

Summary of Past Discussions on KAGRA Upgrade

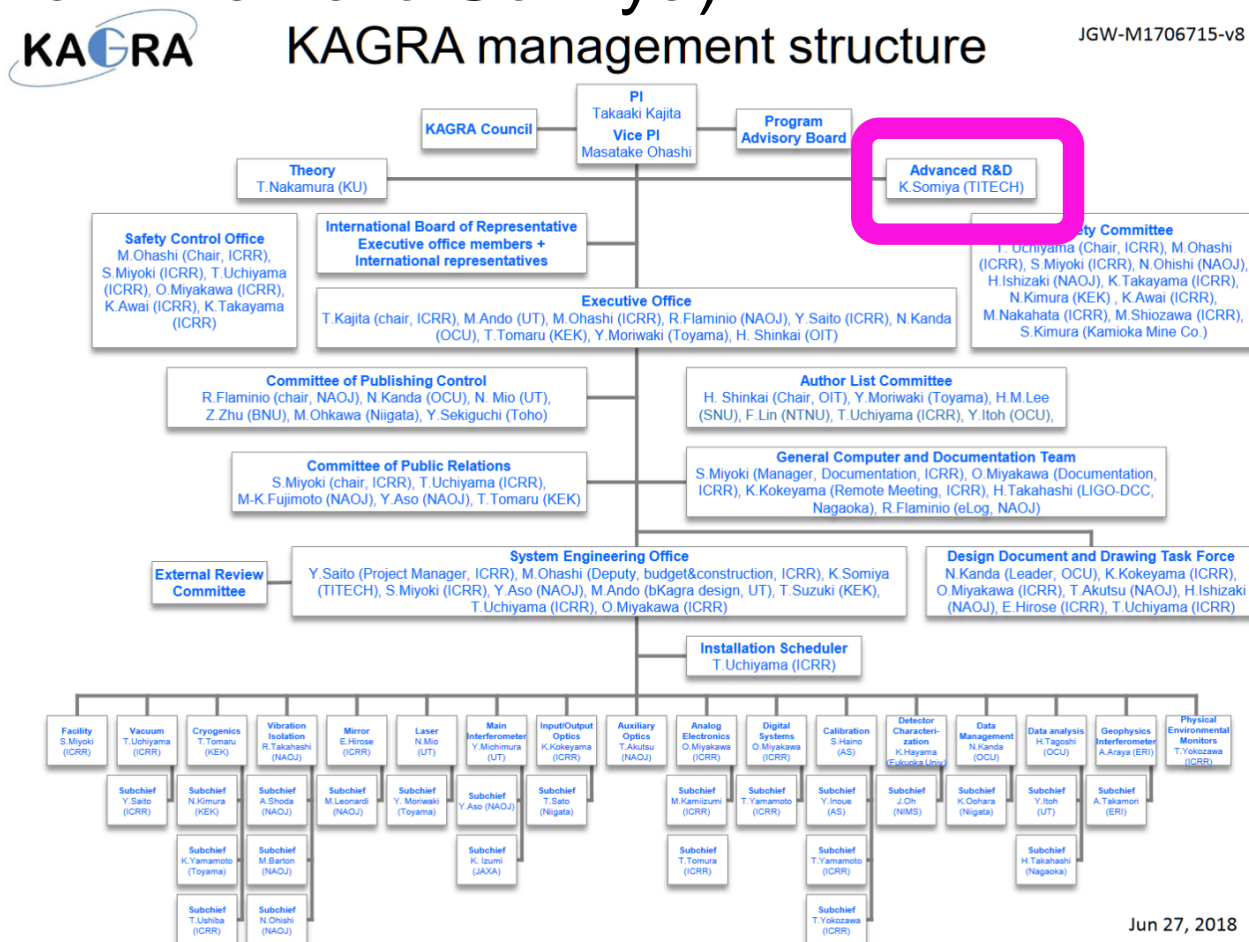
Yuta Michimura

Department of Physics, University of Tokyo

on behalf of the Advanced R&D Group

KAGRA Upgrade Discussions

- Semi-officially started from F2F March 2017
- Mainly lead by Advanced R&D group
(Chair: Kentaro Somiya)

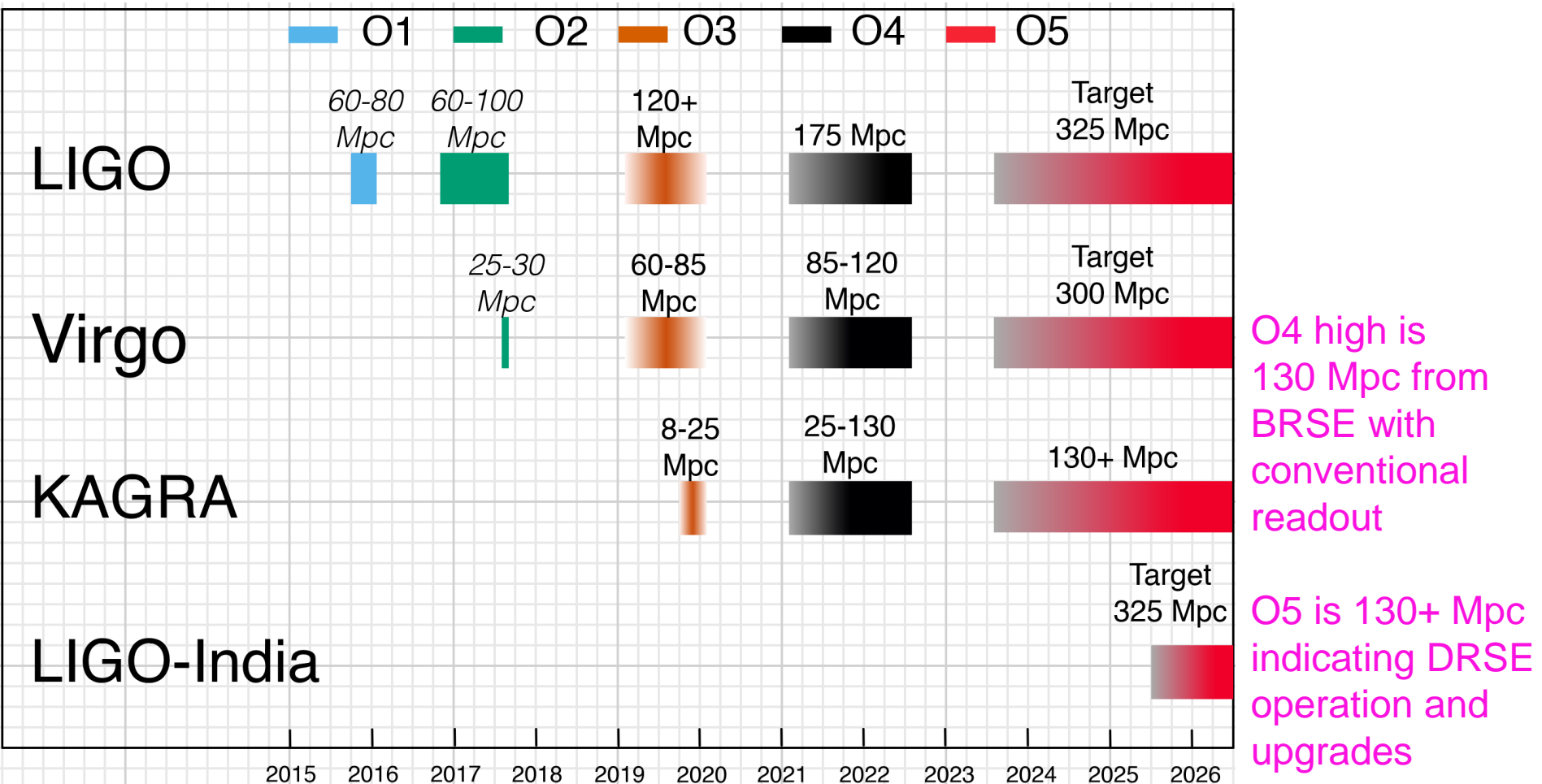


Contents

- LVK Observation Scenario
- History of KAGRA Upgrade Discussions
 - Recap of bKAGRA sensitivity
 - 3 sensitivity curves to start with
 - Science case study
 - Technical feasibility study
 - More realistic plans with budget estimate
 - Summary and suggestion from past studies
- Next Step
- Summary

LVK Observation Scenario

- Possible KAGRA upgrade between O4 and O5

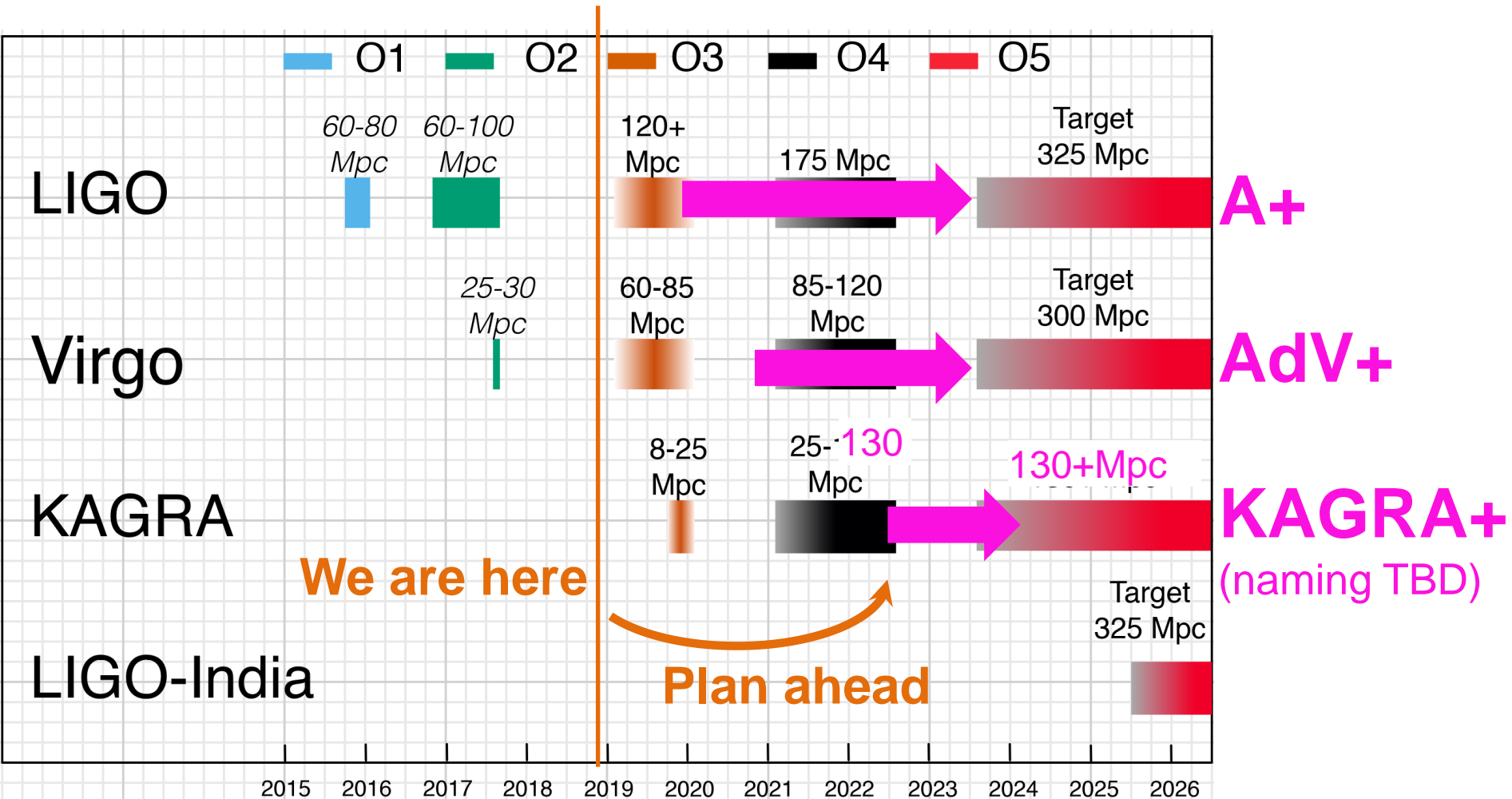


Modified from preliminary timeline from JRPC report 20180913

Approved by EO on Oct 17, 2018 ([JGW-T1809078](#))

LVK Observation Scenario

- Possible KAGRA upgrade between O4 and O5



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- March 2017 F2F @ Niigata U
Proposal to start integrated upgrade study
Call for upgrade plans
- May 2017 KIW3 @ Academia Sinica
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Upgrading KAGRA is Tricky

