

# Prospects for improving the sensitivity of KAGRA gravitational wave detector

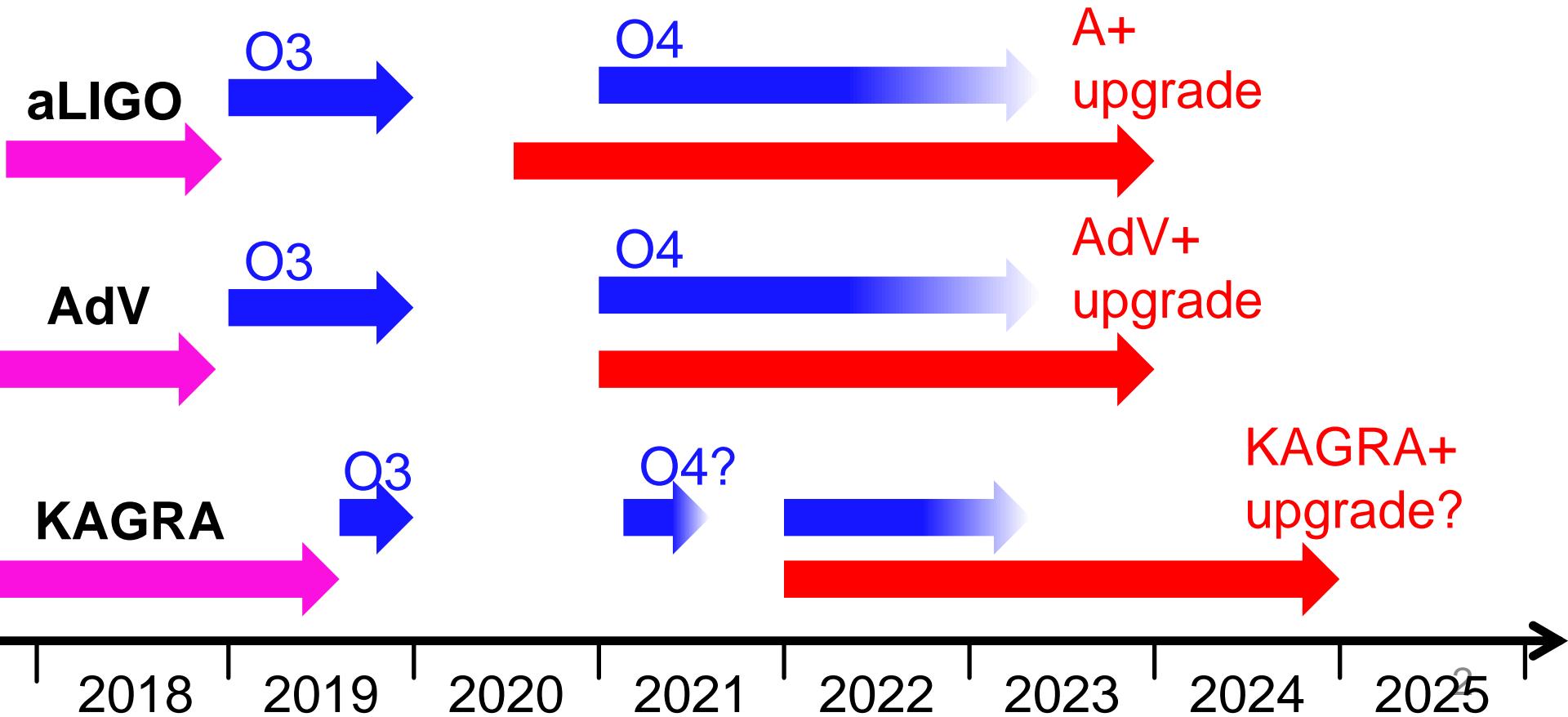
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Masaki Ando, Enomoto, Yutaro Enomoto; Haino, Sadakazu; Hayama, Kazuhiro;  
Hirose, Eiichi; Itoh, Yousuke; Kinugawa, Tomoya; Komori, Kentaro; Leonardi,  
Matteo; Mio, Norikatsu; Nagano, Koji; Nakano, Hiroyuki; Nishizawa, Atsushi;  
Sago, Norichika; Shibata, Masaru; Shinkai, Hisaaki; Takeda, Hiroki; Tanaka,  
Takahiro; Tanioka, Satoshi; Wei, Li-Wei; Yamamoto, Kazuhiro

# Upgrading Current GW Detectors

- Gravitational wave astronomy has begun
- Sensitivity improvements allow **more detections** and **more precise** source parameter estimation

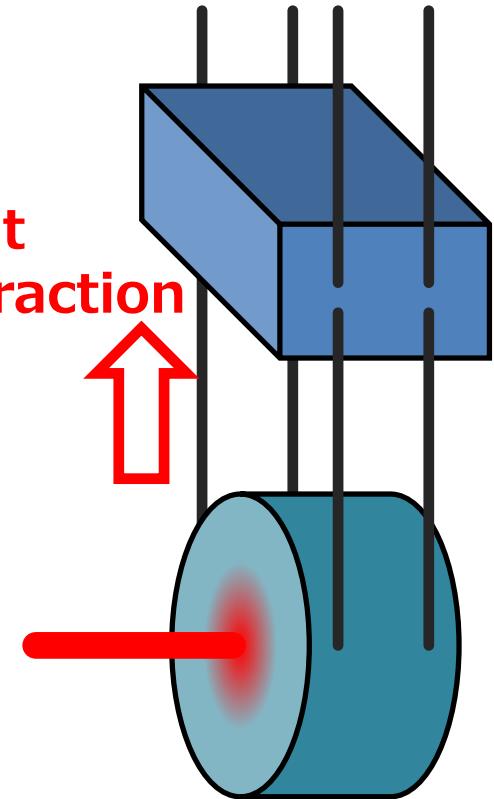


# Upgrading KAGRA is Tricky

- 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 thermal noise reduction

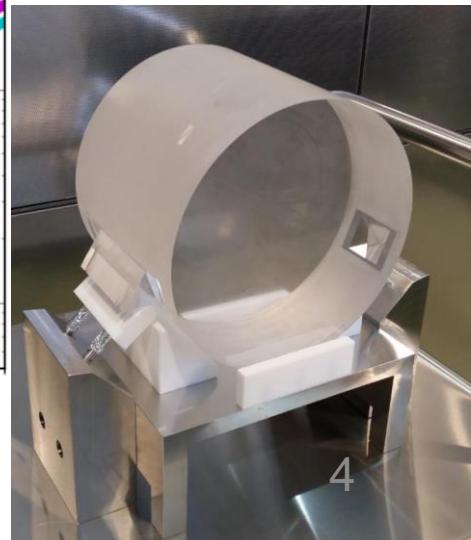
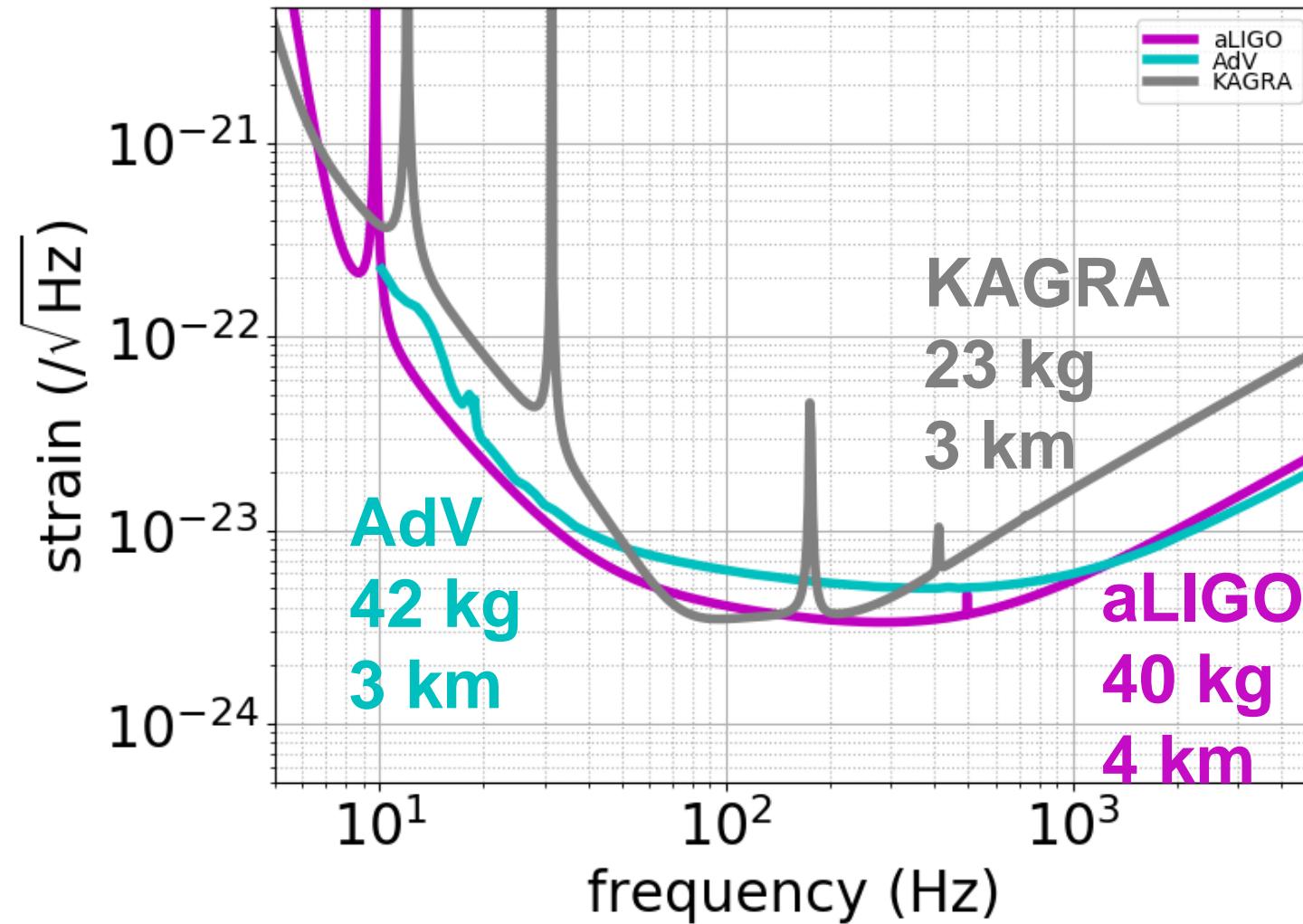
**Dilemma**

