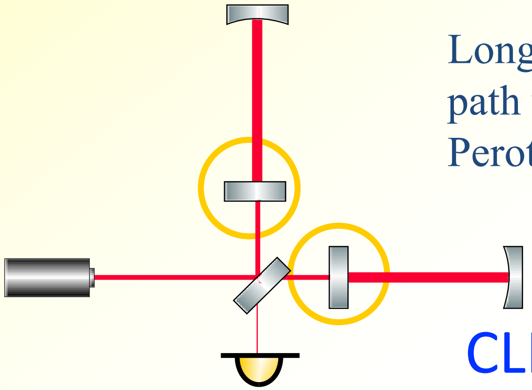
Development of optical configurations

Michelson interferometer (MI)



Keep dark at detection port to reduce shot noise

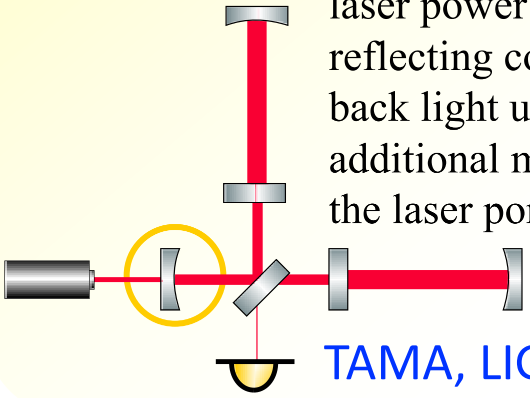
Fabry-Perot MI (FPMI)



Longer folding light path using Fabry-Perot cavity

CLIO

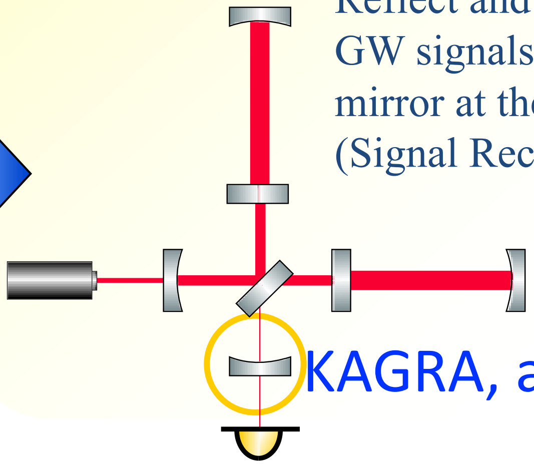
Power recycling (PRFPMI)



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

TAMA, LIGO , VIRGO

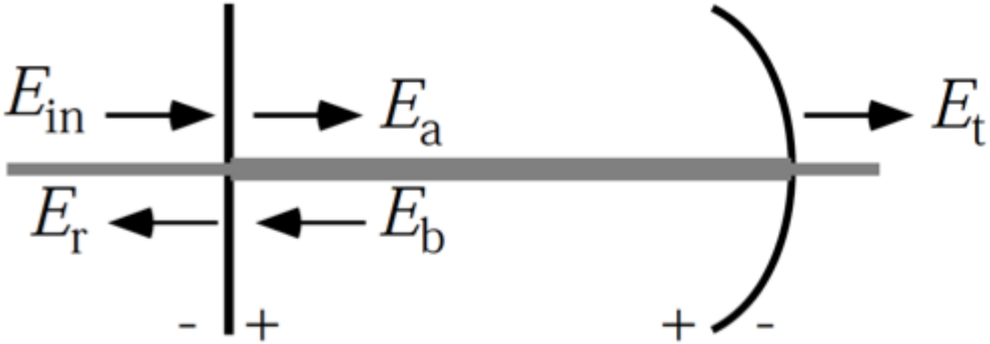
Dual recycling (DR)



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

KAGRA, aLIGO, aVIRGO

Fabry-Perot cavity



振幅透過率: t_F
振幅反射率: r_F

振幅透過率: t_E
振幅反射率: r_E

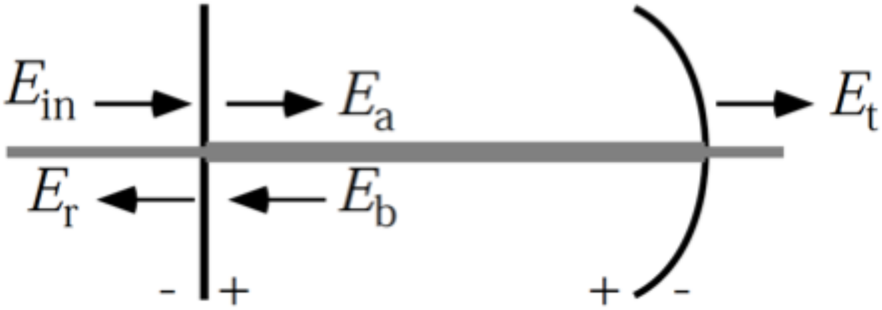
$$E_{in} = E_0 e^{i\Omega t}$$

$$\begin{aligned} E_a &= t_F E_{in} + r_F E_b \\ E_b &= r_E e^{-2i\frac{L\Omega}{c}} E_a \\ E_r &= t_F E_b - r_F E_{in} \\ E_t &= t_E e^{-i\frac{L\Omega}{c}} E_a \end{aligned}$$

$$\Rightarrow$$

$$\begin{aligned} E_a &= \frac{t_F}{1 - r_F r_E e^{-i\Phi}} E_{in} \\ E_b &= \frac{t_F r_E e^{-i\Phi}}{1 - r_F r_E e^{-i\Phi}} E_{in} \\ E_r &= \left(-r_F + \frac{{t_F}^2 r_E e^{-i\Phi}}{1 - r_F r_E e^{-i\Phi}} \right) E_{in} \\ E_t &= \frac{t_F t_E e^{-i\frac{\Phi}{2}}}{1 - r_F r_E e^{-i\Phi}} E_{in} \end{aligned}$$

Fabry-Perot cavity



$$r_{cav}(\Phi) \equiv \frac{E_r}{E_{in}} = -r_F + \frac{{t_F}^2 r_E e^{-i\Phi}}{1 - r_F r_E e^{-i\Phi}}$$

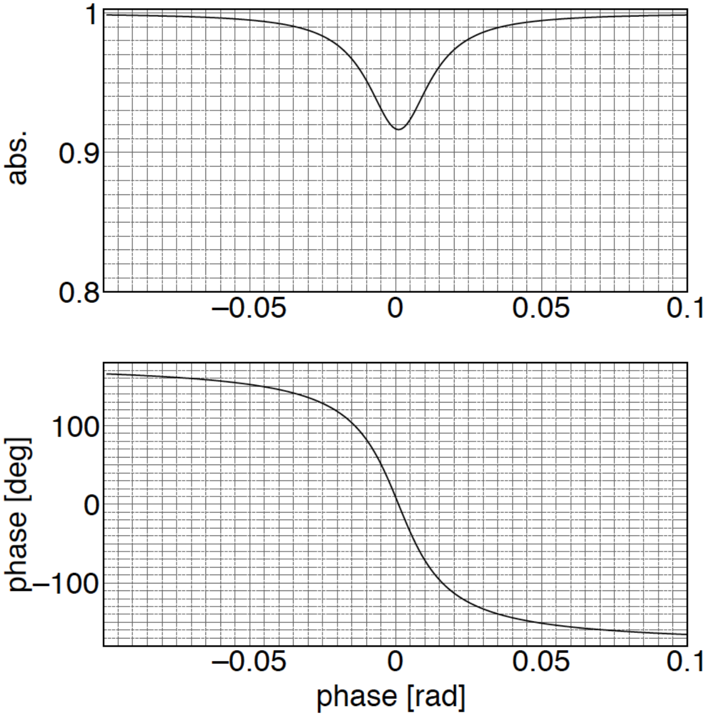
$$t_{cav}(\Phi) \equiv \frac{E_t}{E_{in}} = \frac{t_F t_E e^{-i\frac{\Phi}{2}}}{1 - r_F r_E e^{-i\Phi}}$$

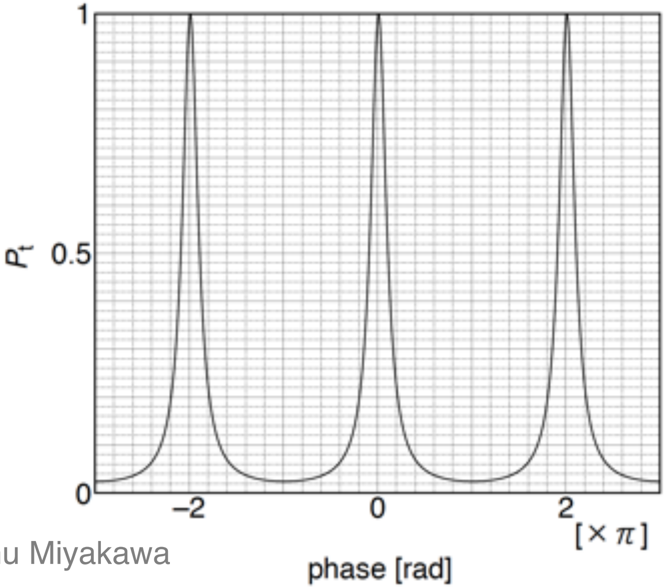
折り返し回数

フィネス

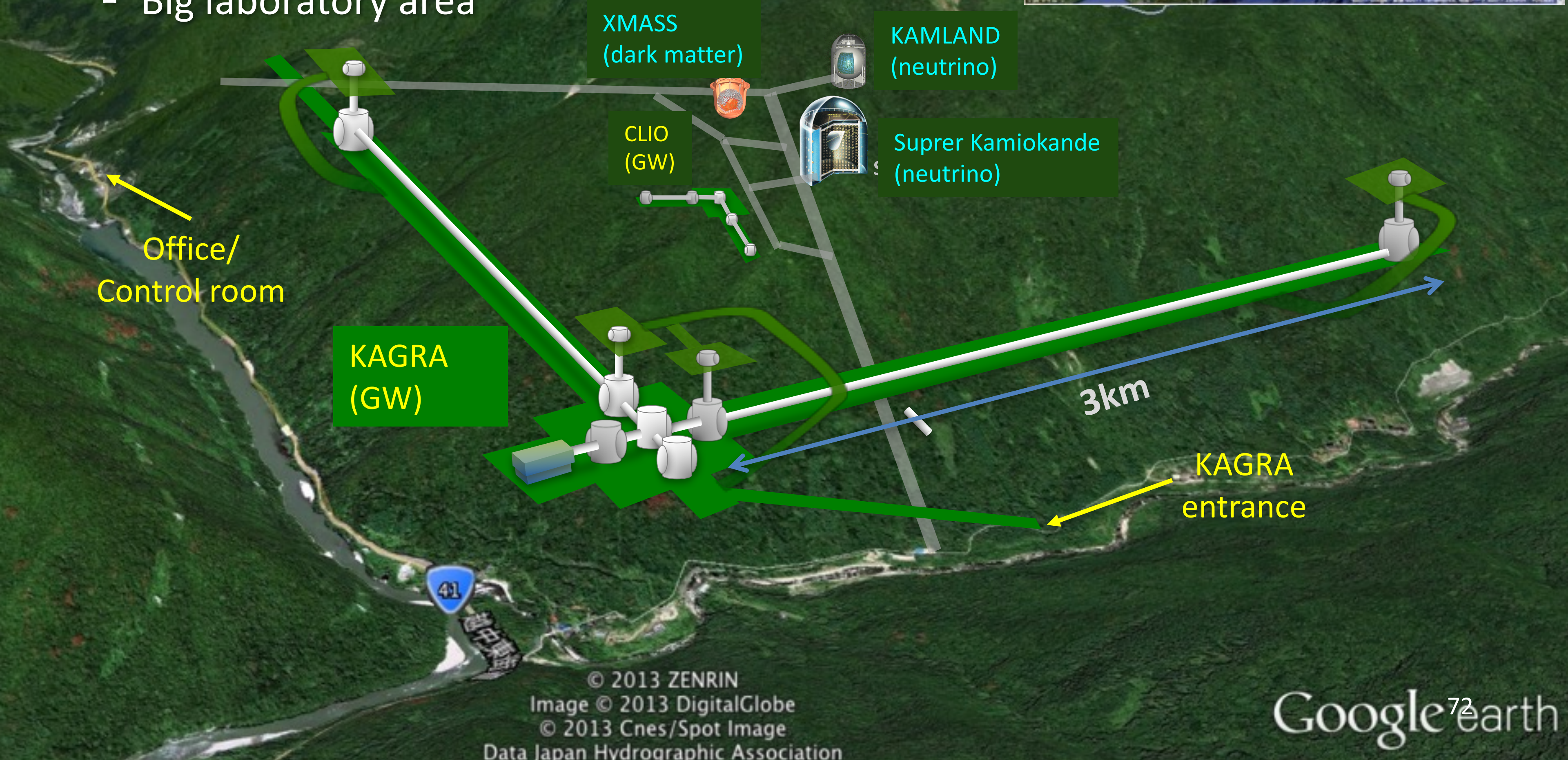
$$\mathcal{F} = \frac{\nu_{FSR}}{\nu_{FWHM}} = \frac{\pi\sqrt{r_F r_E}}{1 - r_F r_E}$$

$$N_{FP} = \frac{2\mathcal{F}}{\pi} = \frac{2\sqrt{r_F r_E}}{1 - r_F r_E}$$

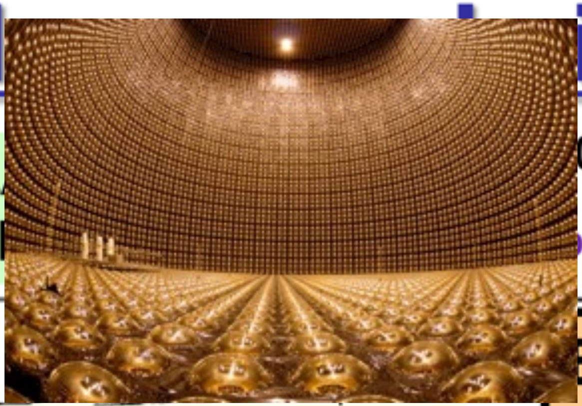




- KAGRA is located in Kamioka mine underground
  - 220km away from Tokyo
  - 360m altitude
- Big laboratory area



