KAGRA F2F Satellite Meeting on Future Upgrade of KAGRA
@ NAOJ

December 4, 2018

Summary of Past Discussions on KAGRA Upgrade

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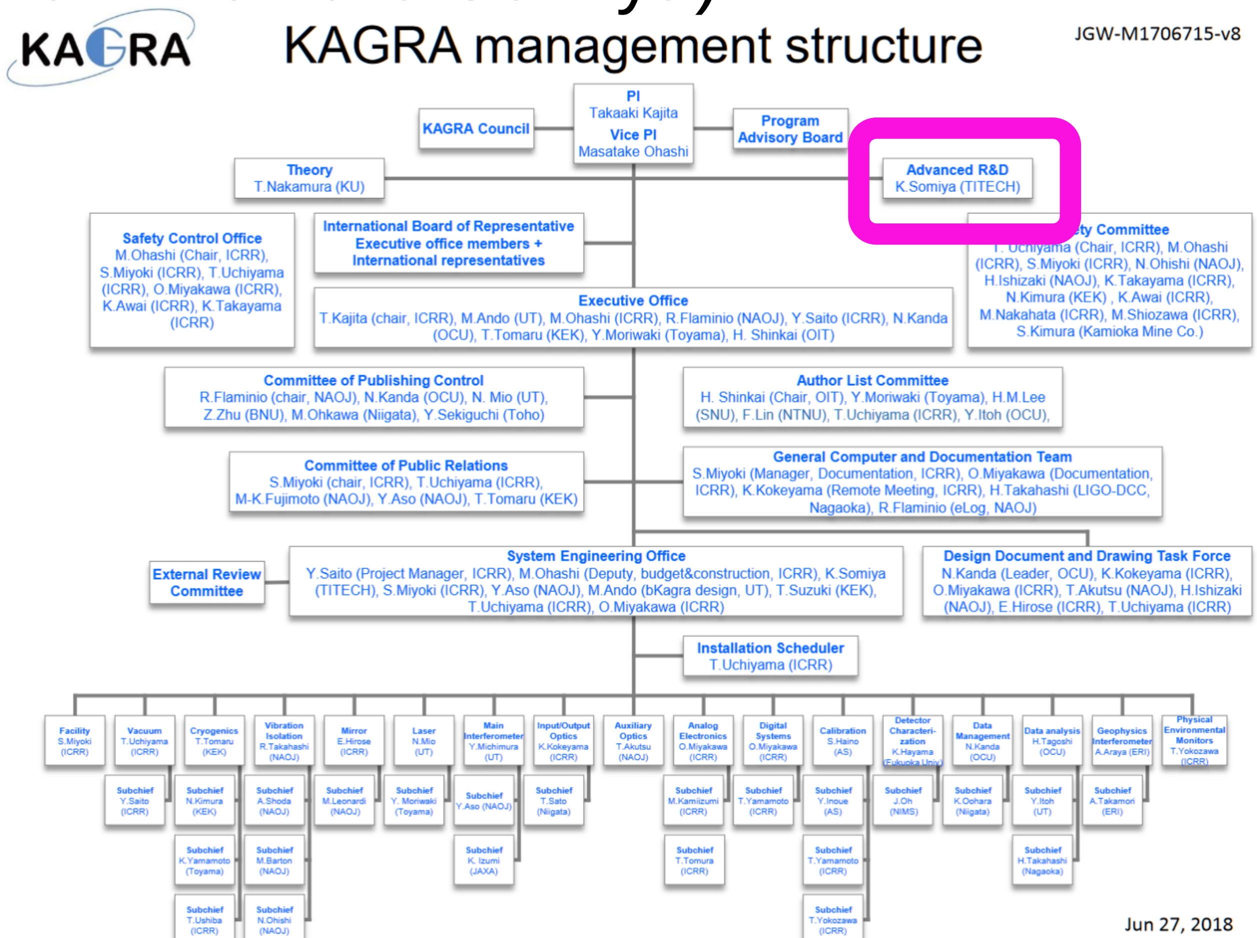
on behalf of the Advanced R&D Group

KAGRA Upgrade Discussions

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



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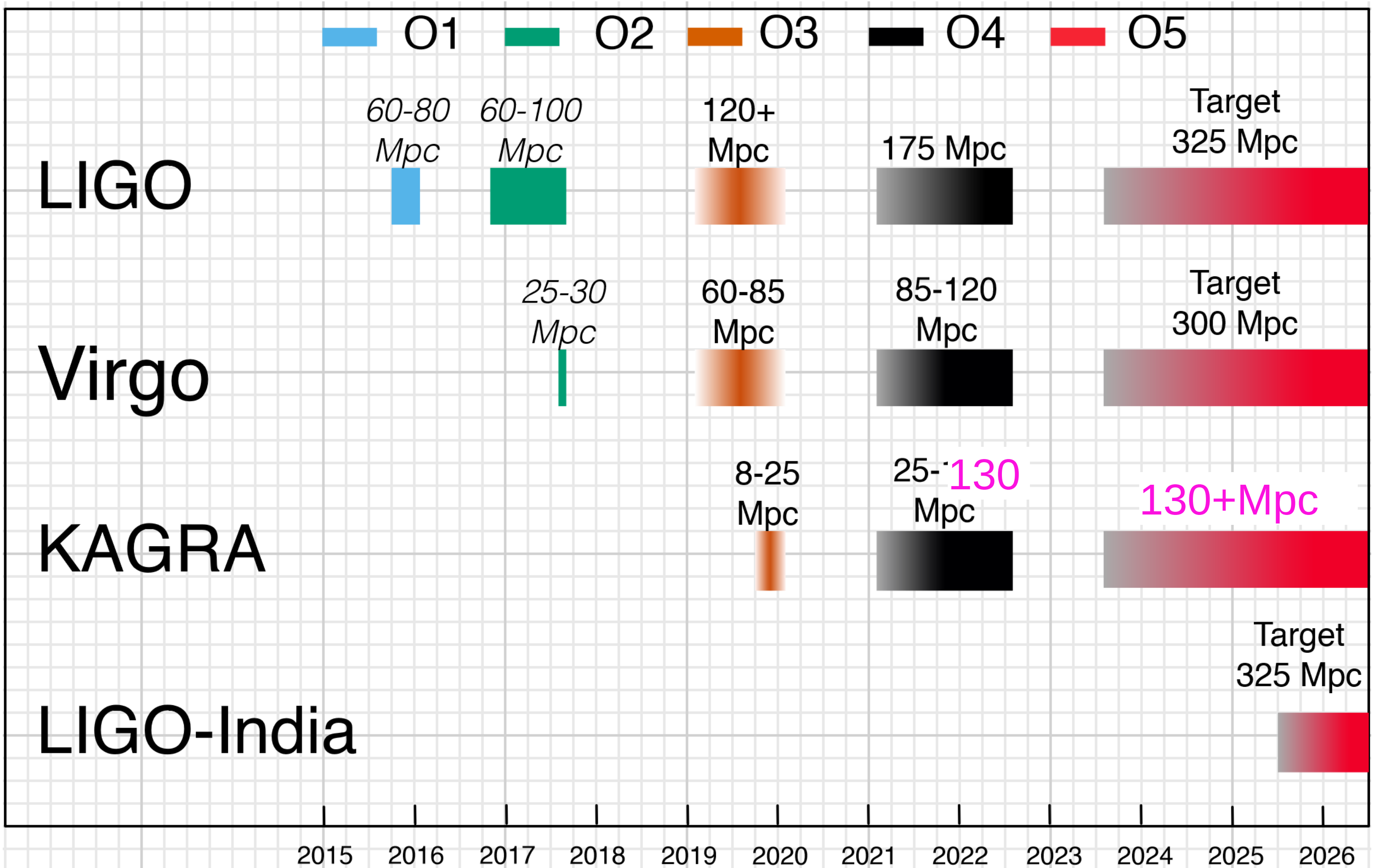
  - Recap of bKAGRA sensitivity
  - 3 sensitivity curves to start with
  - Science case study
  - Technical feasibility study
  - More realistic plans with budget estimate
  - Summary and suggestion from past studies
- Criticism and Next Plans
- Summary

LVK Observation Scenario

- Possible KAGRA upgrade between O4 and O5



O4 high is 130 Mpc from BRSE with conventional readout

O5 is 130+ Mpc indicating DRSE operation and upgrades

Modified from preliminary timeline from JRPC report 20180913
Approved by EO on Oct 17, 2018 (JGW-T1809078)

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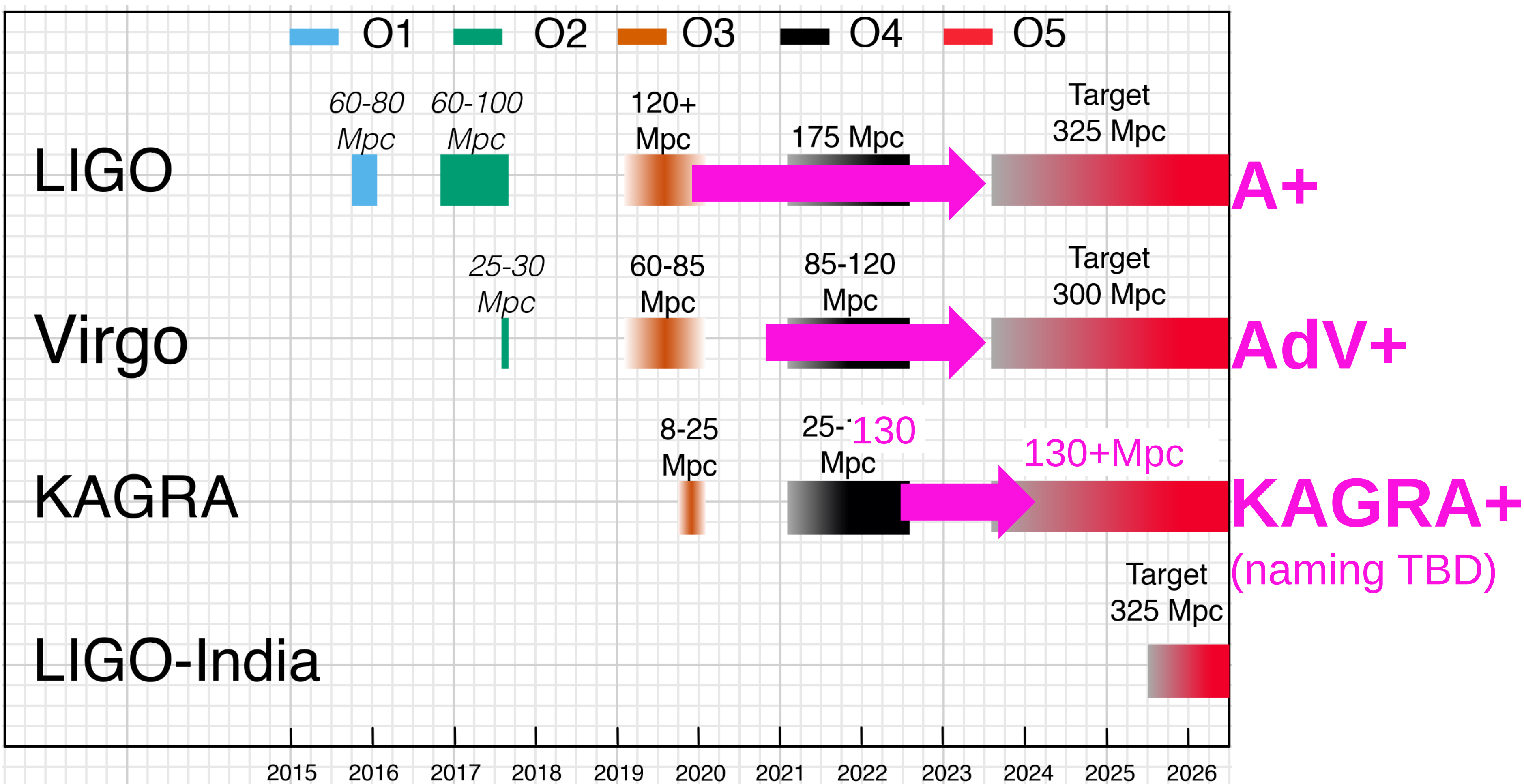

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History of KAGRA+ Discussion

