15th Marcel Grossmann Meeting @ University of Rome "La Sapienza" July 2, 2018

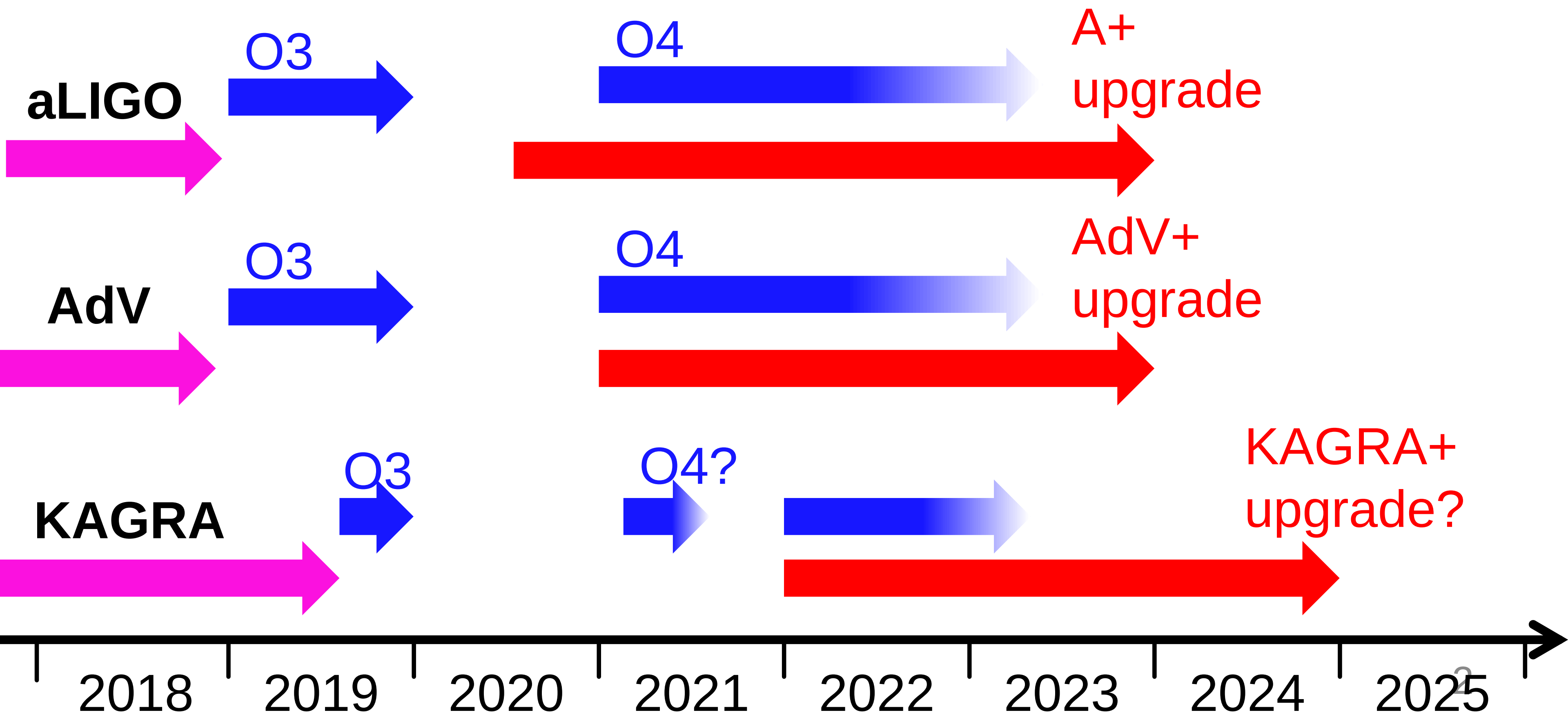
Prospects for improving the sensitivity of KAGRA gravitational wave detector

Yuta Michimura
Department of Physics, University of Tokyo

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

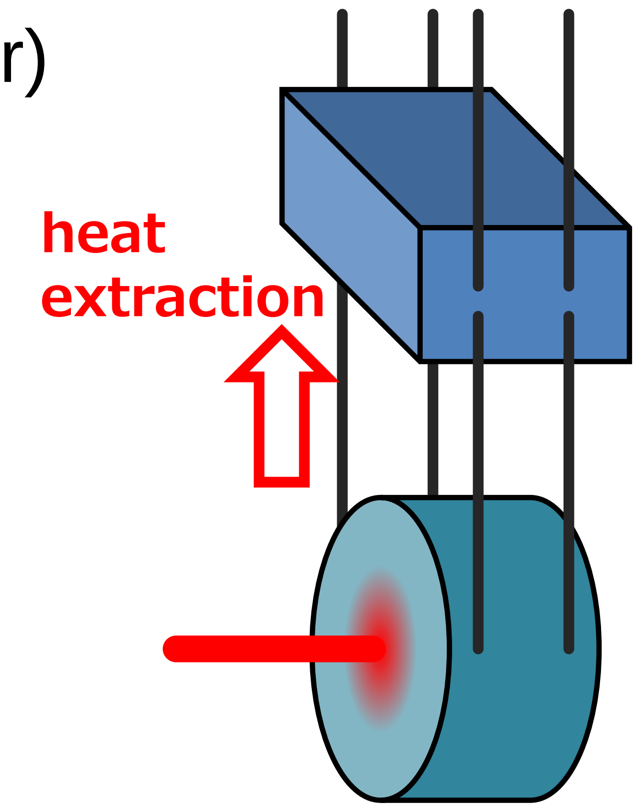
Upgrading Current GW Detectors

- 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

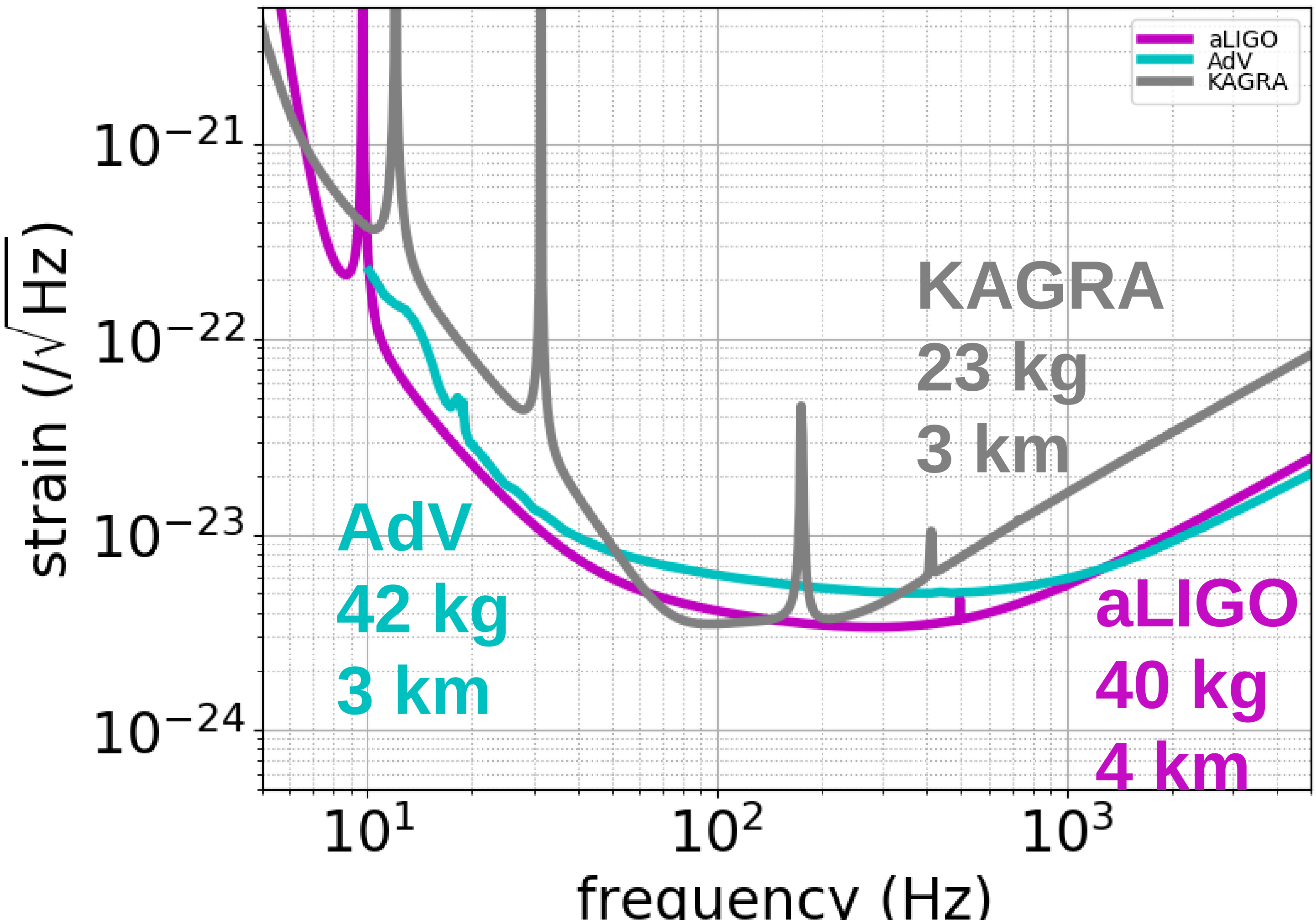
  thinner and longer
  for thermal noise reduction

  ↕ **Dilemma**

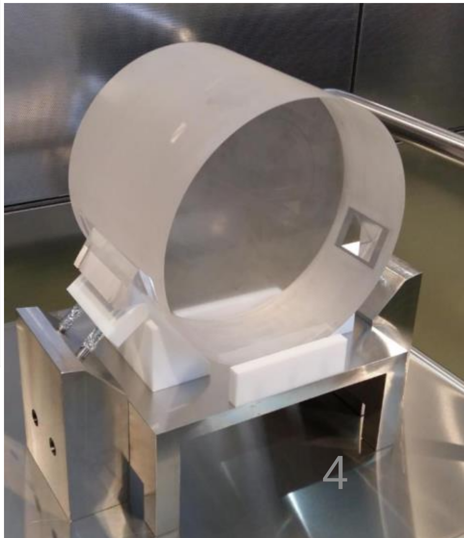
  thicker and shorter
  for heat extraction

