JGW-G2416309
34th KAGRA Face-to-Face Meeting Dec 2024

December 18, 2024

Release of **KAGRA Instrument Science White Paper 2024** and Proposal for Amending Authorship Policy Regarding **Long-Term Experimental Activities**

FSC
FORESTS FOR ALL FOREVER™
Forest Stewardship Council®

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for KAGRA FSC

FSC Activities

https://fsc.org/

https://shitte-erabo.net/fscproducts/fscmark/

Instrument Science White Paper 2024

- Released on December 3, 2024
- Publicly available at JGW-T2416182

paperless!

- Comments welcome!
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WP Writing Workshop

- Oct 2-3, 2024 @ Hiroshima University
- Thanks to Nishizawa-san and ASPIRE-GW

ASPIRE

Instrument Science White Paper 2024

1. **Executive Summary**
2. **Introduction**
   - History from FPC white paper 2019
   - Focus on post-O5 and beyond
3. **Survey of Current Technologies**
   - Over 60 technologies
   - Feasibility score: 0-5
4. **Possible Upgrade Plans**
   - Summary of outstanding issues
   - Example upgrade plans (LF, HF, BB)

Executive Summary

We reviewed over 60 technologies that could potentially be implemented to upgrade KAGRA, evaluating their feasibility on a scale from 0 to 5 according to the criteria detailed in Sec. 3. Each technology was also rated for its relevance to improving low-frequency sensitivity, high-frequency sensitivity, broadband sensitivity, stability, and accuracy, with a score from 0 to 2. A relevance score of 0 indicates minimal or no relevance, 1 indicates moderate relevance, and 2 indicates high relevance or necessity.

To determine the readiness, the feasibility score was multiplied by the relevance score, and we calculated the average of the products for relevance scores of 1–2. This resulted in an average product score of **2.90 for low-frequency, 4.38 for high-frequency, and 3.22 for broadband improvements**. A detailed score table can be found in the last two pages of this section and Google spreadsheet in this link. The overall trend was consistent with the technology scores summarized in the 2019 FSC White Paper [JGW-M1909590].

In addition, we analyzed various example upgrade plans in Sec. 4 to identify the research and development efforts necessary to enhance KAGRA's sensitivity. The high-priority development items are as follows:

- High Q-factor sapphire fibers and blade springs. Blade springs with lower resonant frequencies.
- Large, uniform and low absorption sapphire mirrors.
- Output optics and filter cavity with low optical losses. Technologies to reduce mode-matching losses.
- Technologies for higher power operations.
- Control schemes for higher finesse signal recycling cavity and arm cavities.

Technology Score

- Relevance score: 0-2 for LF, HF, BB, stability, accuracy improvements
- Relevance x Feasibility
- Averaged over technologies

Technology Survey 2024	Feasibility	Relevance: LF	HF	BB	Stability	Accuracy
Average Feasibility x Relevance		2.90	4.38	3.22	2.78	4.00
High power laser	3	0	2	1		
Use of different wavelengths	3	1	1	1		
Multi-carrier injection	0	1	1	1		
Frequency-independent squeezing	5	0	2	0		
Frequency-dependent squeezing	5	1	0	2		
Birefringence compensation	2	0	1	1	1	
Large beam	3	0	0	2		
Large sapphire mass	2	2	0	2		
Silicon test mass	1	1	0	1		
Use of different materials for substrate	0	1	0	1		
Composite mass	0	1	0	1		
Parametric instability mitigation	5	0	2	1	1	
Thermal compensation system	5	0	2	1		
Use of different materials for coating	2	0	0	2		
Non-TEM00 beam	3	0	0	1		
Non-cylindrical mass	0	1	0	1		
Khalili cavity	1	0	0	1		
Gratings	2	0	0	1		
Radiative cooling		1	0	1		
Reducing vibration of cryogenic components	3.5	2	0	0		
Sapphire blade spring improvement	2	2	0	1		
Use of ribbons	2	1	0	1		
Use of long fibers	1	2	0	1		
High conductivity fibers		1	2	1		
Large beam splitter	5	0	1	1		
Low-loss Faraday isolator	5	0	2	2		
Low-loss OMC	5	0	2	2		
Low-loss PD	3	0	2	2		
Adaptive control for better seismic isolation	4	2	0	0	1	
Better damping control	4	2	0	0	1	
Low-frequency vibration isolation	3	2	0	0		
Suspension point interferometer	3	1	0	0	1	
Vertical suspension point interferometer	0	1	0	0		
Newtonian noise studies and cancellation	2	2	0	0	1	
Environmental magnetic noise sensors	5	1	0	0		
Charge noise reduction	0	1	0	0		
Instrumented baffles	3	1	0	0		
Schumann resonance	5	1	0	0		
Thermal noise in non-equilibrium steady state	3	1	0	0		
Gravitational decoherence noise	0	0	0	0		
Phase camera	5	1	0	1		
Machine learning	5	1	1	1	1	1
Noise subtraction methods	5	2	1	1		
Laser induced desorption	0	0	1	1		
Quantum locking	3	1	0	0		
Homodyne readout	3	1	0	2		
Variational readout	2	1	0	1		
Optical spring	4	1	0	0		
Long-SRC	3	0	2	0		
Quantum expander	2	0	1	1		
Intracavity OPA	3	0	1	0		
White-light cavity	2	0	1	0		
PT symmetry	2	0	1	0		
Kerr amplification	2	0	1	0		
Photo-thermal effect	2	1	1	0		
EPR squeezing	3	1	0	1		
Quantum teleportation	1	1	0	1		
Negative effective mass	1	1	0	1		
Speed-meter	1	1	0	0		
Acceleration-meter	1	1	0	0		
Negative intertia	1	1	0	0		
Local readout	1	1	0	0		
Photon counting	2	0	1	0		
Delay line	4	0	0	1		
Displacement noise free interferometer	1	0	0	0		
L resonator	2	0	1	0		
Multi-color calibration	3	0	0	0		1
Tidal compensation using geophysics interferometer		0	0	0	1	
Earthquake monitors		0	0	0	1	

Technology Survey 2024	Feasibility	Relevance: LF	HF	BB	Stability	Accuracy
Average Feasibility x Relevance		2.90	4.38	3.22	2.78	4.00
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Birefringence compensation	2	0	1	1	1	
Large beam	3	0	0	2		
Large sapphire mass	2	2	0	2		
Silicon test mass	1	1	0	1		
Use of different materials for substrate	0	1	0	1		
Composite mass	0	1	0	1		
Parametric instability mitigation	5	0	2	1	1	
Thermal compensation system	5	0	2	1		
Use of different materials for coating	2	0	0	2		
Non-TEM00 beam	3	0	0	1		
Non-cylindrical mass	0	1	0	1		
Khalili cavity	1	0	0	1		
Gratings	2	0	0	1		