Kar d i



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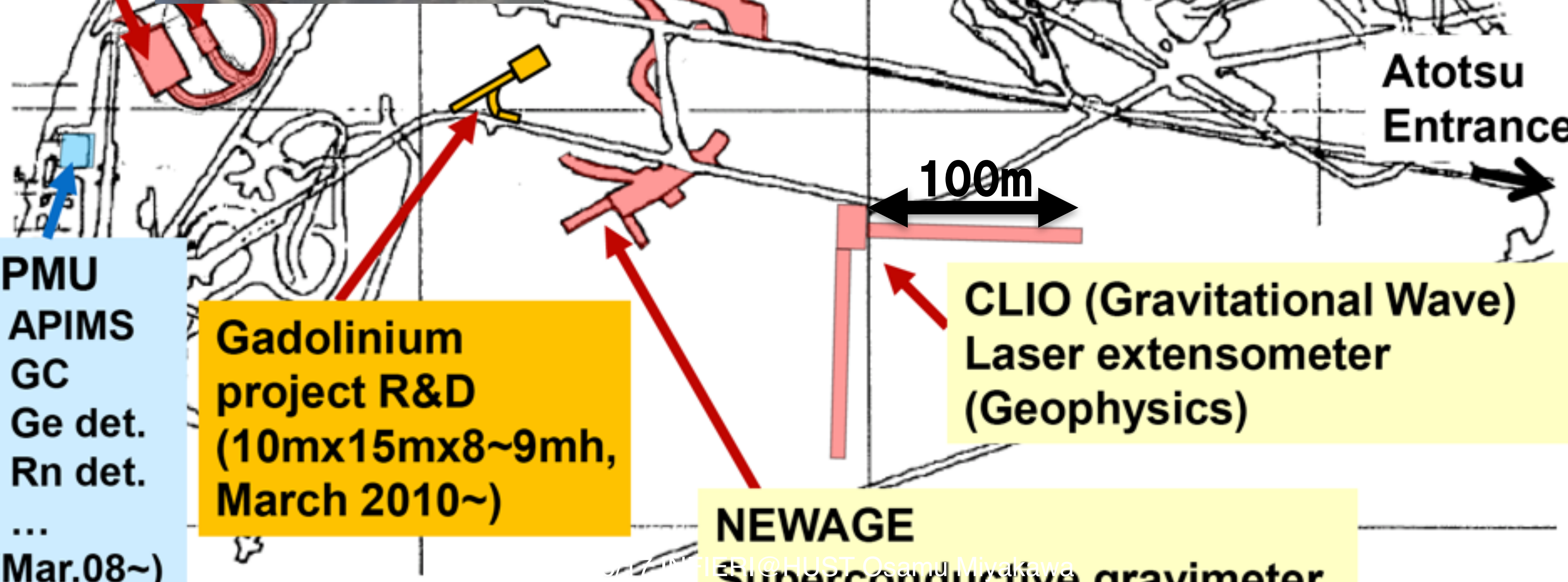
yo.ac.jp/

sites

a g

(LCGT budget is partially approved in this summer)



XMASS
(Mar. 20

CA
(M

Super-Kamiokade

Atotsu Entrance

100m

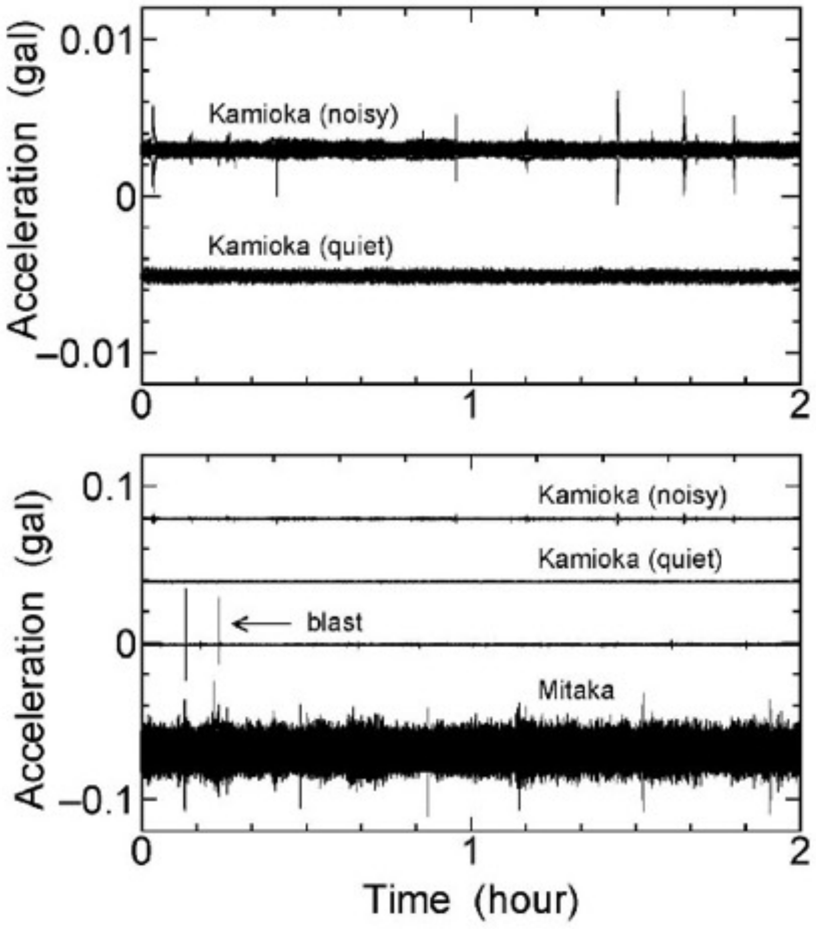
IPMU
APIMS
GC
Ge det.
Rn det.
…
(Mar.08~)

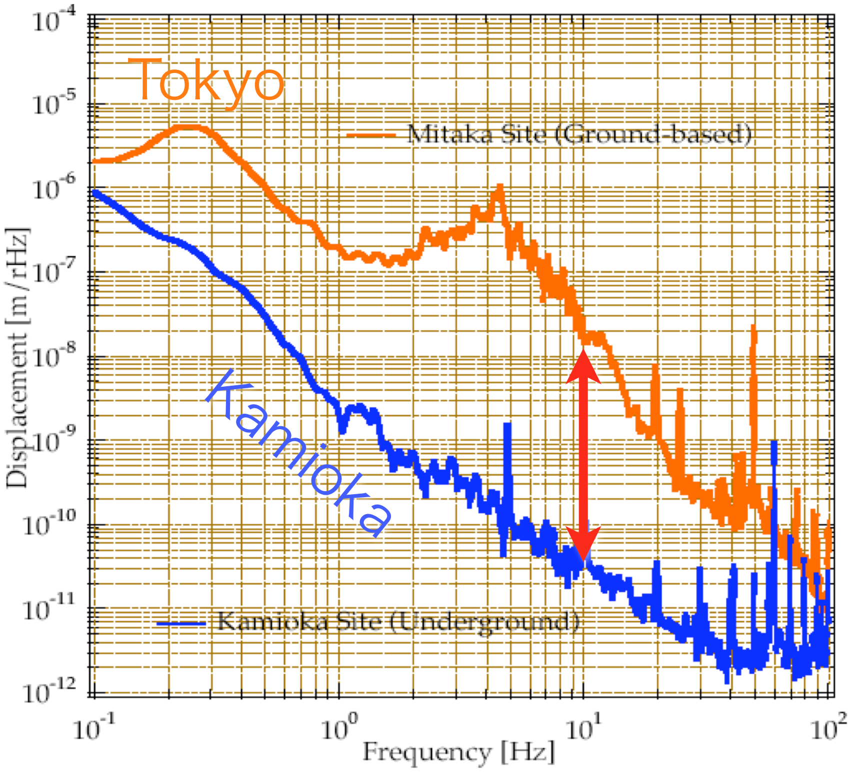
Gadolinium project R&D (10mx15mx8~9mh, March 2010~)

CLIO (Gravitational Wave)
Laser extensometer
(Geophysics)

NEWAGE
Superconductive gravimeter

Underground site is QUIET



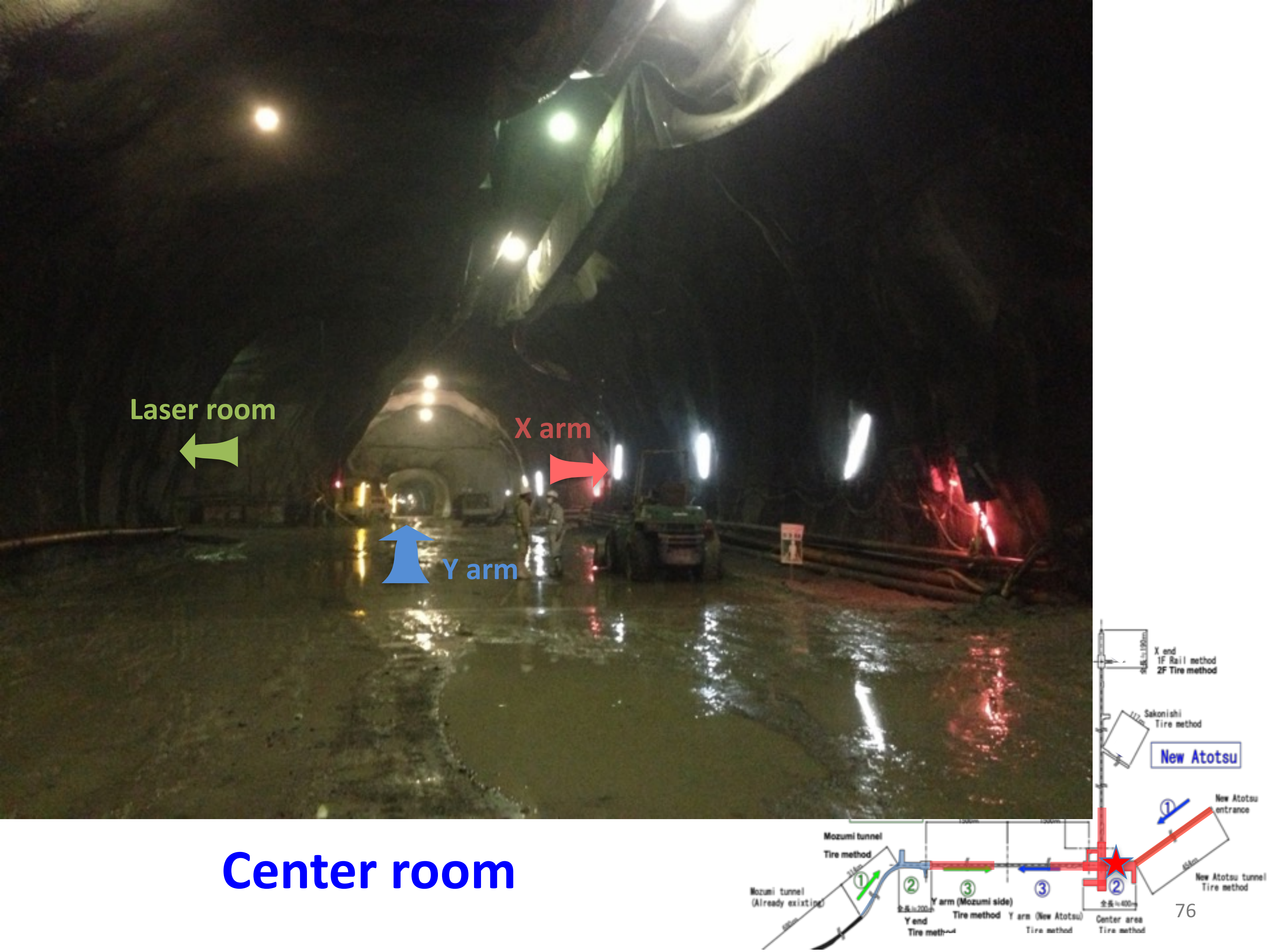


Amplitude of seismic motion

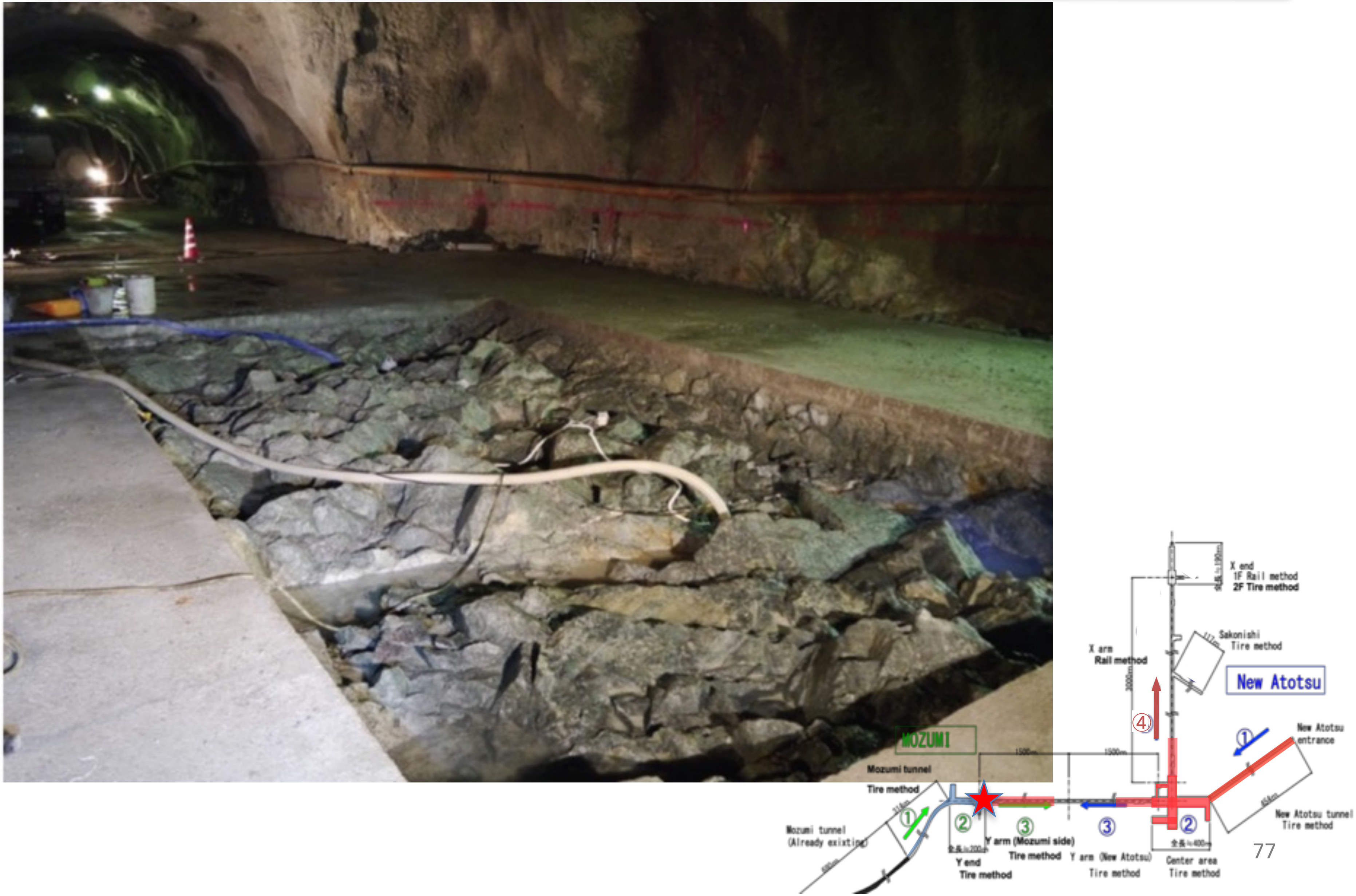
KAGRA

Snow in winter.
Melted snow in April.

