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 \((E = mc^2)\) was emitted as Gravitational waves!
- GW came from 1.3 billion light year away.
- The results show that the general theory of relativity is correct.
Nobel prize for Physics in 2017

• Three LIGO scientists won the Nobel prize by GW detection.
• From left side “Experimentalist”, “Project leader”, “Theorist”
LIGO Chronology
idea to realization ~ 15 years

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

Initial LIGO events
Advanced LIGO events
R&D of aLIGO using iLIGO facility
Opened a new window in 2015 to measure universe aging GWs by efforts of 4000 scientists, engineers during 22 years.
Localization for GW source

- 2 detectors could localize GW source only in very wide range
- 2 LIGO determined $\sim 500 \text{ degree}^2$
  - Too wide to determine where it came from.
- +VIRGO can determine in $\sim 30 \text{ degree}^2$
- +KAGRA can determine in $\sim 10 \text{ degree}^2$
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

Rapid LIGO localization

Rapid LIGO and Virgo localization

360° x 180°
It was also seen in Gamma ray.

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

Lightcurve from *Fermi/GBM* (50 – 300 keV)

Gravitational-wave time-frequency map
Periodic table of elements was replaced by merging neutron stars

- Gold as amount of 10 moons was made in a moment!
## 100 Years of Detector Development

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1916</td>
<td>Einstein predicted gravitational waves</td>
</tr>
<tr>
<td>1960s</td>
<td>Weber Bar at U Maryland</td>
</tr>
<tr>
<td>1969</td>
<td>Weber claimed detection</td>
</tr>
<tr>
<td>1972</td>
<td>Weiss publishes first practical description of laser interferometer</td>
</tr>
<tr>
<td>1974</td>
<td>Hulse and Taylor discovered a binary neutron star system</td>
</tr>
<tr>
<td>1997</td>
<td>Resonant bar detector network begins operation</td>
</tr>
<tr>
<td>2009</td>
<td>LIGO-VIRGO 1 year observation</td>
</tr>
<tr>
<td>2010</td>
<td>LIGO &amp; VIRGO started their upgrades</td>
</tr>
<tr>
<td>2014</td>
<td>BICEP2 reported evidence for cosmological GWs, but it was foreground dust</td>
</tr>
<tr>
<td>2015</td>
<td>LIGO’s first detection (announced in 2016)</td>
</tr>
</tbody>
</table>
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:
\[ G = 8\pi T \]
spacetime curvature \(\leftrightarrow\) 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.

<table>
<thead>
<tr>
<th></th>
<th>Measured shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton theory</td>
<td>0.87arcsec</td>
</tr>
<tr>
<td>Einstein theory</td>
<td>1.75arcsec</td>
</tr>
<tr>
<td>Island of Príncipe</td>
<td>1.61 ± 0.30 arcsec</td>
</tr>
<tr>
<td>Sobral</td>
<td>1.98 ± 0.12 arcsec</td>
</tr>
</tbody>
</table>
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
  \[\rightarrow\]
- Electromagnetic waves

General relativity:
- Acceleration of mass
  \[\rightarrow\]
- Gravitational waves
Distance: $R \Rightarrow \leftarrow 2d$

Observer

$F = F_1 + F_2$

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

Observer

Quadrupole
When GWs come...

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

\[ dL \propto L \]
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?

\[ h \approx \frac{4\pi^2 G M R^2 f_{\text{orb}}^2}{c^4 r} \]

\[ M = 10^3 \text{ kg} \quad R = 1 \text{ m} \]
\[ F = 100 \text{ Hz} \quad r = 1 \text{ m} \]

\[ \approx 10^{-36} !! \]

13 orders smaller !!
(detection limit is $\sim 10^{-23}$)

• GW on the earth is too small.
• Needs massive astronomical events even very far.
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)
  \[ g_{\mu\nu} = \eta_{\mu\nu} = \begin{pmatrix} ct & x & y & z \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \]
- "Curved (distorted)" space-time
  \[ g_{\mu\nu} \neq \eta_{\mu\nu} \]

**Small Perturbation 'h' --> Waves**

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

\[ \left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0 \]
What is Gravitational Wave?

- **Characteristics:**
  - light speed
  - transverse
  - quadrupole
  - (tidal force)

Tidal force on masses will be induced by GW incident.

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

\[
\begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & h_+ & h_x & 0 \\
0 & h_x & -h_+ & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
\begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
\hat{h}_x = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]
Amplitude of Squeeze & Stretch

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

Strain (ratio of squeeze and stretch)

\[ \frac{10^{-10} \text{m}}{10^{11} \text{m}} = 10^{-21} \]

GPS: 10000km above, 1cm accuracy

\[ \frac{10^{-2} \text{m}}{10^7 \text{m}} = 10^{-9} \]
Weber’s Bar Detector in 60s

Pioneer work for experimental search

Aluminum alloy cylinder bar
GWs excite the mechanical resonance

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

Evidence of gravitational waves!