thicker and shorter  
for heat extraction



# 2G Sensitivity Comparison

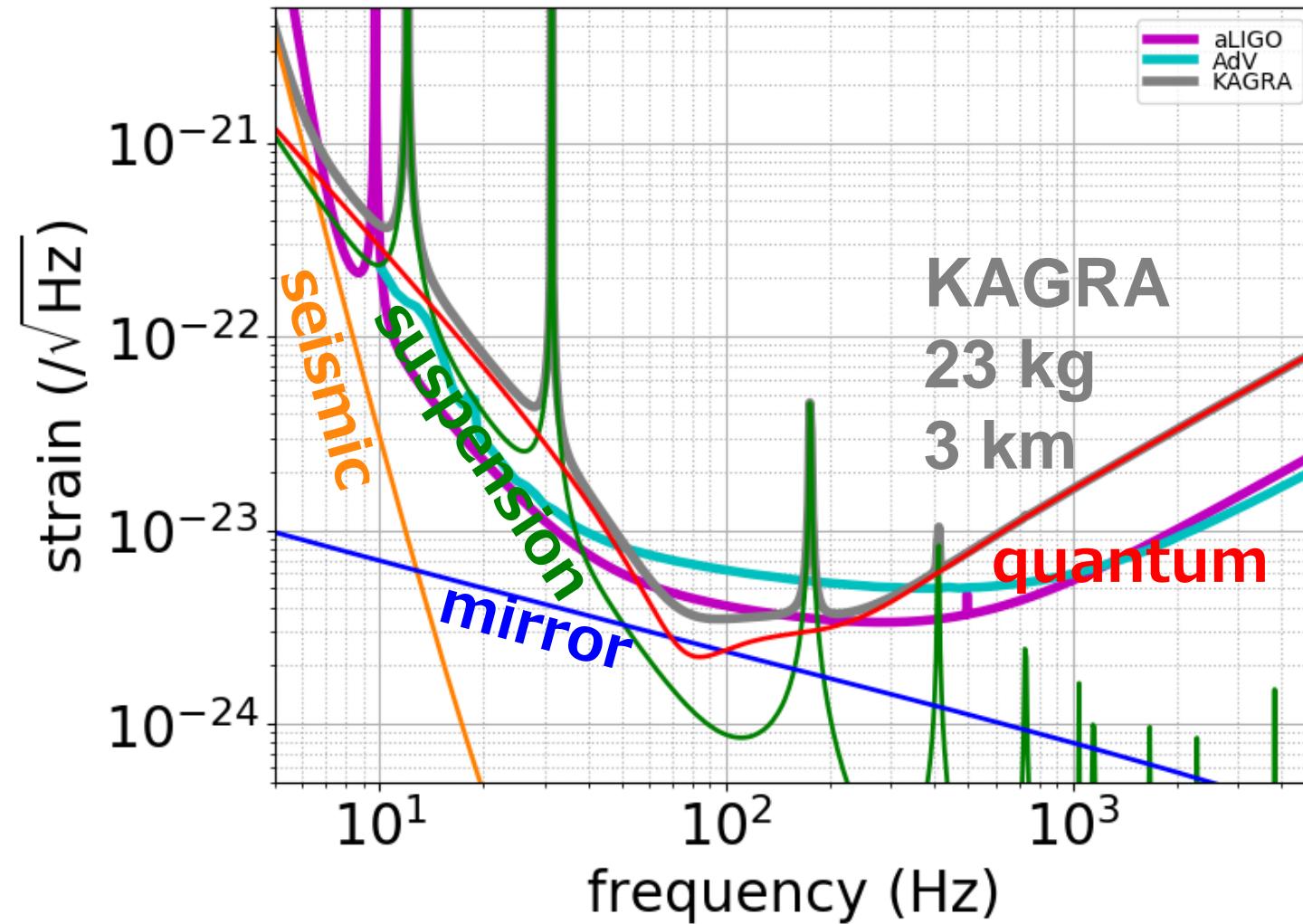
- Not good at low freq. because of **thick and short** fiber (35 cm,  $\varphi 1.6$  mm) to extract heat, and **lower mass**



23 kg was the largest available sapphire mirror

# 2G Sensitivity Comparison

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

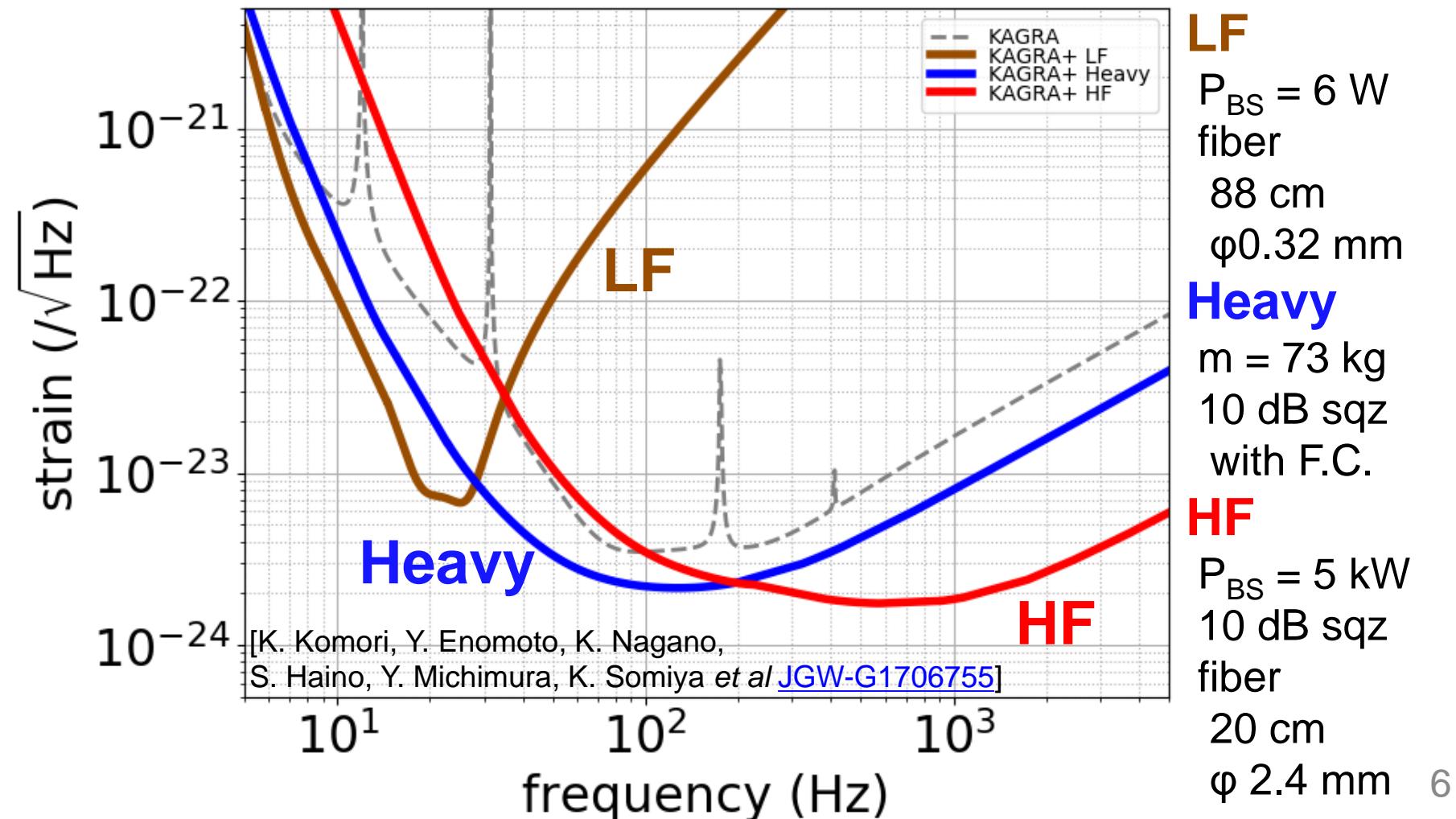


23 kg was  
the largest  
available  
sapphire  
mirror



# 3 KAGRA+ Concepts to Start With

- Low power to focus on **low frequency**, high power to focus on **high frequency**, and **heavier mass**



# Science Case Study

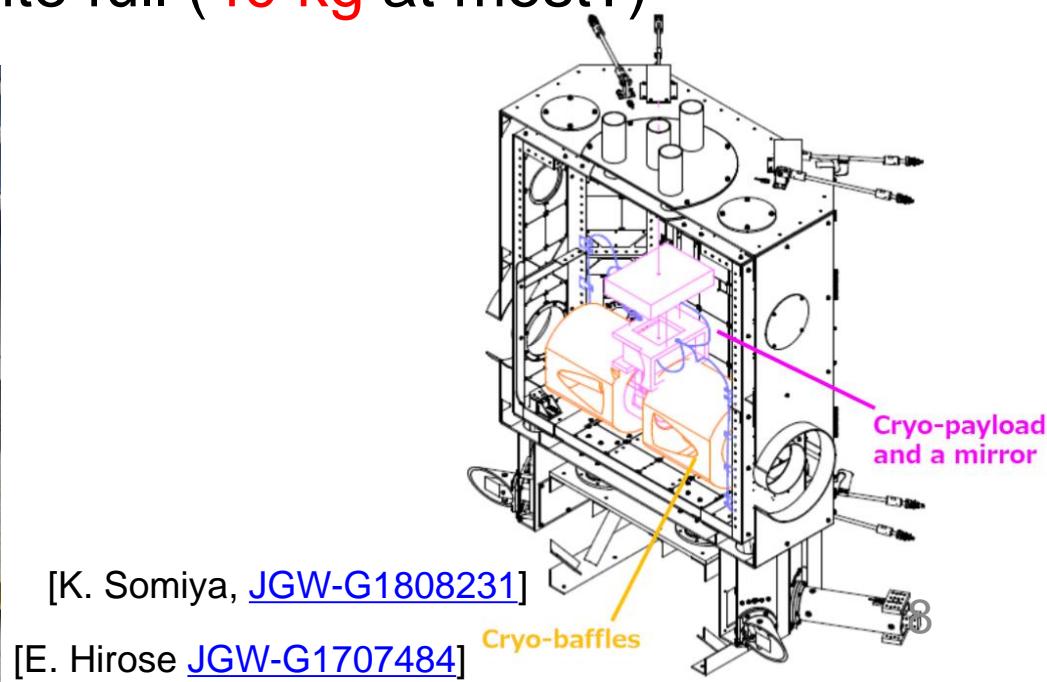
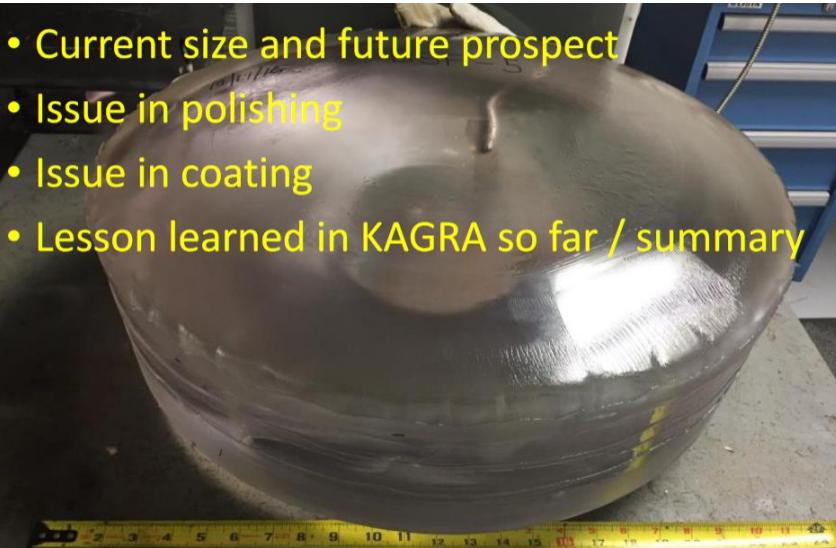
- Although LF has the best inspiral range for heavy BBH ( $\sim 100M_{\text{sun}}$ ), narrow band was **not favorable**

	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](#)]

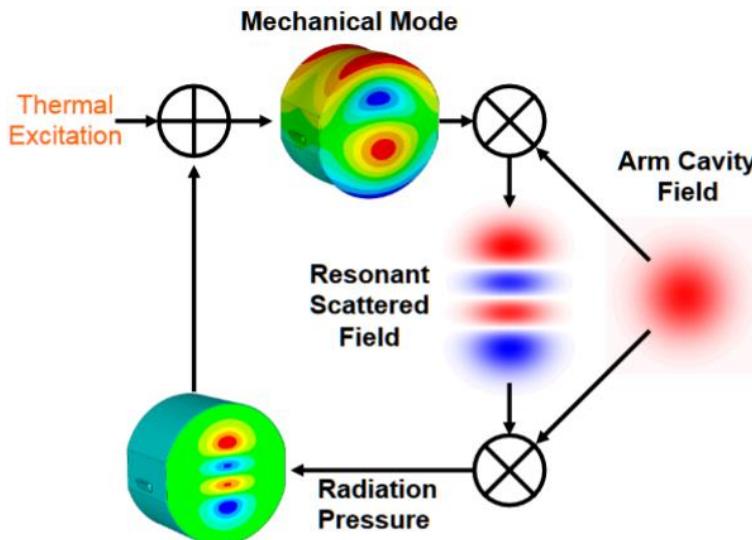
# Feasibility Study: Heavier Mirror

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

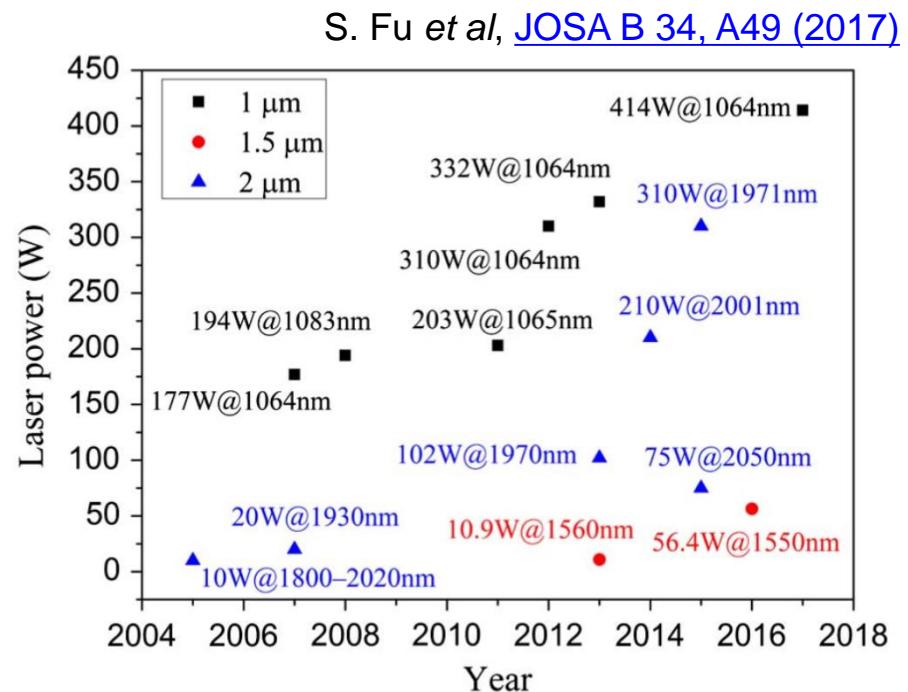


# Feasibility Study: High Power

- 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?



