Laser Interferometry for Gravitational Wave Observations

4. Status of KAGRA

Yuta Michimura
Department of Physics, University of Tokyo
Contents

1. Laser Interferometers (July 25 PM)
   Michelson interferometer
   Fabry-Pérot interferometer

2. Quantum Noise (July 25 PM)
   Shot noise and radiation pressure noise
   Standard quantum limit

3. Sensitivity Design (July 26 AM)
   Force noise and displacement noise
   Inspiral range and time to merger
   Space interferometer design

4. Status of KAGRA (July 26 AM)
   Status of KAGRA detector in Japan
   Future prospects
Global Network of GW Telescopes

- GEO-HF (operation)
- Advanced Virgo (operation)
- KAGRA (construction)
- LIGO-India (approved)
- Advanced LIGO (operation)
Observation Scenario

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LIGO
- 3 BBHs
- 80 Mpc

Virgo
- 7 BBHs
- 30 Mpc

KAGRA
- 1 BNS
- 8-25 Mpc

LIGO-India
- Today

Target
- 330 Mpc

Updated version of Living Reviews in Relativity 21, 3 (2018); available from LIGO-P1200087
Solved and Unsolved Mysteries

• Binary black holes
  - Origin of massive black holes?
  - Intermediate mass black holes?
  - Quasi-normal modes not yet

• Binary neutron stars
  - coincidence with short gamma-ray bursts
    (but too faint; why?)
  - speed of gravitational waves measured
  - do all heavy elements come from BNS mergers?
  - Remnant?
  - Equation of state?
  - Hubble constant tension

• Other sources not detected yet
  - NS-BH, Supernovae, Pulsars, Primordial gravitational waves…….
What’s Next?

• More sensitive, multiple detectors
  - Better source localization with multiple detectors
    Better multi-messenger observations
  - Polarization resolvable with multiple detectors
    Better inclination angle estimation
    Better Hubble constant measurement
    Non-GR polarization search
  - Twofold sensitivity improvement gives
    x8 event rate
    x1/2 parameter estimation error

• Next to join observation: KAGRA
KAGRA Project

- Underground cryogenic interferometer in Japan
- Funded in 2010
- 97 institutes, 460 collaborators (162 authors)

as of Sept 2018
Location of KAGRA
Location of KAGRA

- Guangzhou to Tokyo: 4 hours by airplane
- Tokyo to Toyama: 1 hour by airplane
- Toyama to KAGRA: 40 min drive from Toyama Airport
- KAGRA to SYSU: 1 hour by airplane
KAGRA Site

- Located inside Mt. Ikenoyama
KAGRA Site

- Located inside Mt. Ikenoyama
Kamioka

Mozumi area around GW Office
KAGRA Tunnel

• two 3-km long vacuum pipes for laser beams to go back and forth

Entrance (2016.2.8)
Interferometer Configuration

- **RSE interferometer**
  Resonant Sideband Extraction

- **Cryogenic sapphire test masses**

Laser (140 W, 1064 nm)

3 km

cryogenic sapphire (20 K)

Φ22 cm x t 15 cm
22.8 kg
Design Sensitivity

- Binary neutron star (BNS) range 153 Mpc

![Graph showing sensitivity vs. frequency](graph.png)
KAGRA Timeline

2014
- Tunnel excavation done

2015
- Inauguration of initial-phase facility

2016
- First test run at room temp. (iKAGRA)

2017

2018
- First cryogenic test run (Phase 1)
  KAGRA Collaboration, CQG 36, 165008 (2019)

2019
- Expect to join observing run O3

2020
Observation Scenario

LIGO

Virgo

KAGRA

iKAGRA (room temp.)

bKAGRA Phase 1 (cryogenic)

LIGO-India

Updated version of *Living Reviews in Relativity 21, 3 (2018)*; available from [LIGO-P1200087](https://ligo.org/papers/LIGO-P1200087)
Target Sensitivity for O3

- Aims for 8-25 Mpc in binary neutron star range

![Graph showing target sensitivity for O3 with KAGRA design at 10^-21 to 10^-24 strain (sqrtHz) against frequency (Hz).]
Comparison with LIGO/Virgo

• Aims for 8-25 Mpc in binary neutron star range
If KAGRA Joins O3

- Improves sky coverage, network duty factor, source parameter estimation
- Some parameter degeneracy can be resolved with four detectors (e.g. polarization)

BNS sky localization improves by ~15-30 % if KAGRA is 25 Mpc

JGW-T1910330
Calculation by S. Haino
(L: 120 Mpc, V: 60 Mpc, K: 15 Mpc)
Test of GR with CBC Polarization