Upgrade Plans by Swarm Intelligence

- Interferometer parameters are tuned with particle swarm optimization to

  - **LF plans**

    maximize 100-100 range

  - **HF plans**

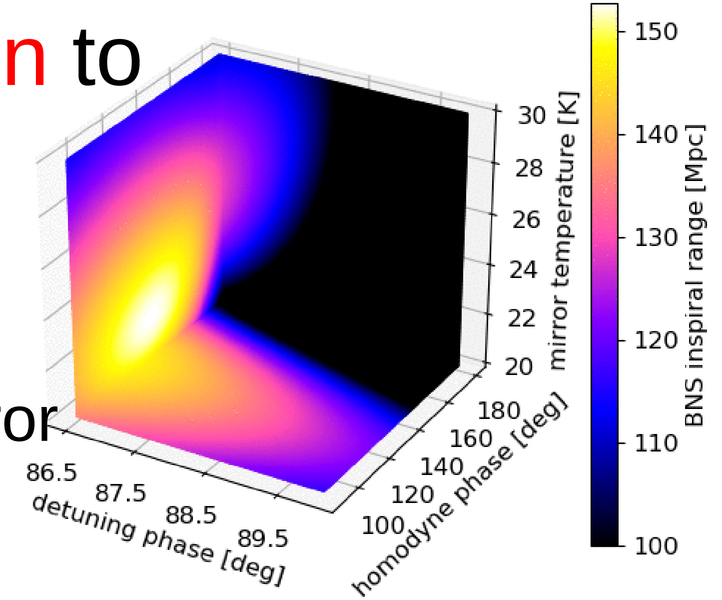
    minimize BNS sky localization error

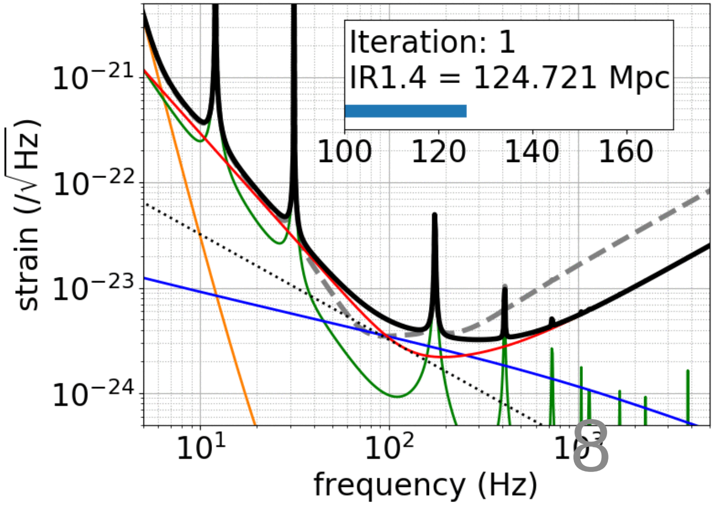
    or

    deep dip above kHz

  - **BB plans**

    maximize 1.4-1.4 range





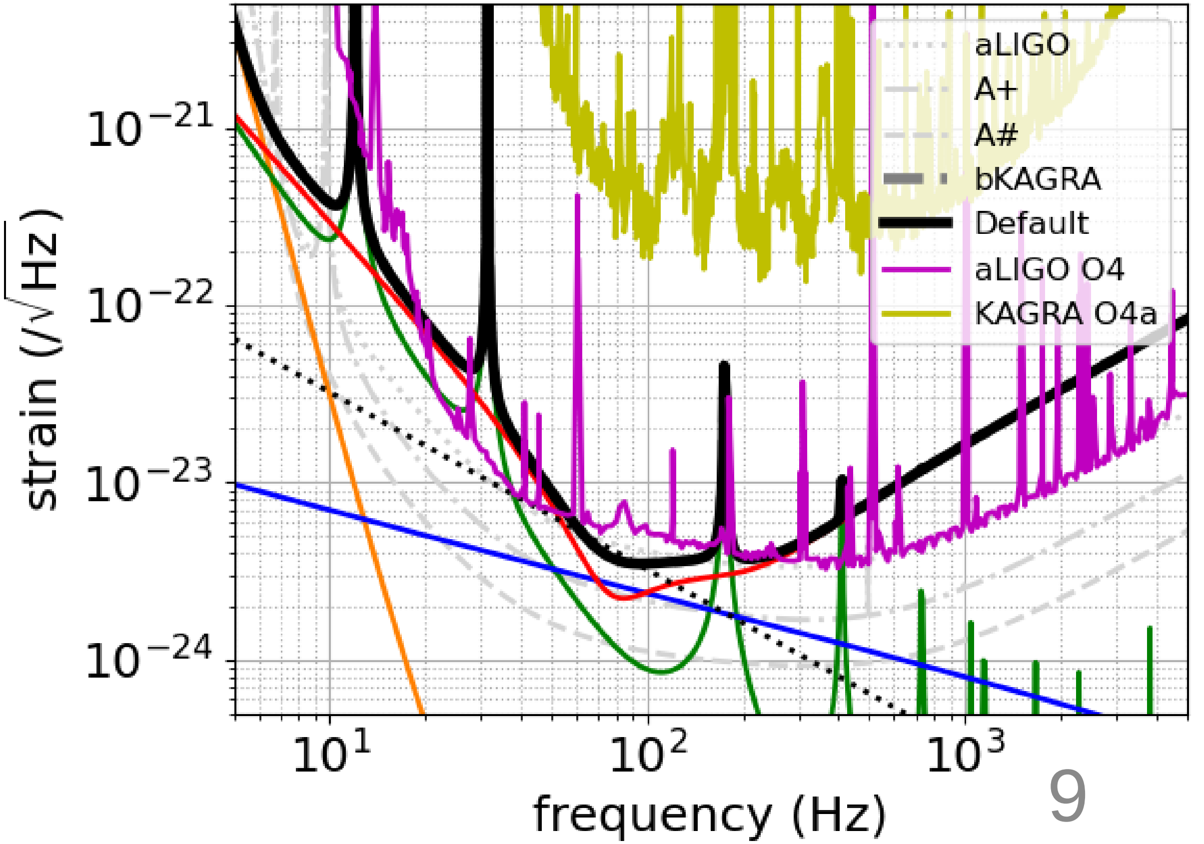
YM+, PRD **97**, 122003 (2018)

Default bKAGRA Design Sensitivity

- Default bKAGRA: Detuned RSE
- NOTE: not all the requirements to achieve these fundamental noises are still not yet achieved

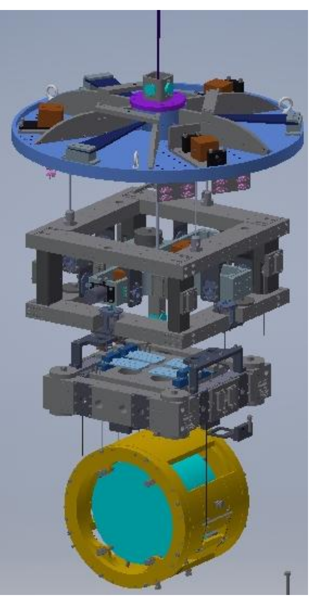
e.g.

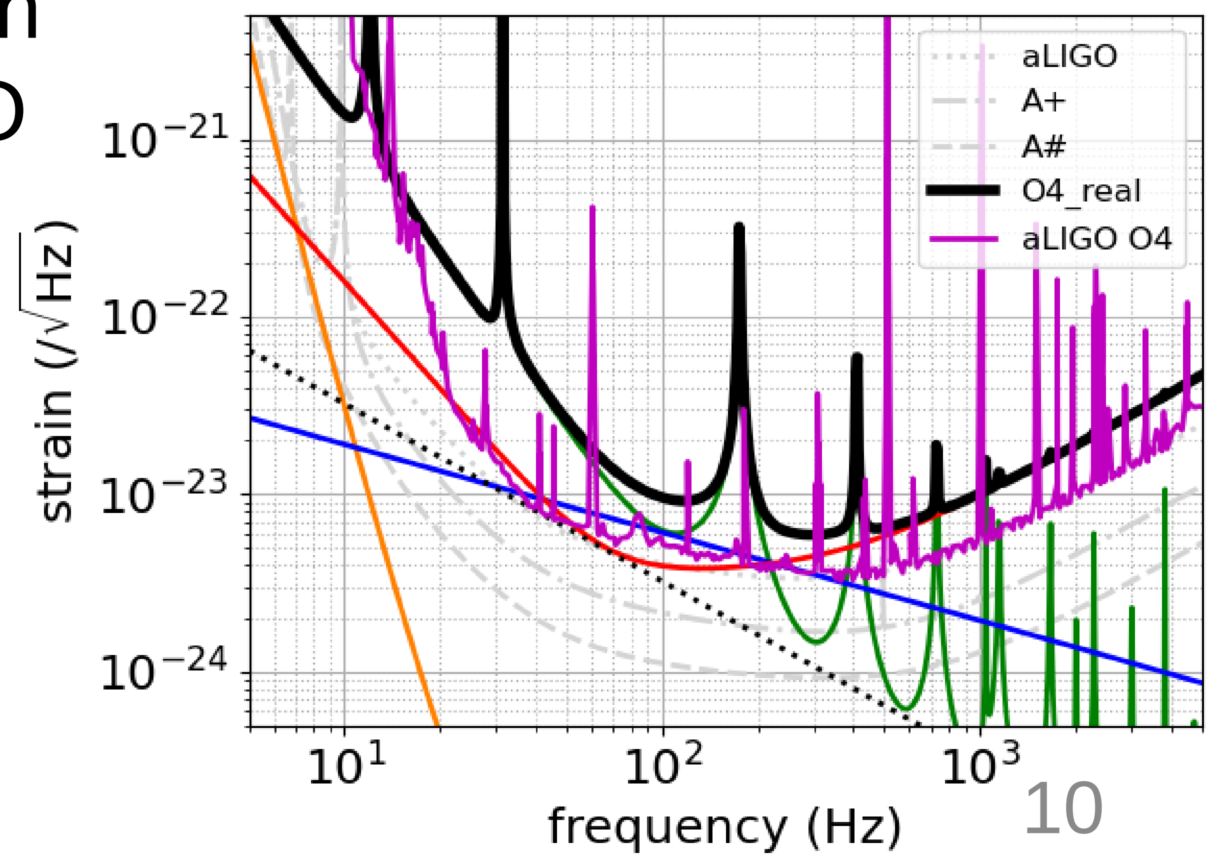
- suspension loss 10^{-4} to 10^{-5}
instead of 2×10^{-7}
- substrate loss 10^{-6}
instead of 10^{-8}
- blade spring loss 4×10^{-5}
instead of 7×10^{-7}
- optical losses still higher by ~ x2