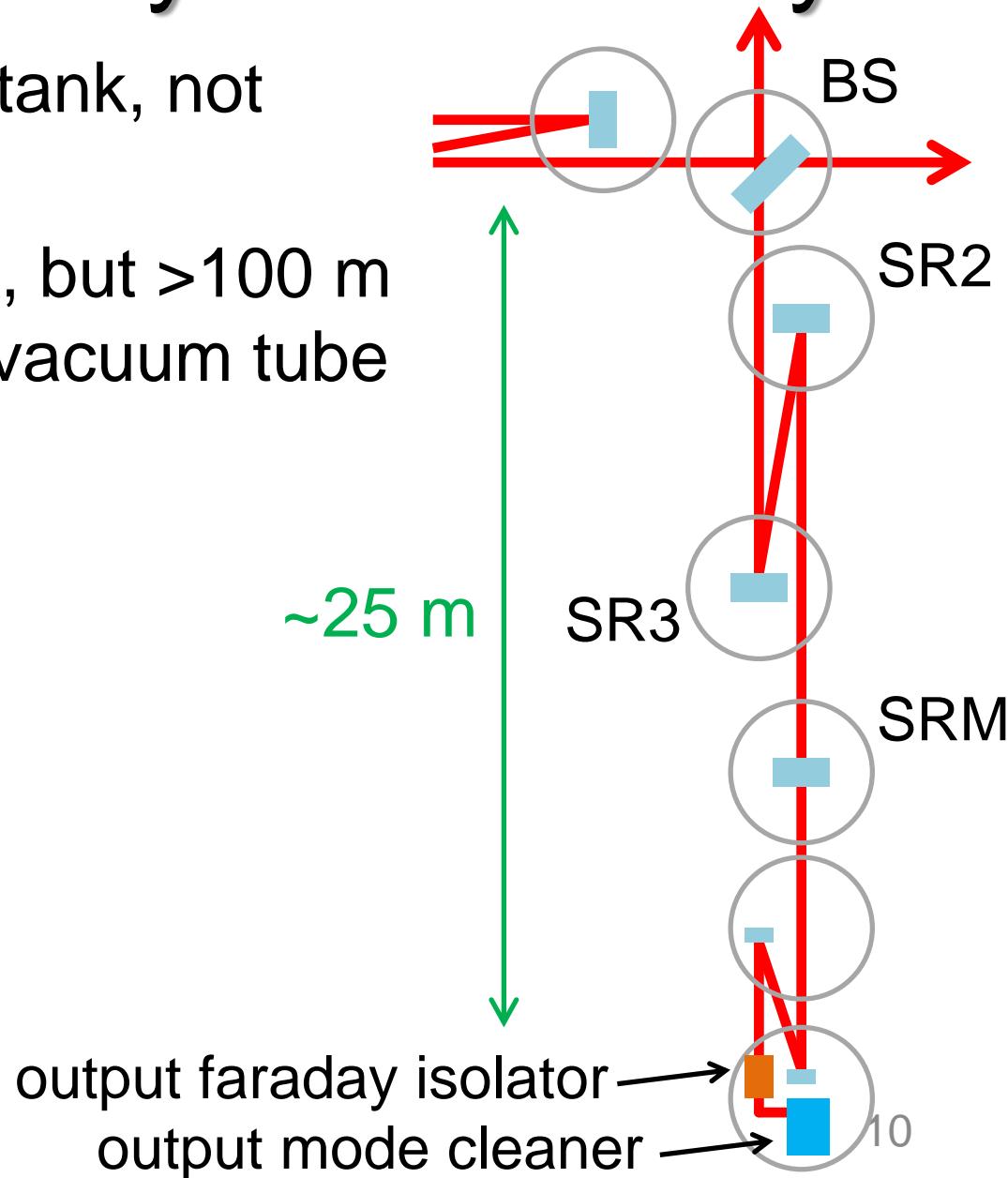
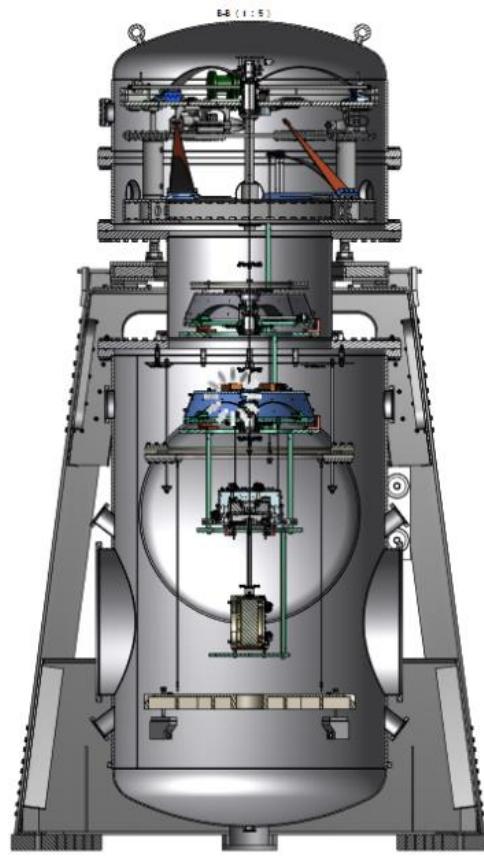
M. Evans et al, [PRL 114, 161102 \(2016\)](#)



**Fig. 7.** Output power evolution of CW single-frequency amplifiers in all-fiber format operating in 1, 1.5, and 2  $\mu\text{m}$  regions.