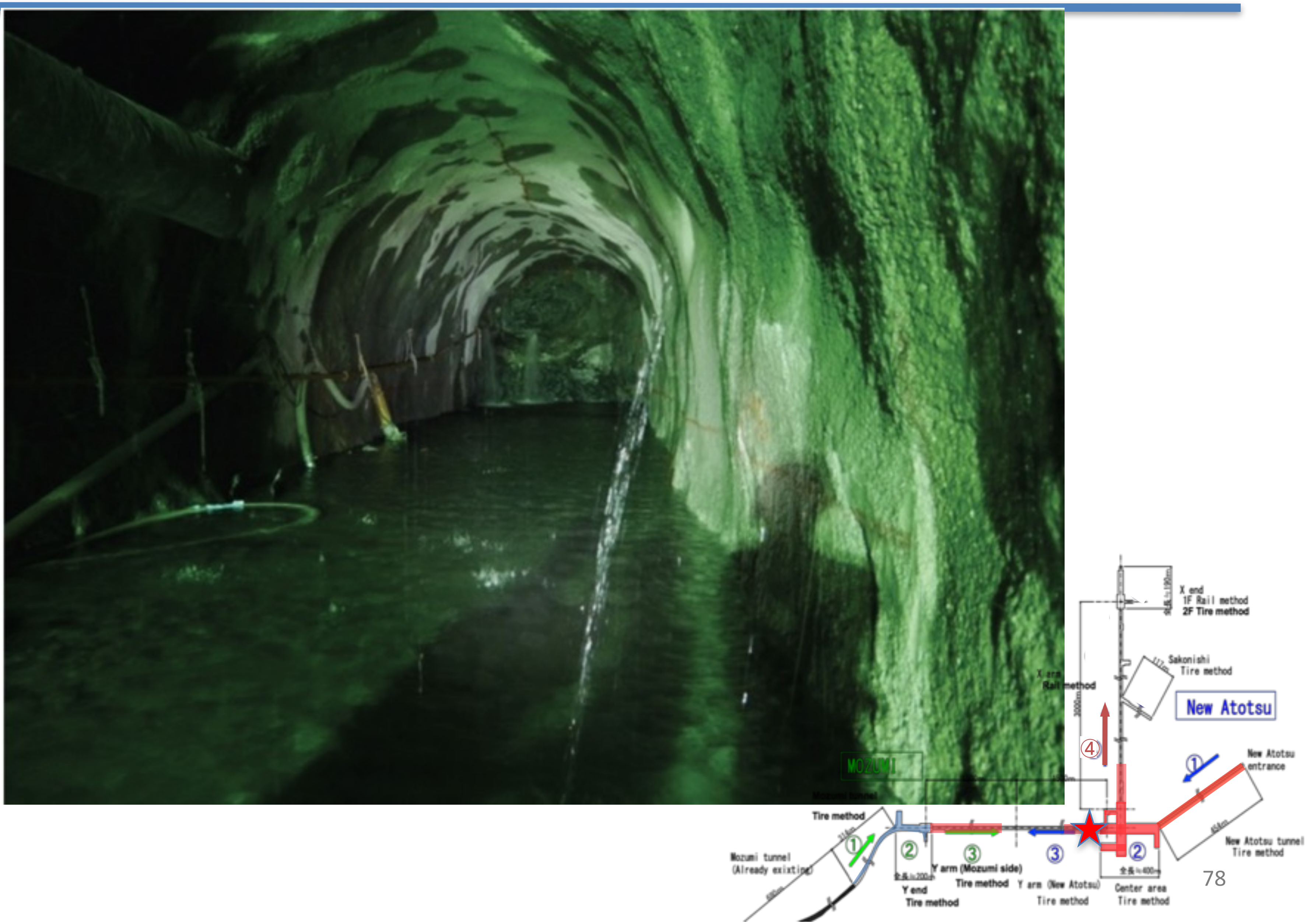
Center room


Laser room
X arm
Y arm
X end
1F Rail method
2F Tire method
Sakonishi
Tire method
New Atotsu
①
New Atotsu
entrance
Mozumi tunnel
Tire method
Mozumi tunnel
(Already existing)
①
②
③
③
②
全長≒200m
Y end
Tire method
Y arm (Mozumi side)
Tire method
Y arm (New Atotsu)
Tire method
全長≒400m
Center area
Tire method
New Atotsu tunnel
Tire method

Y end area for chamber location



Y arm under water

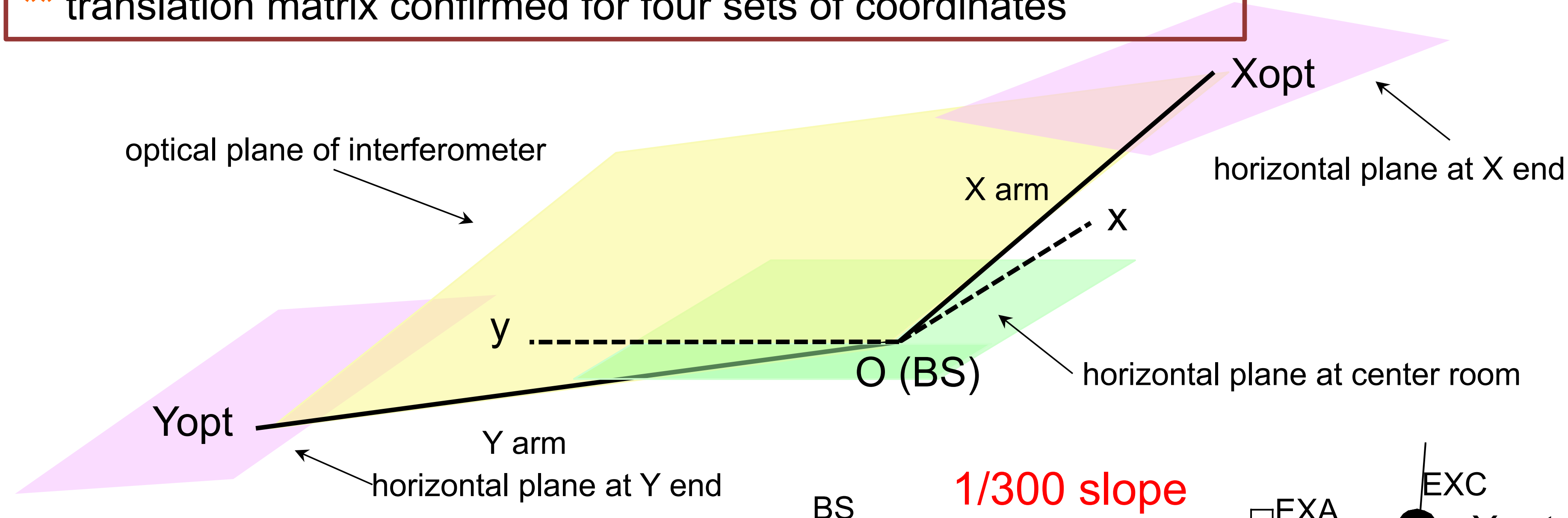


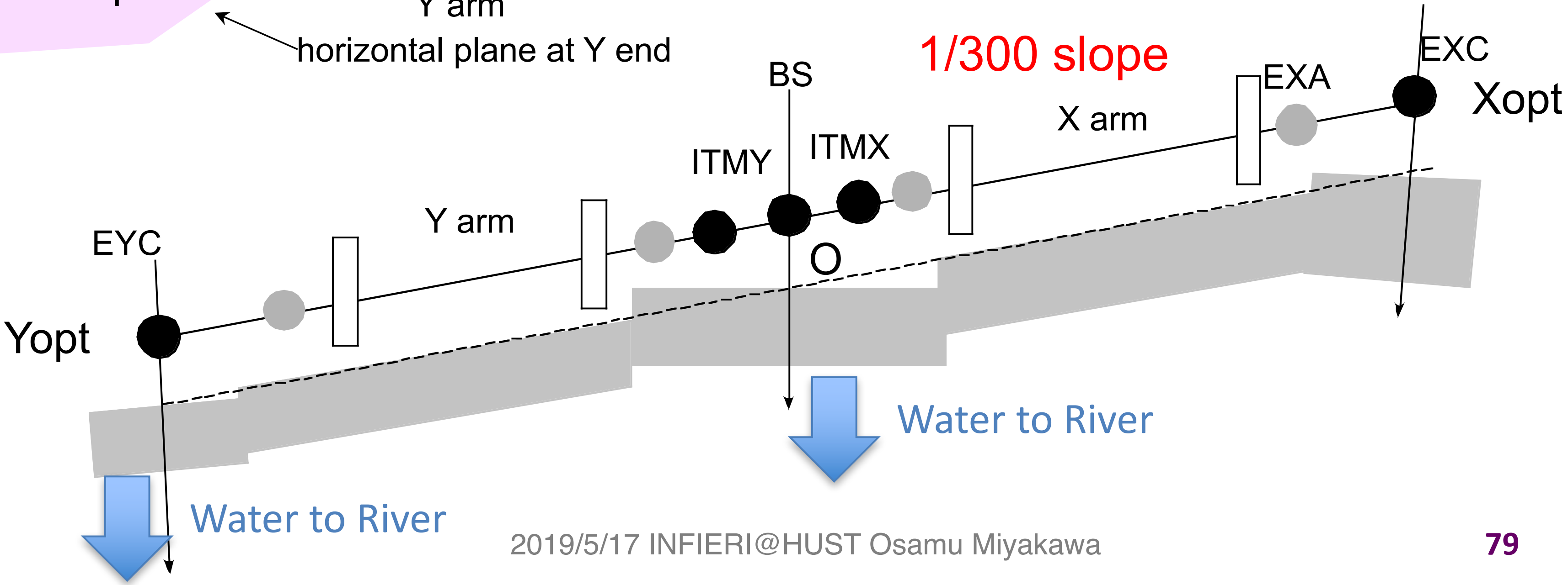
KAGRA Vacuum System

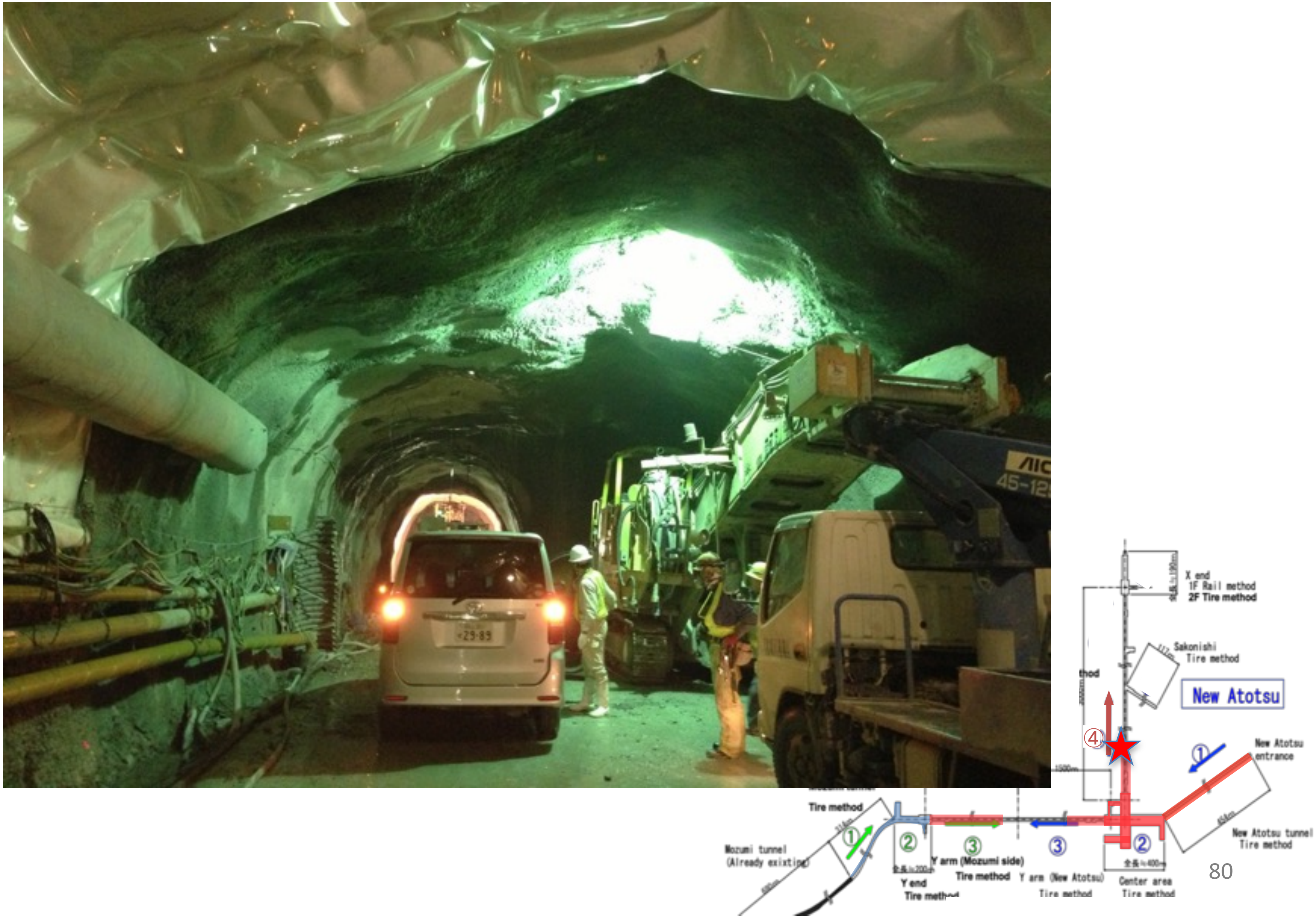
130417 VAC (YS)