• Fourth detector necessary to distinguish four polarizations

• Number of detectors matters!

error reduces to < 1 with KAGRA

BNS w/ K
BBH10 w/ K
BNS HLV
BBH10 HLV

Error in vector-x mode amplitude
Recent News from KAGRA

- Almost everything installed by May 2019
- X-arm completed by January 2019
- Y-arm locked in April 2019
- Y-arm and central part commissioning on-going
- First Engineering Run with X-arm done on June 8, 2019

Temperatures as of June 12 (ITMY/ETMY once reached 22K/24K)
Test Mass Suspension

- 7-stage pendulum over two stories

March 2015
Test Mass Suspension
Shielding Inside Cryostat

laser beam
thermal shield
Observation Scenario

LIGO

Virgo

KAGRA

iKAGRA (room temp.)

bKAGRA Phase 1 (cryogenic)

LIGO-India

Upgrade

Updated version of Living Reviews in Relativity 21, 3 (2018); available from LIGO-P1200087
Advanced LIGO Upgrade: A+

- Reaches 325 Mpc with coating improvement and frequency dependent squeezing

4 km arm
40 kg mirror
Fused silica

Budget approved
NSF $20.4M
UKRI £10.7M
+ Australia

Livingston
O3

Hanford
O3

aLIGO

strain ($/\sqrt{\text{Hz}}$)

frequency (Hz)
Advanced Virgo Upgrade: AdV+

- Reaches 300 Mpc with frequency dependent squeezing, Newtonian noise cancellation, larger mirror

3 km arm
42 kg mirror
Fused silica
How about KAGRA?

- Upgrade study *formally* started in December 2018

![Graph showing strain vs. frequency with marked regions for Seismic Suspension, Gravity Mirror, and Quantum effects, indicating heat extraction areas.](image)
How about KAGRA?

- Different investigation necessary due to cryogenic coating improvement.
  - Larger mirror
  - Black holes
  - Neutron stars
  - Heat extraction
  - Lower power Squeezing
  - Higher power
  - Quantum
  - Coating improvement
  - Larger mirror
Sensitivity Optimization

• Simultaneous tuning of multiple interferometer parameters necessary
• Developed a code to optimize the sensitivity with Particle Swarm Optimization

Y. Michimura+, *PRD* 97, 122003 (2018)
Possible Near Term Upgrade Plans

- Based on technical feasibility, facility and budget constraints (~5M USD)

Y. Michimura+, arXiv:1906.02866

LF (BBH100 Optimized)

HF (BNS sky localization optimized)

Frequency dependent squeezing (BNS optimized)

40 kg mirror (BNS optimized)
Possible Longer Term Upgrade

- Reaches BNS range of 300 Mpc by combining technologies (~20M USD)

Y. Michimura+, arXiv:1906.02866
Possible Longer Term Upgrade

- Comparable to A+ (325 Mpc) and AdV+ (300 Mpc)

Y. Michimura+, arXiv:1906.02866
Horizon Distance Comparison

- $O(10^2)$ events/year with designed sensitivity (~2021)
Horizon Distance Comparison

- $O(10^3)$ events/year with upgrades (~2024)
Science Targets for Each Bands

• **Low frequency**
  IMBHs and their spectroscopy
  (Stochastic GW background, cosmic string)

• **Broadband**
  Test of gravity
  Formation scenario of stellar-mass BBHs
  Multi-messenger observations
  Hubble constant
  (Supernovae and X-ray binaries)

• **High frequency**
  NS physics (EOS, post-merger, ejecta)
  Multi-messenger observations
  Hubble constant
  BH spectroscopy with stellar-mass BBHs
  (Isolated pulsars and magnetors)
(Selected) Science Comparison

- Sensitivity improvement in different bands give different science cases

<table>
<thead>
<tr>
<th></th>
<th>LF</th>
<th>40kg</th>
<th>FDSQZ</th>
<th>HF</th>
<th>Longer</th>
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<tbody>
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<td>IMBH event rate</td>
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<tr>
<td>NS event rate</td>
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<td>NS tidal deformability</td>
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<td>Hubble constant by BBH</td>
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<td>Hubble constant by BNS</td>
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<td>GW polarization test</td>
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<tr>
<td>Stellar-mass BH spectroscopy</td>
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<tr>
<td>IMBH spectroscopy</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Better: +100% +50% +15% -15% -50% -100%
Worse:

* Compared with bKAGRA, assumed A+ and AdV+ Network
* Summarized by A. Nishizawa et al. JGW-G1909934
Effective Progression of Upgrades?