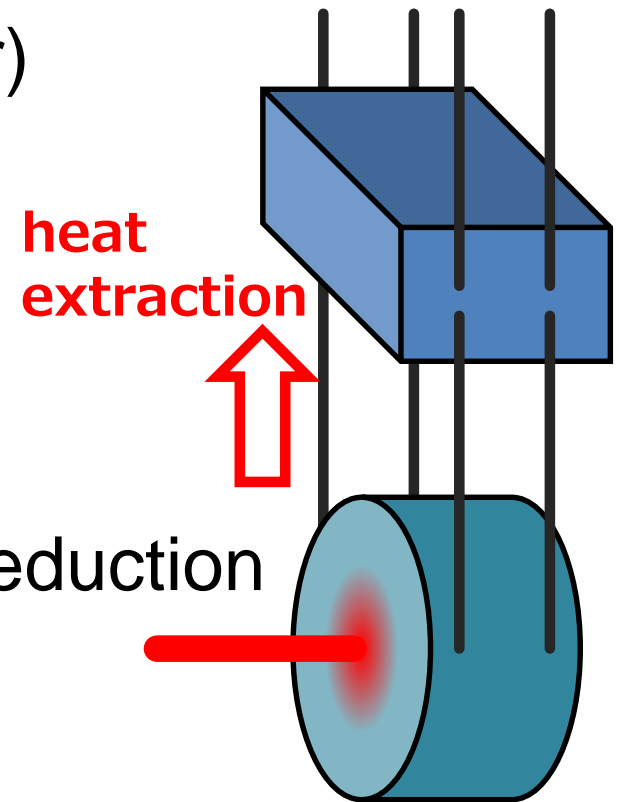
- Only **cryogenic** interferometer among 2G
- Not trivial to do both
 - high power (**400 kW** on mirror)
 - low temperature (**20 K**)

- Sapphire fibers to extract heat
thinner and longer
for suspension thermal noise reduction



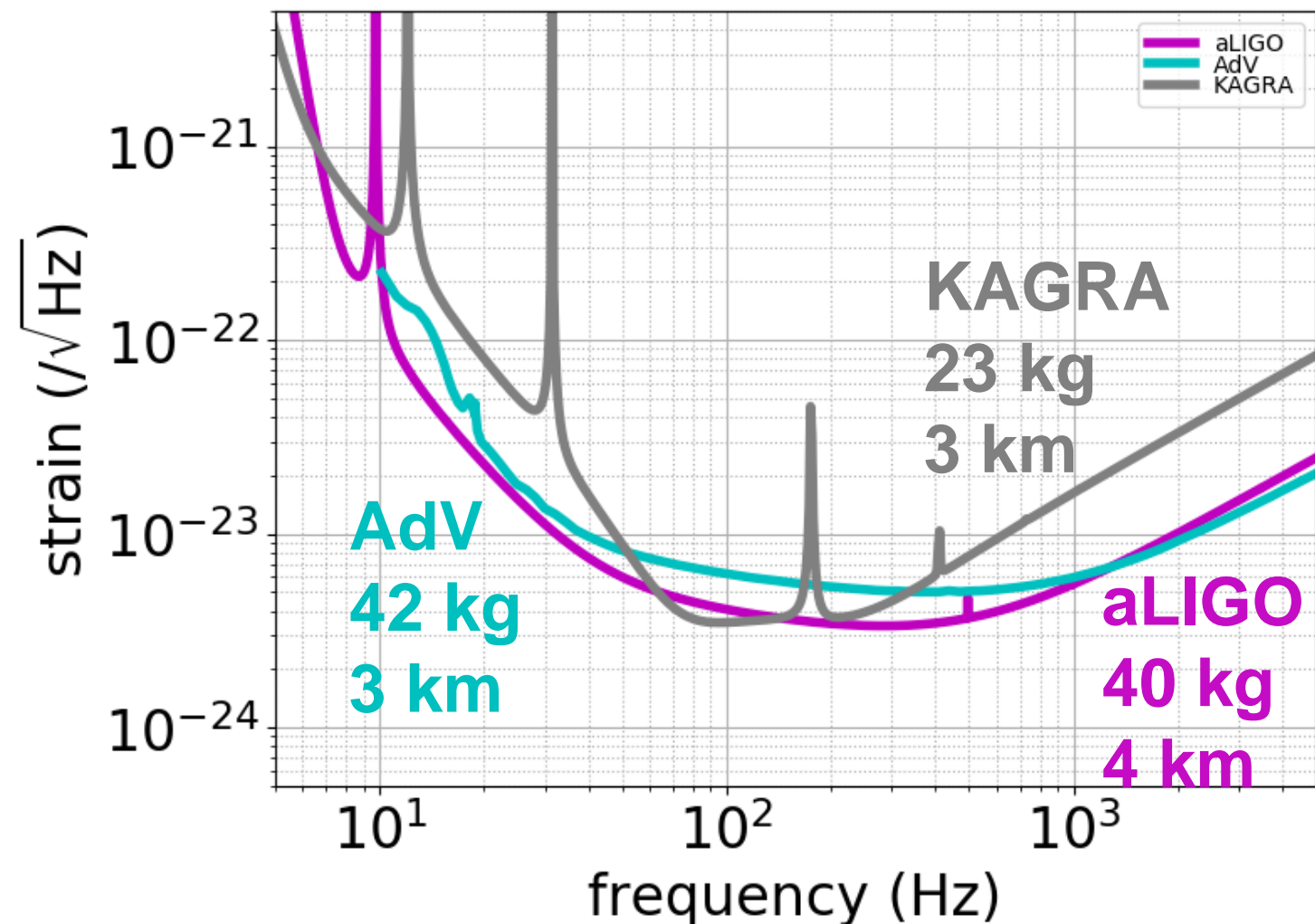
Dilemma

thicker and shorter
for heat extraction

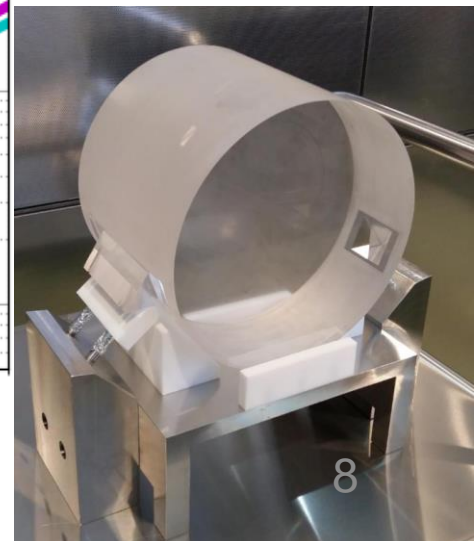


2G Sensitivity Comparison

- Not good at low freq. because of **thick and short** fiber (35 cm, $\phi 1.6$ mm) to extract heat, and **lower mass**

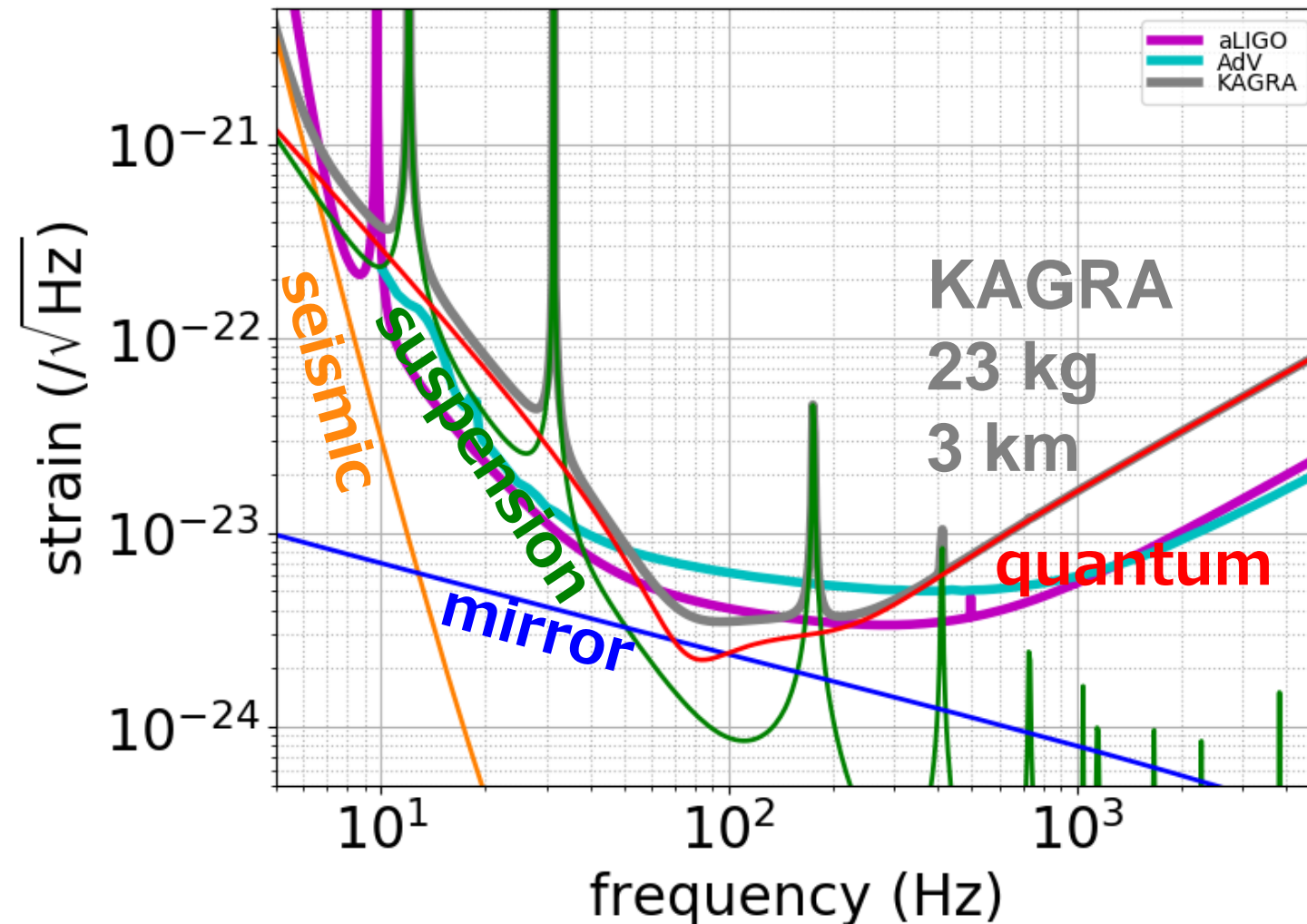


23 kg was the largest available sapphire mirror

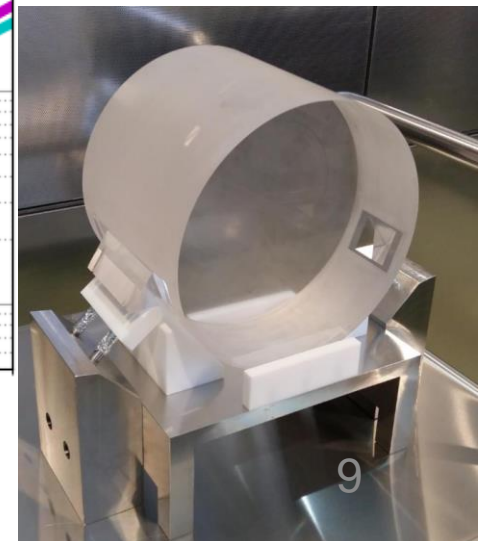


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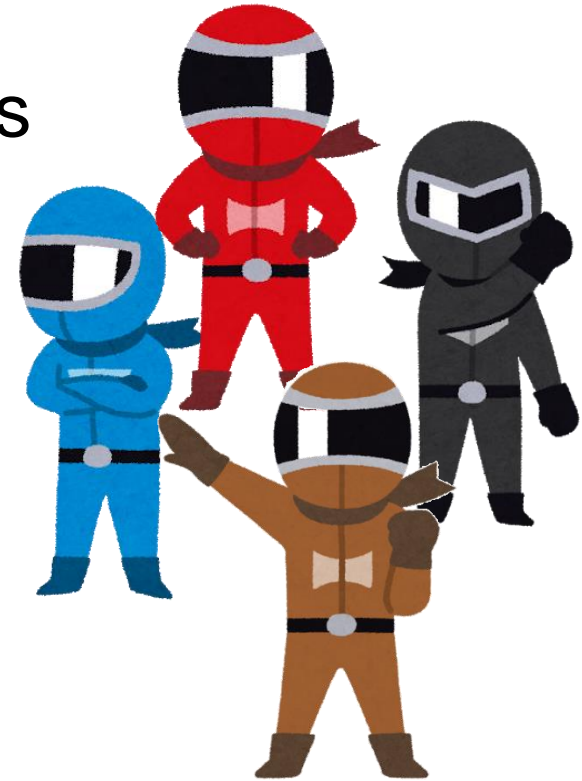