2G Sensitivity Comparison

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

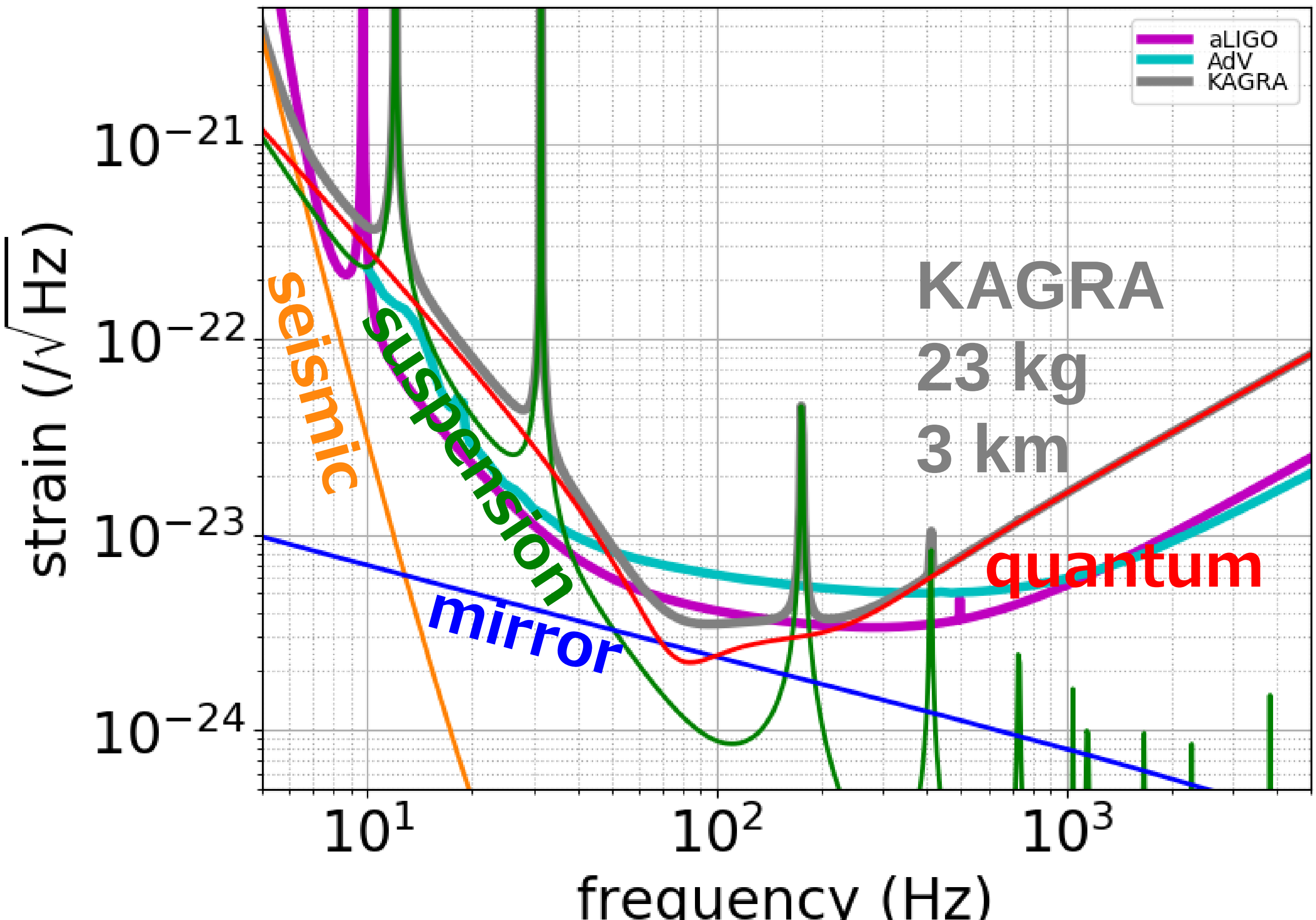


23 kg was the largest available sapphire mirror

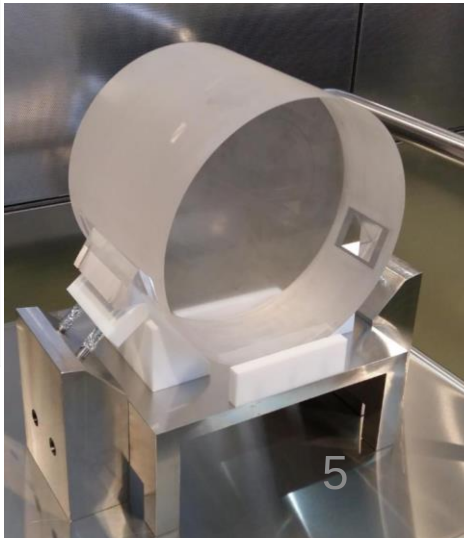


2G Sensitivity Comparison

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

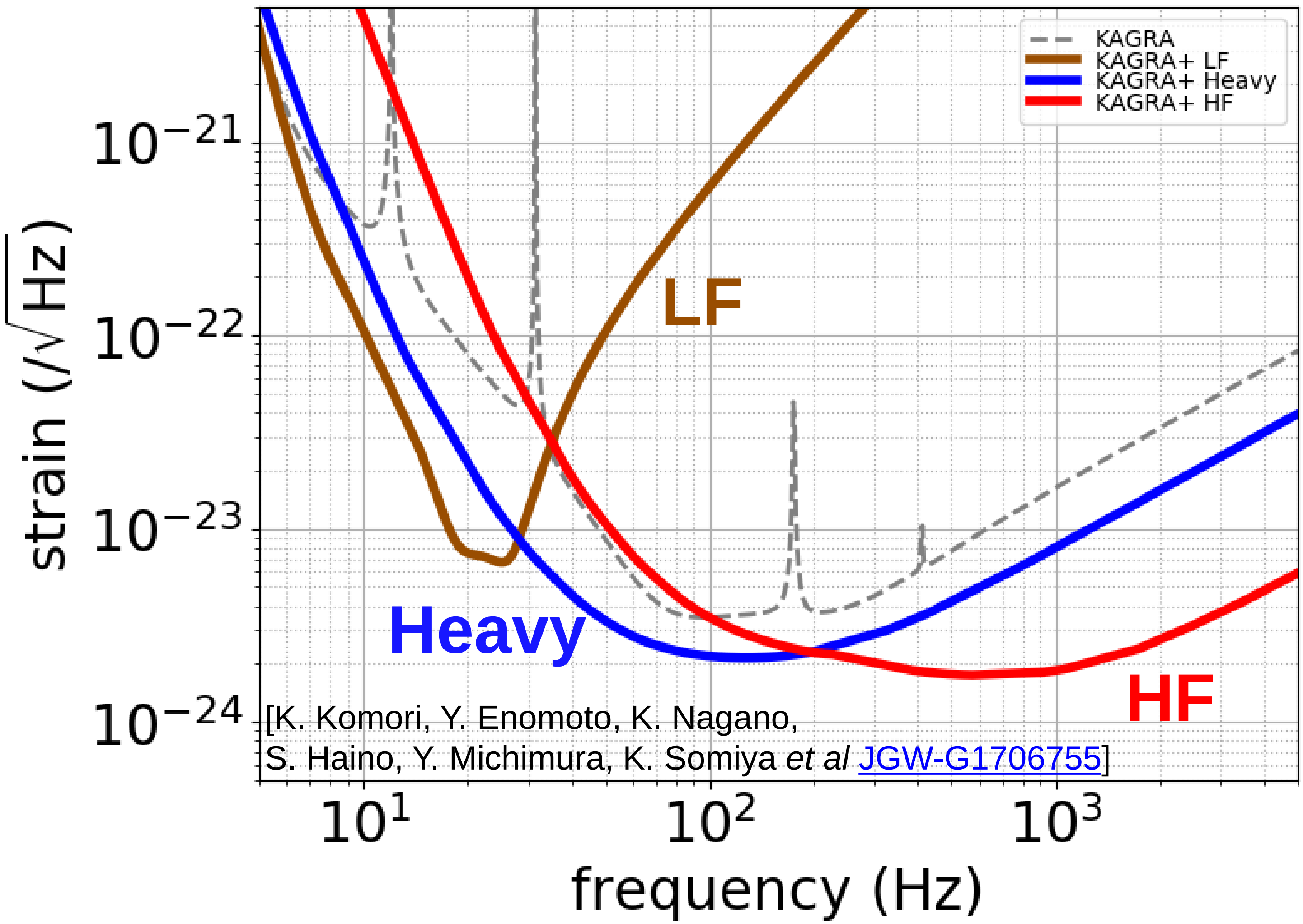


23 kg was the largest available sapphire mirror



3 KAGRA+ Concepts to Start With

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



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

Science Case Study

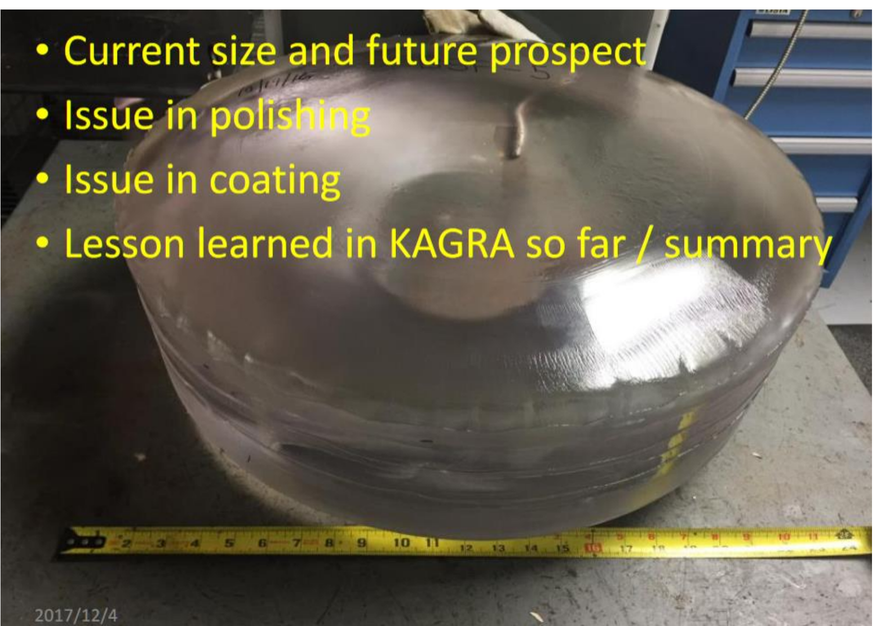
- Although LF has the best inspiral range for heavy BBH (~100M_{sun}), narrow band was not favorable

	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	×	×	△	○

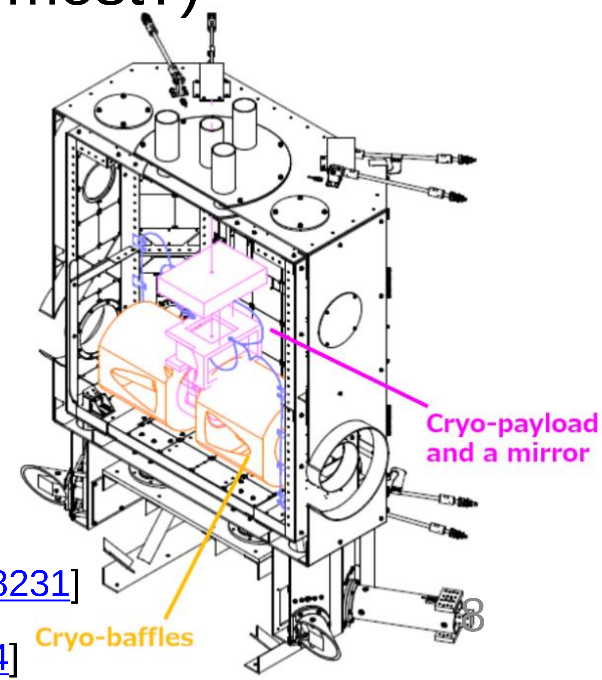
[Based on inputs from K. Hayama, Y. Itoh, T. Kinugawa, H. Nakano, A. Nishizawa, N. Sago, M. Shibata, H. Shinkai, T. Tanaka, *et al* JGW-G1707125]

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?)



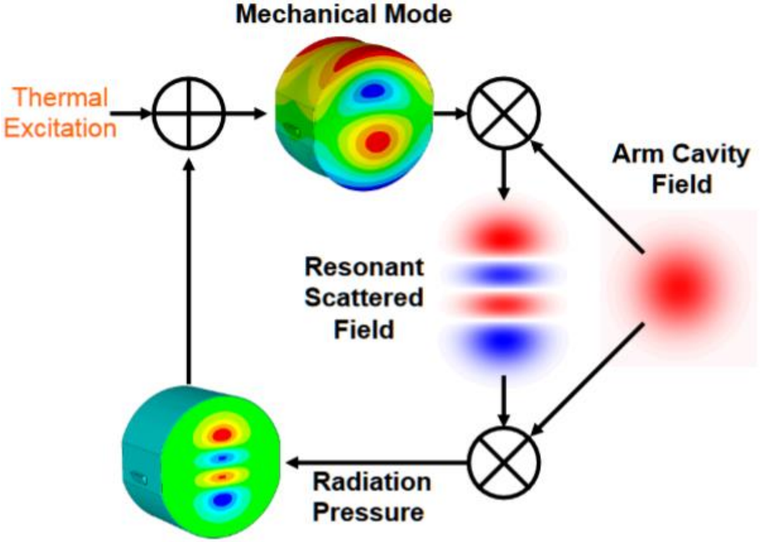
[K. Somiya, JGW-G1808231]



[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)