- March 2017 F2F @ Niigata U
  Proposal to start integrated upgrade study
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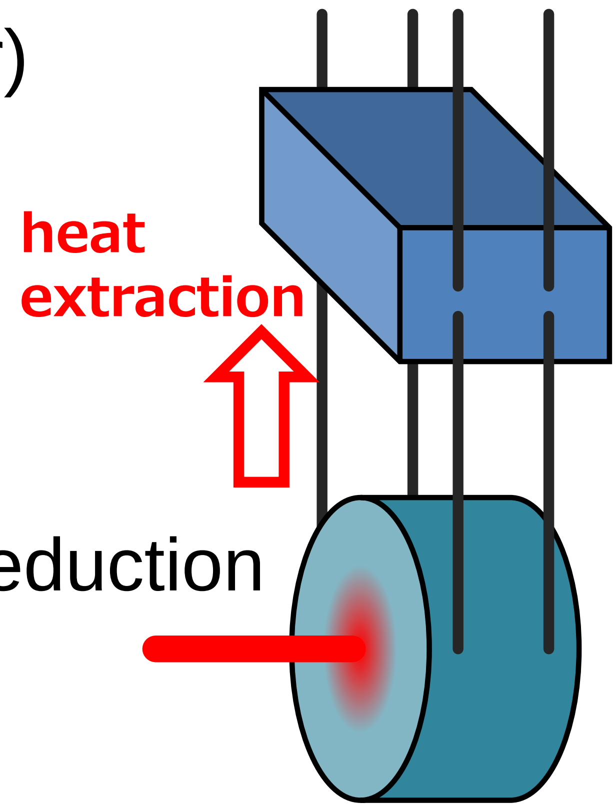
Upgrading KAGRA is Tricky

- 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

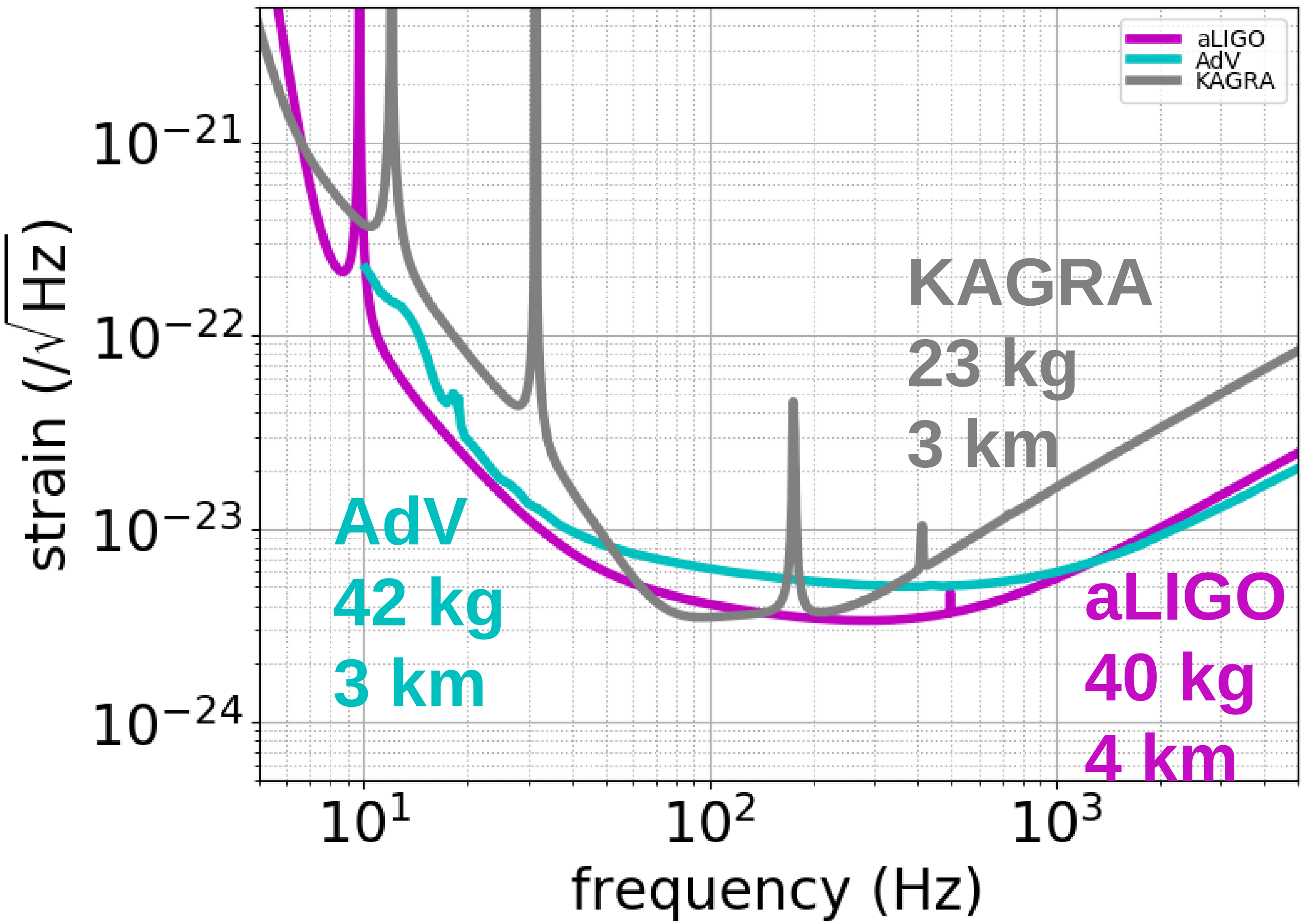
  thinner and longer
  for suspension thermal noise reduction

  ↕ **Dilemma**

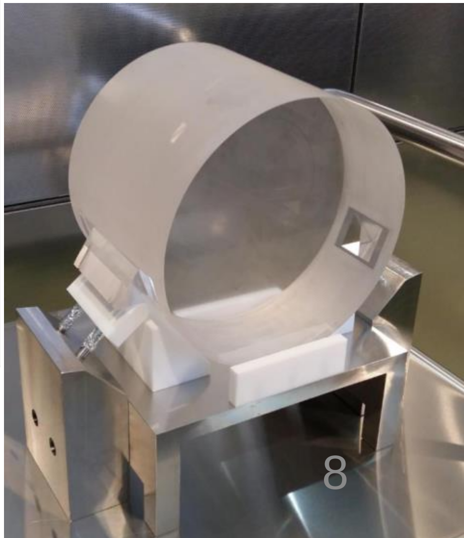
  thicker and shorter
  for heat extraction

2G Sensitivity Comparison

- Not good at low freq. because of thick and short fiber (35 cm, φ1.6 mm) to extract heat, and lower mass



23 kg was the largest available sapphire mirror



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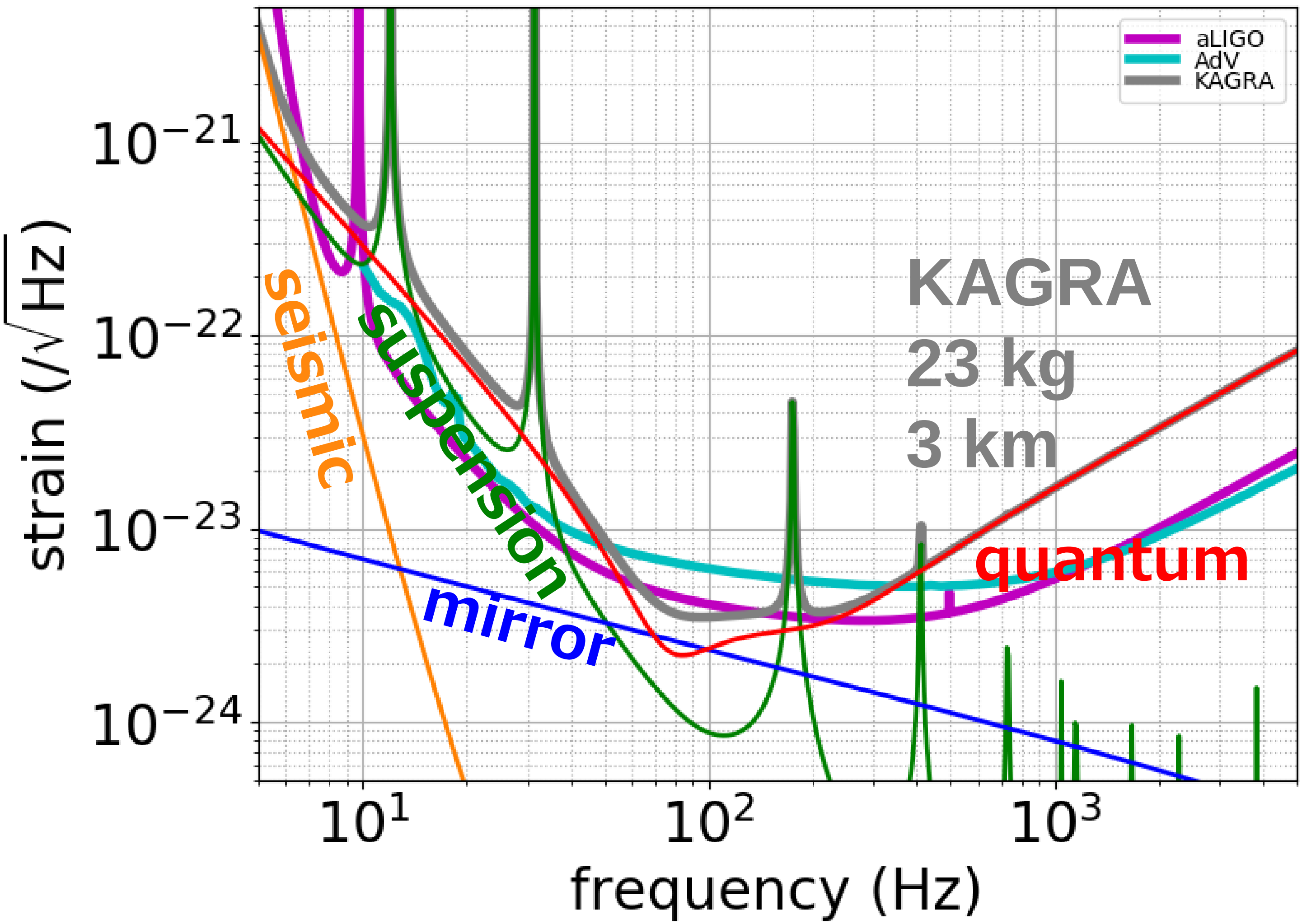