With Current Mechanical Losses

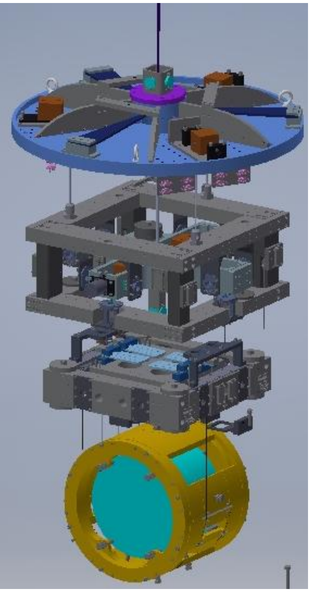
- If we cannot improve the mechanical losses from the current measured values, low frequency sensitivity limit is worse by ~ x5 compared with current aLIGO

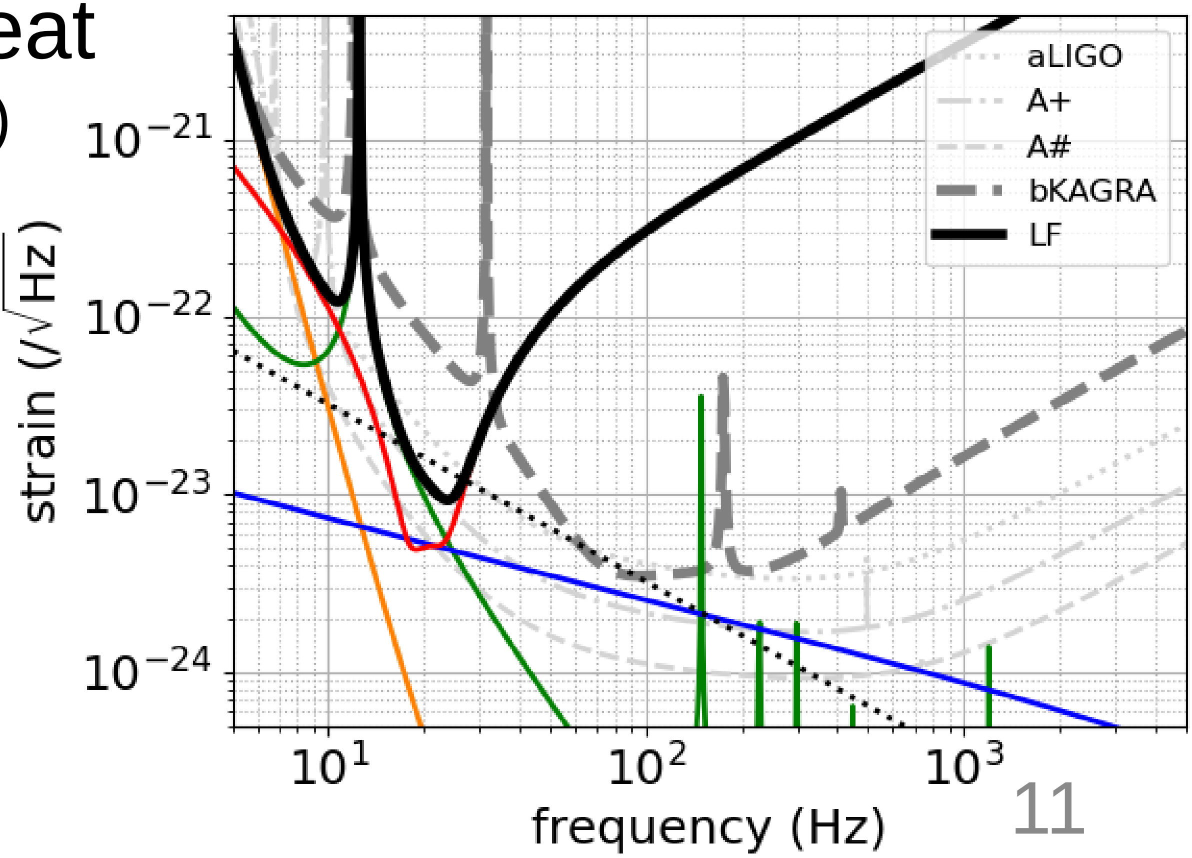




Possible Upgrade Plans

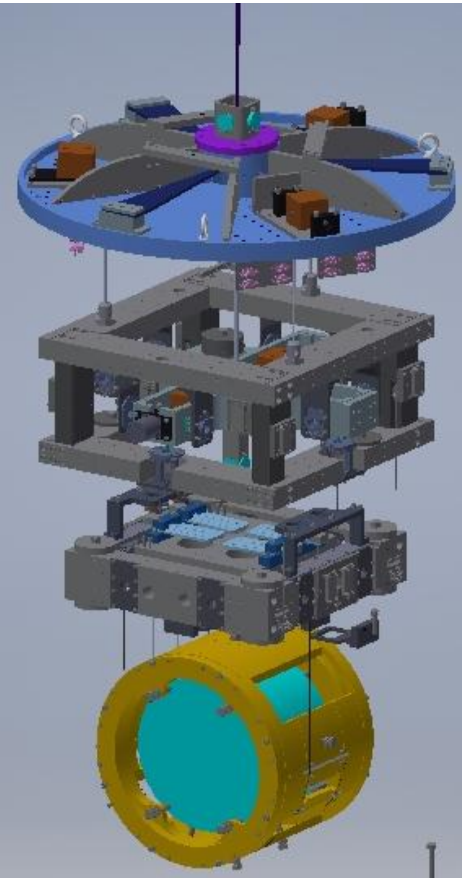
- **LF proposed by FPC in 2019**
- x4 heavier IM mass (82 kg) + Thinner and longer CuBe wires and sapphire fibers + 3 mW extra heat (instead of 50 mW)
- ~ A+ at LF