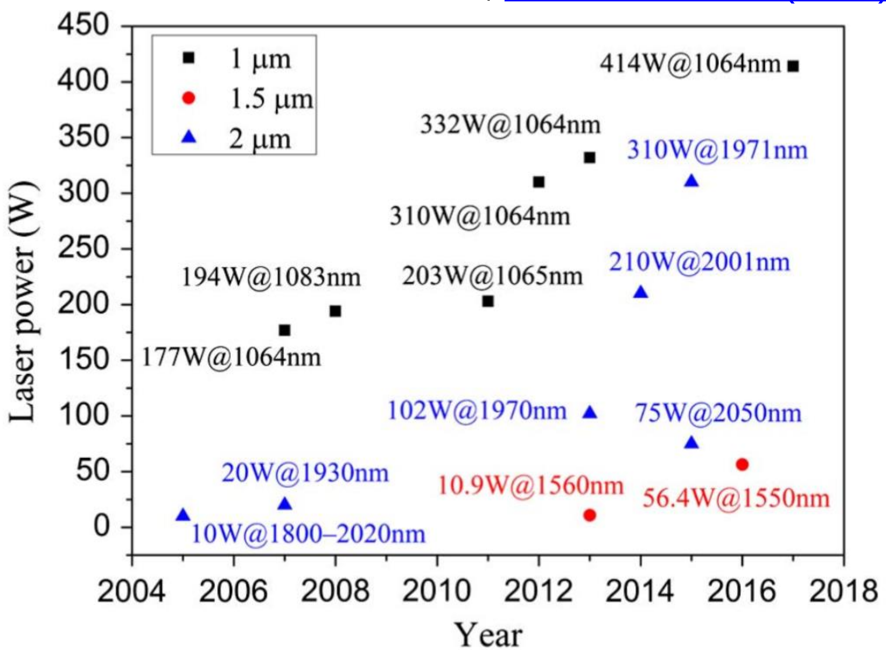
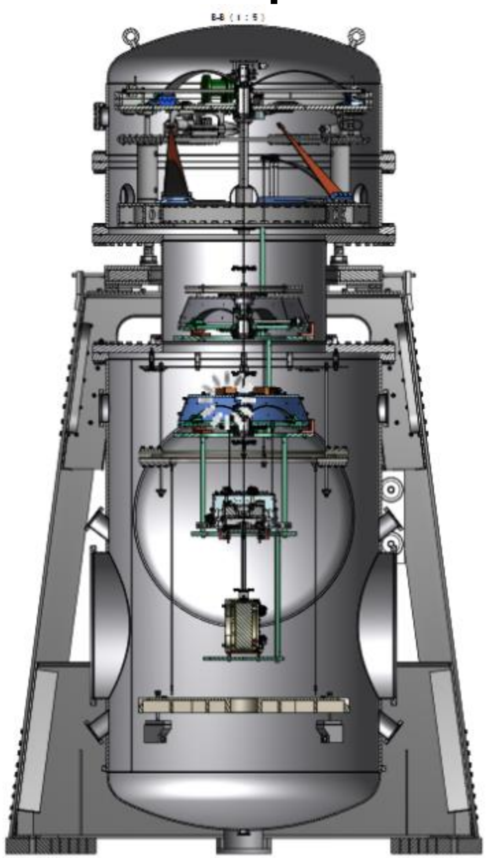
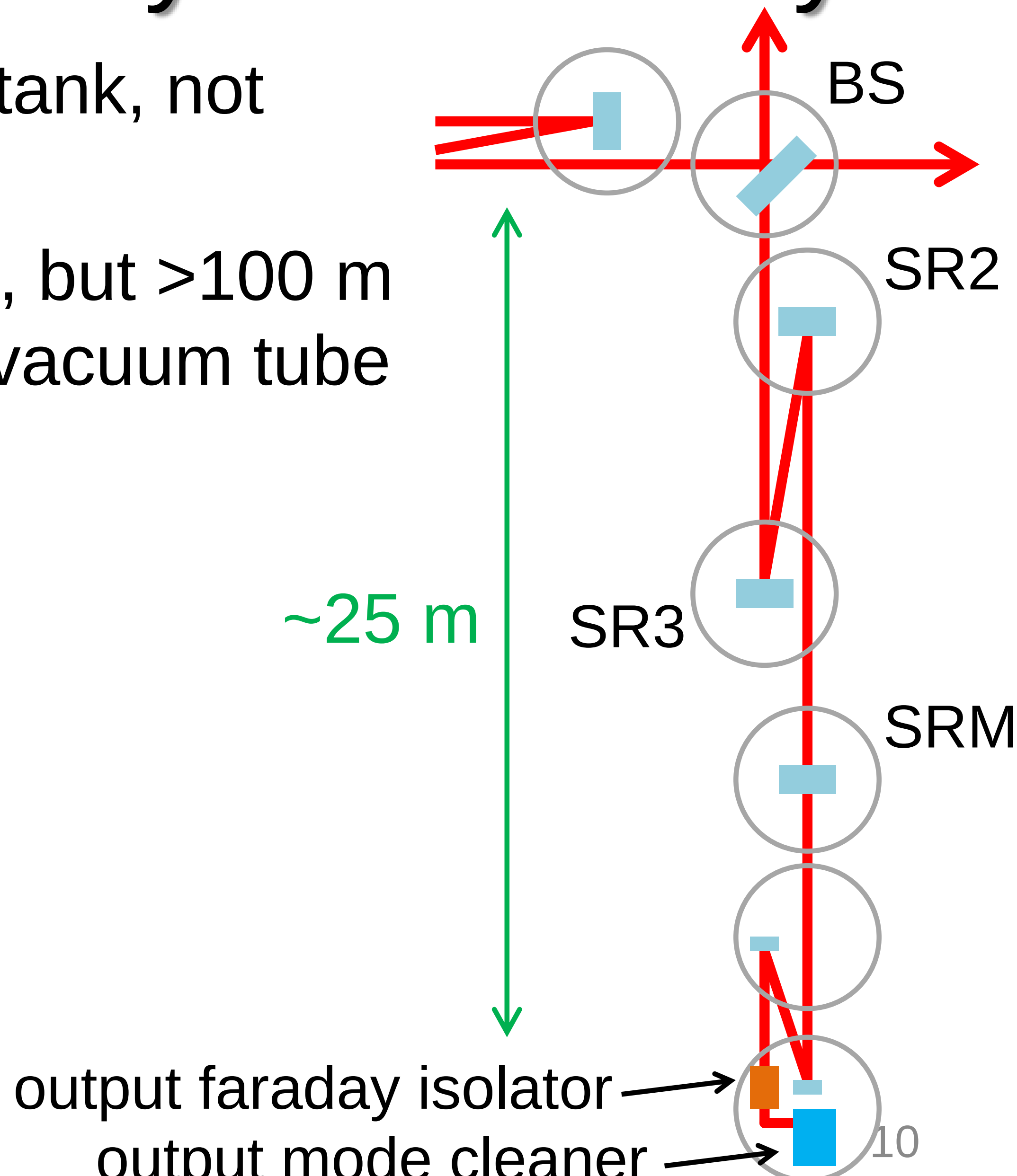


Fig. 7. Output power evolution of CW single-frequency amplifiers in all-fiber format operating in 1, 1.5, and 2 μm regions.

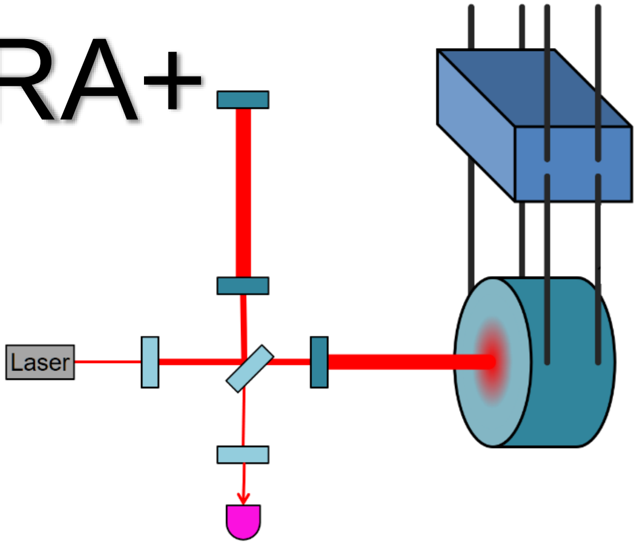
Feasibility Study: Filter Cavity

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





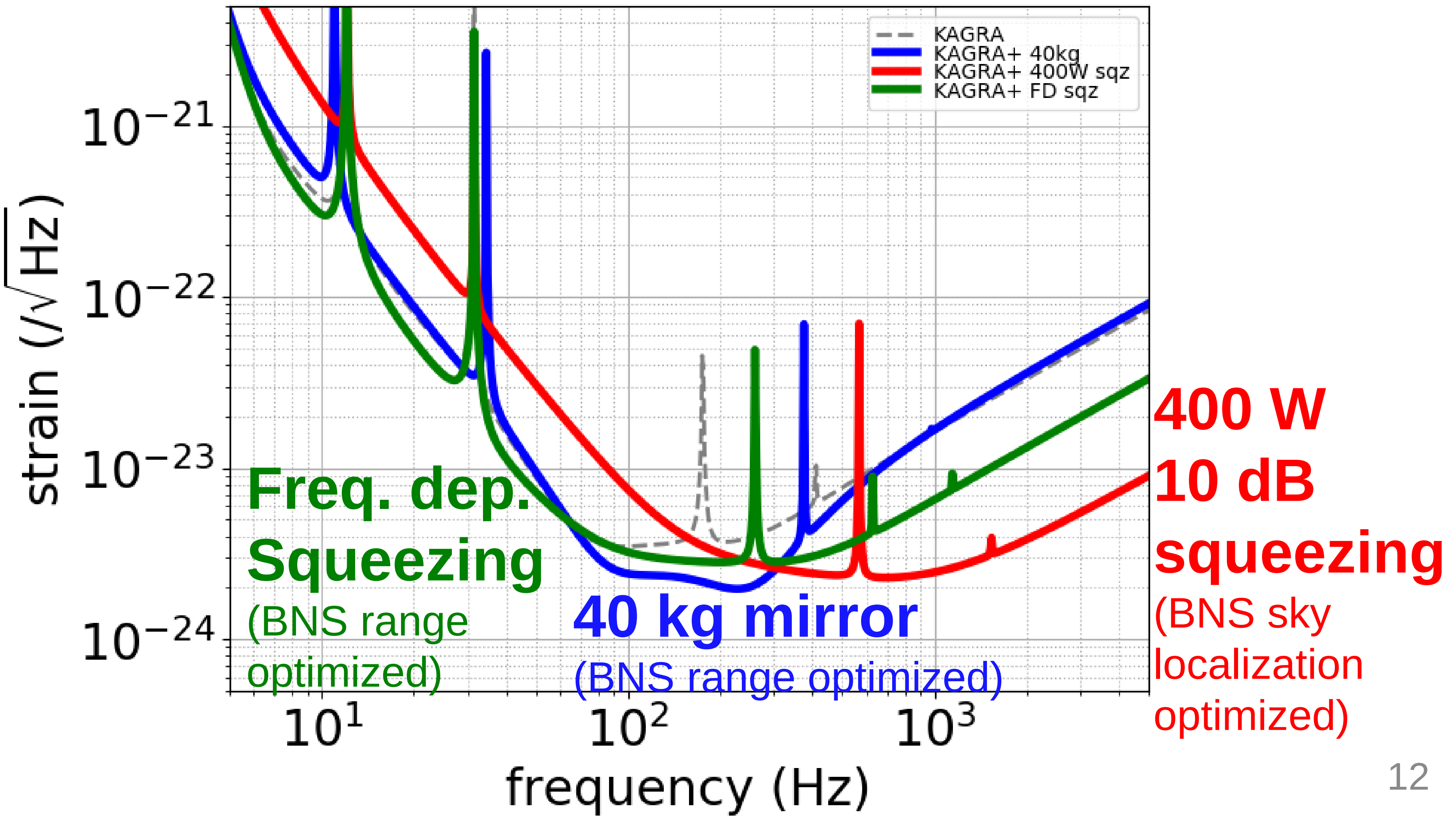
Near Term KAGRA+



- 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
  Y. Michimura et al, [Phys. Rev. D 97, 122003 (2018)]

Near Term Candidates

- Within ~5 years, ~$5M



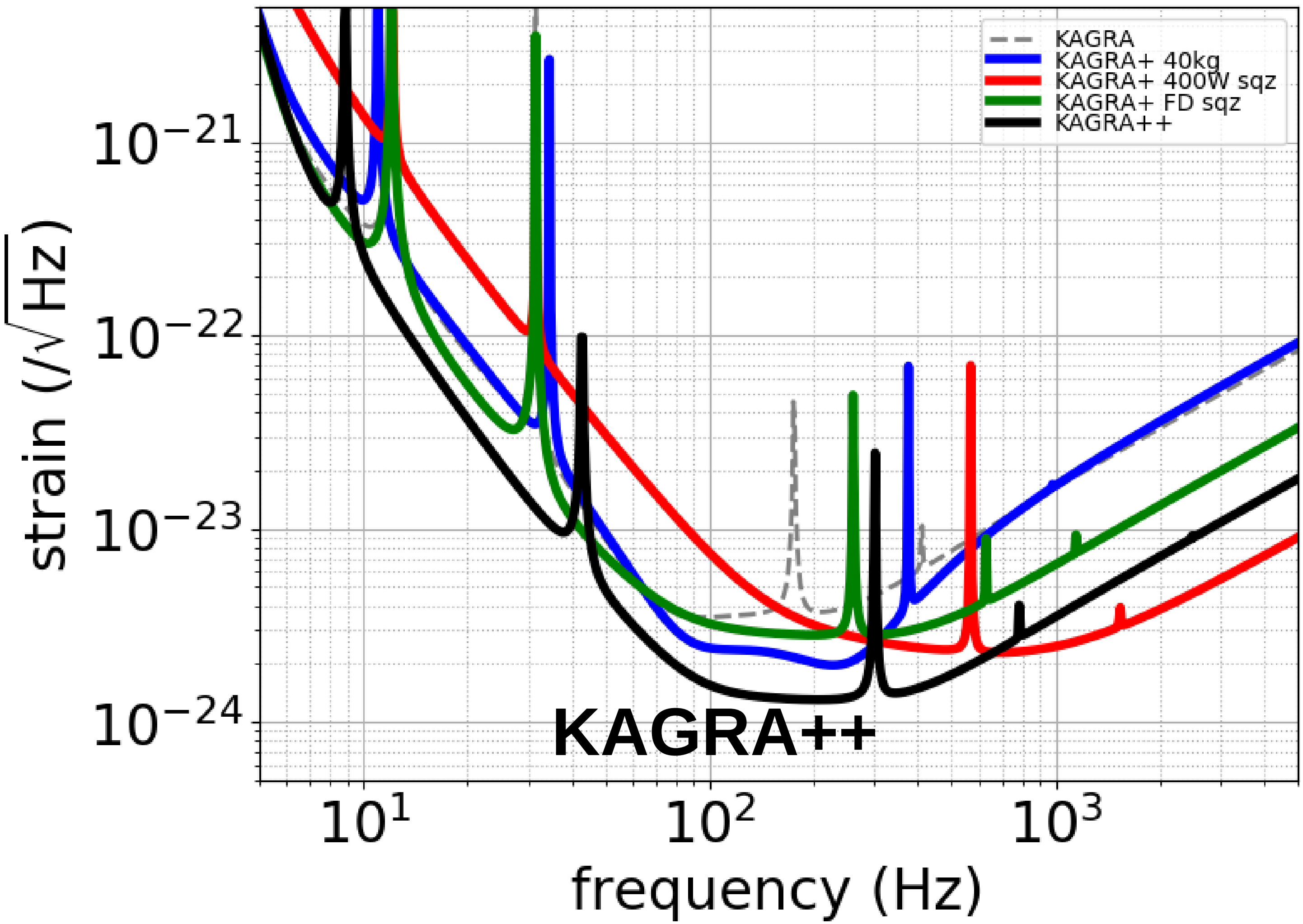
Summary of Near Term Plans

- 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^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