History of KAGRA+ Discussion

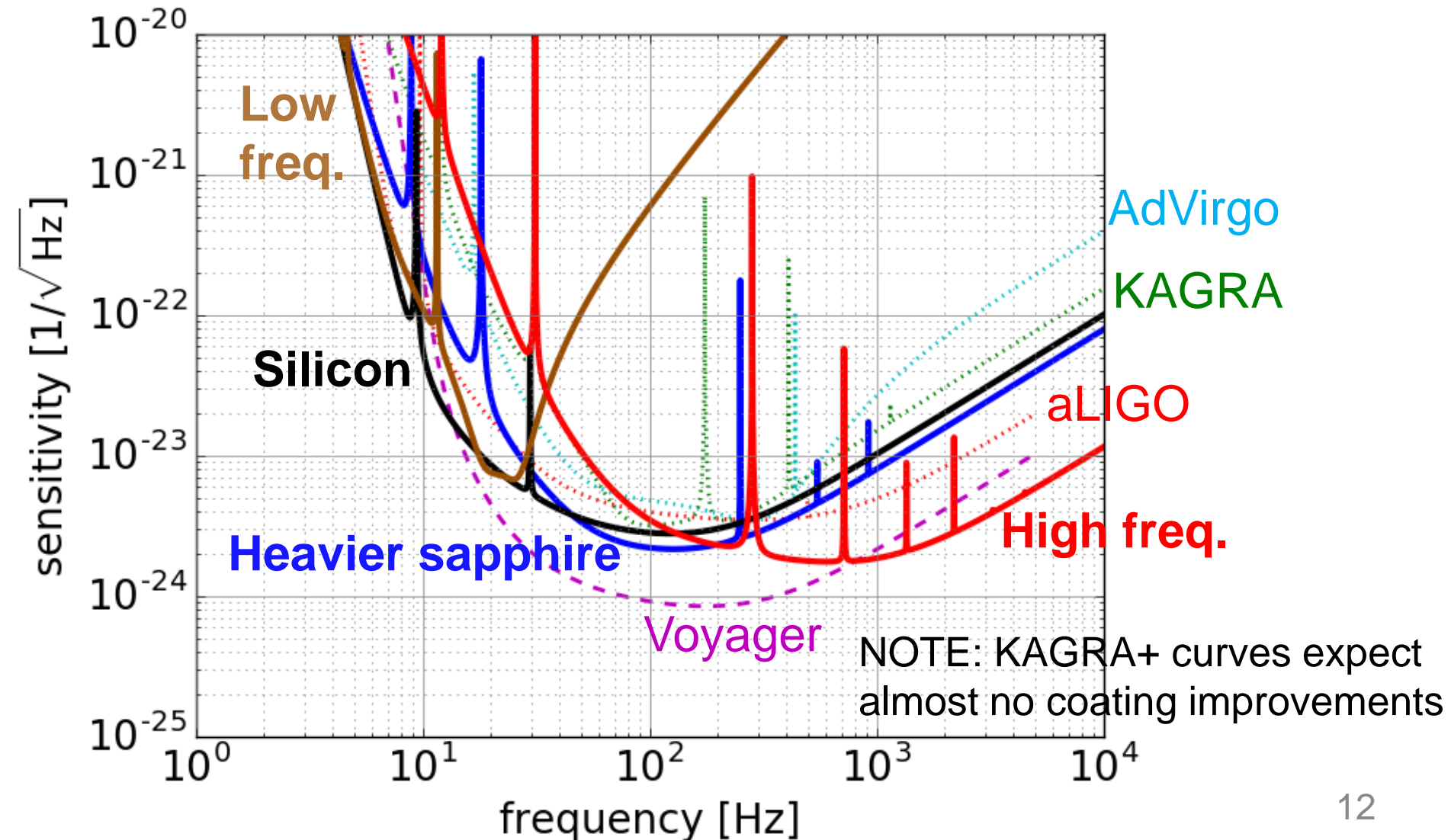
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Four Proposals

- Example sensitivity curves were necessary to start science case study
- Plans technically not too ambitious
- Plan: **Blue** (by Yutaro Enomoto)
use heavier sapphire mirrors
- Plan: **Black** (by Kentaro Komori)
use silicon mirrors
- Plan: **Brown** (by Koji Nagano)
lower the power to focus on low frequency
- Plan: **Red** (by Sadakazu Haino)
increase the power to focus on high frequency¹¹



Sensitivity of Four Proposals

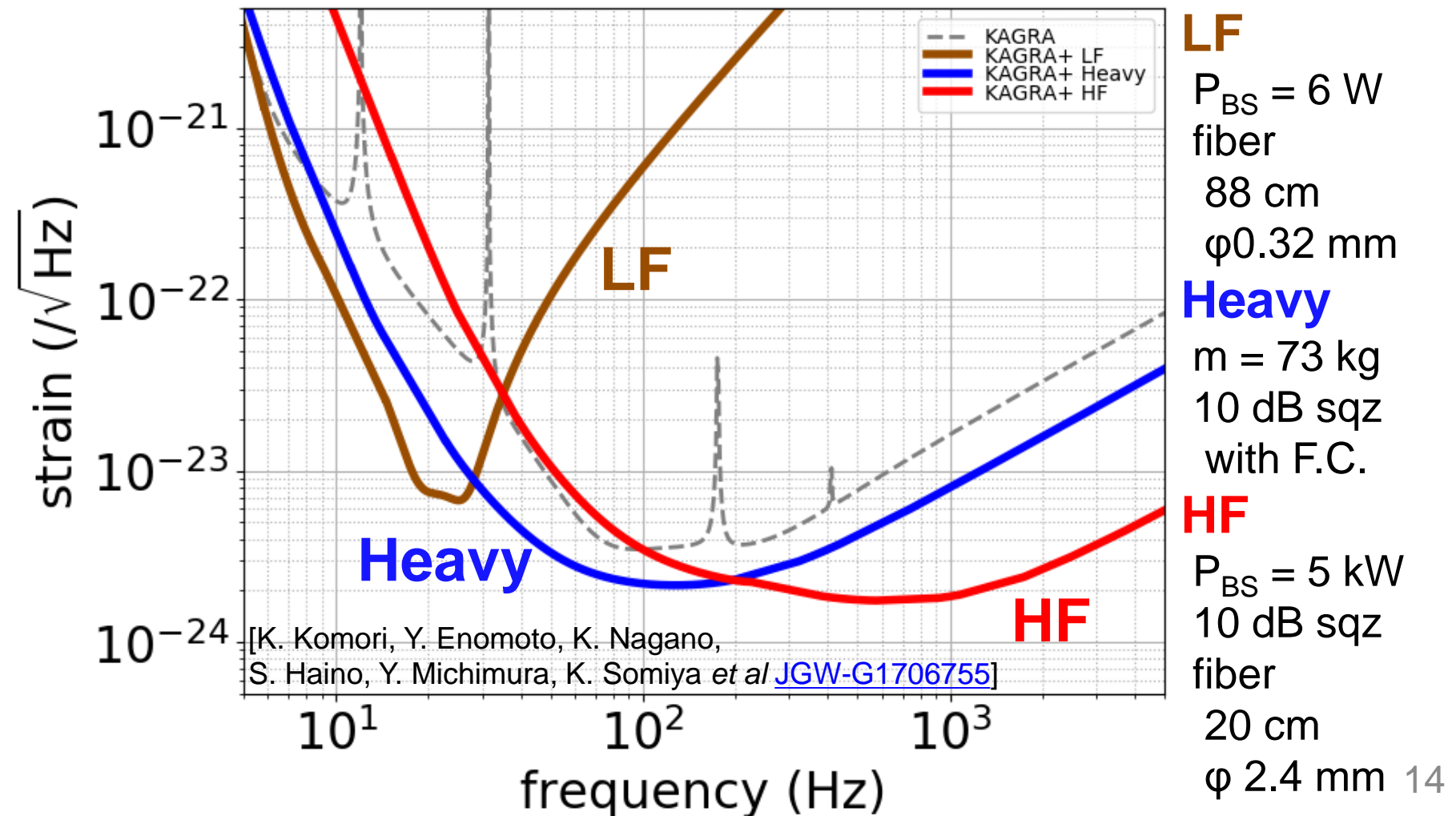


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3 Concepts for Science Case Study

- Sensitivity curves were smoothened, silicon plan was down selected (similar curve with Heavy)



Inputs from Theorists

- Inputs from theorists from various fields
 - QNM from BH merger (by Hiroyuki Nakano)
 - IMBH event rate (by Hisaaki Shinkai)
 - BBH from POP-III (by Tomoya Kinugawa)
 - BBH host galaxy (by Atsushi Nishizawa)
 - Pulsar ellipticity (by Yousuke Itoh)
 - NS equation of state (by Masaru Shibata)
 - Bursts (by Kazuhiro Hayama)
 - Test of GR with inspiral (by Takahiro Tanaka)
 - IMRI (by Norichika Sago)



Summary of Science Case Study

- Although **LF** has the best inspiral range for heavy BBH ($\sim 100M_{\text{sun}}$), narrow band was **not favorable**

	bKAGRA	LF	Heavy	HF
test of GR with BH ringdown	×	×	△	○
existence of IMBH from hierarchical growth	△	△	○	△
existence of stellar-mass BBH from popIII	×	×	×	×
sky localization for BBH (identifying host galaxy)	△	×	○	○
pulsar ellipticity	×	×	△	○
NS equation of state	×	×	△	○

[Based on inputs from K. Hayama, Y. Itoh, T. Kinugawa, H. Nakano, A. Nishizawa, N. Sago, M. Shibata, H. Shinkai, T. Tanaka, *et al* [JGW-G1707125](#)]

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Technical Feasibility Study

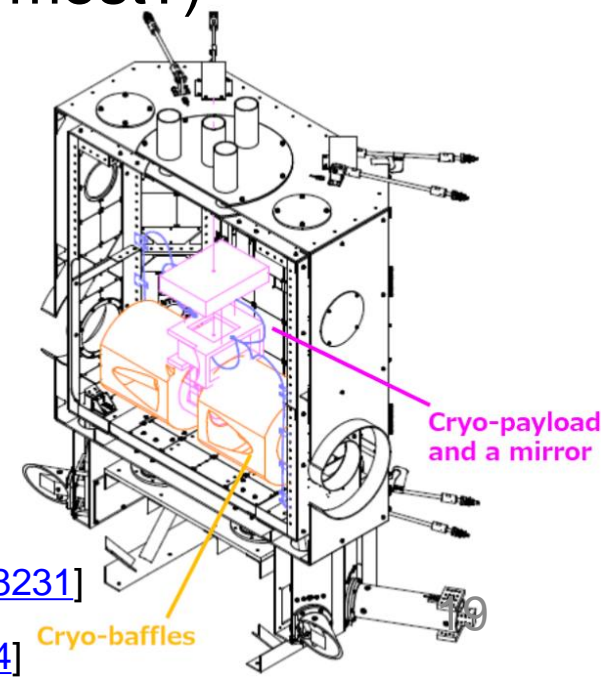
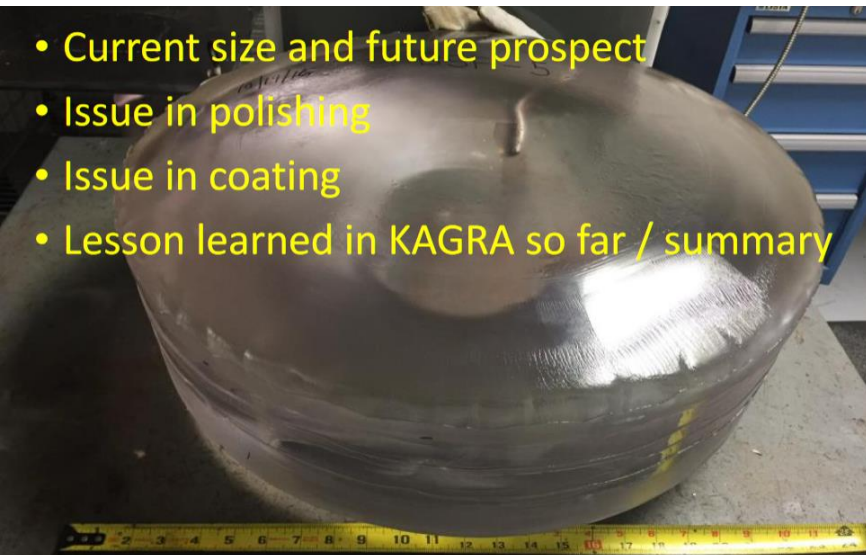
- Dec 2017 F2F Satellite Meeting
- Focused on technical feasibility for **HF** and **Heavy**
- Talks on
 - High power laser (by Li-Wei Wei)
 - Squeezing and filter cavity (by Matteo Leonardi)
 - Bigger sapphire (by Eiichi Hirose)
 - Composite mirror (by Satoshi Tanioka)
 - Heavier mirror for LF
(by Koji Nagano)



Feasibility Study: Heavier Mirror

- Larger sapphire bulk available, but requires R&D for polishing and coating, needs time and money
 - ϕ 55 cm x t 30 cm (~280 kg) mirror would be possible in the future
 - Current one (ϕ 22 cm x t 15 cm, 23 kg) more than 1 year to polish, \$0.6M / mirror
 - Current cryostat is quite full (40 kg at most?)