• **Low frequency** is uncertain since many low frequency excess noises exist

• **40 kg mirror** would be feasible but even larger mirror is required for longer term

• **Higher power laser** and **frequency dependent squeezing** are attractive in terms of feasibility

• **HF** plan has better sensitivity than A+ and AdV+ at high frequencies

• **Higher power laser** → **Squeezing** → **Frequency dependent squeezing** → **Larger mirror** might be an effective progression
Next Generation Detectors

• Laser interferometric detector with 10-40 km arms
• Places not decided yet
Next Generation Detectors

• Einstein Telescope
  - 10 km, 200 kg silicon mirror, underground 10 K and room temperature interferometers
  - Two candidate locations (decide by 2022)
    Sardinia, Italy
    Bergium-Germany-Netherlands border
  - Final design by 2023
  - Anticipate to start installation from 2032

• Cosmic Explorer
  40 km, 320 kg silicon mirror, 120 K

• KAGRA is pioneering cryogenic and underground
Sensitivity of Next Generations

- An order of magnitude improvement
Horizon Distance

- $O(10^5)$ events/year with next generation detectors (~2035)

![Graph showing Horizon Distance with different detector sensitivities and redshifts]
Summary

- KAGRA is an **underground cryogenic** GW detector pioneering technologies for next generation detectors
- First **observing run** with LIGO and Virgo expected late 2019
- KAGRA joining the observation improves **sky coverage**, **network duty factor**, **source parameter estimation**
- KAGRA **upgrade study** on-going, aiming for the upgrade by ~2024
- **Twofold** sensitivity improvement (300 Mpc in BNS range) is feasible for KAGRA
1. Laser Interferometers (July 25 PM)  
https://tinyurl.com/YM20190725-1

2. Quantum Noise (July 25 PM)  
https://tinyurl.com/YM20190725-2

3. Sensitivity Design (July 26 AM)  
https://tinyurl.com/YM20190725-3

4. Status of KAGRA (July 26 AM)  
https://tinyurl.com/YM20190725-4
Additional Slides
## 2G/2G+ Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KAGRA</th>
<th>AdVirgo</th>
<th>aLIGO</th>
<th>A+</th>
<th>Voyager</th>
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</thead>
<tbody>
<tr>
<td>Arm length [km]</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Mirror mass [kg]</td>
<td>23</td>
<td>42</td>
<td>40</td>
<td>80</td>
<td>200</td>
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<td>Mirror material</td>
<td>Sapphire</td>
<td>Silica</td>
<td>Silica</td>
<td>Silica</td>
<td>Silicon</td>
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<td>Mirror temp [K]</td>
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<td>295</td>
<td>295</td>
<td>295</td>
<td>123</td>
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<tr>
<td>Sus fiber</td>
<td>35cm Sap.</td>
<td>70cm SiO₂</td>
<td>60cm SiO₂</td>
<td>60cm SiO₂</td>
<td>60cm SiO₂</td>
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<td>125</td>
<td>125</td>
<td>125</td>
<td>140</td>
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<tr>
<td>Arm power [kW]</td>
<td>340</td>
<td>700</td>
<td>710</td>
<td>1150</td>
<td>3000</td>
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<td>Wavelength [nm]</td>
<td>1064</td>
<td>1064</td>
<td>1064</td>
<td>1064</td>
<td>2000</td>
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<td>Beam size [cm]</td>
<td>3.5 / 3.5</td>
<td>4.9 / 5.8</td>
<td>5.5 / 6.2</td>
<td>5.5 / 6.2</td>
<td>5.8 / 6.2</td>
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<td>SQZ factor</td>
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<td>0</td>
<td>0</td>
<td>6</td>
<td>8</td>
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<td>F. C. length [m]</td>
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<td>none</td>
<td>none</td>
<td>16</td>
<td>300</td>
</tr>
</tbody>
</table>

KAGRA Detailed Parameters

K. Komori et al., JGW-T1707038

• **Optical parameters**
  - Mirror transmission: 0.4% for ITM, 10% for PRM, 15.36% for SRM
  - Power at BS: 674 W
  - Detune phase: 3.5 deg (DRSE case)
  - Homodyne phase: 135.1 deg (DRSE case)