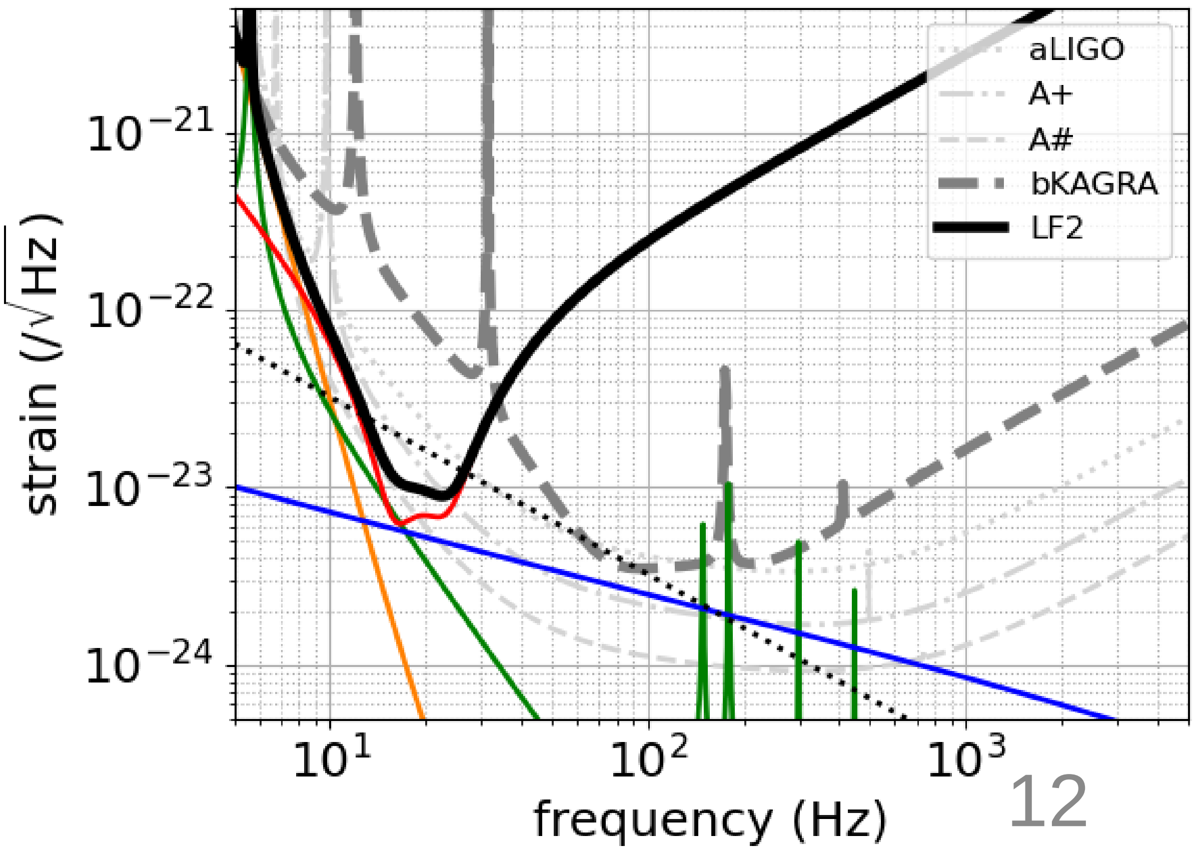




Possible Upgrade Plans

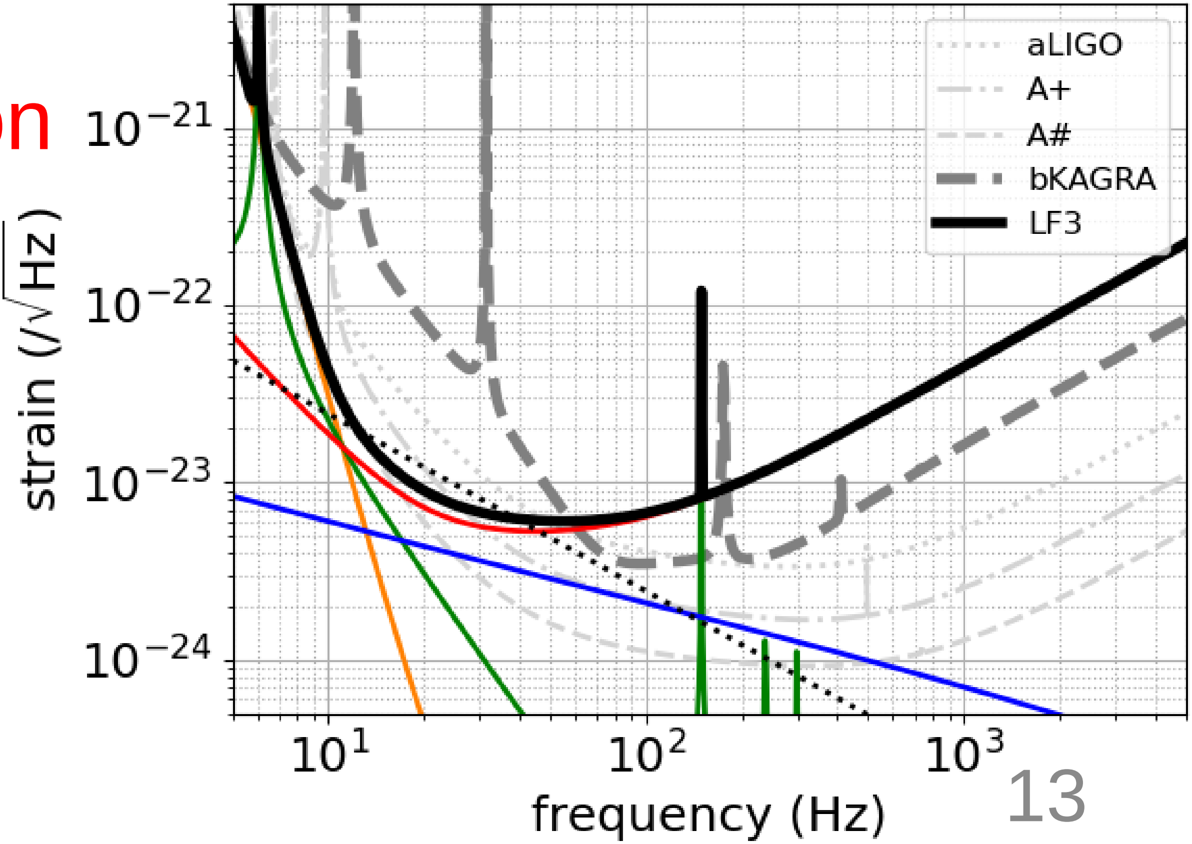
- **LF2**
- LF2019 +
  14.5 Hz to 5 Hz sapphire blade springs





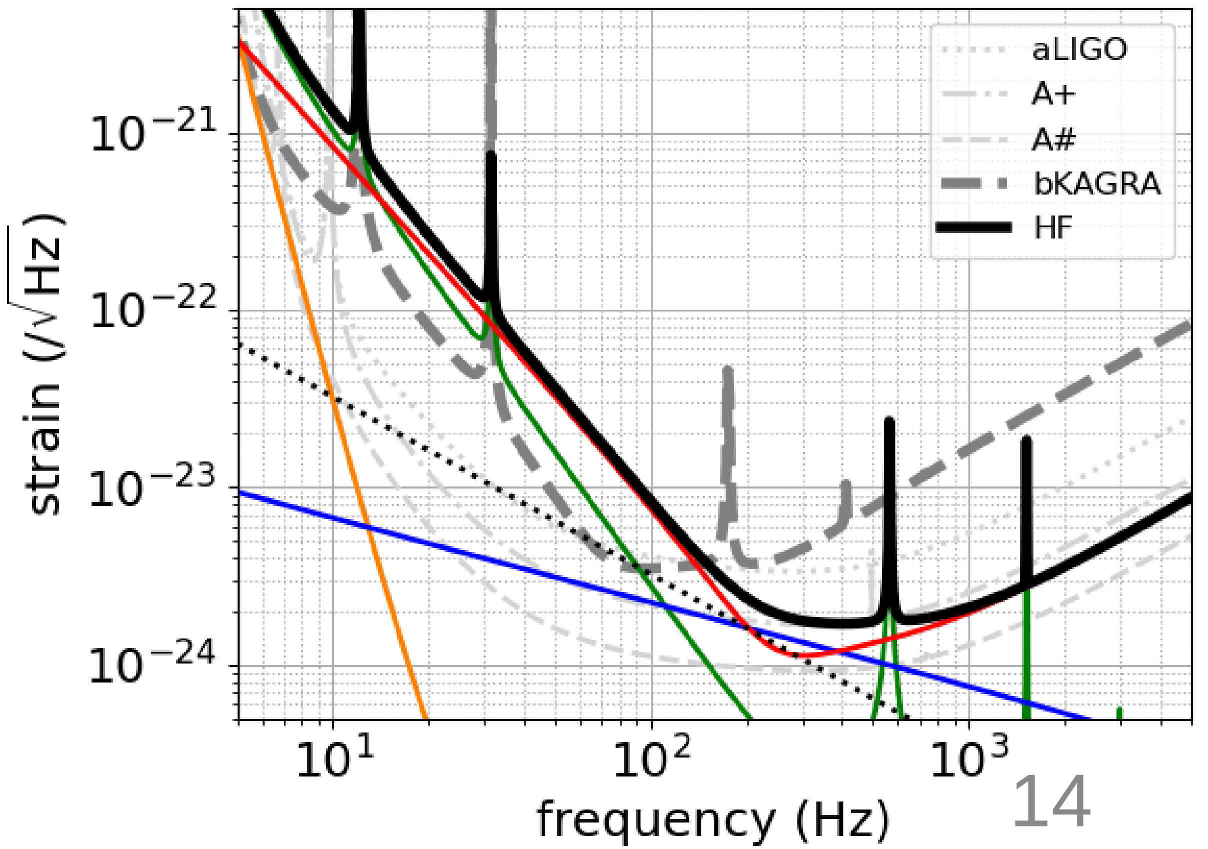
Possible Upgrade Plans

- **LF3**
- LF2 +
  300-m long, 30 ppm loss filter cavity +
  40 kg TM +
  x1/2 absorption
- ~A# at LF



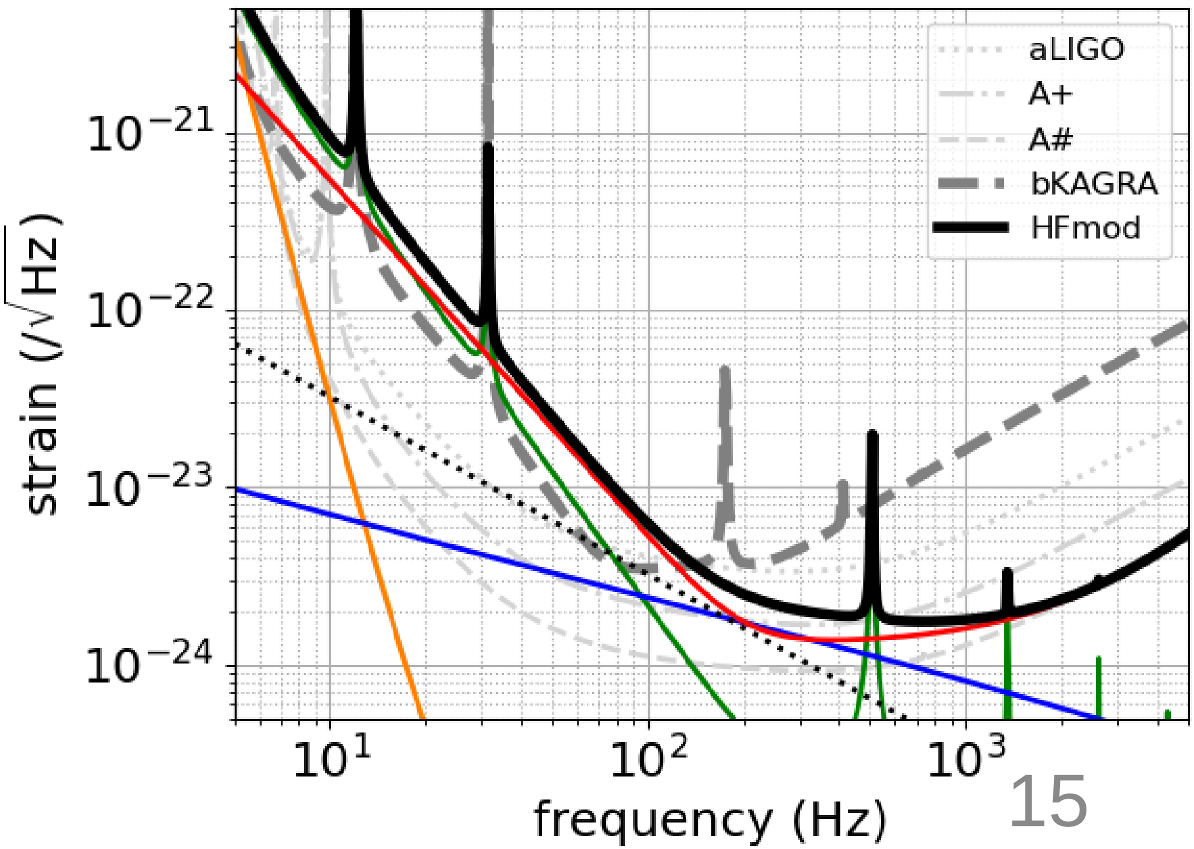
Possible Upgrade Plans

- **HF proposed by FPC in 2019**
- Shorter and thicker sapphire fibers + 3.4 MW/2 in each arm + 6 dB detected squeezing + 90.7% SRM
- Beyond A+ at HF



