2.5+G and KAGRA: bridging between 2G and 3G

S. Haino
KAGRA collaboration
2G sensitivity comparison

![Graph showing 2G sensitivity comparison with frequency on the x-axis and strain (√Hz) on the y-axis, comparing aLIGO, AdV, and KAGRA.](image-url)
2G design sensitivities

K is aiming better than LV at ~100 Hz with cryogenic
2G design sen

\begin{align*}
\text{strain (}/\sqrt{\text{Hz}}) \\
10^{-24} &< 10^{-23} < 10^{-22} < 10^{-21}
\end{align*}

\begin{align*}
\text{frequency (Hz)} \\
10^1 &< 10^2 < 10^3
\end{align*}

\text{KAGRA thermal} \quad \text{aLIGO thermal}
Cryogenic suspension system

Vibration Isolation system

Platform

Marionette

Sapphire Mirror

14 m

Chief: T. Tomaru
KAGRA

Cryogenic system

Vibration Isolation system (300 K) suspended from 2F

Mirror (20 K)

Inner shield (8 K)

Outer shield (80 K)

Cryocooler

Main beam

Beam tube shield

Cryostat and vacuum tube (300 K)
Application of Accelerator technologies to KAGRA

KEK cryogenic center is leading the development of KAGRA cryogenic system

J-PARC neutrino super-conducting beam line

KAGRA cryostat

2.5+G KAGRA
Comparison between 2 and 2.5G

LIGO-T1800044, LIGO-T1800042, VIR-0325B-18, JGW-T1707038

AdV+ Phase I: 160 Mpc
Phase II: 300 Mpc

A+: 325 Mpc
Coating is the key for A+, AdV+

![Graph showing strain sensitivity and frequency for AdV+ Phase-II, with lines representing different scenarios and their corresponding improvements in coating thermal noise.](chart.png)
KAGRA thermal noise

Owing to cryogenic KAGRA thermal noise is already in the middle of aLIGO and A+

... and still the conservative estimation (based on measurements)
KAGRA (cryogenic): $\phi_{\text{Silica}} = 3\times10^{-4}$, $\phi_{\text{Tantala}} = 5\times10^{-4}$
aLIGO (room temp): $\phi_{\text{Silica}} = 5\times10^{-5}$, $\phi_{\text{Tantala}} = 3.6\times10^{-4}$
bKAGRA noise budget

The diagram shows the sensitivity (1/√Hz) as a function of frequency (Hz). The sensitivity curves are labeled as SQL, quantum, mirror, seismic + gravity, and suspension. The total sensitivity curve is also shown.
Suspension and quantum are dominating the low frequency, not seismic + gravity.
bKAGRA feature and issues

• Cryogenic → Low thermal noise
  → Heat extraction (thicker fiber)
  → Suspension noise

• Sapphire → Production mass limit (23 kg)
  → Heat absorption

• Underground → Low seismic and Newtonian noise
  → Not dominant in low freq.
Specific issues for cryogenic

- Not trivial to do both
  - high power (400 kW on mirror)
  - low temperature (20 K)

Thinner and longer fibers preferred for suspension thermal noise reduction

Thicker and shorter preferred for efficient heat extraction
Future Planning Committee (FPC)

• Approved by KAGRA Science Congress (KSC) in Dec./2018 to make the plan for KAGRA+ upgrades and future

• Based on the past discussions, more realistic proposals will be prepared as a white paper

• A few candidates for KAGRA+ upgrades will be discussed and proposed soon (hopefully Apr./2019)

• (Initial) members: C. Kim, K. Komori, M. Leonardi, Y. Michimura, A. Nishizawa, K. Somiya, S. Haino(Chair)
History of KAGRA+ Discussions

• Mar. 2017 F2F @ Niigata U.
• May 2017 KIW3 @ Taiwan
• Aug. 2017 F2F @ U. Toyama
• Dec. 2017 F2F Satellite @ Tokyo Tech.
• Jun. 2018 KIW4 @ Seoul, Korea
• Dec. 2018 F2F Satellite @ NAOJ
  ... and
• Feb 2019 KIW5 @ Perugia
KAGRA’s tough situation

- LVK joint GW detection in O3 is absolutely necessary to go forward to KAGRA+

- At the same time, A+ funding was already approved [1] for 2024-2025 (aka O5)

- For KAGRA+, with the limited resources/time, broadband improvement is not easy

Four proposals

- Example sensitivity curves were necessary to start science case study
- Plans technically not too ambitious

- Plan **Blue** - heavier sapphire mirrors
- Plan: **Black** - silicon mirrors (ambitious for O5 ?)
- Plan: **Brown** - tuning to the low frequency
- Plan: **Red** - high power laser (high frequency)
Example sensitivity curves

![Graph showing sensitivity curves with labels for frequency (Hz) and strain (\(\sqrt{\text{Hz}}\)). The graph includes curves for low frequency (LF), heavy mass with a value of 23 implying 73 kg, and high frequency (HF) with a note that it requires a > 500 W laser.](image)
## Science examples summary

<table>
<thead>
<tr>
<th></th>
<th>bKAGRA</th>
<th>LF</th>
<th>Heavy</th>
<th>HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>test of GR with BH ringdown</td>
<td>✗</td>
<td>✗</td>
<td>✢</td>
<td>○</td>
</tr>
<tr>
<td>existence of IMBH from hierarchical growth</td>
<td>✢</td>
<td>✢</td>
<td>○</td>
<td>✢</td>
</tr>
<tr>
<td>existence of stellar-mass BBH from popIII</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>sky localization for BBH (identifying host galaxy)</td>
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<td>✗</td>
<td>○</td>
<td>○</td>
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<tr>
<td>pulsar ellipticity</td>
<td>✗</td>
<td>✗</td>
<td>✢</td>
<td>○</td>
</tr>
<tr>
<td>NS equation of state</td>
<td>✗</td>
<td>✗</td>
<td>✢</td>
<td>○</td>
</tr>
</tbody>
</table>
Measurability