1. Layout (four planes/floors)

** horizontal floors in each room prepared for installing chambers
** translation matrix confirmed for four sets of coordinates






X end
1F Rail method
2F Tire method
Sakonishi
Tire method
thod
New Atotsu
④
①
New Atotsu
entrance
1500m
Tire method
Mozumi tunnel
(Already existing)
①
②
③
③
②
Y arm (Mozumi side)
Tire method
Y end
Tire method
Y arm (New Atotsu)
Tire method
Center area
Tire method
New Atotsu tunnel
Tire method

KAGRA configuration

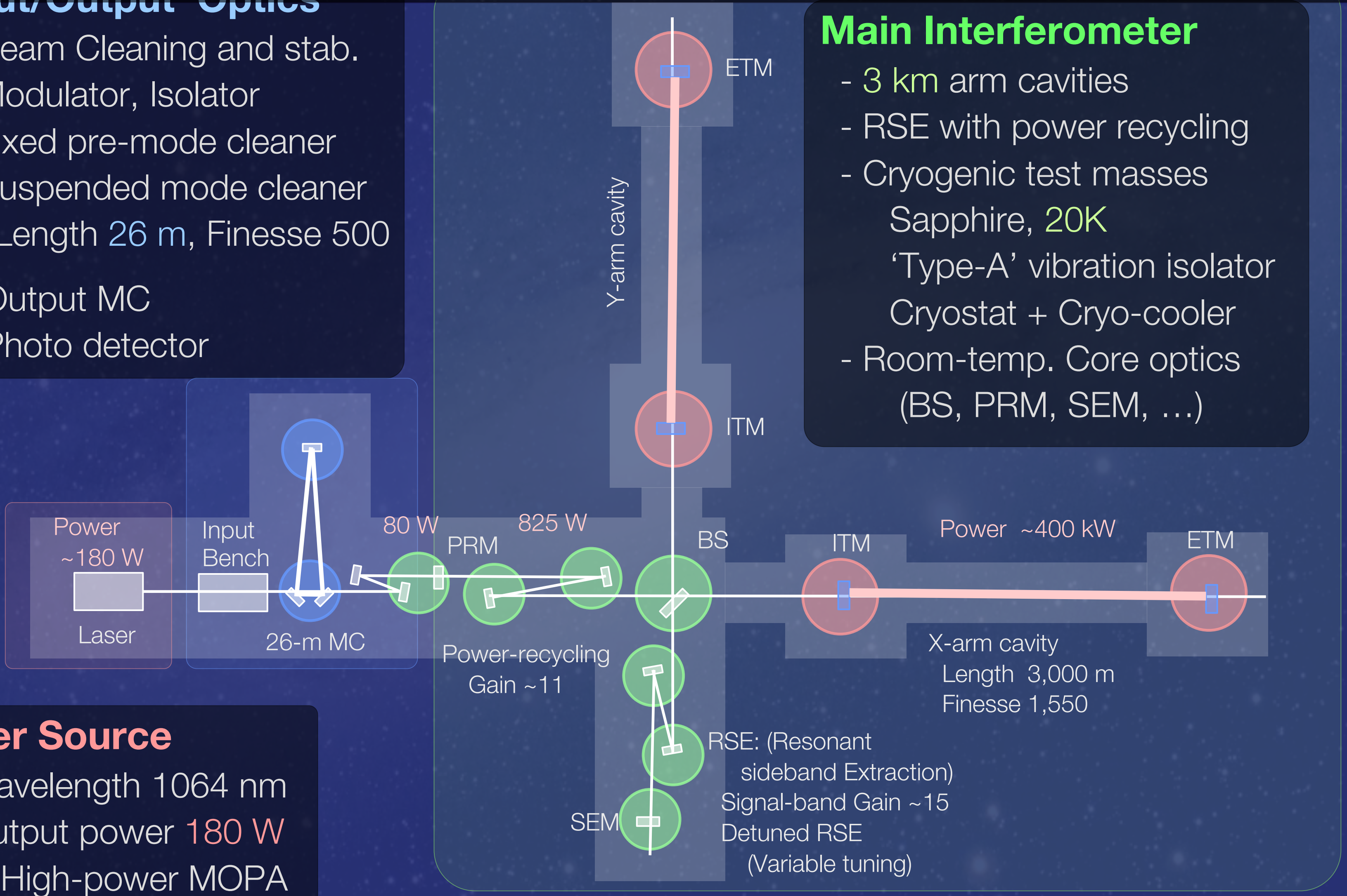
Input/Output Optics

- 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

Technologies to realize large vacuum area

Board

welding

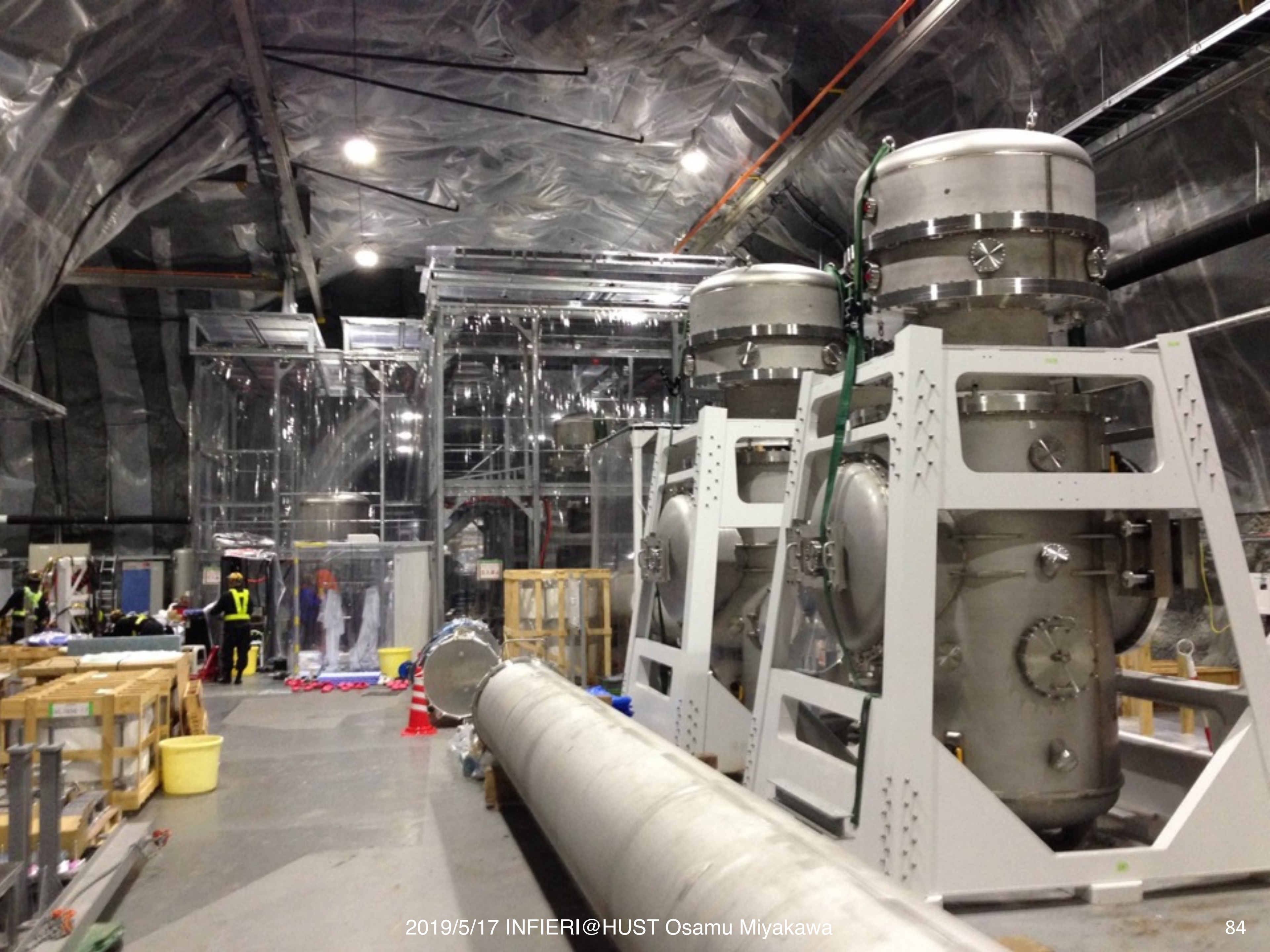
welding flange and bellows

ECB polish

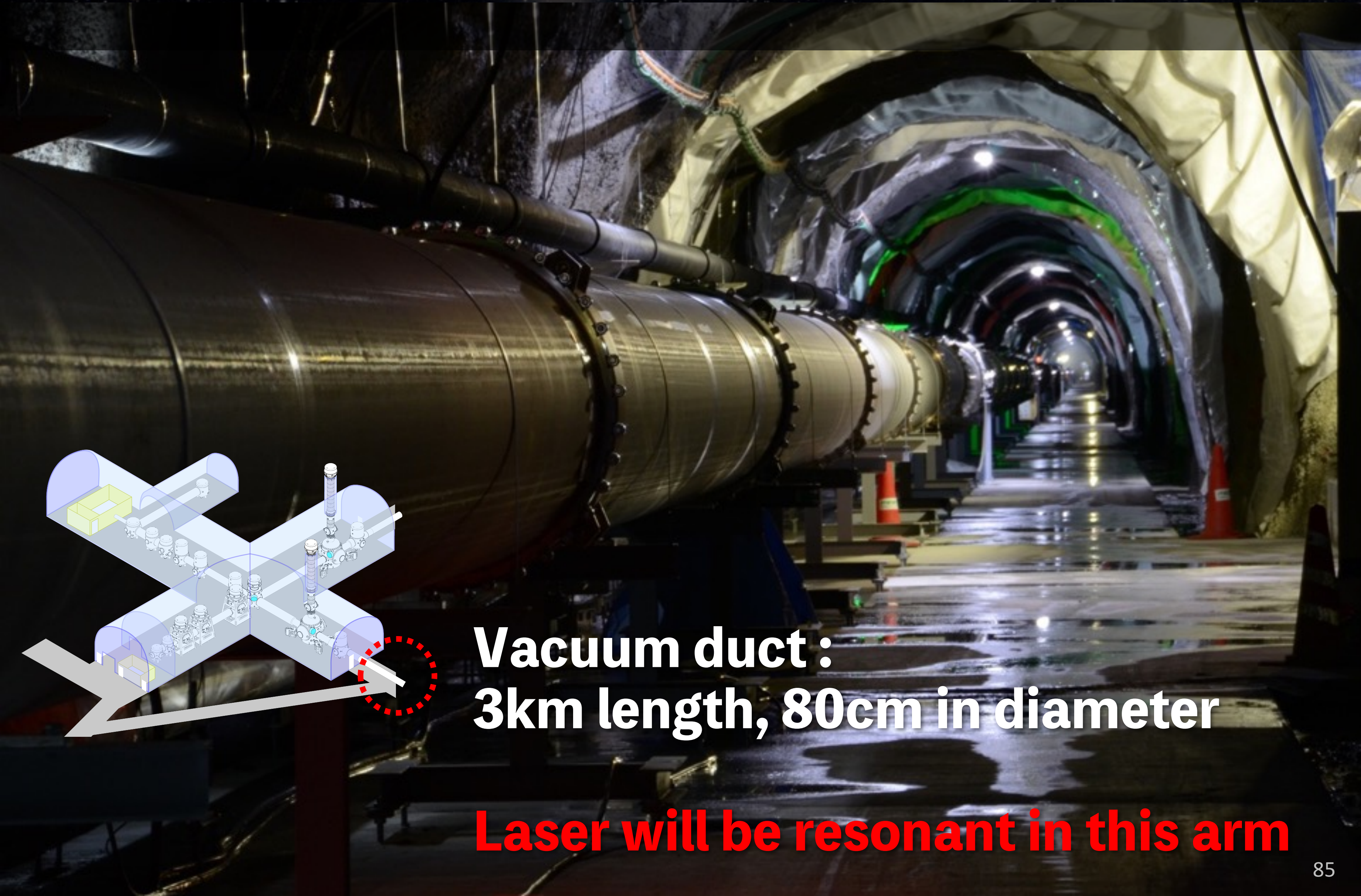
Baking

12m × 0.8m 500本

Corner Station



X-Arm



Vacuum duct :