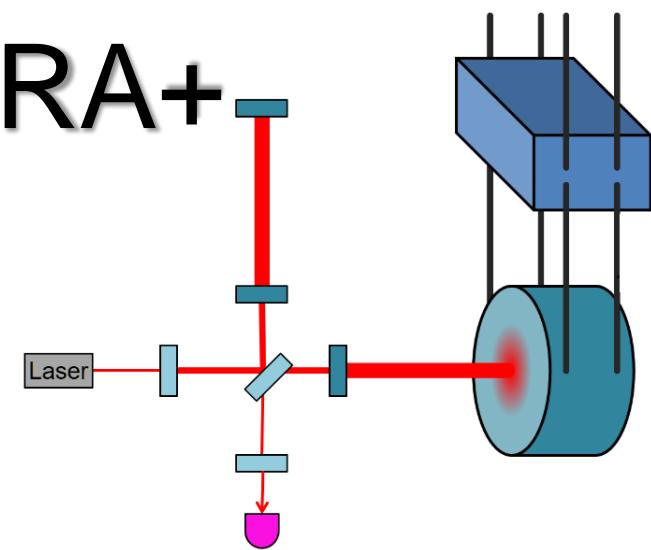
# Feasibility Study: Filter Cavity

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



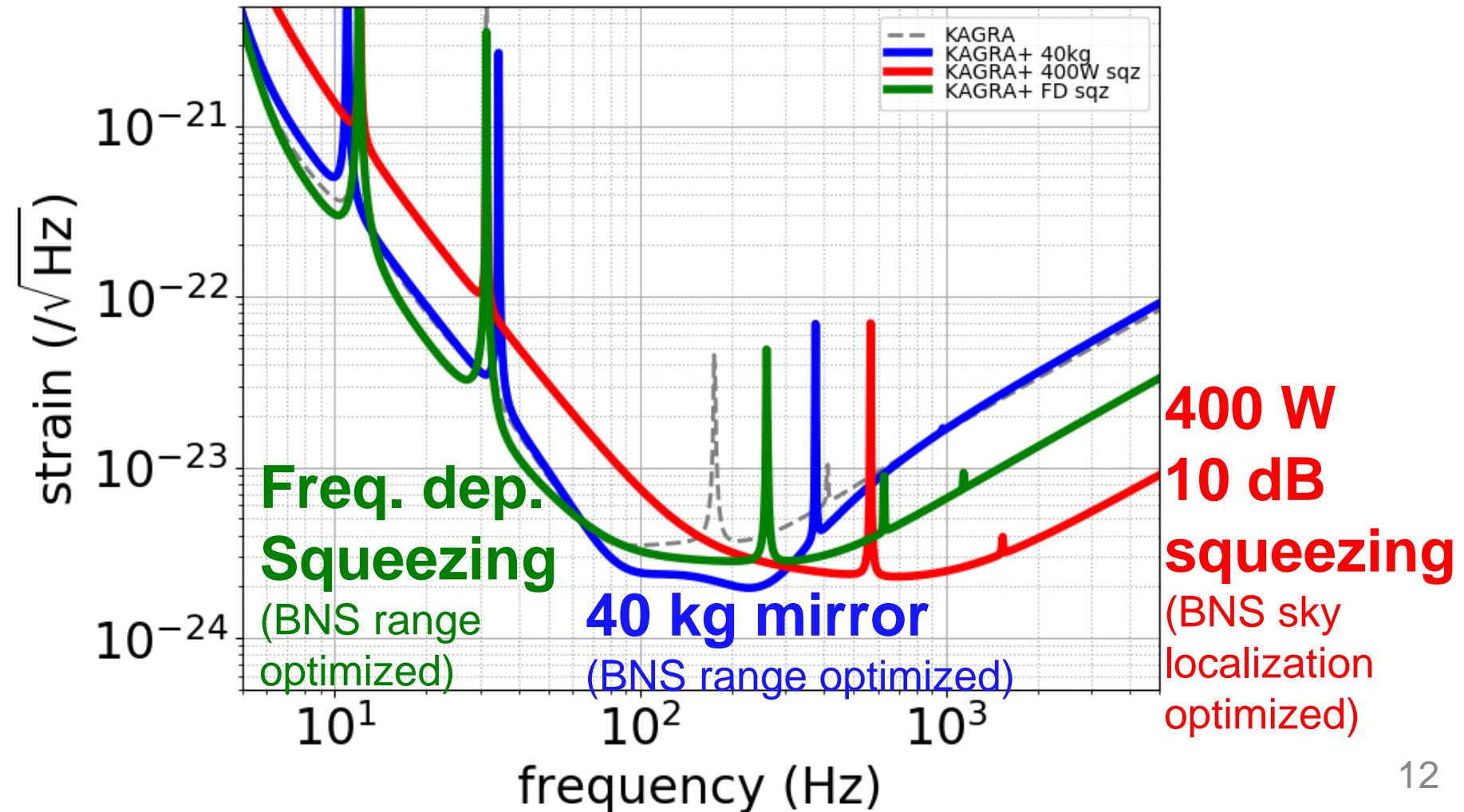
# Near Term KAGRA+

- Within ~5 years, ~\$5M
- 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



# Near Term Candidates

- Within ~5 years, ~\$5M



# Summary of Near Term Plans

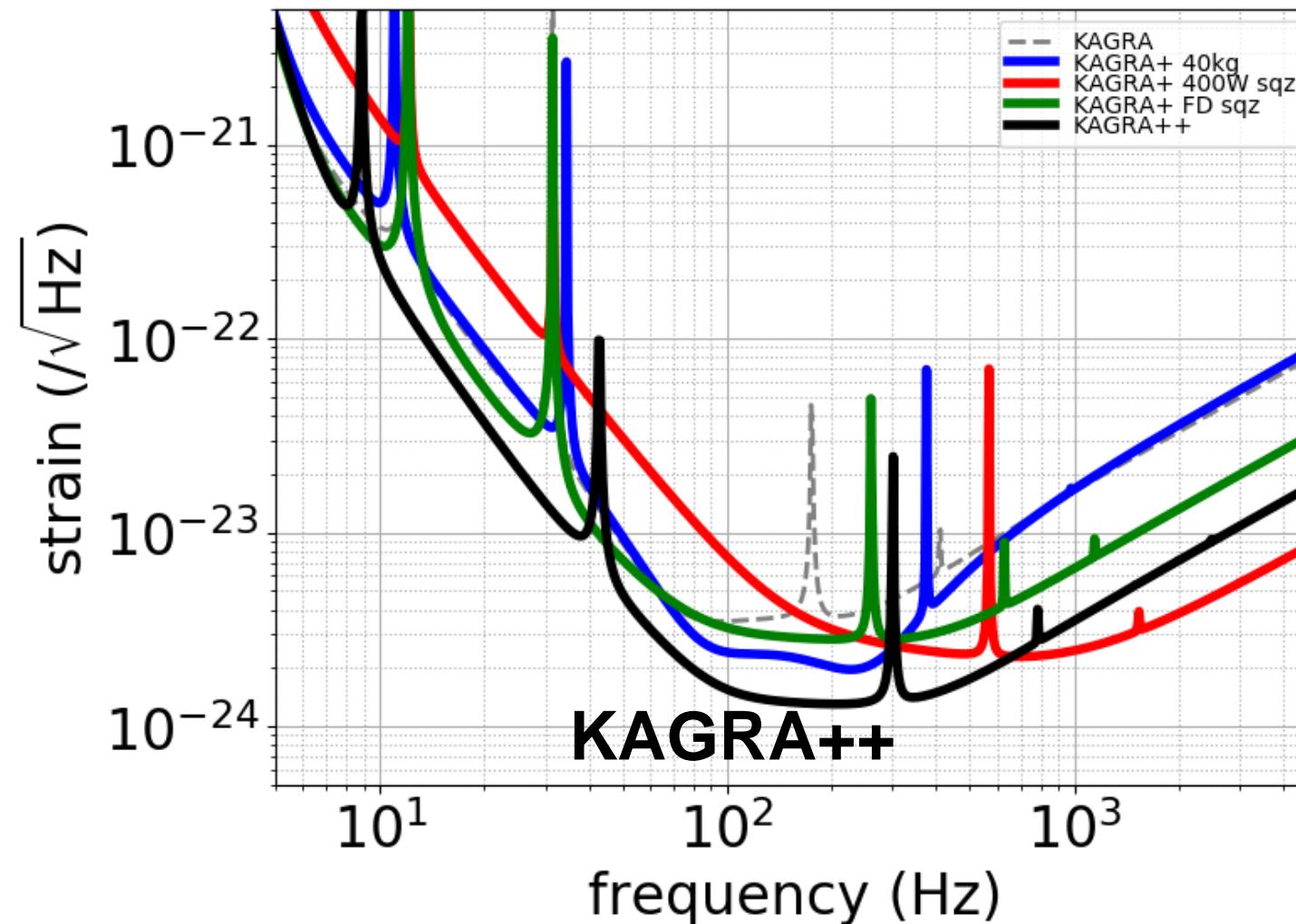
- A. New mirror takes time to fabricate
- B. High power operation is tough
- C. Does it fit in the facility?



	Inspiral range (Mpc)			BNS localize (deg <sup>2</sup> )
	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

# Longer Term Candidate

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

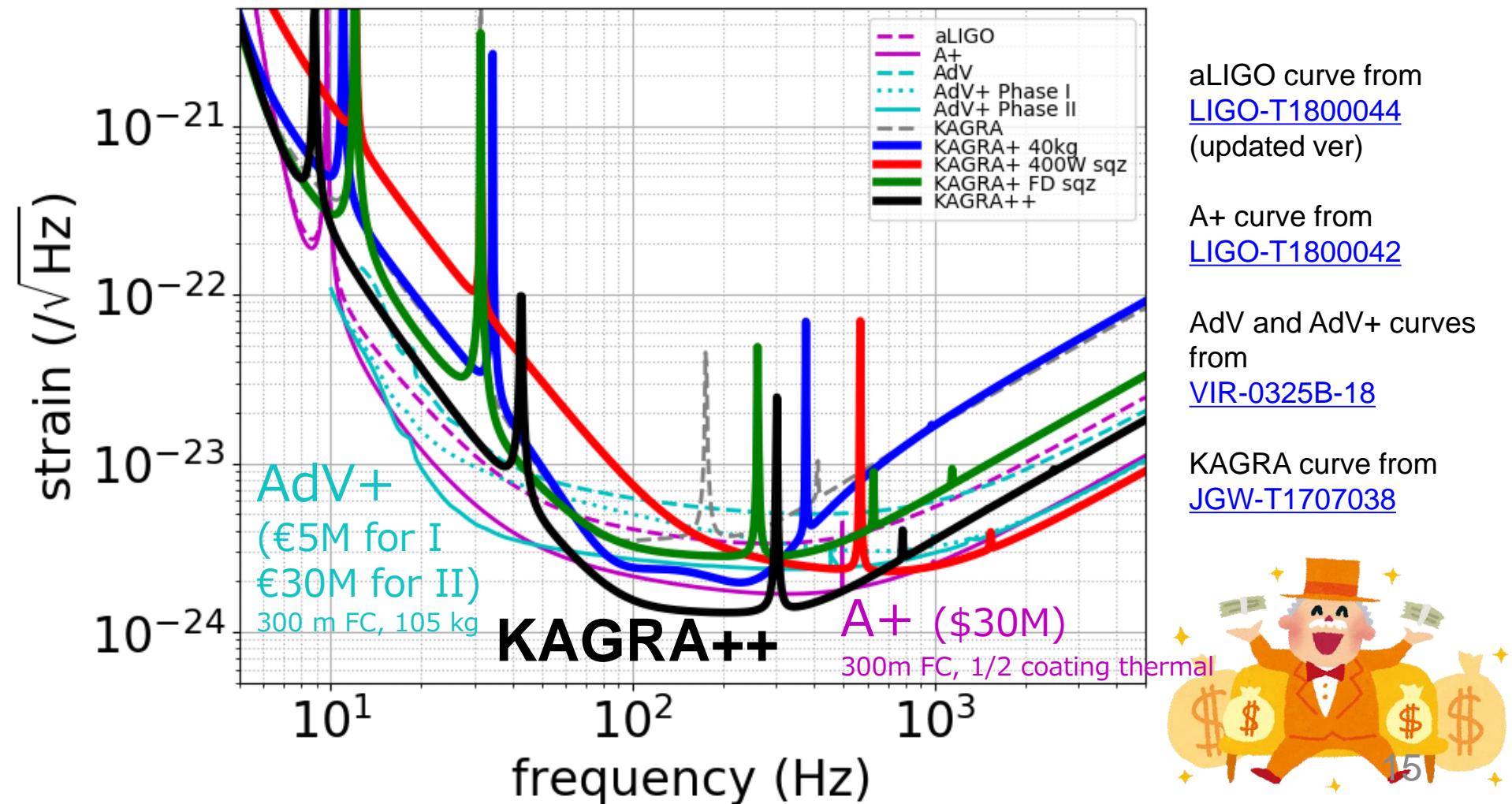


BNS range reaches  
**355 Mpc**

Within  
~ 10 years  
~ \$20M?

# Comparison between 2G and 2G+

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



# Possible Upgrade Strategy

- Still under discussion among KAGRA collaboration

Filter cavity R&D

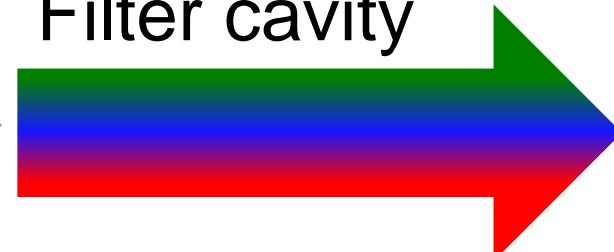
Heavier mirror R&D, fabrication

Coating R&D

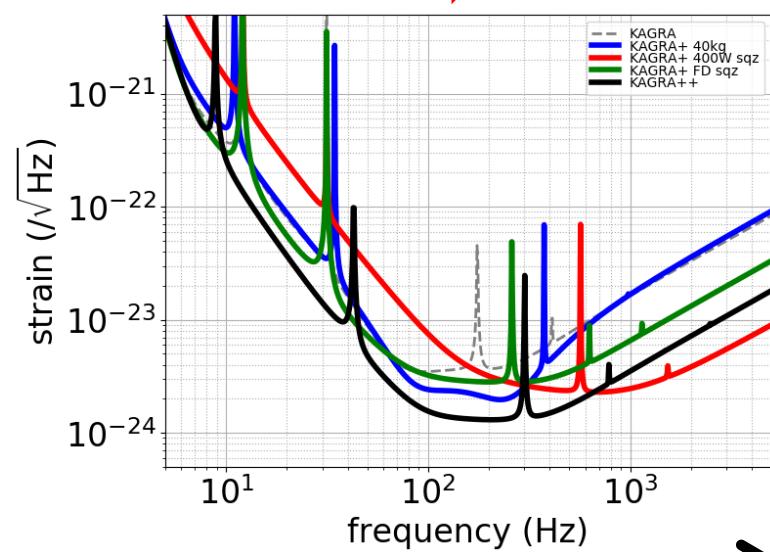
Higher power R&D

Realize KAGRA

Mirror upgrade  
Filter cavity



Higher power  
upgrade



2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 16

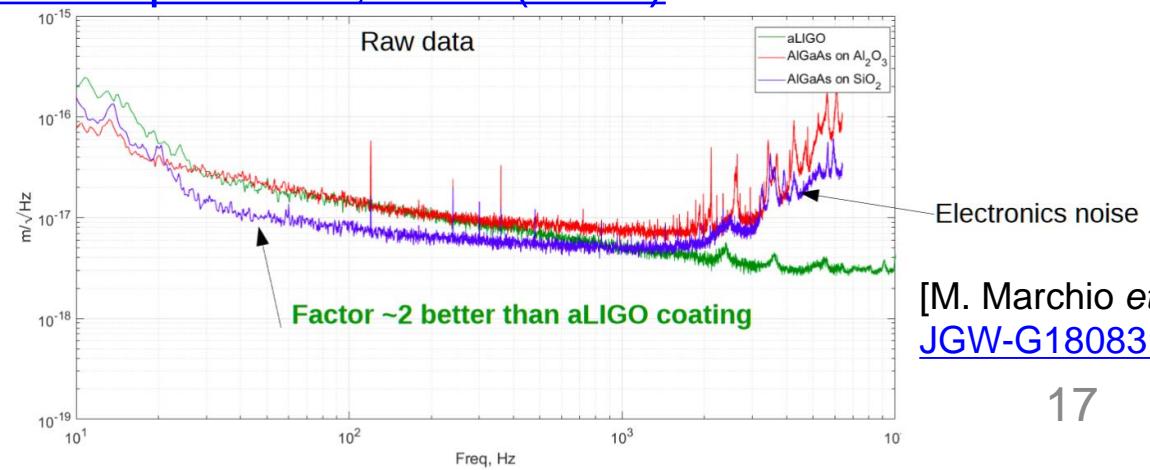
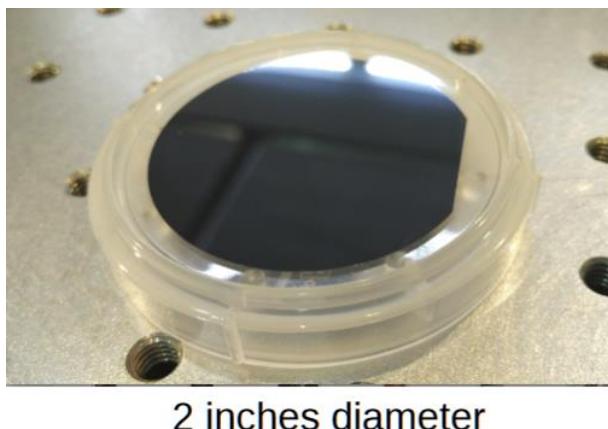
# R&D Activities for Upgrades