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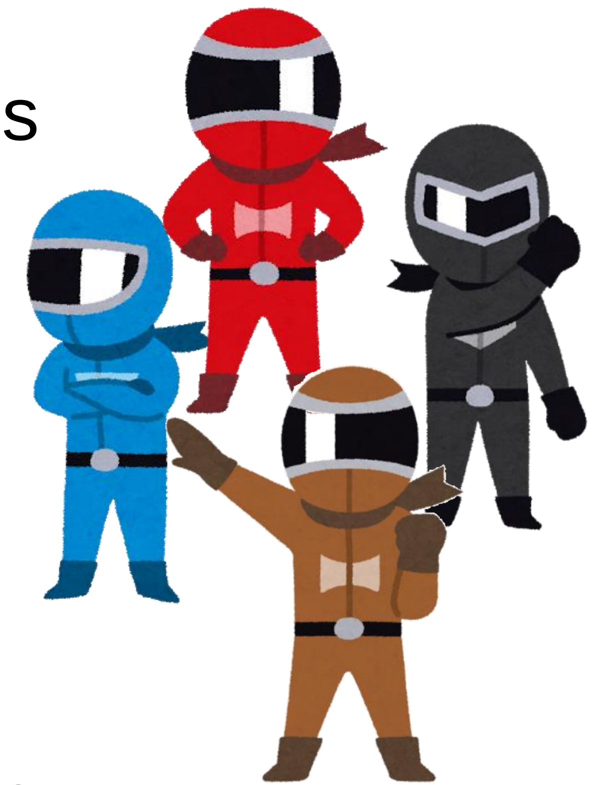
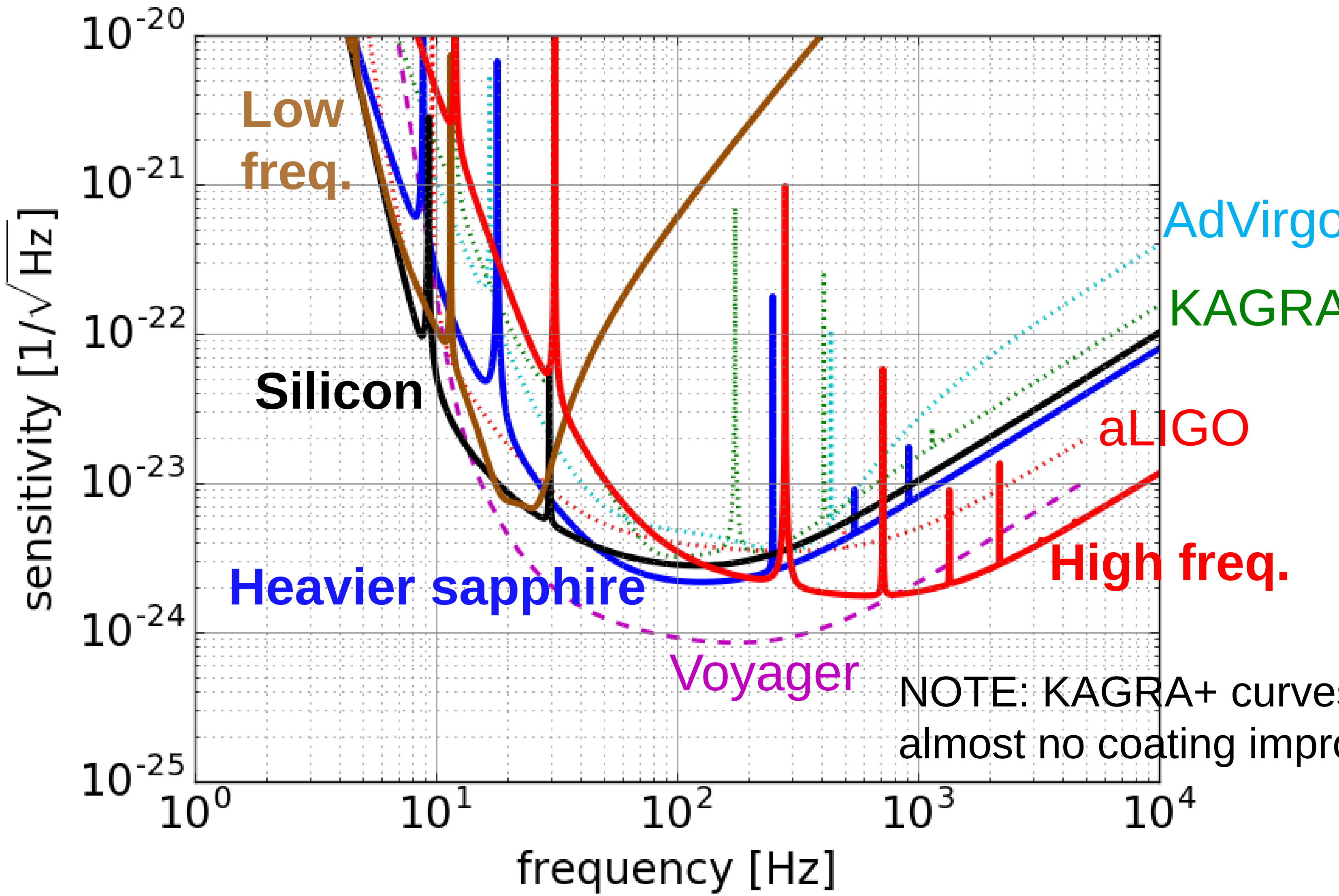
Four Proposals

- 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 frequency

Sensitivity of Four Proposals



NOTE: KAGRA+ curves expect almost no coating improvements

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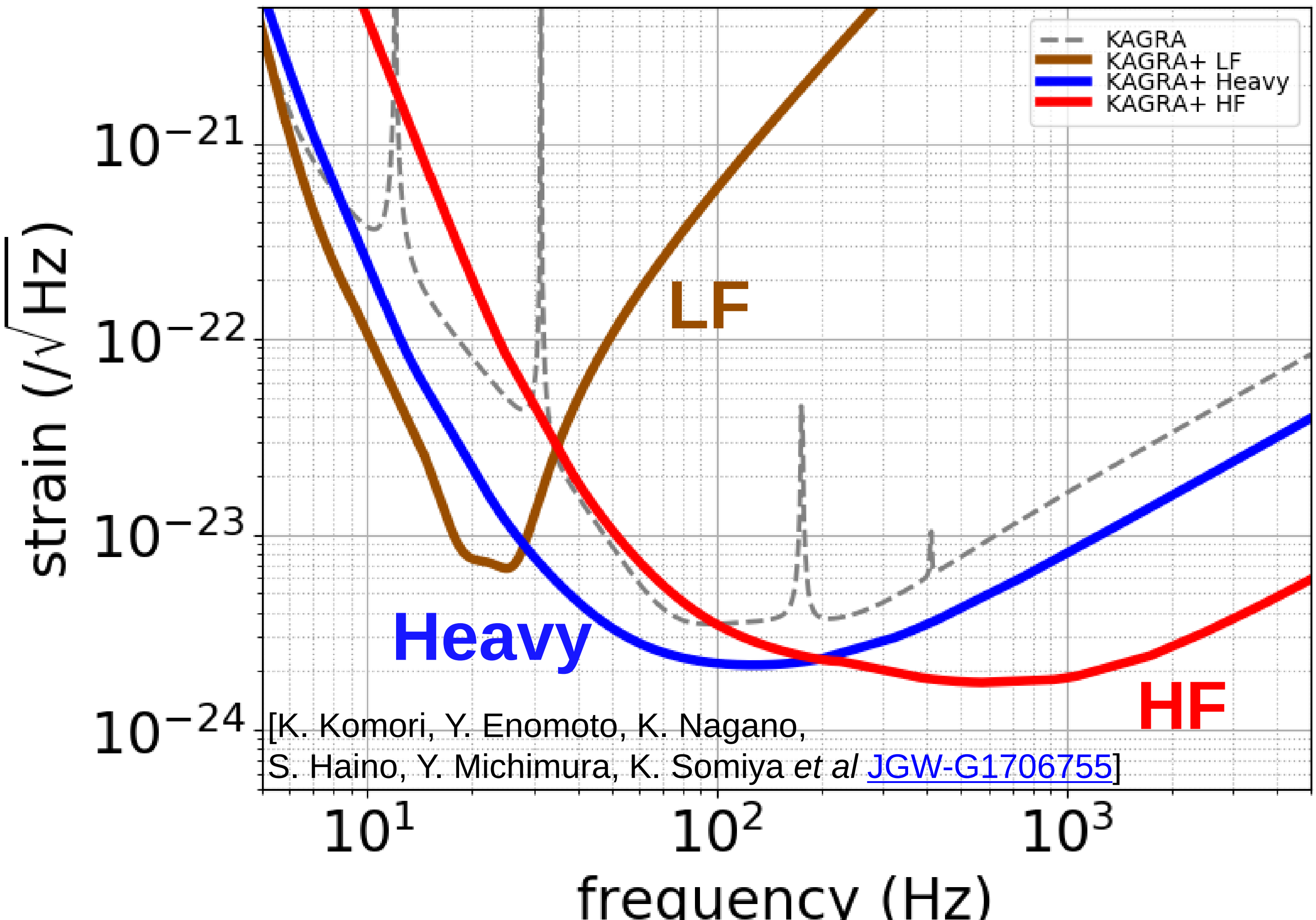
3 Concepts for Science Case Study

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



LF
P_{BS} = 6 W
fiber
88 cm
φ0.32 mm

Heavy
m = 73 kg
10 dB sqz
with F.C.

HF
P_{BS} = 5 kW
10 dB sqz
fiber
20 cm
φ 2.4 mm

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 (~100M_{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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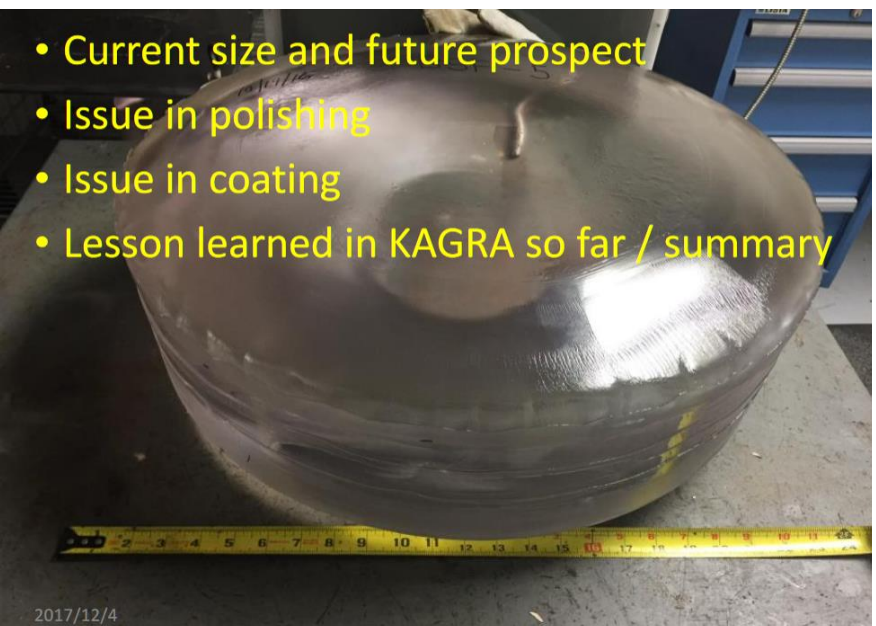
Technical Feasibility Study

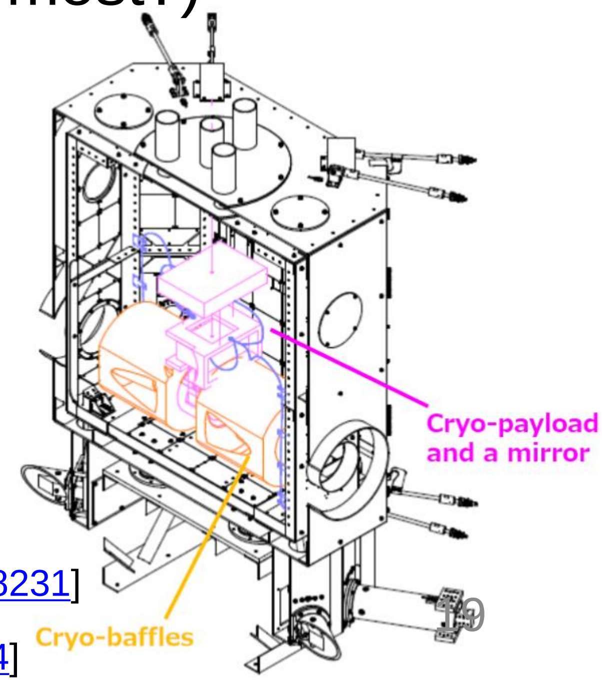
- Dec 2017 F2F Satellite Meeting
- Focused on technical feasibility for HF and Heavy
- Talks on
  High power laser (by Li-Wei Wei)
  Squeezing and filter cavity (by Matteo Leonardi)
  Bigger sapphire (by Eiichi Hirose)
  Composite mirror (by Satoshi Tanioka)

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?)



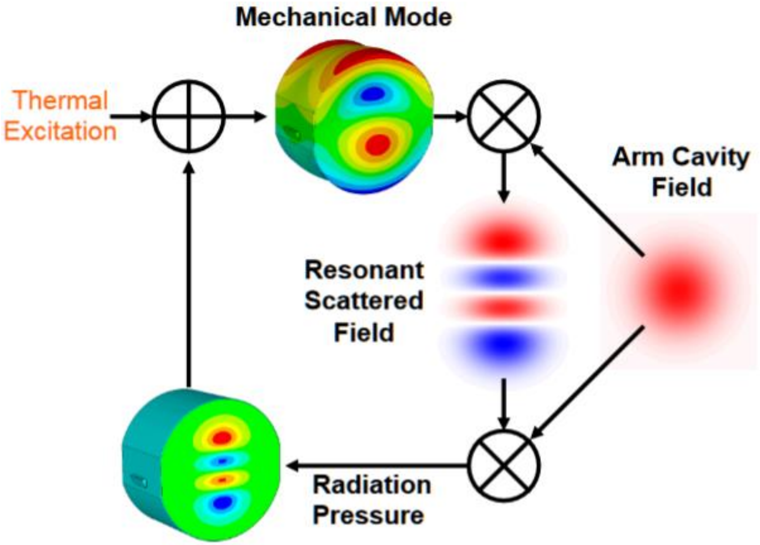
[K. Somiya, JGW-G1808231]



[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?