3km length, 80cm in diameter

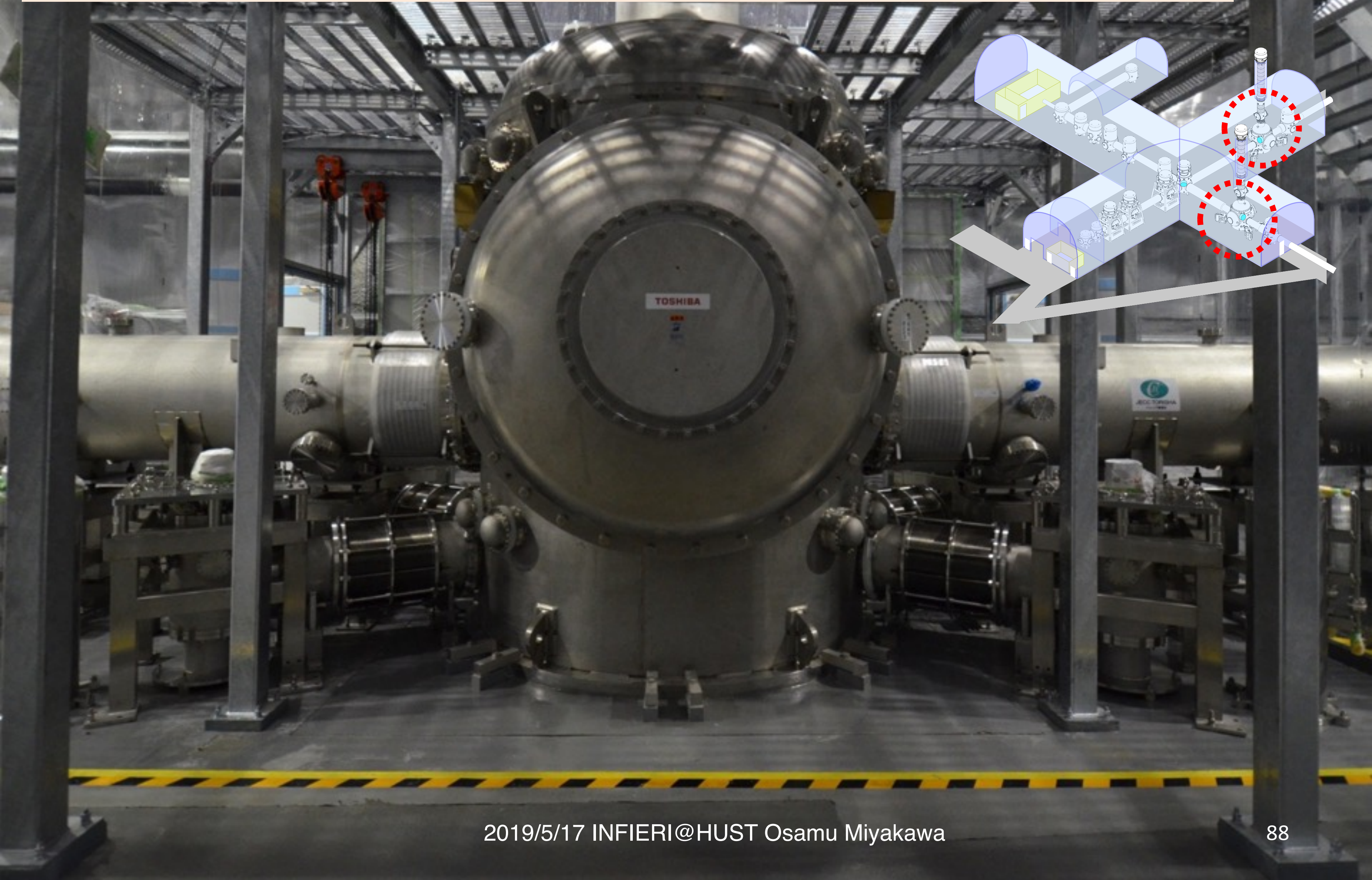
Laser will be resonant in this arm

Y-Arm

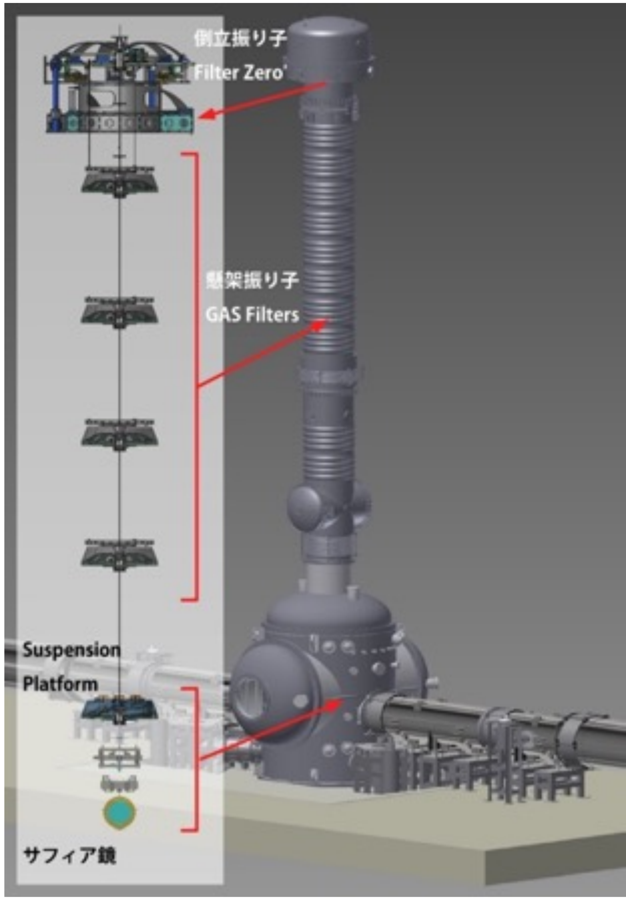
Vacuum duct :
3km length, 80cm in diameter

Laser will be resonant in this arm

Cryostat:
Suspending sapphire mirror and cool it down to 16K



Vibration isolation for mirrors



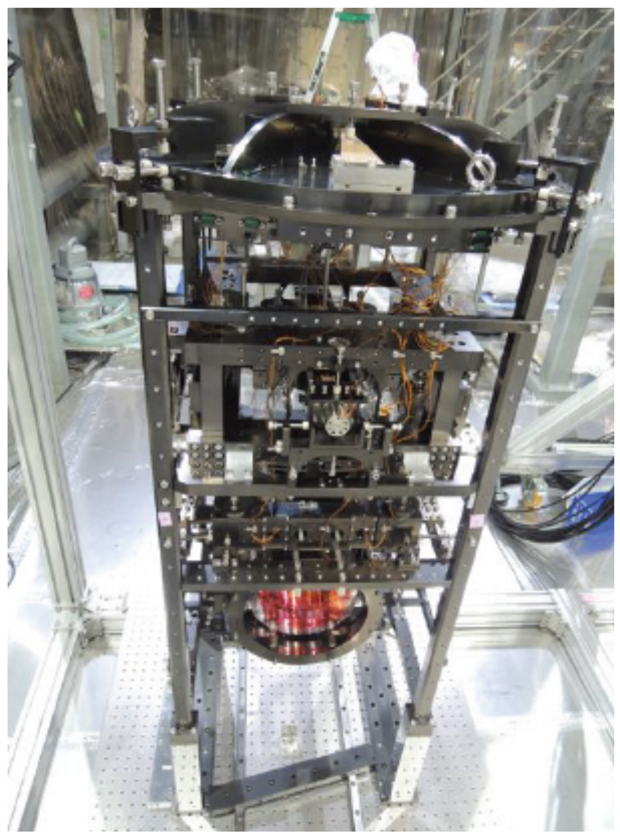
CRYO

All the sapphire mirrors has installed in Nov 2018

ITMX and ITMY

Pictures from K Yamamoto

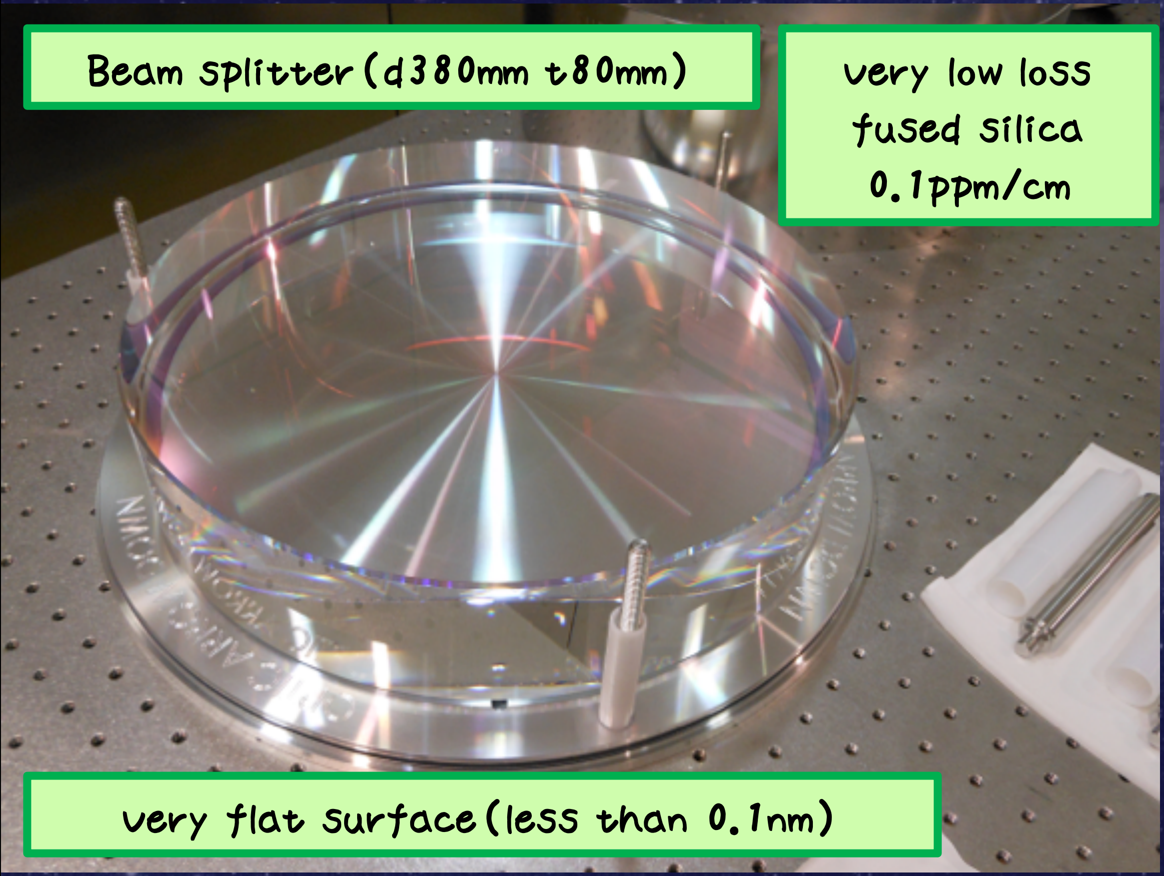
Ears were bonded at Toyama



Bonded mirror is integrated
Into the cryo-payload
And the type-C suspension
at the site

→ See, Ushiba, Yamada,
Fukunaga's talks

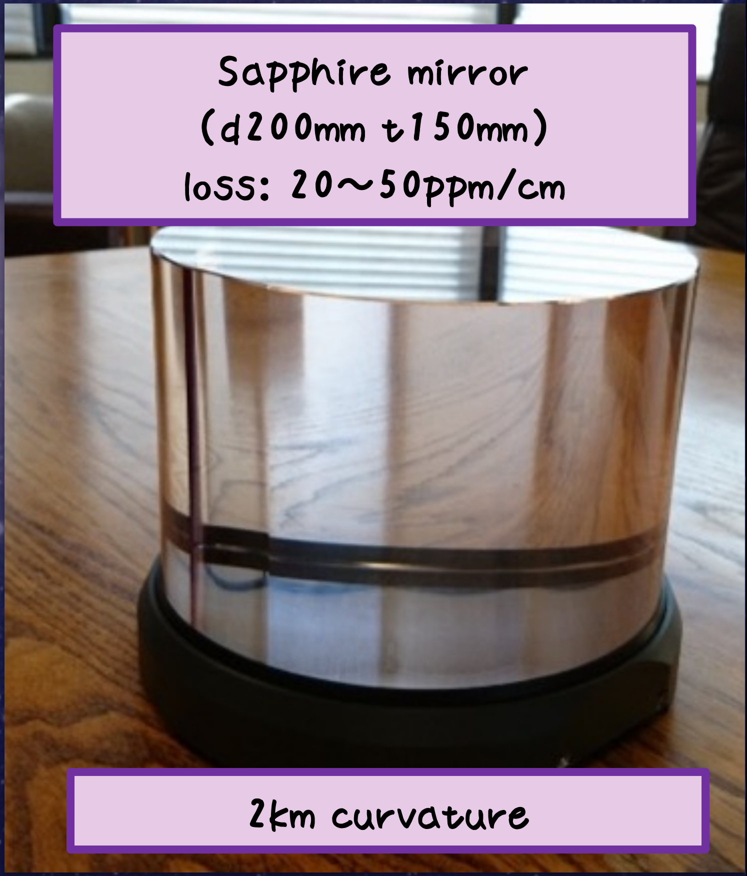
Super polished large scale mirrors



Beam splitter (d380mm t80mm)

very low loss
fused silica
0.1ppm/cm

very flat surface (less than 0.1nm)