Longer Term Candidate

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

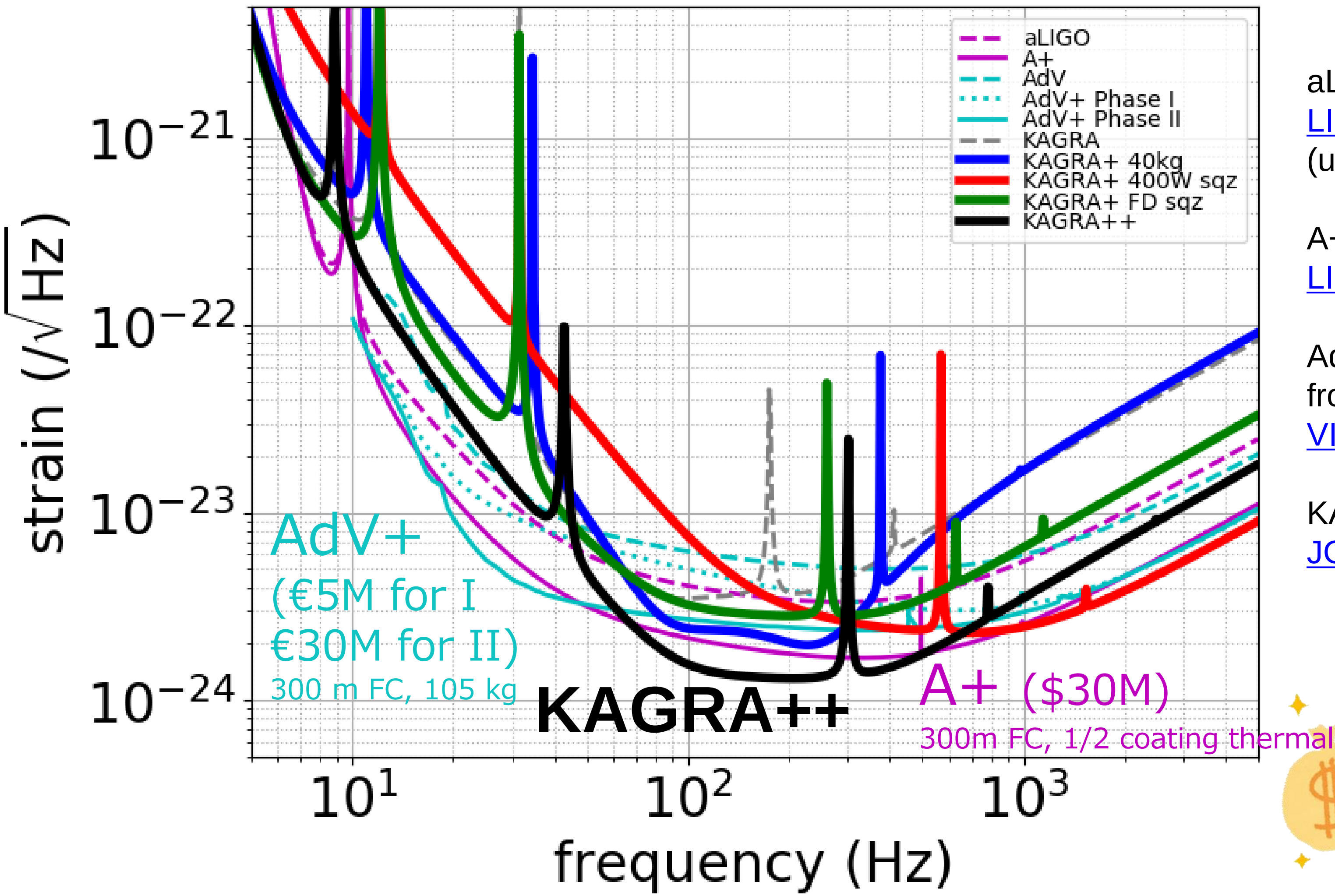


BNS range reaches **355 Mpc**

Within
~ 10 years
~ $20M?

Comparison between 2G and 2G+

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



aLIGO curve from LIGO-T1800044 (updated ver)

A+ curve from LIGO-T1800042

AdV and AdV+ curves from VIR-0325B-18

KAGRA curve from JGW-T1707038

Possible Upgrade Strategy

- Still under discussion among KAGRA collaboration

Filter cavity R&D

Heavier mirror R&D, fabrication

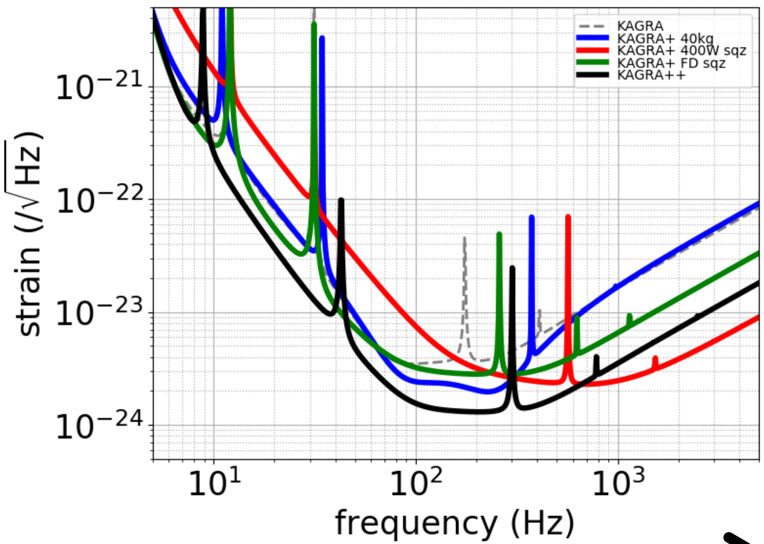
Mirror upgrade
Filter cavity

Coating R&D

Higher power R&D

Higher power upgrade?

Realize KAGRA



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

R&D Activities for Upgrades

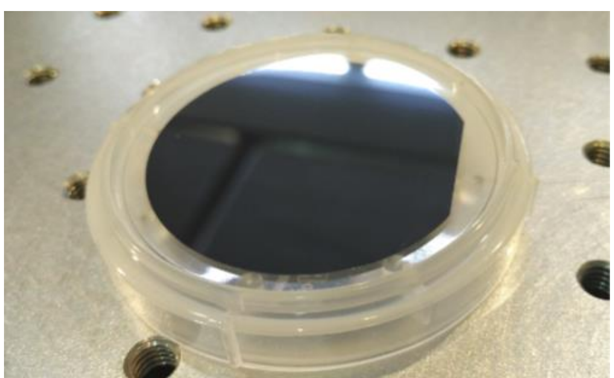
- 300 m filter cavity experiment at TAMA300

  E. Capocasa *et al*, PRD 93 082004 (2016) and arXiv:1806.10506

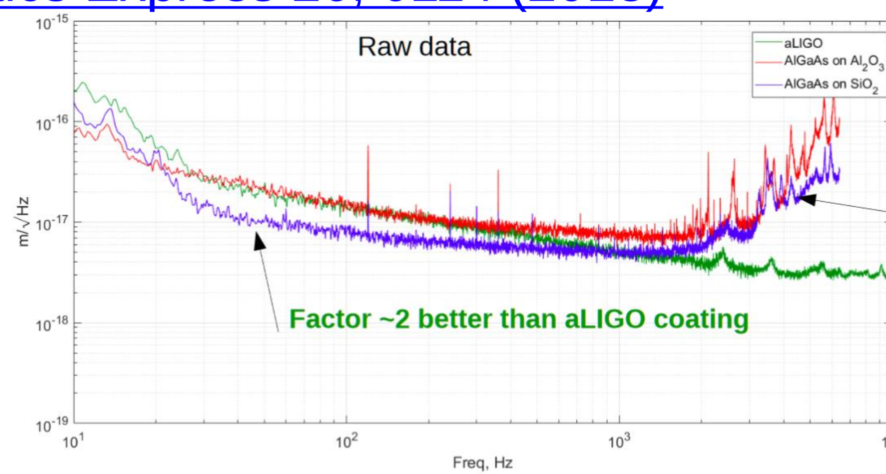
[M. Leonardi *et al*, JGW-G1808310]

- Characterization of crystalline coating on sapphire

  M. Marchio et al, Optics Express 26, 6114 (2018)



2 inches diameter



[M. Marchio *et al*, JGW-G1808310]

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)

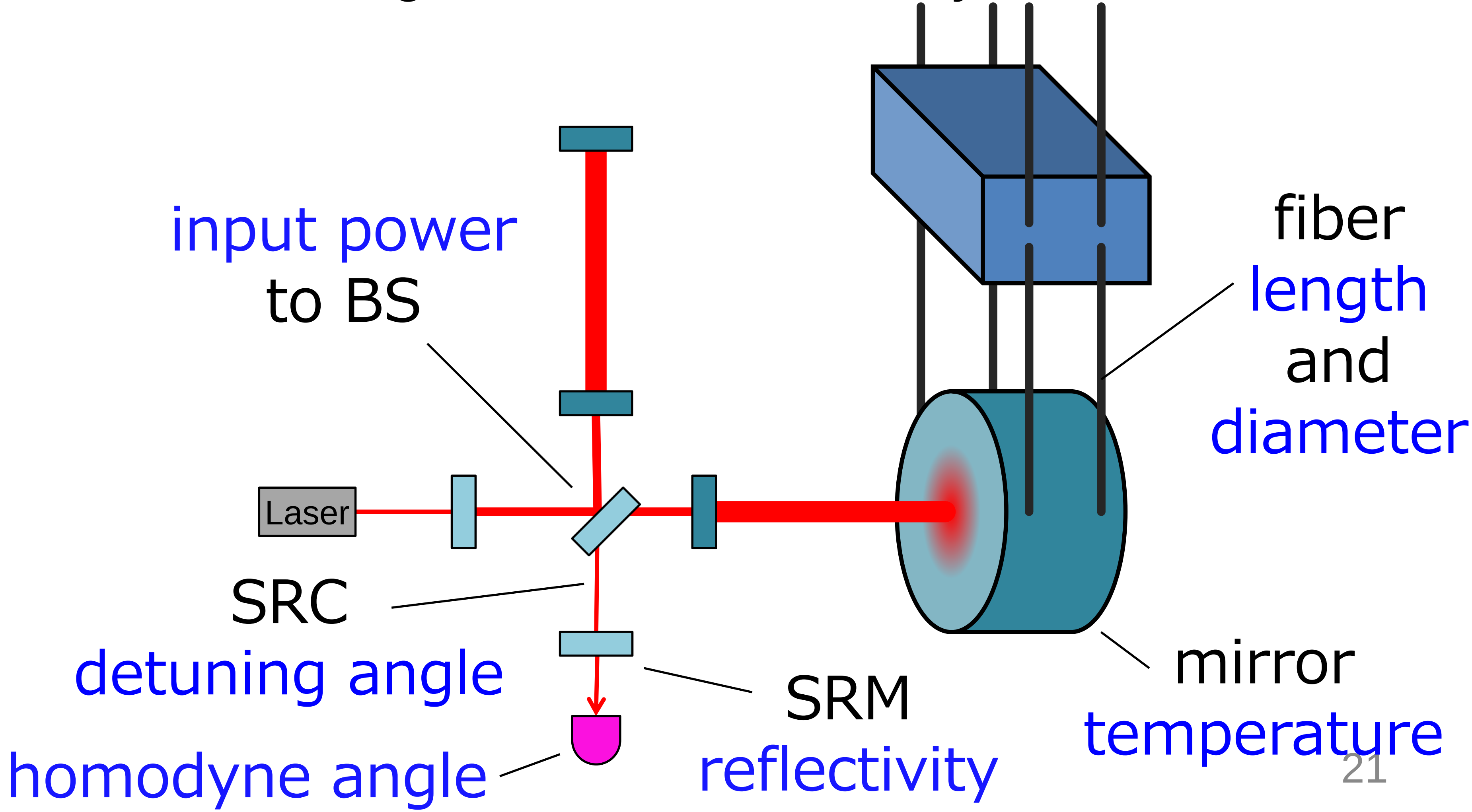
Summary

- 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 by combining all the techniques, with more time and money
- Strategy under discussion in KAGRA collaboration
- Quite active R&D is on going