M. Evans *et al*, PRL 114, 161102 (2016)

S. Fu *et al*, JOSA B 34, A49 (2017)

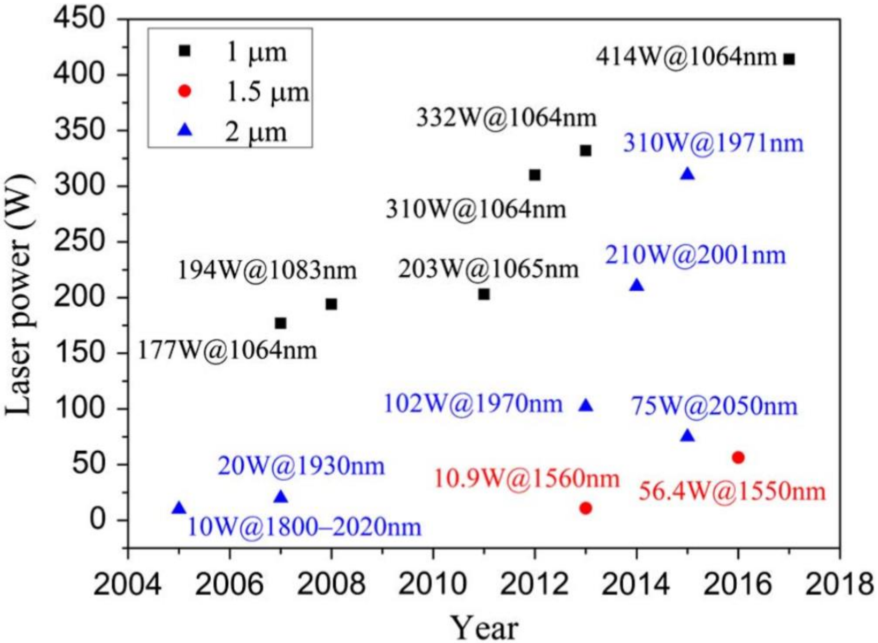
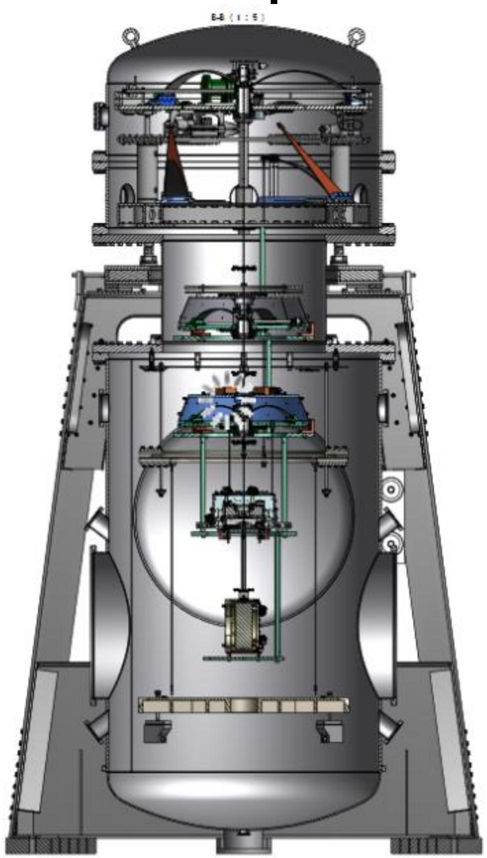
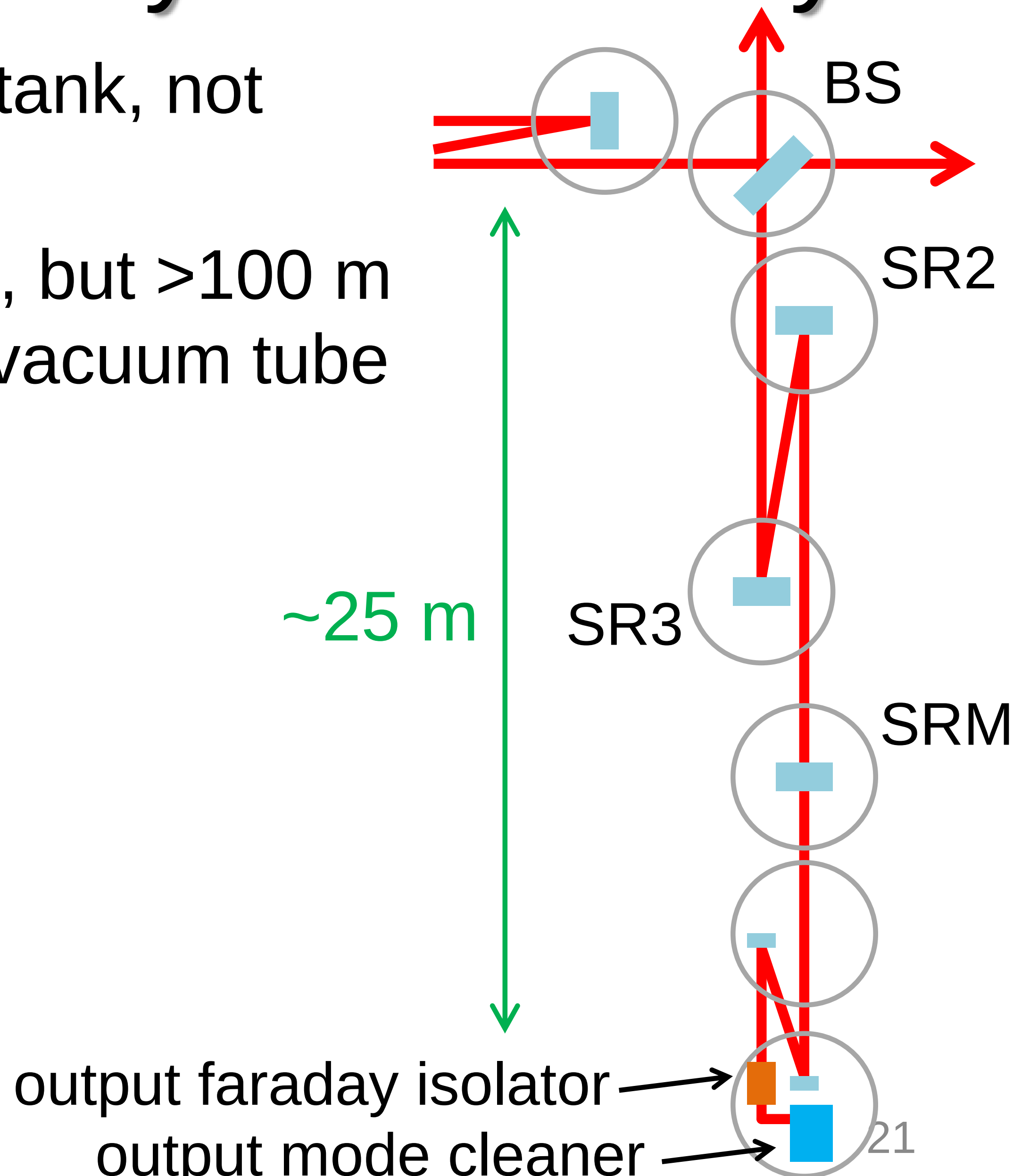


Fig. 7. Output power evolution of CW single-frequency amplifiers in all-fiber format operating in 1, 1.5, and 2 μm regions.

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

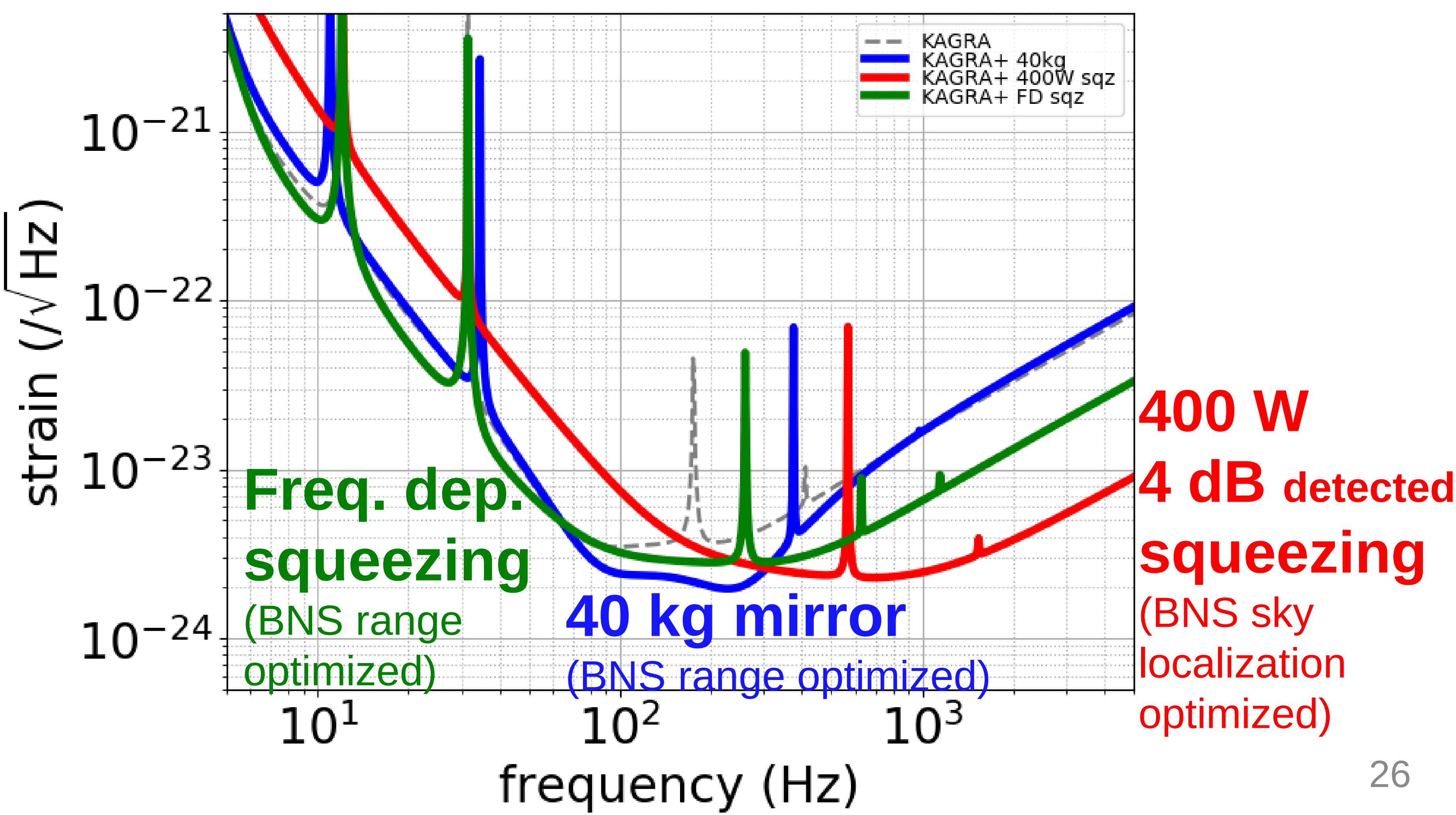
- With budget constraint of ~$5M, within ~5 years