- GW170817 at LV
- Mid. frequencies = SNR
- Low frequencies = Chirp Mass
- High frequencies = deformability
Multiple quasi-normal modes

GW150914-like events based on PRD 90, 124032 (2014)

sensitivity [1/sqrt(Hz)]

frequency [Hz]

L=2, m=2 QNM
L=3, m=2 QNM
L=4, m=4 QNM
bKAGRA
Heavy
LF
HF

30M_sun+30M_sun
z=0.093, 440Mpc average on angles

Heavy

HF

by Nakano
Continuous wave searches

![Graph showing gravitational wave frequency vs. strain amplitude with various markers and lines representing different scenarios and parameters.](image-url)
Continuous wave searches

<table>
<thead>
<tr>
<th>Gravitational wave frequency [Hz]</th>
<th>aLIGO</th>
<th>aLIGO/2 (\sim A^+)</th>
<th>bKAGRA</th>
<th>bK+ LF</th>
<th>bK+ Heavy</th>
<th>bK+ HF</th>
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</thead>
<tbody>
<tr>
<td>-6</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>9</td>
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<td>-8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Accretion balance</td>
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<td>8</td>
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<td>0</td>
<td>3</td>
<td>8</td>
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<td>1</td>
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<td>10</td>
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<tr>
<td>Decayable Magnetic</td>
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<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Possible Near Term Plans

• Candidates would be
  A. 40 kg mirror with better coating
     and new sapphire fibers
     (use existing cryostat and Type-A tower)
  B. 400 W laser with (Freq. indep.) squeezing
     and new sapphire fibers
  C. Frequency dependent squeezing
     and new sapphire fibers
     (Ref: E. Capocasa and R.K. Lee’s talk)

• Sensitivity optimization with particle swarm
KAGRA with high power extension

- Cryogenic sapphire mirrors may have some advantages for high power extension compared with room-temperature Silica mirrors.

- Disadvantages:
  - Heat extraction issue
    (= thicker and shorter fibers)
  - Mass limits
    (= more radiation pressure noise)
Parametric Instability (PI)

- Currently one of the issues for LIGO/Virgo to go to higher power laser

- KAGRA should have advantages of rigid Sapphire mirror to reduce the PI (~1/10 w.r.t. Silica) ~1/5 by higher Young’s modulus (400/73) ~1/2 by number of modes (3/7)

  JGW-T0900057
Thermal lensing comparison

Thermal lensing effect is significantly reduced with cryogenic sapphire mirror

<table>
<thead>
<tr>
<th></th>
<th>Fused silica (300 K)</th>
<th>Sapphire (300 K)</th>
<th>Sapphire (20 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (ppm cm$^{-1}$)</td>
<td>2–20</td>
<td>40–100</td>
<td>90</td>
</tr>
<tr>
<td>$\kappa$ (W m$^{-1}$ K$^{-1}$)</td>
<td>1.4</td>
<td>46</td>
<td>$4.3 \times 10^3$</td>
</tr>
<tr>
<td>$\beta$ (K$^{-1}$)</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$\leq (9 \times 10^{-8})$</td>
</tr>
<tr>
<td>$\alpha \beta / \kappa$ (W$^{-1}$) $\times 10^{-9}$</td>
<td>2–20</td>
<td>1–3</td>
<td>$\leq (2 \times 10^{-4})$</td>
</tr>
</tbody>
</table>

T. Tomaru et al., Class. Quantum Grav. 19 (2002) 1
Long-term upgrades options

KAGRA++ : 100 kg mirror with 1/2 coating thermal, 320 W input, 10 dB input squeezing with 100 m filter cavity
Issues for 100kg sapphire mirrors

- Technological breakthrough to produce 100kg sapphire bulk with GW detector quality

- Current KAGRA cryostat may not be able to afford bigger mirror
  => replacement of cryostat
  => the vacuum tubes (3km arms) may need to be extracted from the tunnel to make the path
Advanced interferometry?

- Extreme RSE (Resonant Sideband Extraction)
  - No PRM, high arm finesse => lower power at ITM
- Speedmeter
- EPR (Einstein-Podolsky-Rosen) entanglement
- ...

2.5+G KAGRA
Possible collaborations with ET

- High power (500W, 1064 nm) laser (ET-HF)
- High power mitigations (e.g. Parametric Instability)
- Efficient heat extraction (fiber, heat link) (ET-LF ?)
- QND to reduce rad. press. noise (e.g. speedmeter)
- Newtonian Noise study at underground site
Speedmeter as an option in ET?

ET workshop at Glasgow

- Seismic: Black Forest
- Newtonian Gravity: 20x subtraction
- Residual Gas: 0.3 nTorr of H₂
- ET single, 120K
- ET-D
- aLIGO design
- ET Facility Limit
- 3MW speedmeter, 40m FC, 30ppm loss
Speedometer

KAGRA may have more benefits from speedometer with:
- combination with high power
- lower radiation pressure noise even with small mirrors
- Shorter filter cavity for freq. dependent squeezing
Summary

• KAGRA Future Planning Committee has just formed and started the discussion of KAGRA upgrades

• Optimization of design with current technology limits and maximum science merits should be considered

• Some of challenges can be shared with 3G (e.g. ET) detector developments
Acknowledgements

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