• **Sapphire mirror parameters**
  - TM size: 220 mm dia., 150 mm thick
  - TM mass: 22.8 kg
  - TM temperature: 22 K
  - Beam radius at ITM: 3.5 cm
  - Beam radius at ETM: 3.5 cm
  - Q of mirror substrate: 1e8
  - Coating: tantala/silica
  - Coating loss angle: 3e-4 for silica, 5e-4 for tantala
  - Number of layers: 22 for ITM, 40 for ETM
  - Coating absorption: 0.5 ppm
  - Substrate absorption: 50 ppm/cm

• **Suspension parameters**
  - TM-IM fiber: 35 cm long, 1.6 mm dia.
  - IM temperature: 16 K
  - Heat extraction: 5800 W/m/K at 20 K
  - Loss angle: 5e-6/2e-7/7e-7 for CuBe fiber/sapphire fiber/sapphire blade

• **Inspiral range calculation**
  - SNR=8, fmin=10 Hz, sky average constant 0.442478

• Seismic noise curve includes vertical coupling, vibration from heatlinks and Newtonian noise from surface and bulk
KAGRA Cryopayload

Platform (SUS, 65 kg)
- 3 CuBe blade springs

Marionette (SUS, 22.5 kg)
- MN suspended by 1 Maraging steel fiber (35 cm long, 2-7mm dia.)
- MRM suspended by 3 CuBe fibers
- Heat link attached to MN

Intermediate Mass (SUS, 20.1 kg, 16 K)
- IM suspended by 4 CuBe fibers (24 cm long, 0.6 mm dia)
-IRM suspended by 4 CuBe fibers

Test Mass (Sapphire, 23 kg, 22 K)
- TM suspended by 4 sapphire fibers (35 cm long, 1.6 mm dia.)
- RM suspended by 4 CuBe fibers

Figure by T. Ushiba and A. Hagiwara
KAGRA Cryostat Schematic
KAGRA Suspensions

Type-A

13.5 m

cryogenic payload

Type-B

3.1 m

Type-Bp

1.7 m

Type-C

0.4 m

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Possible KAGRA Upgrade Plans

Y. Michimura+,
PRD 97, 122003 (2018); JGW-T1809537
Possible KAGRA Upgrade Plans

Y. Michimura+,
PRD 97, 122003 (2018); JGW-T1809537

<table>
<thead>
<tr>
<th></th>
<th>bKAGRA</th>
<th>LF</th>
<th>HF</th>
<th>40kg</th>
<th>FDSQZ</th>
<th>Combined</th>
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<tbody>
<tr>
<td>detuning angle (deg)</td>
<td>$\phi_{\text{det}}$</td>
<td>3.5</td>
<td>28.5</td>
<td>0.1</td>
<td>3.5</td>
<td>0.2</td>
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<td>homodyne angle (deg)</td>
<td>$\zeta$</td>
<td>135.1</td>
<td>133.6</td>
<td>97.1</td>
<td>123.2</td>
<td>93.1</td>
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<td>mirror temperature (K)</td>
<td>$T_{\text{m}}$</td>
<td>22</td>
<td>23.6</td>
<td>20.8</td>
<td>21.0</td>
<td>21.3</td>
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<td>SRM reflectivity (%)</td>
<td>$R_{\text{SRM}}$</td>
<td>84.6</td>
<td>95.5</td>
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<td>92.2</td>
<td>83.2</td>
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<td>fiber length (cm)</td>
<td>$l_{f}$</td>
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<td>99.8</td>
<td>20.1</td>
<td>28.6</td>
<td>23.0</td>
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<td>fiber diameter (mm)</td>
<td>$d_{f}$</td>
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<td>0.45</td>
<td>2.5</td>
<td>2.2</td>
<td>1.9</td>
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<td>$m$</td>
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<td>22.8</td>
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<td>3440</td>
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<td>maximum detected squeezing (dB)</td>
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<td>0</td>
<td>6.1</td>
<td>0.0</td>
<td>5.2 (FC)</td>
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<td>$100M_{\odot}$-$100M_{\odot}$ inspiral range (Mpc)</td>
<td></td>
<td>353</td>
<td>2099</td>
<td>114</td>
<td>412</td>
<td>318</td>
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<td>$30M_{\odot}$-$30M_{\odot}$ inspiral range (Mpc)</td>
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<td>1269</td>
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<td>$1.4M_{\odot}$-$1.4M_{\odot}$ inspiral range (Mpc)</td>
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<td>153</td>
<td>85</td>
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<td>202</td>
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<tr>
<td>median sky localization error (deg$^2$)</td>
<td></td>
<td>0.183</td>
<td>0.507</td>
<td>0.105</td>
<td>0.156</td>
<td>0.119</td>
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