Supplementary Slides

Parameters of Interest

- 7 parameters are relatively easy to be retuned
- Search range based on feasibility



Particle Swarm Optimization

- Particles search the parameter space based on own best position and entire swarm's best known position

$$x_k(t+1) = x_k(t) + v_k(t)$$

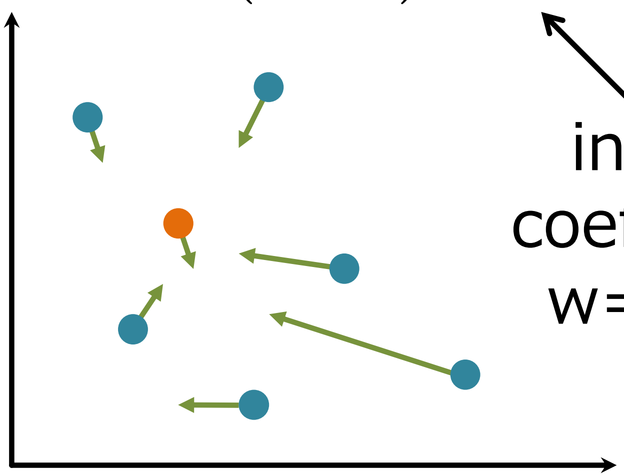
personal best position so far

global best position so far

$$v_k(t+1) = wv_k(t) + c_1 r_1(\hat{x}_k - x_k(t)) + c_2 r_2(\hat{x}_g - x_k(t))$$

inertia coefficient w=0.72

acceleration coefficient c=1.19
random number r ∊ [0,1]



Parameter space

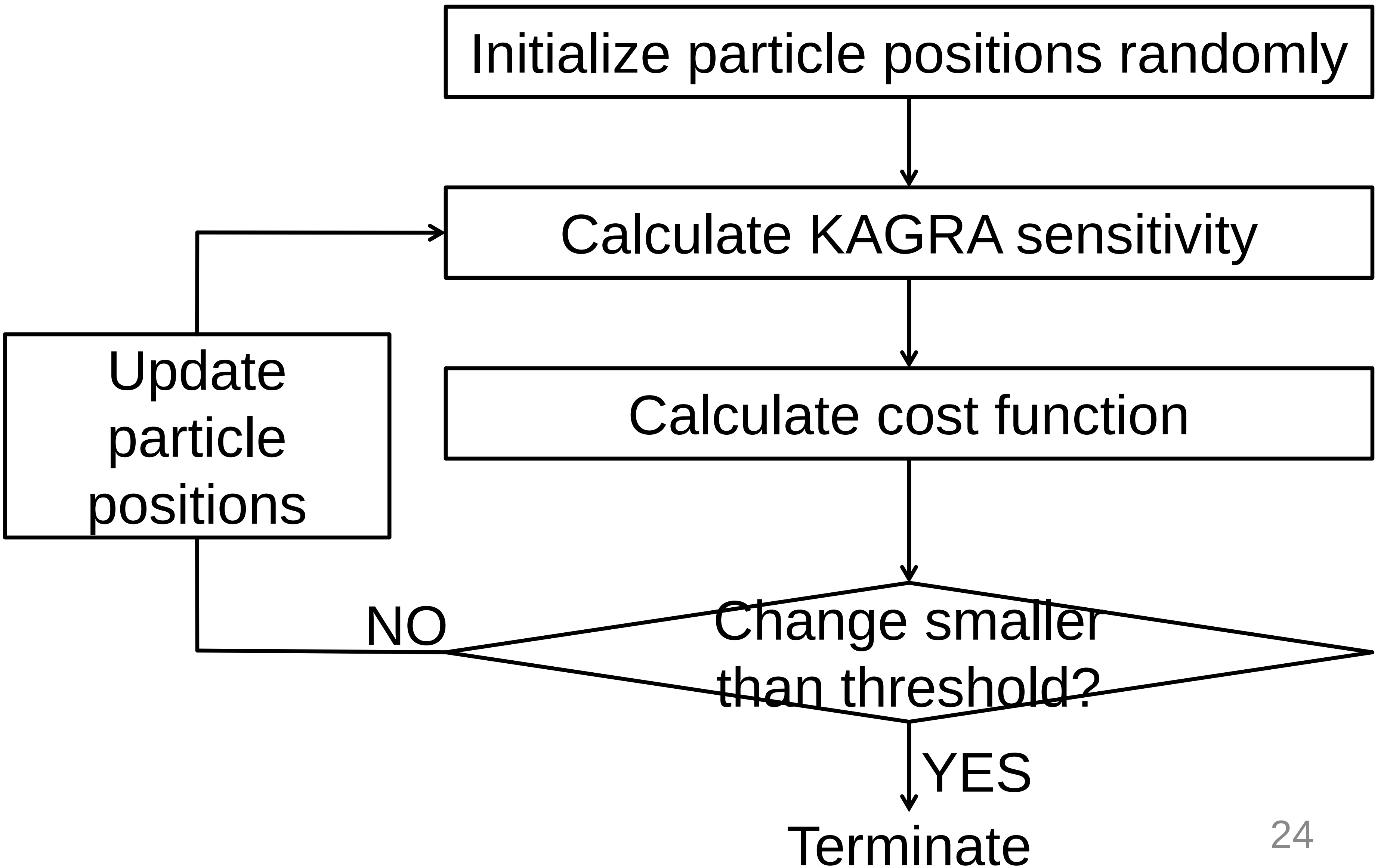
Kennedy & Eberhart (1995)
values for w and c are from Standard PSO 2006

Pros and Cons of PSO

- Fast even for highly multidimensional parameter space ☺
  - uses entire swarm's information to search
- Requires small number of design variables and little prior information ☺
  - basically only swarm size and termination criterion
  - prior information is only search range
- No guarantee for convergence to global maximum
  - stochastic method ☹
- Do not give error of the parameters ☹
  - no direct information on stability of the solution

→ Sounds great for detector design

PSO Algorithm



Swarm Size Determination

- Probability of convergence: ratio of PSO trials resulted within 0.1 Mpc or 10^{-3} deg^2
- Increased swarm size until probability of convergence is larger than 90%

number of params	3	5	7
number of particles	10	20	200
number of iterations	52±13	73±16	60±18
probability of convergence	98 %	96 %	91 %

* From 100 PSO trials

IFO Parameter Search Range

	Lower bound	Upper bound	KAGRA Default	Precision
Detuning angle [deg]	86.5 (or 60) *	90	86.5	0.1
Homodyne angle [deg]	90	180	135.1	3
Mirror temperature [K]	20	30	22	0.09
Power attenuation	0.01	1	1	0.02
SRM reflectivity	0.5	1	0.92 (85%)	6e-4
Wire length [cm]	20	100	35	0.02
Wire safety factor	3	30	12.57 (0.8 mm)	0.07

* Considering SRC nonlinearity, maximum detuning is 3.5 deg
(see Y. Aso+ CQG 29, 124008)

step size which changes BNS inspiral range by 0.1 Mpc

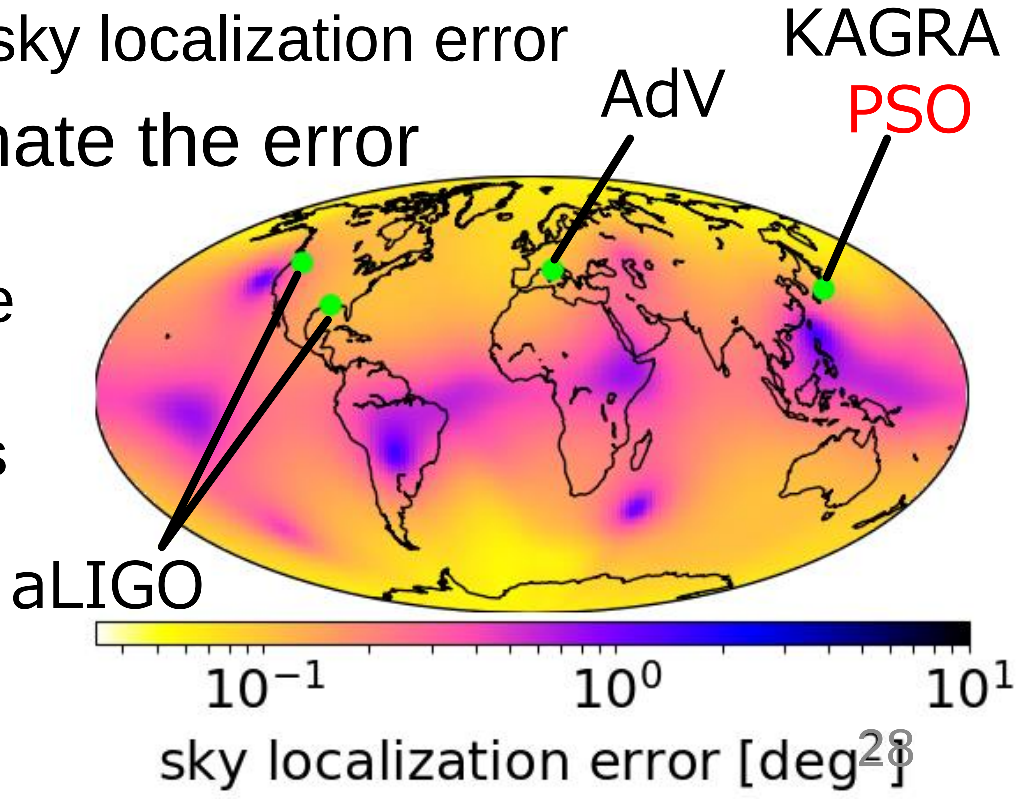
- *Reflecting wall* boundary:
  x=xmax, v=-v if x>xmax
  x=xmin, v=-v if x<xmin

Other Optimization Methods

- Simulated annealing
  tuning cooling schedule is troublesome
- Genetic algorithm
  too many design variables
- Markov chain Monte Carlo
  tend to be dependent on prior distribution
  gives error from posterior distribution
  takes time
- Machine learning
  if the problem well-modeled,
  you don’t need ML