- 300 m filter cavity experiment at TAMA300  
E. Capocasa *et al*, [PRD 93 082004 \(2016\)](#) and [arXiv:1806.10506](#)



[M. Leonardi *et al*,  
[JGW-G1808310](#)]

- Characterization of crystalline coating on sapphire  
M. Marchio et al, [Optics Express 26, 6114 \(2018\)](#)



# R&D Activities for Upgrades

- Coating thermal noise experiment at cryogenic temperatures
- Quantum radiation pressure noise experiment with mg-scale mirror and bar

N. Matsumoto, K. Komori *et al*,  
[PRA 92, 033825 \(2015\)](#)

- Demonstration of parametric signal amplification

K. Somiya *et al*,  
[Phys. Lett. A 380, 521 \(2016\)](#)

..... and more



Cryostat for coating thermal noise  
(Photo by S. Tanioka)



10 mg bar  
(Photo by K. Komori)

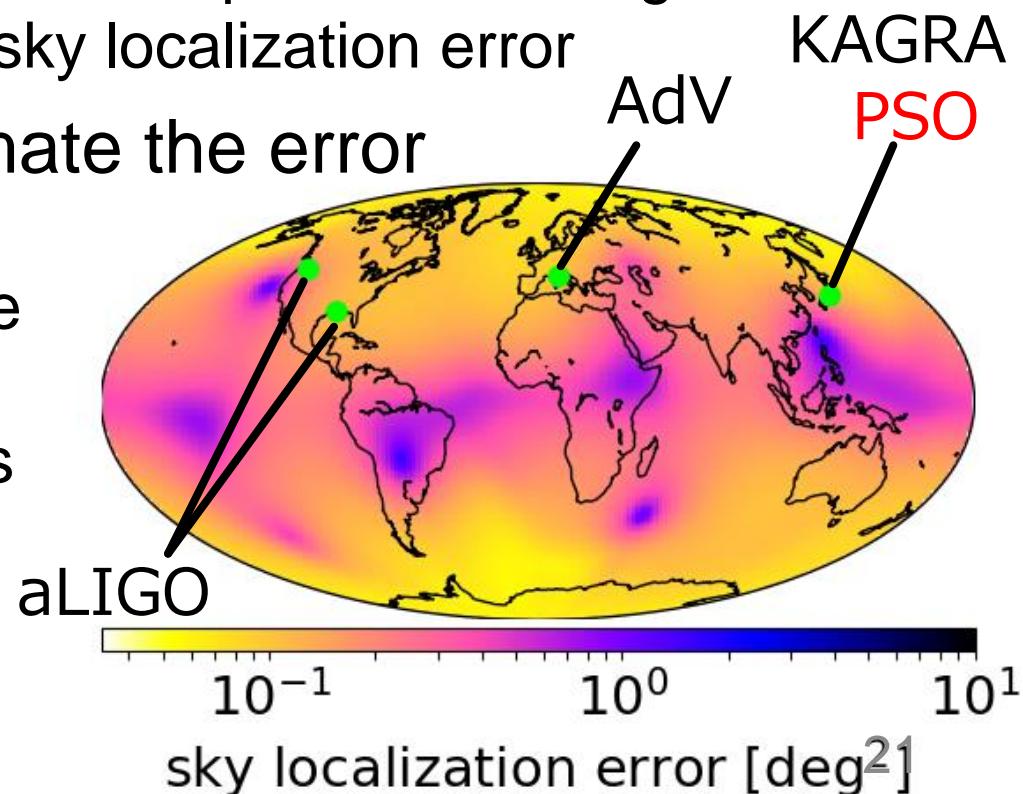
# Summary

- Study of **KAGRA upgrade** aiming for realization in ~2024 has started last year
- **Cryogenic** detectors have unique potential to improve the sensitivity
- Based on scientific target and technical feasibility, we have studied **realistic** near term upgrade plans
  - heavier mirror
  - higher power
  - frequency dependent squeezing
- **Further upgrade possible** with more time and money
- Strategy **under discussion** in KAGRA collaboration
- Quite active **R&D** is on going

# Supplementary Slides

# Sky Localization Optimization

- Cost function:  
**sky localization of GW170817-like binary**
  - 1.25-1.5 Msun at 40 Mpc, inclination 28 deg
  - zero spins, no precession
  - **108 sets** of sky location and polarization angle to derive median of sky localization error
- **Fisher matrix** to estimate the error
  - inspiral waveform to 3.0 PN in amplitude
  - 3.5 PN in phase
  - 11 binary parameters
- **HLVK** global network



# Fisher Matrix Analysis

- Fisher matrix

$$\Gamma_{ij} = 4\Re \int_{f_{\min}}^{f_{\max}} \sum_k \frac{\partial h_k^*(f)}{\partial \lambda^i} \frac{\partial h_k(f)}{\partial \lambda^j} \frac{df}{S_{n,k}(f)}$$

- Covariance

$$\sqrt{\langle (\delta \lambda^i \delta \lambda^j) \rangle} = \sqrt{(\Gamma^{-1})^{ij}}$$

- 11 binary parameters considered

`mc`: chirp mass

`eta`: symmetric mass ratio

`tc, phic`: time and phase for coalescence

`dL`: luminosity distance

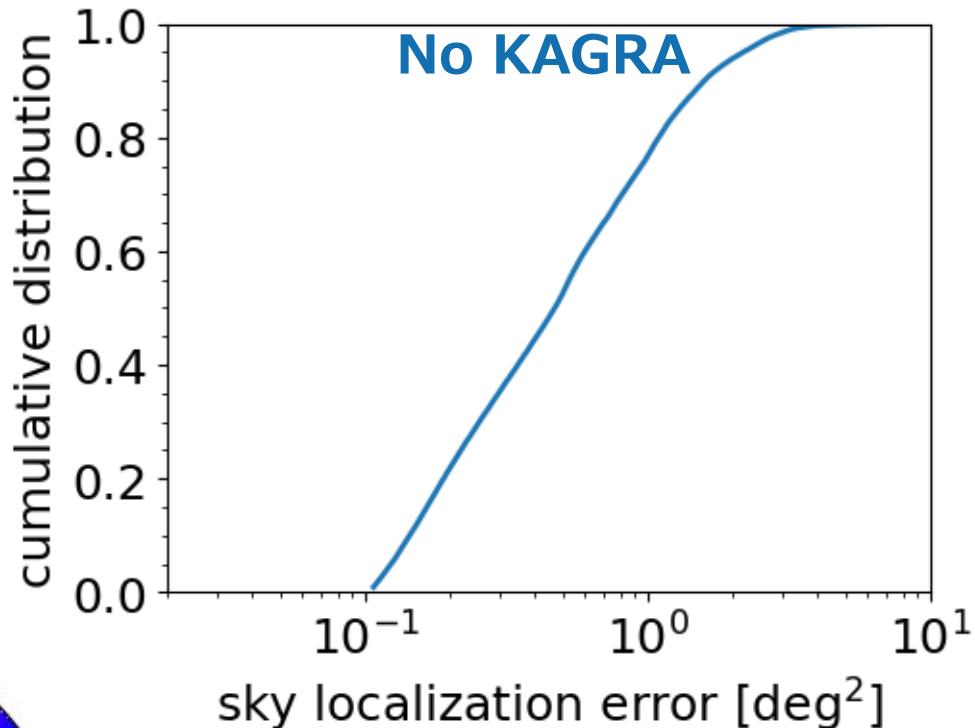
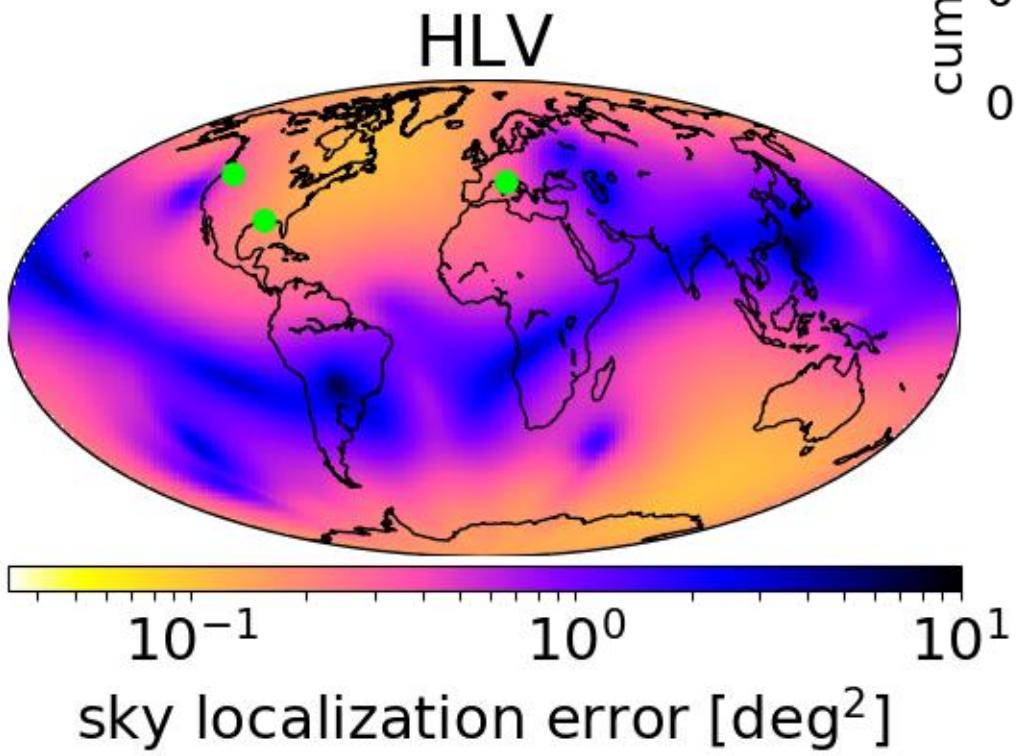
`chis, chia`: symmetric/asymmetric spin     $\chi_{s/a} = (\chi_1 \pm \chi_2)/2$