“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
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

GW International Collaboration was Formed
## Resonant Bar Detector Params

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Features</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allegro</td>
<td>LSU</td>
<td>2300 kg, AL5056 cylinder, 3 m long, 4.2 K 6K</td>
<td>904Hz 7e-19</td>
</tr>
<tr>
<td>Explorer</td>
<td>CERN</td>
<td>AL5056 cylinder, 2270 kg, 3 m long, 2.5 K</td>
<td>3e-21 at 906 and 923 Hz. CQG 19 (2002) 1905-1910</td>
</tr>
<tr>
<td>NIOBE</td>
<td>Western Australia</td>
<td>Niobium, 2-5K.</td>
<td>700Hz. Strain sensitivity of 1e-22 can be achieved.</td>
</tr>
<tr>
<td>AURIGA</td>
<td>Italy</td>
<td>2300 kg, 3 m long, aluminum cylinder 0.1K</td>
<td>4e-22 at 911, 929 Hz (2Hz BW)</td>
</tr>
<tr>
<td>NAUTILO</td>
<td>Italy</td>
<td>Al 5056 cylinder, 2350 kg, 0.1K S1 ‘95-97, S2’98,3 ‘02</td>
<td>908 and 924 Hz. NAUTILUS has a sensitivity 4e-22. Pulsar in NS 1987A CQG 19 (2002) 1911-1917</td>
</tr>
</tbody>
</table>
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
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**
  - Simple, but requires large mirrors; limited $\tau_{\text{stor}}$

- **Fabry Perot interferometer**
  - (LIGO design) $\tau_{\text{stor}} \sim 3$ msec
  - More compact, but harder to control
Lock acquisition for interferometer

Carrier

Sidebands (probes for carrier)

EOM: Modulation

Oscillator ~10MHz

PD

Mixer: Demodulation

Unlocked

Locked

Phase lock

Feedback

Real time control using computers

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

~1nm

Signal [V]

L [m]

+signal

- signal

Lock point (<1pm)

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Alignment control for mirrors

EOM: Modulation

Oscillator ~10MHz

Mixer: Demodulation

QPD (Quadrant photo diode)

L (~1000m)

Misalignment

Feedback

Real time control using computers

TEM01 mode

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Prototypes in 80s - 90s

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
Hanford, WA (LHO)
- Desert area
- 25 km from Richland, WA
- 2 interferometers: 2km & 4km

Livingston, LA (LLO)
- Swamp area
- 50 km from Baton Rouge, LA
- 1 interferometer: 4km

Adapted from “The Blue Marble: Land and Surface, Ocean Color and Sea Ice” at visible.earth.nasa.gov
VIRGO
- Group of French, Italy, Netherland etc.

Pisa, in Italy

3km 3km
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
- 4km Arms
  - aLIGO Livingston 2015
- 3km Arms
  - aVIRGO 2016
- 600m Arms
  - GEO600-HF
- 3km Arms
  - KAGRA 2018
- 4km Arms
  - LIGO India 2023
Sky Localization
arXiv 1304.0670

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</thead>
<tbody>
<tr>
<td></td>
<td>Estimated run duration</td>
<td>4 months</td>
<td>6 months</td>
<td>9 months</td>
<td>(per year)</td>
</tr>
<tr>
<td>Burst range/Mpc</td>
<td>LIGO</td>
<td>40 – 60</td>
<td>60 – 75</td>
<td>75 – 90</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Virgo</td>
<td>—</td>
<td>20 – 40</td>
<td>40 – 50</td>
<td>40 – 80</td>
</tr>
<tr>
<td>BNS range/Mpc</td>
<td>LIGO</td>
<td>40 – 80</td>
<td>80 – 120</td>
<td>120 – 170</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Virgo</td>
<td>—</td>
<td>20 – 60</td>
<td>60 – 85</td>
<td>65 – 115</td>
</tr>
<tr>
<td>Estimated BNS detections</td>
<td>0.0005 – 4</td>
<td>0.006 – 20</td>
<td>0.04 – 100</td>
<td>0.2 – 200</td>
<td>0.4 – 400</td>
</tr>
</tbody>
</table>