- Current size and future prospect
- Issue in polishing
- Issue in coating
- Lesson learned in KAGRA so far / summary

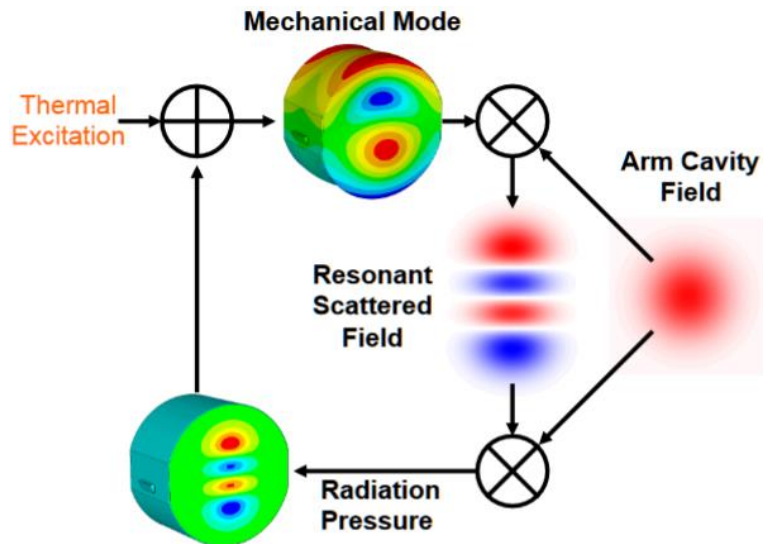


[K. Somiya, [JGW-G1808231](#)]

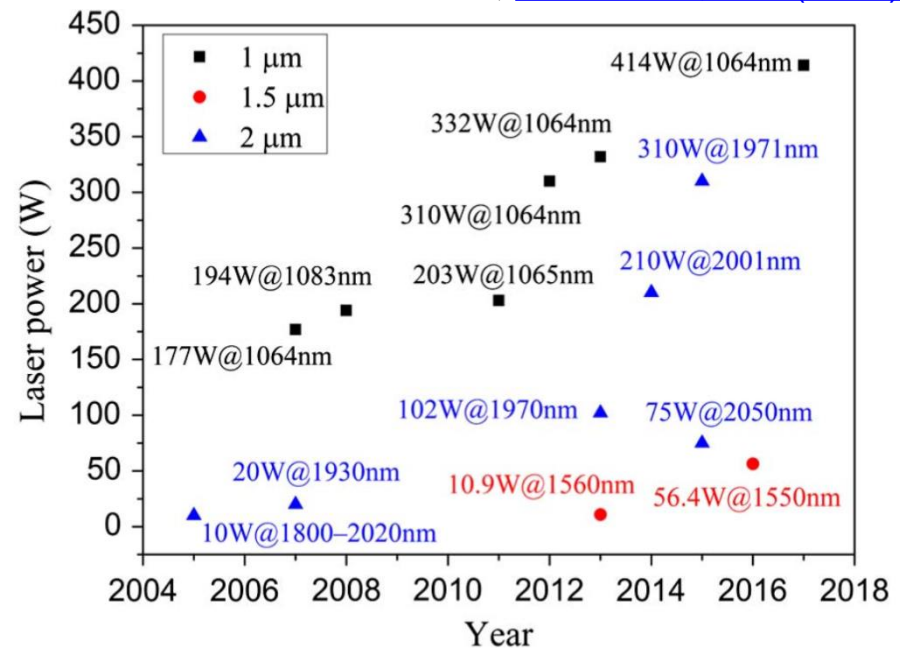
[E. Hirose [JGW-G1707484](#)]

Feasibility Study: High Power

- Higher power laser source at 400 W would be available, but operation is tough
 - thermal compensation
 - parametric instability
 - radiation pressure induced instability etc...
- Could be OK with cryogenic sapphire?



S. Fu *et al*, [JOSA B 34, A49 \(2017\)](#)

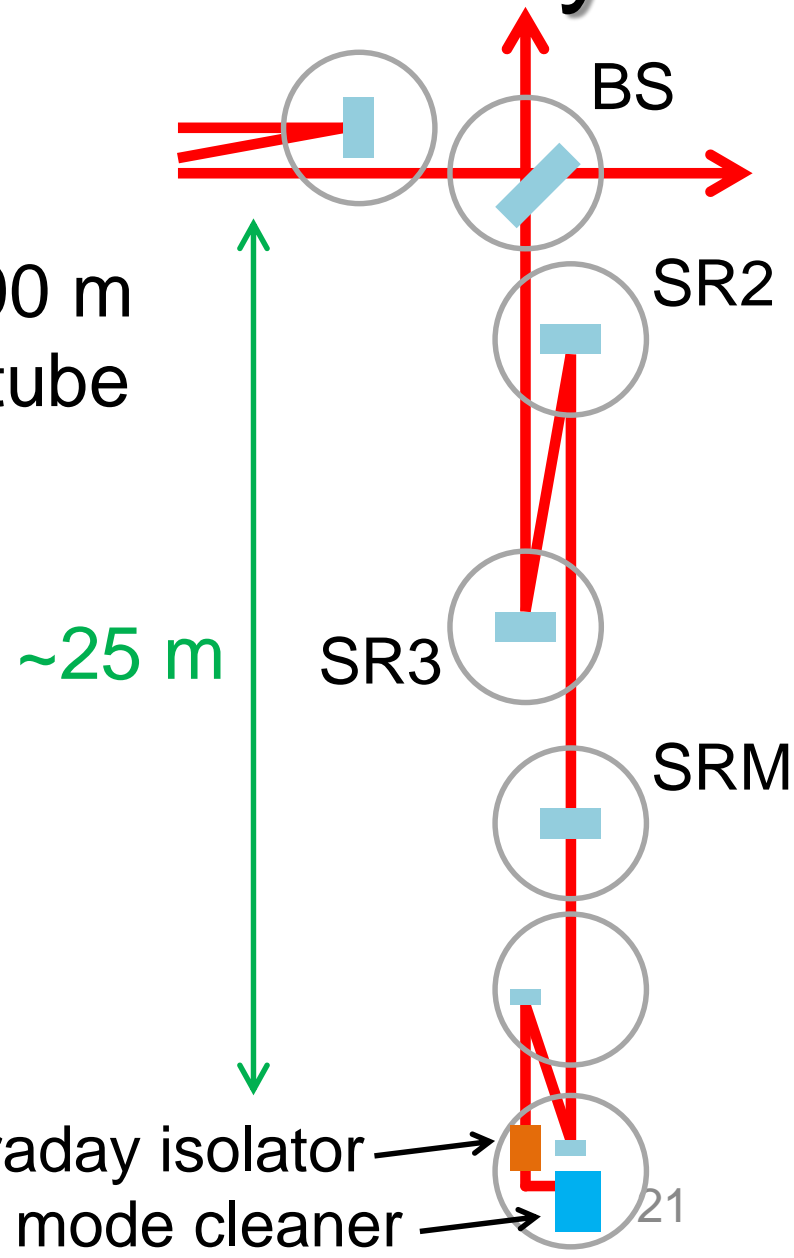
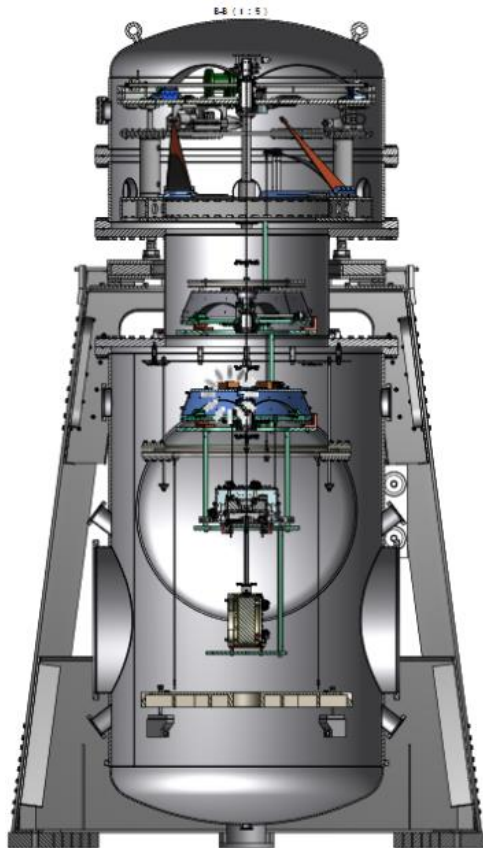


M. Evans *et al*, [PRL 114, 161102 \(2016\)](#)

Fig. 7. Output power evolution of CW single-frequency amplifiers in all-fiber format operating in 1, 1.5, and 2 μm regions.

Feasibility Study: Filter Cavity

- One core optic per tank, not very crowded
- ~30 m could be OK, but >100 m would require new vacuum tube



Summary of Feasibility Study

- For near term upgrade (~5 years)
 - 40kg mirror at most
 - requires time and money
 - 400 W laser
 - study on PI damping necessary
 - ~100m filter cavity
 - technically feasible
 - more study on optical layout necessary
- For longer term upgrade (~10 years)
 - >100kg mirror ?
 - combination of all of them with larger budget

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Rough Estimate on Costs

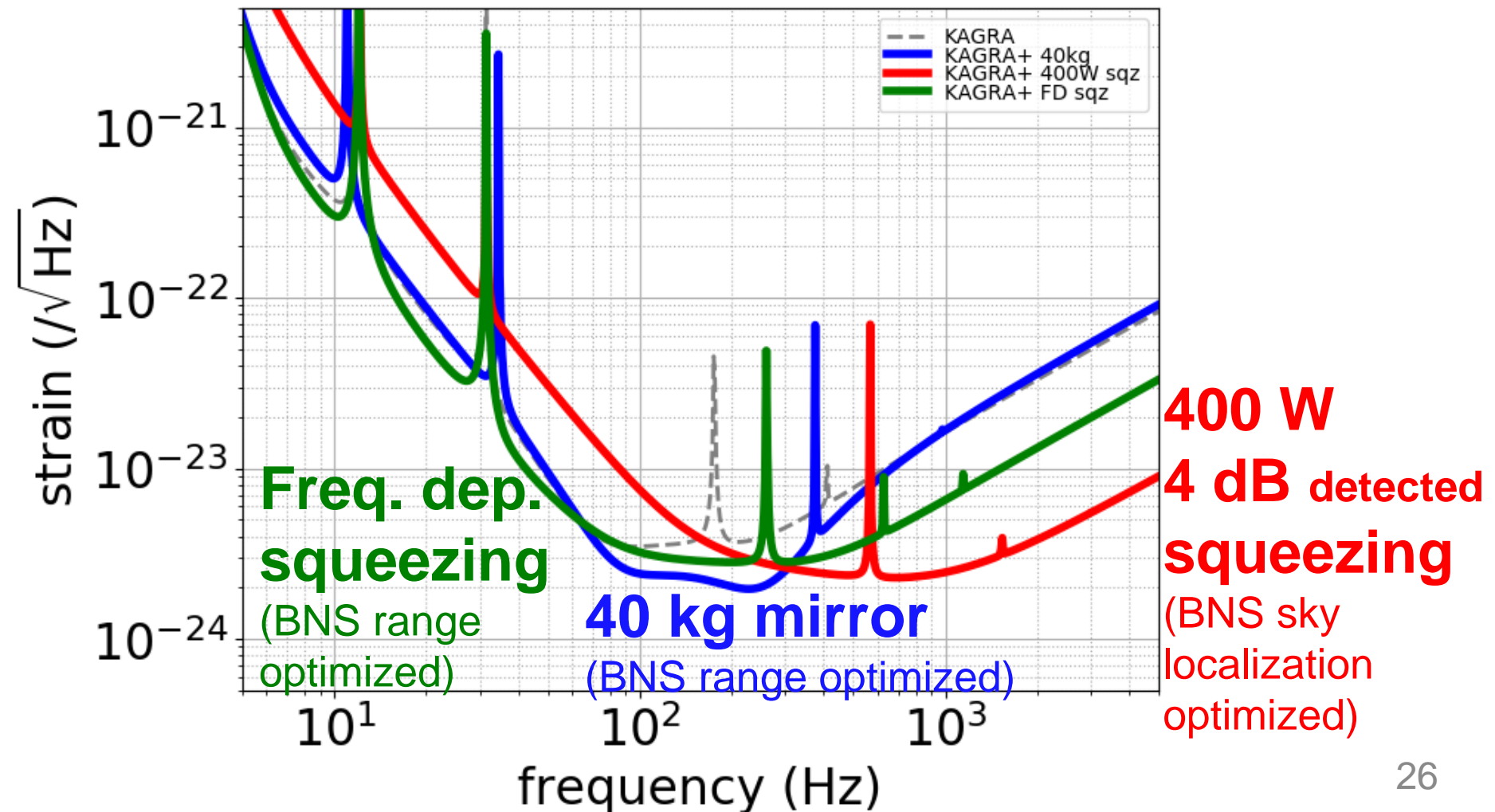
- Based on bKAGRA budget, by Kentaro Somiya
- New sapphire mirrors: \$3M
- Sapphire fiber replacement: \$1M
- Cryopayload replacement: \$4M
- Type-A tower replacement: \$2M
- Frequency independent squeezing: \$1M
- Frequency dependent squeezing: \$3M
- 400 W laser and high power input optics: \$3M
- Recycling mirror replacement (for larger beam): \$1M
- SRM replacement: \$0.1M

Possible Near Term Plans

- ASSUMING budget constraint of
~\$5M, within ~5 years (as a rough idea)
- Candidates would be
 - A. 40 kg mirror with better coating (>\$4M?)
and new sapphire fibers (\$1M?)
(use existing cryostat and Type-A tower)
 - B. 400 W laser (\$3M?) with squeezing (\$1M?)
and new sapphire fibers (\$1M?)
 - C. Frequency dependent squeezing (\$3M?)
and new sapphire fibers (\$1M?)
- Sensitivity optimization with particle swarm
Y. Michimura et al, [Phys. Rev. D 97, 122003 \(2018\)](#)

Sensitivity of Near Term Candidates

- ASSUMING budget constraint of
~\$5M, within ~5 years (as a rough idea)



Summary of Near Term Candidates

- **A.** New mirror takes time to fabricate
- **B.** High power operation is tough
- **C.** Does 100m F.C. fit in the facility?