`thetas, phis`: colatitude / longitude of source

`cthetai`: inclination angle

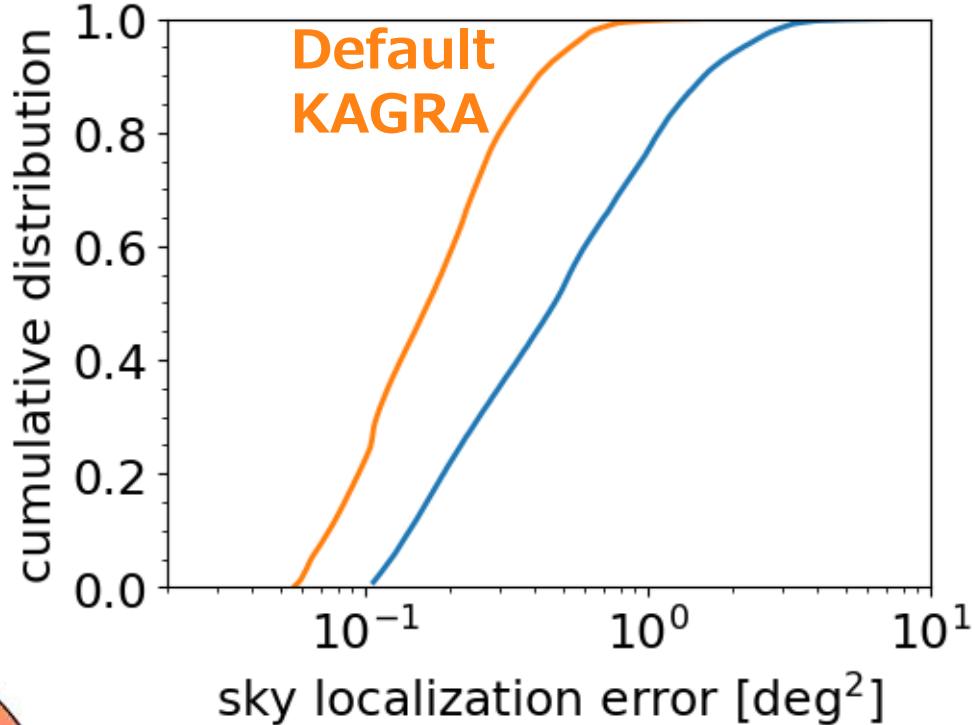
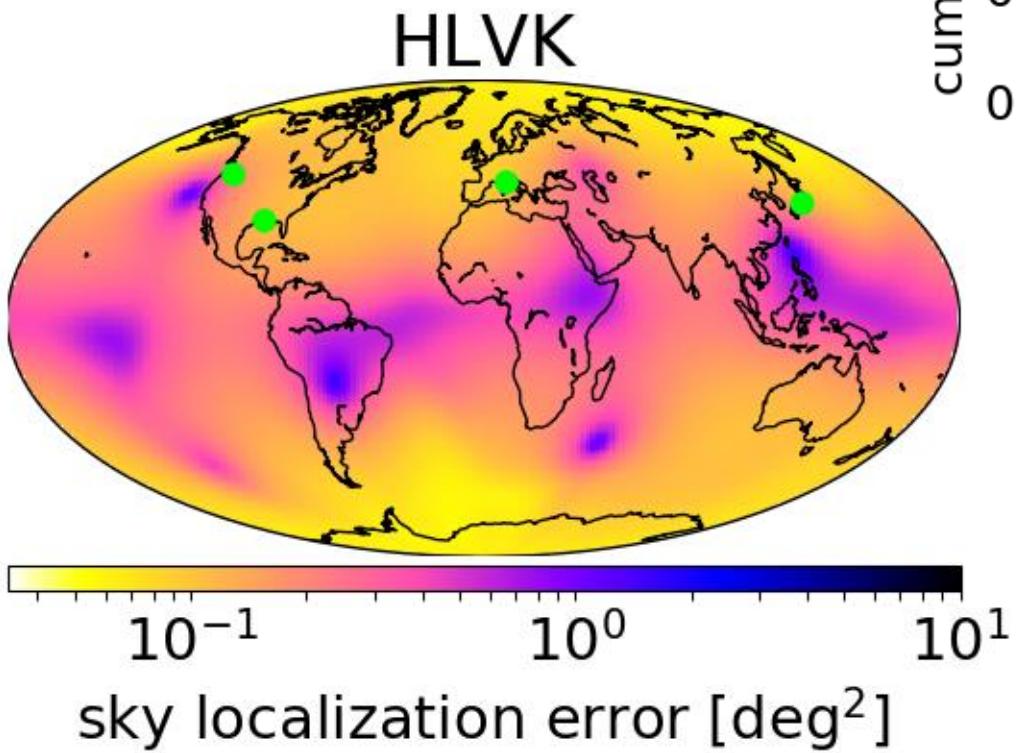
`psip`: polarization angle

# Sky Localization with HLV



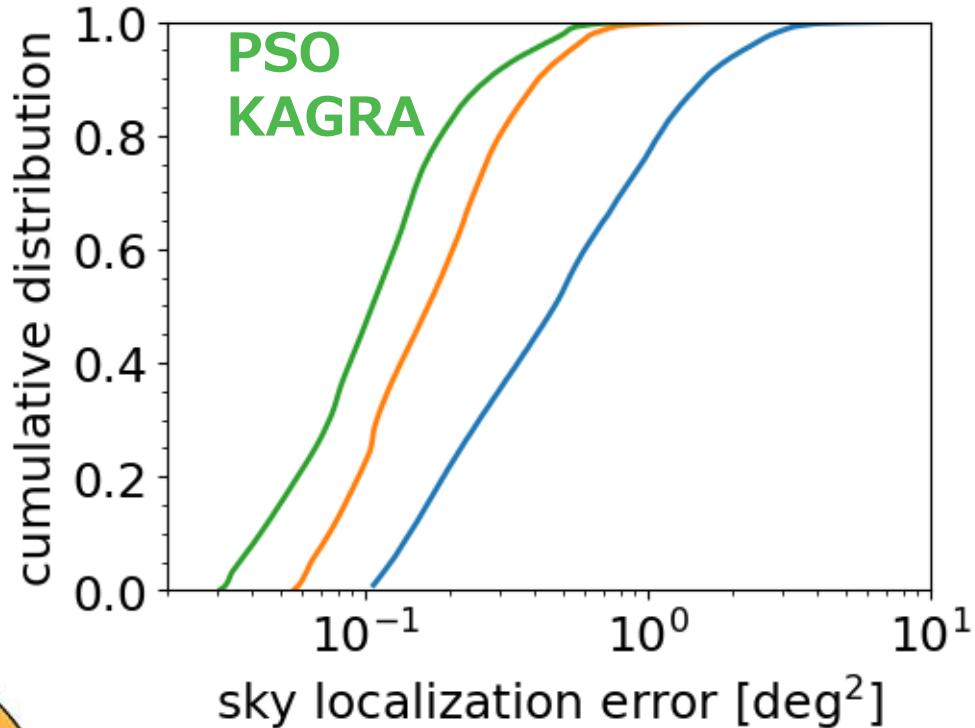
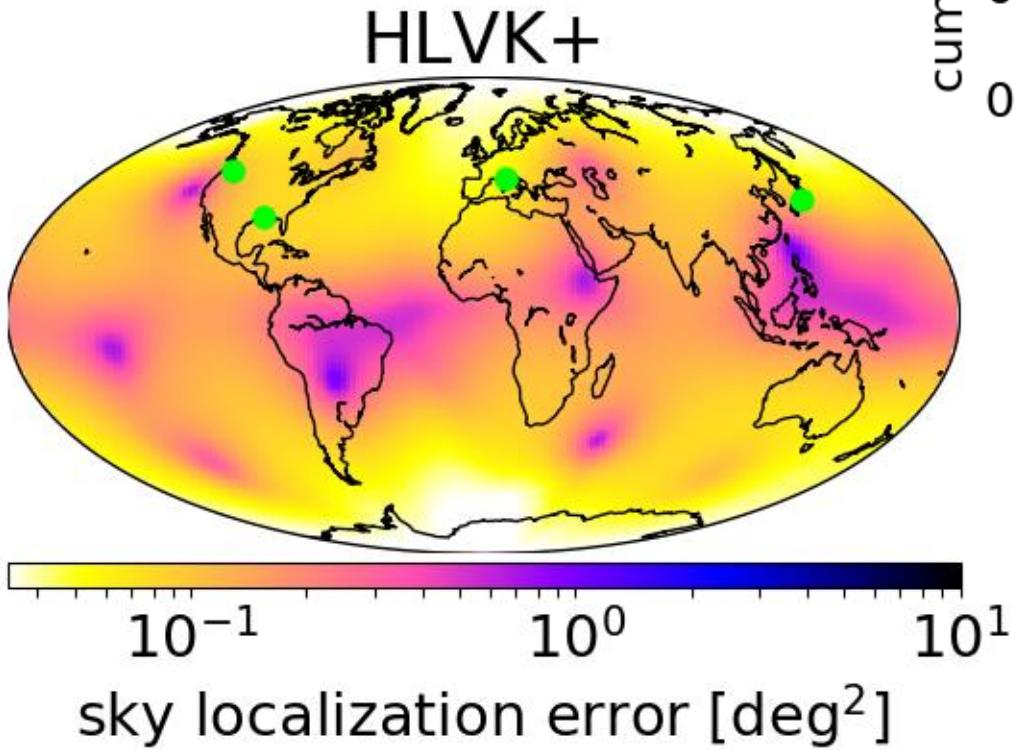
	median
HLV	$0.472 \text{ deg}^2$
HLVK	
HLVK+	

# Sky Localization with HLVK



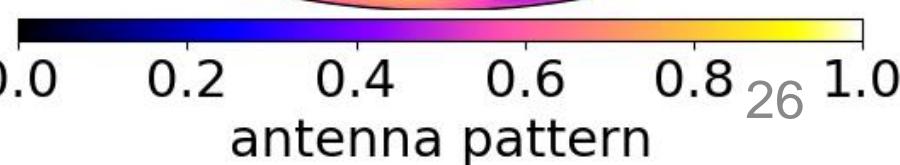
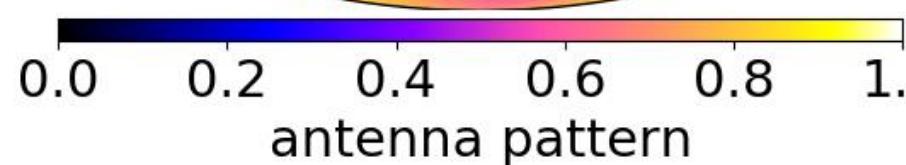
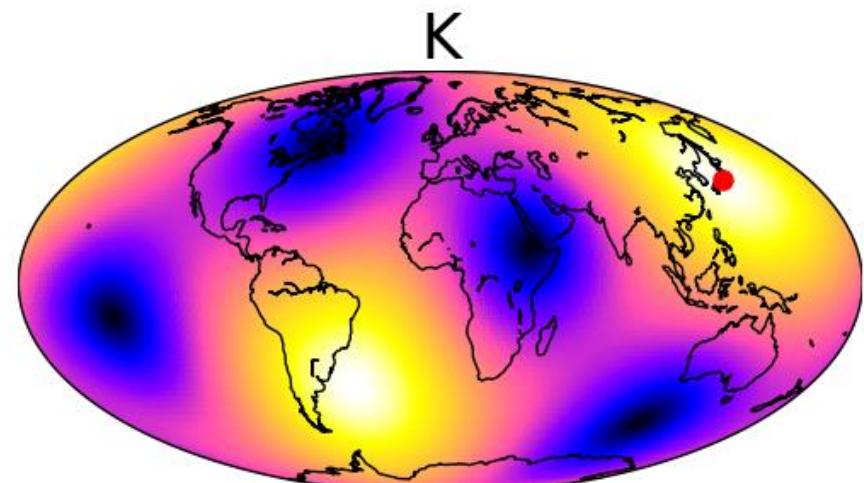
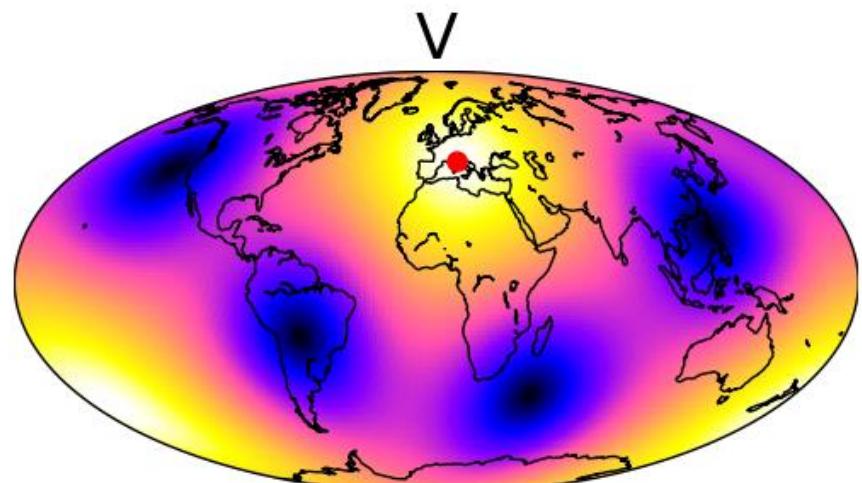
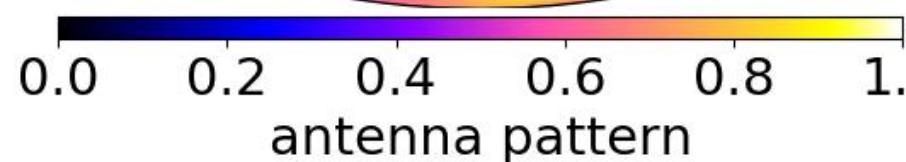
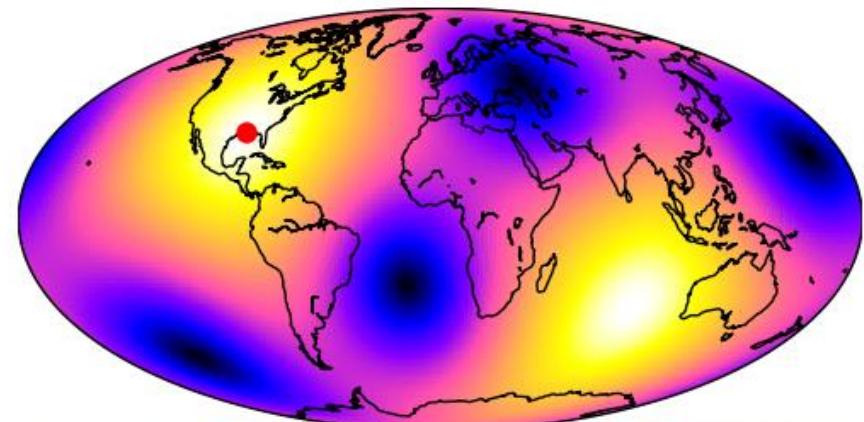
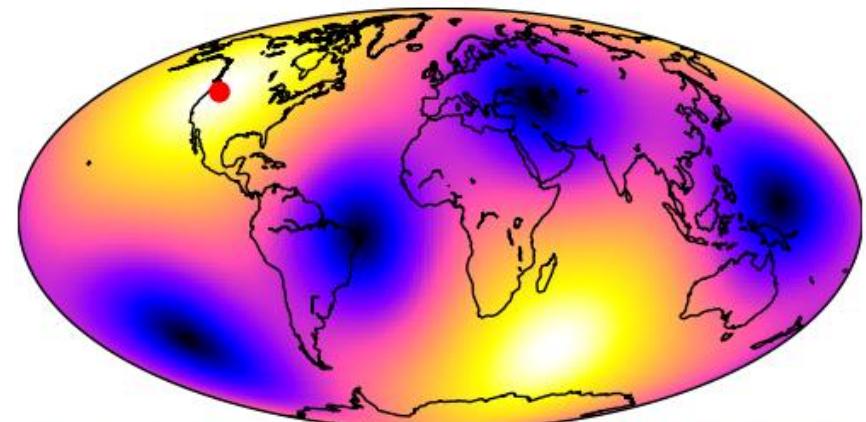
	median
HLV	0.472 deg <sup>2</sup>
HLVK	0.168 deg <sup>2</sup>
HLVK+	