90% CR

<table>
<thead>
<tr>
<th>% within</th>
<th>5 deg²</th>
<th>&lt; 1</th>
<th>2</th>
<th>&gt; 1 – 2</th>
<th>&gt; 3 – 8</th>
<th>&gt; 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 deg²</td>
<td></td>
<td>1</td>
<td>14</td>
<td>&gt; 10</td>
<td>&gt; 8 – 30</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>median/deg²</td>
<td>480</td>
<td>230</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

sought area

<table>
<thead>
<tr>
<th>% within</th>
<th>5 deg²</th>
<th>6</th>
<th>20</th>
<th>—</th>
<th>—</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 deg²</td>
<td></td>
<td>16</td>
<td>44</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>median/deg²</td>
<td>88</td>
<td>29</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
KAGRA is located in Kamioka mine underground:
- 220km away from Tokyo
- 360m altitude
- Big laboratory area
Features of KAGRA

Under ground of Kamioka site

Low temperature mirrors

Variable bandwidth interferometer
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
Underground site is QUIET
Vibration isolation (1)

Frequency [Hz]

Isolation

Higher pendulum frequency

Lower pendulum frequency

\[ \propto \left( \frac{f}{f_0} \right)^{-2} \]
Seismic motion \times

Vibration isolation (2)

\[ \text{Isolation} \propto \left( \frac{f}{f_0} \right)^{-2} \]

- 1 stage
- 2 stages
- 3 stages

Frequency [Hz]
Pendulum in Physics

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

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

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

\[ s = i\omega \]

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

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

Interpretation in Physics

resonant angular 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

\[ \frac{\ddot{x}}{F/m} = \frac{1}{-\omega^2 + i\omega_0 / Q + \omega_0^2} \]

if \( \omega \ll \omega_0 \) \( \Rightarrow \frac{\ddot{x}}{F/m} \rightarrow \frac{1}{\omega_0^2} \) : constant

if \( \omega \gg \omega_0 \) \( \Rightarrow \frac{\ddot{x}}{F/m} \rightarrow \frac{1}{-\omega^2} : f^{-2} \) slope

if \( \omega = \omega_0 \) \( \Rightarrow \frac{\ddot{x}}{F/m} \rightarrow \frac{Q}{i\omega_0^2} : \) resonance

if \( \omega = \omega_0, Q \rightarrow \infty \) \( \Rightarrow \frac{\ddot{x}}{F/m} \rightarrow \infty \) : resonance, no damp

if \( Q = 1/2 \) \( \Rightarrow \) critical damping

if \( Q < 1/2 \) \( \Rightarrow \) over damping

f^{-2} : 2 poles

Q = 100
Q = 10
Q = 1
Q = 1/2

Q corresponds to height of resonant peak.
Inverted pendulum

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

\[ \Rightarrow \text{Lower resonant frequency} \]
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

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

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

Cryostat

Graph showing displacement vs. frequency for different types of masses.
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) improvement

Cryogenics

Mirror ~20K
Suspension ~16K

Sapphire mirror
→ High mechanical Q-value at low temperature

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

→ Cryogenic is a straight-forward way to reduce thermal noise.
Thermal noise (1)

\[ \text{Strain} \propto \sqrt{\frac{T}{Q}} \]

Higher Q

Lower Q

Frequency [Hz]

Strain [Hz^{-1/2}]
Thermal noise (2)

\[ \propto \sqrt{\frac{T}{Q}} \]

- Room temperature
- Cryogenic

Strain [Hz\(^{-1/2}\)]

Frequency [Hz]
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

Photons of Laser light

\[ x_{shot}(f) \propto \sqrt{\frac{\hbar c \lambda}{P}} \]

\[ x_{rp}(f) \propto \frac{1}{mf^2} \sqrt{\frac{\hbar P}{c\lambda}} \]

High Power ? or Low Power ?
To reduce quantum noise?

Reducing laser power reduces the shot noise and increases the radiation pressure noise.
Noises!

- Pendulum thermal noise
- Mirror thermal noise
- Radiation pressure noise
- Shot noise

![Graph showing noise levels vs frequency](image)

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Sensitivity of KAGRA

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

Control

Bright port

Dark port
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

Power recycling (PRFPMI)
- Enhance inside laser power by reflecting coming back light using additional mirror at the laser port