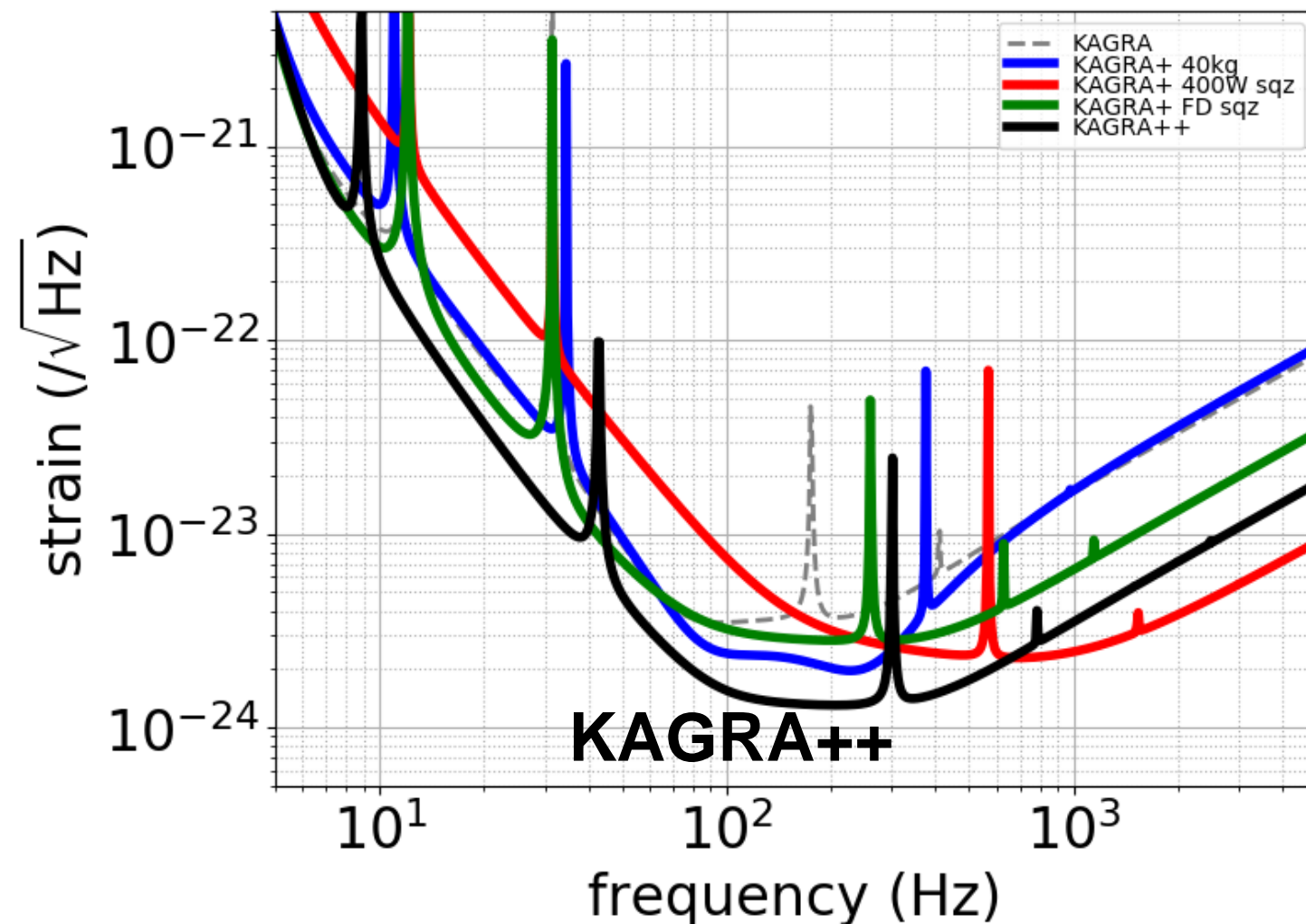
	Inspiral range (Mpc)			BNS localize (deg ²)
	BBH100	BBH30	BNS	
bKAGRA	353	1095	153	0.183
A. 40 kg mirror	339	1096	213	0.151
B. 400 W laser sqz	117	314	123	0.114
C. Freq. dep. sqz	470	1177	181	0.135

GW170817-like binary, median of
sky locations, polarization angle



Longer Term Candidate

- 100 kg mirror with 1/2 coating thermal, 320 W input, 10 dB input squeezing with 100 m filter cavity

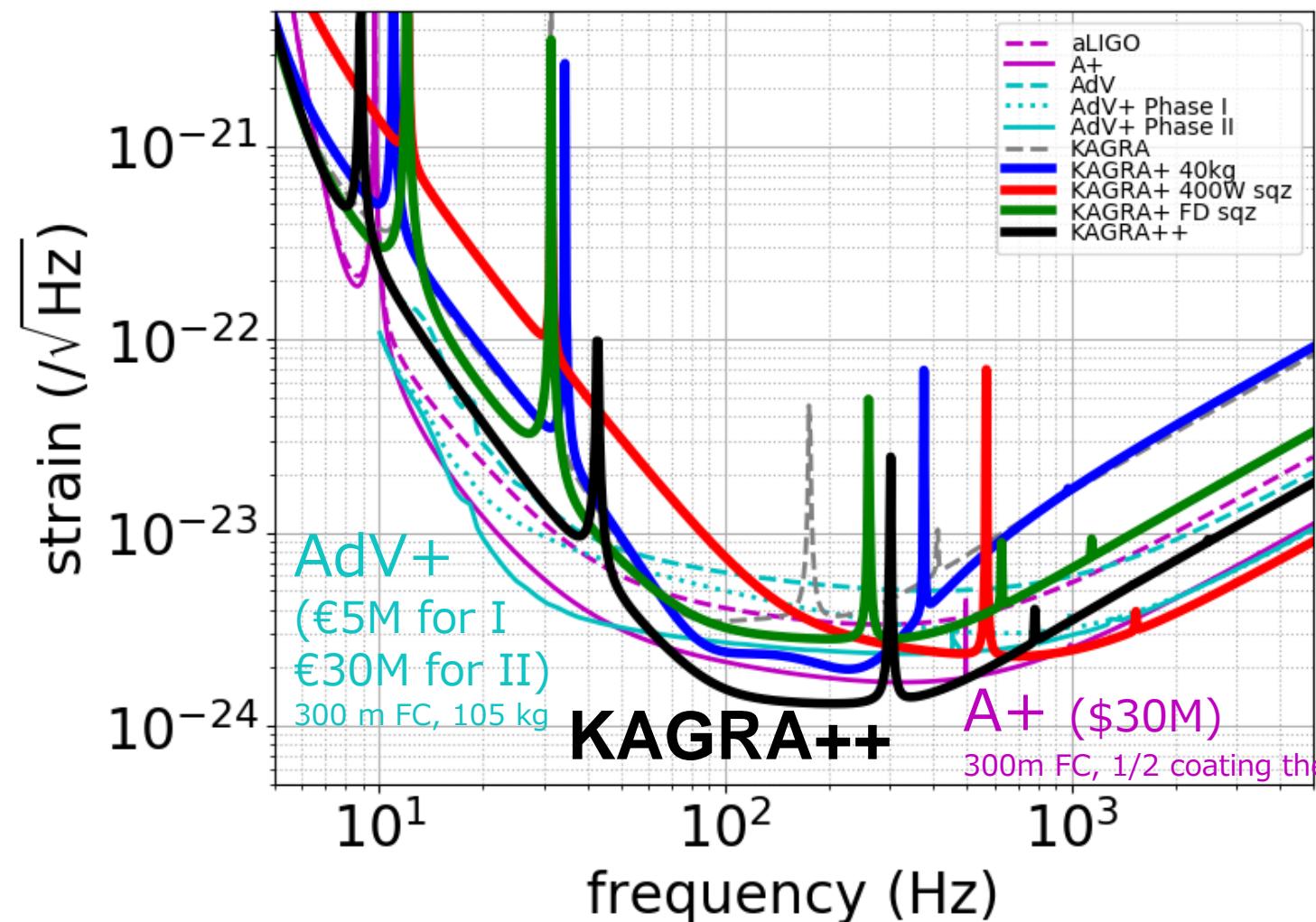


BNS range
reaches
355 Mpc

Within
~ 10 years
~ \$20M?

Comparison between 2G and 2G+

- **A+**: 325 Mpc
- **AdV+ Phase I**: 160 Mpc, **Phase II**: 300 Mpc



aLIGO curve from
[LIGO-T1800044](https://ligo-t1800044)
(updated ver)

A+ curve from
[LIGO-T1800042](https://ligo-t1800042)

AdV and AdV+ curves
from
[VIR-0325B-18](https://vir-0325b-18)

KAGRA curve from
[JGW-T1707038](https://jgw-t1707038)



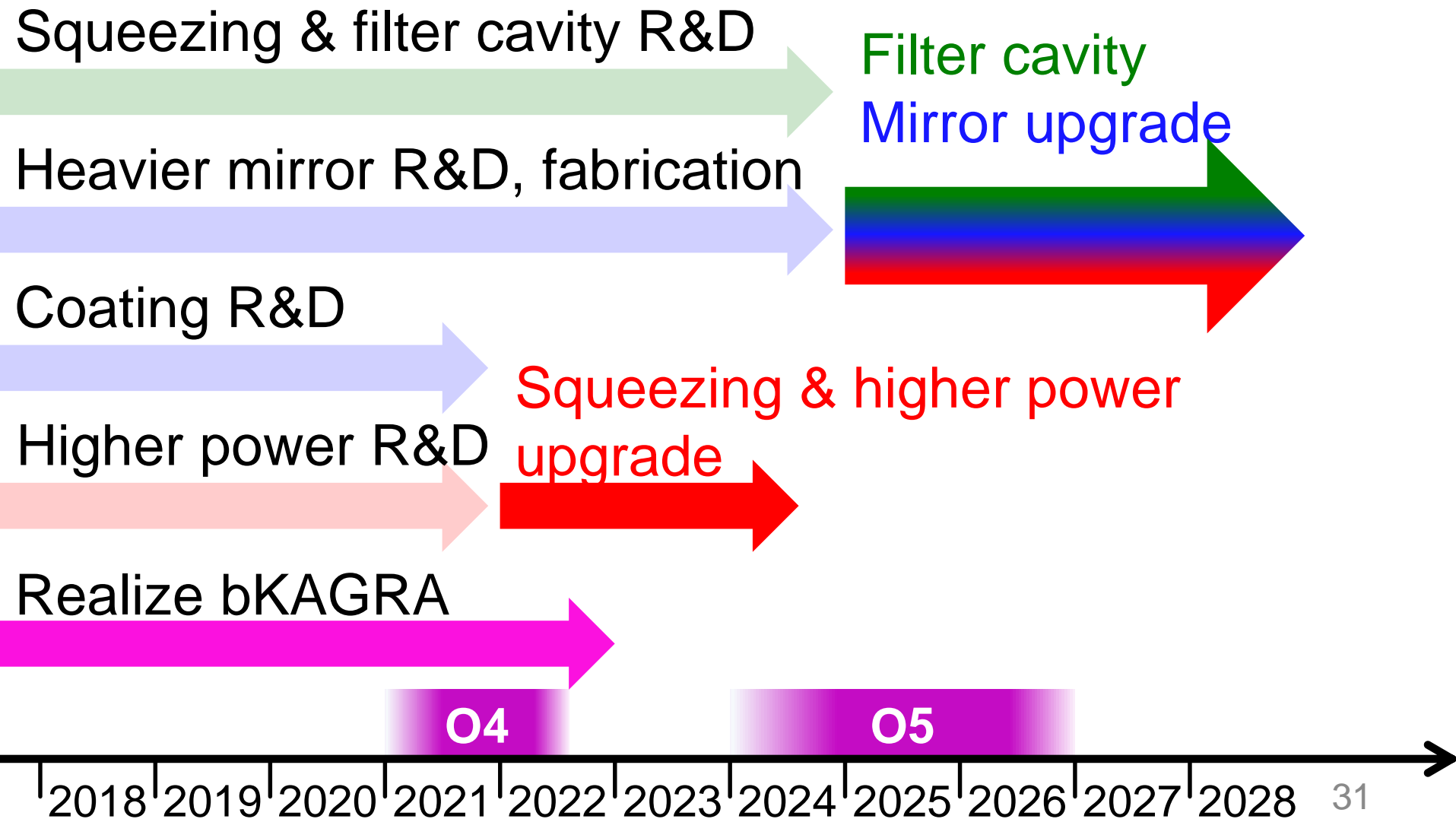
Summary of Past Studies

- **LF** seems technically unfeasible, **HF** has a potential to beat A+ with modest cost, **broadband improvement** would be the most steady upgrade

	LF	HF	Broadband
Cost to beat A+ (very rough idea)	~\$20M?, ~10years? 😐	possibility ~\$5M?, ~5years? 😊	~\$20M?, ~10years? 😐
Feasibility	Narrow band is tough 😞	High power is tough 😞	High 😊
Unique science	Possibility to detect 100Msun BH (x3 than A+) 😊	NS physics (SNR x1.3 than A+) 😊	Contribute to statistics 😐

Suggested Upgrade Strategy

from Advanced R&D group



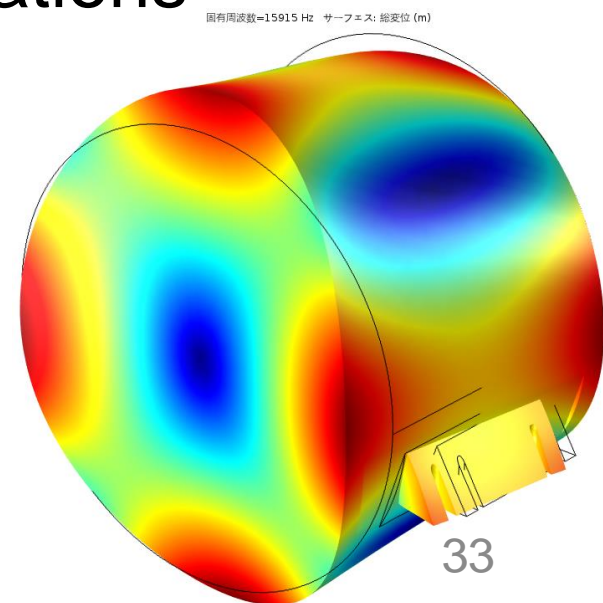
What's Next?