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

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

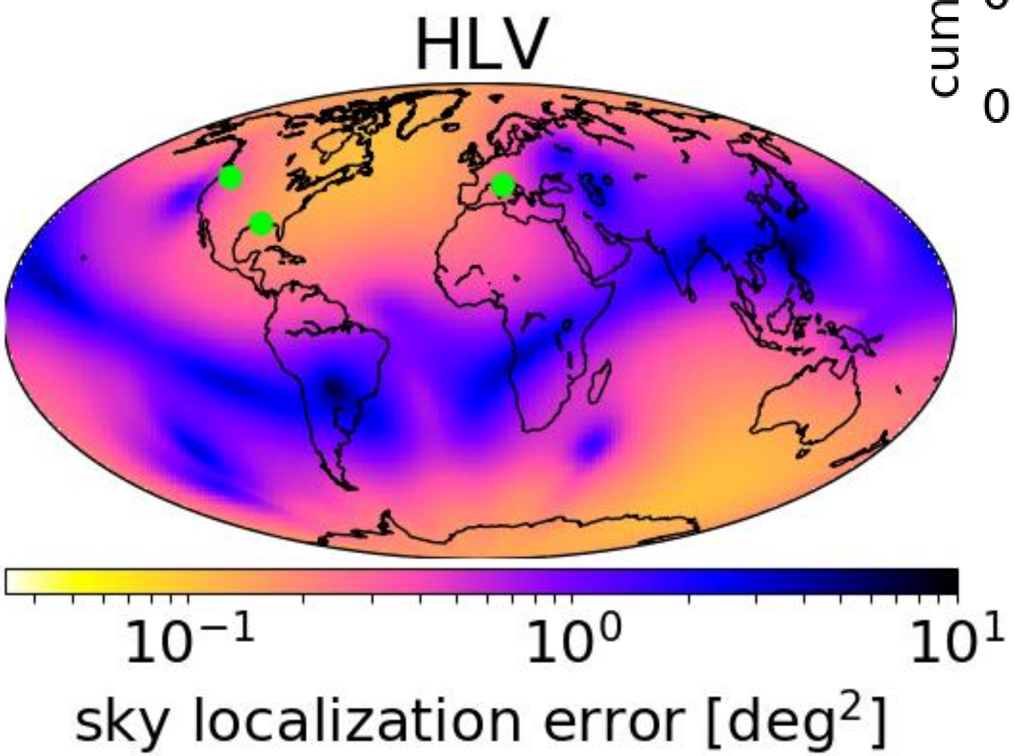
- Covariance

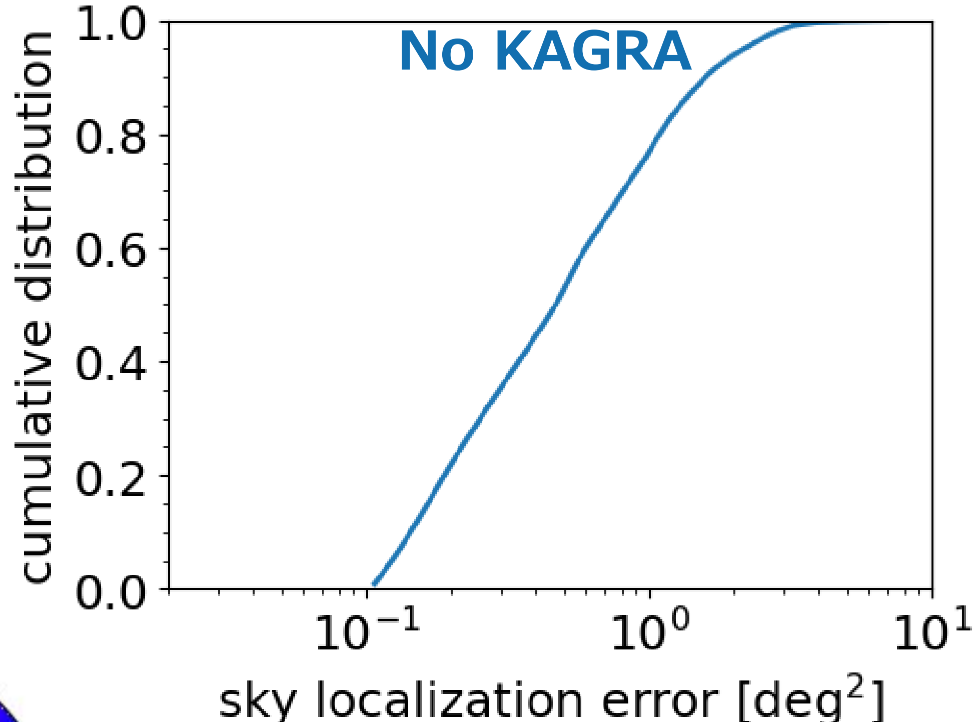
$$\sqrt{\langle(\delta\lambda^i \delta\lambda^j)\rangle} = \sqrt{(\Gamma^{-1})^{ij}}$$

- 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 $\chi_{\mathrm{s/a}} = (\chi_1 \pm \chi_2)/2$
thetas, phis: colatitude / longitude of source
cthetai: inclination angle
psip: polarization angle