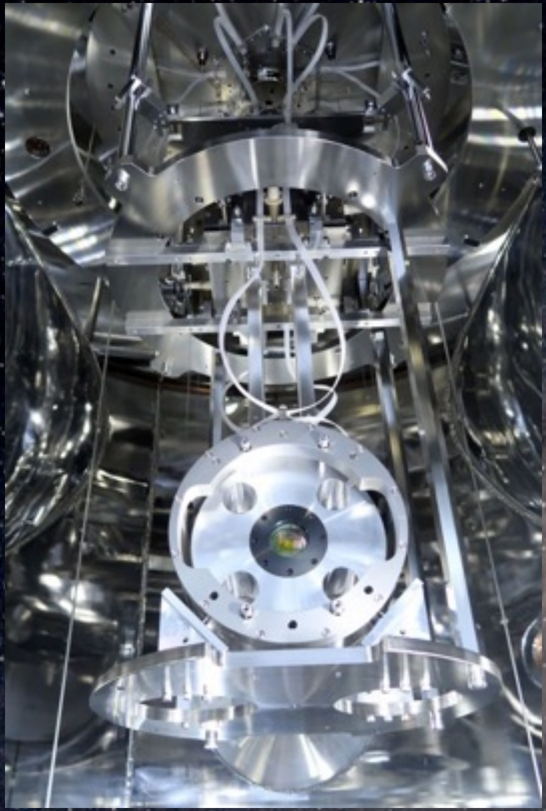


Sapphire mirror
(d200mm t150mm)
loss: 20～50ppm/cm

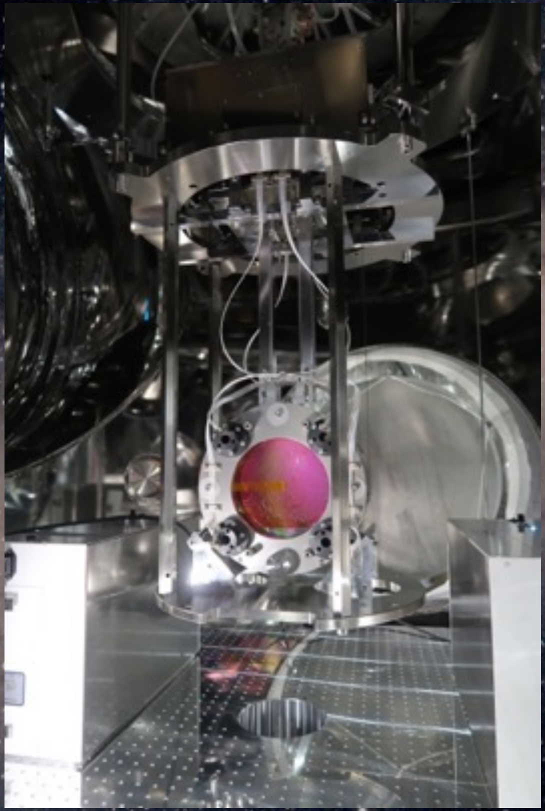
2km curvature

Most recently, all SRs have been installed!

SRM



SR2



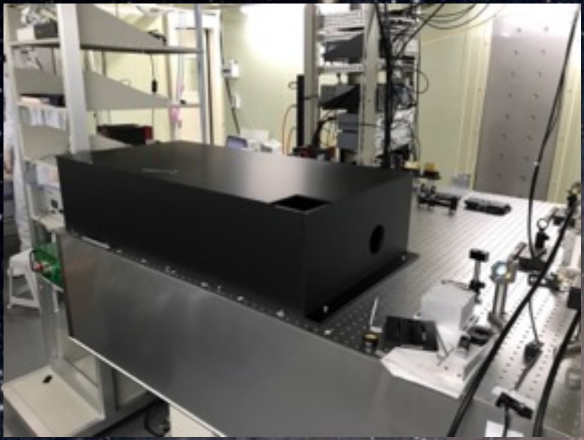
SR3

* SRM has a temporary 2-inch mirror

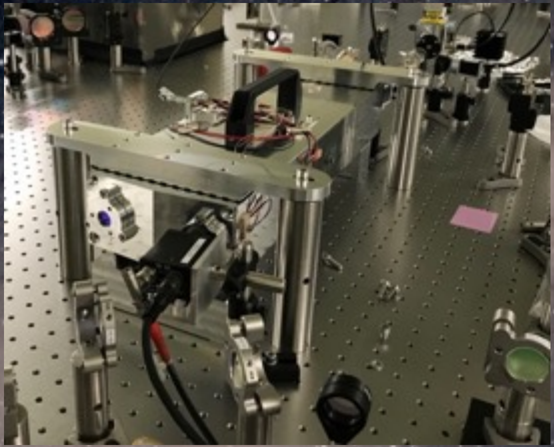
→ See, Burton, Tapia, Fujii, Kozu's talks

Input Optics

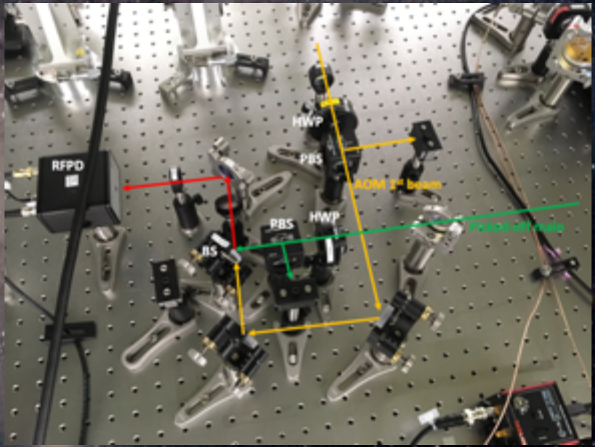
40W laser installed



PMC installed



Mach-Zehnder ifo type
modulation system,
PM&AM monitor system

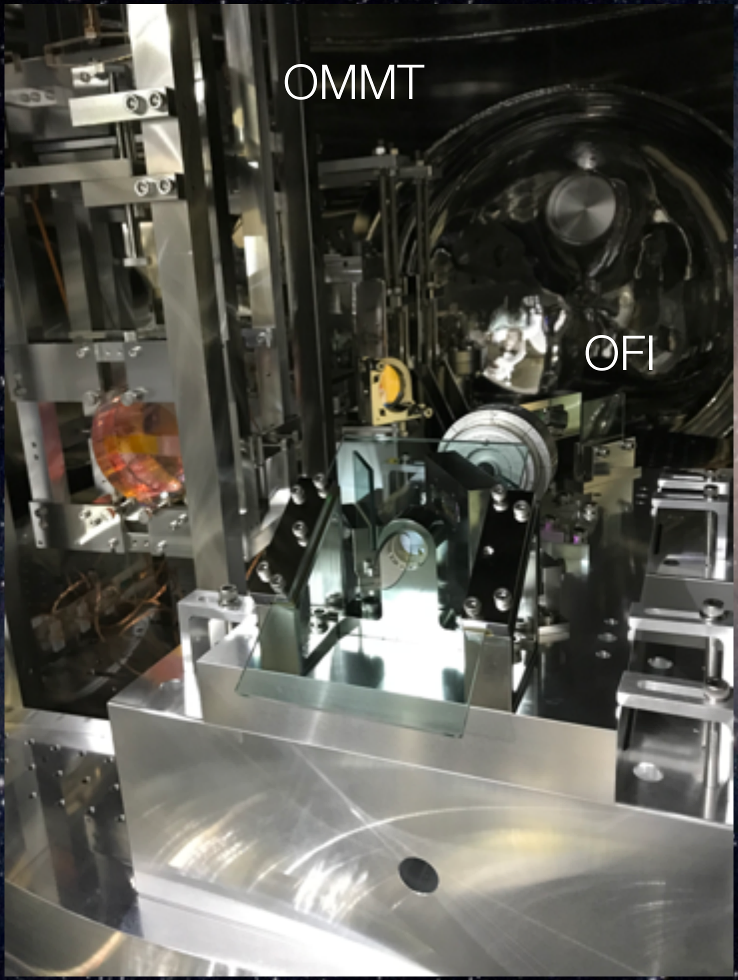


- Input mode cleaner was tested with 10W
- Intensity stabilization is being commissioned
- Frequency stabilization (mode cleaner & reference cavity) has been operating since phase1

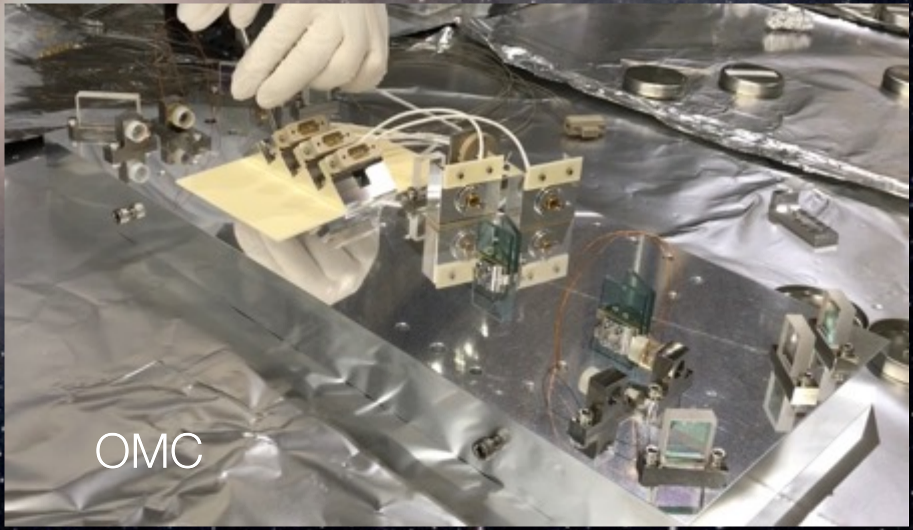
→ See, Nakano's talk

Output Optics

- Output mode cleaner (OMC)
- Output Faraday Isolator (OFI)
- Output mode-matching telescopes (OMMTs) installed!



Nov-Dec 2018



Auxiliary Optics

WAB EX

Transmon EX

NAB IY

- WAB - 3 of 4 installed! The last one delivered at the X end
- Transmitting monitor (TRANSMON) installed in both of the X and Y ends!

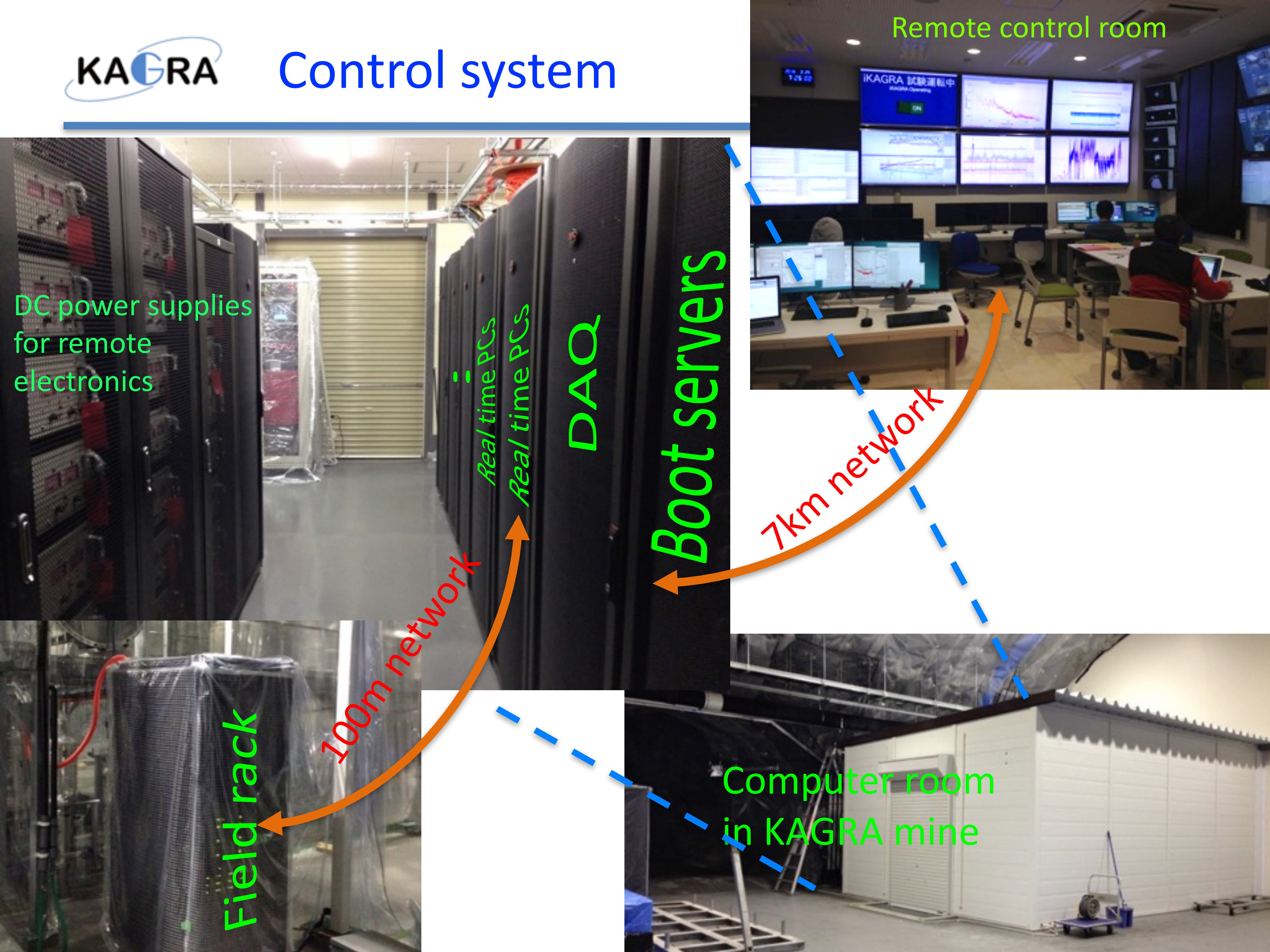
Real time control for interferometer using computers