- 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

- With budget constraint of ~$5M, within ~5 years



Summary of Near Term Candidates

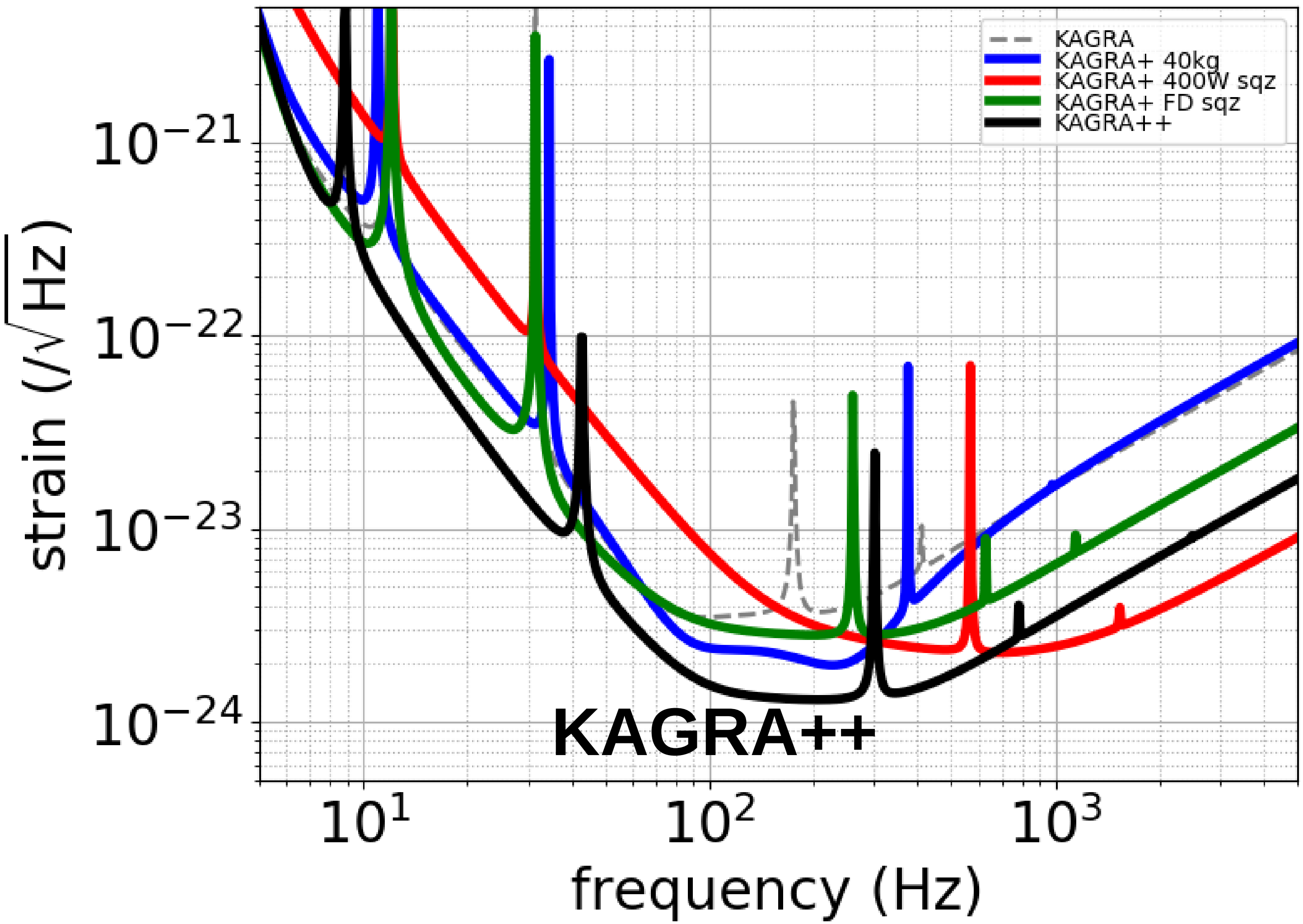
- A. New mirror takes time to fabricate
- B. High power operation is tough
- C. Does 100m F.C. fit in the facility?

	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

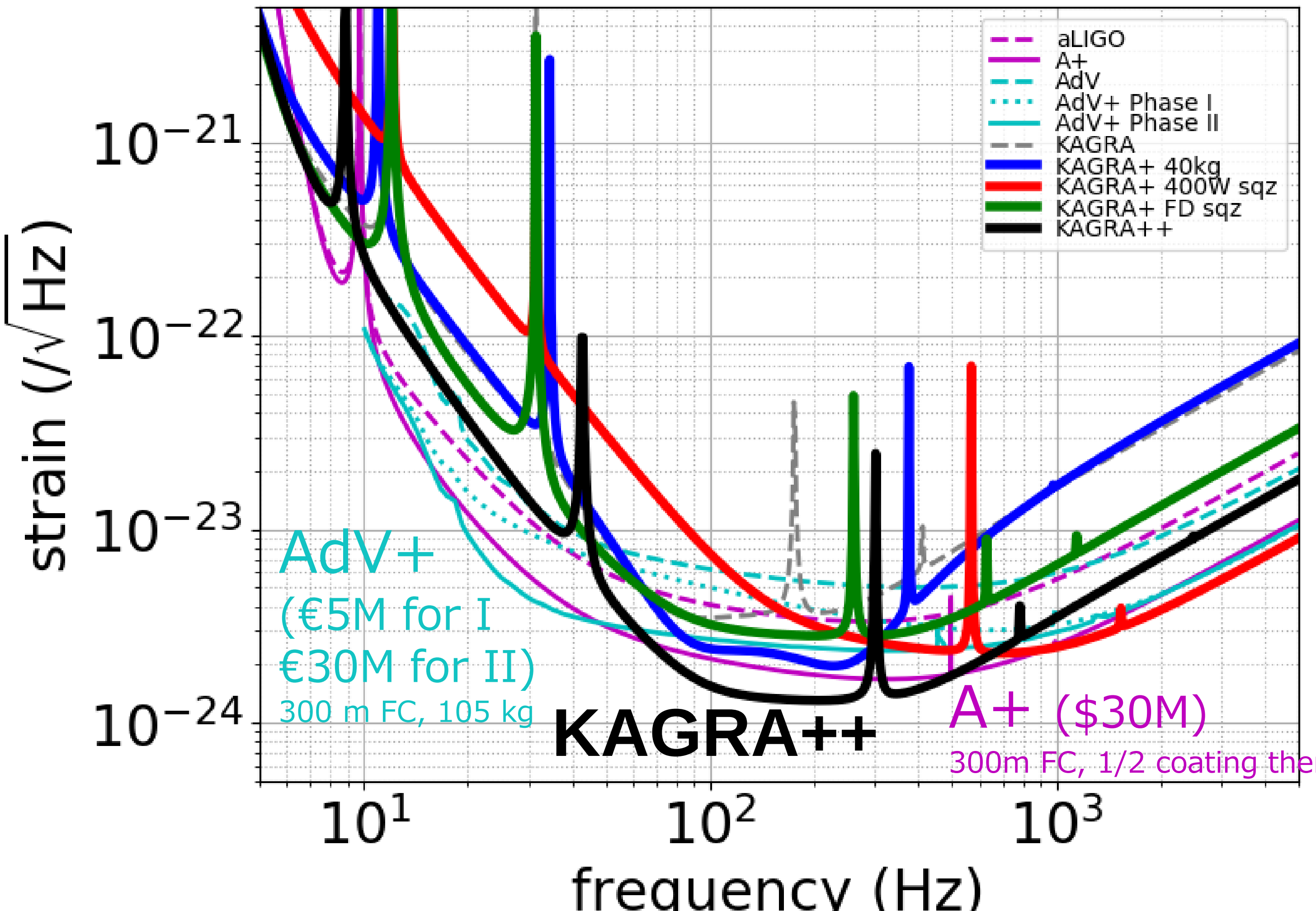


BNS range reaches **355 Mpc**

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 (updated ver)

A+ curve from LIGO-T1800042

AdV and AdV+ curves from [VIR-0325B-18](VIR-0325B-18)

KAGRA curve from [JGW-T1707038](JGW-T1707038)

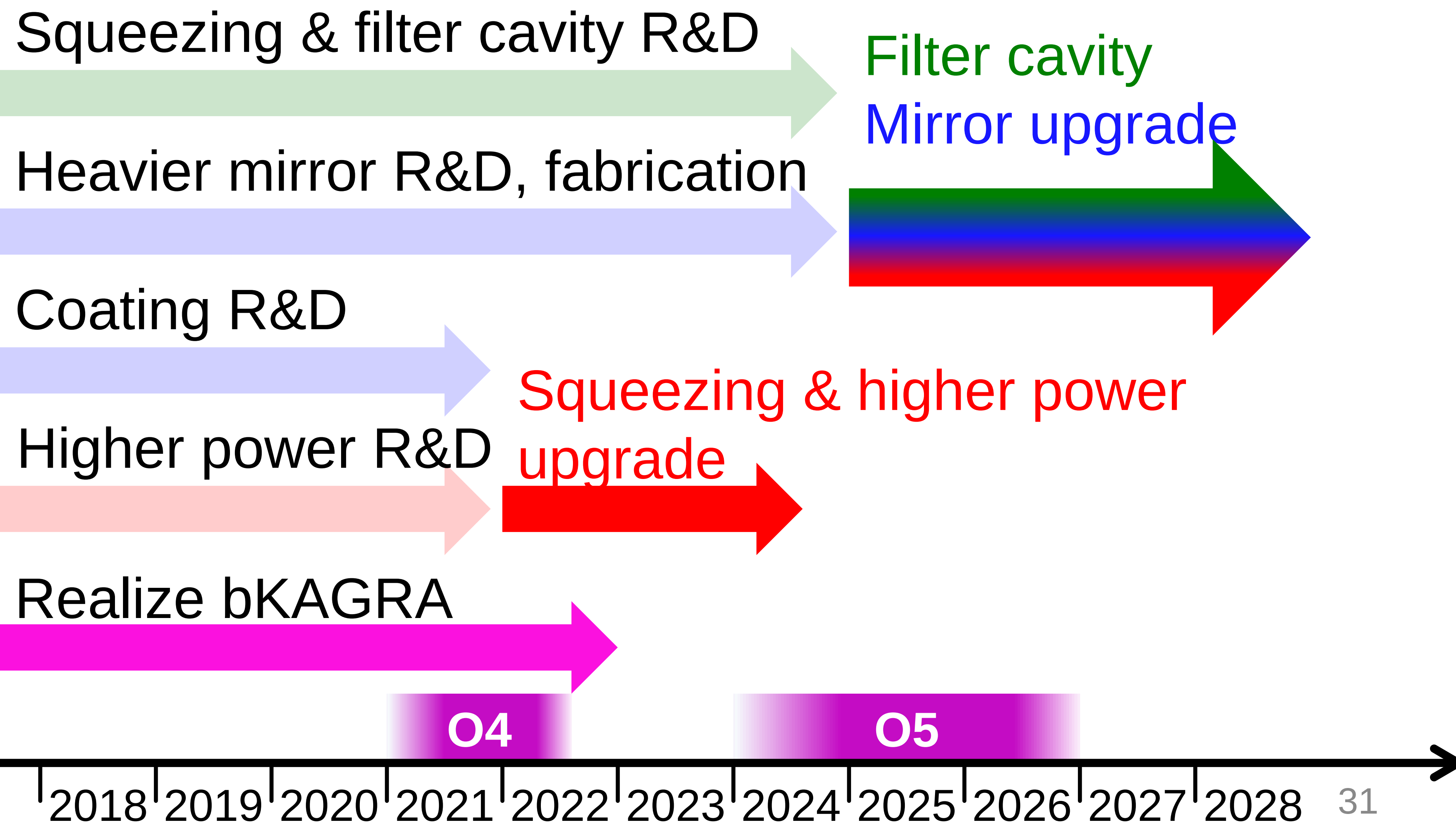
Summary of Past Studies

- 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+	~$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)

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

LIGO parameters from LIGO-T1600119, AdVirgo parameters from JPCS 610, 01201 (2015)