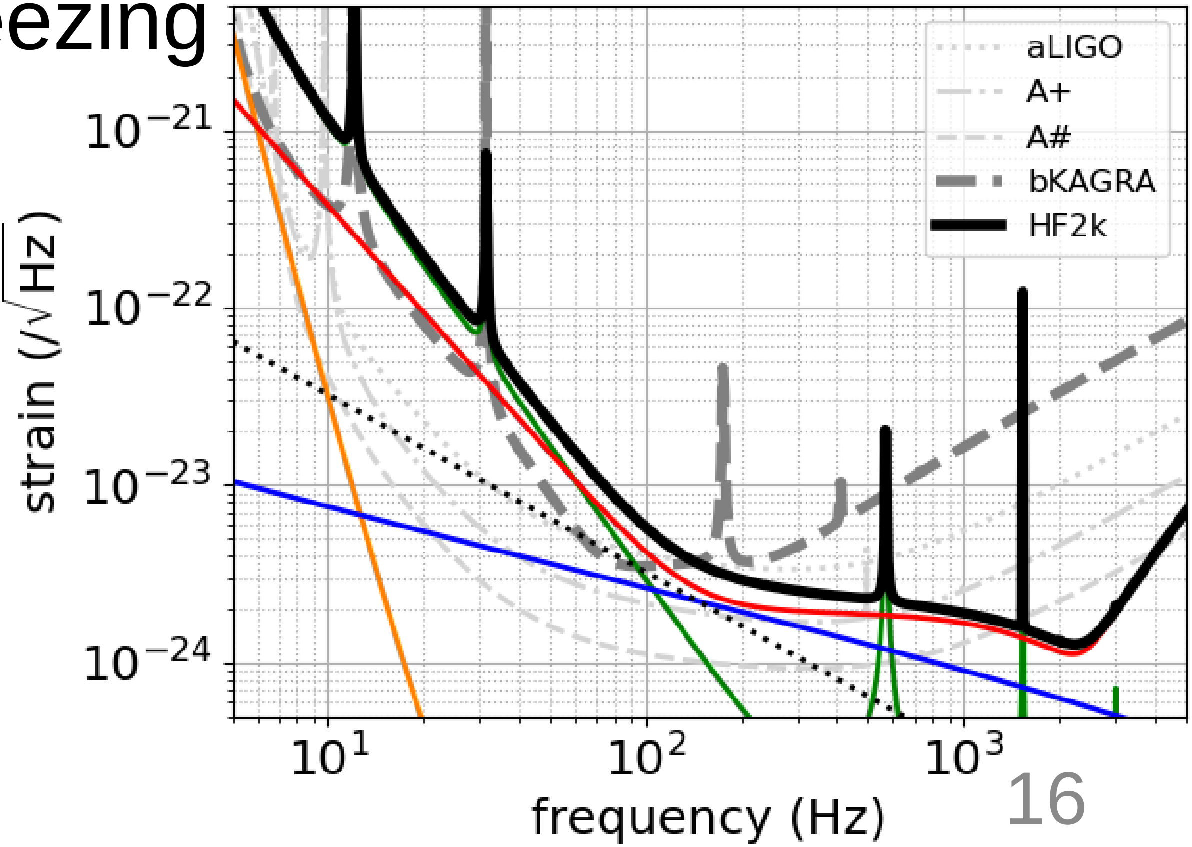
Possible Upgrade Plans

- **HFmod** (similar but different from HFmod by 10 yr TF)
- Shorter and thicker sapphire fibers + 3.1 MW/2 in each arm + 7 dB detected squeezing (lower loss) + 95.6 % SRM
- ~A# at HF



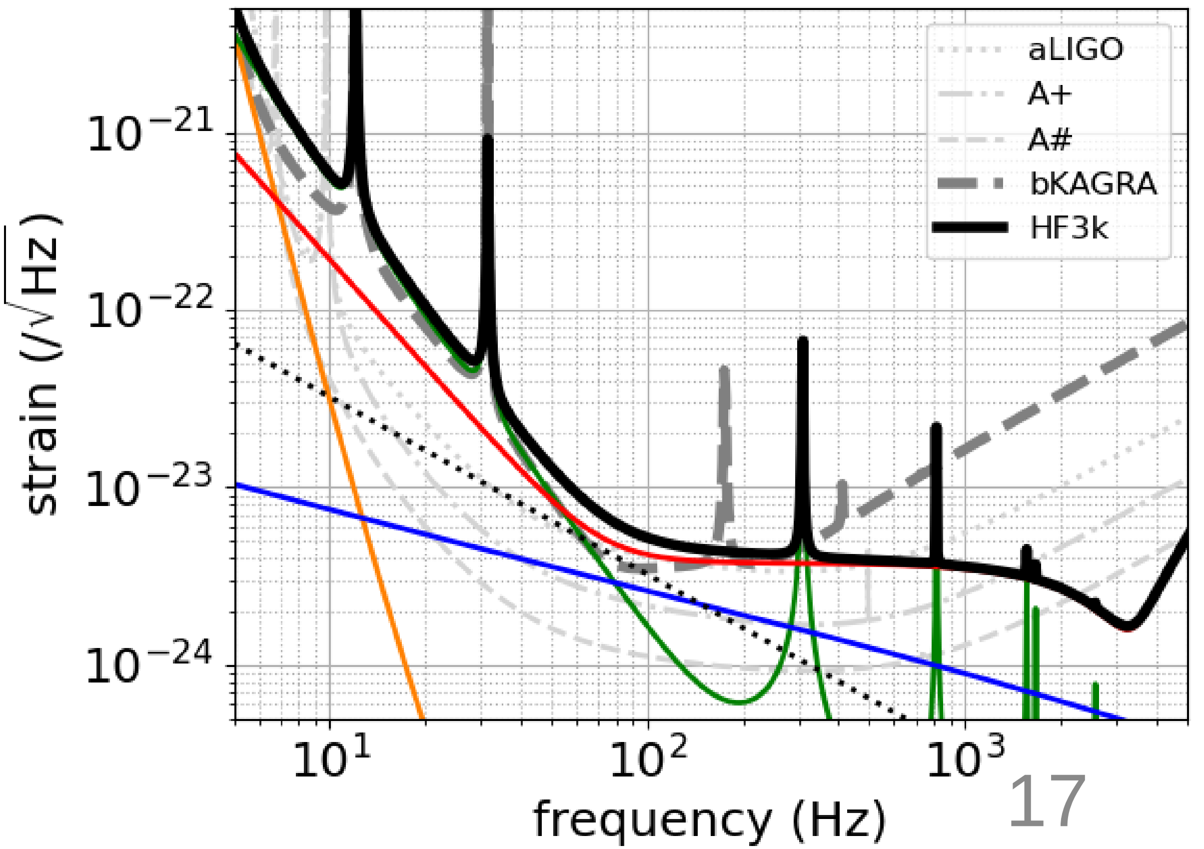
Possible Upgrade Plans

- **HF2k** (similar but different from HF2k by 10 yr TF)
- Short and thicker sapphire fibers + 3.5 MW in each arm + 0.2% ITM + 7 dB detected squeezing (lower loss) + 99.5% SRM
- Beyond A# at ~2 kHz