LIGO control room

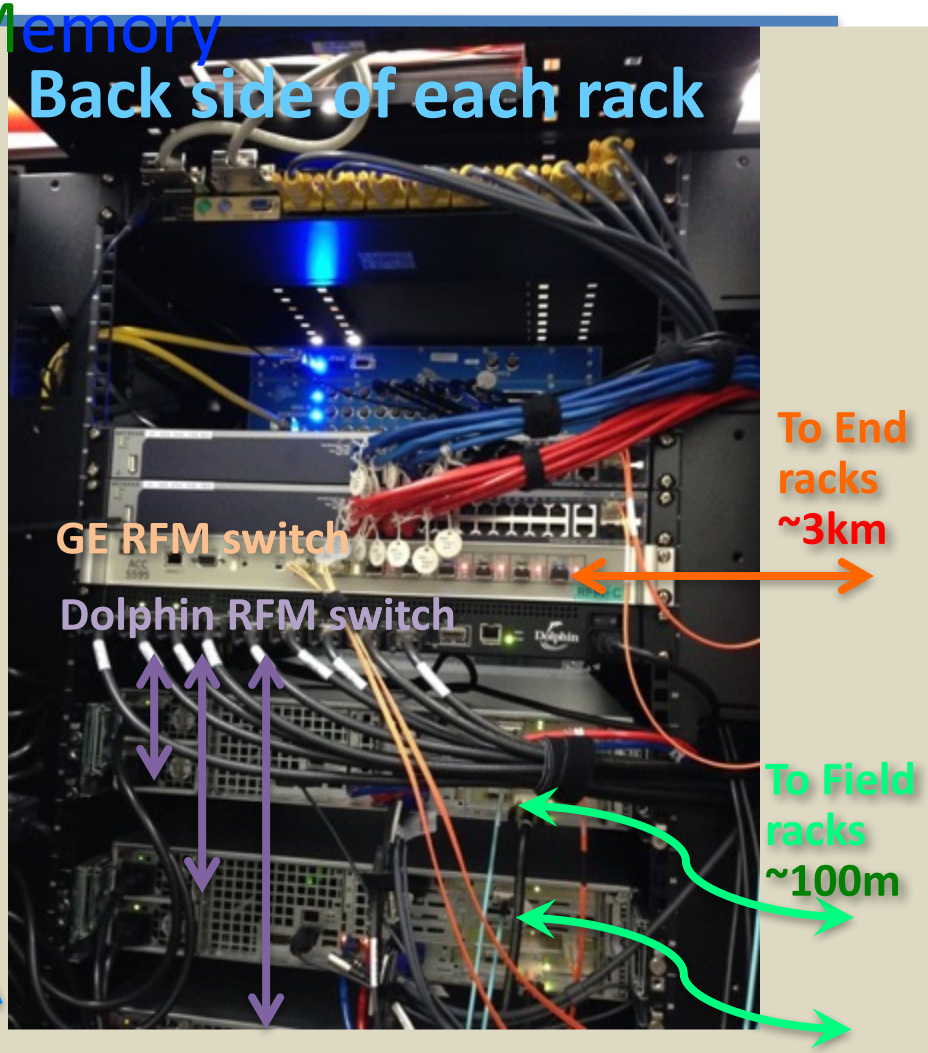
- Recent GW detector allow us to control, measure and tune the interferometer on the PC screen in control room
  - » Importatnt to avoid human noise
- Good software makes a big advance for sensitivity improvement

TAMA300 control panel

Control system



Control signal network for Real Time PCs using ReFlective Memory



Dolphin RFM:
Short distance real time signal ~10m

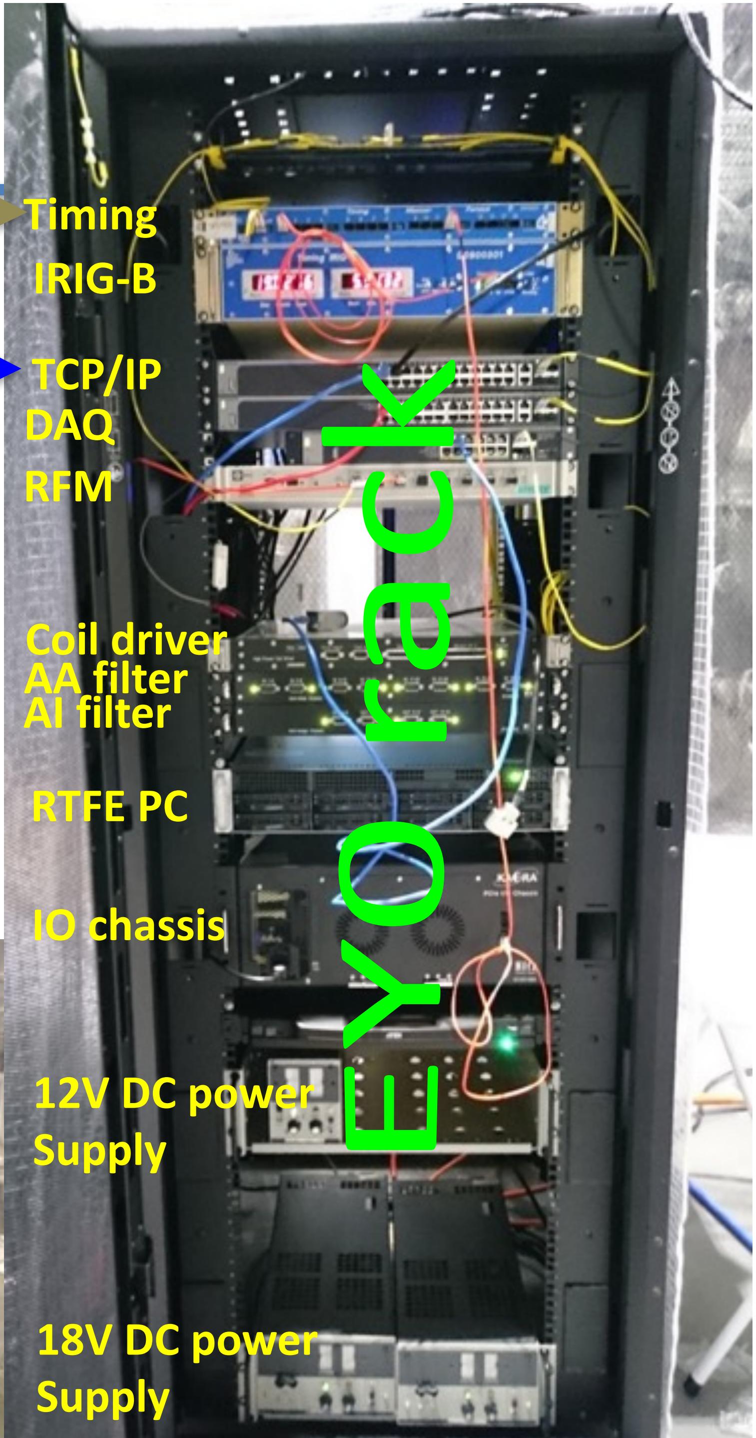
GE RFM:
long distance real time signal ~3km

Field racks

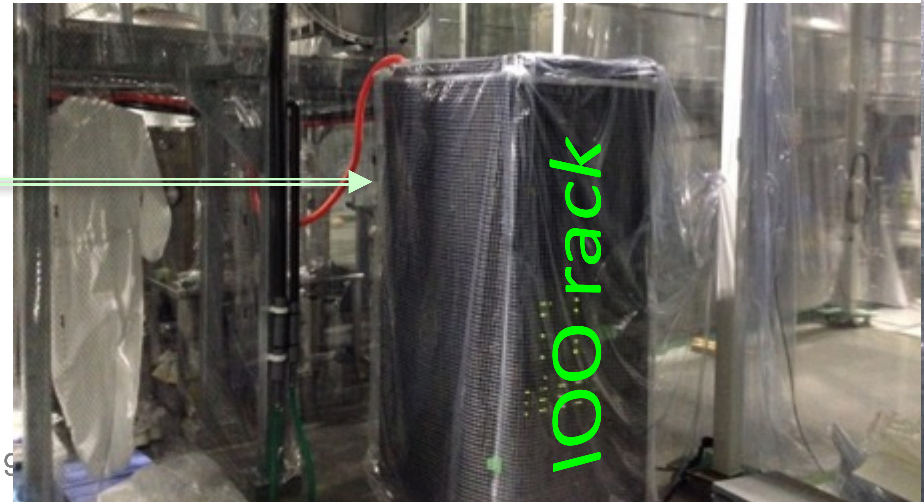
- 11 Field racks have been located at central area(6), Xarm(1), Xend(2) and Yend(2).

- Center Field racks include
  - IO chassis with ADC/DAC
  - AA/AI filter chassis
  - whintieng filter chassis
  - electronic circuit chassis, like coil drivers
  - No real time PCs

- End field racks have real time PC additionally.



RTFE PC to IO chassis ~100m

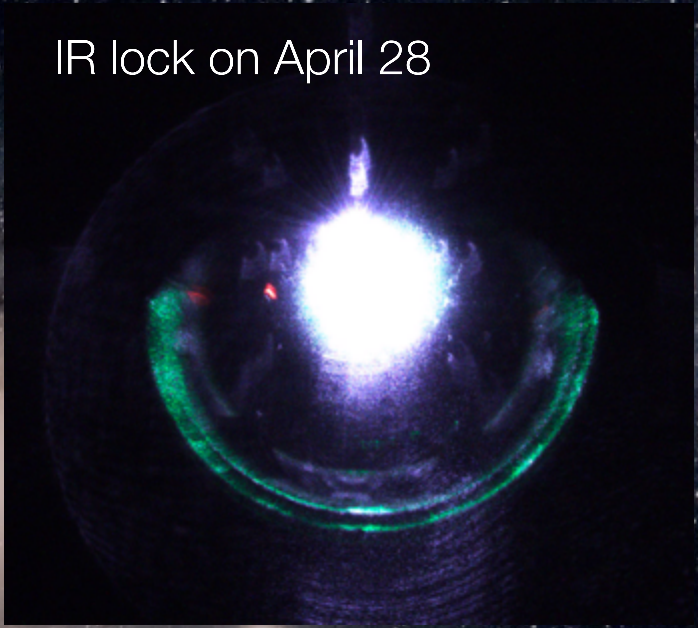


Control room in surface building out of the KAGRA mine

7km away in optical fiber length,
All KAGRA functions can be controlled remotely.
It supports automatic operations.

Arm cavity lock in cryogenic.

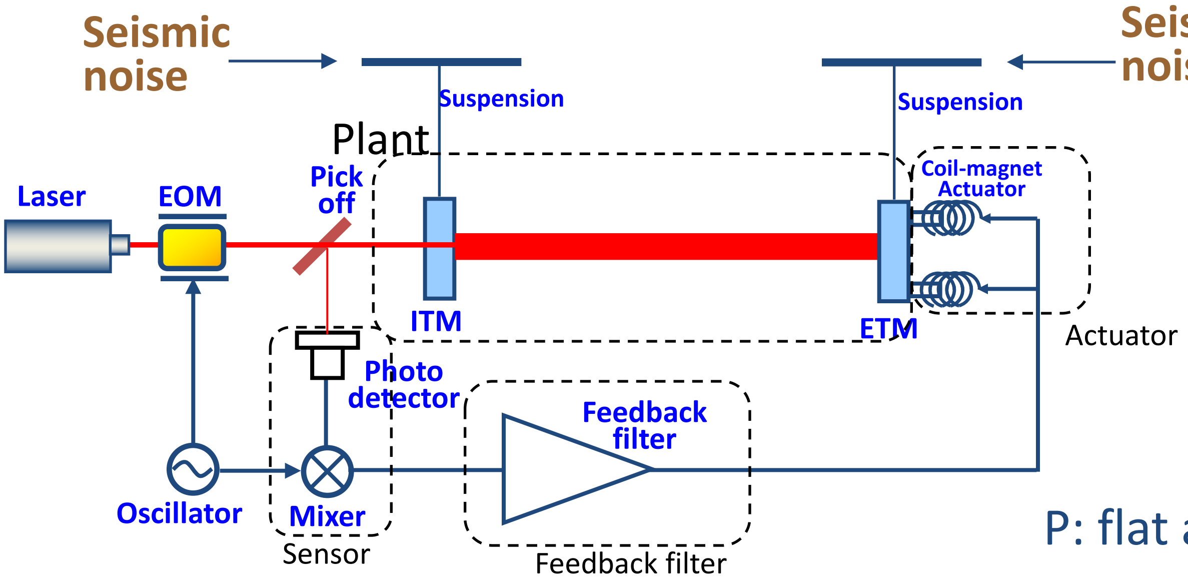

GR lock on April 17


IR lock on April 28

- X arm was re-locked on April 17.
- Y arm was locked with green on April 18.
- Y arm was locked with IR on green on April 28 with frequency control.
  ⇒ Needs mass feedback lock next.

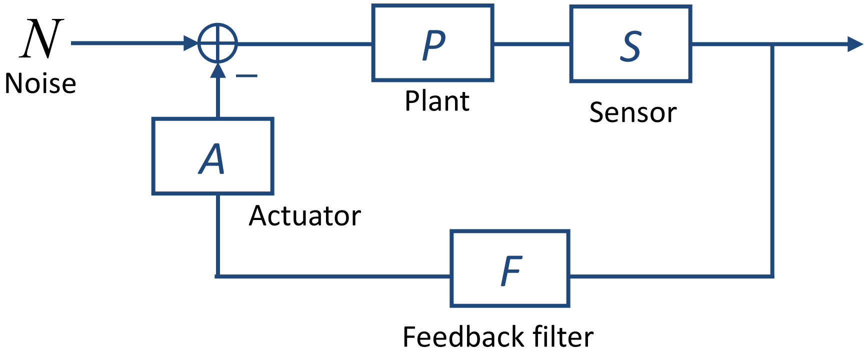
- We can do some IFO experiments during being cooled.

Modeling system: Single Fabry-Perot cavity



Mission:

Make a feedback filter to keep distance between ITM and ETM constant !