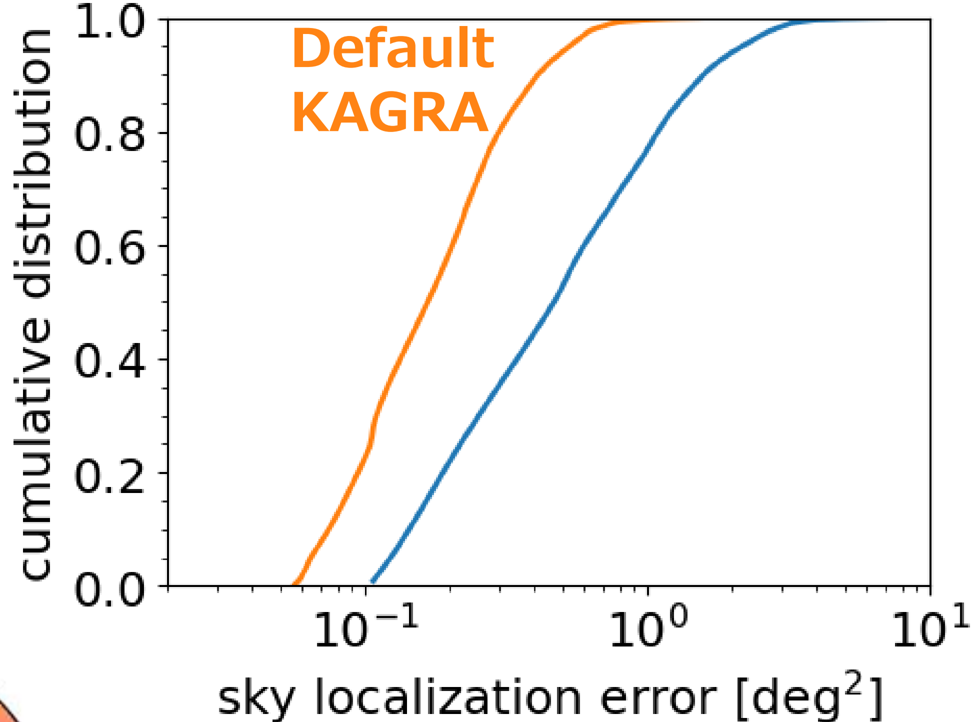
Sky Localization with HLV

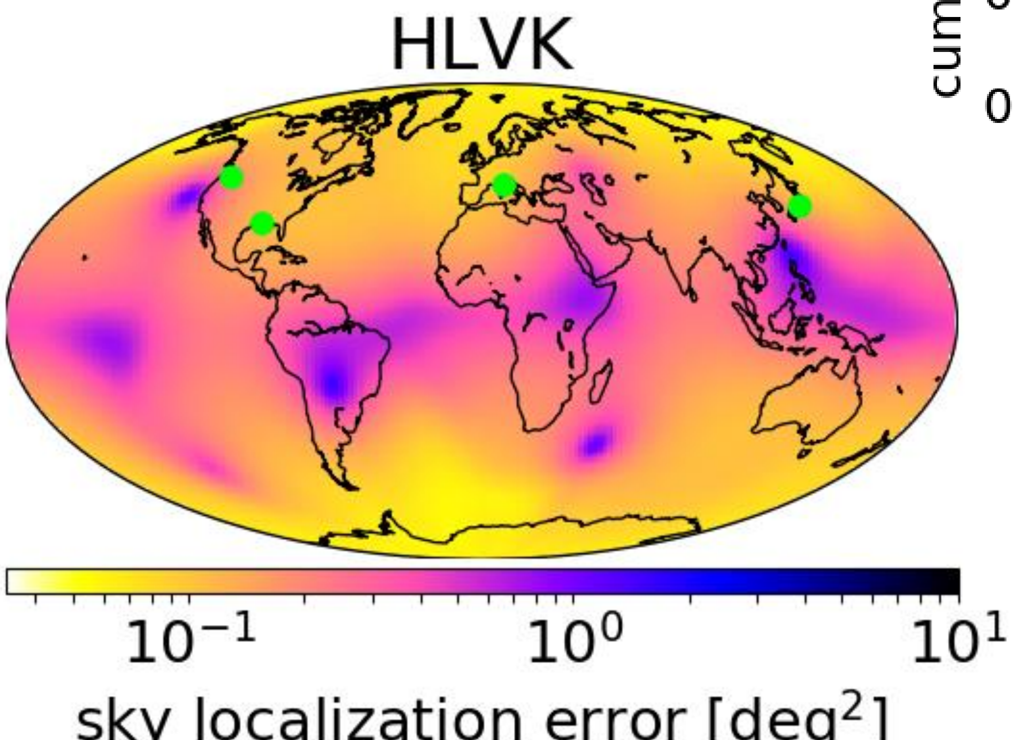




	median
HLV	0.472 deg^2
HLVK	
HLVK+	

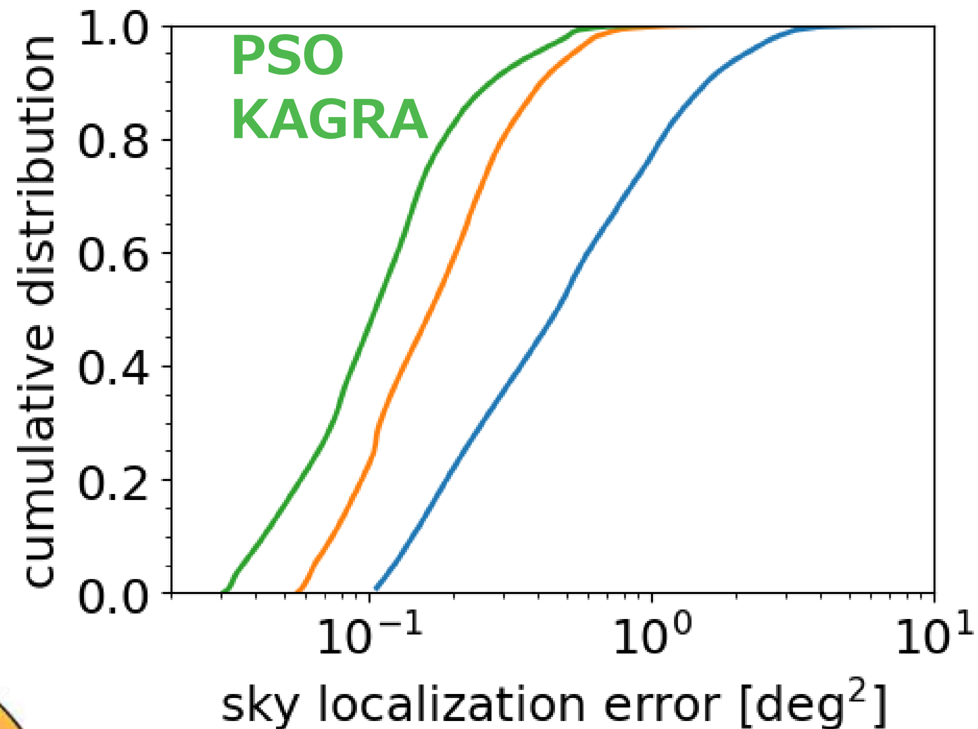
Sky Localization with HLVK

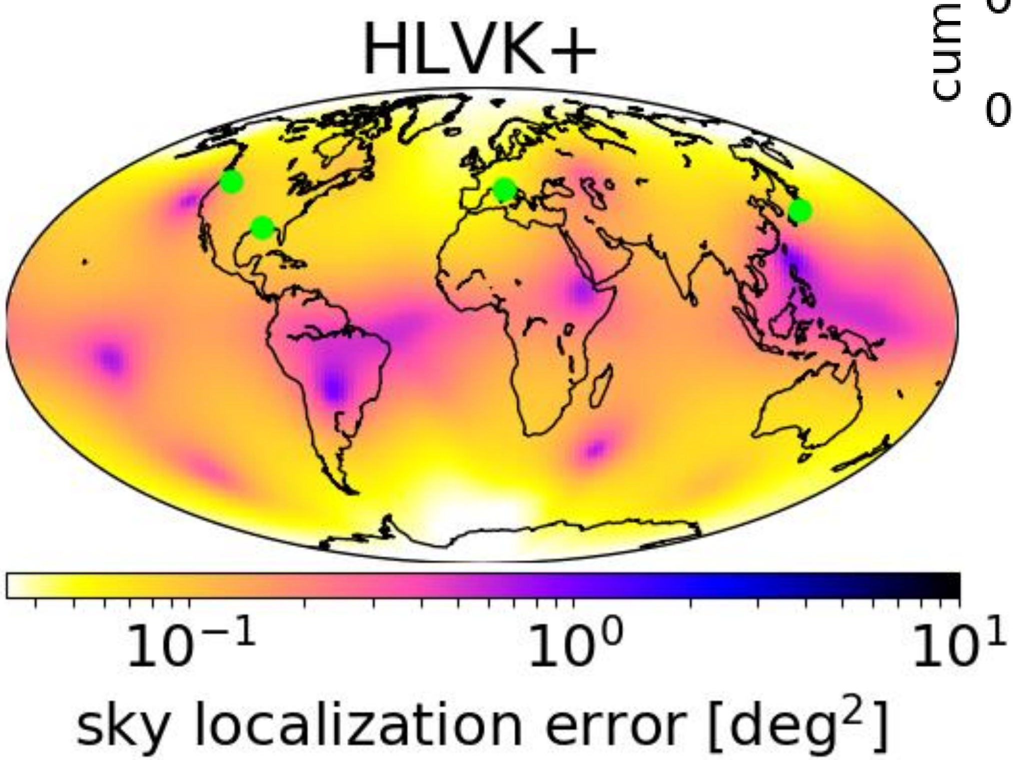




	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	

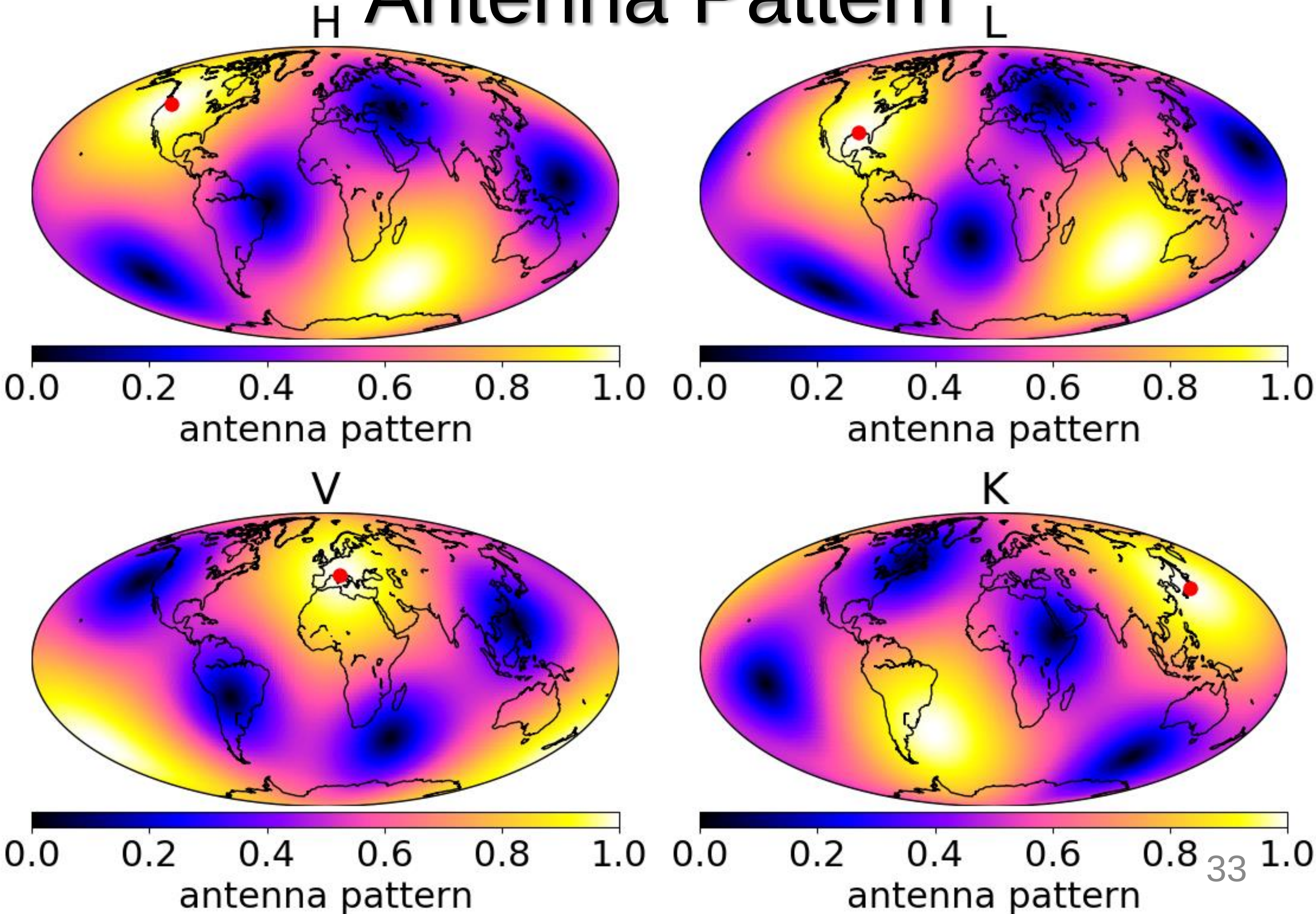
Sky Localization with HLVK+





	median
HLV	0.472 deg^2
HLVK	0.168 deg^2
HLVK+	0.107 deg^2

Antenna Pattern



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)

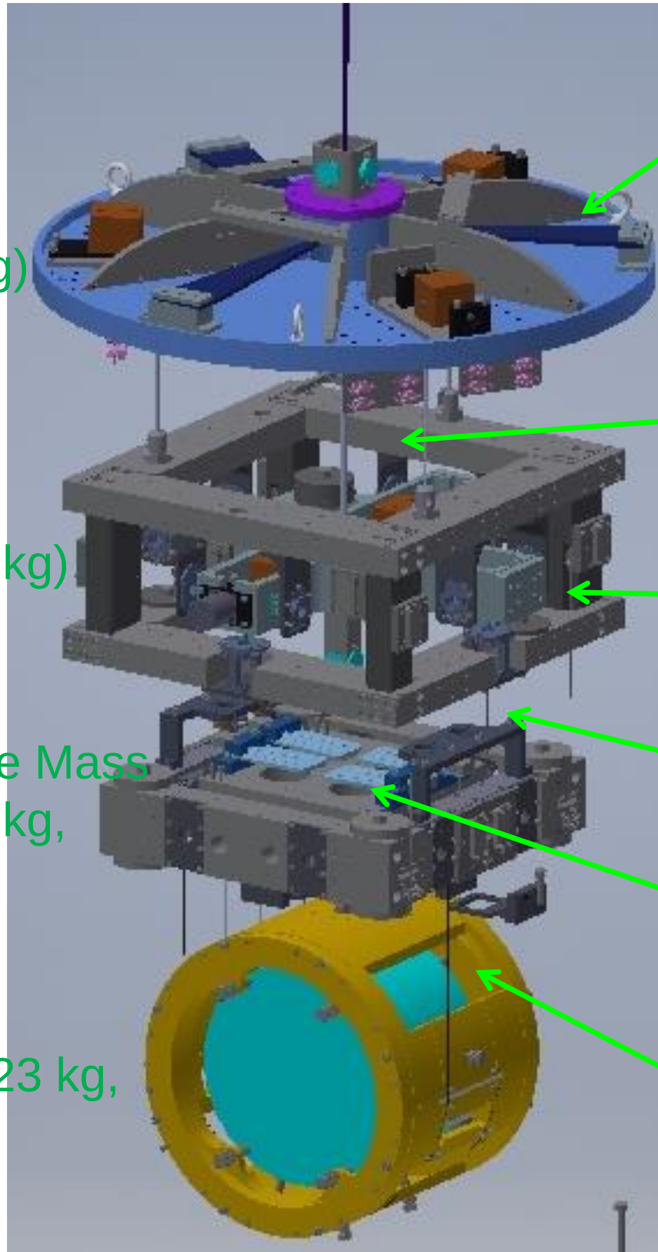
KAGRA Detailed Parameters

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)

3 CuBe blade springs

MN suspended by 1 Maraging steel fiber
(35 cm long, 2-7mm dia.)
MRM suspended by 3 CuBe fibers

Marionette
(SUS, 22.5 kg)

Heat link attached to MN

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

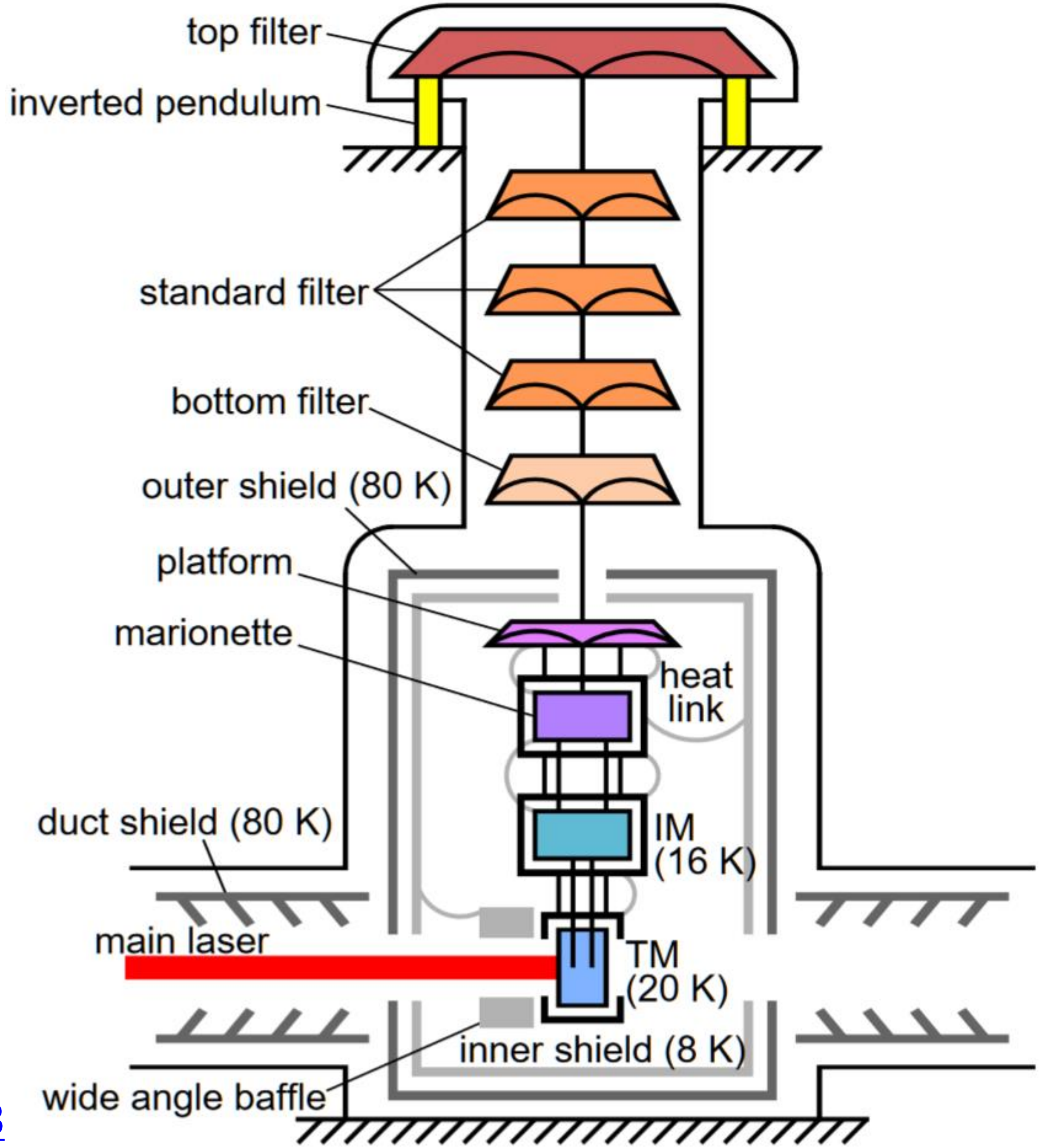
Intermediate Mass
(SUS, 20.1 kg,
16 K)

4 sapphire blades

Test Mass
(Sapphire, 23 kg,
22 K)