Possible Upgrade Plans

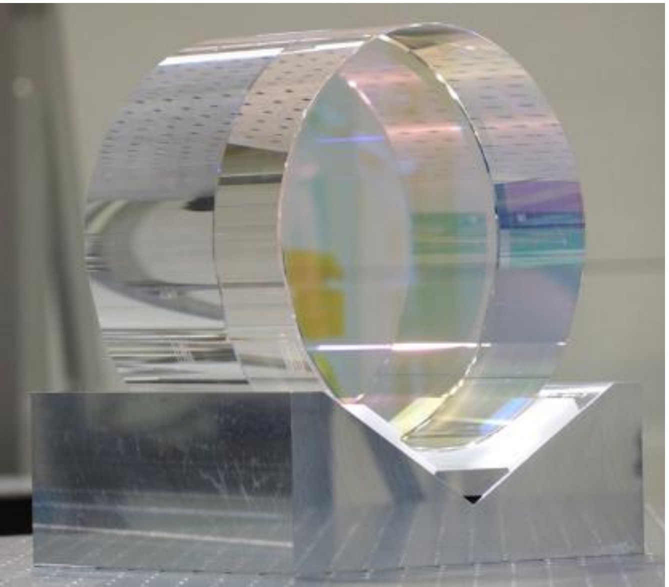
- **HF3k** (similar but different from HF3k by 10 yr TF)
- Short and thicker sapphire fibers + 3.5 MW/2 in each arm + 7 dB detected squeezing (lower loss) + 99.5% SRM

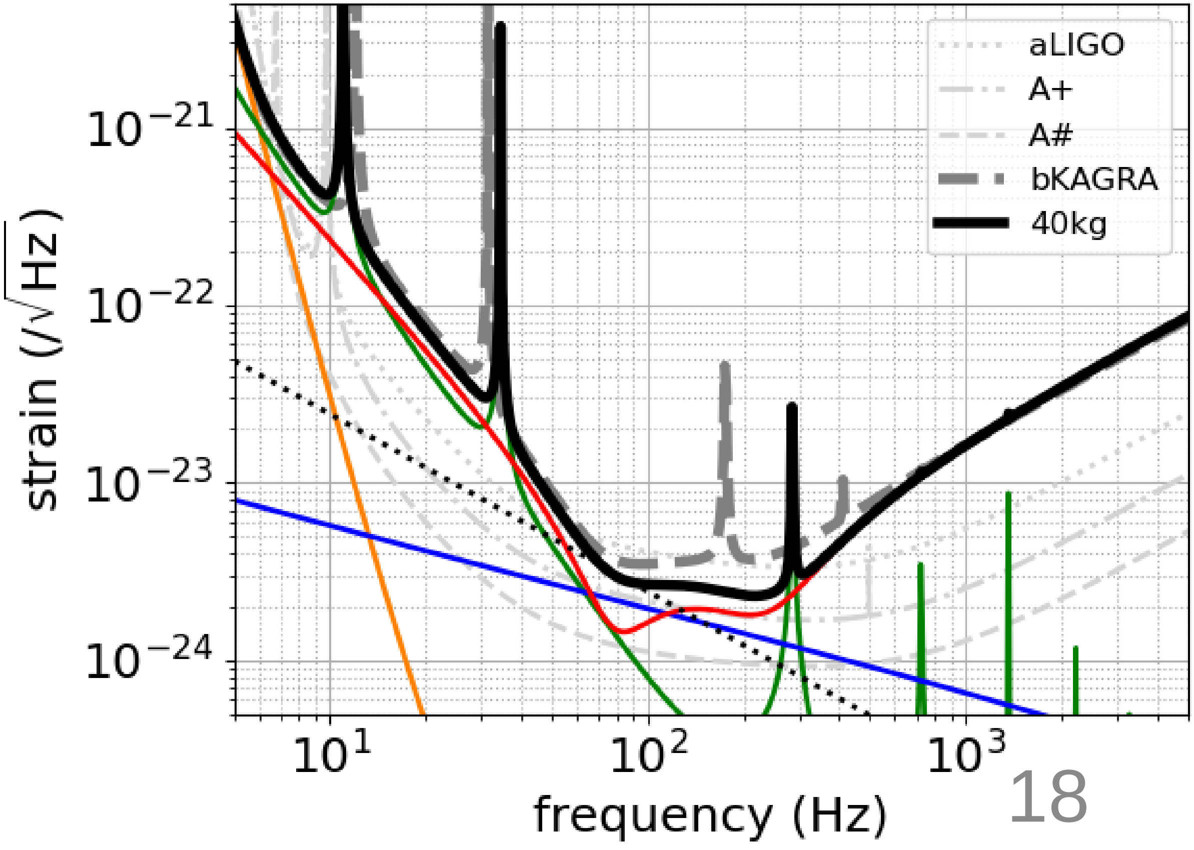


- Beyond A# at ~3 kHz

Possible Upgrade Plans

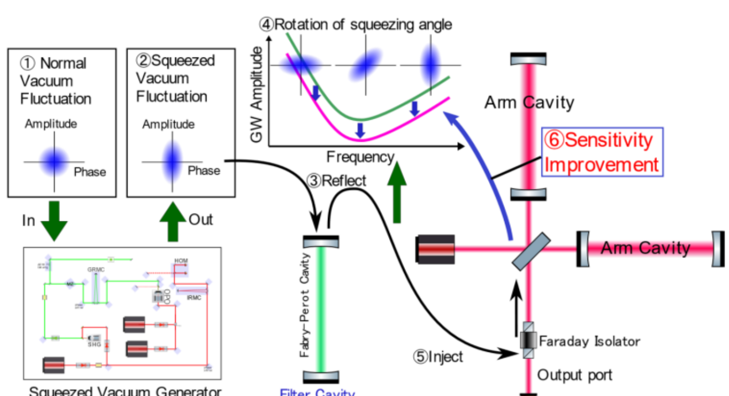
- **40kg proposed by FPC in 2019**
- 40 kg TM (largest mass that can be put into current cryostat without changing shields etc. design)

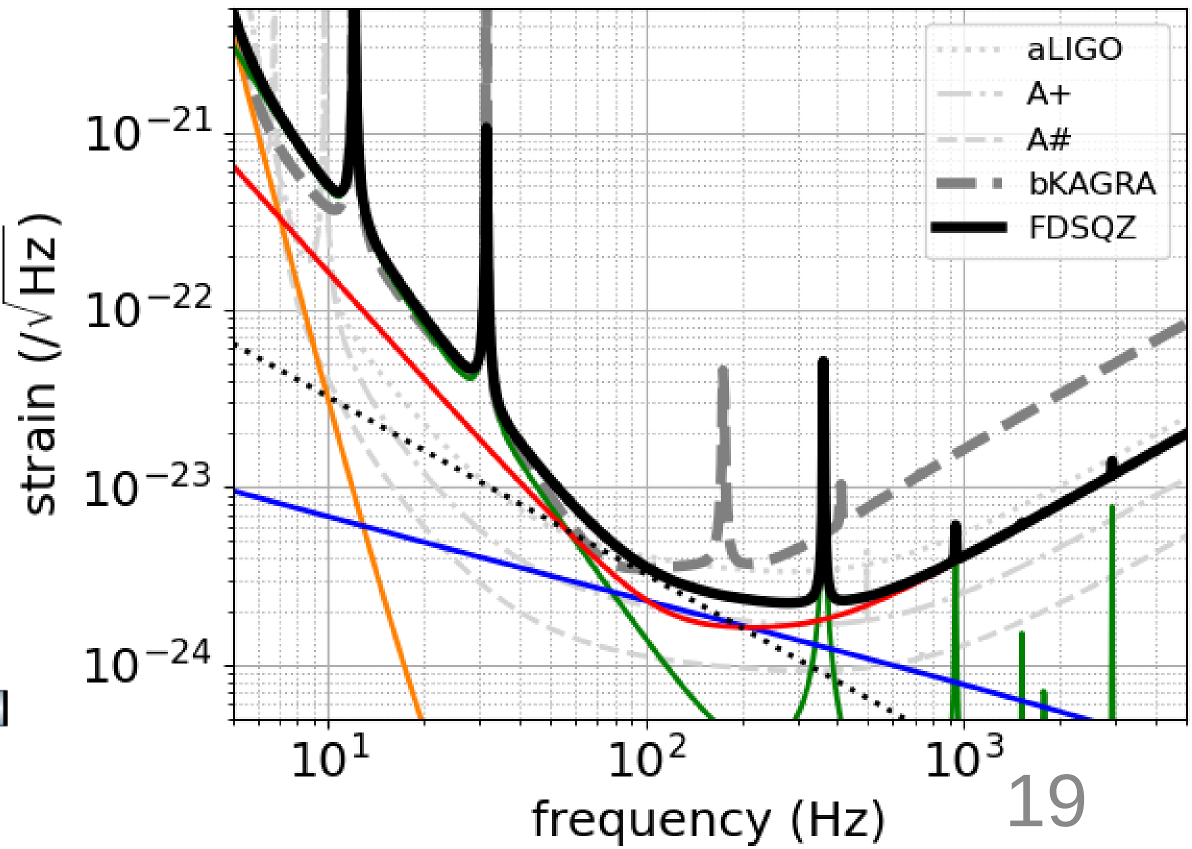




Possible Upgrade Plans

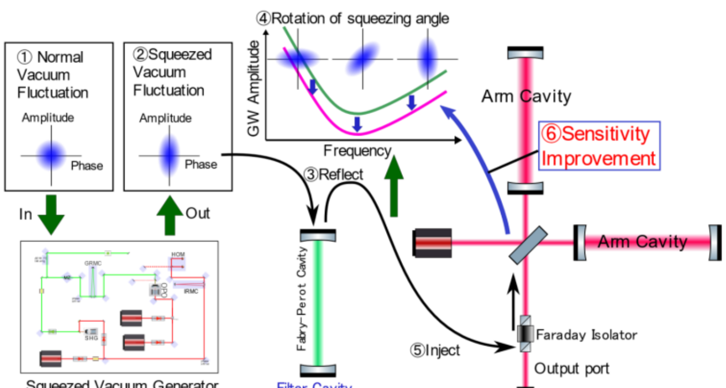
- **FDSQZ proposed by FPC in 2019**
- Frequency dependent squeezing with 30-m filter cavity