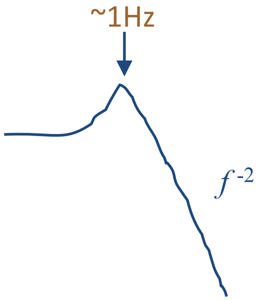


P: flat around resonance

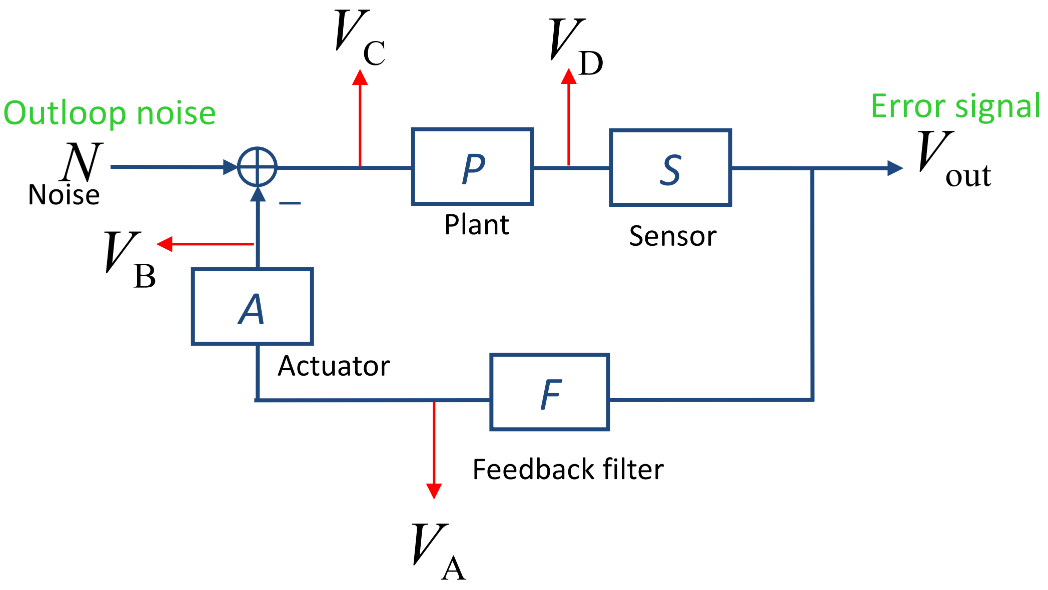
S: flat

F: ??

A: suspension TF



Transfer function from Noise N to error signal V_{out}



$$V_{\mathrm{A}} = F \times V_{\mathrm{OUT}}$$?? using V_{OUT}

$$V_{\mathrm{B}} = A \times V_{\mathrm{A}}$$

$$V_{\mathrm{C}} = N - V_{\mathrm{B}}$$

$$V_{\mathrm{D}} = P \times V_{\mathrm{C}}$$

$$V_{\mathrm{OUT}} = S \times V_{\mathrm{D}}$$

⬇

$$V_{\mathrm{OUT}} = S \times P \times \left(N - A \times F \times V_{\mathrm{OUT}}\right)$$

$$(1 + SPAF)V_{\mathrm{OUT}} = SP \times N$$

$$\therefore V_{\mathrm{OUT}} = \frac{SP}{(1 + SPAF)} \times N = \frac{SP}{(1 + G)} \times N$$

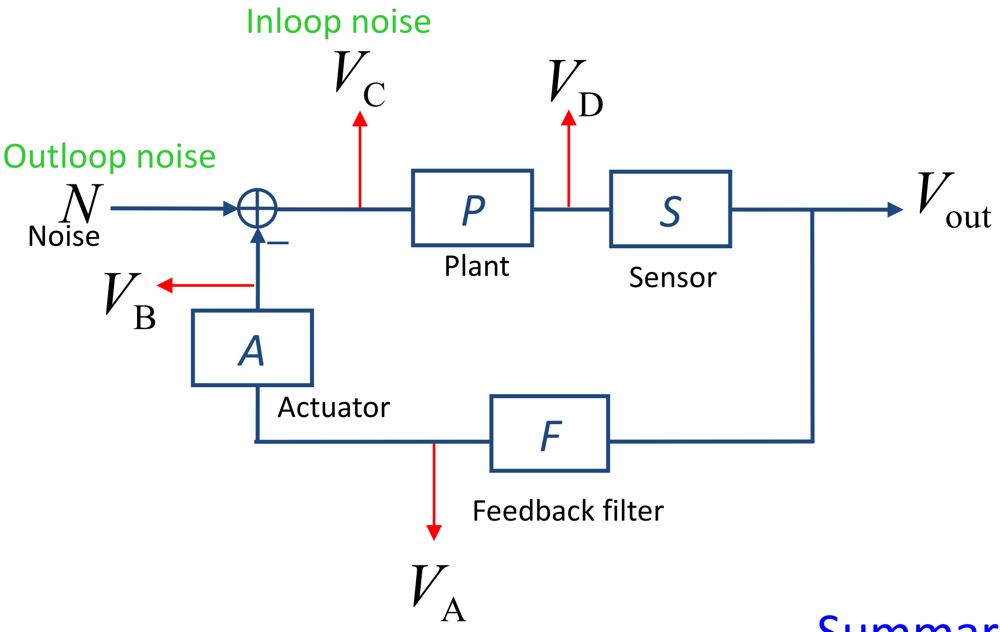
Open loop transfer function :

$$G = SPAF$$

Summary:

Relationship between “Error signal” V_{out} and “Outloop noise” N can be written with “Open loop transfer function” G and “transfer function” P,S.

Transfer function from outloop noise to inloop noise



$$V_C = \frac{V_{out}}{SP} = \frac{1}{SP}\frac{SP}{(1+G)} \times N = \frac{1}{(1+G)} \times N$$

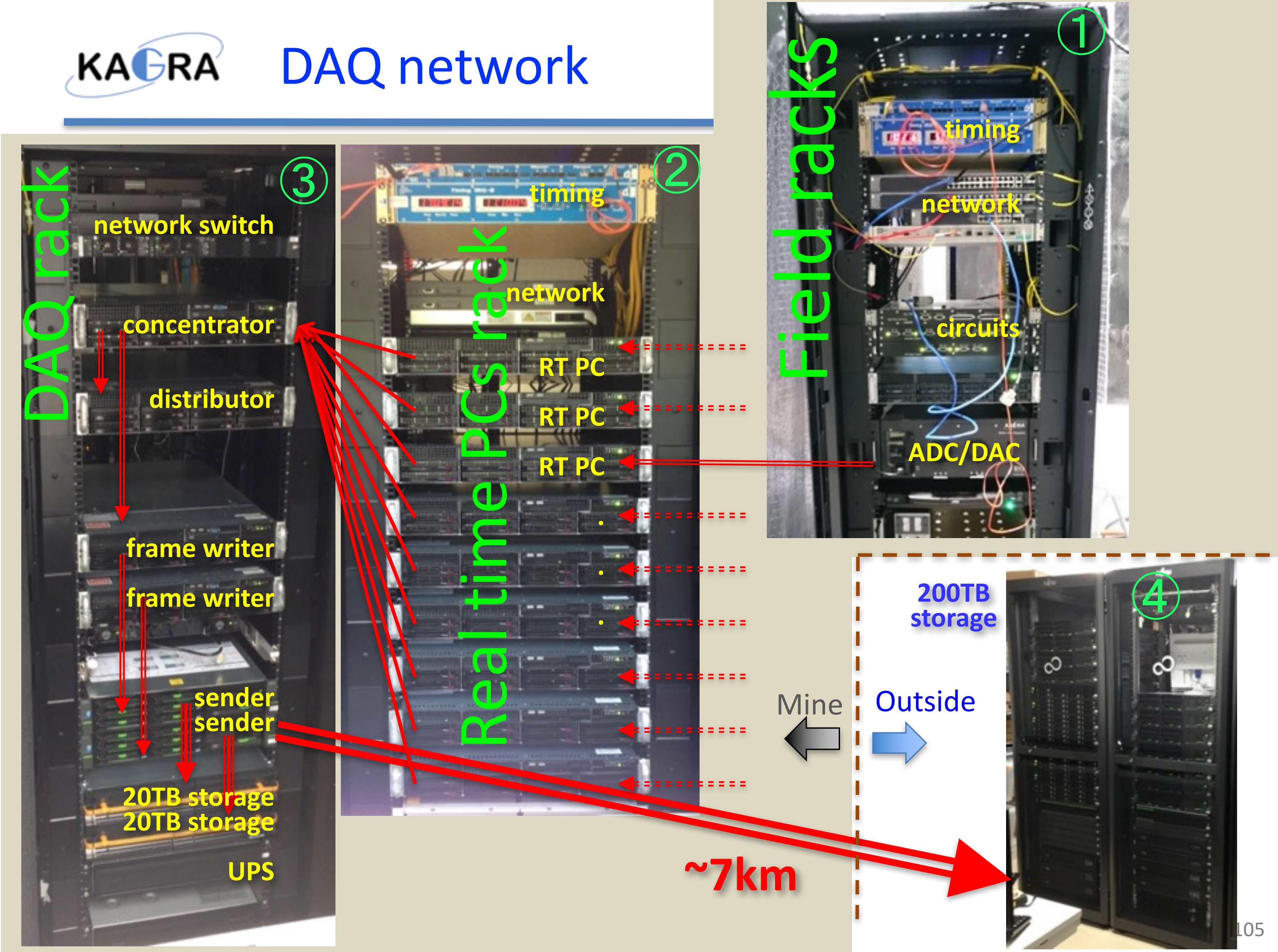
$$\text{if } G >> 1, V_C \approx \frac{N}{G} << N; \text{supression}$$

$$\text{if } G << 1, V_C \approx N; \text{ no suppression}$$

Summary:

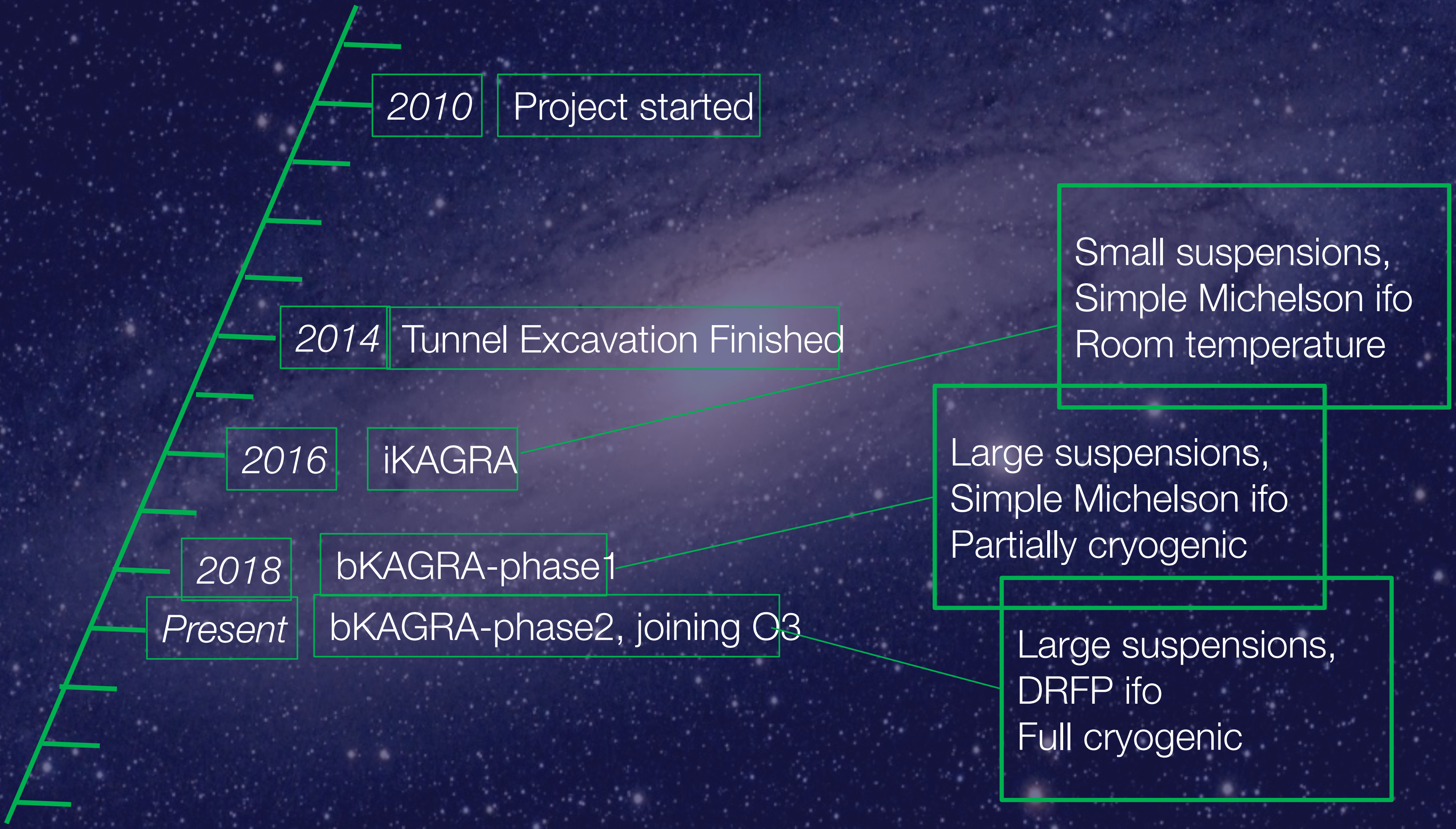
"Outloop noise" N is suppressed by Open loop transfer function G (if G>>1) into "Inloop noise" $N/(1+G)$, then it is multiplied by transfer functions SP through output port.

DAQ network



①
Field racks
timing
network
circuits
ADC/DAC
②
Real time PCs rack
timing
network
RT PC
RT PC
RT PC
.
.
.
③
DAQ rack
network switch
concentrator
distributor
frame writer
frame writer
sender
sender
20TB storage
20TB storage
UPS
~7km
Mine
Outside
④
200TB storage

Timeline of the Project



2010 Project started

2014 Tunnel Excavation Finished

2016 iKAGRA

Small suspensions,
Simple Michelson ifo
Room temperature

2018 bKAGRA-phase1

Large suspensions,
Simple Michelson ifo
Partially cryogenic

Present bKAGRA-phase2, joining O3

Large suspensions,
DRFP ifo
Full cryogenic

To Space in Future.