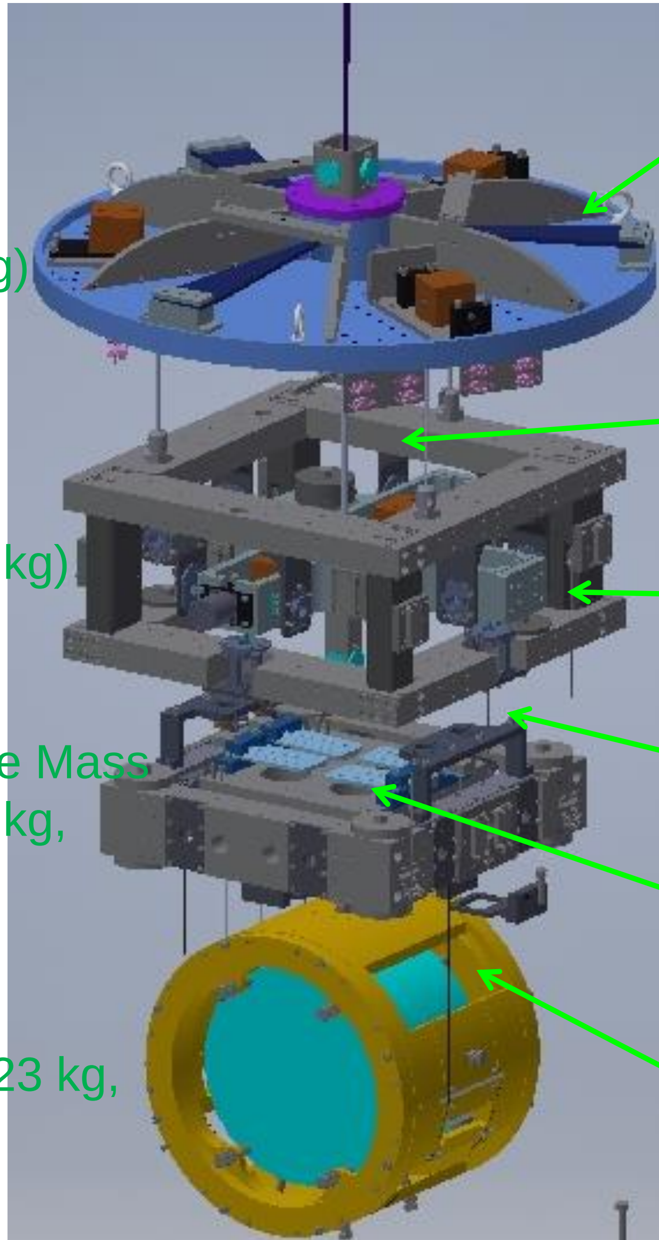
KAGRA Detailed Parameters

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

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

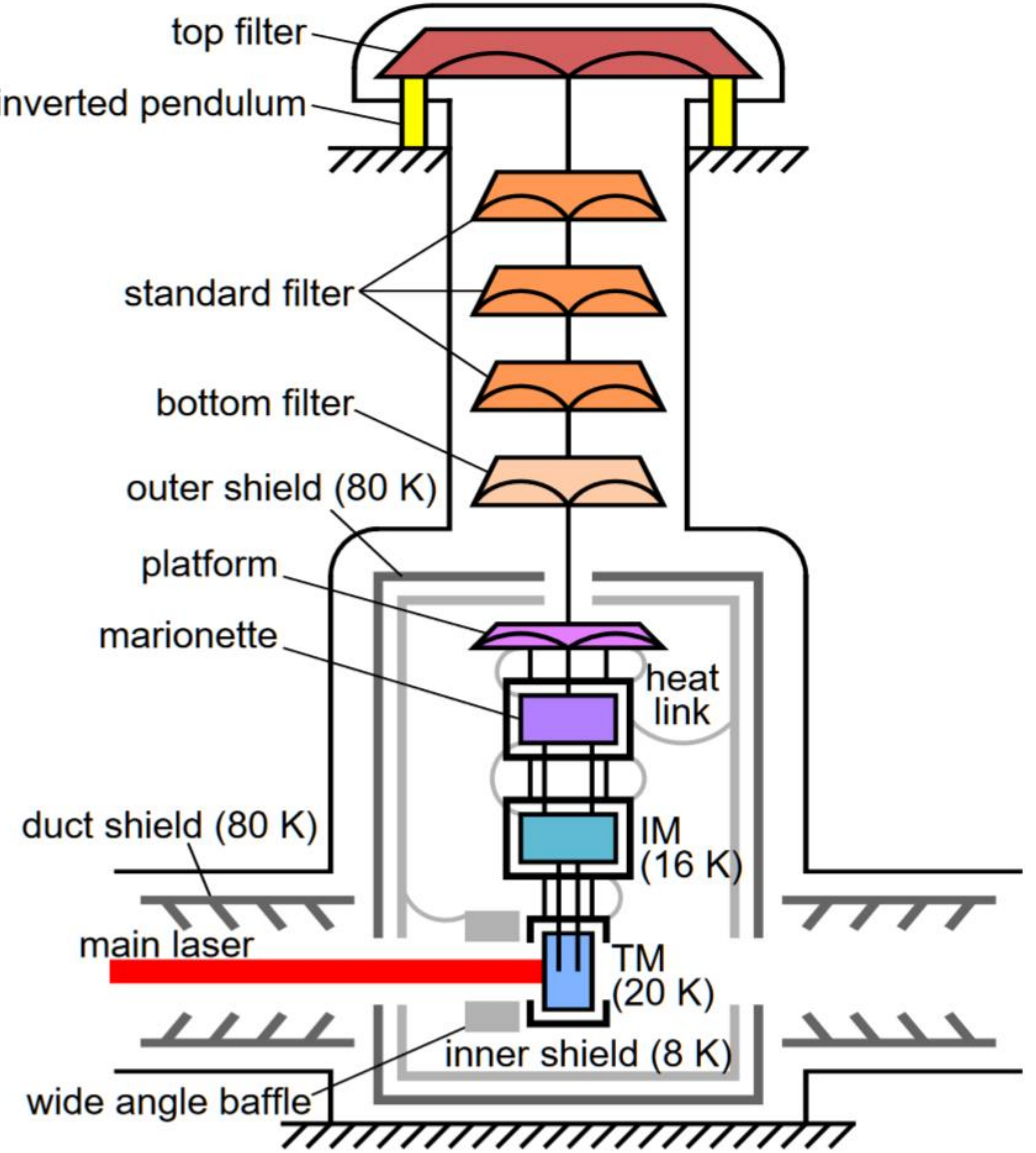
Heat link attached to MN

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

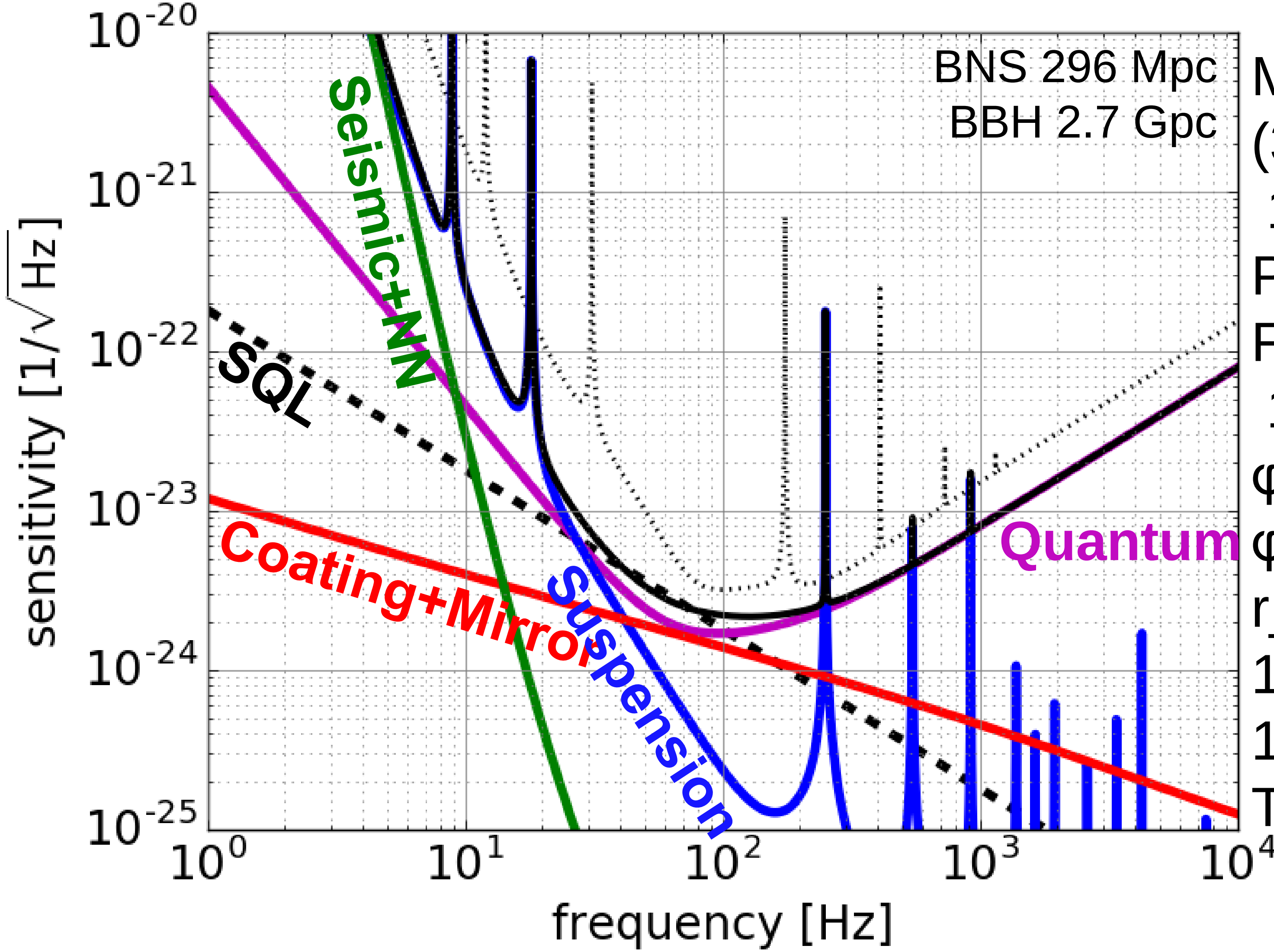
KAGRA Cryostat Schematic



arXiv:1710.04823

KAGRA+ Sensitivity: **Blue**

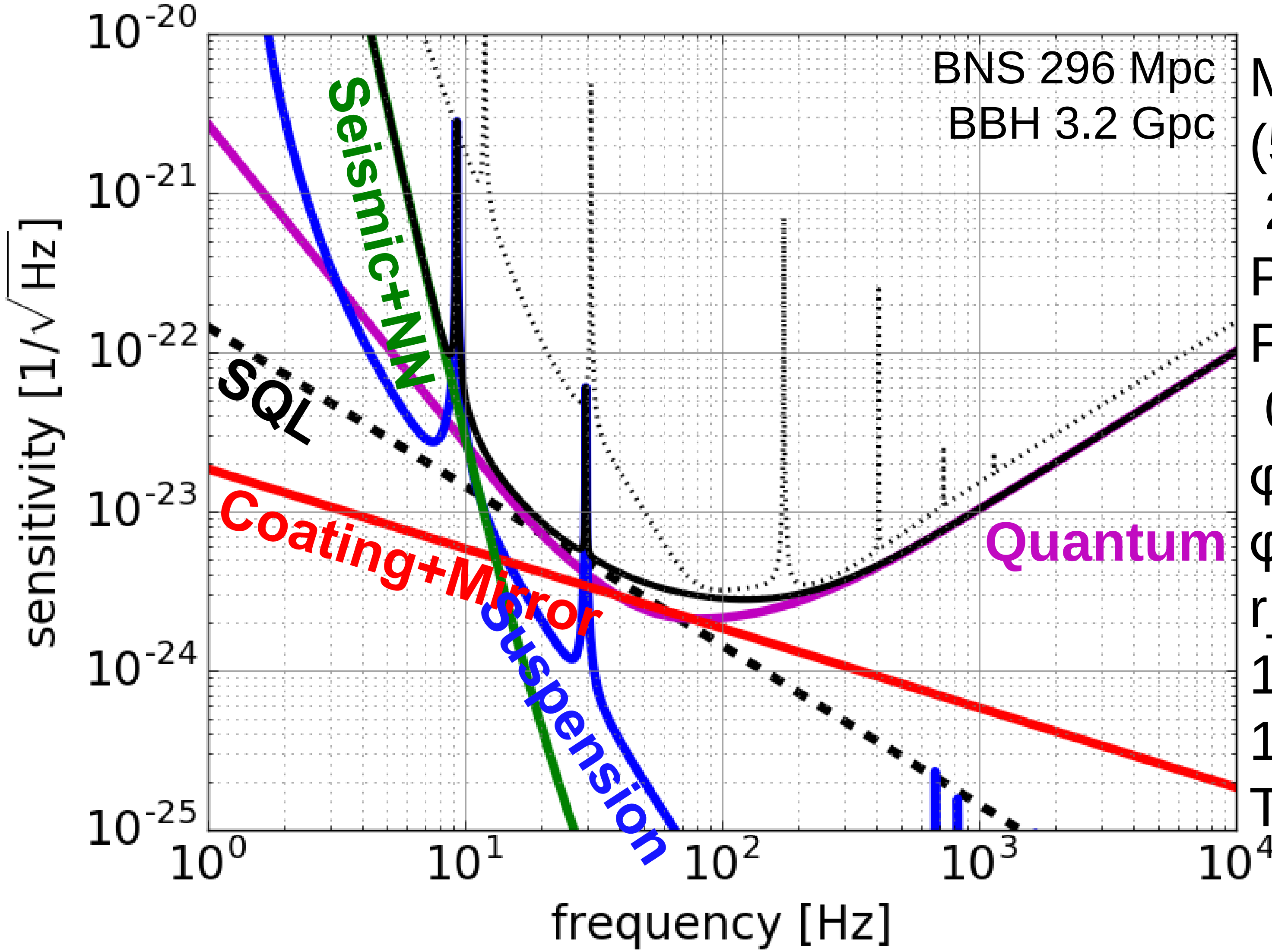
- Heavier sapphire and heavier IM, 20 K



Mass: 73 kg
(36 cm dia.,
18 cm thick)
P_BS: 620 W
Fiber: 35 cm
1.7 mm dia.
φ_susp: 2e-7
φ_coat: 5e-4
r_beam: 5.7 cm
100m F. C.
10 dB input sqz
T_SRM: 32 %