# Sky Localization with HLVK+



	median
HLV	$0.472 \text{ deg}^2$
HLVK	$0.168 \text{ deg}^2$
HLVK+	$0.107 \text{ deg}^2$

# $H$ Antenna Pattern $L$



# 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 <sub>2</sub>	60cm SiO <sub>2</sub>	60cm SiO <sub>2</sub>	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: tantalum/silica
  - Coating loss angle: 3e-4 for silica, 5e-4 for tantalum
  - 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

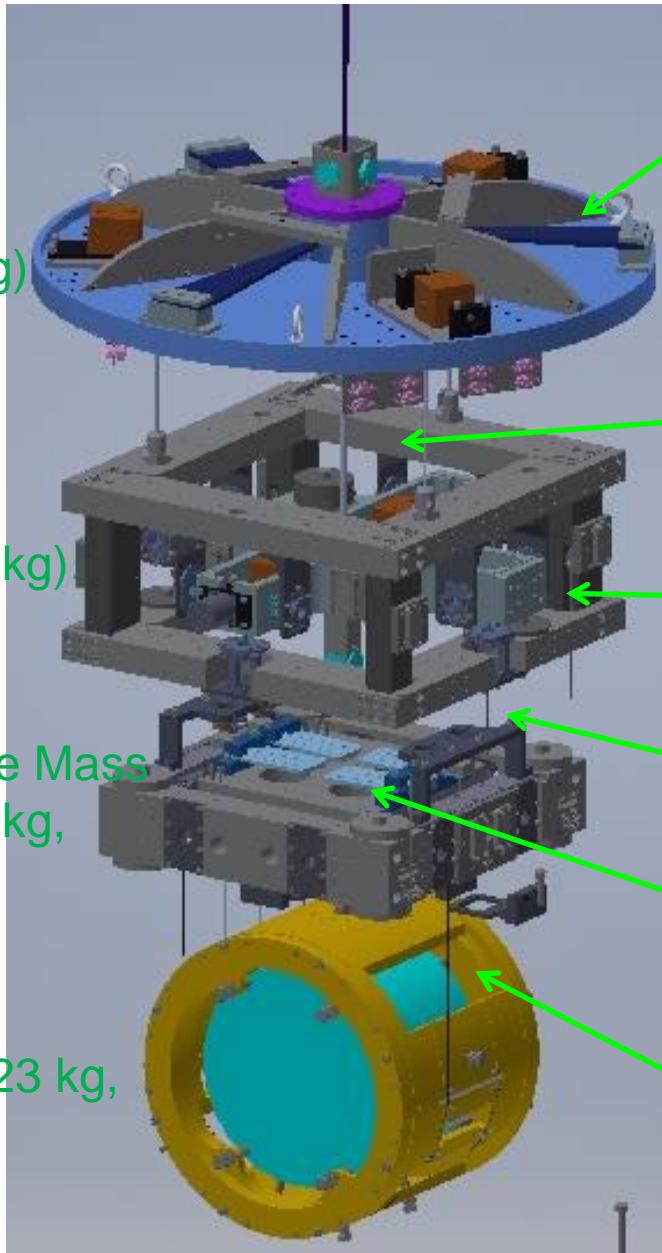
Provided by T. Ushiba and T. Miyamoto

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)