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

TAMA, LIGO, VIRGO

KAGRA, aLIGO, aVIRGO

CLIO

KAGRA
Fabry-Perot cavity

\[ E_{\text{in}} = E_0 e^{i\Omega t} \]

\[
E_{\text{a}} = t_F E_{\text{in}} + r_F E_{\text{b}} \\
E_{\text{b}} = r_E e^{-2i \frac{L \Omega}{c}} E_{\text{a}} \\
E_{\text{r}} = t_F E_{\text{b}} - r_F E_{\text{in}} \\
E_{\text{t}} = t_E e^{-i \frac{L \Omega}{c}} E_{\text{a}}
\]

\[
E_{\text{a}} = \frac{t_F}{1 - r_F r_E e^{-i\Phi}} E_{\text{in}} \\
E_{\text{b}} = \frac{t_F r_E e^{-i\Phi}}{1 - r_F r_E e^{-i\Phi}} E_{\text{in}} \\
E_{\text{r}} = \left(-r_F + \frac{t_F^2 r_E e^{-i\Phi}}{1 - r_F r_E e^{-i\Phi}}\right) E_{\text{in}} \\
E_{\text{t}} = \frac{t_F t_E e^{-i\frac{\Phi}{2}}}{1 - r_F r_E e^{-i\Phi}} E_{\text{in}}
\]
Fabry-Perot cavity

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

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

フィネス
\[ \mathcal{F} = \frac{\nu_{\text{FSR}}}{\nu_{\text{FWHM}}} \]
\[ = \frac{\pi \sqrt{r_F r_E}}{1 - r_F r_E} \]

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

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• KAGRA is located in Kamioka mine underground
  - 220km away from Tokyo
  - 360m altitude
  - Big laboratory area
Underground site is QUIET
Snow in winter.
Melted snow in April.
Center room

Laser room

X arm

Y arm
Y end area for chamber location
Y arm under water
1. Layout (four planes/floors)

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

---

**horizontal floors in each room prepared for installing chambers**

**translation matrix confirmed for four sets of coordinates**

---

**Water to River**

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Water to River
KAGRA configuration

**Input/Output Optics**
- Beam Cleaning and stab.
- Modulator, Isolator
- Fixed pre-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

**Power**
- ~180 W

**Input Bench**
- 26-m MC

**80 W**
- PRM

**825 W**
- BS

**ITM**
- ETM

**X-arm cavity**
- Length 3,000 m
  - Finesse 1,550

**RSE**
- (Resonant sideband Extraction)
  - Signal-band Gain ~15
  - Detuned RSE (Variable tuning)

**Power-recycling**
- Gain ~11

**BS**
- ITM

**Power**
- ~400 kW
Technologies to realize large vacuum area
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
All the sapphire mirrors has installed in Nov 2018

ITMX and ITMY

Pictures from K. Yamamoto

→ See, Ushiba, Yamada, Fukunaga’s talks

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

Ears were bonded at Toyama
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 has a temporary 2-inch mirror.

→ See, Burton, Tapia, Fujii, Kozu’s talks
**Input Optics**

- 40W laser installed
- PMC installed

- Input mode cleaner was tested with 10W
- Intensity stabilization is being commissioned
- Frequency stabilization (mode cleaner & reference cavity) has been operating since phase 1

→ See, Nakano’s talk

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

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

Nov-Dec 2018
Auxiliary Optics

- 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

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

DC power supplies for remote electronics

Remote control room

Computer room in KAGRA mine

Field rack

100m network

7km network

Boot servers

DAQ

Real time PCs

Real time PCs
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

To End racks ~3km
To Field racks ~100m

Back side of each rack
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/Al filter chassis
  - whintieng filter chassis
  - electronic circuit chassis, like coil drivers
  - No real time PCs

- End field racks have real time PC additionally.
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.

- **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

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

\[ V_A = \text{Using } V_{OUT} \]
\[ V_B = A \times V_A \]
\[ V_C = N - V_B \]
\[ V_D = P \times V_C \]
\[ V_{OUT} = S \times V_D \]

\[ V_{OUT} = S \times P \times (N - A \times F \times V_{OUT}) \]
\[ (1 + SPAF) V_{OUT} = SP \times N \]

\[ \therefore V_{OUT} = \frac{SP}{1 + SPAF} \times N = \frac{SP}{1 + G} \times N \]

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

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.

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

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

if $G << 1$, $V_C \approx N$; no suppression
DAQ network

Field racks

Real time PCs rack

① Timing

② Timing

③ Network switch

④ Timing

External switch

Concentrator

Distributor

Frame writer

Frame writer

Sender

Sender

20TB storage

20TB storage

20TB storage

UPS

200TB storage

Mine

Outside

~7km
Timeline of the Project

2010 | Project started

2014 | Tunnel Excavation Finished

2016 | iKAGRA

2018 | bKAGRA-phase1

Present | bKAGRA-phase2, joining O3

Small suspensions, Simple Michelson ifo Room temperature

Large suspensions, Simple Michelson ifo Partially cryogenic

Large suspensions, DRFP ifo Full cryogenic

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Gravity is talking. LISA will listen.

To Space in Future.