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

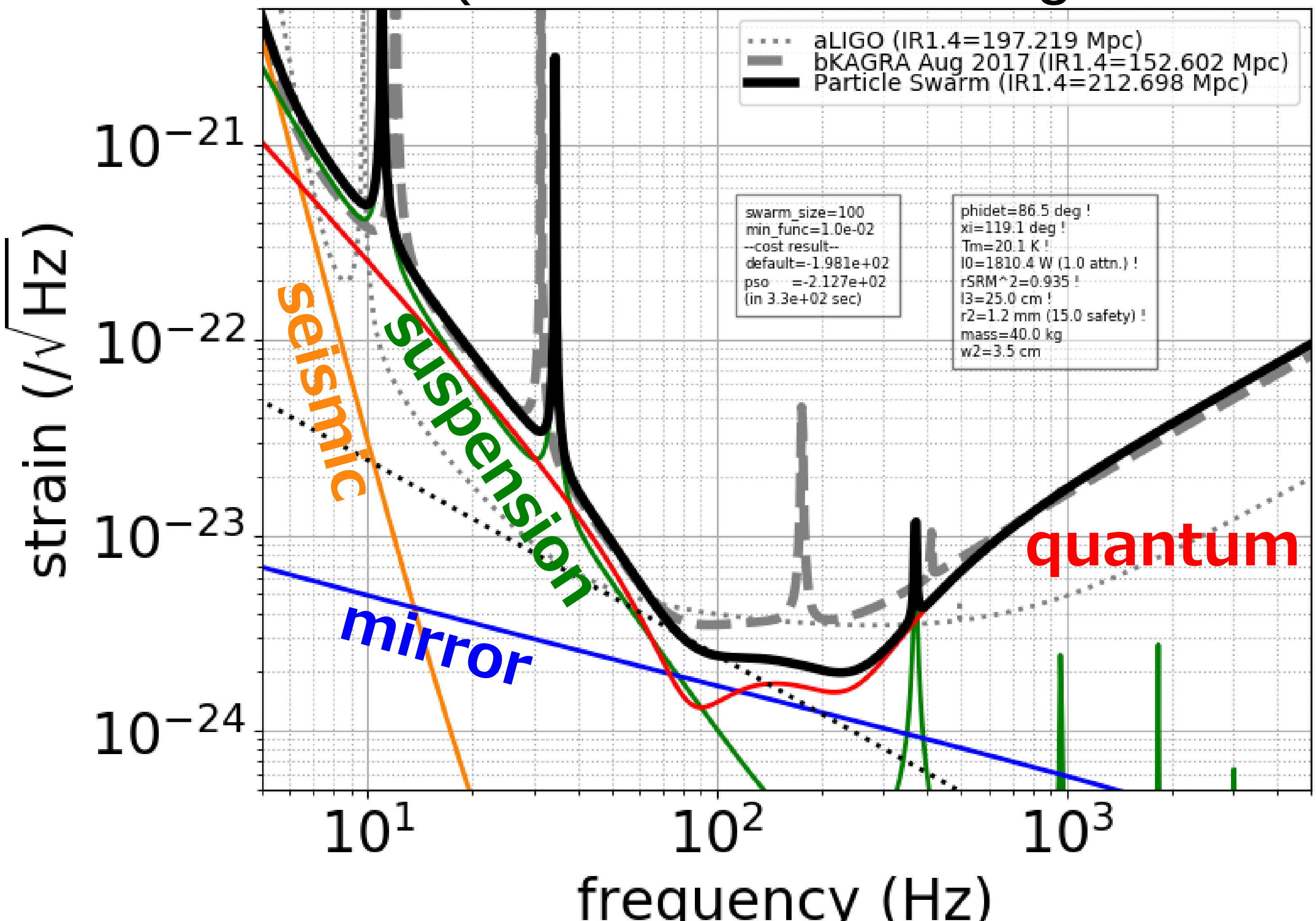
KAGRA Cryostat Schematic



arXiv:1710.04823

Plan A: 40 kg Mirror

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

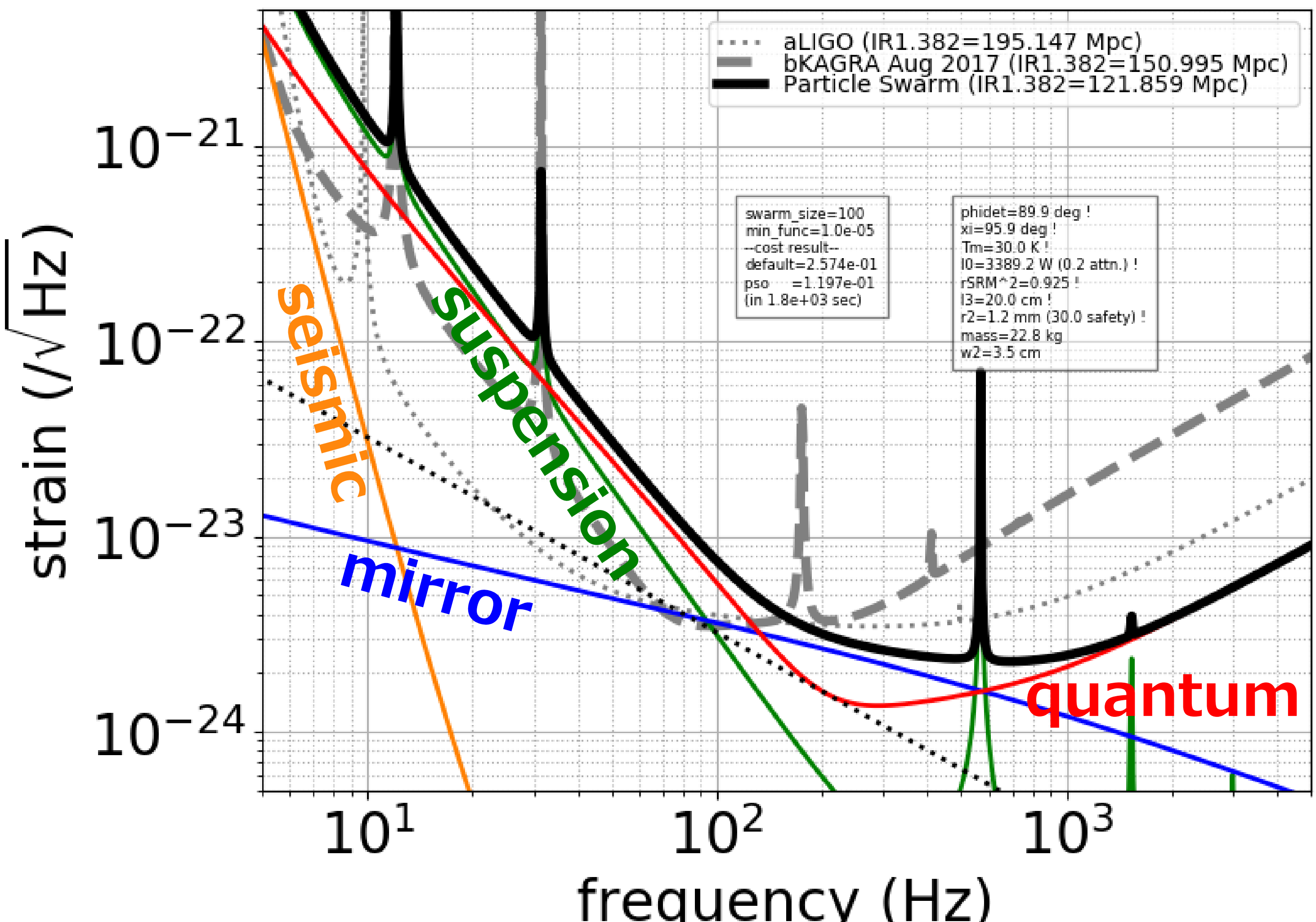


Good for mid frequency improvement → BNS range optimized

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

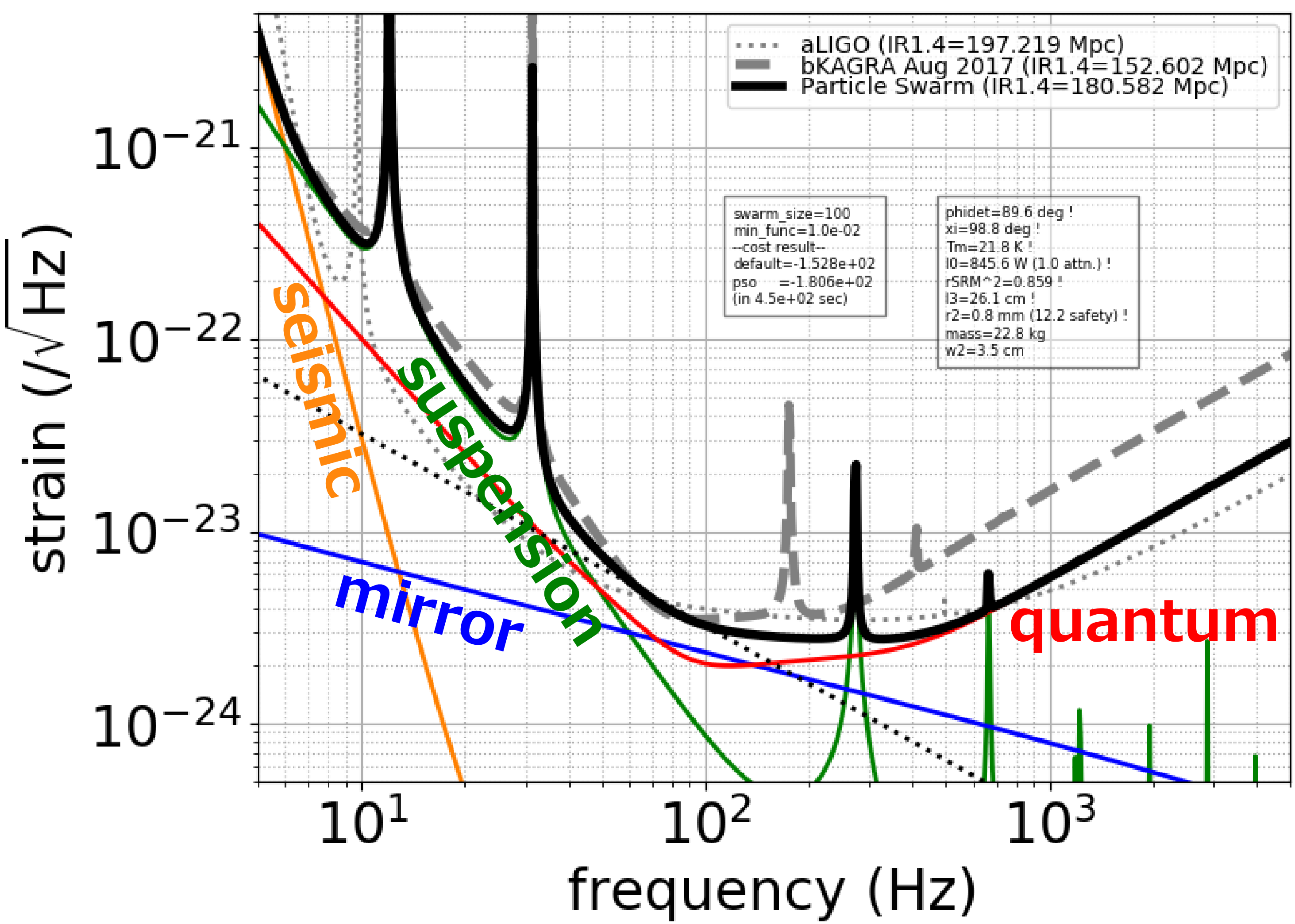


Good for high frequency improvement → BNS range optimized

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

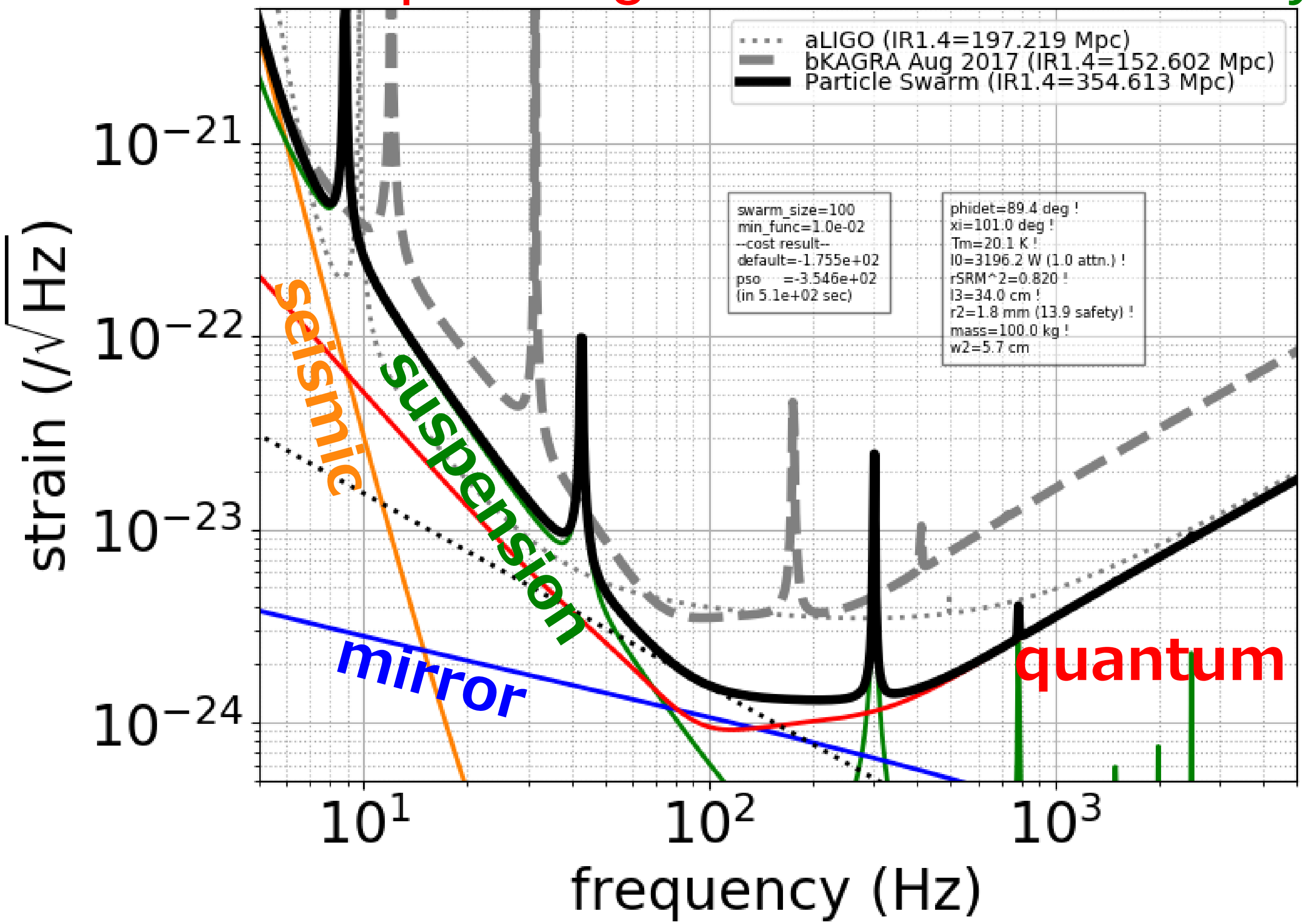


Broadband improvement → BNS range optimized

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

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