KAGRA+ Sensitivity: **Black**

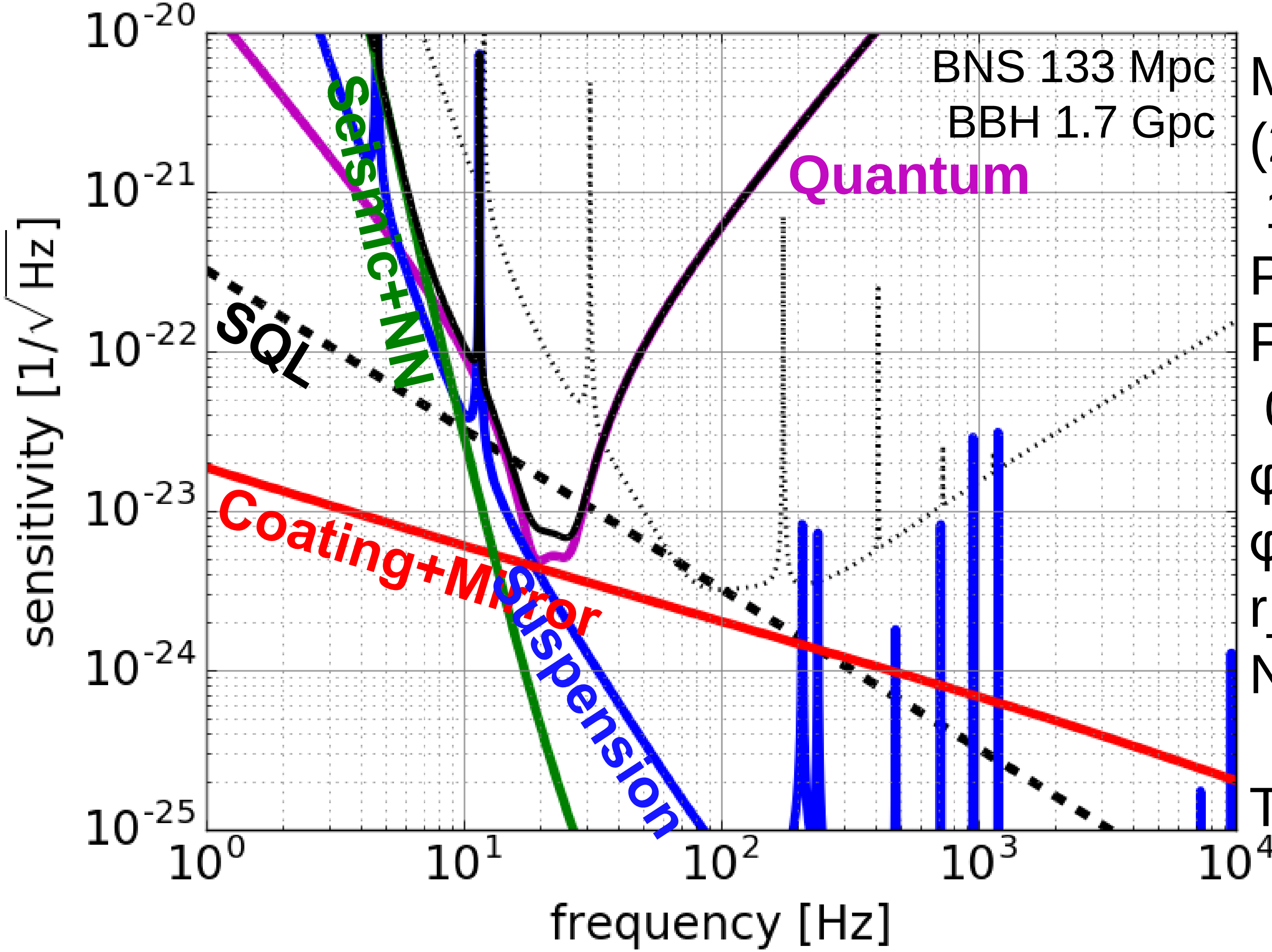
- Silicon 123 K, 1550 nm, radiative cooling



Mass: 114 kg
(50 cm dia.,
25 cm thick)
P_BS: 500 W
Fiber: 30 cm,
0.8 mm dia.
φ_susp: 1e-8
φ_coat: 1e-4
r_beam: 8.6 cm
100m F. C.
10 dB input sqz
T_SRM: 16 %

KAGRA+ Sensitivity: **Brown**

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

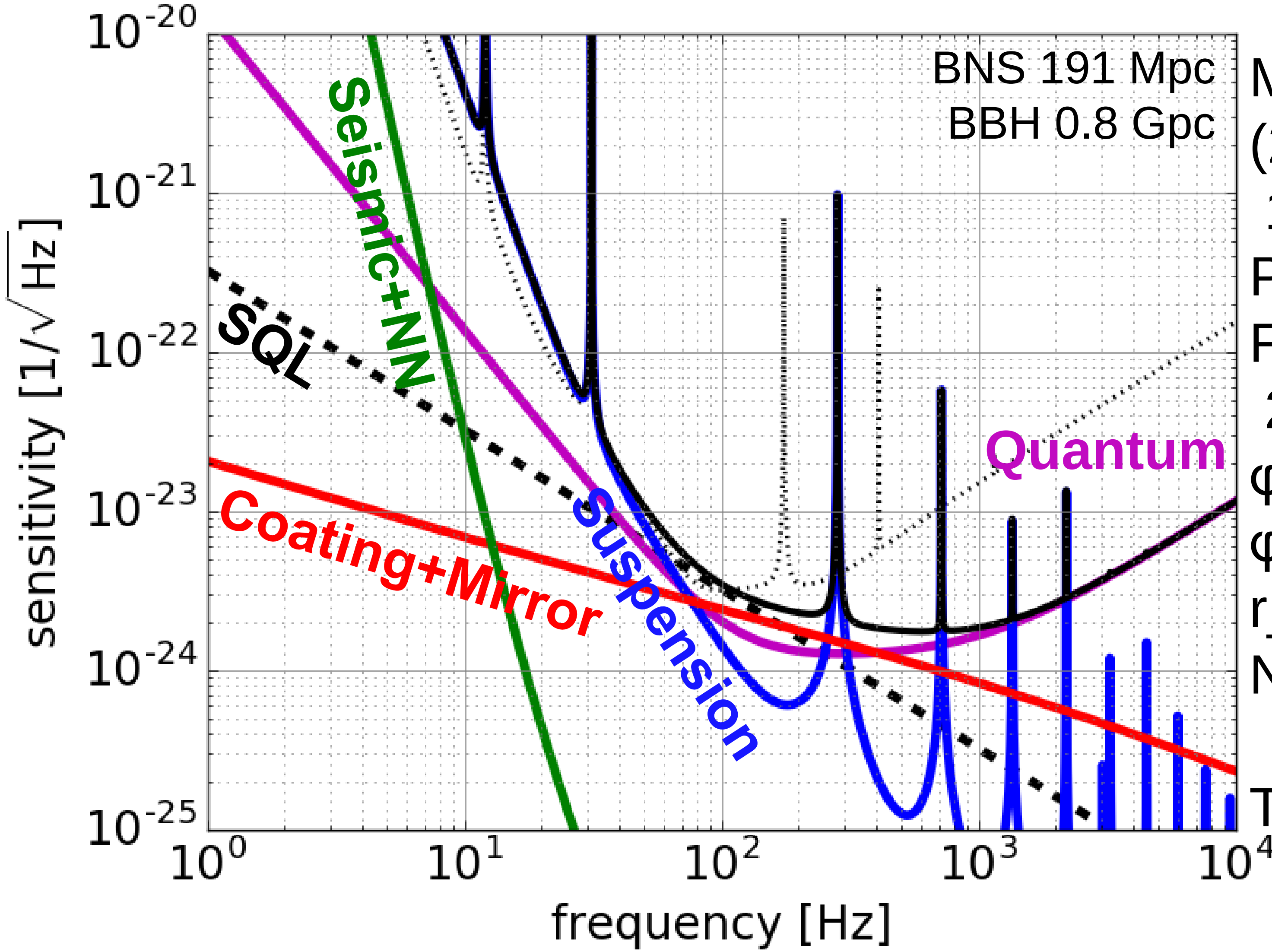


Mass: 23 kg
(22 cm dia.,
15 cm thick)
P_BS: 5.7 W
Fiber: 88 cm,
0.32 mm dia.
φ_susp: 2e-7
φ_coat: 5e-4
r_beam: 3.5 cm
No sqz

T_SRM: 4.35 %

KAGRA+ Sensitivity: Red

- Same test mass, high power, 24 K

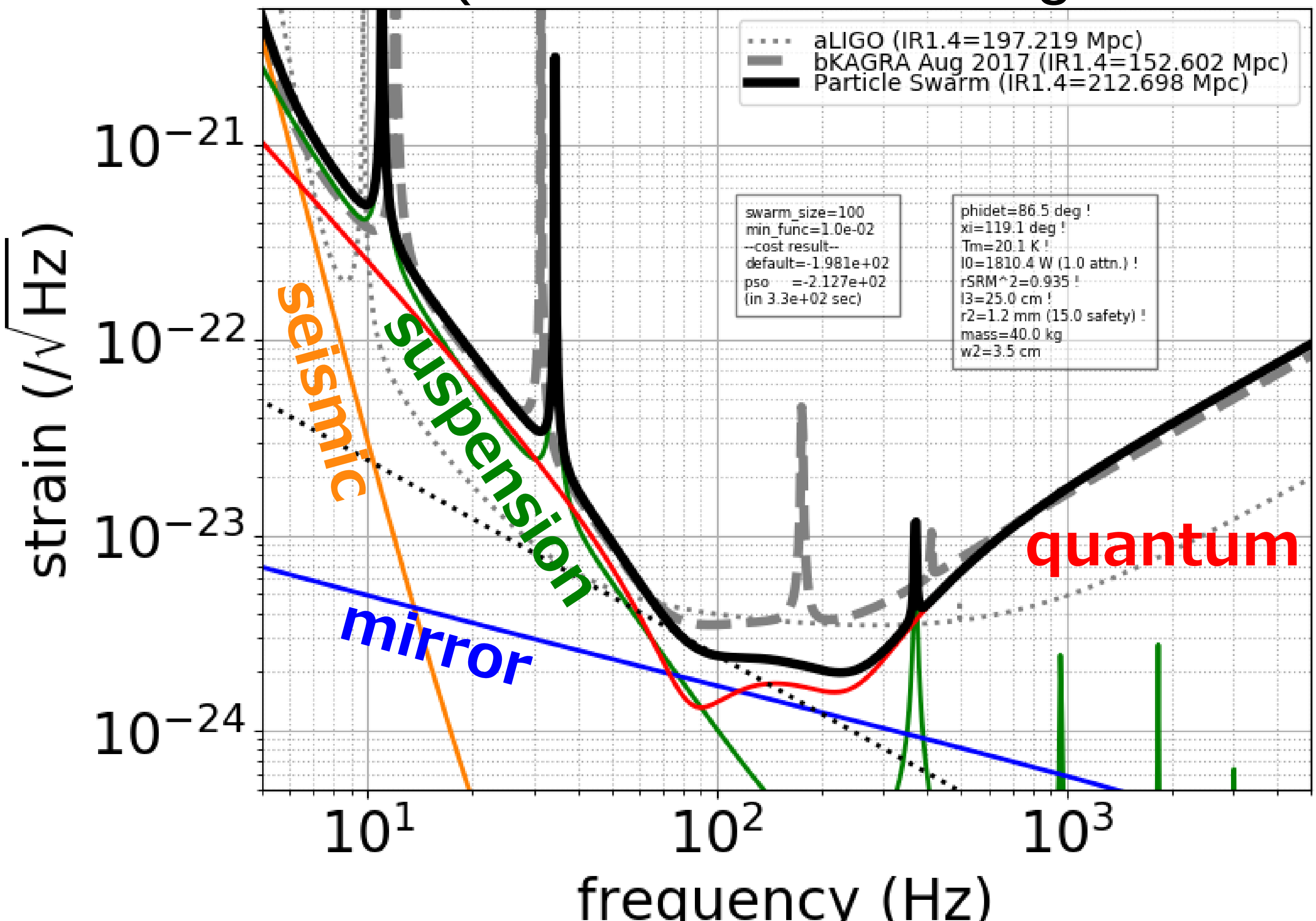


Mass: 23 kg
(22 cm dia.,
15 cm thick)
P_BS: 5.2 kW
Fiber: 20 cm,
2.4 mm dia.
φ_susp: 2e-7
φ_coat: 5e-4
r_beam: 3.5 cm
No sqz