- Collaboration-wide agreement on upgrade plan
 - thorough explanation to collaboration
- Even more realistic and feasible plan
 - including budget, manpower, schedule
 - how to get the budget?
- Task assignment to people/institutes
Work Breakdown Structure
- Integrated R&D (Project R&D)



Research Topics

- Larger mirror
- Better coating at cryogenic temperature
- Better cryopayload for larger mirror
- Parametric instability mitigation
- Squeezer and filter cavity designed for KAGRA
- Filter cavity infrastructure investigations
- Higher power laser
- Newtonian noise mitigation



Summary

- We have been sneakily but steadily studying KAGRA upgrade from F2F March 2017
- Studies on science case, technical feasibility, budget estimate were roughly done
 - various inputs from theorists and R&D experimentalists
- Our suggestion (NOT CONCLUSION)
 - Near term: Squeezing and/or higher power laser
 - Longer term: Filter cavity and heavier mirror
- Now time to make the plan even more realistic and feasible, to get things started

Supplementary Slides

2G/2G+ Parameter Comparison

	KAGRA	AdVirgo	aLIGO	A+	Voyager
Arm length [km]	3	3	4	4	4
Mirror mass [kg]	23	42	40	80	200
Mirror material	Sapphire	Silica	Silica	Silica	Silicon
Mirror temp [K]	22	295	295	295	123
Sus fiber	35cm Sap.	70cm SiO ₂	60cm SiO ₂	60cm SiO ₂	60cm Si
Fiber type	Fiber	Fiber	Fiber	Fiber	Ribbon
Input power [W]	67	125	125	125	140
Arm power [kW]	340	700	710	1150	3000
Wavelength [nm]	1064	1064	1064	1064	2000
Beam size [cm]	3.5 / 3.5	4.9 / 5.8	5.5 / 6.2	5.5 / 6.2	5.8 / 6.2
SQZ factor	0	0	0	6	8
F. C. length [m]	none	none	none	16	300

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
- **Inspirial range calculation**
 - SNR=8, $f_{min}=10$ Hz, sky average constant 0.442478
- Seismic noise curve includes vertical coupling, vibration from heatlinks and Newtonian noise from surface and bulk

KAGRA Cryopayload

Provided by T. Ushiba and T. Miyamoto

Platform
(SUS, 65 kg)

Marionette
(SUS, 22.5 kg)

Intermediate Mass
(SUS, 20.1 kg,
16 K)

Test Mass
(Sapphire, 23 kg,
22 K)

3 CuBe blade springs

MN suspended by 1 Maraging steel fiber
(35 cm long, 2-7mm dia.)

MRM suspended by 3 CuBe fibers

Heat link attached to MN

IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)

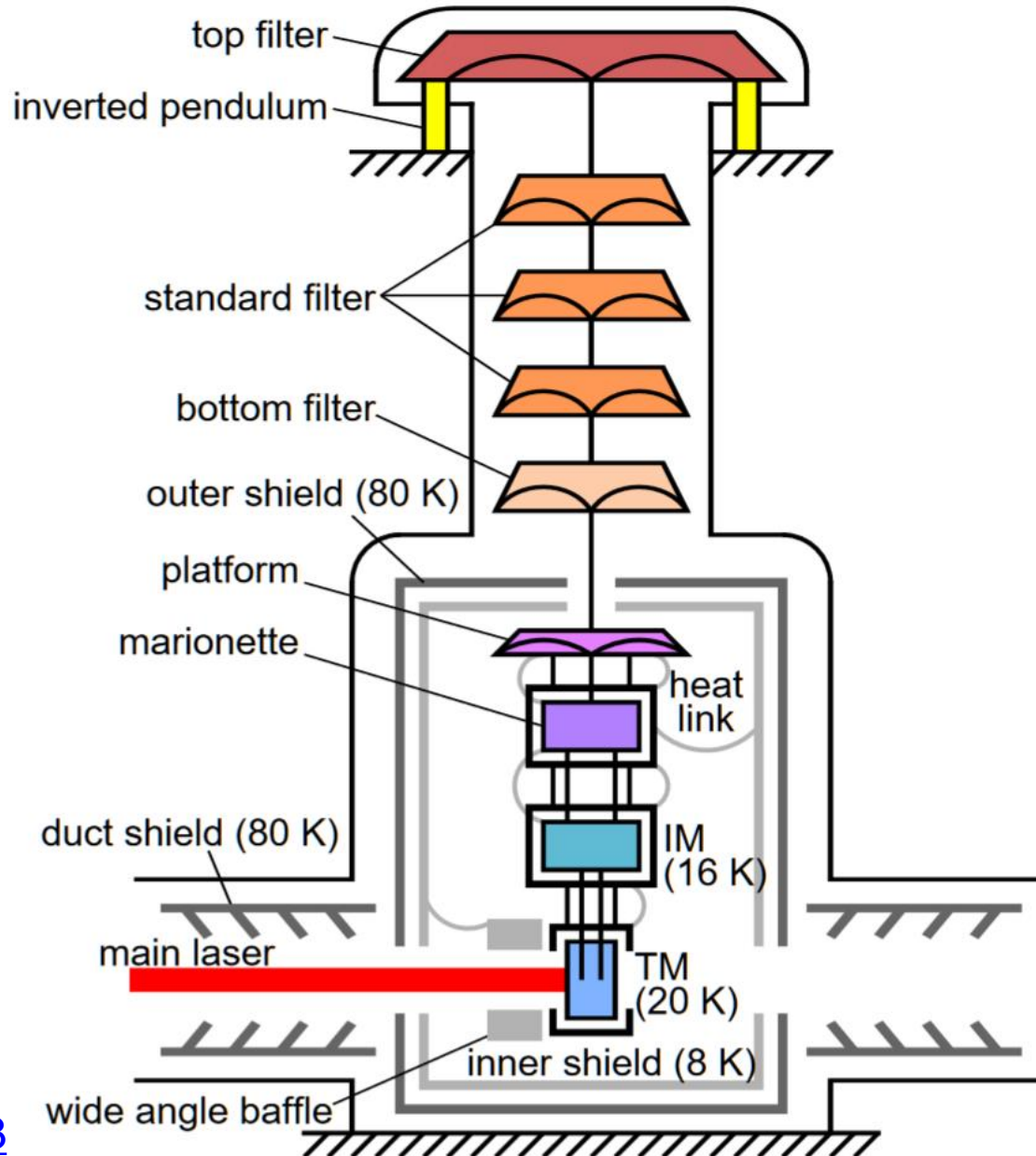
IRM suspended by 4 CuBe fibers

4 sapphire blades

TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)