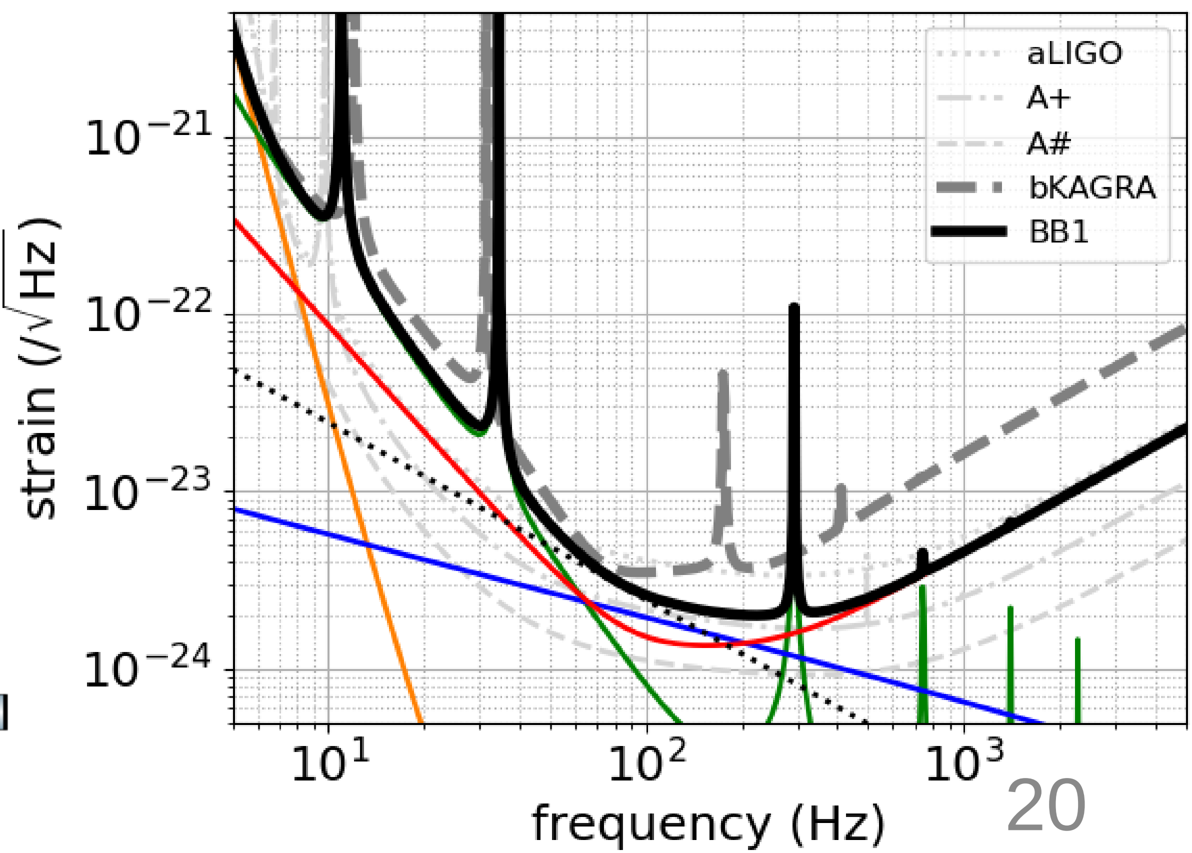




Possible Upgrade Plans

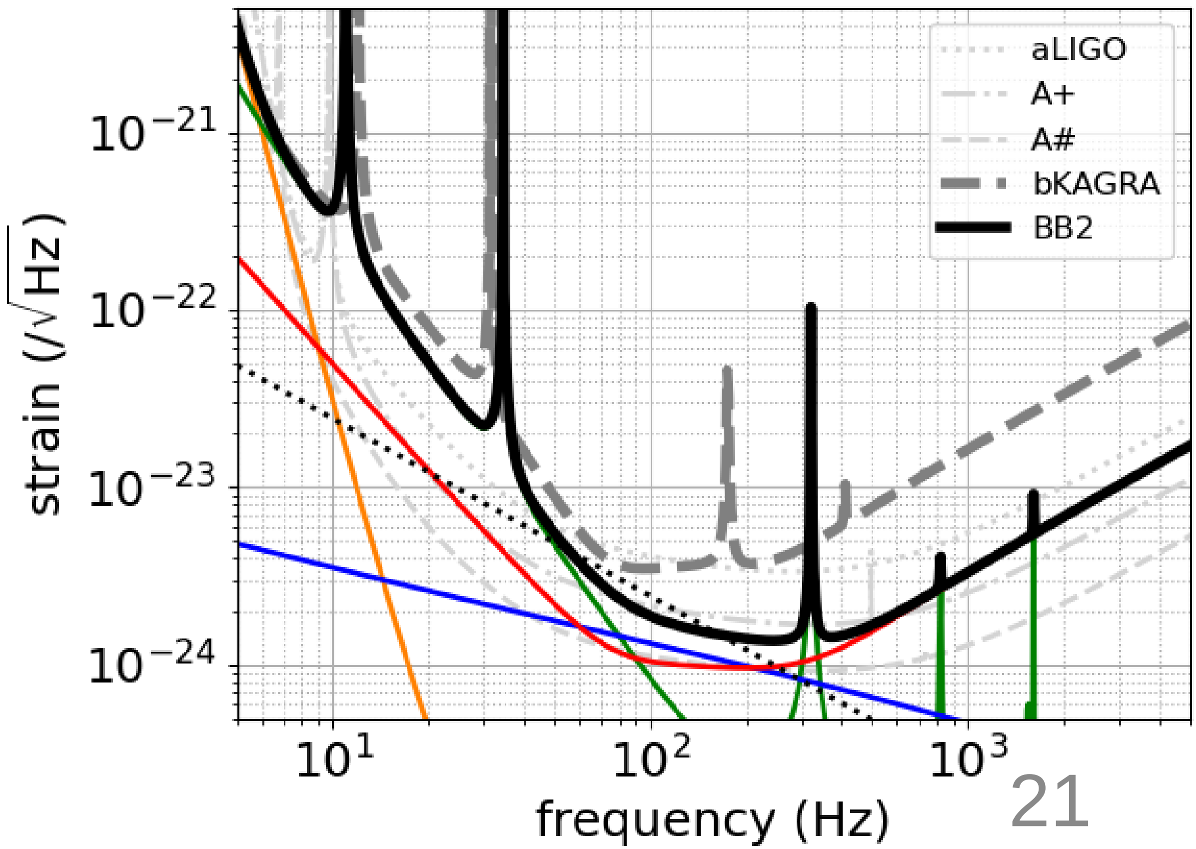
- **BB1**
- 40 kg TM + 85-m filter cavity (studied by KFC project) giving 5 dB detected squeezing