T_SRM: 4.94 %

Plan A: 40 kg Mirror

- Also assumes factor of 2 coating loss angle reduction (no beam size change assumed)

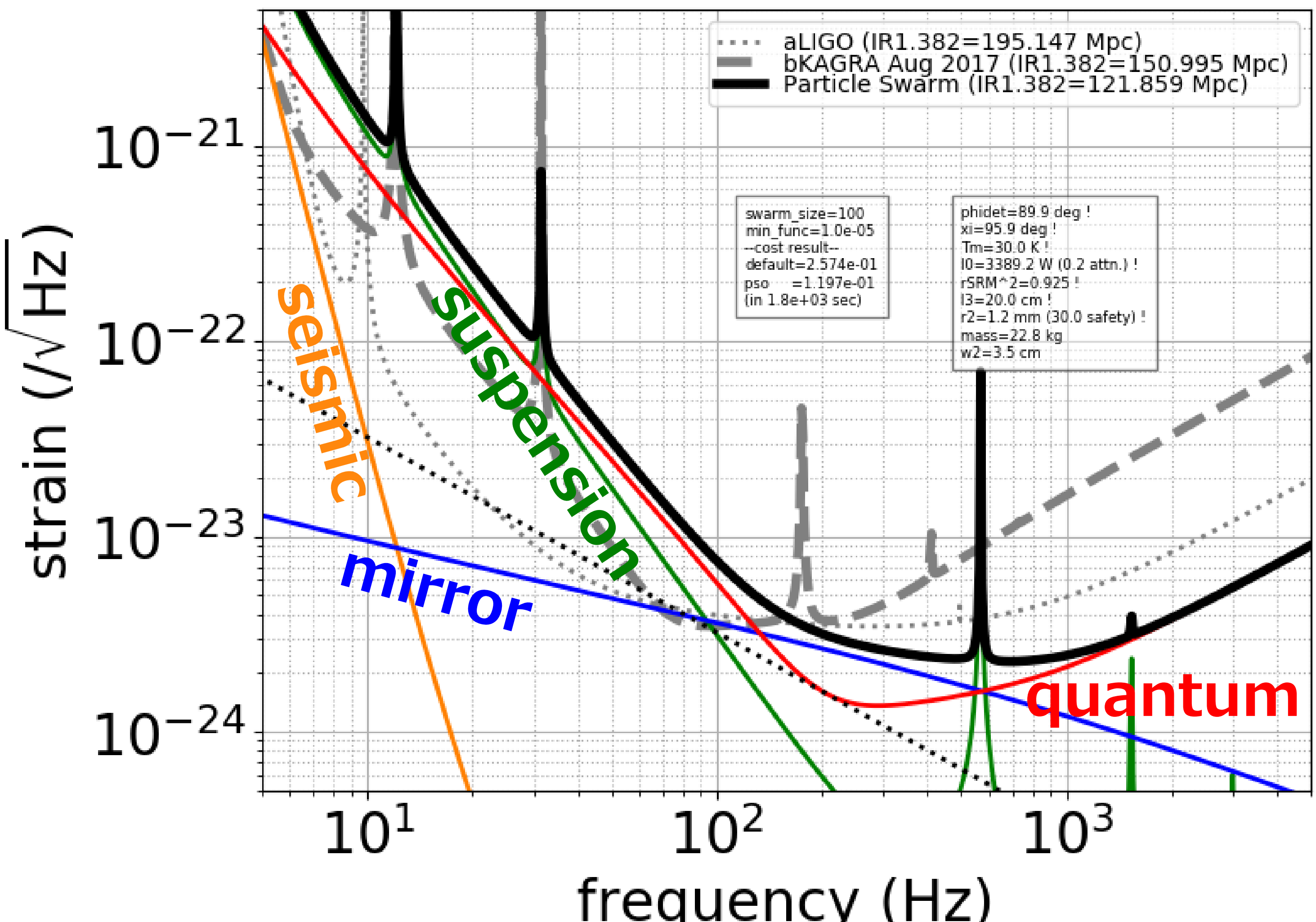


Good for mid frequency improvement → BNS range optimized

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

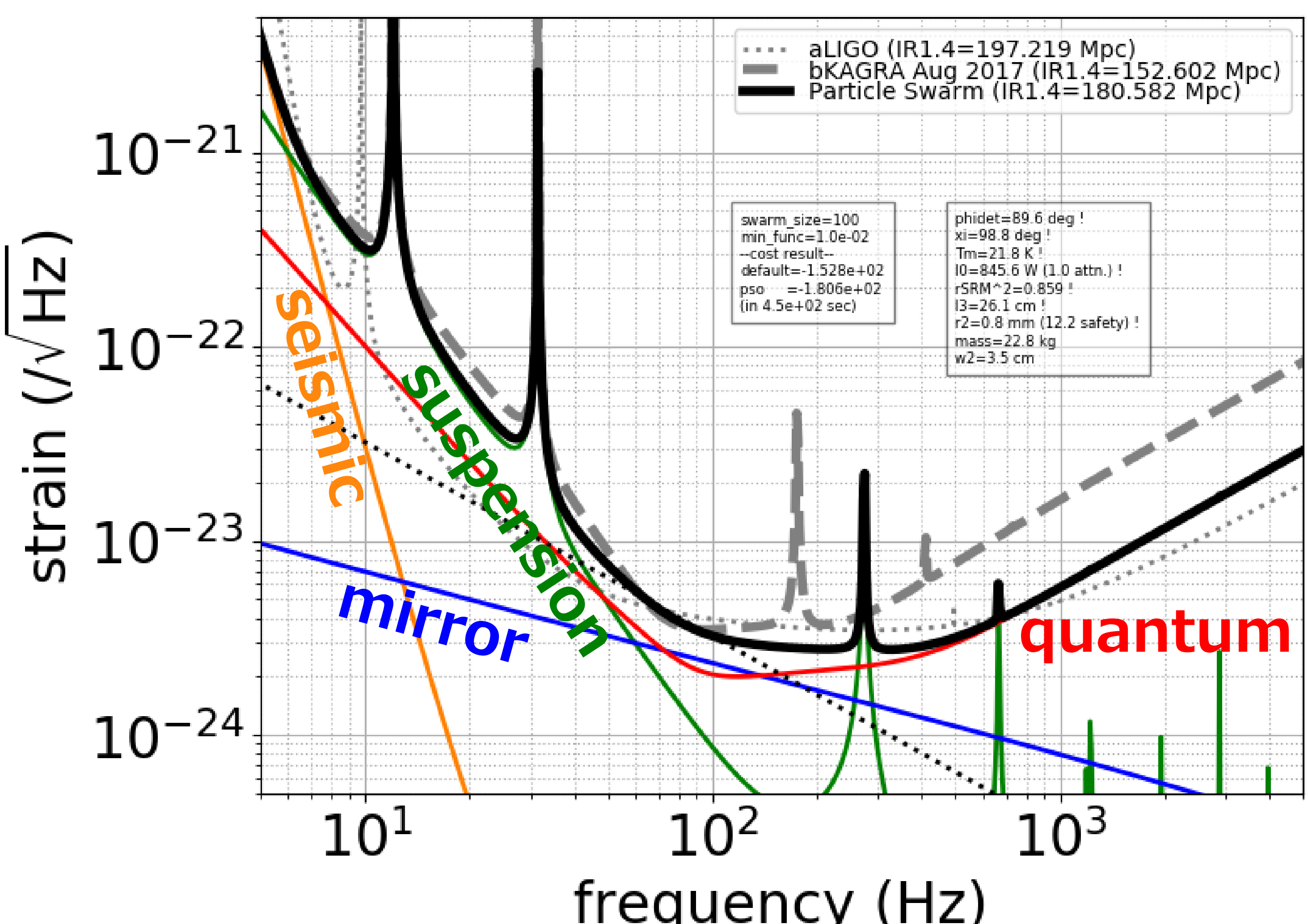


Good for high frequency improvement → BNS range optimized

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

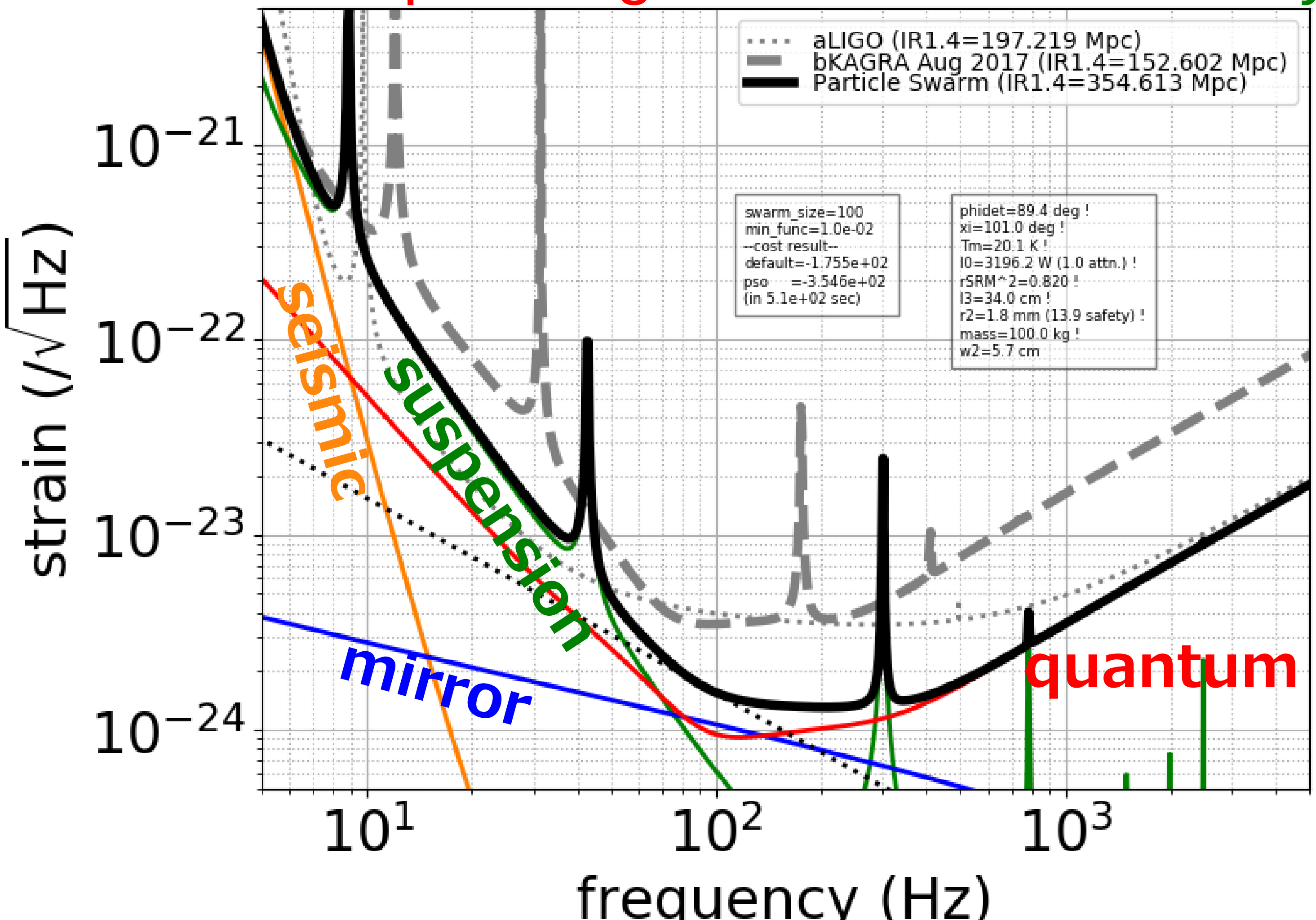


Broadband improvement → BNS range optimized

T=21.8 K
85 W input
thinner fiber
26.1 cm
φ0.8 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