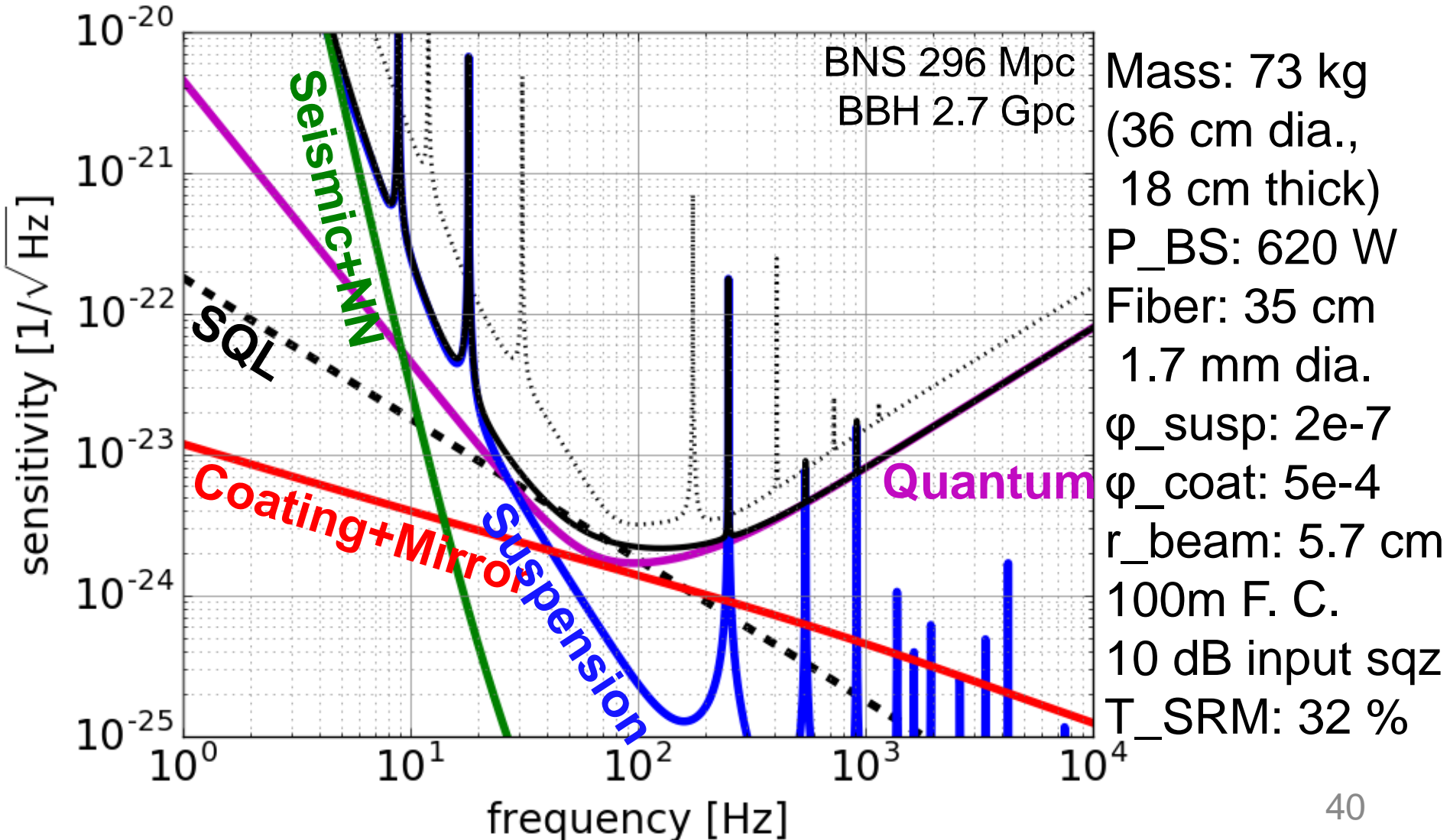
RM suspended by 4 CuBe fibers

KAGRA Cryostat Schematic



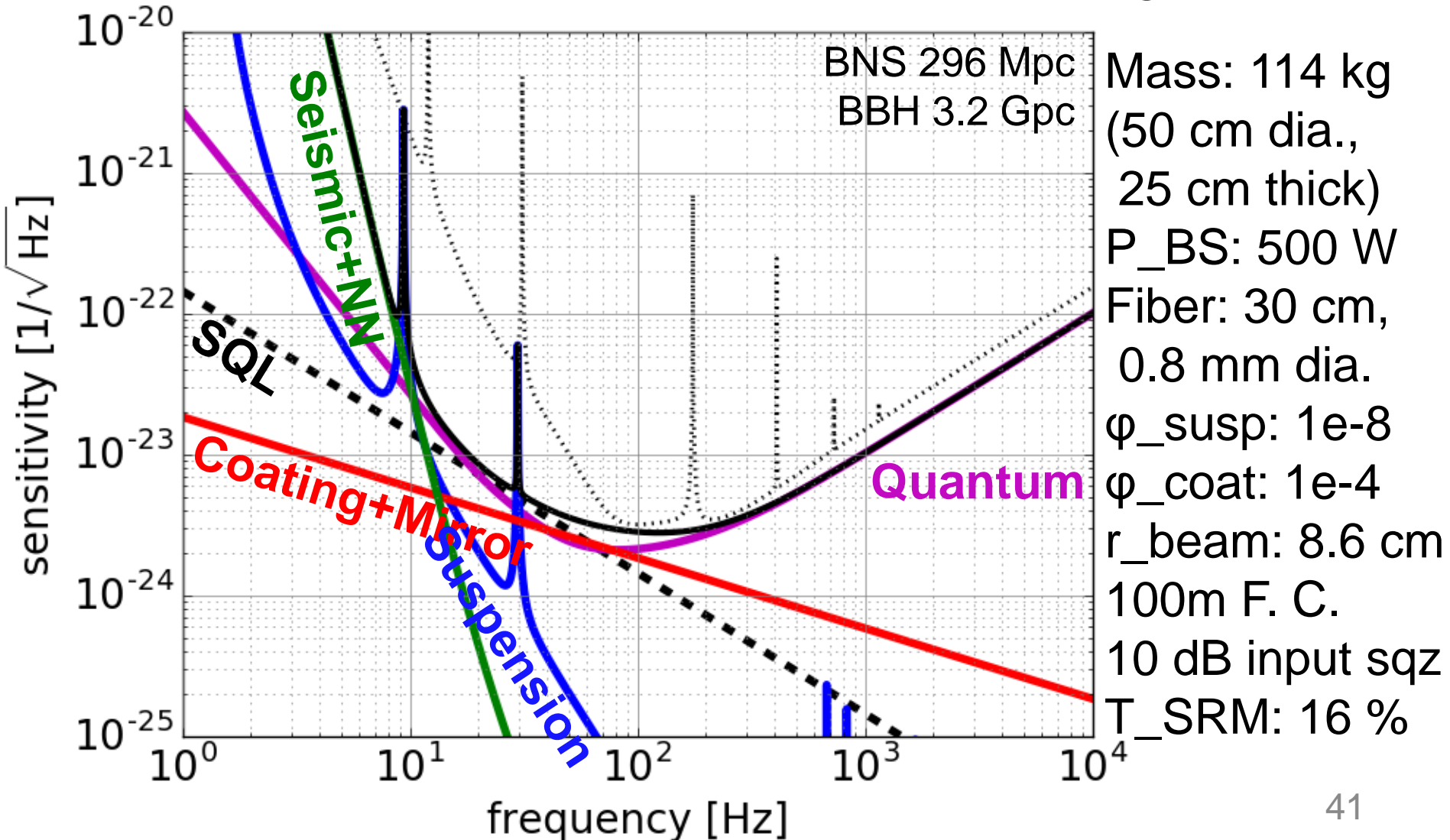
KAGRA+ Sensitivity: Blue

- Heavier sapphire and heavier IM, 20 K



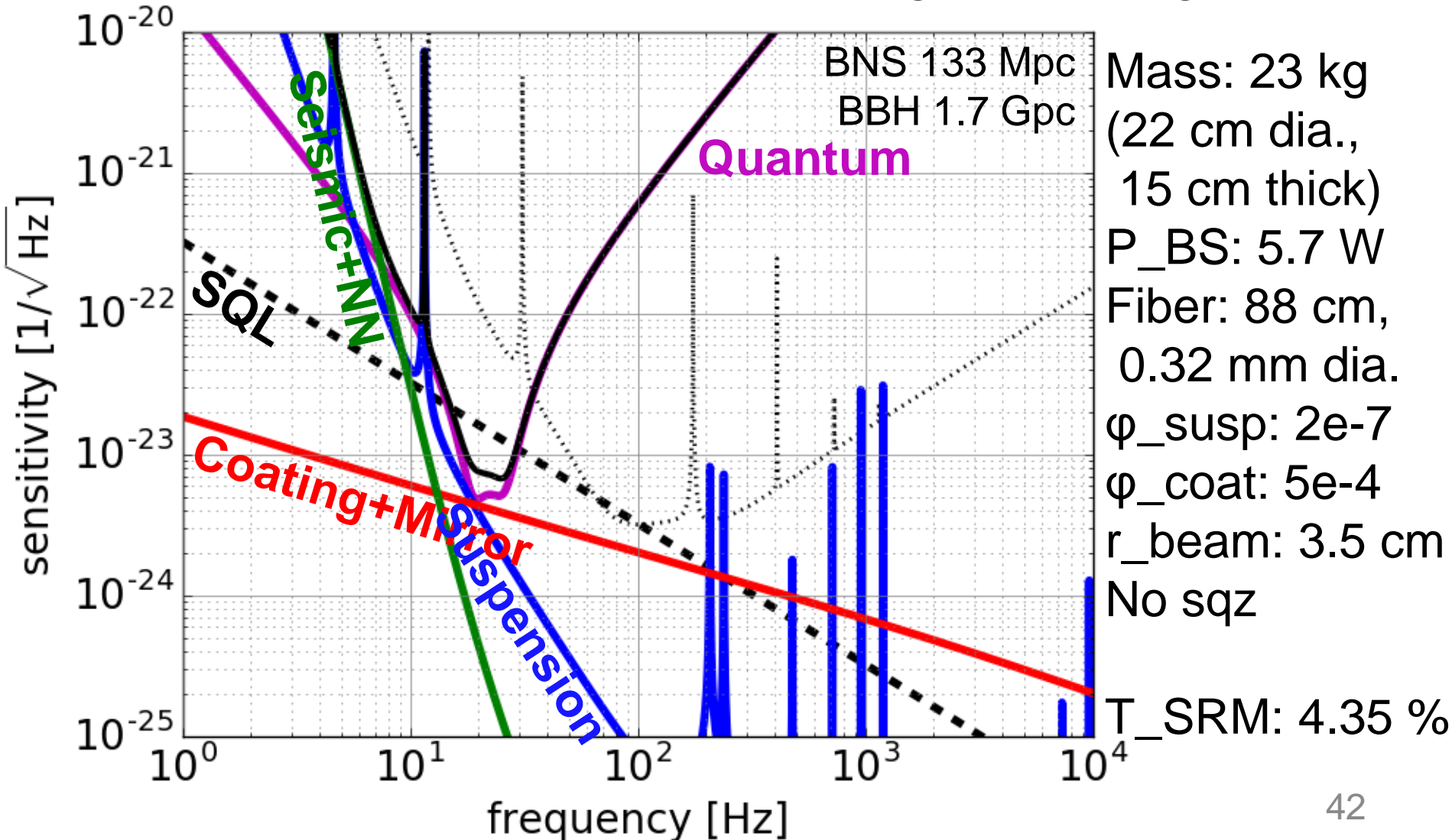
KAGRA+ Sensitivity: **Black**

- Silicon 123 K, 1550 nm, radiative cooling



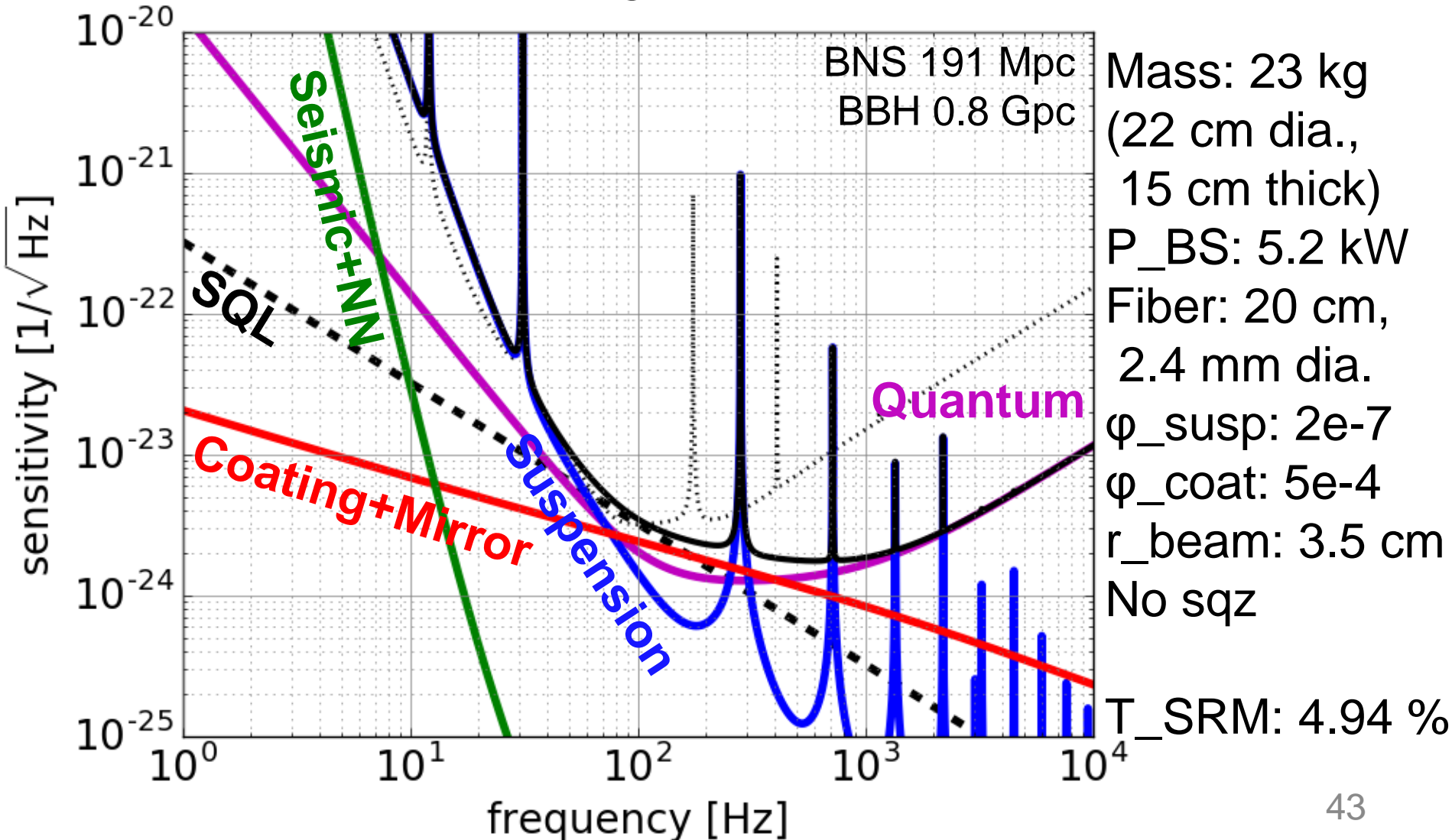
KAGRA+ Sensitivity: **Brown**

- Same test mass, low power, high detuning, 20 K



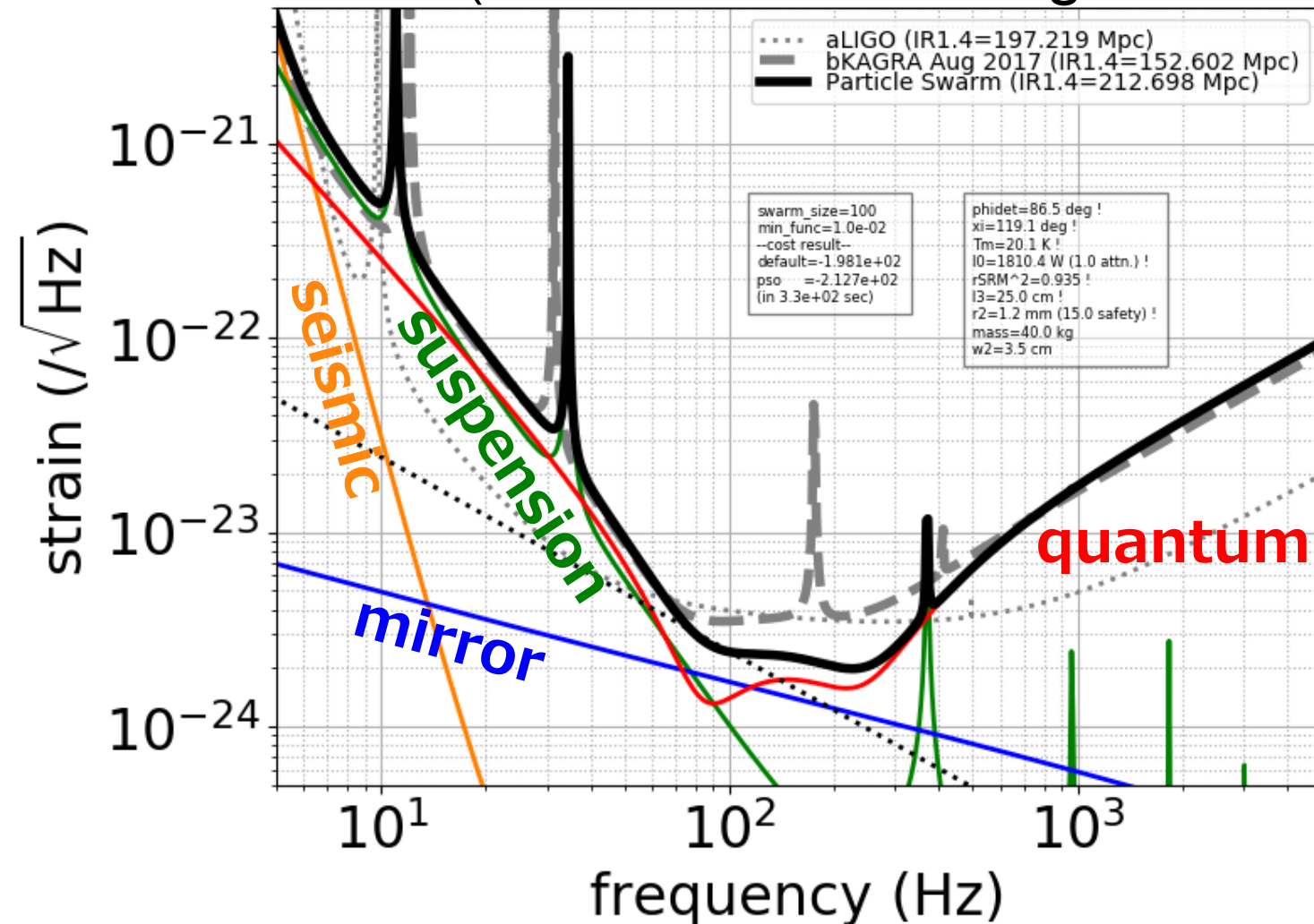
KAGRA+ Sensitivity: **Red**

- Same test mass, high power, 24 K



Plan A: 40 kg Mirror

- Also assumes factor of 2 coating thermal noise reduction (no beam size change assumed)