Possible Upgrade Plans

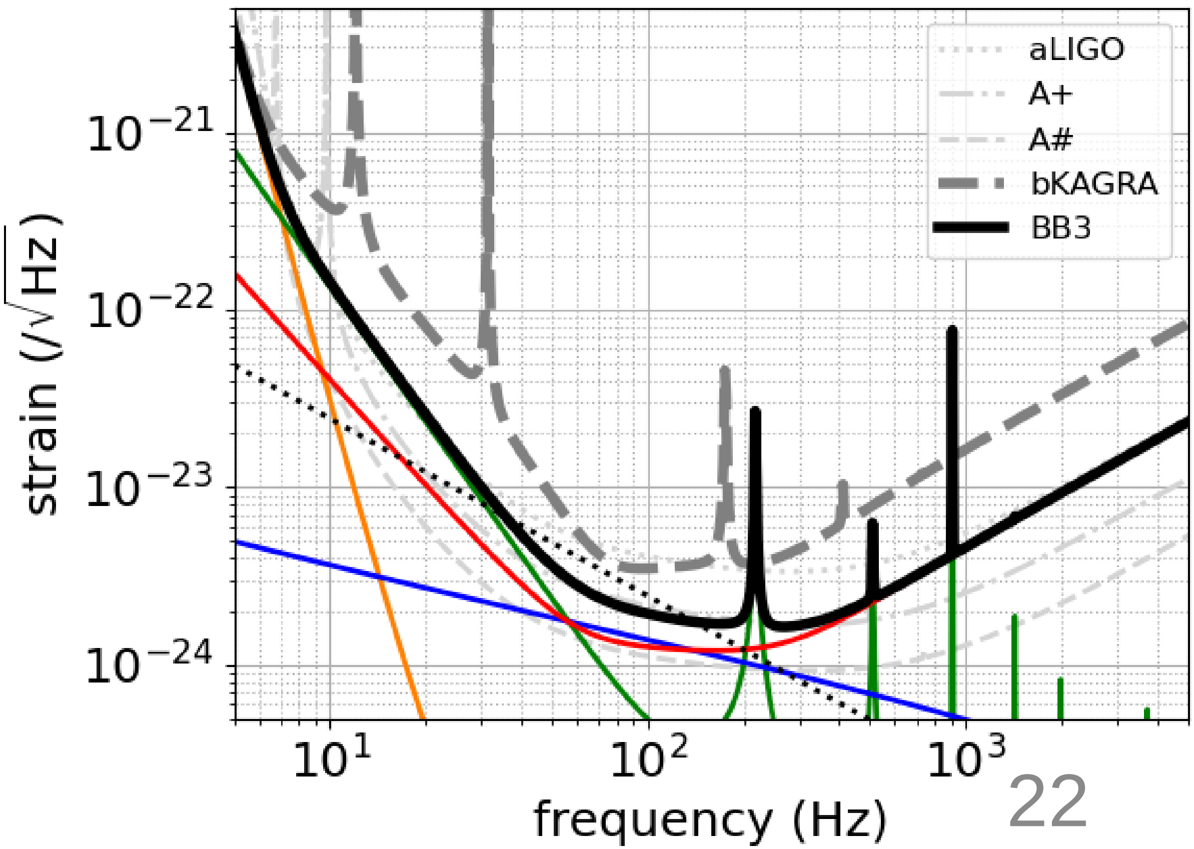
- **BB2**
- BB1 +
  9.1 dB detected squeezing (lower loss)



Possible Upgrade Plans

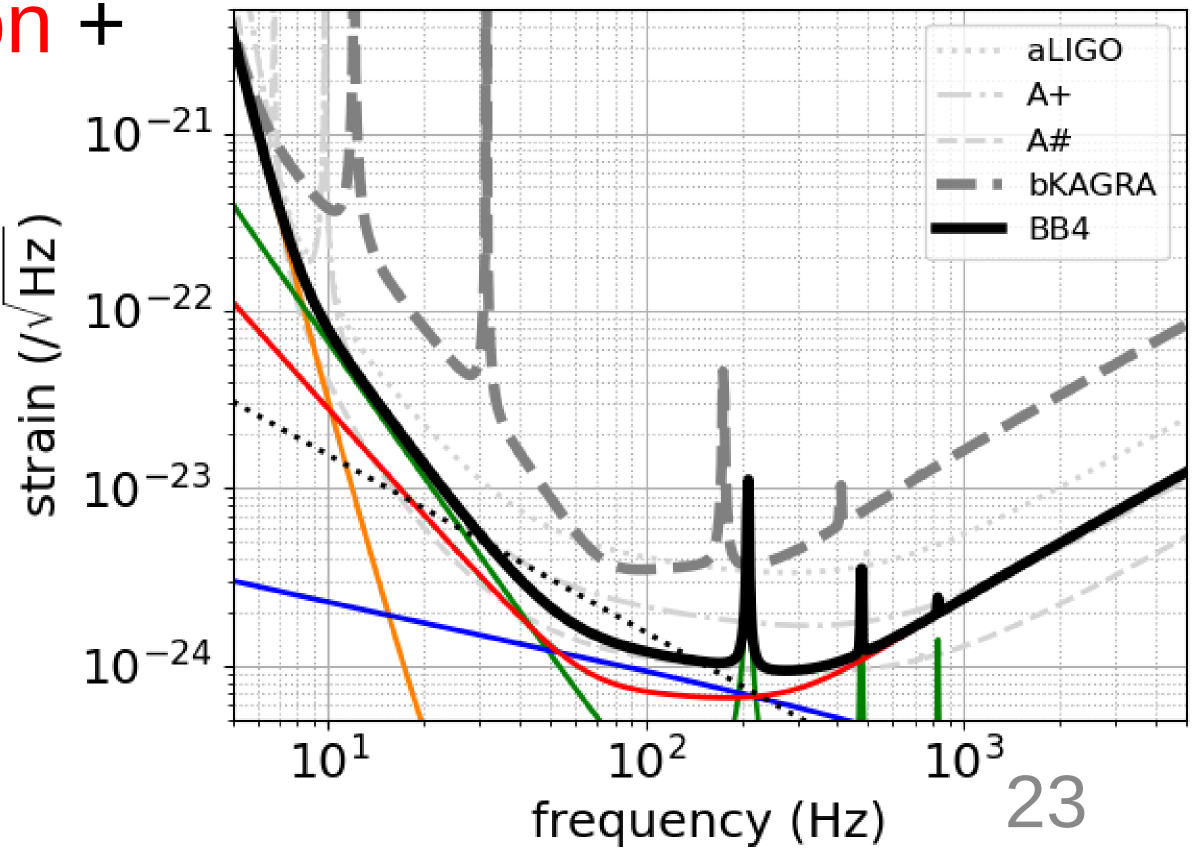
- **BB3**
- BB2 +
  LF2019 improvements + 5 Hz blade springs

- ~A+ at mid freq.



Possible Upgrade Plans

- **BB4**
- BB3 + 100 kg TM + x1/4 coating thermal noise + x1/4 absorption + 2.9 MW/2 in each arm



- ~A# at mid freq.

Lessons Learned

- Improvements in sapphire fibers and blade springs are crucial for LF improvements
- Improvements in sapphire mirrors and coatings are crucial for mid. frequencies
- Developments in lower loss optics, high power operations, and higher finesse arm cavities and SRC are crucial for HF improvements
- To compete with A#, HF would be most feasible
- Even with less sensitive BB plans, KAGRA's contributions to the network observation are important. Needs further study.

ChatGPT-4o

Recommendation

Low-Frequency Focus

KAGRA is uniquely positioned to specialize in the low-frequency range due to its underground location and quieter seismic environment. This would make KAGRA a vital player in the global network by filling a gap in low-frequency sensitivity. While technically challenging, breakthroughs here could offer transformational science, including earlier inspiral detection and new tests of general relativity.

High-Frequency as a Secondary Option

If low-frequency upgrades are deemed too challenging or resource-intensive, focusing on high-frequency sensitivity would still provide unique contributions, particularly for neutron star science and exotic physics.

Broadband as a Balanced Approach

If resources allow, broadband sensitivity remains a safe and productive option, aligning KAGRA closely with LIGO, Virgo, and future detectors, but risks reducing its uniqueness.

Ultimately, the decision should reflect KAGRA's **technical feasibility**, **budget**, and its **desired scientific role** within the global network.

Proposal to allow for long term experimental activities for KAGRA authorship

Current Authorship Policy

- Long-term activities may count up to 15% of research time in total. Long term activities are defined in the data analysis and theoretical subgroup's task lists.
- Why not include experimental R&Ds? JGW-M1503490-v7

The contributions are evaluated and judged both in quality and quantity.

✶ Quality: Contributions must be useful to the project. Contributions for research and development activities authorized by the project are also included.

✶ Quantity: Each author must spend for the KAGRA project an effort of at least 30% of his/her research time in the year preceding the update of the author list. Contributions to KAGRA shift works are counted twice in the effort calculation.

✶ Long-term activities may count up to 15% of research time in total. Long term activities are defined in the data analysis and theoretical subgroup's task lists.

✶ Outreach activities may count up to 10% of his/her research time.

Amendment Proposal

- Long-term activities may count up to 15% of research time in total. Long term activities are defined in the data analysis and theoretical subgroup's task lists.

Proposed amendment

- Long-term activities may count up to 15% of research time in total. Long term activities are defined in the data analysis, theoretical subgroup, and instrumental science task lists.

Summary Table for Authorship

Activity		Management	White Paper	Time frame	Author-ship
Data analysis / Theory		KSC-DAC/ Theory Group	**LVK** Observational Science WP	Short Term	<= 100%
				Long Term	<= 15% in total
Experiment	Project task	EO-SEO/ Operations	**LVK** Operations WP	Short Term	<= 100%
	Project R&D	KSC-FSC-PRDC	**KAGRA Instrument Science WP**	Short Term	<= 100%
	Advanced R&D	KSC-FSC		Long Term	<= 0% → **<= 15%**
EPO		KSC-EPO	**LVK** Communications and Education WP	-	<= 10%

Note that current KAGRA Instrument Science WP does not include tasks under SEO. Instrument Science WPs for LIGO, Virgo, KAGRA are independent right now.

Summary

- KAGRA Instrument Science White Paper 2024 is released
- Any comments welcomed
- Welcome to join FSC or FWG

- FWG 4th open meeting on December 19 @ Ookayama