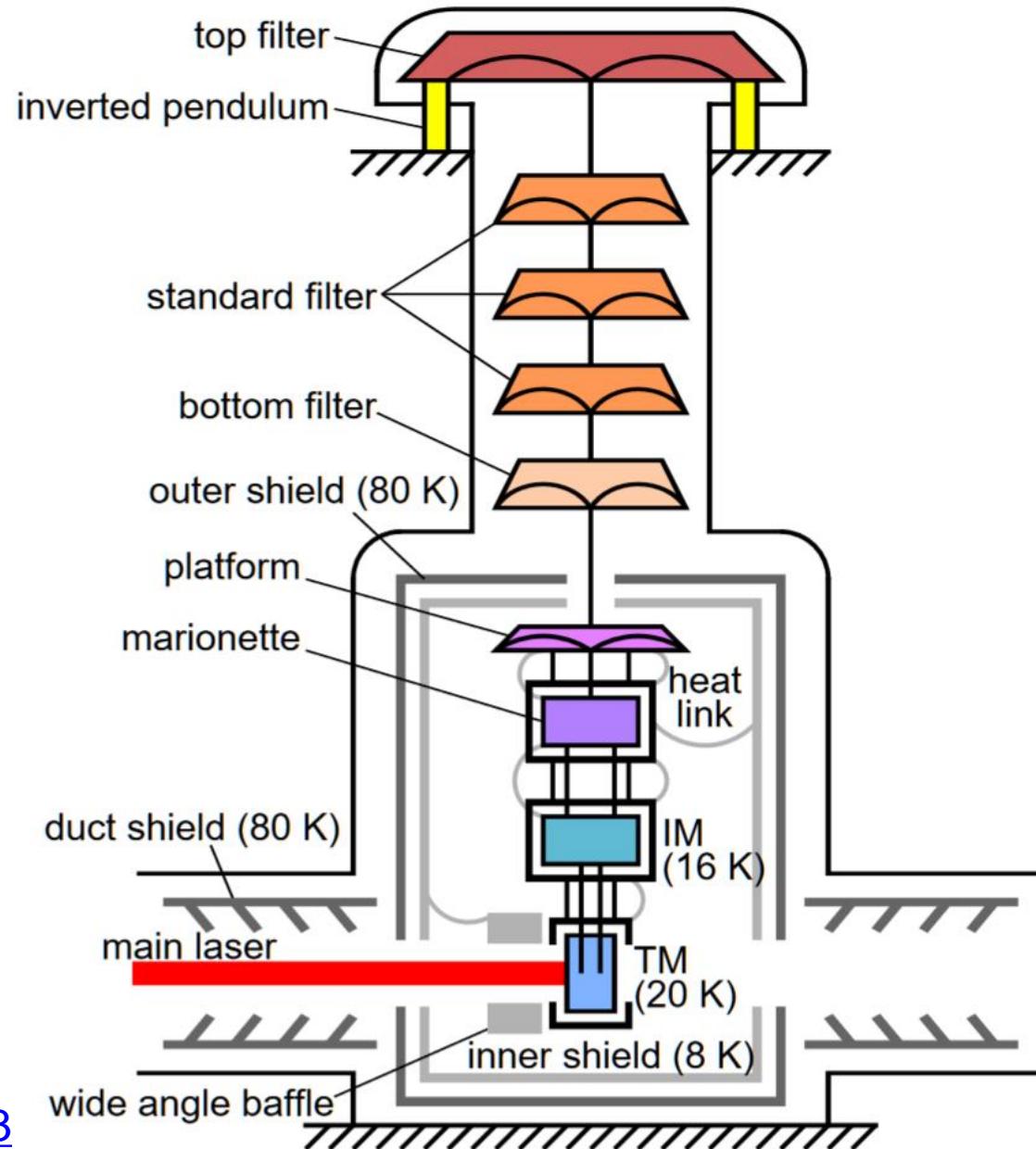
IRM suspended by 4 CuBe fibers

4 sapphire blades

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

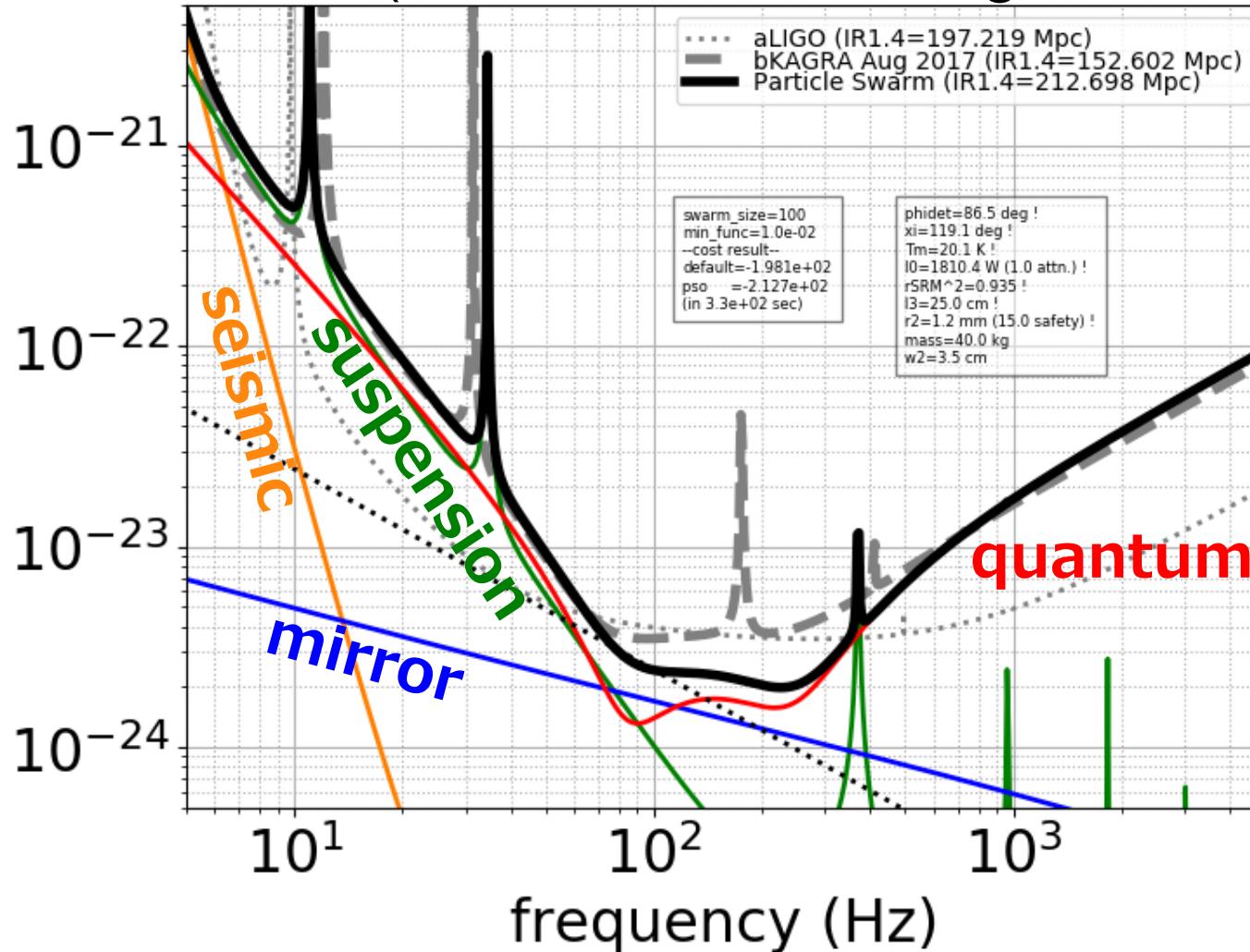
RM suspended by 4 CuBe fibers

# KAGRA Cryostat Schematic



# Plan A: 40 kg Mirror

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

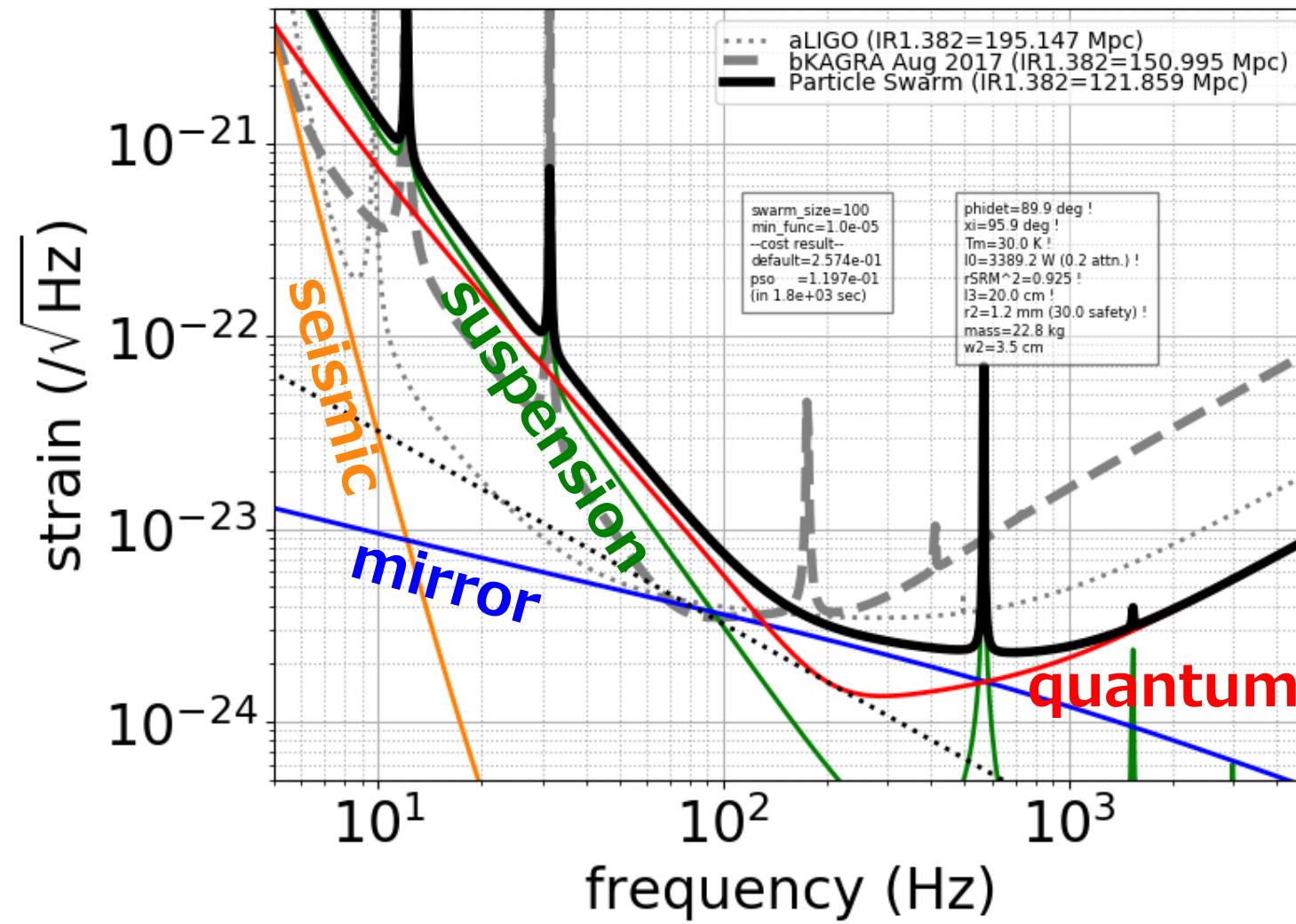


Good for mid frequency improvement  
→ BNS range optimized

$T=20.1$  K  
181 W input  
thicker fiber  
25.0 cm  
 $\phi$ 1.2 mm  
(thicker to allow for higher power)

# Plan B: 400 W Laser with SQZ

- Assumes 10dB input SQZ

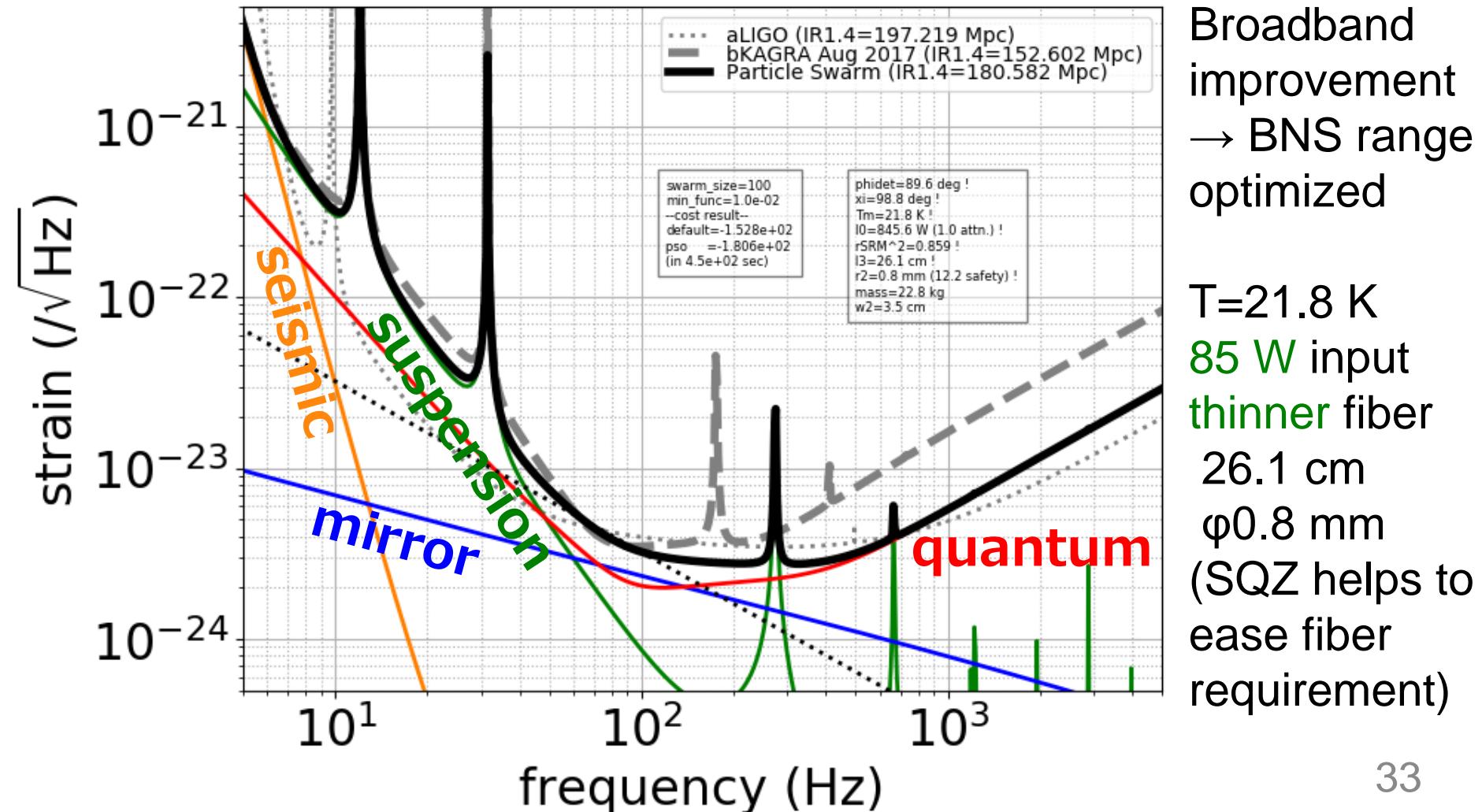


Good for high frequency improvement  
→ BNS range optimized

T=29.8 K  
330 W input  
**shorter and thicker** fiber  
20.1 cm  
 $\varphi$ 1.2 mm  
(high power with high temperature)<sup>32</sup>

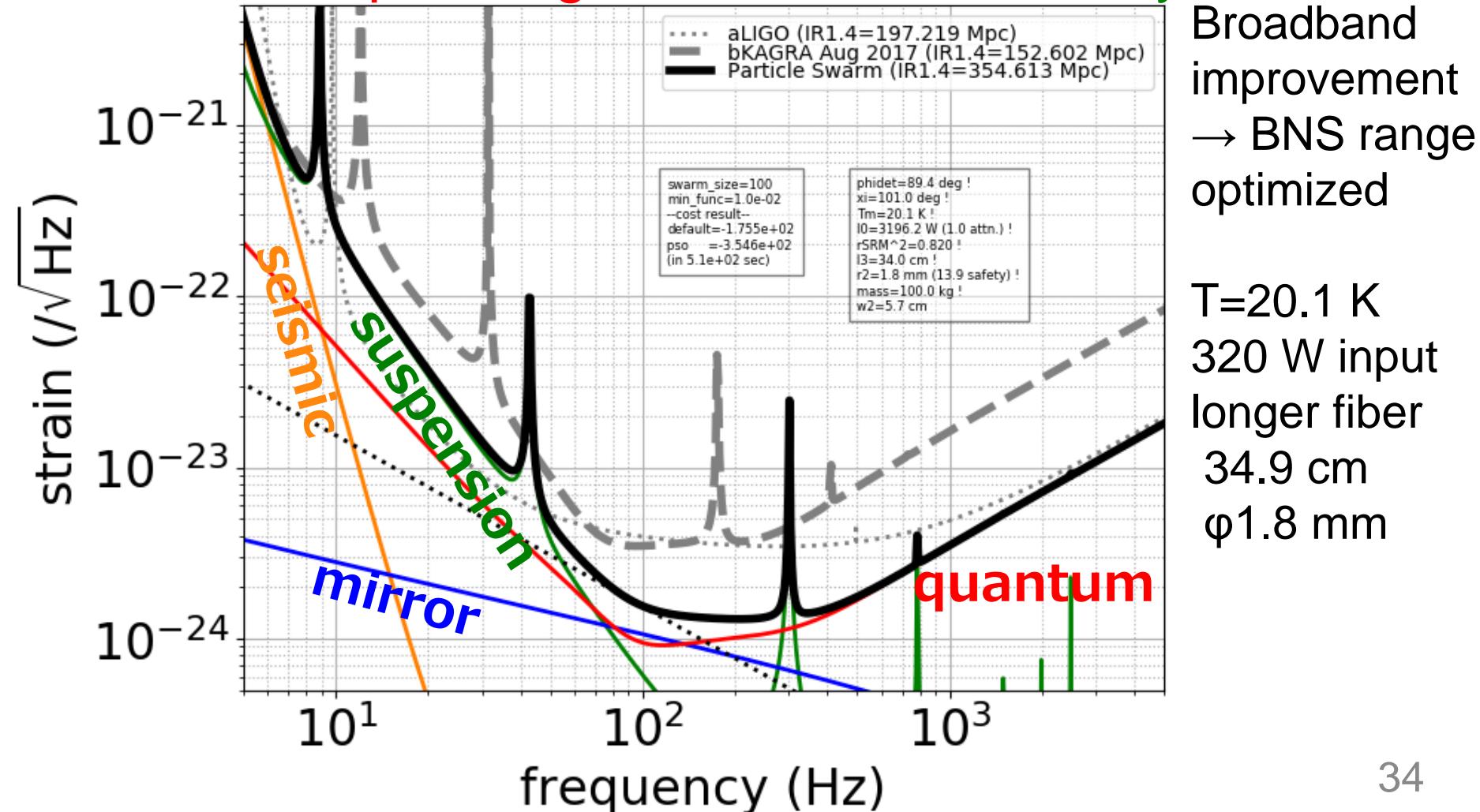
# Plan C: Freq. Dependent SQZ

- Assumes 10dB input SQZ and 100 m filter cavity



# Longer Term Candidate

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



# Very Rough Estimates

- New 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