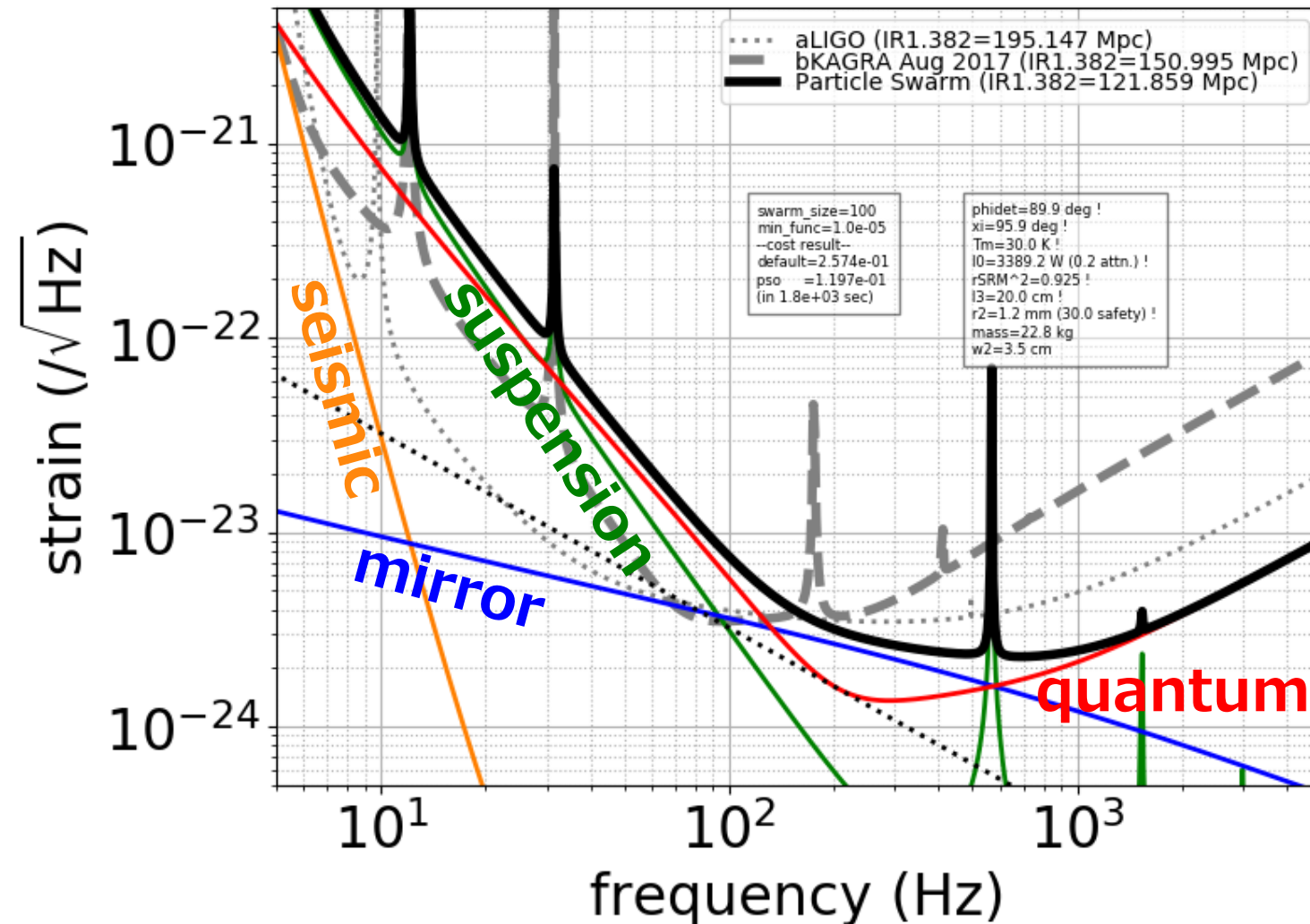


Good for mid frequency improvement
→ BNS range optimized

T=20.1 K
181 W input
thicker fiber
25.0 cm
φ1.2 mm
(thicker to allow for higher power)

Plan B: 400 W Laser with SQZ

- Assumes 10dB input SQZ

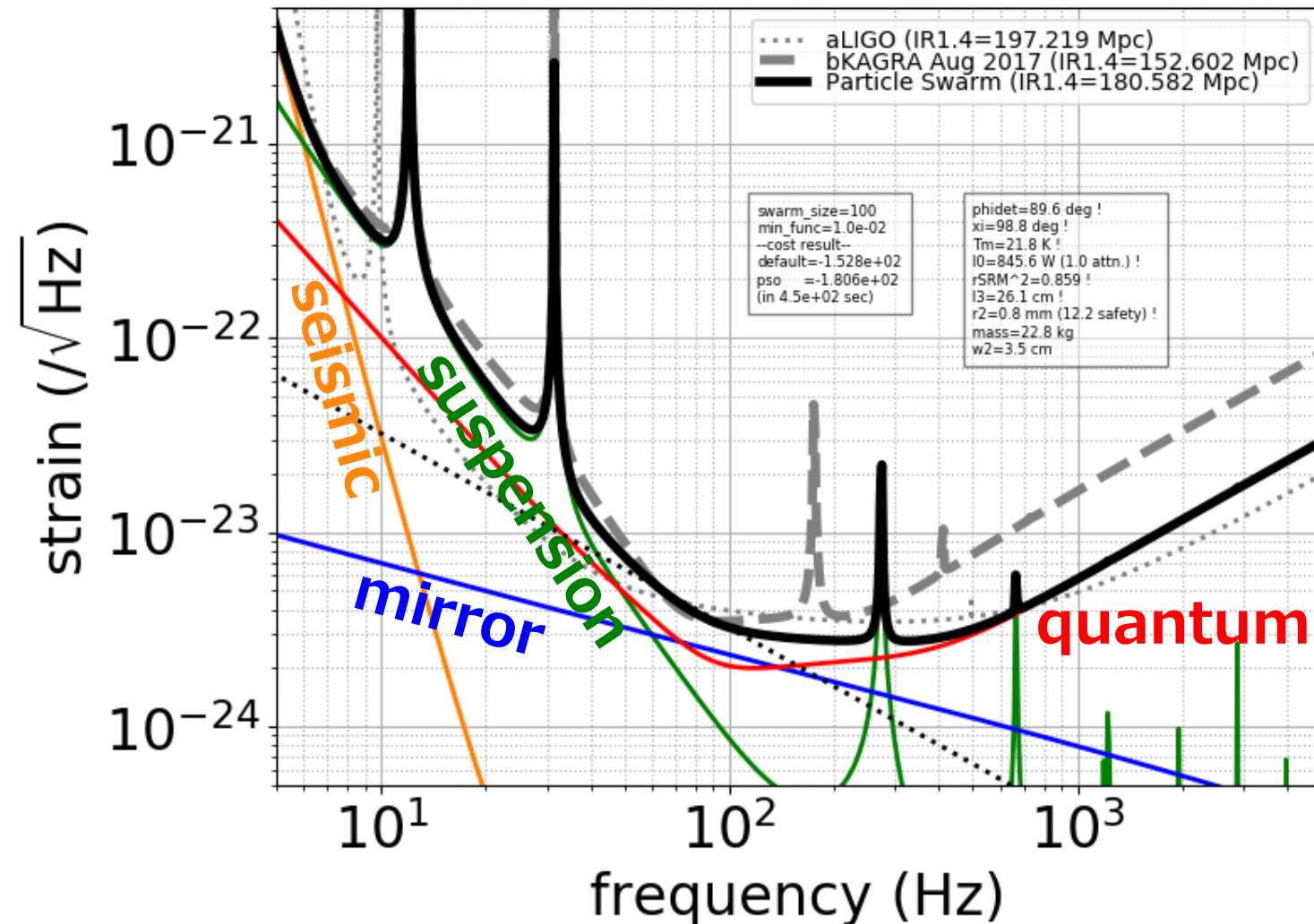


Good for high frequency improvement
→ BNS range optimized

T=29.8 K
330 W input
shorter and thicker fiber
20.1 cm
φ1.2 mm
(high power with high temperature)

Plan C: Freq. Dependent SQZ

- Assumes 10dB input SQZ and 100 m filter cavity

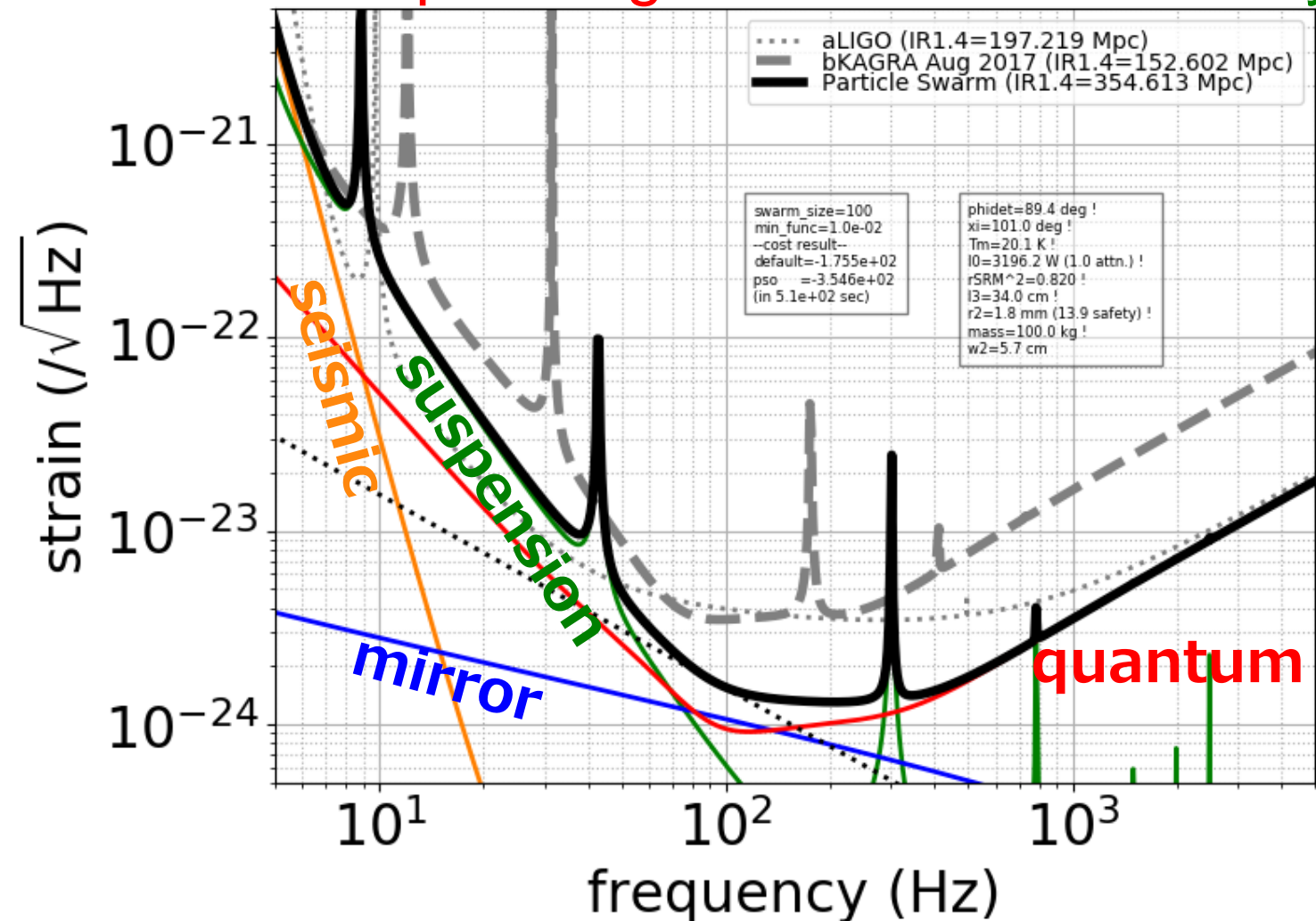


Broadband
improvement
→ BNS range
optimized

T=21.8 K
85 W input
thinner fiber
26.1 cm
 ϕ 0.8 mm
(SQZ helps to
ease fiber
requirement)

Longer Term Candidate

- 100 kg mirror with 1/2 coating thermal, 320 W input, 10 dB squeezing with 100 m filter cavity



Broadband improvement
→ BNS range optimized

T=20.1 K
320 W input
longer fiber
34.9 cm
φ1.8 mm